Thank you for having me

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MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

my talk

sebastian-achim.mueller@mpi-hd.mpg.de

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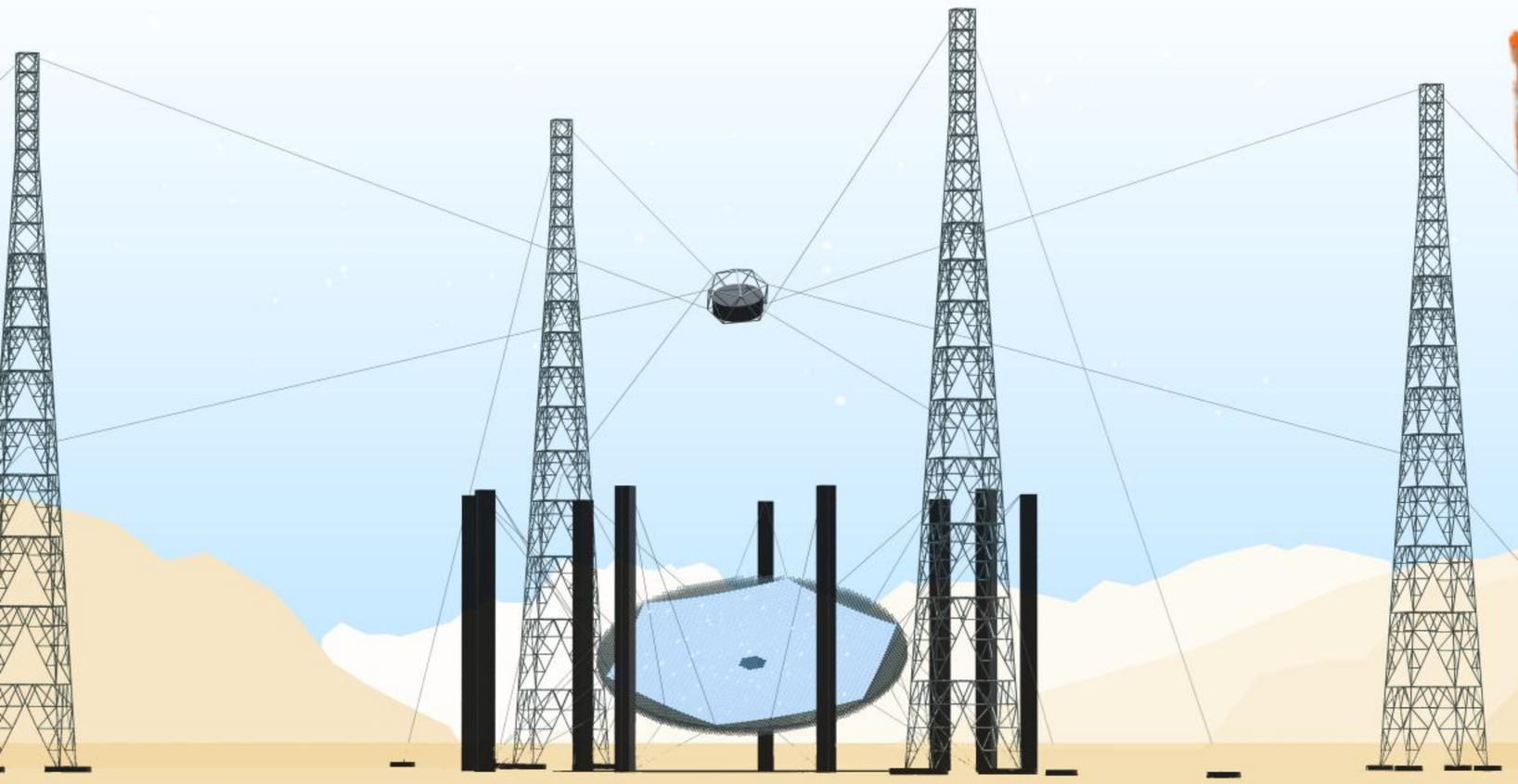
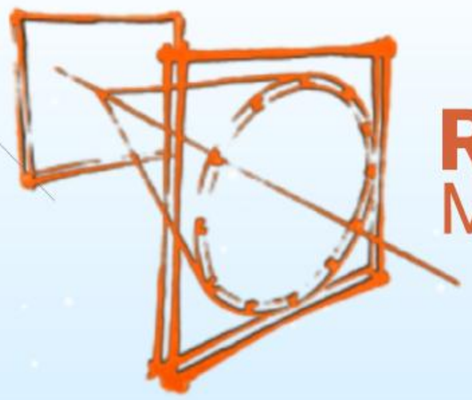
is about:





RICH 2025
Mainz

Overcoming the Limits of Cherenkov Telescopes

sebastian-achim.mueller@mpi-hd.mpg.de

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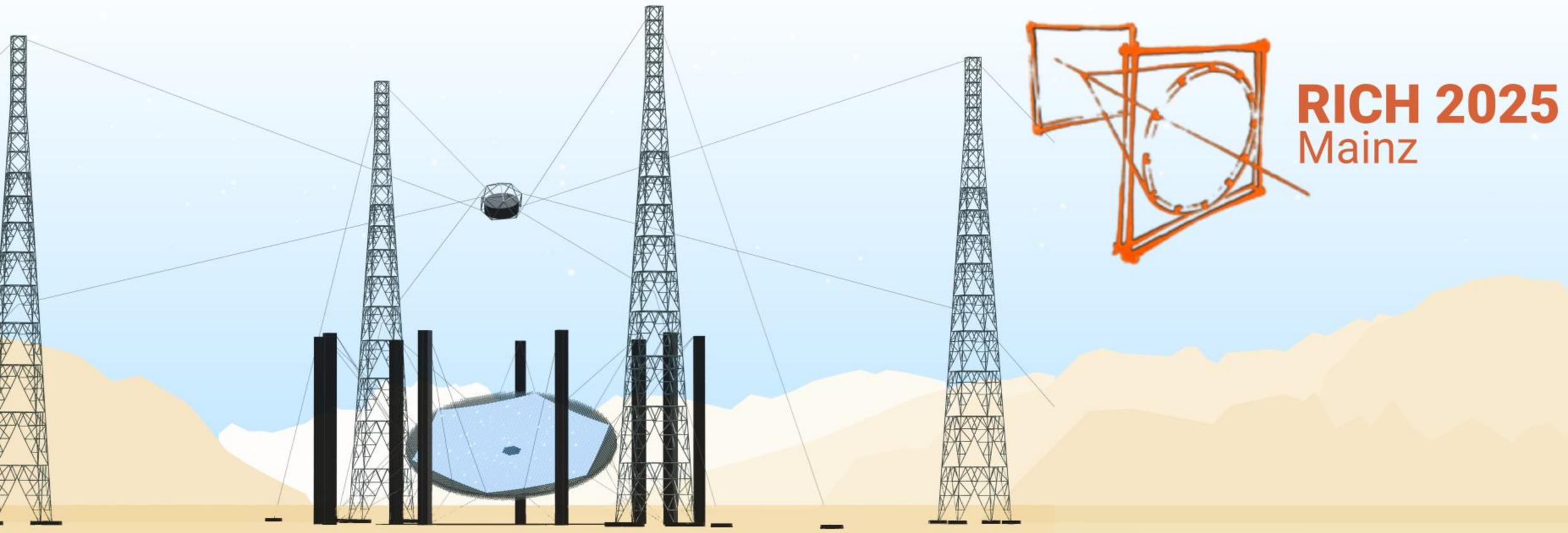
Overcoming the limits



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Overcoming the Limits of Cherenkov Telescopes

sebastian-achim.mueller@mpi-hd.mpg.de

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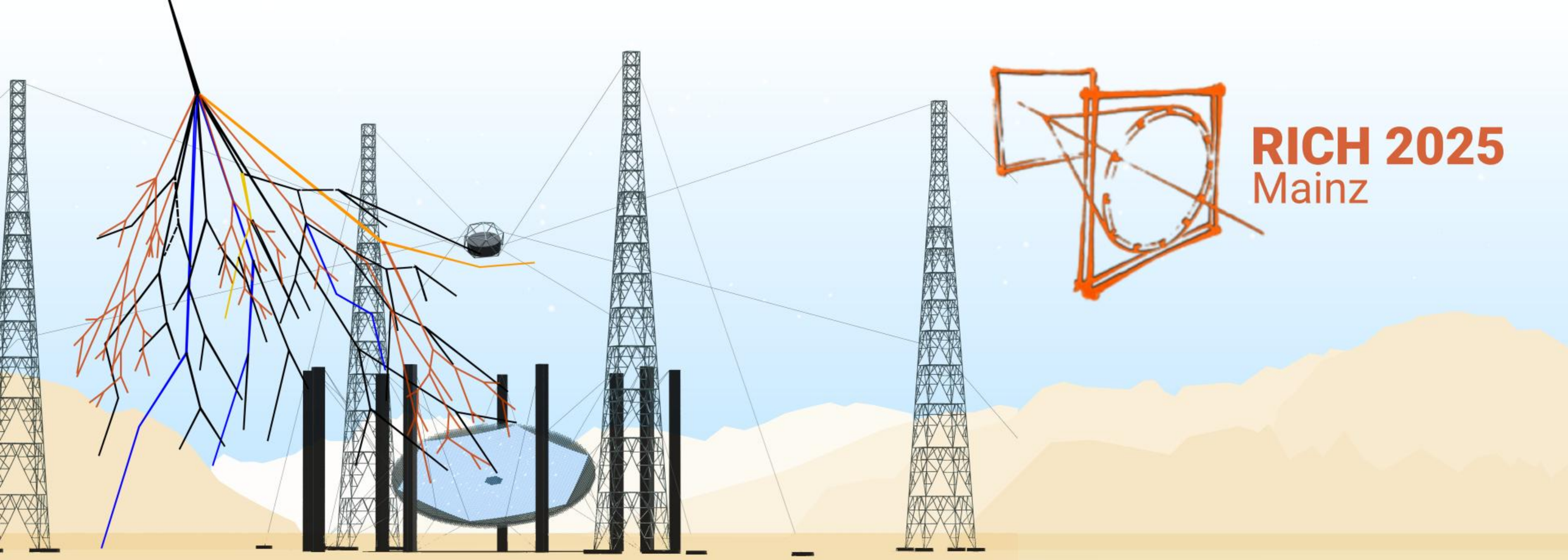
of Cherenkov telescopes



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Overcoming the Limits of Cherenkov Telescopes

Cherenkov Plenoscope

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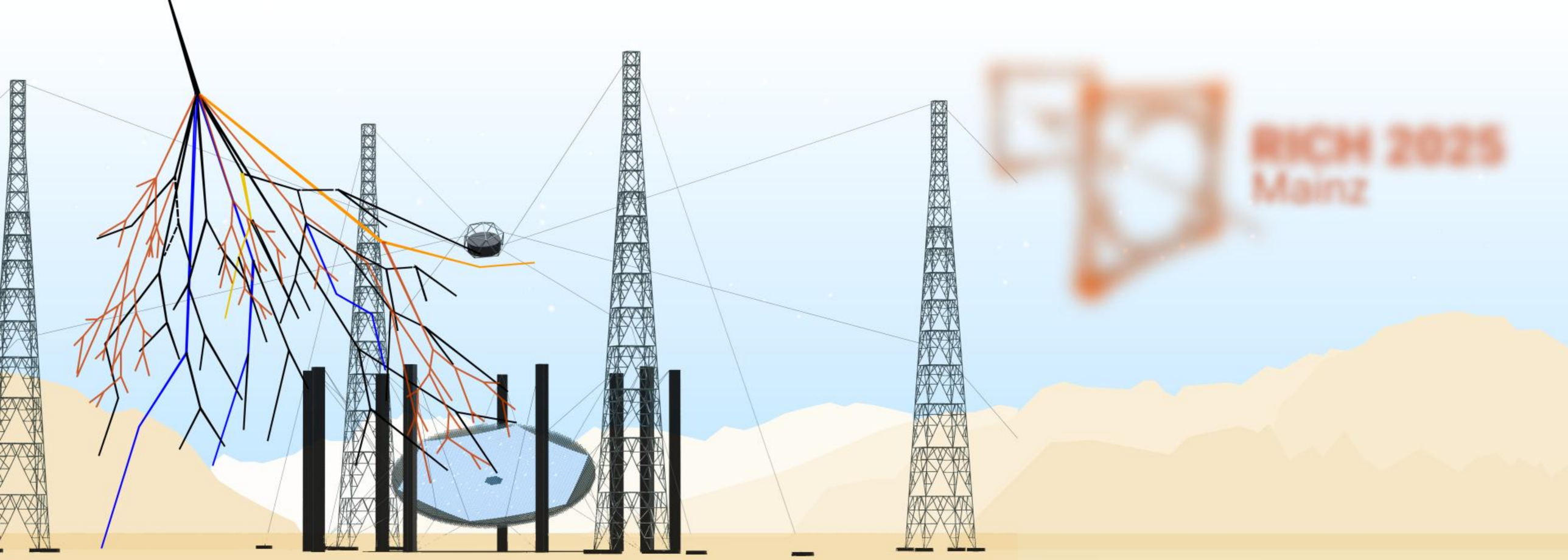
with the novel Cherenkov plenoscope



Overcoming the Limits of Cherenkov Telescopes

Cherenkov Plenoscope

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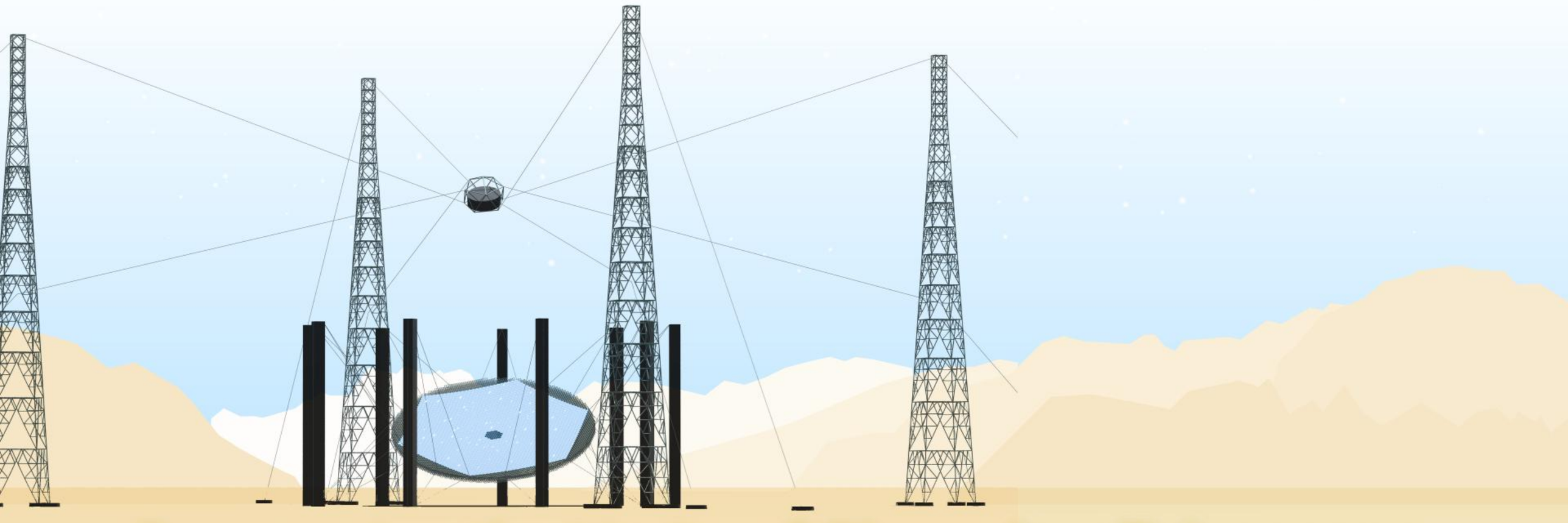
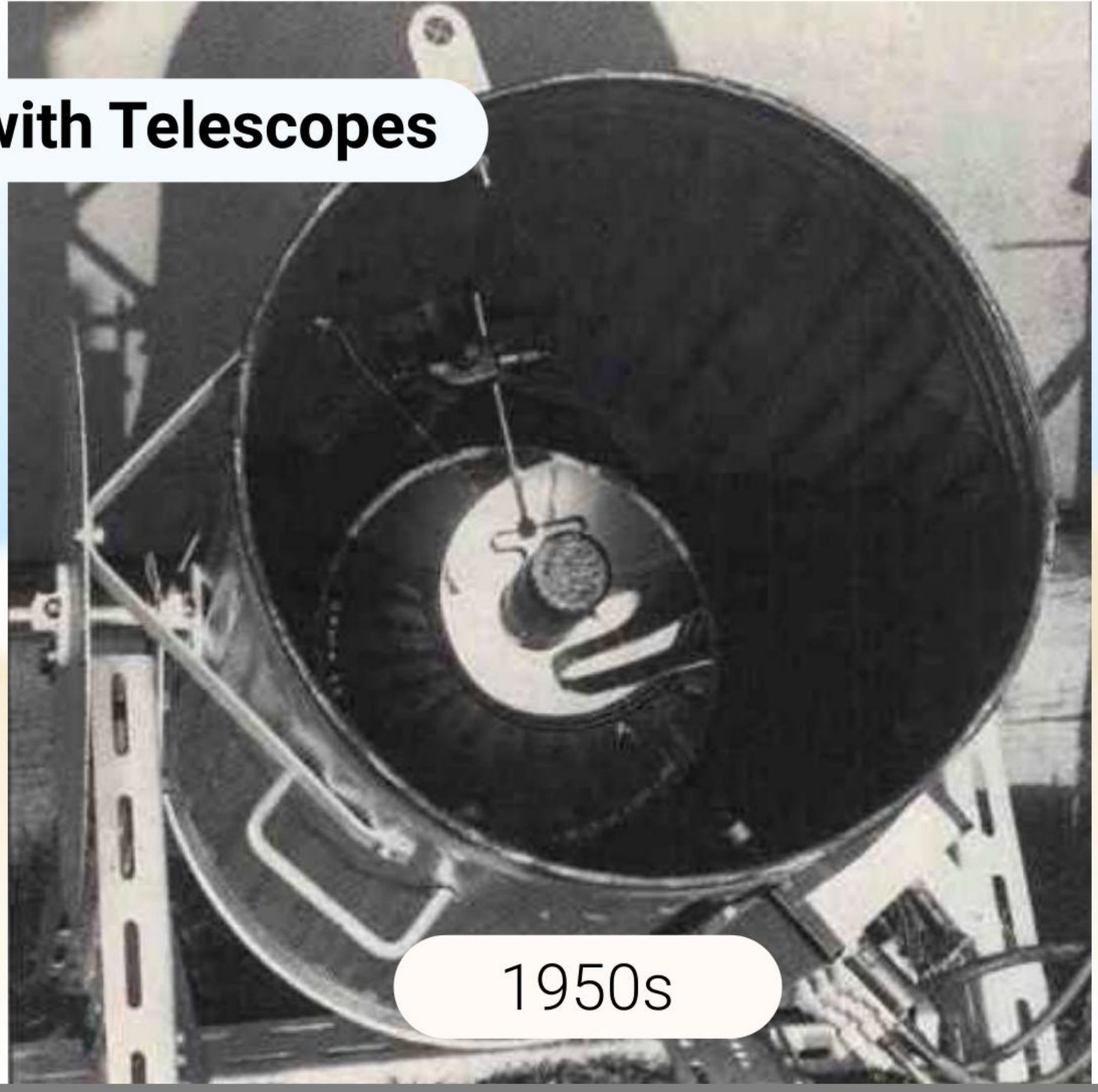


Cherenkov Plenoscope

RICH2025

Imaging with Telescopes

Imaging with Telescopes

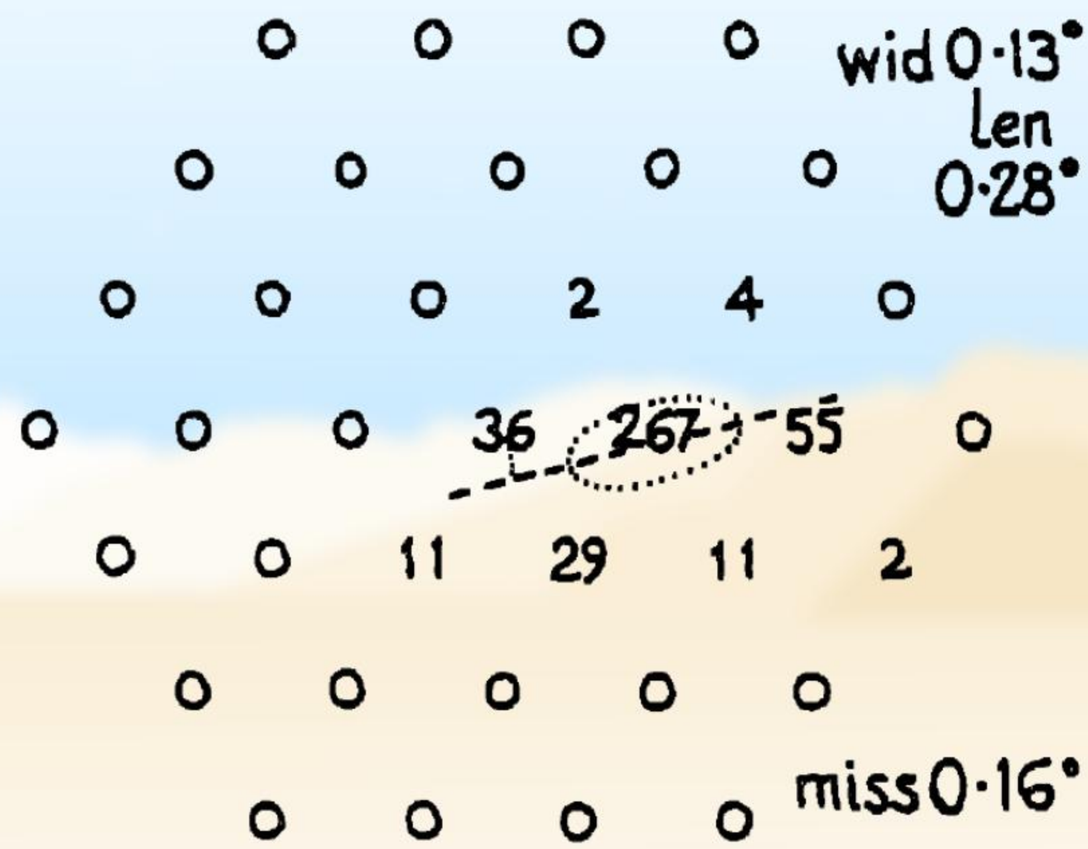


1950s

Galbraith, W., Jelley, J.V. 1953
Light Pulses from the Night Sky
associated with Cosmic Rays.
Nature 171: 349-350.

Since we discovered Cherenkov radiation from airshowers, we tried to use it for astronomy.

Imaging with Telescopes

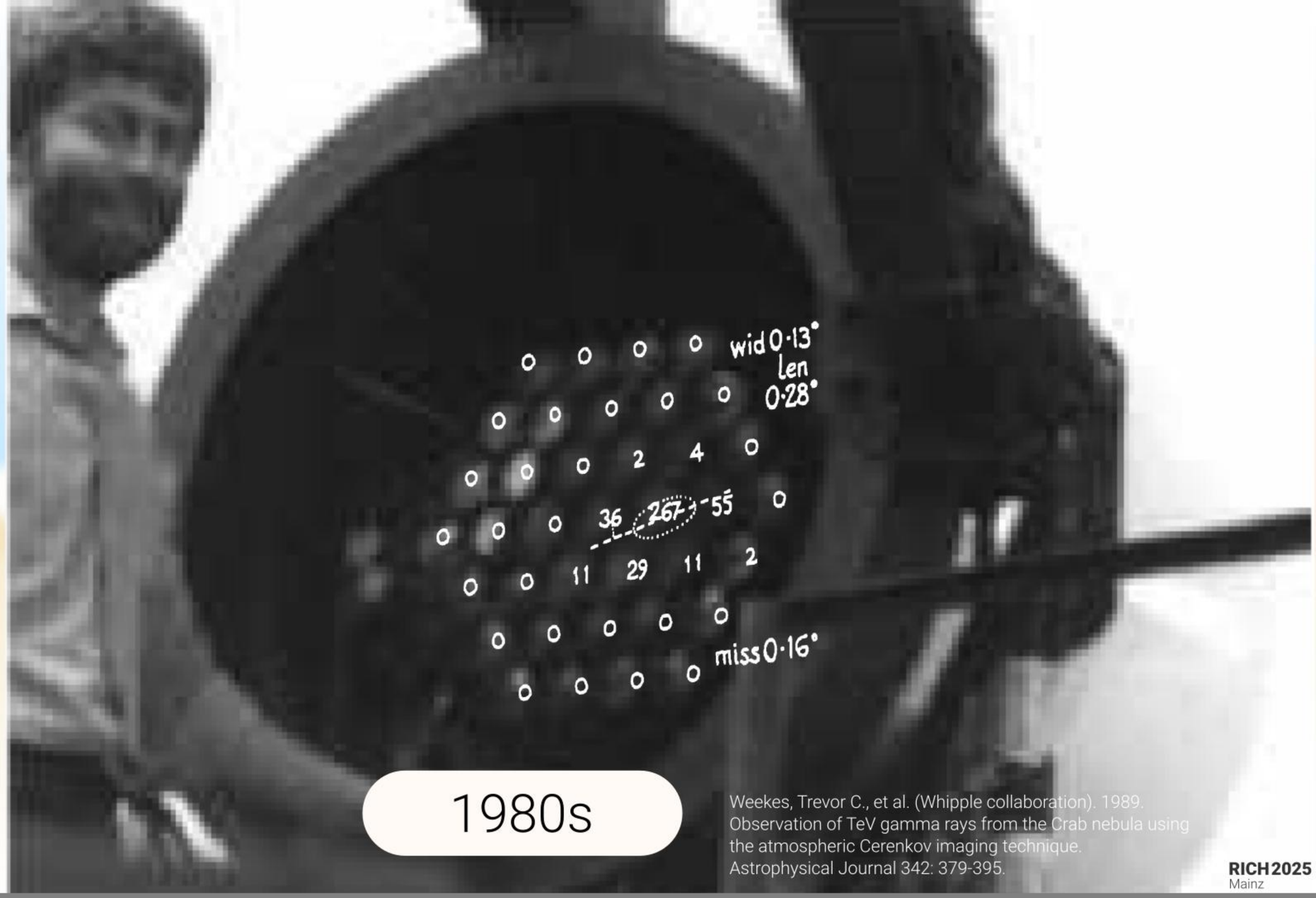


1980s

Michael A. Hillas, 1985
Cerenkov light images of EAS produced by primary gamma,
ICRC 1985, Vol.3

Notably Hillas, Weeks and friends started to think about imaging.

Imagine

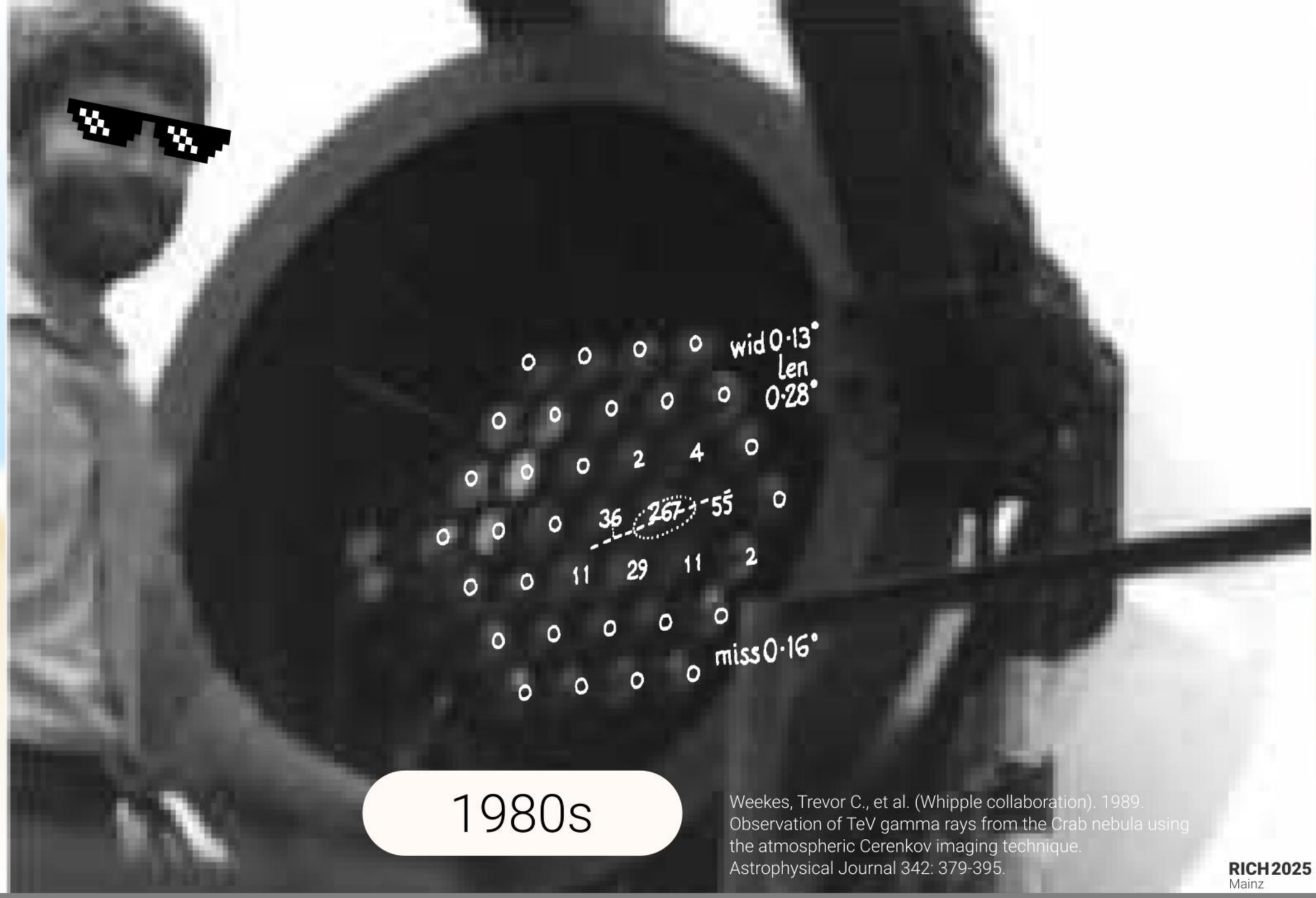


1980s

Weekes, Trevor C., et al. (Whipple collaboration). 1989. Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique. Astrophysical Journal 342: 379-395.

And imaging turned out to be a good idea.

Imagine



1980s

Weekes, Trevor C., et al. (Whipple collaboration). 1989. Observation of TeV gamma rays from the Crab nebula using the atmospheric Cerenkov imaging technique. Astrophysical Journal 342: 379-395.

In fact, imaging worked so well

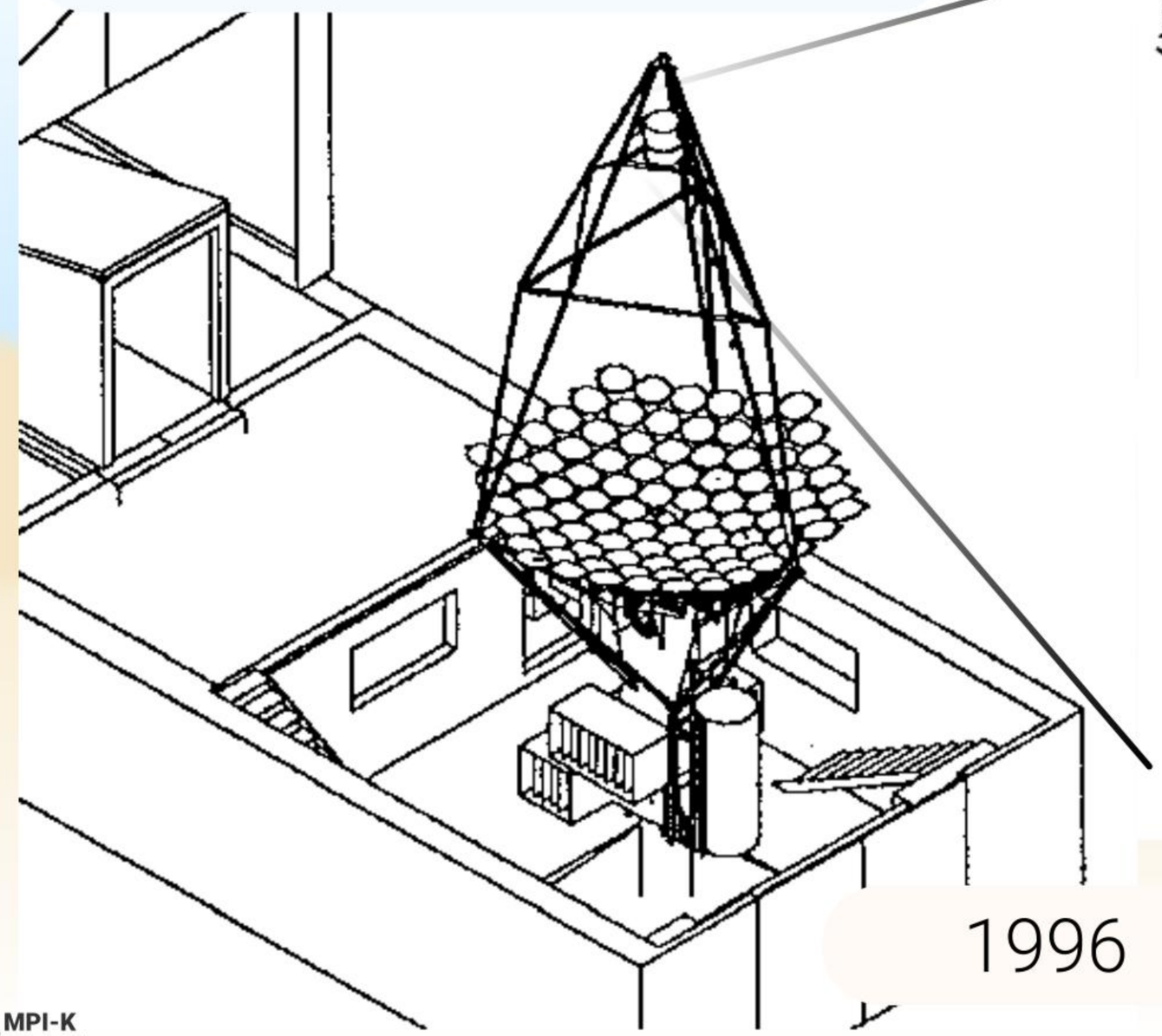
Imaging with Telescopes

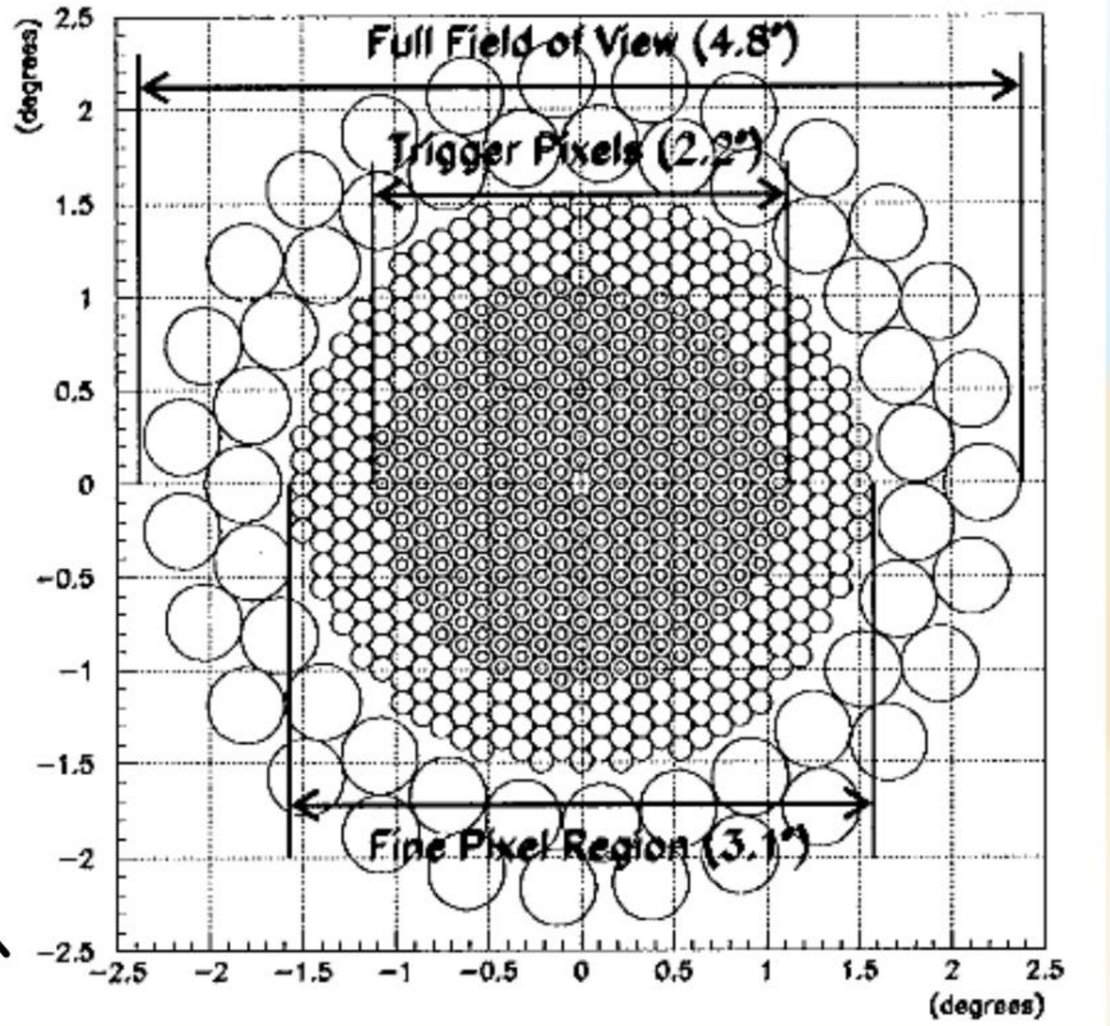
1992

Towards a major atmospheric Cherenkov detector for TeV astroparticle physics

that we all came together to rush 'Towards a mayor atmospheric Cherenkov detector for astroparticle physics'. From here on, we pushed on three key aspects in particular to lower the energy threshold and imporve the reconstruction power for cosmic gamma rays.

Imaging with Telescopes



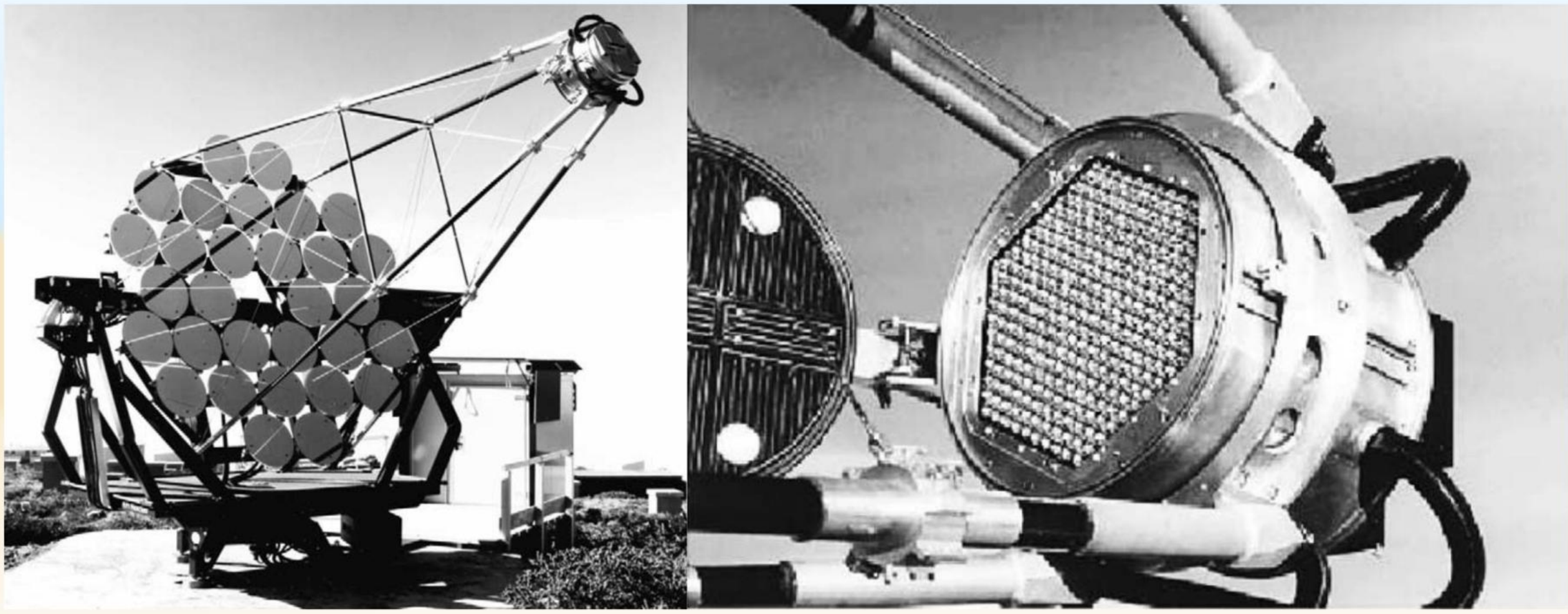


1996

Barrau A., Bazer-Bachi R., Beyer E. et al., 1998
The CAT imaging telescope for very-high-energy gamma-ray astronomy
Nuclear Instruments and Methods Vol.416 II p.278-292

This is: Finer pixelation.

Imaging with Telescopes

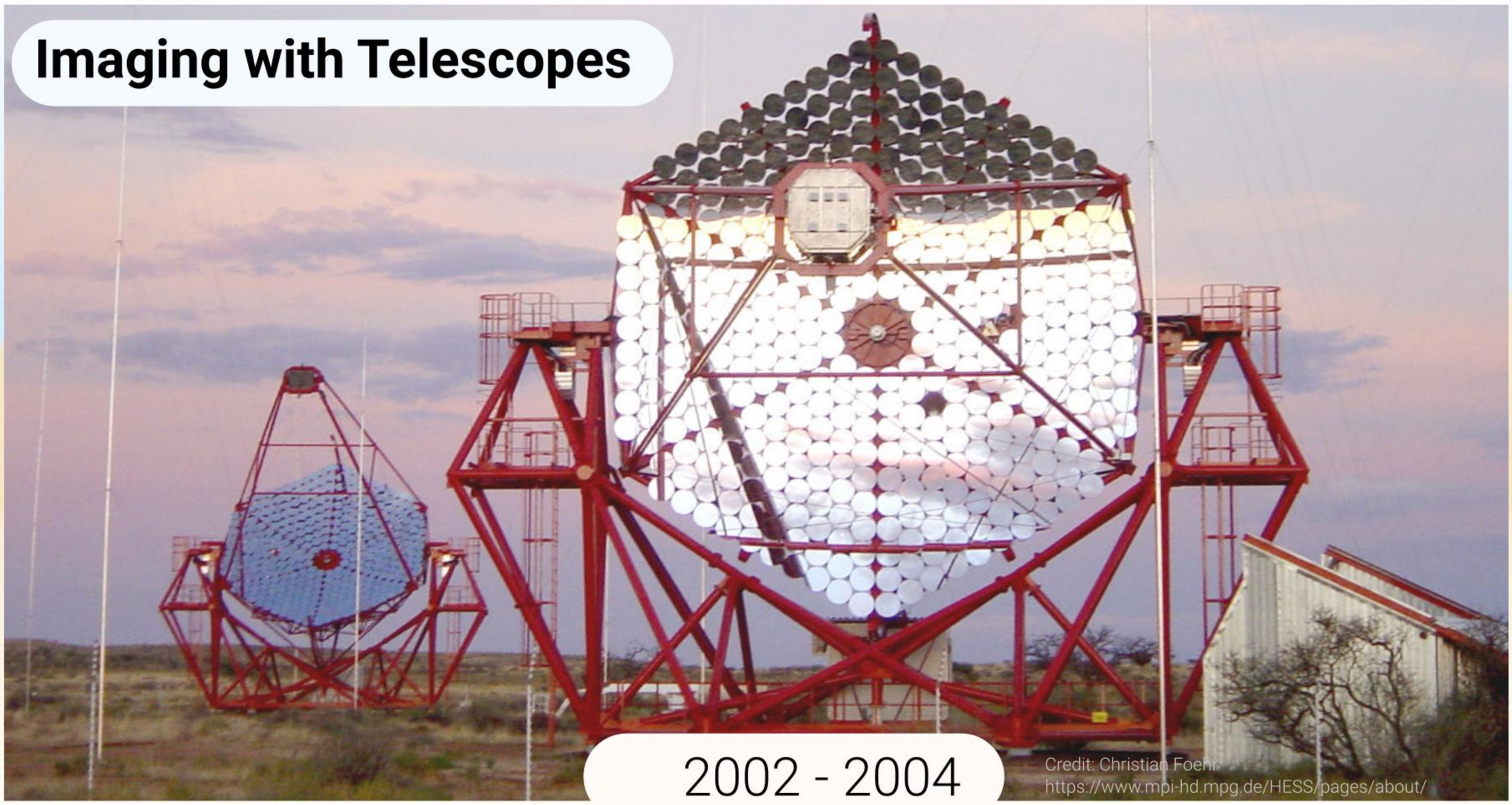


1997

Puehlhofer, G. and Bolz, O. and Goetting, N., 2003
The technical performance of the HEGRA system of imaging air Cherenkov telescopes
Astroparticle Physics, Vol.20 III, p267-291

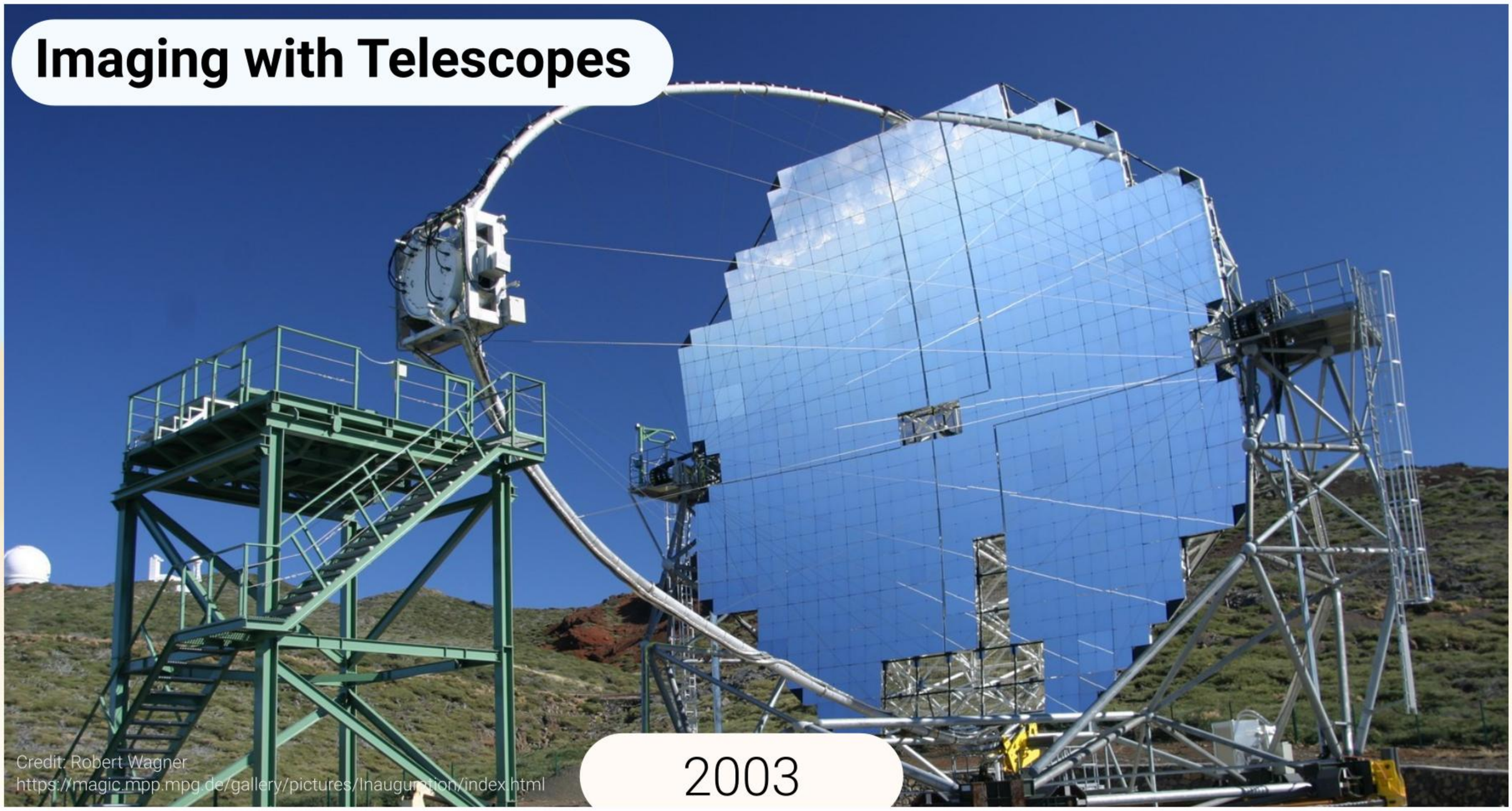
Finer pixelation and moving up onto mountains.

Imaging with Telescopes



Larger mirrors and moving up into the highlands.

Imaging with Telescopes

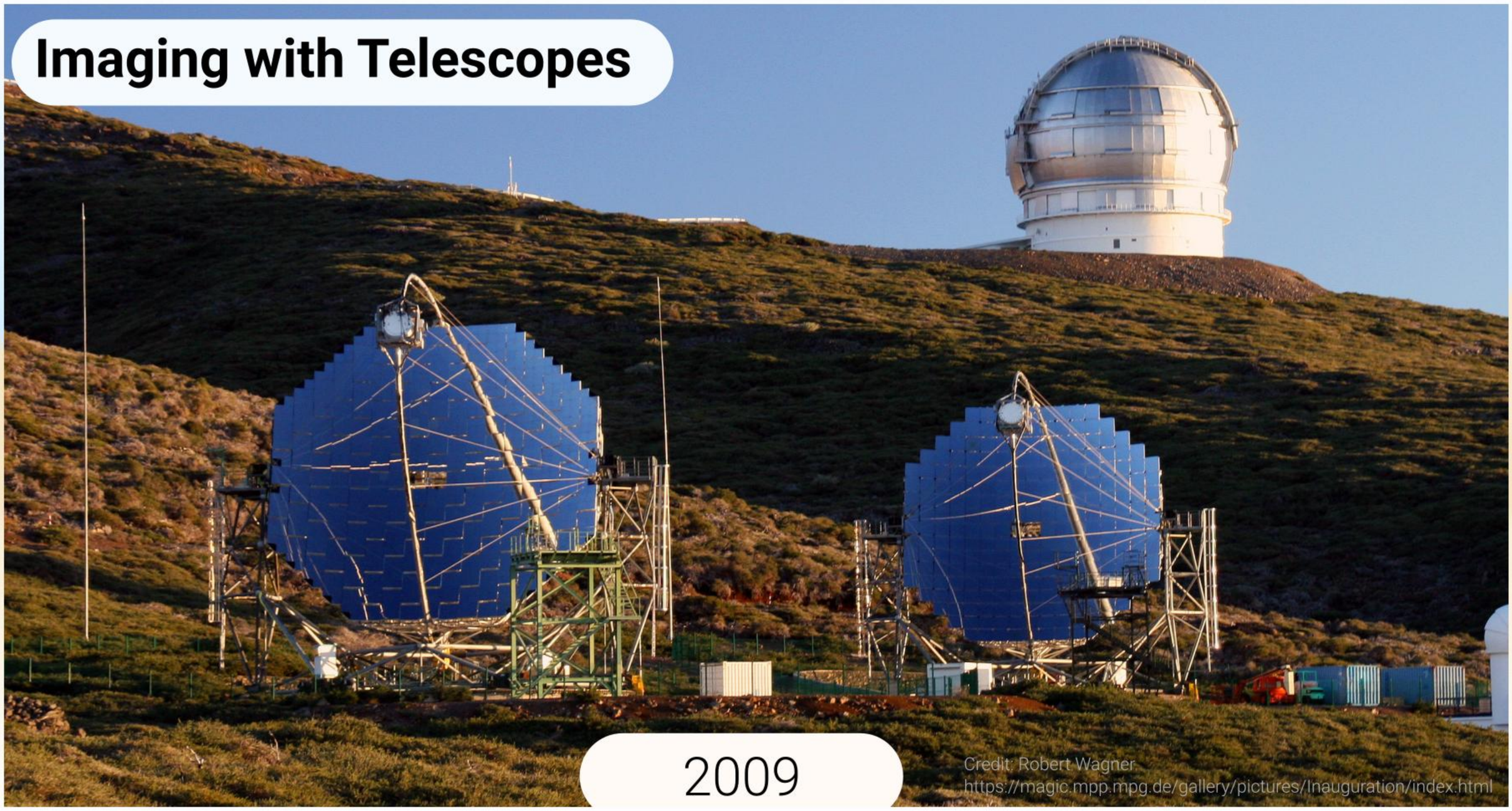


Credit: Robert Wagner
https://magic.mpp.mpg.de/gallery/pictures/Inauguration/index.html

2003

Larger mirrors ...

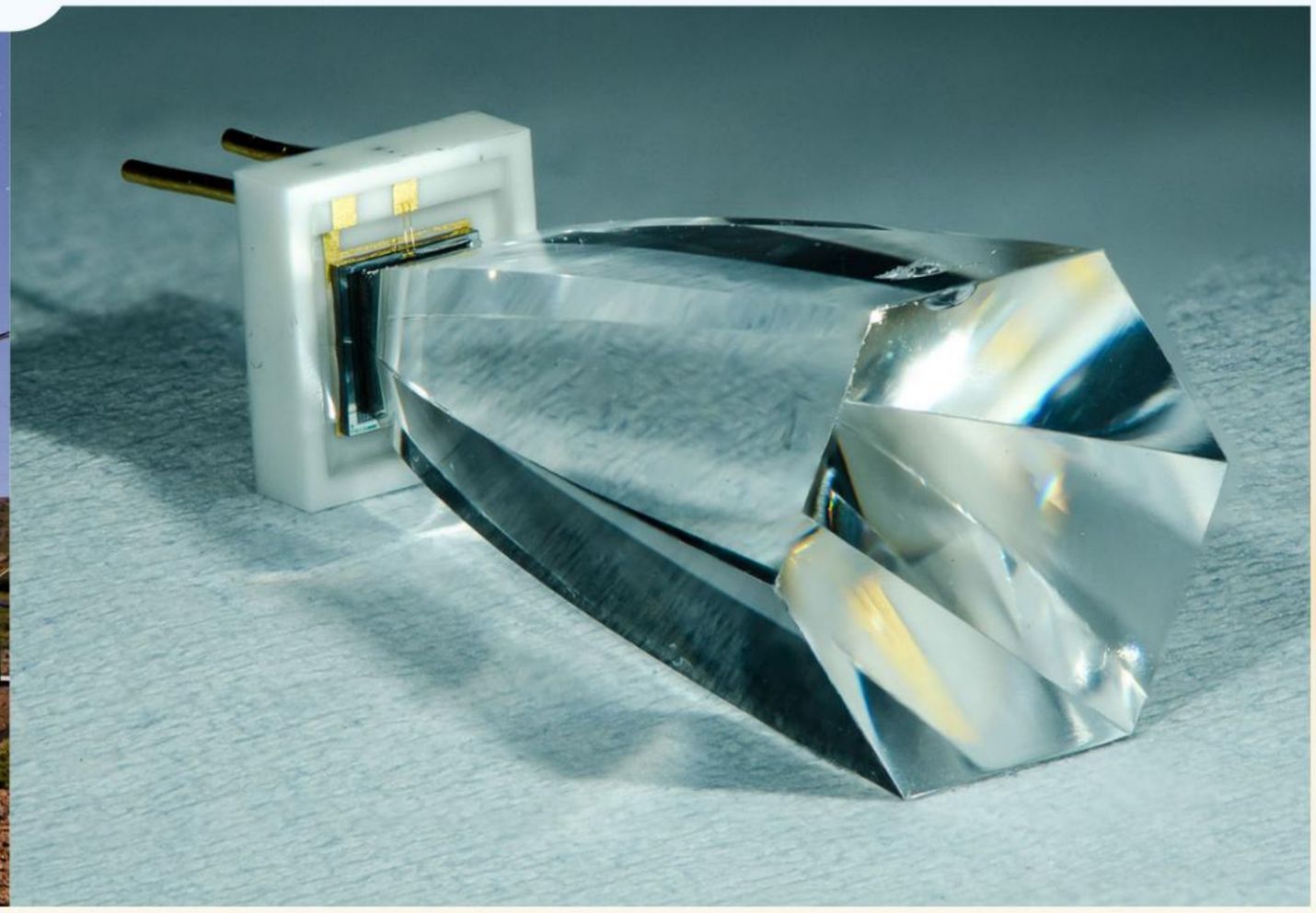
Imaging with Telescopes



... and finer pixelation.

Imaging with Telescopes

Credit: Jens B. Buss

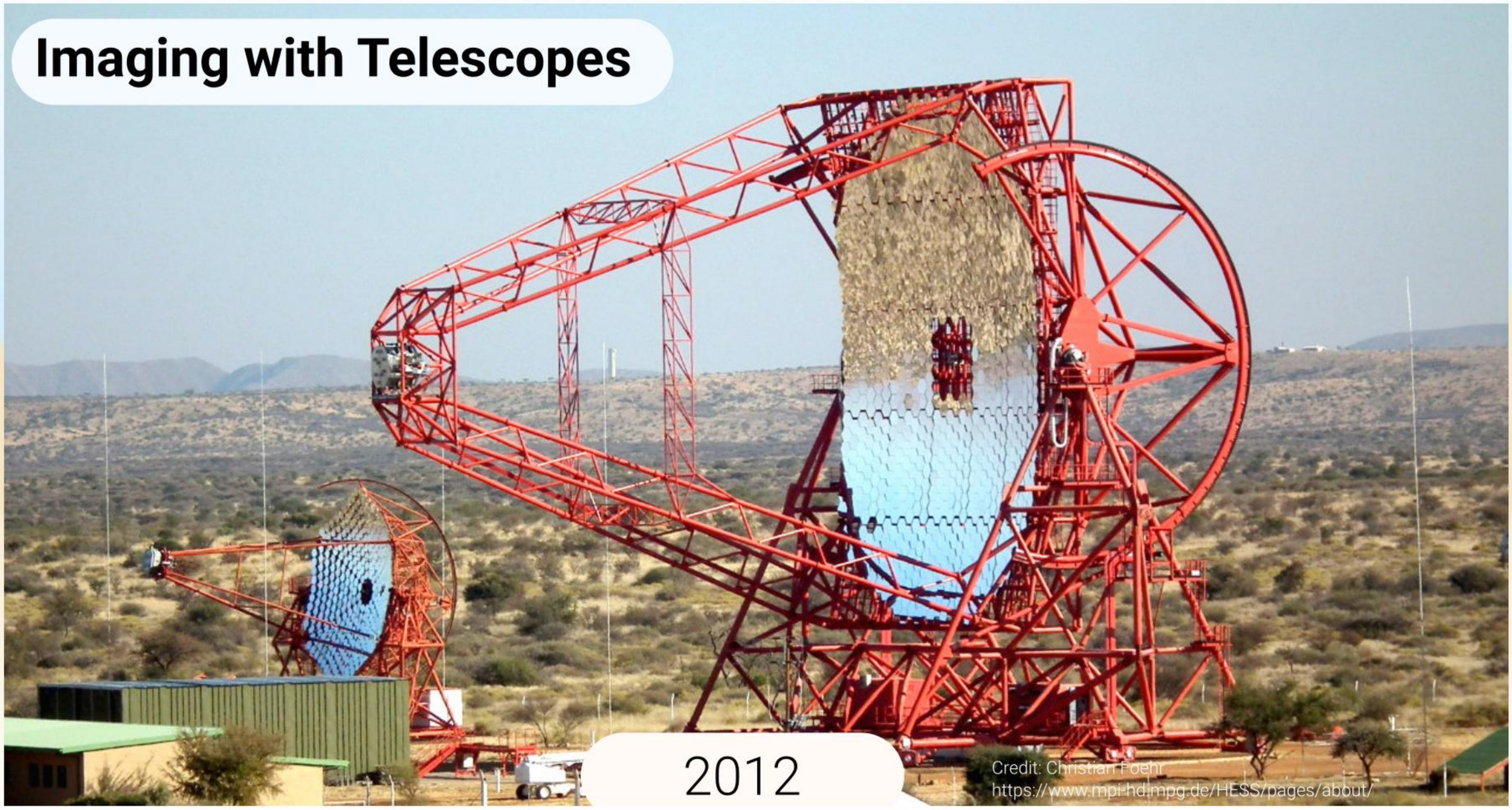


Credit: Thomas Kraehenbuehl

2011

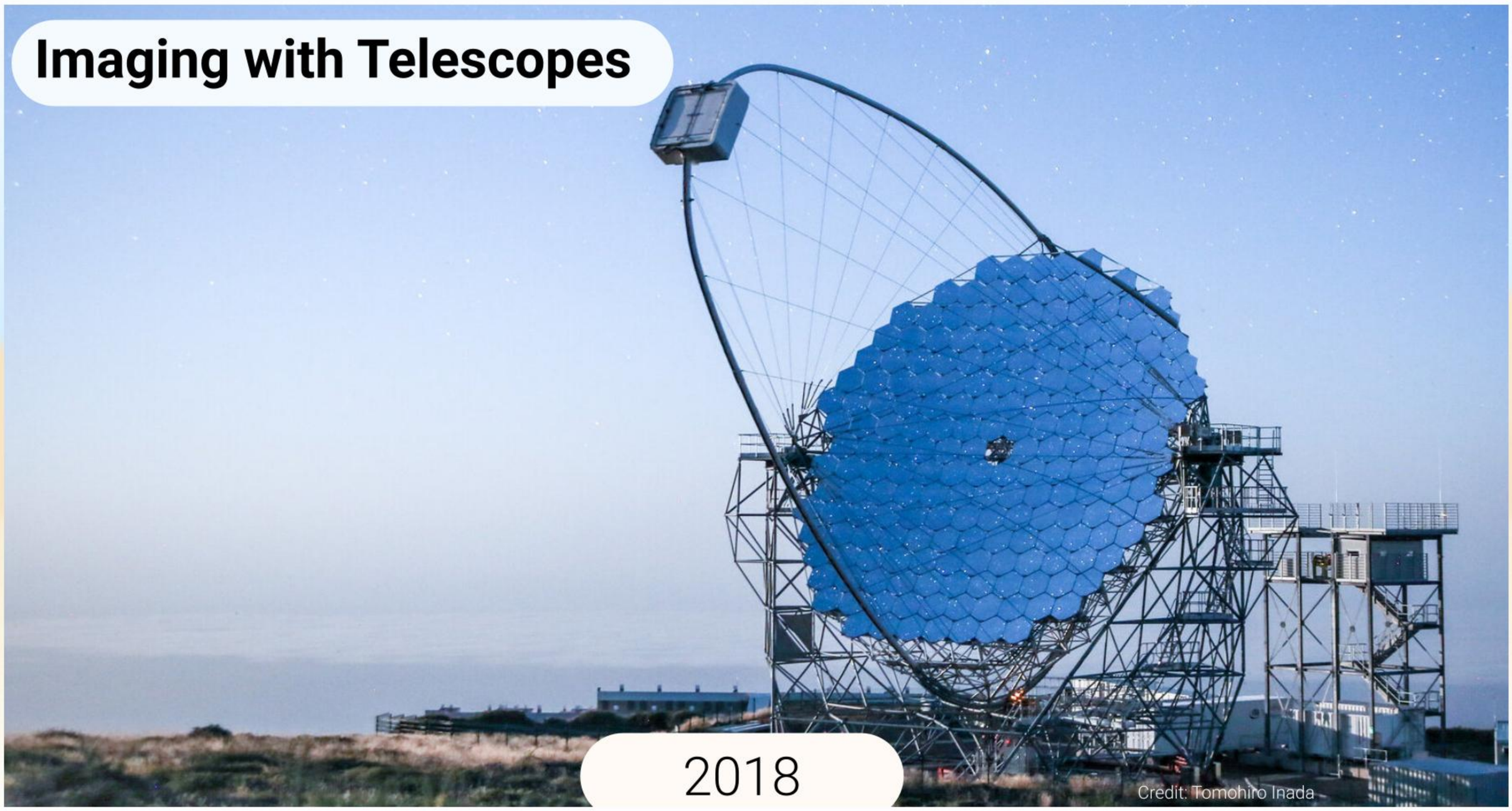
Finer pixelation.

Imaging with Telescopes



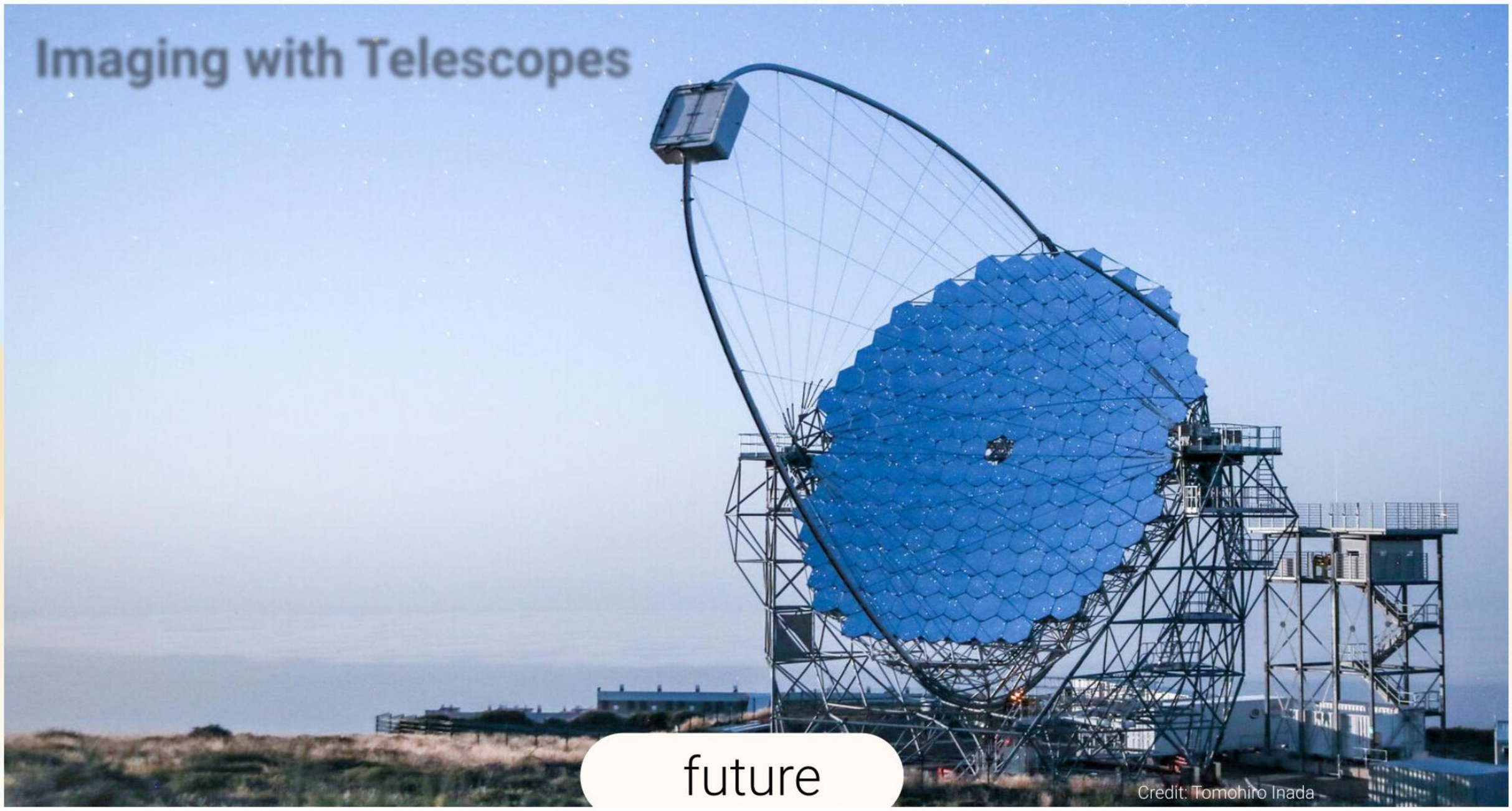
Larger mirrors and finer pixelation.

Imaging with Telescopes



Imaging with Cherenkov telescopes has come a long way.

Imaging with Telescopes



But now that we have entered the latest, and truely amazing, generation of telescopes ...

Limits of Telescopes

... the physical limits of imaging with telescopes start to show.

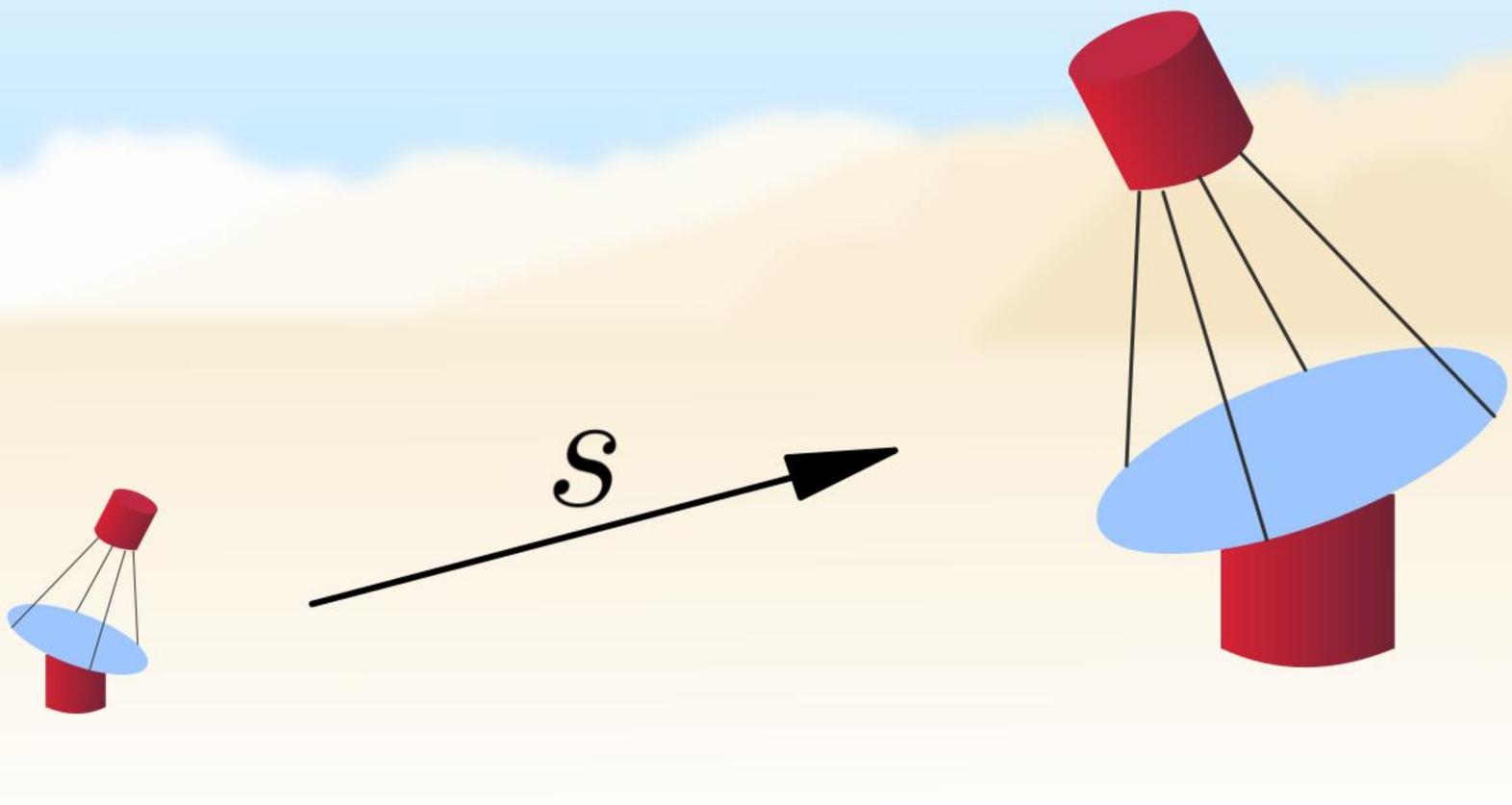
Limits of Telescopes

square-cube-law

The square-cube-law makes it increasingly difficult to build...

Limits of Telescopes

square-cube-law

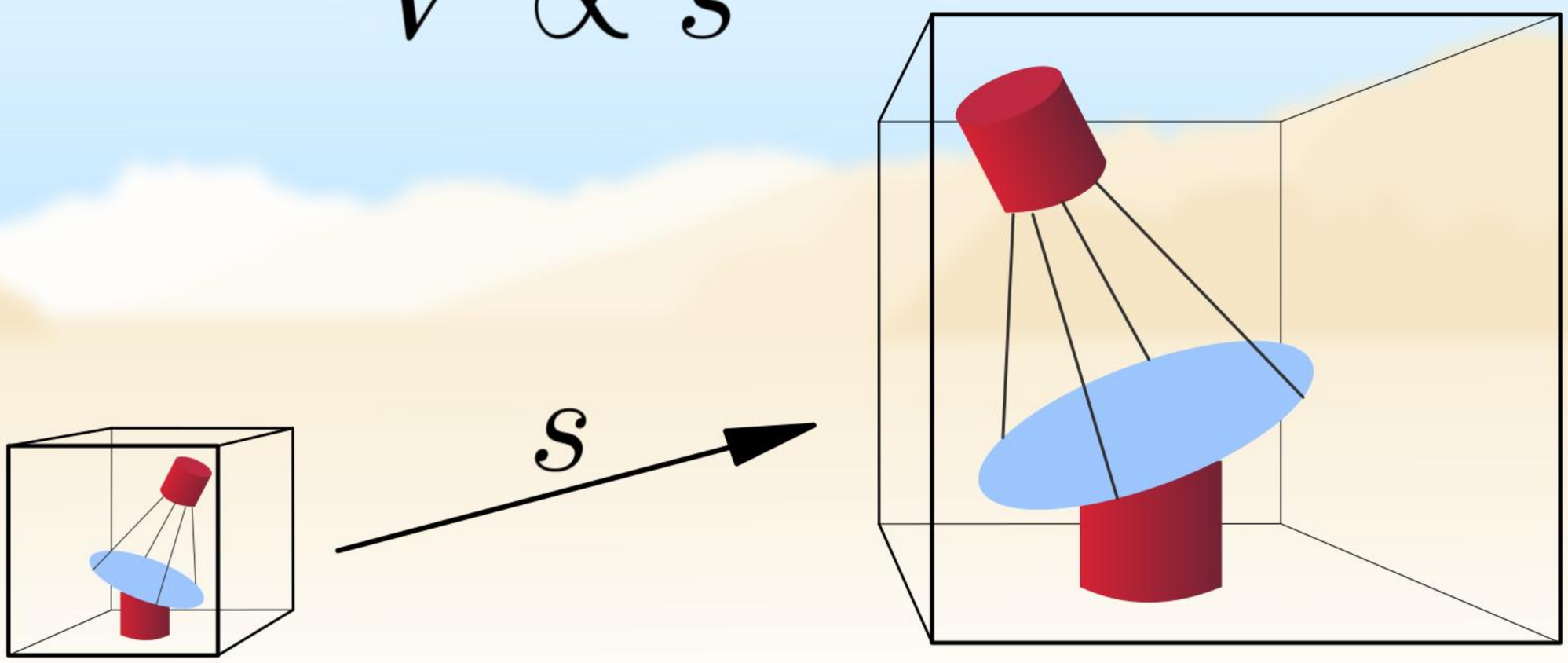


ever larger telescopes because

Limits of Telescopes

square-cube-law

$$V \propto s^3$$

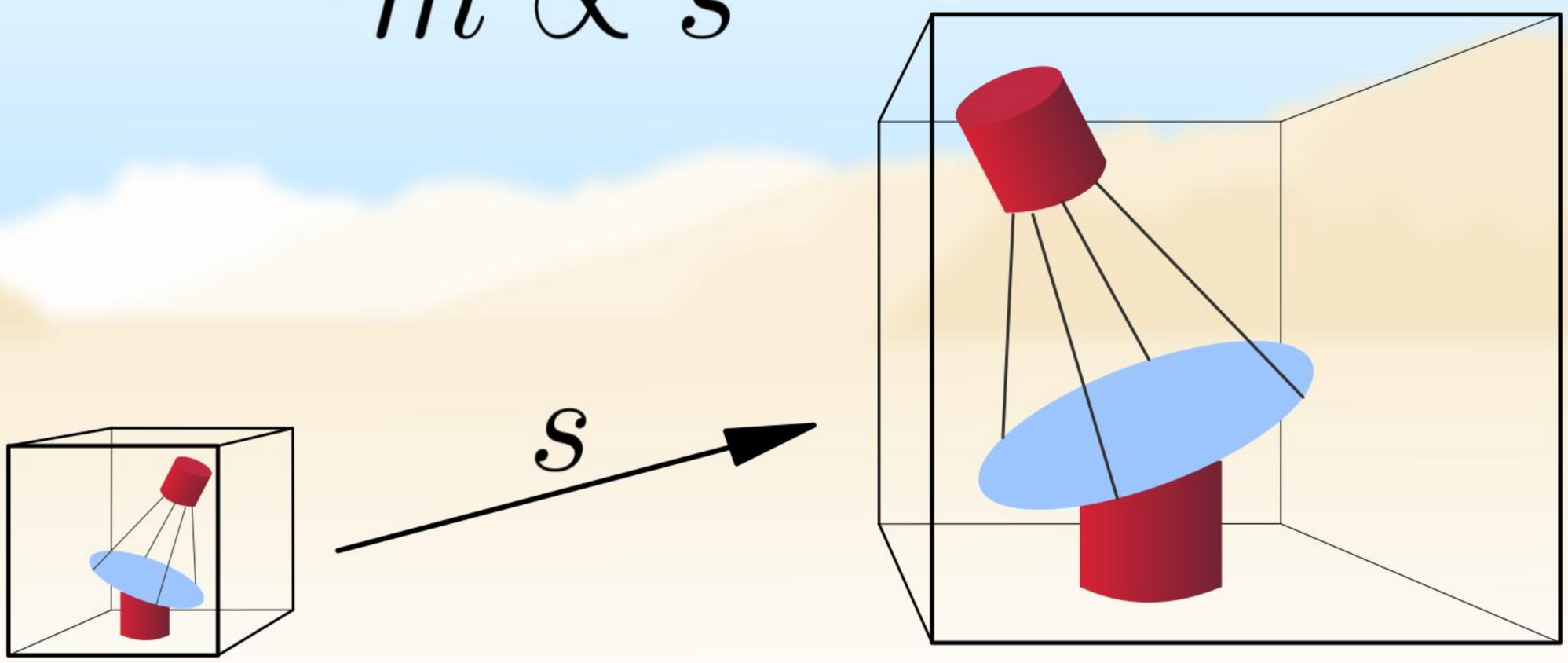


the volume

Limits of Telescopes

square-cube-law

$$m \propto s^3$$

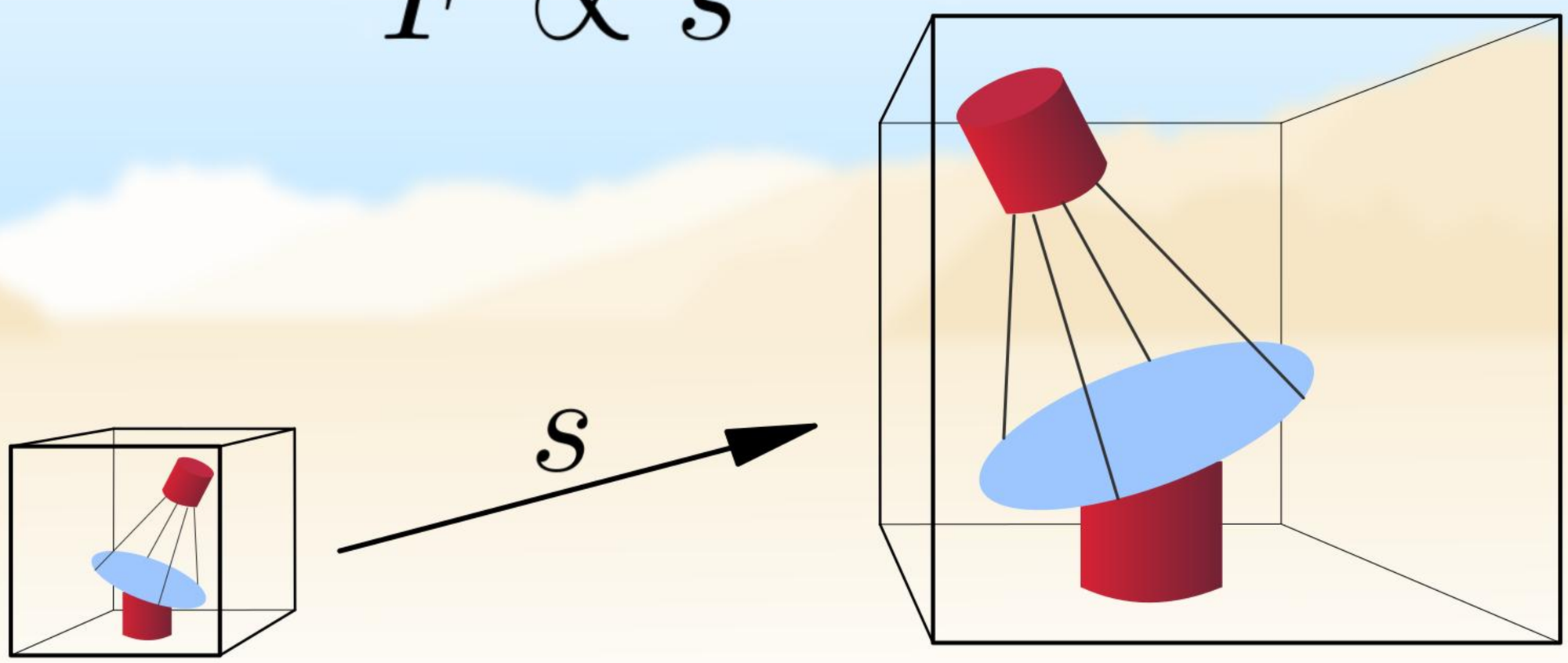


and thus the mass

Limits of Telescopes

square-cube-law

$$F \propto s^3$$



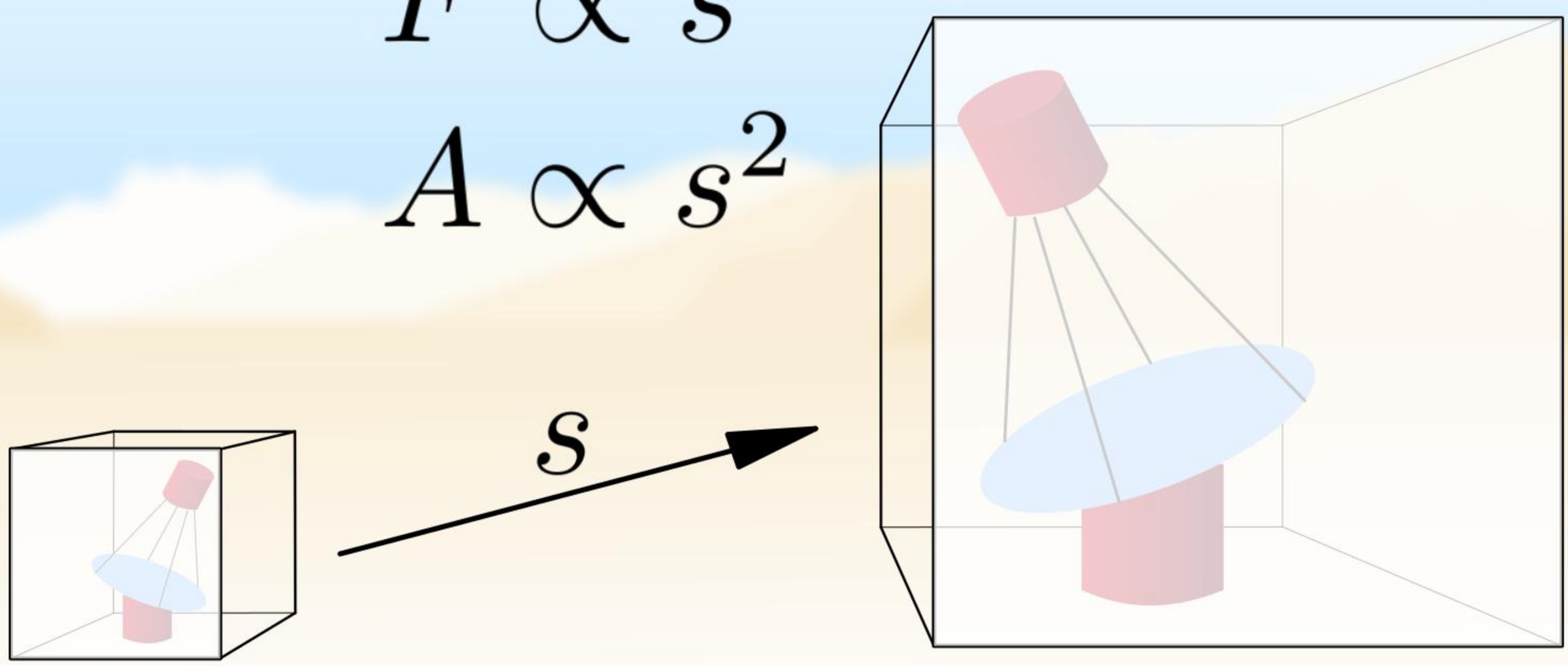
and thus the gravitational forces scale cubic.

Limits of Telescopes

square-cube-law

$$F \propto s^3$$

$$A \propto s^2$$



whereas the areas which have to tolerate these forces only scale quadratic.
While the square-cube-law can be postponed by spending more resources and engineering

Limits of Telescopes

depth-of-field

the physical limit of a narrowing depth-of-field can not. It turns out that the three key measures we pushed on to lower the energy threshold and improve the reconstruction power, this is ...

Limits of Telescopes

depth-of-field

larger (D, f)

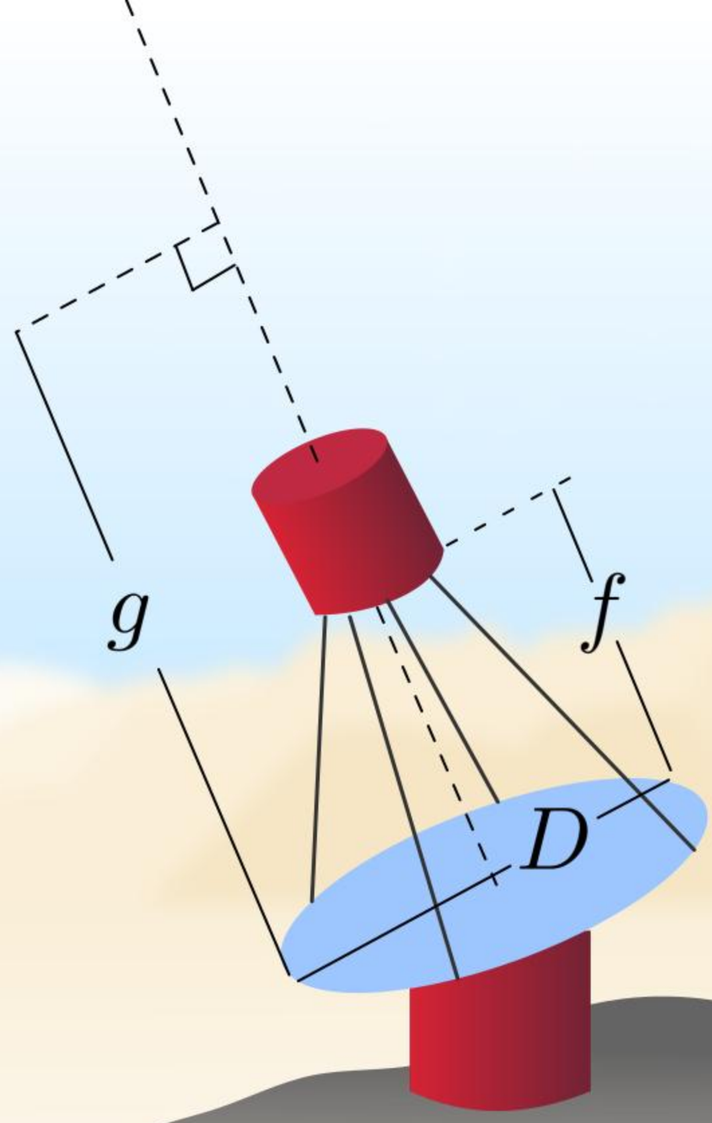
larger mirrors

Limits of Telescopes

depth-of-field

larger (D, f)

on mountains, closer to shower (g)



moving up onto mountains

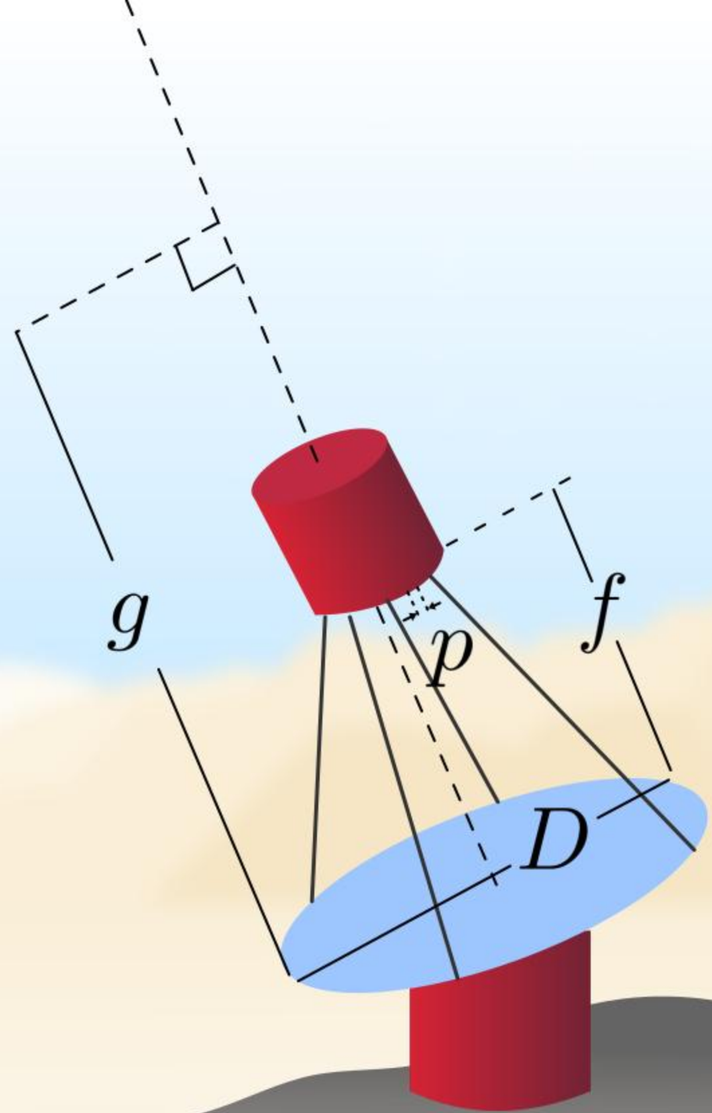
Limits of Telescopes

depth-of-field

larger (D, f)

on mountains, closer to shower (g)

finer pixelation (p)



and finer pixelation

Limits of Telescopes

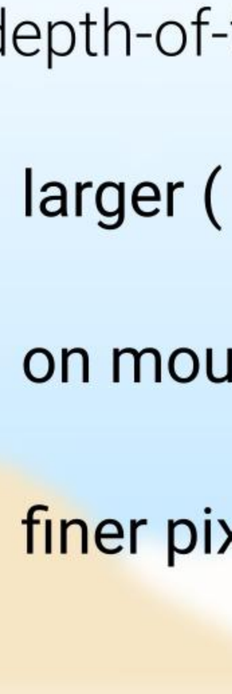
depth-of-field

larger (D, f)

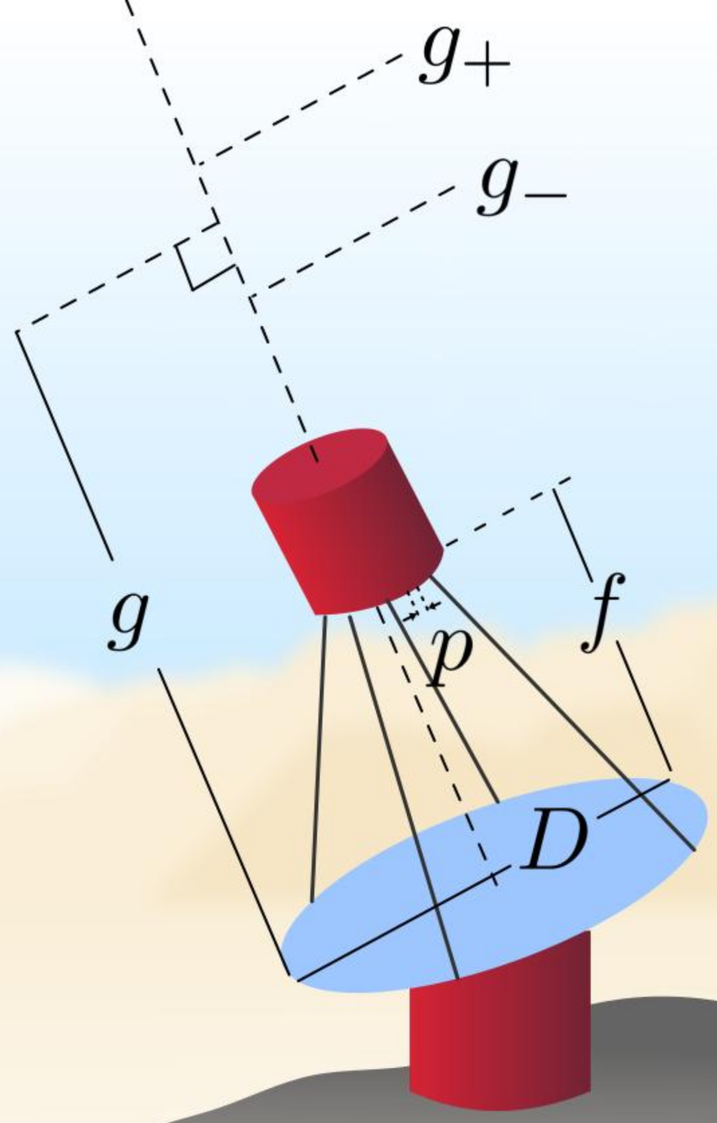
on mountains, closer to shower (g)

finer pixelation (p)

$$g_{\pm} = g(1 \pm pg/(2fD))$$



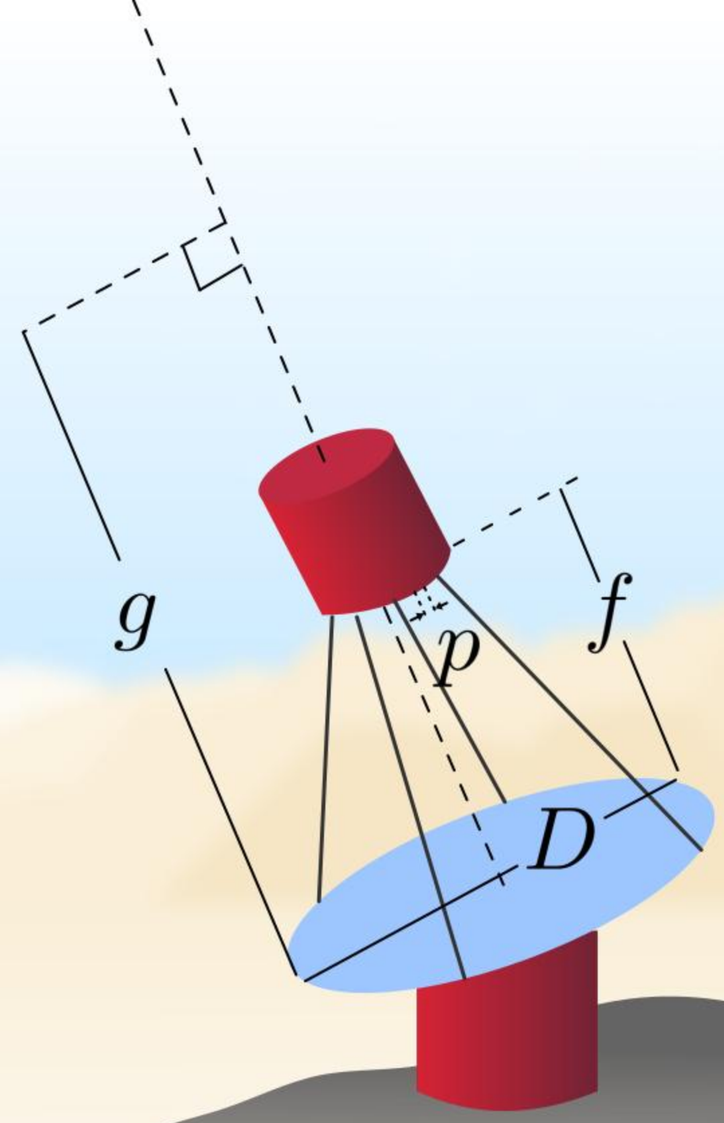
K. Bernloehr et al. 2013
Monte Carlo design studies for the Cherenkov Telescope Array
Astroparticle Physics, vol.43 p.171-188



all narrow the telescope's depth-of-field and thus blurr its images.

Limits of Telescopes

depth-of-field



$$g_{\pm} = g(1 \pm pg/(2fD))$$

K. Bernloehr et al. 2013
Monte Carlo design studies for the Cherenkov Telescope Array
Astroparticle Physics, vol.43 p.171-188

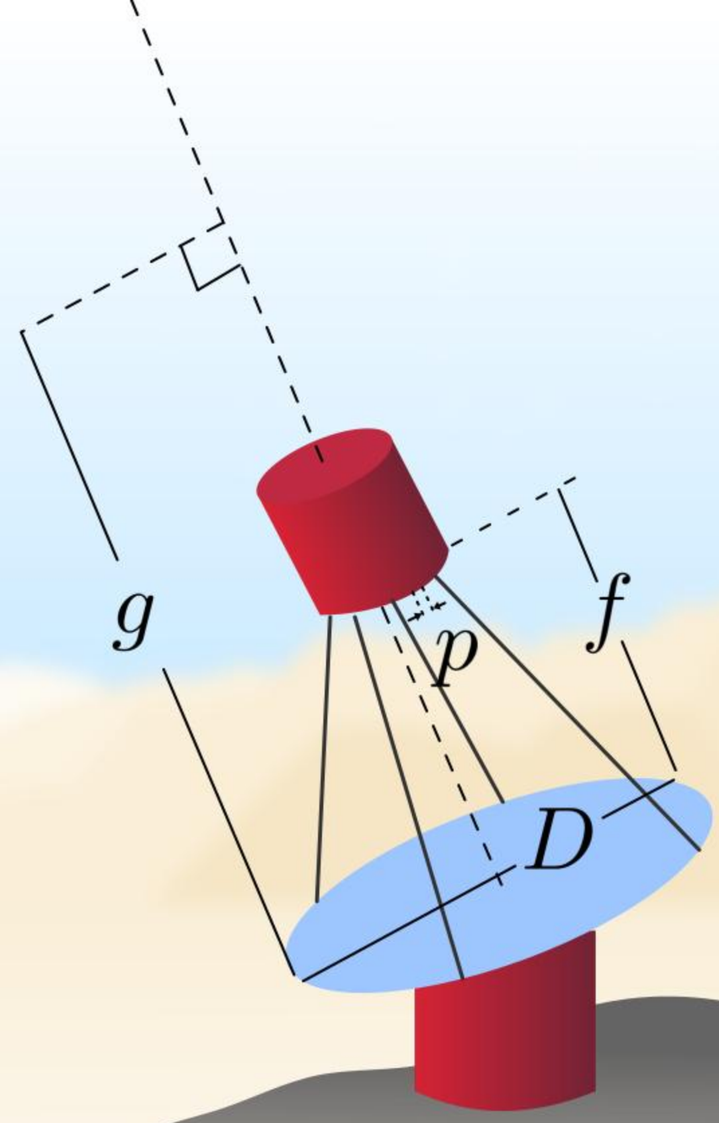
For example, and for reasons which will become obvious in a few moments, an instrument ...

Limits of Telescopes

depth-of-field

$$D = 71\,\mathrm{m}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



with a seventy one meter mirror, ...

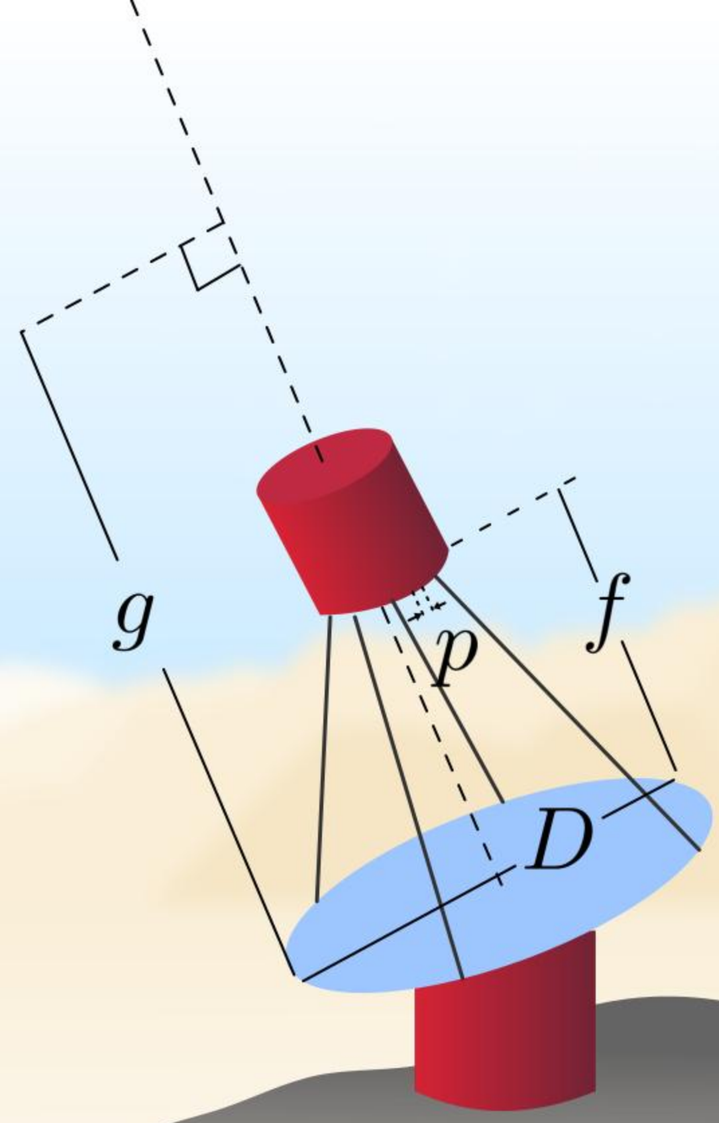
Limits of Telescopes

depth-of-field

$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$g_\pm = g(1 \pm pg/(2fD))$$



a focal-ratio of one point five, ...

Limits of Telescopes

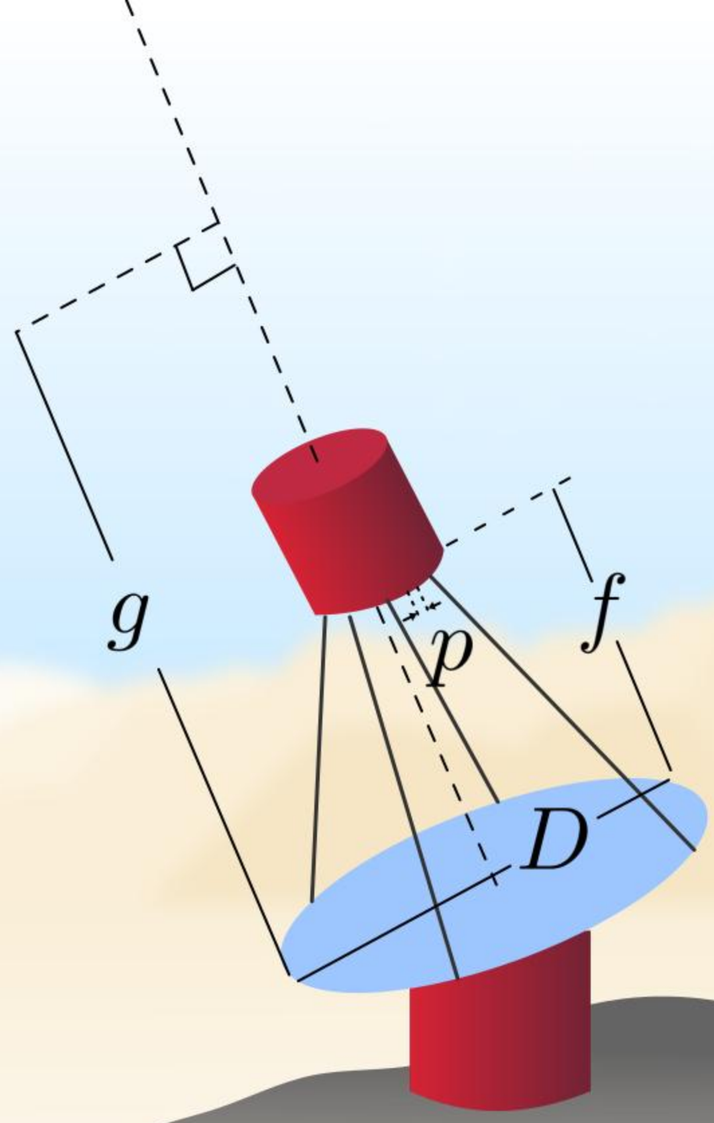
depth-of-field

$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g_\pm = g(1 \pm pg/(2fD))$$



a fine pixelation, ...

Limits of Telescopes

depth-of-field

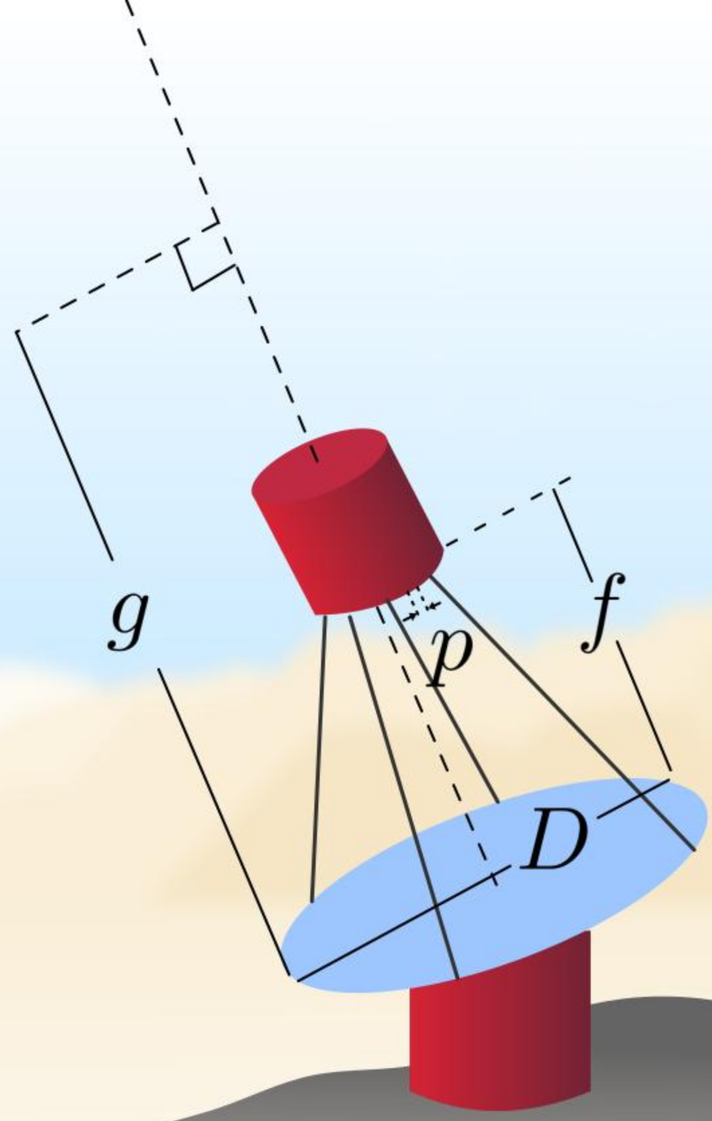
$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g = 10\,\mathrm{km}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



and its focus set to ten kilometers ...

Limits of Telescopes

depth-of-field

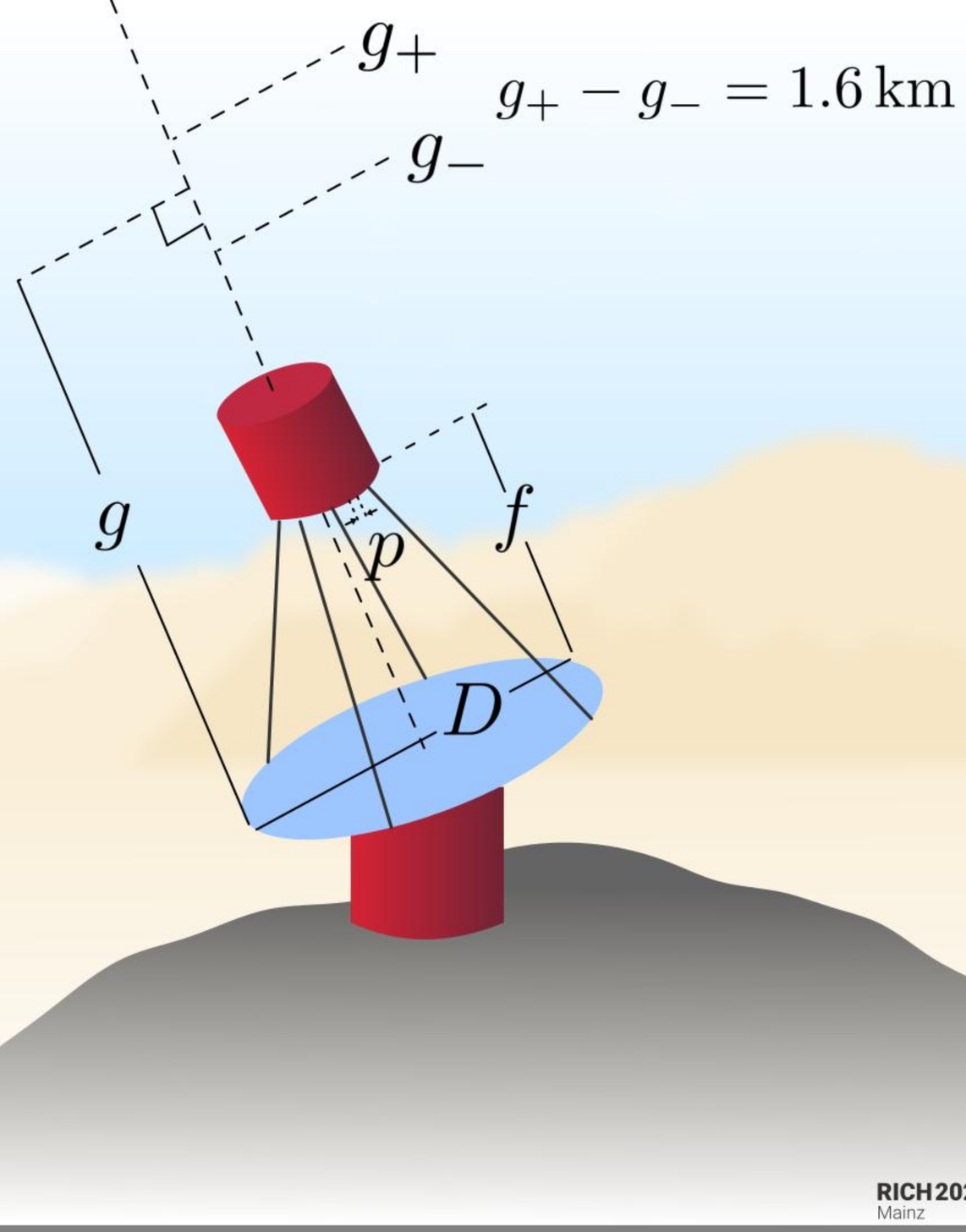
$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g = 10\,\mathrm{km}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



will only be able to make a sharp image within a one point six kilometer narrow range.

Limits of Telescopes

depth-of-field

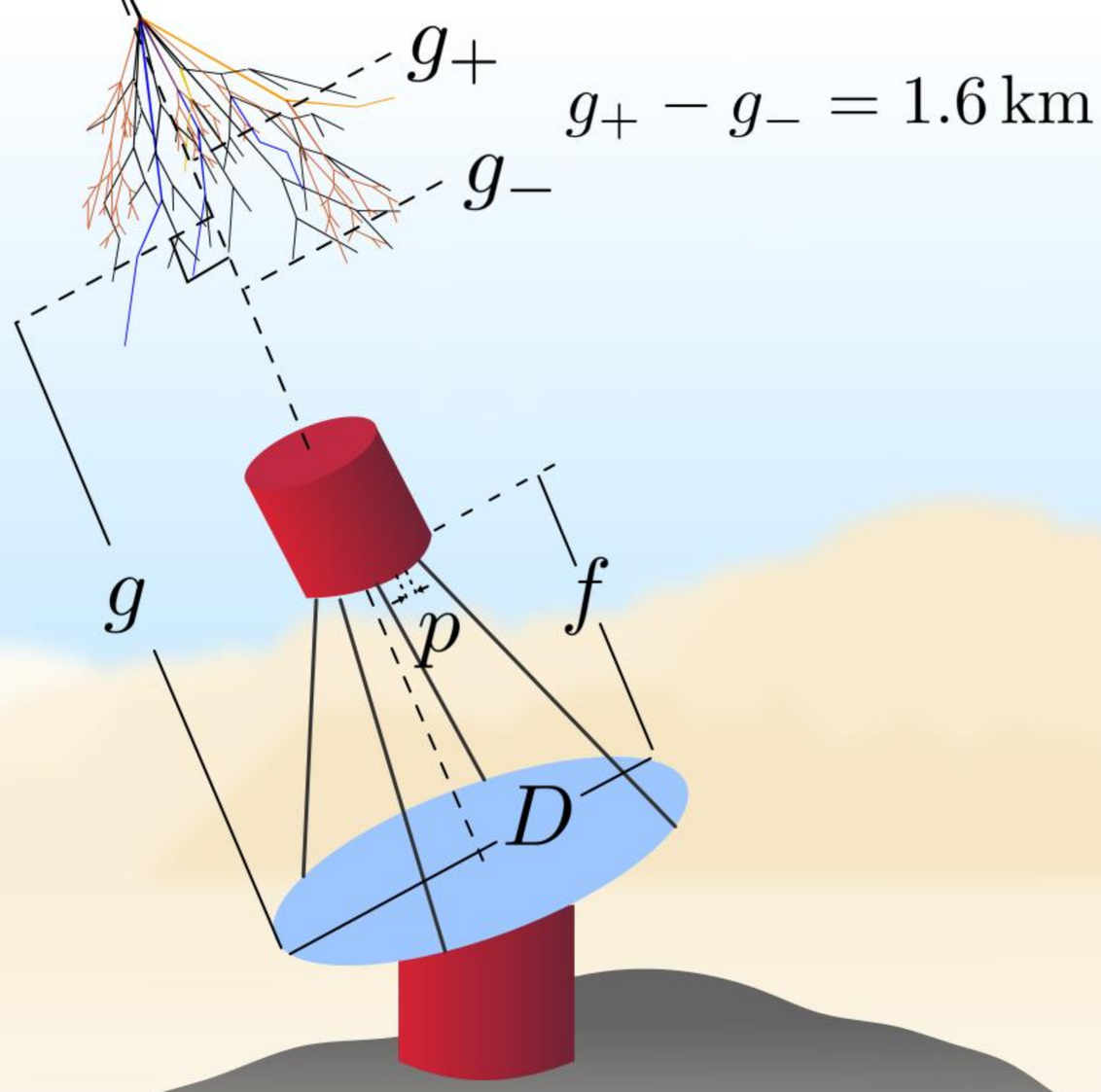
$$D = 71\,\mathrm{m}$$

$$f/D = 1.5$$

$$p = 124\,\mathrm{mm}\ (0.067°)$$

$$g = 10\,\mathrm{km}$$

$$g_\pm = g(1 \pm pg/(2fD))$$



This is a problem because the showers which we want to observe exceed this sharp range by about an order of magnitude.

Motivation

It turns out that the telescope's

Motivation

depth-of-field

aberrations

suffering from aberrations,

Motivation

deformations and misalignments

depth-of-field

aberrations

the cause of its narrow depth-of-field,

Motivation

deformations and misalignments

depth-of-field

and the telescope's suffering from deformations and misalignments are all related to

Motivation

the telescope

Motivation

with its mirror

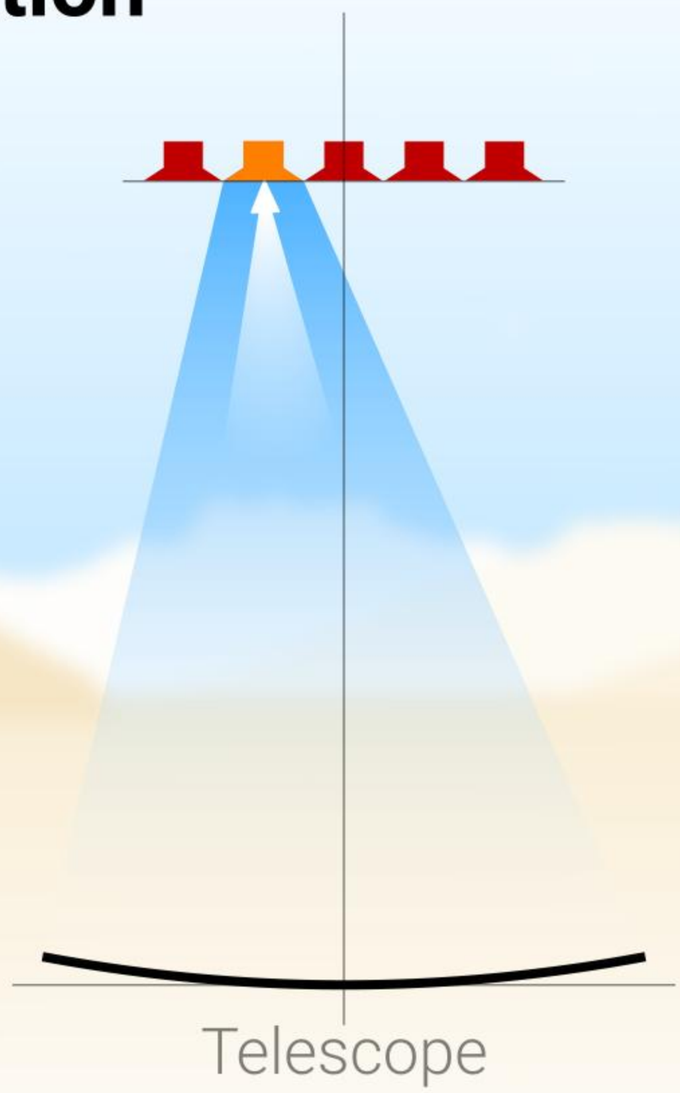
Motivation

and its camera

Motivation

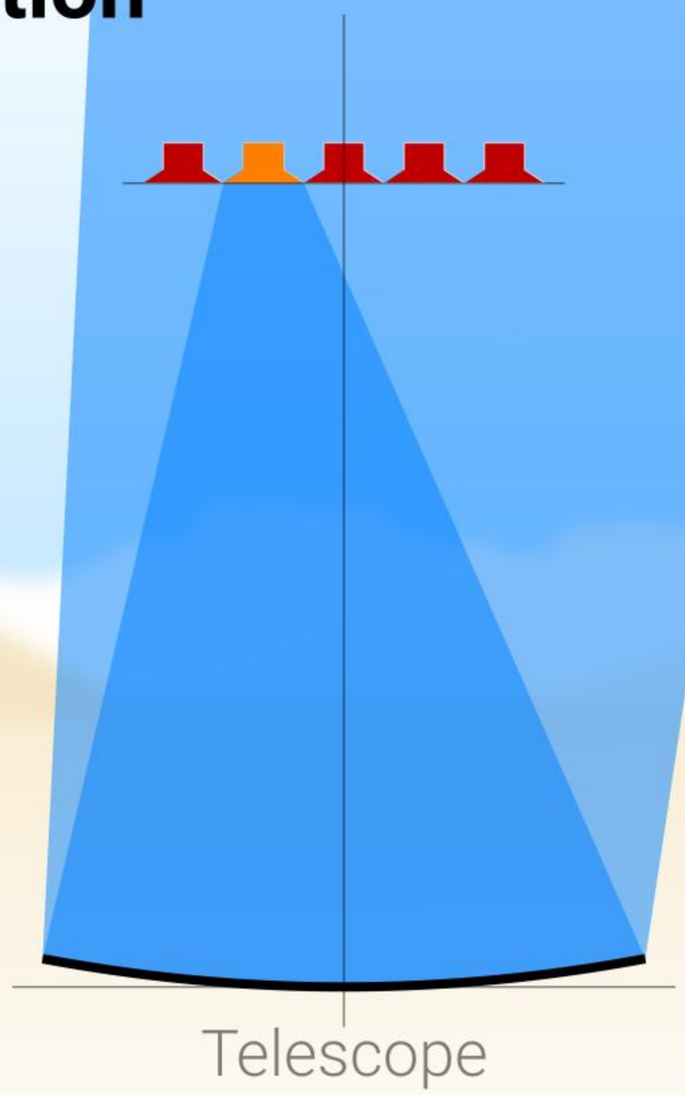
full of photosensors

Motivation



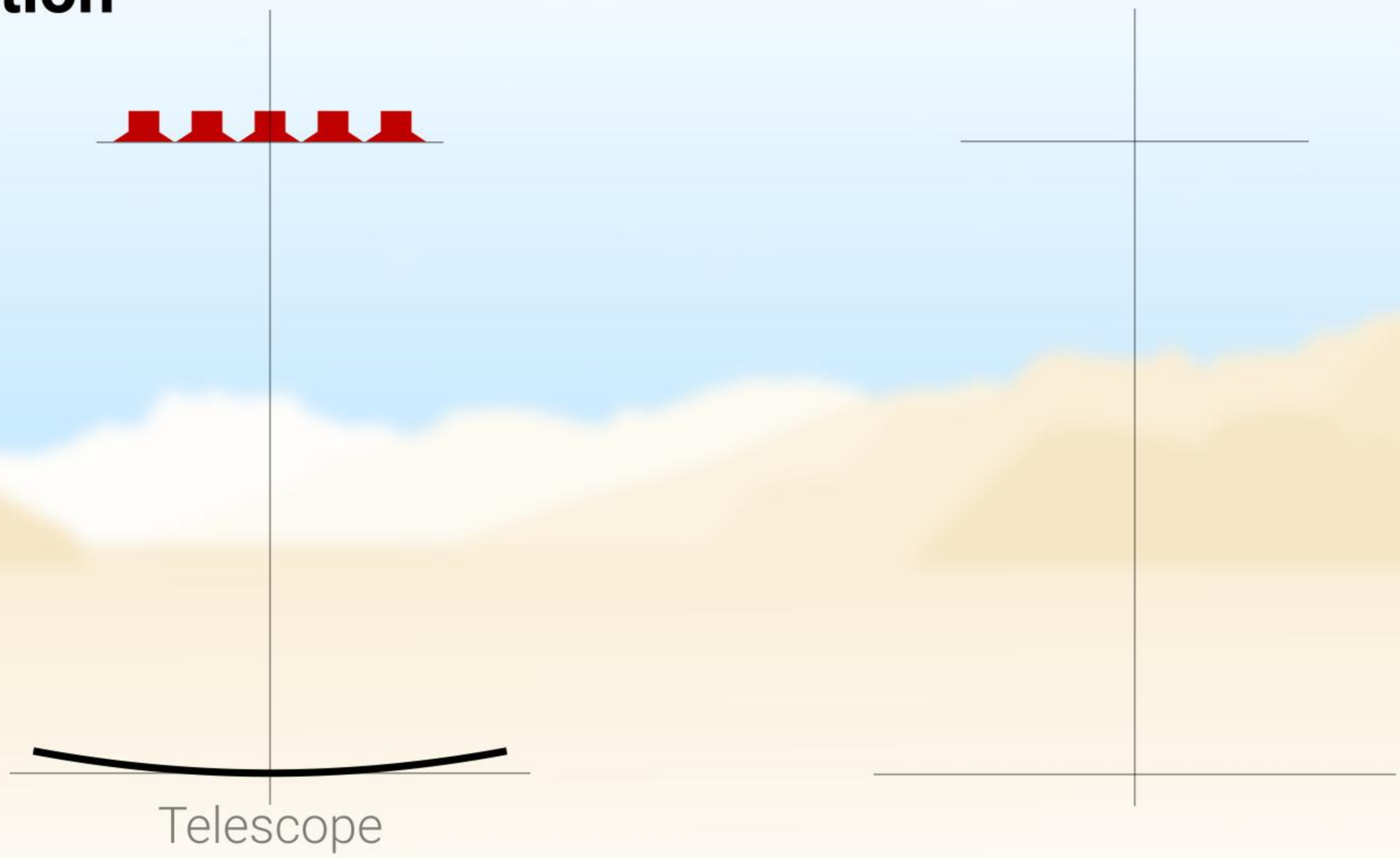
not knowing where a photon was reflected on its mirror.

Motivation



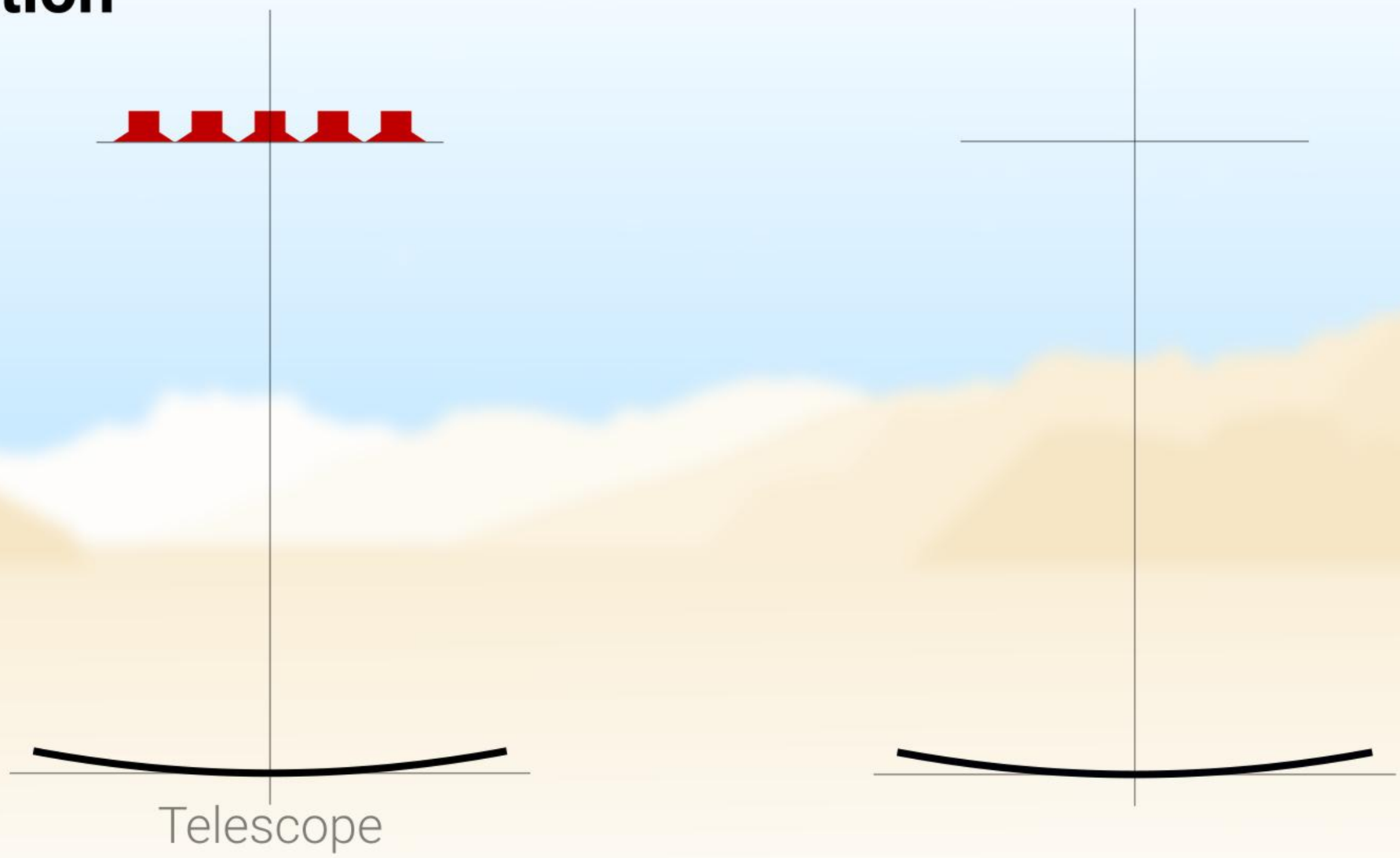
All the photons with trajectories in this beam of light will be absorbed by the same photosensor.

Motivation



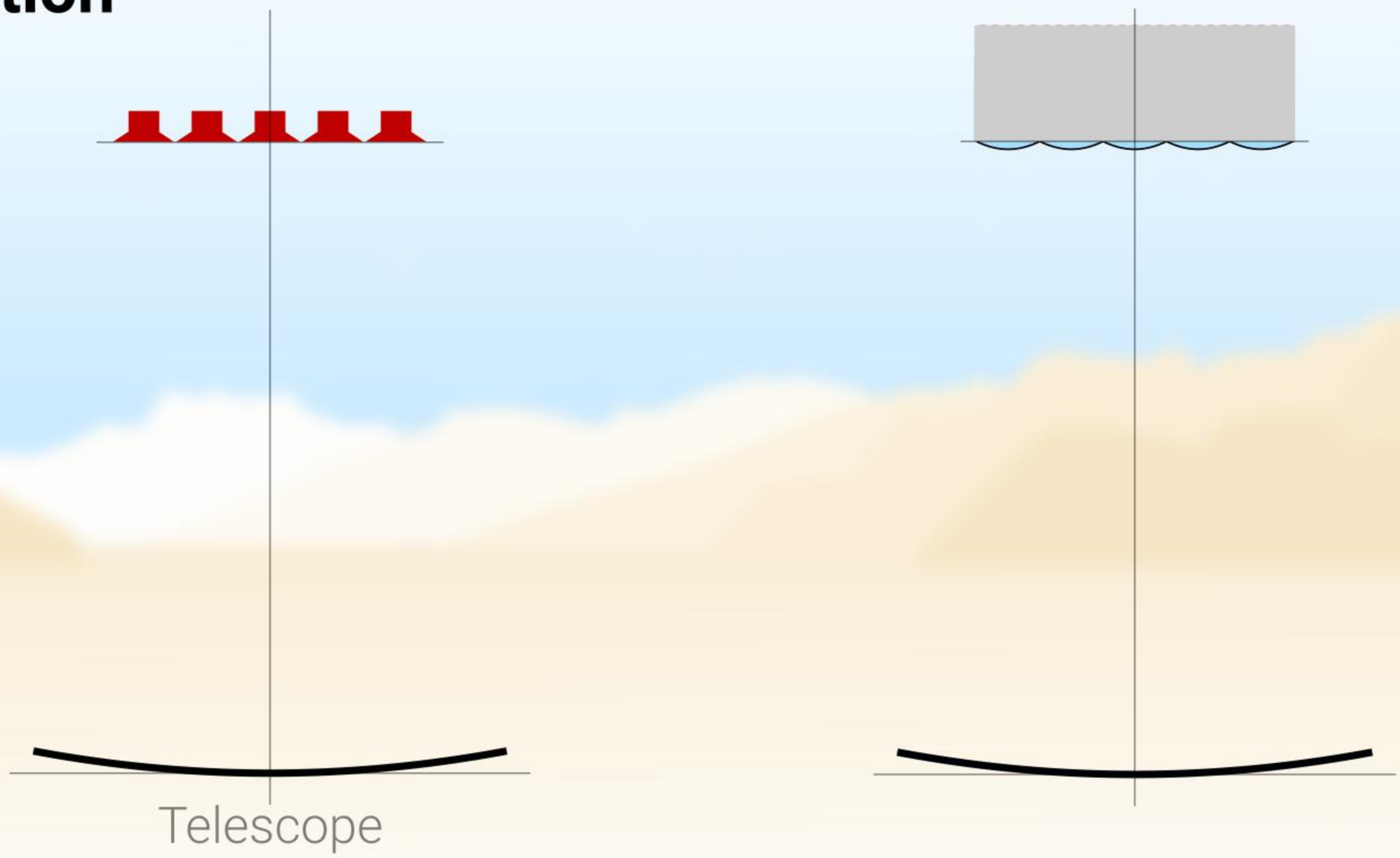
Now imagine there was a new class of instrument

Motivation



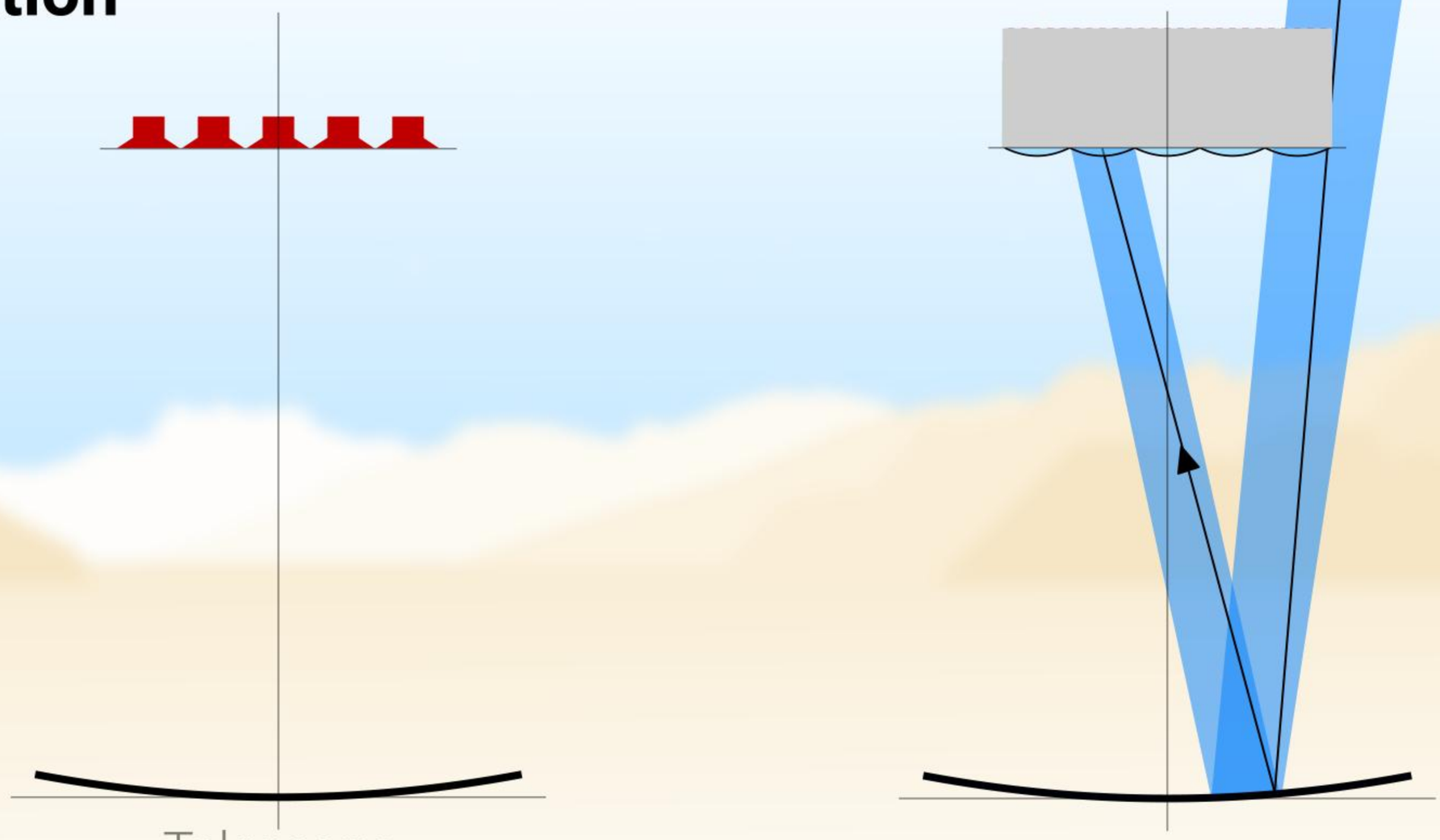
which had a mirror just like the telescope

Motivation



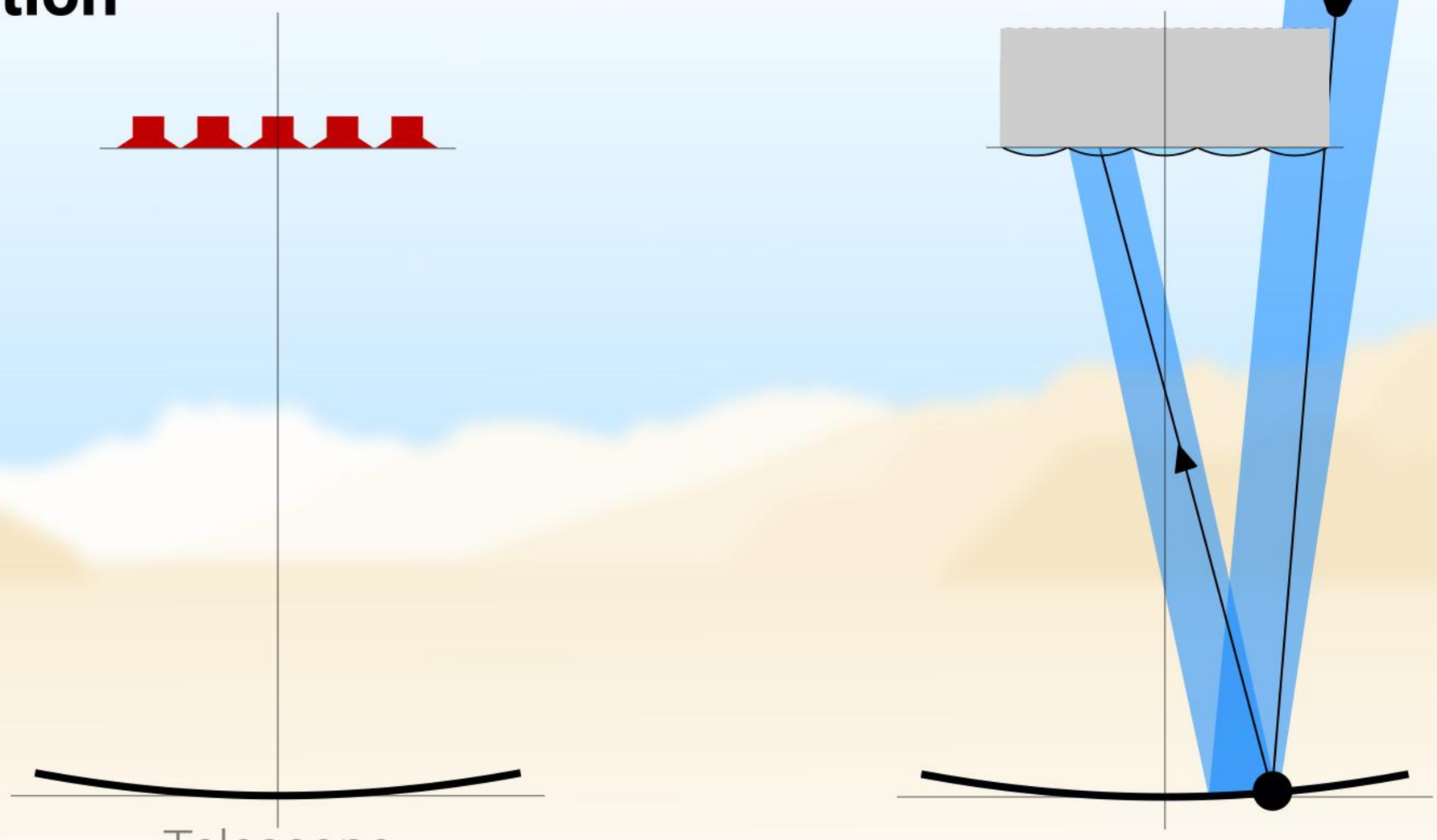
but a camera capable of measuring

Motivation



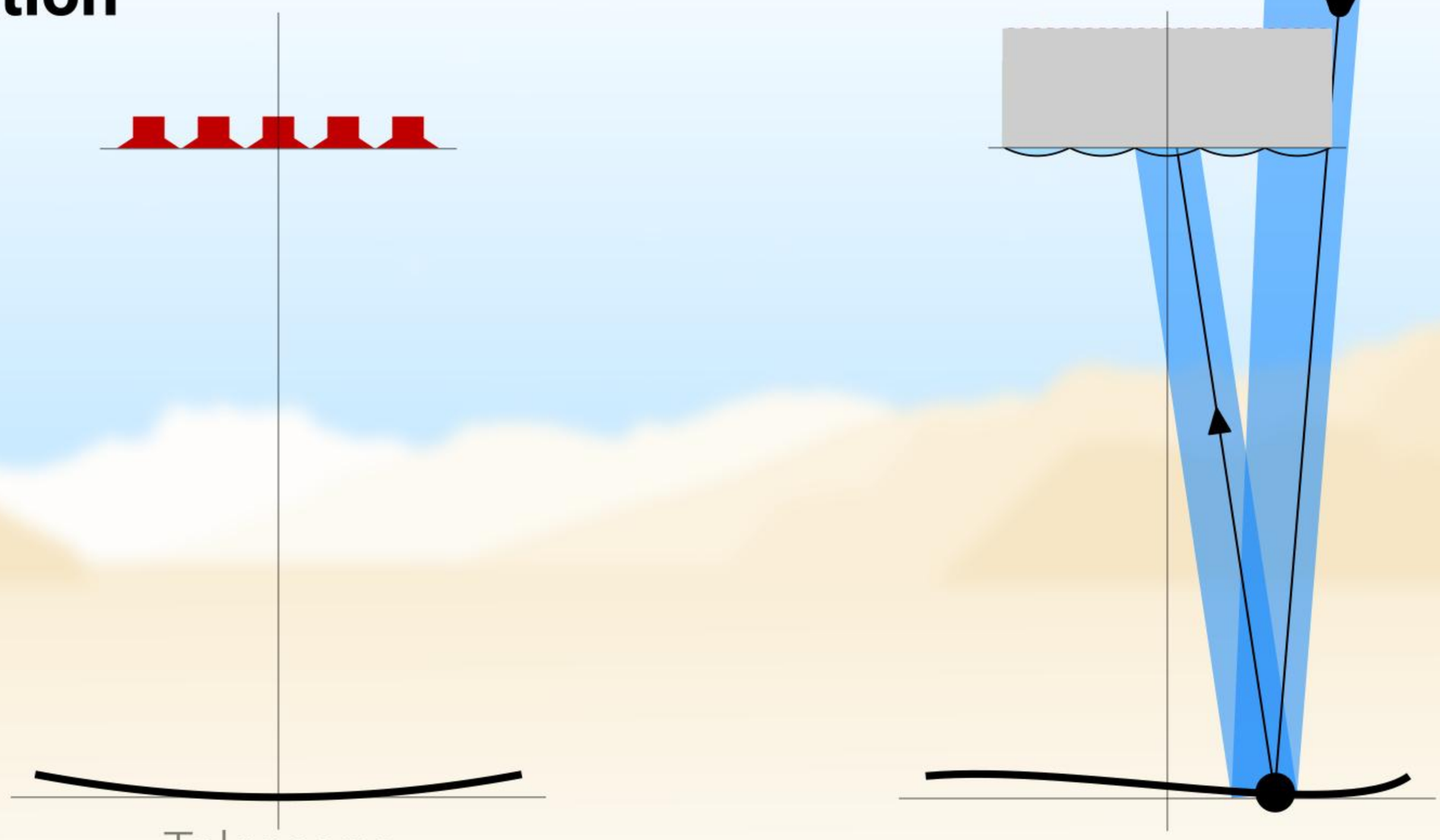
finer beams of light.

Motivation



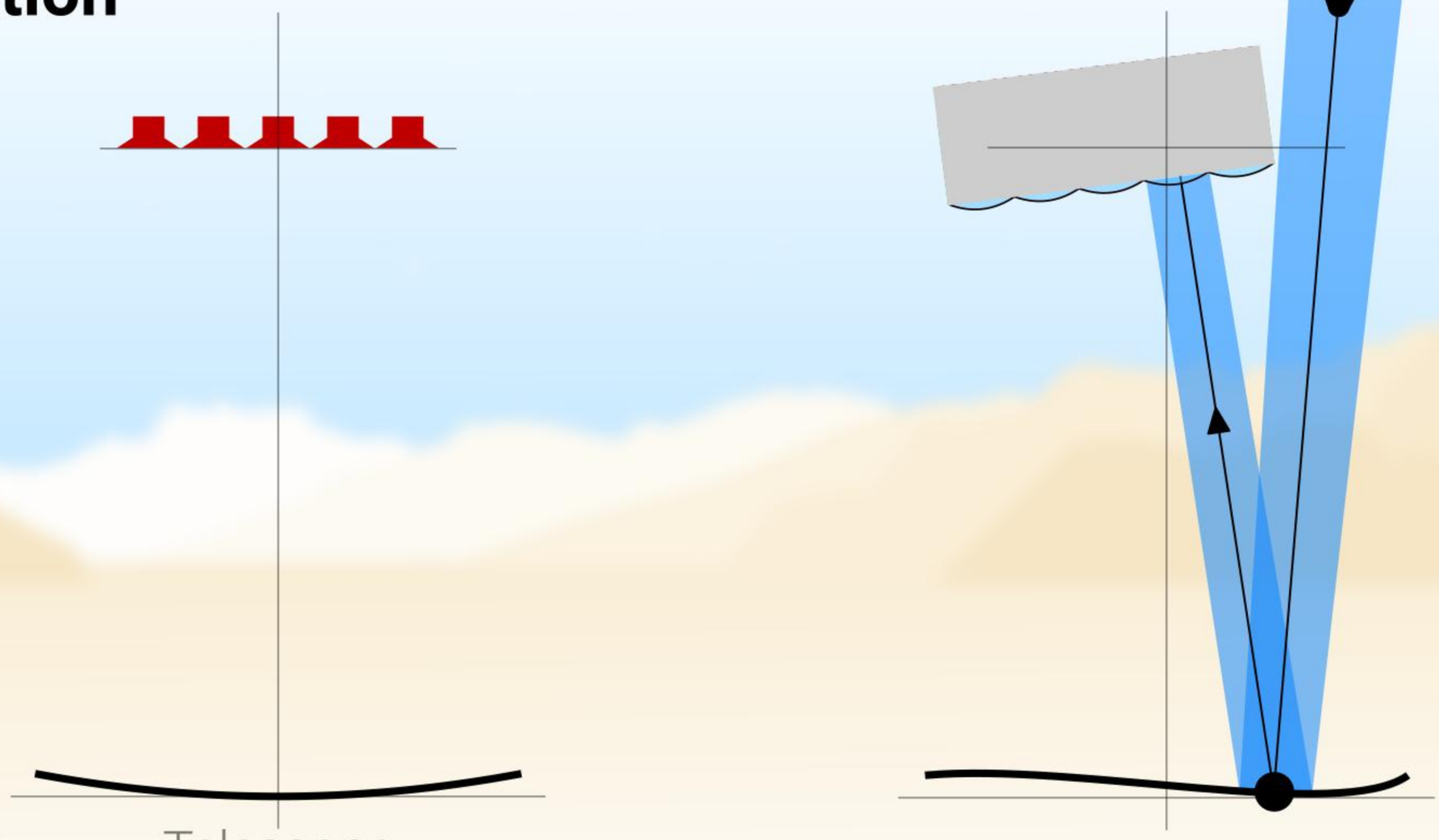
After all, the observables we are after to reconstruct the shower are the Cherenkov photon's direction and impact position.

Motivation



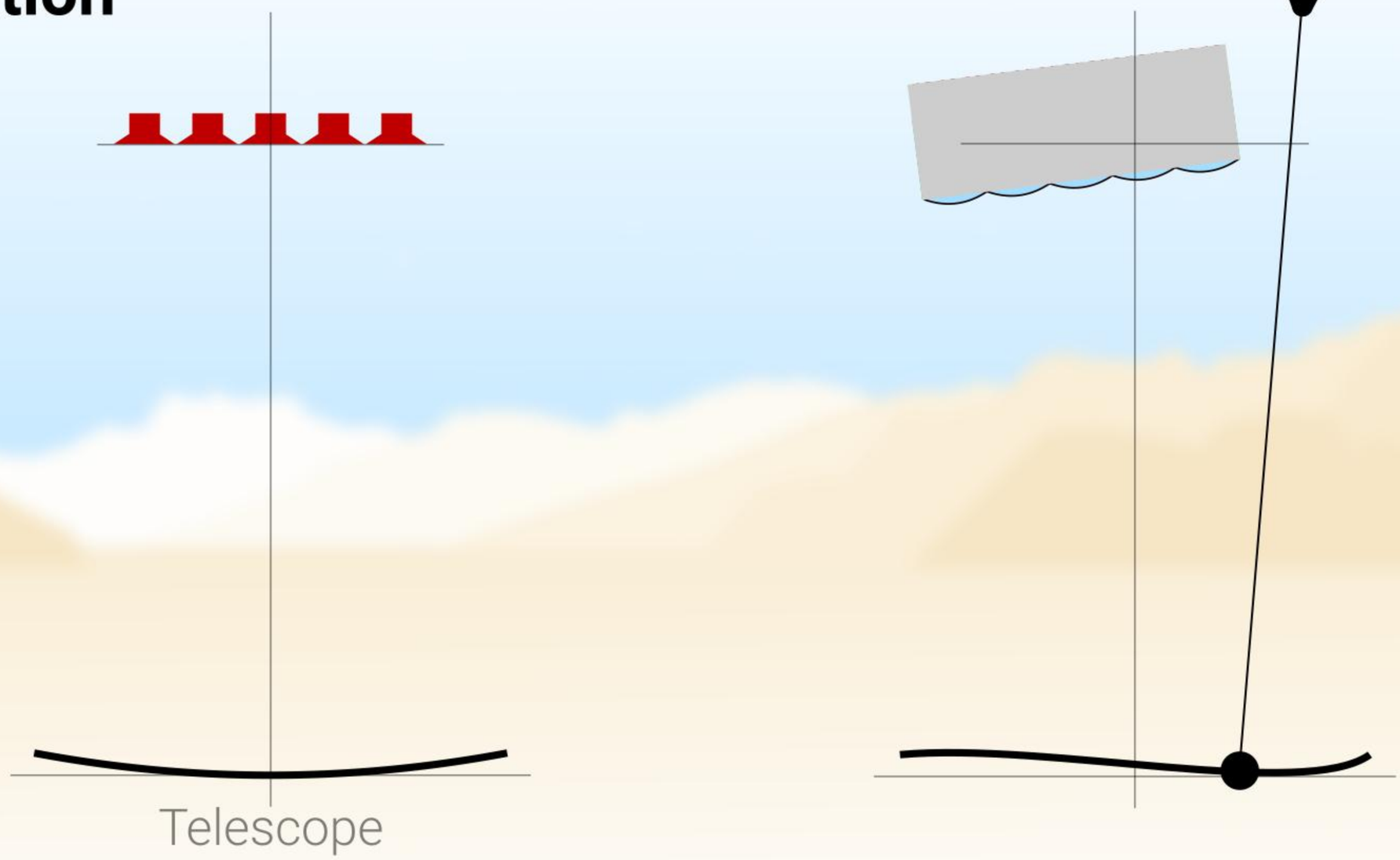
Now even when the mirror of the novel instrument was deformed

Motivation



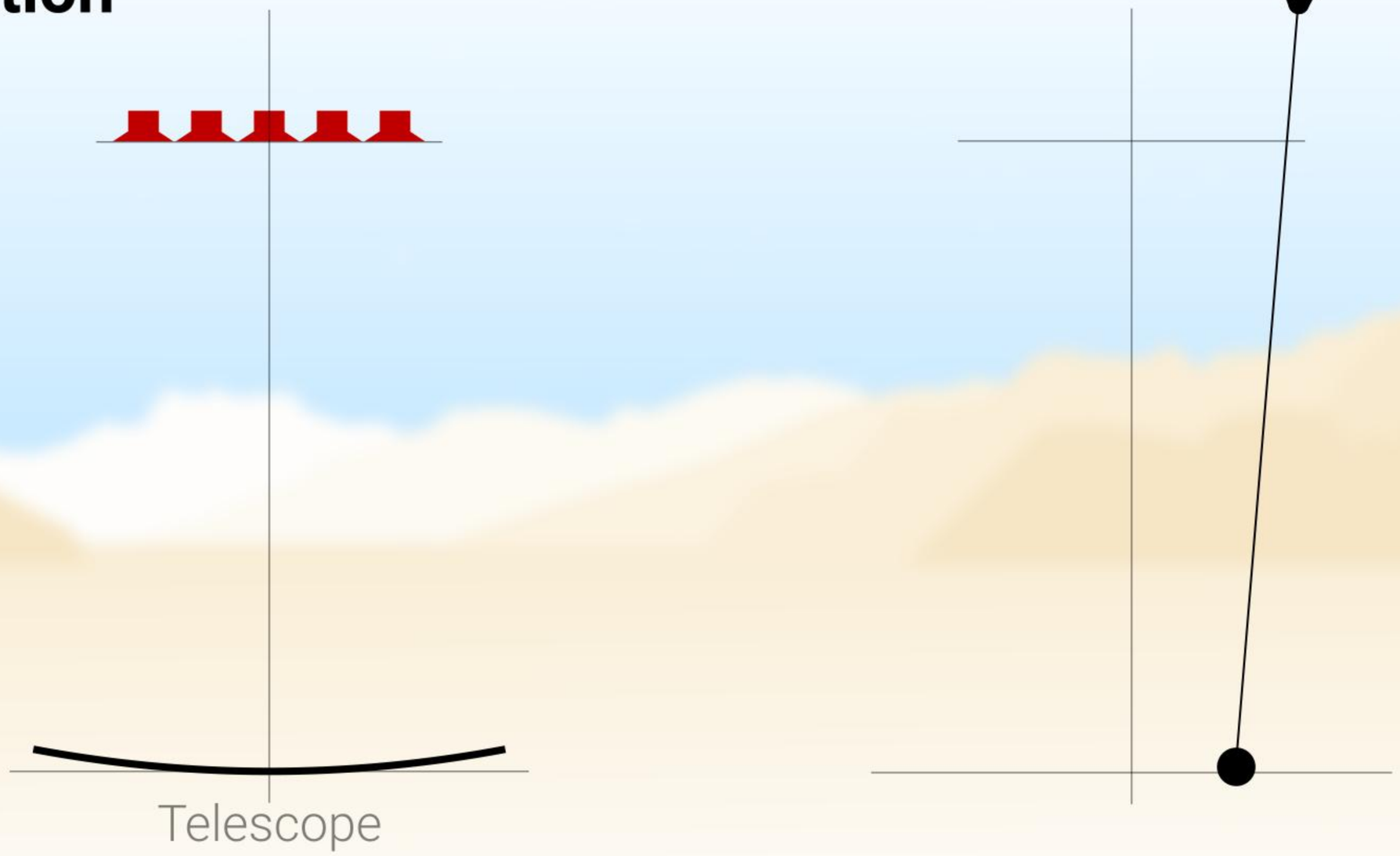
or its camera was misaligned, the fine beams would still allow to constrain the trajectory of the photon with respect to the atmosphere.

Motivation



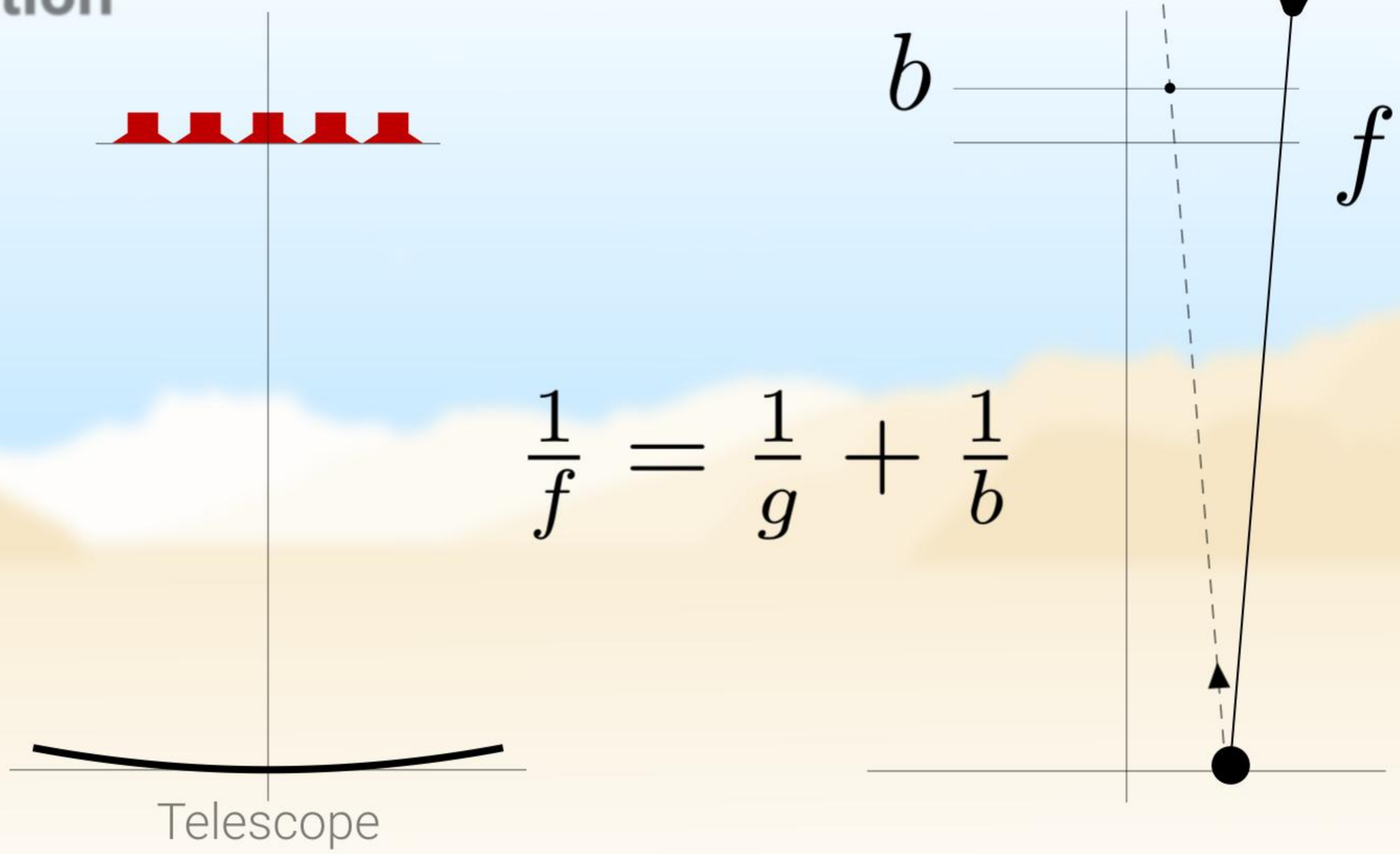
At this point, we can mentally leave all the optics behind ...

Motivation

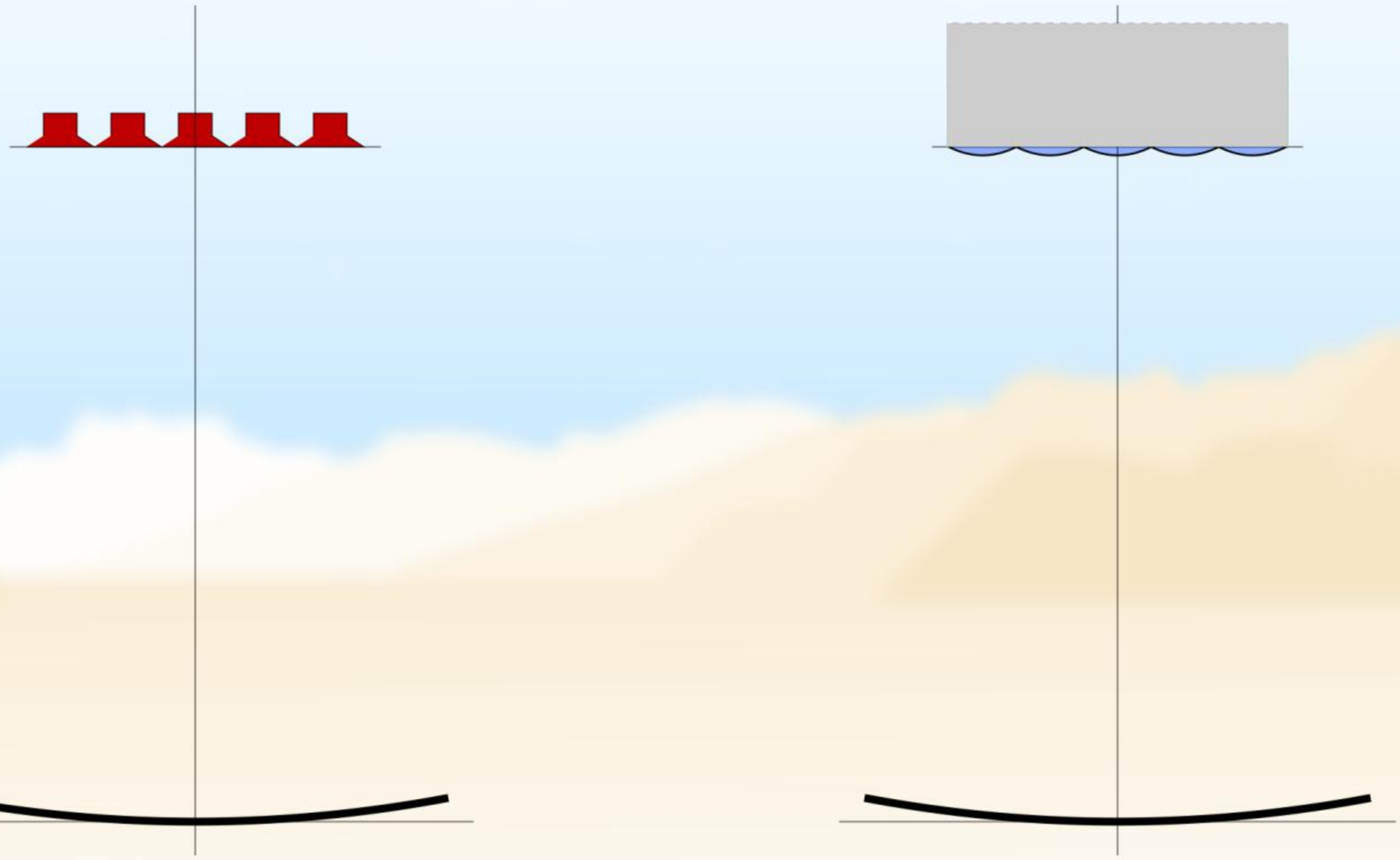


and concentrate on the bundle of measured trajectories instead.

Motivation

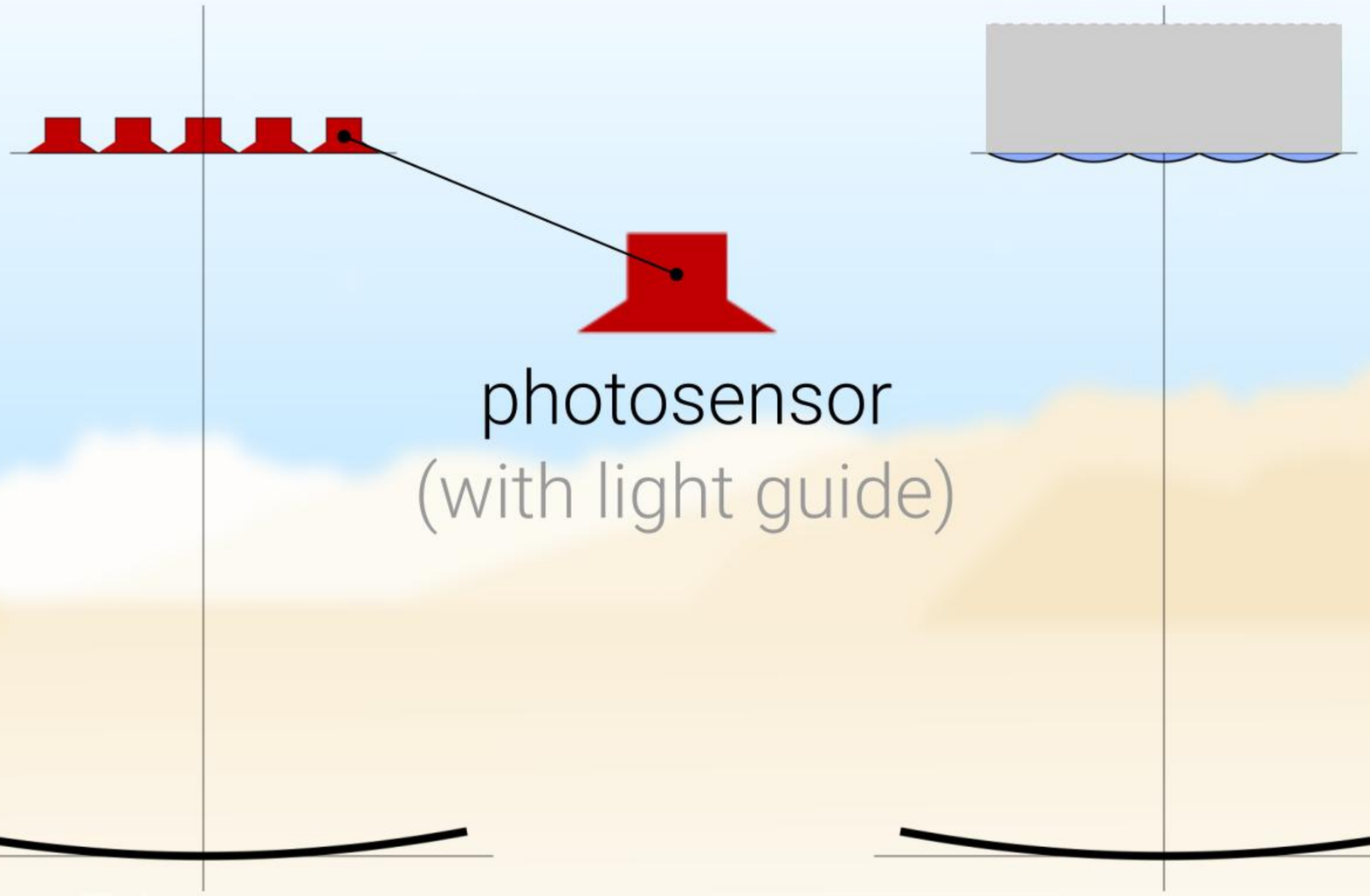


Now we can trace these photon through a model of a perfect imaging optics, such as the thin lens. Here we can compute images free of aberrations and with the focus set to any depth we want.



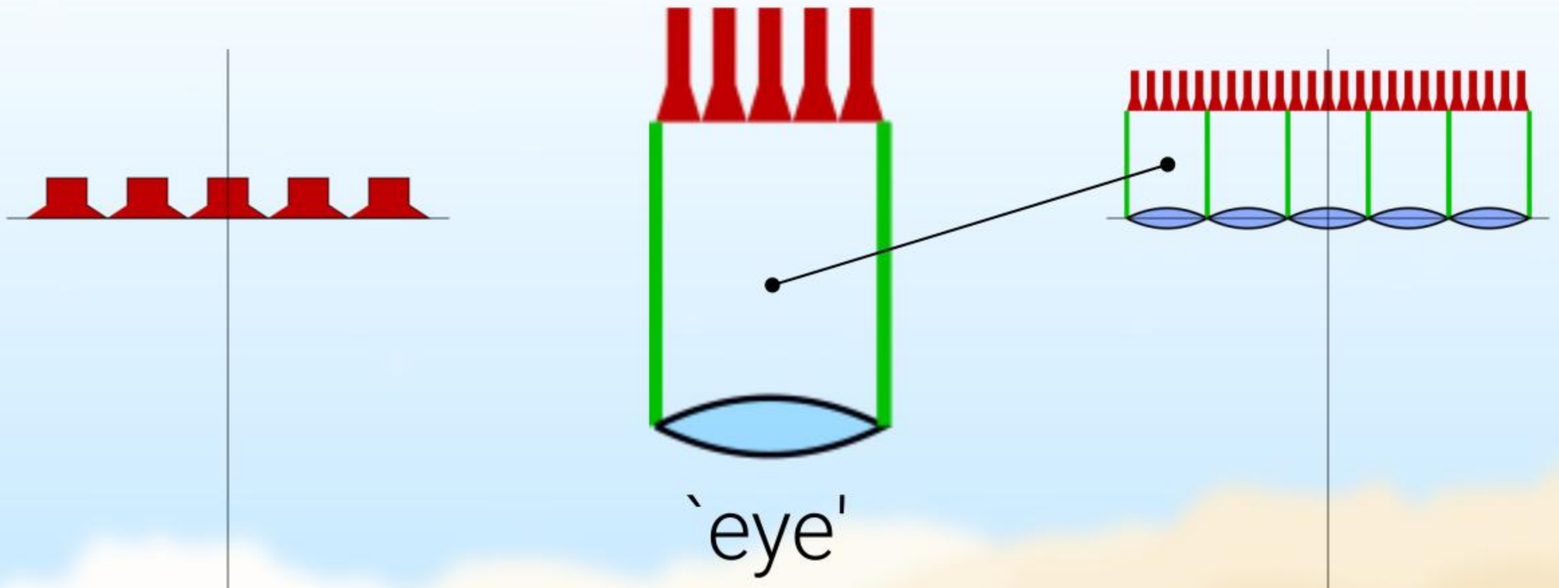
To build such an instrument

Optics



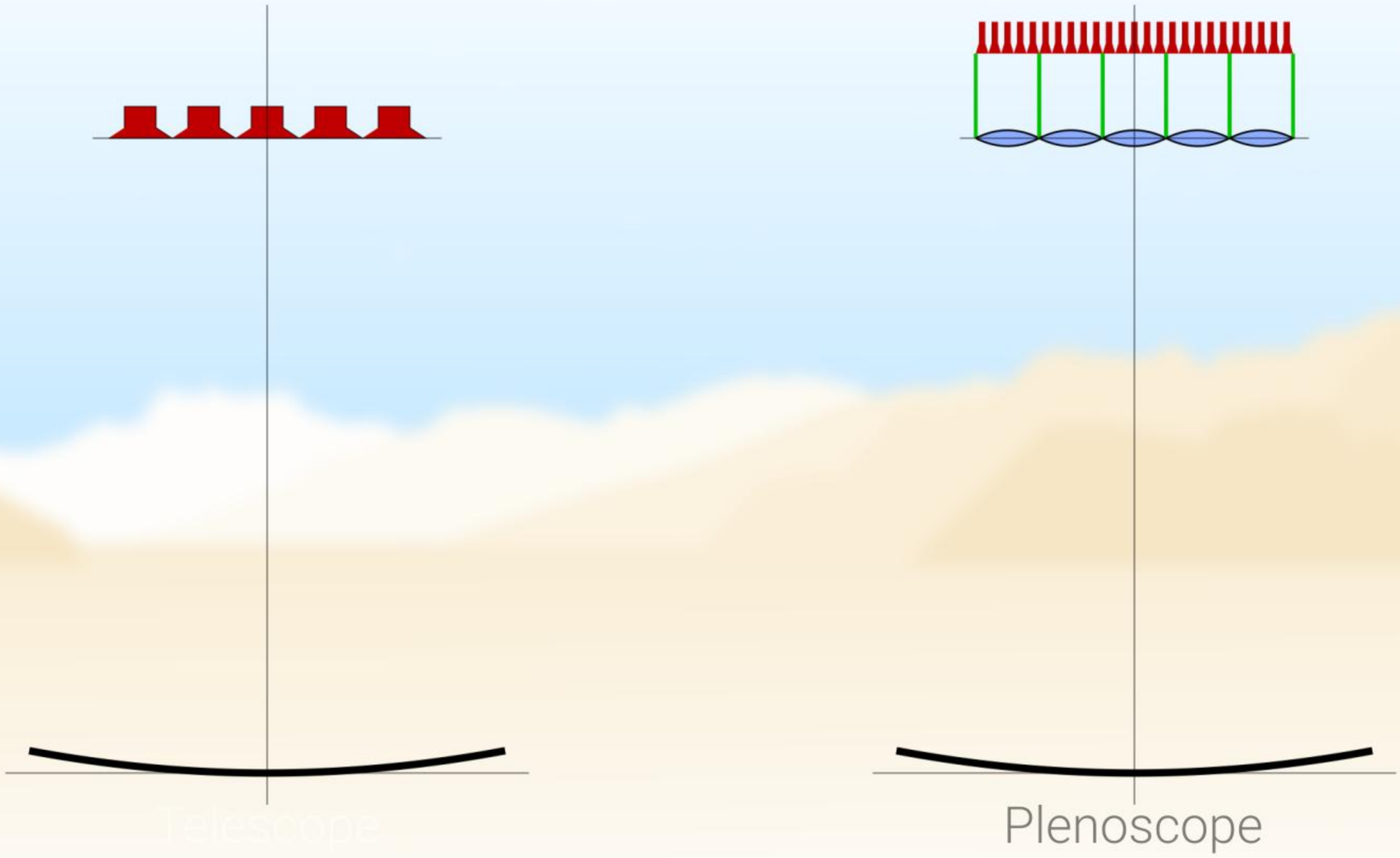
we upgrade each photosensor of the telescope

Optics



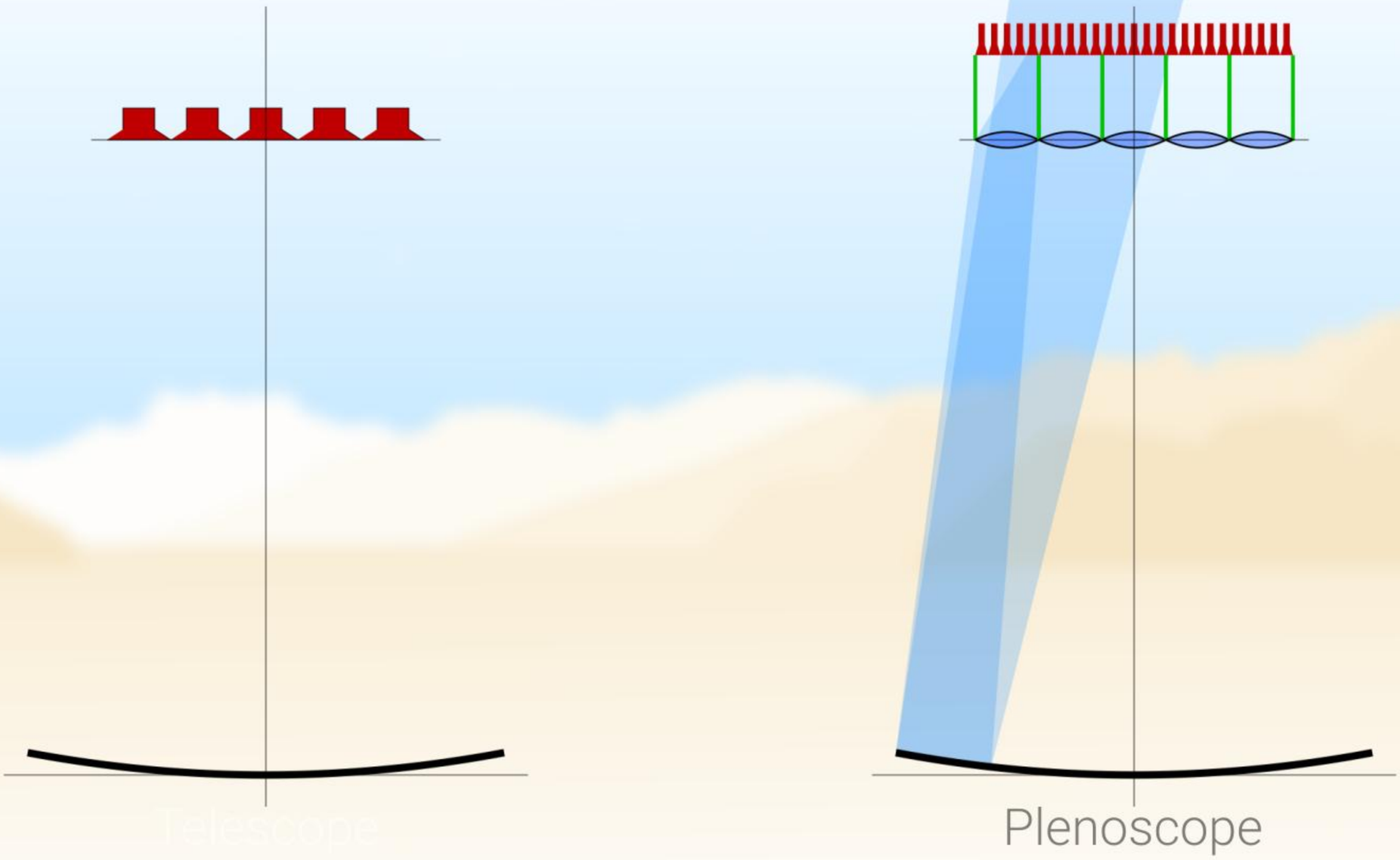
with an 'eye' made out of a lens and an opposing array of photosensors.

Optics



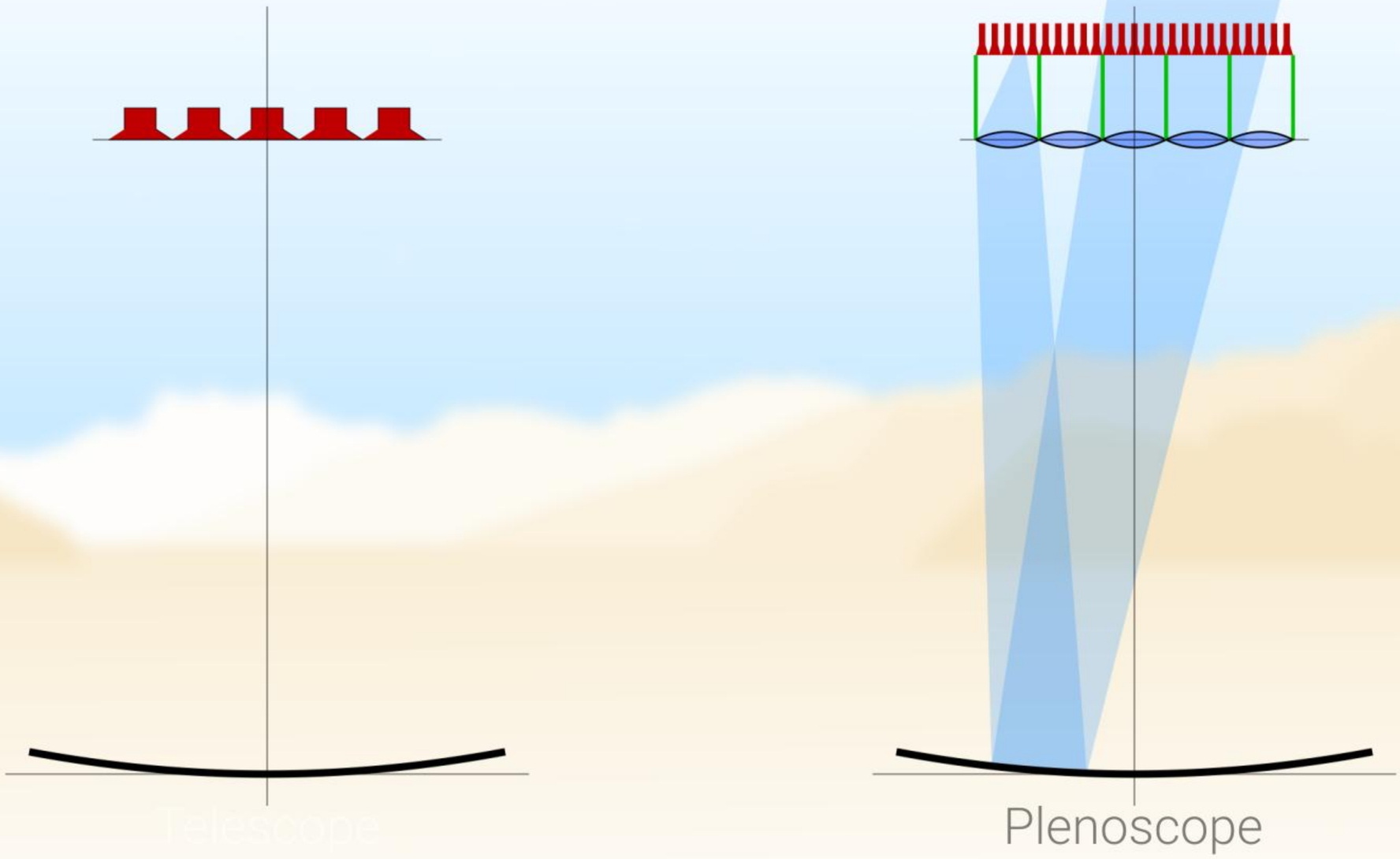
The resulting Cherenkov plenoscope

Optics



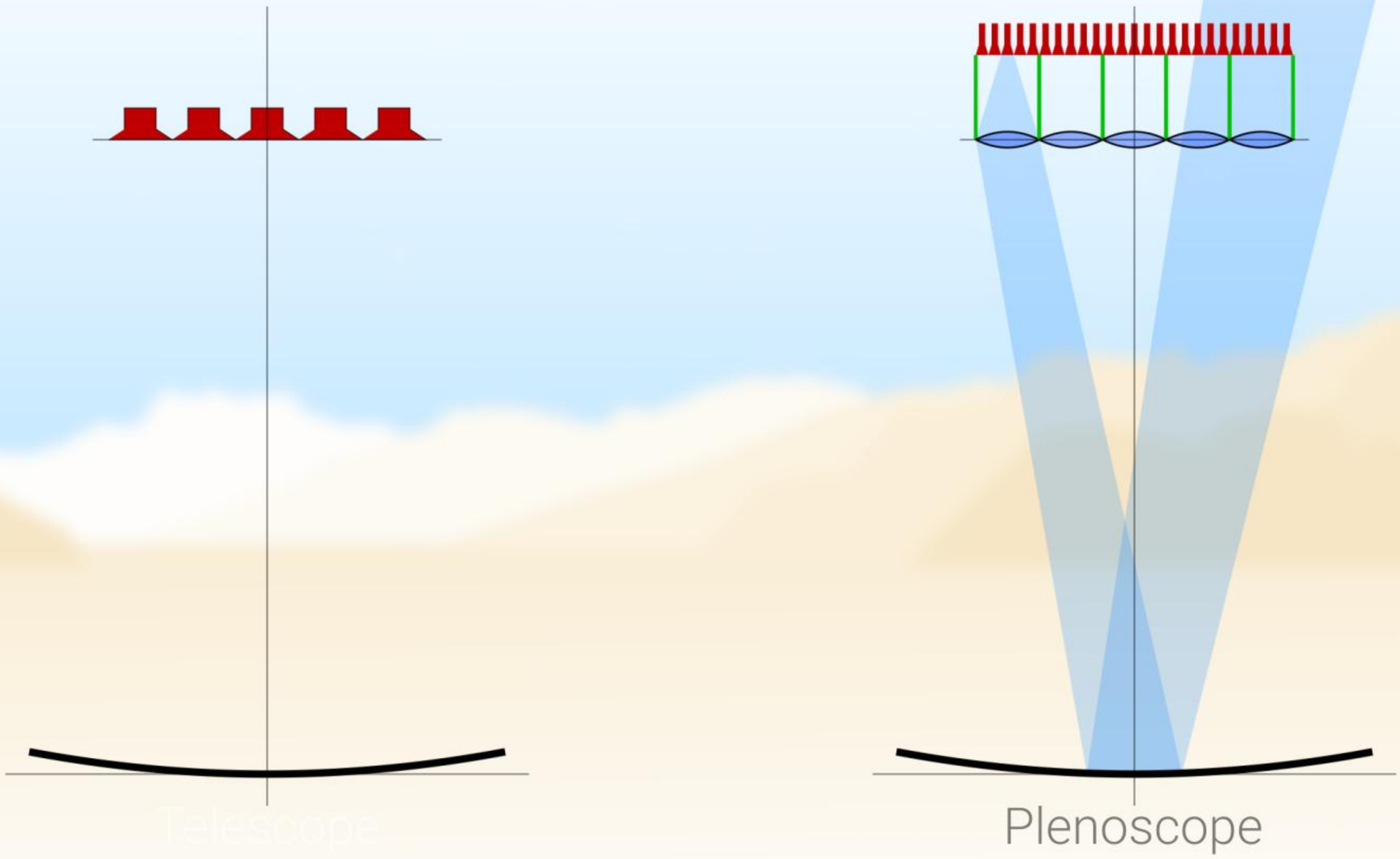
has much

Optics



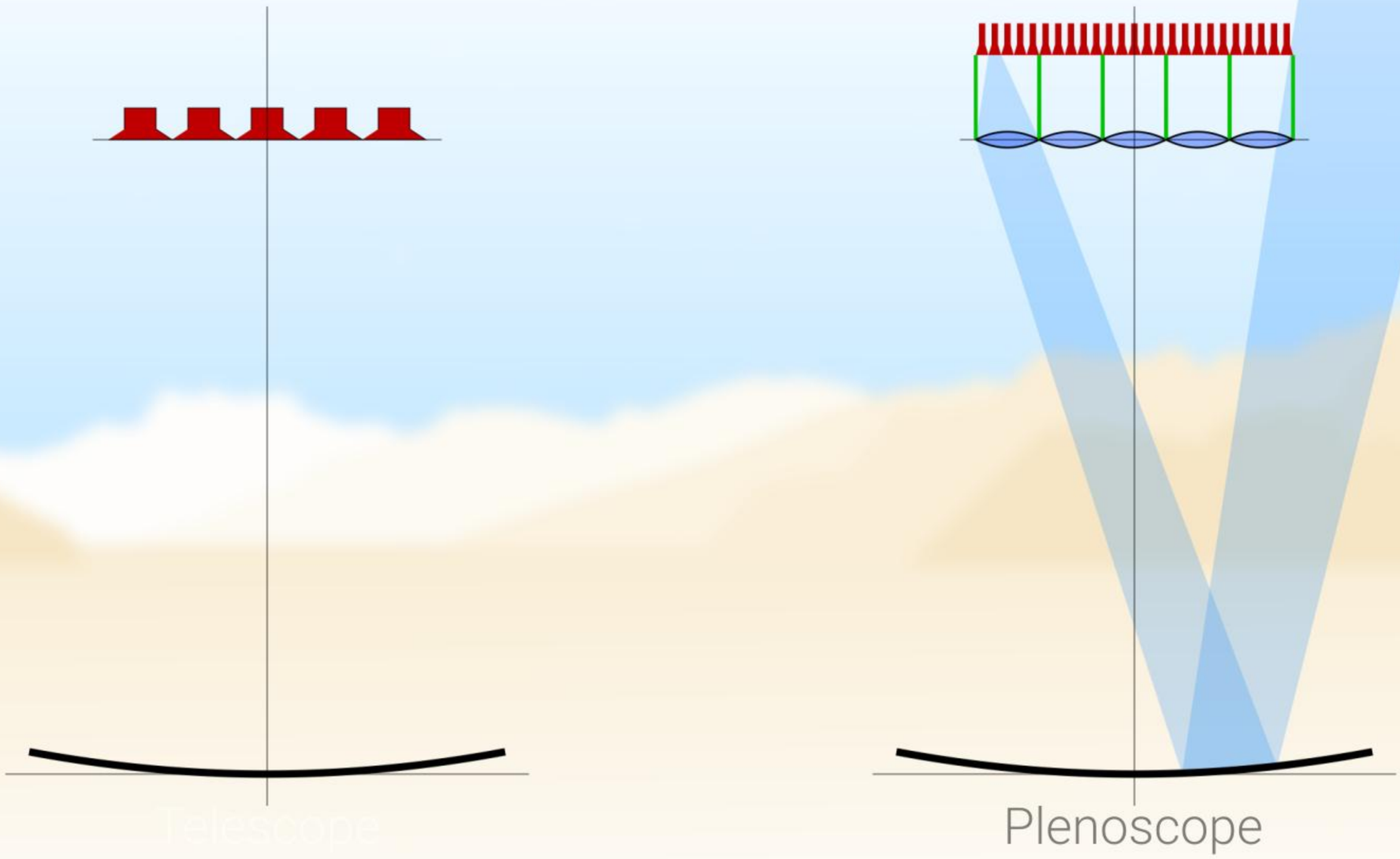
finer beams

Optics



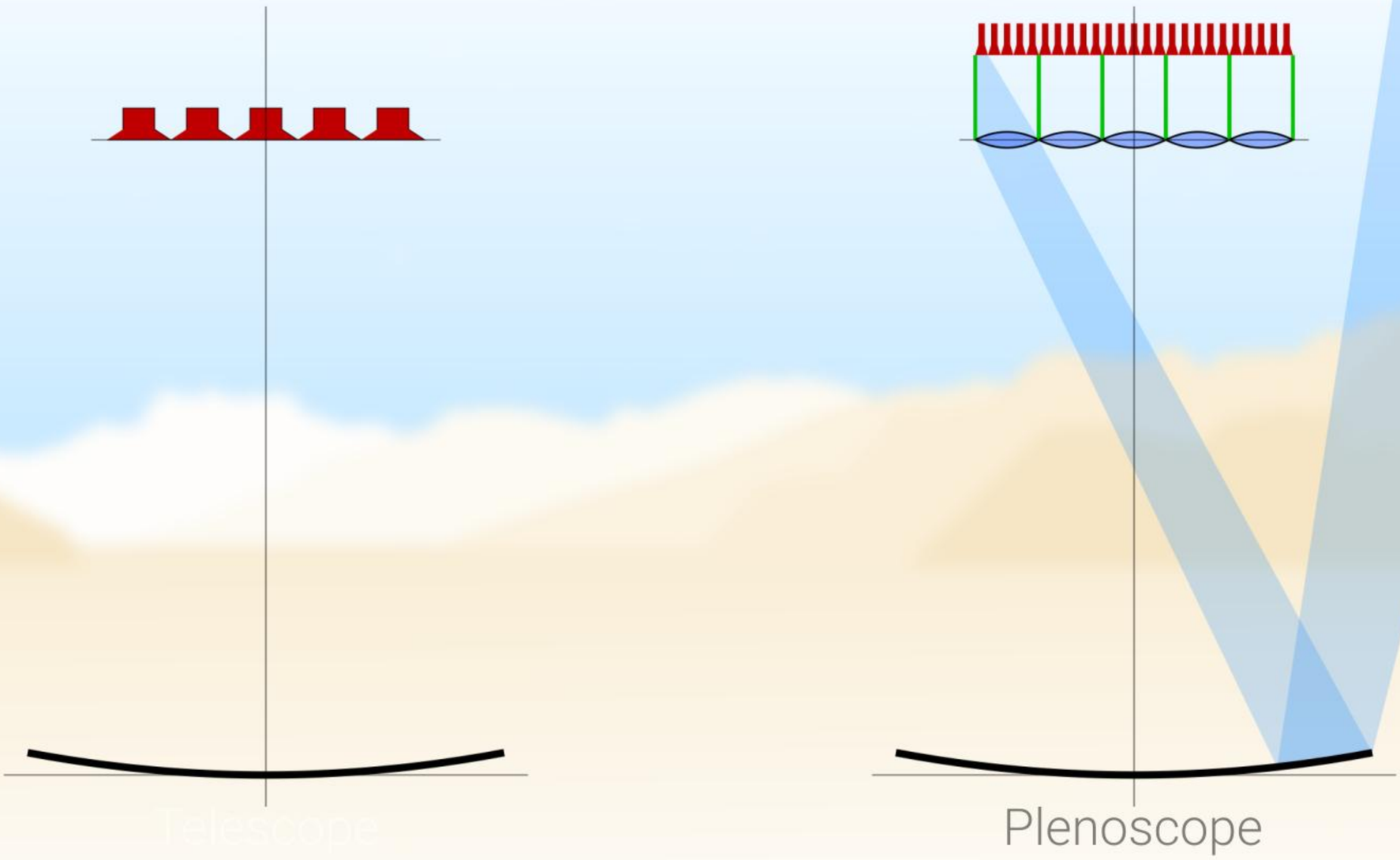
and

Optics



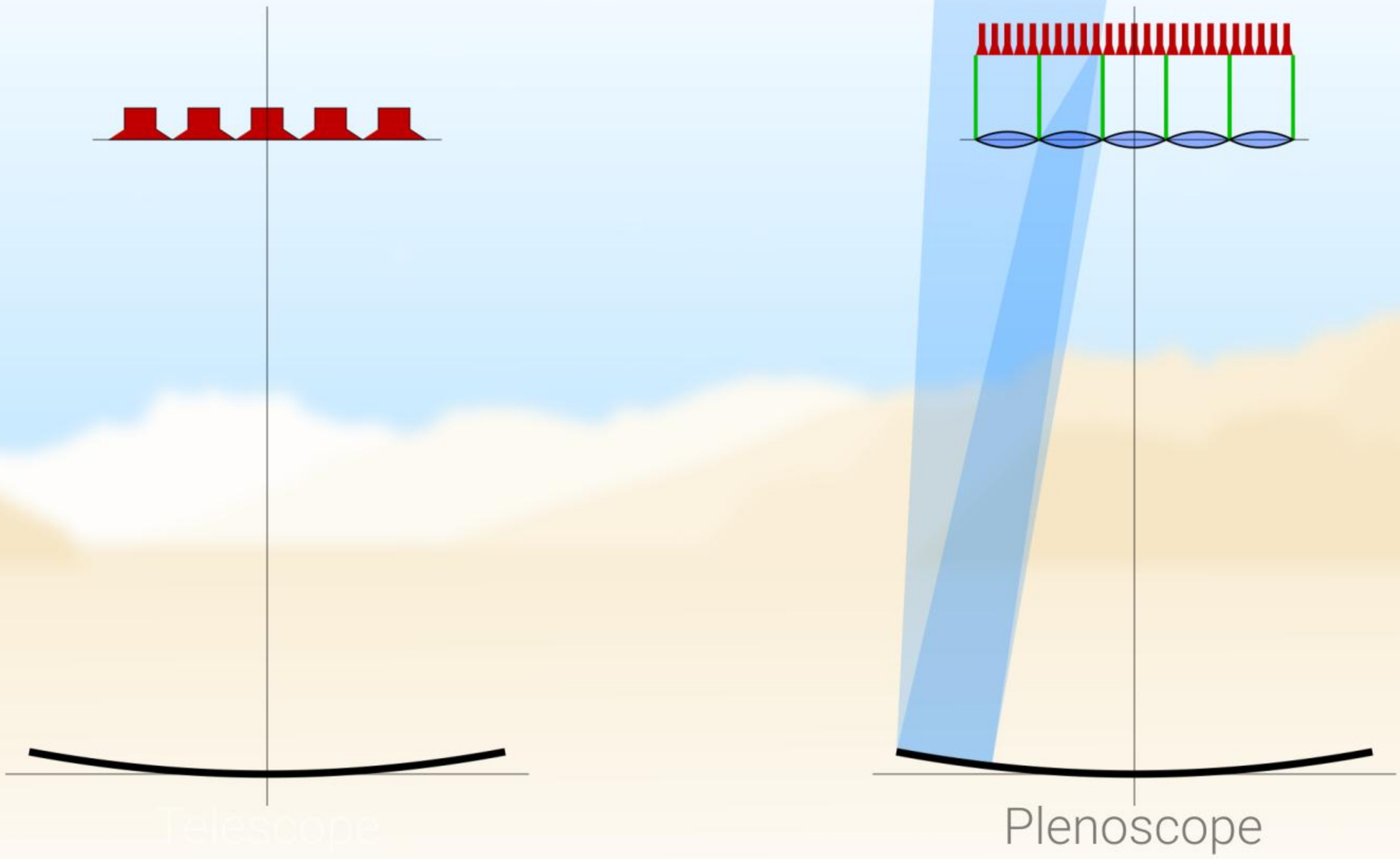
thus

Optics



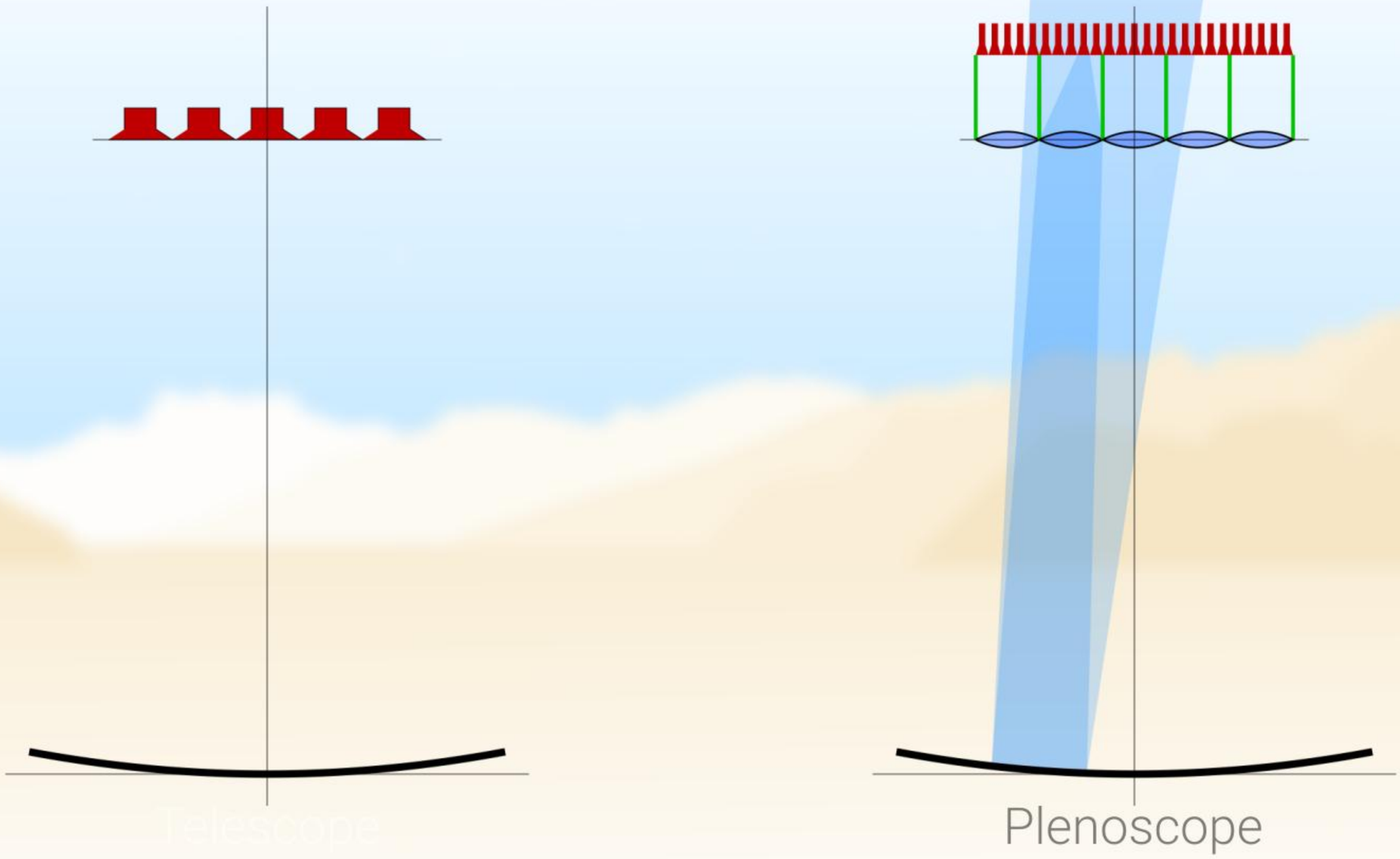
can

Optics



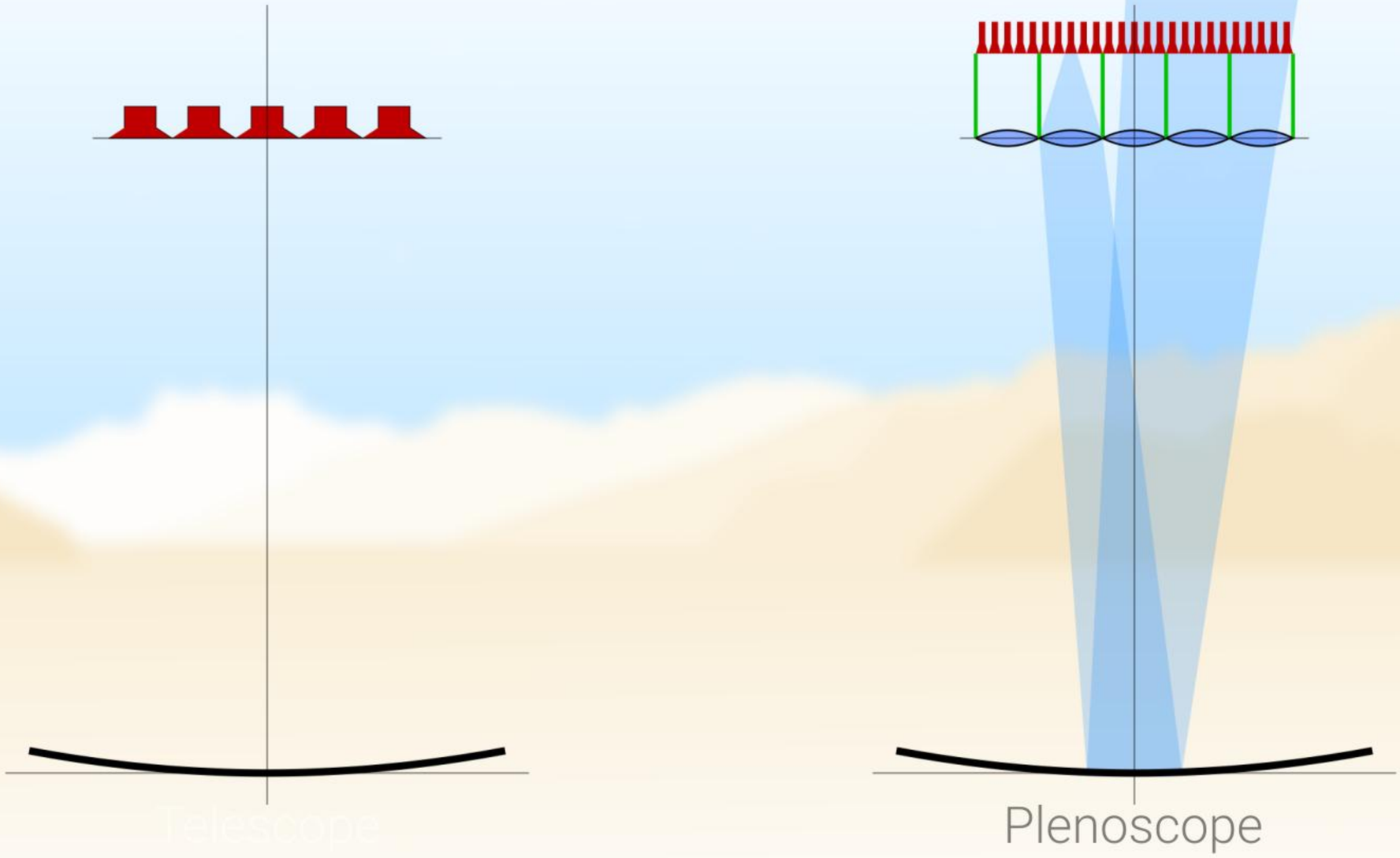
constrain

Optics



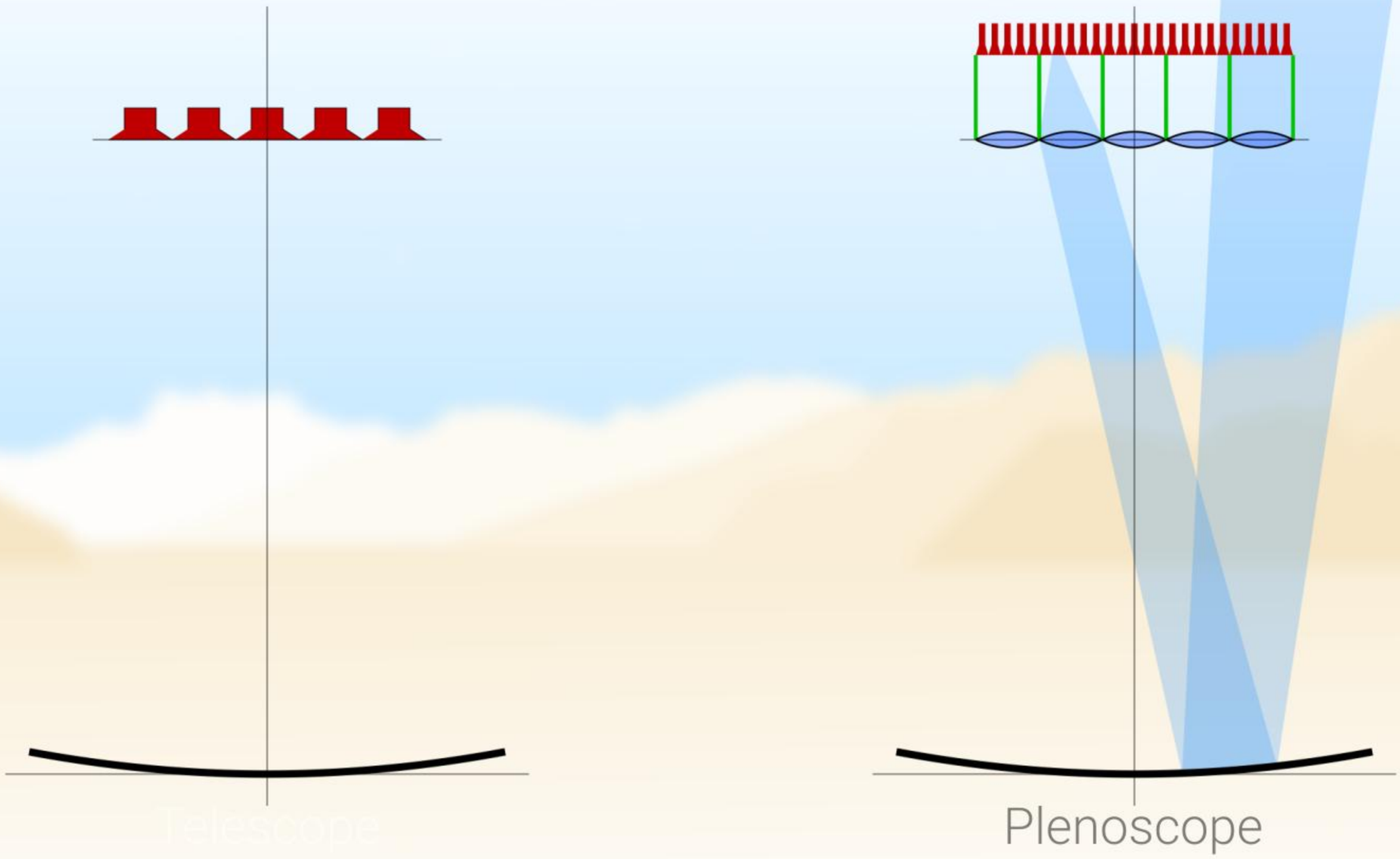
the

Optics



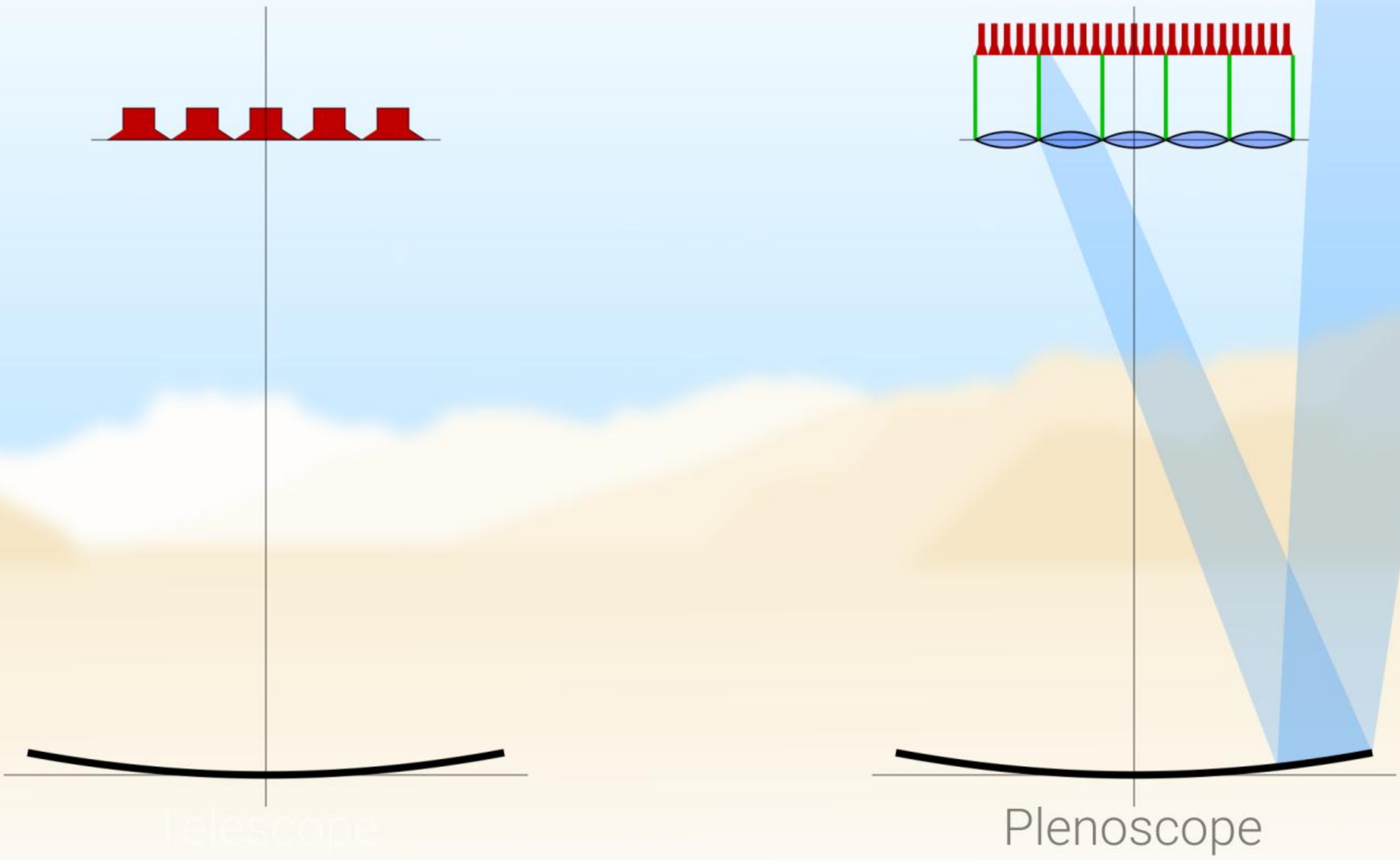
trajectories

Optics



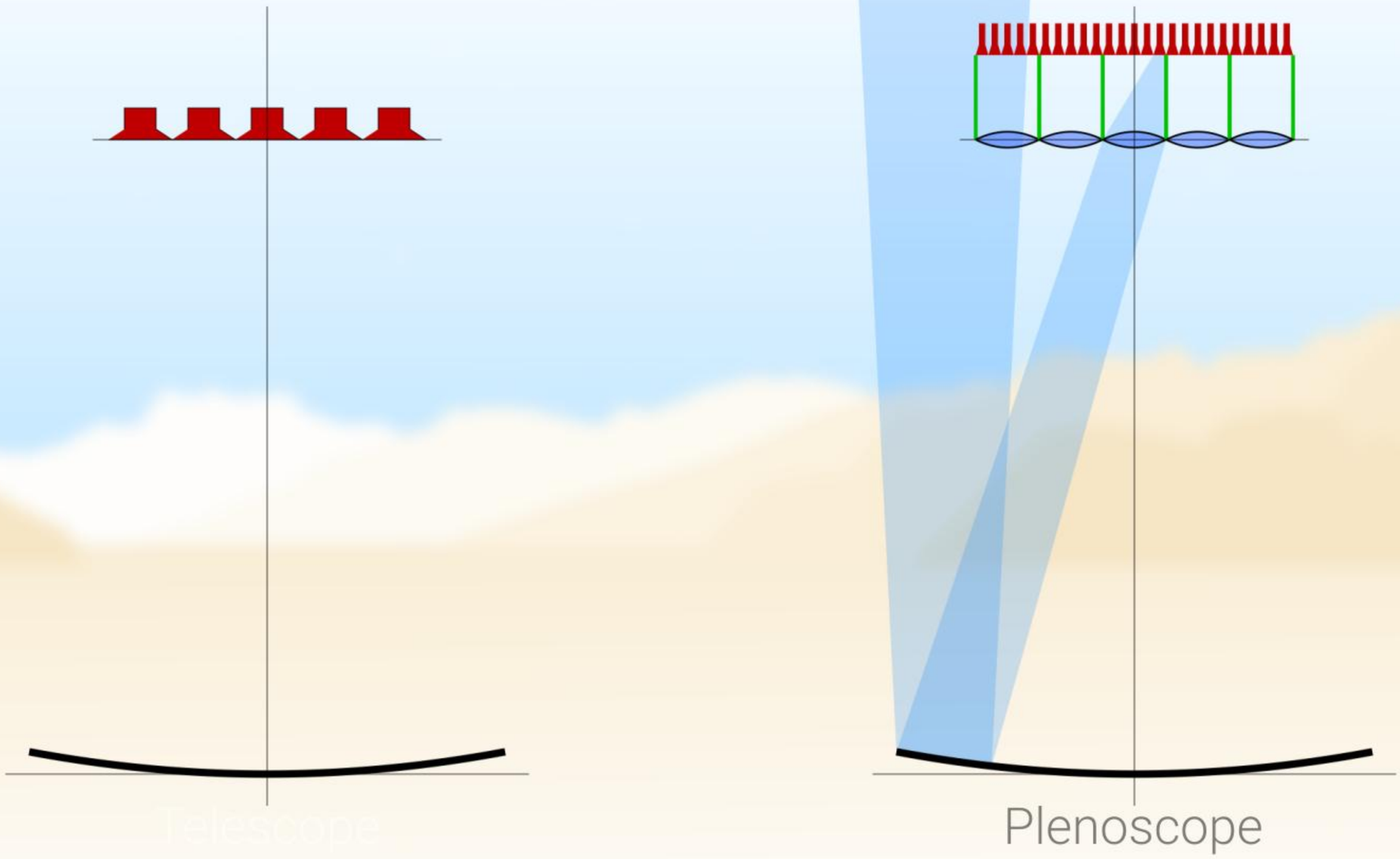
of

Optics



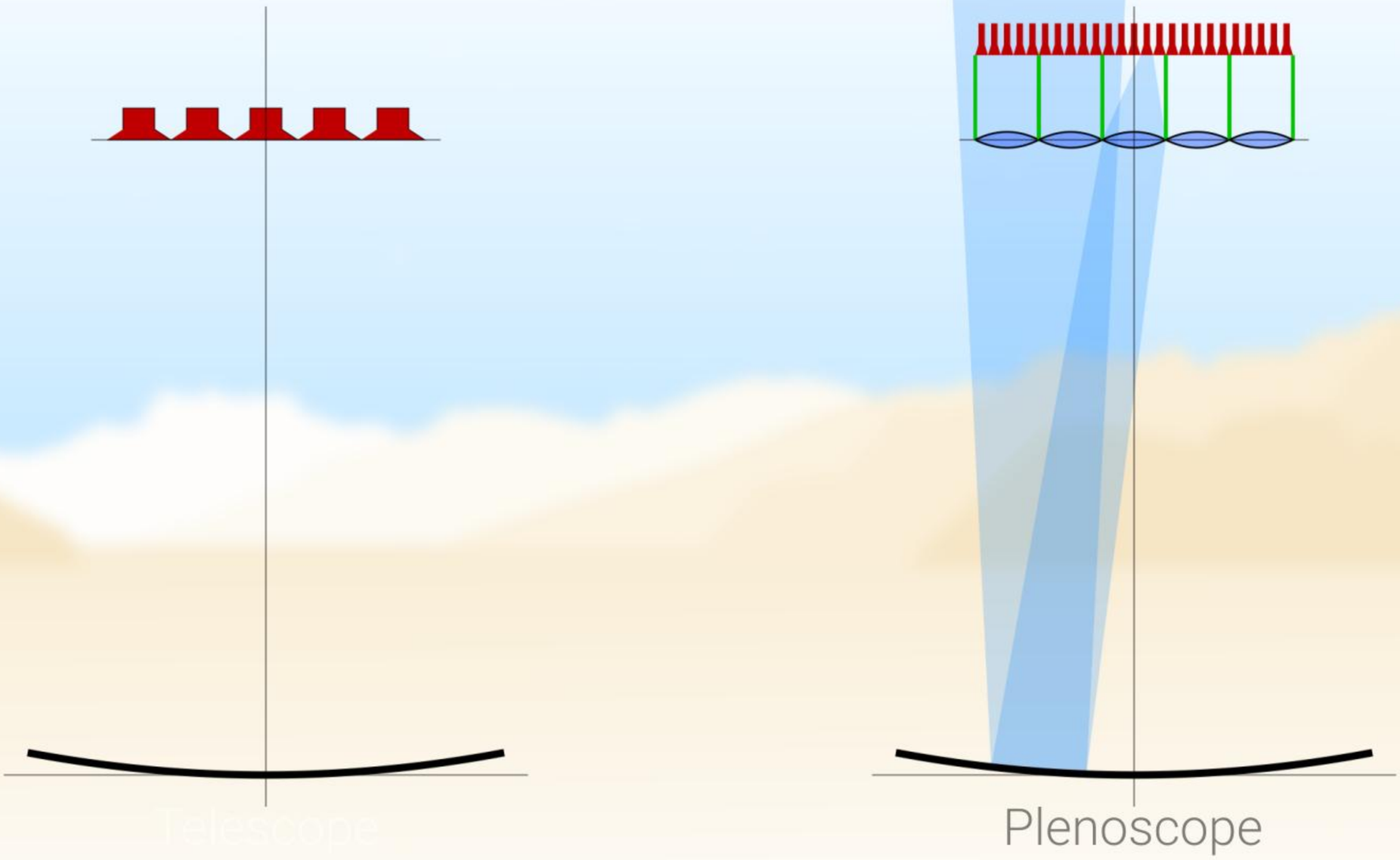
photons

Optics



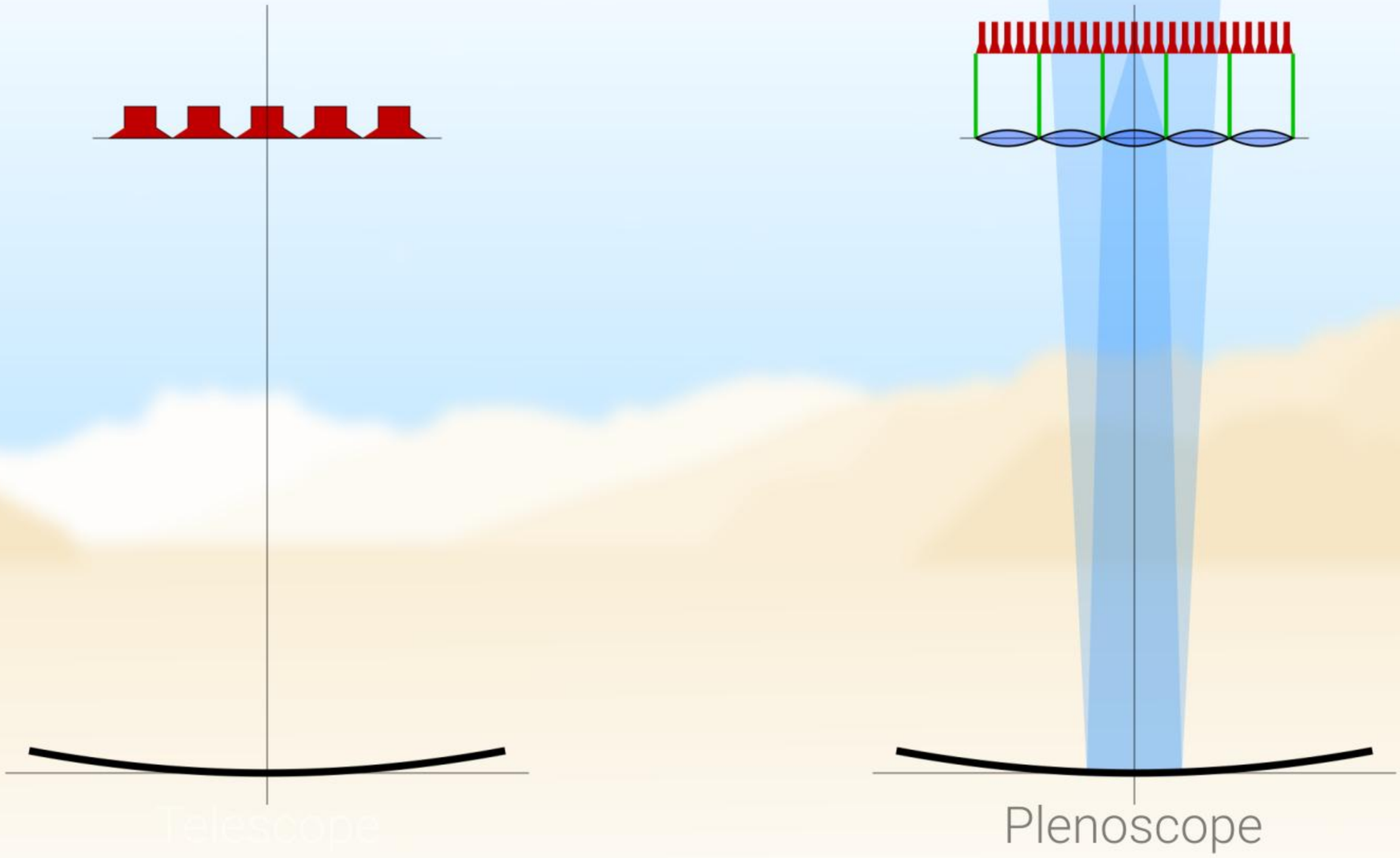
much

Optics



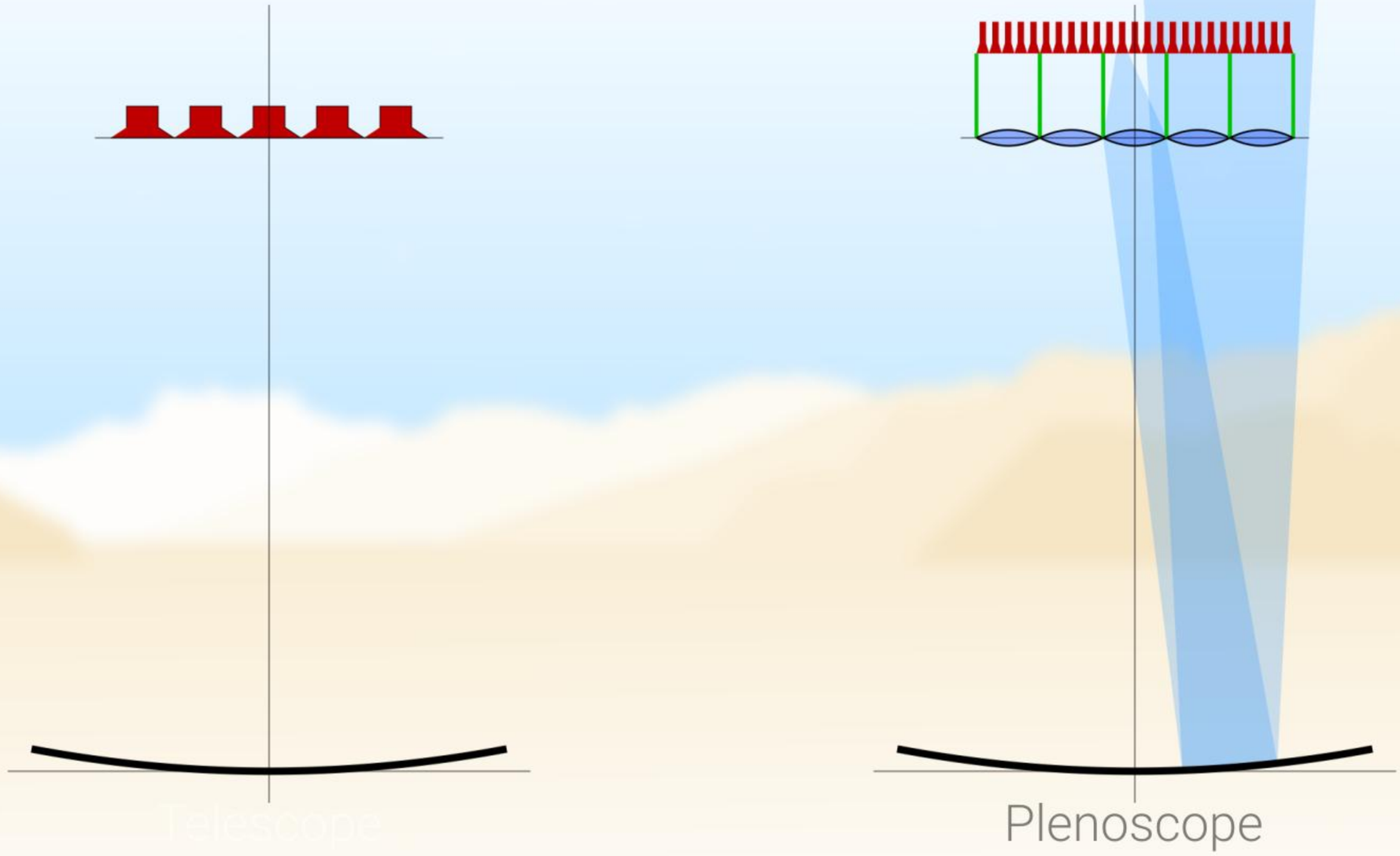
better

Optics



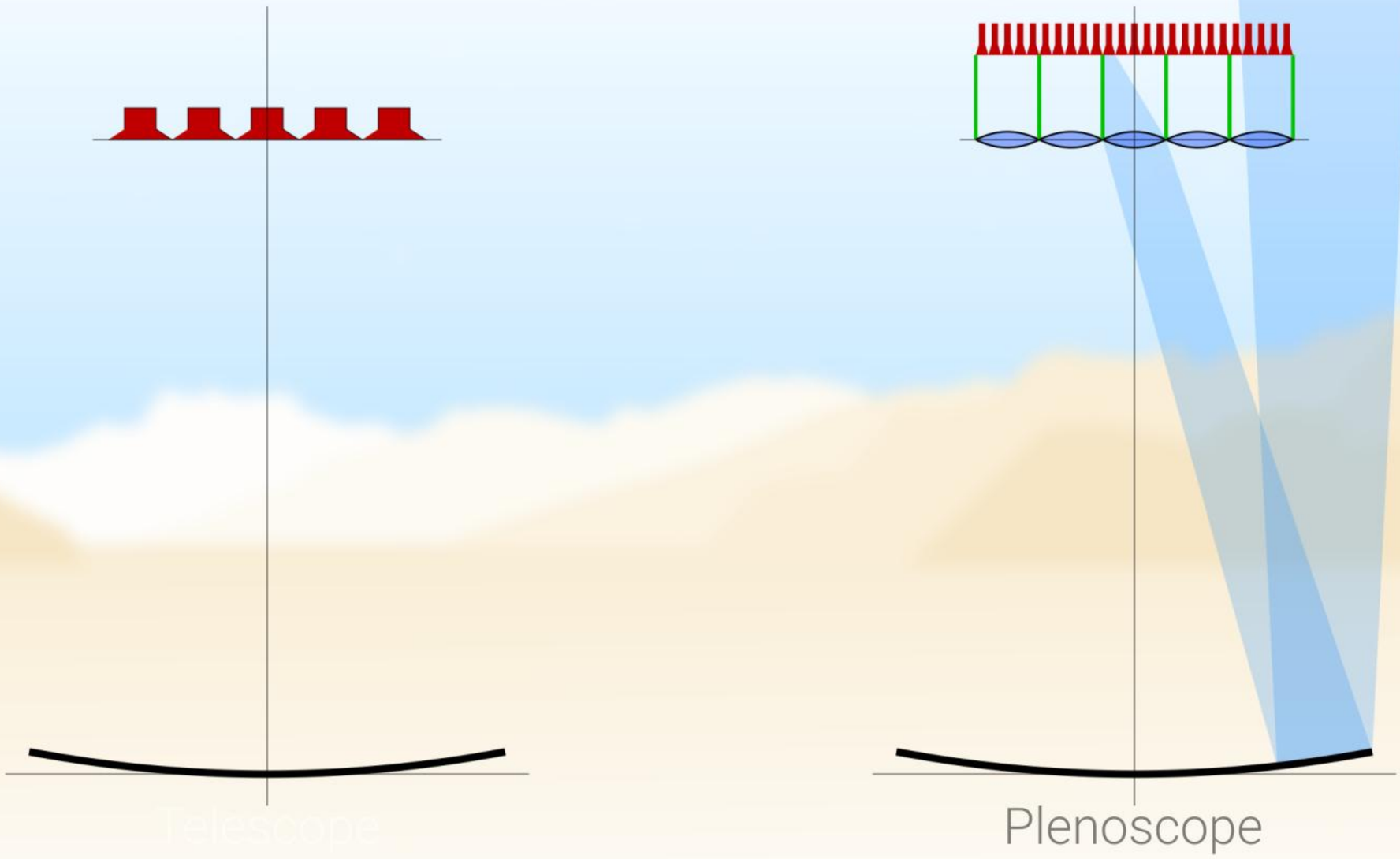
than

Optics



a

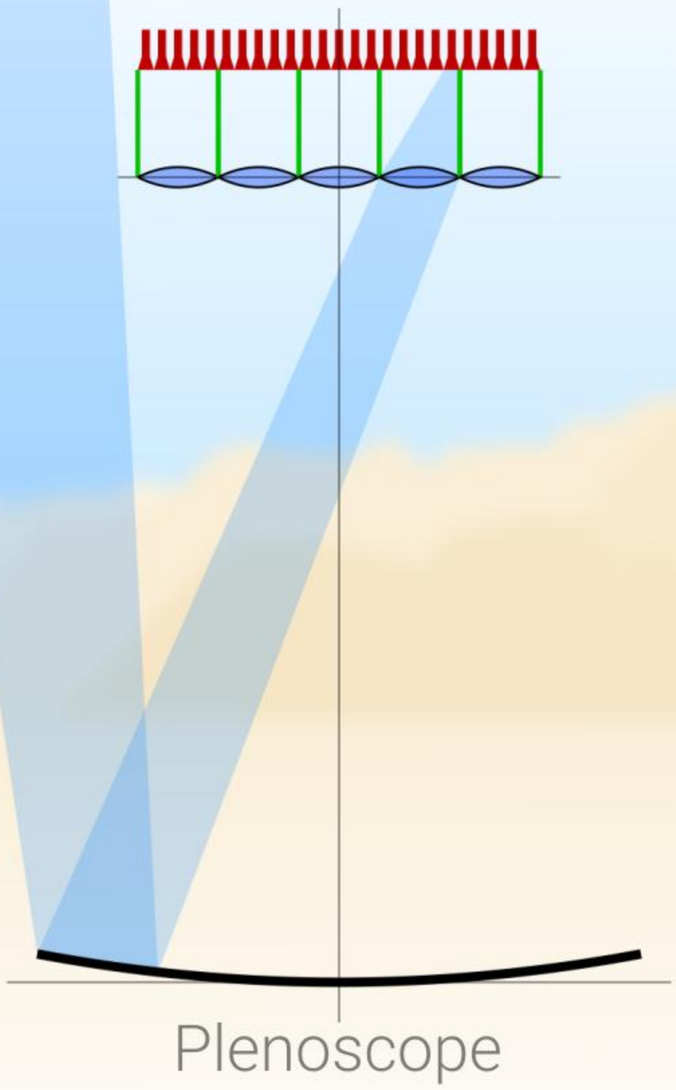
Optics



telescope.

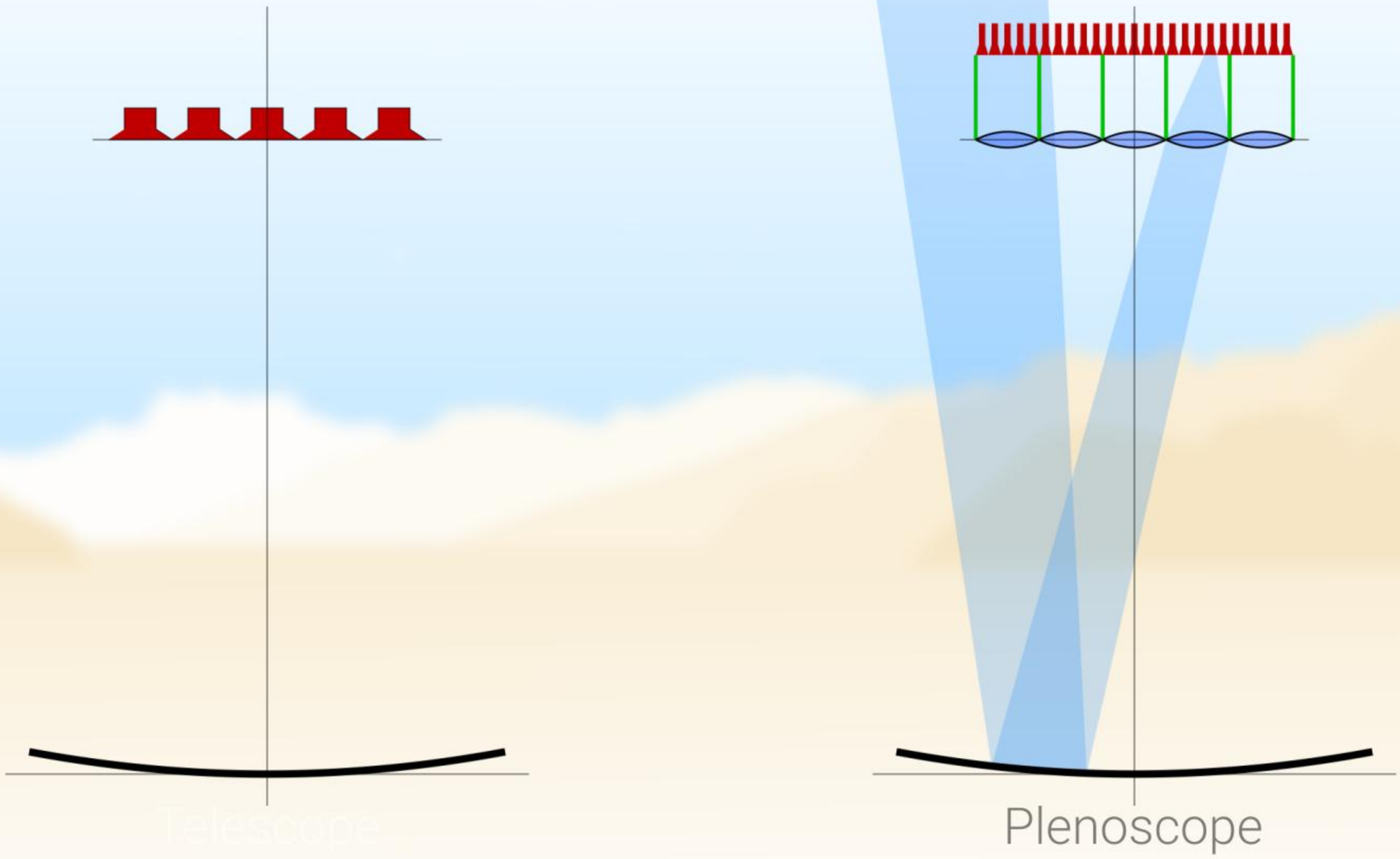
Optics

Telescope

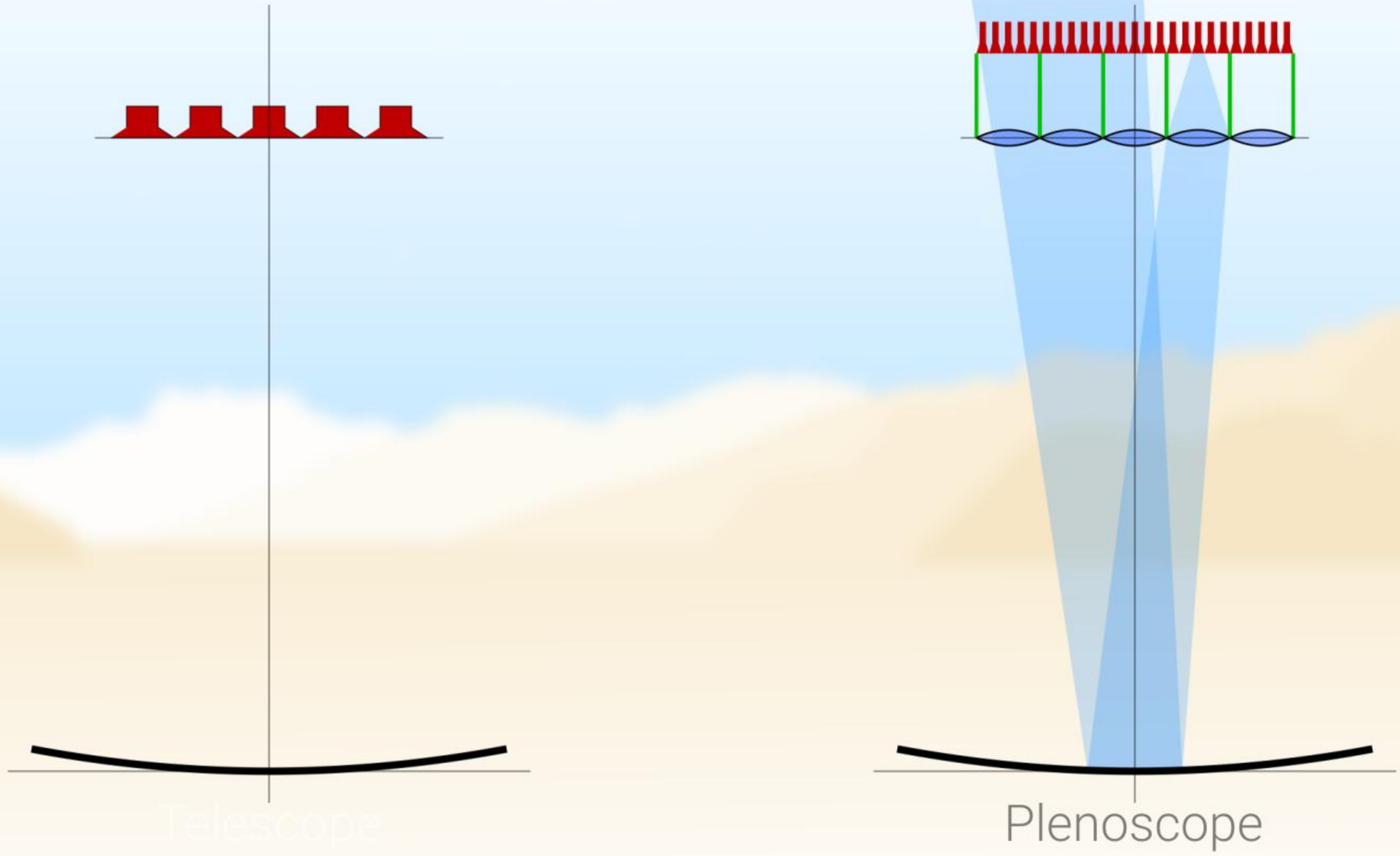


Plenoscope

Optics



Optics



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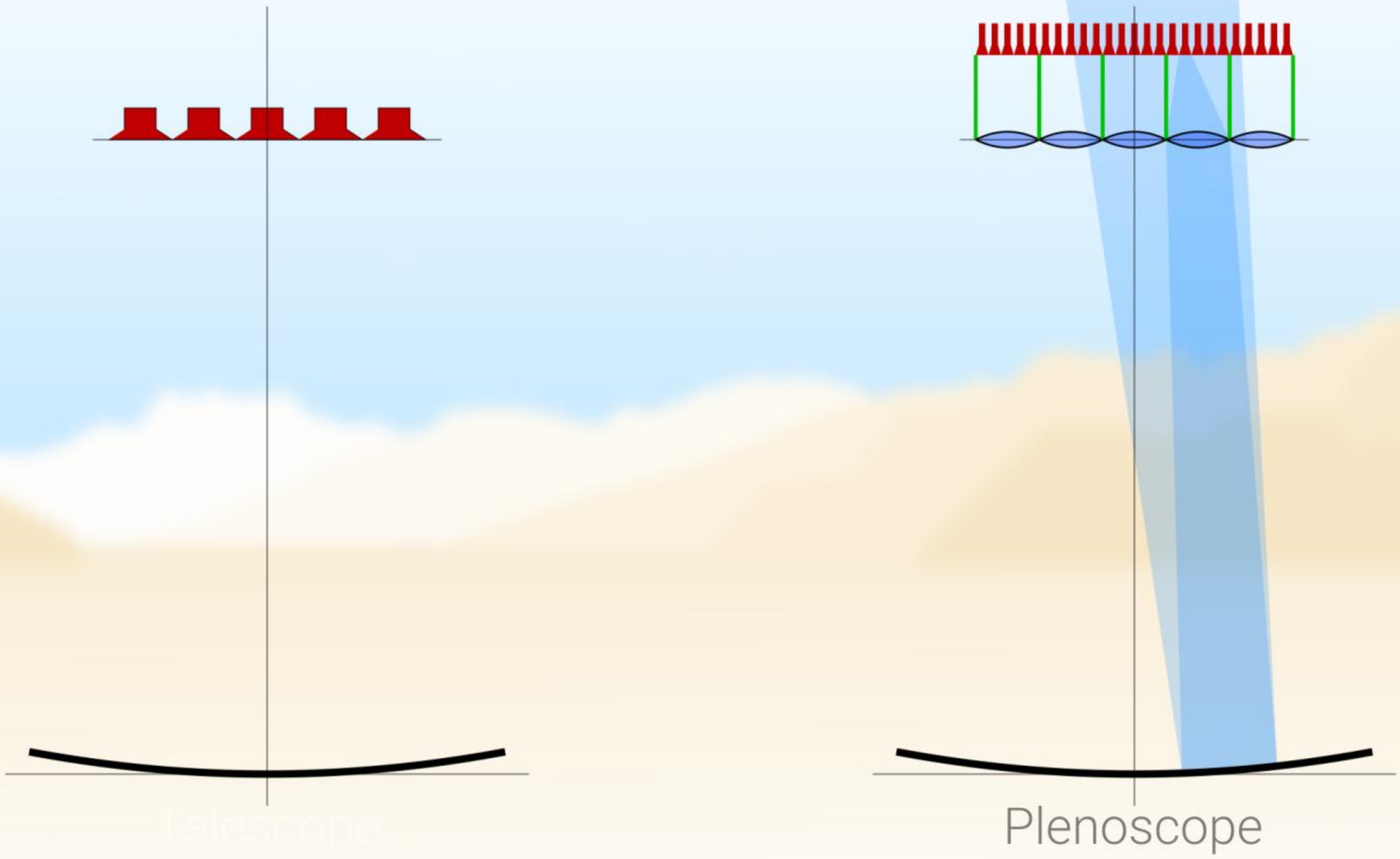

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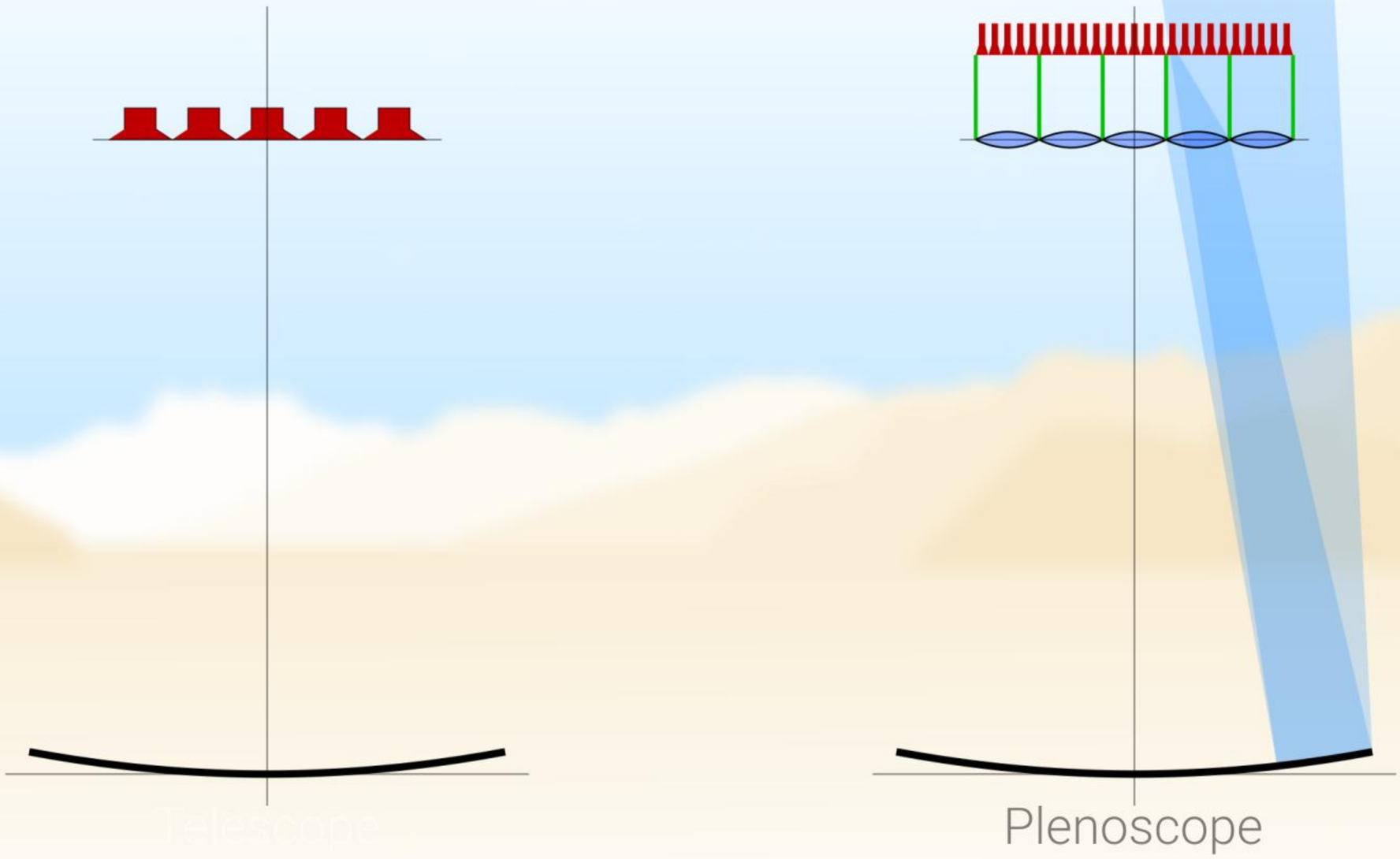

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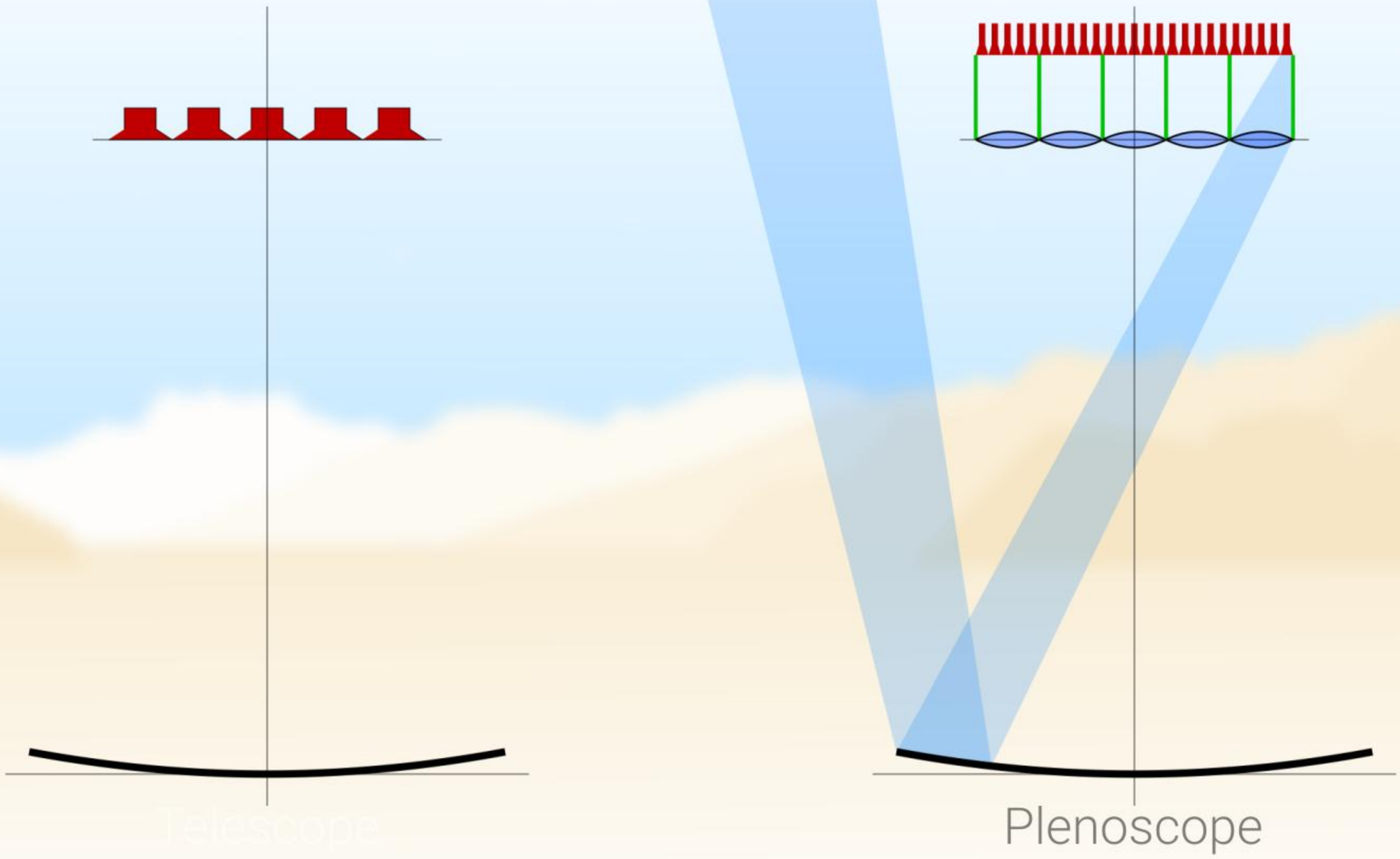

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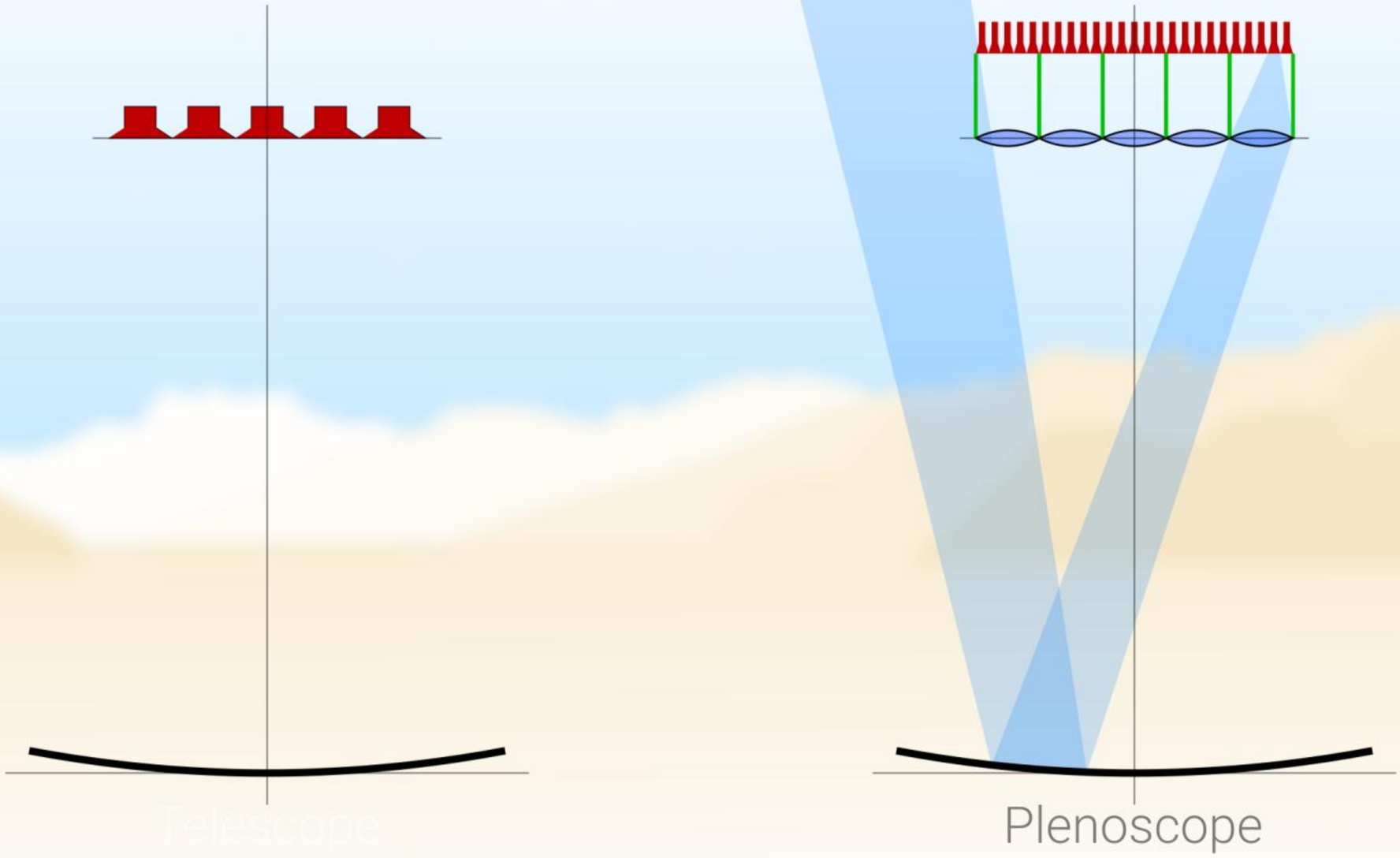

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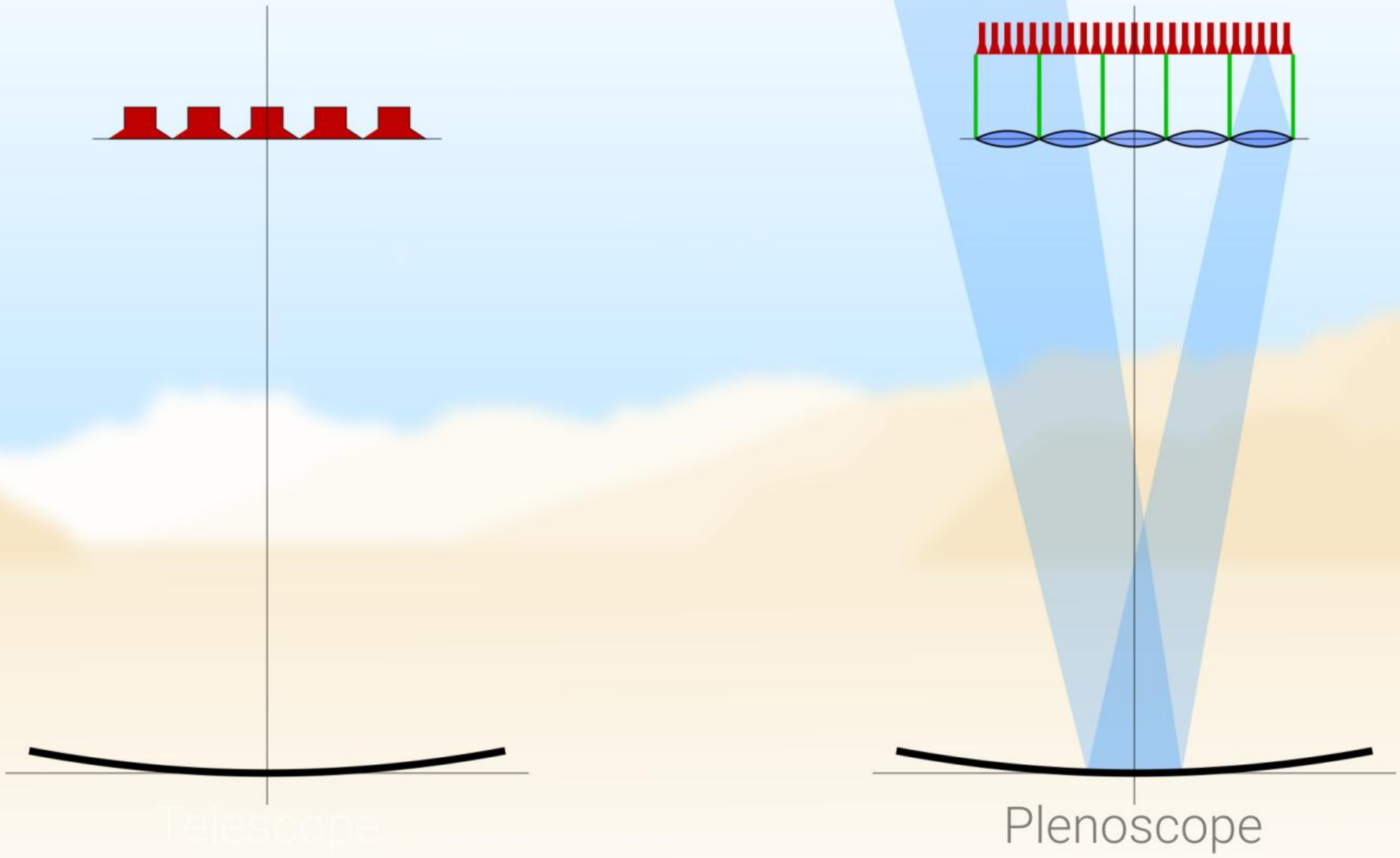

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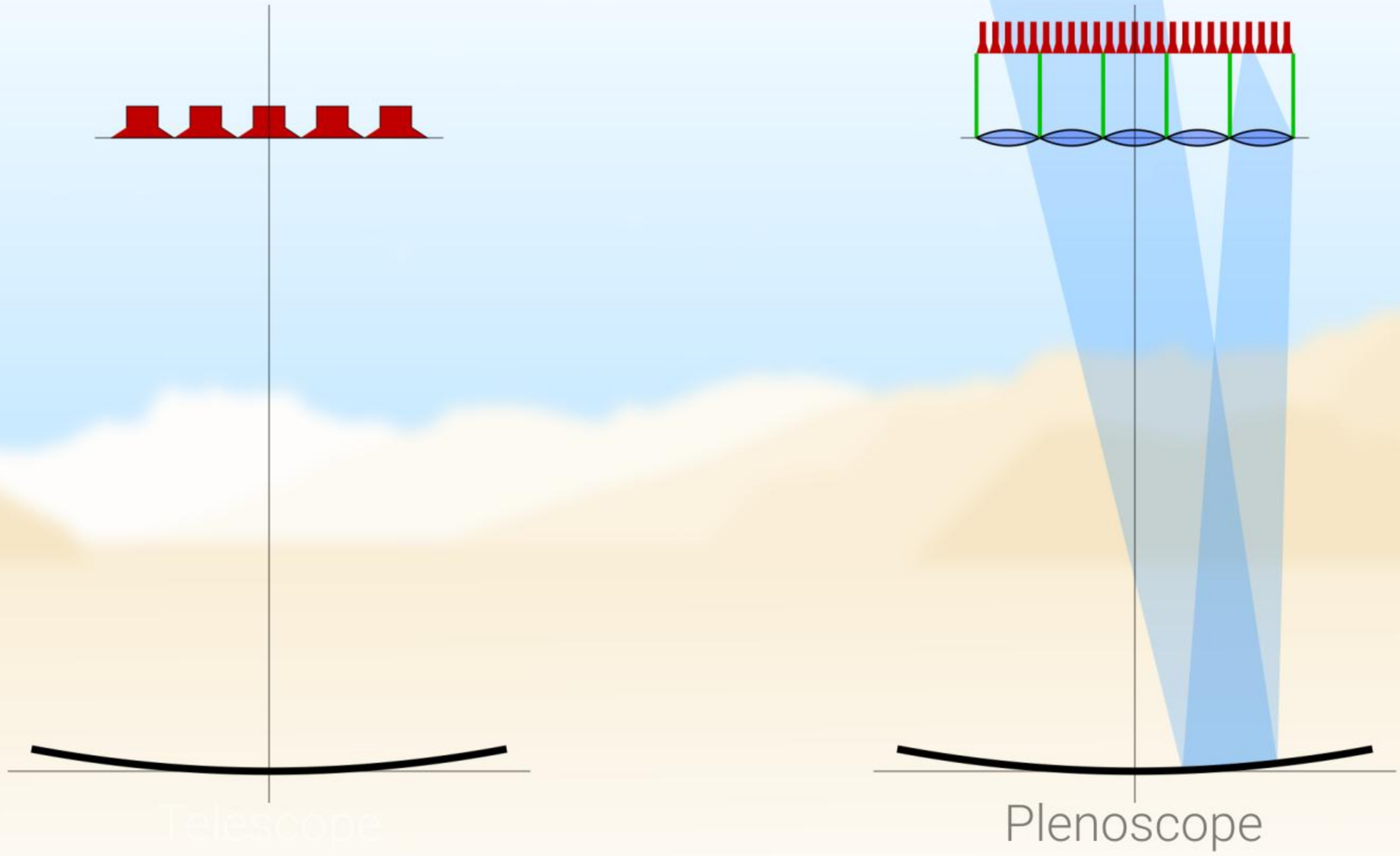

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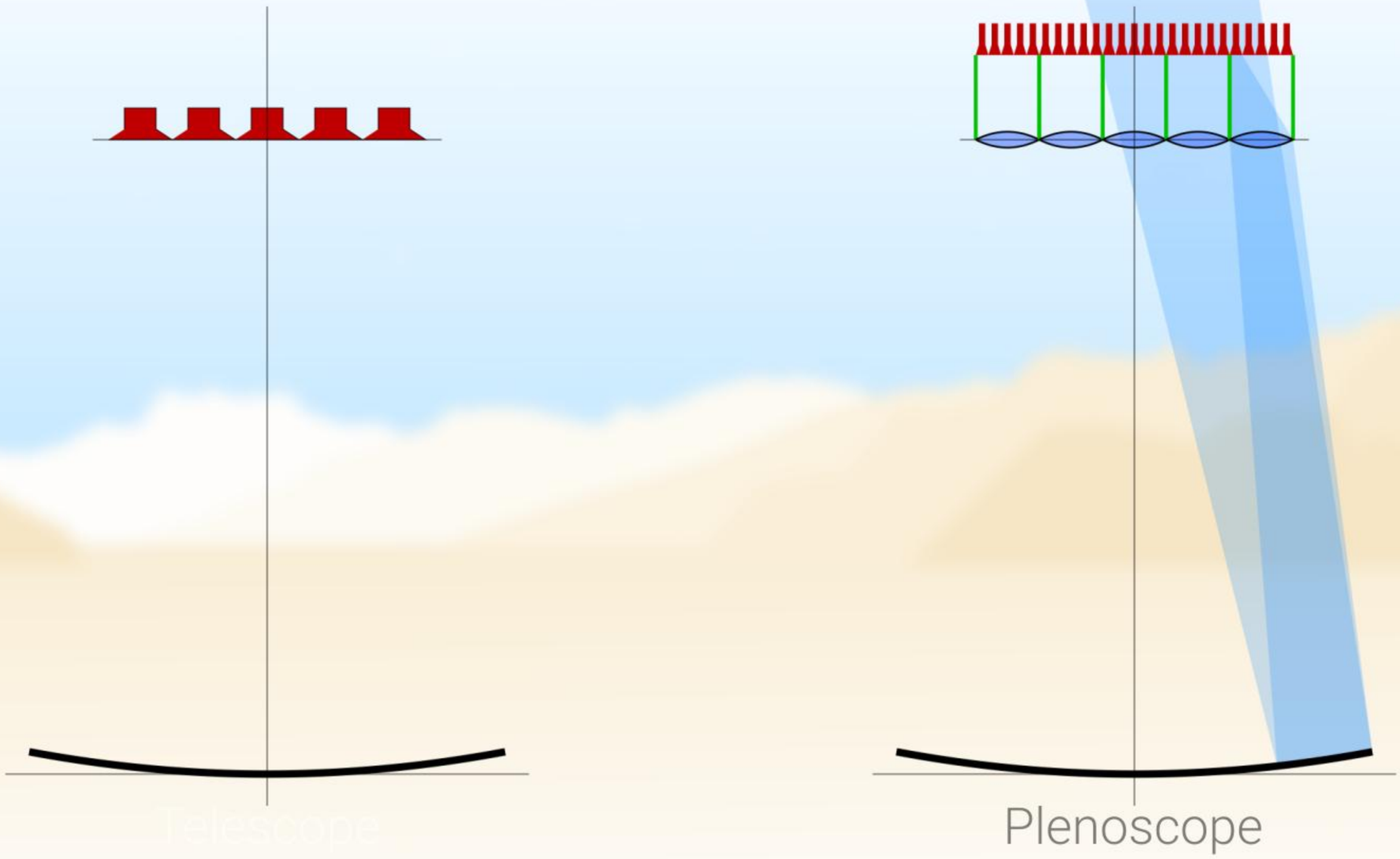

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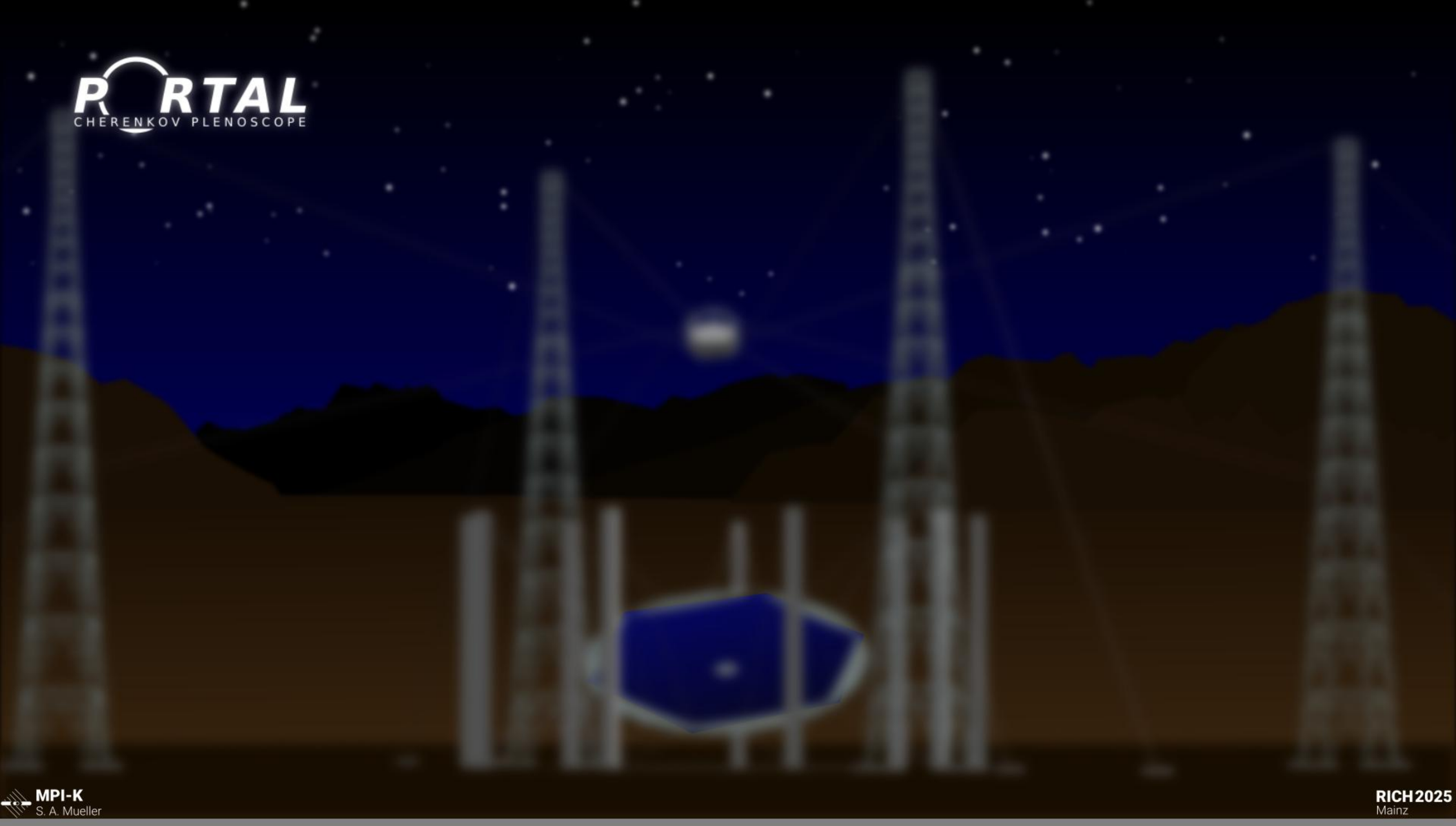
PORTAL
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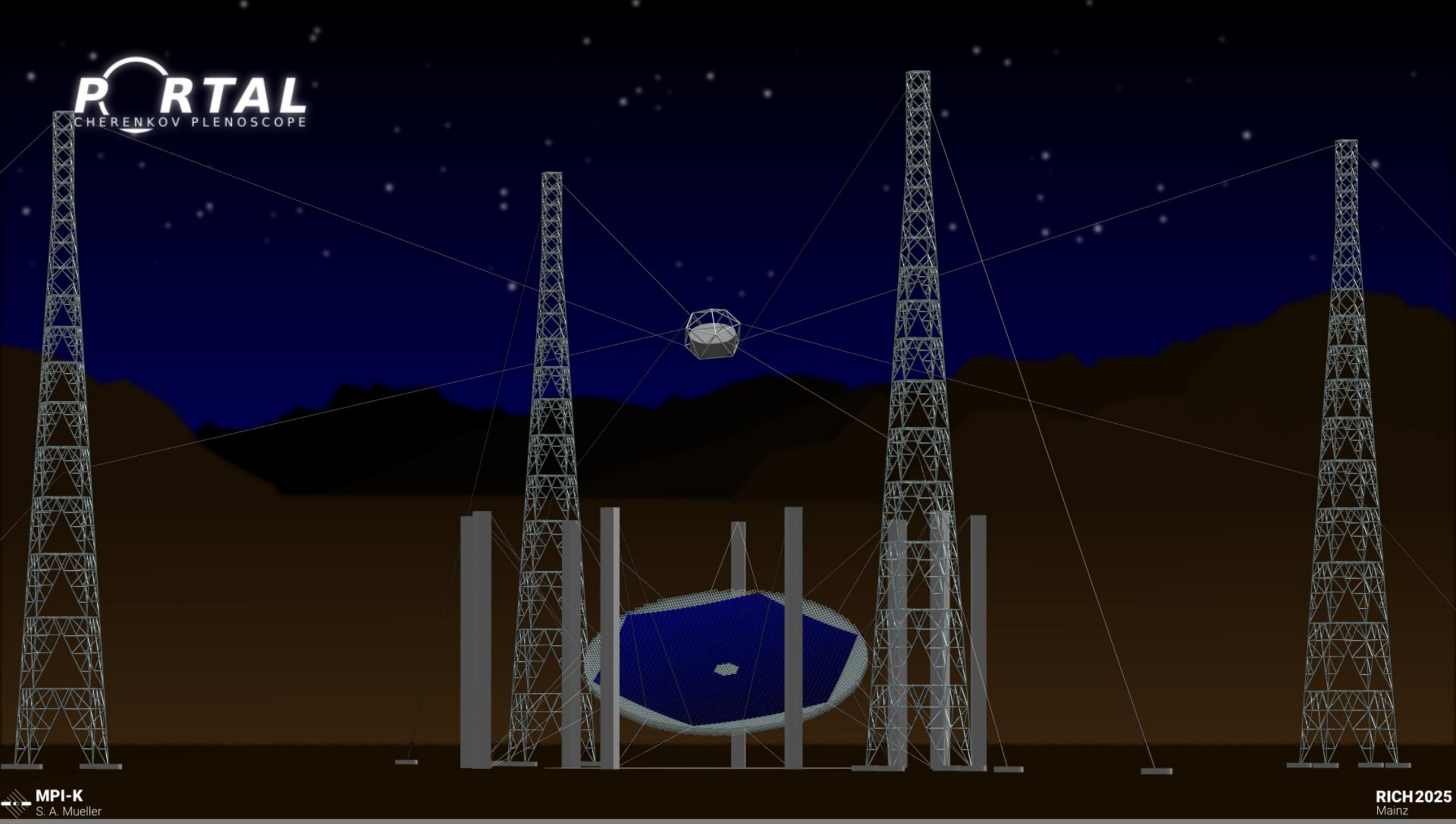
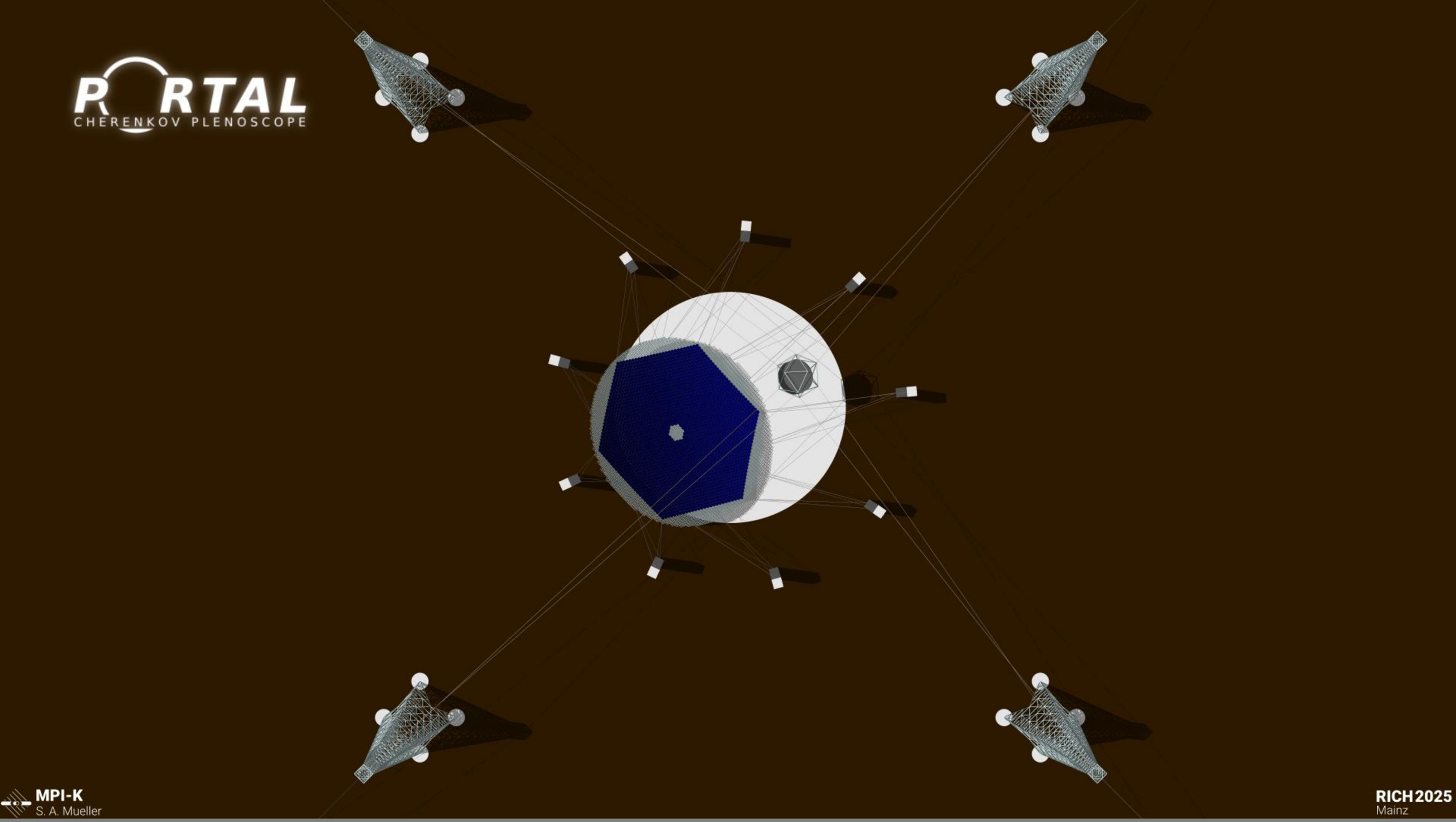
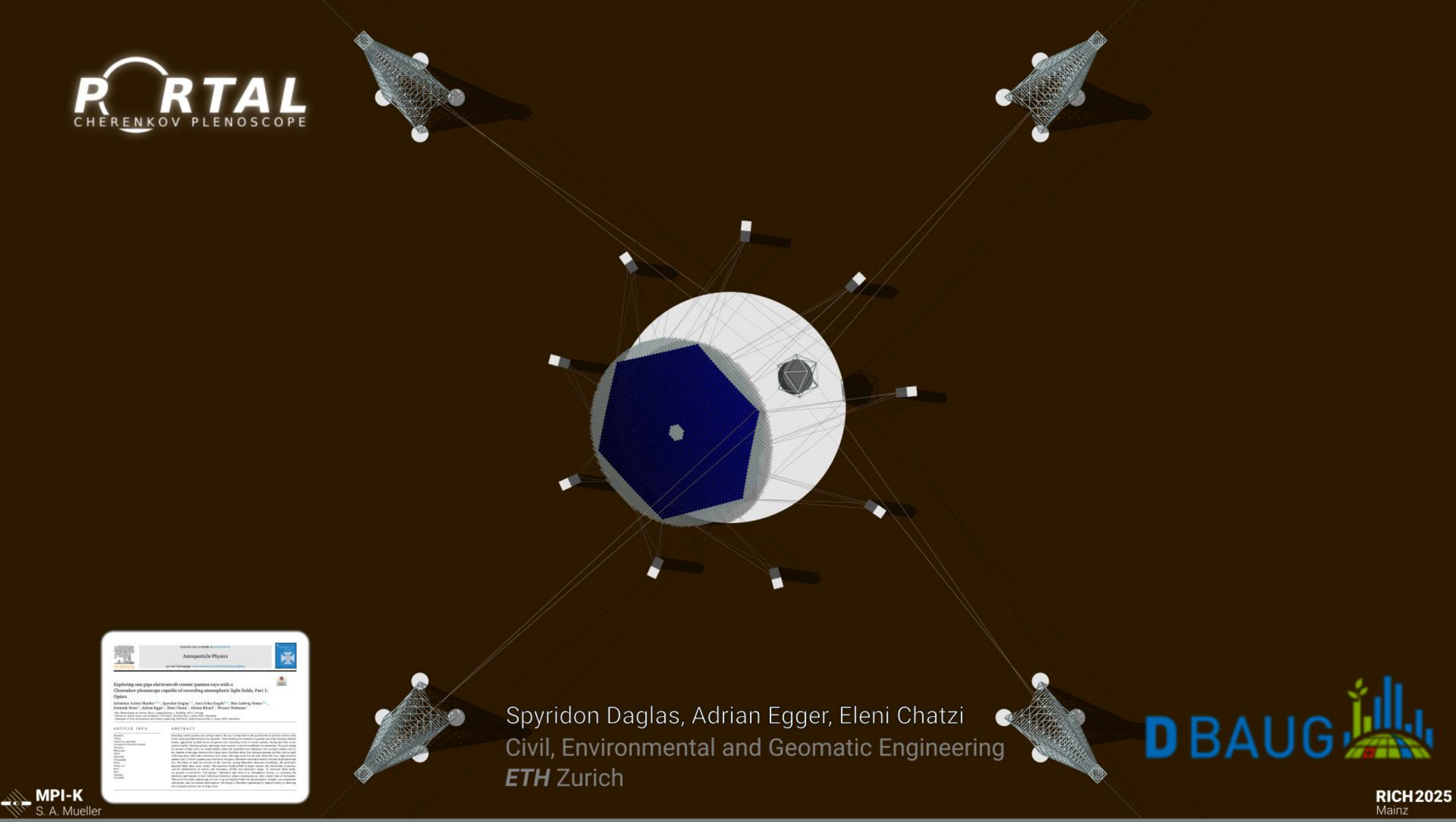


To discuss the optical performance, we now take a look at a specific design for a Cherenkov plenoscope named Portal.



Portal's goal is to lower the energy threshold of the atmospheric Cherenkov method down to one giga electronvolt.



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Civil, Environmental and Geomatic Engineering
ETH Zurich

MPI-K
S. A. Mueller

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Mainz

So together with our colleagues from civil engineers, ...

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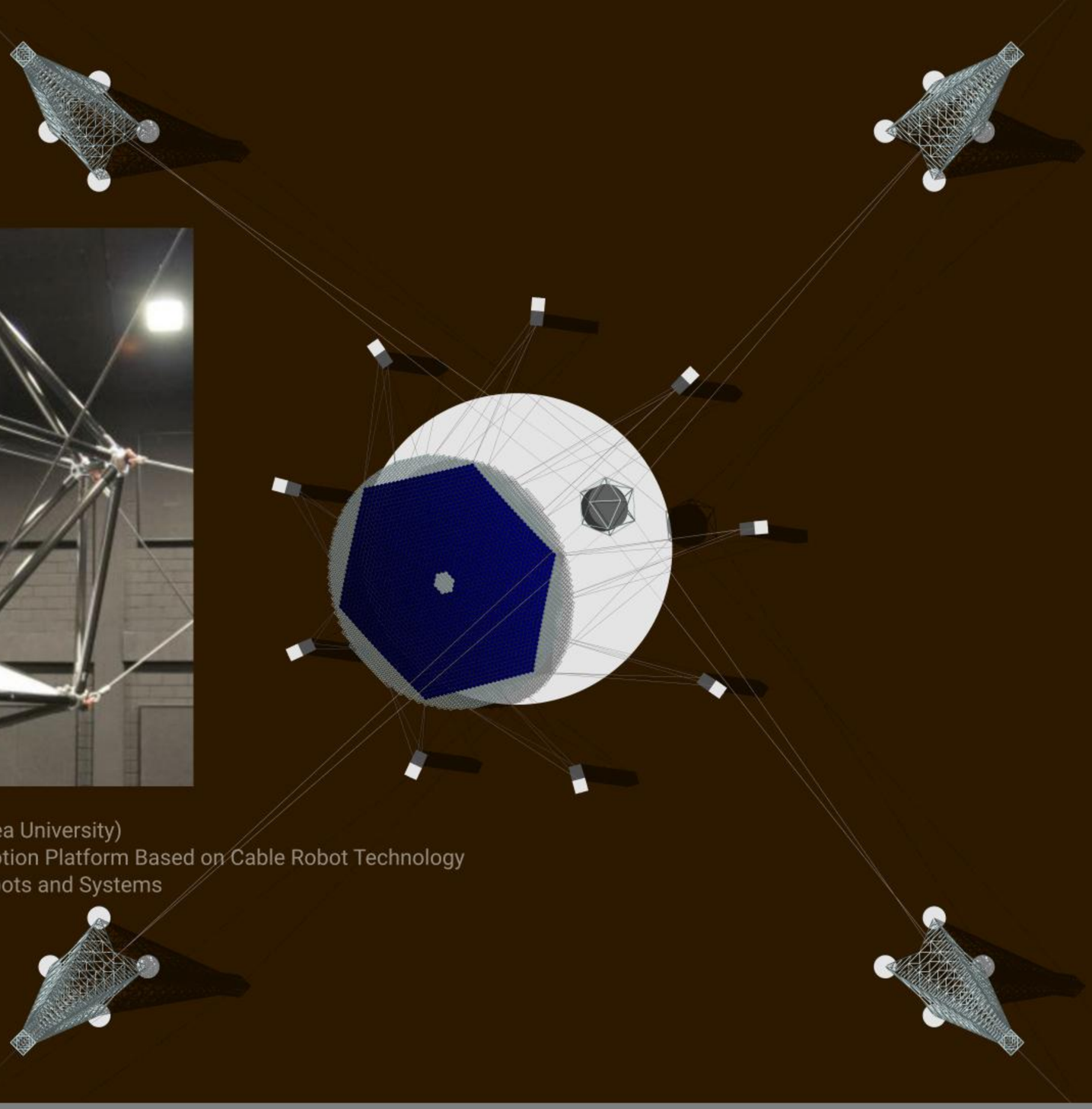
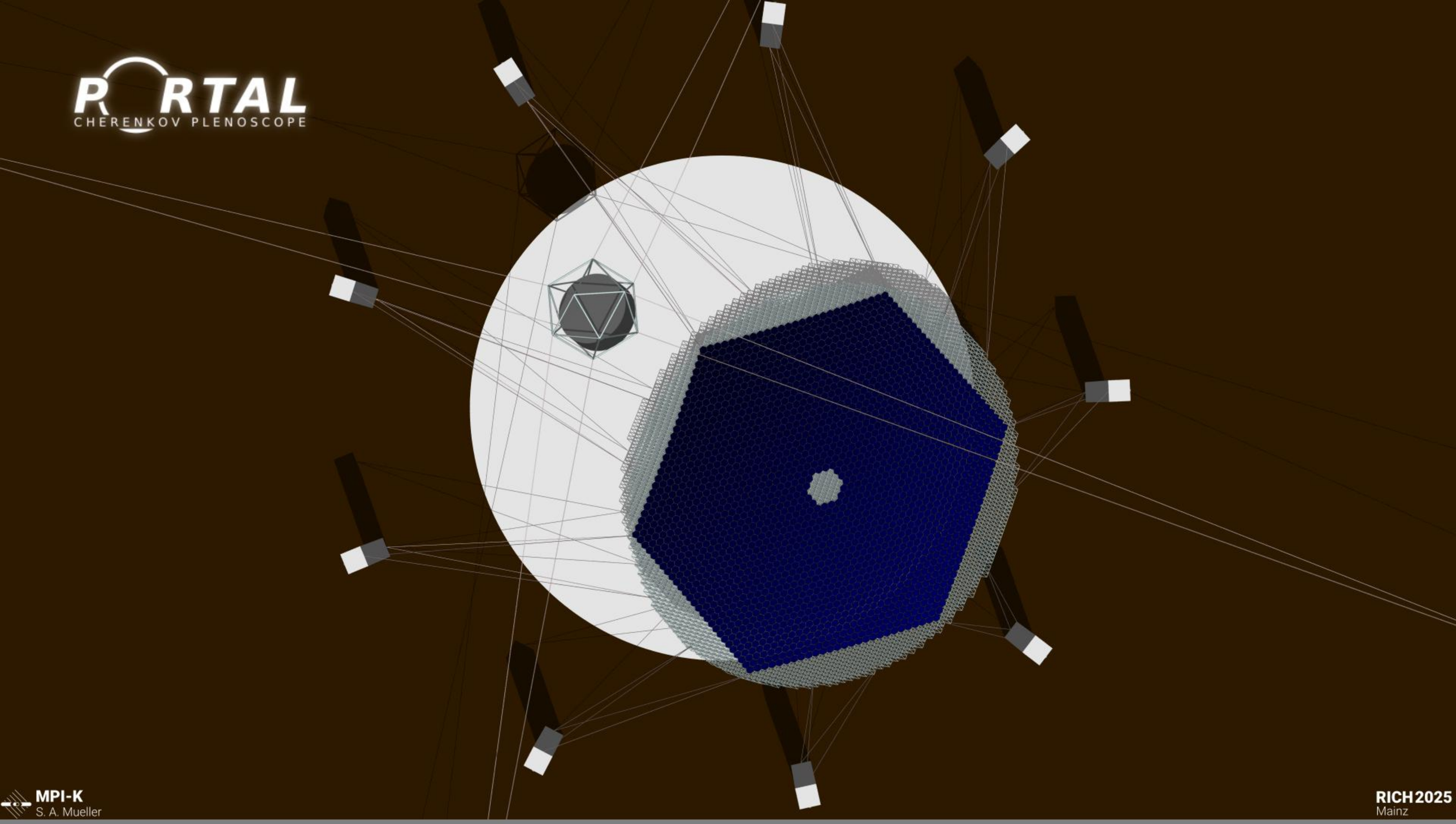
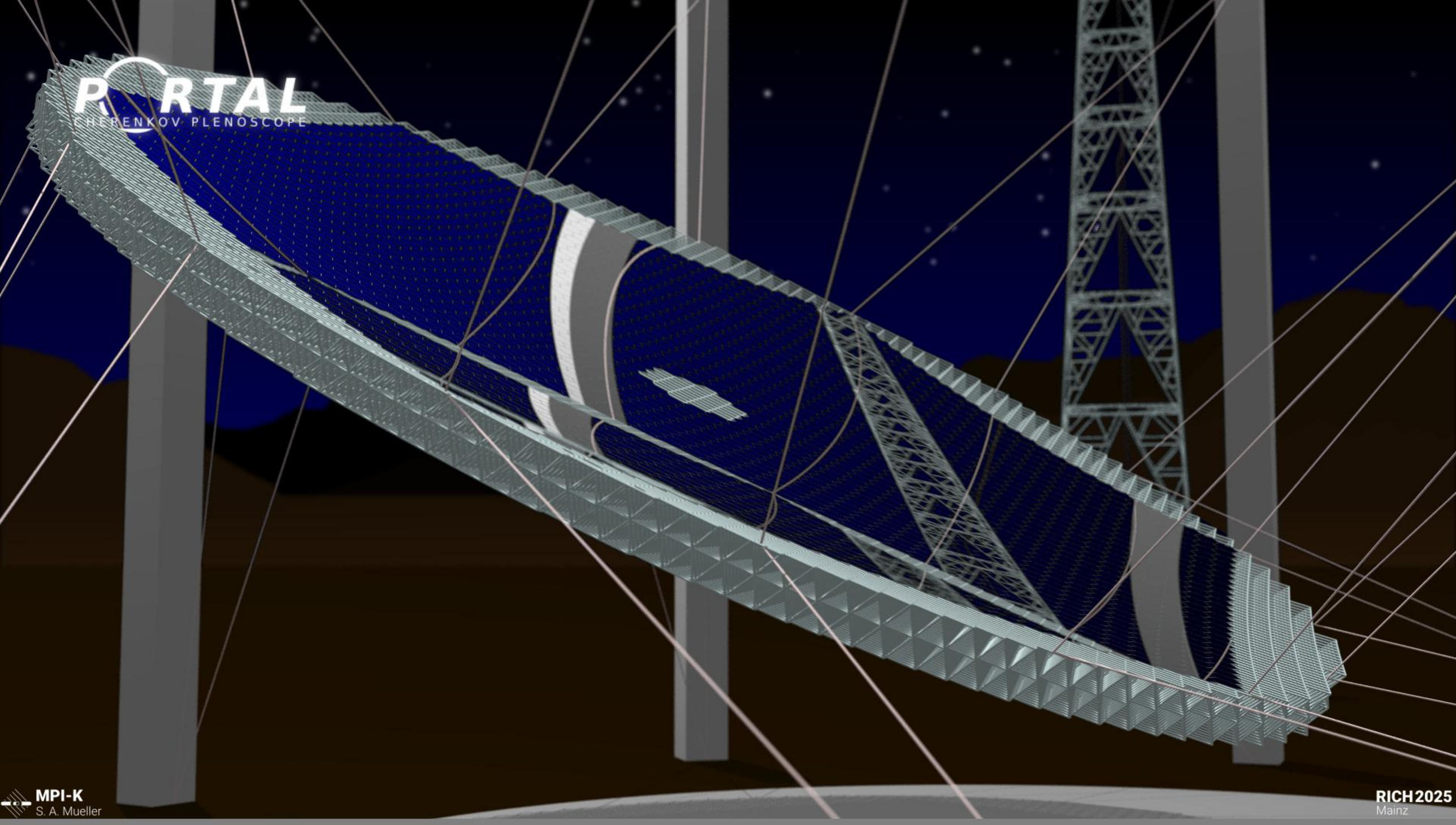
Philipp Miermeister et al. 2016
(Fraunhofer IPA, MPI bio. Cybernetics, Korea University)
The CableRobot Simulator: Large Scale Motion Platform Based on Cable Robot Technology
International Conference on Intelligent Robots and Systems
Daejeon, Korea



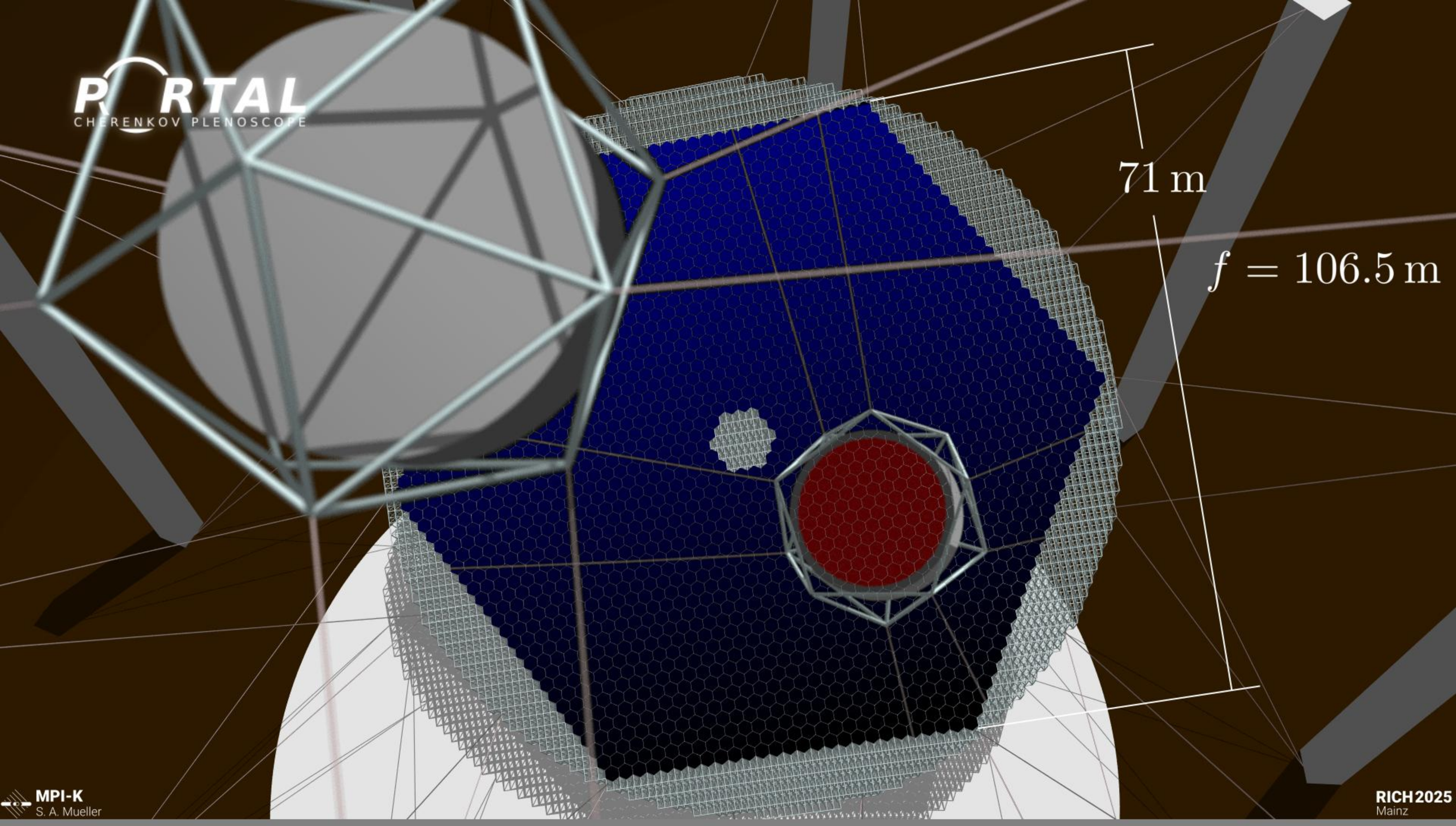
we gave Portal two independent cable-robots to mount and point its camera



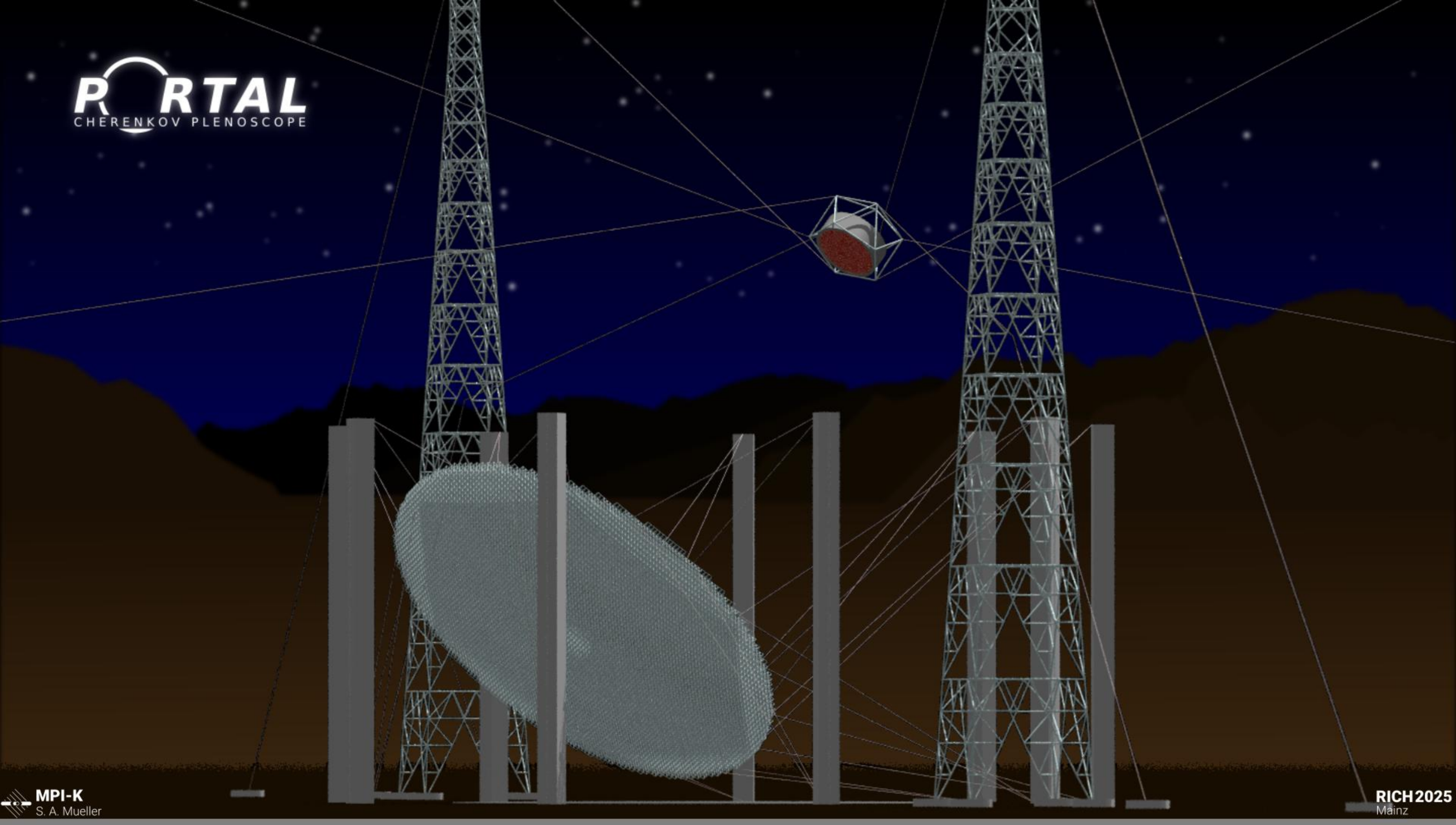
and mirror separately.



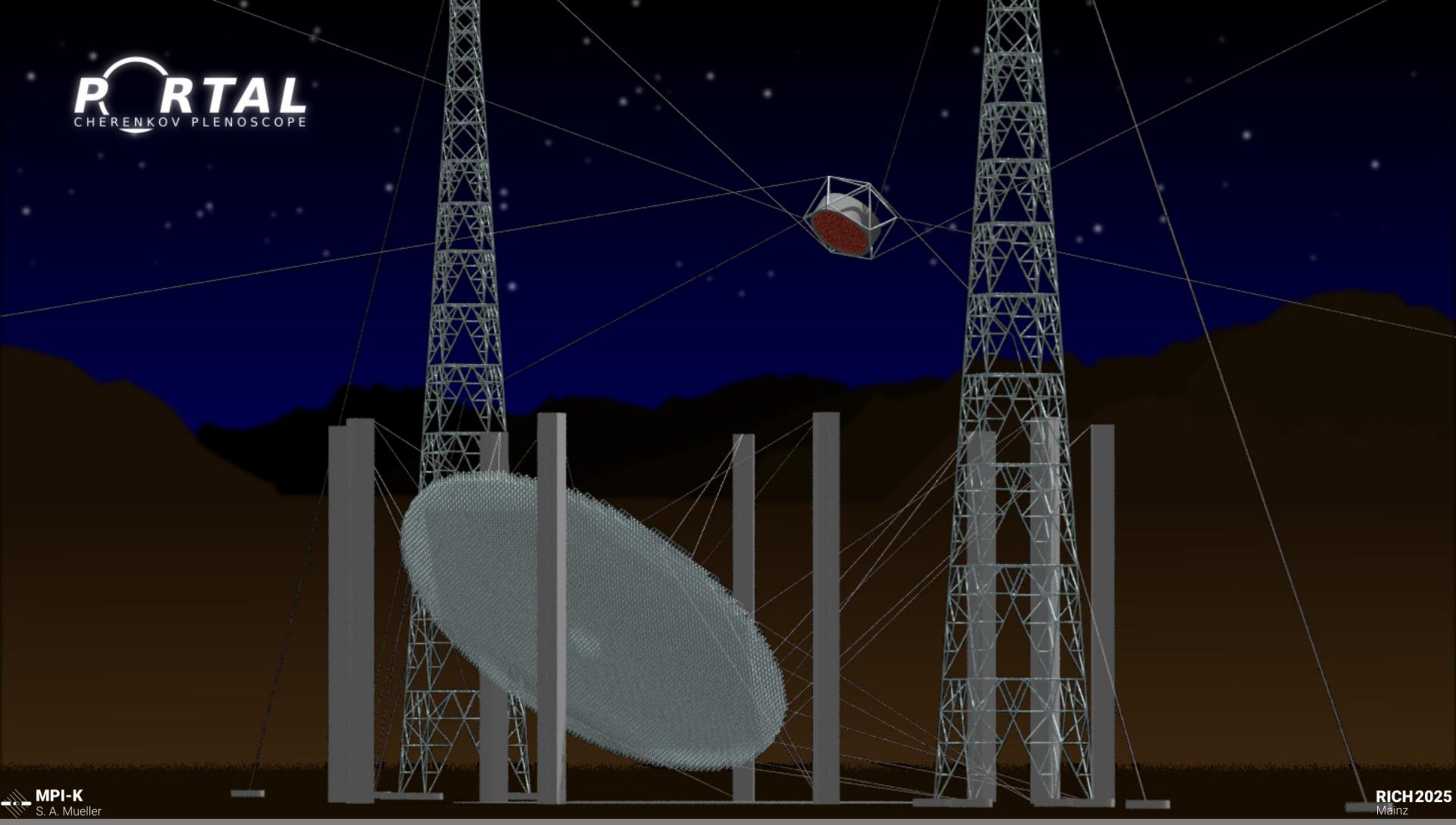
Portals mirror is seventy one meters in diameter,



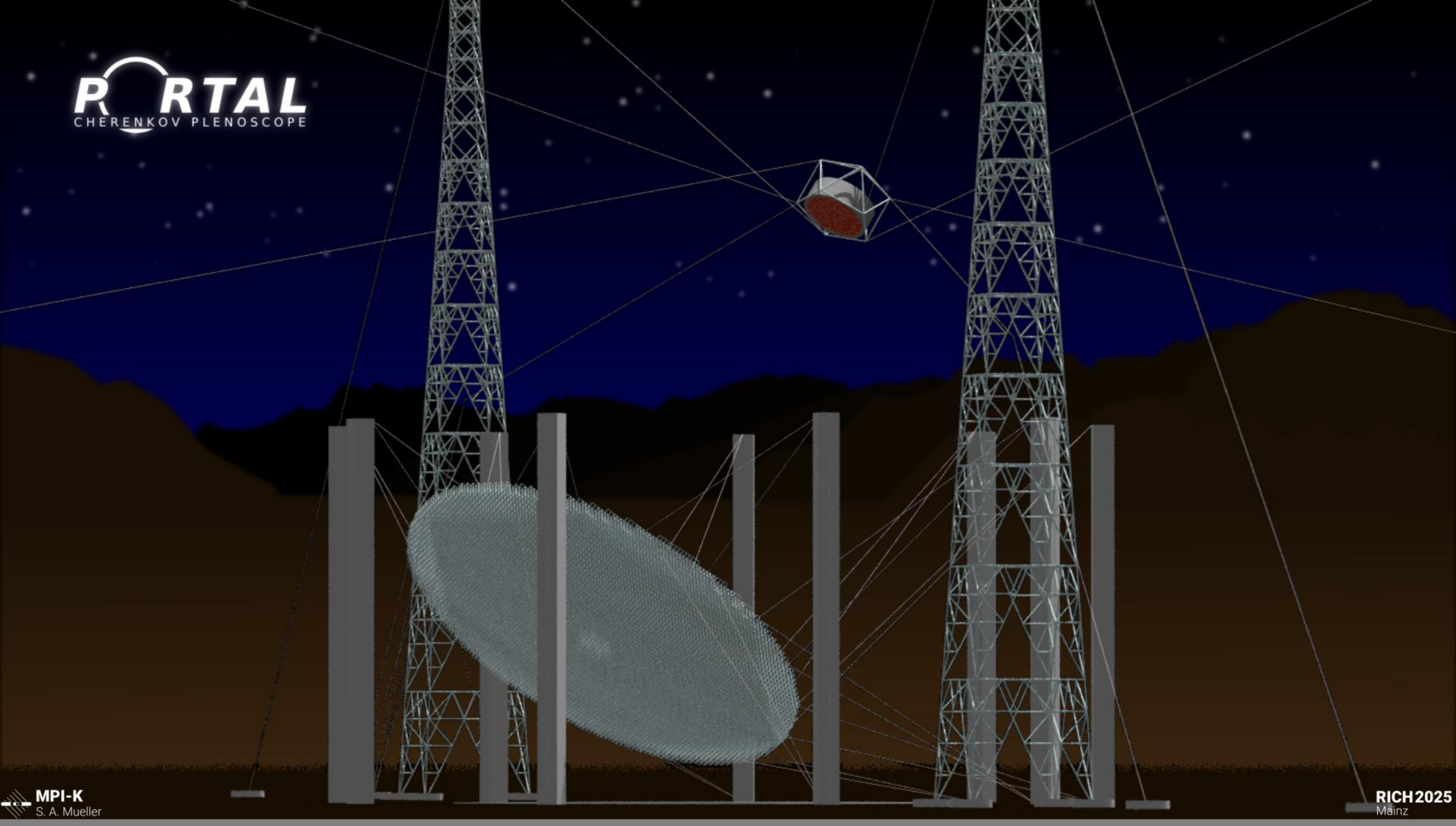
has a focal-ratio of one point five.



When pointing, the cablerobots move in opposite directions to effectively rotate both mirror and camera around their common center.



Unlike the altitude-azimuth mount, the cablerobot has no singularity near the zenith what allows it to always move along the great circle and thus makes it intrinsically faster.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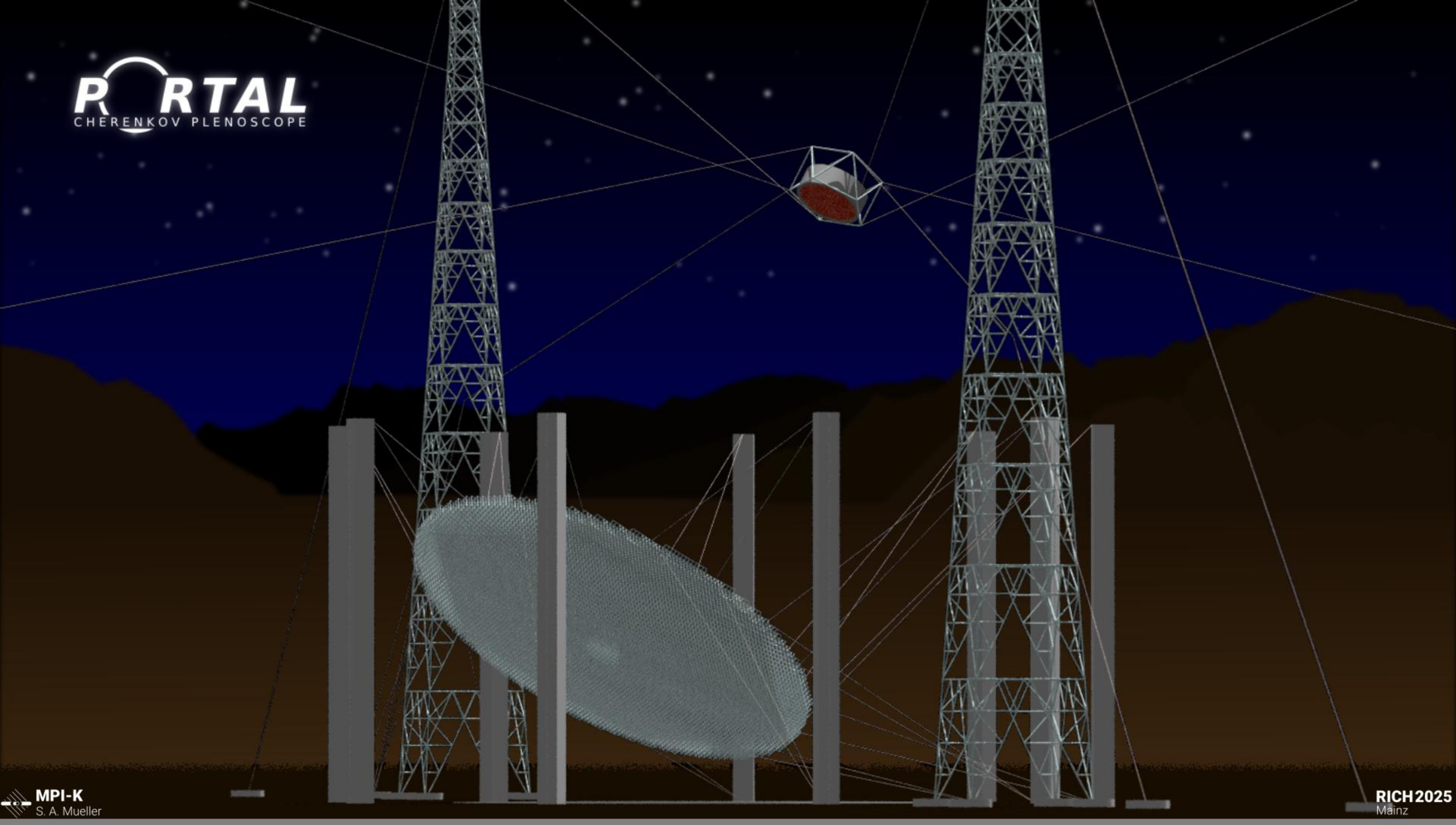
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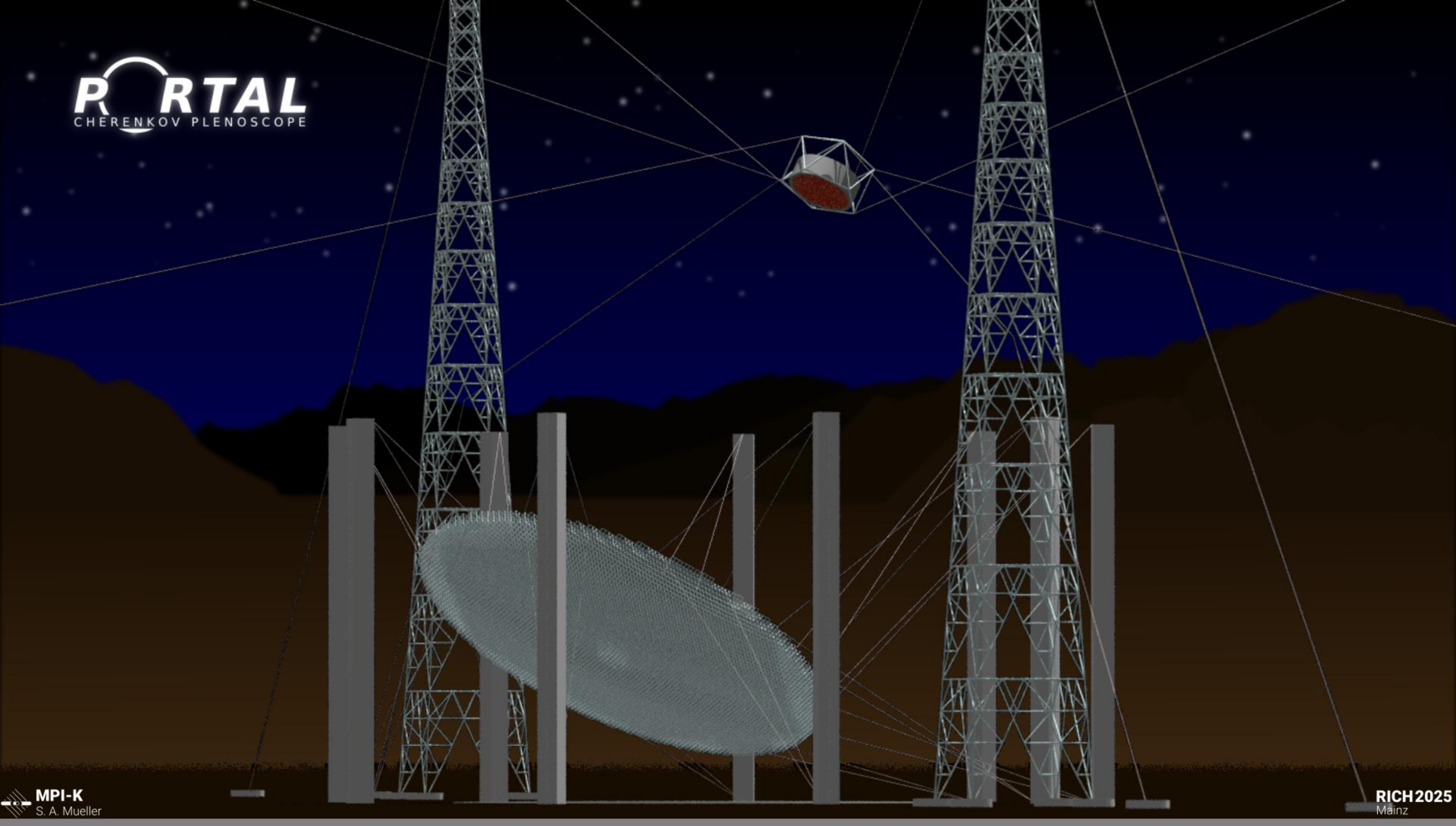
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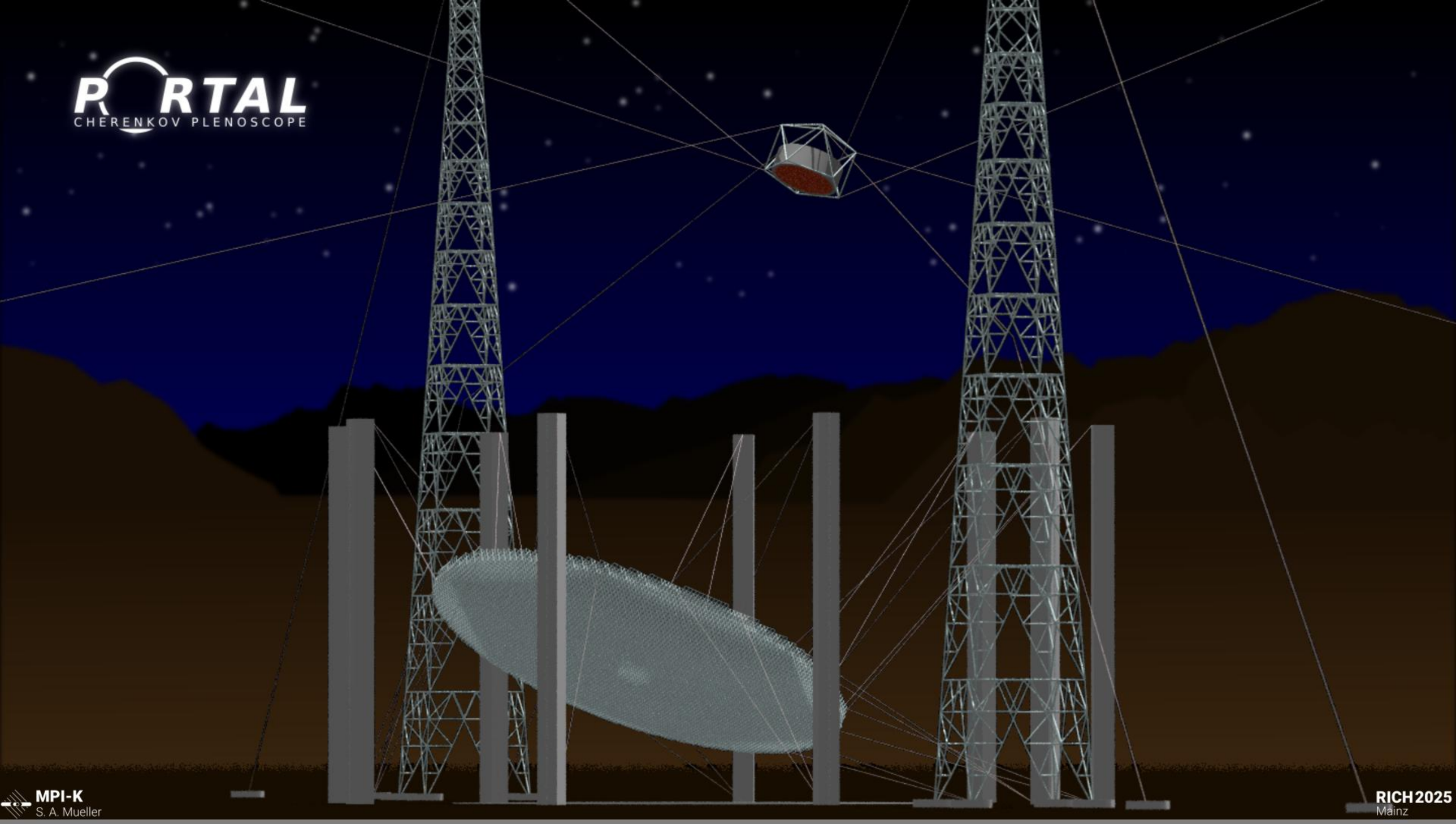
CHERENKOV PLENOSCOPE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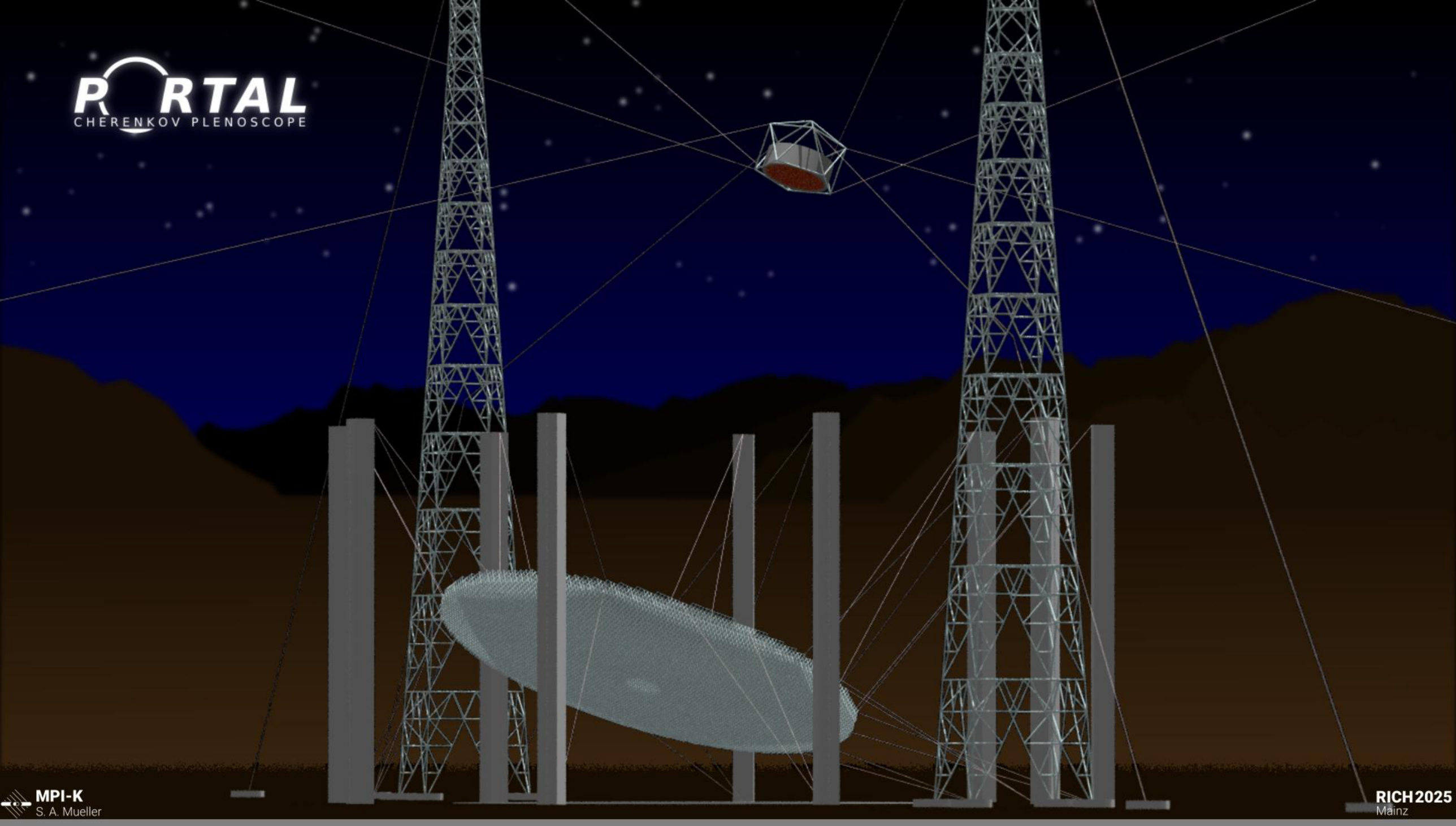
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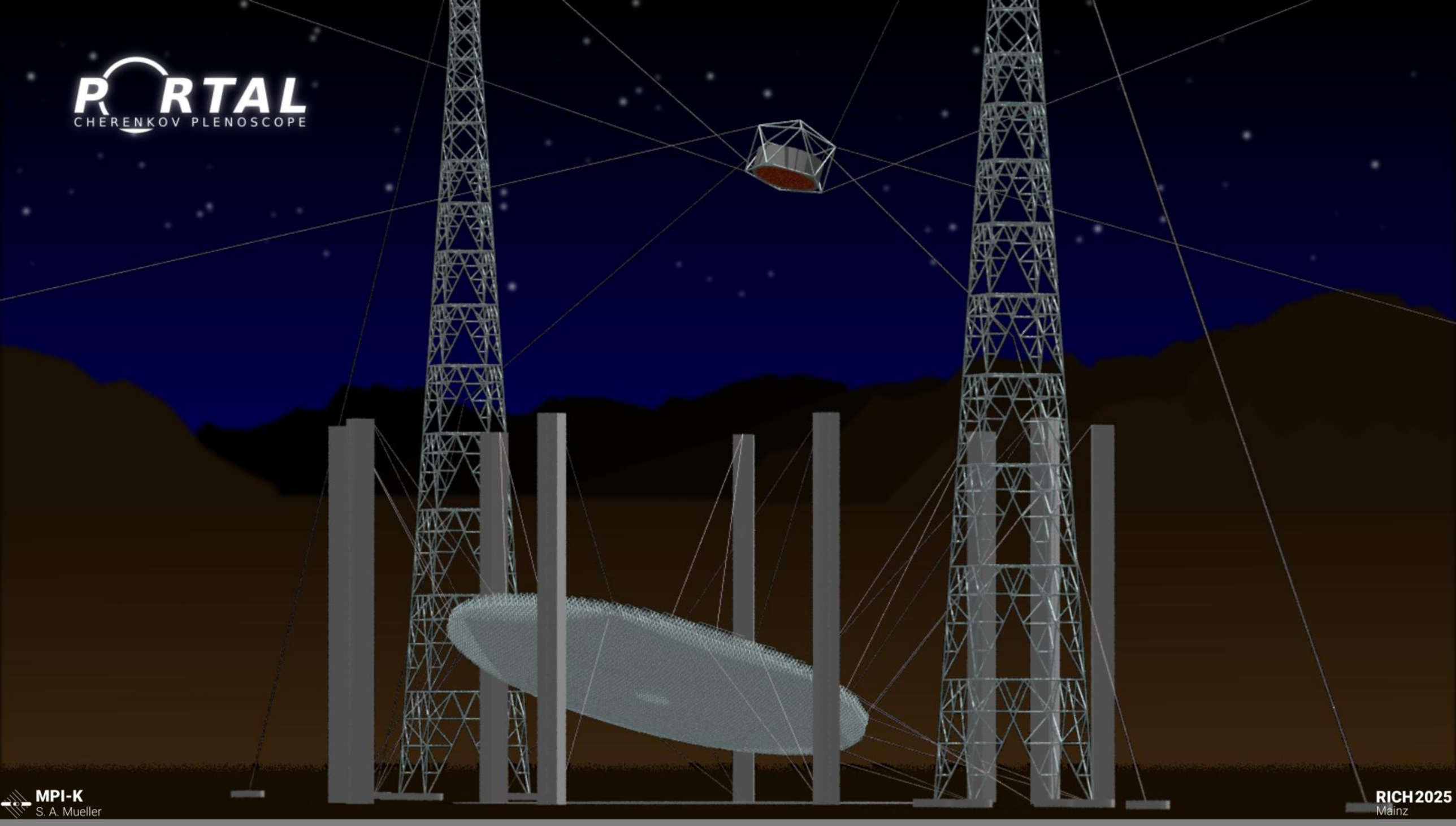
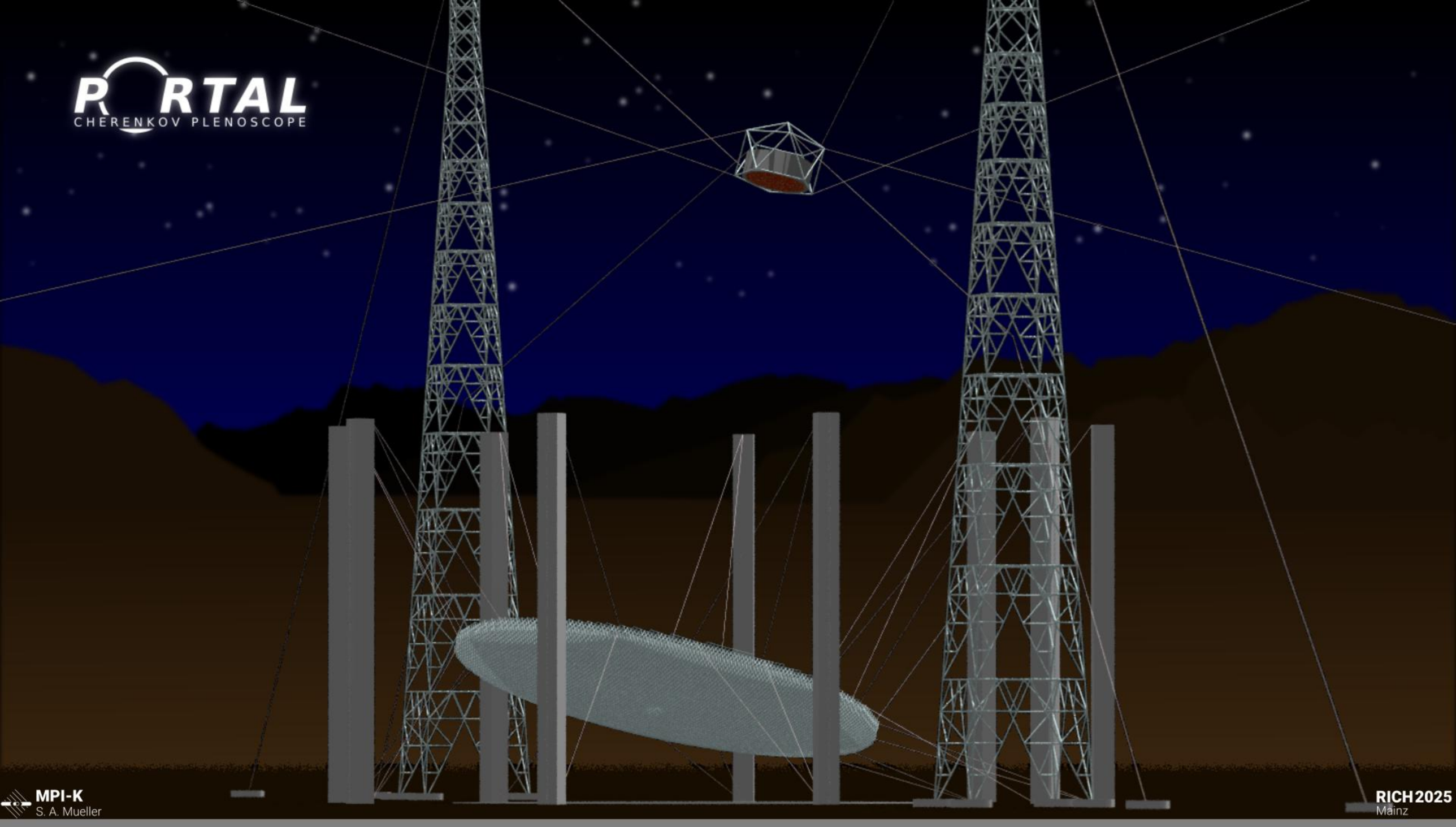

PORTAL
CHERENKOV PLENOSCOPE


PORTAL
CHERENKOV PLENOSCOPE
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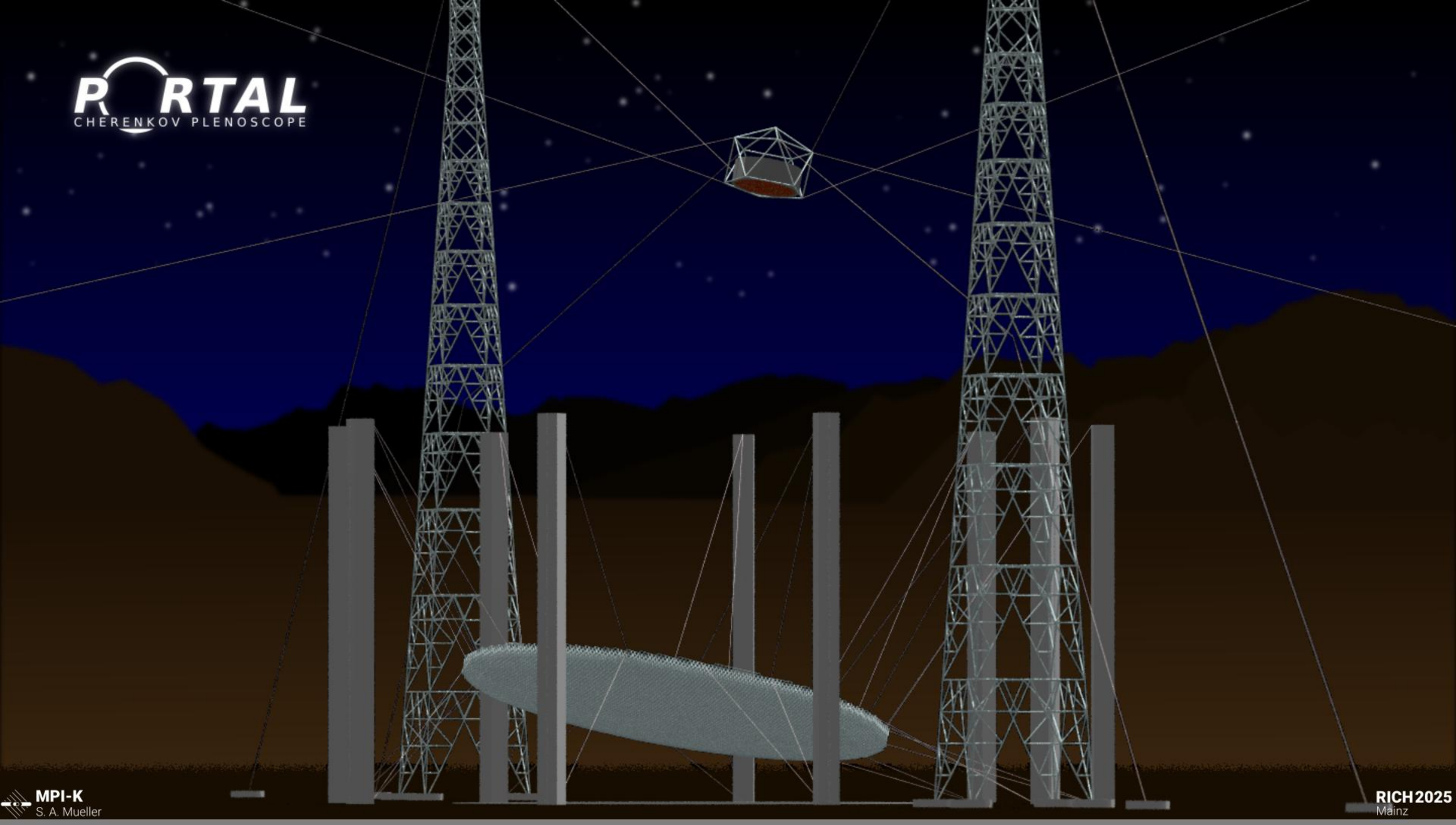
Mainz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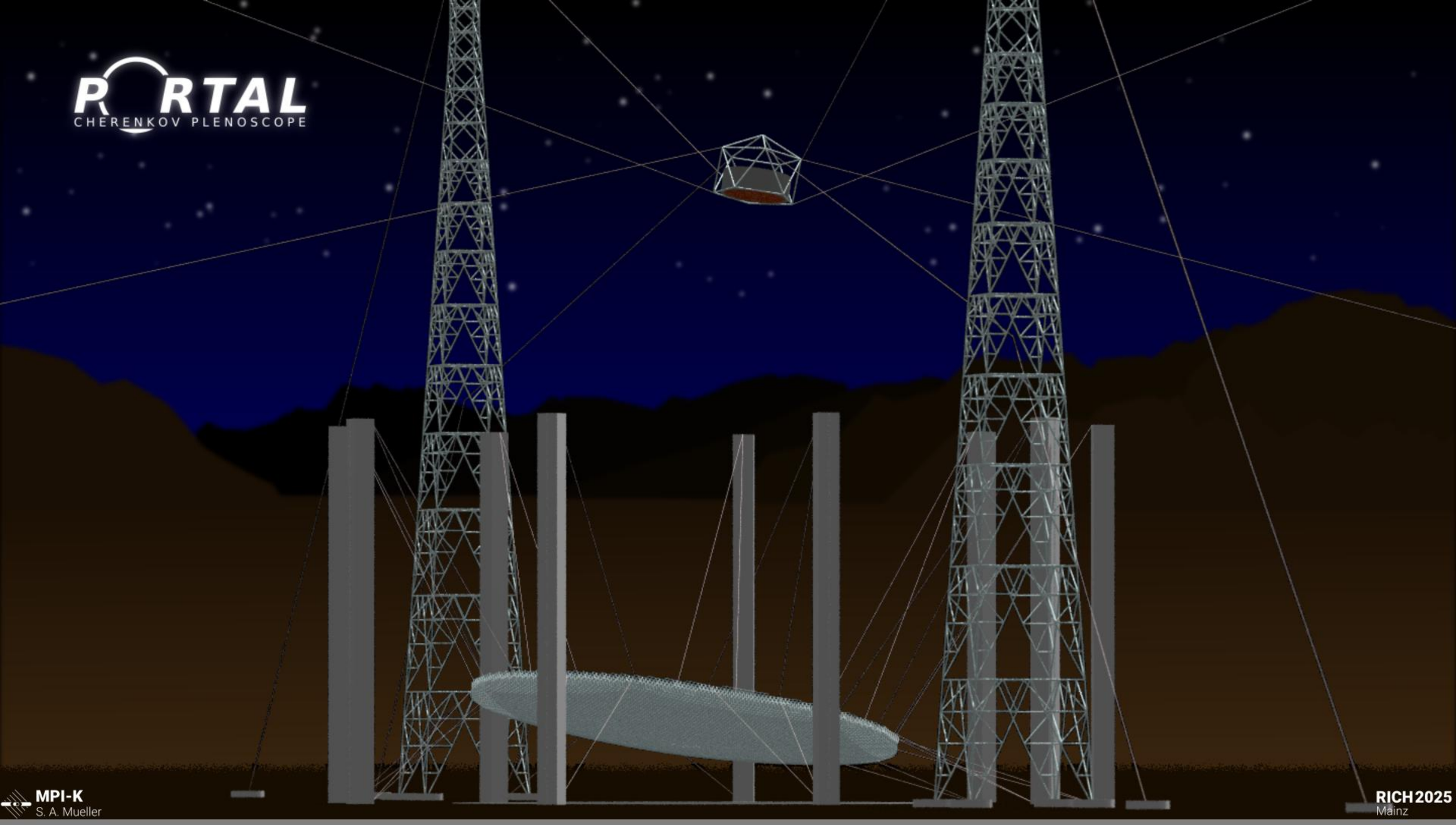
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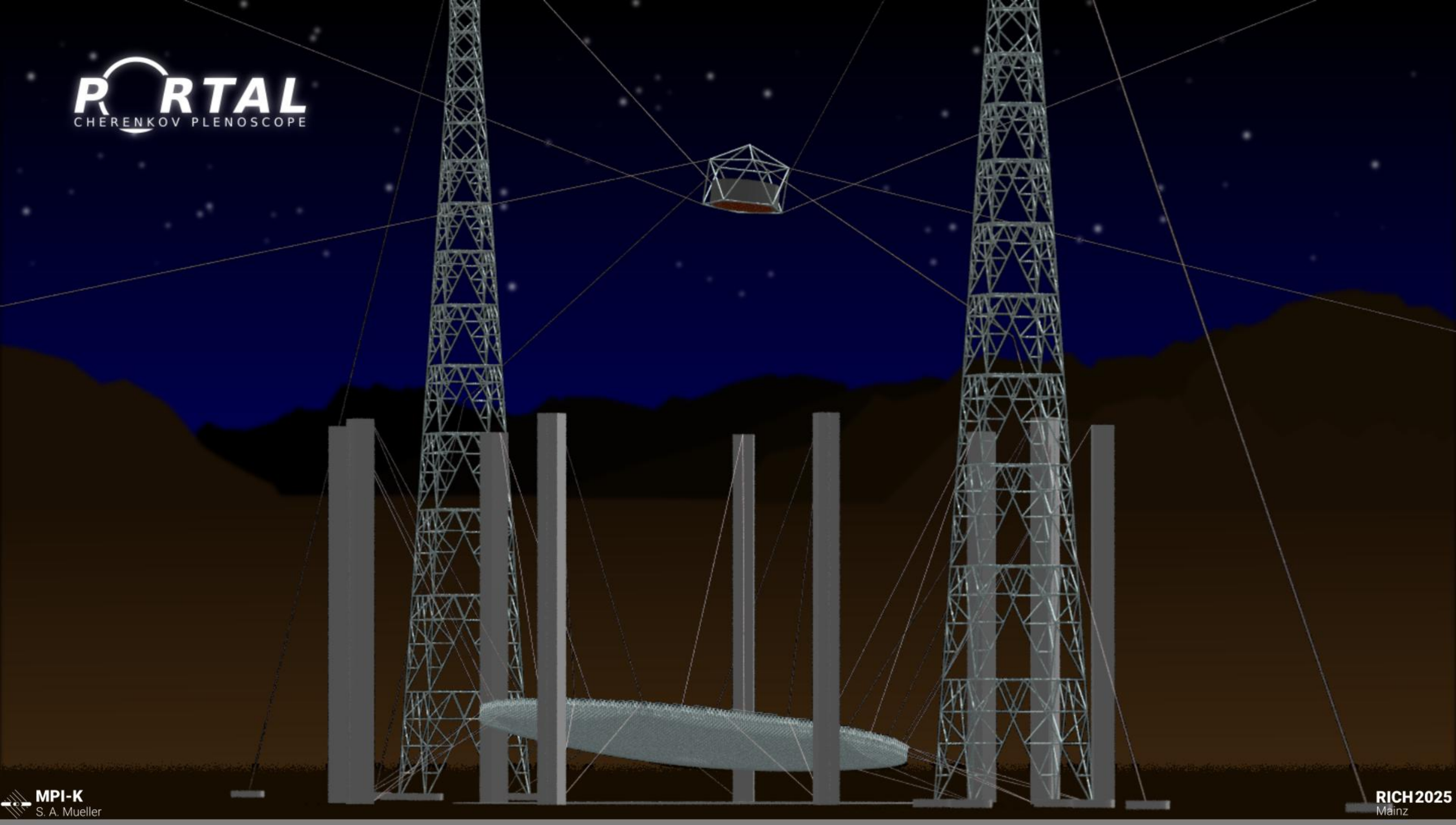
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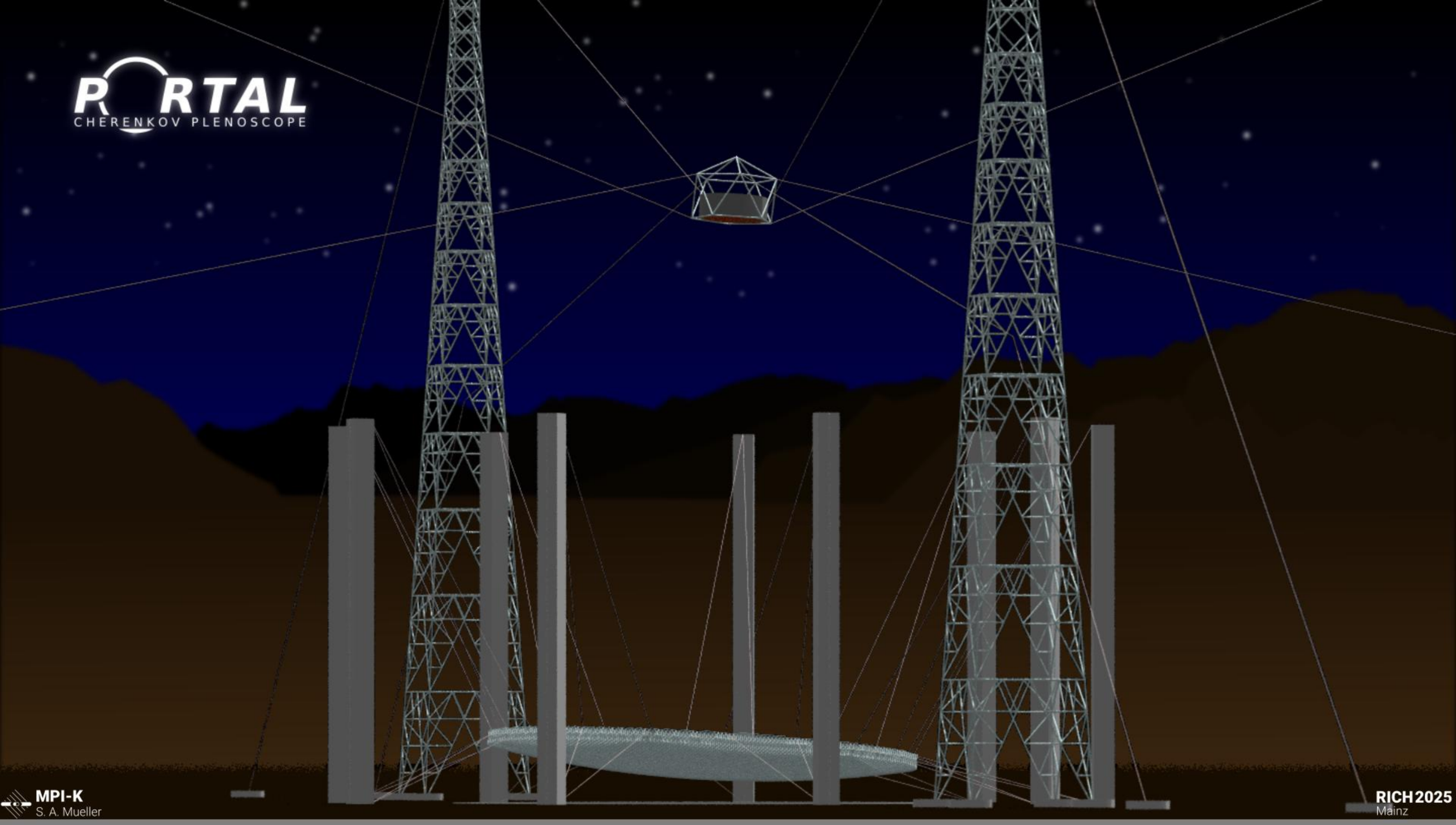
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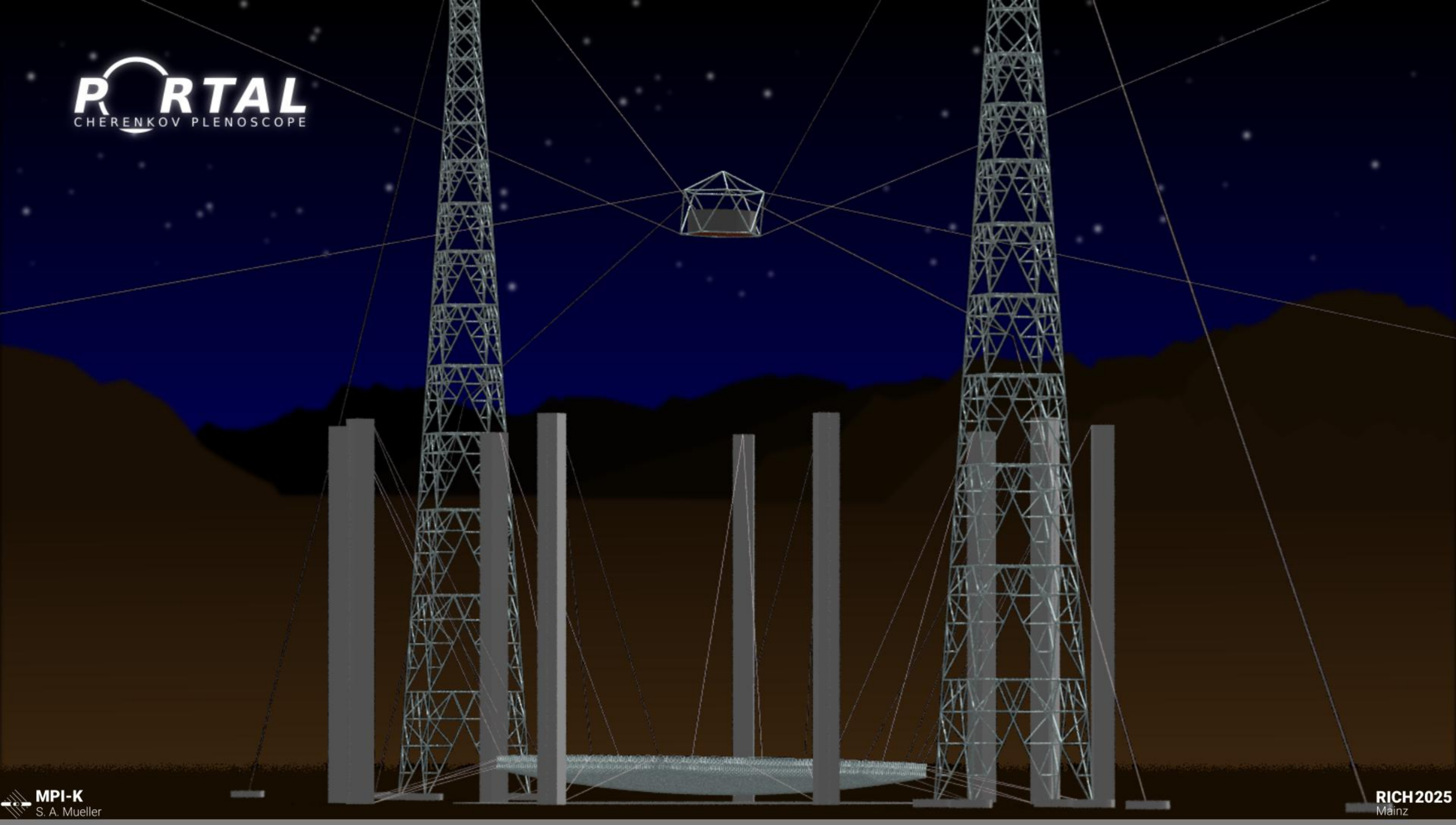
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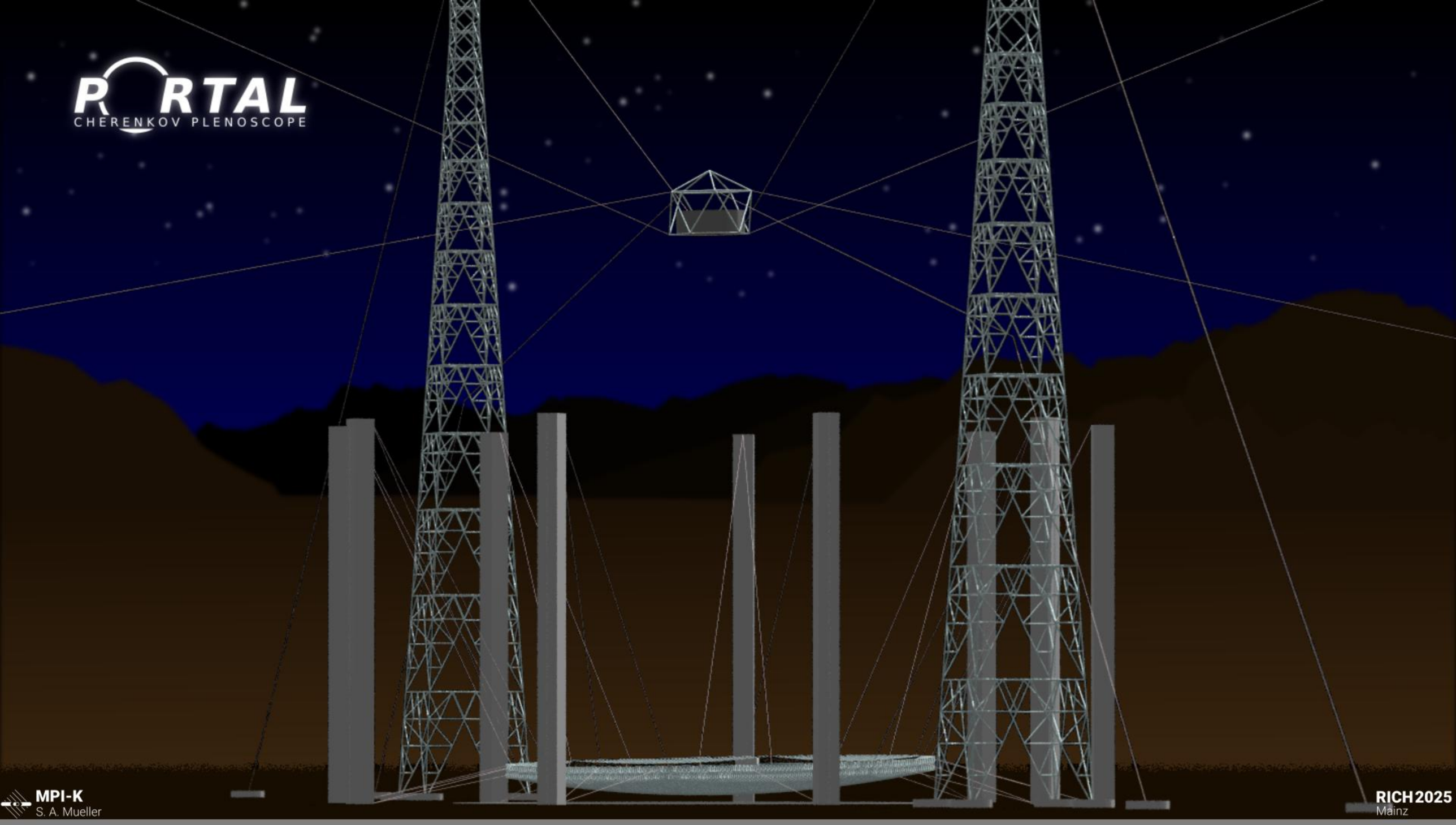
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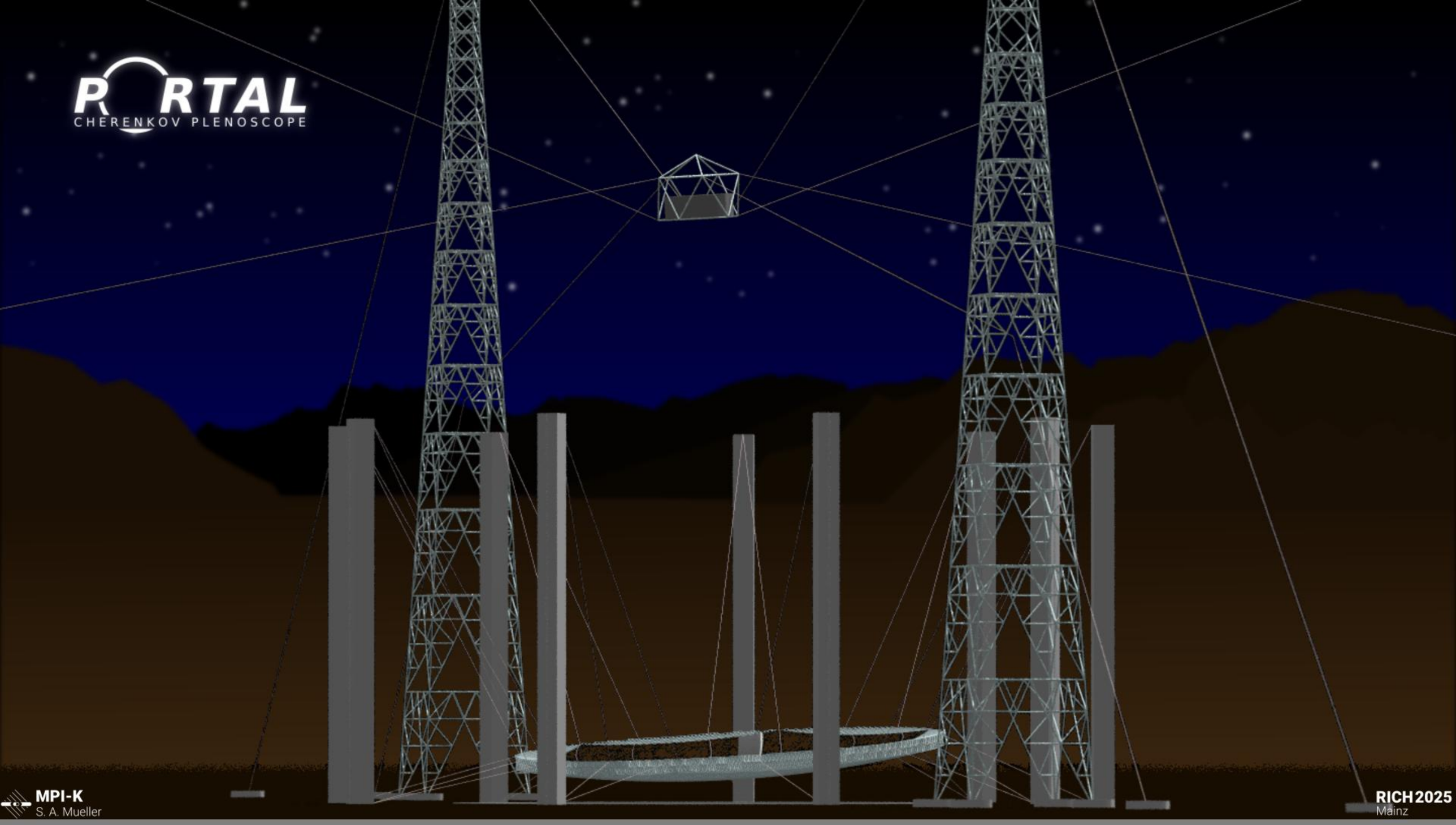
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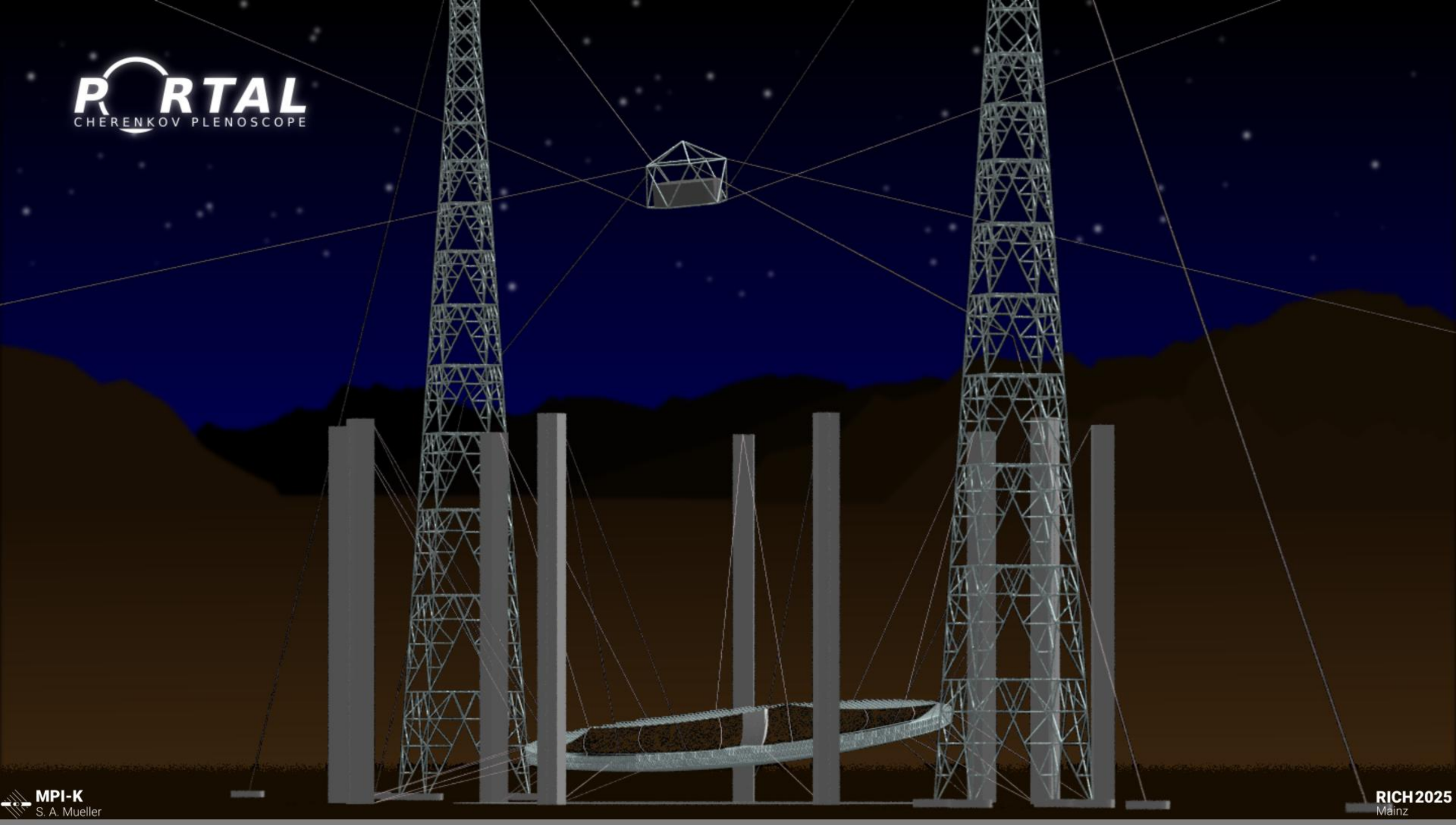
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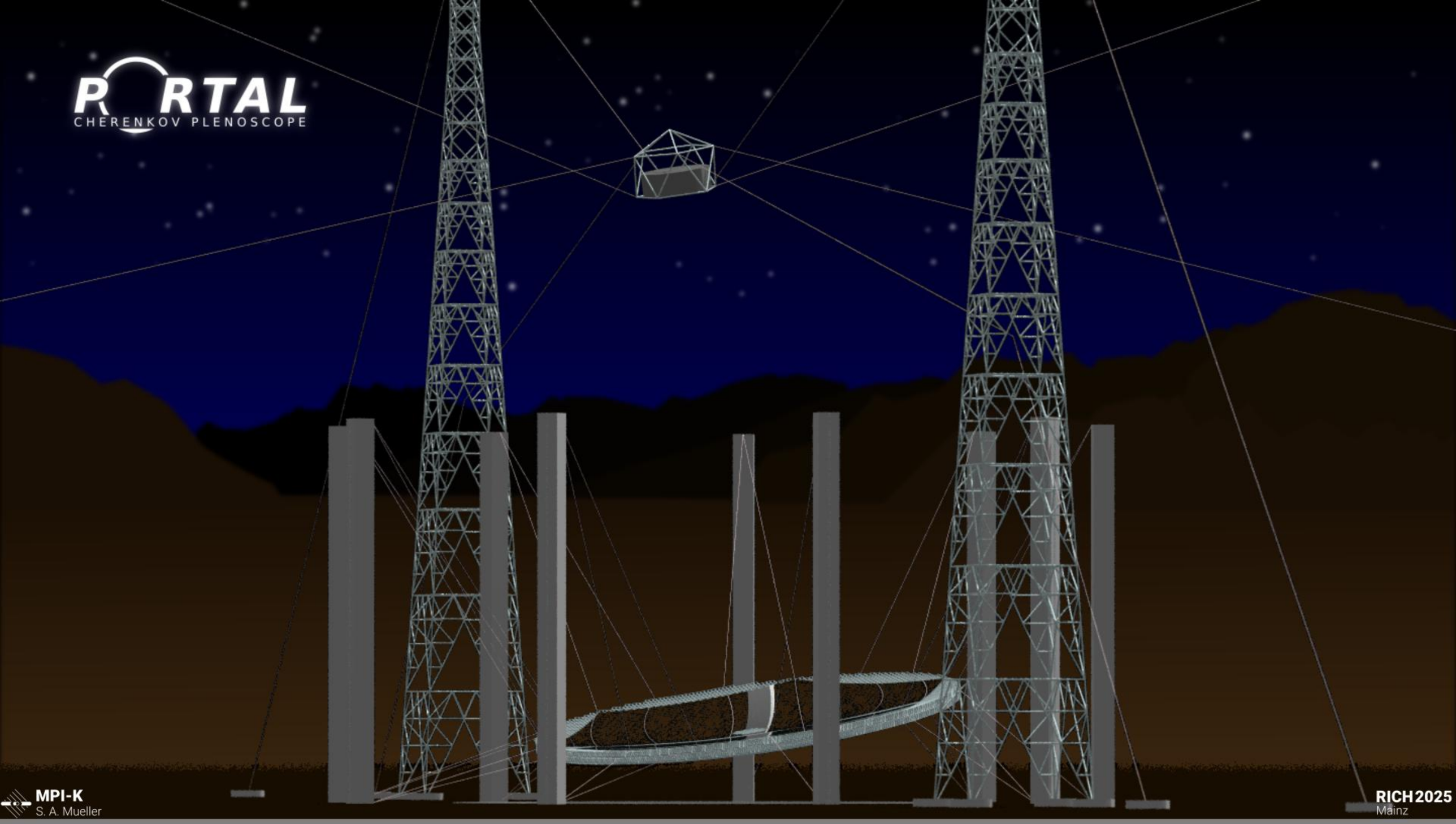
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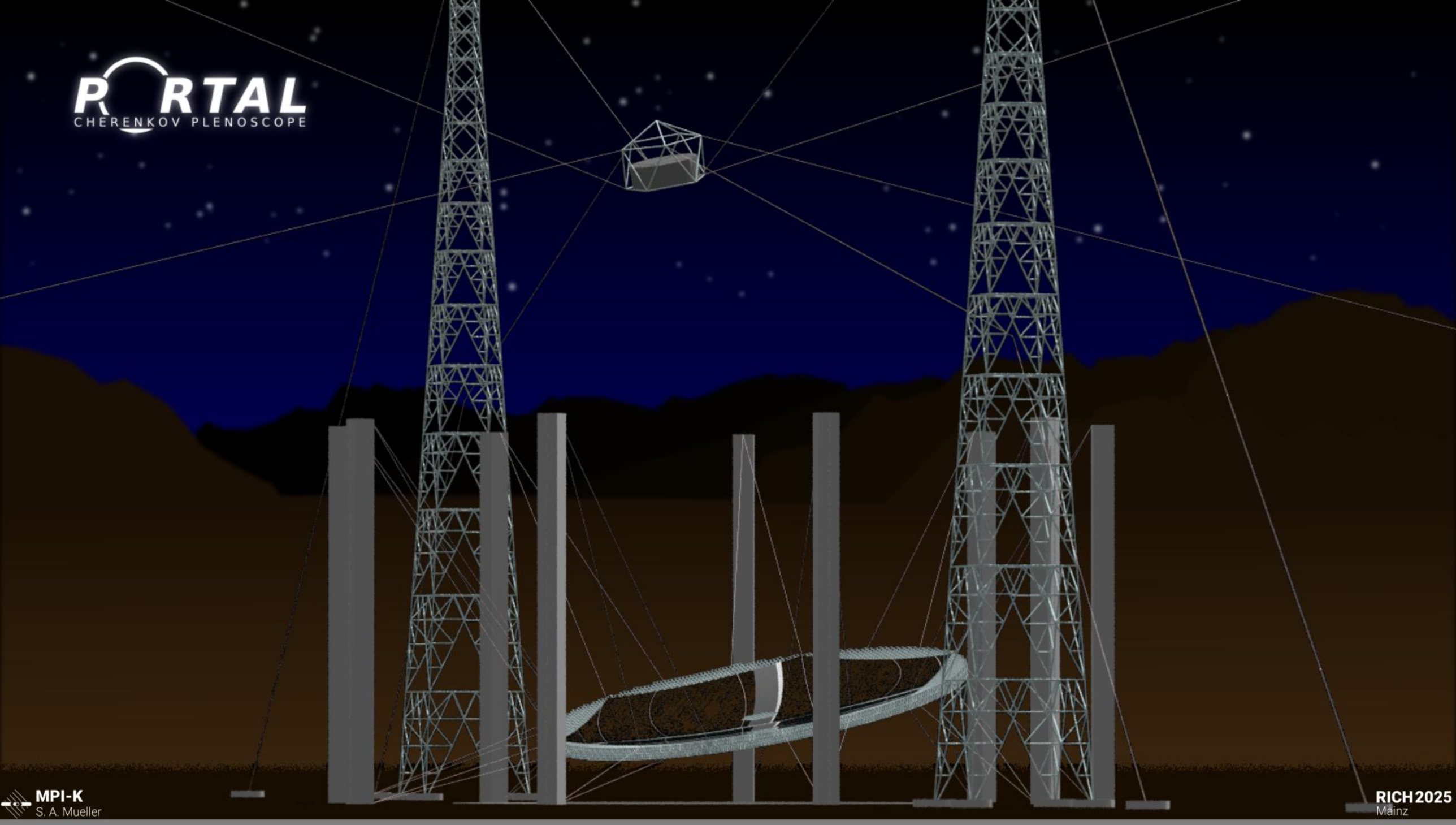
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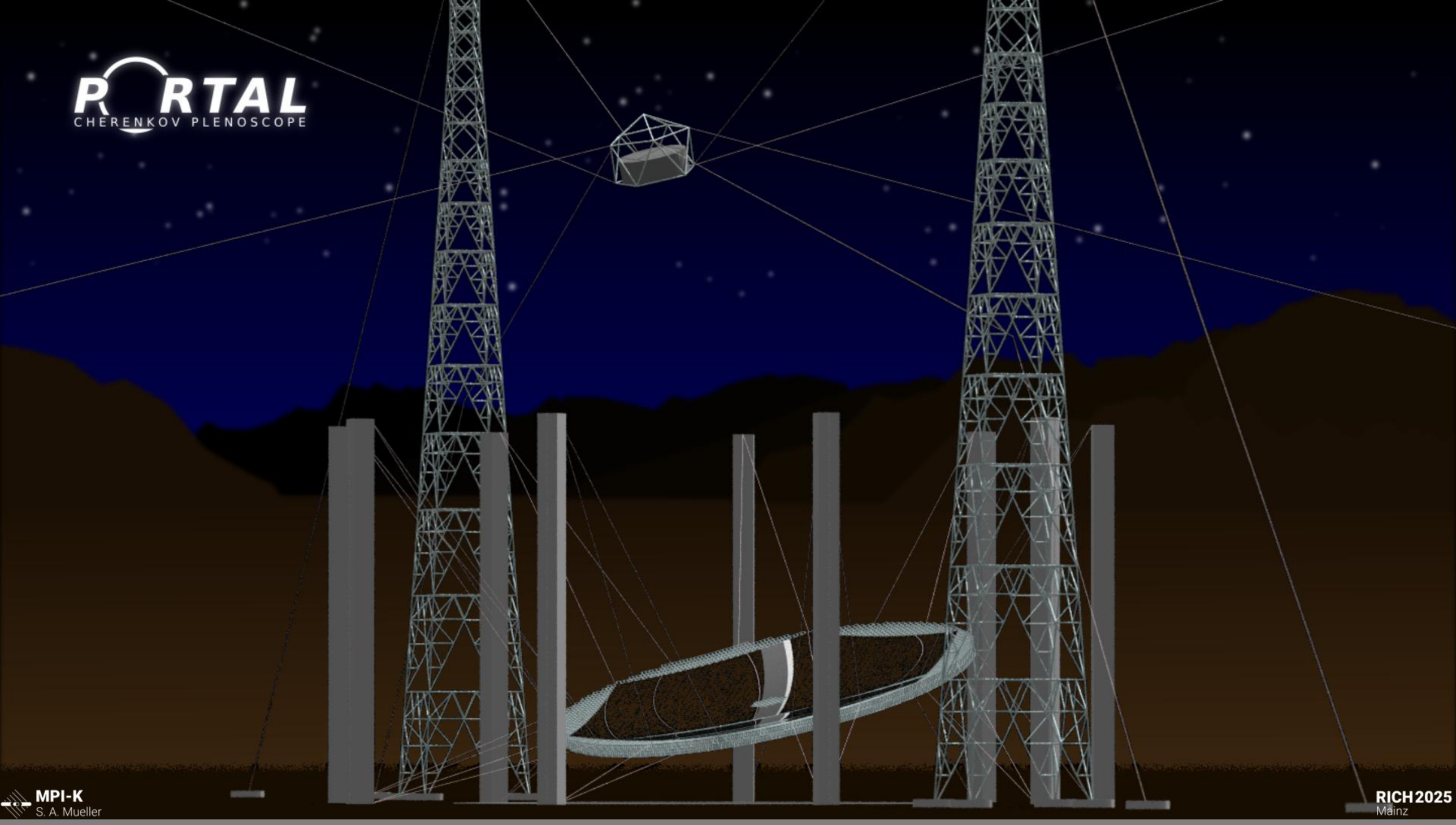
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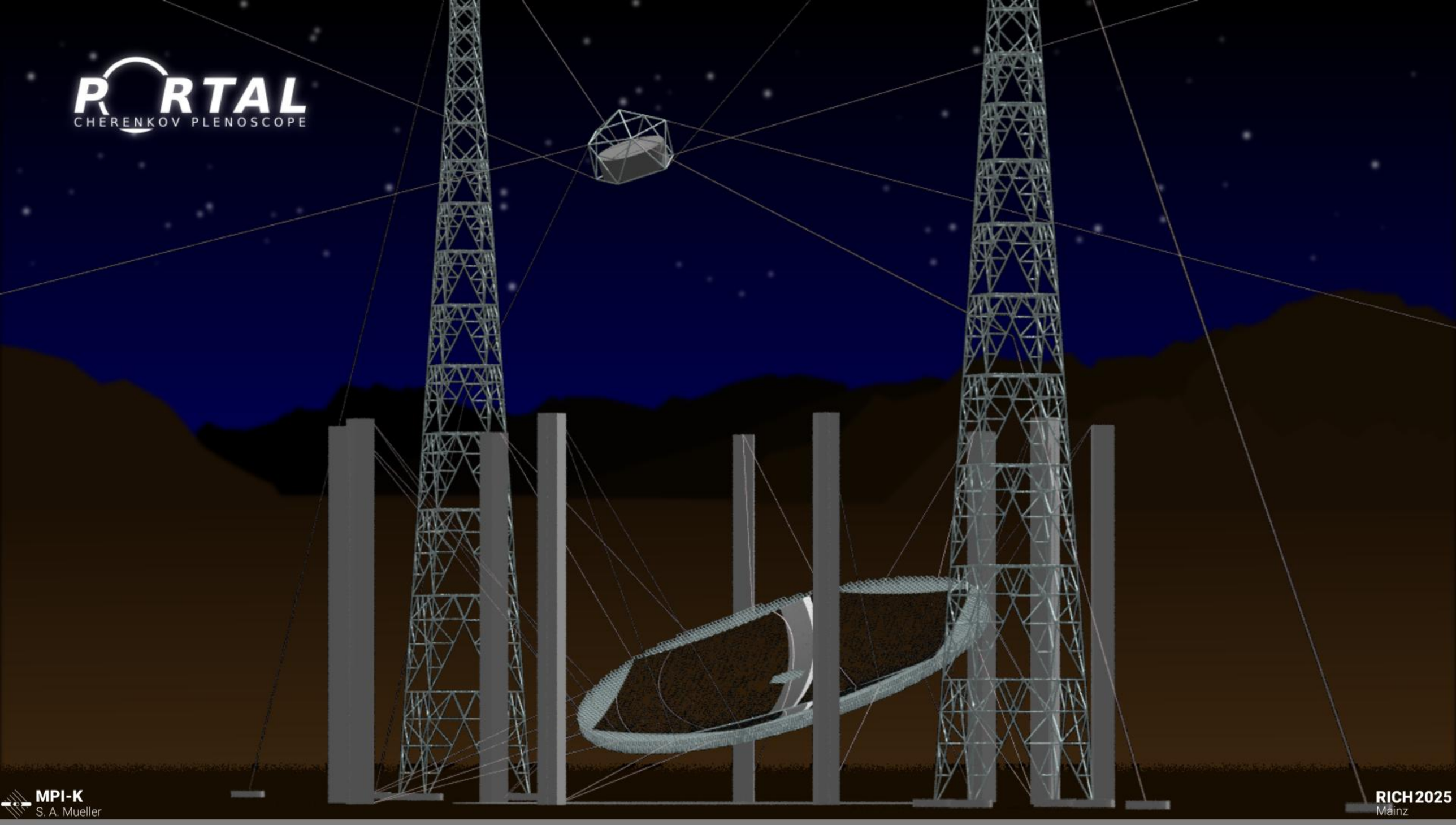
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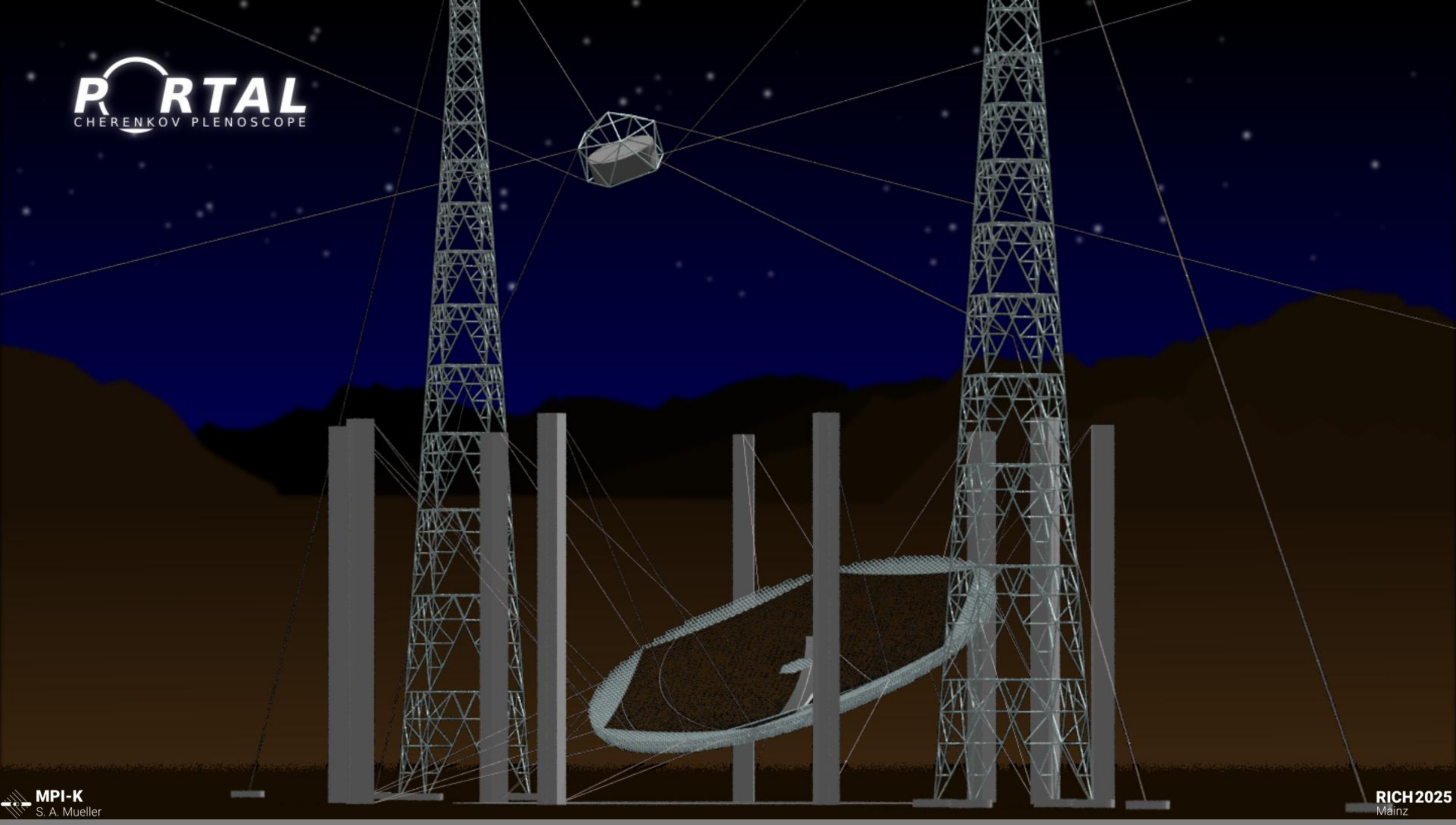
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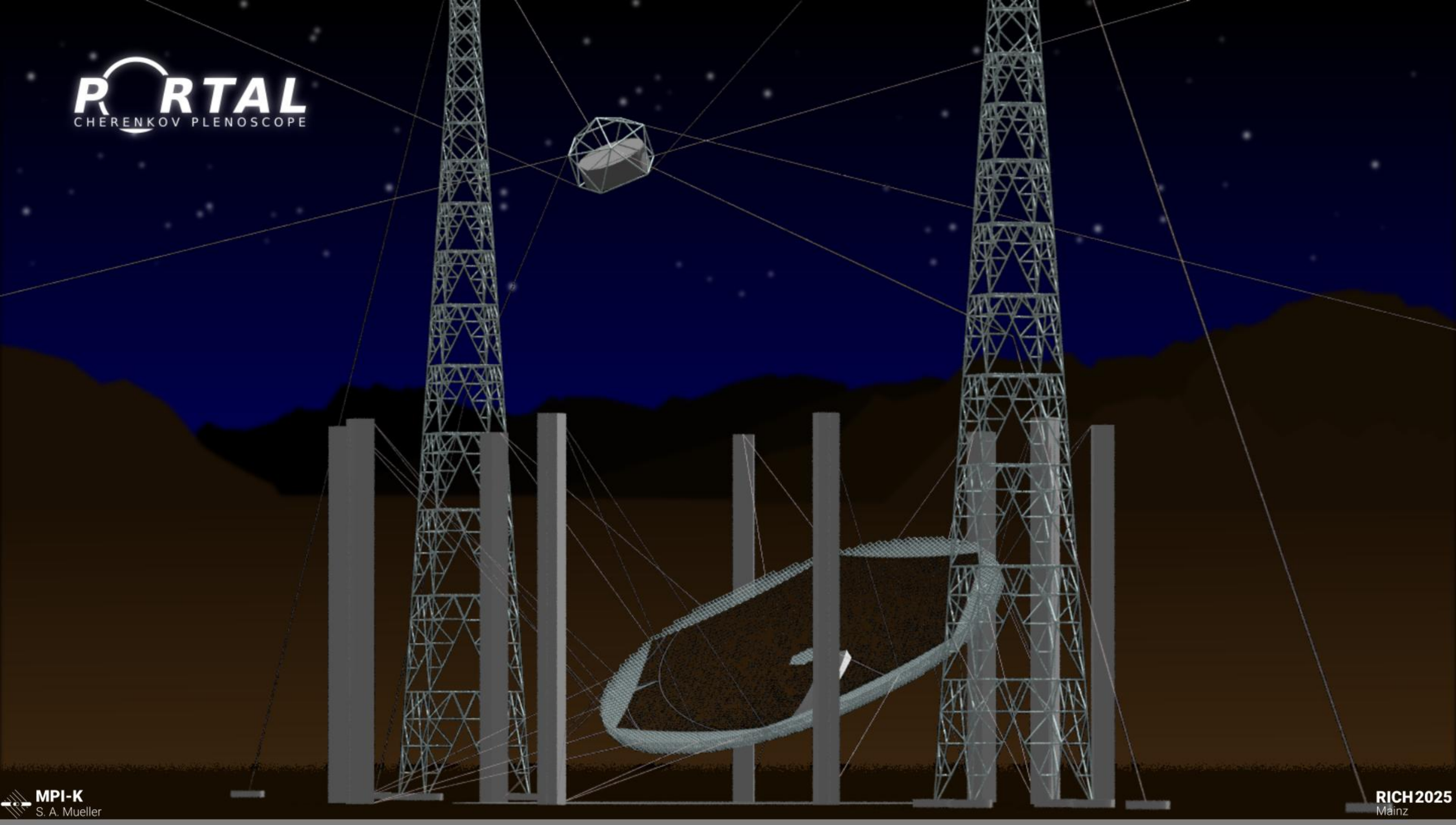
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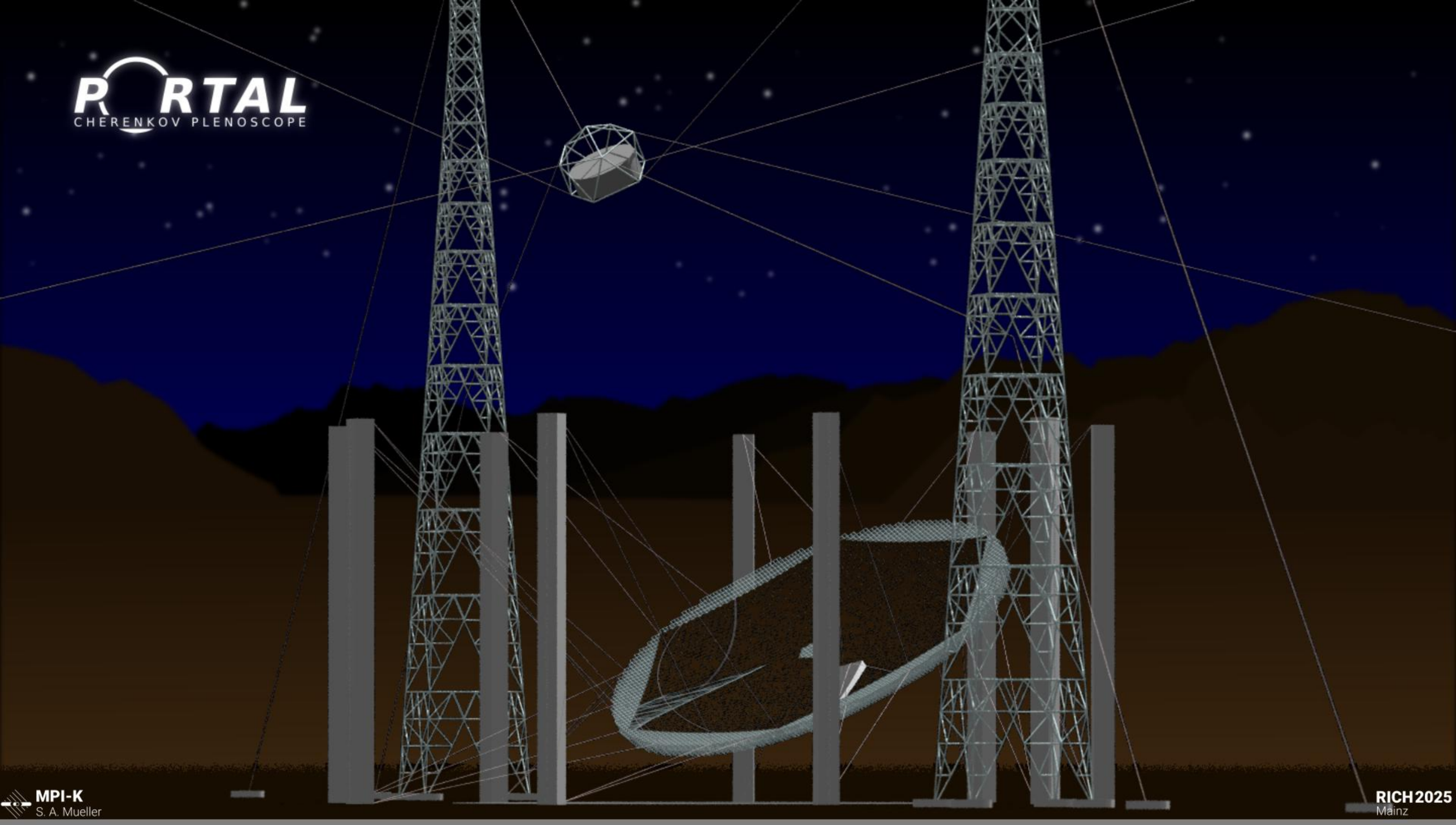
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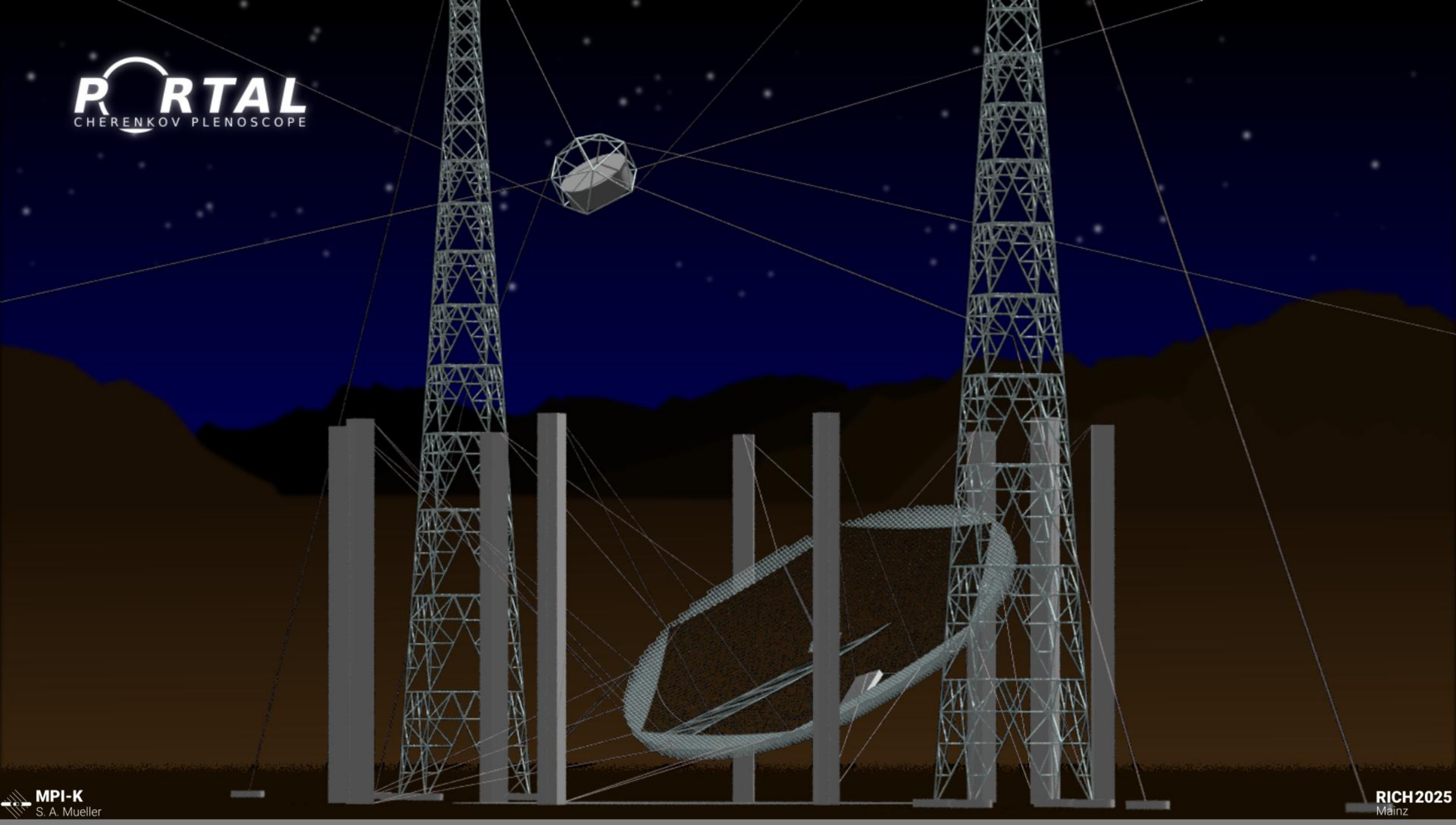
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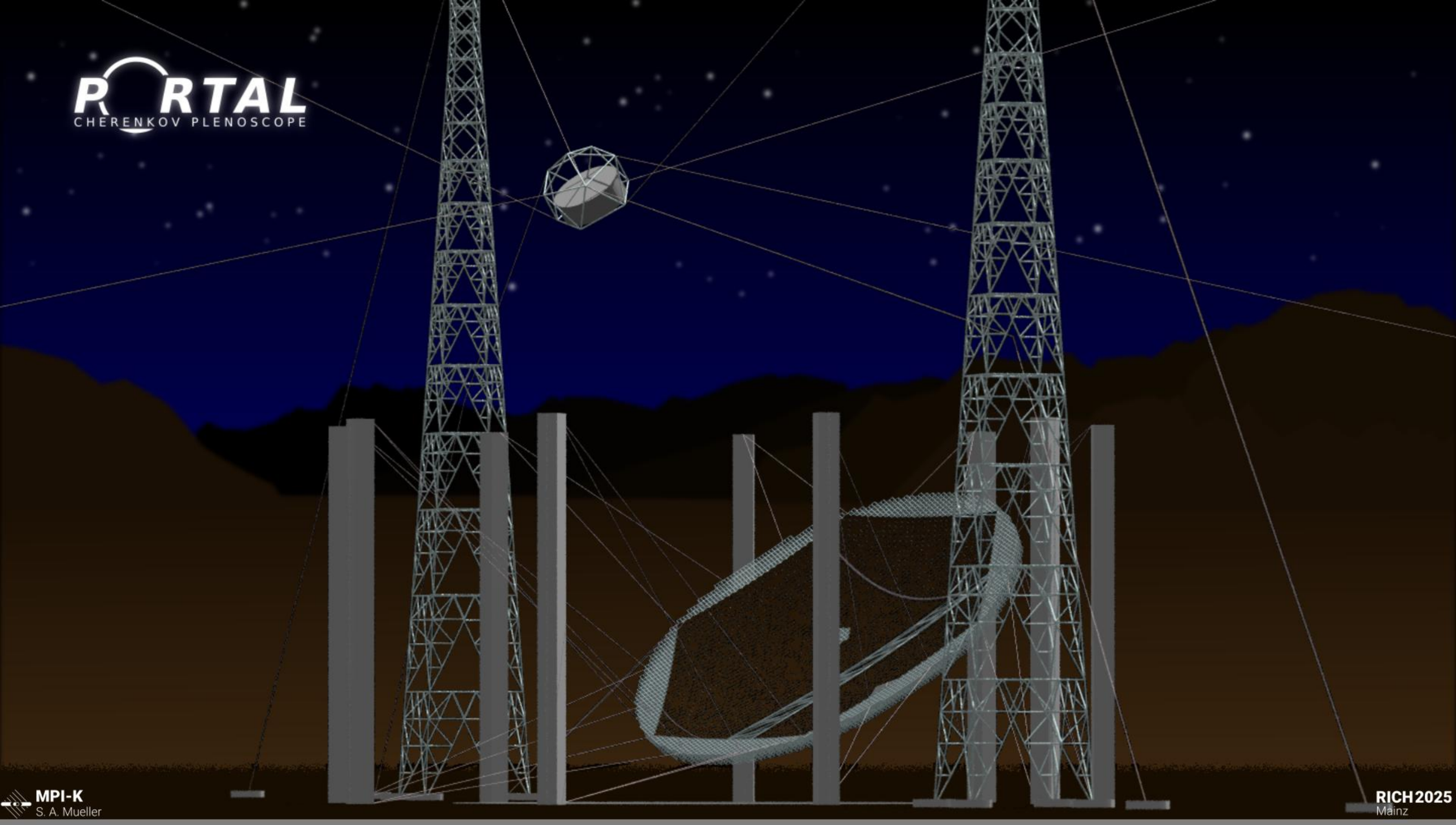
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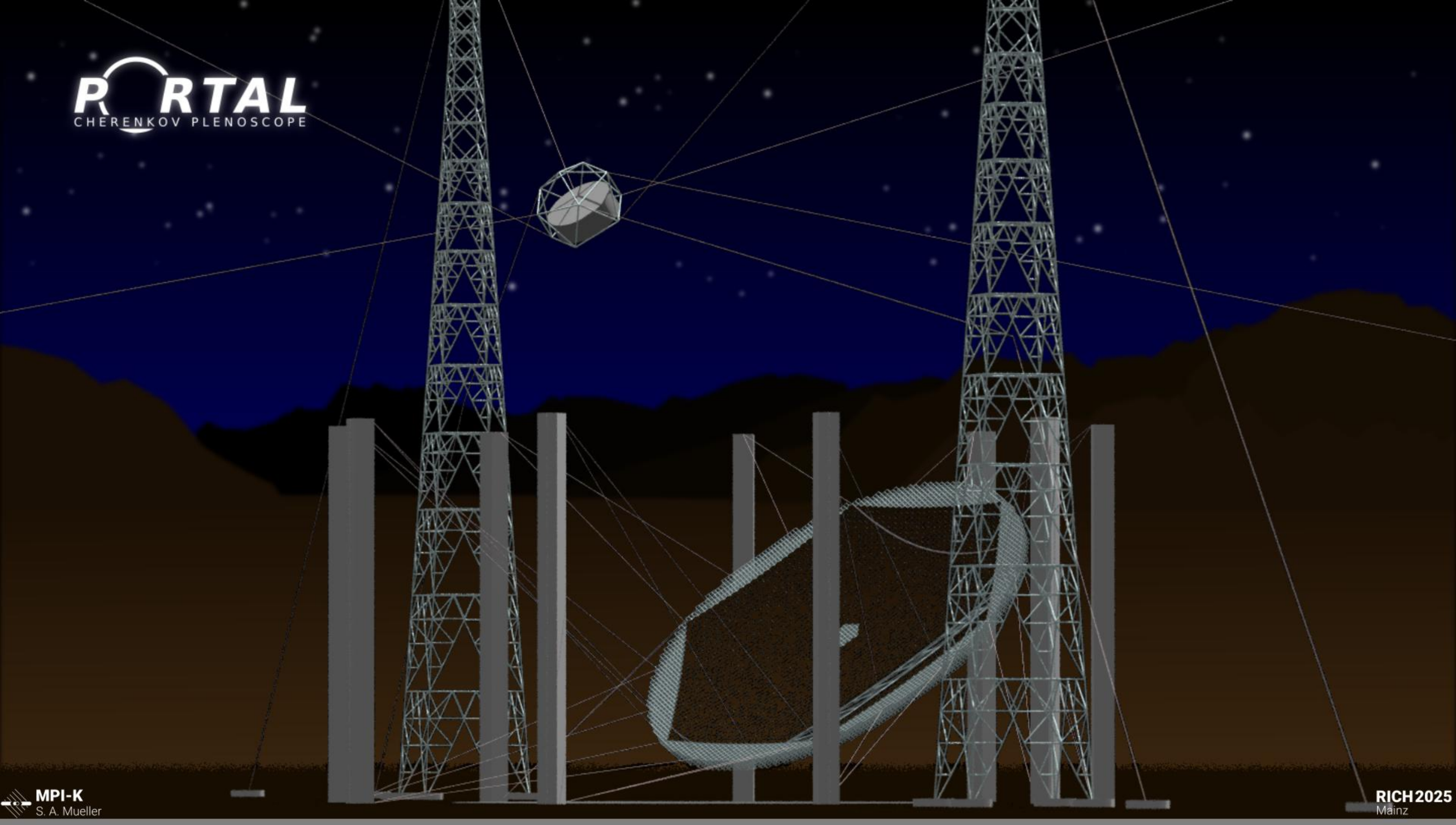
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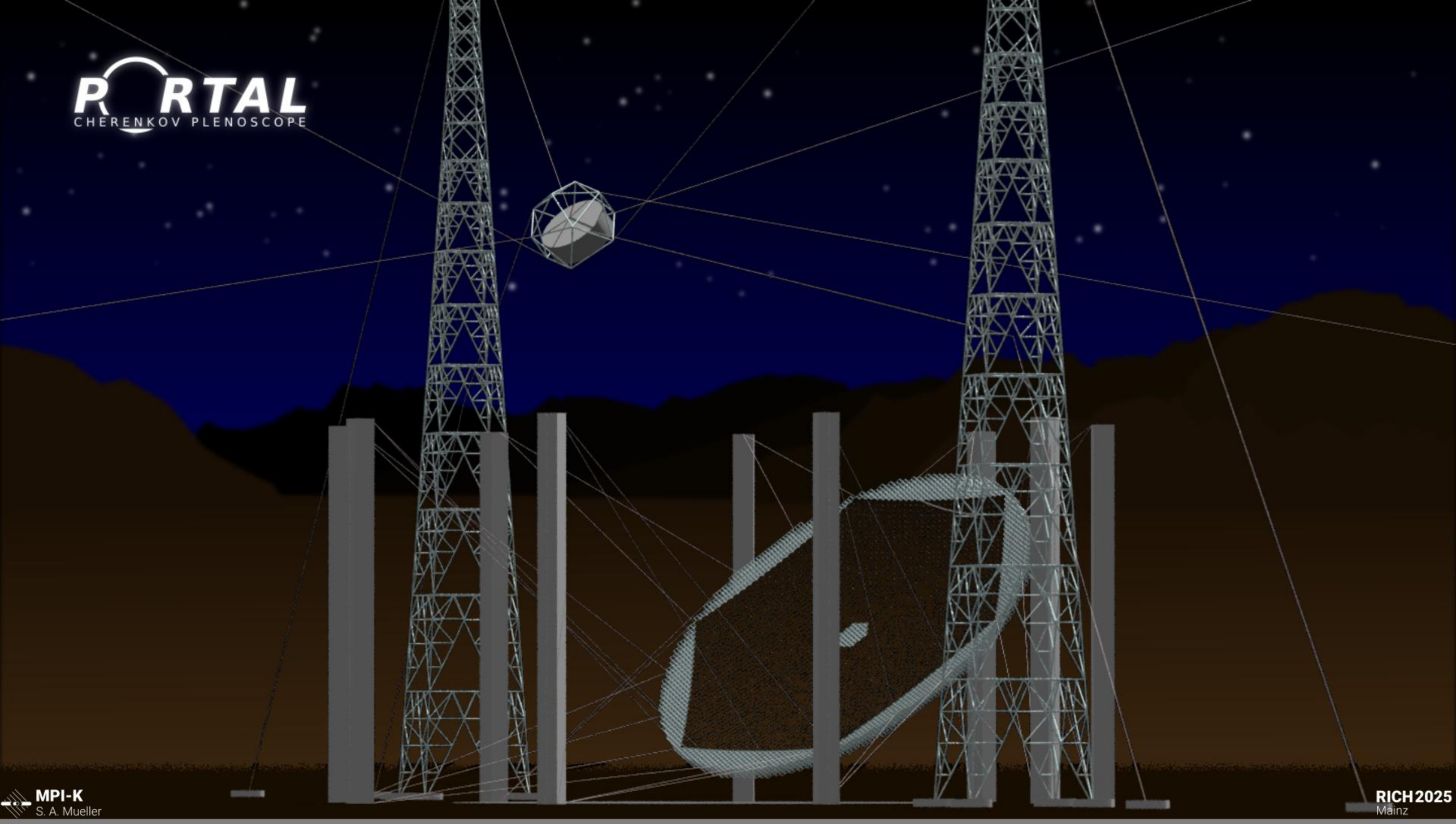
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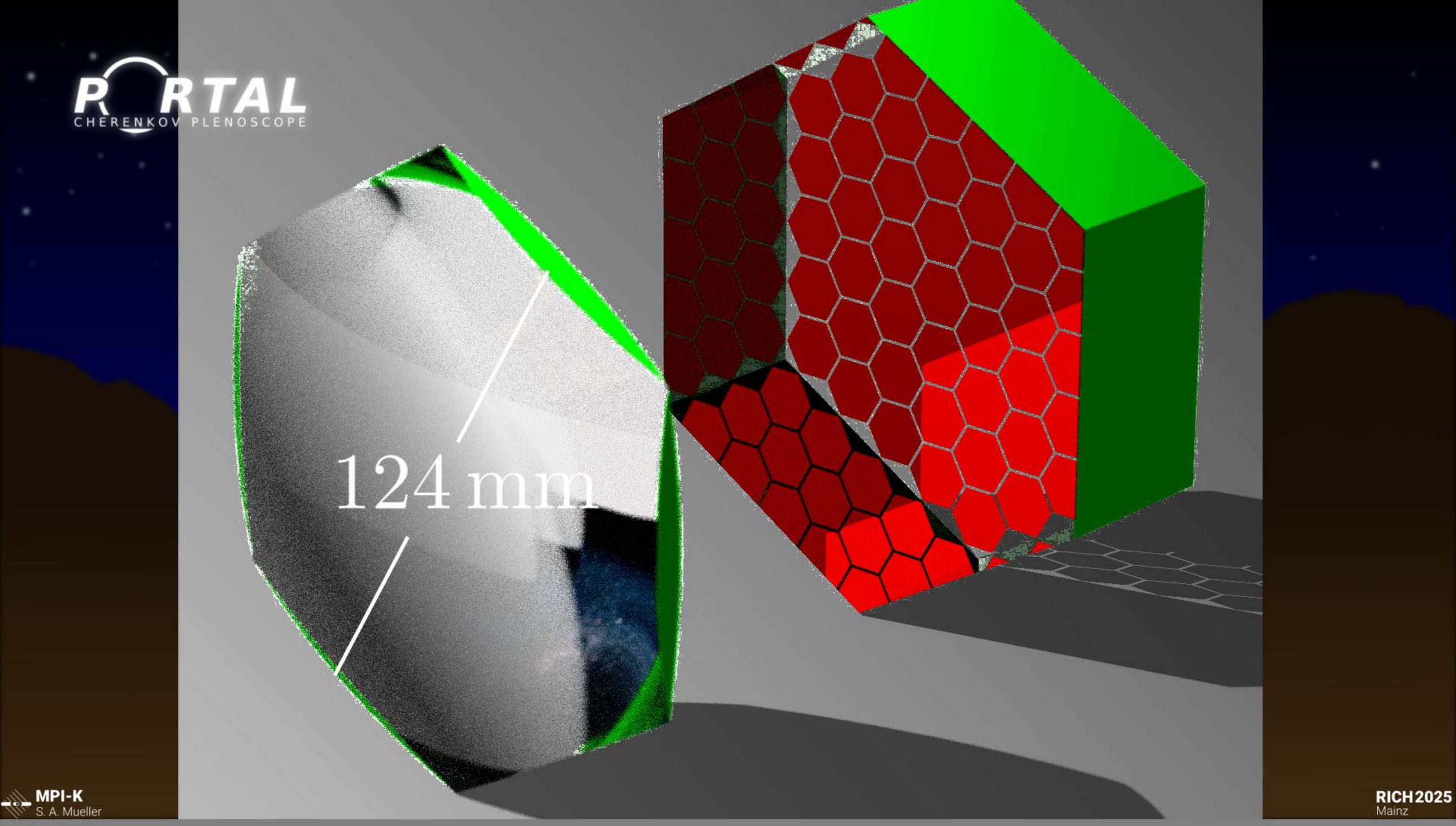
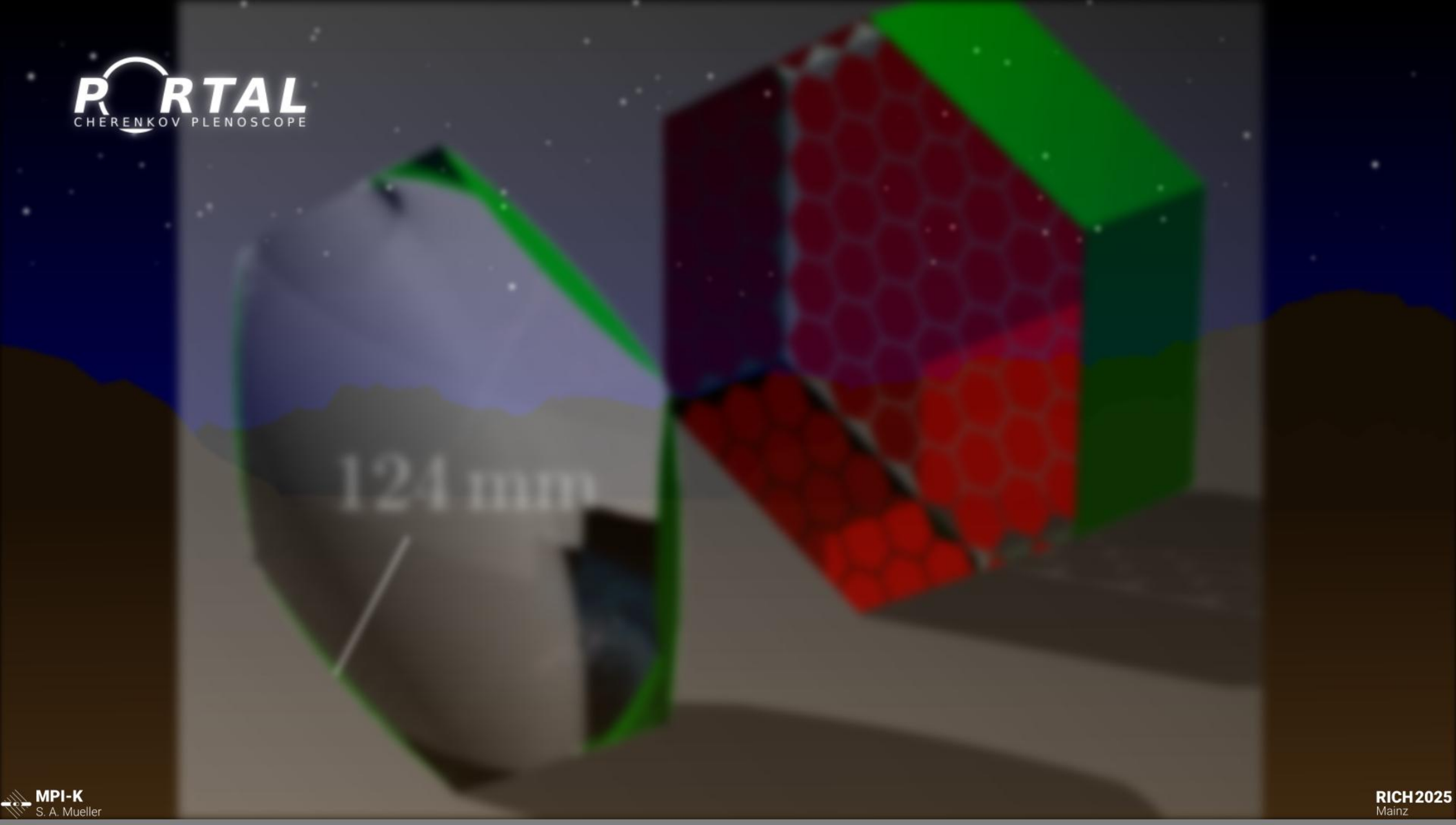
CHERENKOV PLENOSCOPE



Portal's eyes are made out of a spherical lens and an array of sixty one red photosensors.


PORTAL
CHERENKOV PLENOSCOPE
124 mm

PORTAL
CHERENKOV PLENOSCOPE

PORTAL

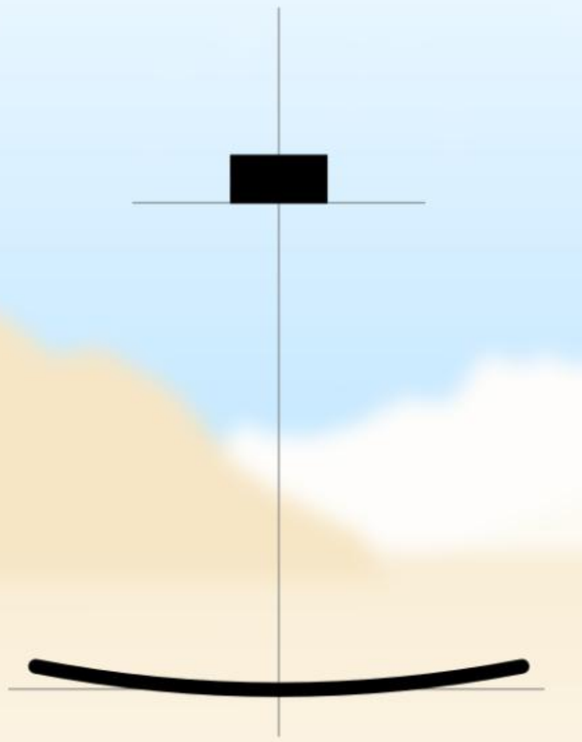
Optics

Optics

cameras

To compare the plenoscope to a telescope,

Optics
cameras

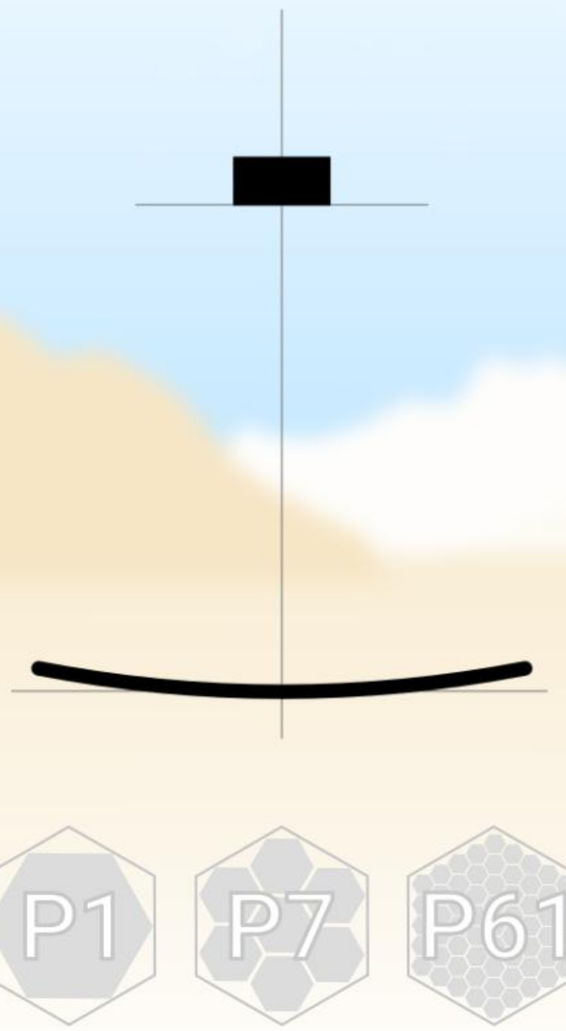


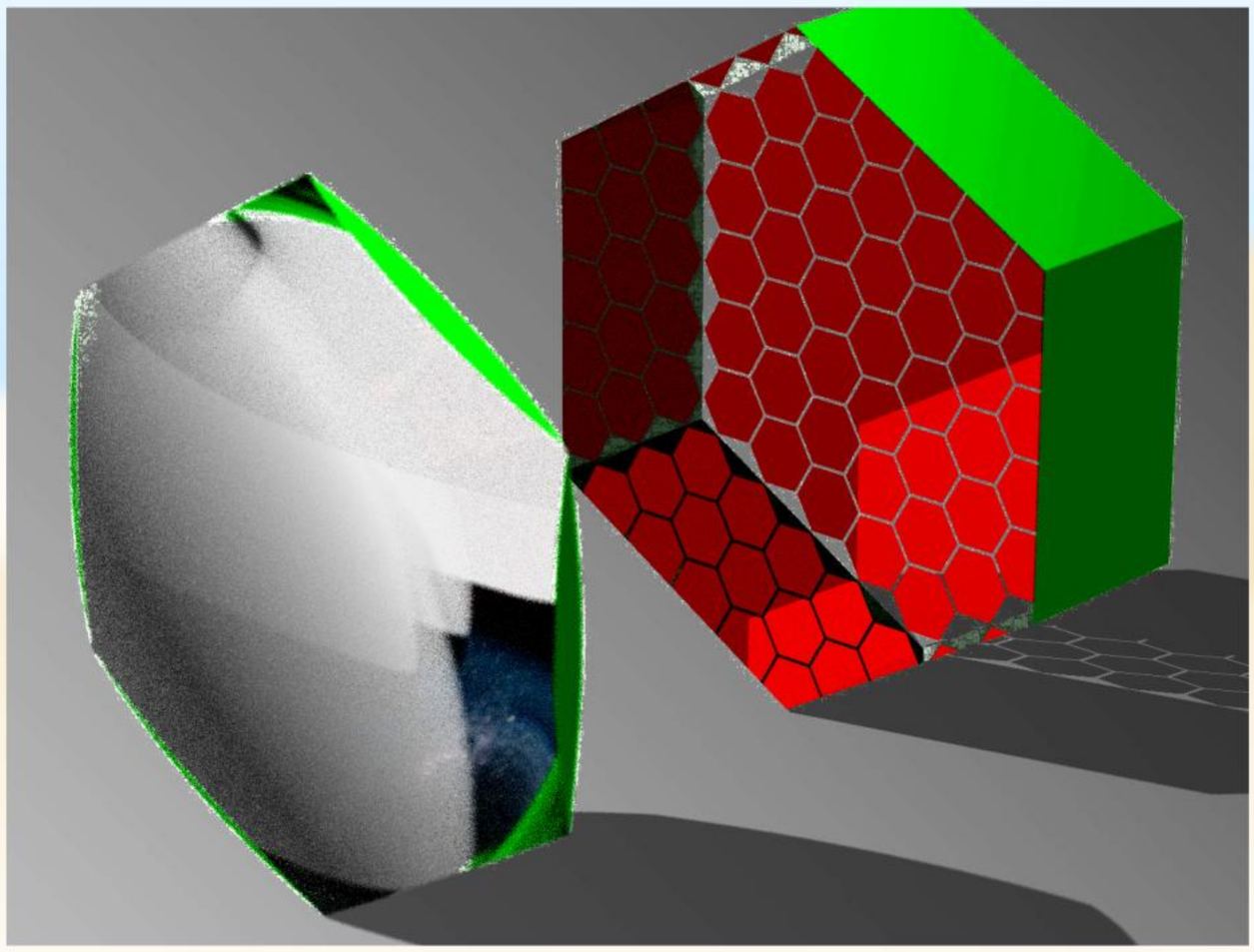
P1 P7 P61

and to get a feeling for the scaling of plenoptic perception we introduce two more instruments which are identical to Portal. Except for

Optics

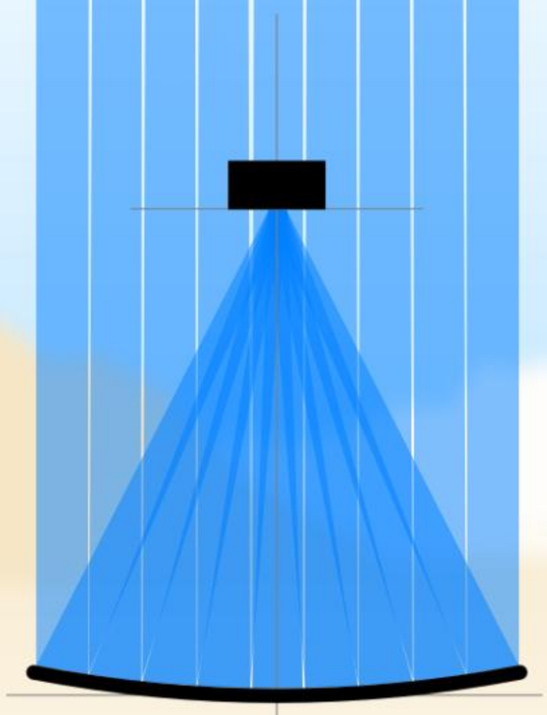
cameras

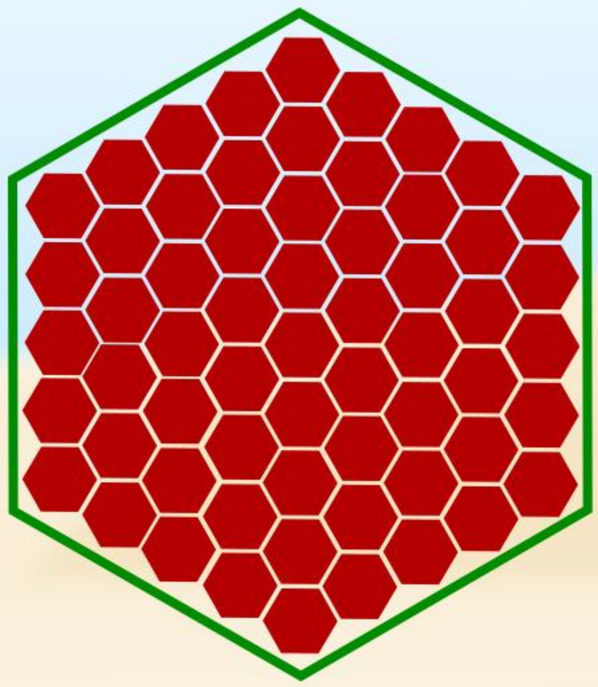




Where Portal has sixty-one photosensors

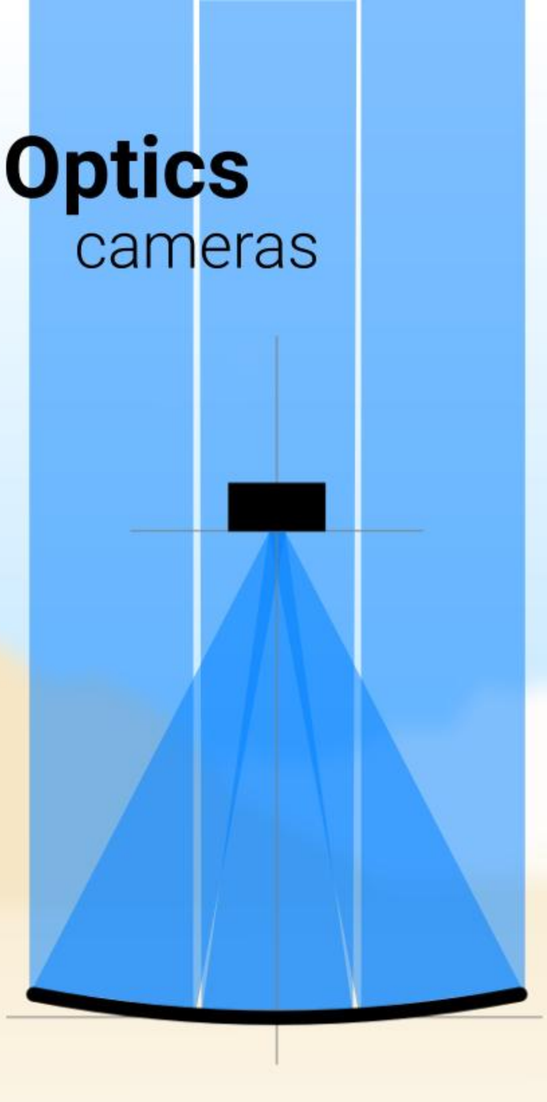
Optics
cameras

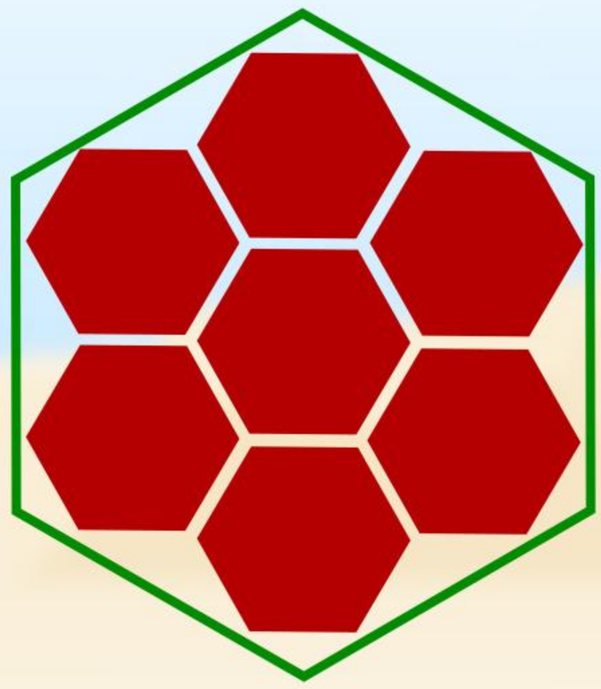




61 impact positions / mirror
(plenoscope)

in each eye

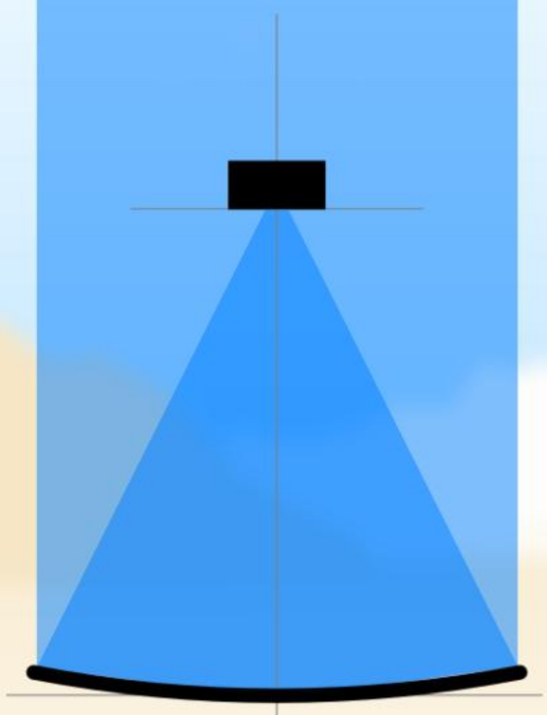


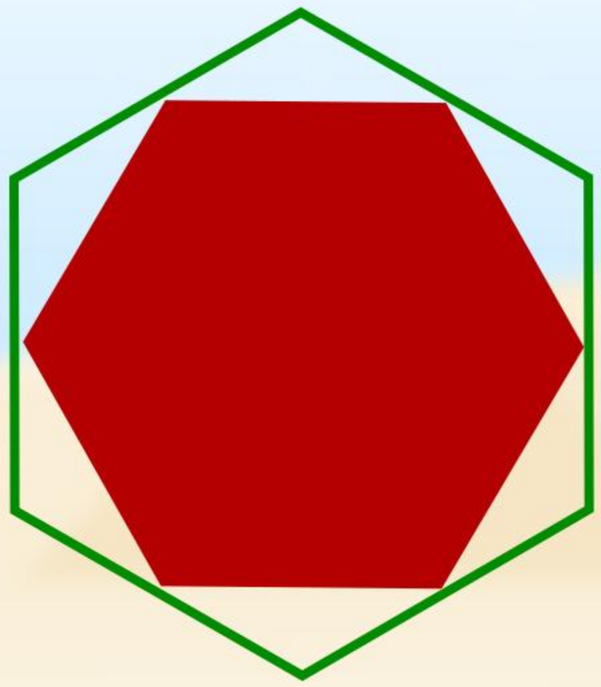


7 impact positions / mirror
(plenoscope)

the plenoscope named p-seven has only seven photosensors in its eye.

Optics
cameras



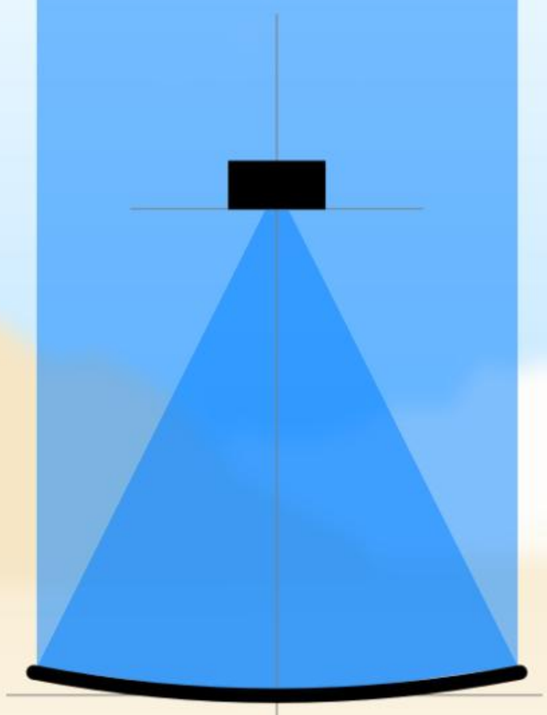


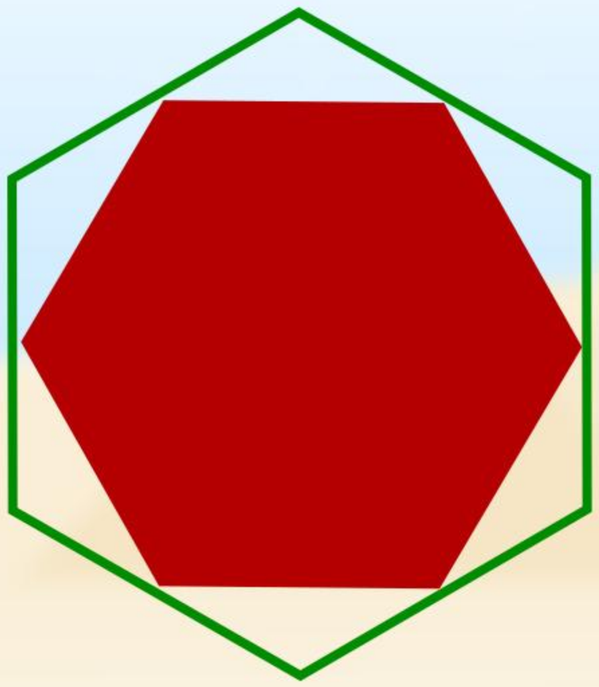
1 impact position / mirror
(telescope)

And the telescope named p-one, only has one photosensor in its eye.

Optics

cameras

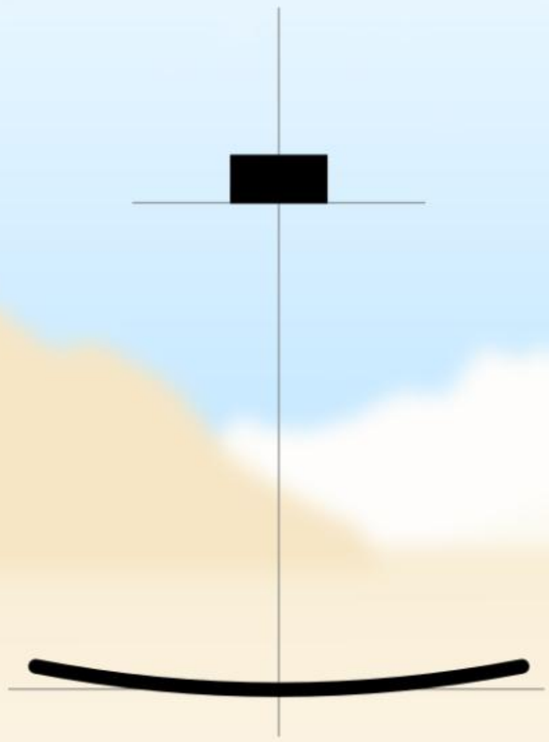




1 impact position / mirror
(telescope)

Optics

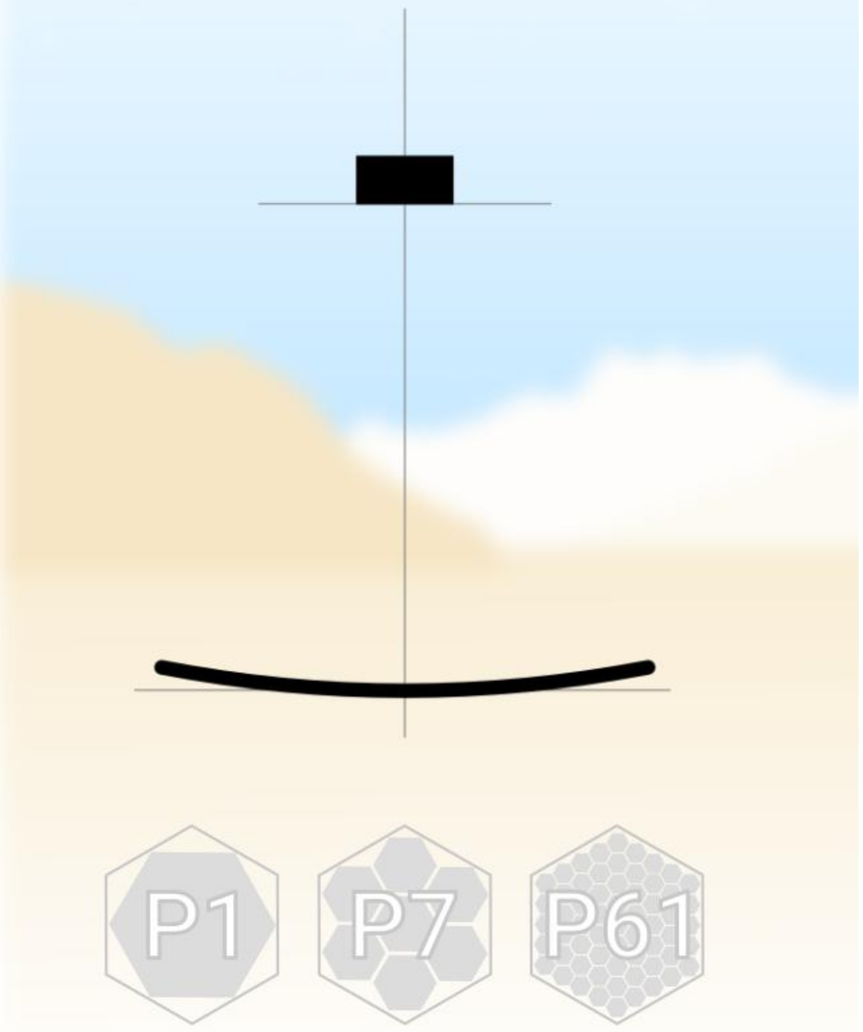
mirror deformations

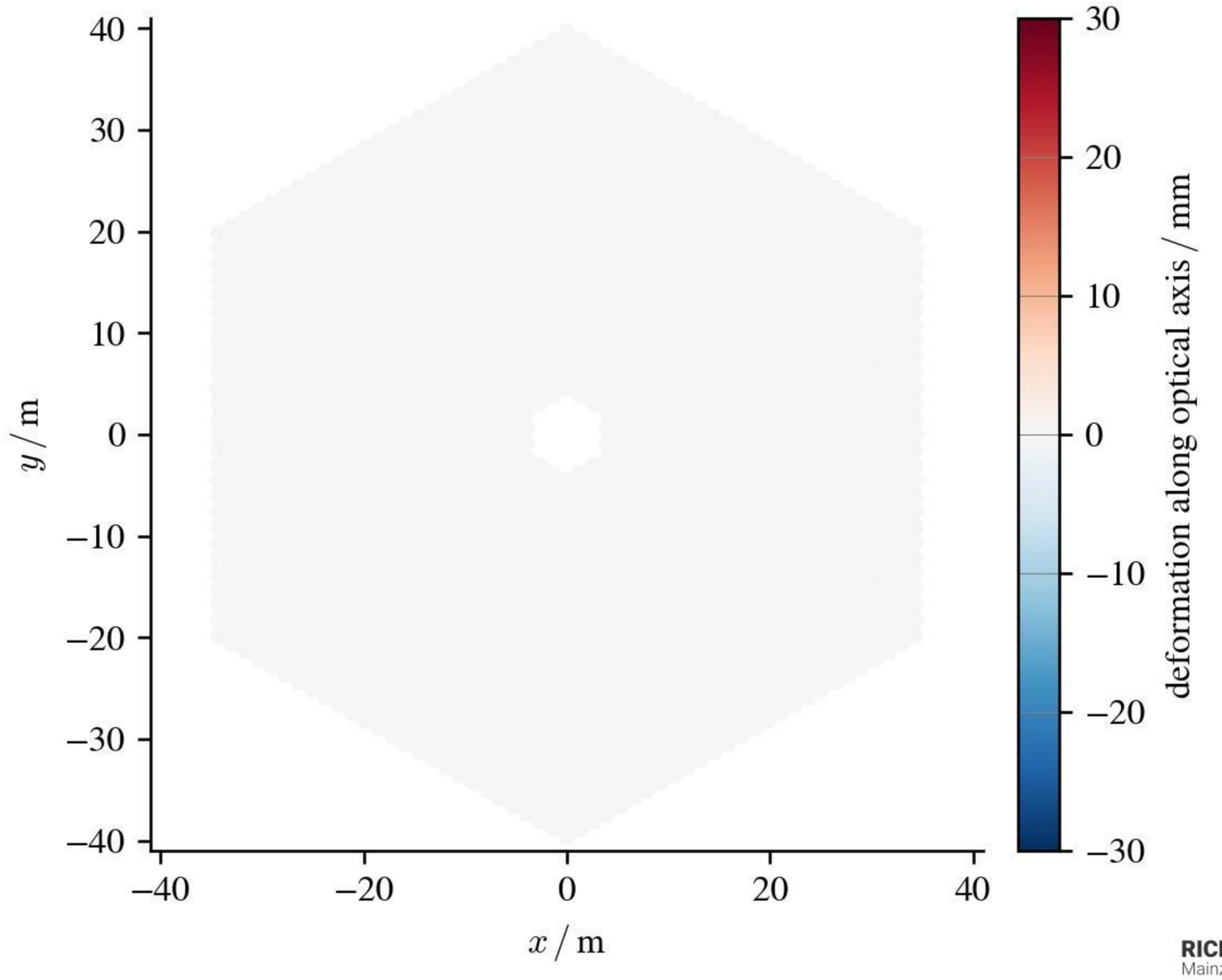


Further, we will also benchmark the optical performance when the optics is deforemd and misaligned.

Optics

mirror deformations

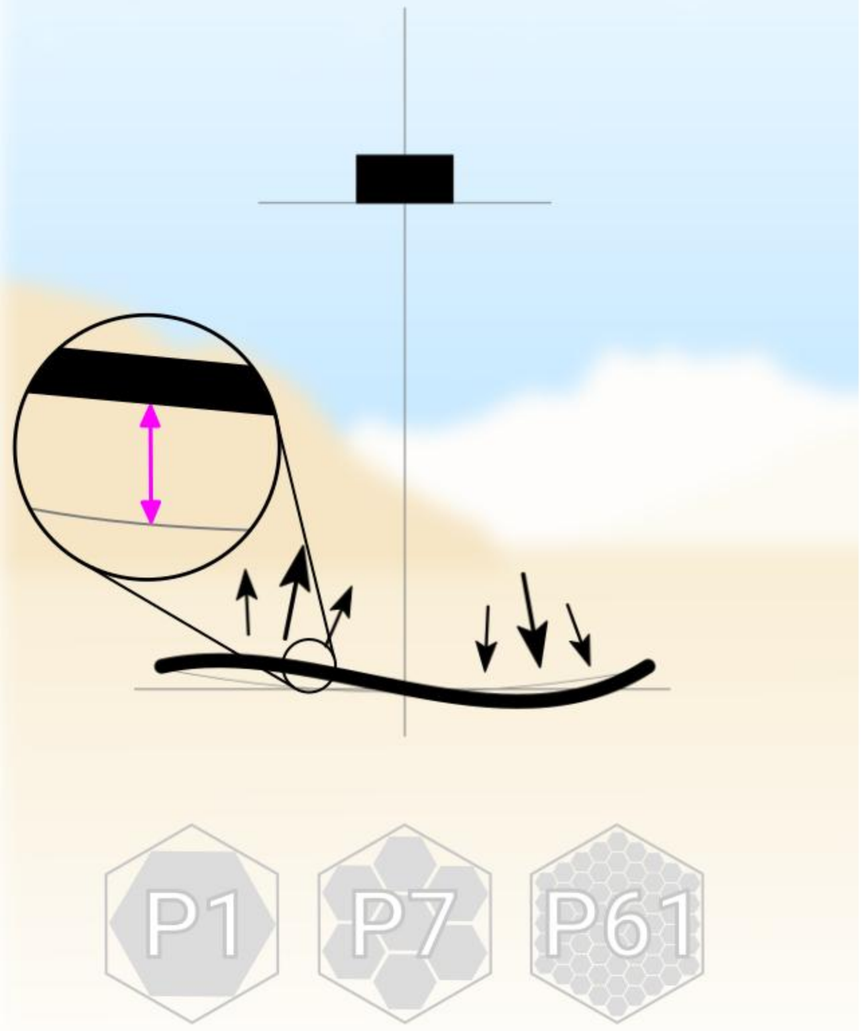


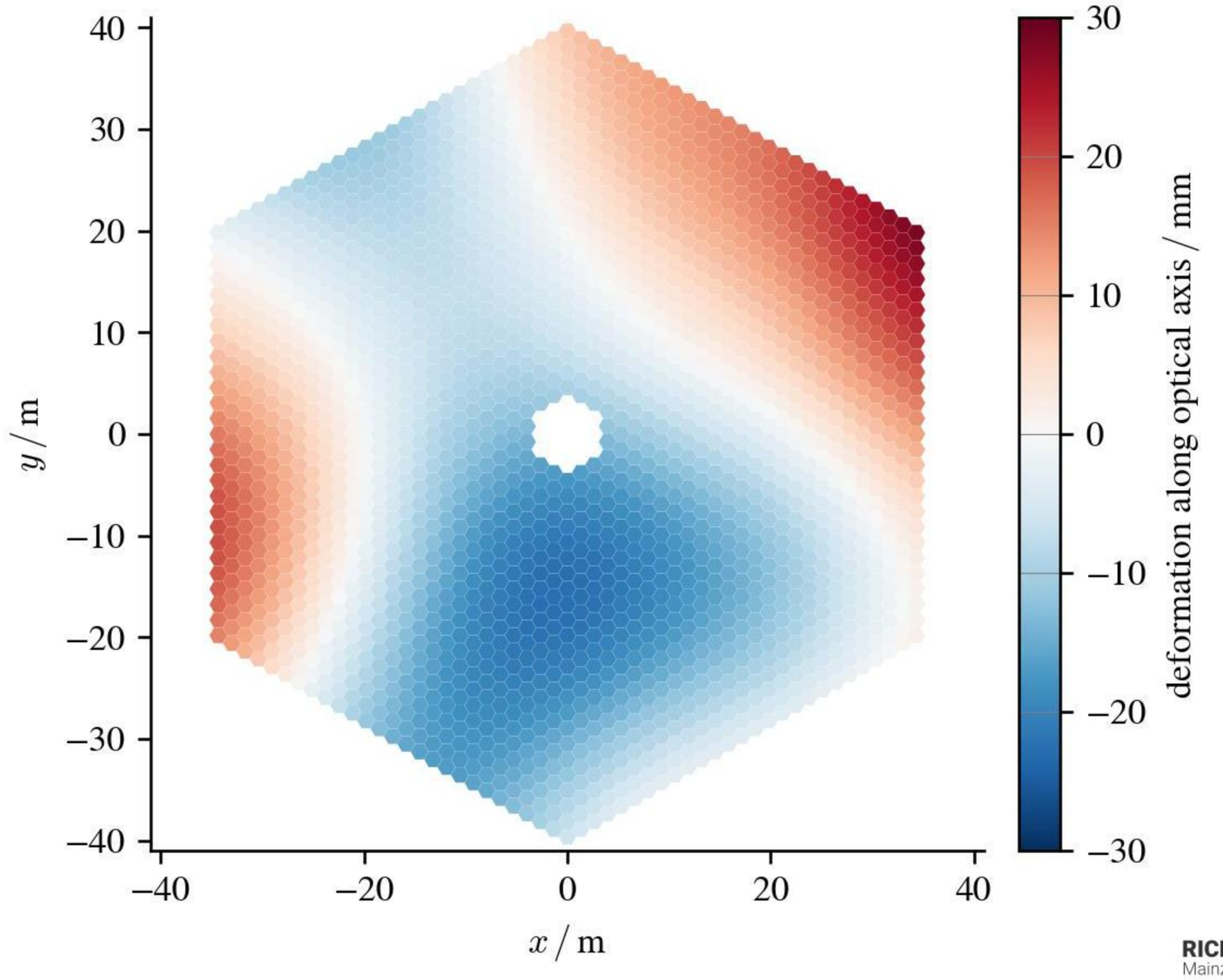


Se we deform the ...

Optics

mirror deformations

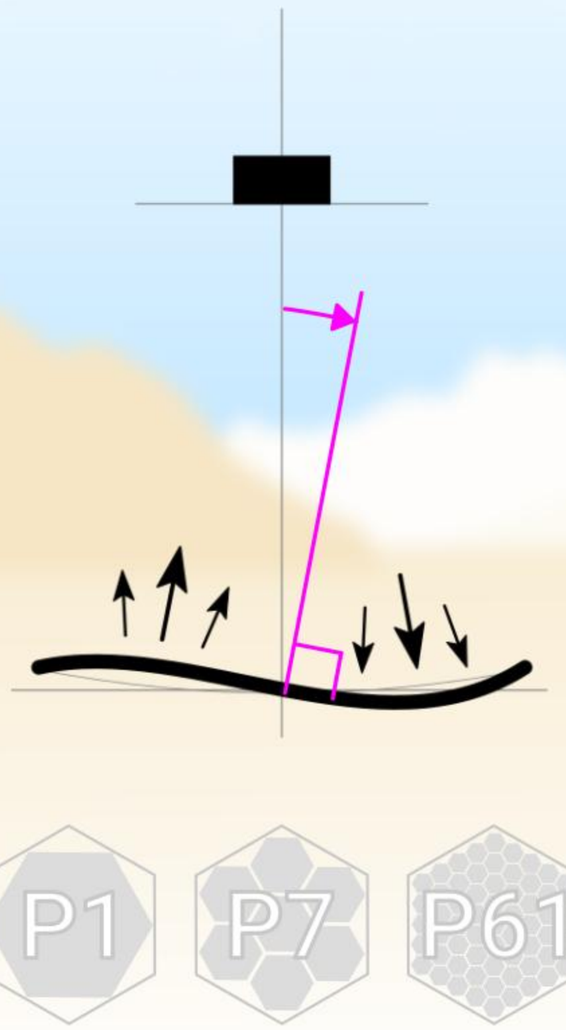


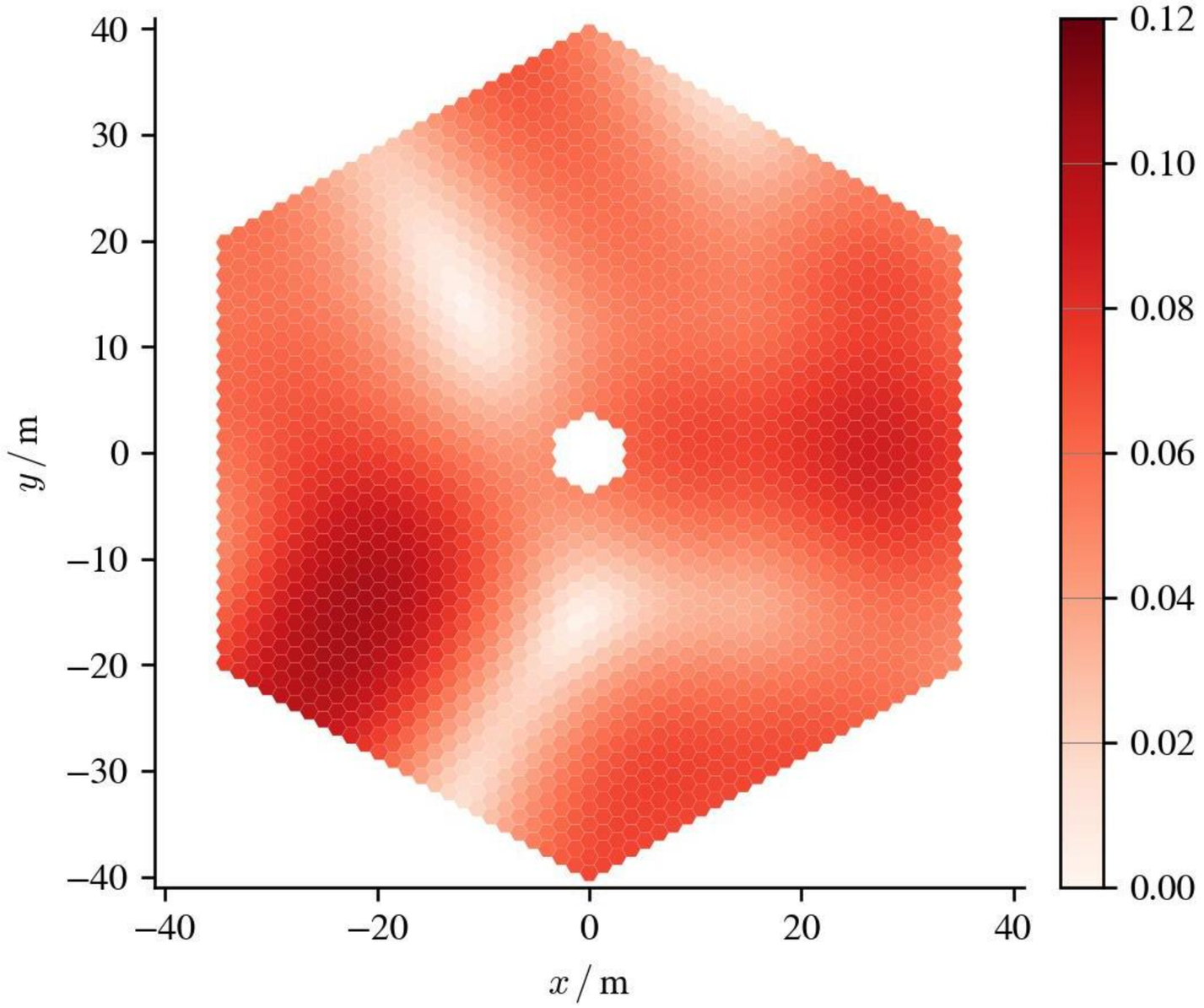


mirror on purpose ...

Optics

mirror deformations





in a way that will turn out to be significant.

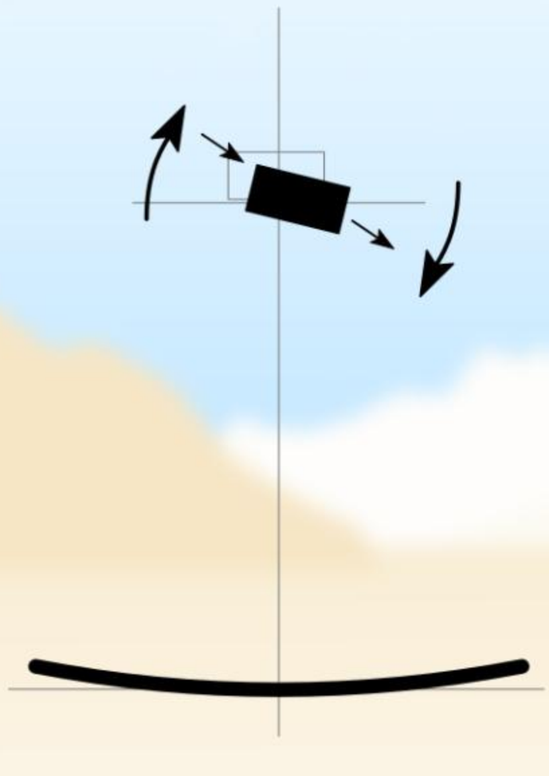
Optics

camera misalignment

And we also misalign ...

Optics

camera misalignment



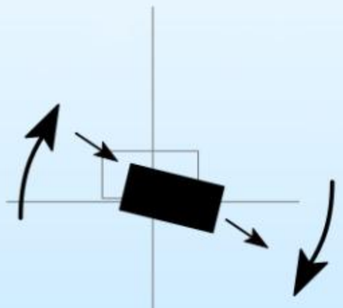
$$
\begin{aligned}
\text{Tait-Bryan-}xyz &= (1.0,\ 3.0,\ 5.0)^\circ \\
\text{translation-}xyz &= (-100,\ 200,\ -532.5)\,\text{mm} \\
&= (-0.1,\ 0.2,\ -0.5)\%f
\end{aligned}
$$

P1 P7 P61

the camera on purpose ...

Optics

camera misalignment



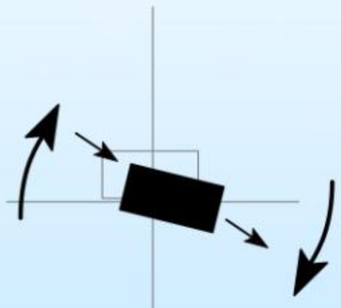
$$\begin{aligned} \text{Tait-Bryan-}xyz &= (1.0,\, 3.0,\, 5.0)^\circ \\ \text{translation-}xyz &= (-100,\, 200,\, -532.5)\,\text{mm} \\ &= (-0.1,\, 0.2,\, -0.5)\%f \end{aligned}$$

$$g = 10.0\,\text{km} \rightarrow g \approx 18.6\,\text{km}$$

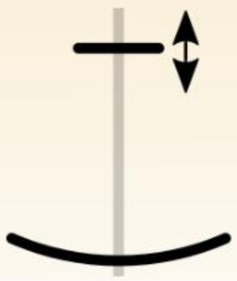
in a way that will turn out to be significant, too.

Optics

camera misalignment



$$\begin{aligned} \text{Tait-Bryan-}xyz &= (1.0,\, 3.0,\, 5.0)^\circ \\ \text{translation-}xyz &= (-100,\, 200,\, -532.5)\,\text{mm} \\ &= (-0.1,\, 0.2,\, -0.5)\%f \end{aligned}$$



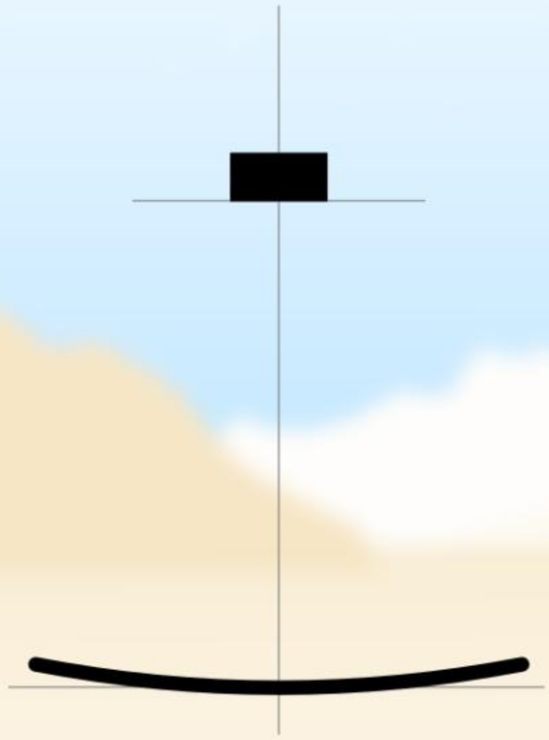
$$g = 10.0\,\text{km} \rightarrow g \approx 18.6\,\text{km}$$

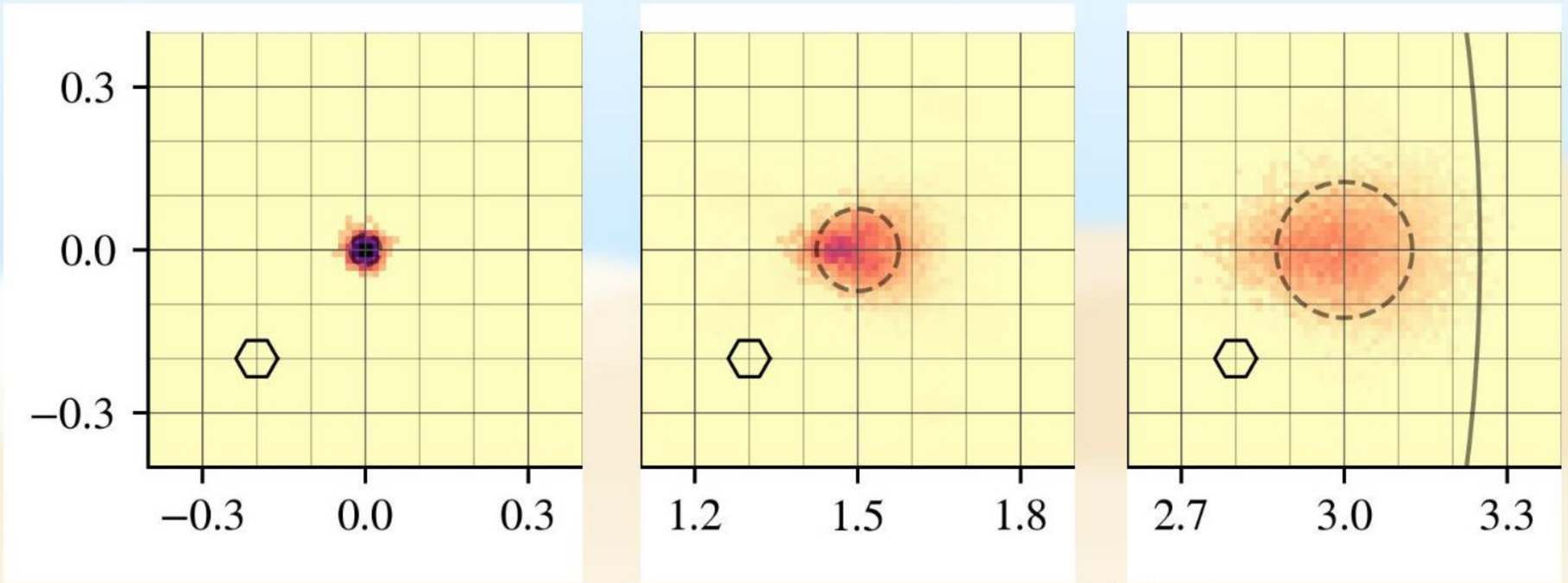
Optics

performance

Now lets have a look at the point-spread-functions.

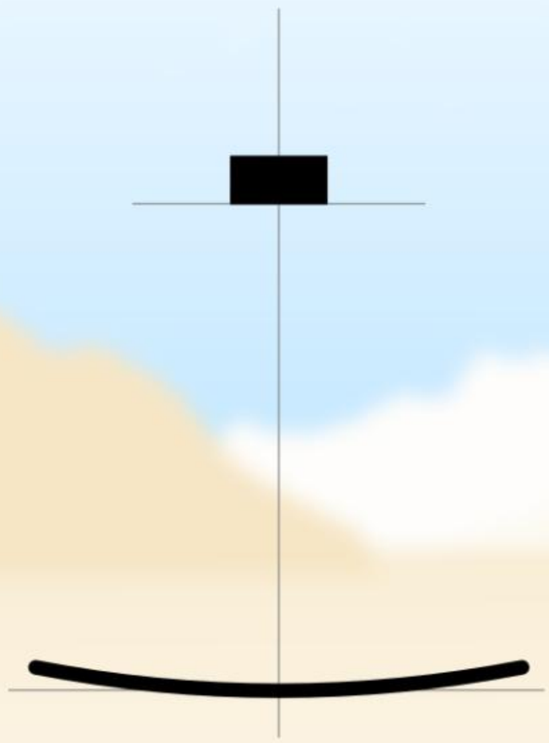
Optics
performance

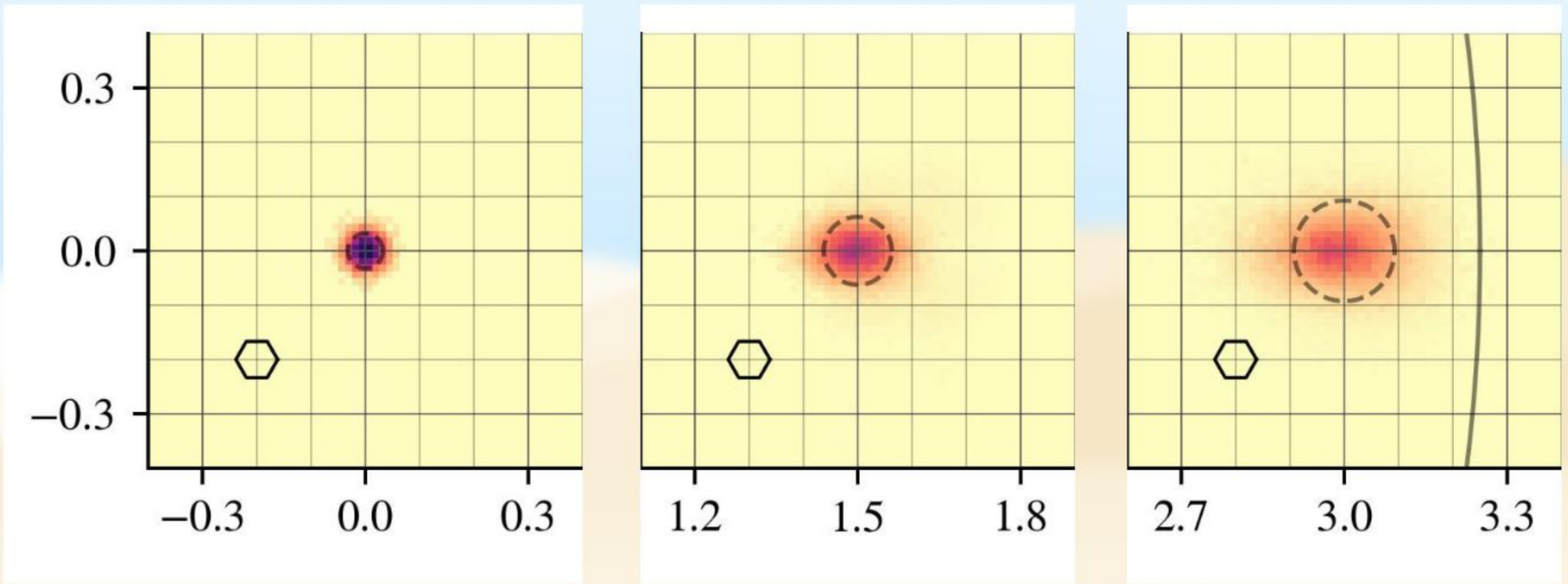




We start with the telescope p-one when the mirror is in good shape and the camera is well aligned. As we expect, the center of the image is sharp but aberrations quickly blur the image when we go off the optical axis.

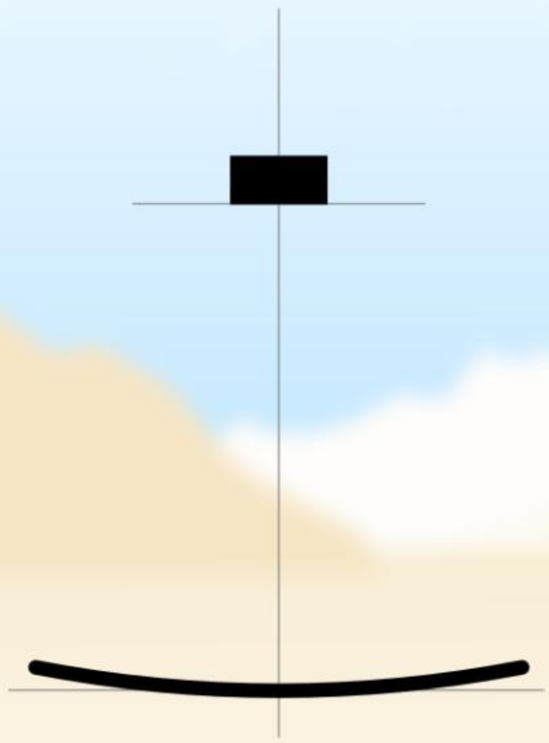
Optics
performance

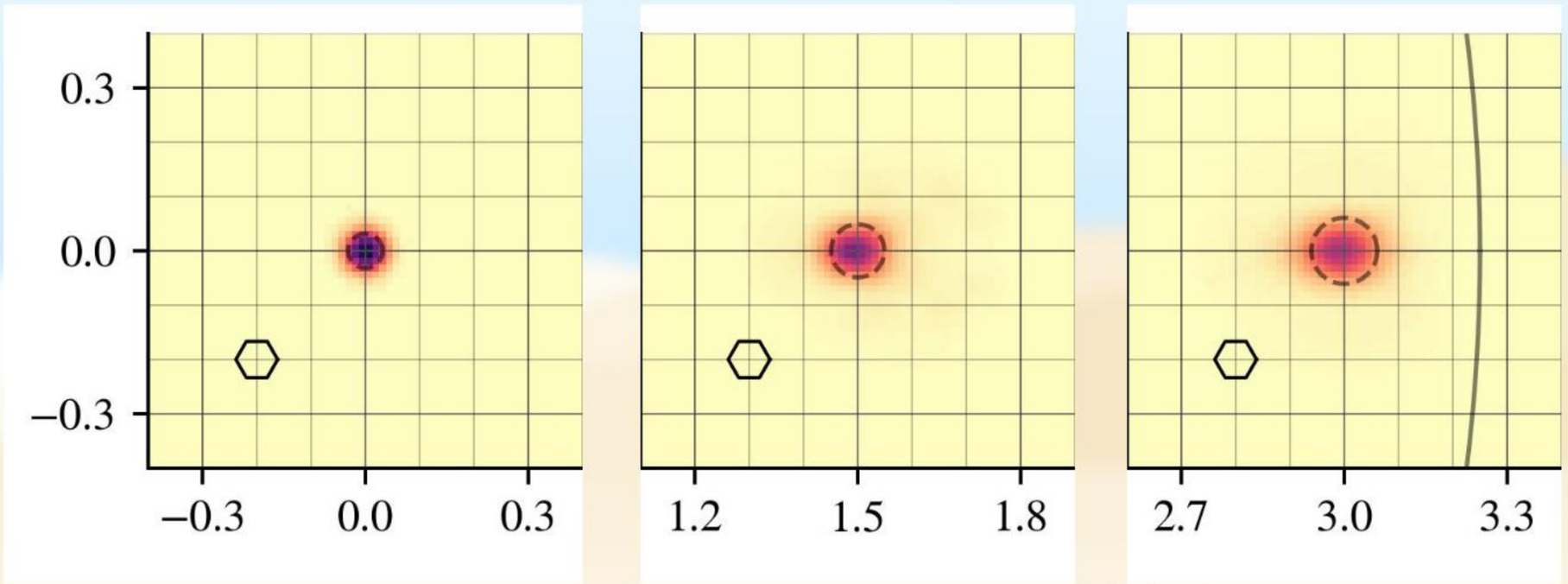




Alredy the plenoscope p-seven is able to reduce the aberrations significantly.

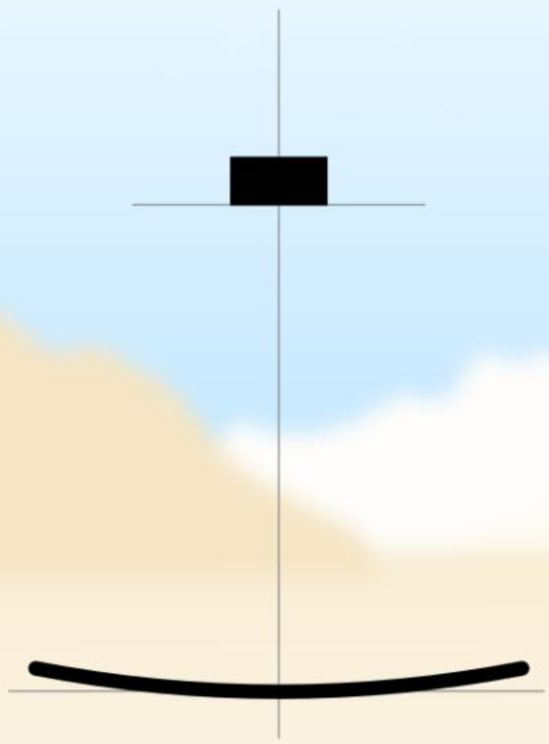
Optics
performance

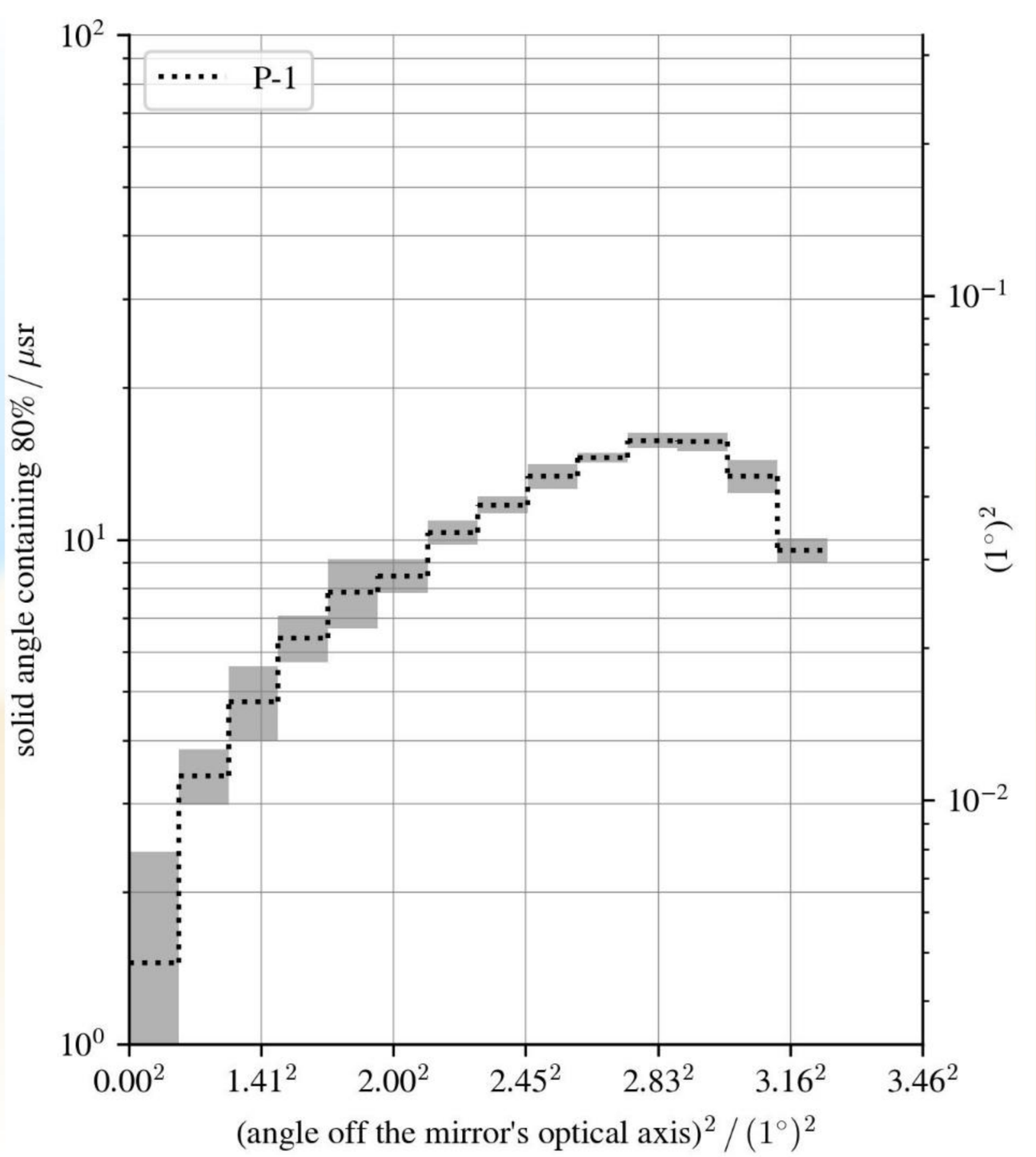




With the Portal plenoscope p-sixty-one, aberrations are practically gone.

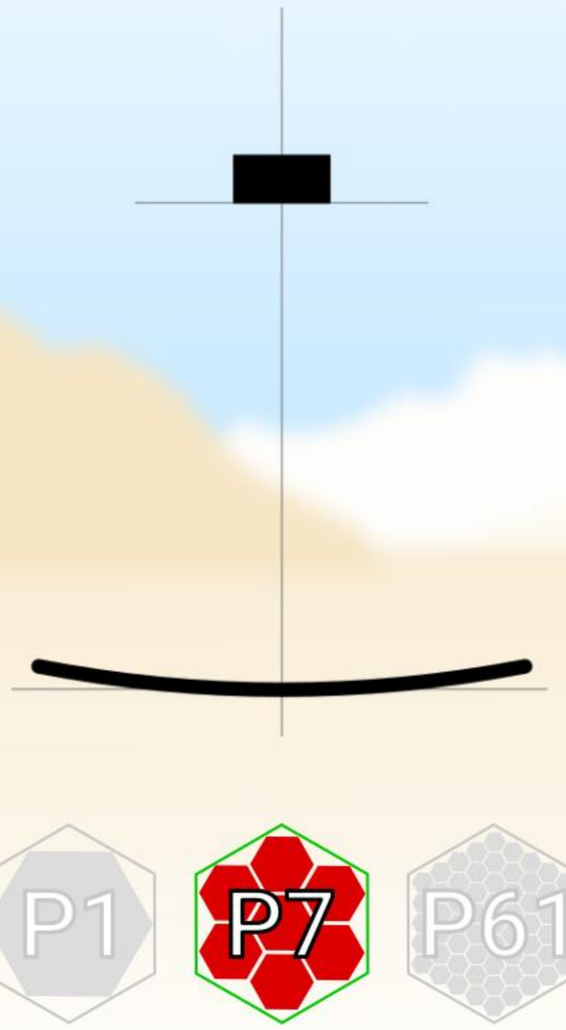
Optics
performance

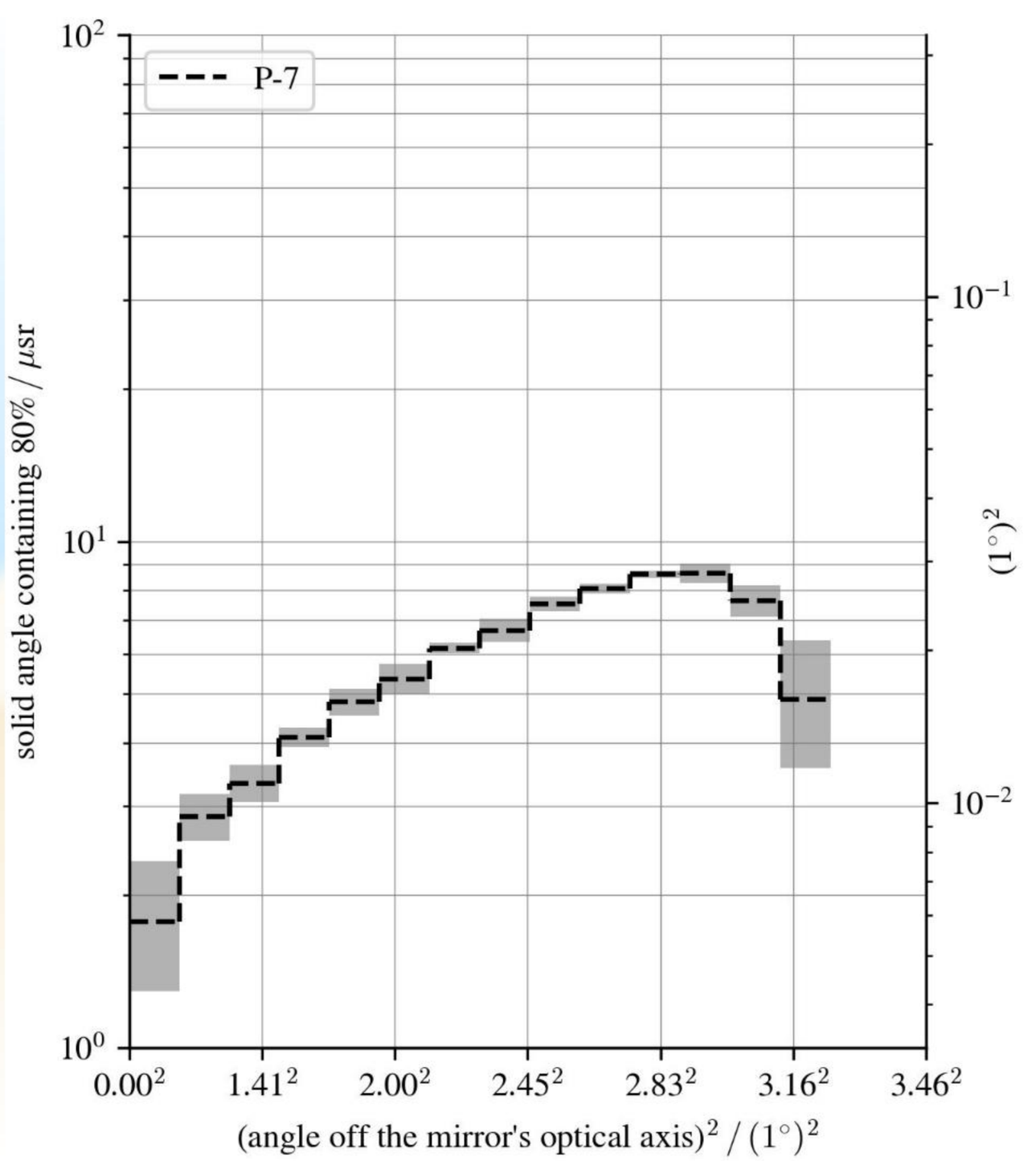




This is again the telescope p-one. We see the solid angle of its point-spread-function versus the angle off the optical axis.

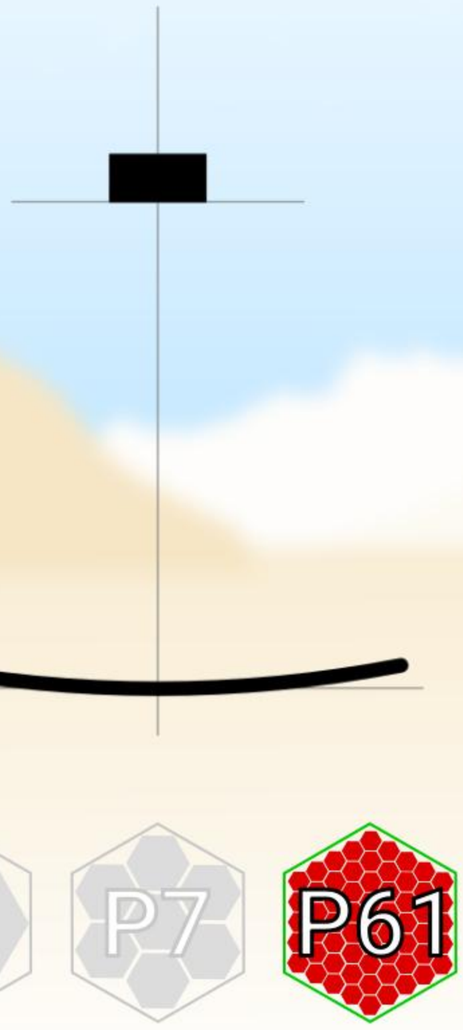
Optics
performance

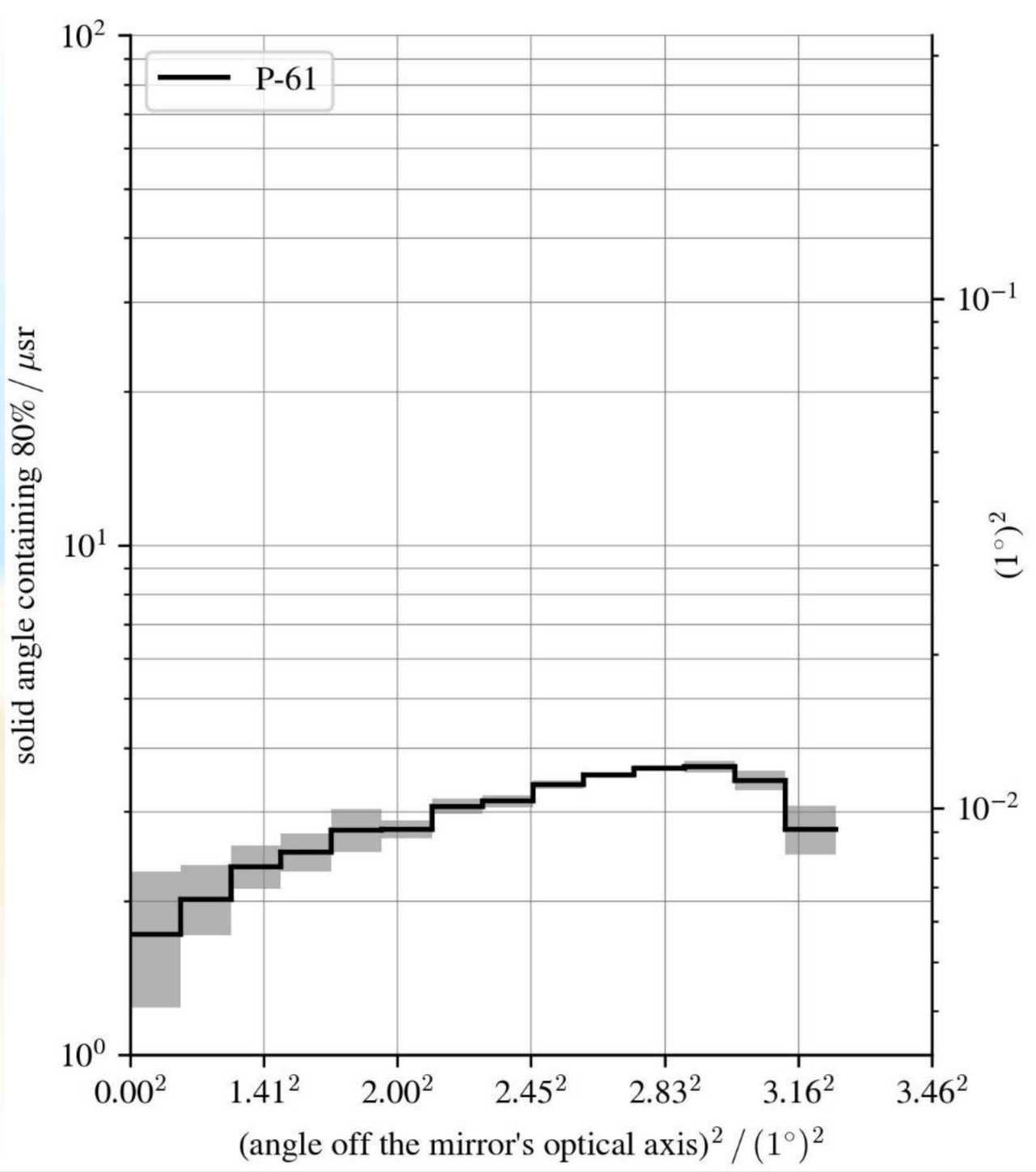




By contrast, here is the plenoscope p-seven ...

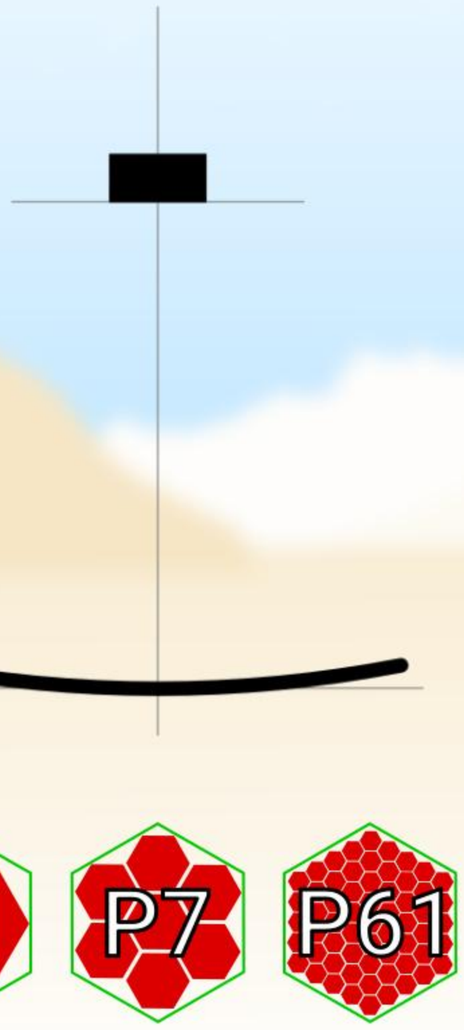
Optics
performance

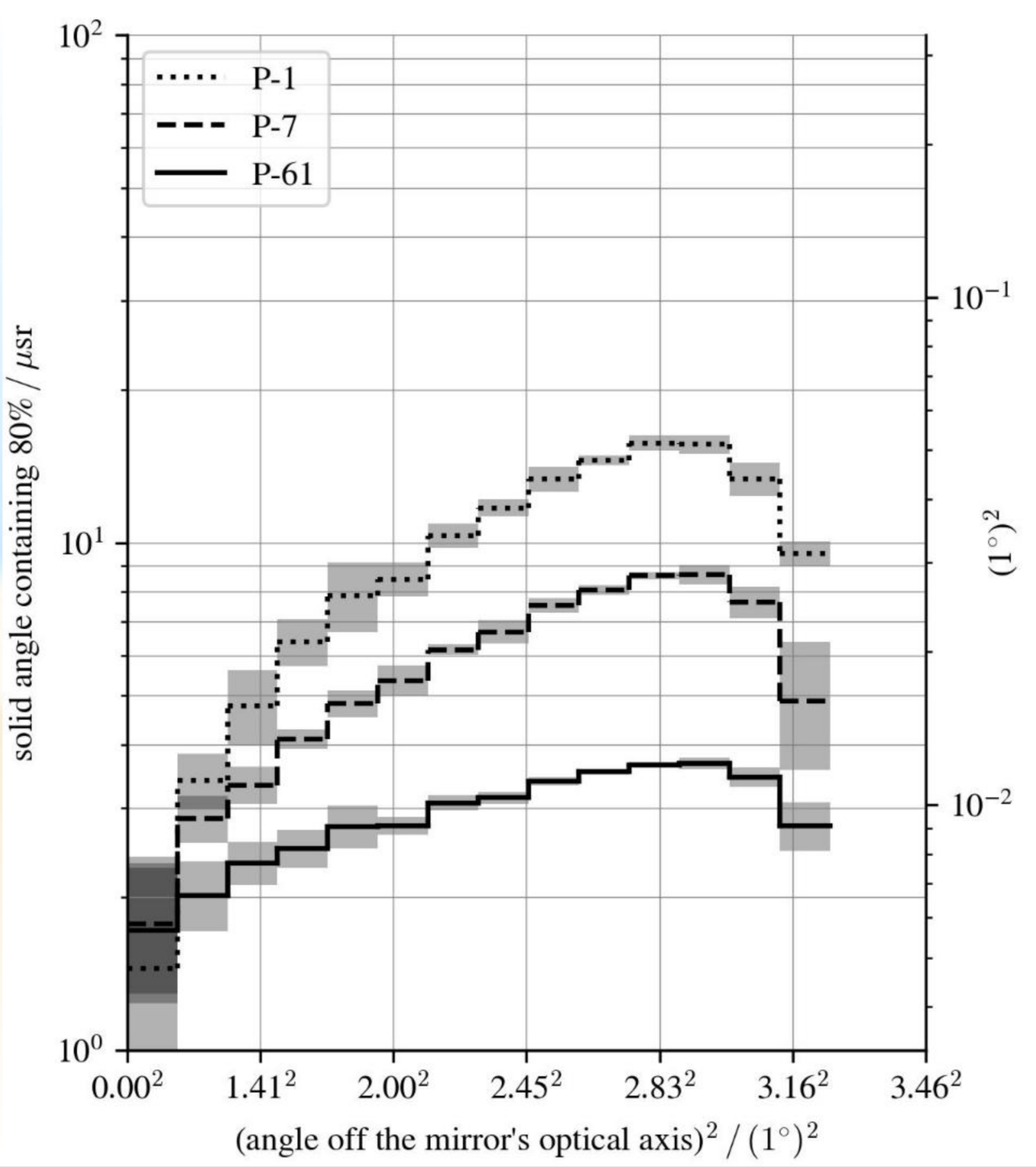




and the Portal plenoscope p-sixty-one.

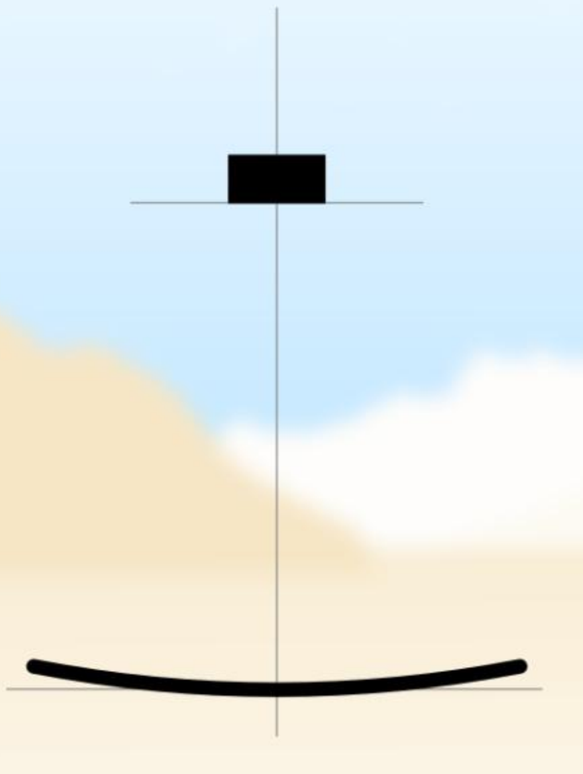
Optics
performance





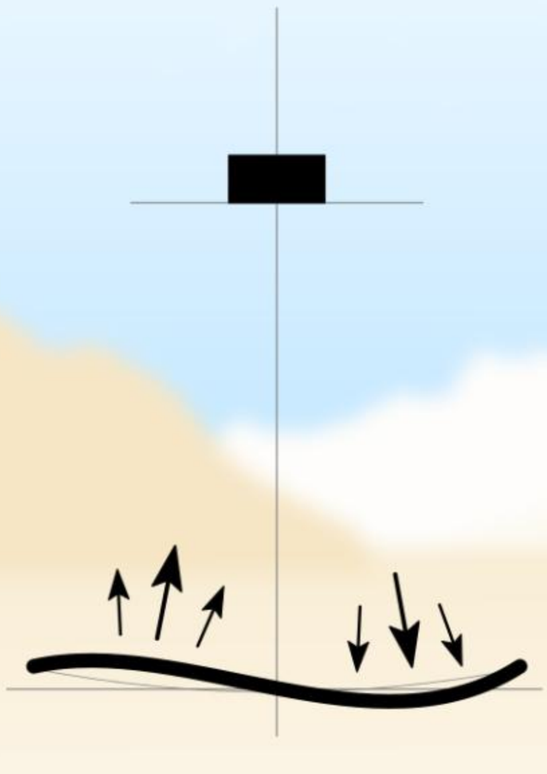
Here they are all together. Note, that this is a logarithmic scale.

Optics
performance



Ok, but what if ...

Optics
performance



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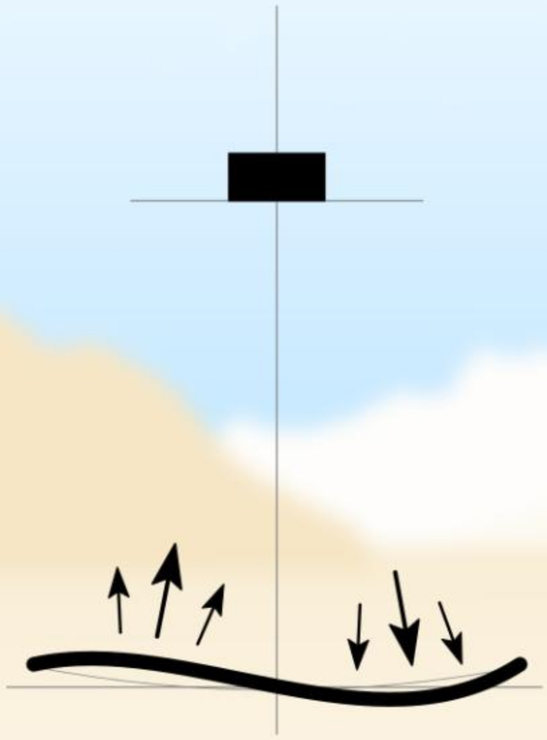
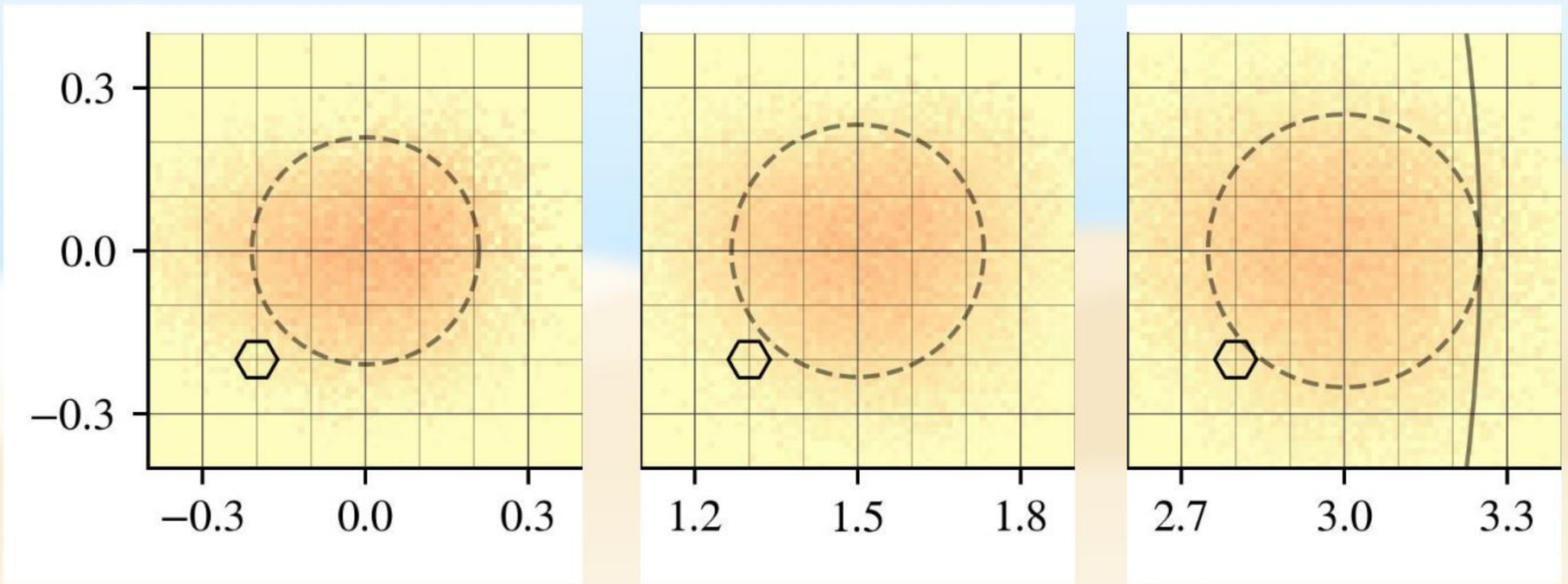
the mirror is beeing deformed?

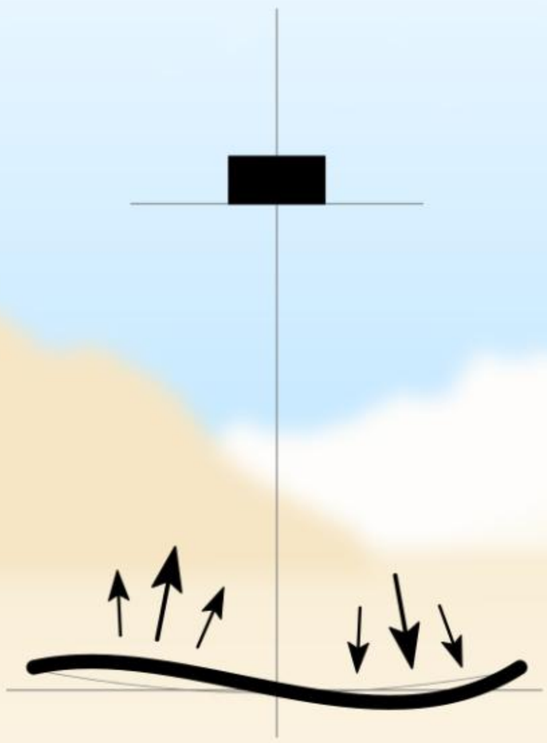
Optics
performance

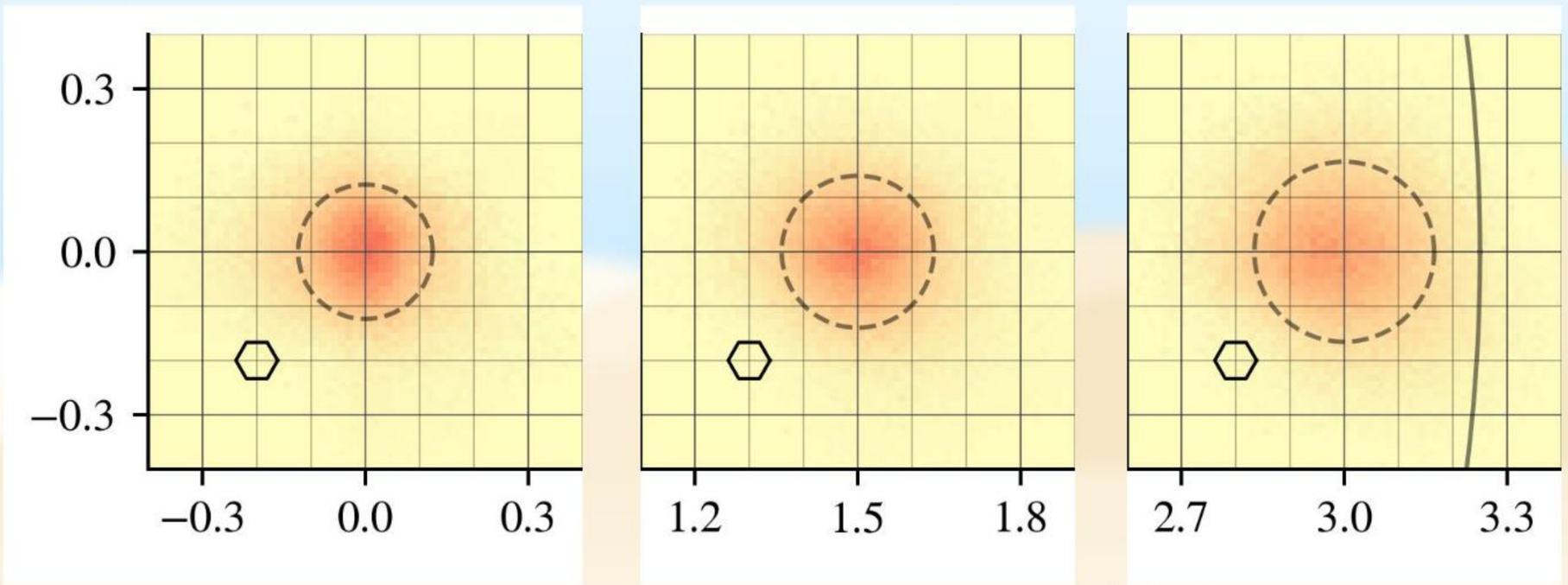




Oooofff. As expected the telescope p-one does not like this.

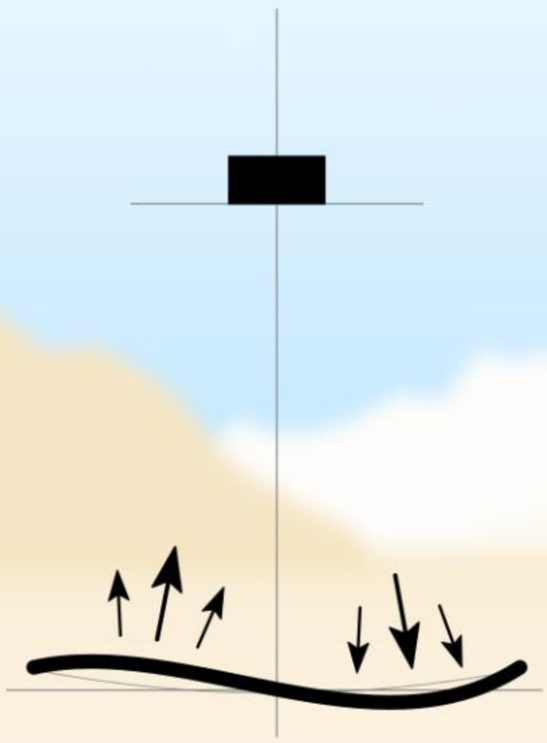
Optics
performance

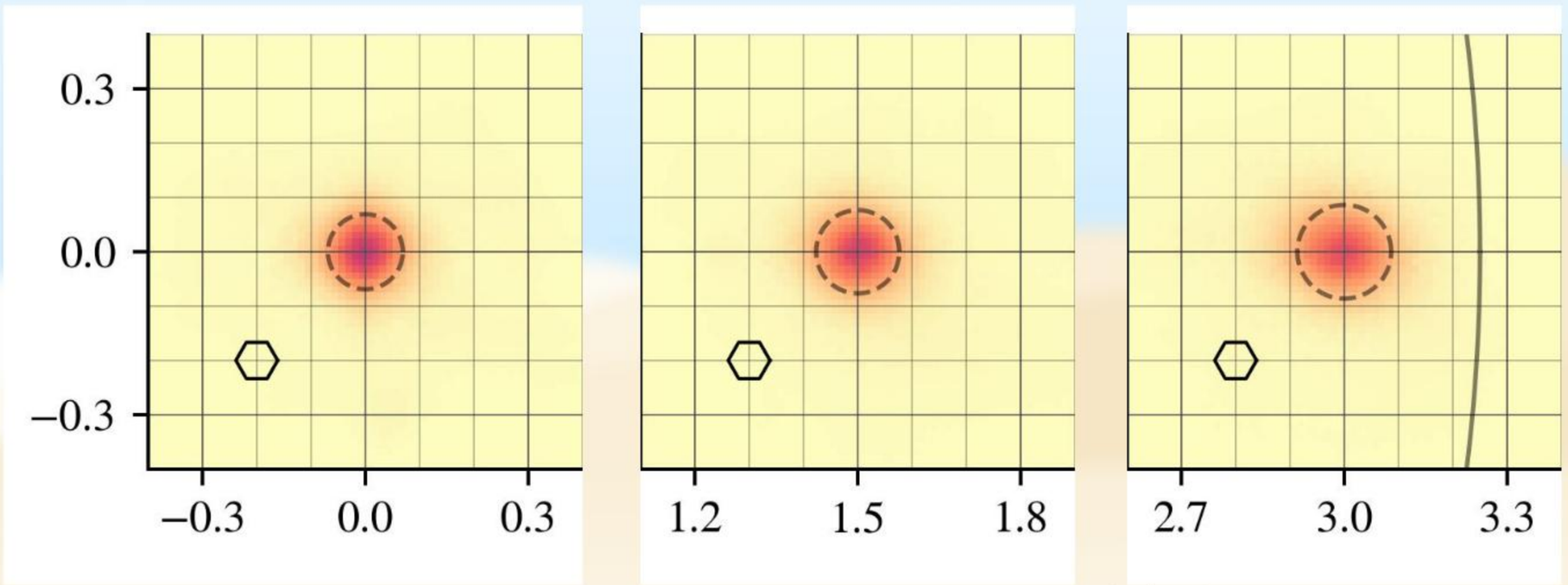




By contrast, this is the plenoscope p-seven, ...

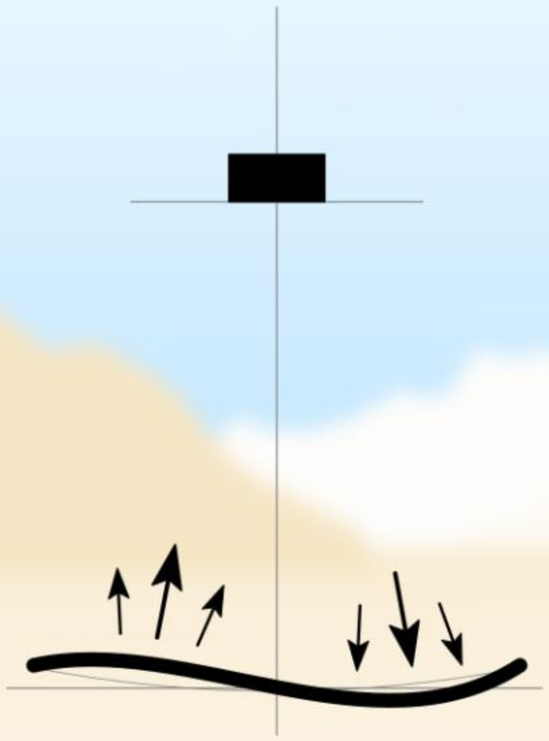
Optics
performance

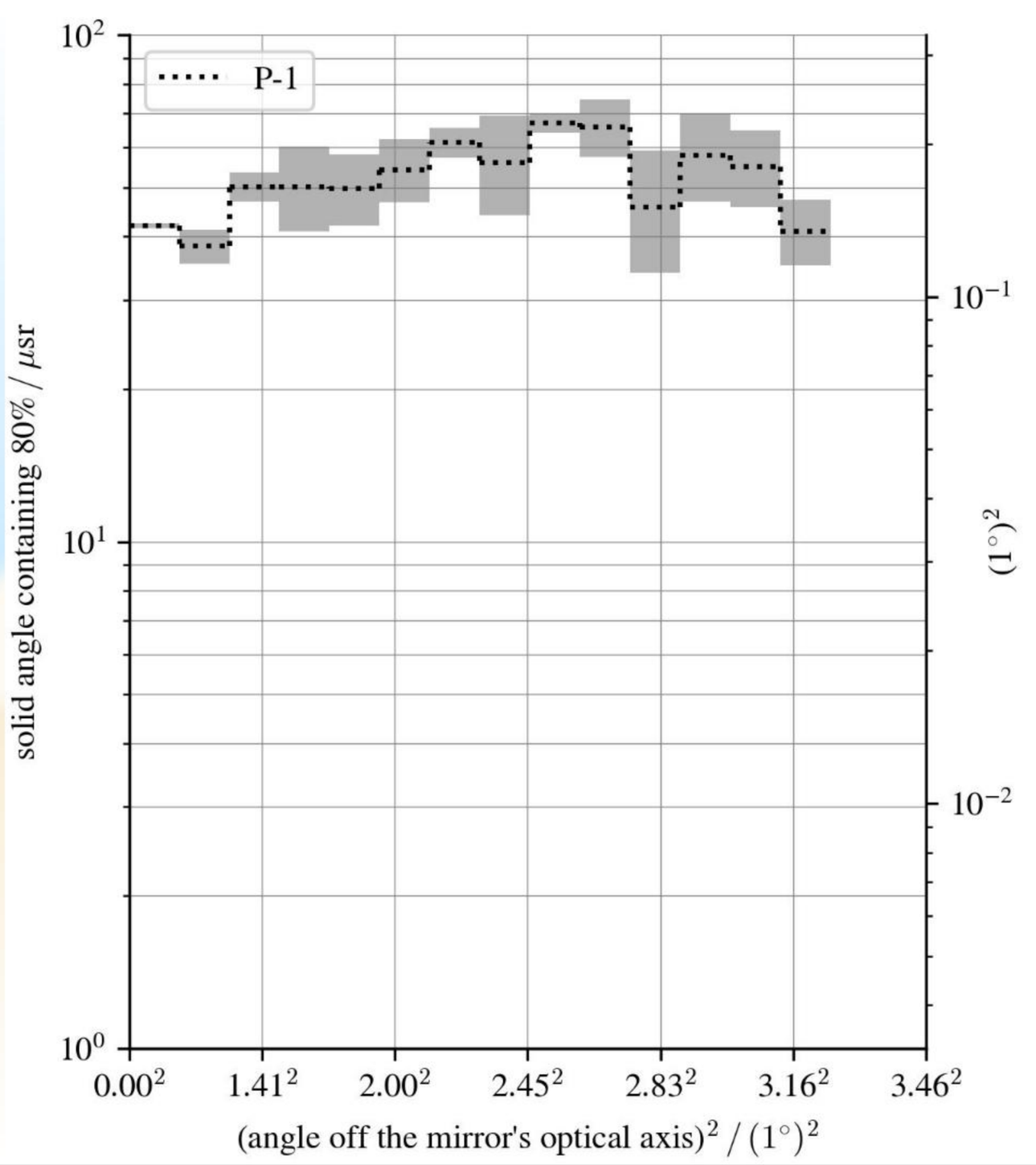




and this is the Portal plenoscope p-sixty-one. Looks like we are back in gamma ray observation business!

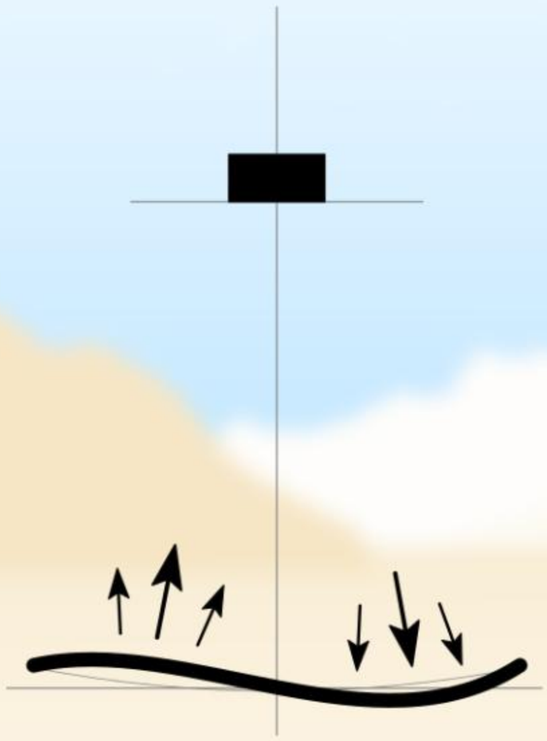
Optics
performance

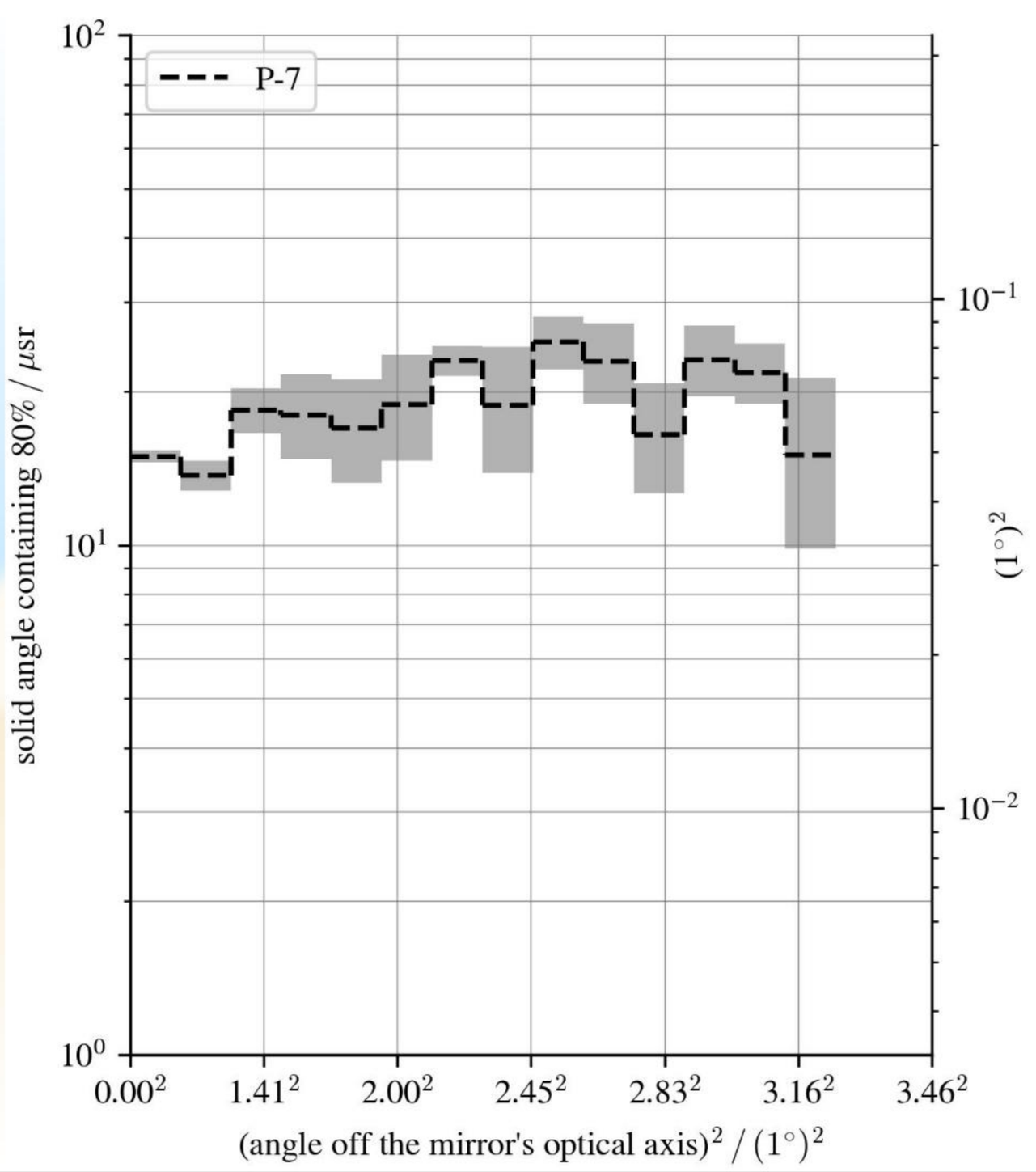




Telescope p-one, ...

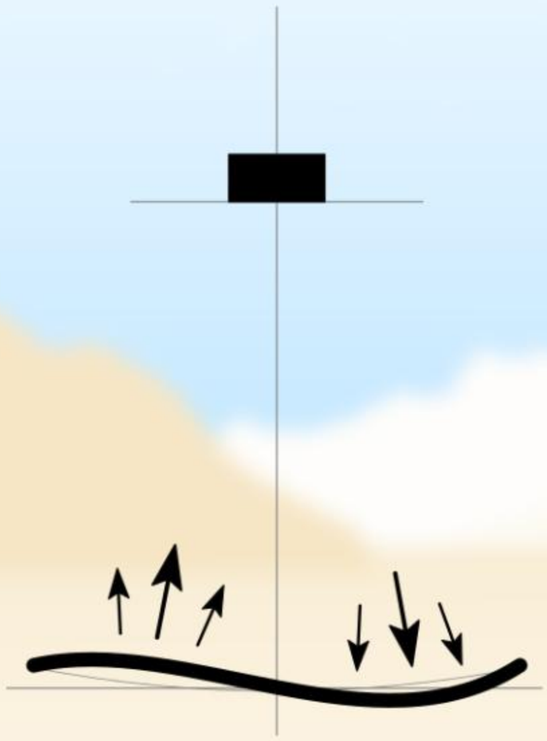
Optics
performance

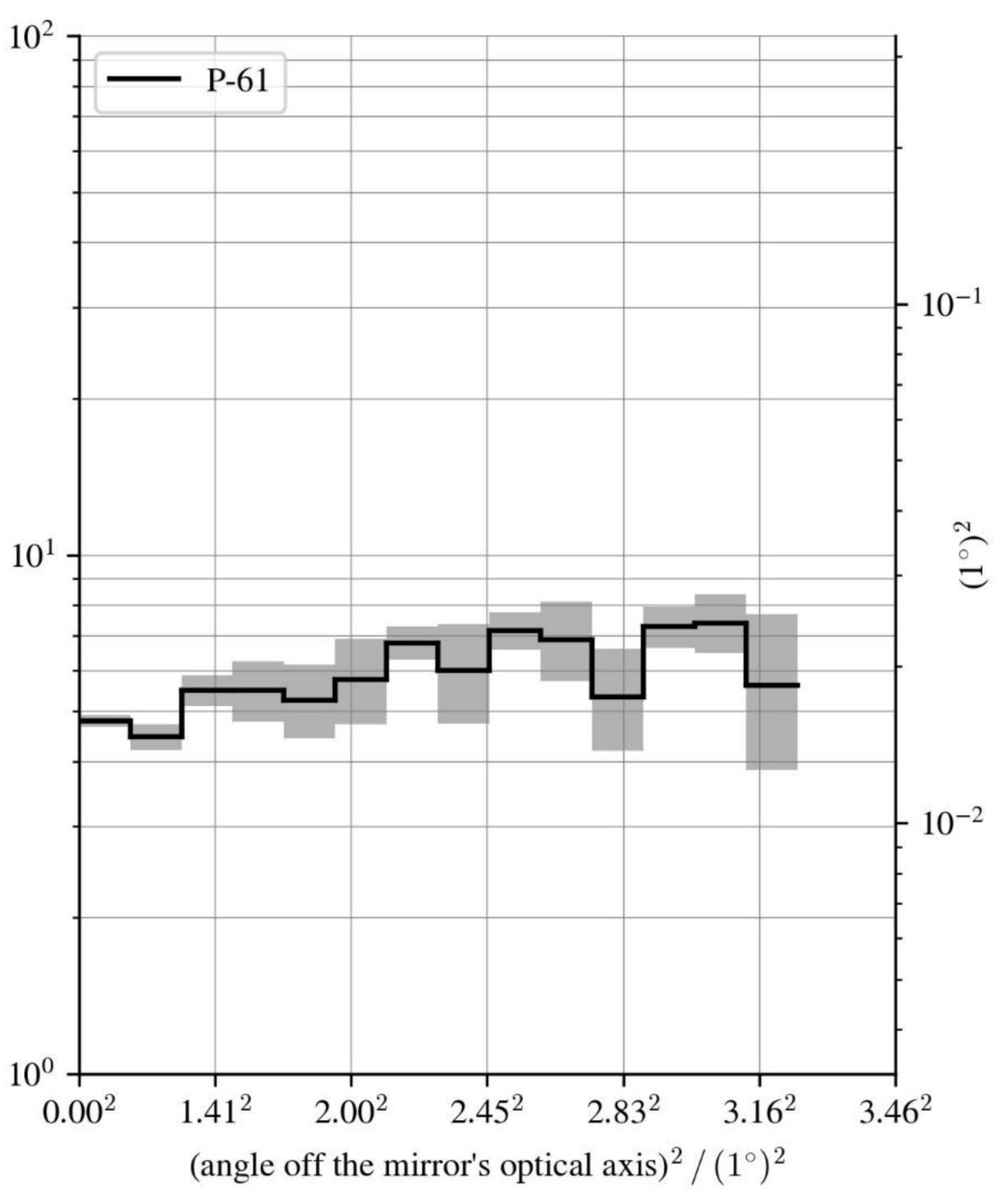




plenoscope p-seven

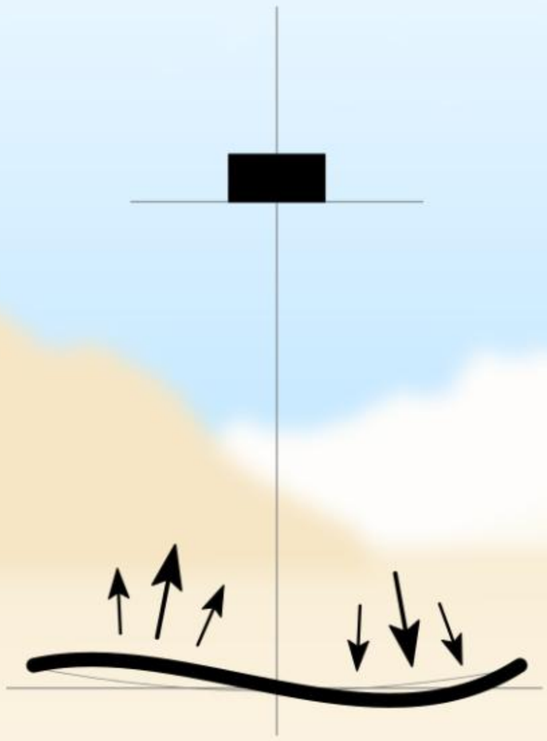
Optics
performance

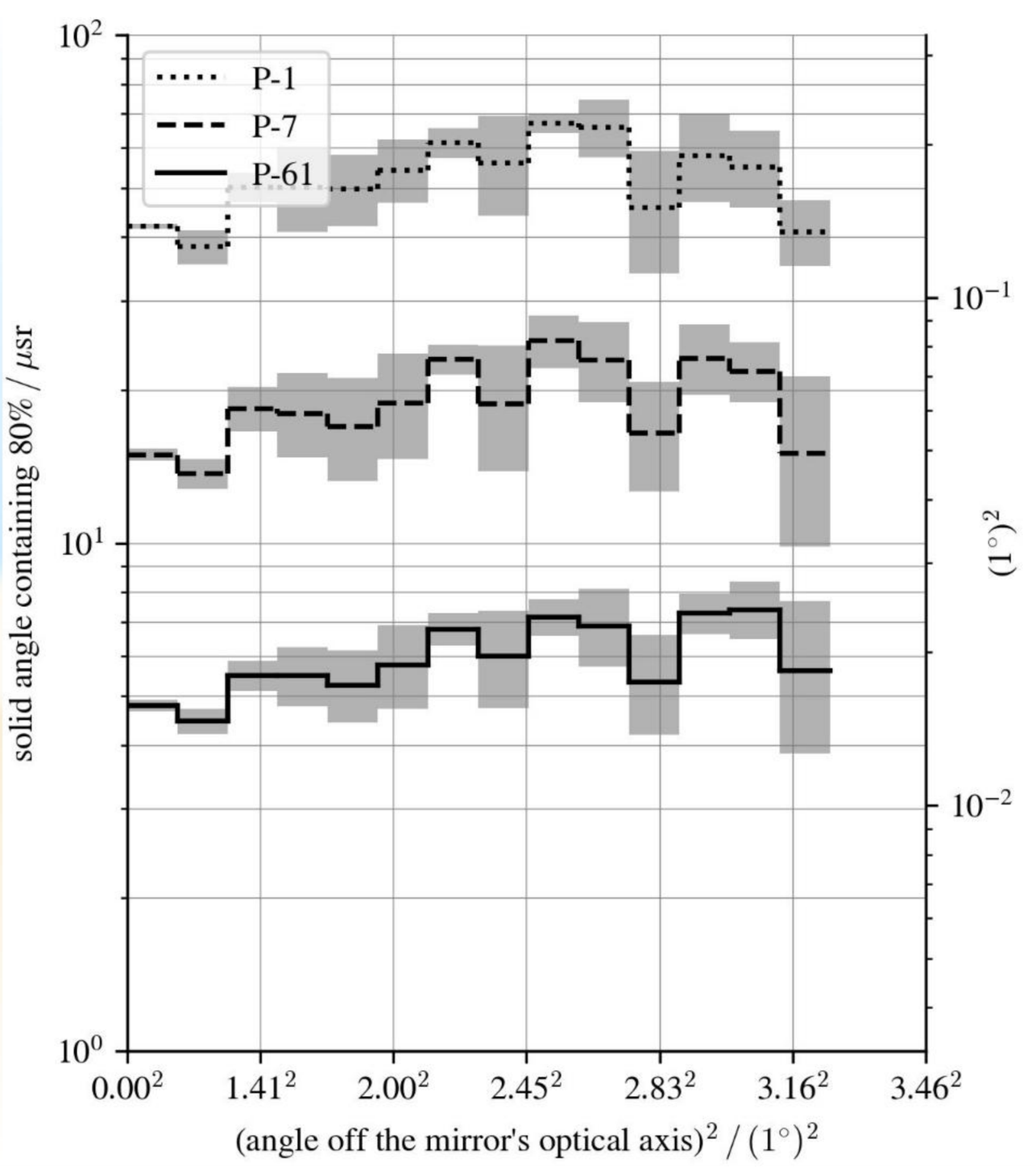




and Portal plenoscope p-sixty-one.

Optics
performance





There are worlds between these instruments.

Optics
performance

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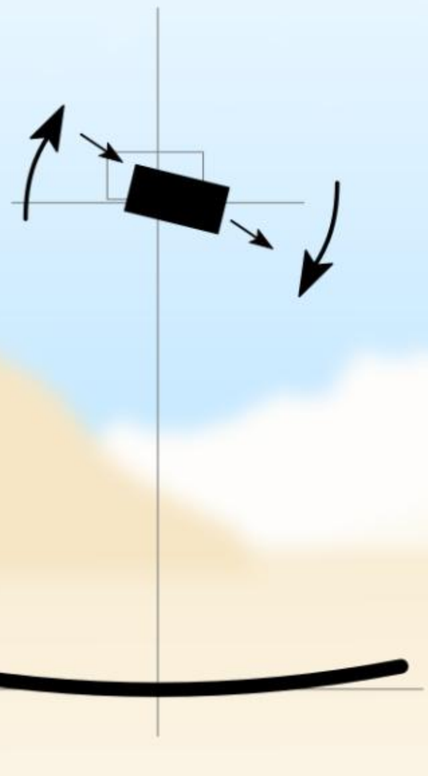
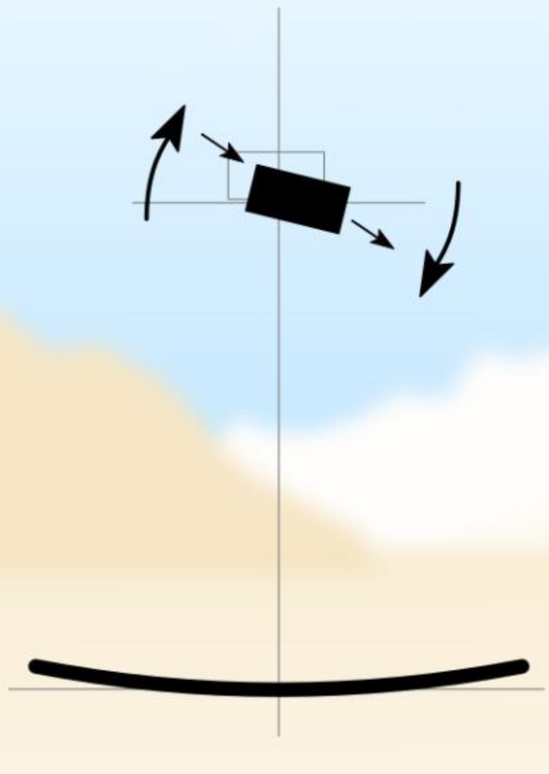
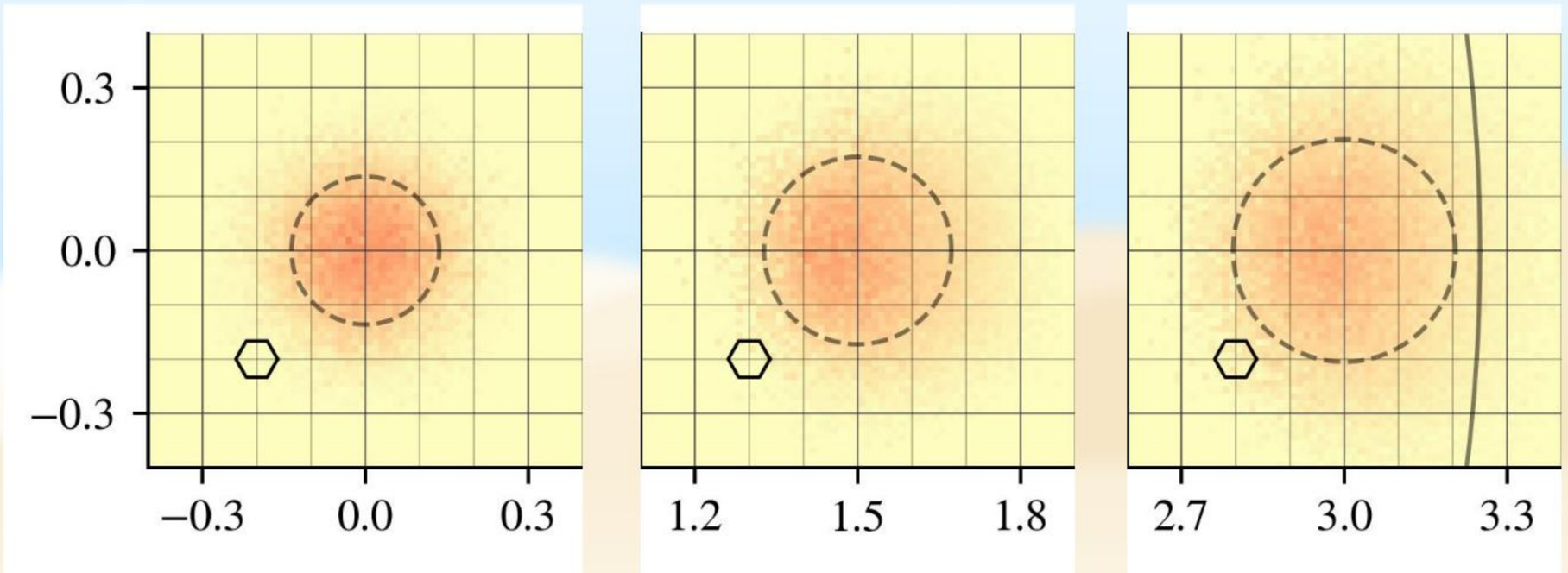
Optics
performance



Now what if the camera is beeing misaligned?

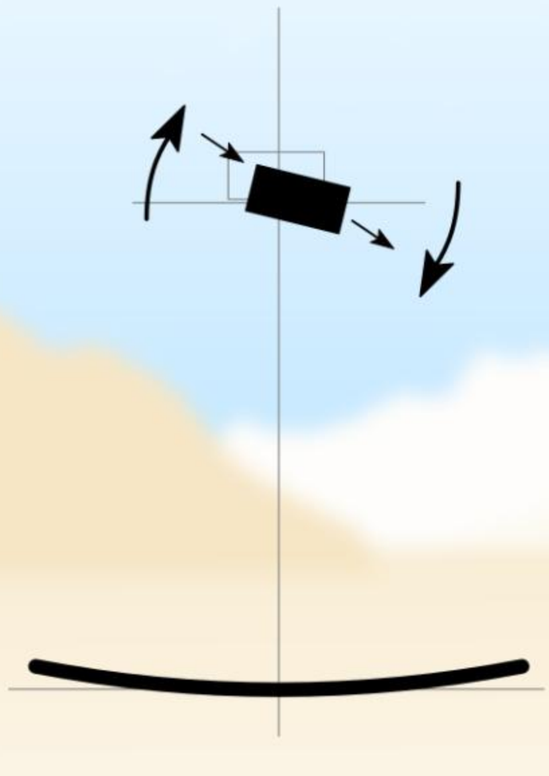
Optics
performance

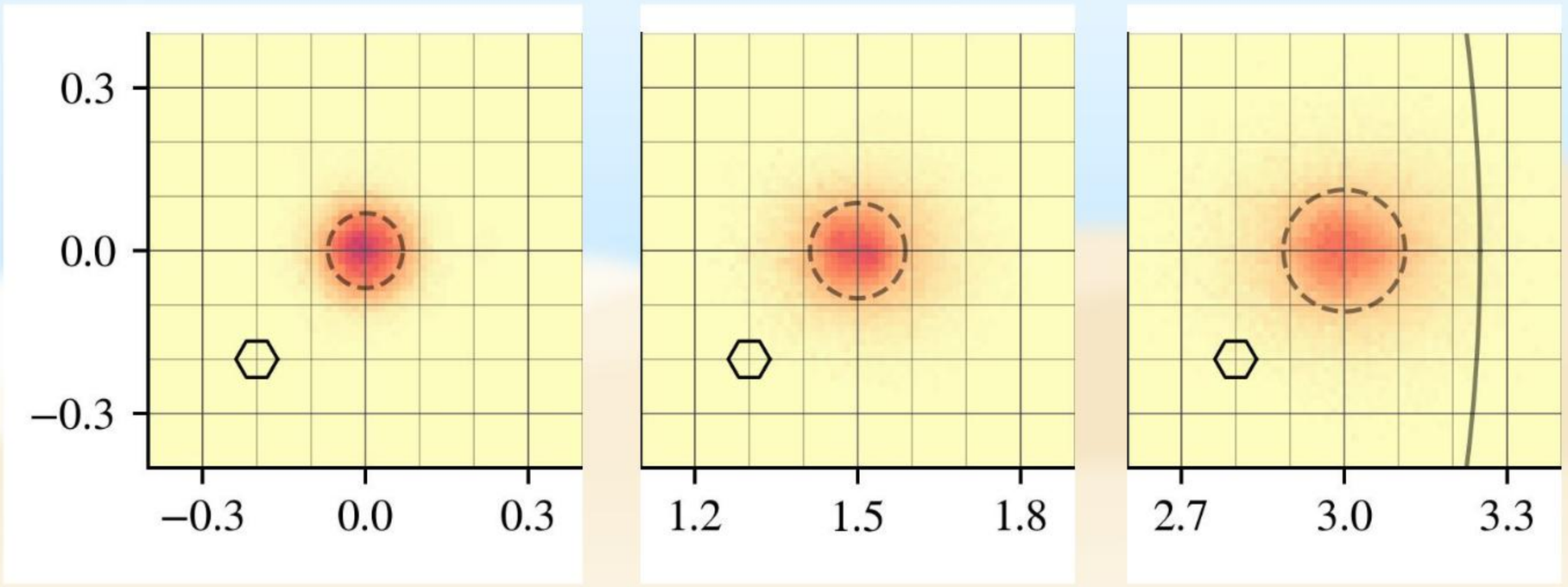




Again, the telescope p-one does not like this at all.

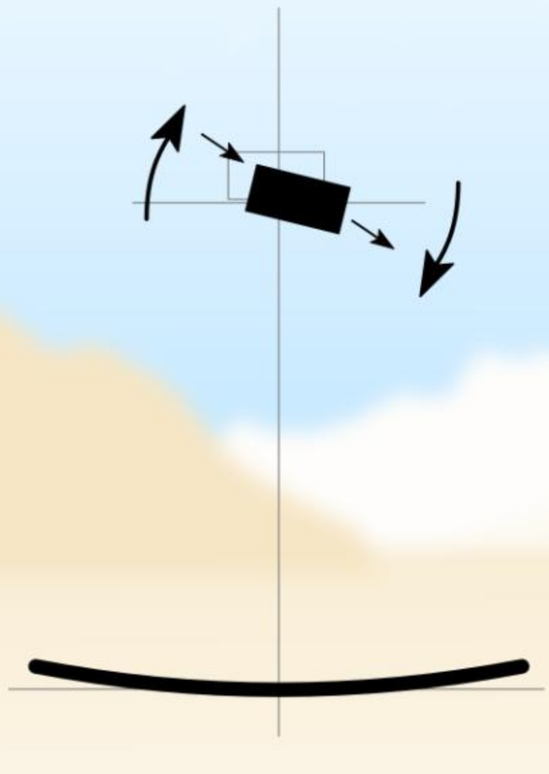
Optics
performance

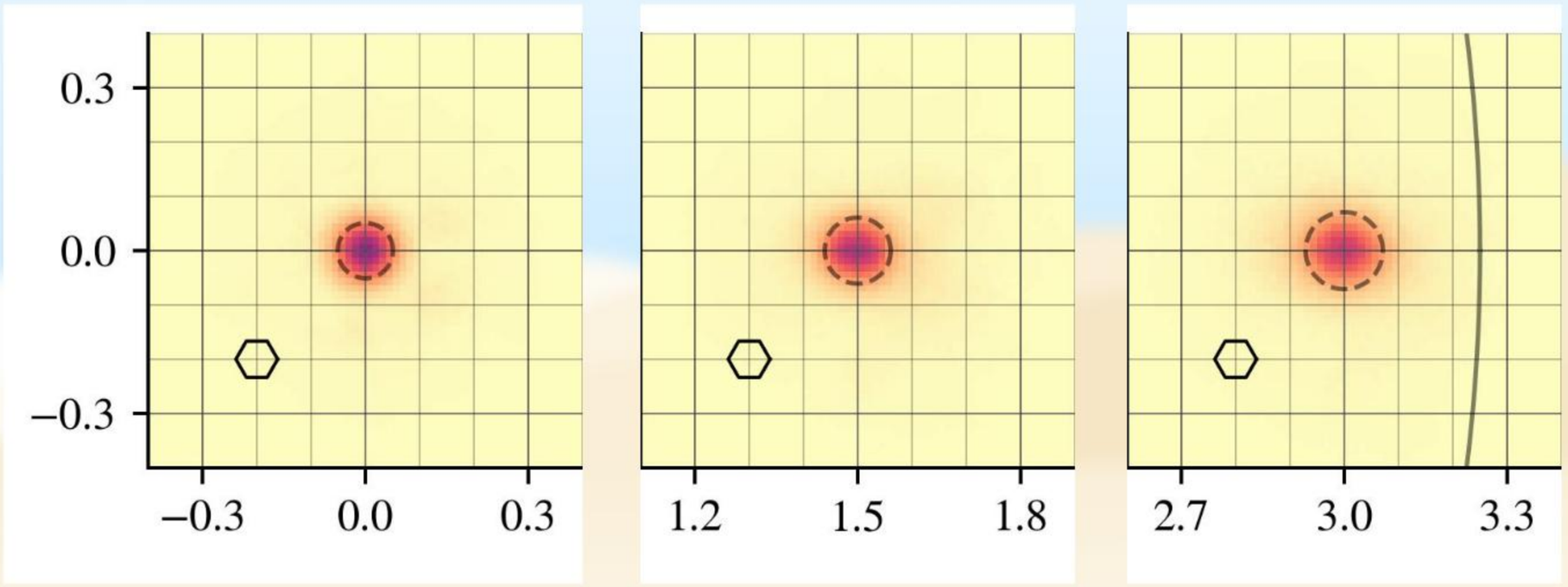




By contrast, the plenoscope p-seven,

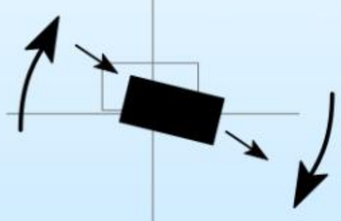
Optics
performance

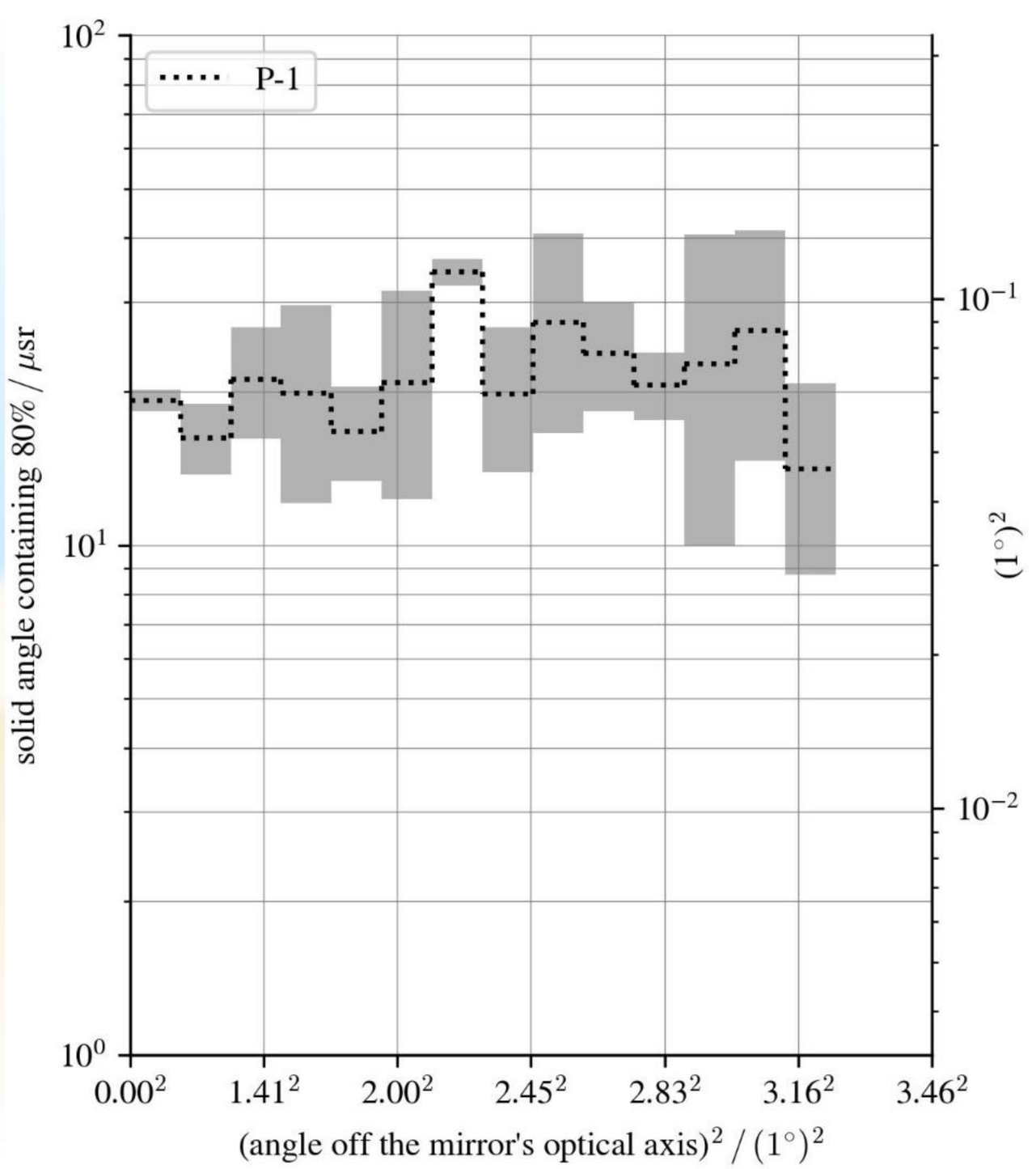




and especially the Portal plenoscope p-sixty-one brings us back into buisness.

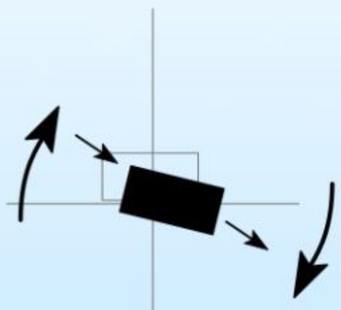
Optics
performance

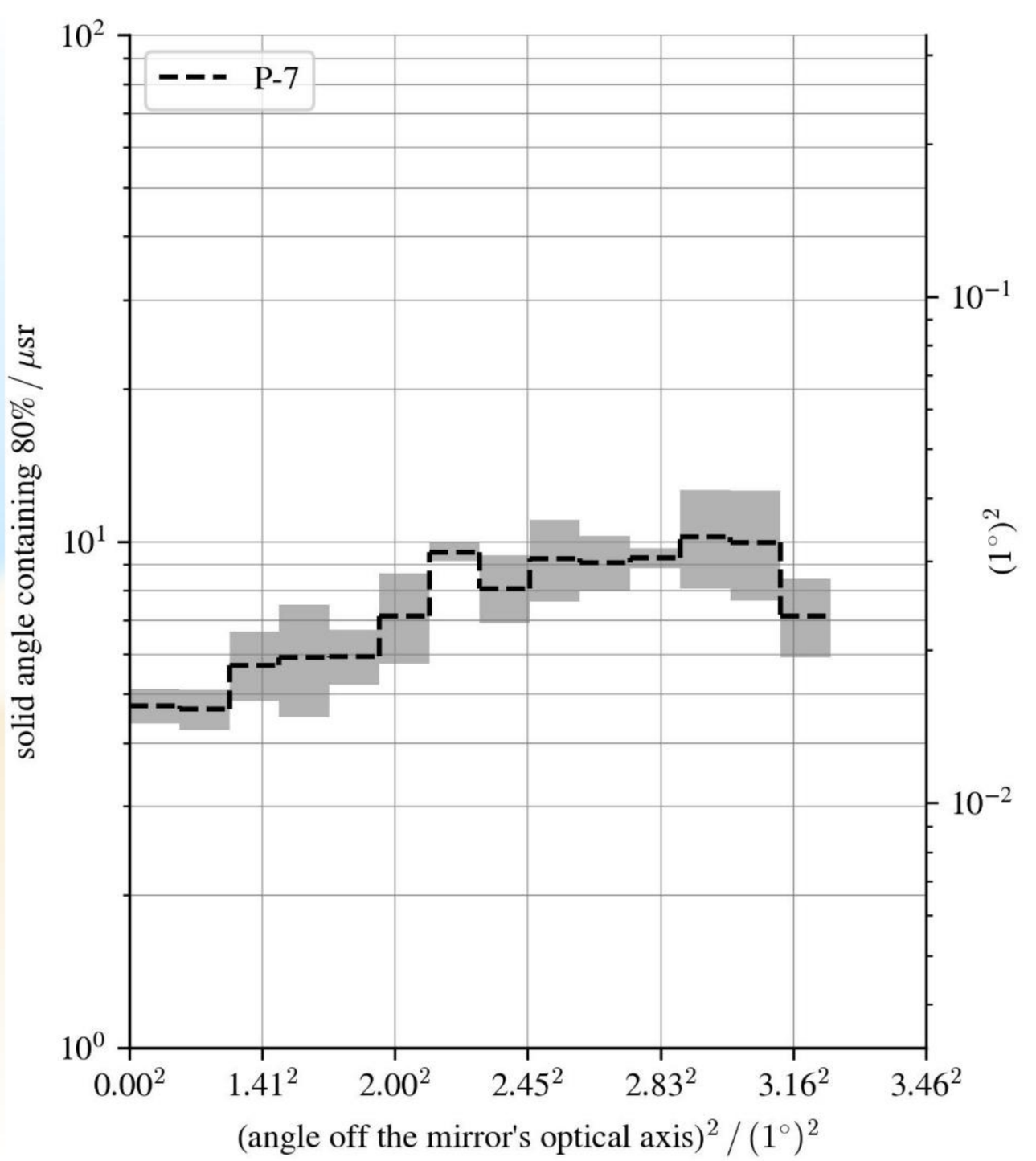




Telescope p-one,

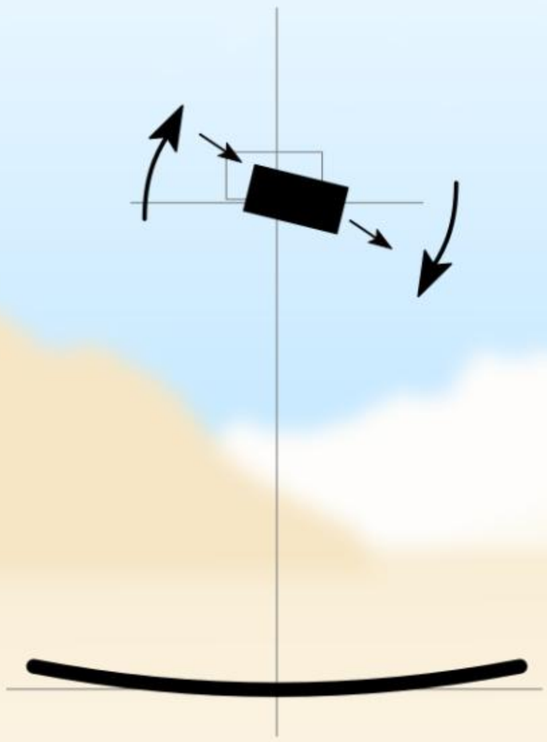
Optics
performance

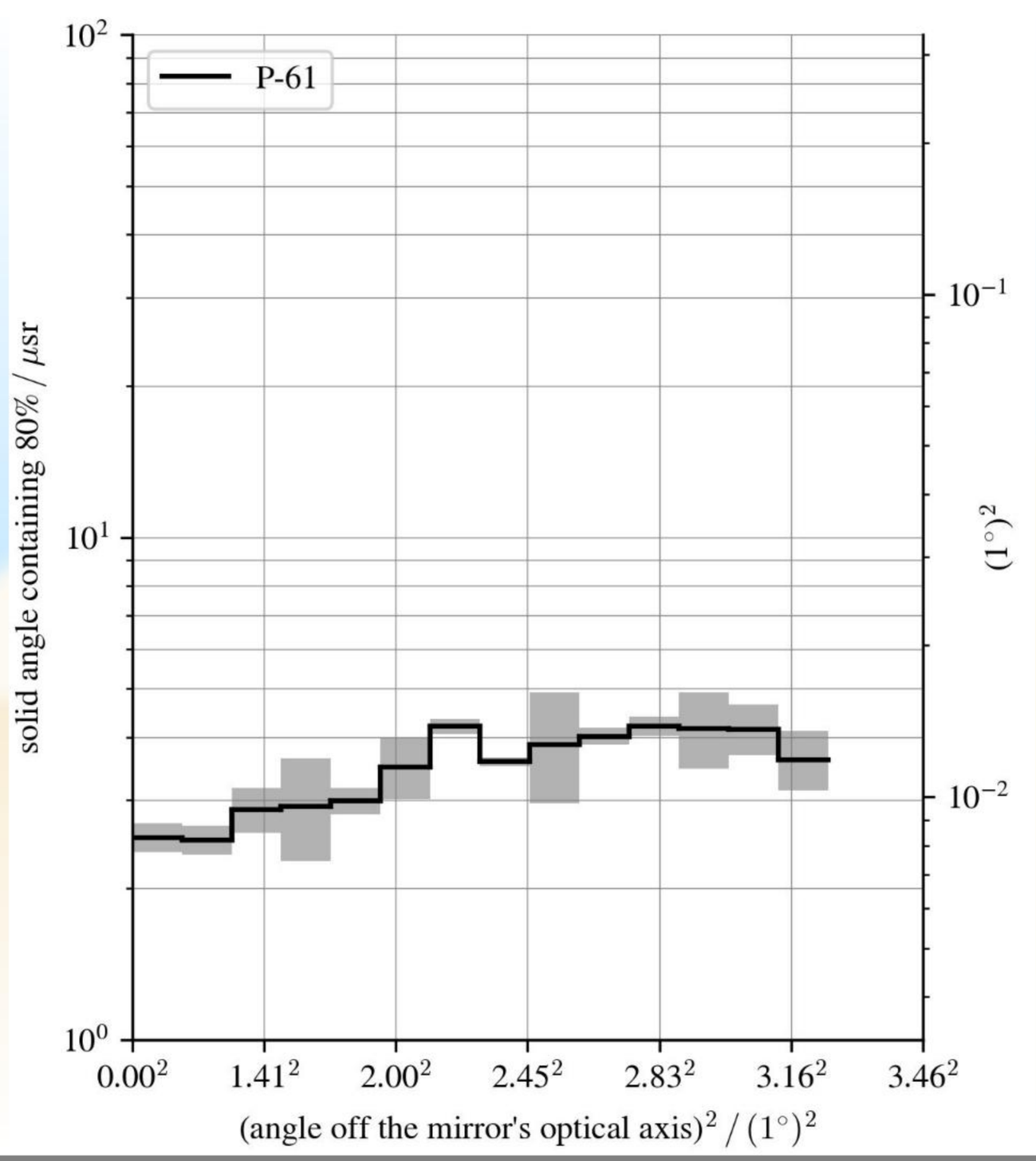




plenoscope p-seven,

Optics
performance

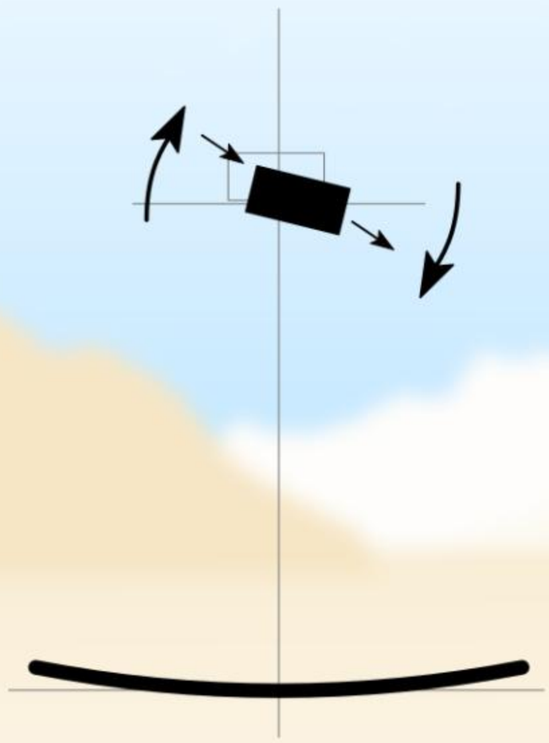


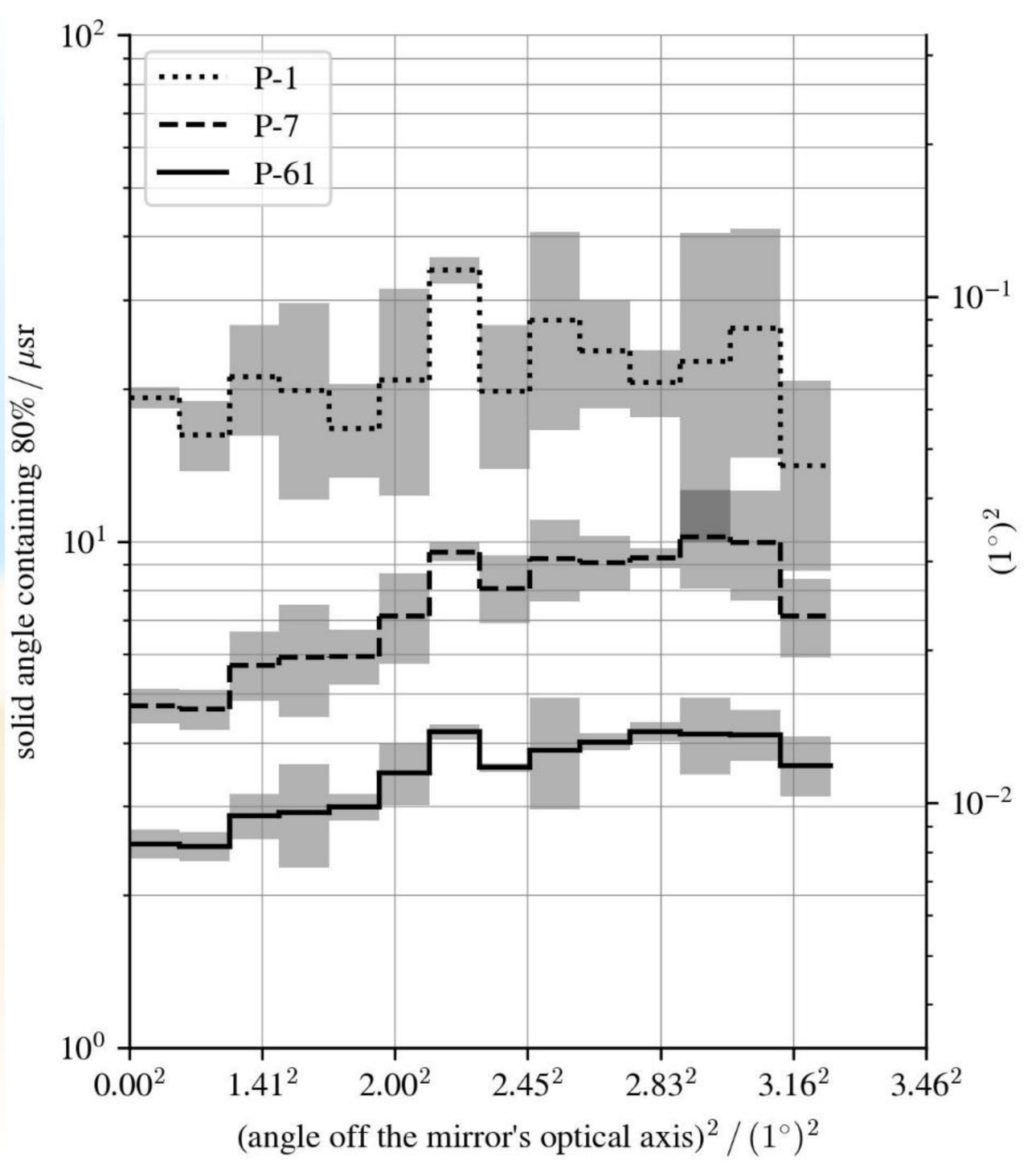


and the Portal plenoscope p-sixty-one.

Optics

performance

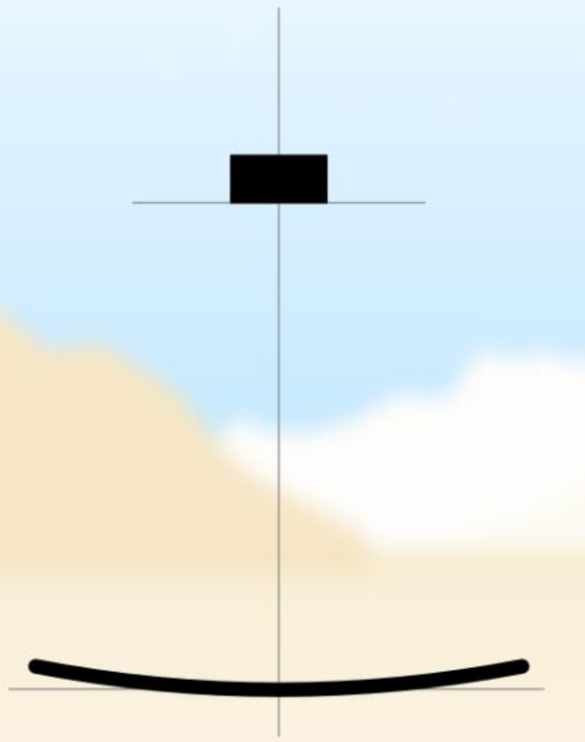




I think it is safe to say: The plenoscope is in a class of its own.

Optics

refocussing to any depth



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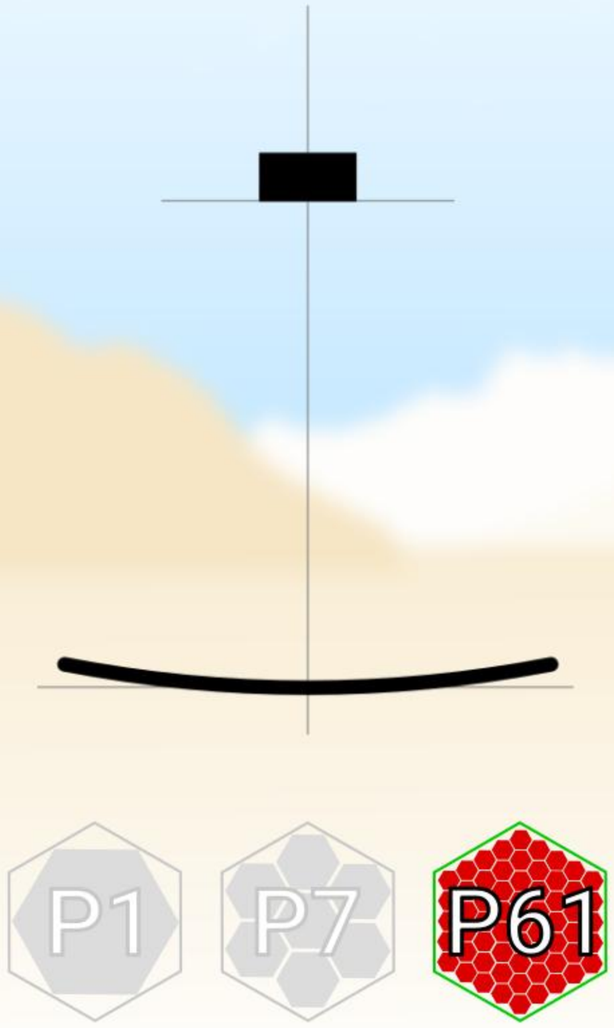
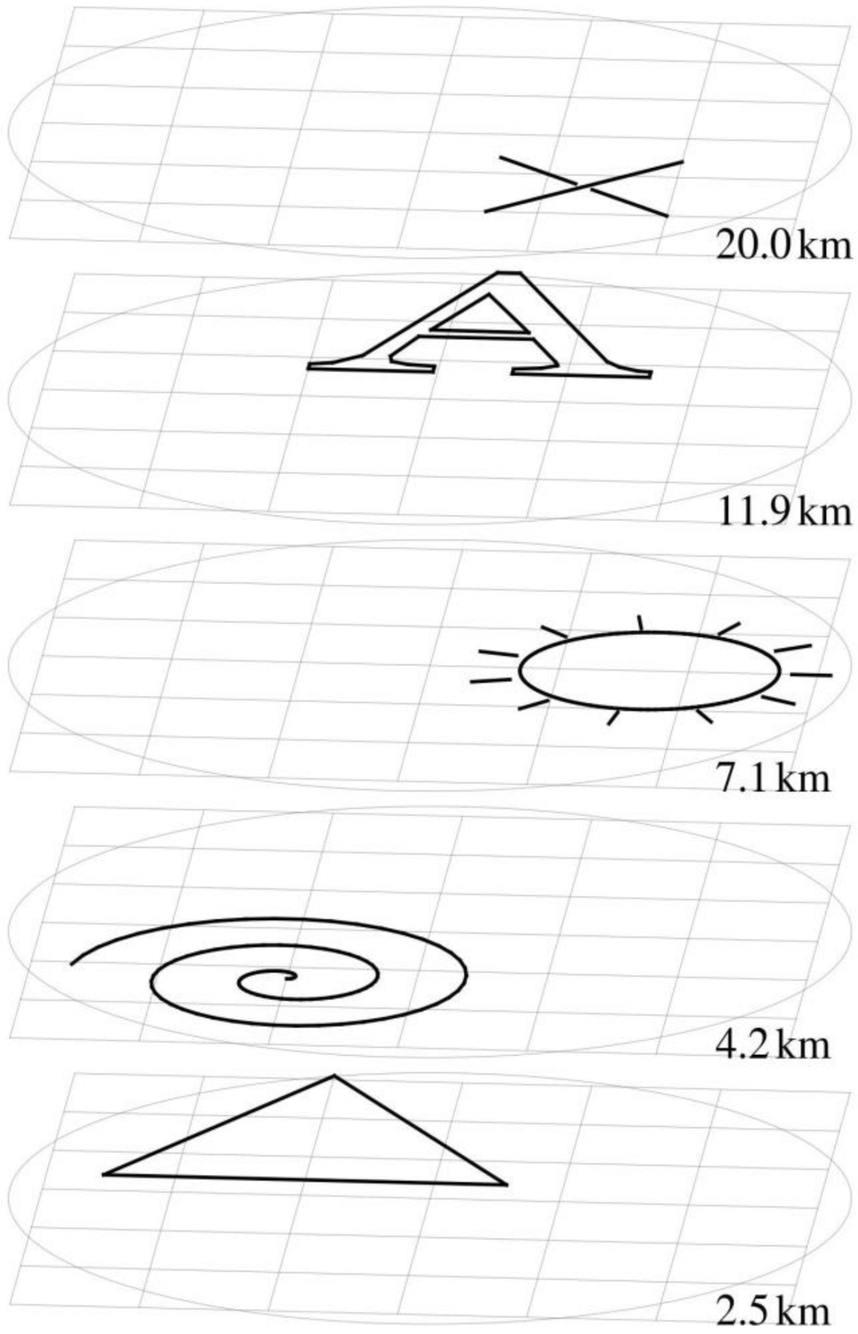
Another unique feature of the plenoscope is its ability to refocus images in post after the recording. To demonstrate this, we set up ...

Optics

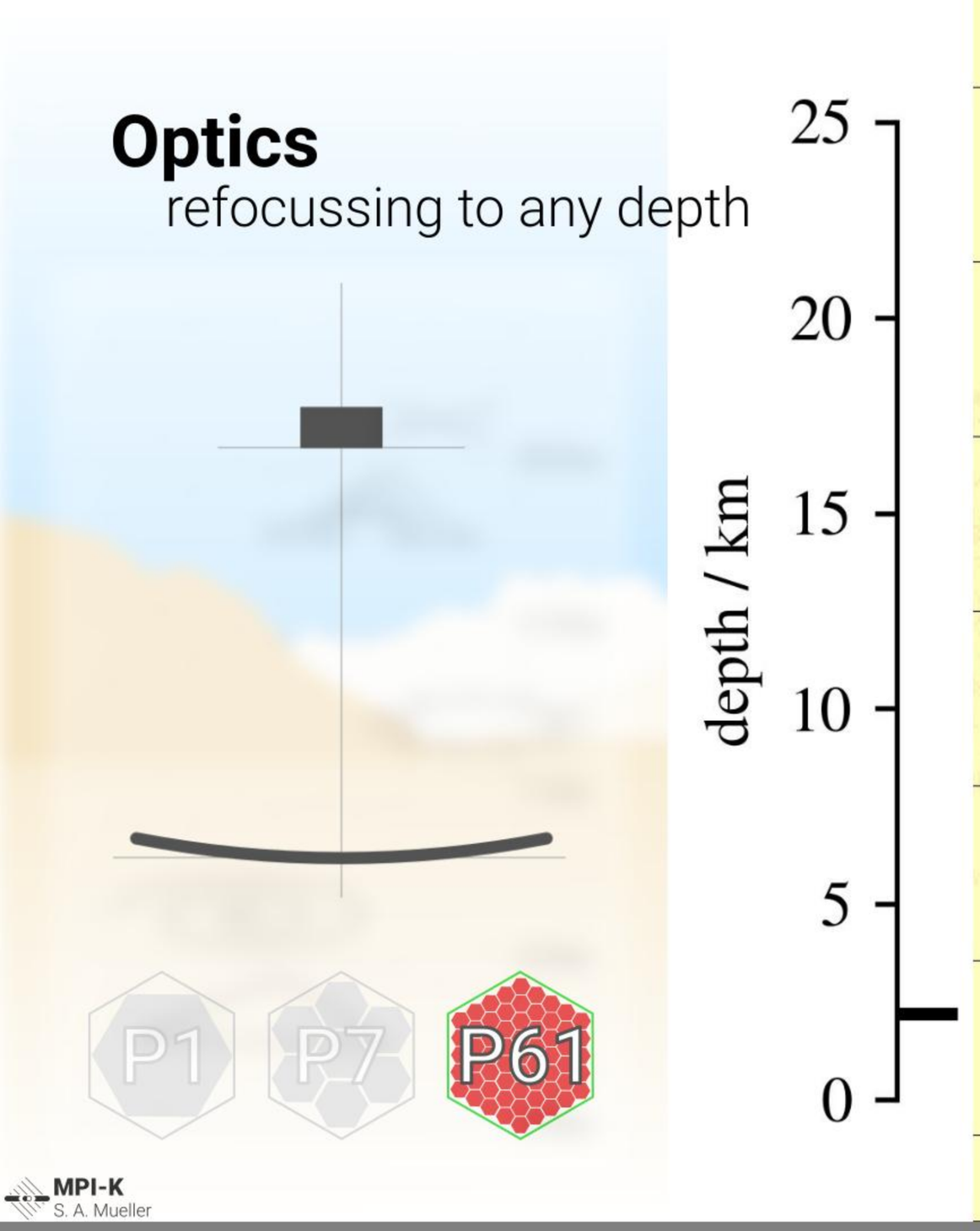
refocussing to any depth





phantom in atmosphere

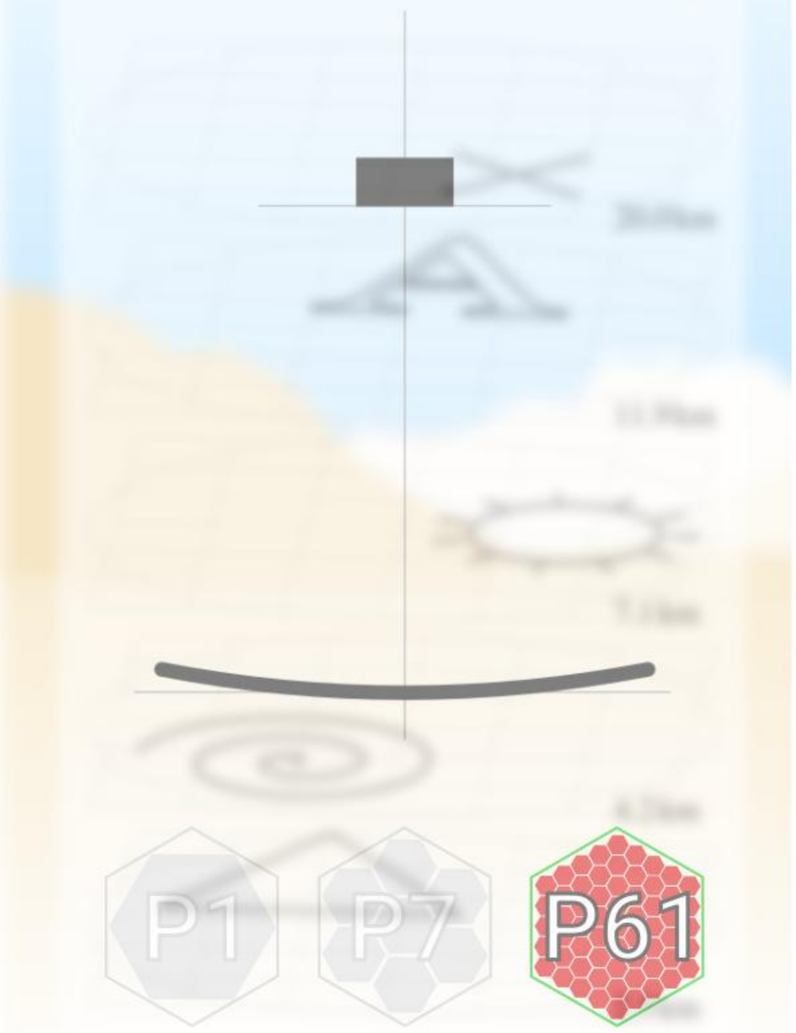
a phantom source. The pahntom source was chosen so that everyone can formulate a clear expectation of what a refocussed image should look like.

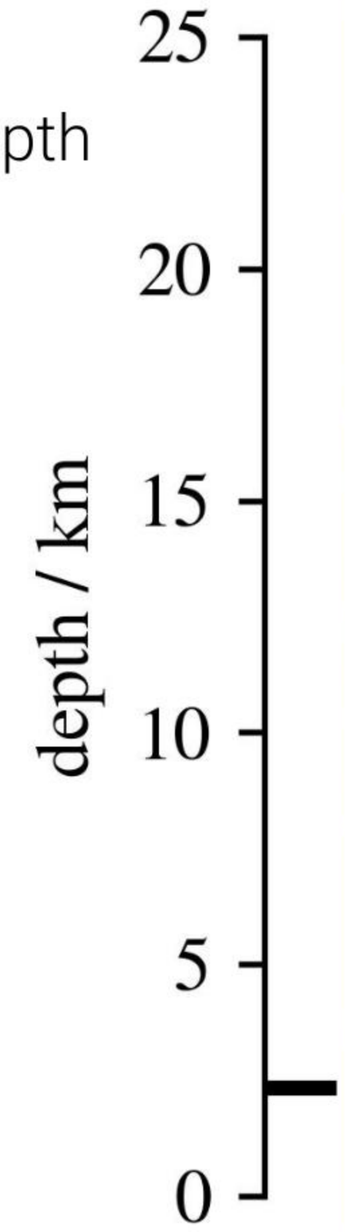


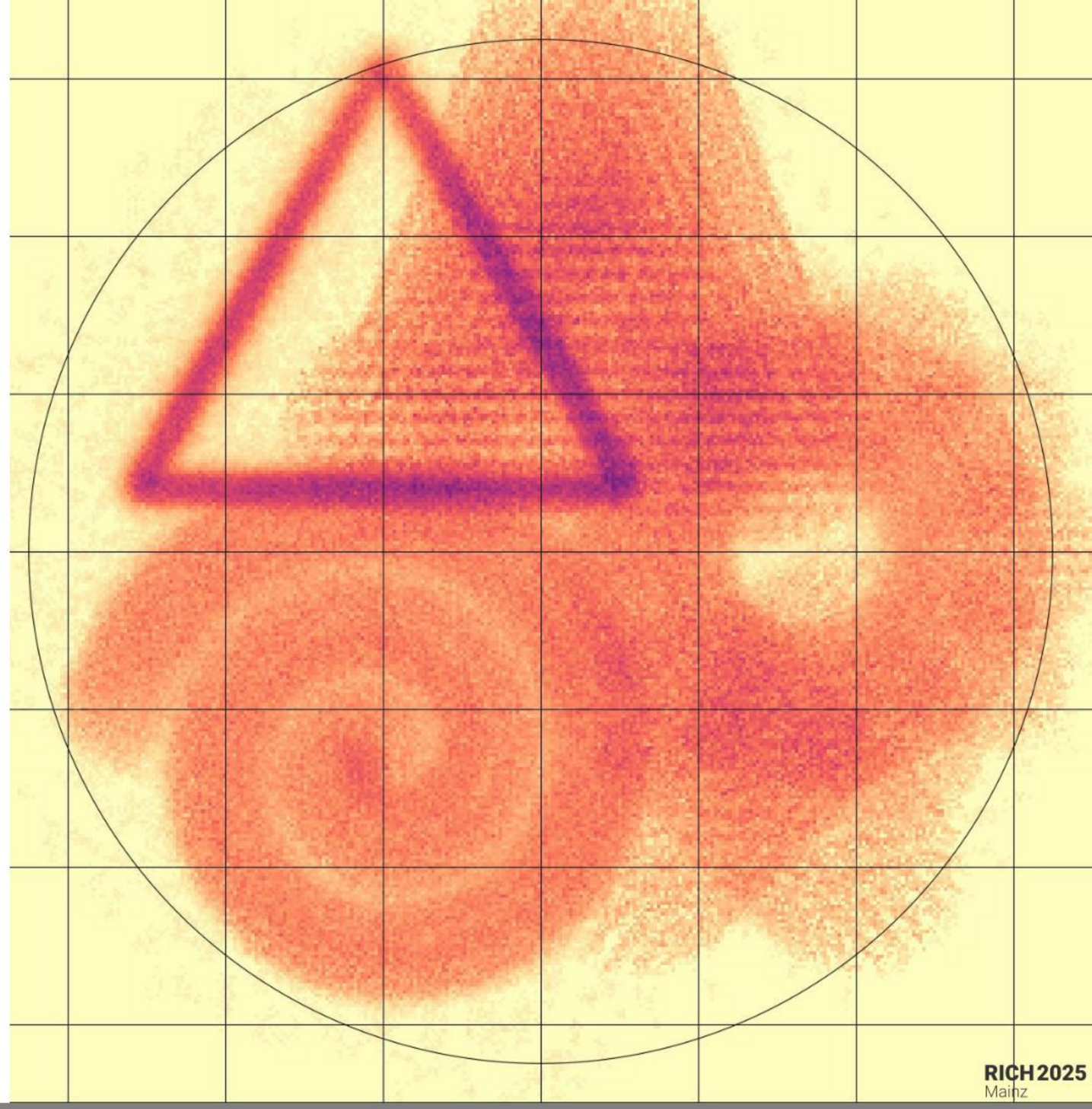
So we project the recordings onto an image with its focus set to two kilometers.

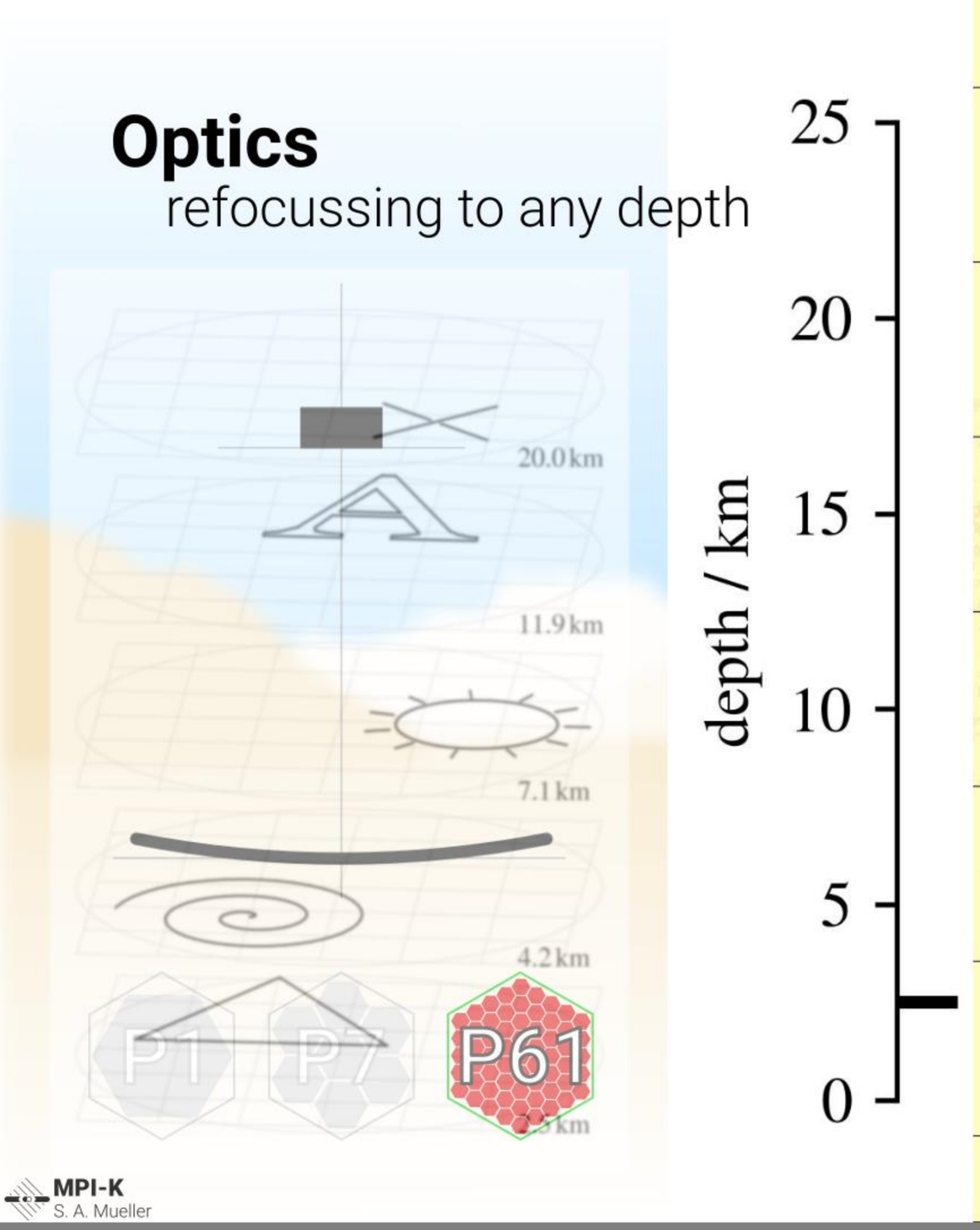
Optics

refocussing to any depth





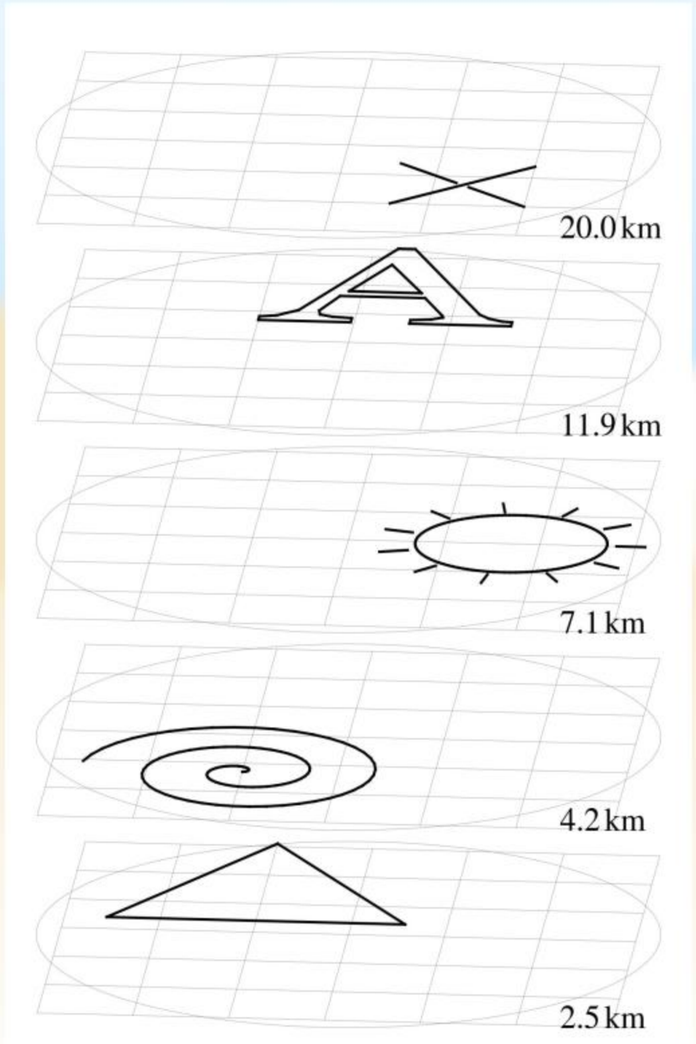


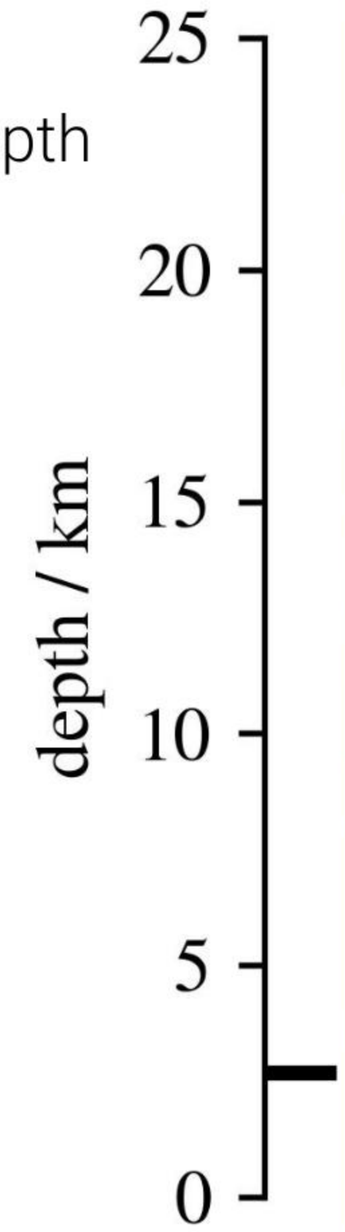


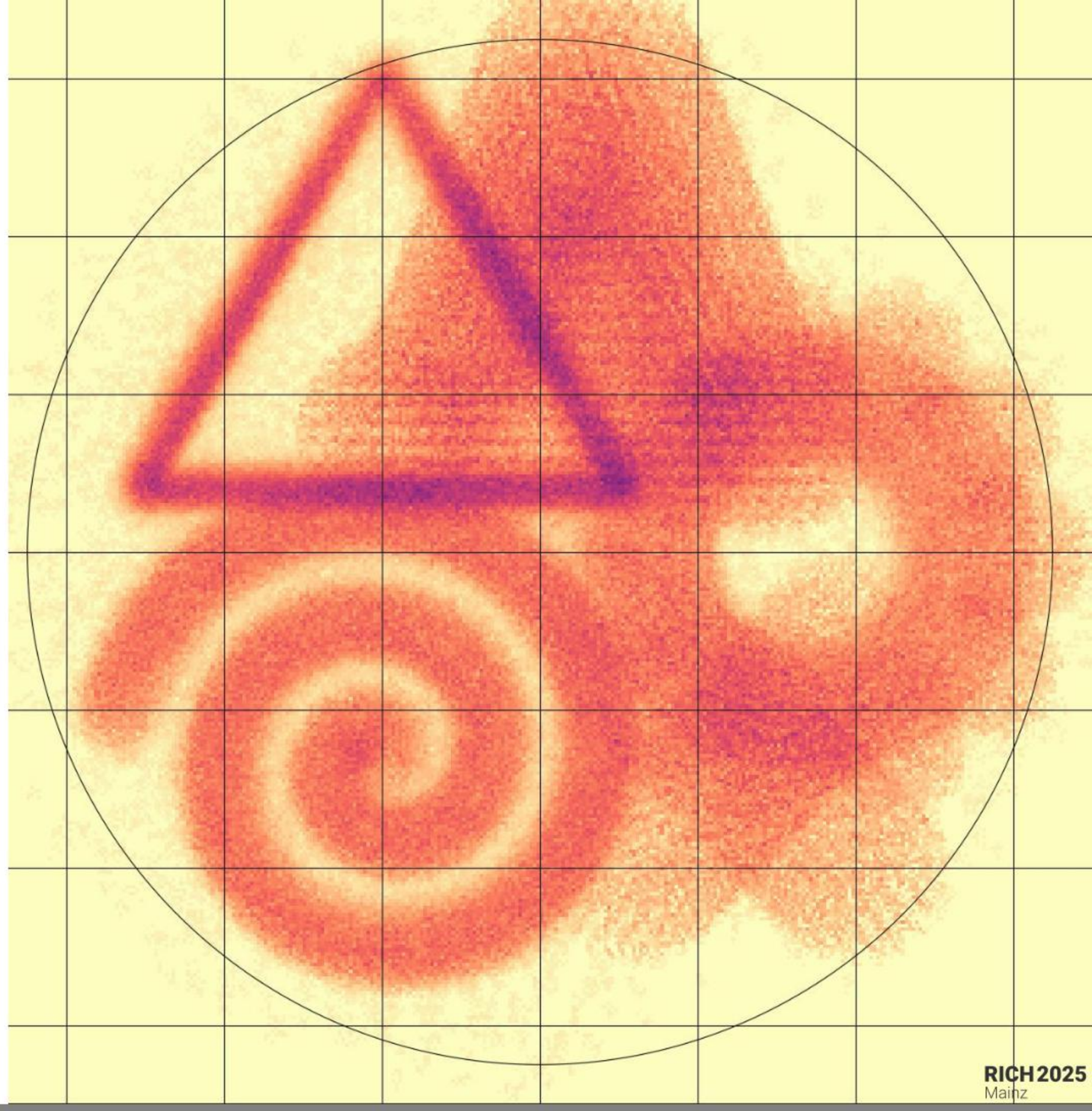
First, we find the triangle at about two to three kilometers. Remeber the triangle, it is going to be important later.

Optics

refocussing to any depth

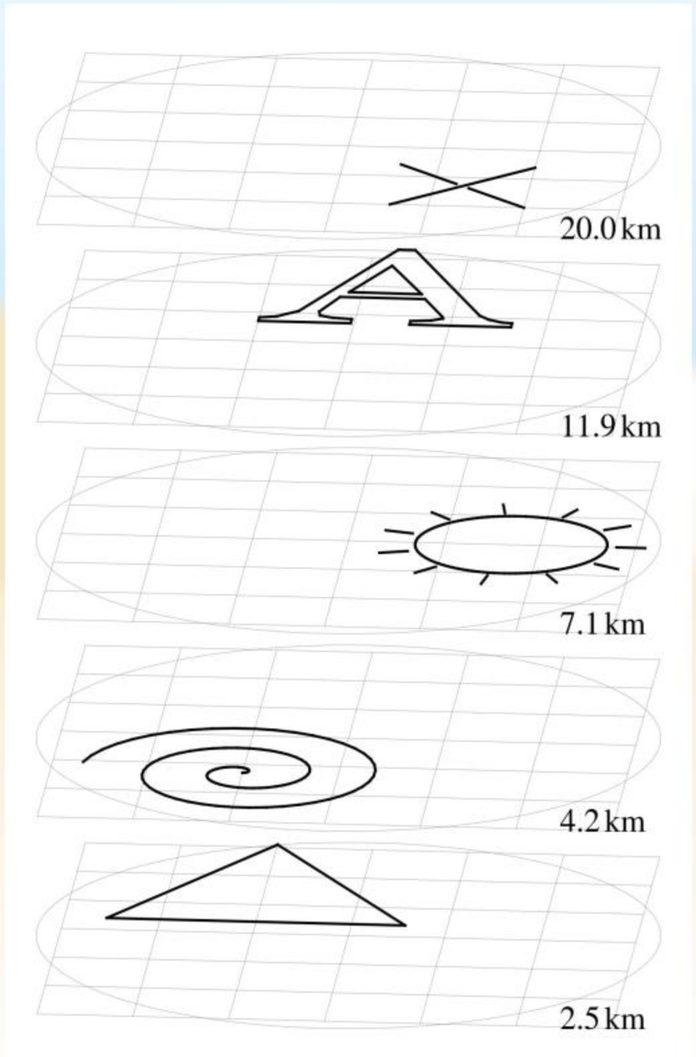


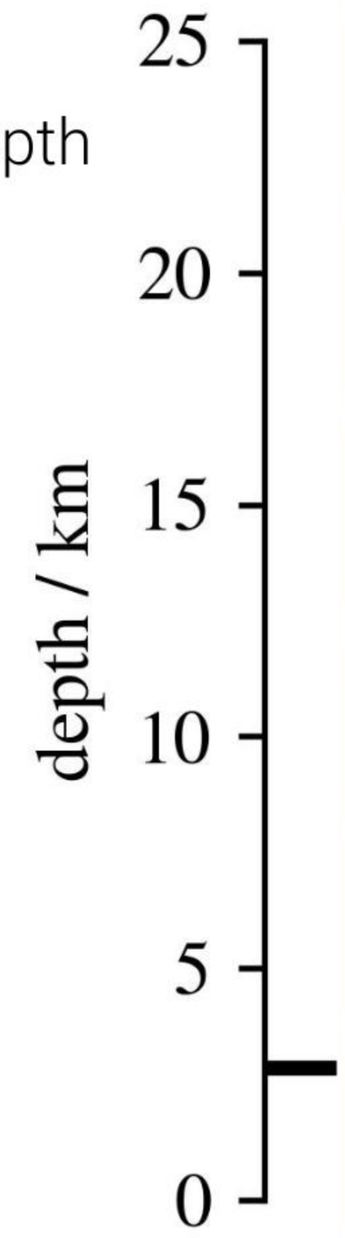


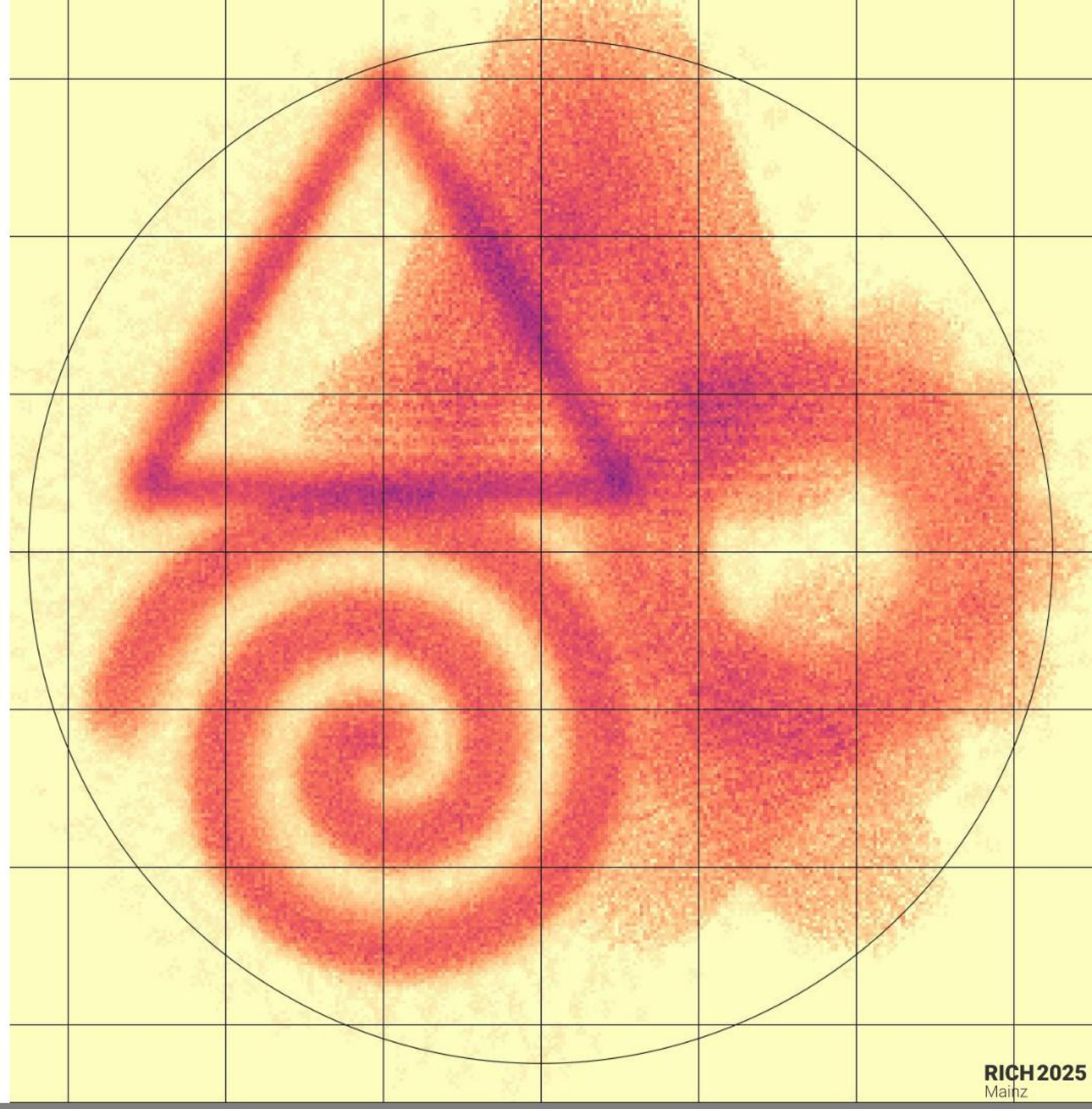


Optics

refocussing to any depth

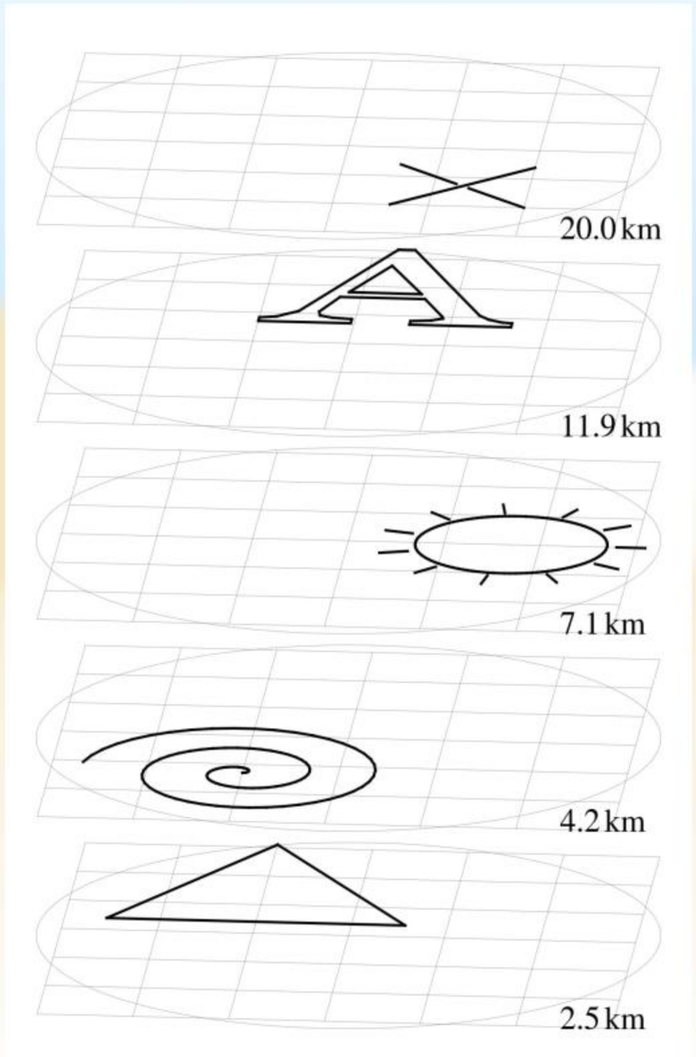


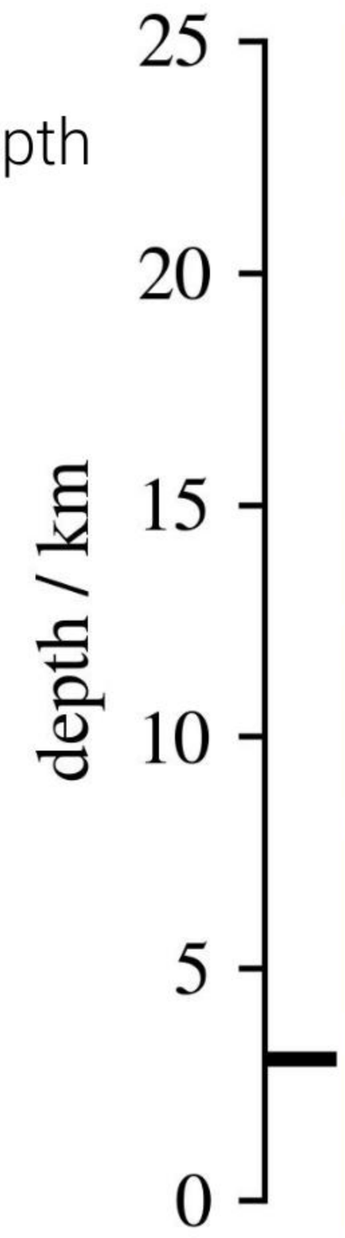


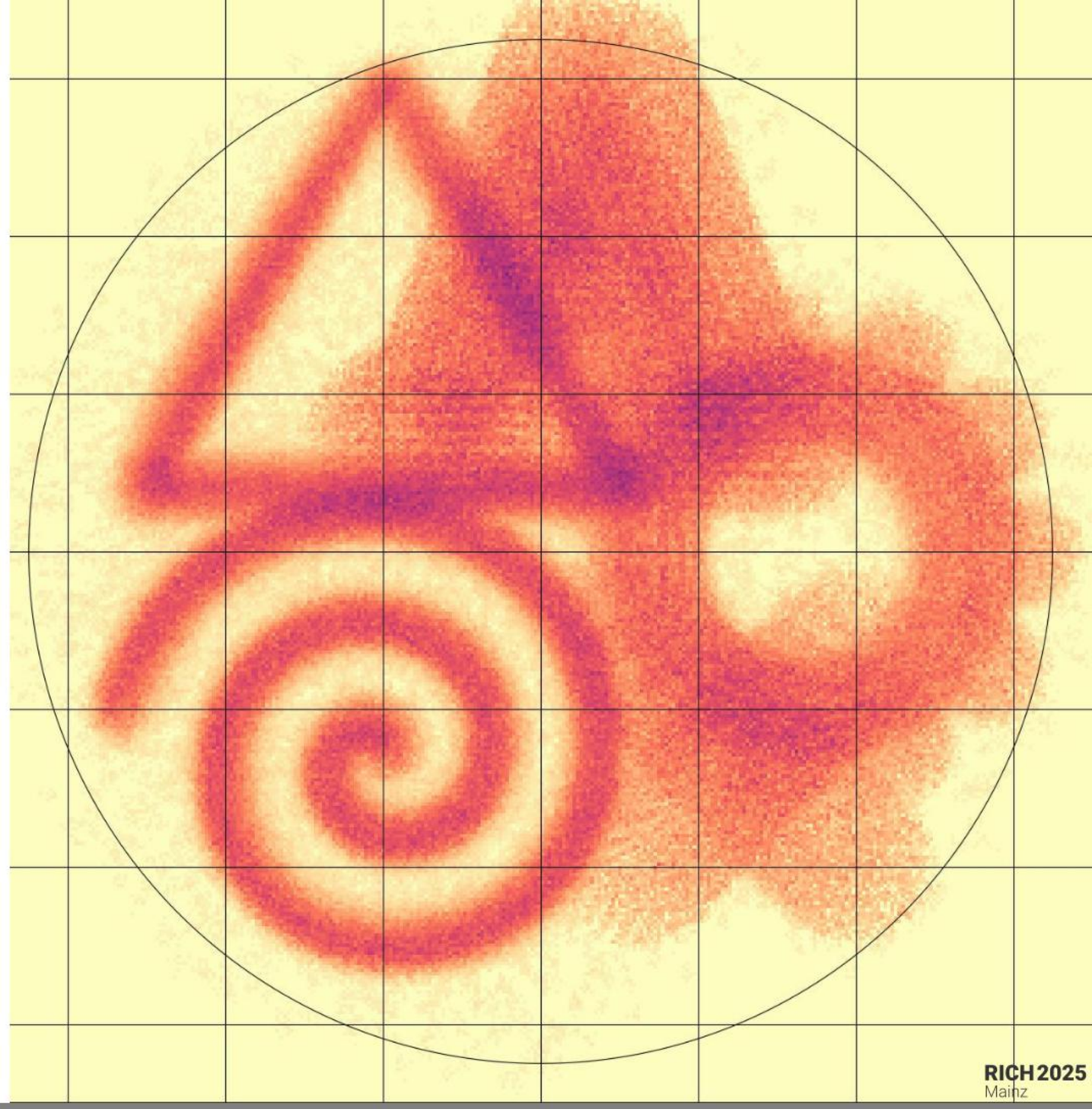


Optics

refocussing to any depth

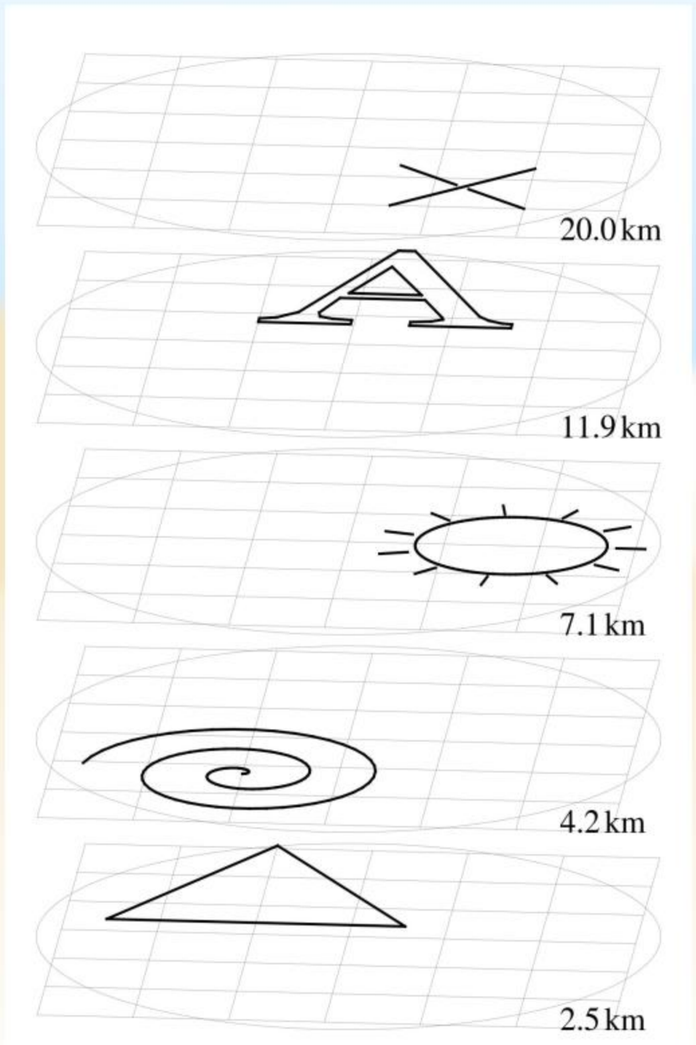


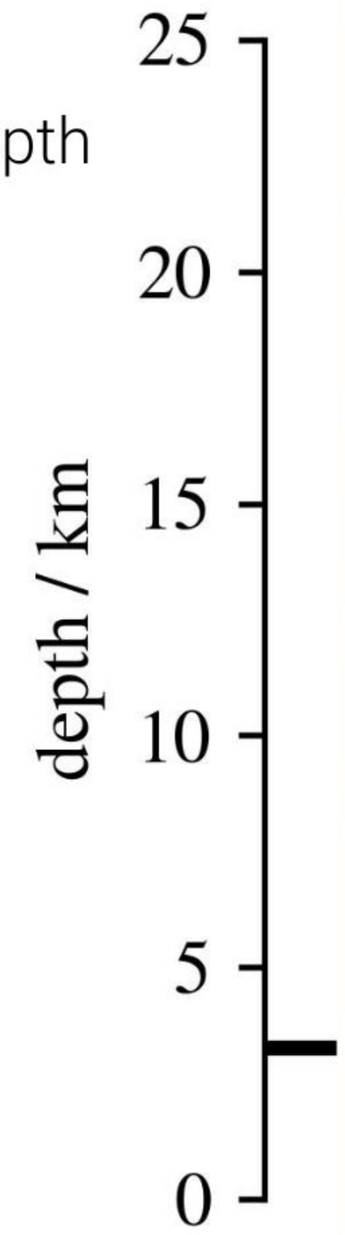


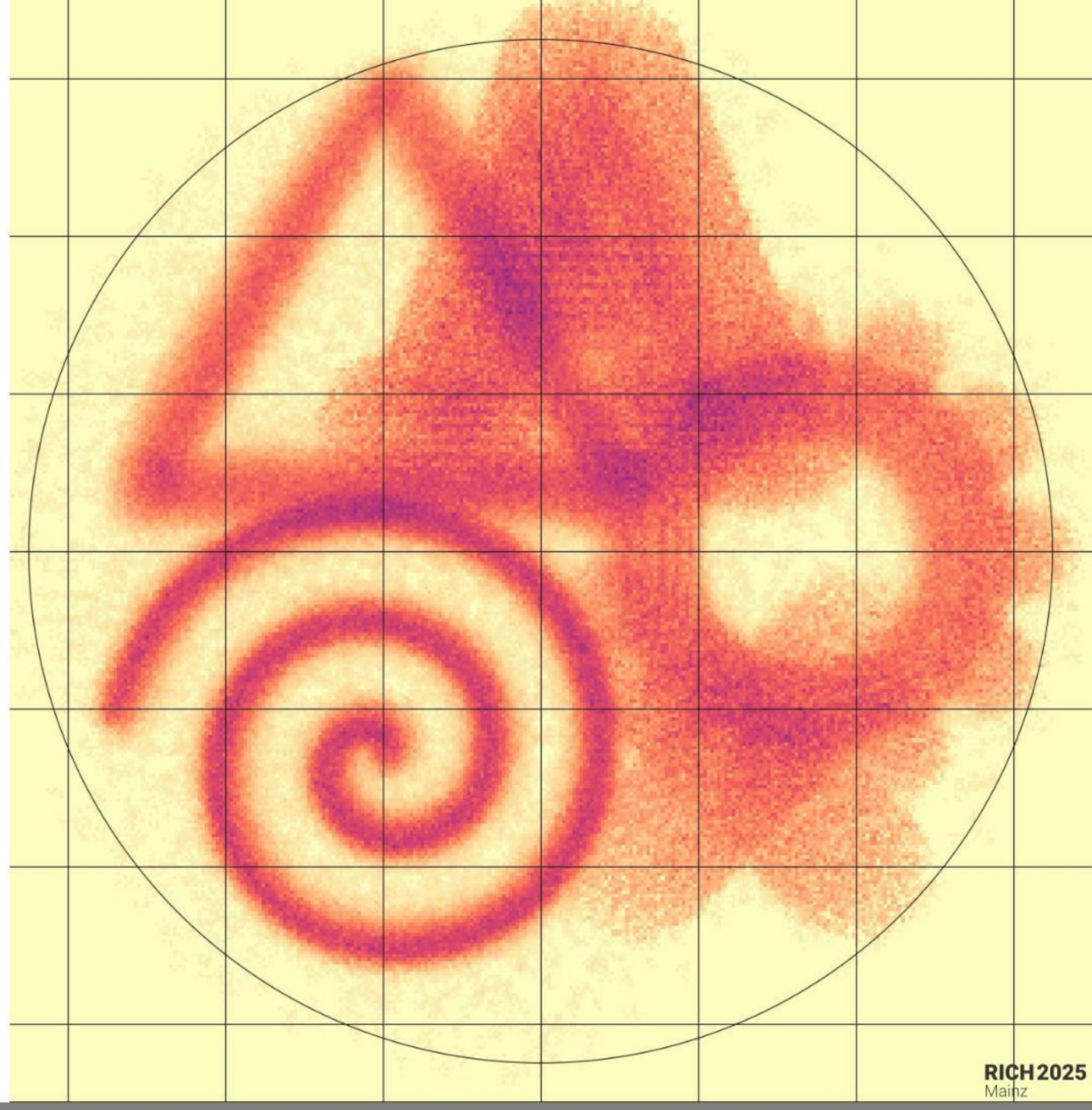


Optics

refocussing to any depth

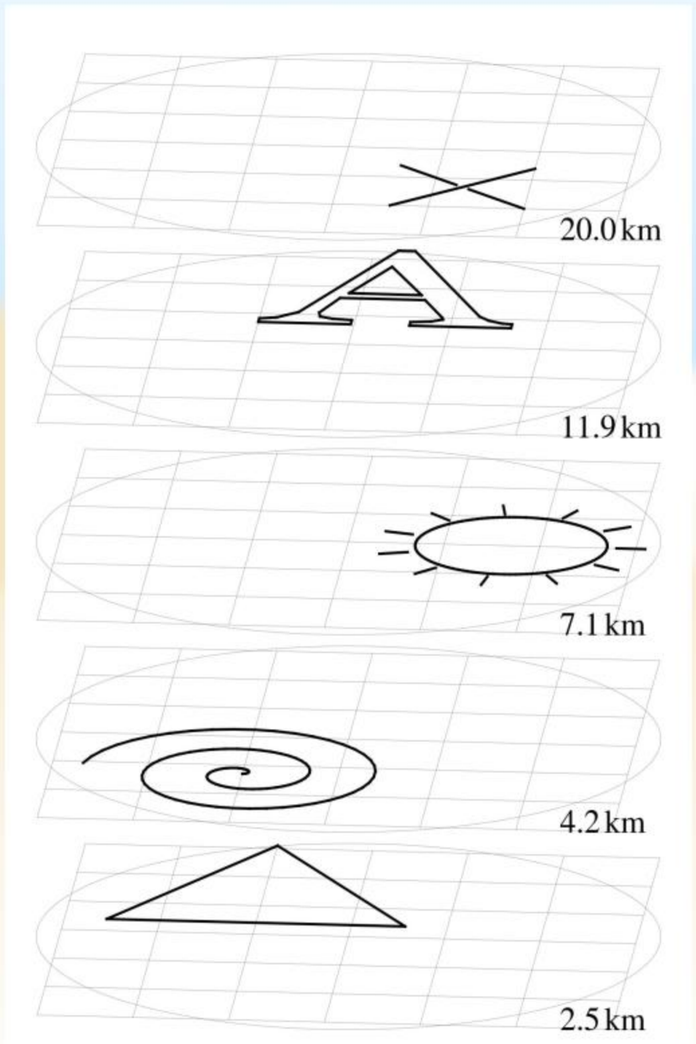


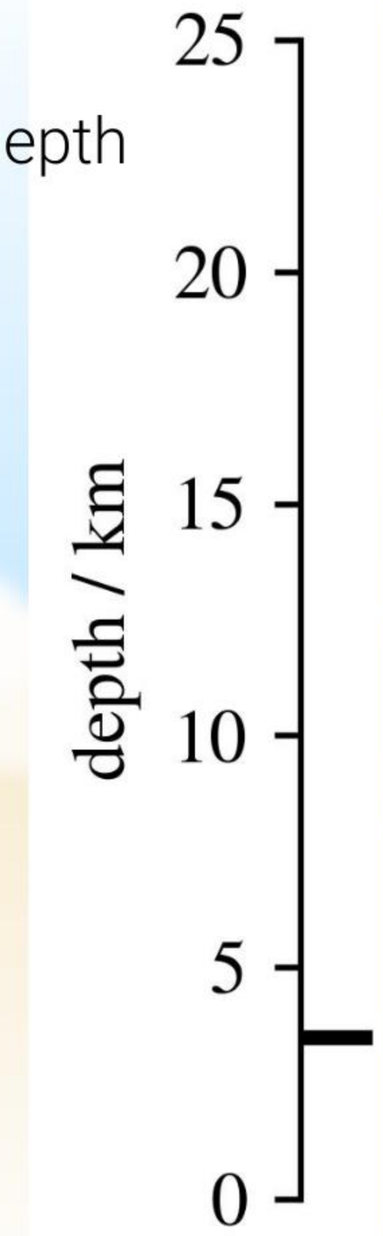


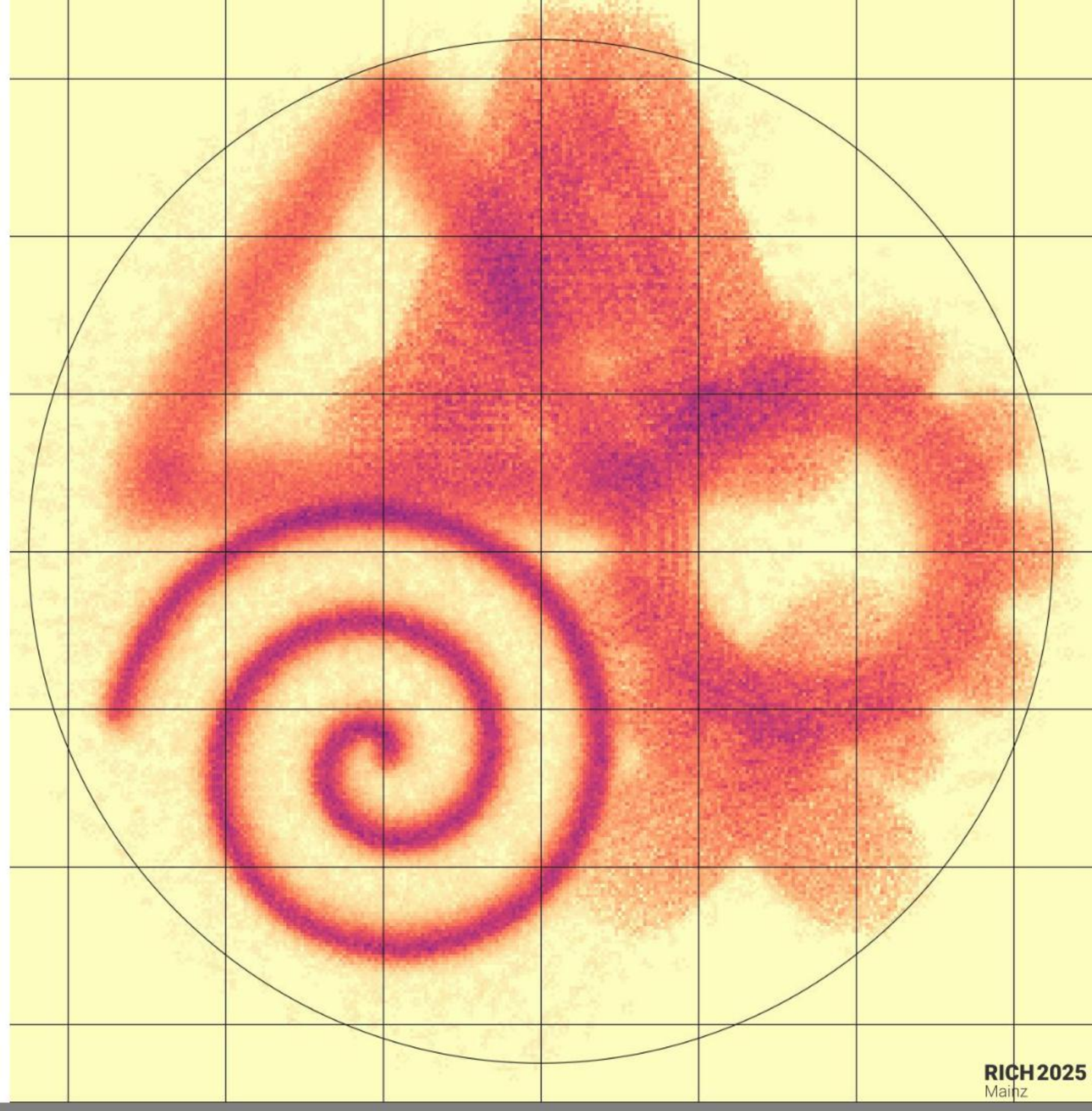


Optics

refocussing to any depth

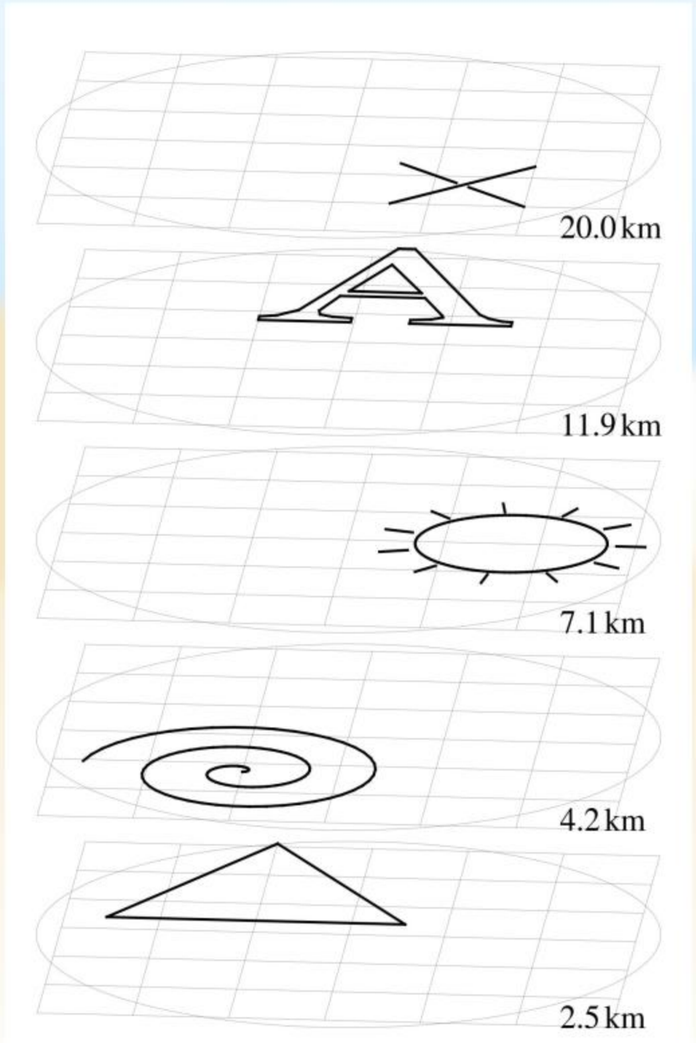


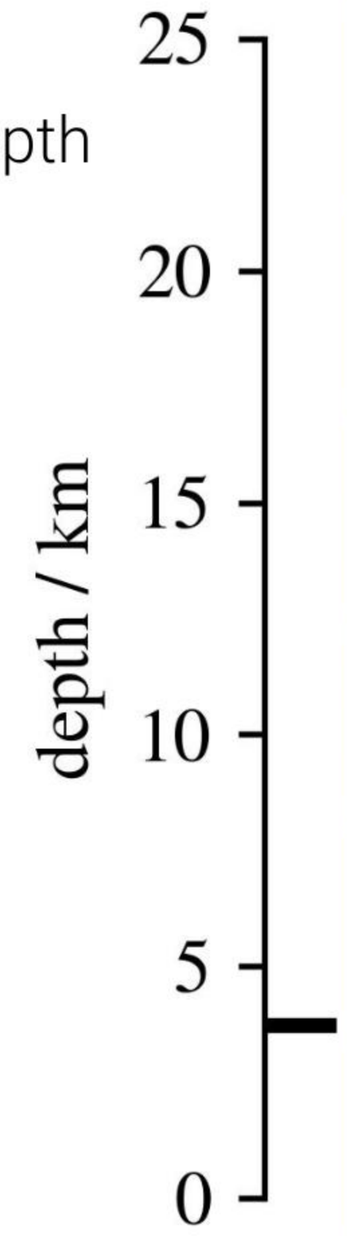


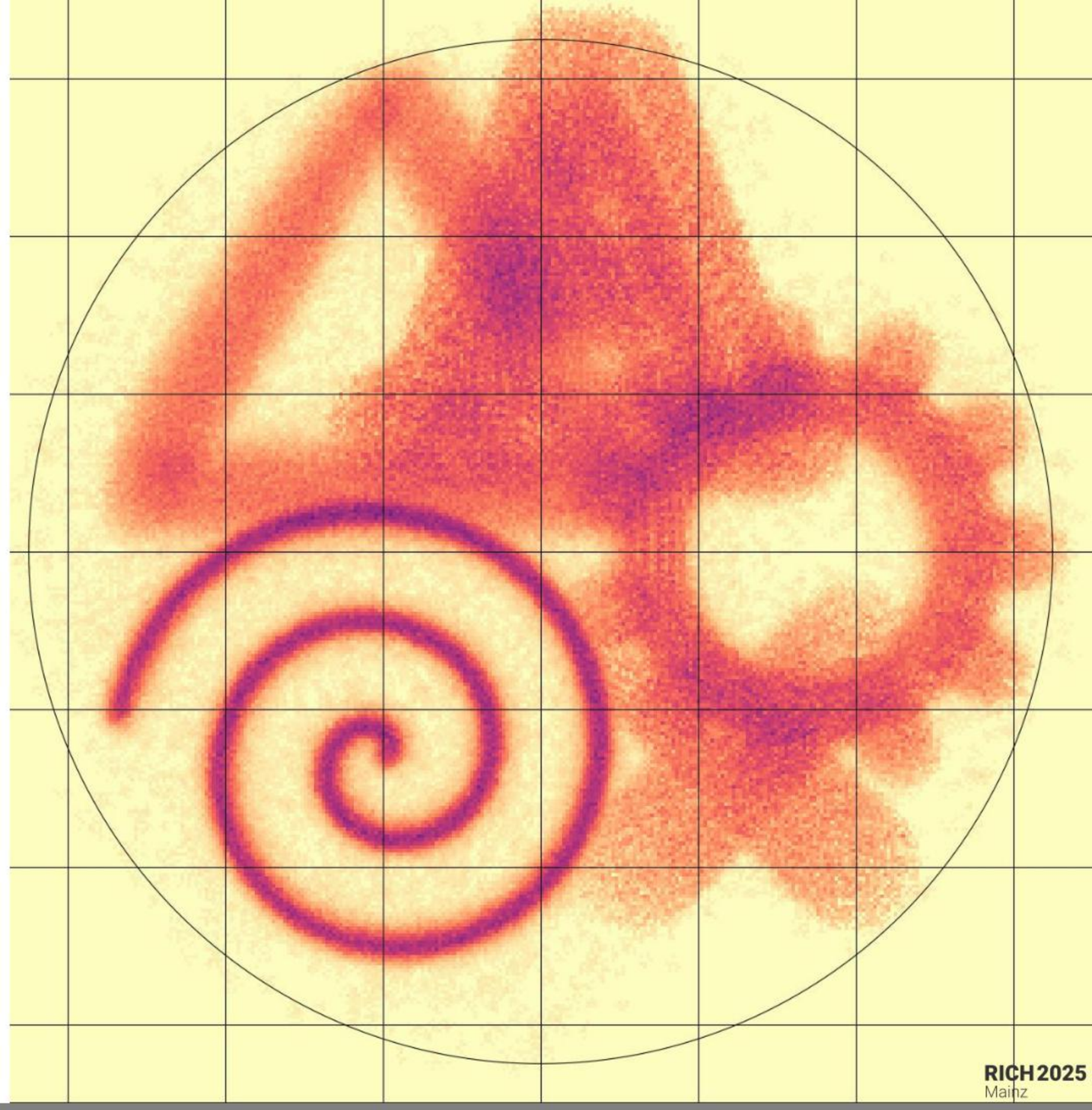


Optics

refocussing to any depth

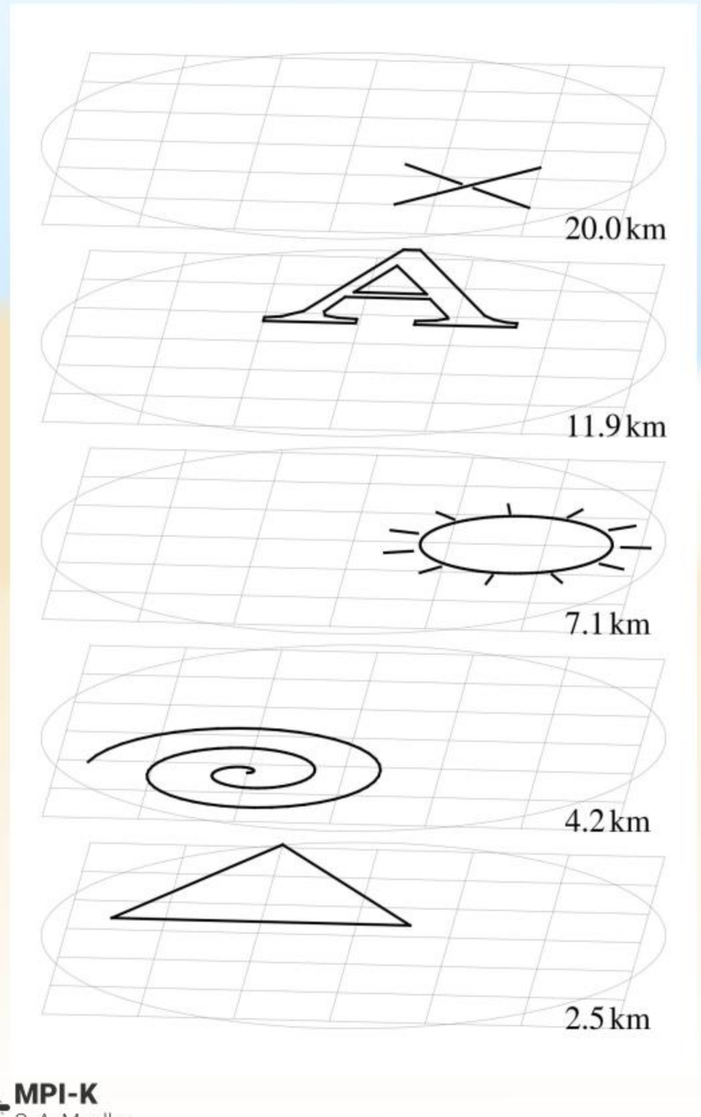


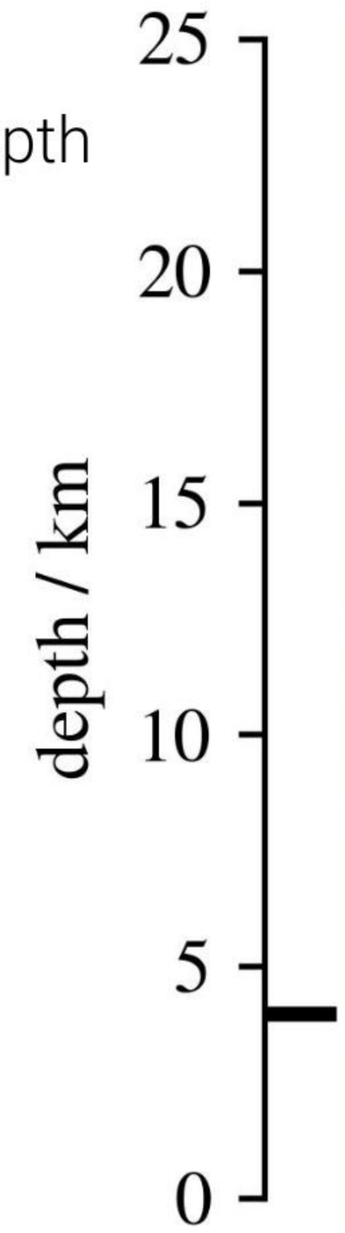


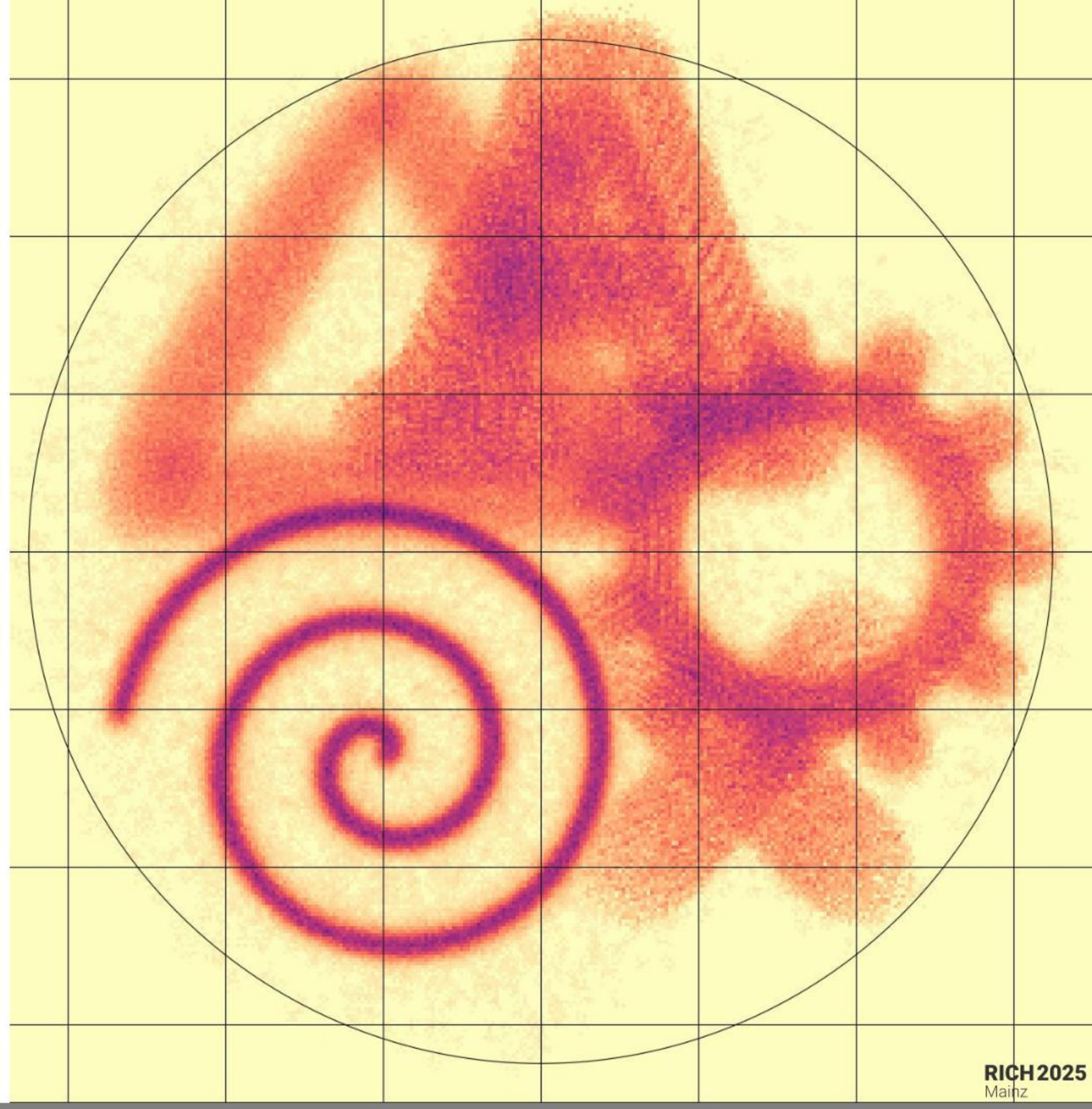


Optics

refocussing to any depth

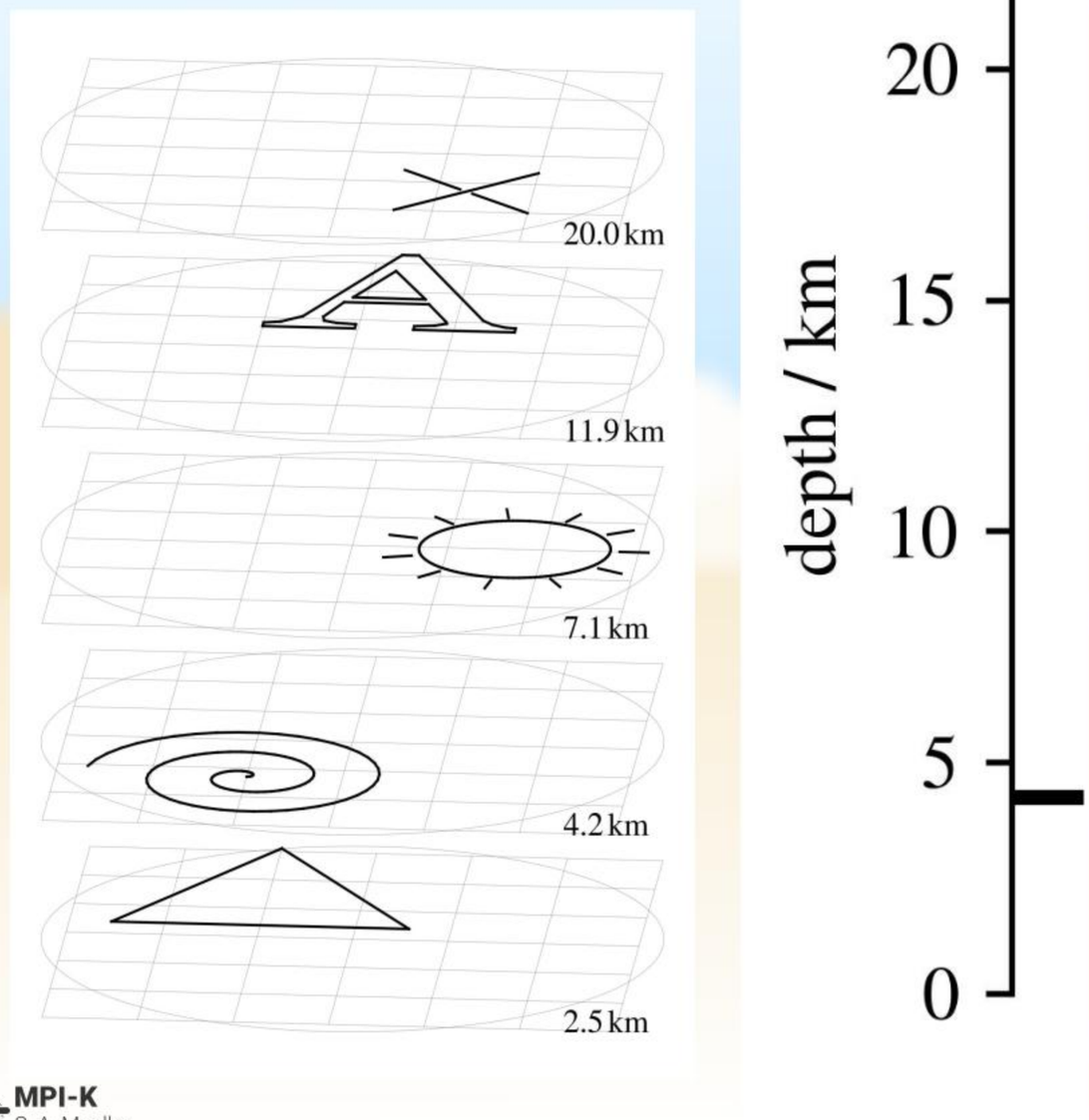


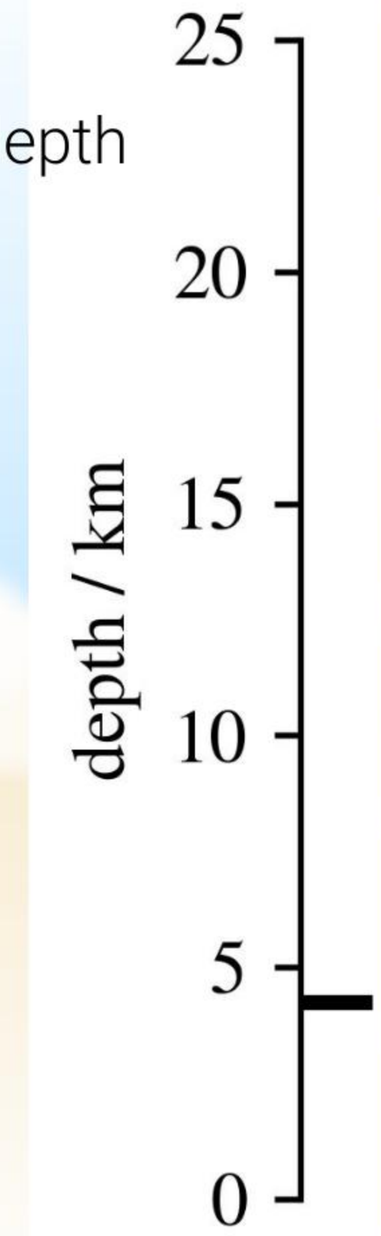


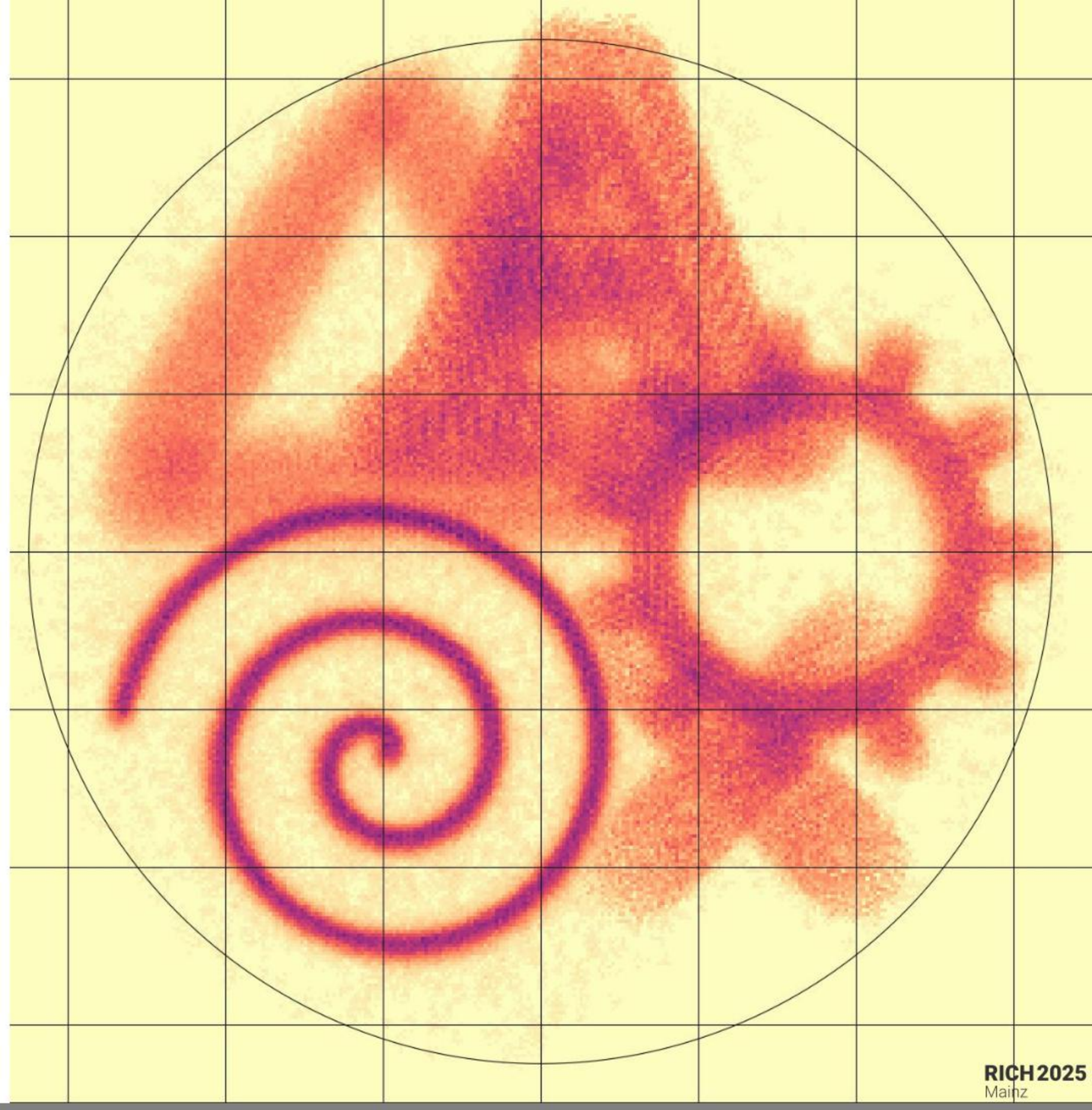


Optics

refocussing to any depth





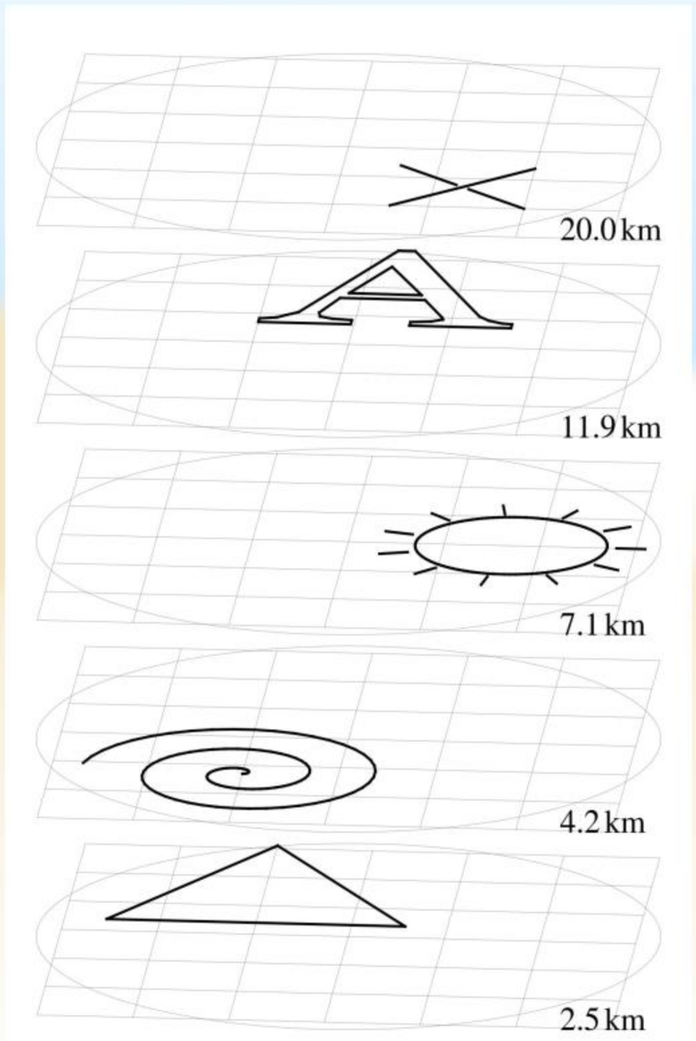


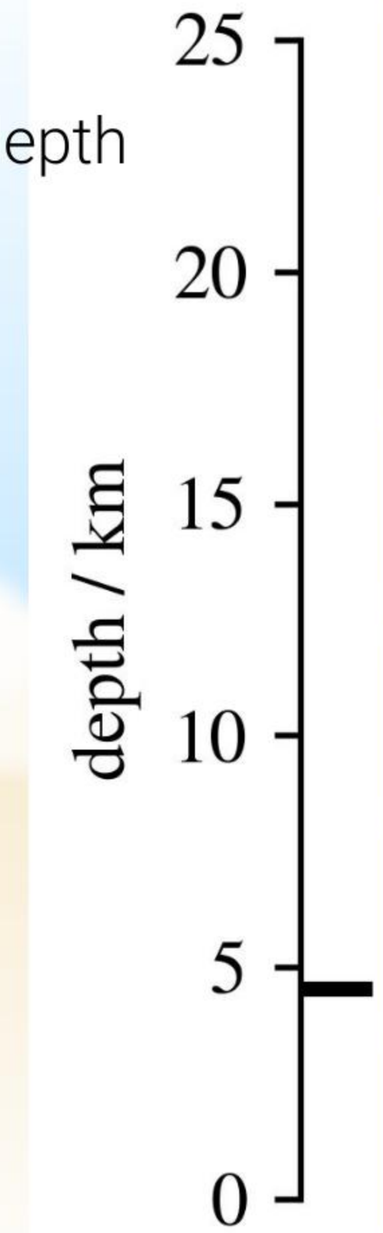
MPI-K
S. A. Mueller

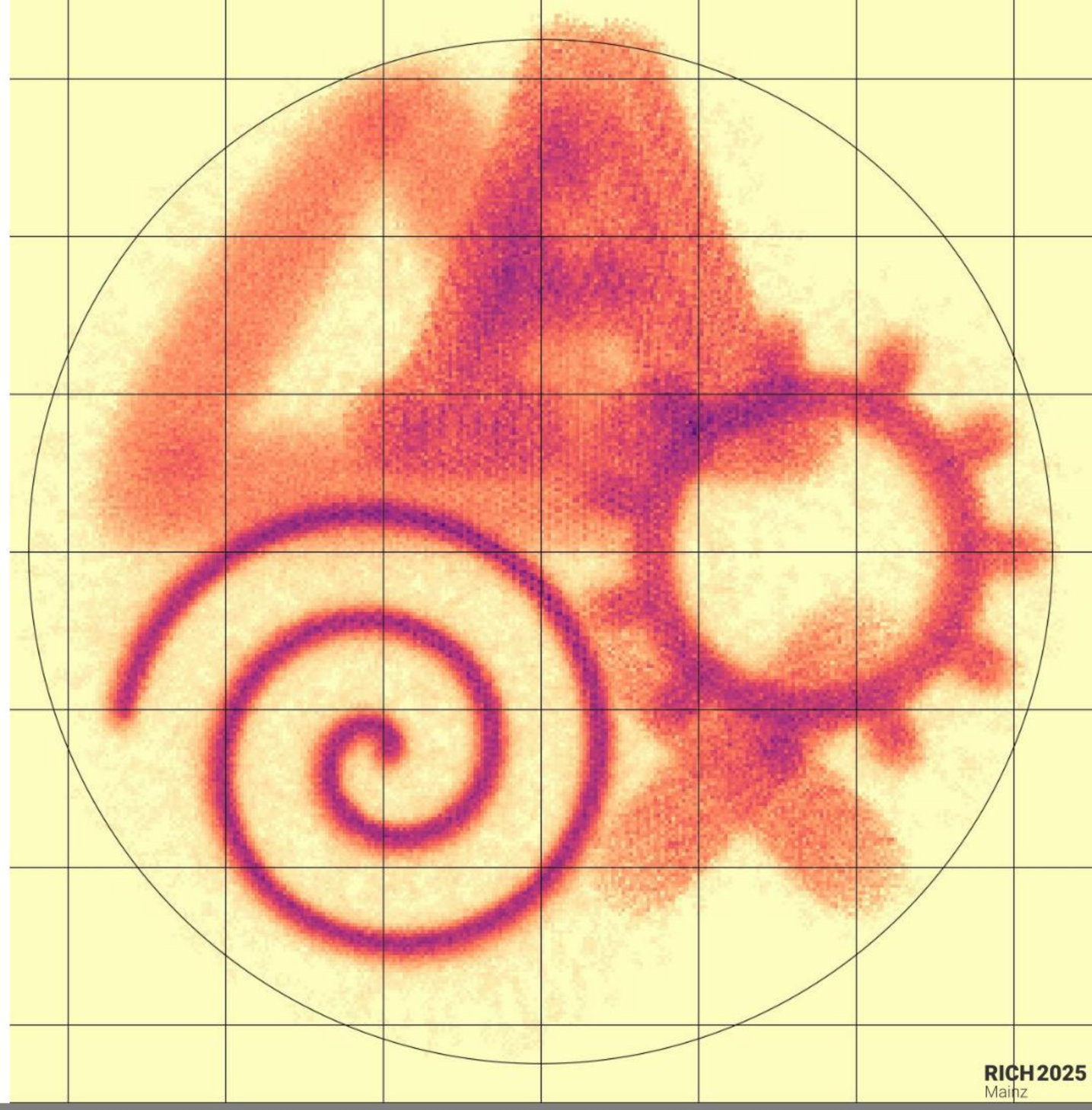
At about four kilometers, we find the spiral to be sharpest. Note how flat the image is. The spiral looks sharp over the entire field-of-view.

Optics

refocussing to any depth

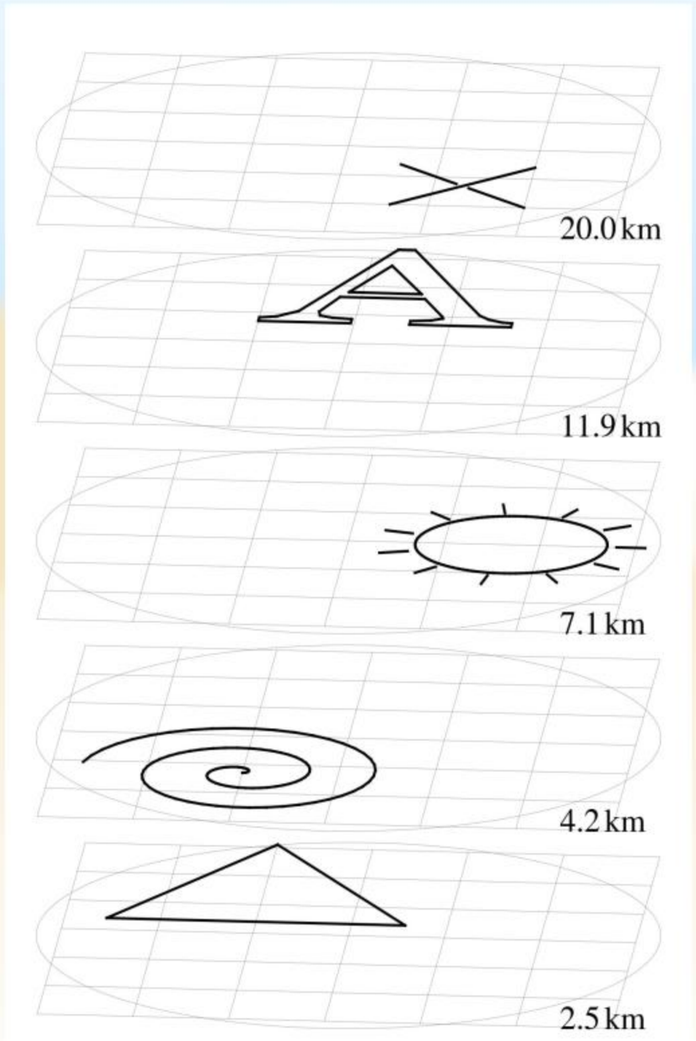


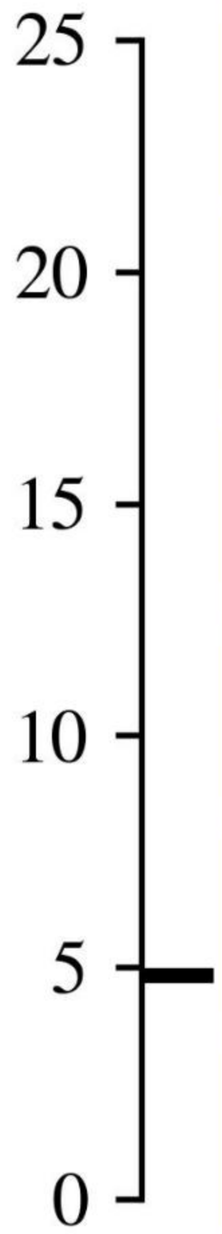


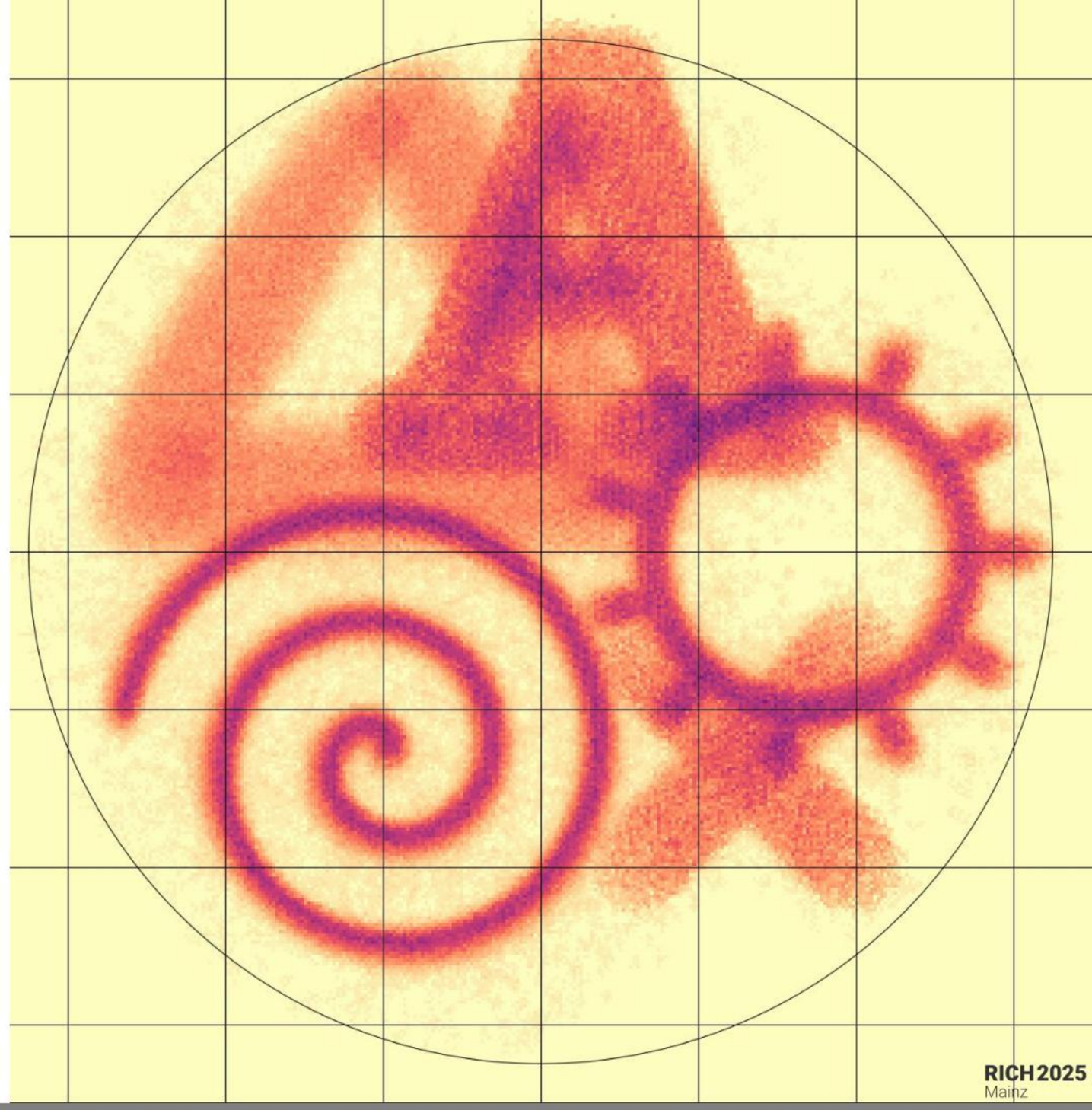


Optics

refocussing to any depth

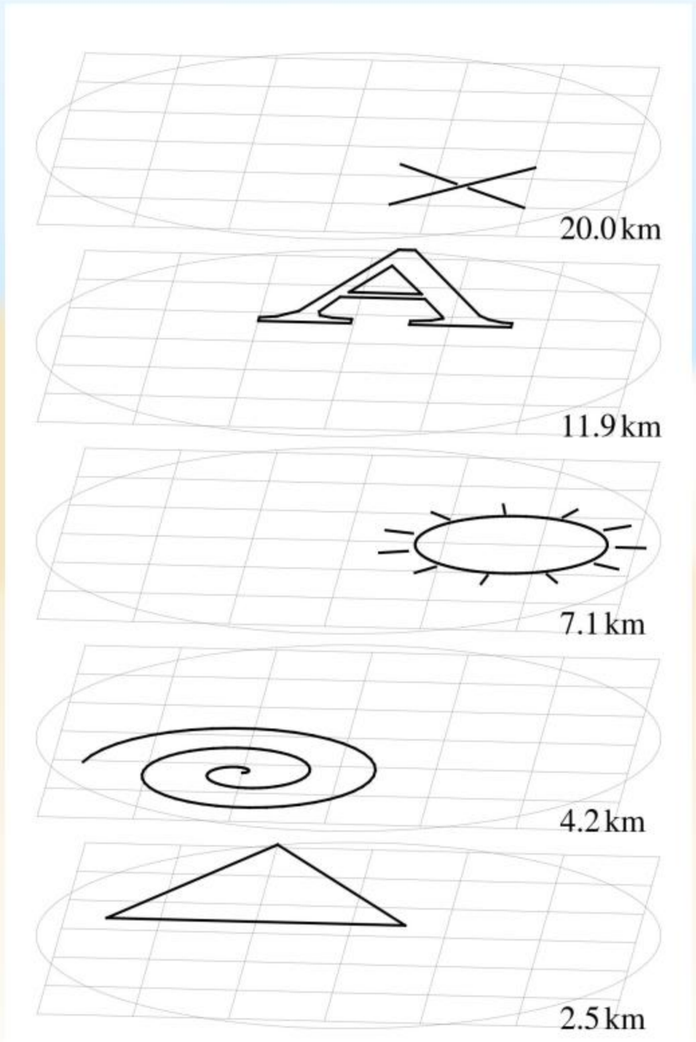


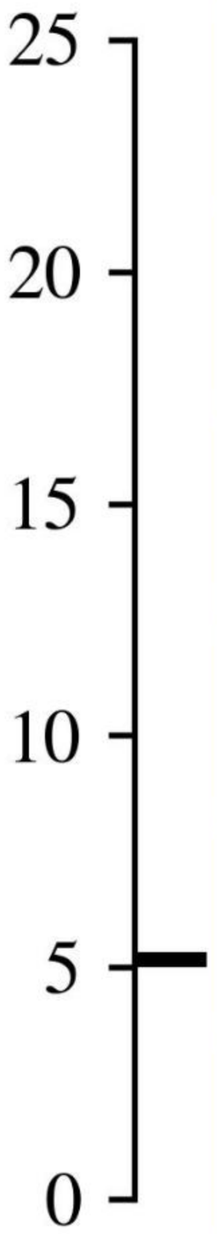


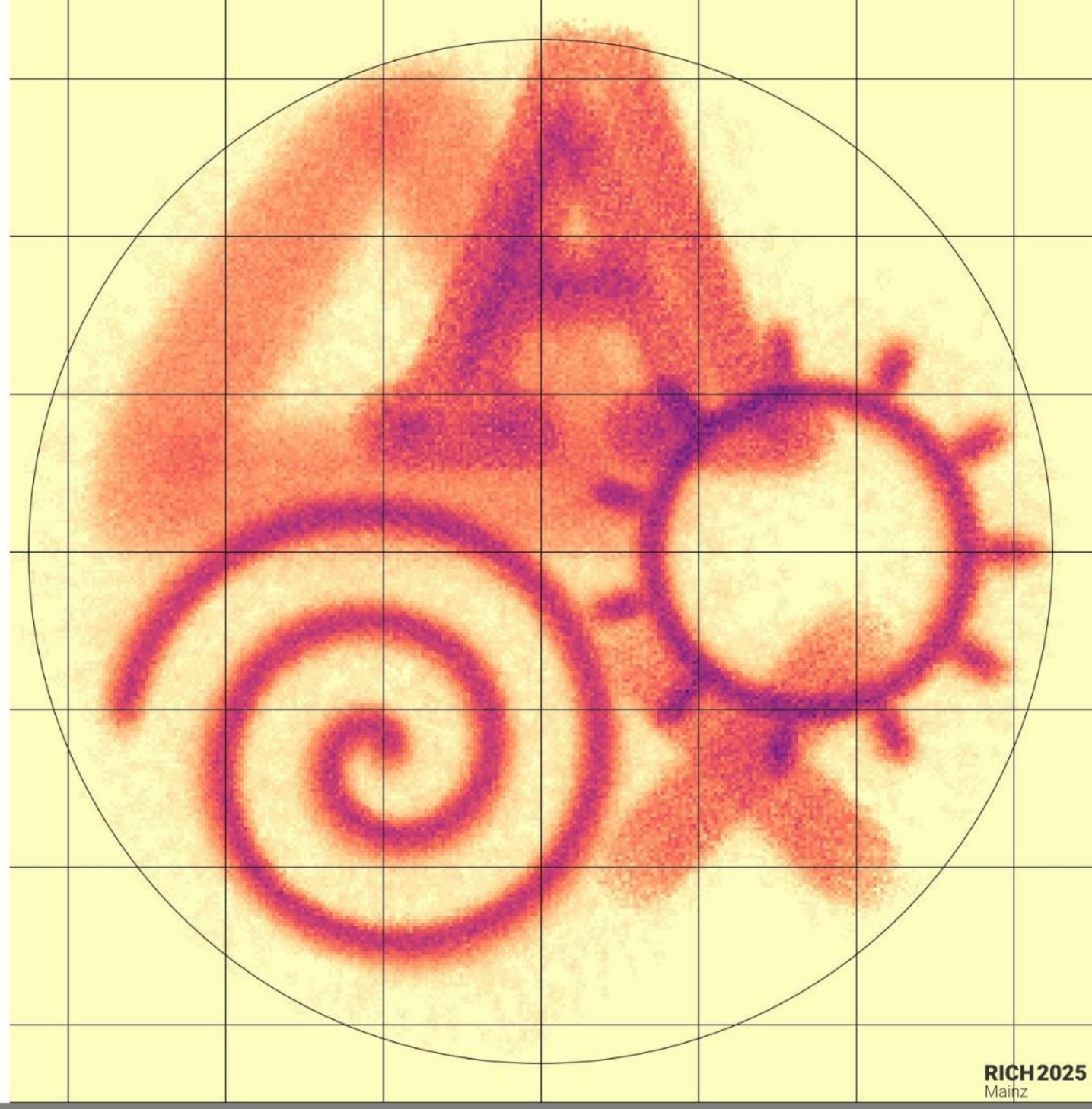


Optics

refocussing to any depth

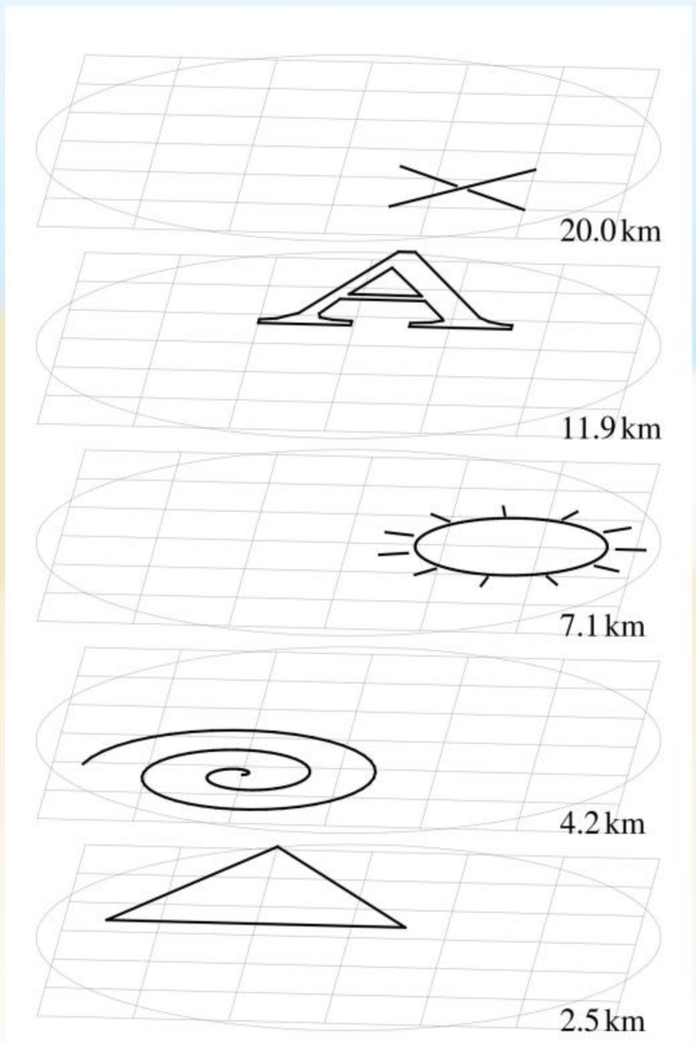


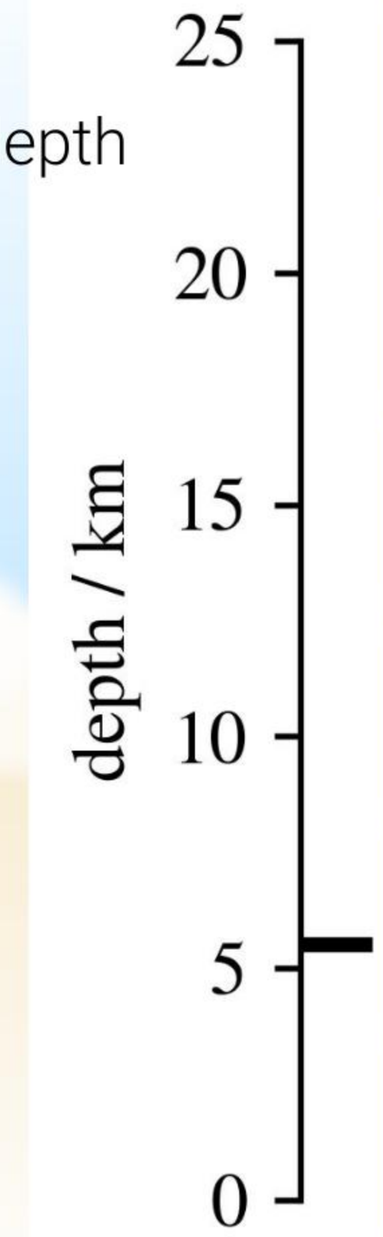


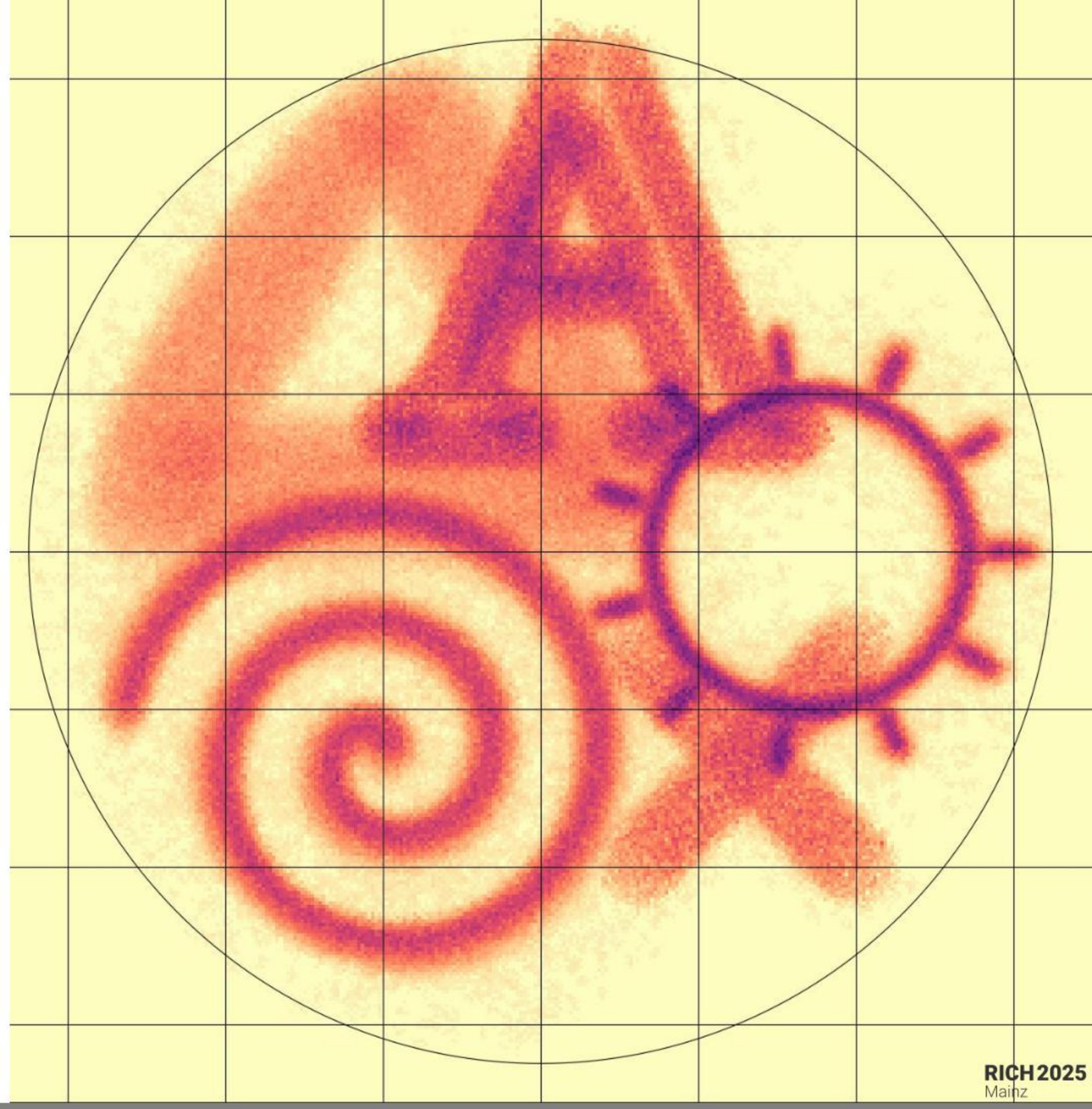


Optics

refocussing to any depth

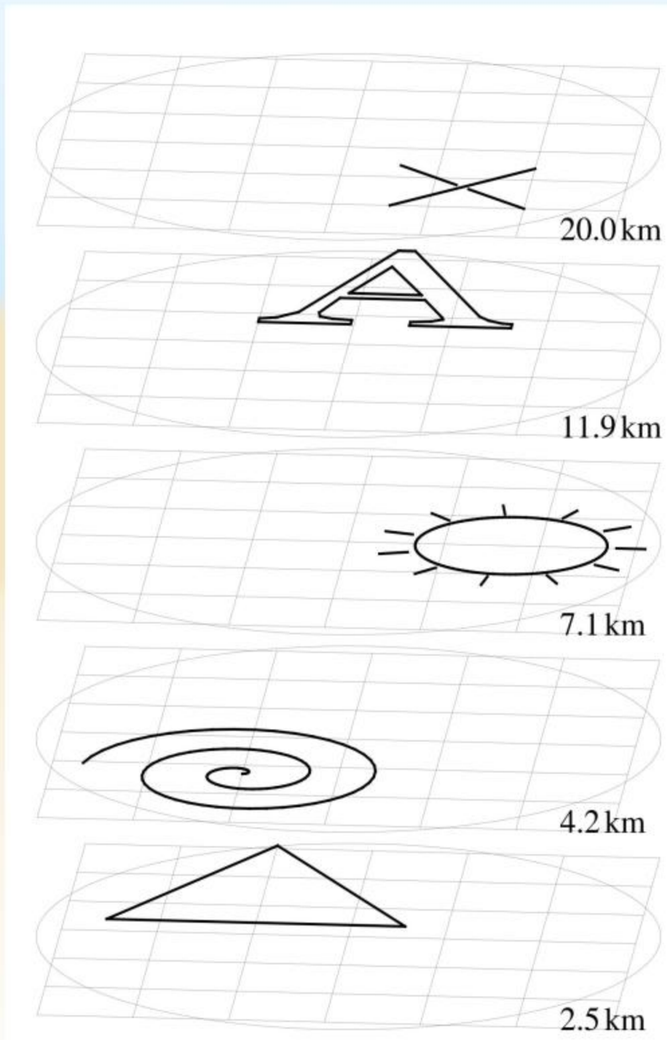


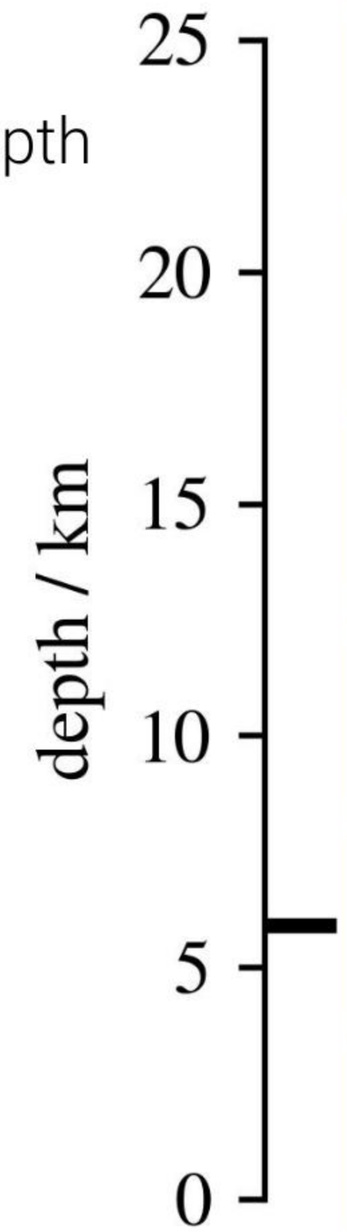


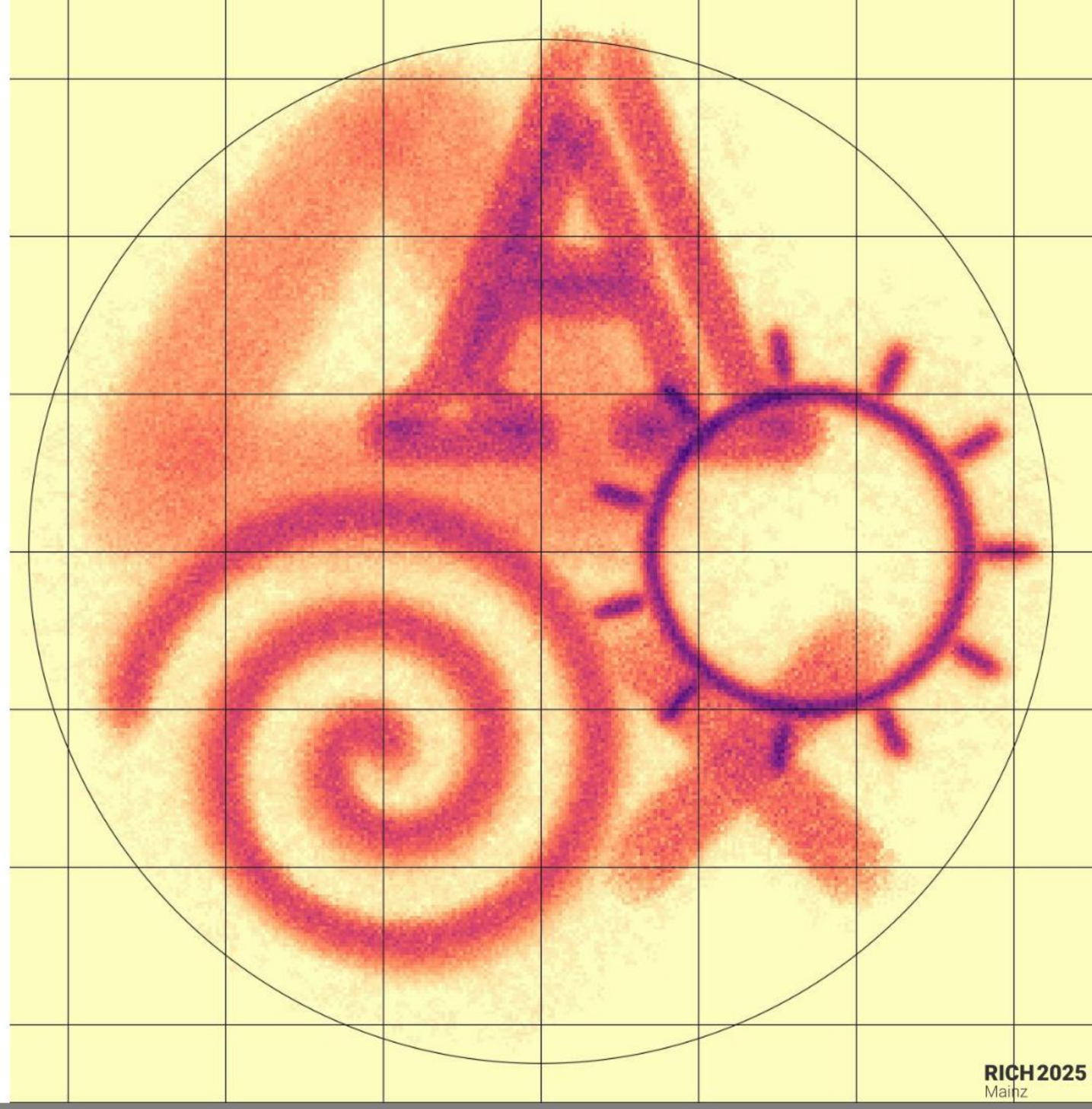


Optics

refocussing to any depth

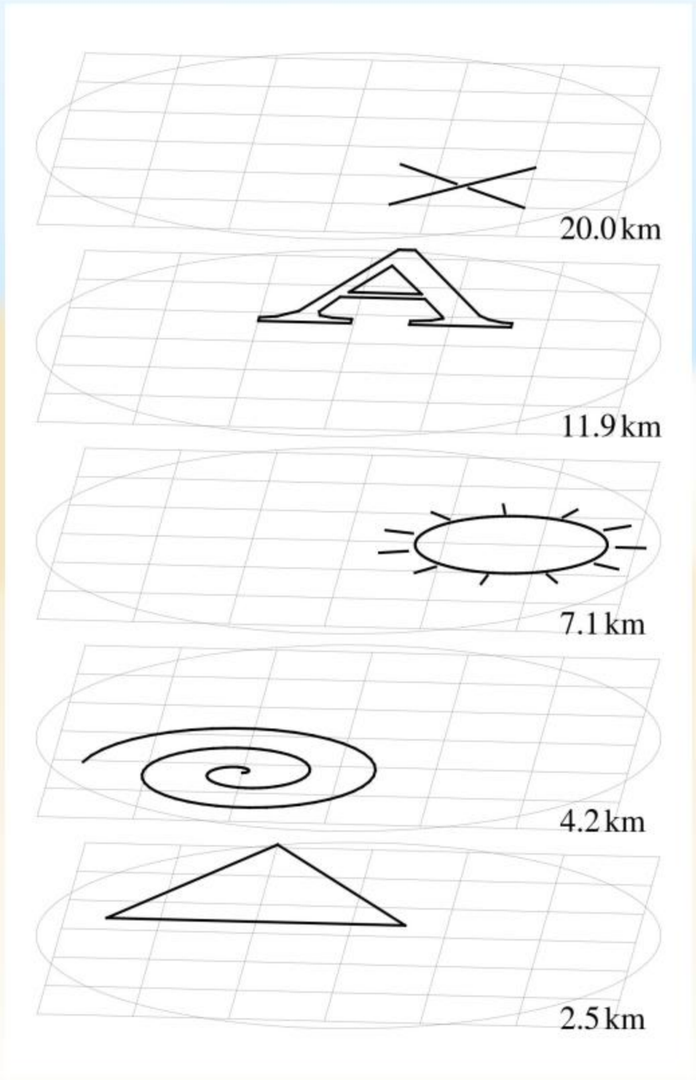


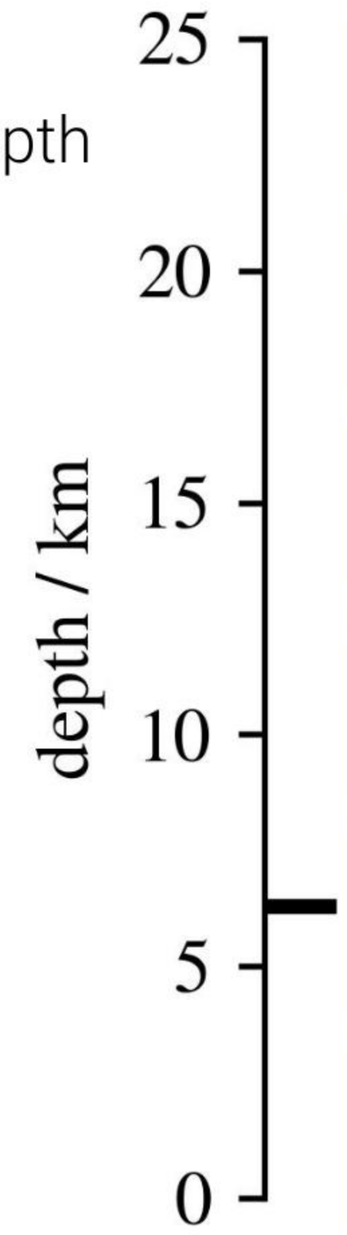


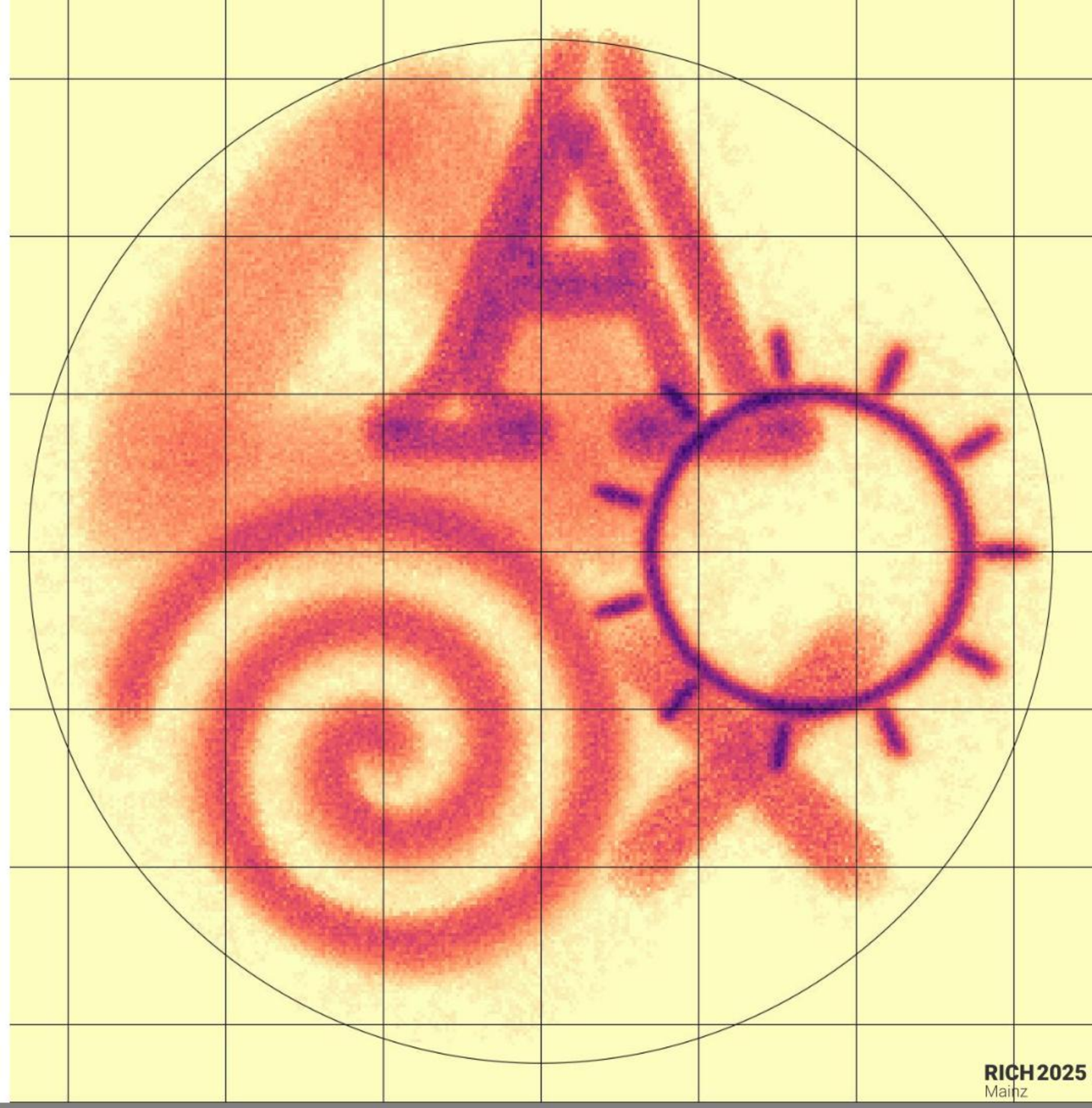


Optics

refocussing to any depth

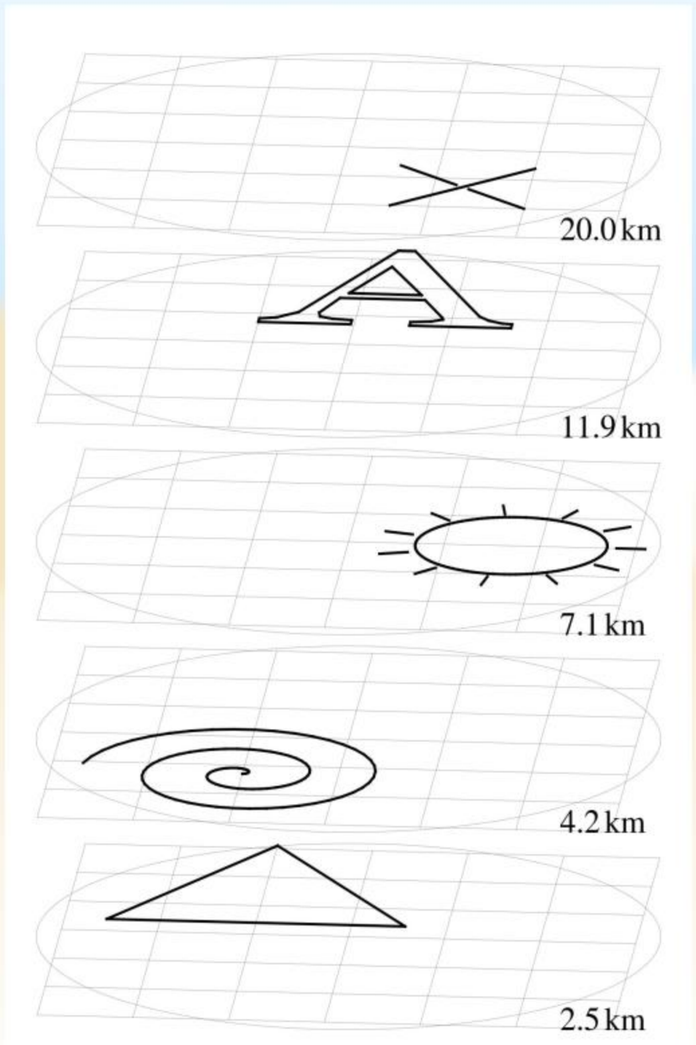


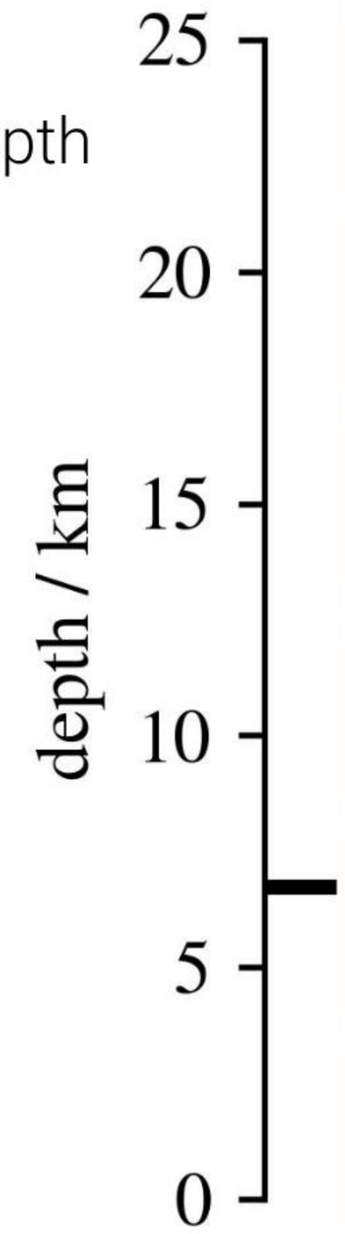


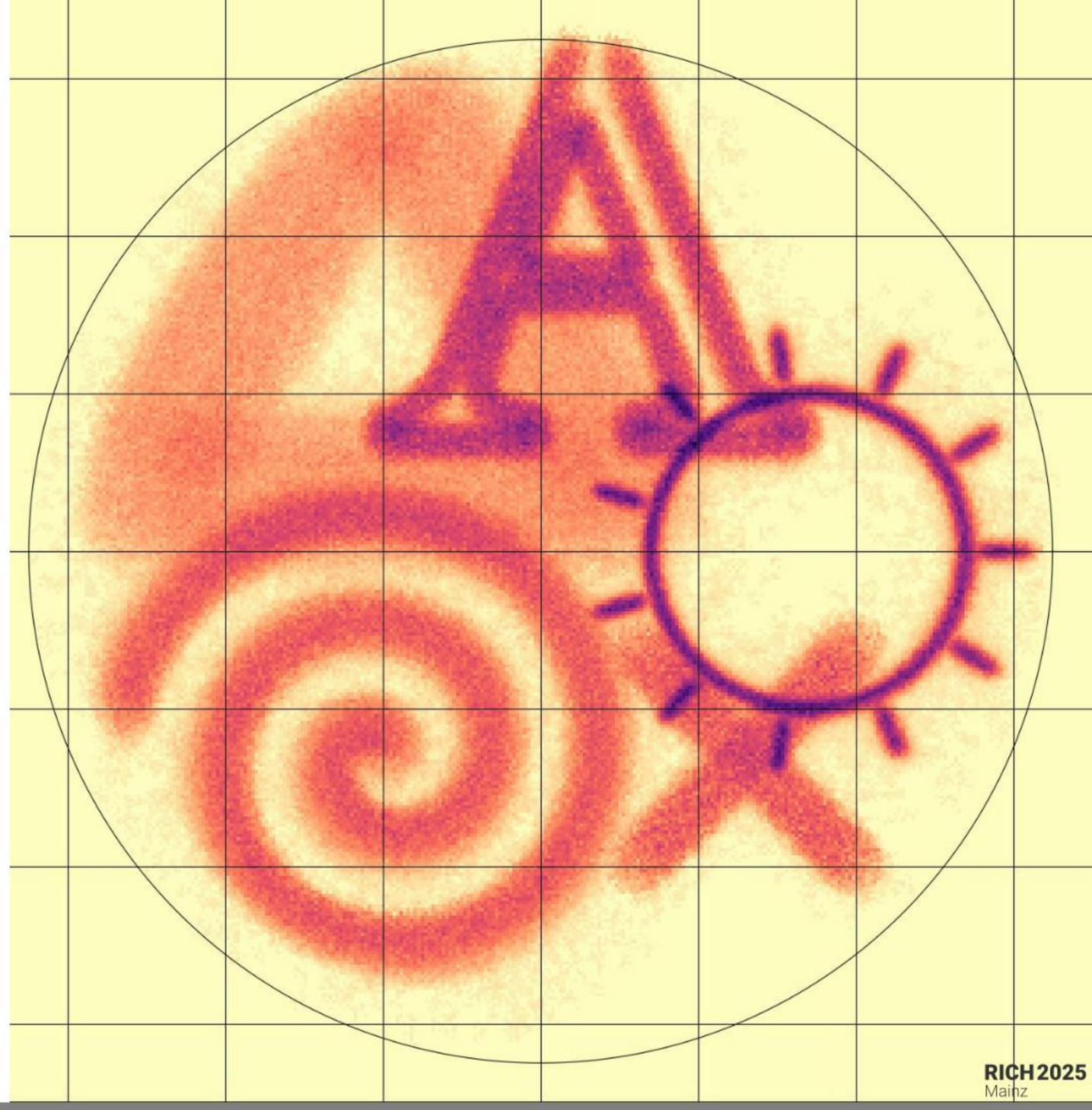


Optics

refocussing to any depth

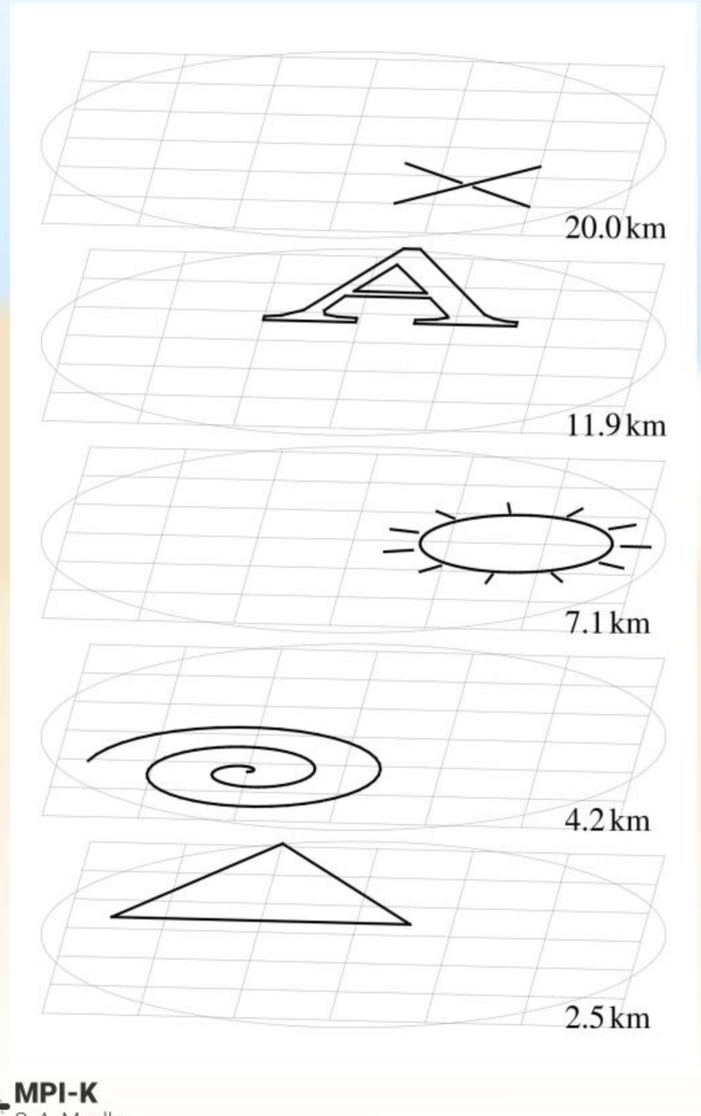


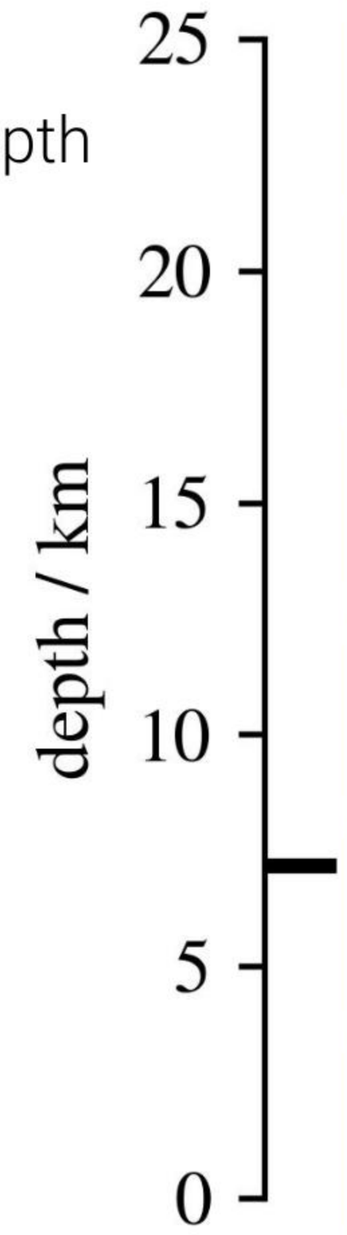


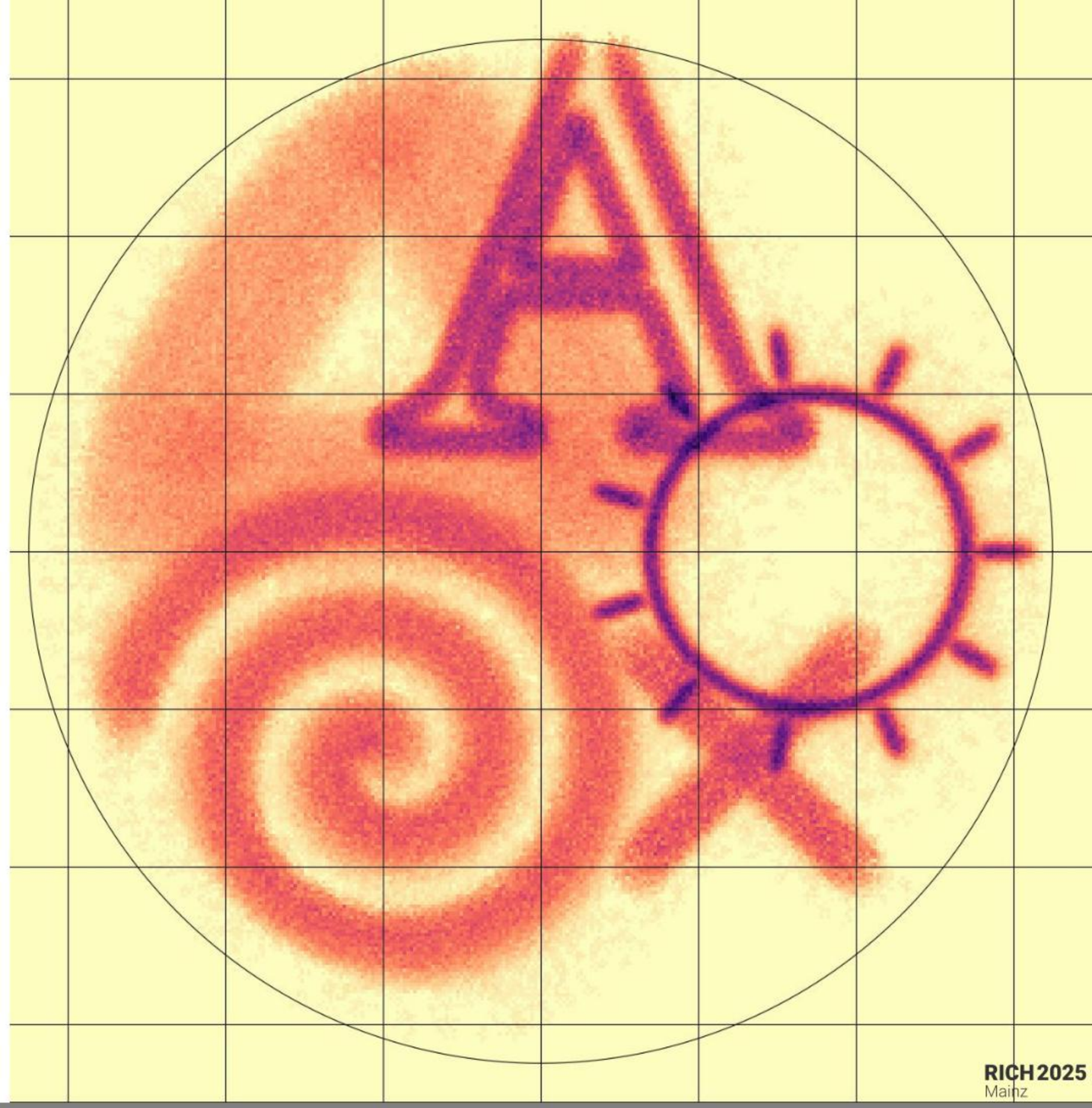


Optics

refocussing to any depth

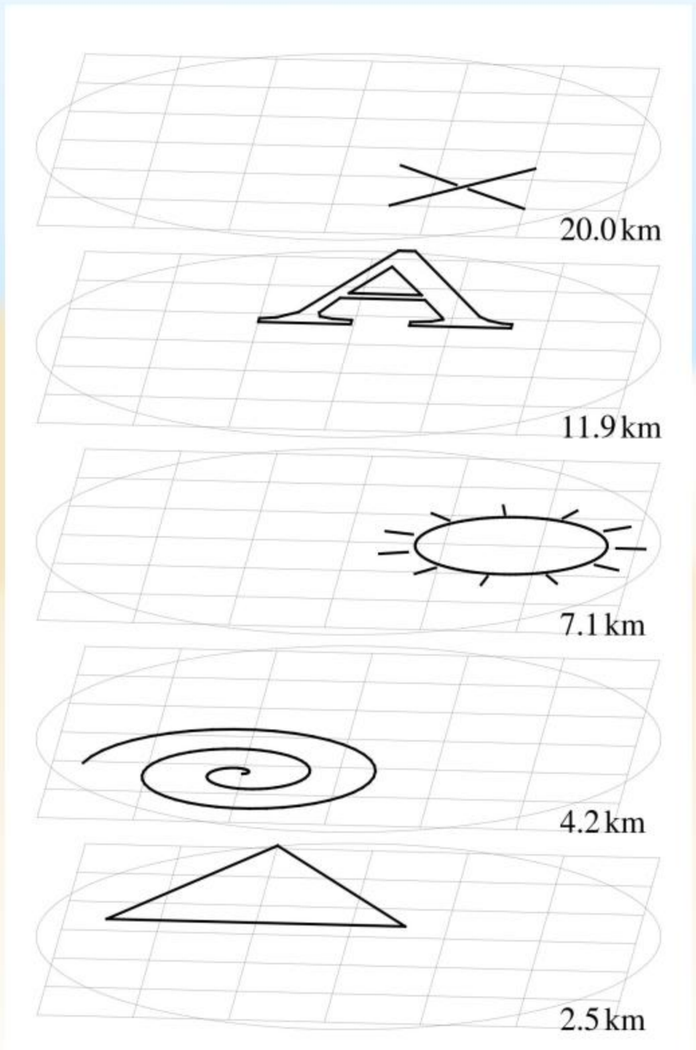


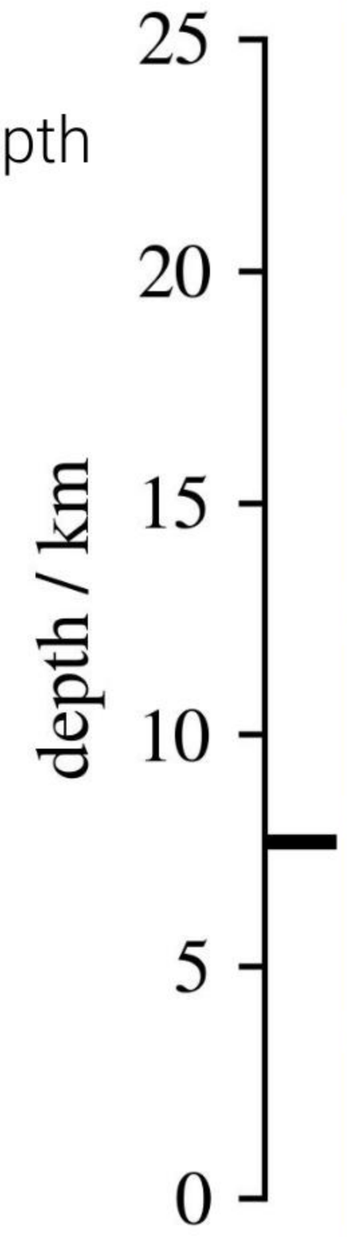


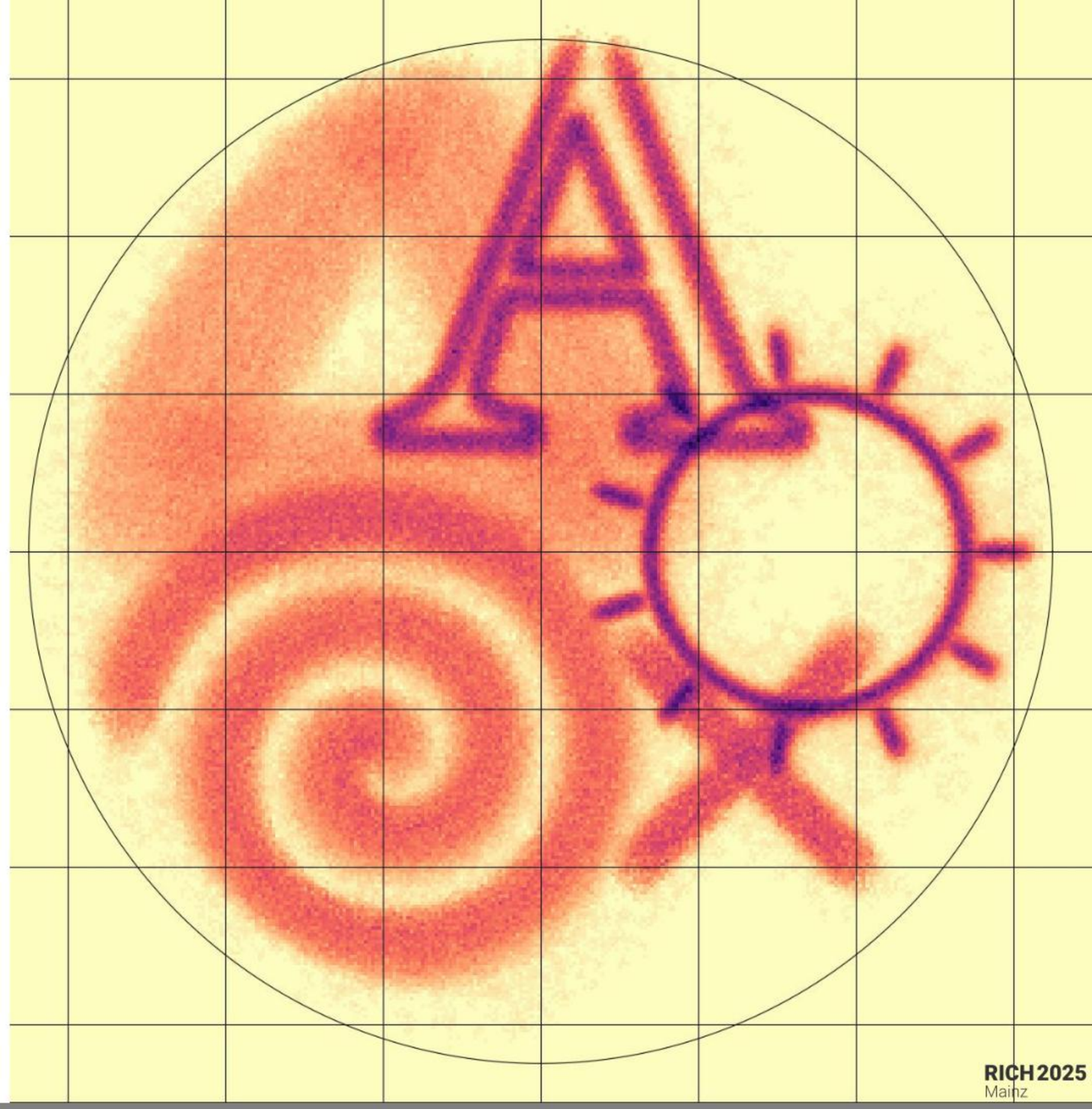


Optics

refocussing to any depth







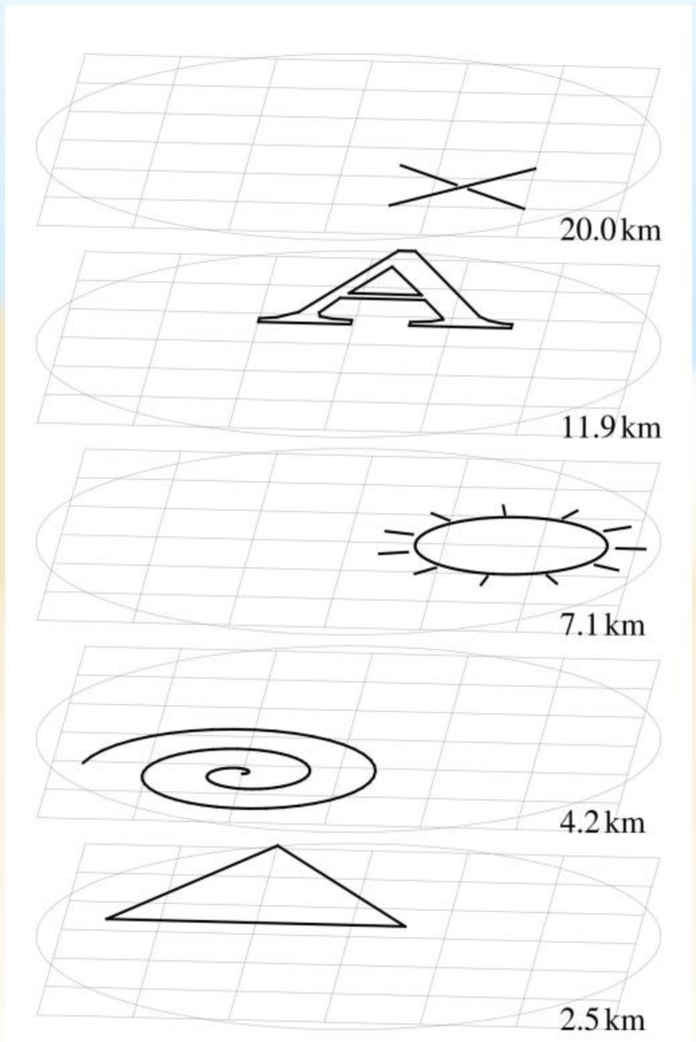
MPI-K
S. A. Mueller

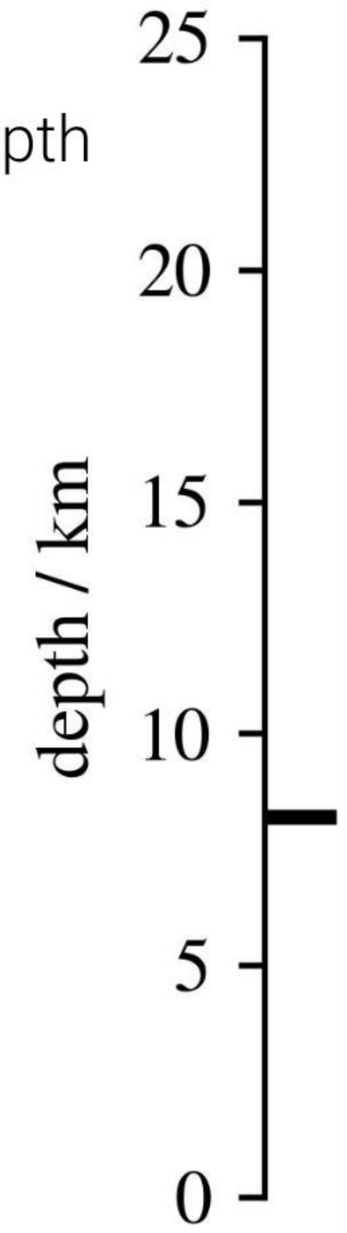
RICH 2025
Mainz

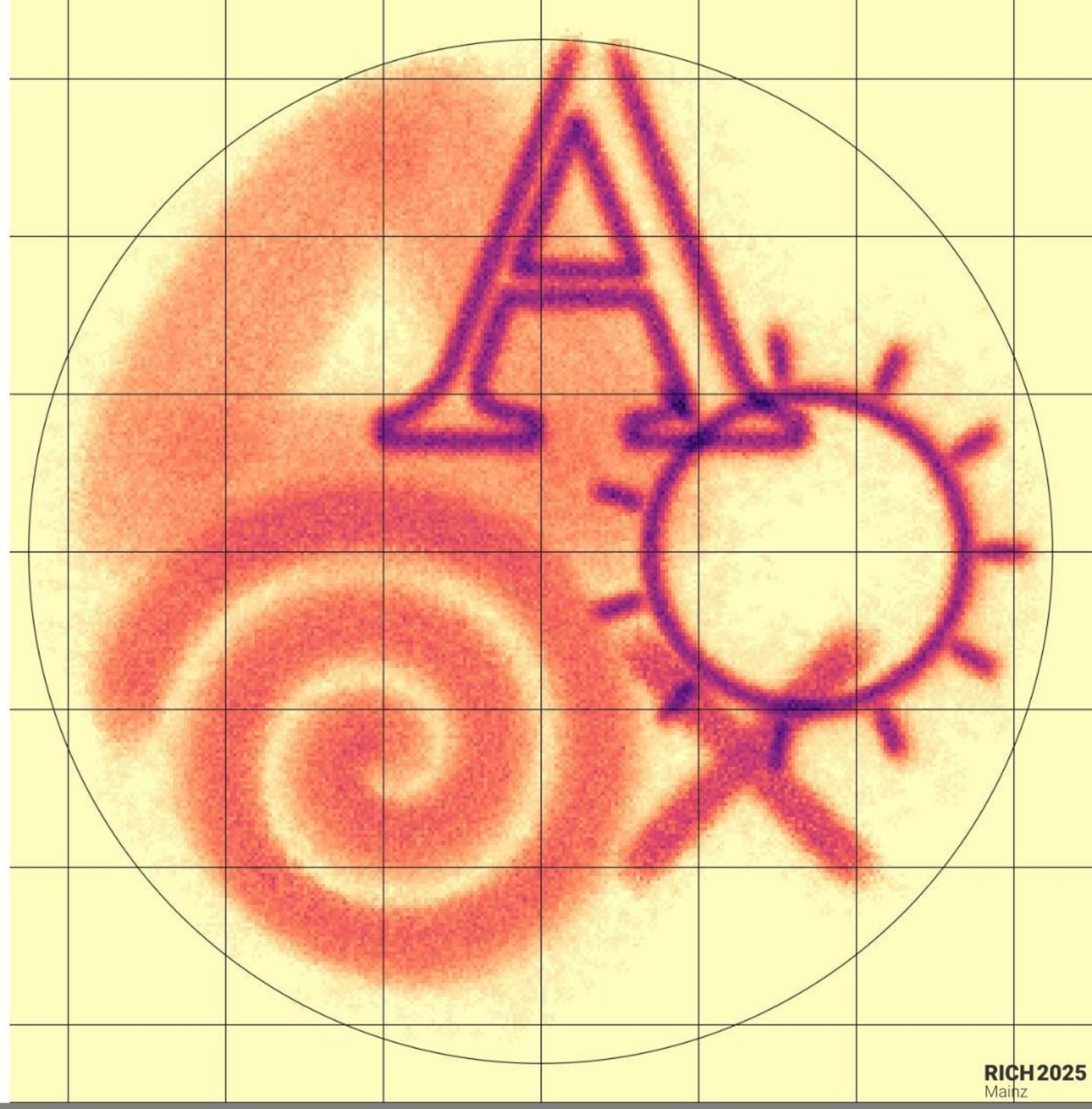
At about seven kilometers we find the sun with its flares. Again, look how flat the image is. One can hardly see any aberrations.

Optics

refocussing to any depth

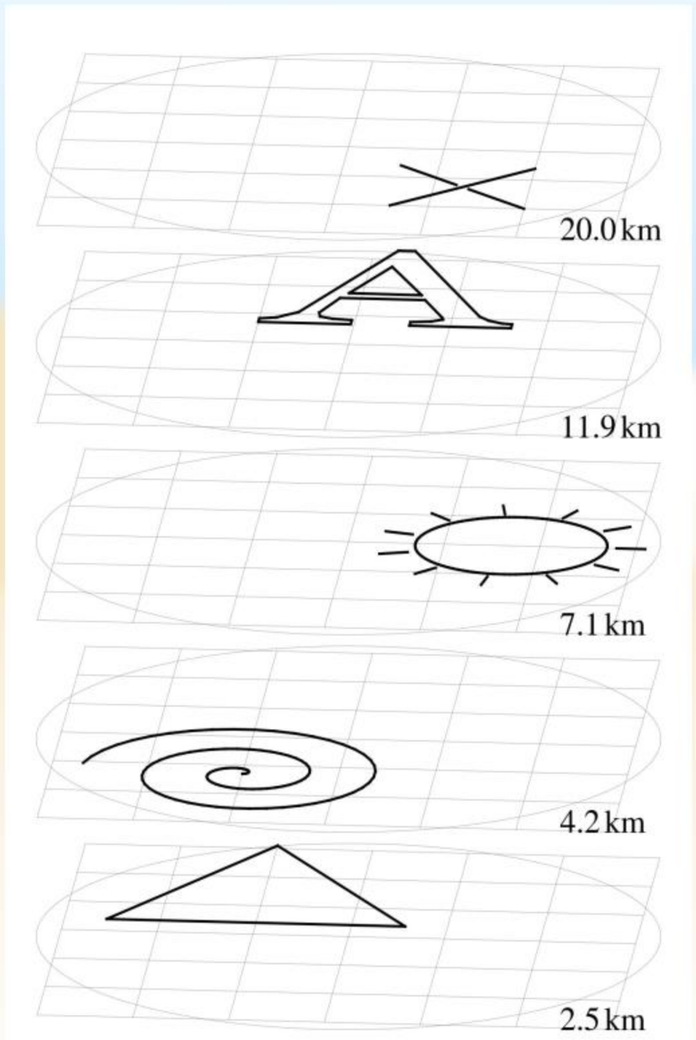


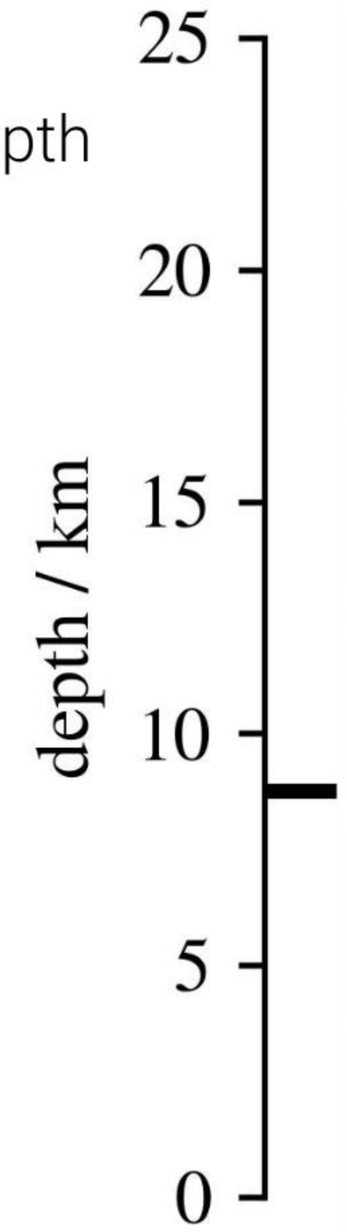


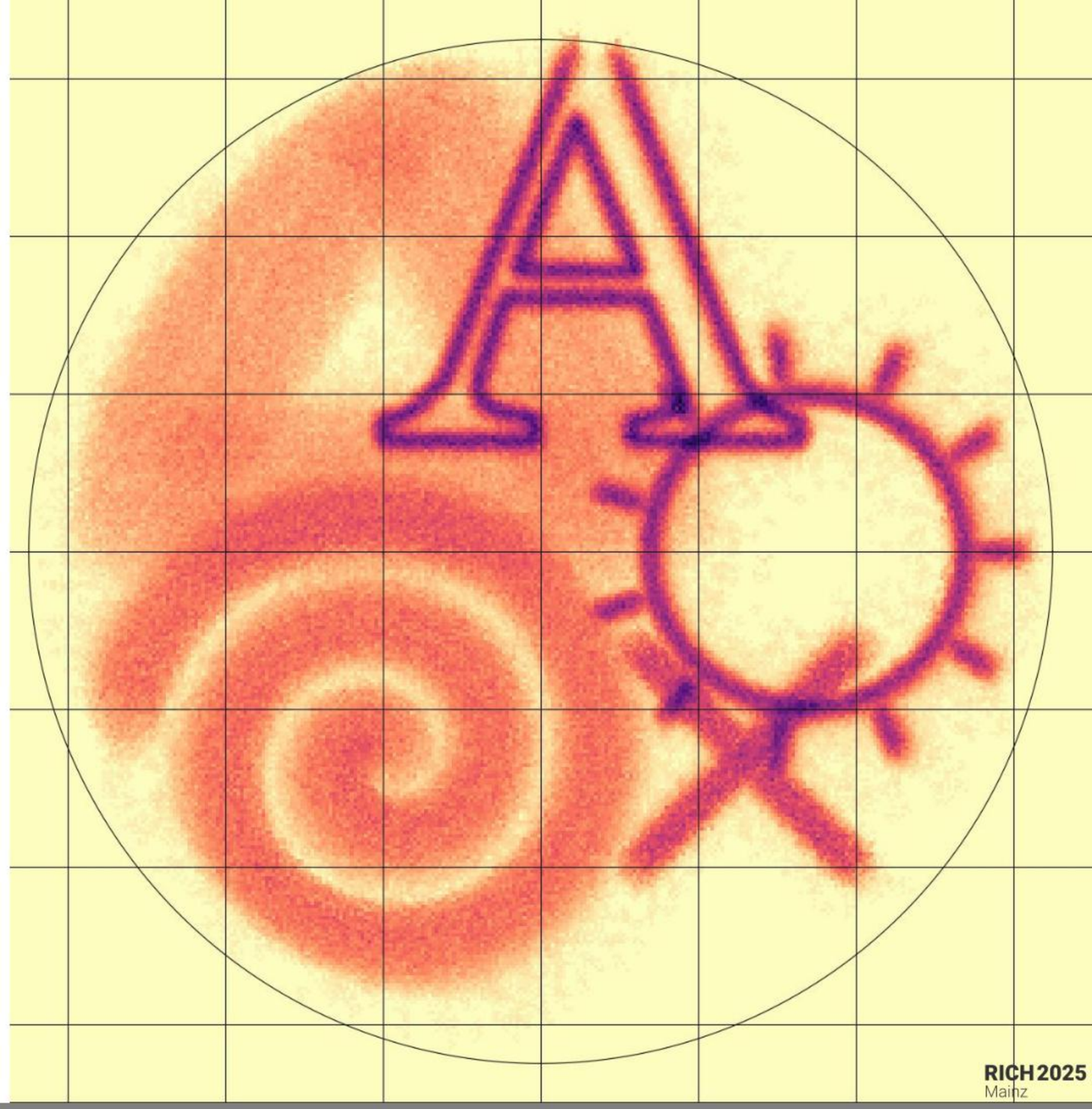


Optics

refocussing to any depth

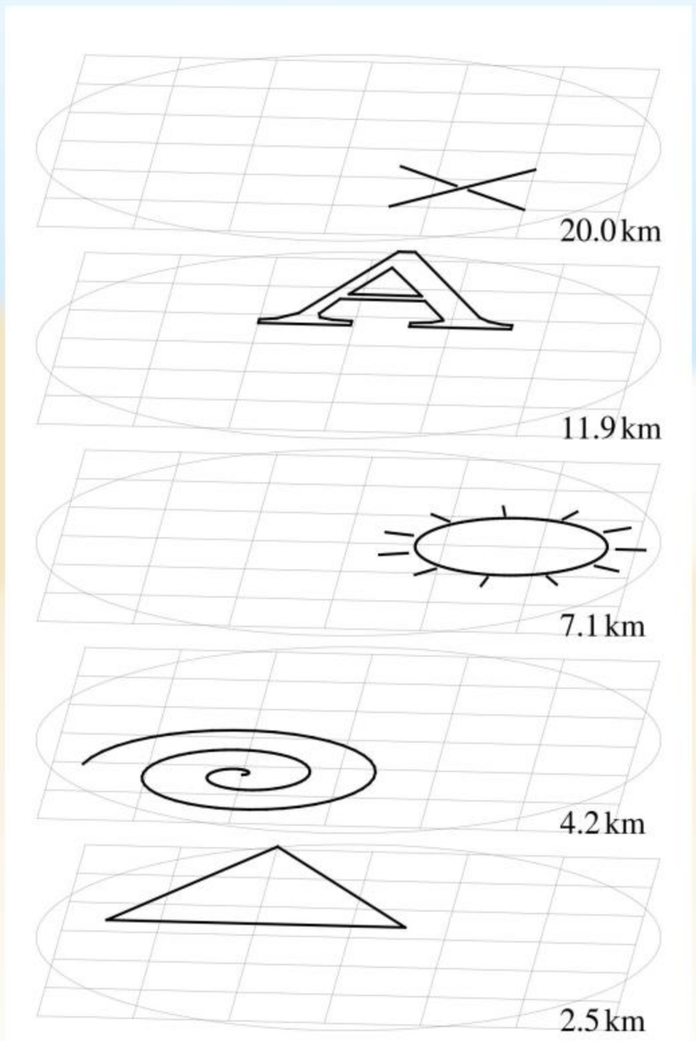


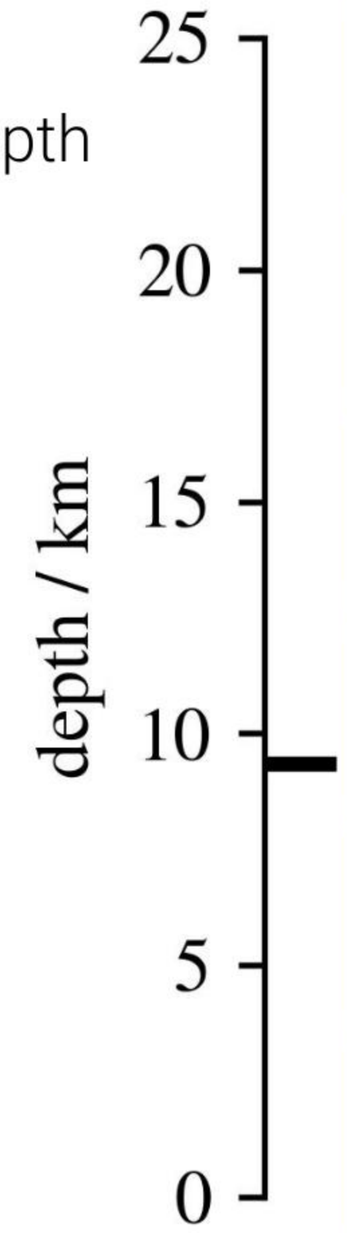


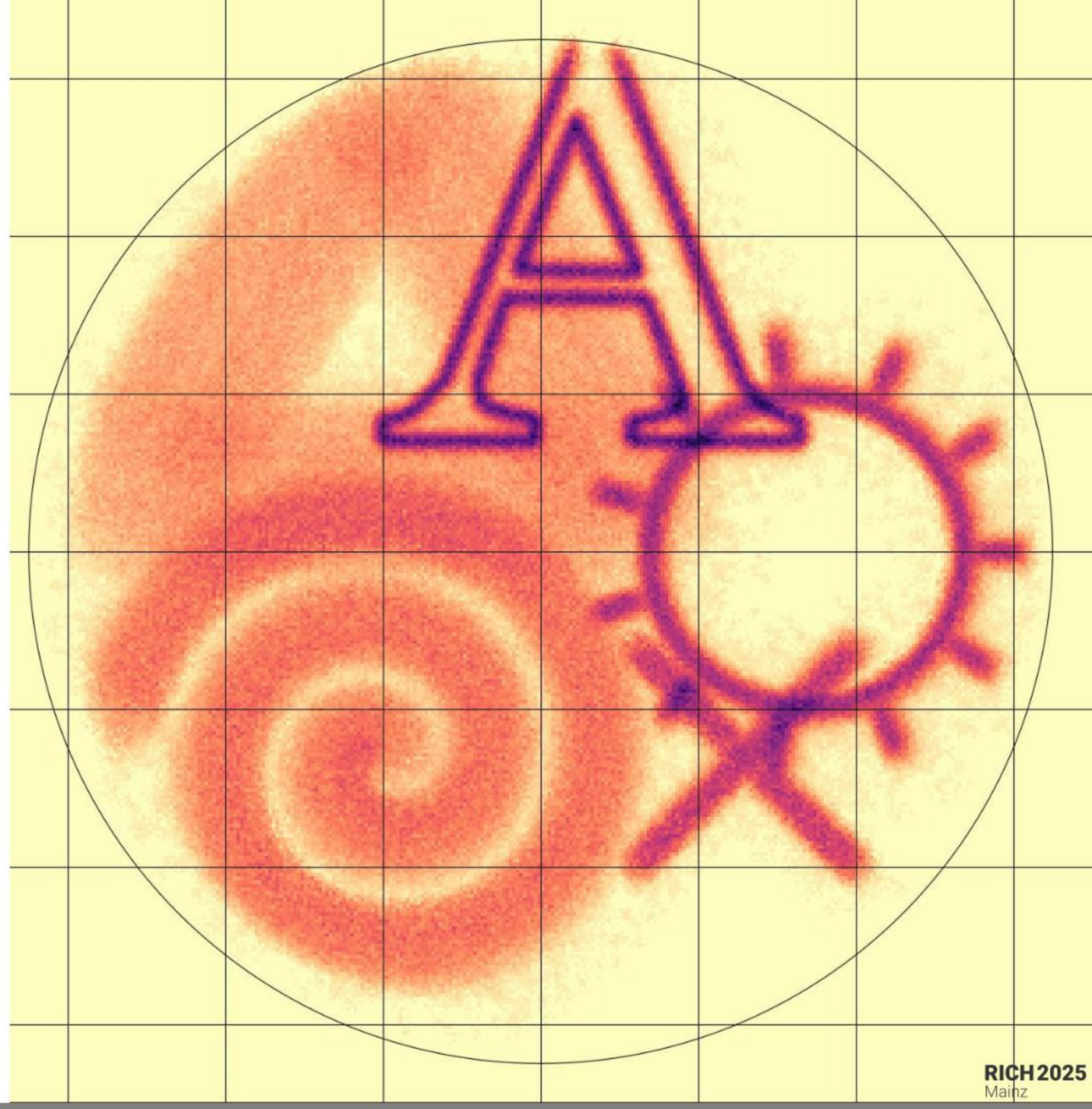


Optics

refocussing to any depth

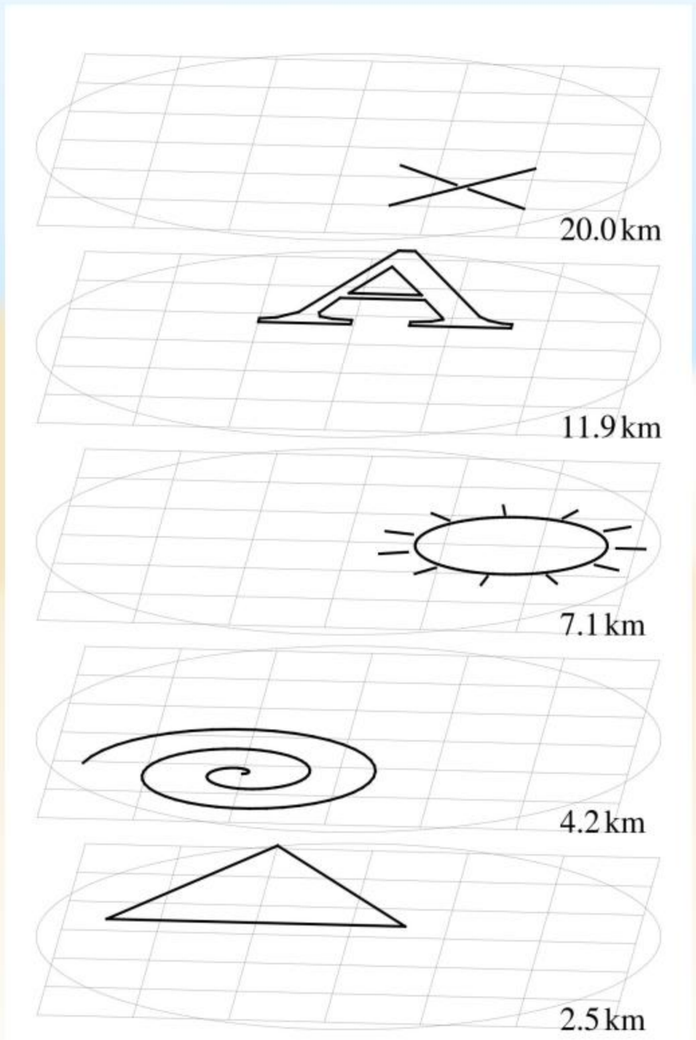


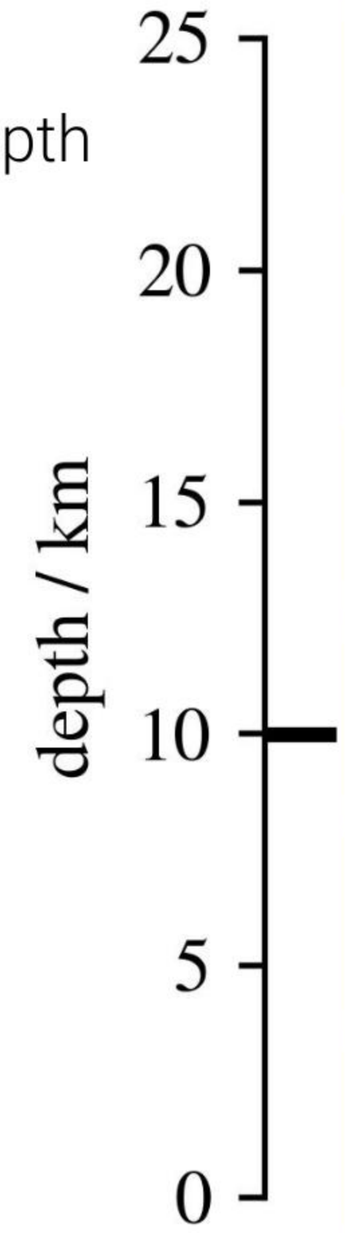


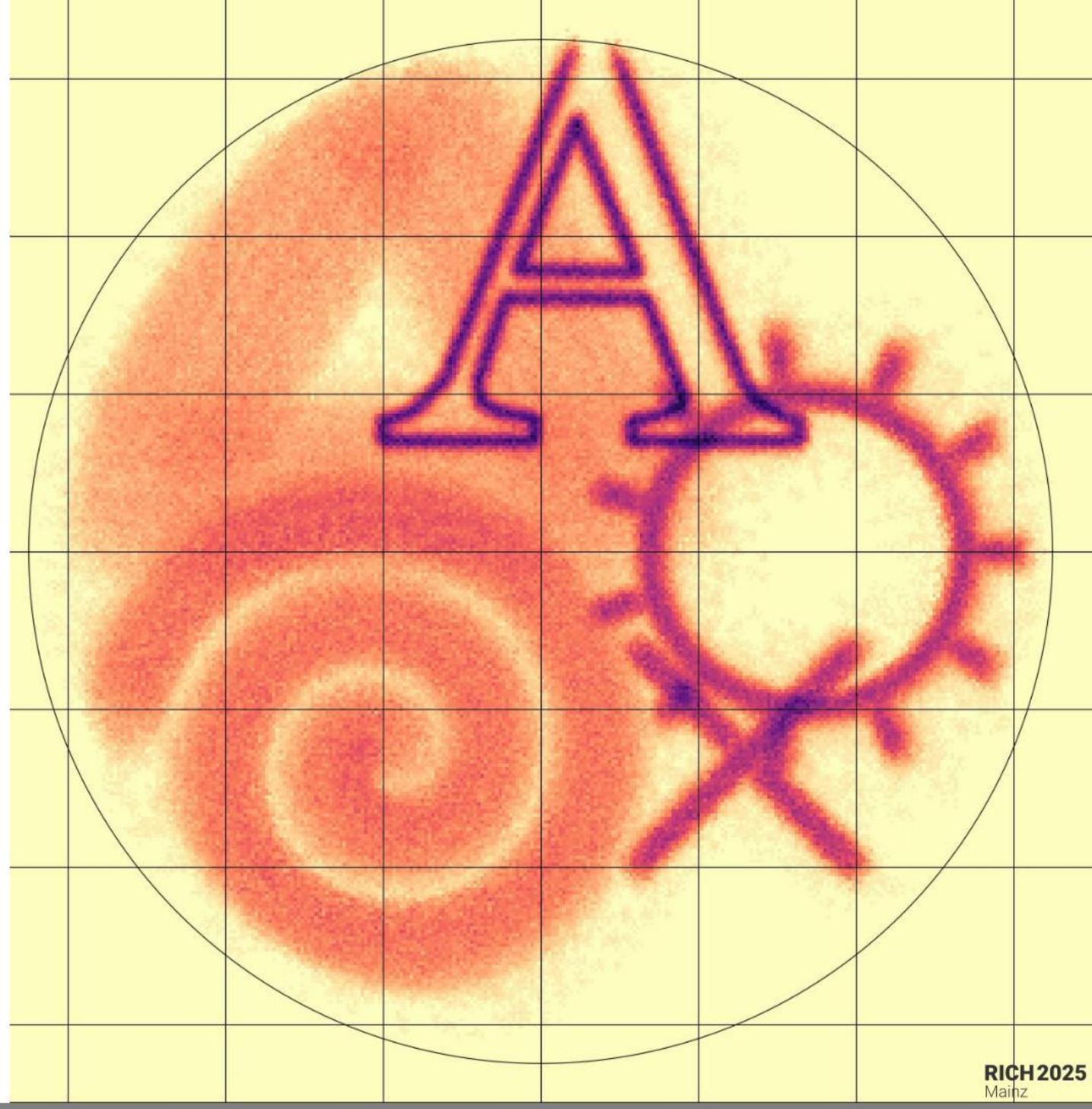


Optics

refocussing to any depth

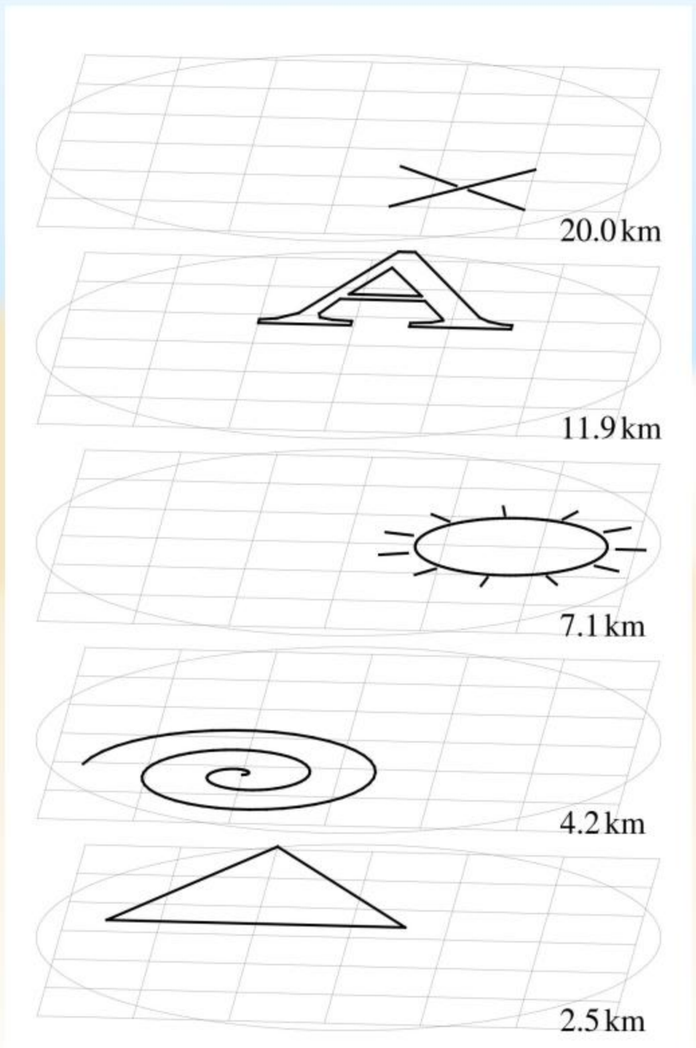


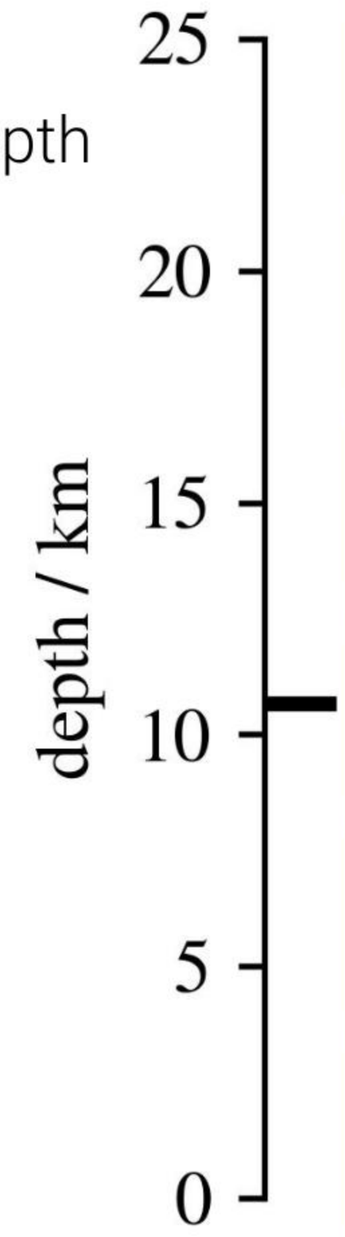


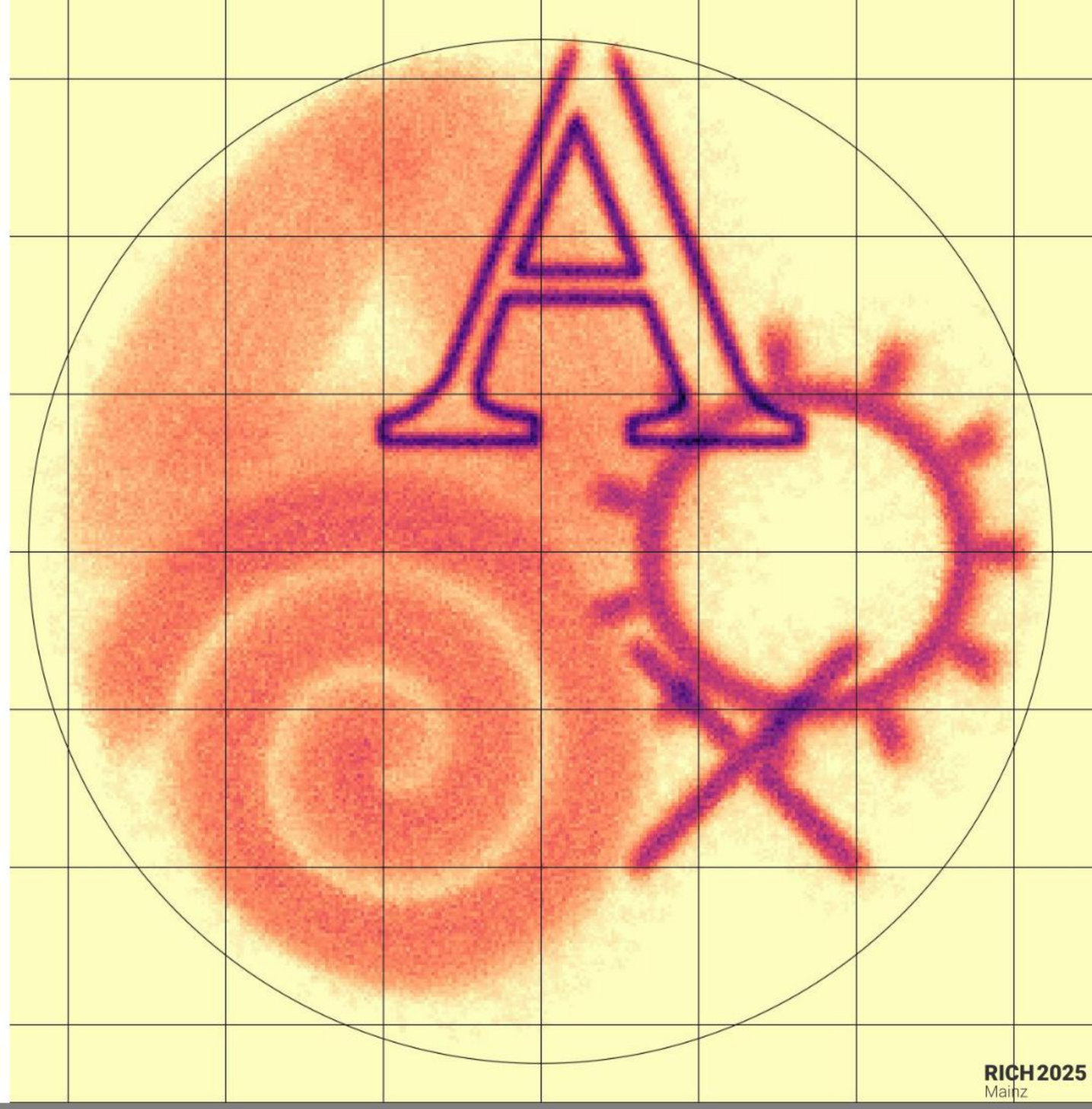


Optics

refocussing to any depth

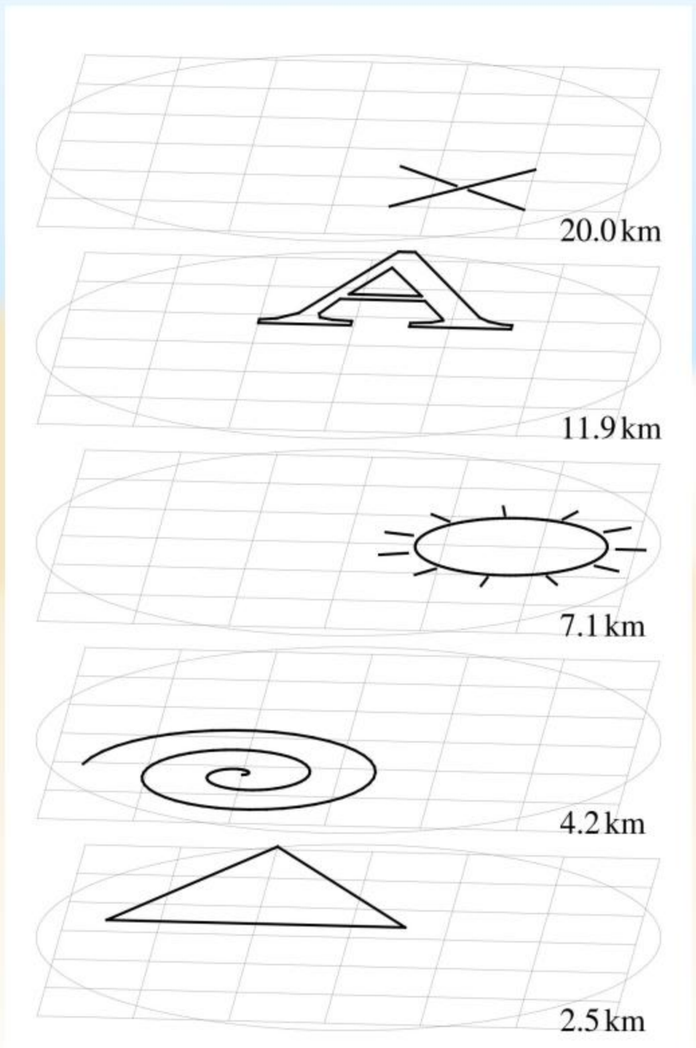


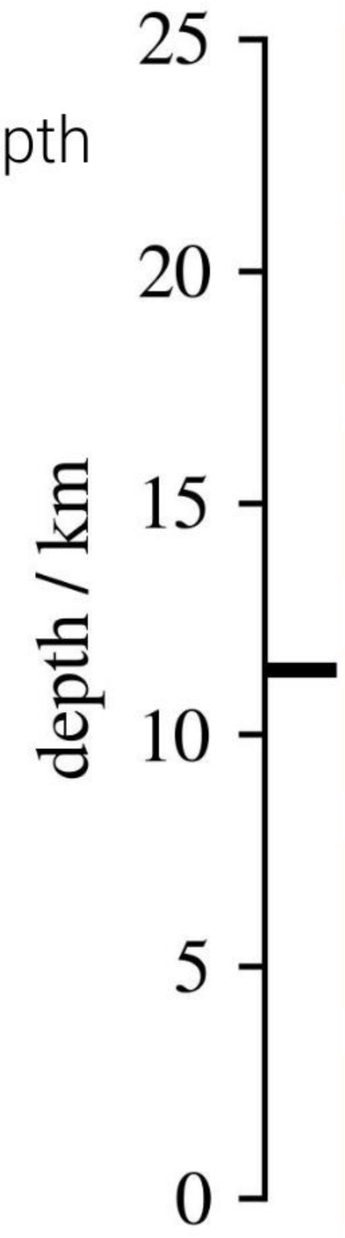


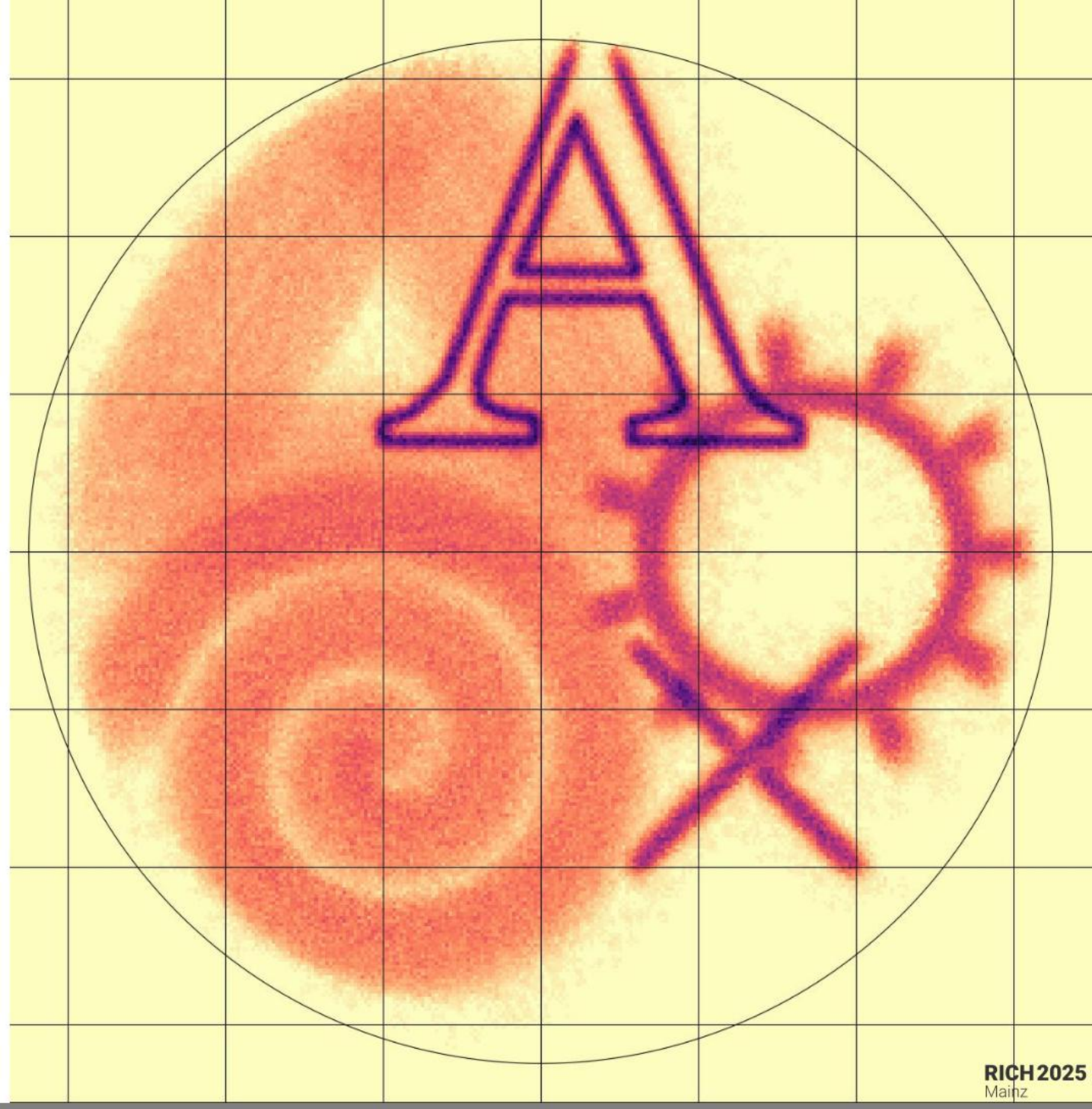


Optics

refocussing to any depth







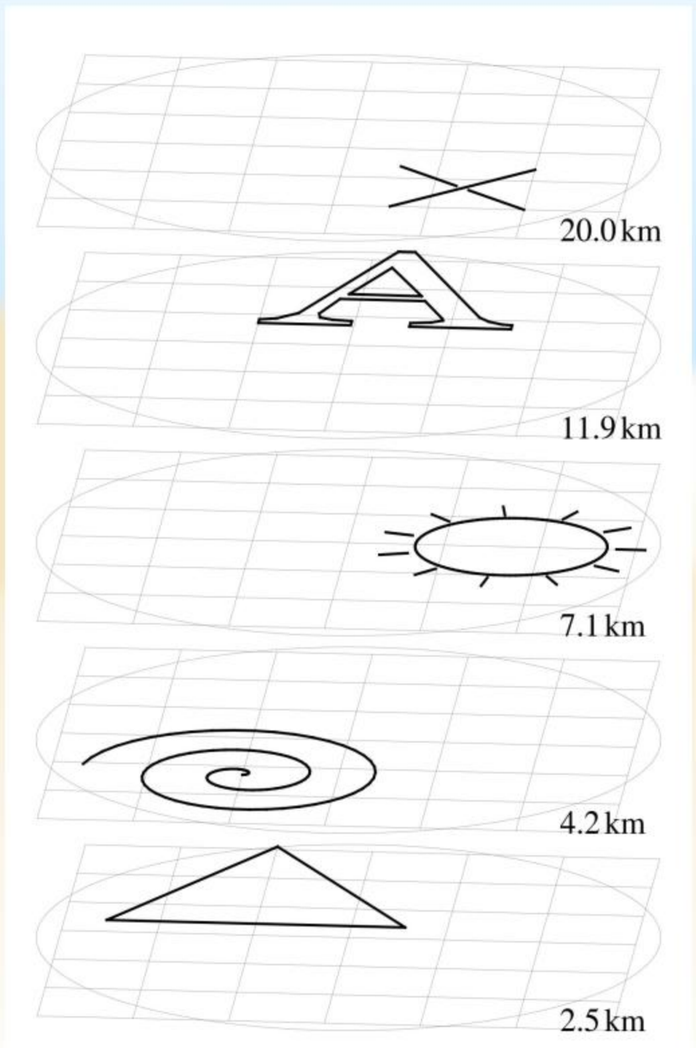
MPI-K
S. A. Mueller

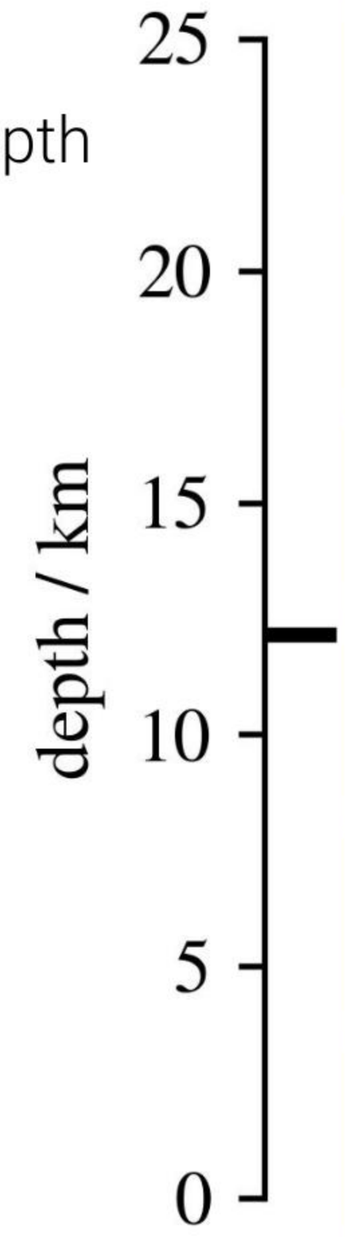
RICH 2025
Mainz

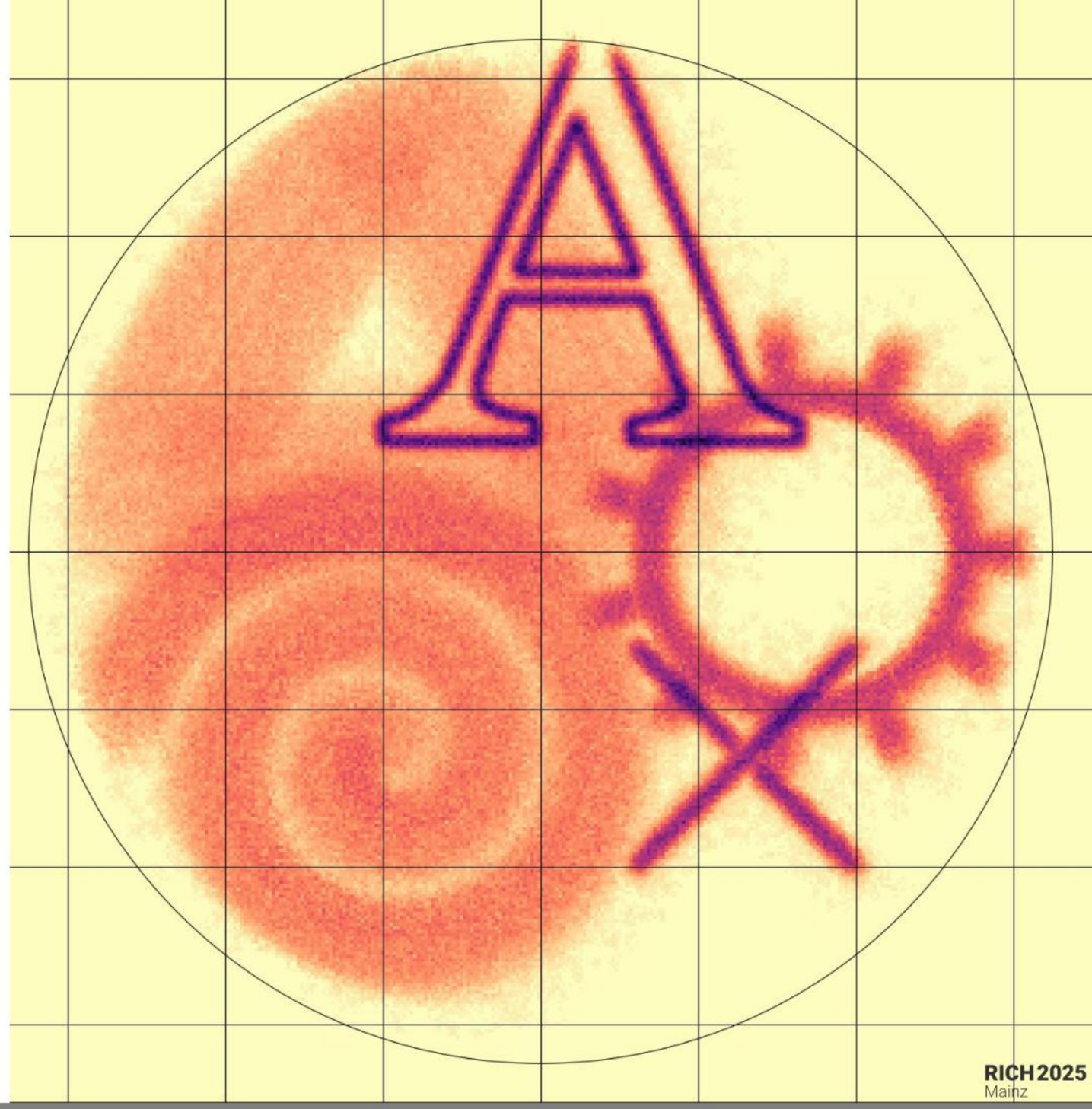
At twelve kilometers we find the capital letter 'A'. Look how straight the line are. There is no sign of distortions.

Optics

refocussing to any depth

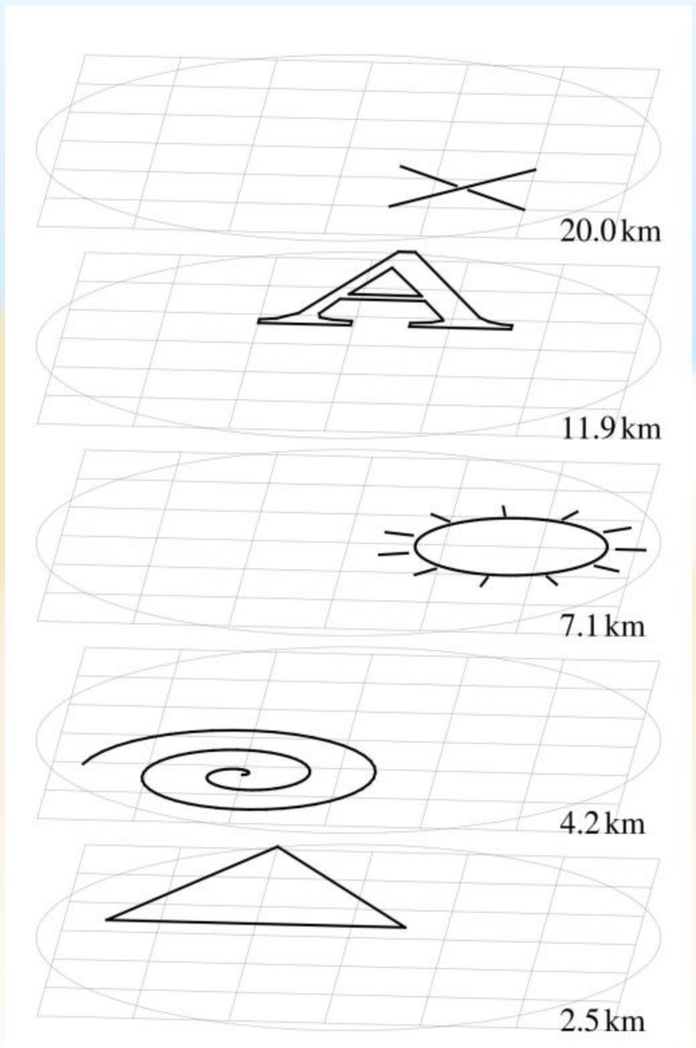


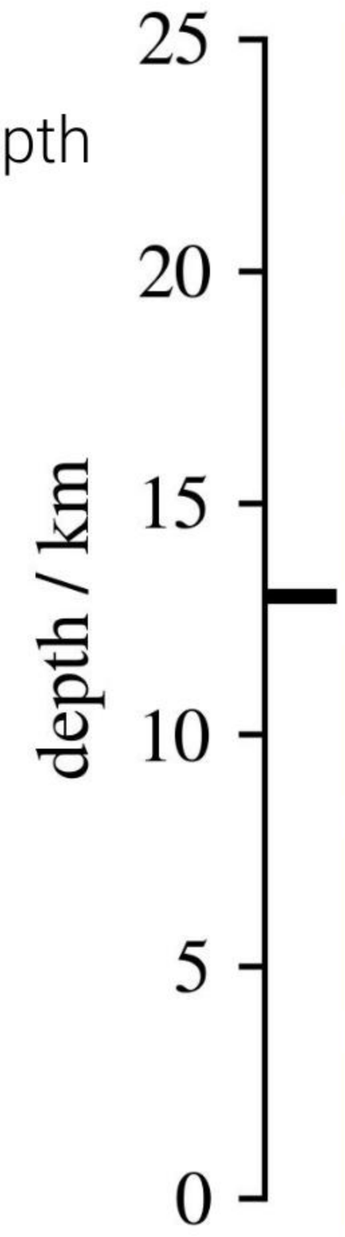


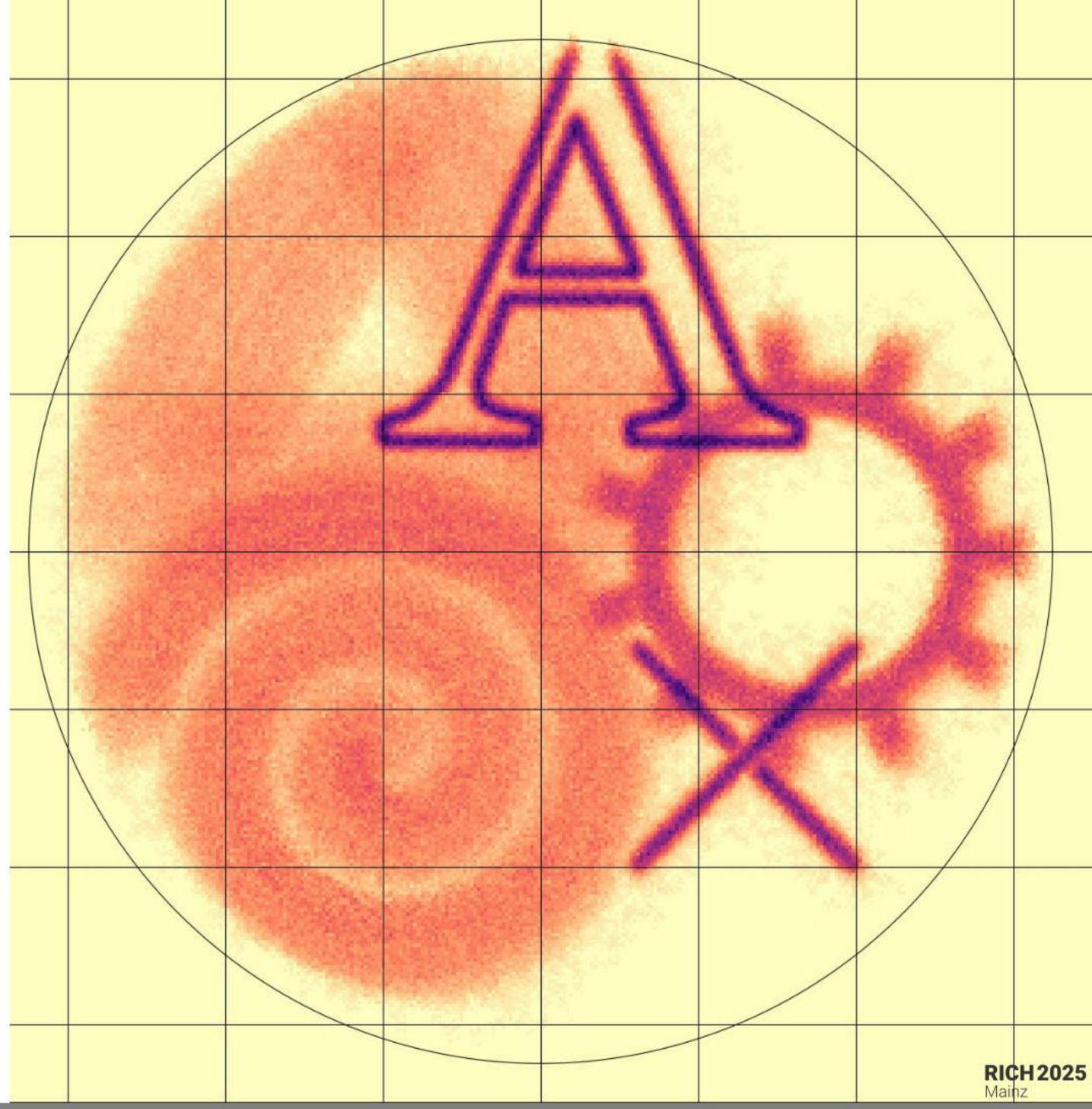


Optics

refocussing to any depth

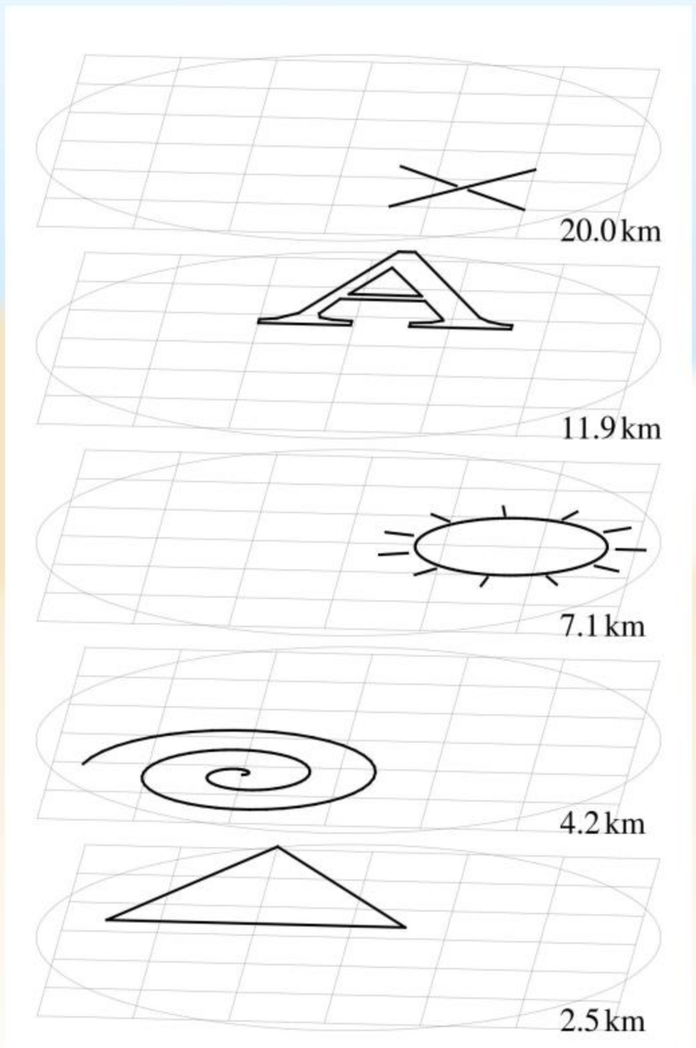


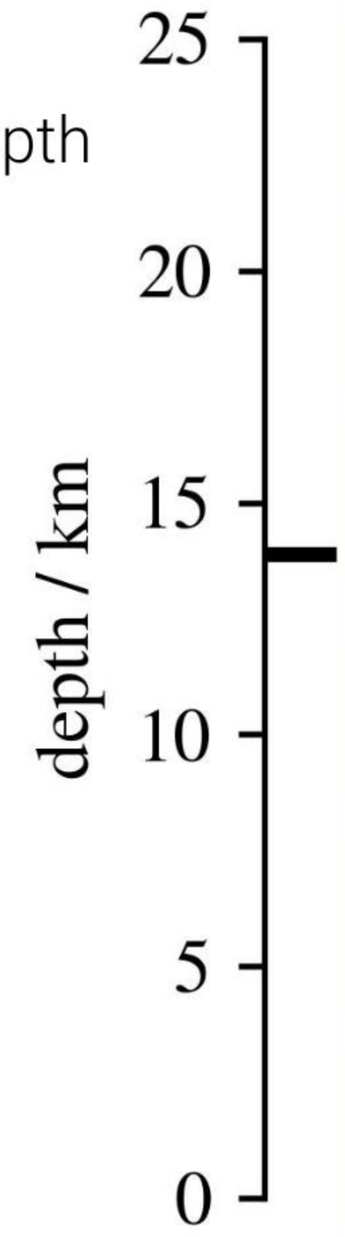


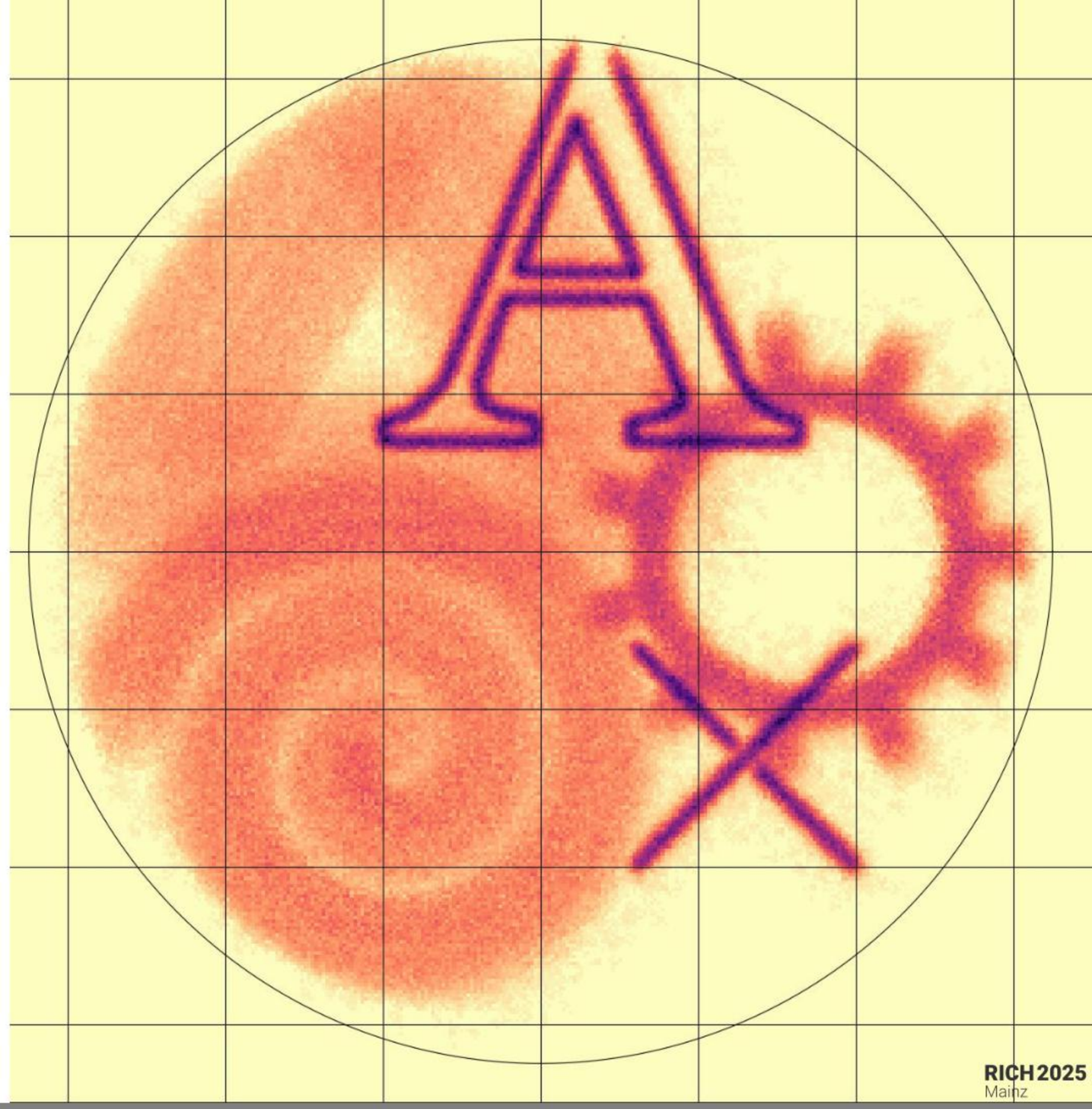


Optics

refocussing to any depth

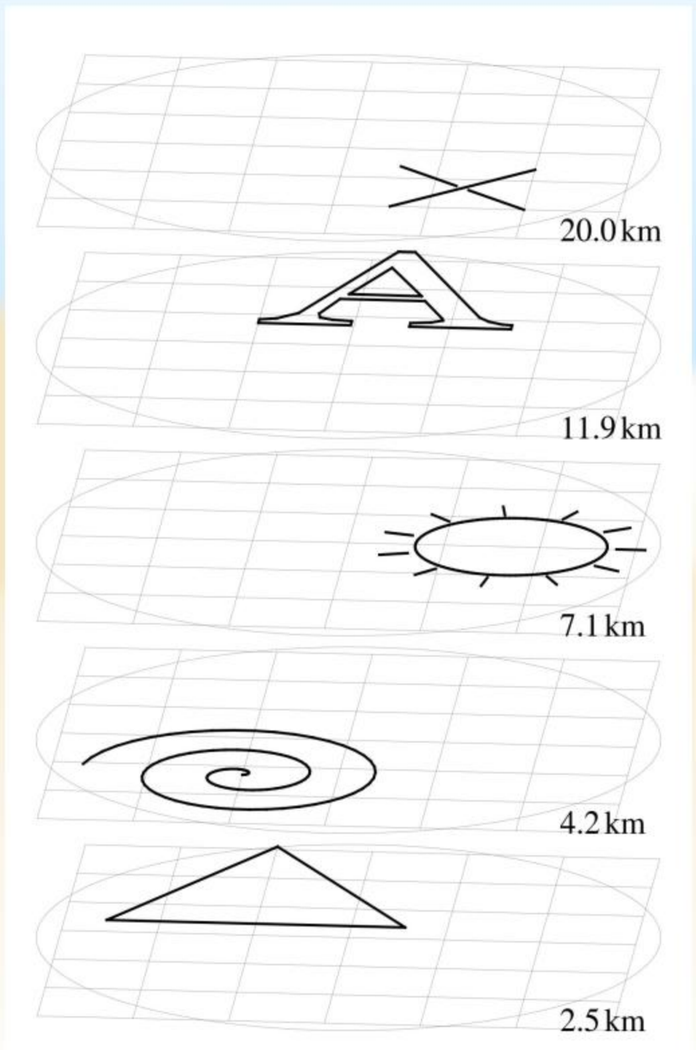


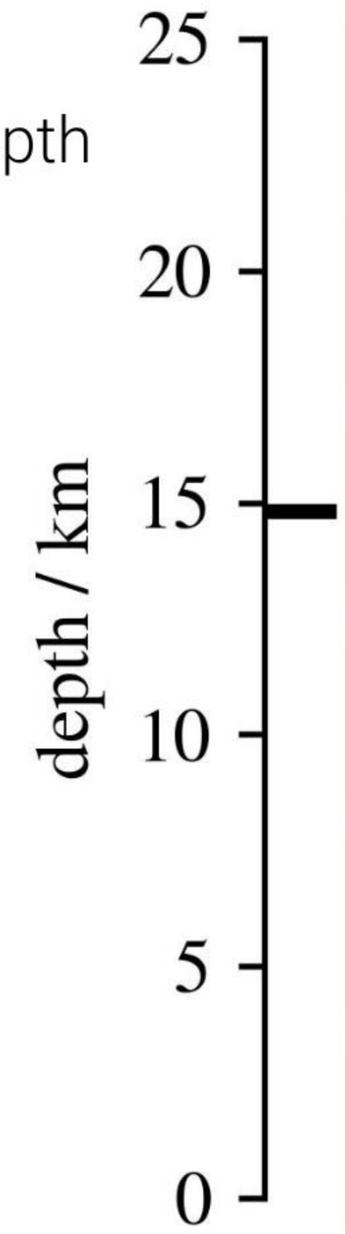


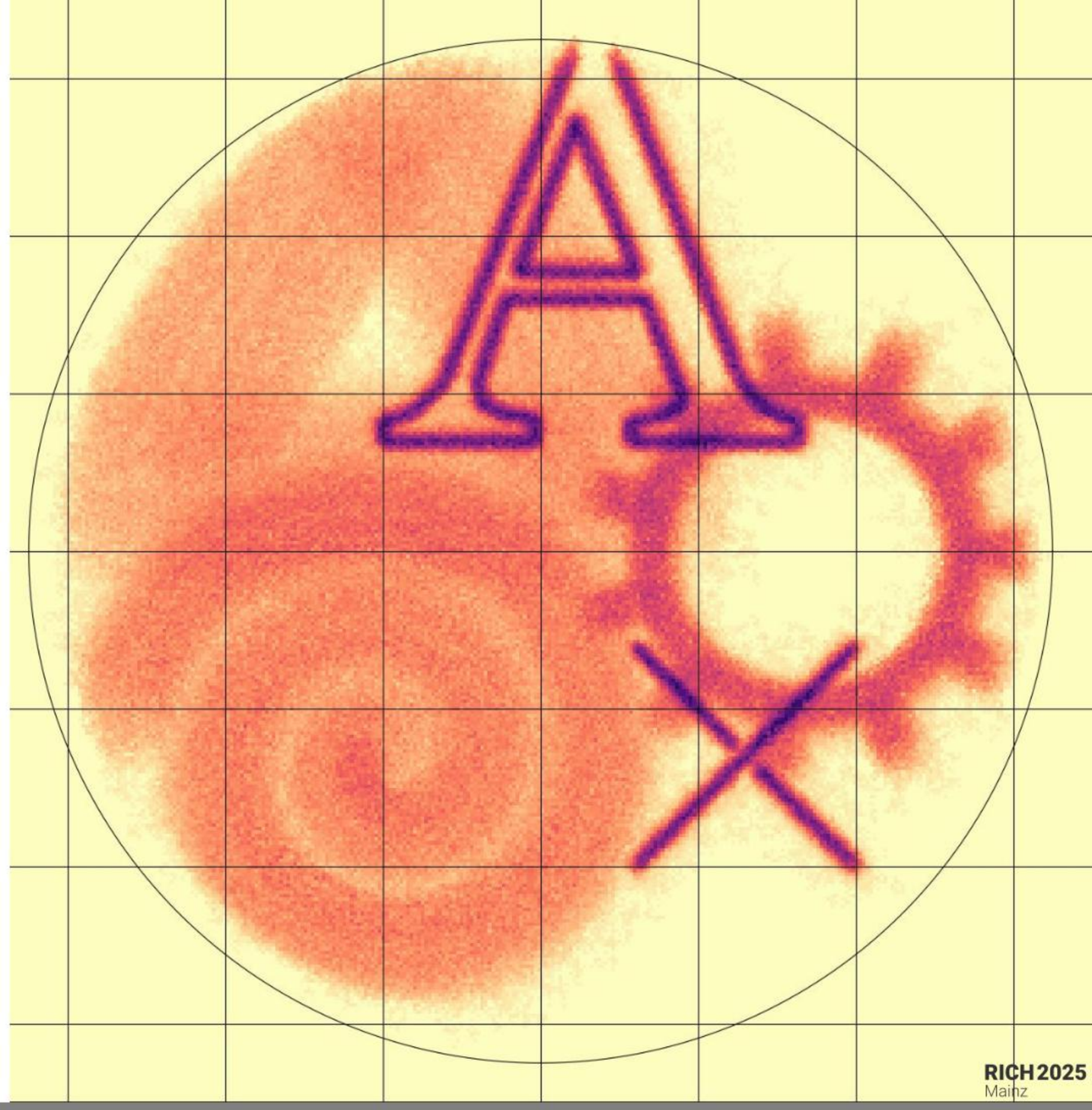


Optics

refocussing to any depth

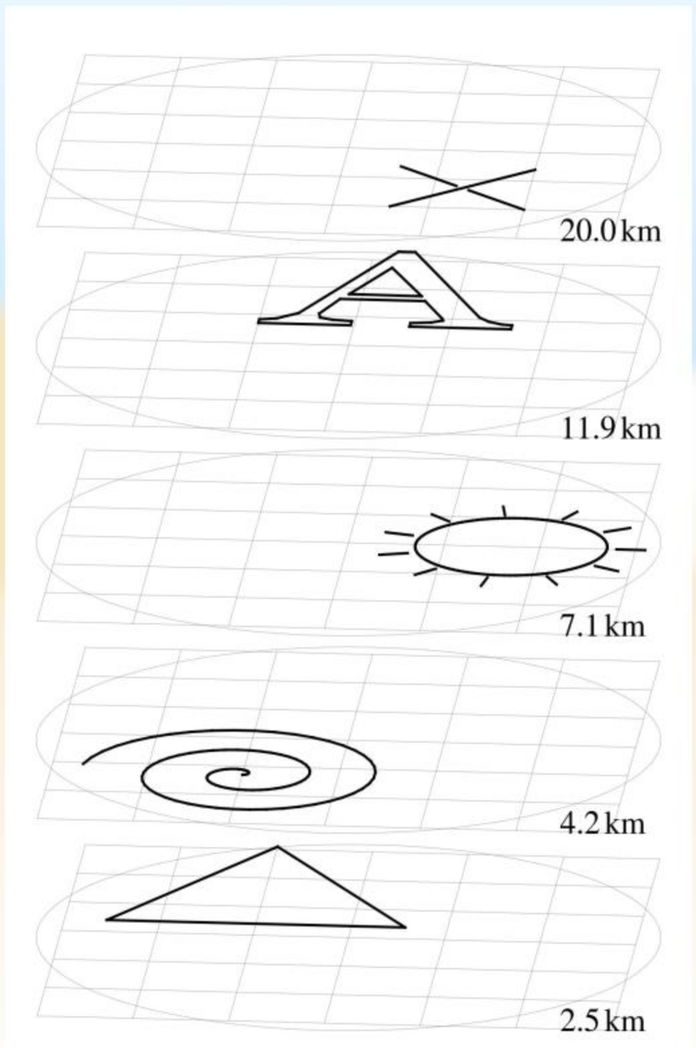


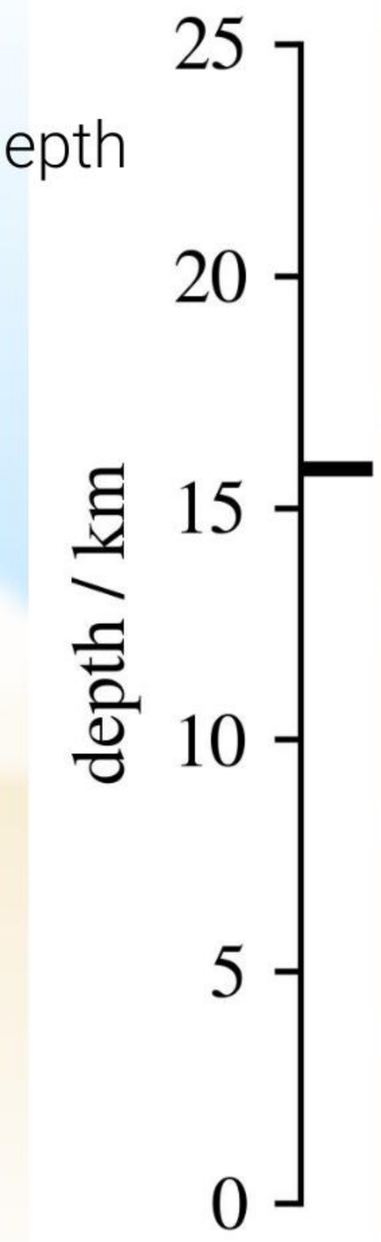


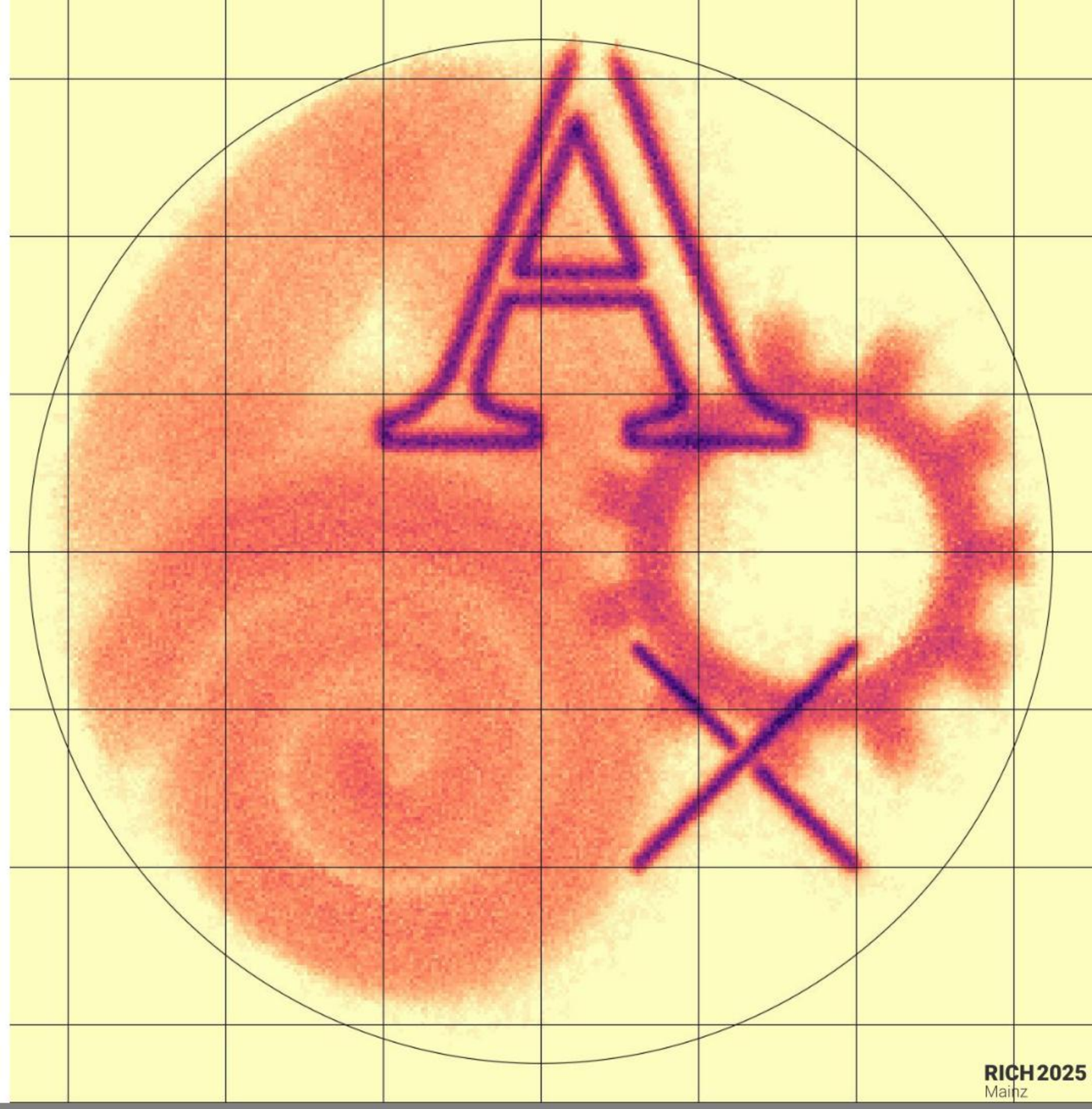


Optics

refocussing to any depth

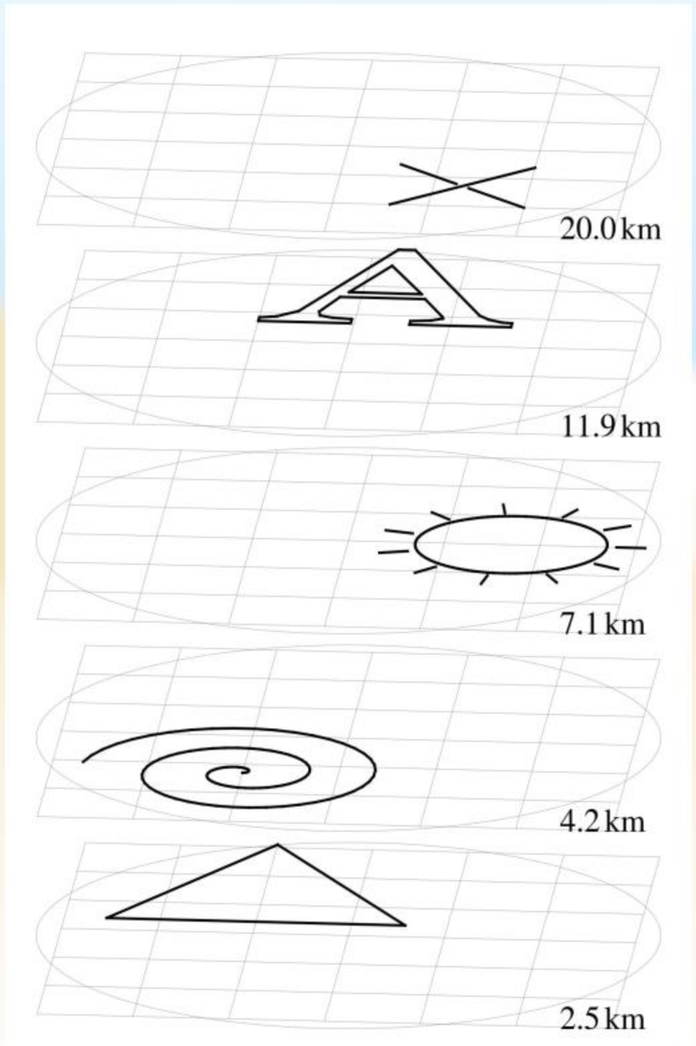


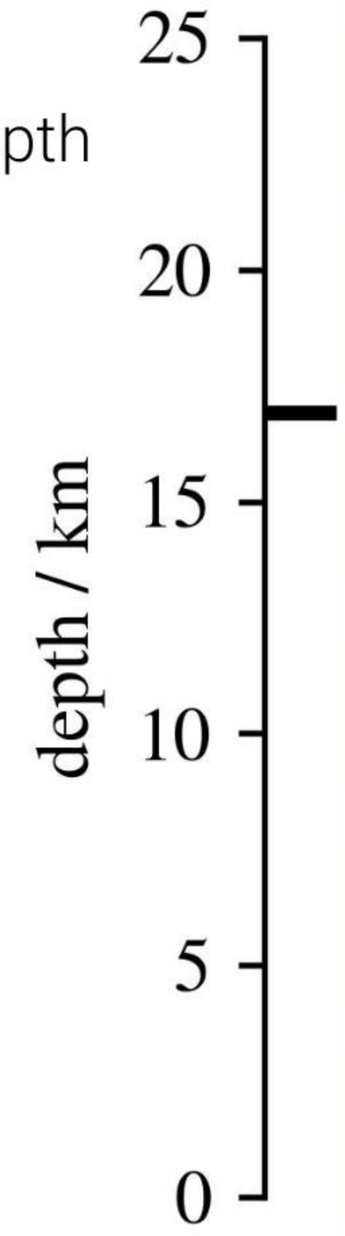


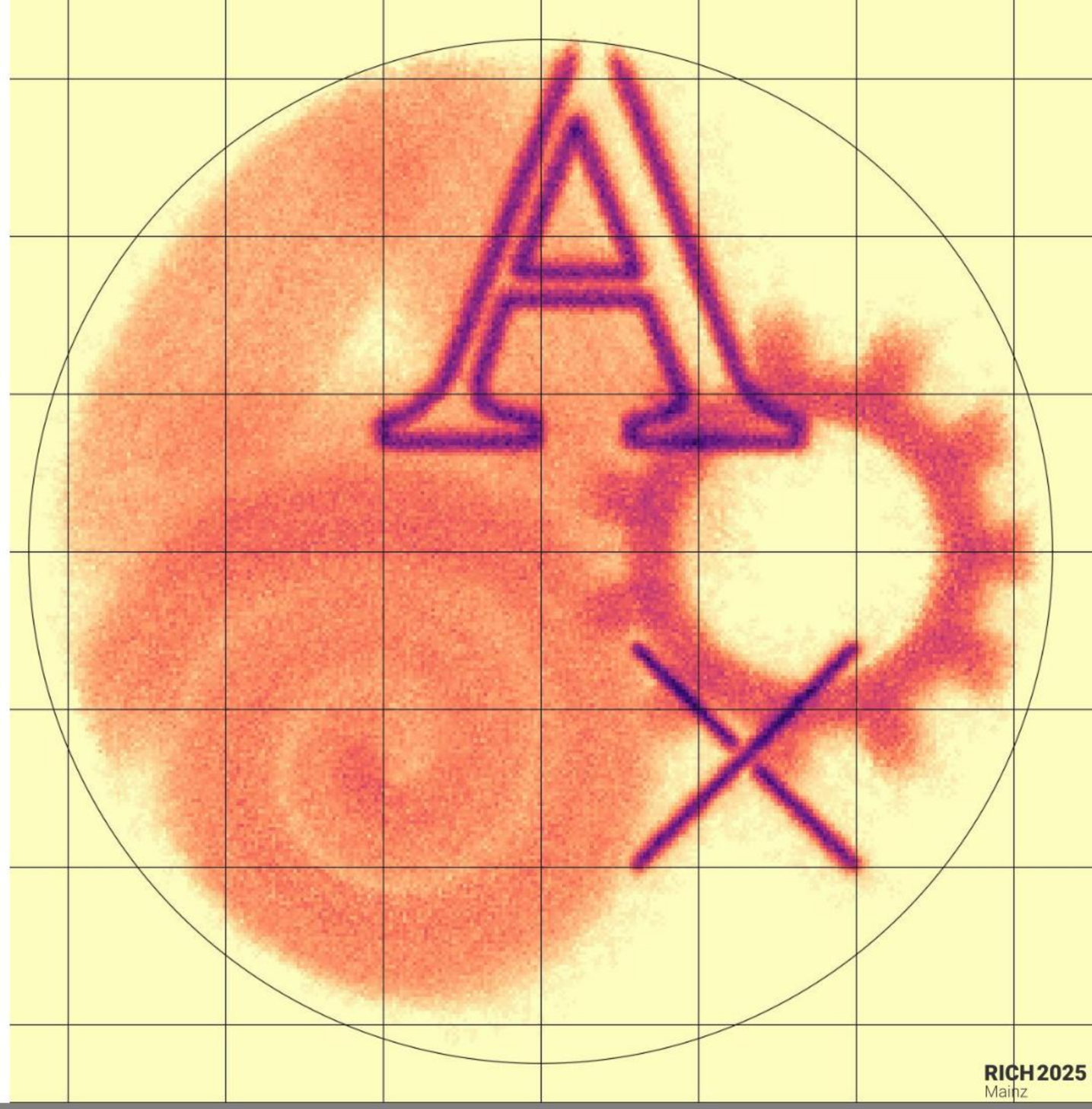


Optics

refocussing to any depth



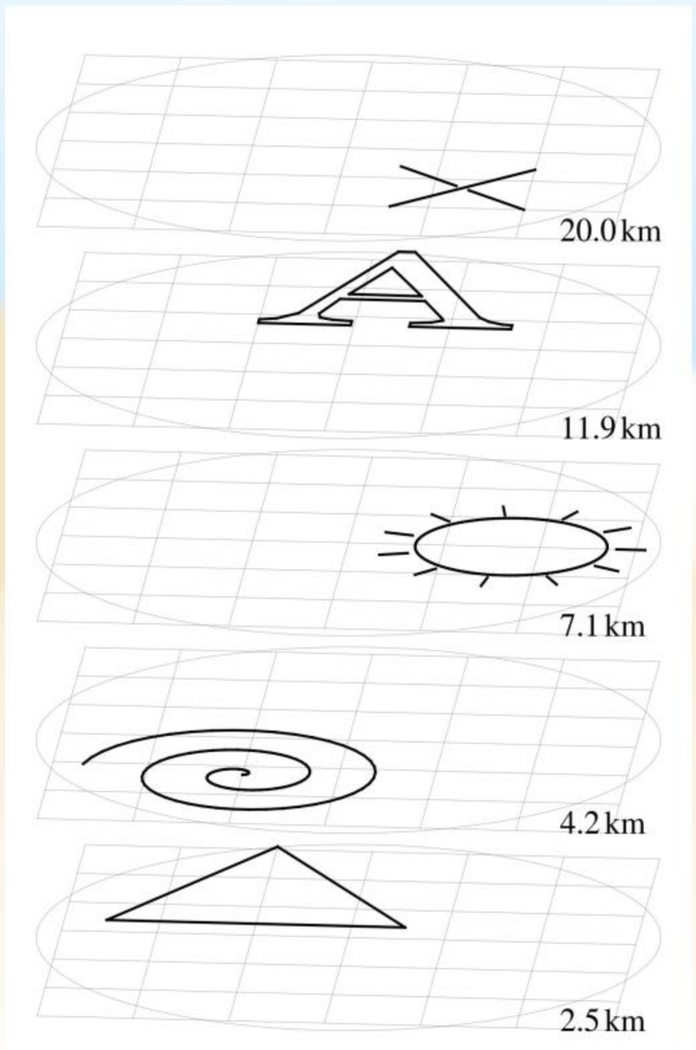


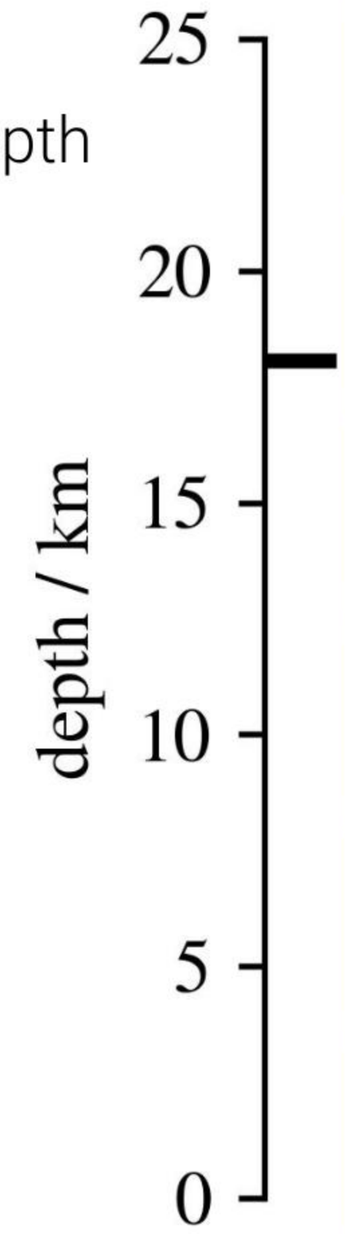


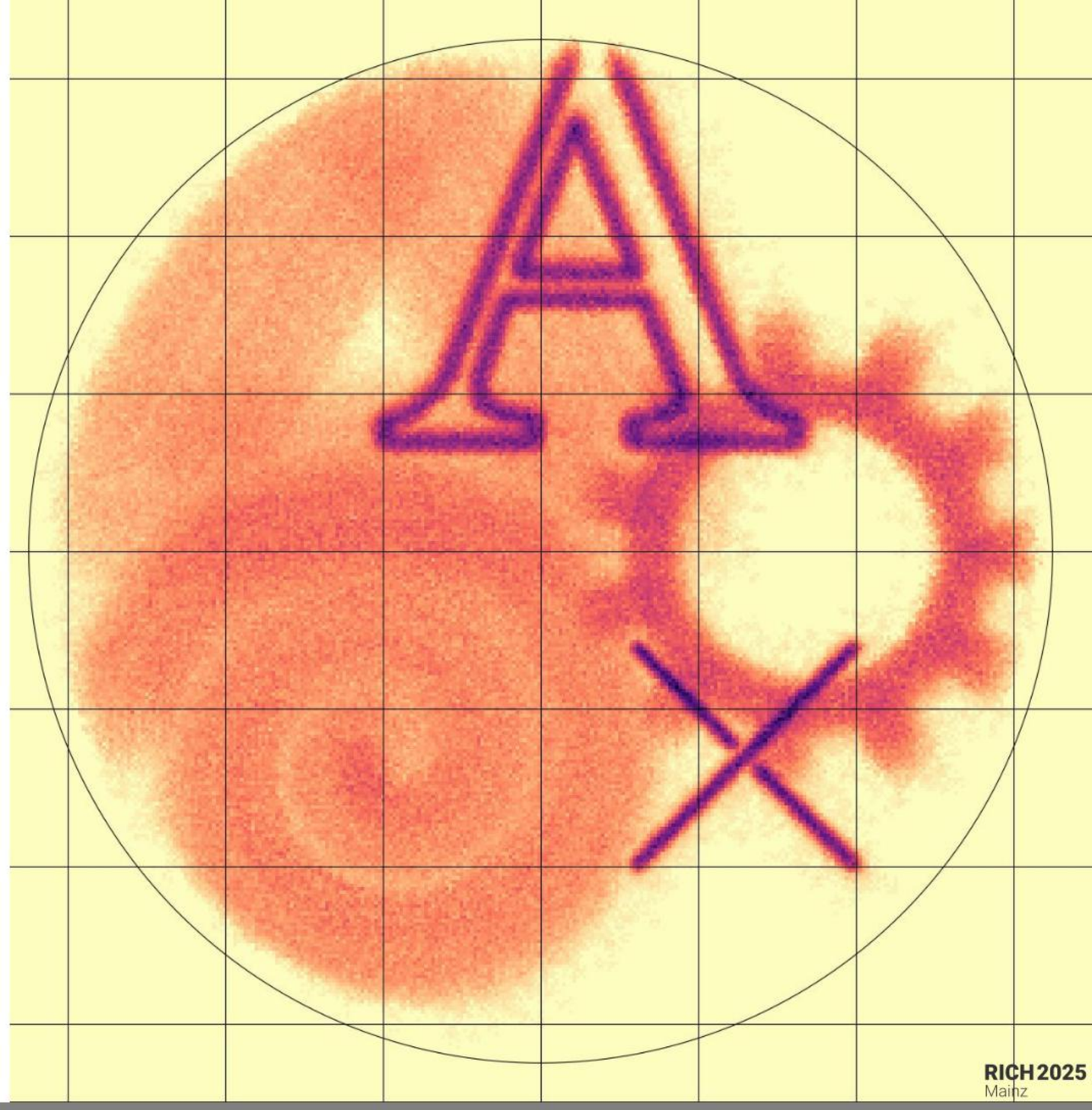
And finally, at about twenty kilometers we find the cross.

Optics

refocussing to any depth

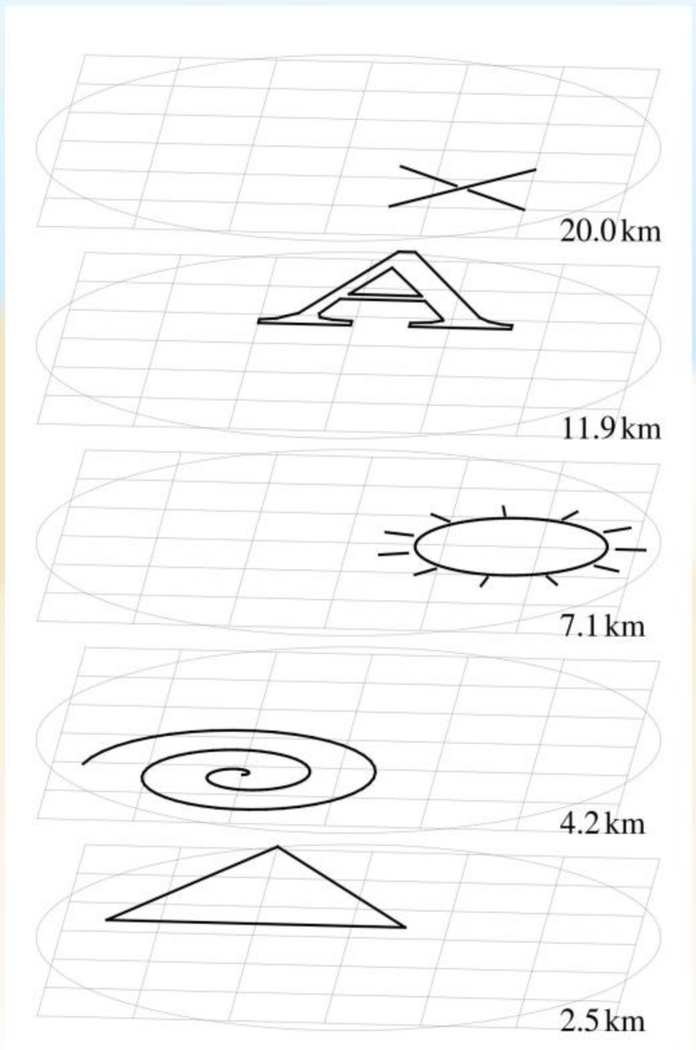


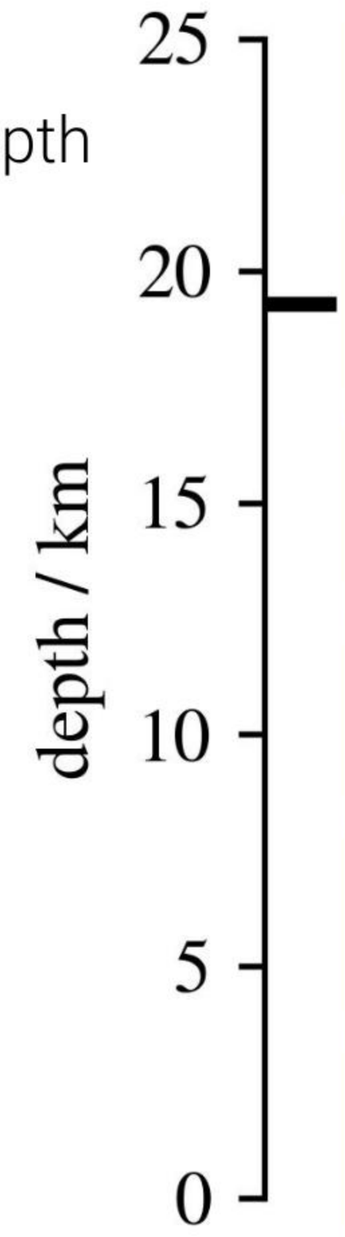


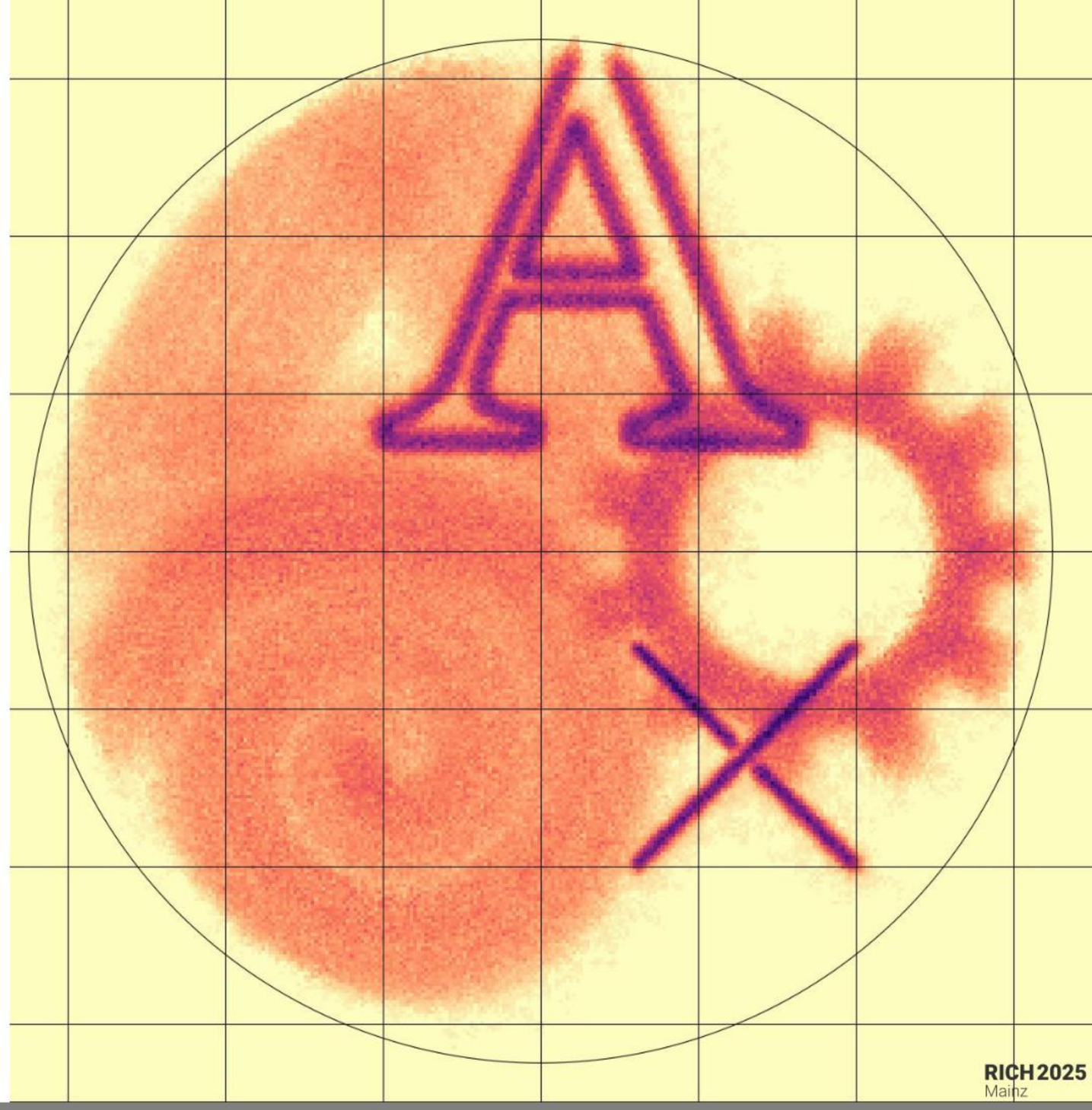


Optics

refocussing to any depth



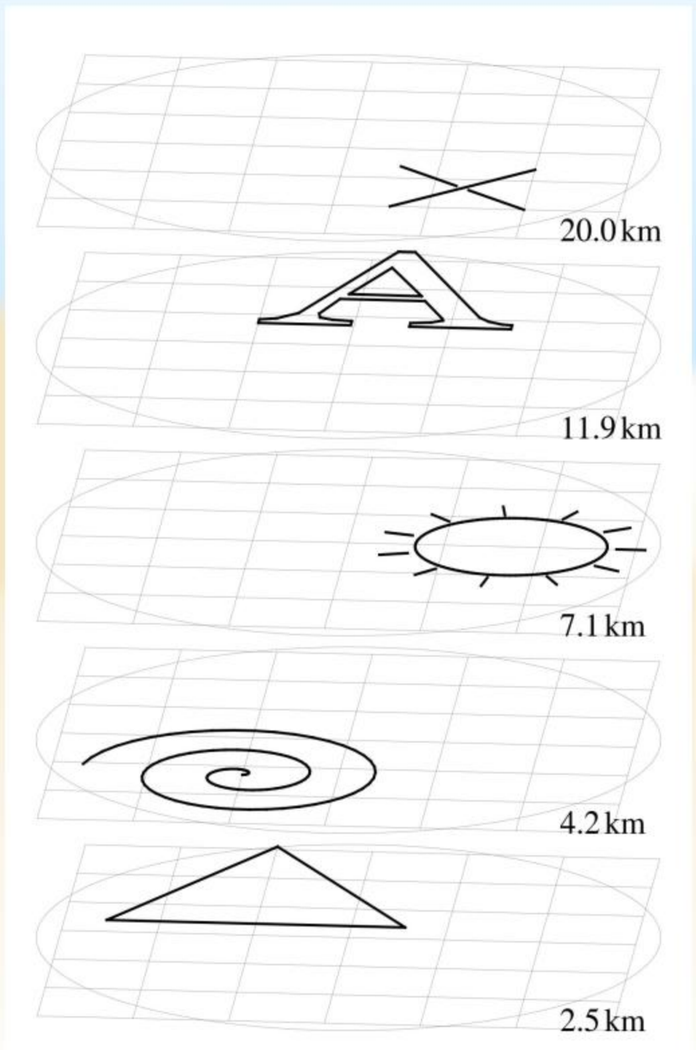


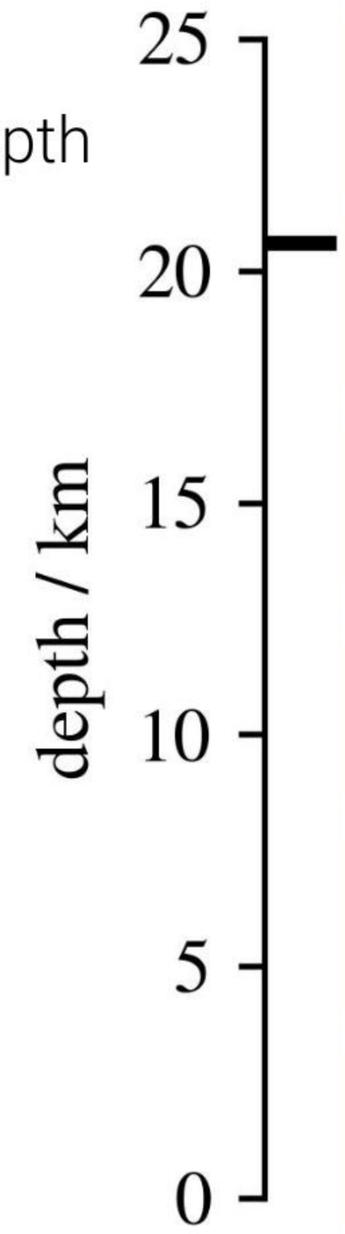


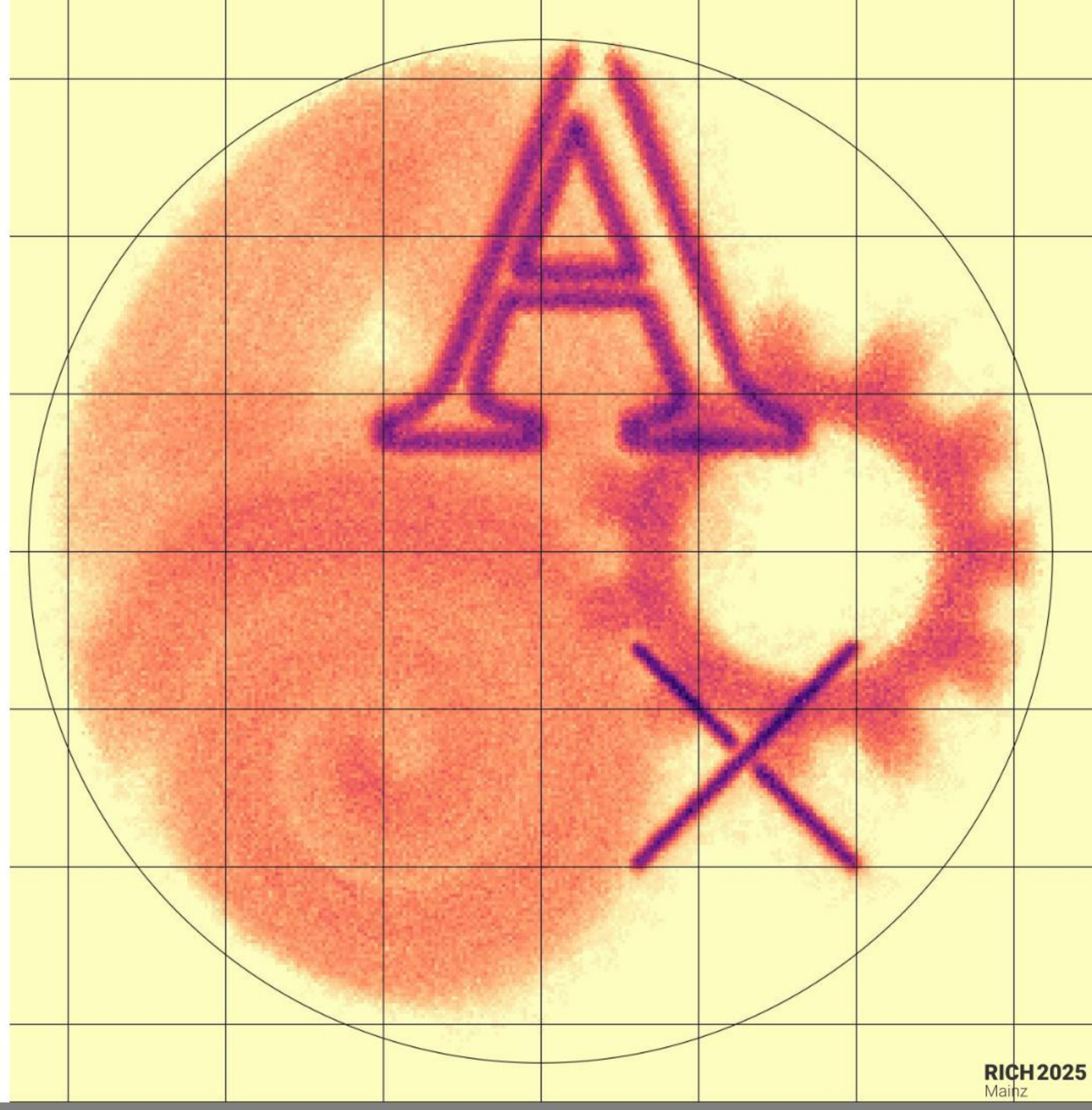
Now wait a moment. I told you the triangle will be important later on. But where is the triangle gone? The triangle is blurred beyond recognition. If this image was recorded by a telescope, you would not have known that there was a triangle. This is what the physical limit of a narrow depth-of-field is all about.

Optics

refocussing to any depth

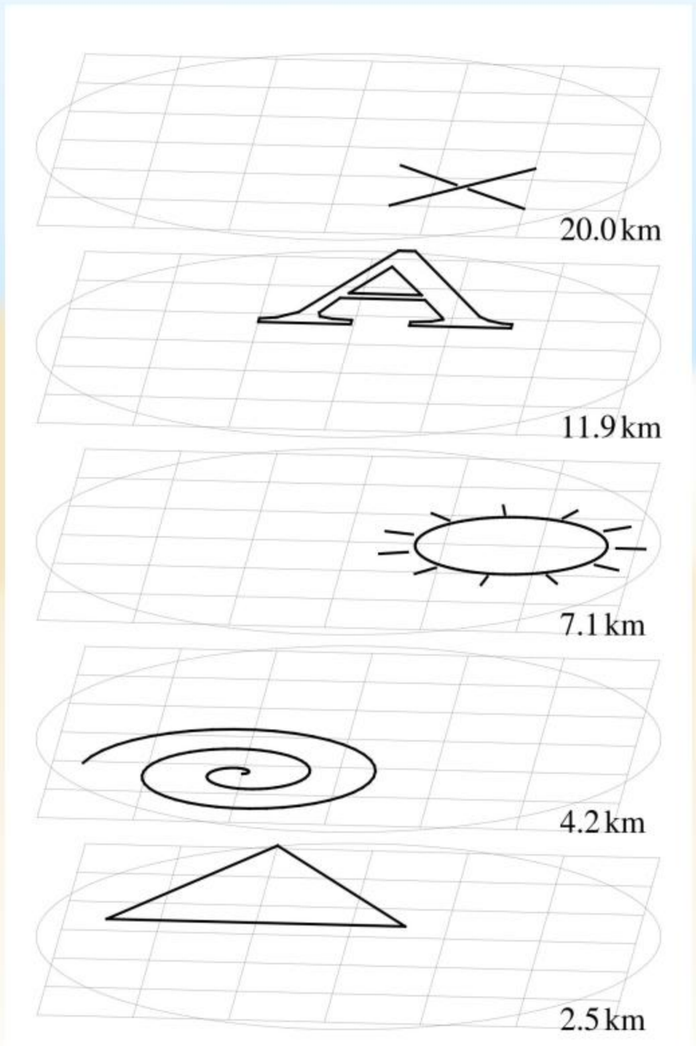


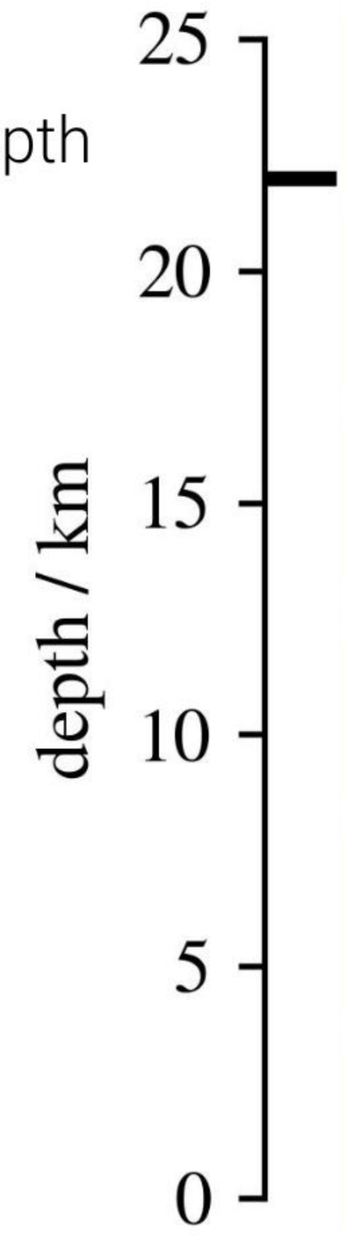


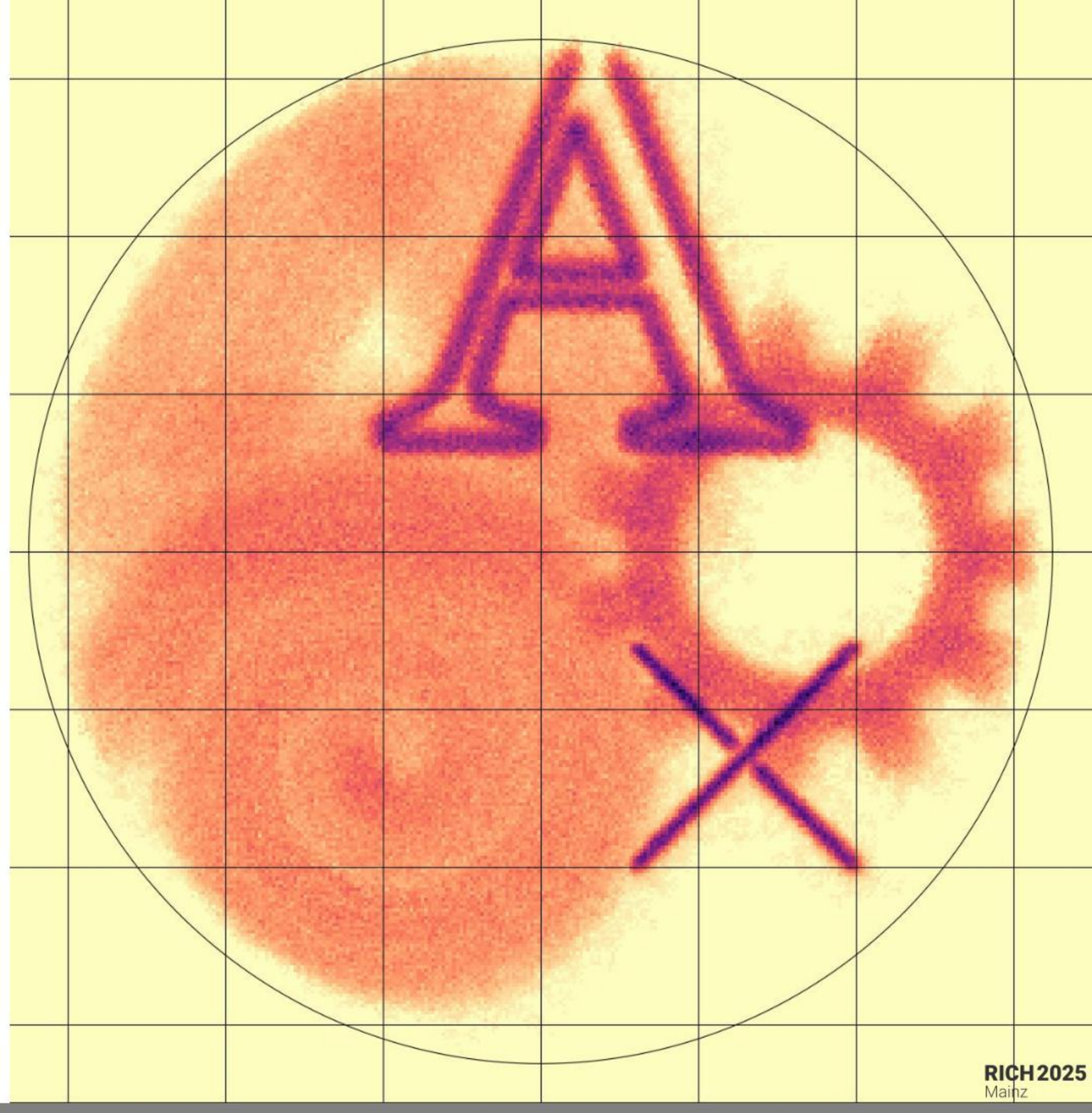


Optics

refocussing to any depth

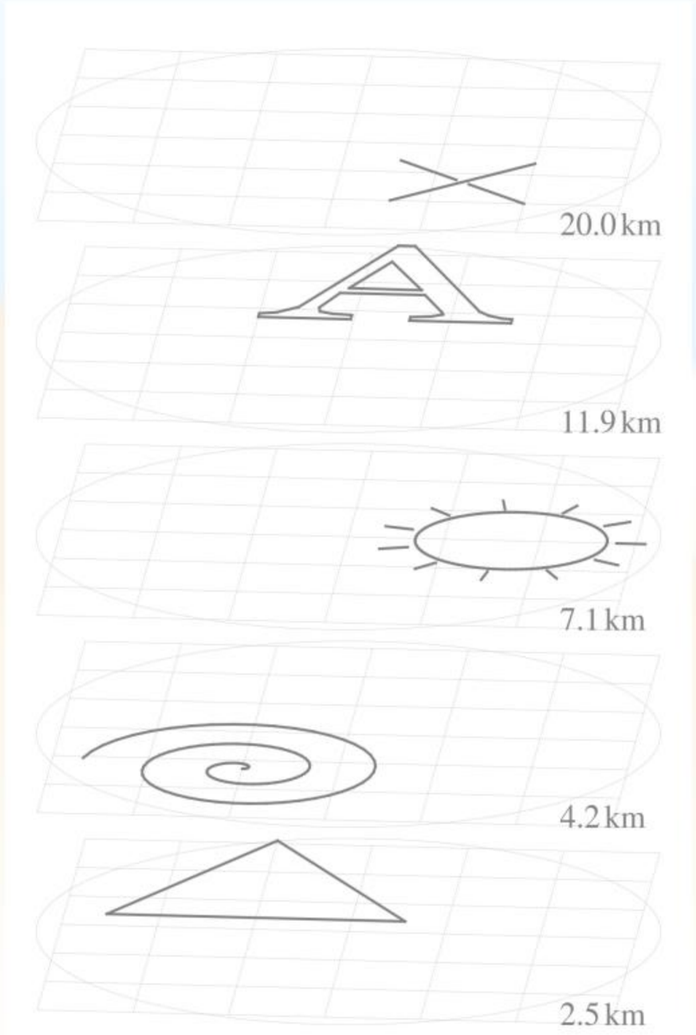


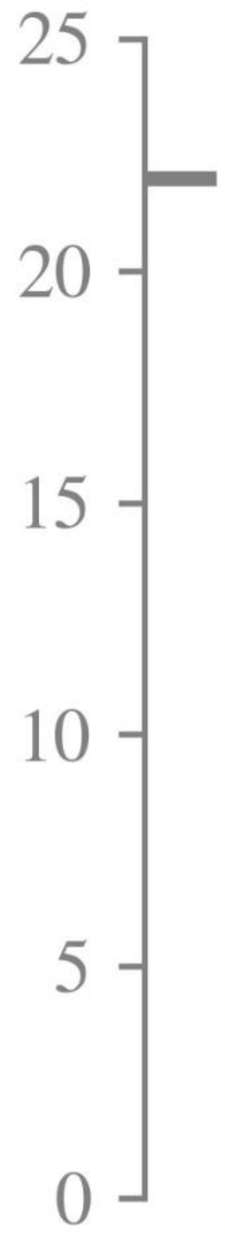


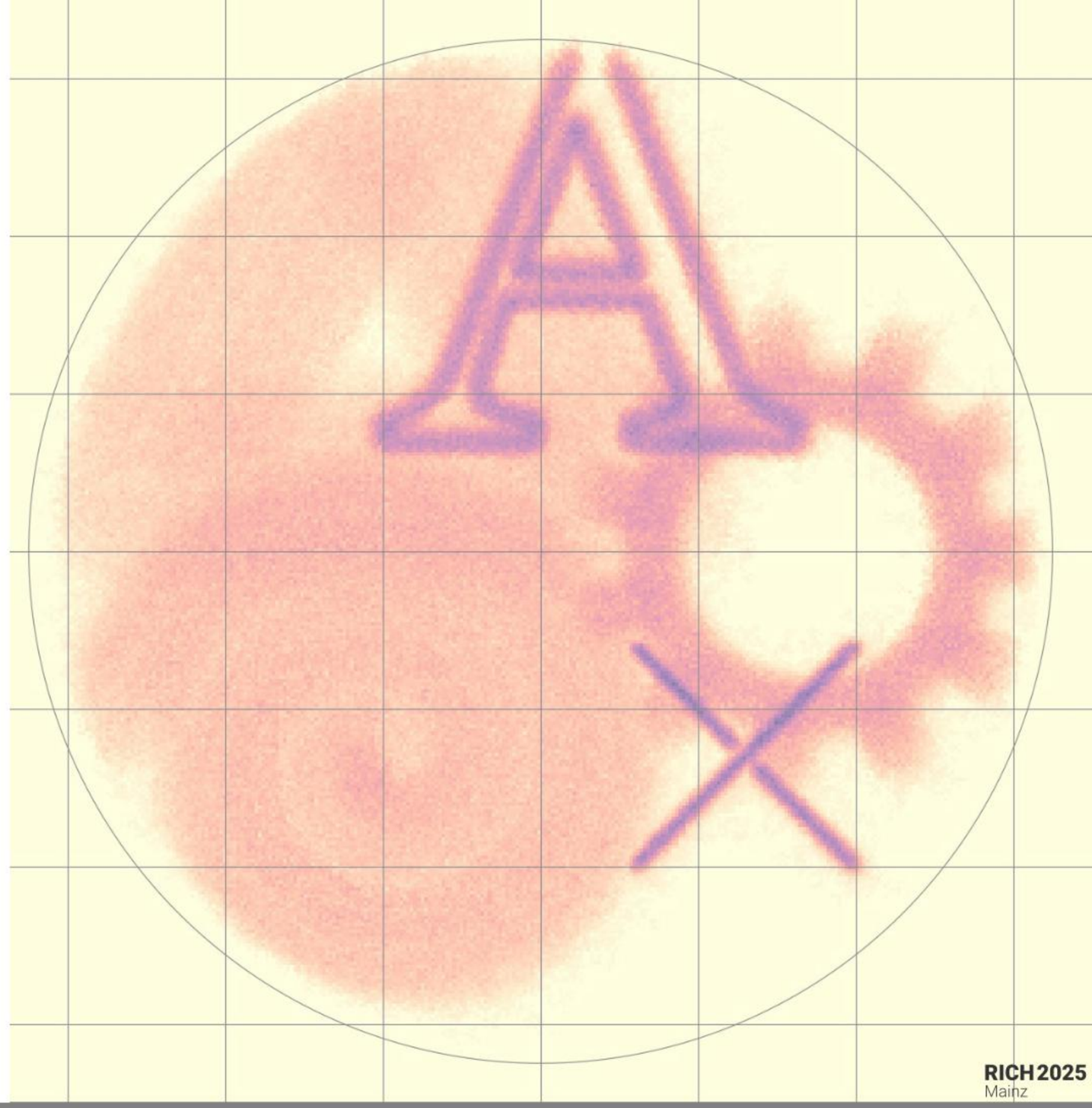


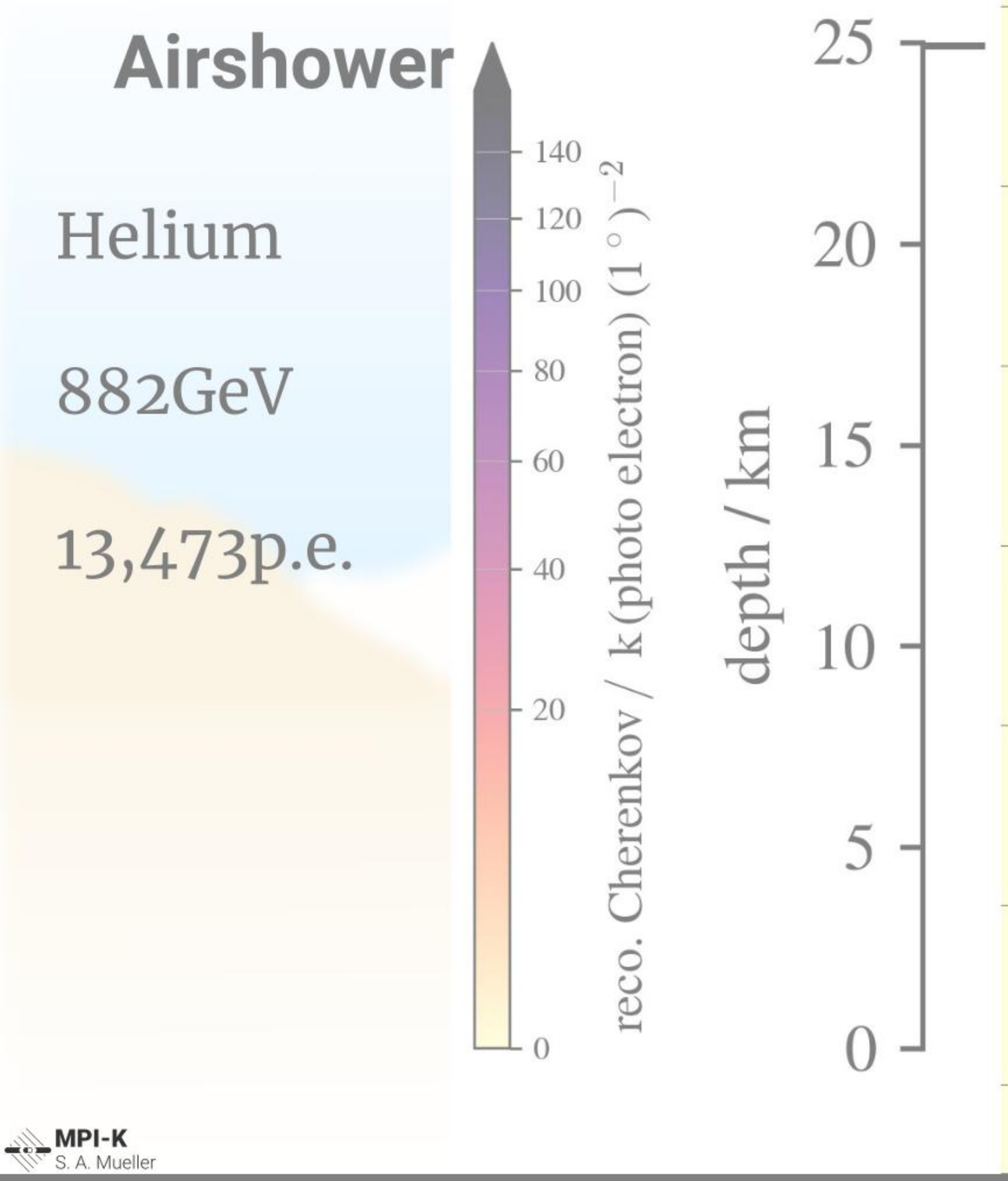
Optics

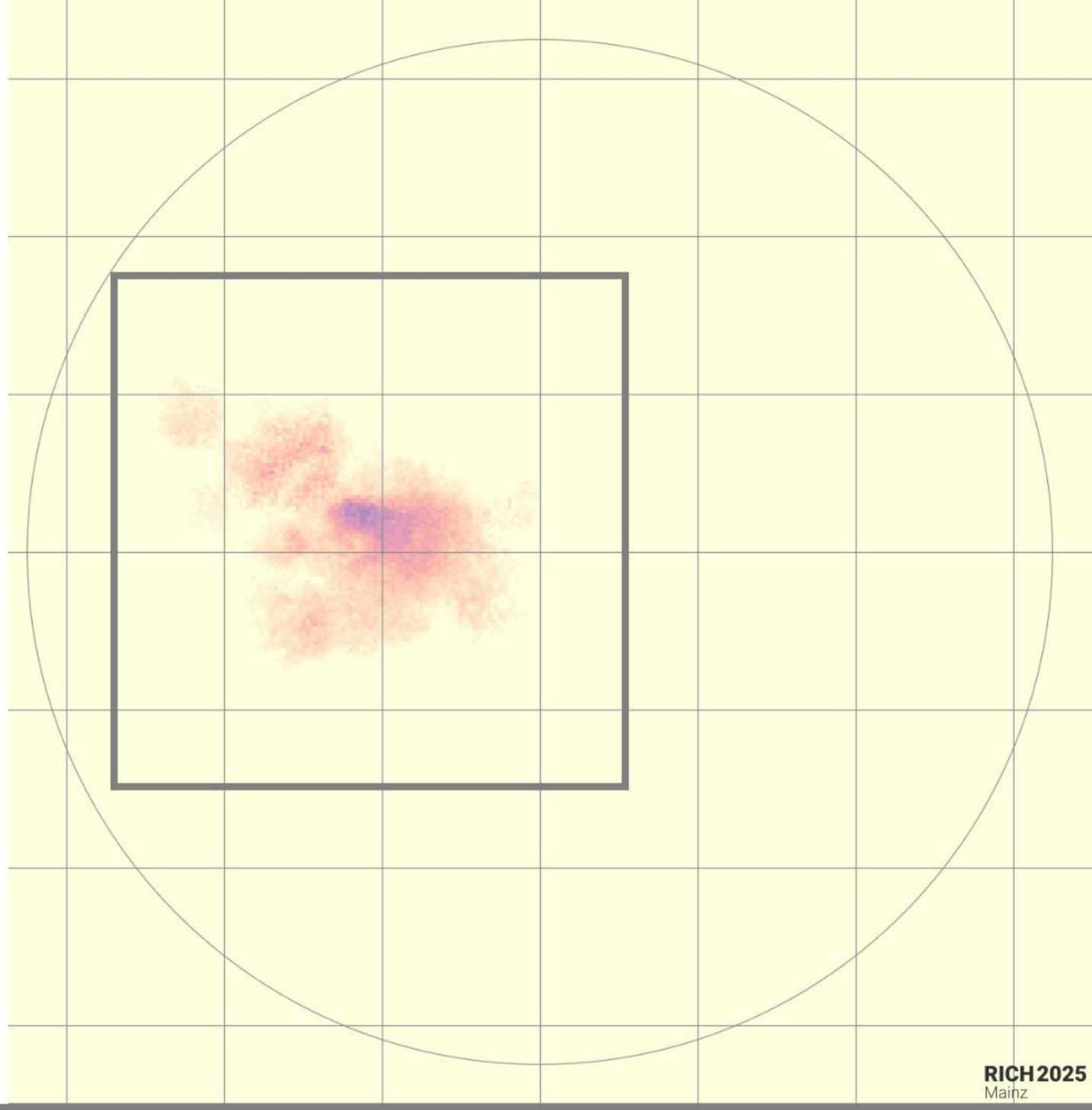
refocussing to any depth



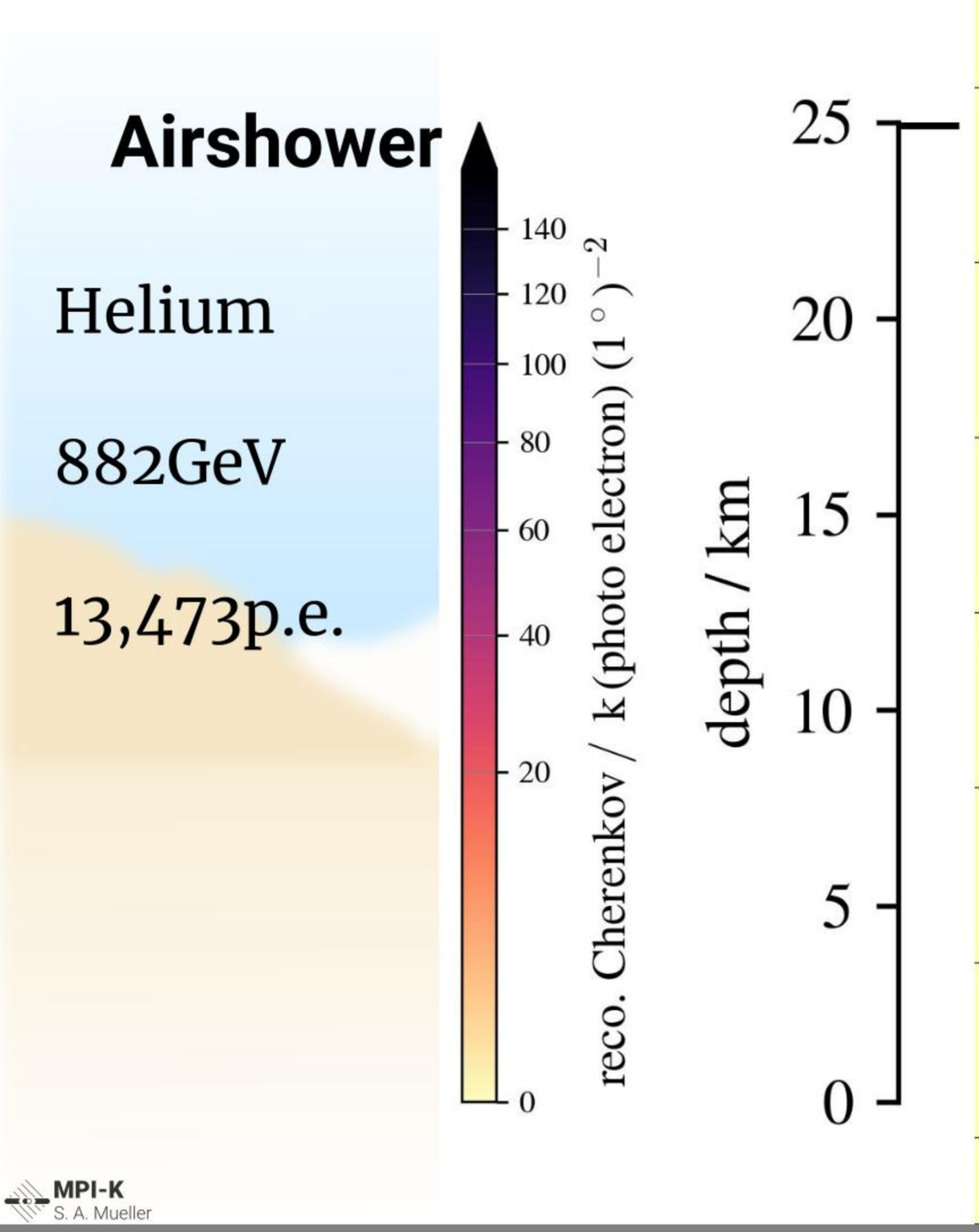


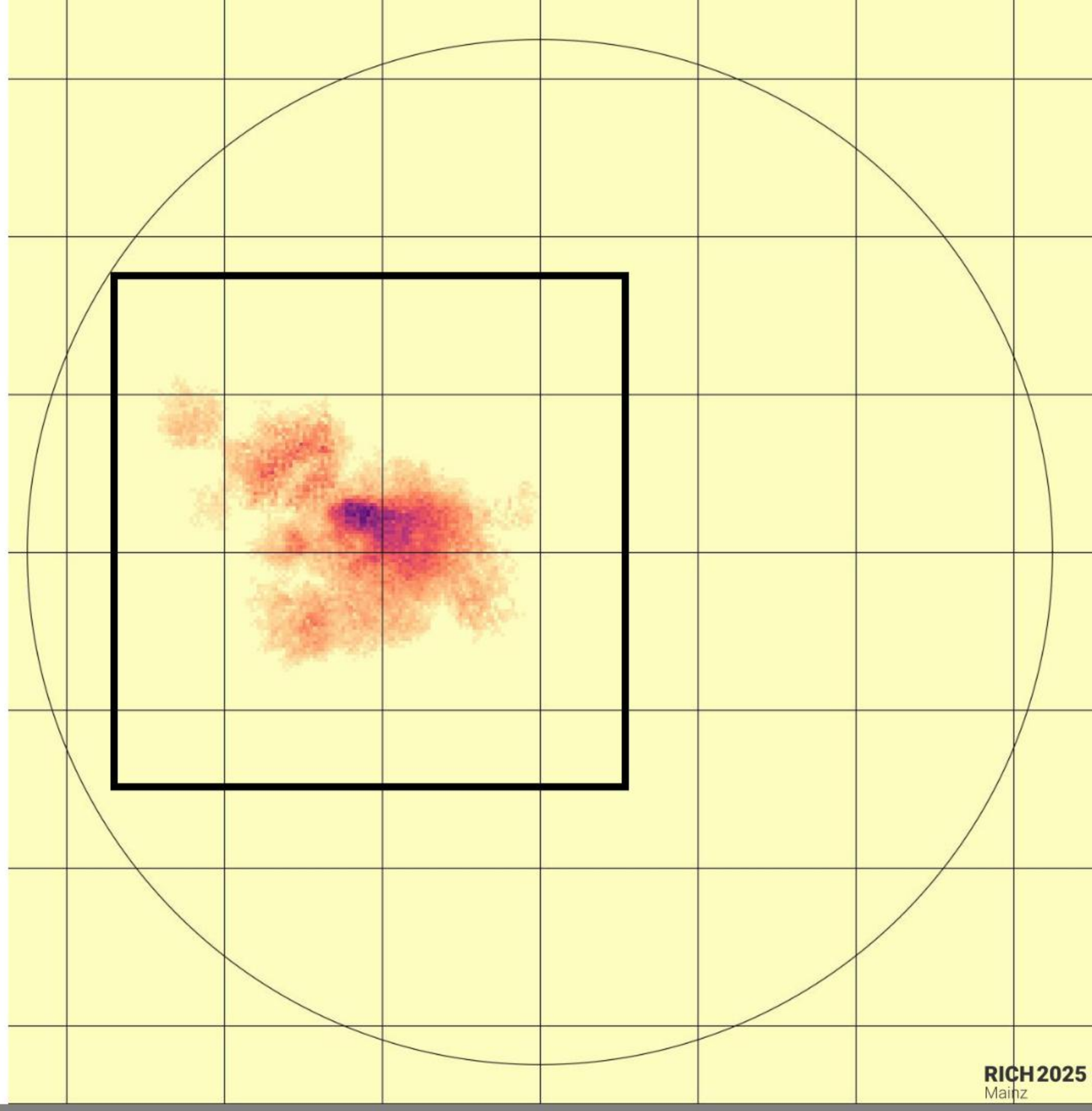




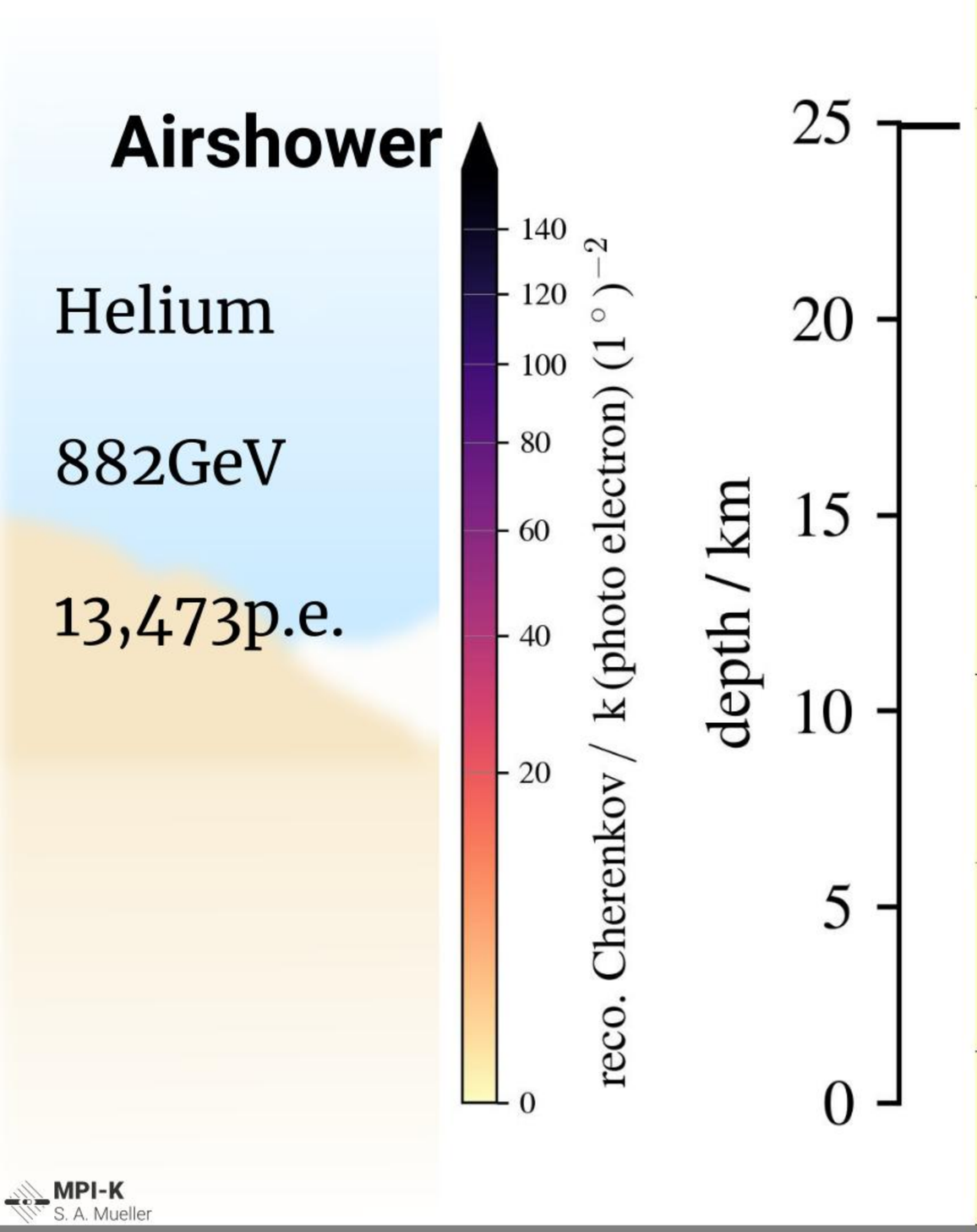


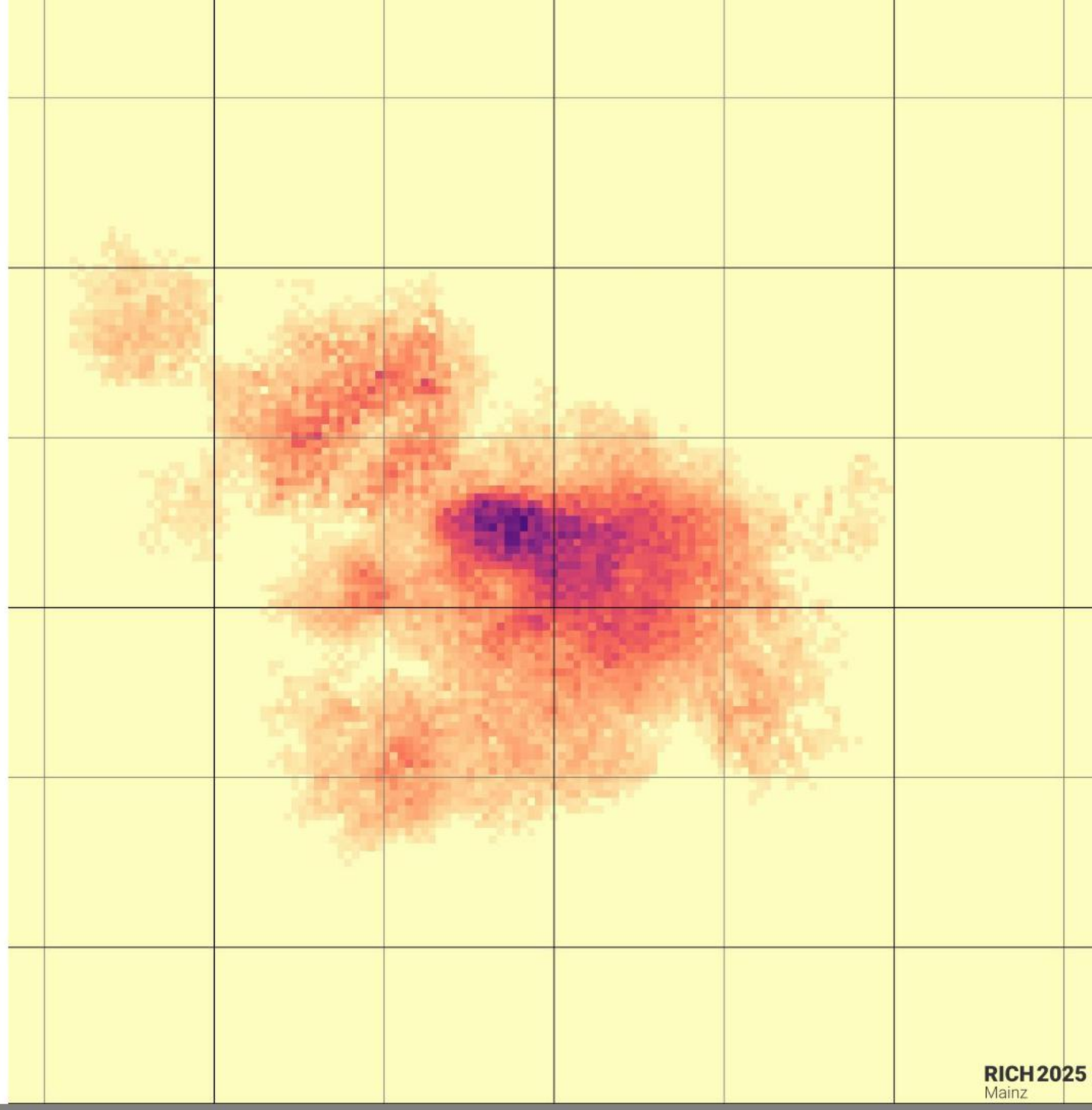
Now we observe a ninehundred GeV helium airshower.





We will zoom in onto the black square.





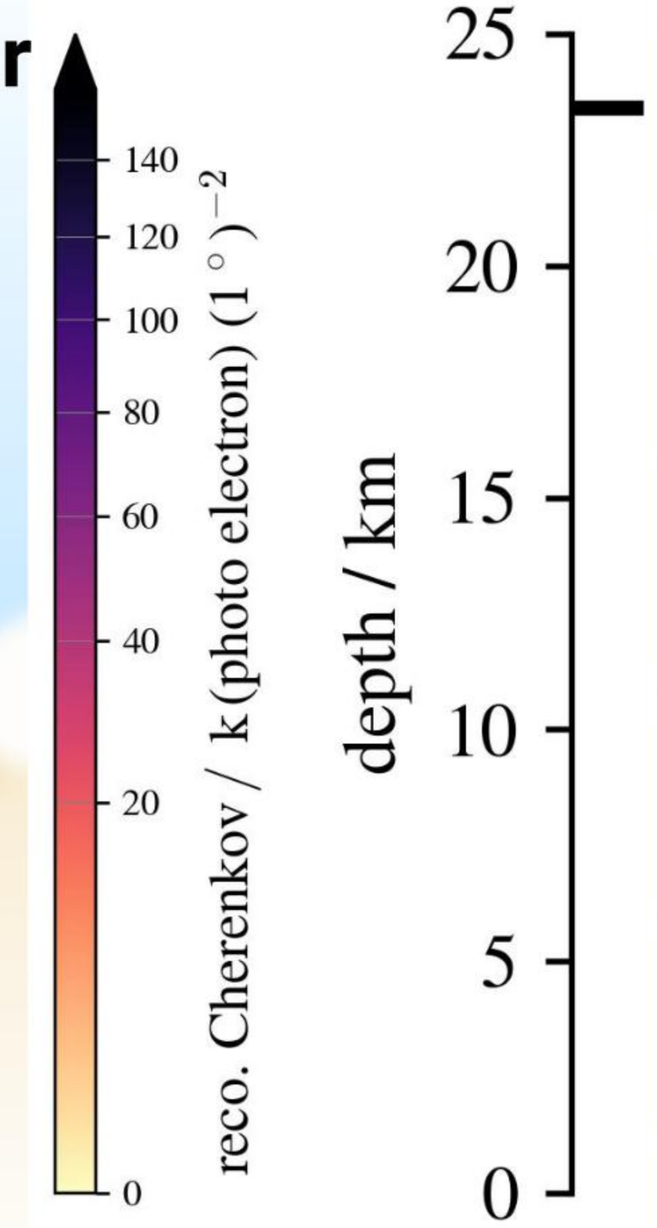
The plenoscope turns the two dimensional `islands' from telescope images into three dimensional jets.

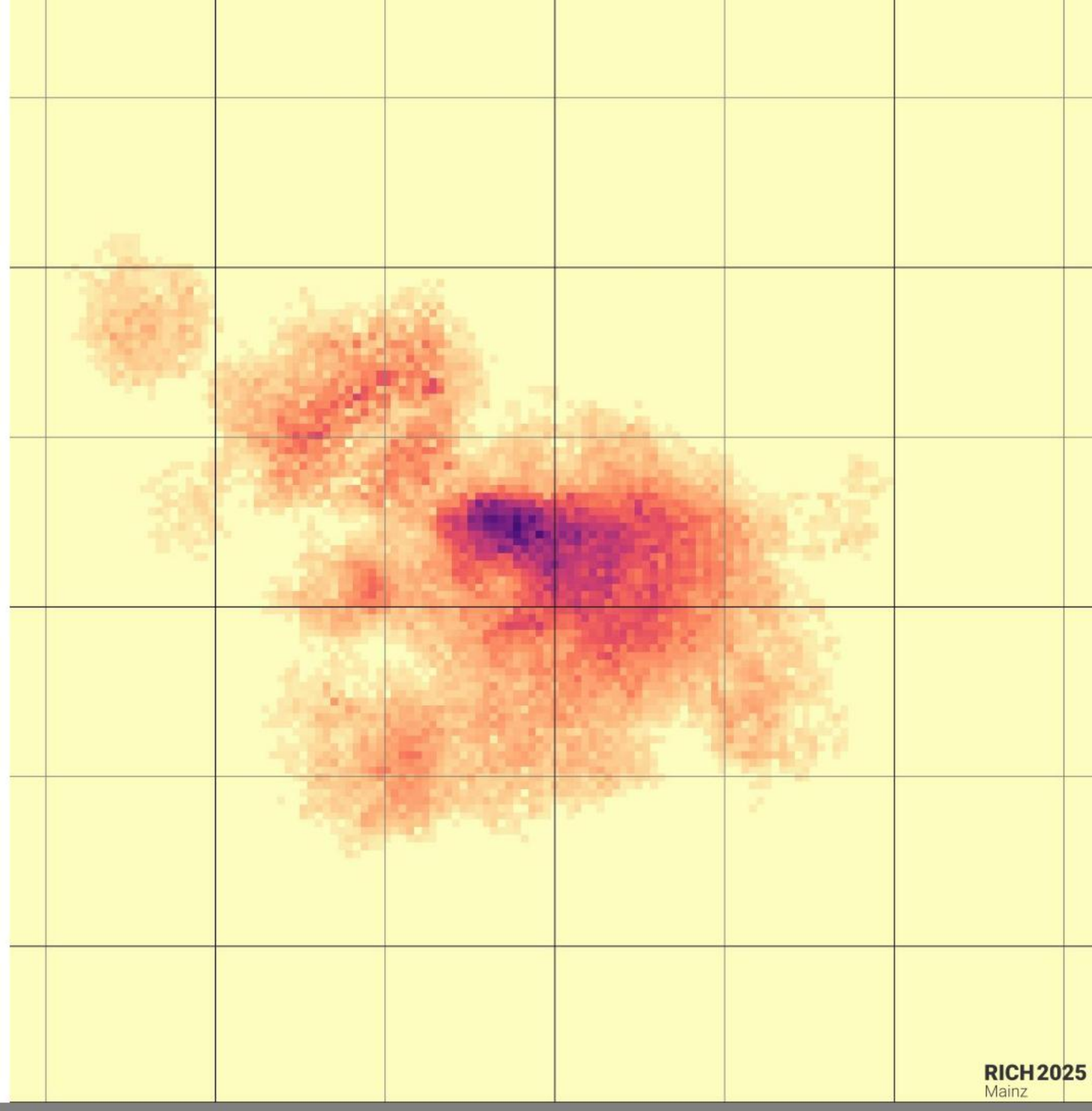
Airshower

Helium

882GeV

13,473p.e.



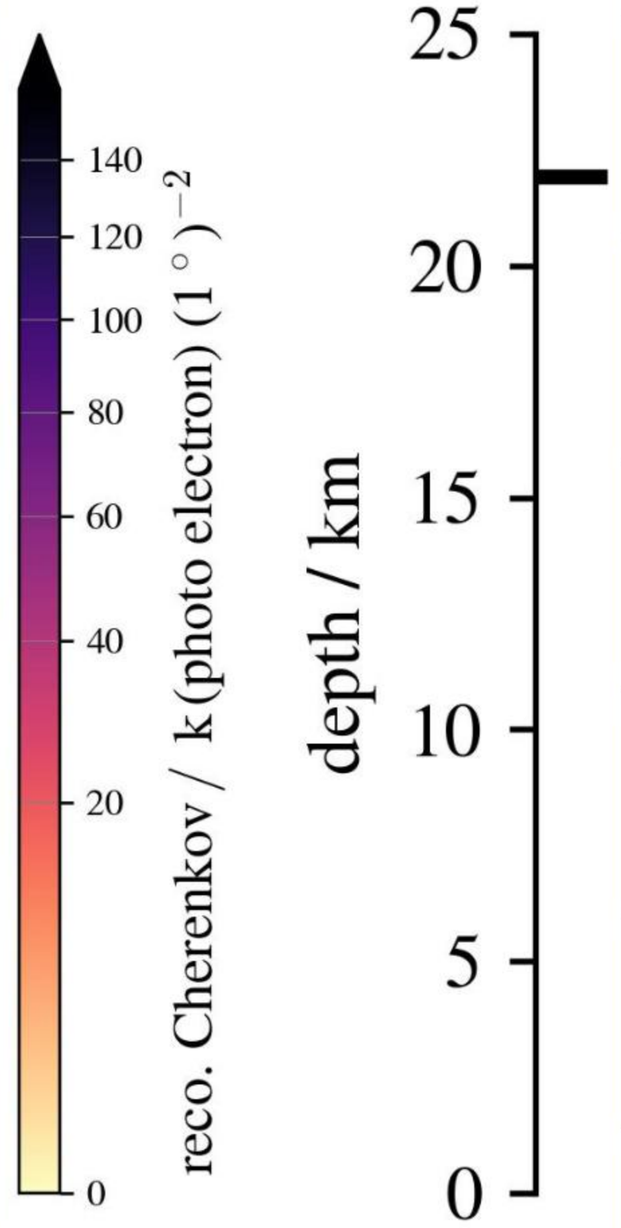


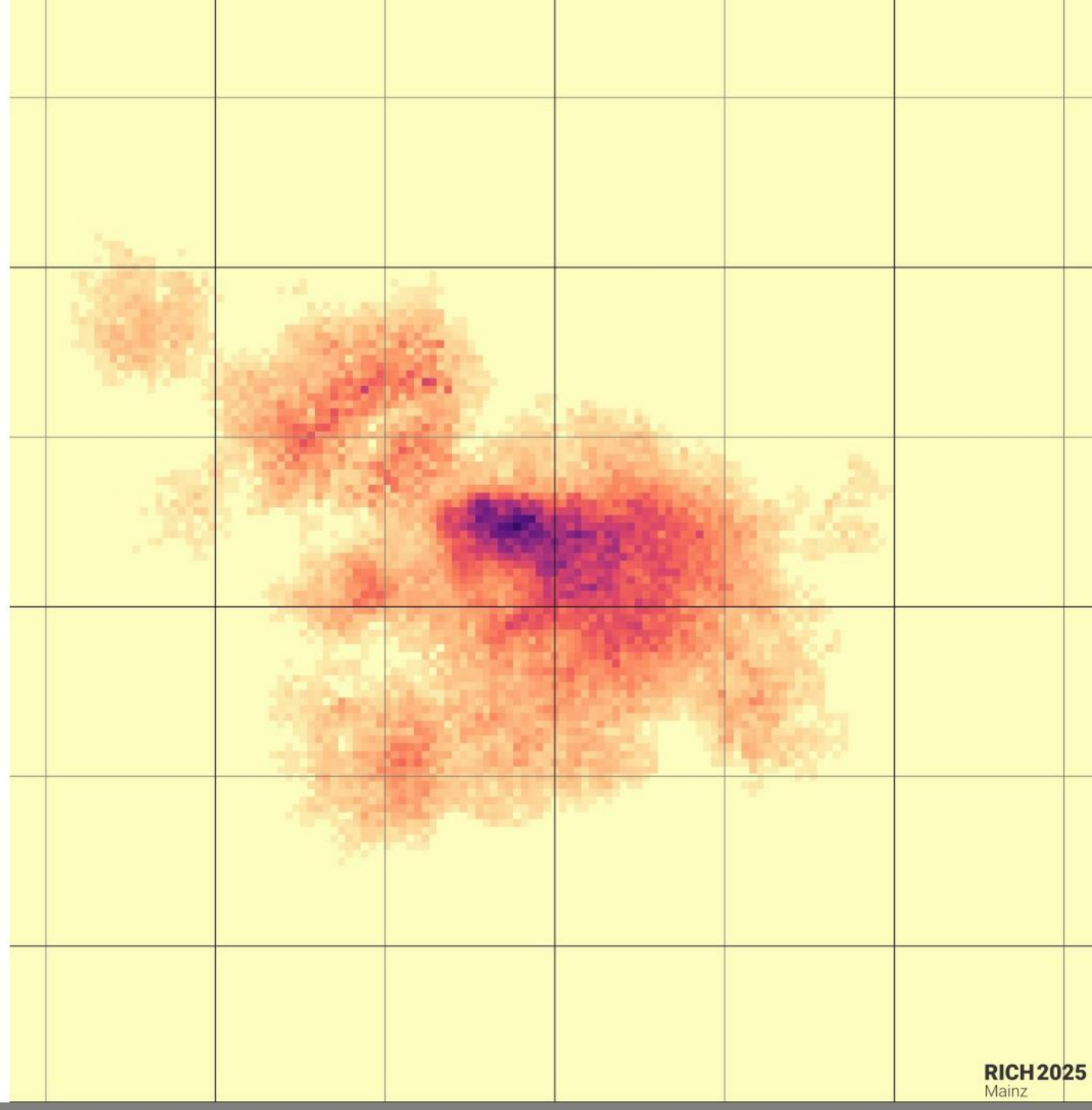
Airshower

Helium

882GeV

13,473p.e.



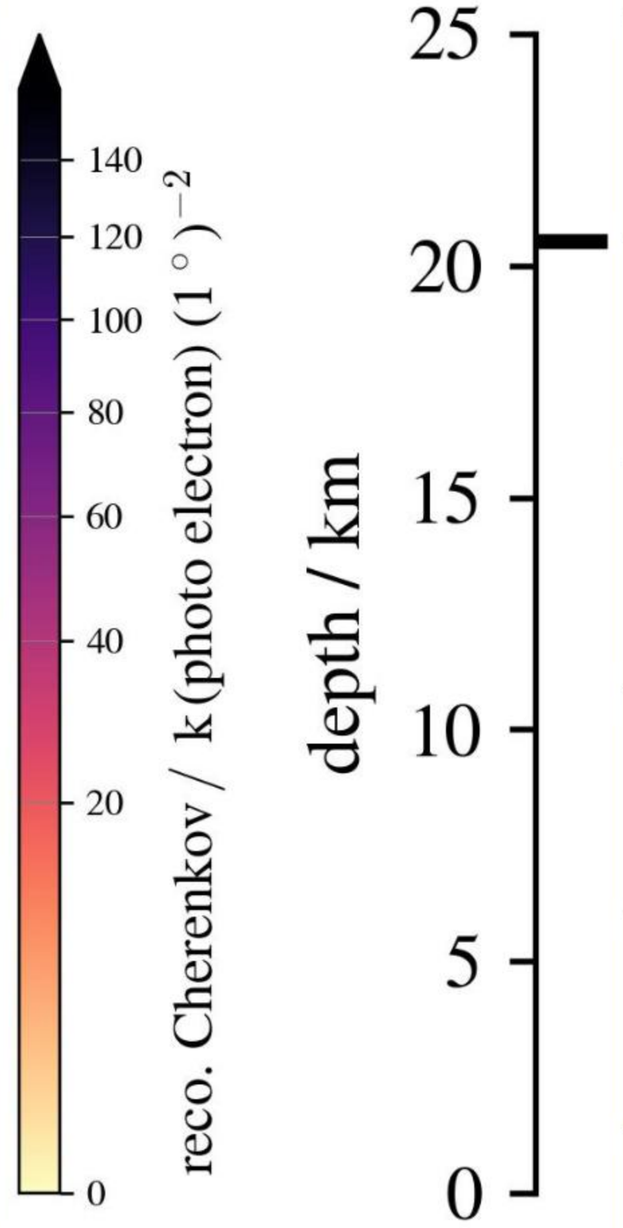


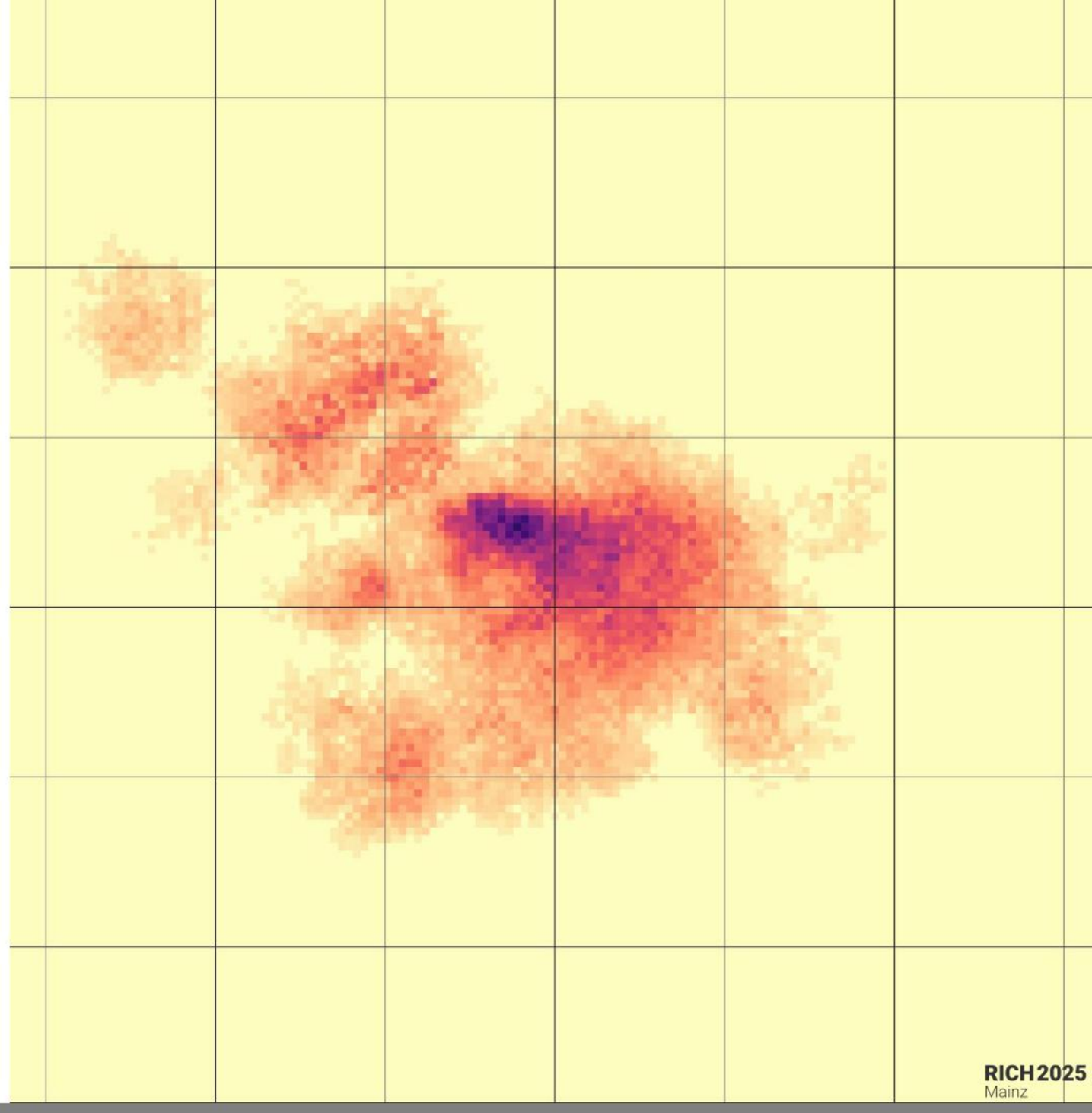
Airshower

Helium

882GeV

13,473p.e.



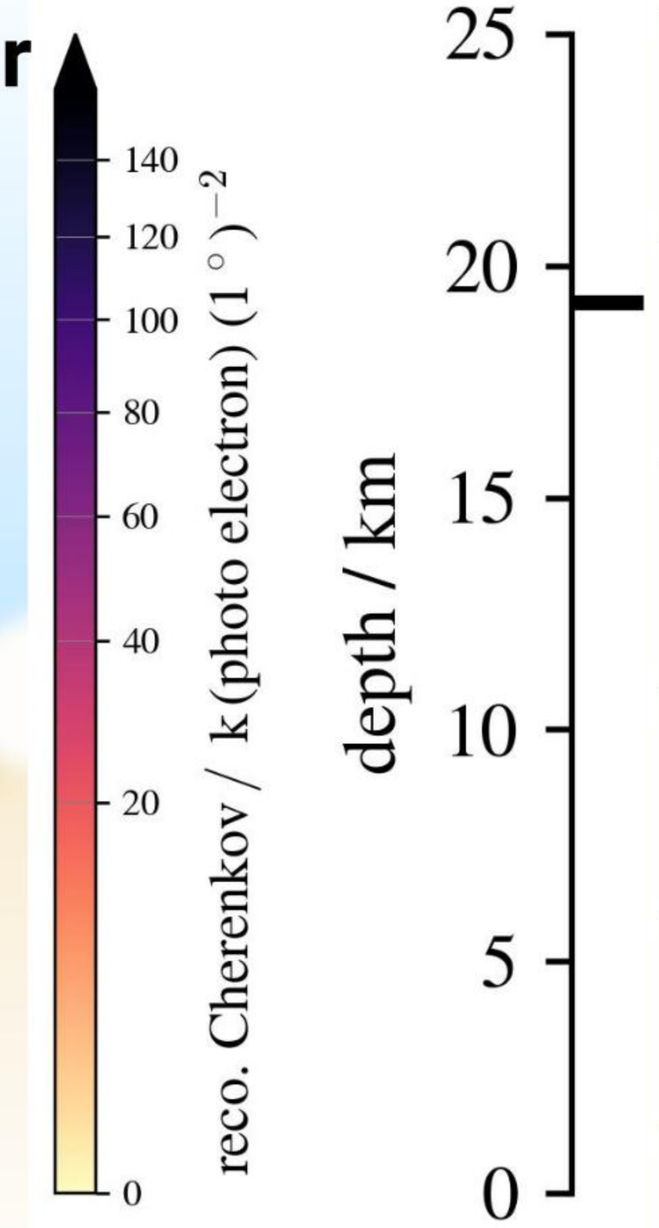


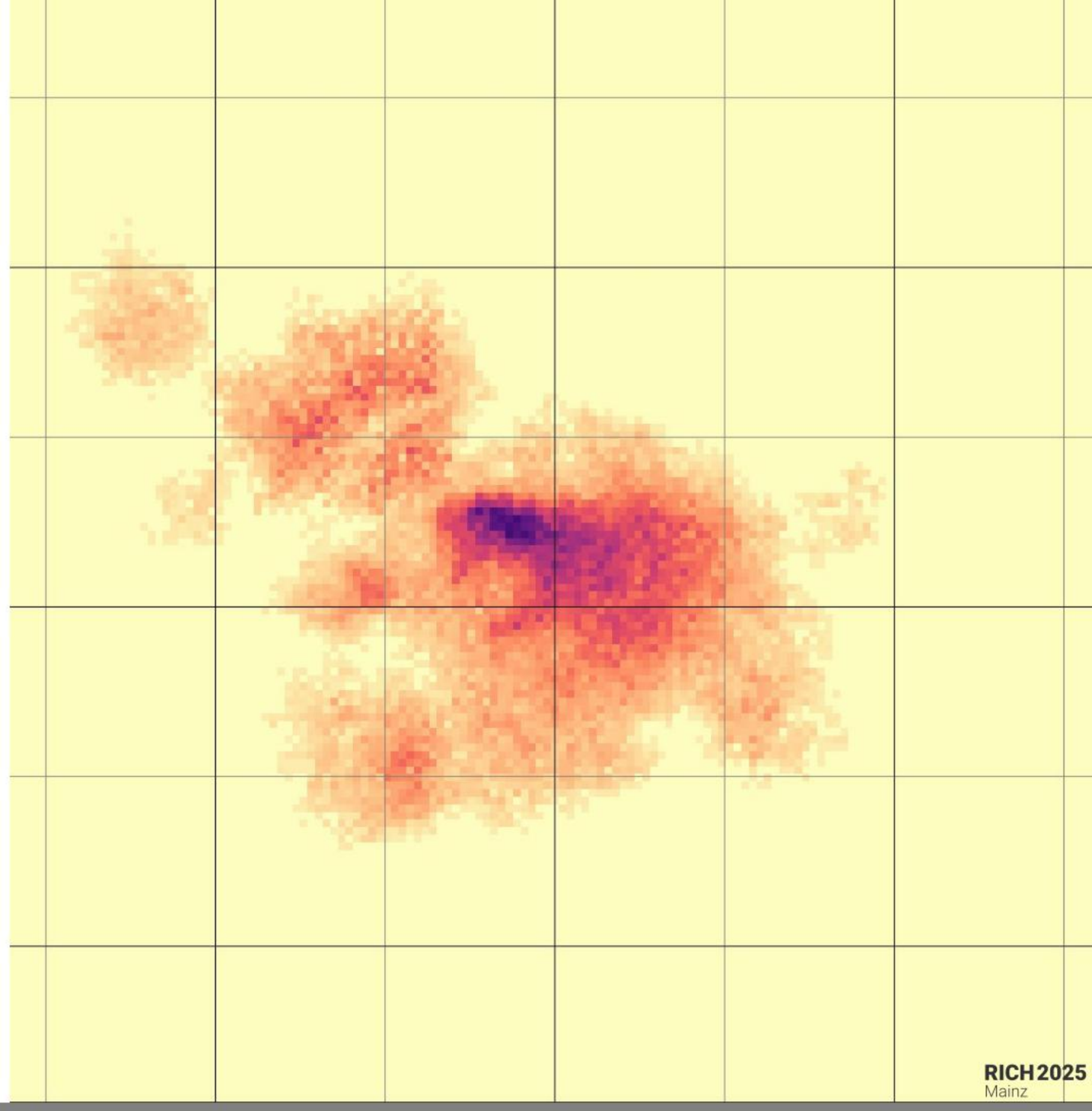
Airshower

Helium

882GeV

13,473p.e.



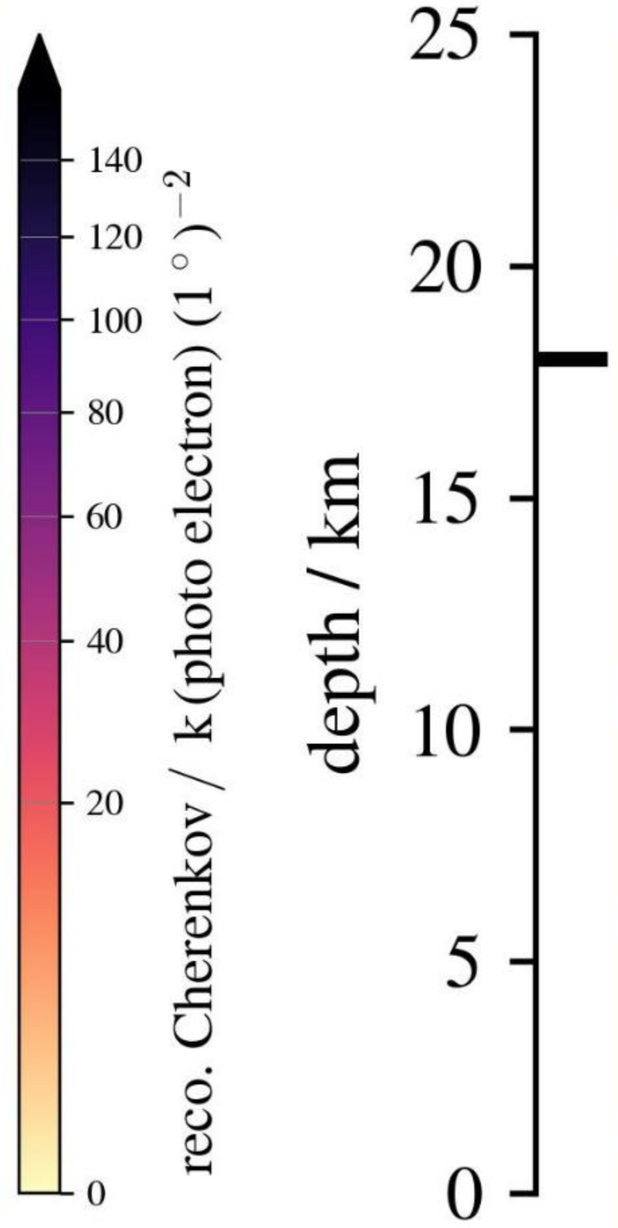


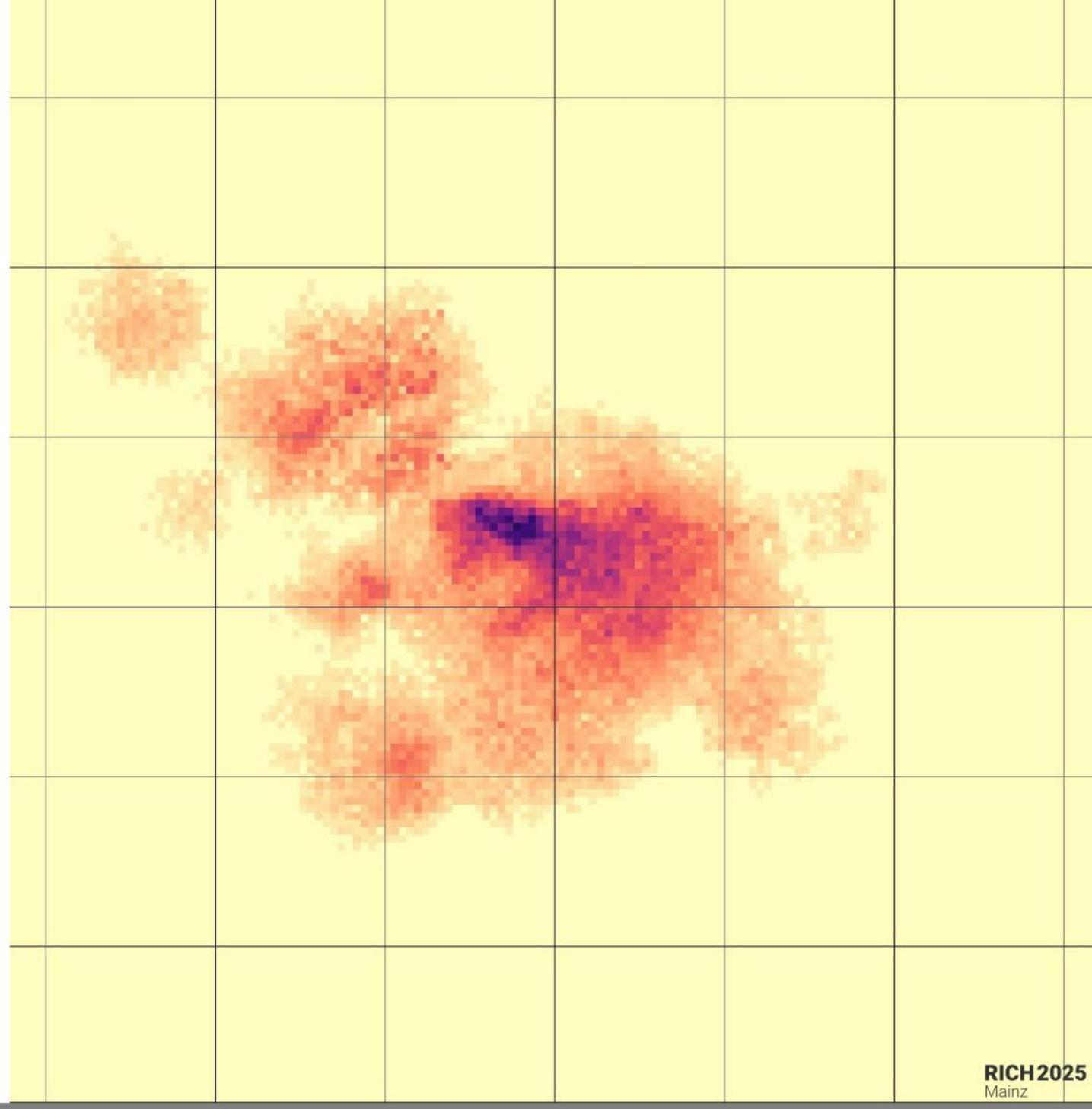
Airshower

Helium

882GeV

13,473p.e.





Airshower

Helium

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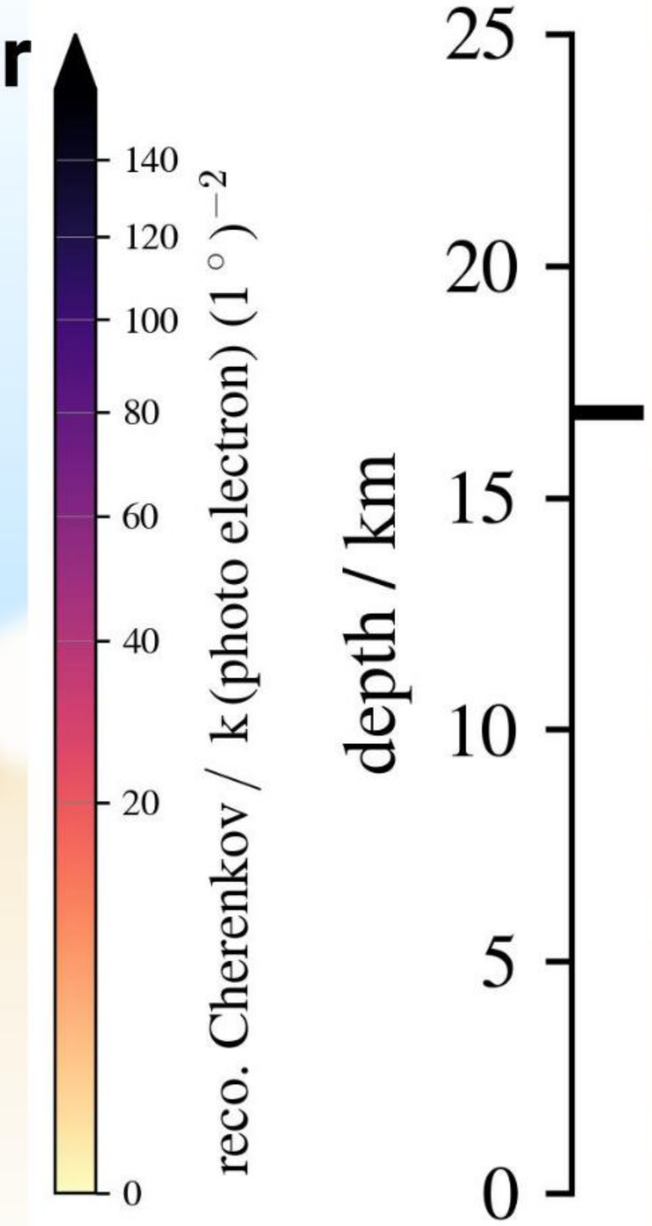
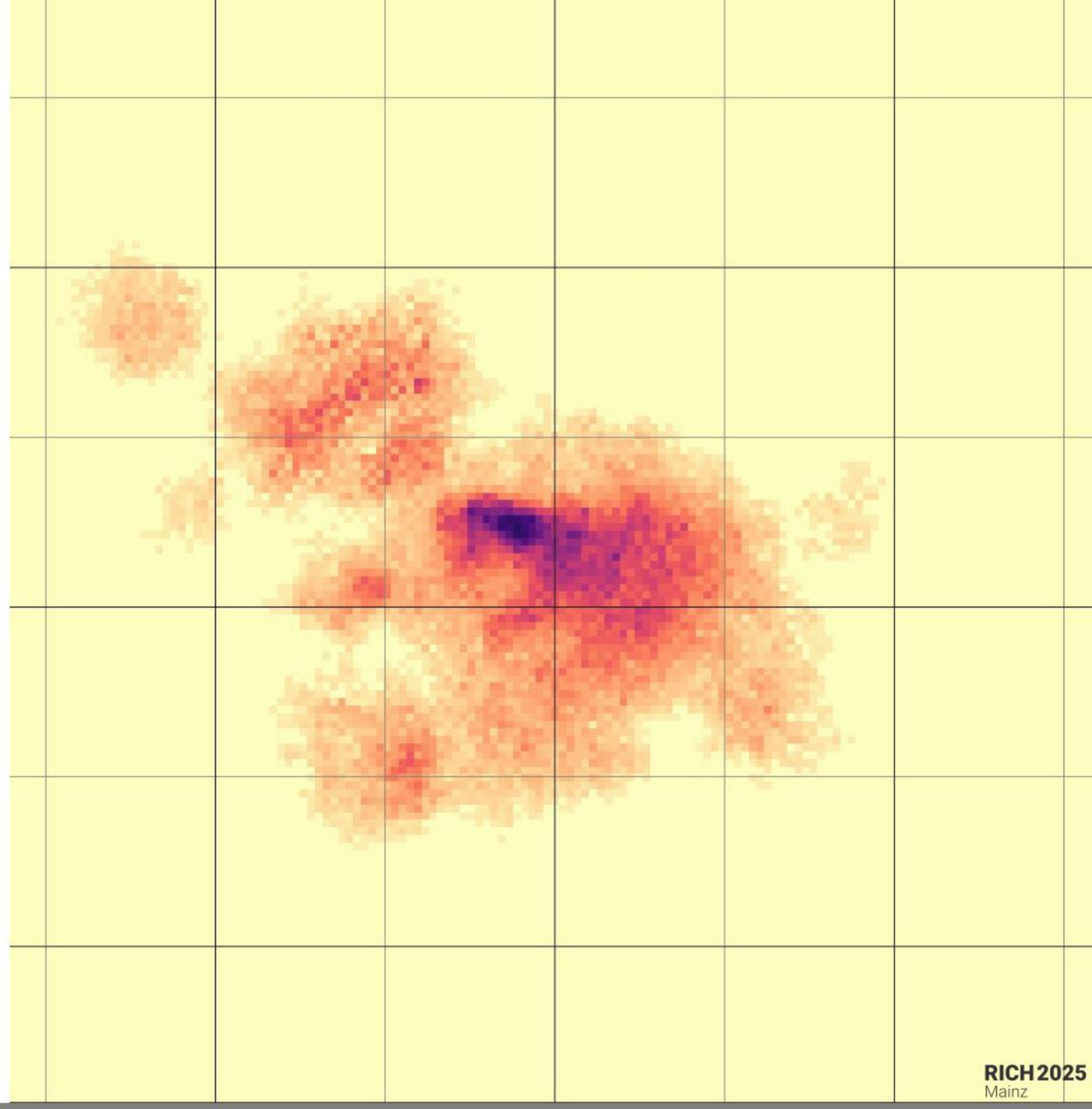
13,473p.e.





Airshower

Helium

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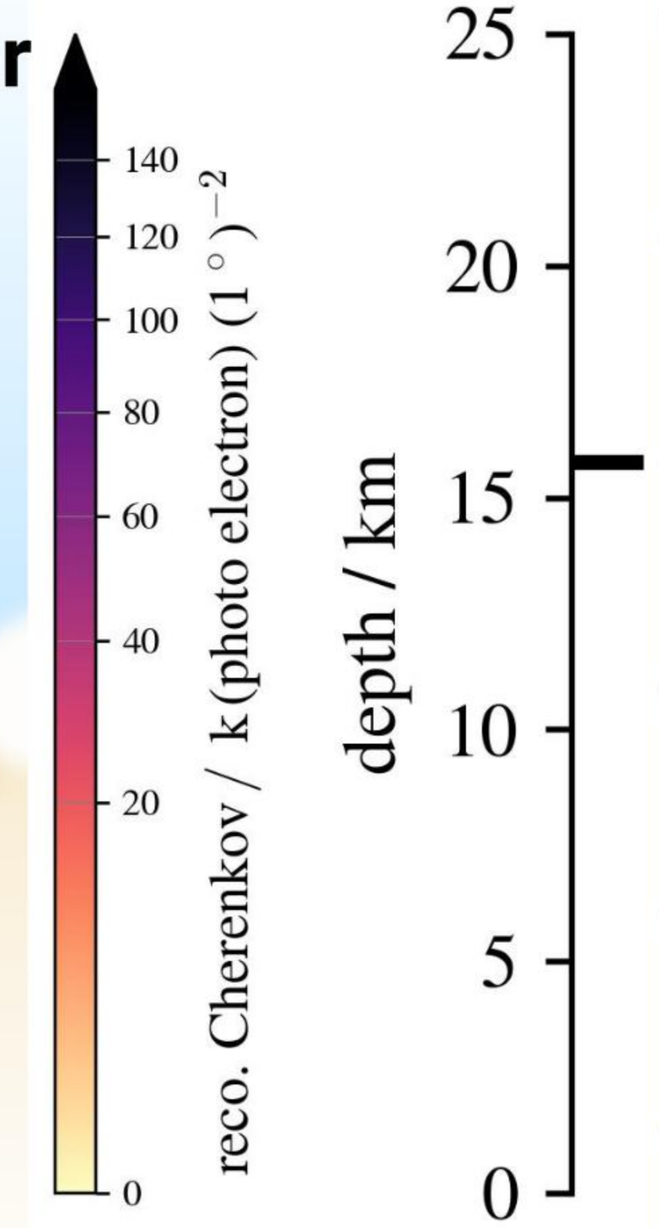

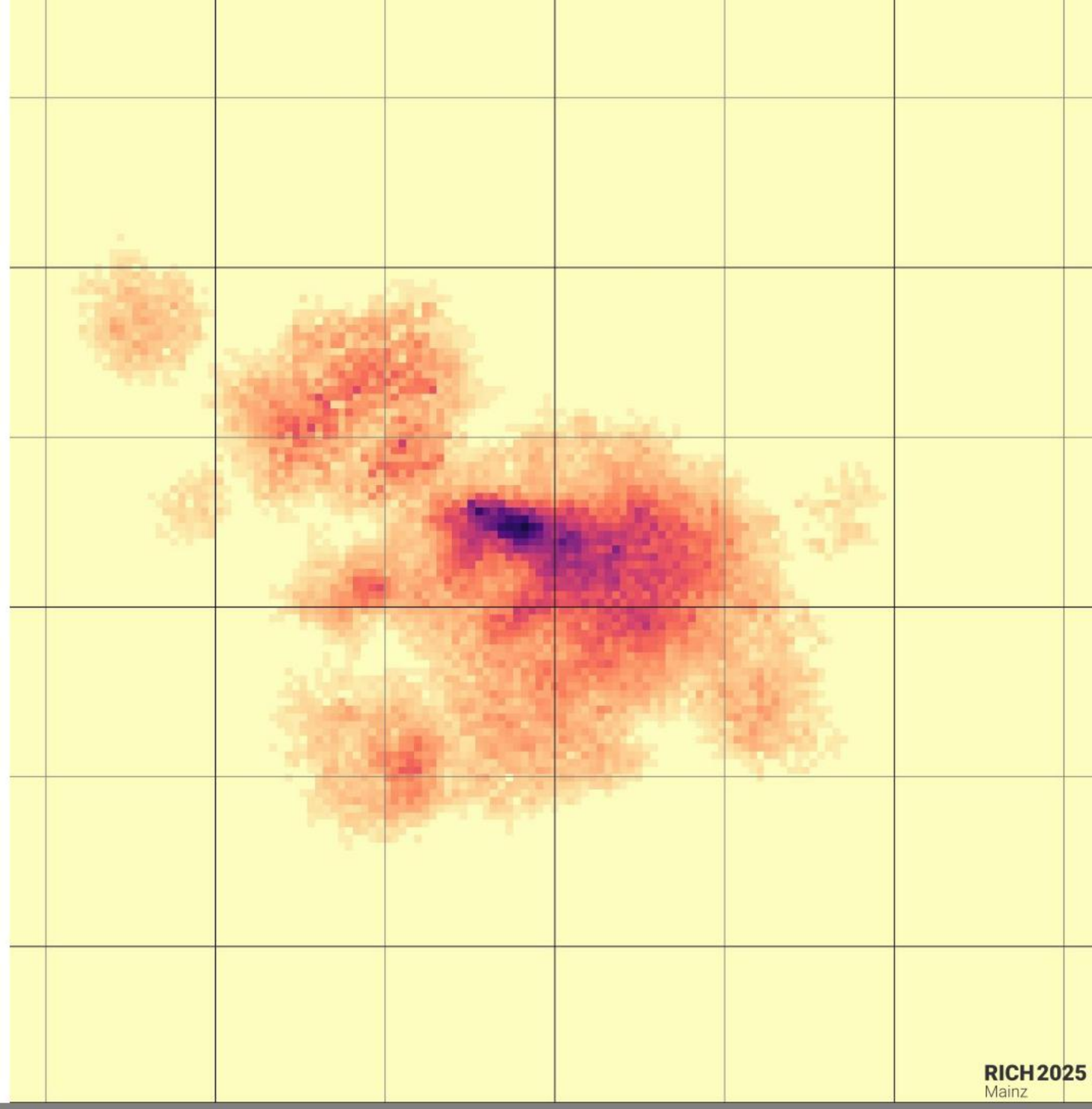

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Helium

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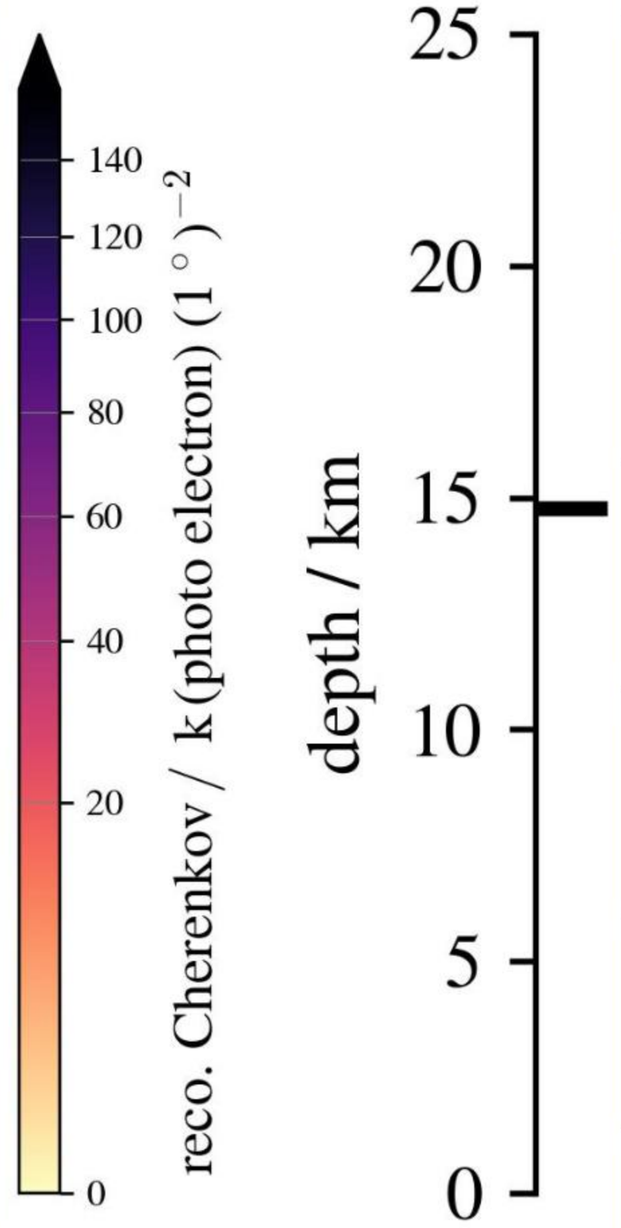

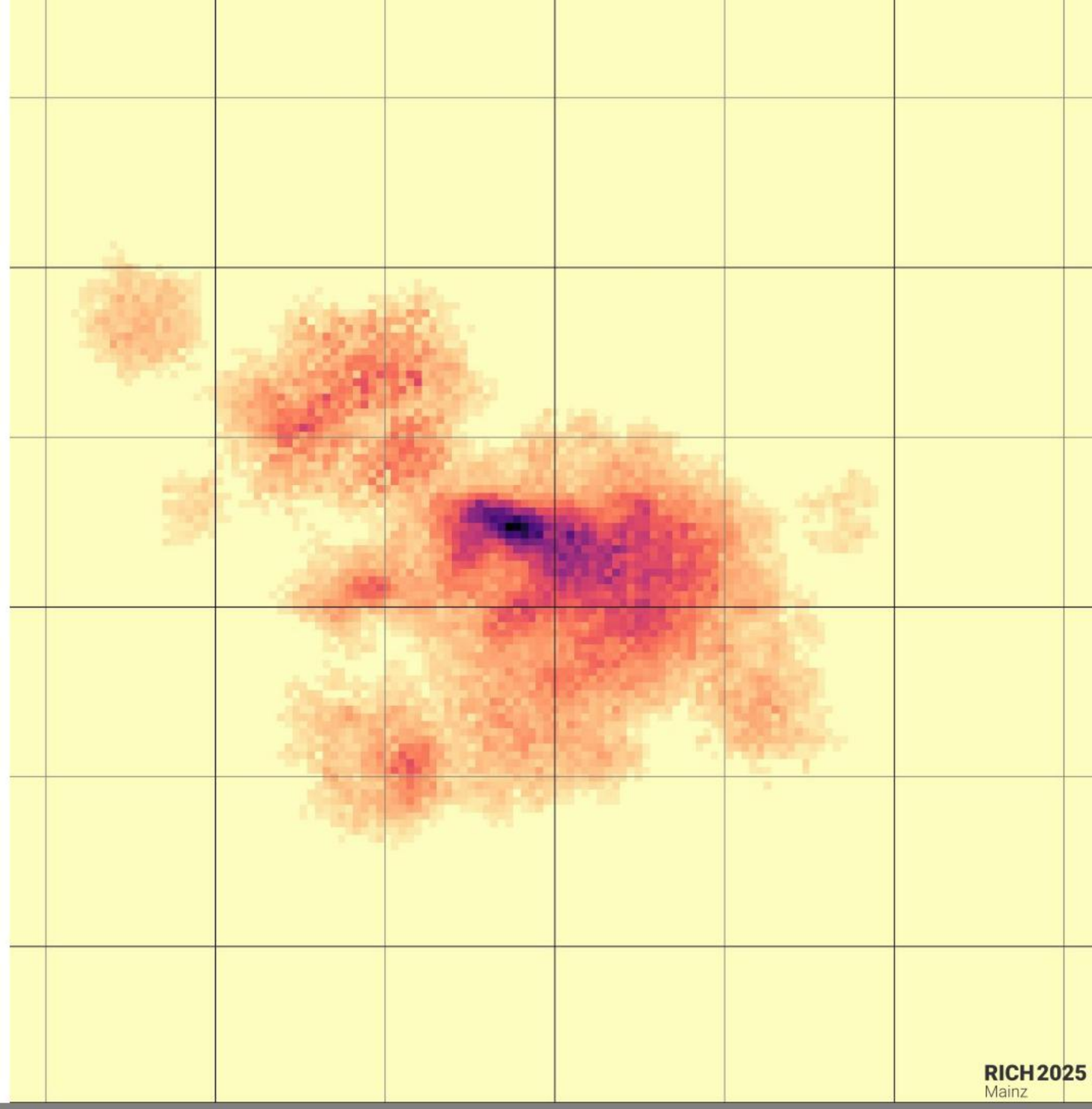

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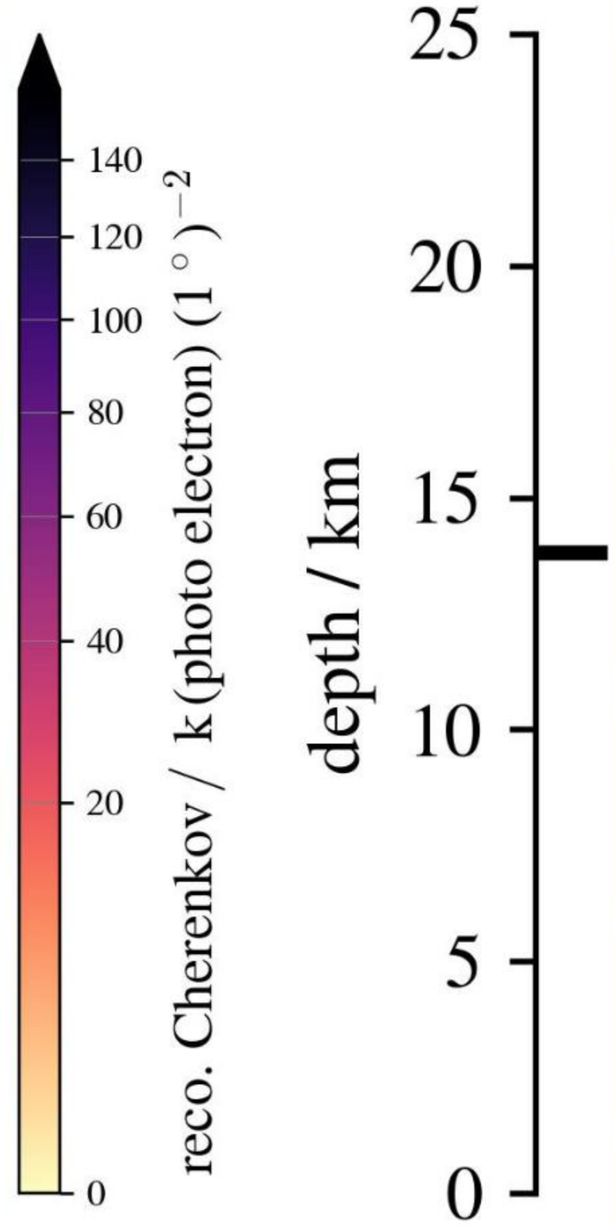

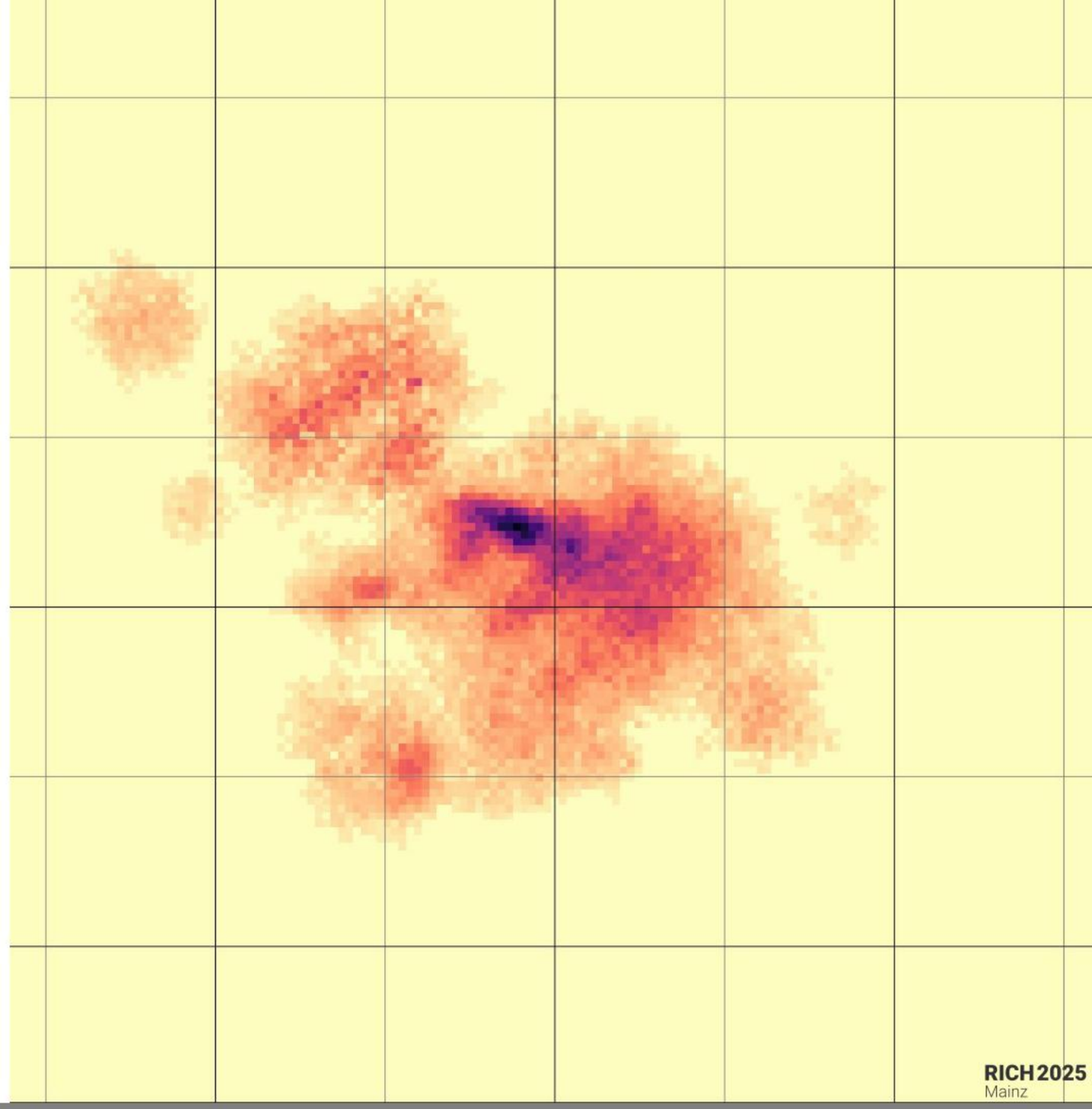

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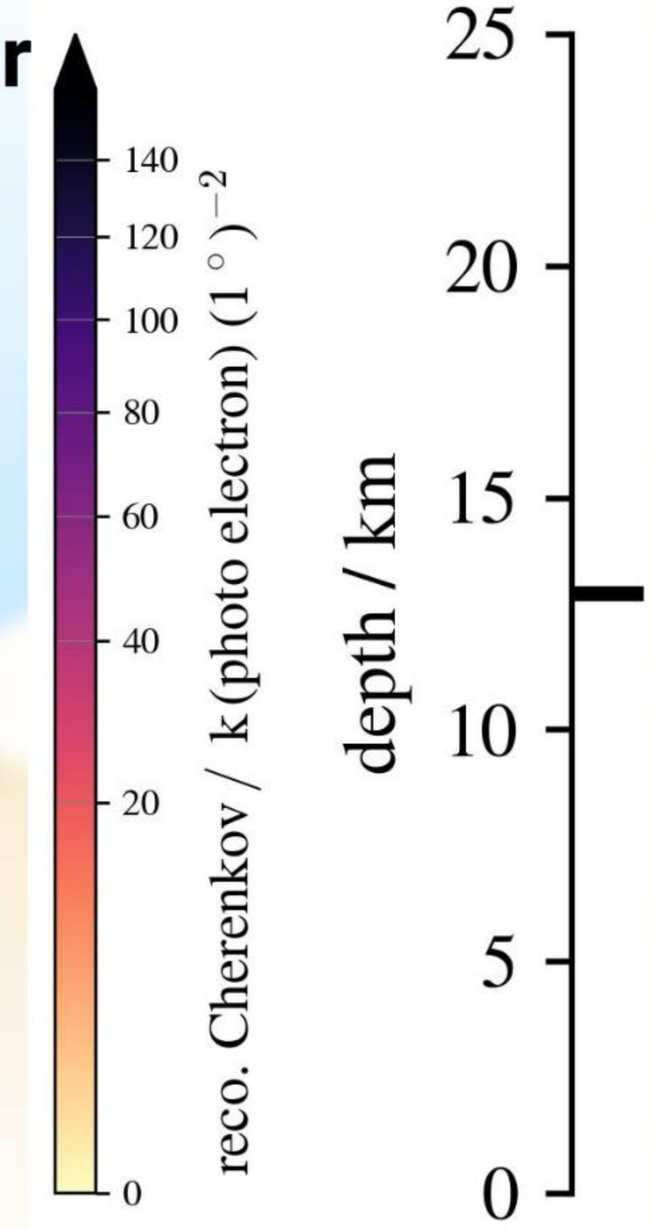

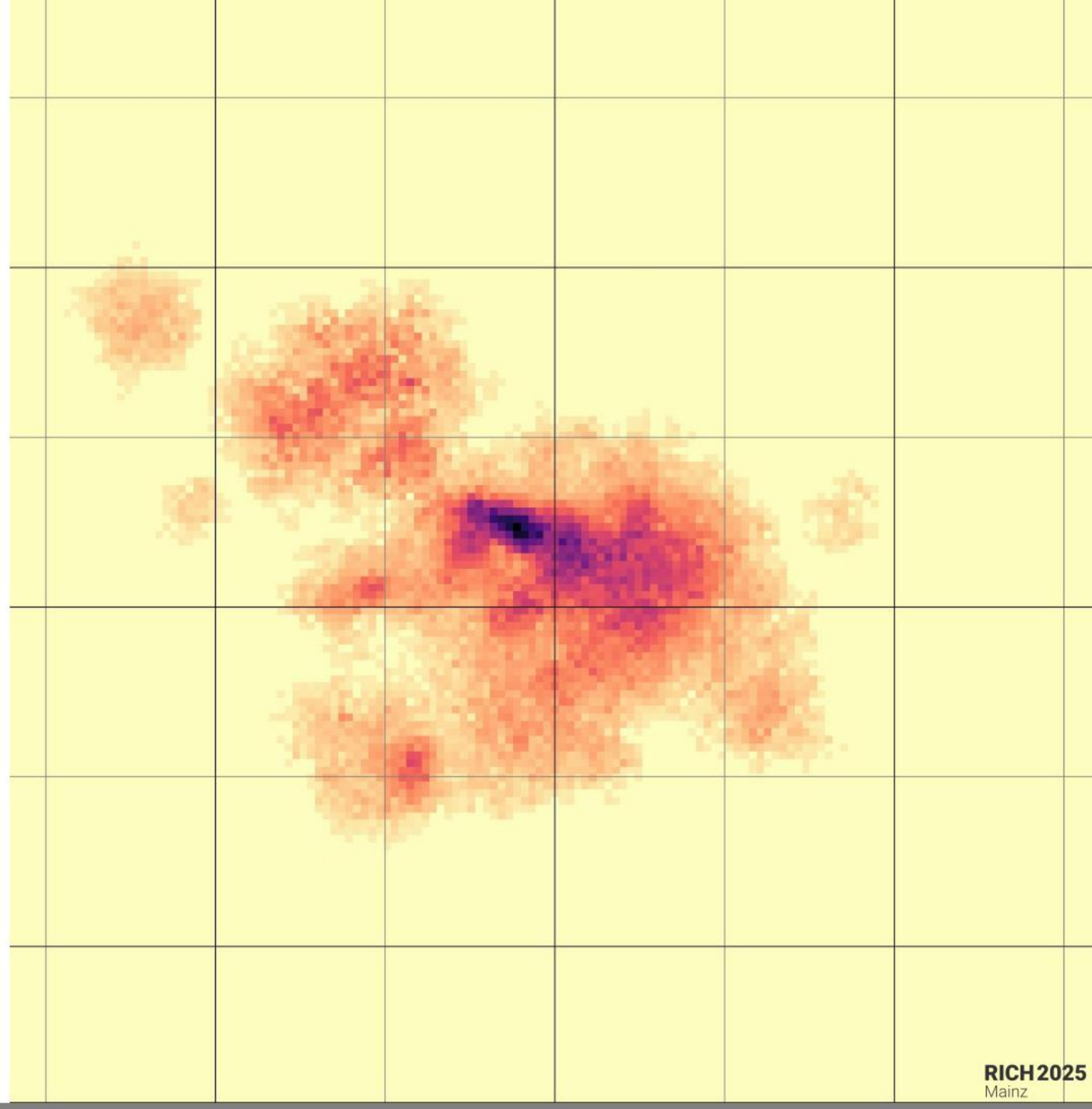

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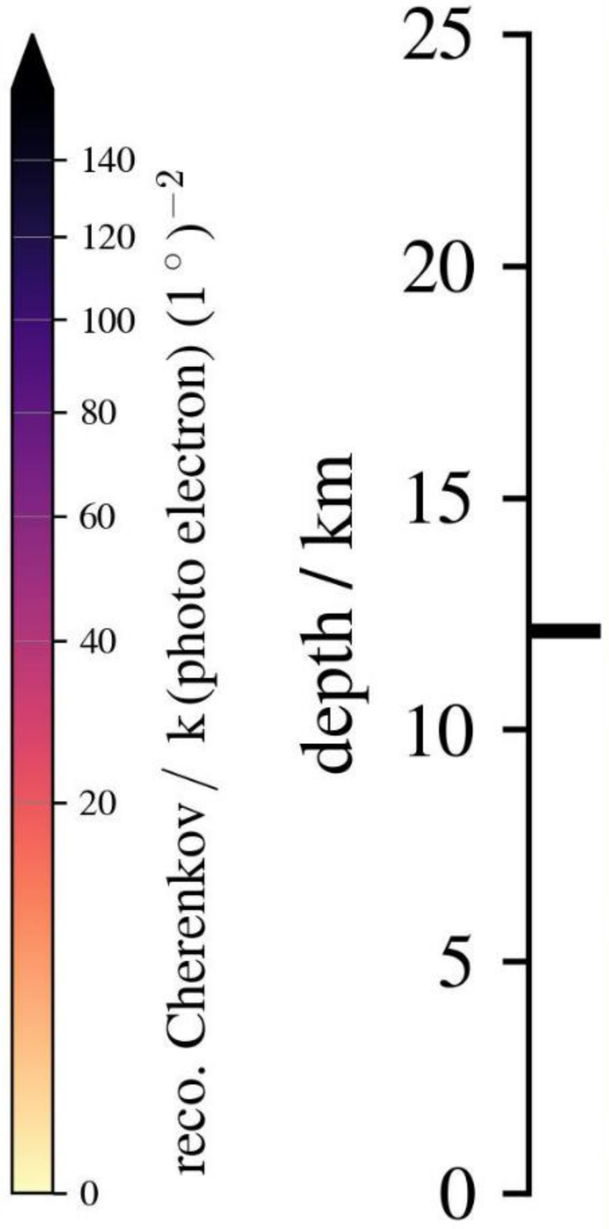

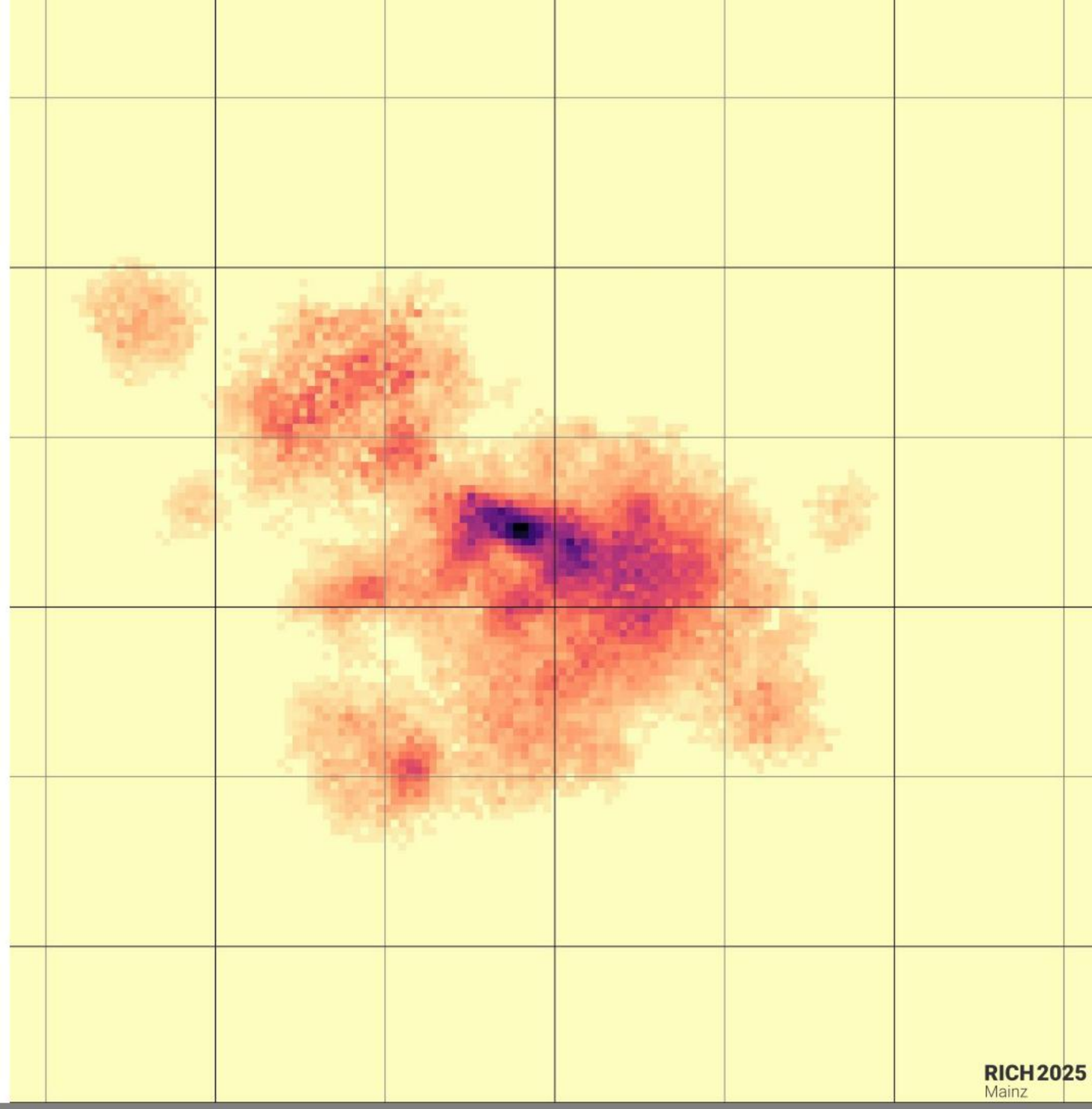

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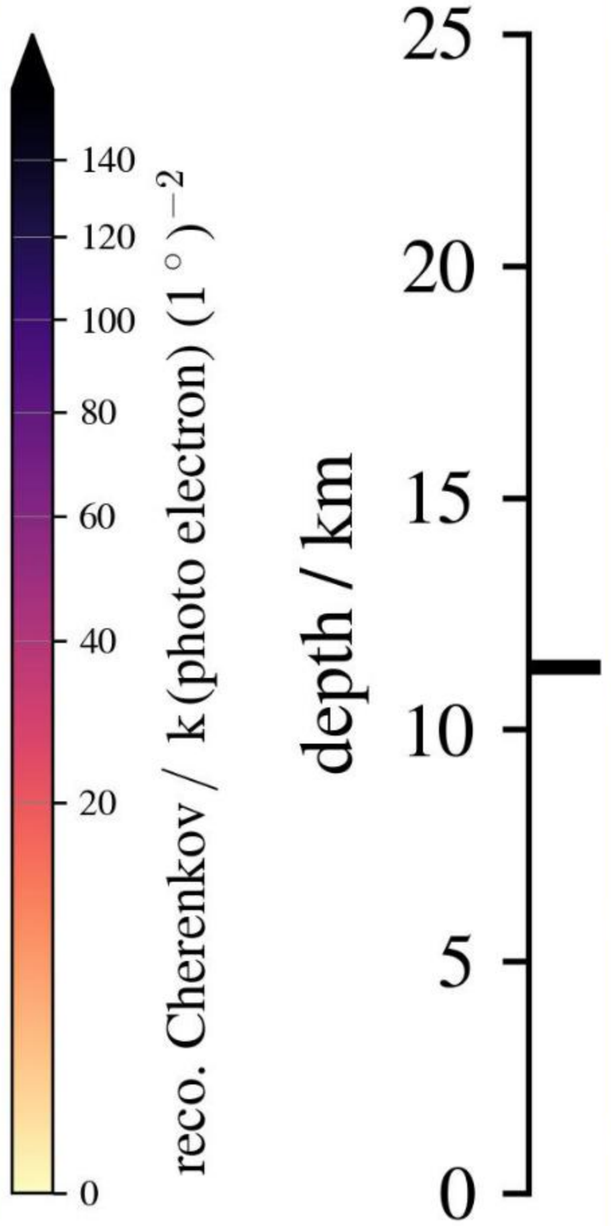

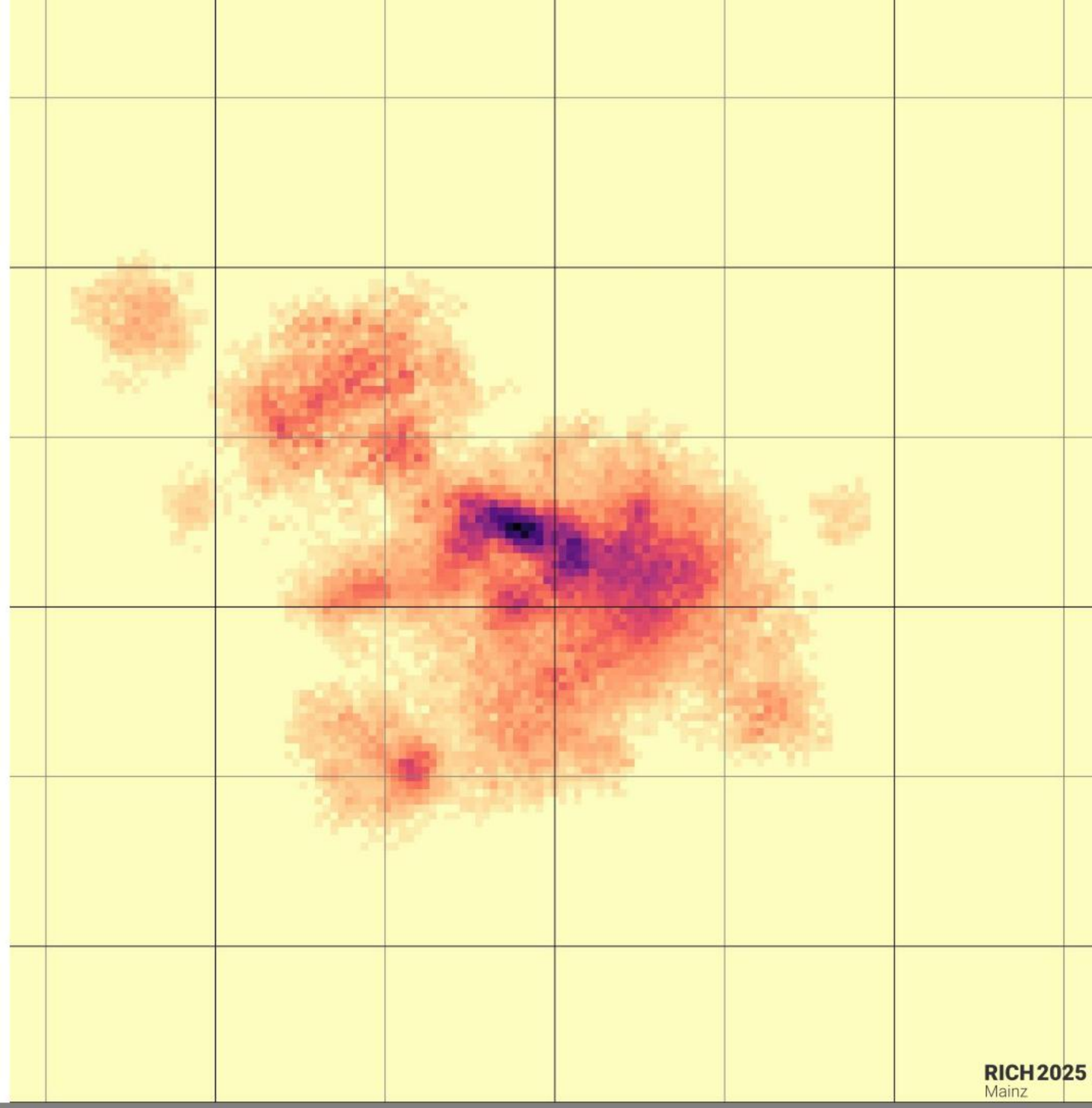

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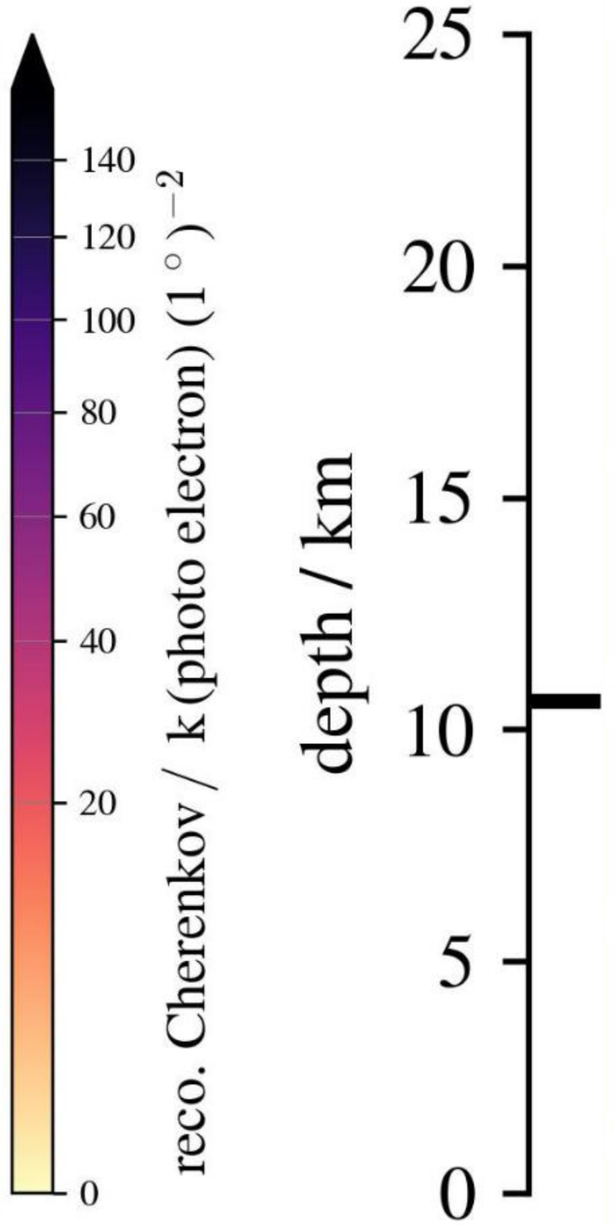

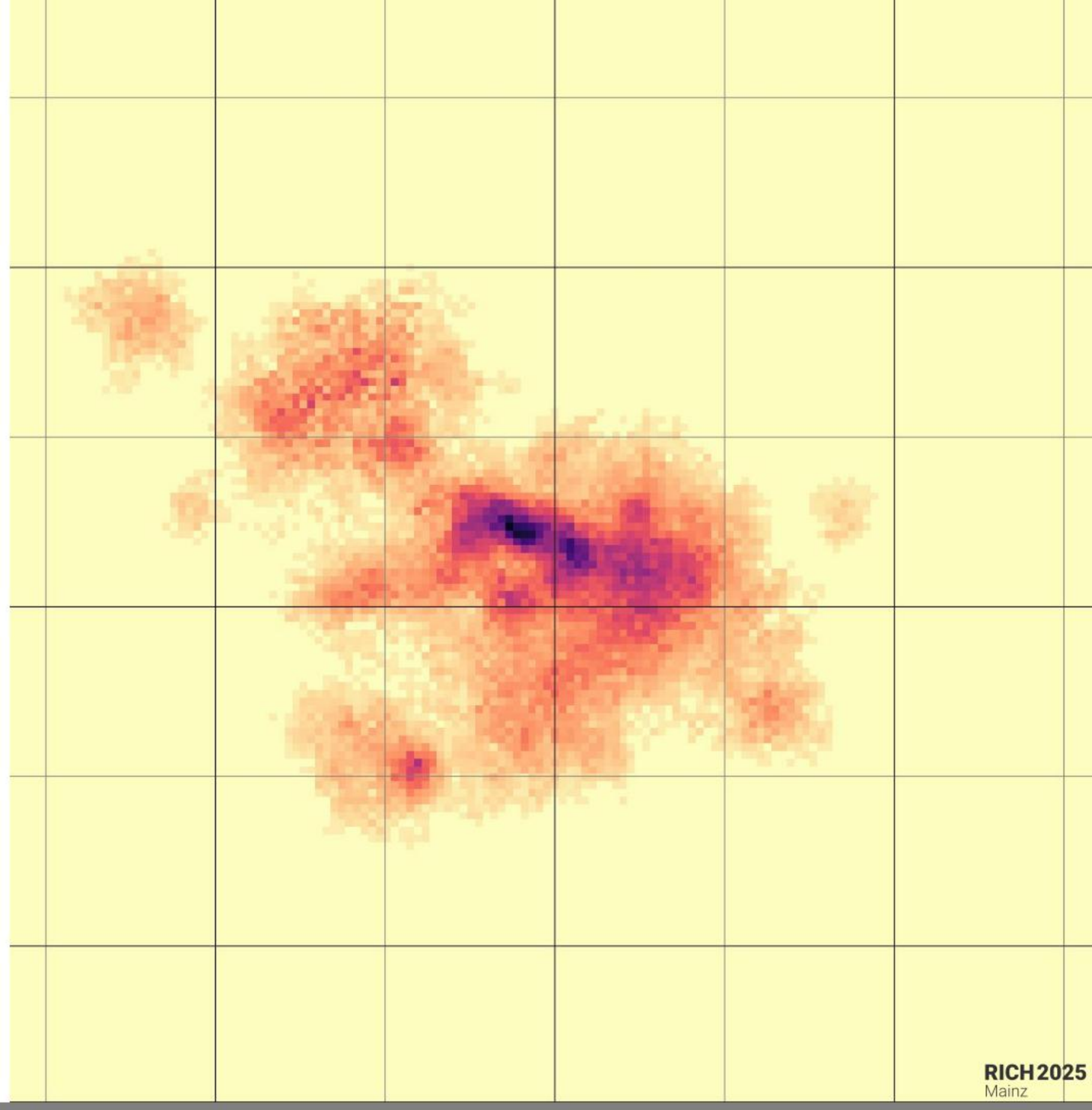

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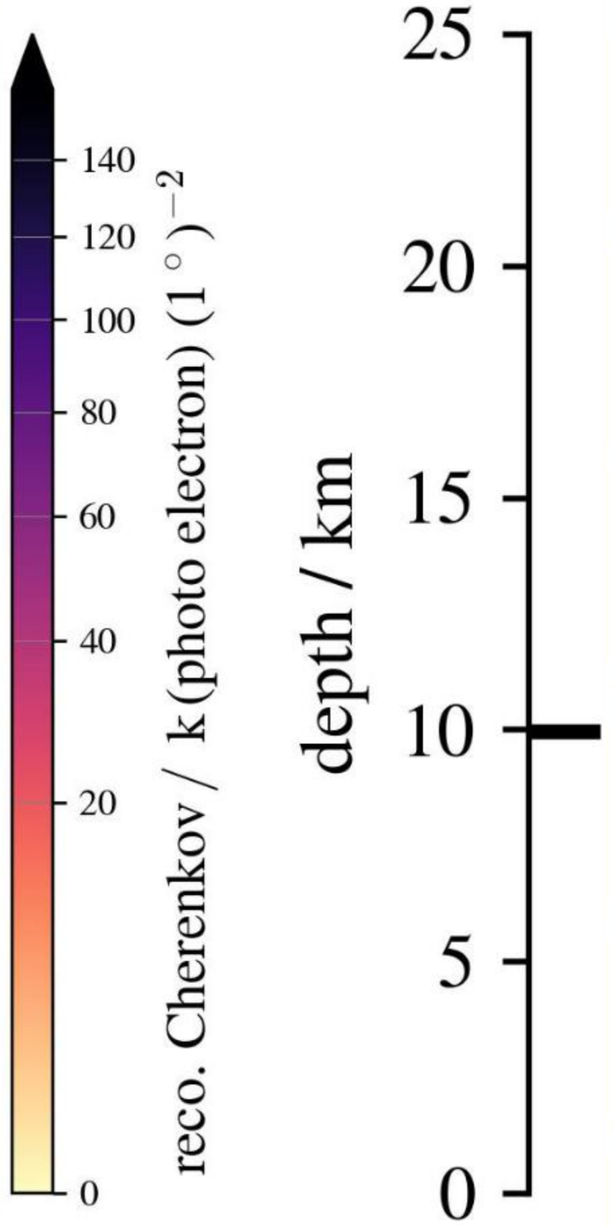

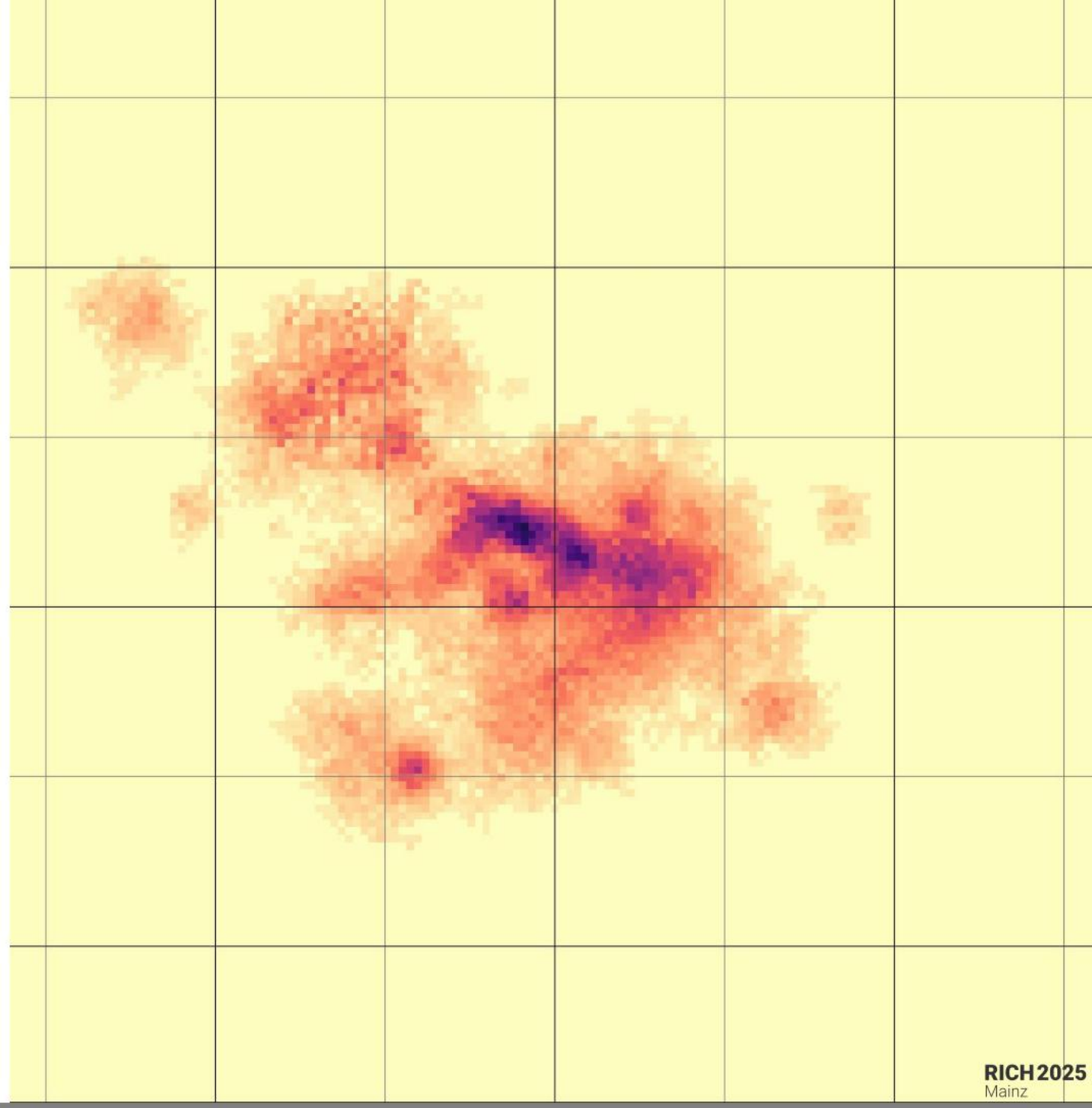

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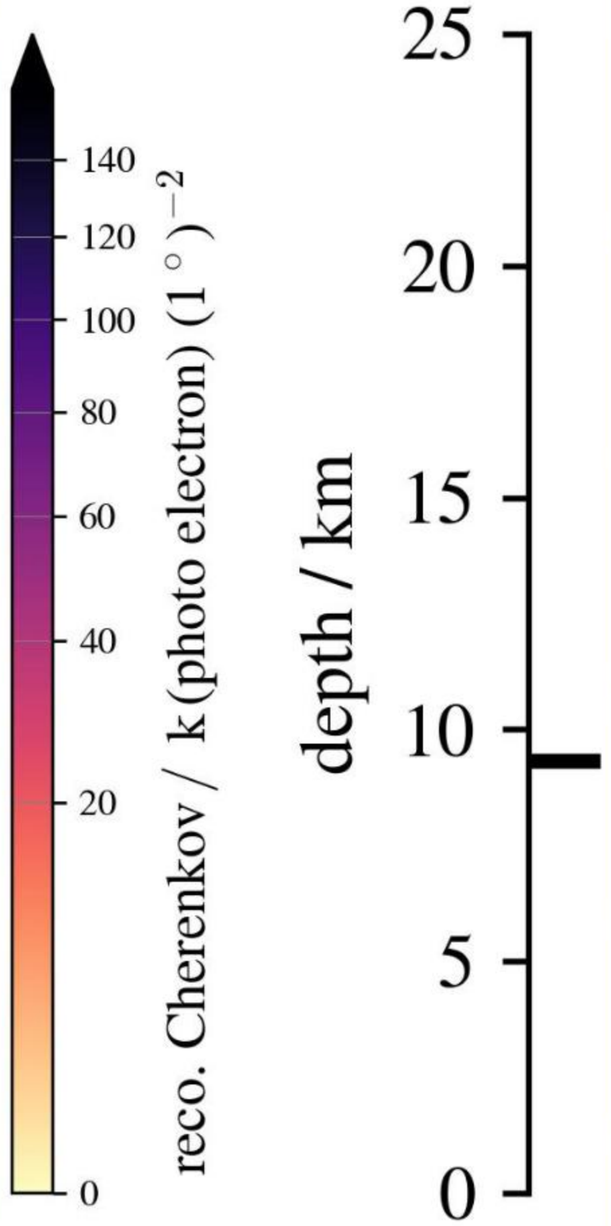

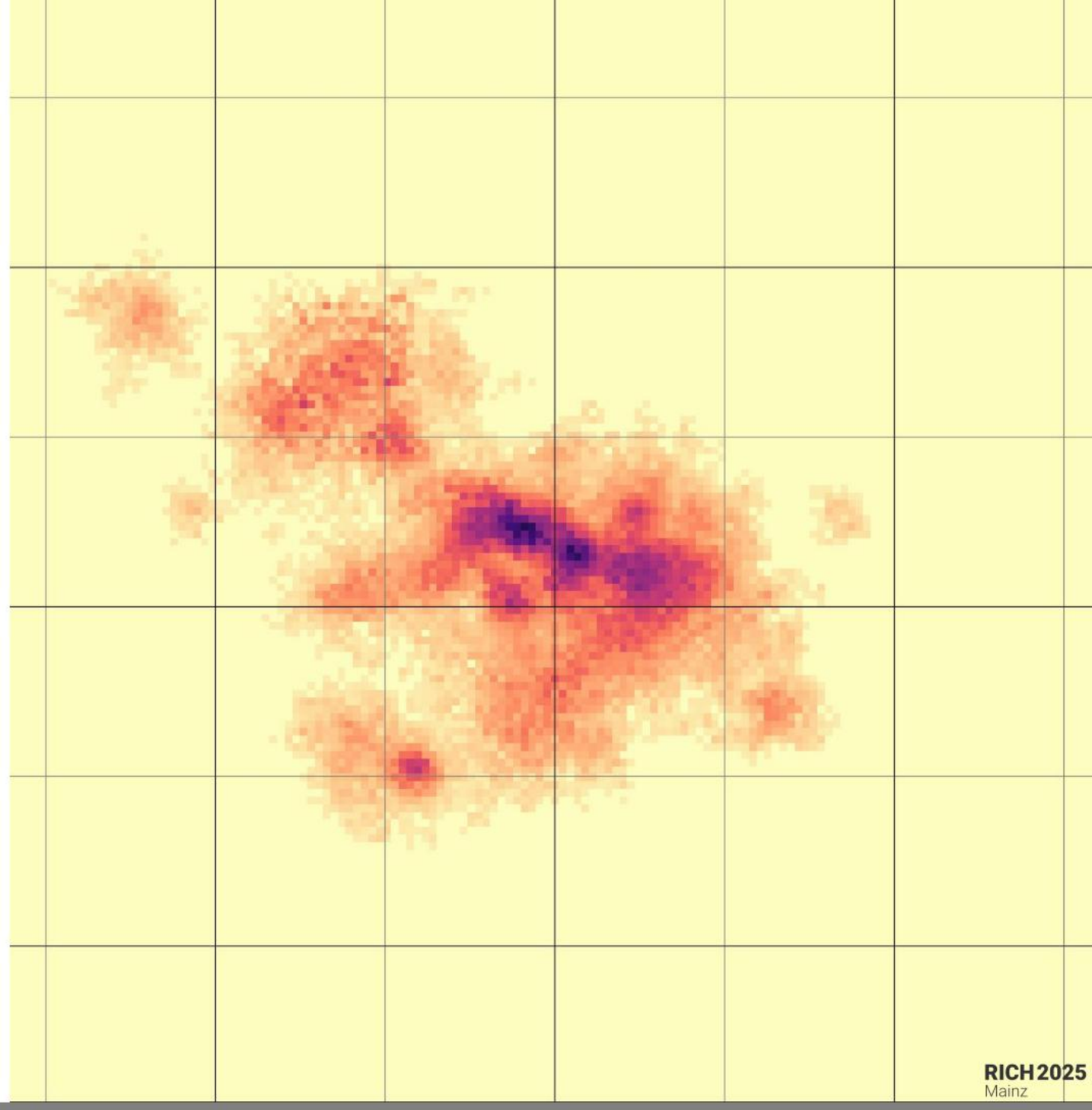

Airshower

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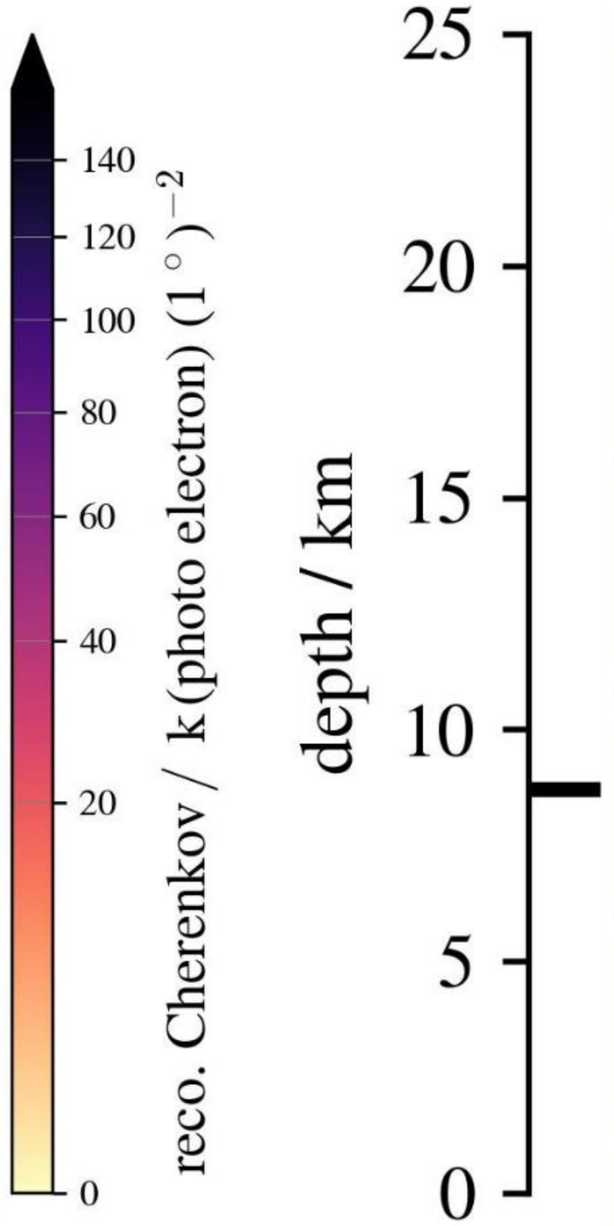

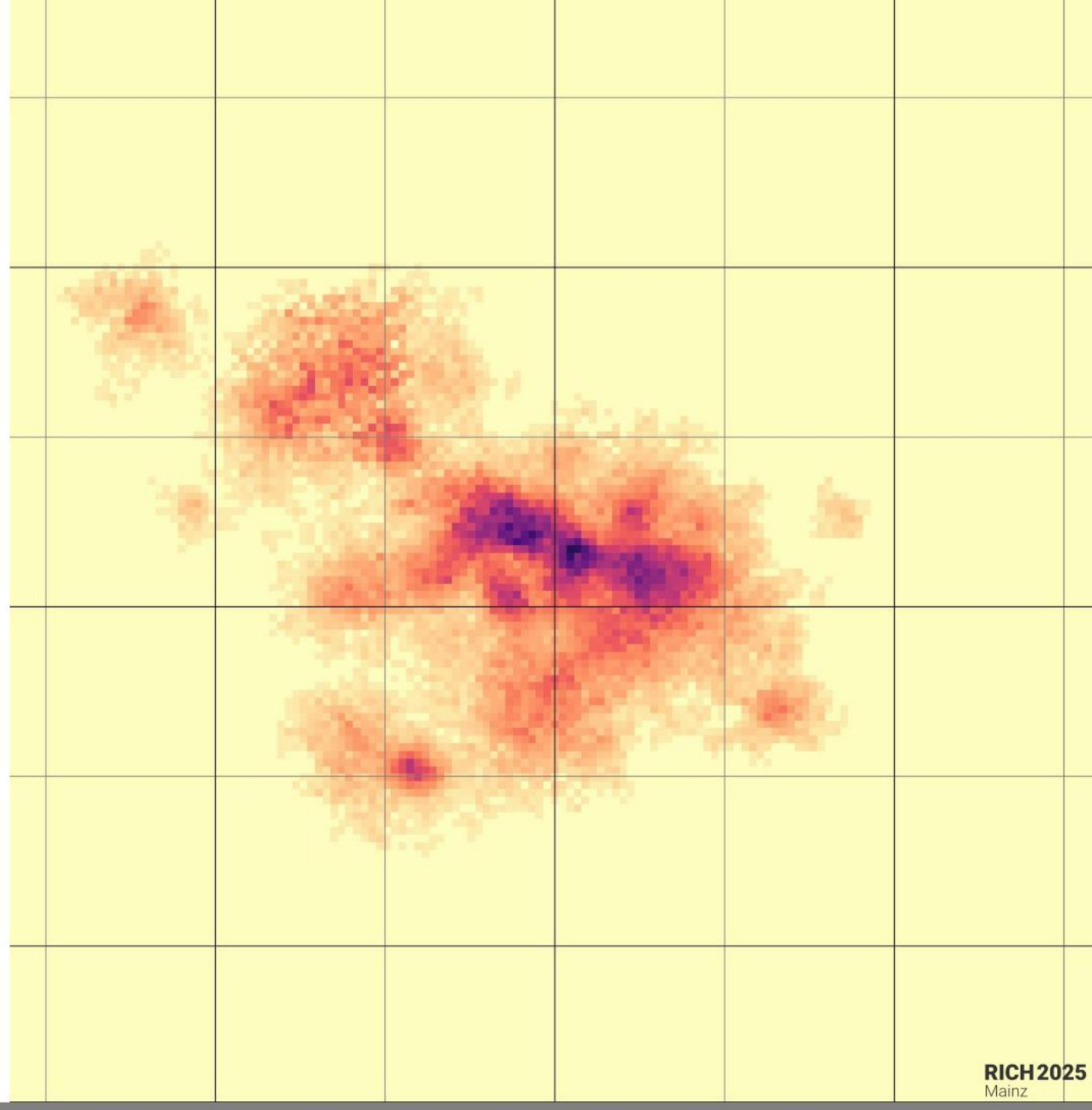

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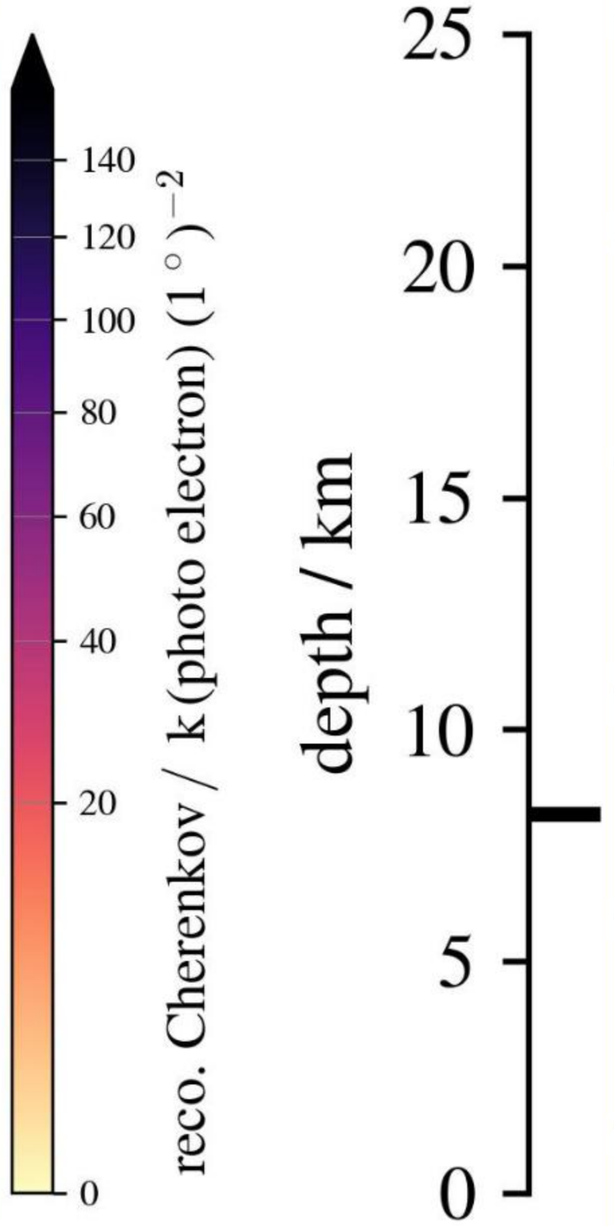

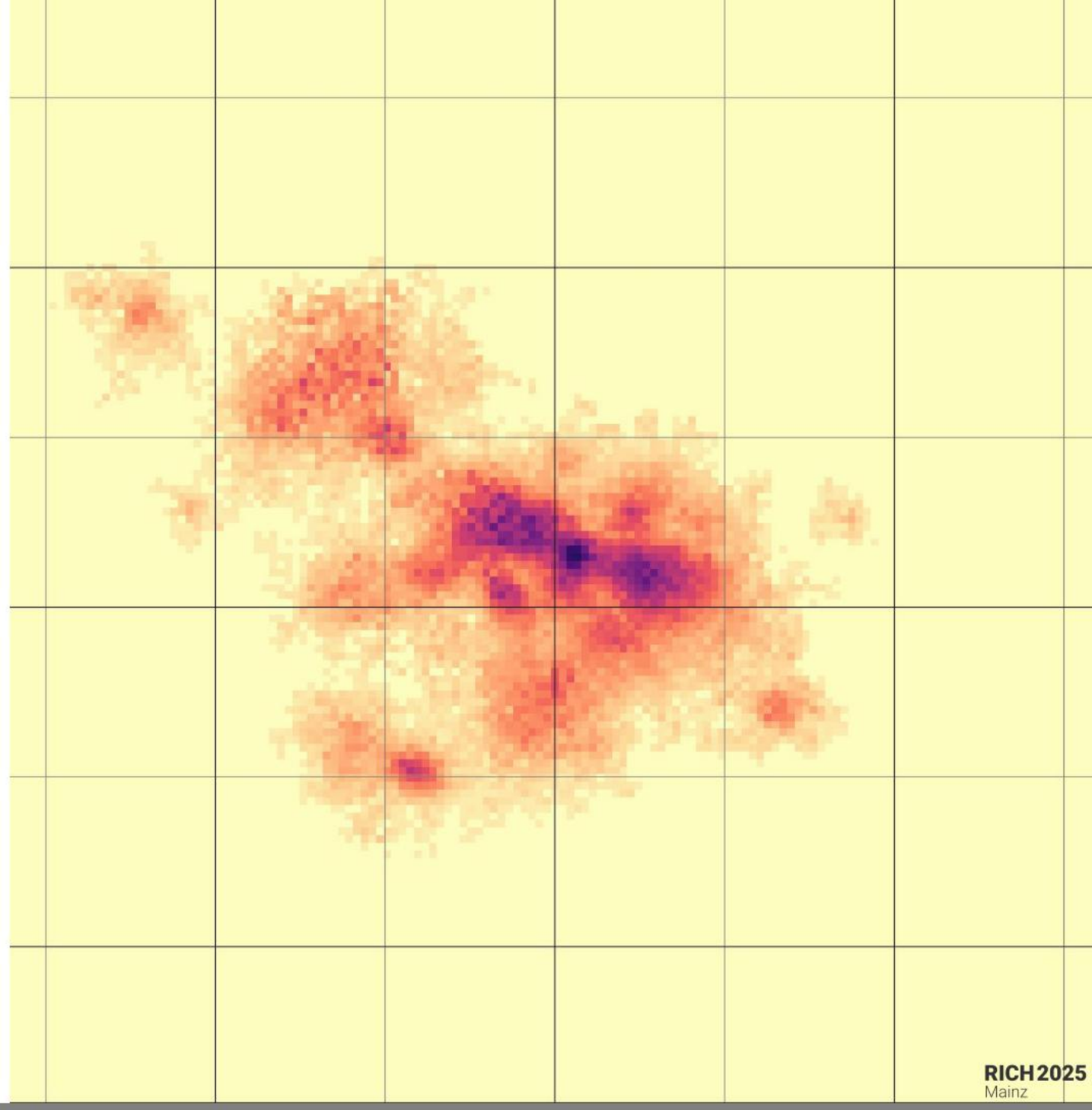

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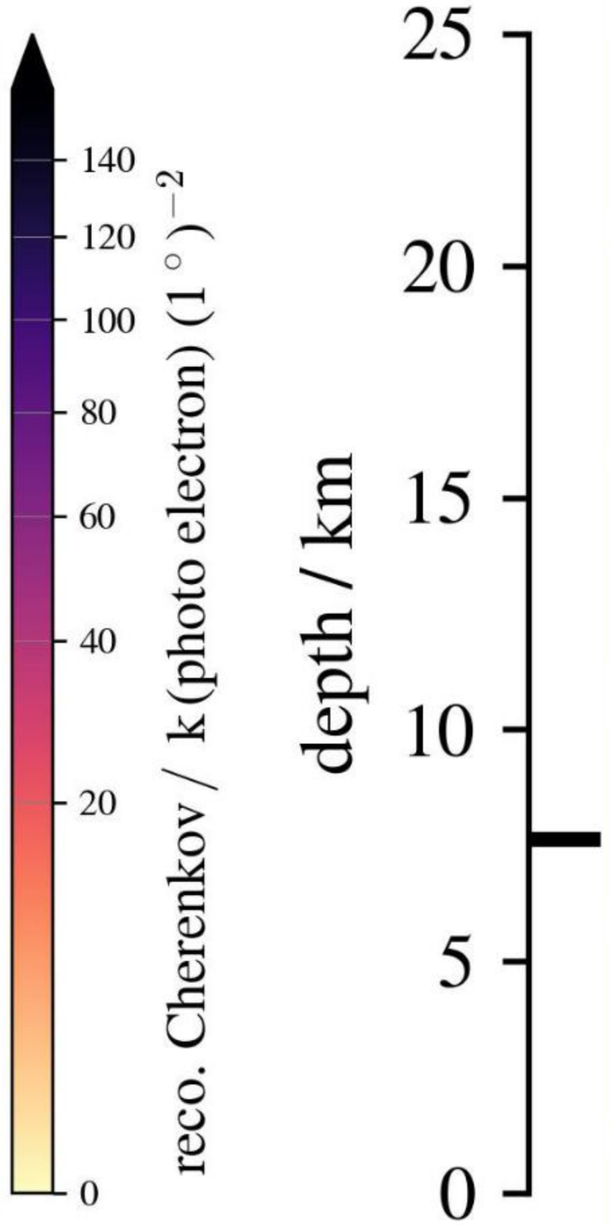

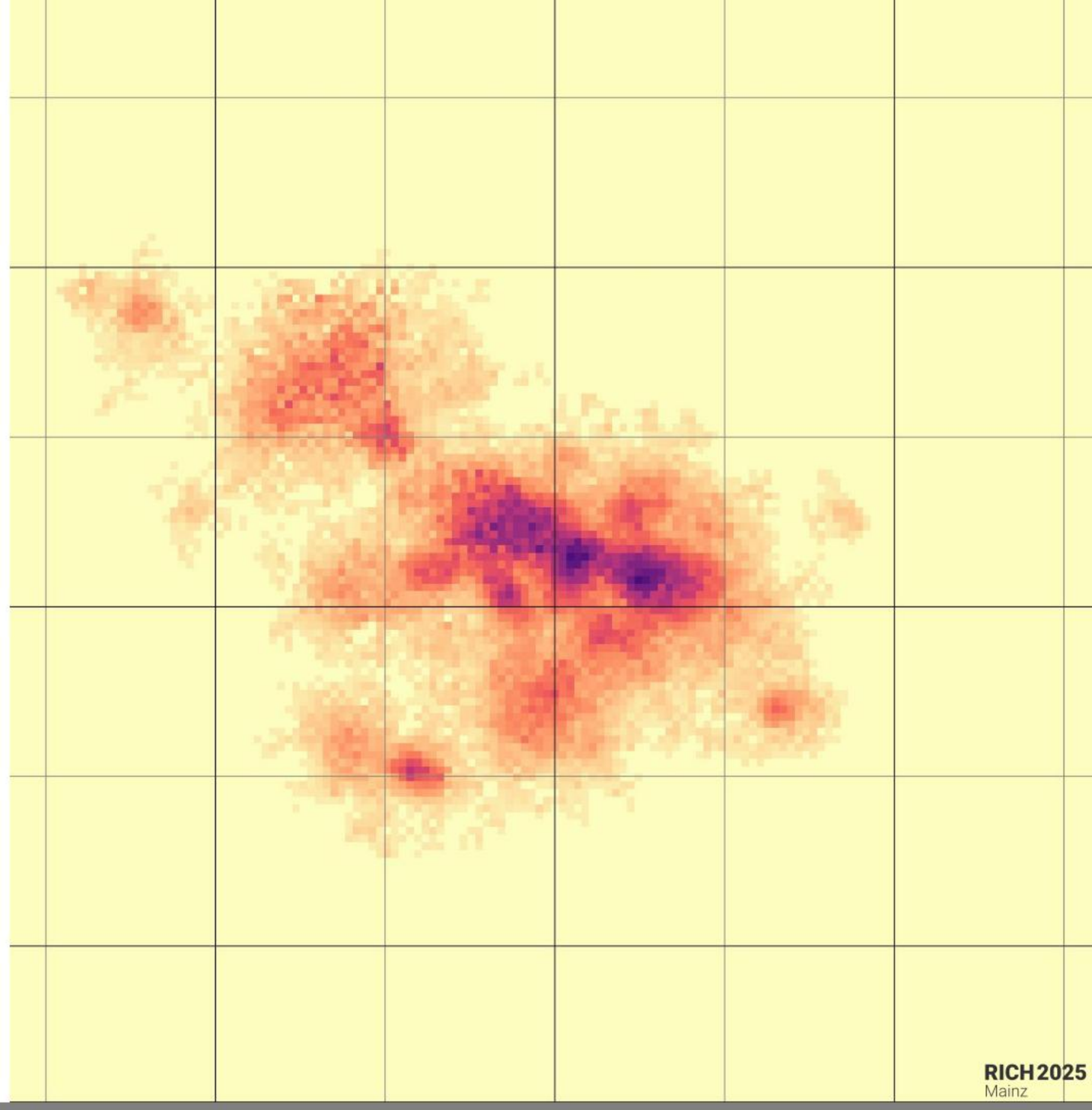

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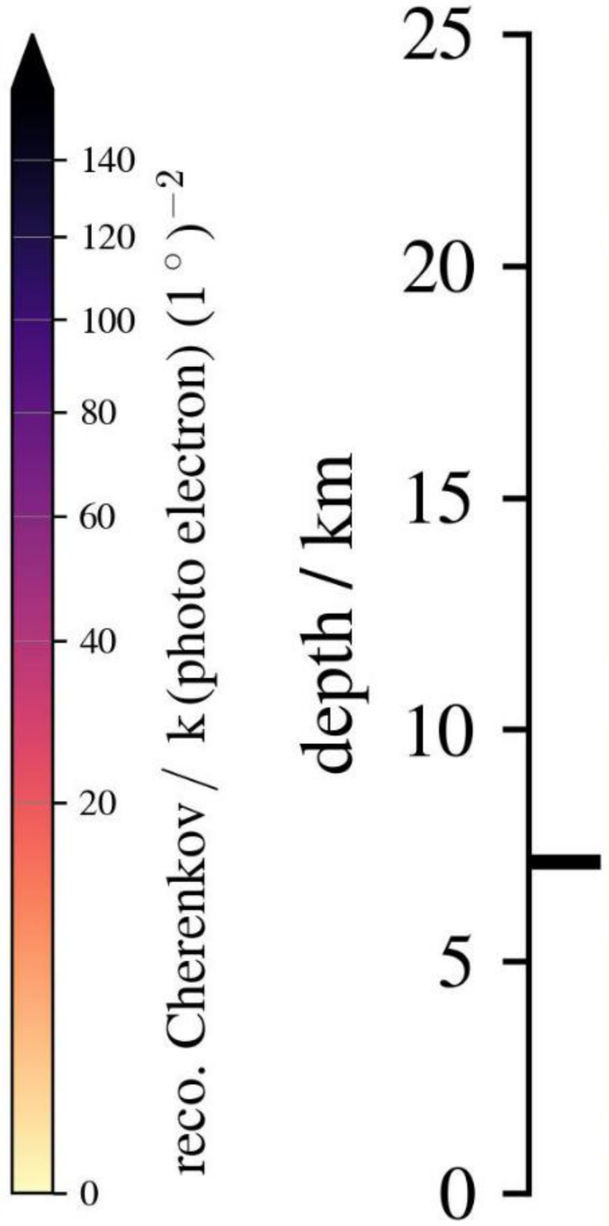

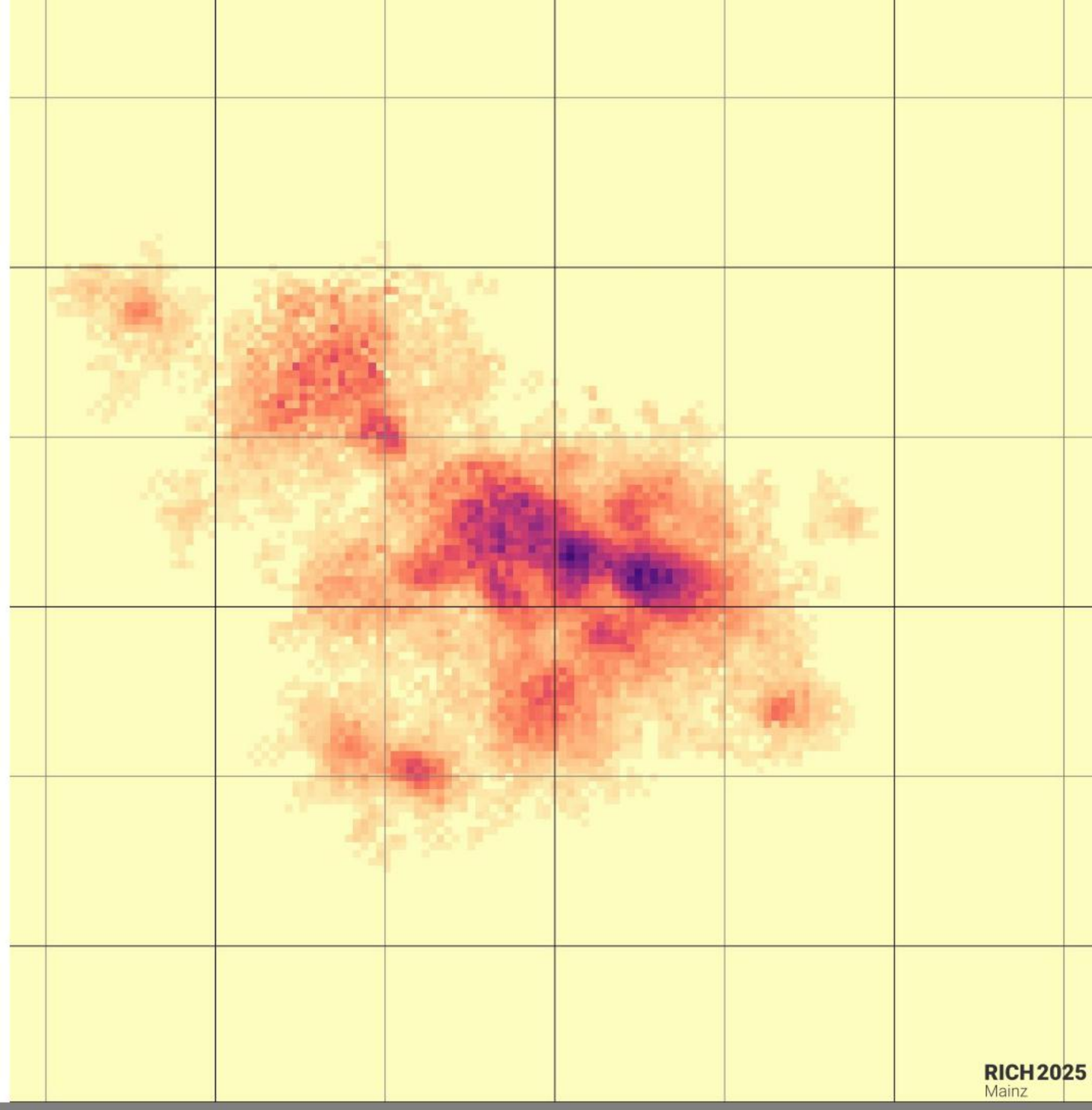

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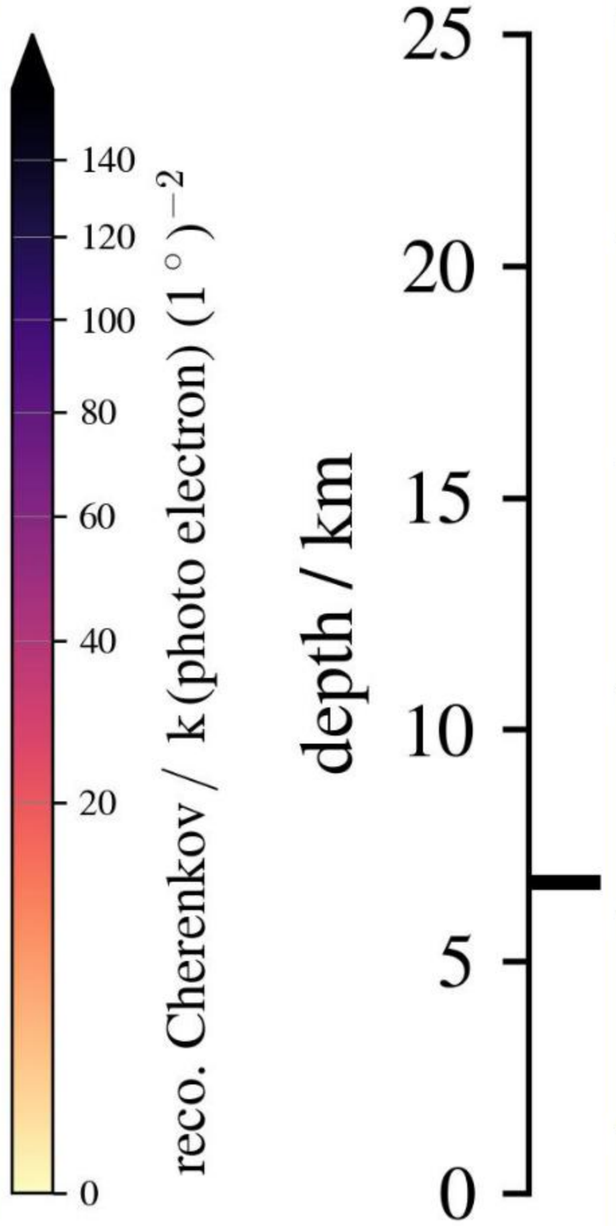

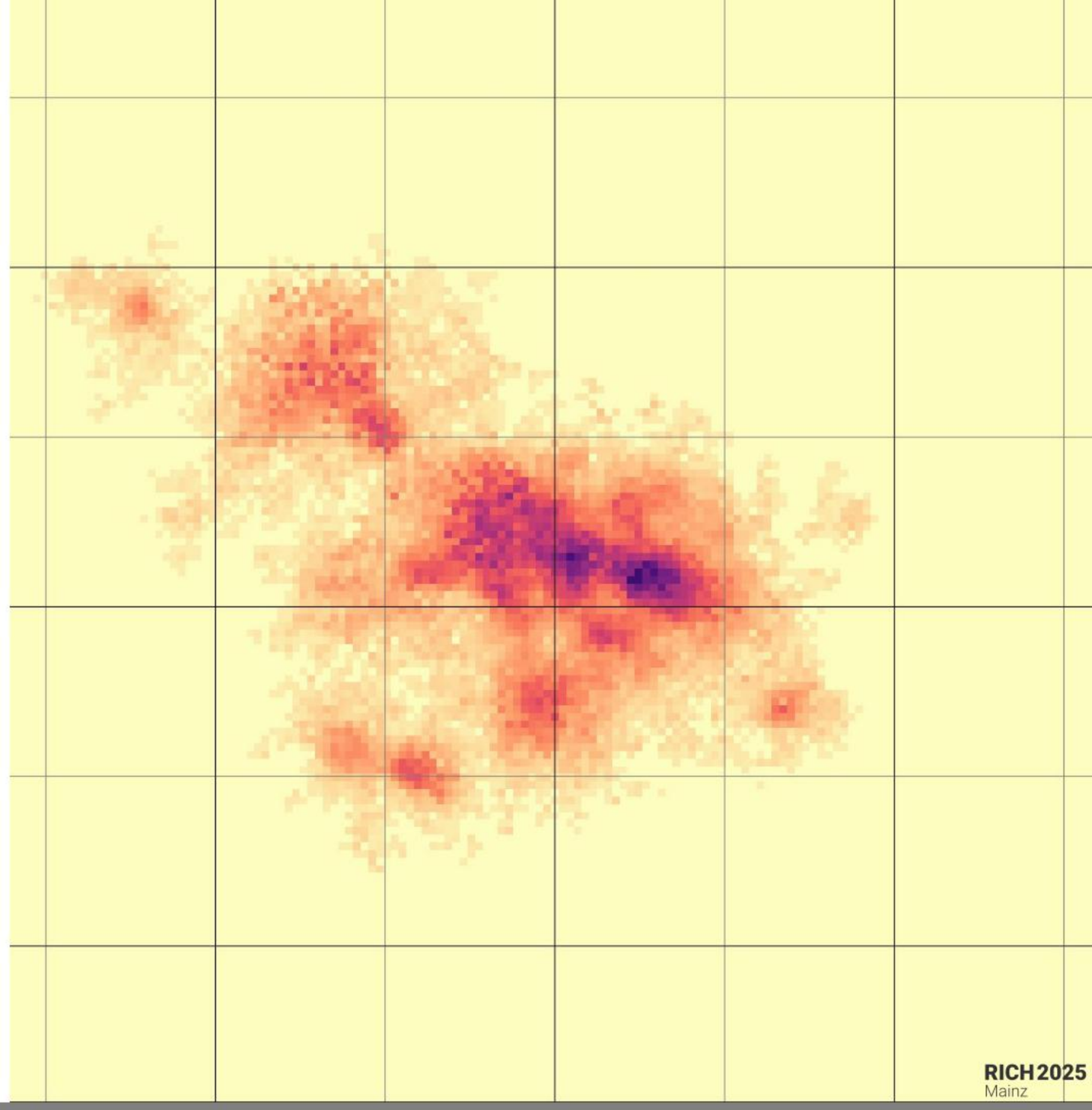

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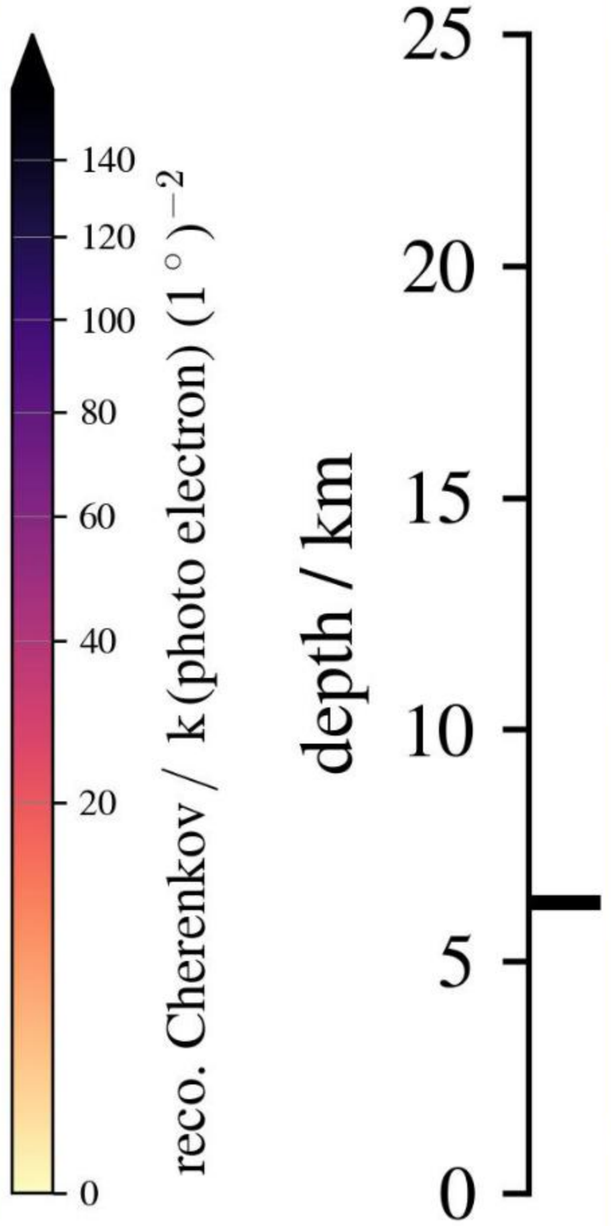

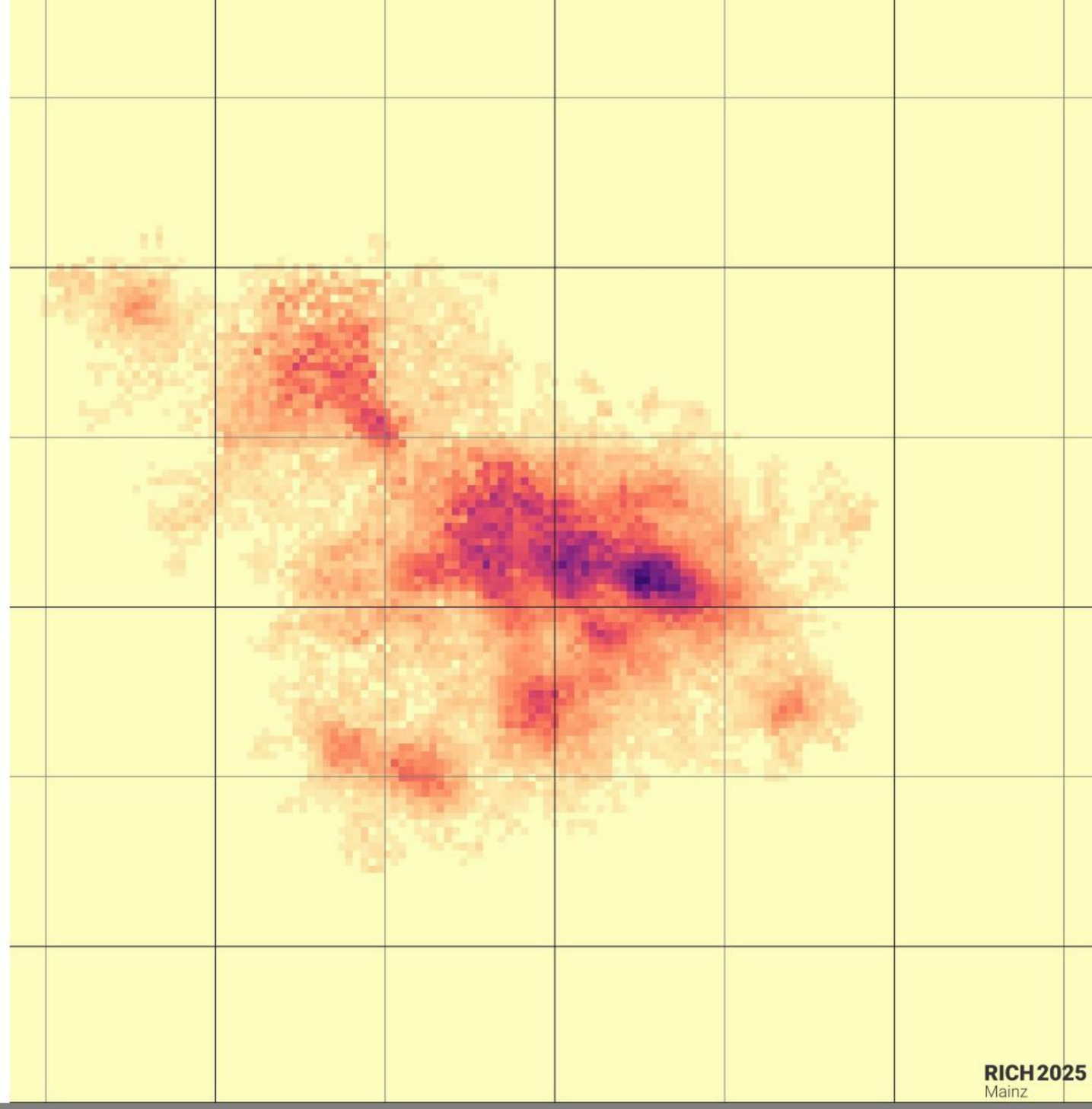

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Helium

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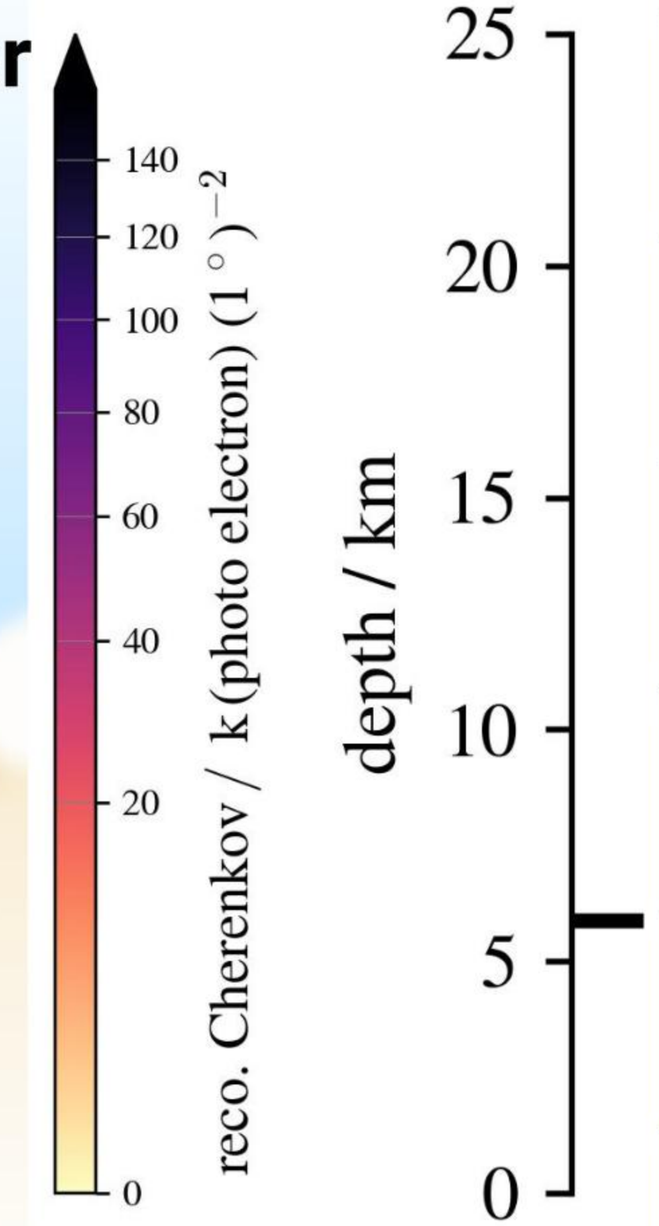

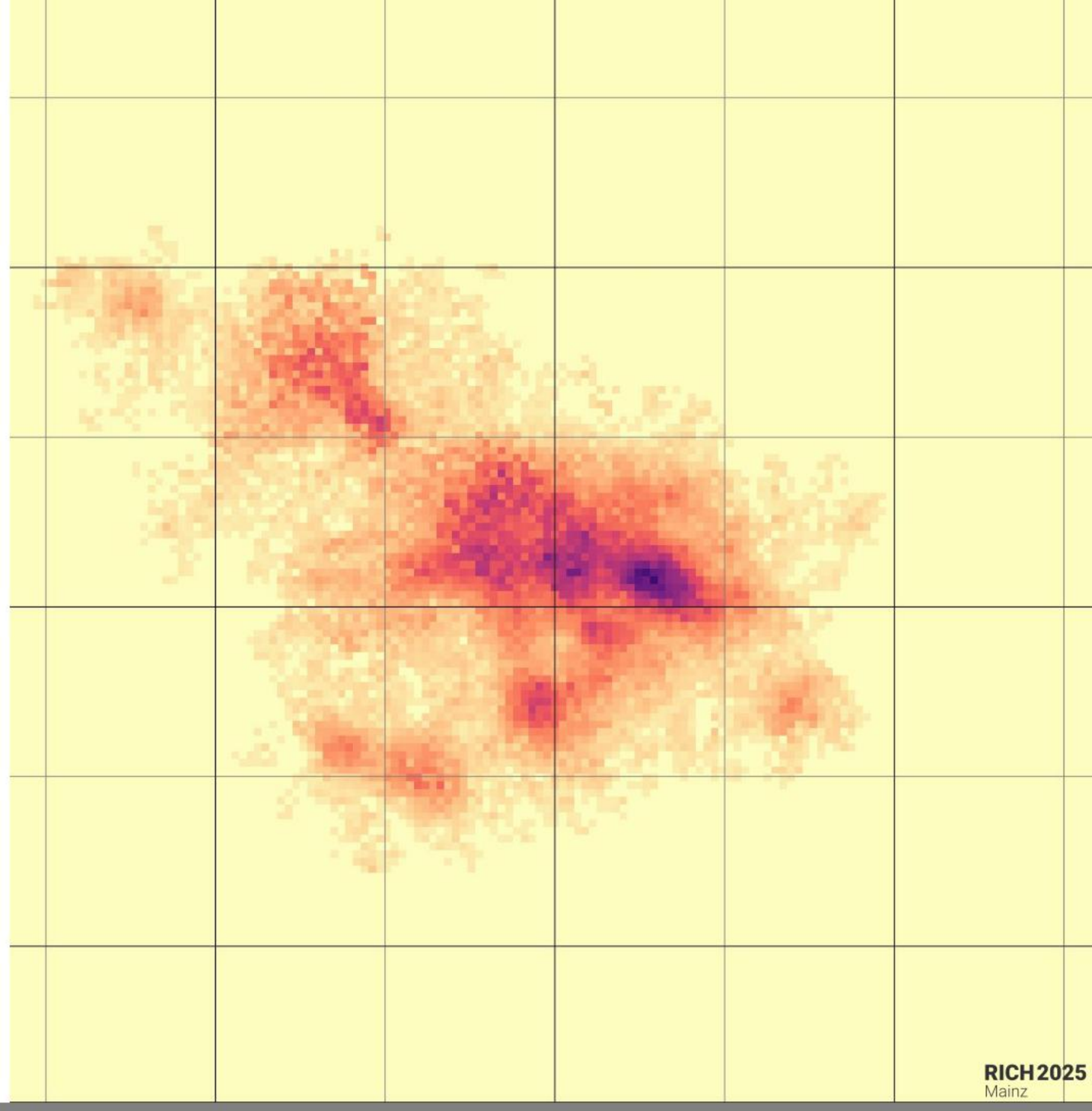

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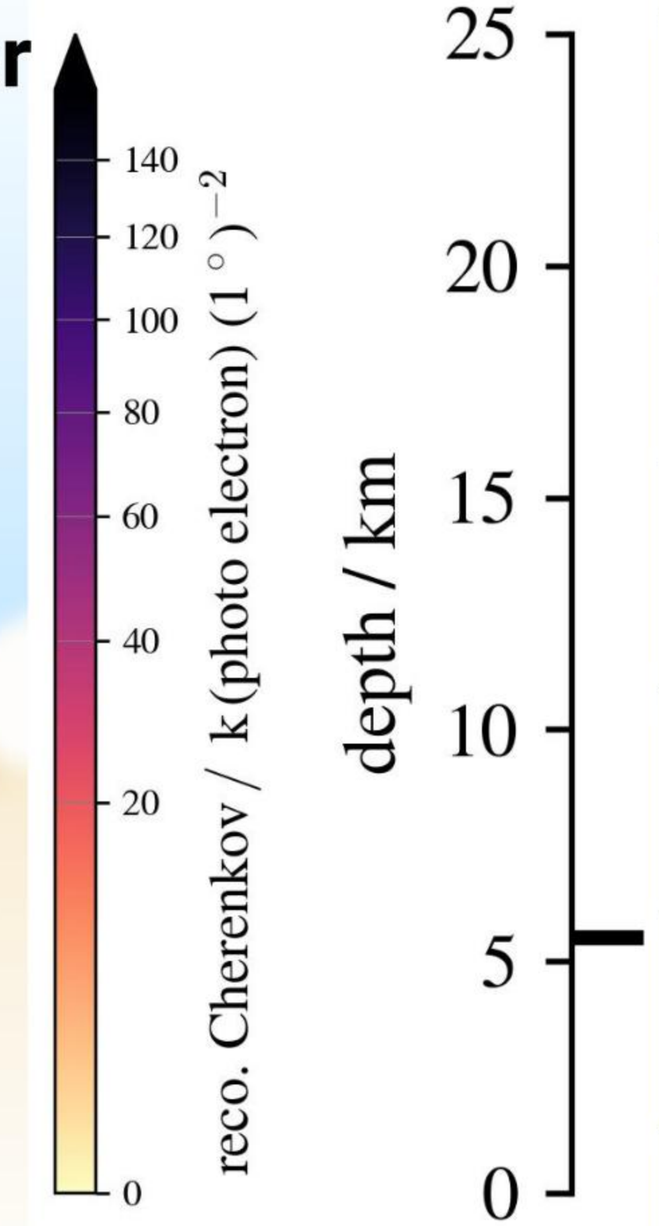

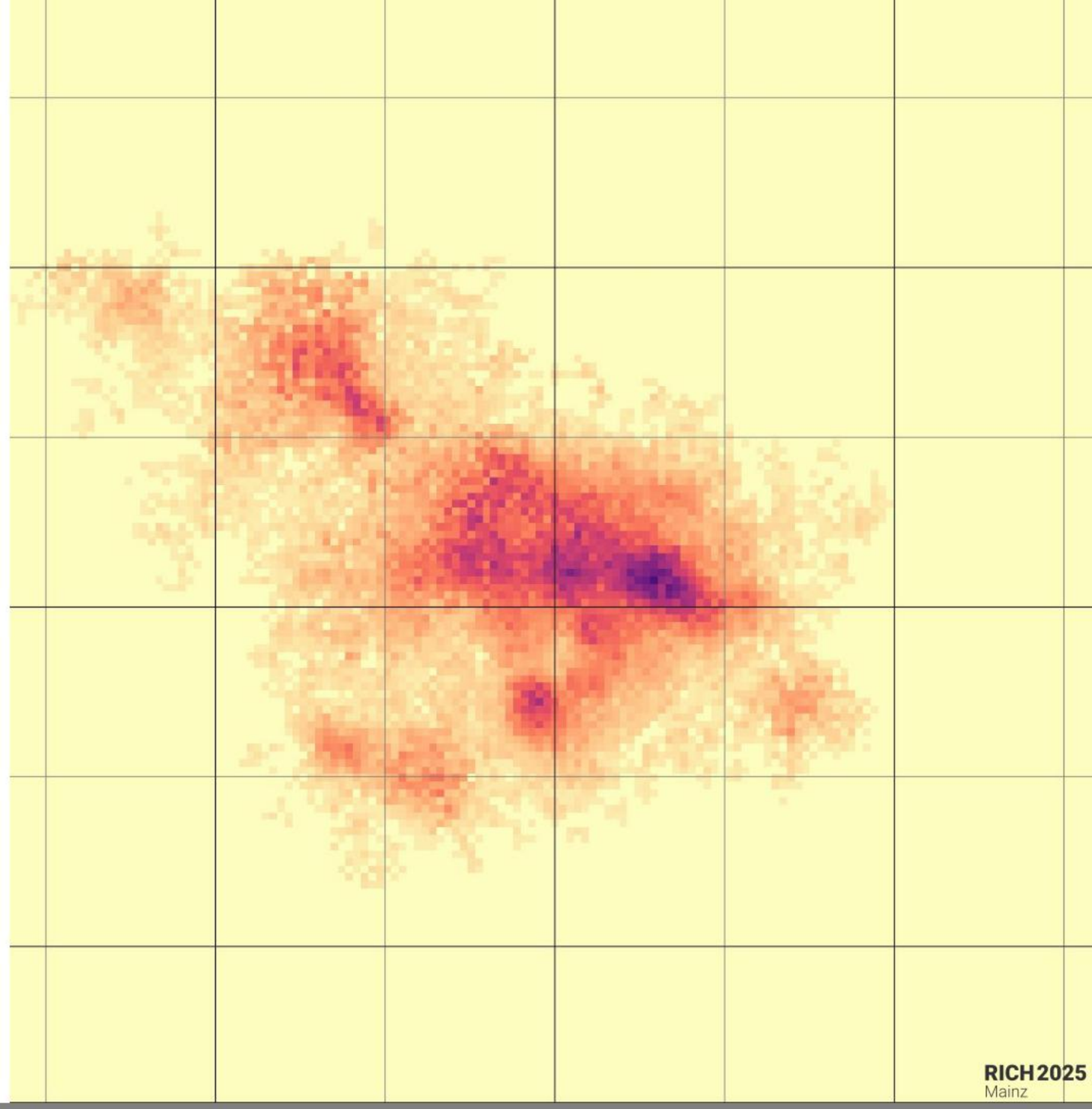

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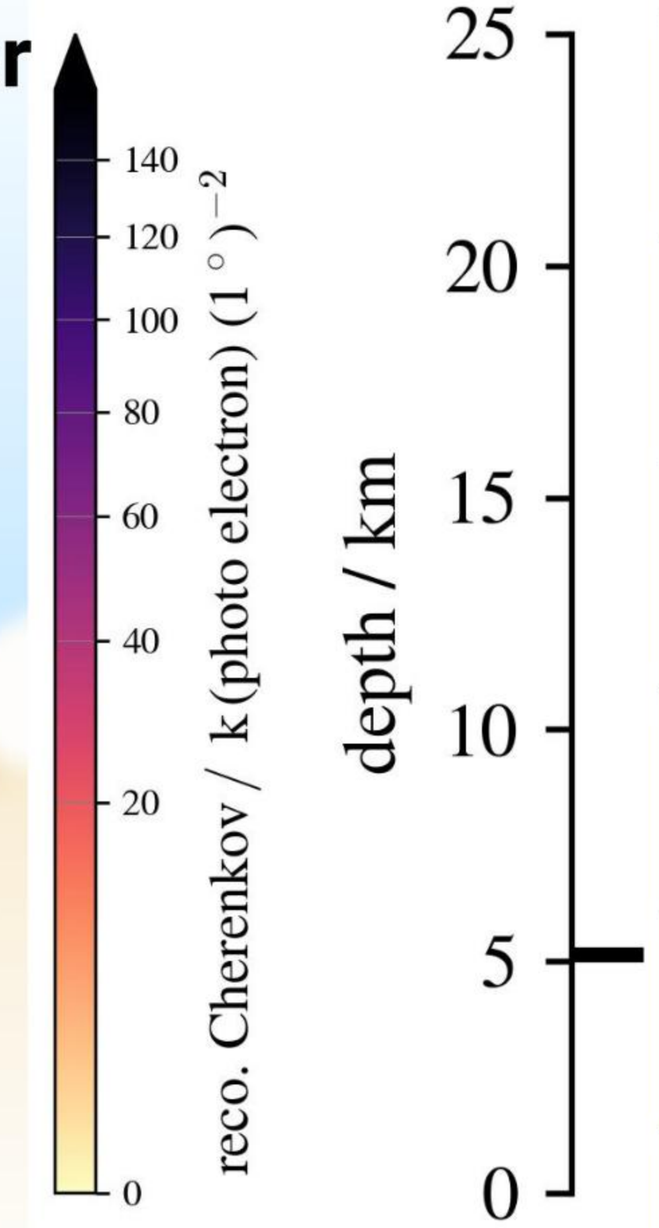

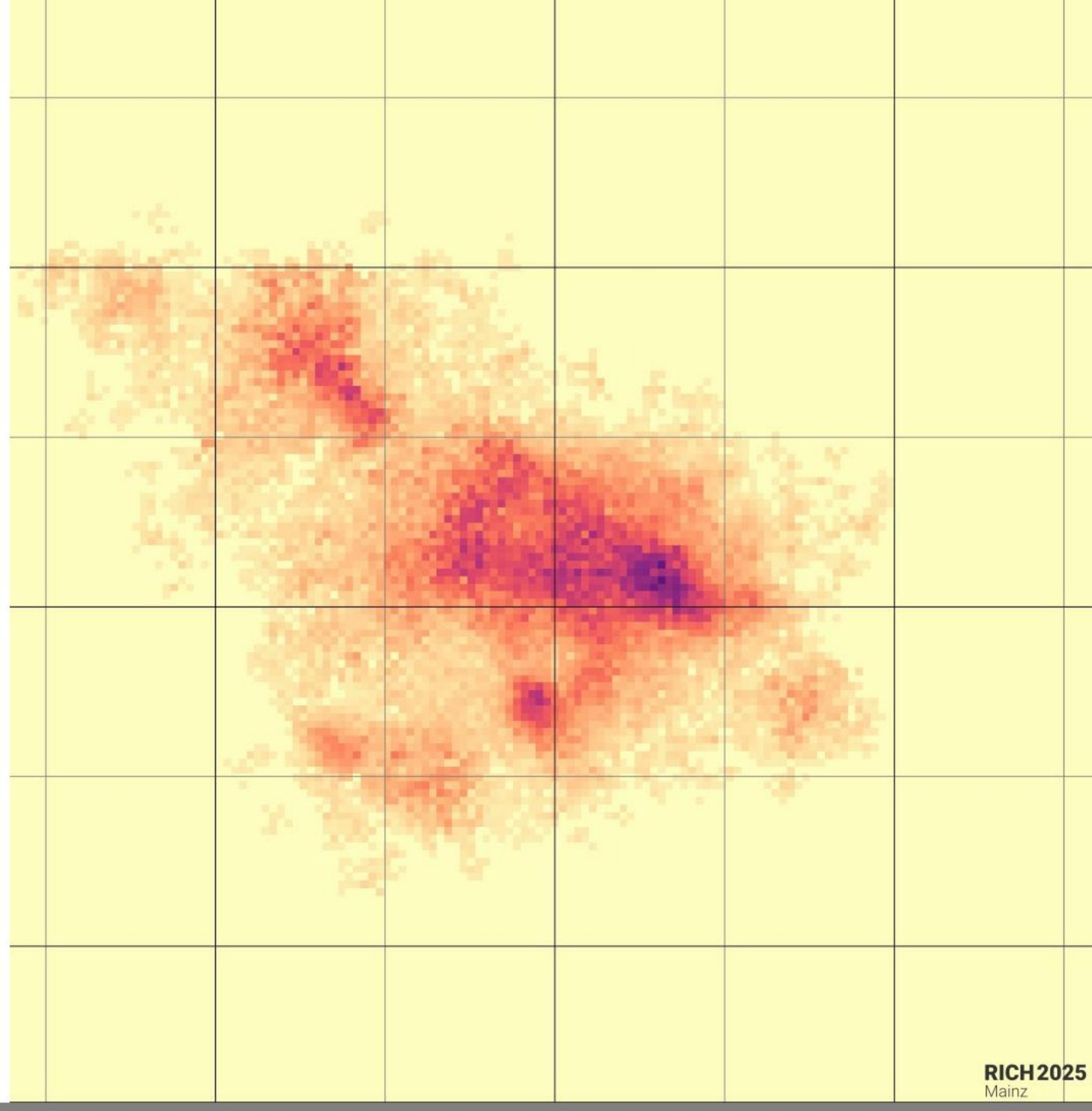

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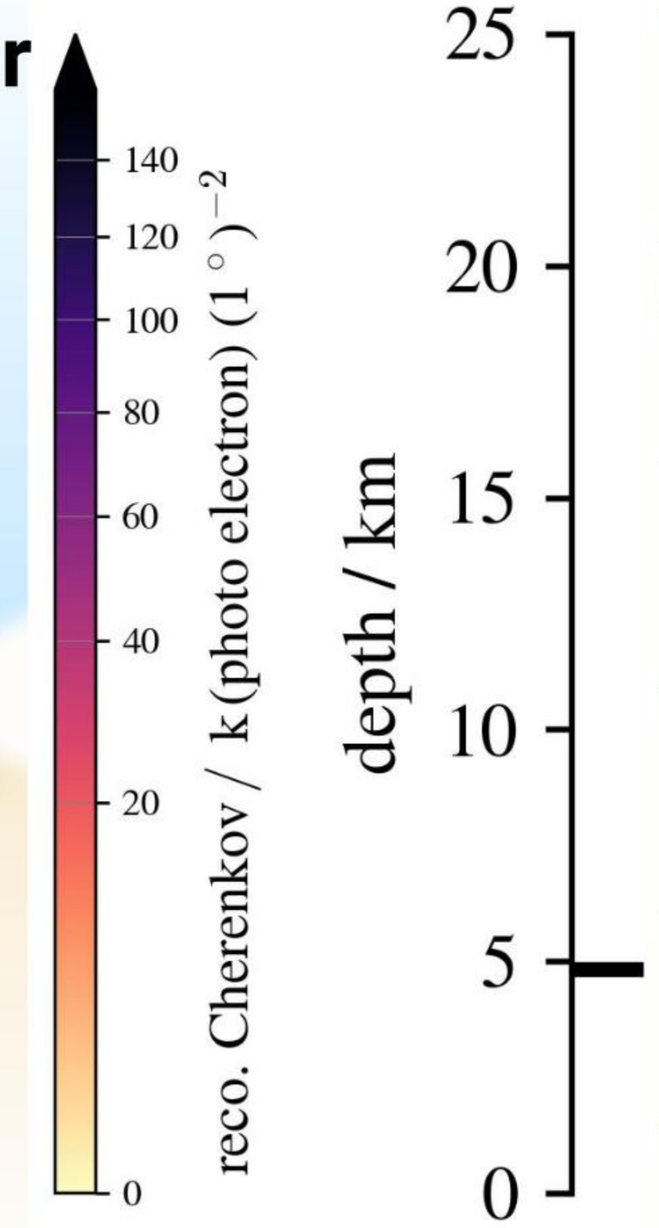

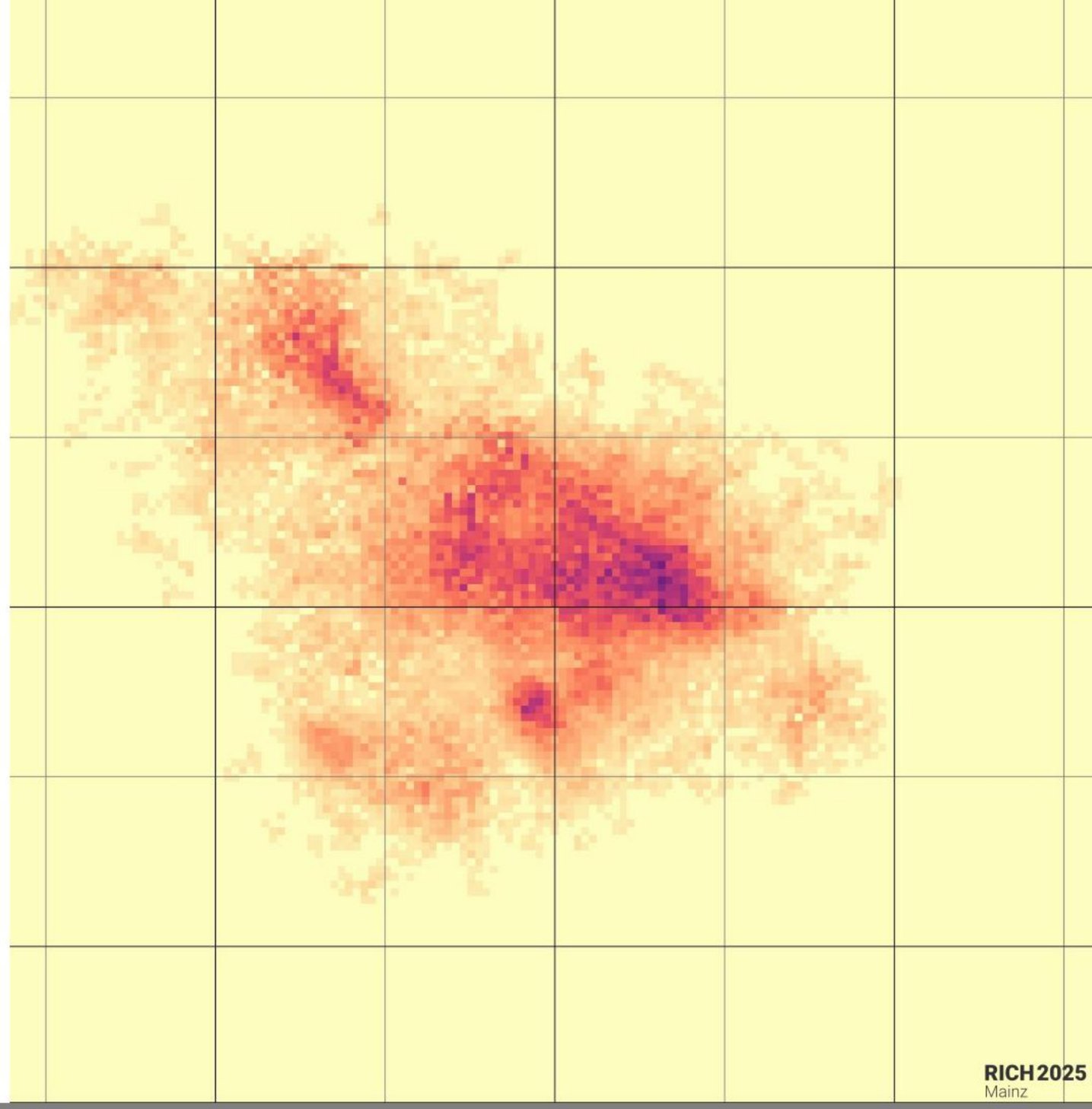

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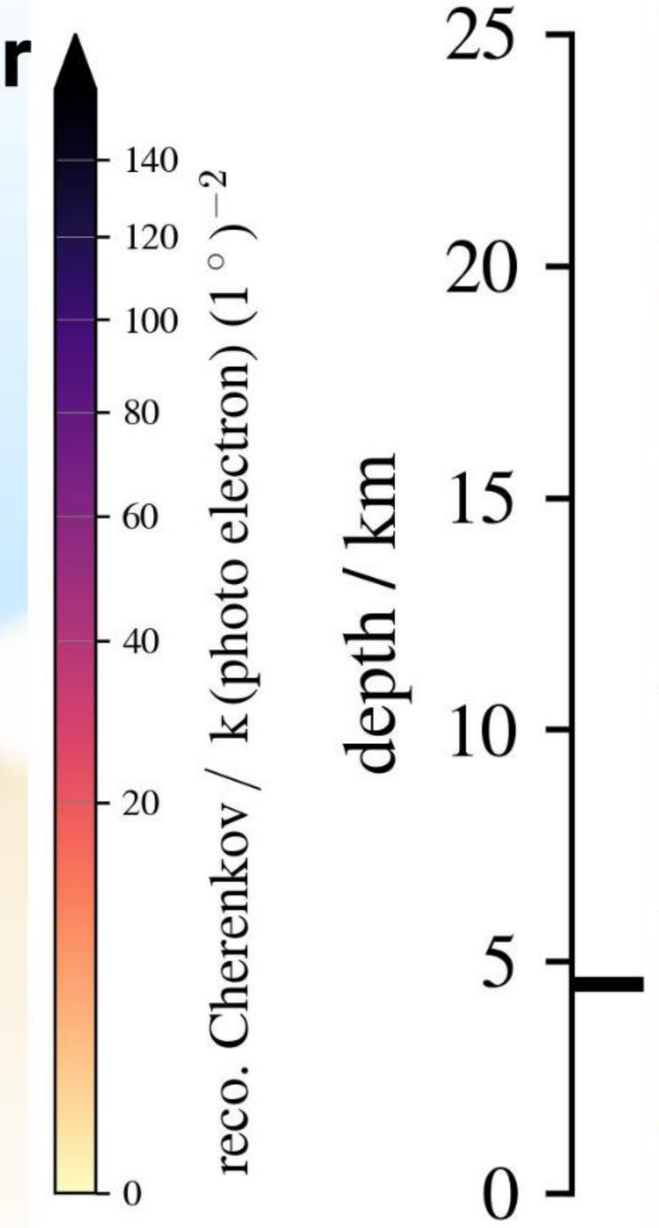

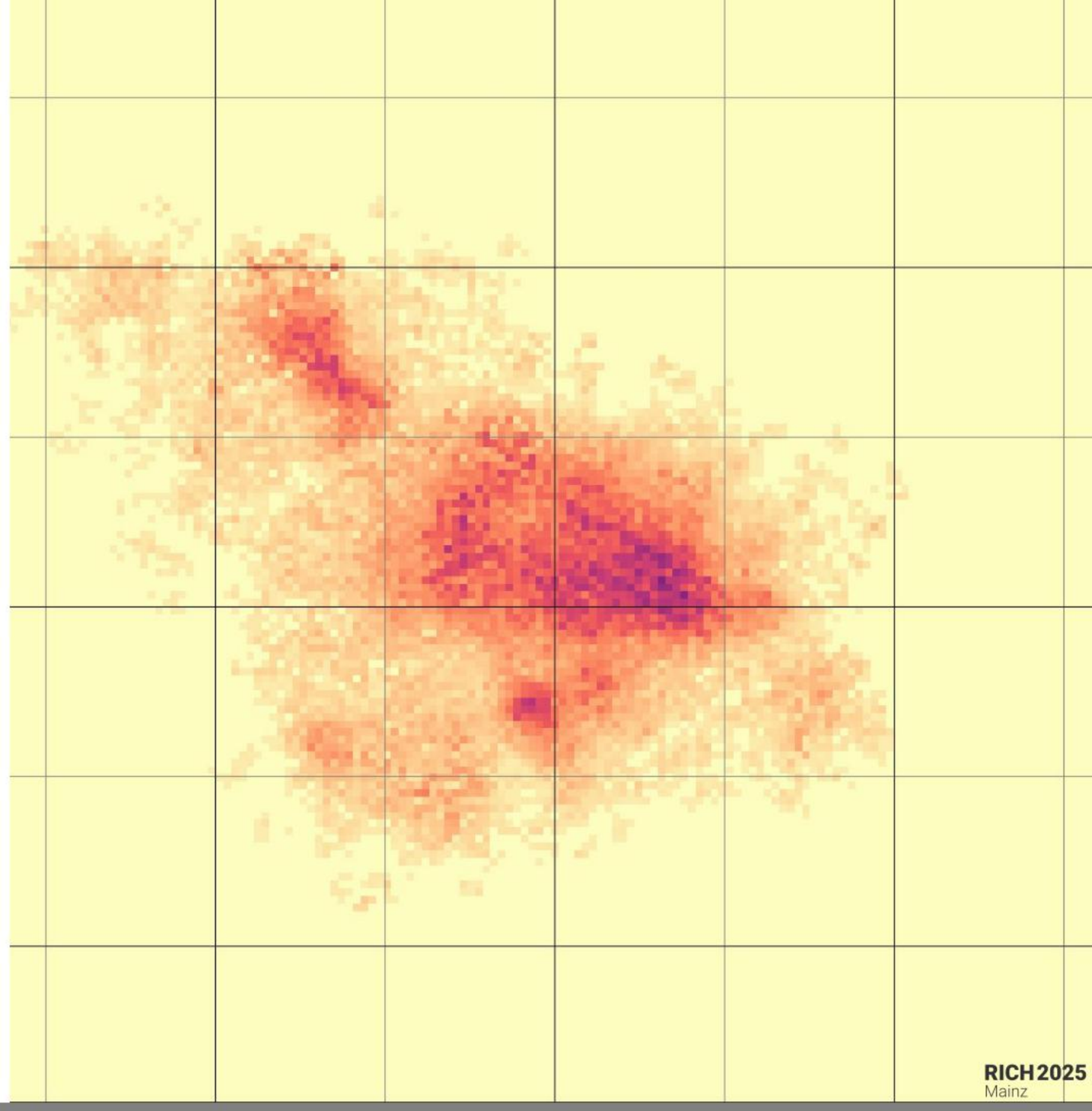

Airshower

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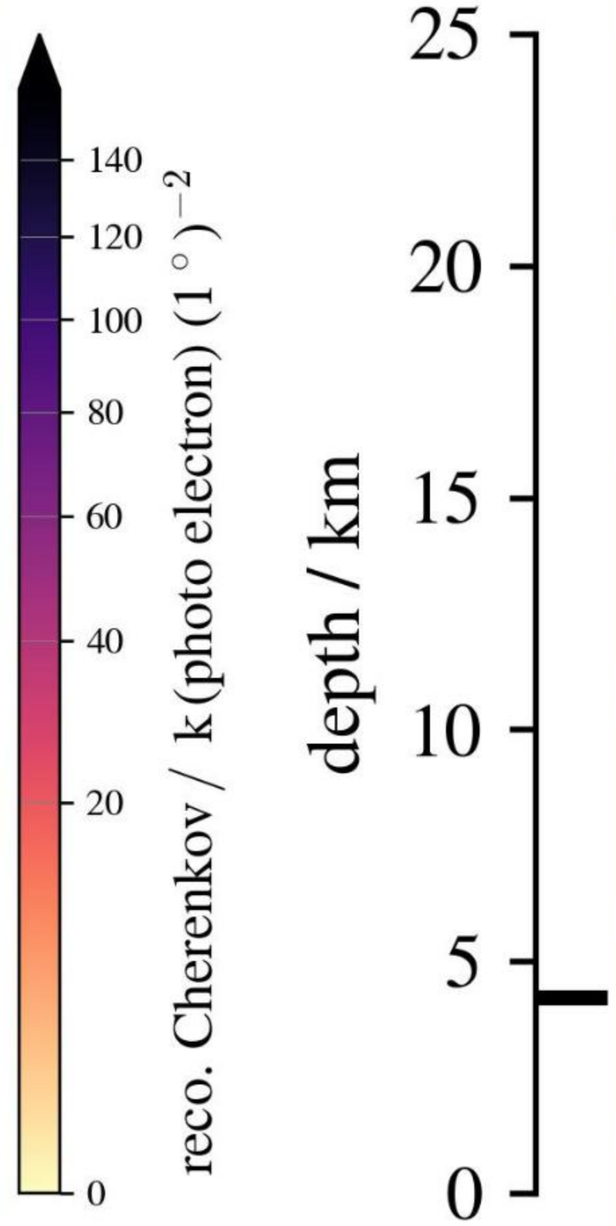

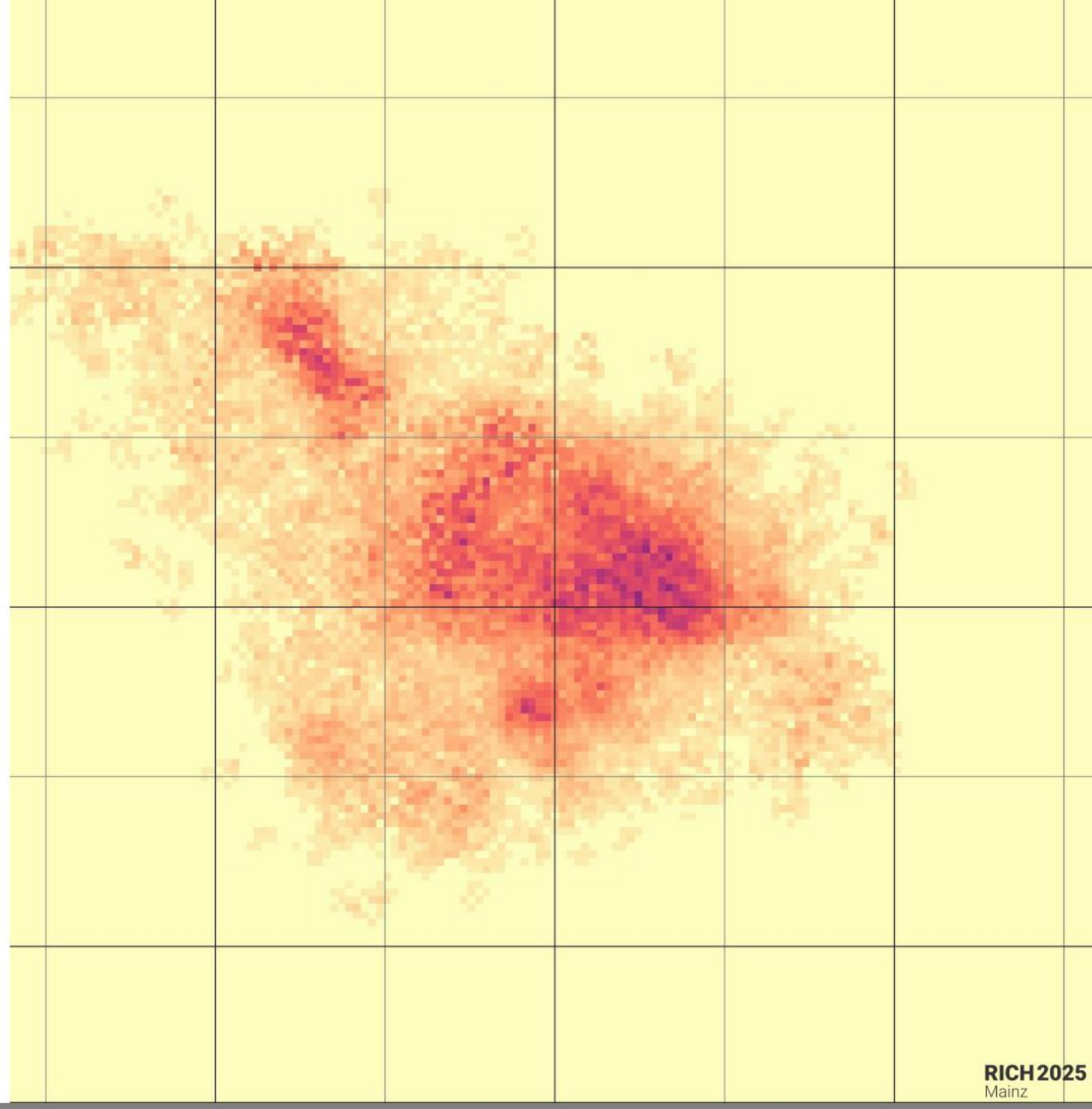

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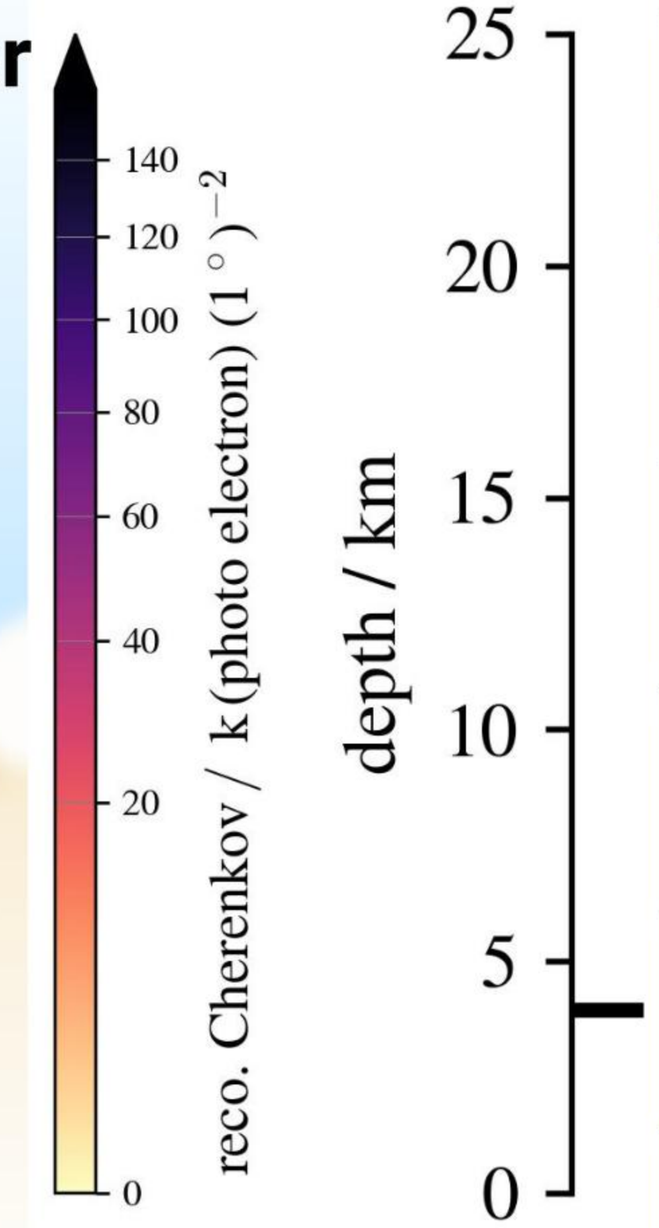

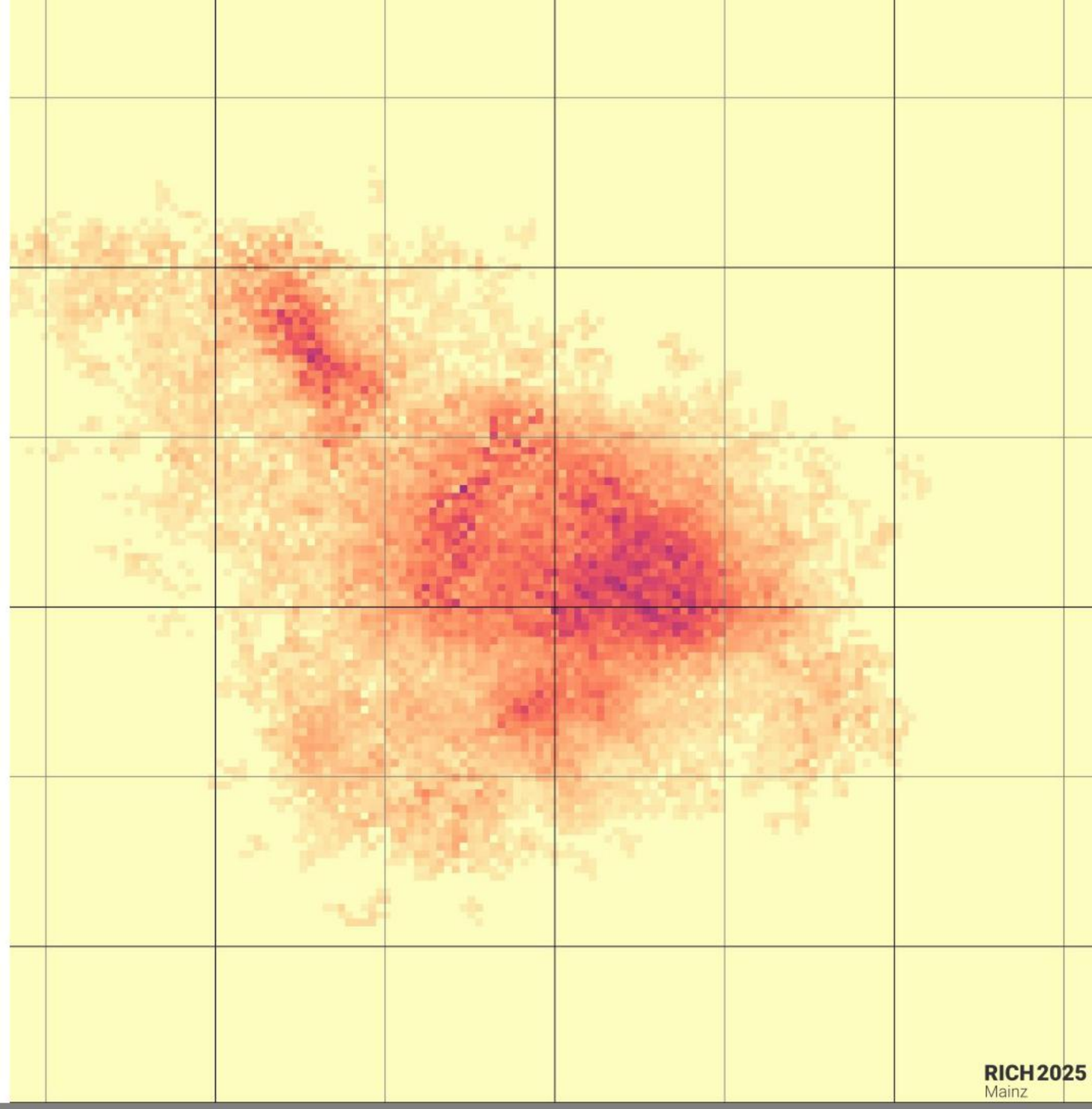

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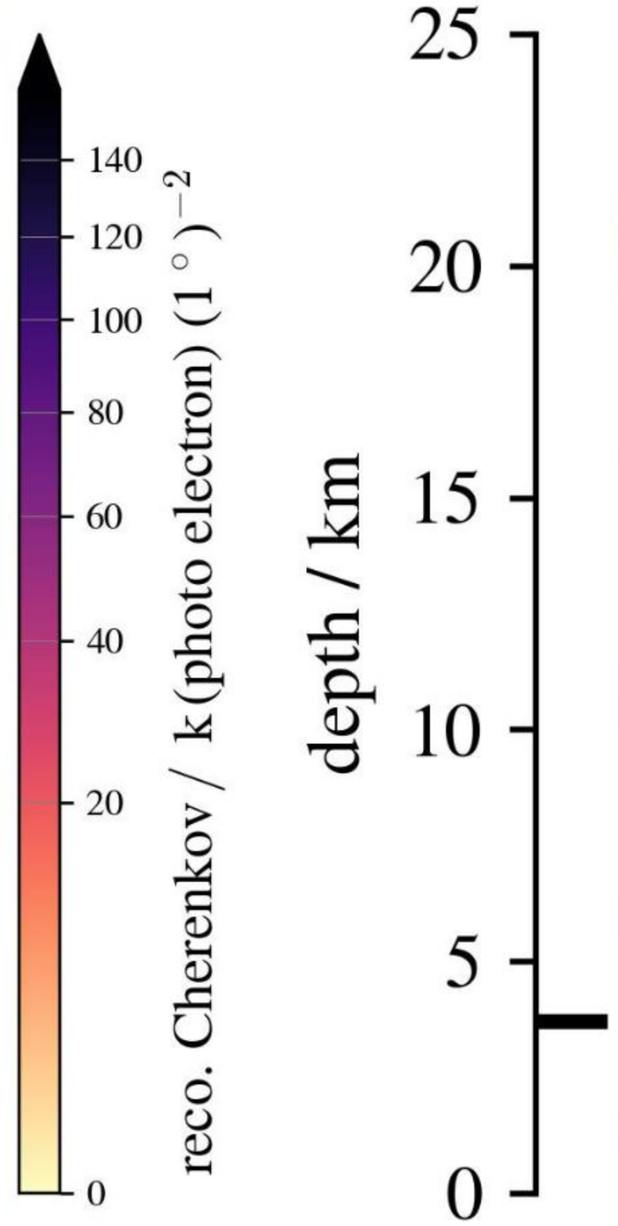

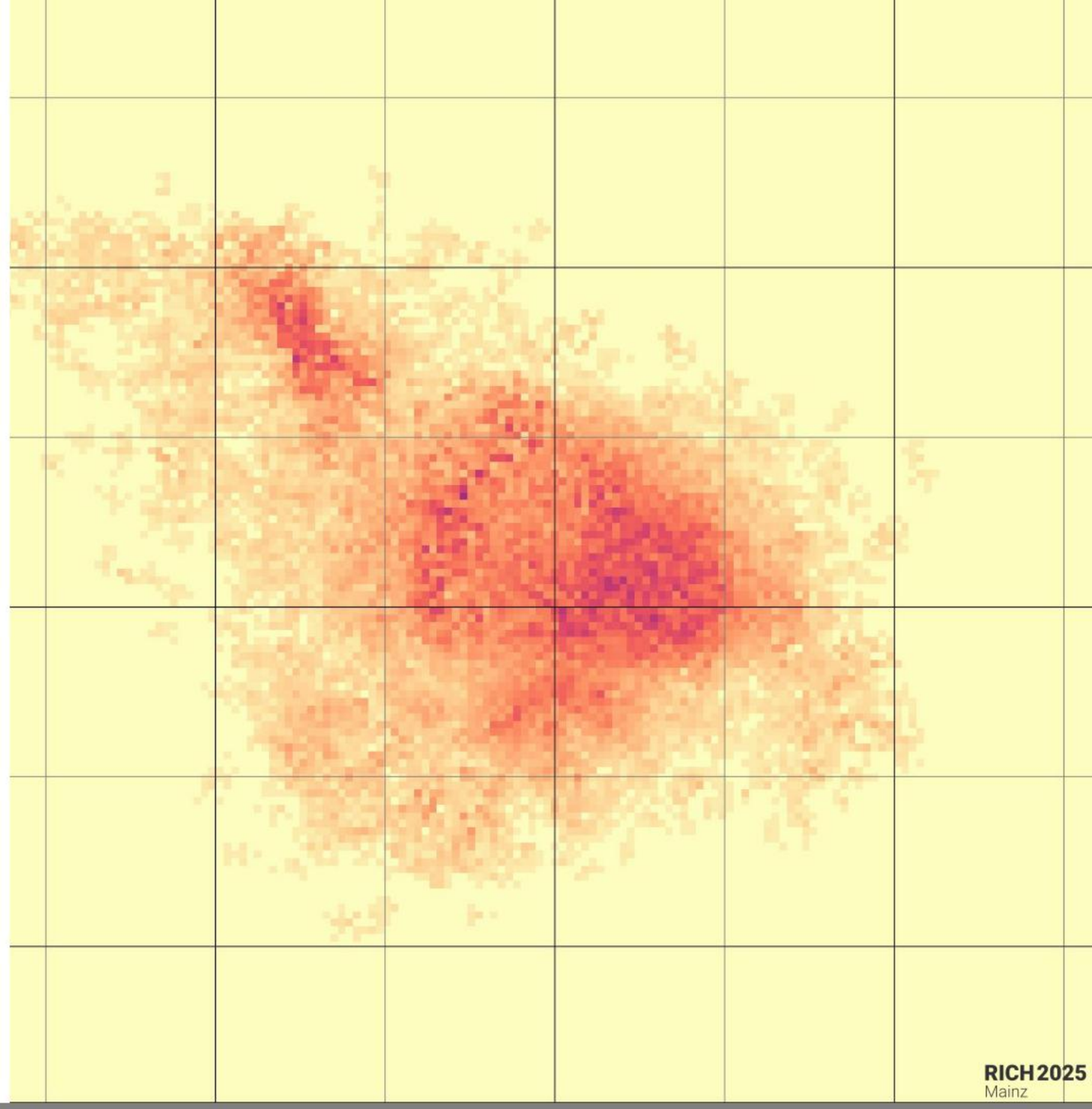

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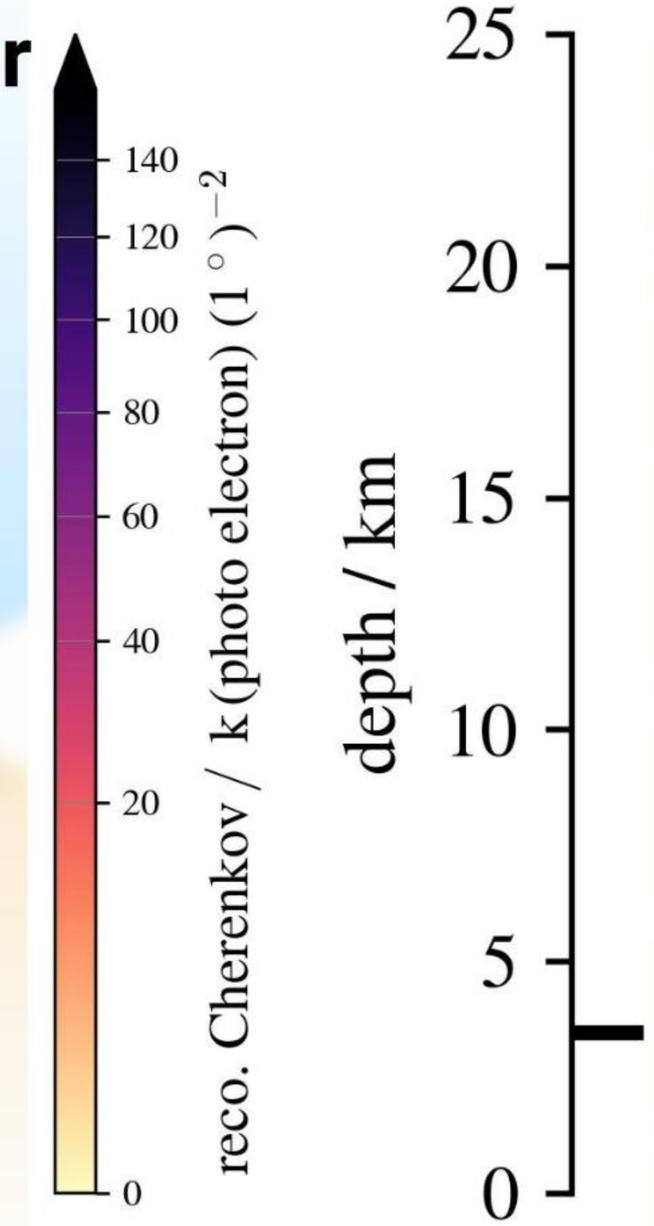

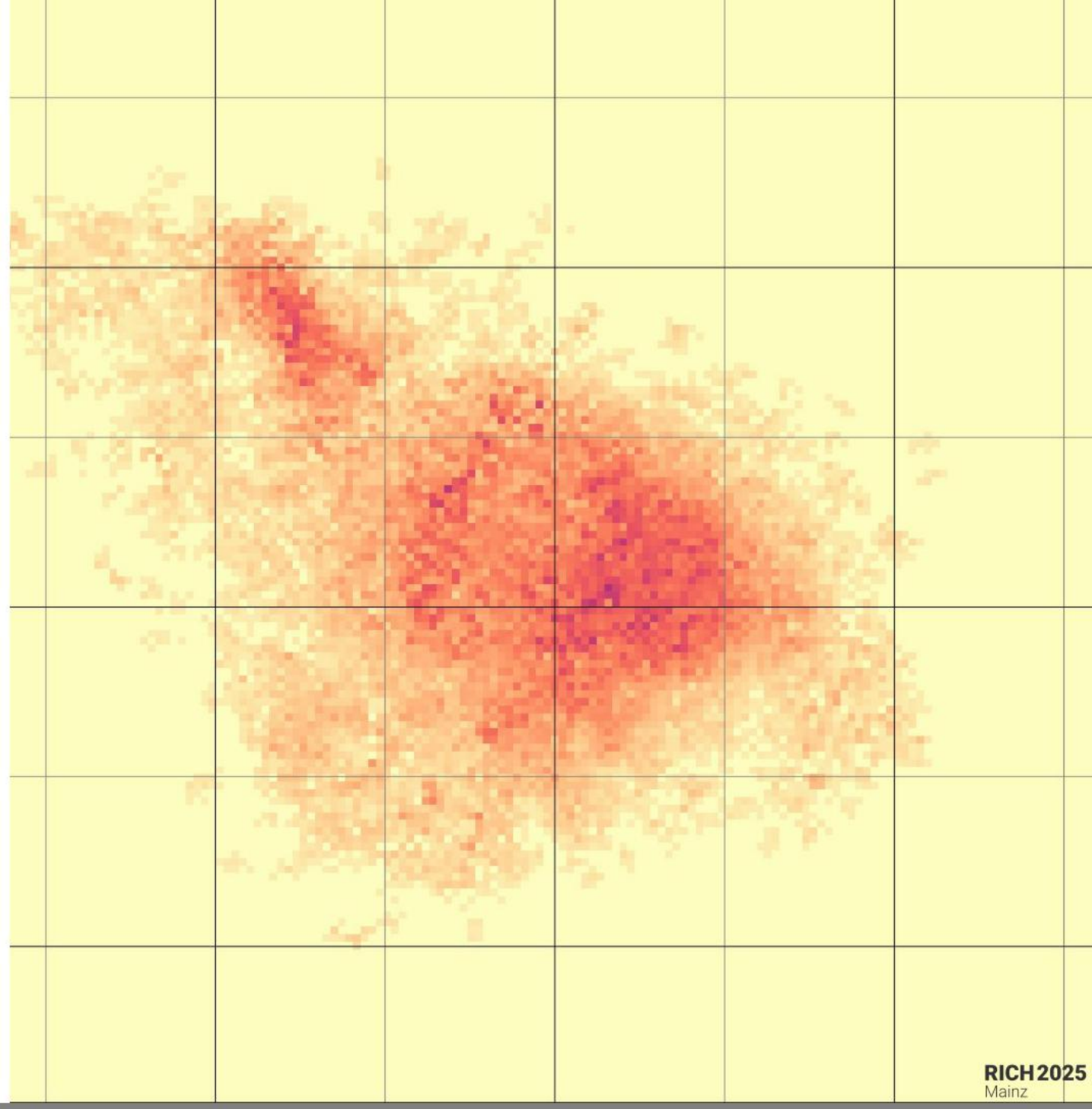

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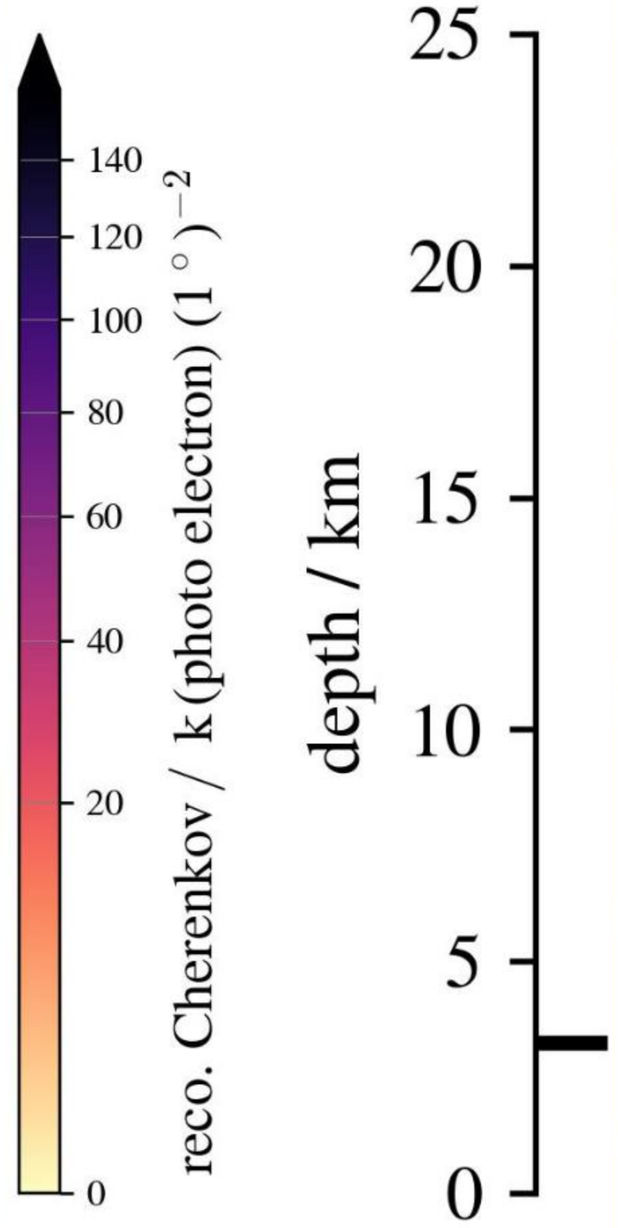

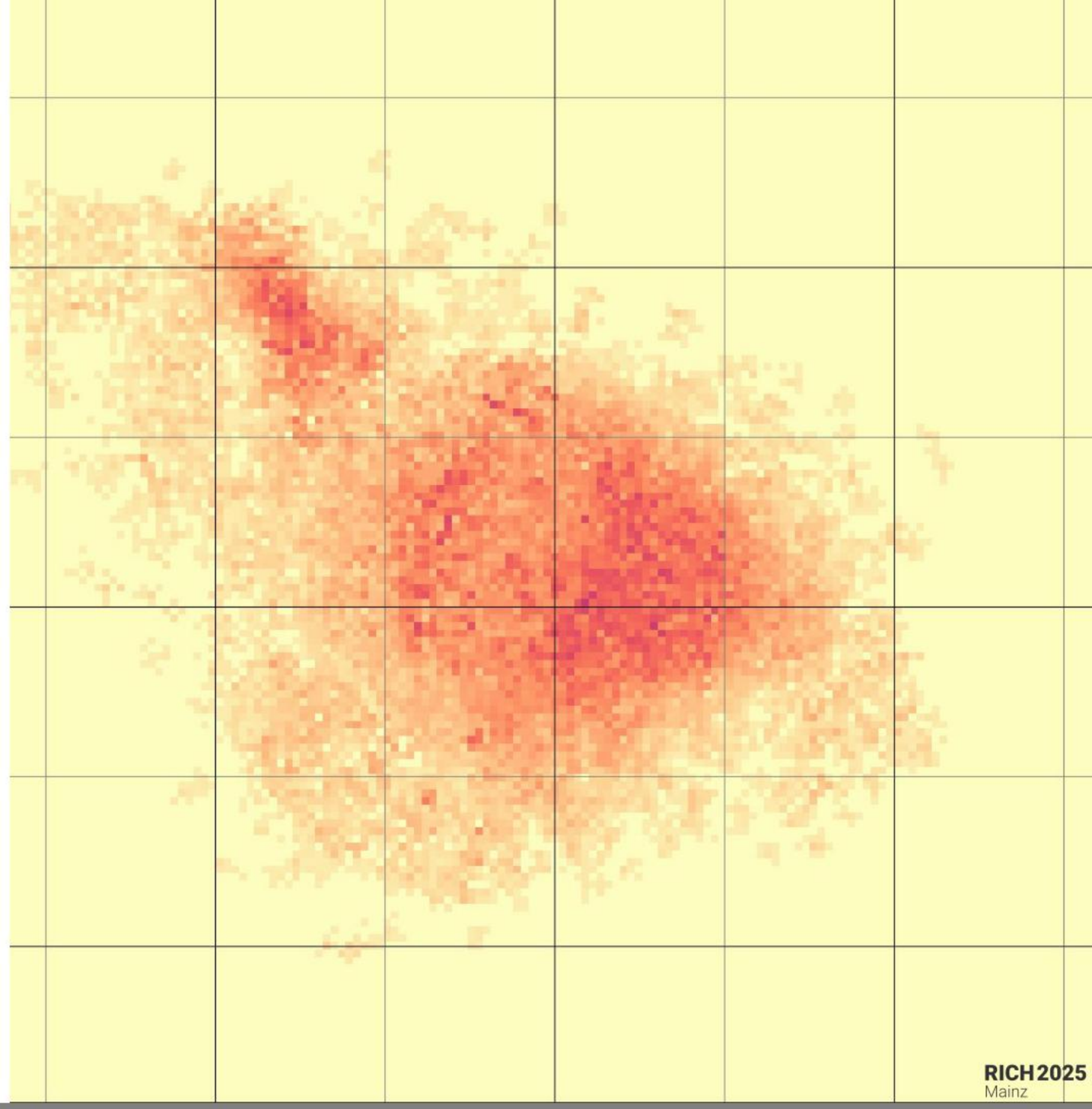

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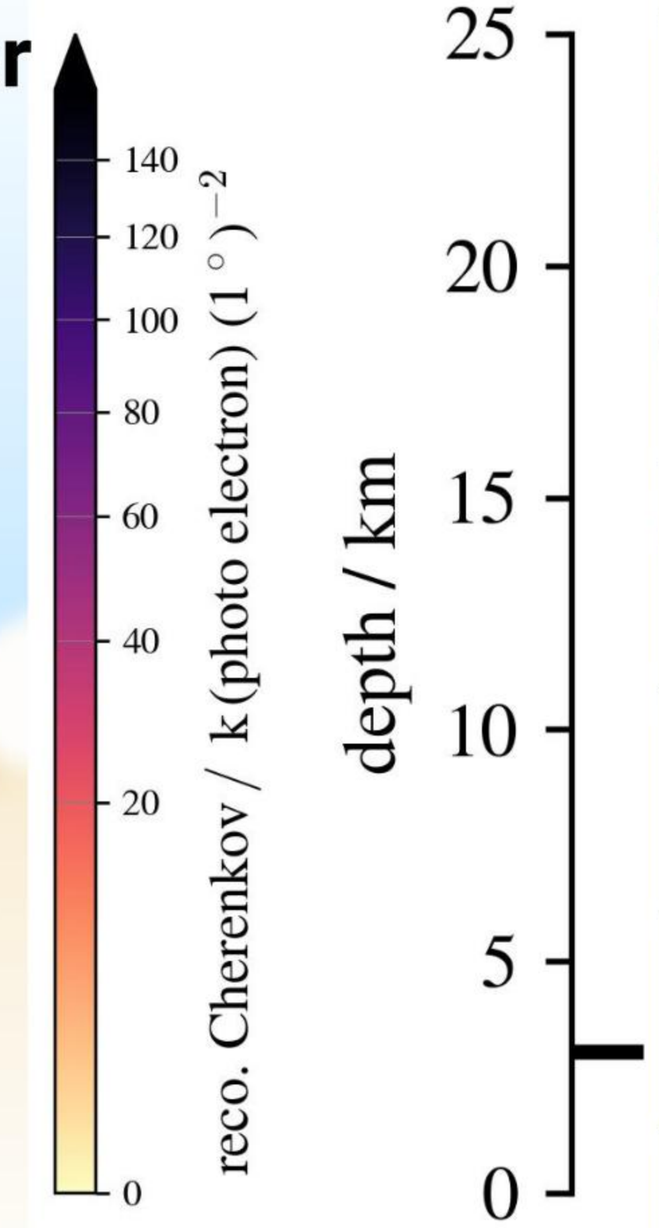
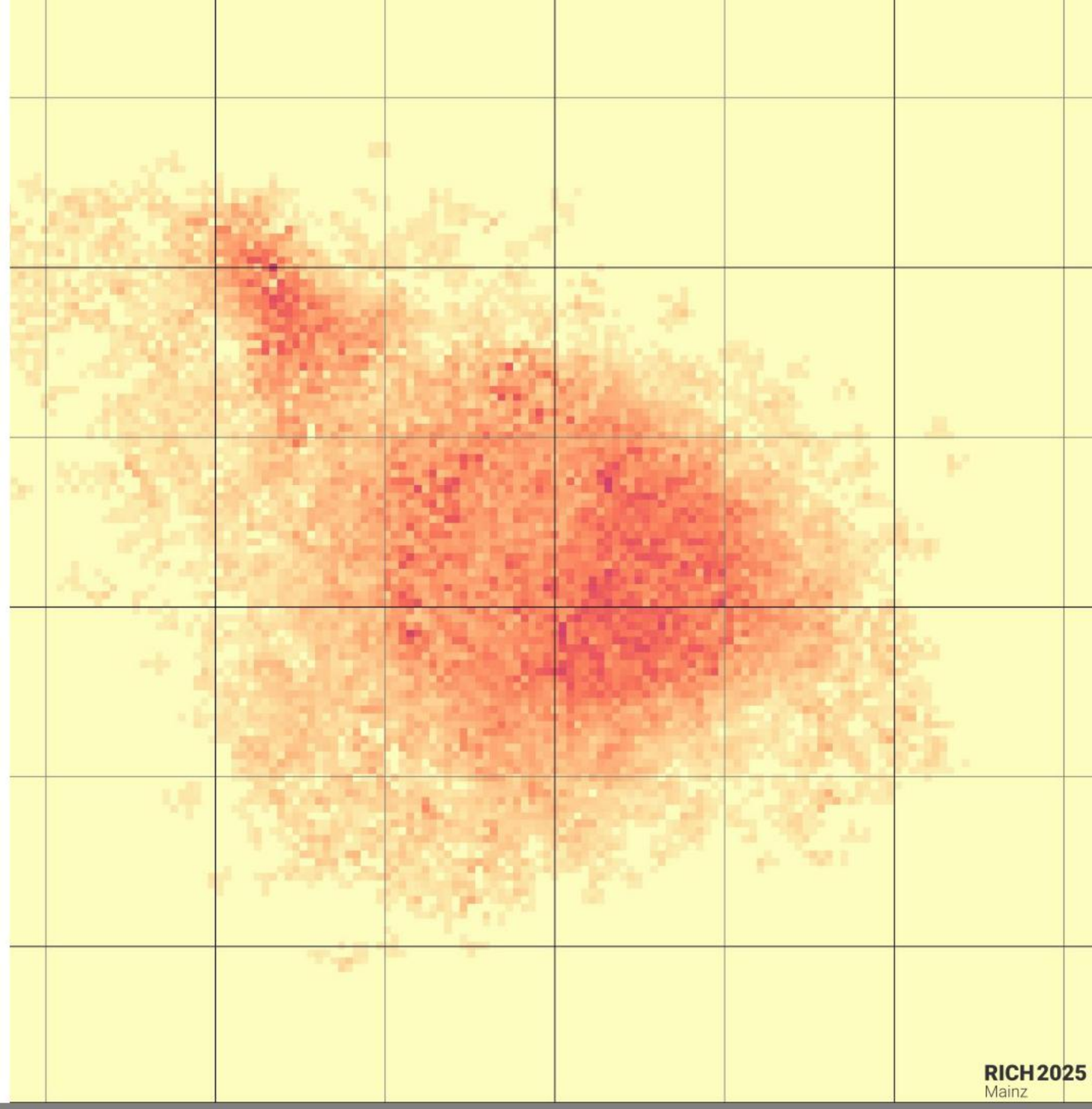
882GeV

13,473p.e.



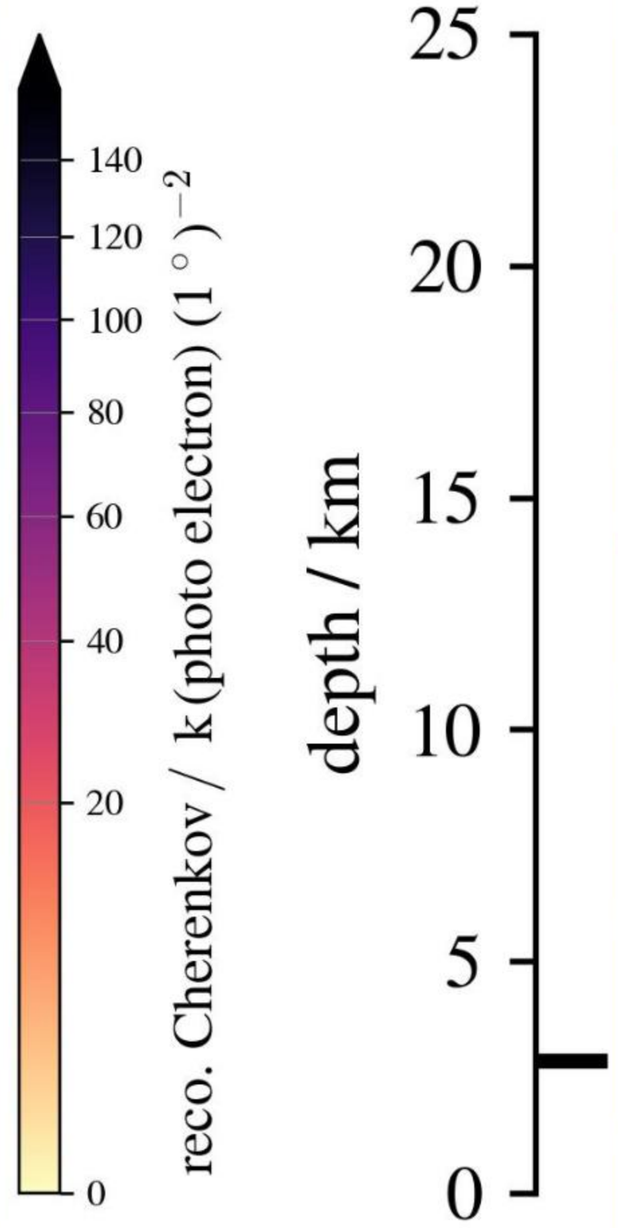


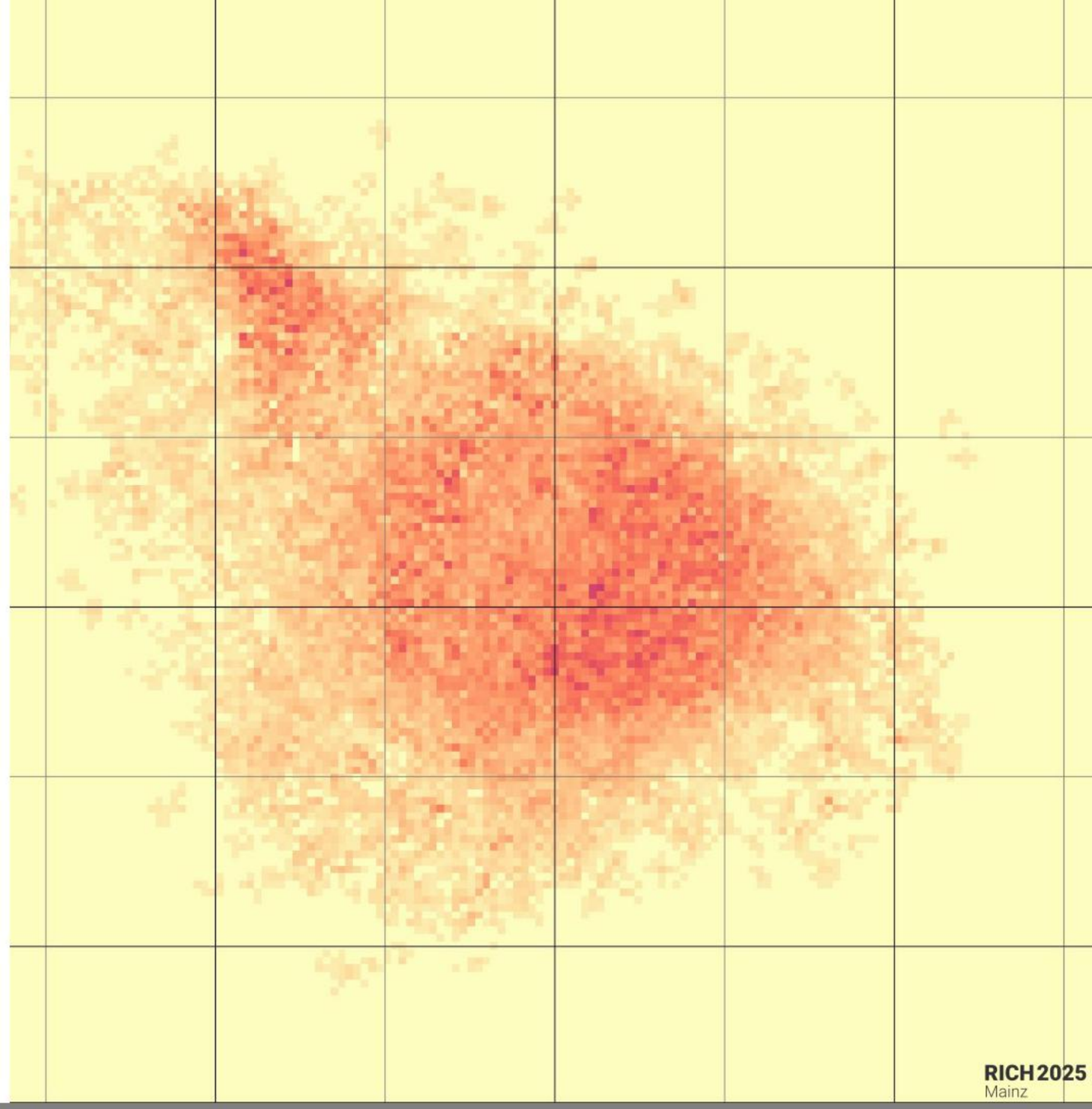
Airshower

Helium

882GeV

13,473p.e.



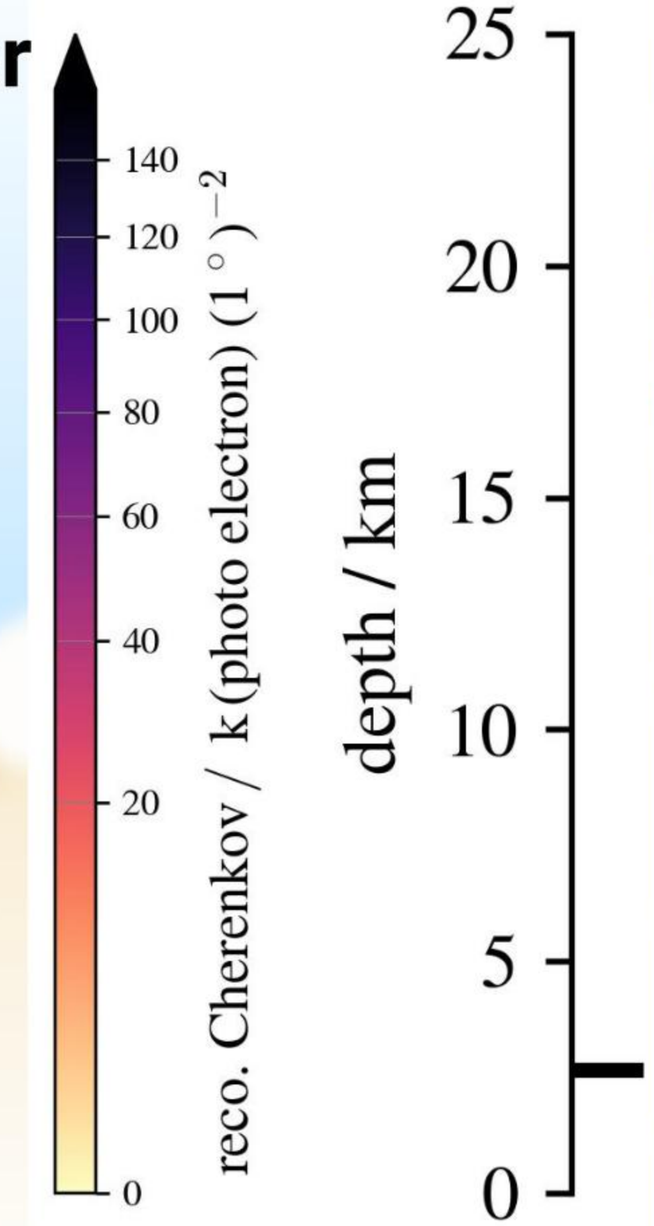


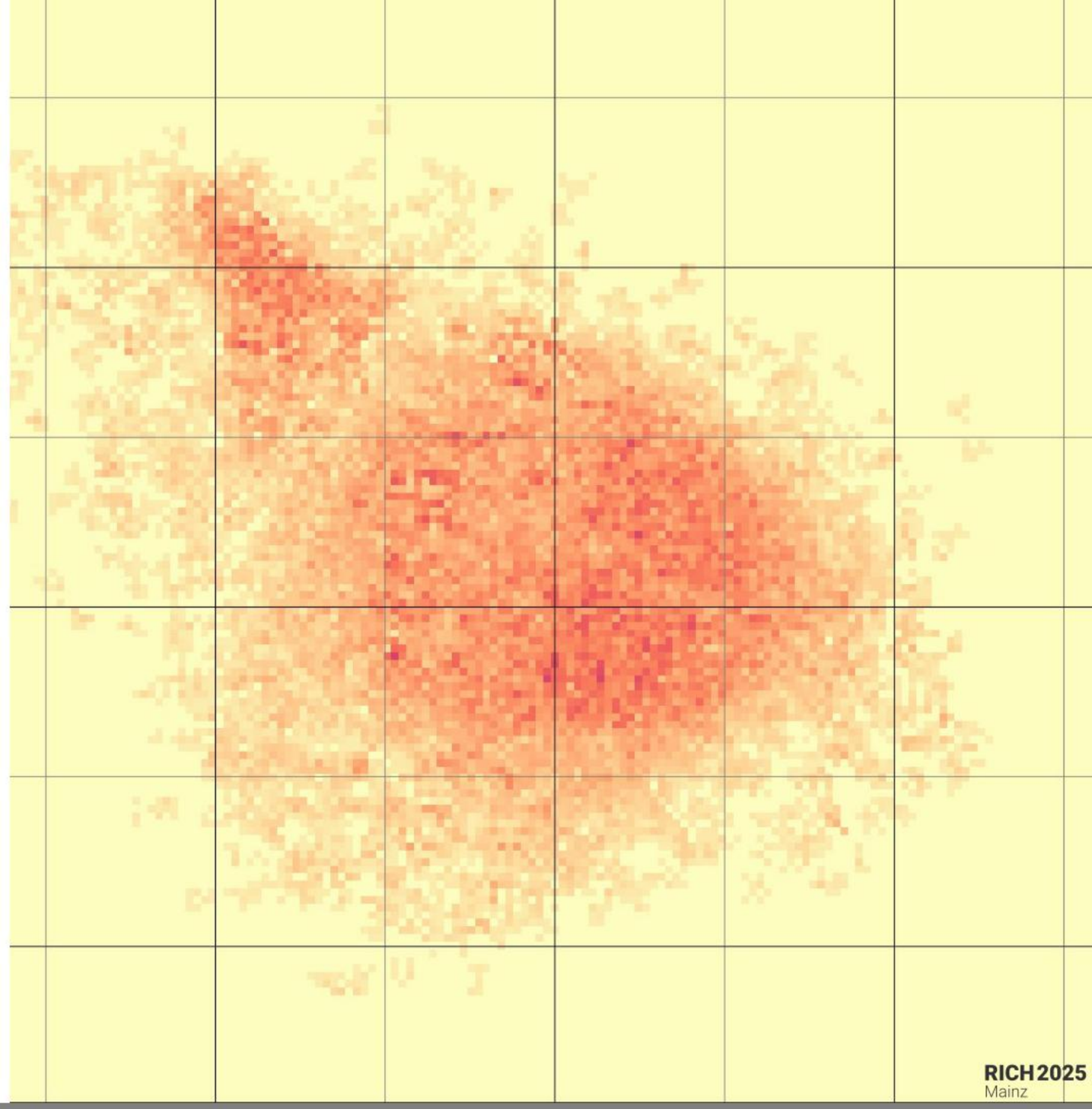
Airshower

Helium

882GeV

13,473p.e.



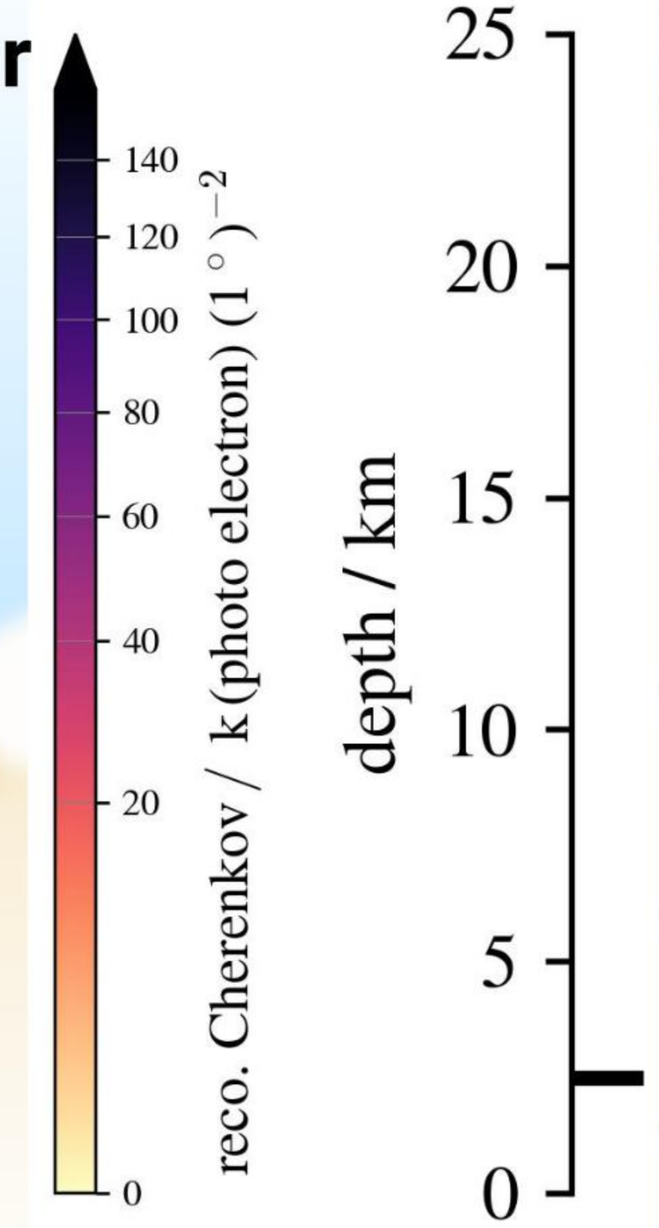


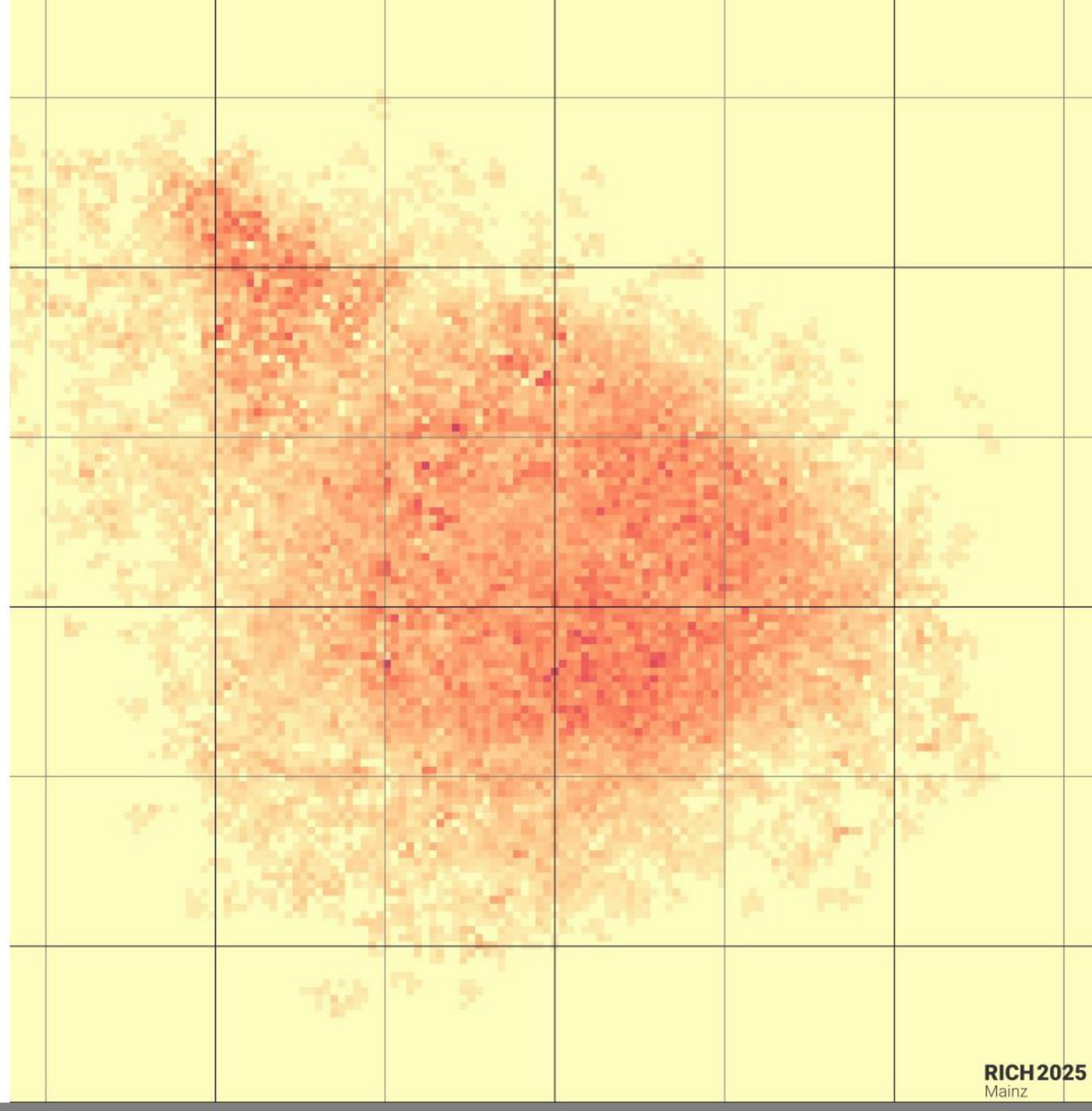
Airshower

Helium

882GeV

13,473p.e.





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Helium

882GeV

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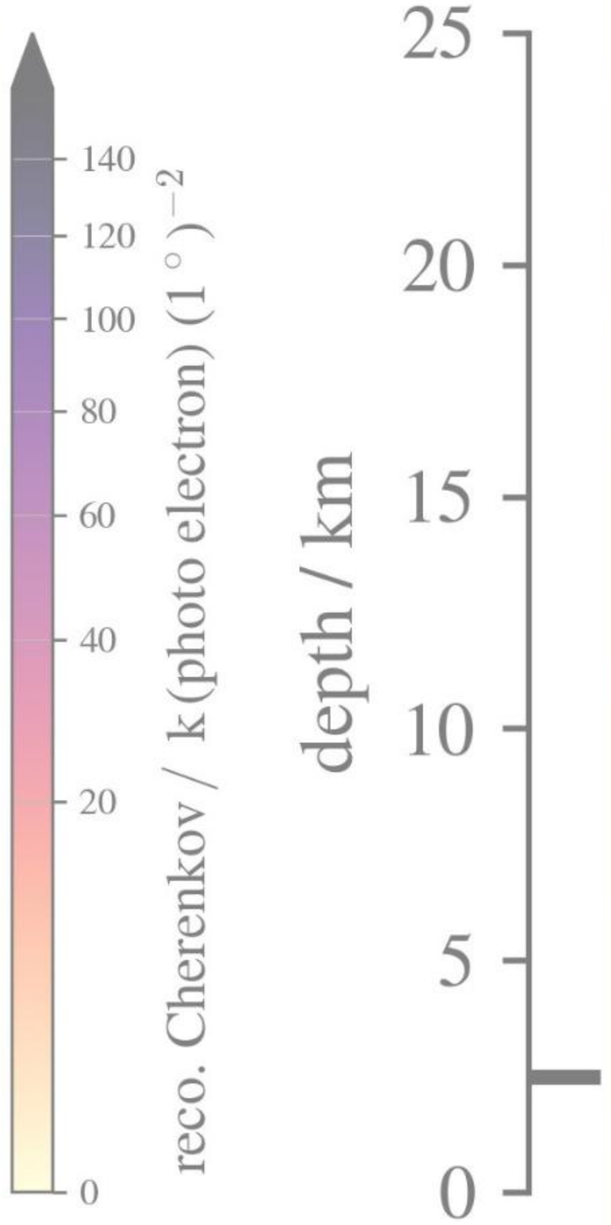
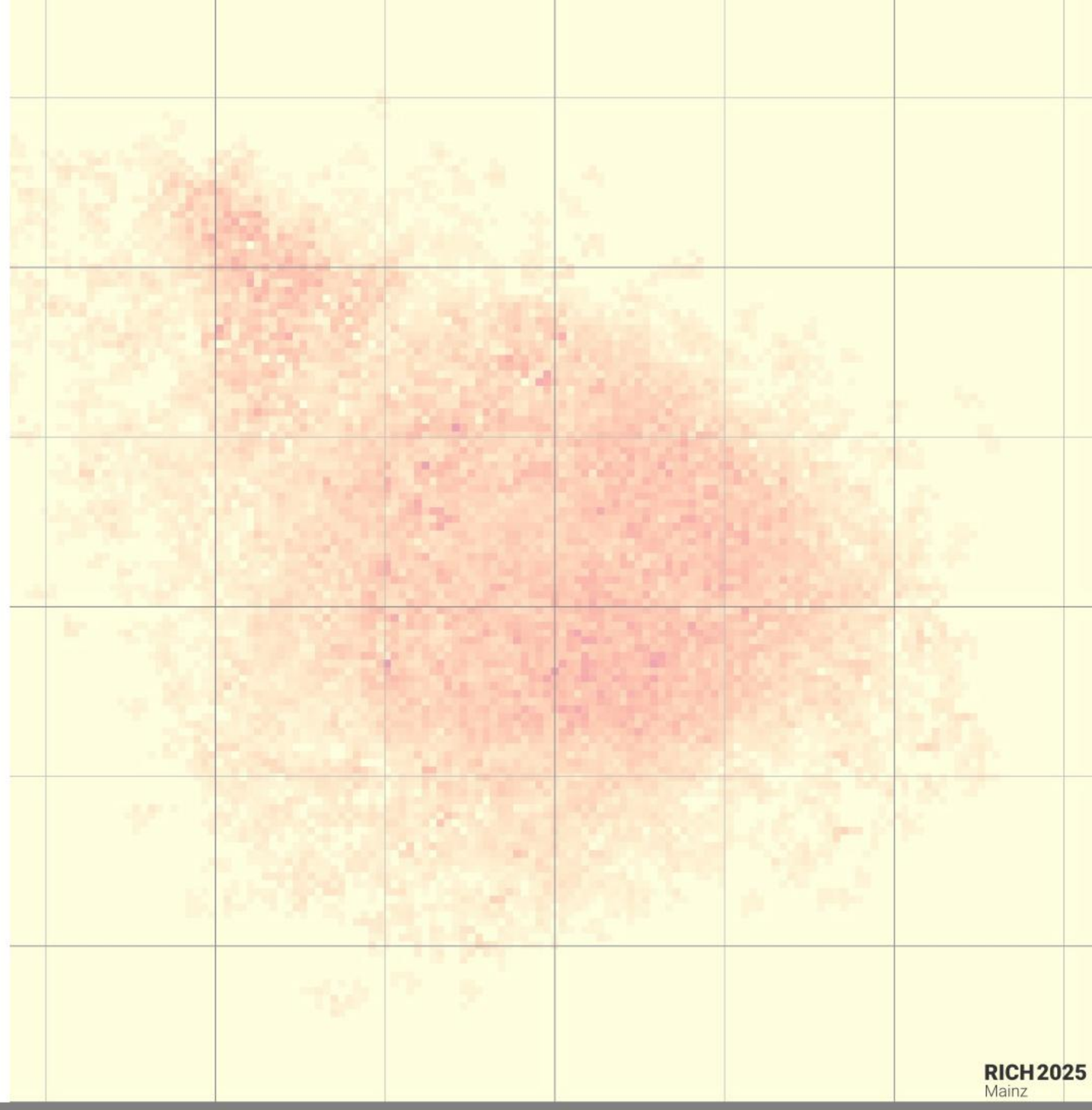




Airshower

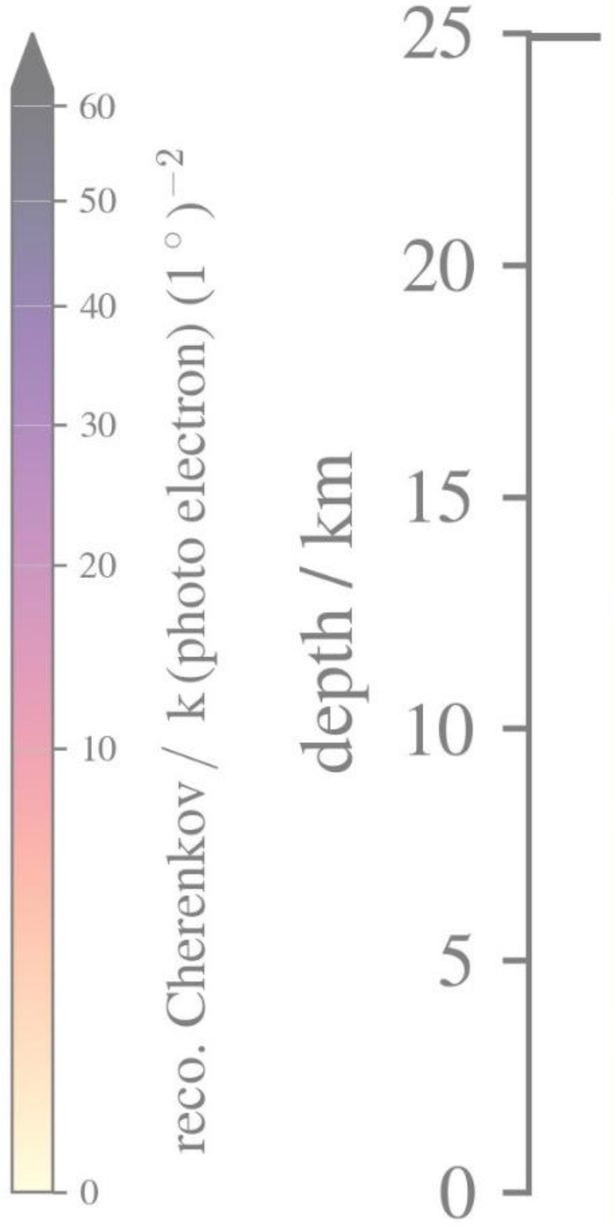
Proton

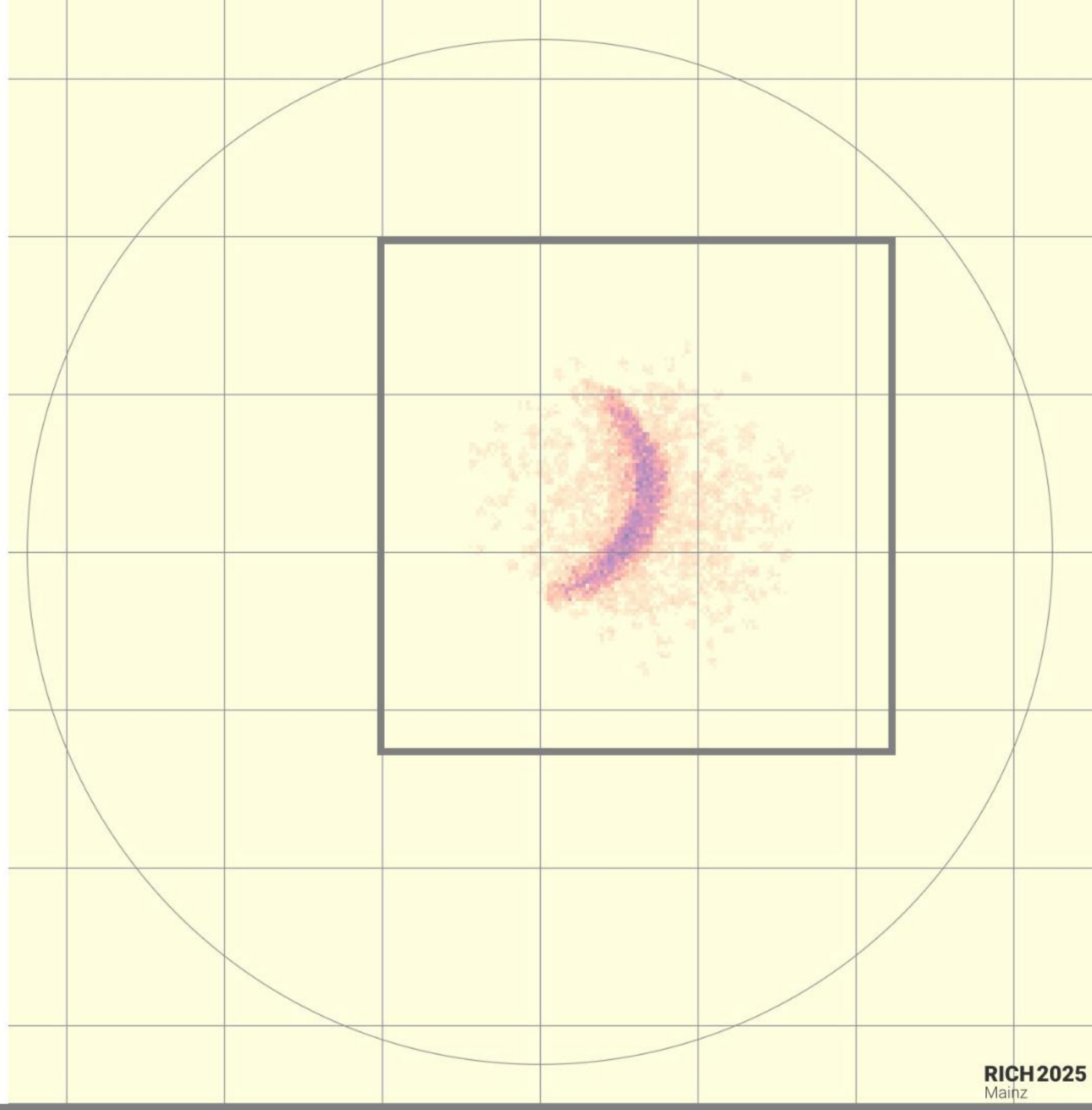
44GeV

4,814p.e.

Muon ring?

core > 1km





The plenoscope no longer misidentifies parts of Cherenkov rings to be high altitude airshowers as it can refocus to reveal nearby muons.

Airshower

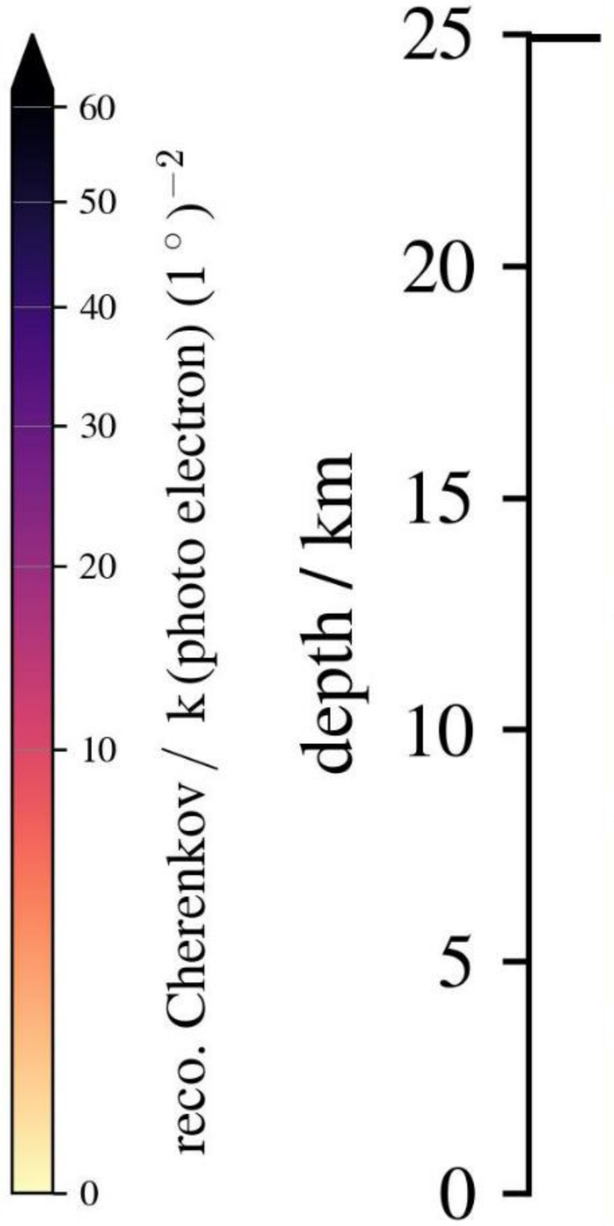
Proton

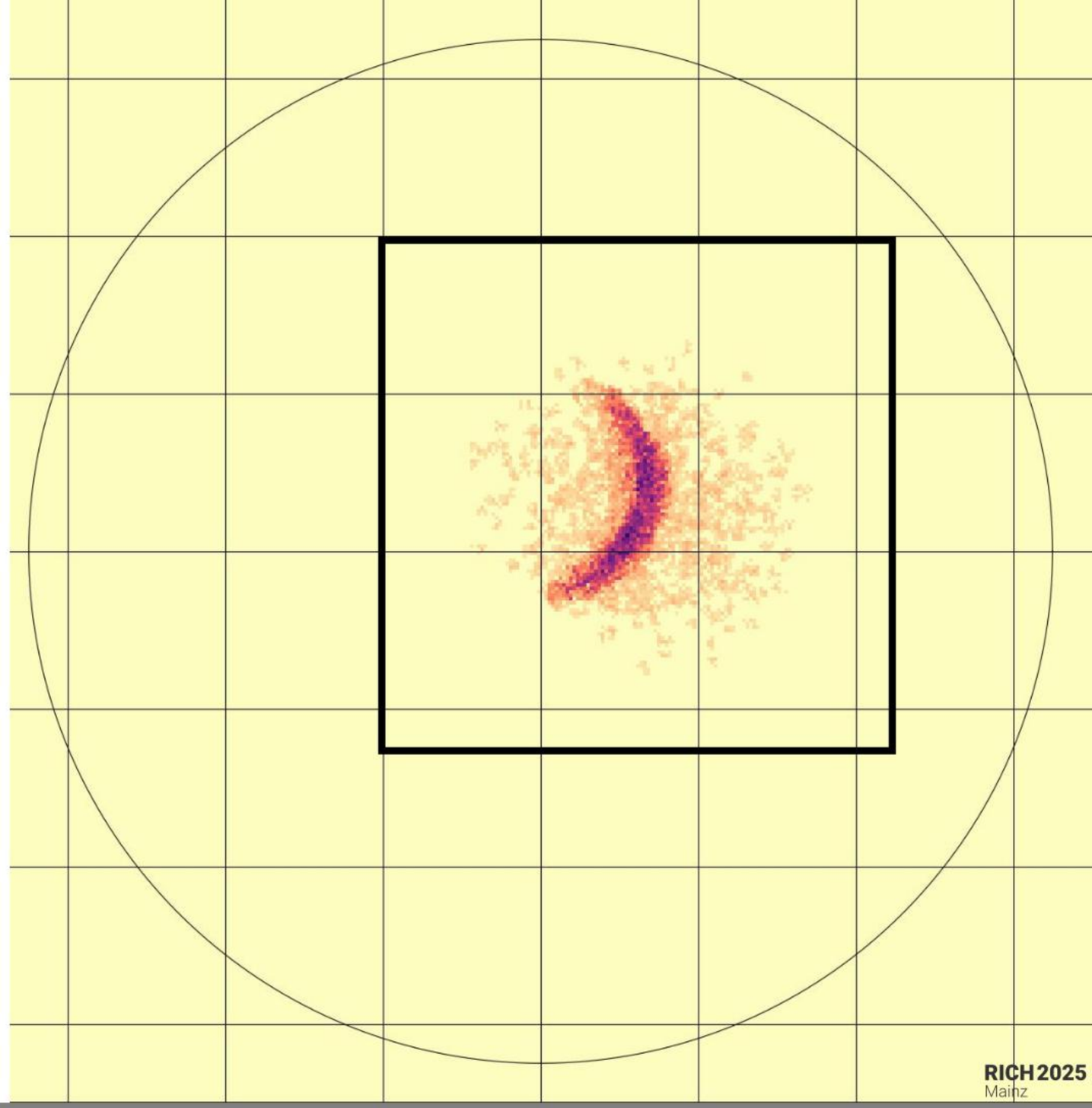
44GeV

4,814p.e.

Muon ring?

core > 1km





Airshower

Proton

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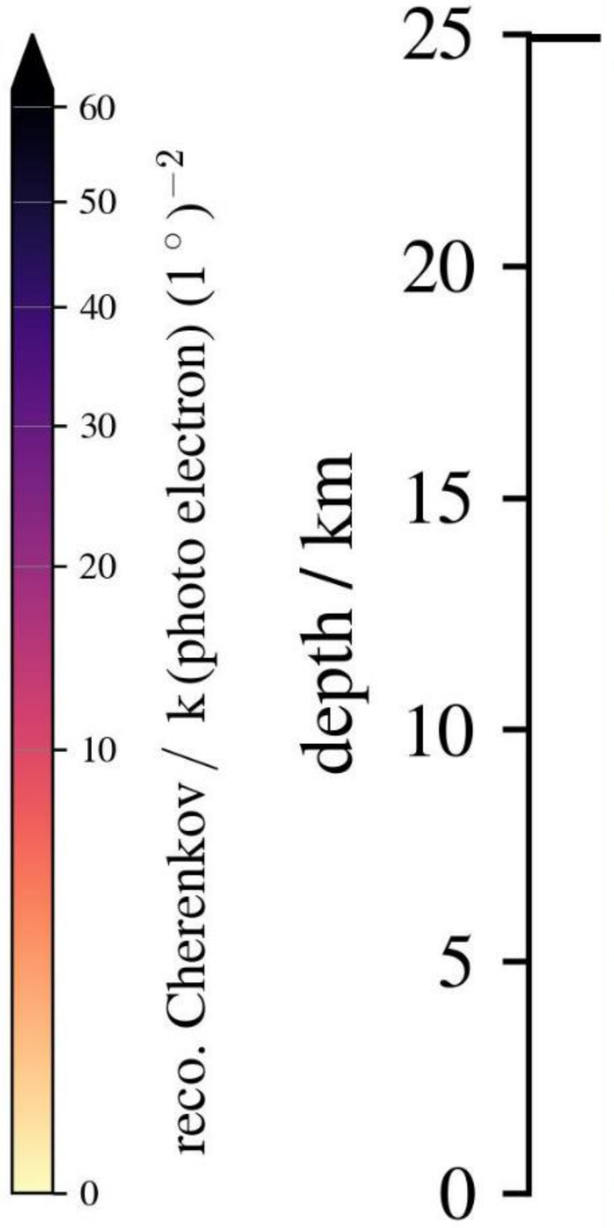
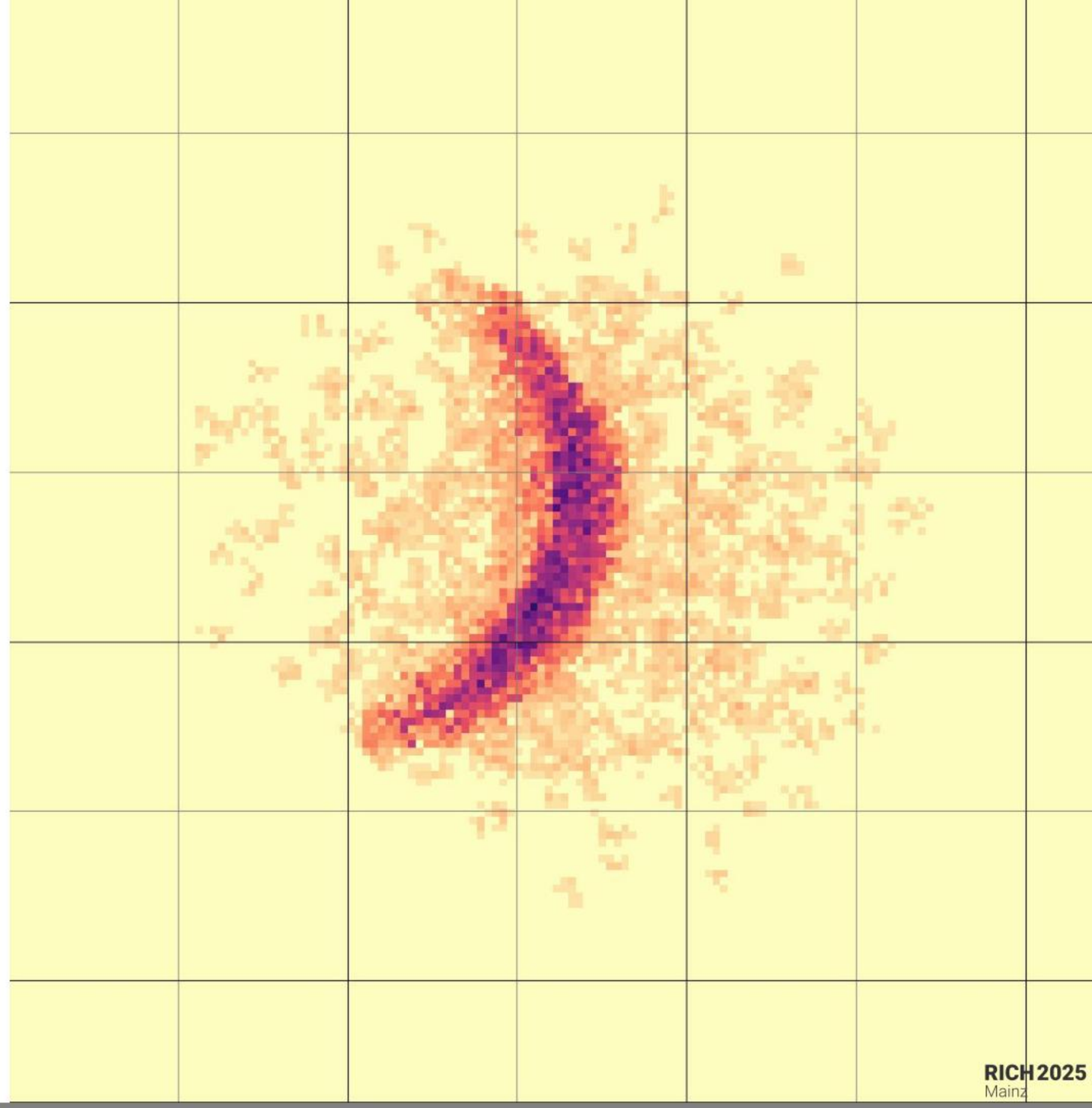
4,814p.e.

Muon ring?

core > 1km





Airshower

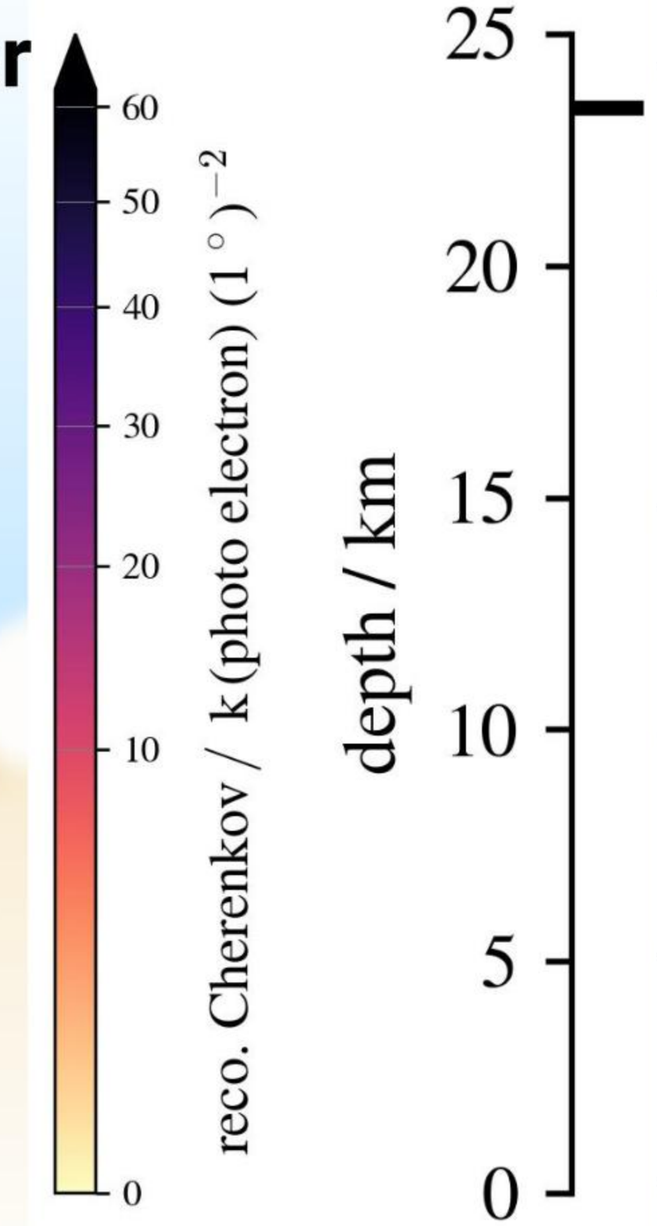
Proton

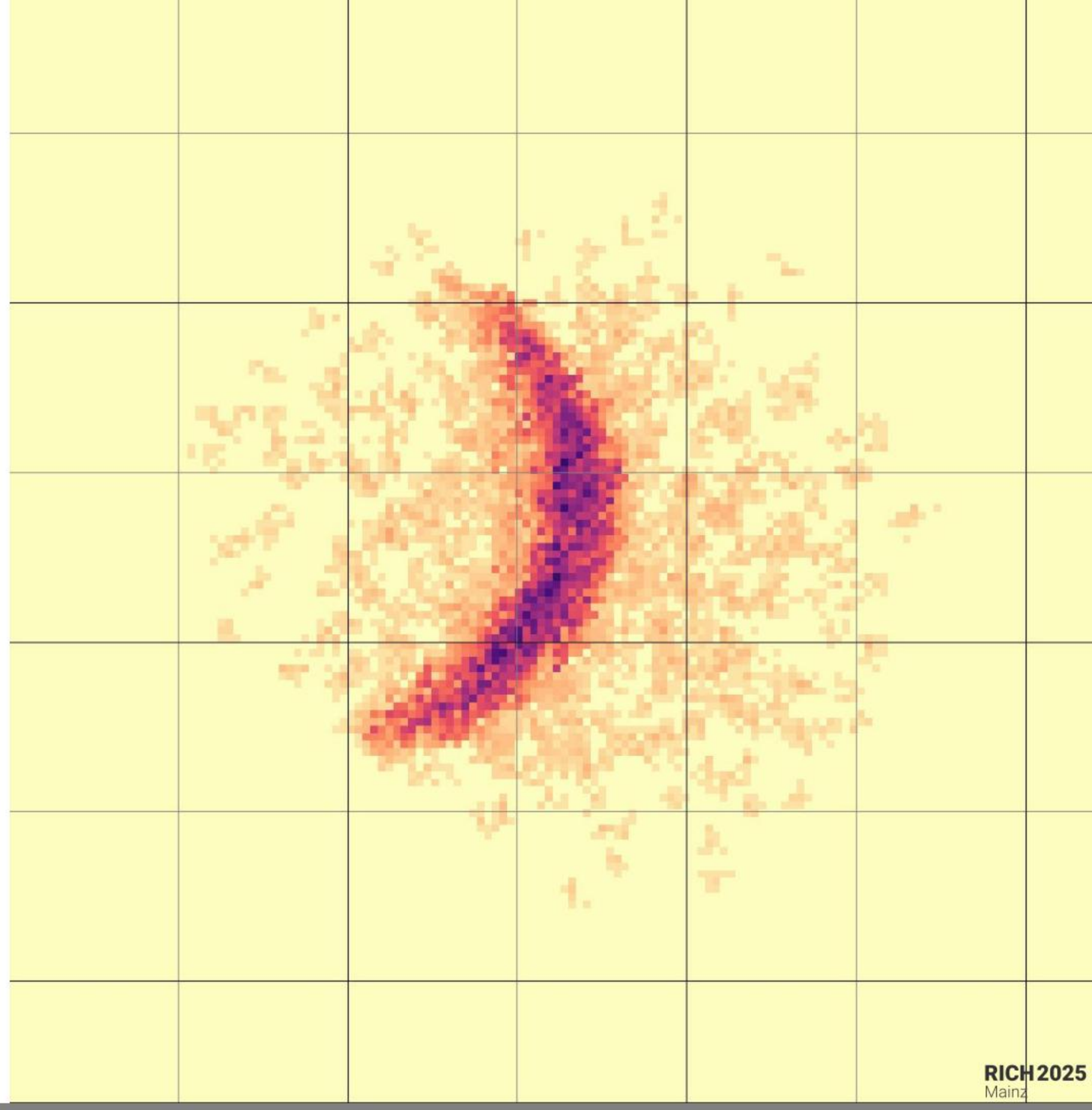
44GeV

4,814p.e.

Muon ring?

core > 1km





Airshower

Proton

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Muon ring?

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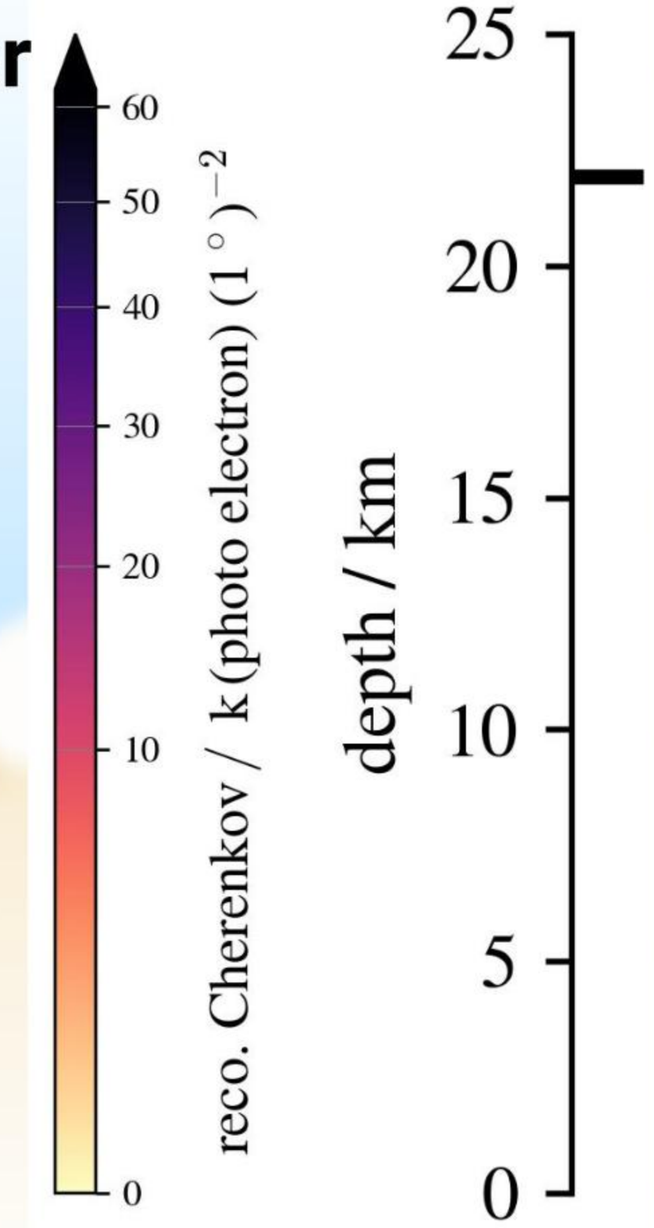

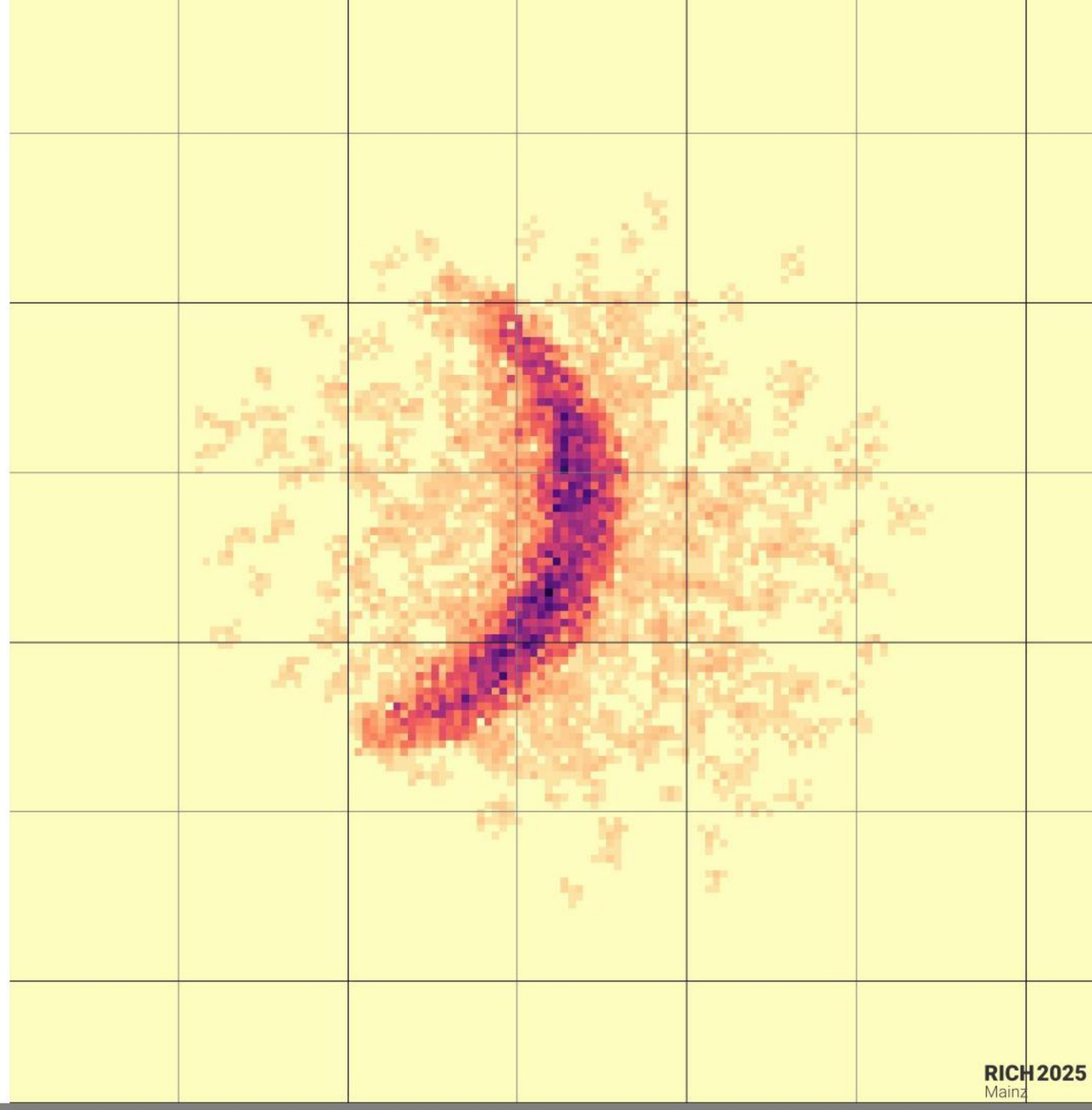

Airshower

Proton

44GeV

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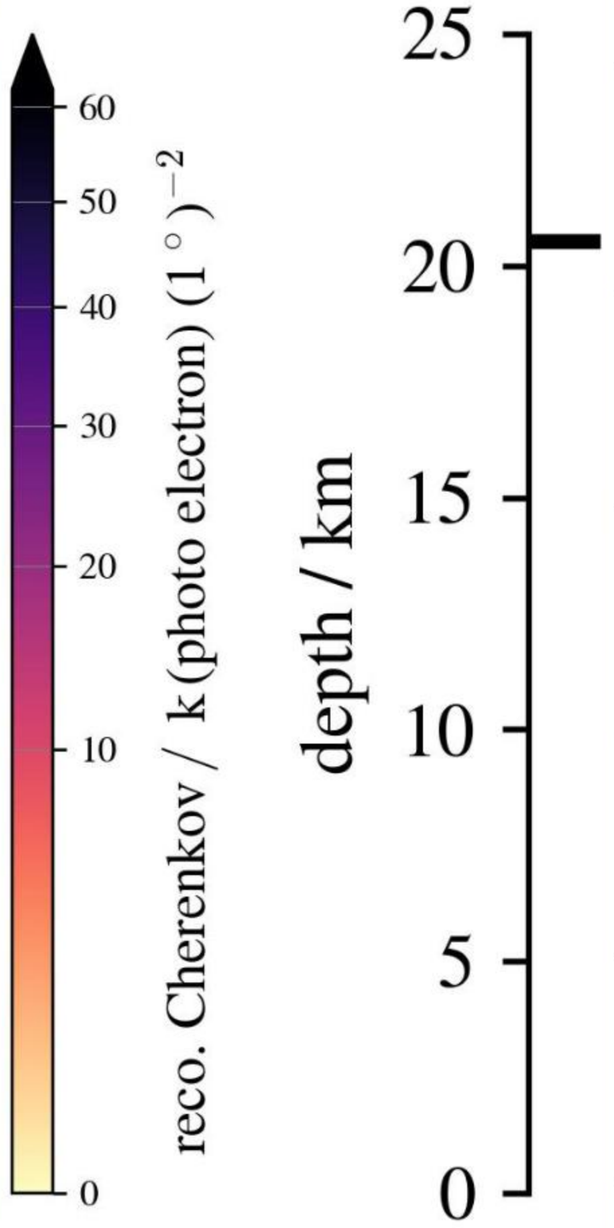
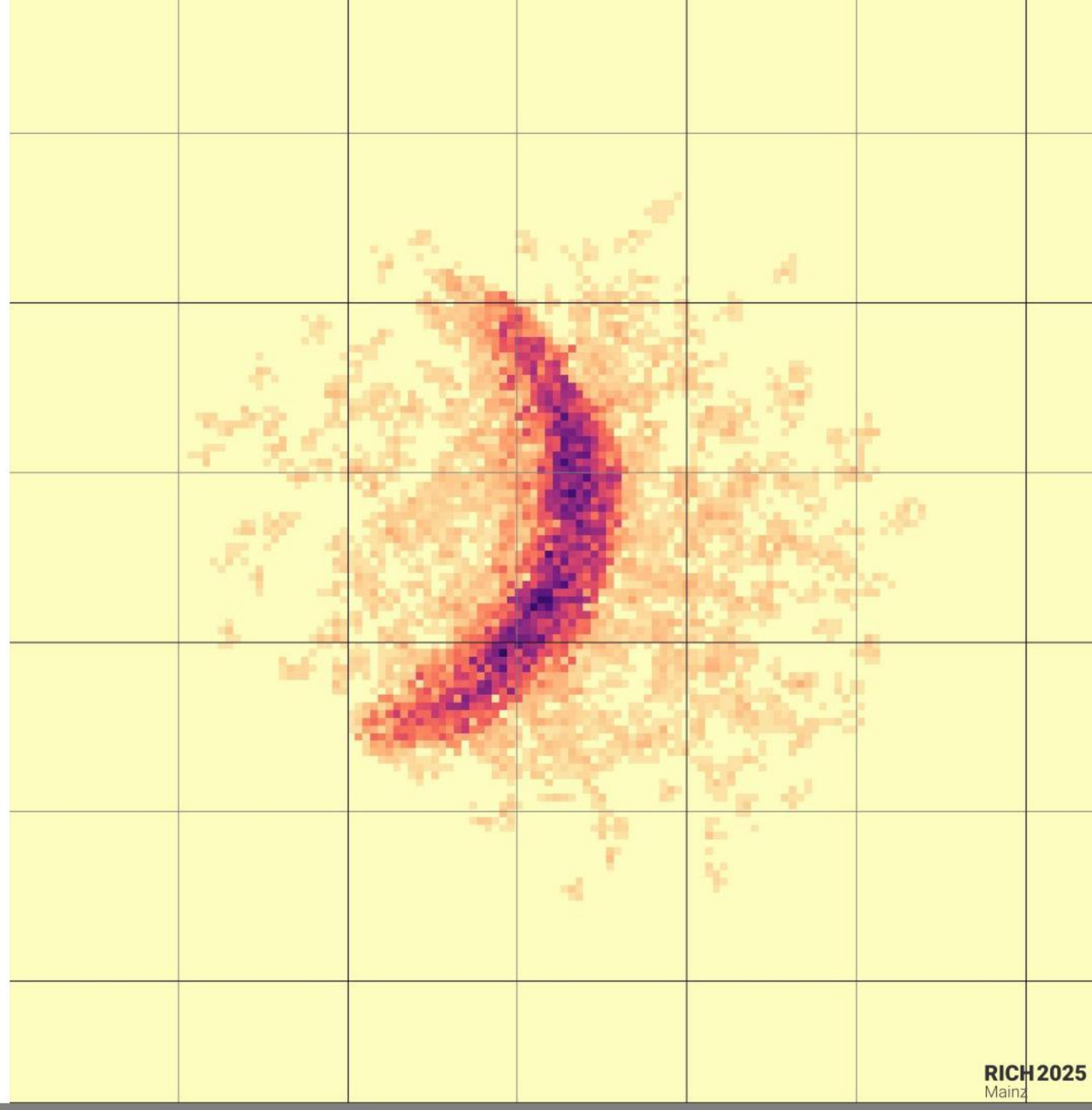
Muon ring?

core > 1km





Airshower

Proton

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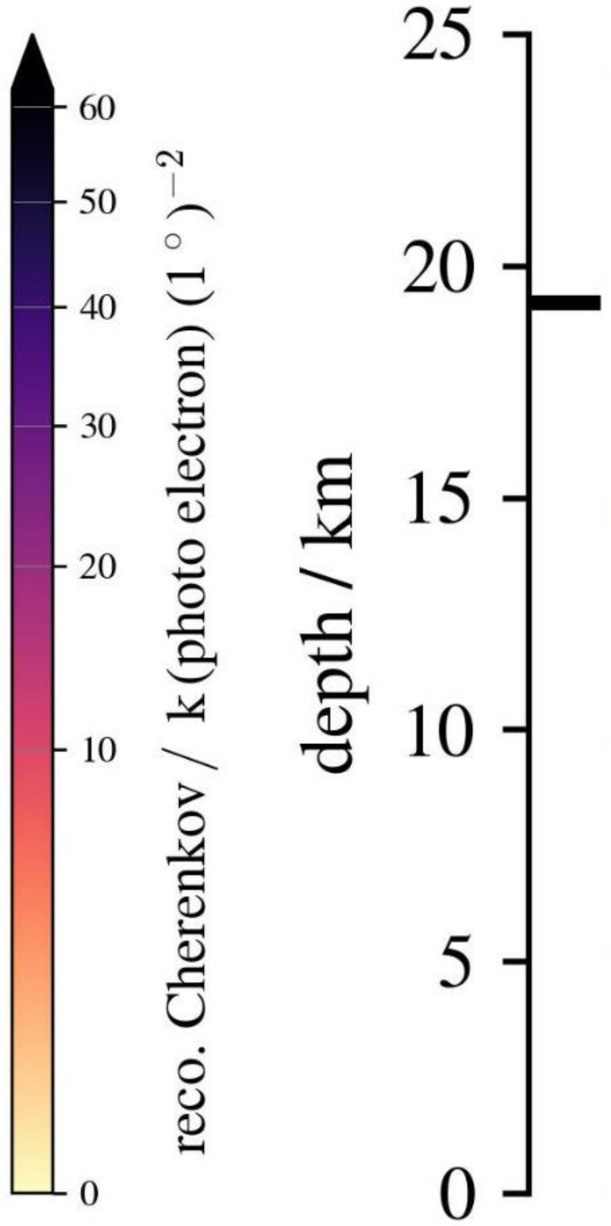

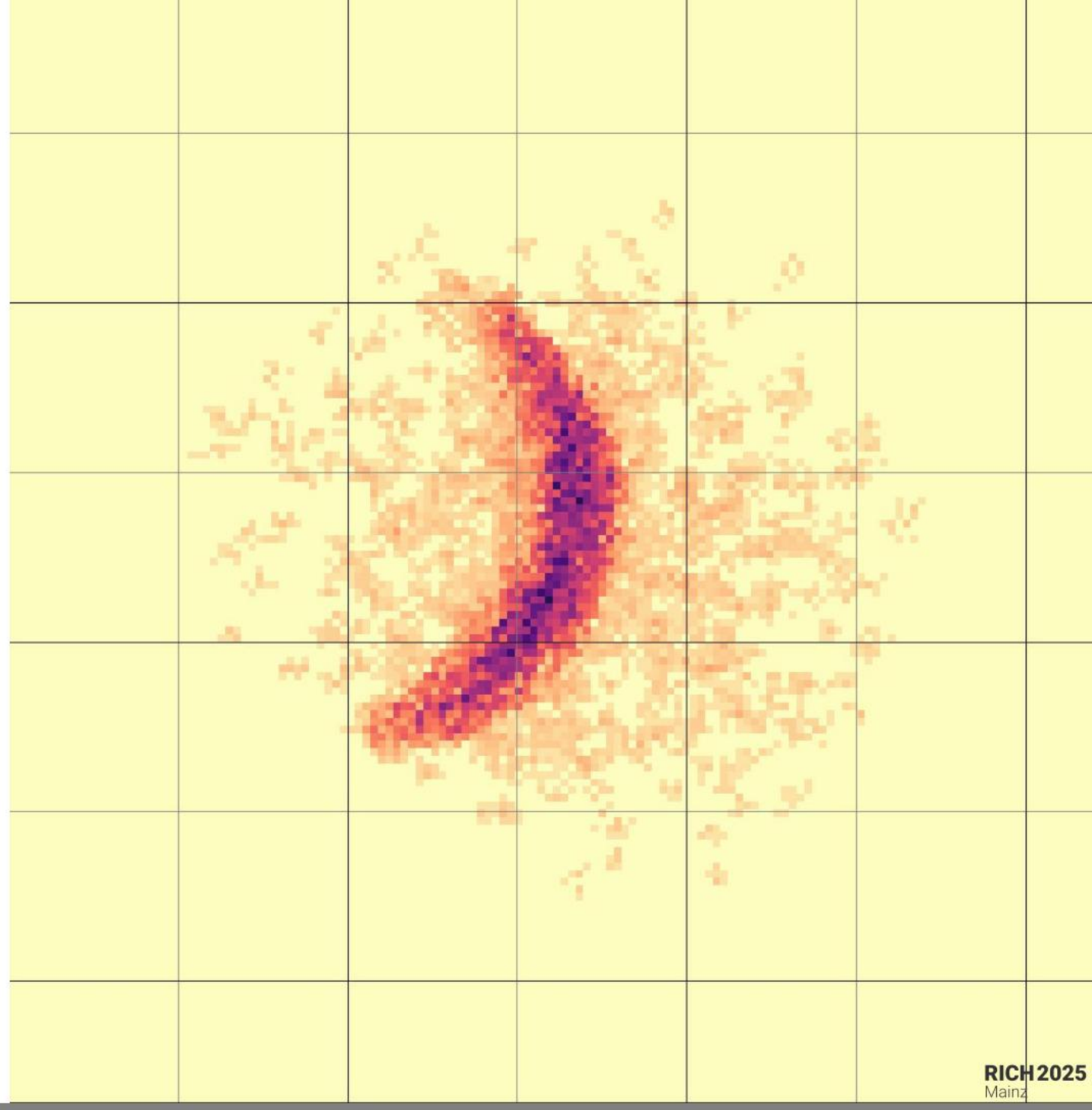

Airshower

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Muon ring?

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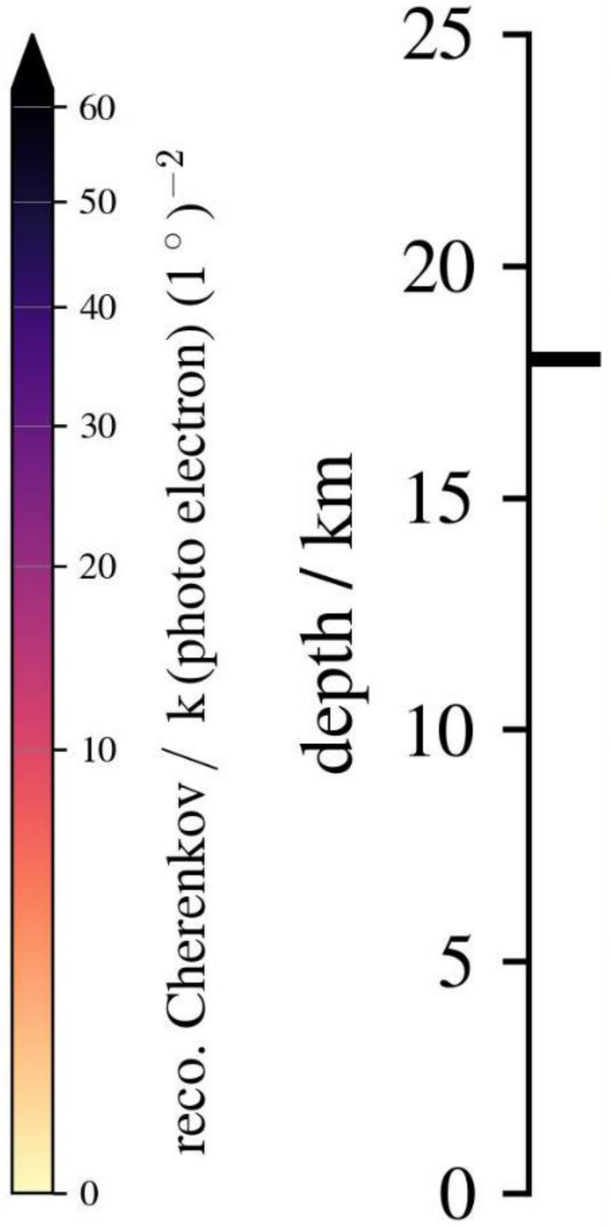

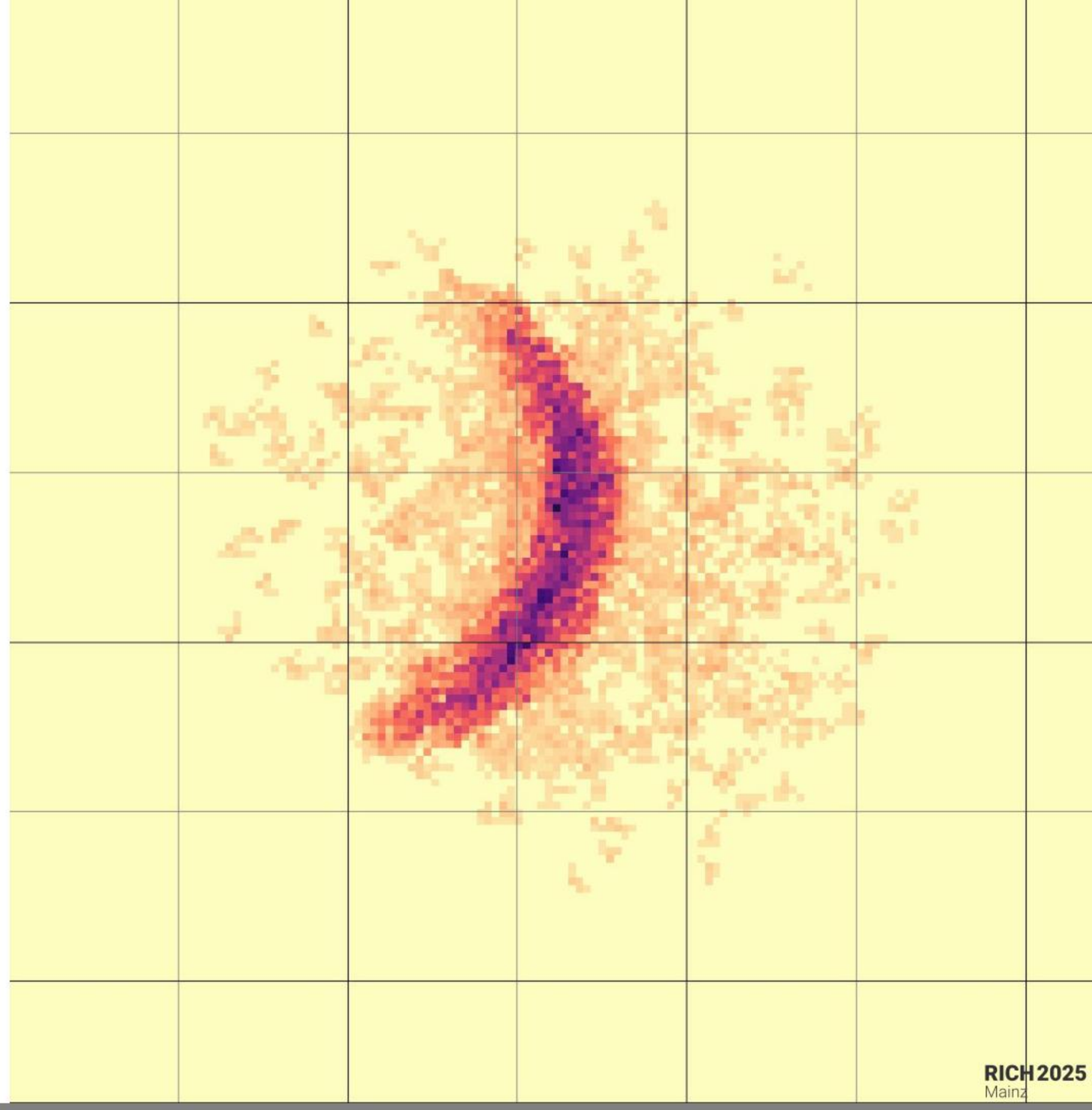

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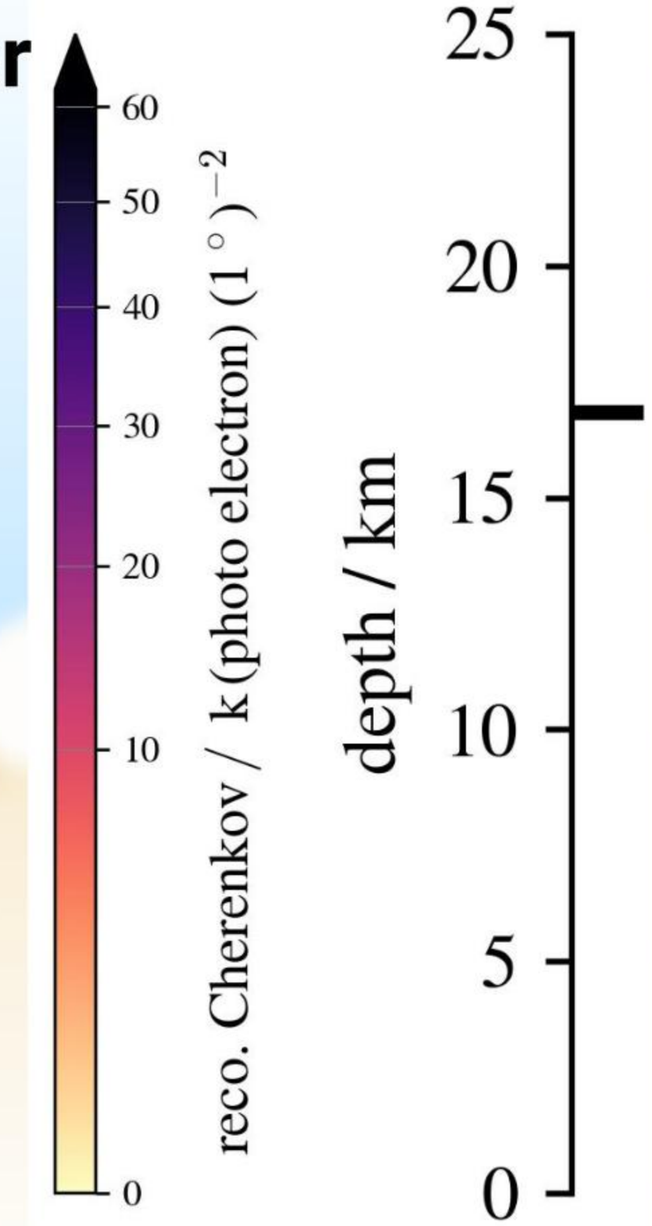

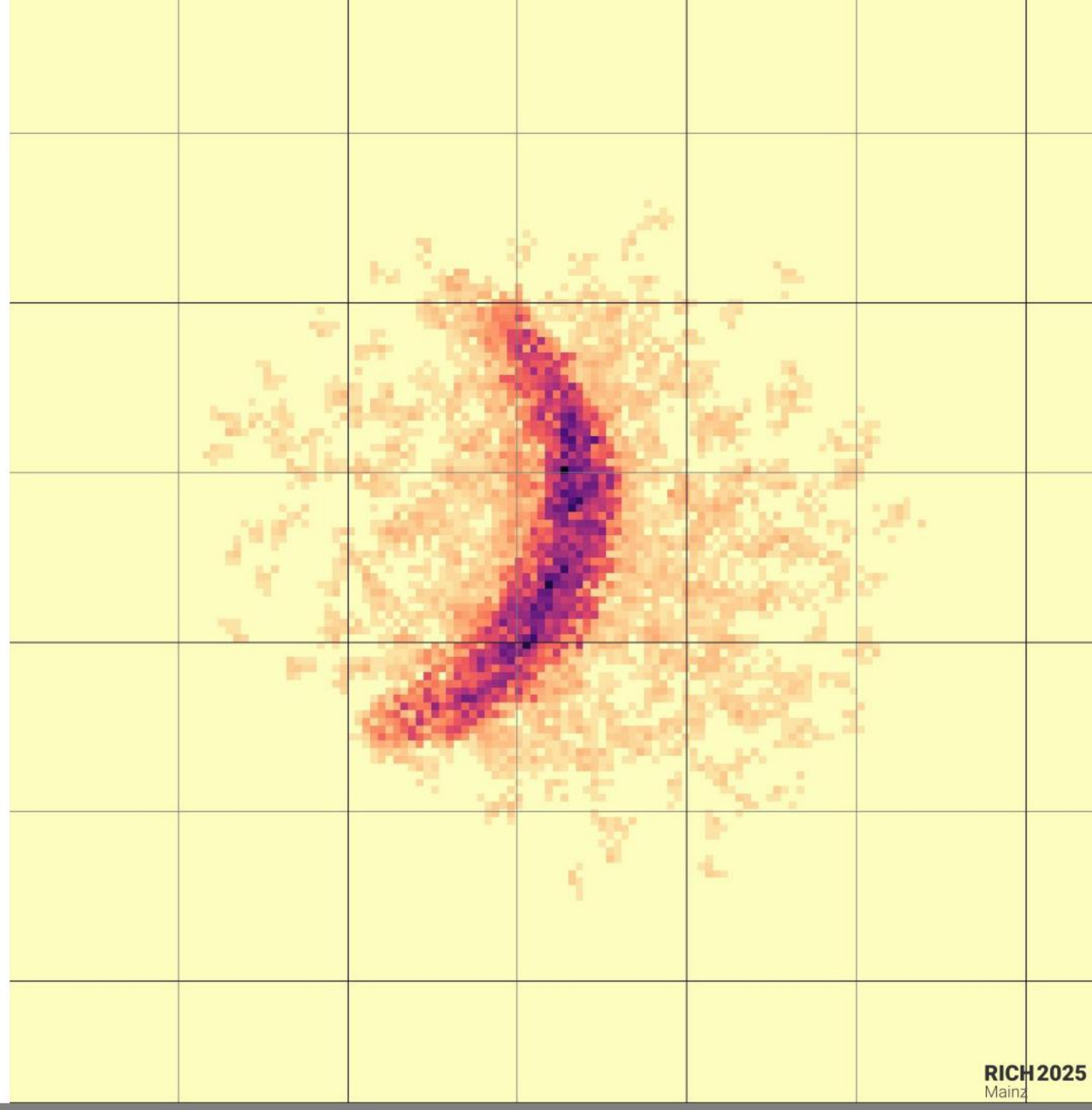

Airshower

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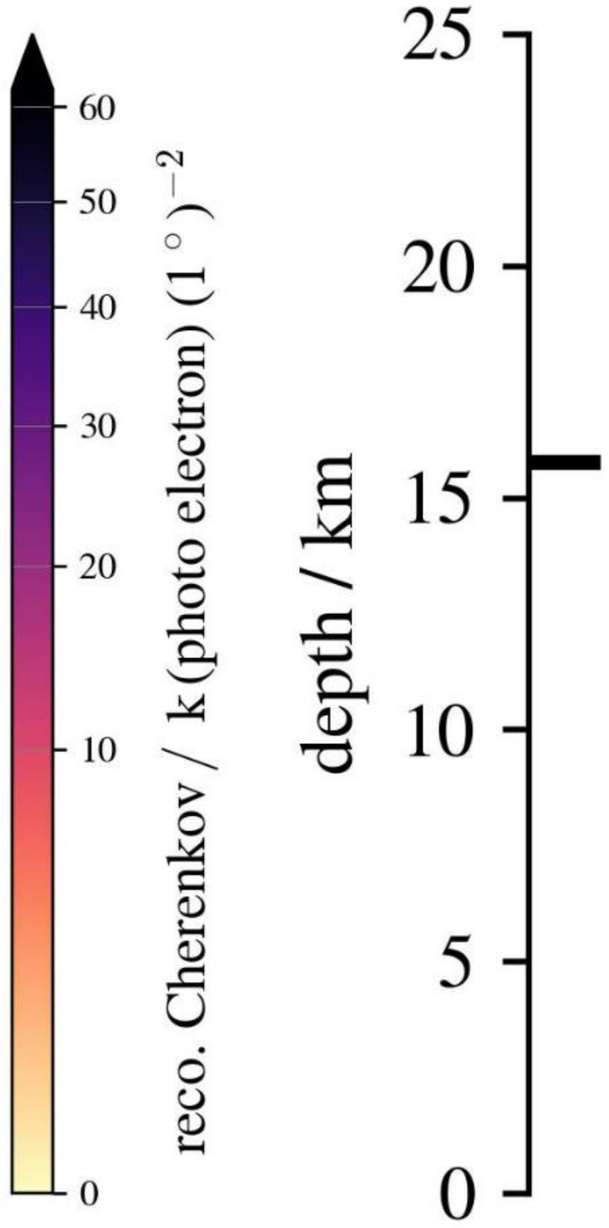

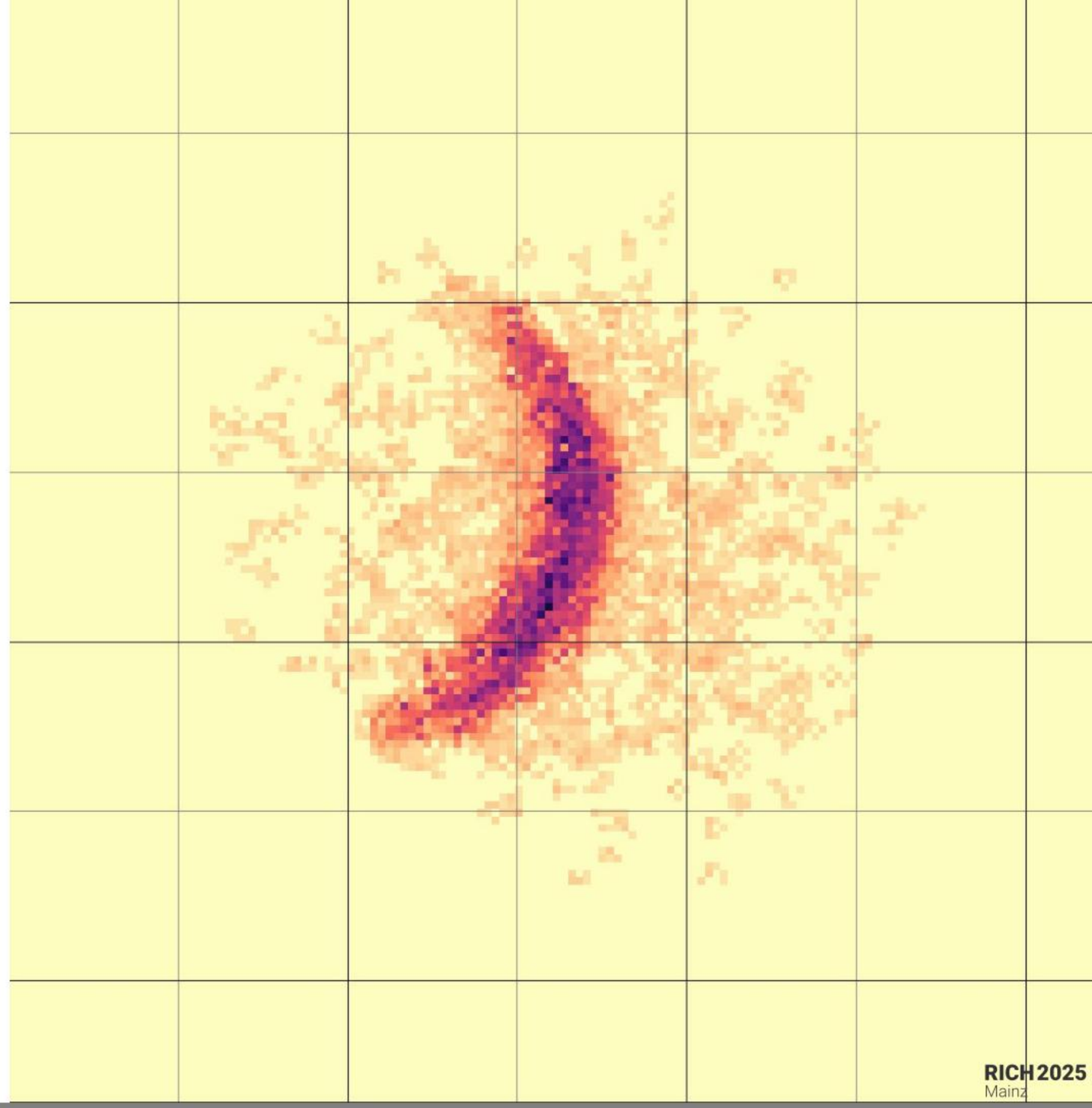

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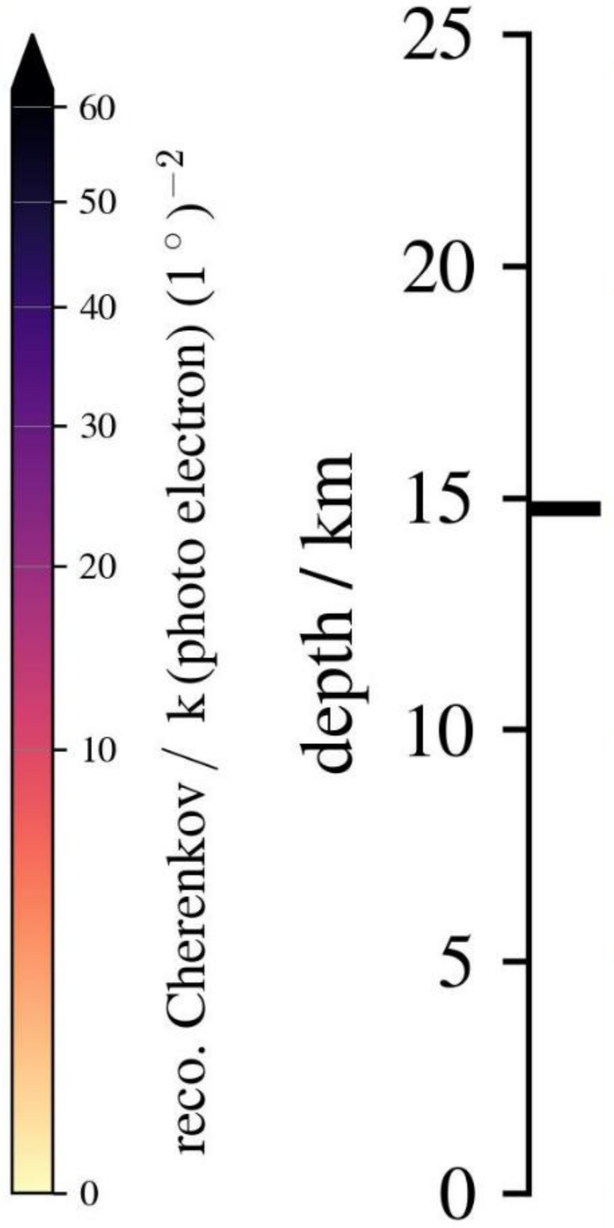

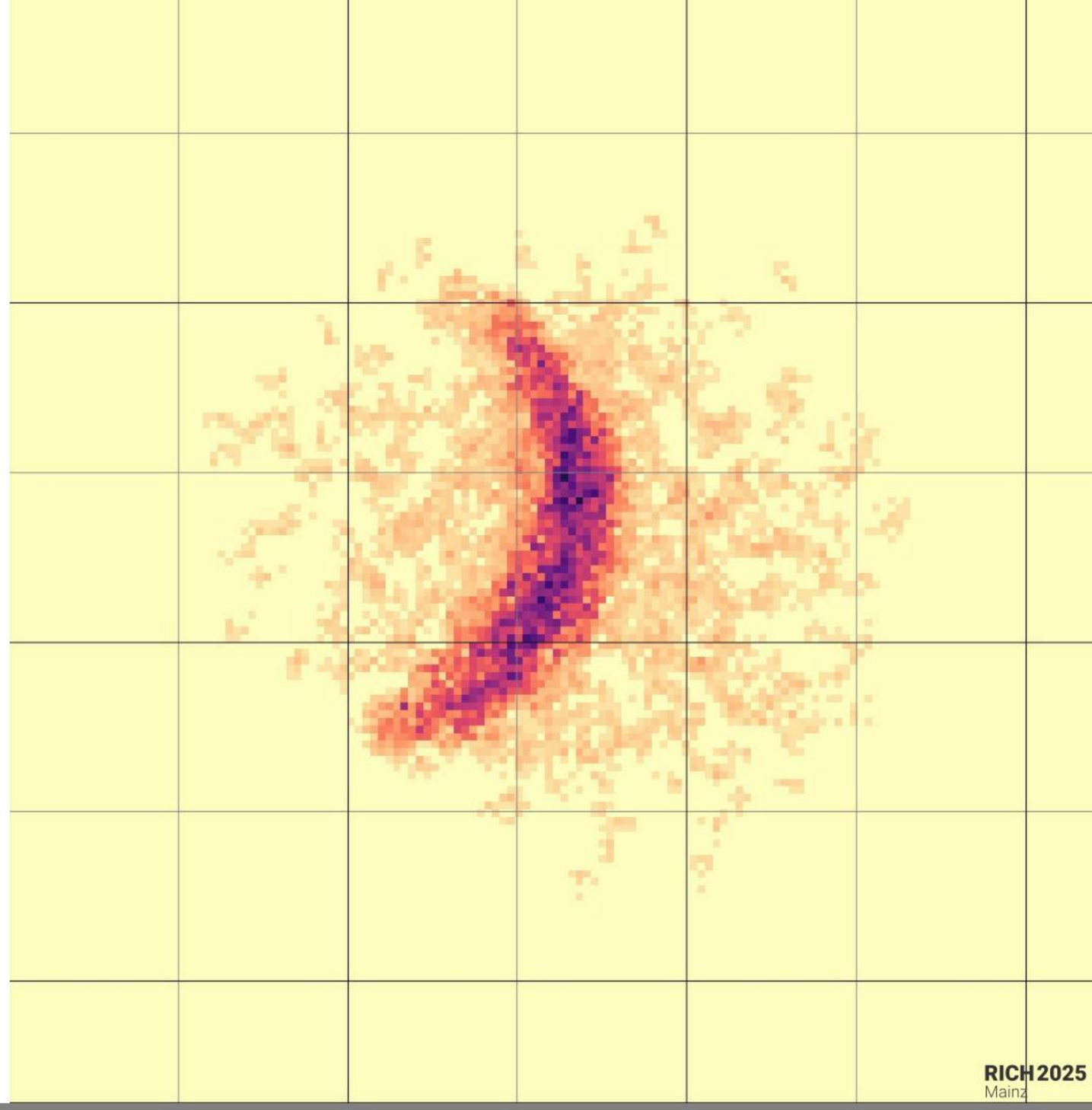

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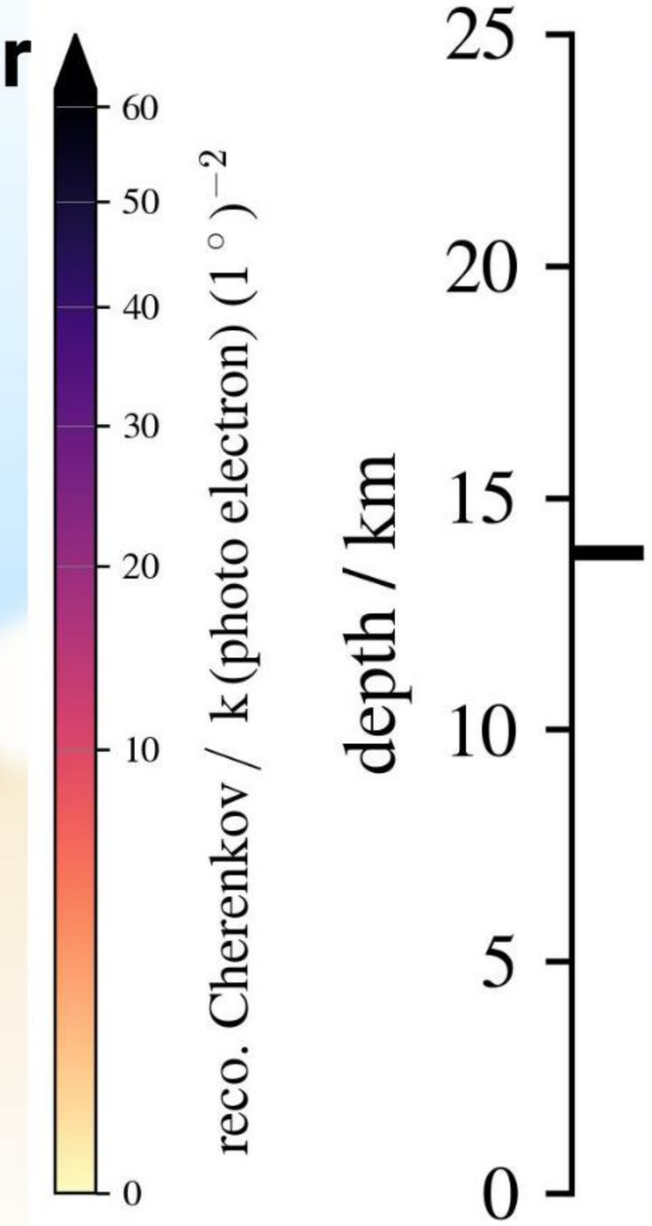

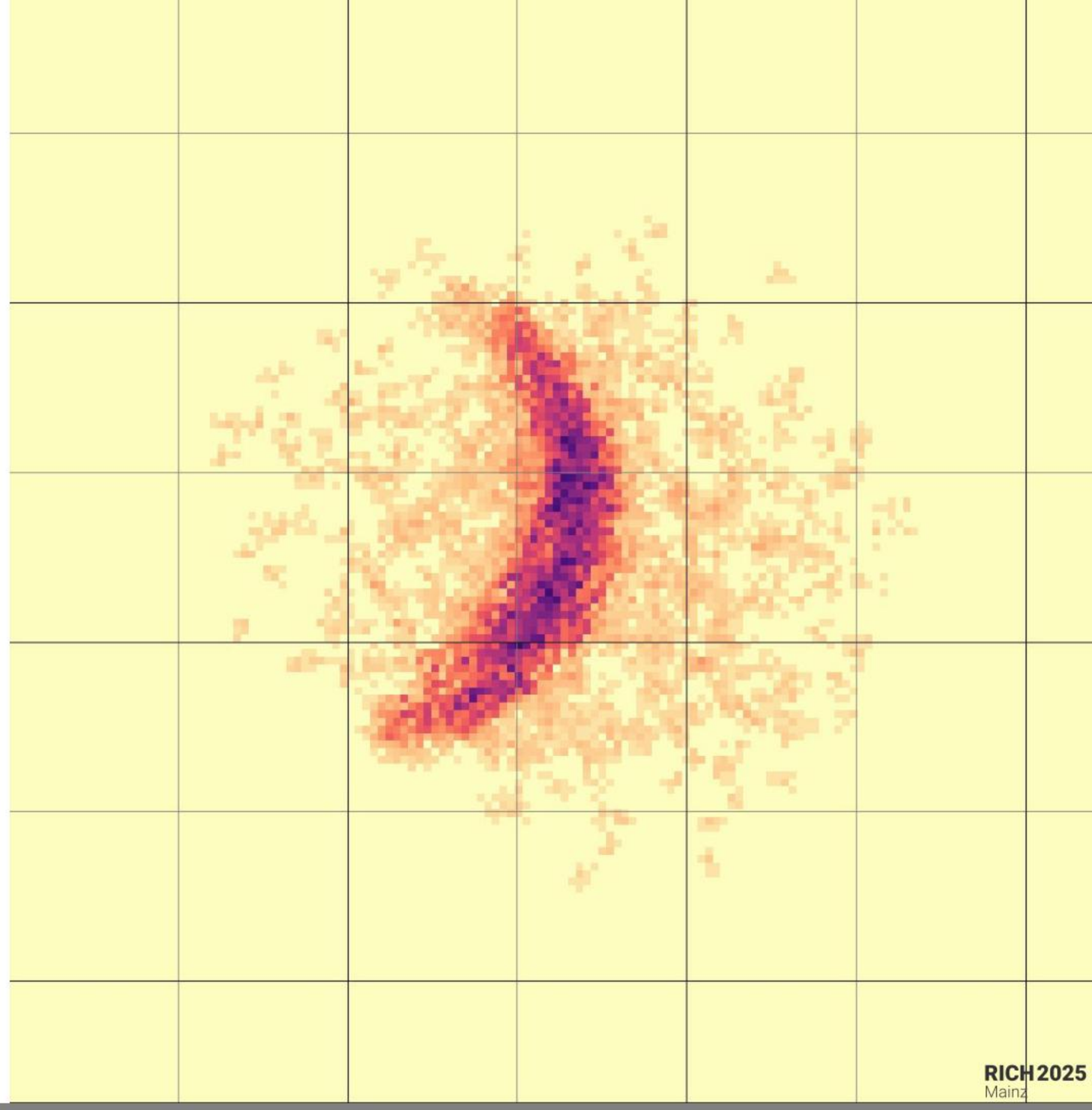

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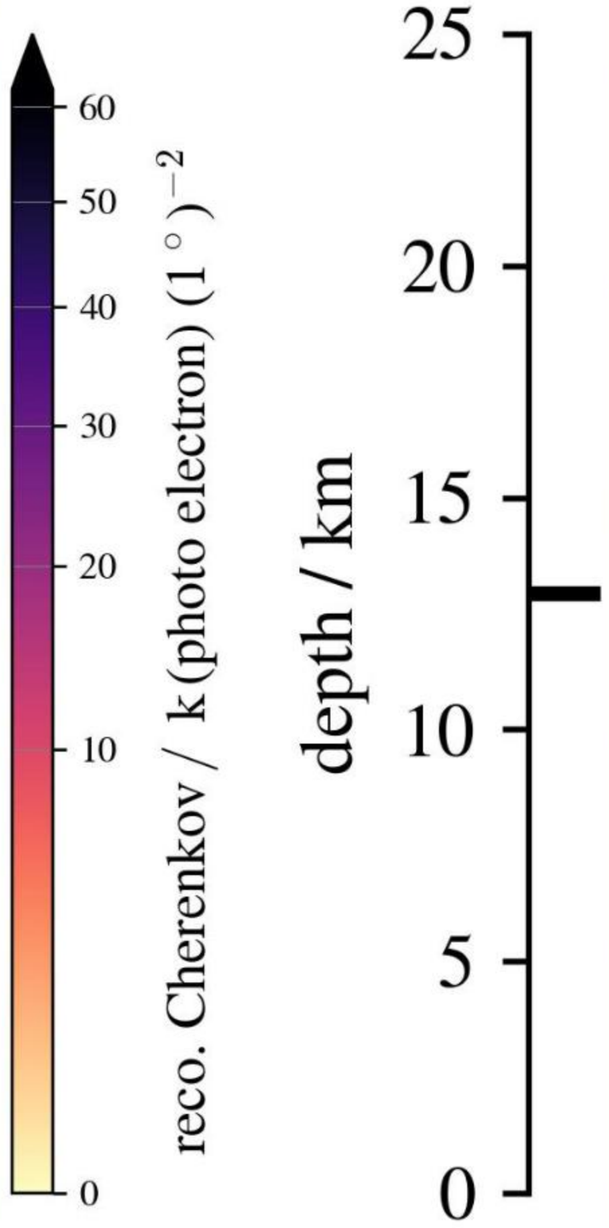

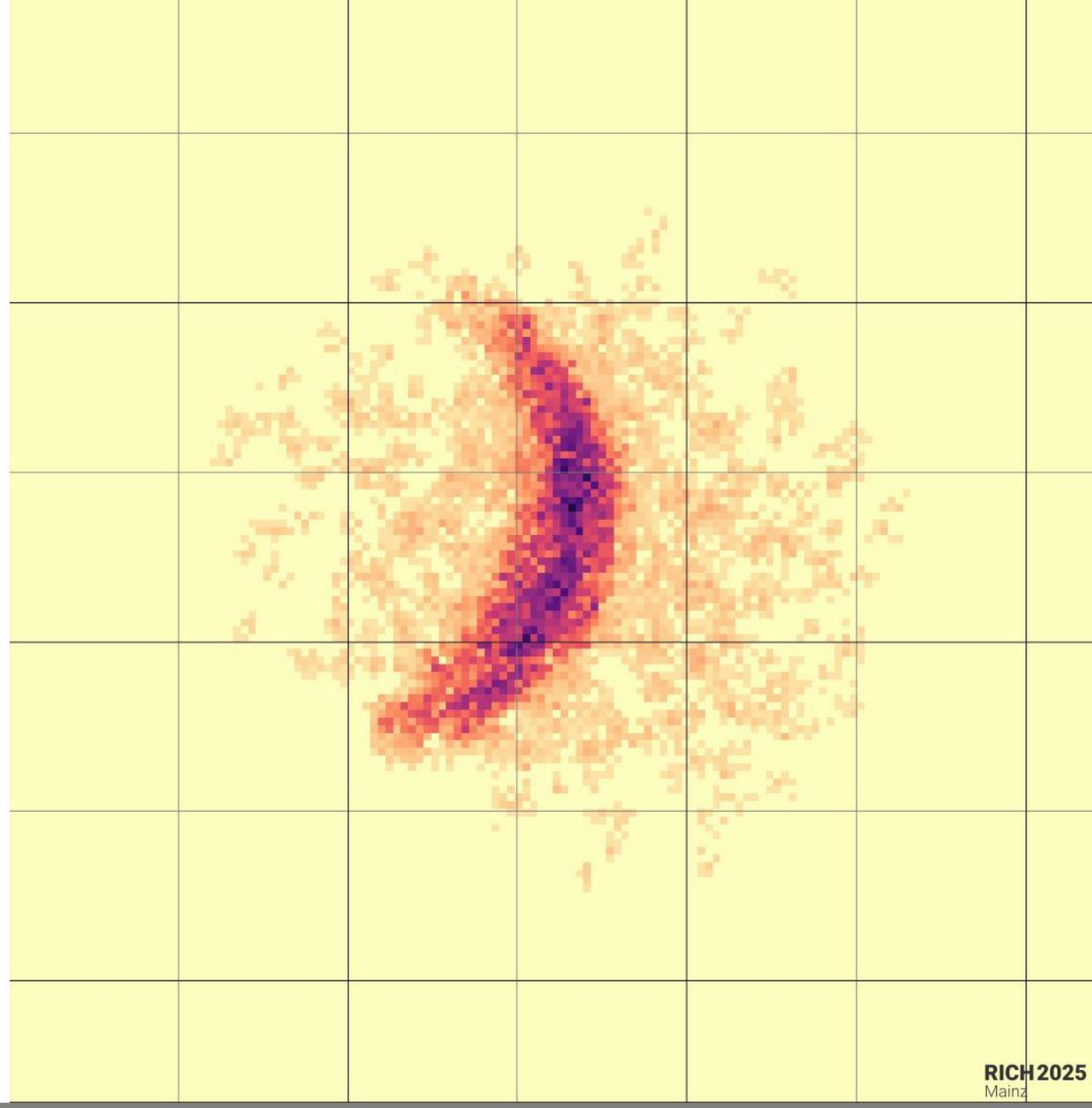

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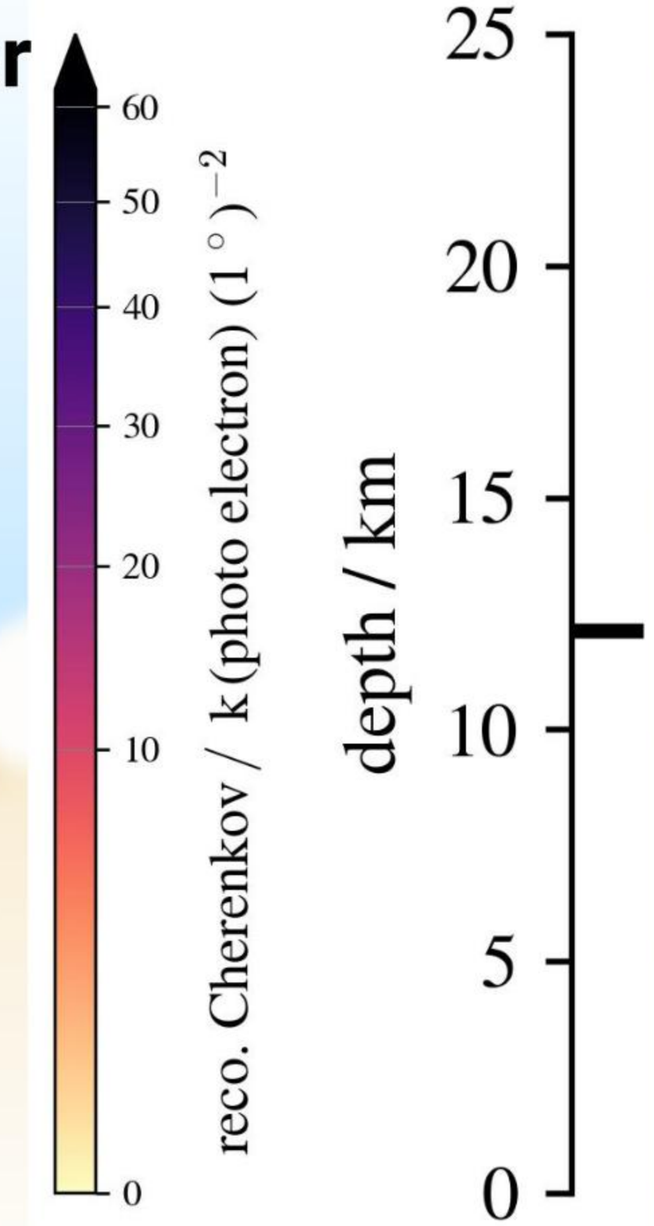

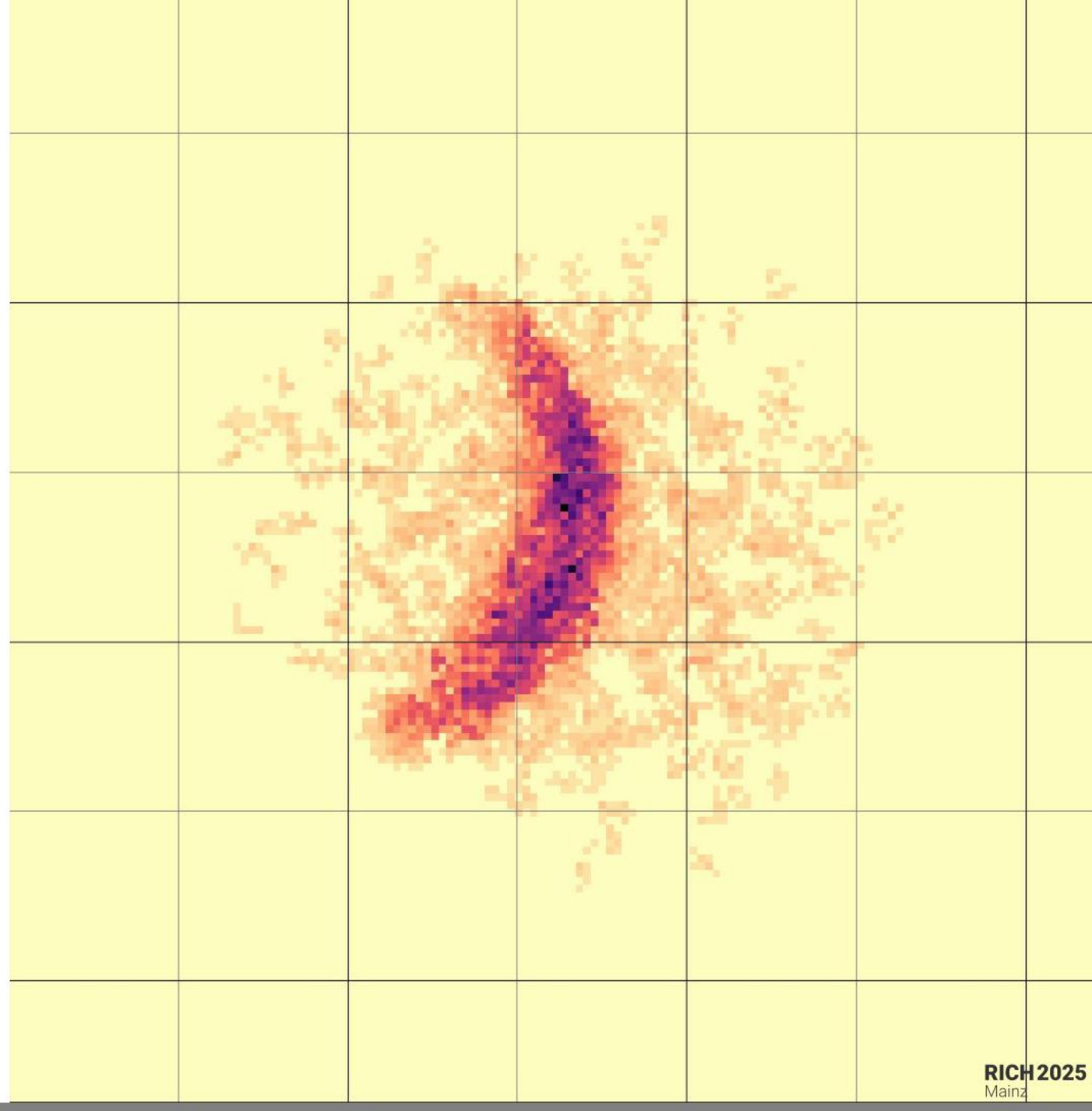

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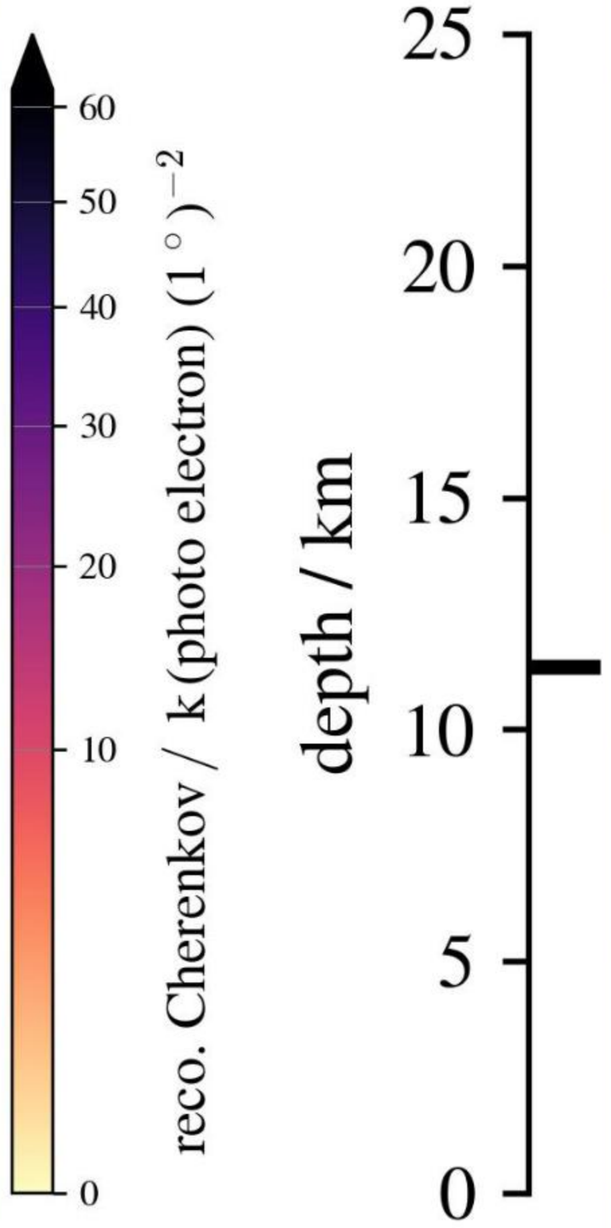

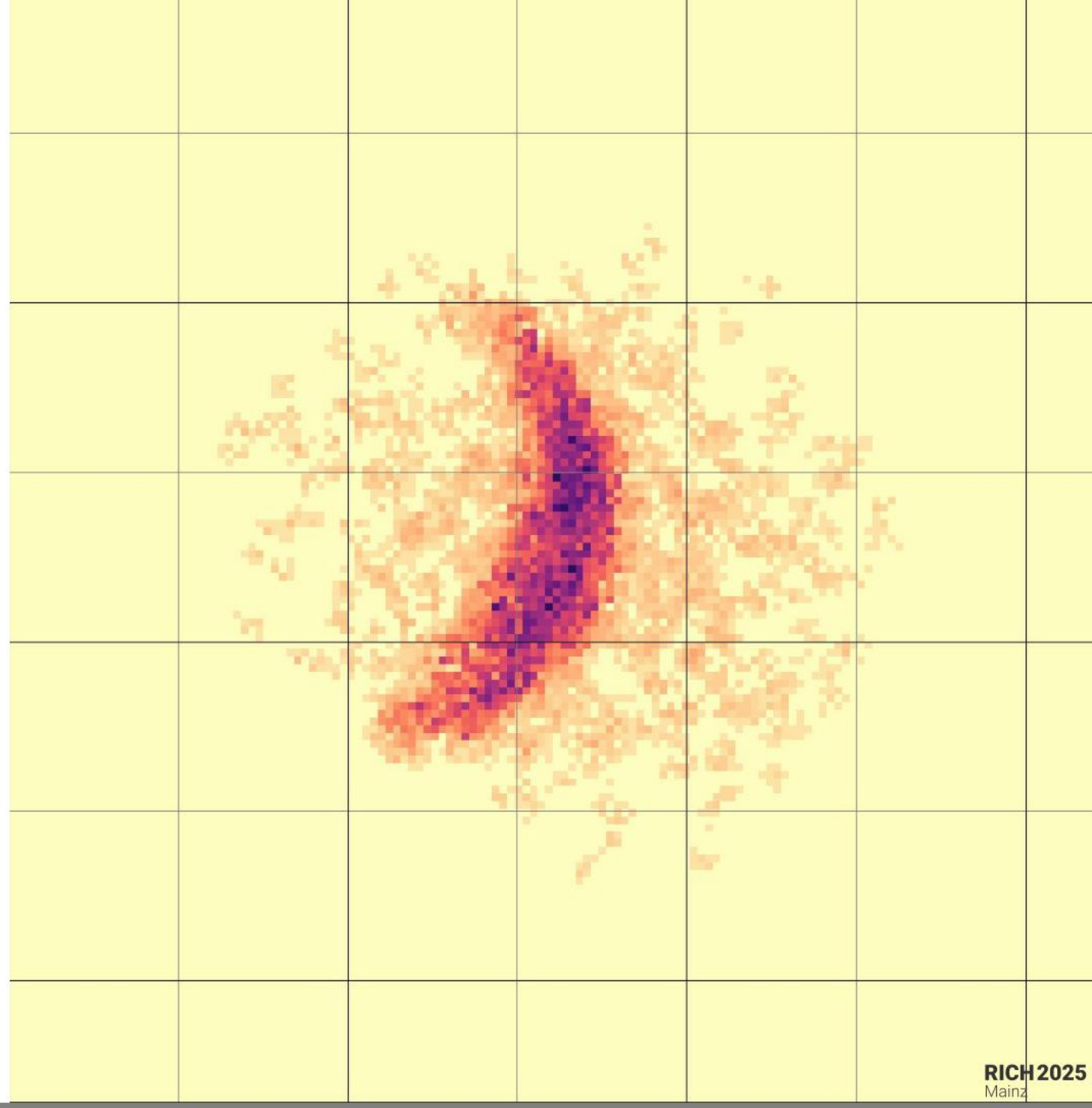

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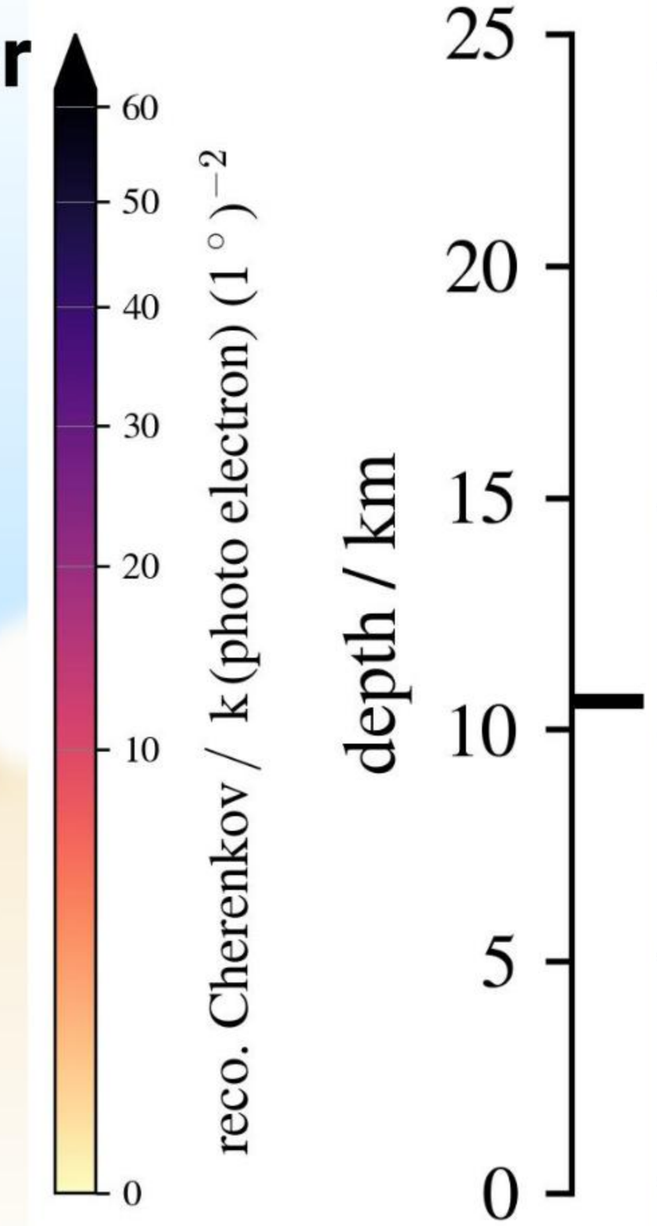

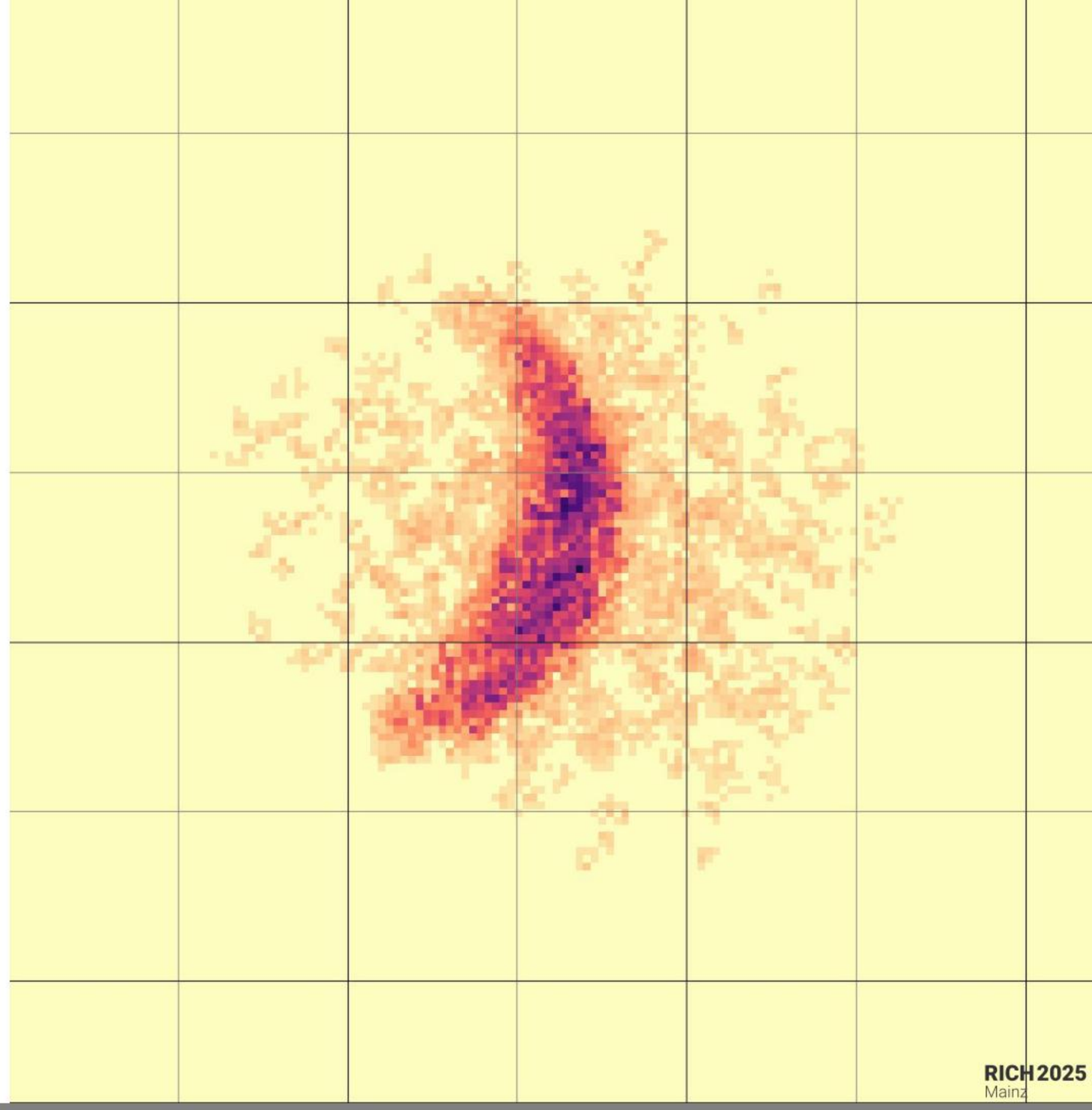

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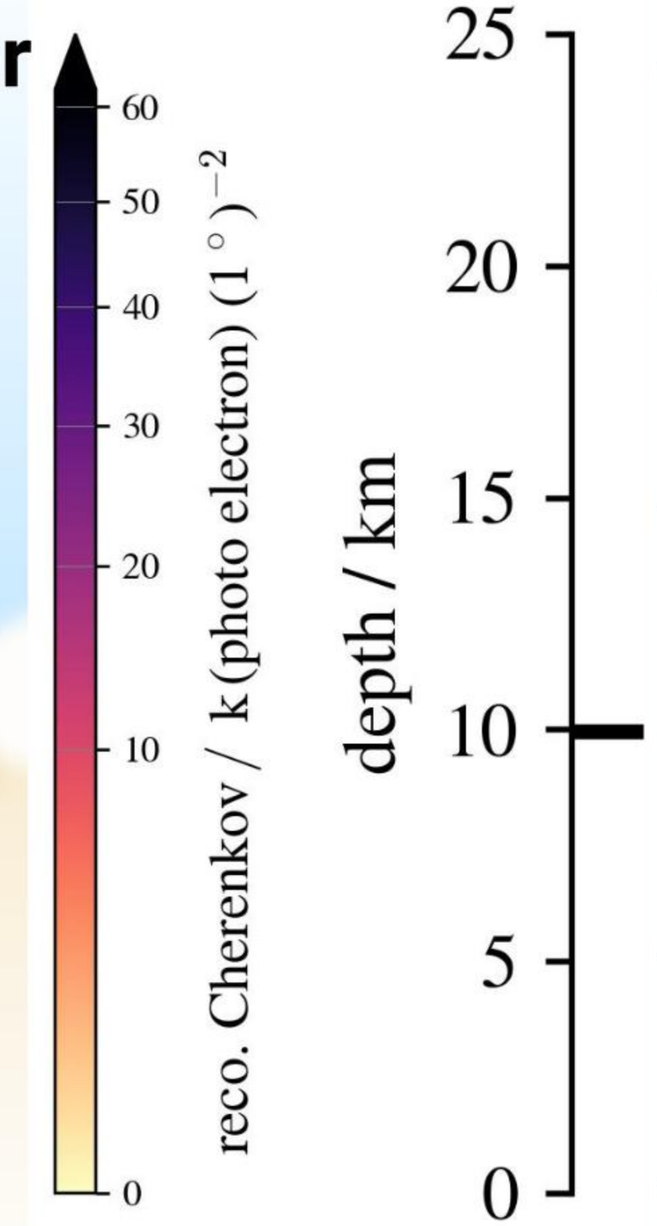

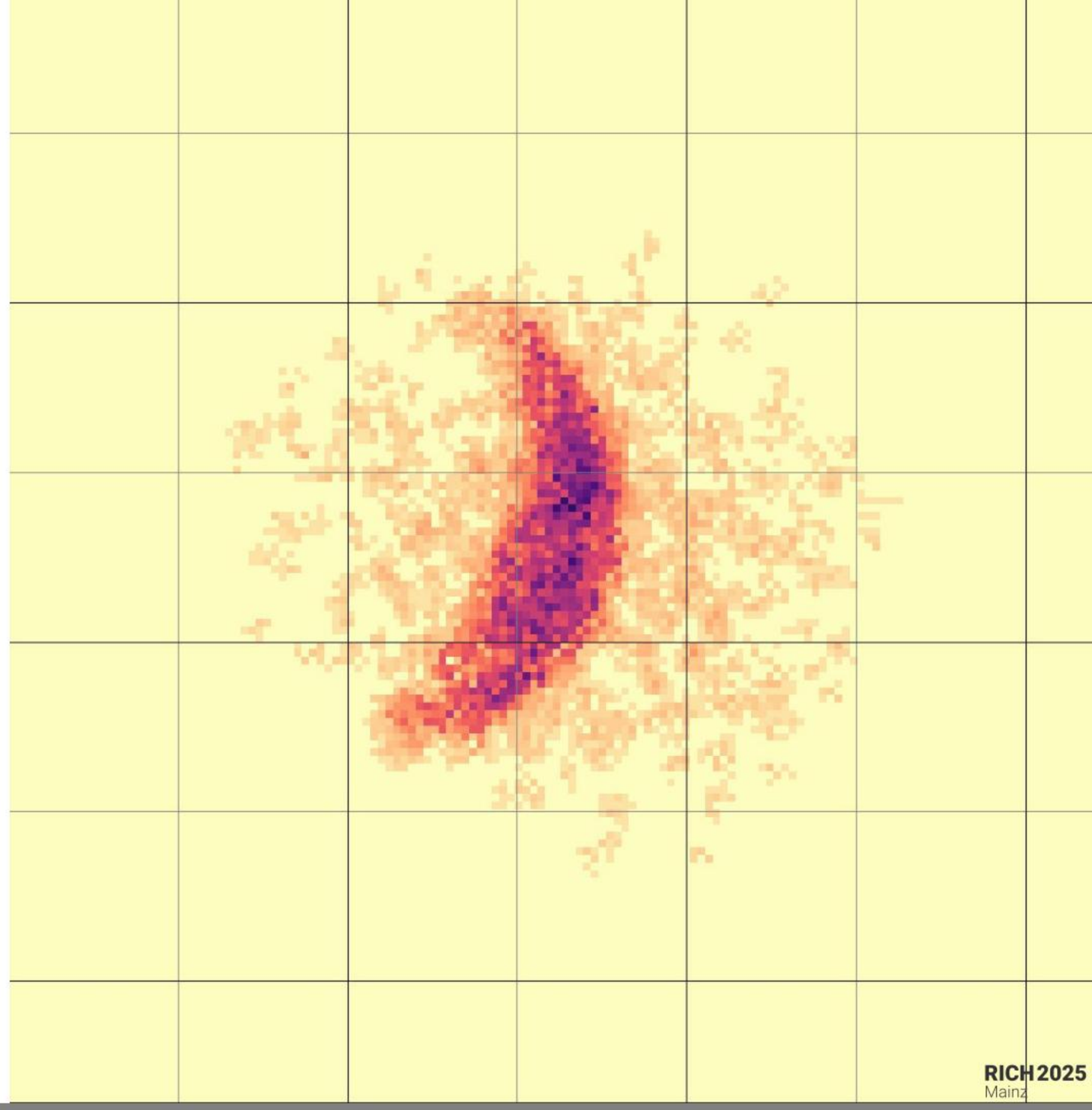

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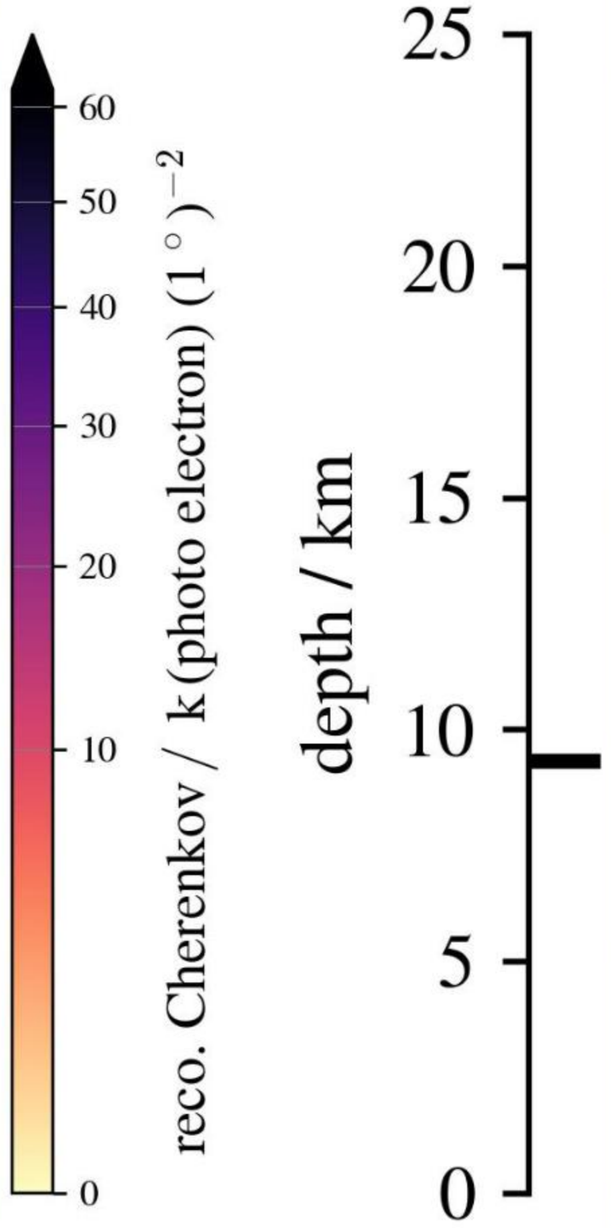

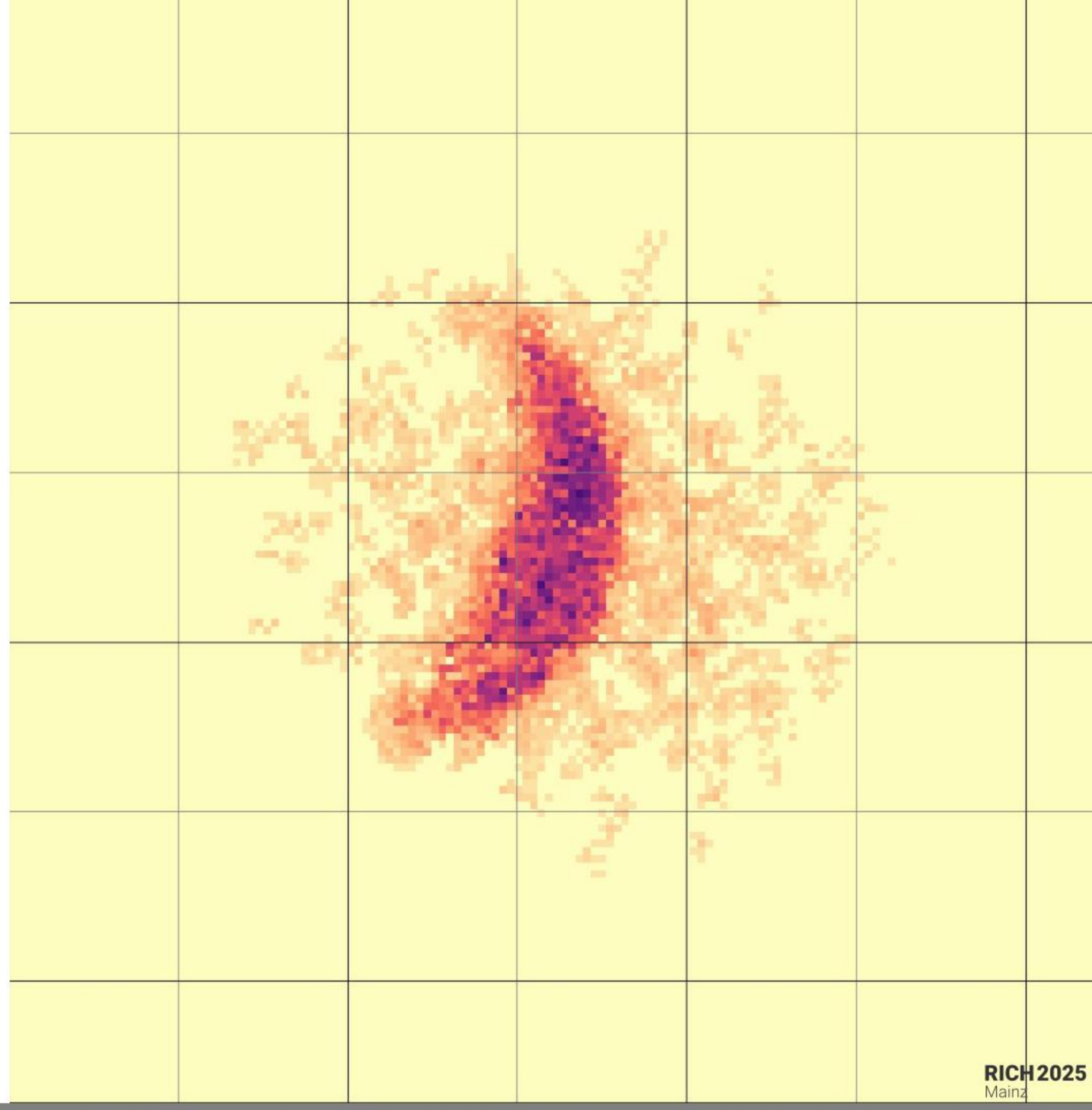

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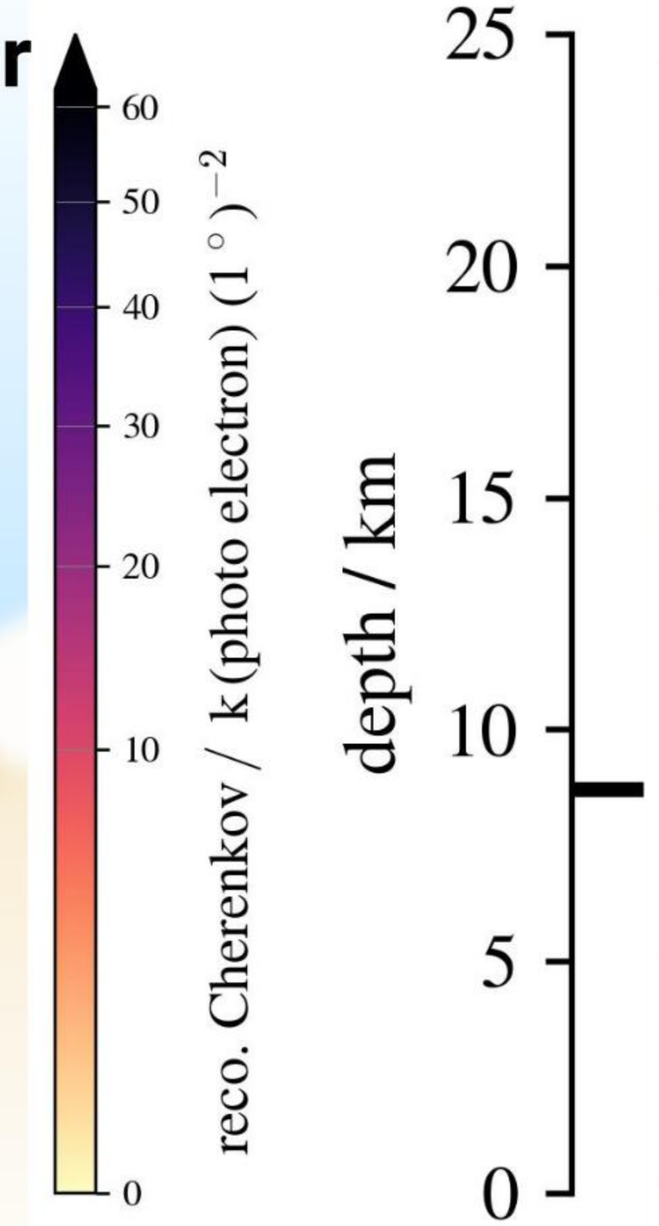

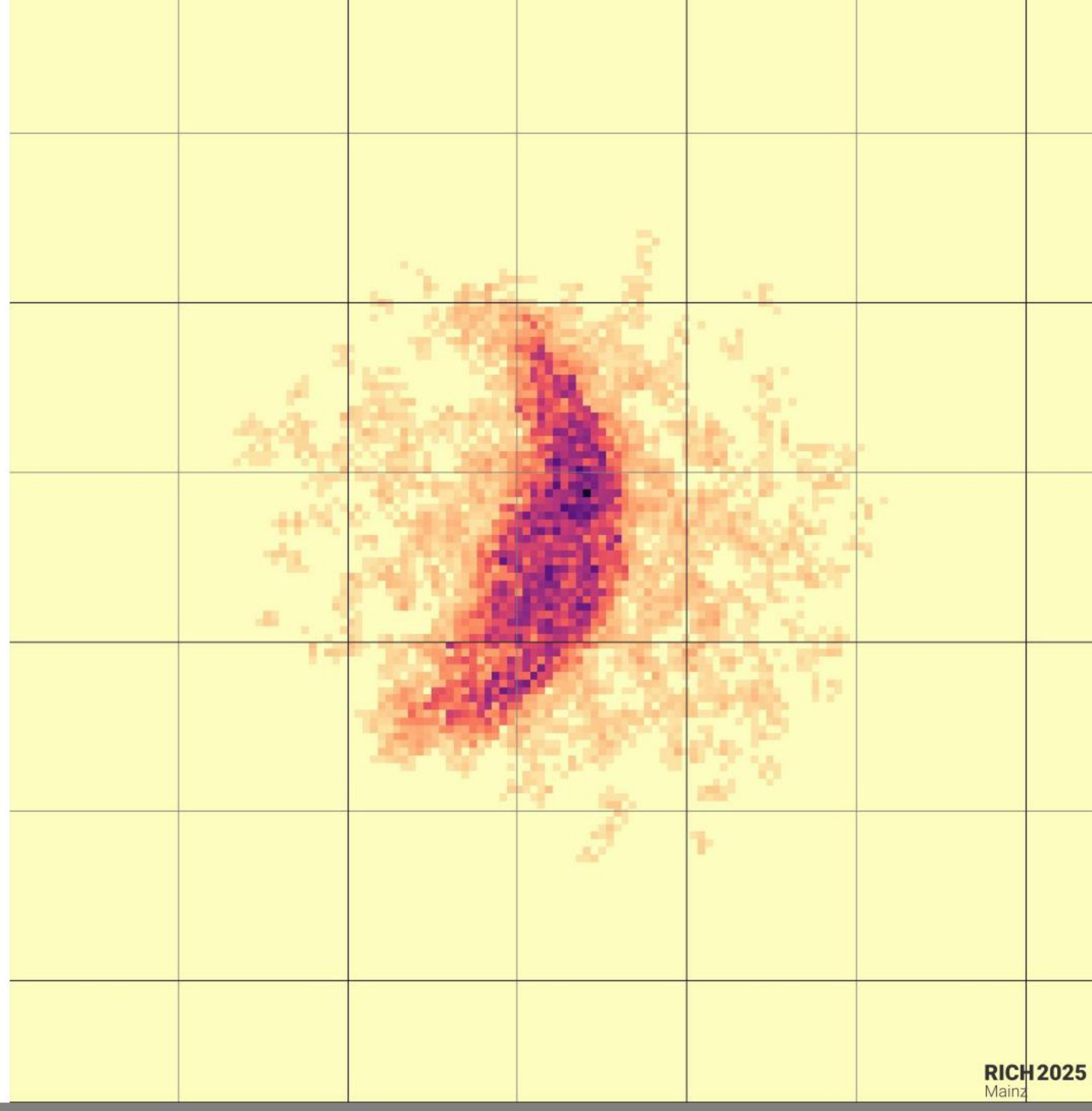

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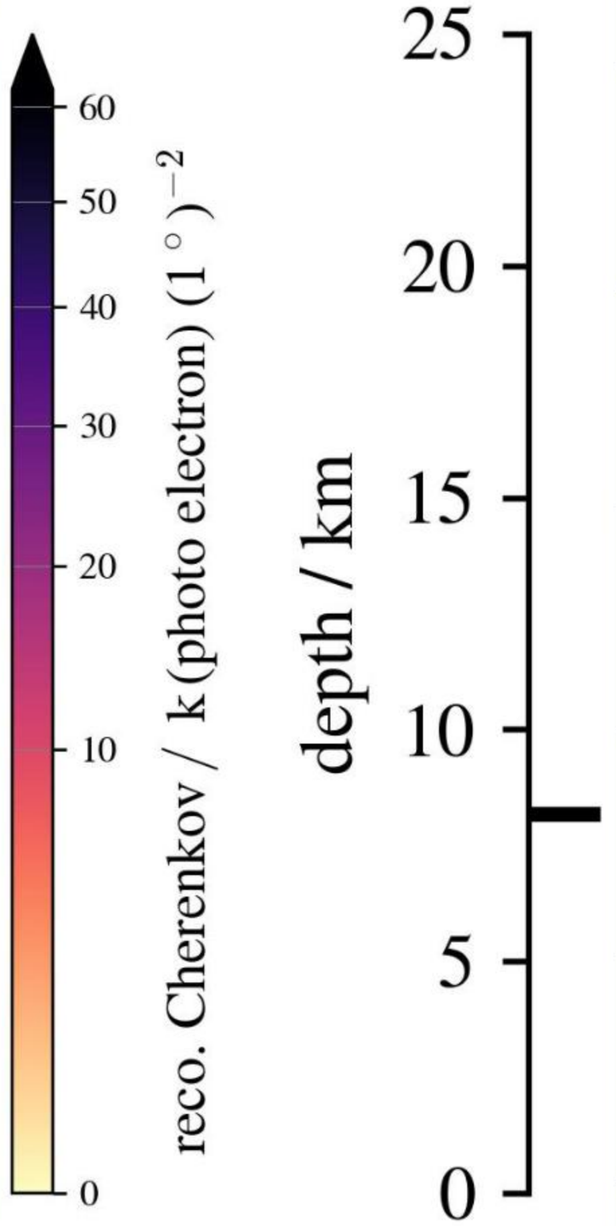

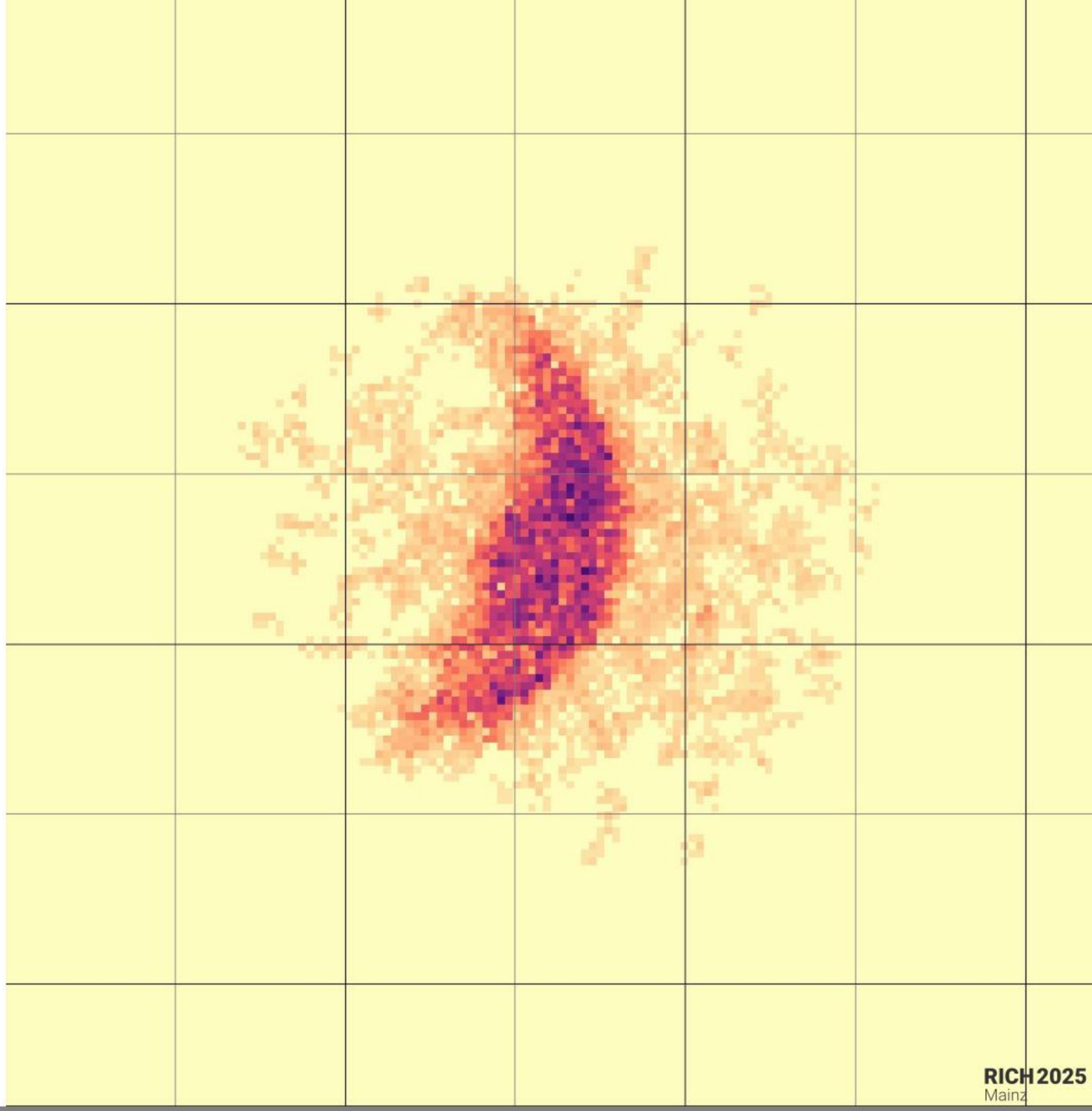

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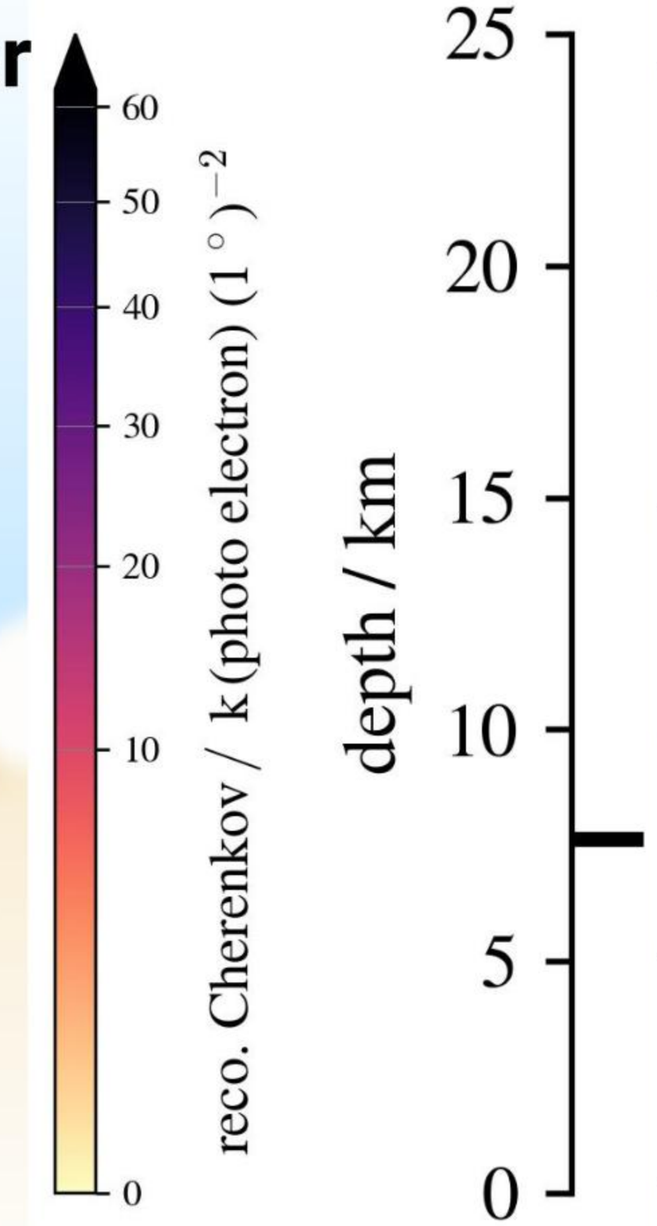

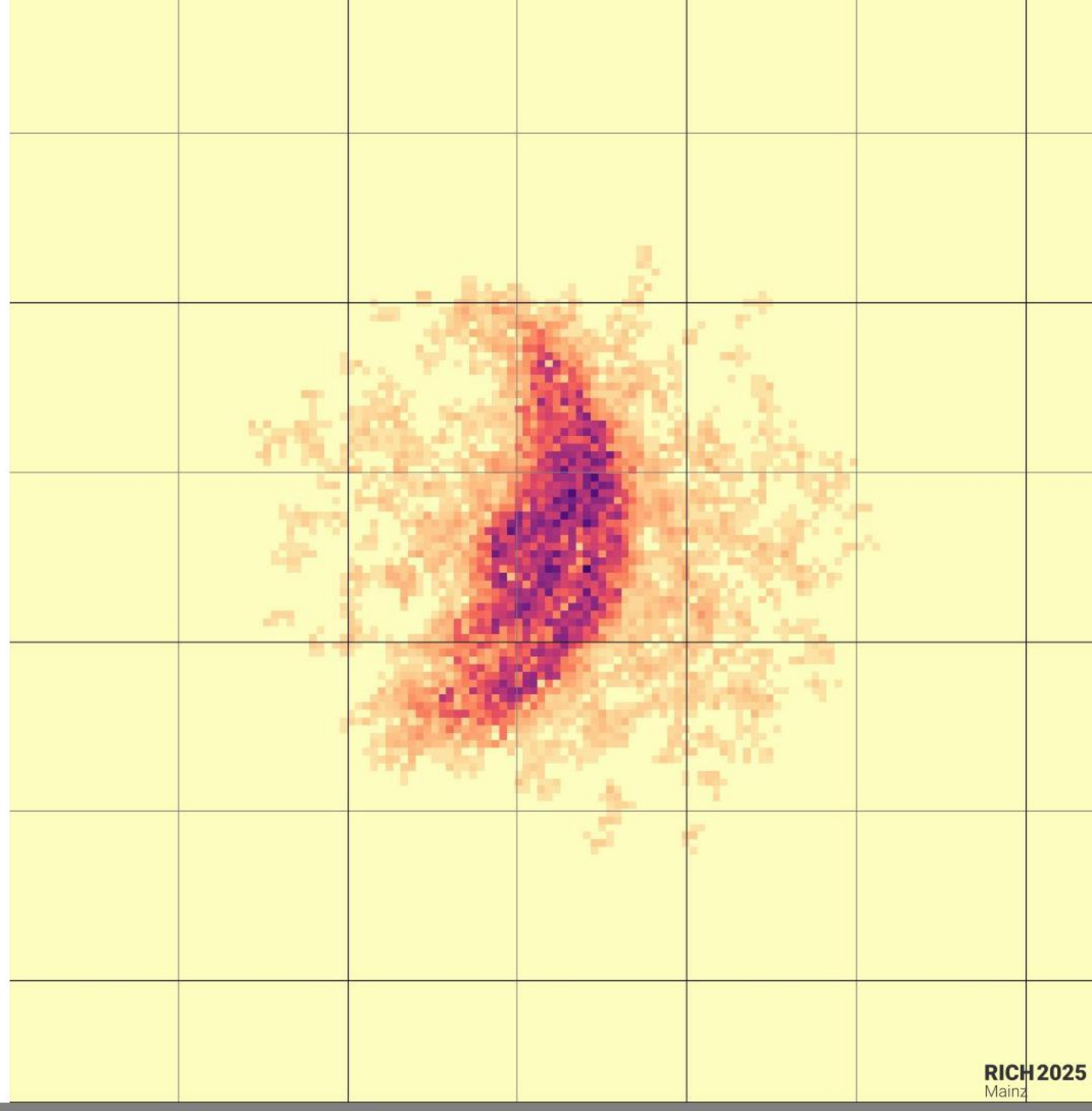

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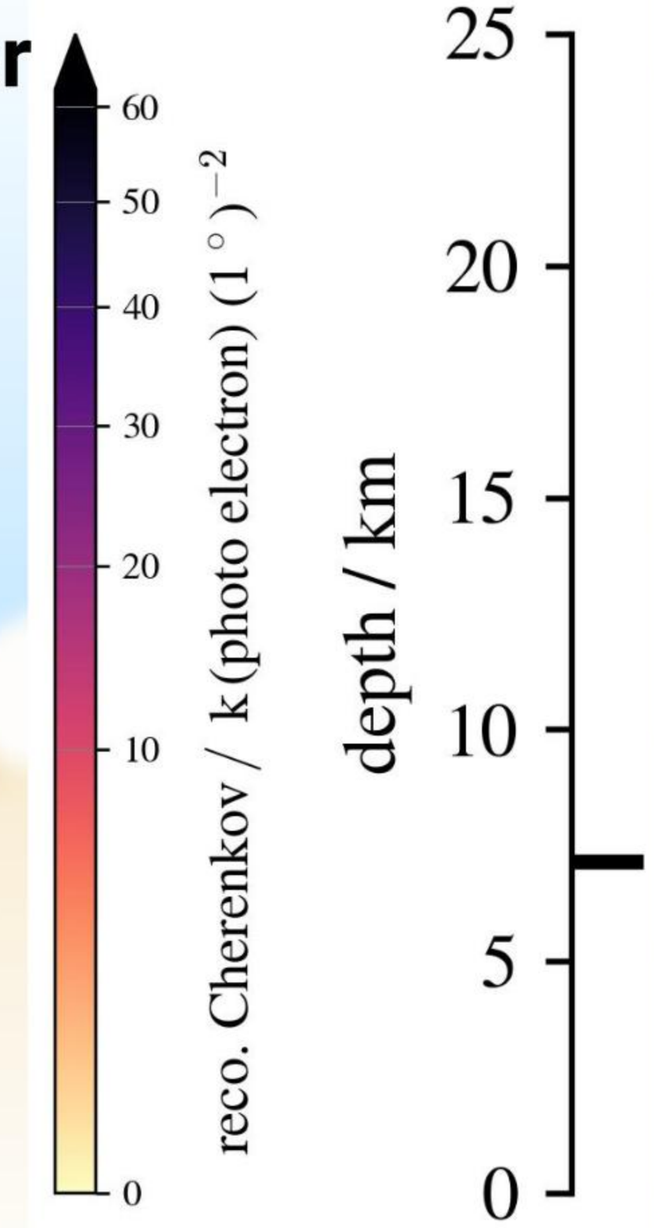
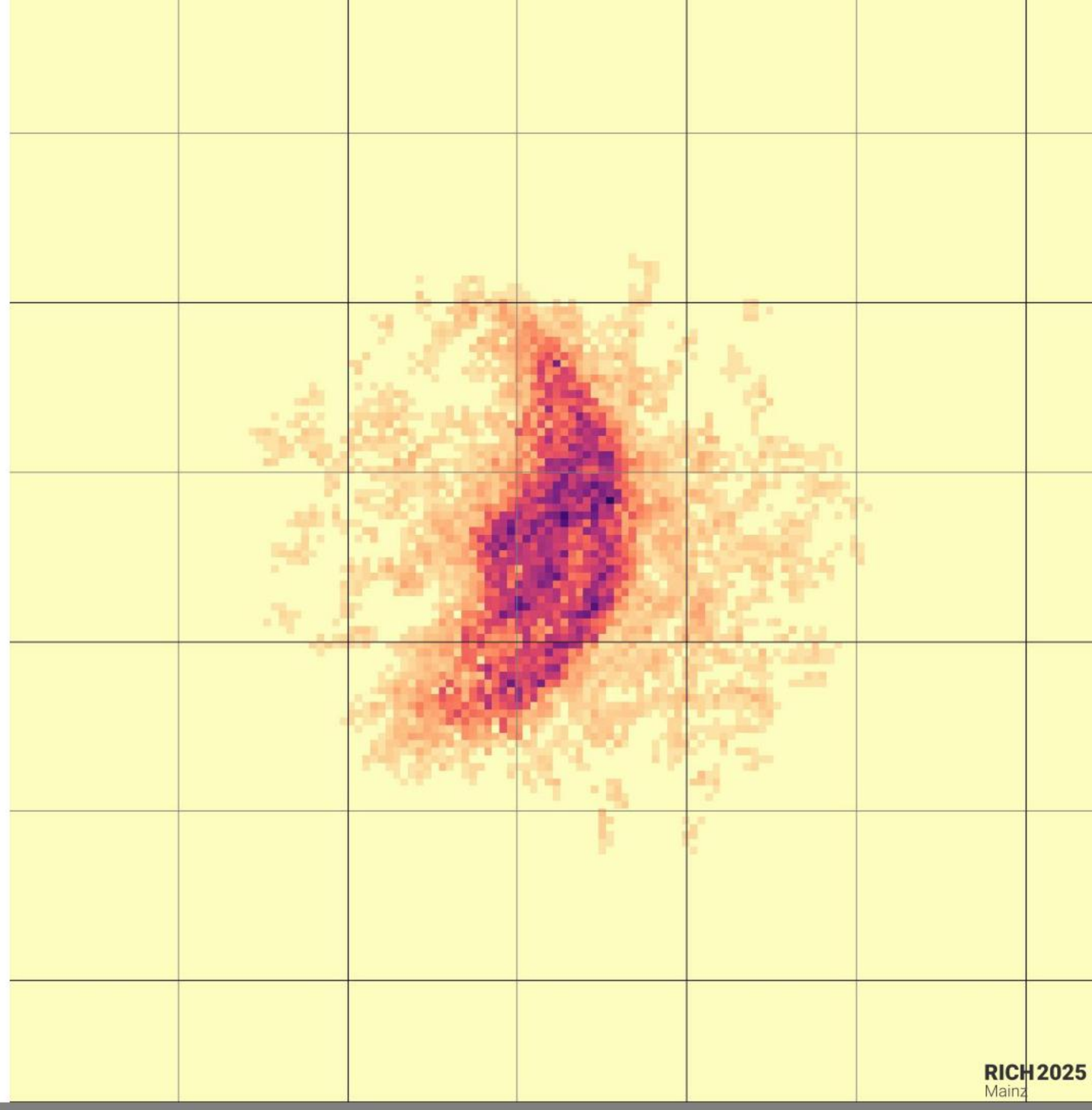
core > 1km





Airshower

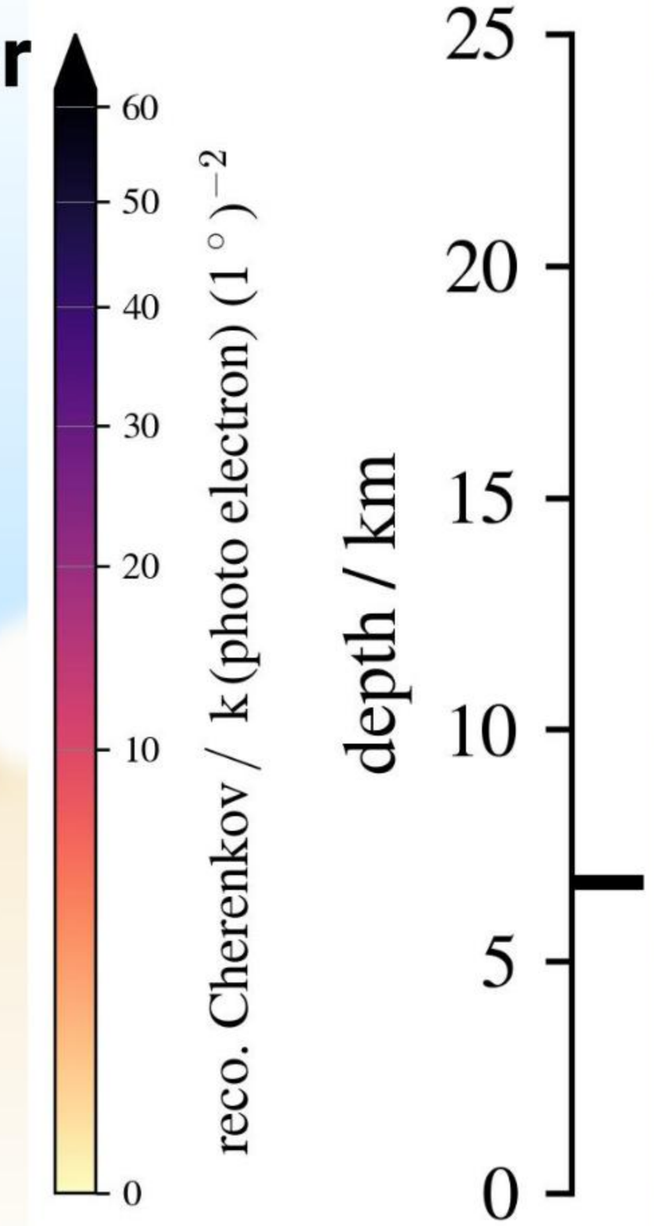
Proton

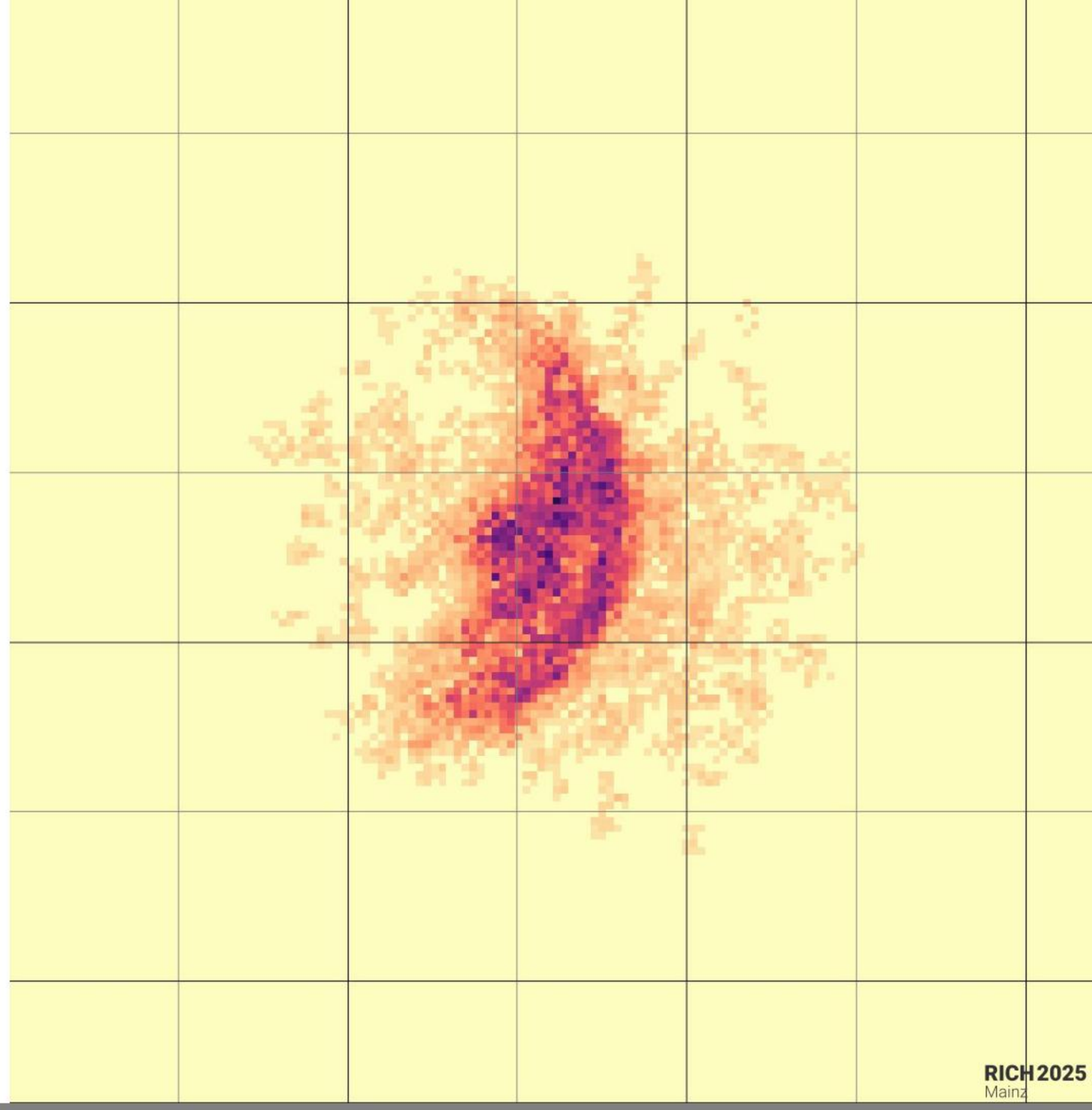
44GeV

4,814p.e.

Muon ring?

core > 1km





Airshower

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Muon ring?

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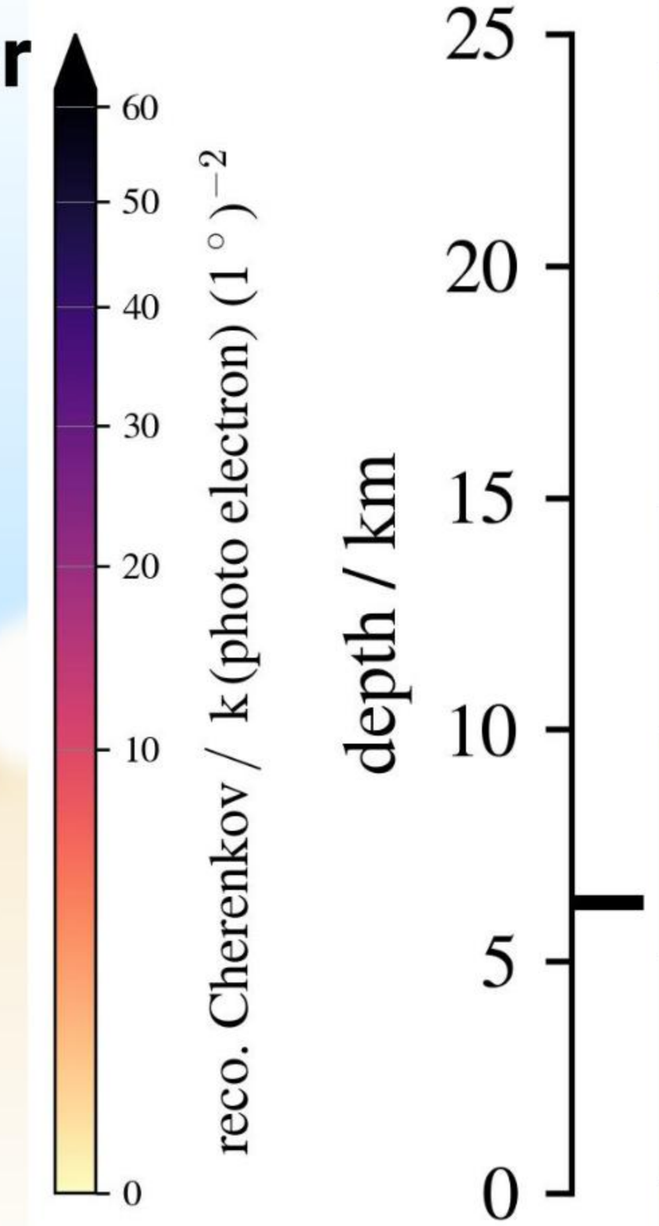

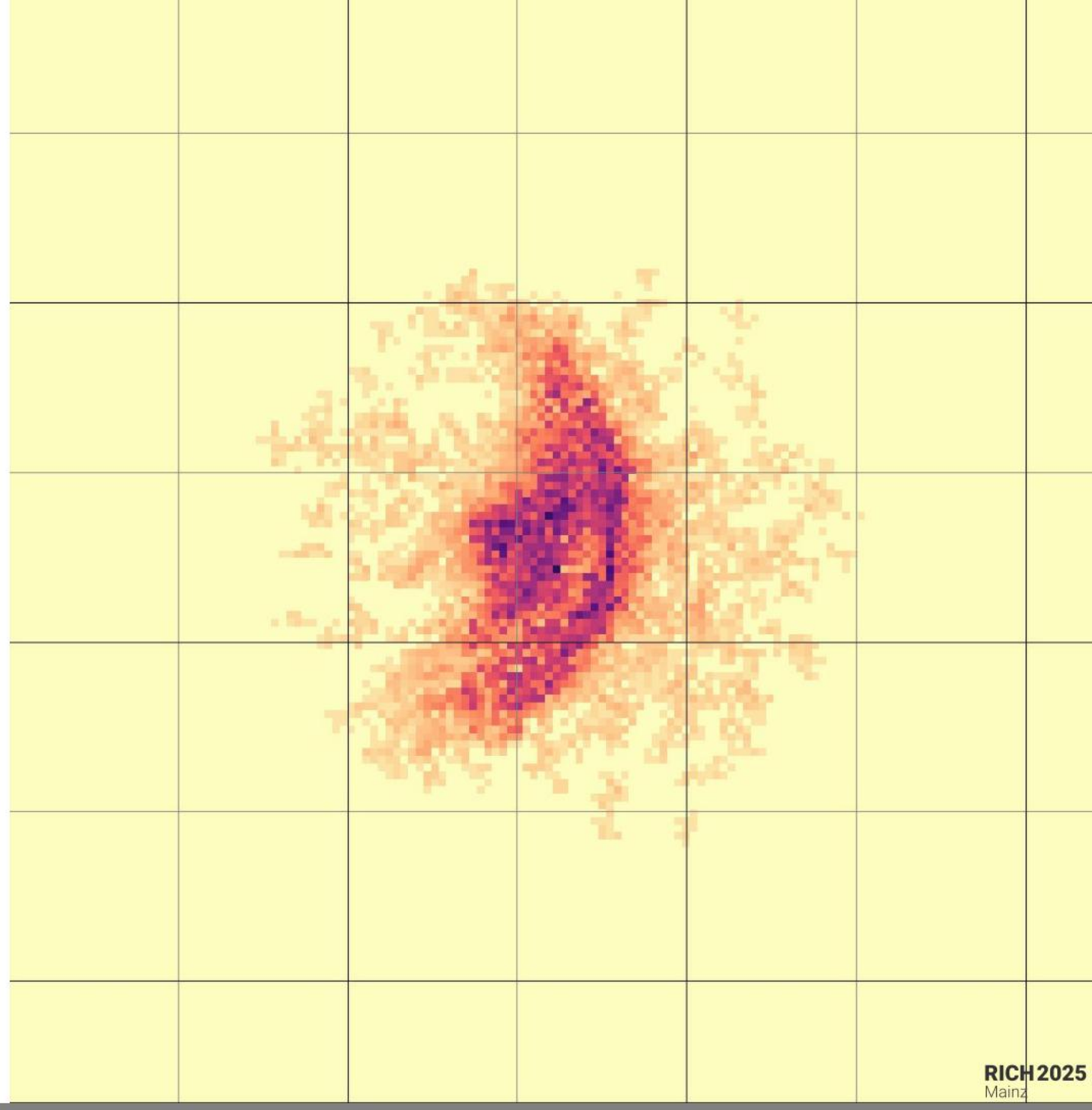

Airshower

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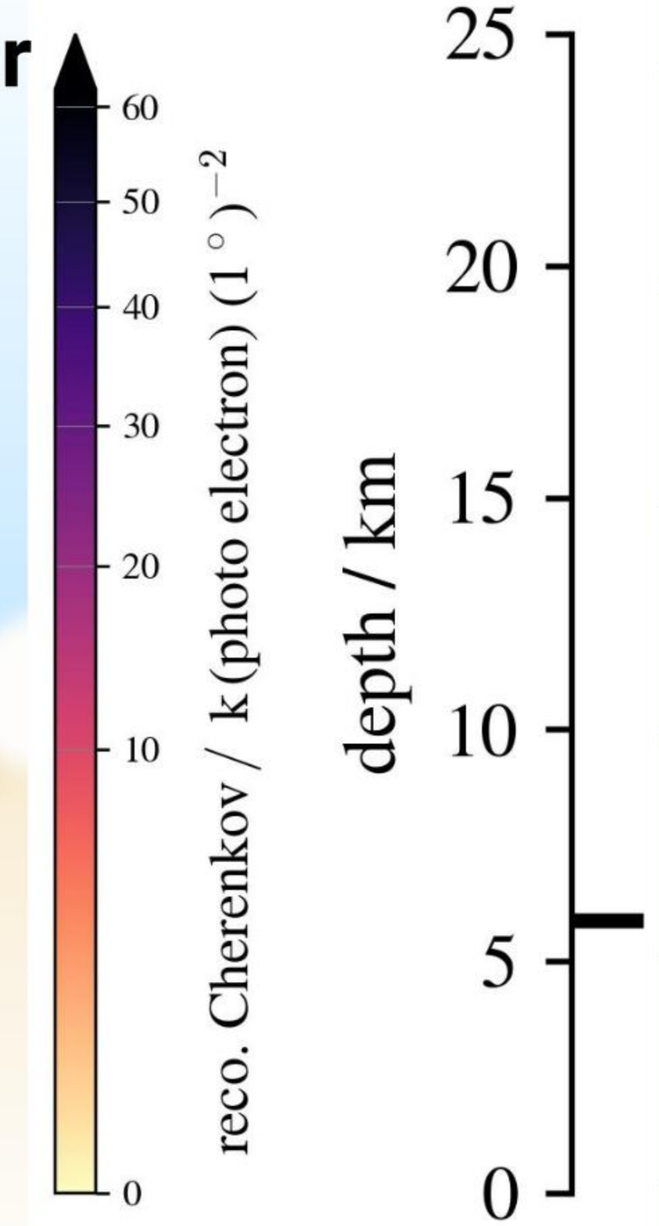

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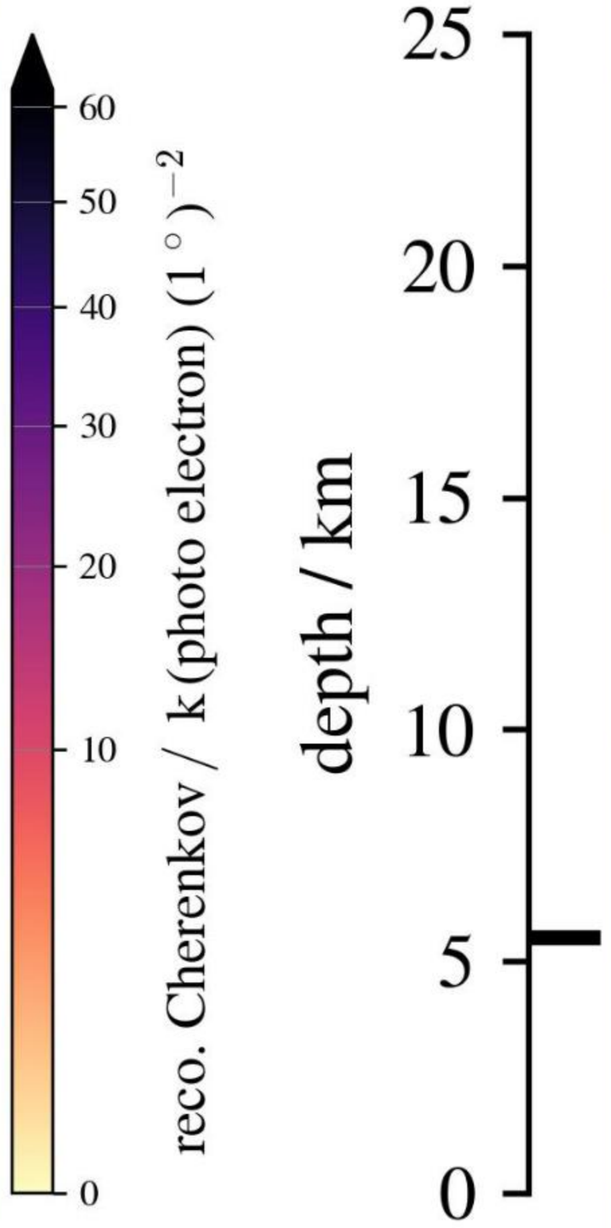

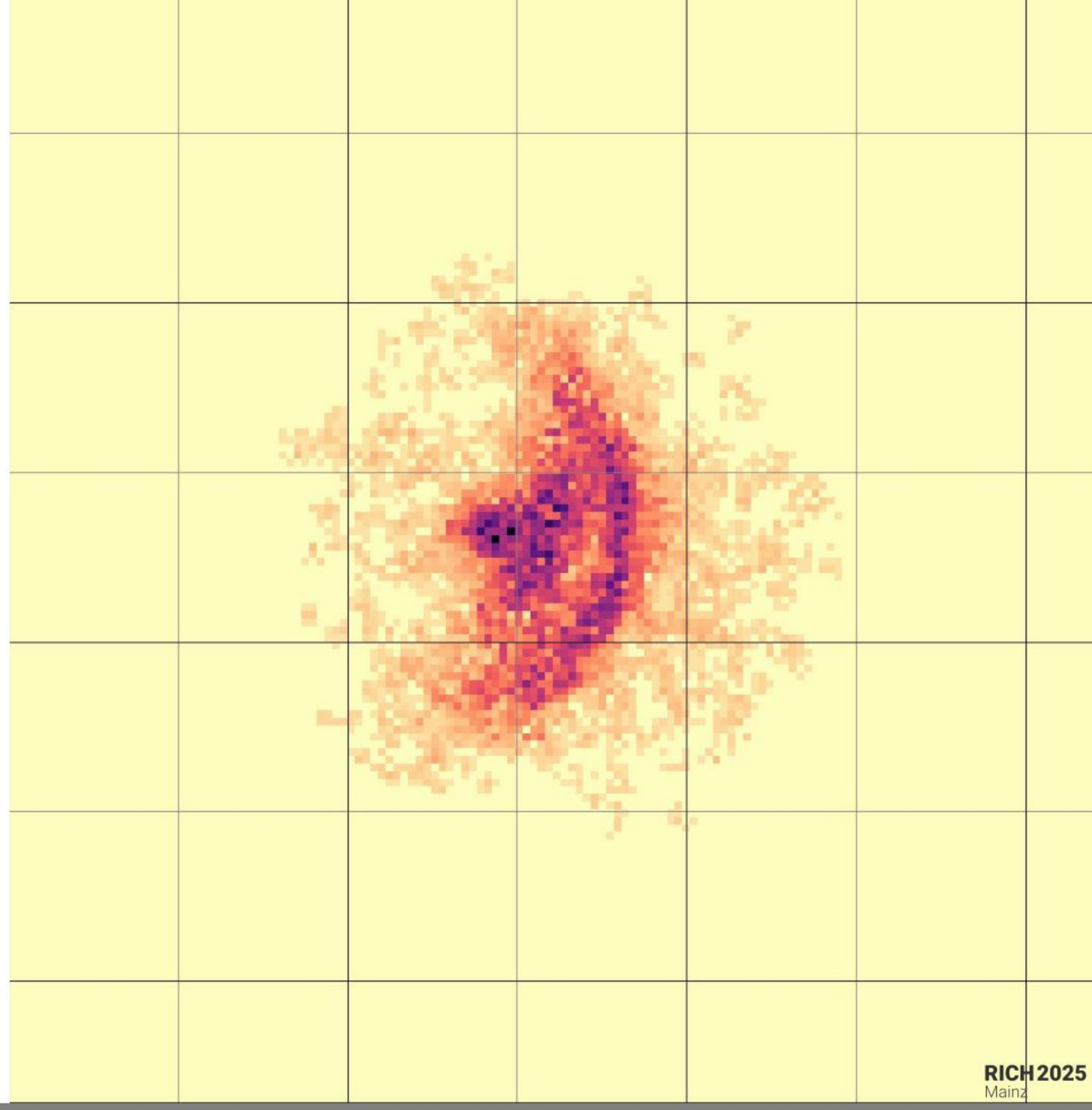

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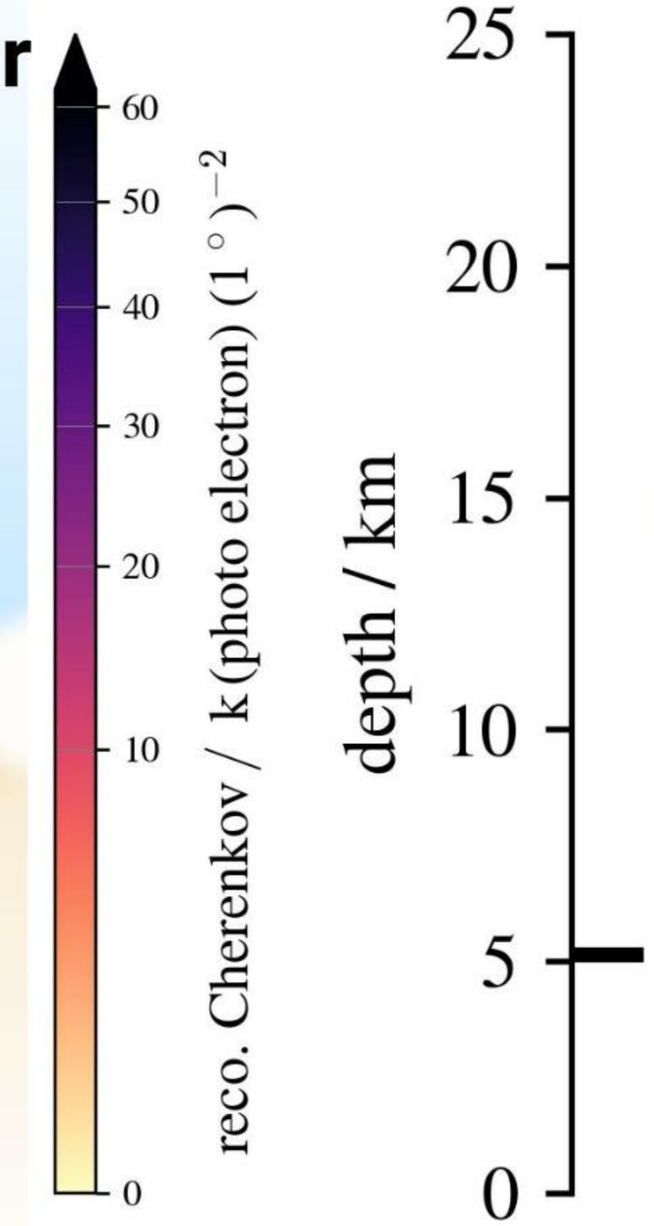

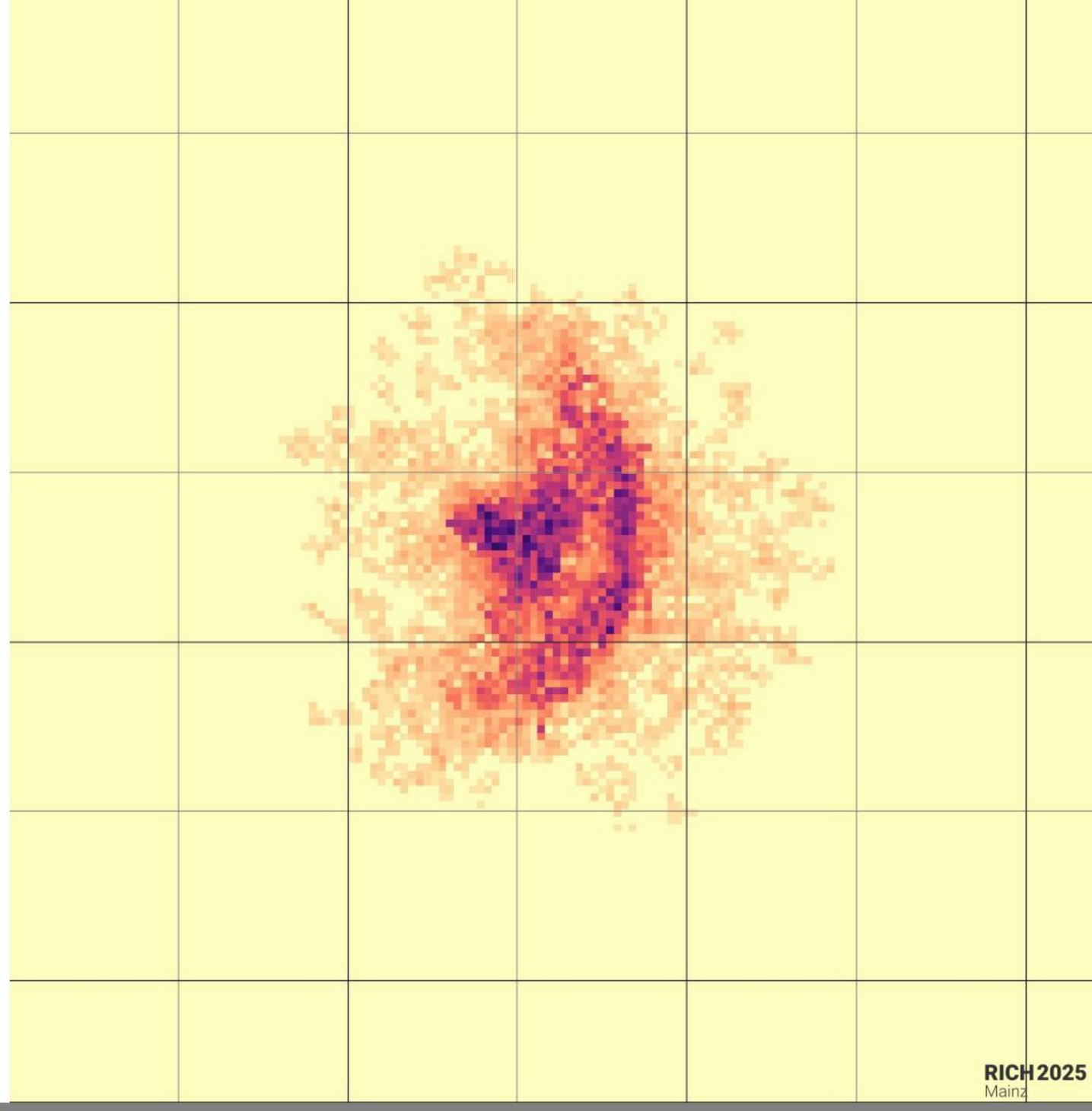

Airshower

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Muon ring?

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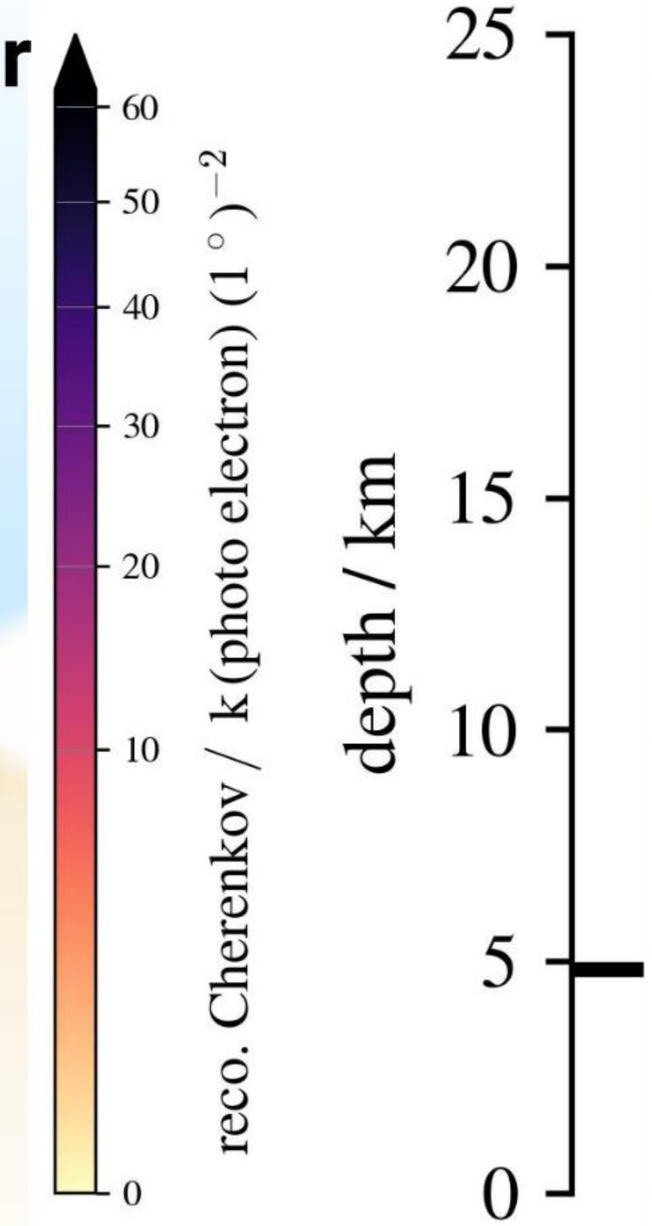

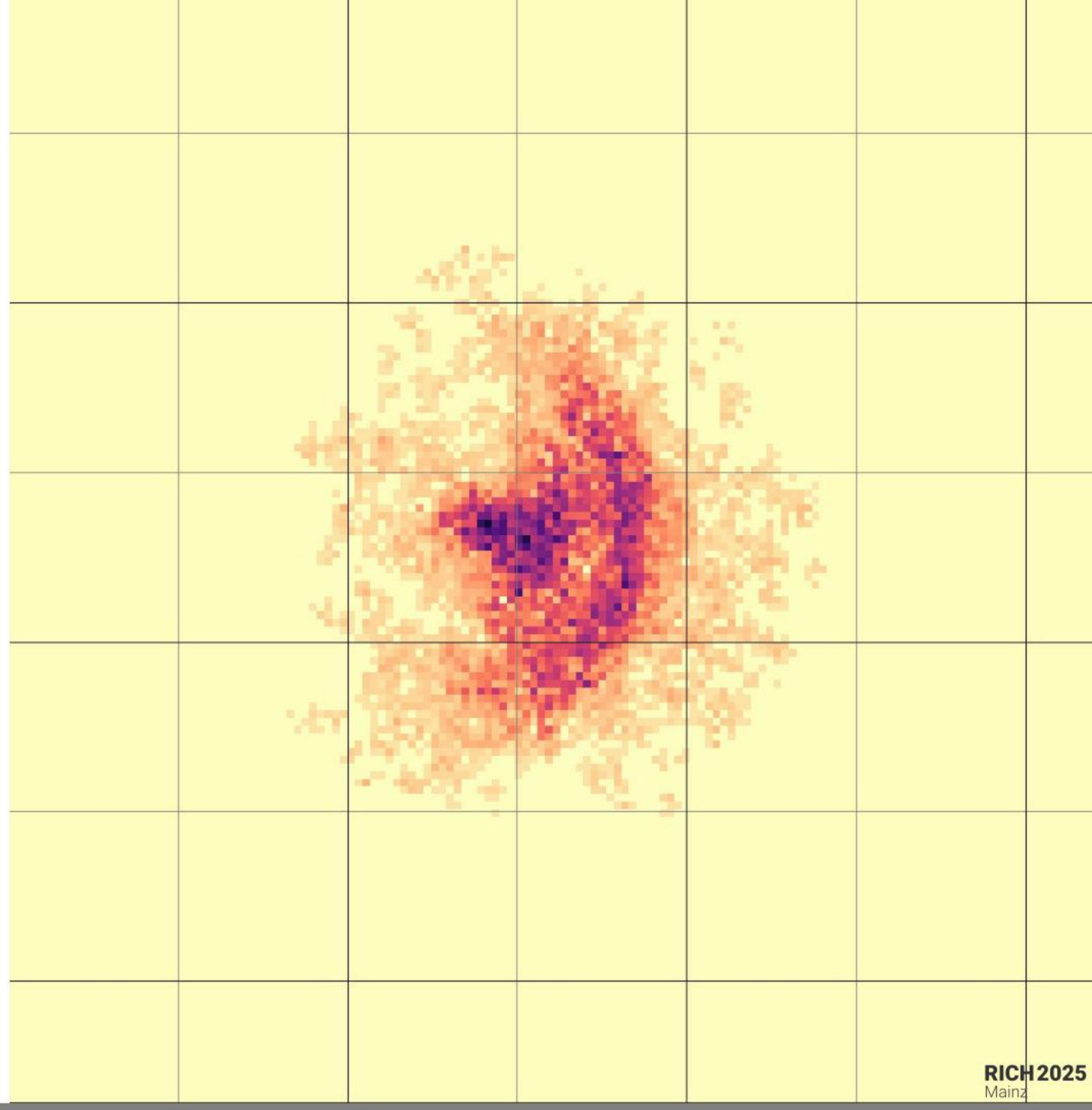

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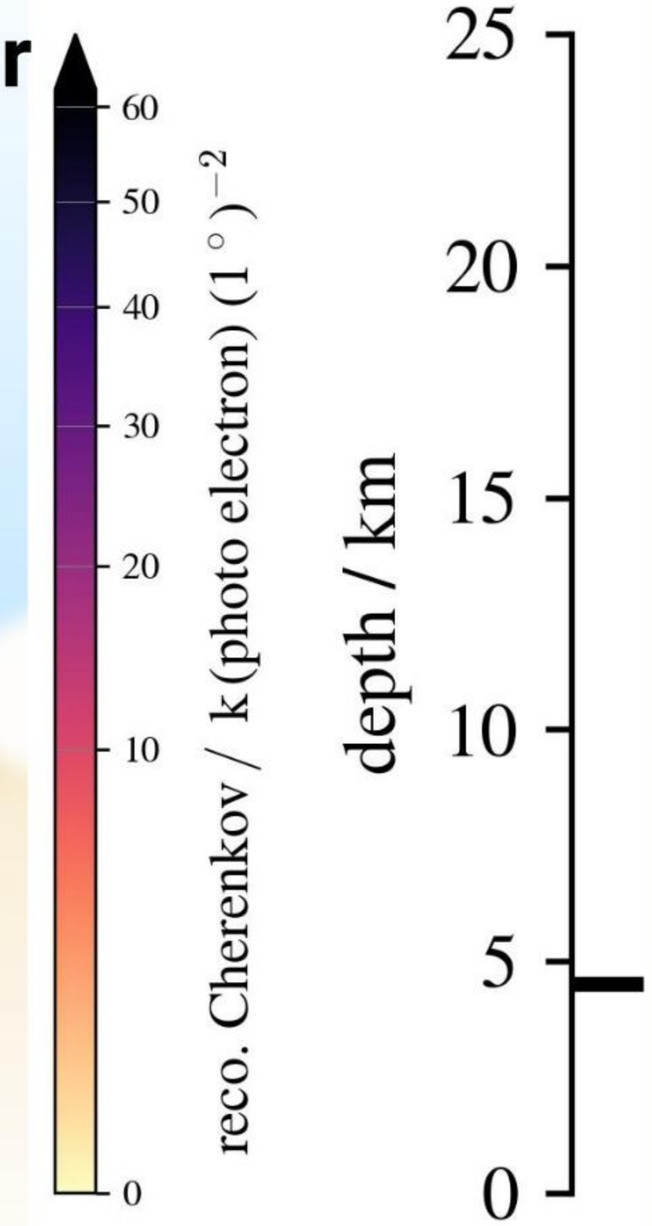

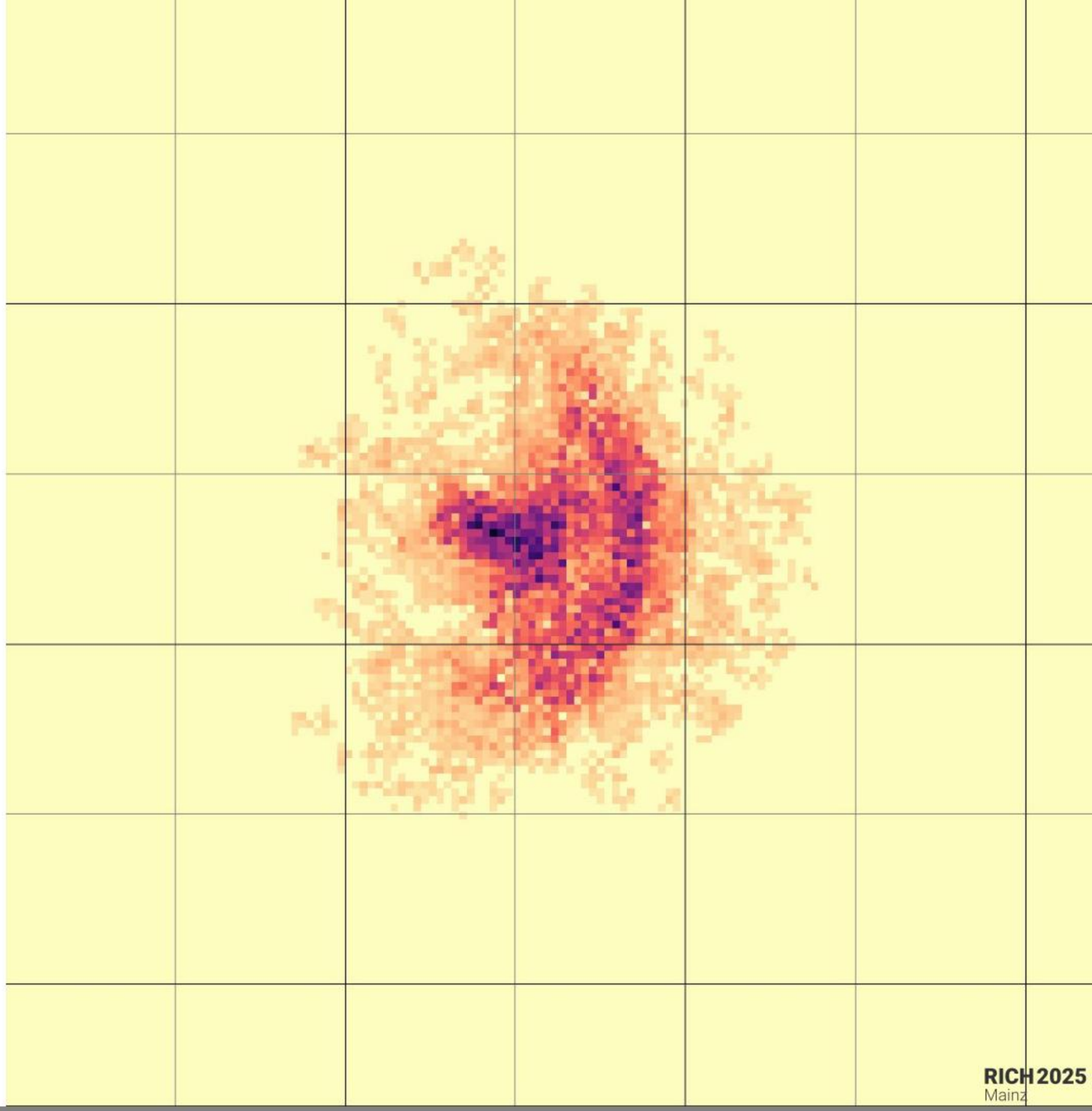

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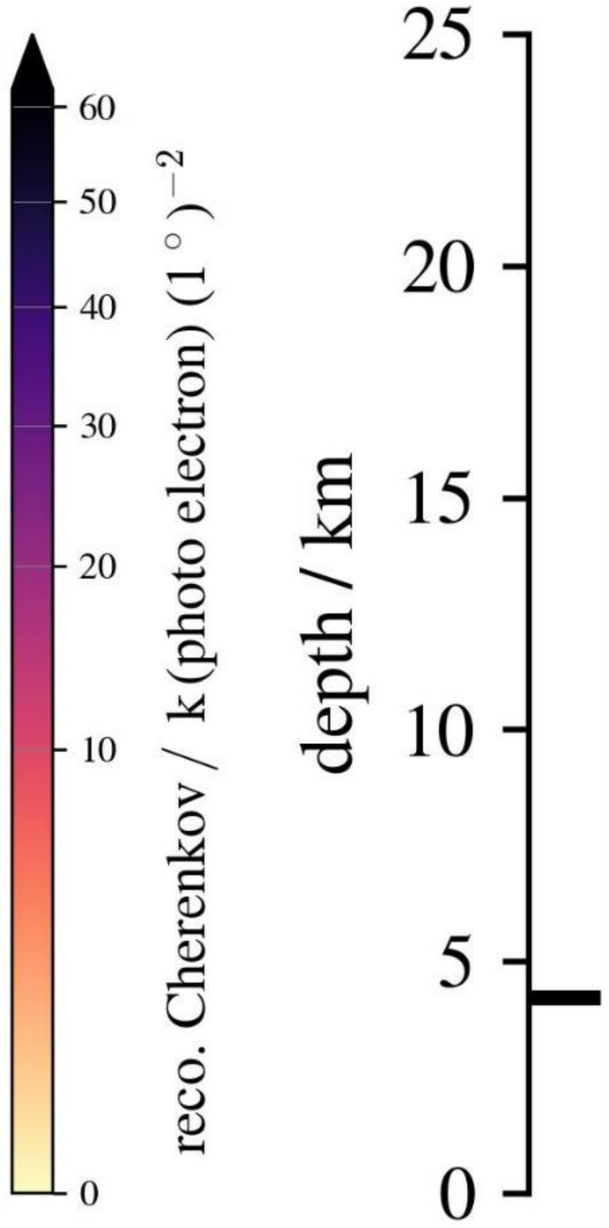

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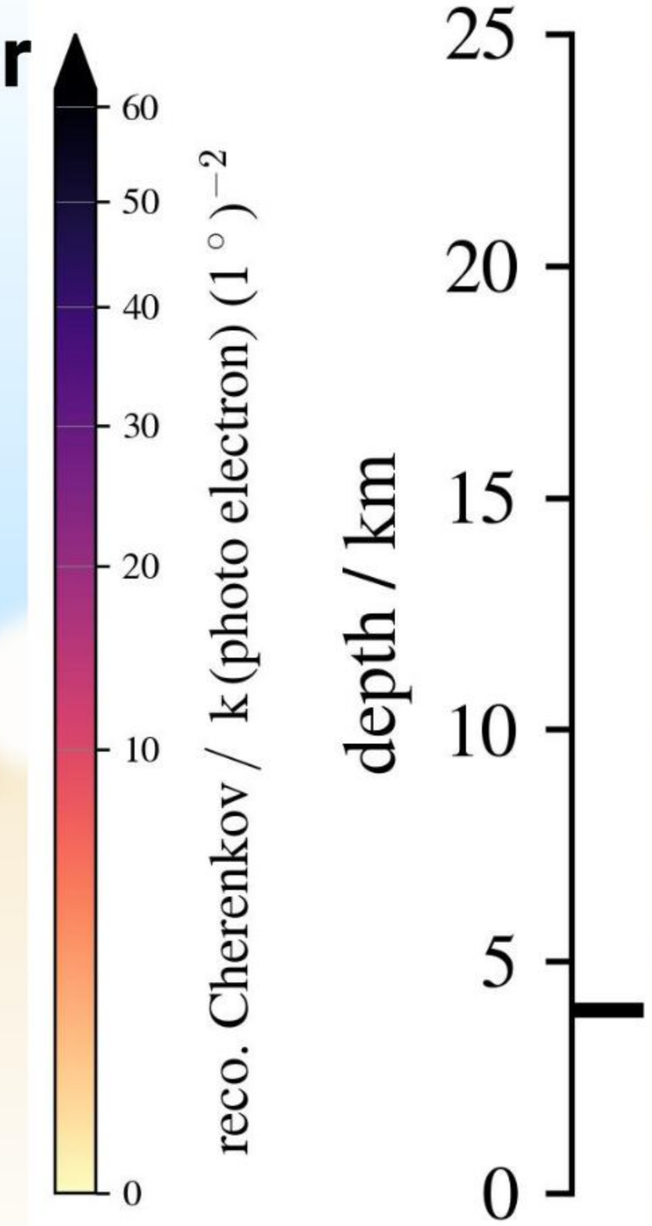

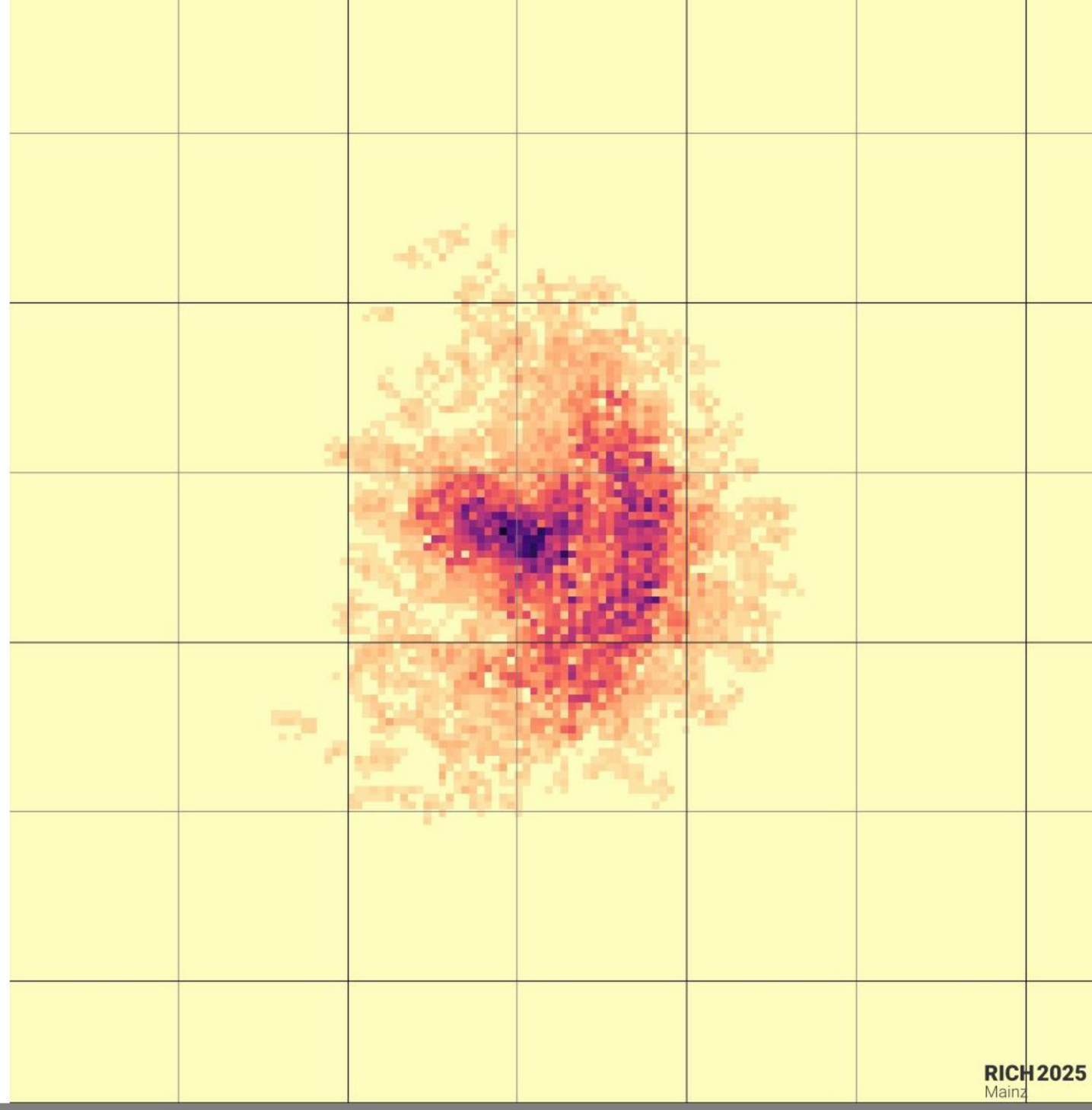

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Muon ring?

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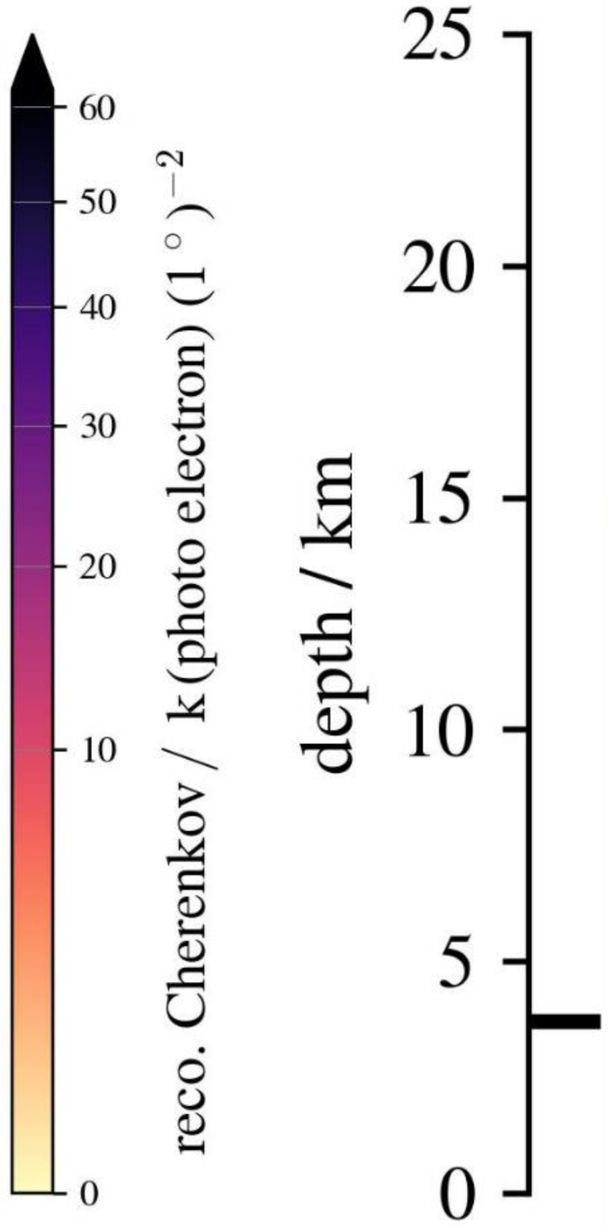

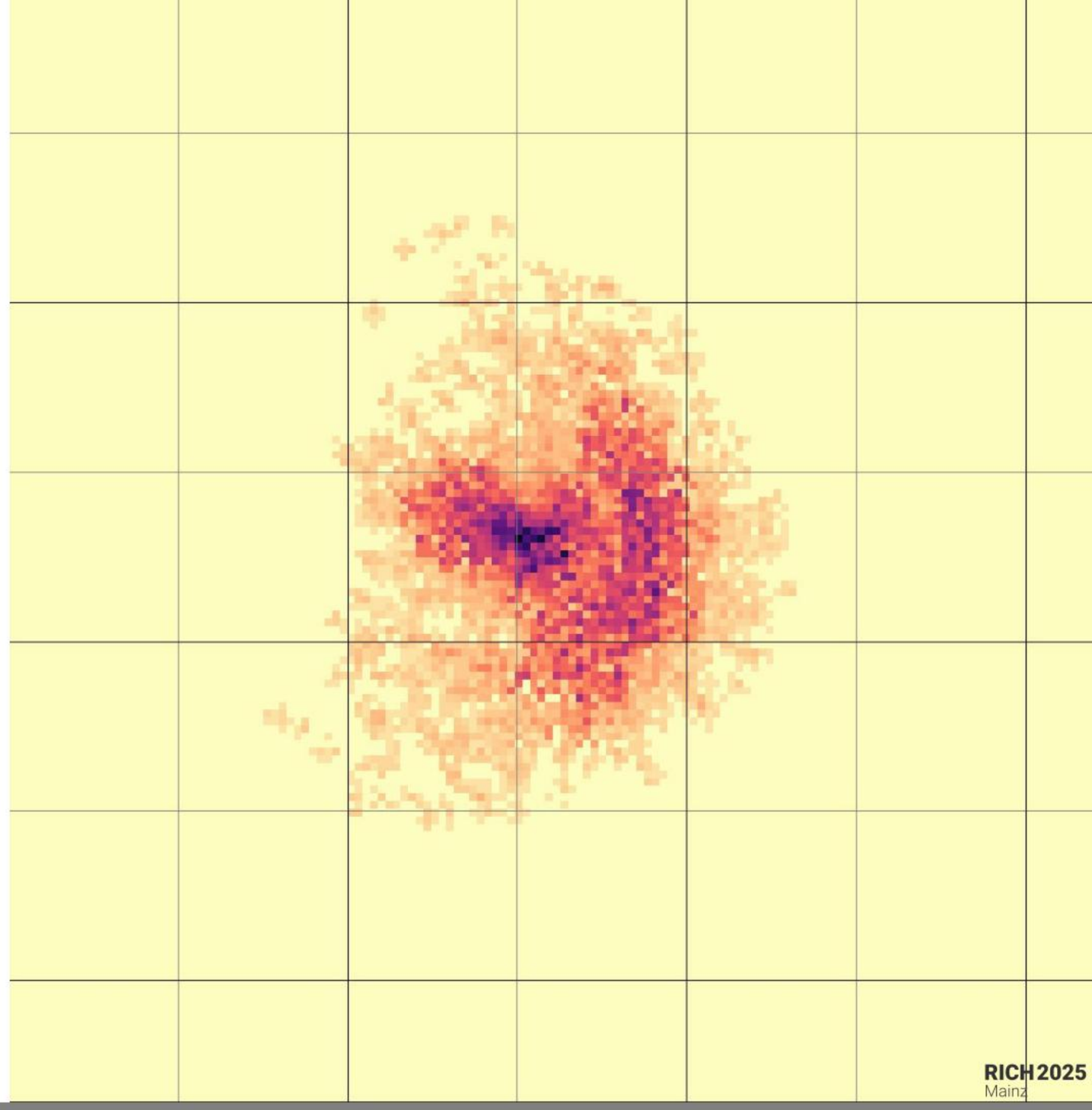

Airshower

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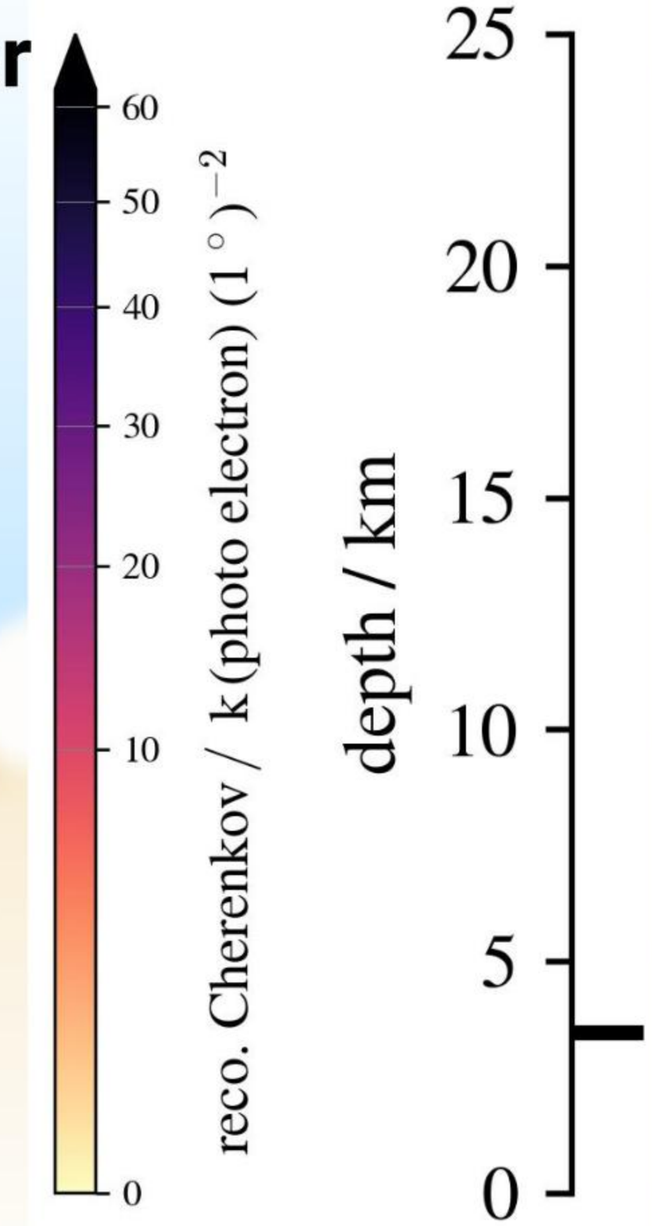

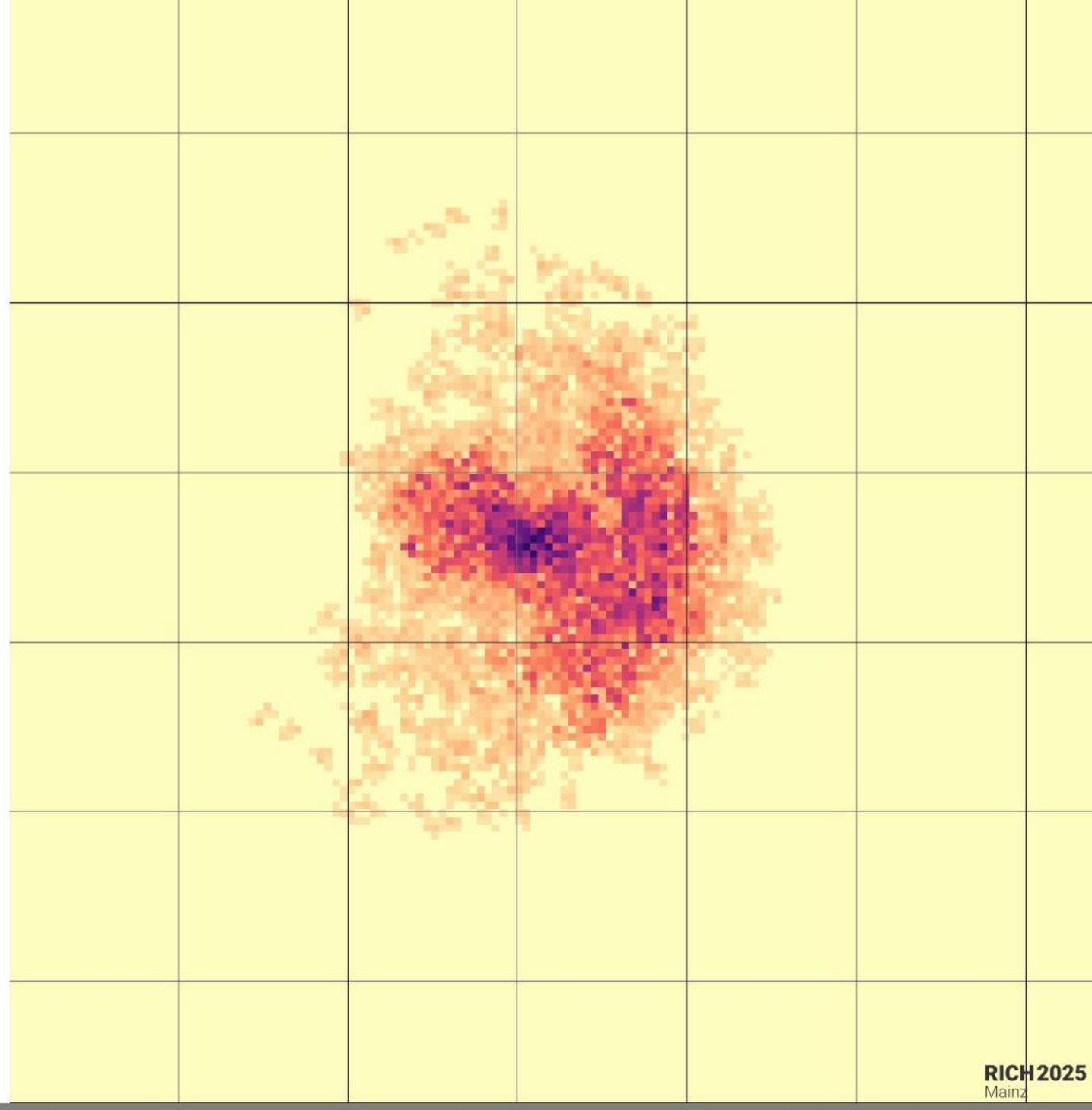

Airshower

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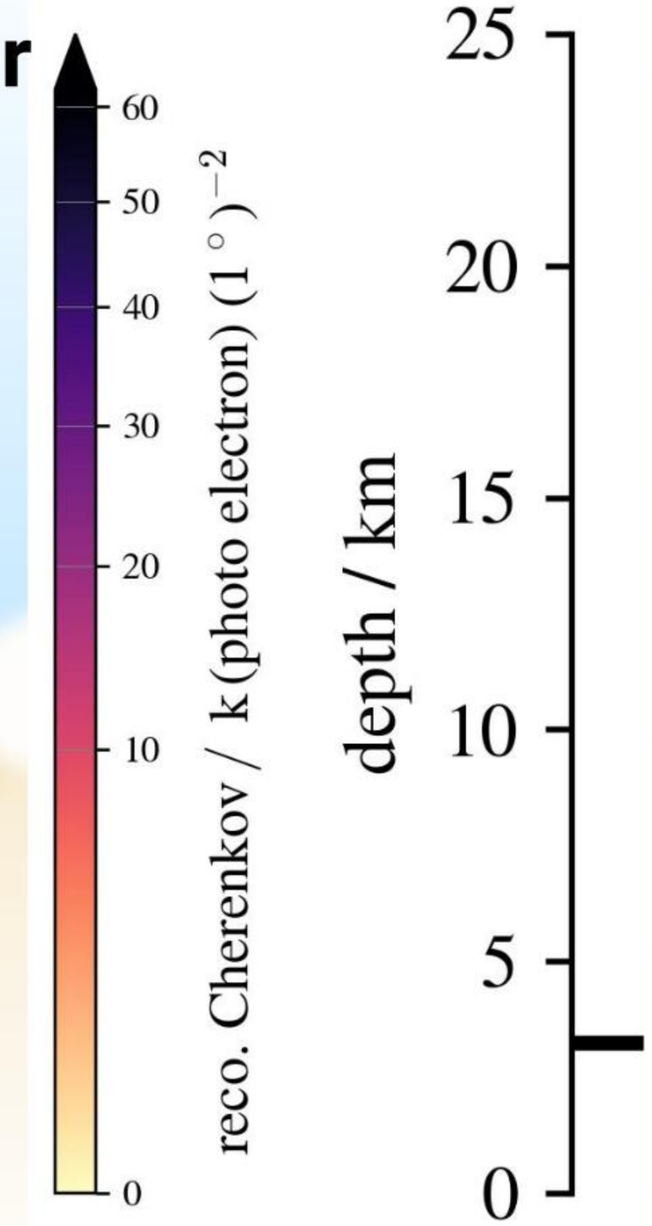

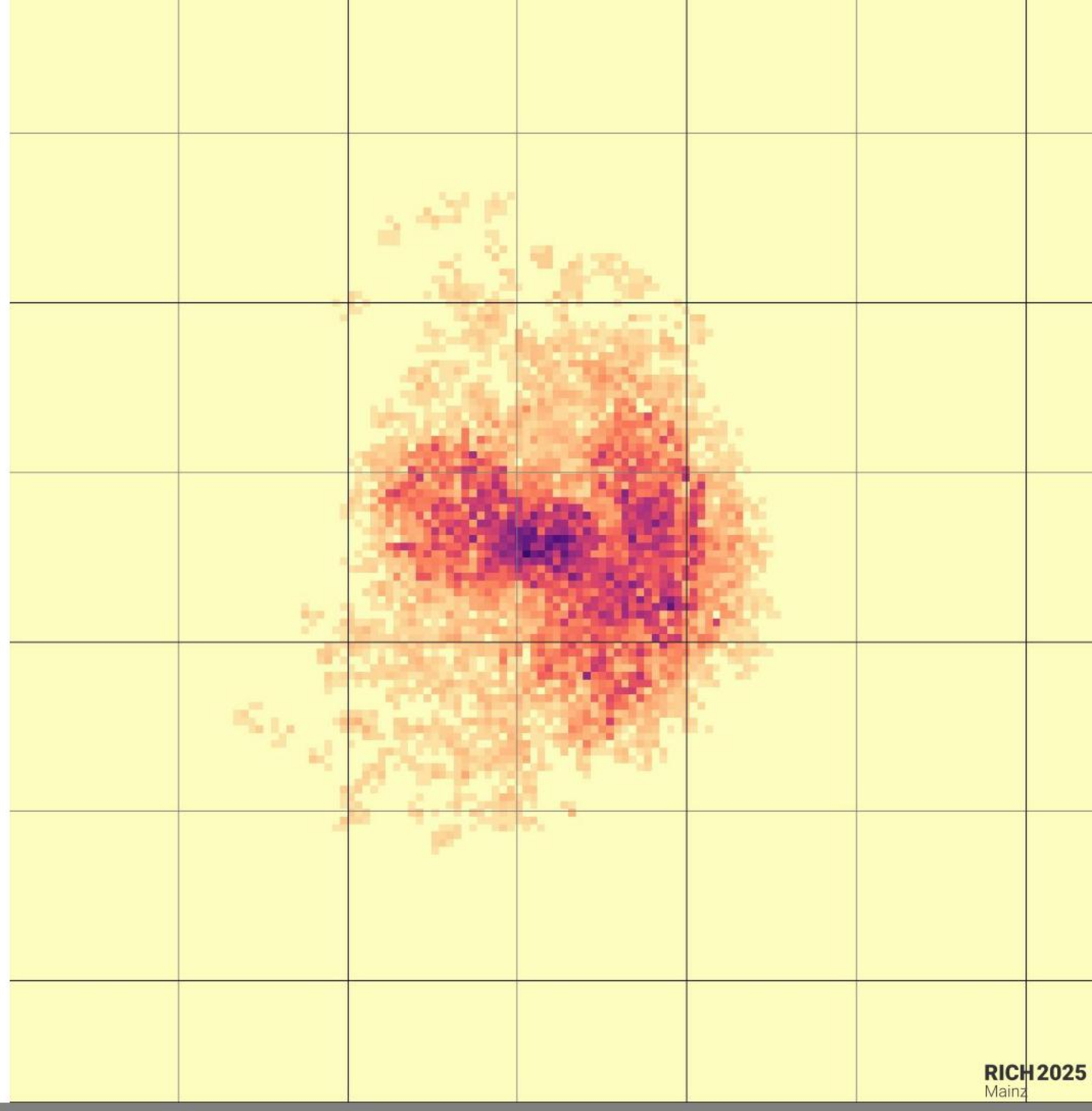

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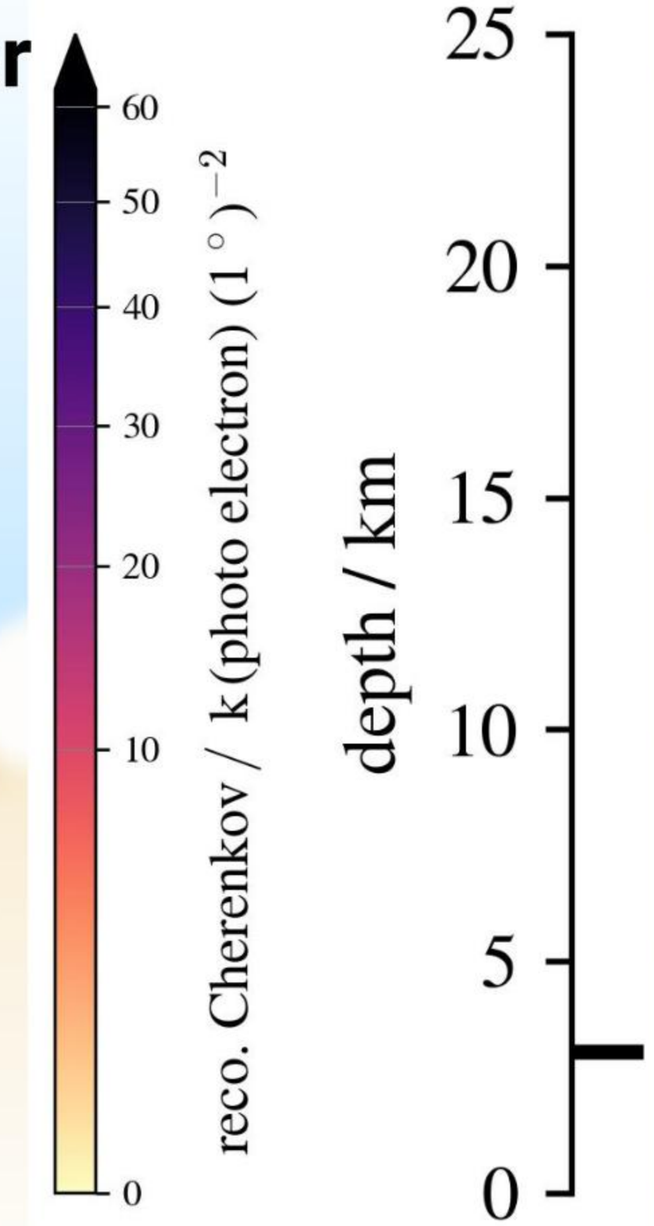

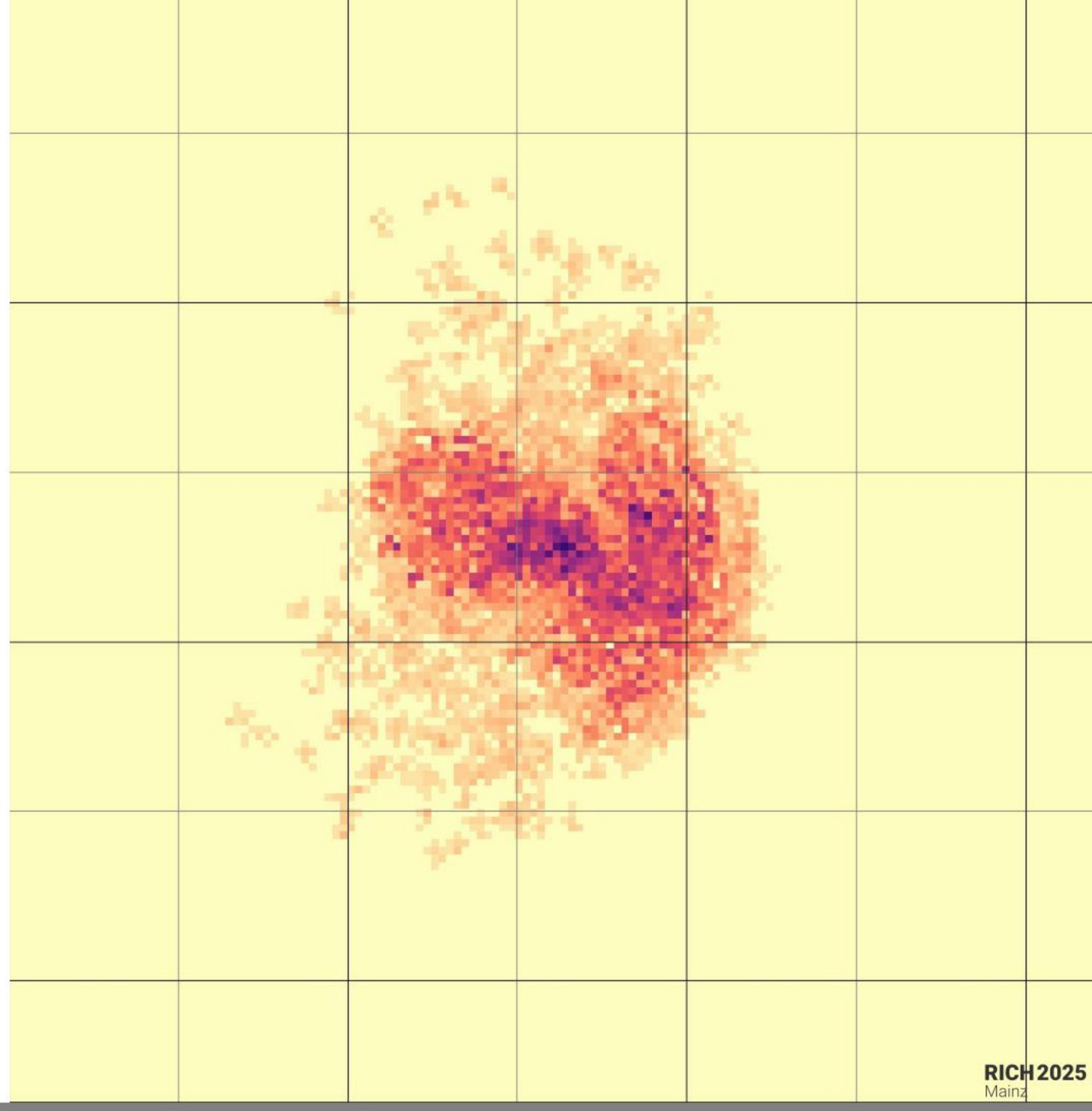

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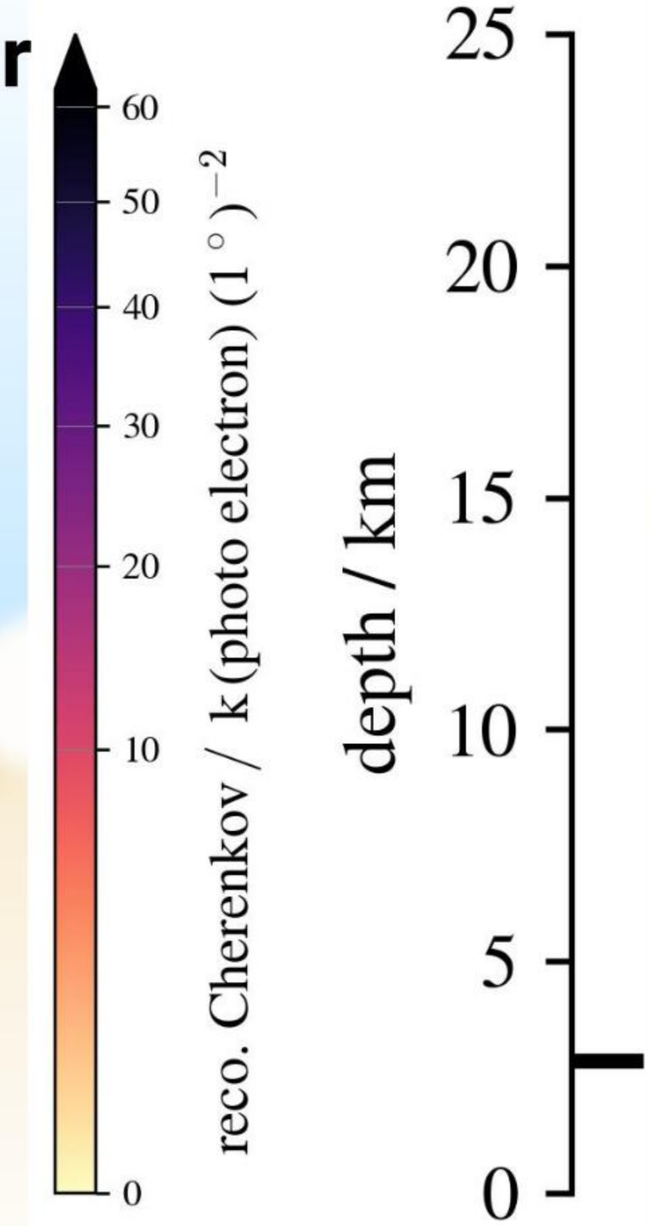

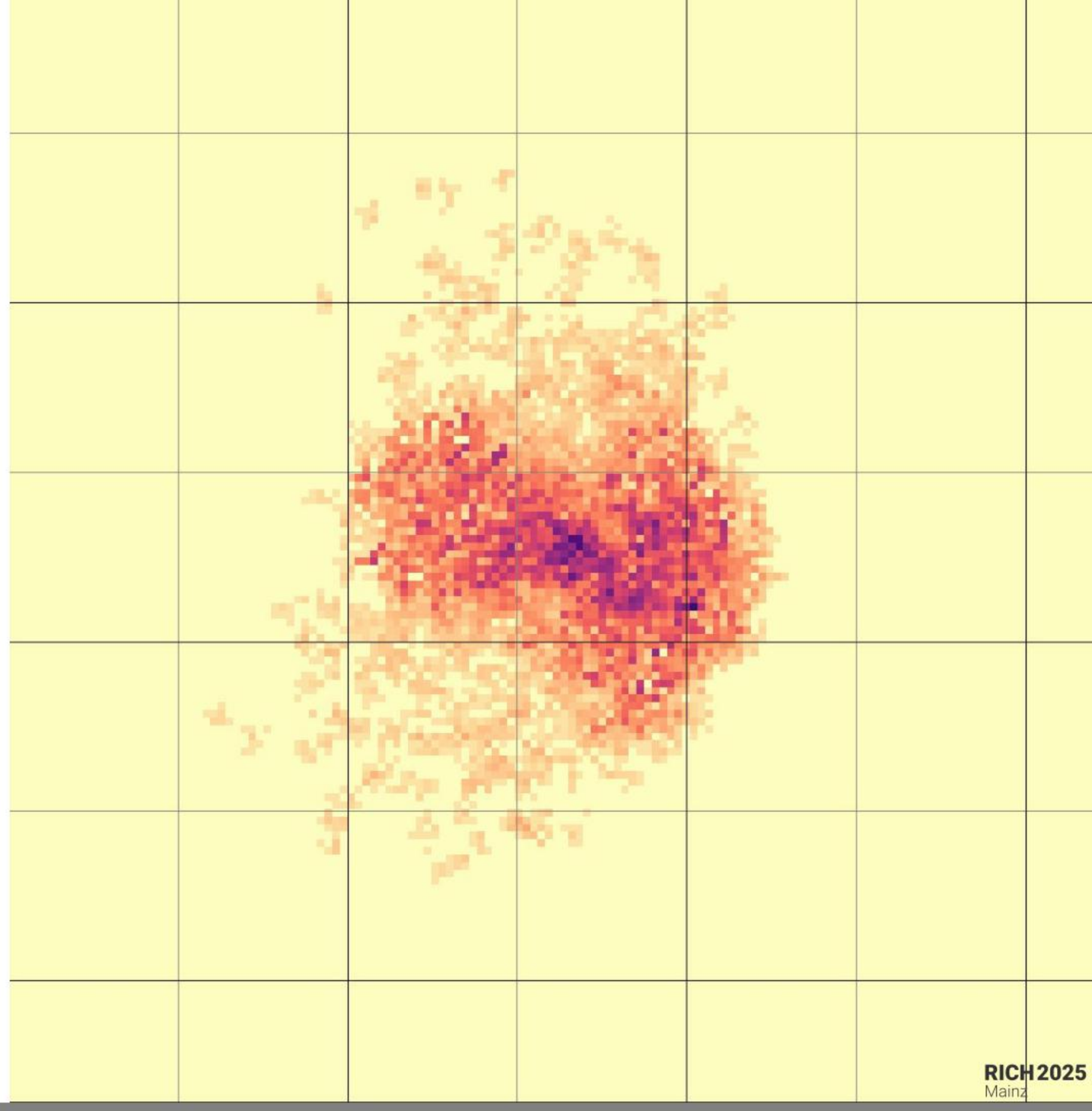

Airshower

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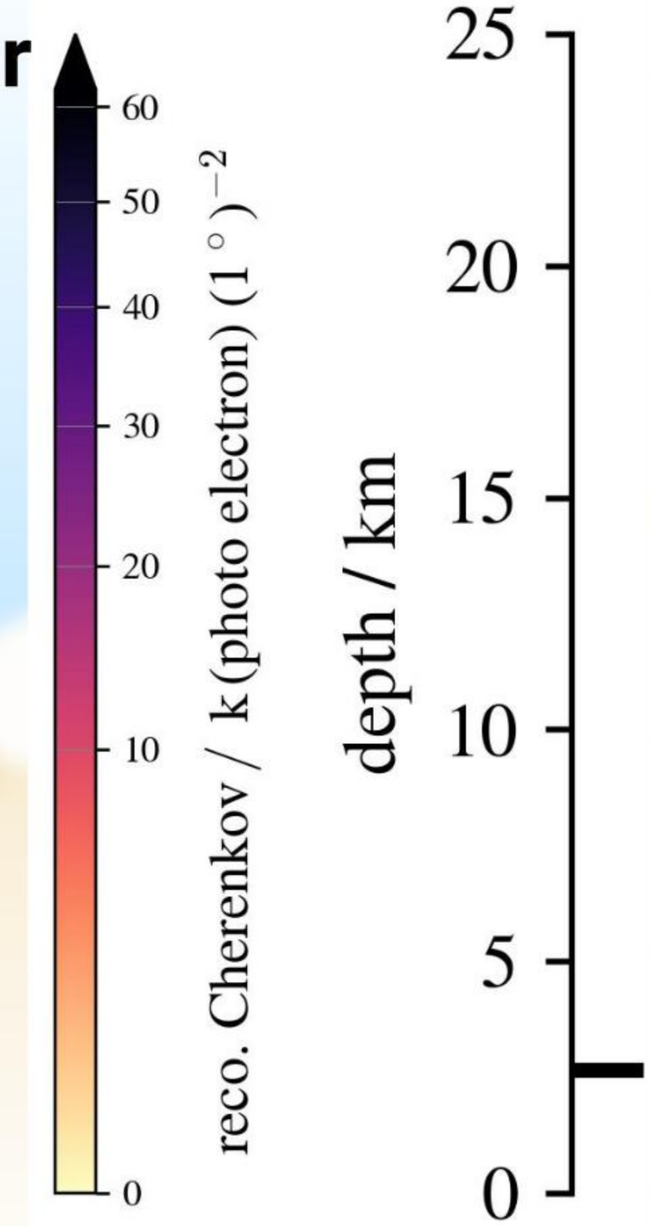

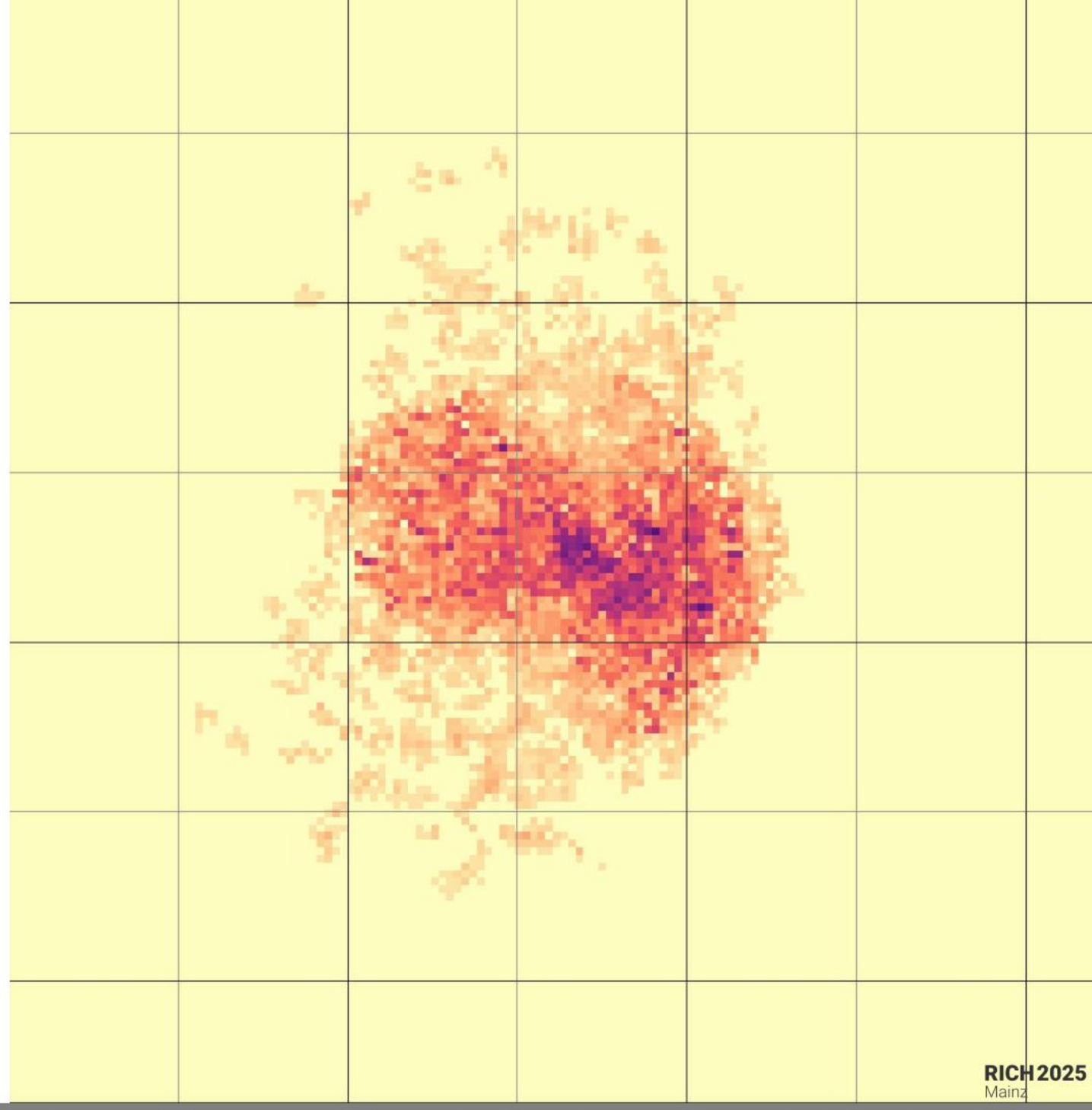

Airshower

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Muon ring?

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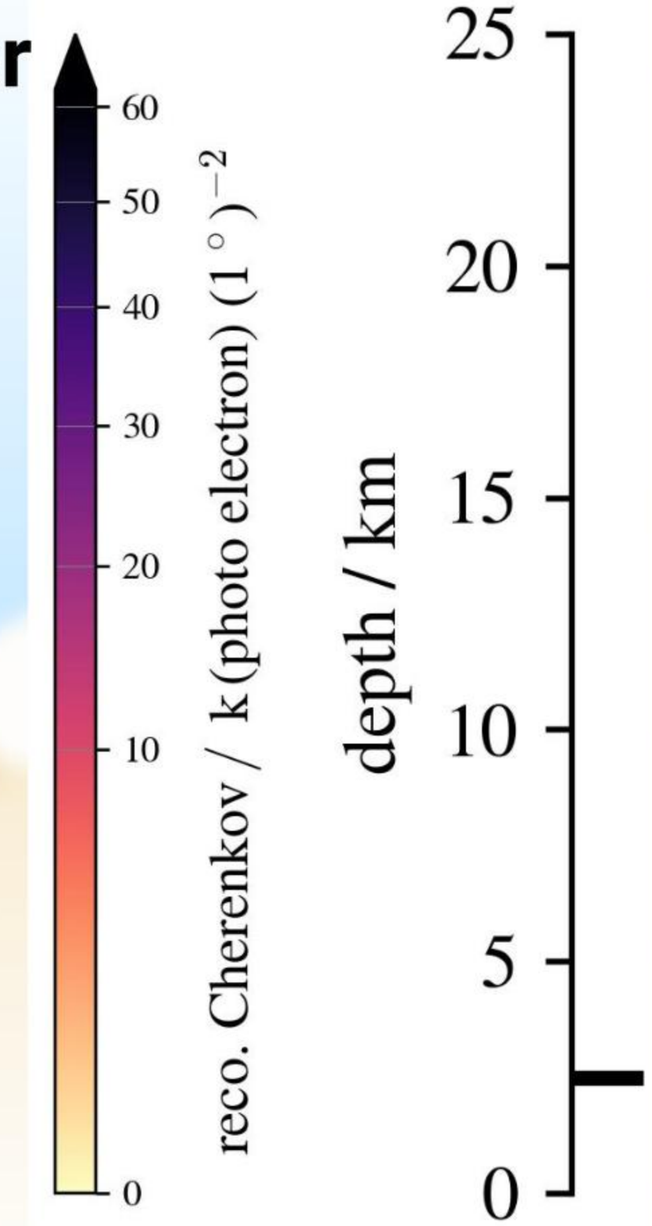

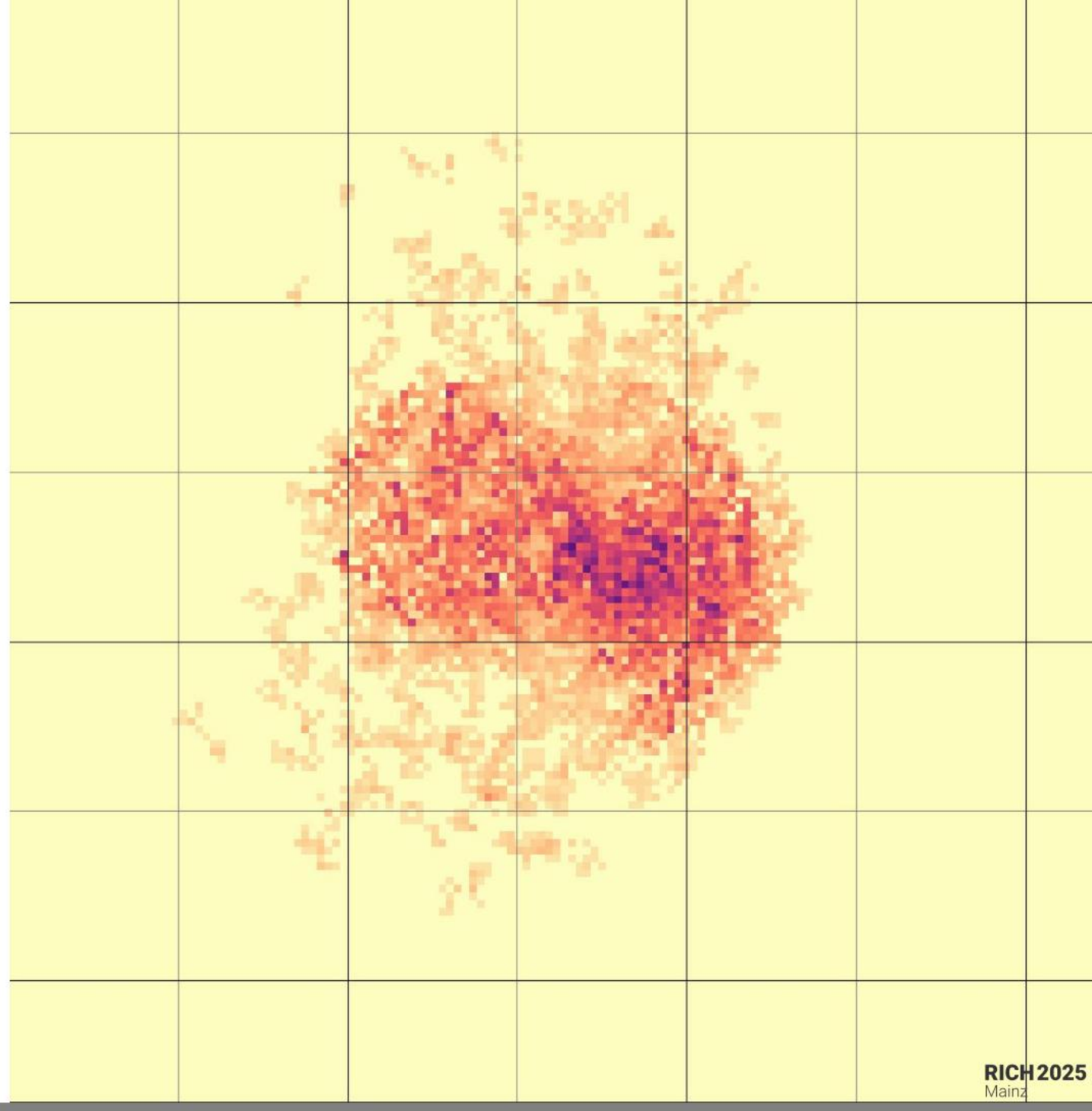

Airshower

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Muon ring?

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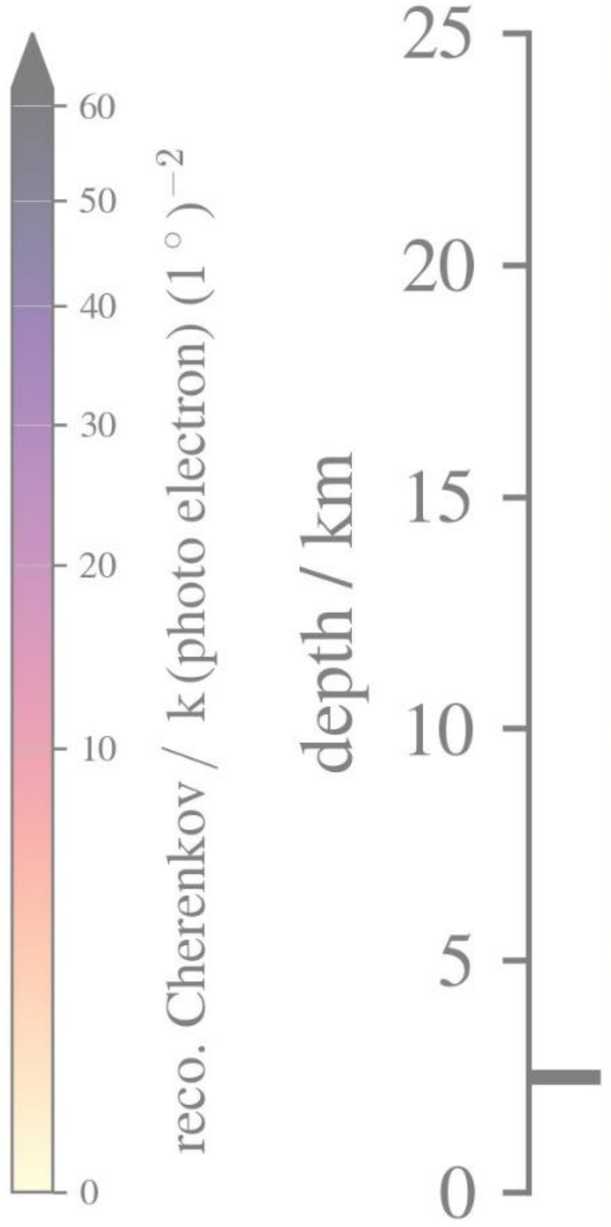
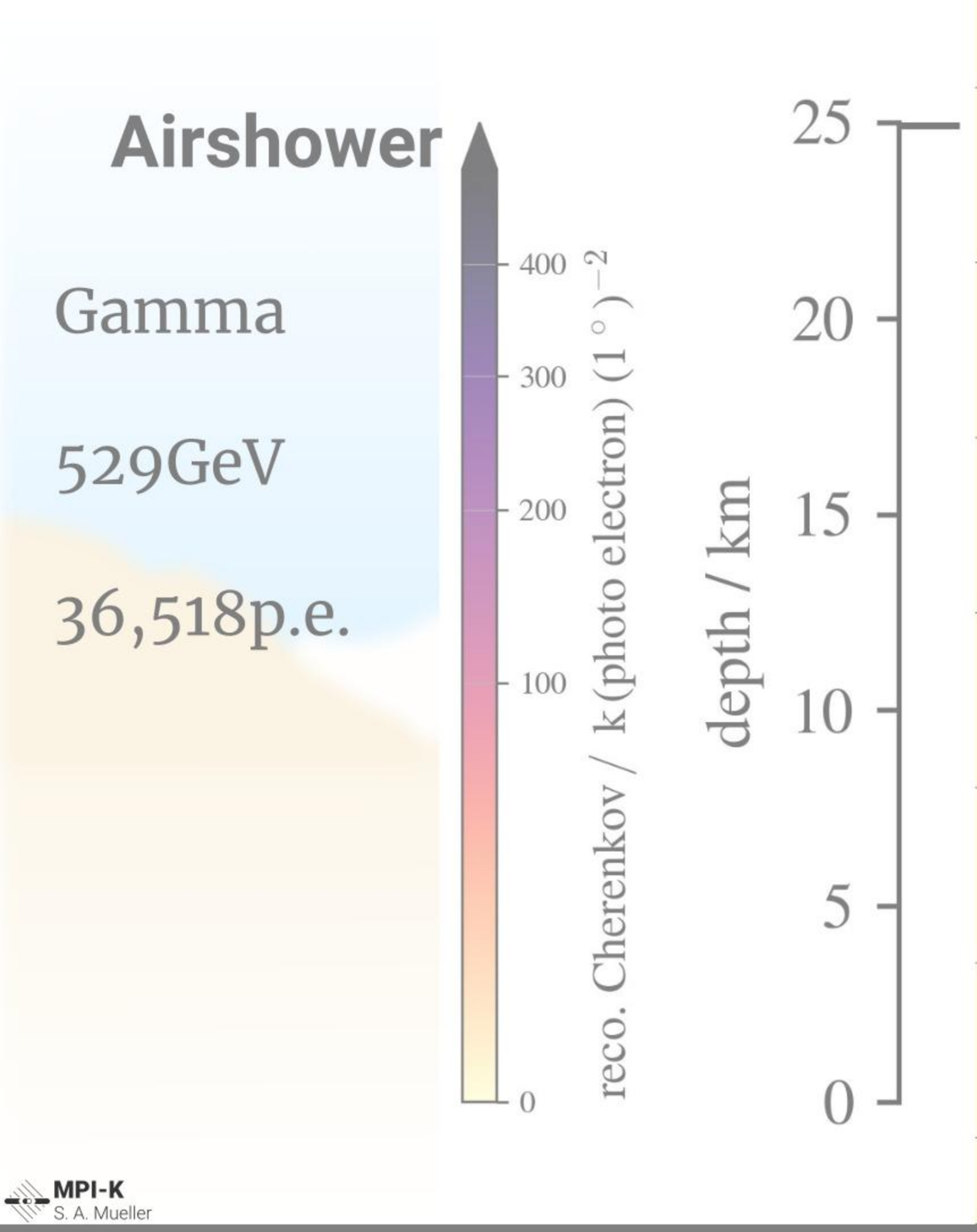
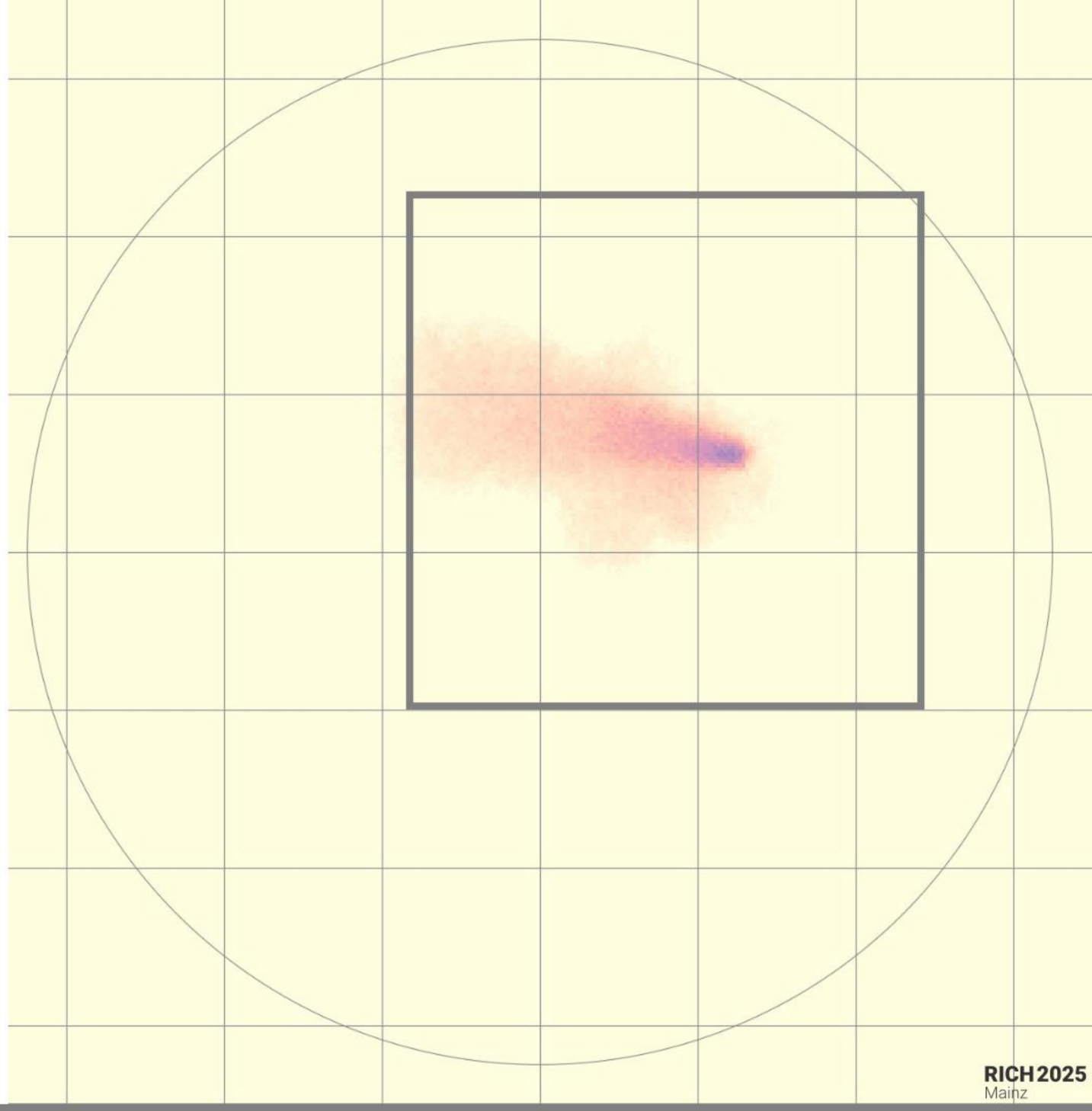
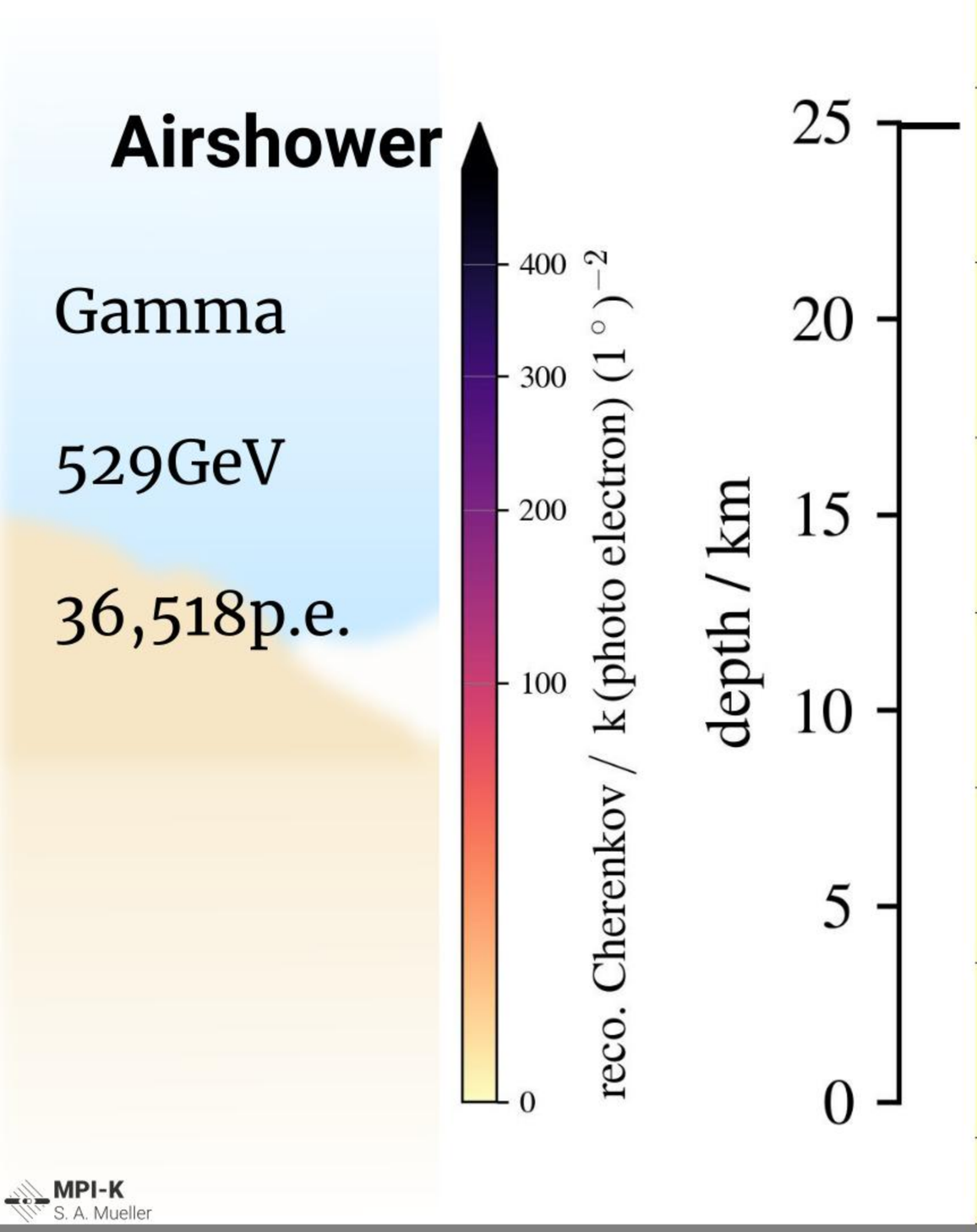
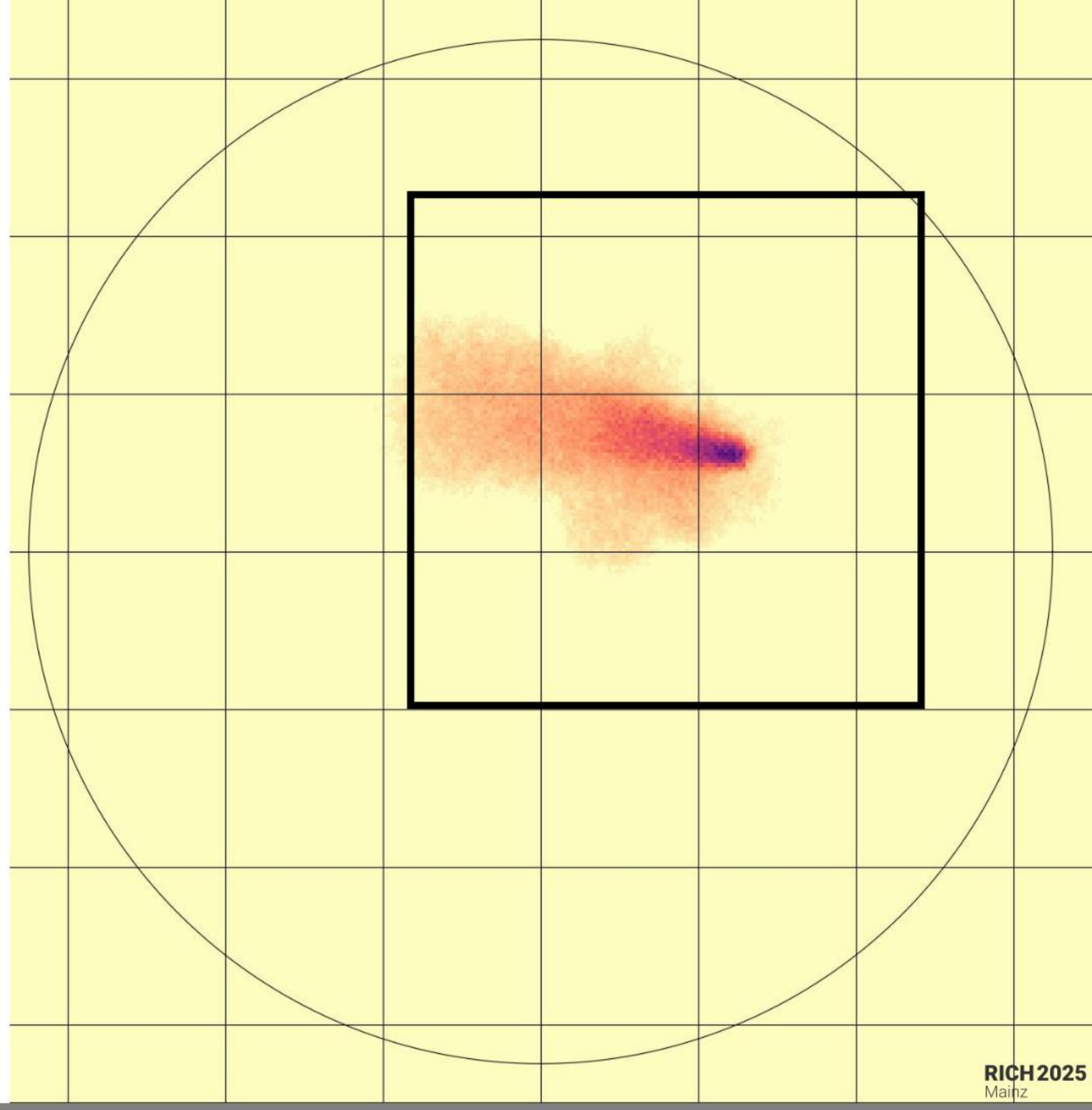






A fivehundred GeV gamma ray.





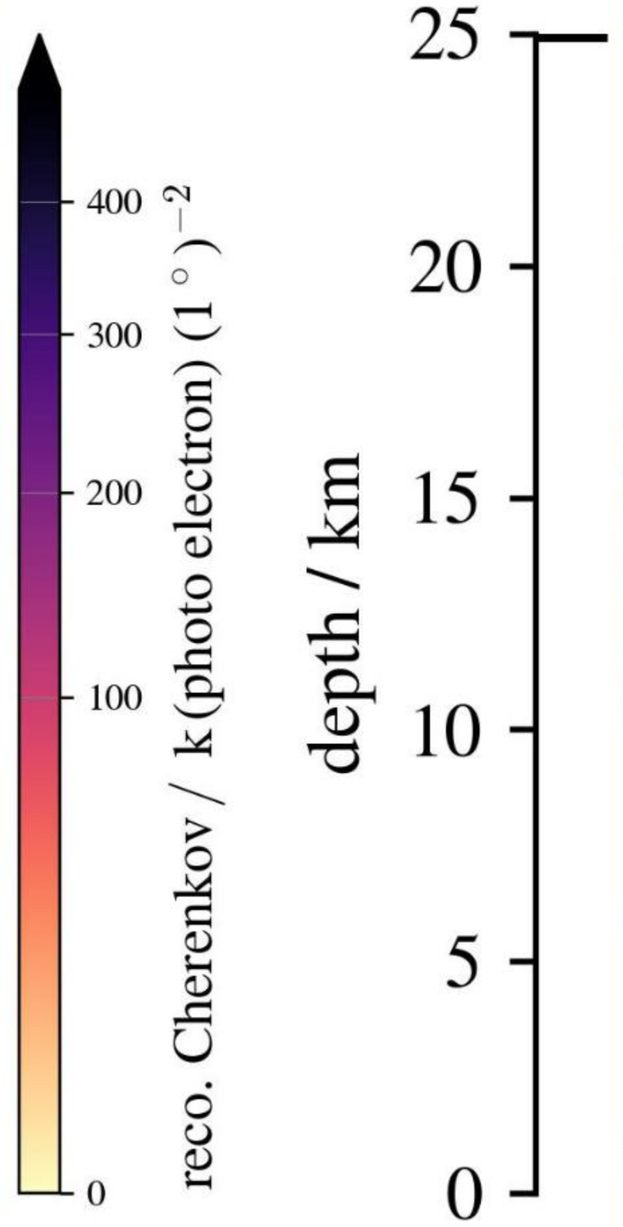
I will not comment on this one. Instead I want to invite you to wonder with me what Travor Weekes and Micheal Hillas would have commented on this.

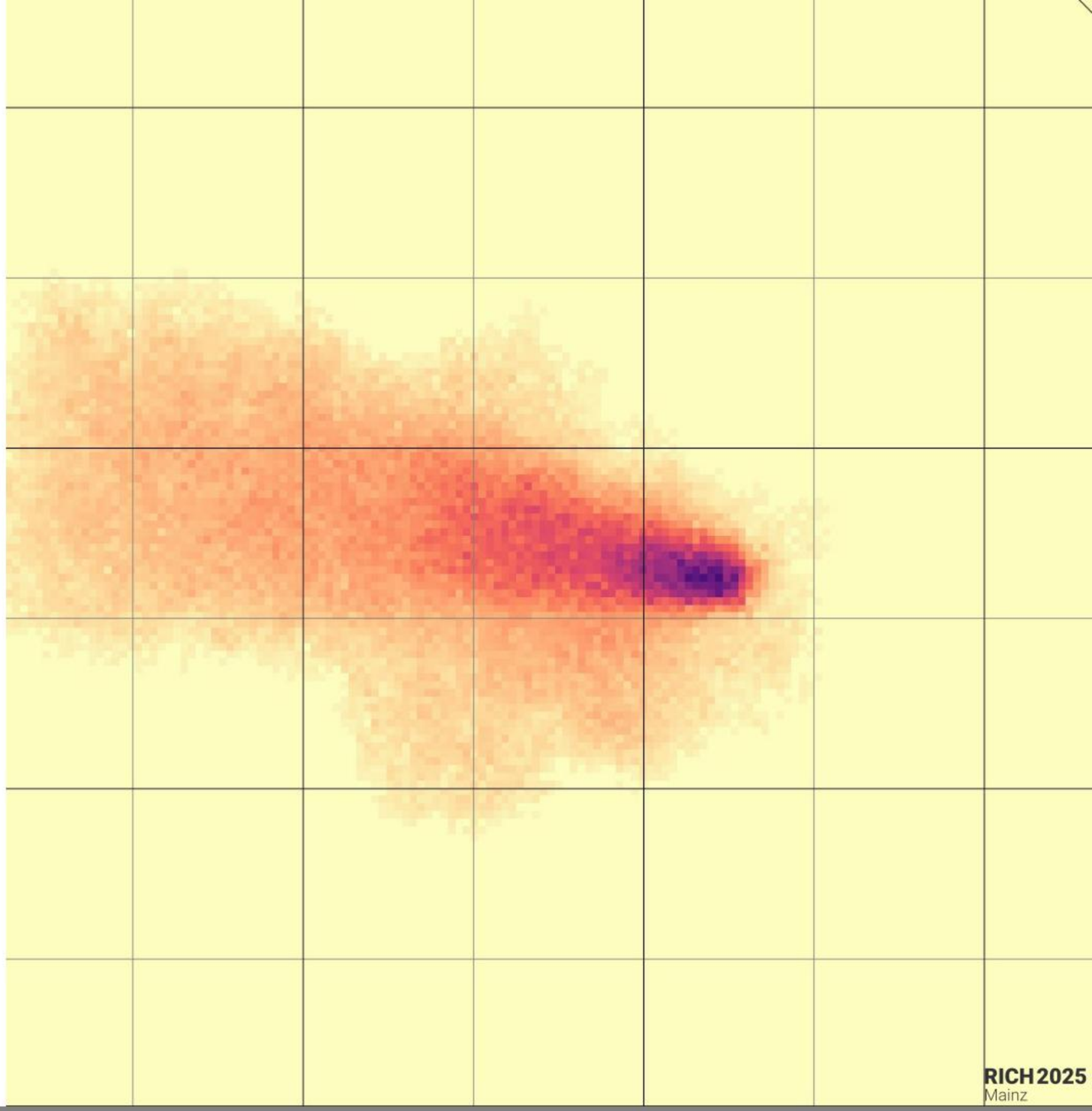
Airshower

Gamma

529GeV

36,518p.e.



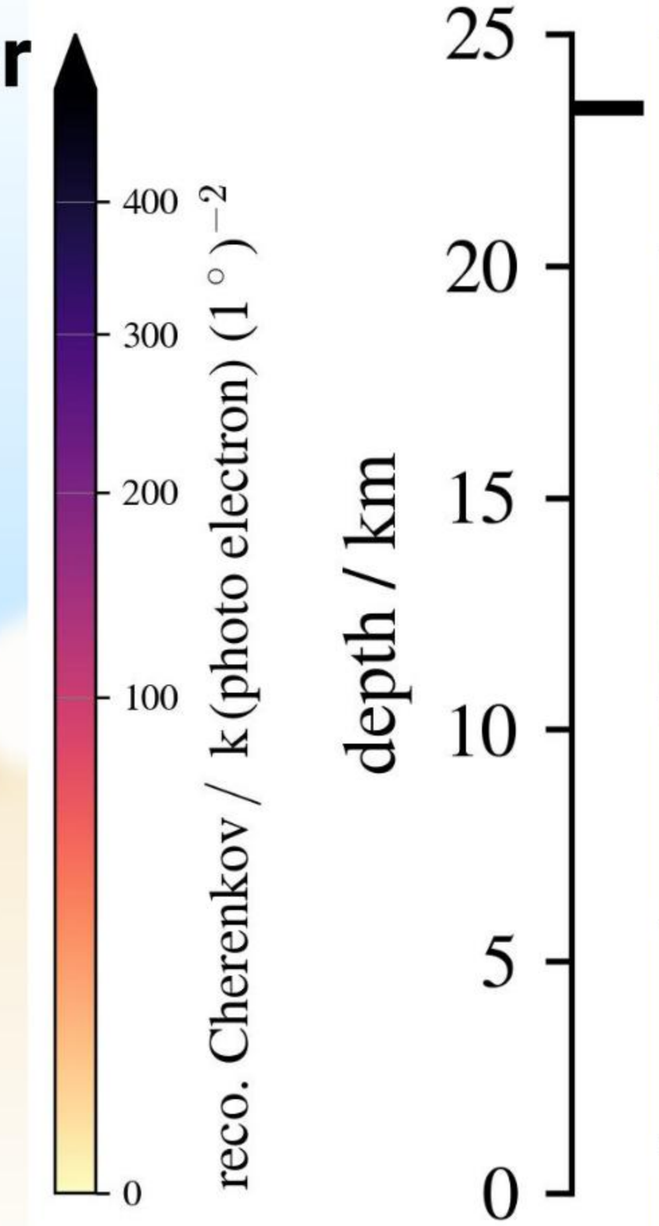


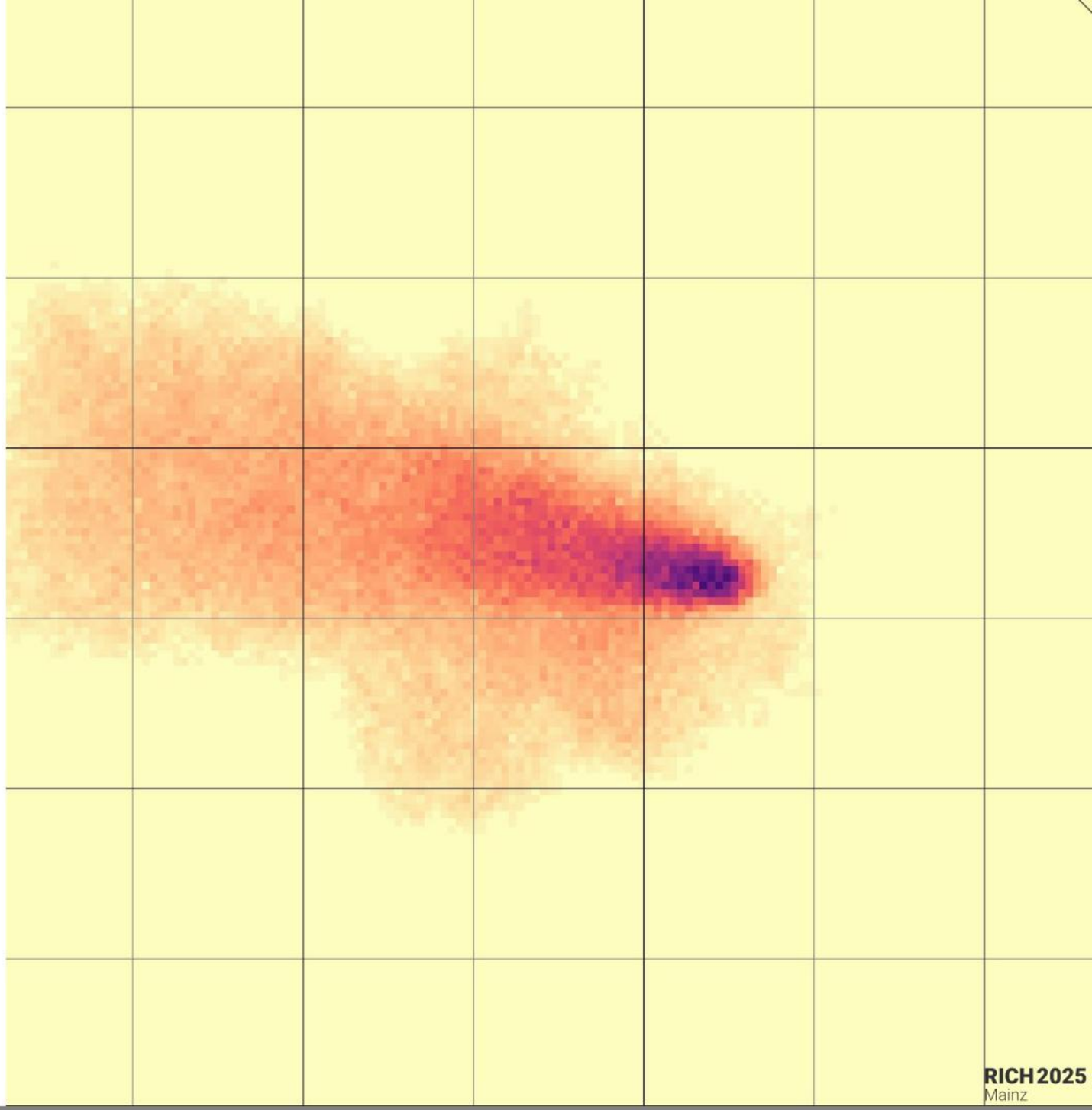
Airshower

Gamma

529GeV

36,518p.e.



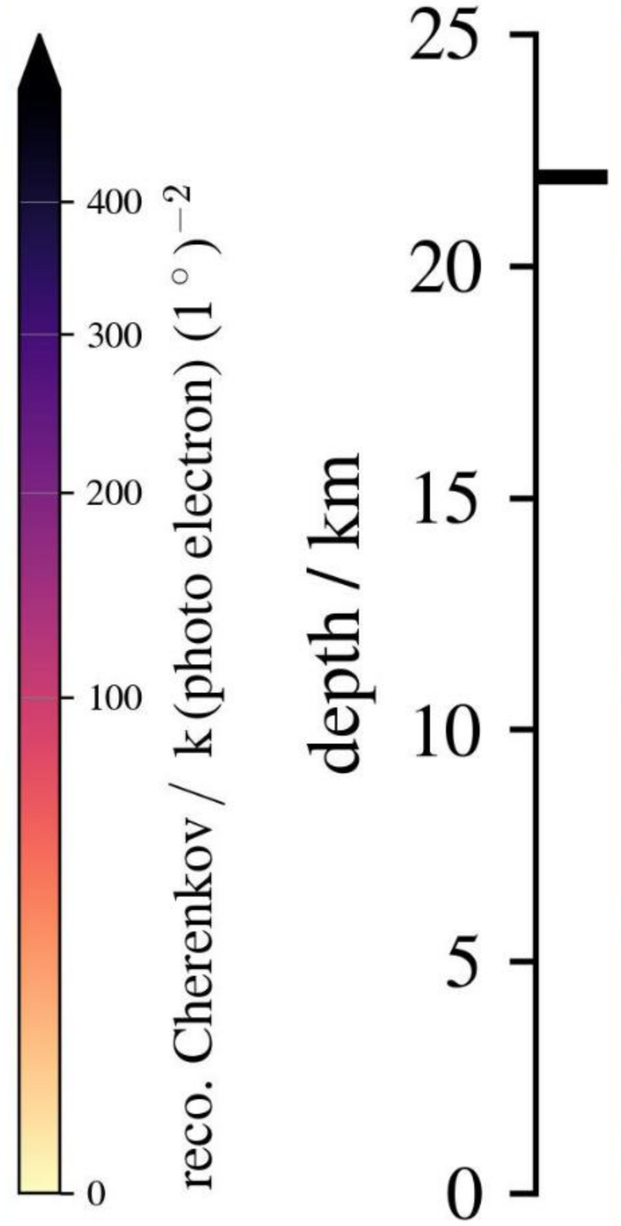


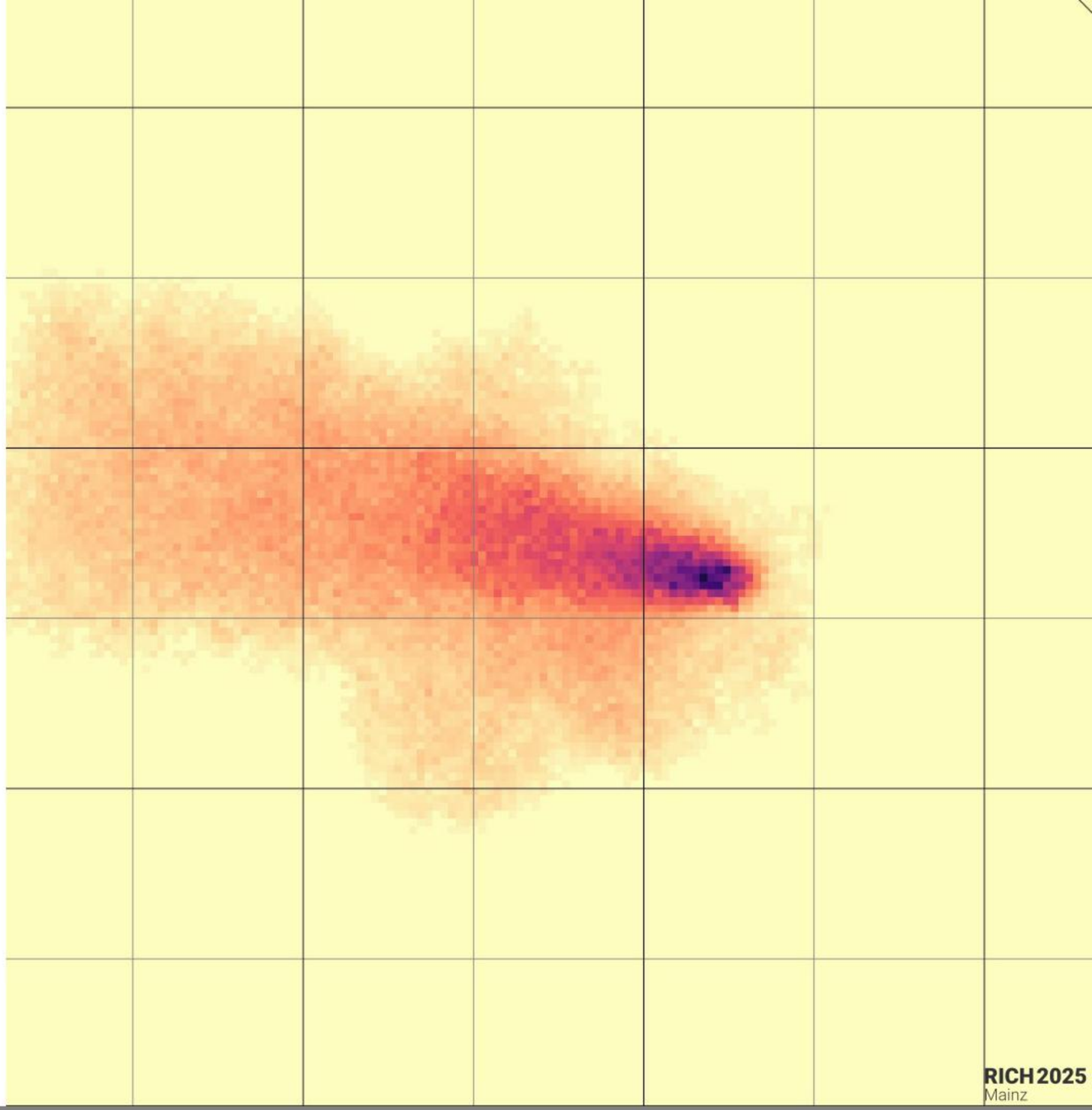
Airshower

Gamma

529GeV

36,518p.e.





Airshower

Gamma

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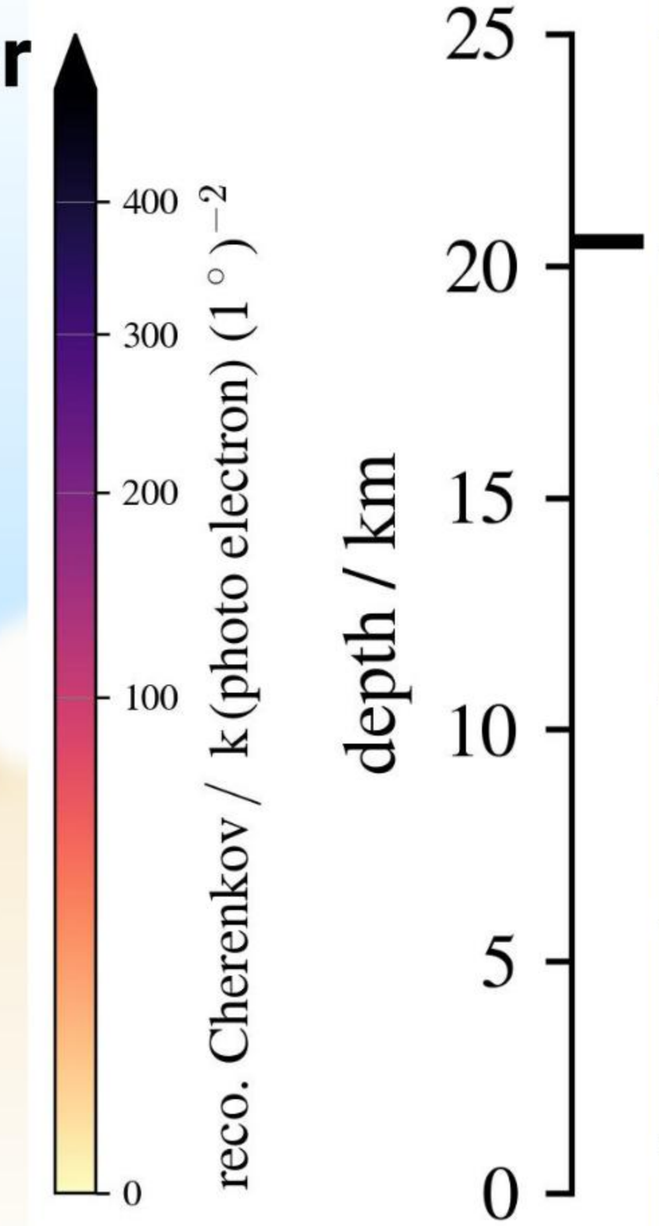

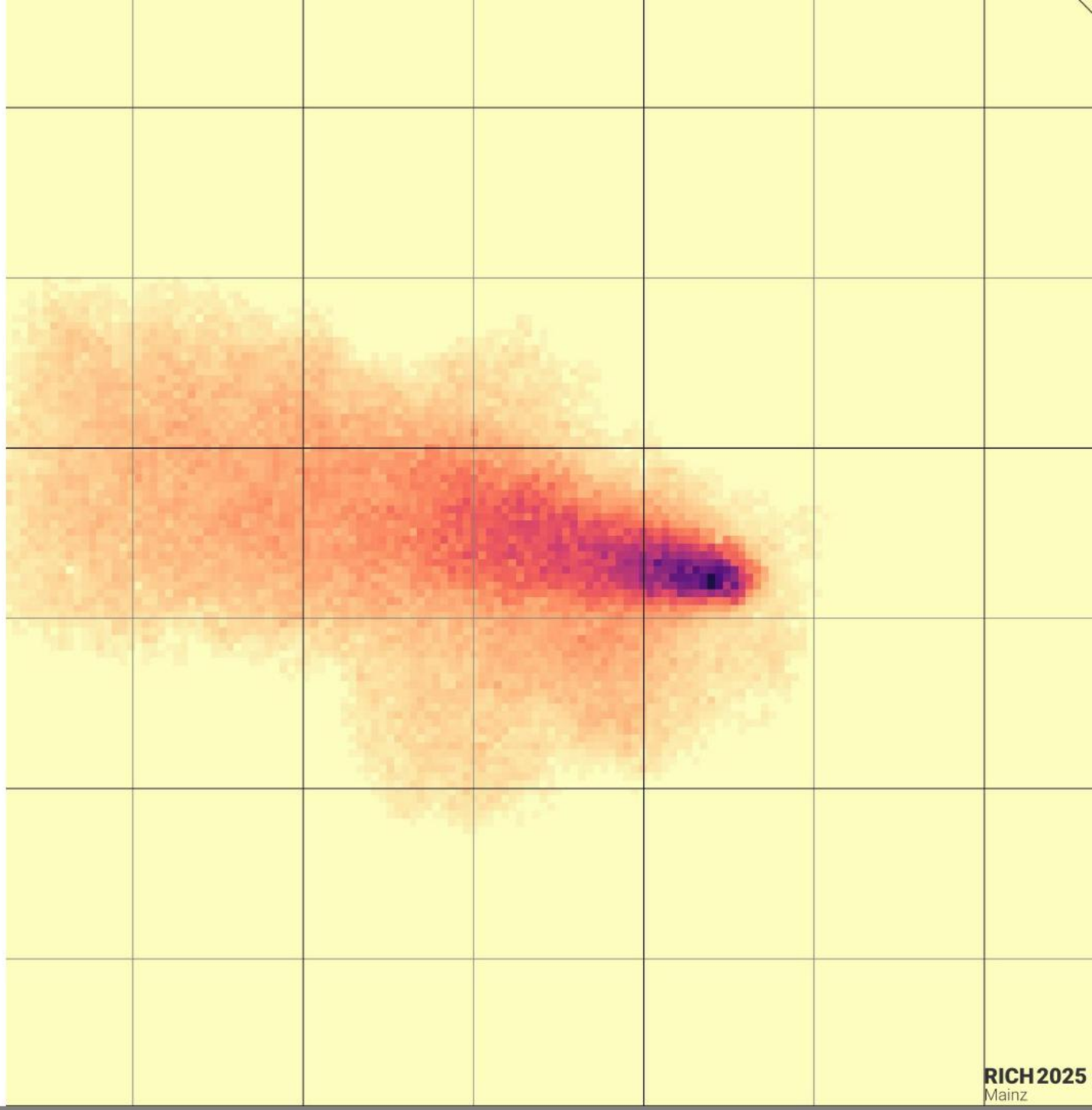

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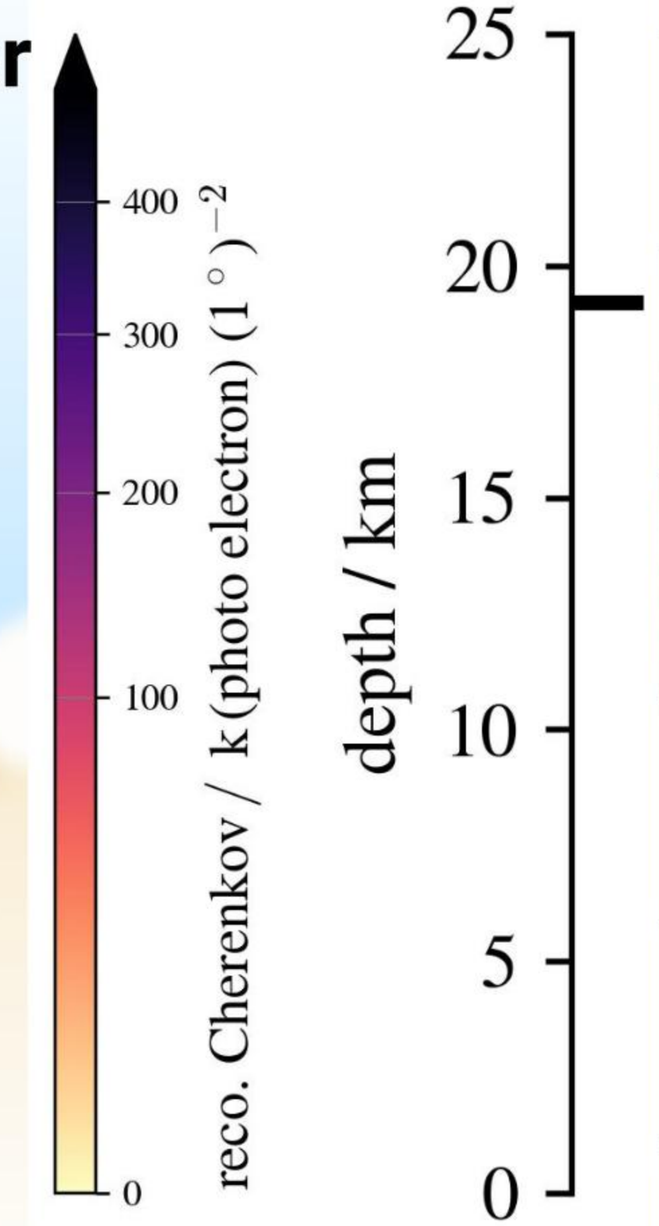

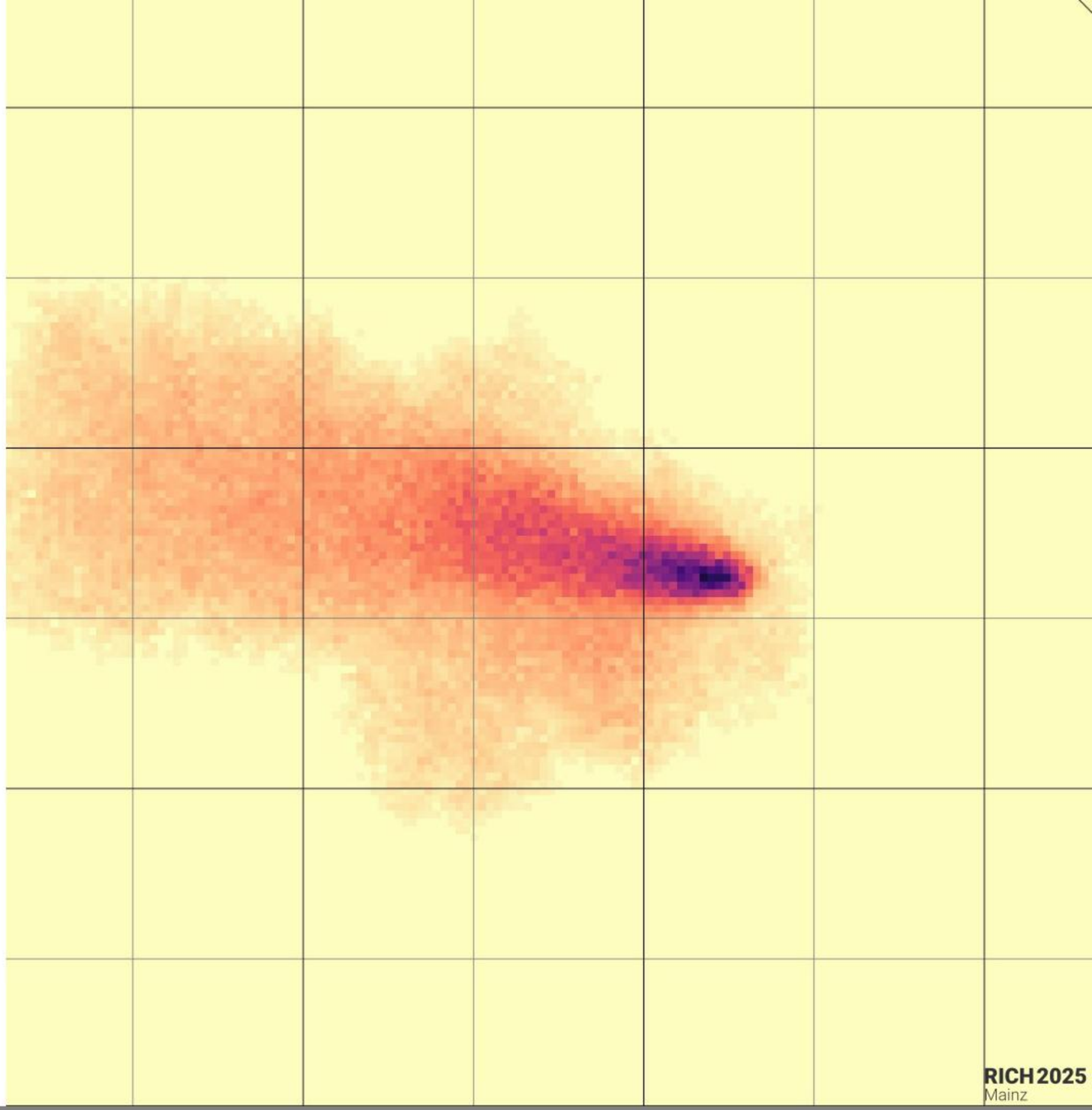

Airshower

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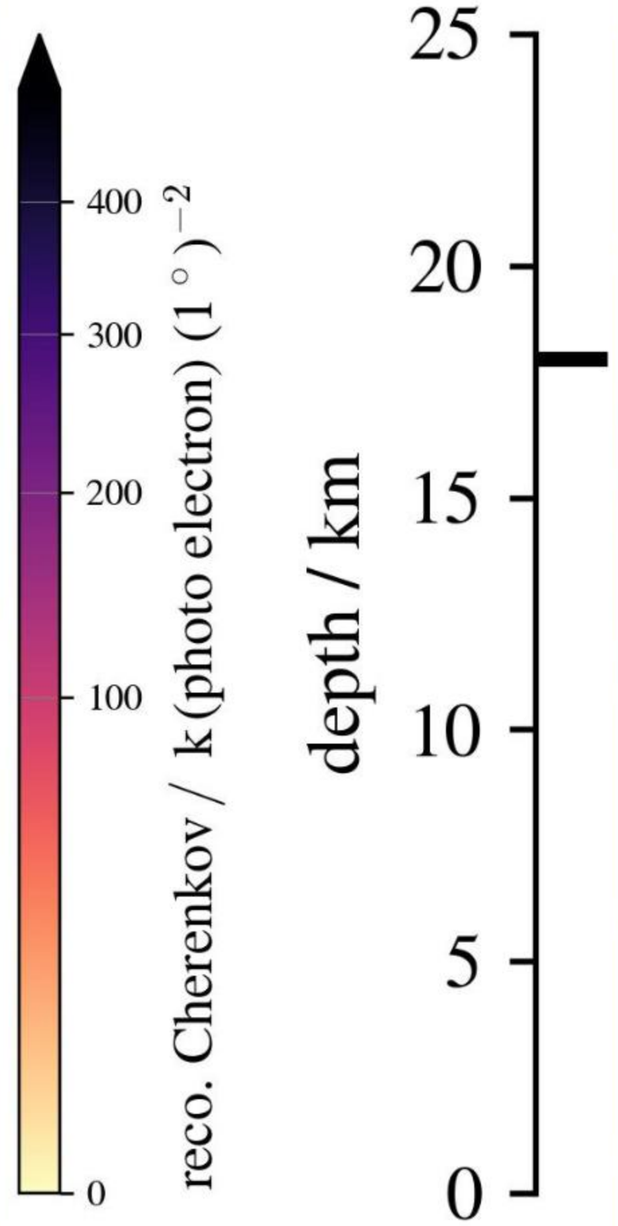

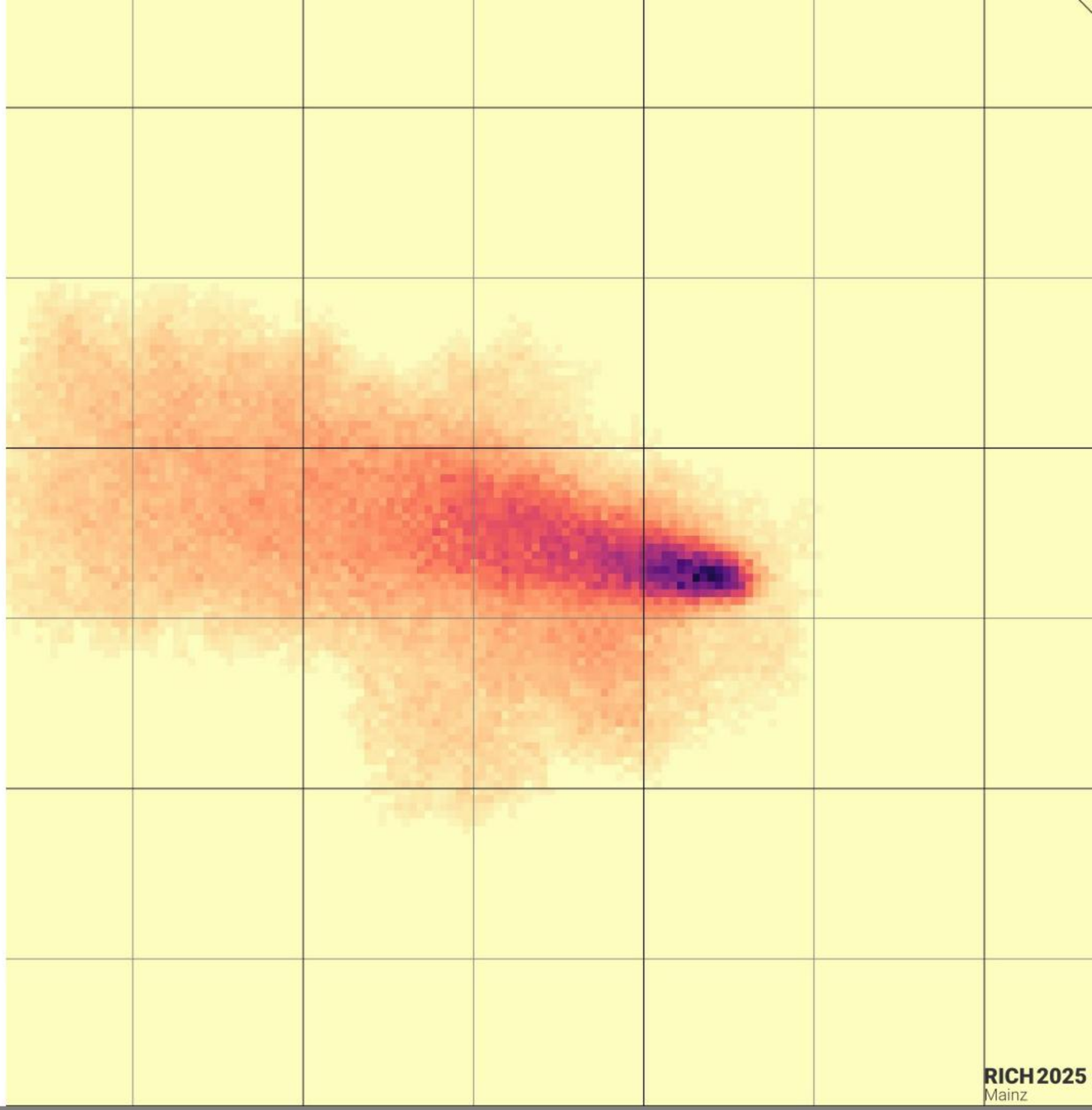

Airshower

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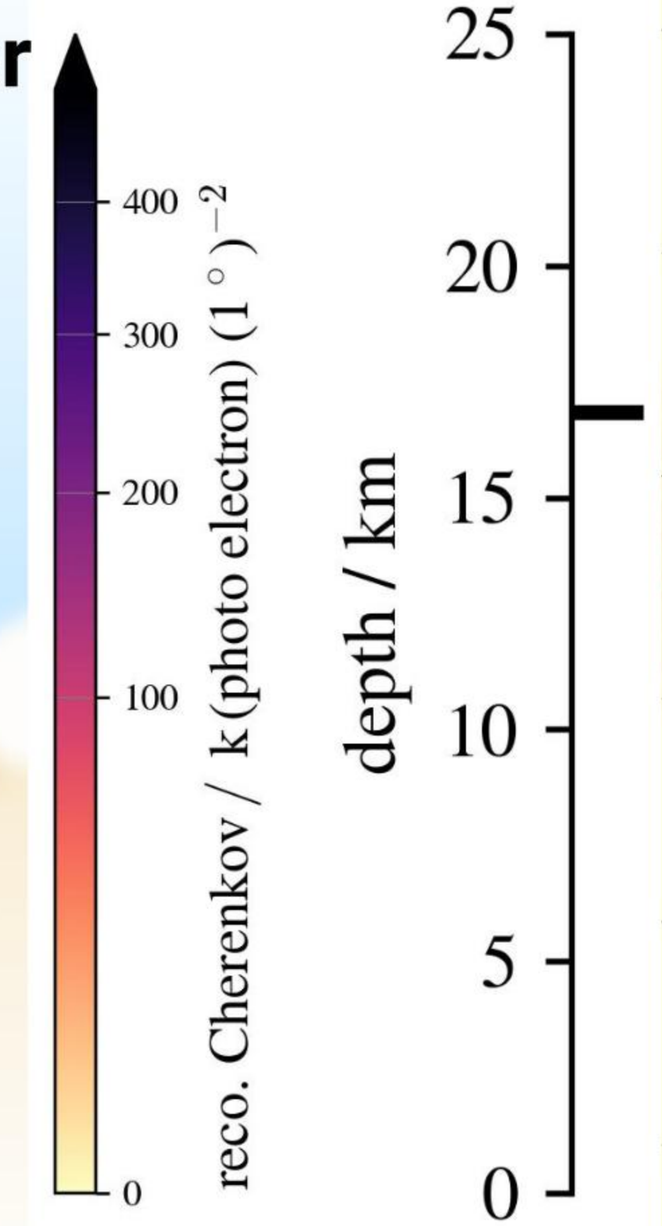

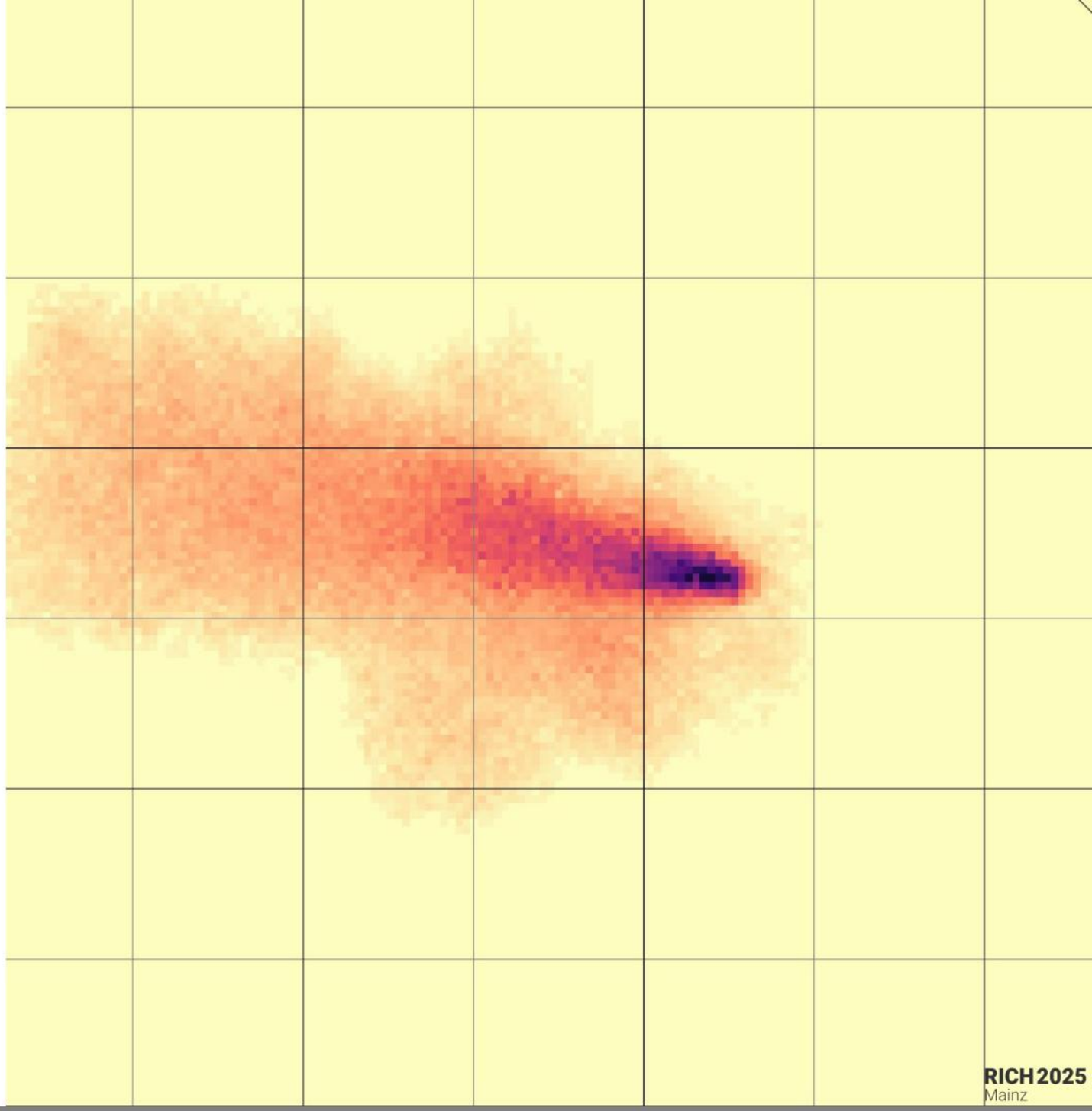

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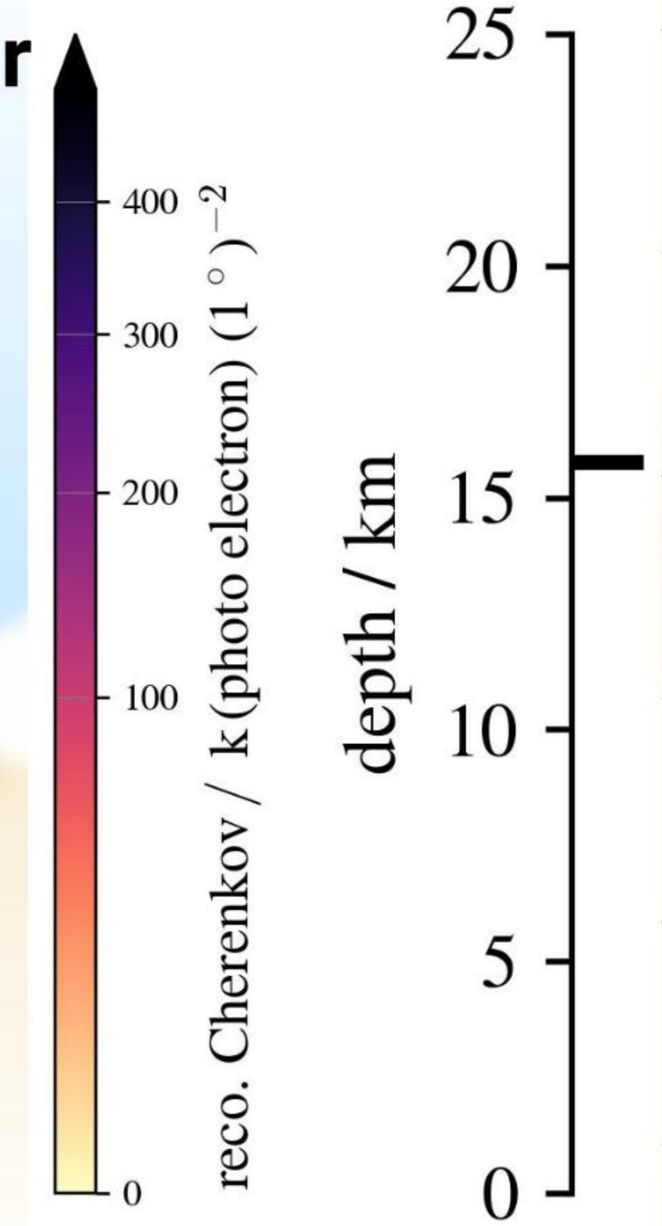

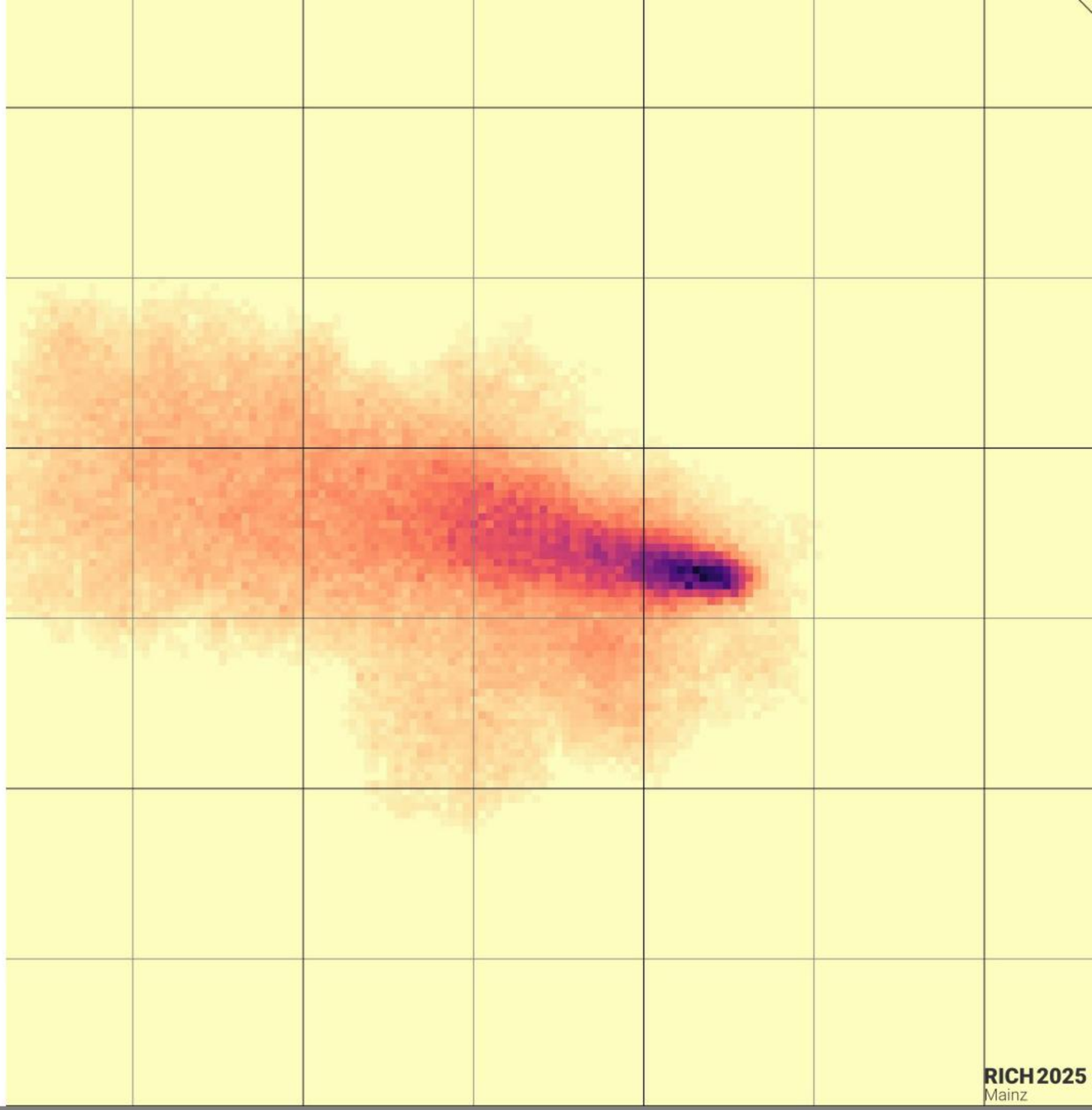

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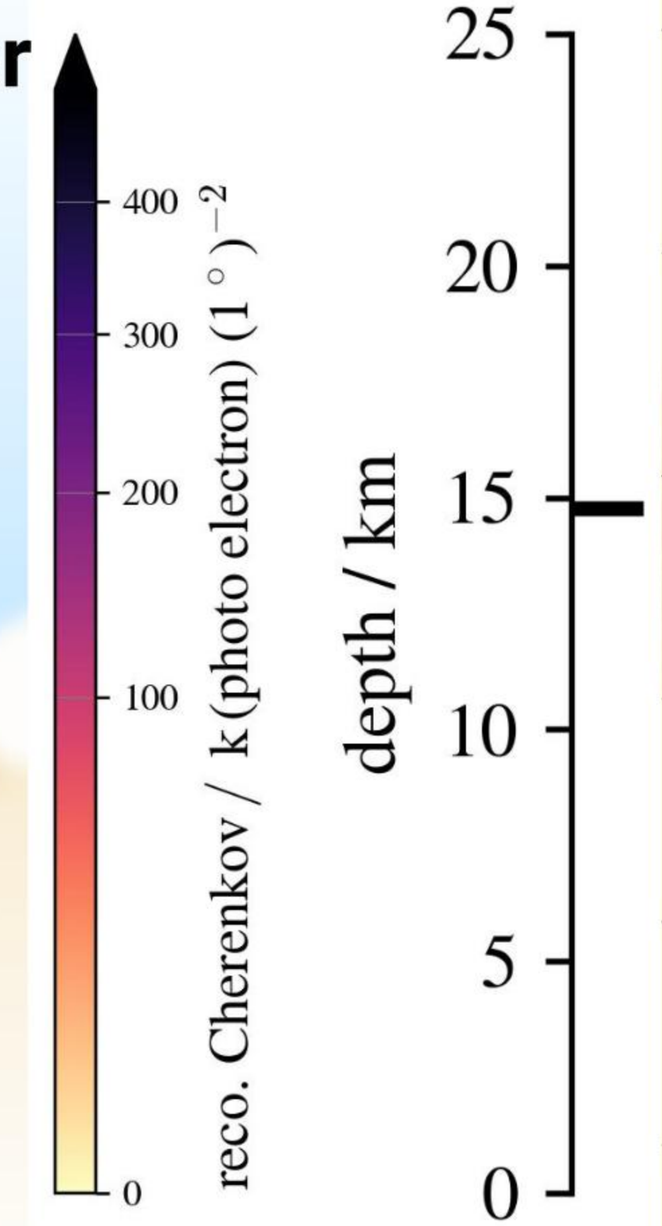
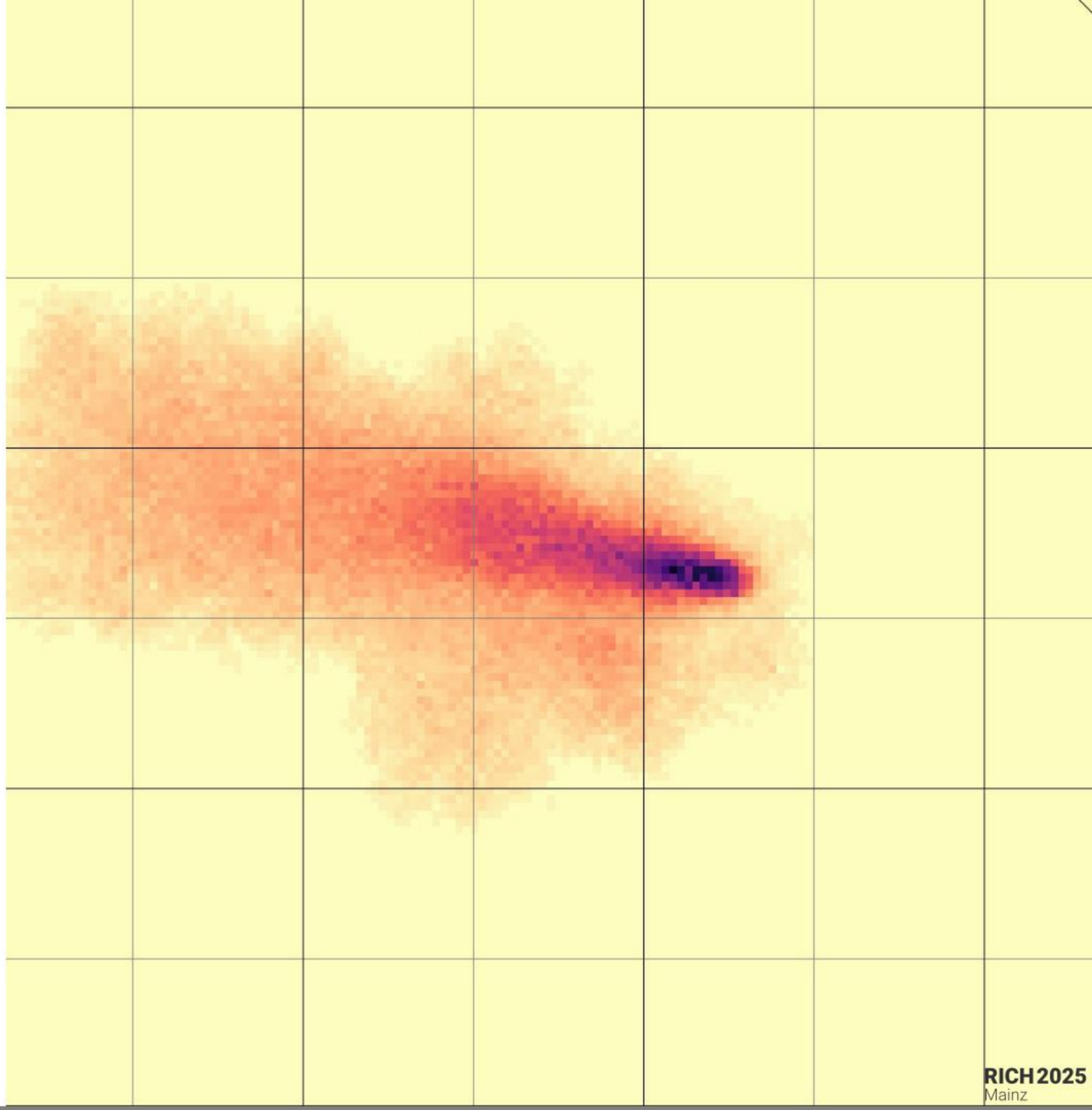
529GeV

36,518p.e.



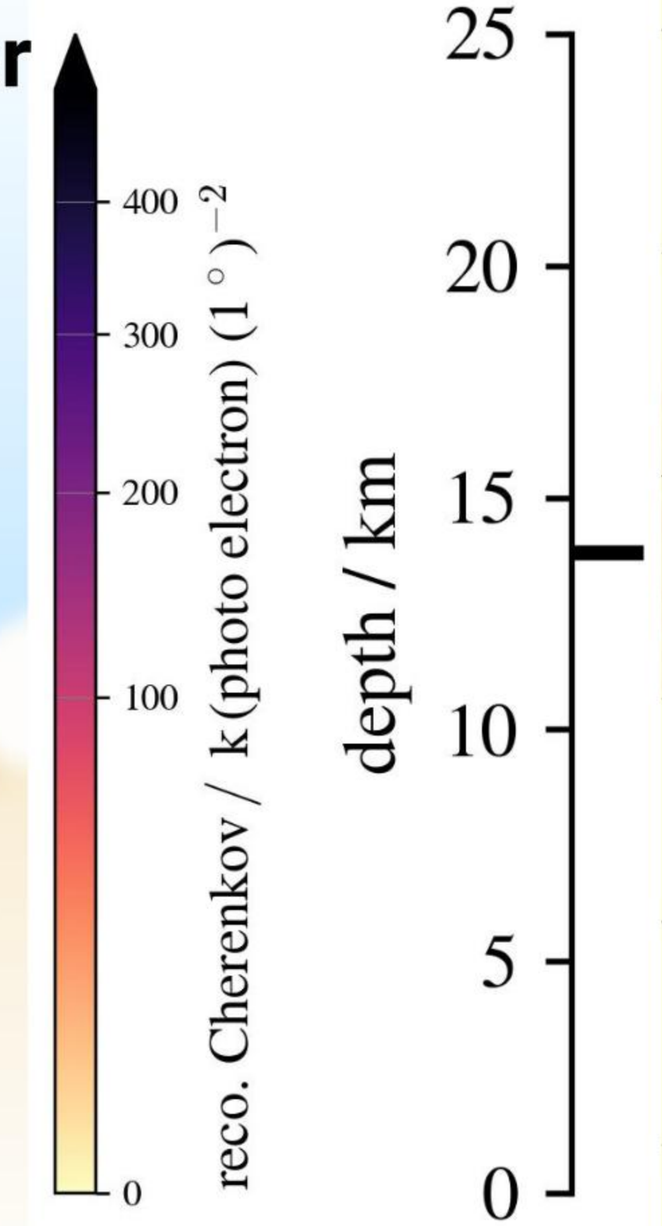


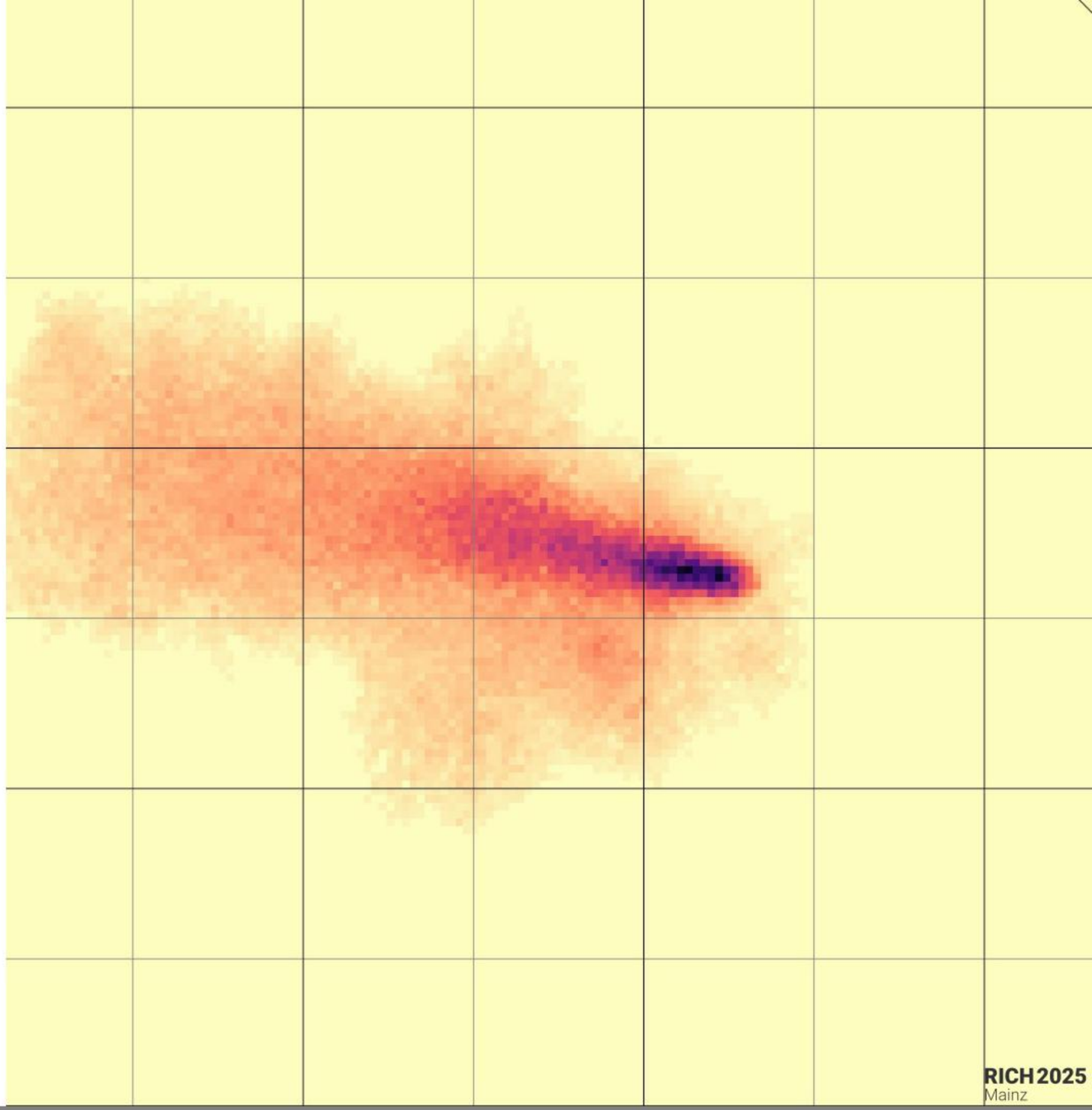
Airshower

Gamma

529GeV

36,518p.e.



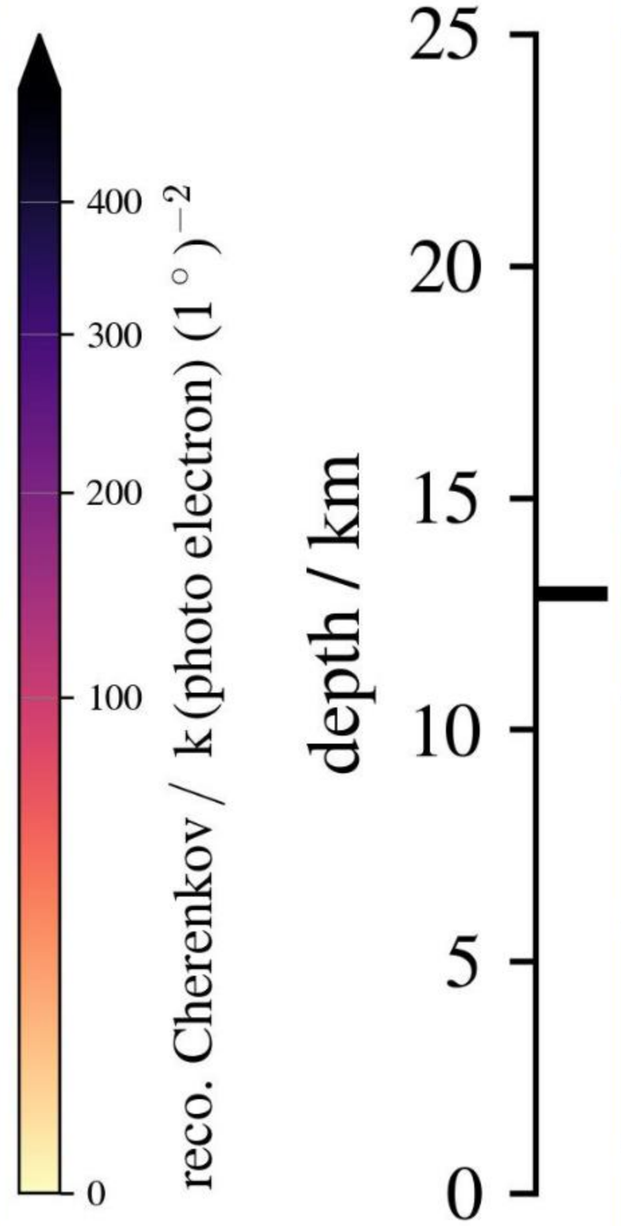


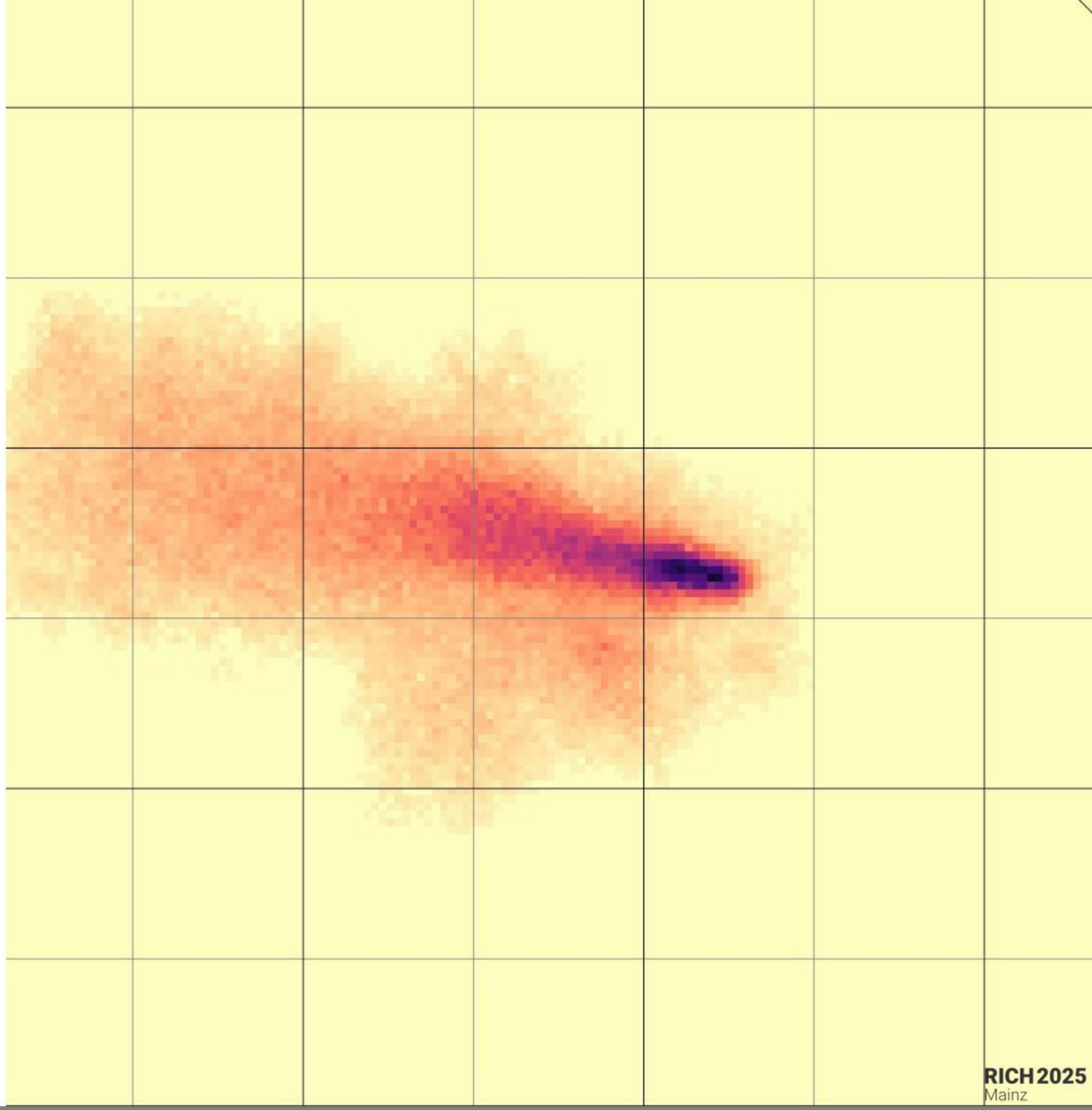
Airshower

Gamma

529GeV

36,518p.e.



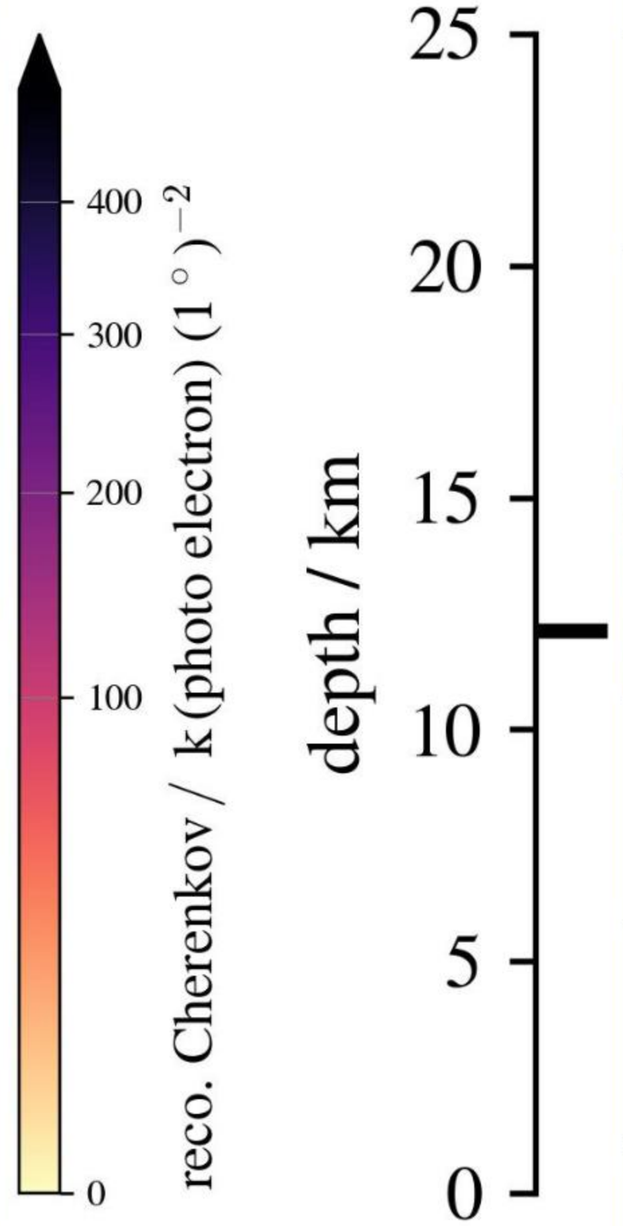


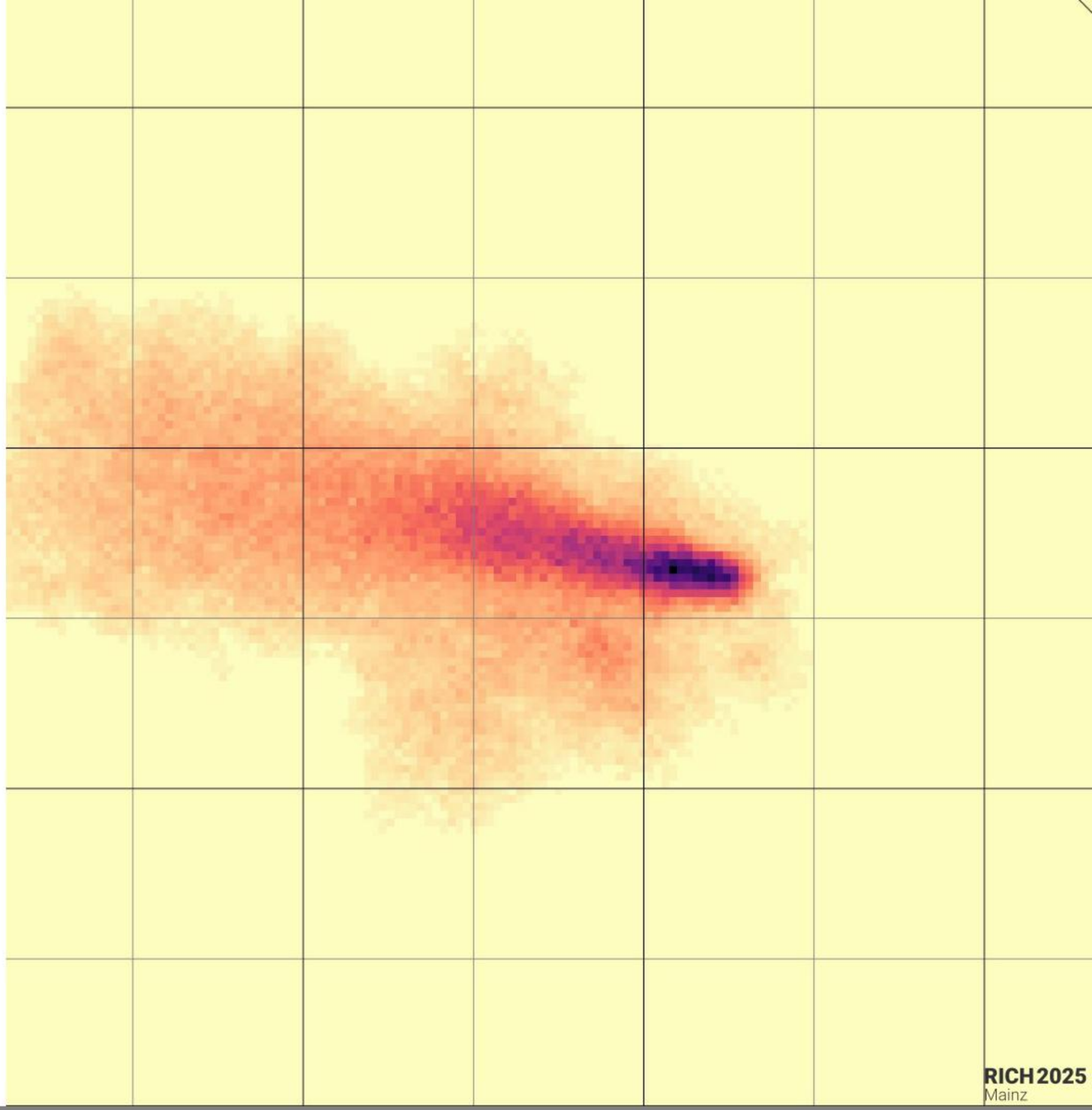
Airshower

Gamma

529GeV

36,518p.e.



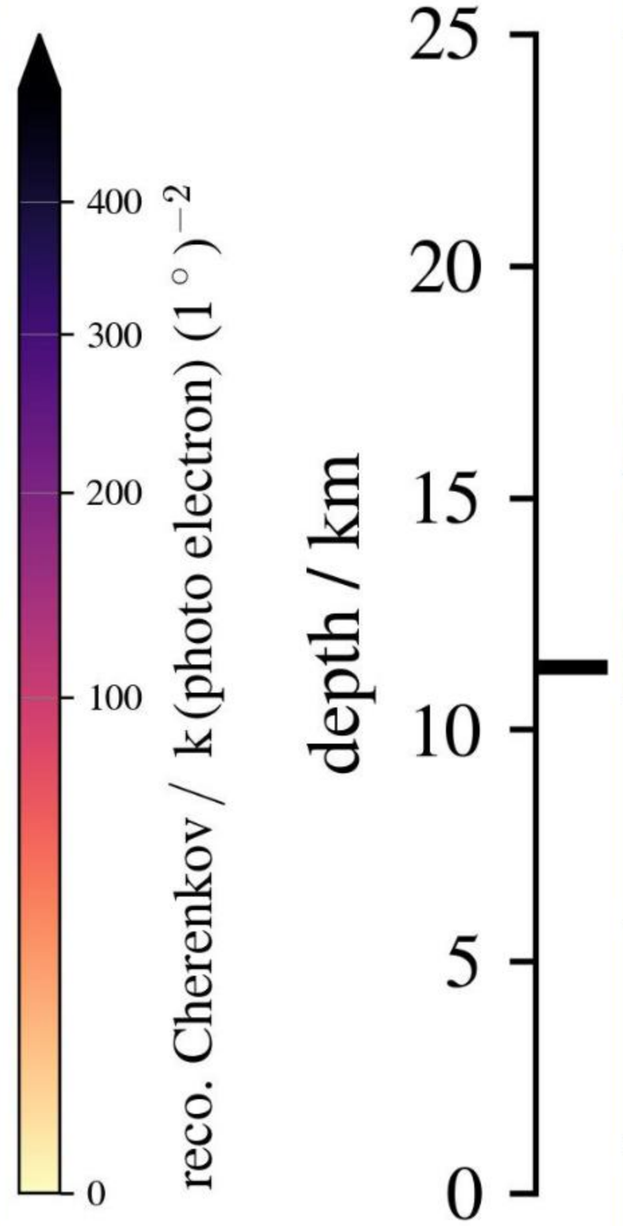


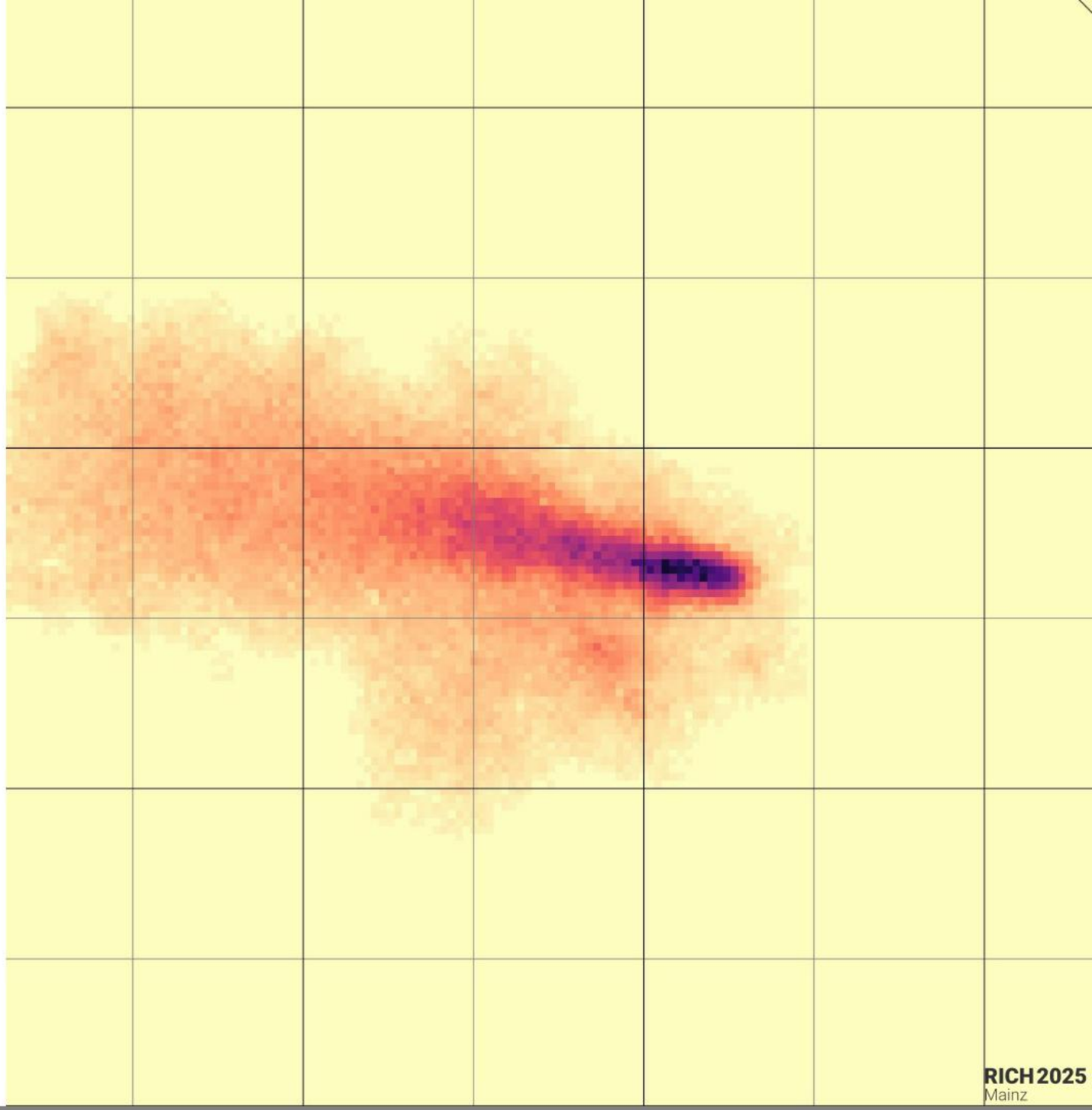
Airshower

Gamma

529GeV

36,518p.e.



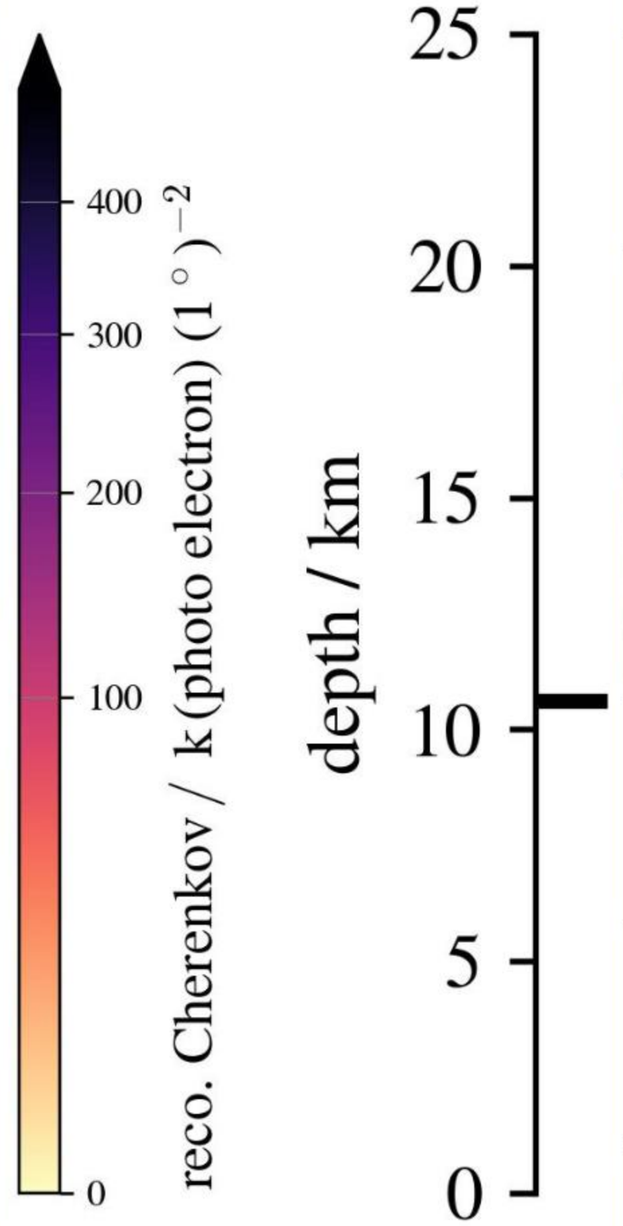


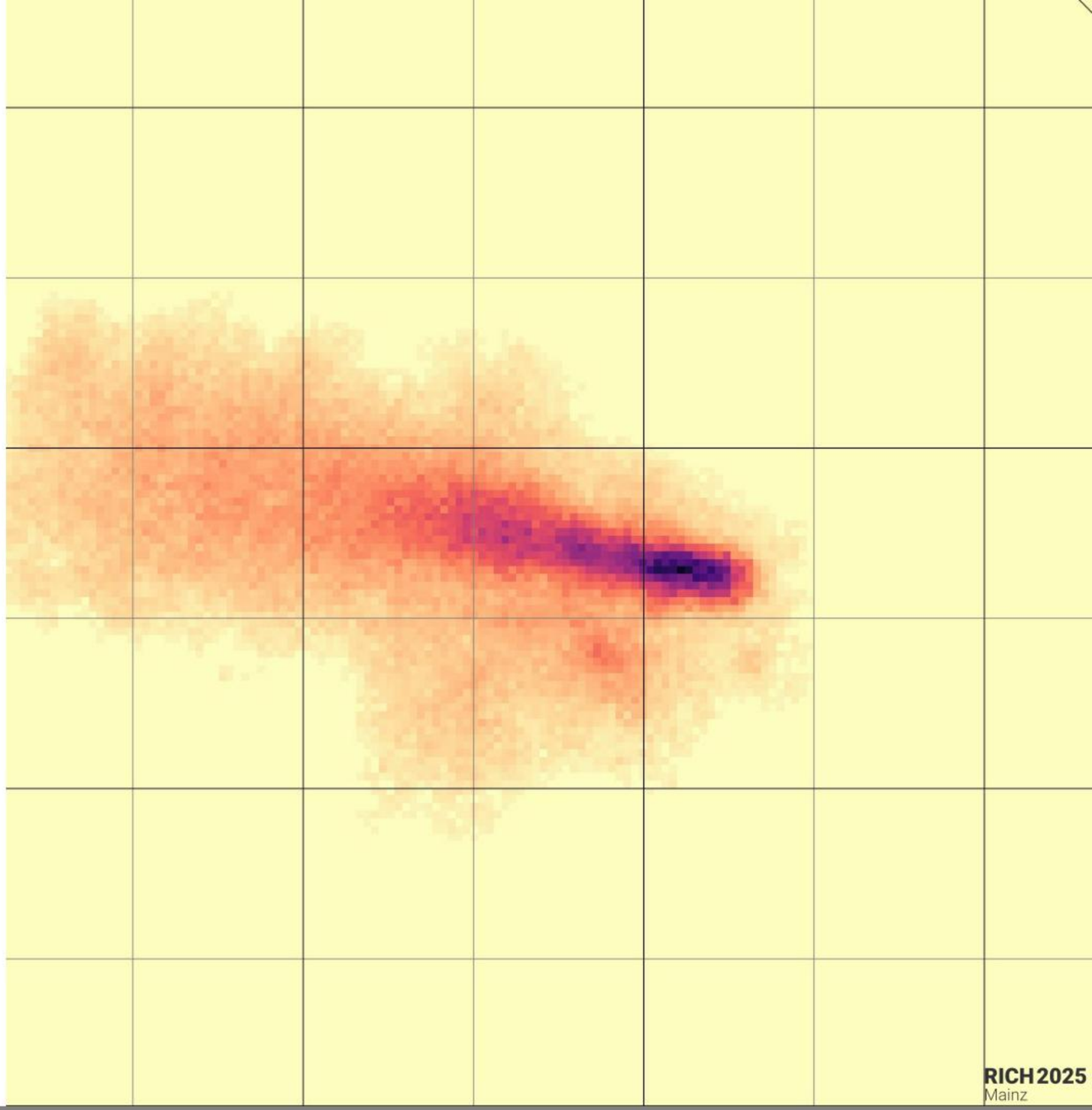
Airshower

Gamma

529GeV

36,518p.e.



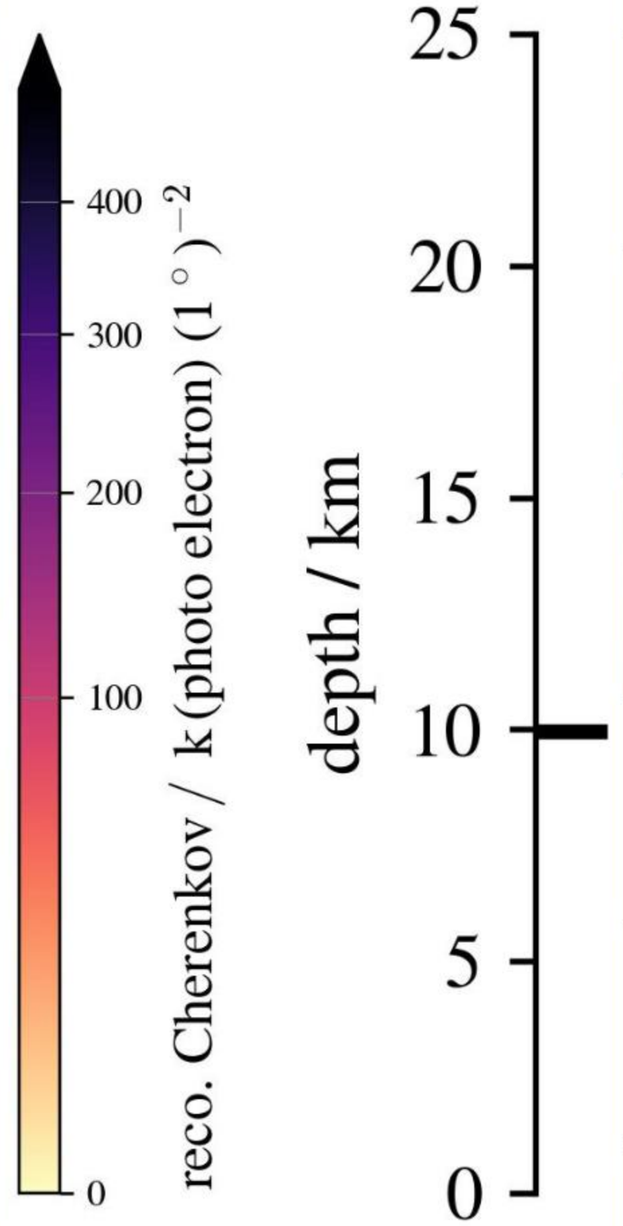


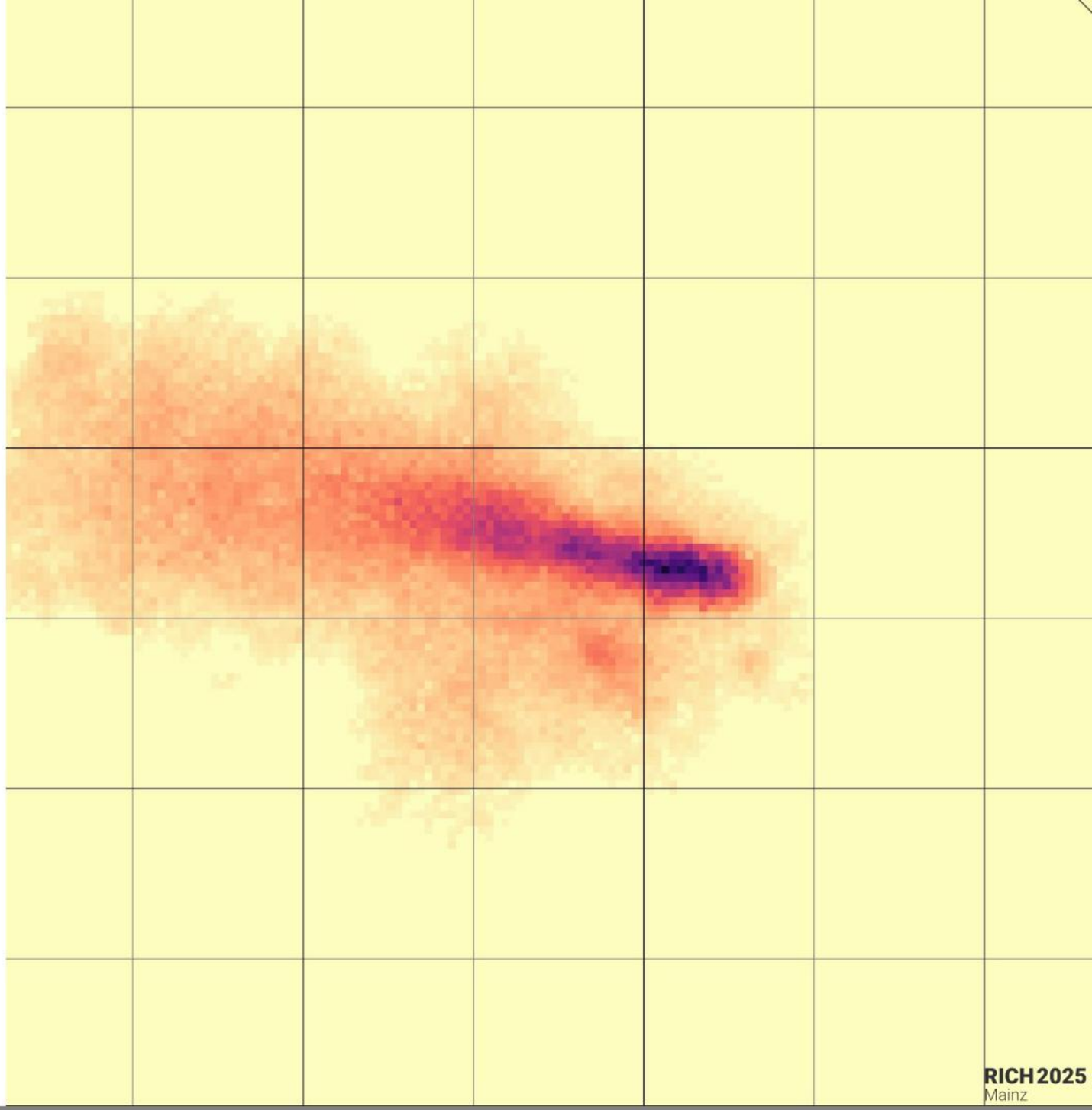
Airshower

Gamma

529GeV

36,518p.e.



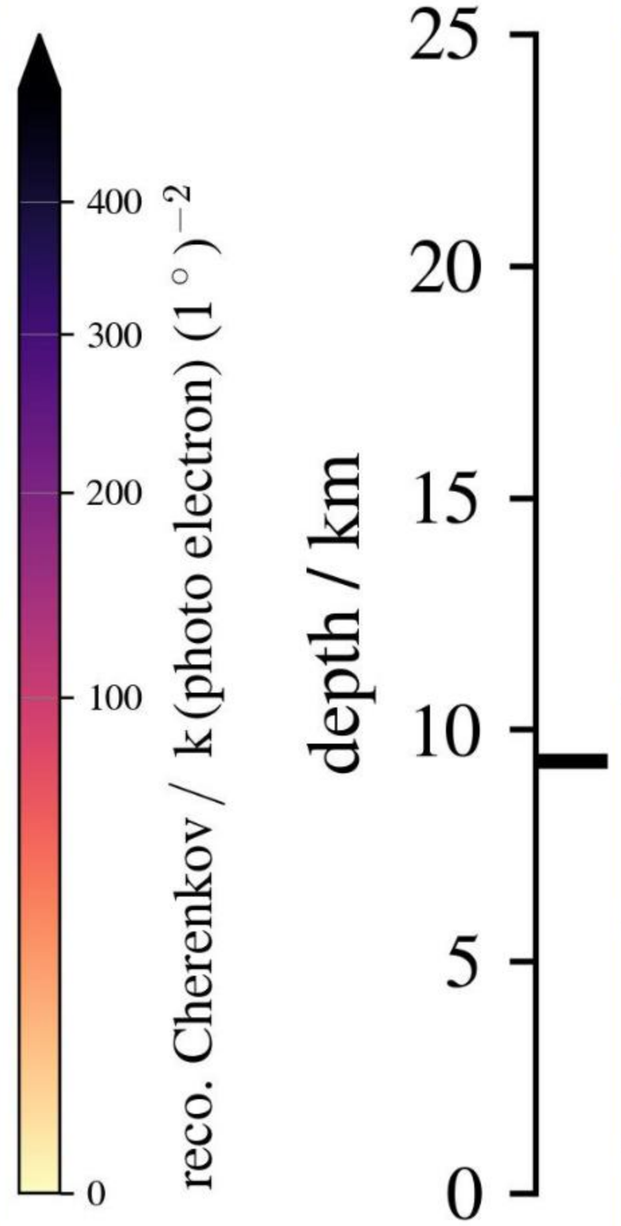


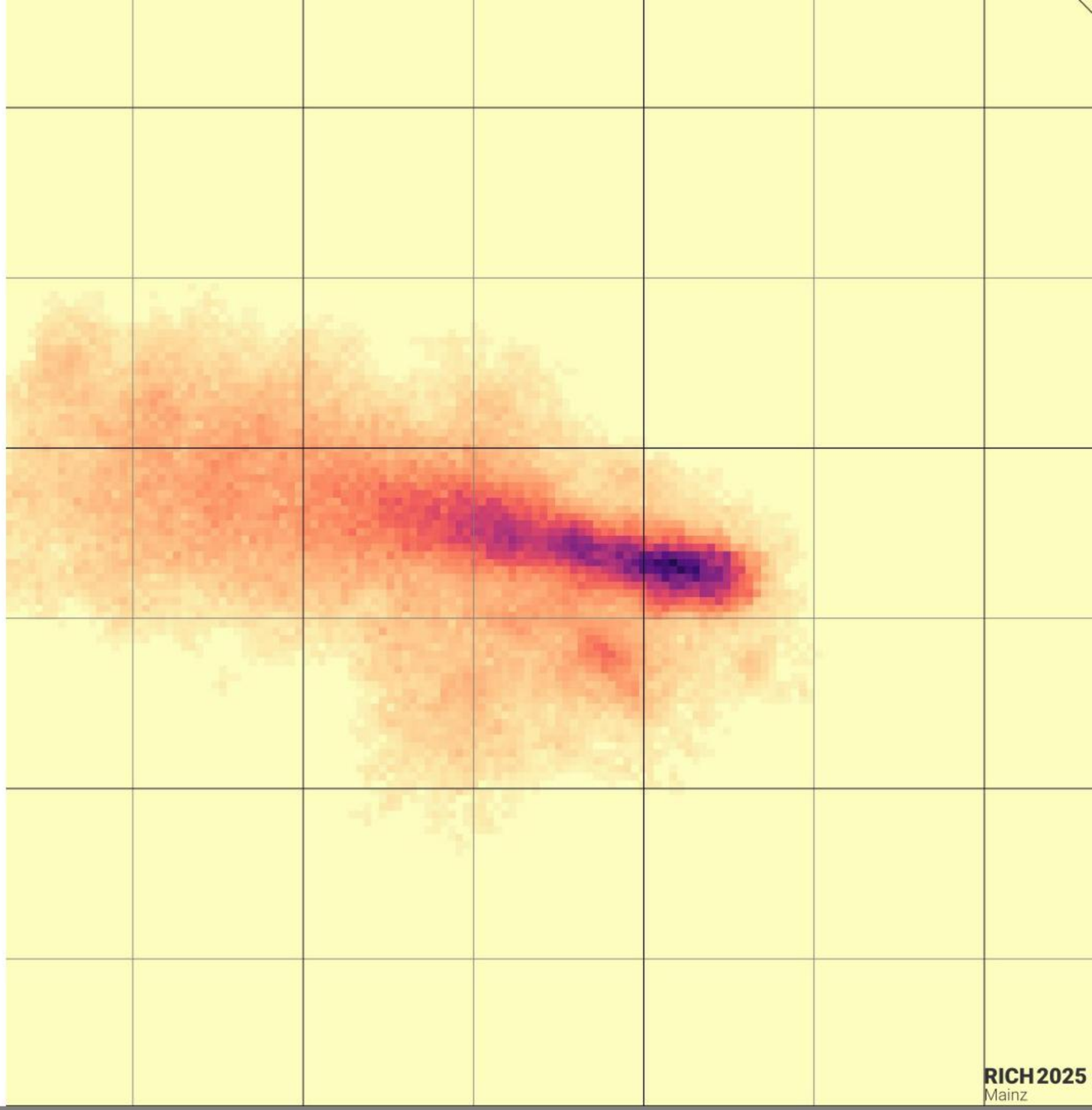
Airshower

Gamma

529GeV

36,518p.e.



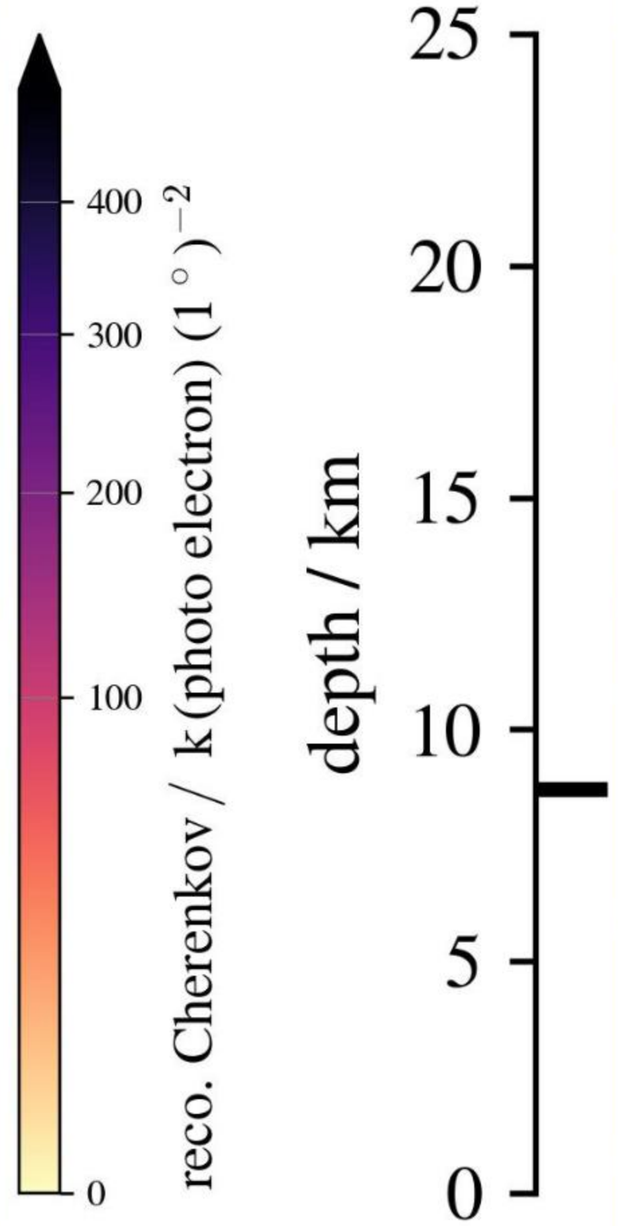


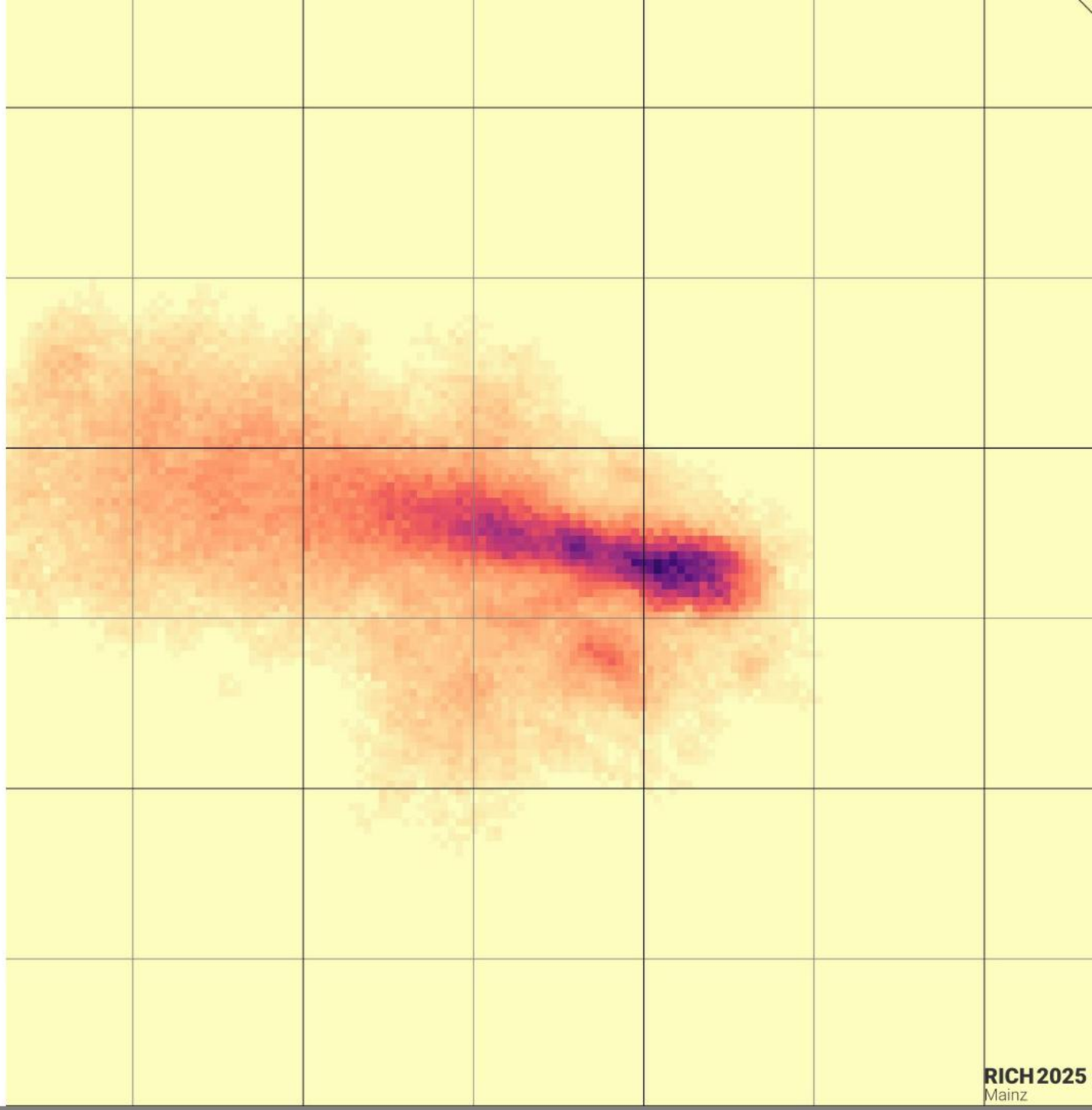
Airshower

Gamma

529GeV

36,518p.e.





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Gamma

529GeV

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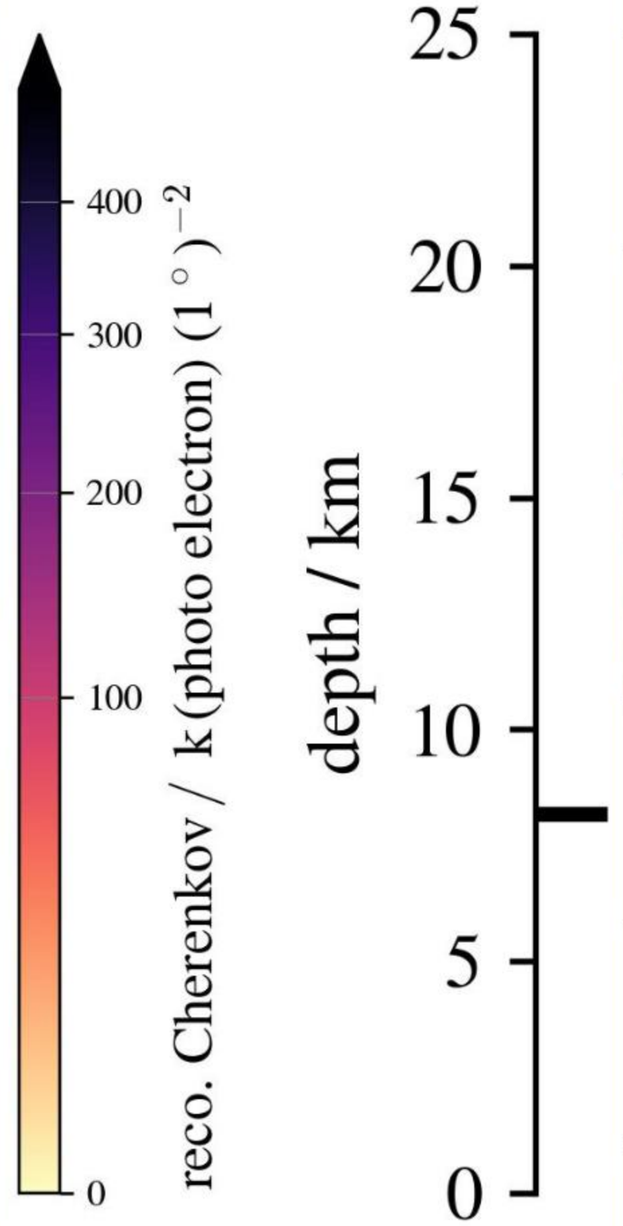

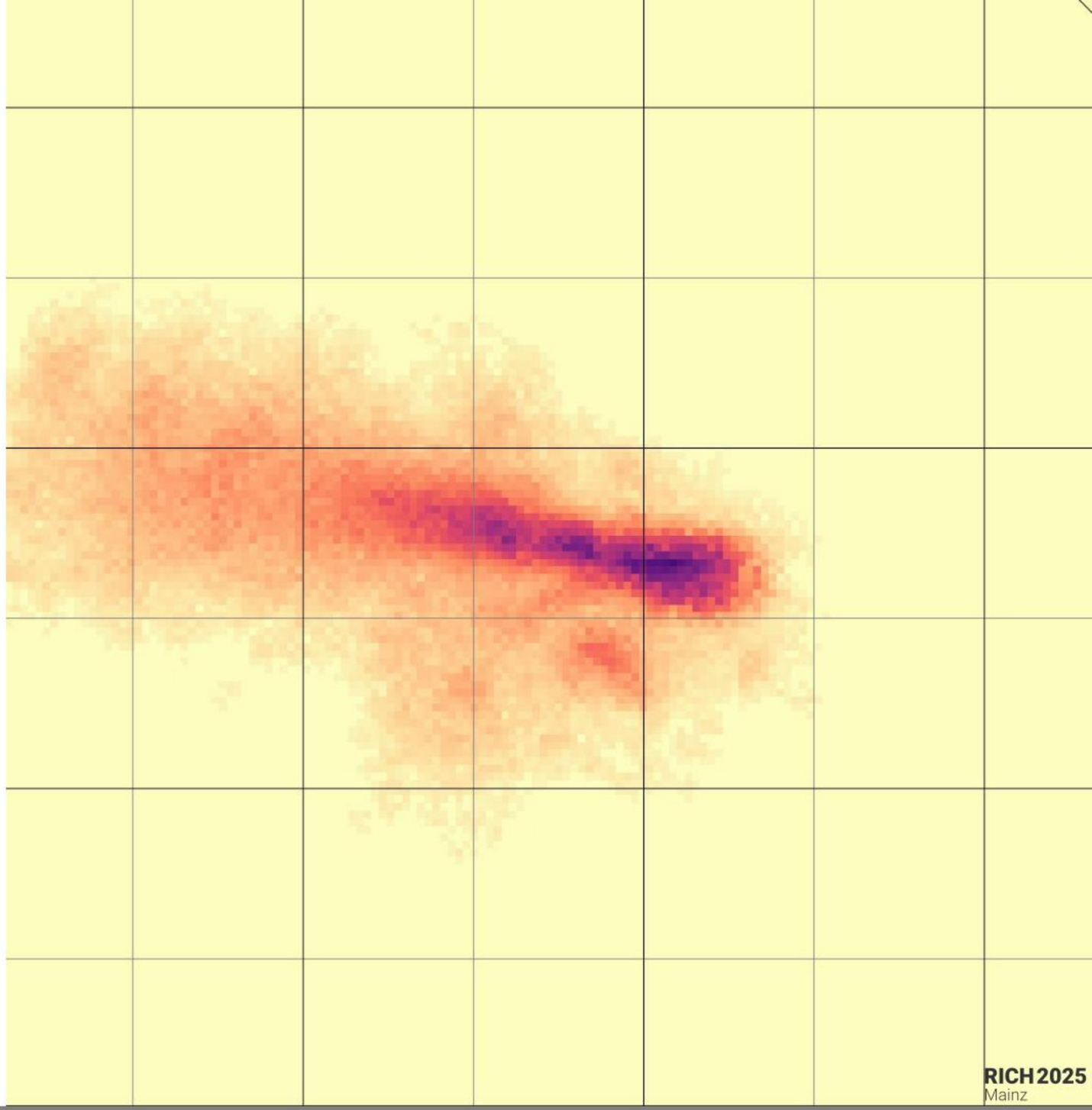

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Gamma

529GeV

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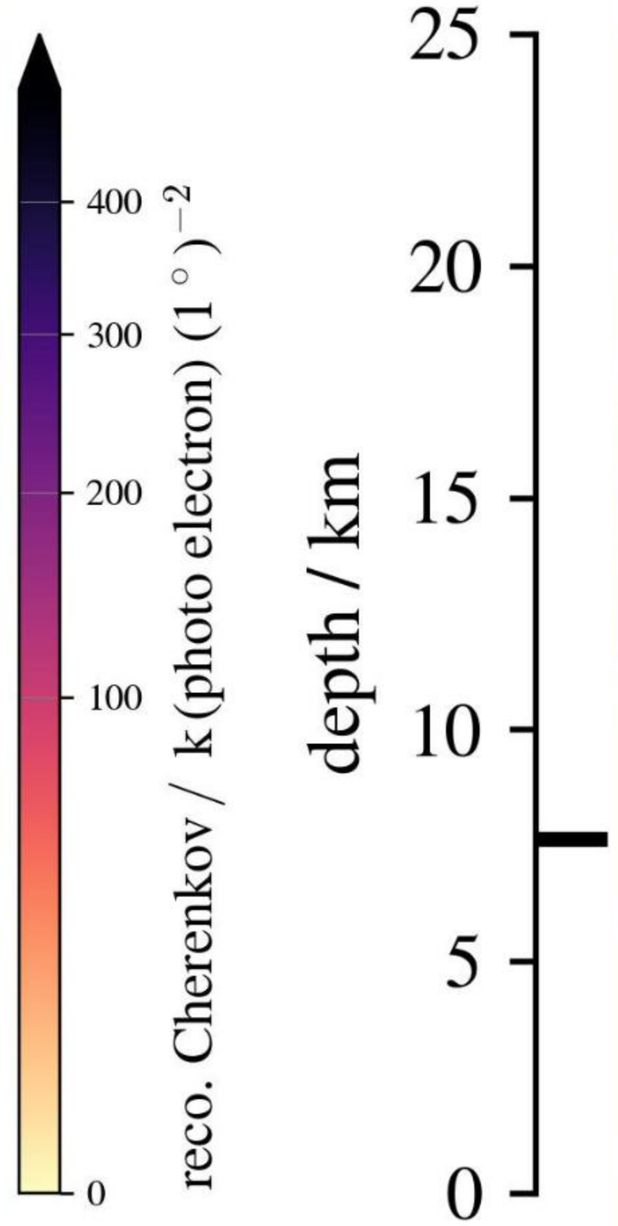

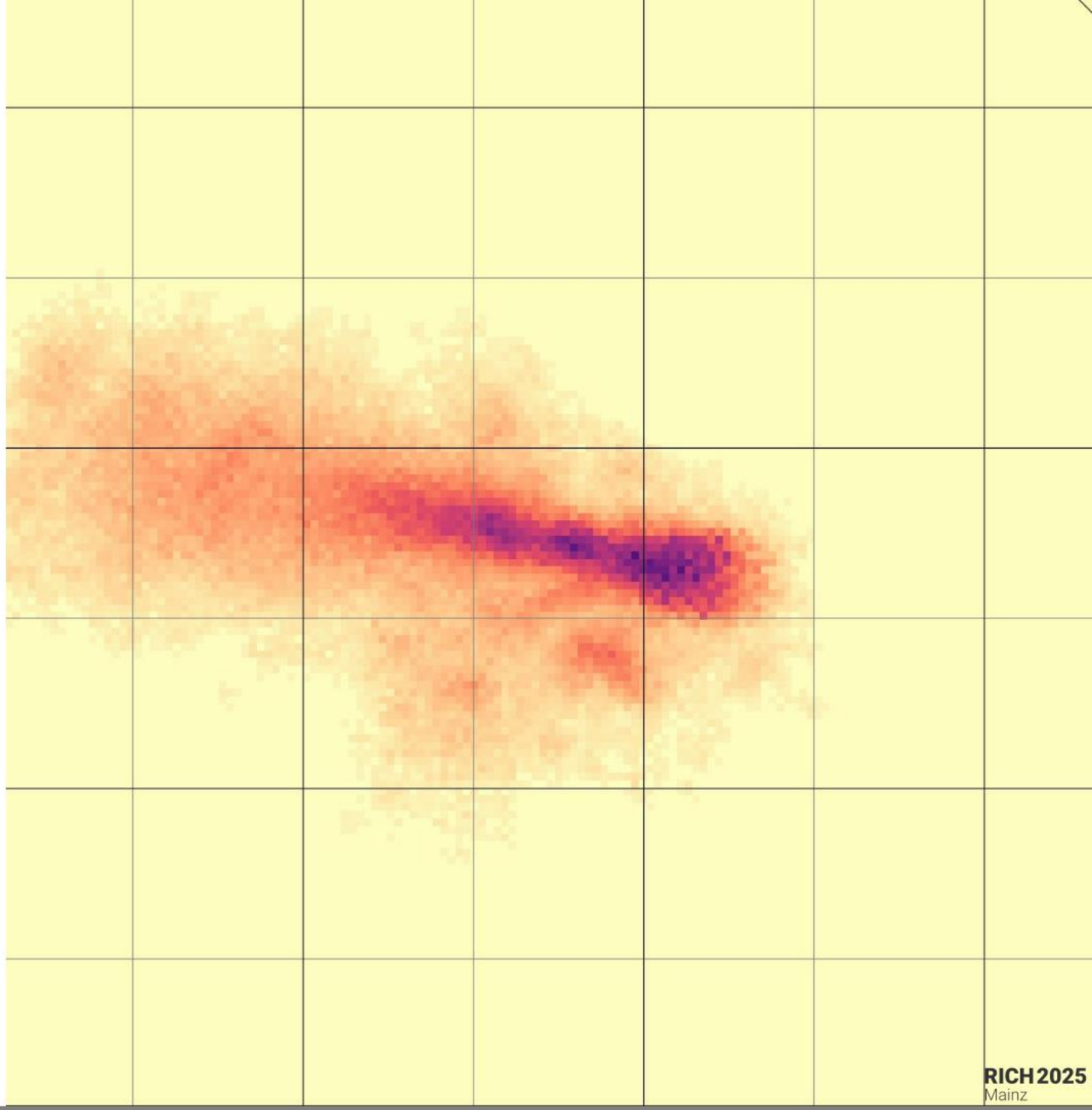

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Gamma

529GeV

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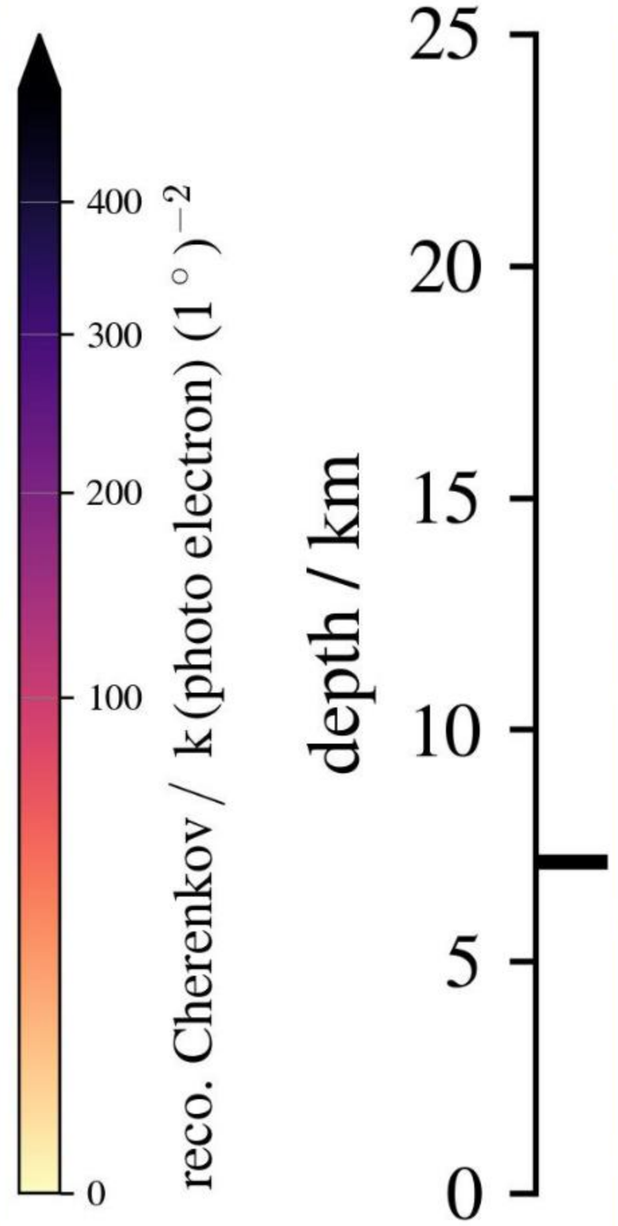

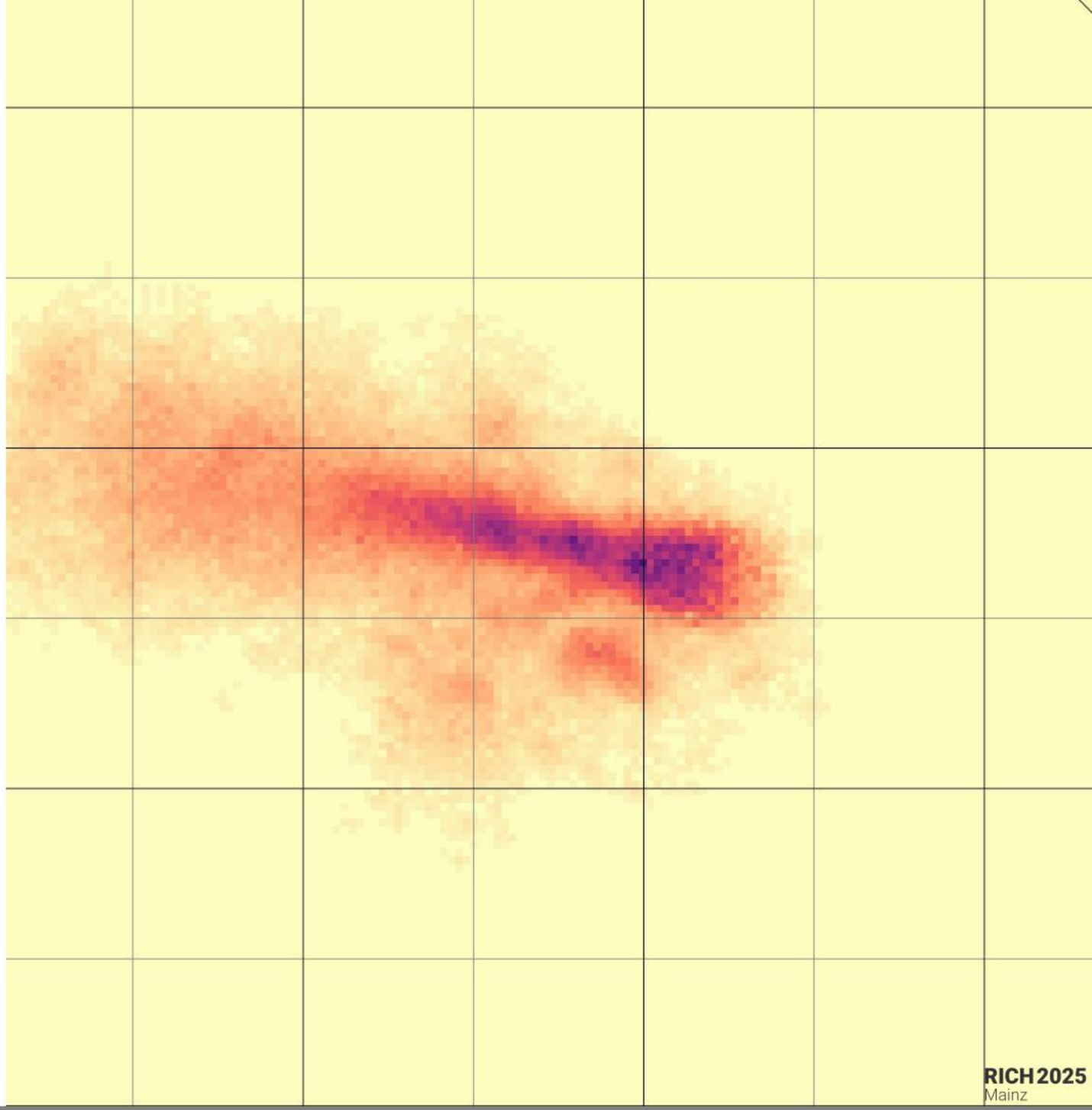

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Gamma

529GeV

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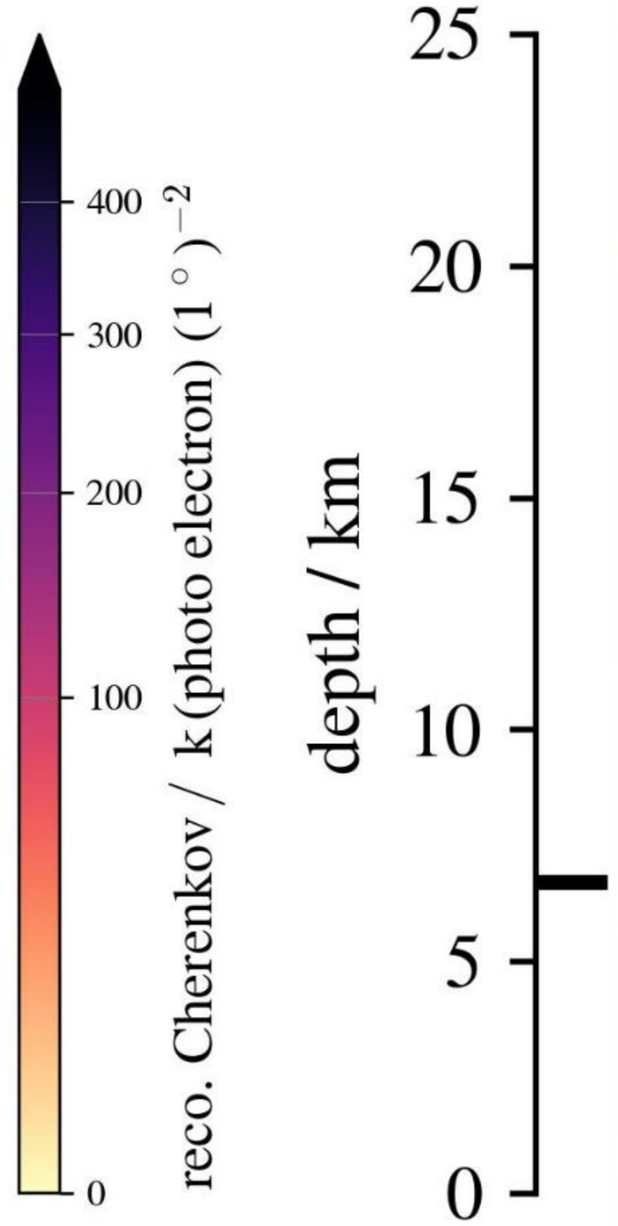

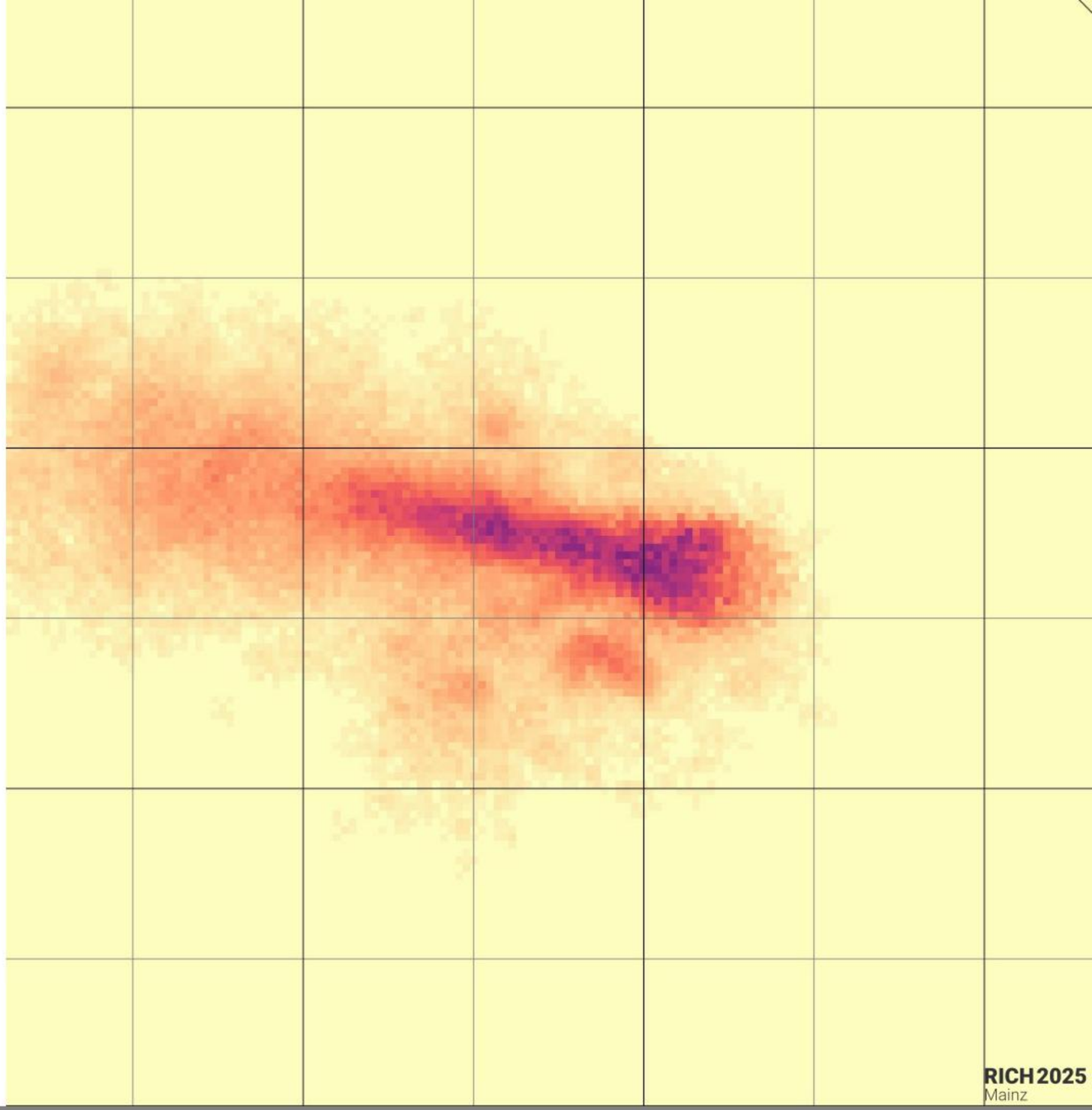

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Gamma

529GeV

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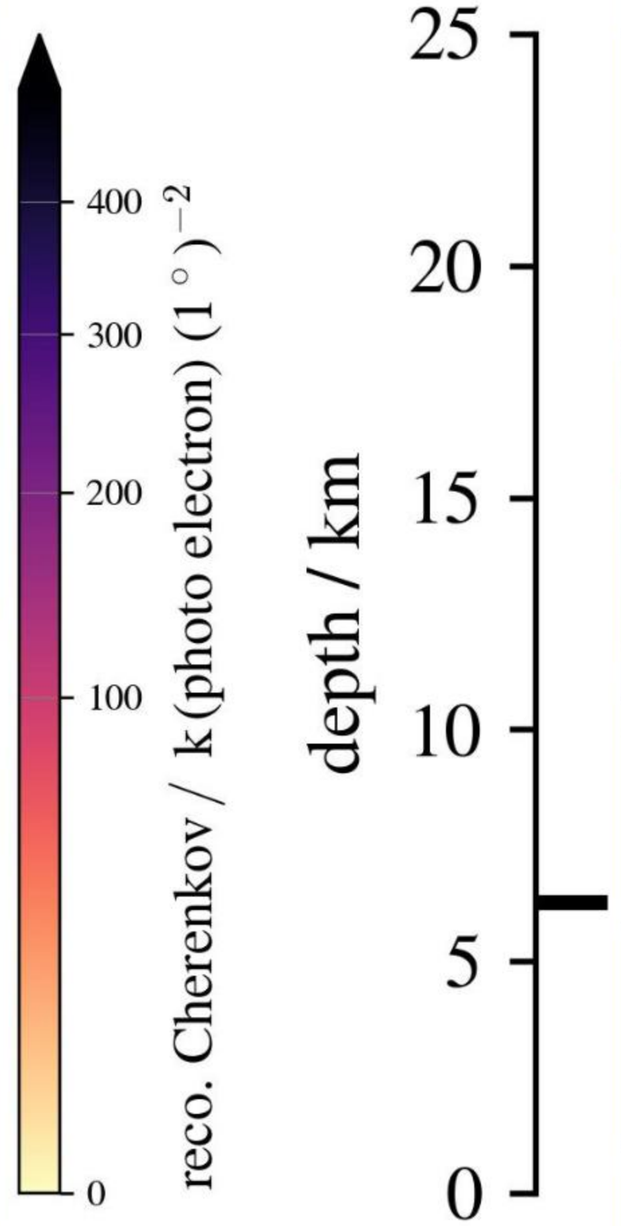

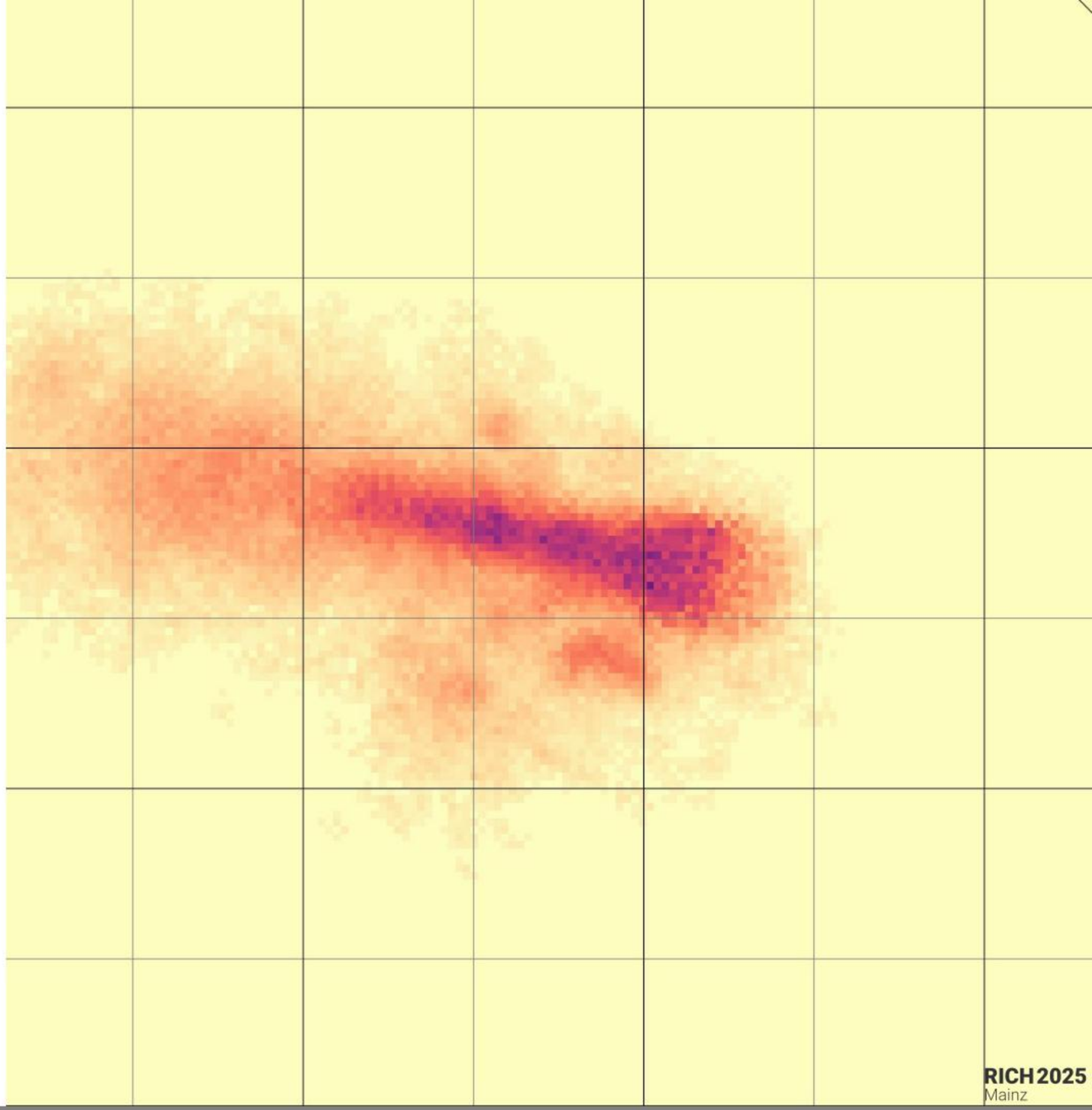

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529GeV

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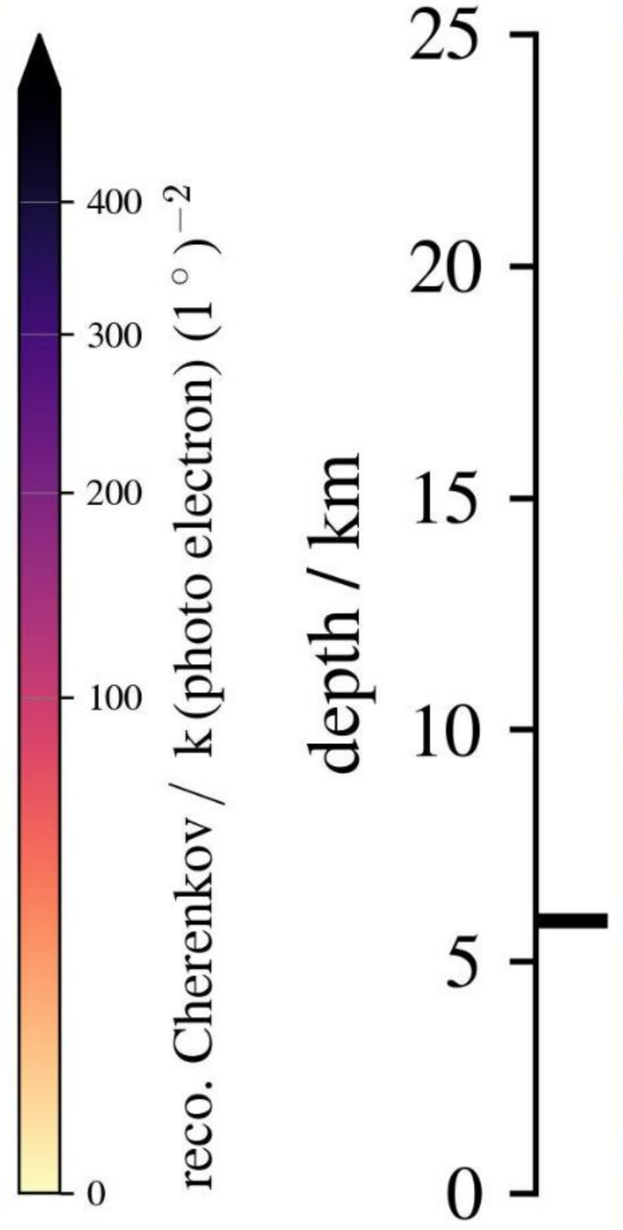

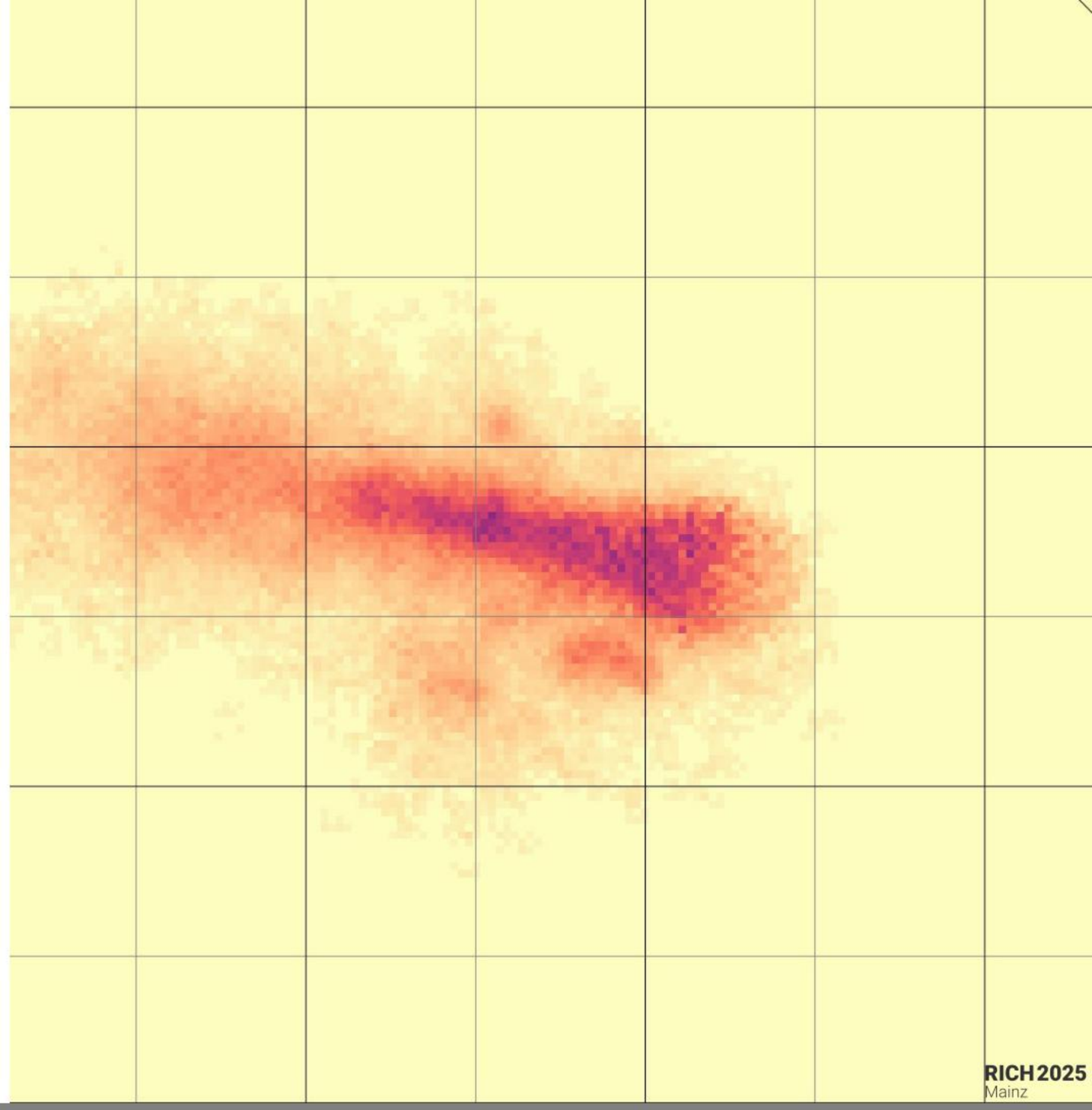

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Gamma

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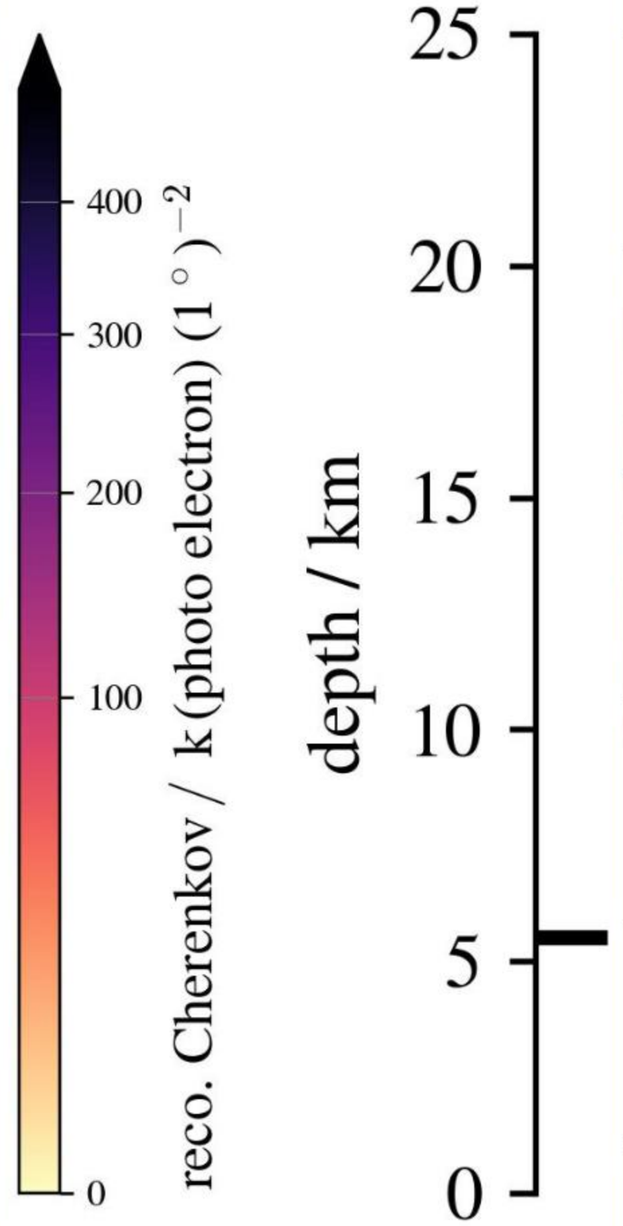

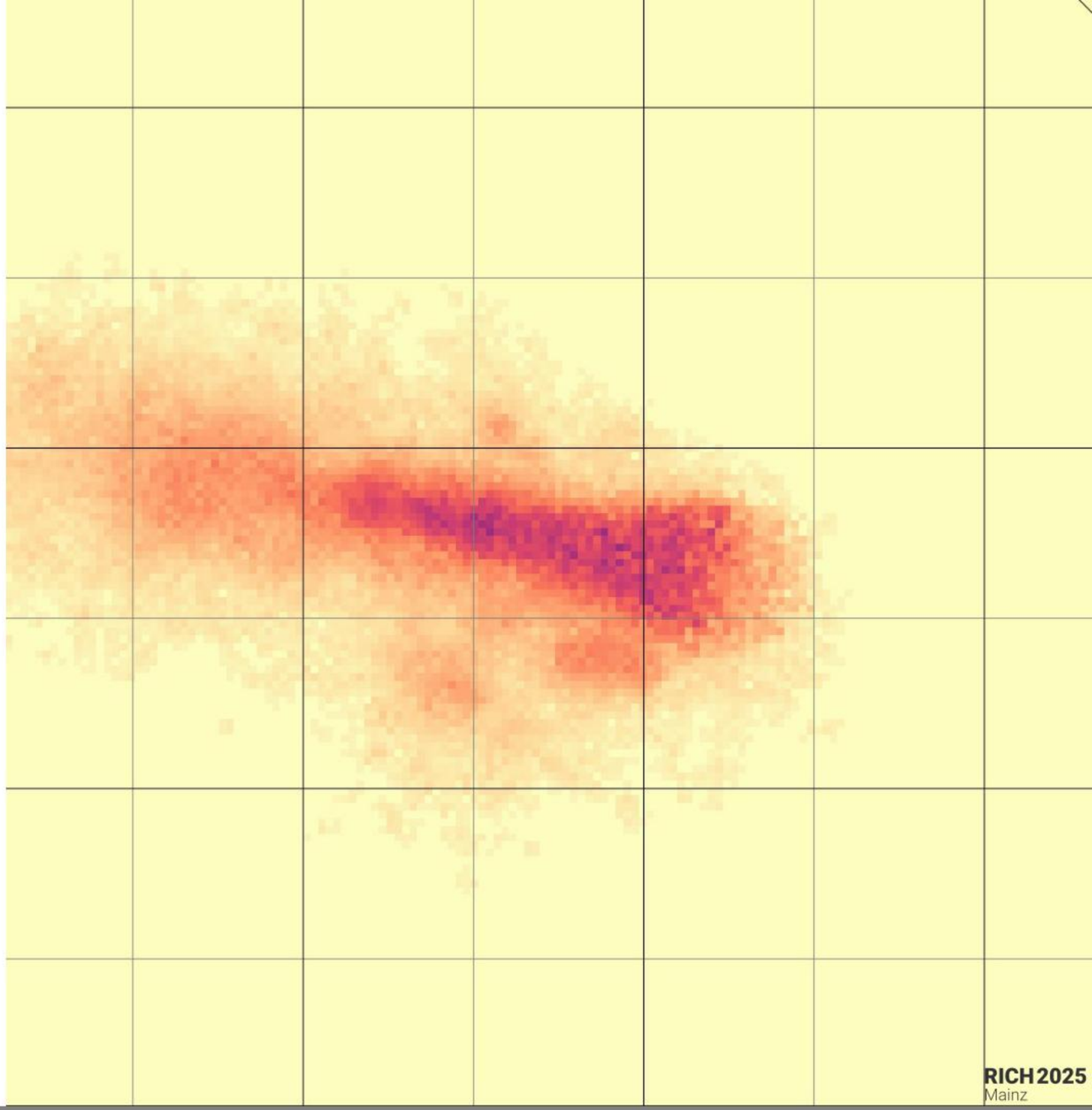

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Gamma

529GeV

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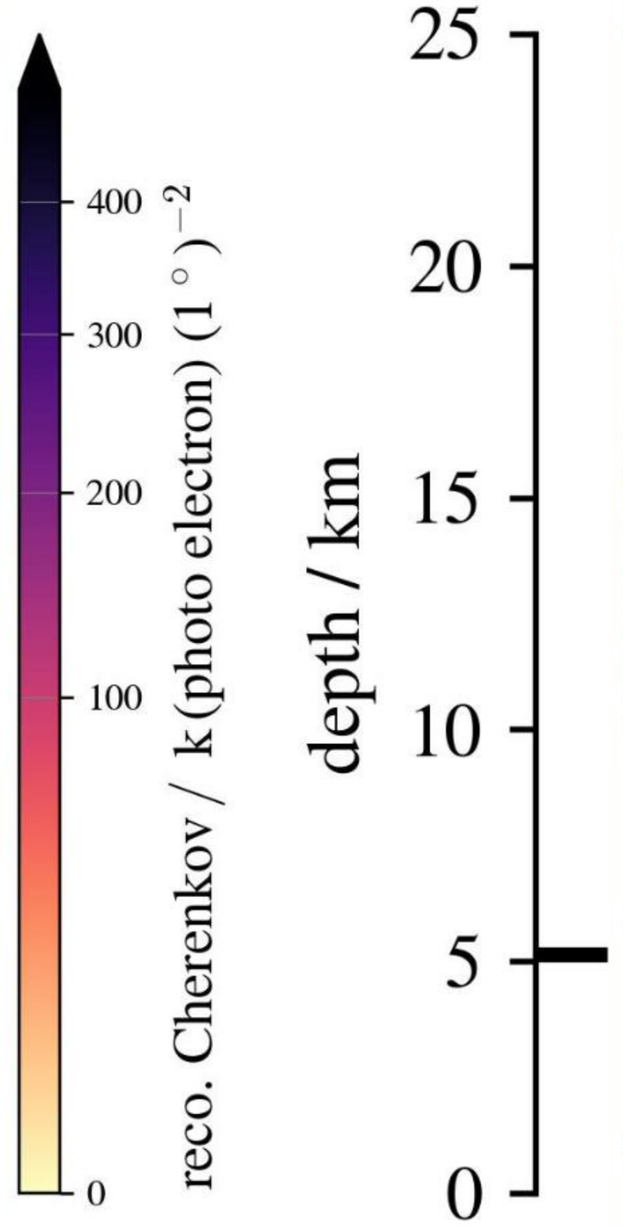
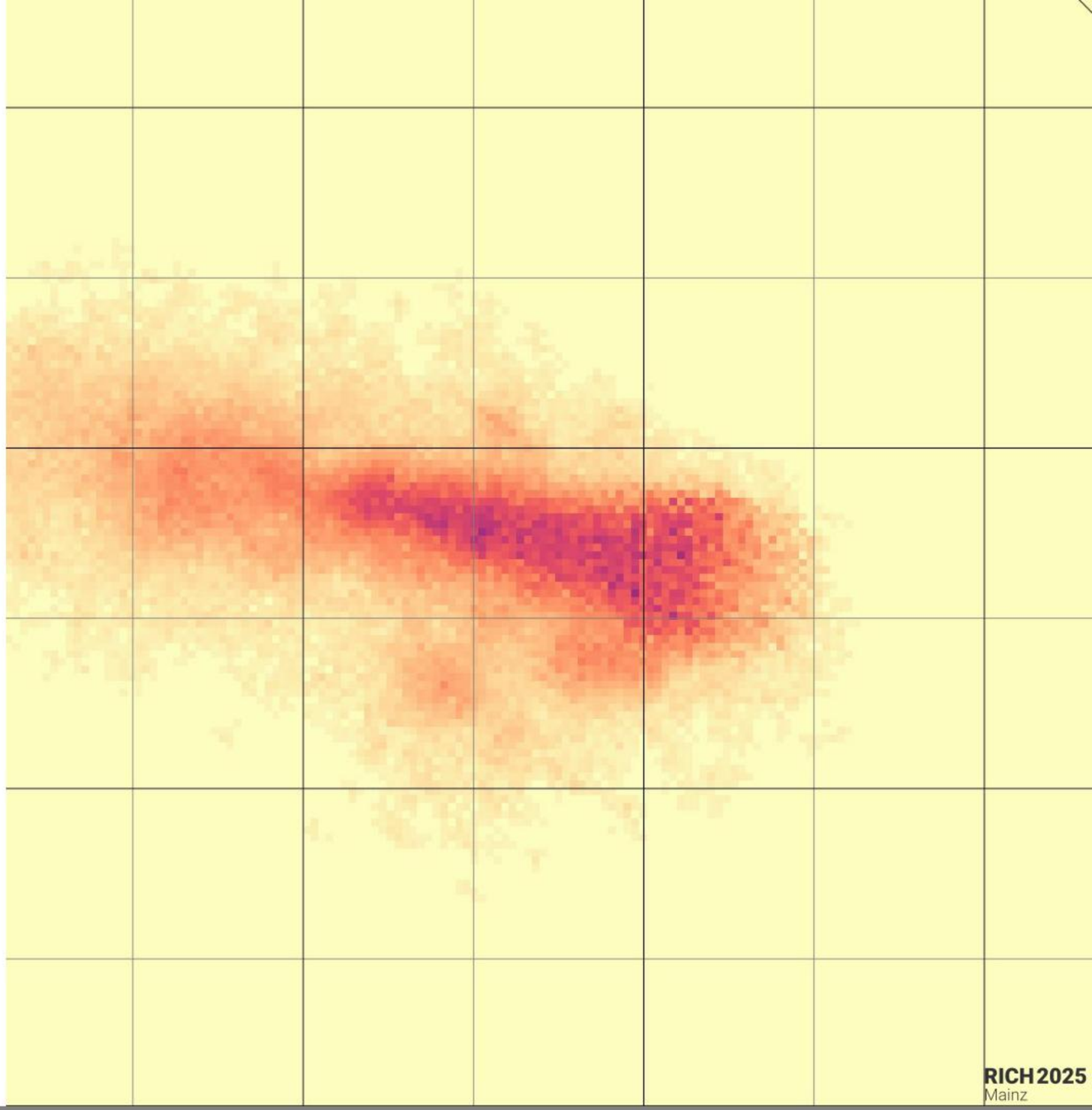


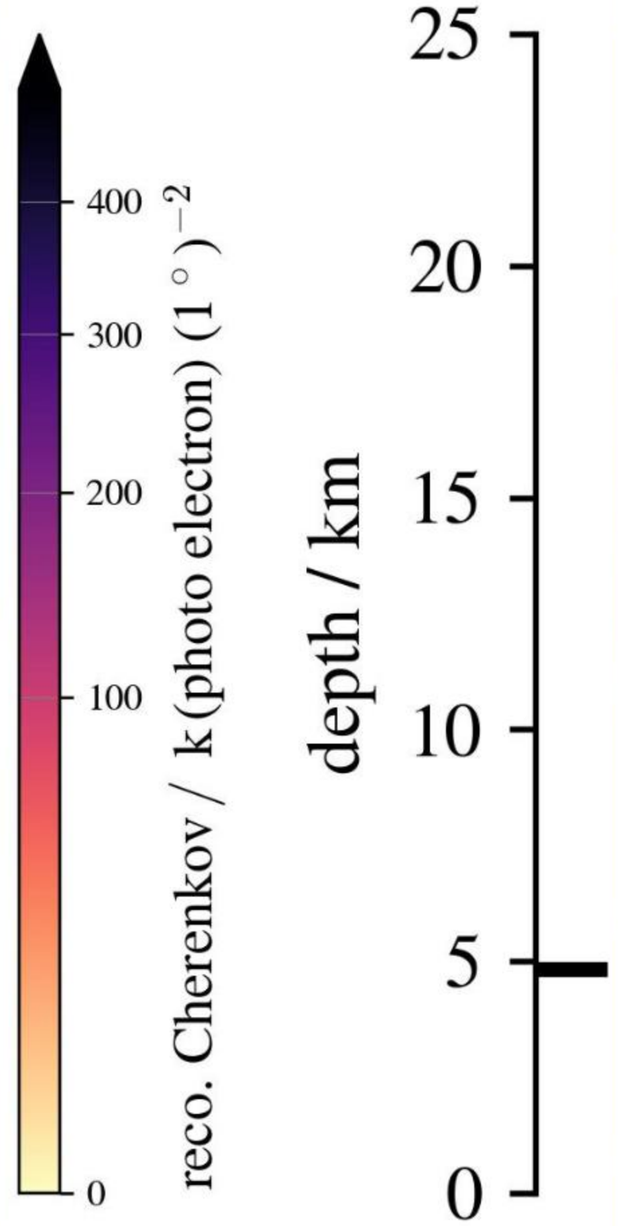


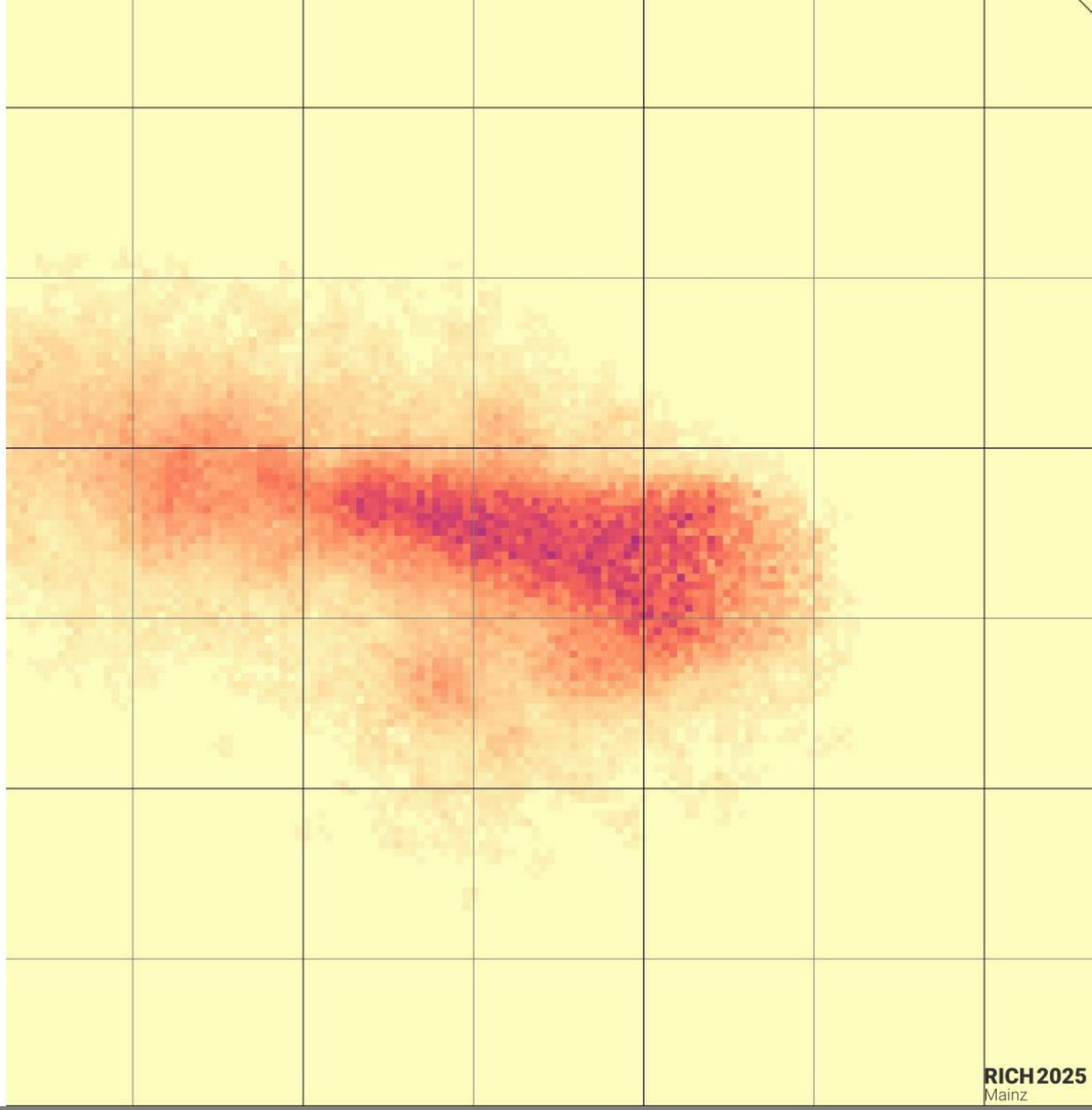
Airshower

Gamma

529GeV

36,518p.e.





Airshower

Gamma

529GeV

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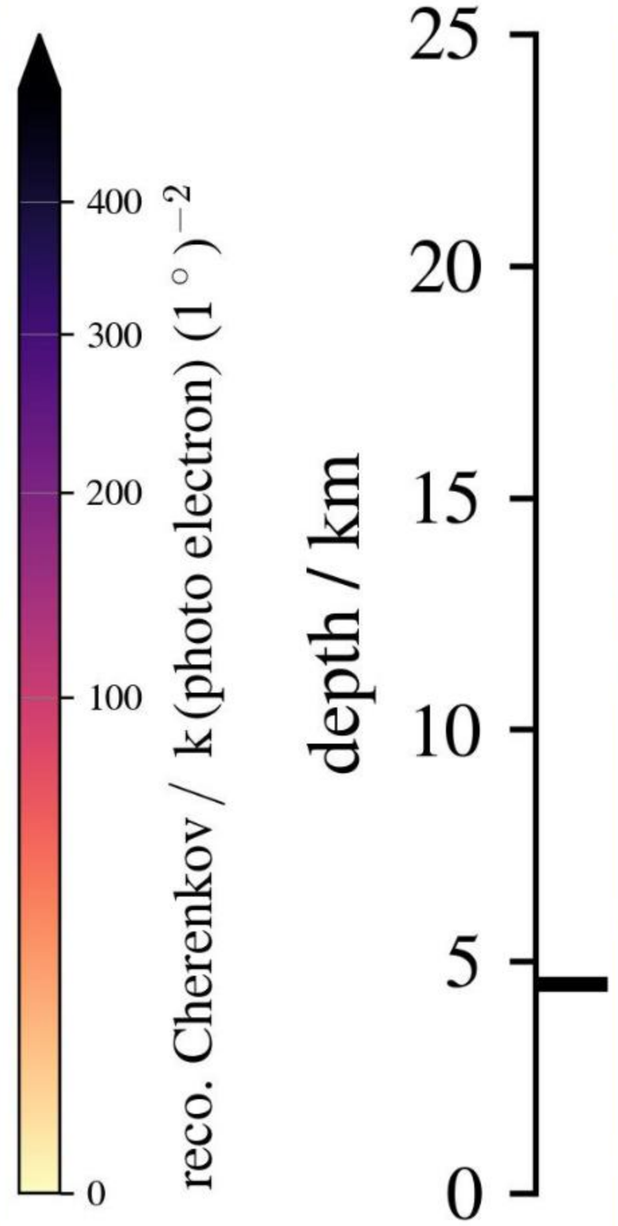

Airshower

Gamma

529GeV

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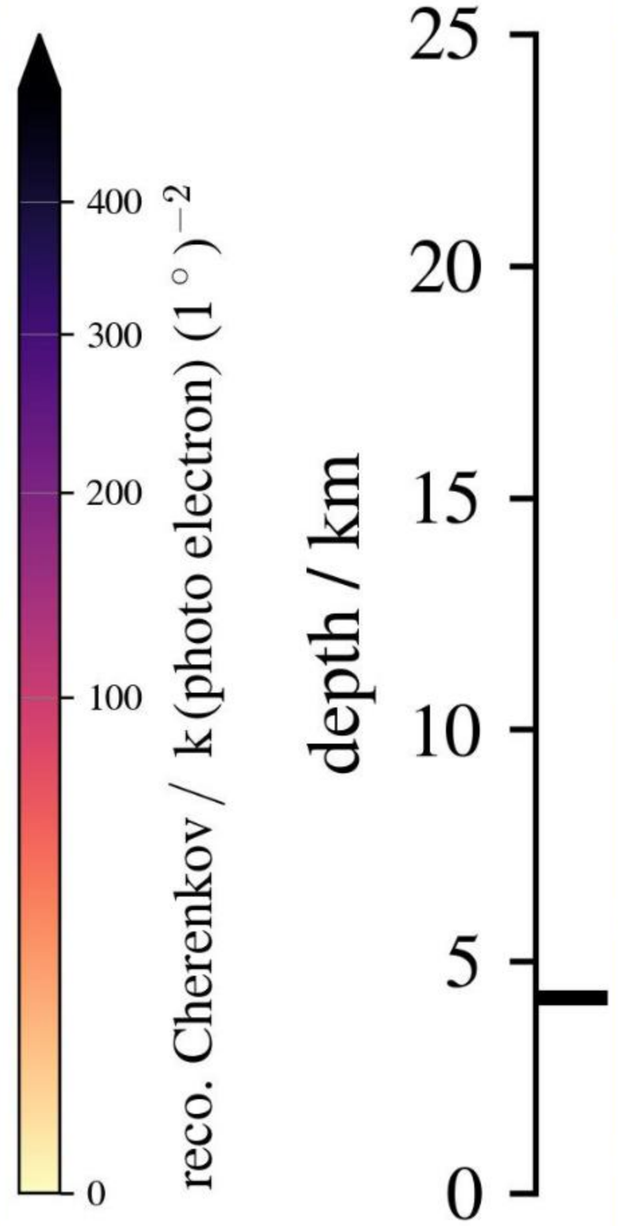
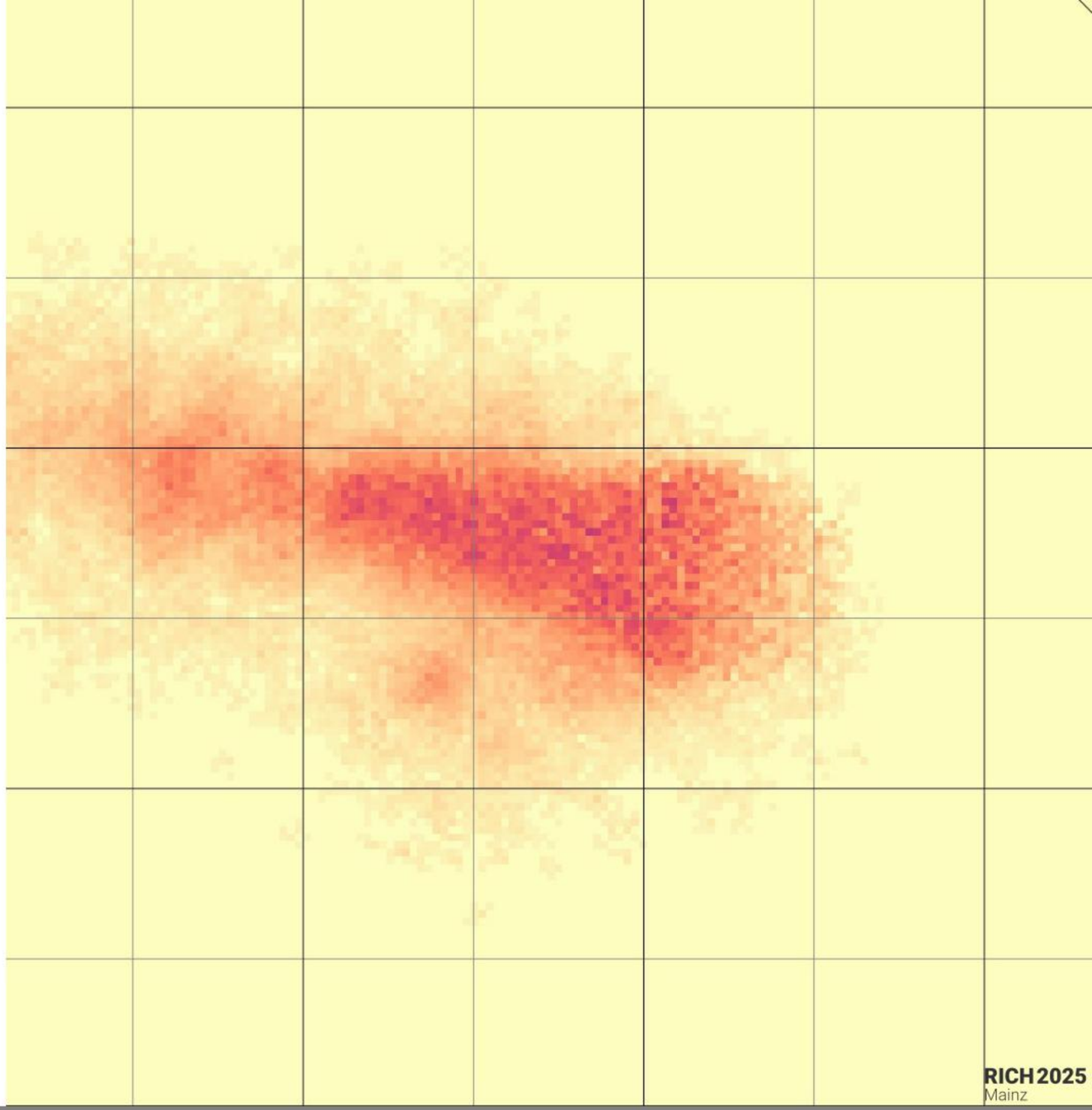


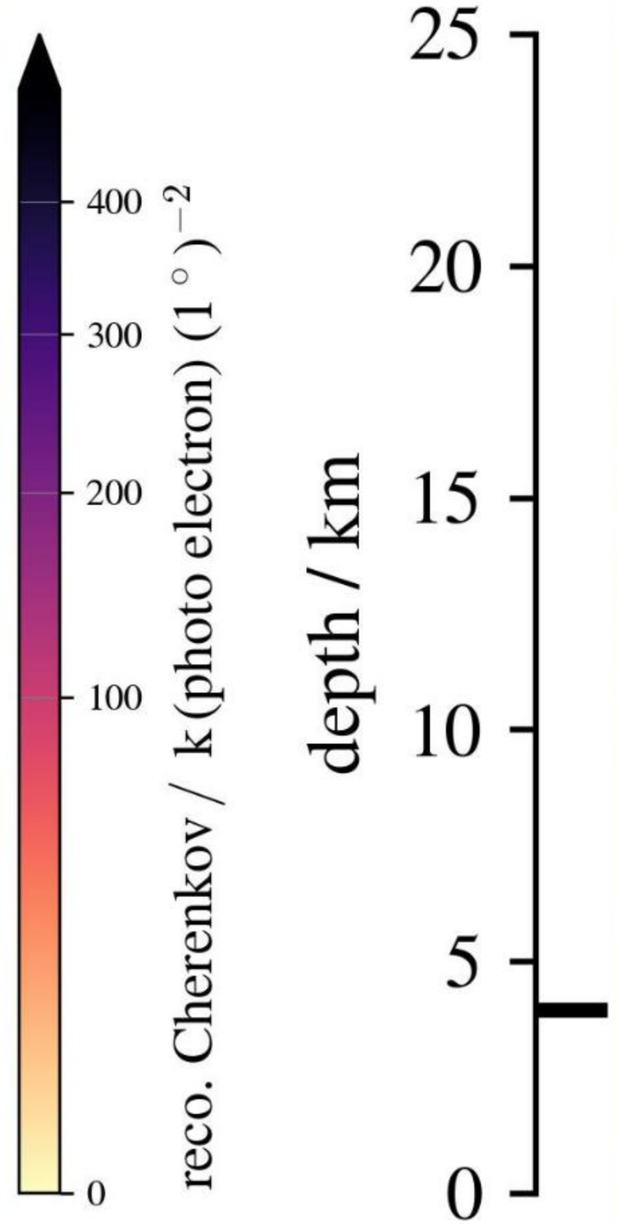


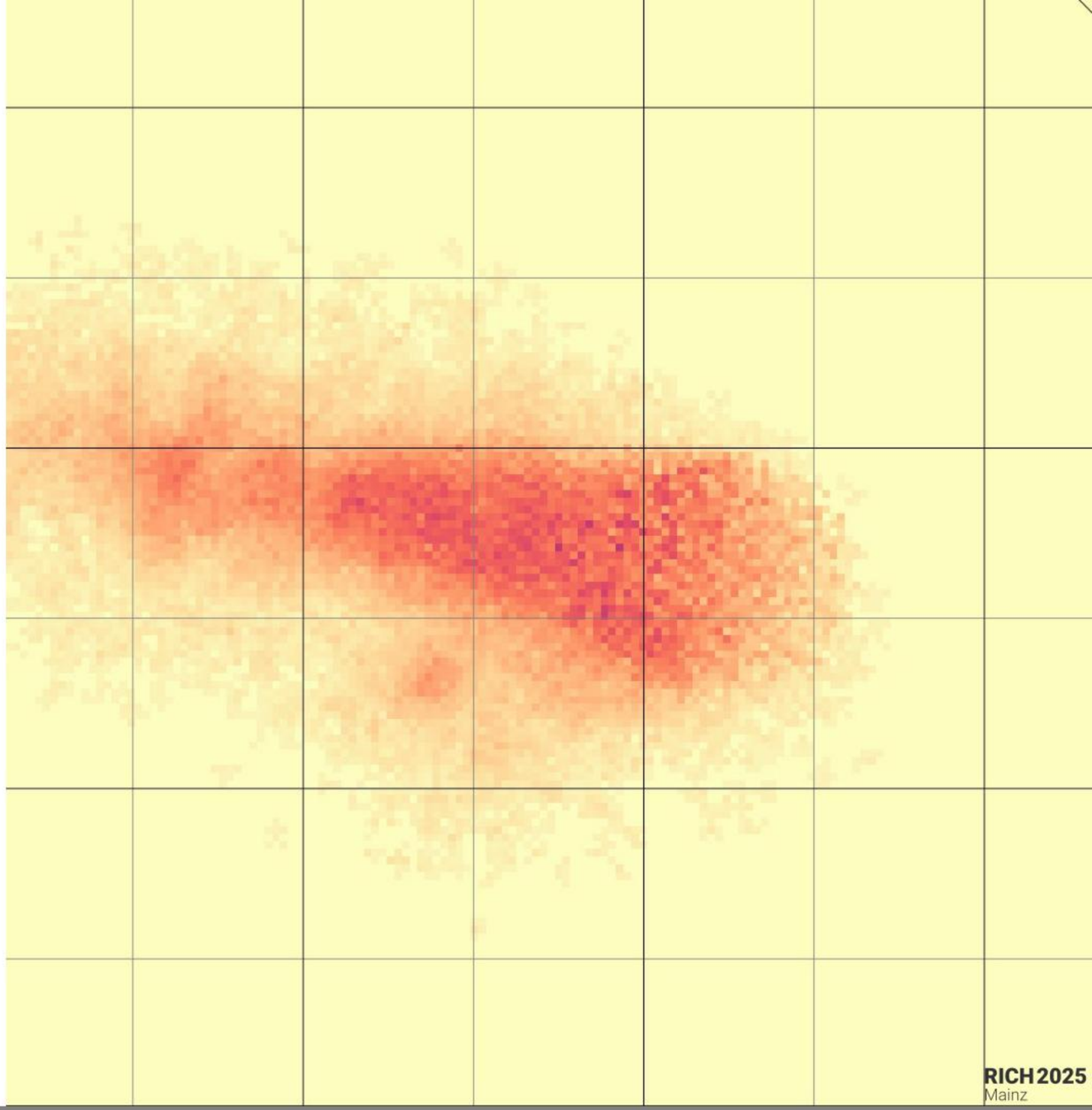
Airshower

Gamma

529GeV

36,518p.e.





Airshower

Gamma

529GeV

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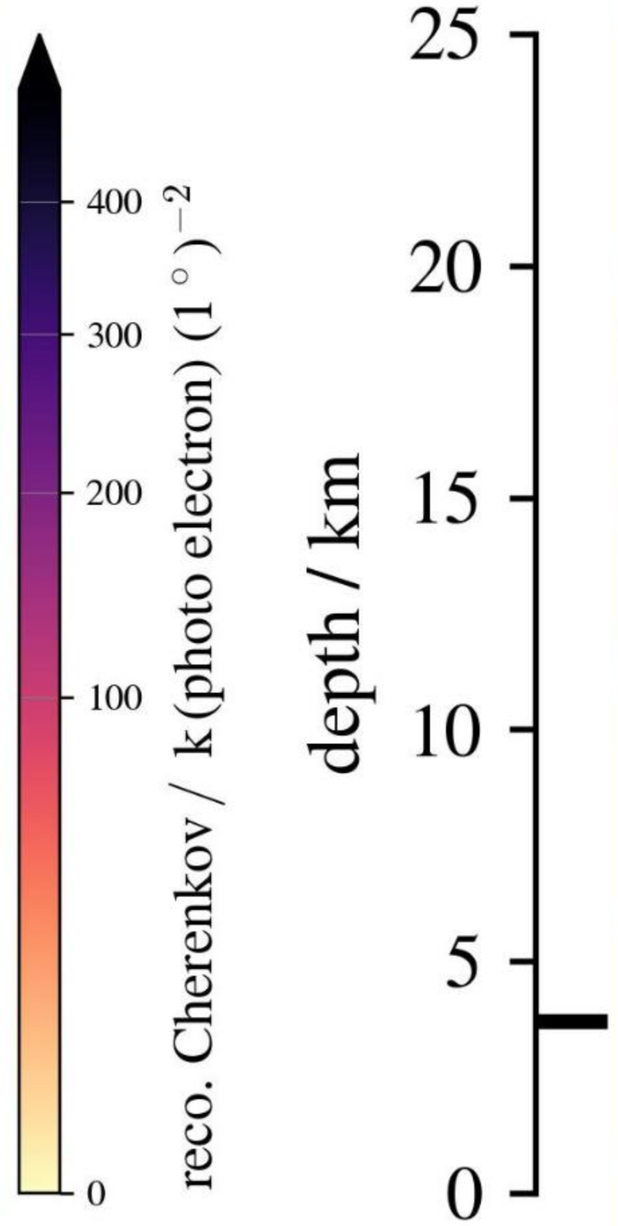

Airshower

Gamma

529GeV

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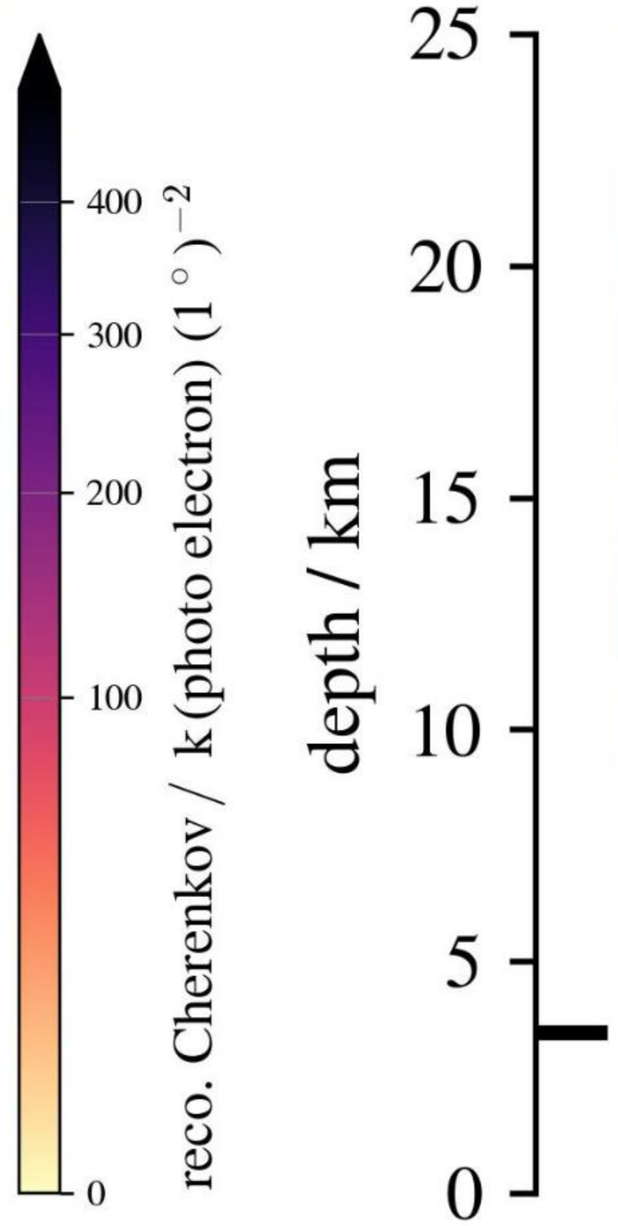
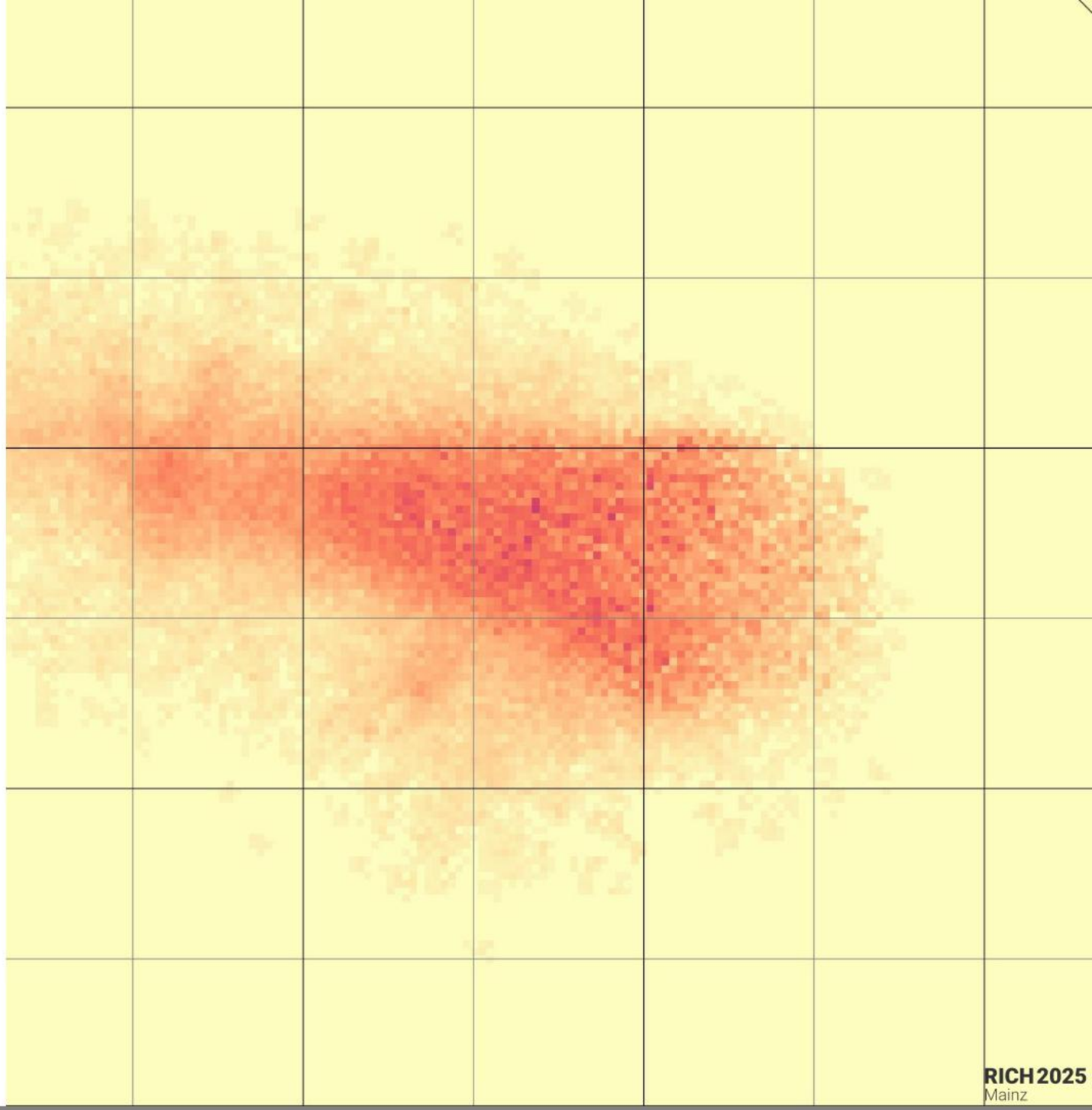


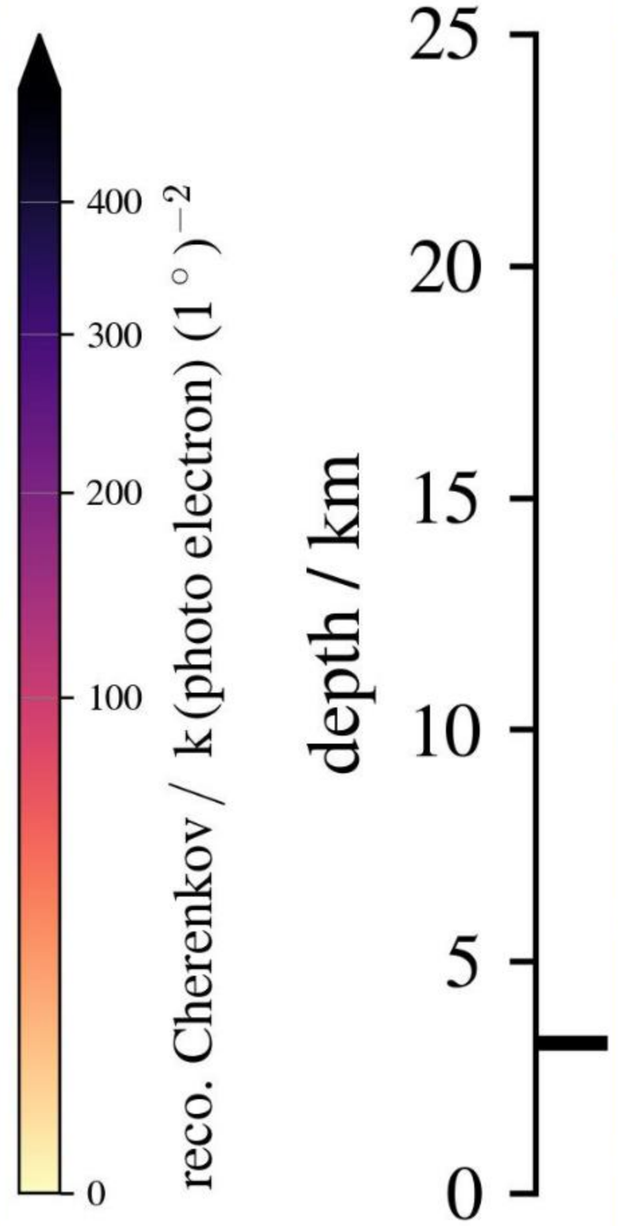


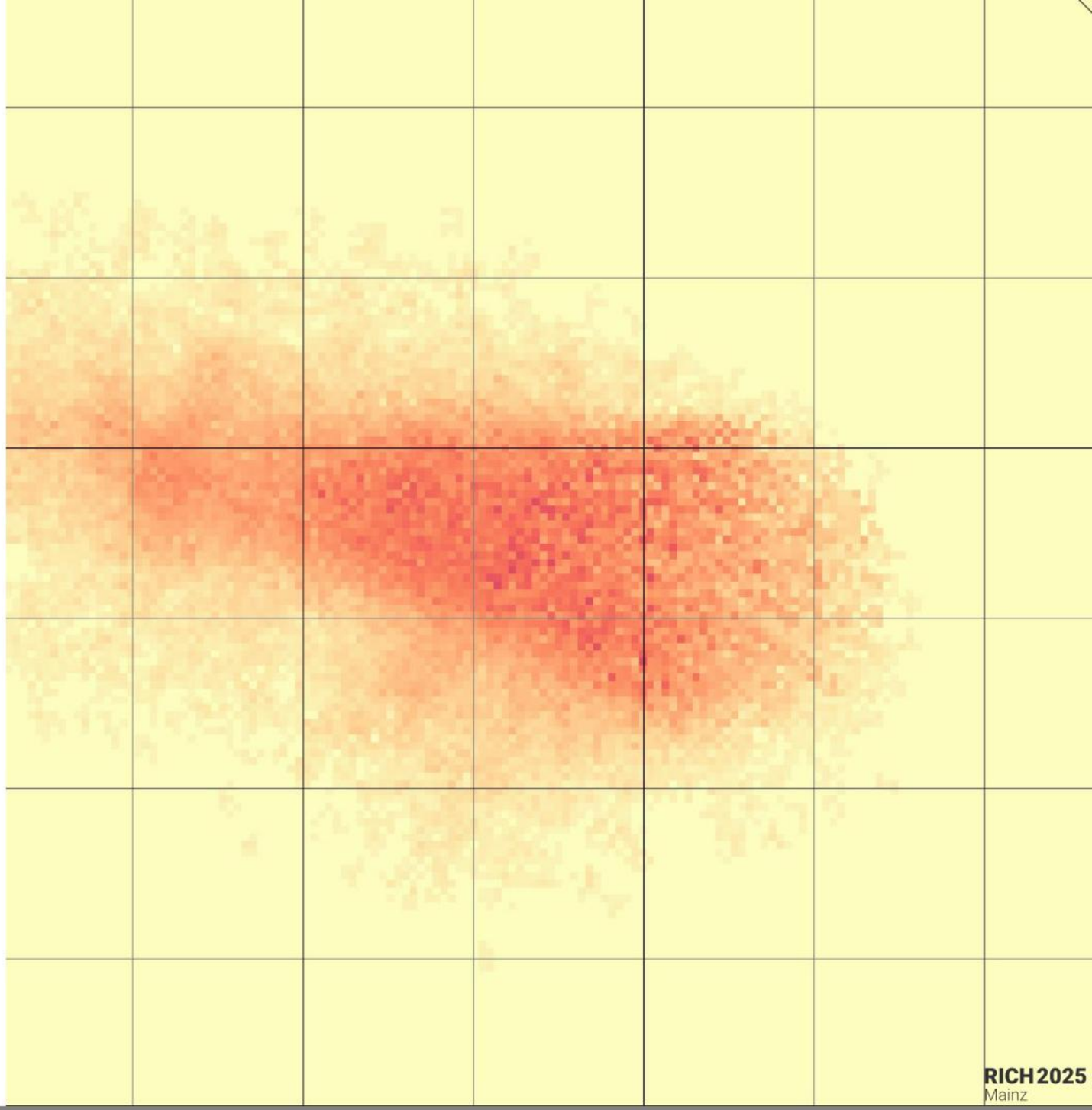
Airshower

Gamma

529GeV

36,518p.e.



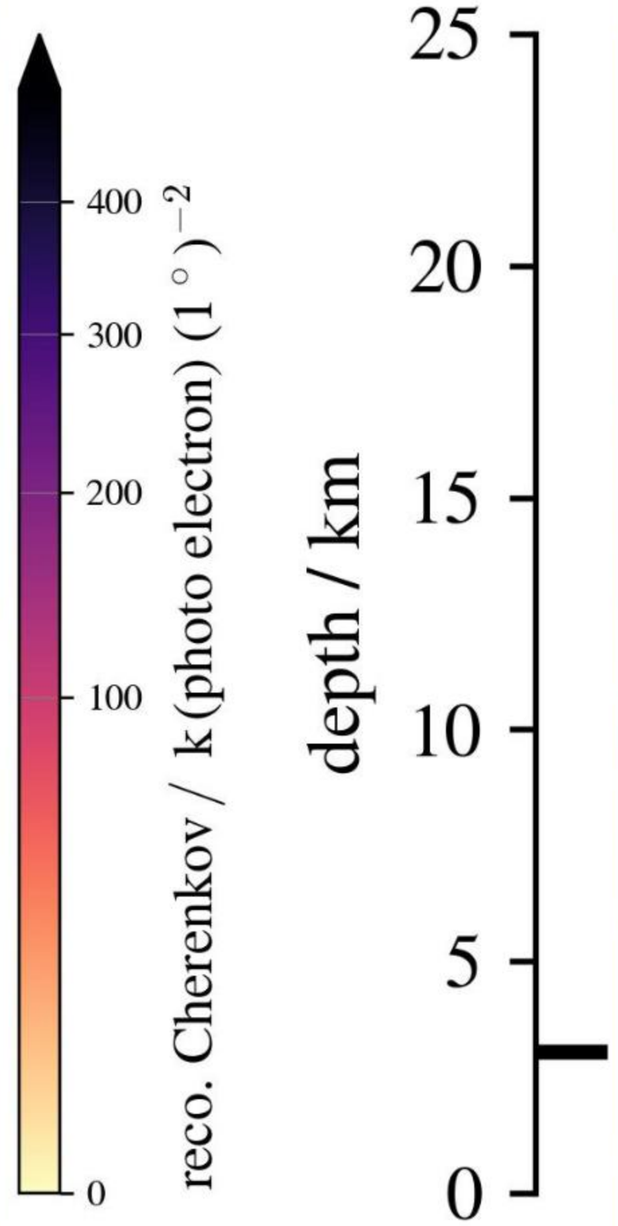


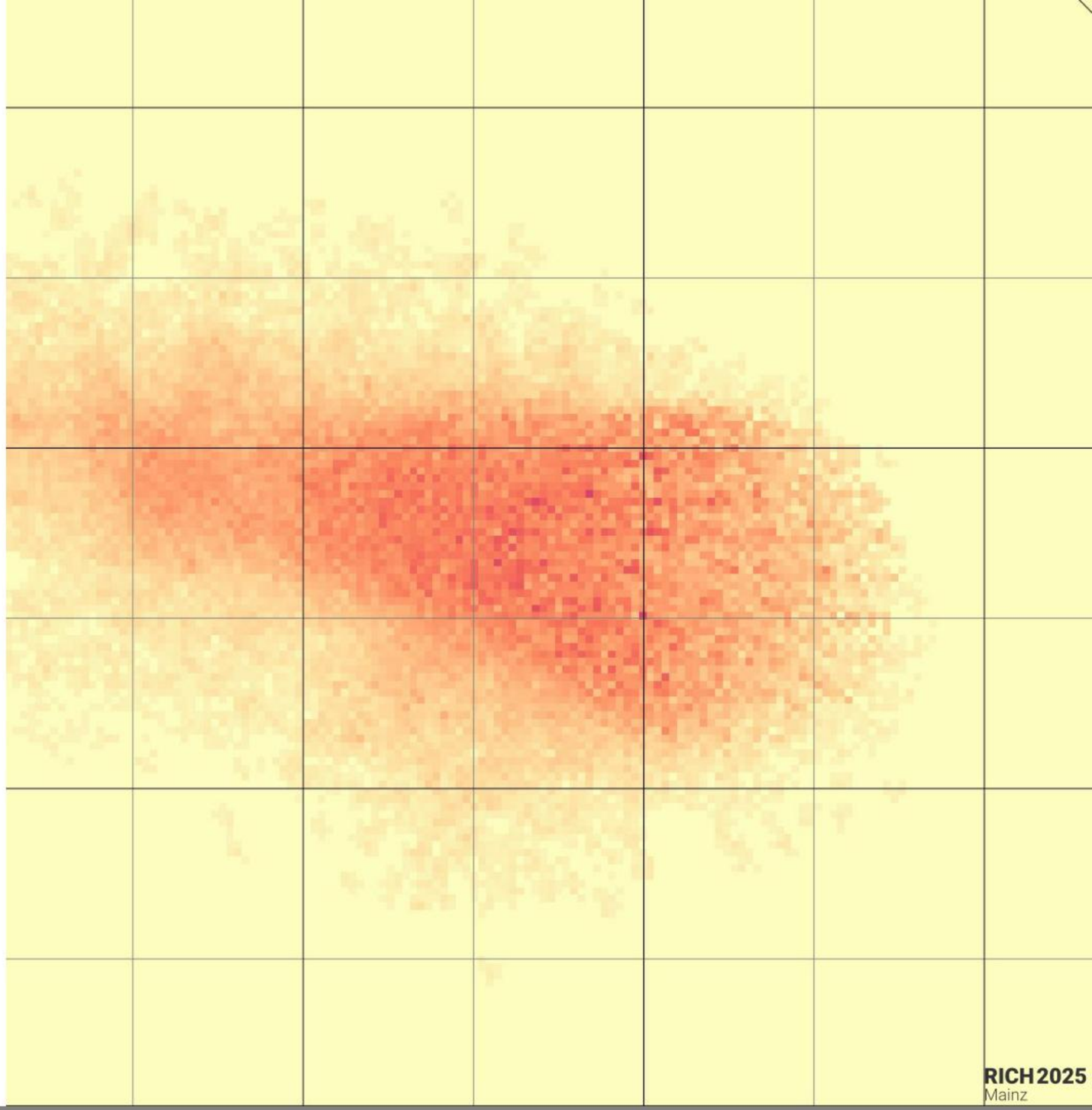
Airshower

Gamma

529GeV

36,518p.e.



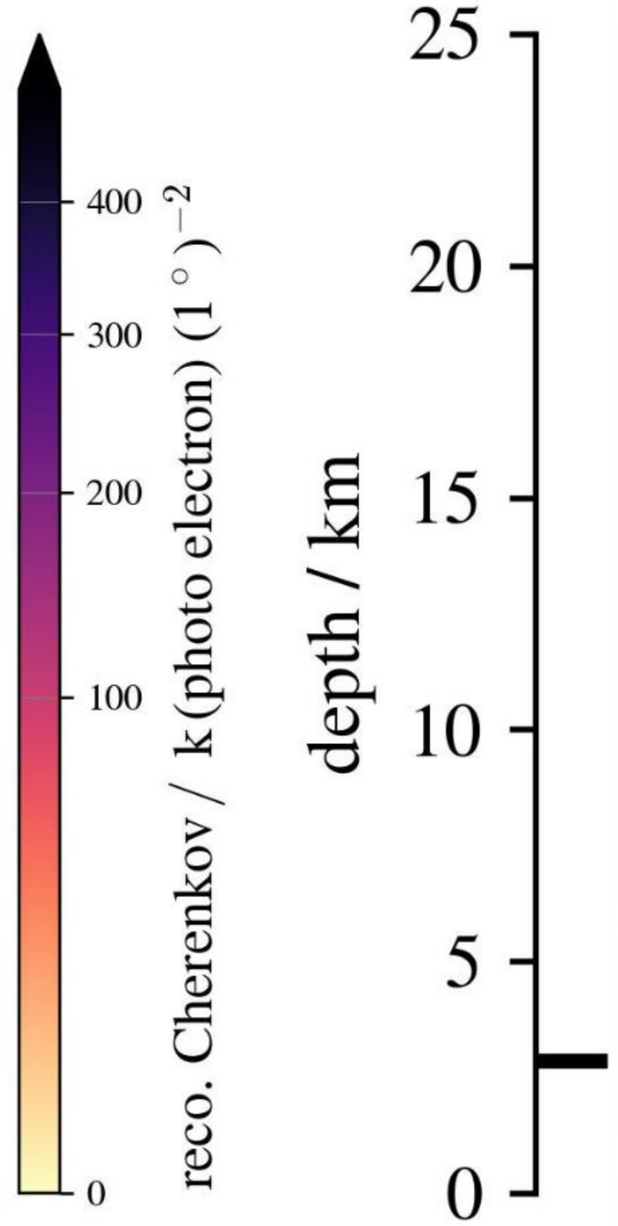


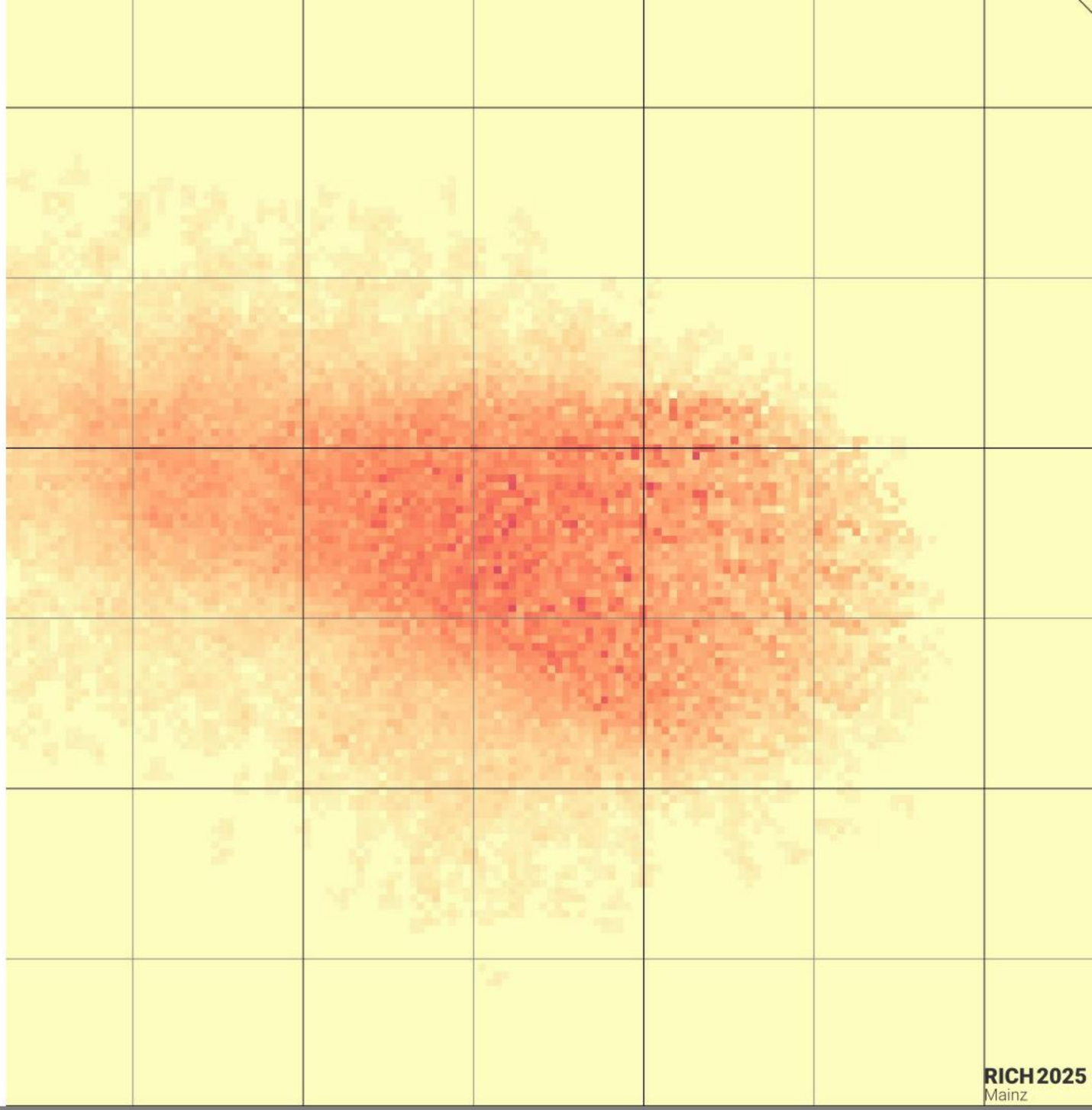
Airshower

Gamma

529GeV

36,518p.e.



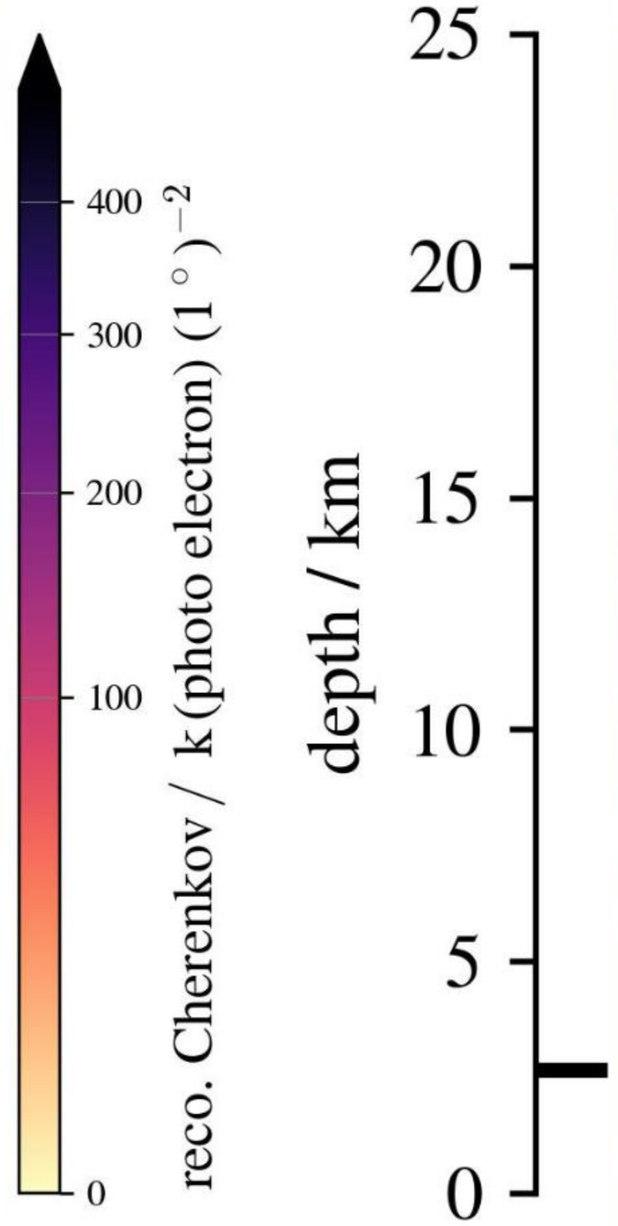


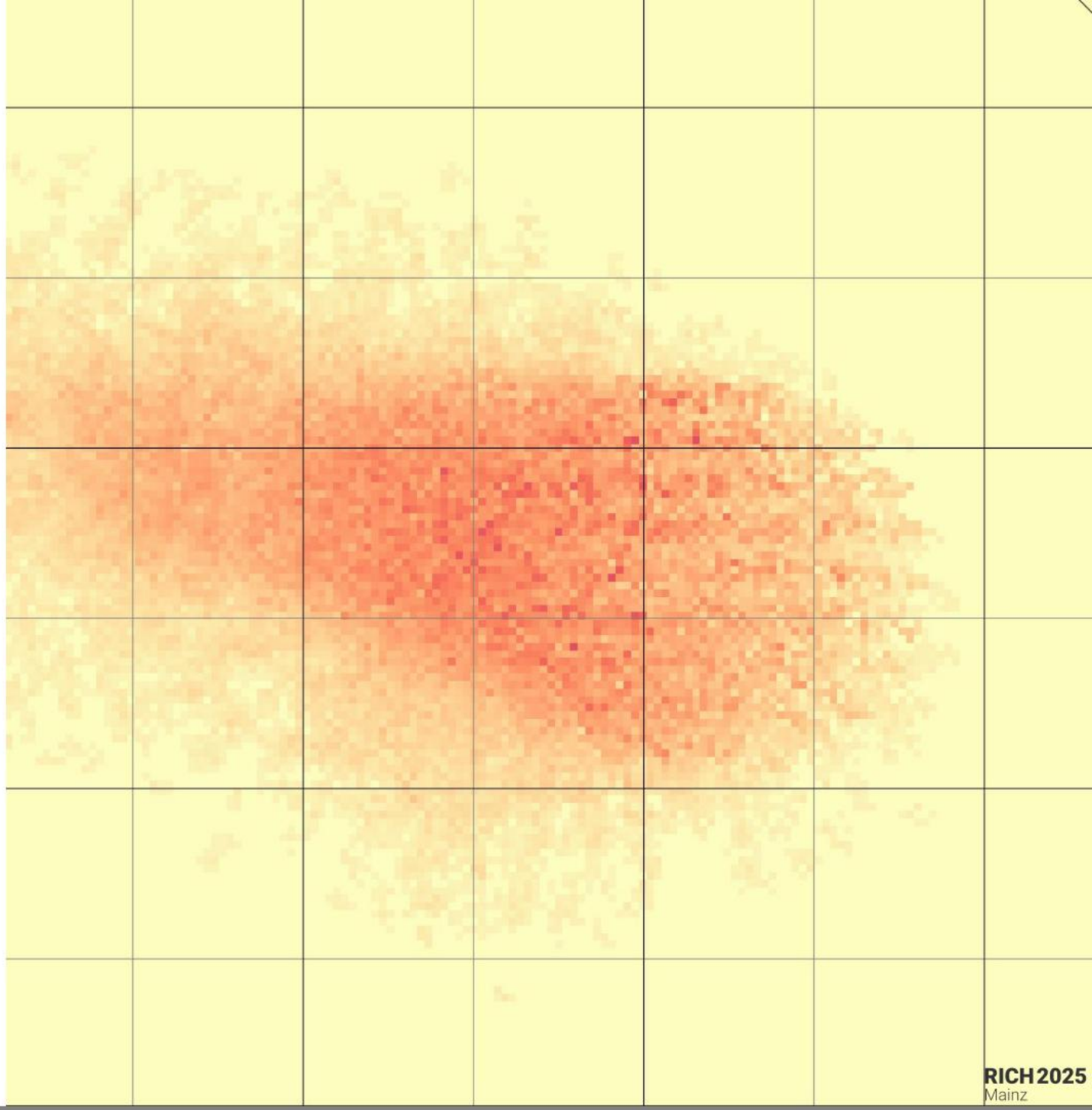
Airshower

Gamma

529GeV

36,518p.e.



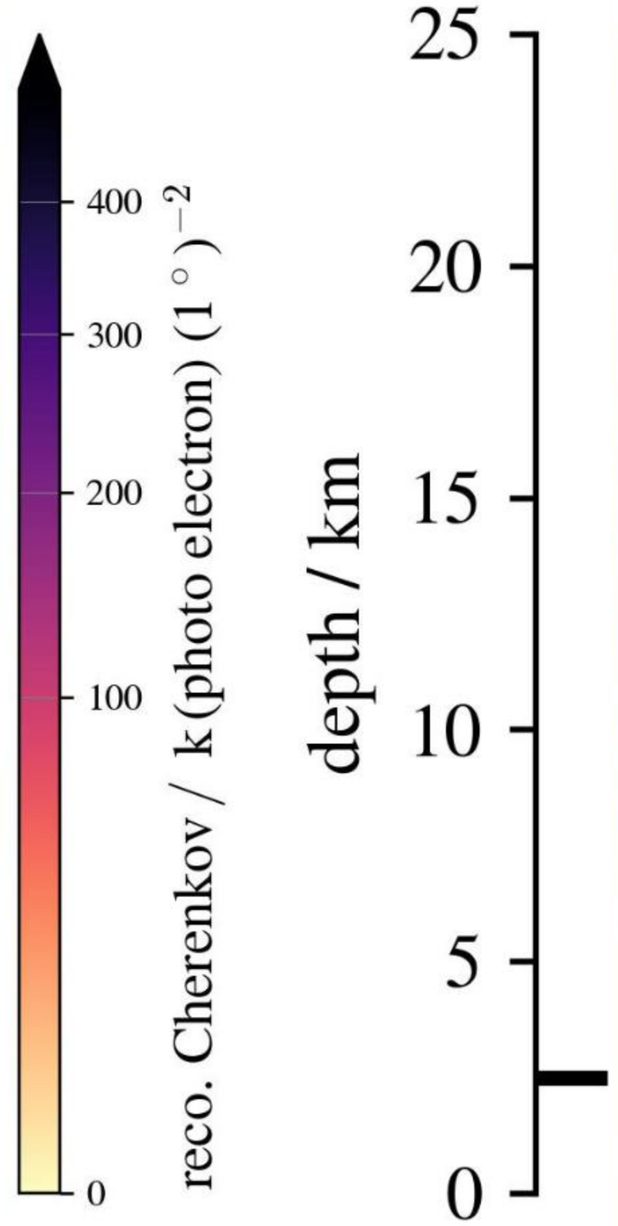


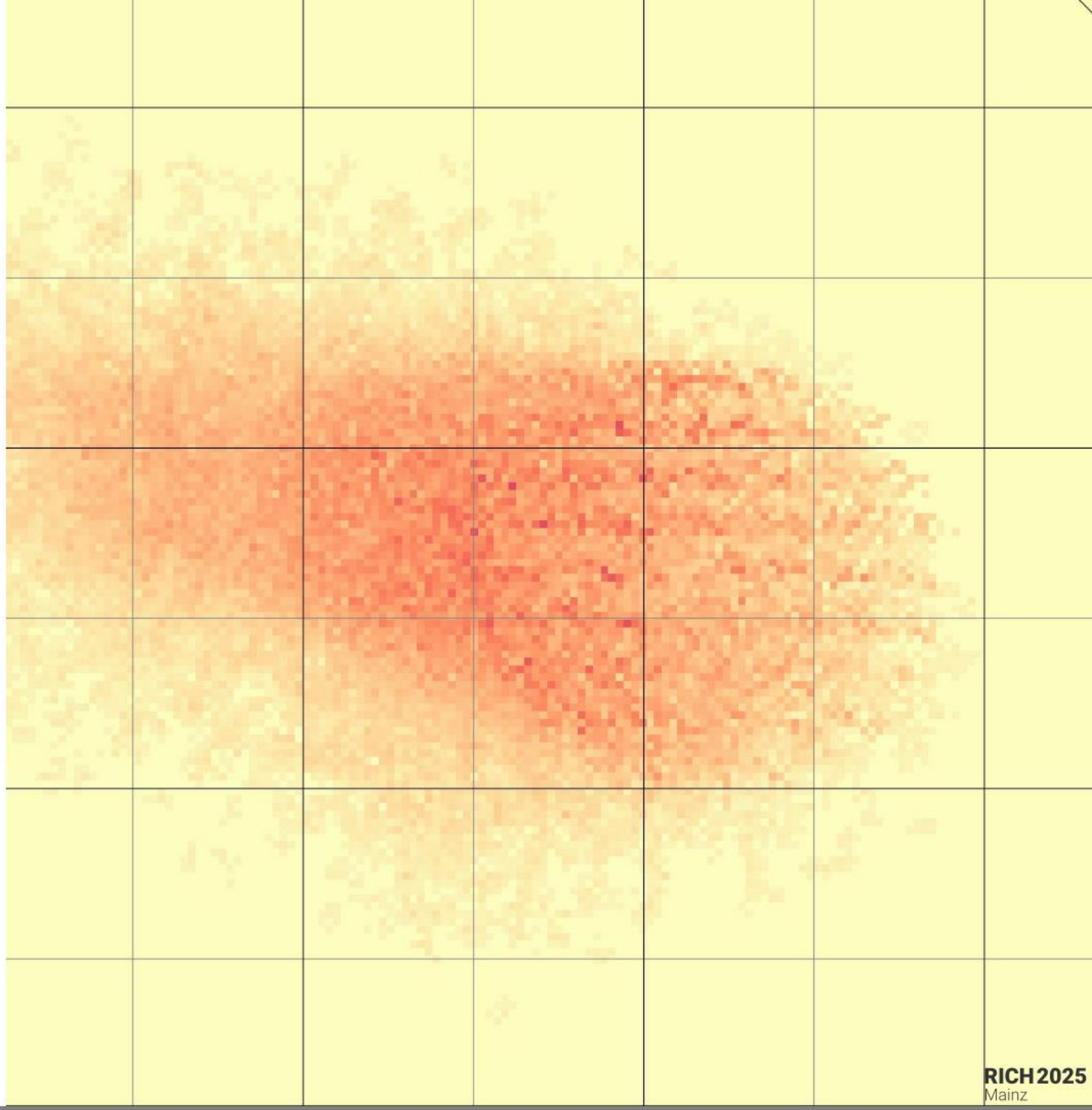
Airshower

Gamma

529GeV

36,518p.e.





Airshower

Gamma

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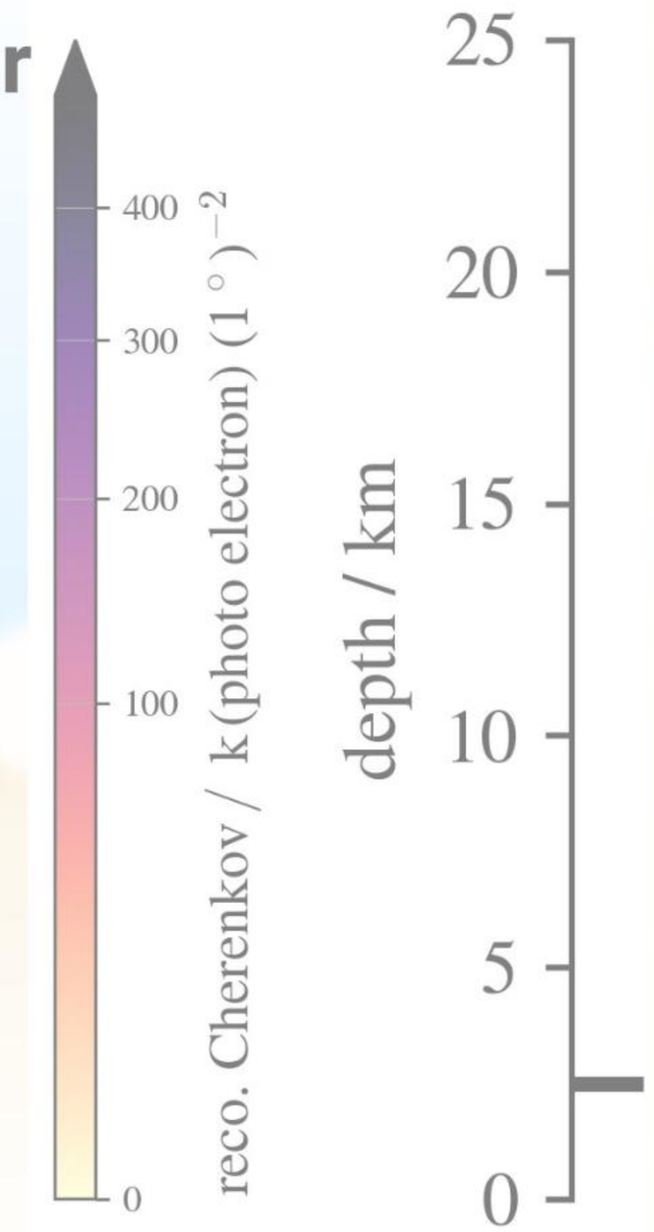
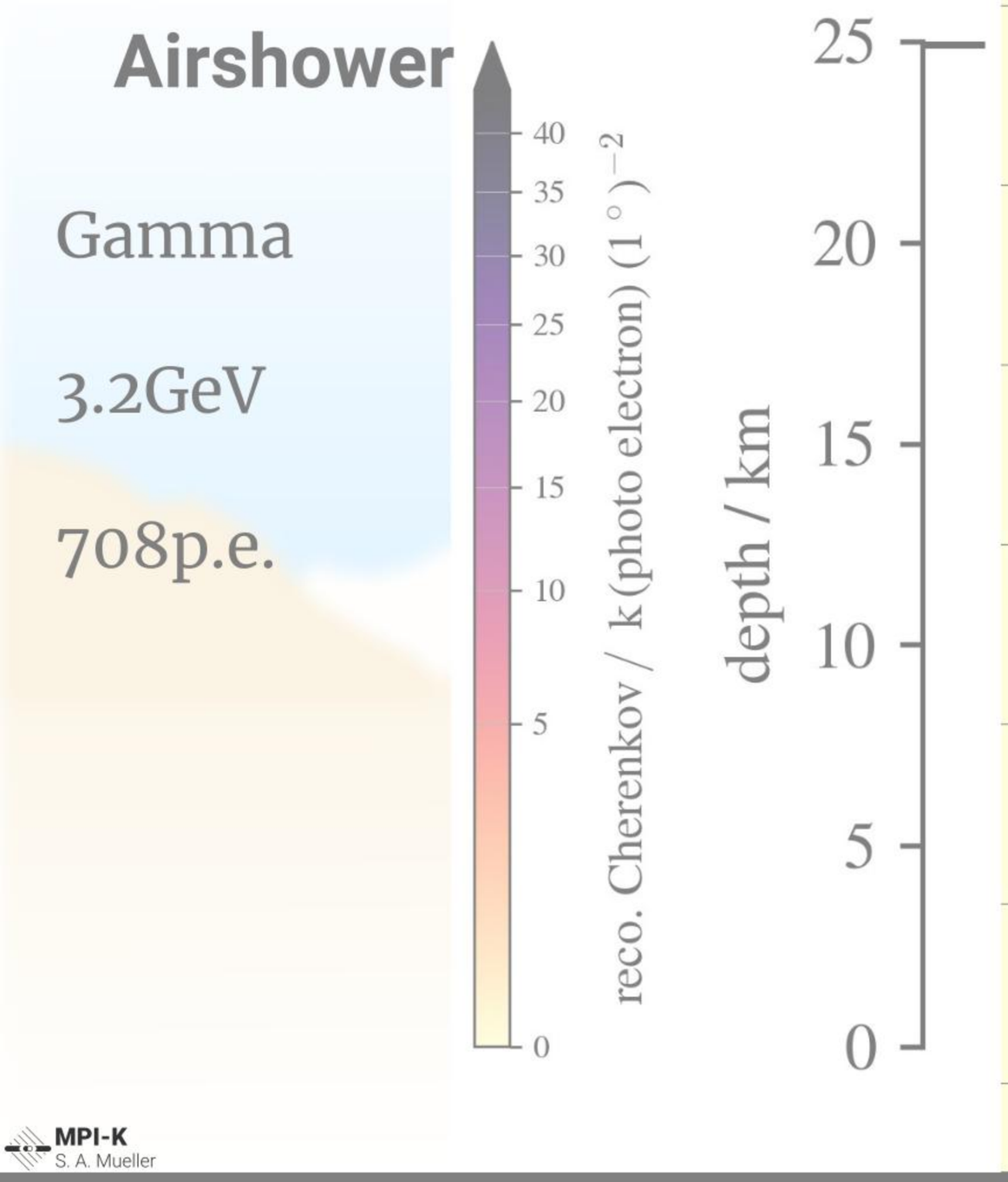
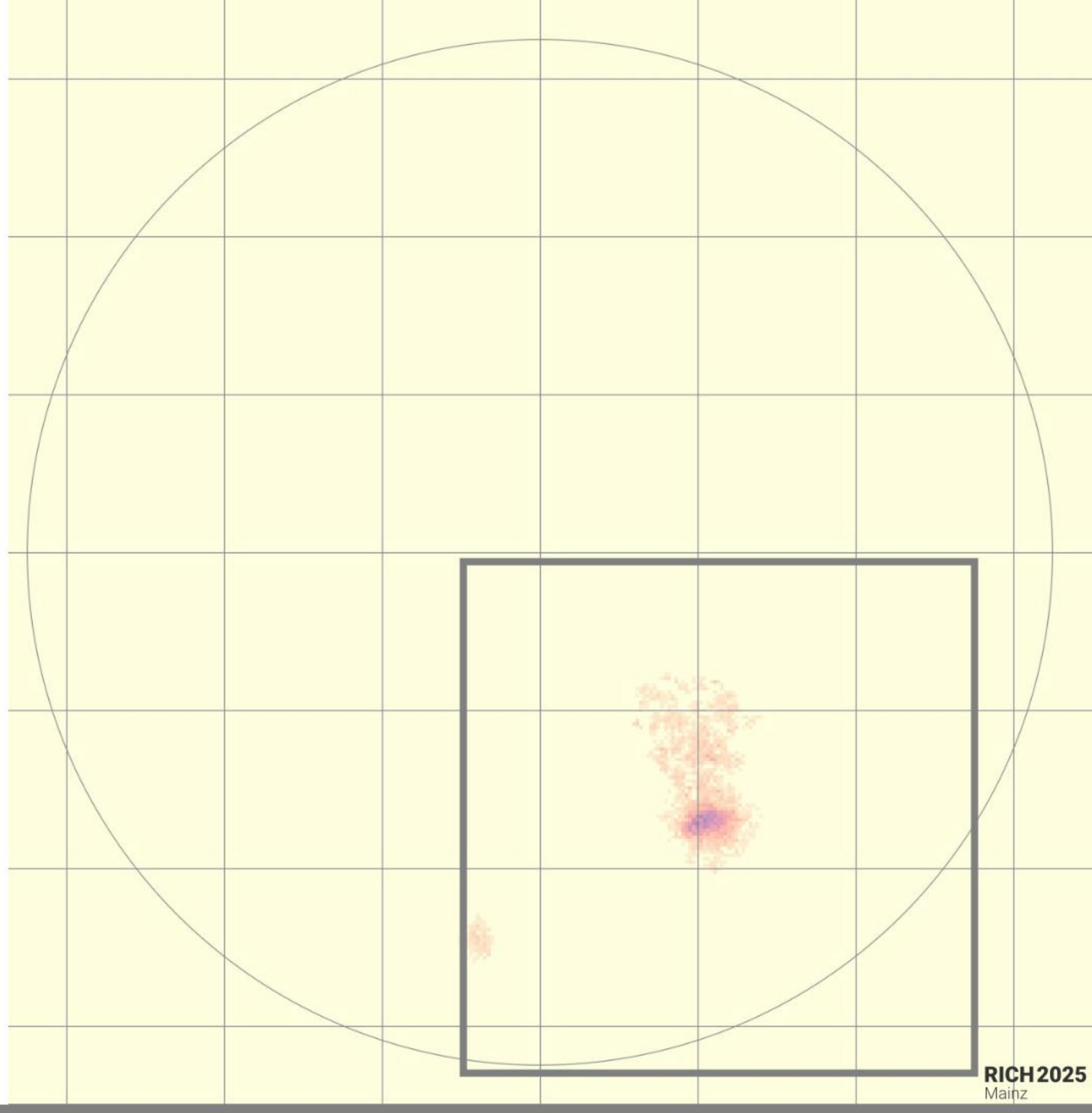
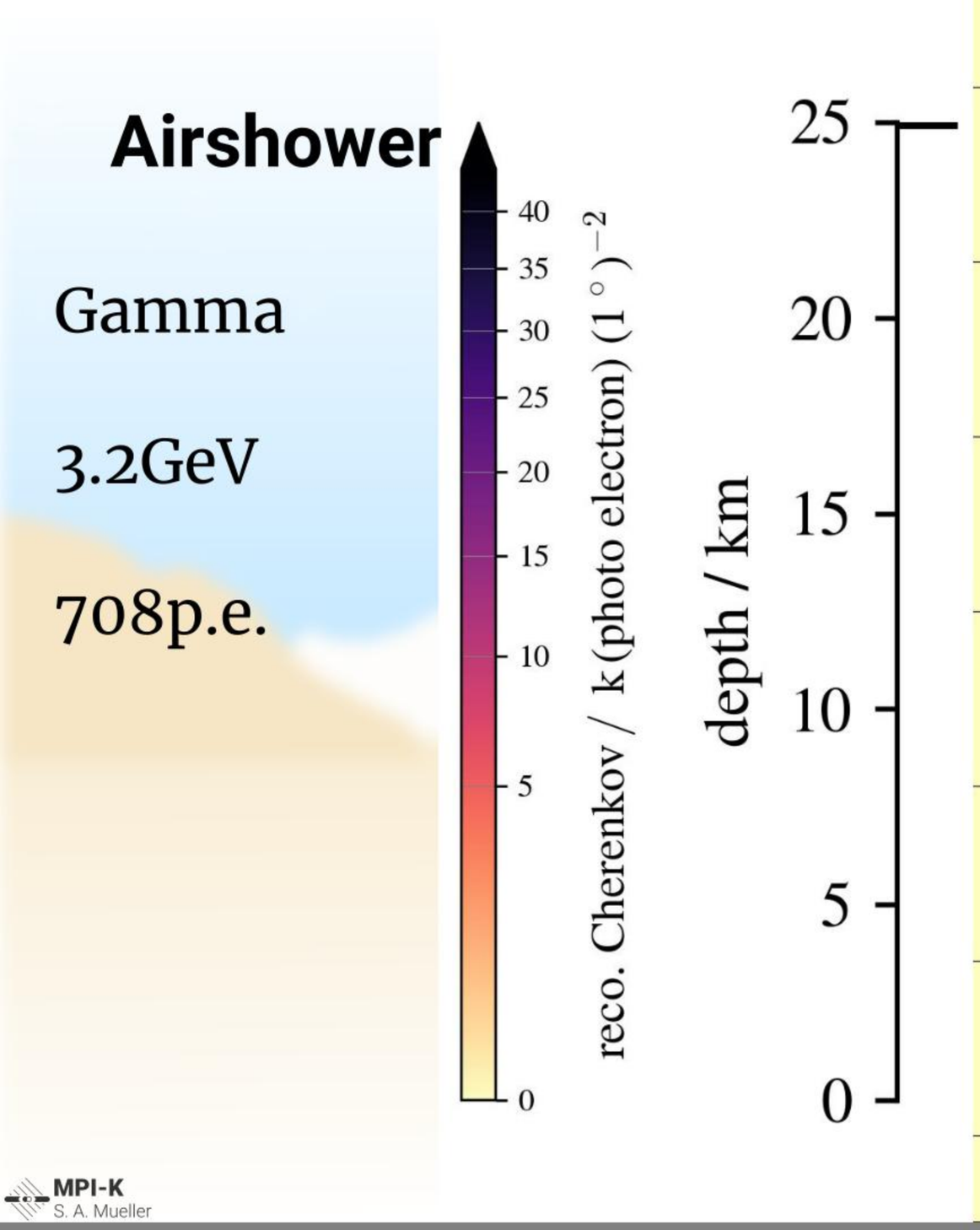
36,518p.e.

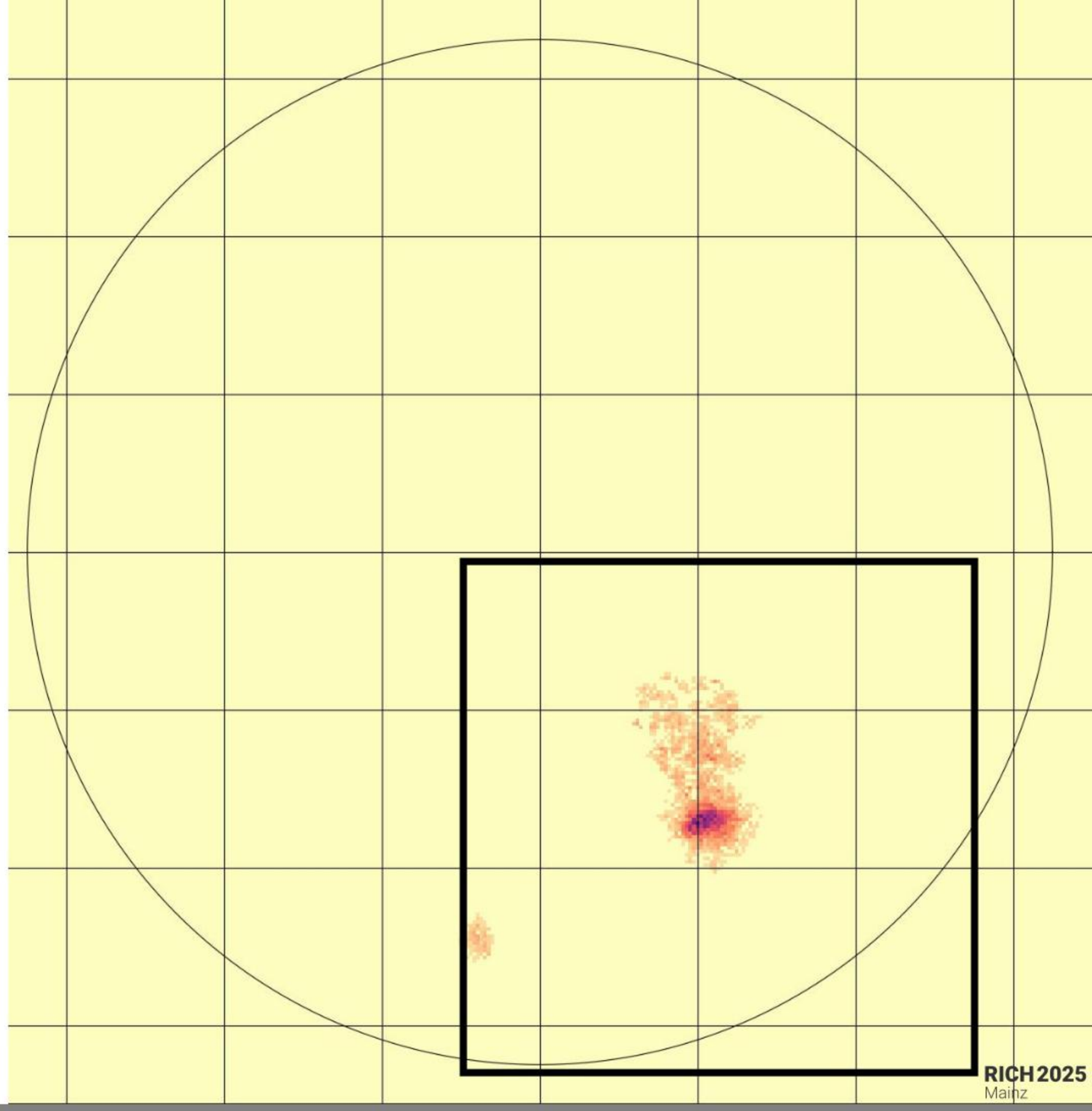






And at the low energy frontier





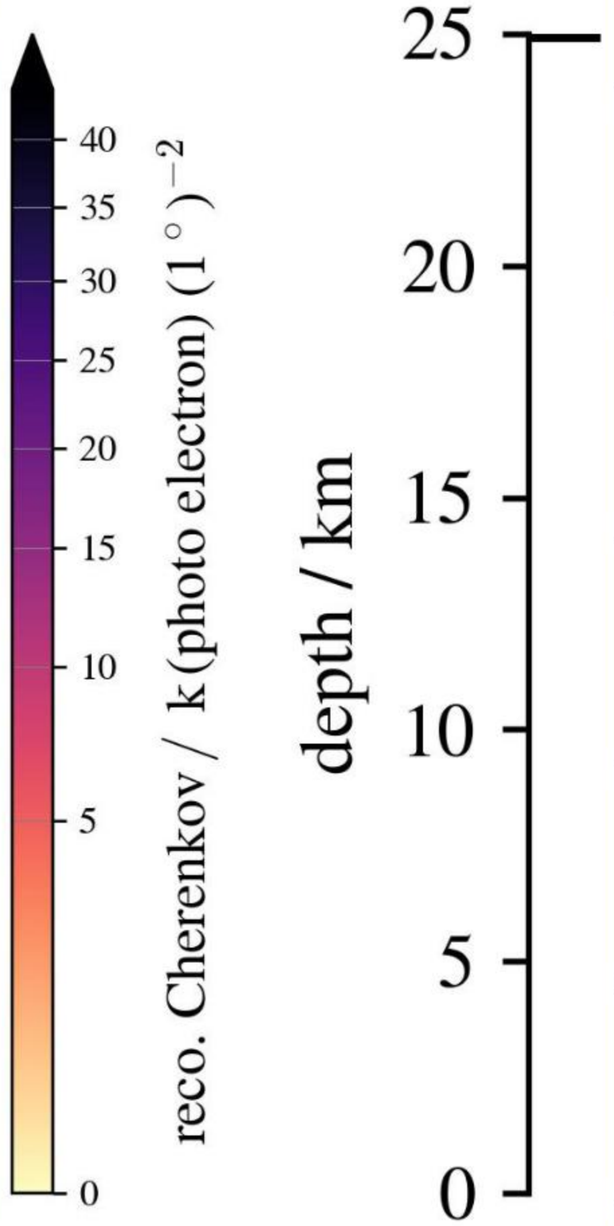
the race to extract better features has just begun.

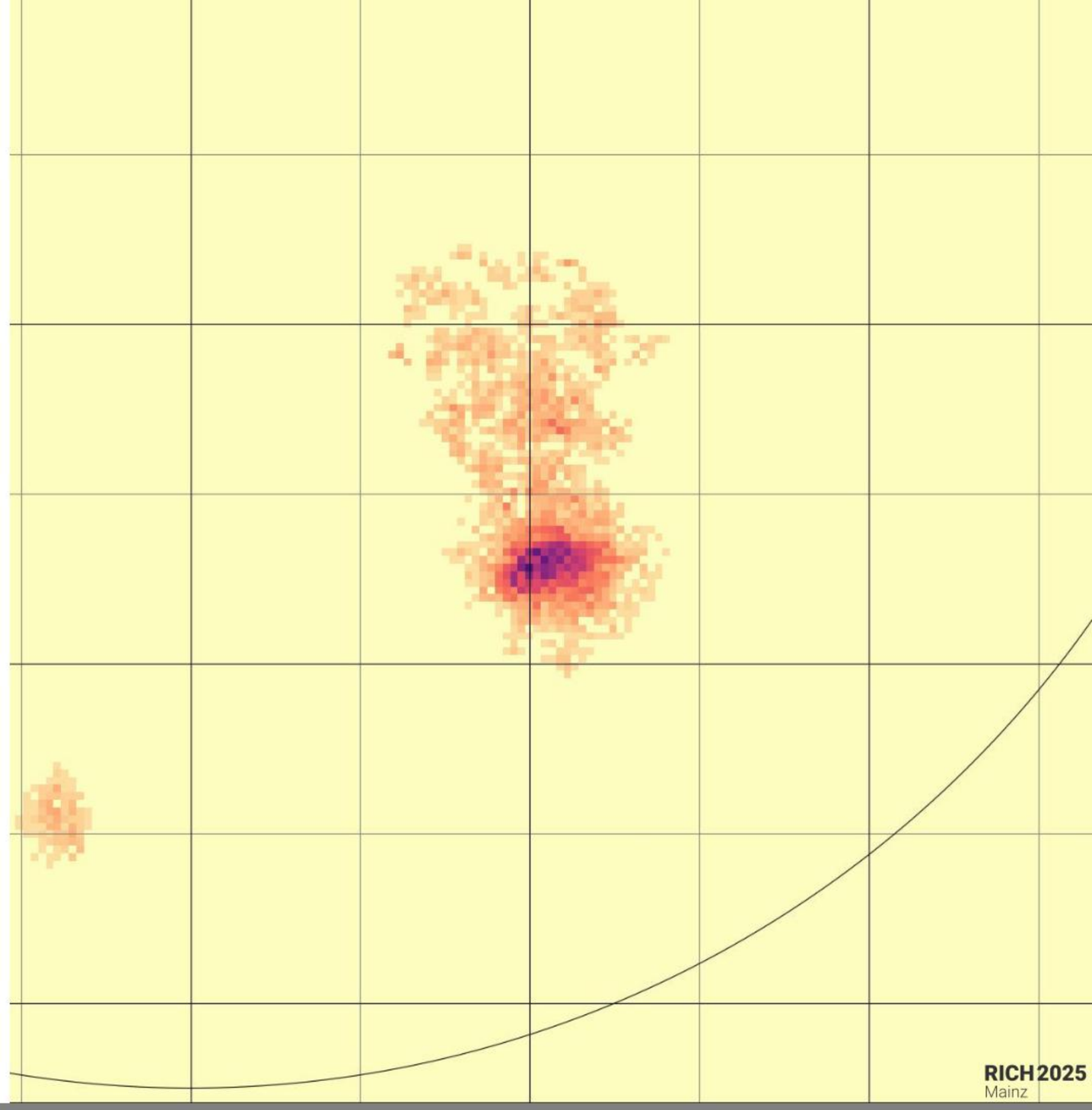
Airshower

Gamma

3.2GeV

708p.e.



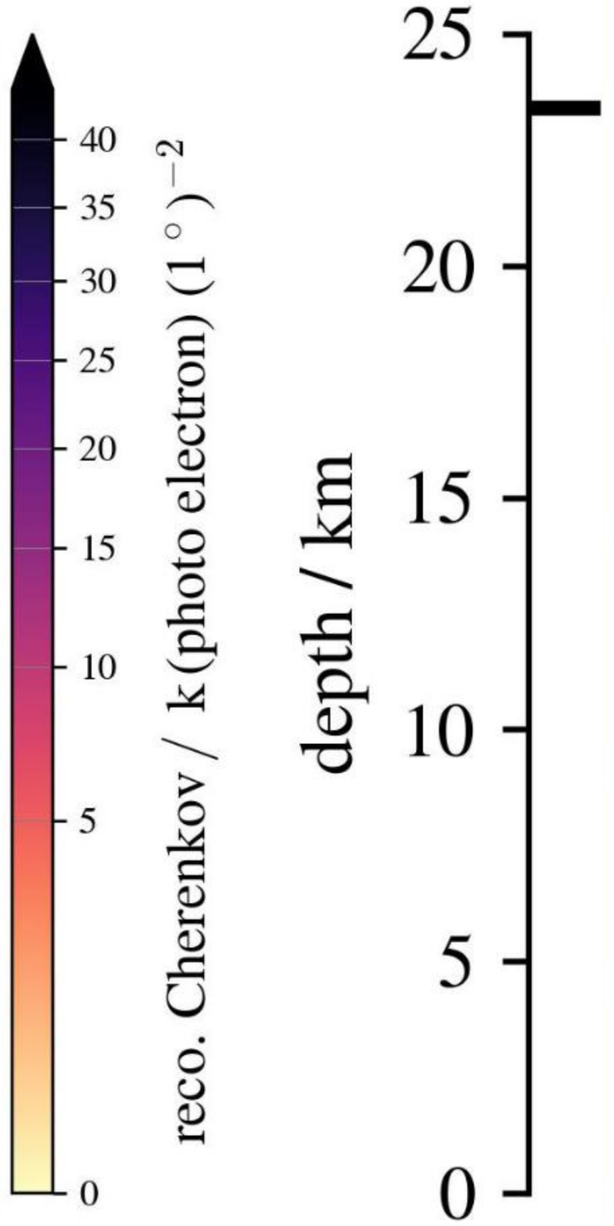


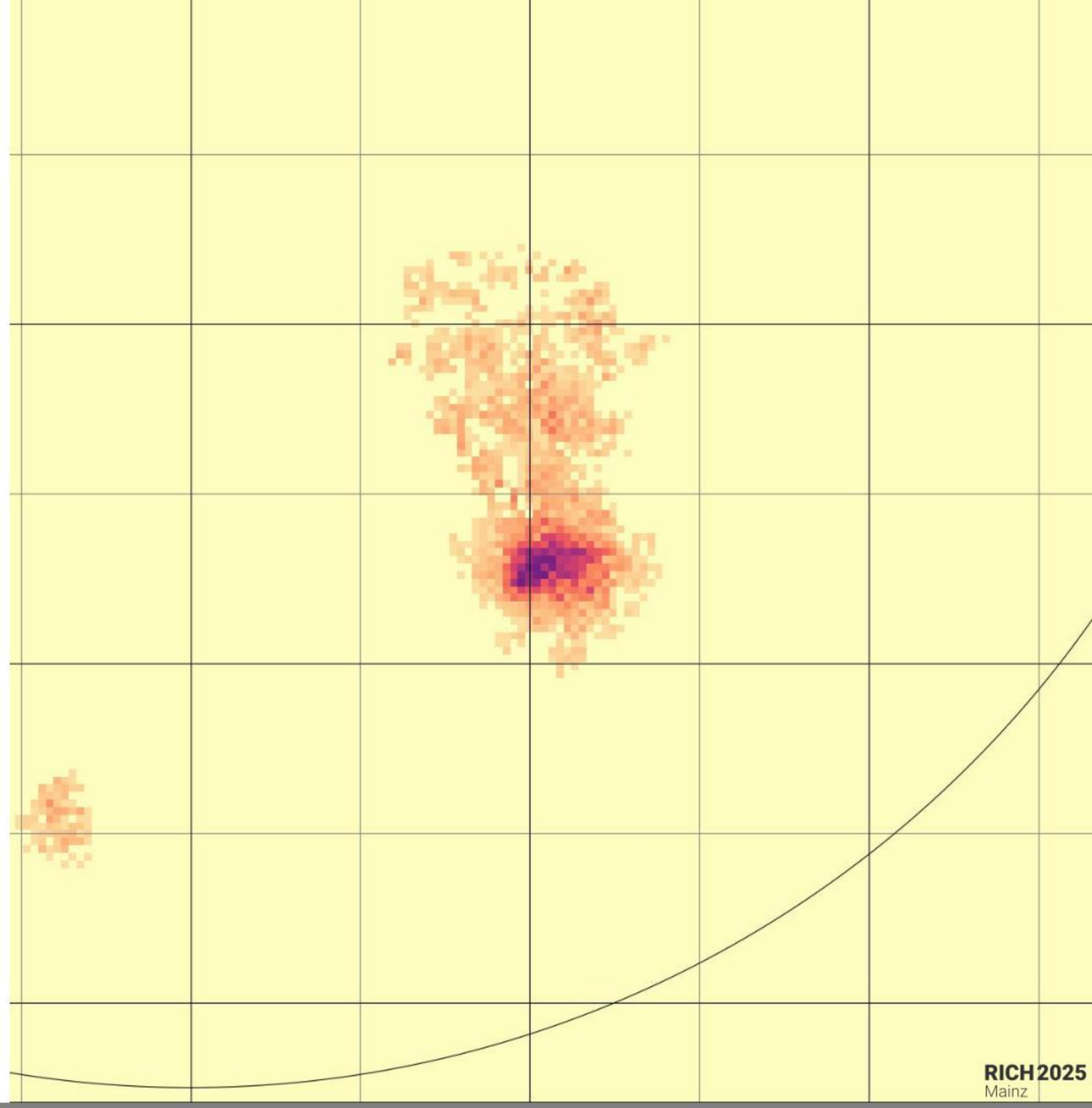
Airshower

Gamma

3.2GeV

708p.e.



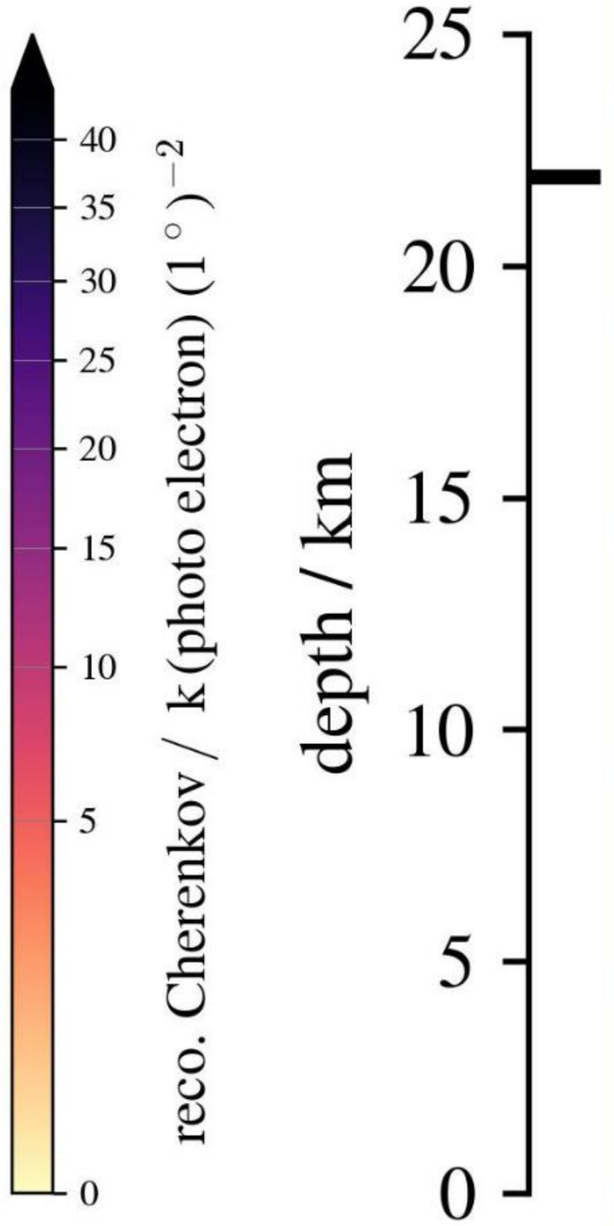


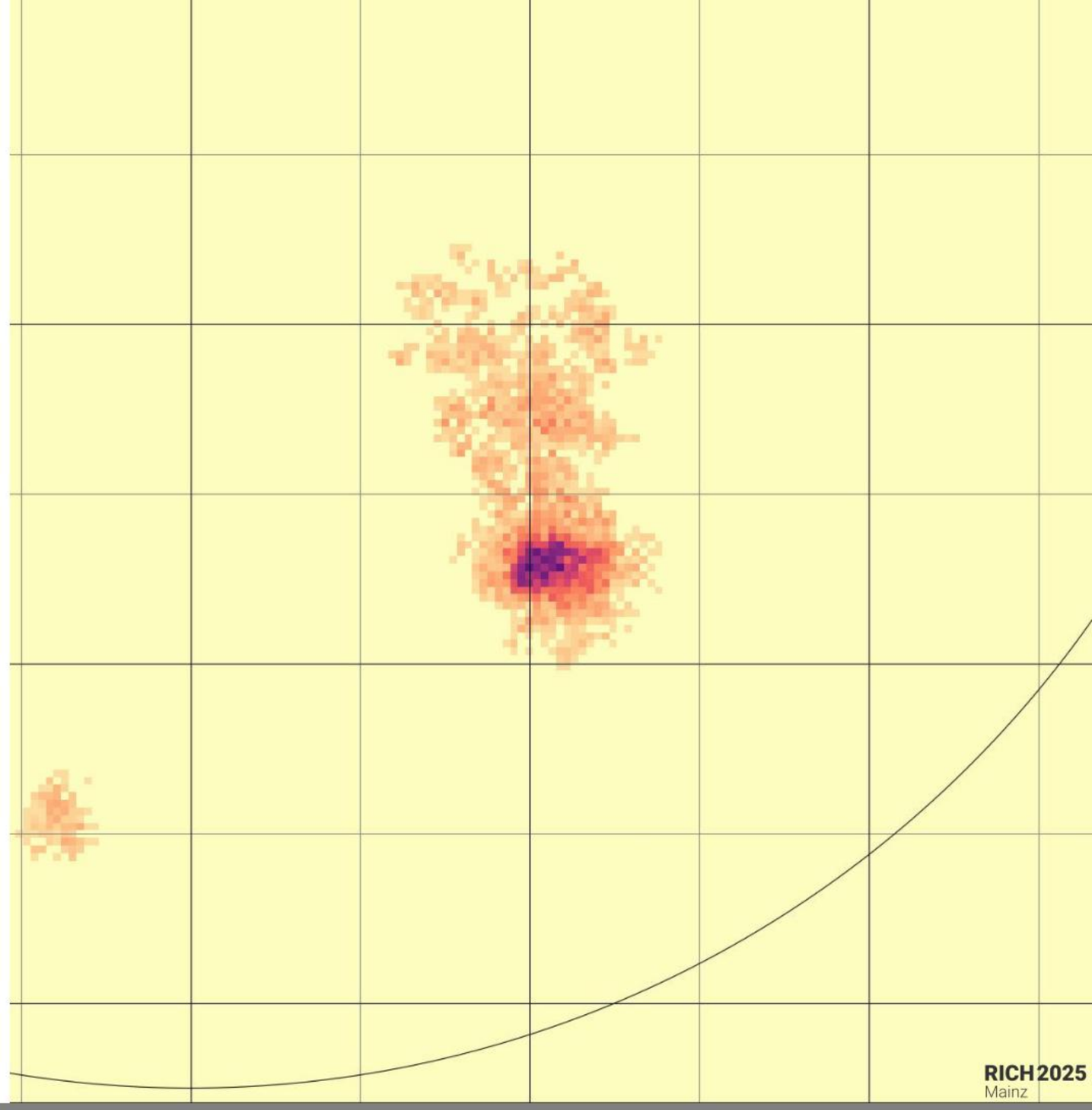
Airshower

Gamma

3.2GeV

708p.e.



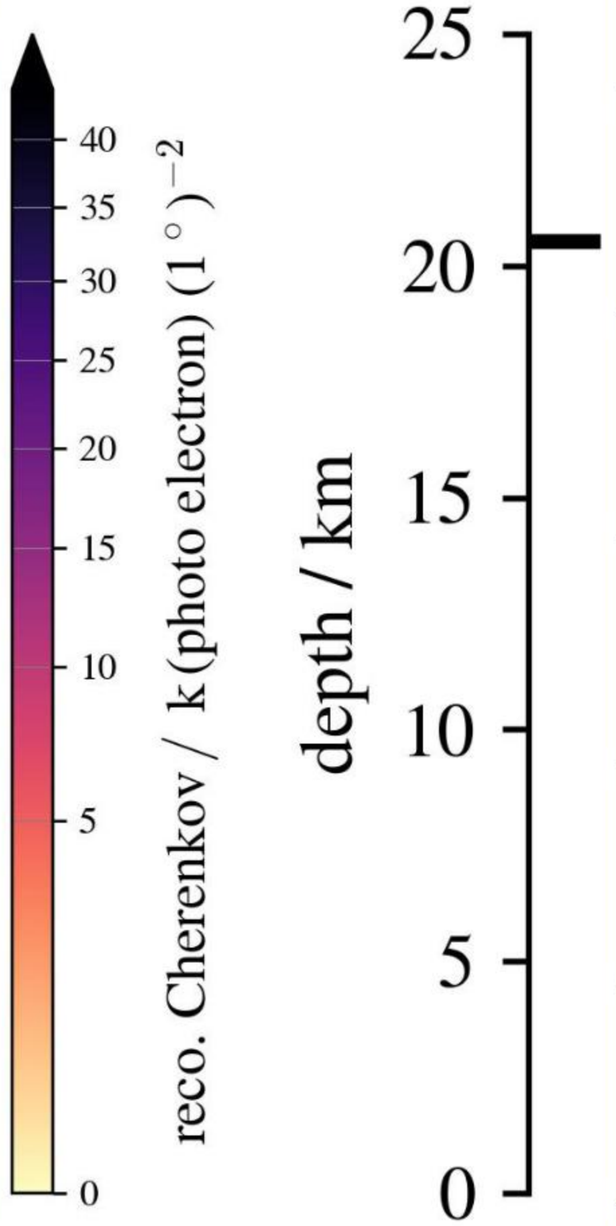


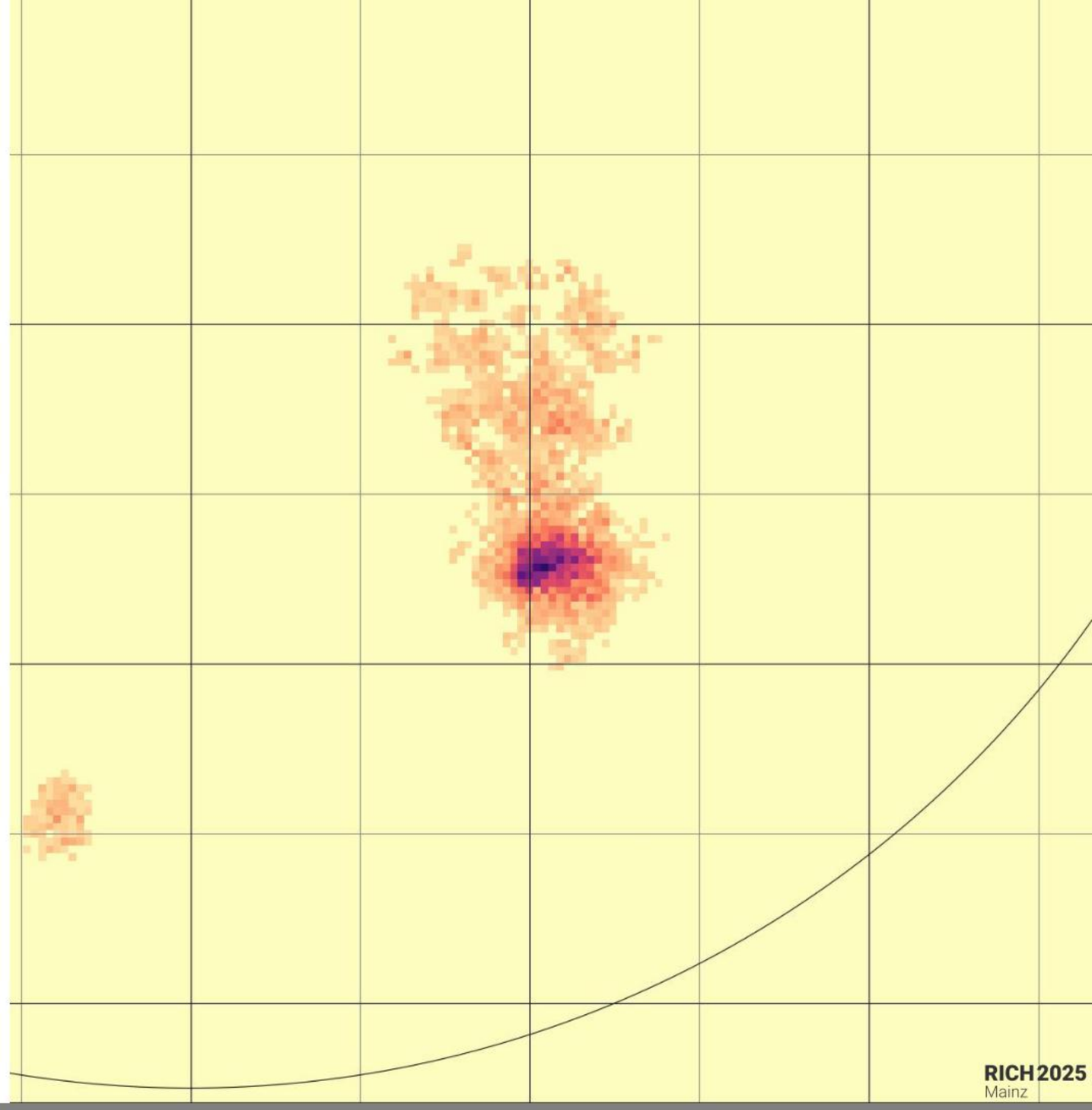
Airshower

Gamma

3.2GeV

708p.e.



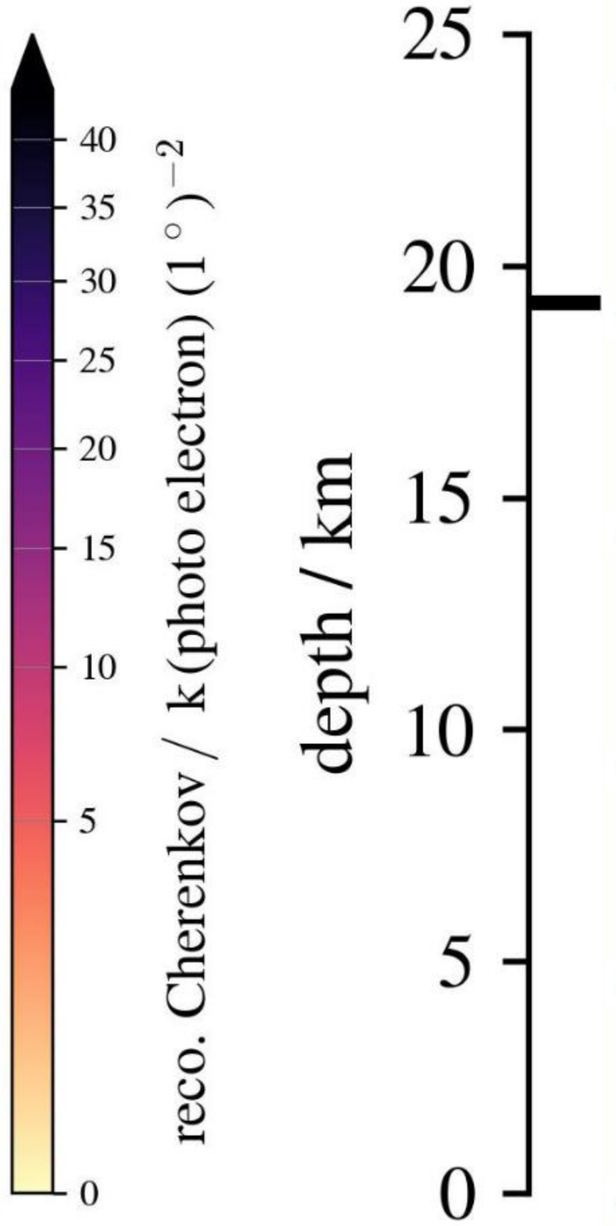


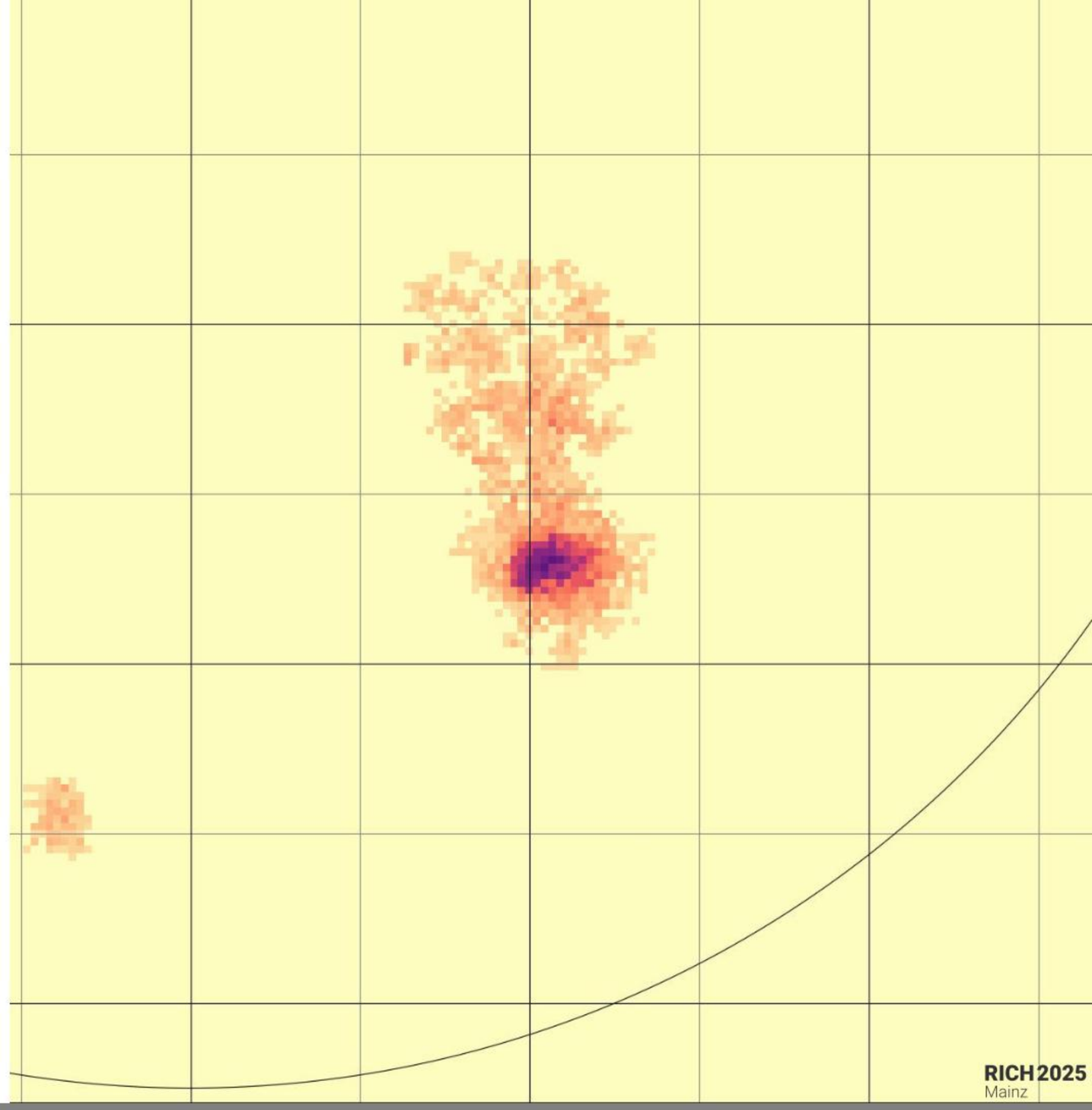
Airshower

Gamma

3.2GeV

708p.e.



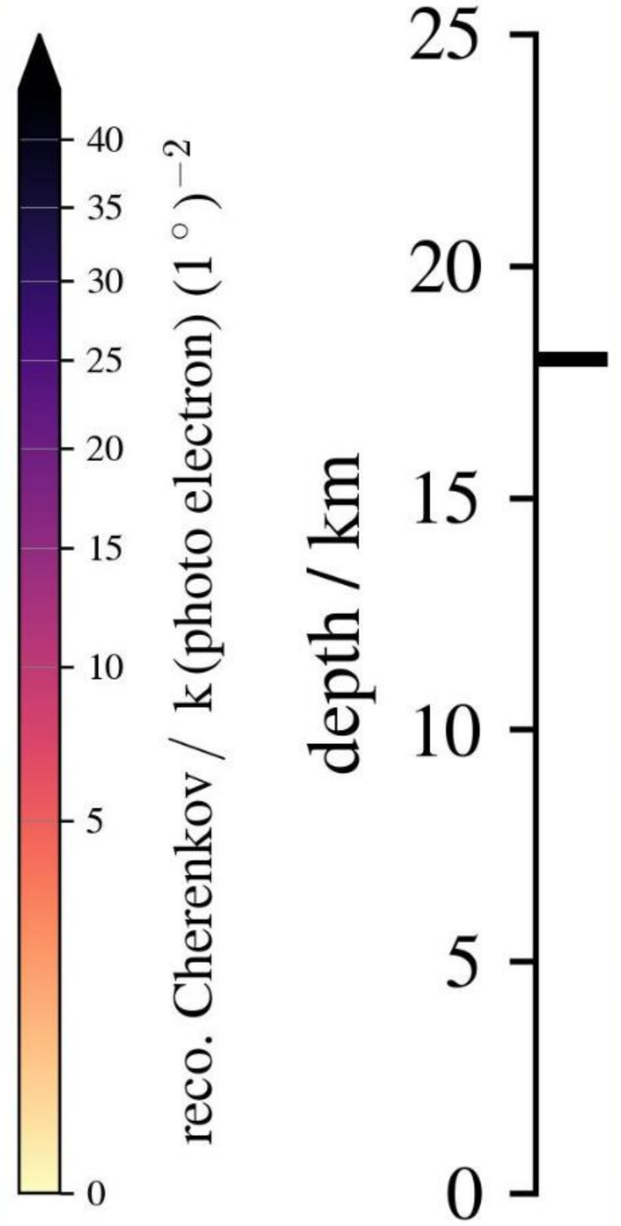


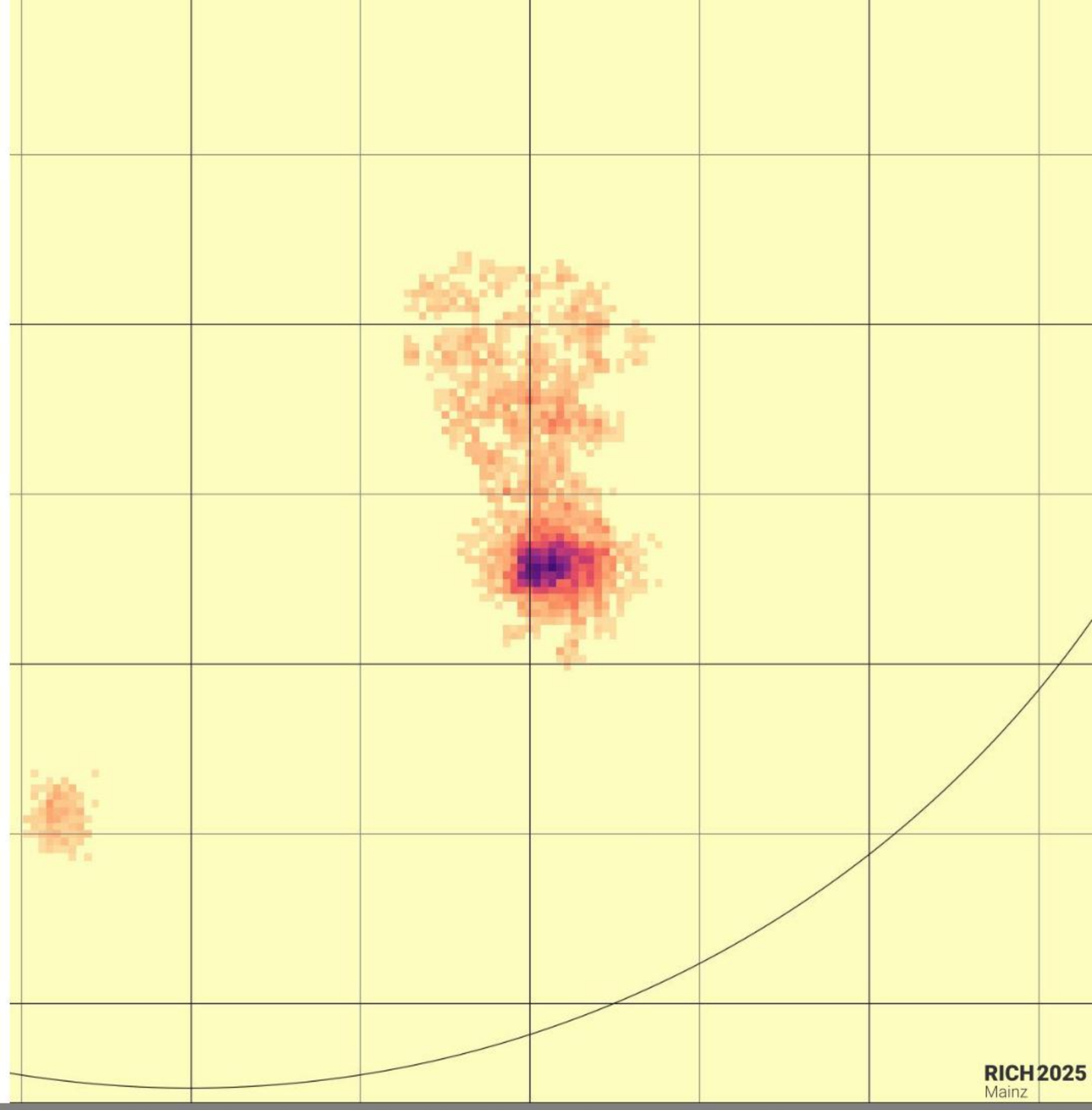
Airshower

Gamma

3.2GeV

708p.e.



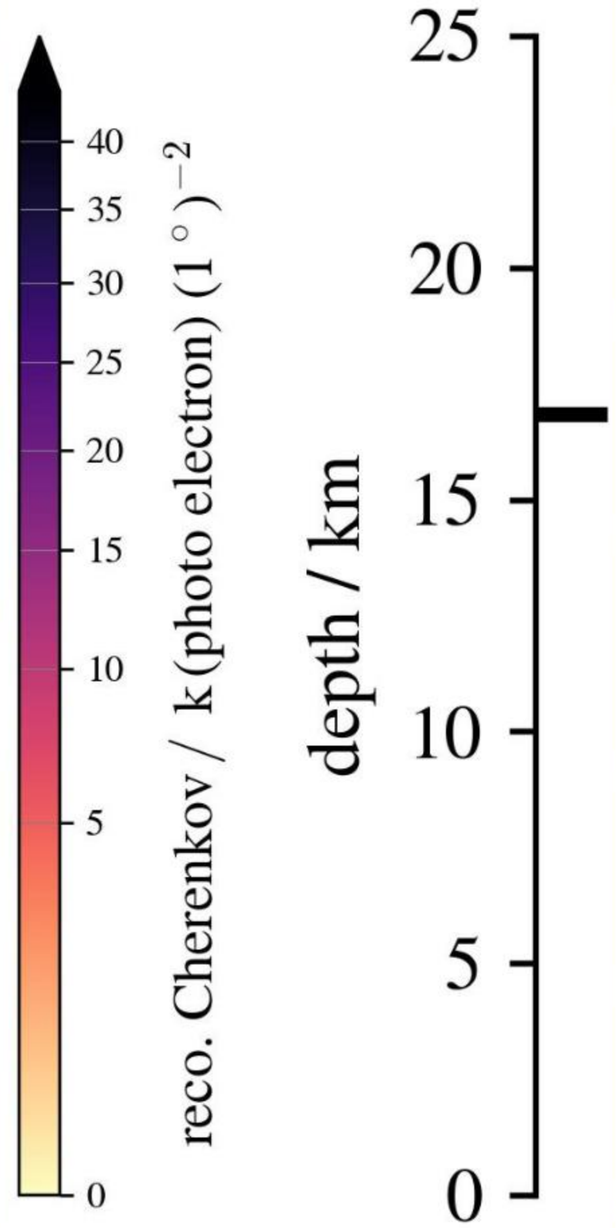


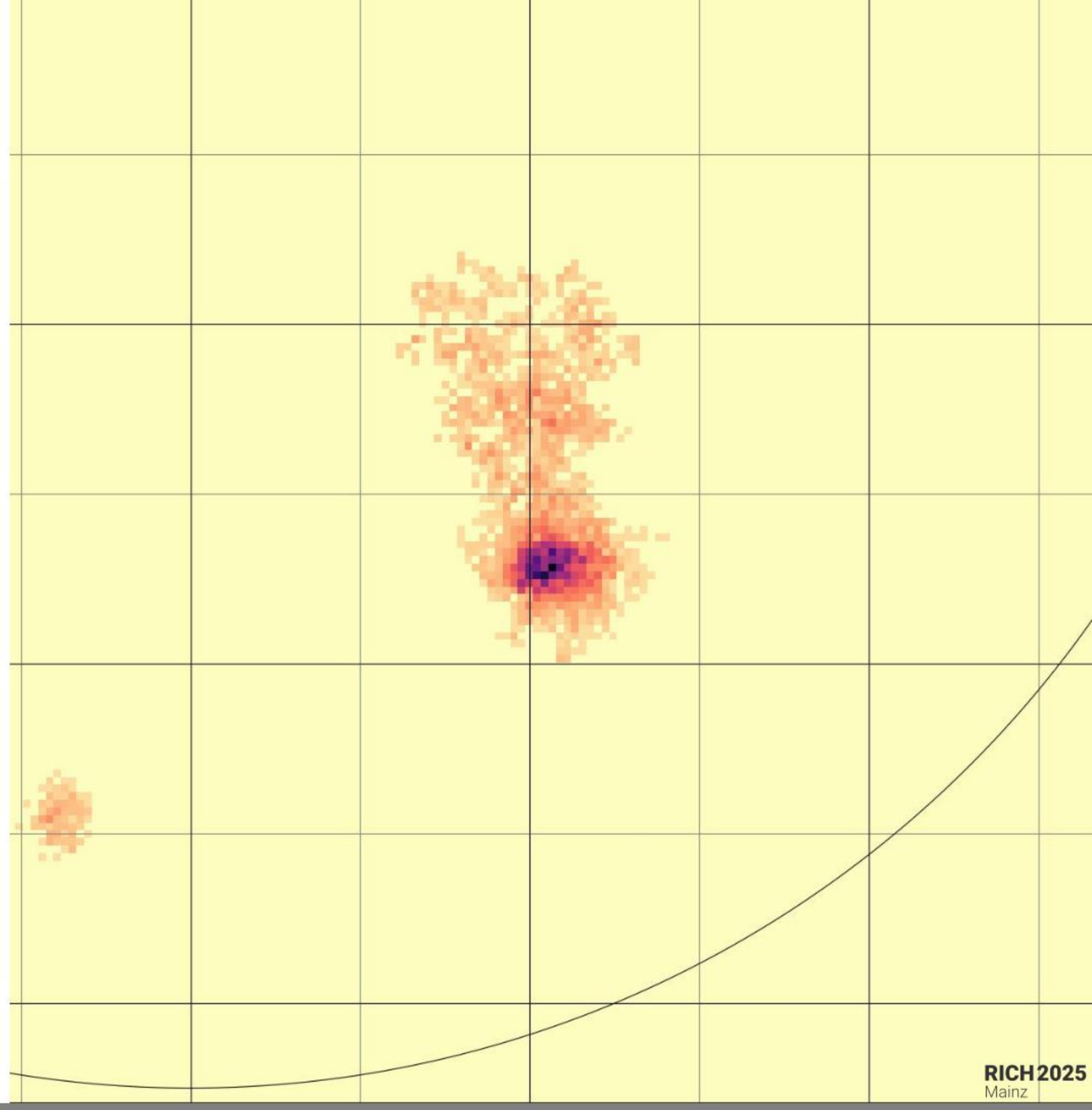
Airshower

Gamma

3.2GeV

708p.e.



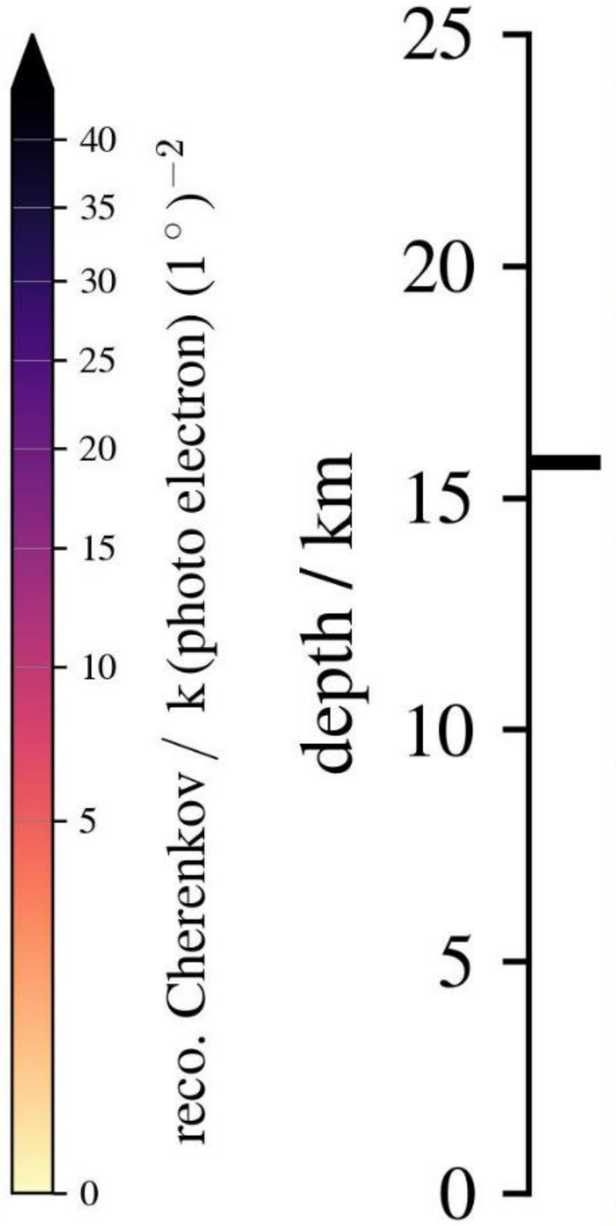


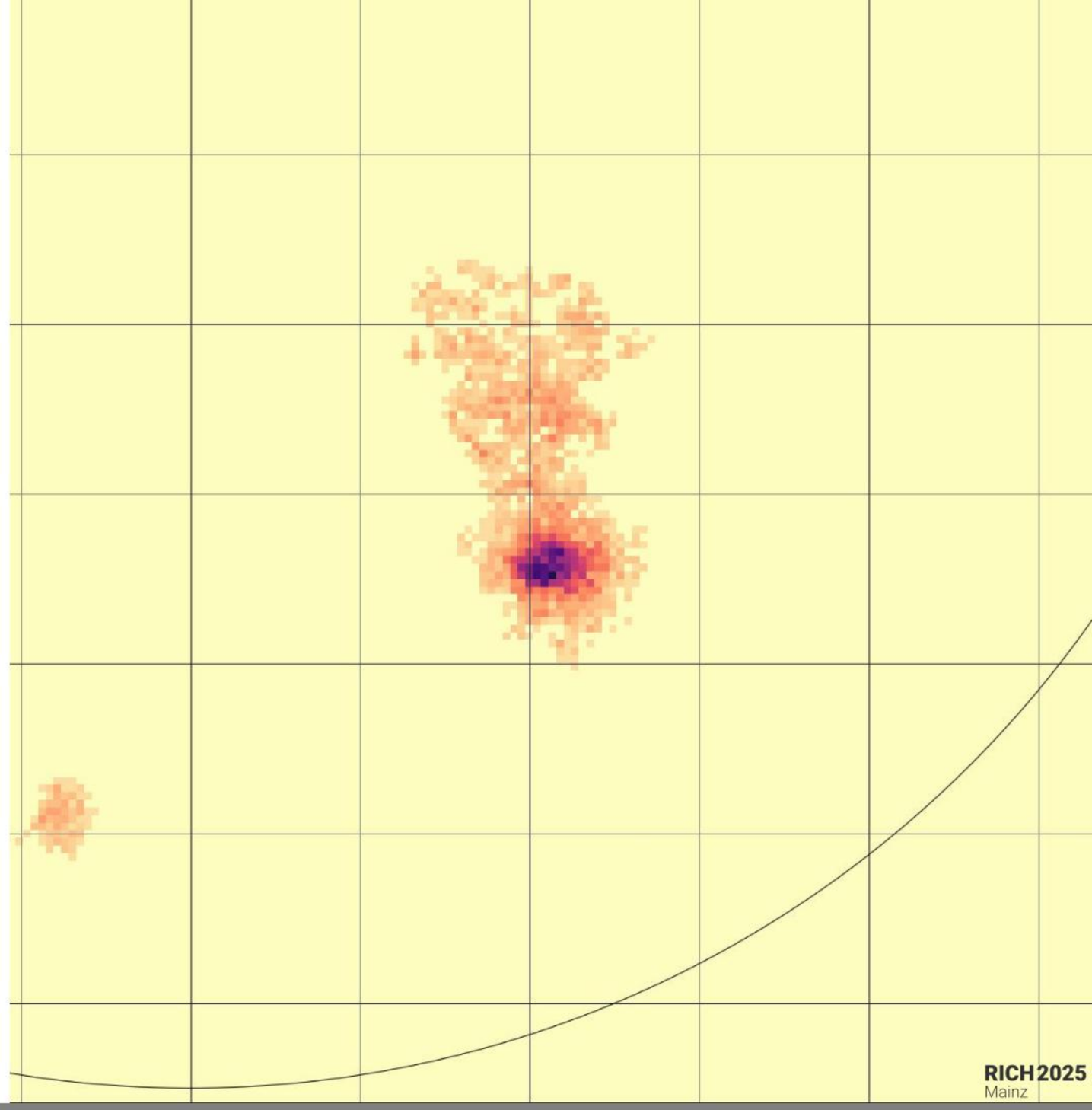
Airshower

Gamma

3.2GeV

708p.e.



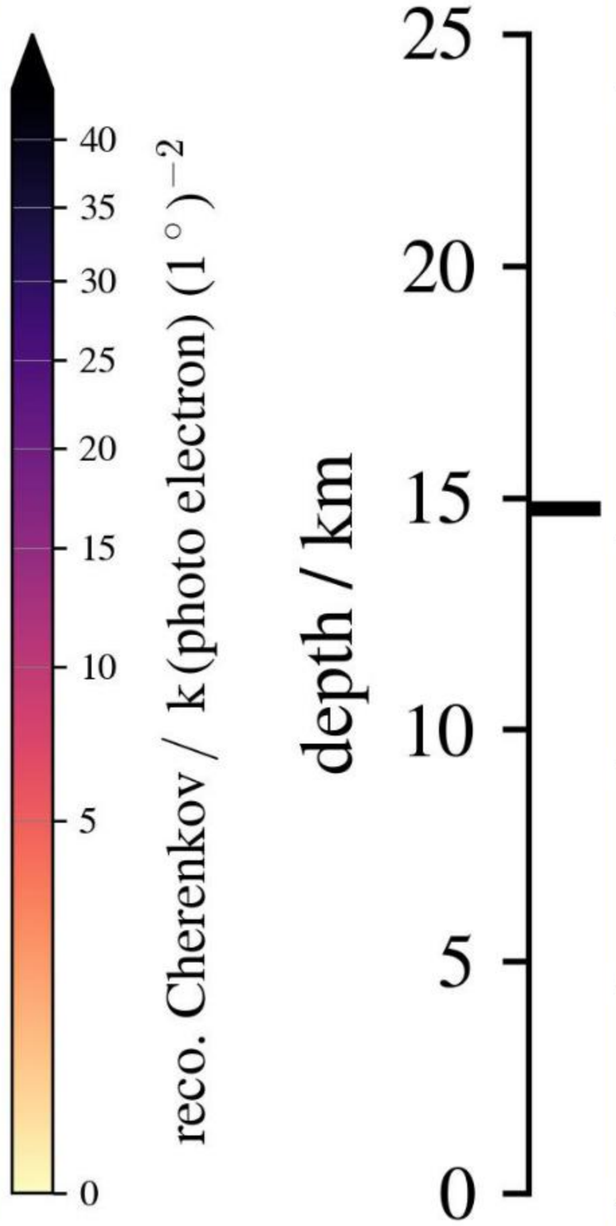


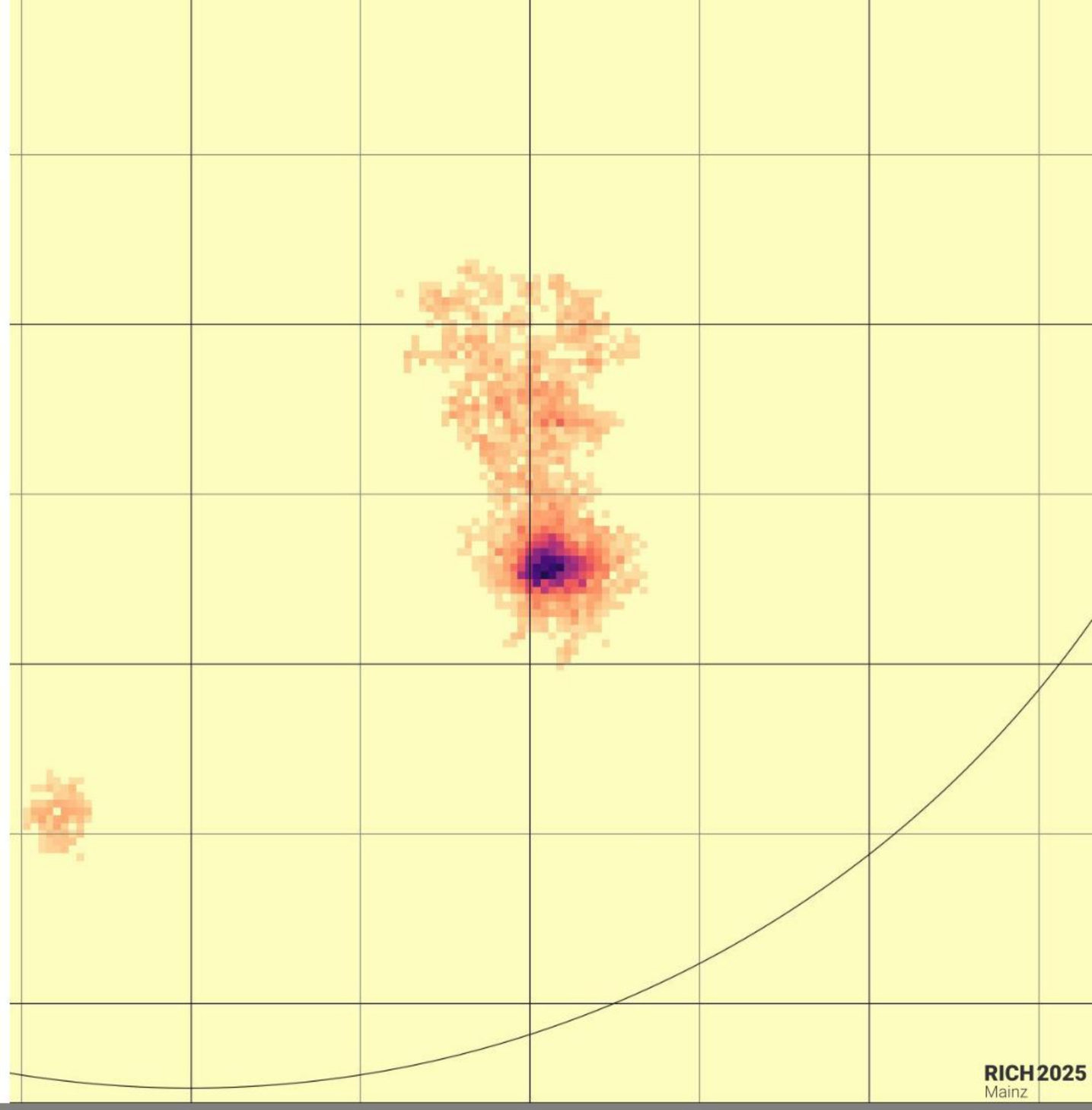
Airshower

Gamma

3.2GeV

708p.e.



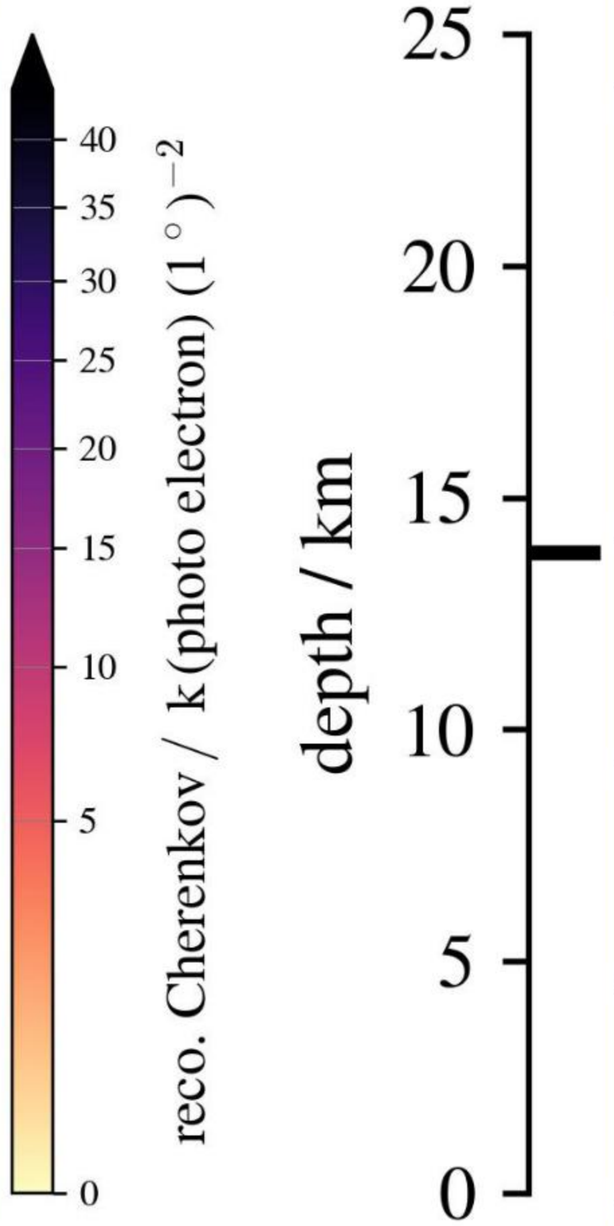


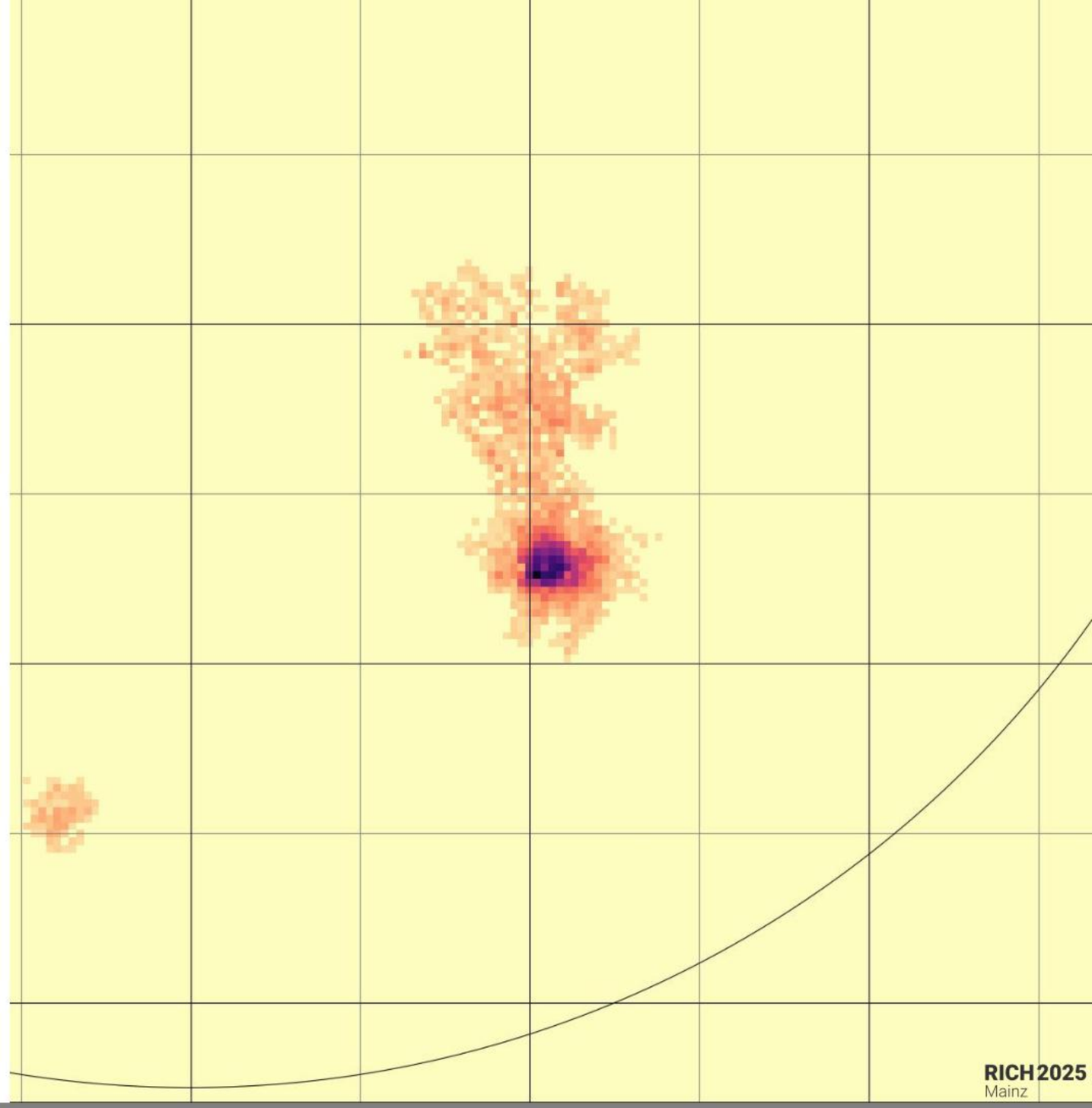
Airshower

Gamma

3.2GeV

708p.e.



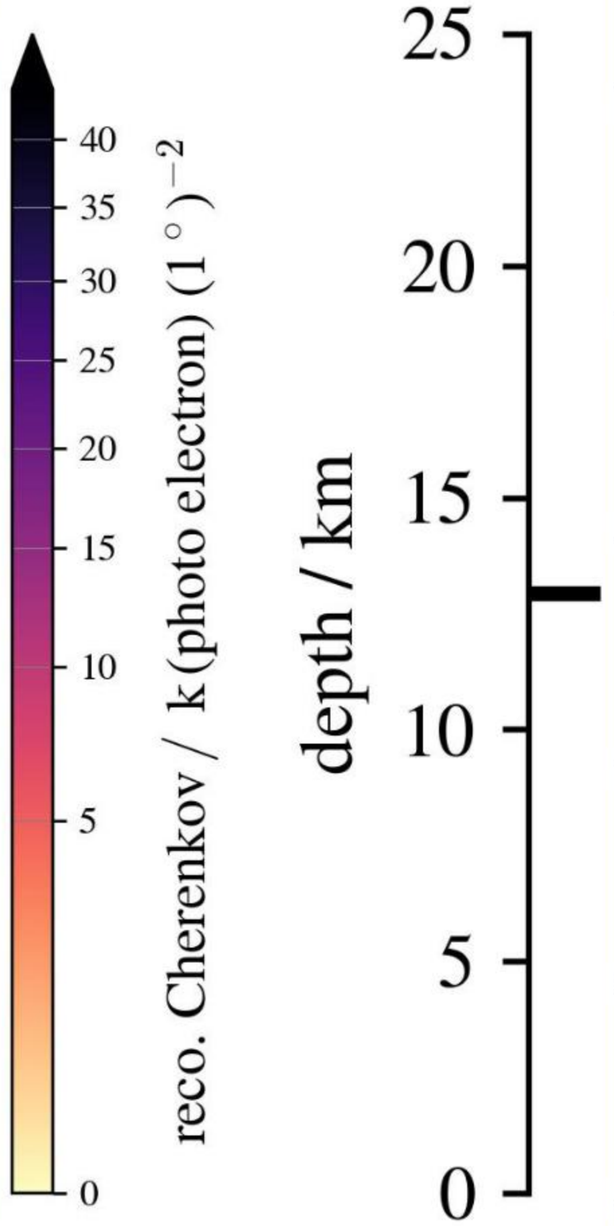


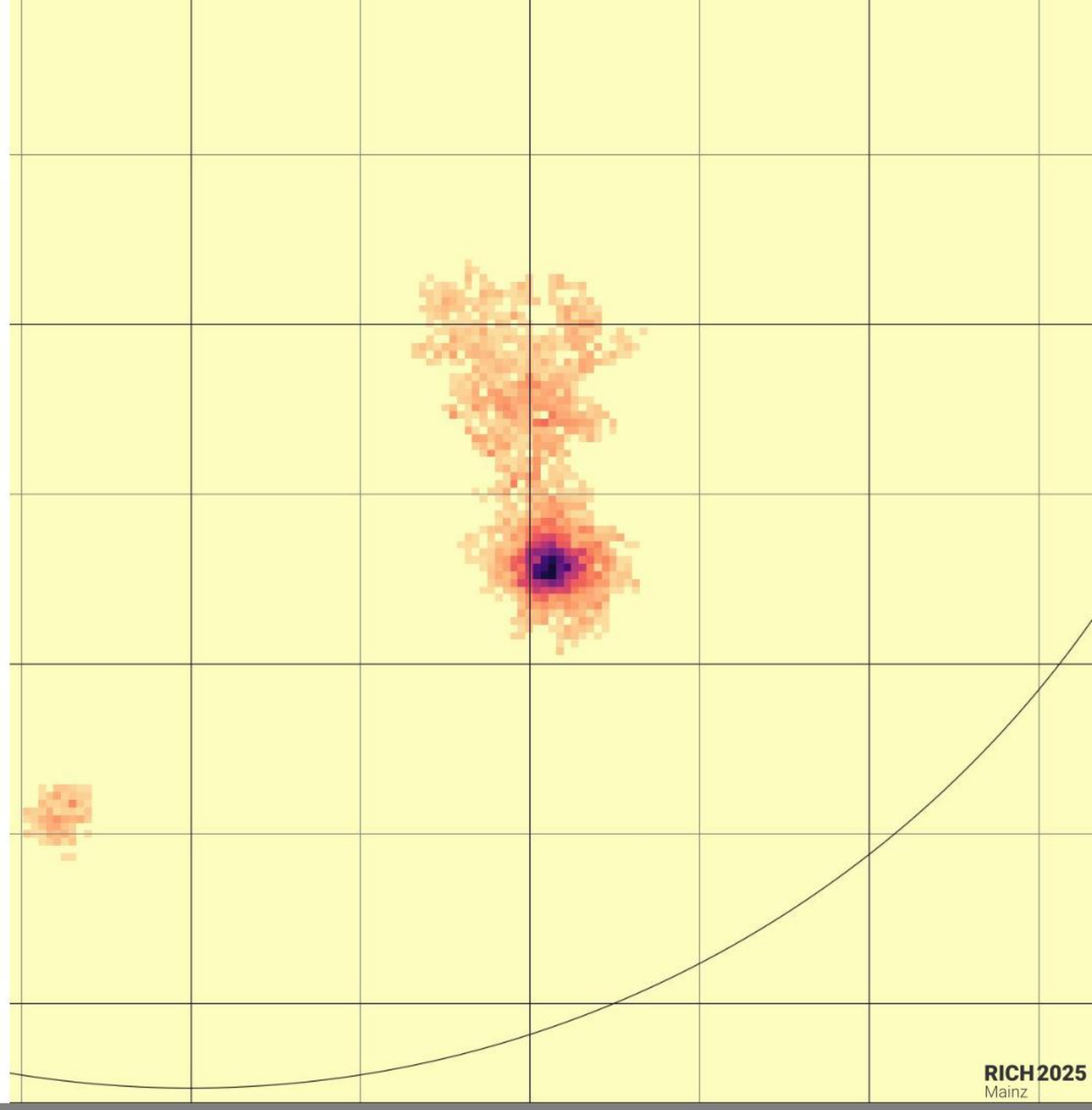
Airshower

Gamma

3.2GeV

708p.e.



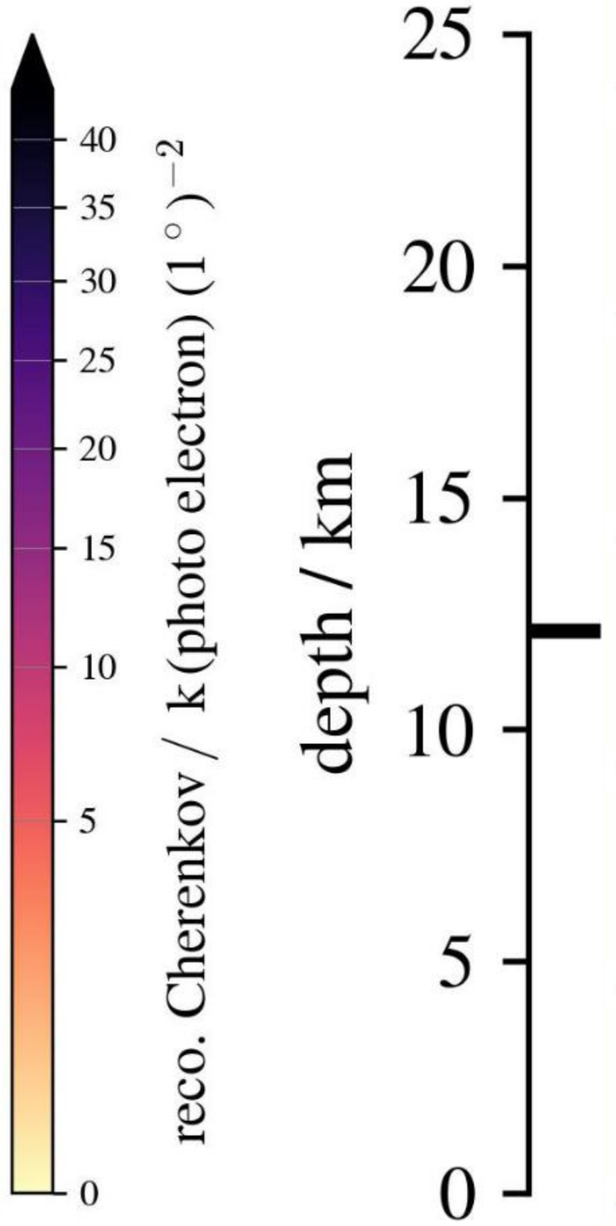


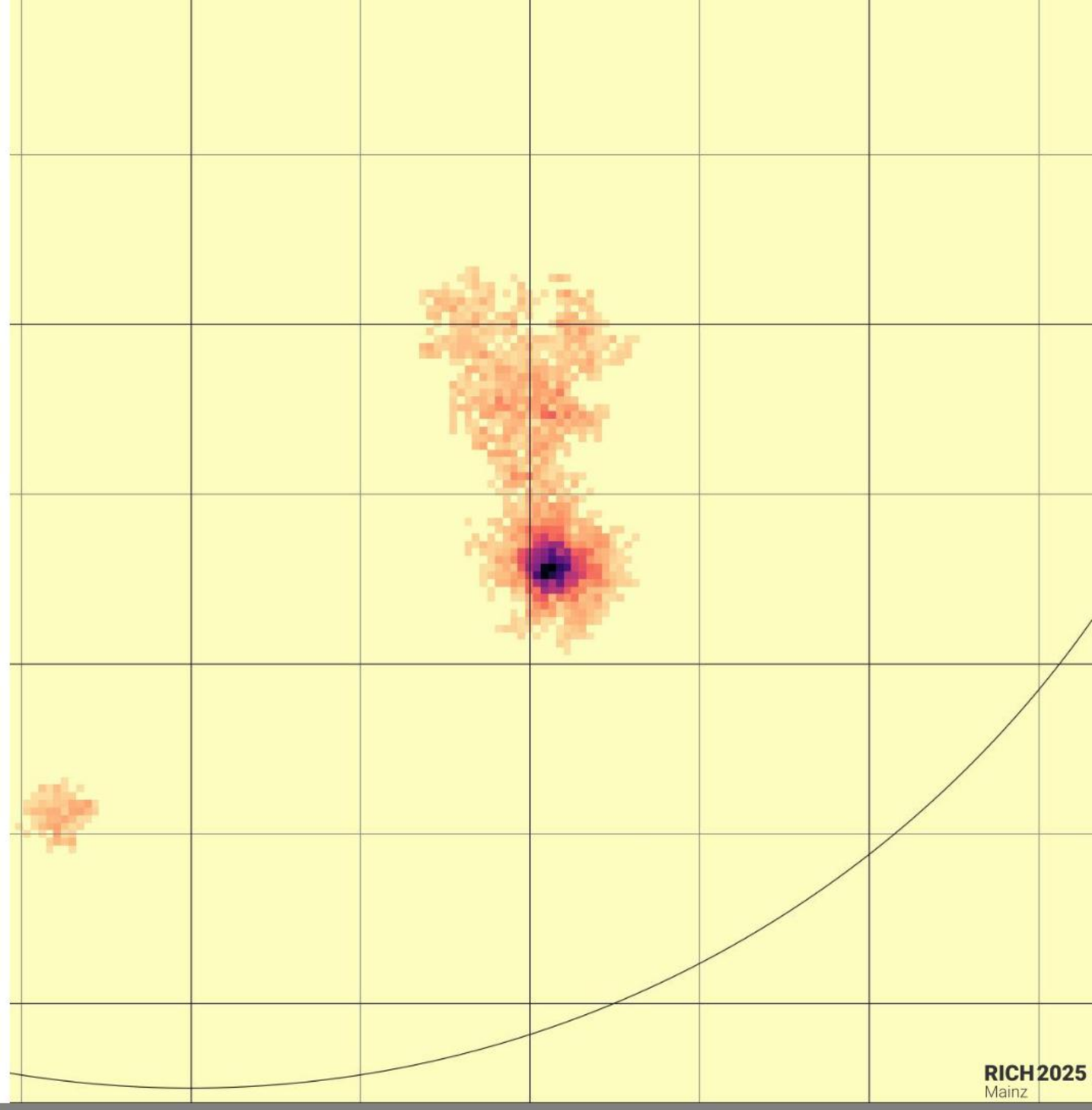
Airshower

Gamma

3.2GeV

708p.e.



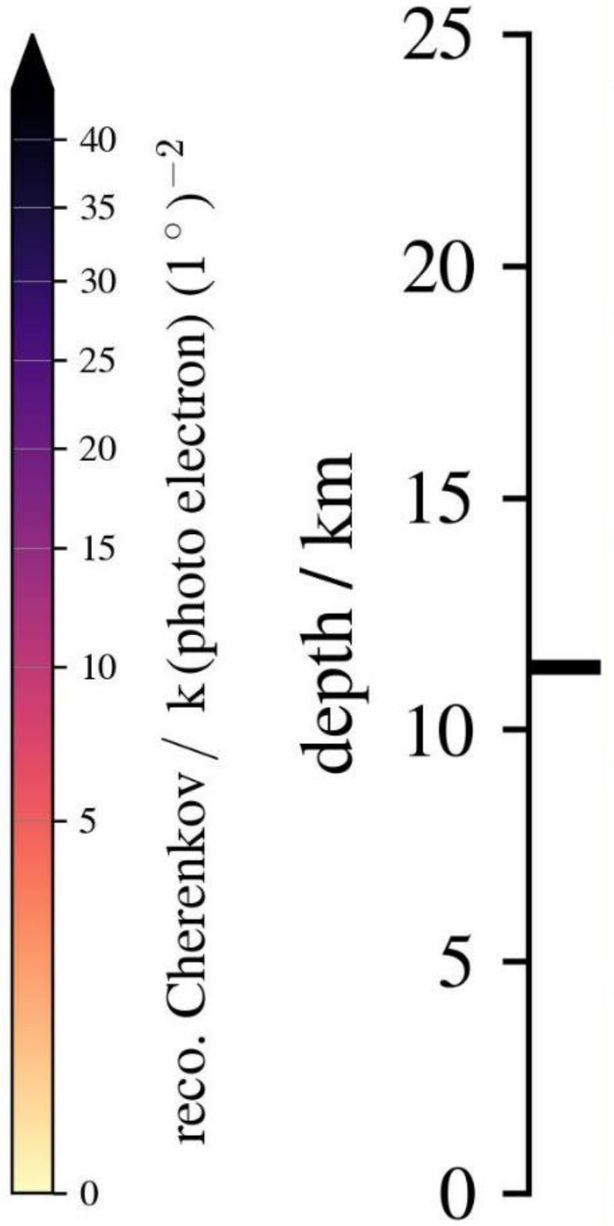


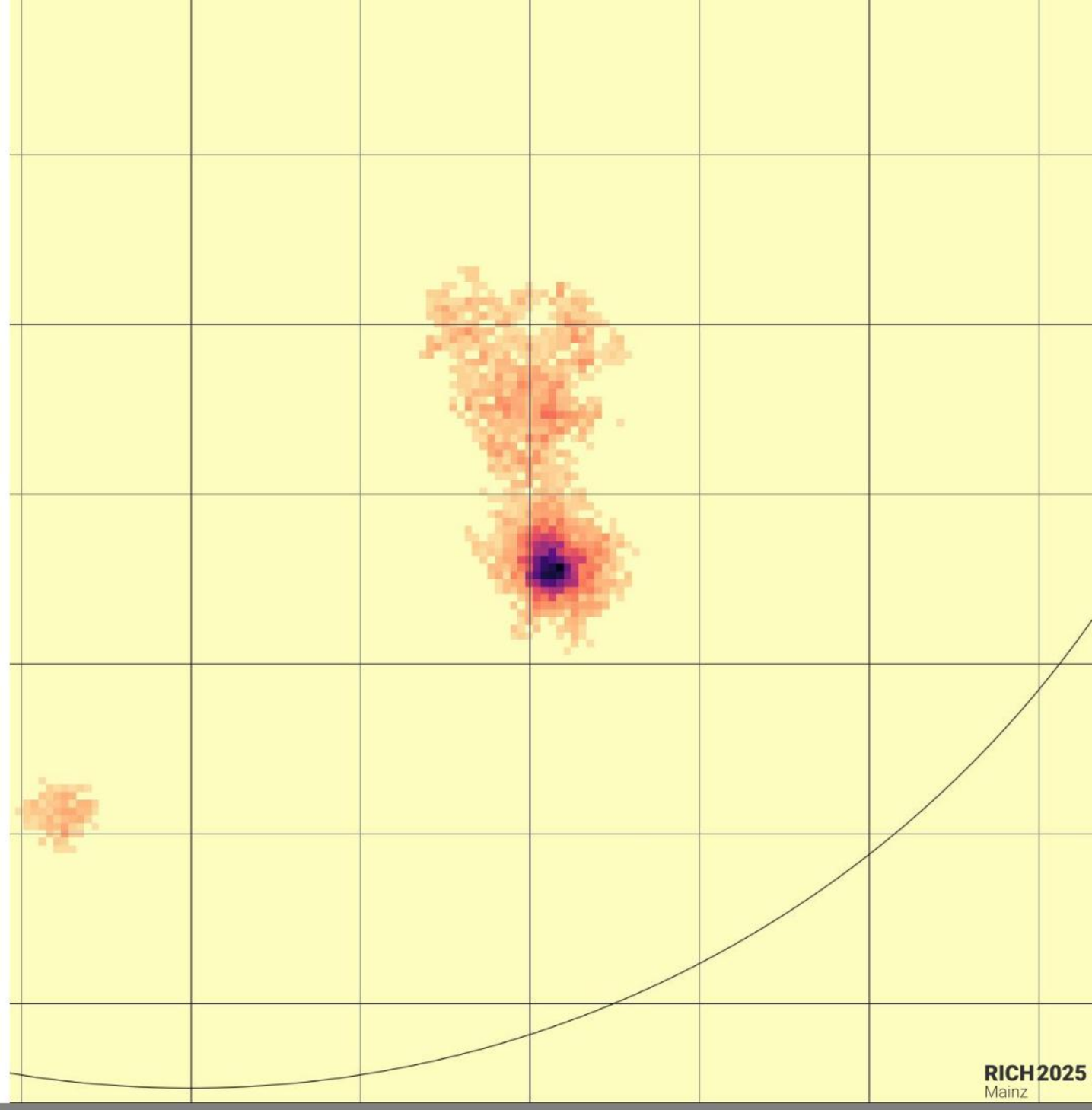
Airshower

Gamma

3.2GeV

708p.e.



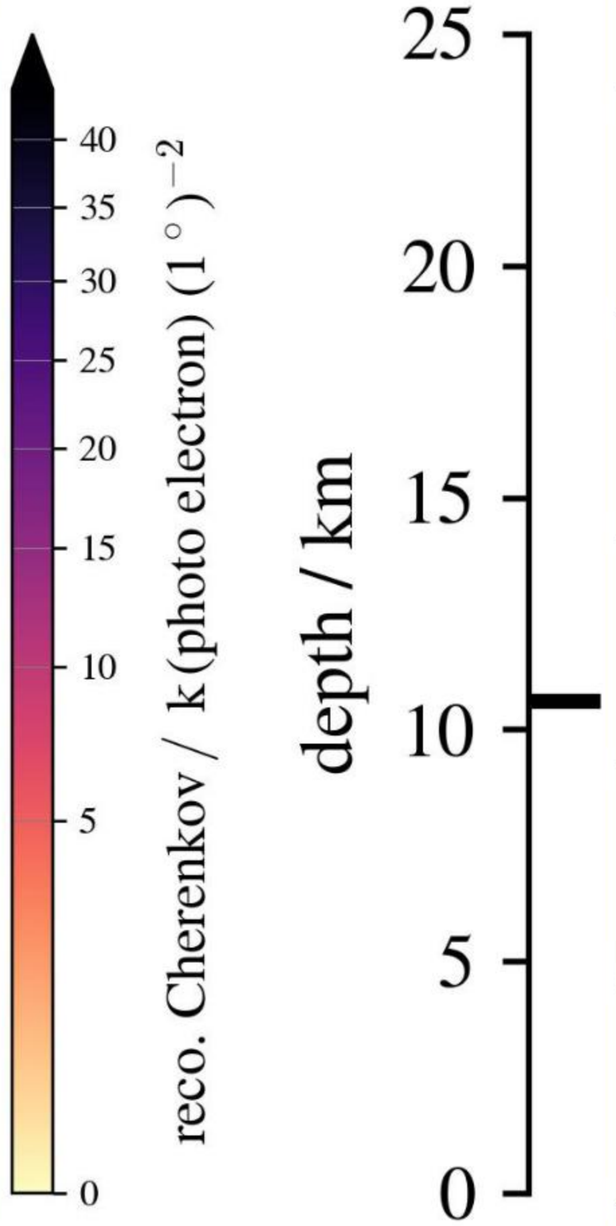


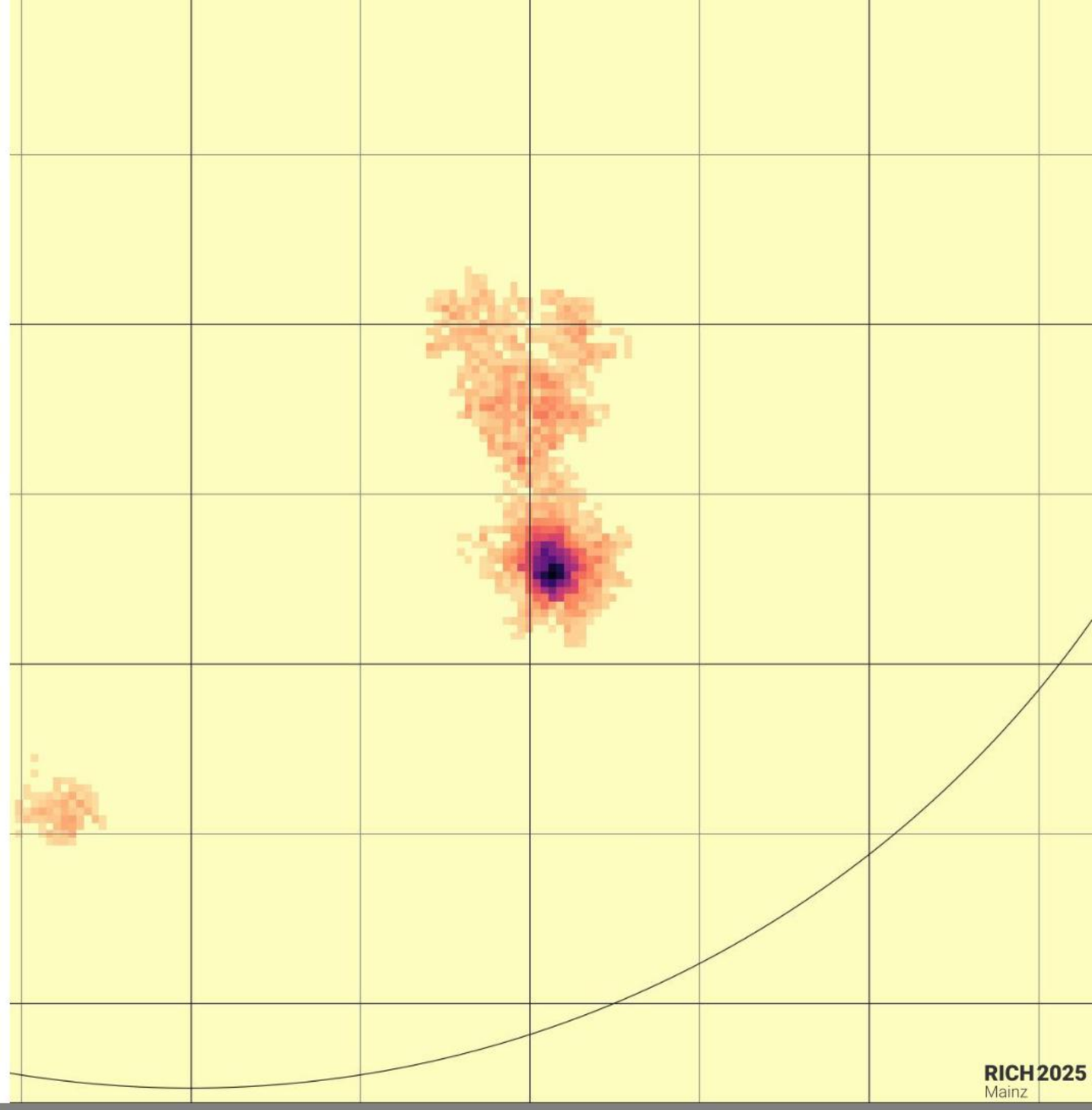
Airshower

Gamma

3.2GeV

708p.e.



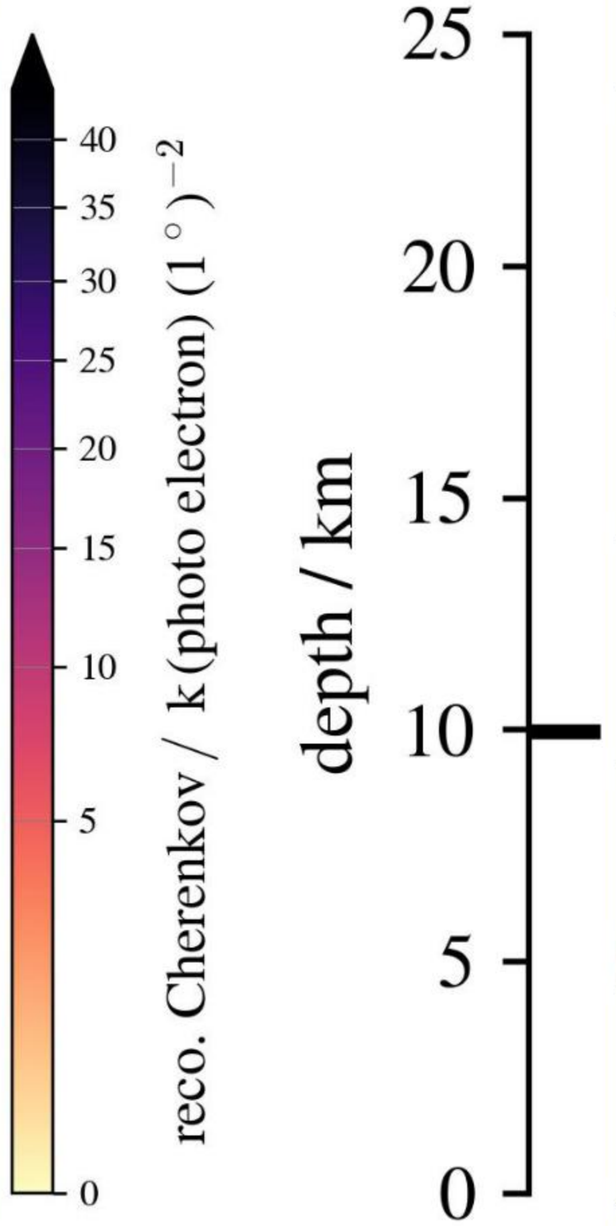


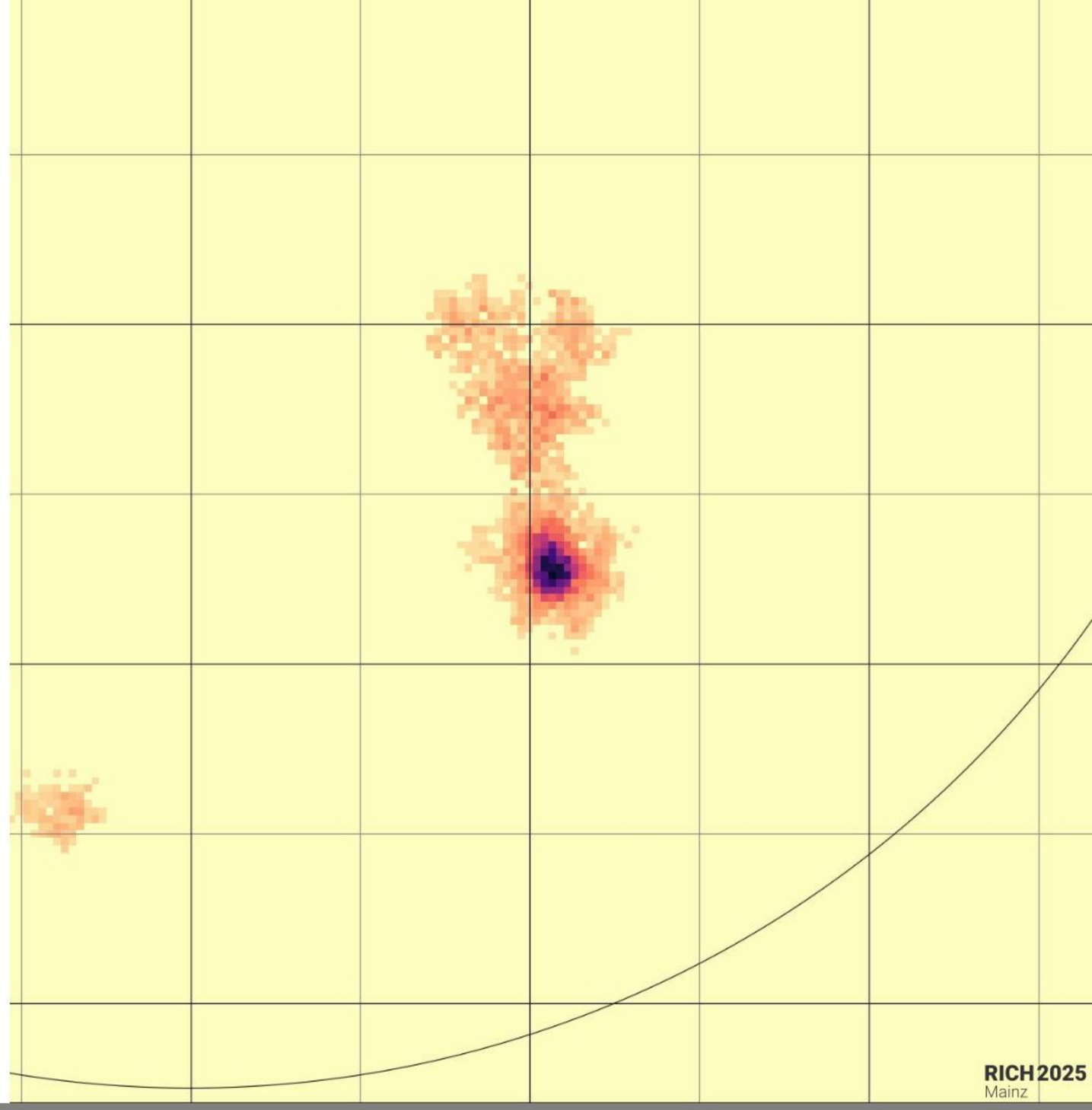
Airshower

Gamma

3.2GeV

708p.e.



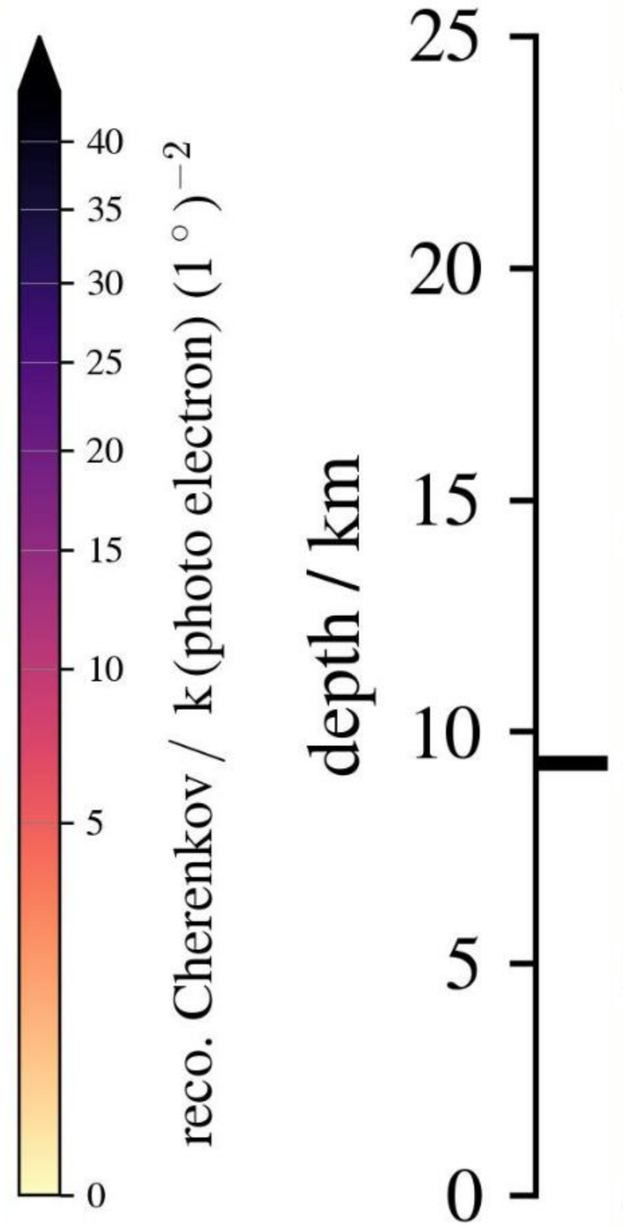


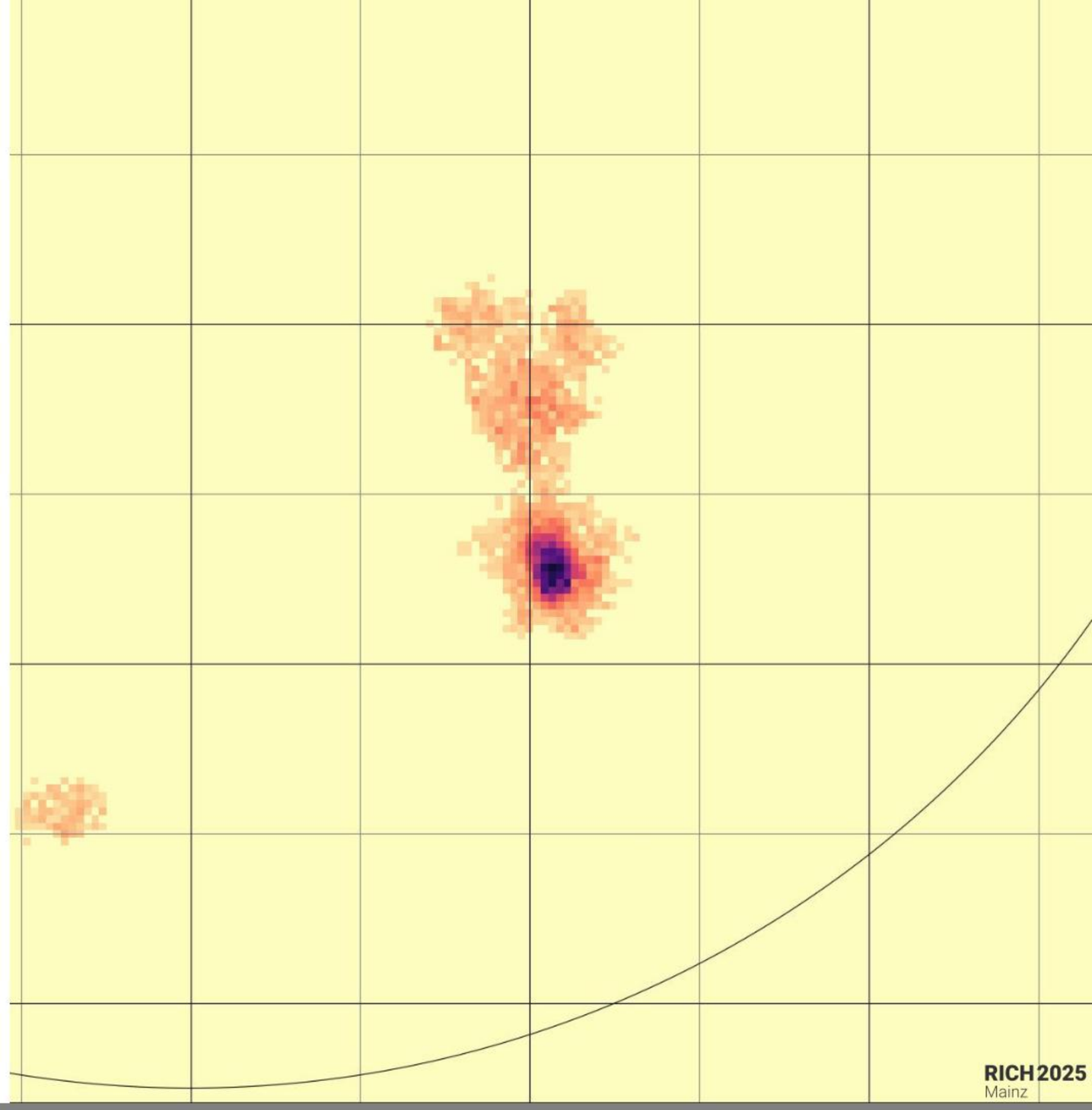
Airshower

Gamma

3.2GeV

708p.e.



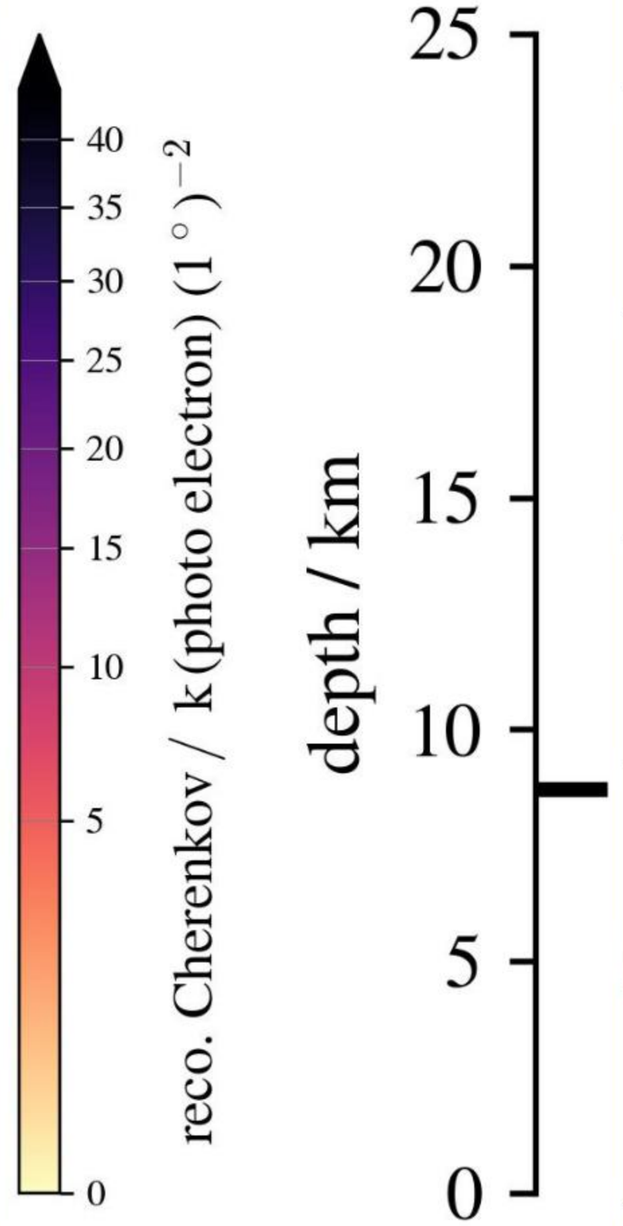


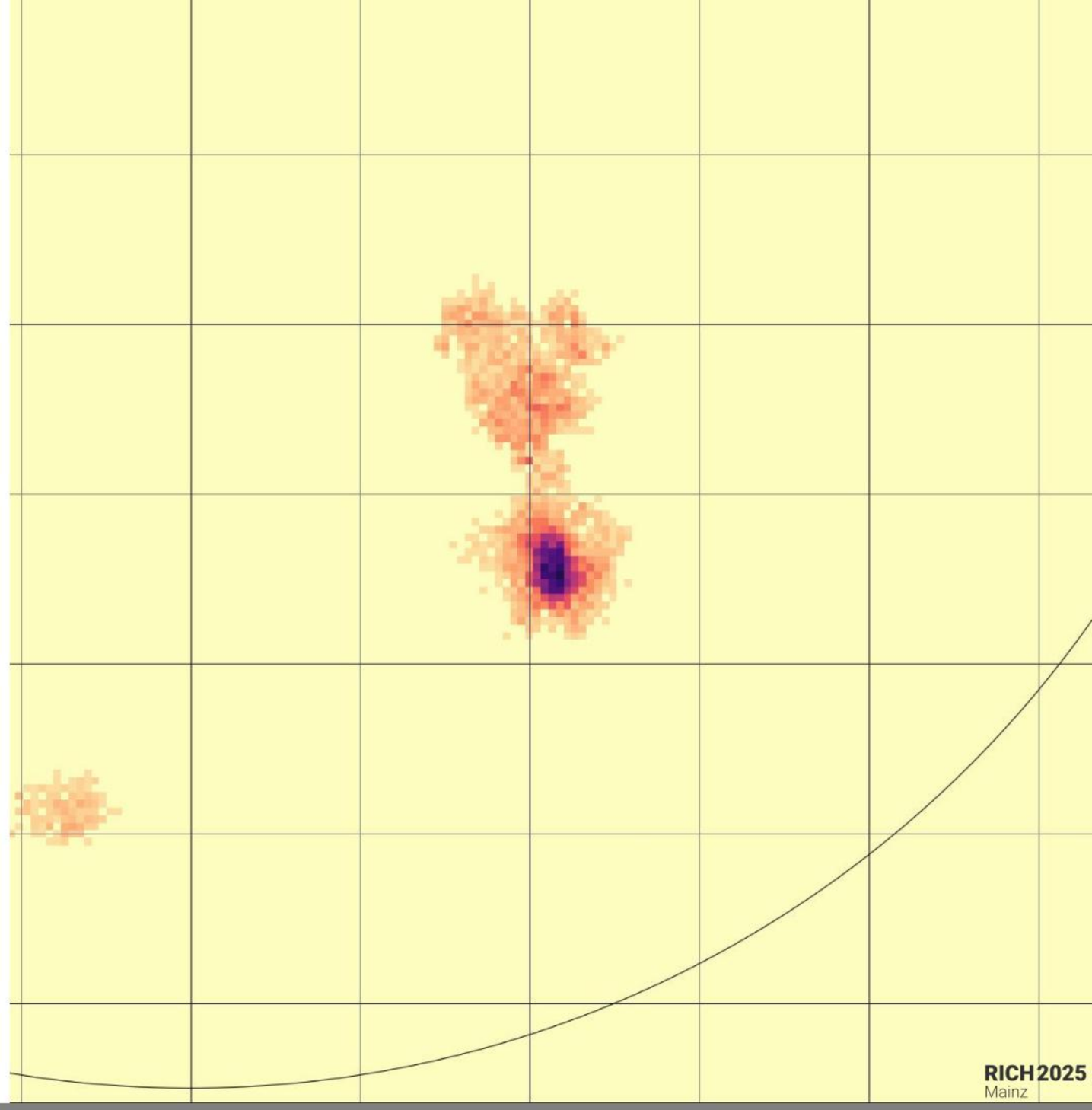
Airshower

Gamma

3.2GeV

708p.e.



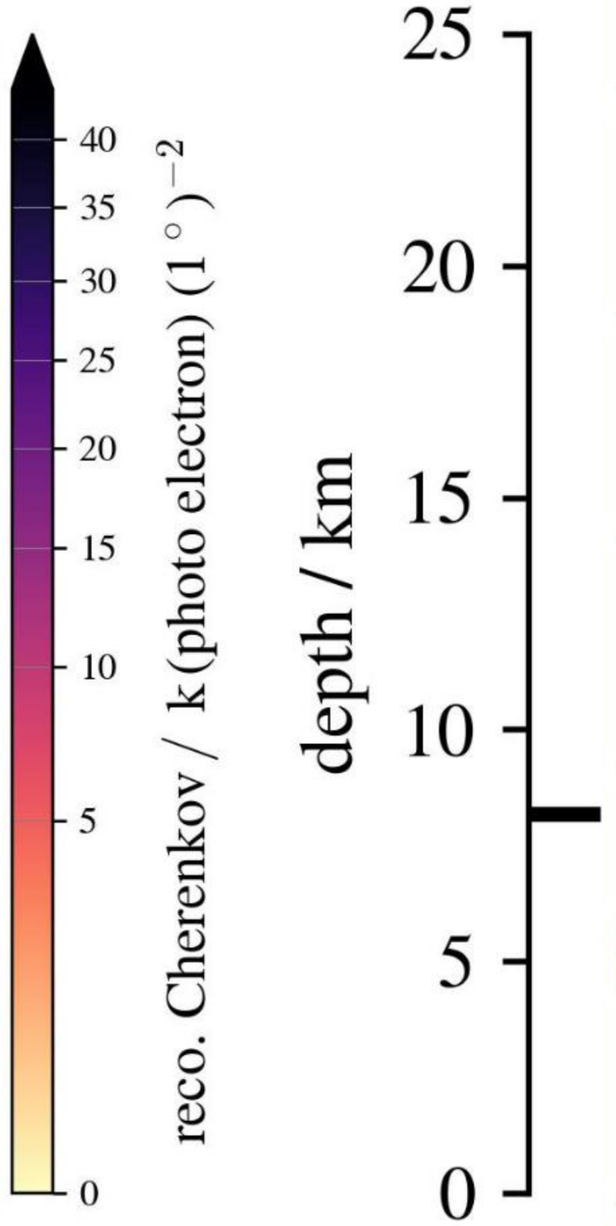


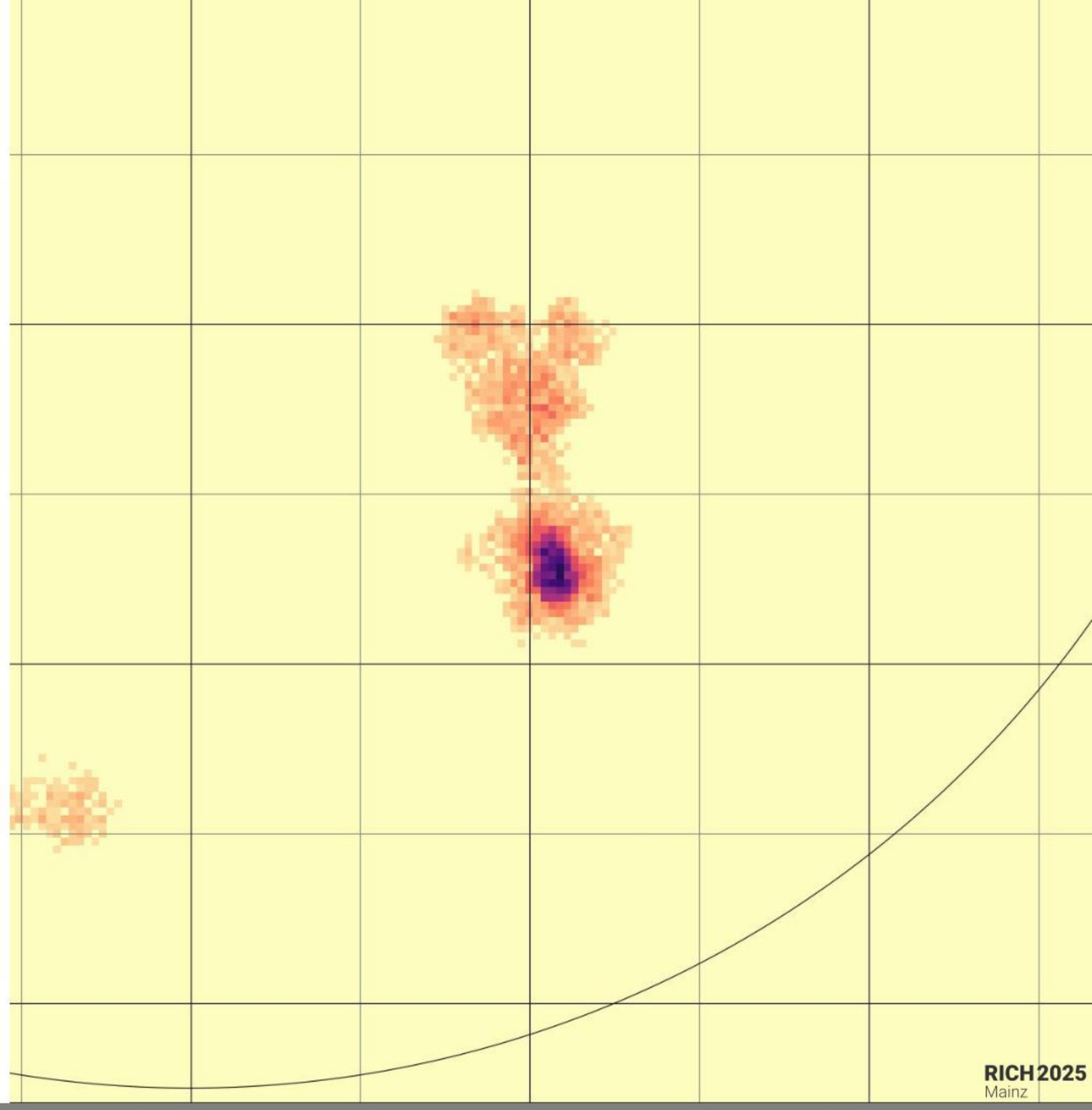
Airshower

Gamma

3.2GeV

708p.e.



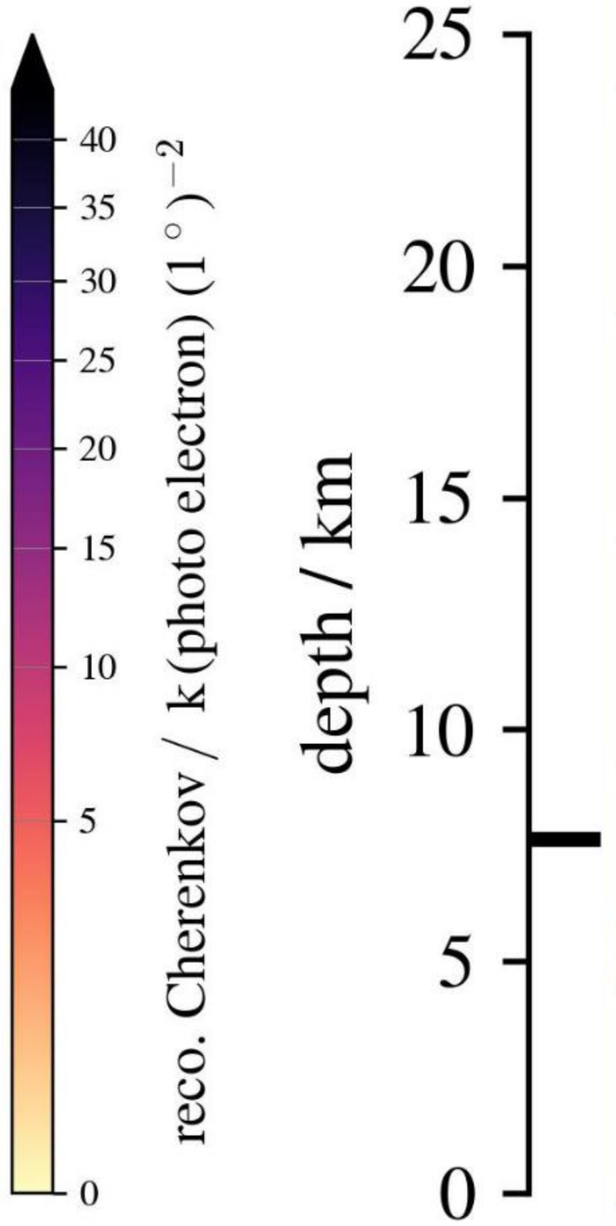


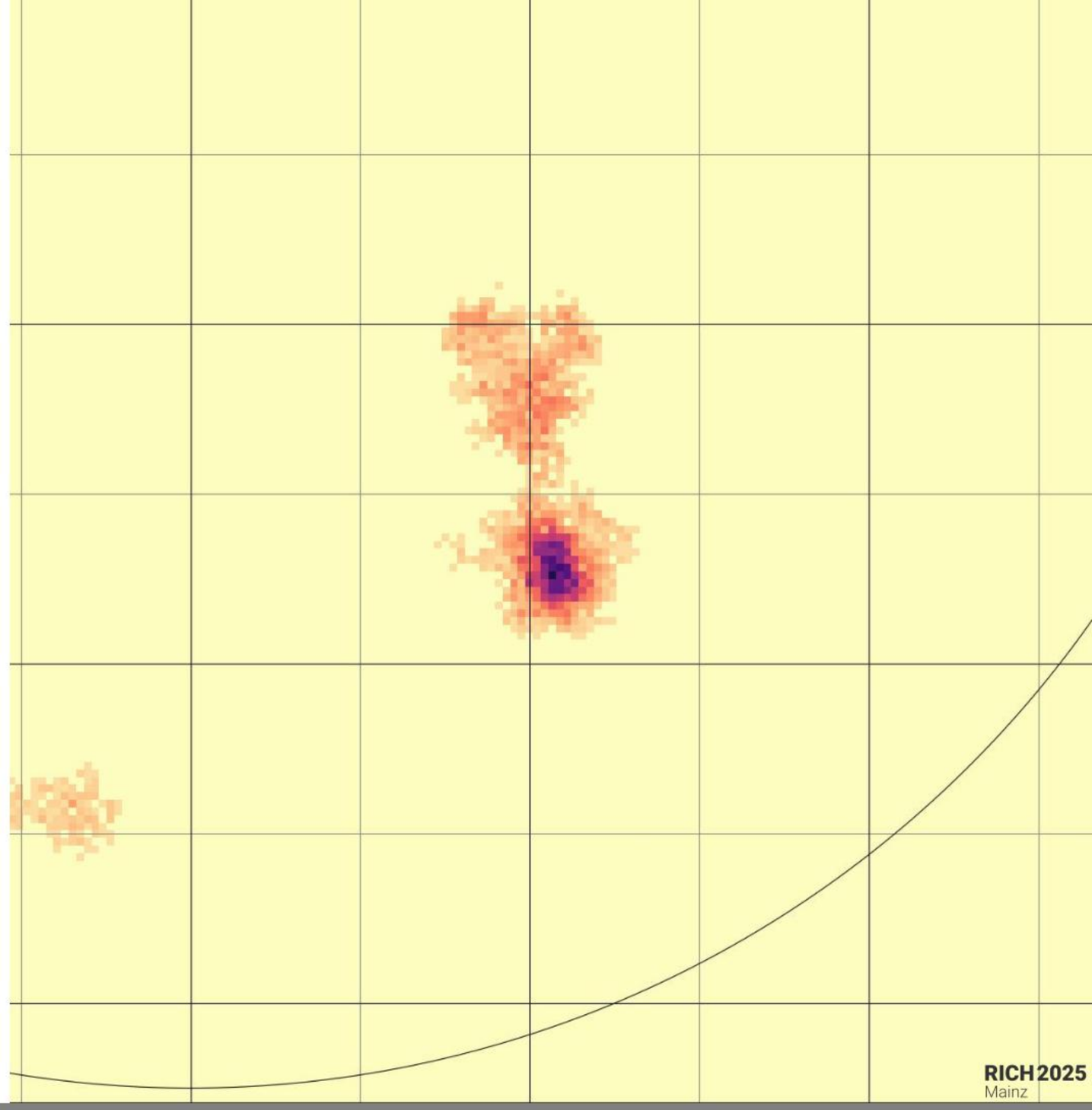
Airshower

Gamma

3.2GeV

708p.e.



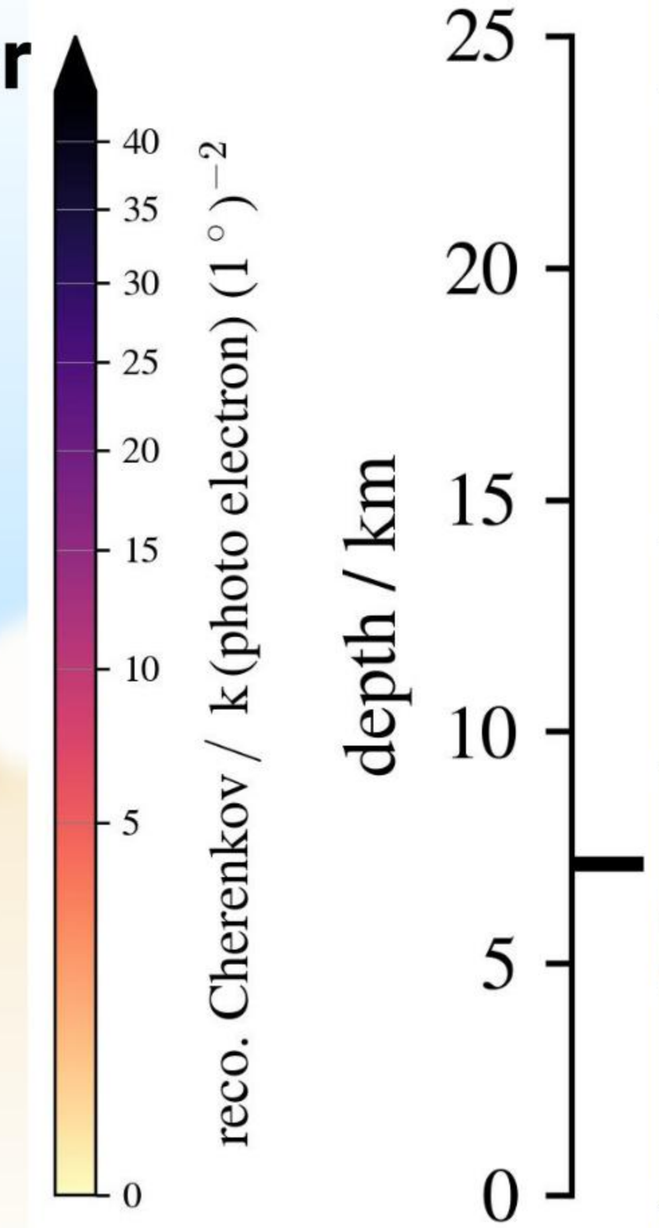


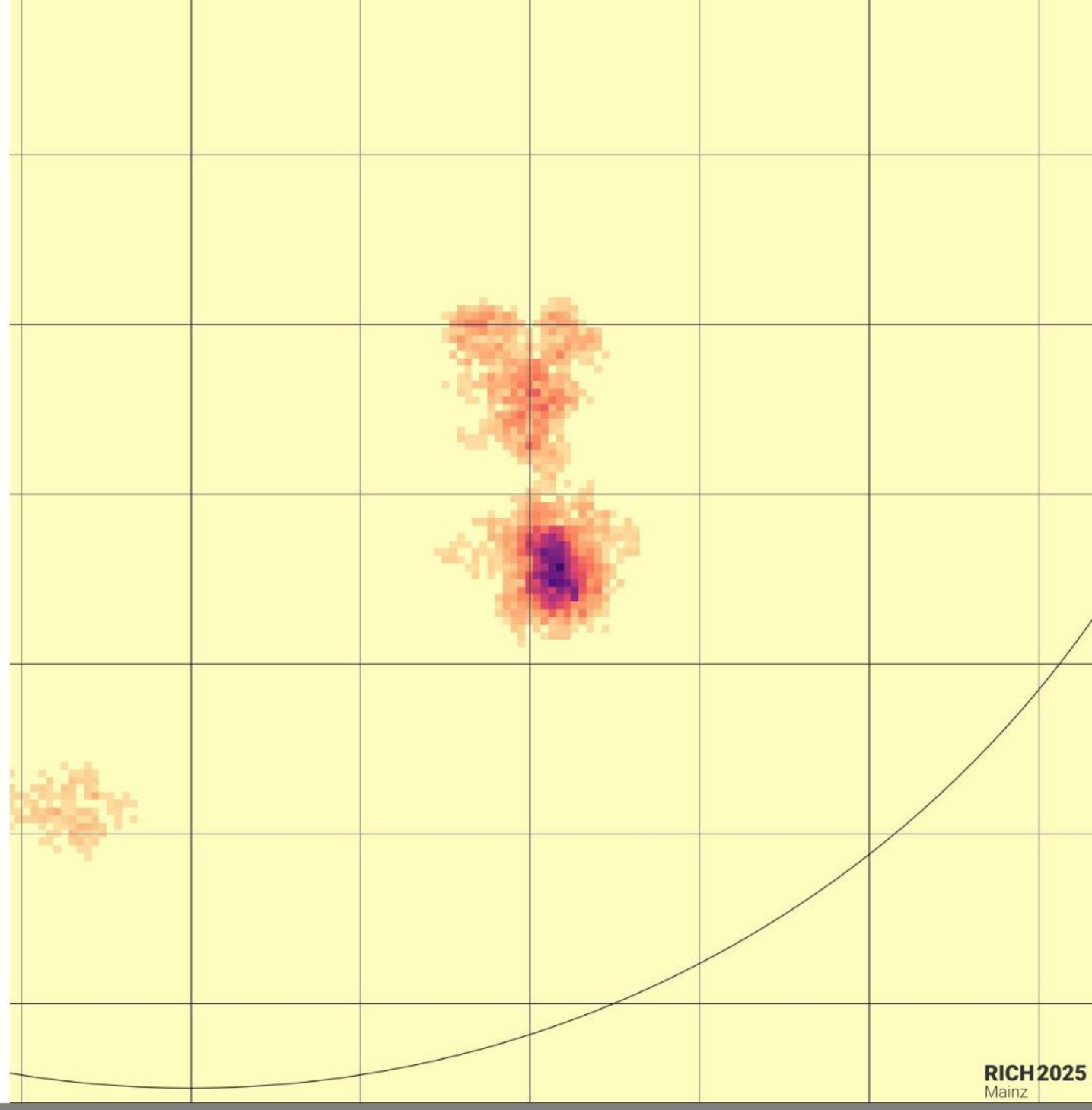
Airshower

Gamma

3.2GeV

708p.e.



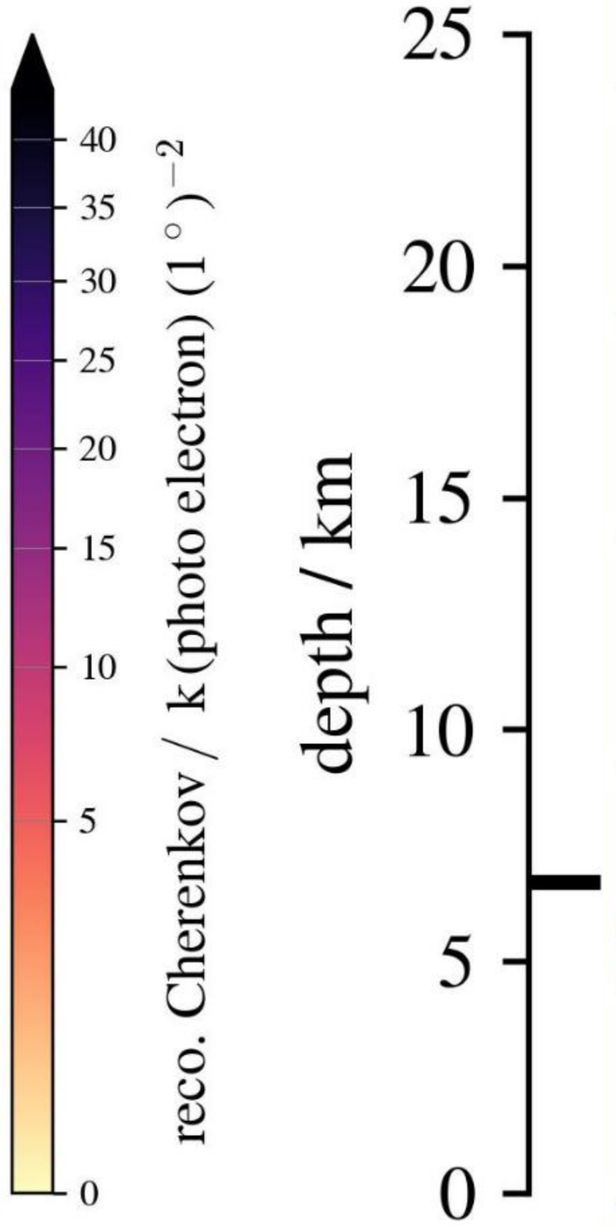


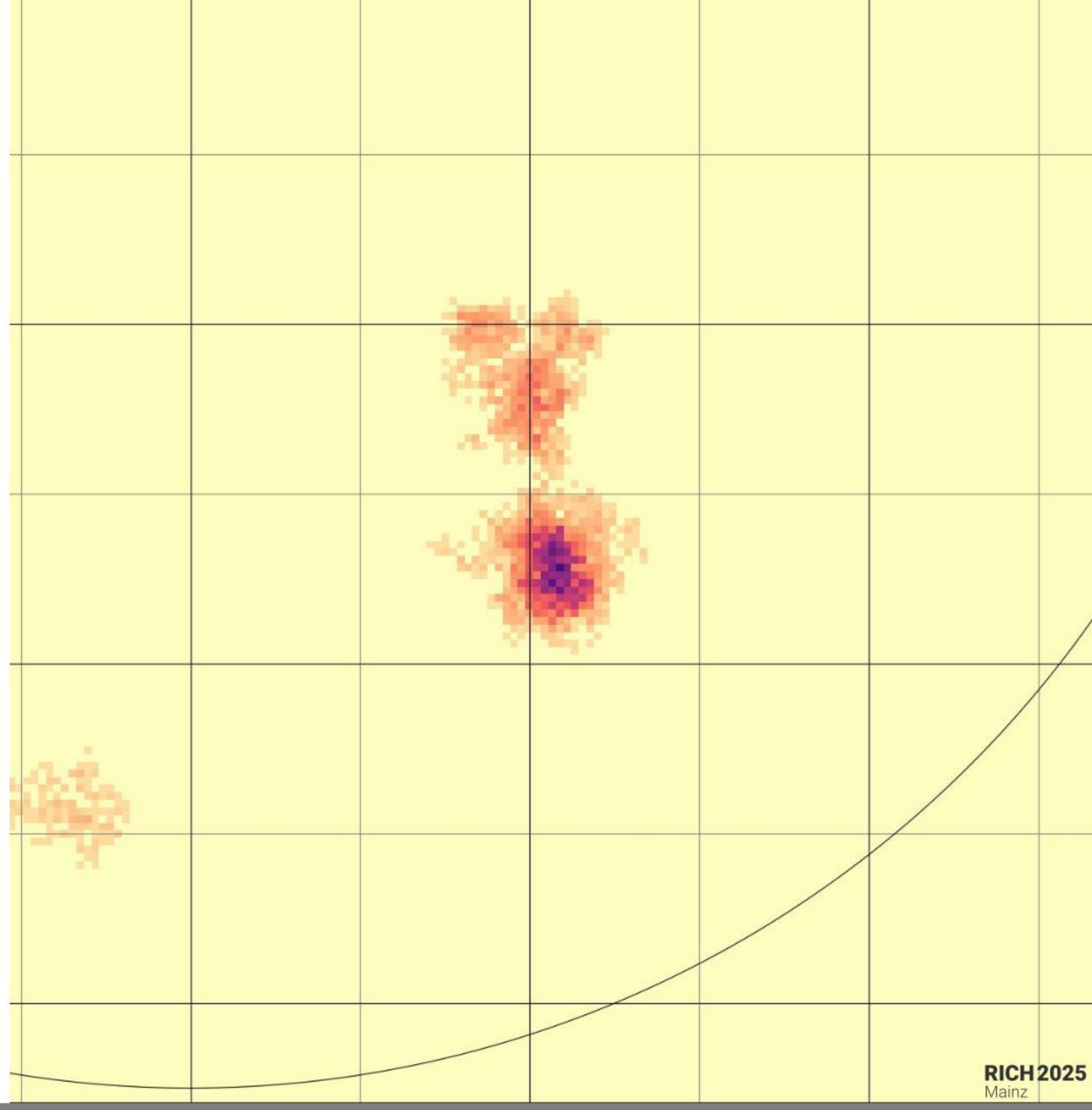
Airshower

Gamma

3.2GeV

708p.e.



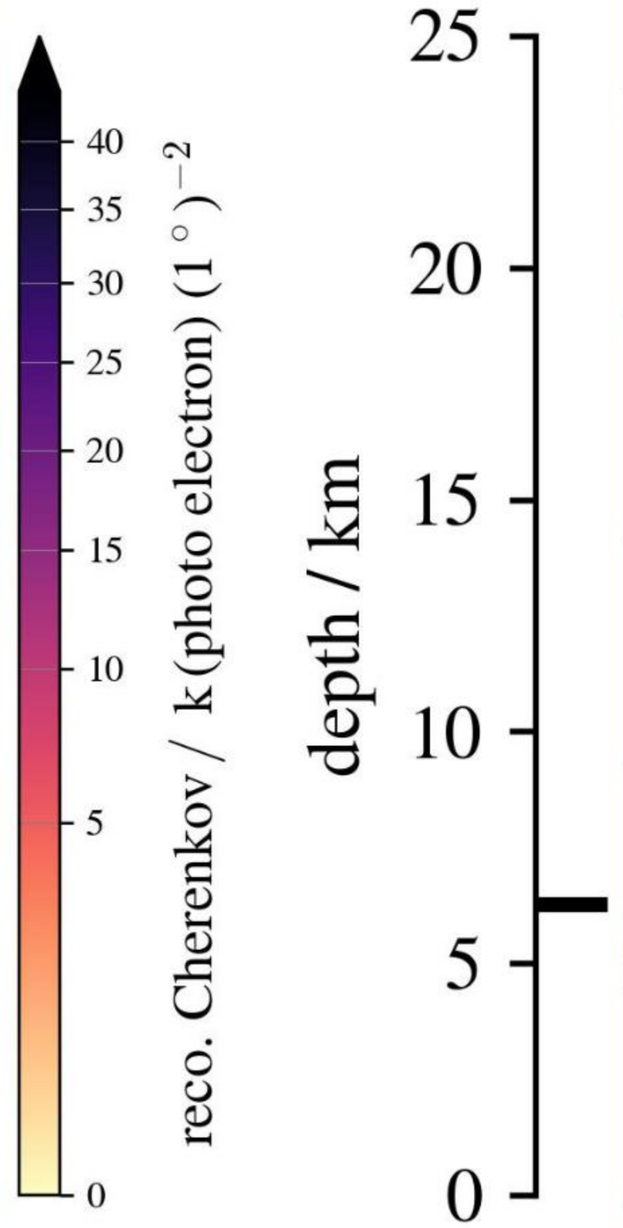


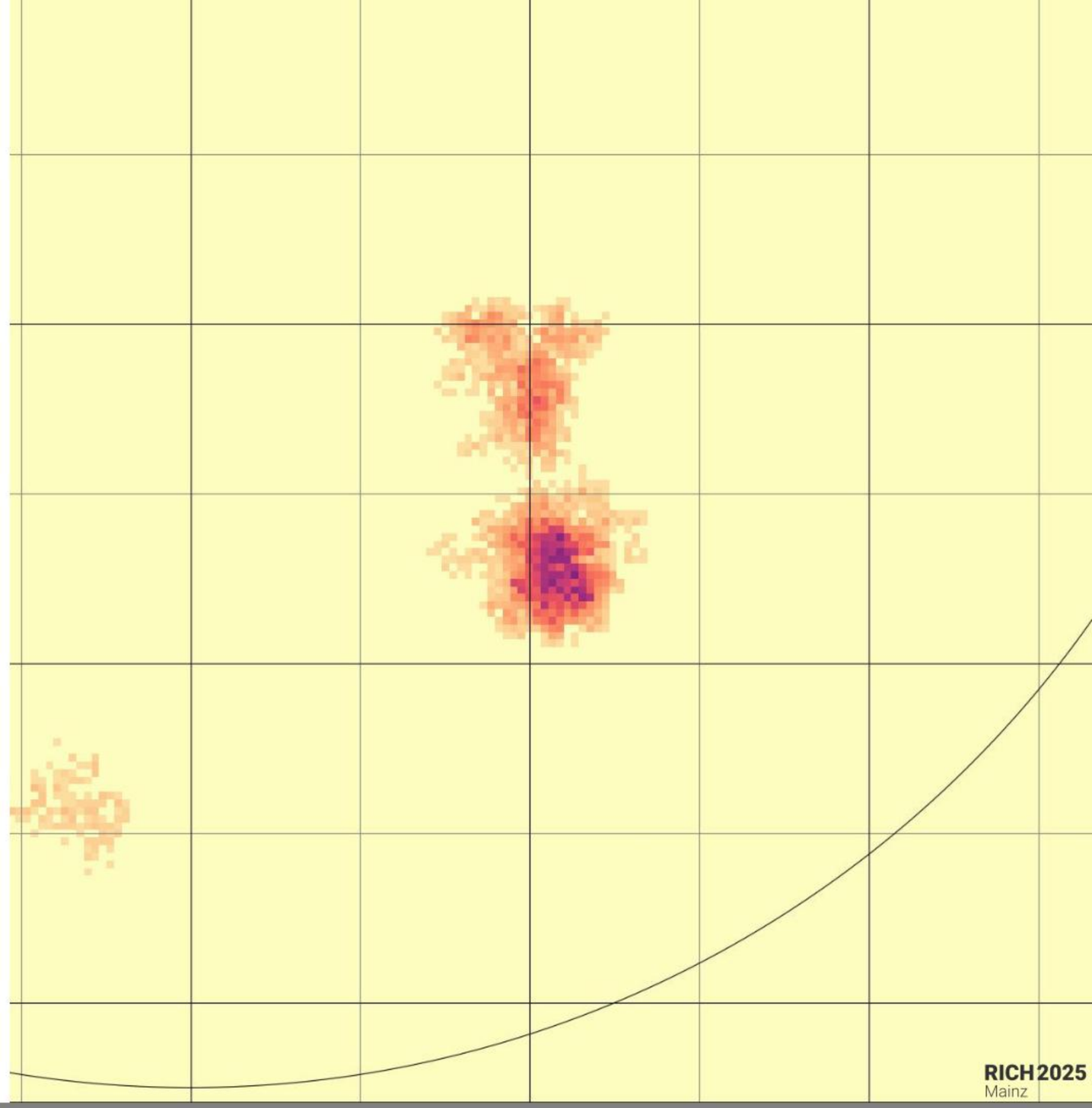
Airshower

Gamma

3.2GeV

708p.e.



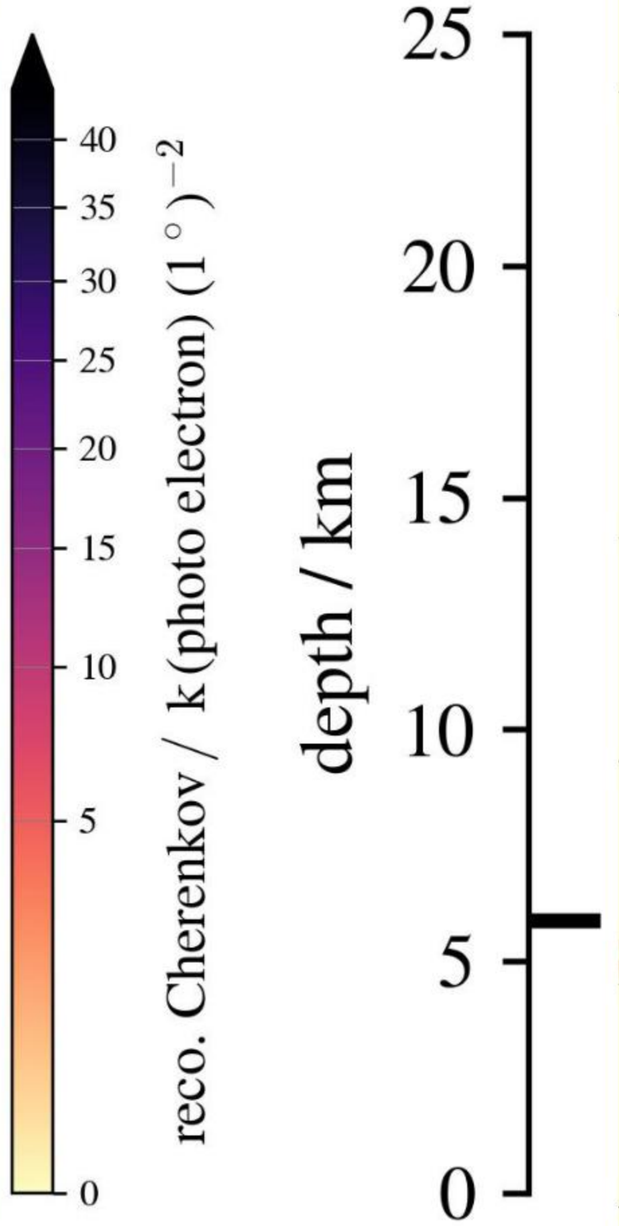


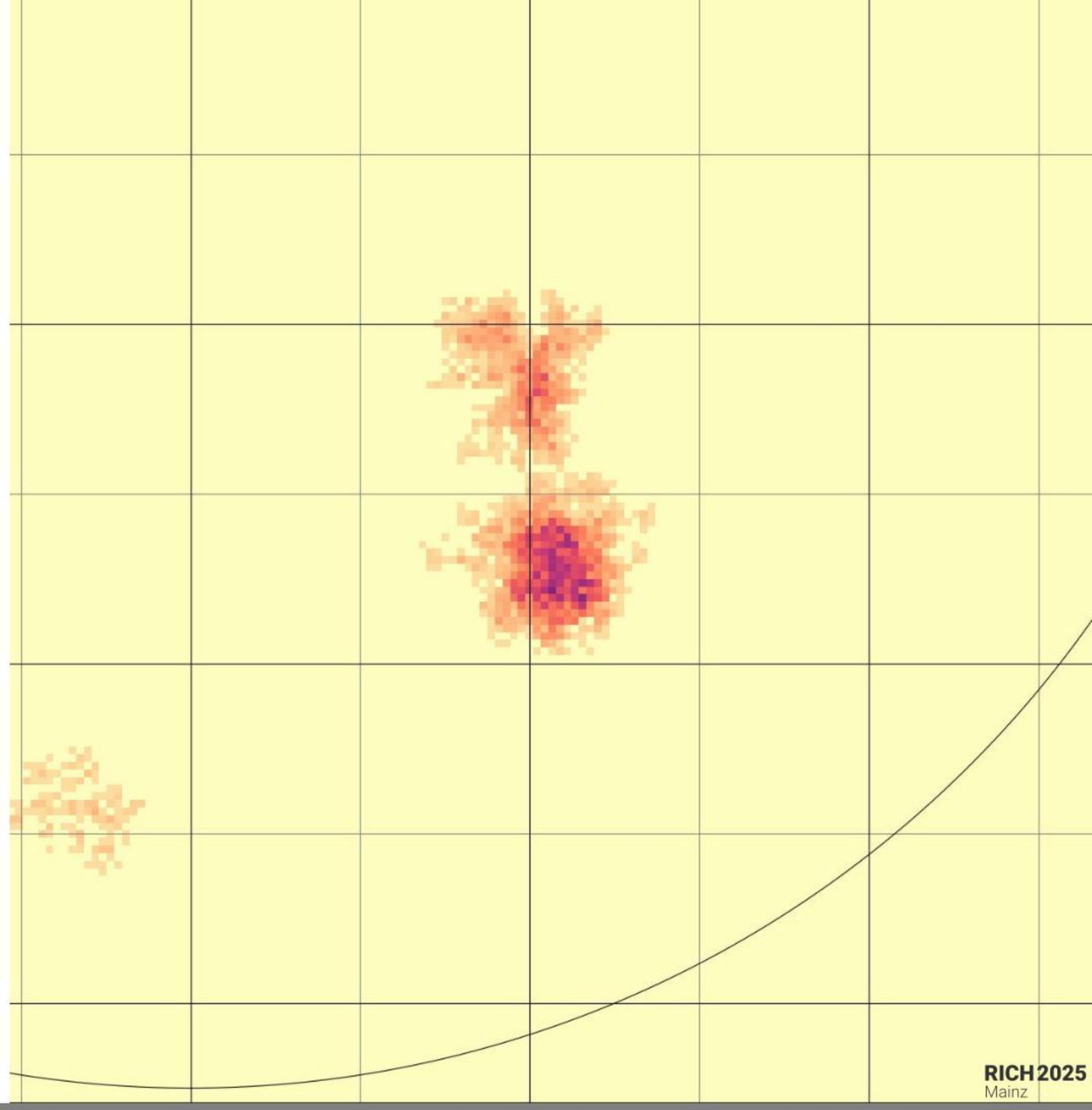
Airshower

Gamma

3.2GeV

708p.e.



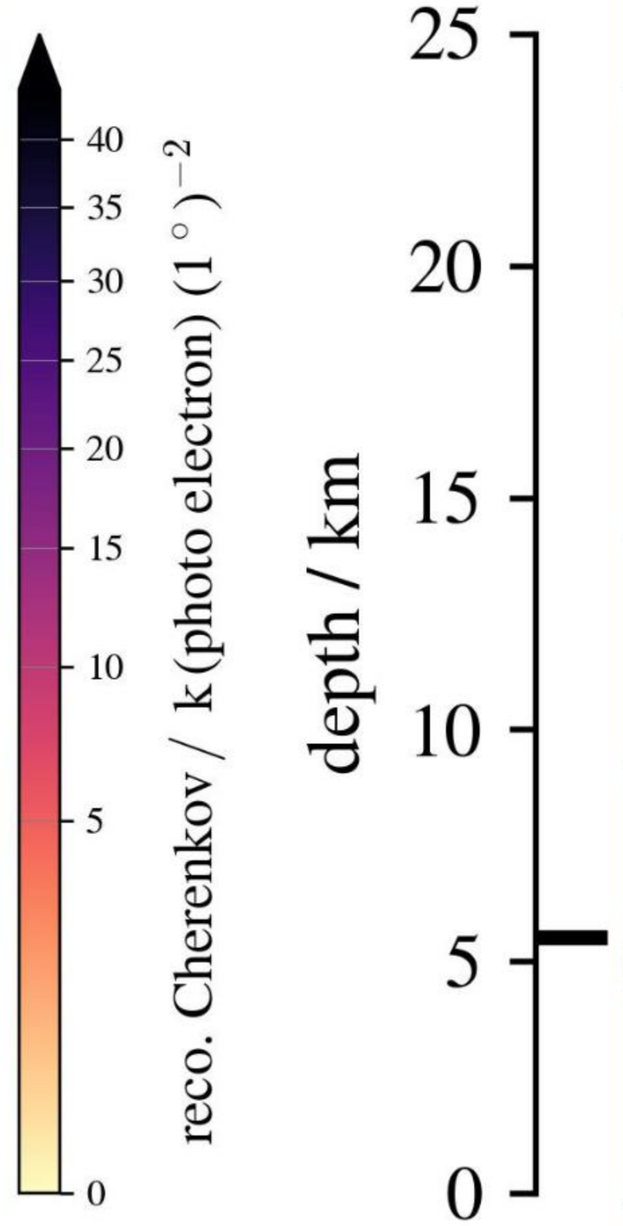


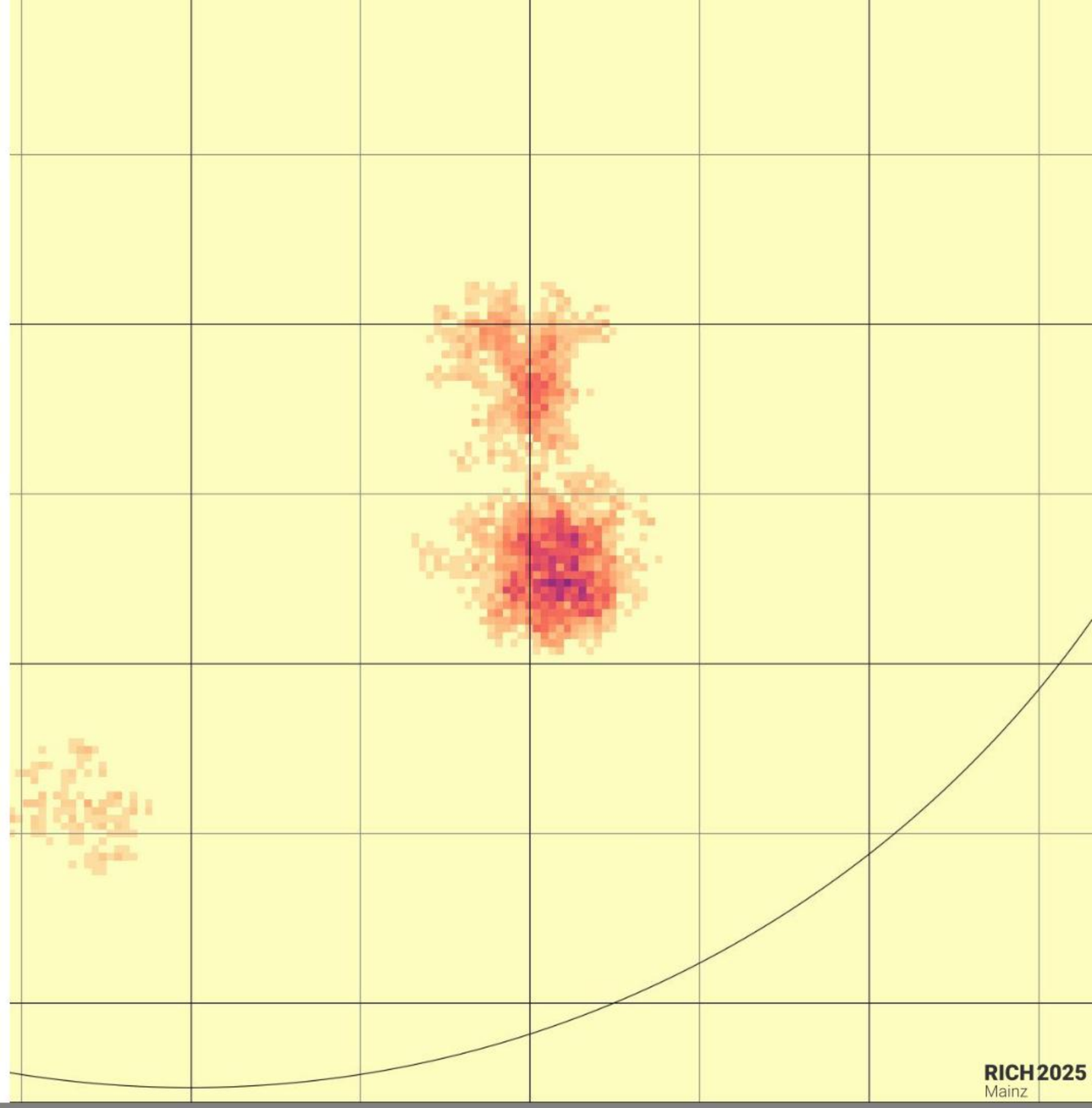
Airshower

Gamma

3.2GeV

708p.e.



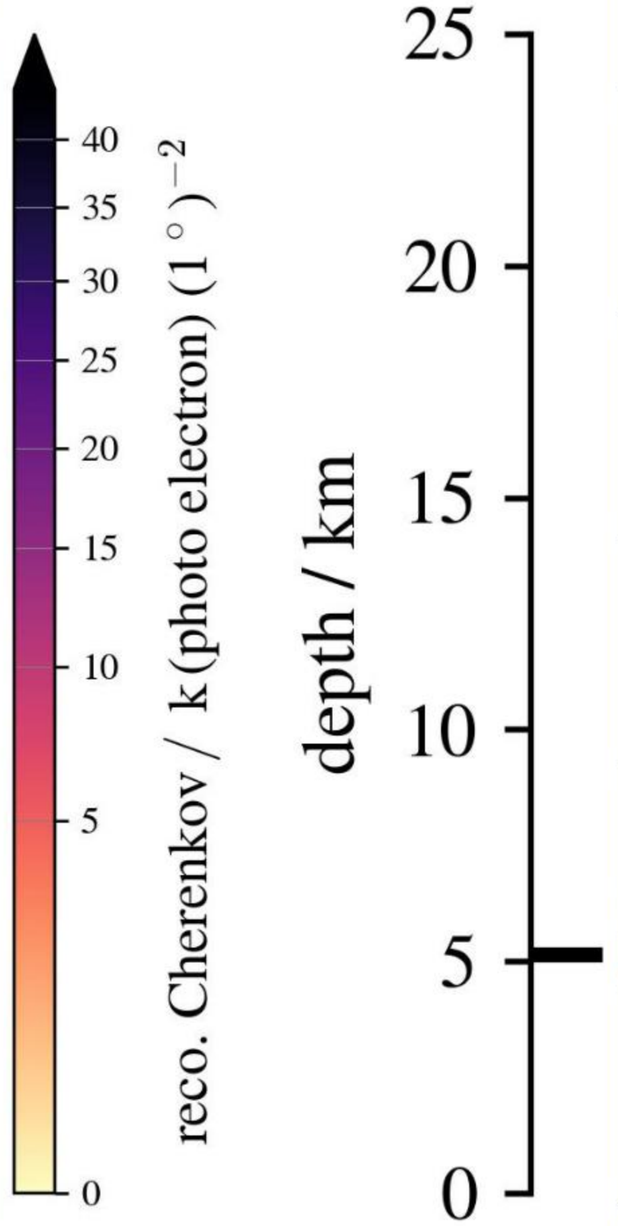


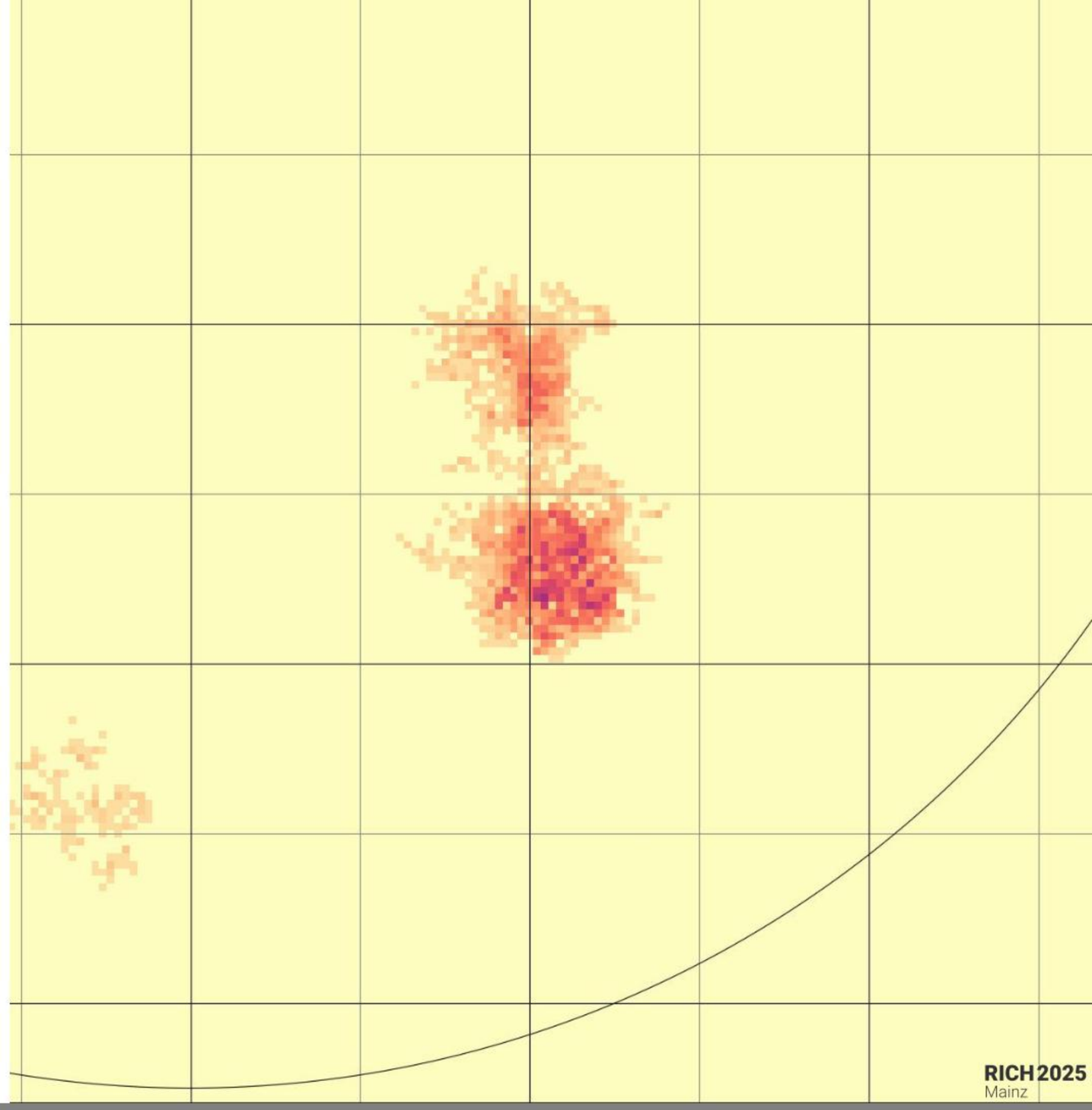
Airshower

Gamma

3.2GeV

708p.e.



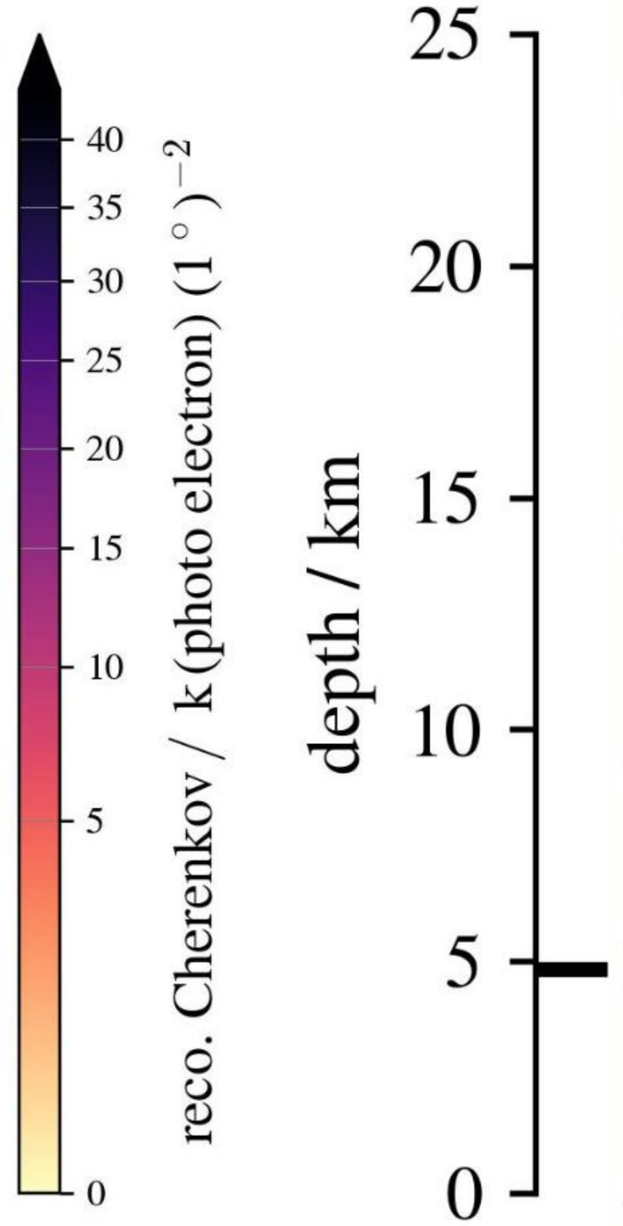


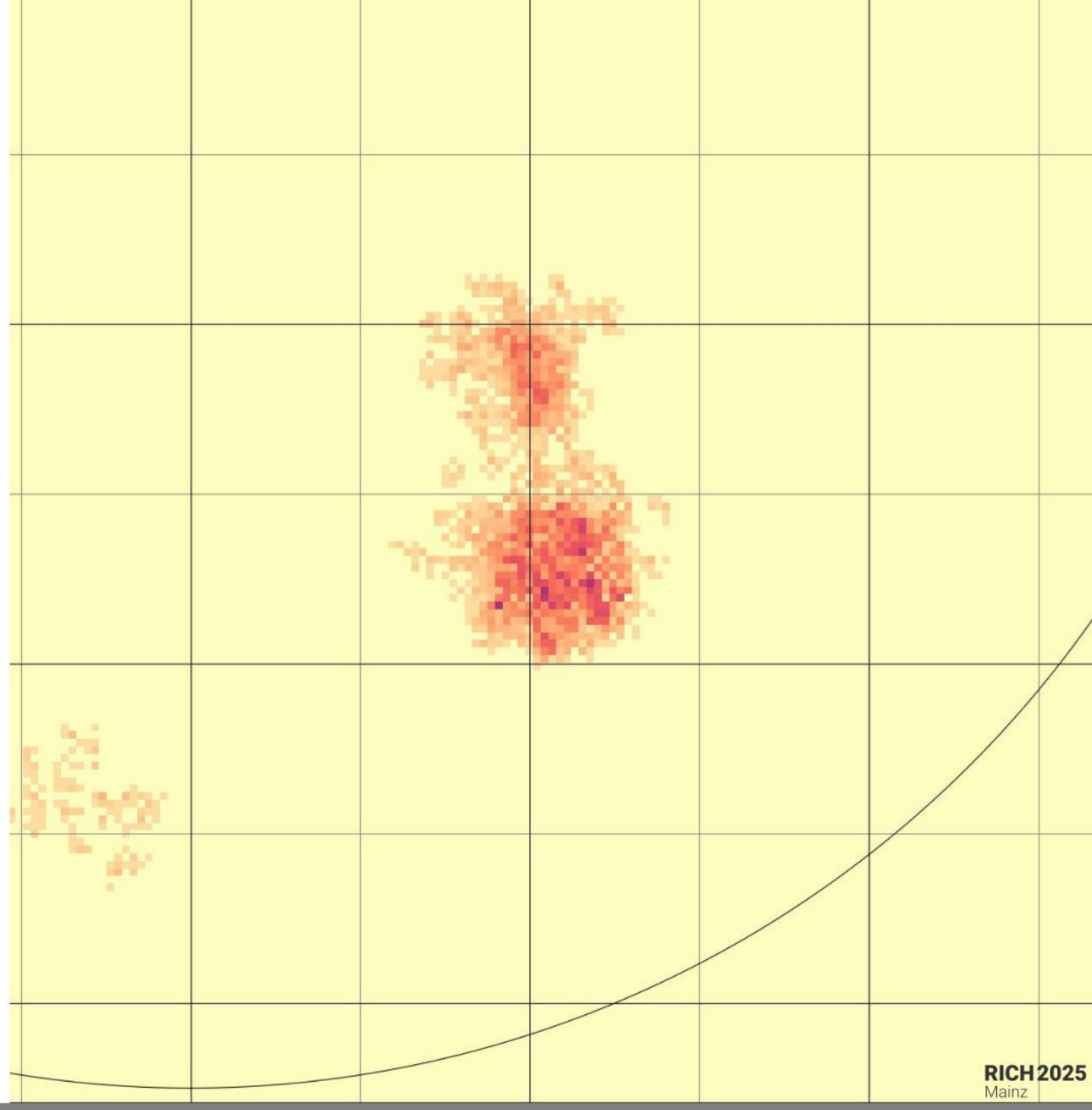
Airshower

Gamma

3.2GeV

708p.e.



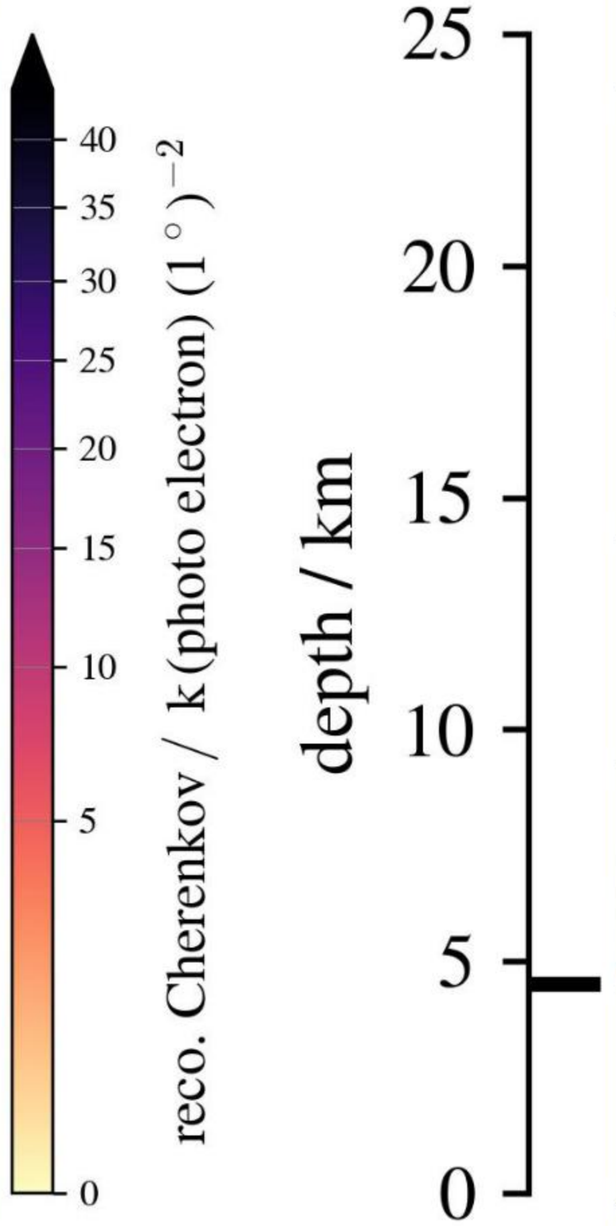


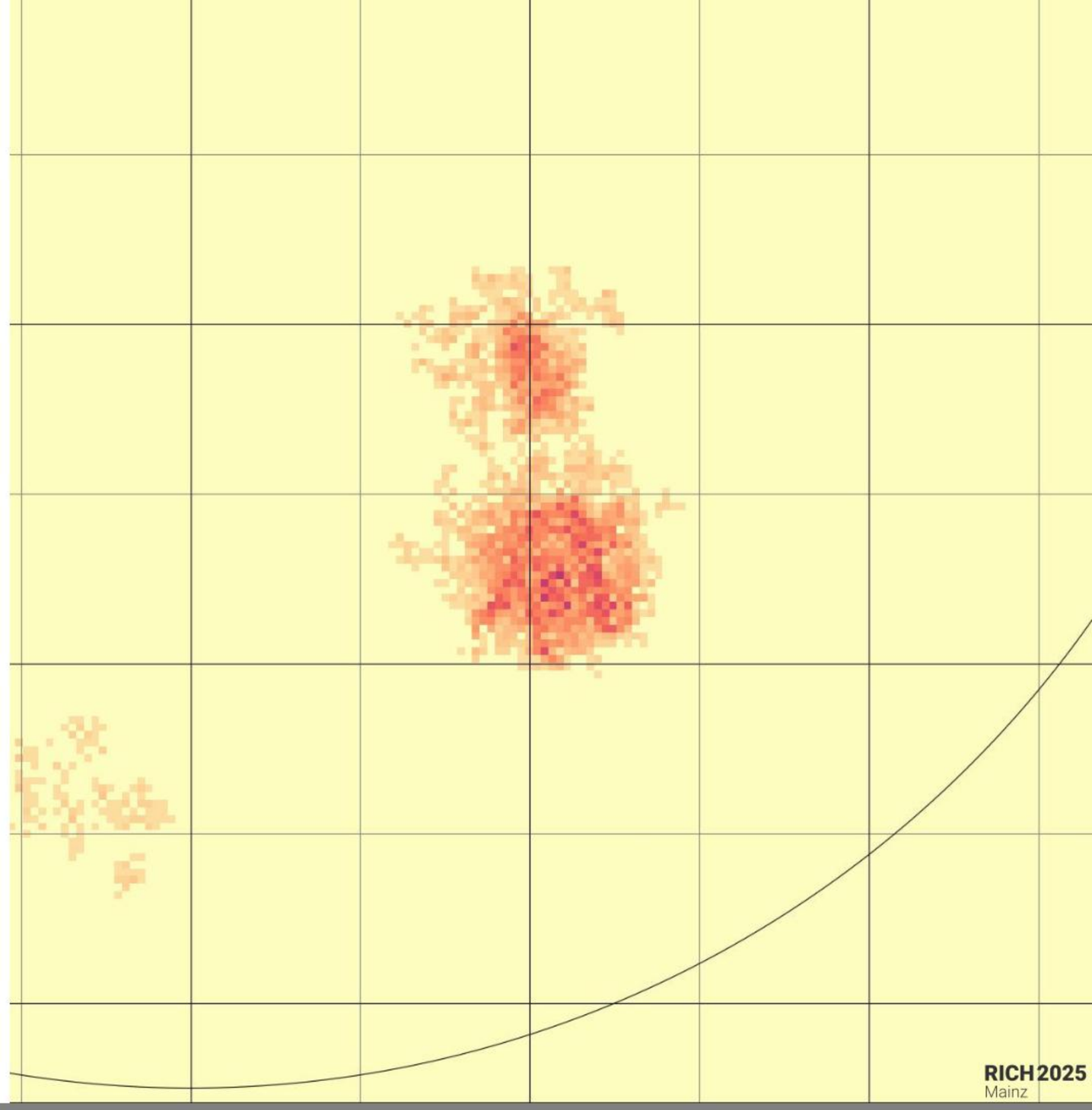
Airshower

Gamma

3.2GeV

708p.e.



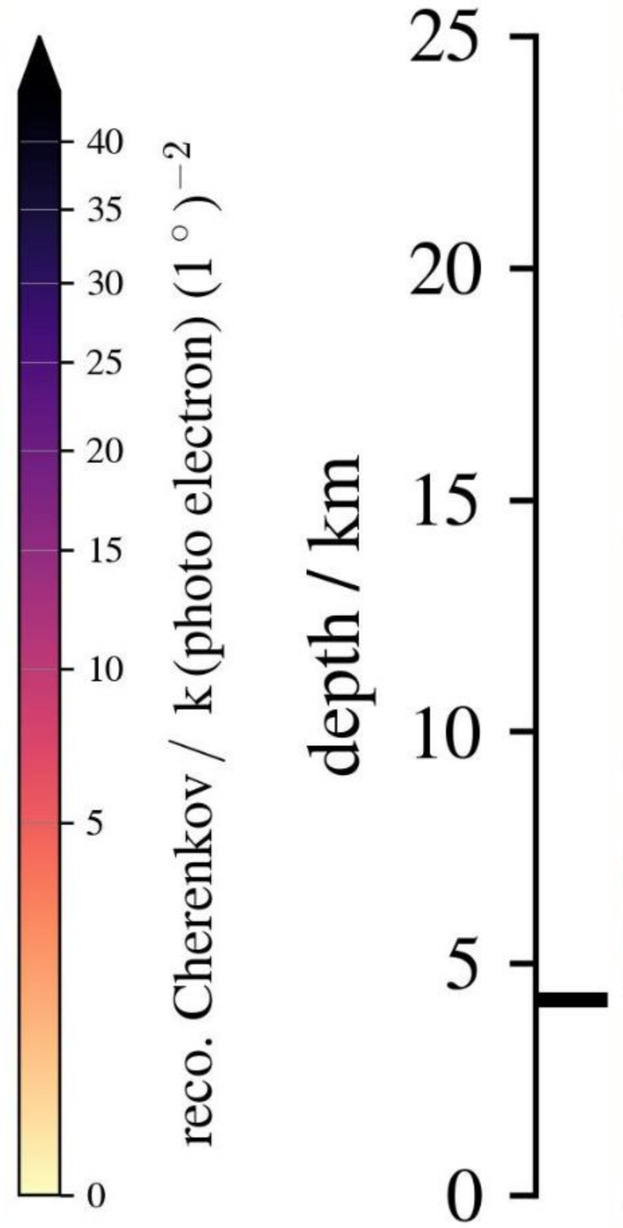


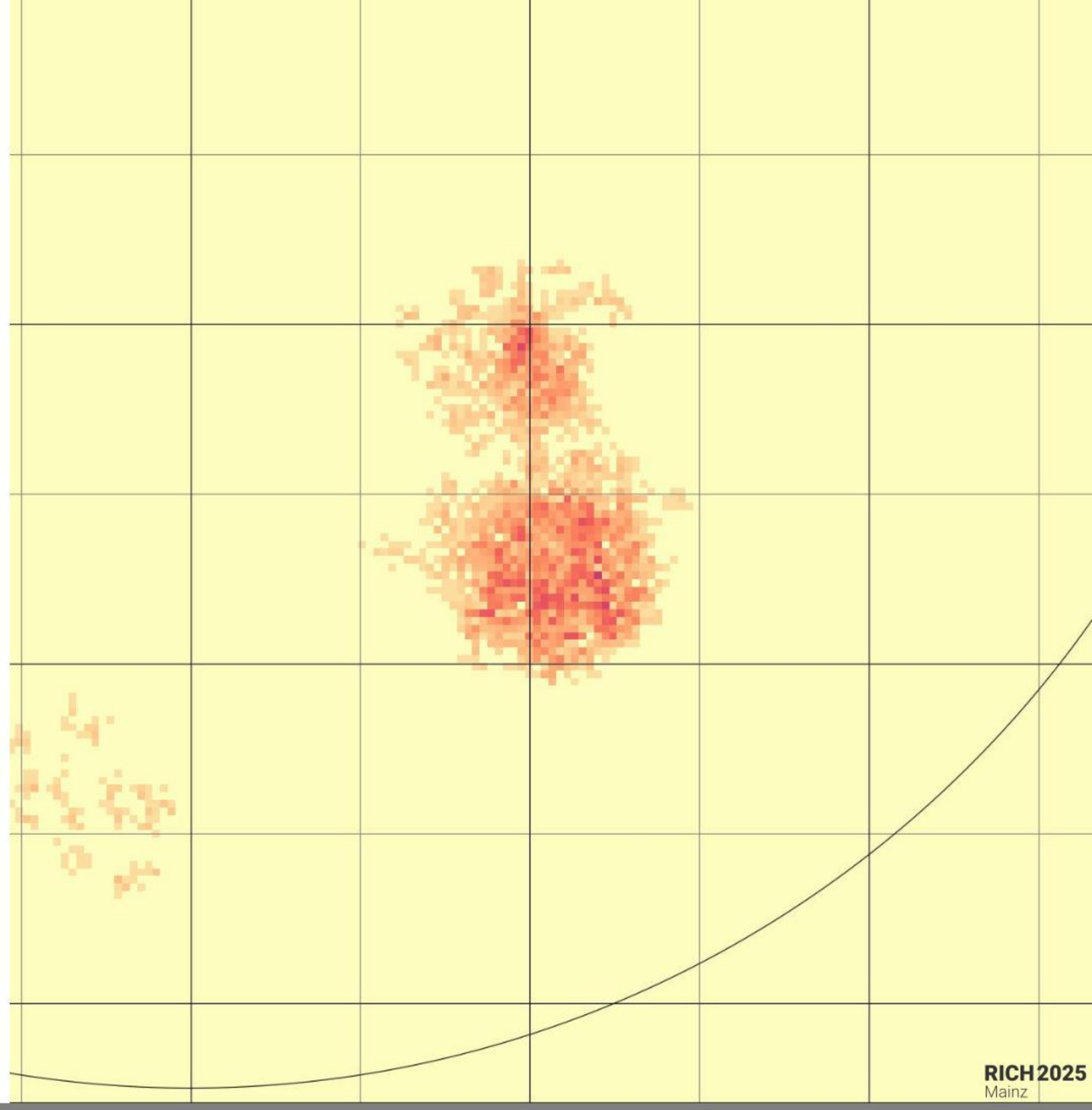
Airshower

Gamma

3.2GeV

708p.e.





Airshower

Gamma

3.2GeV

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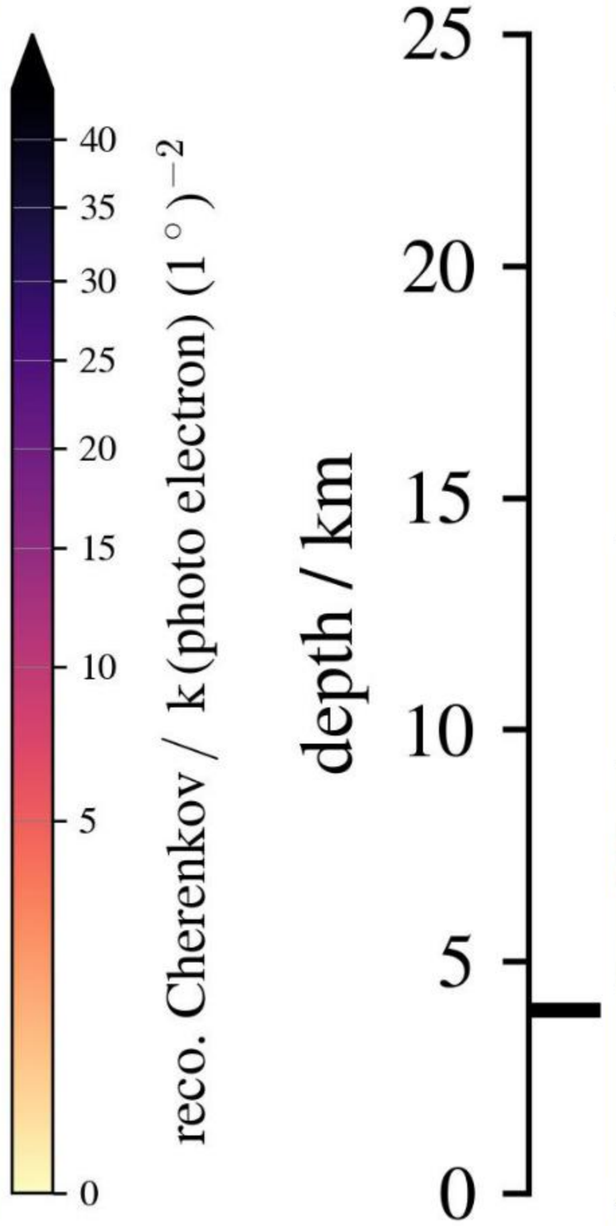
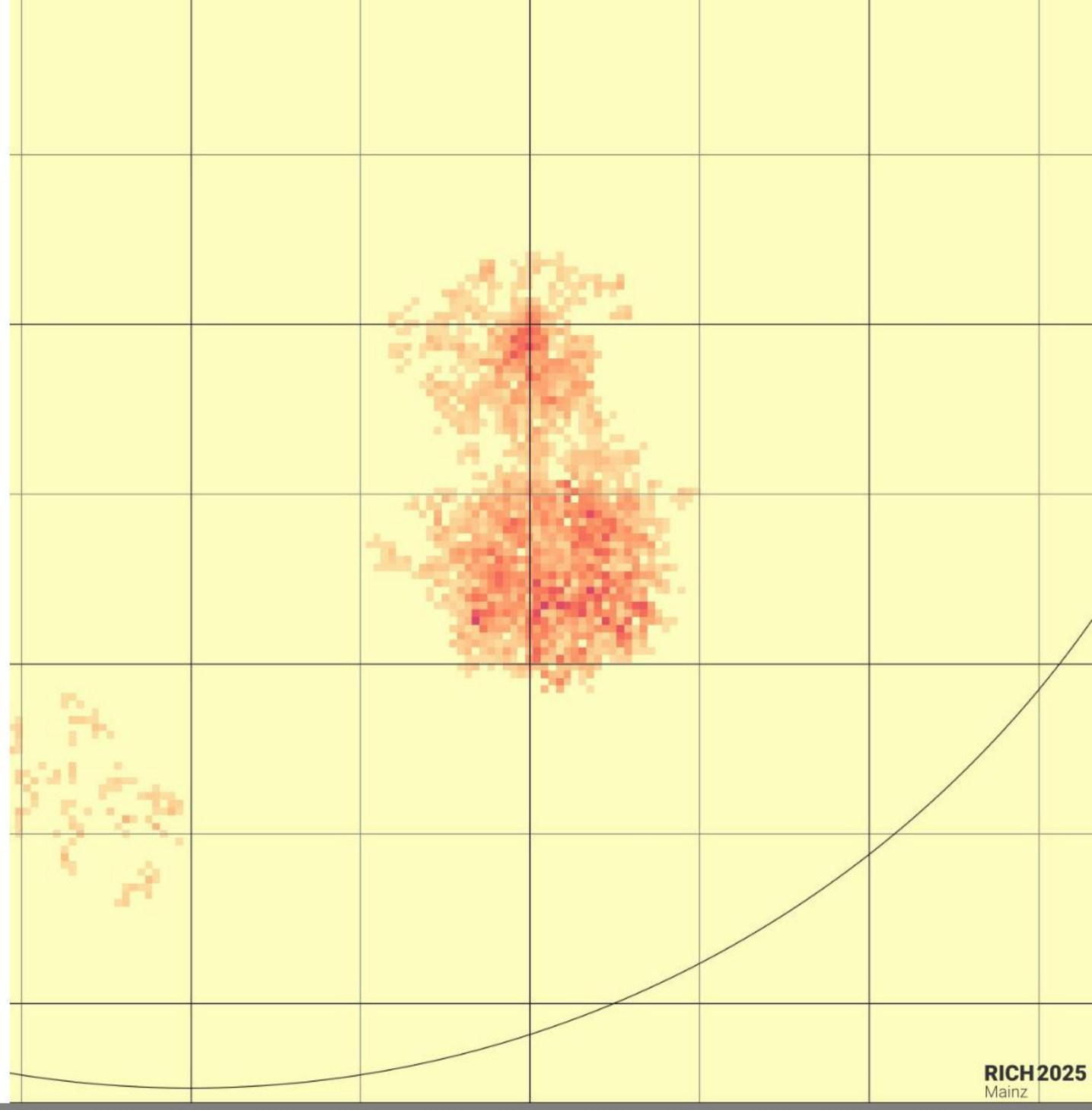


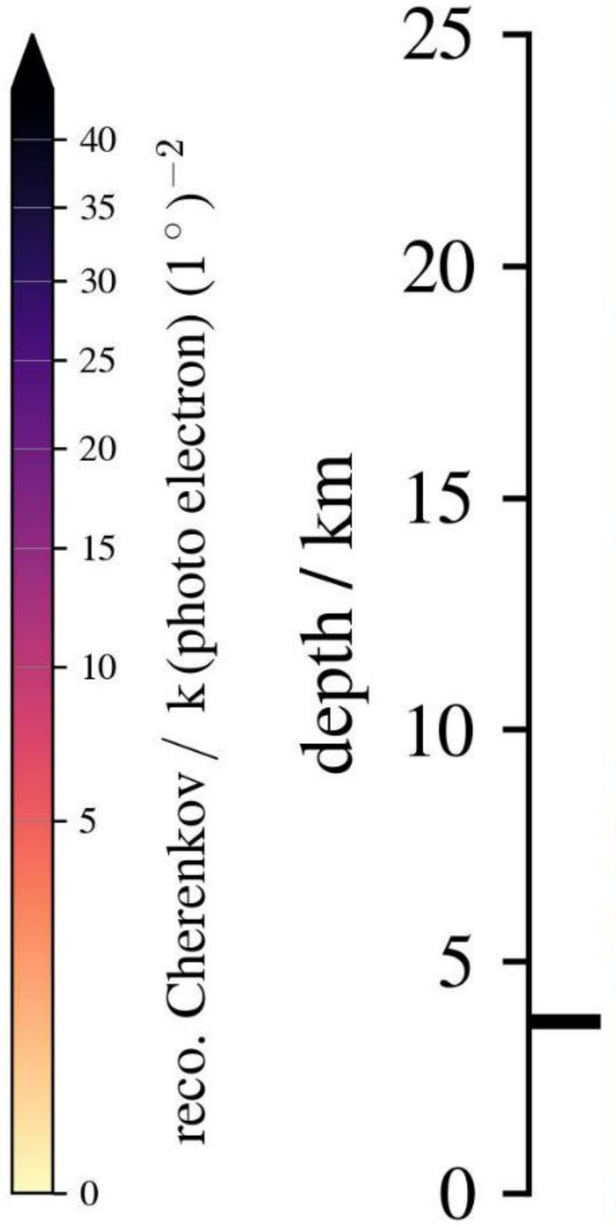


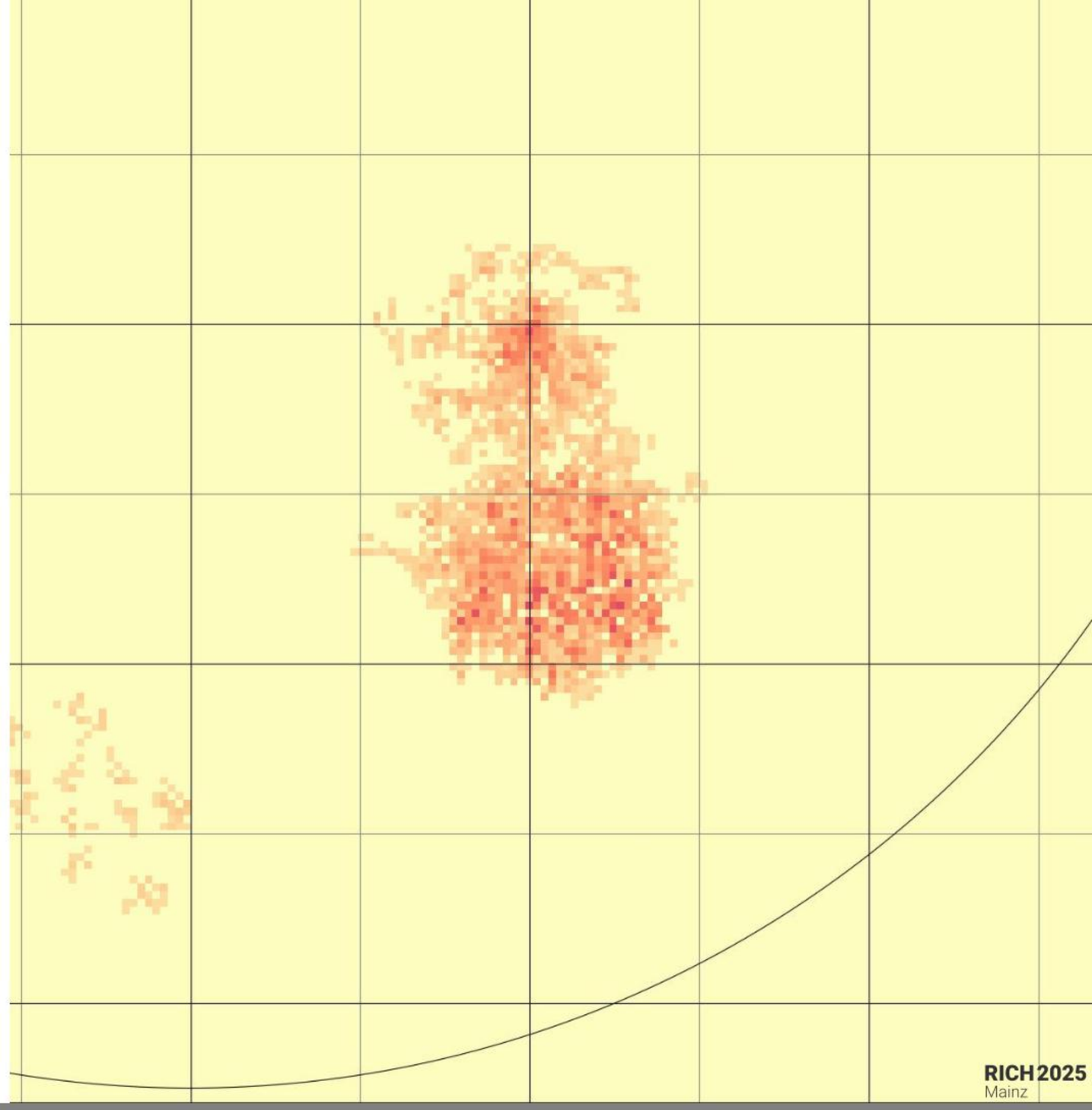
Airshower

Gamma

3.2GeV

708p.e.



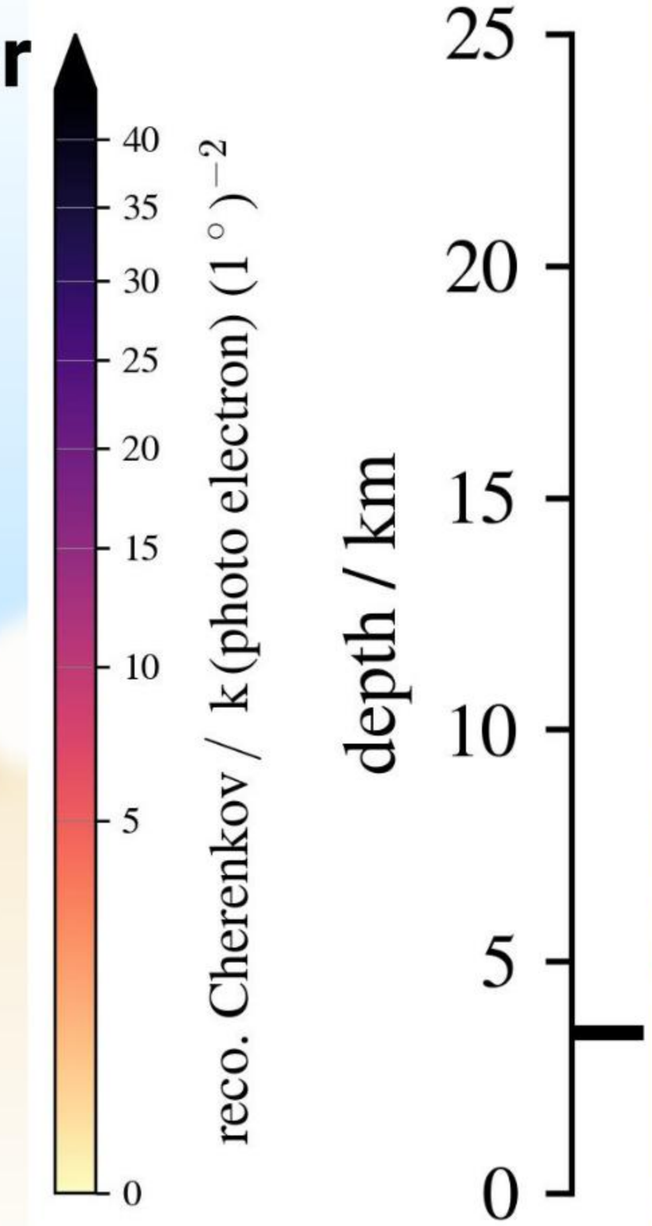


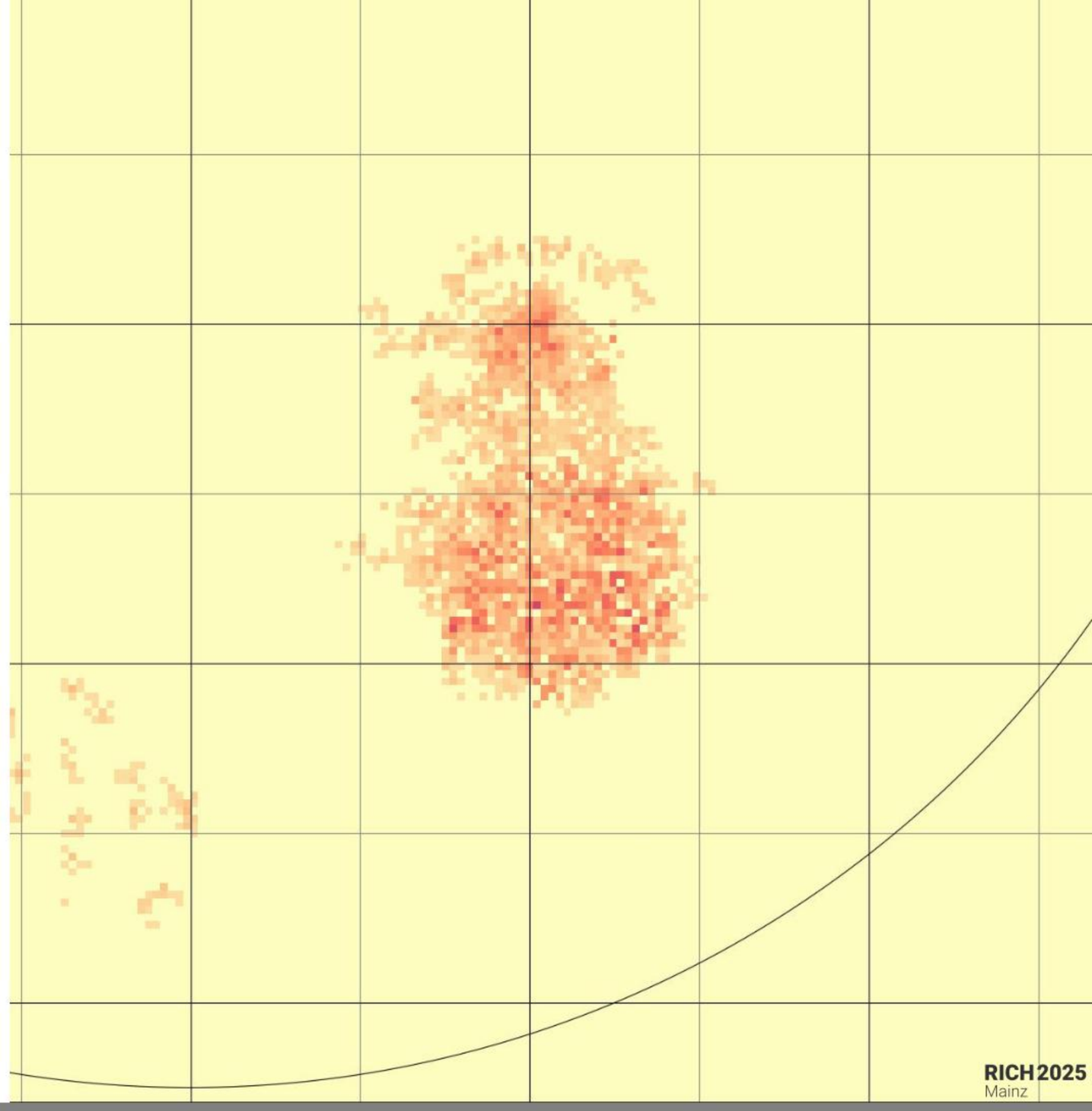
Airshower

Gamma

3.2GeV

708p.e.



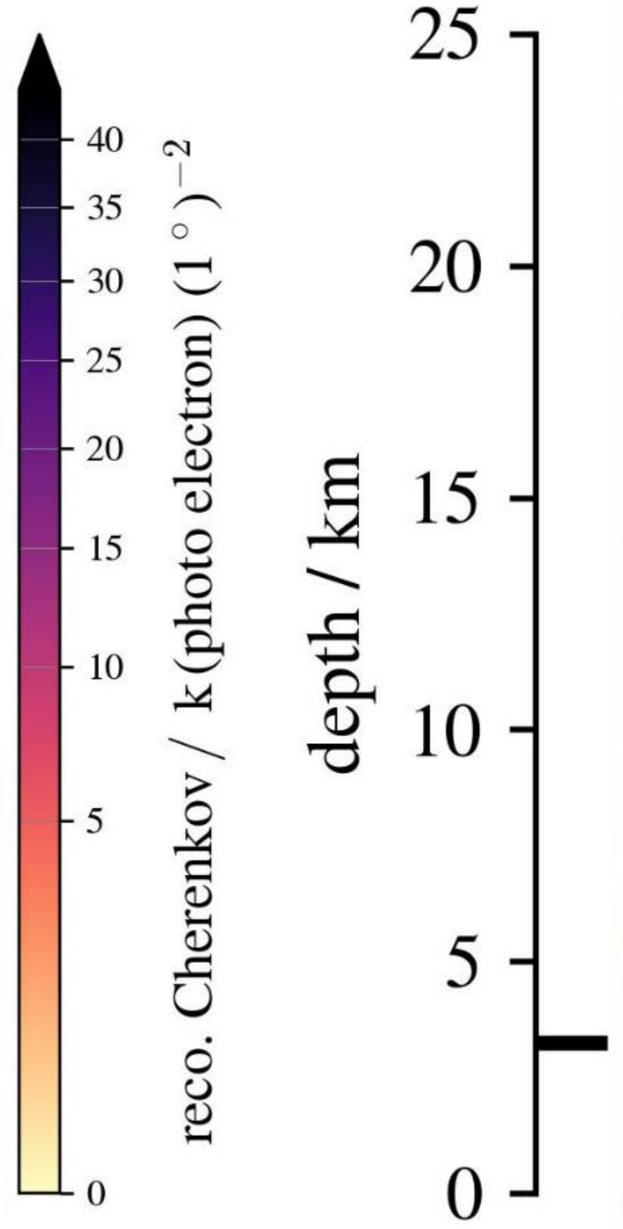


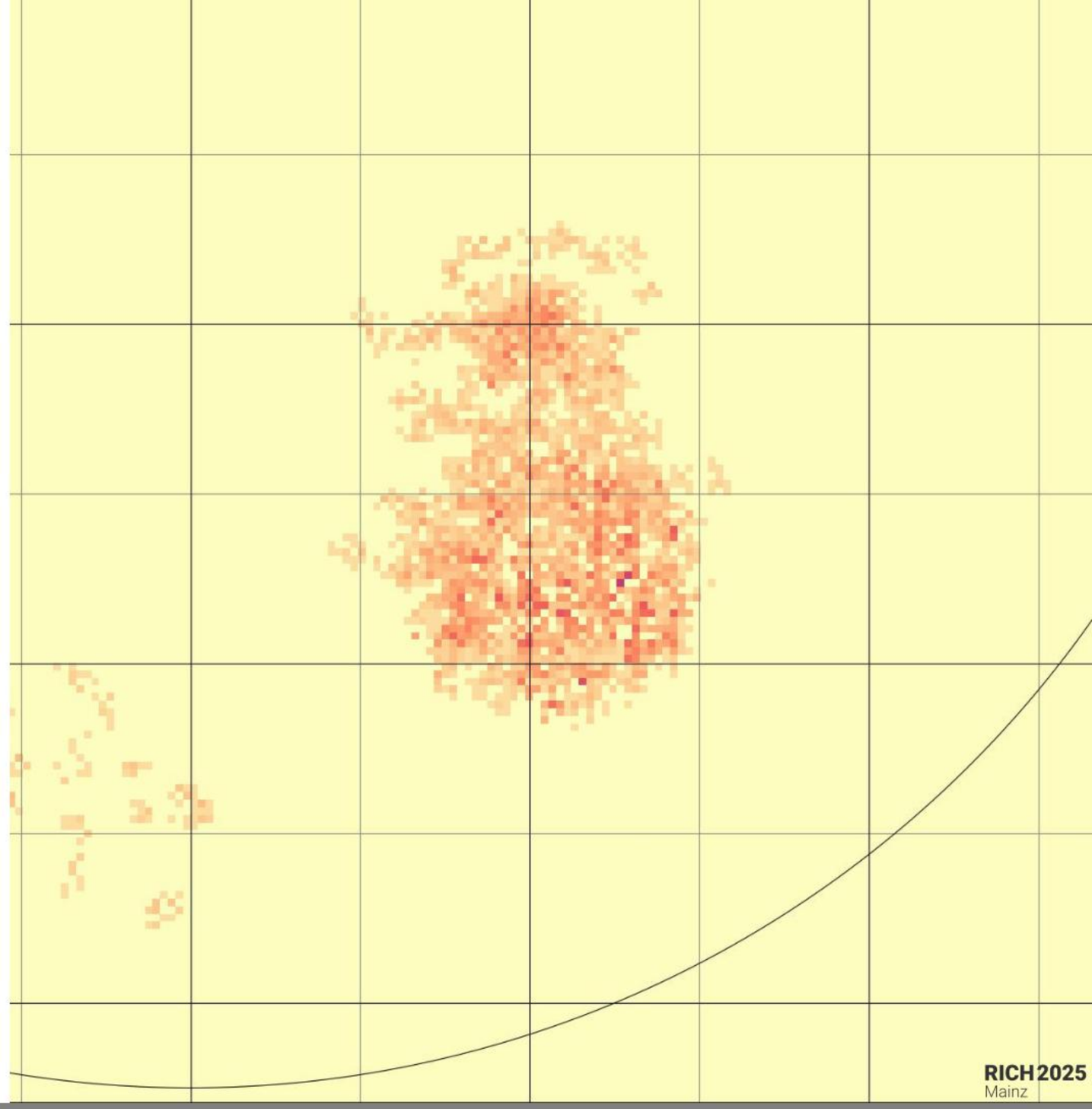
Airshower

Gamma

3.2GeV

708p.e.



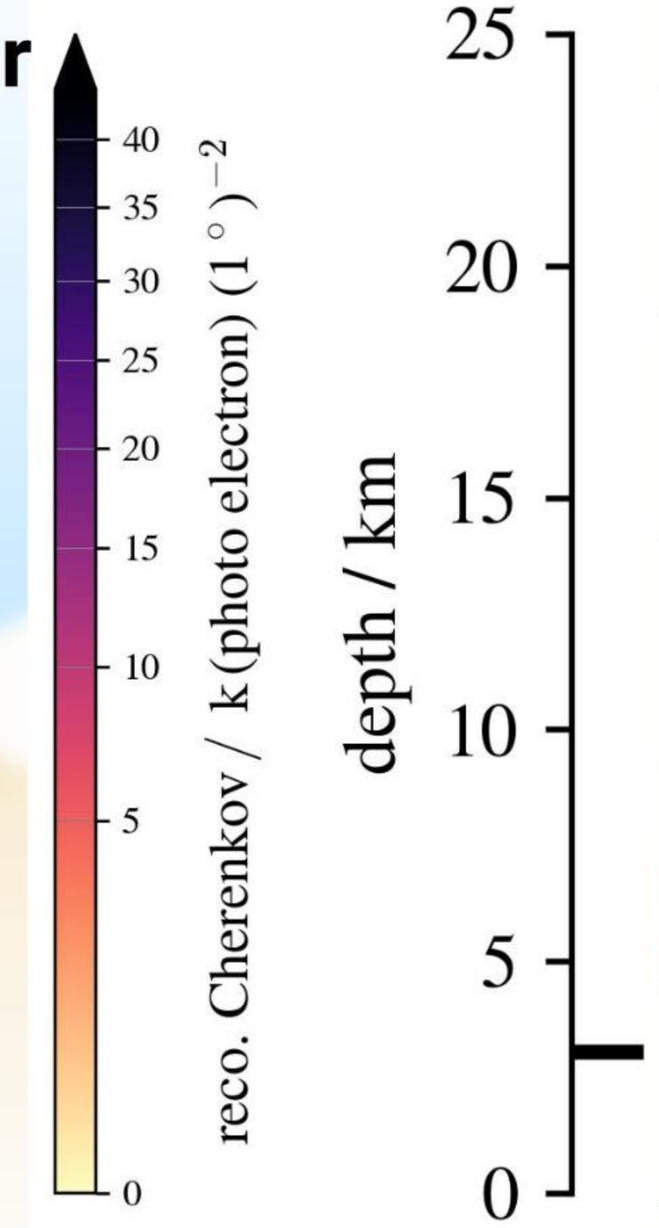


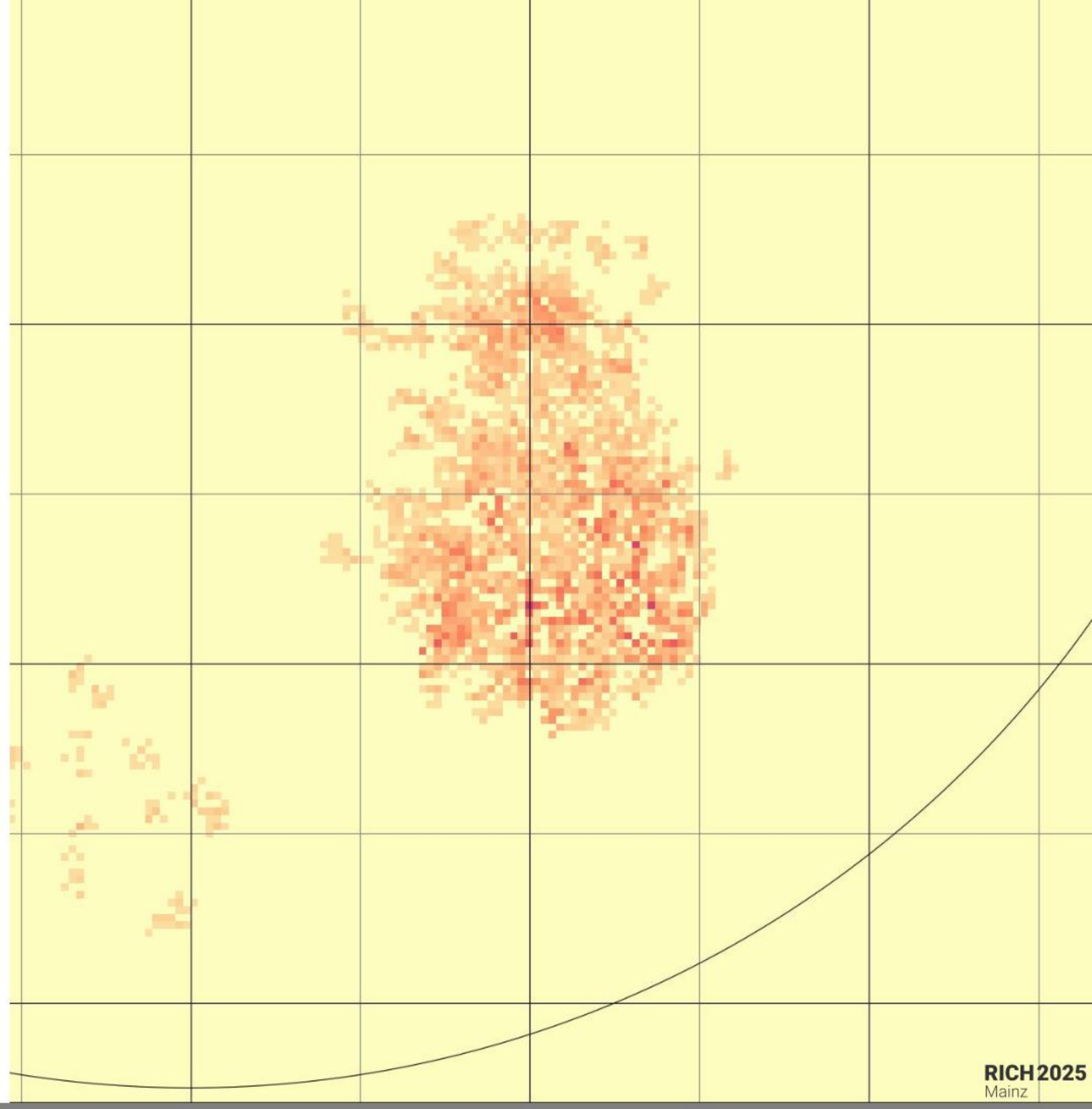
Airshower

Gamma

3.2GeV

708p.e.





Airshower

Gamma

3.2GeV

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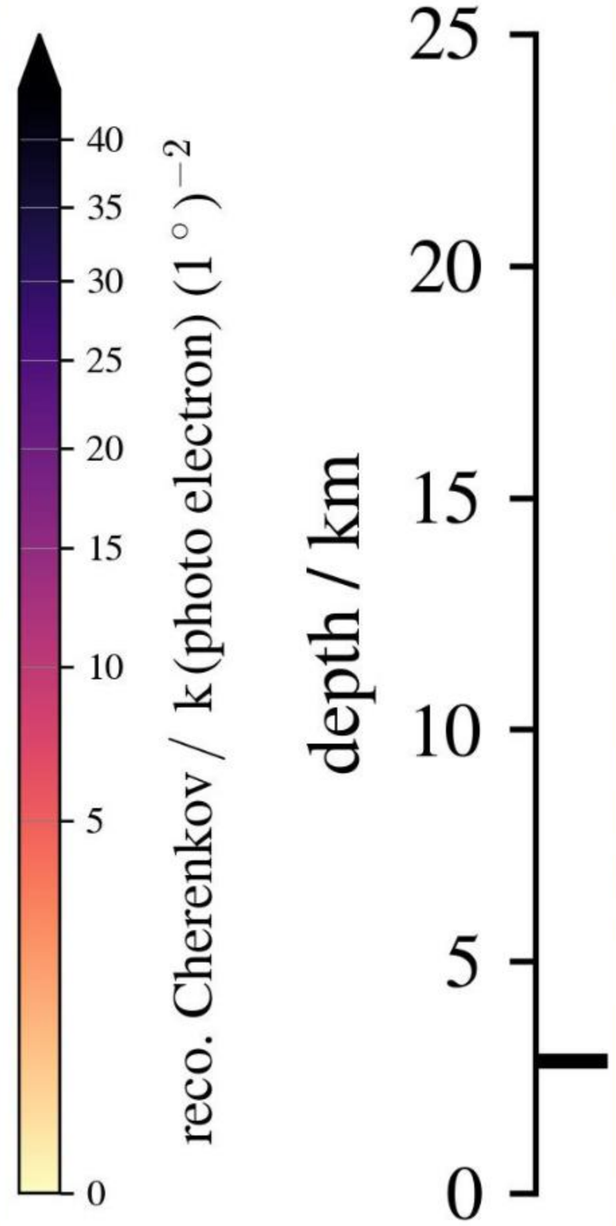
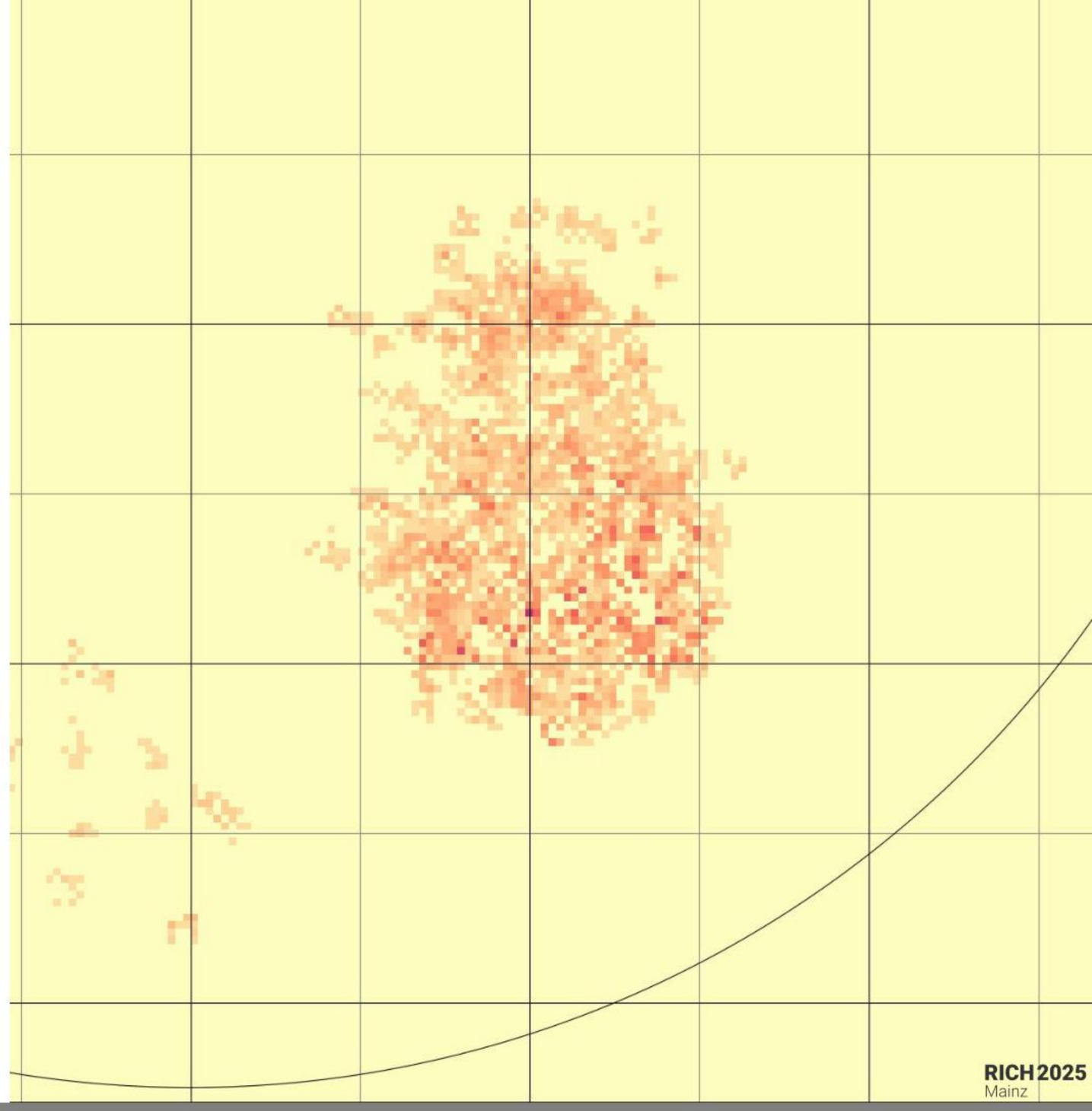


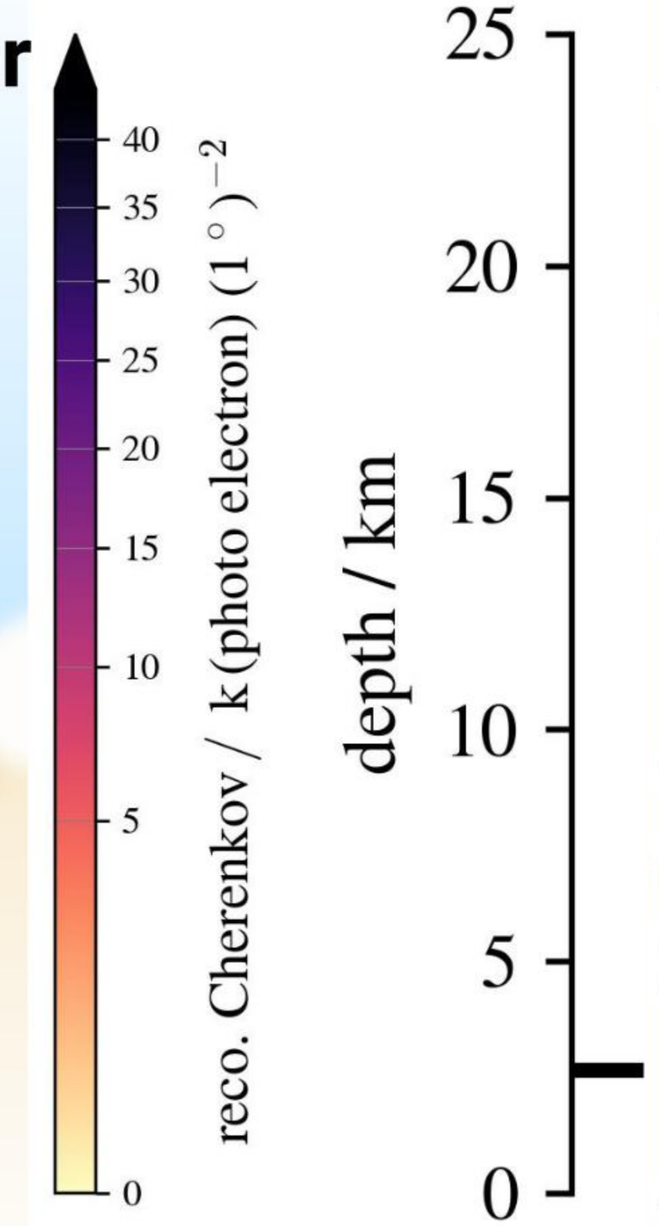


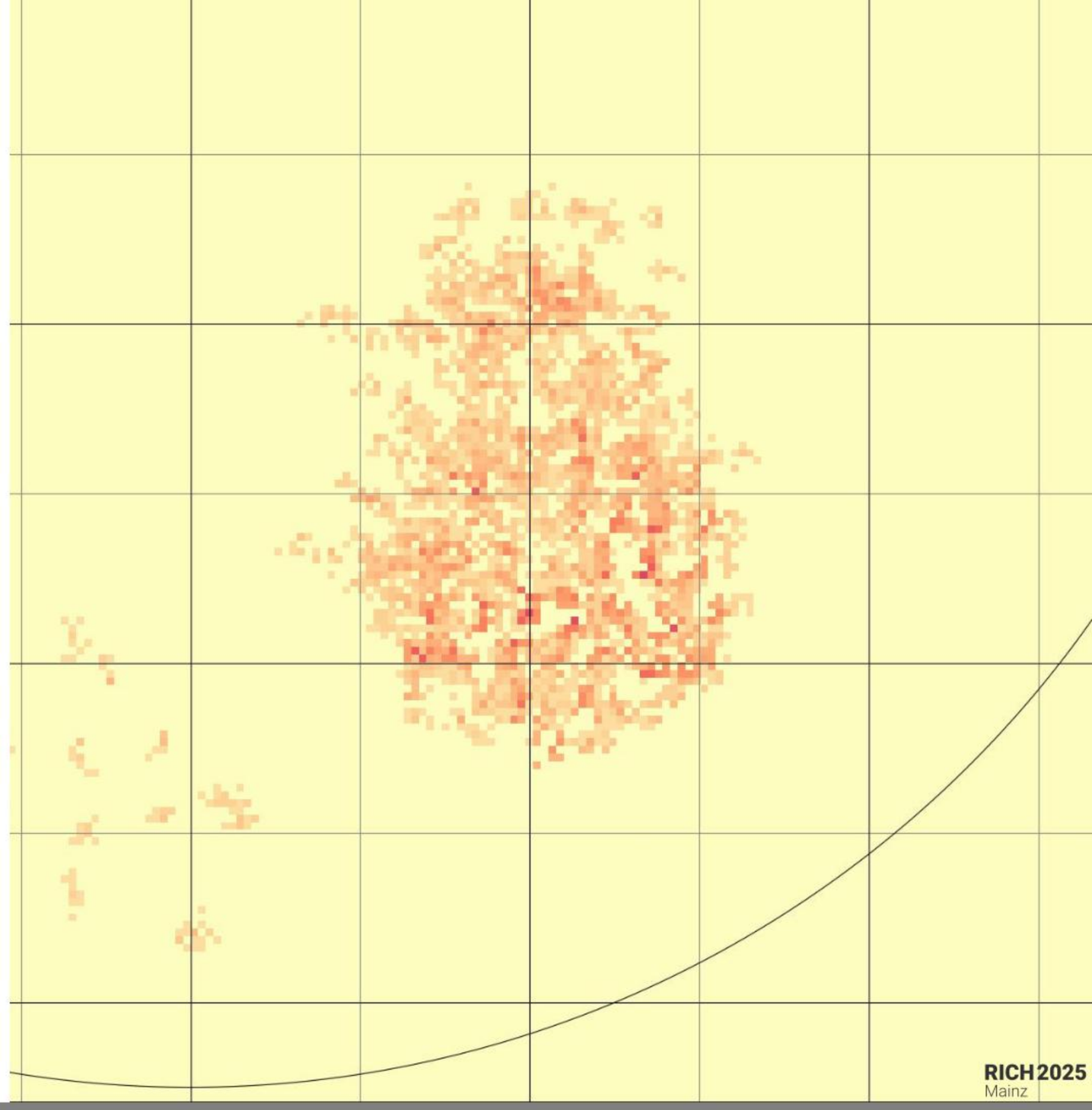
Airshower

Gamma

3.2GeV

708p.e.



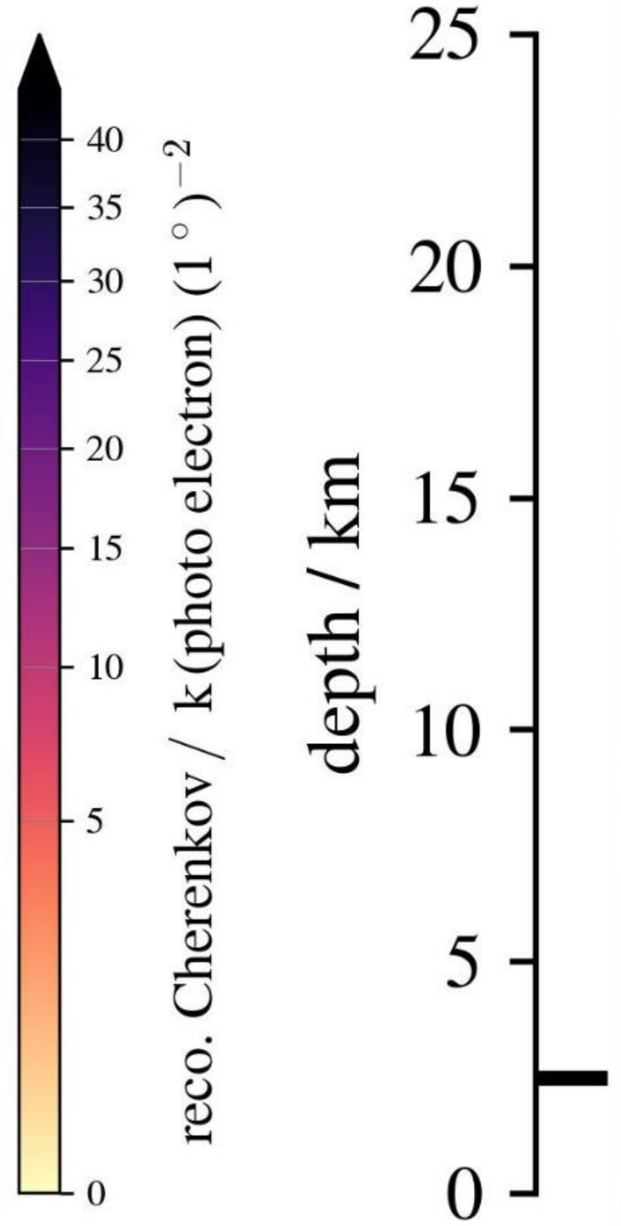


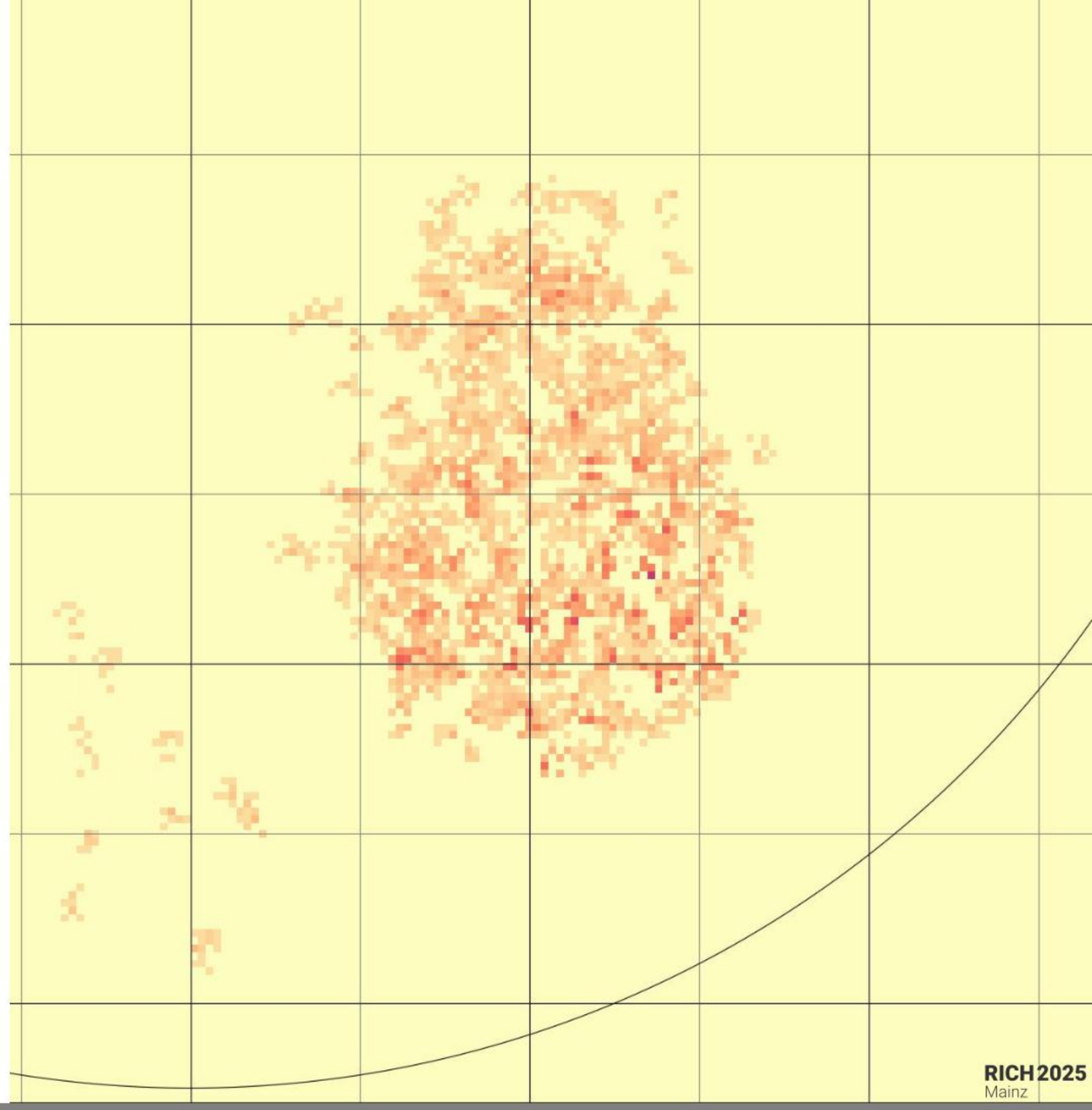
Airshower

Gamma

3.2GeV

708p.e.



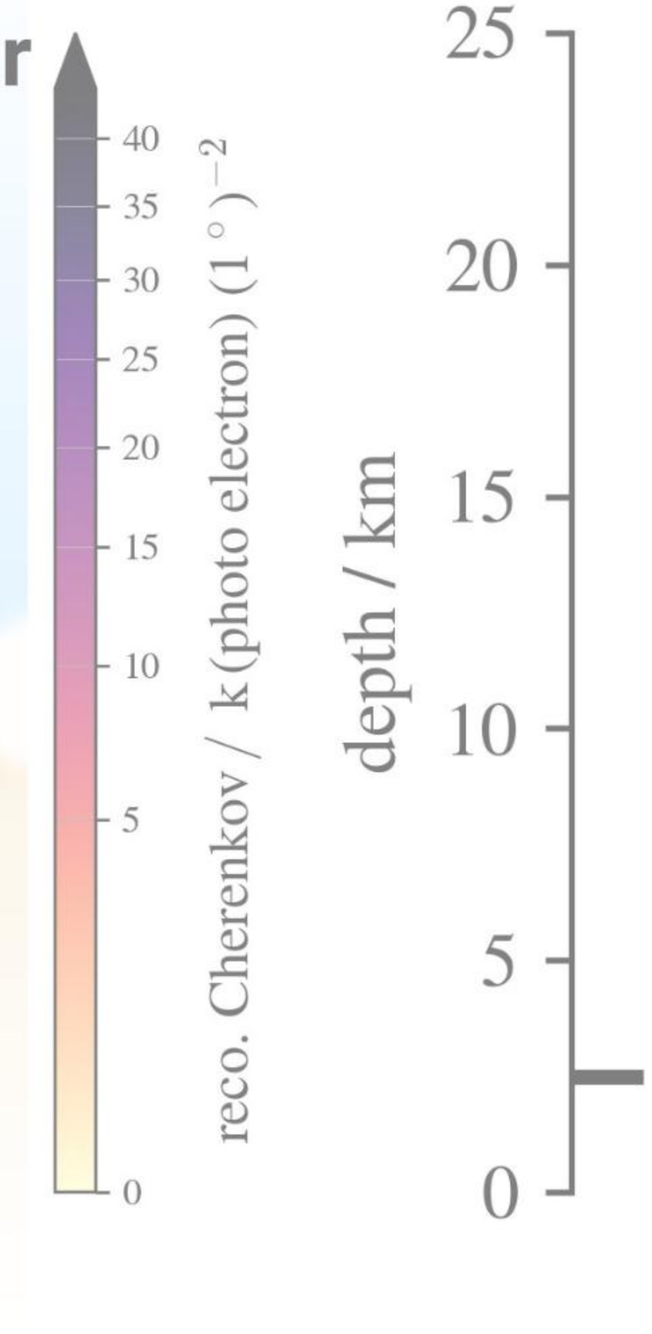


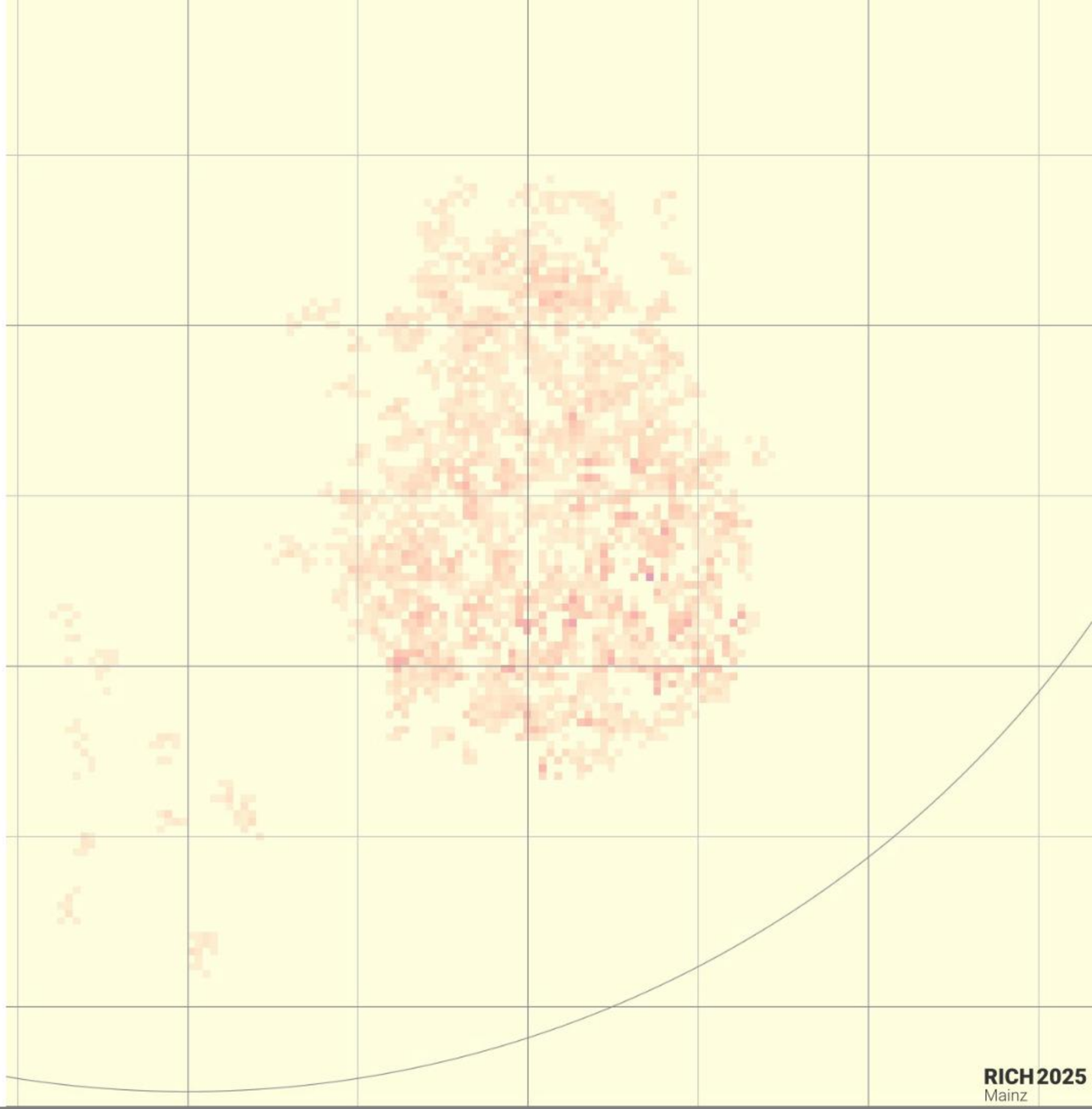
Airshower

Gamma

3.2GeV

708p.e.

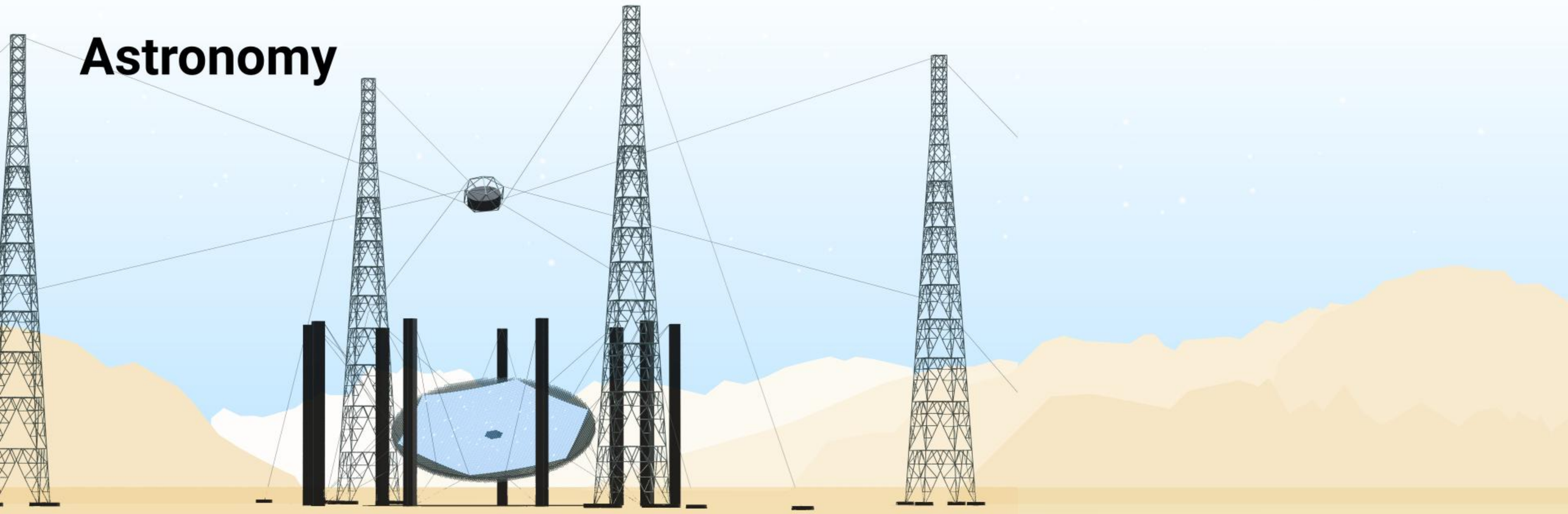




Astronomy

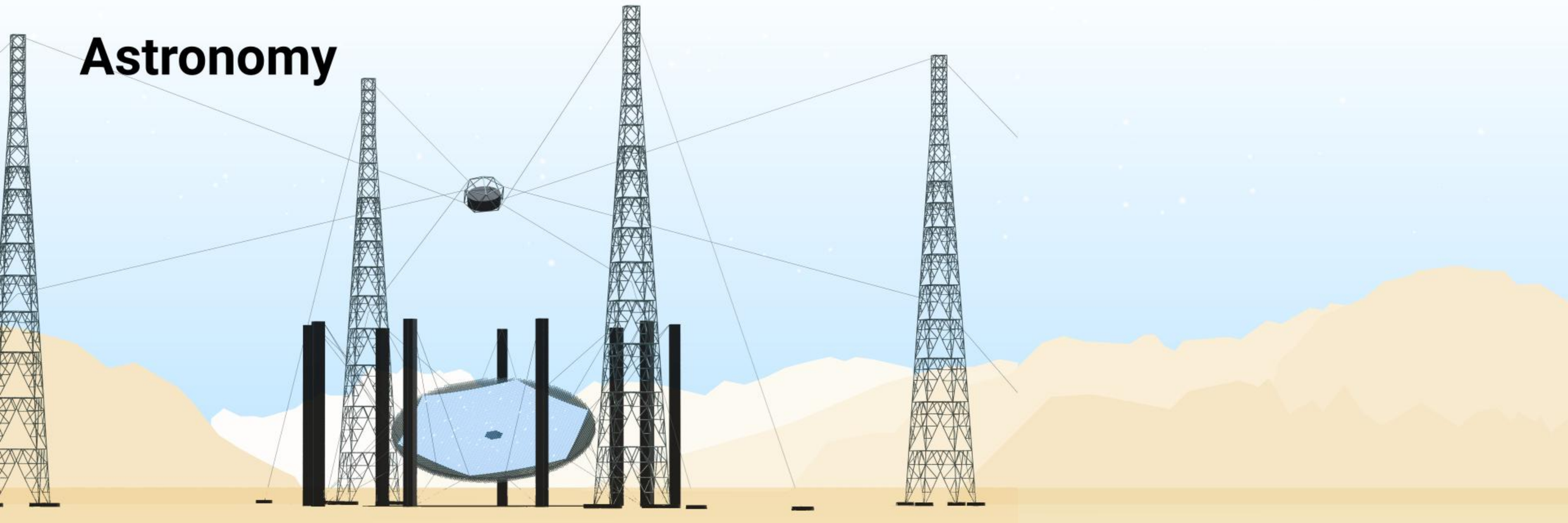
For those of you interested in astronomy

Astronomy



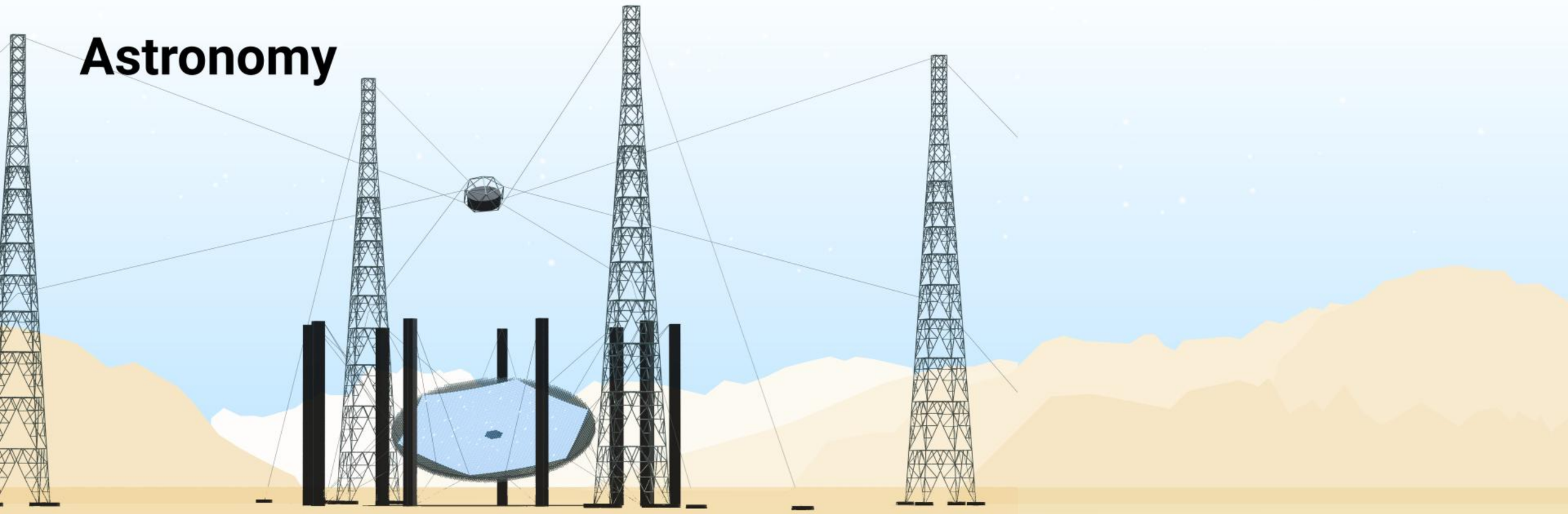
Werner and I will be happy to discuss our findings with you in the upcoming days.

Astronomy



Preliminary. Not peer reviewed. Production run 2025-03-21, analysis run 2025-09-10.
See: https://github.com/cherenkov-plenoscope/starter_kit

Astronomy



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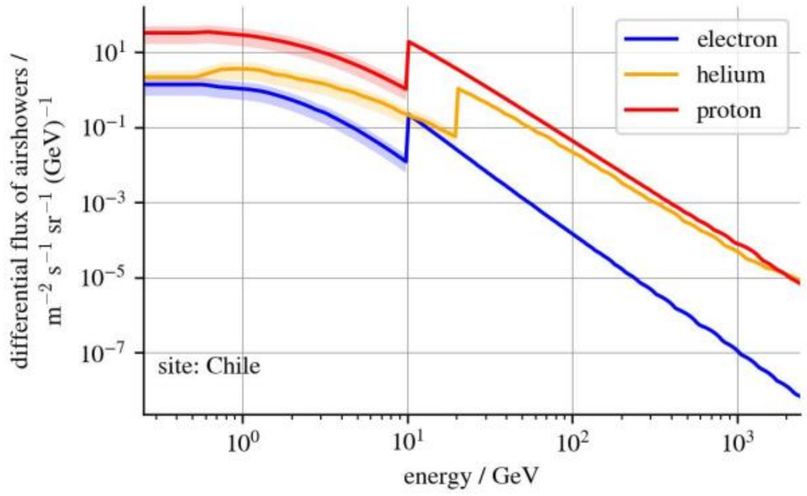

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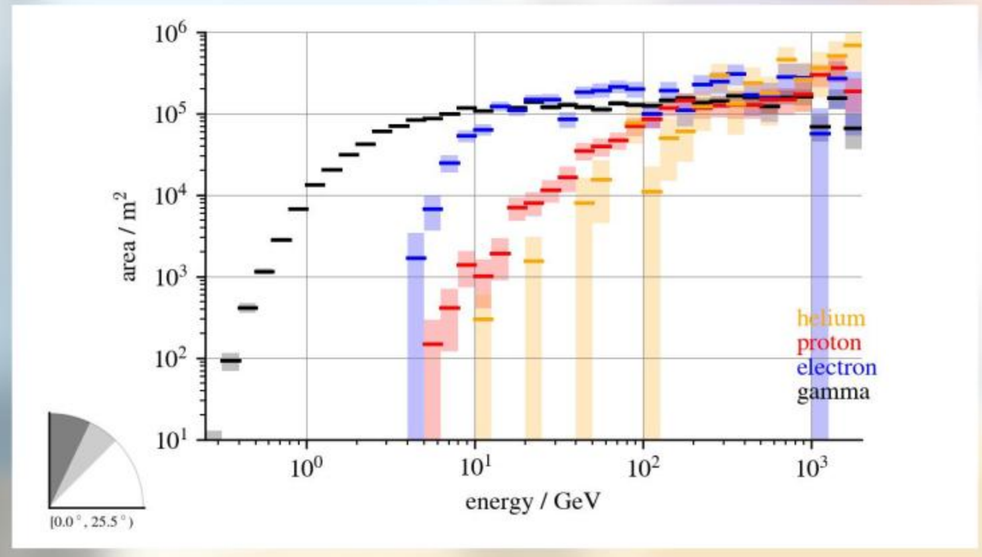

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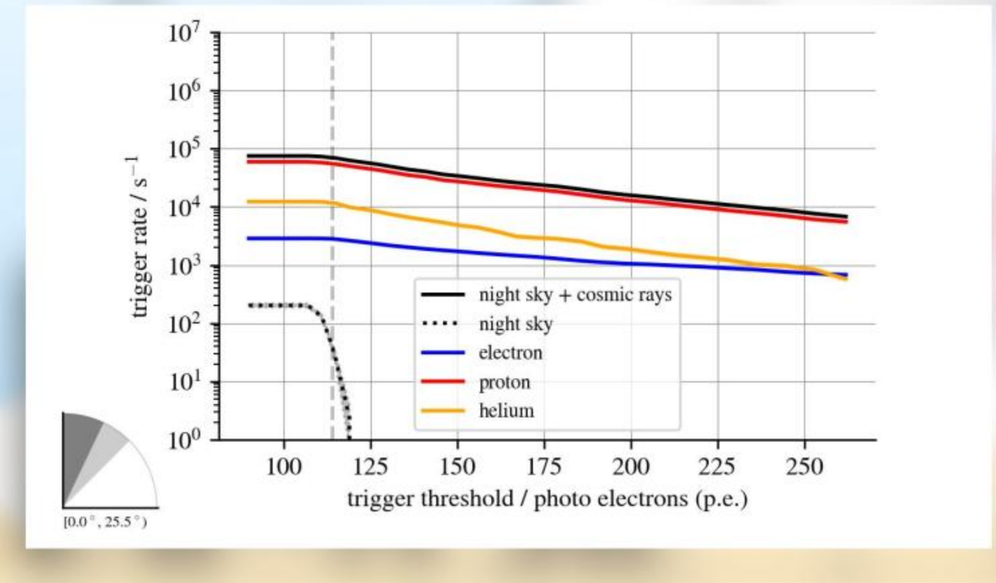

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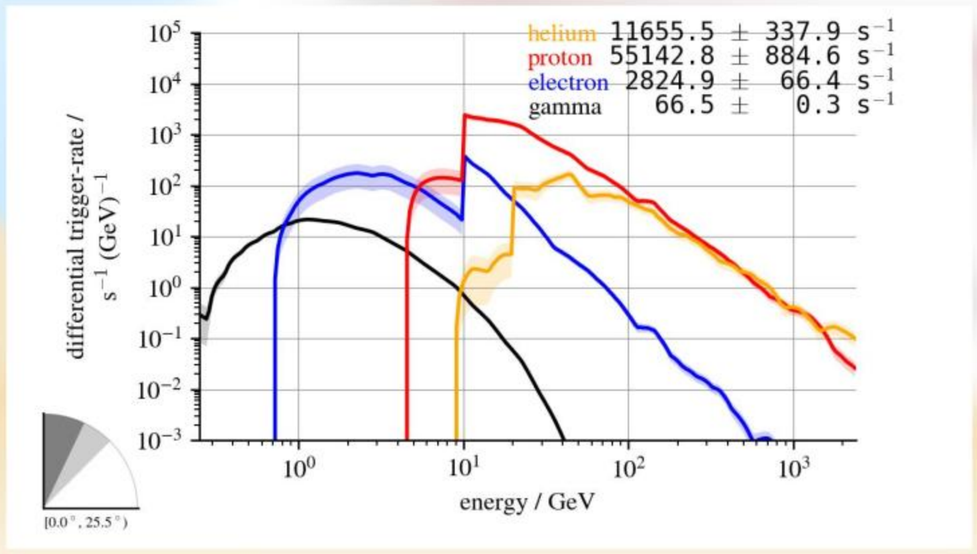

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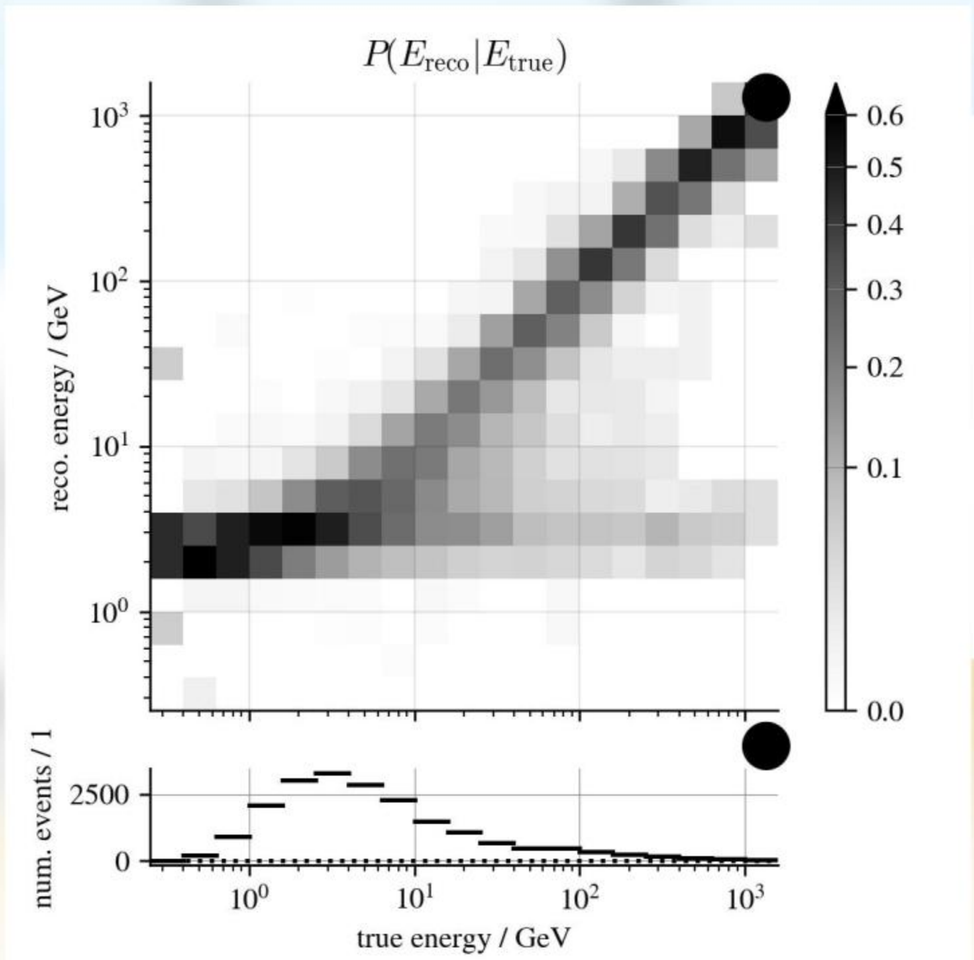

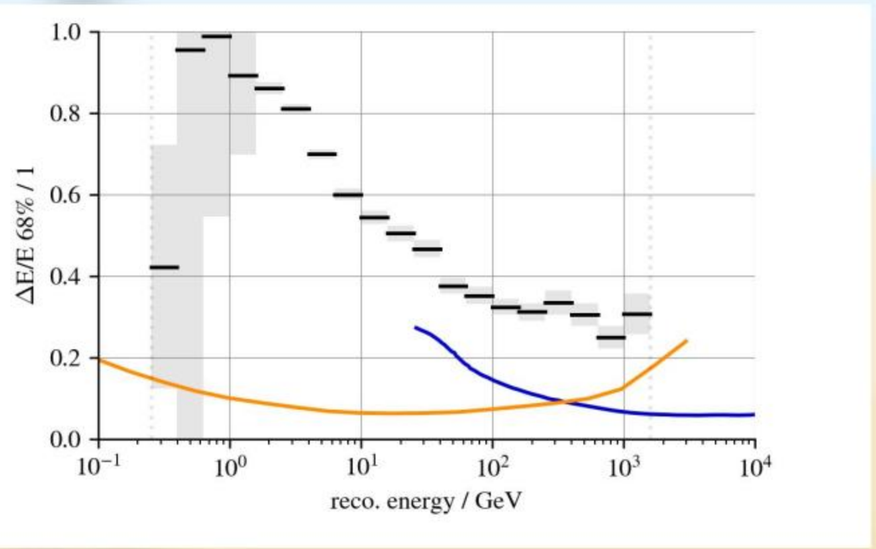

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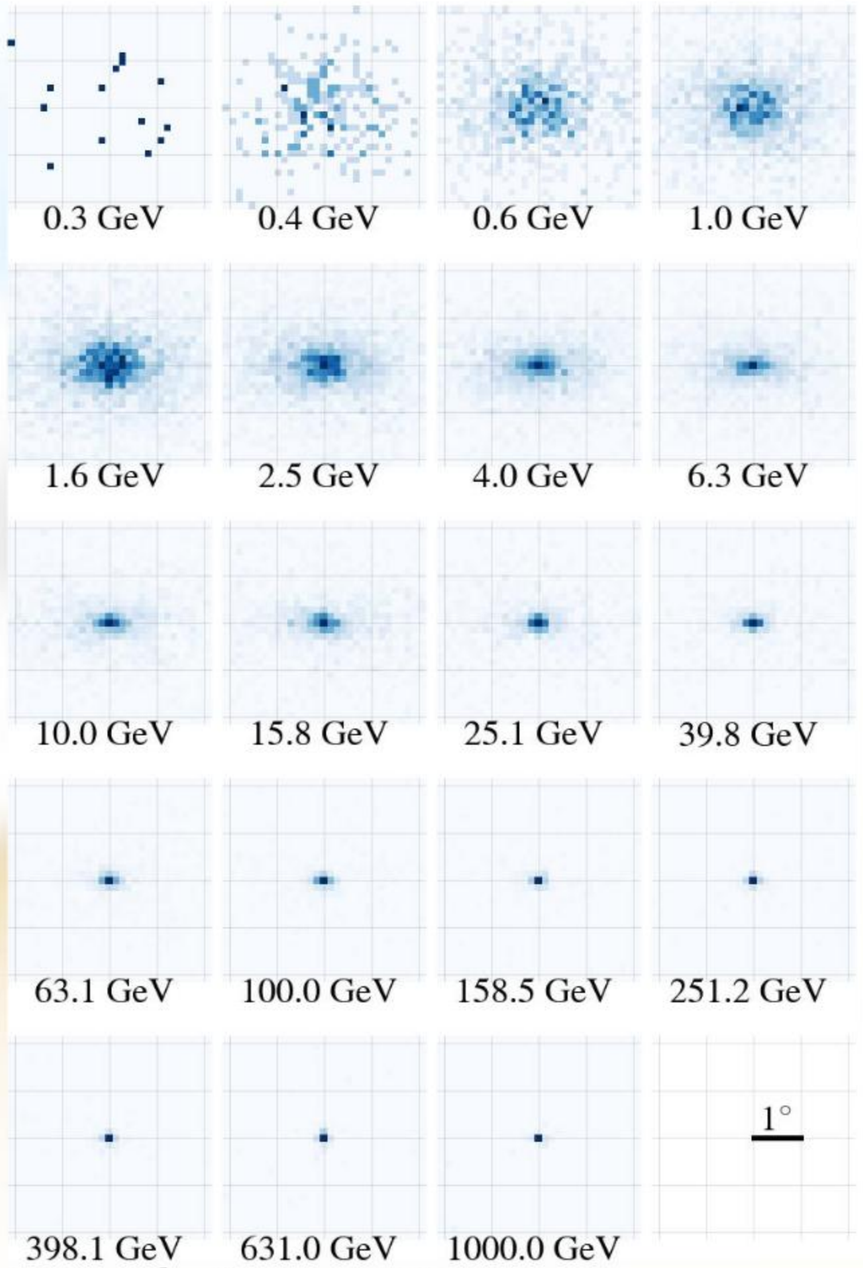

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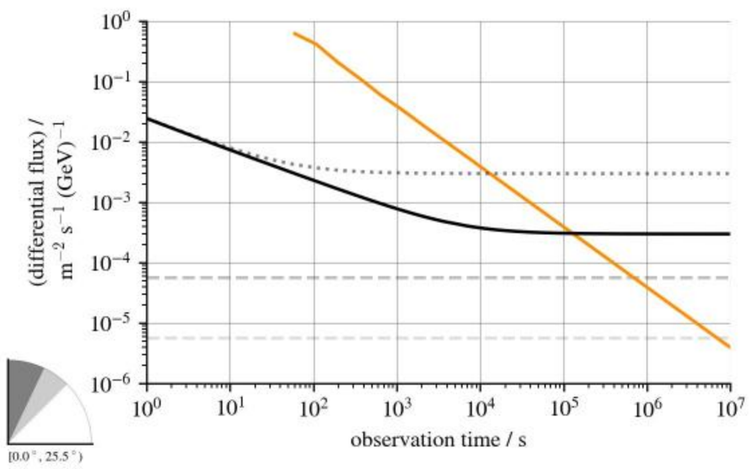

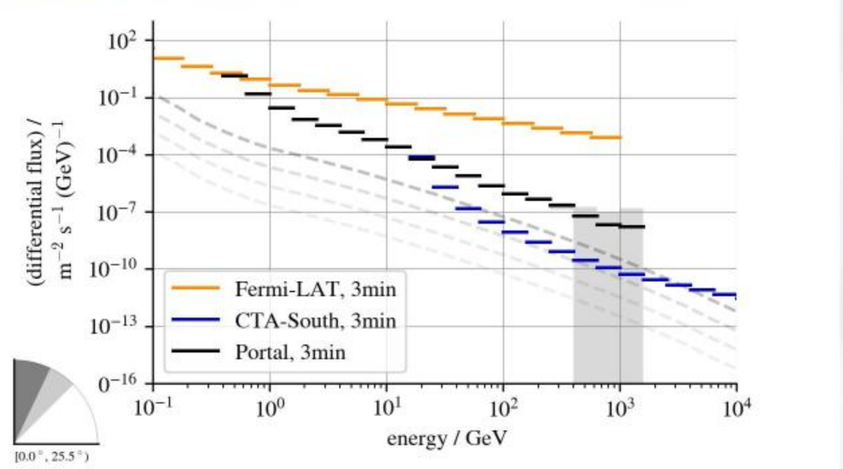

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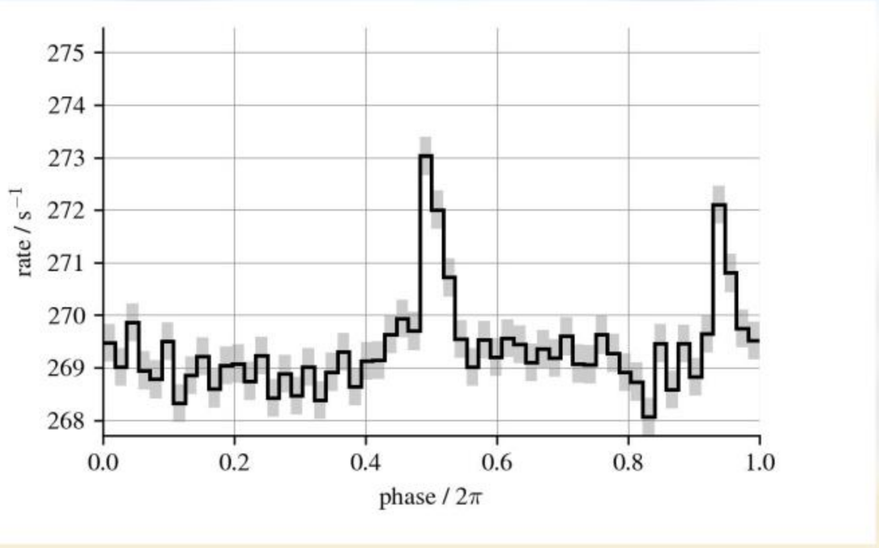

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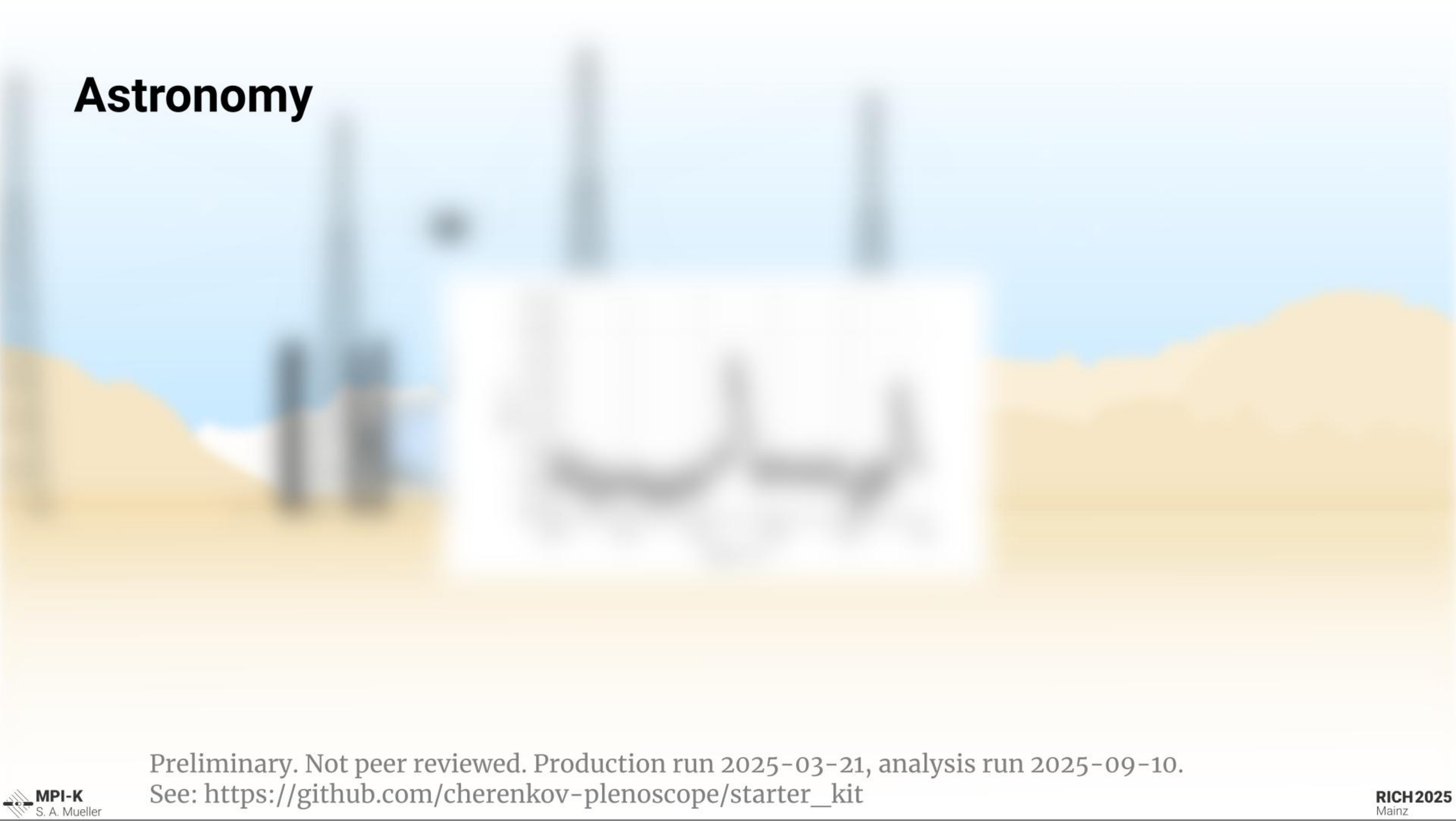

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Astronomy

Astronomy

History of plenoptics

But for those who want to learn more about plenoptics, we compiled a brief overview.

History of plenoptics

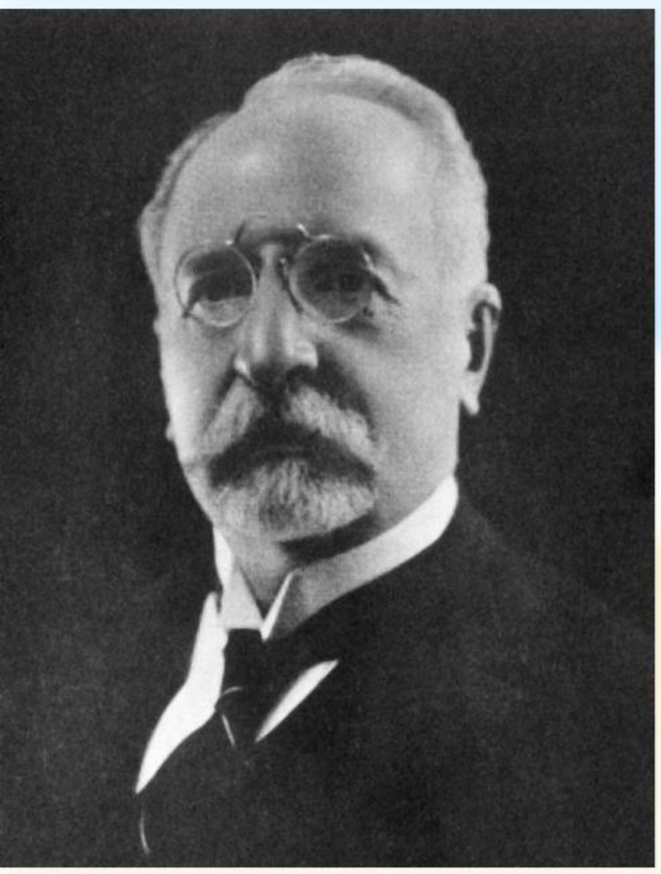
(light fields, wavefronts, integral images, lenticular optics)

Light fields, wavefronts, integral images, and lenticular optics are all related to plenoptic perception

History of plenoptics

1904

Hartmann's `Filter' or `Mask'



Zeitschrift für Instrumentenkunde.

Redaktionskuratorium:

Geh. Reg.-Rat Prof. Dr. **H. Landolt**, Vorsitzender, Prof. Dr. **A. Westphal**, geschäftsführendes Mitglied, Prof. Dr. **E. Abbe**, Dr. **H. Krüss.**

Redaktion: Prof. Dr. **St. Lindeck** in Charlottenburg-Berlin.

XXIV. Jahrgang. **Januar 1904.** Erstes Heft.

Objektivuntersuchungen.

Von

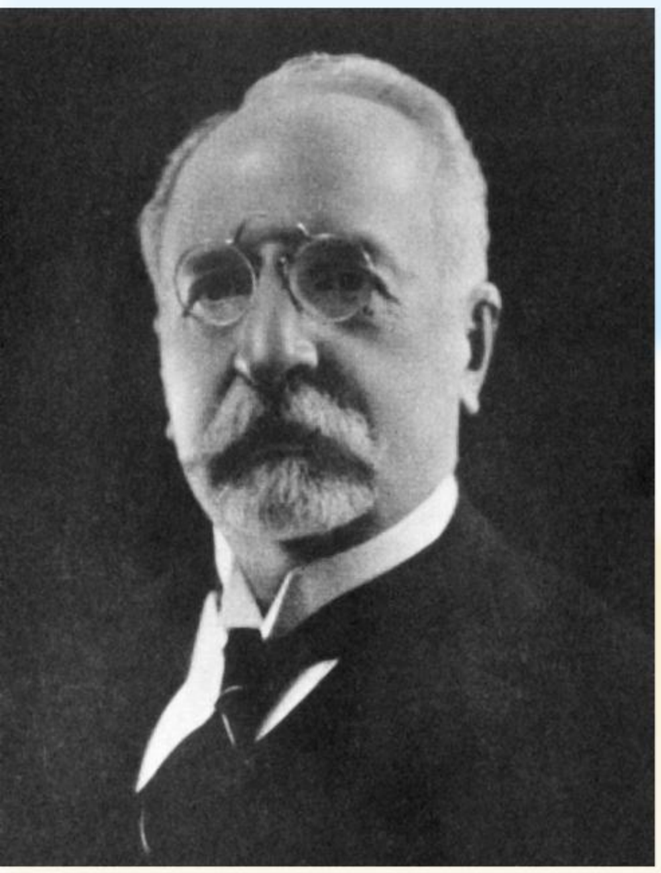
J. Hartmann in Potsdam.

J. Hartmann, Objektivuntersuchungen, Zeitschrift fuer Instrumentenkunde, Vol. 1, 1904

In nineteen-o-four, Hartmann started to investigate aberrations systematically by using masks on imaging lenses.

History of plenoptics 1904

Hartmann's `Filter' or `Mask'



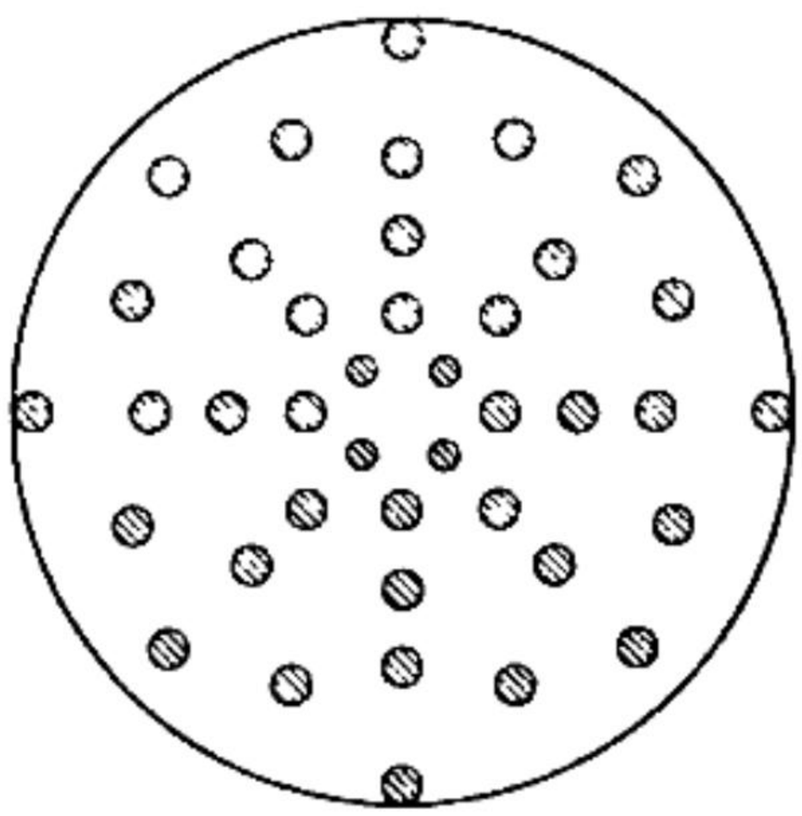


Fig. 2.

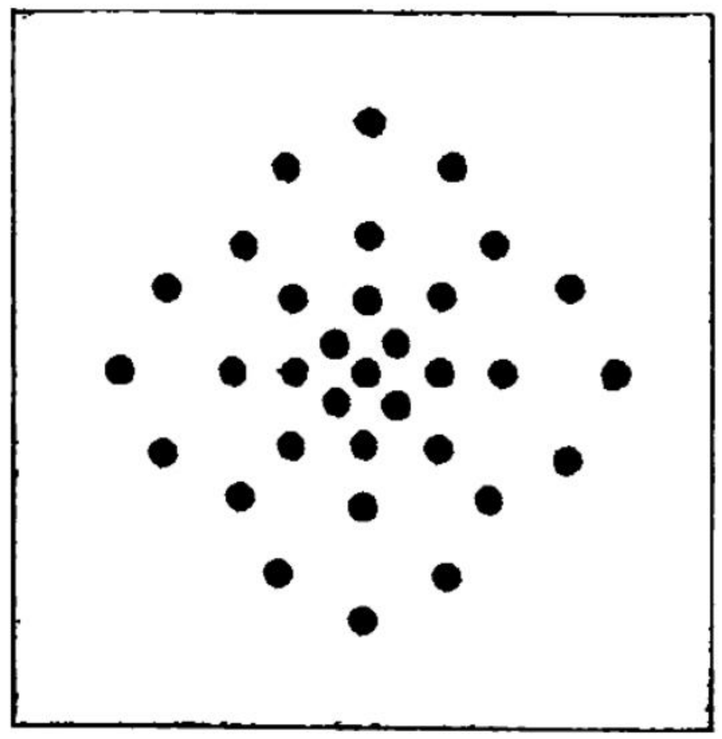


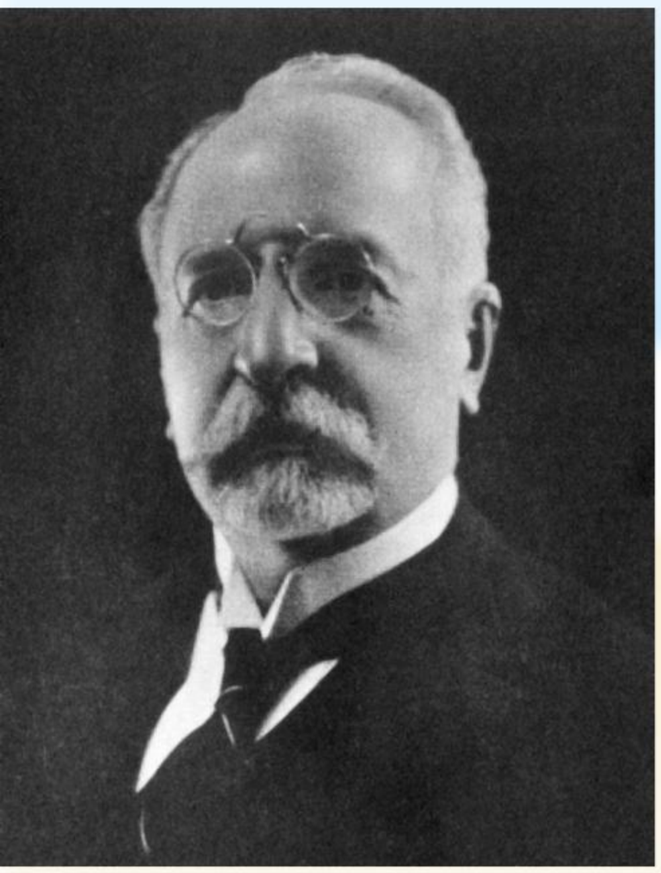
Fig. 4.

J. Hartmann, Objektivuntersuchungen, Zeitschrift fuer Instrumentenkunde, Vol. 1, 1904

History of plenoptics

1904

Hartmann's `Filter' or `Mask'



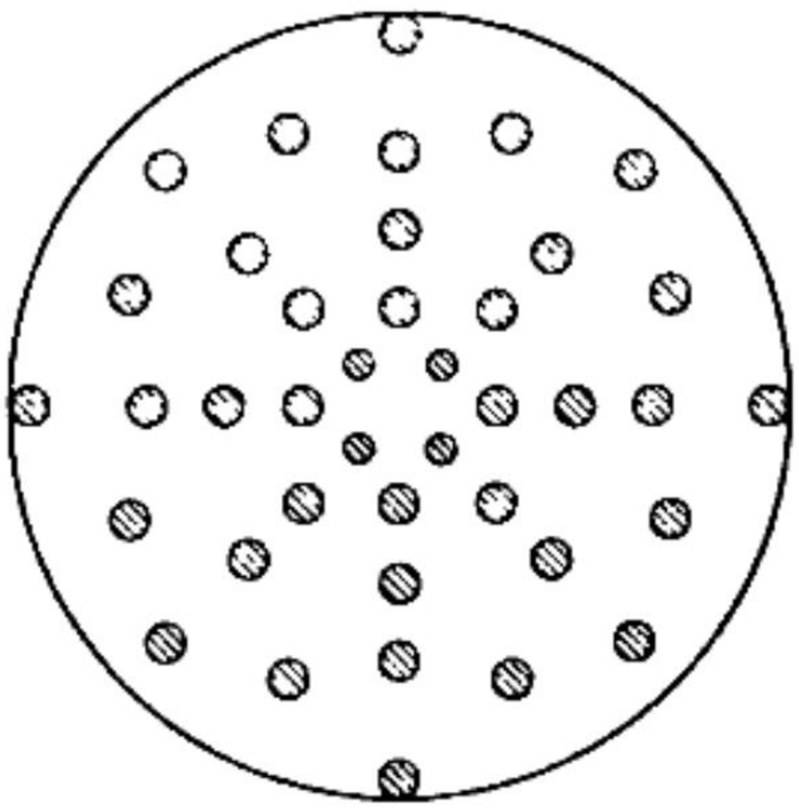


Fig. 2.

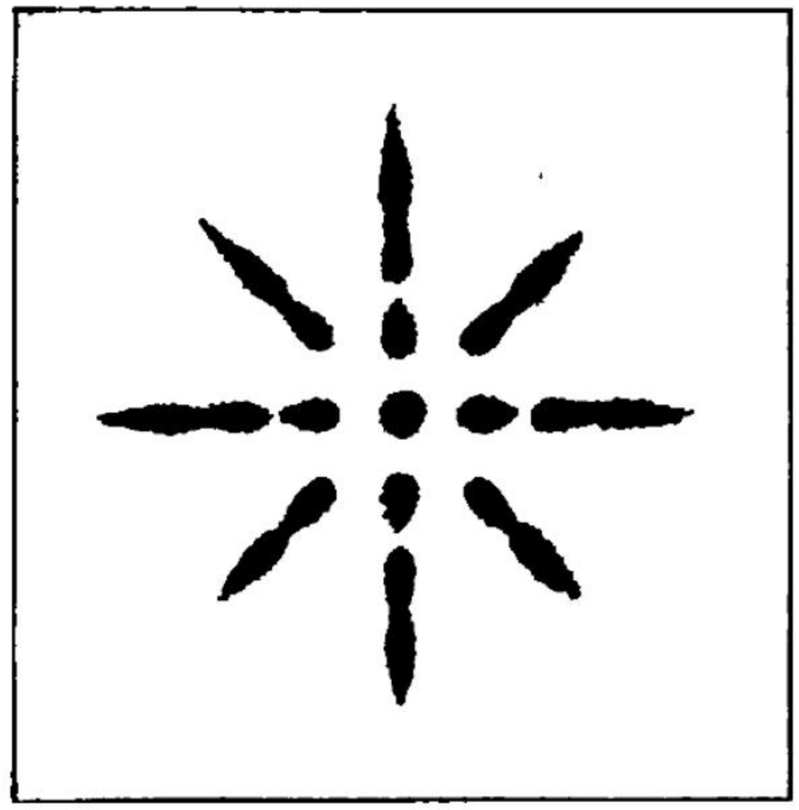


Fig. 3.

J. Hartmann, Objektivuntersuchungen, Zeitschrift fuer Instrumentenkunde, Vol. 1, 1904

History of plenoptics 1908

Lippmann's display

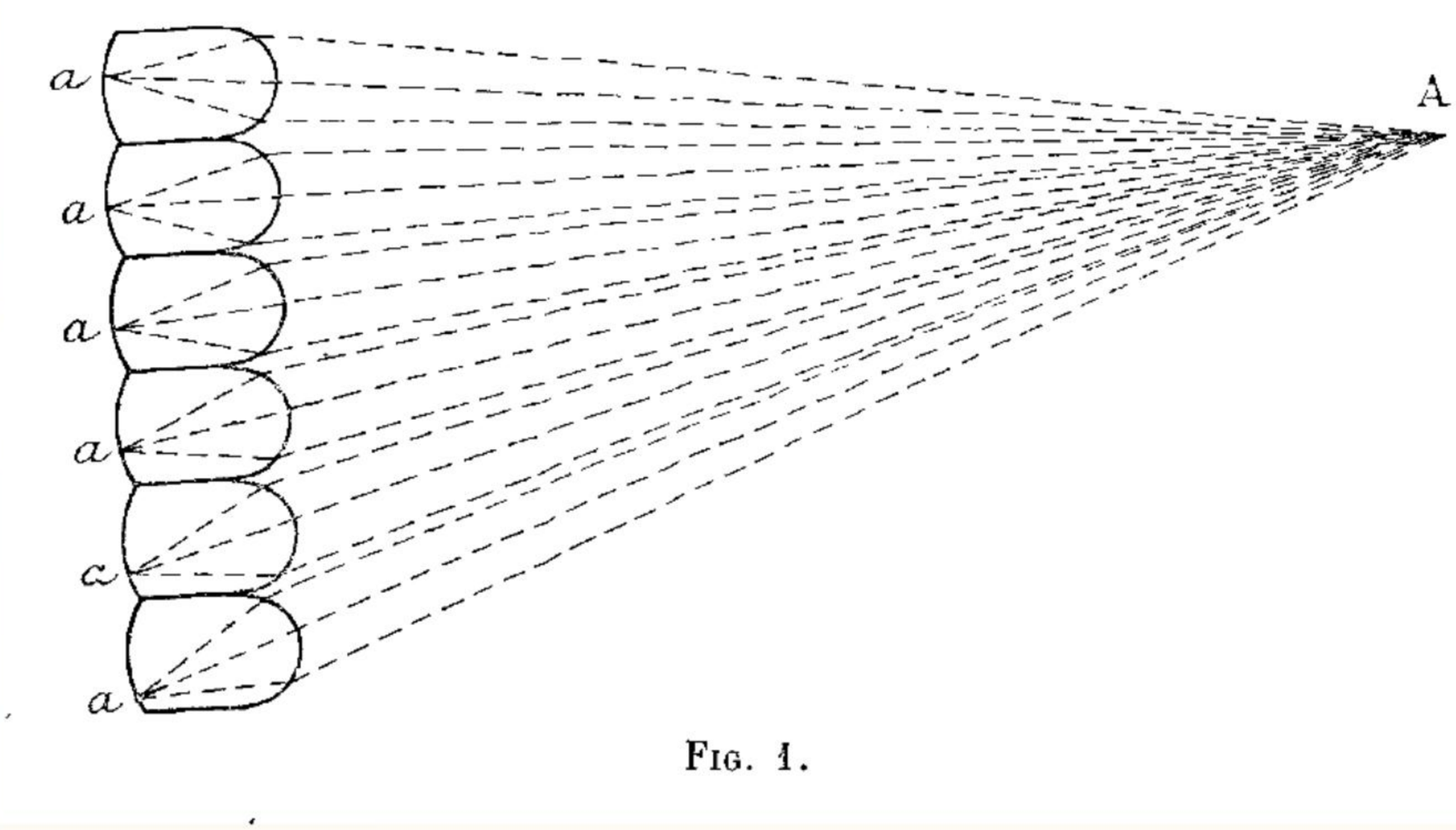


Fig. 1.

G. Lippmann, Epreuves reversibles donnant la sensation du relief, J. Phys. Theor. Appl. 7 821-825, 1908

In nineteen-o-eight, Lipmann suggested to use an array of lenses to build a display which would allow the perception of depth. Lipmann proposed to use an array of lenses for this.

History of plenoptics

Lippmann's display in (1D)
(lenticular display)

1940s until today

By World Imaging - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=11736454

In the nineteen-fourties, Lipmanns's lens array became a reality.

History of plenoptics

Lippmann's display in (1D)
(lenticular display)

1940s until today

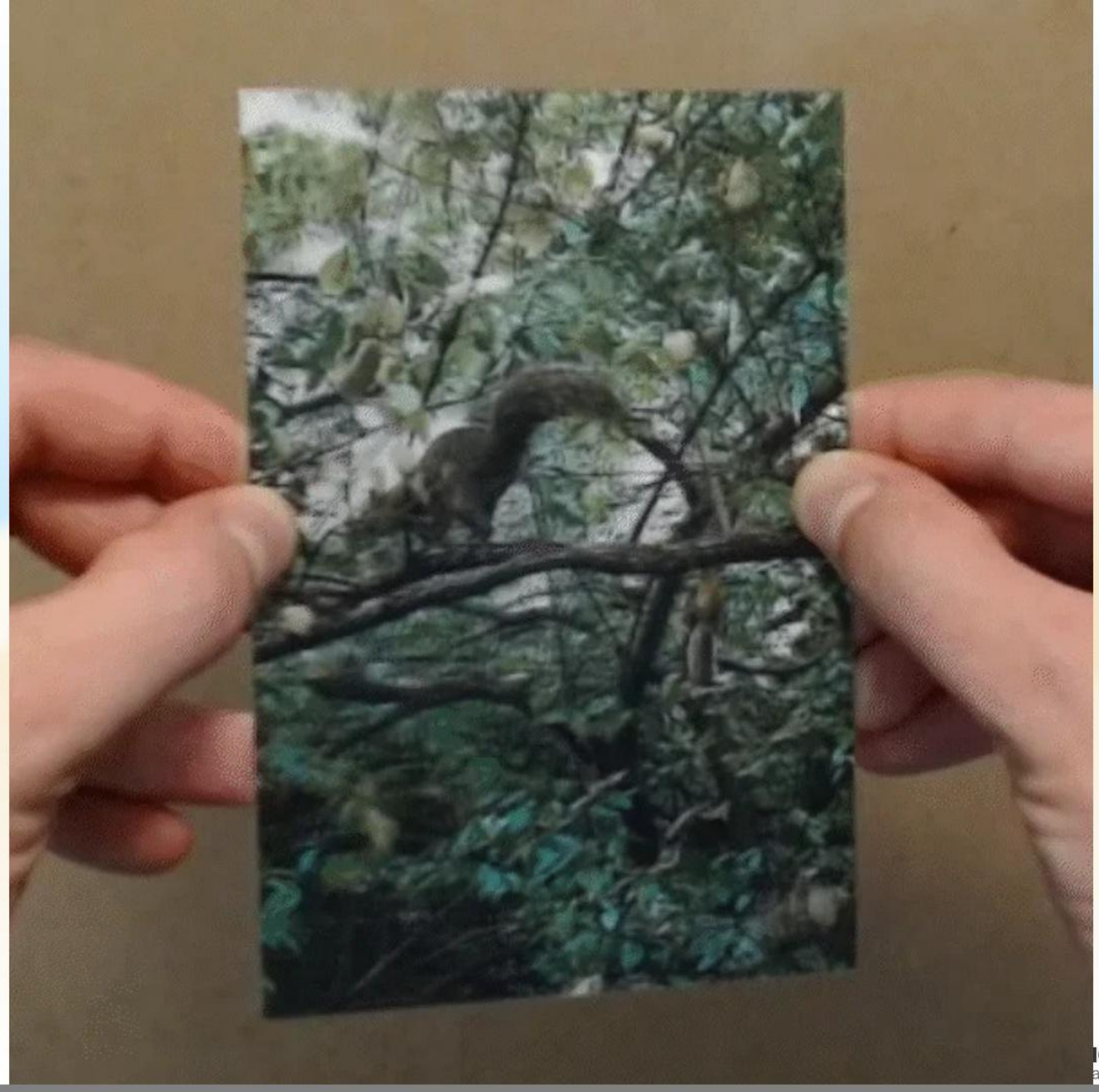
since 1980s

https://petapixel.com/2023/02/15/photographer-makes-real-life-gifs-via-lenticular-printing/

And dedicated cameras were made to create the required `integral images'.

History of plenoptics

Lippmann's display in (1D)
(lenticular display)

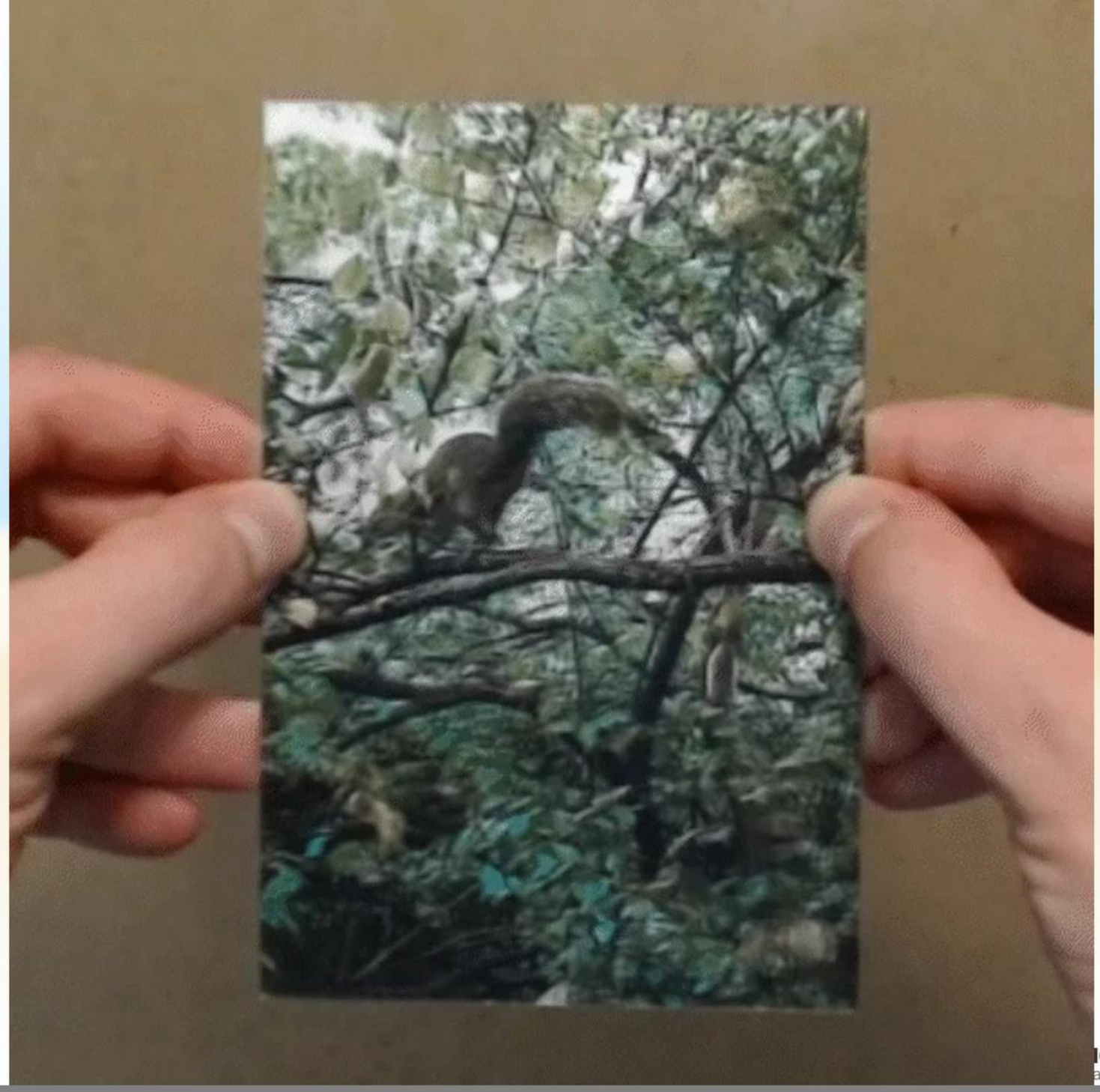


https://petapixel.com/2023/02/15/photographer-makes-real-life-gifs-via-lenticular-printing/

Since then, children are mesmerized by these lenticular displays.

History of plenoptics

Lippmann's display in (1D)
(lenticular display)

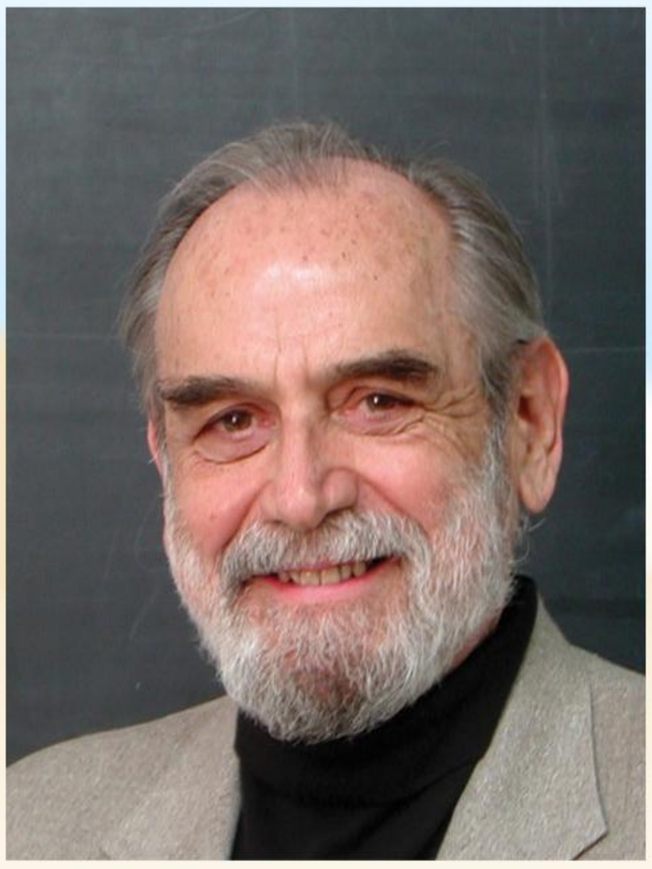


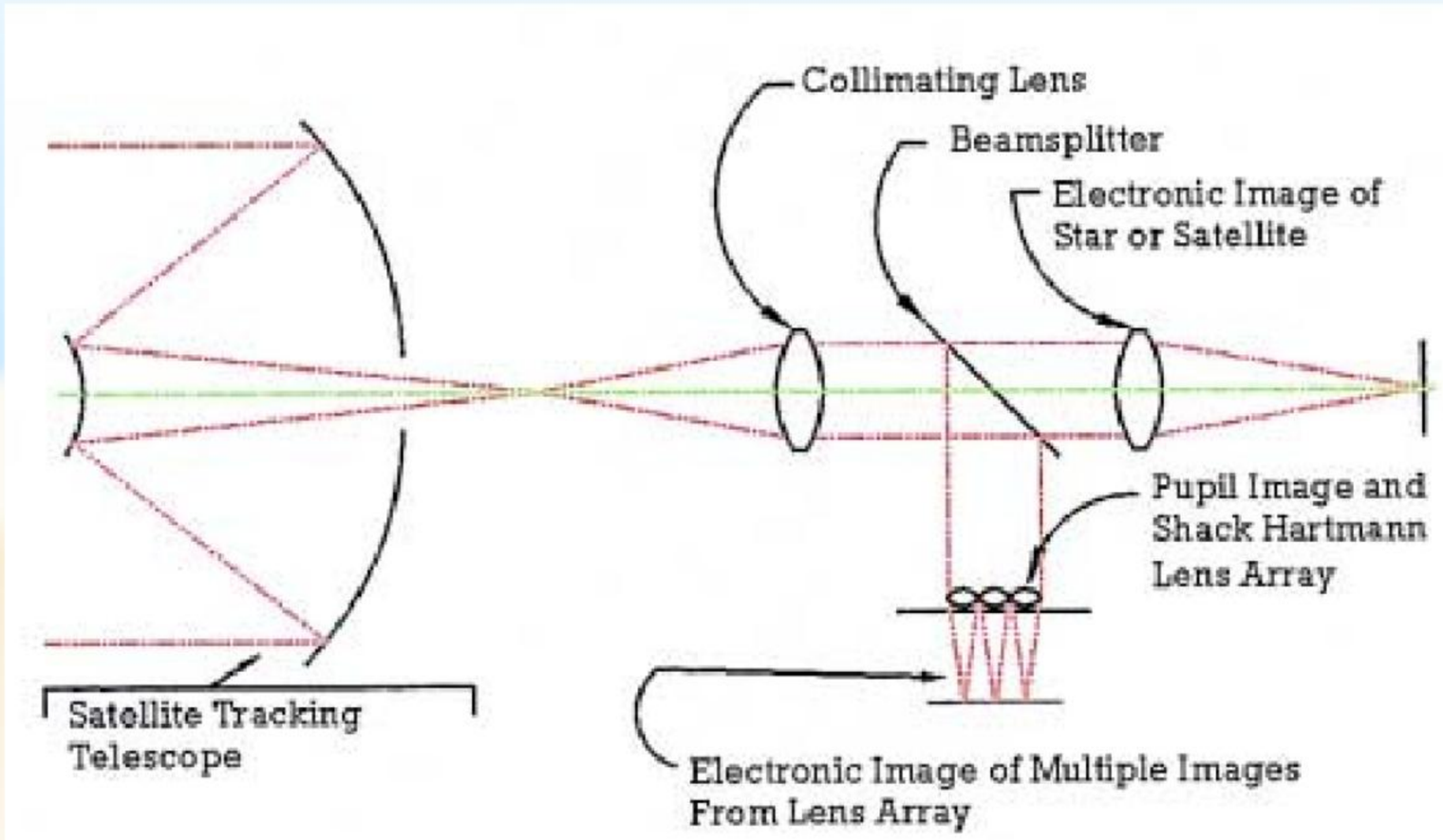
https://petapixel.com/2023/02/15/photographer-makes-real-life-gifs-via-lenticular-printing/

History of plenoptics

Shack's and Platt's lens array

1960 - 1970





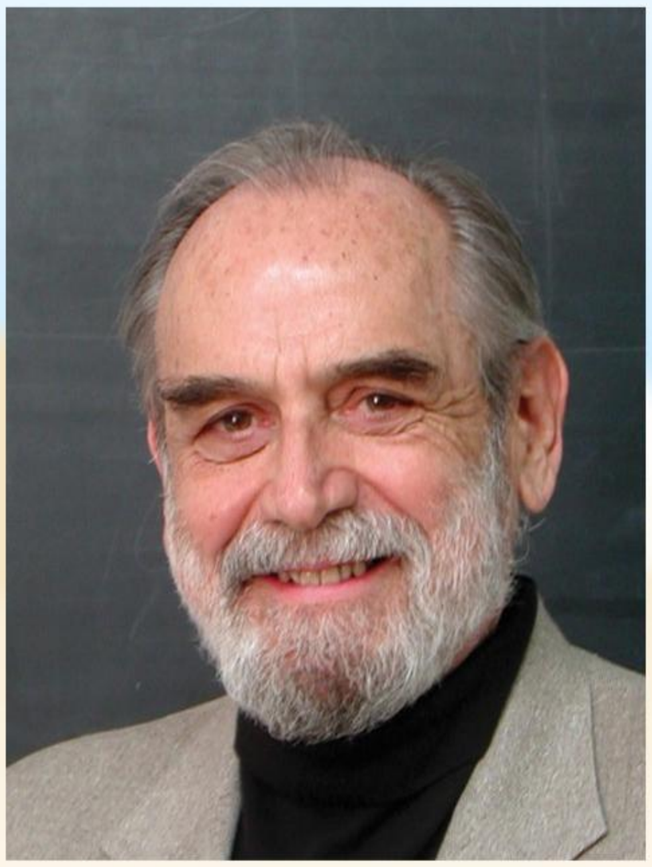
R. Shack and B. C. Platt, History and principles of Shack-Hartmann wavefront sensing
Journal of refractive surgery, Vol.17 No.5, p573-p577, 2001

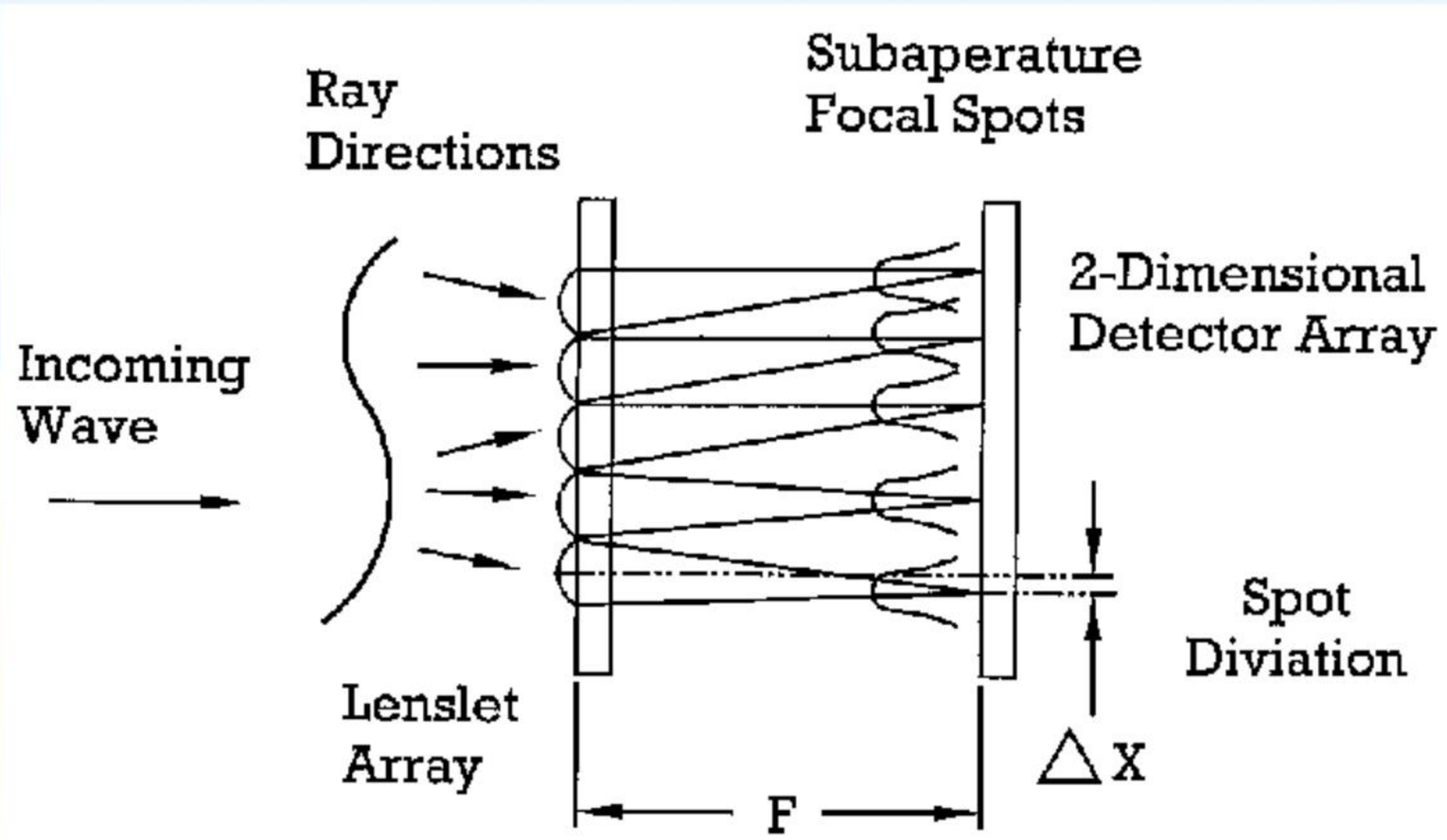
In a more serious environment, Shack was asked to develop a camera to track satellites from ground. But atmospheric distortions limited all progress. Shack realized that with Hartmann's filter one could monitor distortions caused by the atmosphere.

History of plenoptics

1960 - 1970

Shack's and Platt's lens array





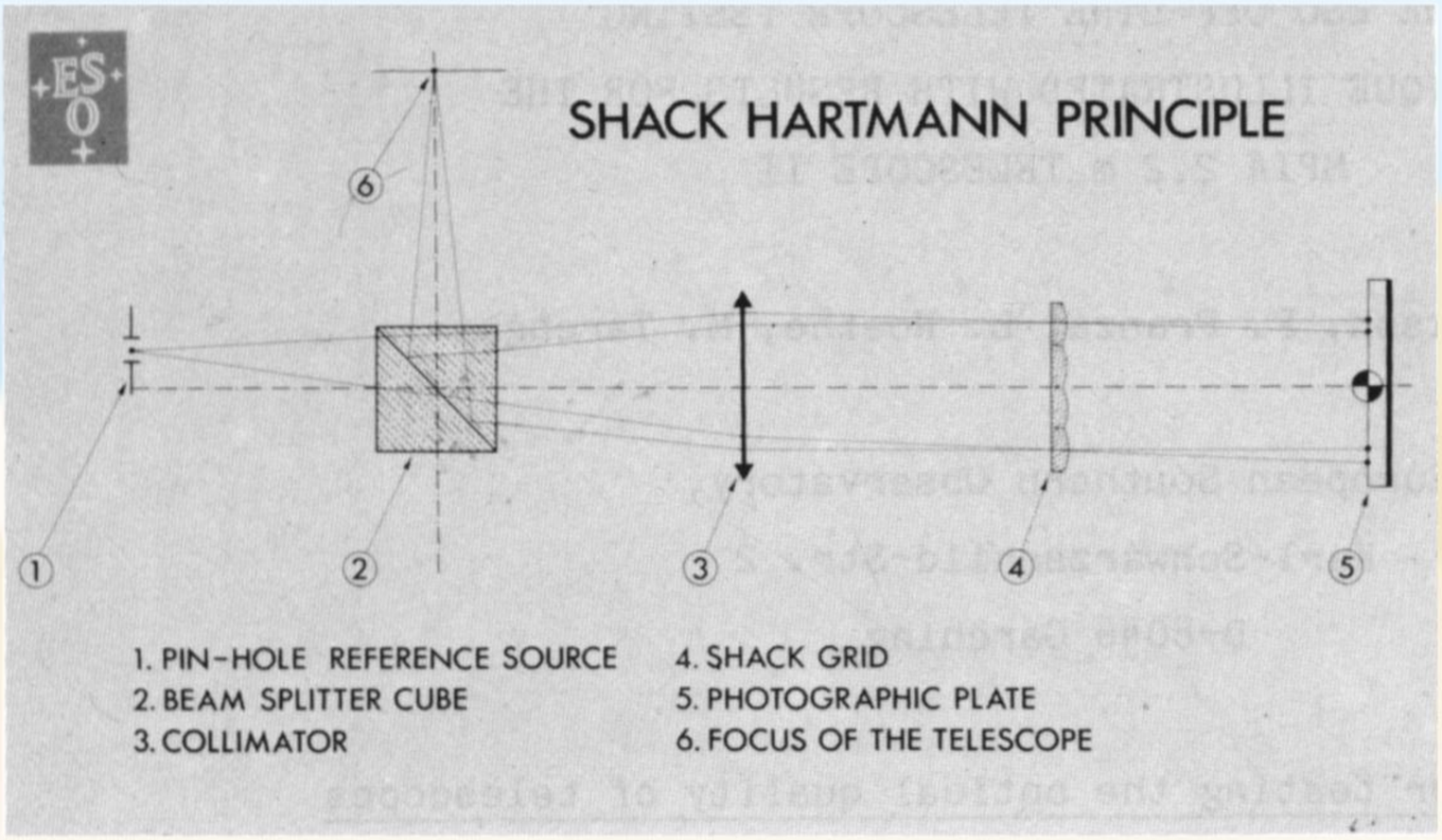
R. Shack and B. C. Platt, History and principles of Shack-Hartmann wavefront sensing
Journal of refractive surgery, Vol.17 No.5, p573-p577, 2001

And Shack's studend, Platt, came up with a practical solution: An array of lenses.

History of plenoptics

Wilson's testing technique

1984



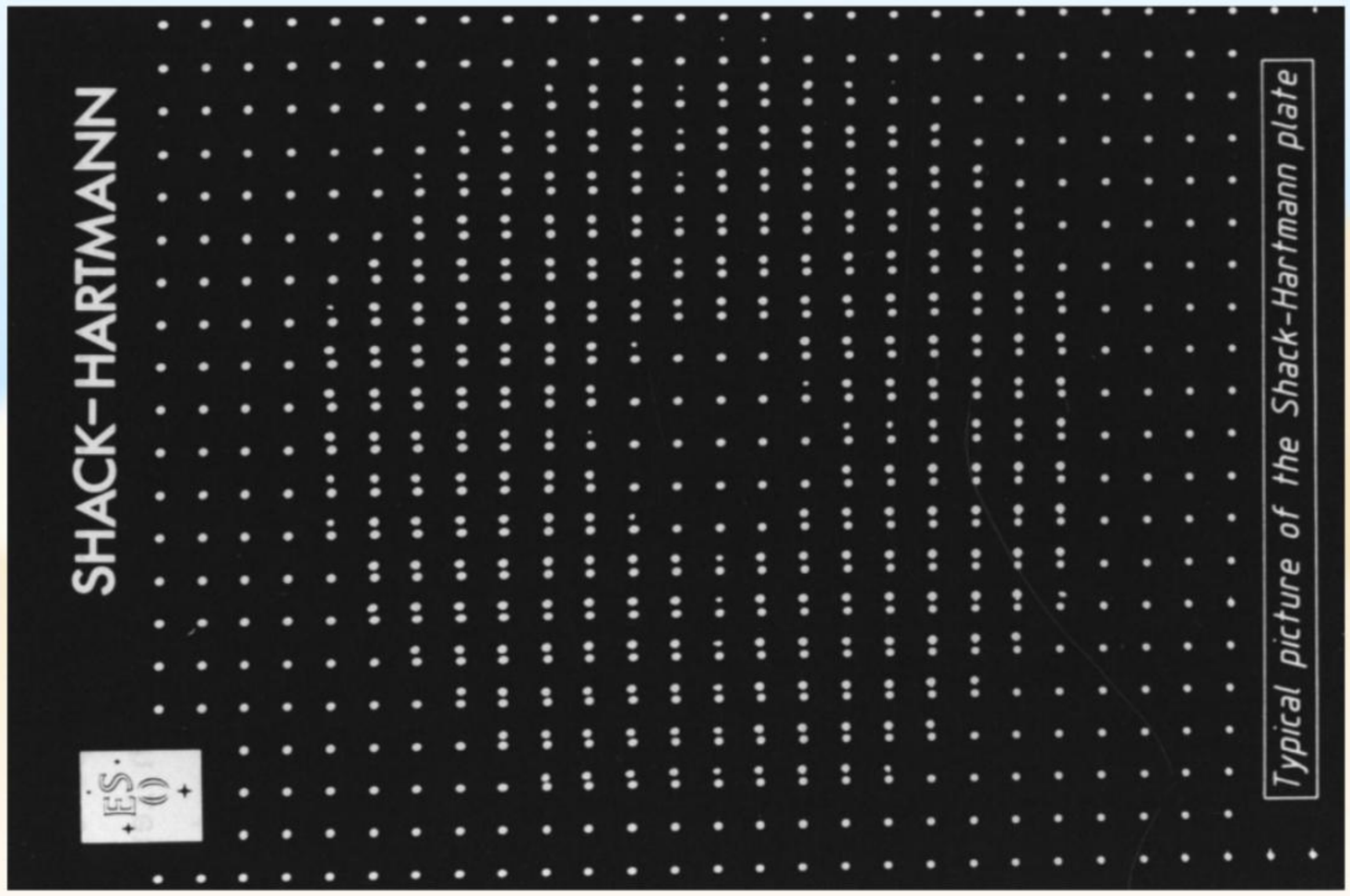
R.N. Wilson, F. Franza, L. Noethe, and M. Tarenghi
The ESO off-line telescope testing technique illustrated with MPIA 2.2 m Telescope II
International Astronomical Union Colloquium, Vol.79, p119-p130, 1984

One of Platt's lens arrays made its way to the european southern observatory where Wilson realized the potential to characterize telescope optics.

History of plenoptics

Wilson's testing technique

1984

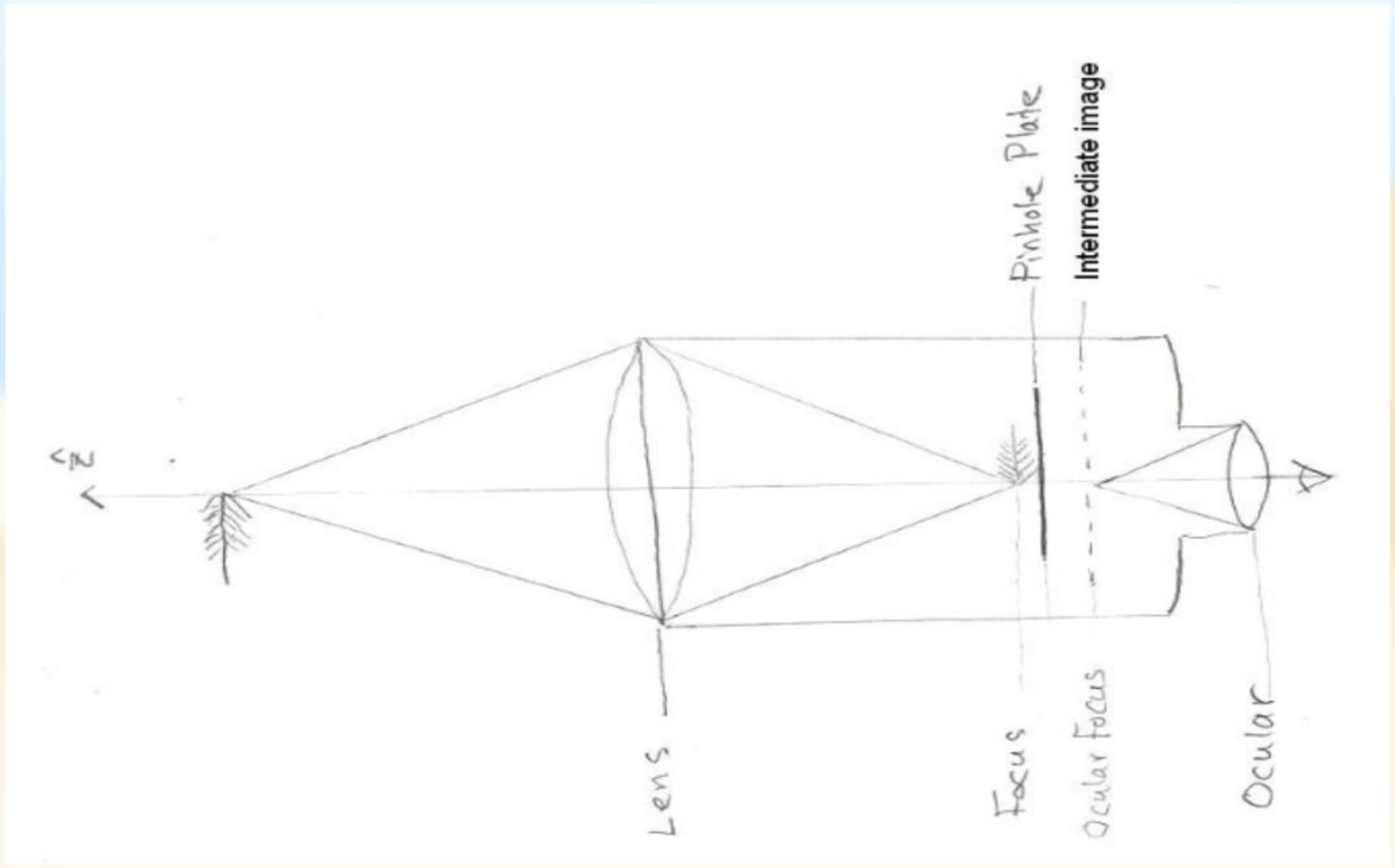


R.N. Wilson, F. Franza, L. Noethe, and M. Tarenghi
The ESO off-line telescope testing technique illustrated with MPIA 2.2 m Telescope II
International Astronomical Union Colloquium, Vol.79, p119-p130, 1984

These efforts eventually lead to today's atmospheric correction systems.

History of plenoptics 2002

Bergholm's hand-held plenoscope



F. Bergholm, E. Renlund, and K. Friskopp, The Plenoscope Concept and Image Formation, Swedish Society for Automated Image Analysis Symposium (SSAB) Vol.1 p75-p78, 2002

In 2002, Bergholm designs a hendheld optics which allows a single eye to perceive depth.

History of plenoptics 2002

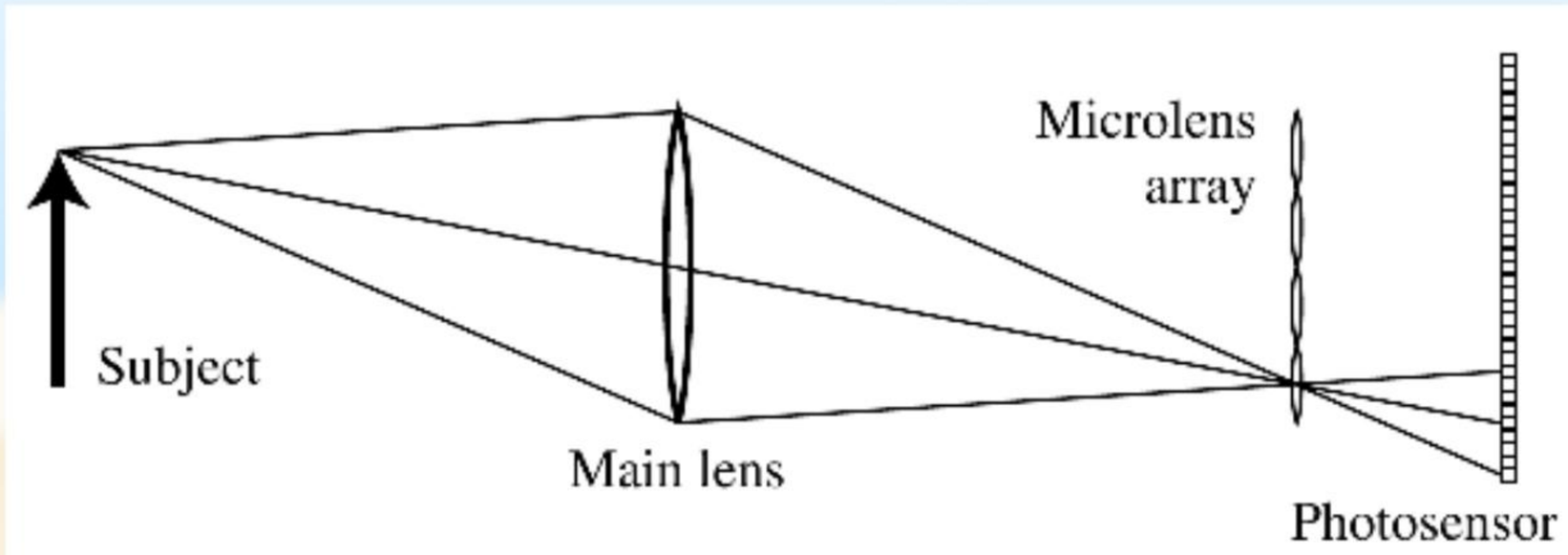
Bergholm's hand-held plenoscope

F. Bergholm, E. Renlund, and K. Friskopp, The Plenoscope Concept and Image Formation, Swedish Society for Automated Image Analysis Symposium (SSAB) Vol.1 p75-p78, 2002

Beginning in 2005, a group of computer vision and graphics experts at Stanford

History of plenoptics 2005

Ng et al. hand-held plenoptic camera

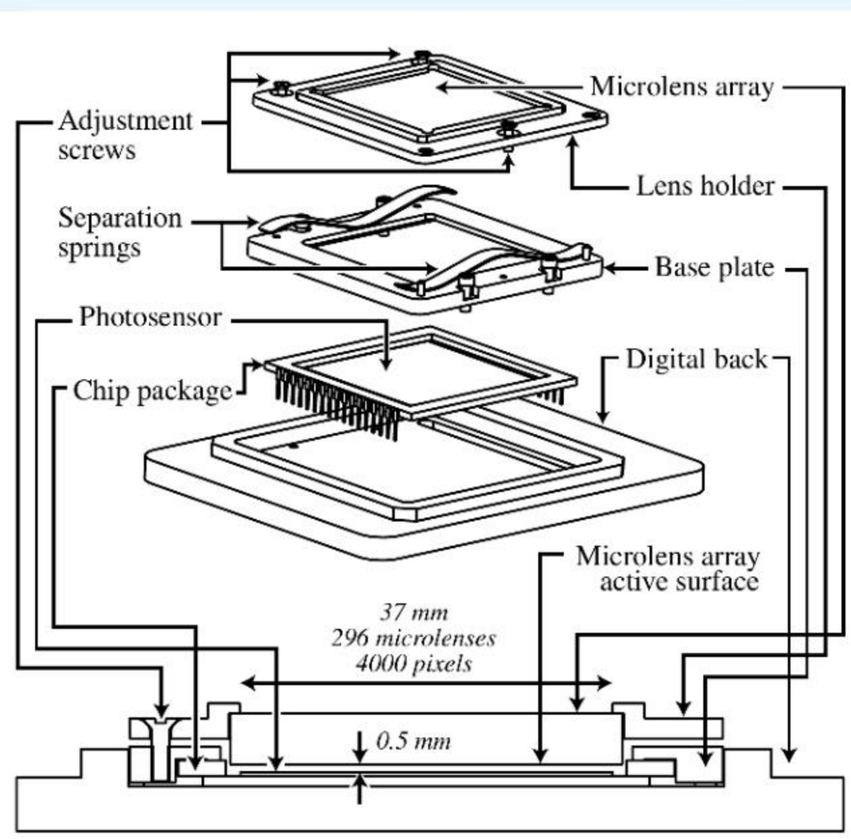


R. Ng, M. Levoy, M. Bredif, G. Duval, M. Horowitz, and P. Hanrahan
Light field photography with a hand-held plenoptic camera
Computer Science Technical Report CSTR, Vol.2 No.11, 2005

build the first handheld plenoptic camera.

History of plenoptics 2005

Ng et al. hand-held plenoptic camera



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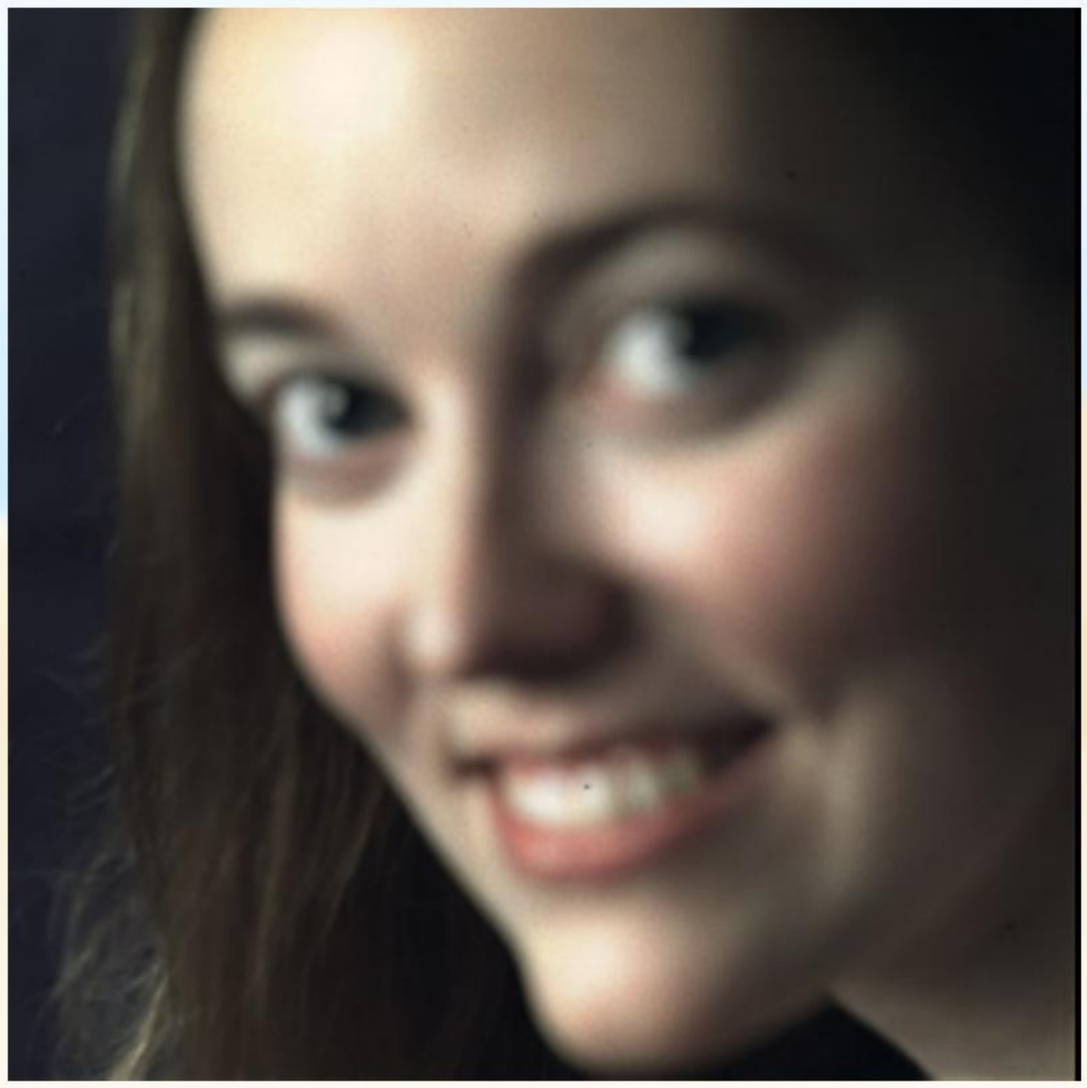
Light field photography with a hand-held plenoptic camera
Computer Science Technical Report CSTR, Vol.2 No.11, 2005

Ng realizes the potential to refocus images.

History of plenoptics 2005

Ng et al. hand-held plenoptic camera



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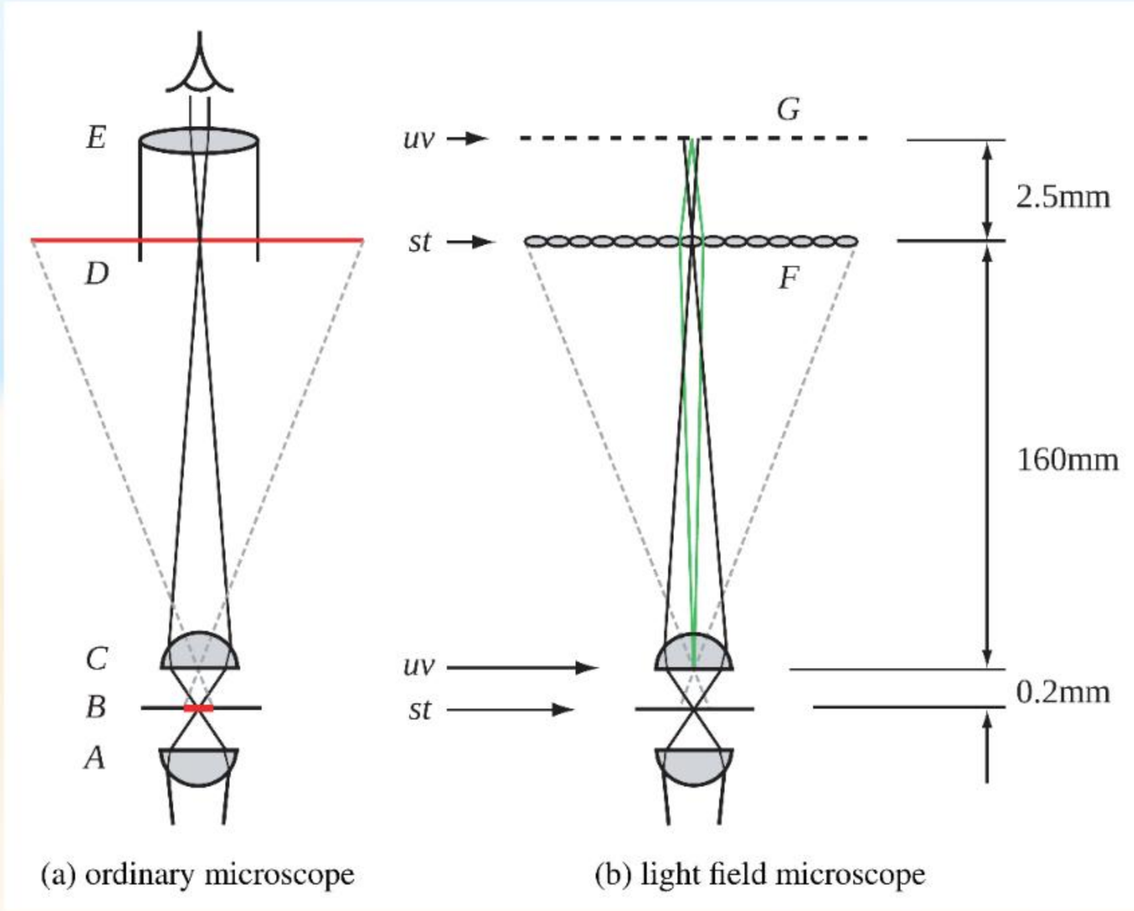
History of plenoptics 2006

M. Levoy et al: light field microscopy



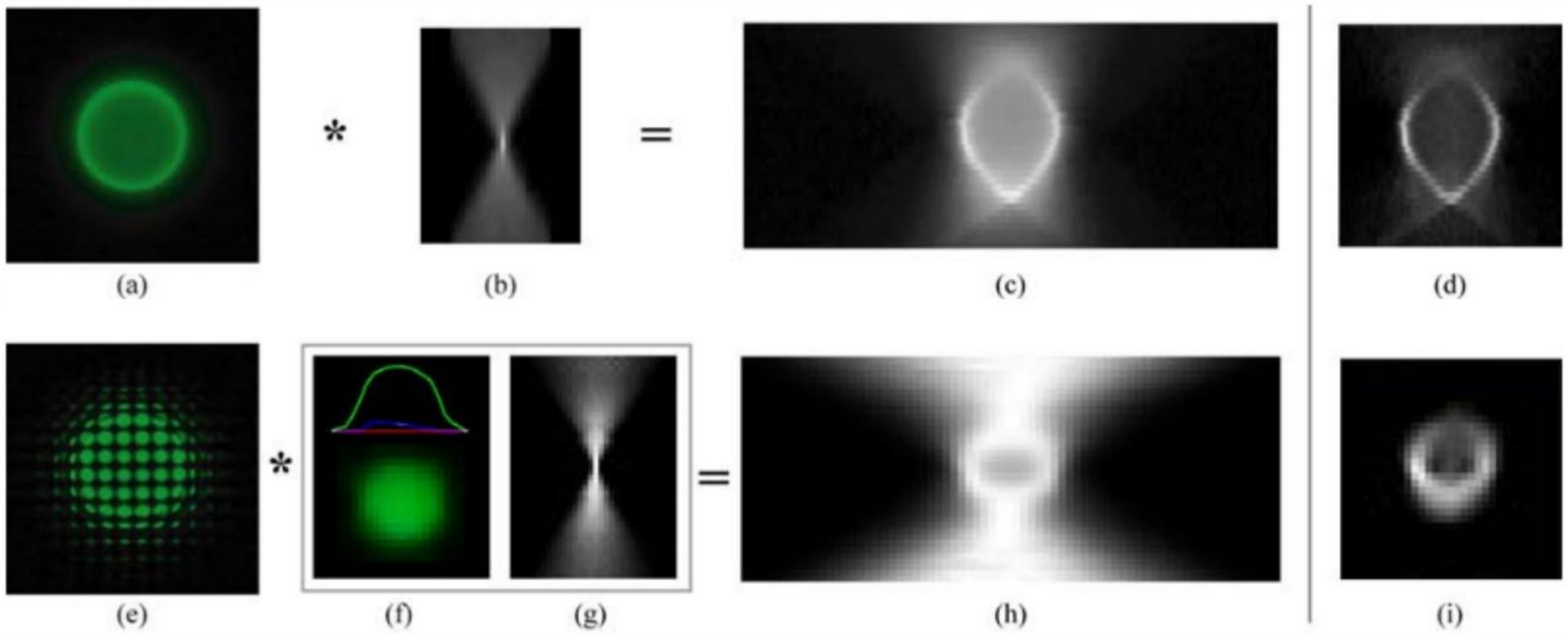
(a) ordinary microscope (b) light field microscope

M. Levoy, R. Ng, A. Adams, M. Footer, and M. Horowitz
Light Field Microscopy, ACM Transactions on Graphics (TOG), SIGGRAPH
Vol.25 No.3, p924-p934, 2006

Levoy proposes to build a light field microscope to overcome the depth-of-field limits in microscopy.

History of plenoptics 2006

M. Levoy et al: light field microscopy



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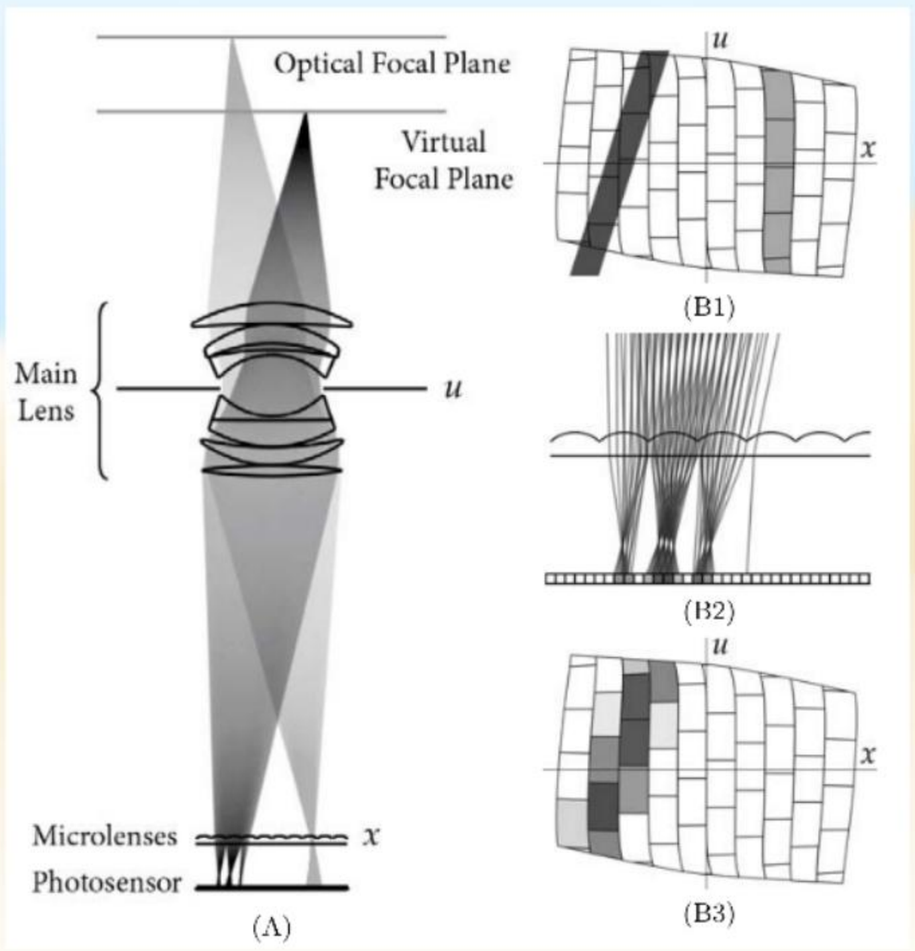
Light Field Microscopy, ACM Transactions on Graphics (TOG), SIGGRAPH
Vol.25 No.3, p924-p934, 2006

History of plenoptics 2006

P. Hanrahan and R. Ng: Compensate aberrations

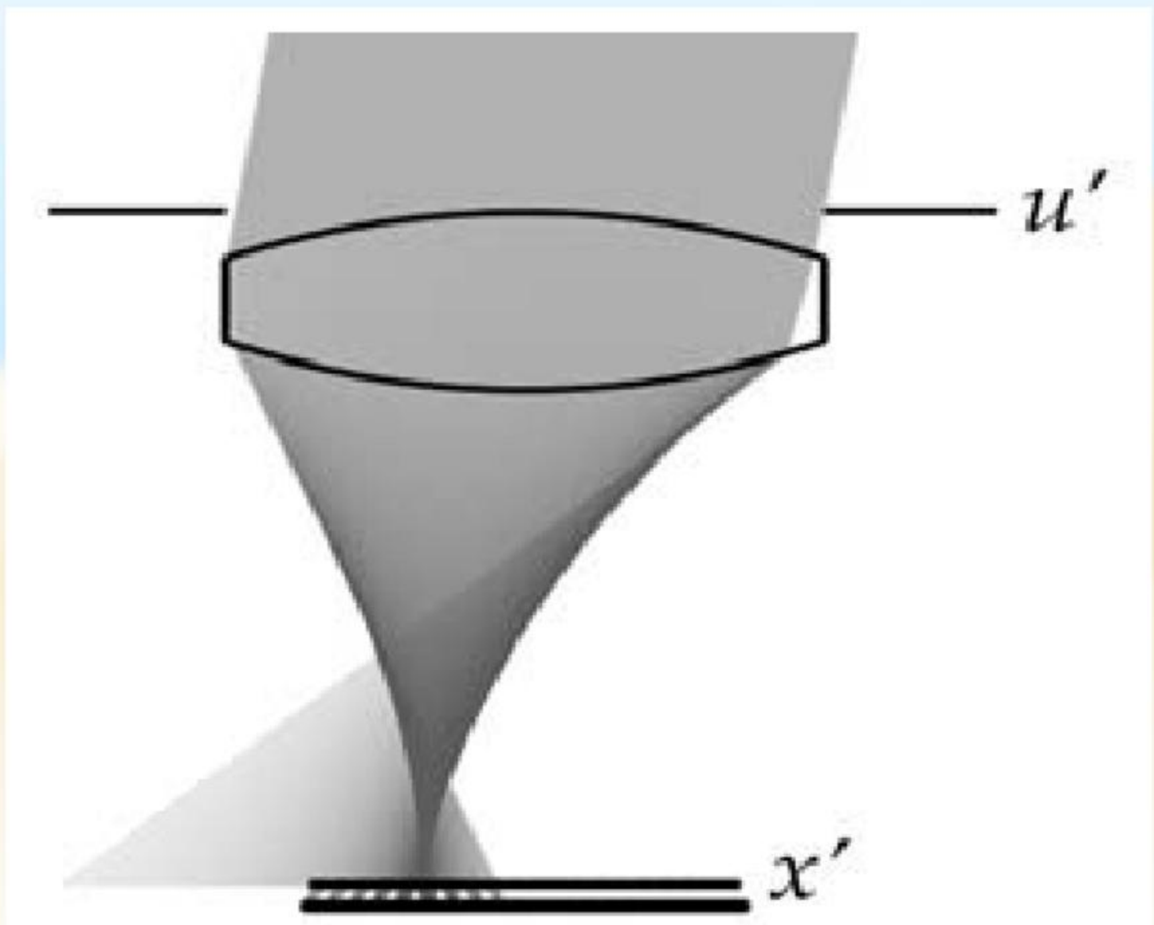


R. Ng and P. Hanrahan
Digital Correction of Lens Aberrations in Light Field Photography,
International Optical Design Conference, Optical Society of America, WB2, 2006

And Hanrahan realizes the potential to resolve aberrations.

History of plenoptics 2006

P. Hanrahan and R. Ng: Compensate aberrations



R. Ng and P. Hanrahan
Digital Correction of Lens Aberrations in Light Field Photography,
International Optical Design Conference, Optical Society of America, WB2, 2006

History of plenoptics

2006

R. Ng starts up Lytro

Based on what they found, Ng and friends found the company `Lytro'.

History of plenoptics

2006

R. Ng starts up Lytro

History of plenoptics

Lippmann's display (1D)

2011

TOSHIBA

Toshiba 55LZ2 TV, Internationale Funkaustellung (IFA), Berlin, 2011
Pictures taken from: www.computerbase.de

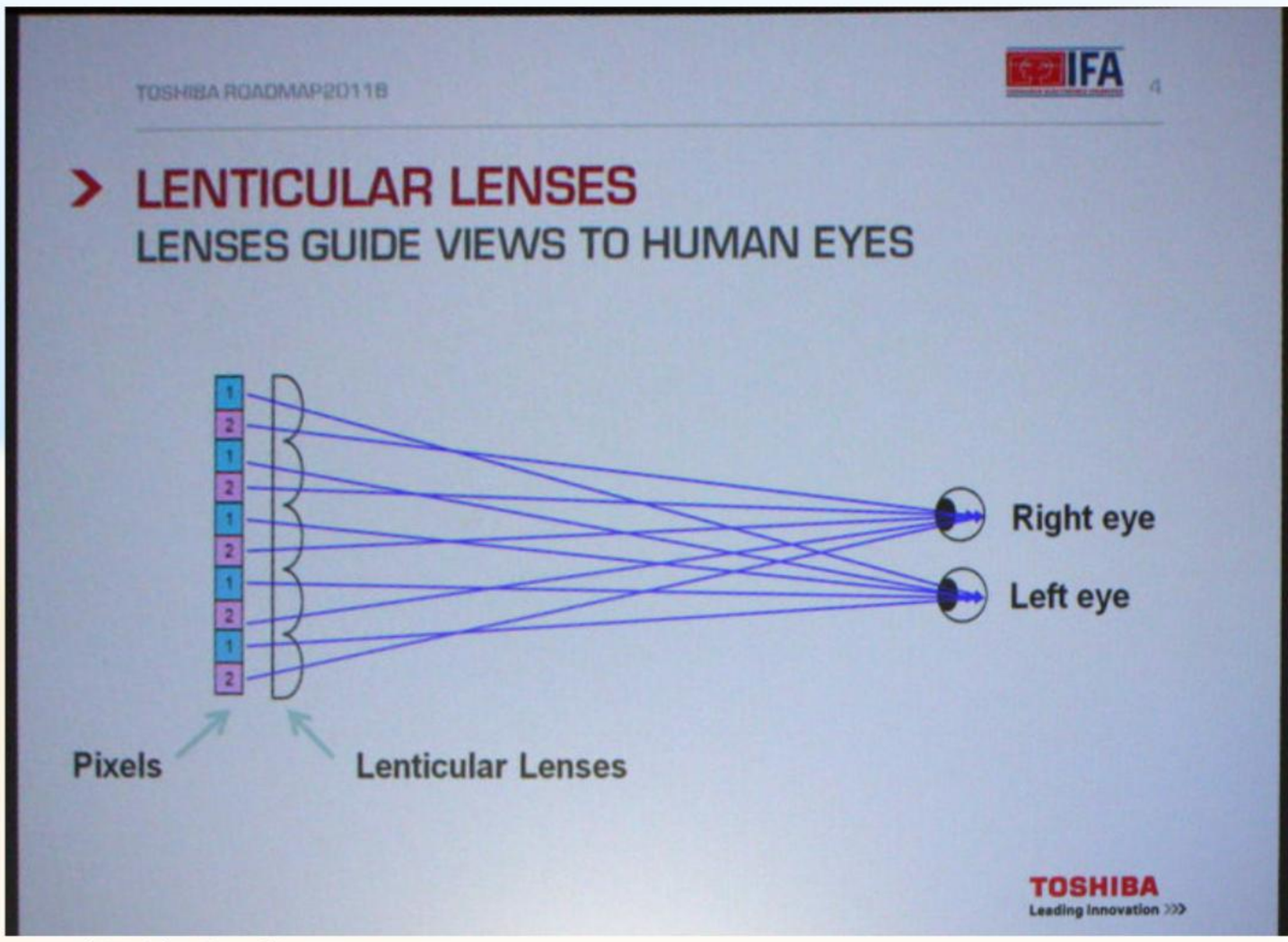
In 2011, toshiba realizes Lippmann's display for motion pictures.

History of plenoptics

Lippmann's display (1D)

2011

TOSHIBA



Toshiba 55LZ2 TV, Internationale Funkaustellung (IFA), Berlin, 2011
Pictures taken from: www.computerbase.de

History of plenoptics 2015

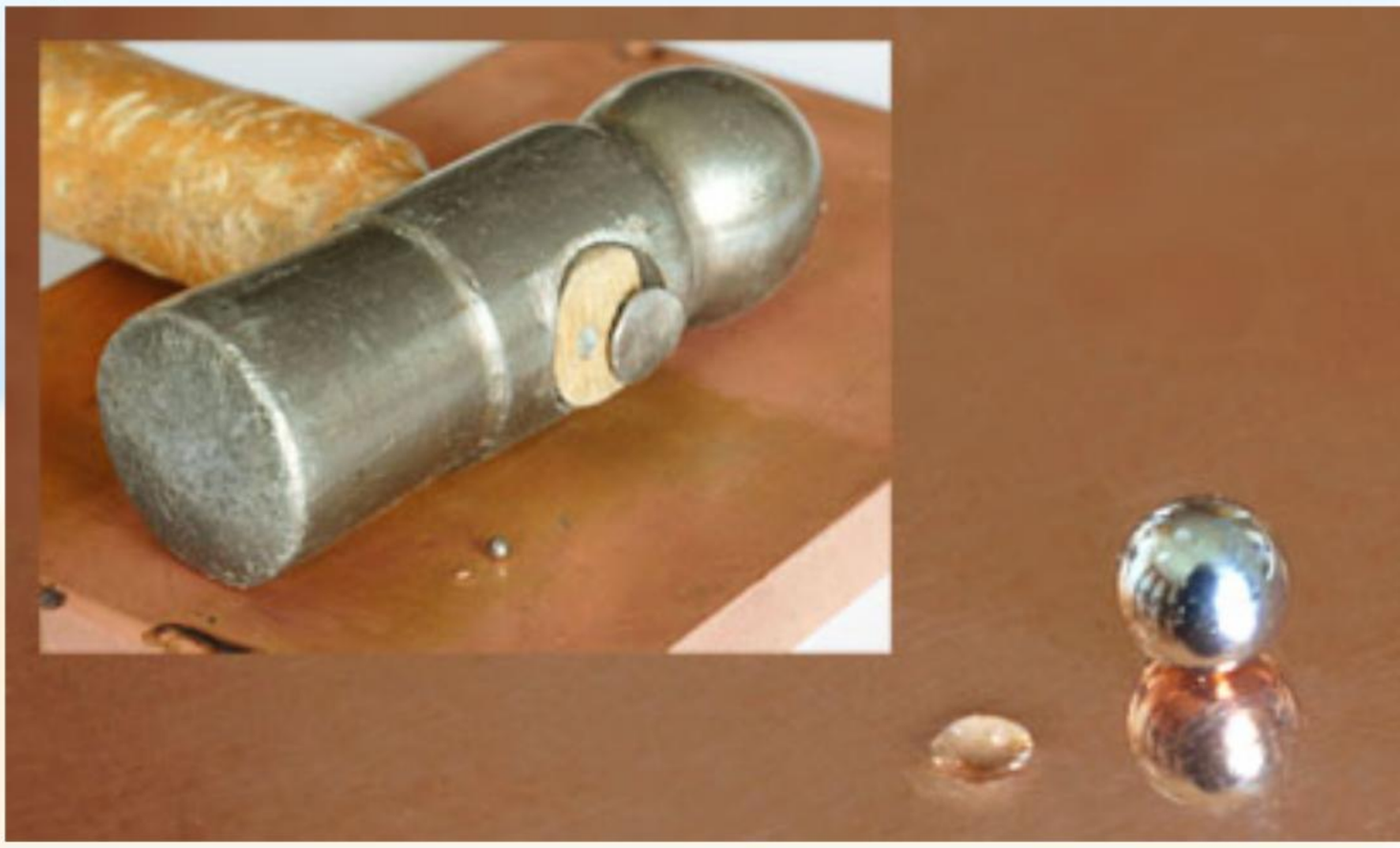
Wernersson: How to build a lens array

Mats Wernersson, An Experimental Plenoptic Camera
The Camera Maker, http://cameramaker.se/Lightfield.htm, 2015

And in 2015, the photographer Wernersson

History of plenoptics 2015

Wernersson: How to build a lens array



Mats Wernersson, An Experimental Plenoptic Camera
The Camera Maker, http://cameramaker.se/Lightfield.htm, 2015

documents how he build

History of plenoptics 2015

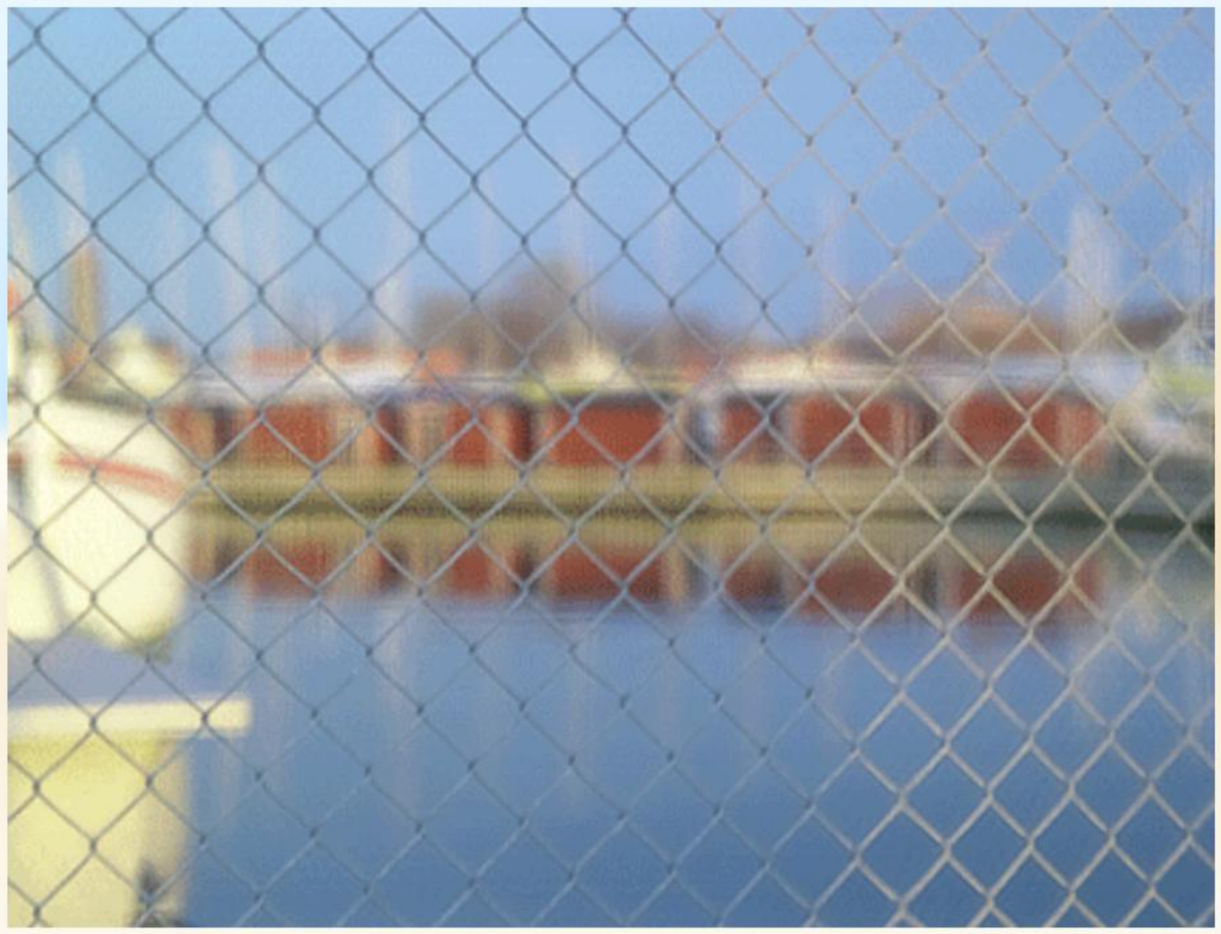
Wernersson: How to build a lens array

Mats Wernersson, An Experimental Plenoptic Camera
The Camera Maker, http://cameramaker.se/Lightfield.htm, 2015

a light field camera from scratch.

History of plenoptics 2015

Wernersson: How to build a lens array



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Wernersson: How to build a lens array

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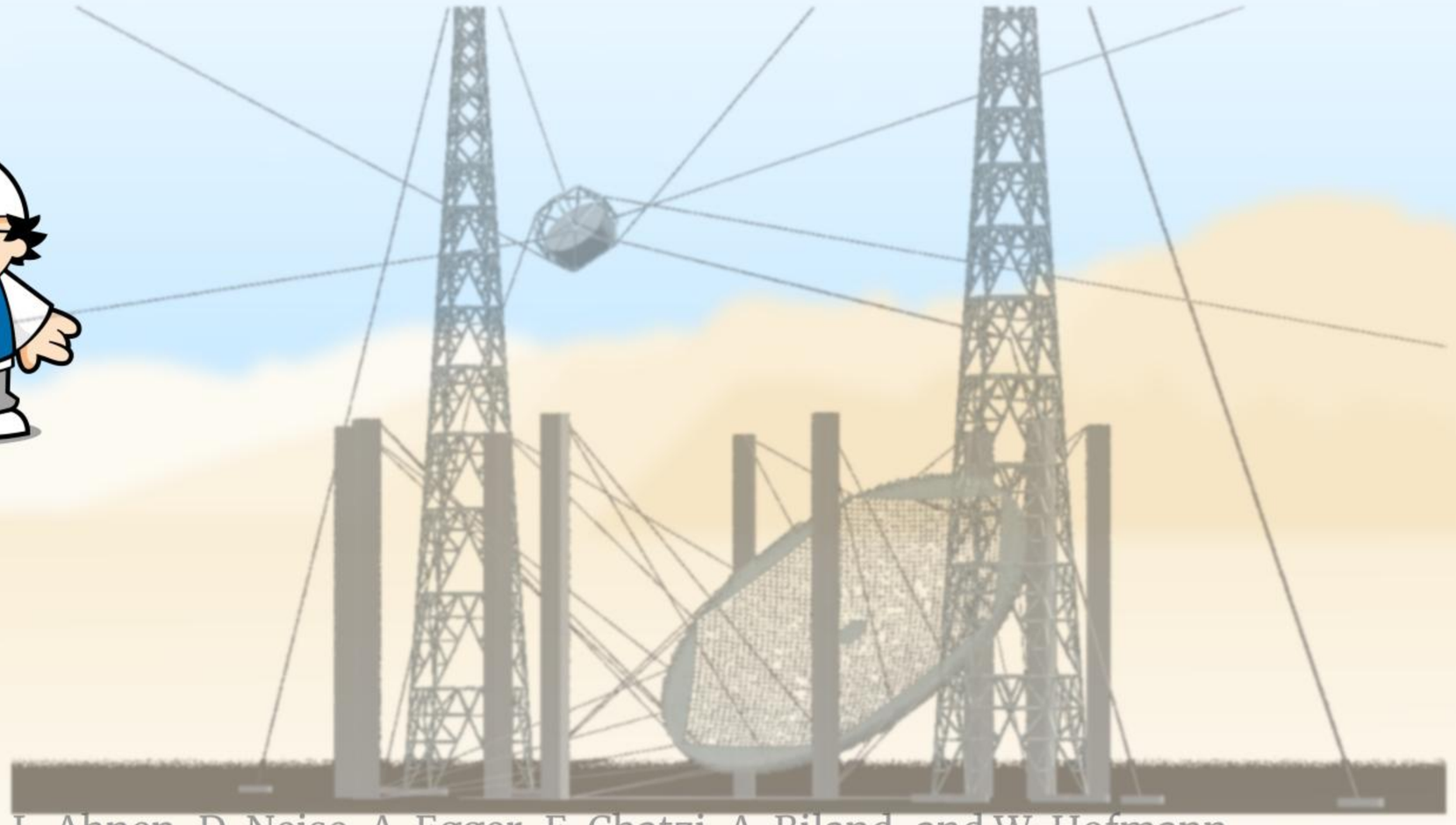
The Camera Maker, http://cameramaker.se/Lightfield.htm, 2015

History of plenoptics 2018 - 2024

S. A. Mueller et al.: Cherenkov Plenoscope for Gamma-Ray Astronomy

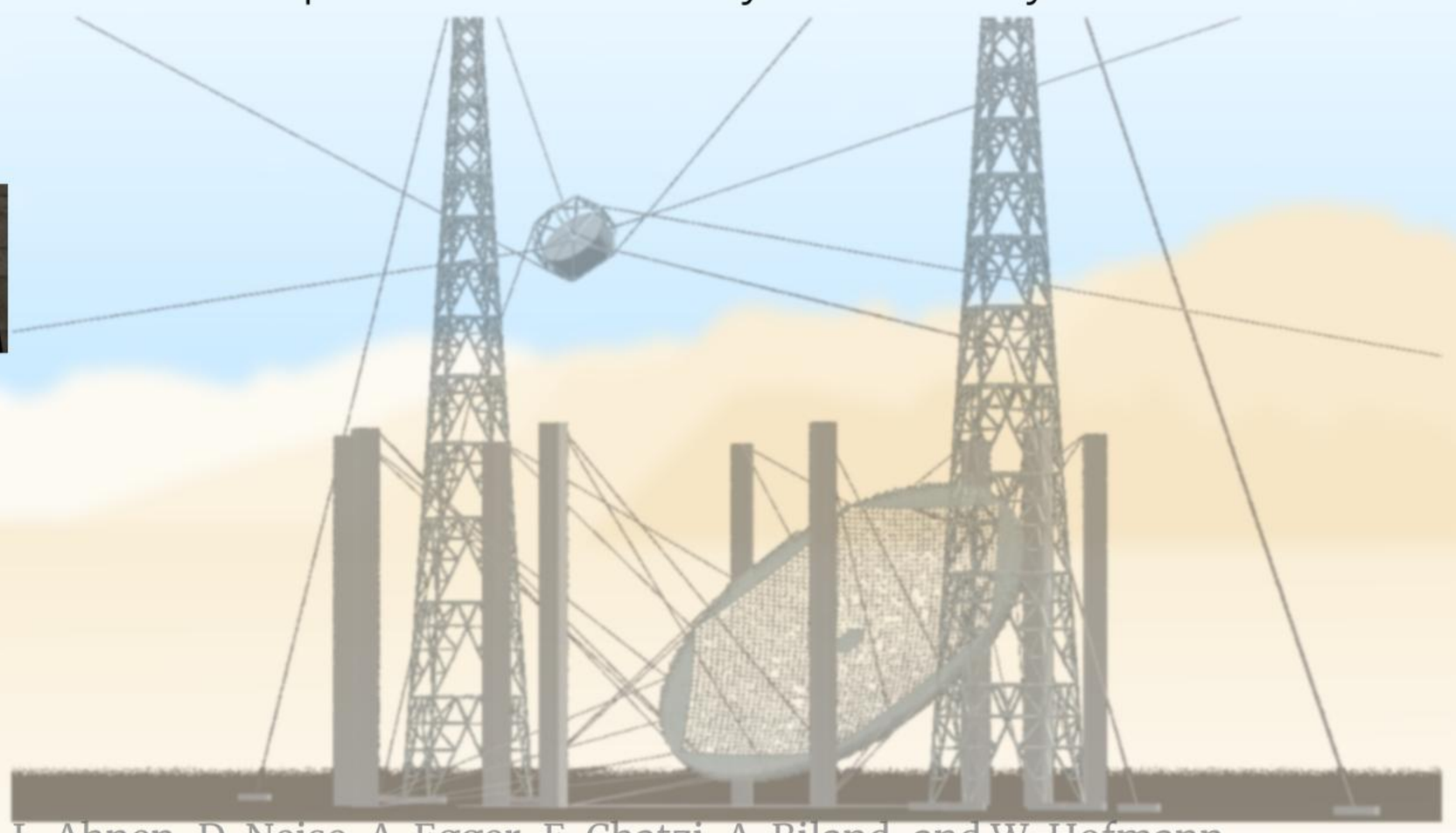


S. A. Mueller, S. Daglas, A. A. Engels, M. L. Ahnen, D. Neise, A. Egger, E. Chatzi, A. Biland, and W. Hofmann, Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics, Astroparticle Physics, Vol.158, 2024

And finally, ... wait three seconds...

History of plenoptics 2018 - 2024

S. A. Mueller et al.: Cherenkov Plenoscope for Gamma-Ray Astronomy

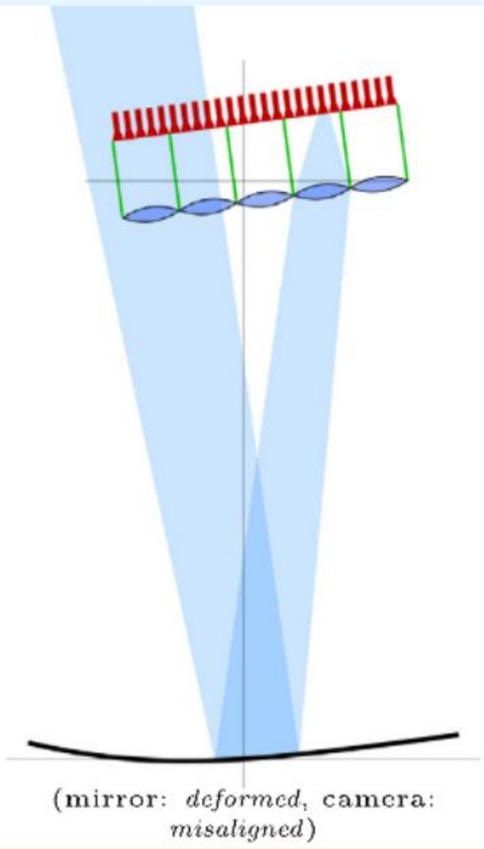


S. A. Mueller, S. Daglas, A. A. Engels, M. L. Ahnen, D. Neise, A. Egger, E. Chatzi, A. Biland, and W. Hofmann, Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics, Astroparticle Physics, Vol.158, 2024

And finally, if I may say so,

History of plenoptics 2018 - 2024

S. A. Mueller et al.: Cherenkov Plenoscope for Gamma-Ray Astronomy



$$I_g = U(g) \cdot \mathcal{R}_h$$

with the imaging matrix

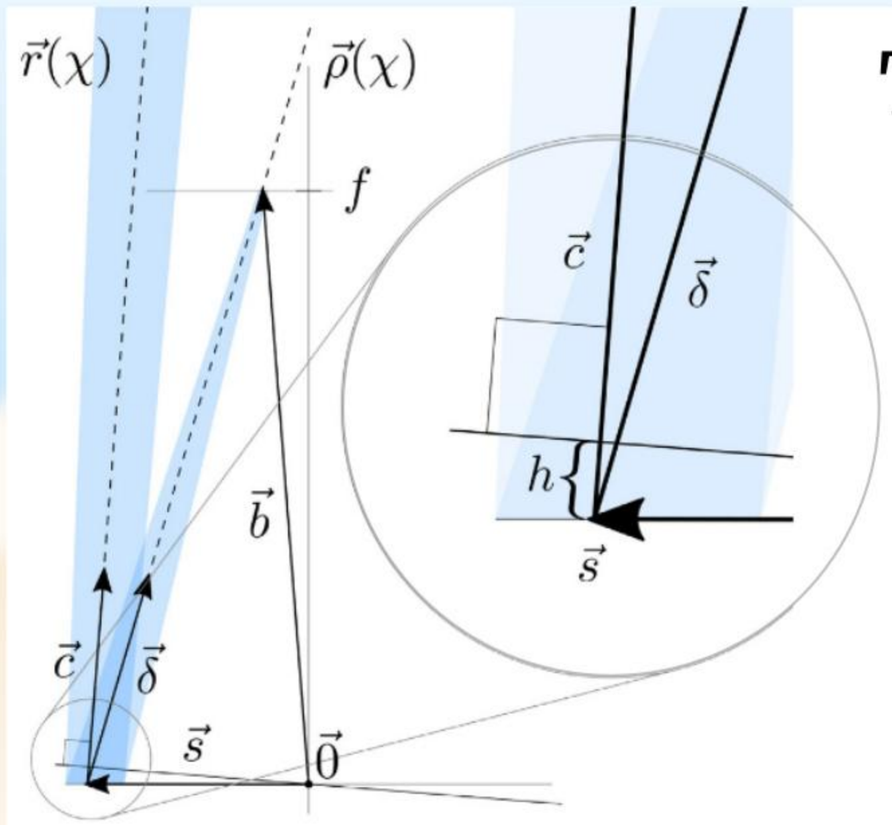
$$U(g) = \begin{bmatrix} u_{1,1}(g) & u_{1,2}(g) & \cdots & u_{1,K}(g) \\ u_{2,1}(g) & u_{2,2}(g) & \cdots & u_{2K}(g) \\ \vdots & \vdots & \ddots & \vdots \\ u_{N,1}(g) & u_{N,2}(g) & \cdots & u_{N,K}(g) \end{bmatrix}$$

S. A. Mueller, S. Daglas, A. A. Engels, M. L. Ahnen, D. Neise, A. Egger, E. Chatzi, A. Biland, and W. Hofmann, Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics, Astroparticle Physics, Vol.158, 2024

We contributed a concise compute formalism which includes aberrations, distortions, misalignments, and deformations in one step. That is a novelty.

2018 - 2024

S. A. Mueller et al.: Cherenkov Plenoscope for Gamma-Ray Astronomy



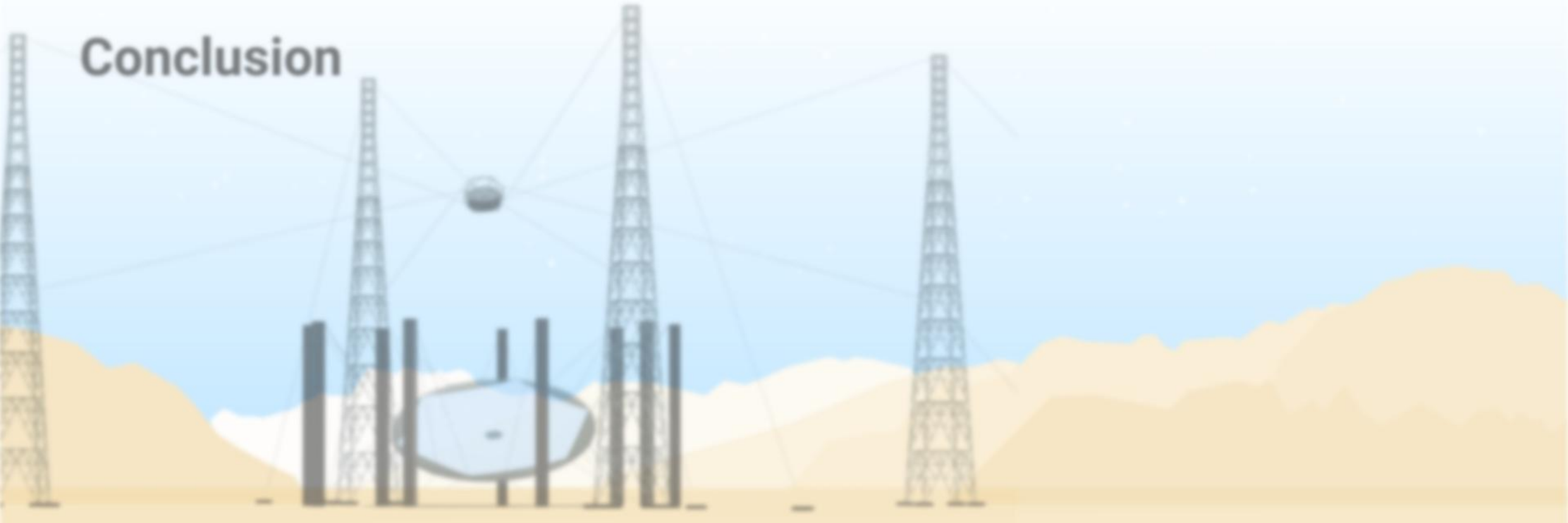
Timing in images

Correcting aberrations in the time domain.

S. A. Mueller, S. Daglas, A. A. Engels, M. L. Ahnen, D. Neise, A. Egger, E. Chatzi, A. Biland, and W. Hofmann, Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics, Astroparticle Physics, Vol.158, 2024

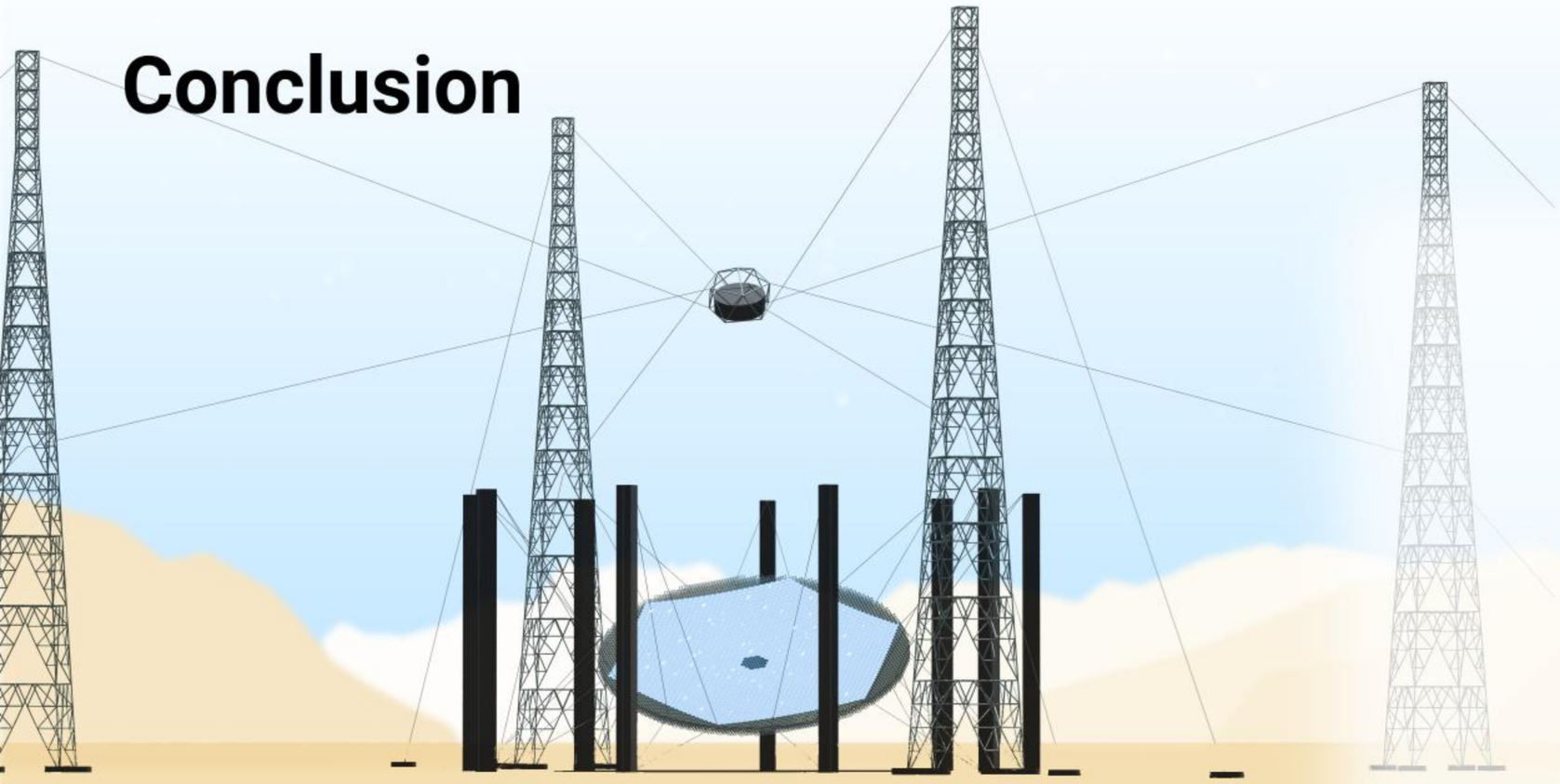
And, as far as I can tell, we were the first to discuss the compensation of aberrations in the time domain. A rare problem, but very much appreciated by people hunting nanosencond flashes of Chernekov light.

Conclusion



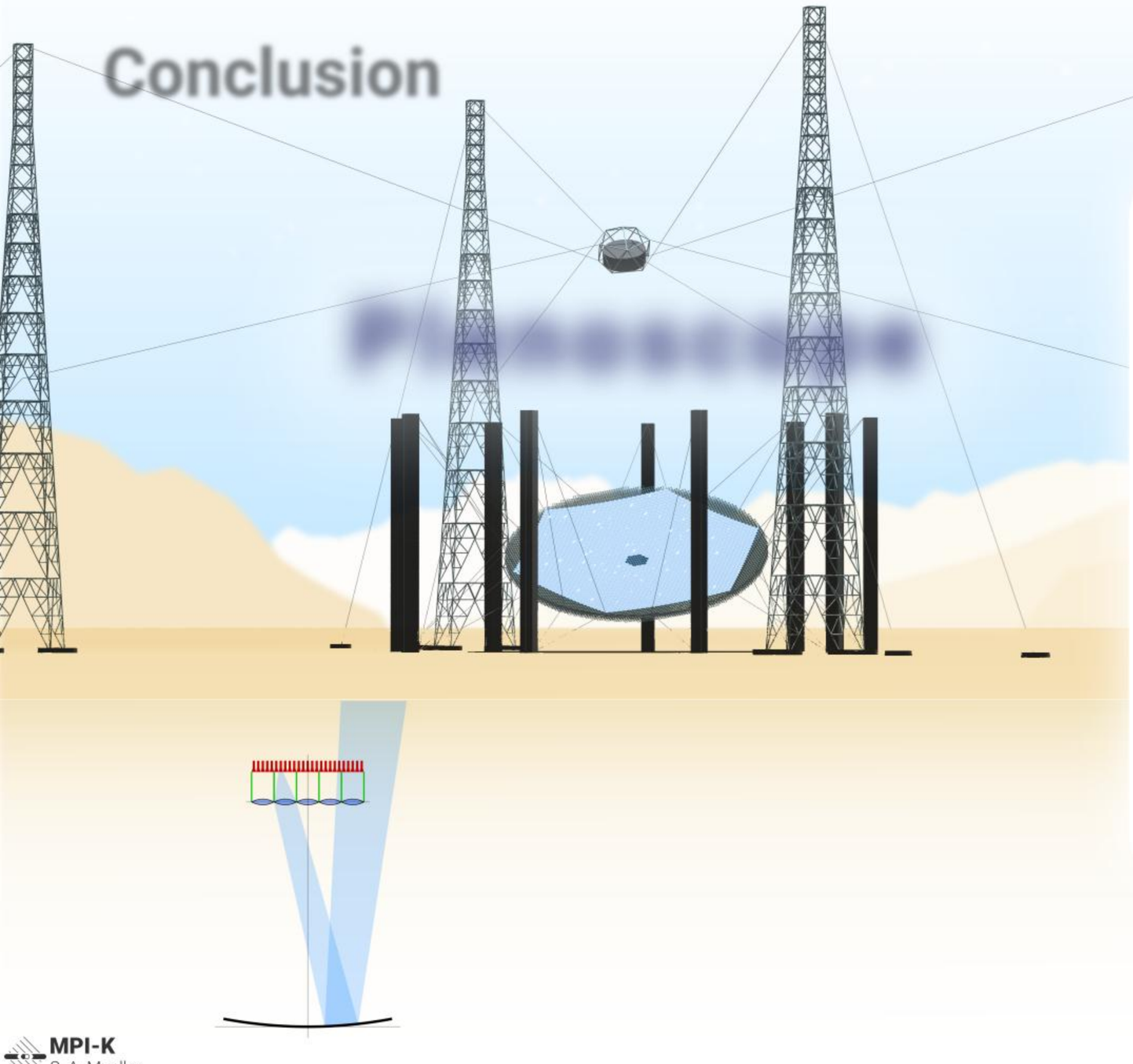
In conclusion:

Conclusion



The Cherenkov plenoscope has the potential to push the atmospheric Cherenkov method beyond the physical limts of the telescope.

Conclusion



Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics

Sebastian Achim Mueller [a,b,*], Spyridon Daglas [c,1], Axel Arbet Engels [b,2], Max Ludwig Ahnen [b,3], Dominik Neise [b], Adrian Egger [c], Eleni Chatzi [c], Adrian Biland [b], Werner Hofmann [a]

[a] Max-Planck-Institute for Nuclear Physics, Saupfercheckweg 1, Heidelberg, 69117, Germany
[b] Institute for Particle Physics and Astrophysics, ETH-Zurich, Otto-Stern-Weg 5, Zurich, 8093, Switzerland
[c] Department of Civil, Environmental and Geomatic Engineering, ETH-Zurich, Stefano-Franscini-Platz 5, Zurich, 8093, Switzerland

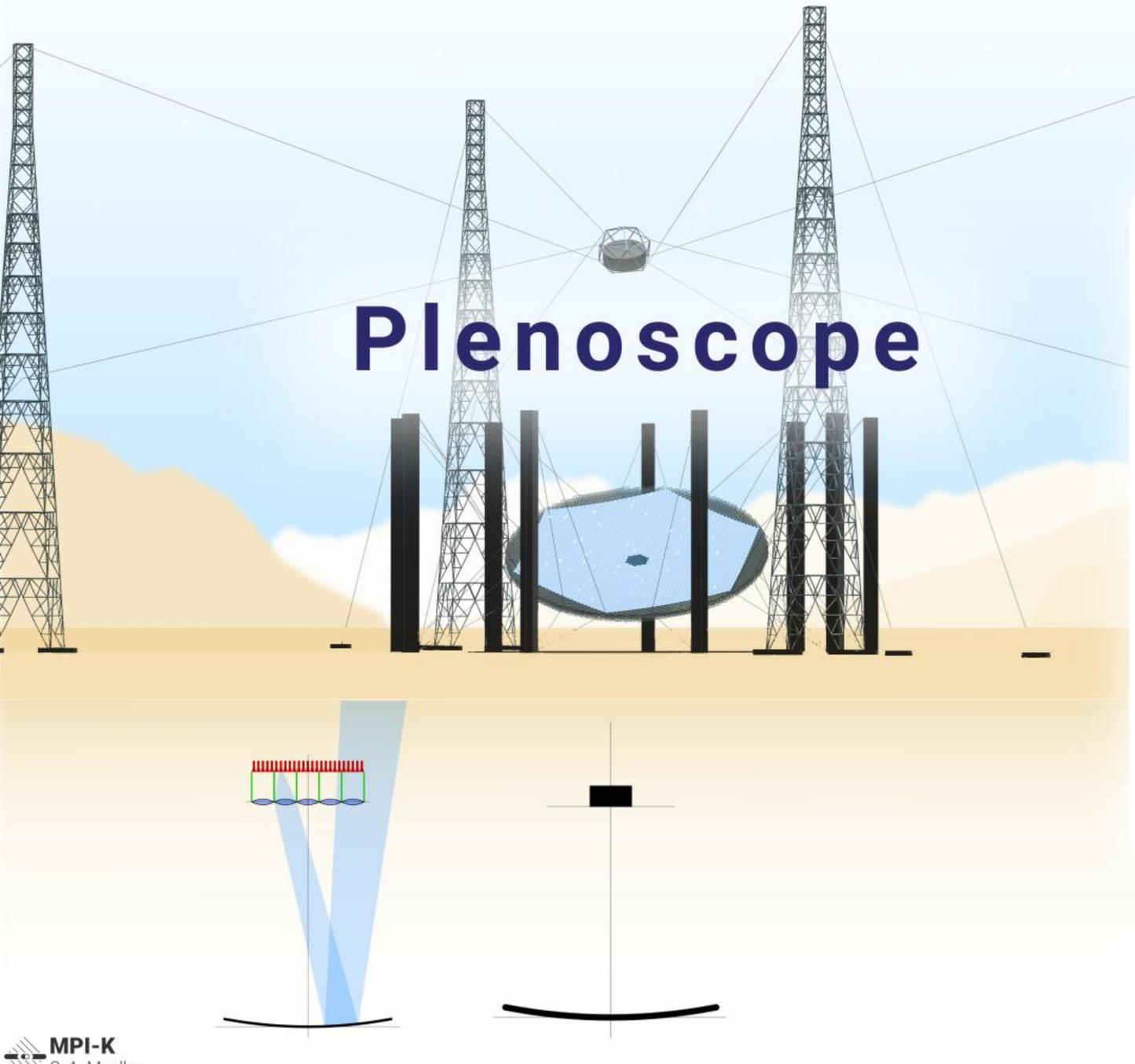
ARTICLE INFO

Keywords:
Timing
Gamma ray astronomy
Atmospheric Cherenkov method
Telescope
Plenoscope
Optics
Light field
Tomography
Stereo
Cosmic ray
Burst
Flare
Transient
Variability

ABSTRACT

Detecting cosmic gamma rays at high rates is the key to time-resolve the acceleration of particles within some of the most powerful events in the universe. Time-resolving the emission of gamma rays from merging celestial bodies, apparently random bursts of gamma rays, recurring novas in binary systems, flaring jets from active galactic nuclei, clocking pulsars, and many more became a critical contribution to astronomy. For good timing on account of high rates, we would ideally collect the naturally more abundant, low energetic gamma rays in the domain of one giga electronvolt in large areas. Satellites detect low energetic gamma rays but only in small collecting areas. Cherenkov telescopes have large collecting areas but can only detect the rare, high energetic gamma rays. To detect gamma rays with lower energies, Cherenkov-telescopes need to increase in precision and size. But when we push the concept of the –far/tele– seeing Cherenkov telescope accordingly, the telescope's physical limits show more clearly. The narrower depth-of-field of larger mirrors, the aberrations of mirrors, and the deformations of mirrors and mechanics all blur the telescope's image. To overcome these limits, we propose to record the –full/plenum– Cherenkov-light field of an atmospheric shower, i.e. recording the directions and impacts of each individual Cherenkov photon simultaneously, with a novel class of instrument. This novel Cherenkov plenoscope can turn a narrow depth-of-field into the perception of depth, can compensate aberrations, and can tolerate deformations. We design a Cherenkov plenoscope to explore timing by detecting low energetic gamma rays in large areas.

The concept of modelling beams of light and computing images after the fact has great potential to widen the vield-of-view



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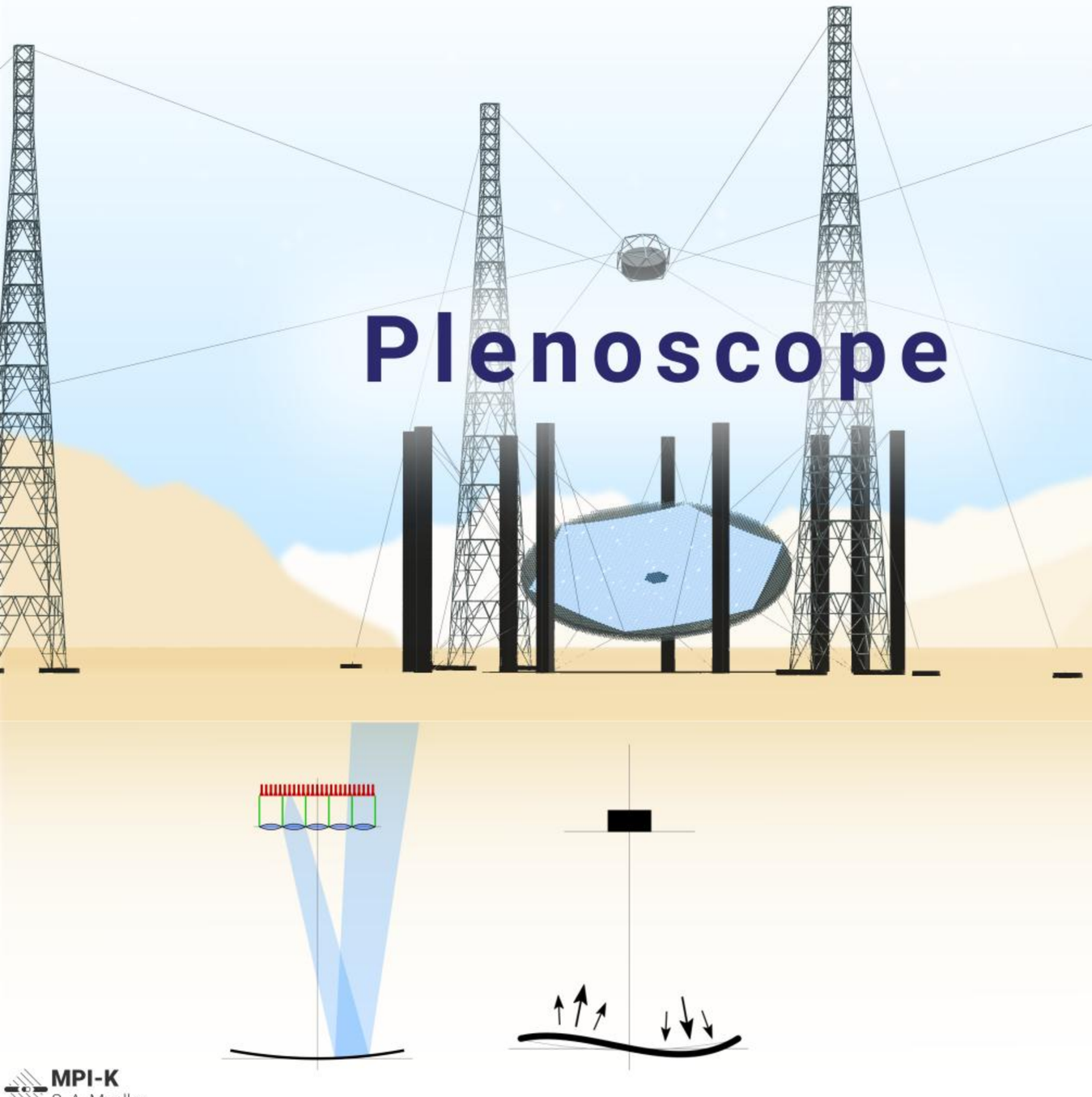
to compensate



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Exploring one giga electronvolt cosmic gamma rays with a Cherenkov plenoscope capable of recording atmospheric light fields, Part 1: Optics

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[b] Institute for Particle Physics and Astrophysics, ETH-Zurich, Otto-Stern-Weg 5, Zurich, 8093, Switzerland
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ARTICLE INFO

Keywords:
Timing
Gamma ray astronomy
Atmospheric Cherenkov method
Telescope
Plenoscope
Optics
Light field
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Stereo
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Flare
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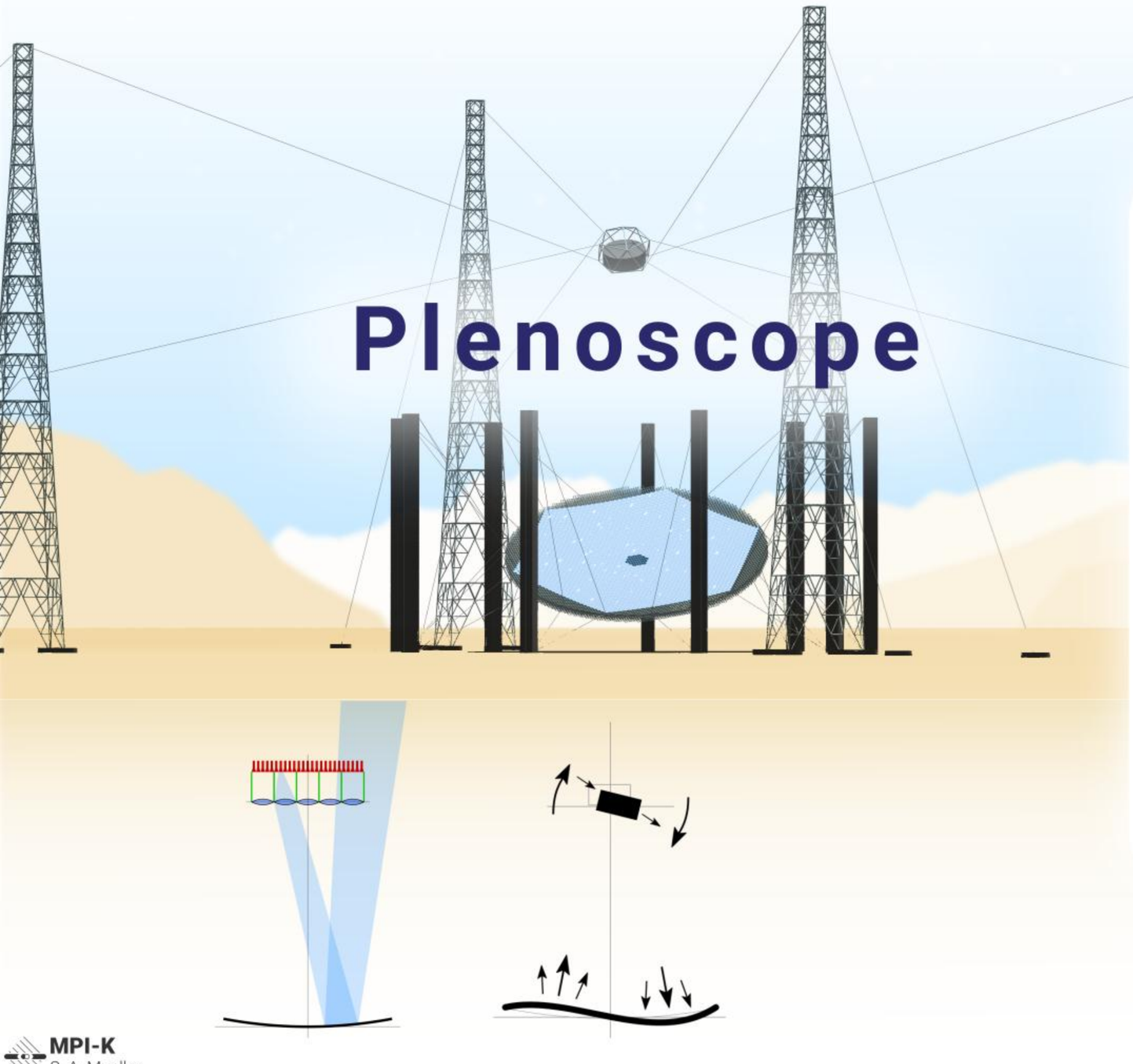
ABSTRACT

Detecting cosmic gamma rays at high rates is the key to time-resolve the acceleration of particles within some of the most powerful events in the universe. Time-resolving the emission of gamma rays from merging celestial bodies, apparently random bursts of gamma rays, recurring novas in binary systems, flaring jets from active galactic nuclei, clocking pulsars, and many more became a critical contribution to astronomy. For good timing on account of high rates, we would ideally collect the naturally more abundant, low energetic gamma rays in the domain of one giga electronvolt in large areas. Satellites detect low energetic gamma rays but only in small collecting areas. Cherenkov telescopes have large collecting areas but can only detect the rare, high energetic gamma rays. To detect gamma rays with lower energies, Cherenkov-telescopes need to increase in precision and size. But when we push the concept of the –far/tele– seeing Cherenkov telescope accordingly, the telescope's physical limits show more clearly. The narrower depth-of-field of larger mirrors, the aberrations of mirrors, and the deformations of mirrors and mechanics all blur the telescope's image. To overcome these limits, we propose to record the –full/plenum– Cherenkov-light field of an atmospheric shower, i.e. recording the directions and impacts of each individual Cherenkov photon simultaneously, with a novel class of instrument. This novel Cherenkov plenoscope can turn a narrow depth-of-field into the perception of depth, can compensate aberrations, and can tolerate deformations. We design a Cherenkov plenoscope to explore timing by detecting low energetic gamma rays in large areas.

deformations in the mirror,



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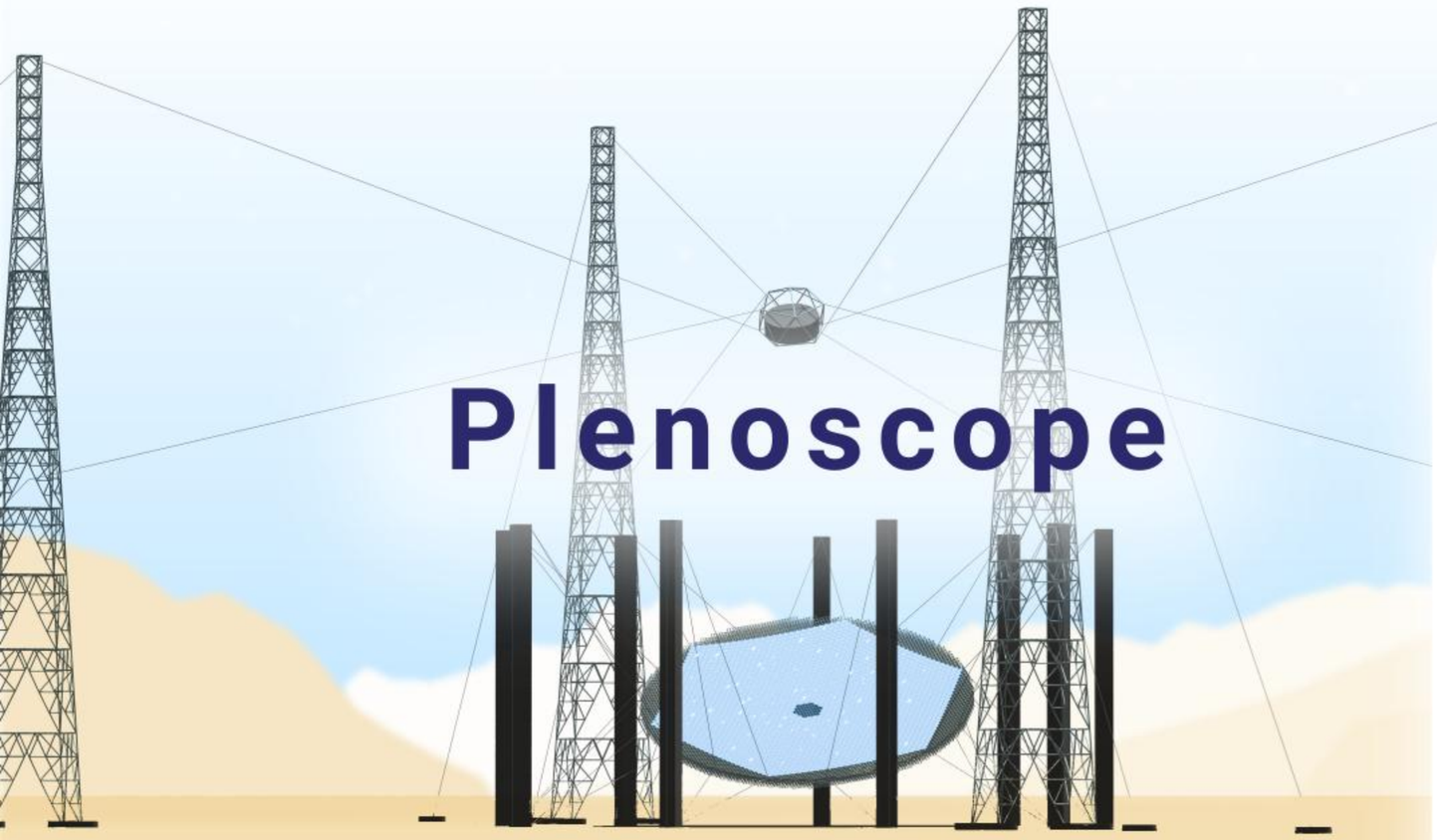

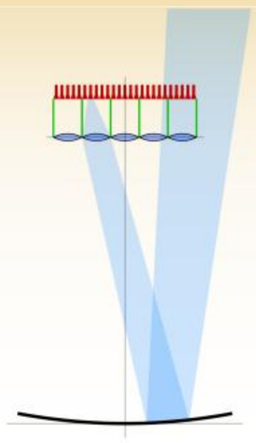

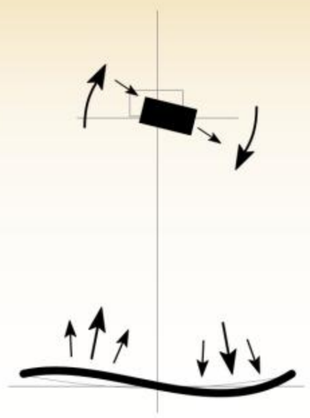

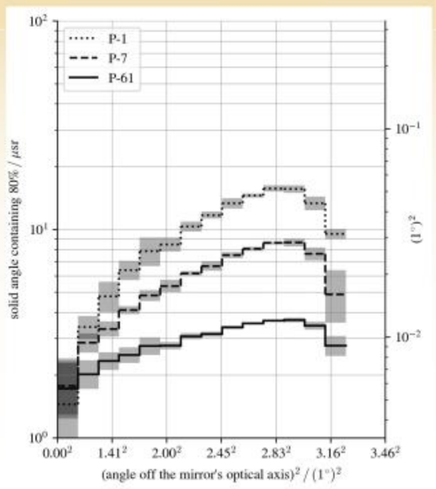

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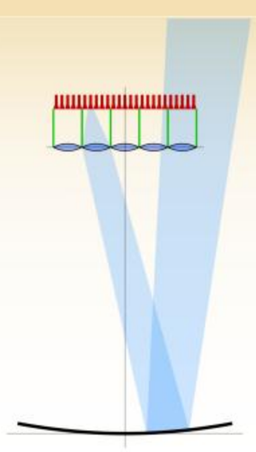
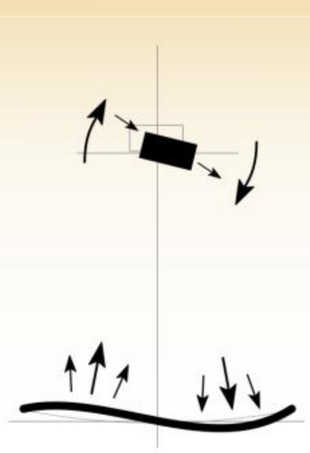
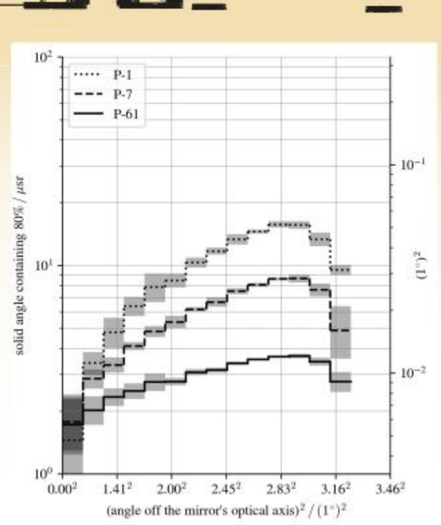
and to effectively overcome astronomy's arch nemesis: aberrations.

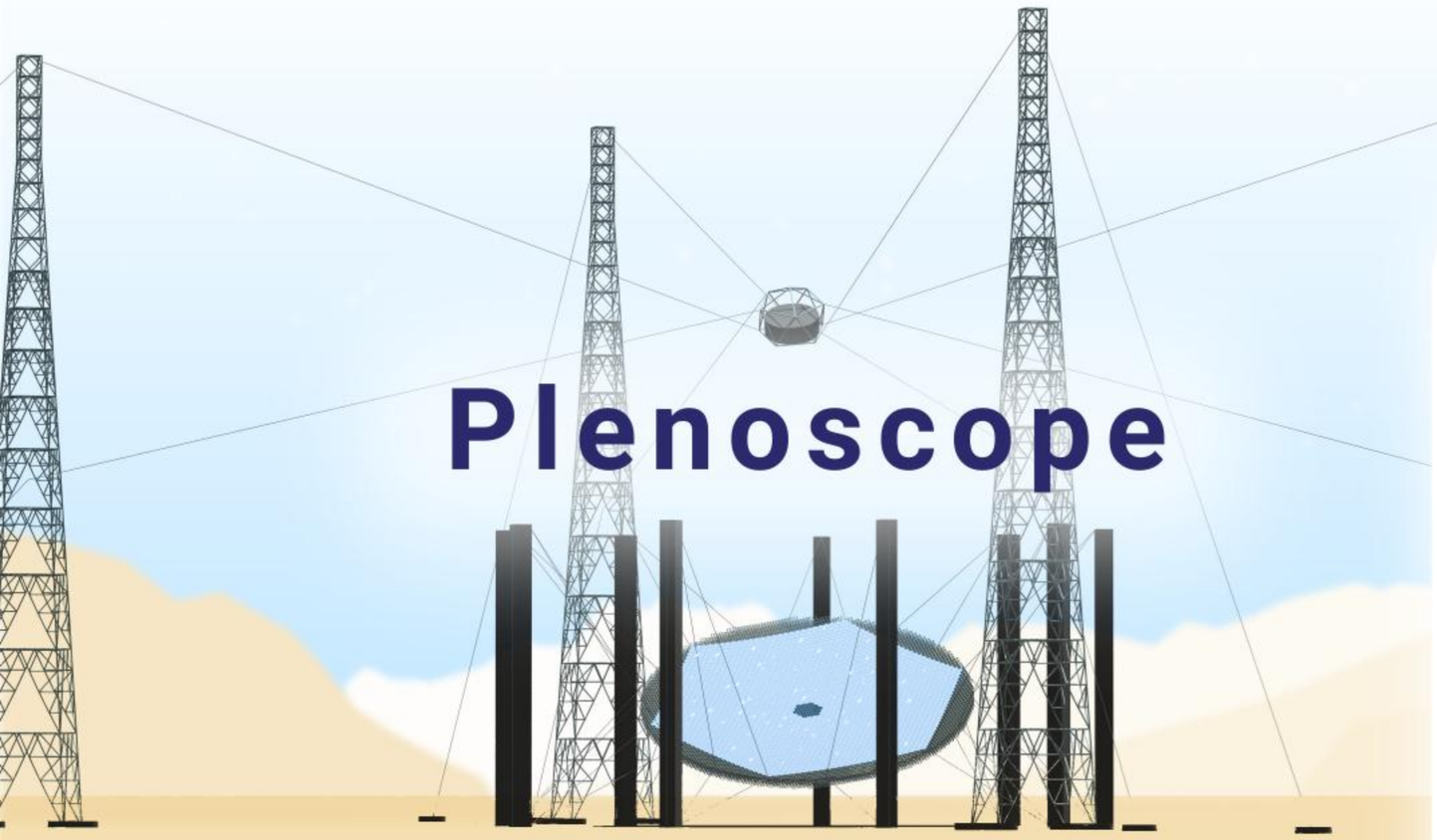
Plenoscope

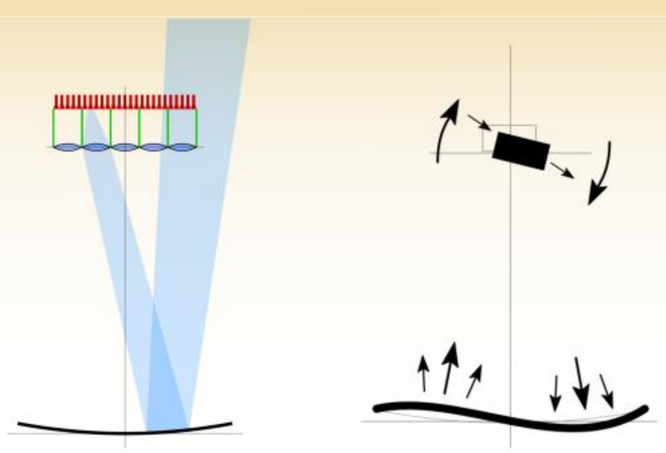


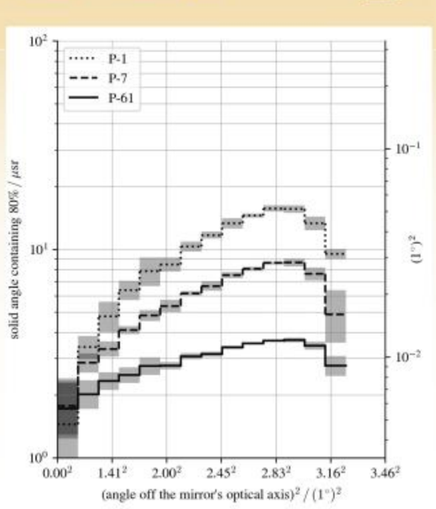


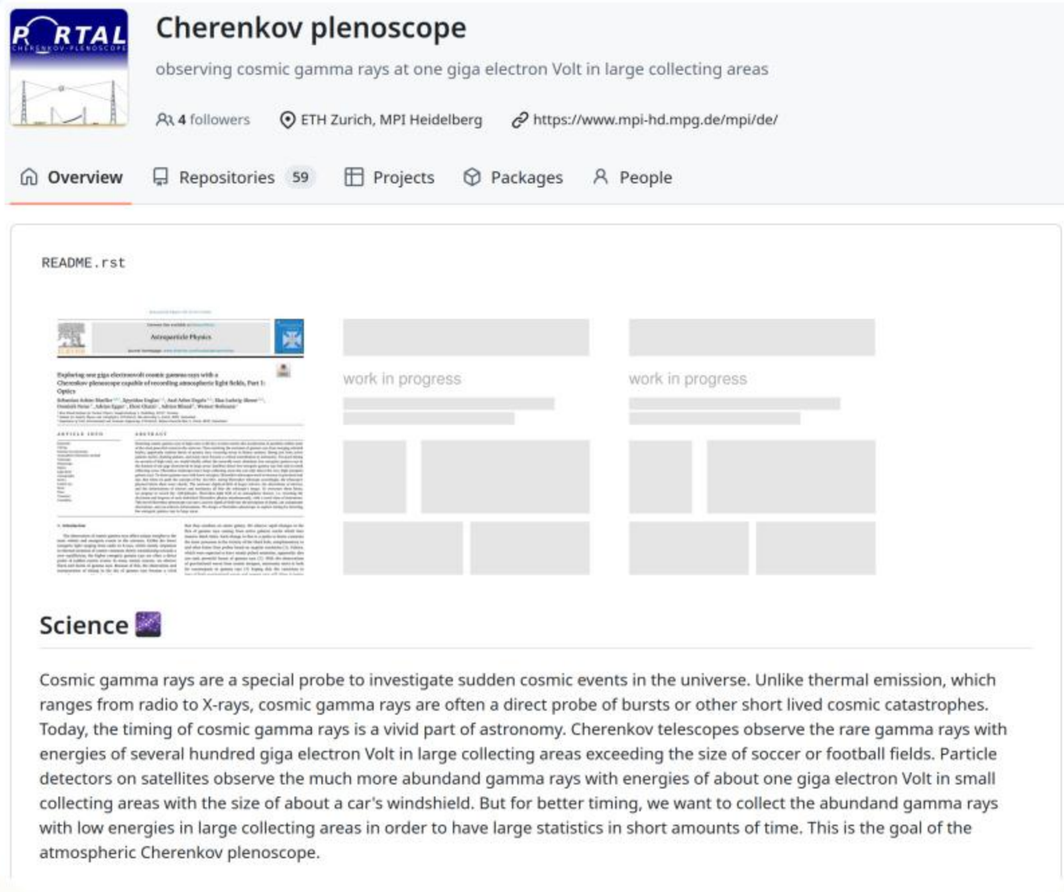


Now that my scientific career is coming to an end, I want to thank Felicitas Pauss and Adrian Biland from the ETH-Zurich as well as Jim Hinton and Werner Hofmann from the Max-Planck-Institute for Nuclear Physics in Heidelberg for their support and contributions to the Cherenkov plenoscope project.









github.com/cherenkov-plenoscope