Neutrino Astronomy

How, where and why

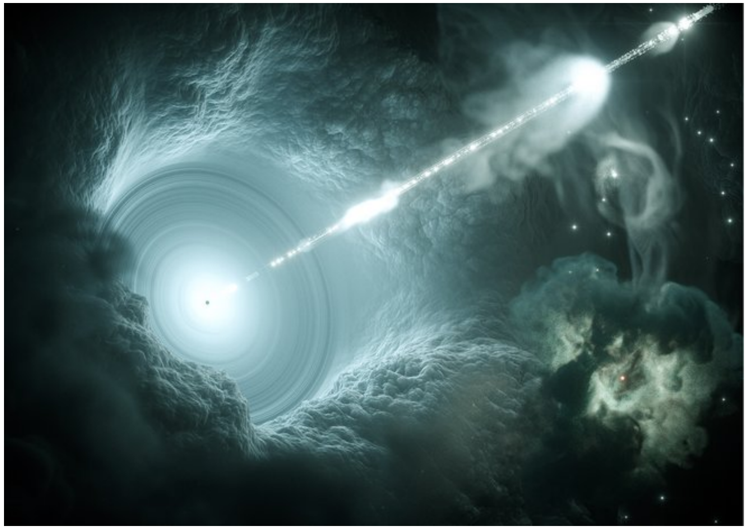
Anna Nelles
GSI, 2020

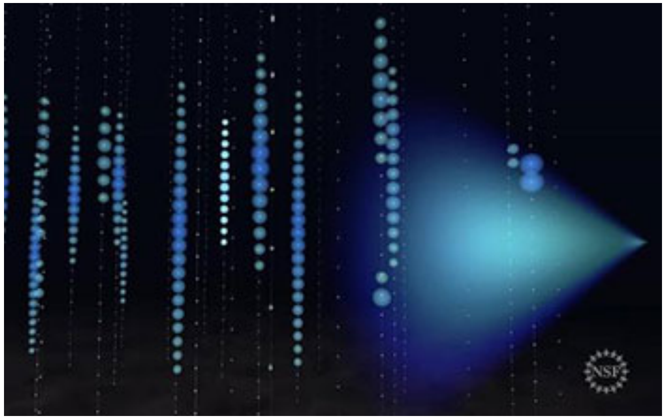
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
ecap ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS
DESY.

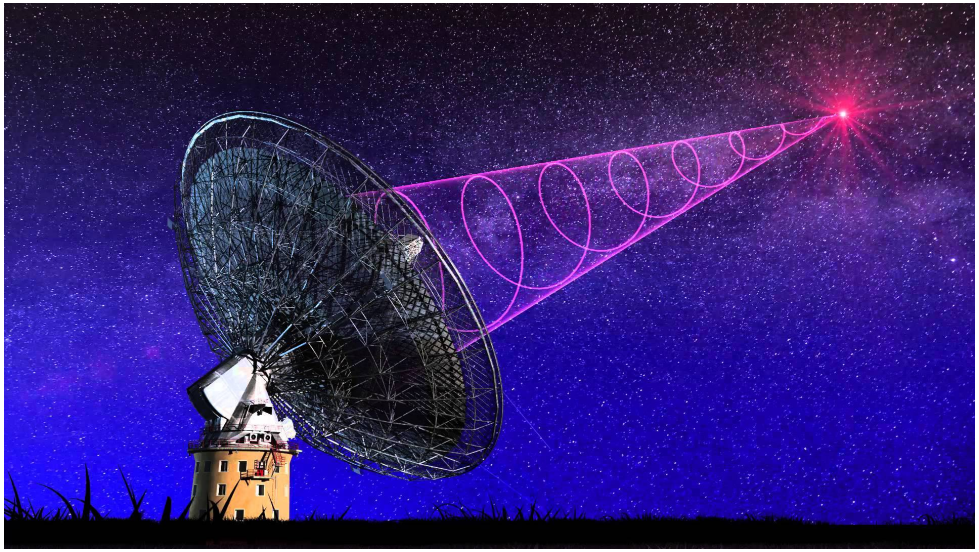
Outline

Why, how and where

- What are high energy neutrinos and why are they interesting?
- How can we detect high energy neutrinos?
- What are current experimental efforts?



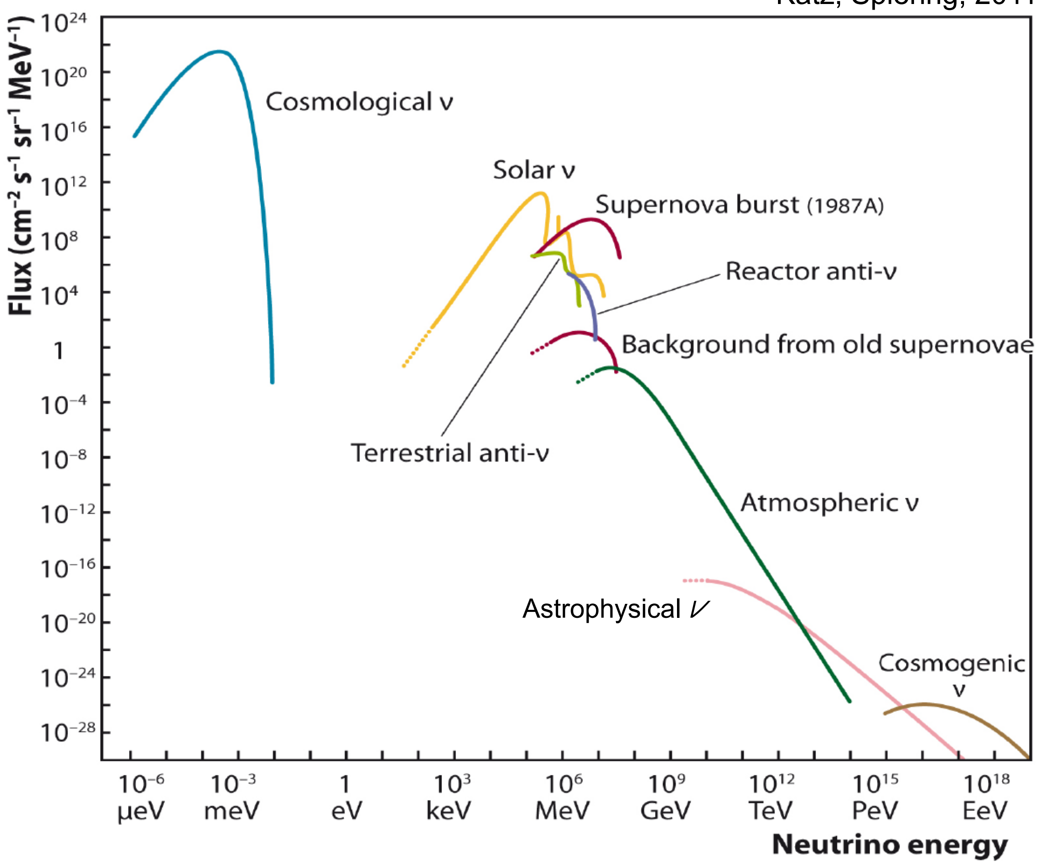




High Energy Neutrinos

Assuming everyone has heard about neutrinos already

Katz, Spiering, 2011



My field: Really only the "highest energies"

- We have only known since 2013 that these exist
- But: highest energy of neutrino measured "only" ~30 PeV
- Experimentally there is more room to grow

High Energy Neutrinos

- (Brief) theoretical motivation

Victor Hess, 1912

High Energy Neutrinos

(Brief) theoretical motivation

- **We don't know which sources accelerate hadrons to the highest energies**


Victor Hess, 1912

High Energy Neutrinos

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(Brief) theoretical motivation

- Ultra-High Energy Cosmic Rays exist, but sources unclear
- Arrival directions do not contain much information about the sources, deflection of these charged particles in magnetic fields
- Sources have to be extragalactic

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High Energy Neutrinos

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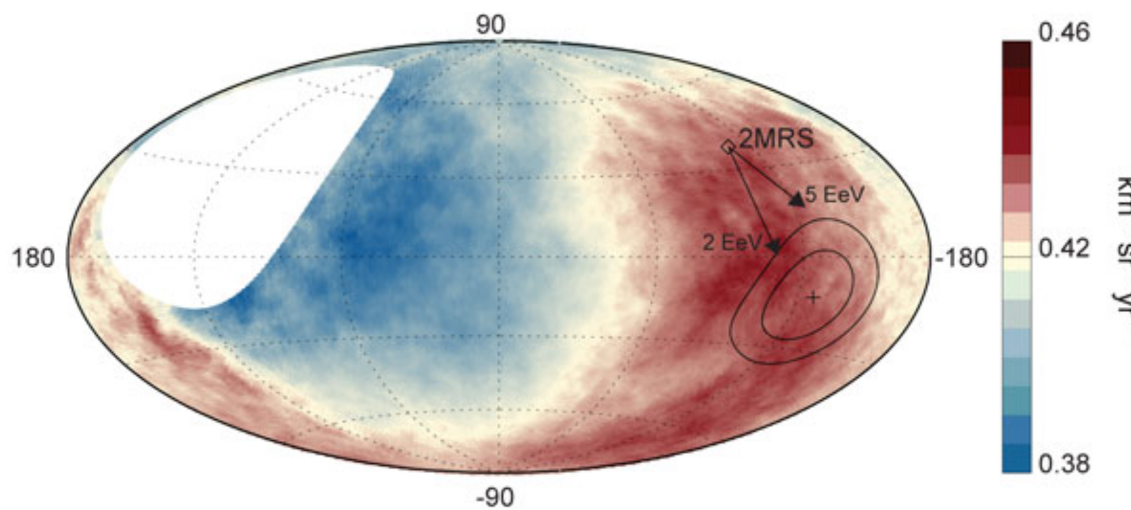
Victor Hess, 1912



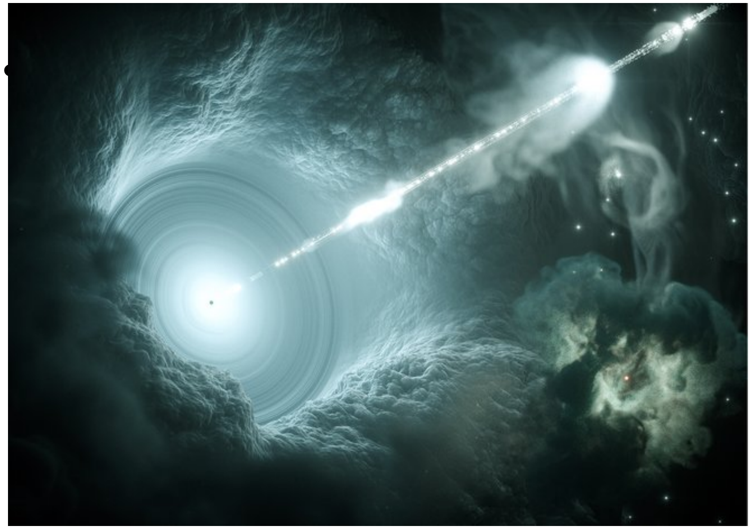
Pierre Auger Collaboration, 2018

High energy neutrinos

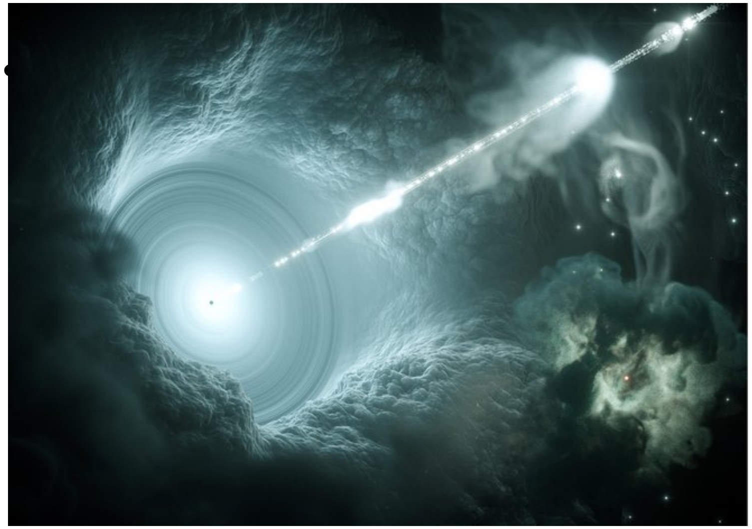
- What could the sources be?

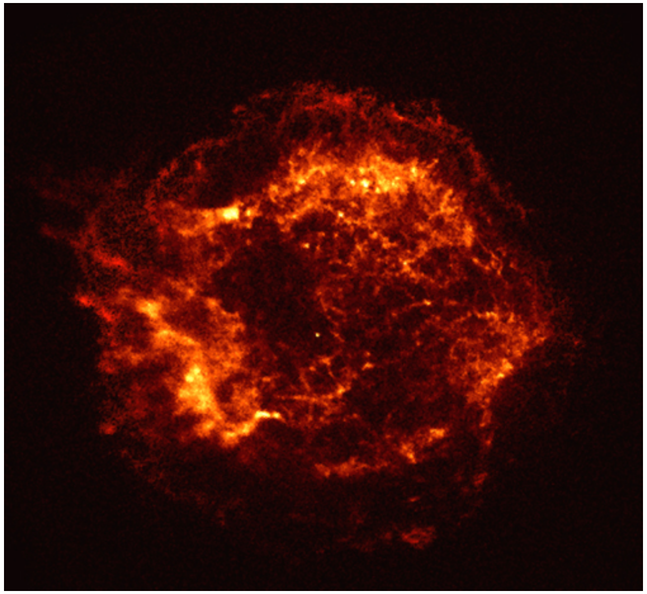
High energy neutrinos

•

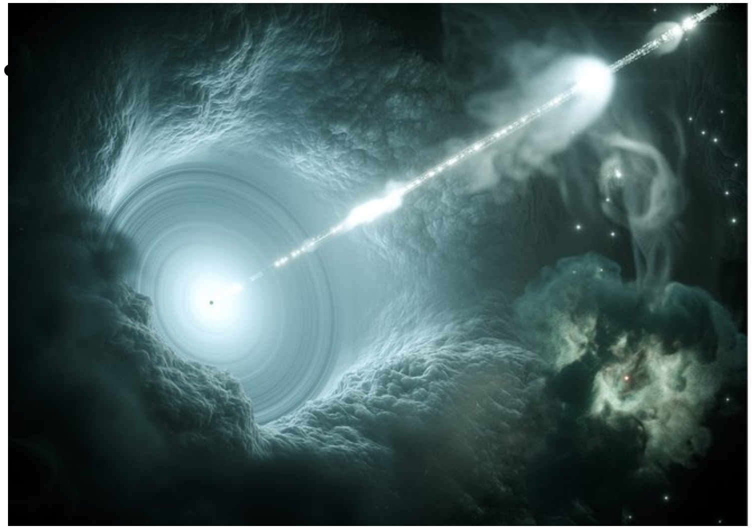


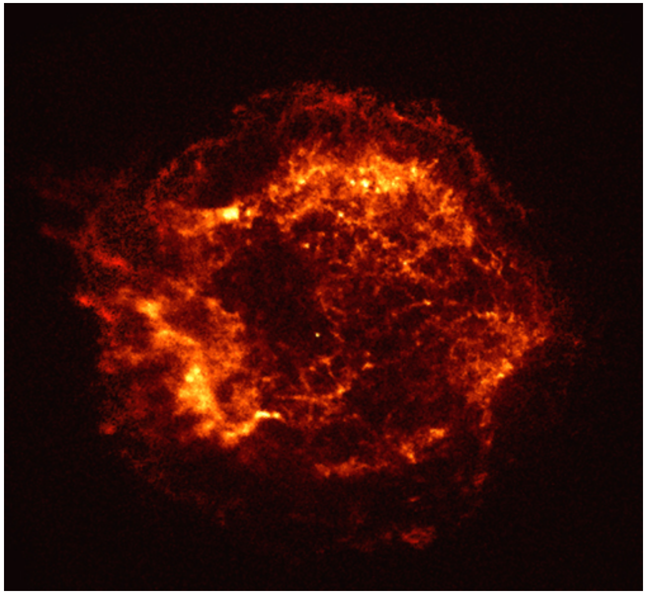
High energy neutrinos

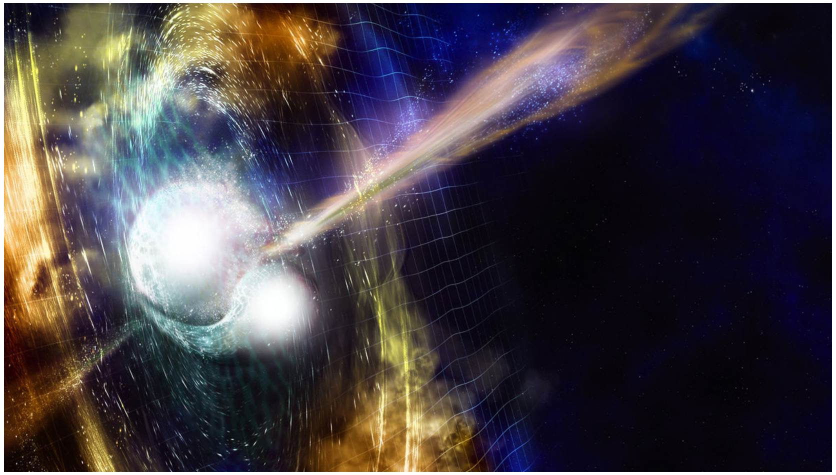




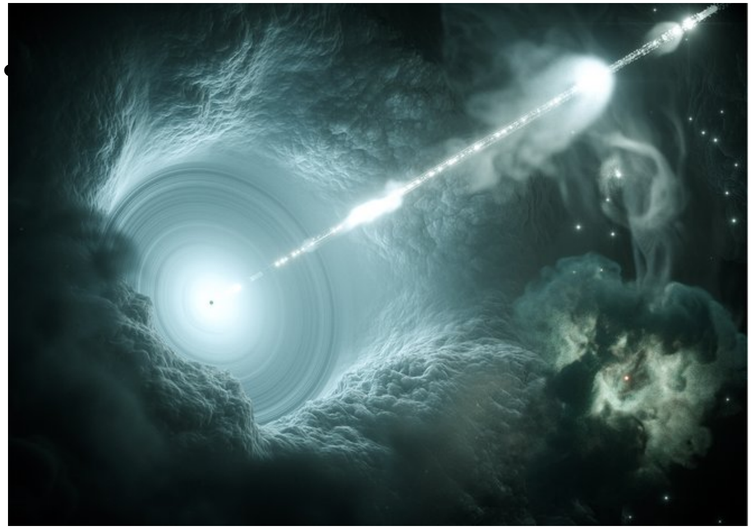
High energy neutrinos

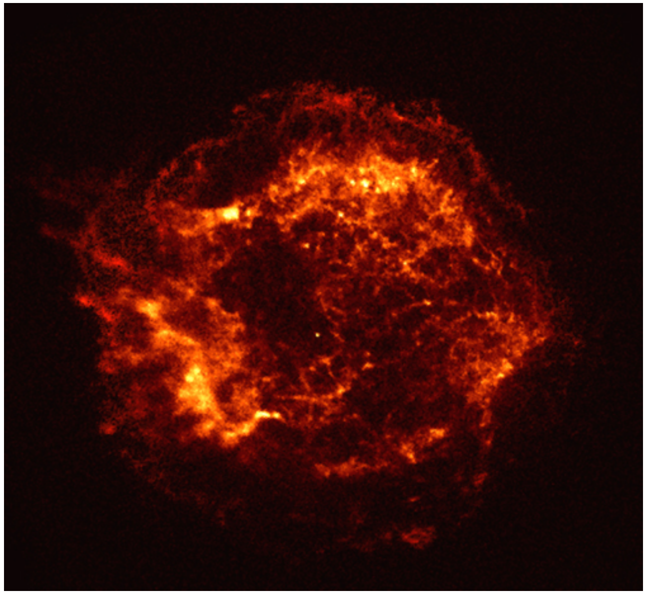


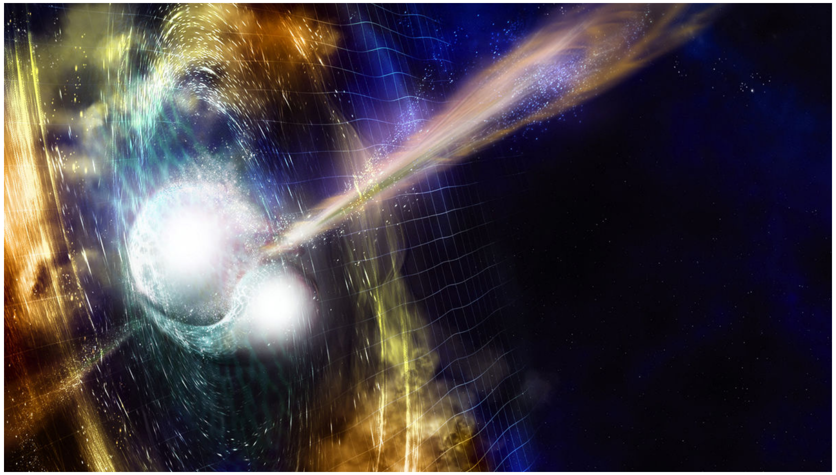


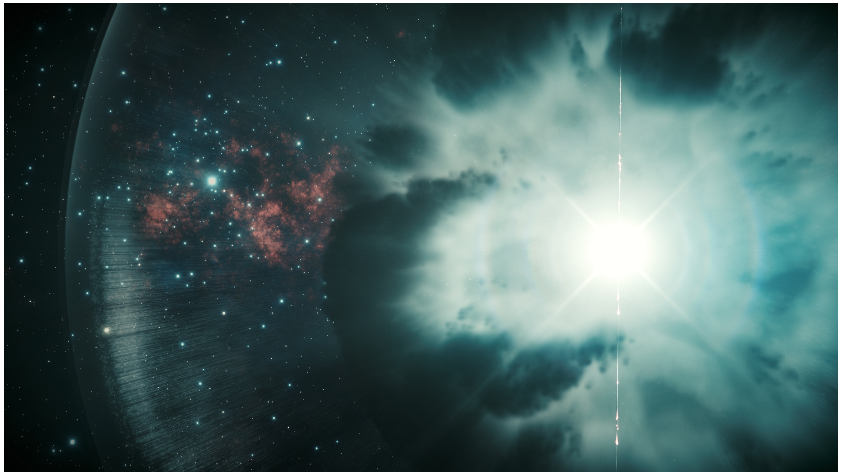


High energy neutrinos



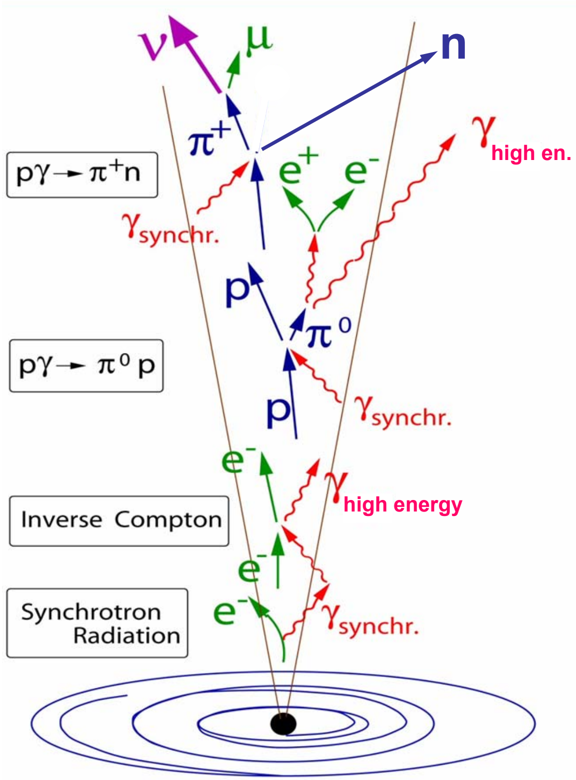






High Energy Neutrinos

(Brief) theoretical motivation



Katz, Spiering, 2011

Sources that accelerate cosmic rays, also produce neutrinos and gammas

- Very fundamental picture
- Not all cosmic ray sources need to be bright in gamma rays, they might be obscured
- But it is really hard "to get rid of" neutrinos

High Energy Neutrinos

(Brief) theoretical motivation

p + nucleus $\rightarrow \pi + X$

$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \pi + p/n$

$\pi^{+/-} \rightarrow \nu$ + lepton

$\pi^{0} \rightarrow \gamma\gamma$

Neutrinos can also be produced at a distance to the sources

- Protons can interact with CMB or IR background
- Delta-resonance suggests that cross-section for this is high — if cosmic rays are protons at $>6\times10^{19}$ eV
- If cosmic rays are predominantly heavier particles, then nuclear spallation and neutrino production less effective
- Models for neutrino flux prediction vary greatly
- But detection of high energy neutrino will restrict the models significantly

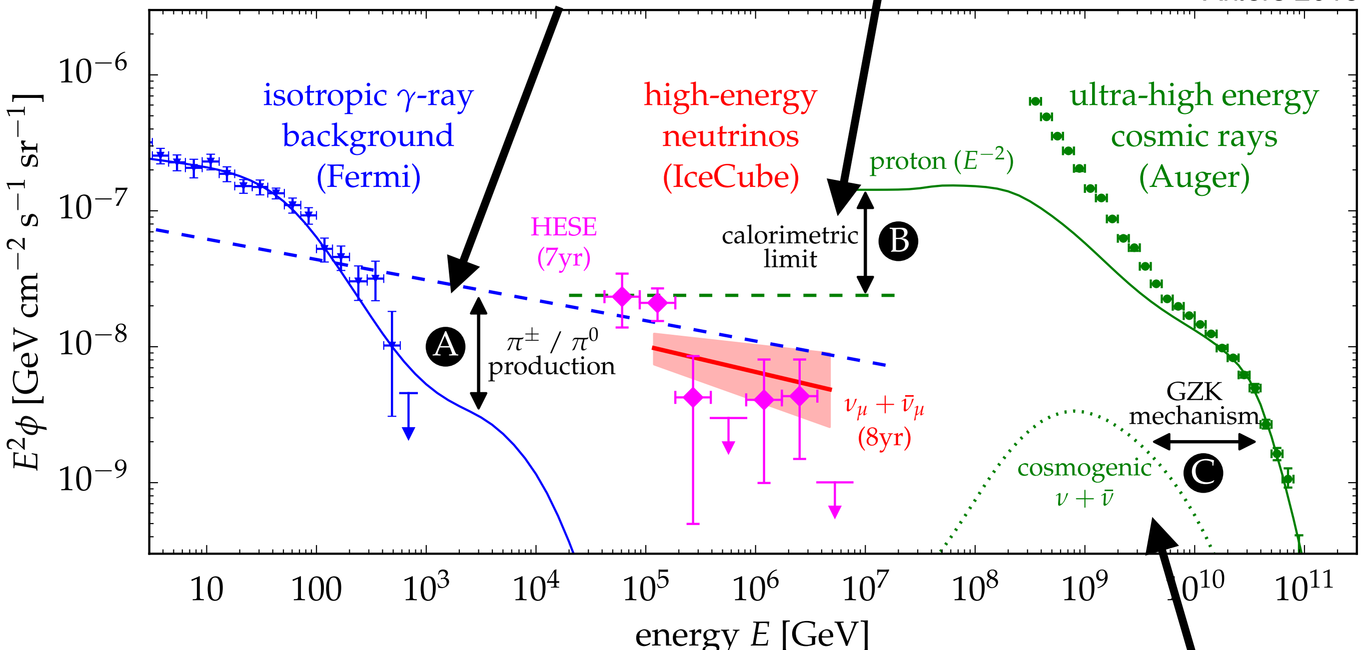
High Energy Neutrinos

(Brief) theoretical motivation

There cannot be more energy in neutrinos than in cosmic rays, if they are produced together

Connection during production

Ahlers 2018



Cosmic-rays interact with CMB and IR background

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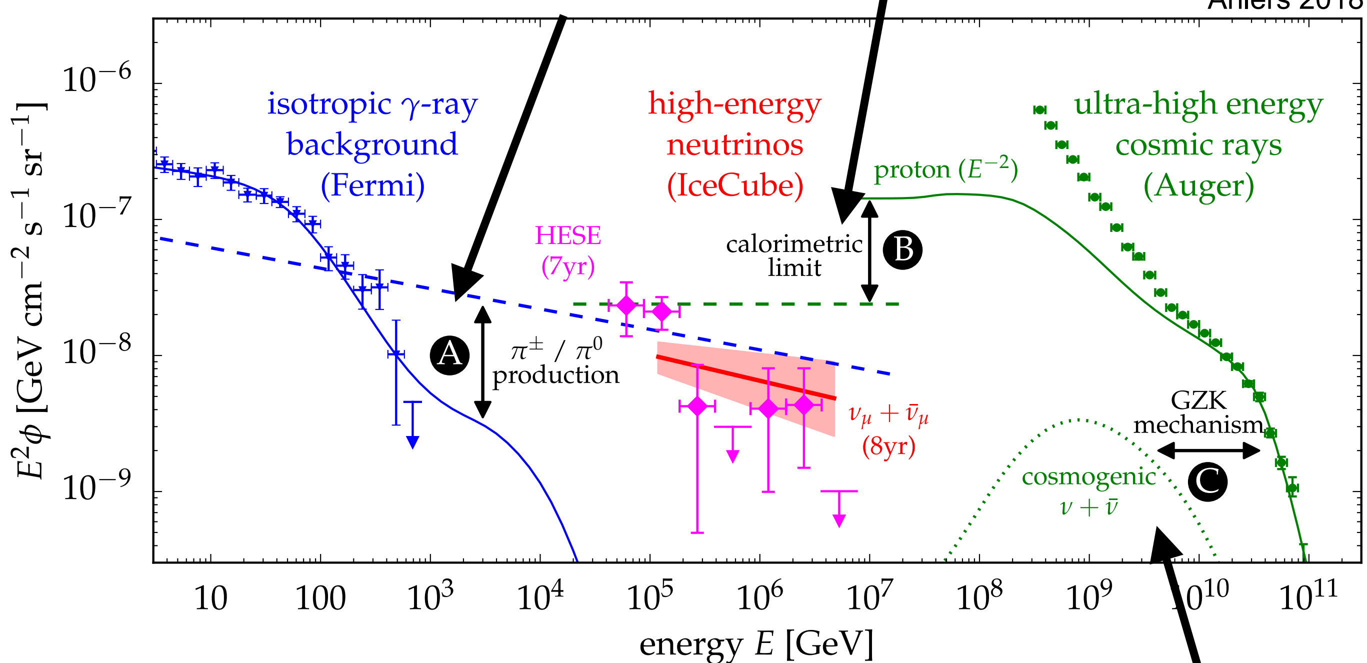


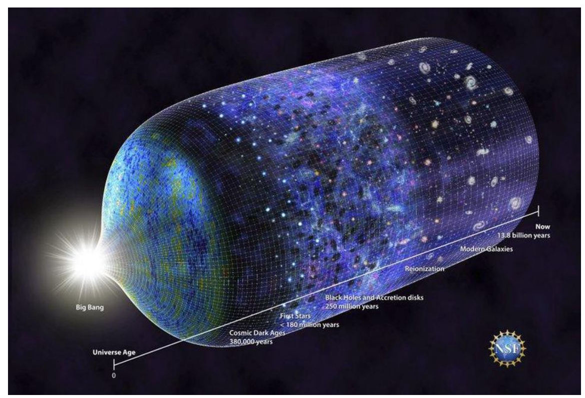
Cosmic-rays interact with CMB and IR background

Multi-messenger astronomy

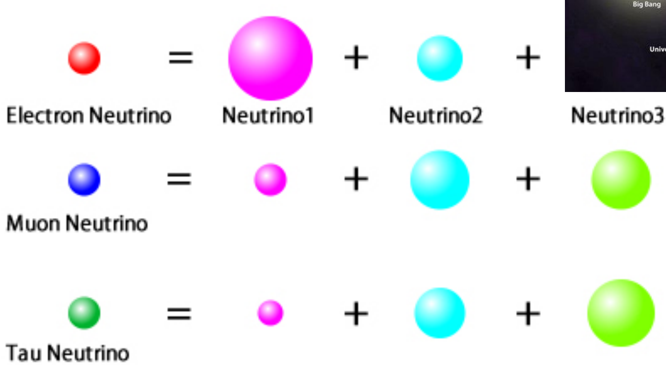
High Energy Neutrinos

Other motivations

- Searching for the sources of Ultra-High Energy Cosmic Rays is clearly main motivation
- But once you have a detector, there are many additional motivations



Dark Matter, Cosmology



Neutrino Oscillations + Properties

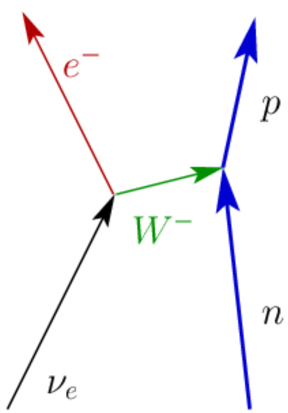
New Particle Physics

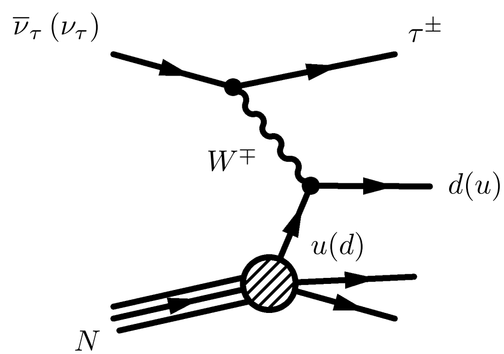
How to detect a high energy neutrino?

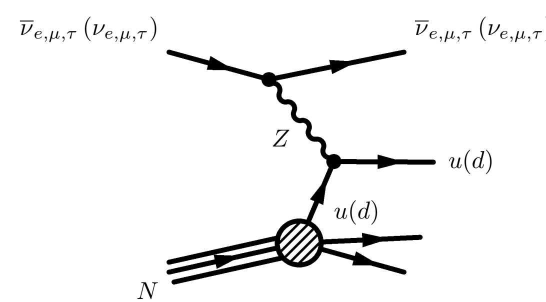
Experimentalists perspective

We never detect neutrinos — we detect their interactions

- Experimentalists have no (not much) interest for precise interaction, only for resulting product (that carries most of the energy)
- Hadronic shower
- Electron = electromagnetic shower
- Muon (long lifetime, energy loss)
- Tau = first shower, medium lifetime, second shower ("double bang")





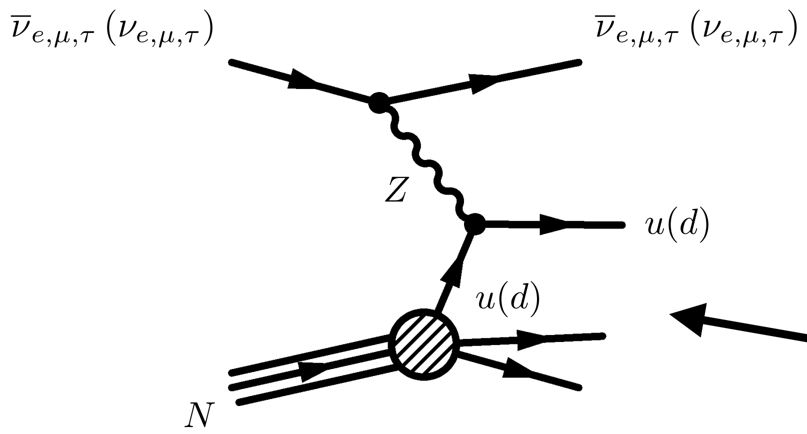


Neutrino Interactions

Details

Outgoing neutrino, not visible

Neutral current



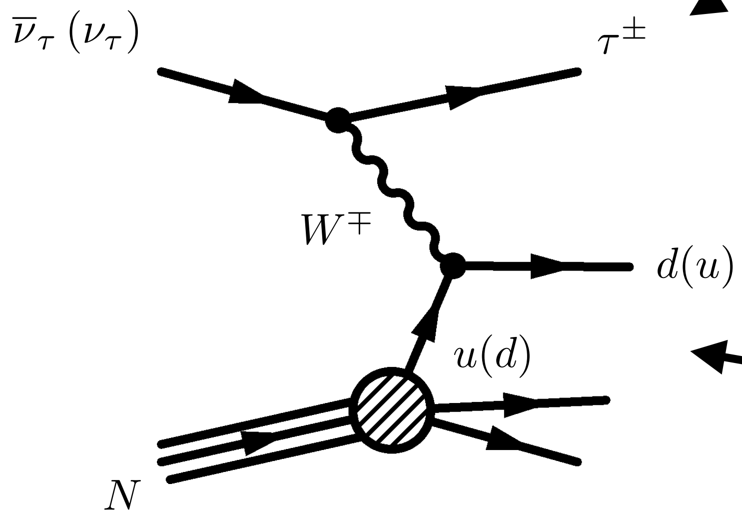
hadronic fragments and pions generate hadronic shower

Deep-inelastic neutrino-nucleon scattering

Neutrino Interactions

Details

Charged current



Outgoing τ = decays or radiates energy

Outgoing μ = radiates energy

Outgoing e = electromagnetic shower

hadronic fragments and pions generate hadronic shower

Deep-inelastic neutrino-nucleon scattering

Choose a detection method

One way to see the resulting particles

Neutrino flux is extremely small

- At 10^{15} eV: 0.01 neutrinos per (year, km^2, sr)
- At 10^{18} eV: 10^{-9} neutrinos per (year, km^2, sr)
- Most practical, if your interaction volume is also your detector
- You cannot build something like ATLAS or CMS in this size

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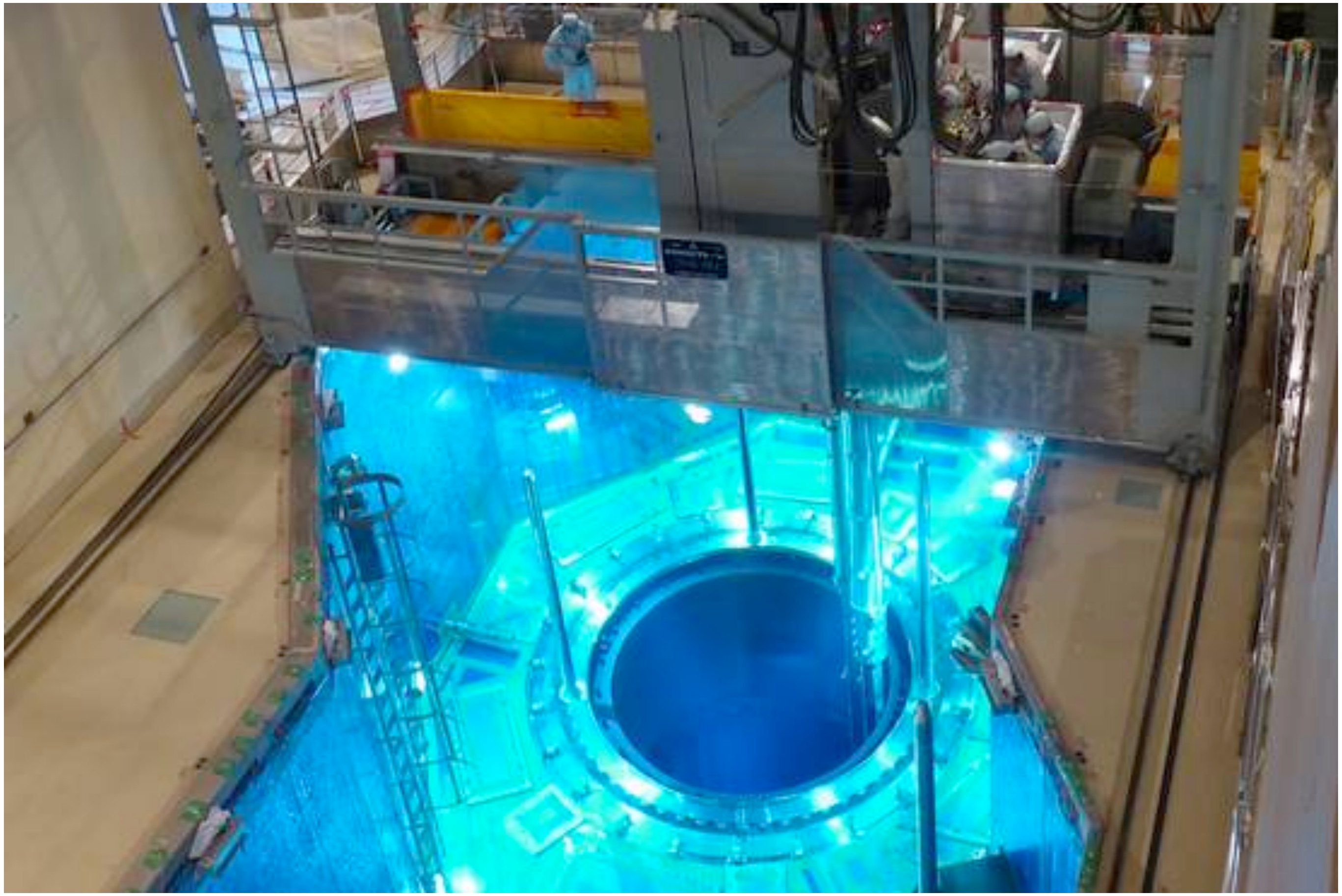
- Typical (low energy) neutrino experiment: liquid with high Z to measure nuclear recoil or other single particles
- At these high energies, not necessary, the signatures will be strong
- What is available in large quantities at Earth at no (low) costs:
- **Air, water, ice**

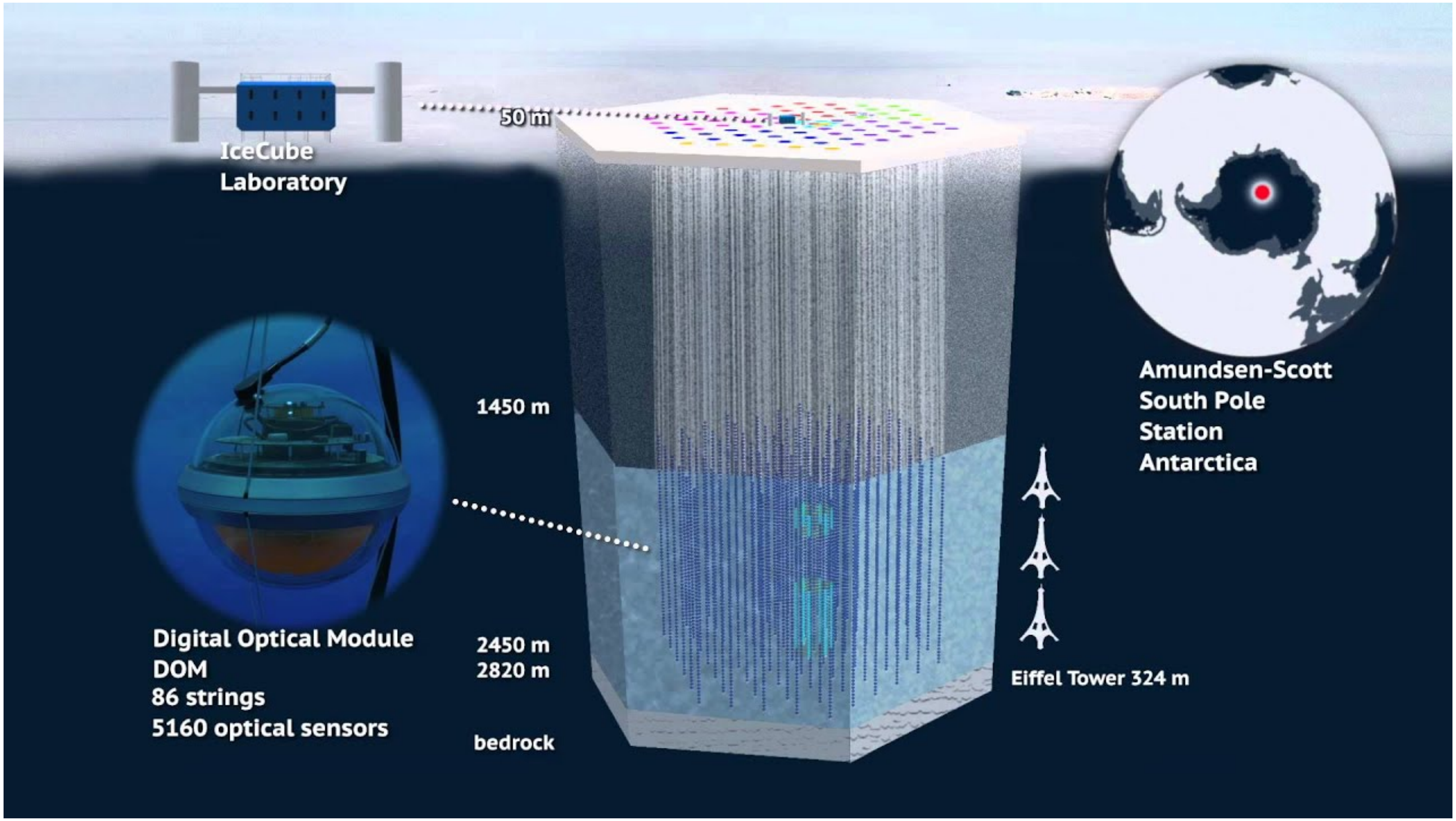
Optical signatures

Cherenkov light



Detection concept

A forest of detectors

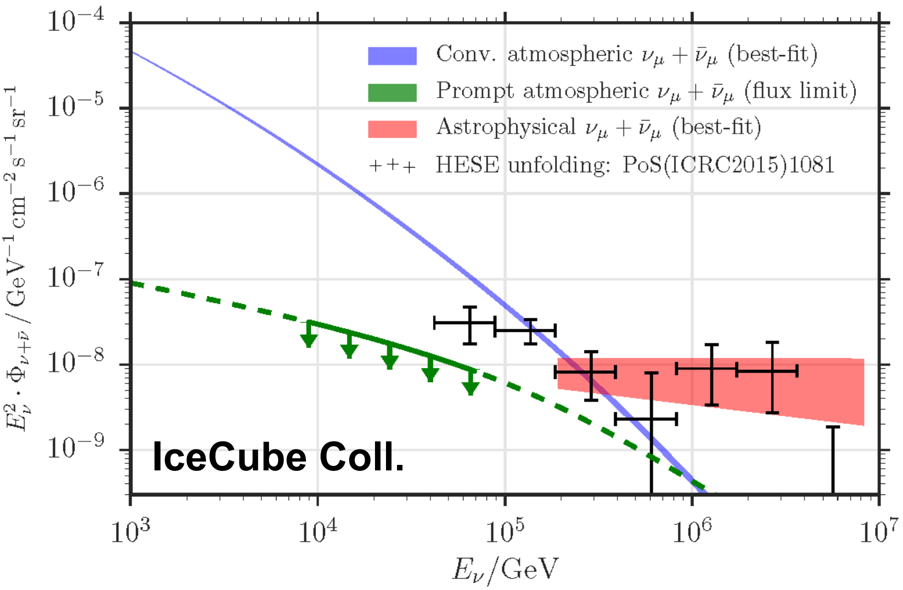


Detection concept

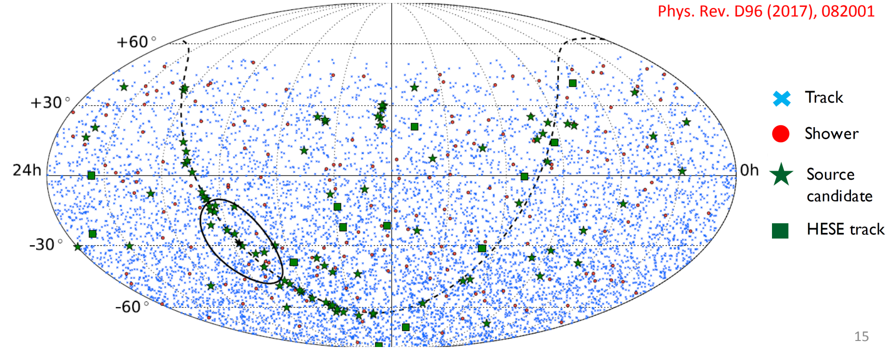
A forest of detectors

Exciting results

(Recent) experimental results

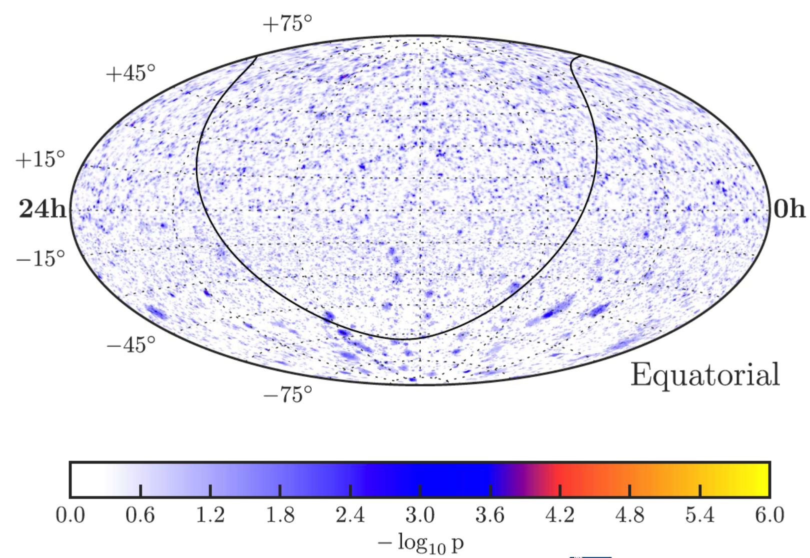


Phys. Rev. D96 (2017), 082001



Antares Coll.

There is more than atmospheric neutrinos, but no point-sources in arrival directions …

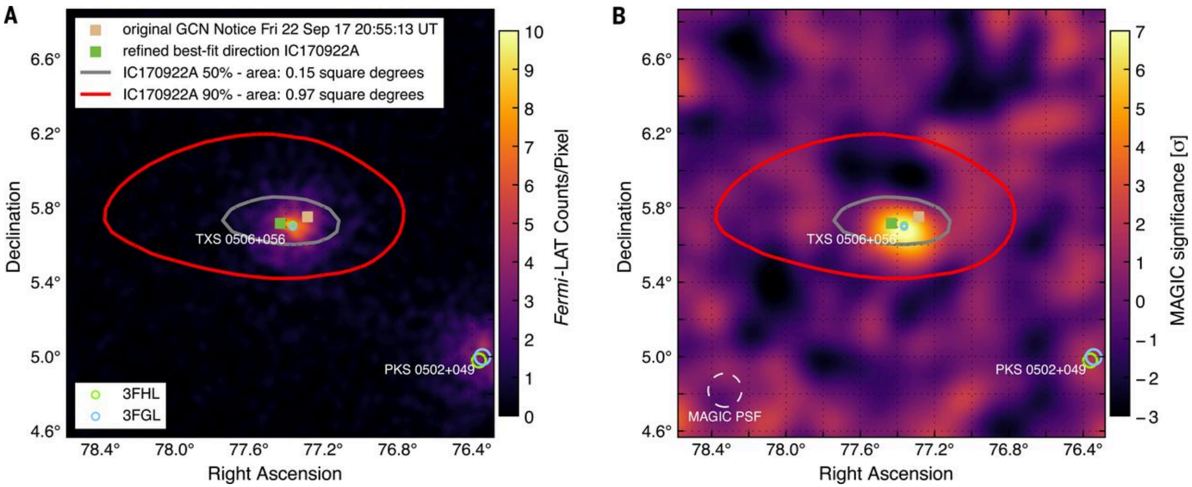


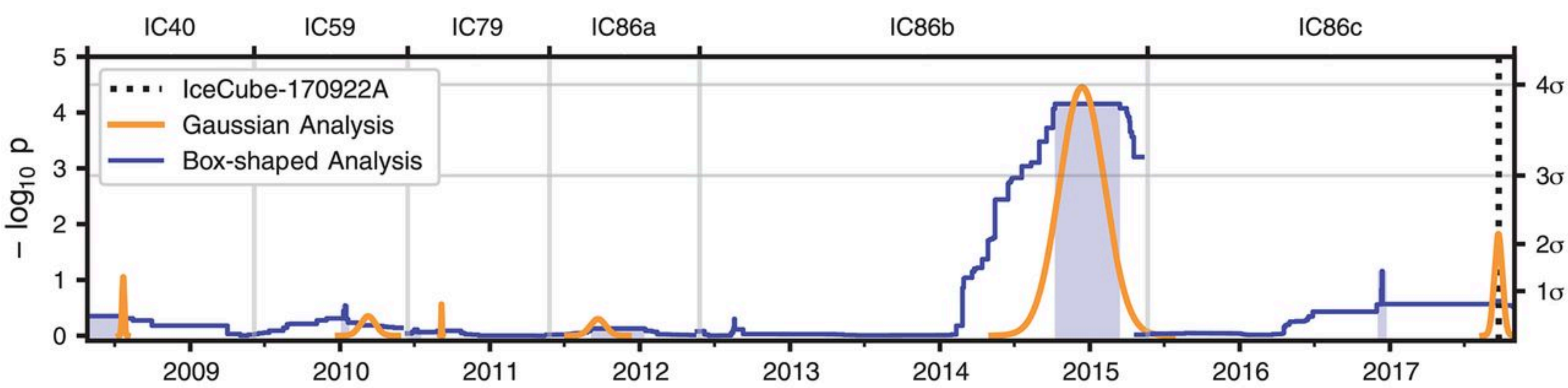
IceCube Coll.

Exciting results

(Recent) experimental results

But …
Coincidence in time and direction between a gamma-ray flare and high energy neutrino



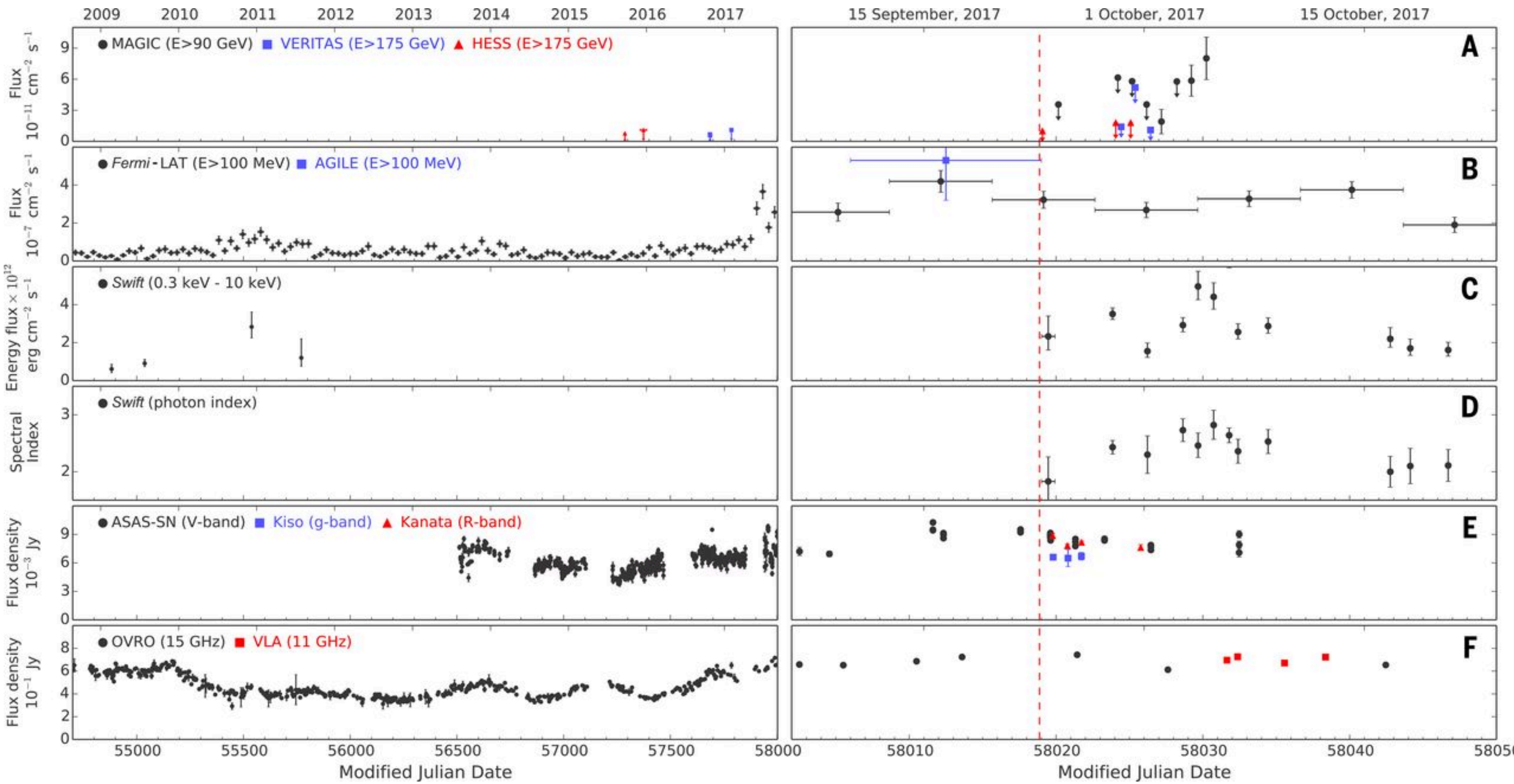


Exciting results

(Recent) experimental results

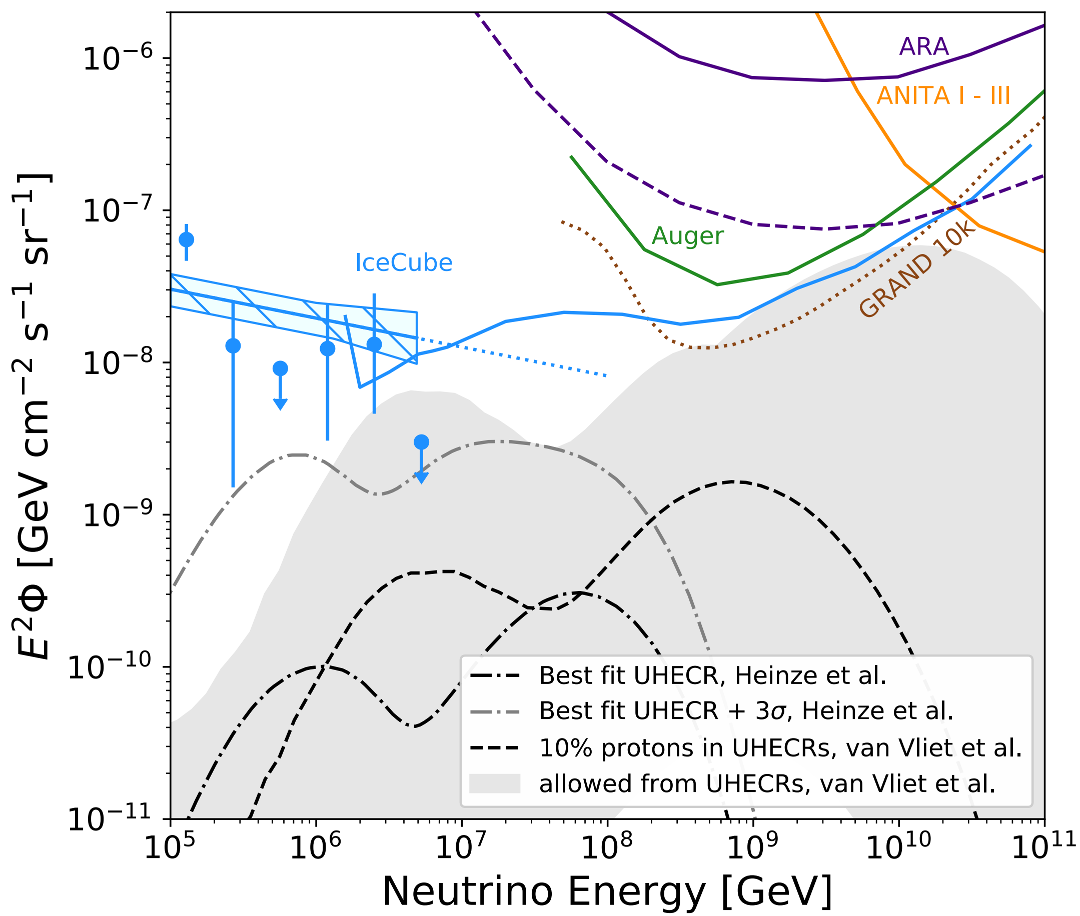
But …

Coincidence in time and direction with high energy neutrino



But … energy

We haven't yet reached where we wanted to be …



Going to higher energies

What can be done?

The flux at higher energies is too low:

- even IceCube is too small to detect neutrinos of > 10^{16} eV
- flux roughly once in 10 km^3 per 10 years
- IceCube would need to be a factor of 100 bigger
- string spacing limited by attenuation length of light in ice, strings have to be close, bigger volume too costly

Different material with longer attenuation length for light

(similarly abundant at low costs)

OR

Different signal with longer attenuation length

(also caused by neutrinos)

Going to higher energies

What can be done?

The flux at higher energies is too low:

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- flux something like once in 10 km^3 per 10 years
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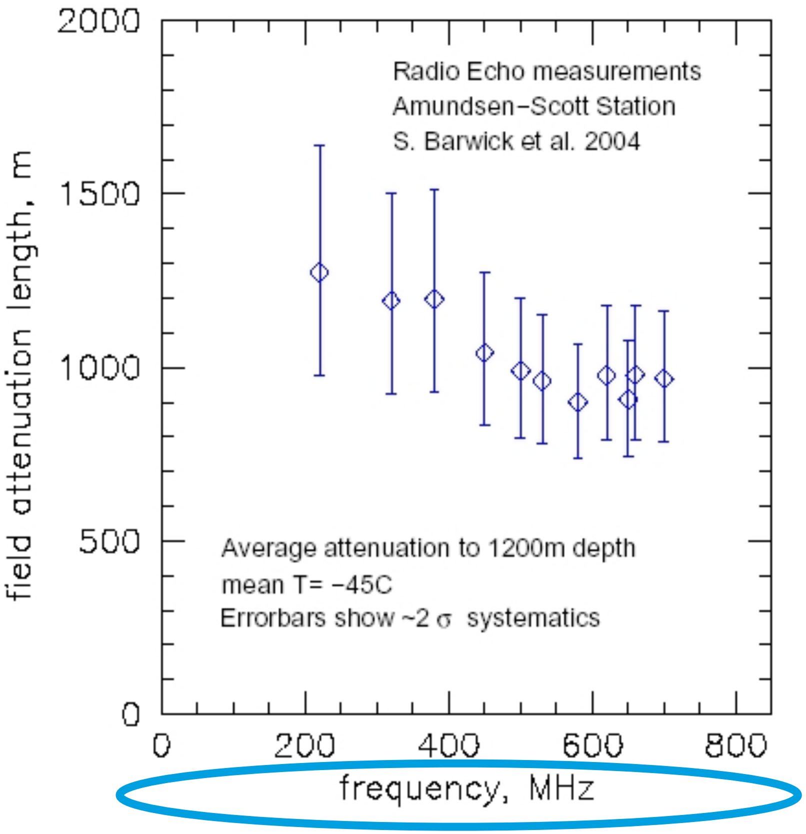
South pole, cold ice: 1km



Instead of working on an established project

Start from scratch and study the principles

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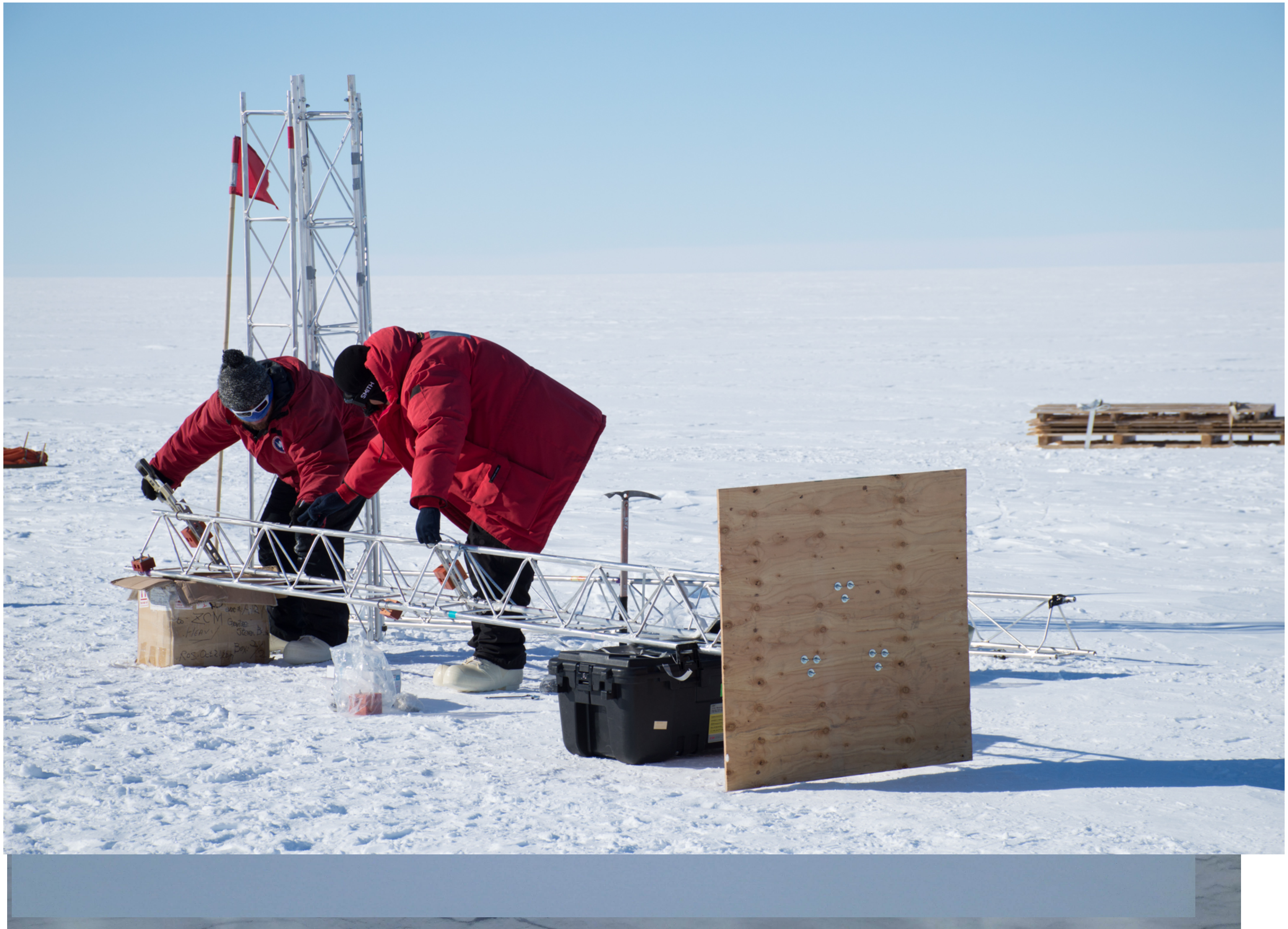

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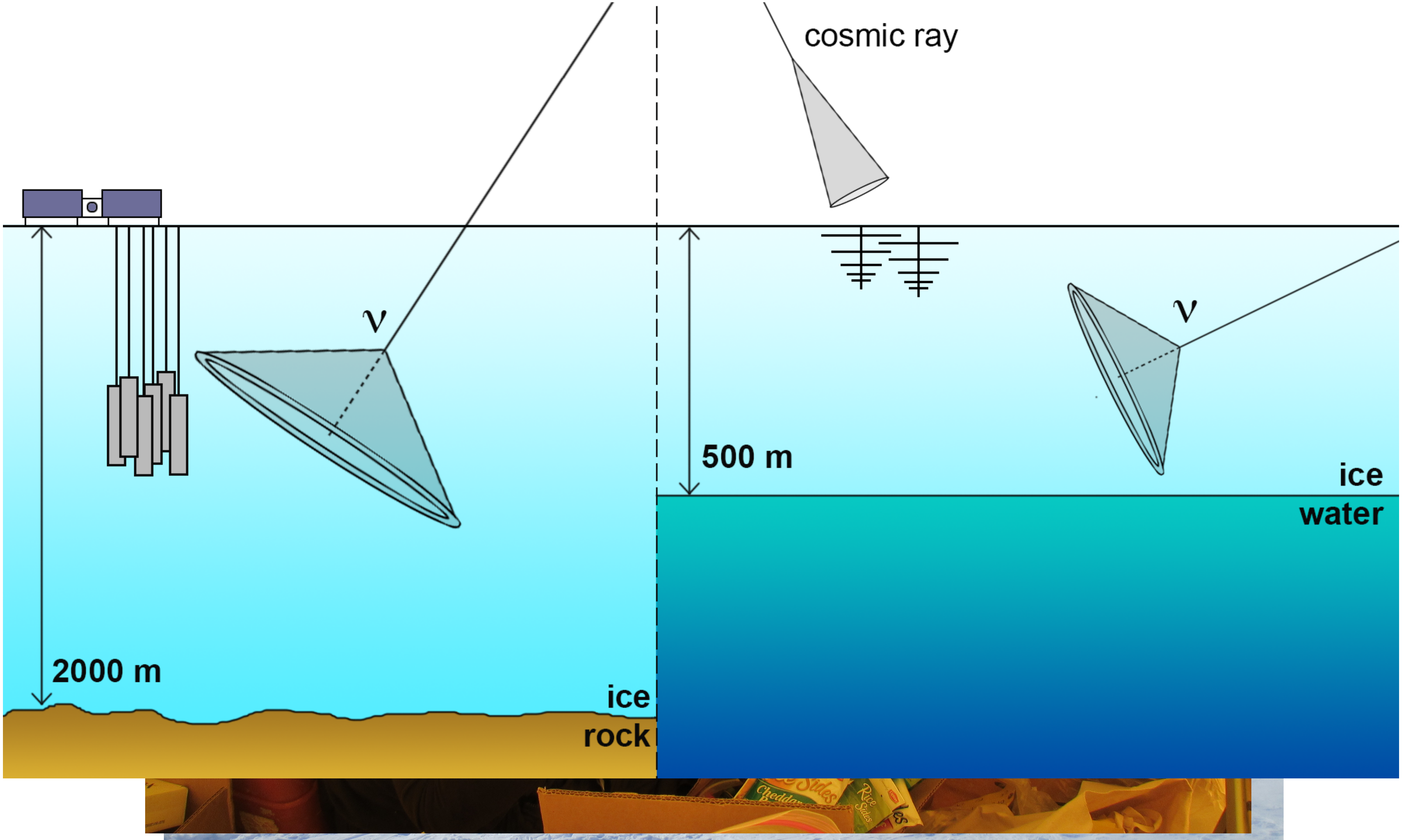
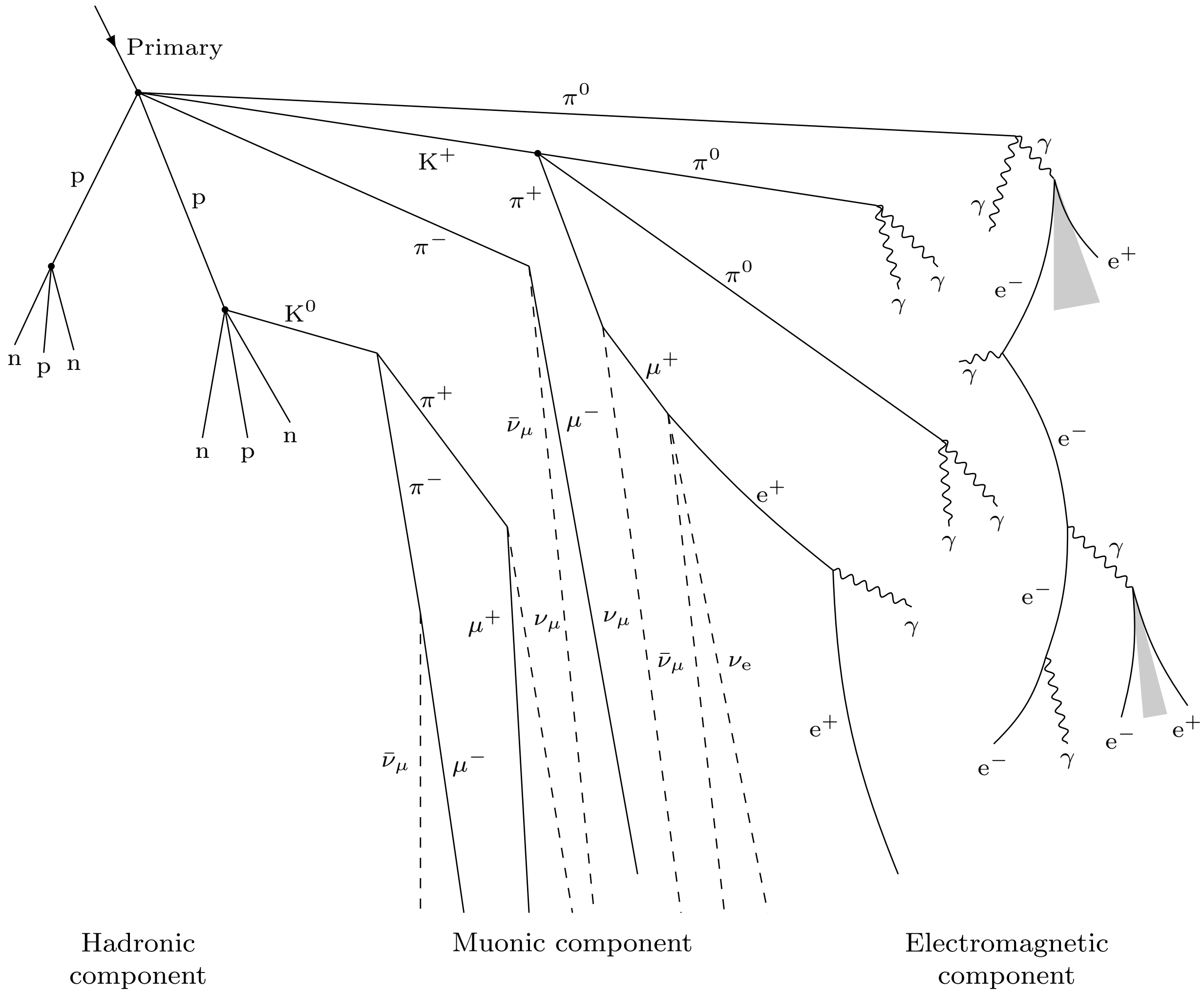


Radio signals

A theoretical introduction

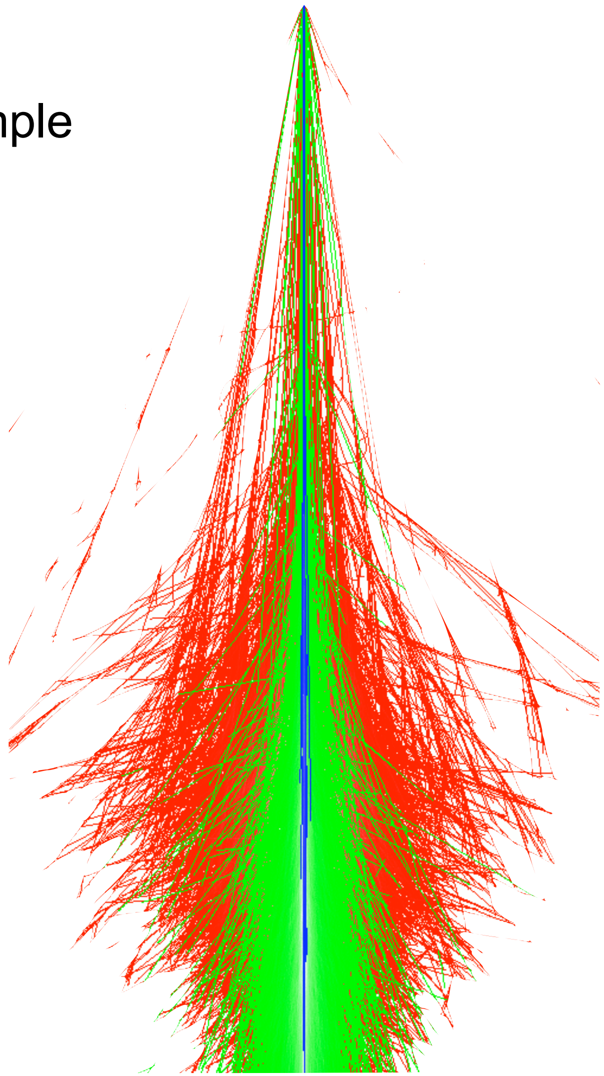
- Highly energetic particles interact with medium and create shower of secondary particles
- Generally one distinguishes hadronic and electromagnetic showers
- Hadronic showers always have a electromagnetic component



Radio emission of particle showers

A theoretical introduction

- Radio emission of showers can be explained from simple first principles
- Three ingredients:
  - **Magnetic field**
    (*Geomagnetic field, Lorentz-force*)
  - **Charge imbalance**
    (*Particle Physics processes*)
  - **Relativistic compression**
    (*Ray optics and relativity*)



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A theoretical introduction

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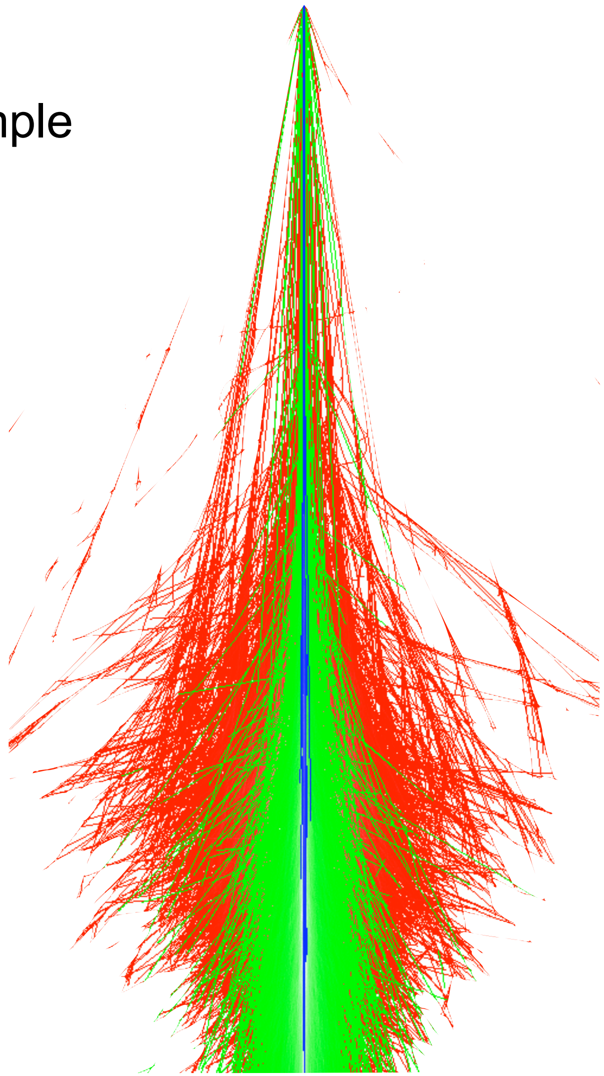
- Three ingredients:

  - **Magnetic fiel**
    (*Geom ... ld, Lorentz-force*)

  Irrelevant for neutrinos

  - **Charge imbalance**
    (*Particle Physics processes*)

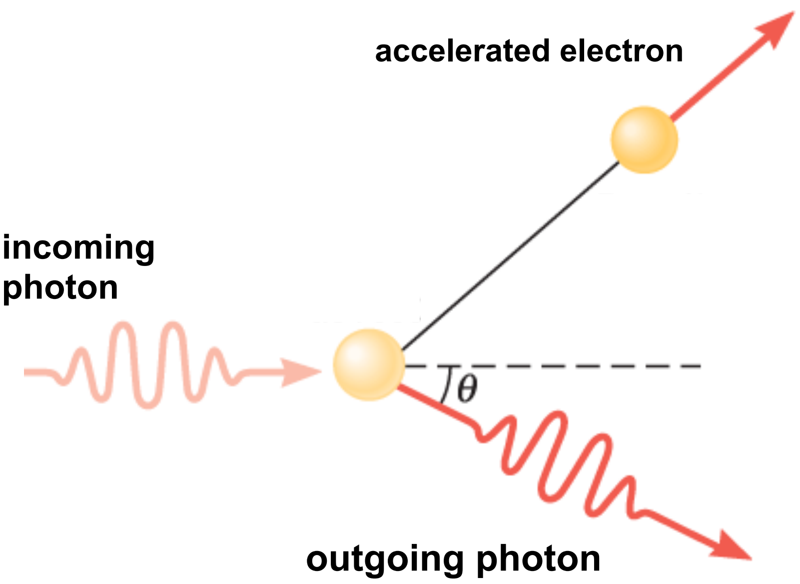
  - **Relativistic compression**
    (*Ray optics and relativity*)



Radio emission of particle showers

Askaryan effect

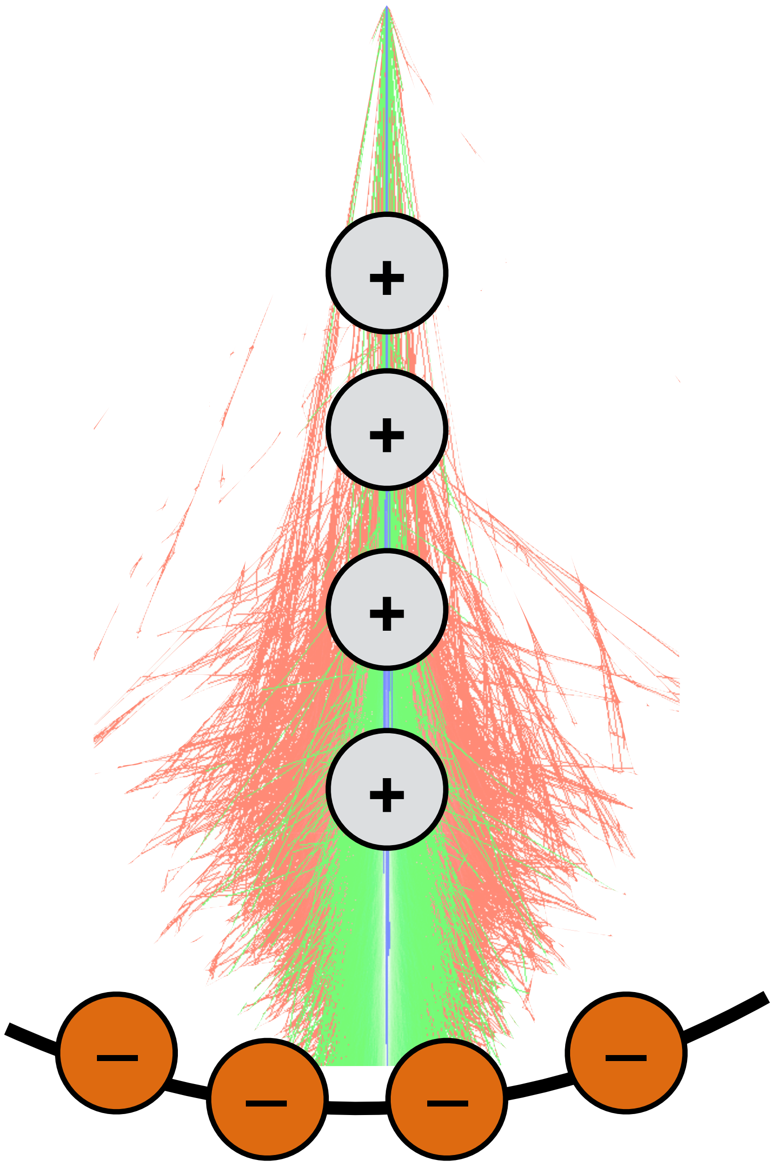
- Remember: numerous high energy photons, positrons electrons in shower
- In atmosphere: only electrons, no positrons
- Shower particles interact with particles in the atmosphere



Radio emission of particle showers

Askaryan effect

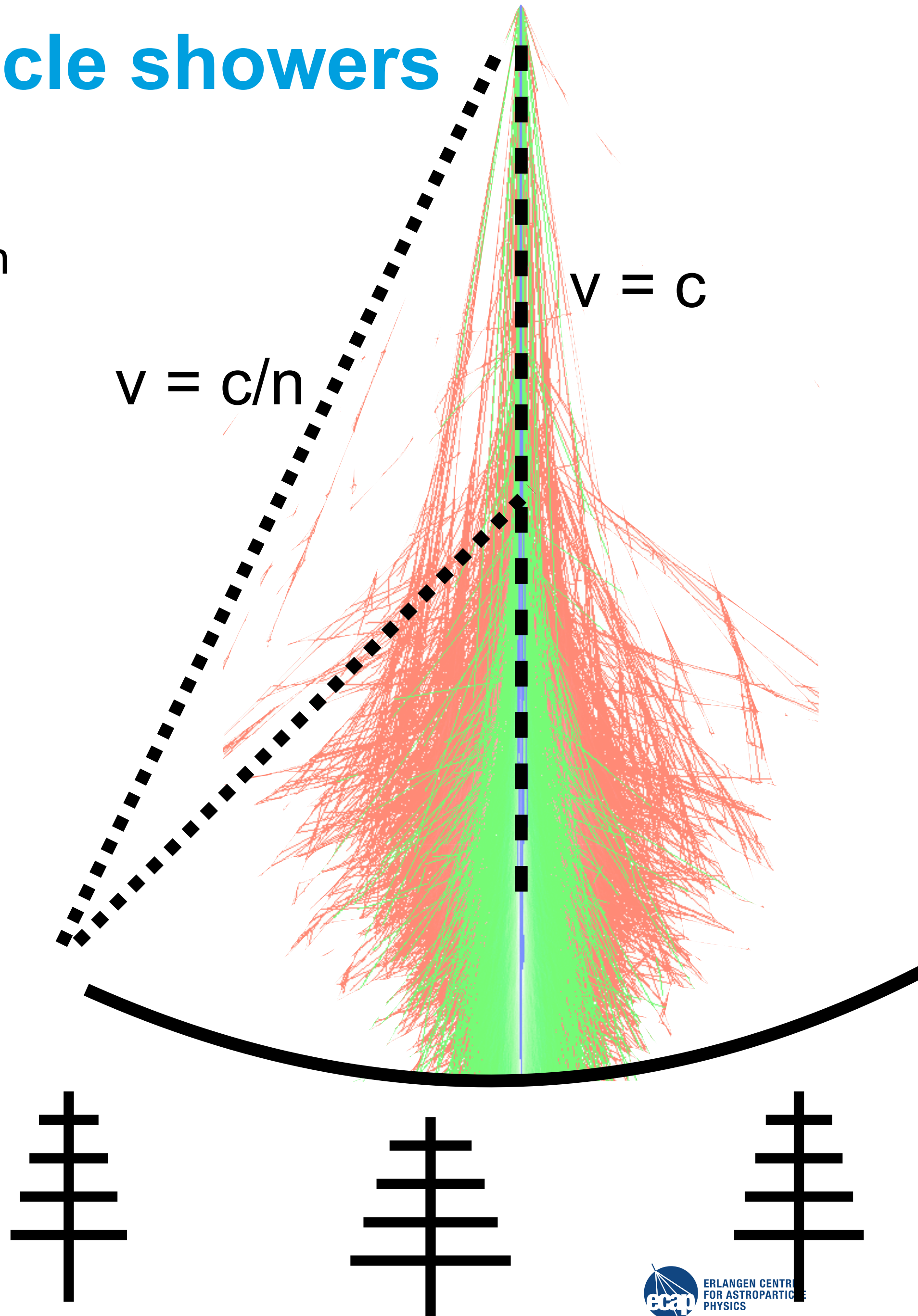
- Charge separation along axis
- Shower front is negative, axis positively charged
- Current along axis, changing as function of time/height
- Also here: changing current induces electric emission



Radio emission of particle showers

Cherenkov-like effects

- Shower is faster than its emission at n = 1.003



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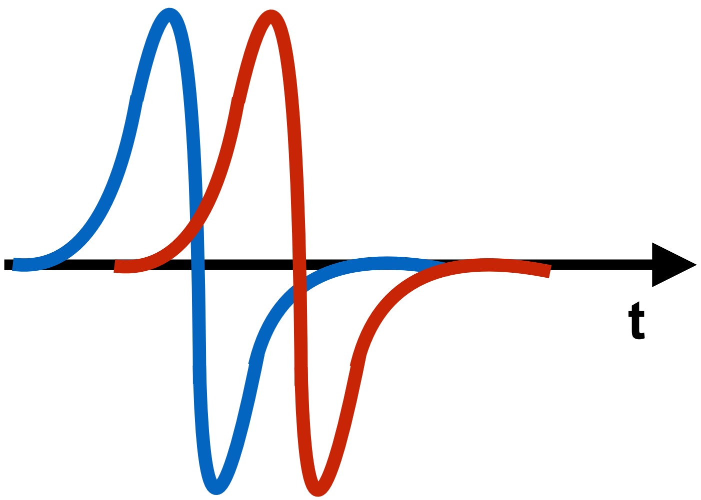
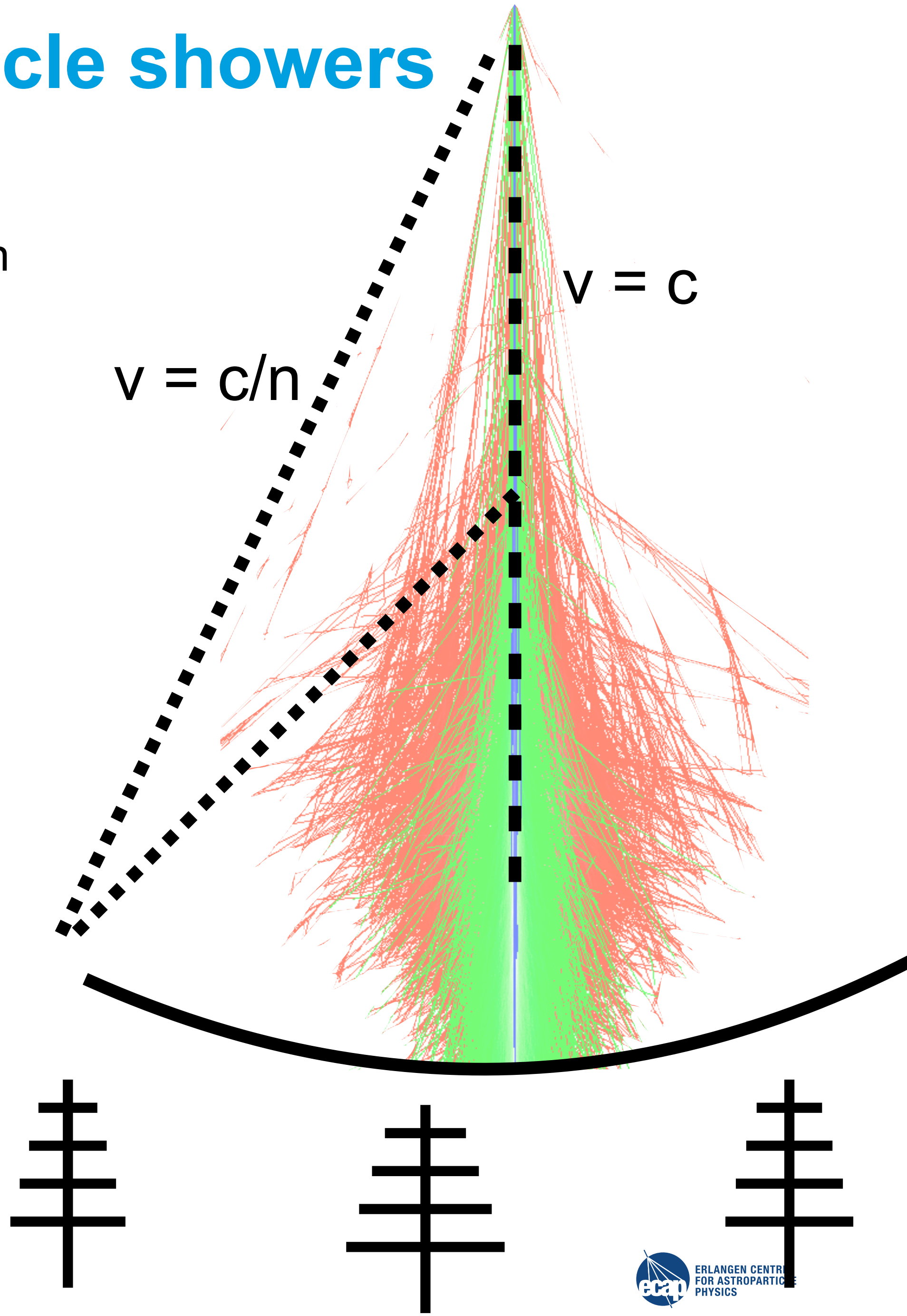
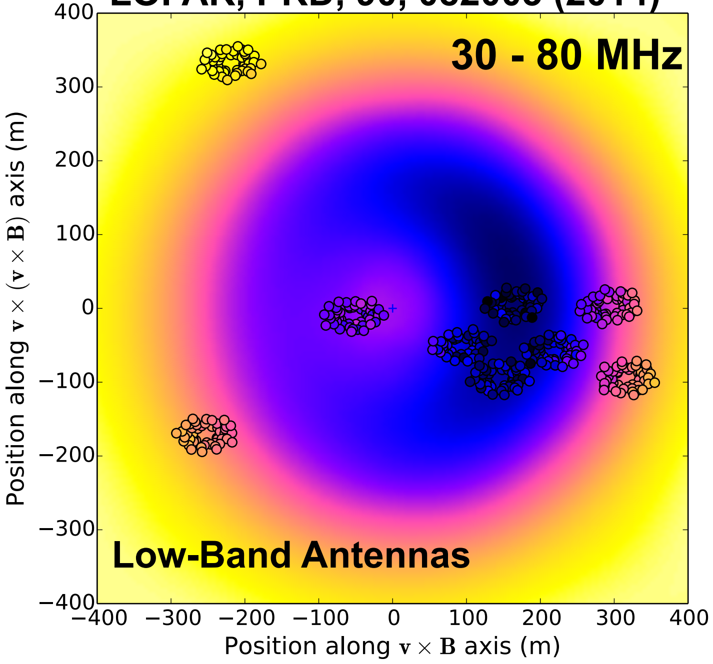


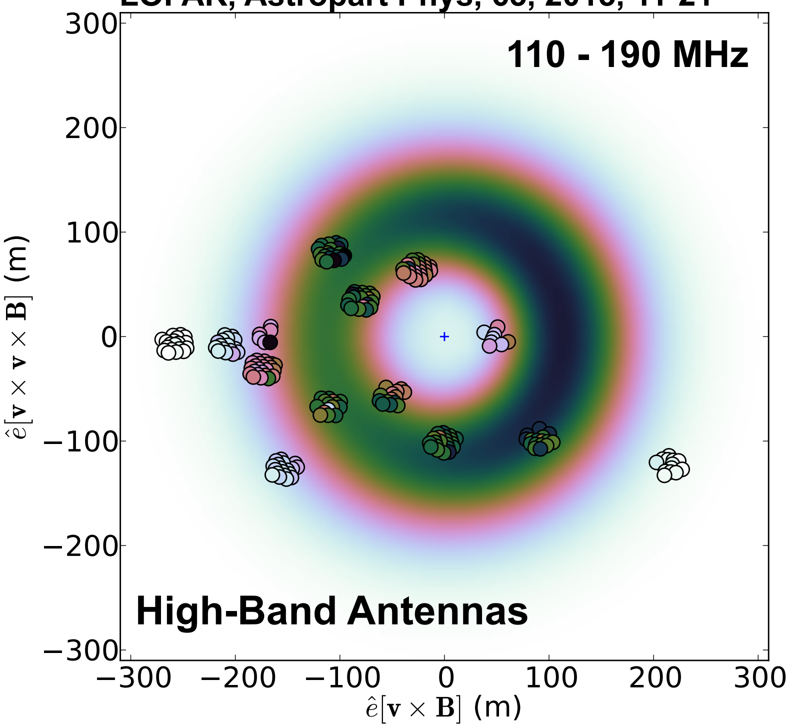
- Signal gets enhanced when it arrives in phase = coherence
- Enhancement at the Cherenkov angle



Radio emission of particle showers

Do we know this from theory only?

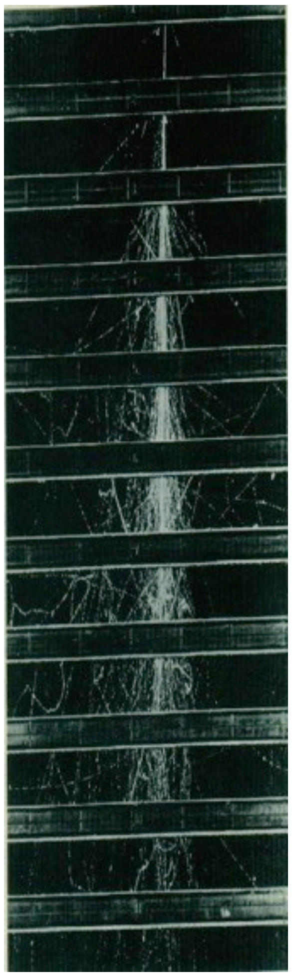




- We have seen this emission in air showers
- Theory works (as far as we can tell)

Radio detection

Air showers vs. showers in medium

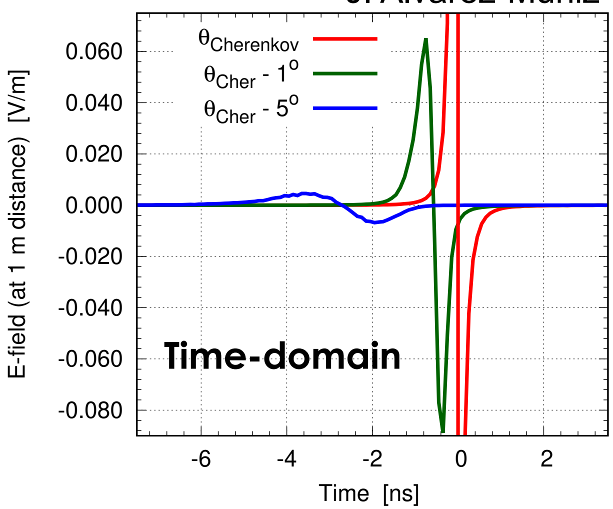


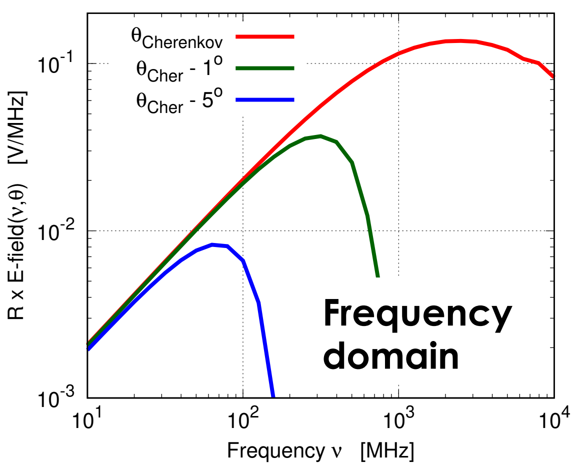
- A shower from a neutrino interaction is subject to same emission mechanisms
- Emission confirmed in accelerator experiments at SLAC, for both no magnetic field (Phys. Rev. D 72(2005)023002) and with magnetic field (PRL 116(2016)141103)
- **Simulations predict measurable neutrino signal > 10^{16} eV in radio above "normal" backgrounds**
- First detection of neutrino radio signal still to be done

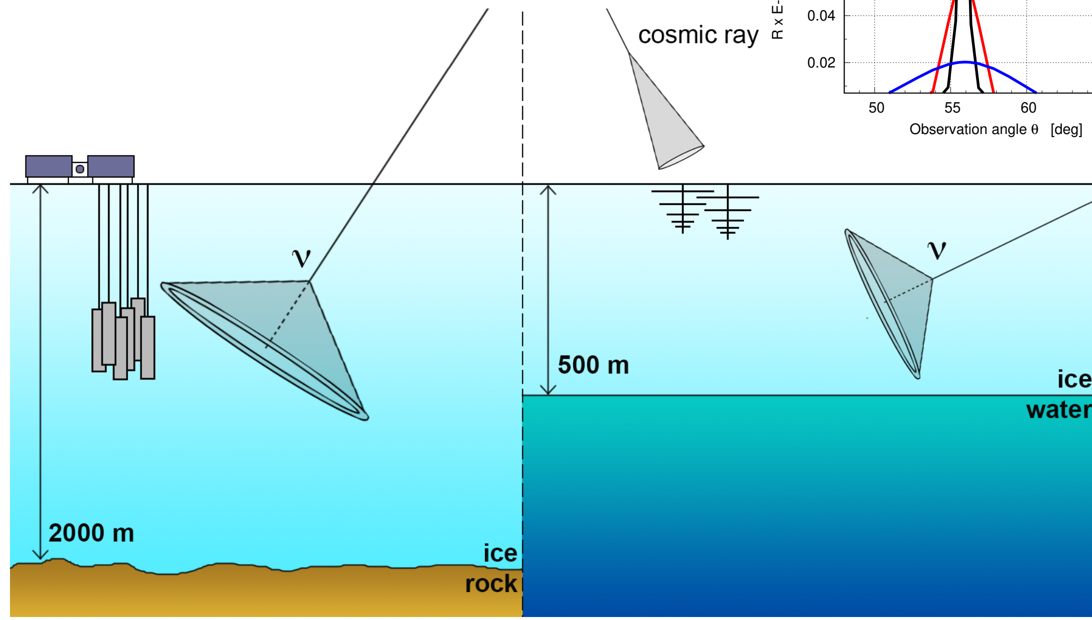
Radio Detection

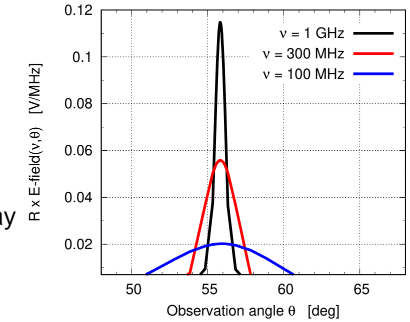
What are we looking for?

J. Alvarez-Muniz









- Short nano-second scale broad-band pulse
- Amplitude scales with energy of neutrino

Radio Detection

Basic signal propagation theory

‘fluffy’ snow

more and more compact ice

Snell’s law

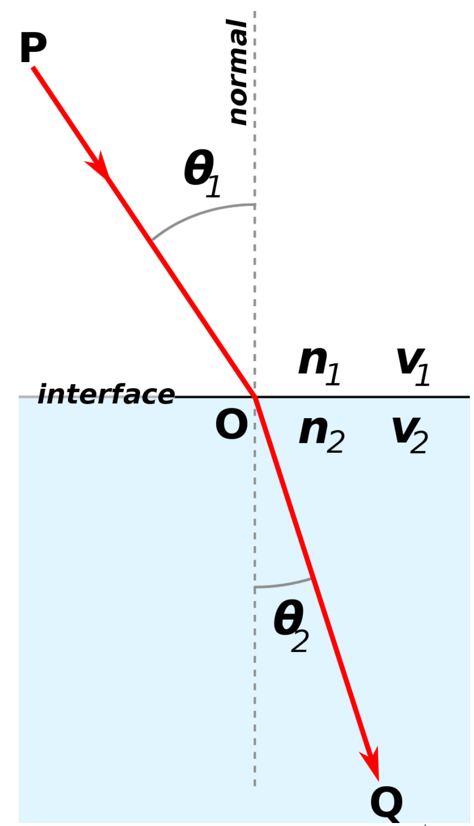
$$n_1 \cdot \sin(\theta_1) = n_2 \cdot \sin(\theta_2)$$

$$\frac{c}{n_1} \cdot \sin(\theta_1) = \frac{c}{n_2} \cdot \sin(\theta_2)$$

$$v_1 \cdot \sin(\theta_1) = v_2 \cdot \sin(\theta_2)$$

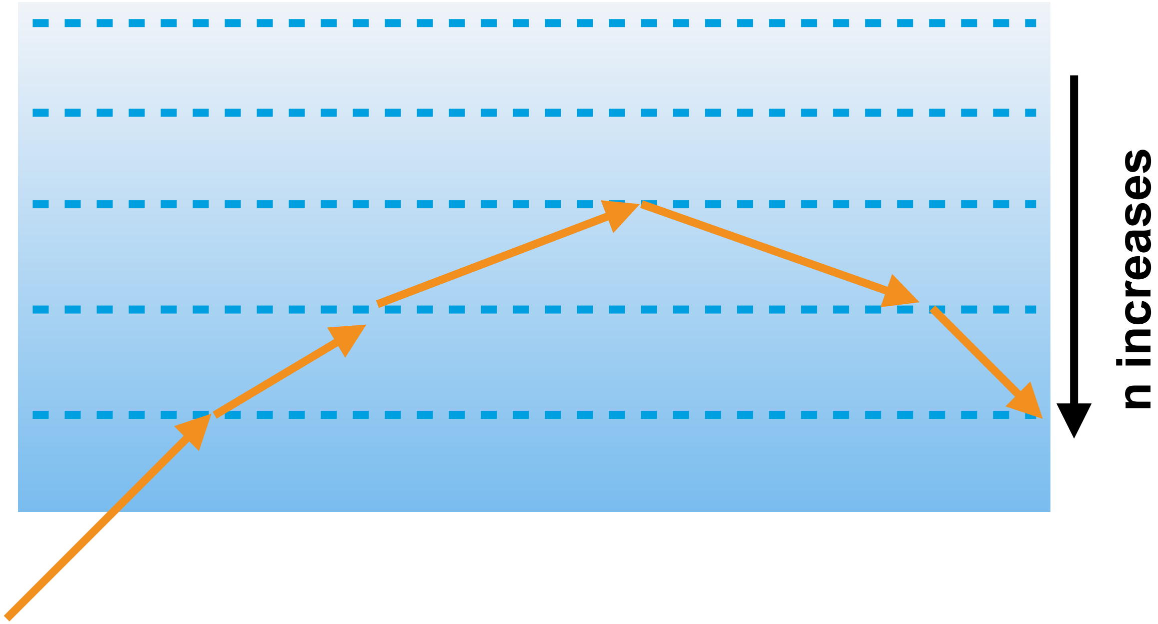
Schytt equation: (ice)

$$n = 1 + 0.78 \cdot \rho/\rho_0$$



Radio Detection

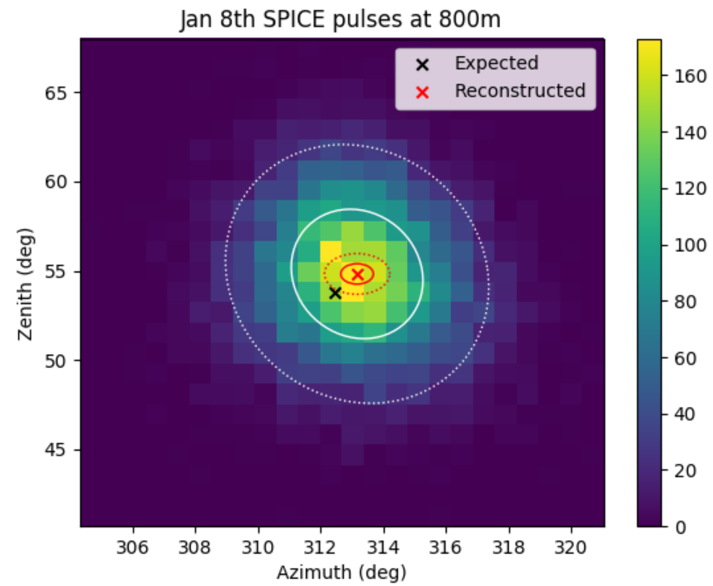
Basic signal propagation theory

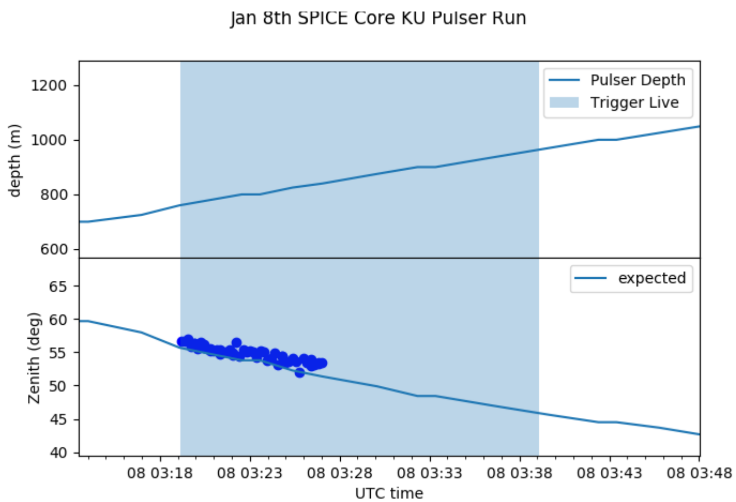


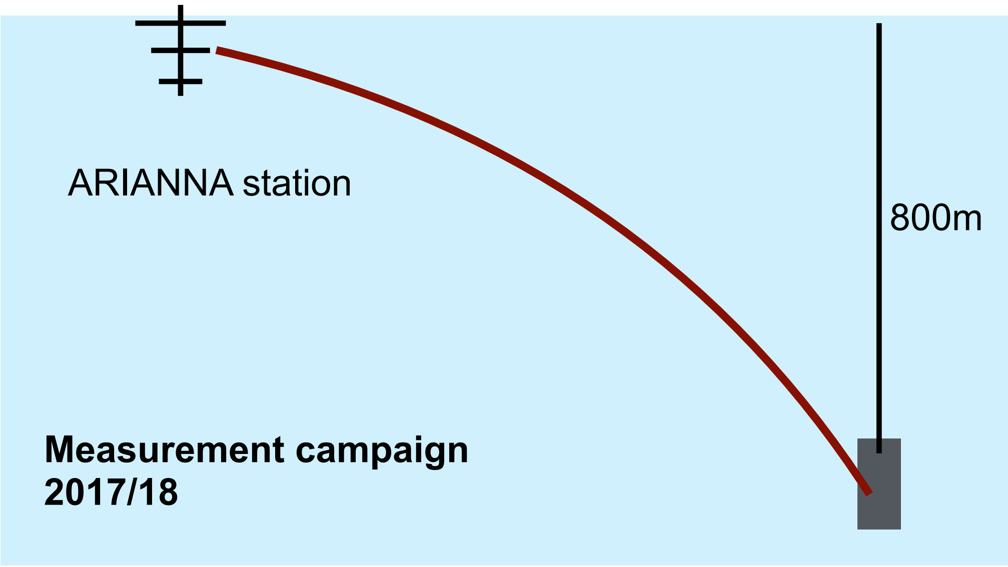
- Approximate smooth ice with small layers of increasing index of refraction
- Radiation near the surface (almost) never travels horizontally, all ray paths are curved
- Signal that was from below can reach detector from above

Radio Detection

Signal propagation in the experiment



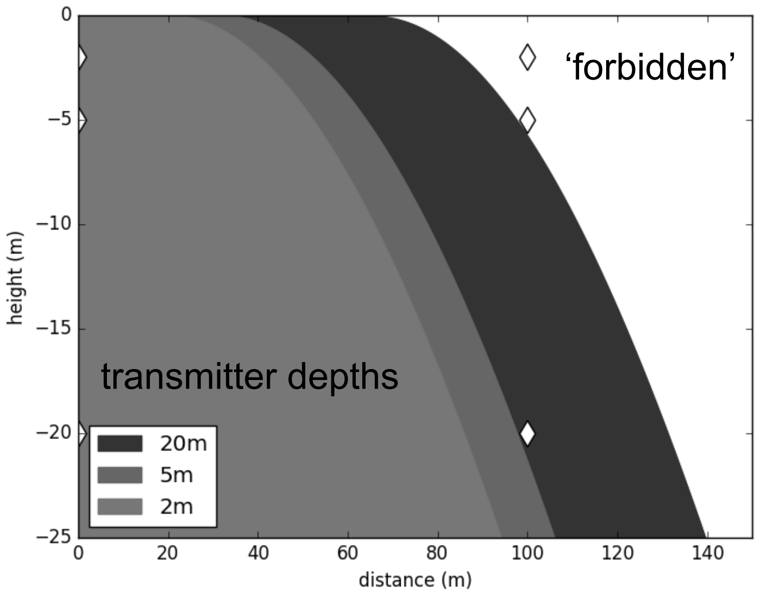




- Excellent angular reconstruction of pulse in deep ice, with the assumption of bend rays

Radio Detection

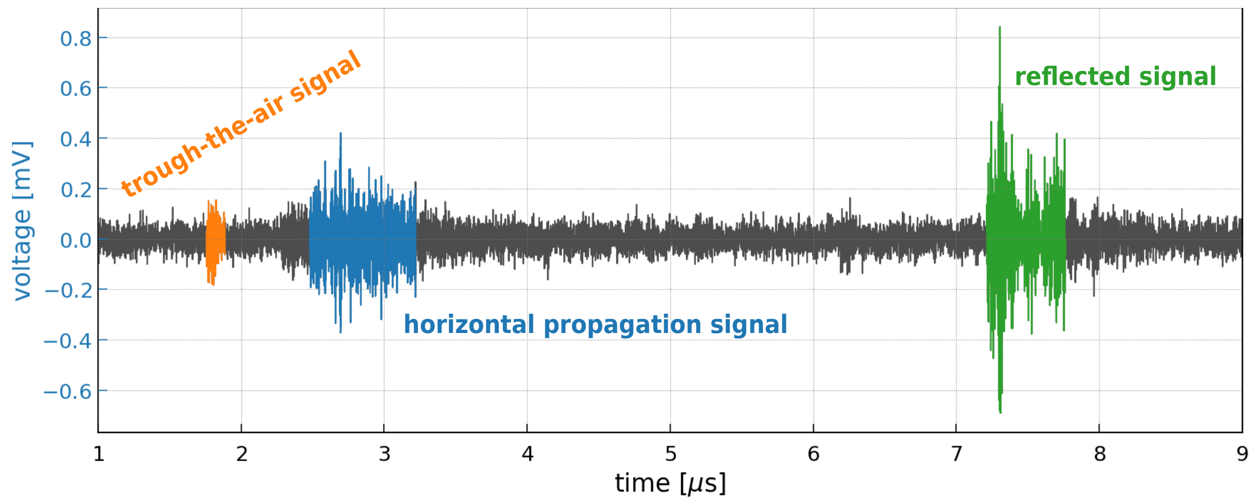
Signal propagation in the experiment



- The theory predicts forbidden zones
- They are observed and also not observed

Barwick et al., JCAP07(2018)055

- Real polar ice is not smooth

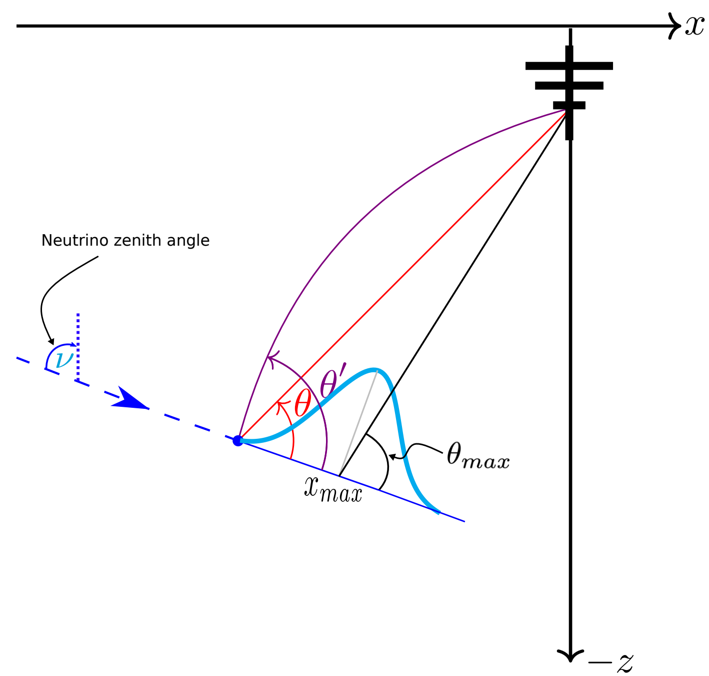


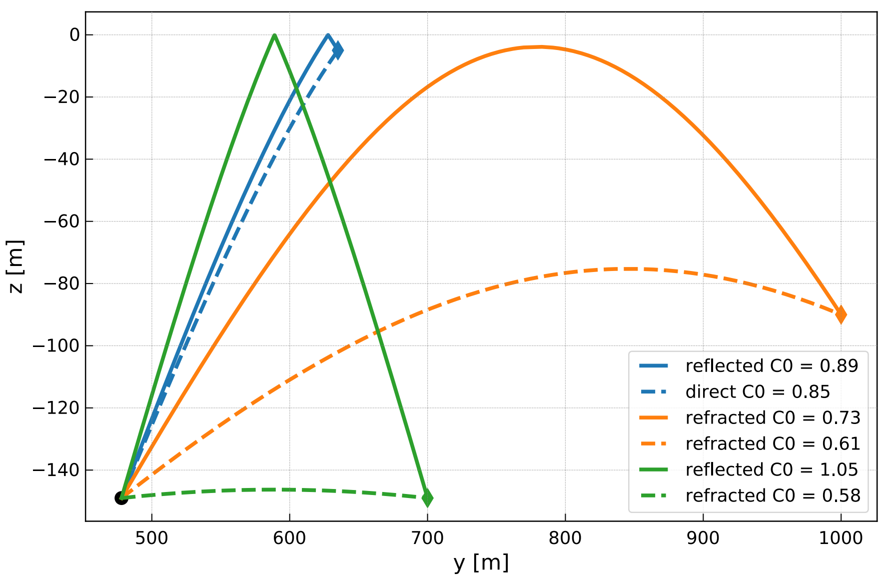
NuRadioMC

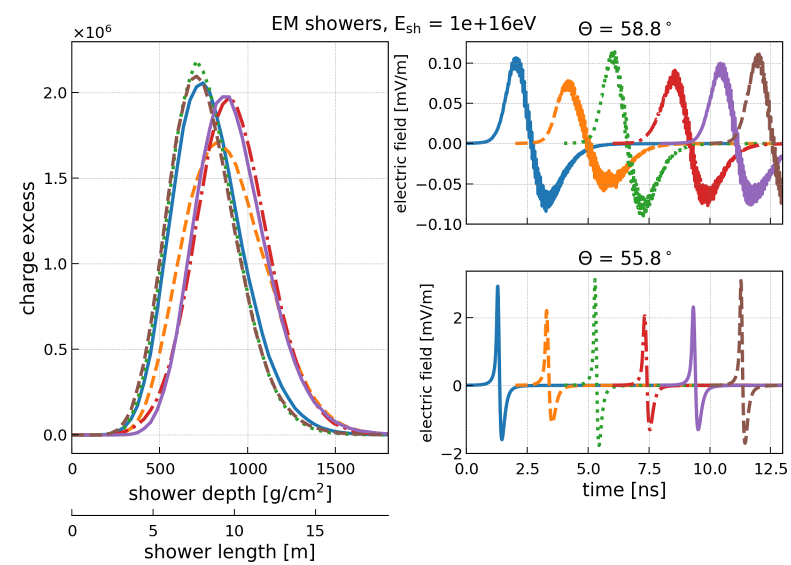
Simulation of neutrino signals

Glaser et al., EPJ-C in press

- Simulation of radio signals now as complex as optical simulations
- With a thorough understanding we can now design large-scale instruments



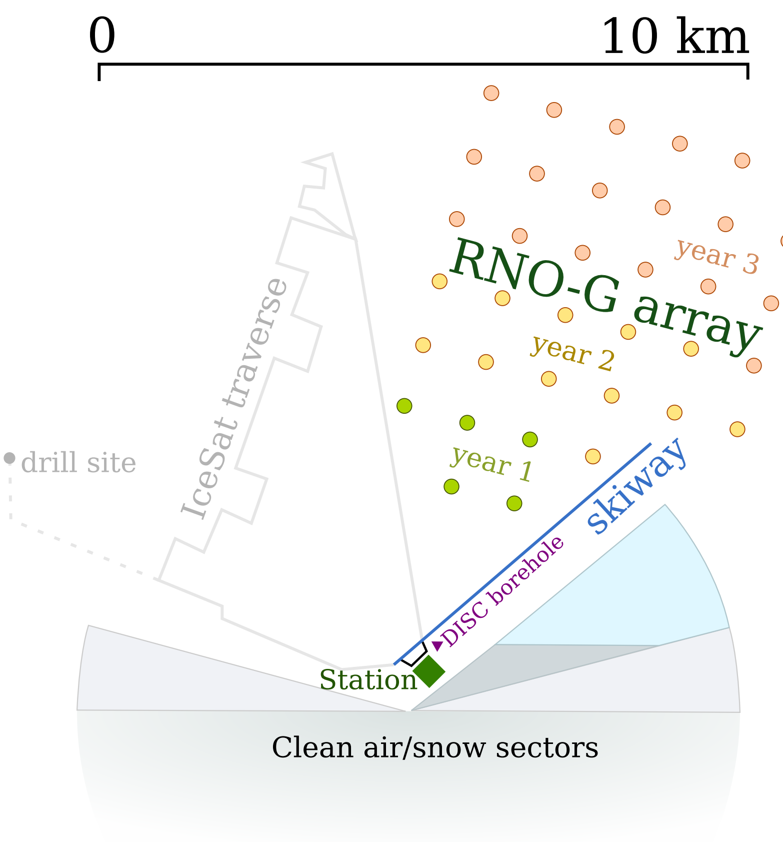


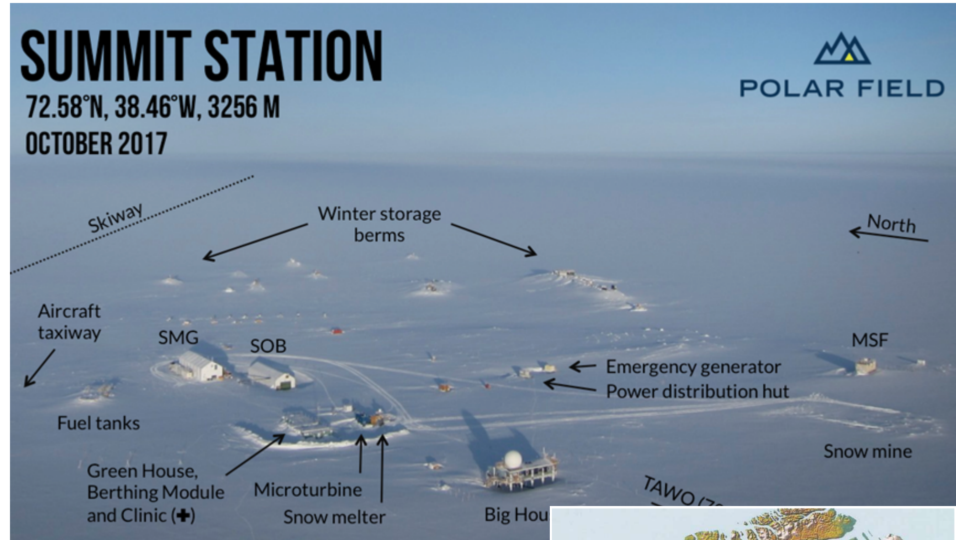


Going to higher energies

Something more concrete

Radio Neutrino Observatory

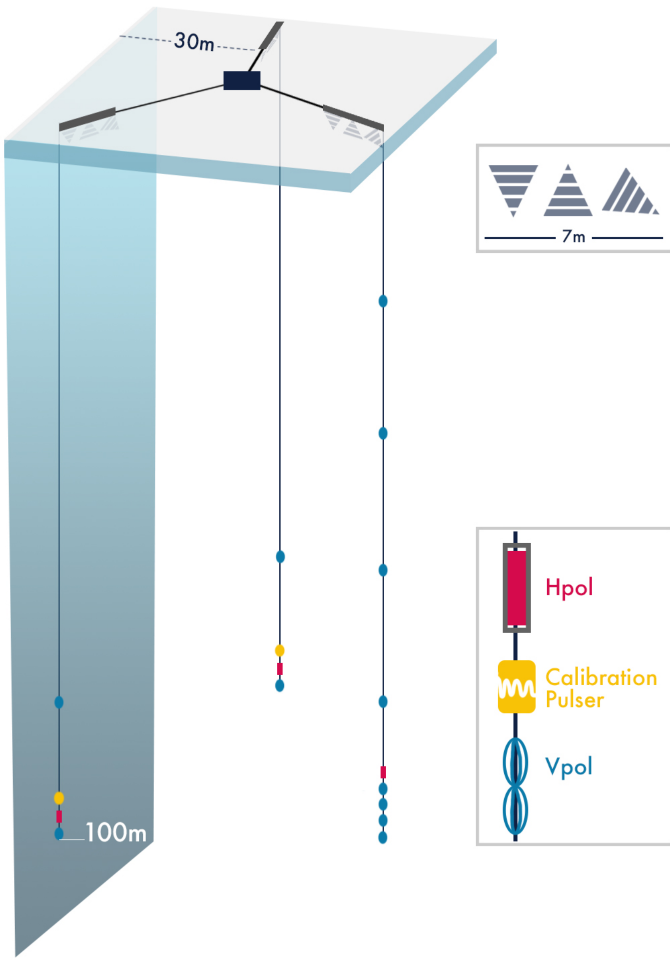




- After lots of proof-of principle experiments: first scale-up to large array

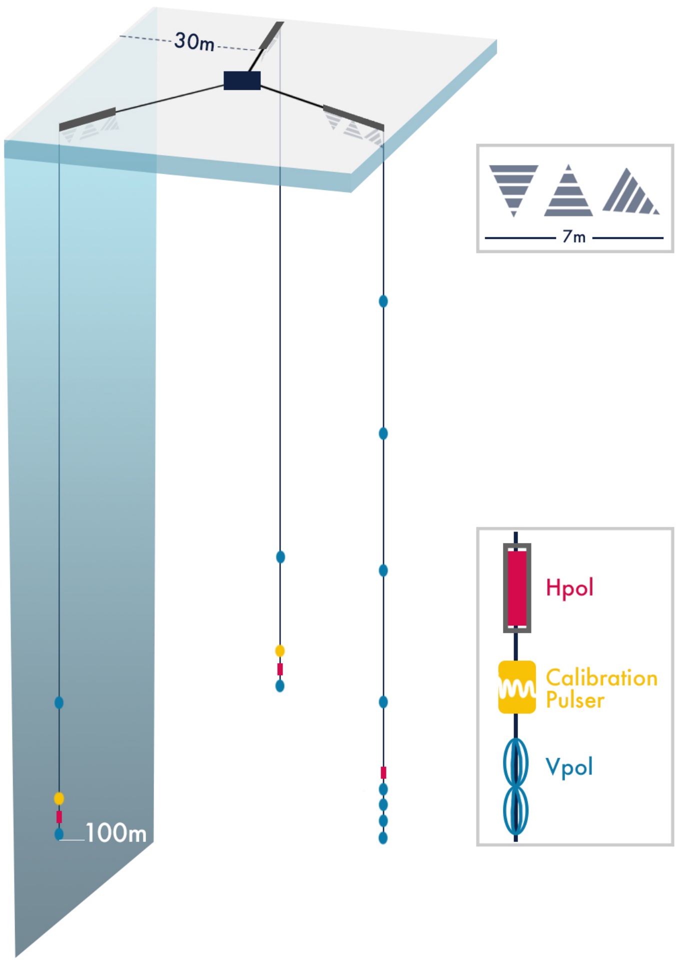
The RNO-G approach

What will be built



The RNO-G approach

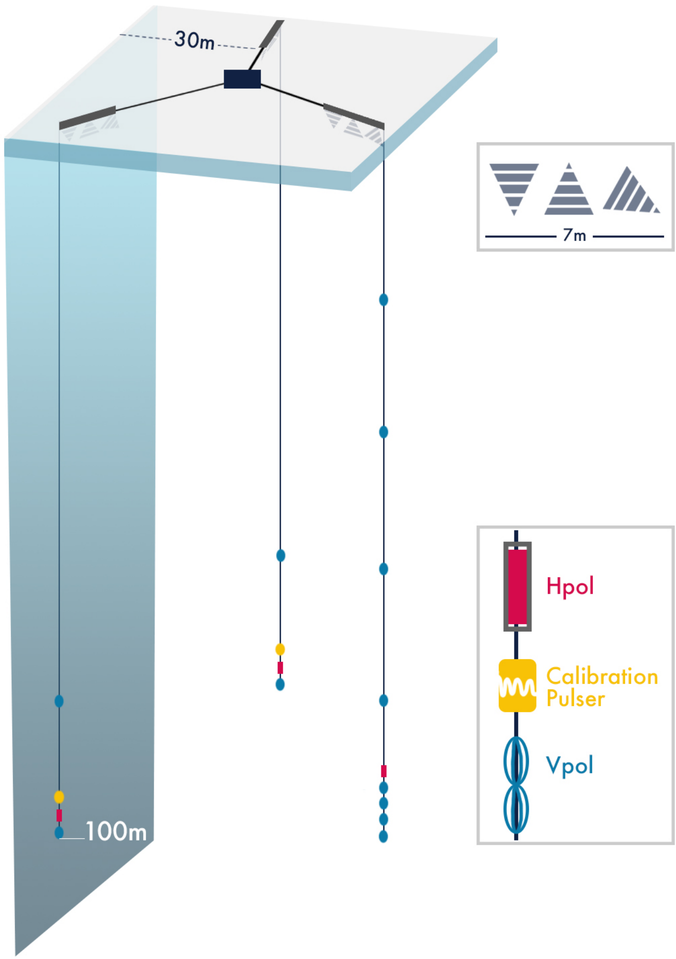
The single components



- Log-periodic dipole antennas (**LPDA**) at the surface:
- High-gain antennas with very good response to neutrino signals, but too big to fit in a hole
- At the surface subject to ray-bending = not all trajectories reach these antennas
- Antennas at the surface also act as cosmic ray veto
- 3x3 antennas to detect all arrival directions and polarizations

The RNO-G approach

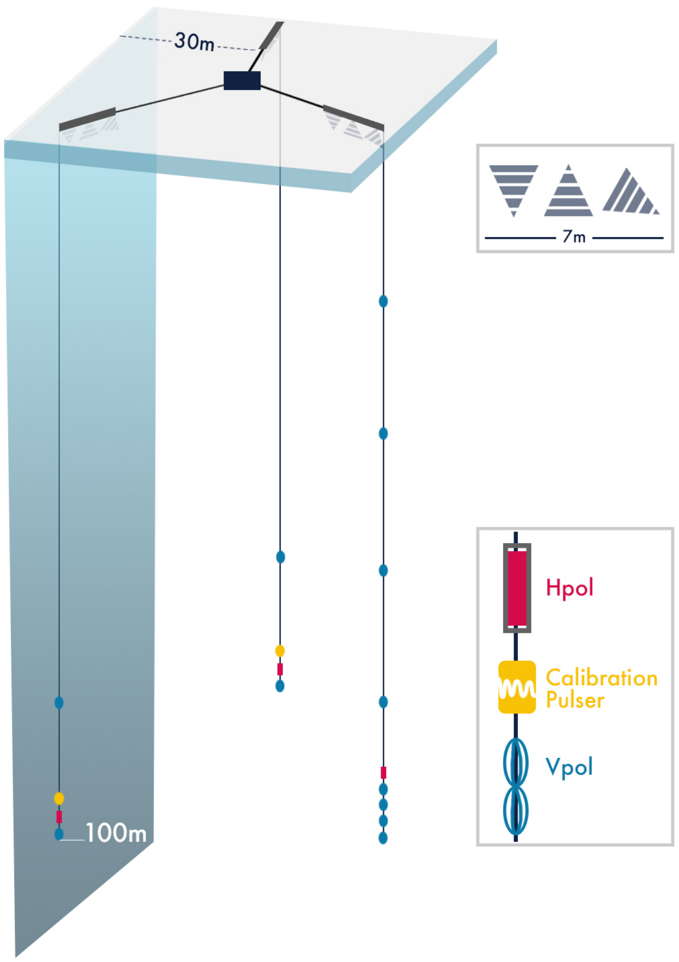
The single components



- Bicone antennas and quad-slot antennas in 100 meter deep holes
- the deeper the better (ray shadowing)
- 100 meters achievable with a fast mechanical drill (cheap)
- two different types of antennas to cover all polarizations
- small antennas have less gain and are typically less broad-band

The RNO-G approach

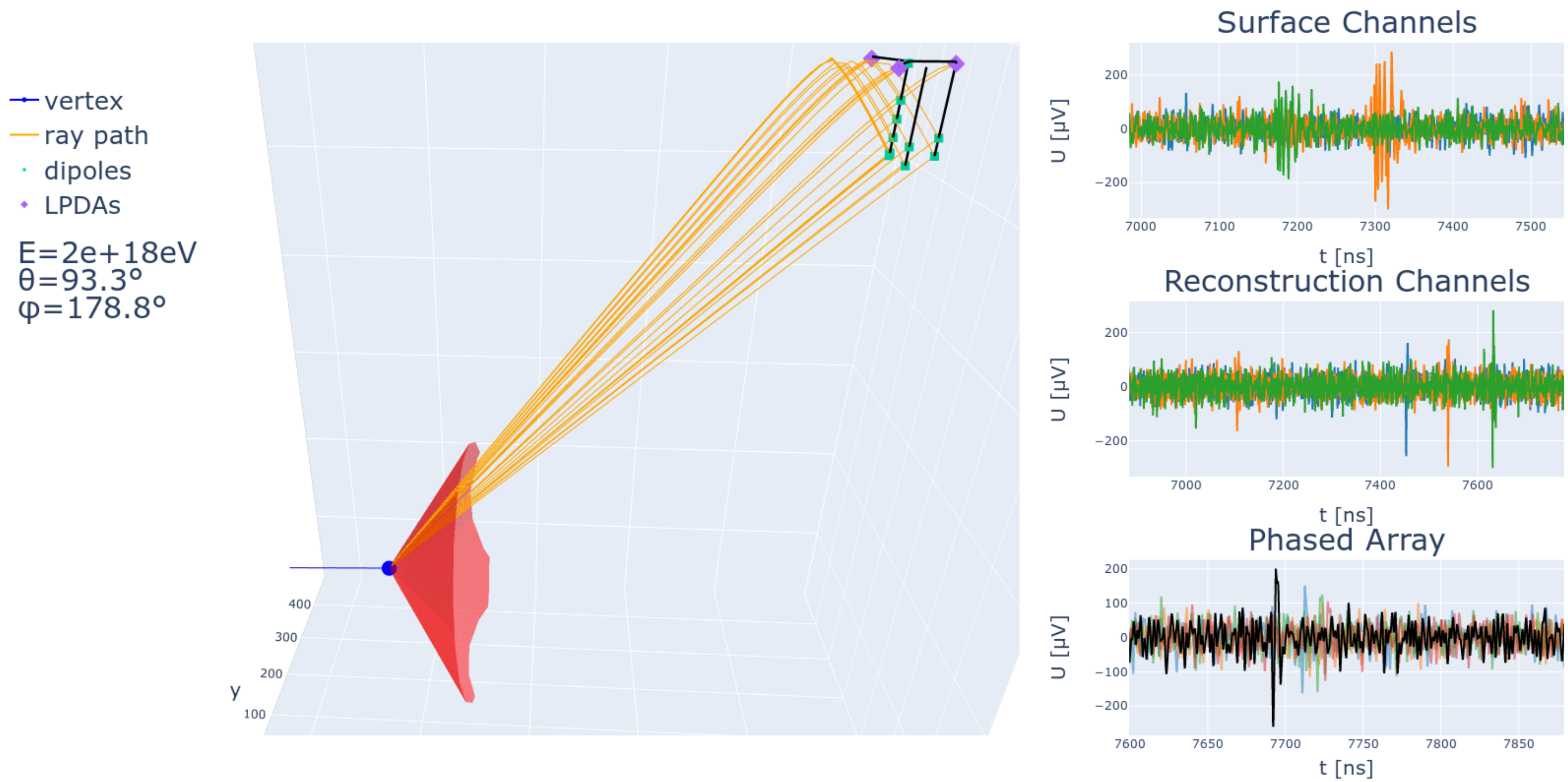
The single components



- Station geometry:
- Three strings to reconstruct arrival direction
- One string with many antennas to make the reconstruction of the vertex distance a one-dimensional problem
- String also hosts the phased array trigger
- The lower the threshold the better the sensitivity

The RNO-G approach

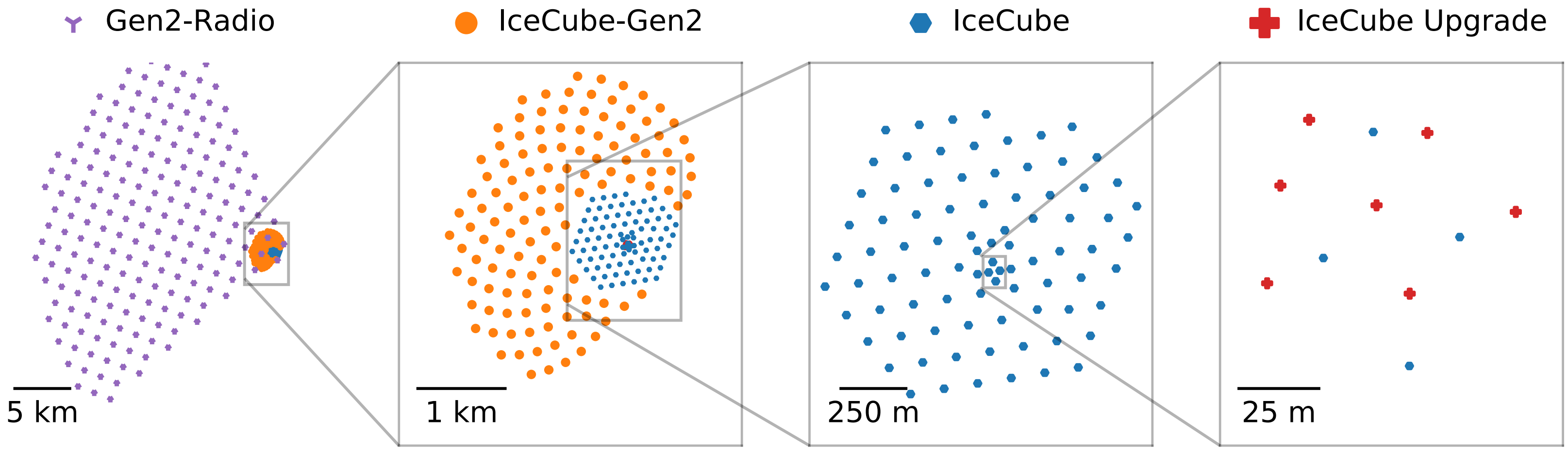
What do the signals look like



Full RNO-G simulation, C. Welling

The long-term plan

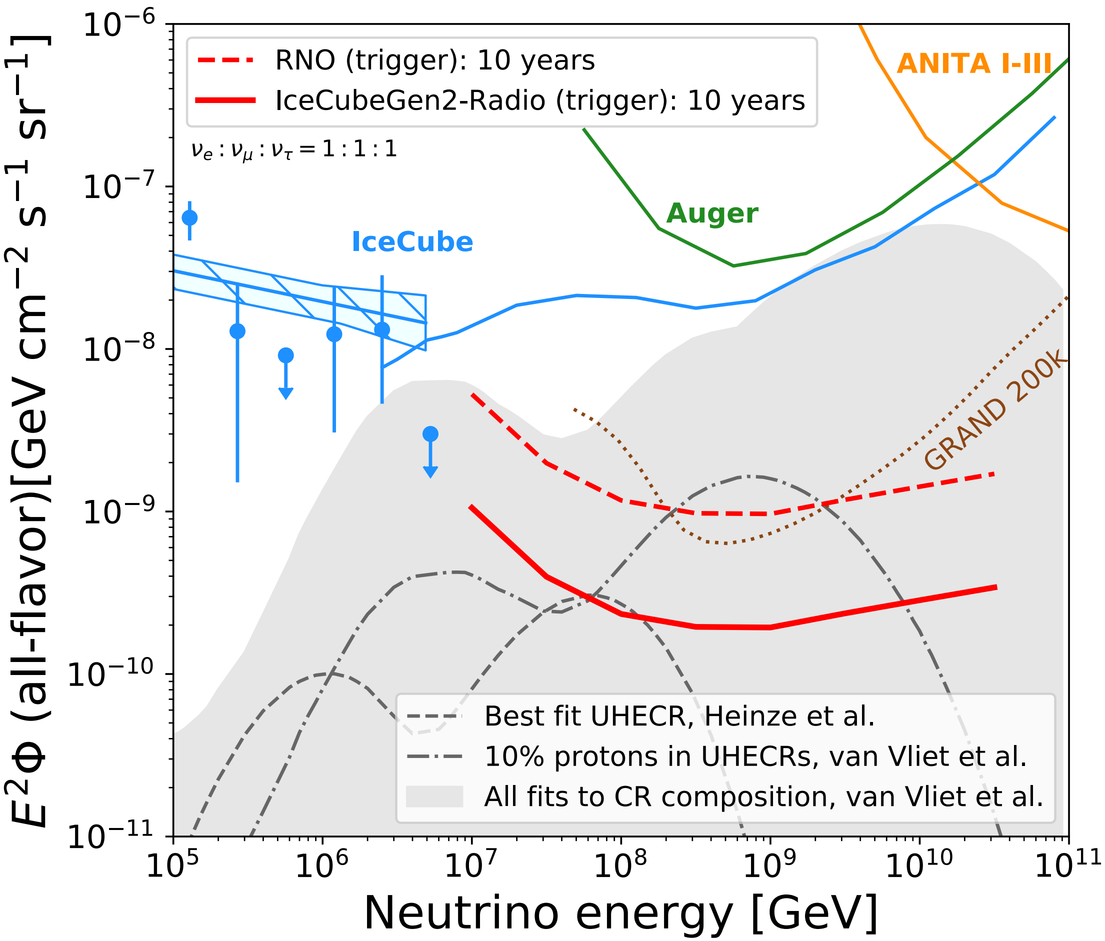
What after we are done with RNO-G



- Beyond 2024 the US is planning to build IceCube-Gen2 at South Pole
- A large radio array is part of Gen2 and RNO-G is the pathfinder for it

RNO-G

And the neutrino landscape



- RNO-G might get lucky
- IceCube-Gen2 will hit it out of the park
- Or close the field of cosmic ray astronomy forever

Conclusions

Radio detection of neutrinos

- **How:** A lot of antennas in ice that triangulate the coherent radio emission from a neutrino induced shower
- **Where:** First in Greenland, later at South Pole
- **Why:** Because neutrinos are a key messenger to understand how the universe accelerates particles and thereby teach us about extreme objects like active galactic nuclei or neutron star mergers