Probing the MeV Frontier with IceCube: Supernovae, Transients and Future Directions

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Source: IceCube/NSF

RICH2025 - XII International Workshop on Ring Imaging Cherenkov Detectors | Mainz, Germany

*http://icecube.wisc.edu


MeV to PeV sensitivity!
Astrophysical ν ($\sim 10^2$ yr^{-1})
Atmospheric ν ($\sim 10^5$ yr^{-1})
Atmospheric μ ($\sim 10^{11}$ yr^{-1})
Potential ‘exotics’ (Unknown)
We have over 10 yr of data!
ICECUBE
Astrophysics
Neutrino Physics
BSM
And much more!

PHYSICS AT MEV SCALES

Supernova Monitoring in realtime

Fast transient features

Supernova Searches

BSM Physics

And more…

PHYSICS AT MEV SCALES

ICECUBE

1

Supernovae

- Supernova Monitoring in realtime
- Fast transient features
- Supernova Searches
- BSM Physics

And more…

2

Other transients

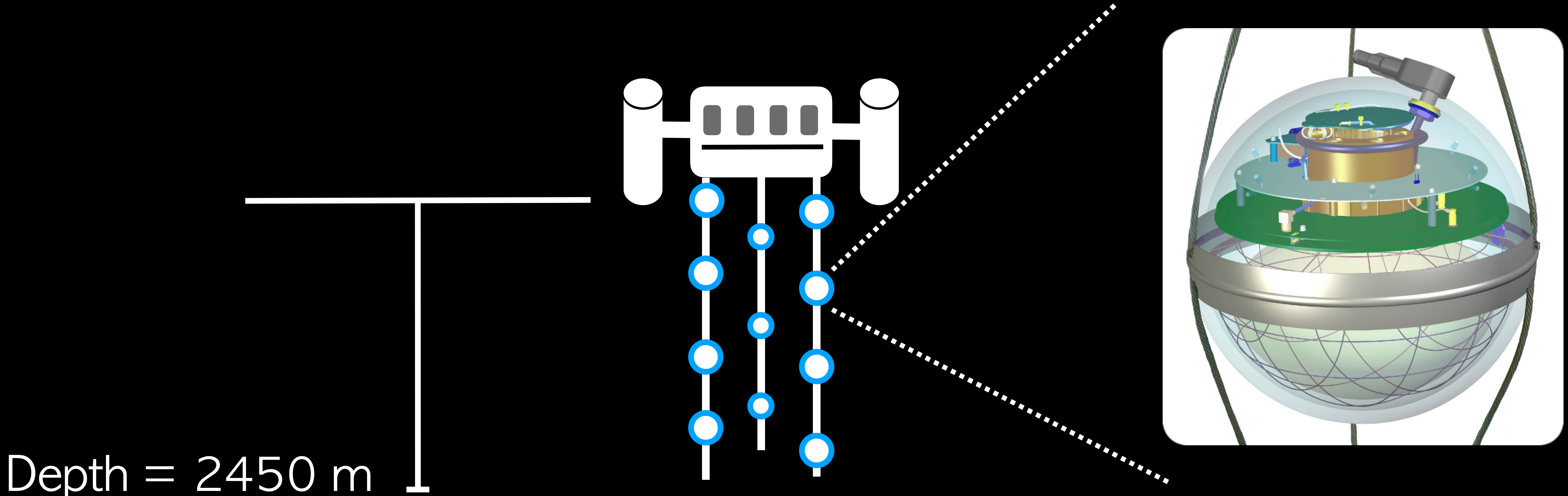
- Neutron Star Merger Searches
- Gamma-Ray Bursts

PHYSICS AT MEV SCALES

ICECUBE

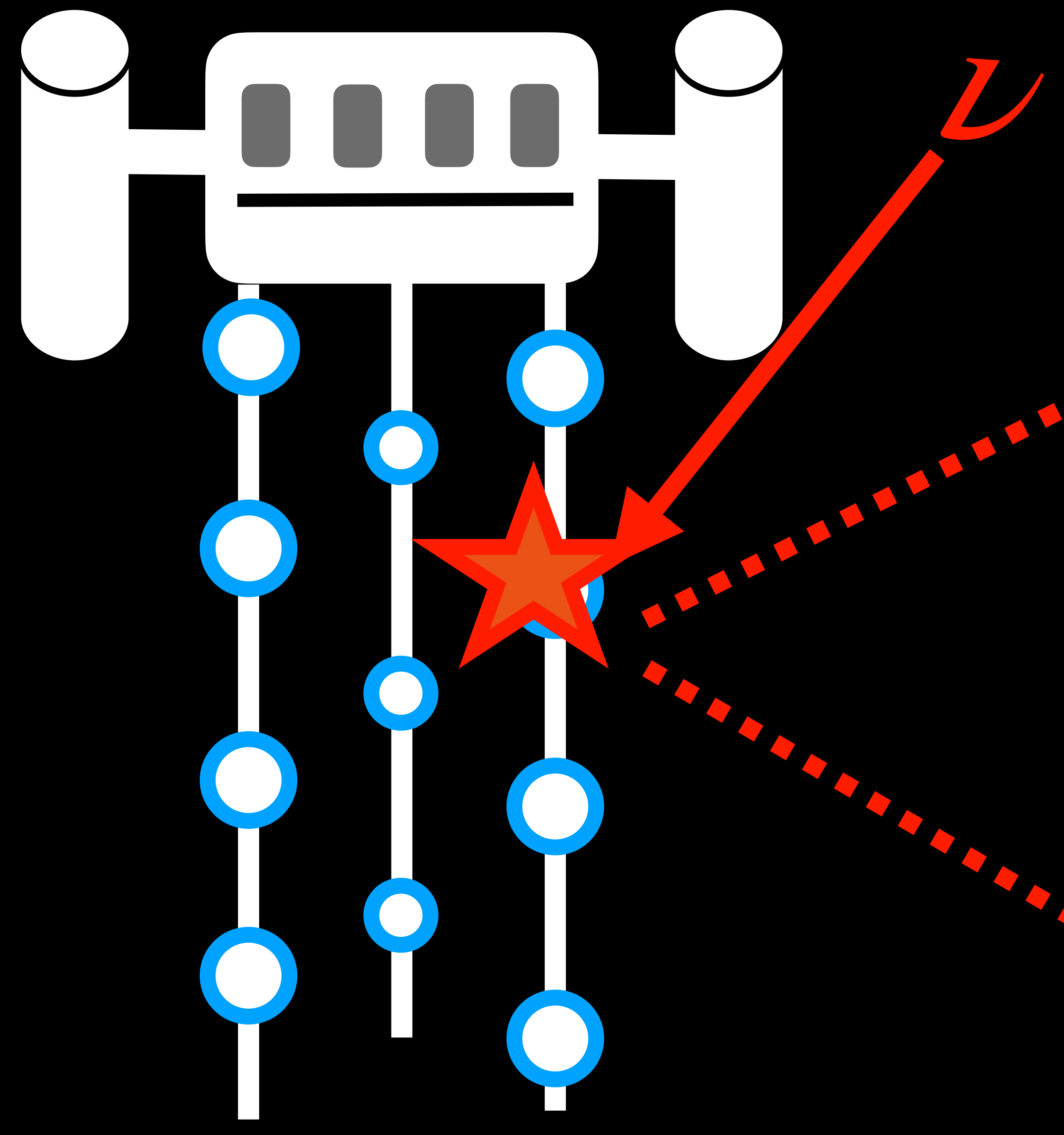
Located at the South Pole

5160 sensors buried in $1 km^3$ of ice

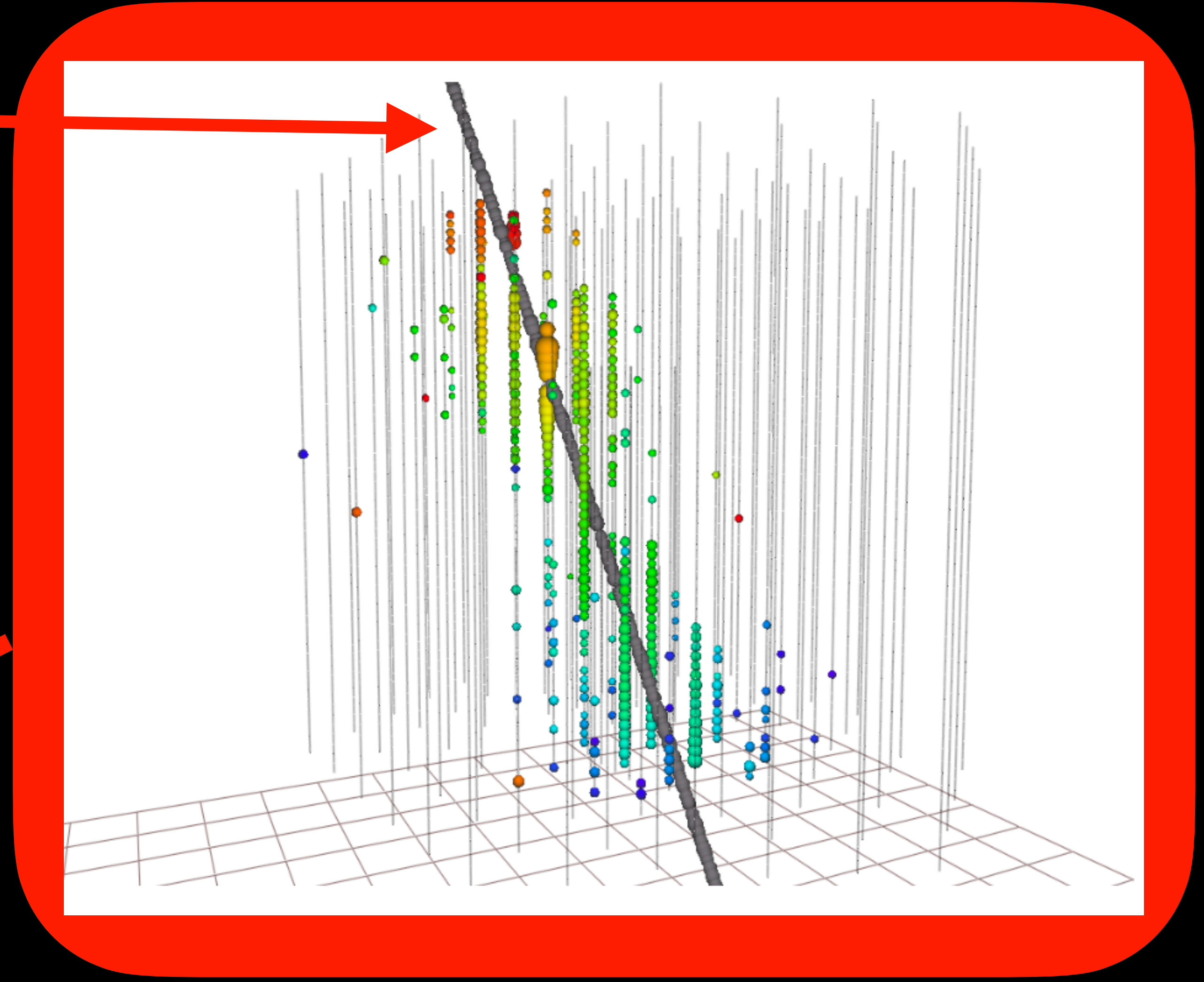


We detect Cherenkov light produced when charged particles pass through ice

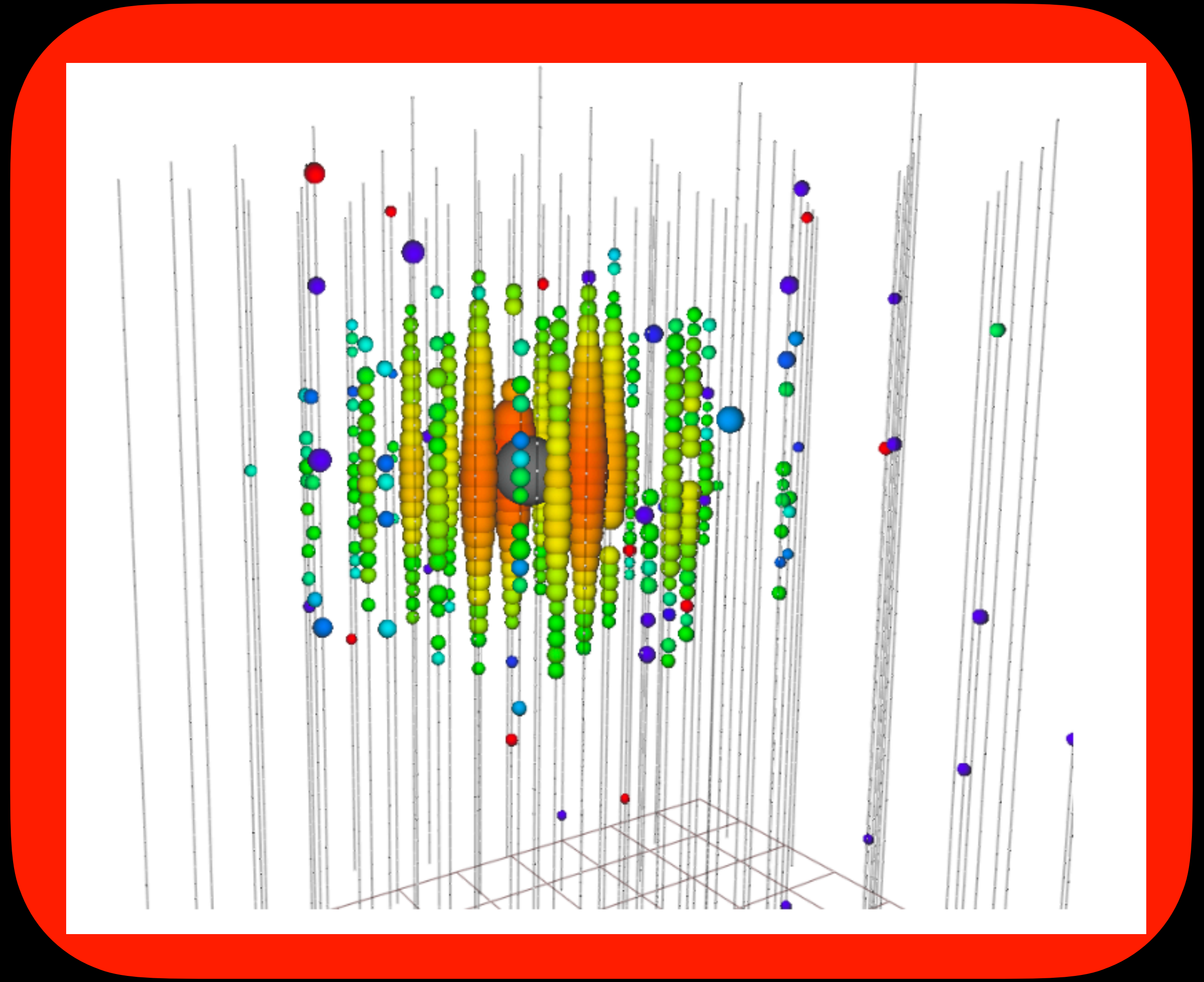
MeV ν | >GeV - PeV ν



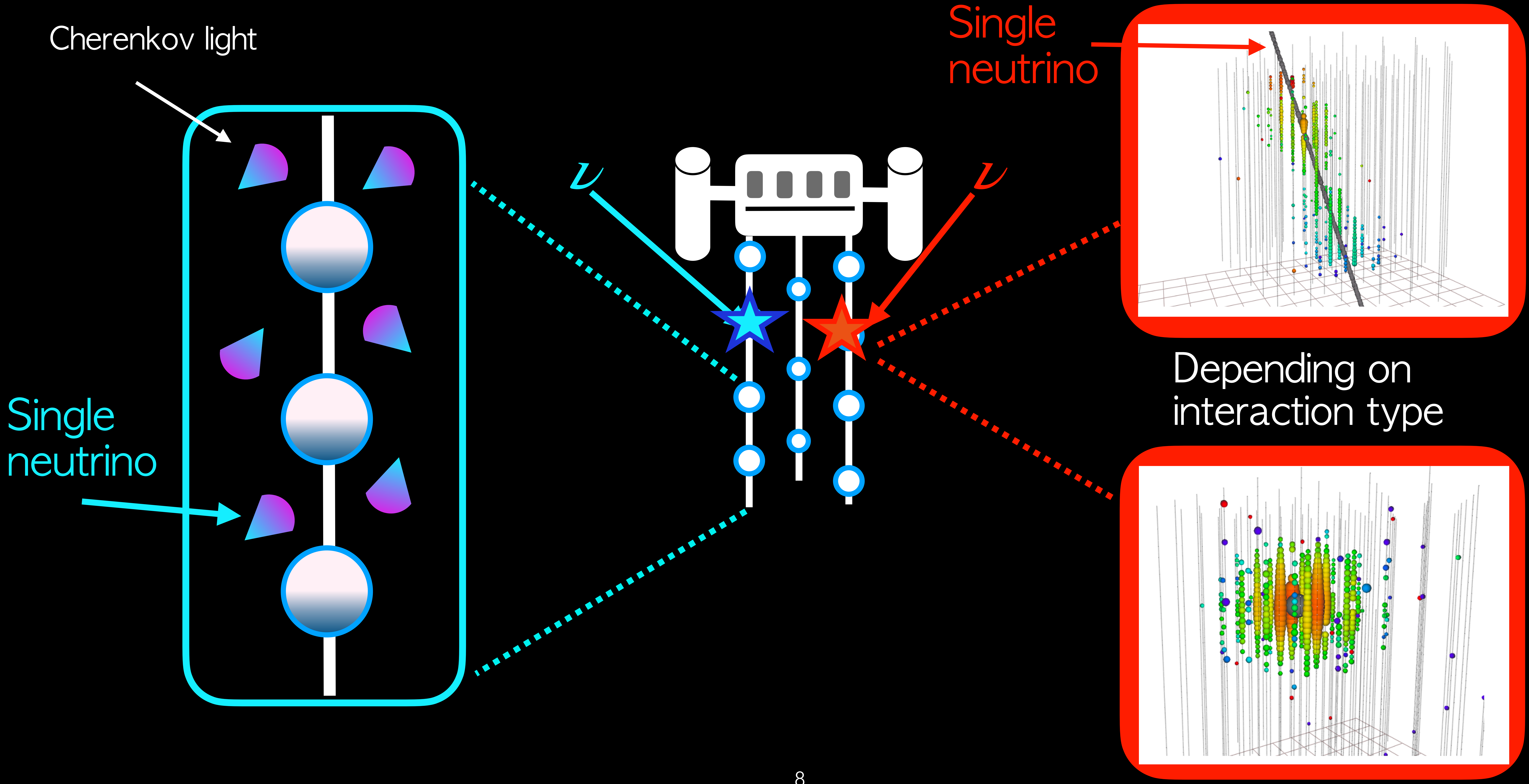
Single neutrino



Depending on interaction type



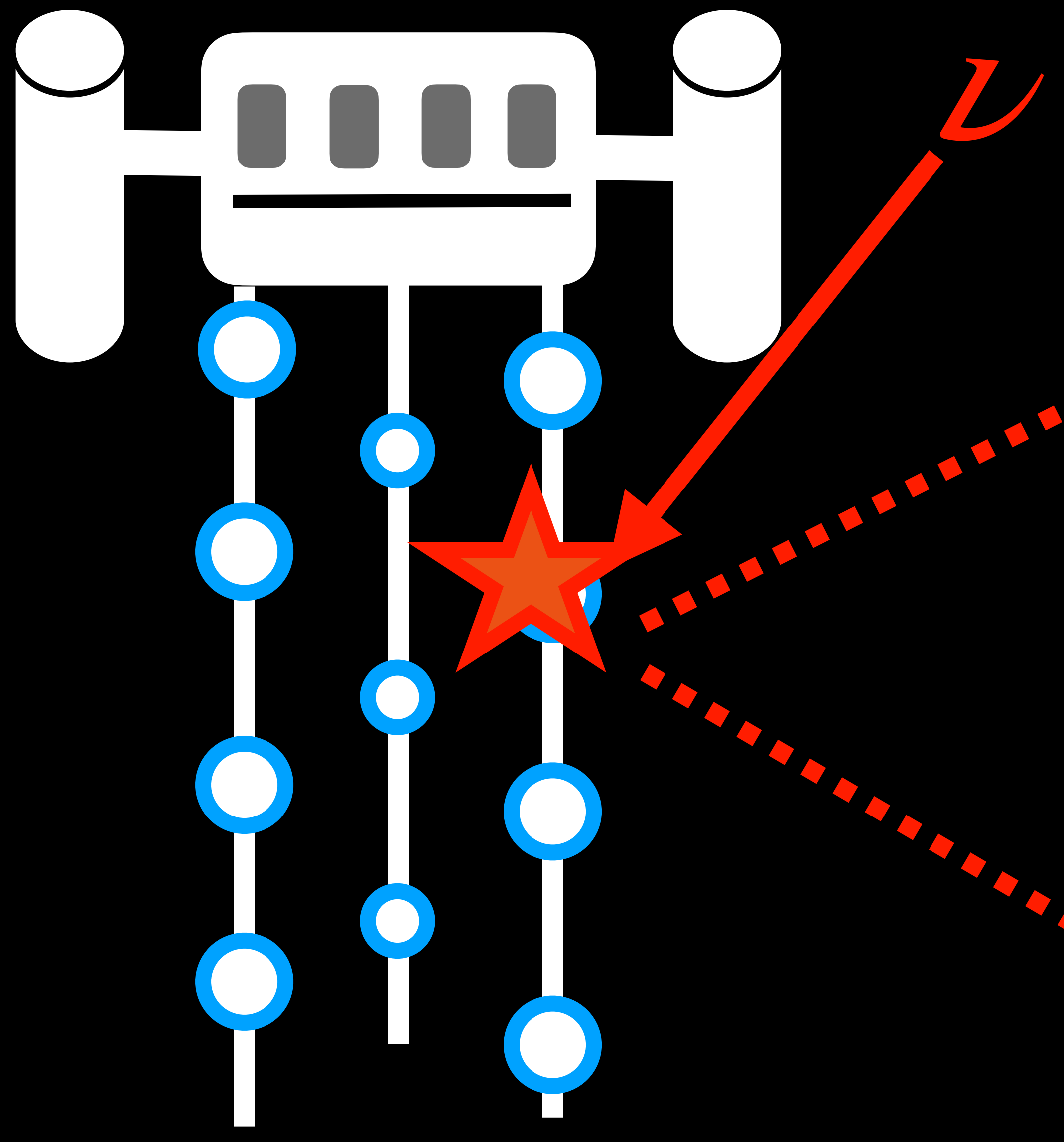
MeV ν — >GeV - PeV ν



MeV ν ⟩GeV - PeV ν

In-Ice MeV Interactions

- Dominant: $\bar{\nu}_e + p \rightarrow n + e^+$ ($\sim 94\,\%$)
- Cross-section: $\sim E_\nu^2$
- Cherenkov Photons: $\sim E_\nu^3$
- e^+ track length: 0.56 cm (E_{e^+}/MeV)
    - Cherenkov photons: 180 (E_{e^+}/MeV)
    - Background (dark ct. + decays): 500 Hz (~ 250 Hz after dead time)



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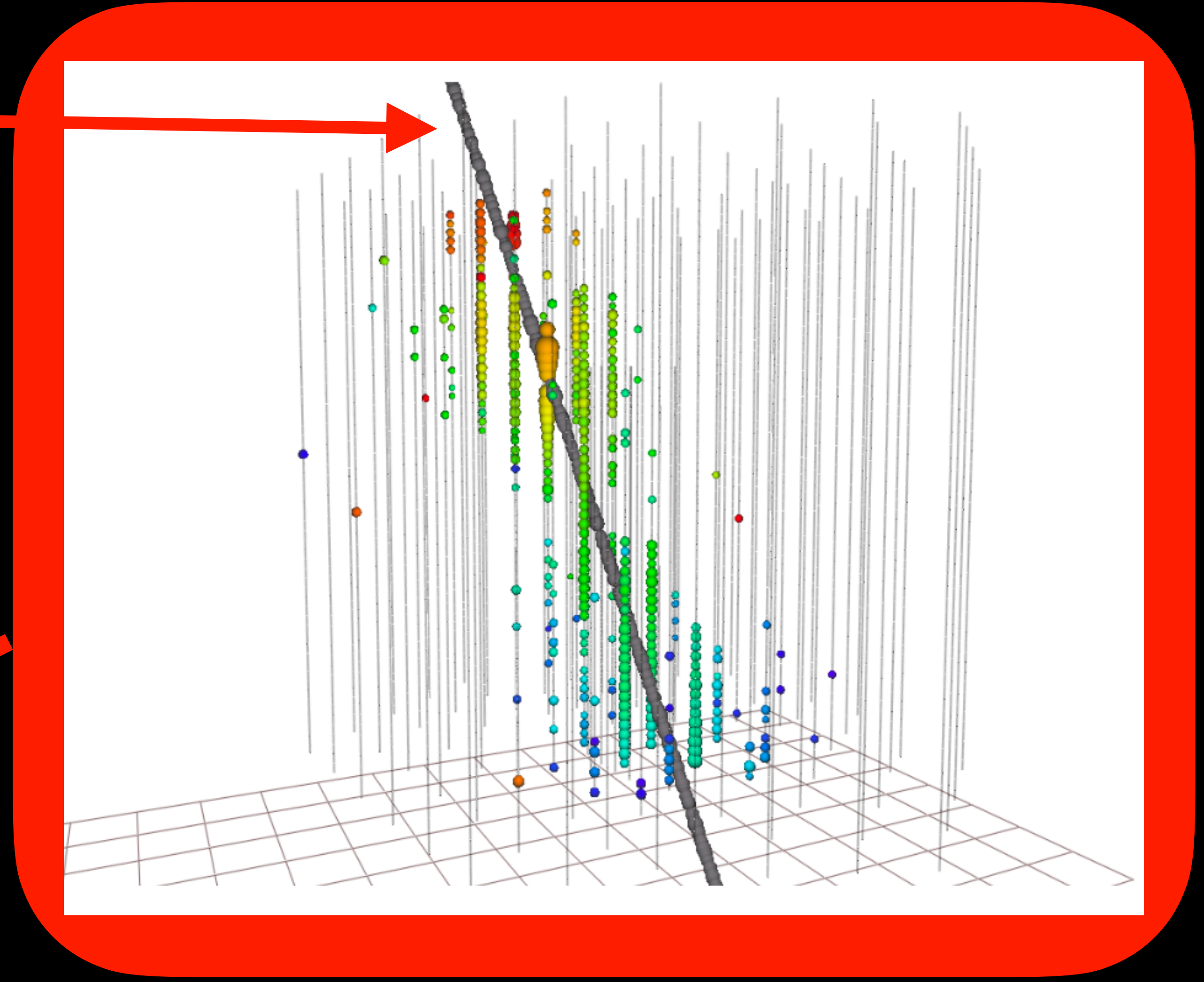

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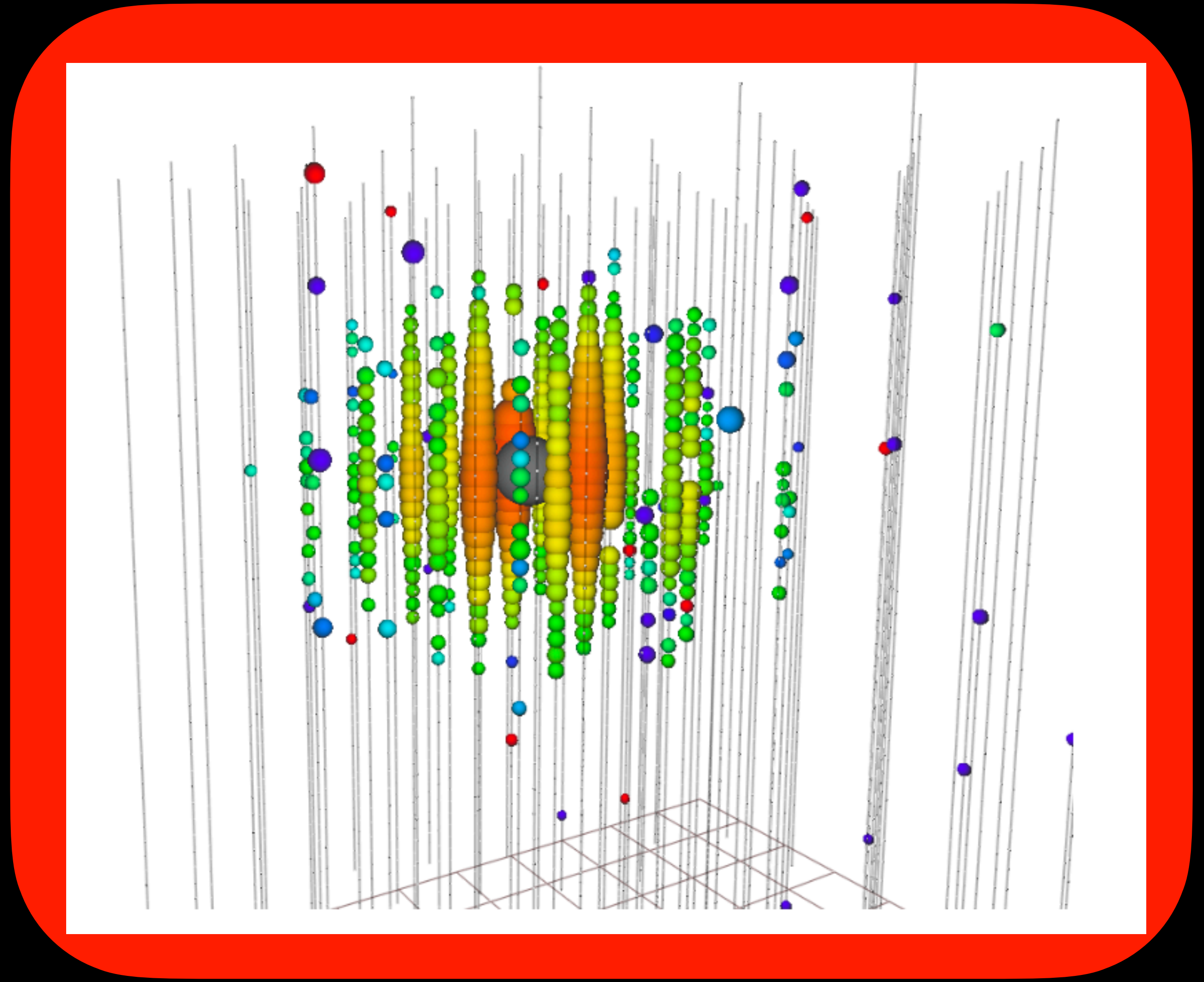
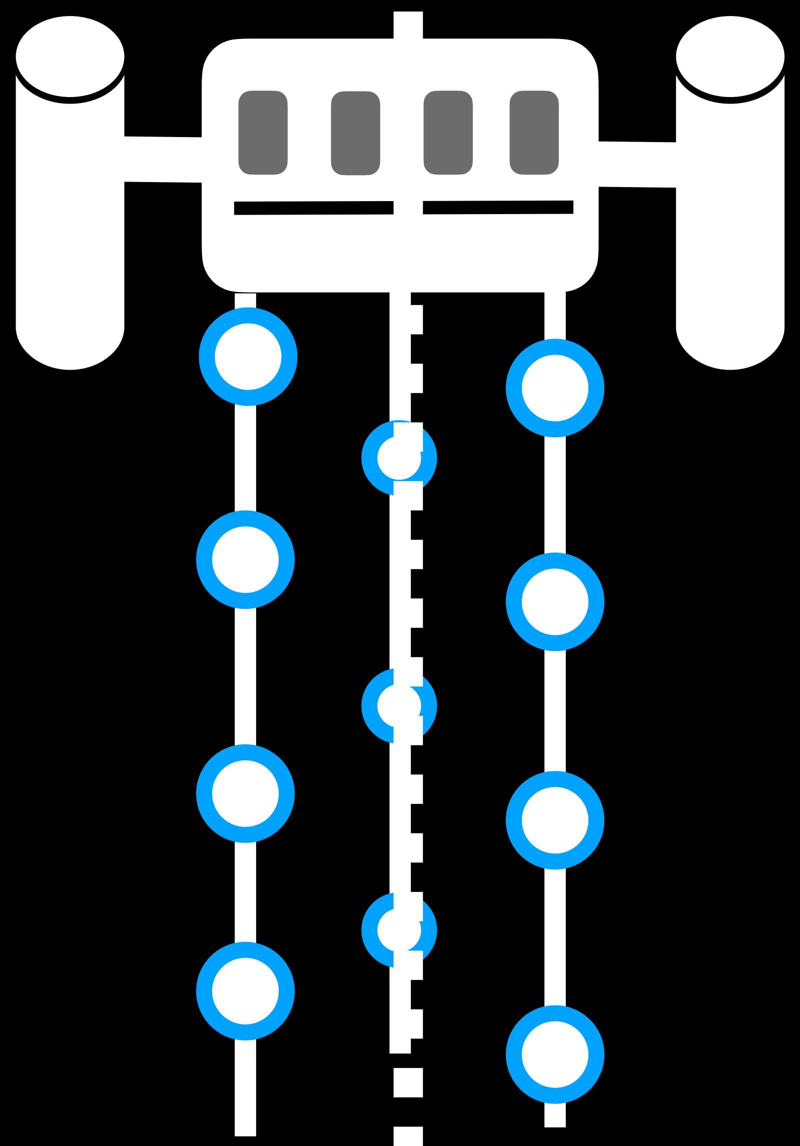


MeV ν 〉GeV - PeV ν

Different approach depending on energy

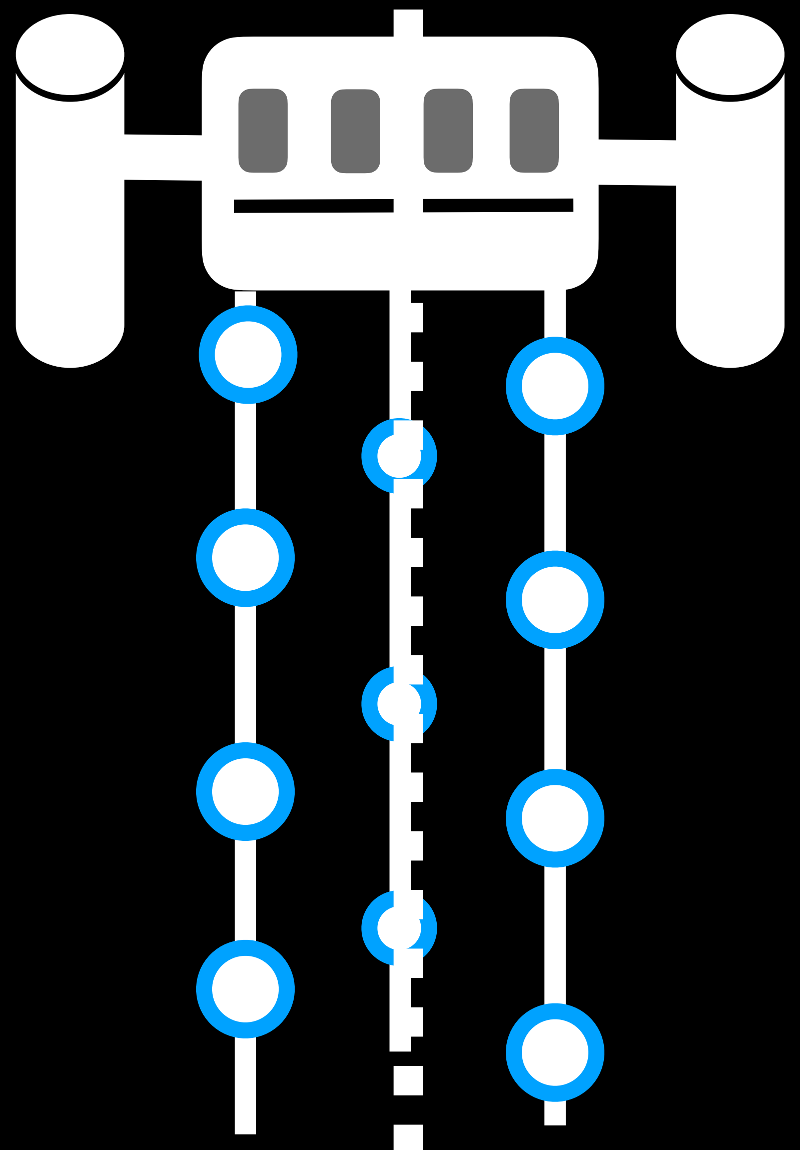


- We can reconstruct direction and energy of neutrinos
- We search for astrophysical neutrinos using direction and energy information to separate from noise: we can use single neutrinos.

MeV ν | >GeV - PeV ν

Different approach depending on energy

- No direction or direct energy information
- Search for an increase in total detector count above noise: High flux of neutrinos in a burst



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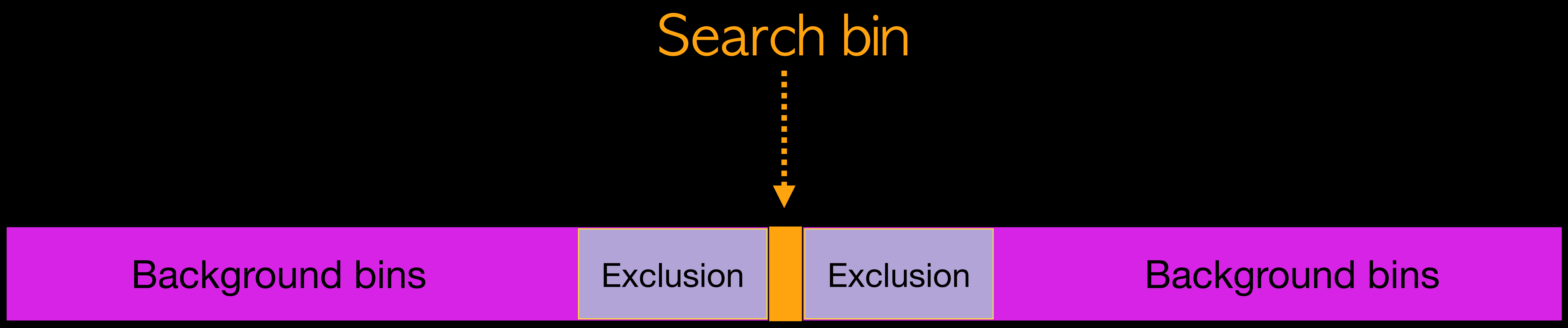
HOW WE SEARCH FOR MEV NEUTRINOS

We look for a collective increase in detector rate

How significant is the deviation in the bin of interest compared to an average?



We compare the rate in the search bin to the average in the background bins.

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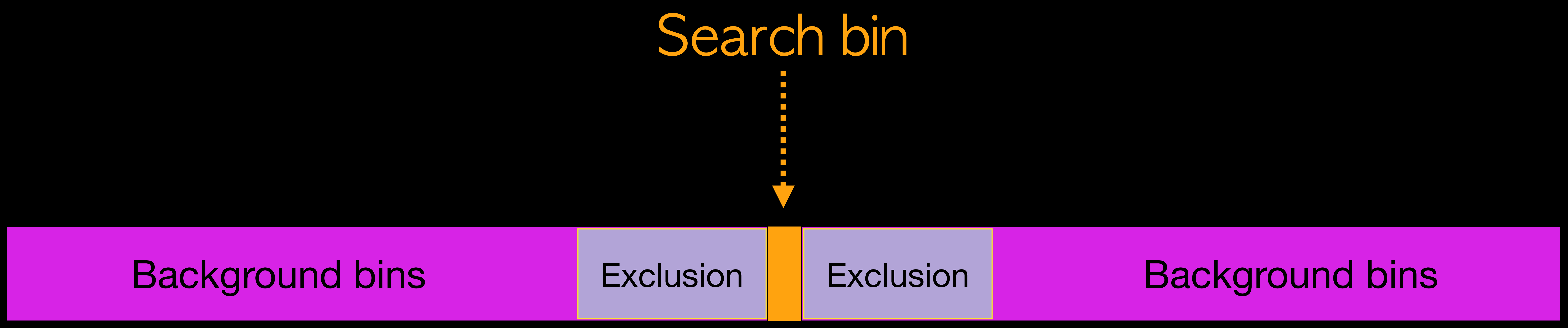


We compare the rate in the search bin to the average in the background bins.

This results in a test statistic $\xi = \frac{\Delta\mu}{\sigma_{\Delta\mu}} = \frac{\text{deviation from sliding average}}{\text{uncertainity of deviation}}$

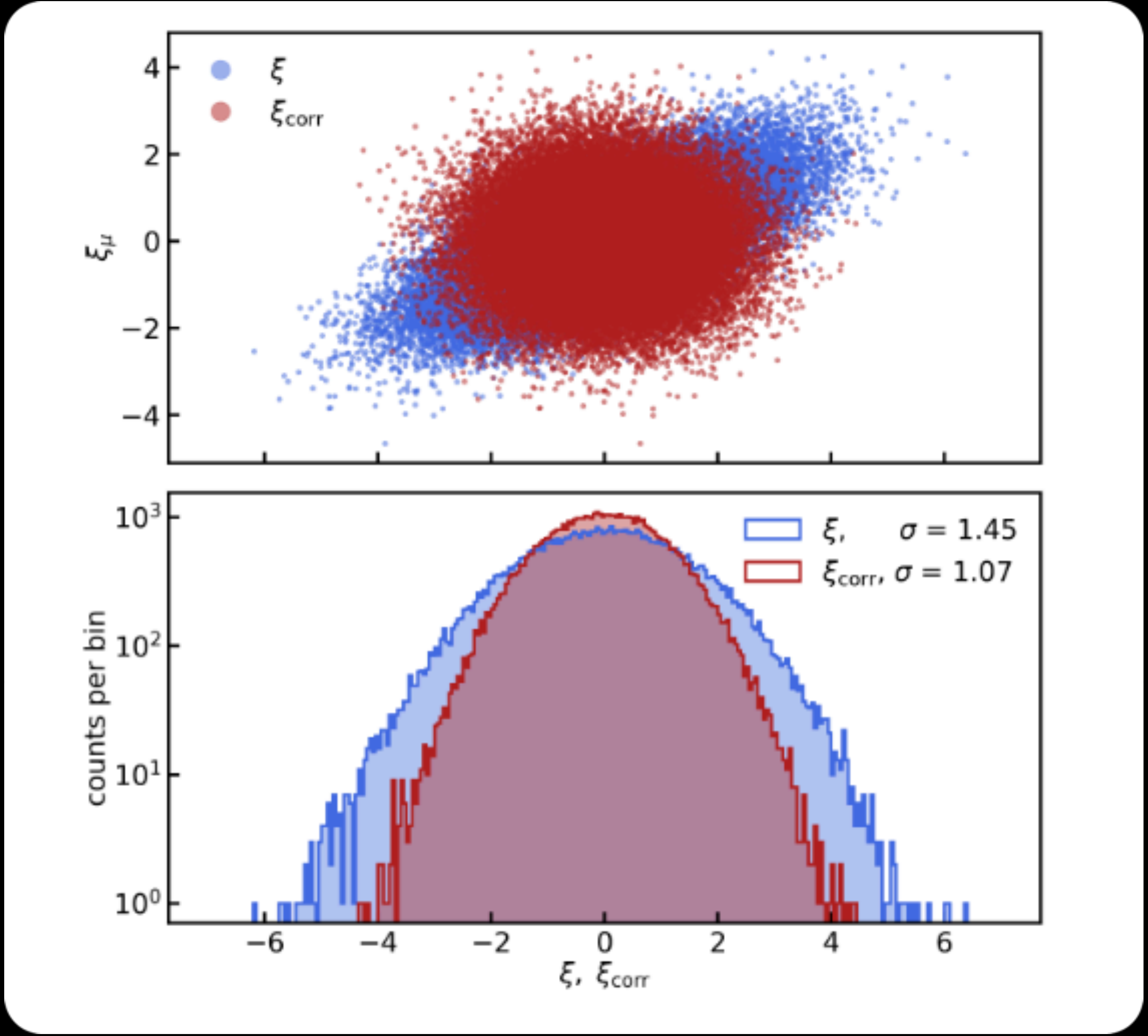
BACKGROUND SOURCES

Background sources: Thermal noise, radioactive decay, atmospheric muons

- Single DOM correlations: Noise ≈ Poissonian distribution. We apply a deadtime at the DAQ stage. Reduces rate from 540 Hz to 286 Hz.

- DOM-to-DOM correlations: Atmospheric μ produce correlated hits when passing through the detector. To remove them, we apply a linear correction to ξ using muon rates at the time of trigger.

ξ': Test statistic with the atmospheric μ contribution removed



Credit: R. Abbasi at al., IceCube Collaboration, 2024, ApJ 961, 84

MEV DETECTION SYSTEM

ONLINE: SNDAQ

- Supernova Data Acquisition System (SNDAQ) monitors the detector in realtime for an excess in detector hits
  - Sliding search window
  - Bin size is 2 ms —> rebin to 0.5, 1.5, 10 and 4 s (motivated by supernova physics)
  - Produces a dataset of the detector hits: SN Data (0.5 s bins)
  - This is a reduced dataset consisting of only the hits

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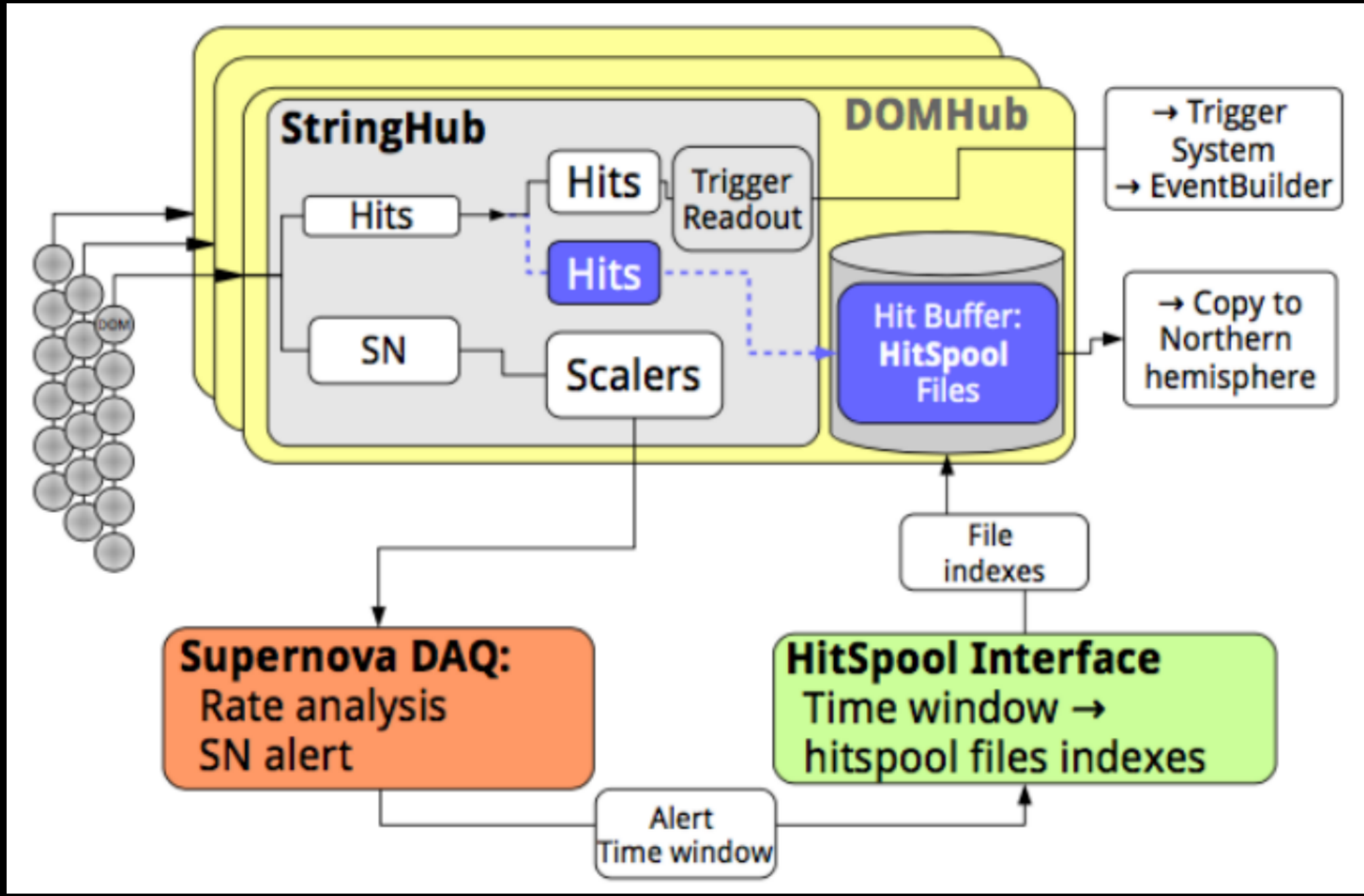
OFFLINE: HitSpool



Credit: D. Heereman (Ph.D., 2015)

- We can also access the full information of each photon hit via HitSpool (Data available 24/48 hrs after a trigger)
- We can then process this offline to get a higher resolution (ns) and better background handling.

CORE-COLLAPSE SUPERNOVAE

$E_{tot} \sim 10^{53}\ erg$

Supra-nuclear densities

End of star's lifecycle

ν

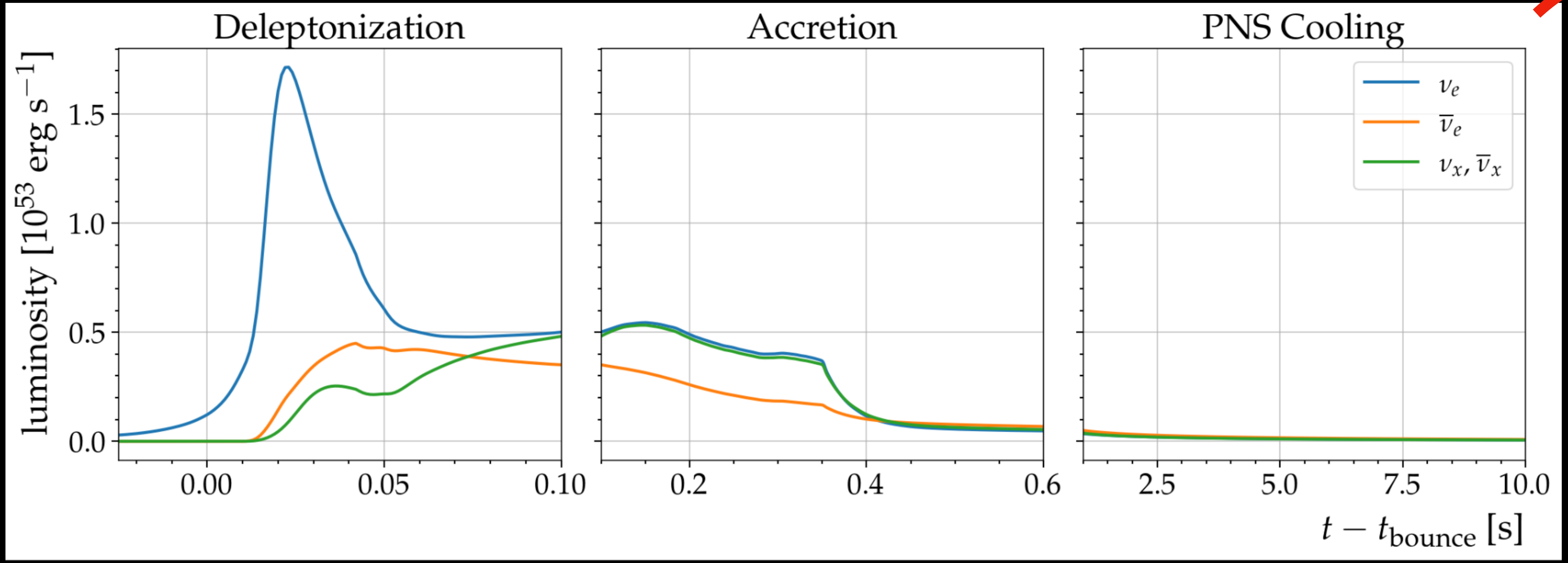
99% of energy!

Nucleosynthesis of heavy elements

Gives birth to neutron stars and black holes!

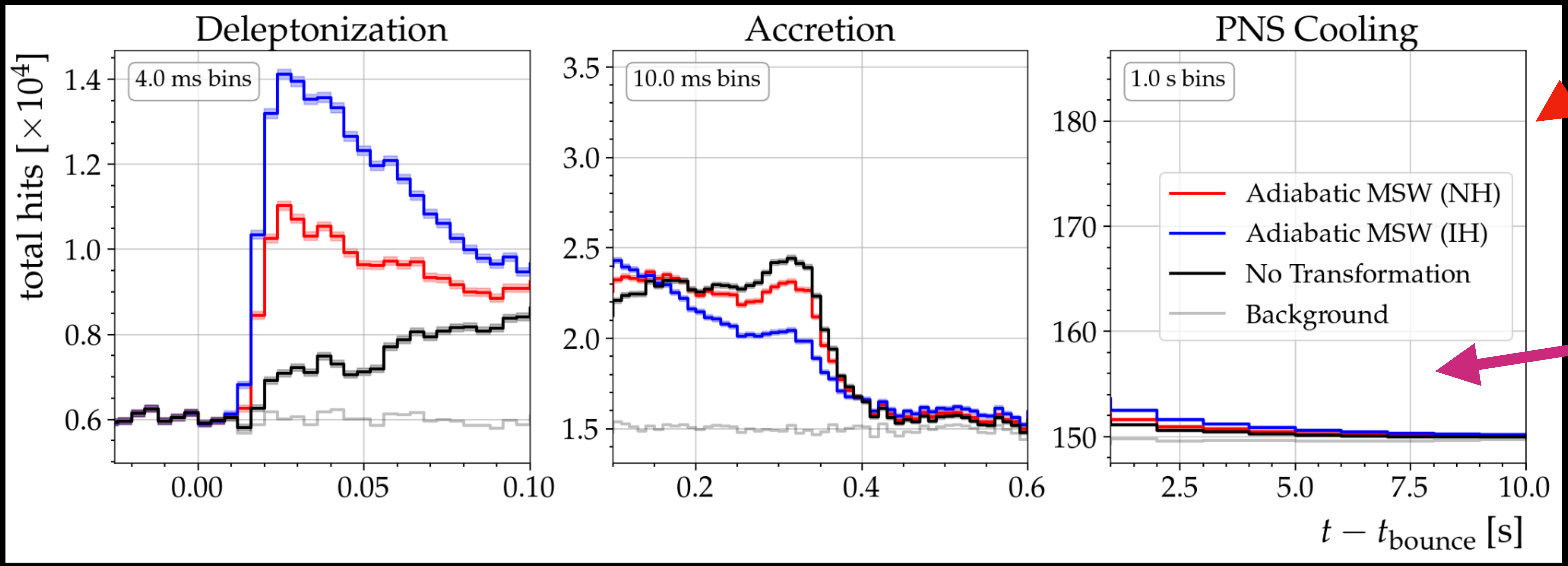
Very very hot (MeV)

EXPECTED SIGNATURES



Simulation of ν luminosity

(10 kpc)



Detector hits

Simulations: Nakazato+ 2013
Credit: S. Griswold, Neutrino2020

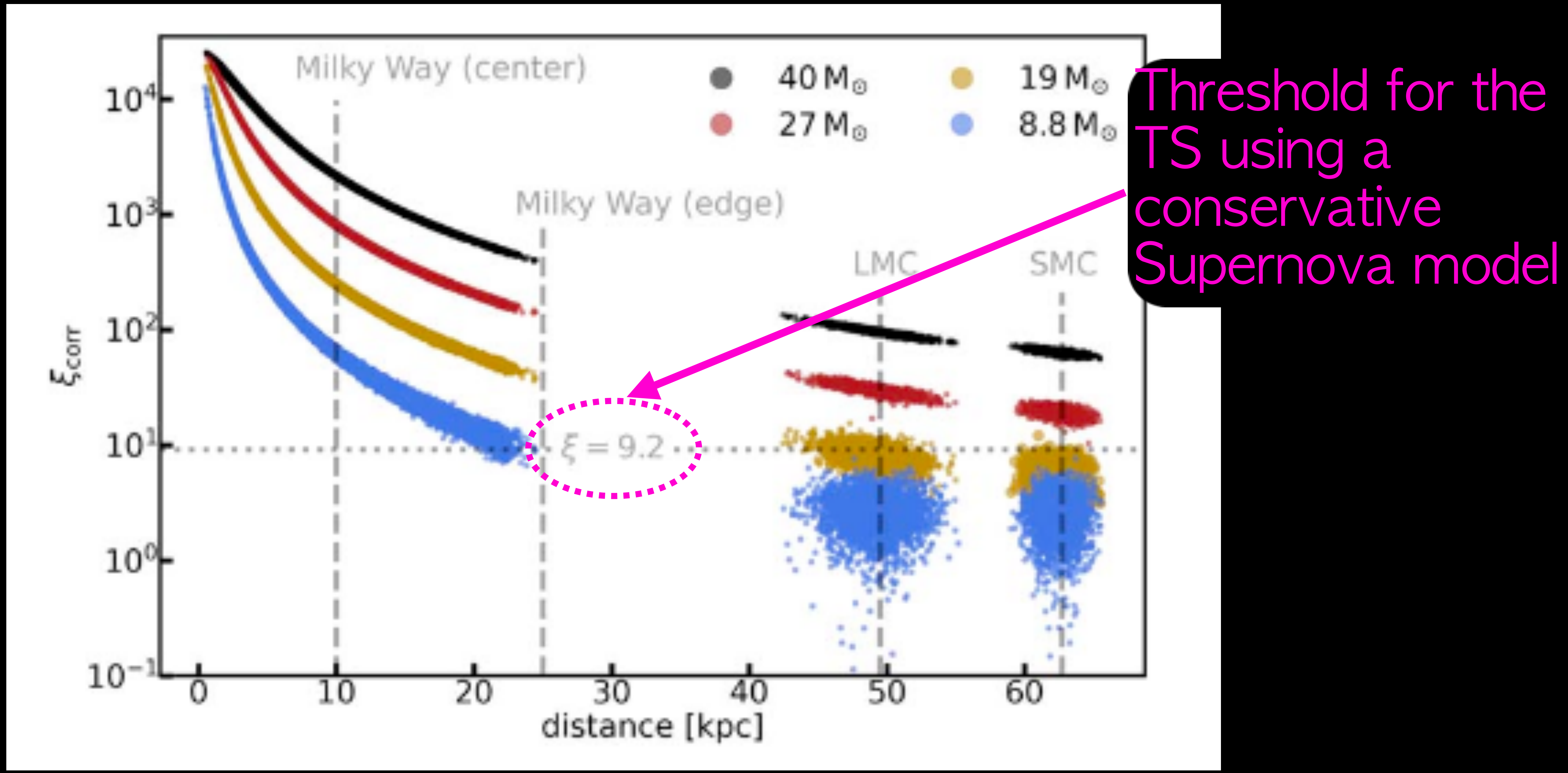
SUPERNOVA EARLY WARNING SYSTEM (SNEWS)

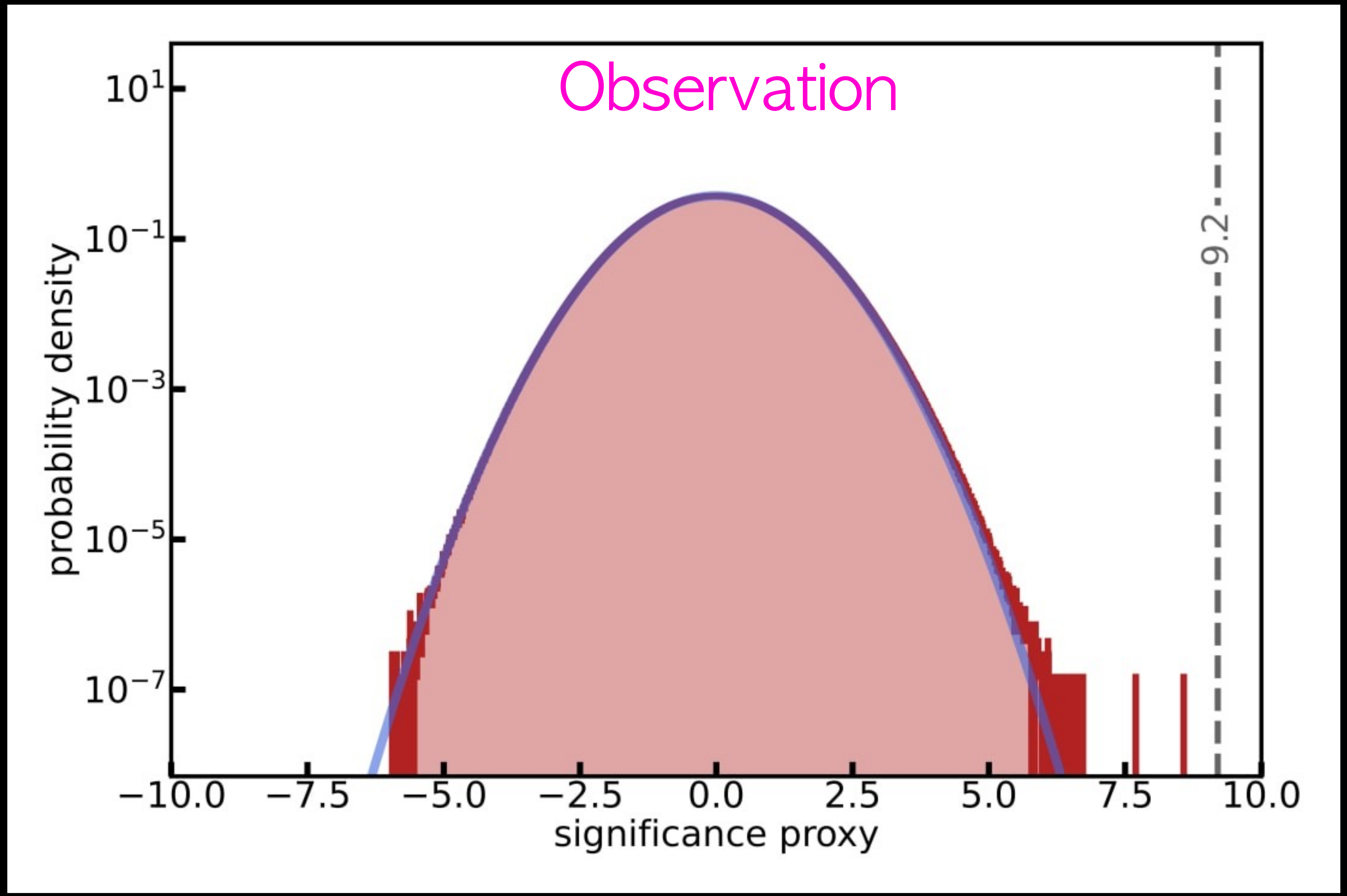
Credit: SNEWS 2.0

SUPERNOVA EARLY WARNING SYSTEM (SNEWS)

Credit: SNEWS 2.0

RESULTS: GALACTIC SEARCH OF CCSNE



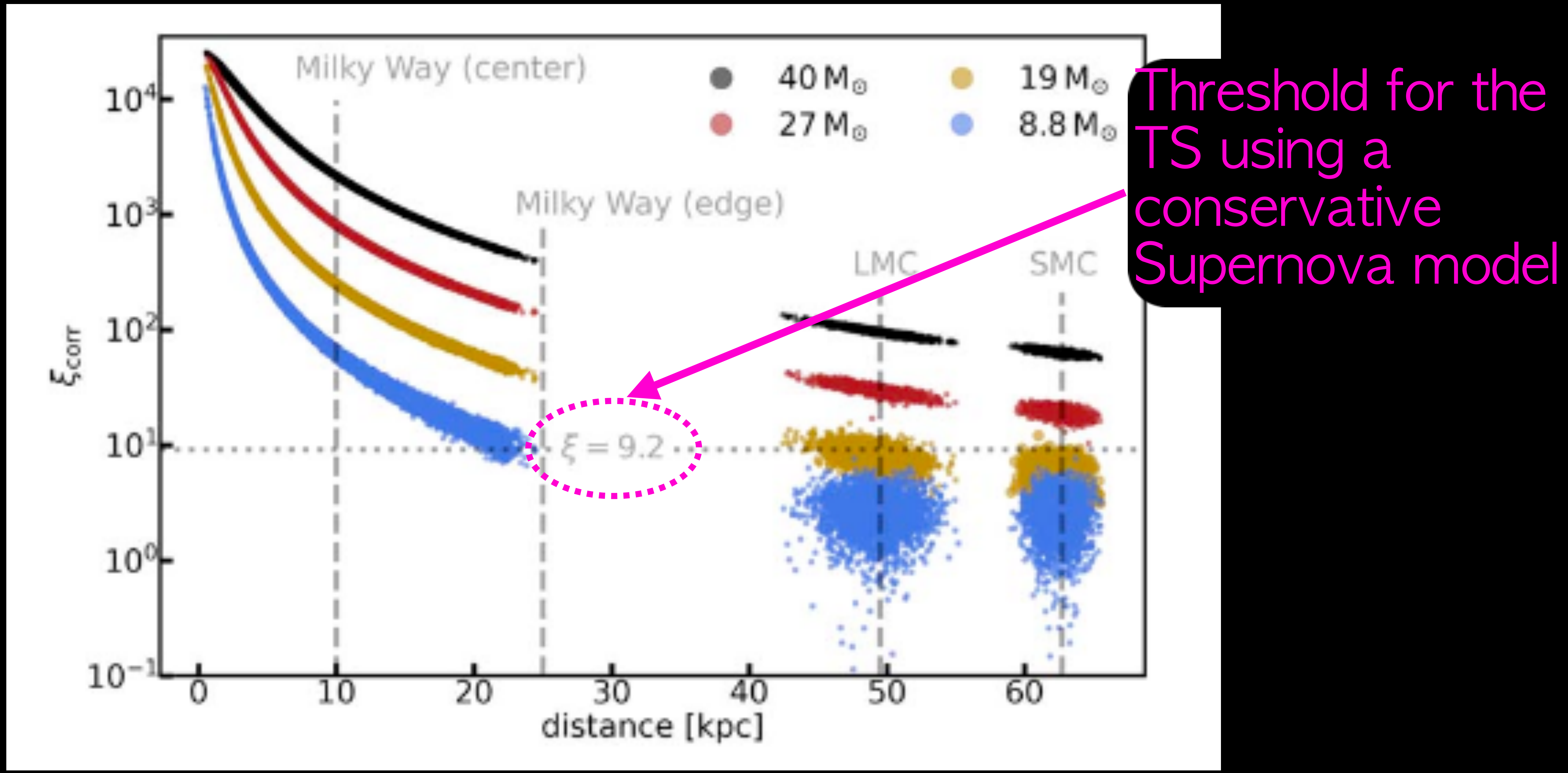


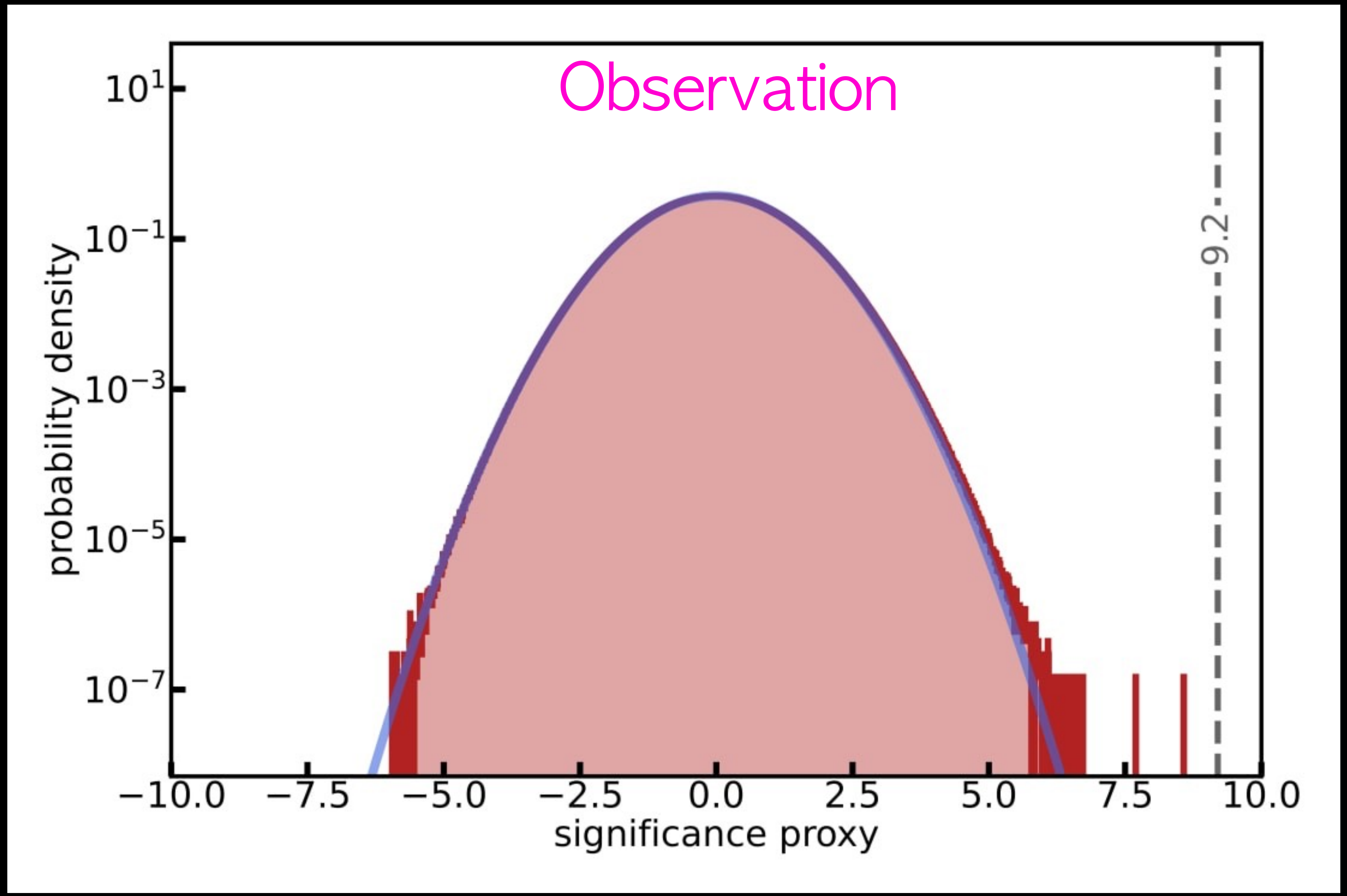
-Searched for an MeV neutrino burst from Galactic Supernova

-Results: 90% UL on the rate of Galactic Supernova (25 kpc): $0.23\ \mathrm{yr}^{-1}$

R. Abbasi et al. Search for Galactic Core-Collapse Supernovae in a Decade of Data Taken with the IceCube Neutrino Observatory, 2024 ApJ 961 84

RESULTS: GALACTIC SEARCH OF CCSNE





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-Results: 90% UL on the rate of Galactic Supernova (25 kpc): $0.23\ \text{yr}^{-1}$ (Strongest model-independent limits to date)

Other constraints by ν detectors:

Super-K $< 0.29\ \text{yr}^{-1}$

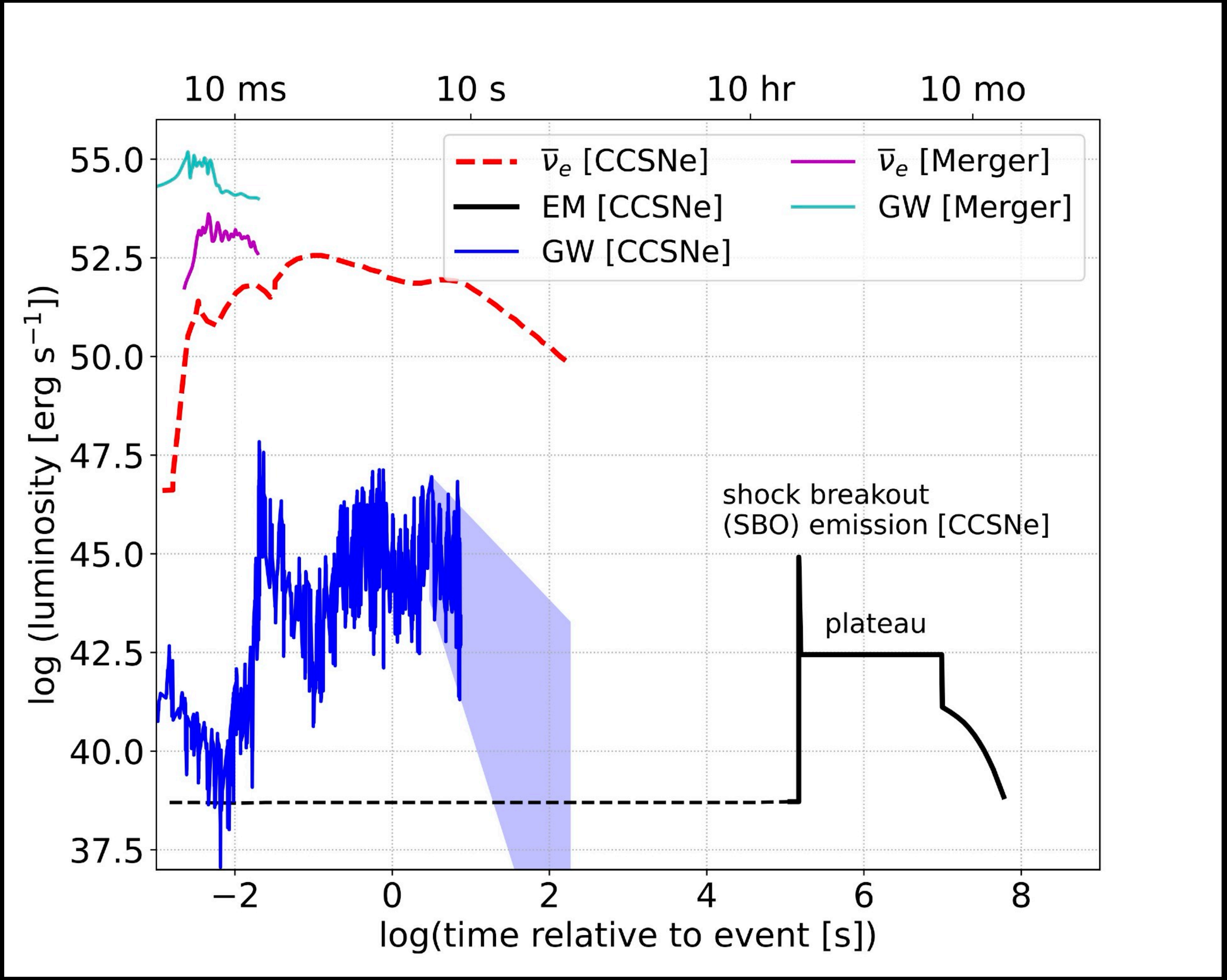
KamLAND $< 0.15\ \text{yr}^{-1}$

R. Abbasi et al. Search for Galactic Core-Collapse Supernovae in a Decade of Data Taken with the IceCube Neutrino Observatory, 2024 ApJ 961 84

OTHER TRANSIENTS

NEUTRON STAR MERGERS

One example. Not exhaustive!



Mergers with at least one NS could produce a burst ($\mathcal{O}(ms - s)$) of MeV neutrinos correlated with GW.

Mostly isotropic emission

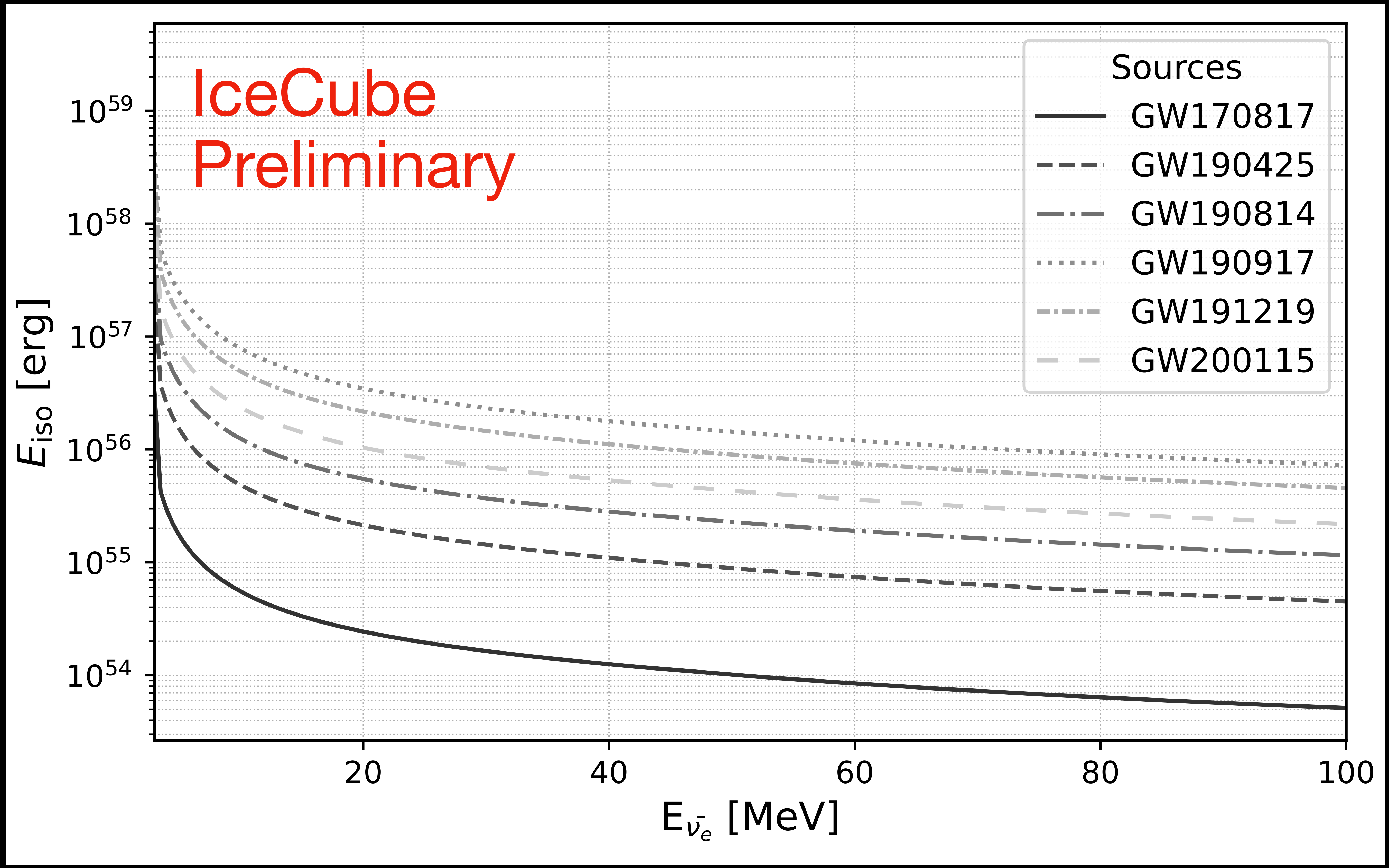
Flux is dominated by $\bar{\nu}_e$ due to neutron-rich matter.

Luminosity $\approx 10^{52} - 10^{54}$ergs

Adapted from Cusinato et al. Eur. Phys. J. A (2022) **58**: 99, and Nakamura et al. MNRAS, Volume 461, Issue 3, 21 September 2016, Pages 3296–3313

RESULTS: NEUTRON STAR MERGERS

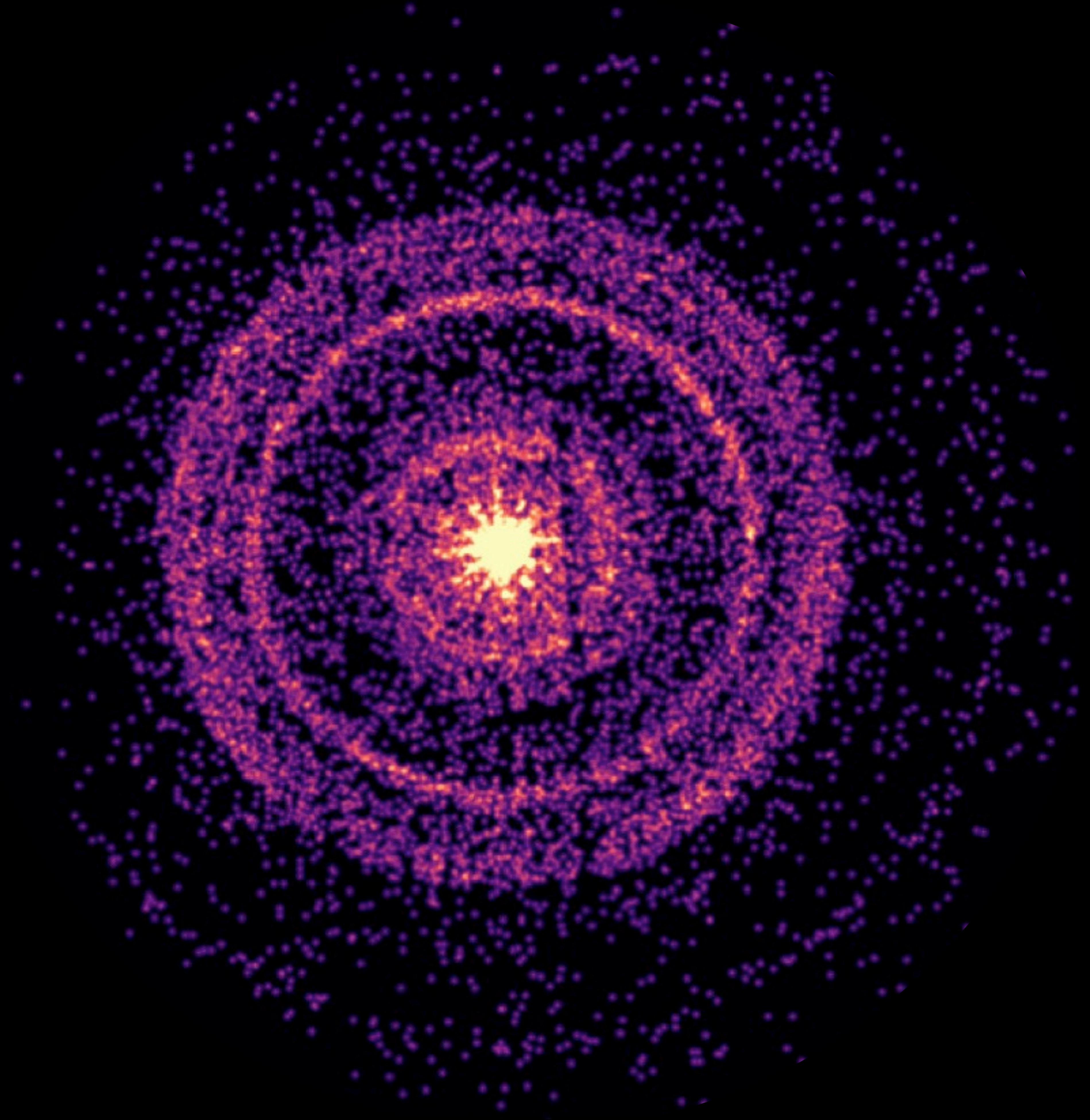
- First IceCube constraints on MeV neutrino emission from GW sources.
  - Searched for thermal neutrino emission from GW sources using LVK catalogs O1-O3.
  - No significant excess for either individual sources or the population study.
  - We set U.L. on the thermal neutrino emission from BNS/NSBH, which are potential thermal neutrino emitters.



GRB 221009A

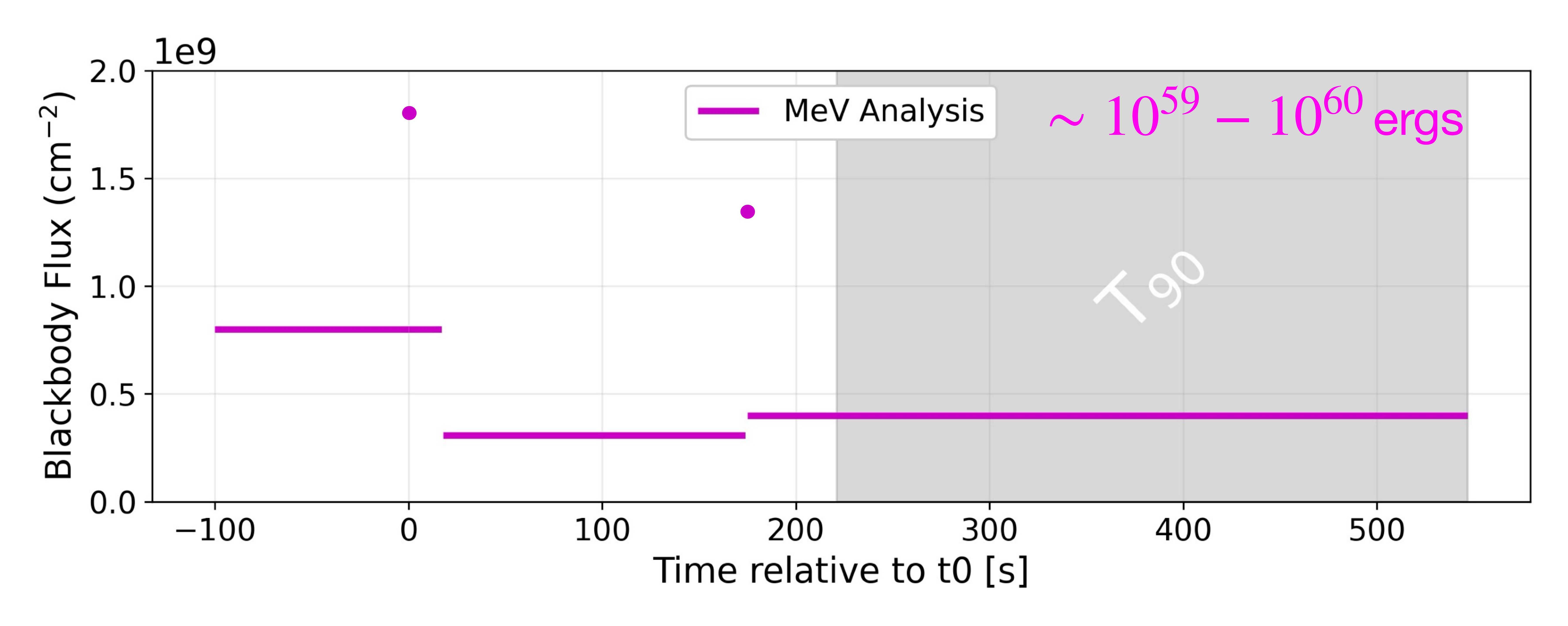
- First detected by GBM (Fermi gamma ray satellite) on the 9th of October 2022.
- One of the brightest gamma ray burst (GRB) and first >TeV γ-rays detected. Bursts this bright occur only once every 10,000 years!
- Very close GRB ($\approx$ 740 Mpc), or about 20 times closer than average GRB.

GRBs can coincide with supernovae: MeV neutrinos



X-ray image of GRB 221009A emission scattering off dust (Williams et al. 2023)

RESULTS: GRB 221009A



- Searched for neutrinos in wide energy range (MeV to PeV)

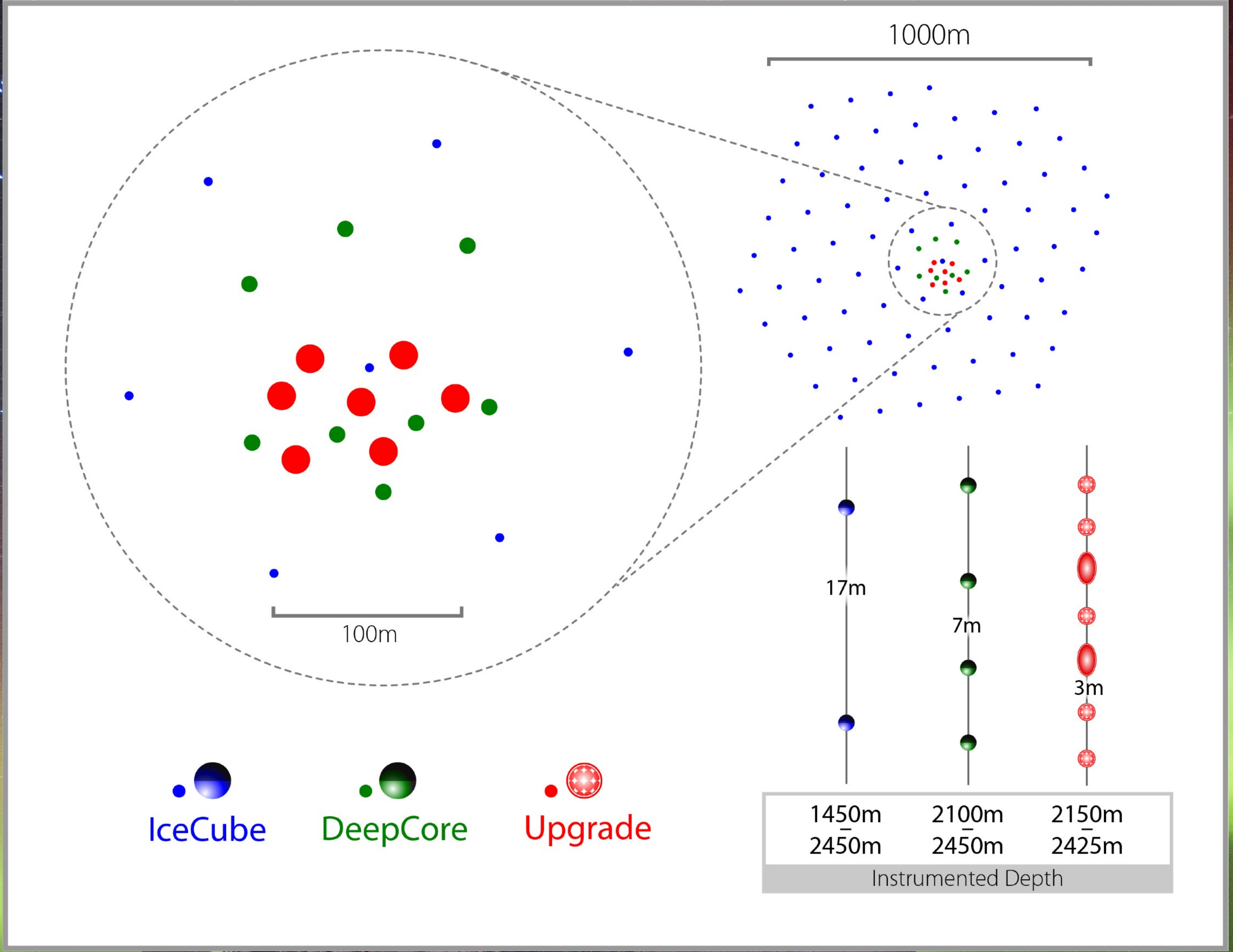
- Results: Placed UL for this source.

R. Abbasi et al., Limits on Neutrino Emission from GRB 221009A from MeV to PeV Using the IceCube Neutrino Observatory, 2023 ApJL 946 L26

FUTURE…

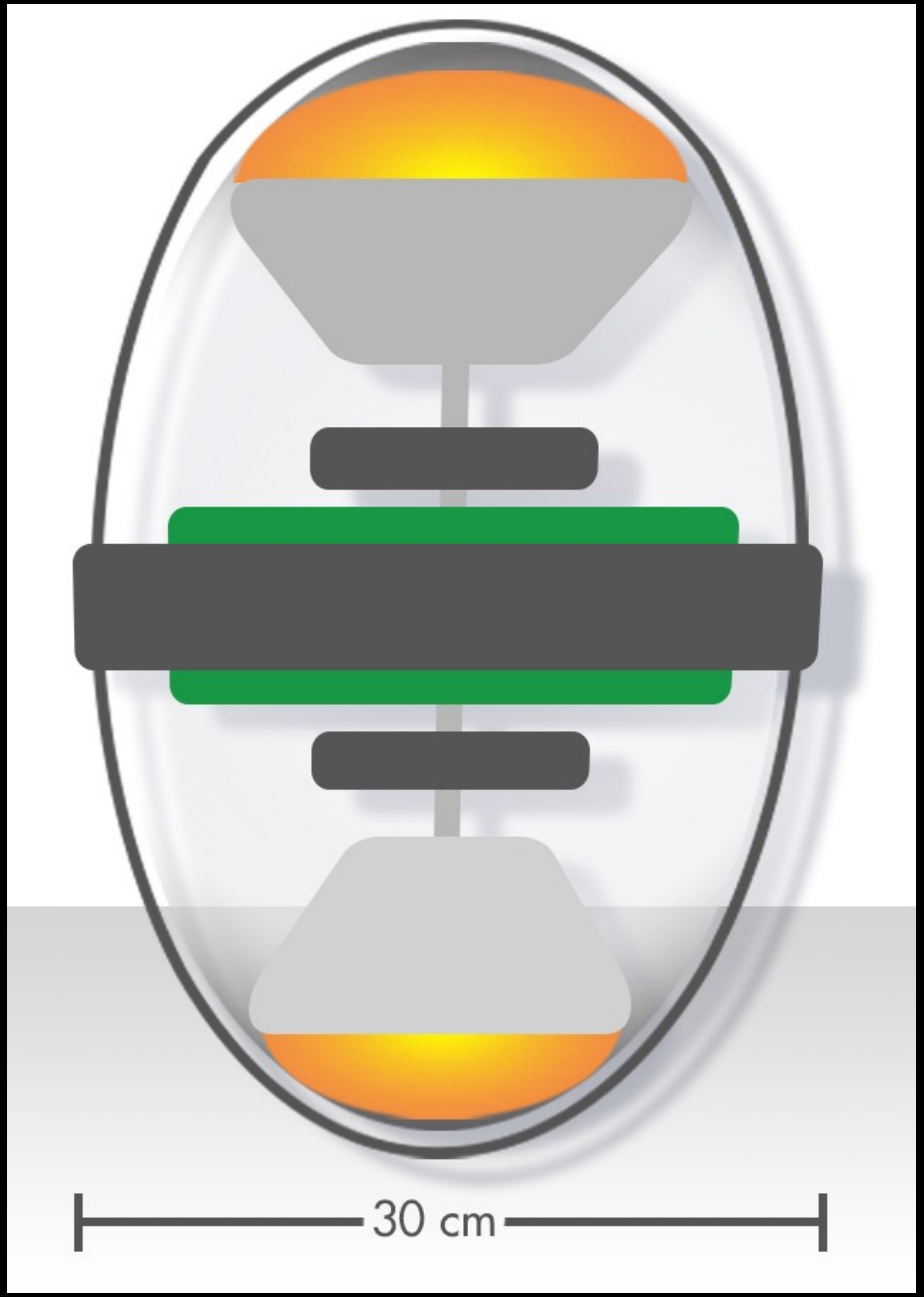
NEAR FUTURE: ICECUBE UPGRADE

- Currently under deployment (Drilling in 2025-2026)
- 7 new 'strings' with ~ 700 new sensors.
- Smaller string spacing improves:
  - Systematic calibration of ice optical properties
  - Improved angular/energy resolution

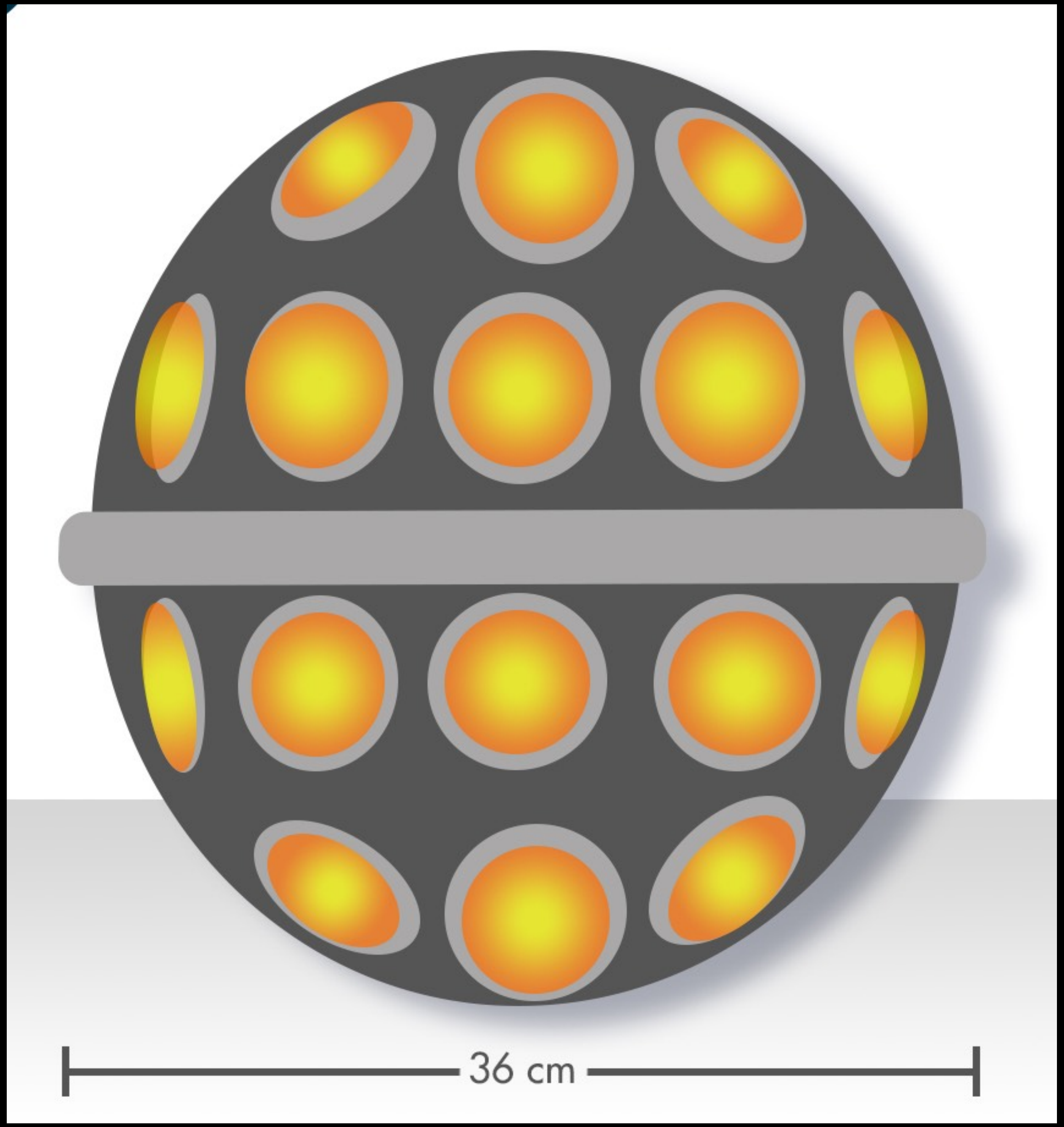


NEW OPTICAL SENSORS: D-EGG AND MDOM

D-Egg



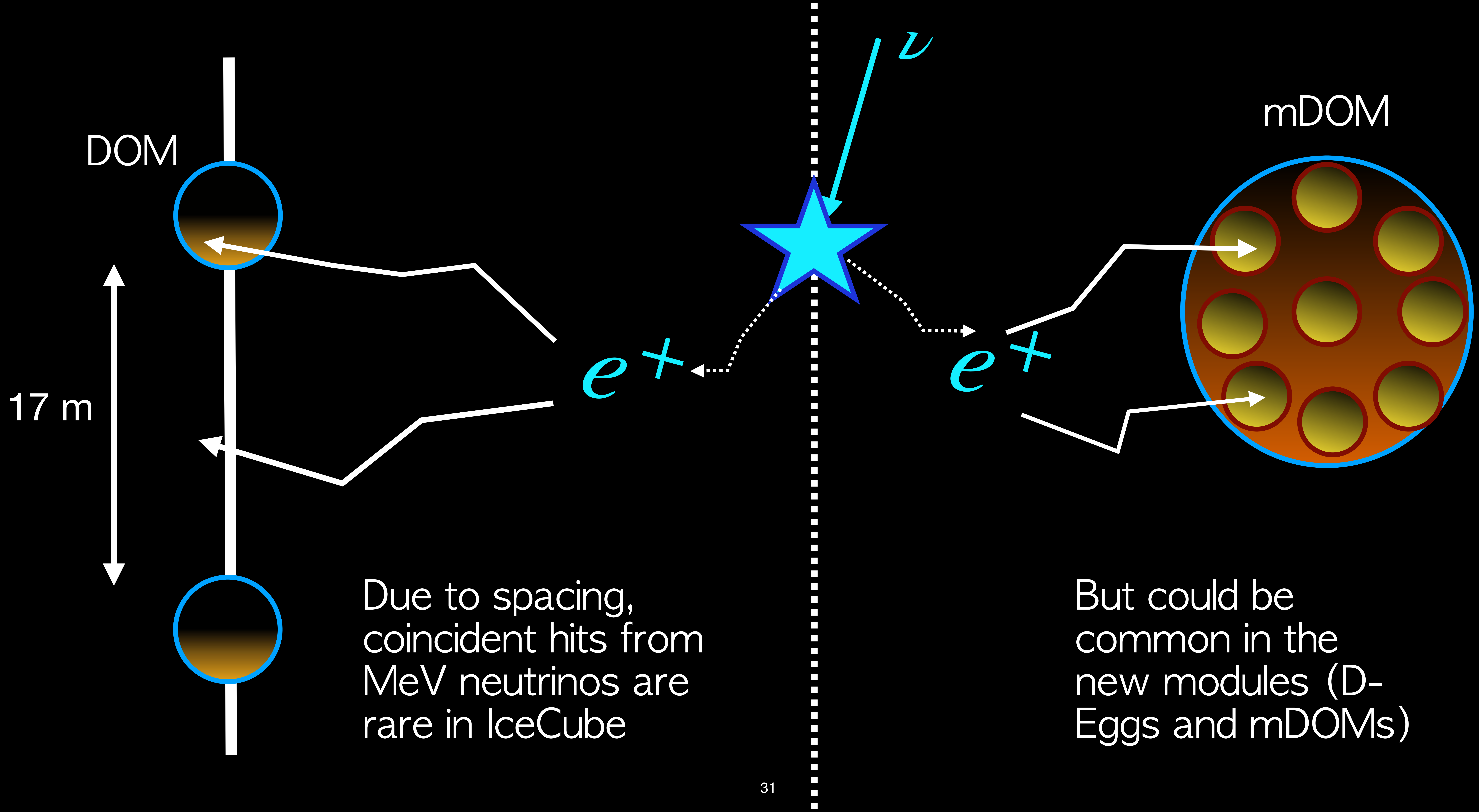
mDOM



New modules provide with 4π coverage (improves effective volume and event resolution)

-LED flashers and cameras for improved ice calibration

WHAT CAN WE DO WITH UPGRADE?

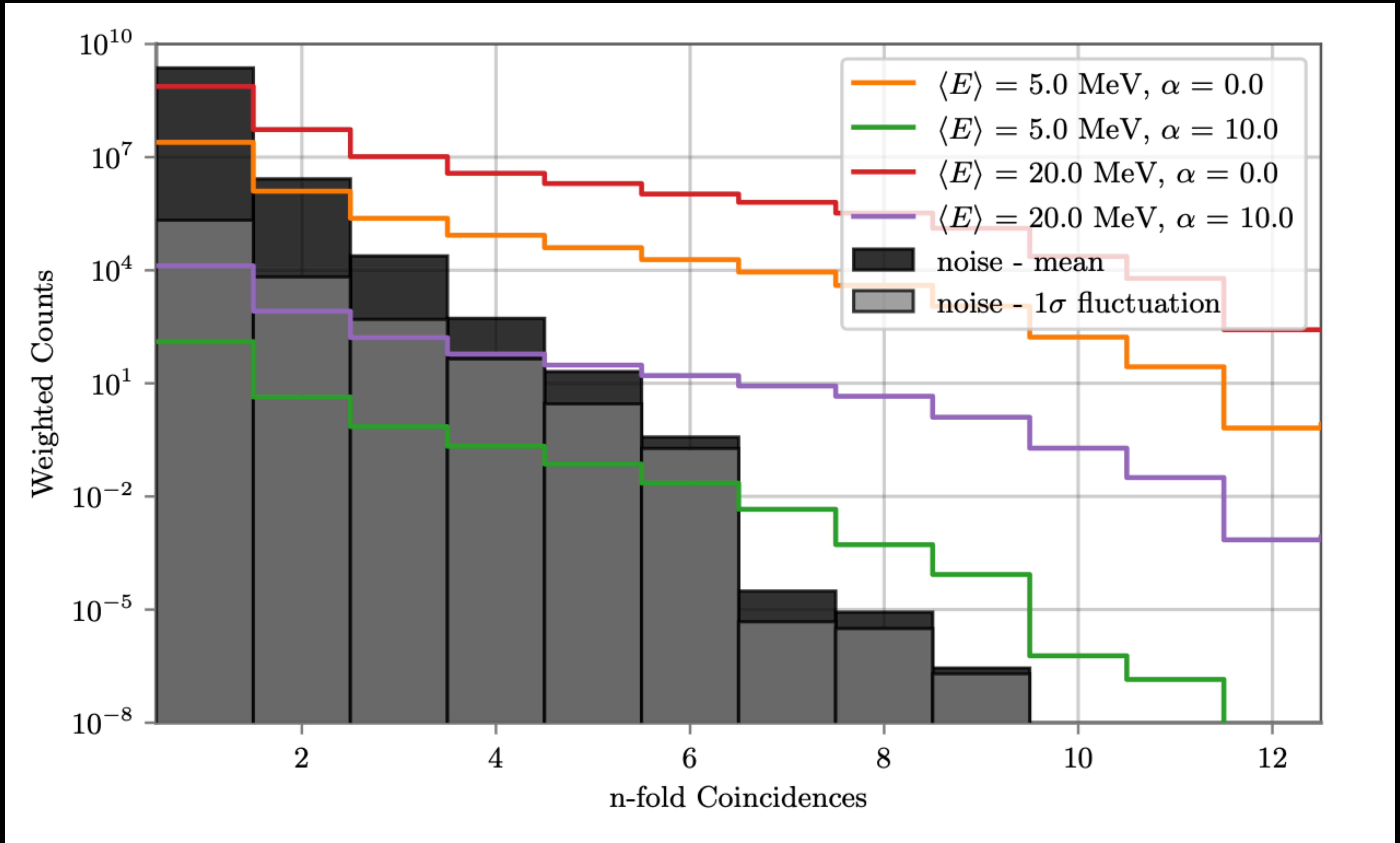


Due to spacing, coincident hits from MeV neutrinos are rare in IceCube

But could be common in the new modules (D-Eggs and mDOMs)

NEW OPTICAL SENSORS: D-EGG AND MDOM

Background / signal coincidences in 20 ns



N-fold hit coincidence could help us drive our background down

Credit: F. Sprenger 2019

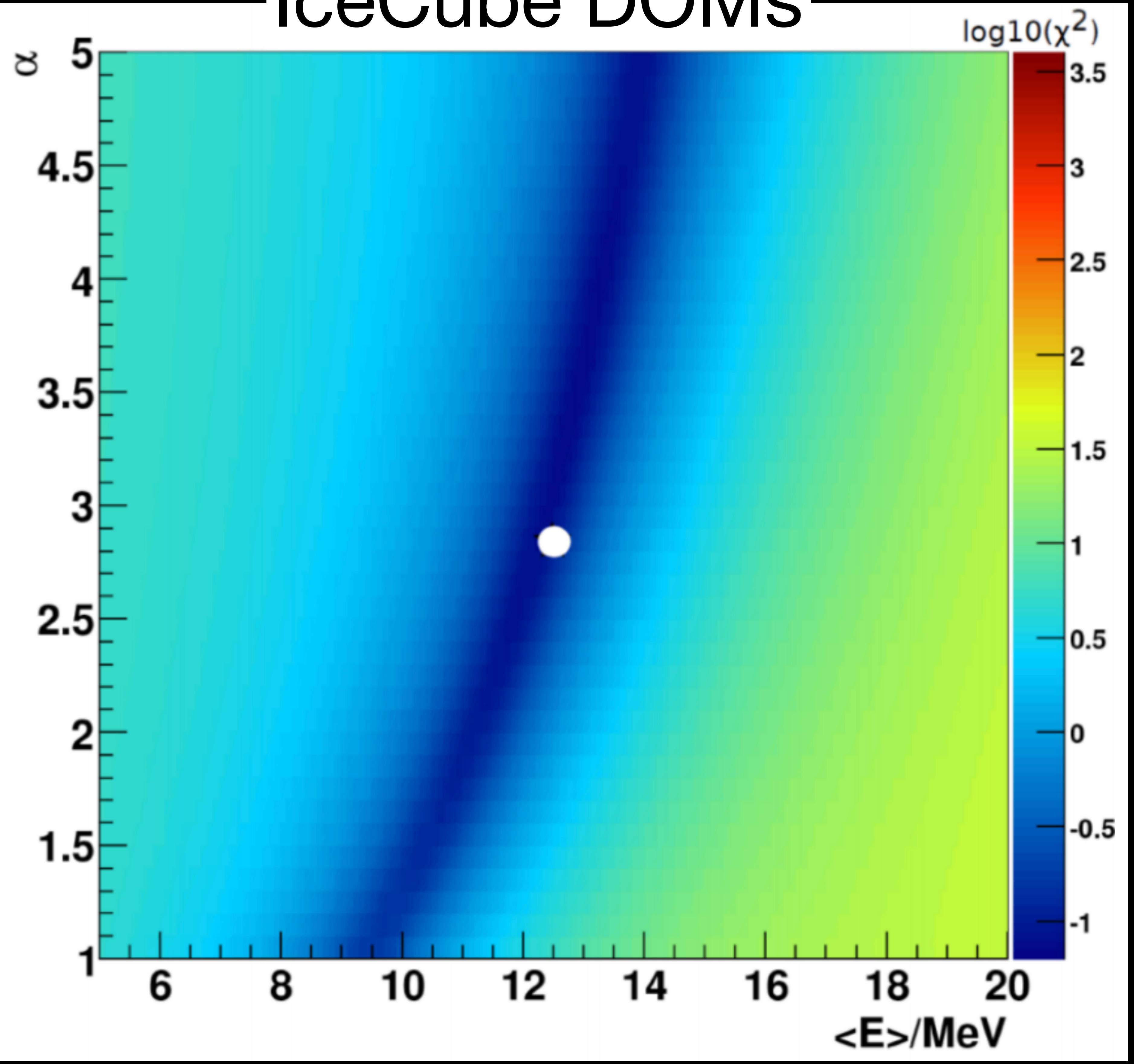
WHAT CAN WE DO WITH UPGRADE?

CCSN spectral shape is well approximated by: $f(E_\nu) \sim E_\nu^\alpha e^{-(\alpha+1)E_\nu/<E_\nu>}$

α and $< E_\nu >$ dependent on neutrino flavor & time

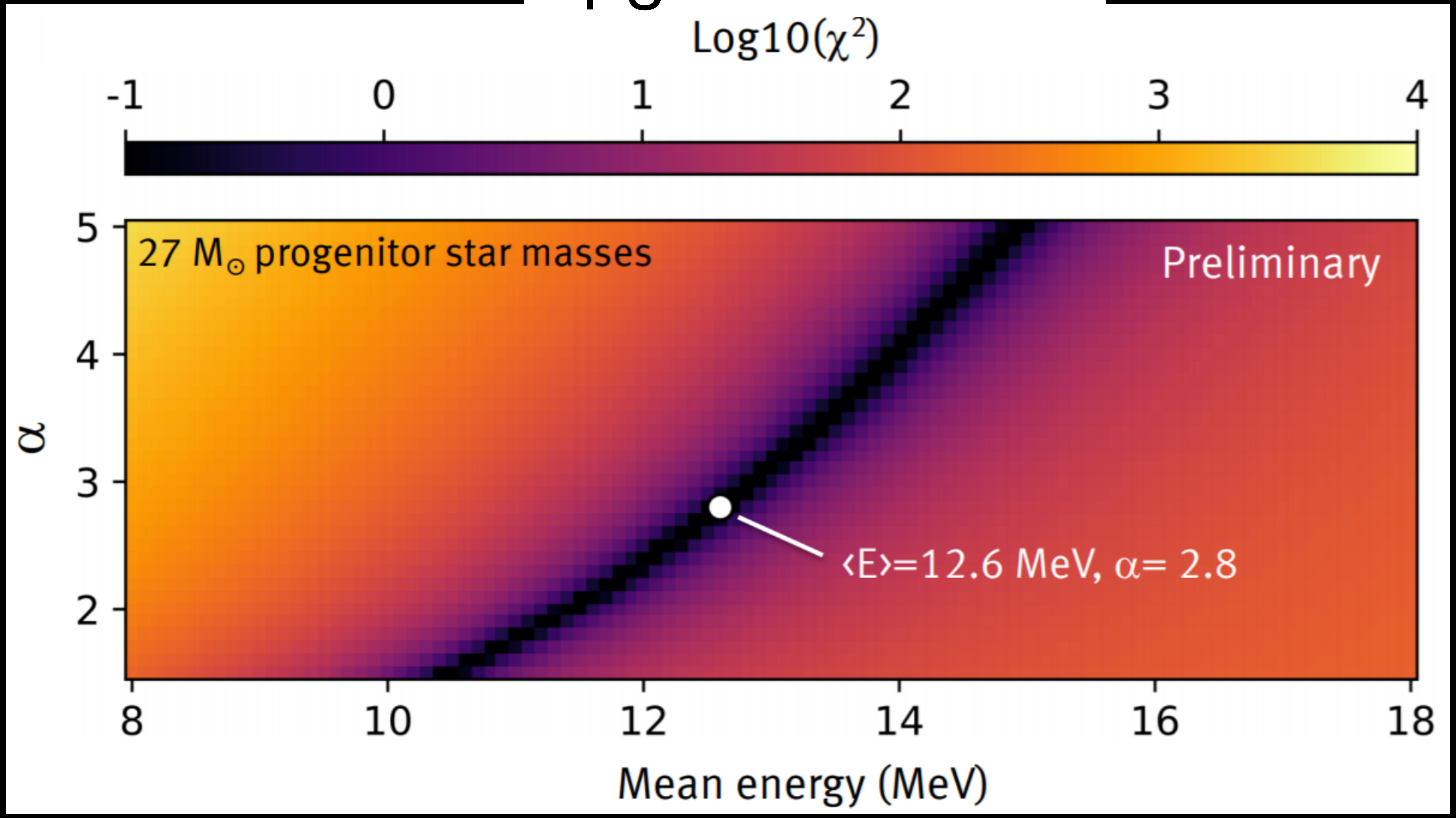
$< E_\nu > = 12.6$ MeV and $\alpha = 2.8$

IceCube DOMs



Credit: L. Köpke
8th Symp. Large TPCs, 2017

Upgrade mDOMs

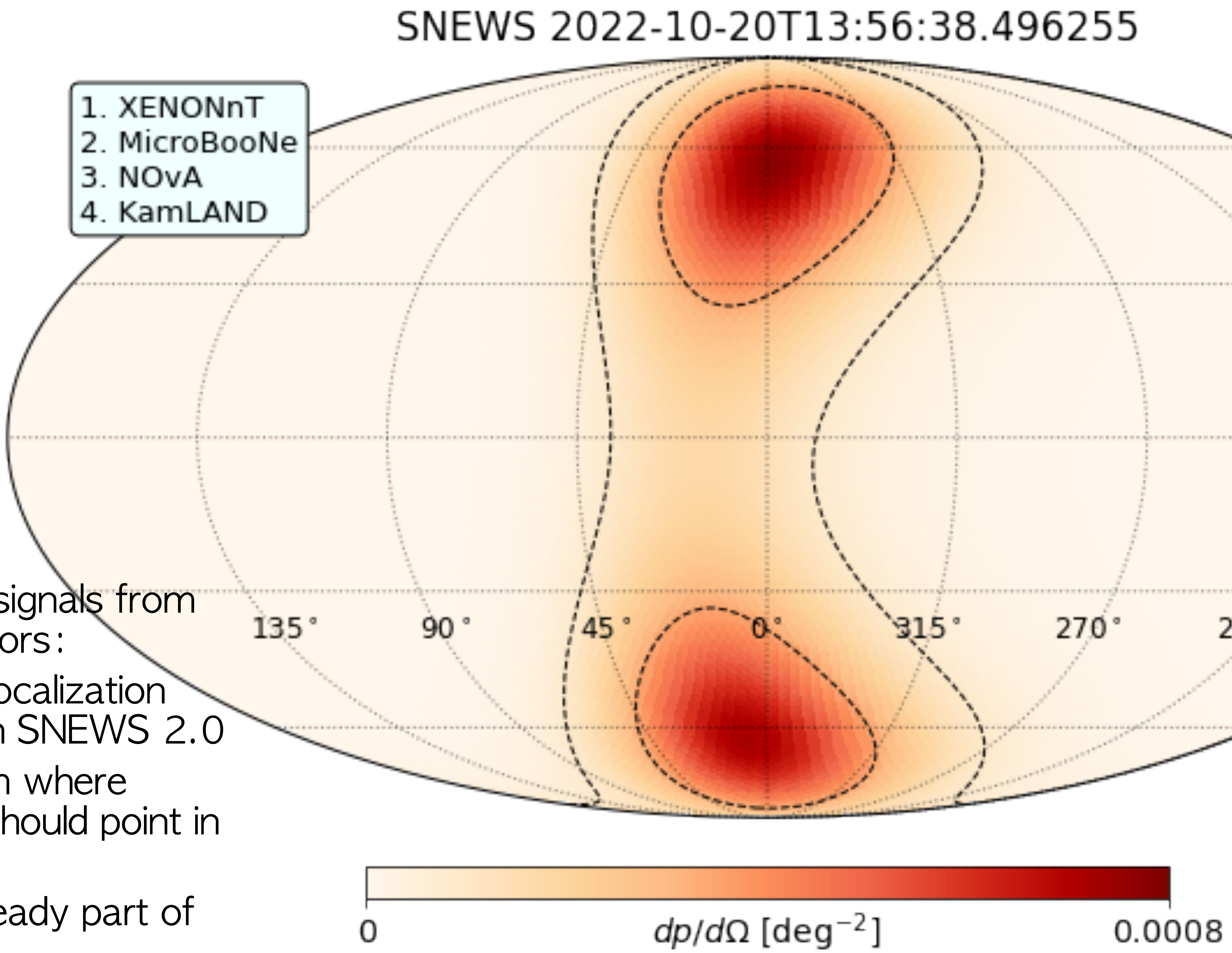


Credit: C. Lozano, Neutrino 2018

Resolution: $\sigma(E)/ < E > \leq 5\,\%$

UPCOMING: SNEWS 2.0

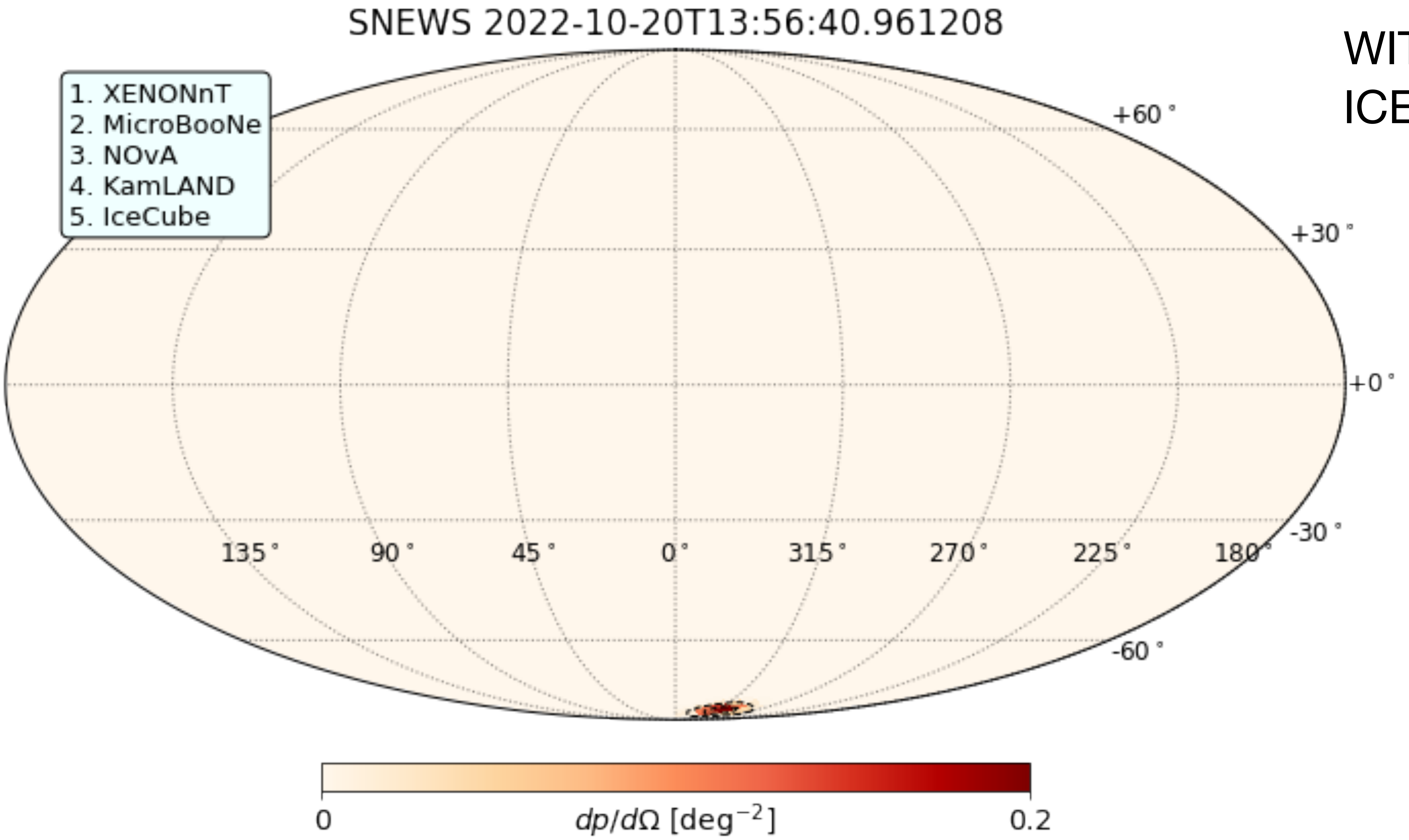
WITHOUT ICECUBE



By combining signals from multiple detectors:

- Progenitor localization possible with SNEWS 2.0
- Helps inform where telescopes should point in the sky
- IceCube already part of firedrills!

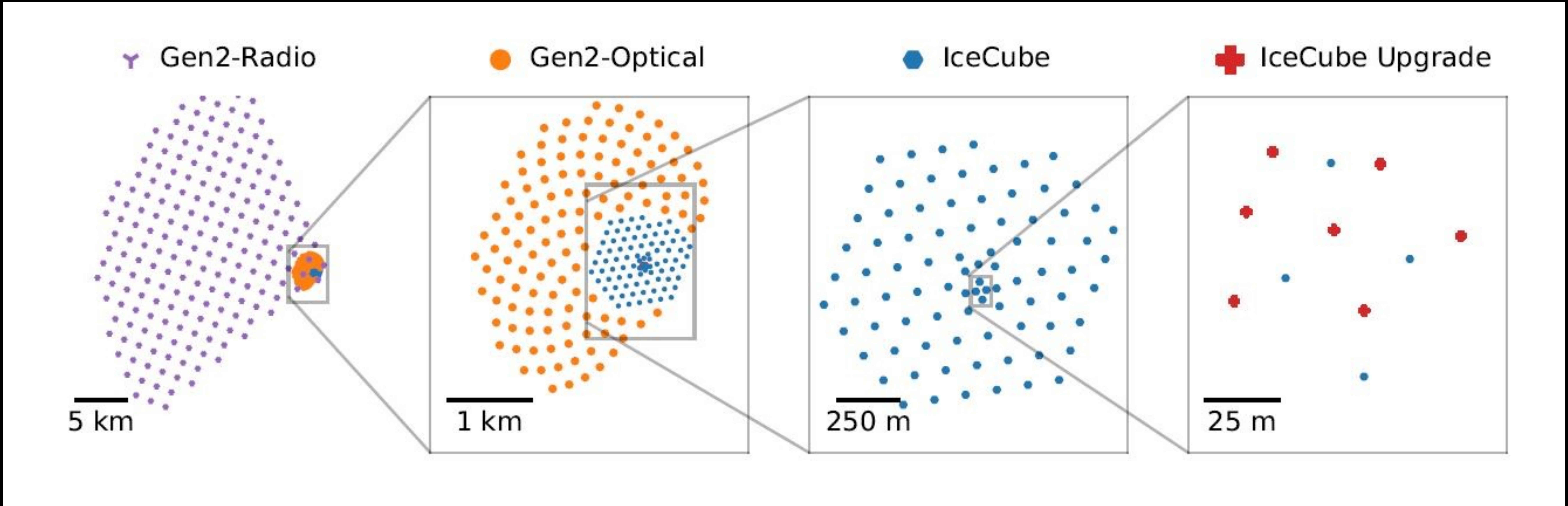
UPCOMING: SNEWS 2.0



WITH ICECUBE

ICECUBE GEN2

GEN2 ARRAY

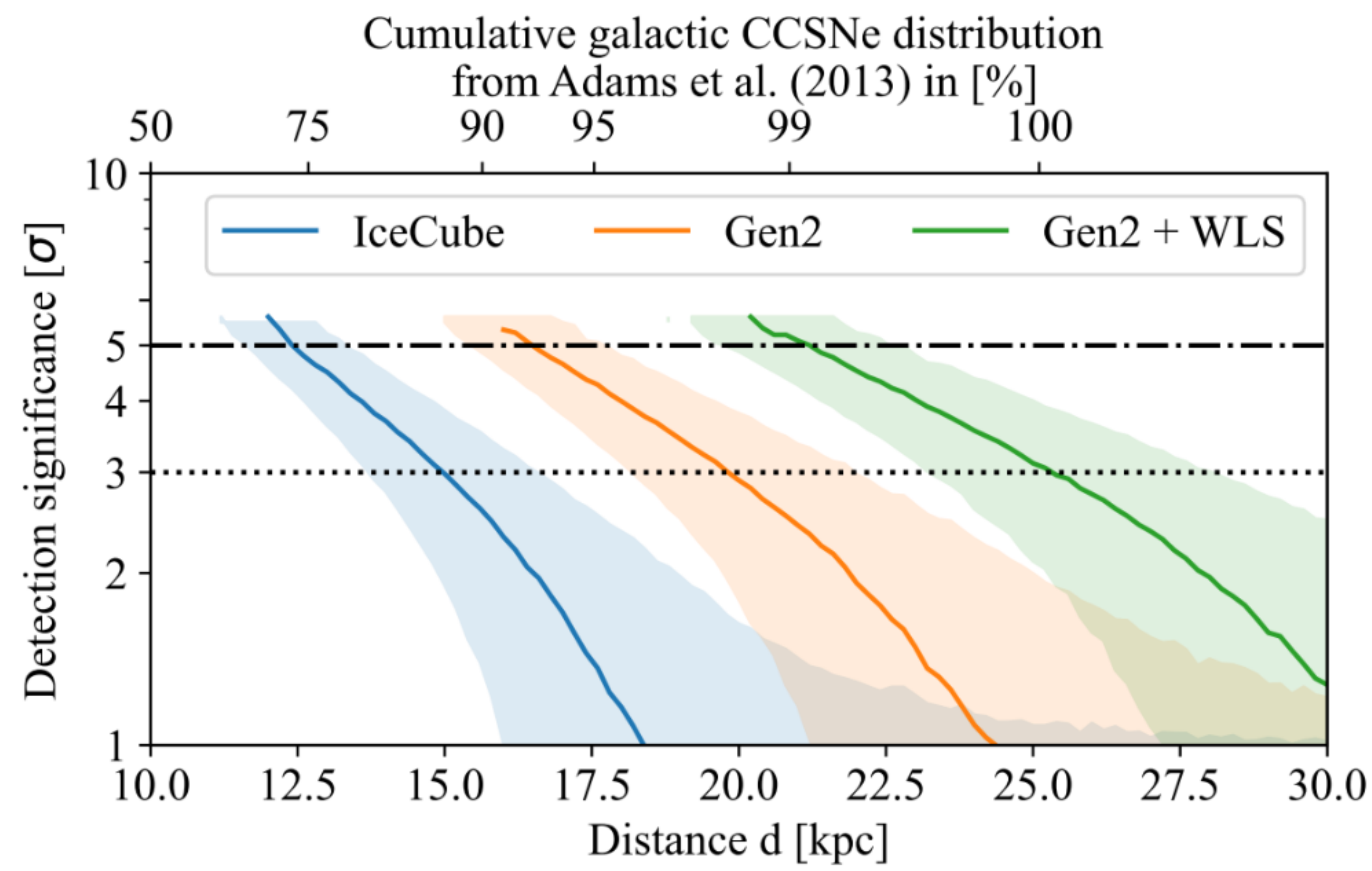


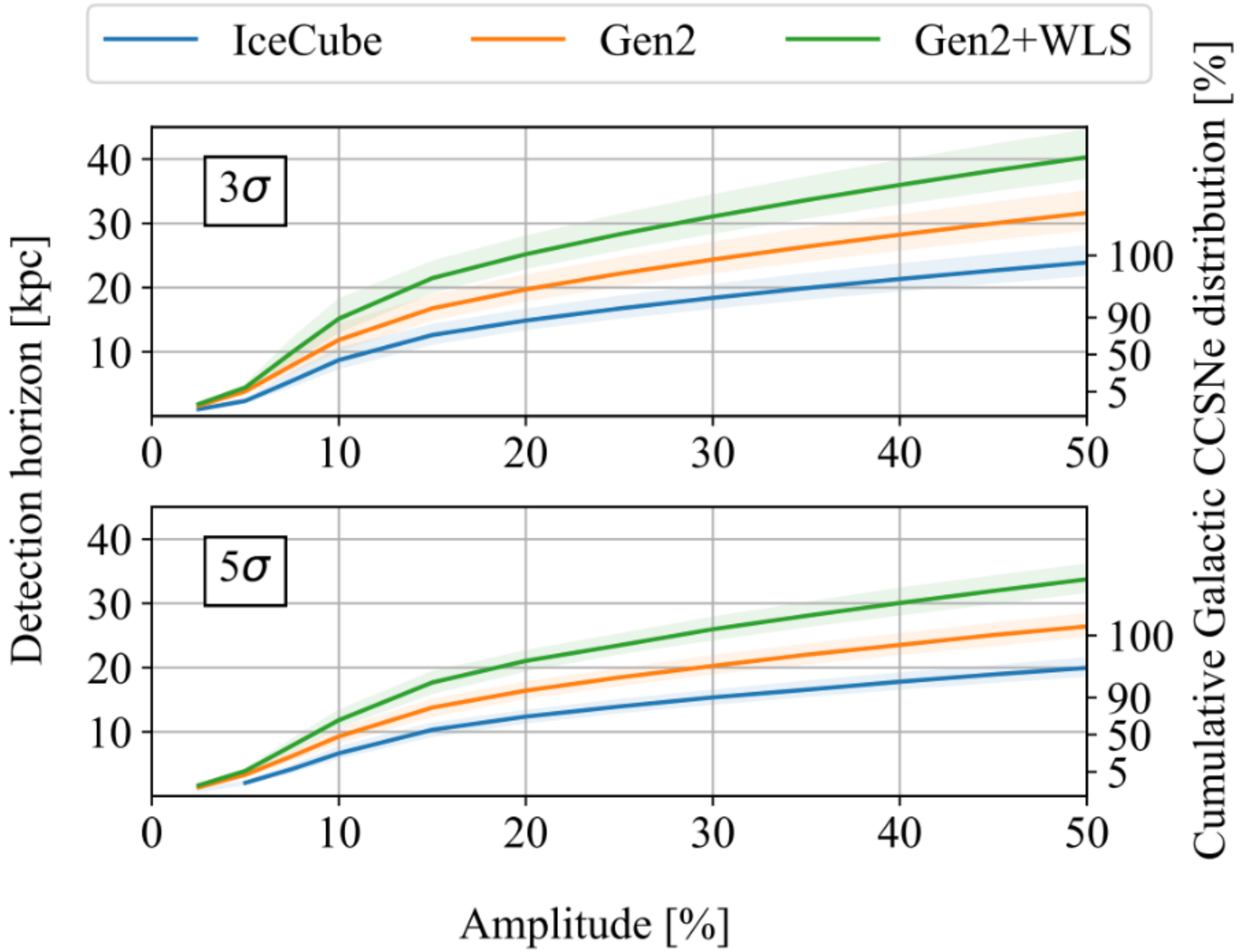
Credit: IceCube-Gen2 TDR: https://icecube-gen2.wisc.edu/science/publications/tdr/

FAST TRANSIENT FEATURES FROM CCSN

CCSNe could have fast time features in the neutrino luminosity

With IceCube Gen2 we could potentially reach our entire Milky Way





Credit: Beise J., et al. (2025)

Much more that I cannot cover

BSM physics (Axion-Like Particles) ⟶
Come talk to me if interested!

Constraining neutrino mass ordering

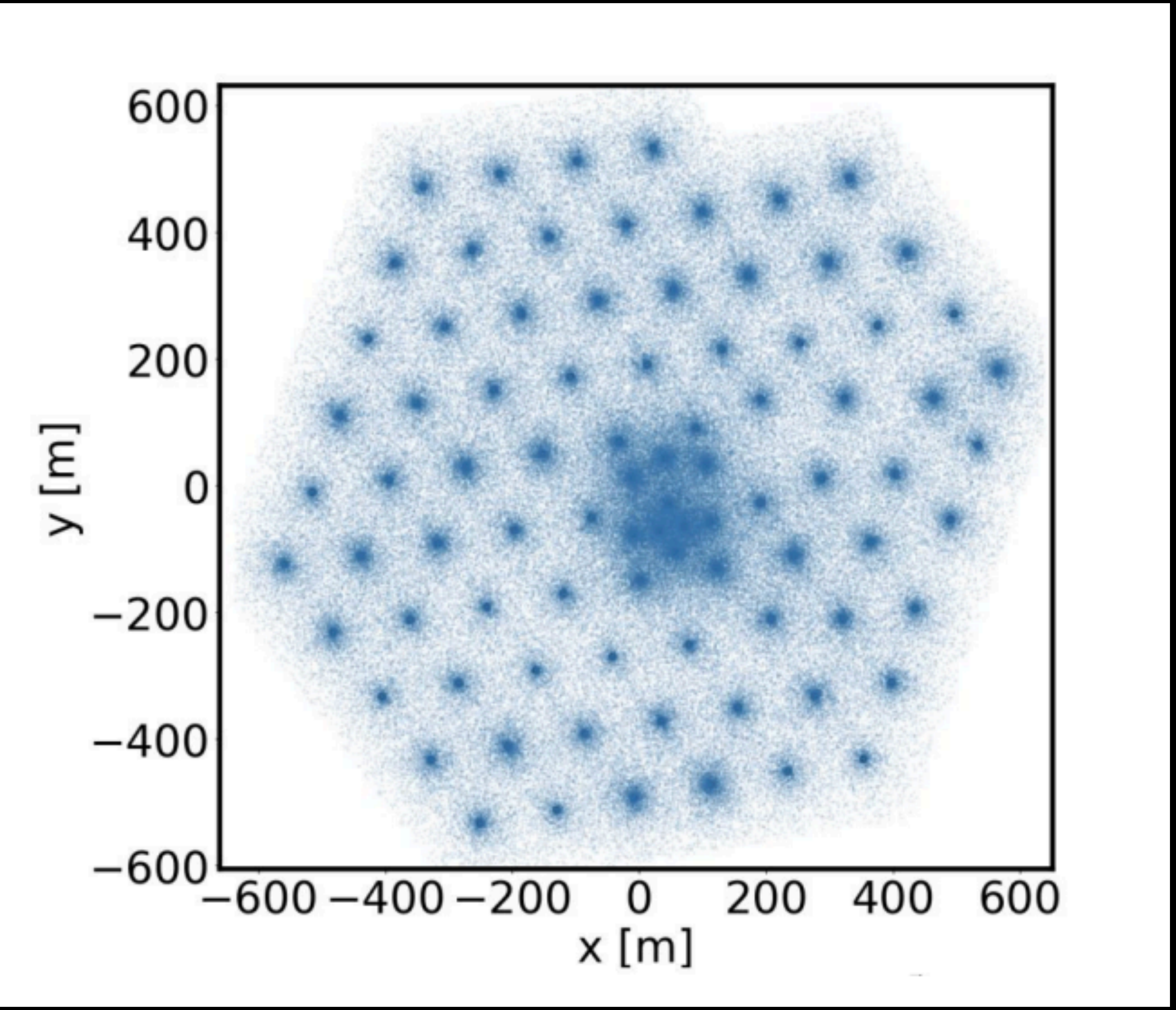
Other MeV searches

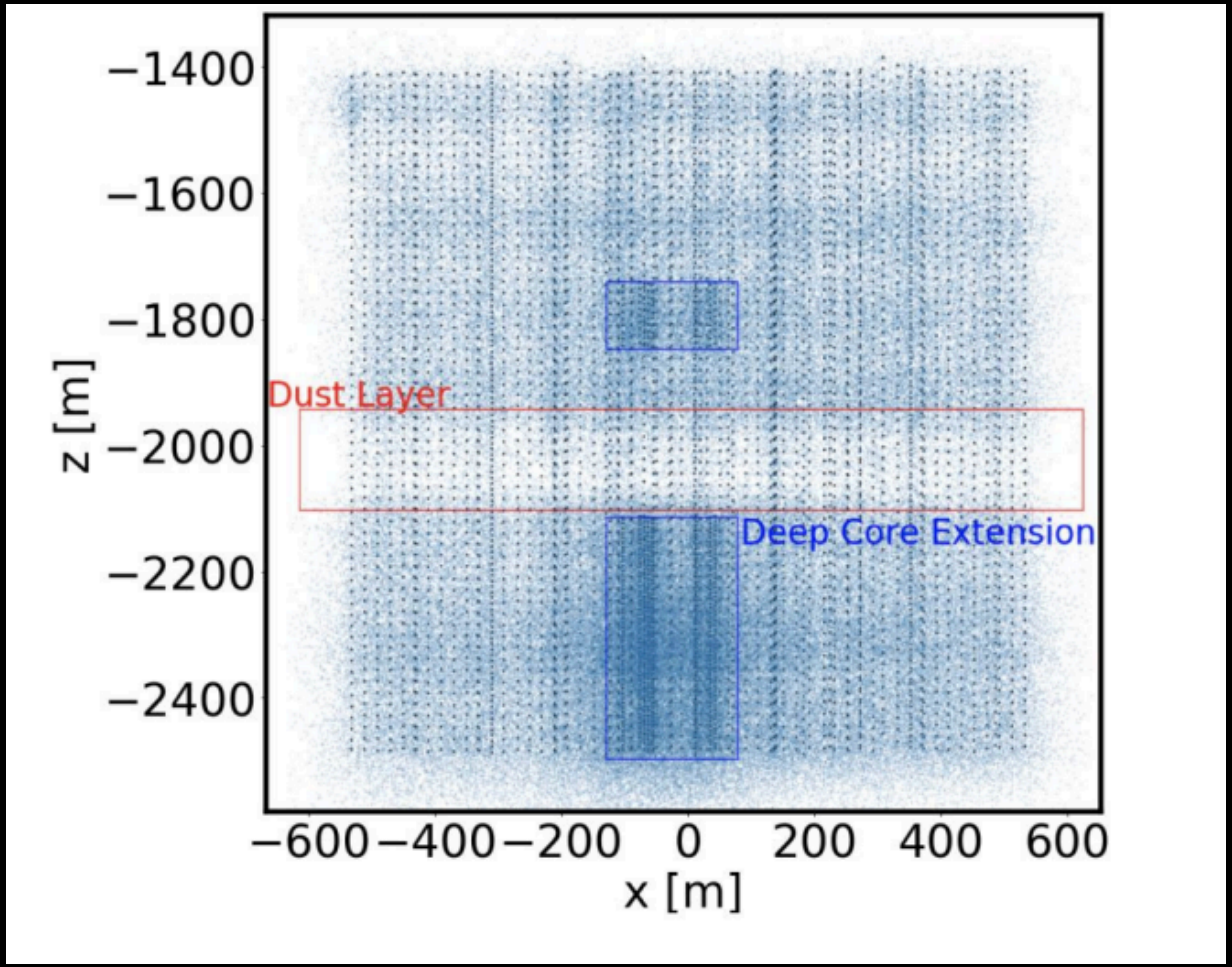
SUMMARY

- IceCube is a unique observatory that can detect astrophysical neutrinos across a wide energy range, including MeV, with over 10 years of statistics.
- The MeV physics is active and spans a wide range, from transient searches to dark matter/BSM physics with a highlight of the realtime supernova burst monitor with >99% uptime.
  - Recent results: U.L for Galactic Supernova, Neutron Star Mergers and Gamma-Ray Bursts.
- Many exciting opportunities in the future: with IceCube Upgrade, constrain supernova parameters. With Gen2, possibility to do even more, such as fast-time feature searches in our entire Galaxy.

INTERACTIONS IN ICE

Simulated MeV IBD vertices

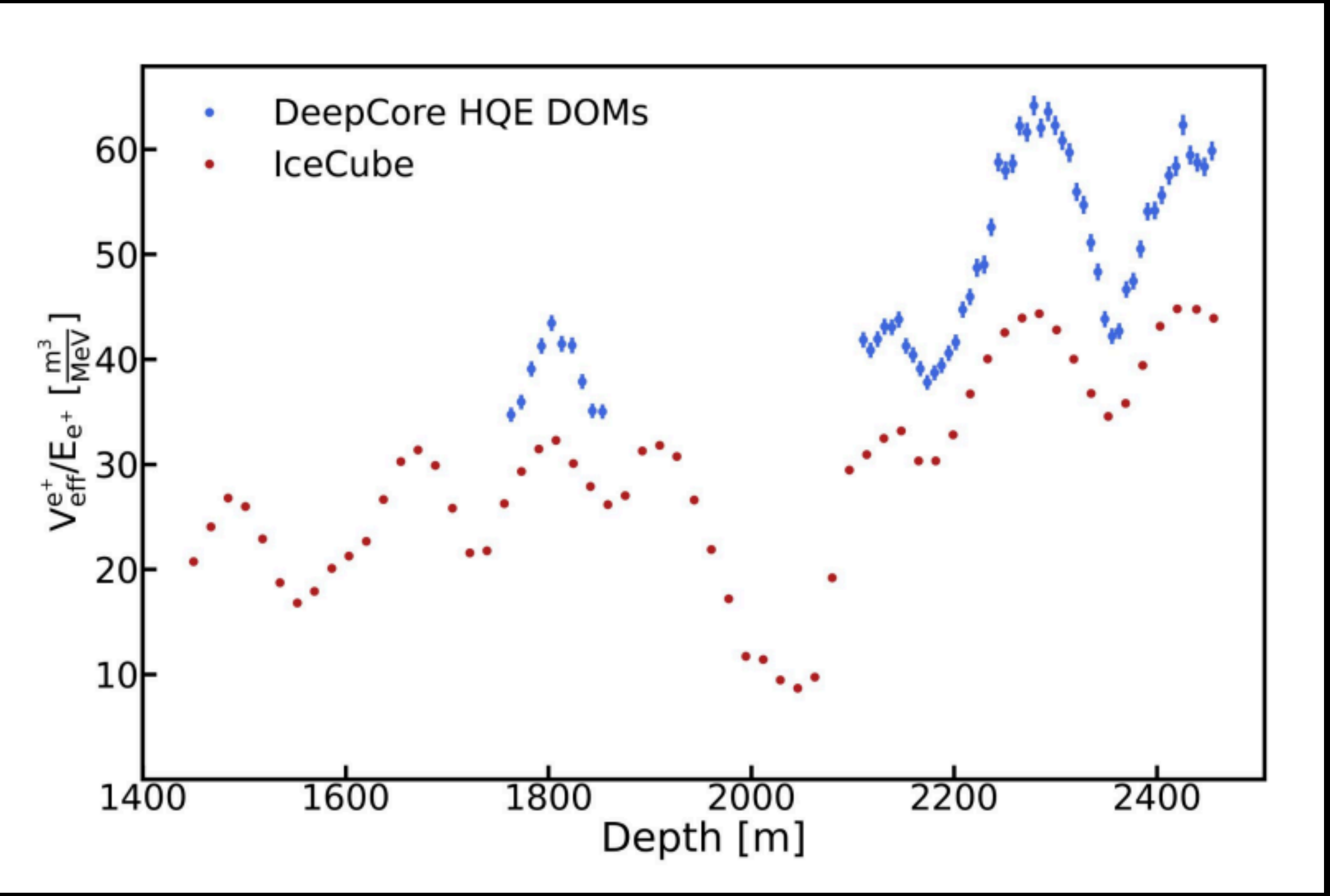


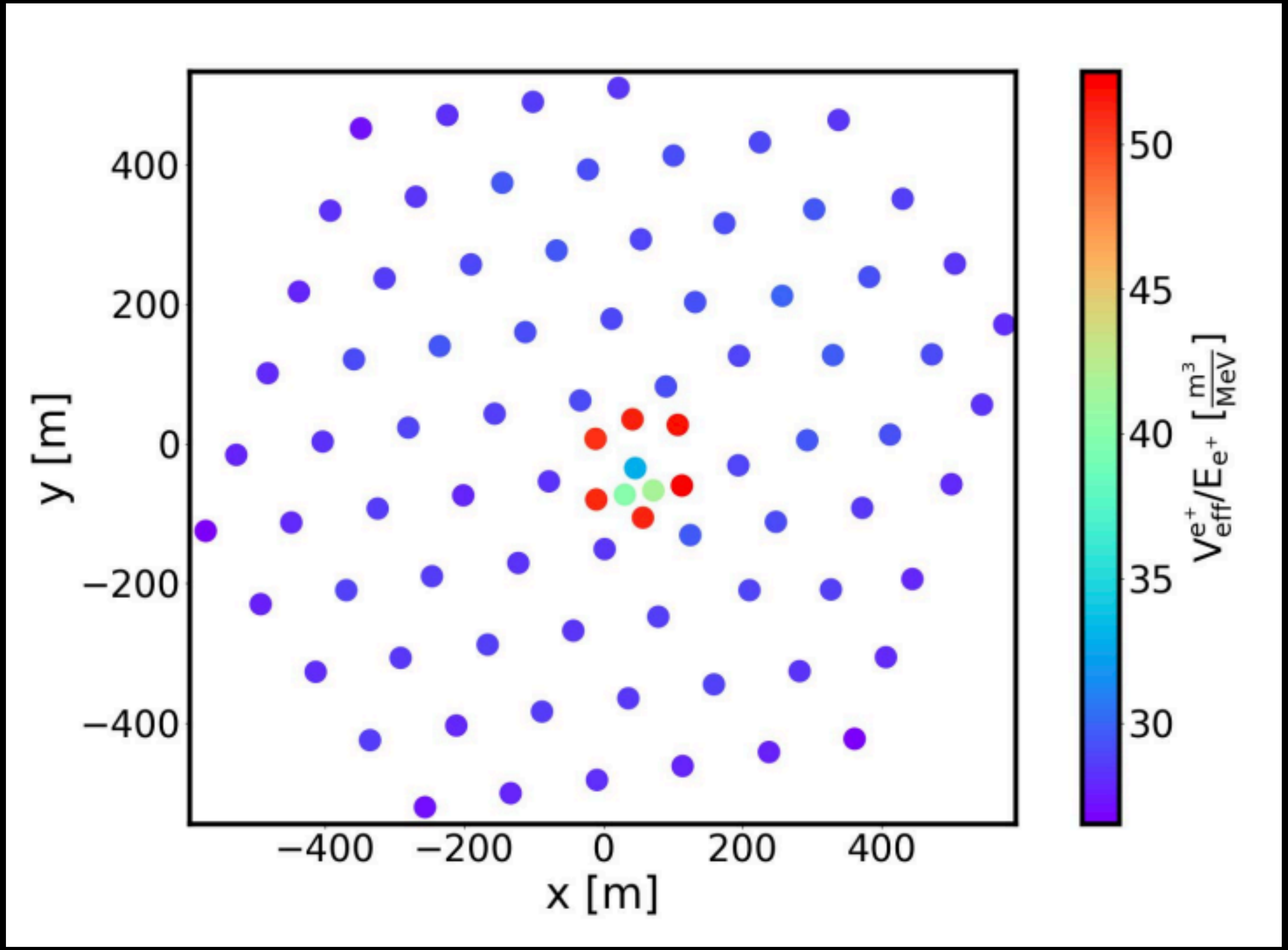


Credit: R. Cross, A. Fritz, S. Griswold, PoS(ICRC19)

EFFECTIVE VOLUME

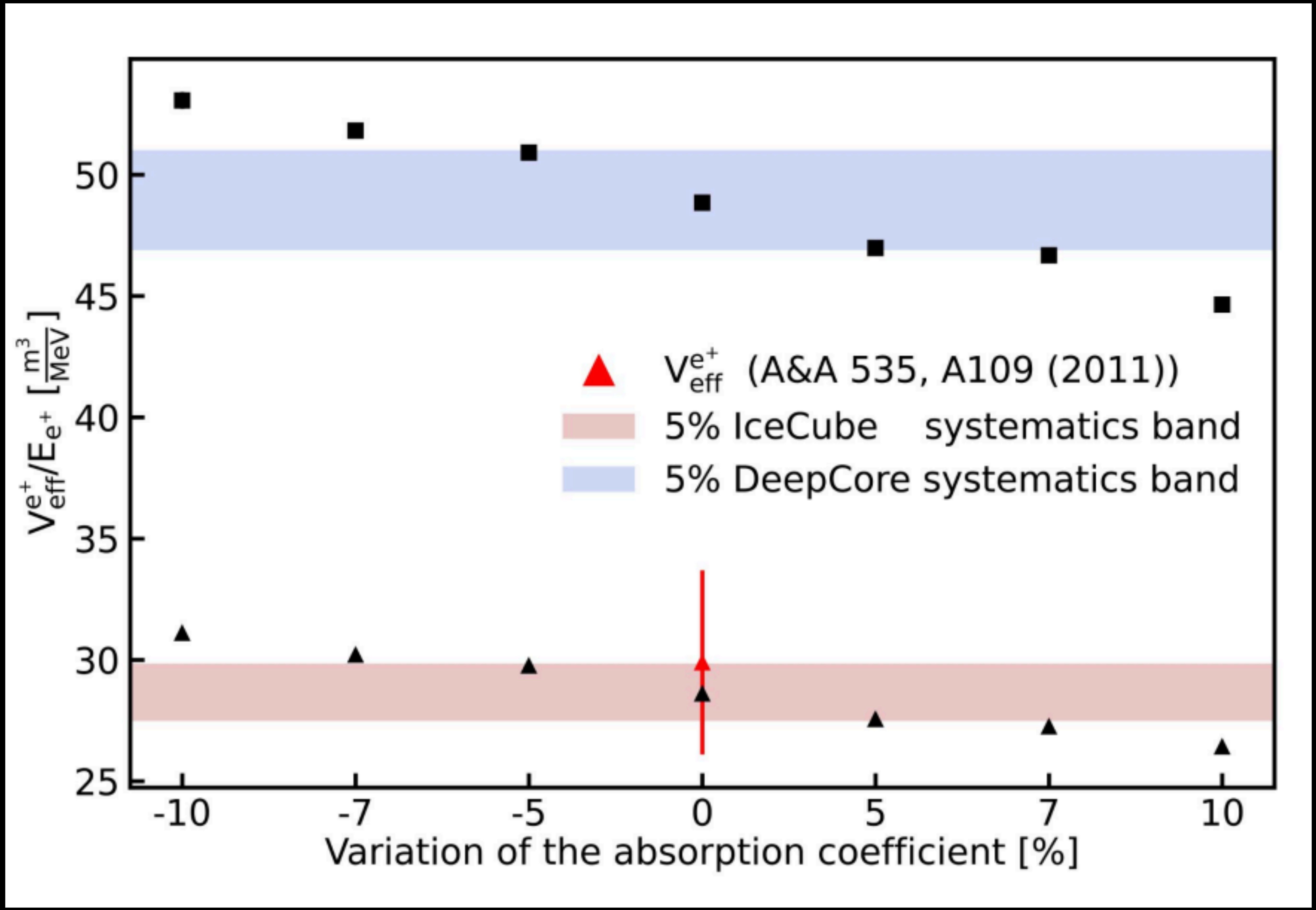
Per DOM effective volume $m^3\ MeV^{-1}$





Credit: A. Fritz (IceCube Collaboration), 2024

SYSTEMATIC UNCERTAINTIES



Systematic Uncertainty	Relative Size [%]
Rate deviation in sliding average window	± 1.6
Ice density vs. depth	± 0.2
Mean $e^{\pm}$ track length in ice	± 5.0
Ice optical properties	[-3.6, +4.1]
DOM efficiency	± 10.0
Artificial deadtime	± 3.0
Cross Sections (e^+p, e^-p, e-O)	< ± 1, < ± 1, ± 0.2
zenith-dependent neutrino oscillation in Earth	[-0.2, +4.9]
Total	[-15.0, +16.2]

Credit: A. Fritz (IceCube Collaboration), 2024