



ICECUBE
NEUTRINO OBSERVATORY



WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Atmospheric, Astrophysical and Cosmogenic neutrinos (part 2)



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Last lecture, we discussed the two types of background:

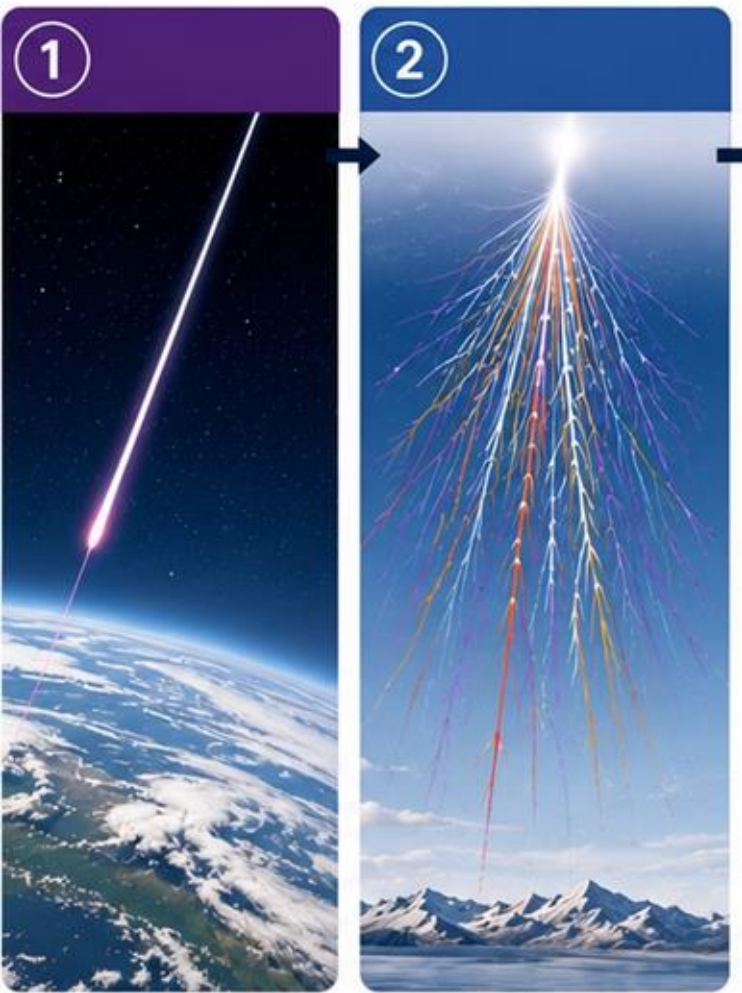
Cosmic ray muons

Cosmic ray neutrinos

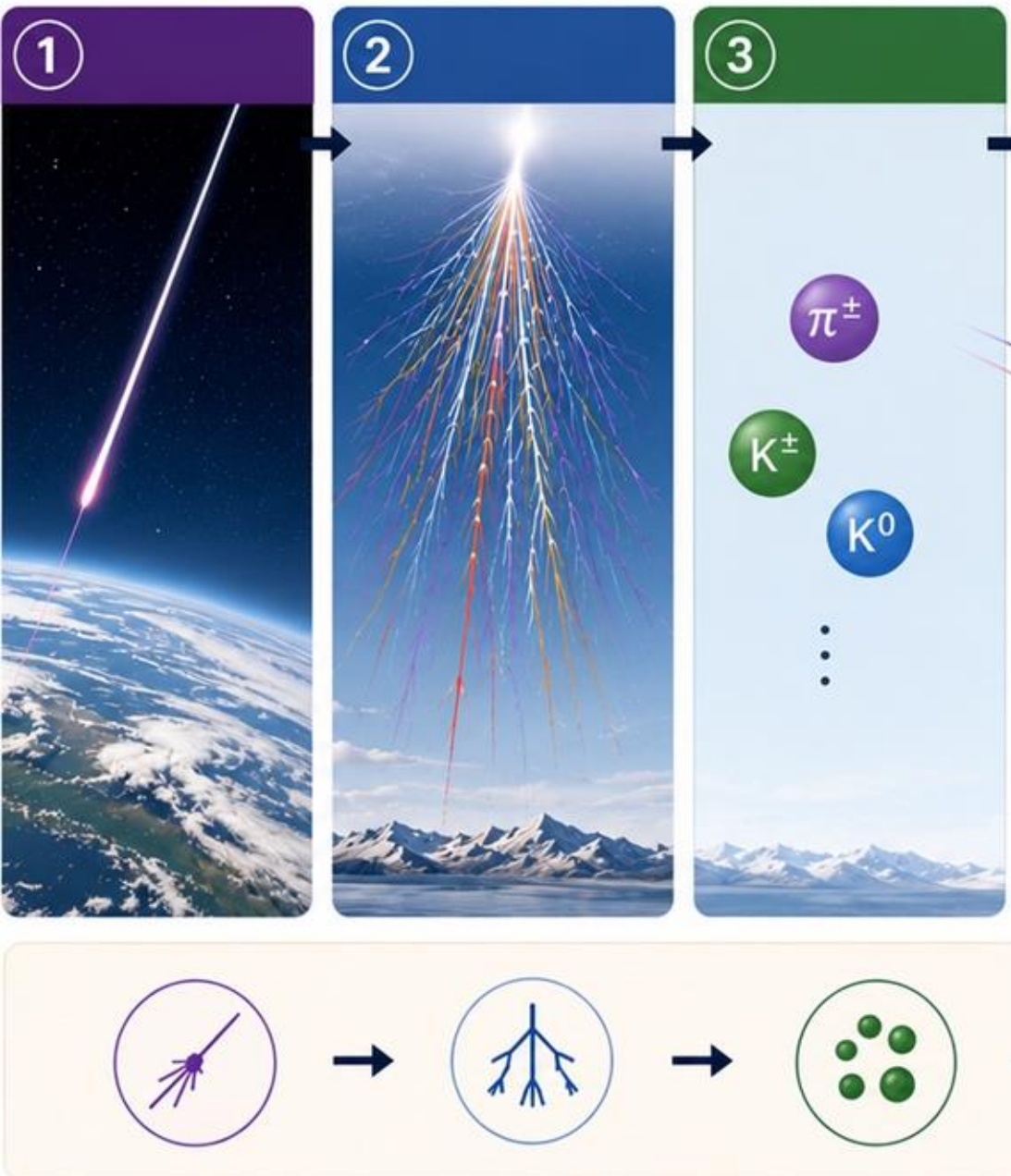
Cosmic Ray (Assuming Some Primary Flux Model)



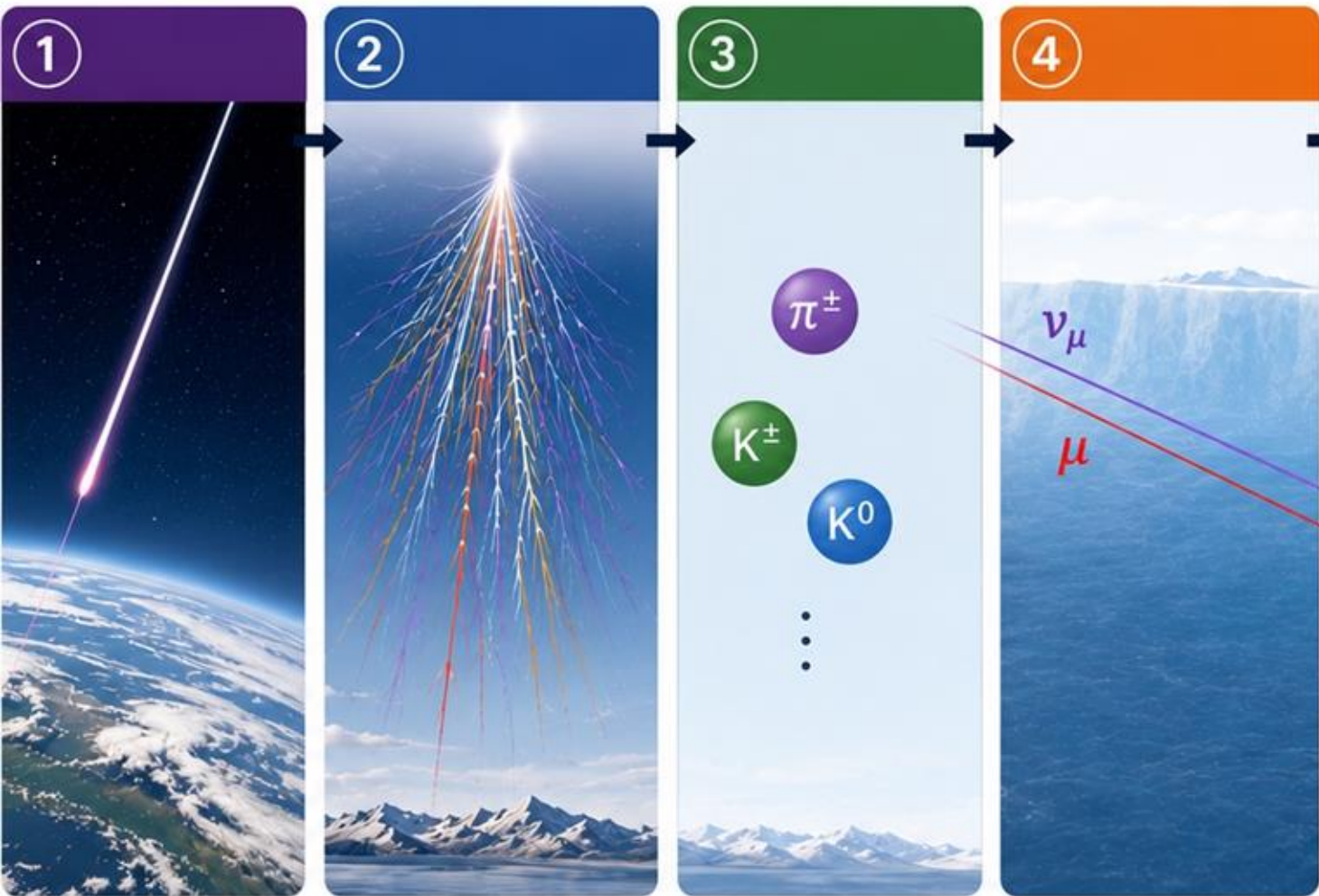
Air shower



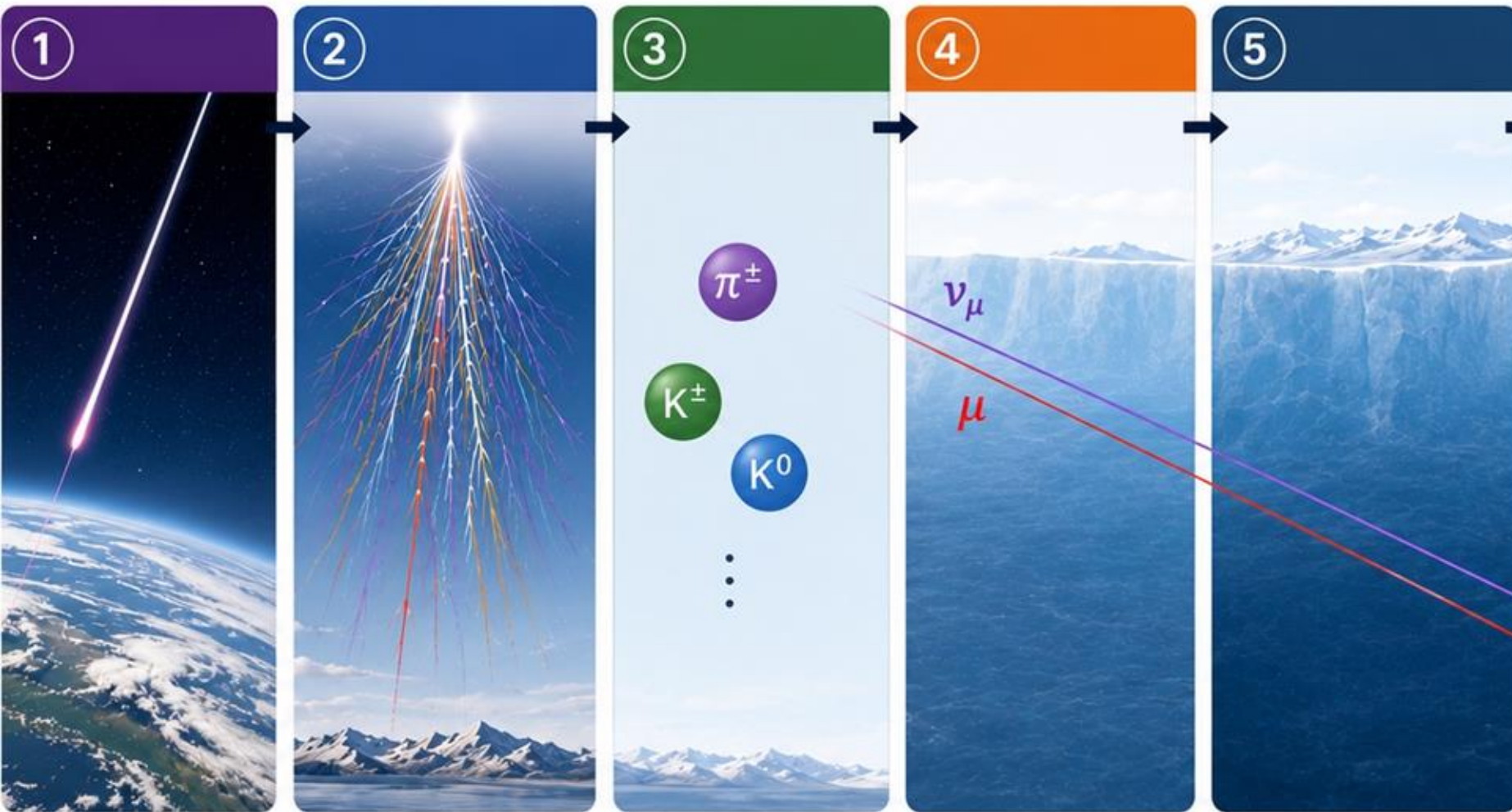
Meson Production (Assuming Some Hadronic Interaction Model)



Atmospheric Neutrinos and Muons



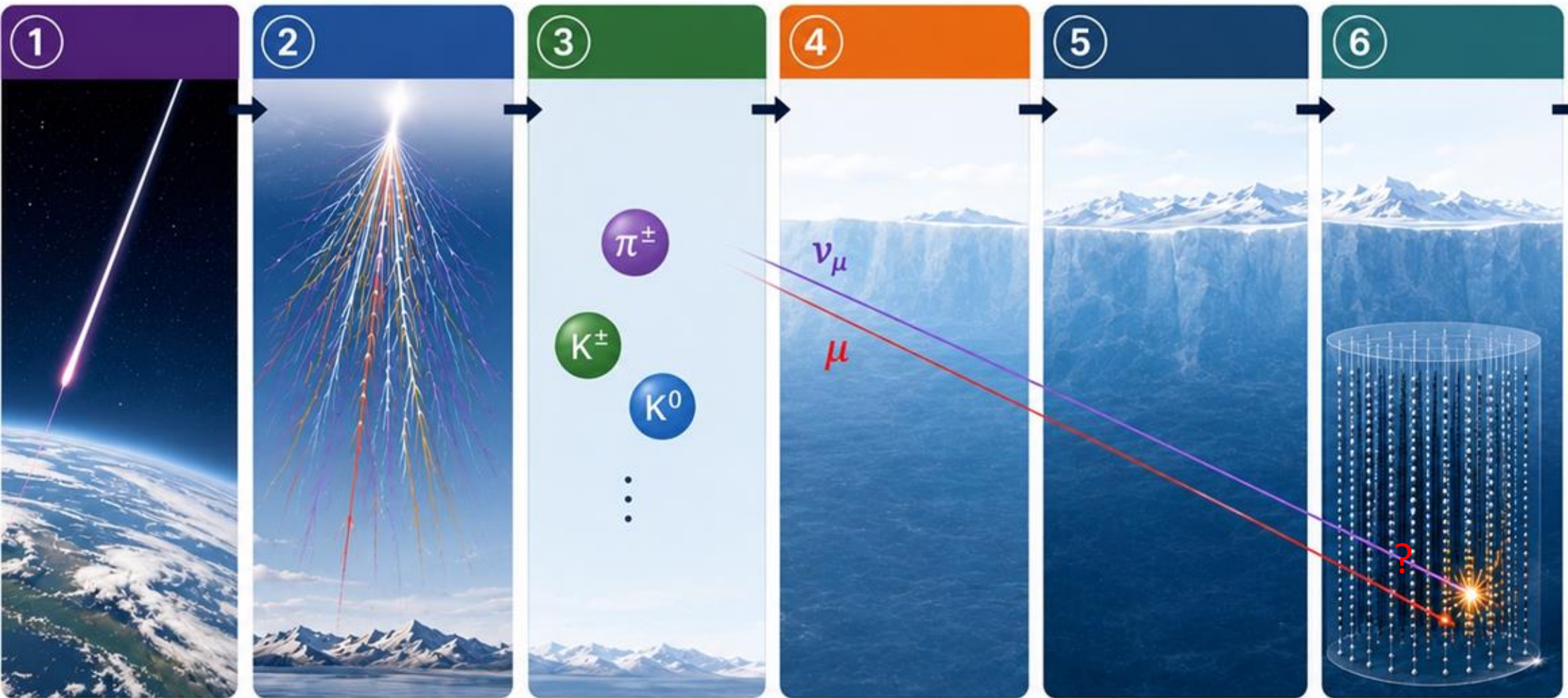
Muon Reaches IceCube detector in the Southern Sky



What probability
for the muon to
reach the
detector?



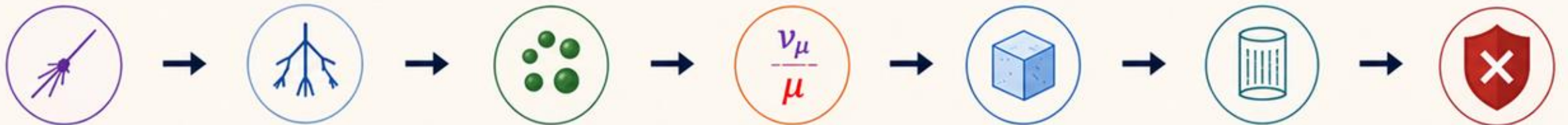
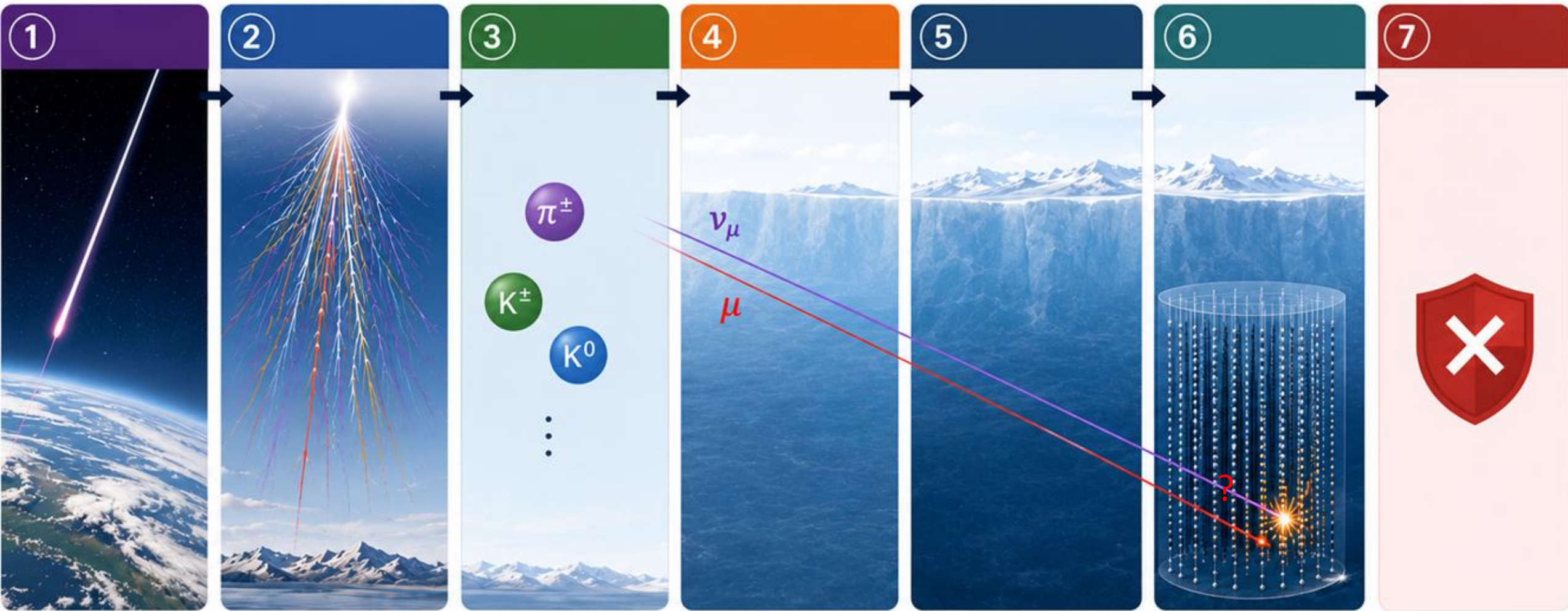
Muon inside the Detector



For the muon to leave detectable light?



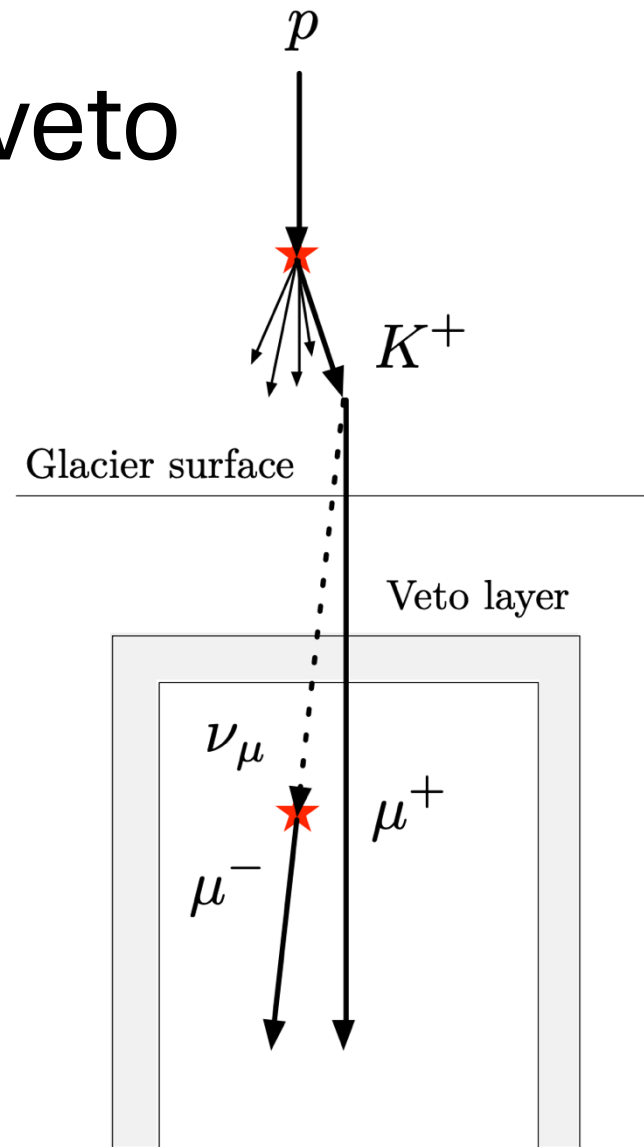
Reject Atmospheric Neutrino due to Muon



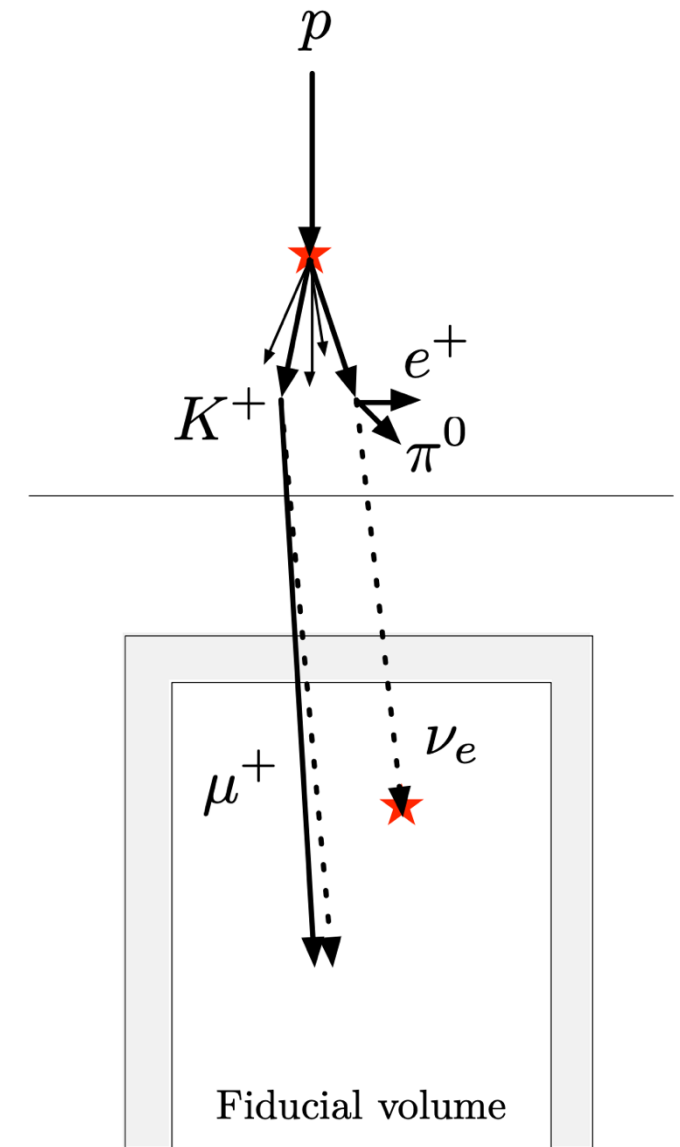
We introduced self-veto

Atmospheric nu are produced in cosmic-ray air showers.

- Up-going
 - Earth absorbs the muons
 - → atmospheric nu remain
- Down-going
 - shower muons can enter the veto layer



Veto by correlated muon

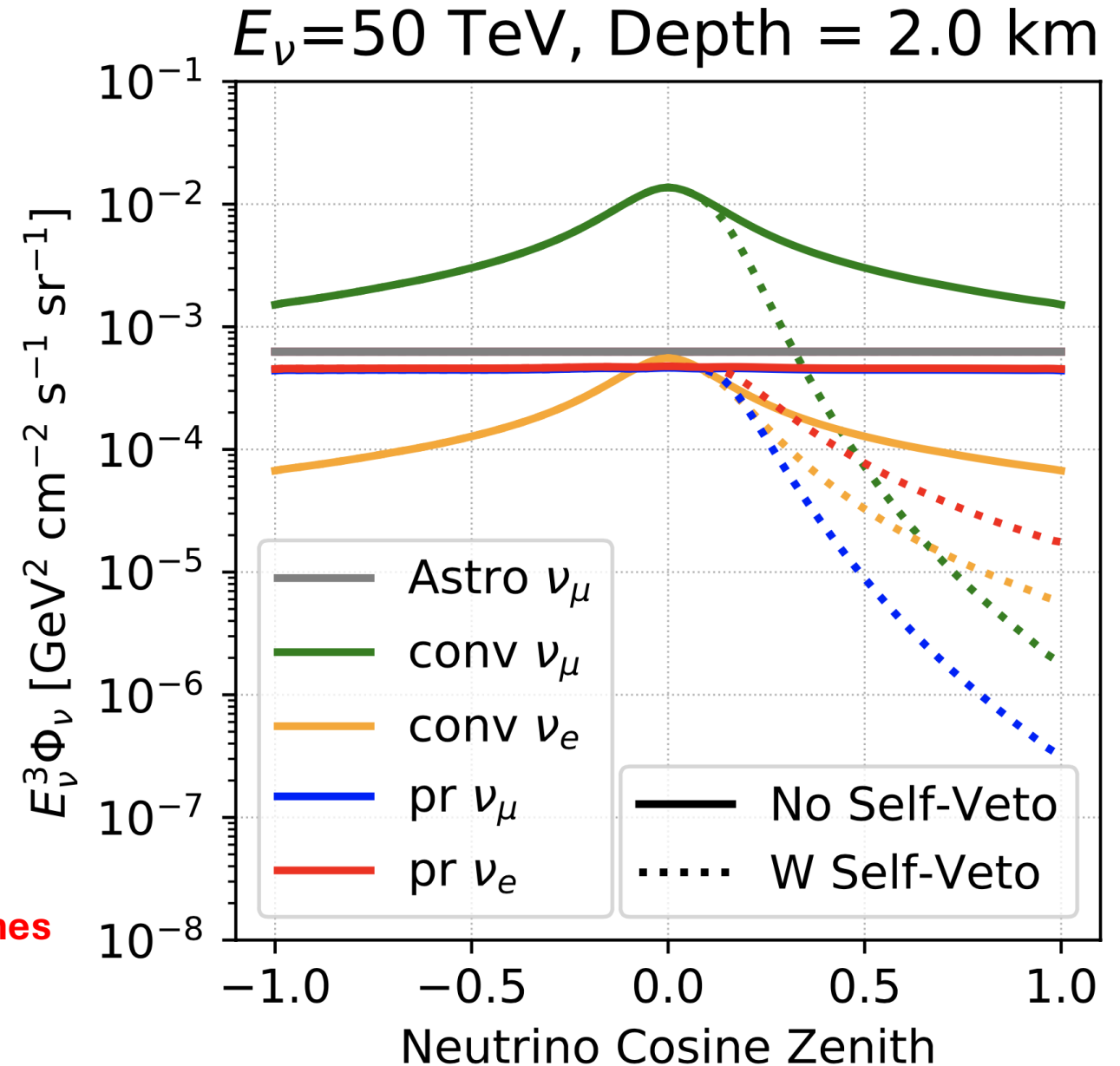


Veto by uncorrelated muon

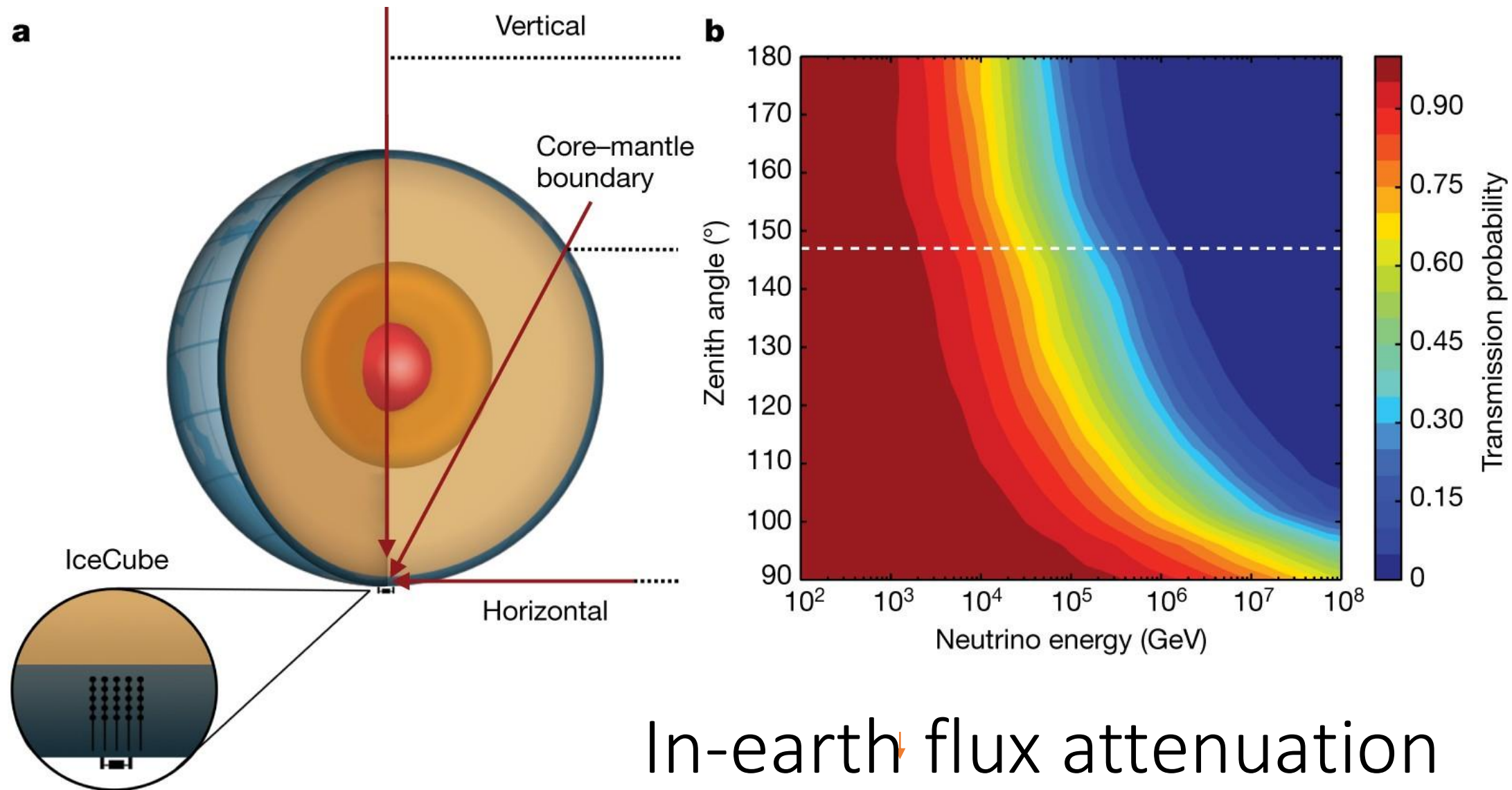
For high-energy starting events, the downgoing region can become **surprisingly astrophysical-rich after veto cuts**, because the veto suppresses both atmospheric muons and downgoing atmospheric neutrinos.

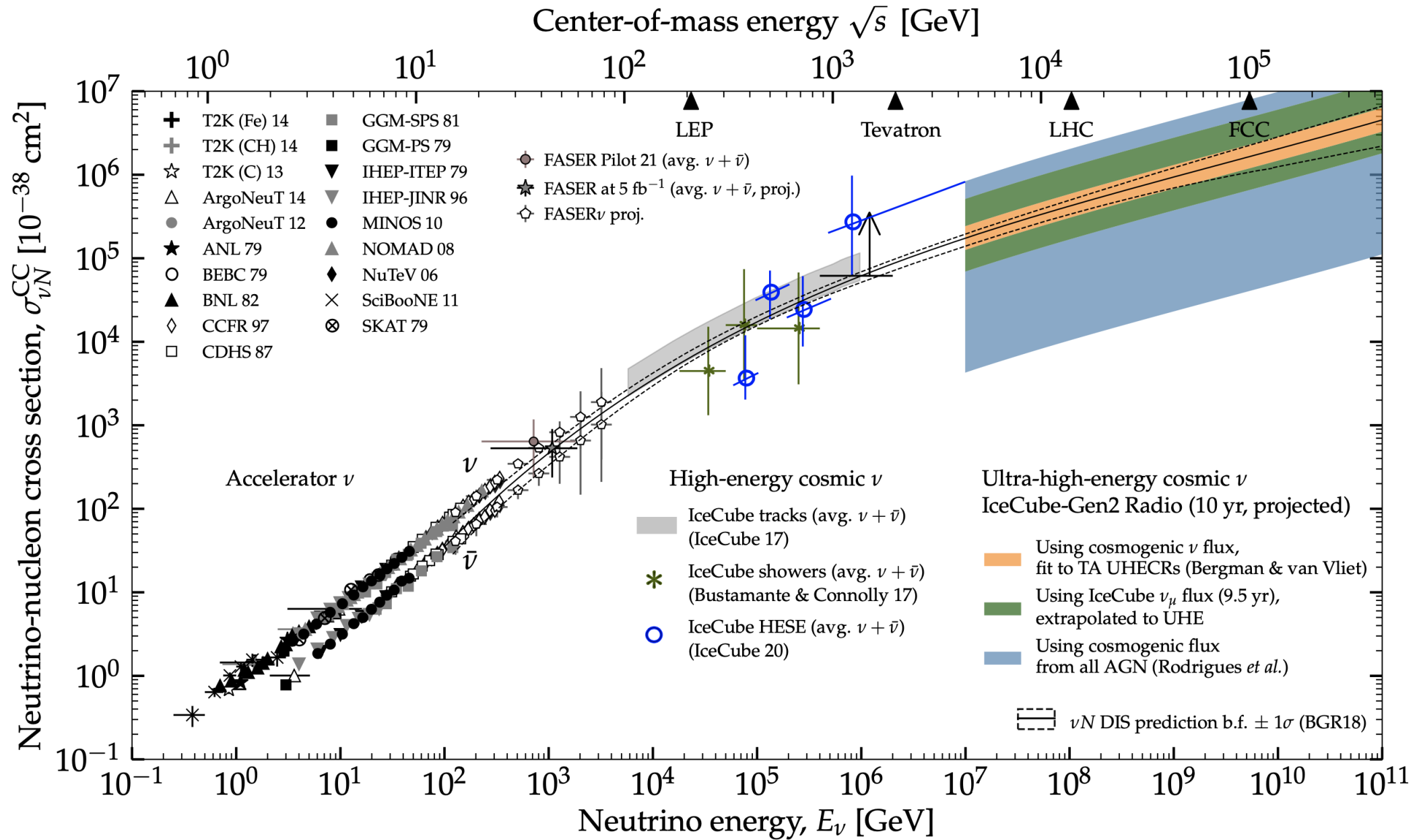
This has direct impacts on neutrino source searches

We will come back to this

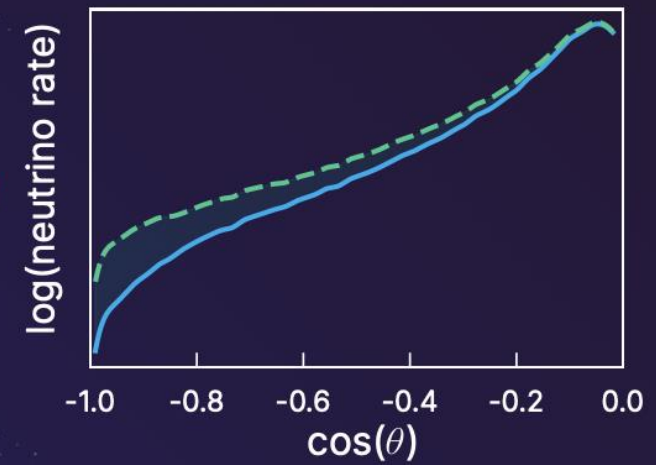
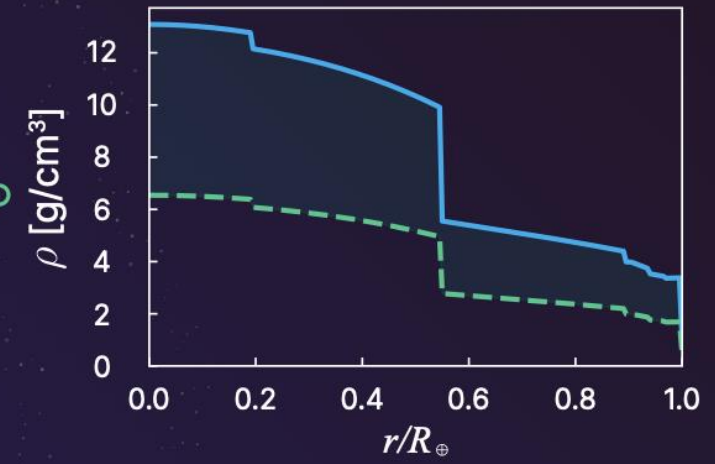
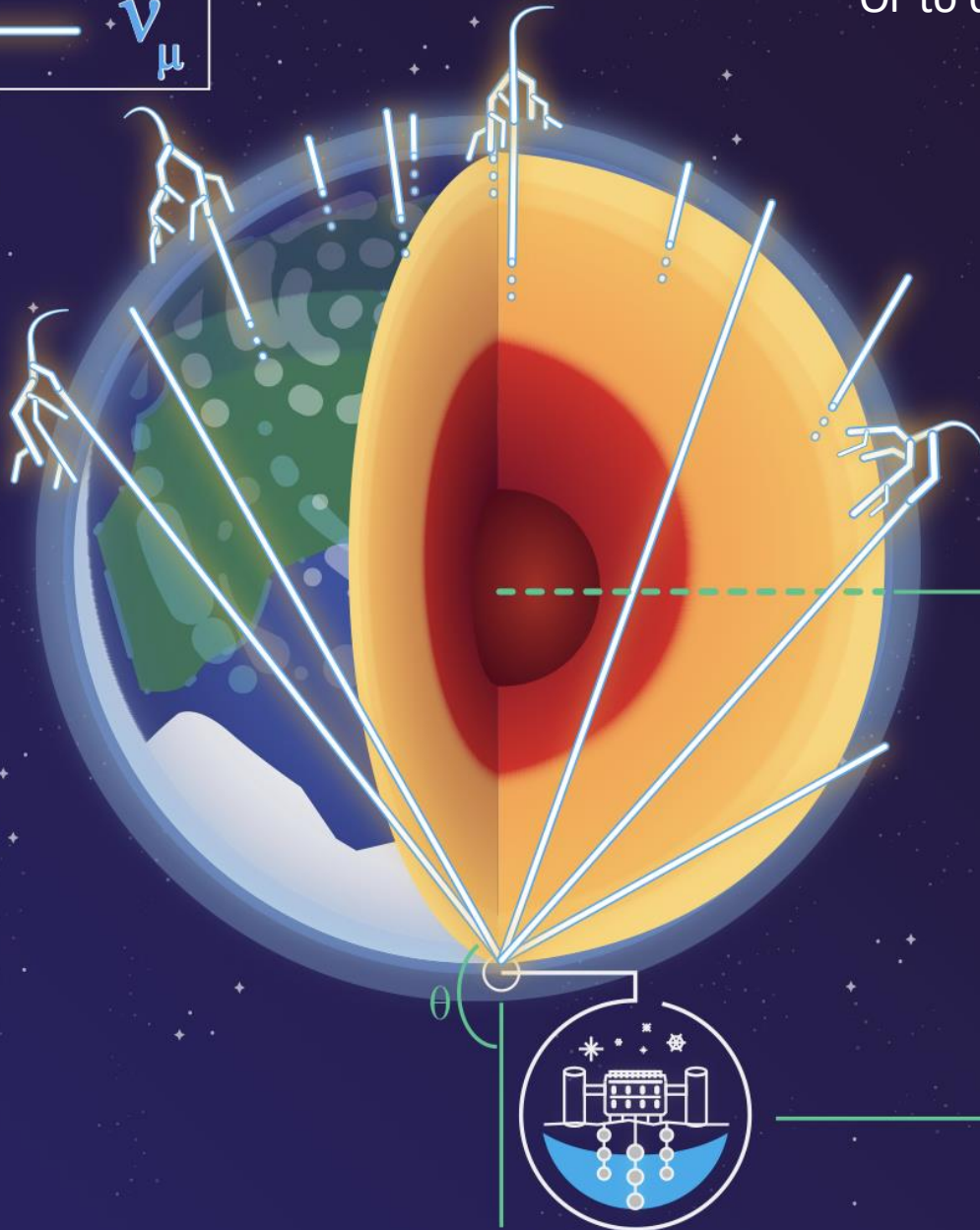


Using zenith angle information can also constrain cross section





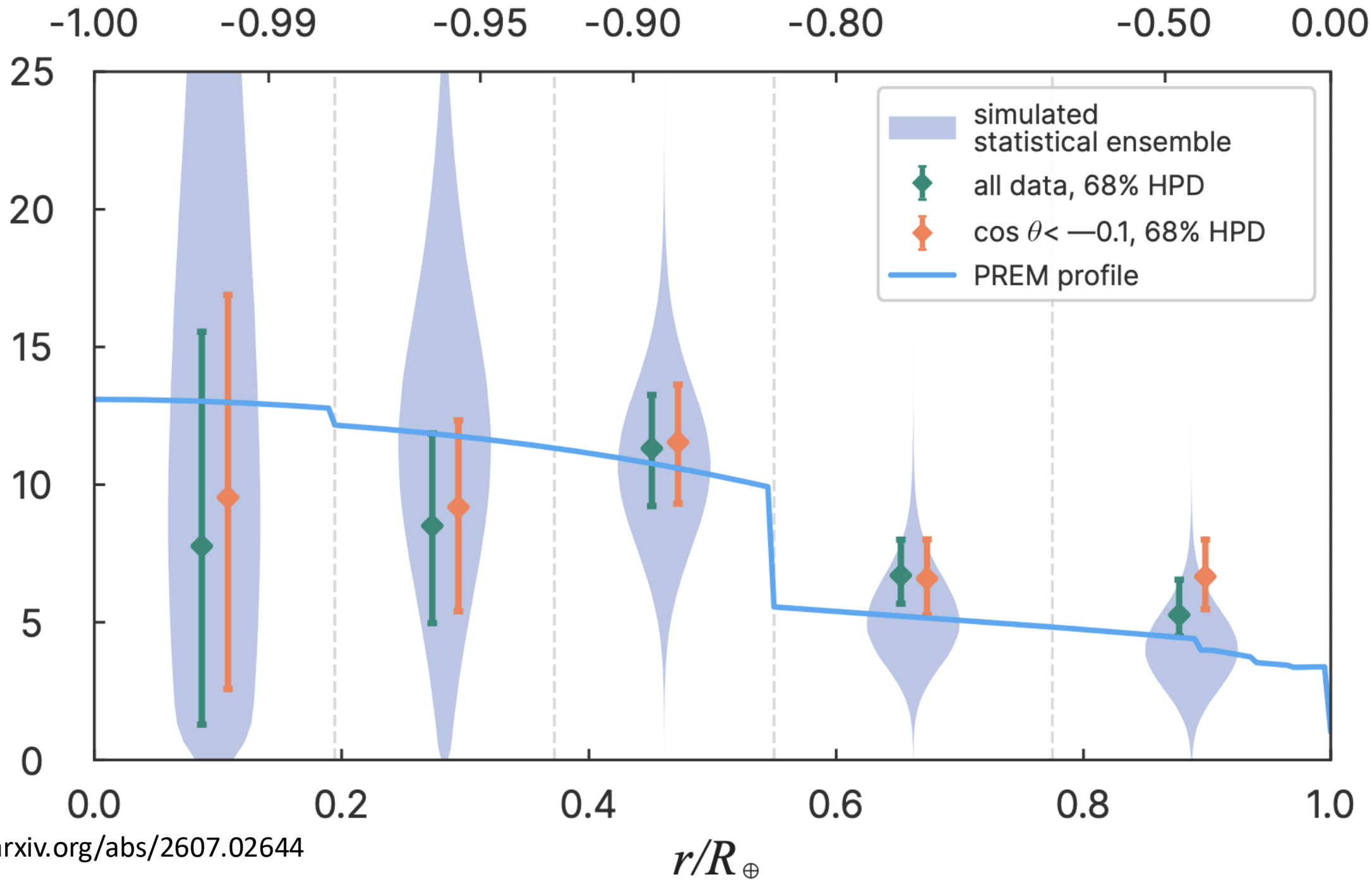
Or to do tomograph of Earth

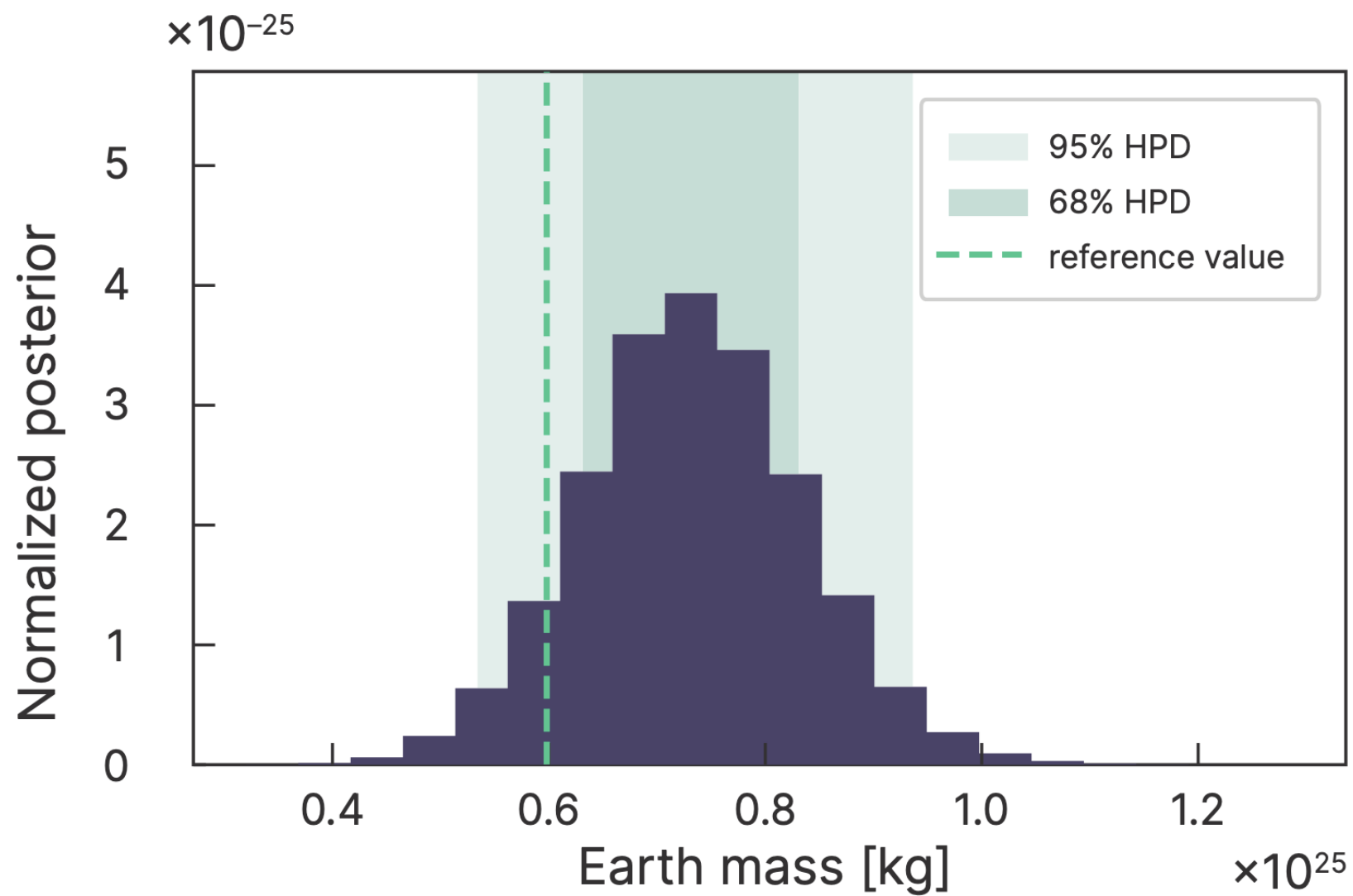


<https://arxiv.org/abs/2607.02644>

IceCube

Density [g/cm^3]

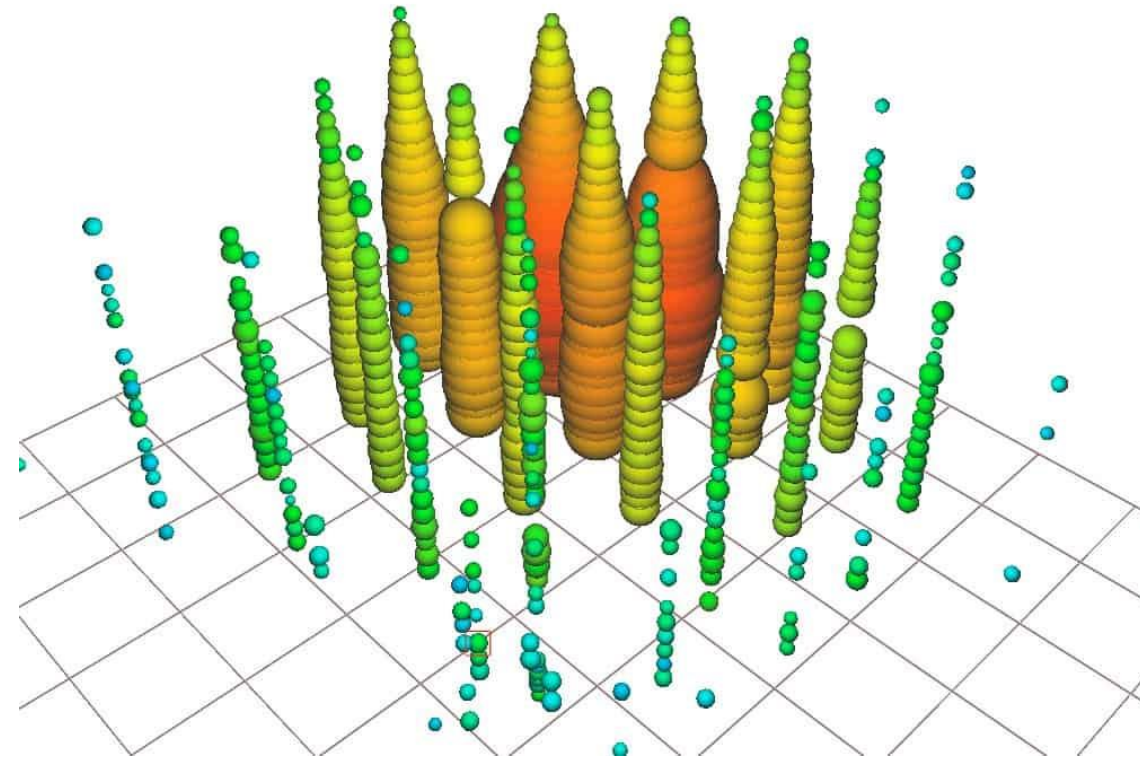
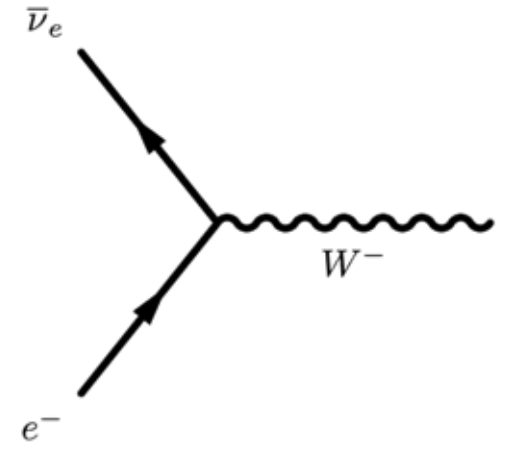
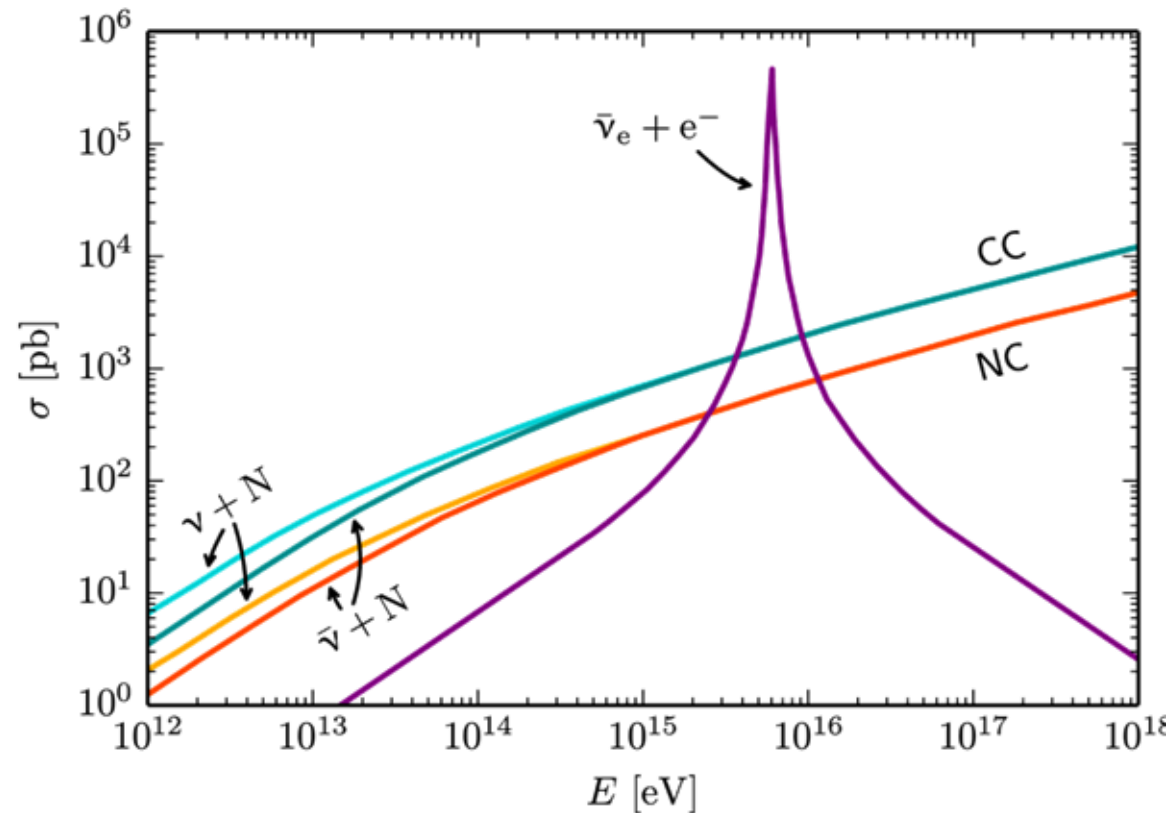




Last lecture, we talked about W boson (Glashow) resonance

Nature 591, 220–224 (2021)

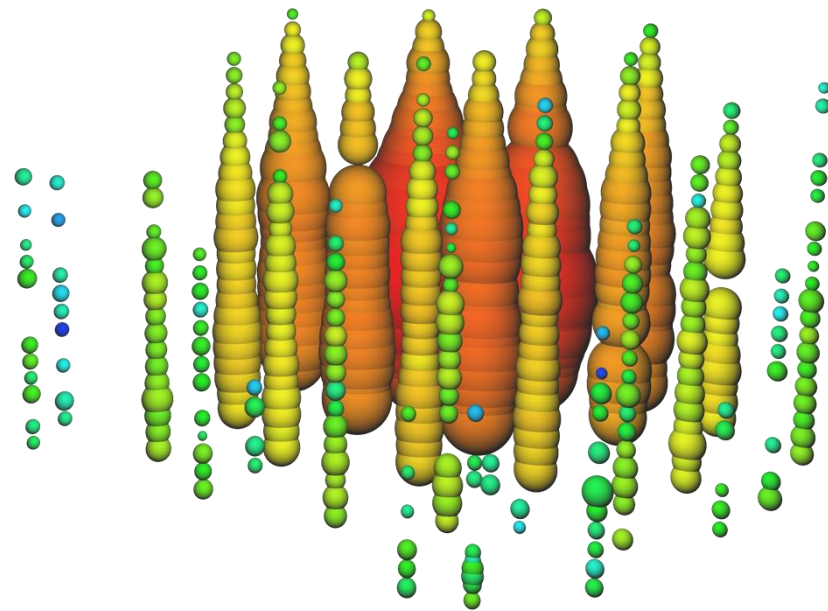
$$s = M_W^2 = 2m_e E_\nu, \quad \text{so } E_R = \frac{M_W^2}{2m_e} = 6.3 \text{ PeV}$$



~ to scale

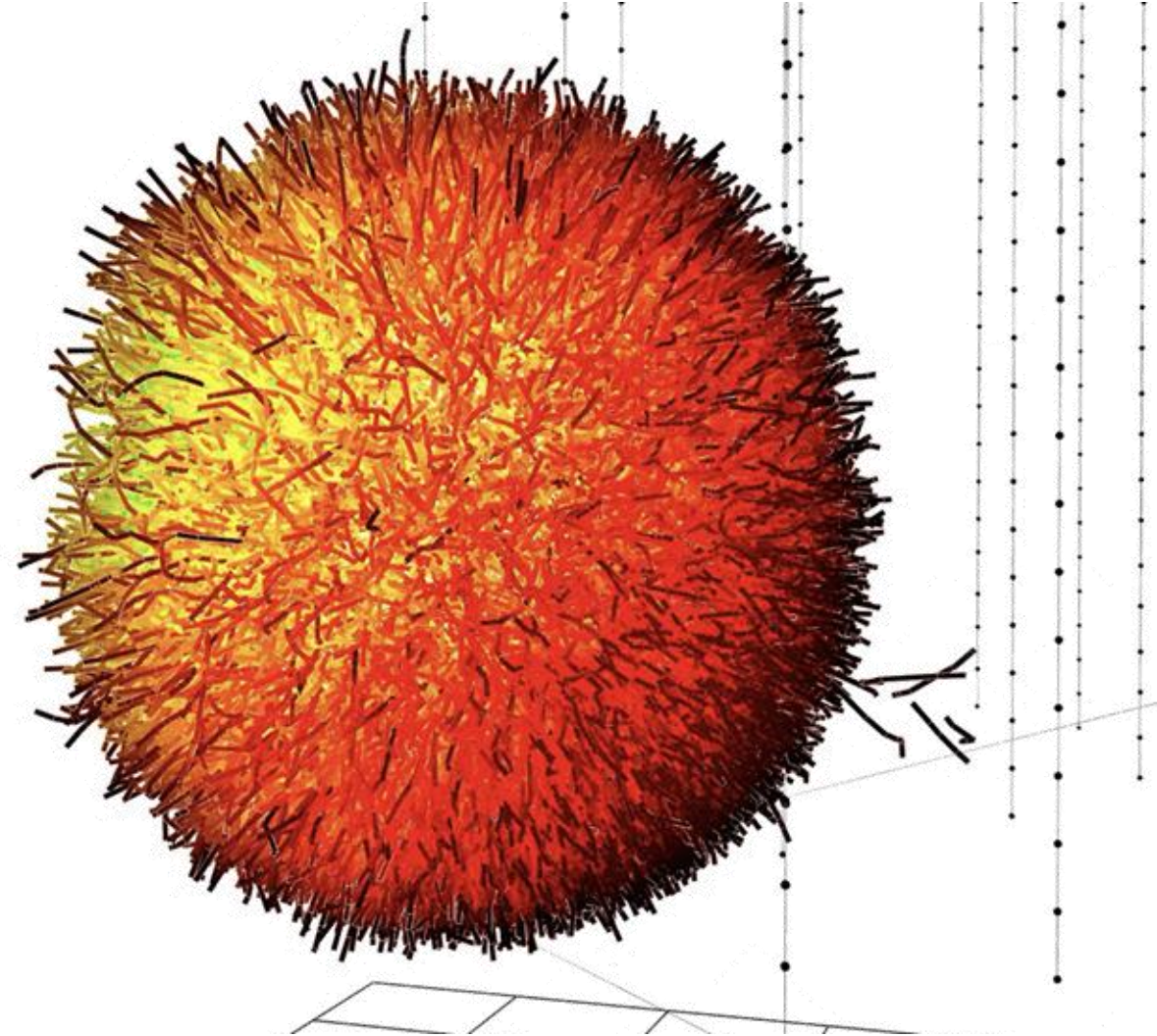
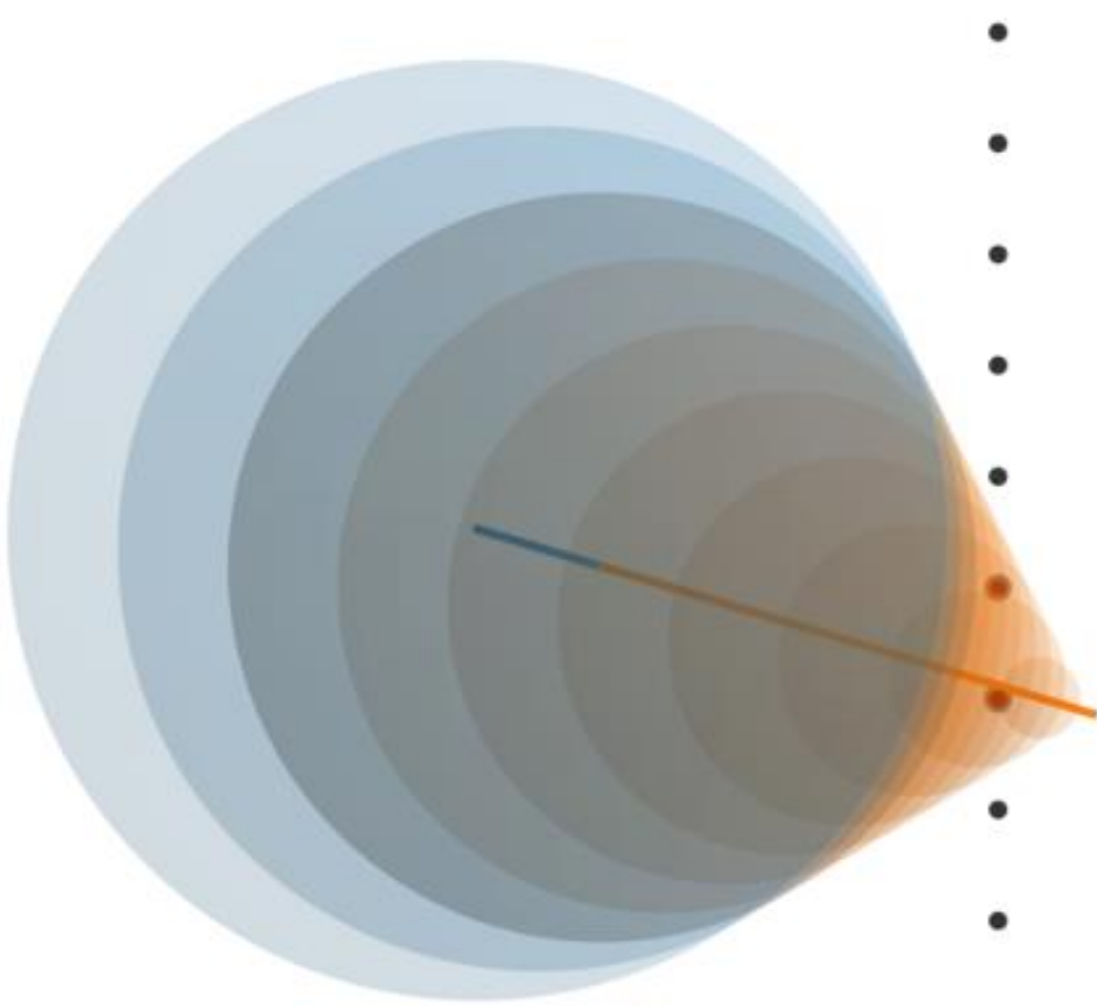


IceCube Lab at surface



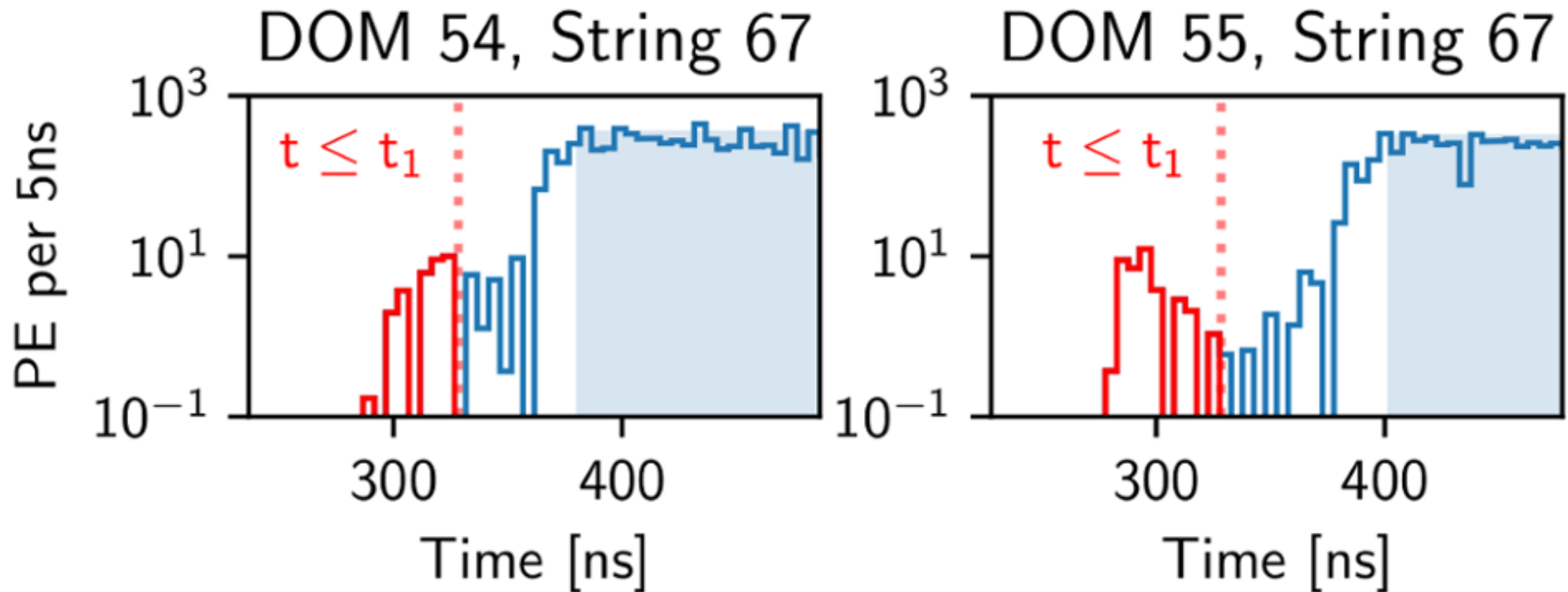


$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow X$$



Early hits from muons in the hadronic shower!

supporting evidence for W-boson to hadrons



Nu/nubar ratio and Astrophysical sources

Idealised p-gamma model

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^+ + n \\ \pi^0 + p \end{cases}$$

will lead, after pion decay

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu, \\ \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \end{aligned}$$

$$p + p \rightarrow \begin{cases} \pi^+ + \text{anything} & 1/3 \text{ of all cases} \\ \pi^- + \text{anything} & 1/3 \text{ of all cases} \\ \pi^0 + \text{anything} & 1/3 \text{ of all cases} \end{cases}$$

TABLE I: Neutrino flavor ratios at source, component of $\bar{\nu}_e$ in total neutrino flux at Earth after mixing and decohering, and consequent relative strength of Glashow resonance, for six astrophysical models. (Neutrinos and antineutrinos are shown separately, when they differ.)

	Source flavor ratio		Earthly flavor ratio		$\bar{\nu}_e$ fraction in flux ($\mathcal{R}$)
$pp \rightarrow \pi^\pm$ pairs	(1:2:0)		(1:1:1)		18/108 = 0.17
w/ damped $\mu^\pm$	(0:1:0)		(4:7:7)		12/108 = 0.11
$p\gamma \rightarrow \pi^+$ only	(1:1:0)	(0:1:0)	(14:11:11)	(4:7:7)	8/108 = 0.074
w/ damped μ^+	(0:1:0)	(0:0:0)	(4:7:7)	(0:0:0)	0
charm decay $D, \Lambda c \rightarrow \ell + \nu \ell + X$	(1:1:0)		(14:11:11)		21/108 = 0.19
neutron decay $n \rightarrow p e^- \bar{\nu}_e$	(0:0:0)	(1:0:0)	(0:0:0)	(5:2:2)	60/108 = 0.56

Z boson resonance?

$$E \approx m_\phi^2 / (2m_\nu)$$

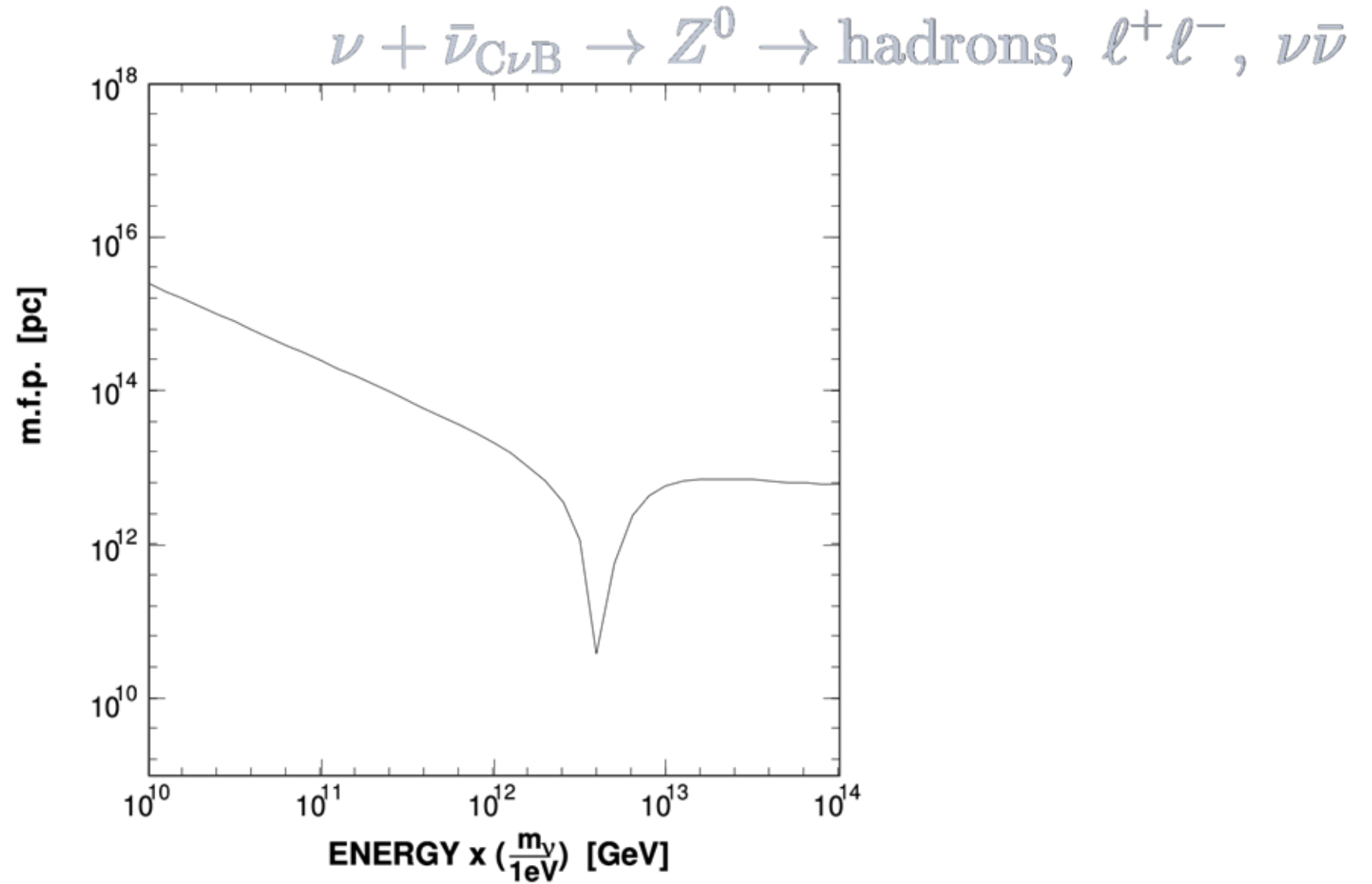
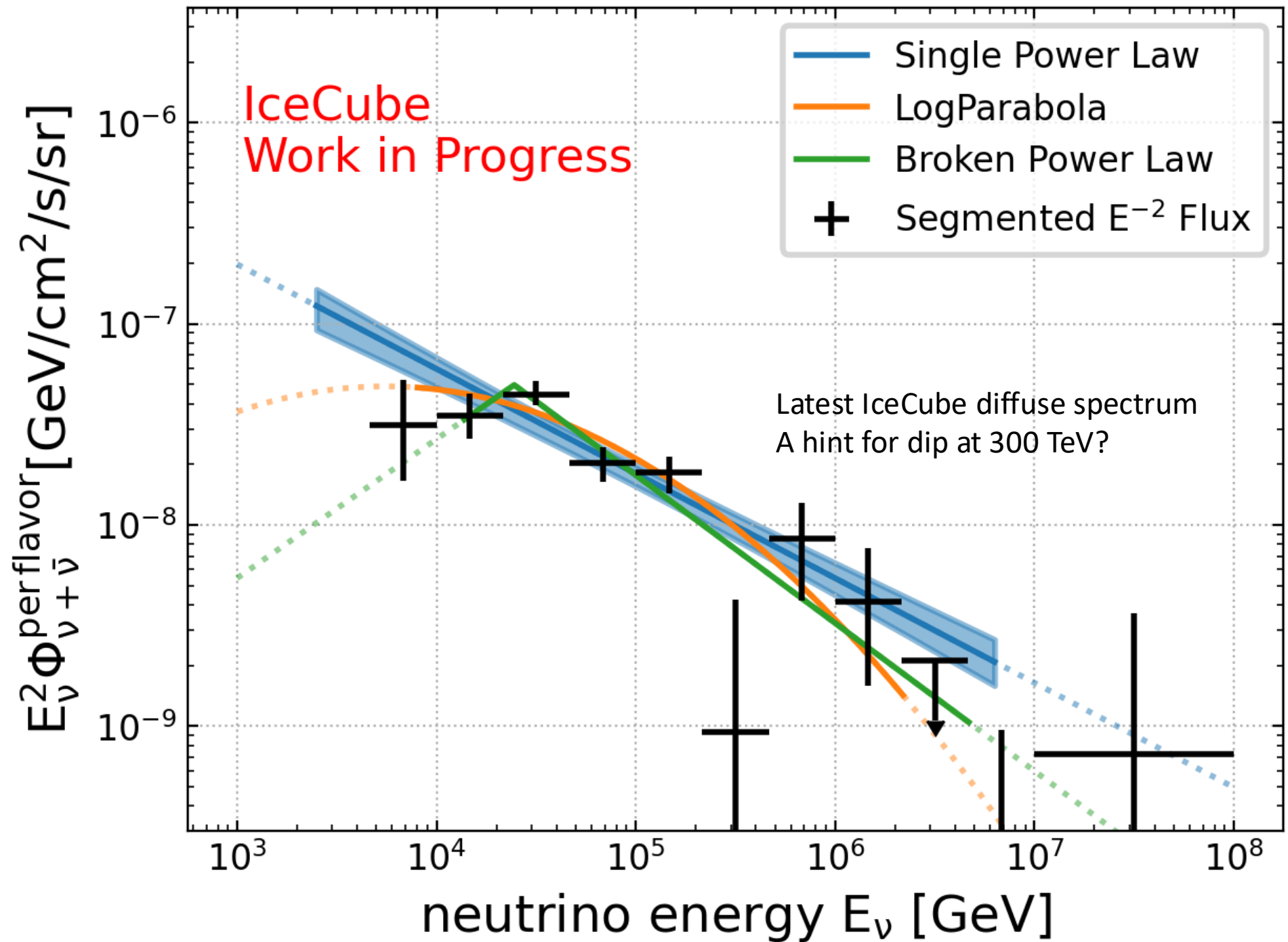
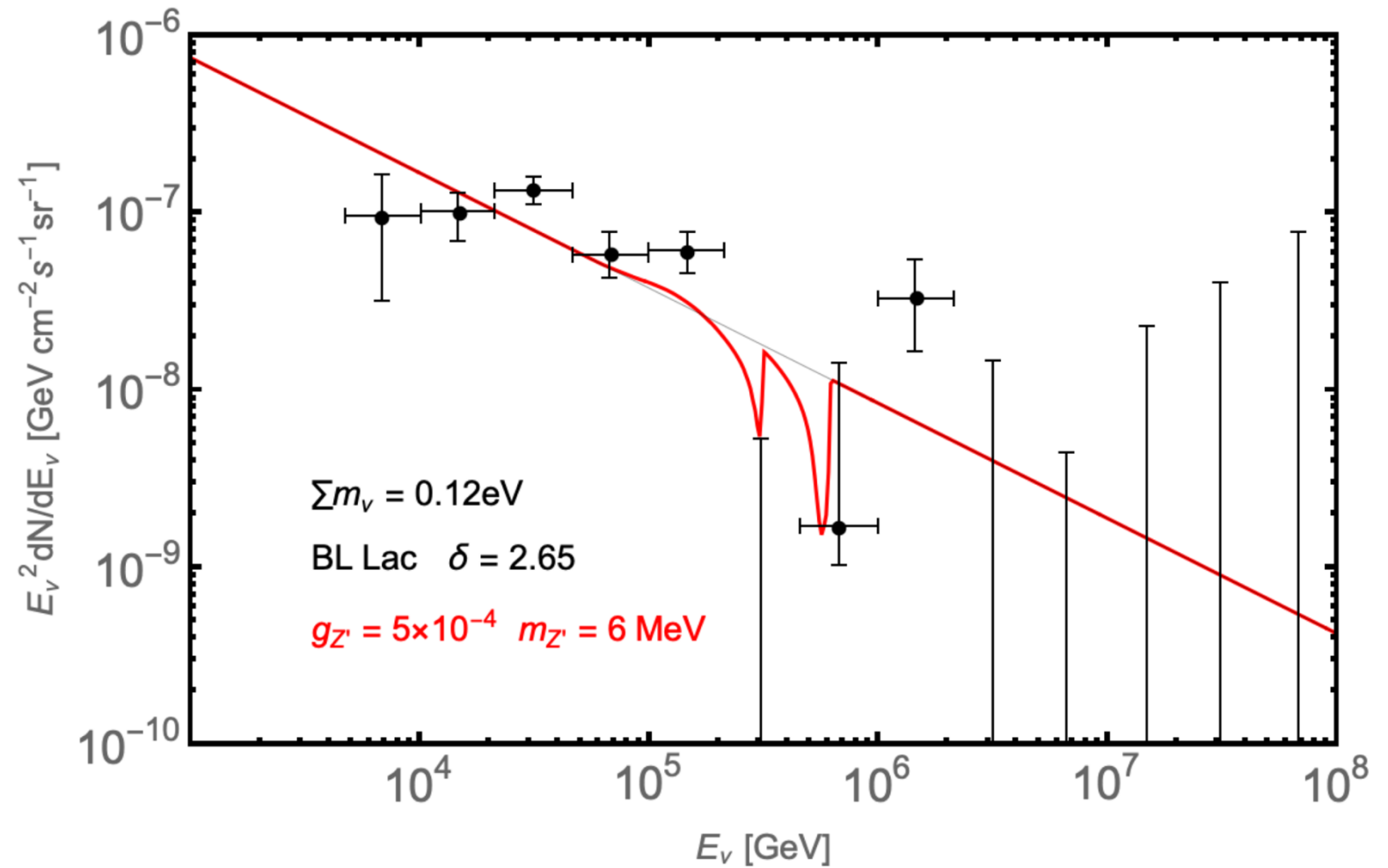
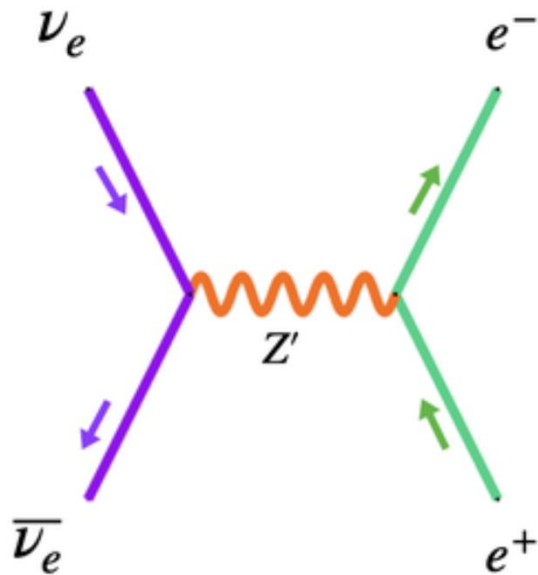


Figure 8. Mean free path of UHE neutrinos in C ν B field. Only the SM neutrino-neutrino interactions are involved. The sharp resonance structure appears due to the interactions via s-channel of Z^0 boson. The possible BSM interactions involving neutrinophilic mediator are expected to form a similar structure at $E_\nu \gtrsim 10^6$ GeV range, which would distort spectral shape of neutrinos. Figure reproduced from Ref. [278].

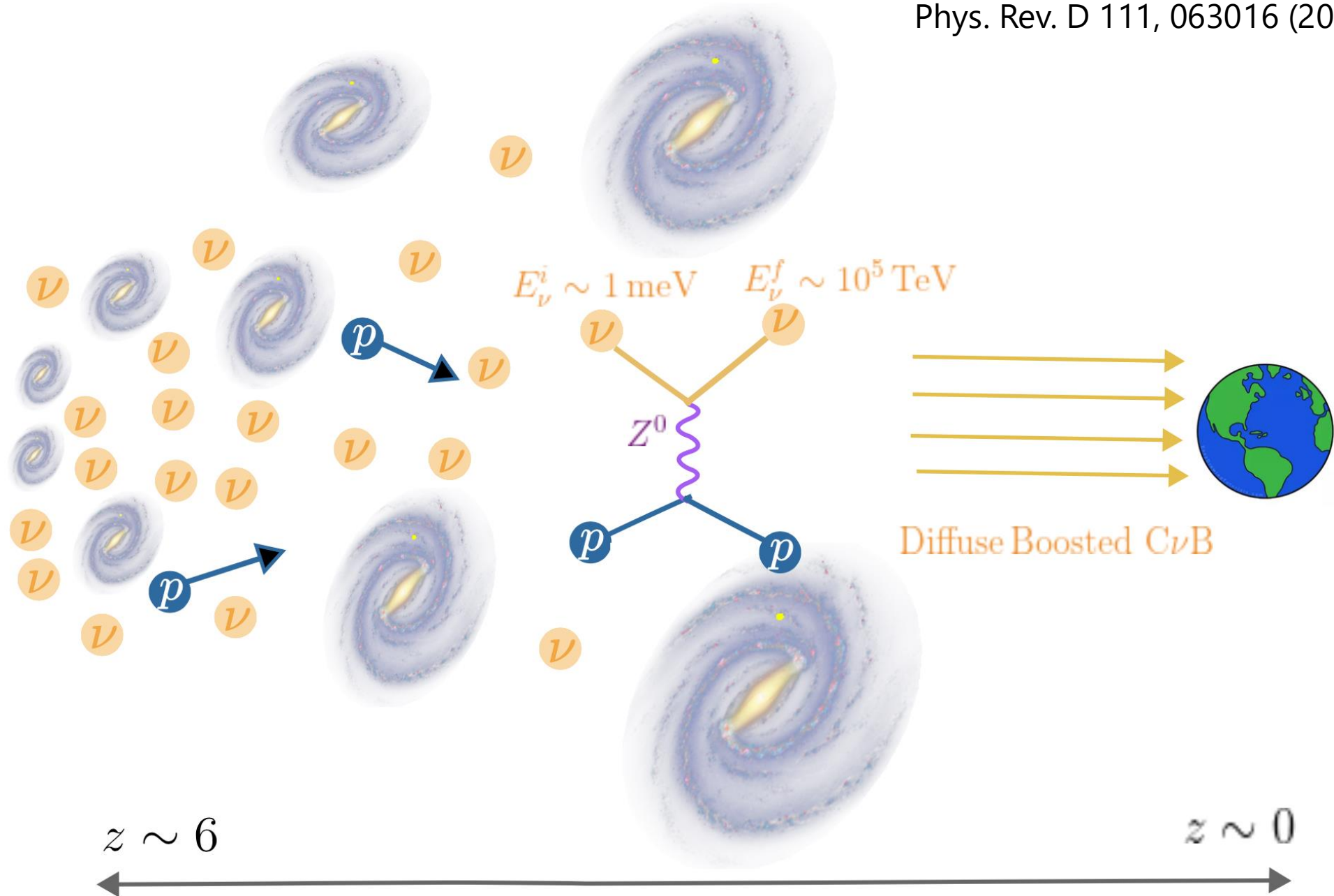


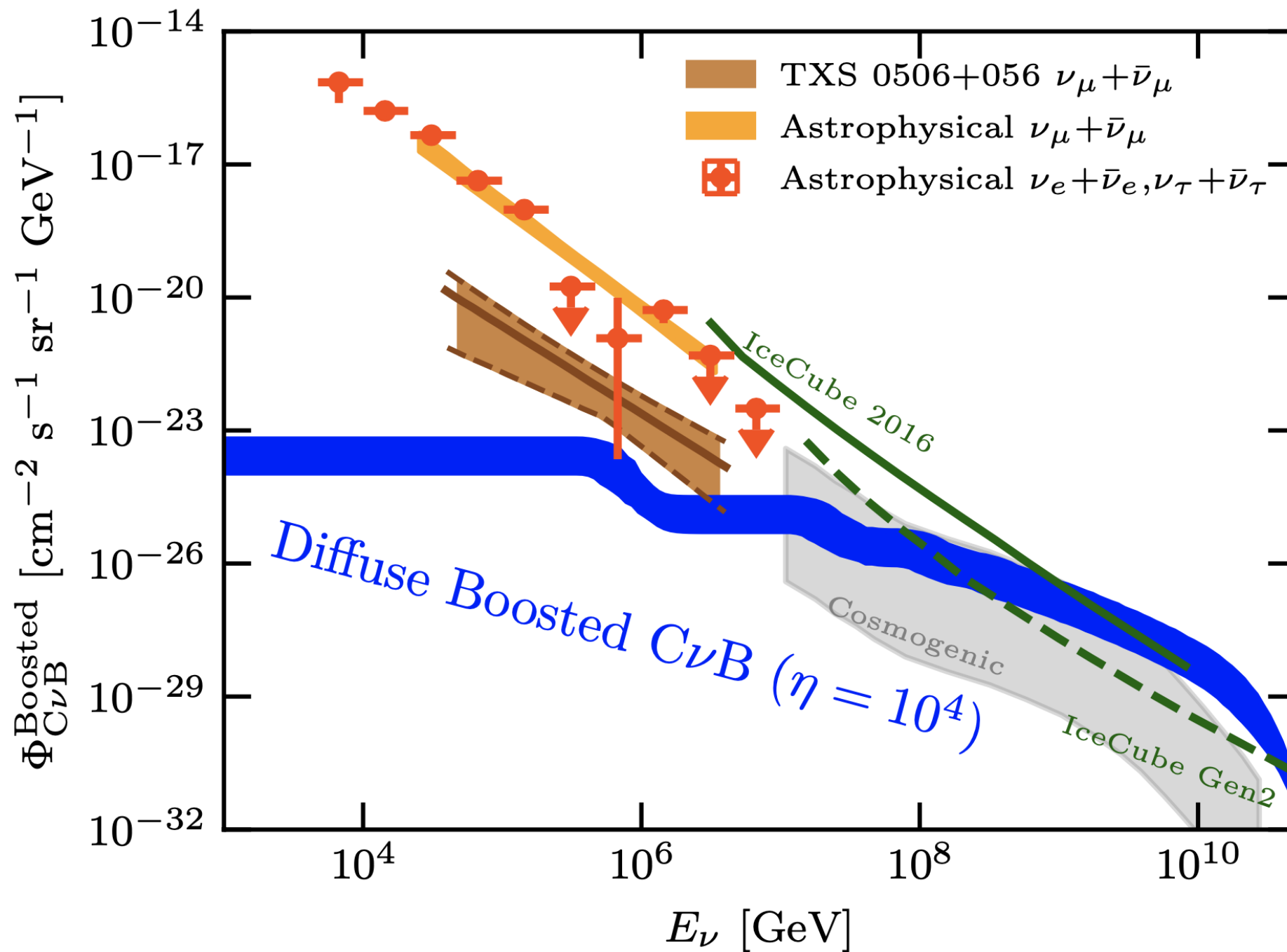
Z' resonance?

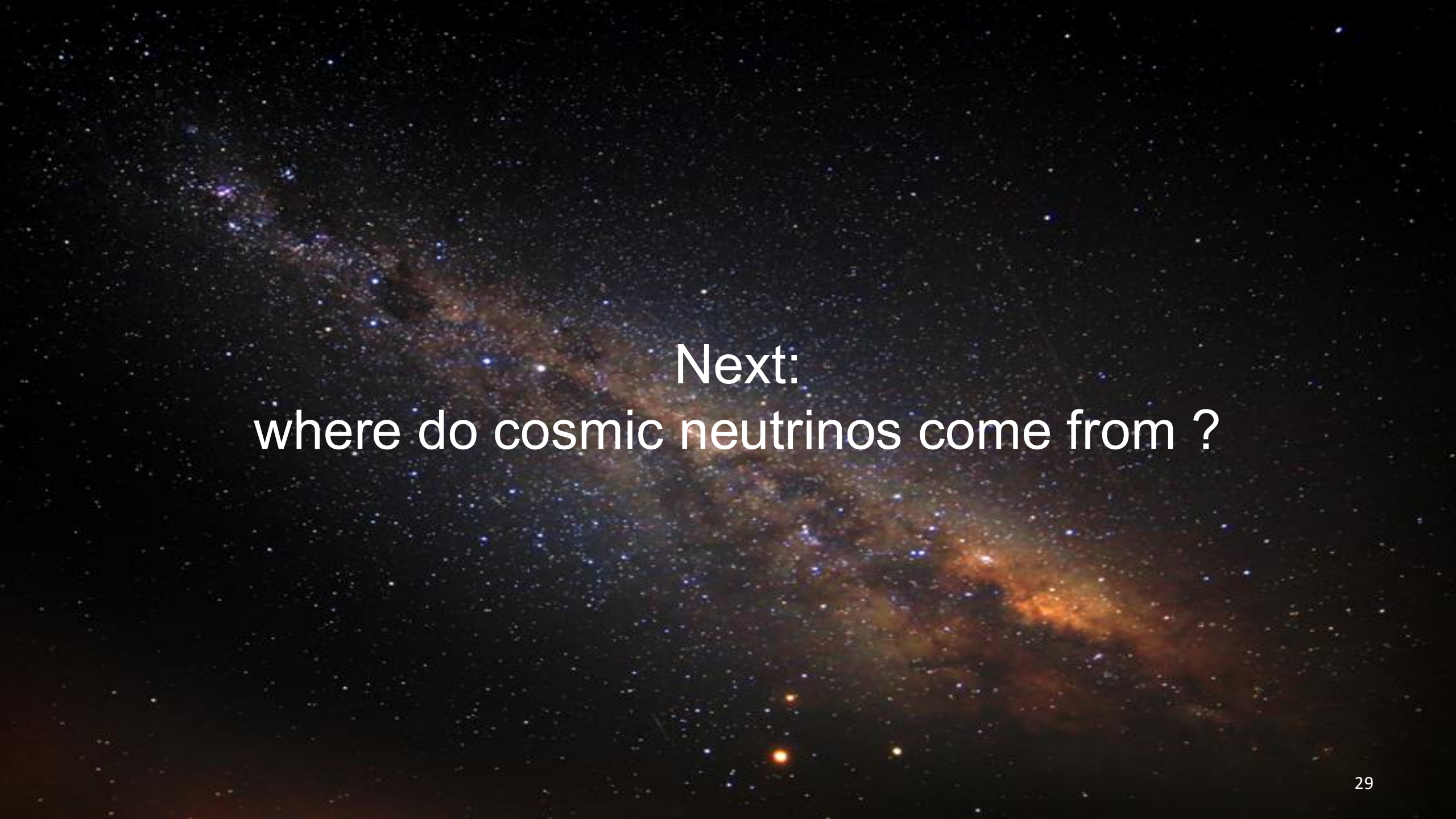
- $m_{Z'} \sim 10$ MeV



<https://arxiv.org/pdf/2302.03571>

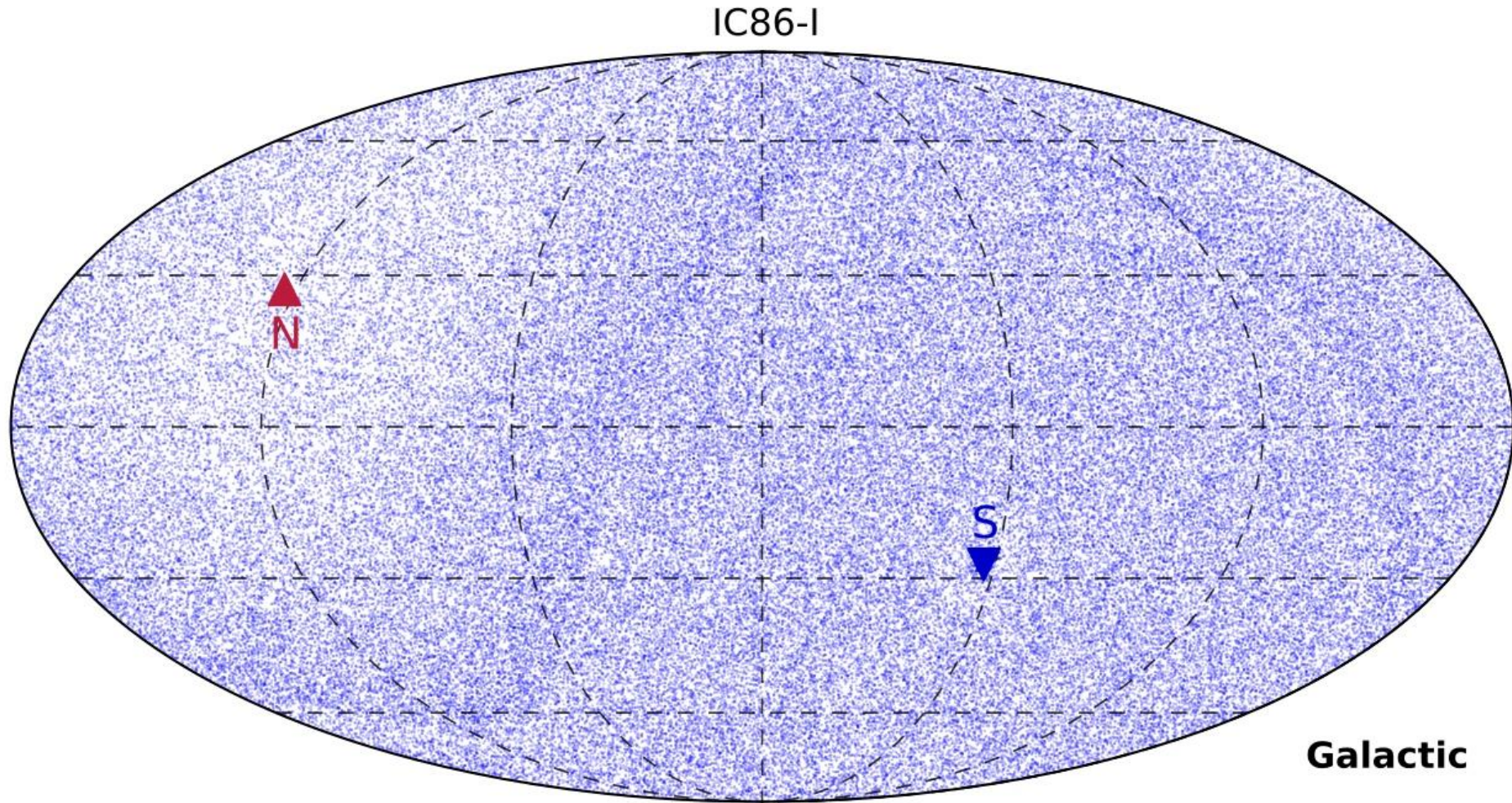






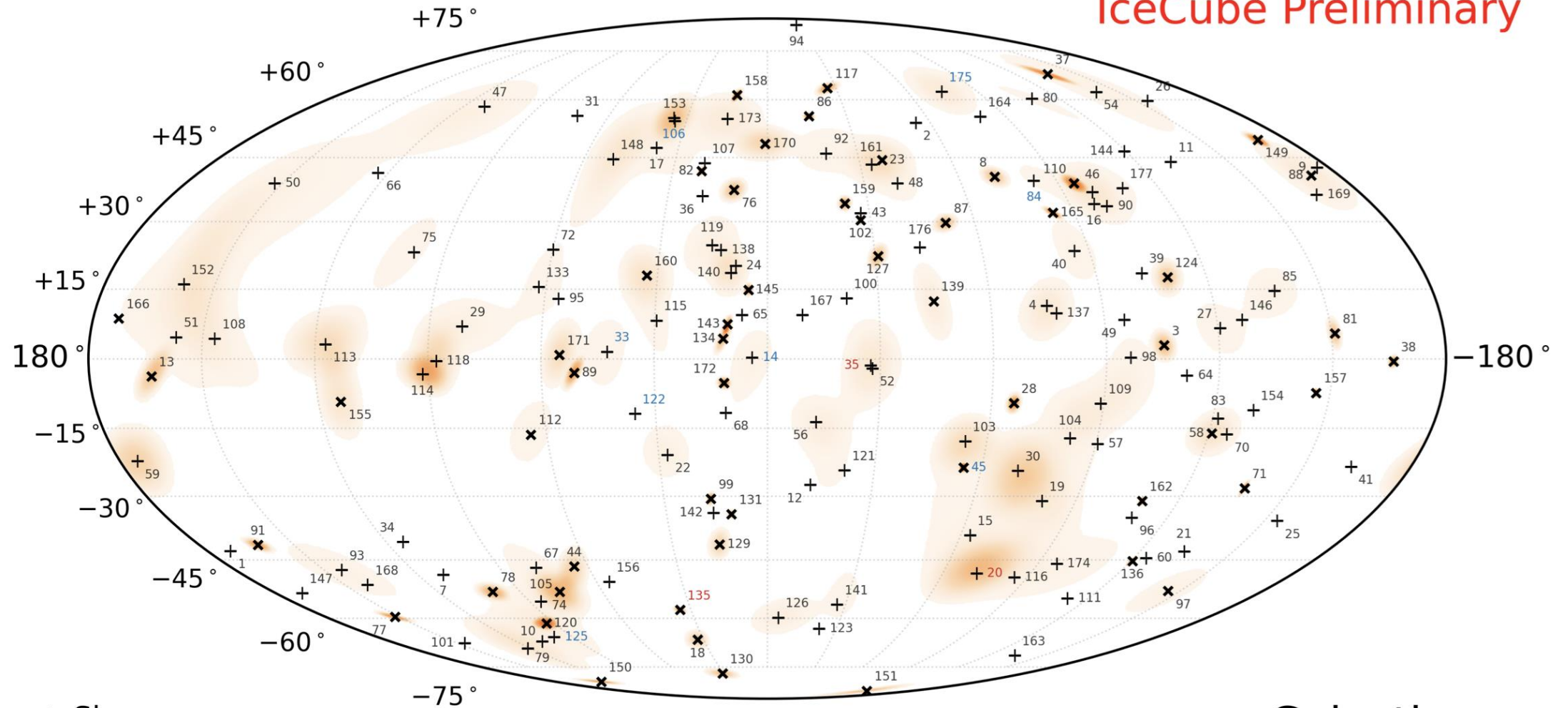
Next:
where do cosmic neutrinos come from ?

Reminder:



138322 neutrino candidates in one year
>120 cosmic neutrinos (depending on the spectrum)
~12 separated from atmospheric background with $E > 60$ TeV

IceCube Preliminary



+ Shower
x Track

Galactic

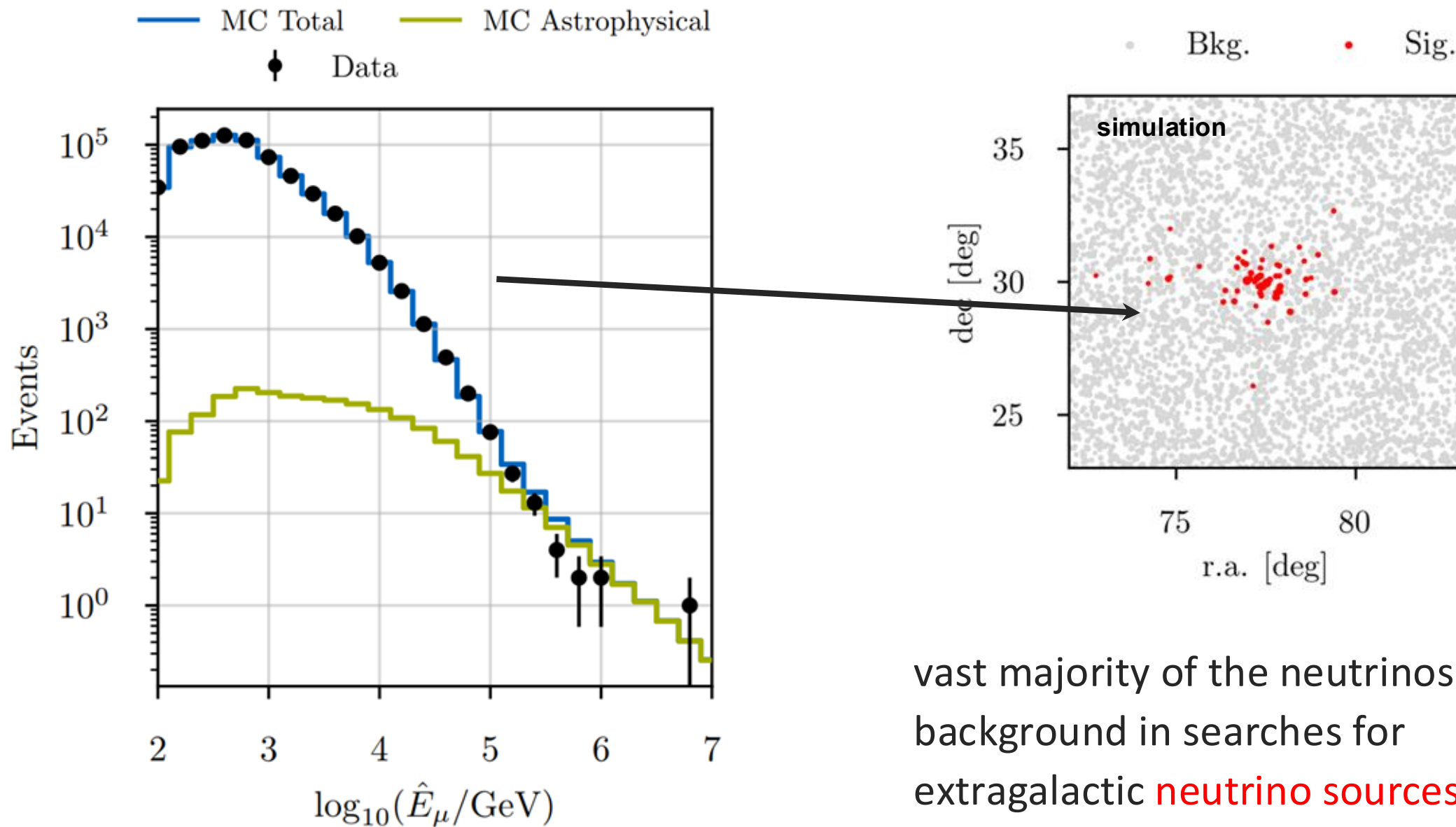
PoS-ICRC2023-1030

$E < 300 \text{ TeV}$

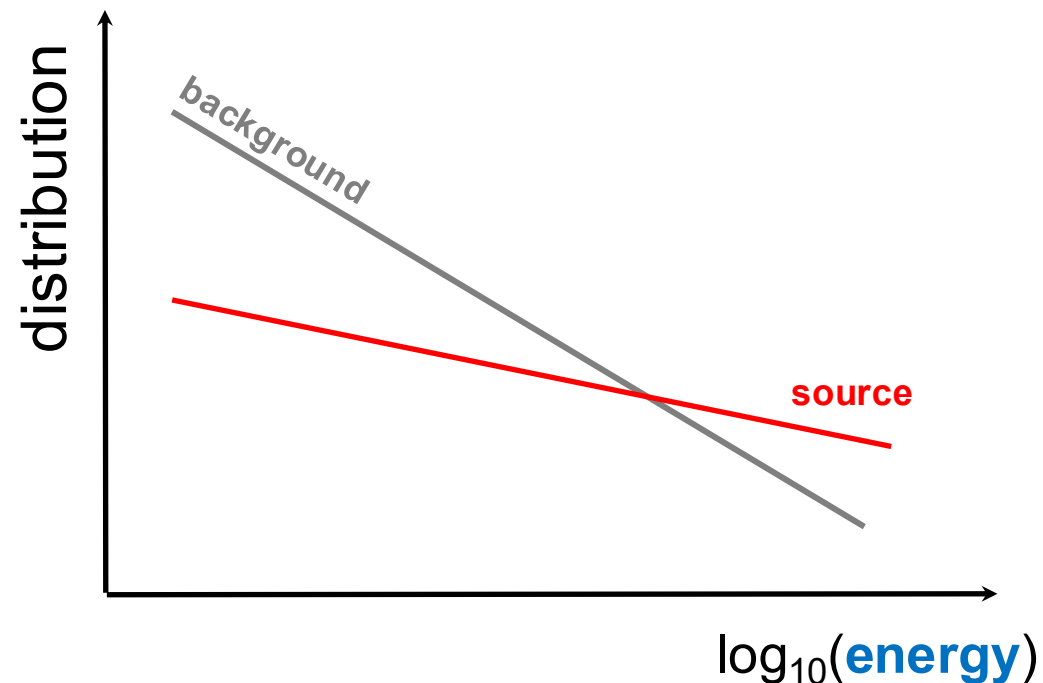
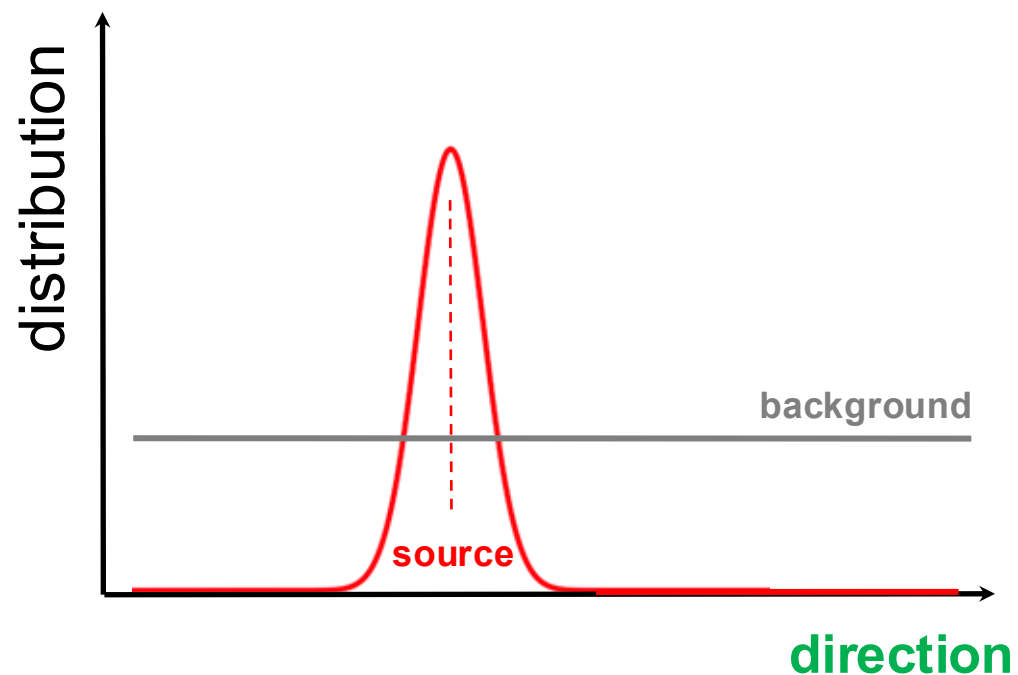
$300 \text{ TeV} < E < 1 \text{ PeV}$

$1 \text{ PeV} < E$

Searching for neutrino sources

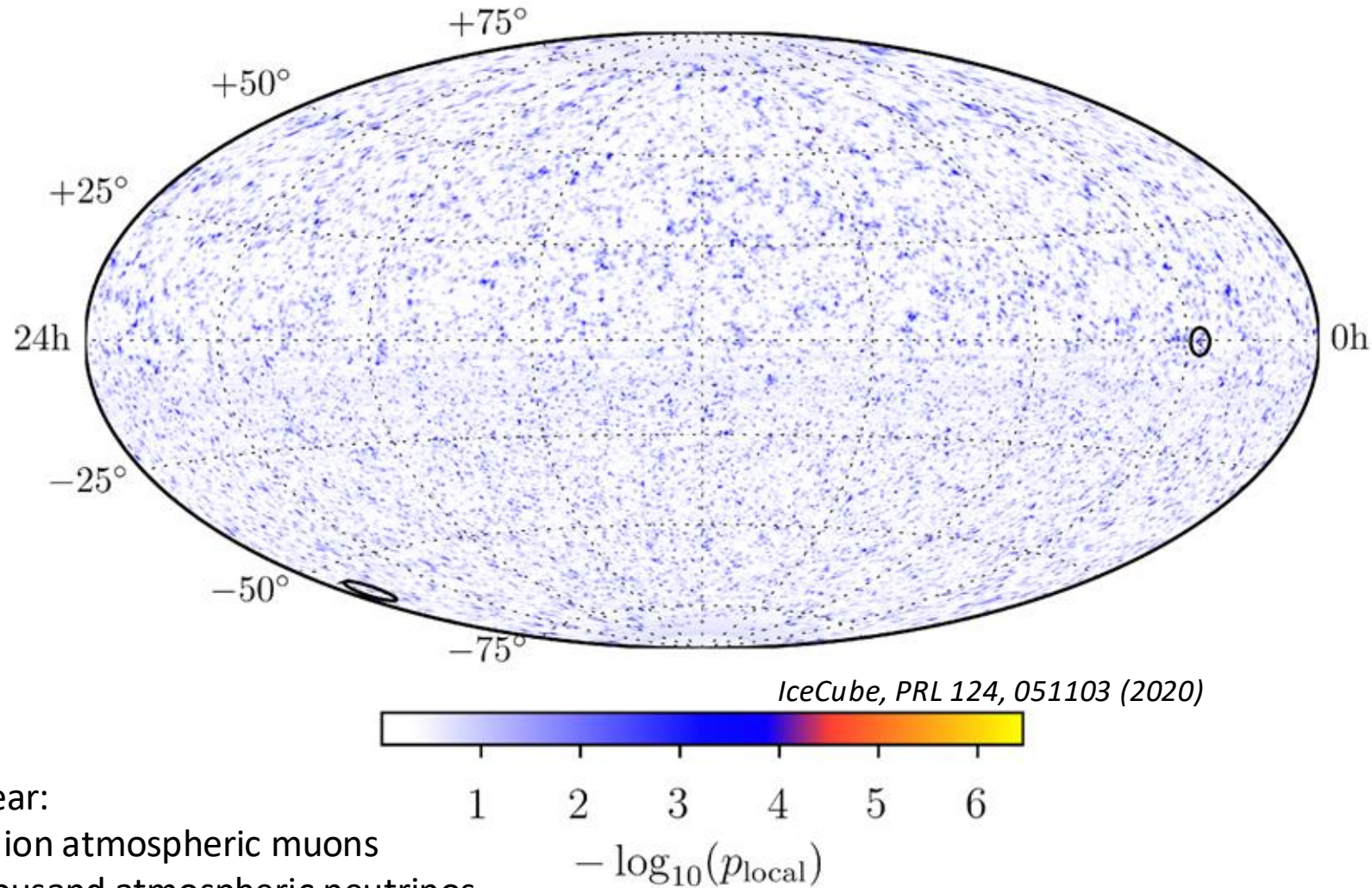


Searching for neutrino sources



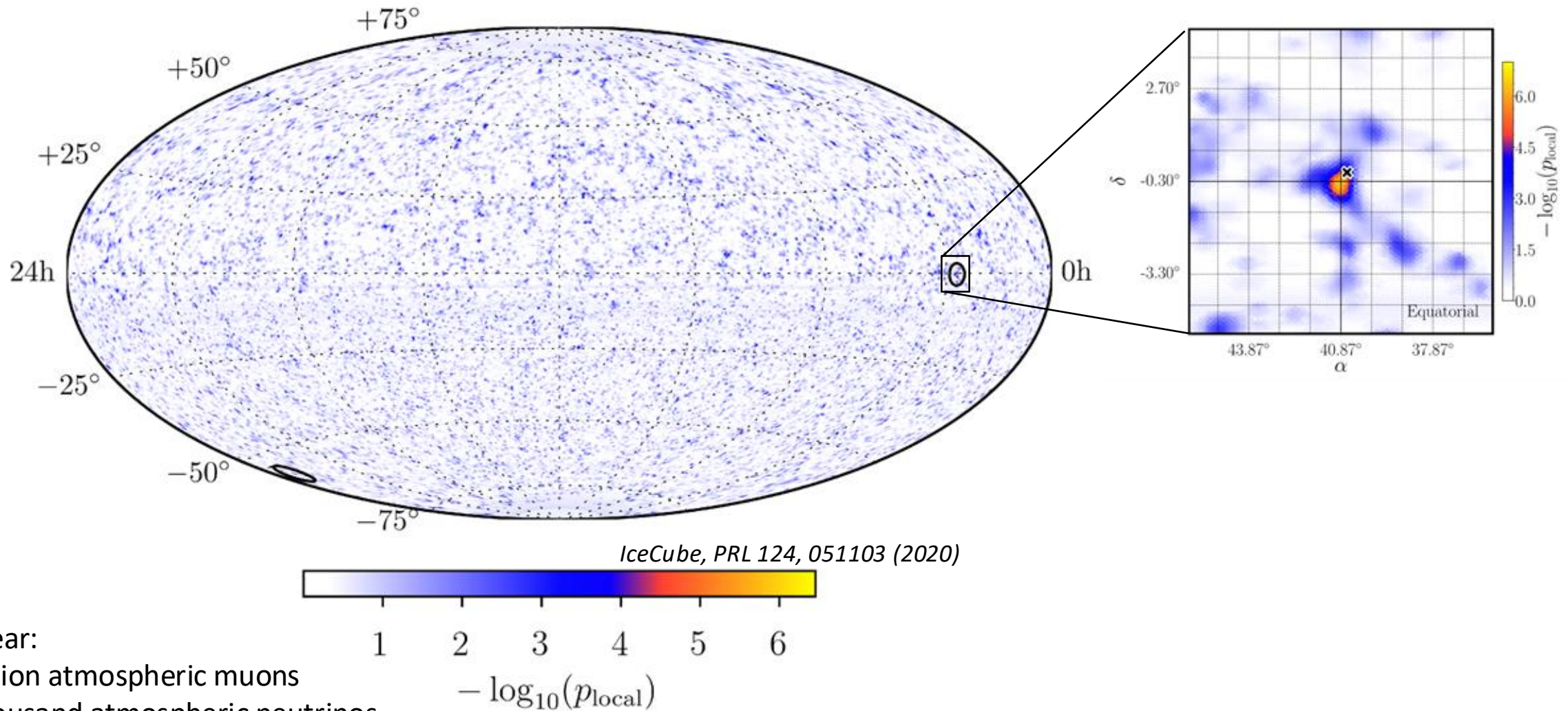
need good reconstruction of **directions** and **energies**
and model of how they differ between **signal** and background

Prior IceCube results: time-integrated neutrino source search

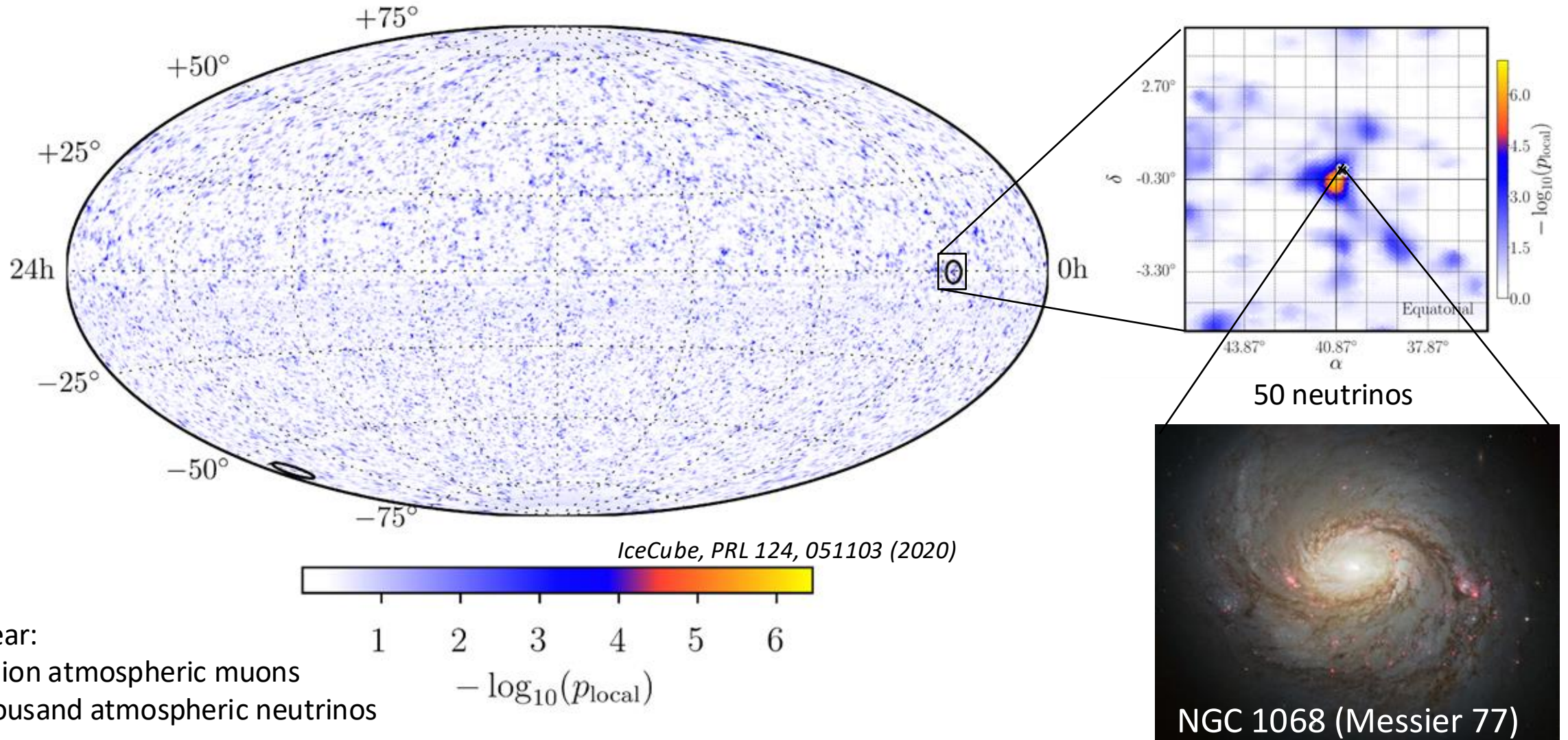


Per year:
90 billion atmospheric muons
80 thousand atmospheric neutrinos

Prior IceCube results: searching for statistical evidence of clustering

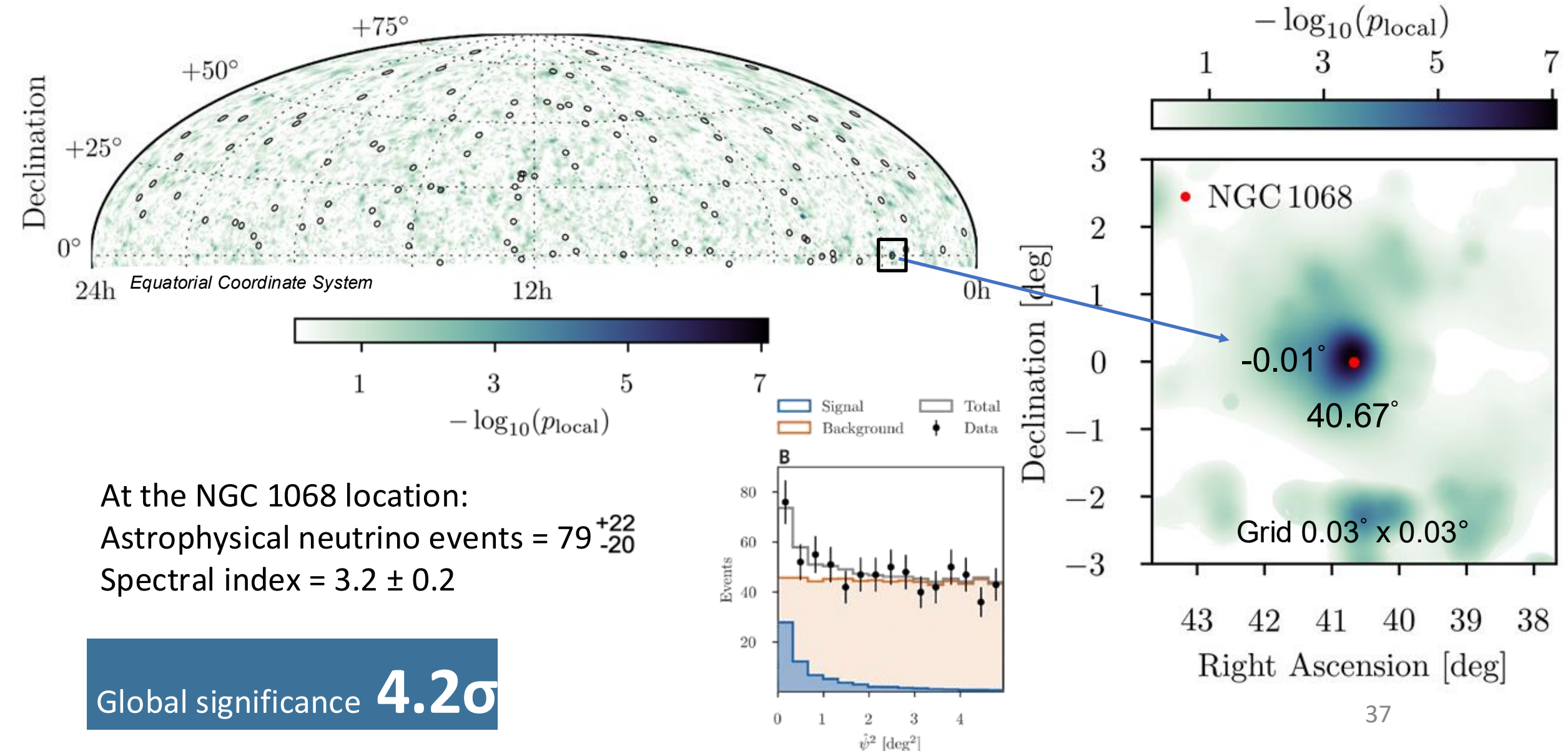


Most significant position on sky: consistent with NGC 1068 (Messier 77), a Seyfert II galaxy (2.9σ)

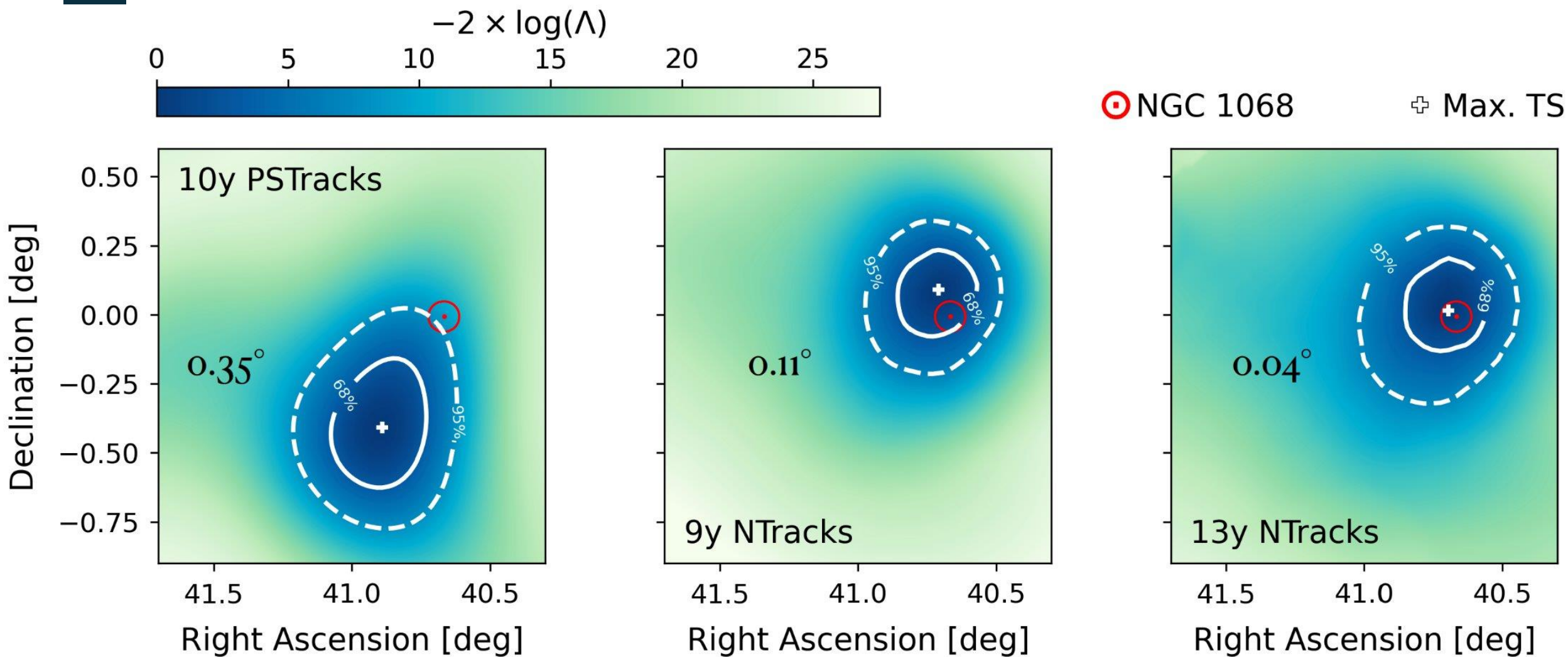


Evidence for neutrino emission from NGC 1068

Improved detector calibration



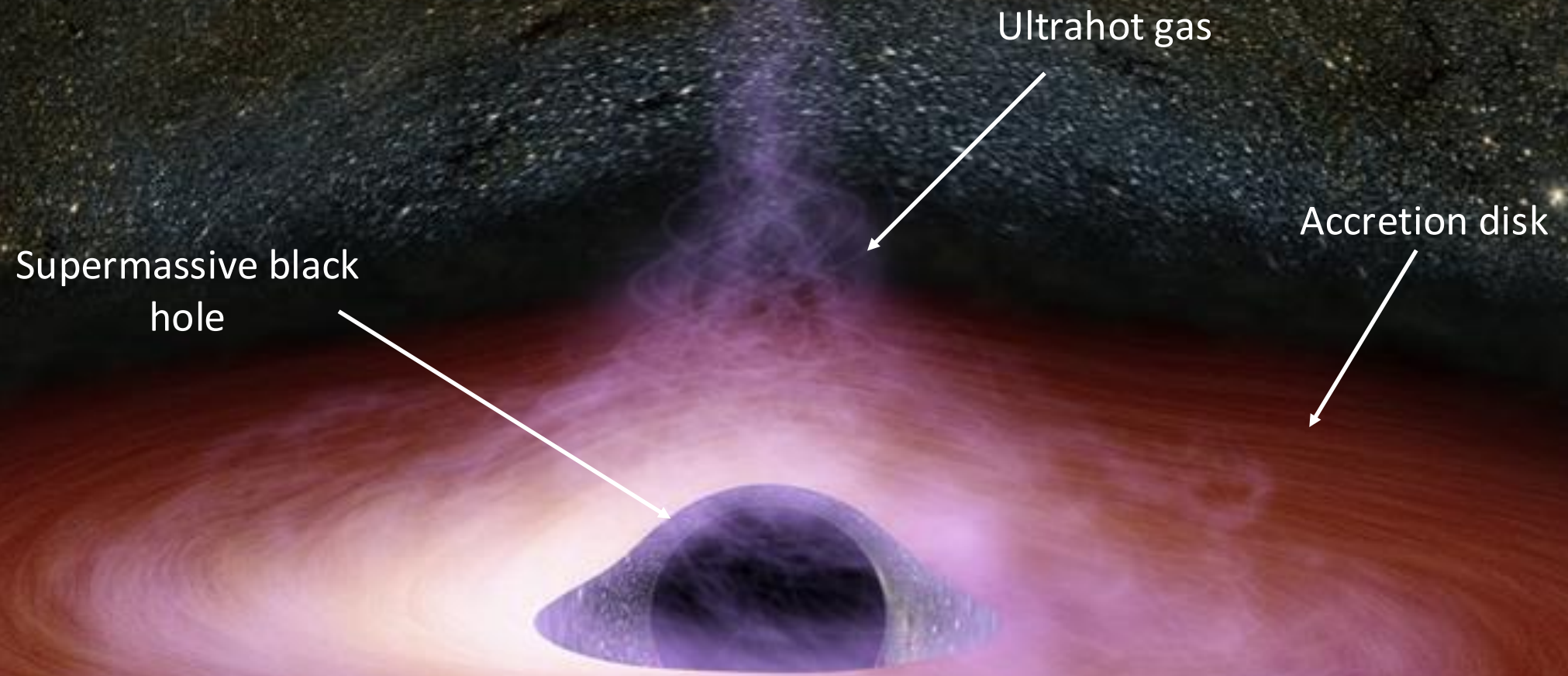
New result: hotspot gets closer to NGC1068



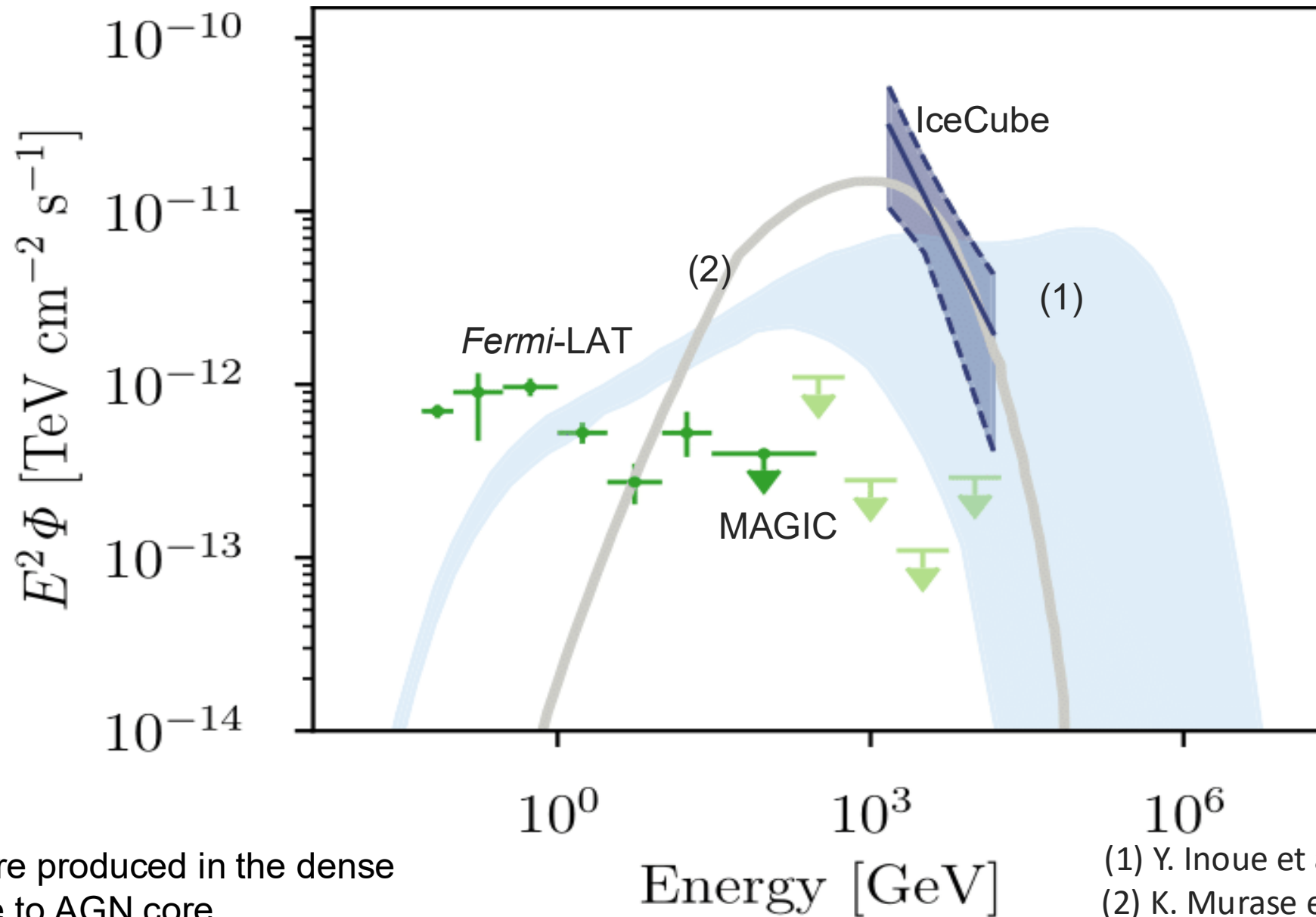
NGC 1068: a non-jetted AGN with an obscured black hole



NGC 1068 and the obscured core



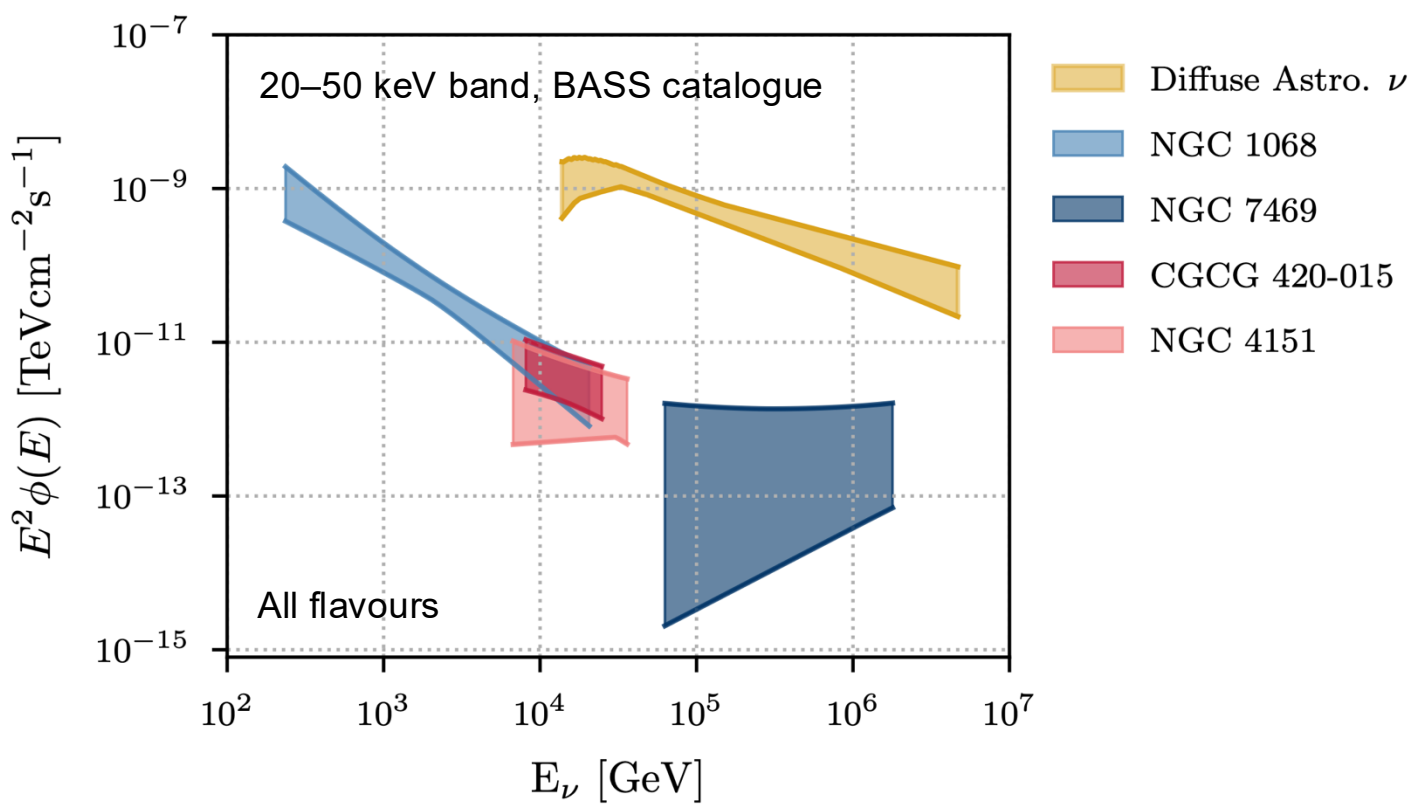
NGC 1068: a cosmic obscured accelerator



X-ray bright Seyfert (non-jetted) galaxy

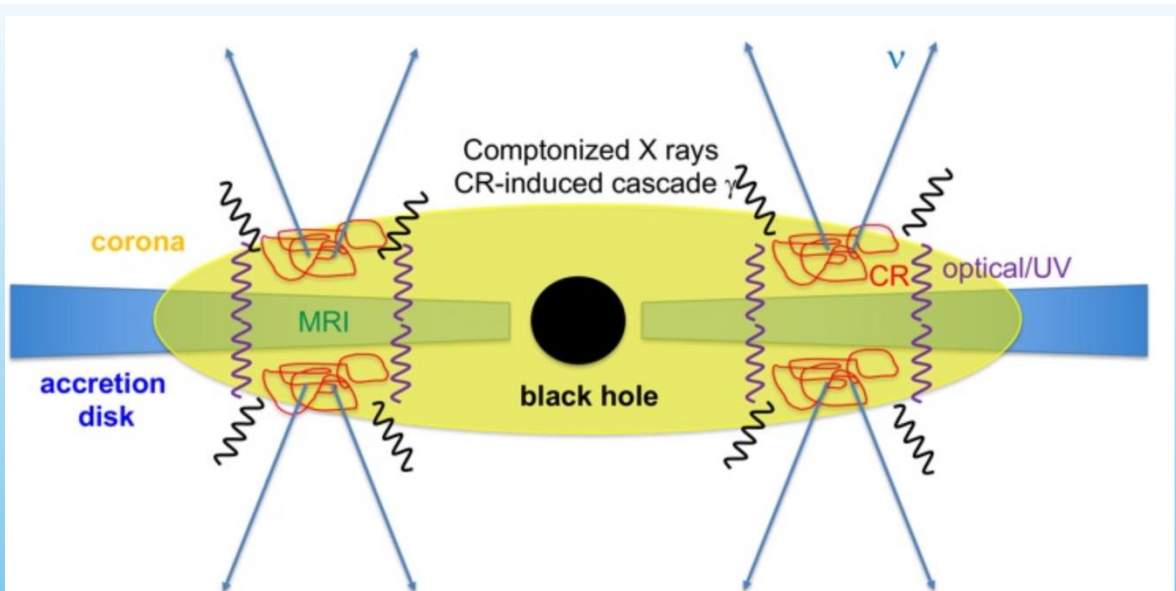
* 3.3 σ over binomial test (11 sources, excluding NGC1068)

NGC 7469	345.82	8.87	5.5	1.9	4.1 (3.8 σ)
11 Sources					4.8 (4.2 σ)
NGC 4151	182.64	39.41	27.6	2.7	2.9 (3.1 σ)
CGCG 420-015	73.36	4.06	35.3	2.7	2.4 (2.7 σ)
Cygnus A	299.87	40.73	3.4	1.6	2.2 (2.5 σ)
LEDA 166445	42.68	54.70	57.1	4.4	1.8 (2.1 σ)
NGC 4992	197.27	11.63	27.3	2.9	1.6 (2.0 σ)
NGC 1194	45.95	-1.10	43.2	4.4	1.5 (1.8 σ)
Mrk 1498	247.02	51.78	39.9	3.6	1.4 (1.7 σ)
MCG +4-48-2	307.15	25.73	36.7	3.2	1.4 (1.7 σ)
NGC 3079	150.49	55.68	33.8	3.6	1.3 (1.7 σ)
Mrk 417	162.38	22.96	4.4	2.0	1.3 (1.6 σ)



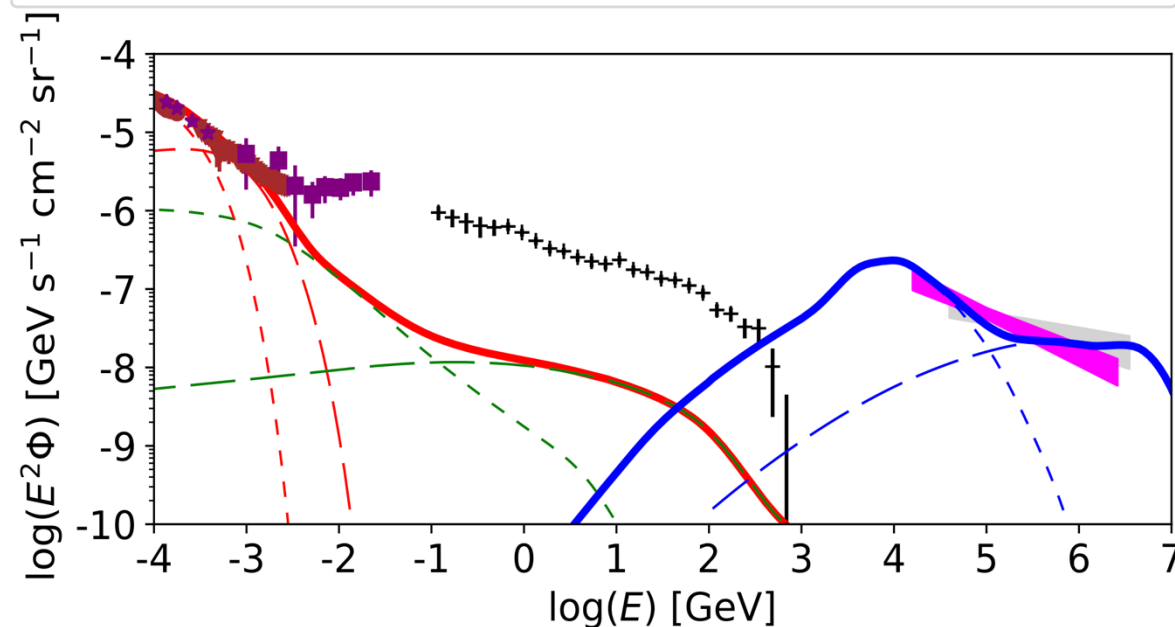
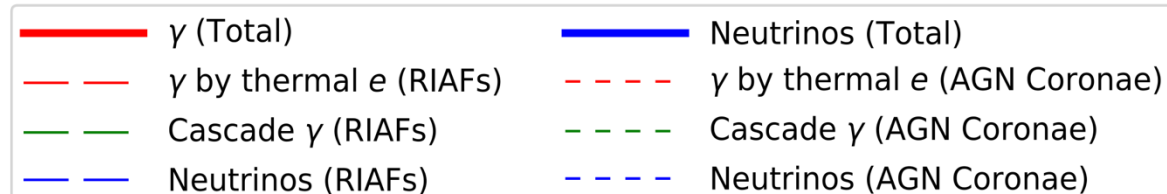
Possible linking gamma-ray obscured X-ray bright populations with extragalactic diffuse flux

$$E_p \varepsilon_\gamma \approx \frac{m_\Delta^2 - m_p^2}{4} \approx 0.2 \text{ GeV}^2 \quad E_\nu \varepsilon_\gamma \approx 10^{-2} \text{ GeV}^2$$



accretion disk + “corona”
opt/UV=multi-temperature blackbody
X-ray=Compton by thermal electrons

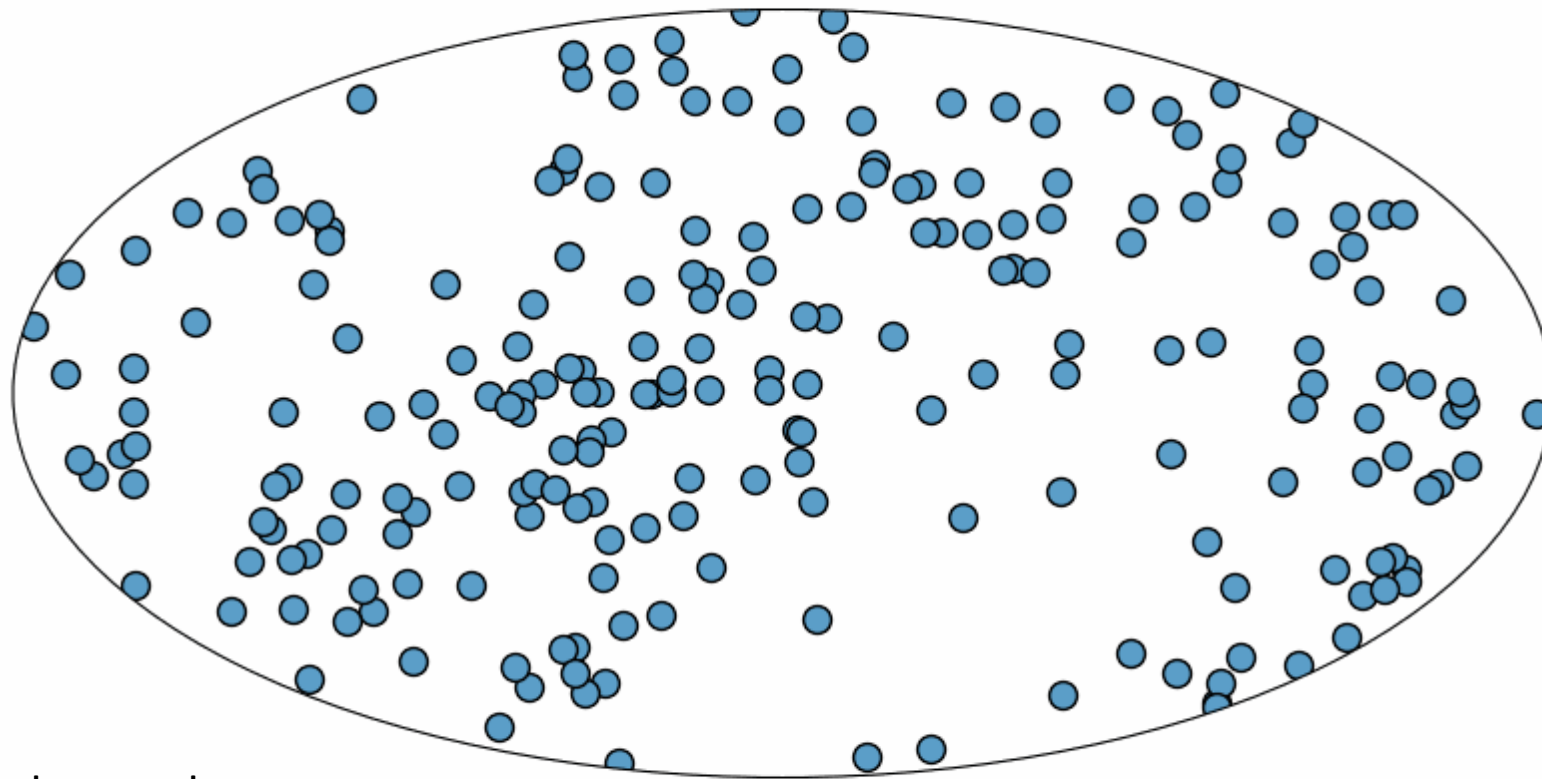
KM, Kimura & Meszaros 20 PRL
 Kimura, KM & Meszaros 21 Nature Comm.



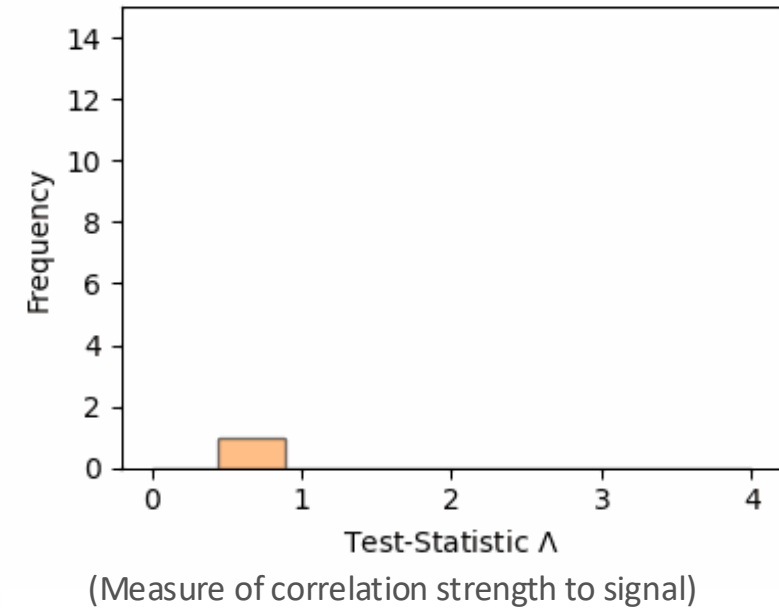


What about our home galaxy?

Unbinned Poisson likelihood



- Background
- Signal



$$\text{TS} \equiv 2 \ln \left(\frac{\max_{n_s} \mathcal{L}(n_s)}{\mathcal{L}(n_s = 0)} \right) = 2 \ln \left(\frac{\mathcal{L}(\hat{n}_s)}{\mathcal{L}(n_s = 0)} \right)$$

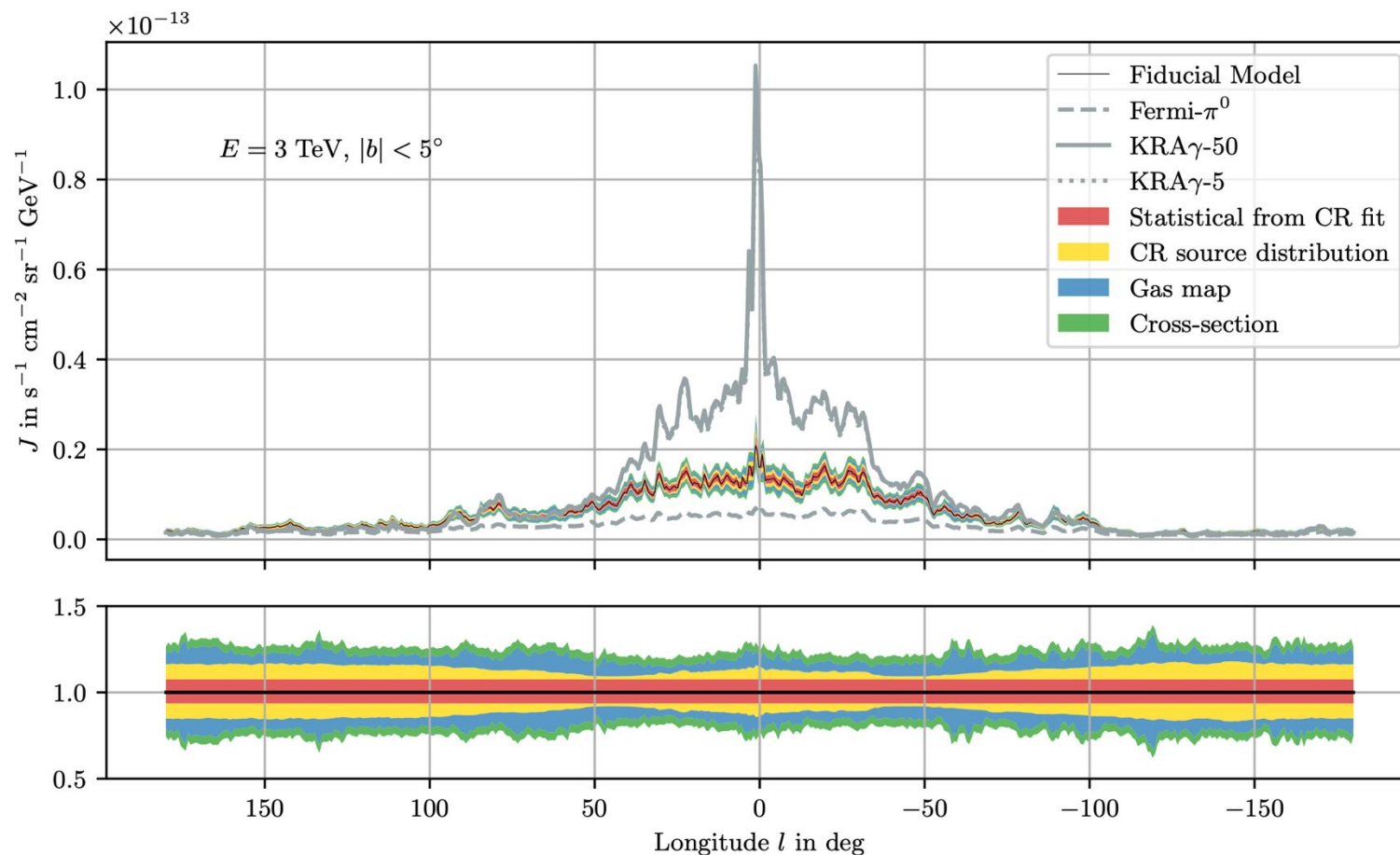
Neutrinos from the Milky Way



History of cosmic-ray propagation in the Galaxy

Diffuse models

- Radially-dependent diffusion? -> strong GC emission
- Uniform diffusion -> weak GC emission



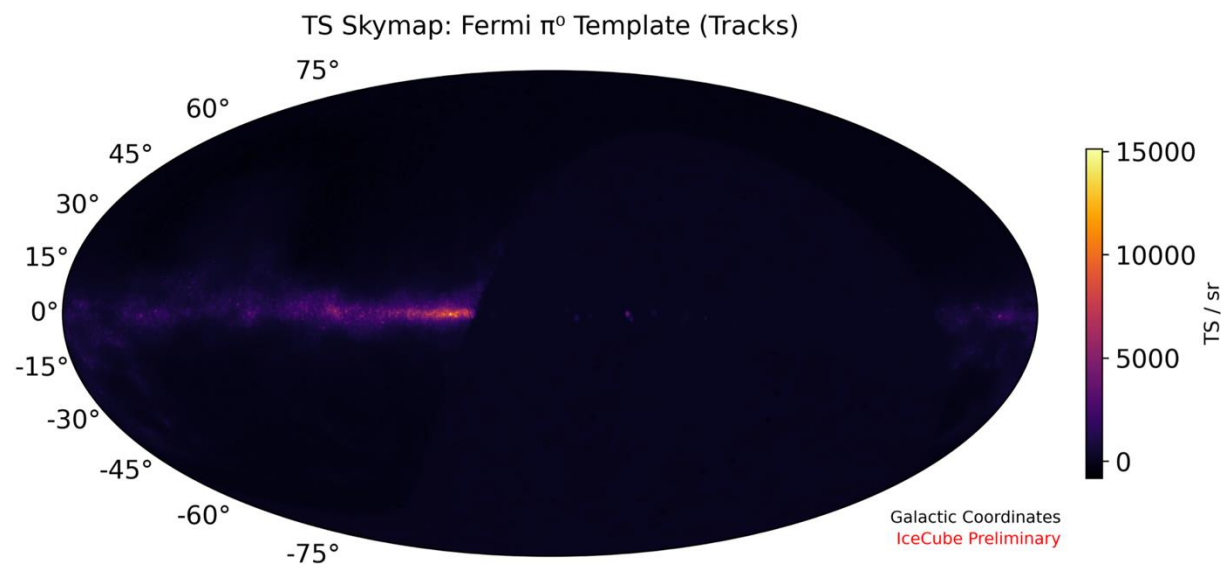
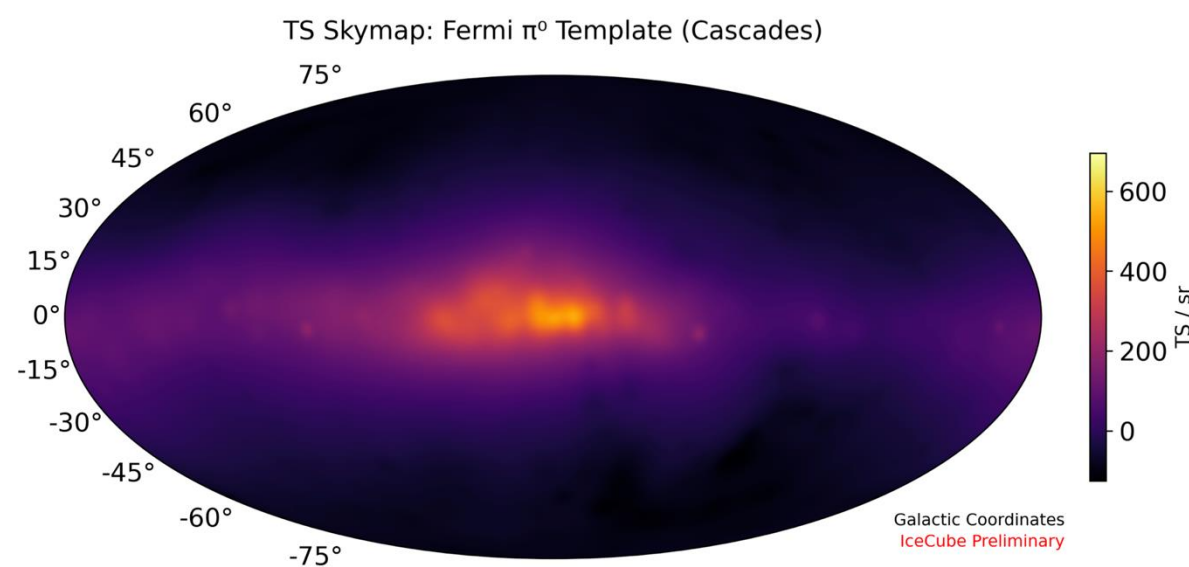
Schwefer, Mertsch, Wiebusch, 2023 ApJ 949 16

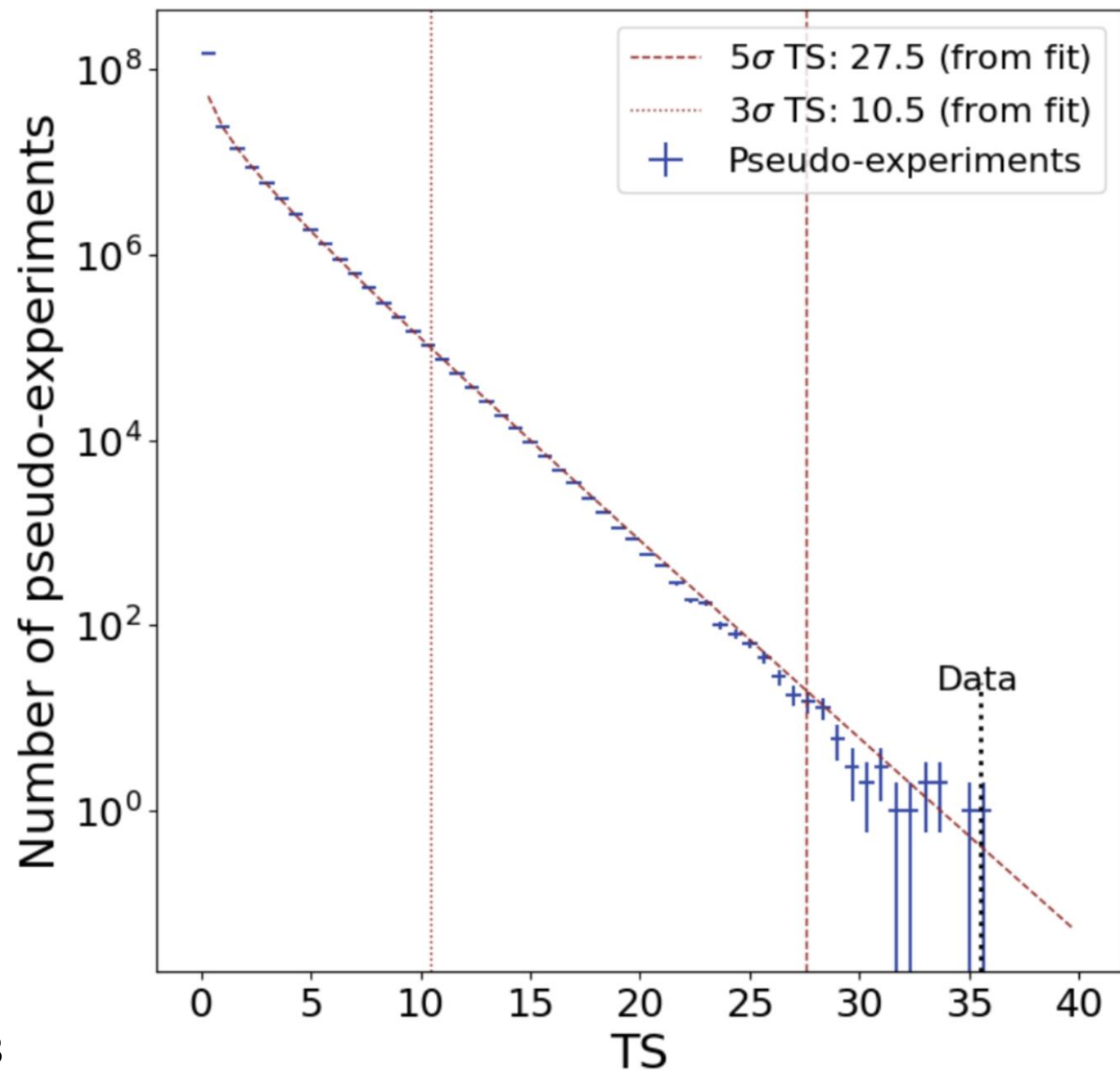
Unblinded result

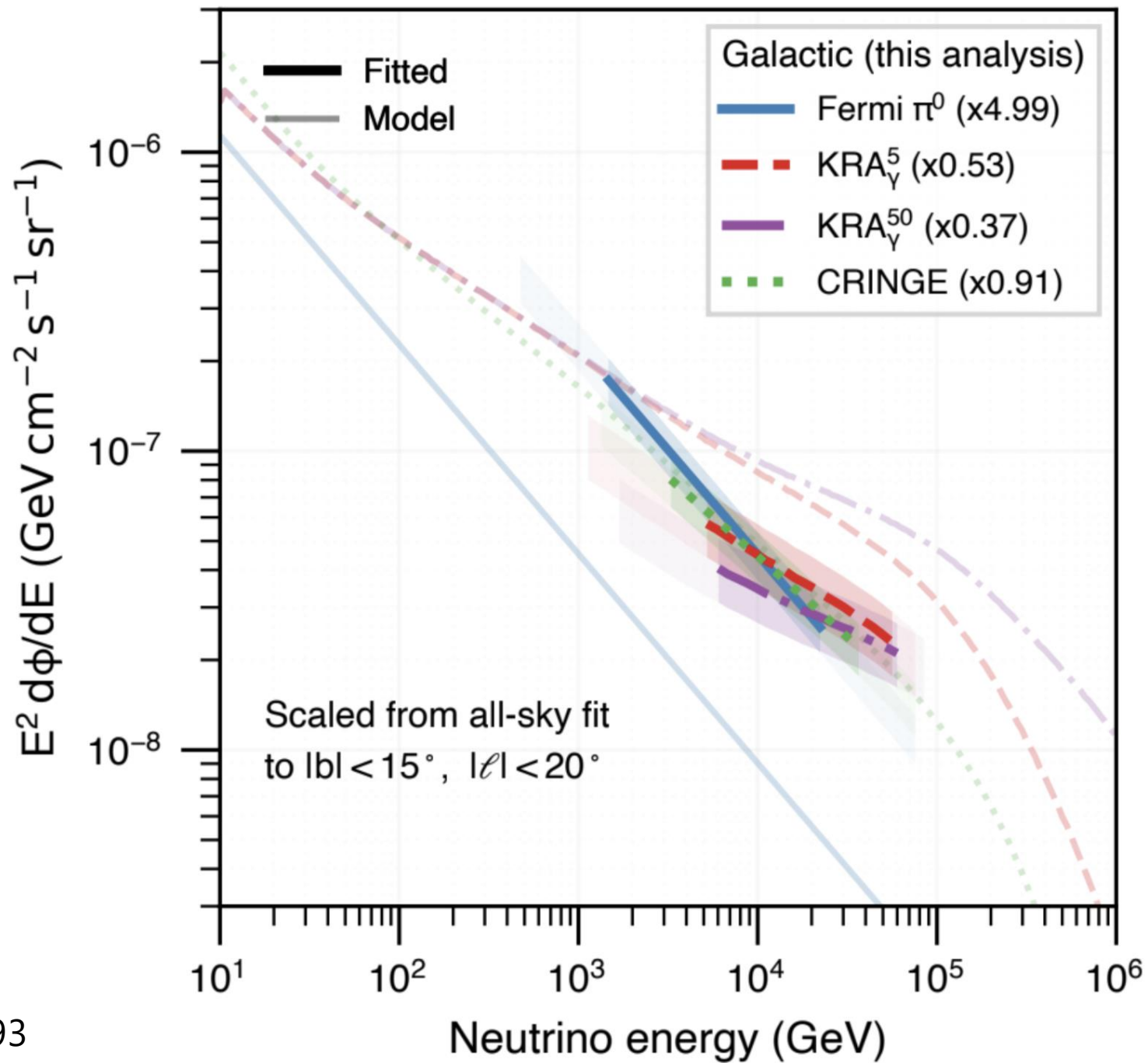
PoS-ICRC2025-1193



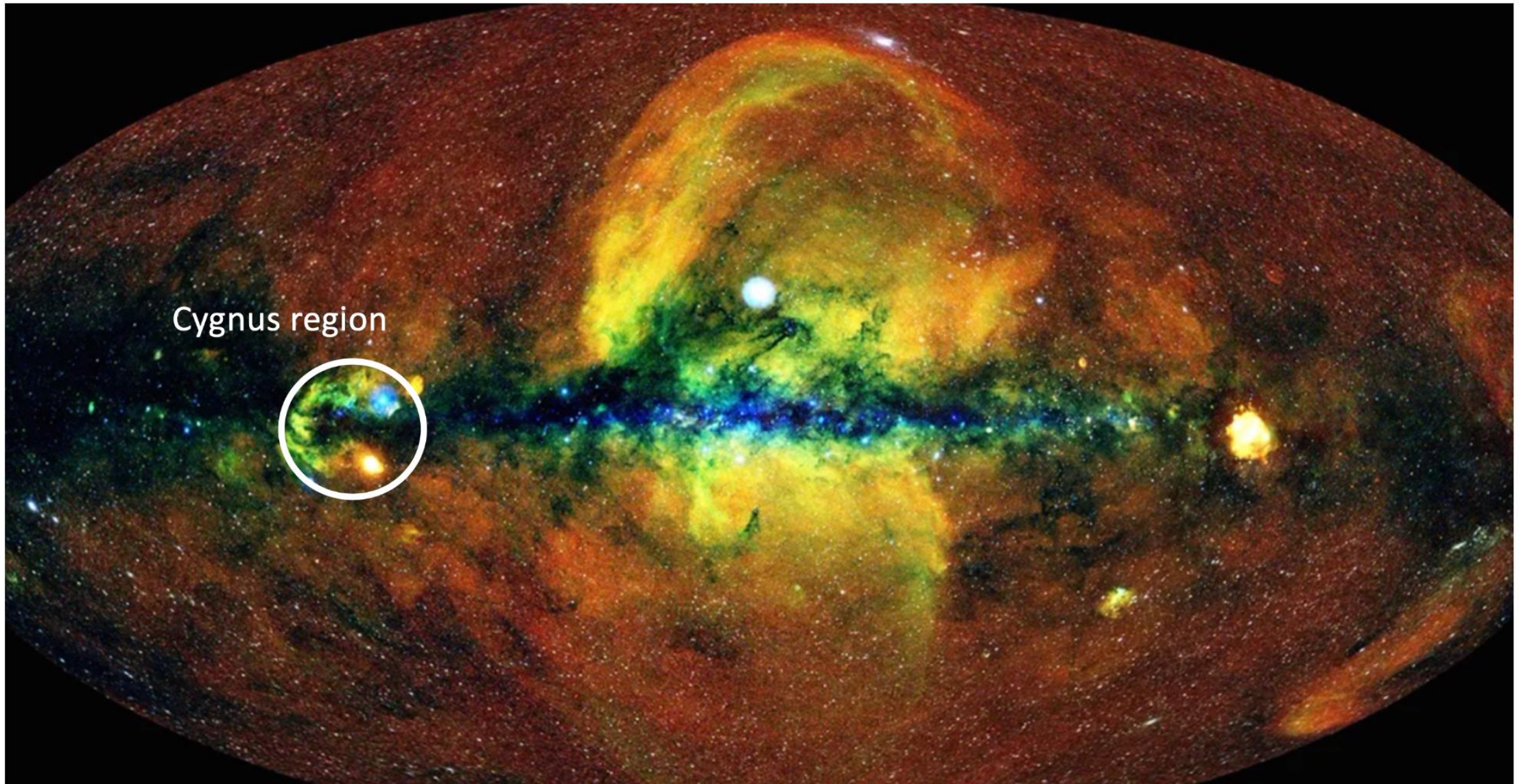
- 12 years of all-flavour data including showers and tracks
- Improved reco and systematics
- Tested against 4 diffuse emission models





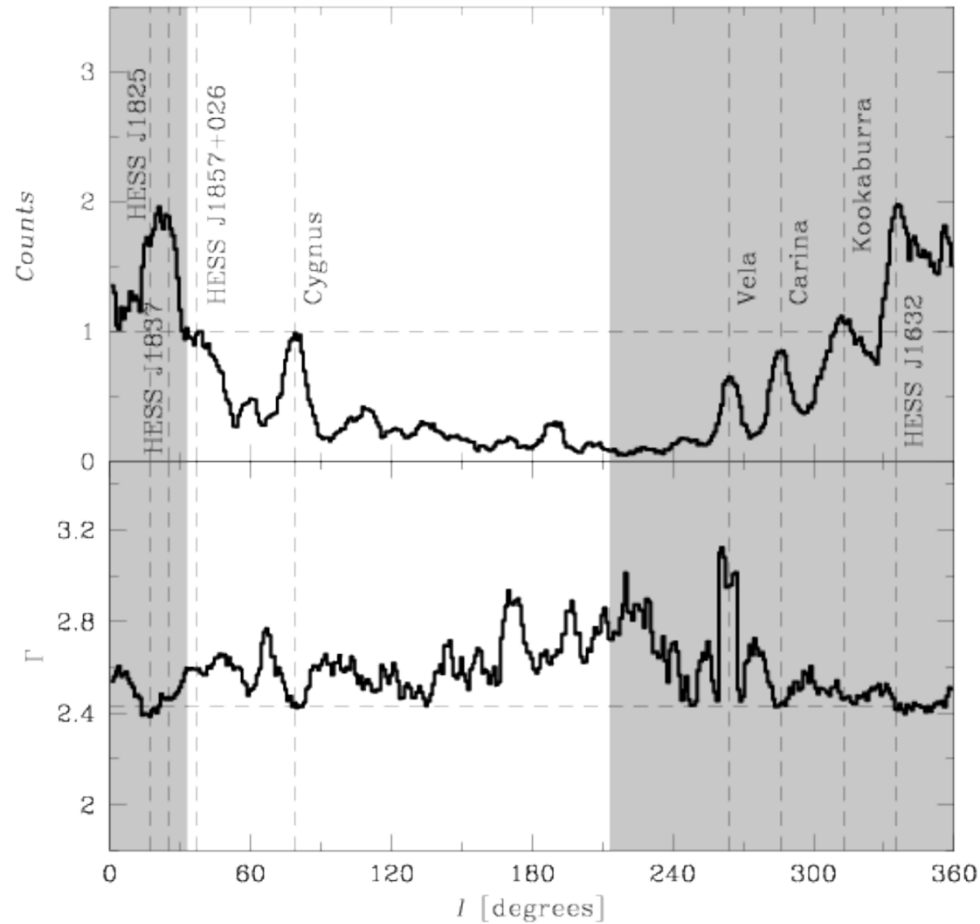


Cygnus Cocoon Bubble

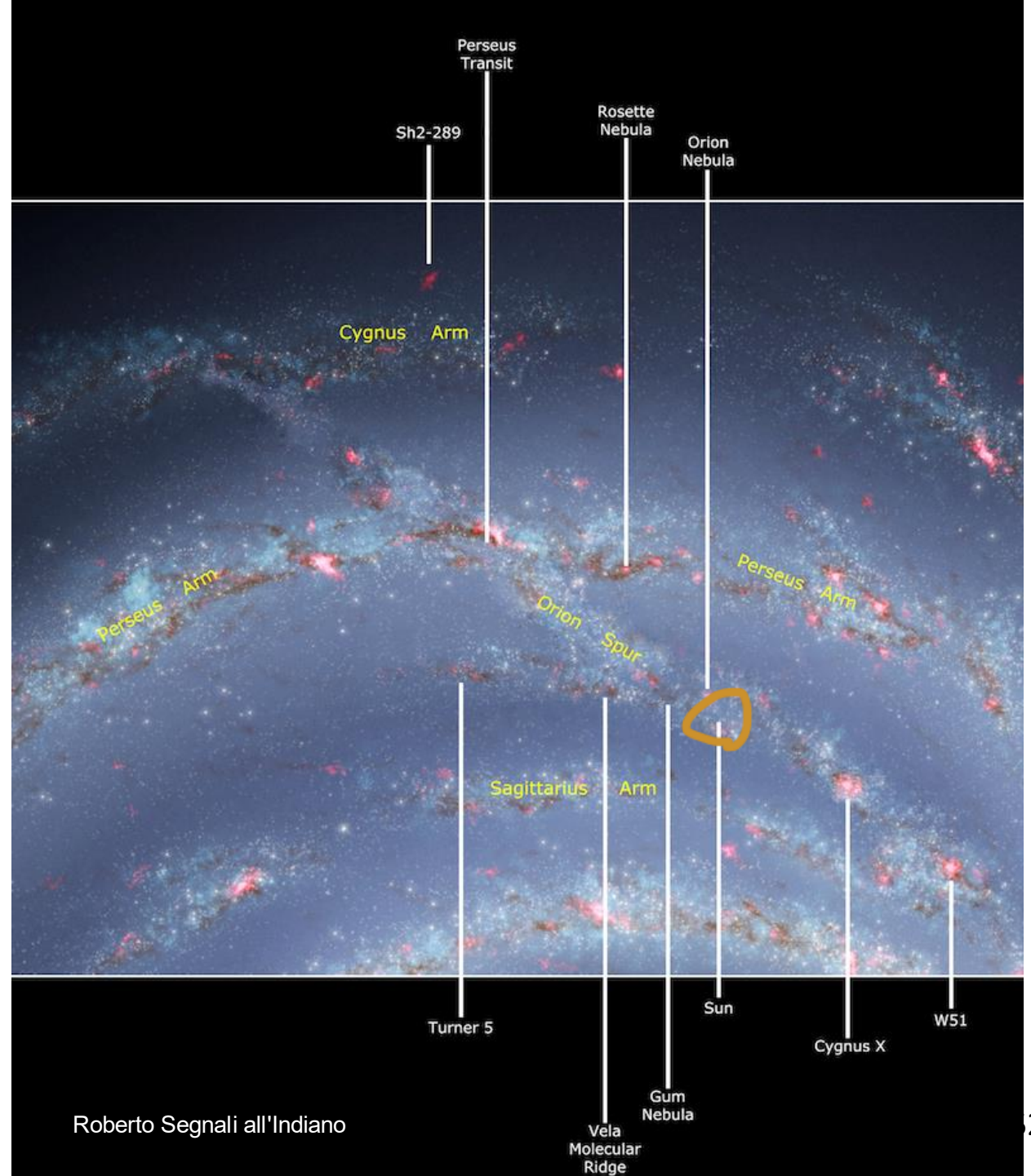


X-ray (0.3-2.3 keV) sky map eROSITA

Cygnus bubble: A superposition of unrelated structures along the local Galactic arm? A&A 560, A67 (2013)



Fermi-LAT, $E > 100$ GeV, 4 σ Gaussian smoothed

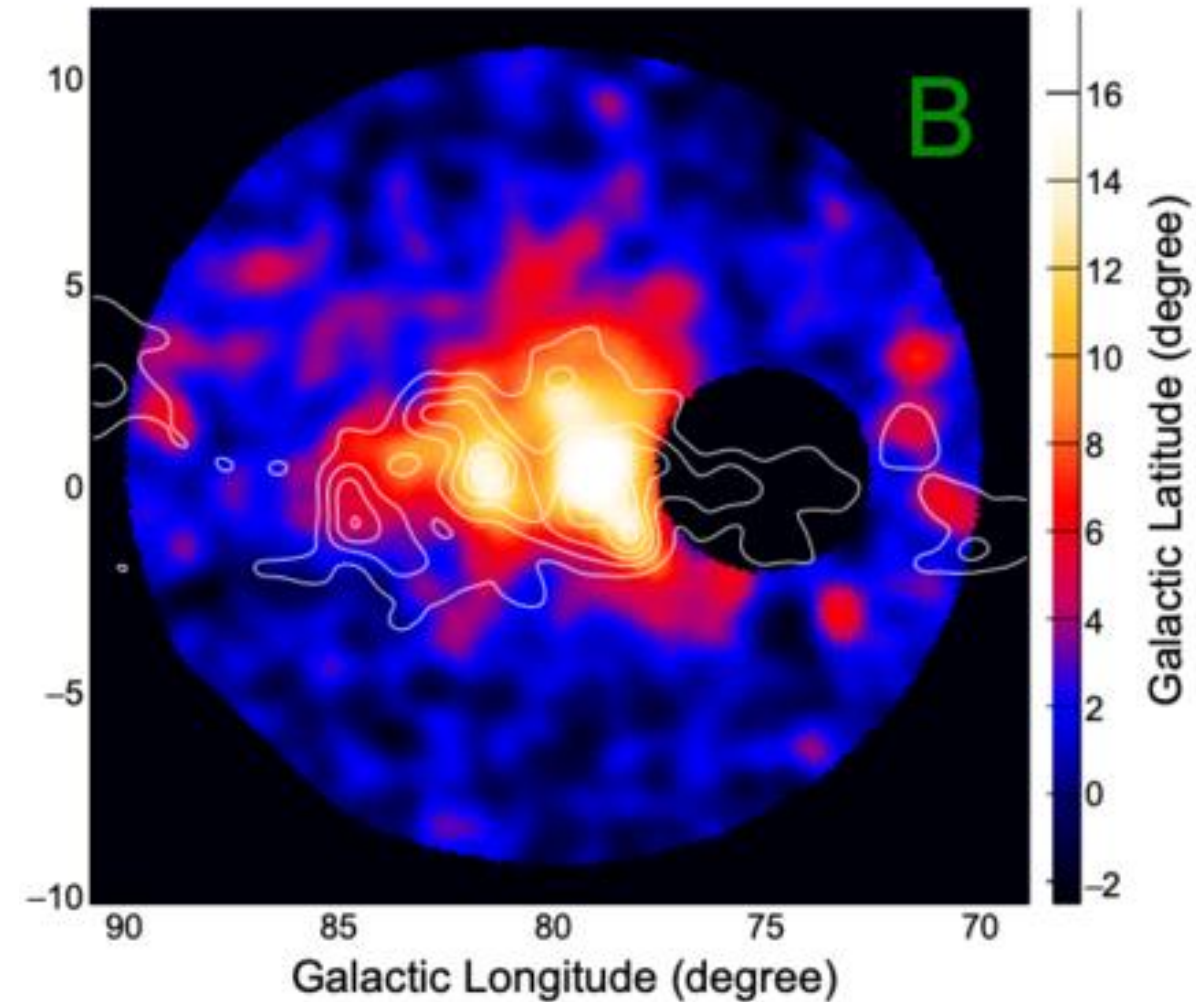
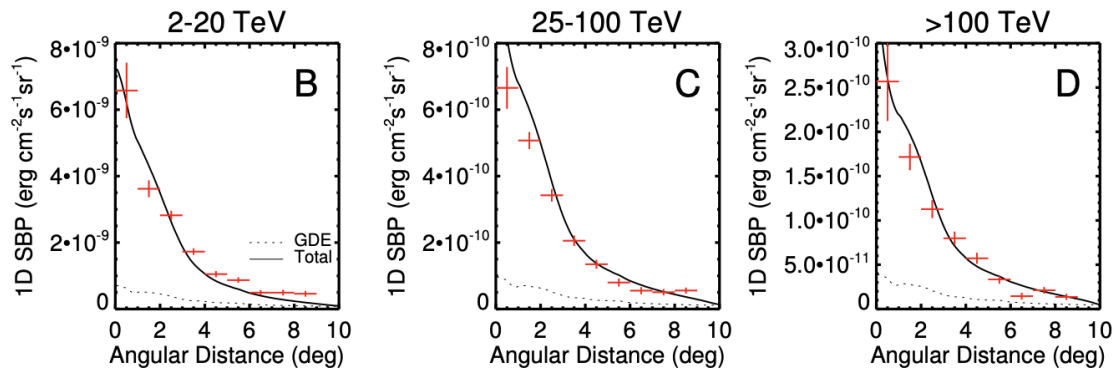
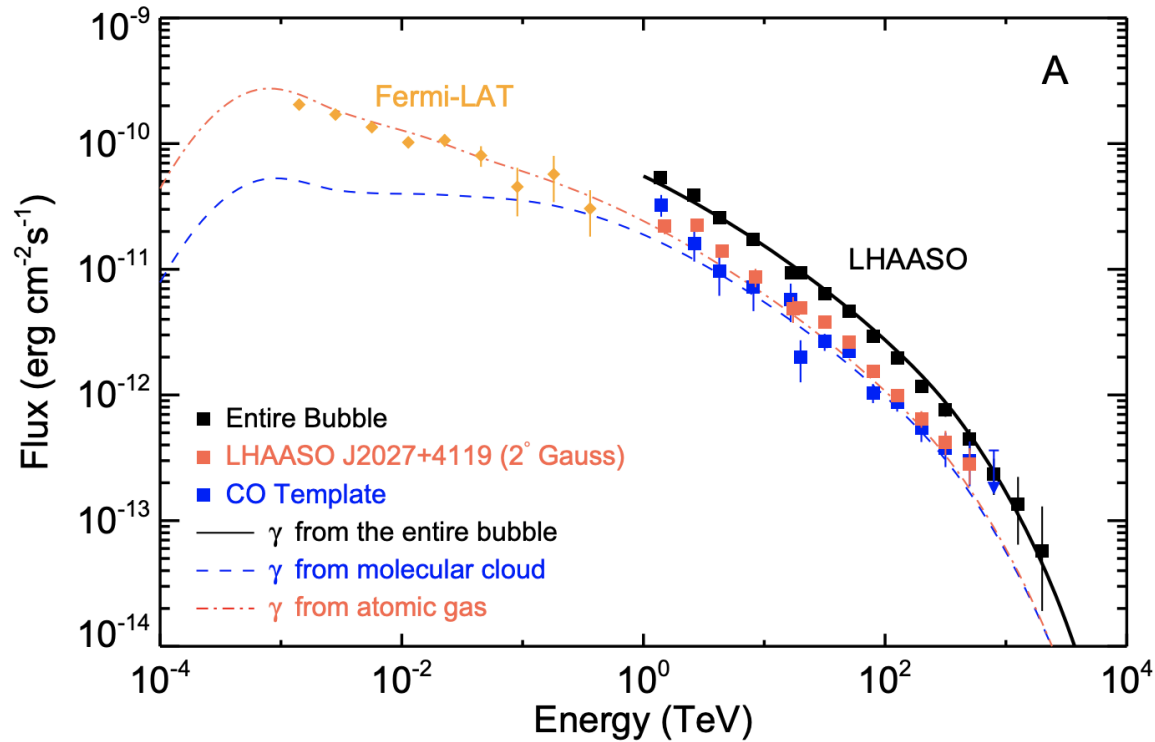


Roberto Segnali all'Indiano

Next discovery? On-going analysis

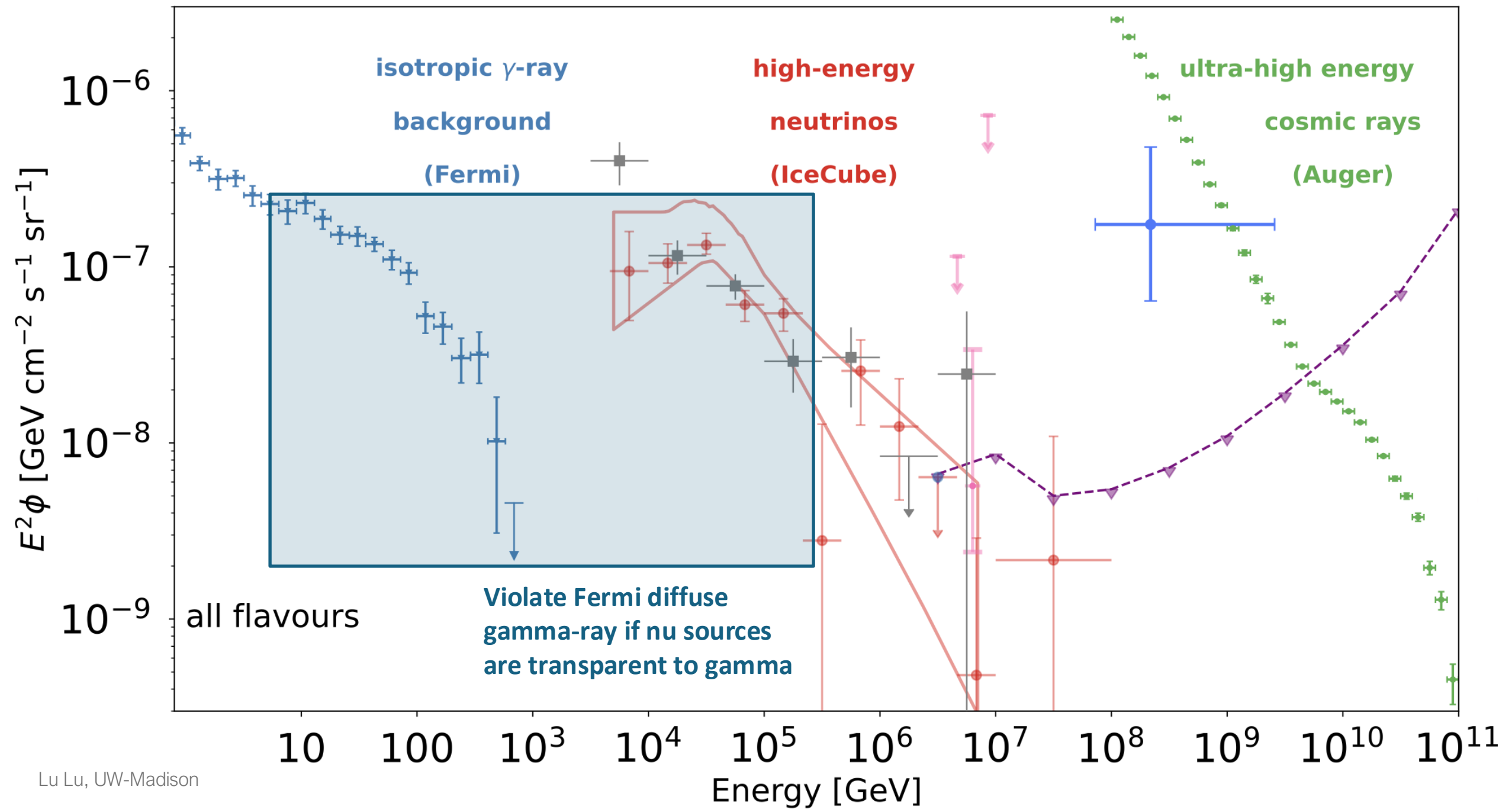
Cygnus Cocoon Bubble

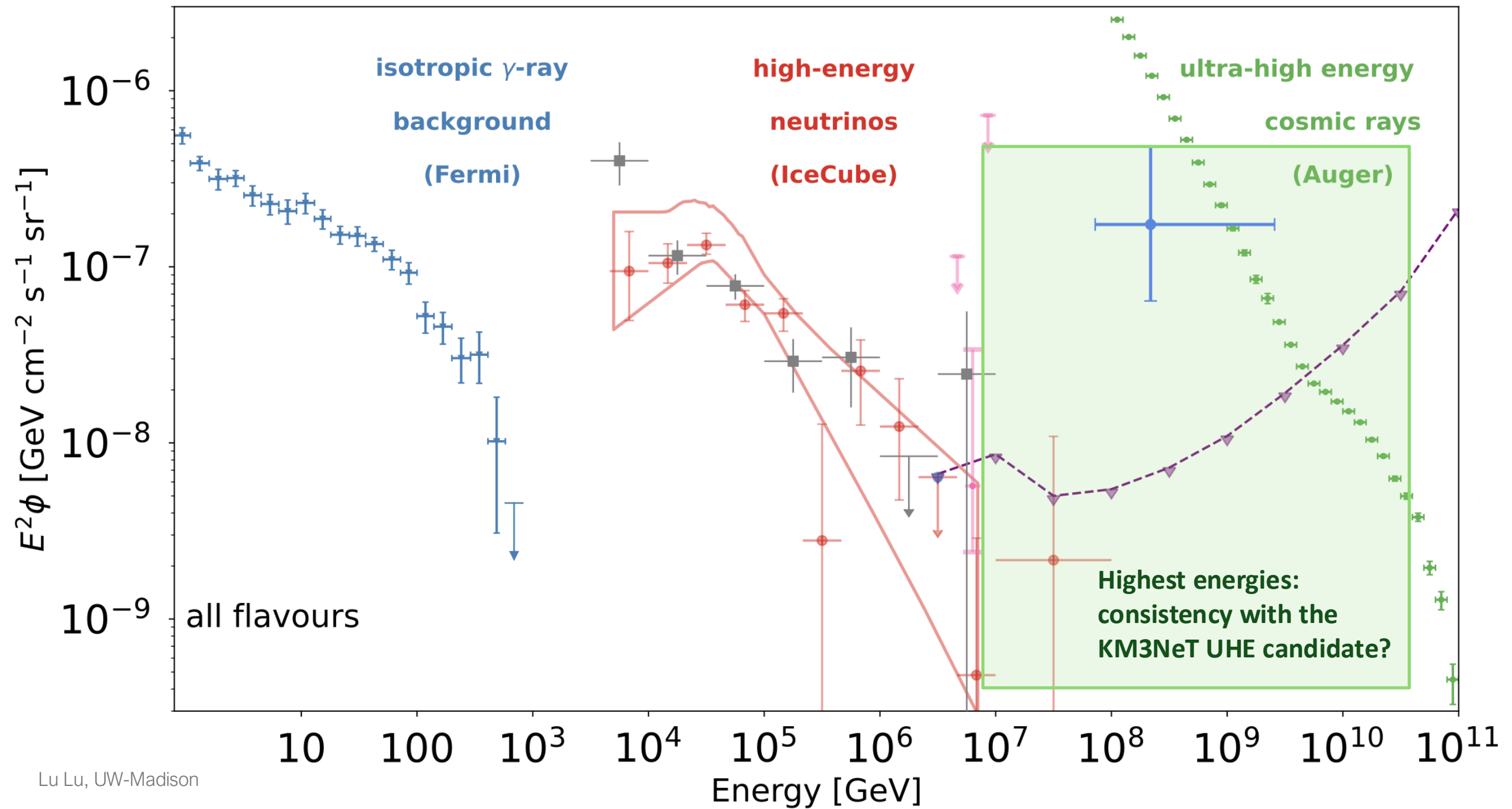
<https://doi.org/10.1016/j.scib.2023.12.040>





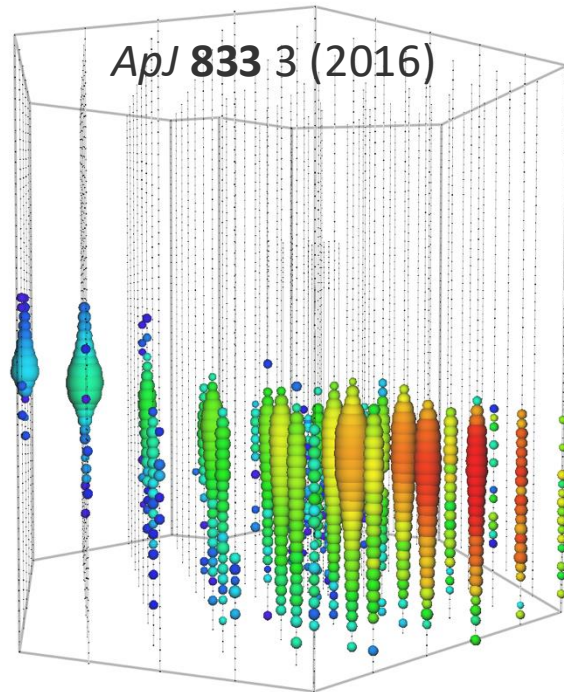
Next:
Ultra-high-energy neutrinos



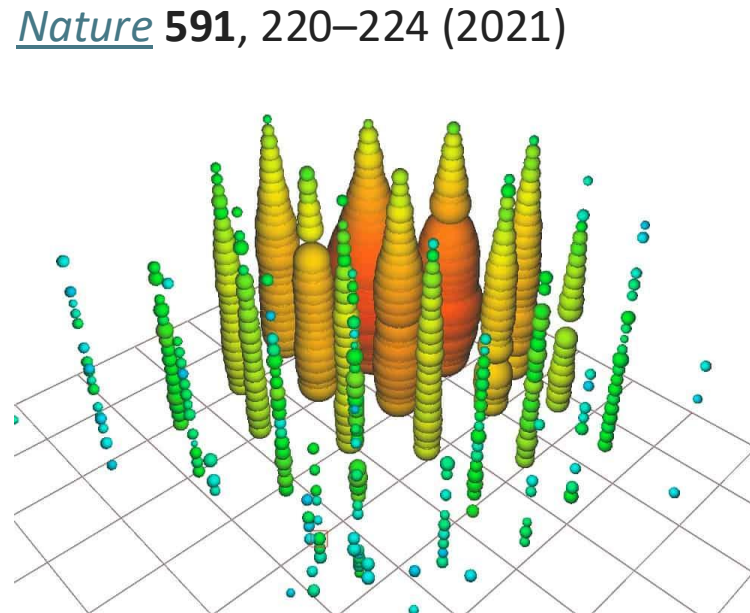


The highest energy neutrinos

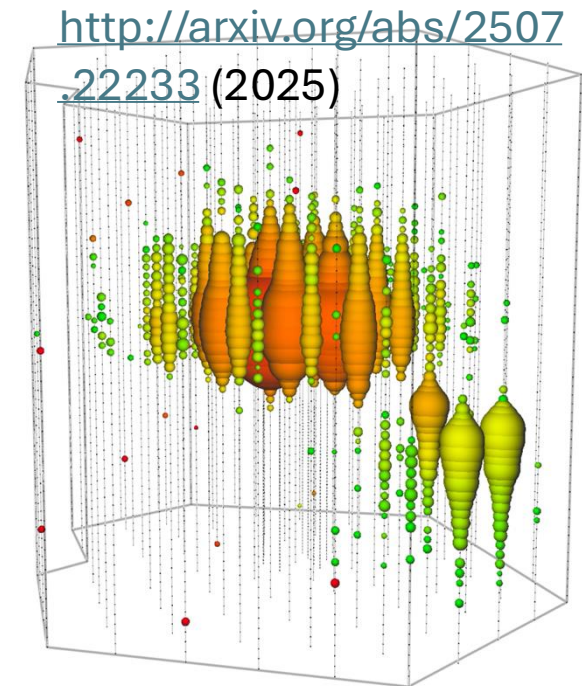
3 events with neutrino energy > 5 PeV over a decade of data taking



Muon energy: 4.5 ± 1.2 PeV
Nu energy ~ 9 PeV



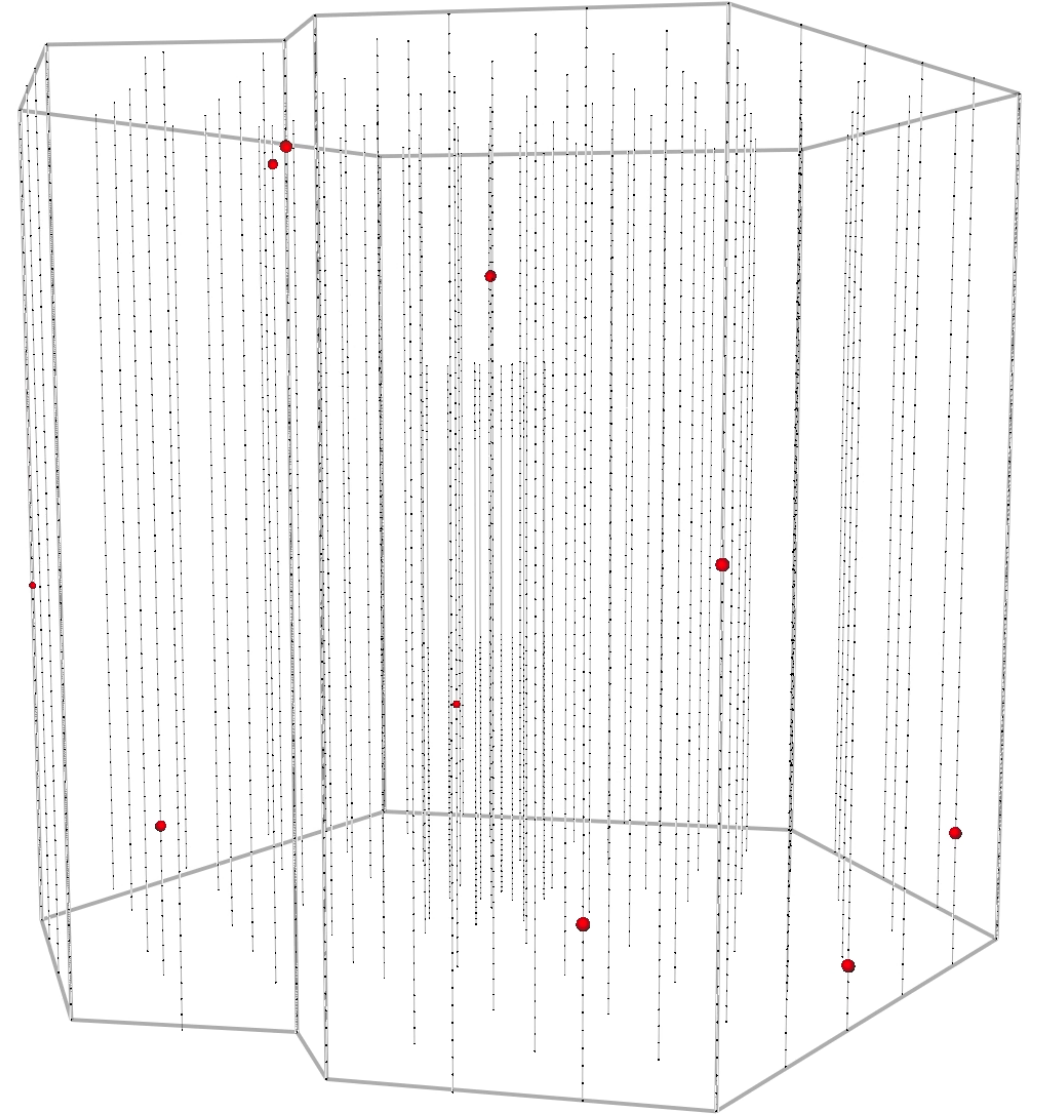
Deposited energy: 6.05 ± 0.72 PeV
Nu energy ~ 6.3 PeV



Nu energy $\sim 11.4 \pm 2.5$ PeV

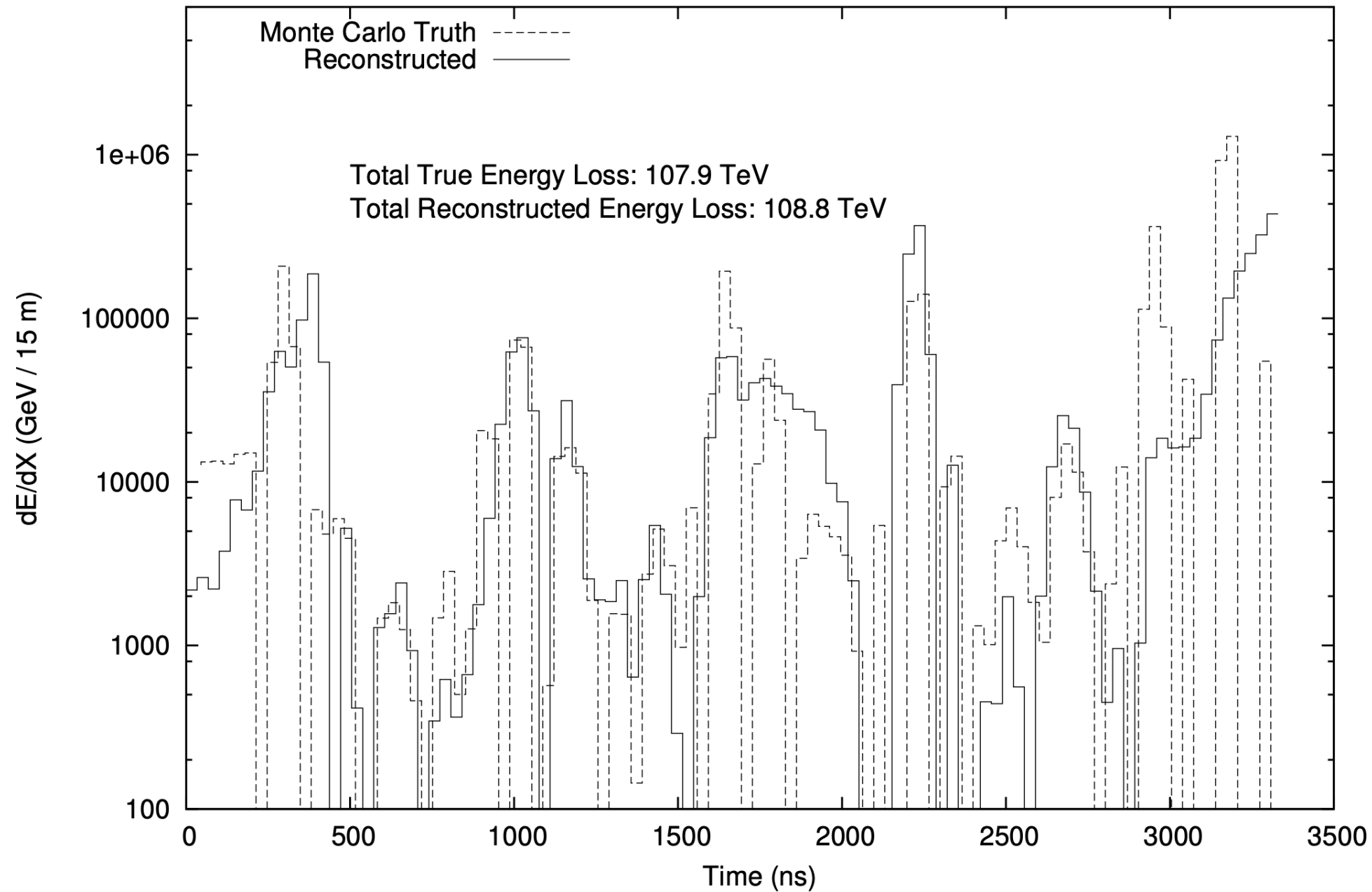
ICECUBE'S HIGHEST ENERGY NEUTRINO

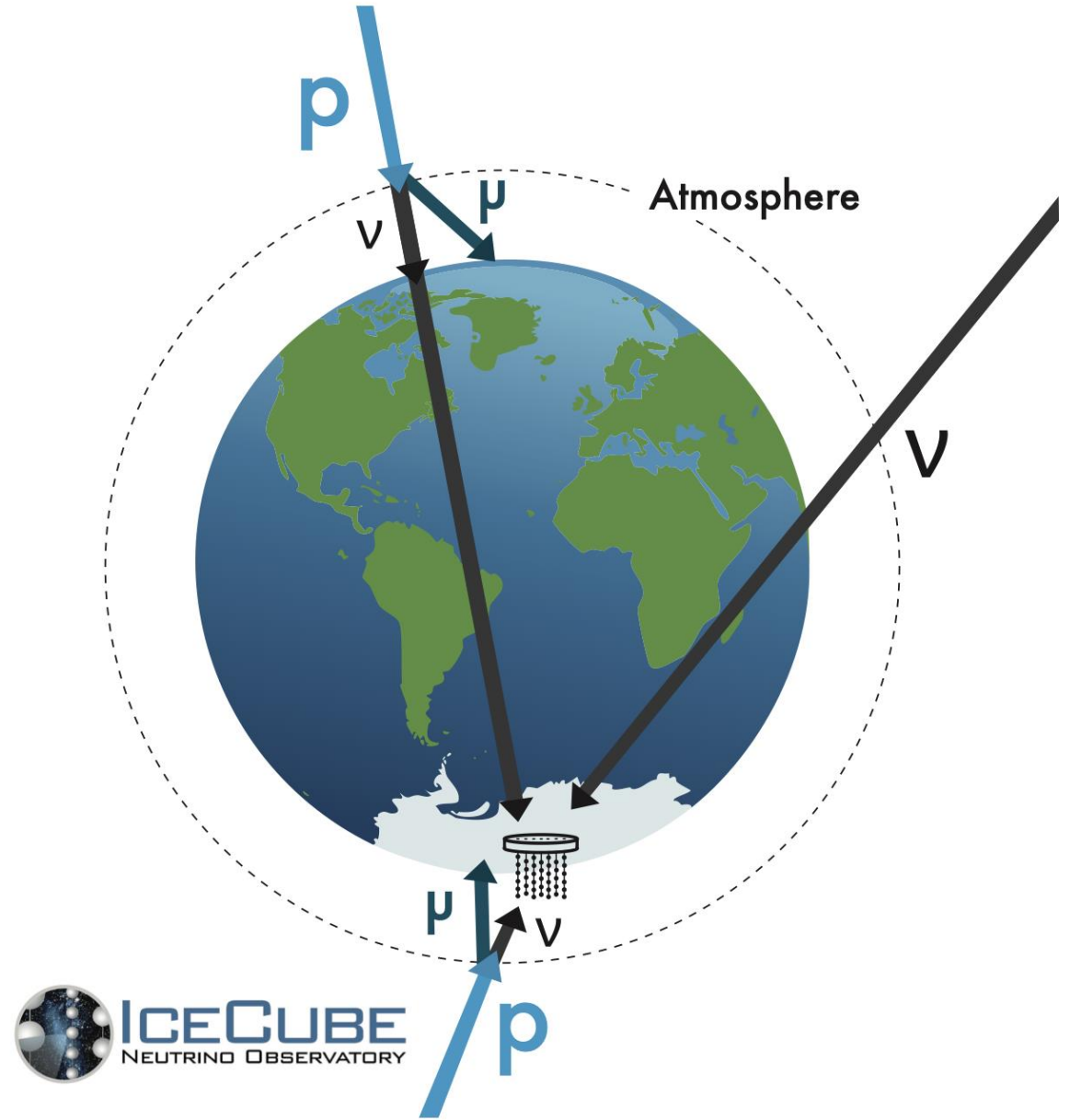
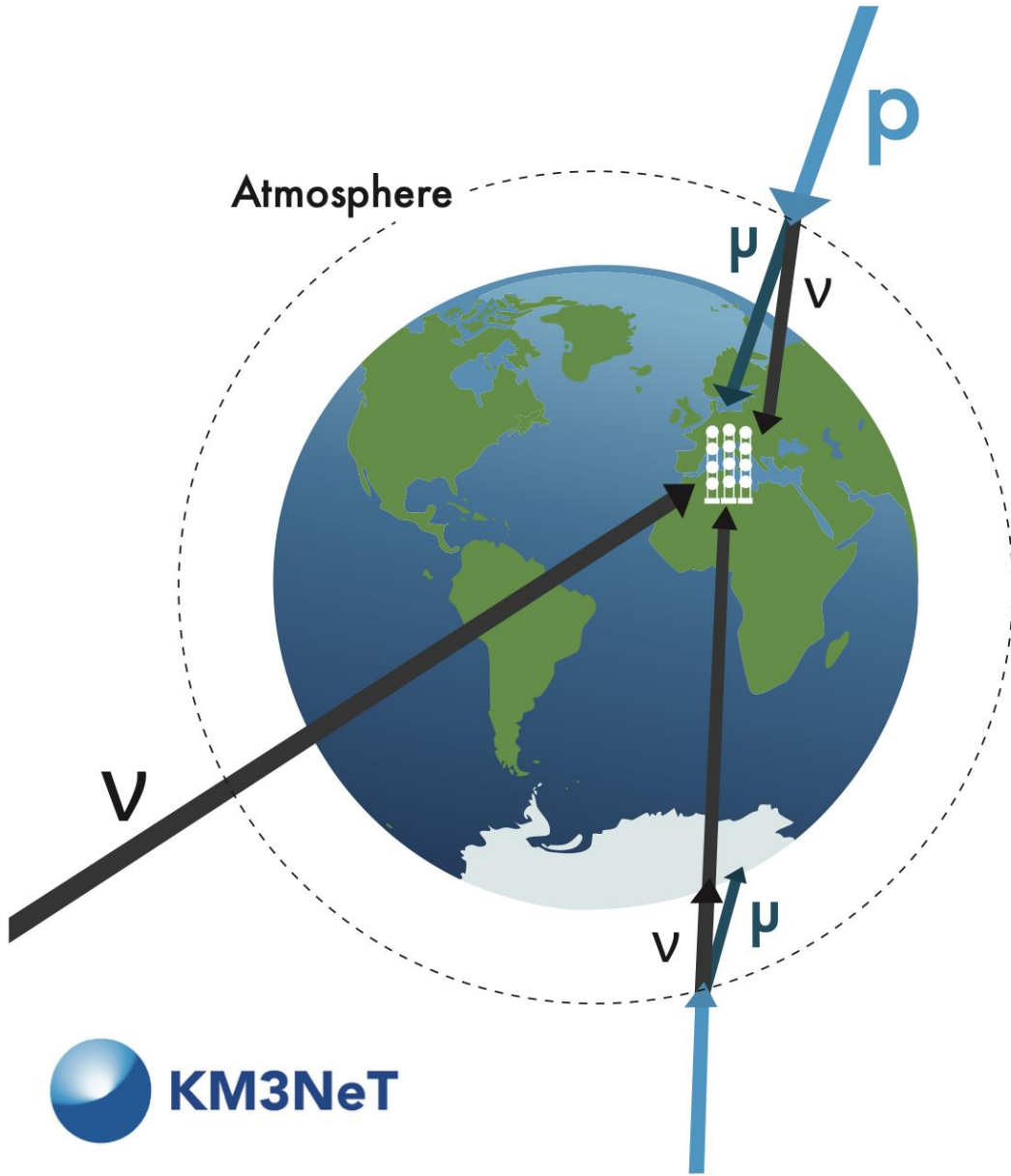
- Muon neutrino with contained vertex position
- Deposited energy 4.8 PeV
- $dE/dx \sim 1.125 \text{ TeV/m}$ over last 400m
- Resimulation: **neutrino energy**
 $11.6 \pm 2.6 \text{ PeV}$

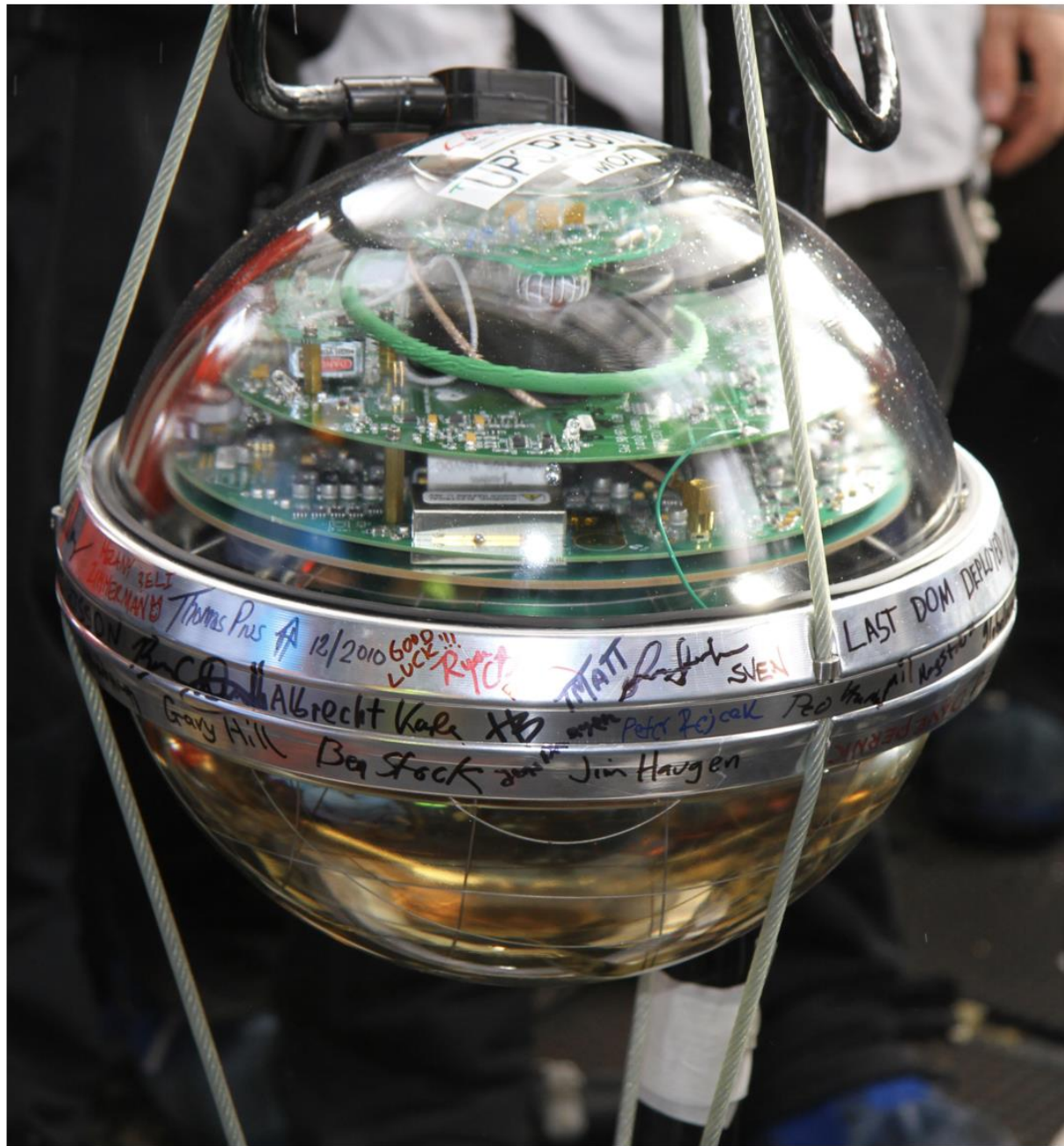


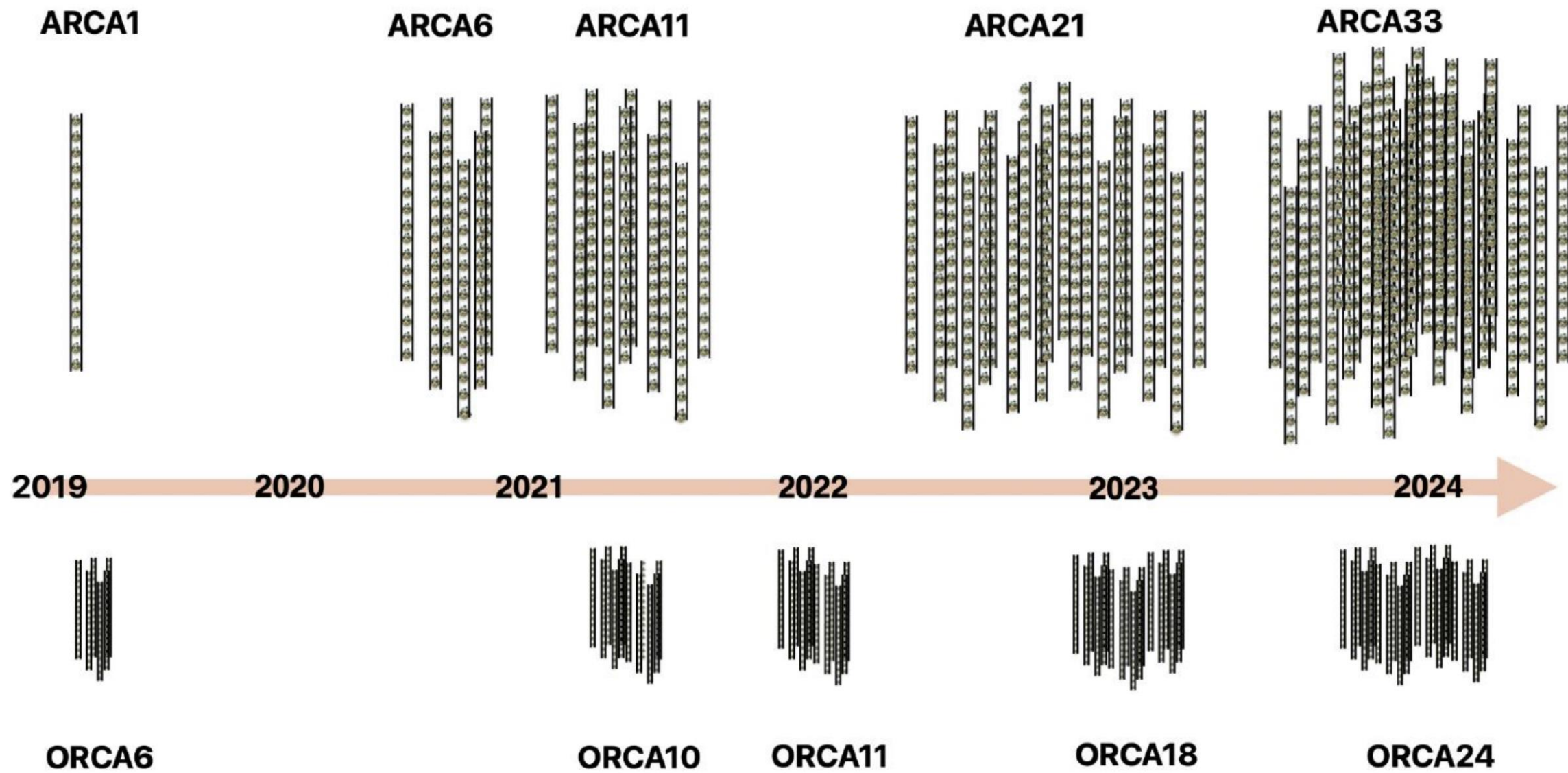
Likely Astrophysical origin instead of cosmogenic

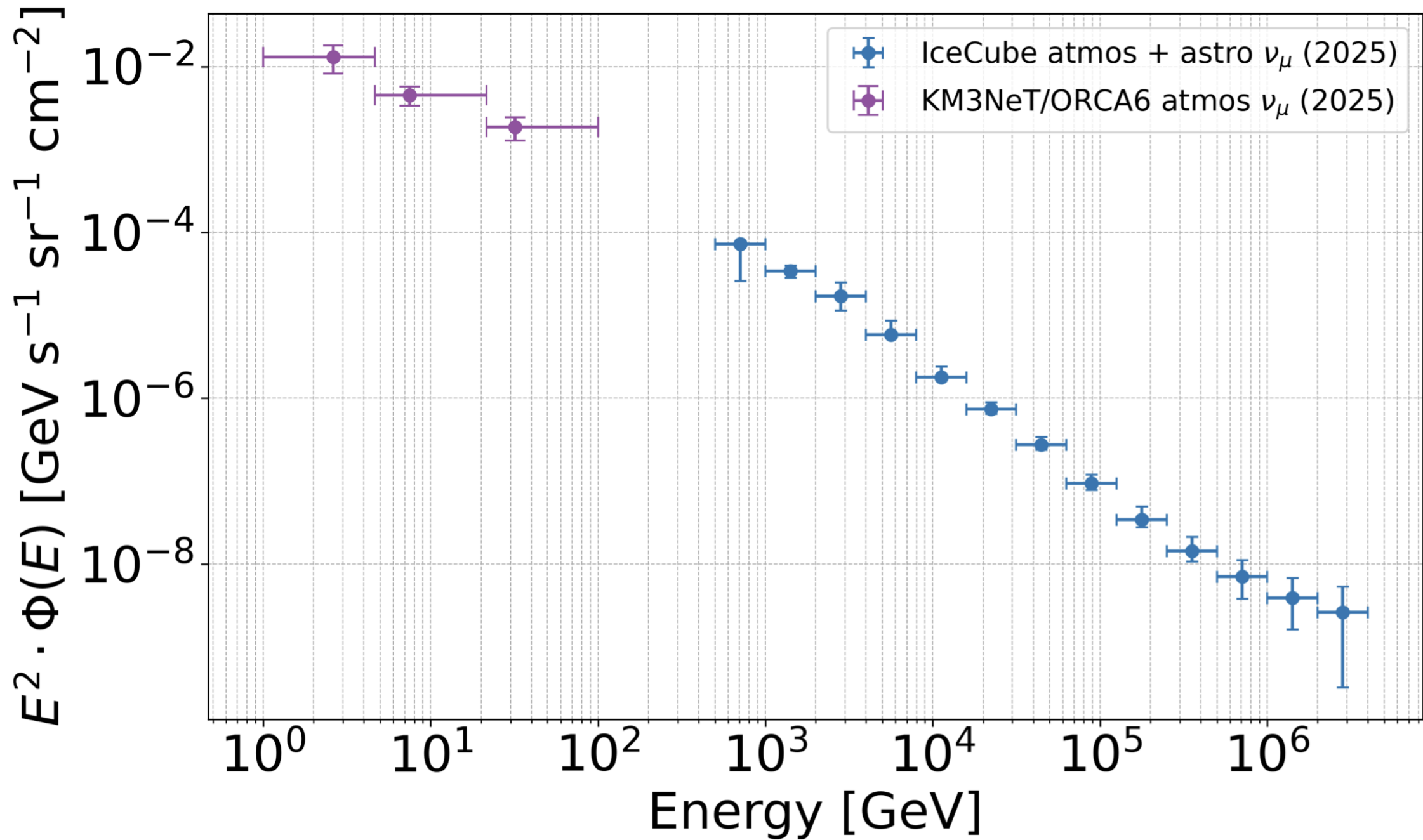
Differential Energy Reconstruction of 5 PeV Muon in IC-86







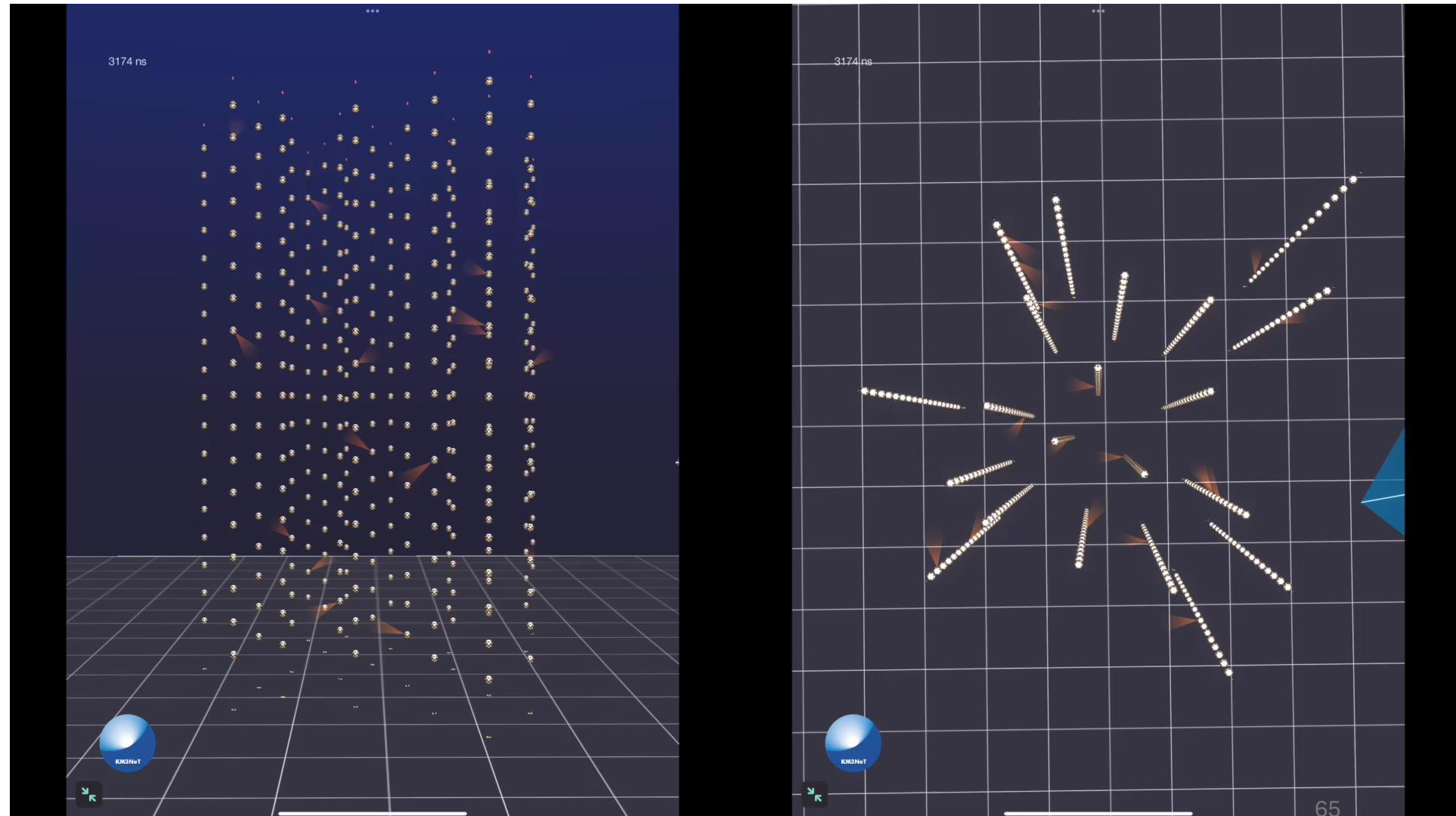
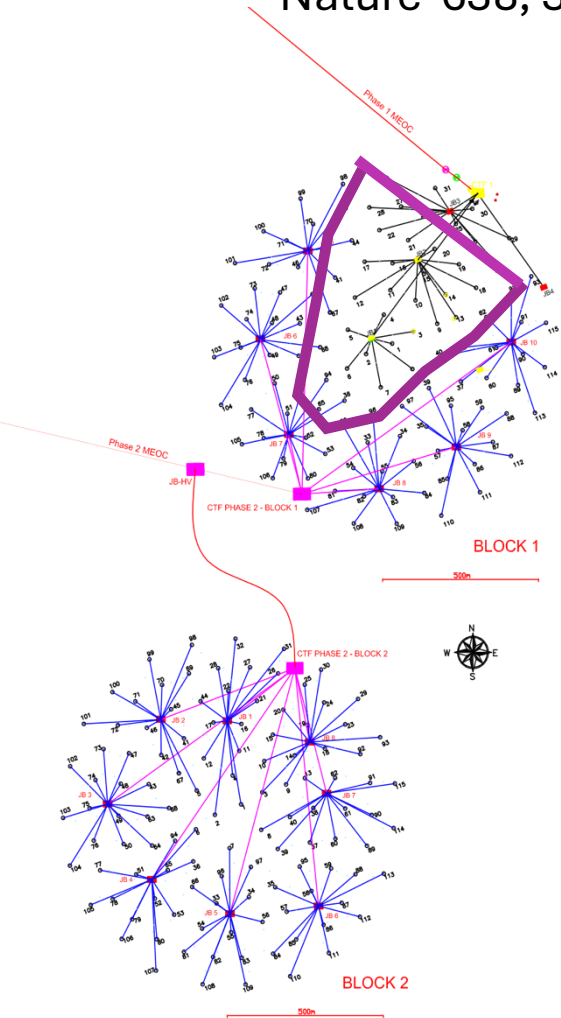


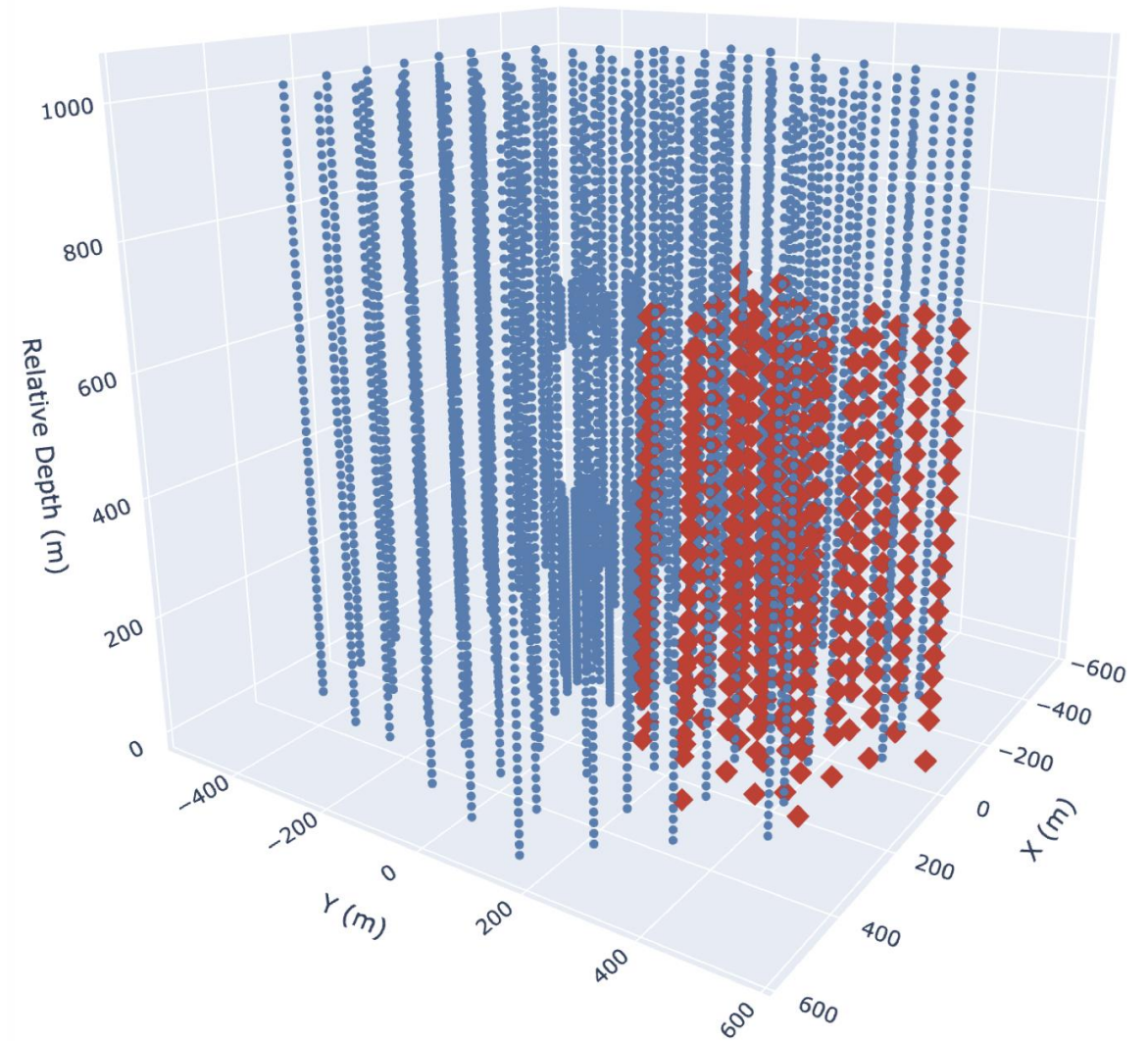
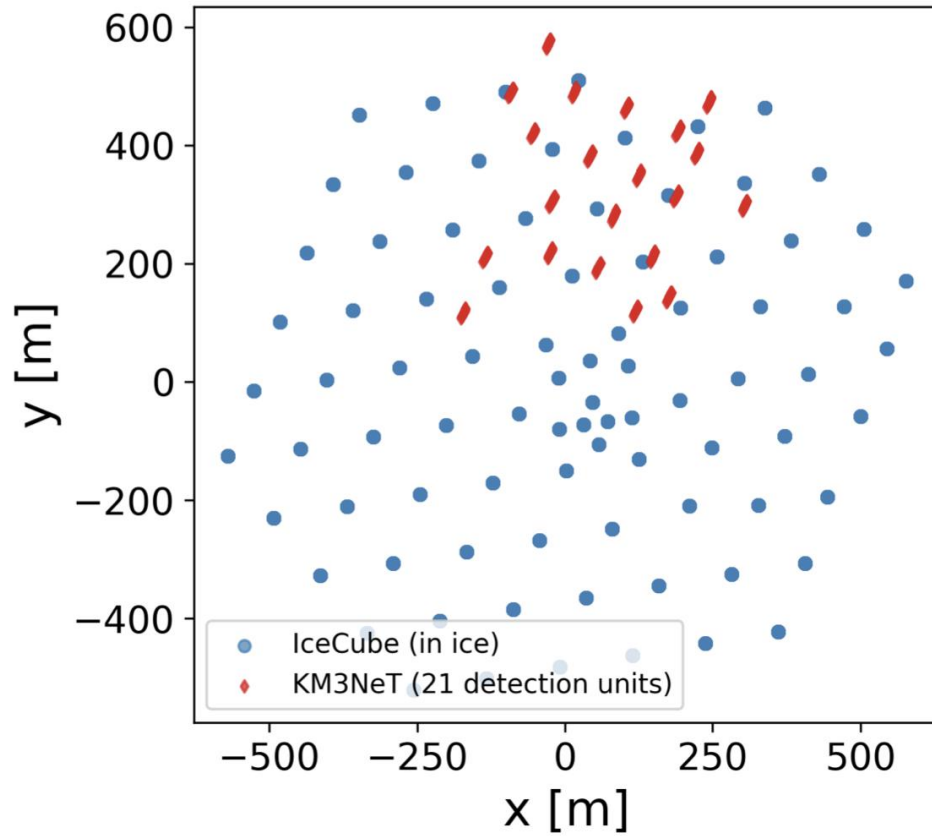


Km3net – an intriguing event

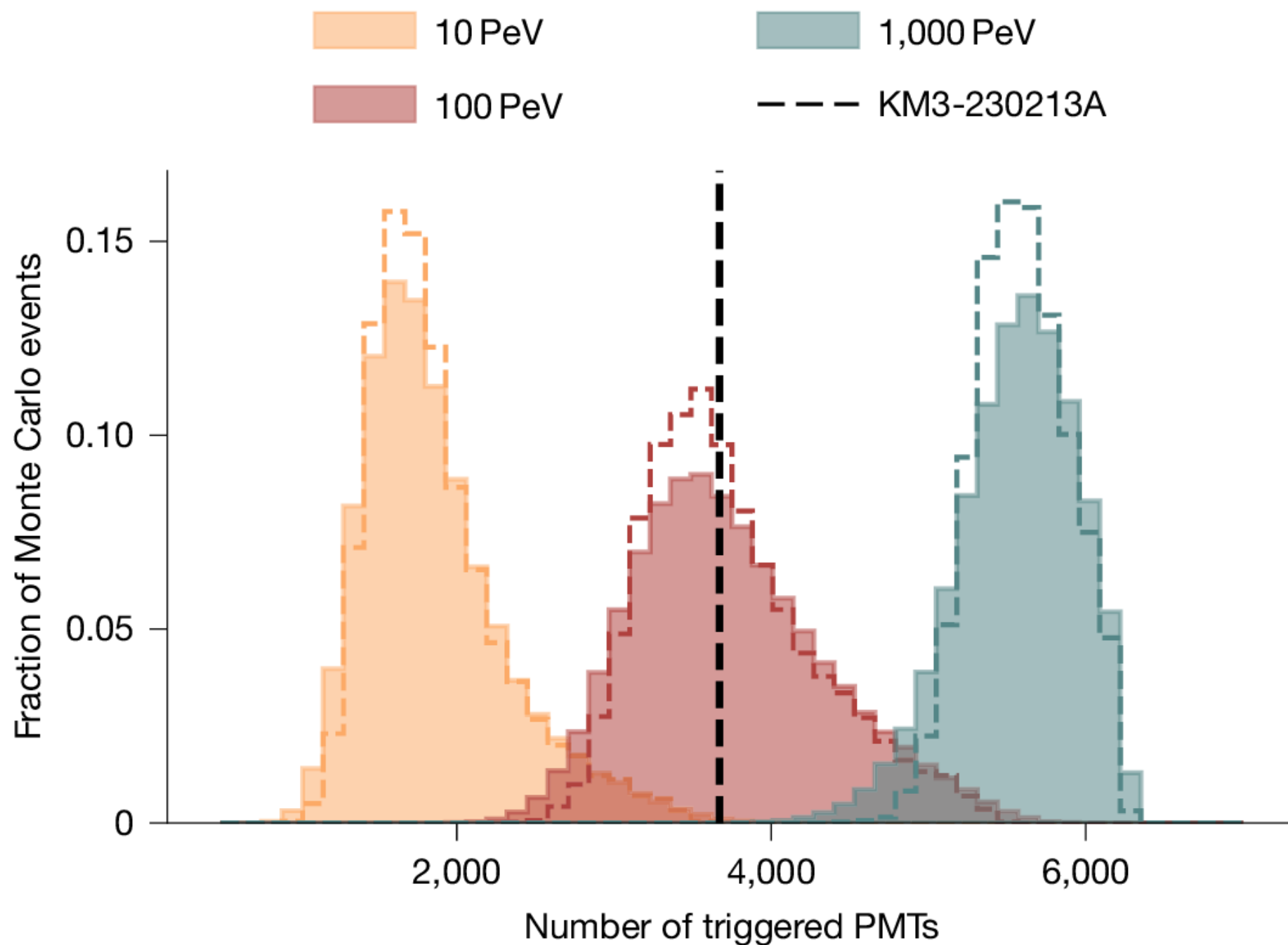
Nature 638, 376–382 (2025)

See ICHEP [talk](#) from Paschal Coyle

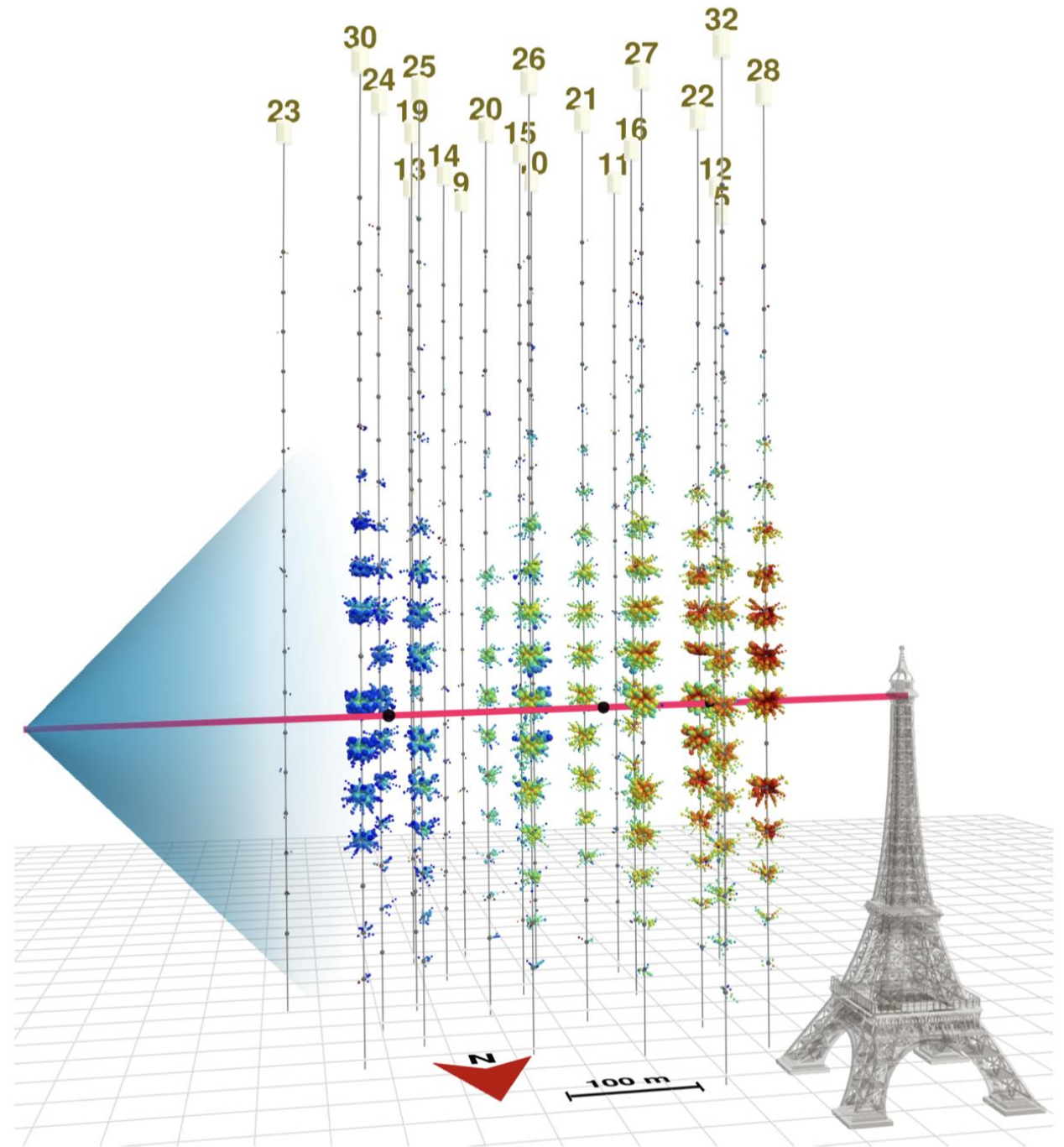
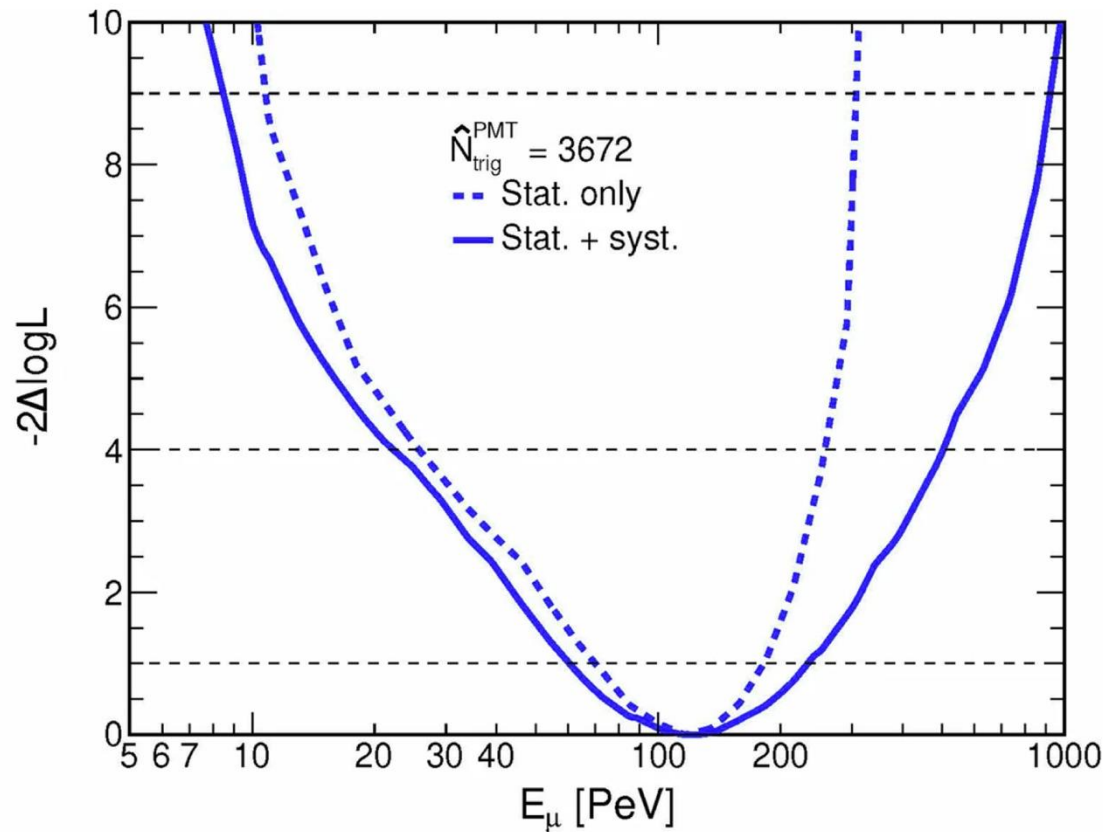




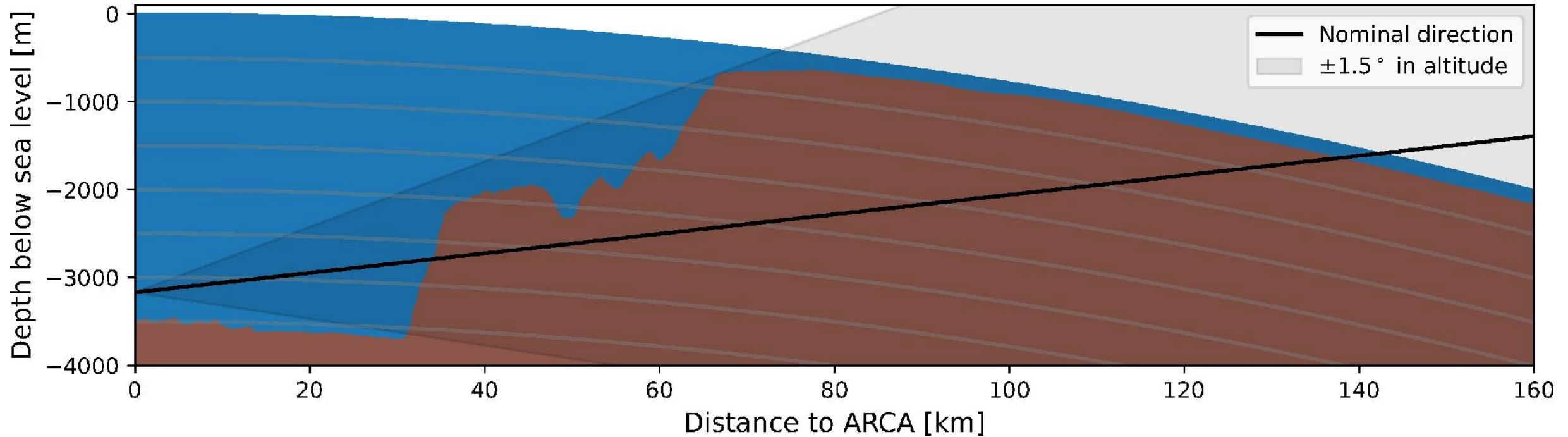
Muon energy

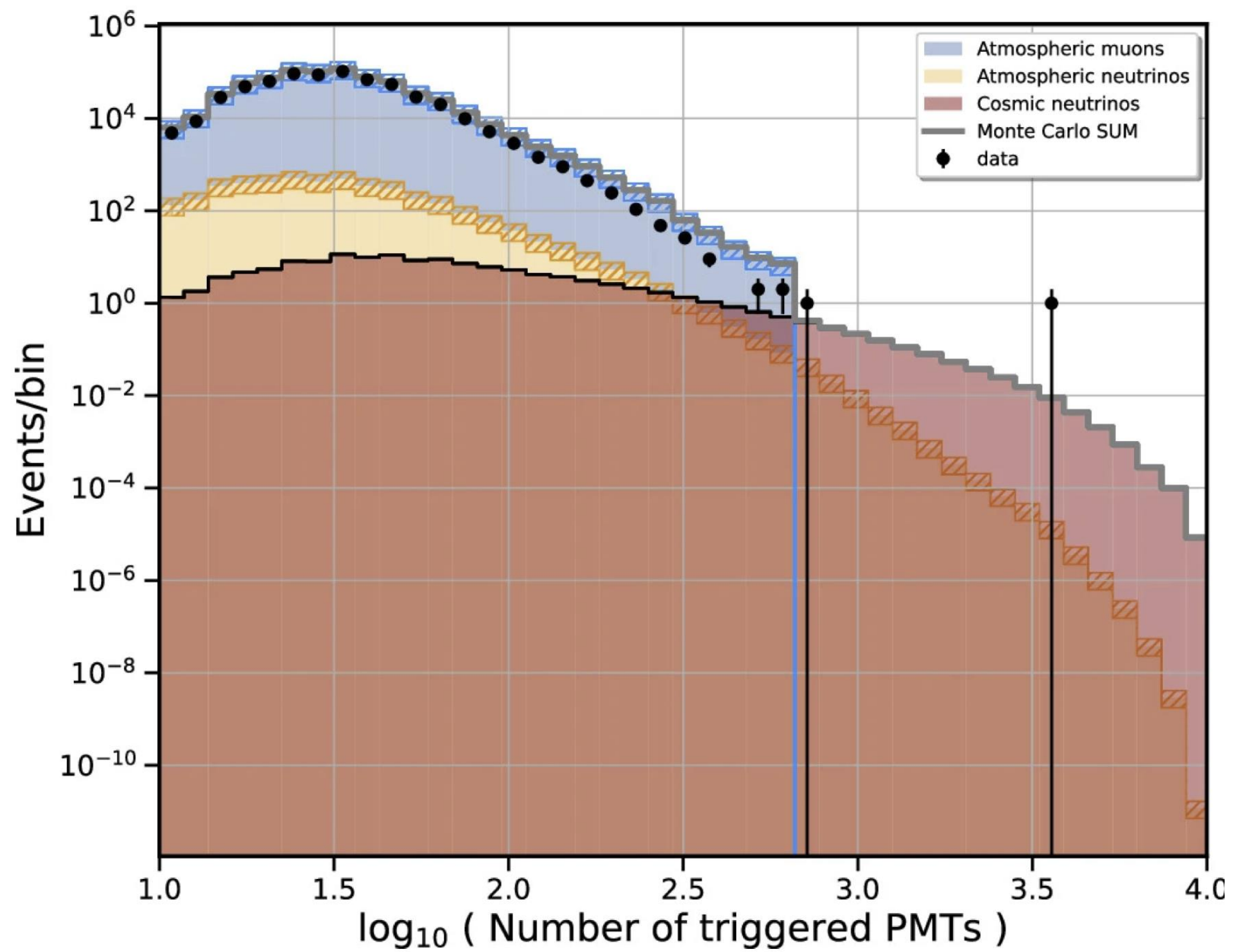


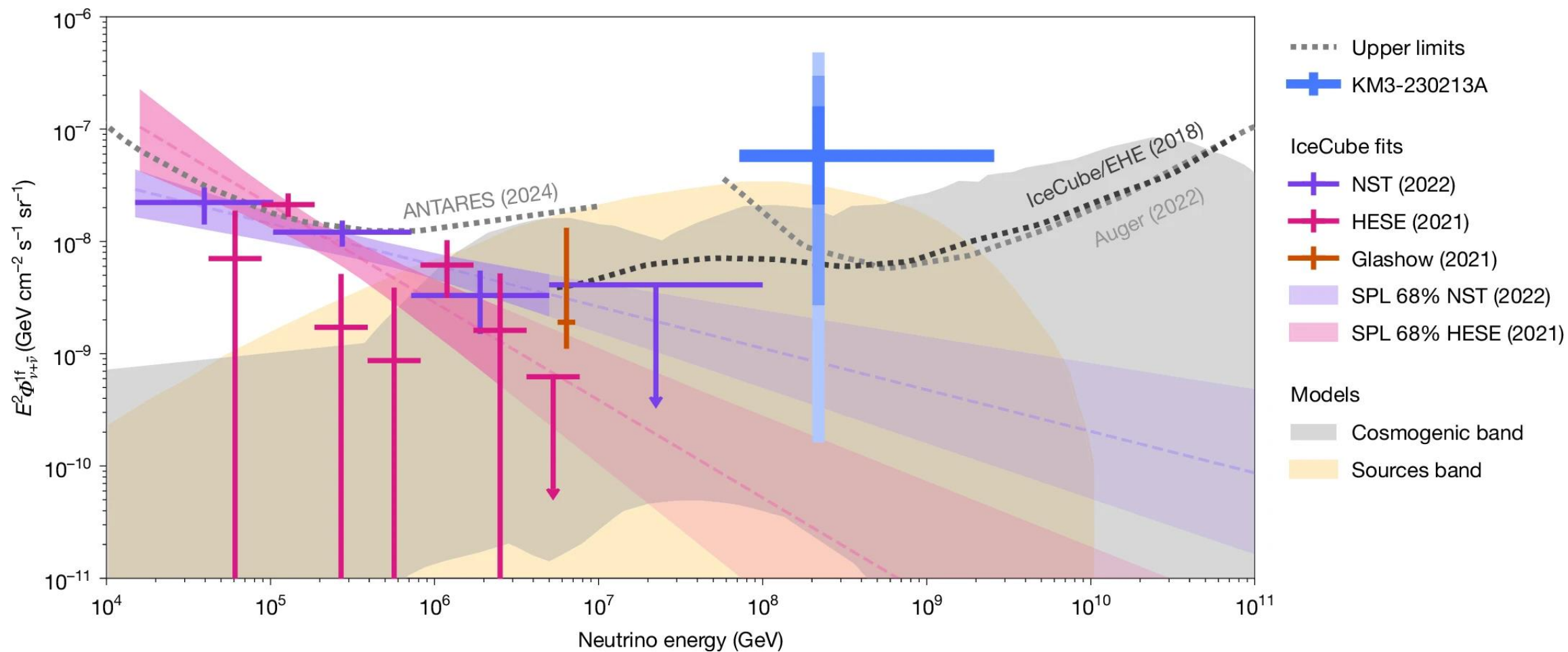
Energy proxy: number of PMTs

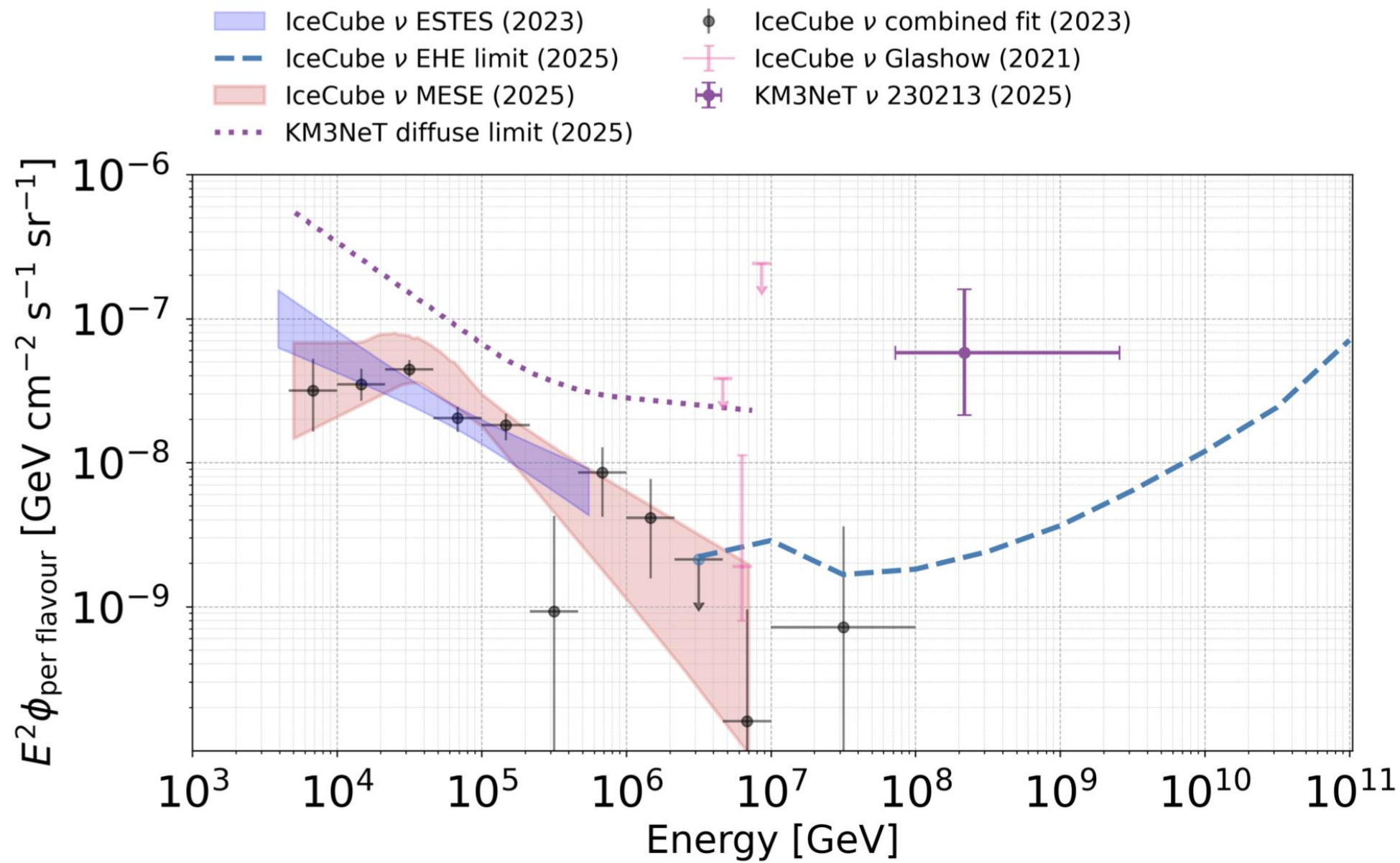


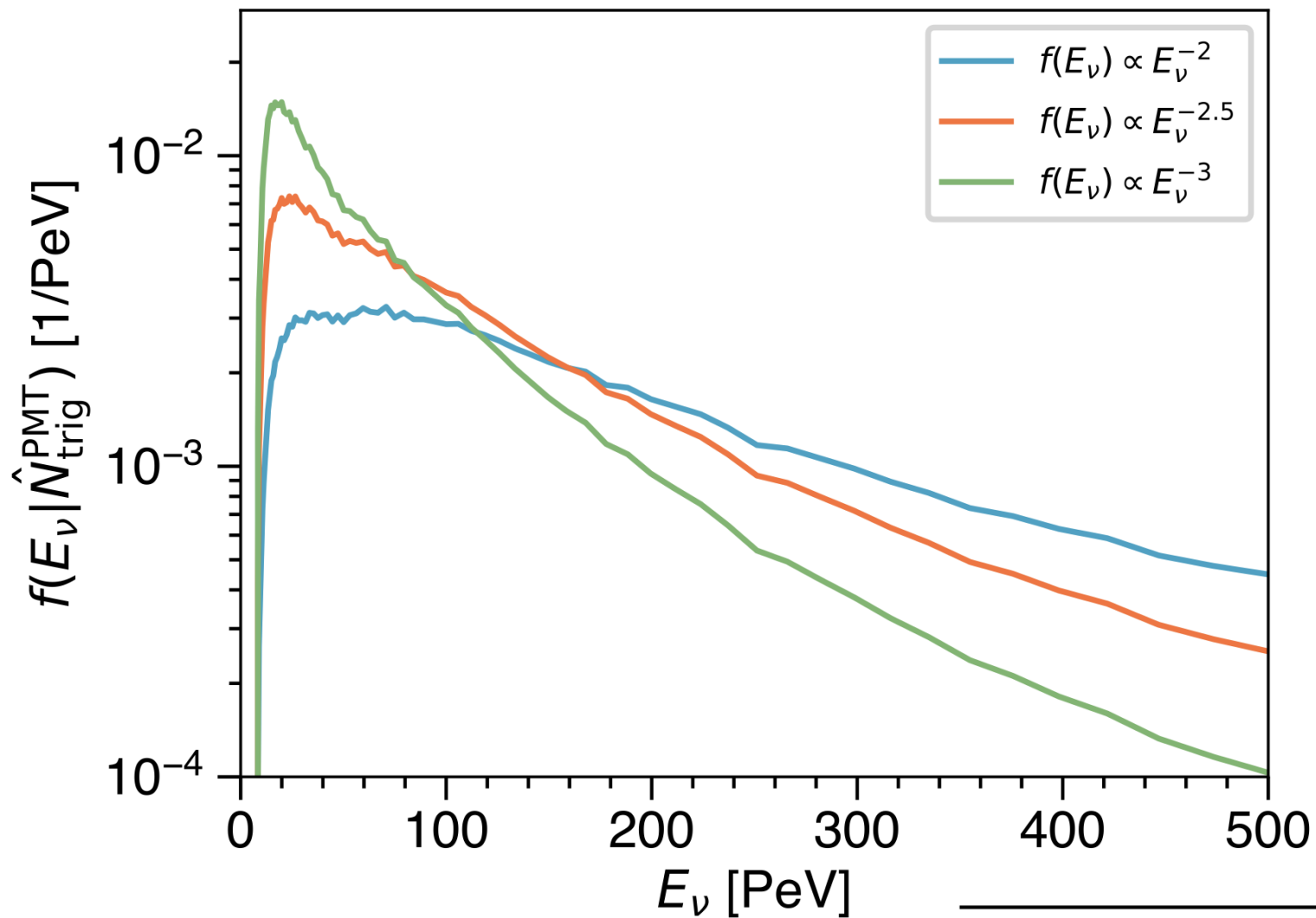
Zenith angle as the main argument of not a background









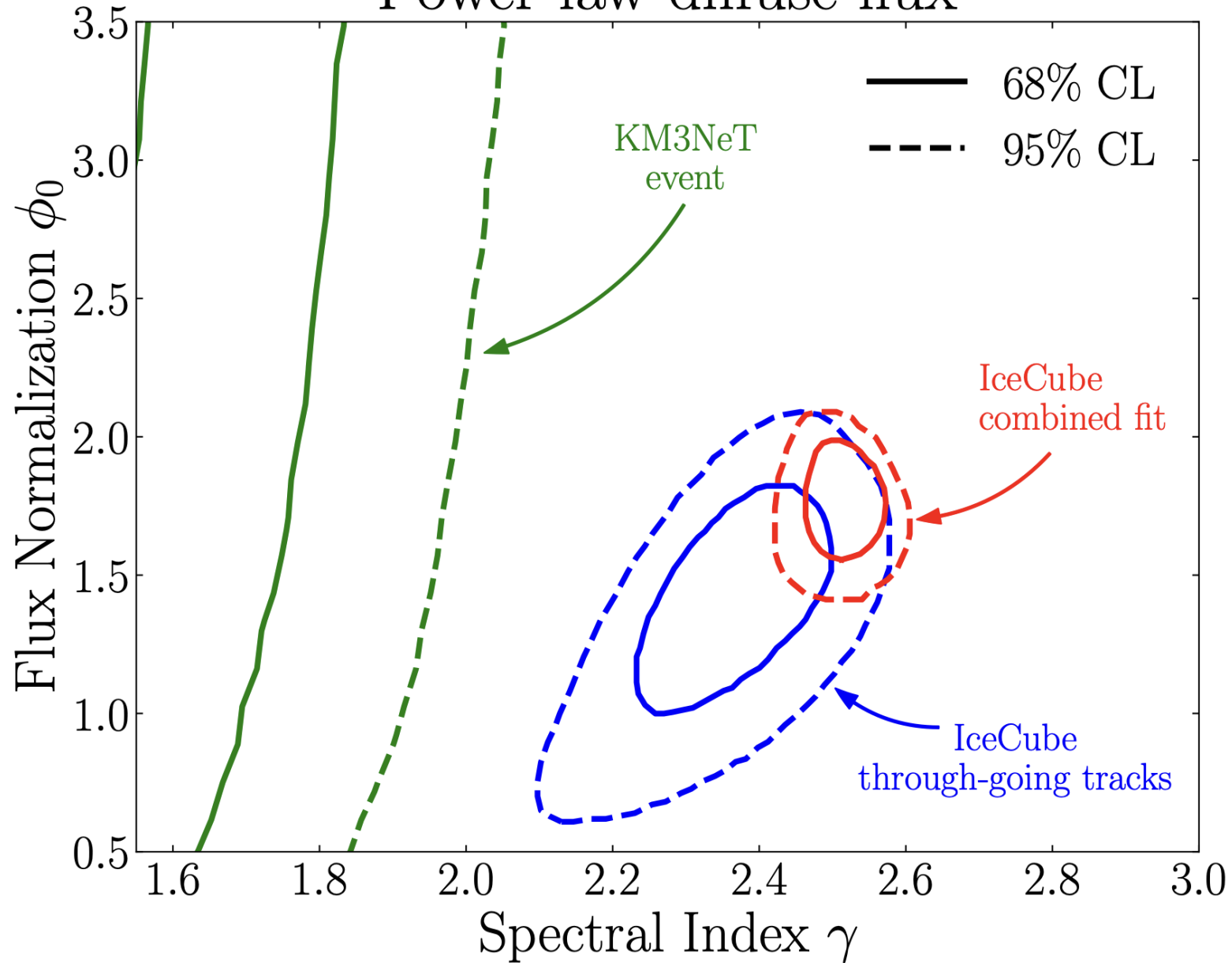


- Assuming E^{-2} spectrum:
- $\rightarrow E_\nu = 220_{-110}^{+570}$ PeV
- $\rightarrow$ Strong prior dependence, large energy uncertainty

Lu and Yuan *Highlights in High-Energy Physics* **2025**, 1 (2), 19.

Spectral index (γ)	Mode [PeV]	16% [PeV]	50% [PeV]
2	70	70	225
2.5	25	35	110
3	20	20	60

Power-law diffuse flux



Tension and possible origins

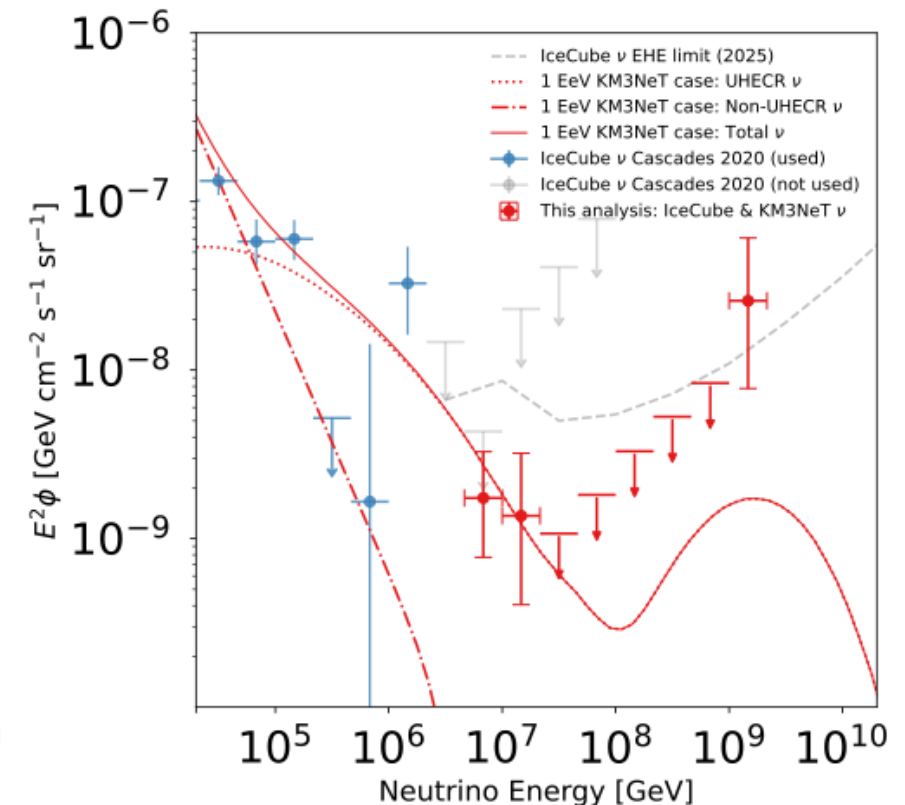
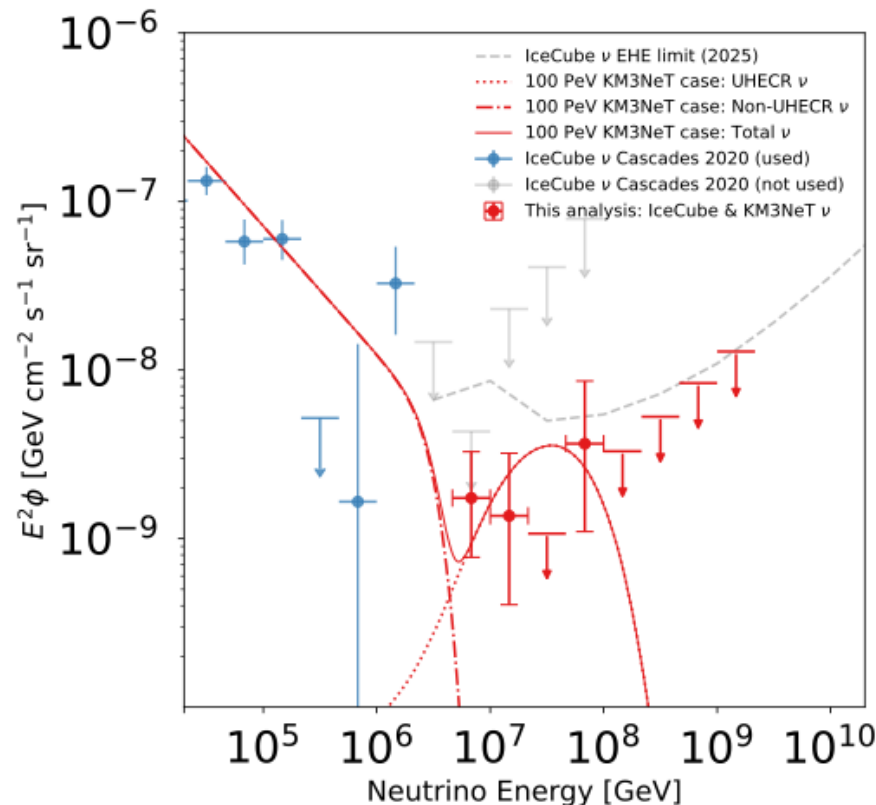


KM3NeT-only flux: expect >70 events 72 TeV – 2.6 EeV from IceCube's EHE analysis (2025 PRL 135 031001)

Combined analysis (IceCube + KM3NeT + Pierre Auger): Tension reduces to $\sim 2-3\sigma$. (arXiv:2502.04508, 2025 PRX 15 031016)

Possible origin of the event:

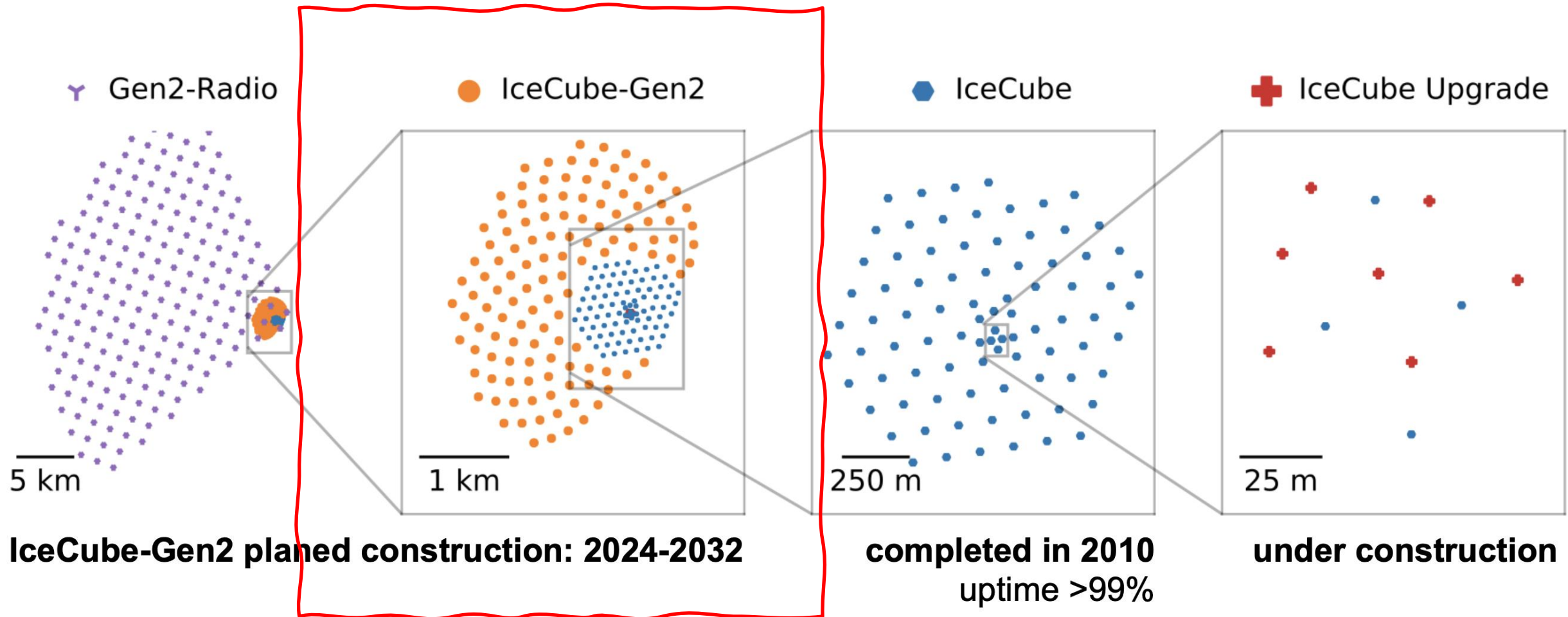
- p- γ at source: bump from the at around 30 PeV
- GZK cosmogenic neutrino



- PhD in University of Leeds (UK) and University of Wuppertal (Germany)
- Postdoc in Chiba University (Japan)



Future: optimising for from 10^9eV to 10^{19}eV



GeV...TeV...PeV...EeV

IceCube Gen2-optical, 10 times larger



Gentoo penguin

● Gen2-Optical

1 km

120 additional cables
12,000 optical sensors

Scope: 1. The Optical Cherenkov Array

The main detector component.

Surface Area: $\sim 6.5 \text{ km}^2$ (0.9)

Instrumented depth: 1.26 km (1.0)

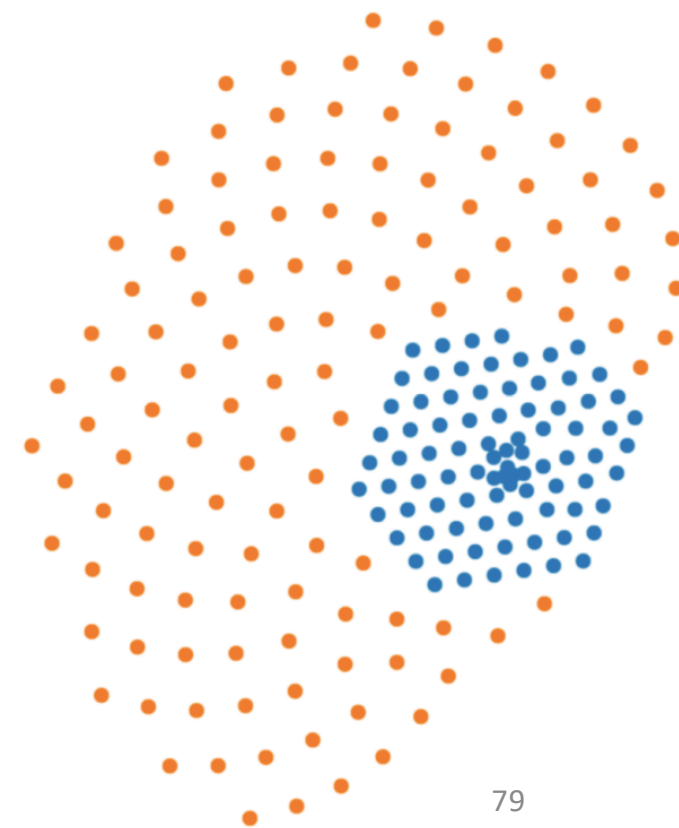
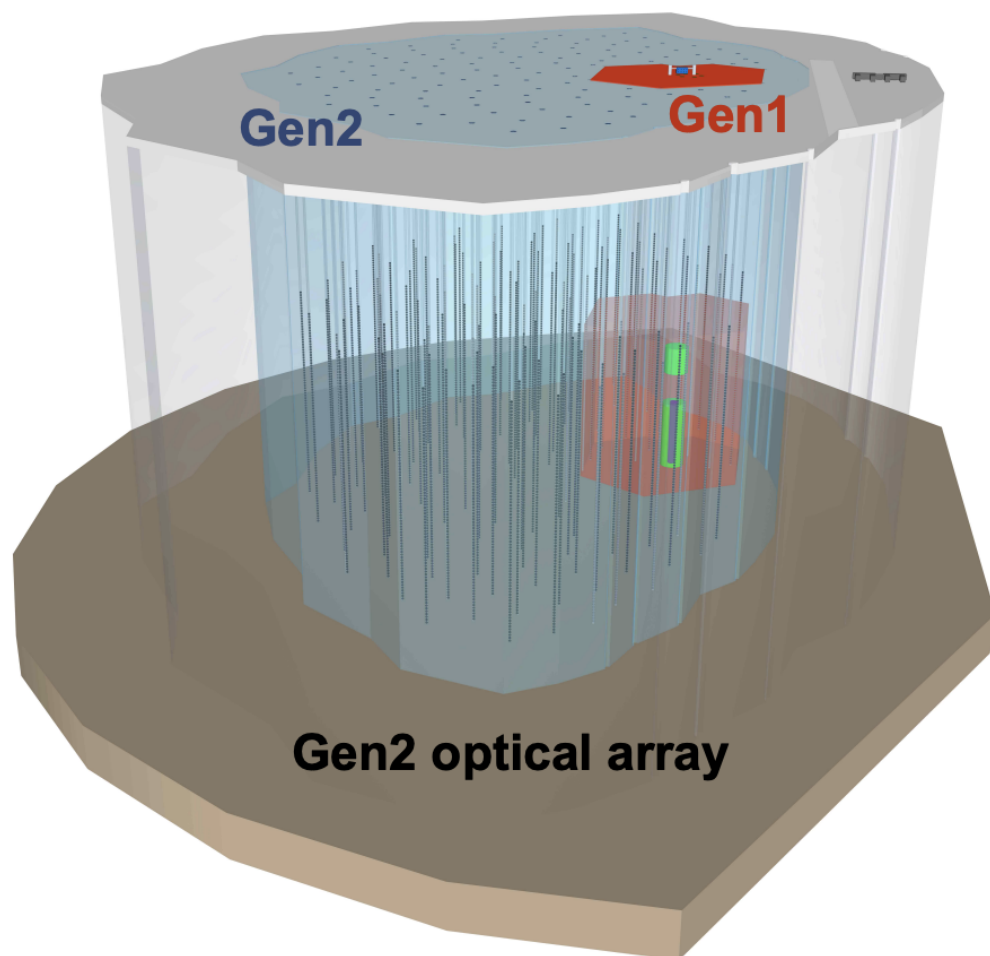
Instrumented Volume: 8 km^3

Order of magnitude increase

9600 optical sensors

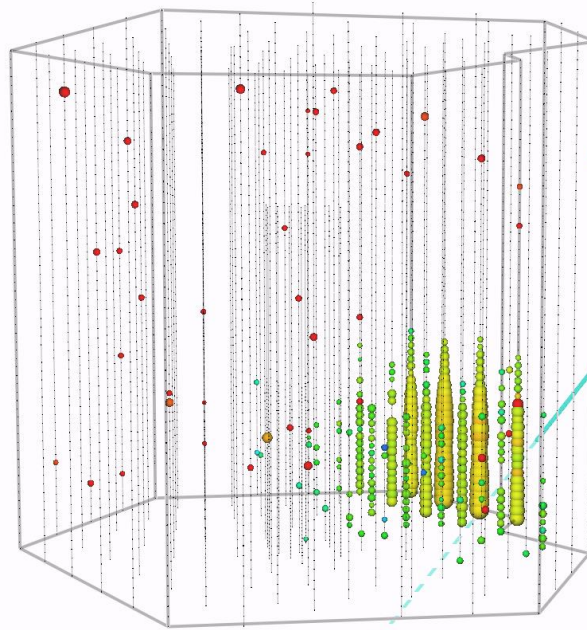
—> 8 x Photon detection area

120 strings



CAN YOU GUESS WHAT TYPE OF EVENT IS THIS?

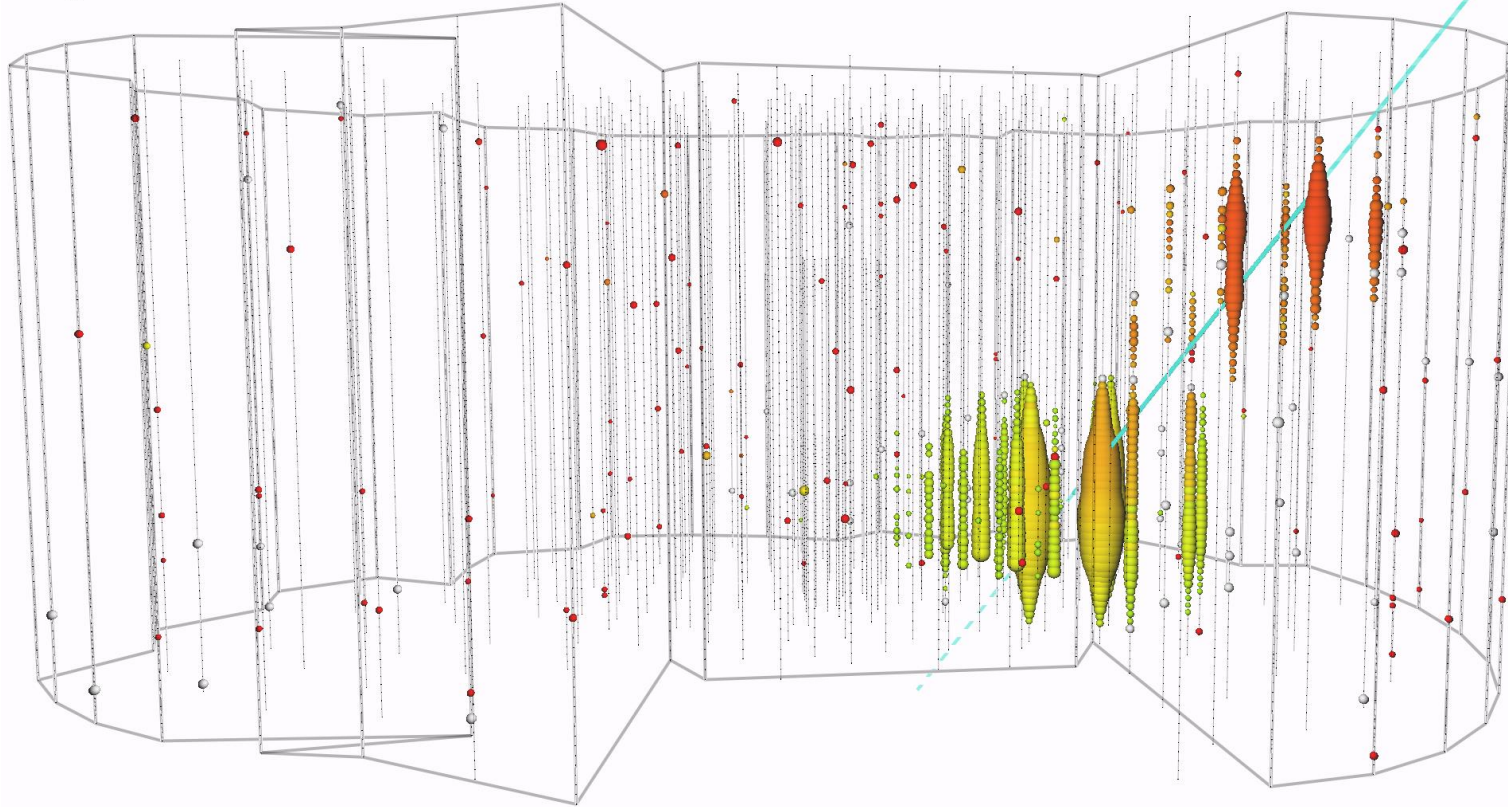
Neutrino? Background?



Partially contained cascades: one of the most difficult topologies to rescue in IceCube

THE SAME NUTAU EVENT SEEN IN ICECUBE-GEN2

Interaction:
NuTau -> TauMinus + Hadrons
Primary
Type : NuTau
Energy: 1.80e+07GeV
Neutrino
Type : NuTau
Energy: 1.80e+07GeV

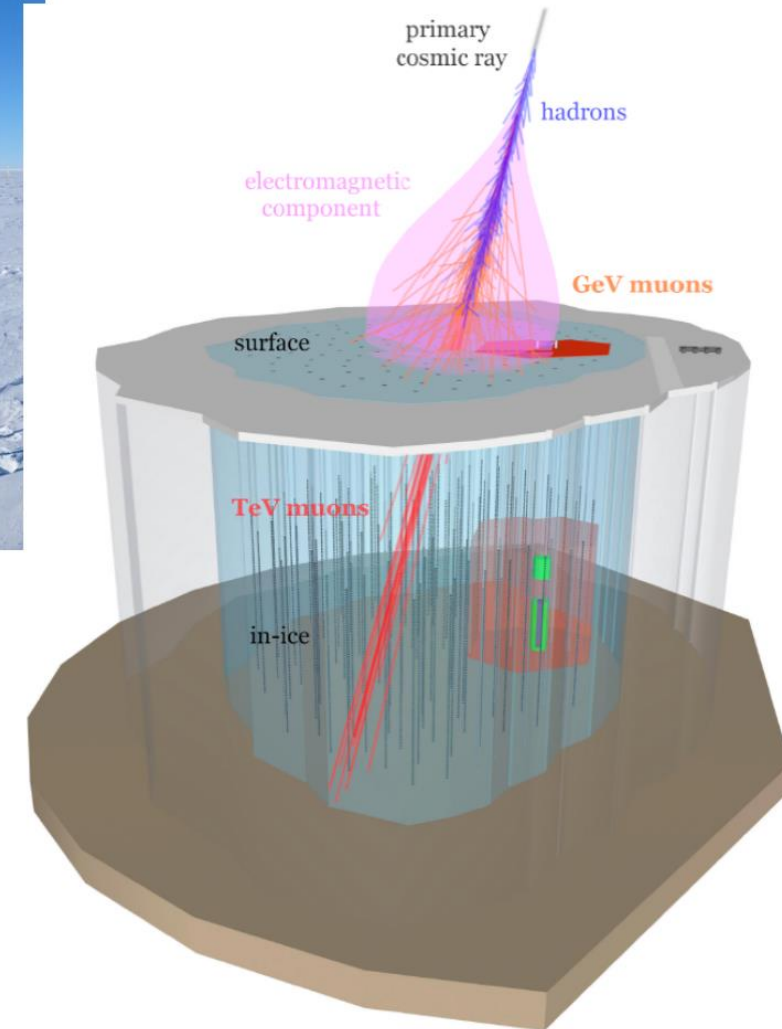
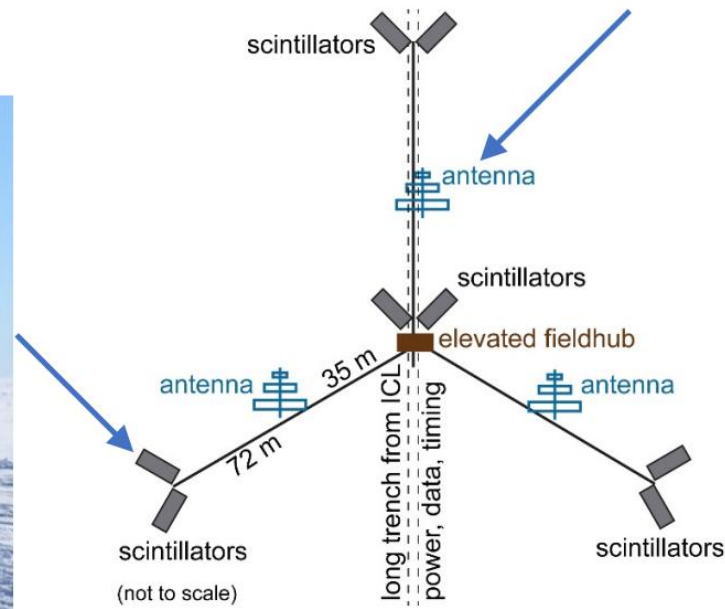
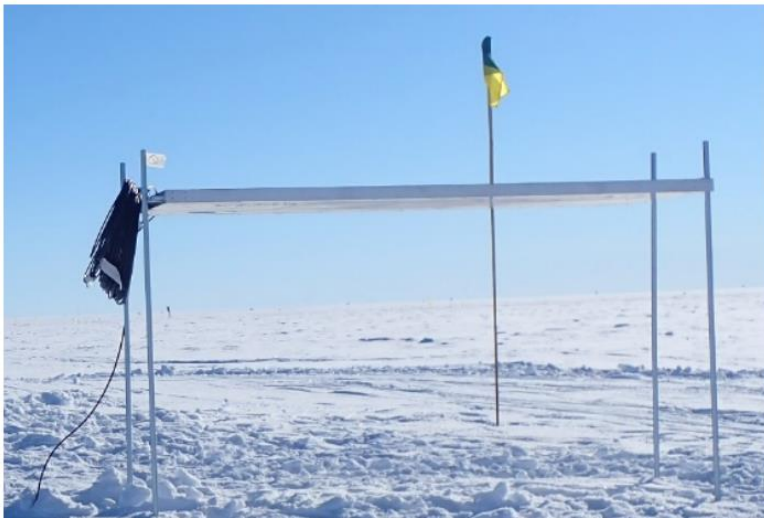


10 PeV ~ 500m

This event has been selected by the double cascade selection for Gen2

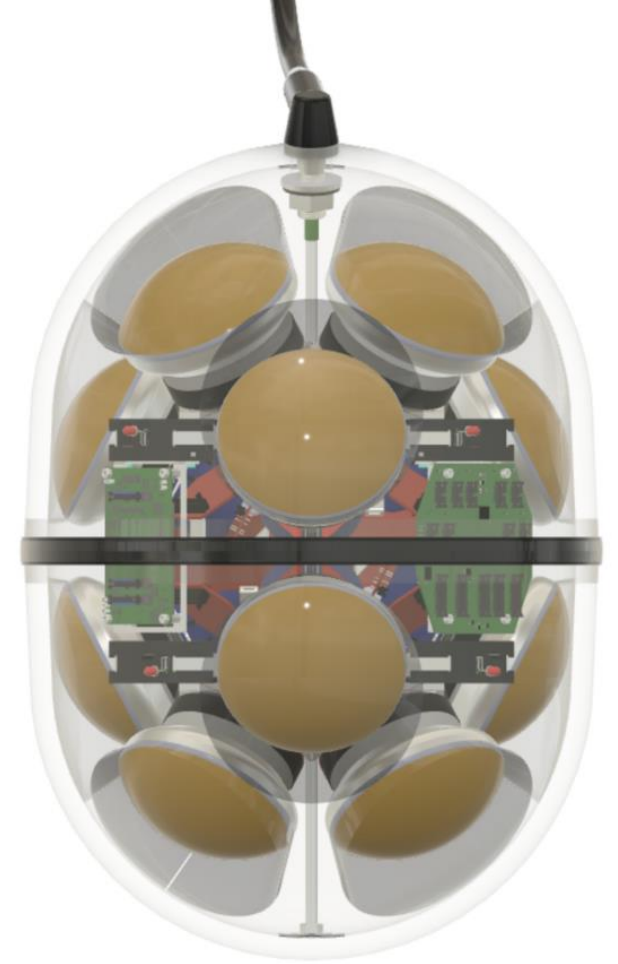
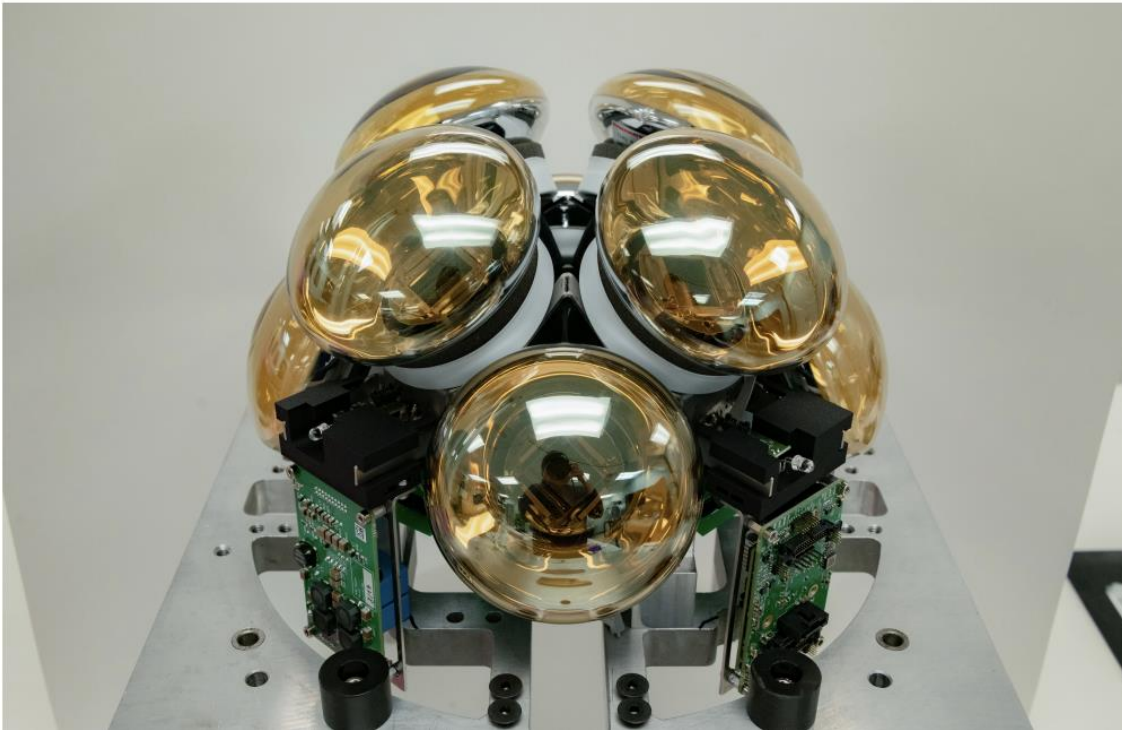
Scope: 2. The Surface Array

- Veto for larger and purer sample of PeV neutrino candidates
- High accuracy for cosmic rays in the PeV to EeV region
 - particle physics in air showers
 - cosmic-ray astrophysics



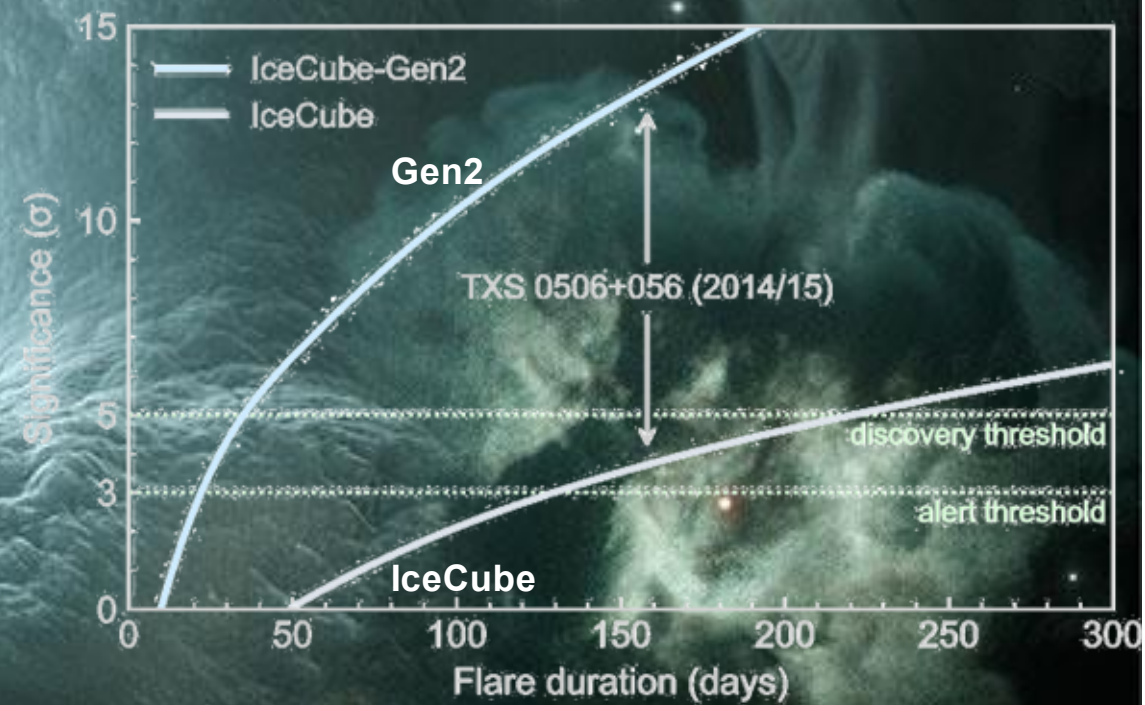
Sensor and Electronics

- **MDOM concept**
- **4-inch PMTs developed for IceCube-Gen2**
(Hamamatsu and NNVT)
- **4 x sensitivity**
- **100 times dynamic range**
- **Less power ($<5\text{W/DOM}$)**

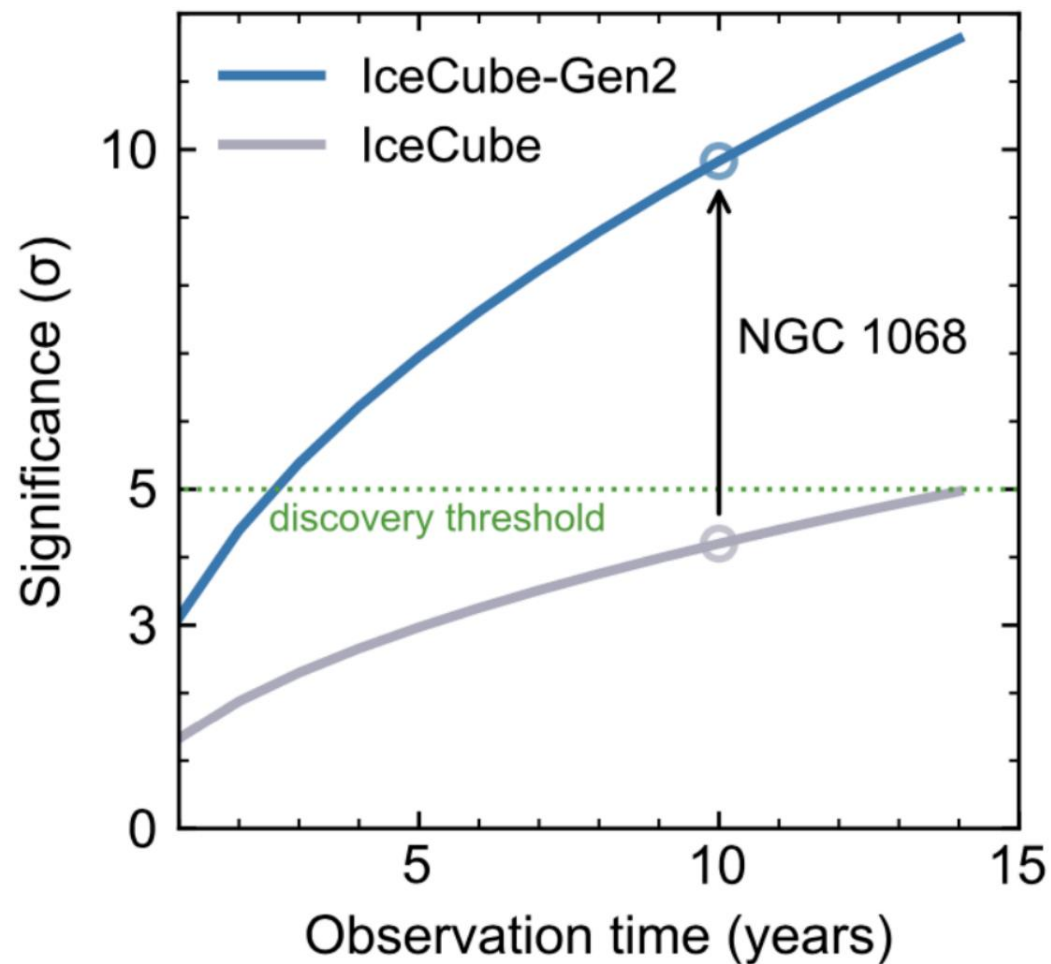


16 or 18 x 4 inch PMT
Diameter: 31 cm

GeV...TeV...PeV...EeV

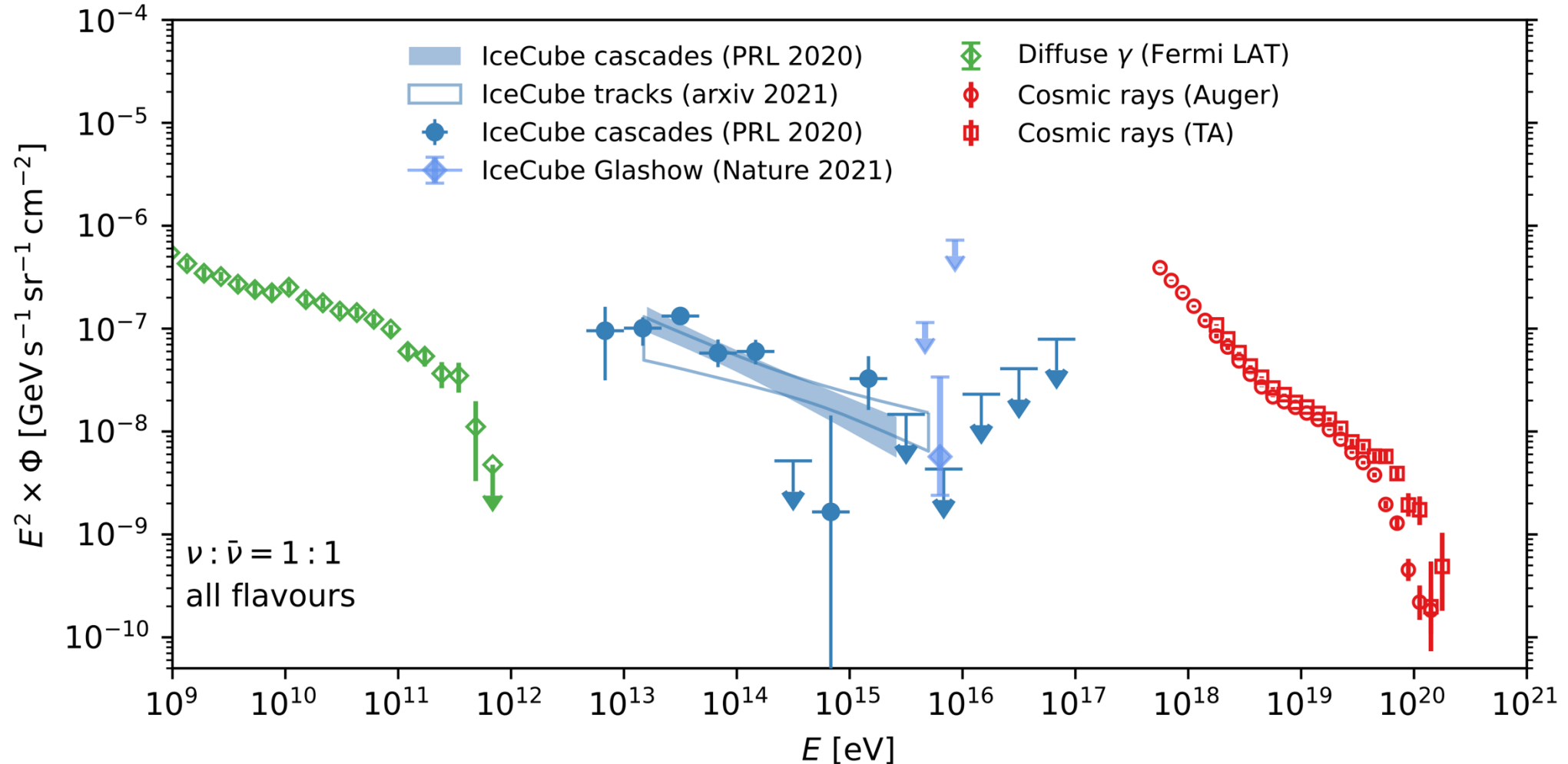


5 sigma in < 2 years
10 sigma in 10 years.



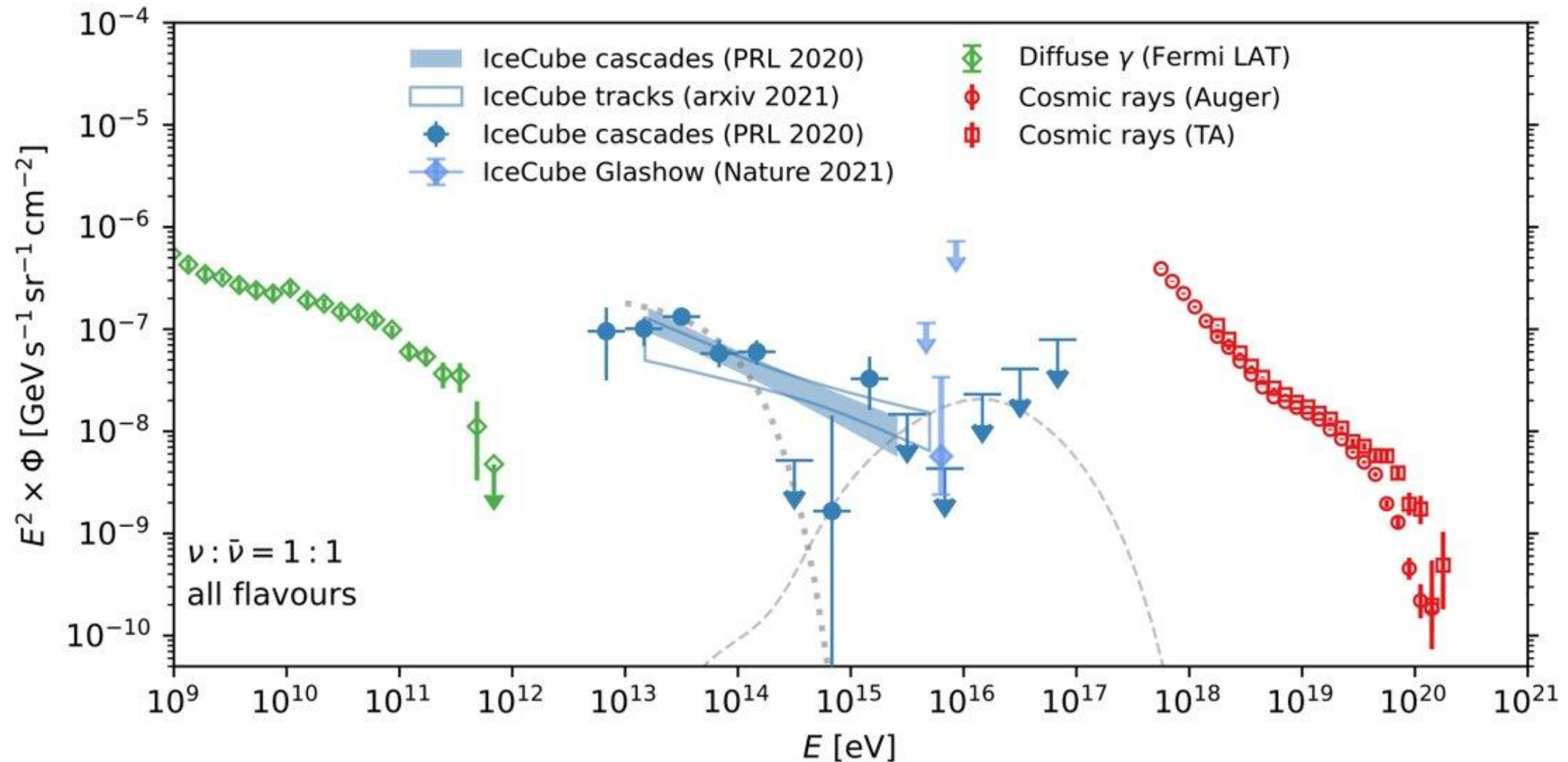
NGC 1068 in ICeCube-Gen2

ICECUBE: ESTABLISHED DIFFUSE NEUTRINO FLUX



Energy density similar with gamma and UHECR

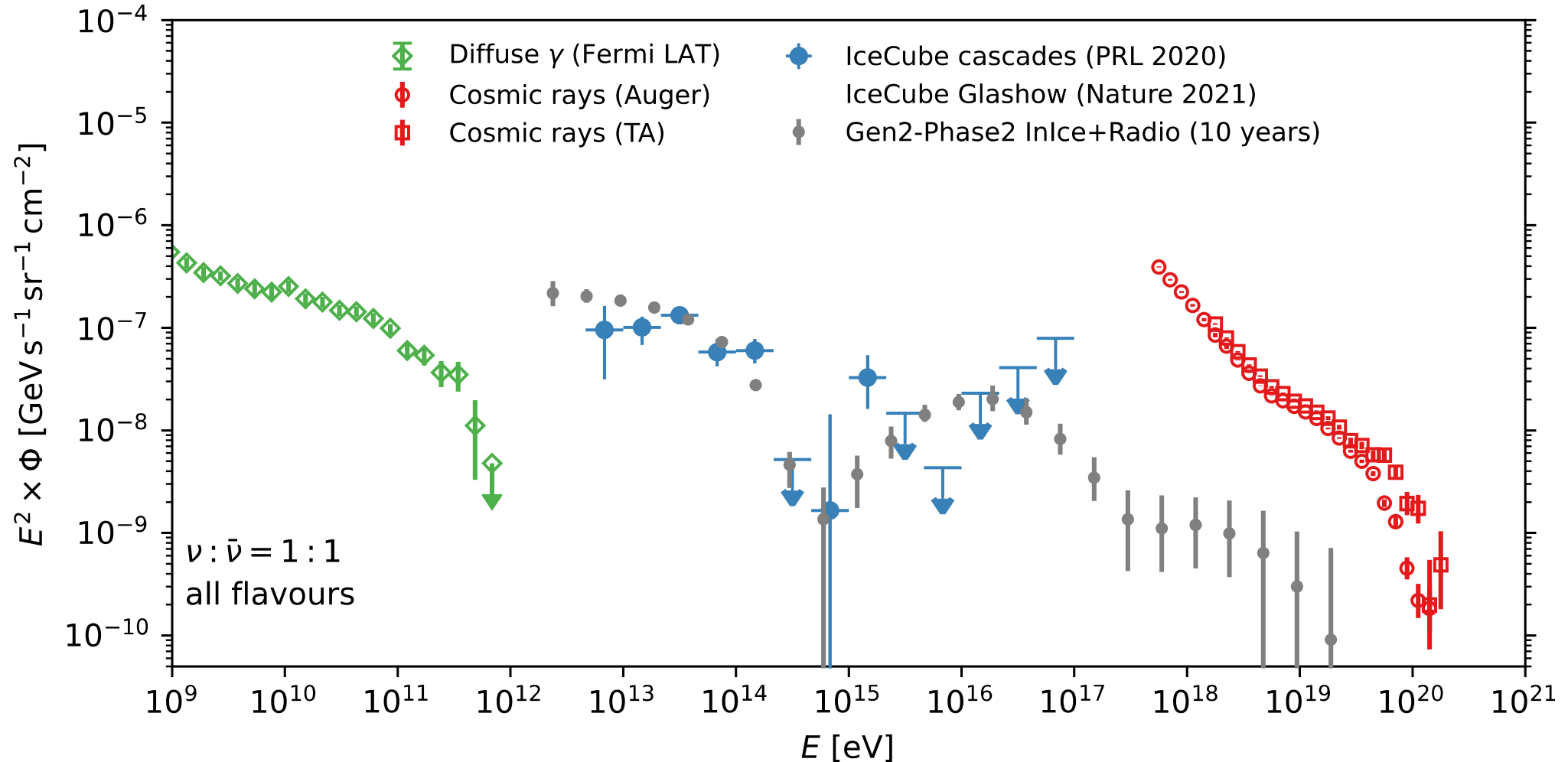
10 PEV NEUTRINOS GATEWAY TO 10^{20} EV PARTICLES



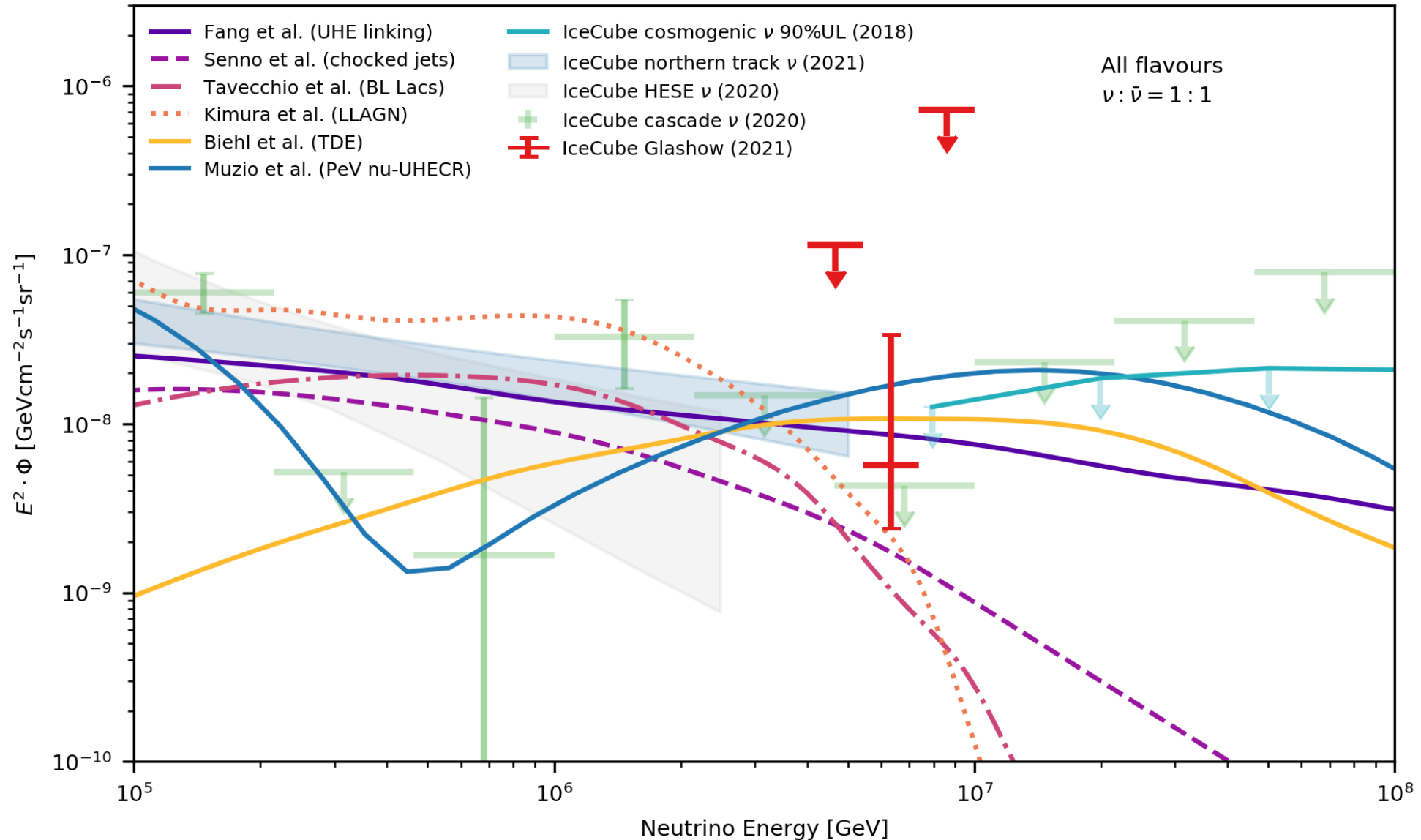
A common origin with UHECR?

10 YEARS OF GEN2 DATA TAKING

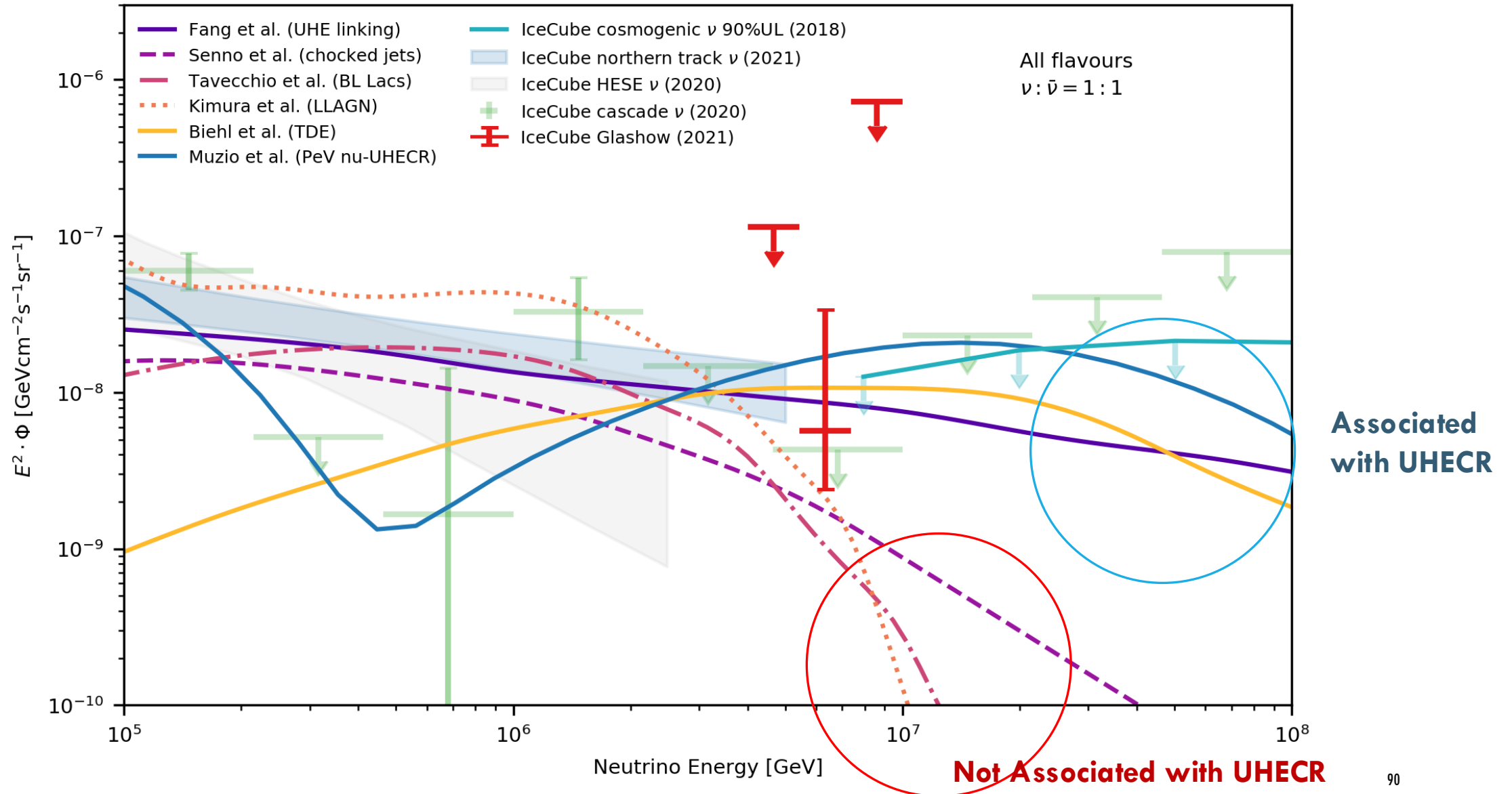
Pin down 10 PeV connection with UHECR



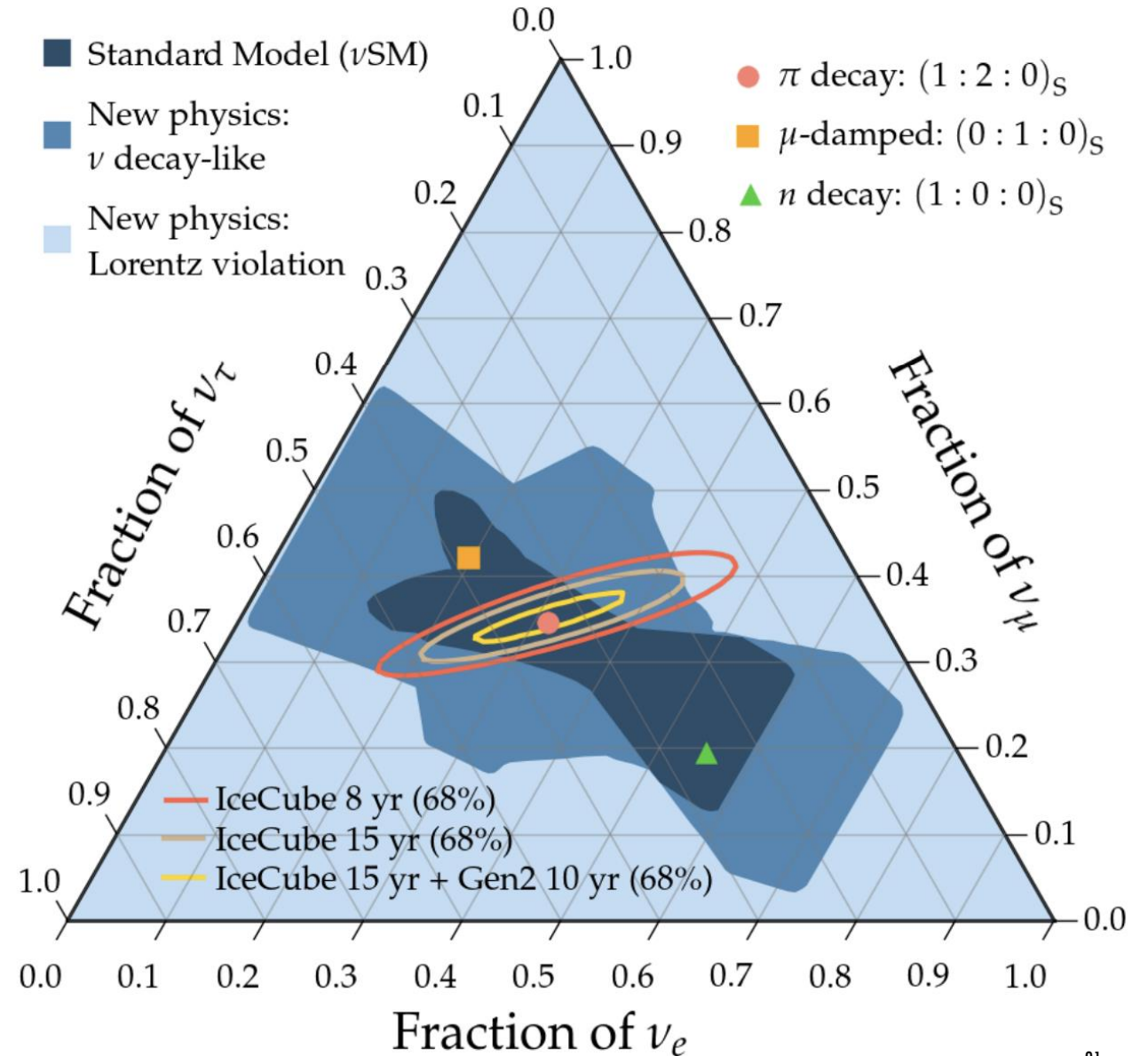
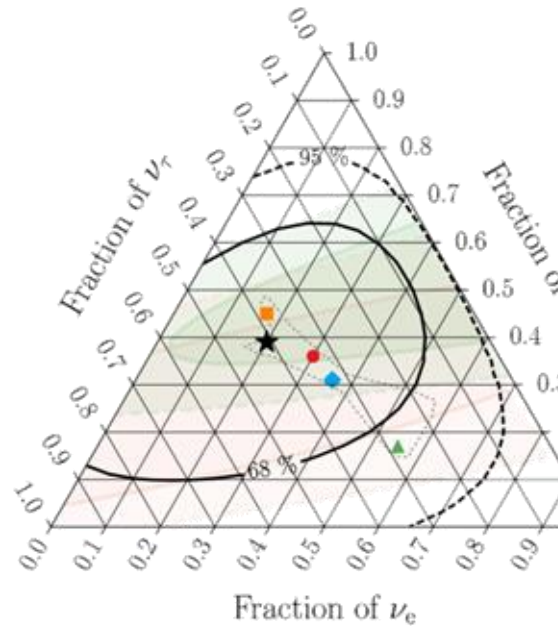
10 -100 PEV KEY TO UNDERSTAND SOURCE ORIGINS



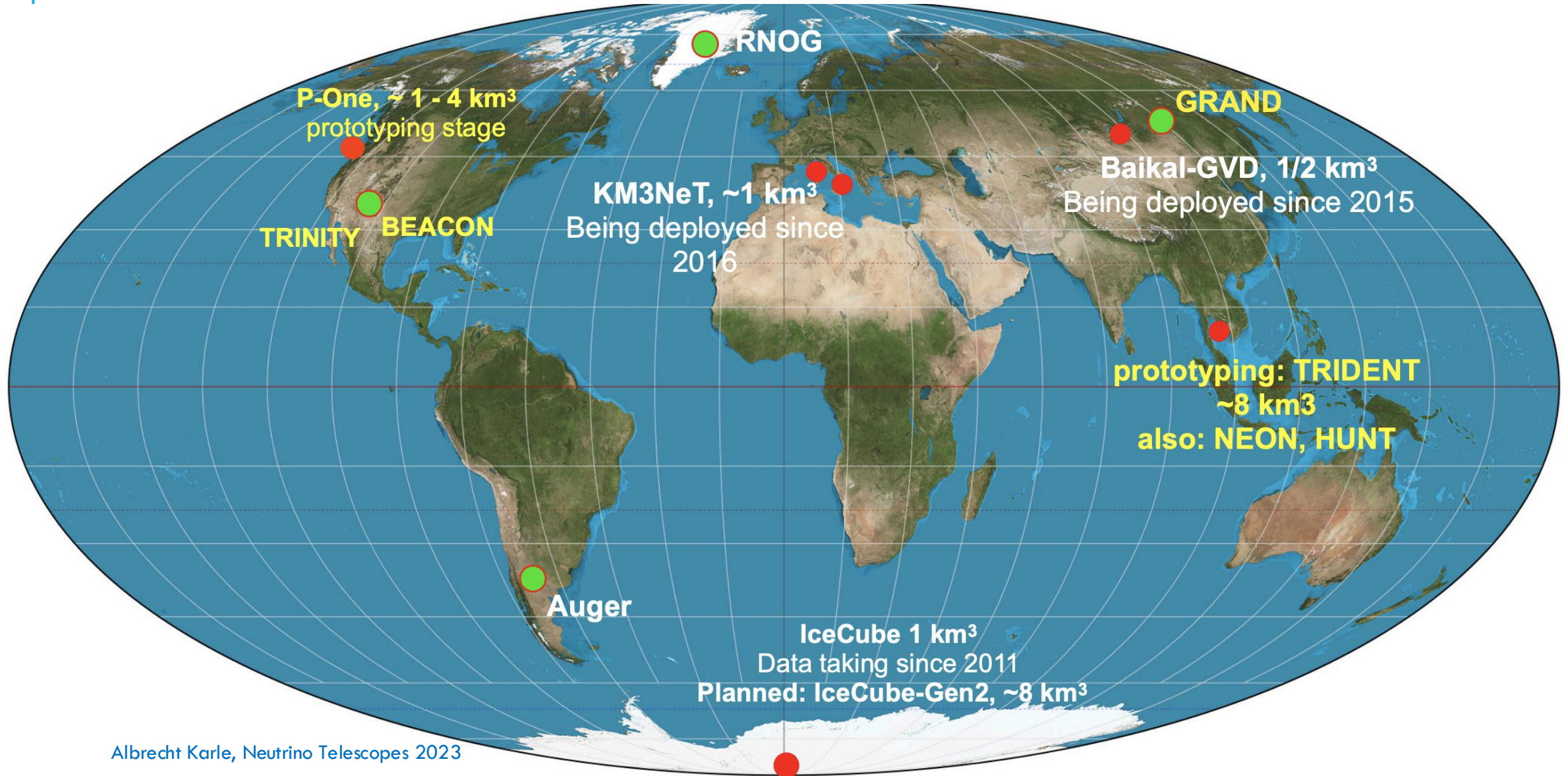
10 -100 PEV KEY TO UNDERSTAND SOURCE ORIGINS



GEN2: BEYOND STANDARD MODEL WITH FLAVOUR



UNDER WATER/ICE CHERENKOV LANDSCAPE



KM3NET

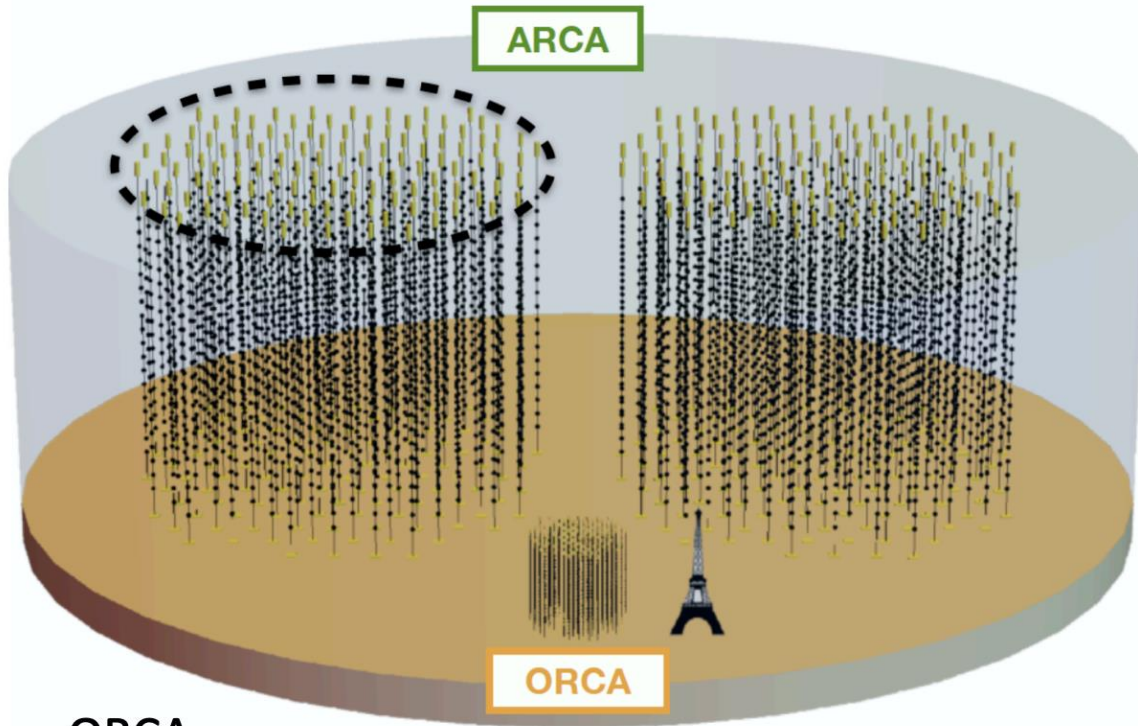
ARCA

100 km from Sicily

Instr. Mass: 2×0.5 Gt

1 Block:

115 strings (detection units)
each with **18 optical sensors**



ORCA

40 km from Toulon, France

Instr. mass: 5-8 Mtons

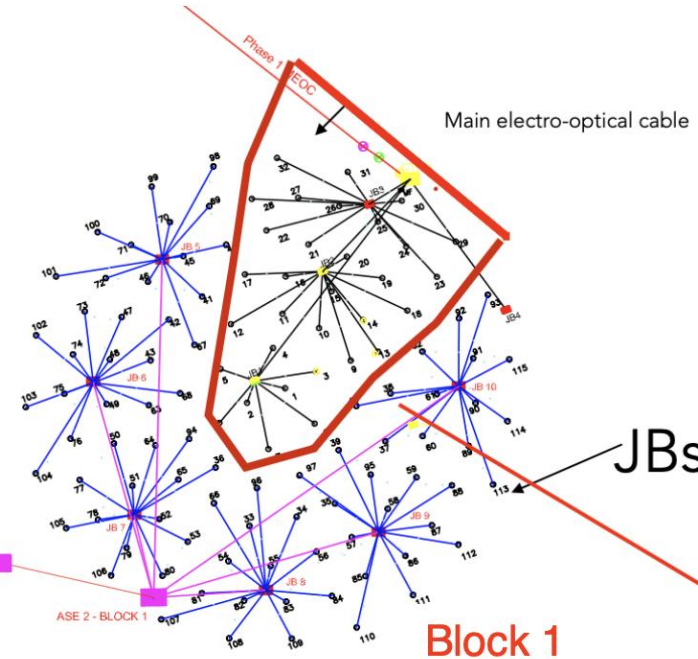
status: 11 of 115 DUs deployed



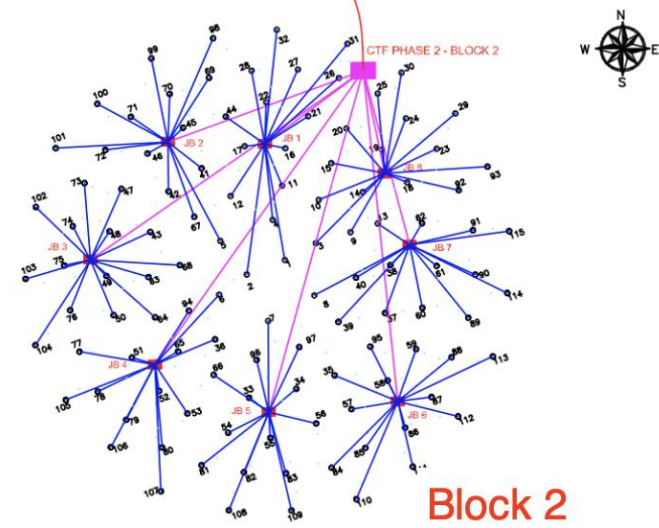
ARCA (Italy)

Main electro-optical cable

Phase 2 MEOC



**28 (of 230) DUs
deployed**
504 optical modules

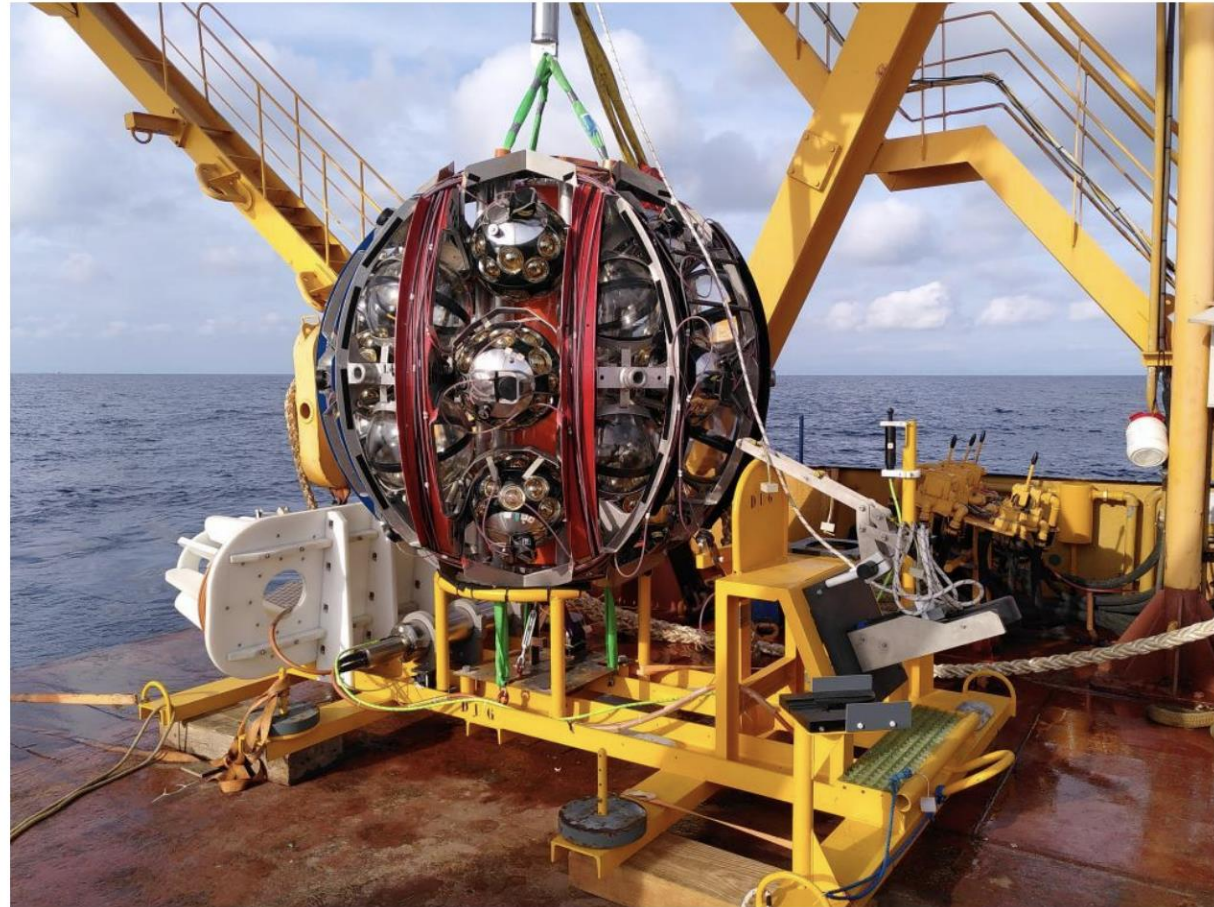


KM3NET



- 31 3-inch PMTs in 17-inch glass sphere (cathode area $\sim 3 \times 10$ -inch PMTs)
- Pioneered the concept of multi-PMT modules, with directional information: directionality, cost.

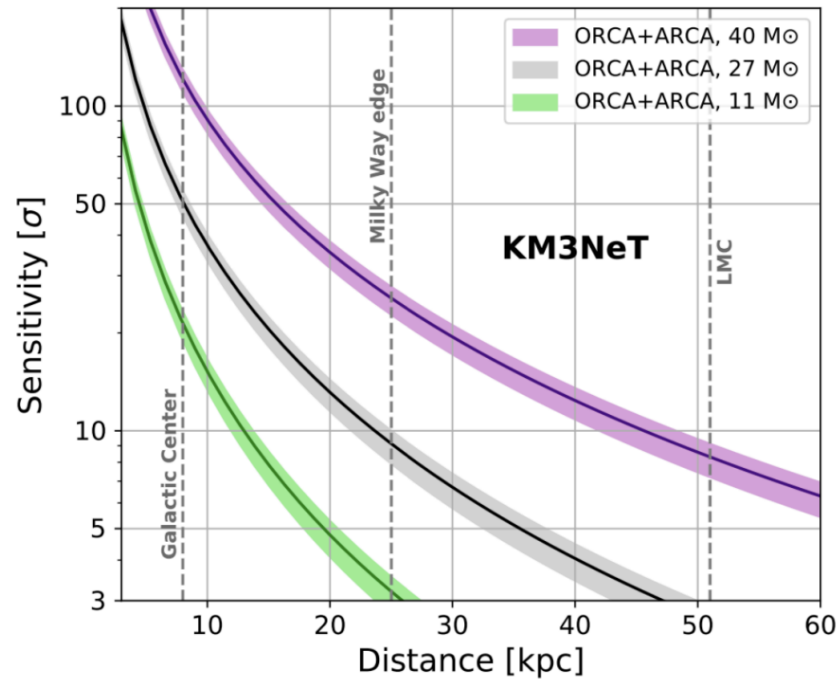
- Unique deployment scheme from a vessel:
A sphere of spheres.



KM3NET

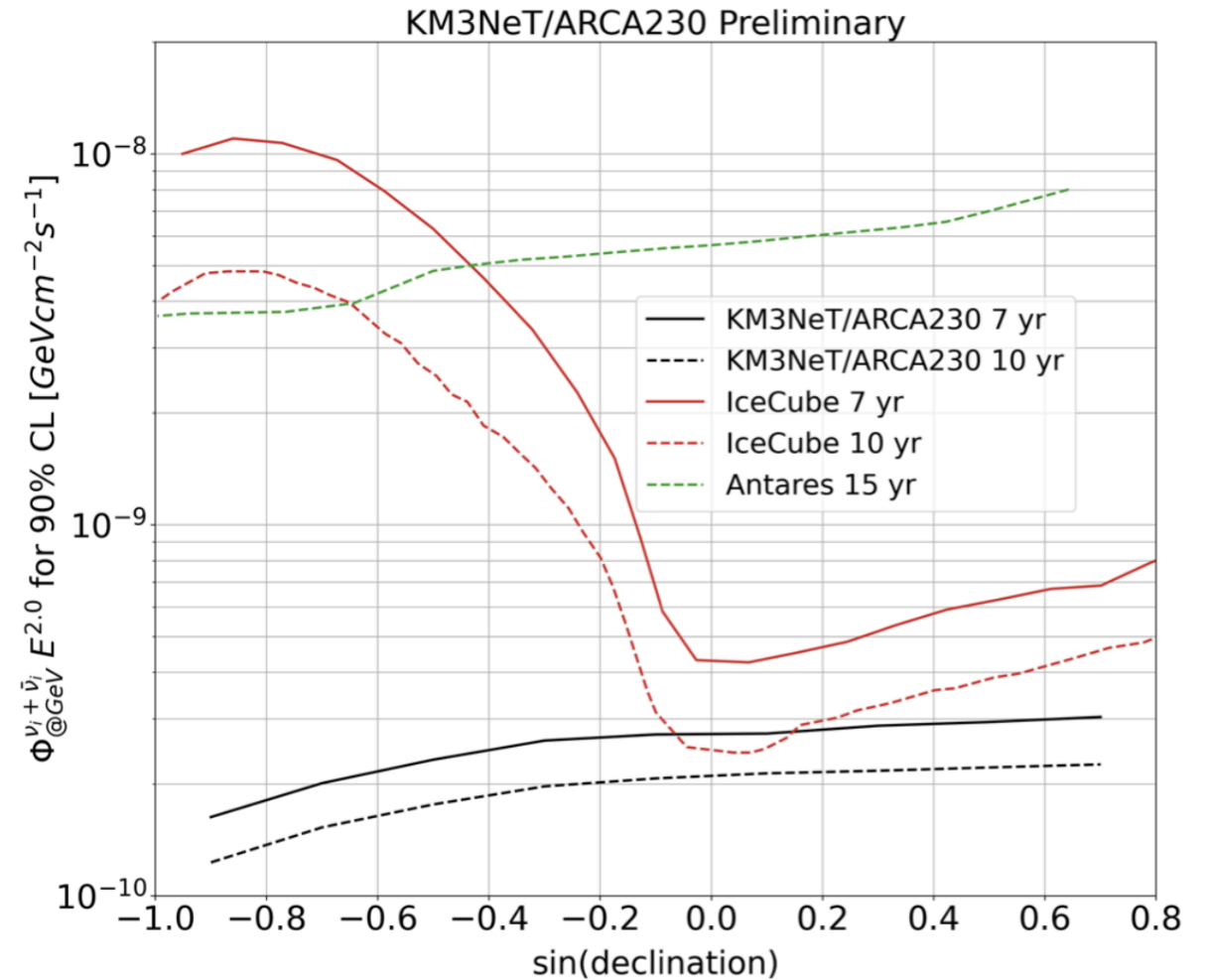
- A milestone on Supernova detection in water

Demonstration of multi-PMT potential to reject noise from sea water.



>5 σ for ARCA+ORCA for 27 $M_{\odot}$ at a distance <35kpc

- Projected sensitivity to E^{-2} point sources



SOUTHERN SKY IMPROVEMENTS WITH ICECUBE

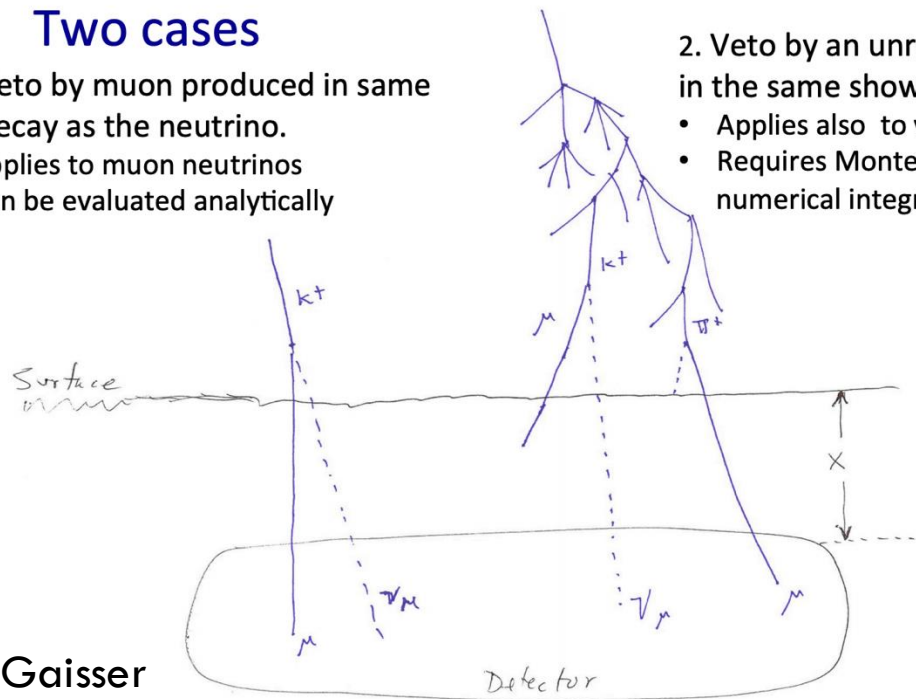


Atmospheric neutrino self veto

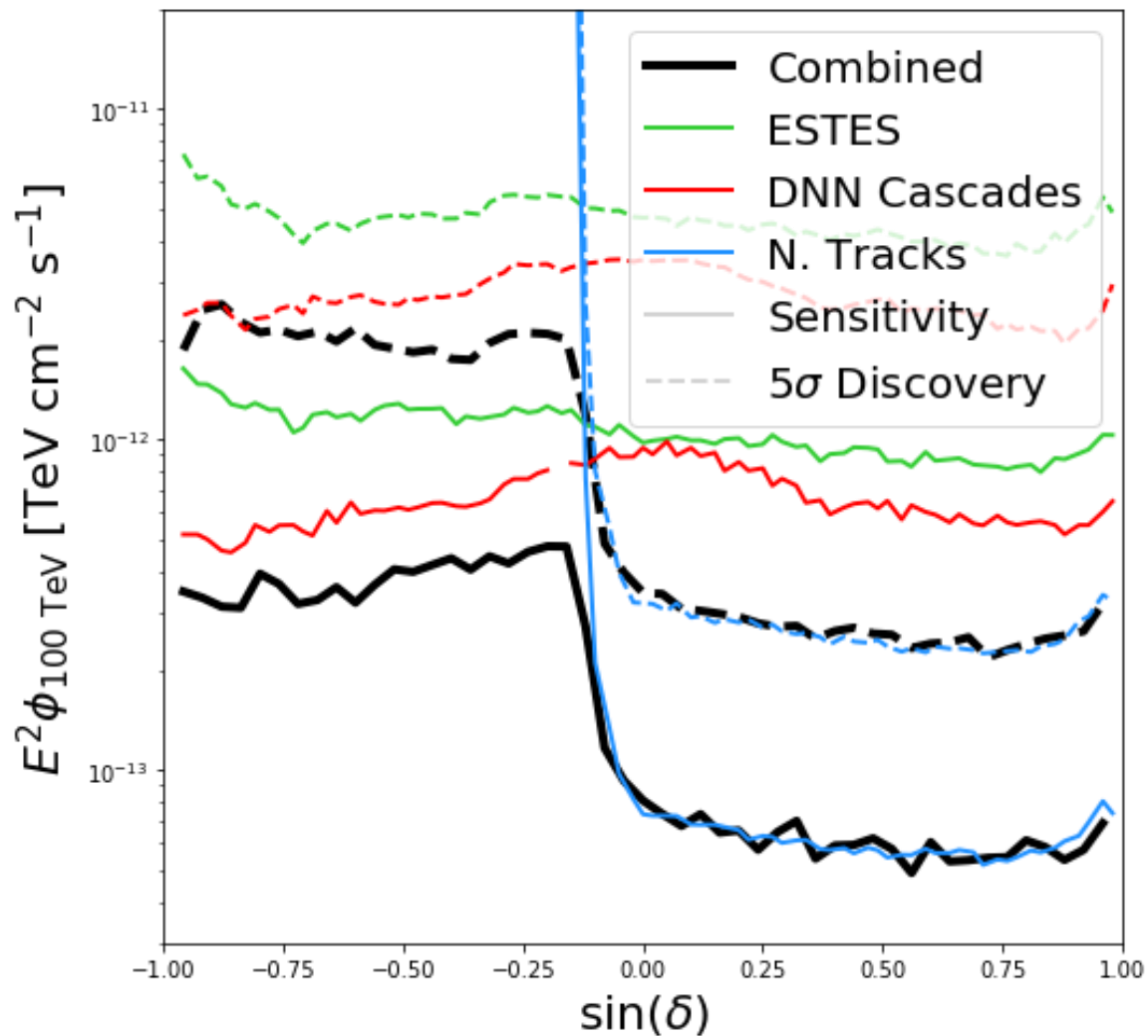
Two cases

1. Veto by muon produced in same decay as the neutrino.
 - Applies to muon neutrinos
 - Can be evaluated analytically

2. Veto by an unrelated μ in the same shower
 - Applies also to ν_e
 - Requires Monte Carlo or numerical integration

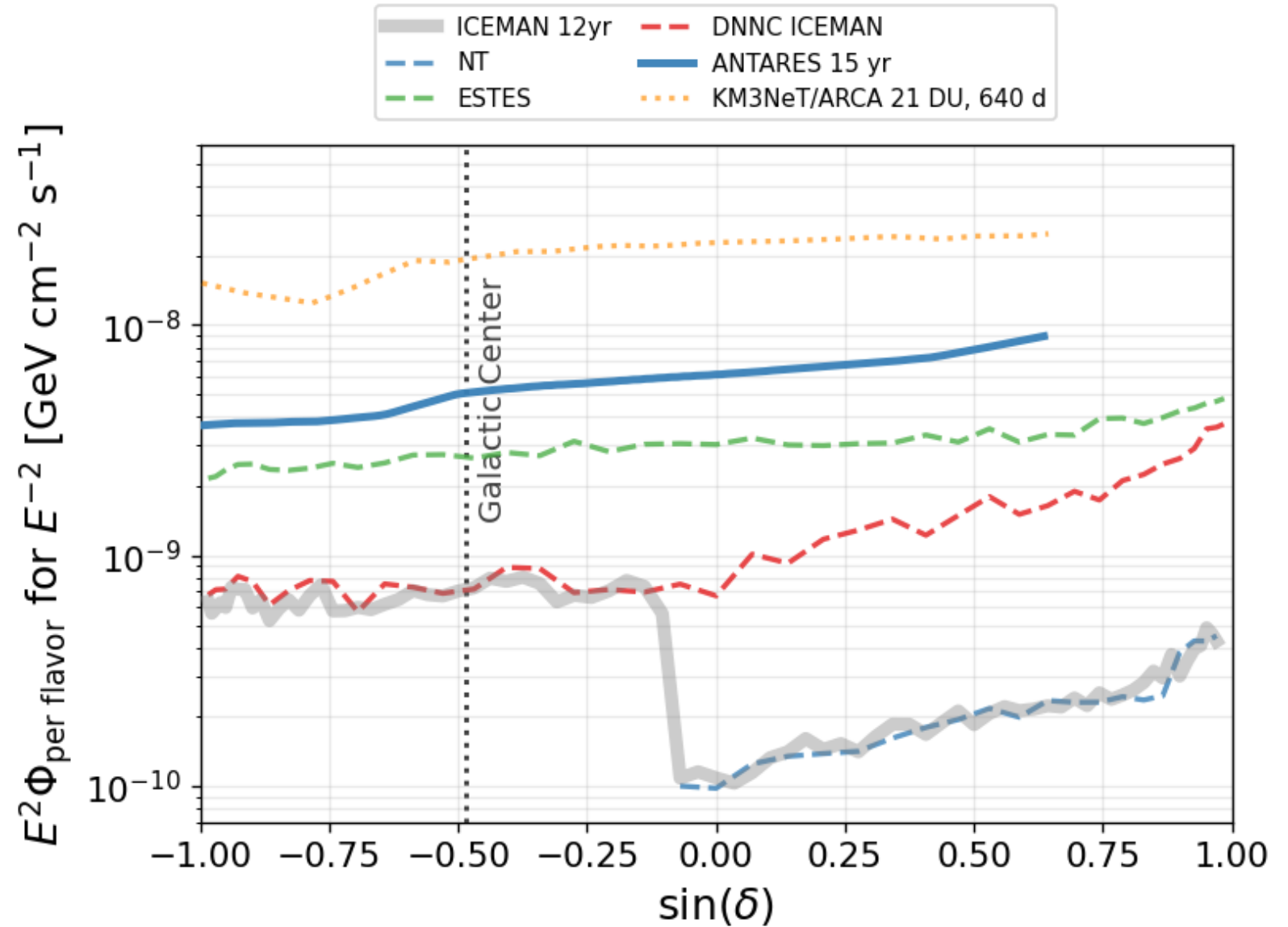


Tom Gaisser



SENSITIVITY: LOWER IN THE PLOT IS BETTER

Thanks to self-veto effect, IceCube has opened up the southern sky



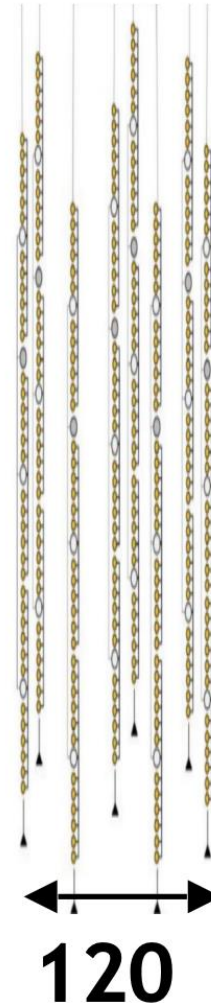
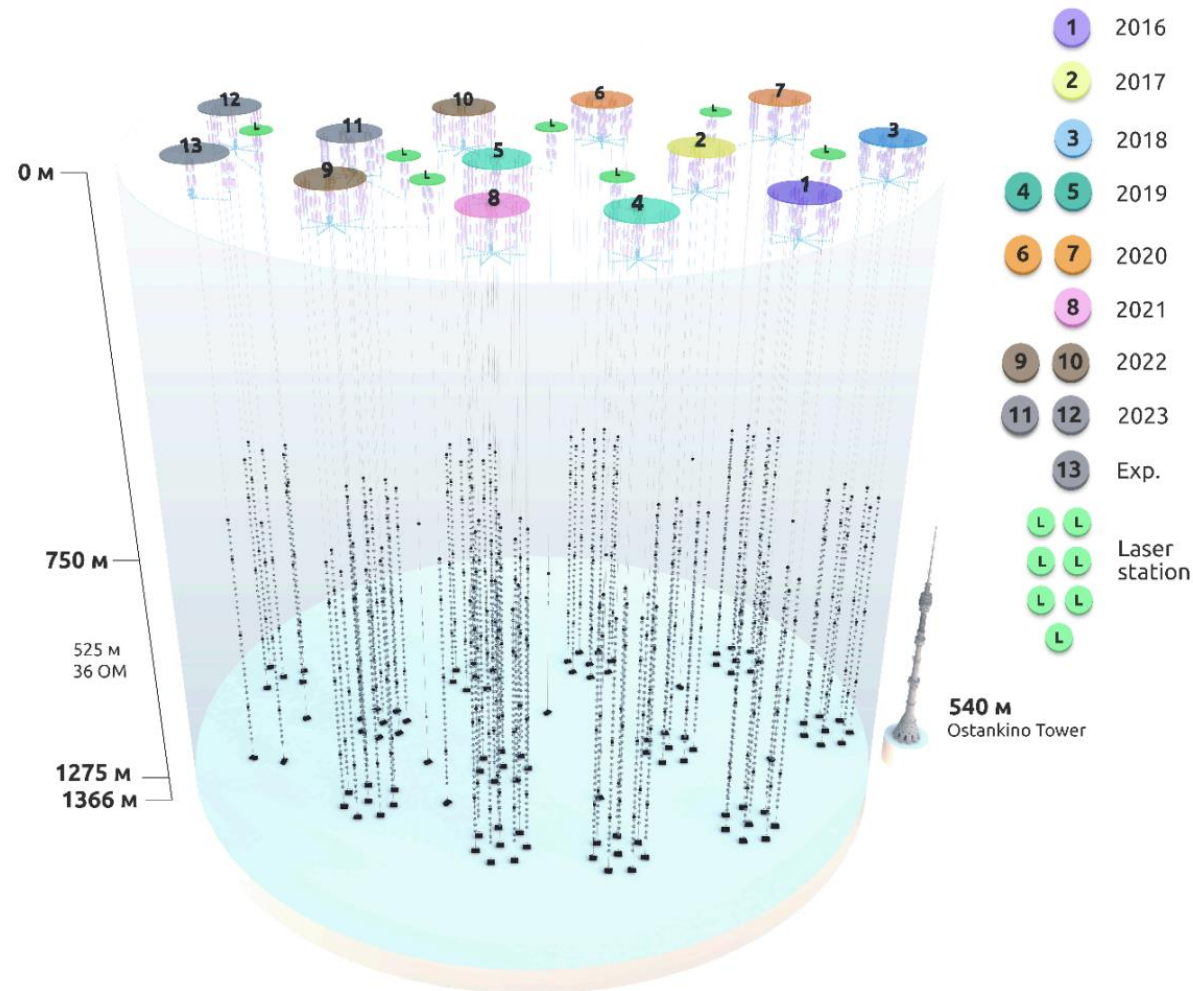
- Lake Baikal, Siberia
- Deployment in March/April from ice cover
- Clusters with 8 strings, each with 36 10" PMTs



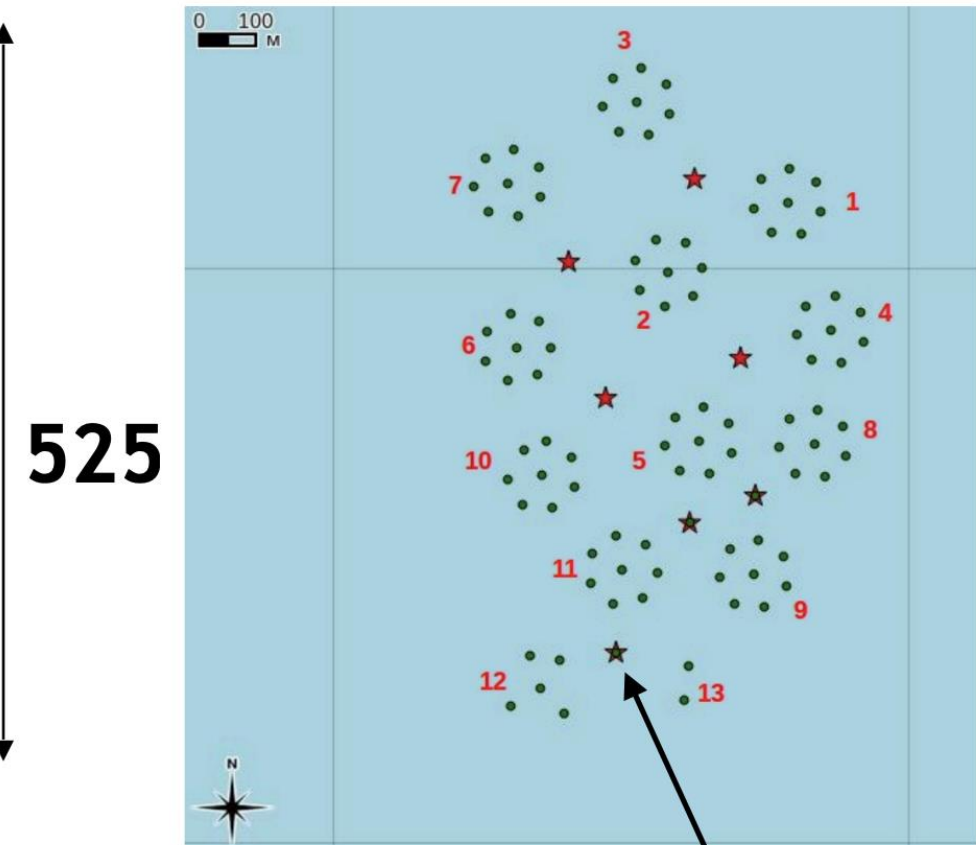
Baikal GVD - in construction

18 Clusters of 8 strings with 36 sensors each

Instrumented volume: $\sim 1/2 \text{ km}^3$



In construction since 2015.
Status fall 2022:
12 of 18 stations deployed

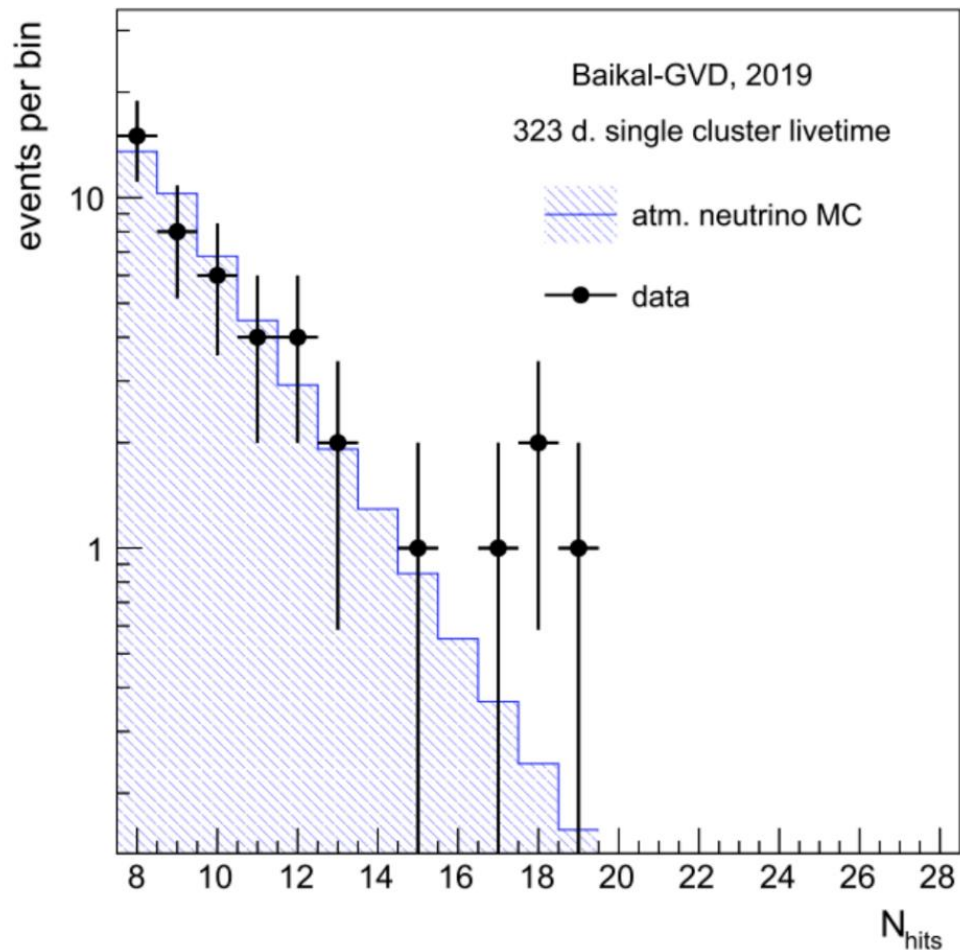


3 In-fill strings added

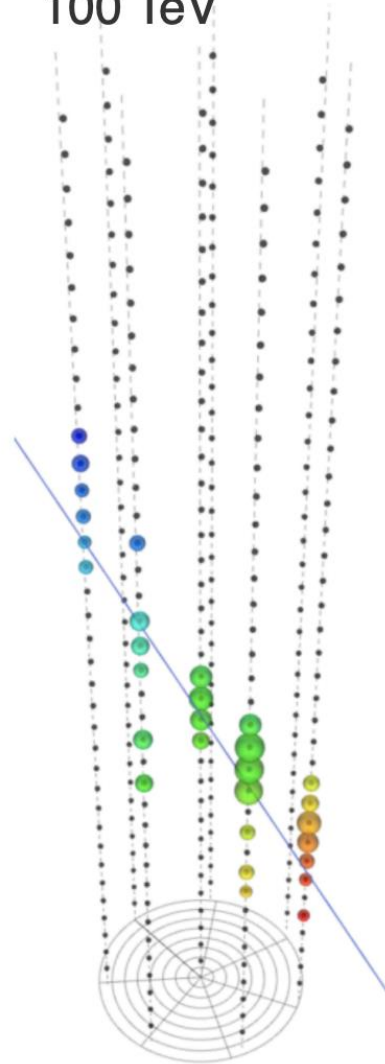
Baikal GVD - data

Reject background at 3 sigma

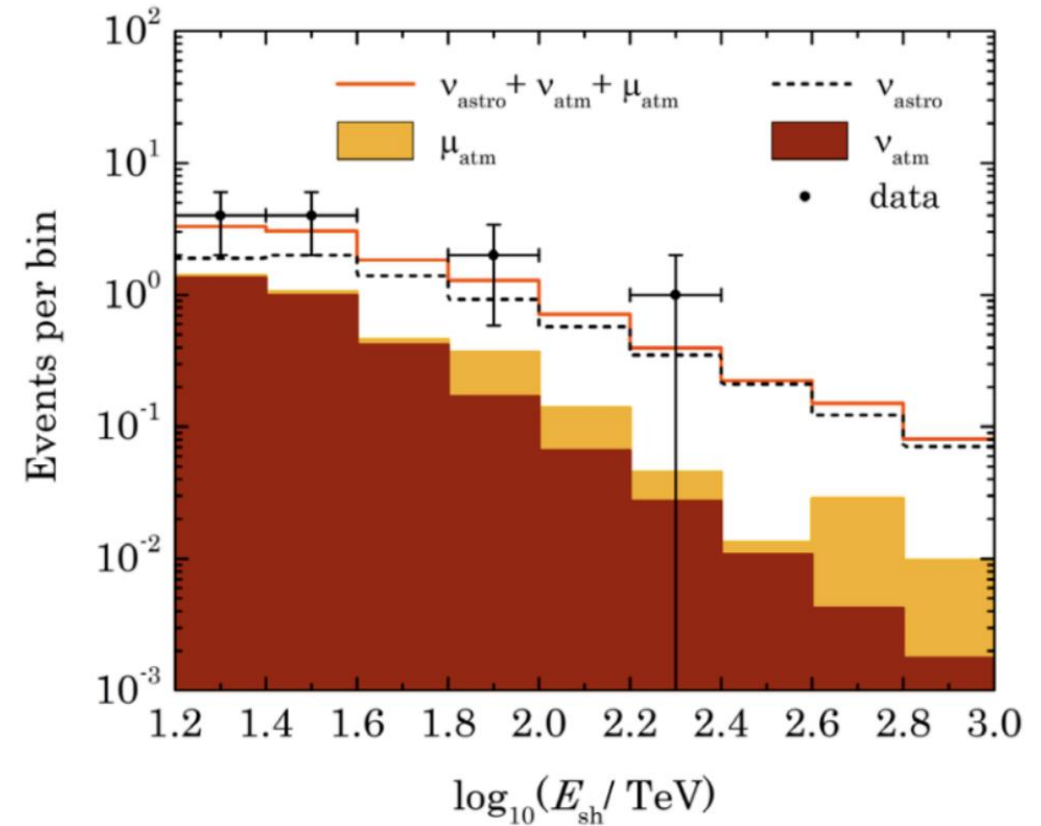
Upgoing muon distribution vs MC



Upgoing muon,
100 TeV



Upgoing cascade events
with astrophysical
component.



PACIFIC OCEAN NEUTRINO EXPERIMENT: P-ONE

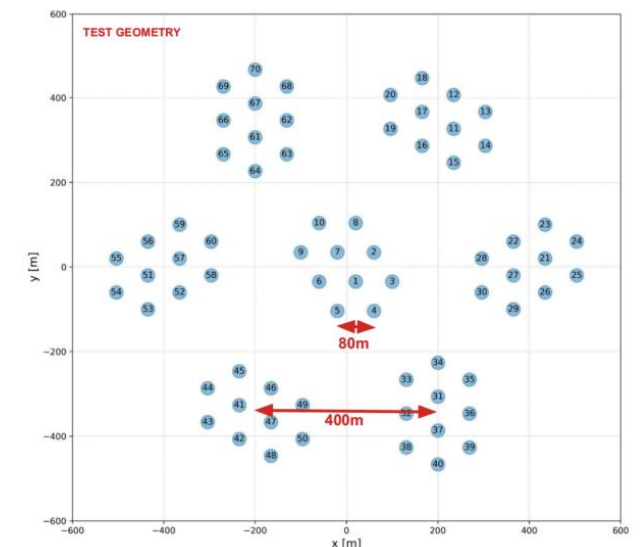
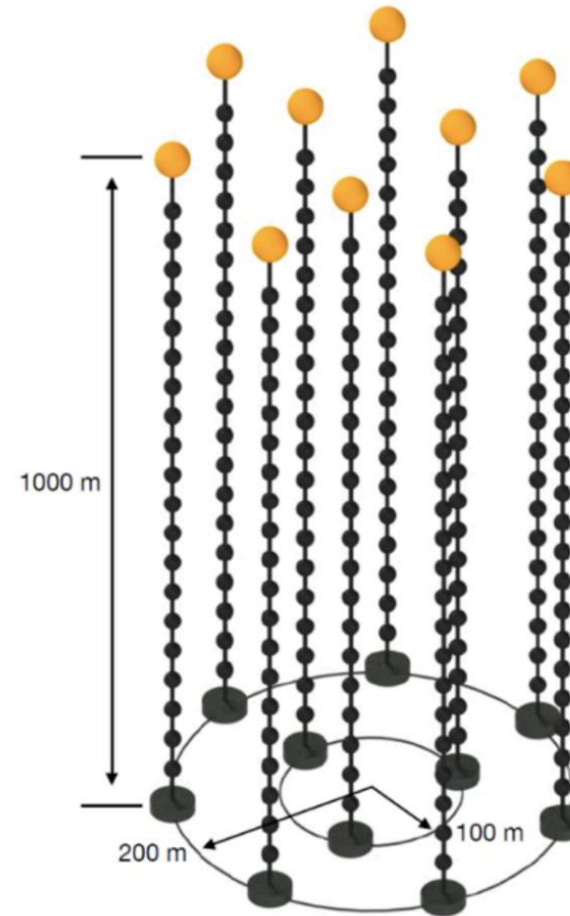
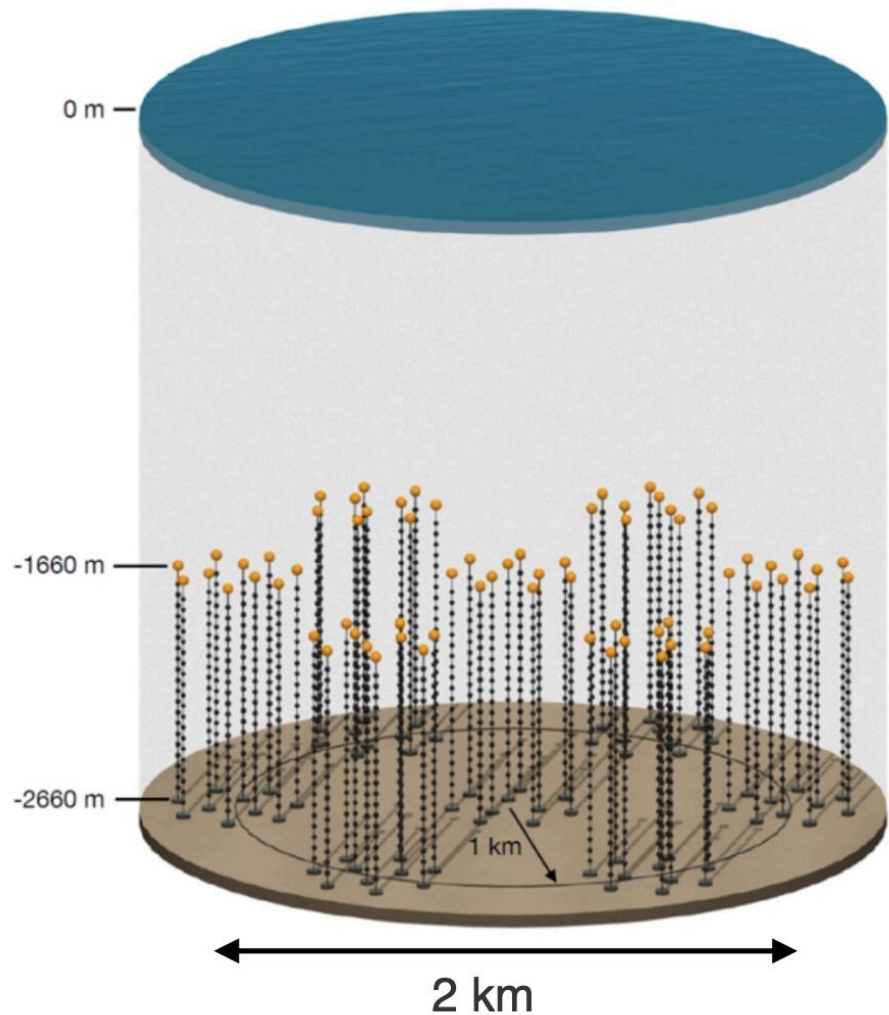
Proposed project in R&D and prototyping phase

Conceptual Design:

7 clusters x 10 strings x 20 DOMs
total: 70 strings, 1400 sensors

diameter, height
(prel.): 400m, 1 km

Targeted energy range:
> 10 TeV



P-ONE

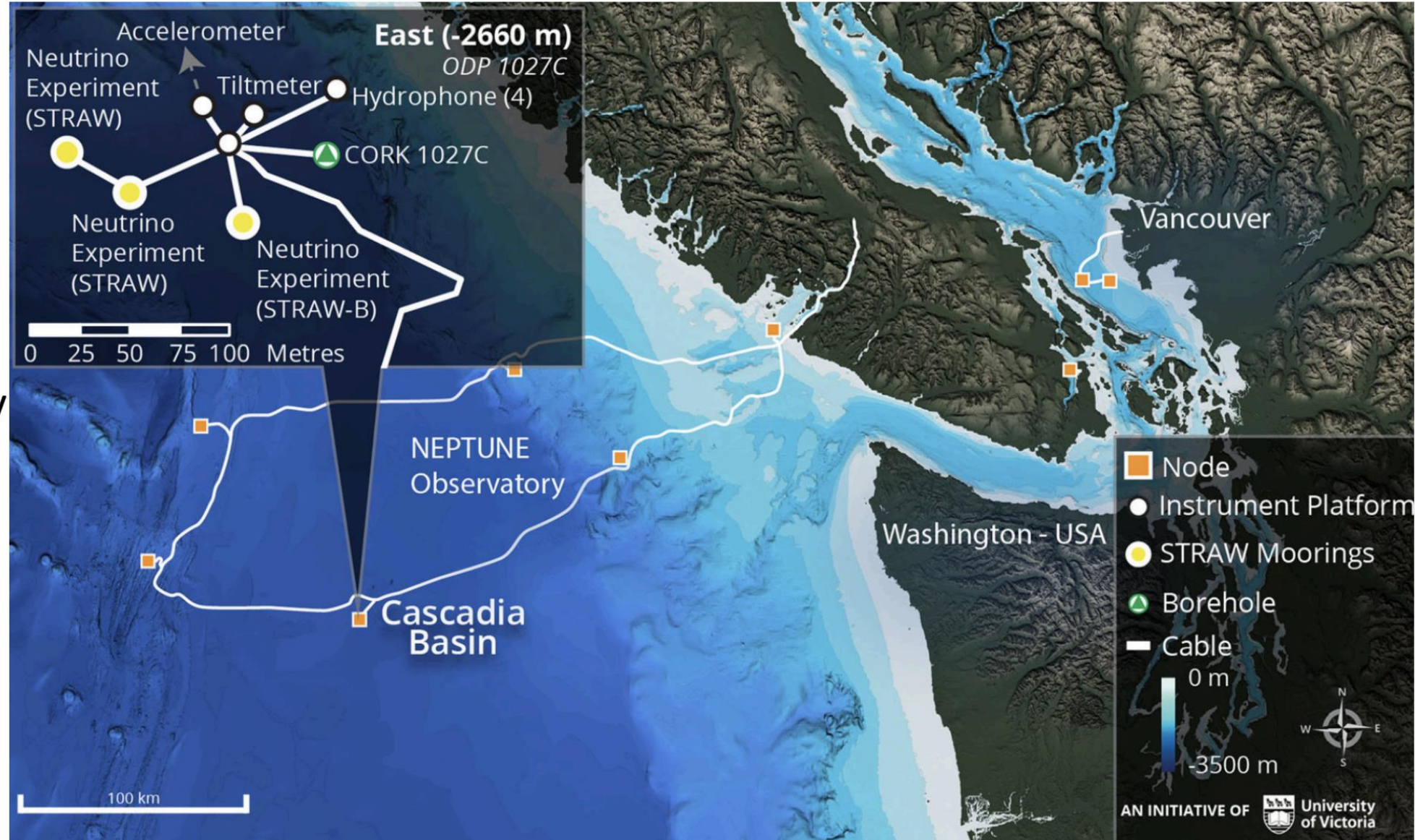
Proposed project in R&D and prototyping phase

Location: Pacific Ocean
near Vancouver

Depth: 2600m

Logistical support
infrastructure:

Interface, anchoring and
deployment operation by
ONC (Ocean Network
Canada)



P-ONE

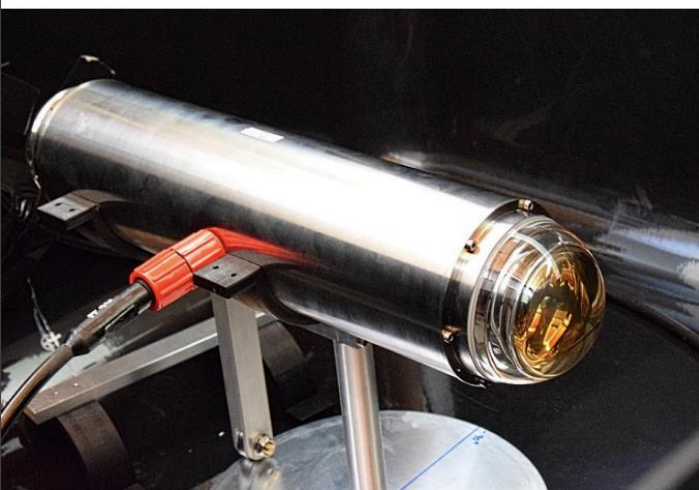
- Completed 2 pathfinder missions (STRAW)
- P-ONE-1 - one string - in 2024
- P-ONE demonstration cluster 2024-2027 (funded)

Attenuation length reported as **~28m** (at 450nm) comparable to other sites.

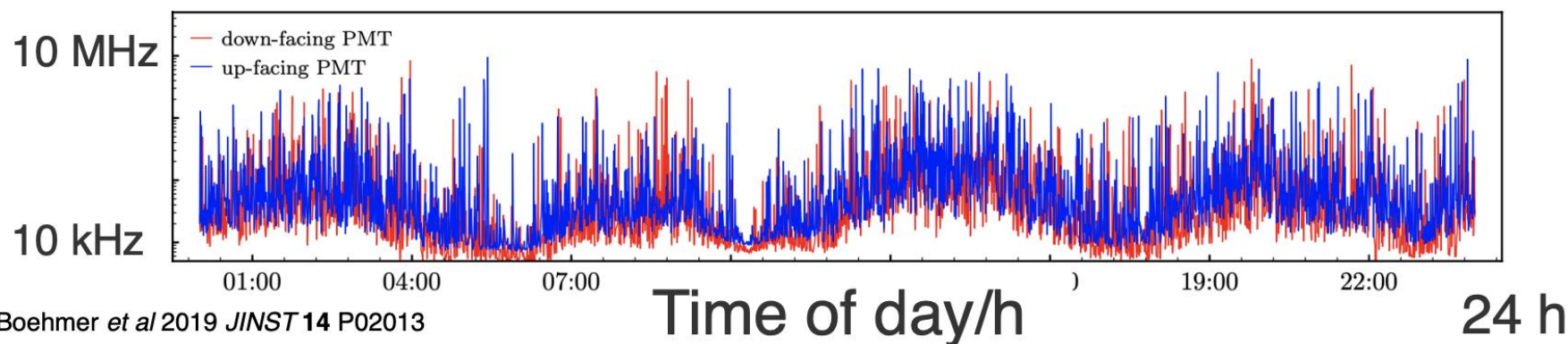


[The European Physical Journal C](#)

volume 81, Article number: 1071 (2021)



Noise rate in a 3 inch PMT



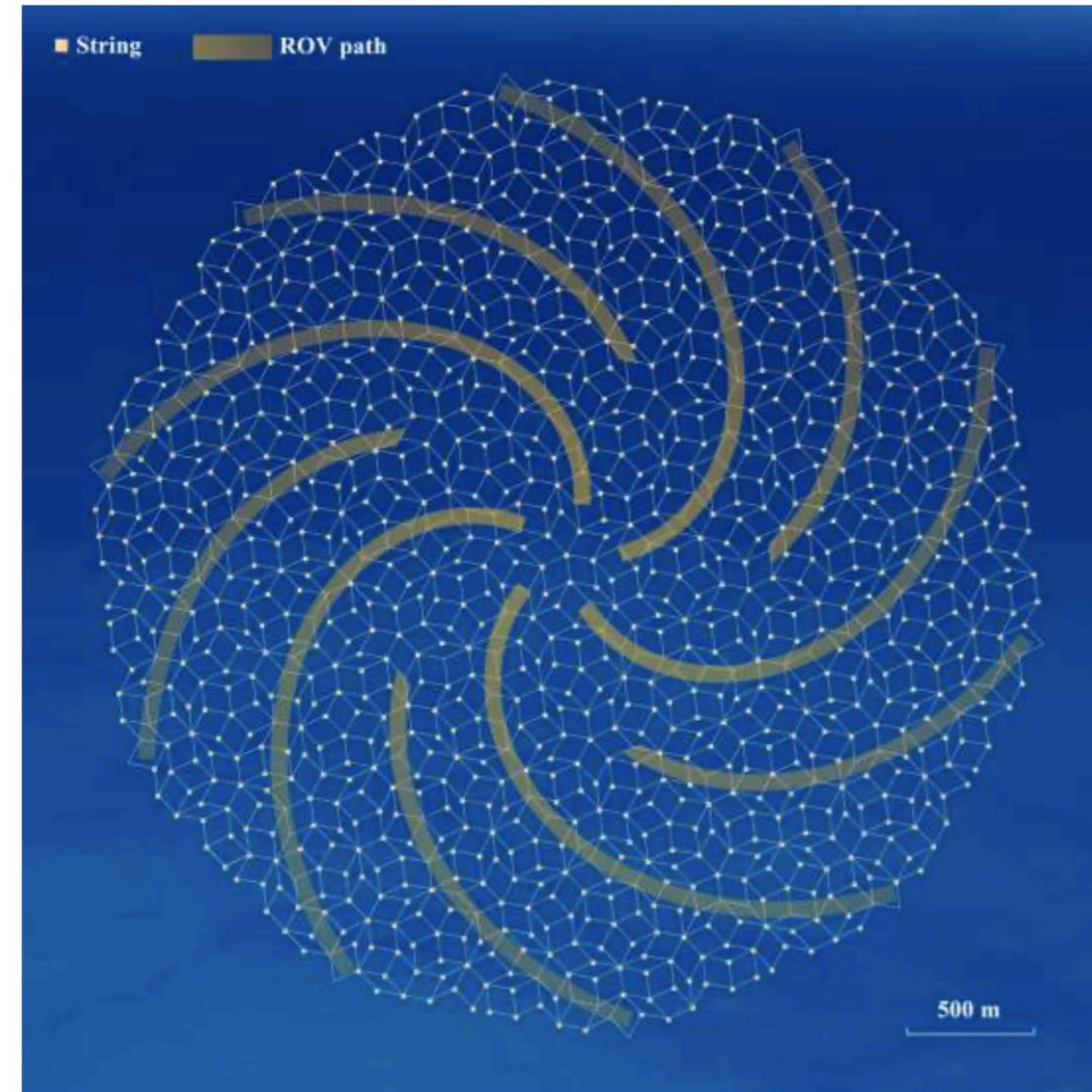
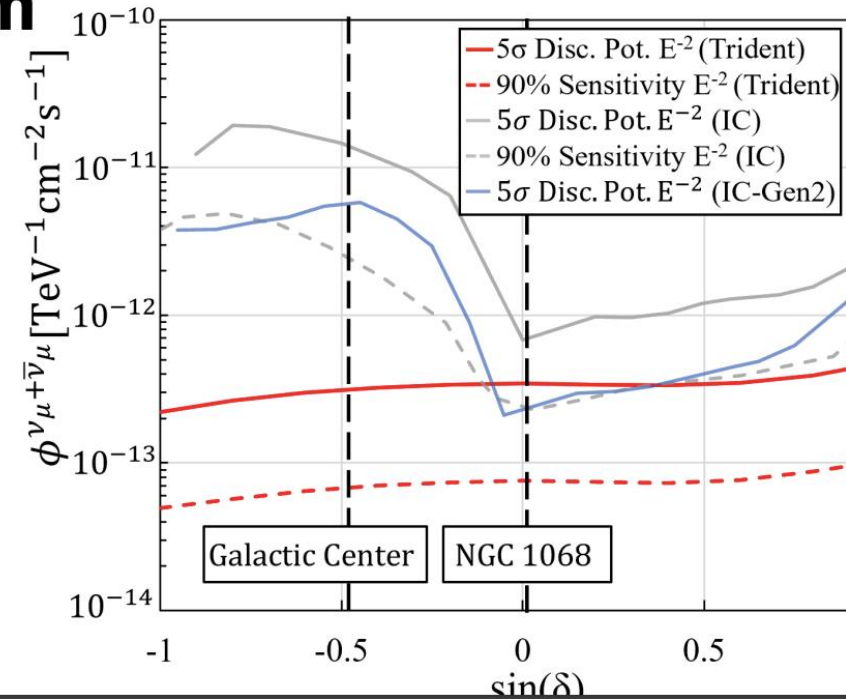
M. Boehmer *et al* 2019 *JINST* **14** P02013

Proposed project in R&D and prototyping phase

Nature Astronomy (2023). 10.1038/s41550-023-02087-6

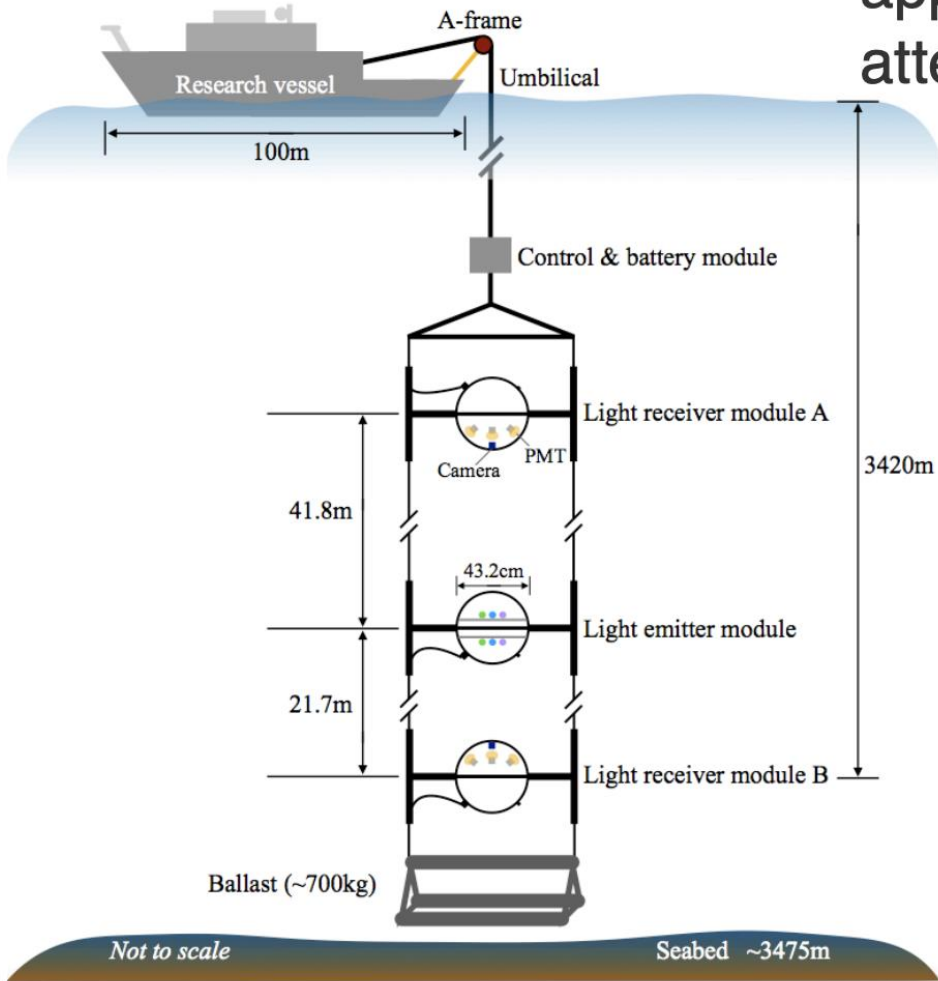
Scope:

- **1211 strings**
- 30 hDOMs per string
- **7.5 km³** (=10 km² x 750m)
- Location: South China Sea
- Depth: **3475m**



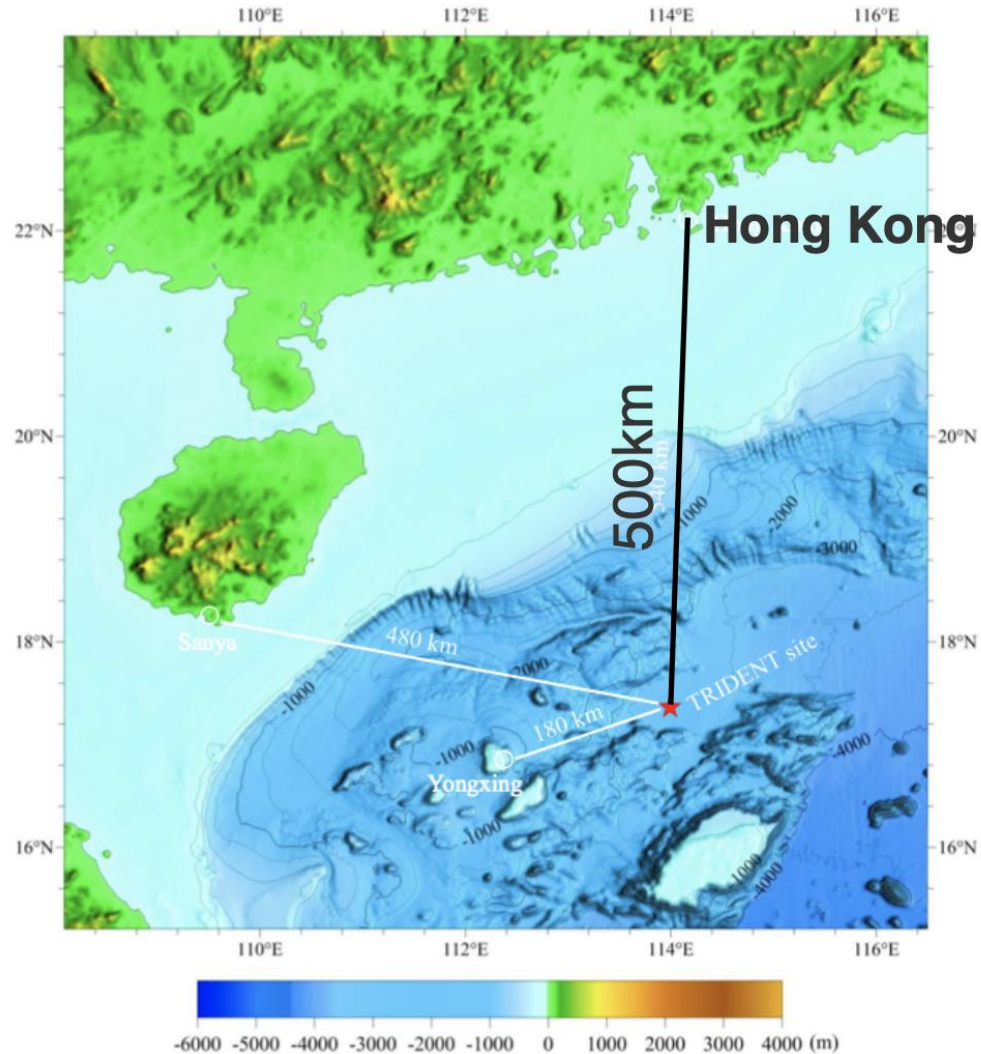
TRIDENT: Exploration

Optical properties,
appear reasonable:
attenuation: 20 - 30 m

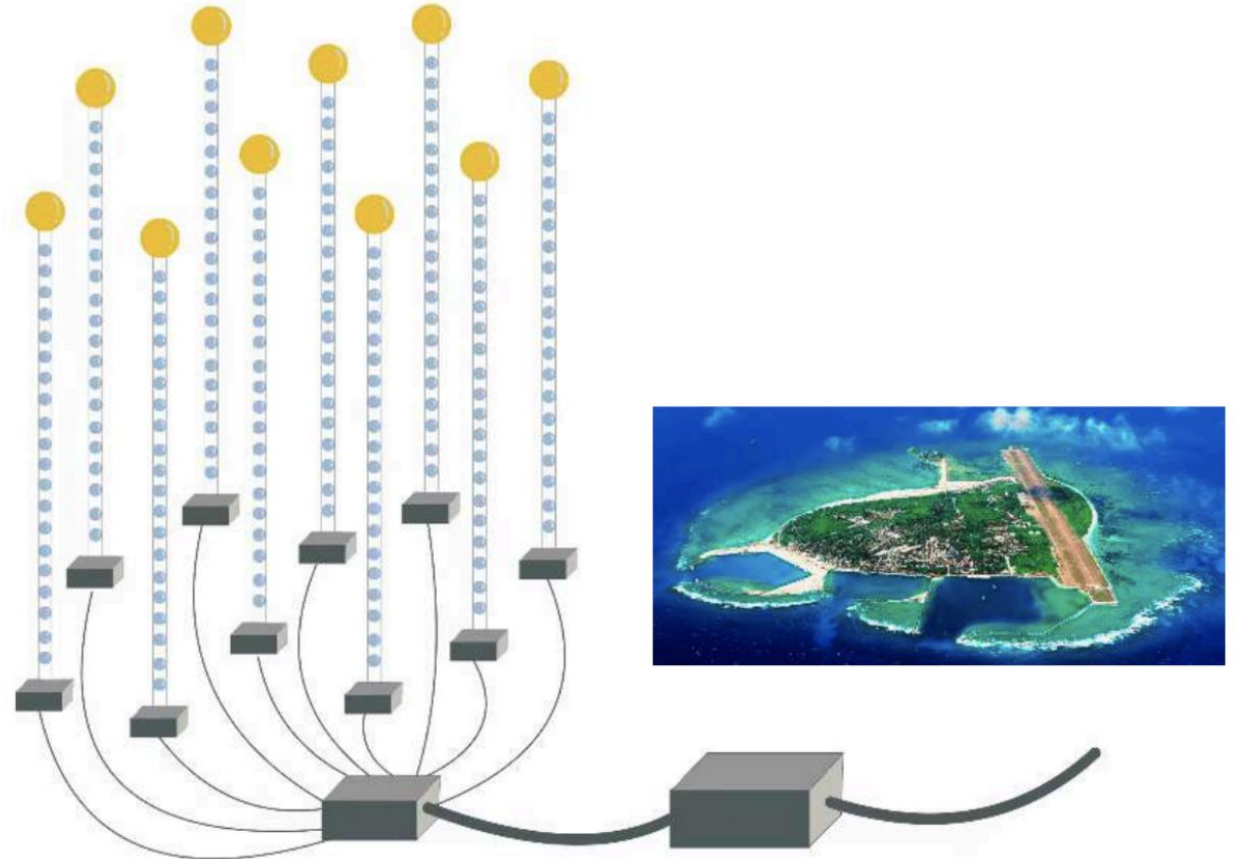


TRIDENT:

Location: South China Sea



Phase 1 project 2022-2026: in progress
10 strings + deep sea cable



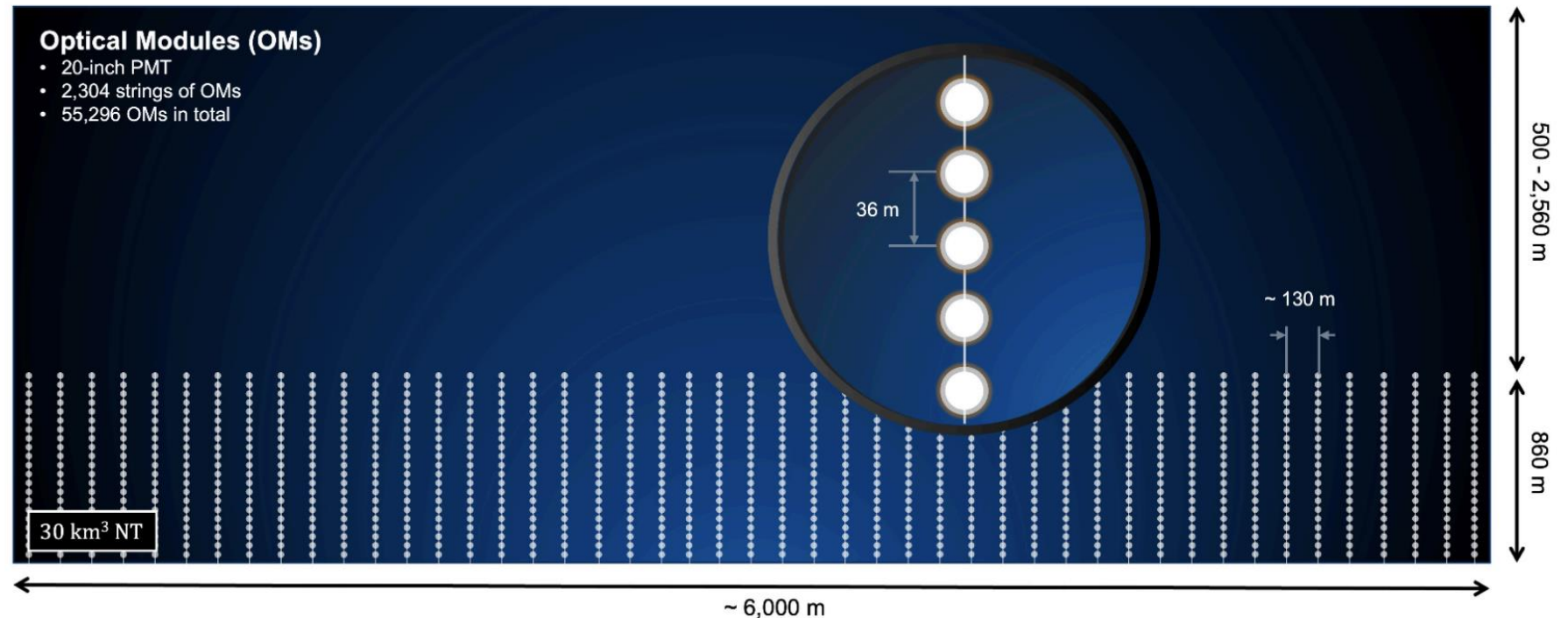
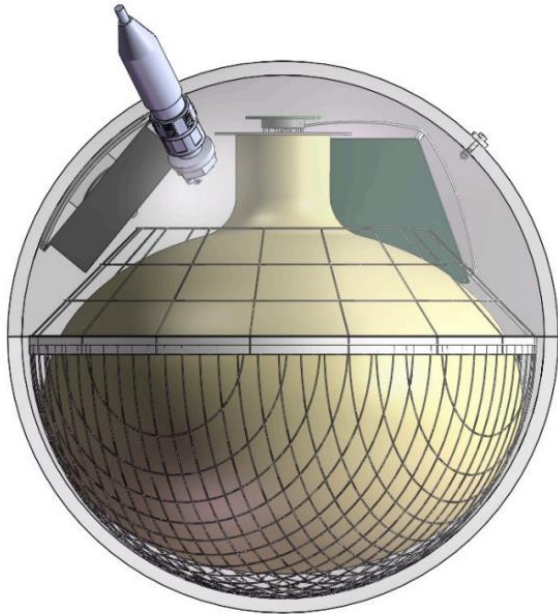
HUNT - H stands for Huge

Huge underwater NT

Outline presented at the ICRC

55,000 PMT of 50 cm diameter
2304 strings of 24 PMTs, 860m long
Instrumented volume 30 km²

Location: in consideration: Baikal or somewhere
South China Sea
prototype string in Lake Baikal planned



NEON

Several contributions to ICRC

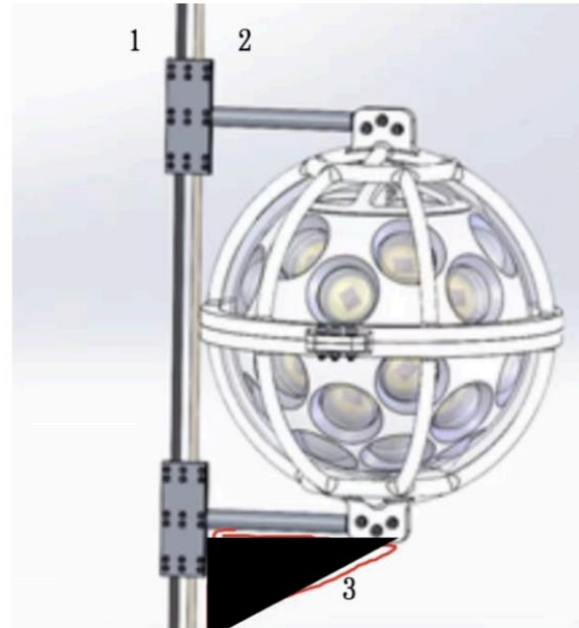
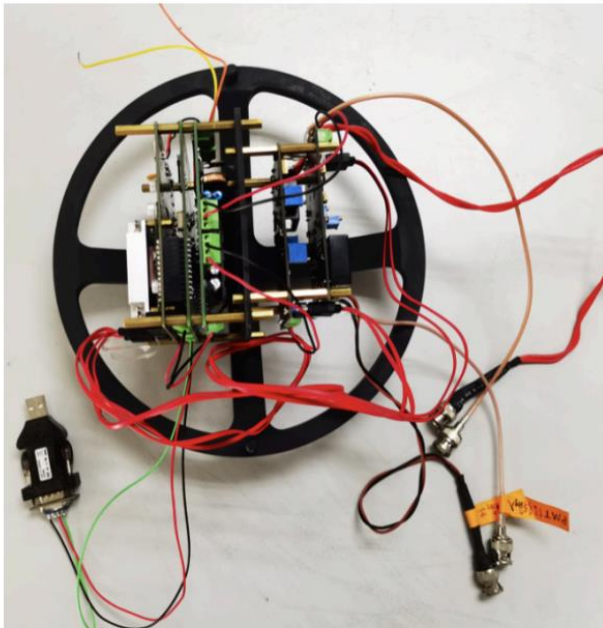
South China Sea

Instrumented volume: $\sim 1 \text{ km}^3$

Location:

South China Sea TBD

Simulation studies
Hardware R&D
presented at ICRC



POLARIS

- Latest proposal
- Candidate site off Taiwan's east coast on a 3 km flat plateau

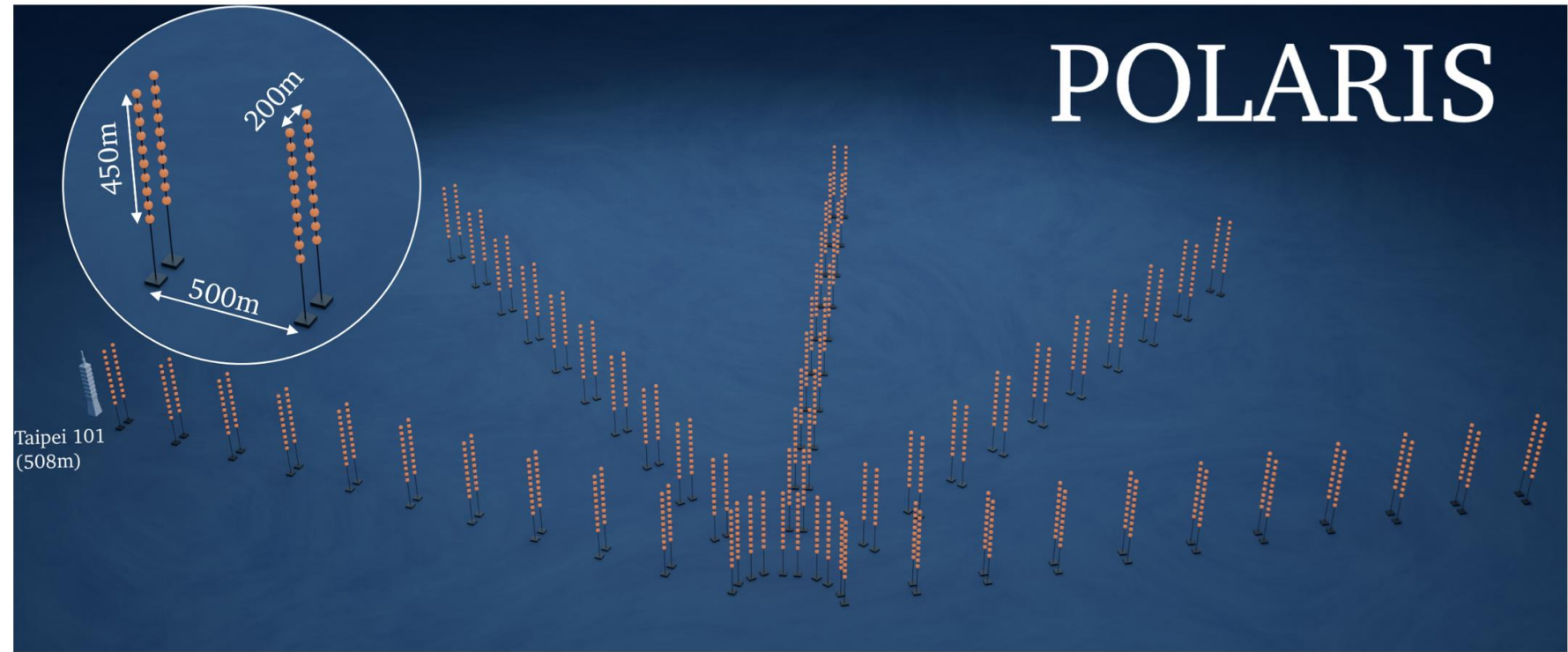


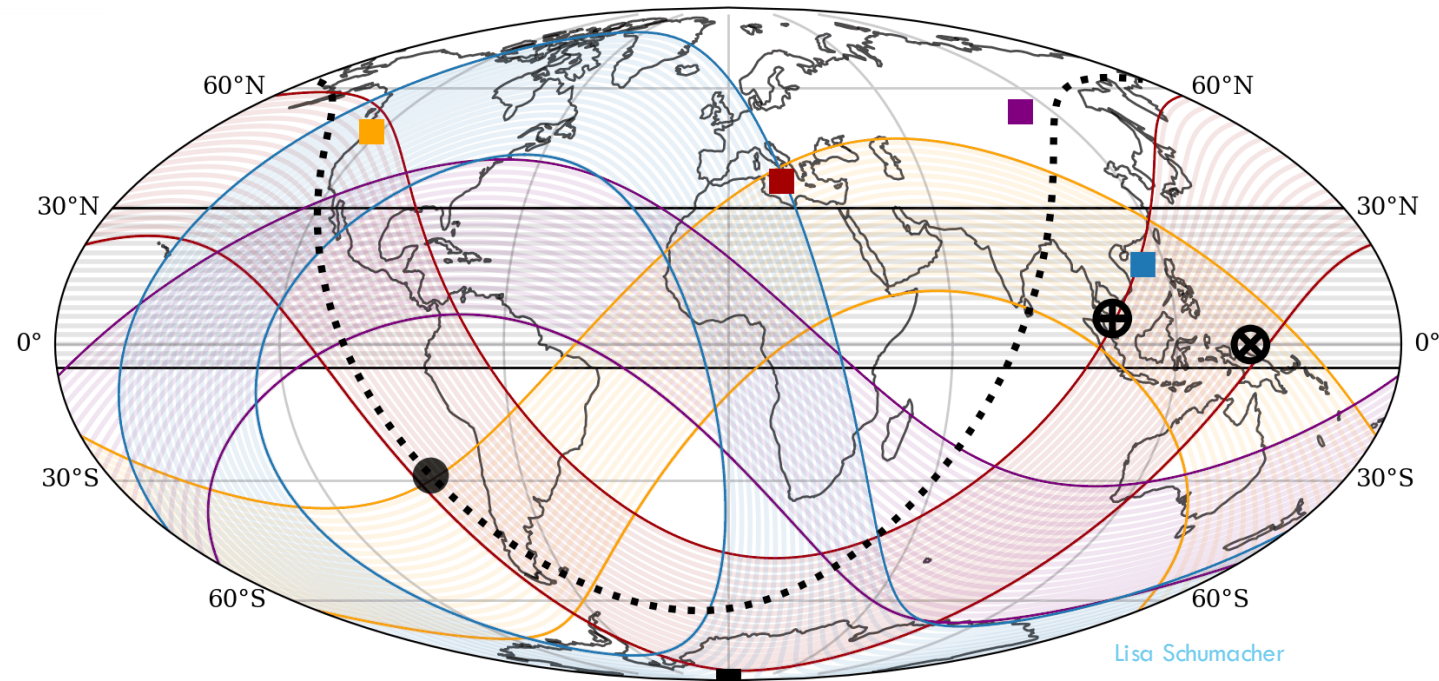
Figure 1. Illustration of the five-arm POLARIS detector geometry with perpendicular string pairs (gates) at 500 m intervals. Each DOM in the top view represents a vertical string with 10 DOMs of 50 m spacing over 450 m height. Each arm is instrumented with 220 DOMs, totaling to 1100 DOMs for the whole detector.

<https://arxiv.org/pdf/2604.12521>

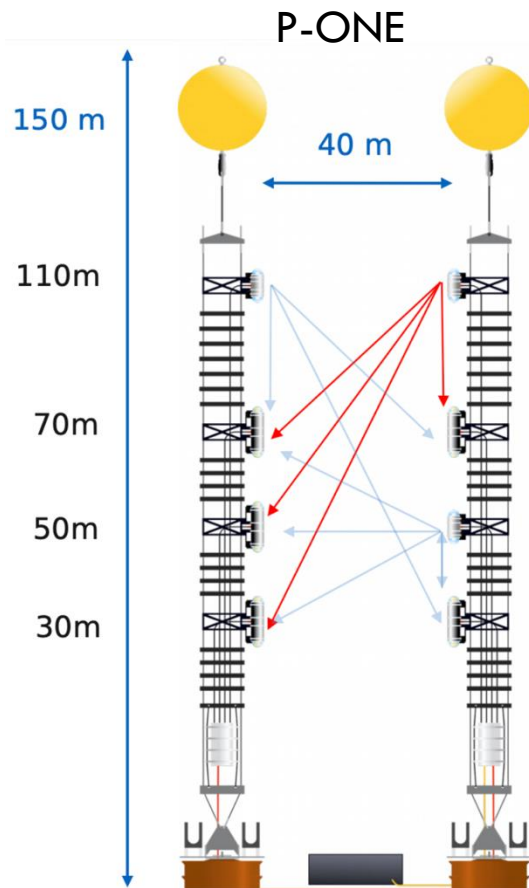


SKY COVERAGE

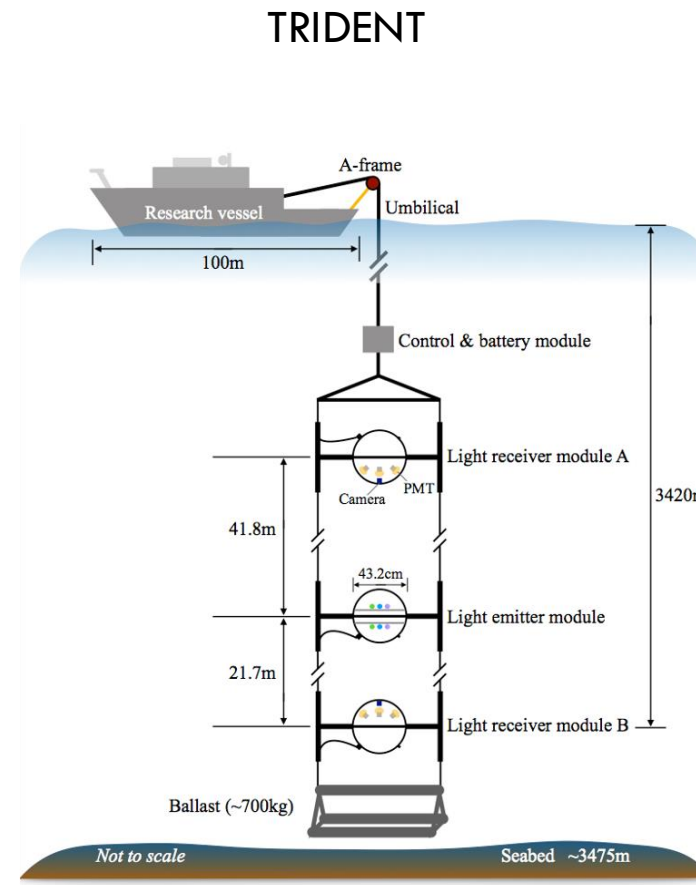
A global neutrino network to cover the full sky



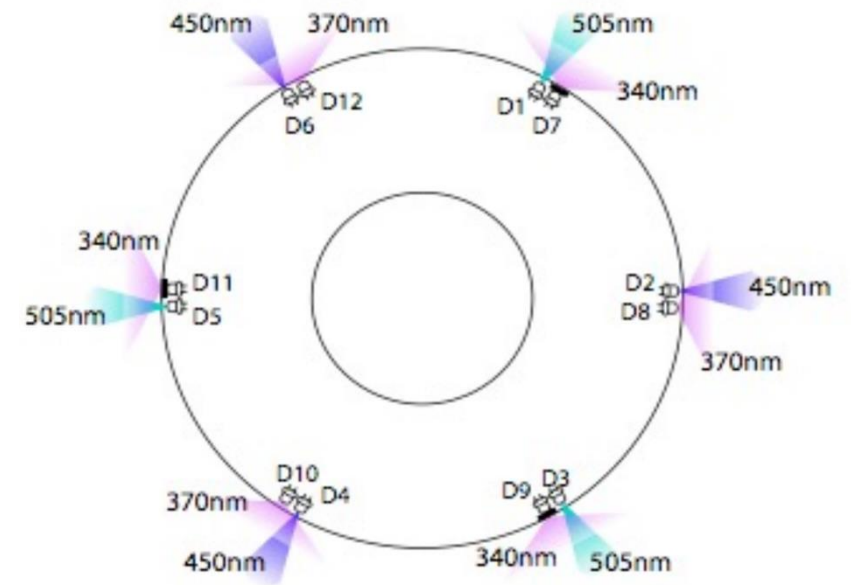
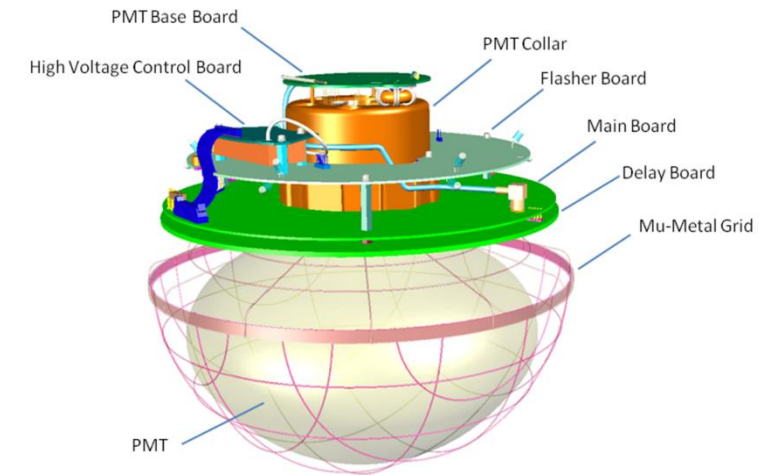
ATTENUATION PROPERTIES



Matthias Danninger
Lake Louise 2022



TRIDENT Collaboration
arxiv: 2207.04519v1

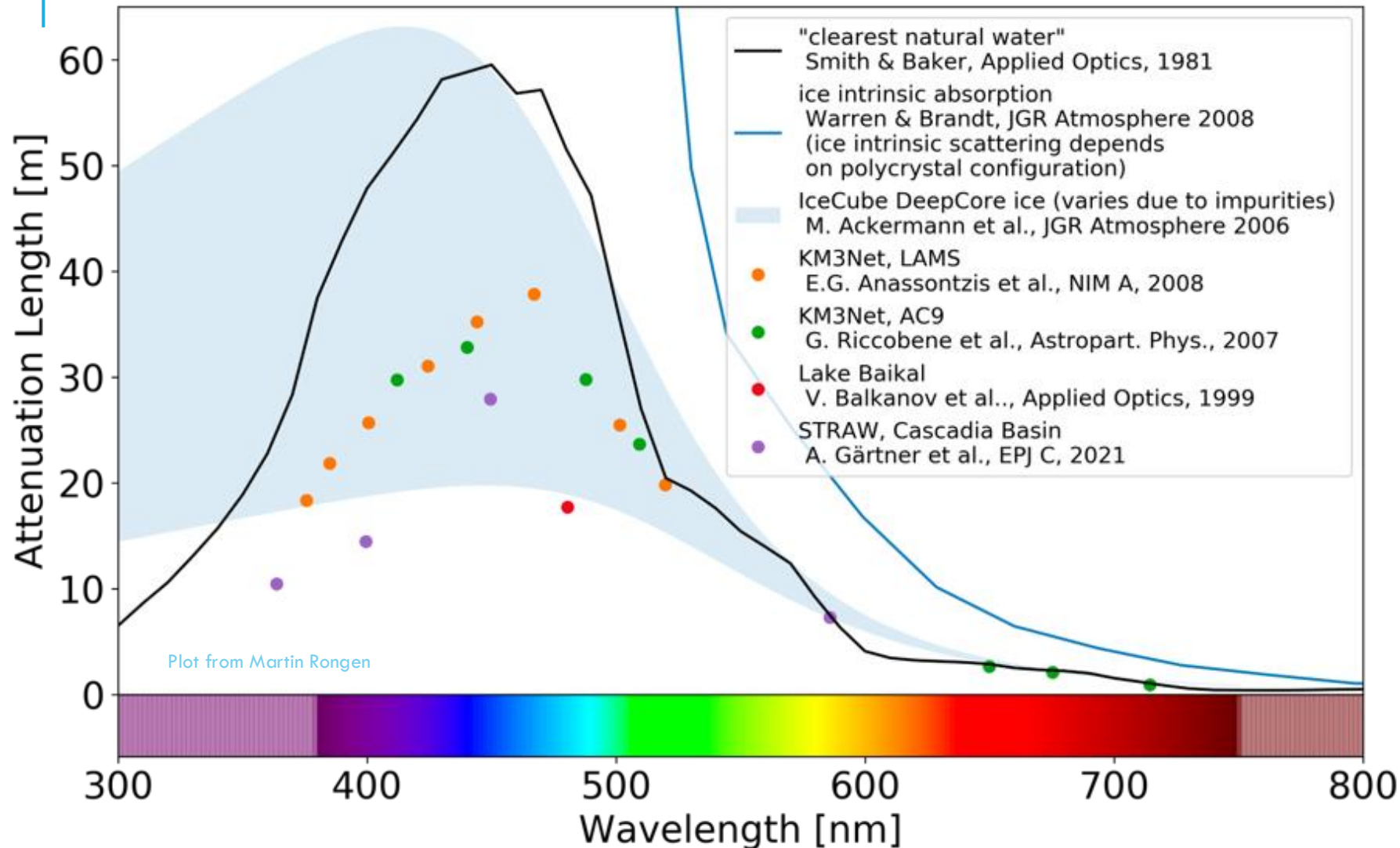


IceCube 'cDOM' flasher calibration

ATTENUATION MEASUREMENTS

Water: less scattering, more absorption

Ice: less absorption, more scattering



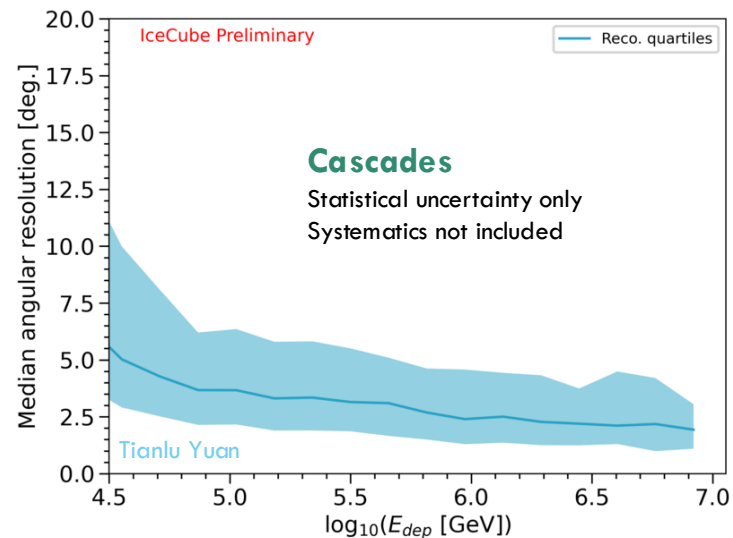
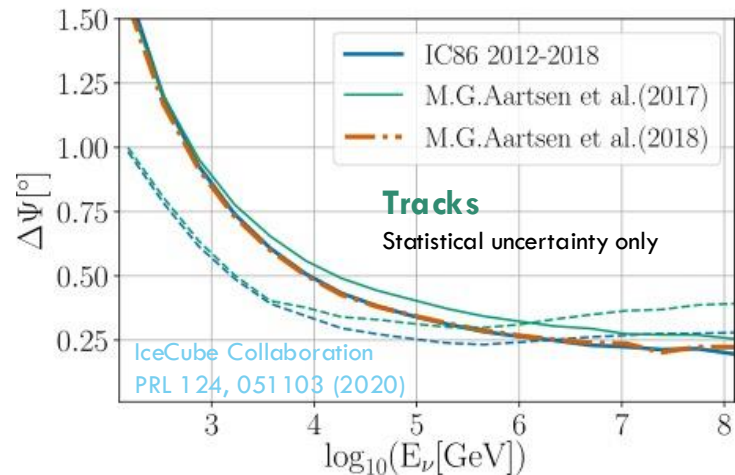
$$I(r) = \frac{I_0}{r^2} e^{\frac{-r}{\lambda_{att}}}$$

$$\frac{1}{\lambda_{att}} = \frac{1}{\lambda_{sct}} + \frac{1}{\lambda_{abs}}$$

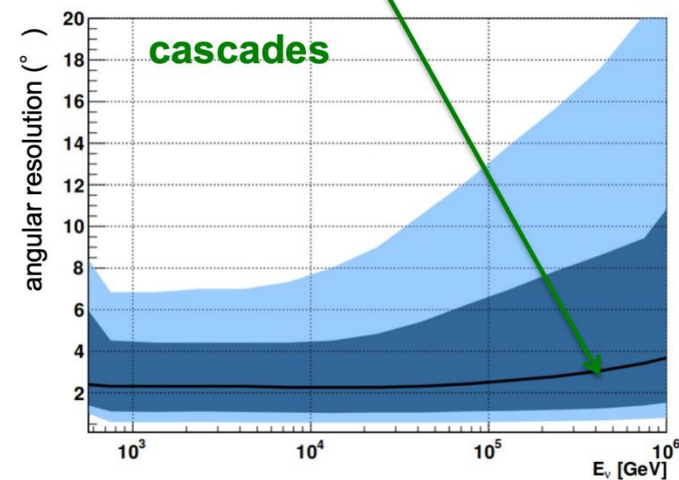
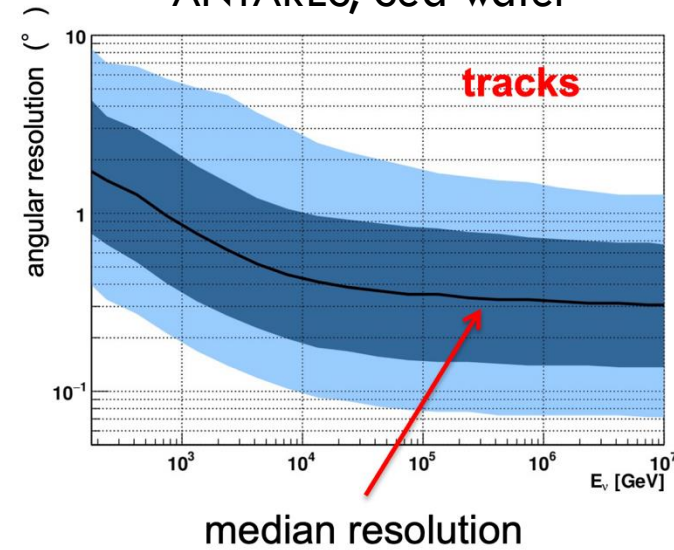
ICE VS WATER (EXISTING EXPERIMENTS)

Angular resolution for tracks and cascades

IceCube, Antarctic ice



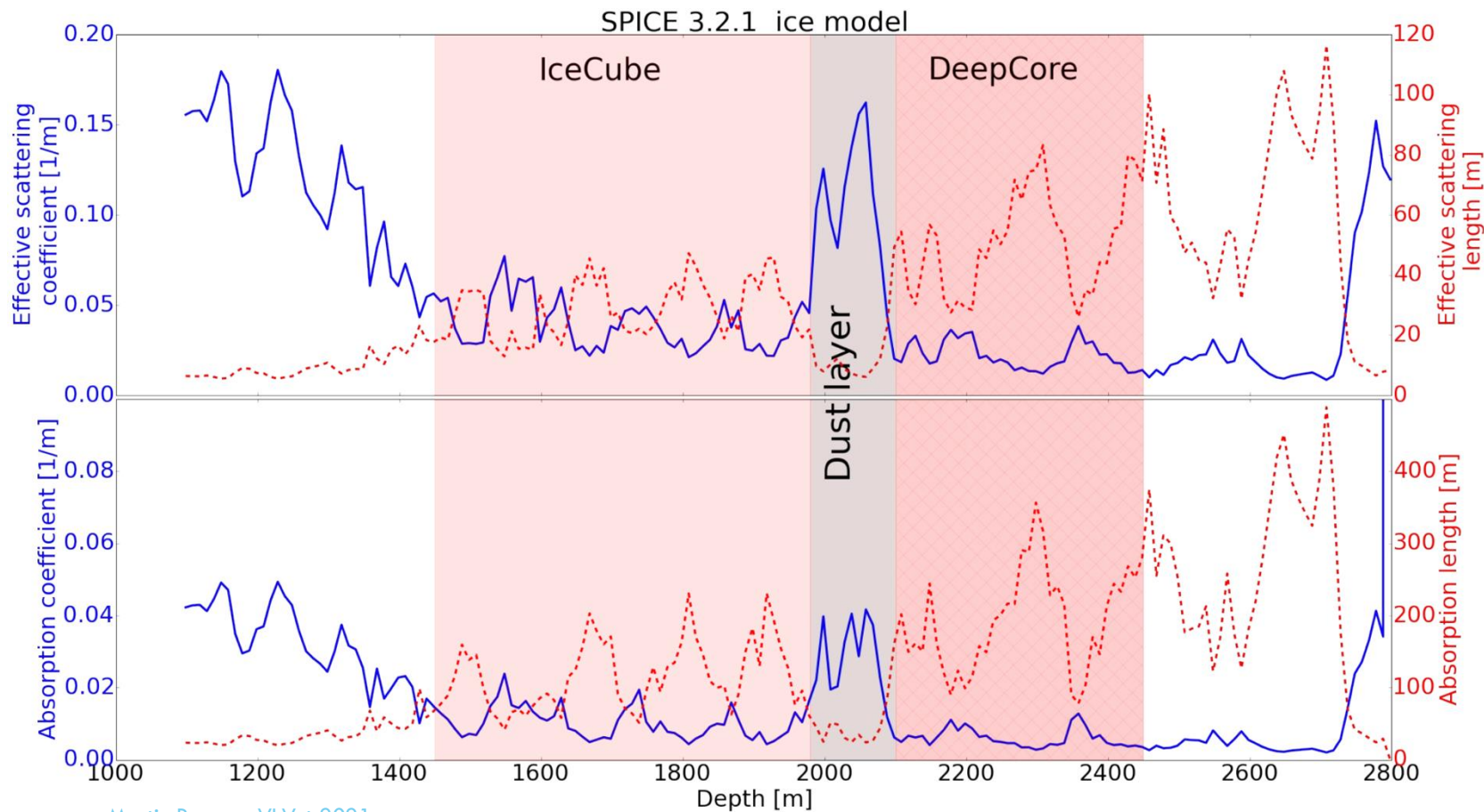
ANTARES, Sea water



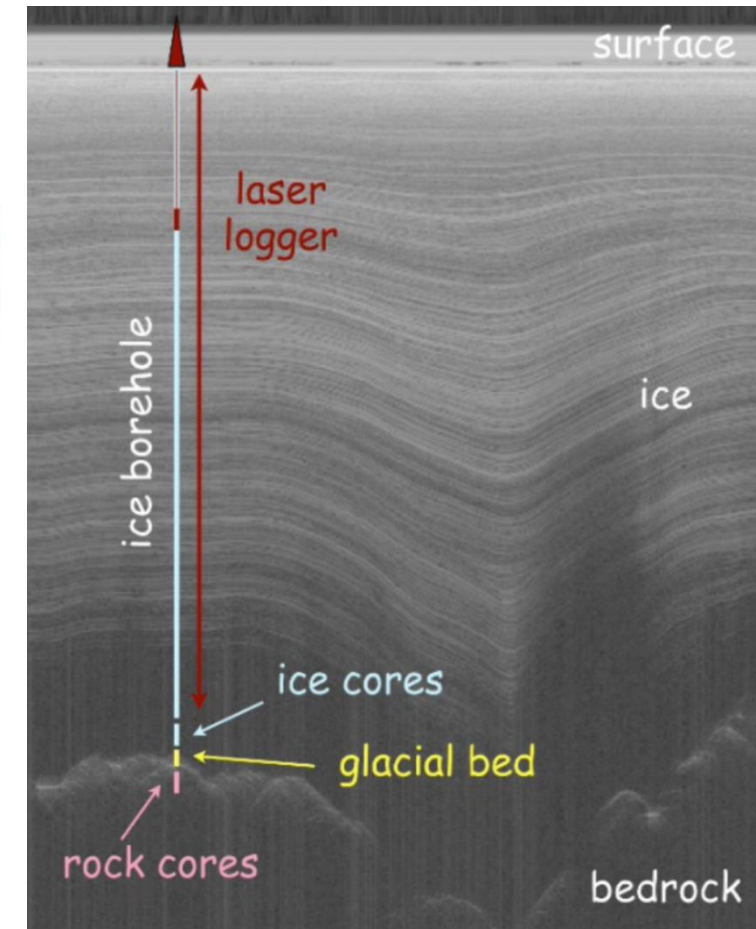
ANTARES Monte Carlo, JCAP01 (2021) 064
Antoine Kouchner, 33rd Rencontres de Blois

HIGHLIGHT: CHALLENGE IN ICE

Layered ice models, ice tilt (down-hill)



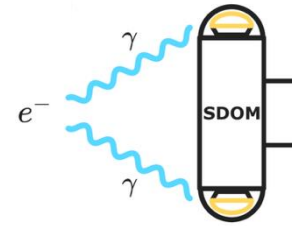
Martin Rongen, VLVnt 2021



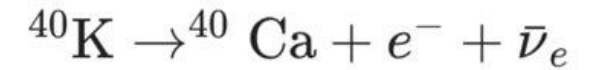
Dmitry Chirkin, SCAR 2022

115

HIGHLIGHT: CHALLENGE IN WATER



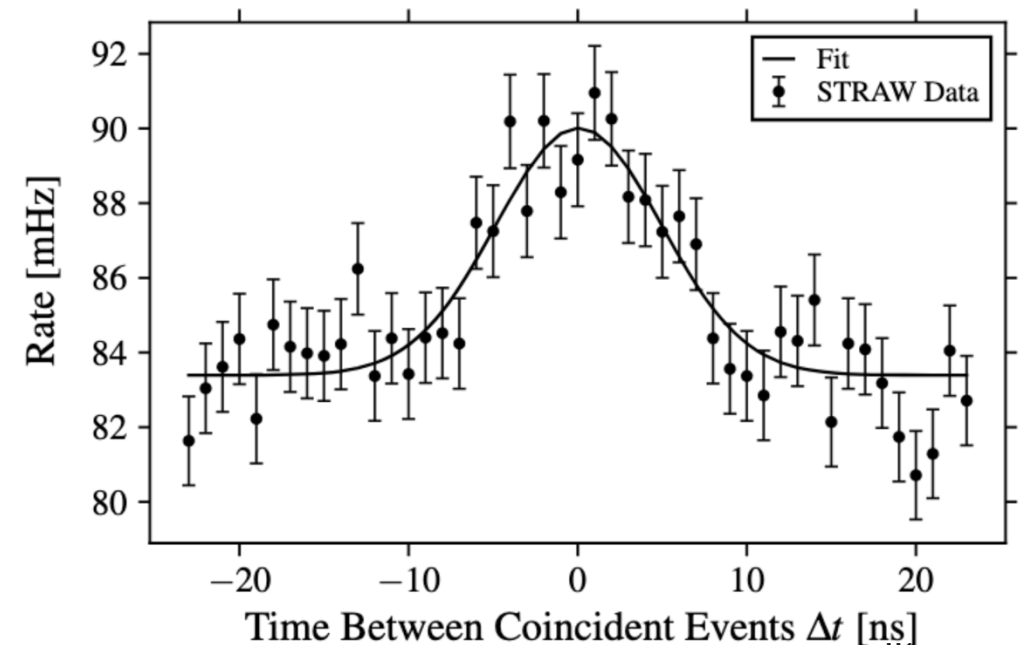
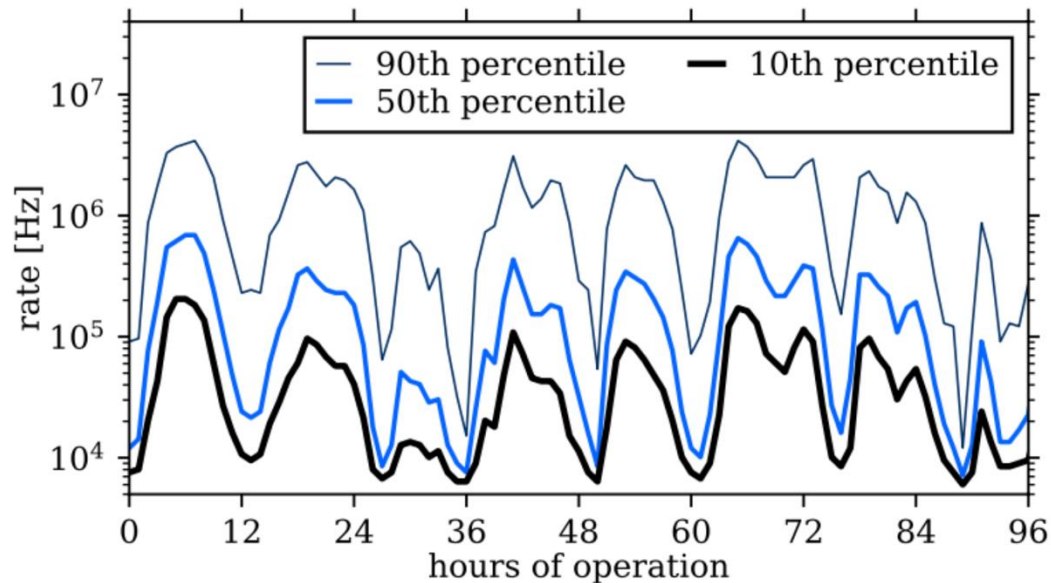
Deep sea water is
saltier than Antarctic ice!



Salinity from this work: $2.5 \pm 1.4\%$

Salinity from ONC: $3.482 \pm 0.001\%$

Salinity at ANTARES site: 3.844%

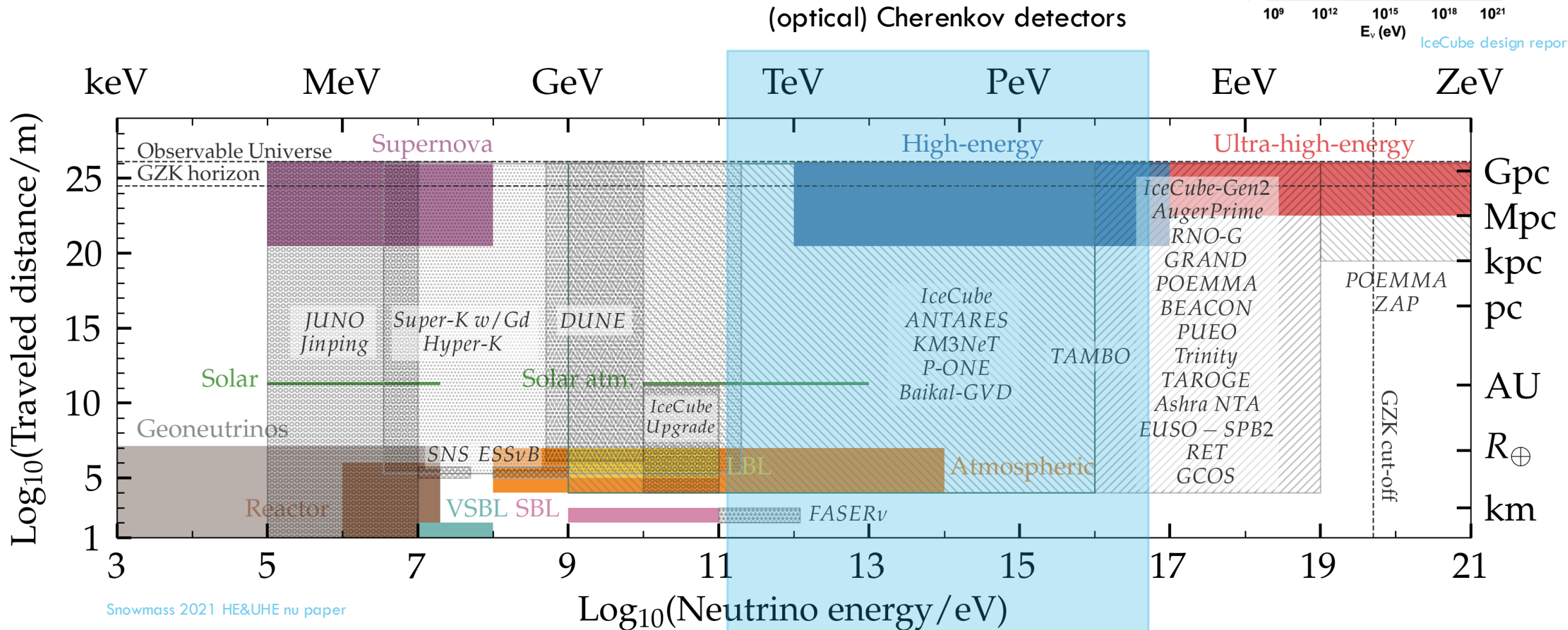


NEUTRINO TELESCOPES AT DIFFERENT STAGES

Table 3. List of operational and planned Cherenkov neutrino telescopes. [†] ICRC 2025 design study value, subject to optimisation.

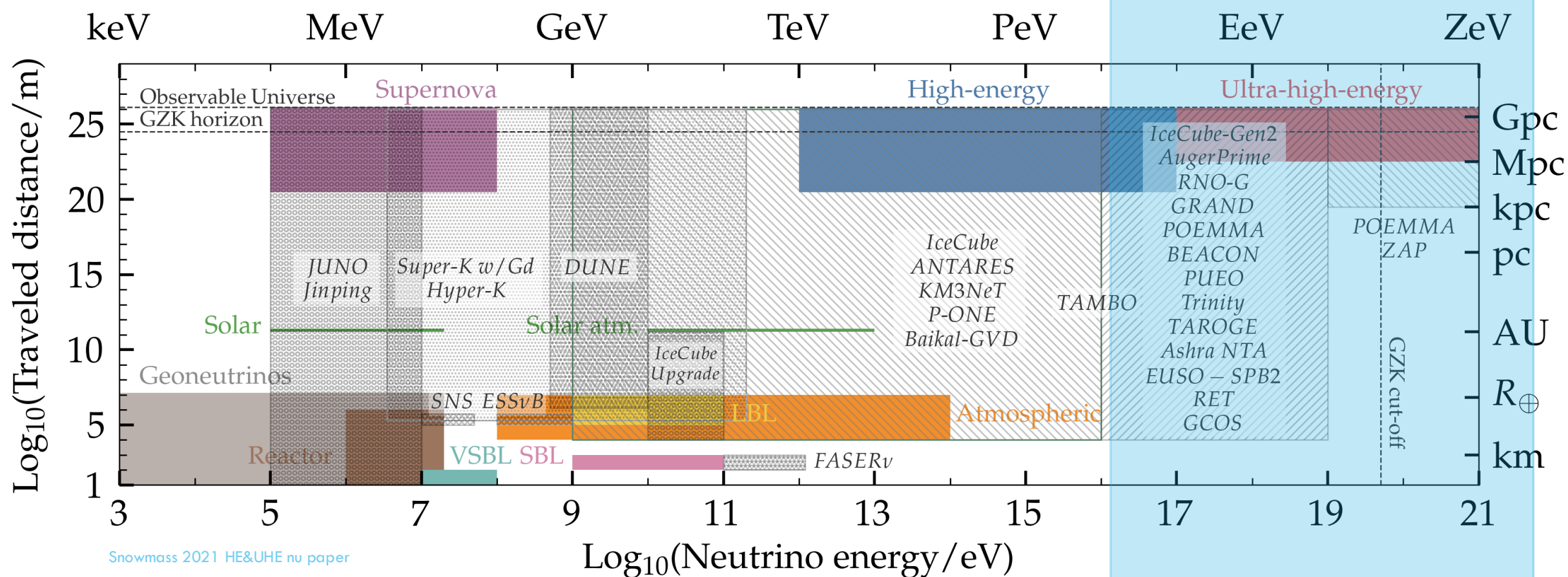
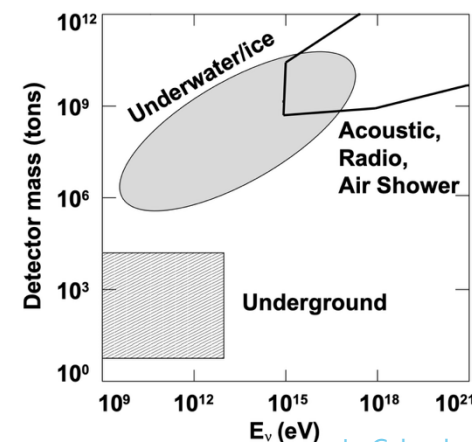
Experiment	Site (s)	Volume [km ³]	Site Depth [m]	Horizontal Spacing [m]	Vertical Spacing [m]
IceCube	South Pole	~1	~2450 (ice)	125	17
IceCube-Gen2	South Pole	~8 (proposed)	~2700 (ice)	240	17
KM3NeT–ARCA	Mediterranean Sea	~1 (target)	~3500 (sea)	90–100	36–40
Baikal–GVD	Lake Baikal	~1 (target)	~1360 (lake)	60 (intra); ~300 (inter)	15
P-ONE	Pacific Ocean	1 (proposed)	2660 (sea)	~100	50
TRIDENT	South China Sea	~7.5–8 (proposed)	2800–3400 (sea)	70–110	30–40
NEON	South China Sea	~10 (proposed)	1700–3500 (sea)	100	30
HUNT	South China Sea & Baikal	~30 (proposed)	Baikal 1360; SCS 2560–3420	~130 [†]	36

NEUTRINO DETECTIONS



Snowmass 2021 HE&UHE nu paper

MOVING TOWARDS THE HIGHEST ENERGIES



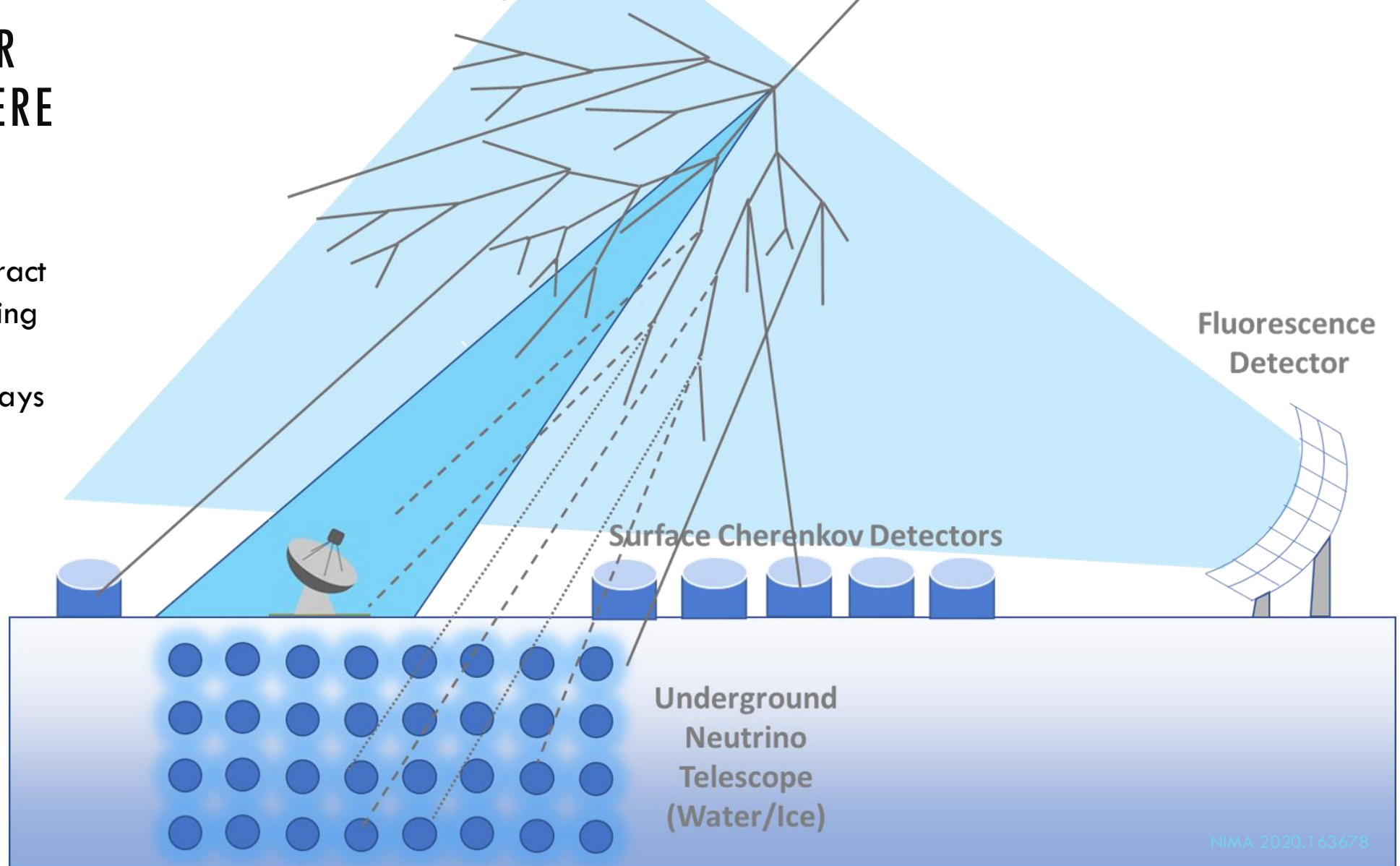
Snowmass 2021 HE&UHE nu paper

AIR SHOWER: BACKGROUND AND SIGNAL

ICE, WATER
ATMOSPHERE

Signal: neutrinos interact
in air or earth-skimming

Background: cosmic rays



COSMOGENIC NEUTRINOS

$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$

$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$3k_B T$ effective energy for Planck spectrum of CMB

$$\epsilon' = 3k_B T = 4 \times 2.73 \times 8.62 \times 10^{-5} \text{ eV}$$

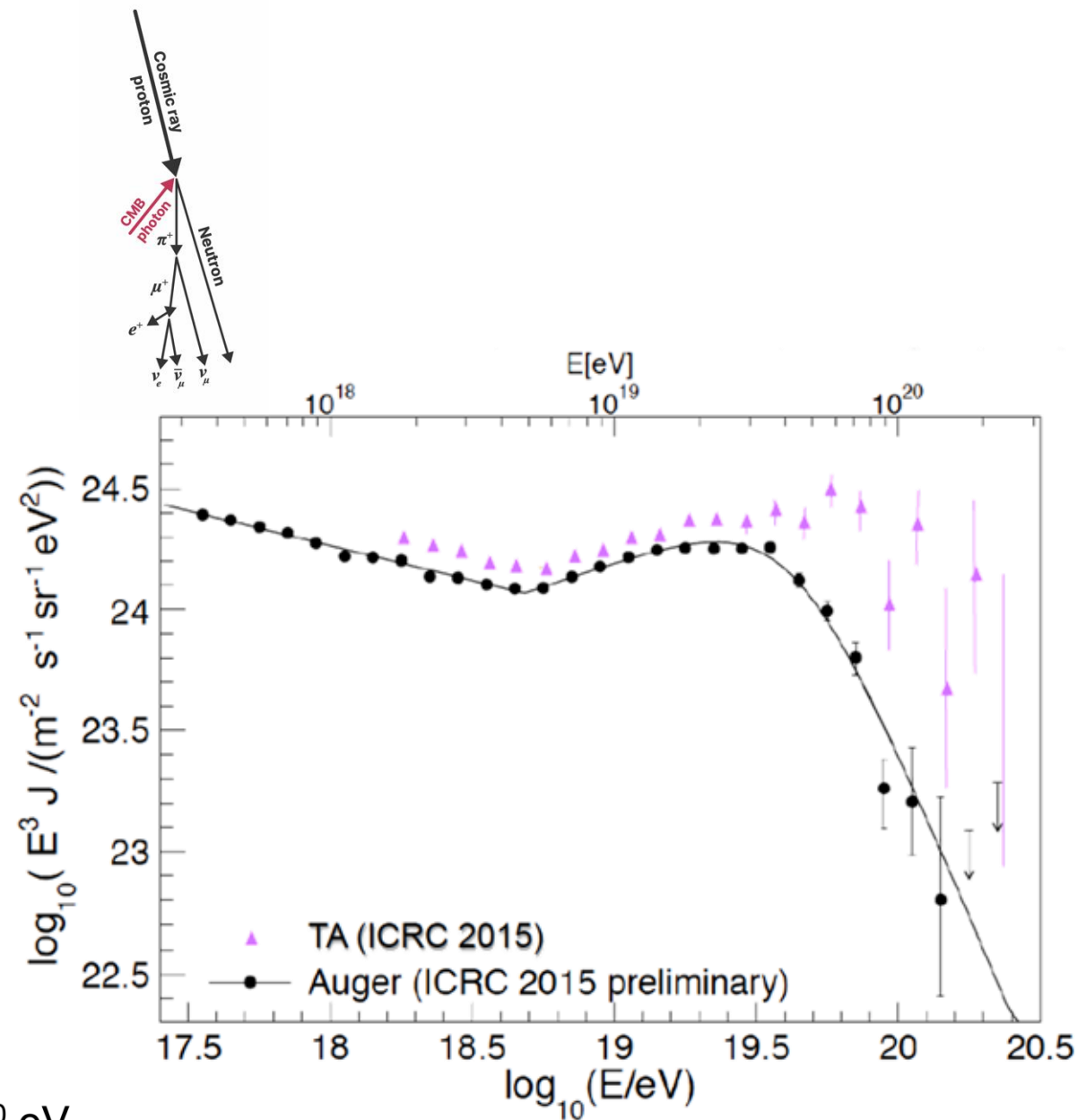
$$\epsilon = \frac{m_\Delta^2 - m_p^2}{2m_p} \sim 340 \text{ MeV}$$

$$\gamma_p = \frac{\epsilon'}{\epsilon} = 2 \cdot 10^{11}$$

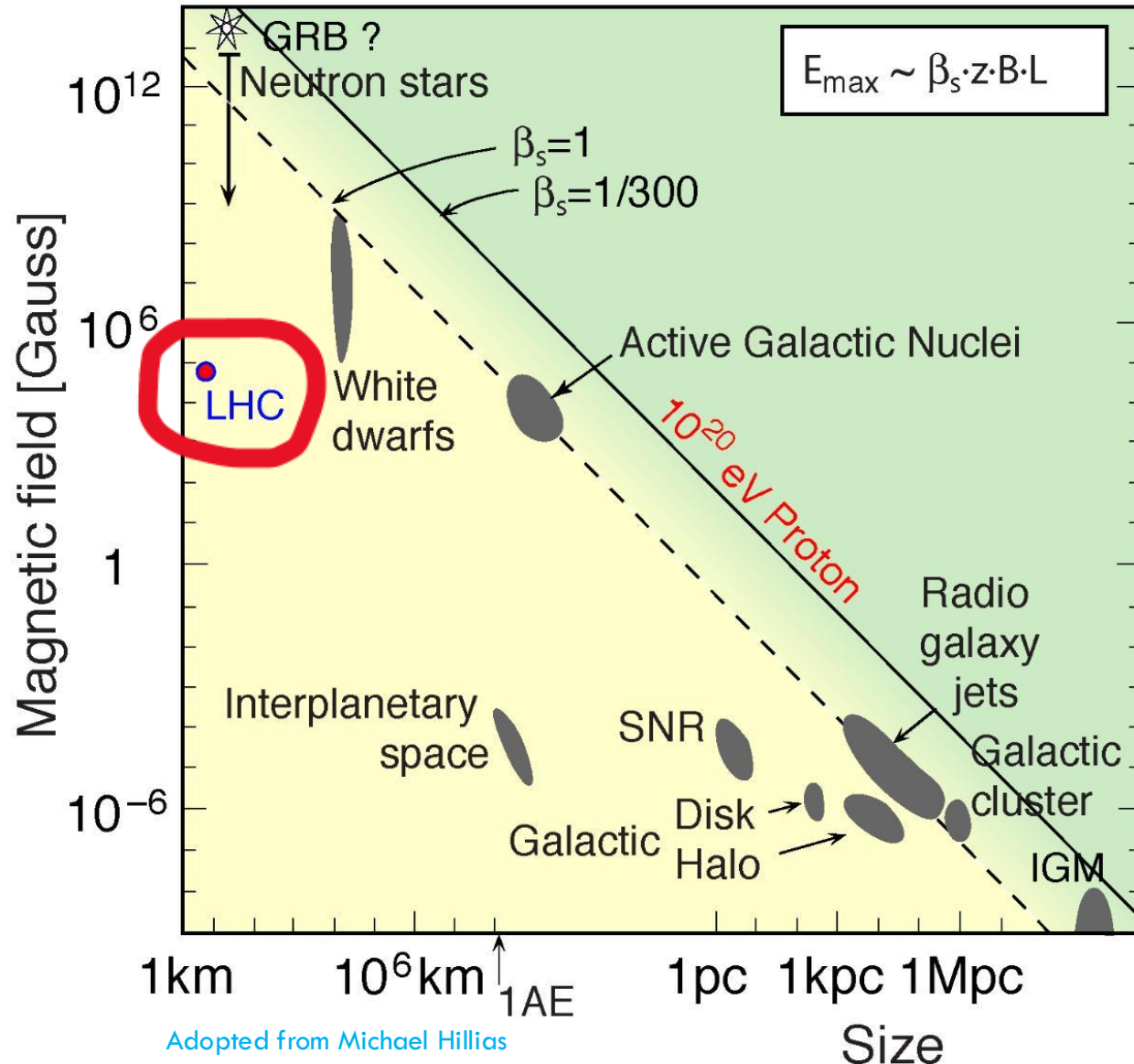
⇒ Hence the threshold

energy of the proton in the CM is $E'_p \sim \gamma_p m_p = 2 \cdot 10^{20} \text{ eV}$

Integrating over Planck
spectrum $E_{p,th} \sim 5 \cdot 10^{19} \text{ eV}$



NATURE ACCELERATORS



The highest energy particles:
charged cosmic rays $> 10^{20}$ eV

Acceleration mechanism unknown

Conditions of source environment:
 $E \approx \beta \cdot z \cdot B \cdot L$

Cosmic rays are deflected in Galactic magnetic field -> How do we find their true origins?

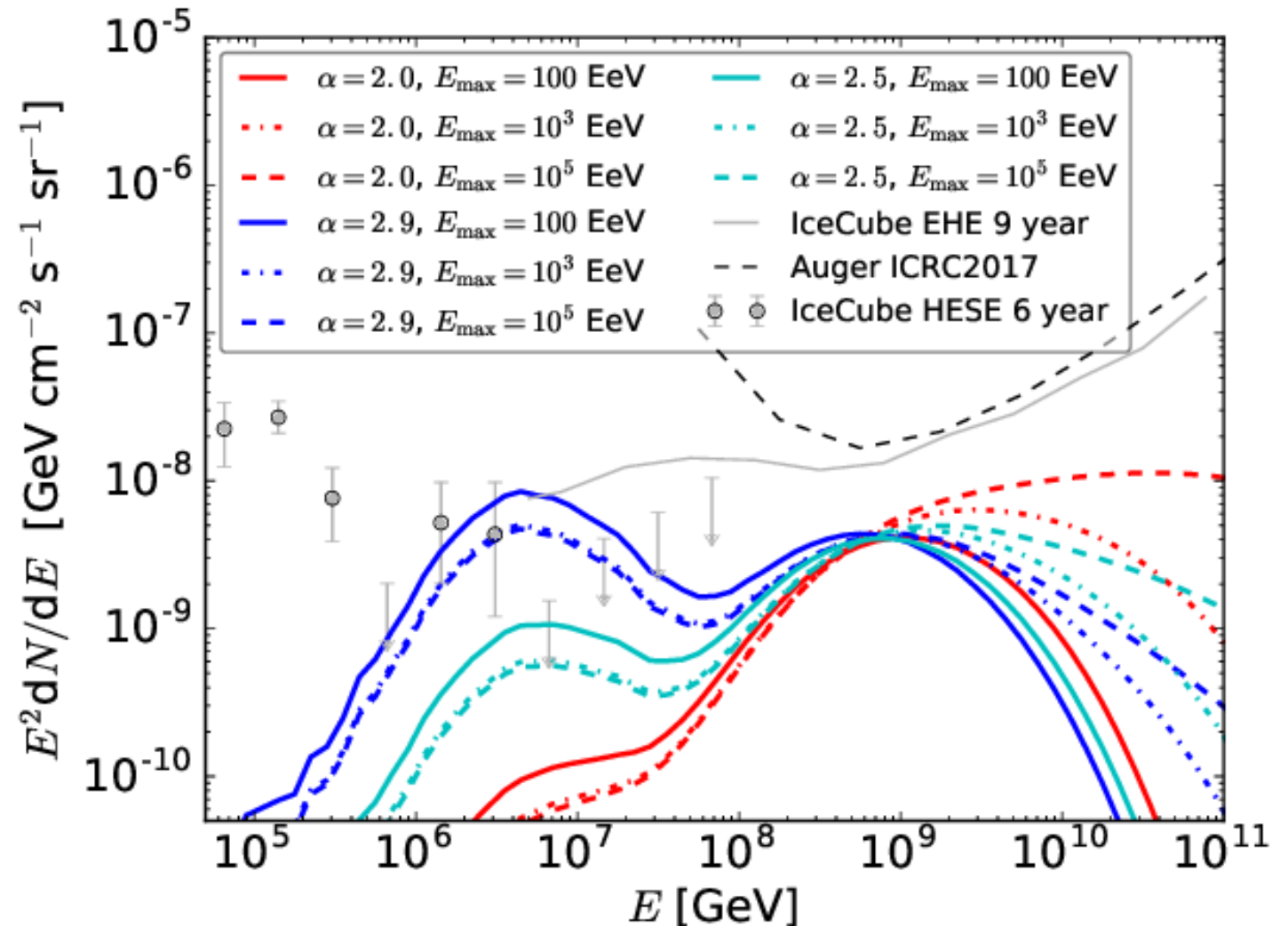
COSMOGENIC NEUTRINOS

Depending on many source parameters

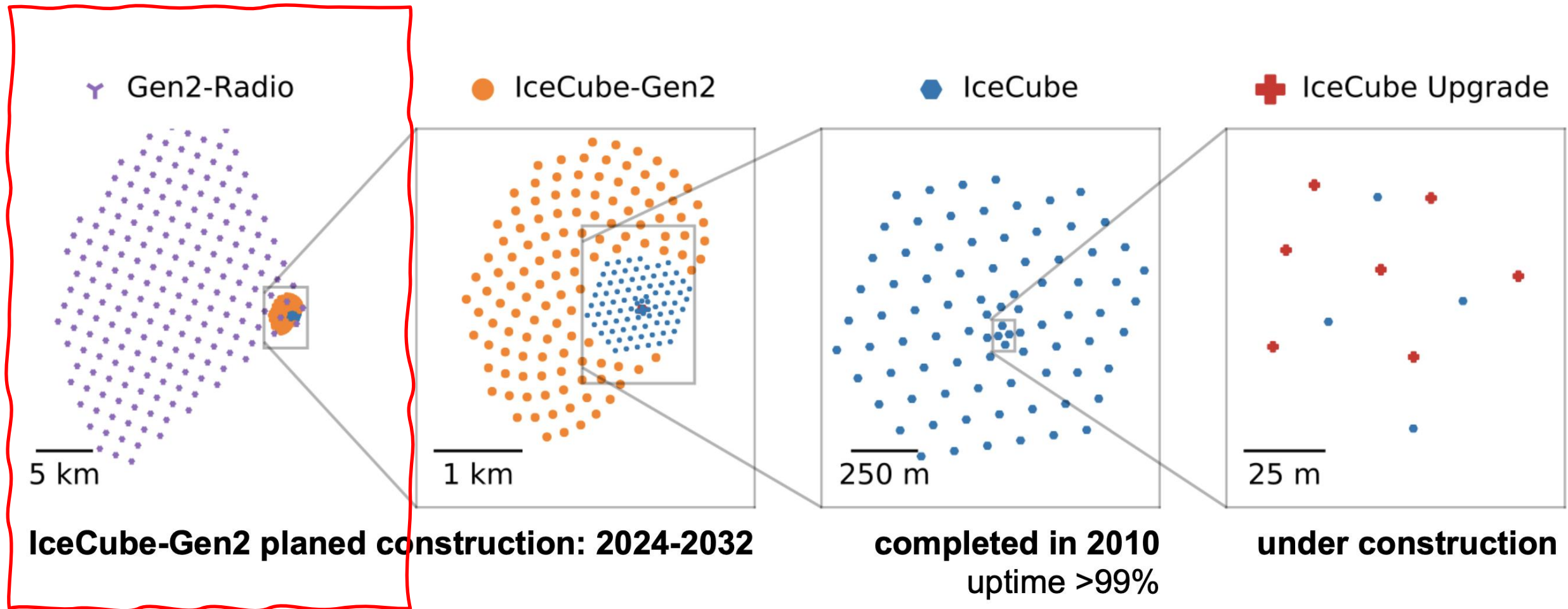
Mass composition of cosmic rays

Source density distributions

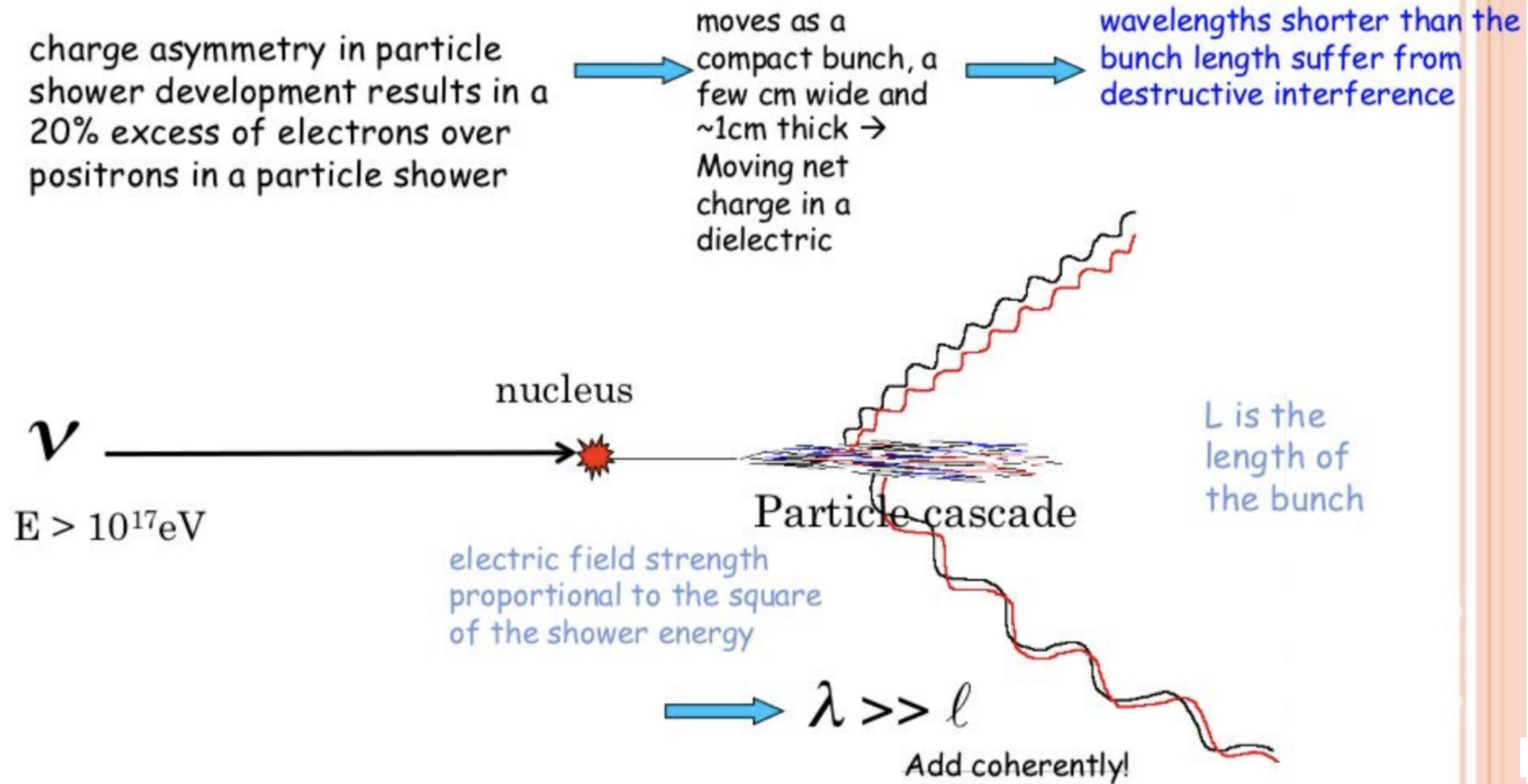
But guaranteed flux



Future: optimising for from 10^9eV to 10^{19}eV



Coherent Cherenkov -> Askaryan radiation (1962)



Using massive ice sheets as target for radio detection

Requirement: a lot of ice

- South Pole
- Ross Ice Shelf (coast of Antarctica)
- Greenland



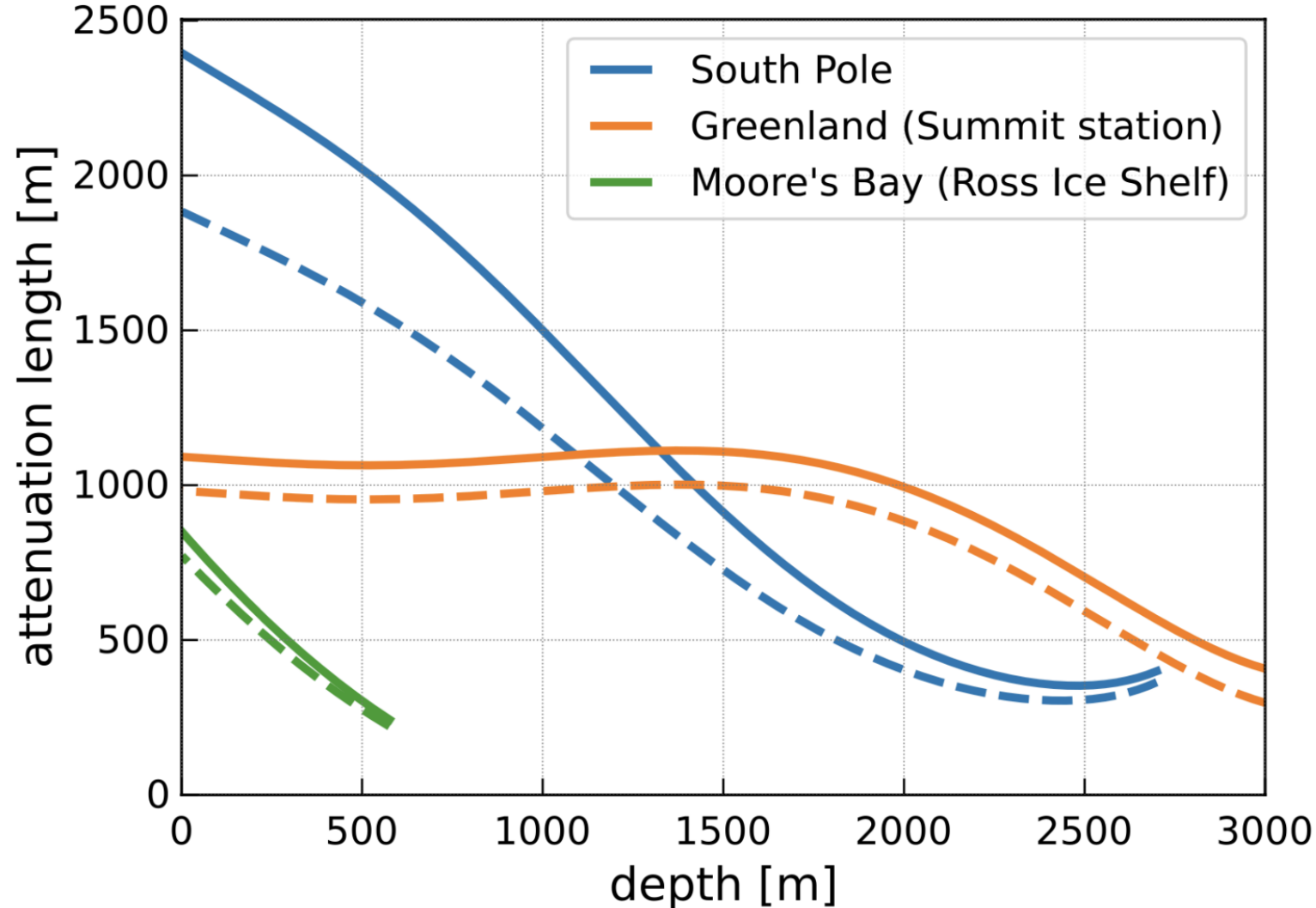
Greenland



Antarctica

Using massive ice sheets as target for radio detection

Attenuation length vs Depth



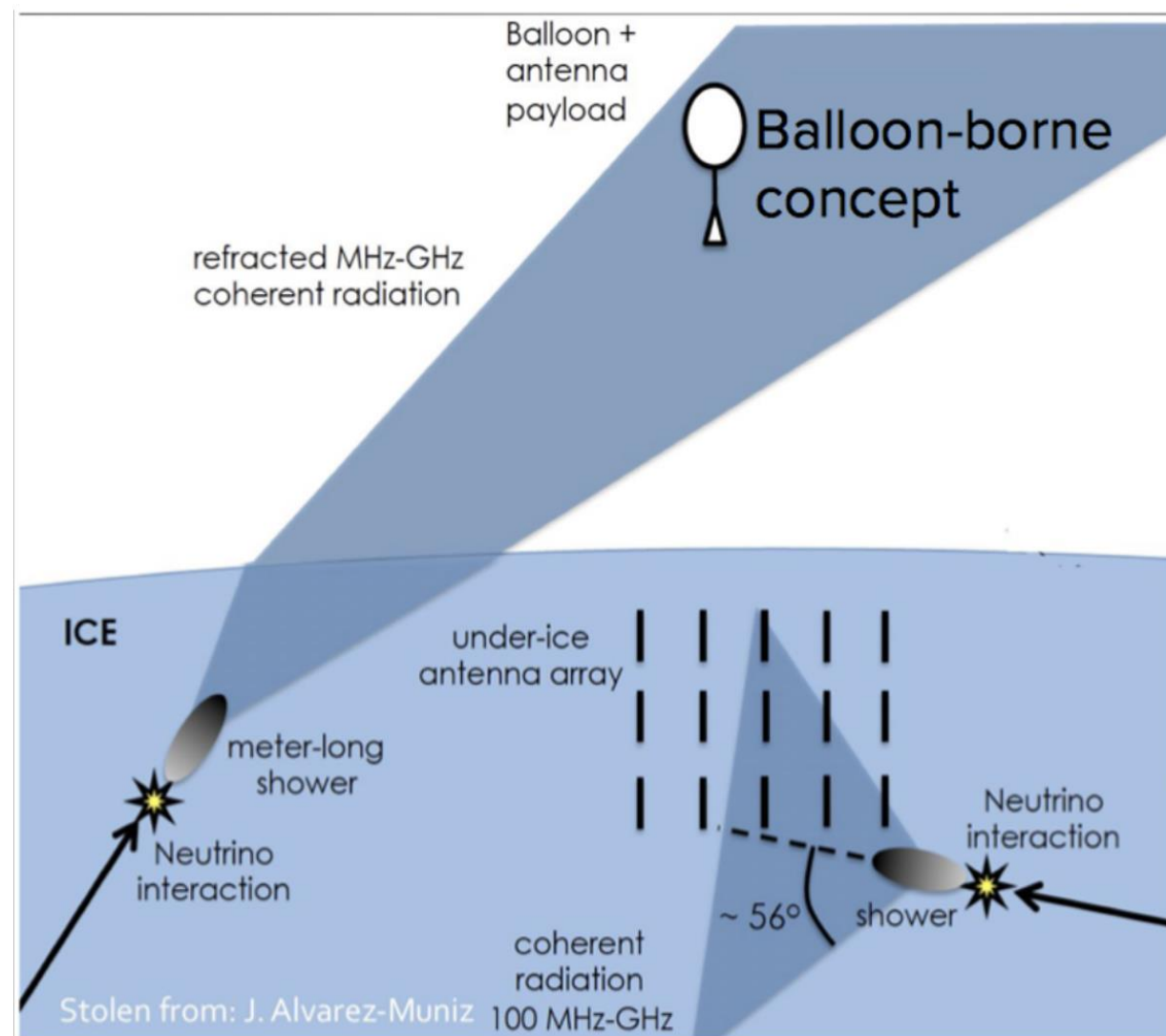
Strong function of temperature.

South Pole is the coldest ice
(-55degC at the top)

Using massive ice sheets as target for radio detection

Askaryan: coherent radio transient from high energy cascade at Cherenkov angle

Signal grows with energy²



ANITA:

Higher energy threshold due to larger distance to interaction

next → PUEO

impressive improvement by phased array triggering
Threshold ~ 1000 PeV

Successful flight in 2026! Data analysis on-going

In-ice, Lower energy threshold: 30 PeV

Pioneering:

RICE: South Pole (coldest → best ice)

ARIANNA: Moore's Bay

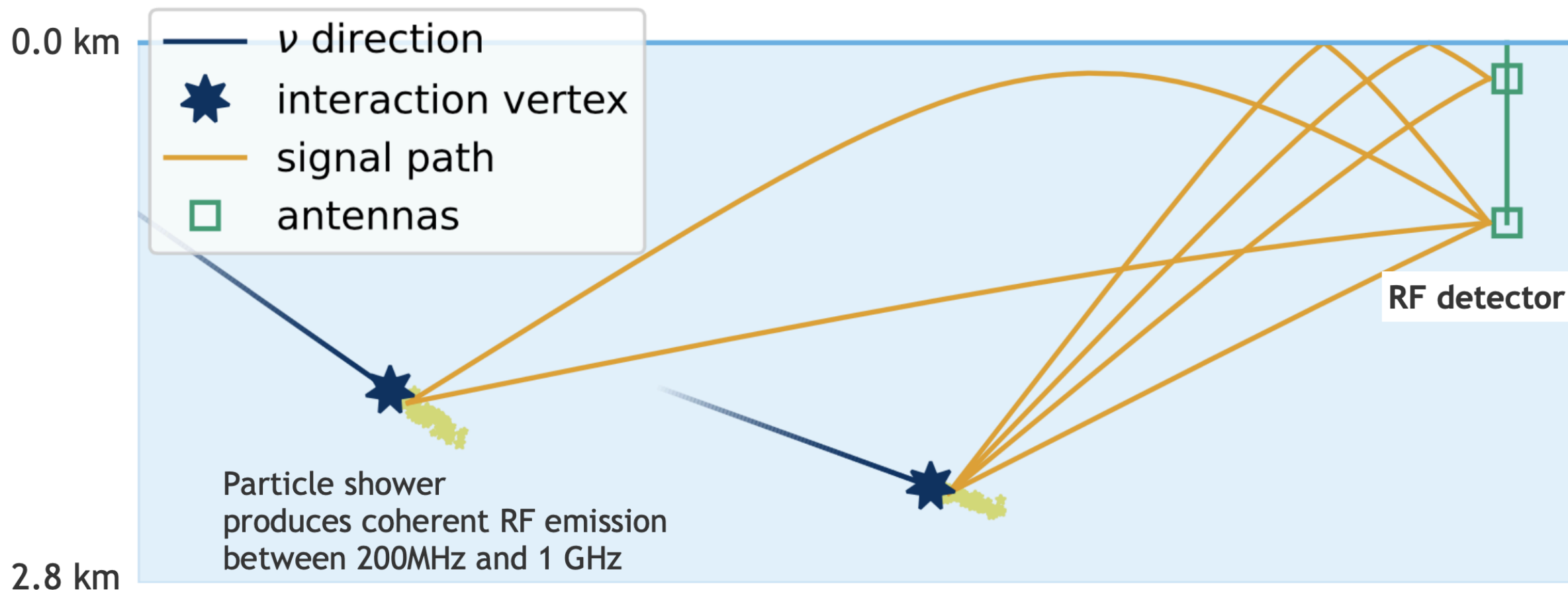
Askaryan Radio Array: South Pole - still running

RNO-G: Greenland

seen also as 'Phase 1' for Gen2 Radio

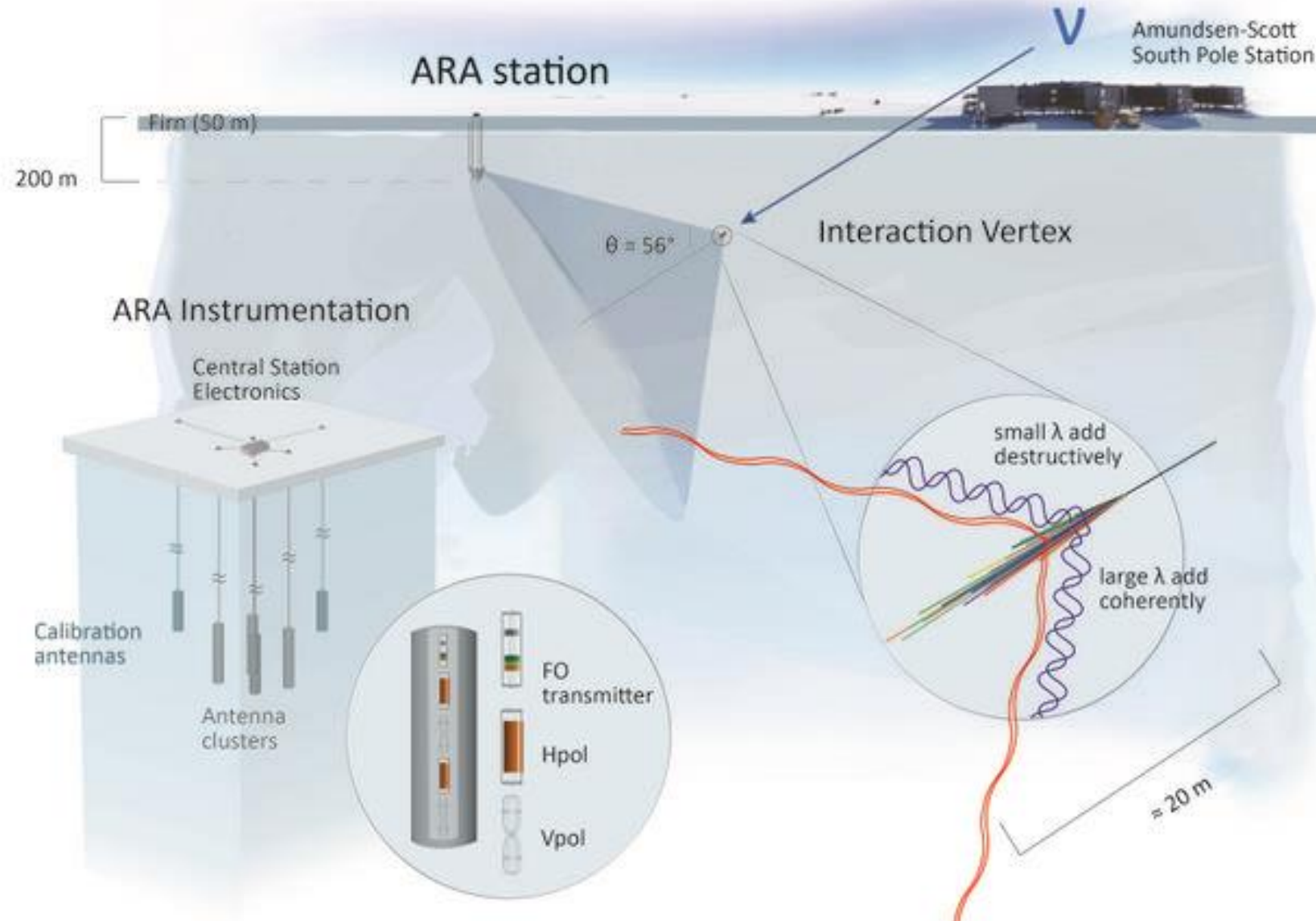
Using massive ice sheets as target

Askaryan: coherent radio transient from high energy cascade at Cherenkov angle
Signal grows with energy²





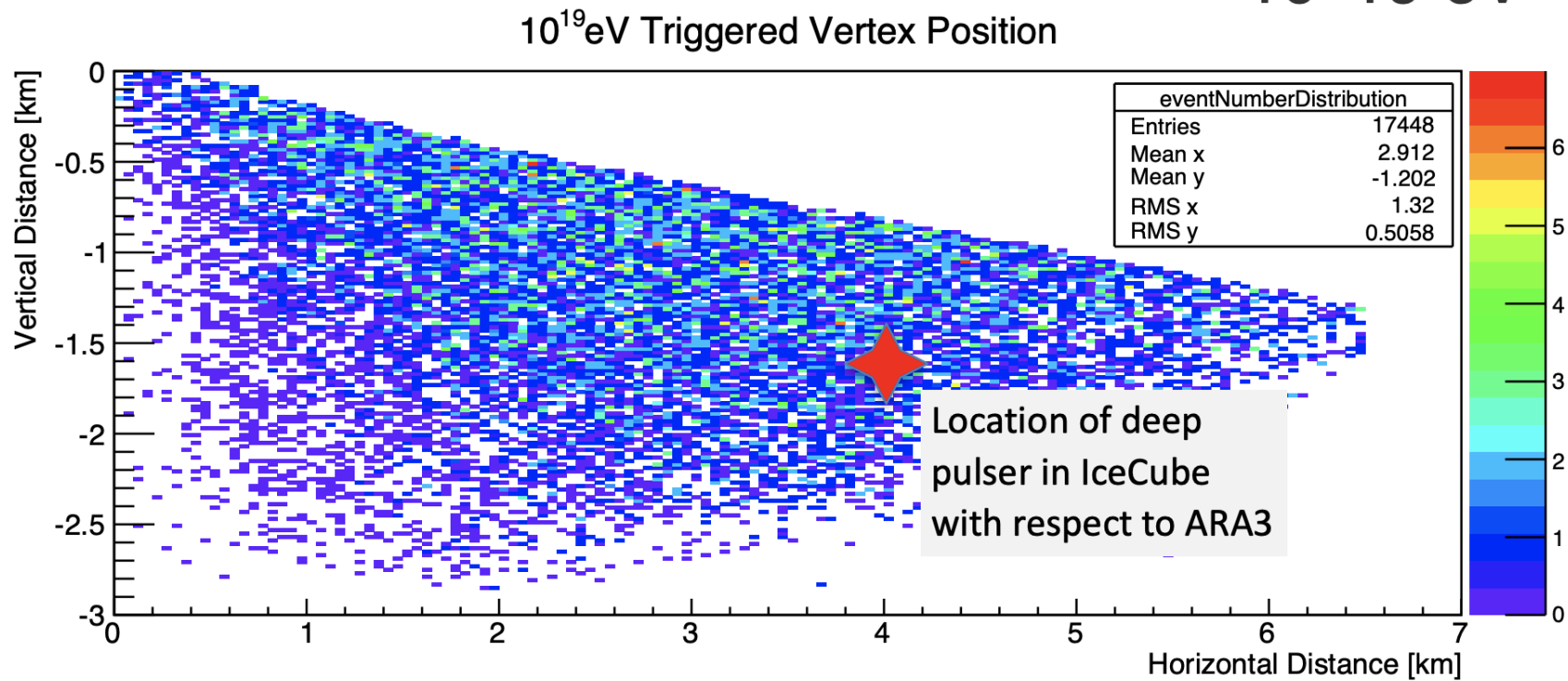
Detection of ultrahigh-energy neutrinos in ARA



Depth and effective volume at South Pole.

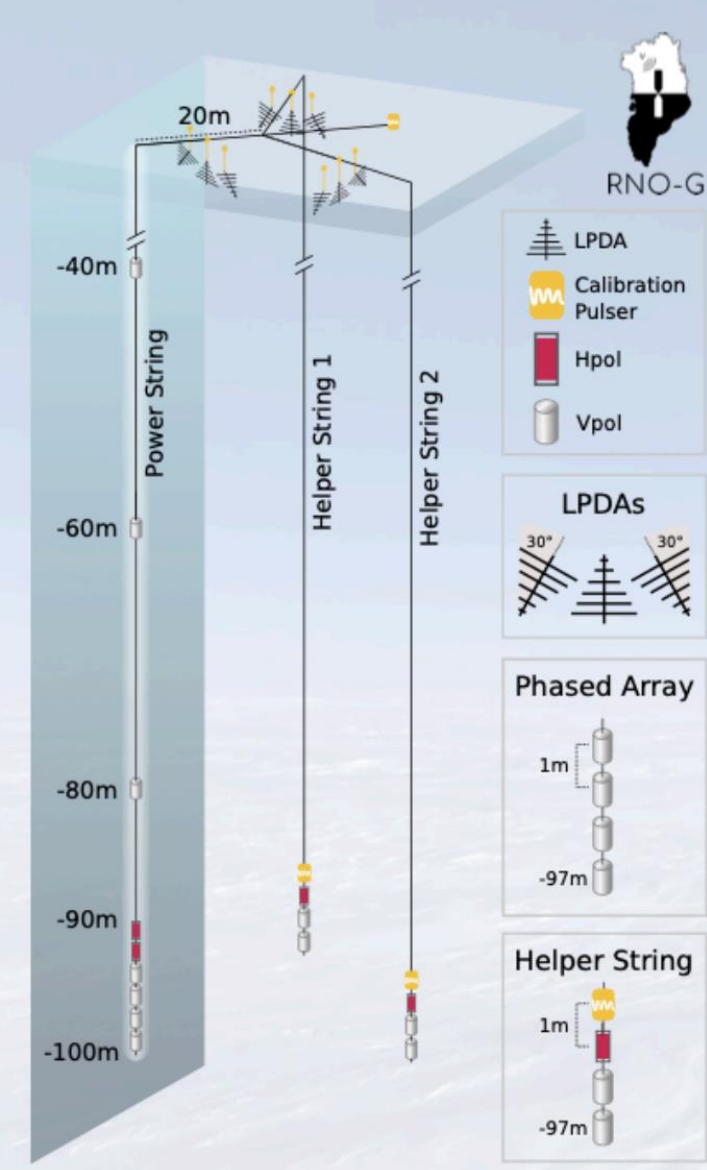
Simulated neutrino events triggering
ARA station at 200m

10^{19} eV

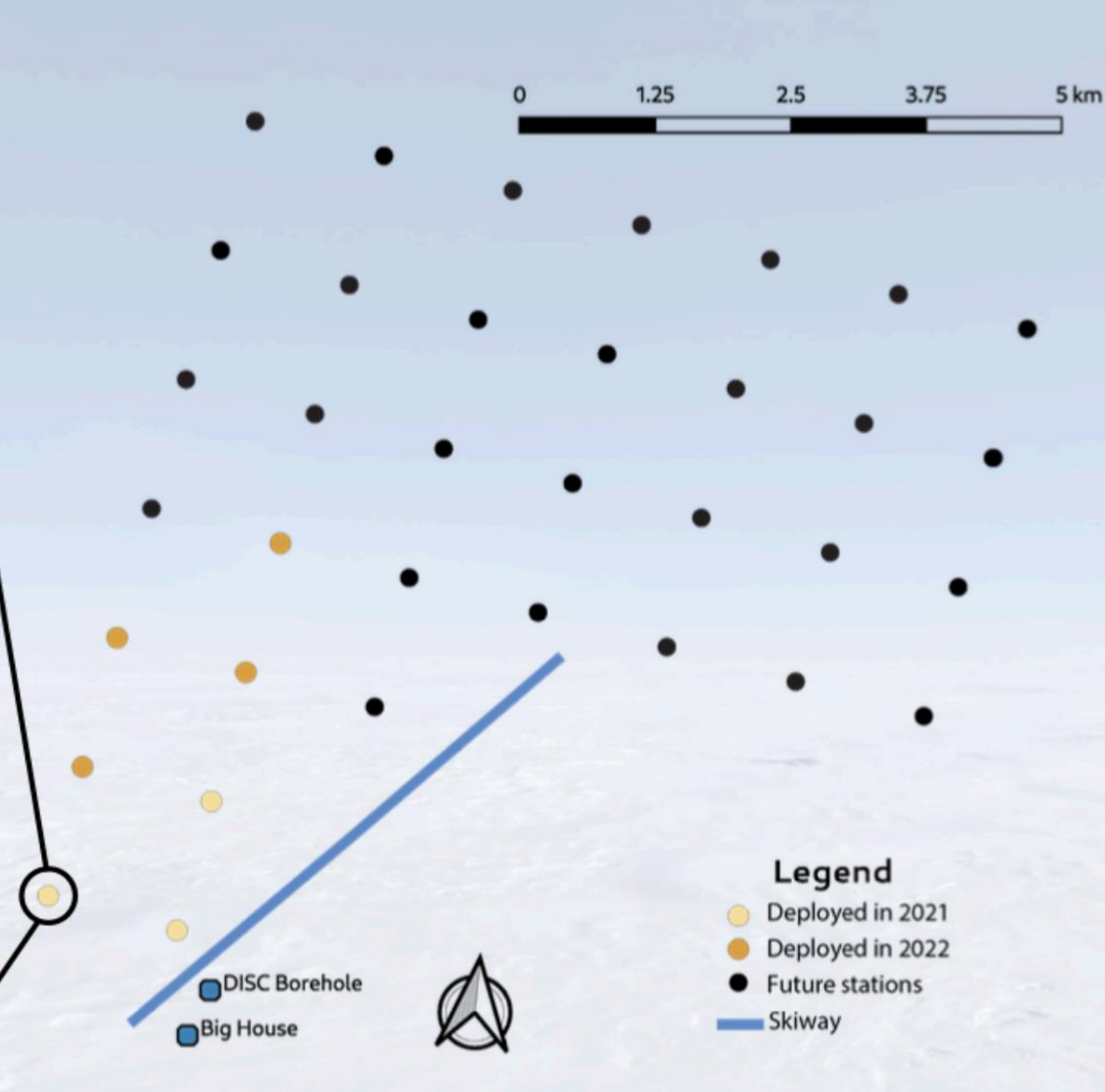


RNO-G: Radio Neutrino Observatory - Greenland

Hybrid station with 24 antennas



35 stations on 1.25 km grid



RNO-G: implements lessons learned from ARA, ARIANNA, Phased Array.

7 stations built, continued construction in the next several years.

RNO-G: Radio Neutrino Observatory - Greenland

Challenge: Reliable and fast drilling

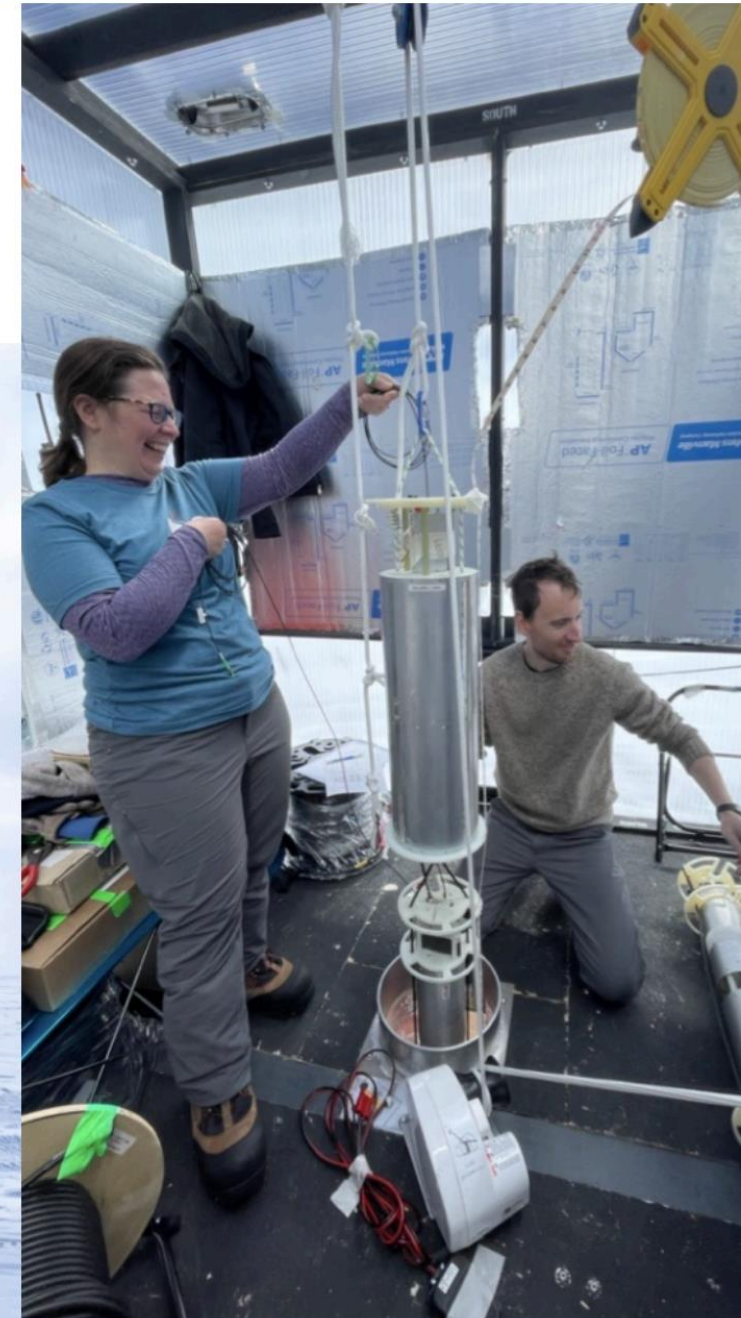
Drilling determines the schedule

Deployed 3 and 4 stations in past seasons (3 holes, 100m, per season)

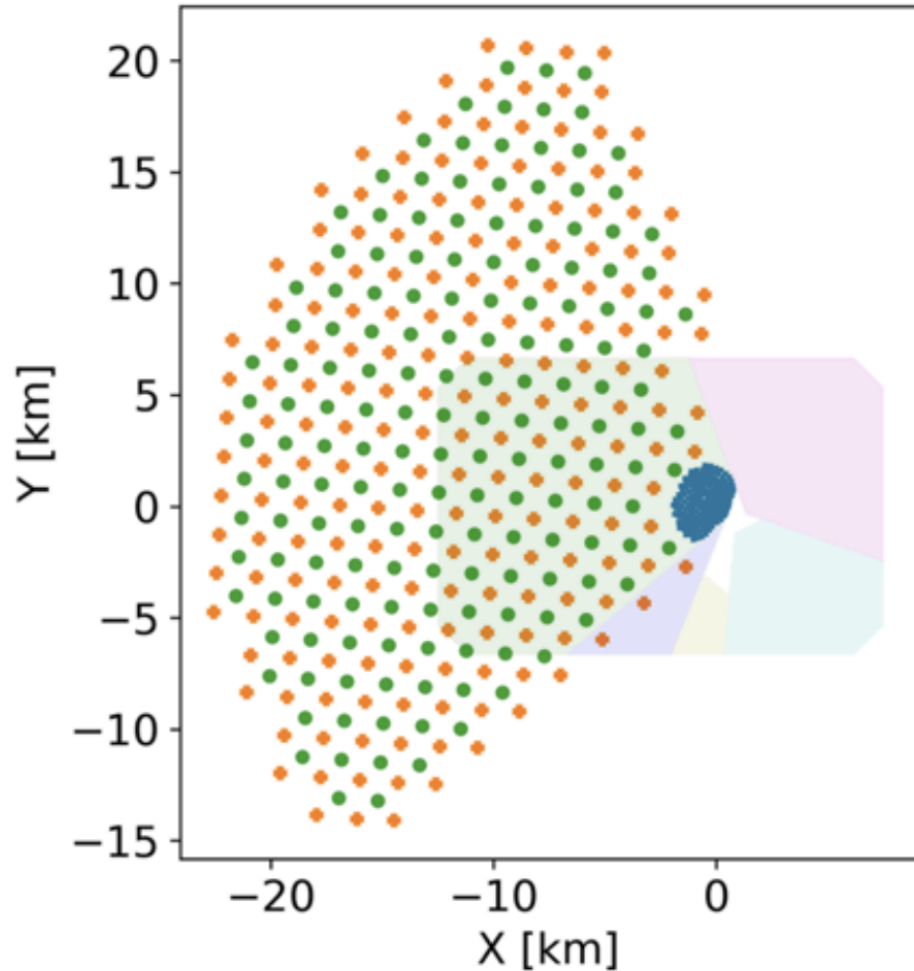
Team is hoping build one station in 3 days.

Sometimes bad weather.

RNO-G will provide important input for Gen2 Radio.



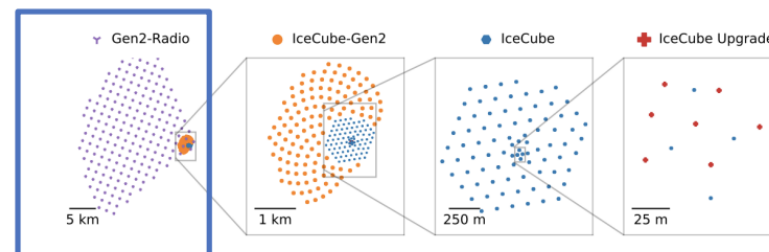
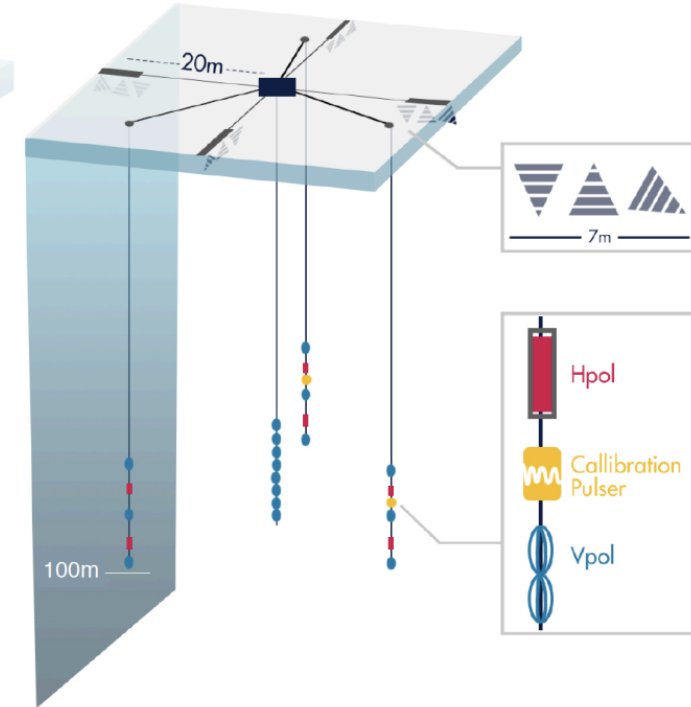
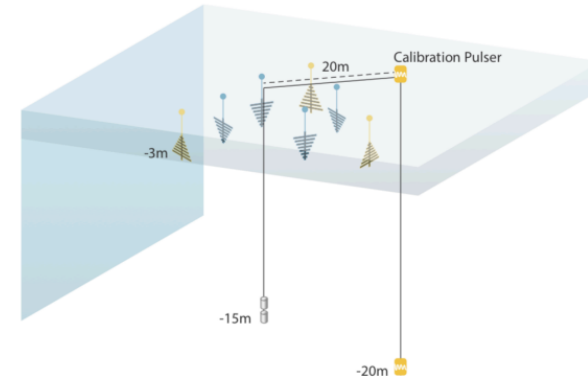
The IceCube-Gen2: the radio array



Area: 500 km²

300 stations

1000 km³ of ice volume



Heritage: ANITA (Antarctica from balloon), [ARA](#) (South Pole), RNO-G (Greenland)

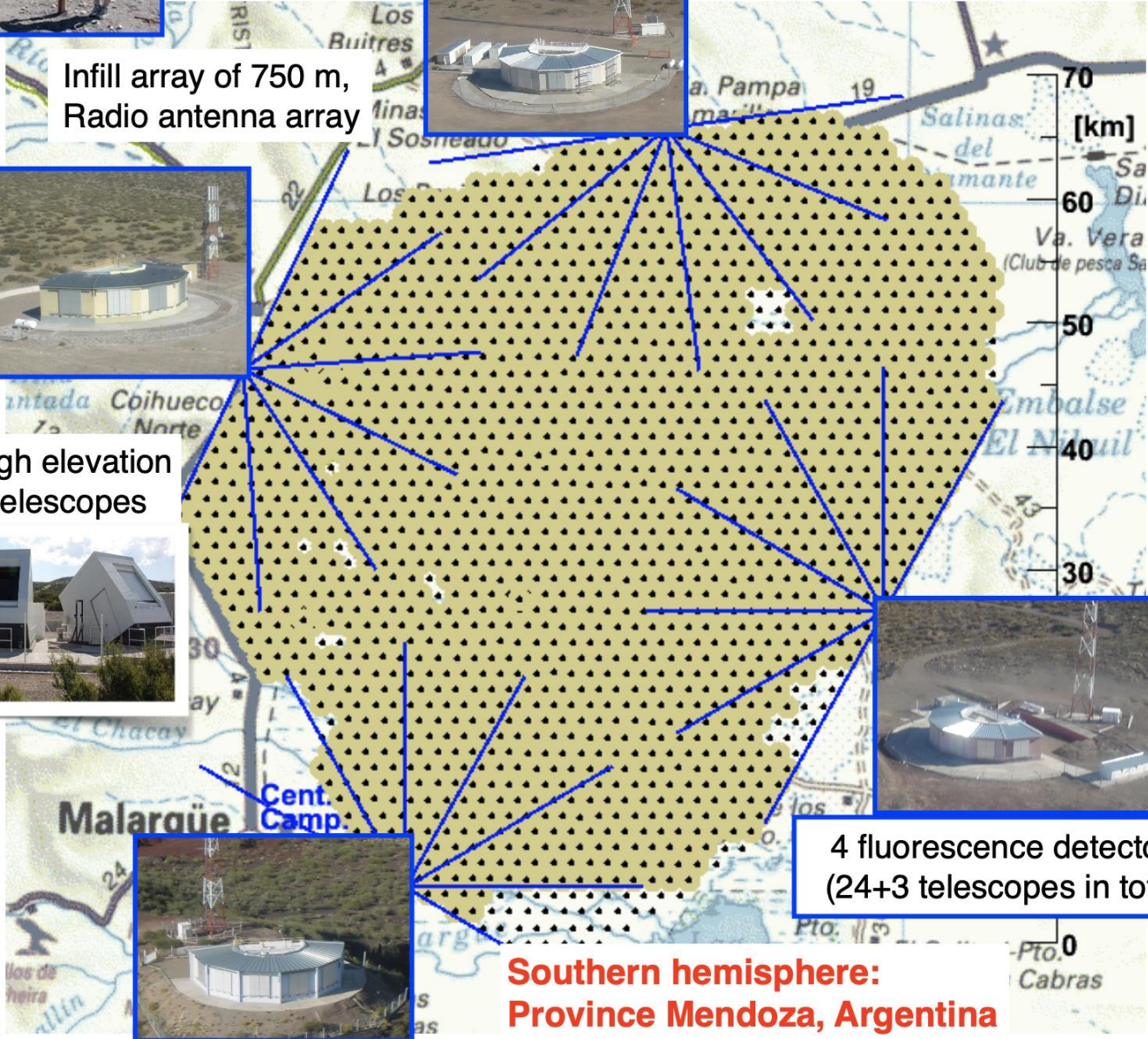
The Pierre Auger Observatory (3000 km²)



Infill array of 750 m,
Radio antenna array



High elevation
telescopes

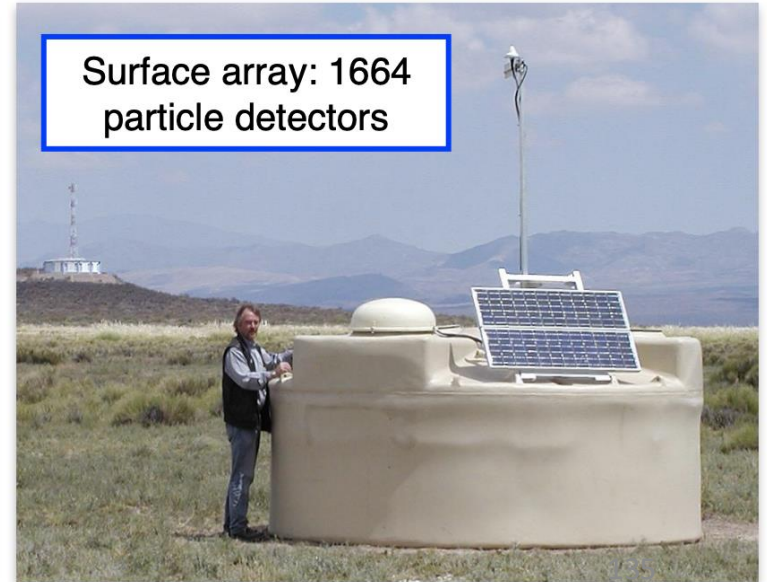


4 fluorescence detectors
(24+3 telescopes in total)

**Southern hemisphere:
Province Mendoza, Argentina**



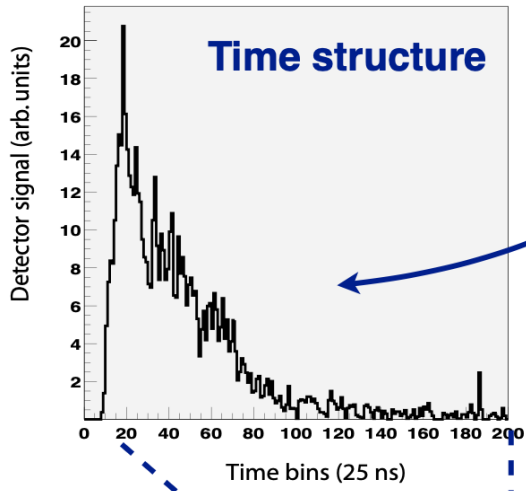
Surface array: 1664
particle detectors



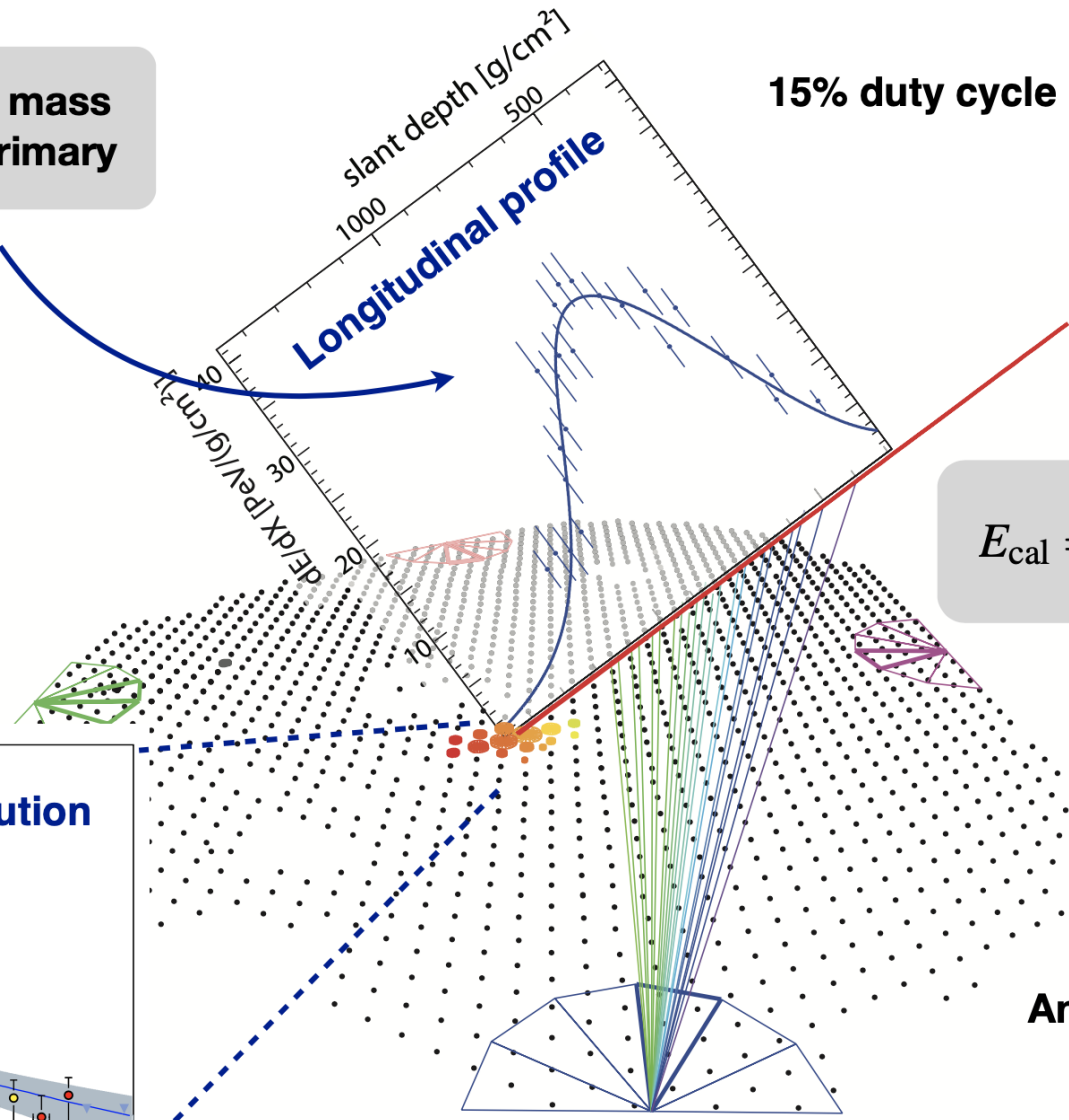
Current state of the art of UHE cosmic ray detection

Sensitivity to mass and type of primary

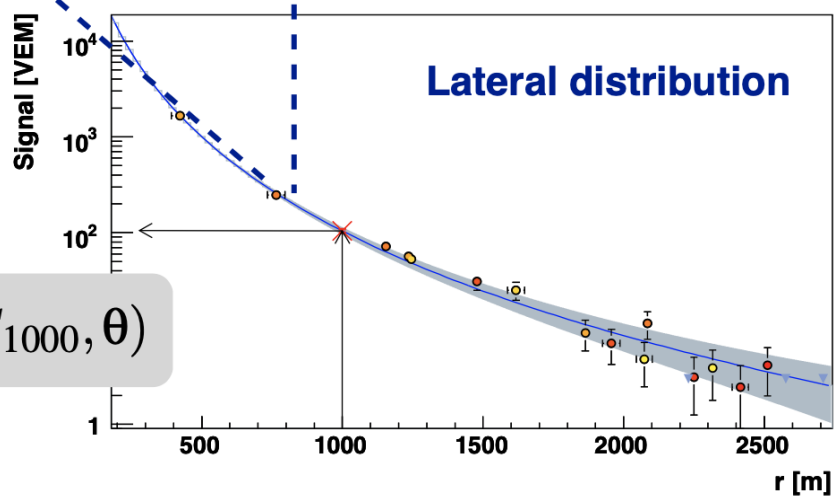
15% duty cycle



100% duty cycle



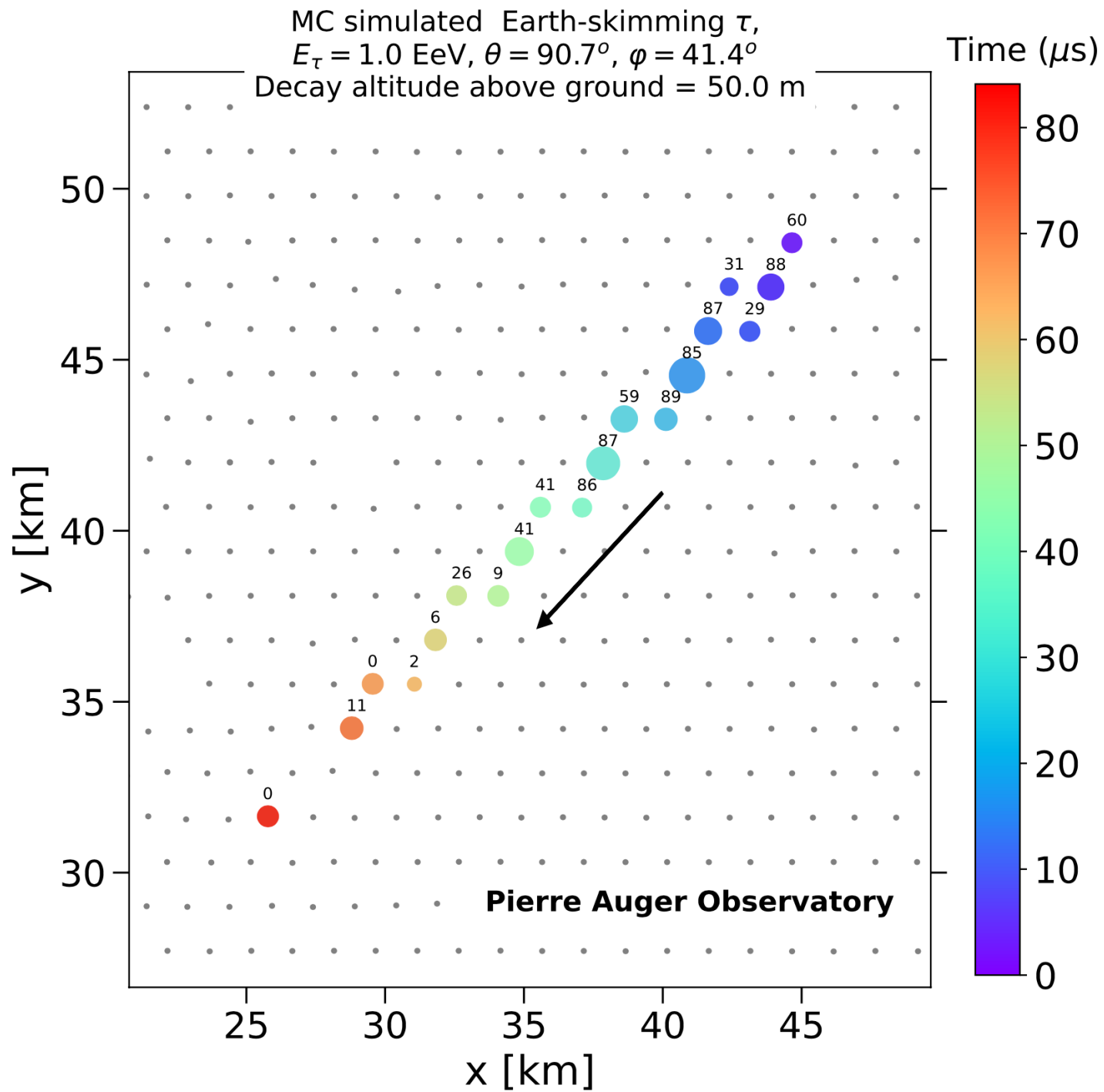
$$E_{\text{cal}} = \int_0^\infty \left(\frac{dE}{dX} \right)_{\text{obs}} dX$$



$$E_{\text{rec}} = f(S_{1000}, \theta)$$

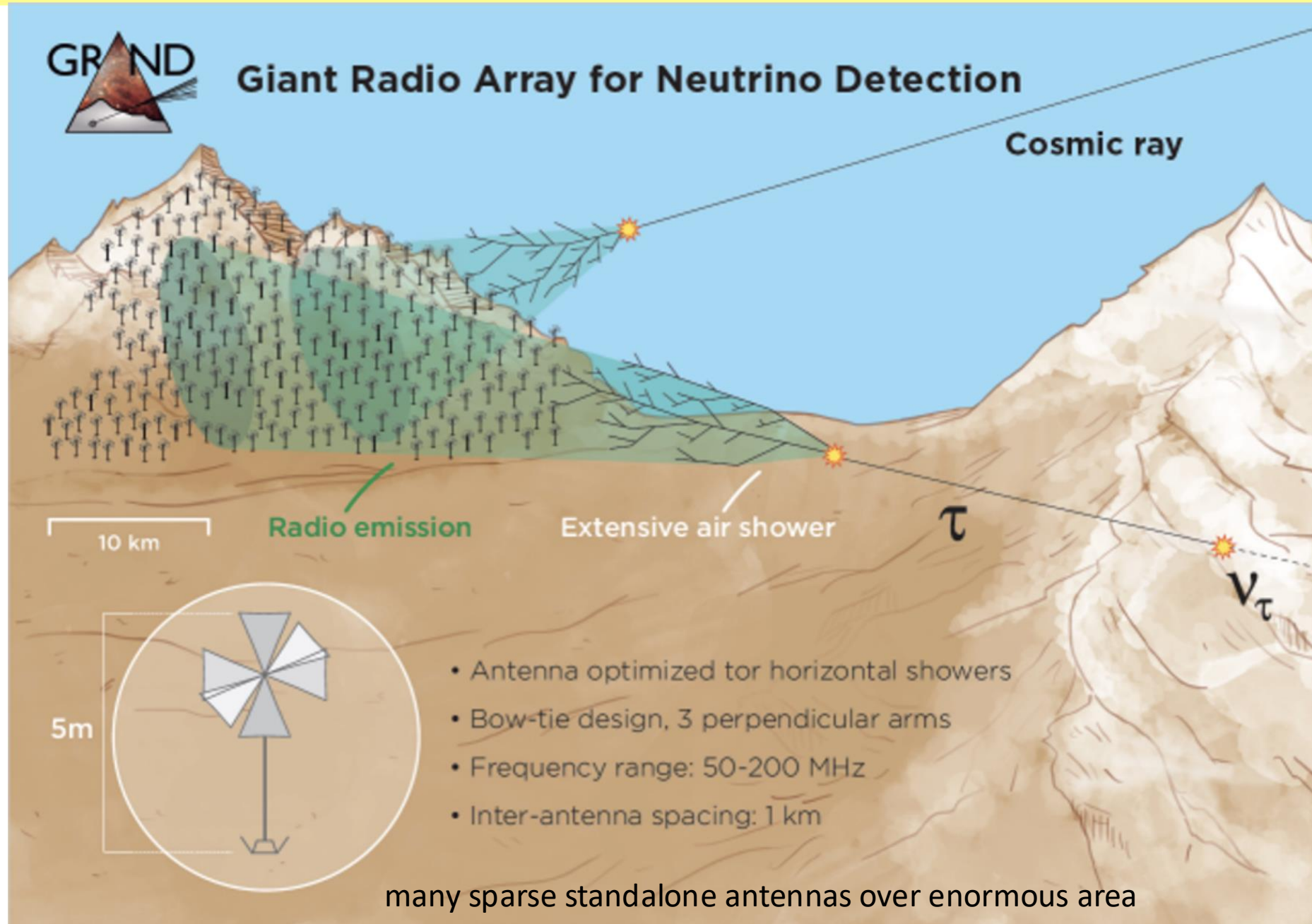
Angular resolution
~ 1.5° – 0.5°

Example: event observed with Auger Observatory



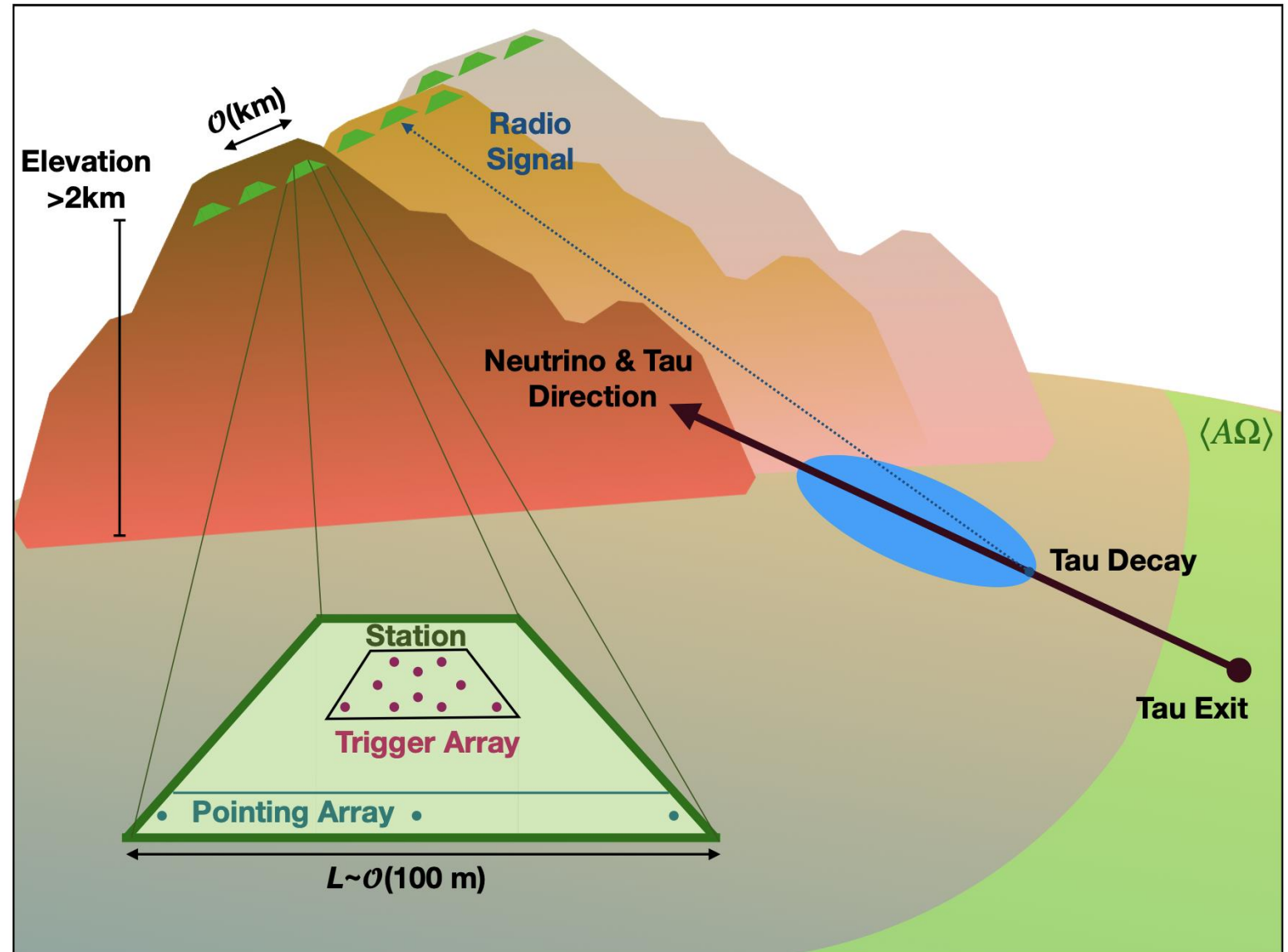
GRAND: 200,000 antennas for horizontal taus

proposed



BEACON

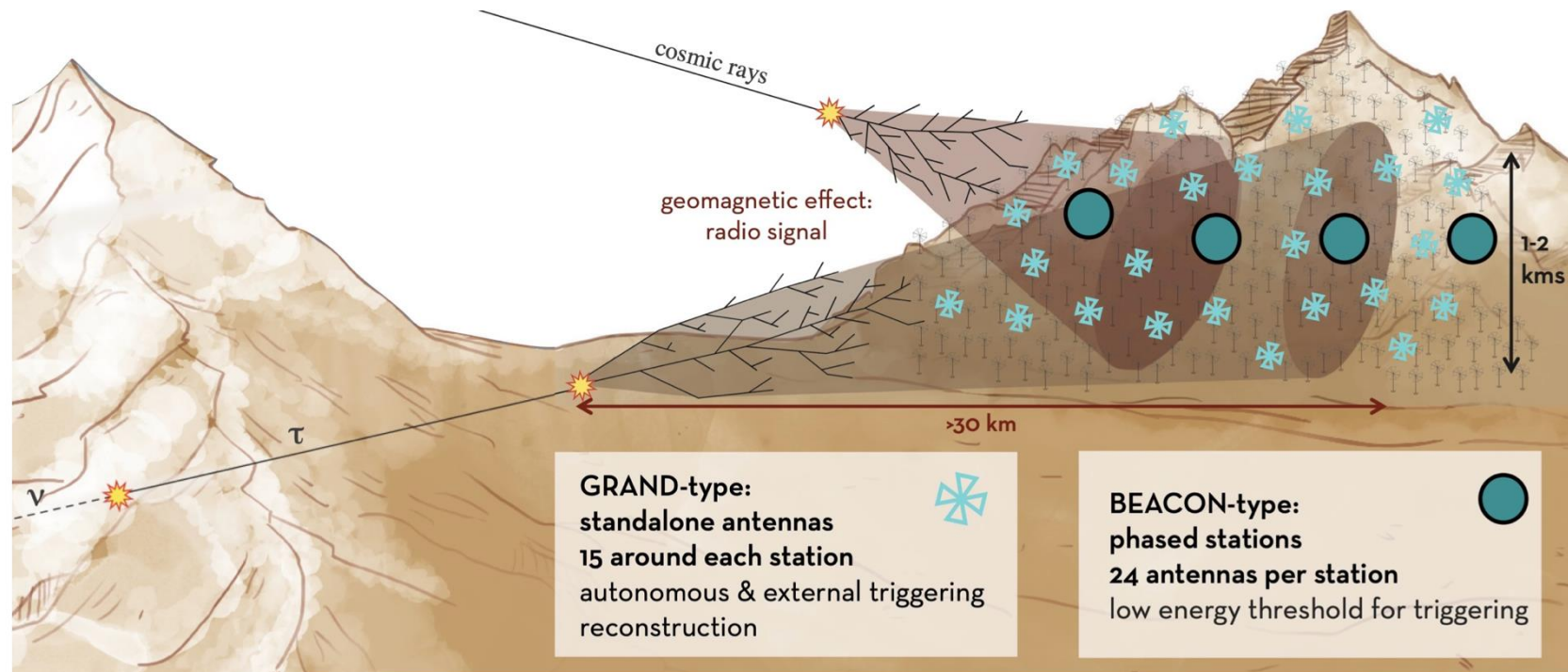
- prototype deployed at the White Mountain Research Station of California
- Compact phased array



HERON

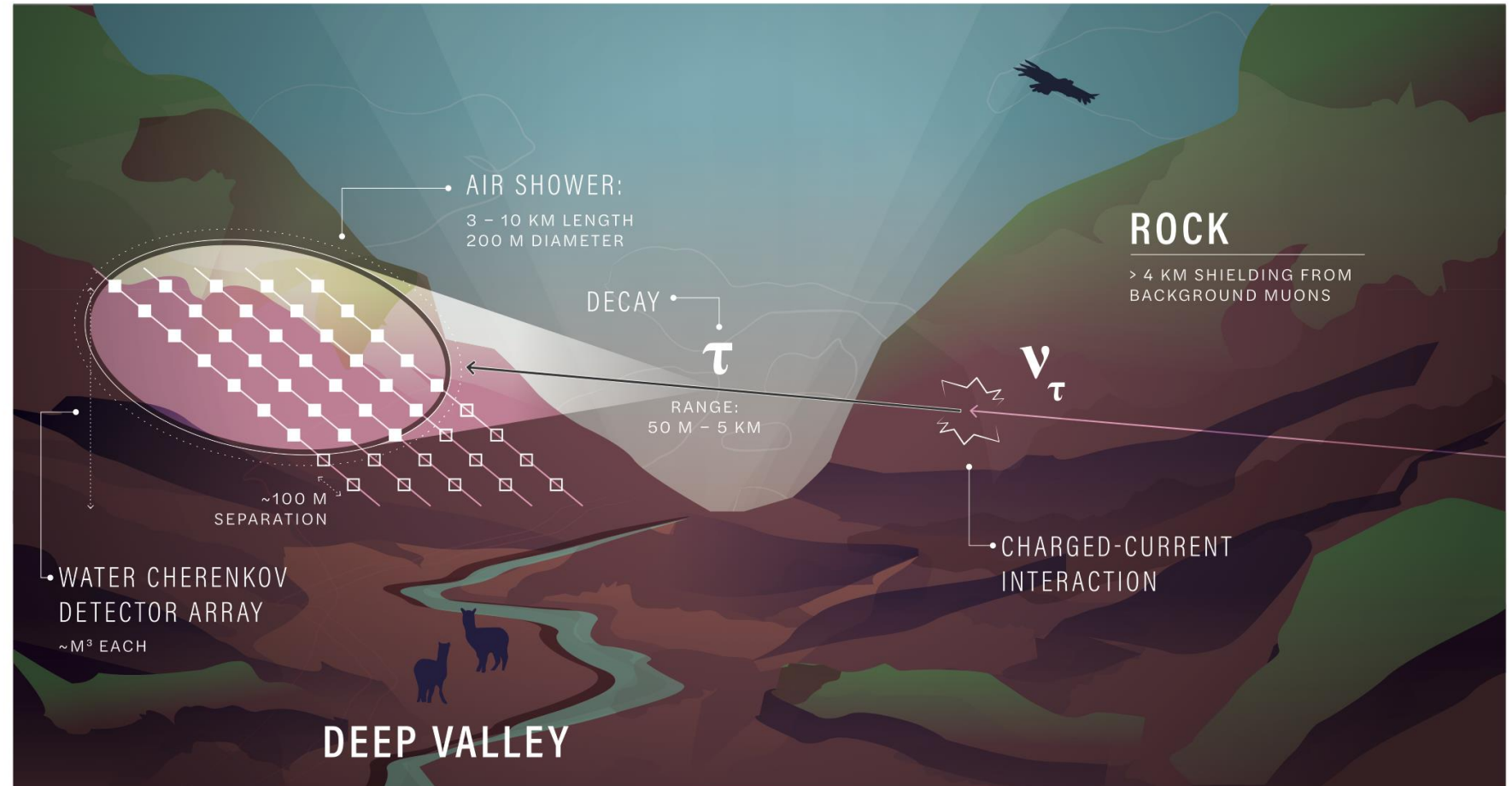
<https://arxiv.org/pdf/2507.04382>

- GRAND x BEACON
- The Hybrid Elevated Radio Observatory for Neutrinos



TAMBO

- Colca Valley in Peru
- Airshower from tau decay
- Water Cherenkov or scintillator



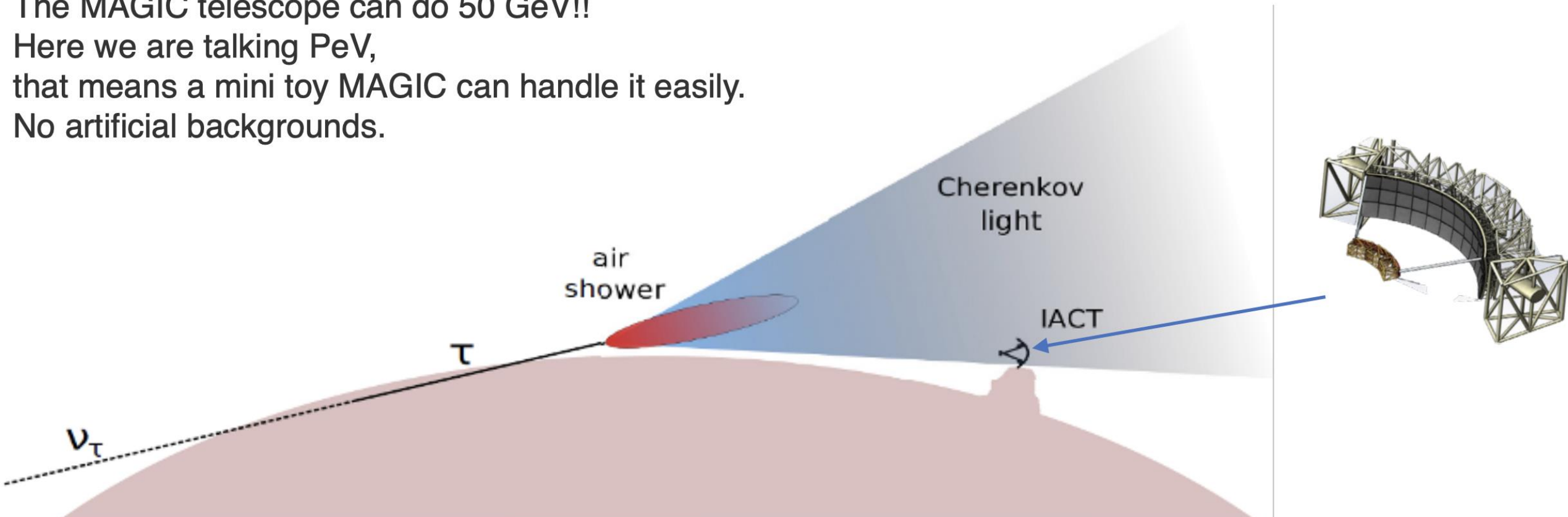
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

Trinity: View upward taus mountain with Cherenkov telescope

Advantage:
Low Energy threshold for emerging tau neutrinos

Nepomuk Otte

For ref.:
The MAGIC telescope can do 50 GeV!!
Here we are talking PeV,
that means a mini toy MAGIC can handle it easily.
No artificial backgrounds.



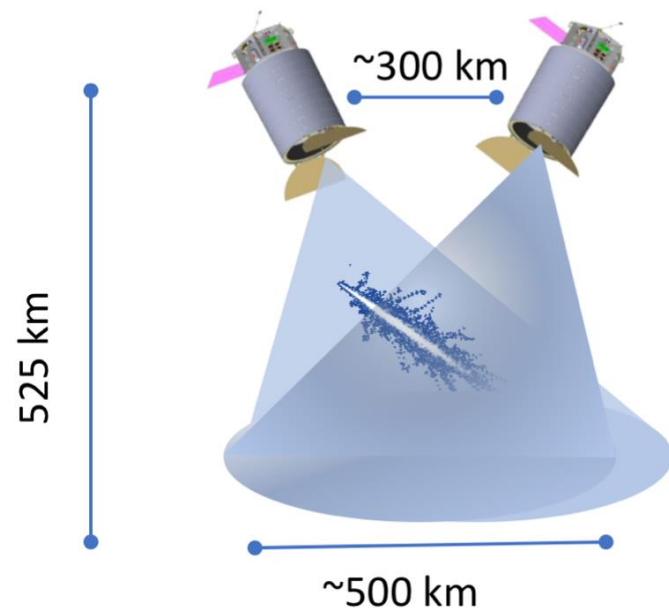
POEMMA

@Hallsie

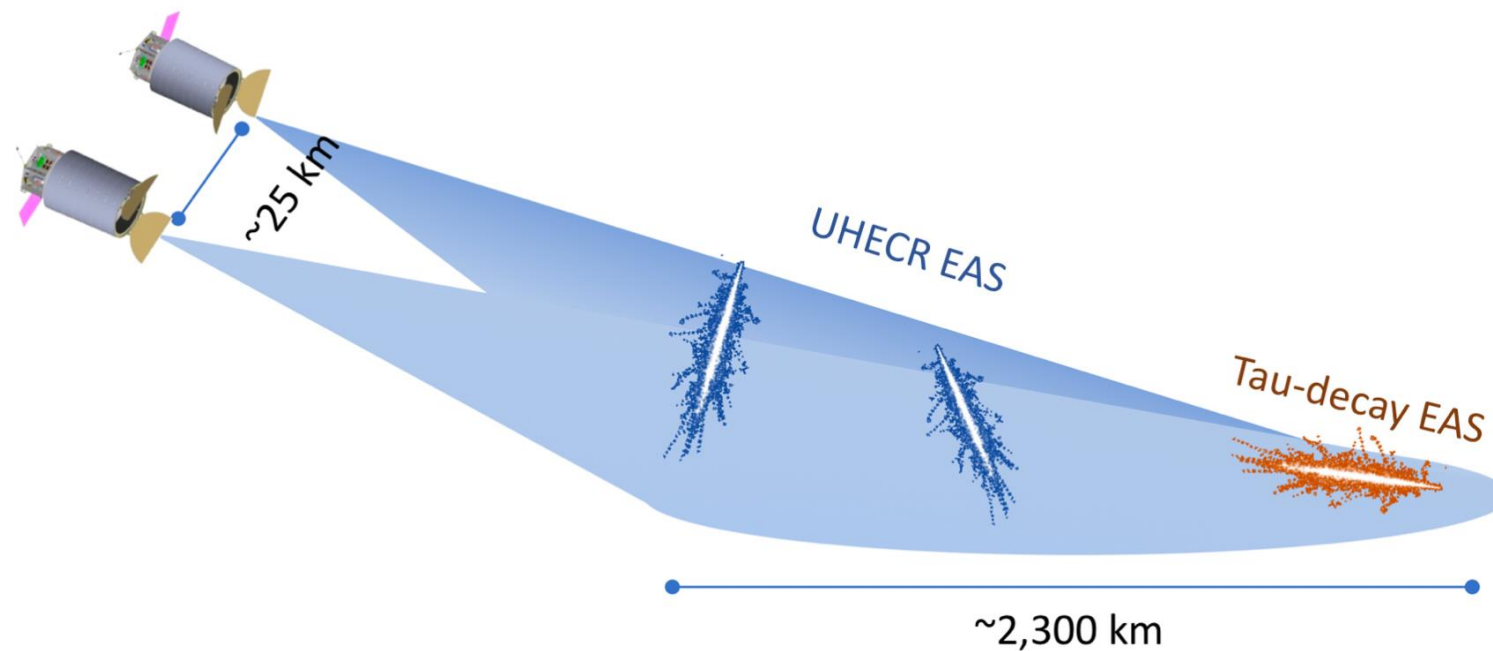


Space based neutrino Telescope

POEMMA-Stereo

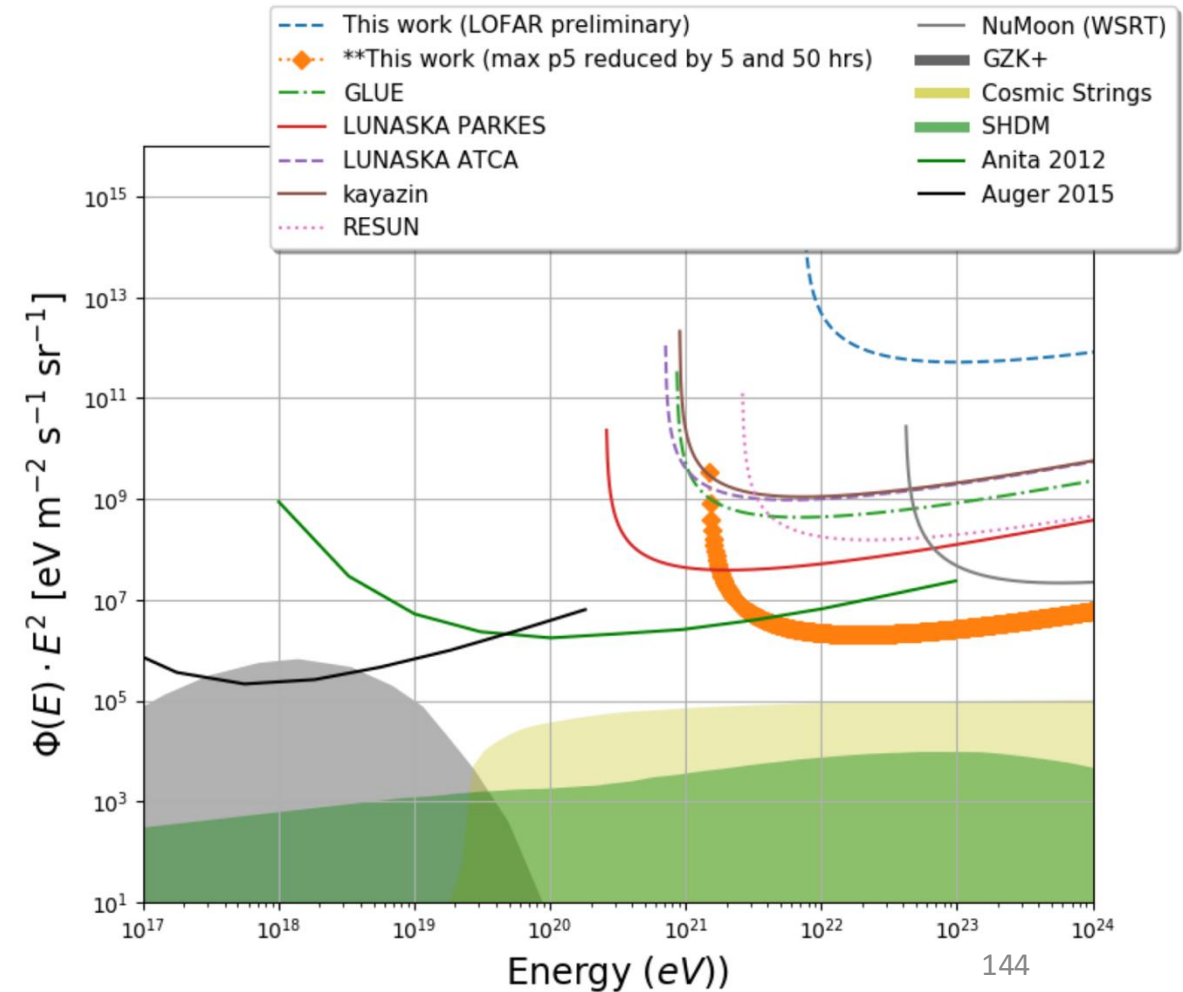


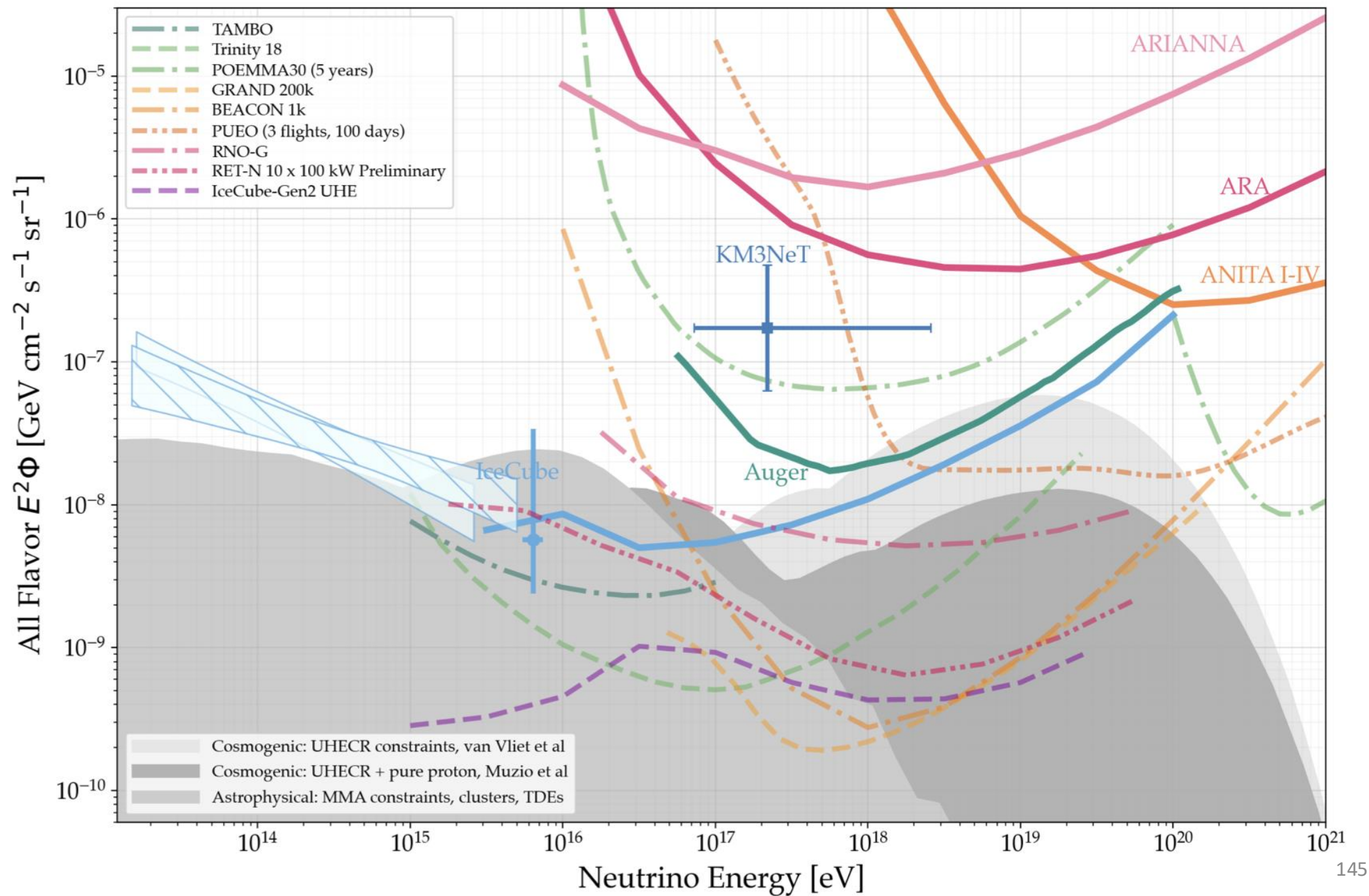
POEMMA-Limb



The NuMoon experiment: Lunar detection of neutrinos with LOFAR

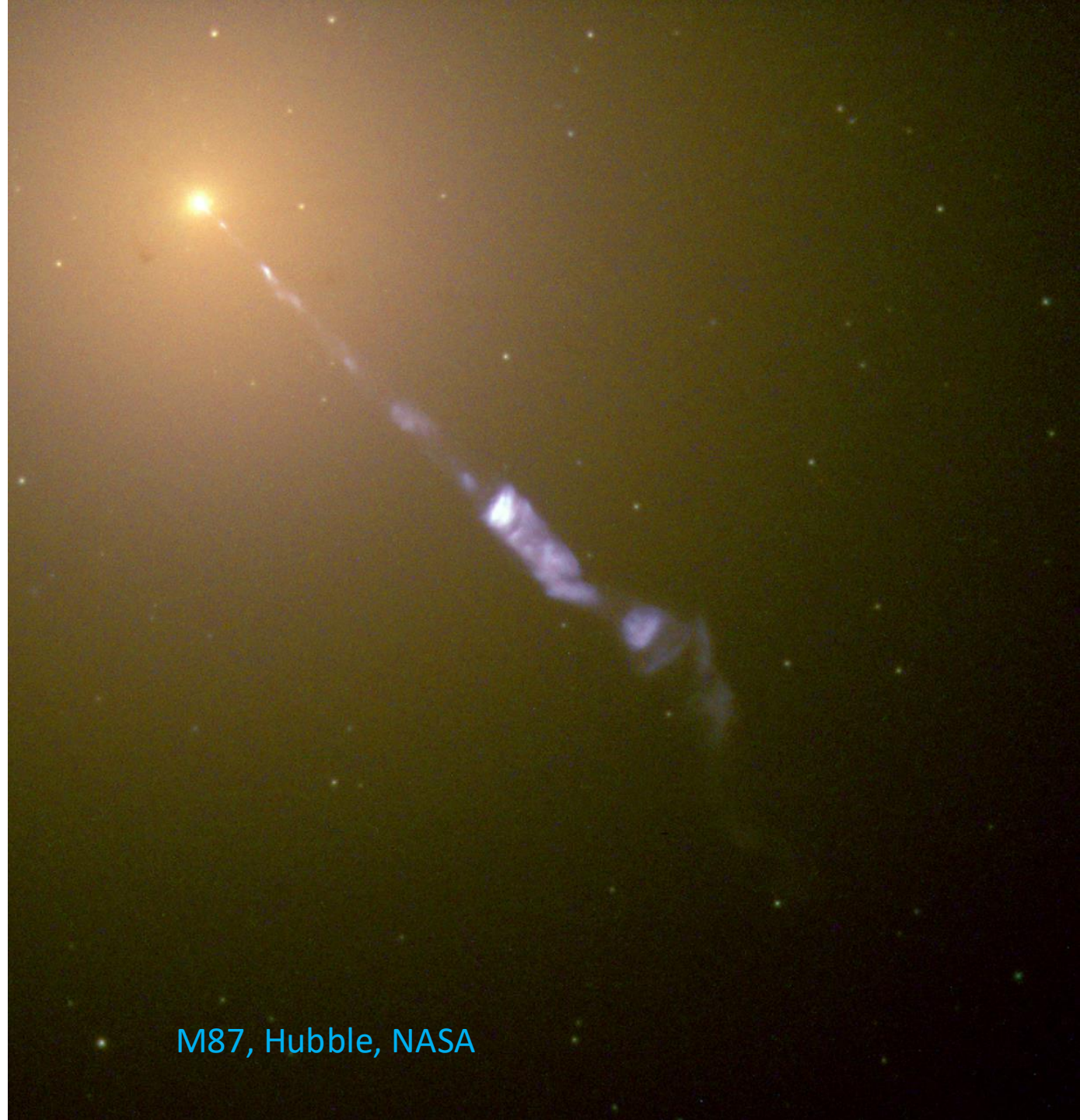
- Neutrinos interact with the moon: Lunar Askaryan
- High energy threshold due to moon-earth distance





Nature's accelerators

- M87 is about 55 million light-years away from the Earth.
 - Early primates long before humans existed on Earth
- Jet length: super massive blackhole with a relativistic jet of about 5000 light years
 - ~3 billion times the distance from Earth to the Sun (~ 8 light minute)



M87, Hubble, NASA

“The Cosmos is within us.
We are made of star-stuff.
We are a way for the
Universe to know itself.”

-- Carl Sagan

