

High-Energy Astrophysical Neutrinos

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NNN 2025

October 3rd, 2025



NNN25

The 24th International Workshop
on Next Generation Nucleon Decay
and Neutrino Detectors



Hubble



Will Thompson – NNN 2025.

JWST



Credit: NASA, ESA, CSA, STScI; J. DePasquale, A. Koekemoer, A. Pagan

Hubble

Neutrino astronomy in last decade



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JWST

Neutrino astronomy in next decade



Credit: NASA, ESA, CSA, STScI; J. DePasquale, A. Koekemoer, A. Pagan

Why neutrino astronomy?

- Neutrinos are:
 - (Very) weakly interacting
 - Electrically neutral
- This means they:
 - Can pass through dense areas of space unimpeded
 - Are not bent by magnetic fields
- But also makes them difficult to detect

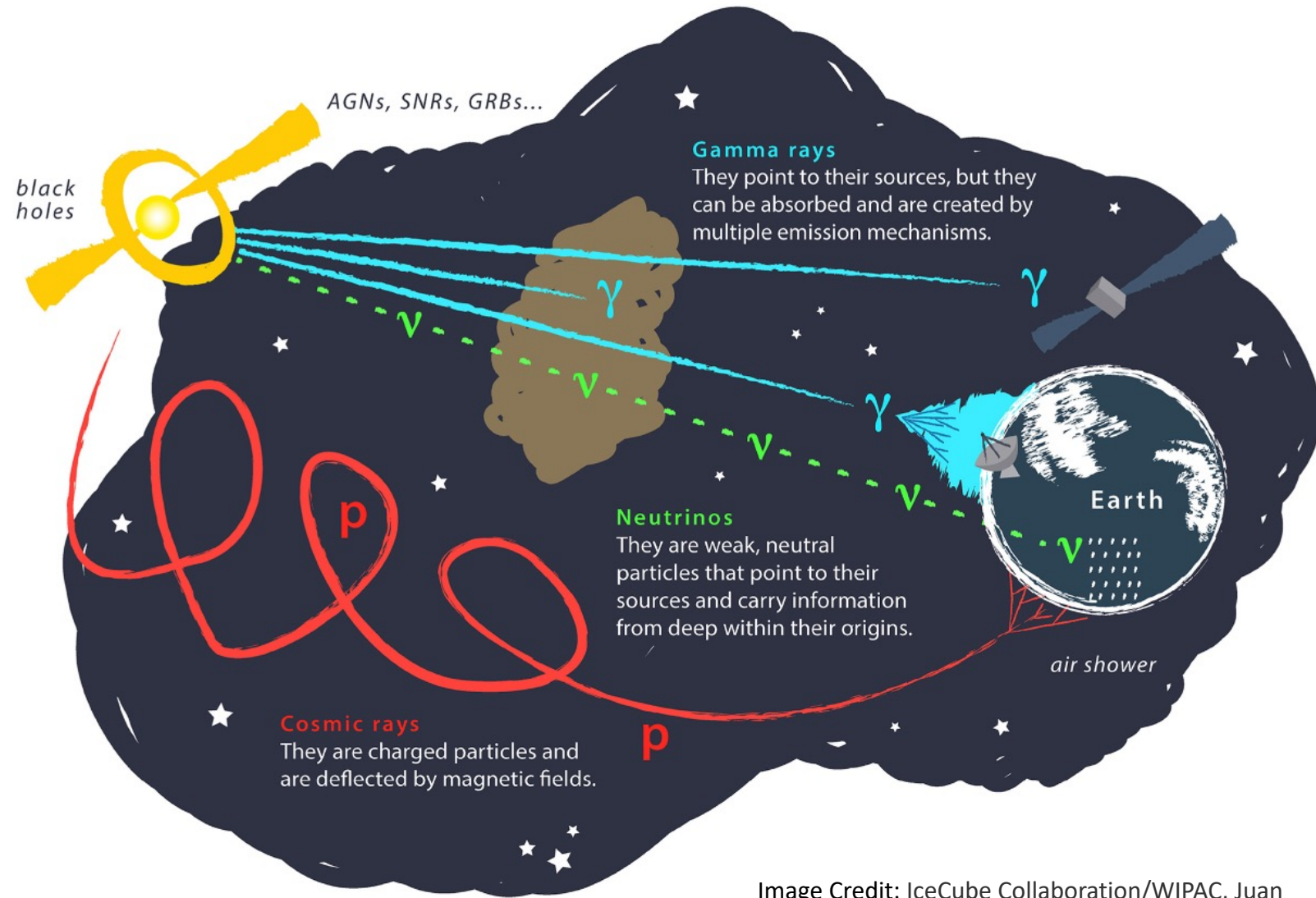
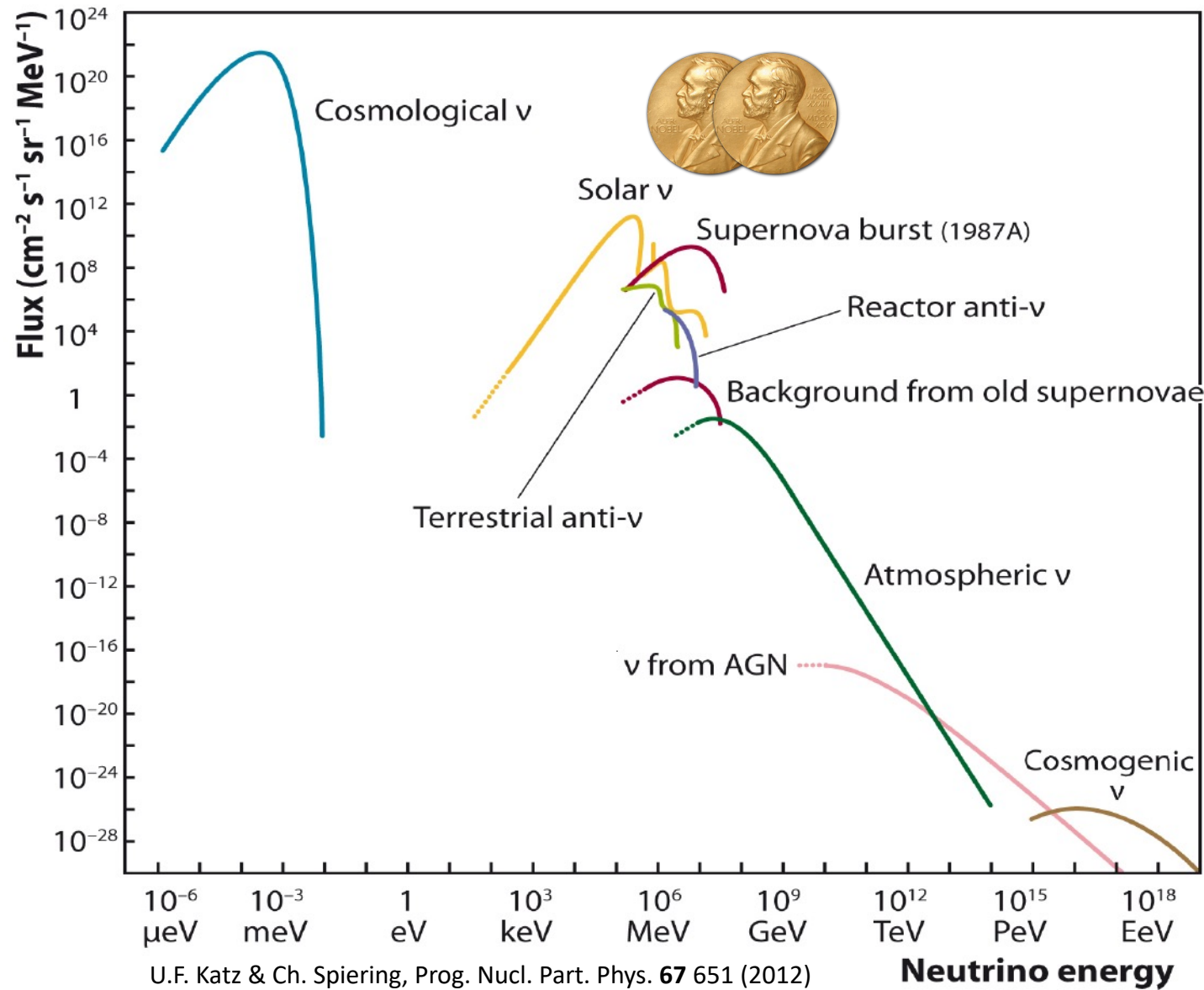


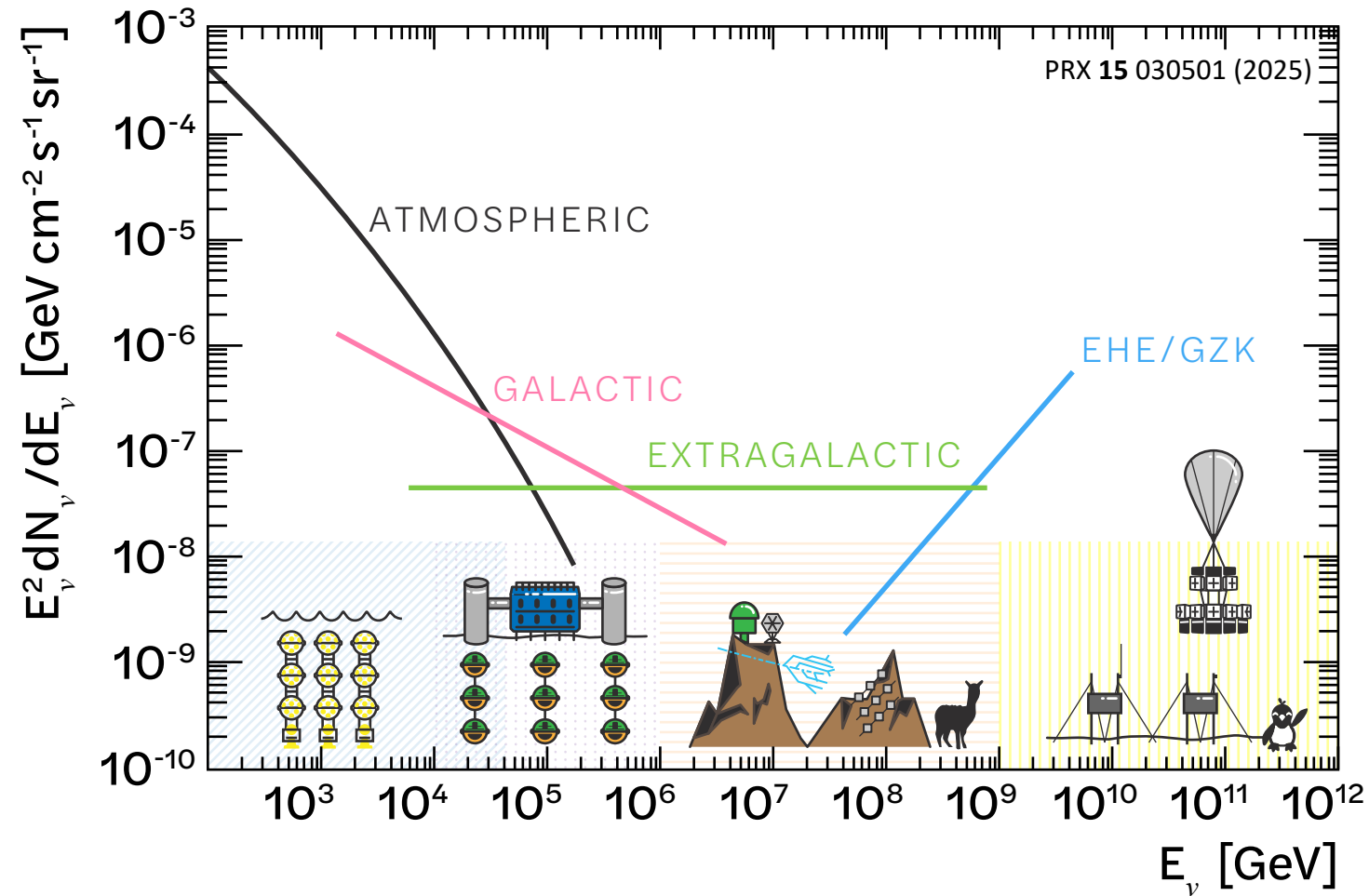
Image Credit: IceCube Collaboration/WIPAC, Juan Antonio Aguilar, and Jamie Yang.

The low flux also doesn't help...



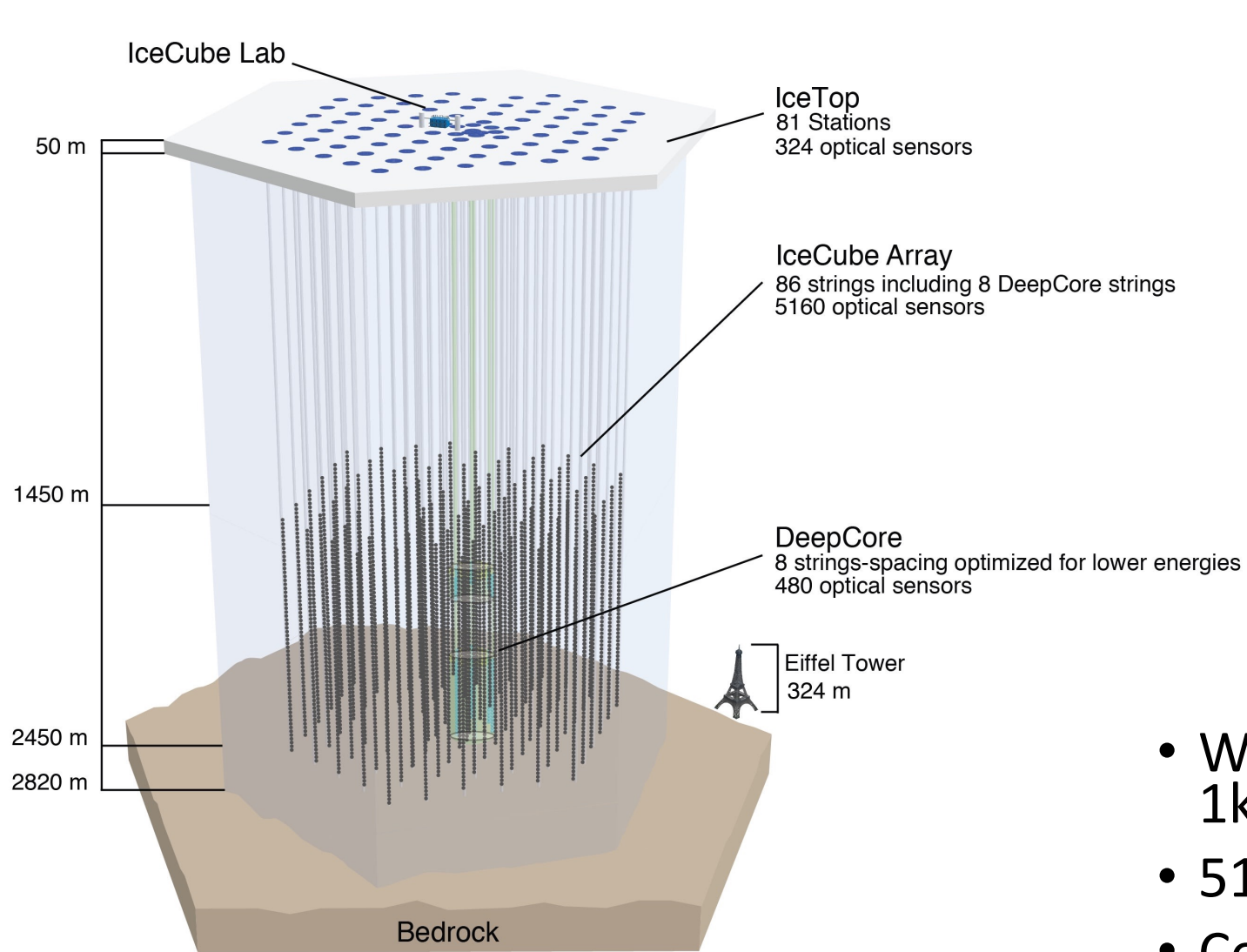
30 orders of magnitude!

How do we build enormous detectors?

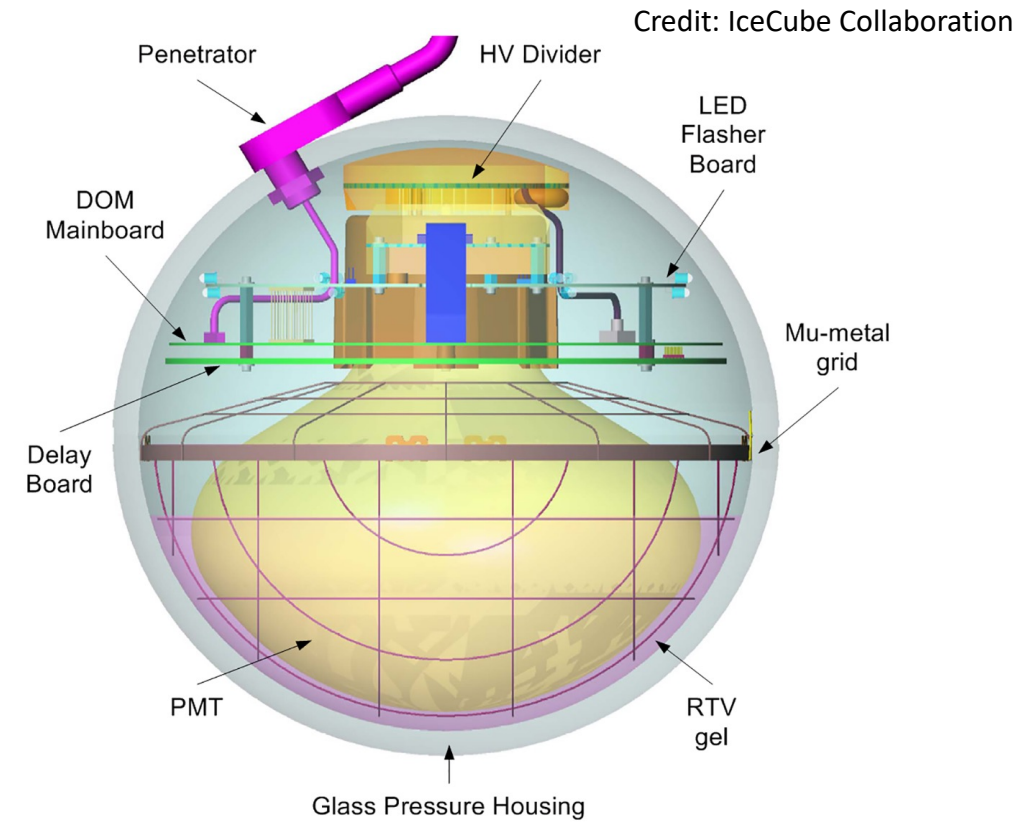


Neutrino astronomy: the science of using natural features in clever ways to detect rare events

The IceCube Neutrino Observatory

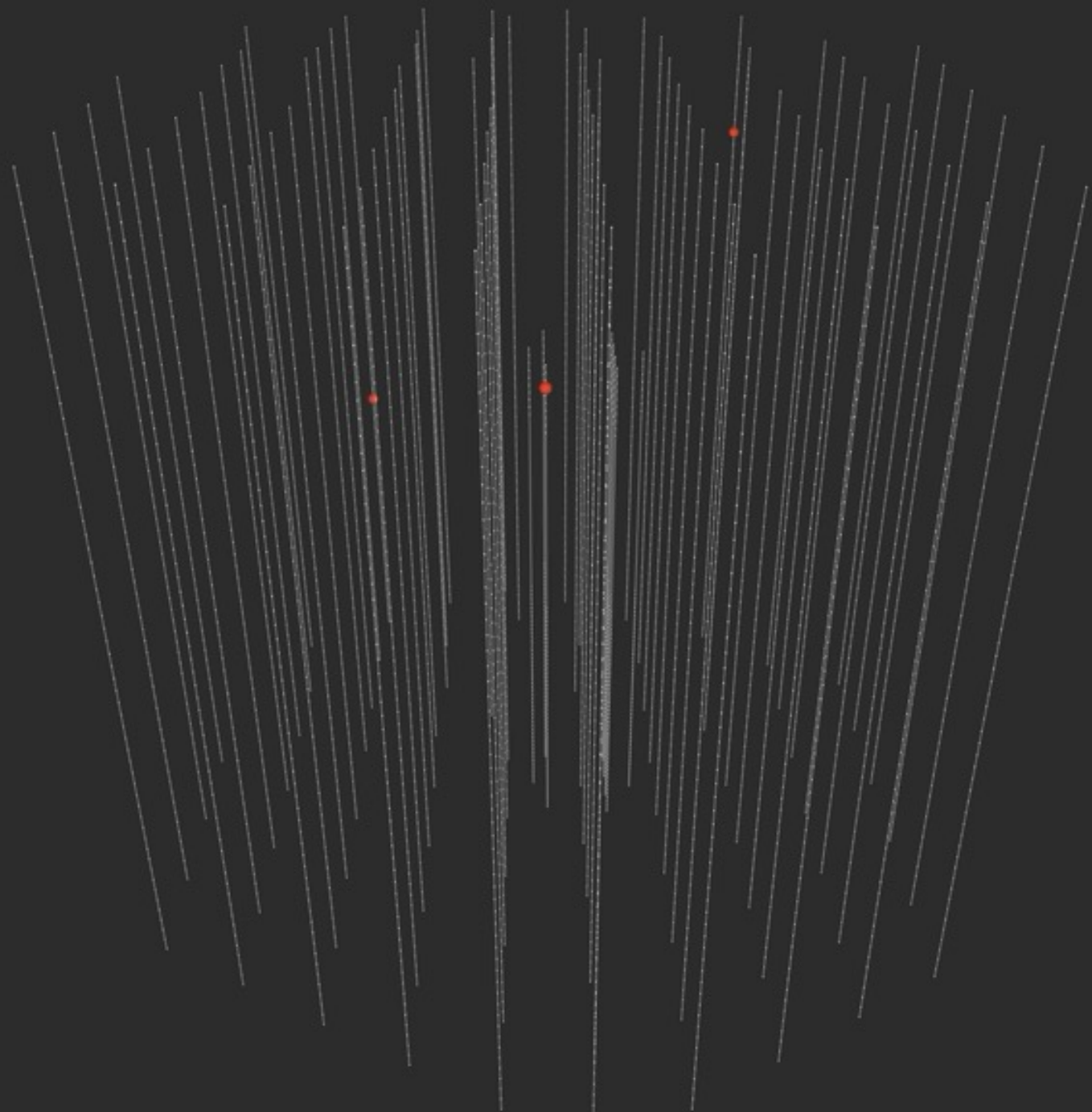


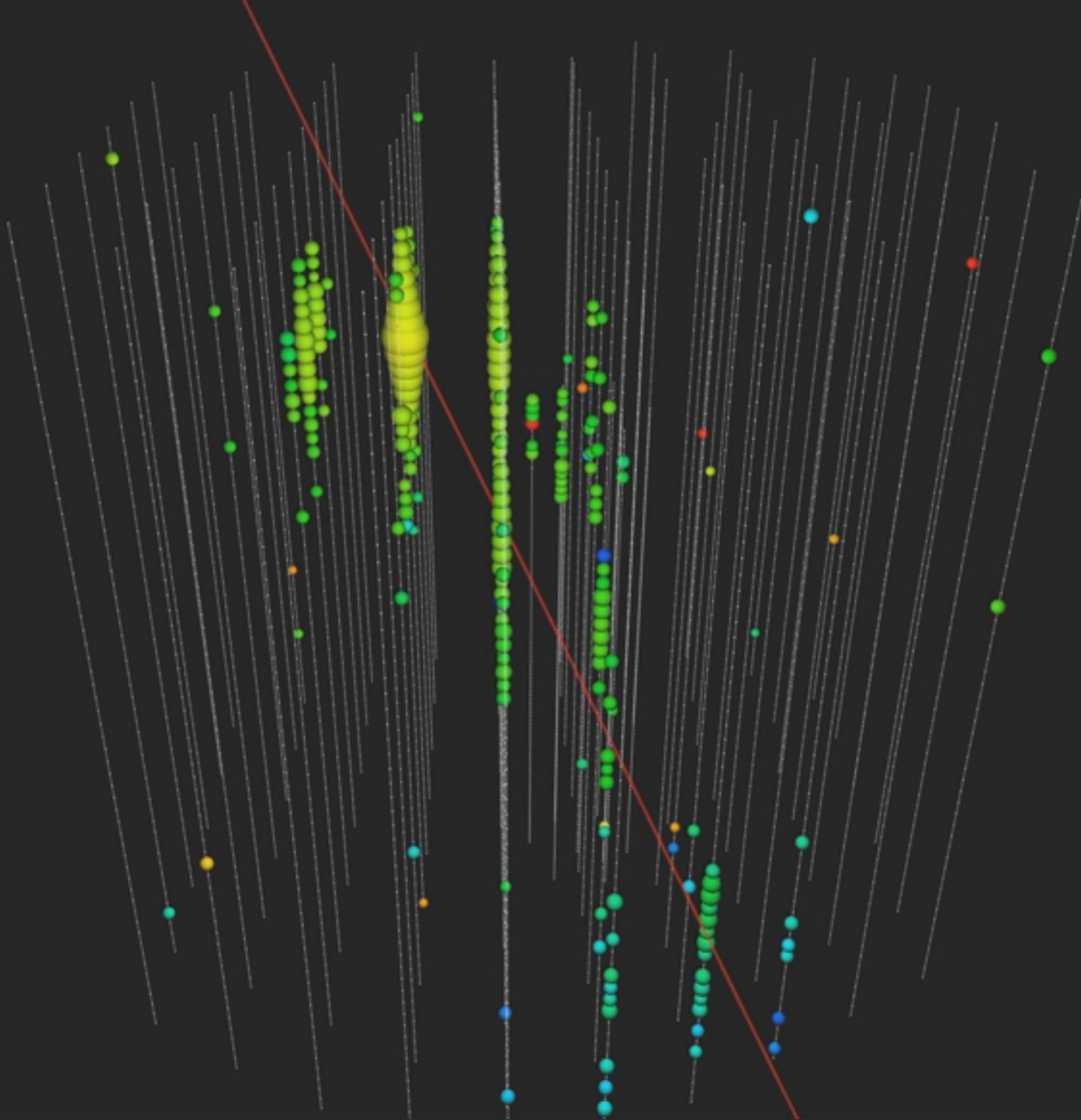
Credit: IceCube Collaboration

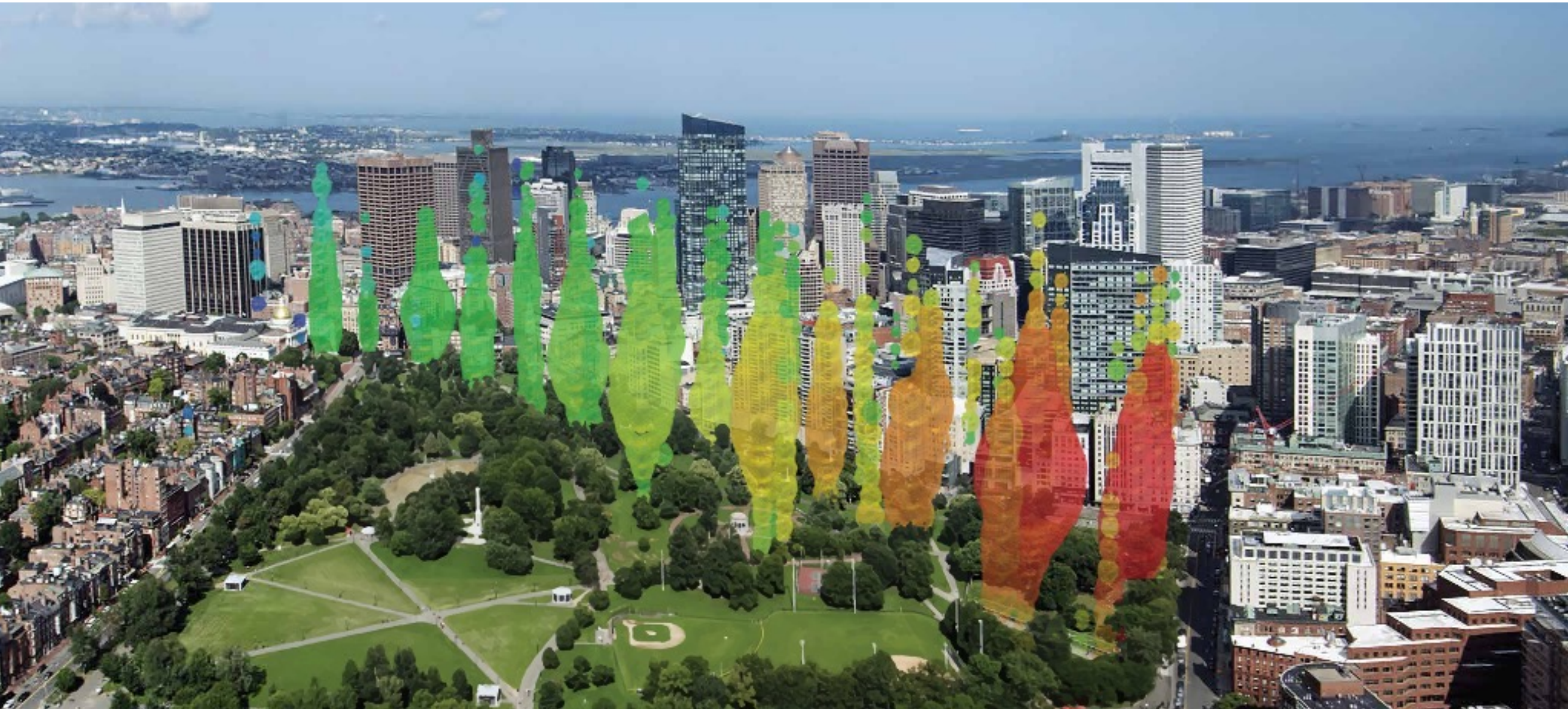


Credit: IceCube Collaboration

- World's largest neutrino detector – 1km^3
- 5160 DOMs
- Completed in 2010



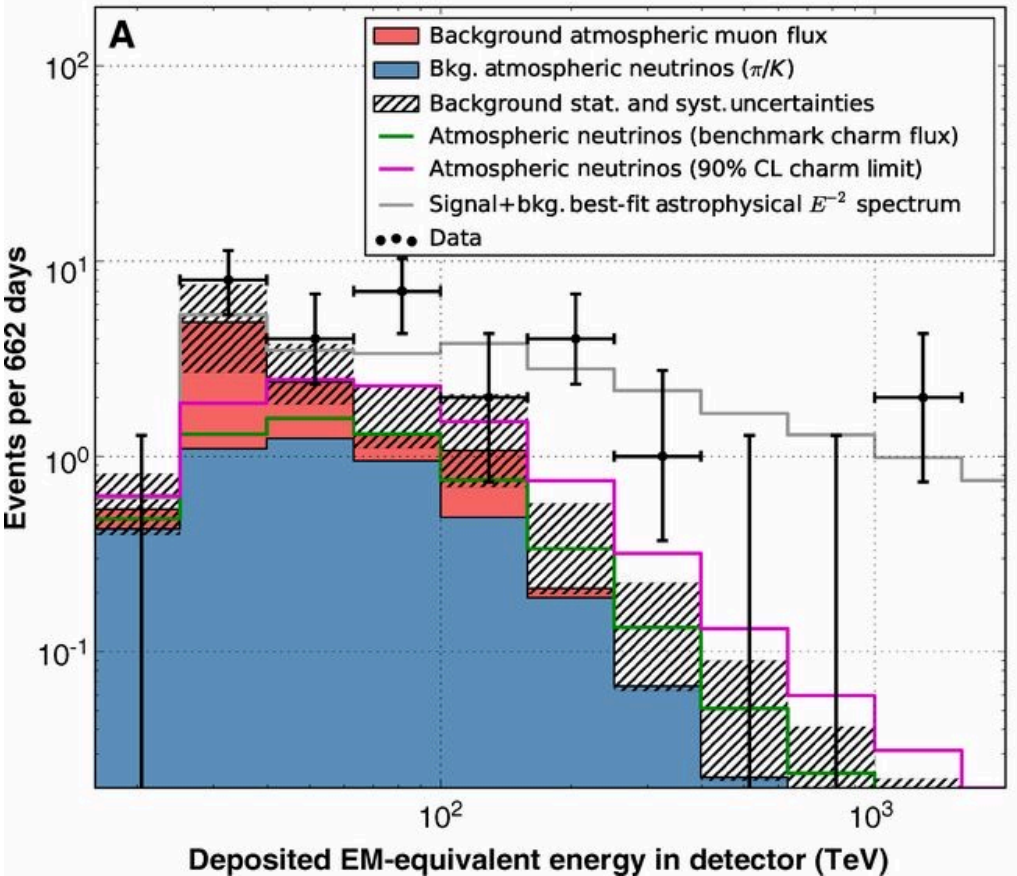




Ancient History

$\approx 2 \cdot 10^{-6}$ MYA

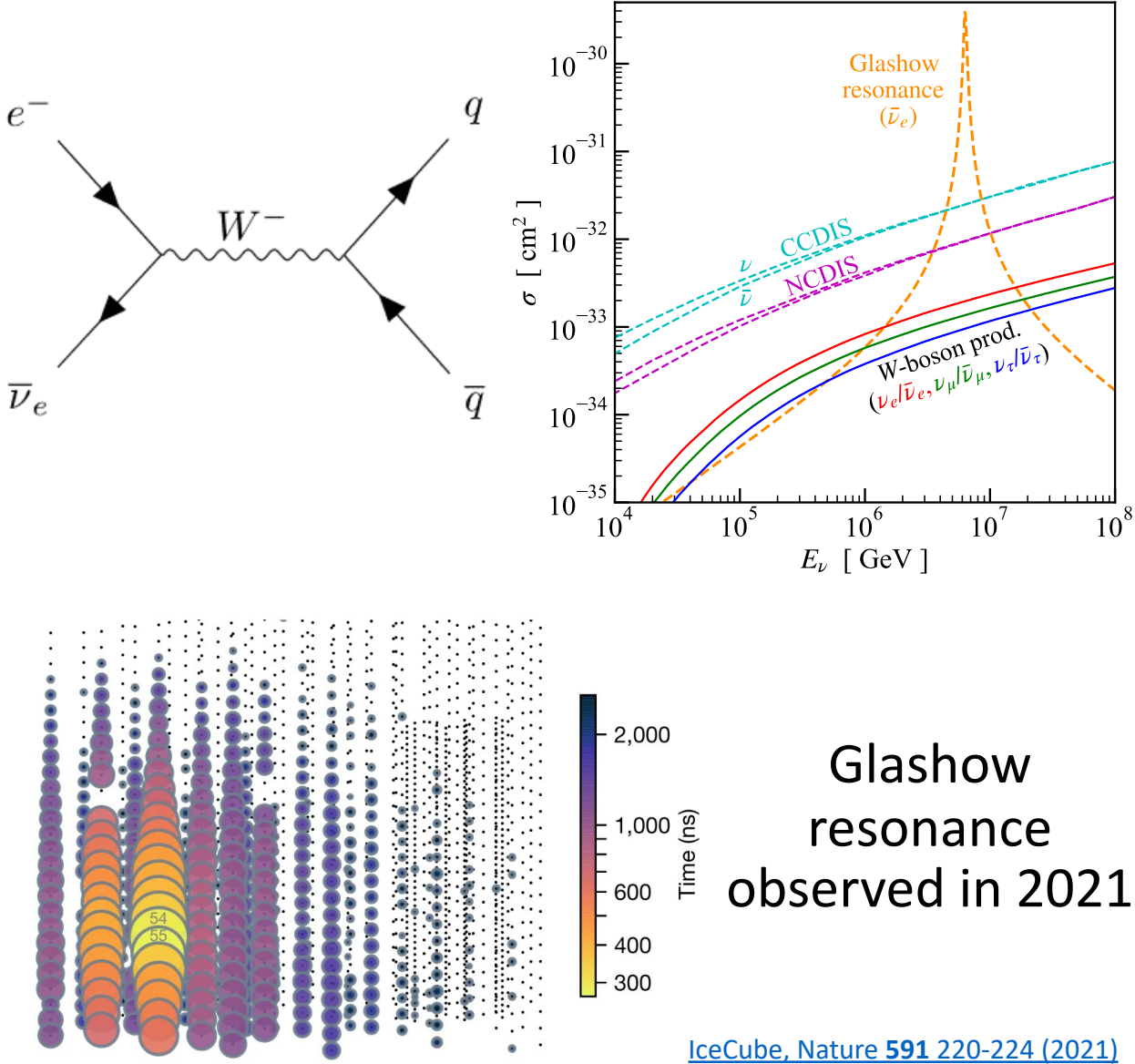
Astro & particle physics with IceCube



High-energy astro ν first observed in 2013

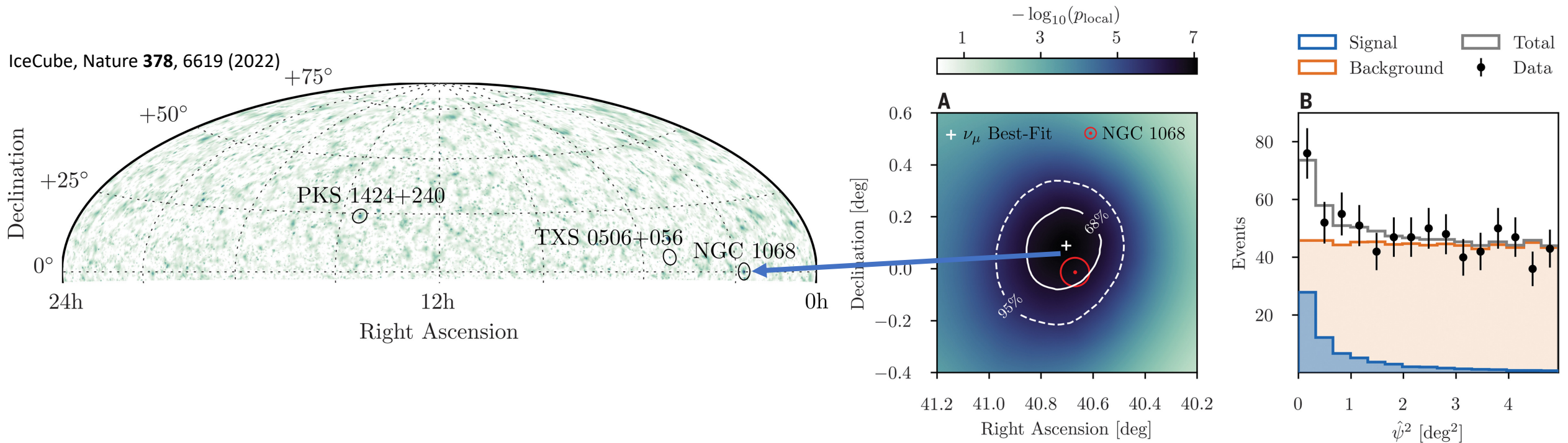
Diffuse, all-sky “glow”

[IceCube, Science 342 6161 \(2013\)](#)

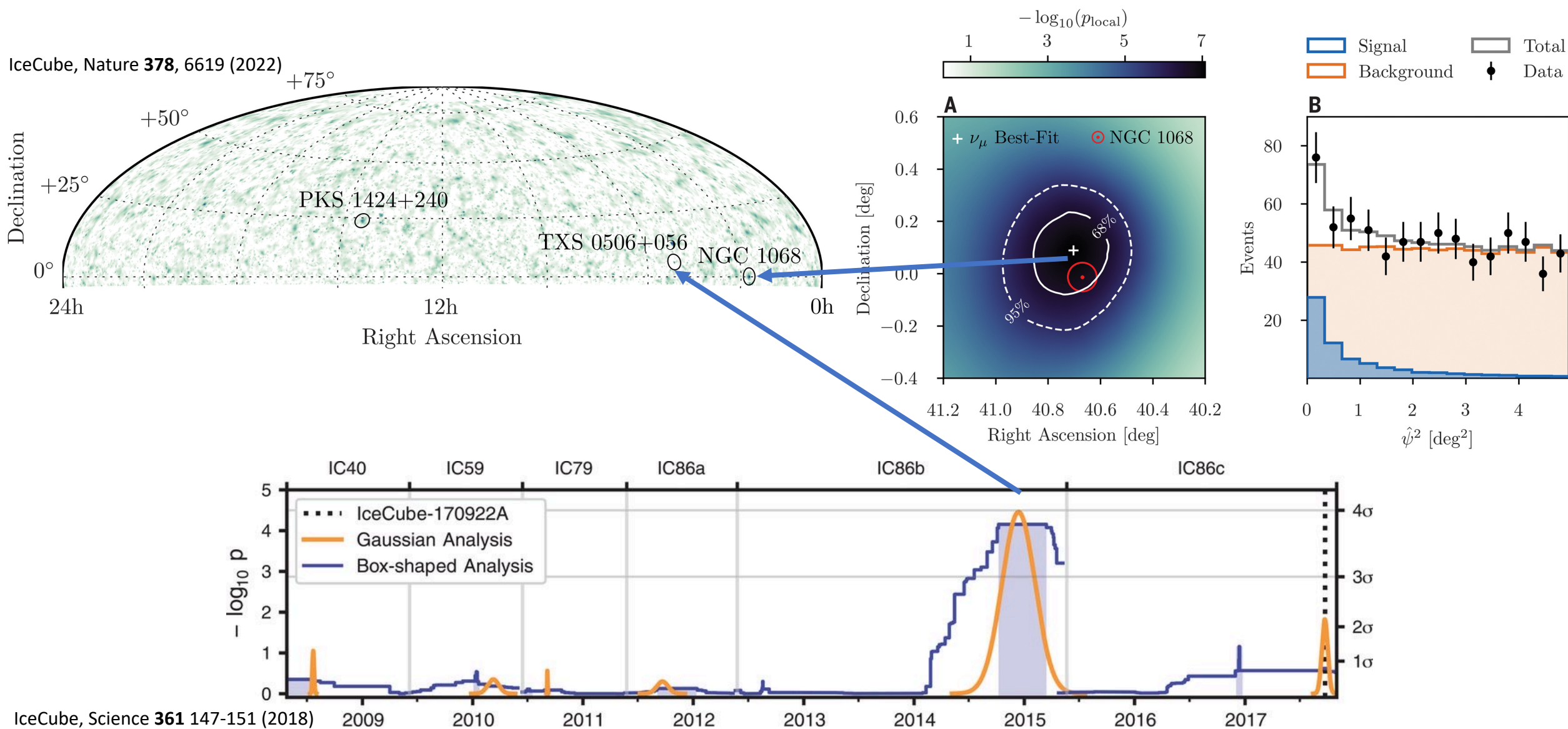


[IceCube, Nature 591 220-224 \(2021\)](#)

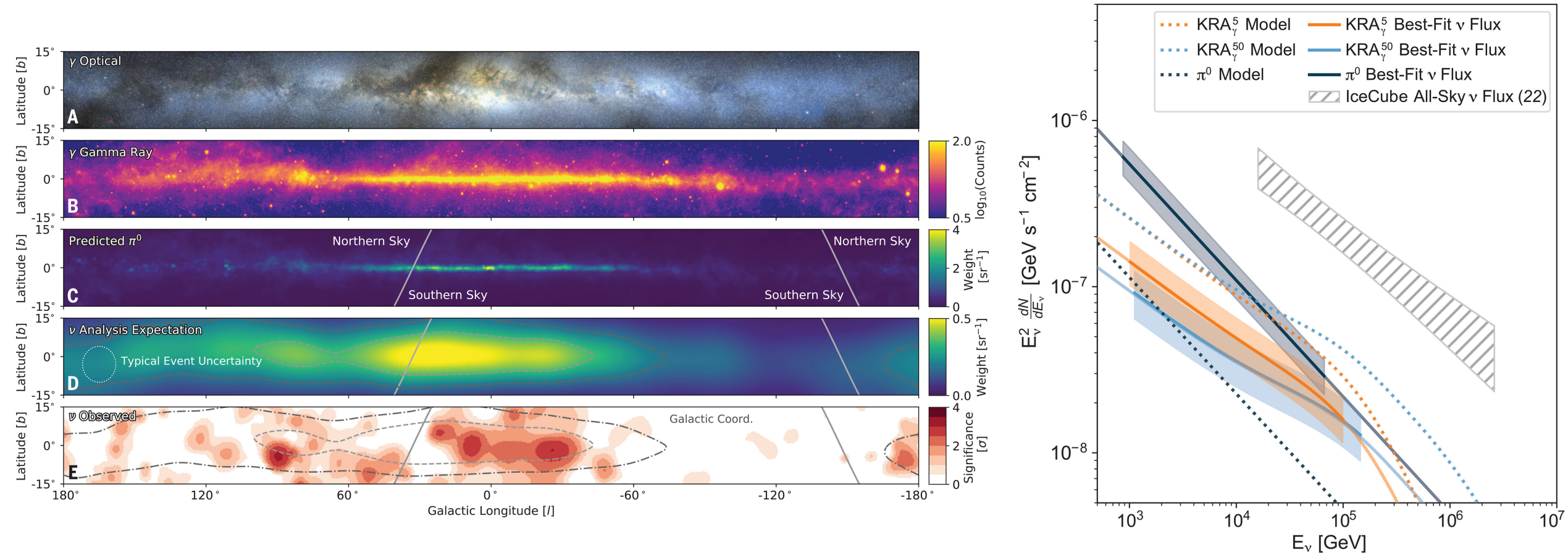
Point sources also observed!



Point sources also observed!



And a very special source



Neutrinos from Galactic plane observed at 4.5σ (2023)

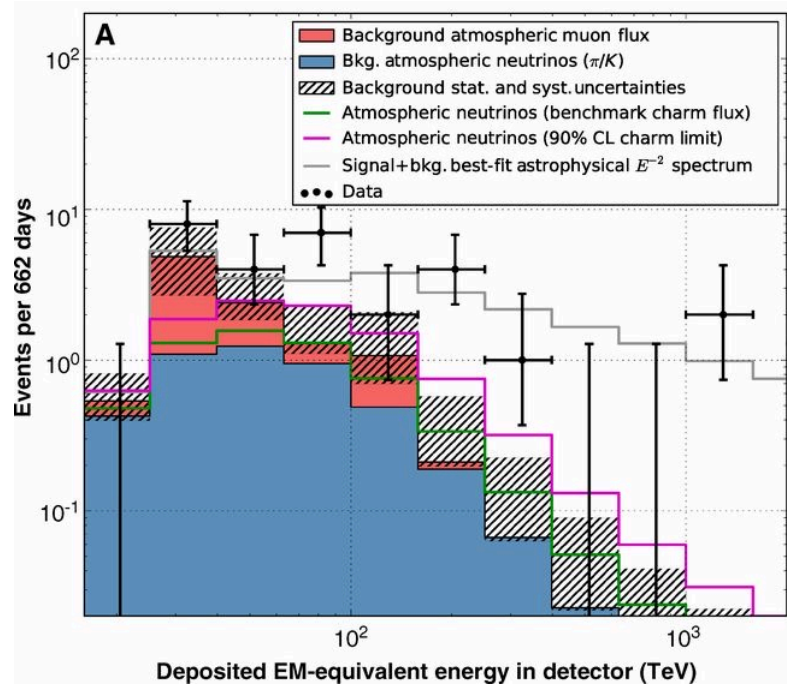
Contemporary Results

~ Now

Diffuse flux: Resolving detailed structure

2013

[IceCube, Science \(2013\)](#)

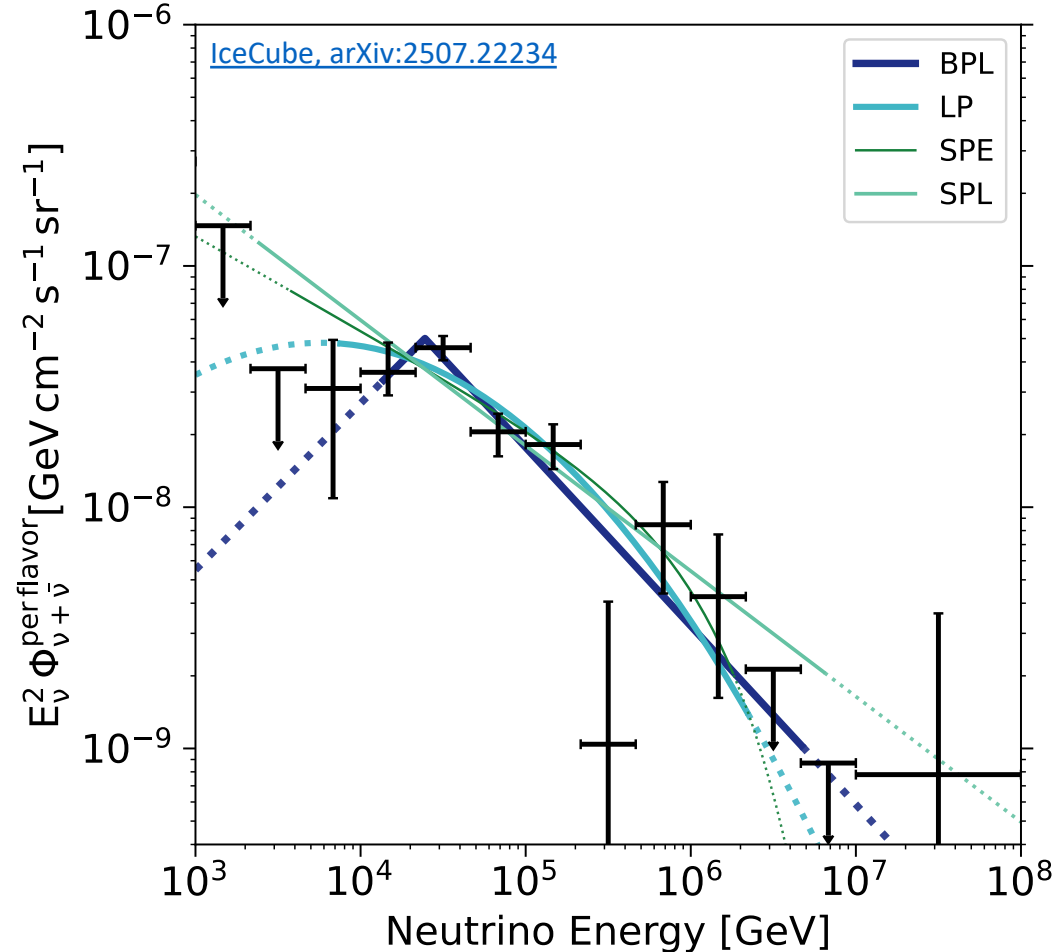


SPL b.f.: $\Phi \propto E^{-\gamma}$ ($\gamma = 2.55$)

BPL b.f.: $\Phi \propto \begin{cases} E^{-\gamma^1}, & E < E_b \\ E^{-\gamma^2}, & E > E_b \end{cases}$

2025

[IceCube, arXiv:2507.22234](#)

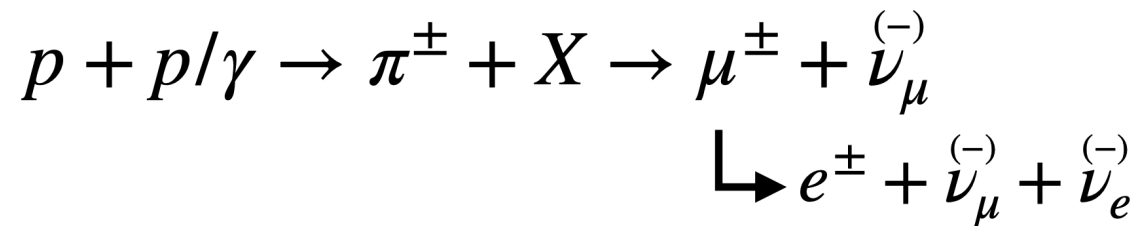


- Single power law spectrum disfavored at $>4\sigma$ for first time!
- Multiple source components? New physics?

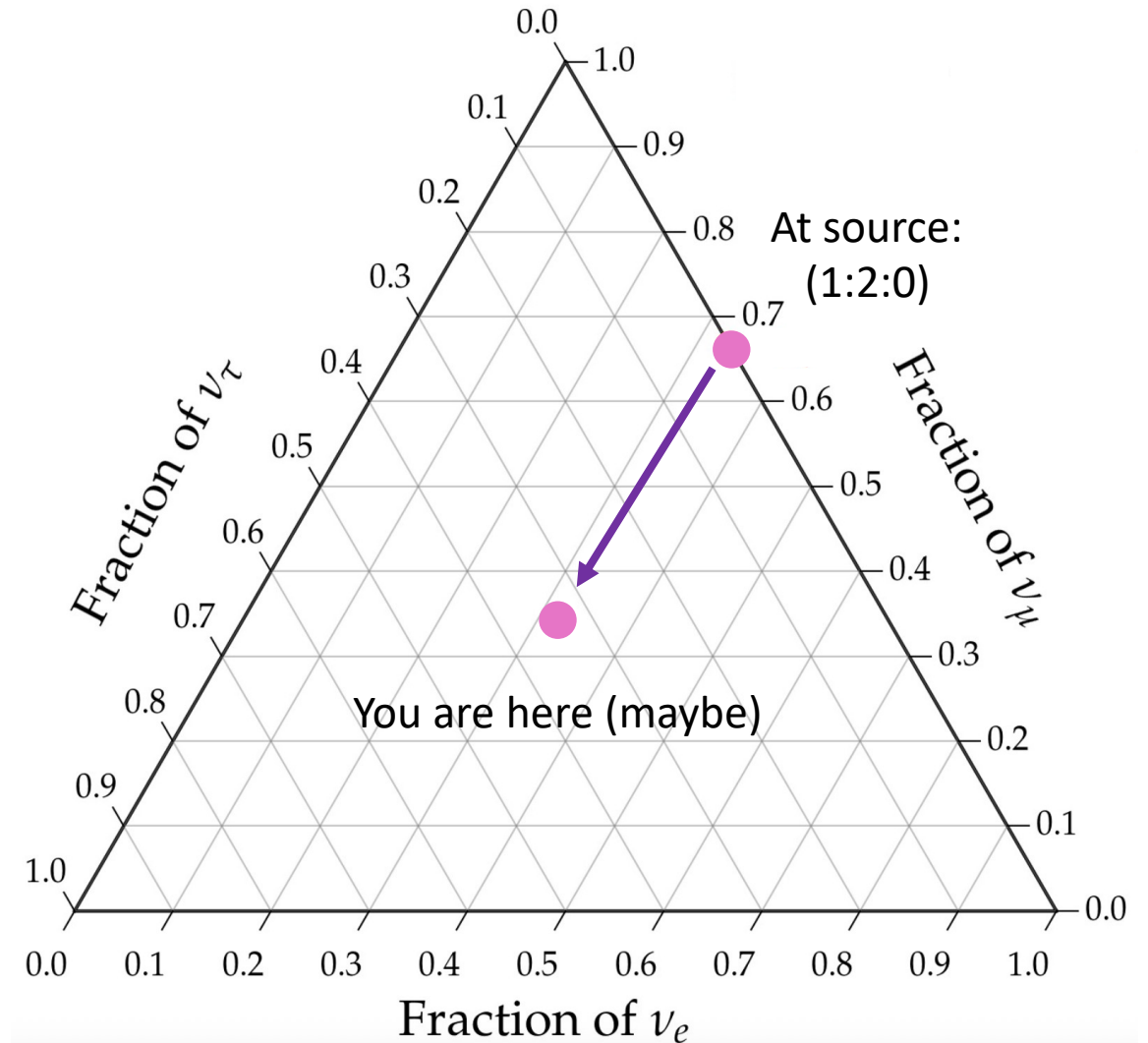
Probing neutrino sources with flavor ratios

Flavor ratio at Earth carries information on properties of source

Example: pion production



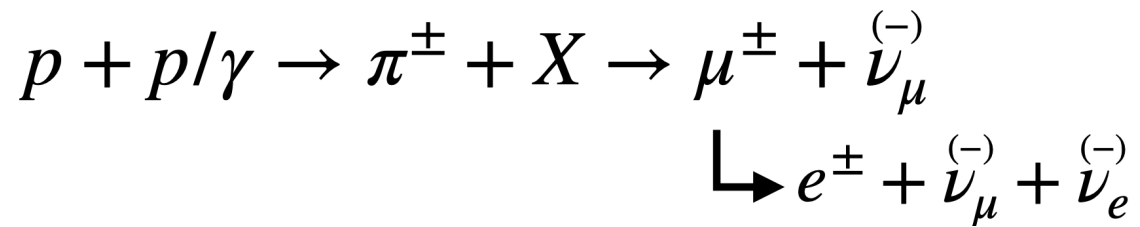
At source: (1:2:0)



Probing neutrino sources with flavor ratios

Flavor ratio at Earth carries information on properties of source

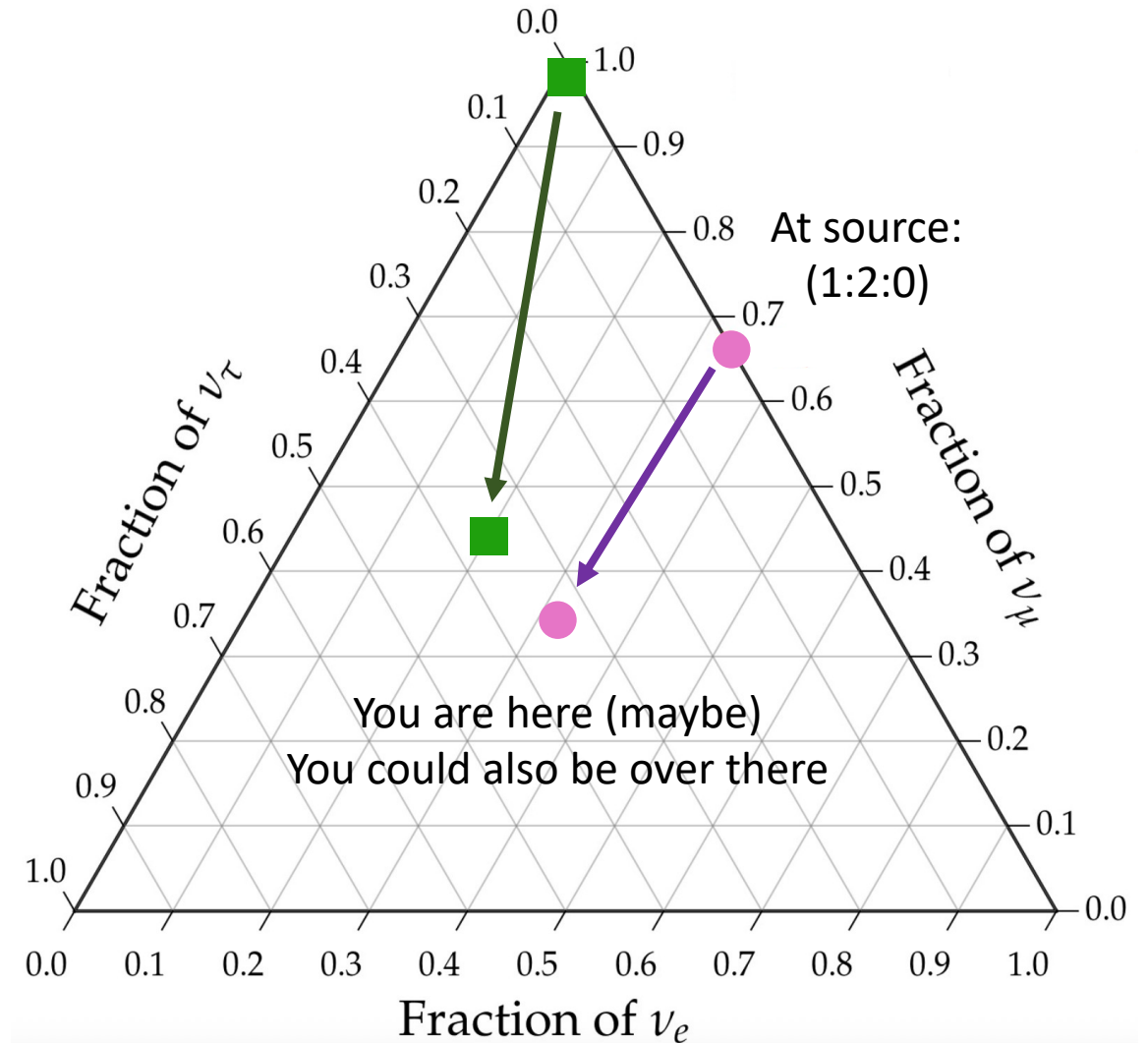
Example: pion production



At source: (1:2:0)

Compare: muon-damped production

At source: (0:1:0)



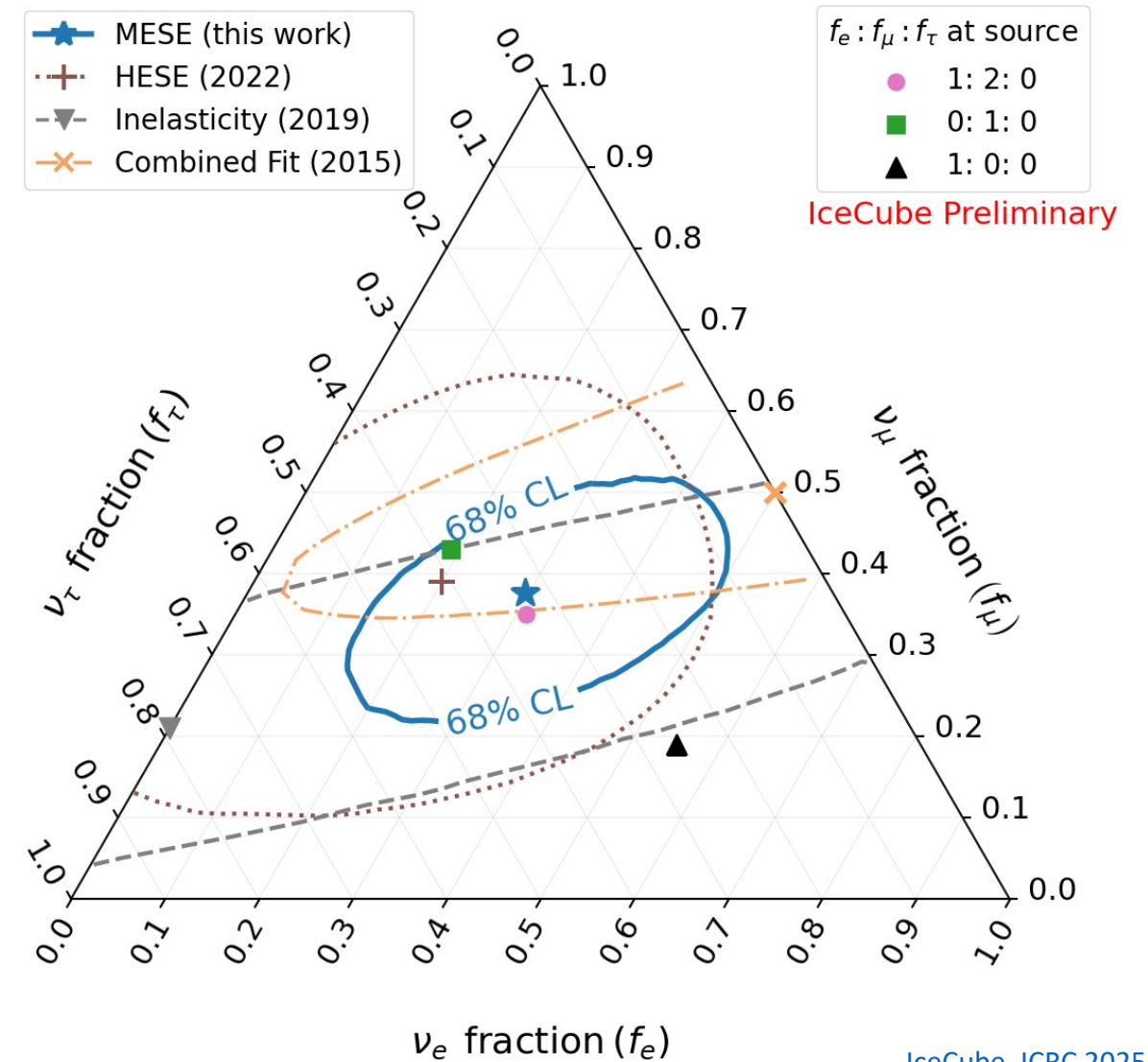
Probing neutrino sources with flavor ratios

New flavor measurement with IceCube MESE dataset (>1 TeV, starting events)

First time all flavors non-zero at 1σ

Best fit close to SM pion production expectation

Neutron-only production excluded at $\sim 2\sigma$

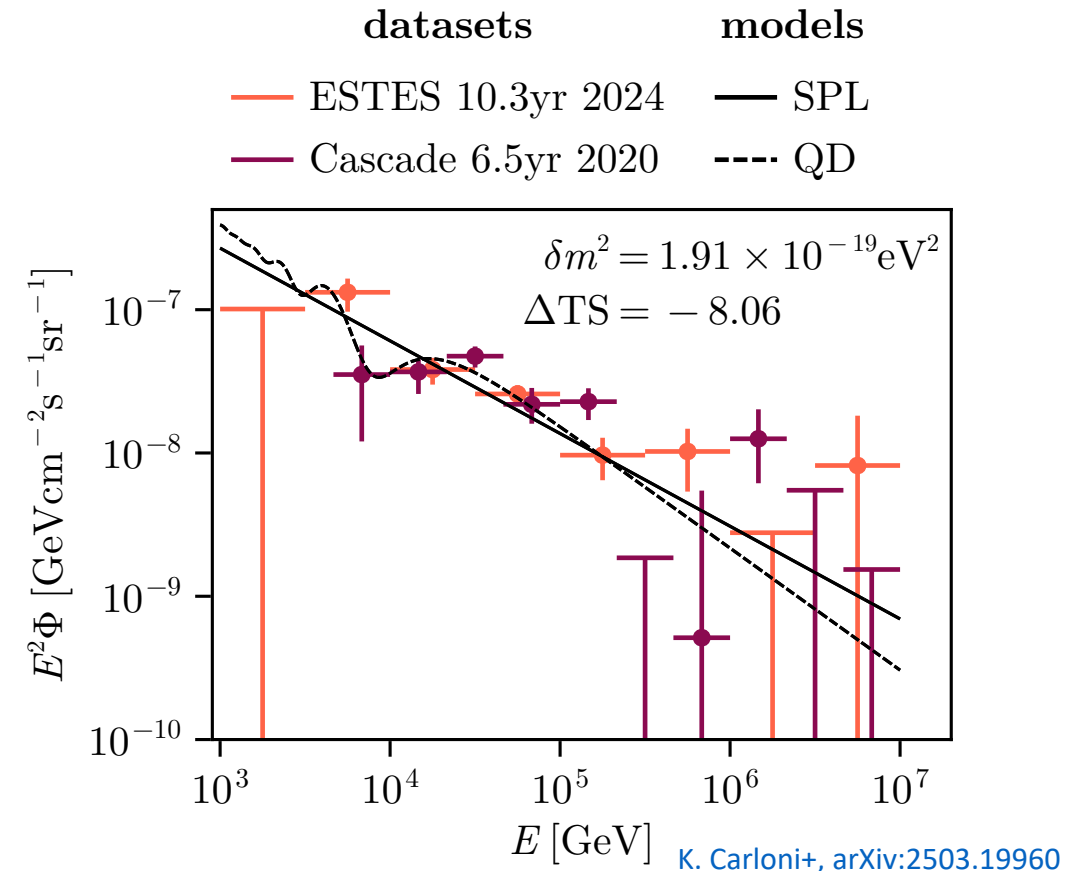
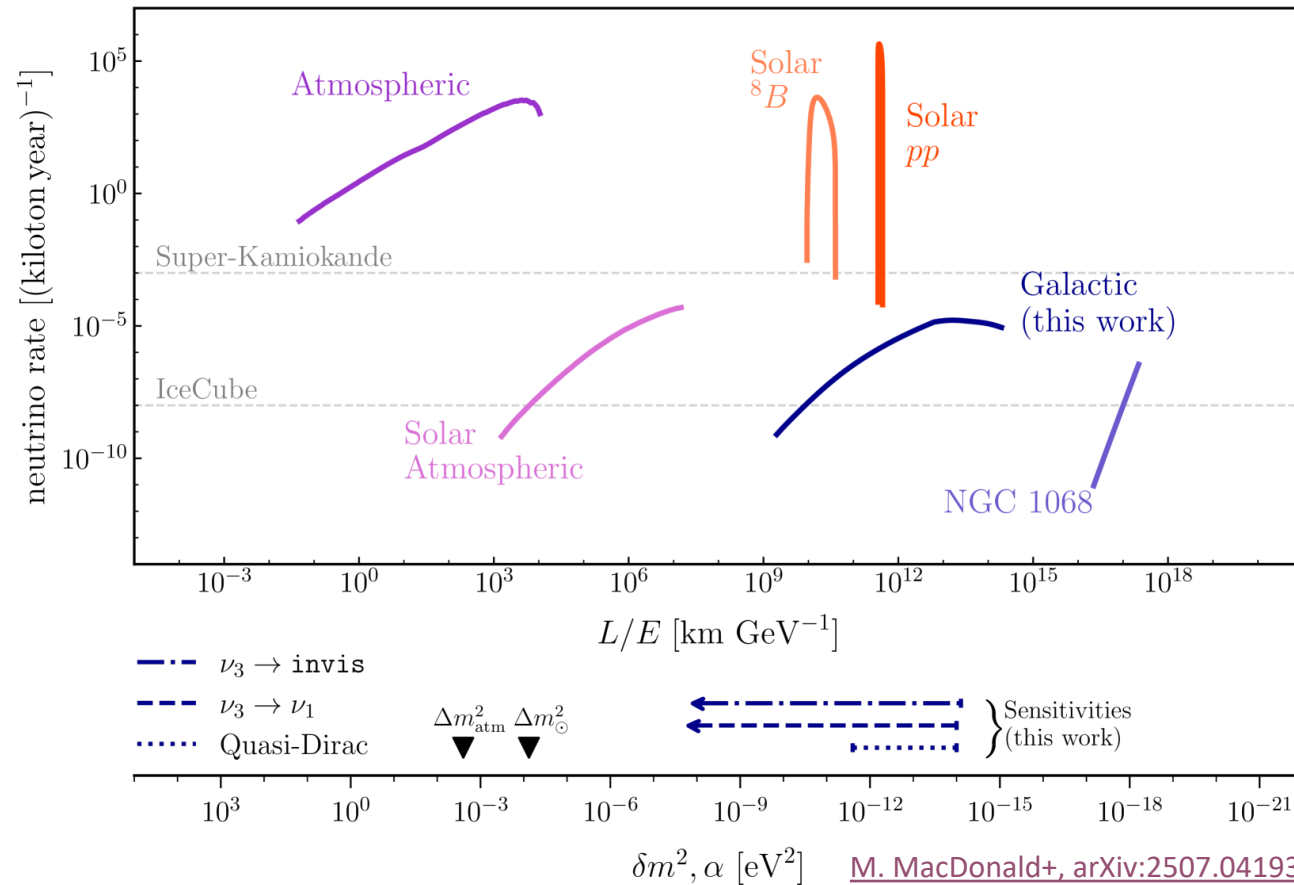


Can also probe BSM physics

Astrophysical neutrinos travel over great distances with enormous energies

Opens up new oscillation space

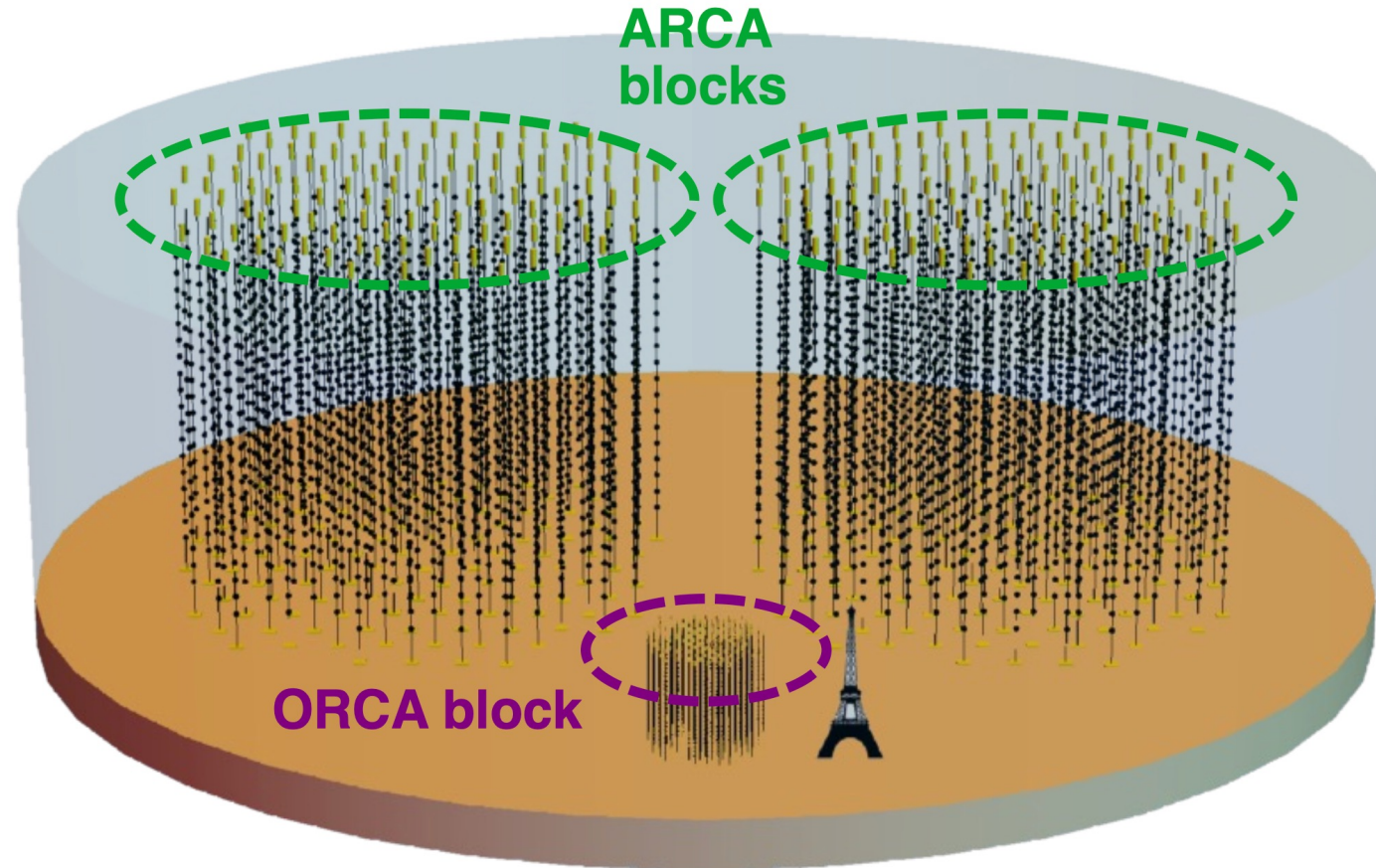
Ex: Quasi-Dirac ν : $\delta m^2 = 1.9 \times 10^{-19} \text{ eV}^2$ preferred at 2.8σ



The KM3NeT detector

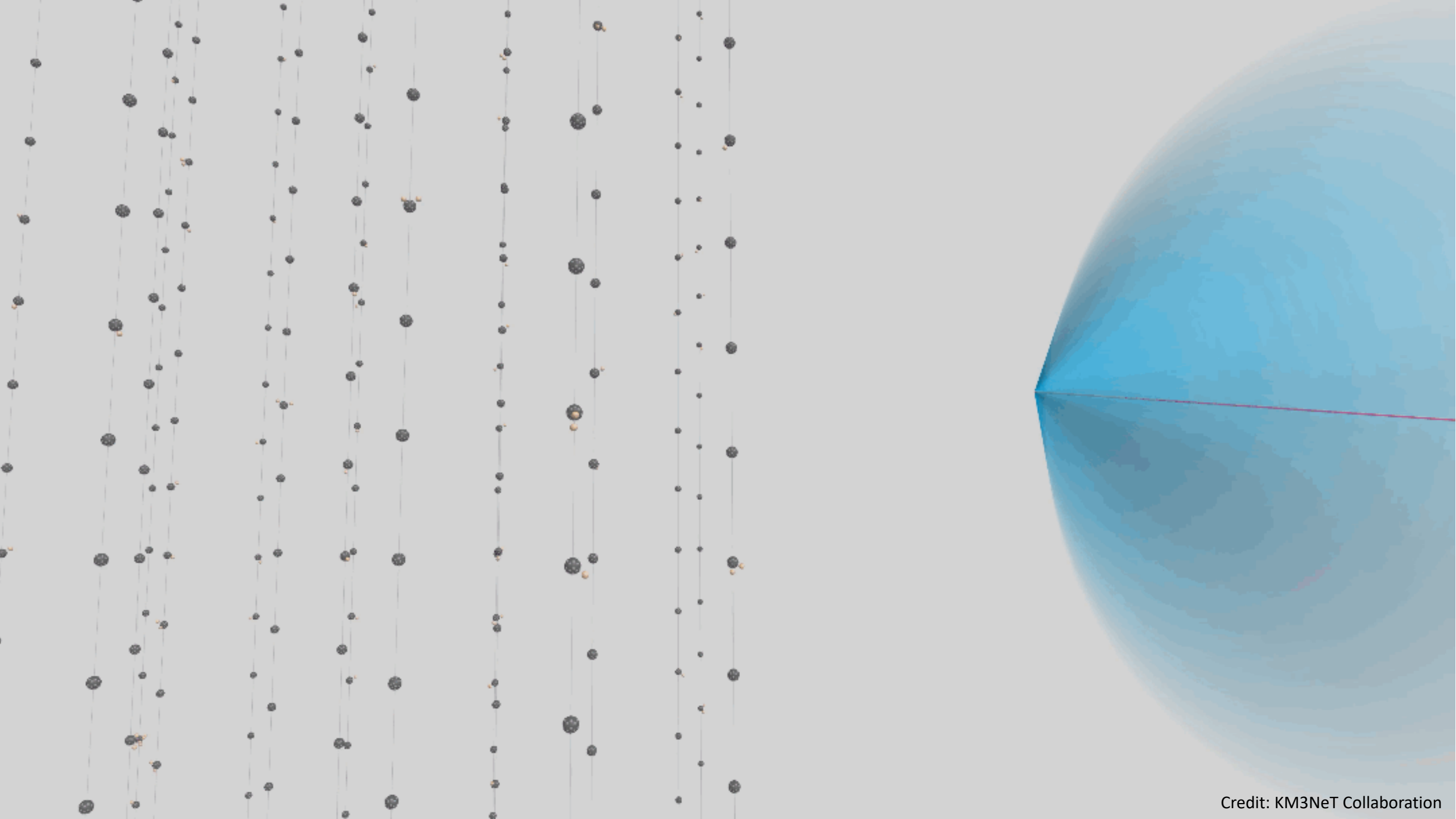
Final configuration: 1 km³, 230 strings, 4100 optical modules, 90 m (36 m) horizontal (vertical) spacing

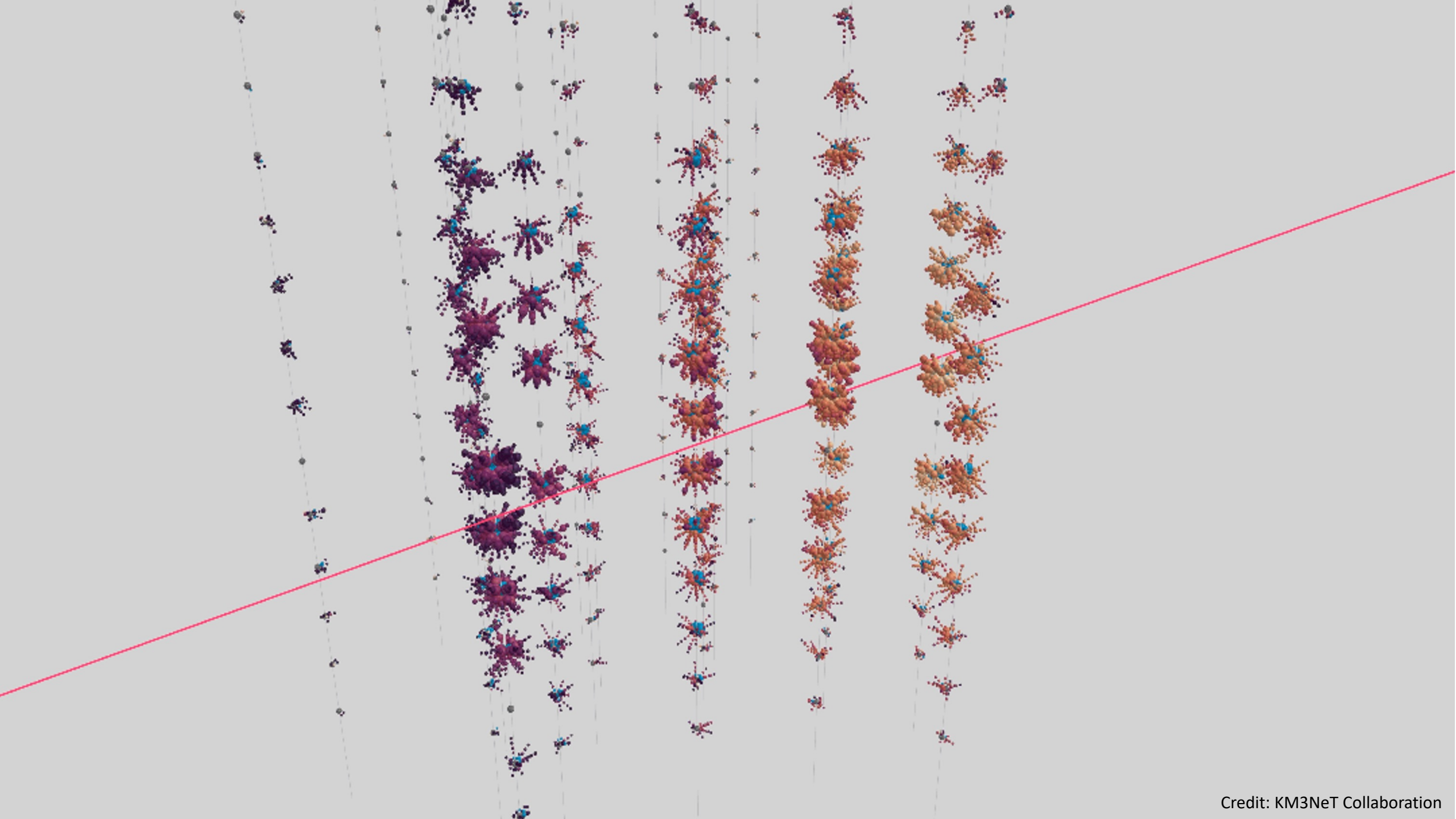
Current configuration: ~14% complete



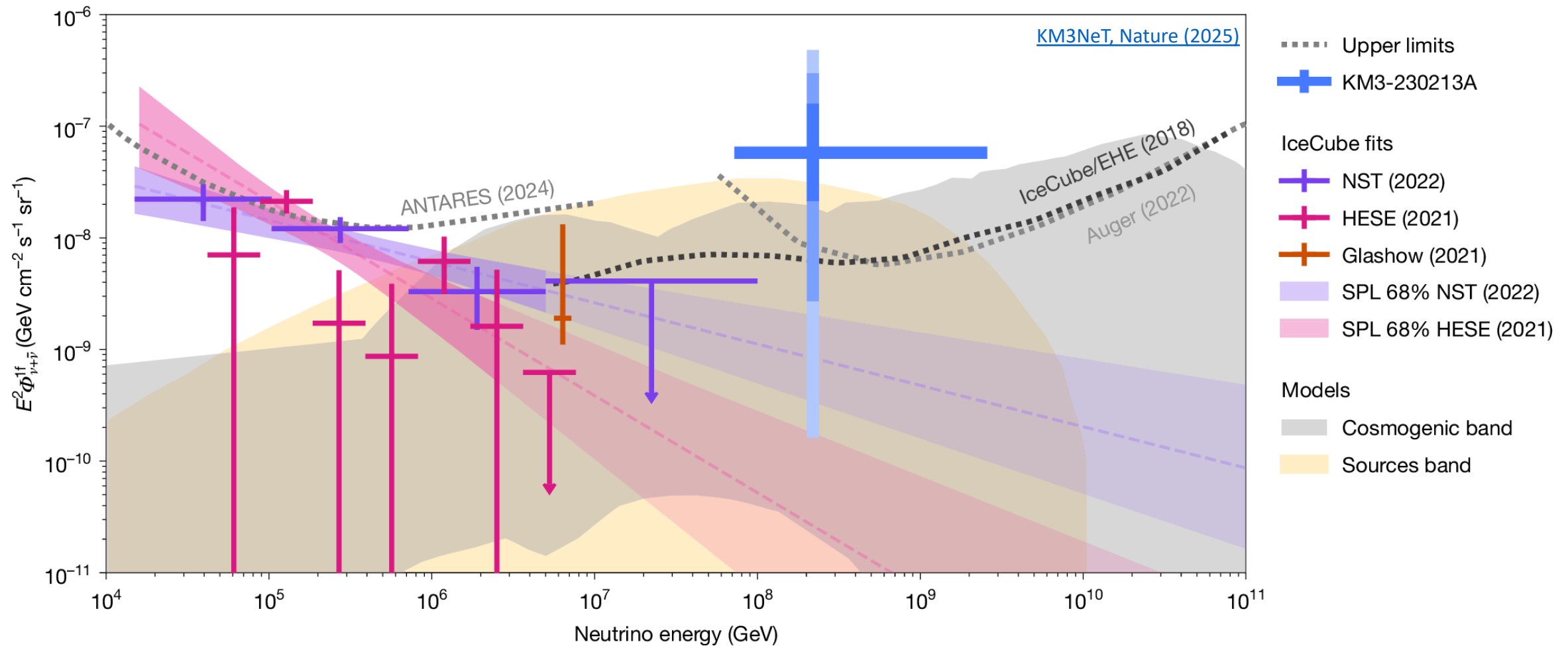
Final configuration: 0.007 km³, 115 strings, 2070 optical modules, 20 m (9 m) horizontal (vertical) spacing

Current configuration: ~20% complete





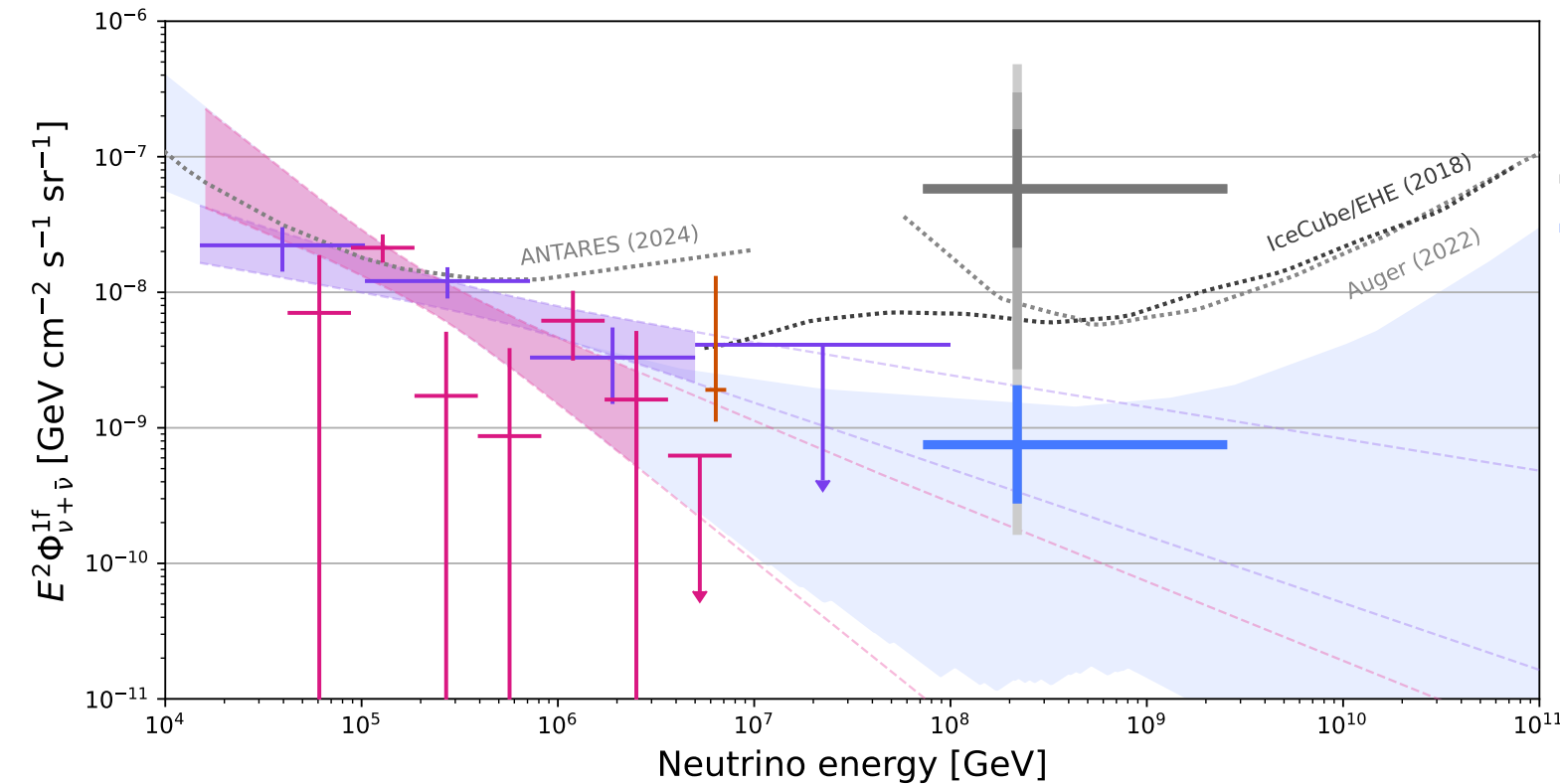
First >100 PeV neutrino



120 PeV muon $\rightarrow$ 220 PeV neutrino!

Why hasn't IceCube seen a similar UHE neutrino? Is this compatible?

Compatibility in the global landscape



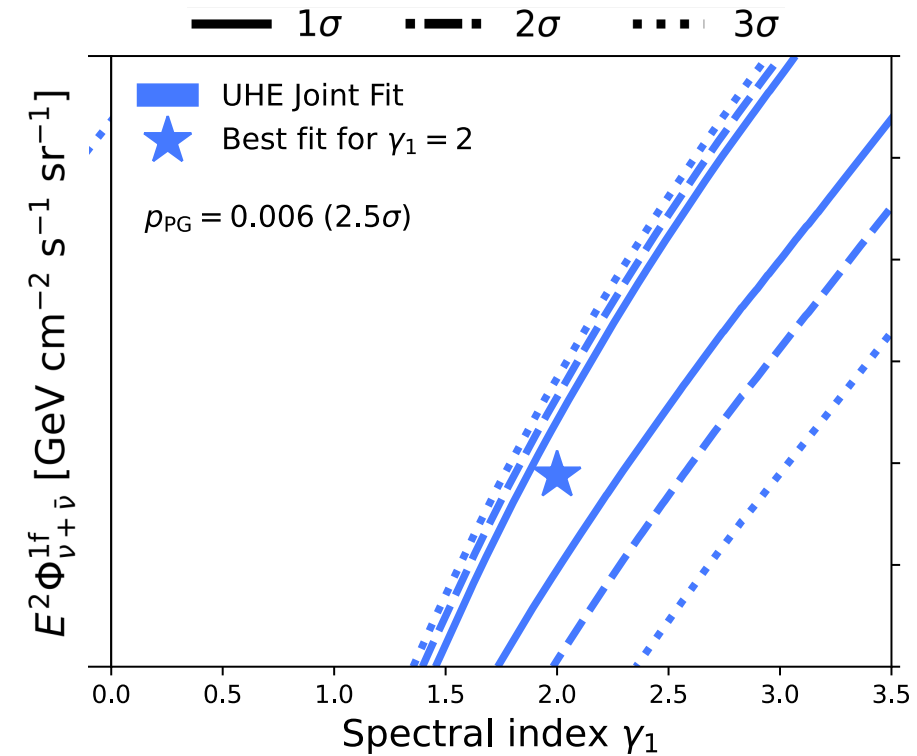
..... Upper limits

KM3NeT

- KM3-230213A E^{-2} fit
- Joint E^{-2} fit
- Joint BPL fit (this work)

IceCube fits

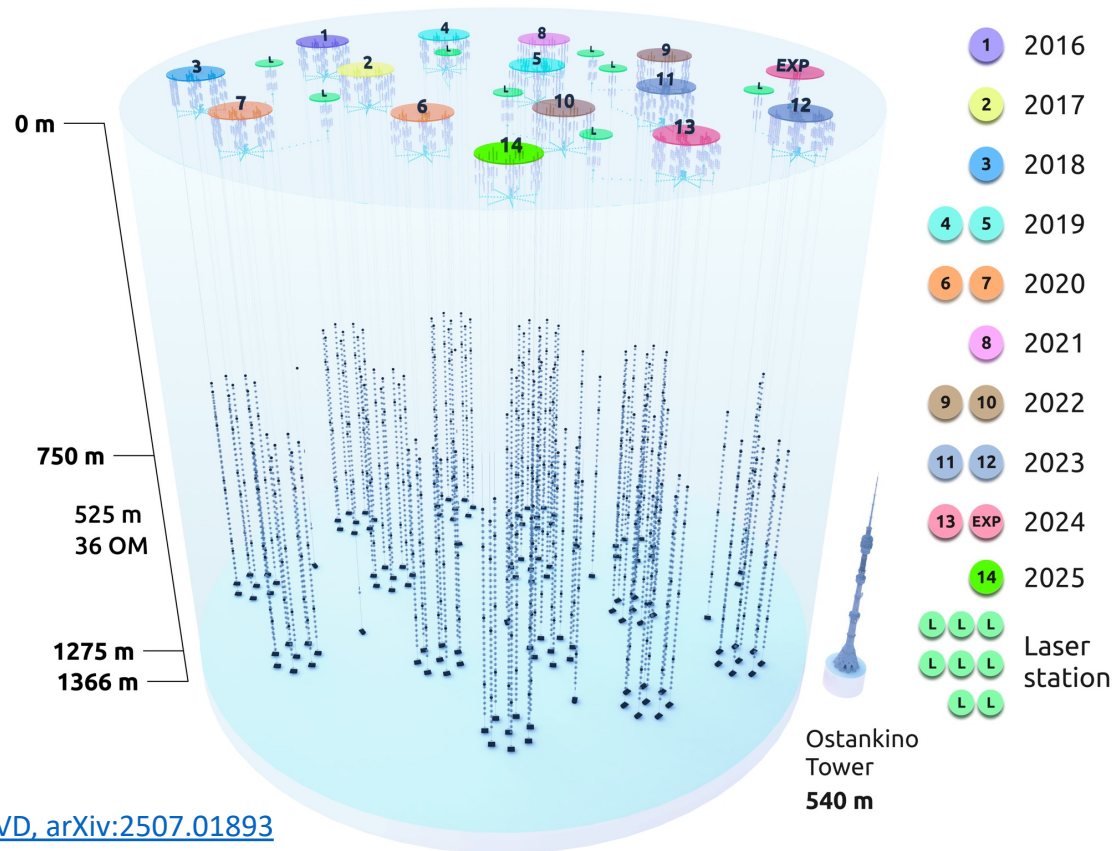
- NST (2022)
- HESE (2021)
- Glashow (2021)
- SPL 68% NST (2022)
- SPL 68% HESE (2021)



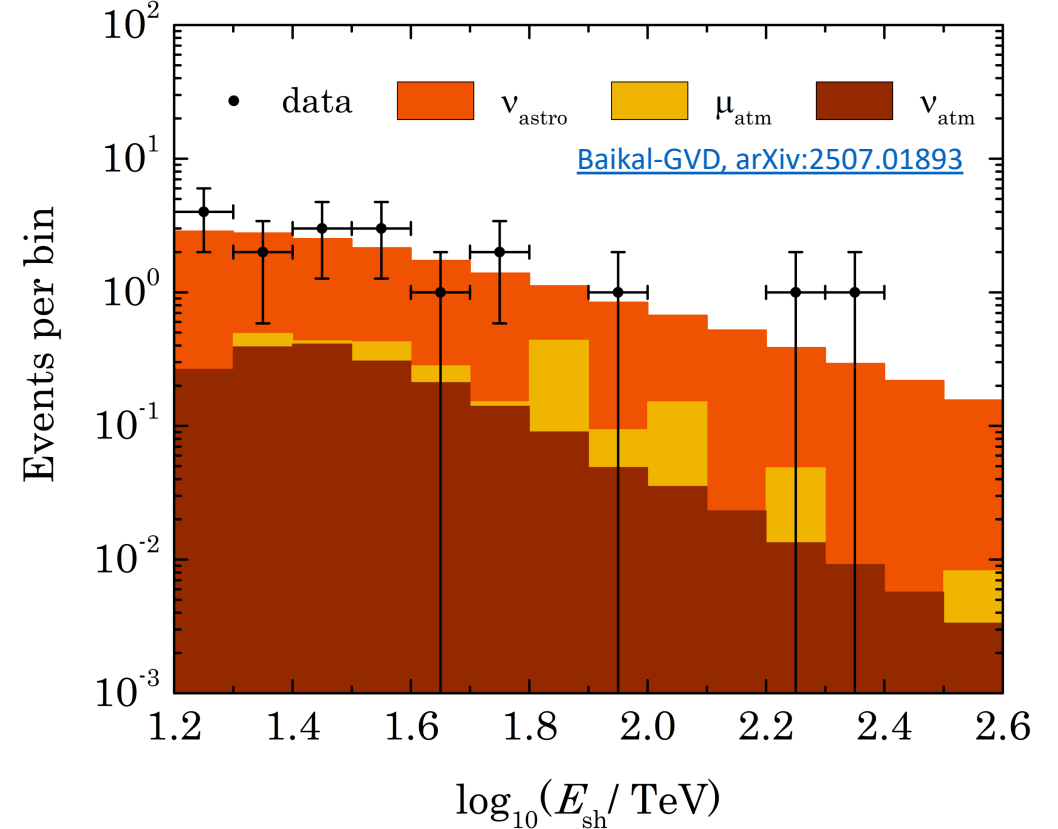
2.5-3.0 σ tension with joint fit
depending on model and dataset used

[KM3NeT, PRX 15 031016 \(2025\)](#)

Baikal GVD: Observation of diffuse flux at $>5\sigma$



[Baikal-GVD, arXiv:2507.01893](https://arxiv.org/abs/2507.01893)



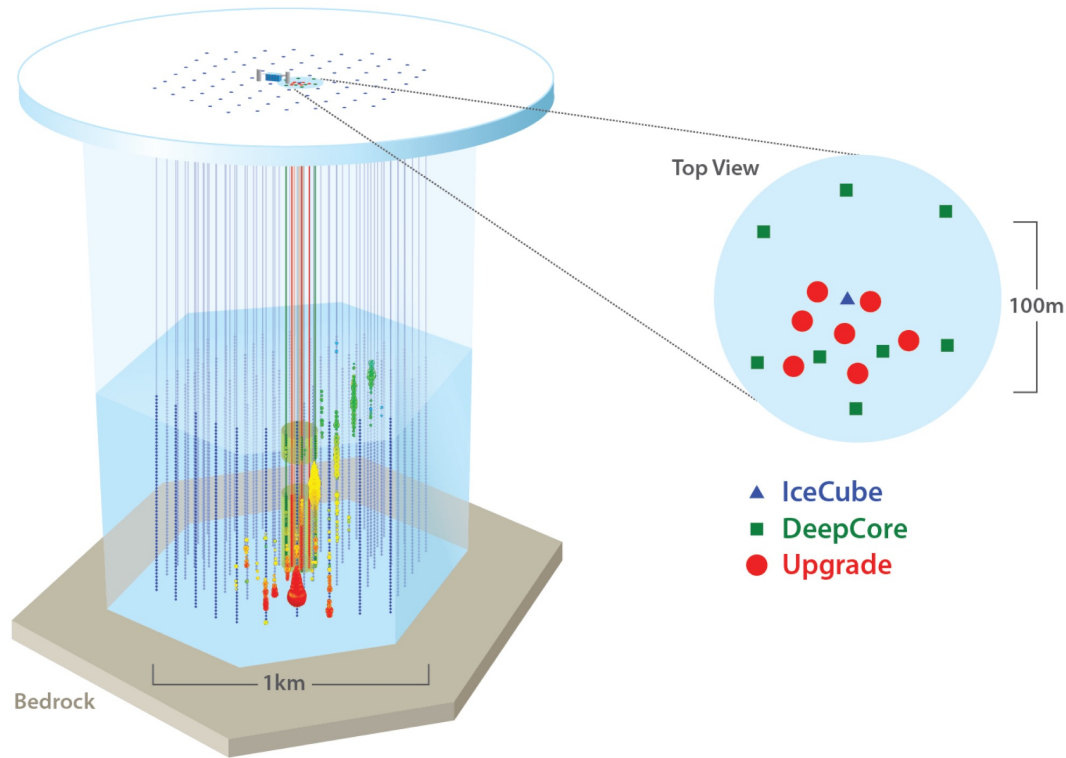
Final configuration: $1 \text{ km}^3 \sim 6000$ optical modules
Current config: 0.7 km^3 , 117 strings in 14 clusters

Diffuse flux observed at 5.1σ !

The Future

Soon, hopefully (Now-2040s)

IceCube Upgrade – Deploying in a few months!



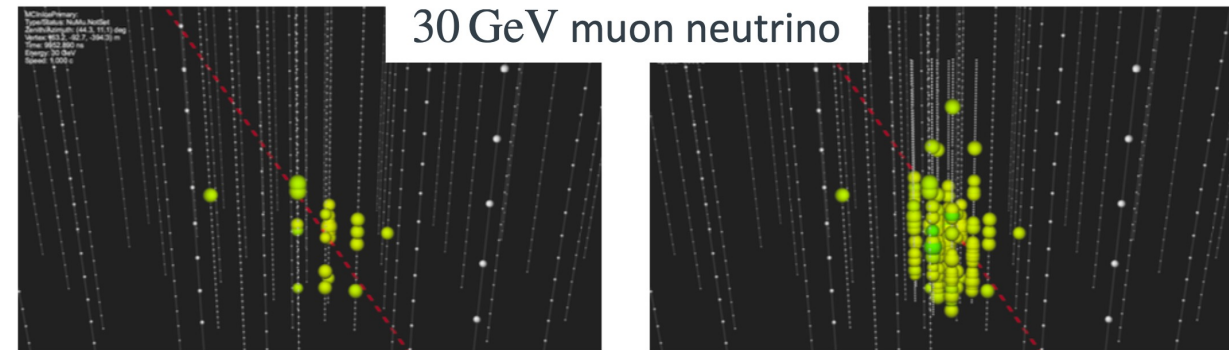
700+ new optical sensors and calibration devices on 7 strings (200 Mtons)

Focus: lower-energy physics ($\lesssim 100$ GeV) & detector calibration

mDOM



D-Egg

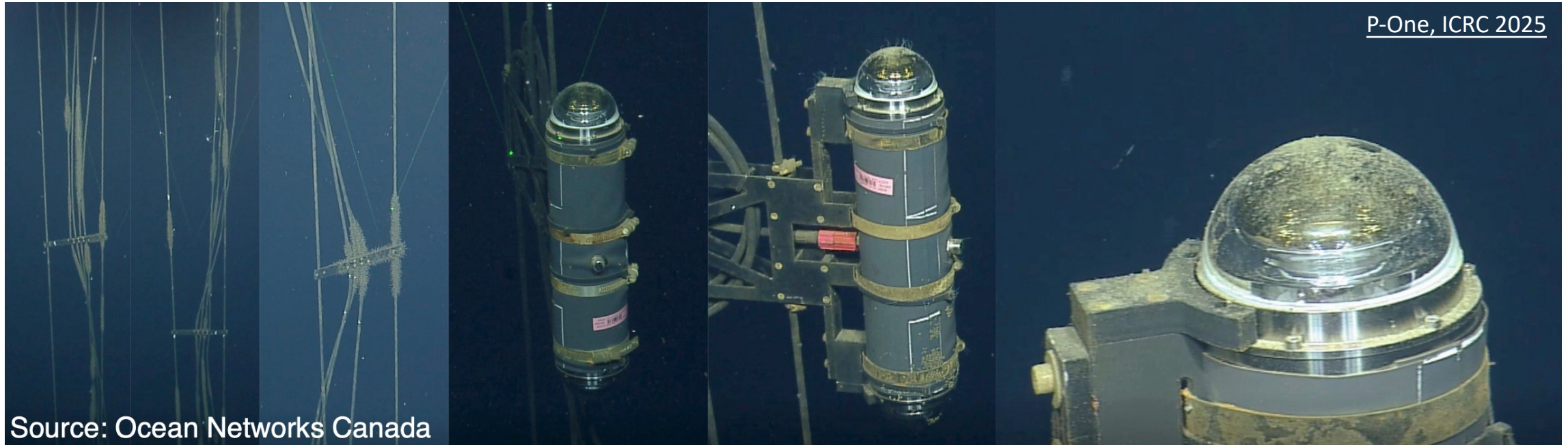
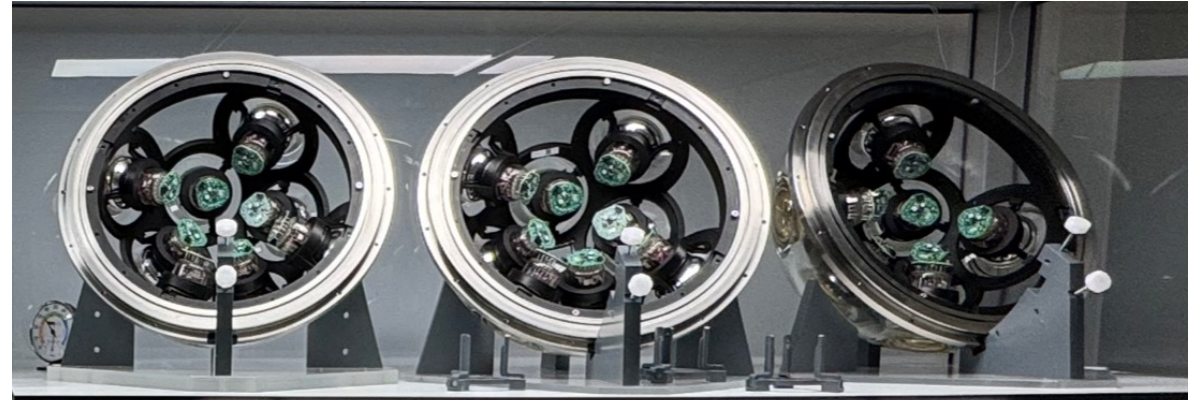


Current detector

With Upgrade

P-ONE – Pacific Ocean Neutrino Experiment

- Optical modules under construction
- Proof-of-concept string scheduled to deploy in 2026
- P-ONE demonstrator funded



... and in the Western Pacific



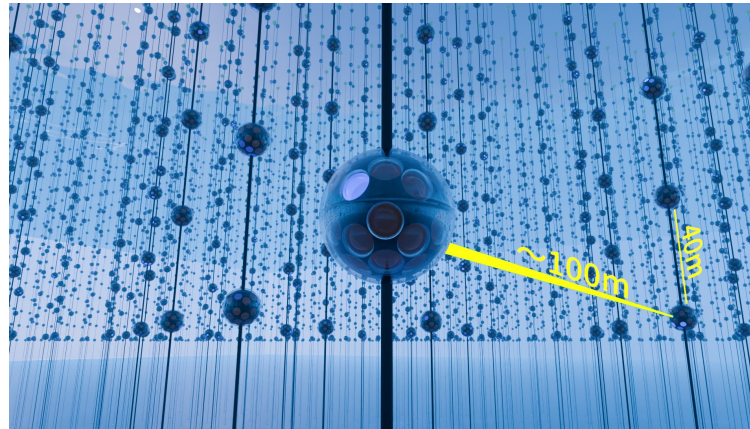
TRIDENT
海 | 铃 | 计 | 划



- 8 km³ effective volume
- Sensitive to TeV-EeV ν
- Status: test strings deployed for seawater characterization

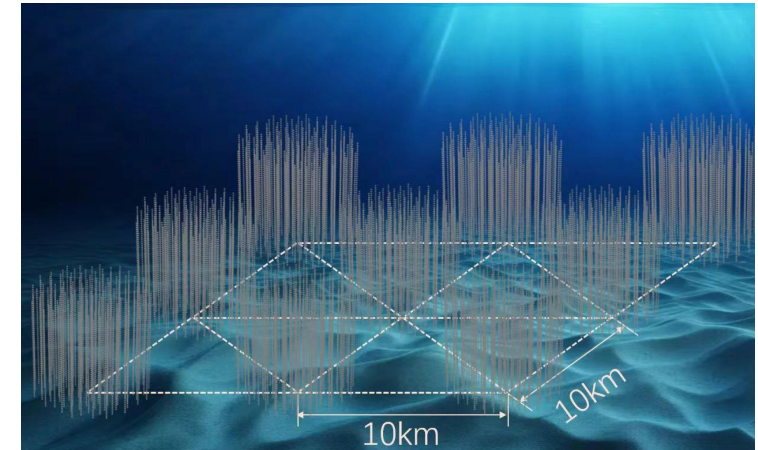
[TRIDENT, TeVPA 2024](#)

NEON



- 10 km³ effective volume
- Sensitive to TeV-PeV ν
- Status: design stage

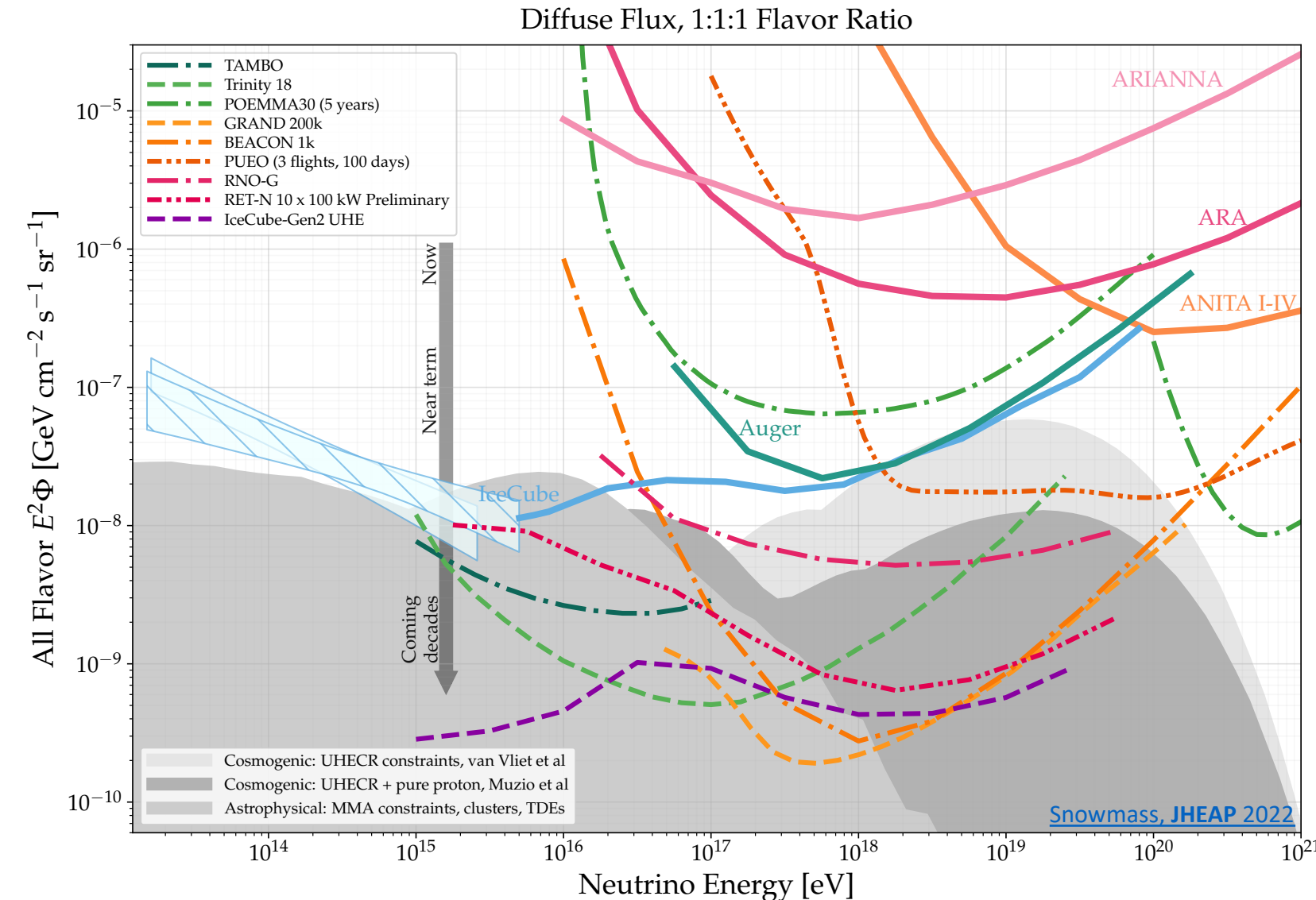
[NEON, Astro. Part. Phys. 171 103123 \(2025\)](#)



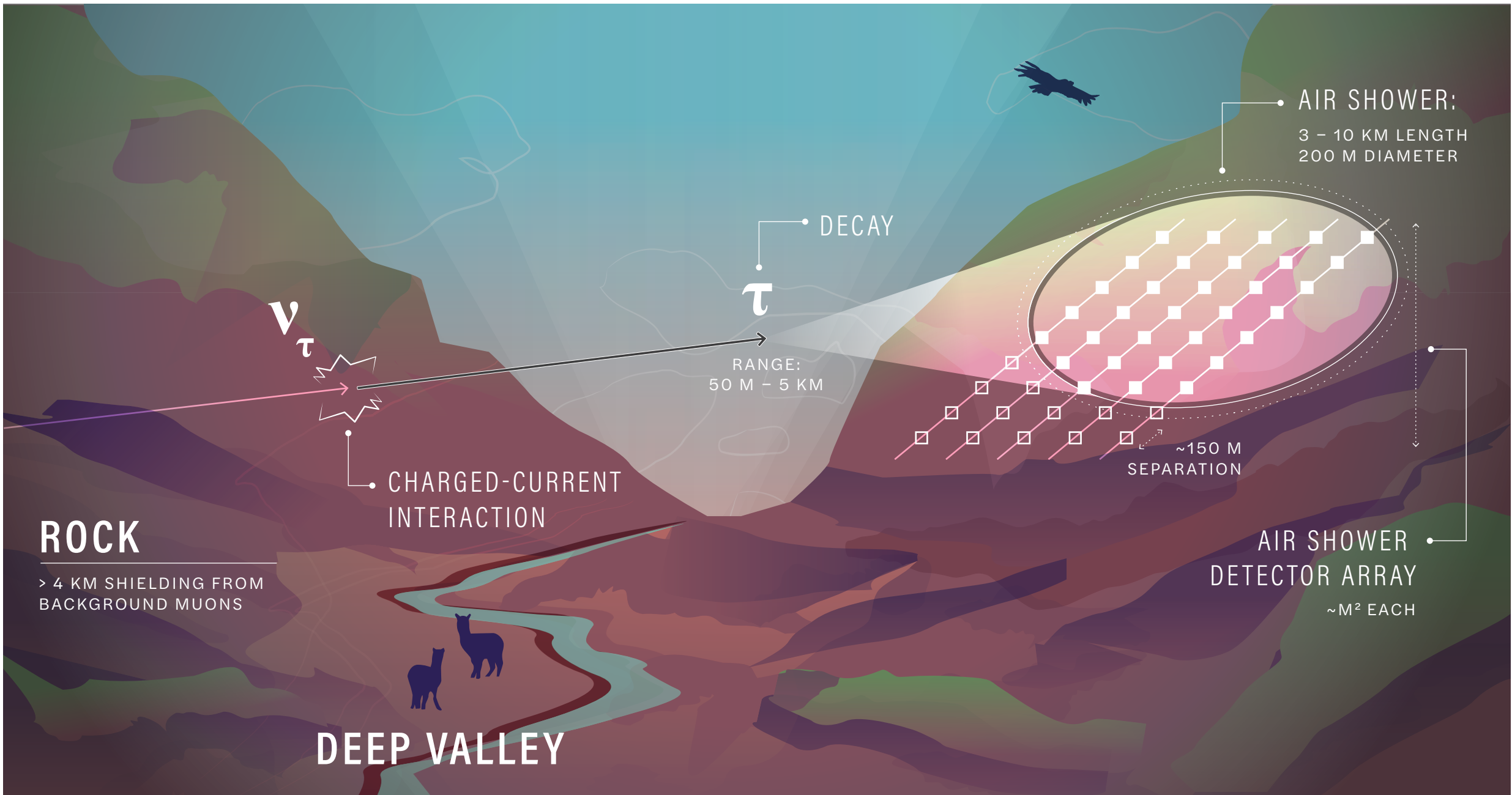
- 30 km³ effective volume
- Sensitive to 100 TeV-100 PeV ν
- Status: prototype strings deployed

[HUNT, ICRC 2025](#)

Next generation will push to even higher energies



- Snowmass called for development of higher-energy observatories
- Primary goals:
 - Increased source sensitivity
 - Discover cosmogenic neutrino flux



ROCK

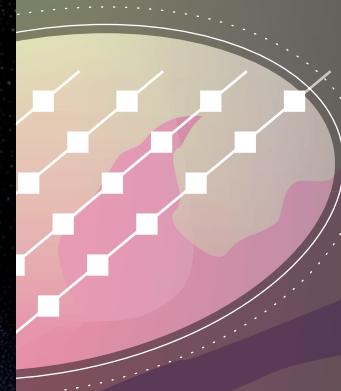
> 4 KM SHIELDING FROM
BACKGROUND MUONS

v
 τ



Will Thompson ~ NNN 2025

AIR SHOWER:
3 – 10 KM LENGTH
200 M DIAMETER

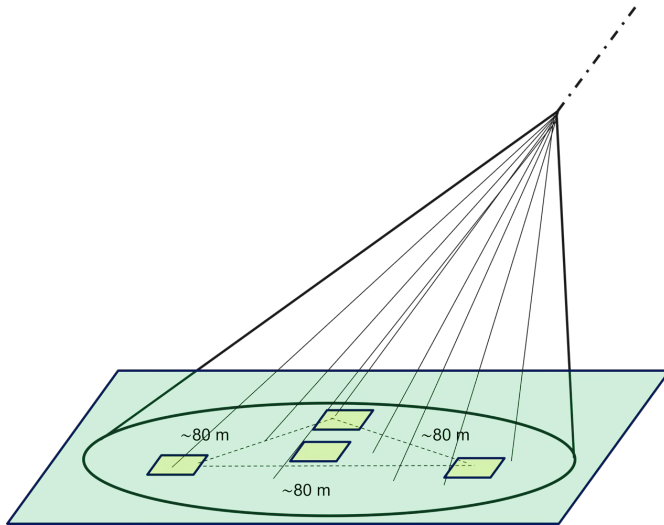


50 M
TION

AIR SHOWER
DETECTOR ARRAY
~M² EACH

TAMBO timeline

Today:
TAMBO-4

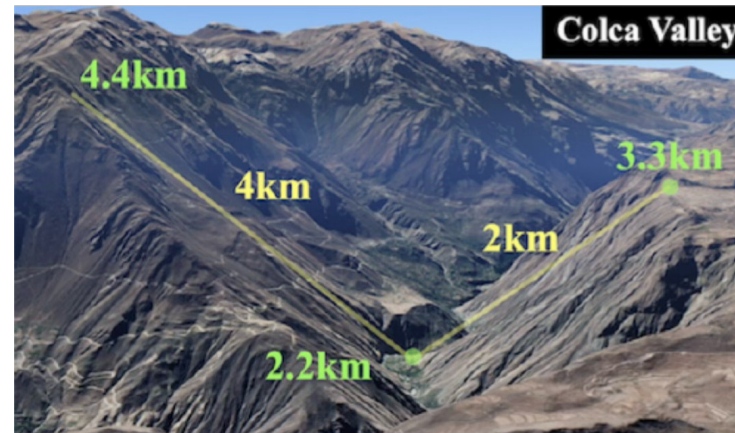


Small test array

Detector & electronics prototypes

2025-2028:
TAMBITO (TAMBO-100)

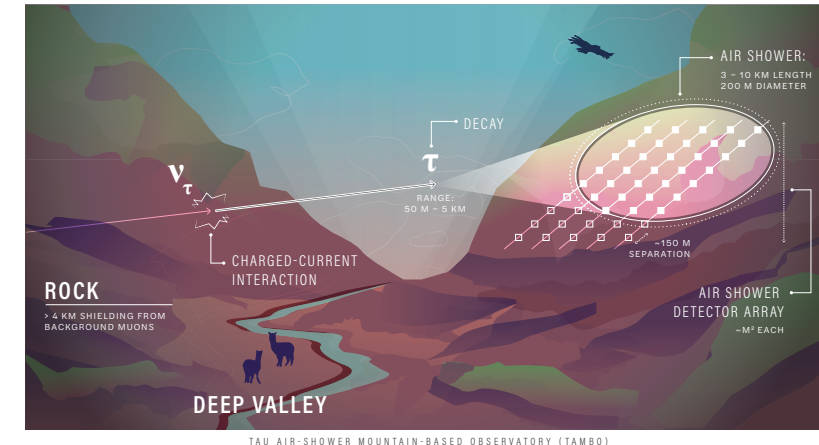
FUNDED!



Pilot array

Deployment techniques,
backgrounds, responsible siting

2028-:
TAMBO-5k

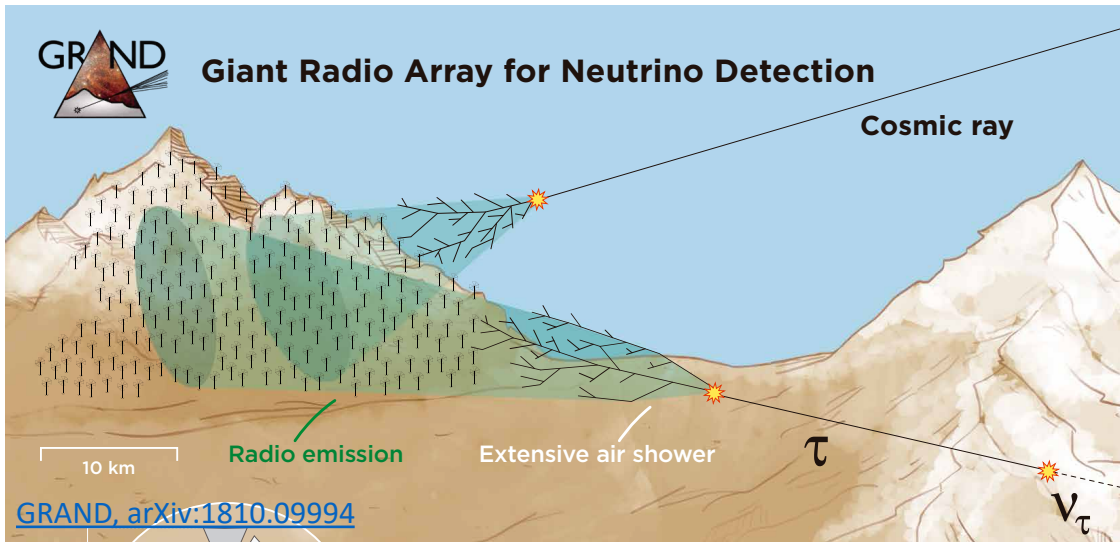
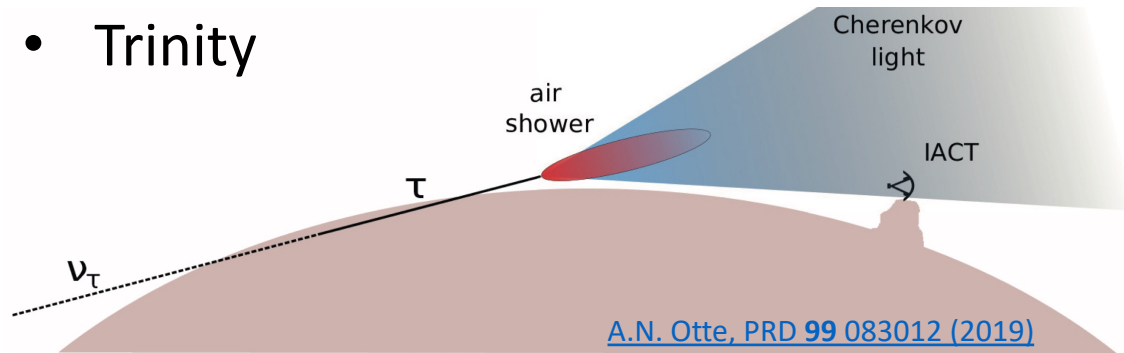


Target full size array

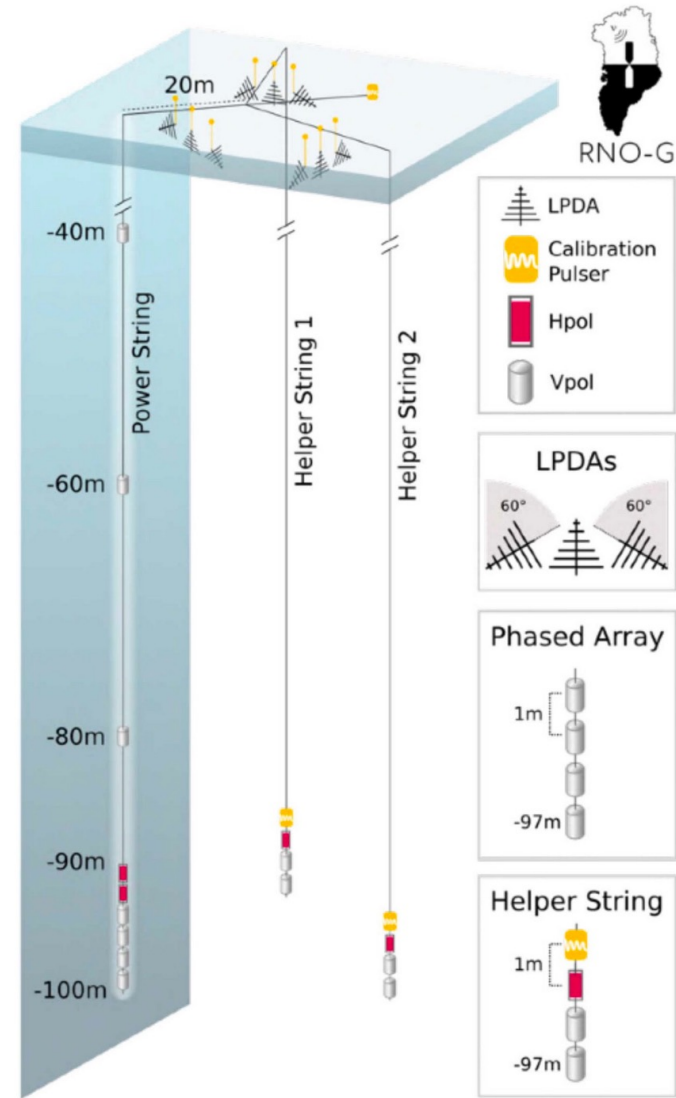
Development of radio & air-Cherenkov telescopes

Atmospheric fluorescence:

- Trinity



In-air radio: GRAND, BEACON, PBR

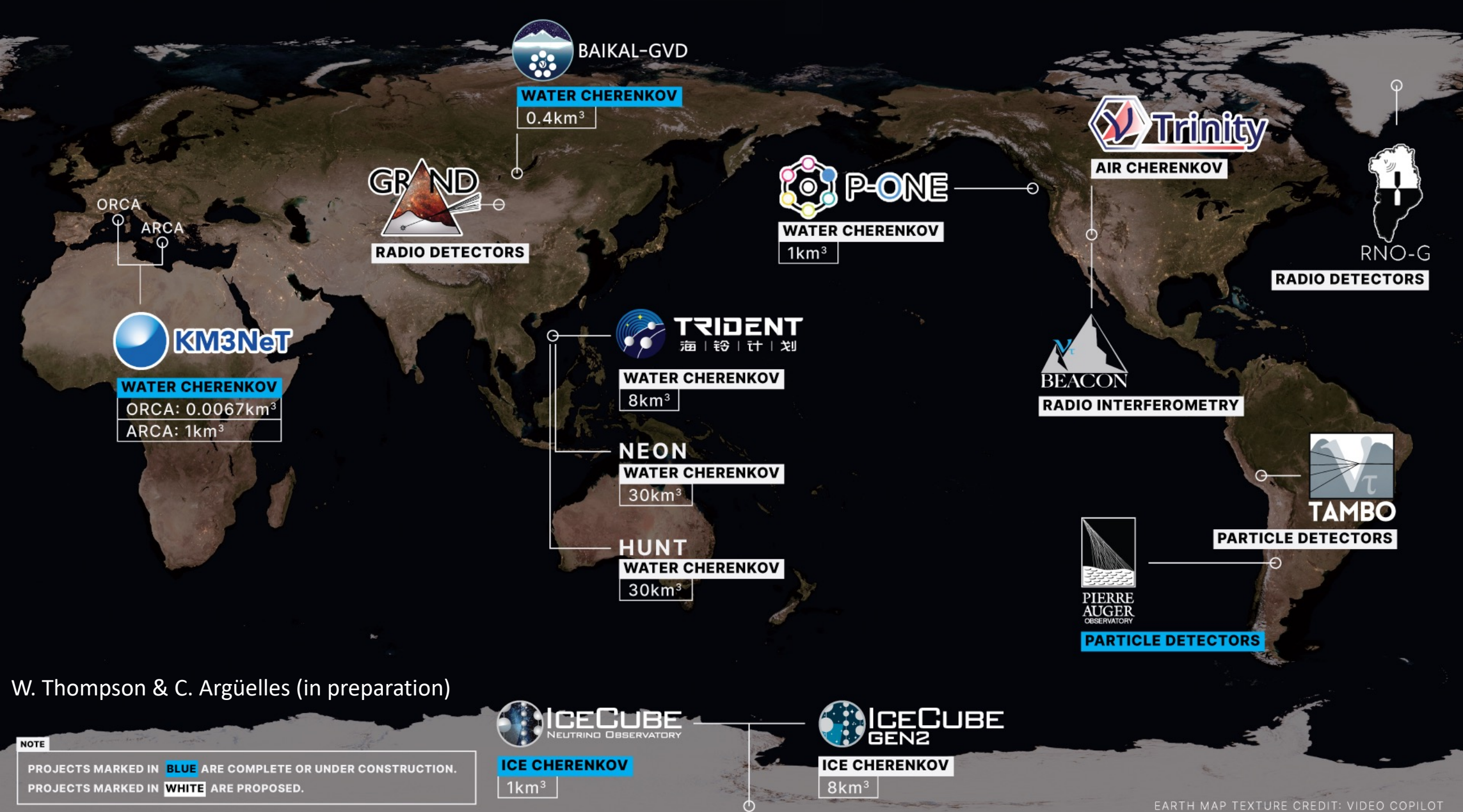


In-ice radio:

- ARA
- ARIANNA
- RNO-G
- IceCube-Gen2
- RET

Summary

- Neutrino telescopes are moving from discovery of astrophysical objects to more detailed study
- IceCube is no longer the only game in town
 - Interesting measurements by KM3NeT, Baikal-GVD; other water Cherenkov telescopes forthcoming
- Experiments using new detection schemes are extending the energy reach of neutrino telescopes to above 100 PeV

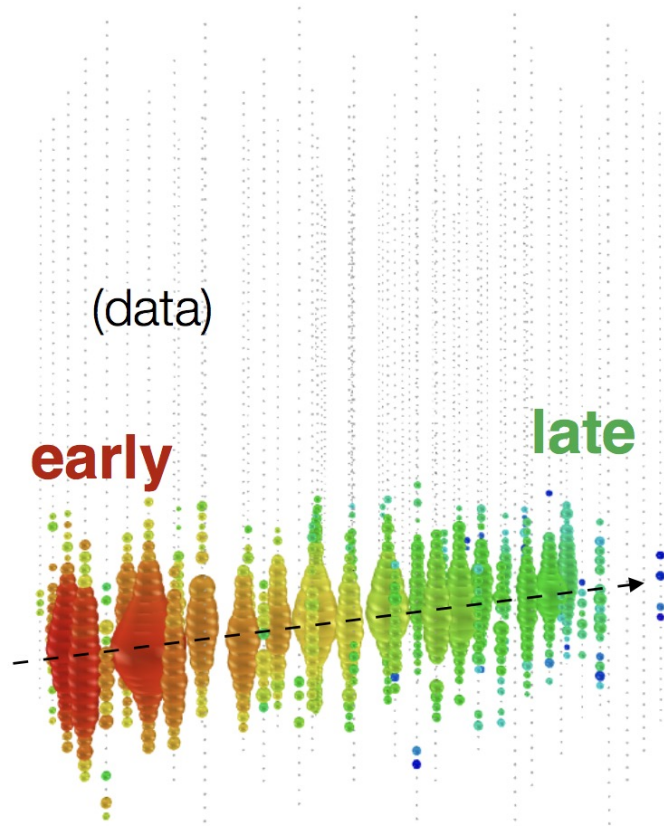


W. Thompson & C. Argüelles (in preparation)

Backup

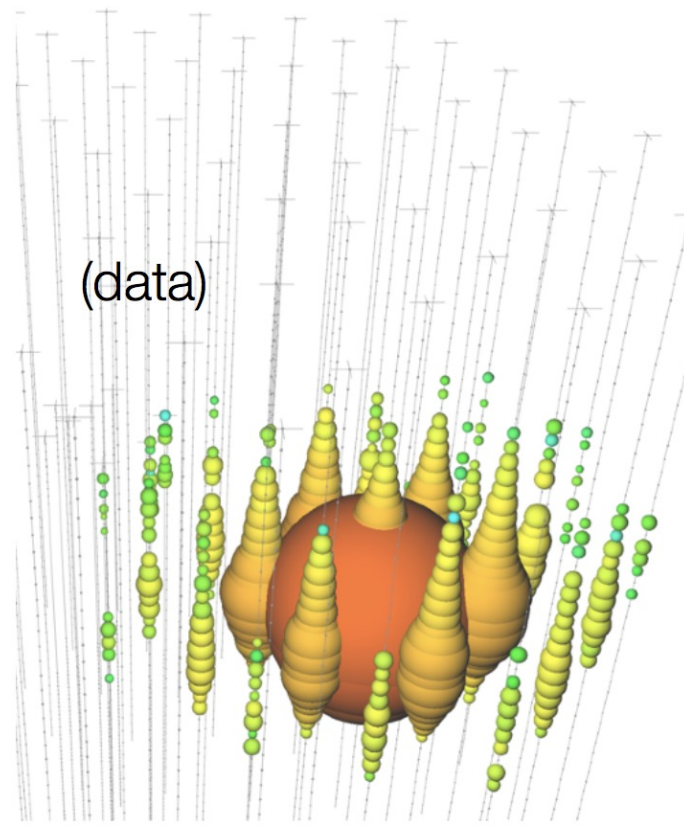
Different Flavors = Different Morphologies

Tracks



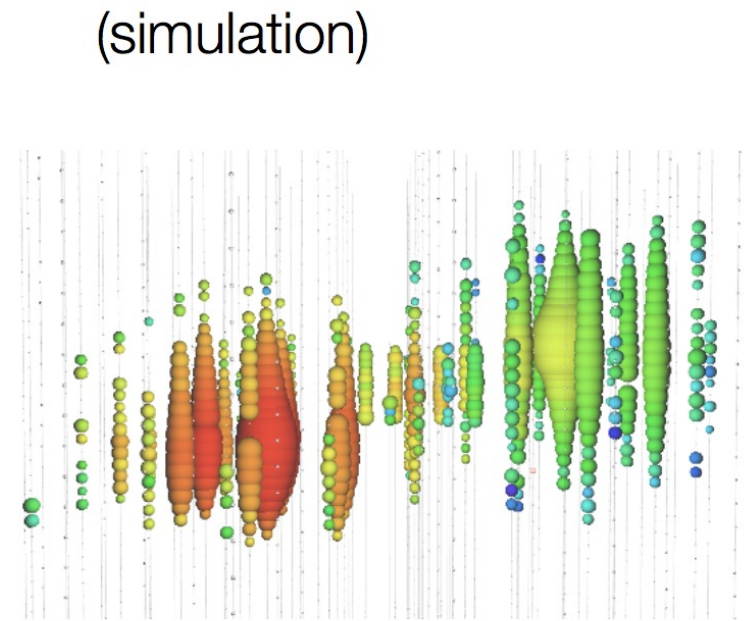
Charged current ν_μ

Cascades



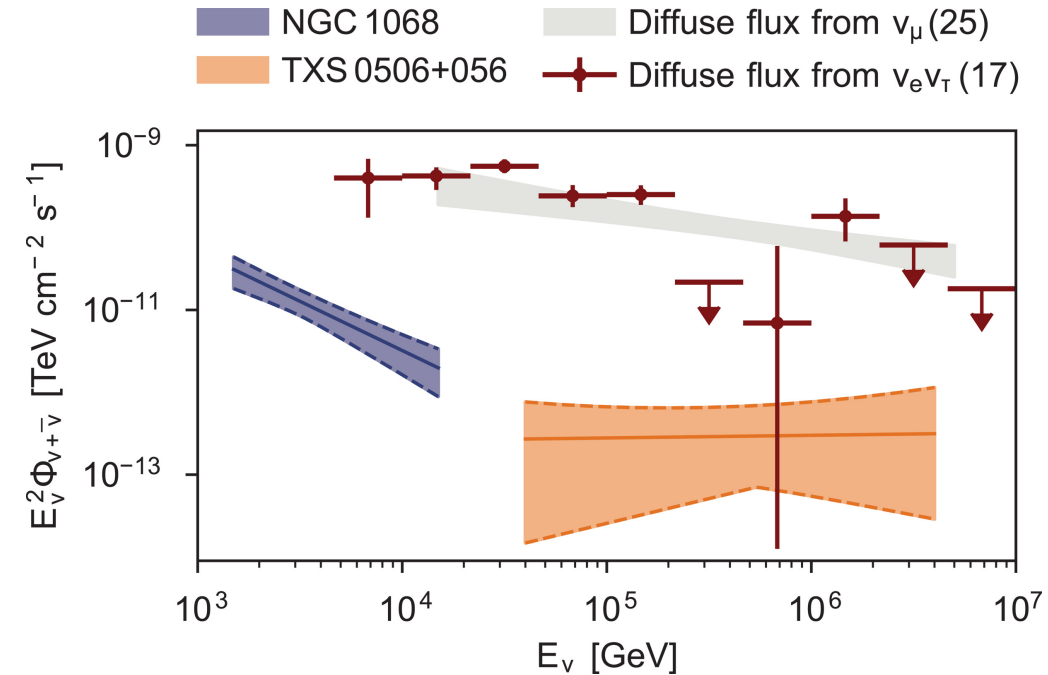
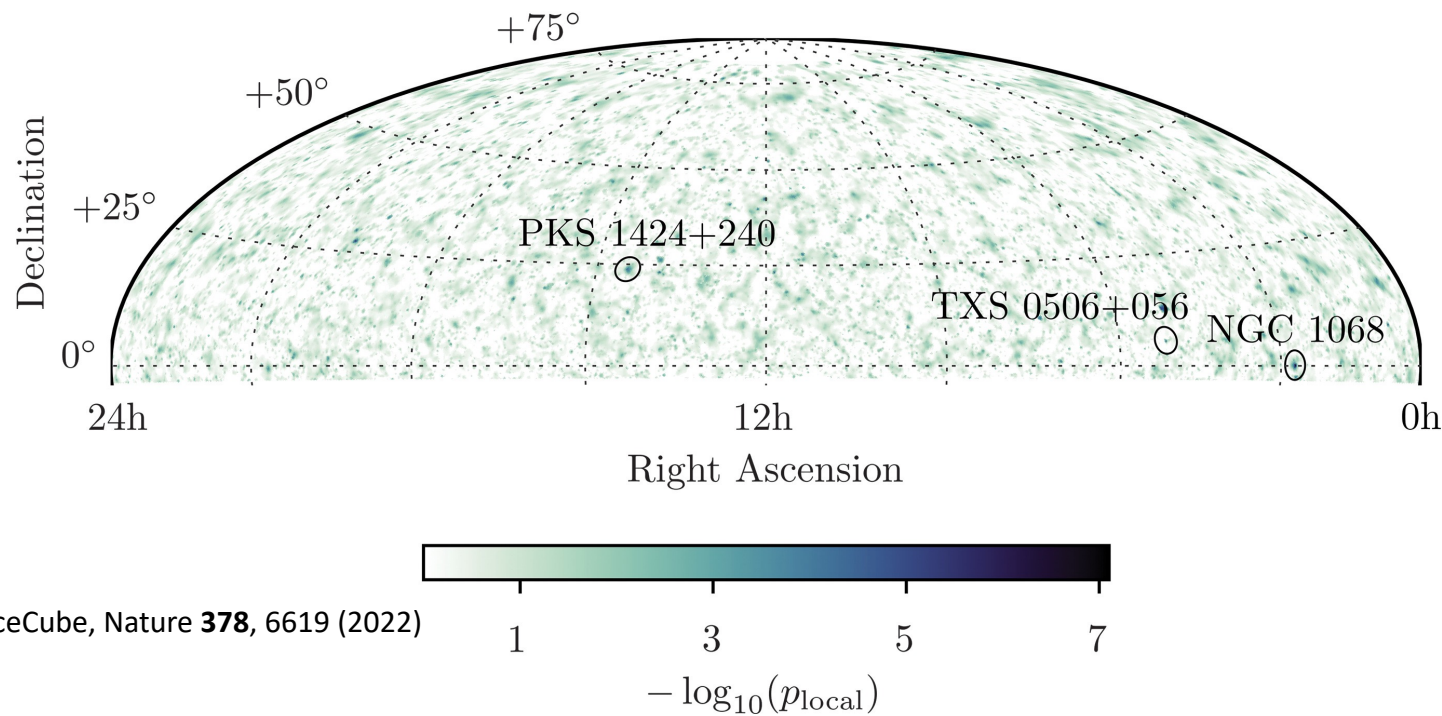
Neutral current / charged current ν_e

Double Cascades



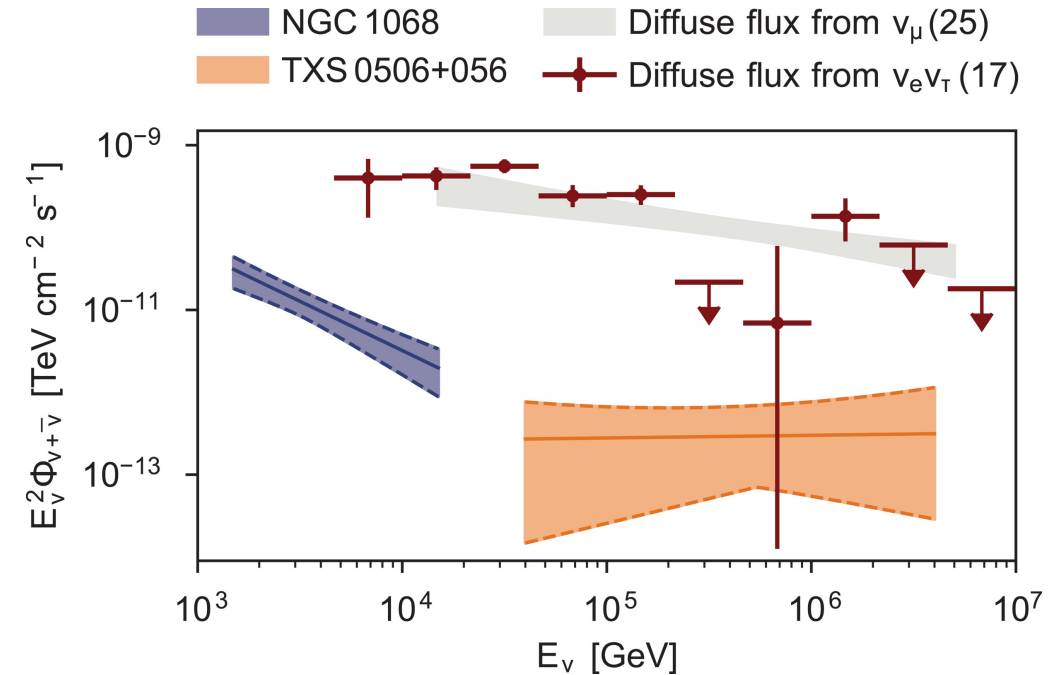
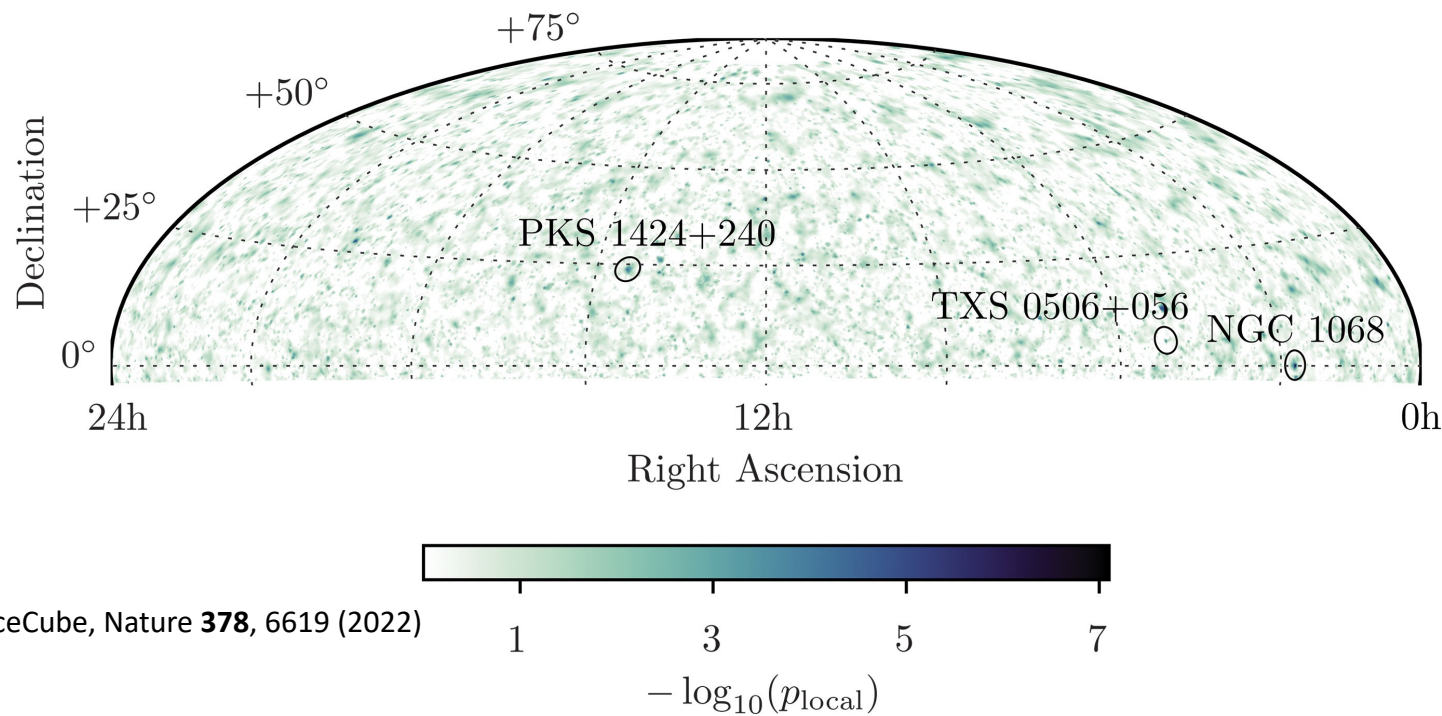
Charged current ν_τ

Where Are the Sources?



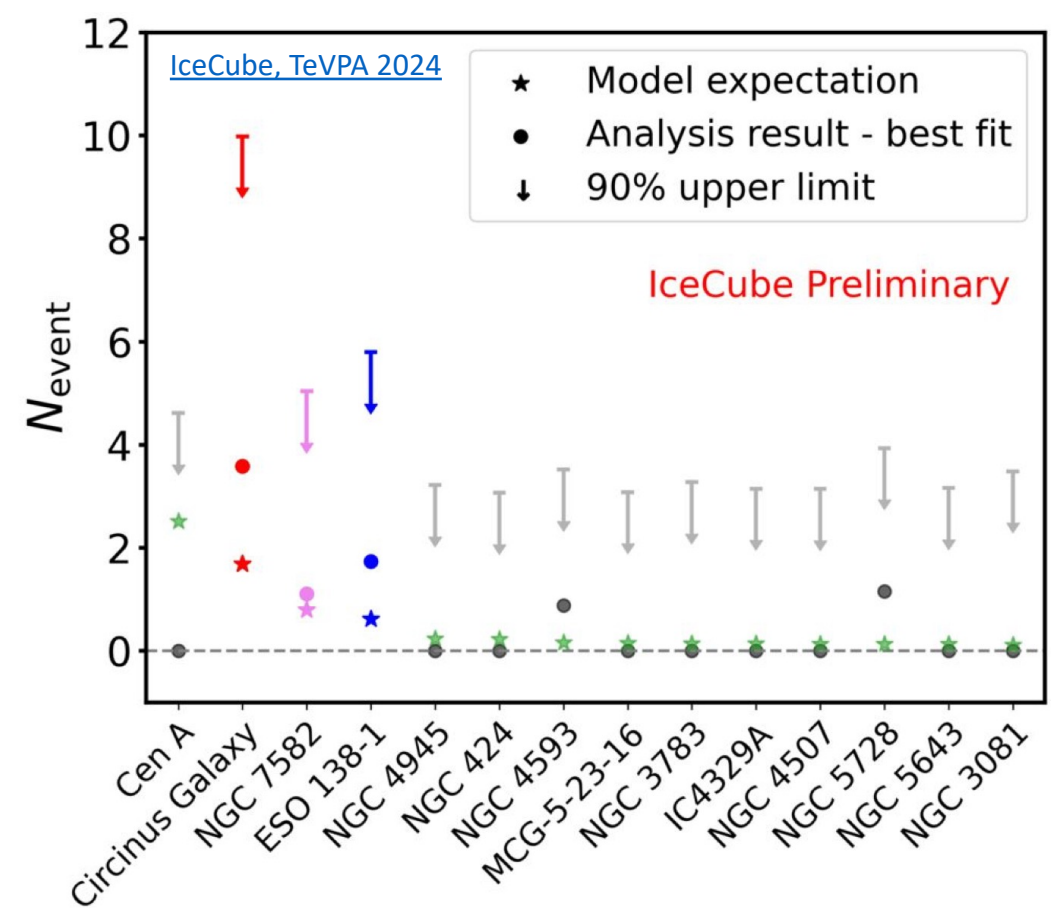
- Number of known neutrino sources increased by $\infty\%$ in last eight years

Where Are the Sources?

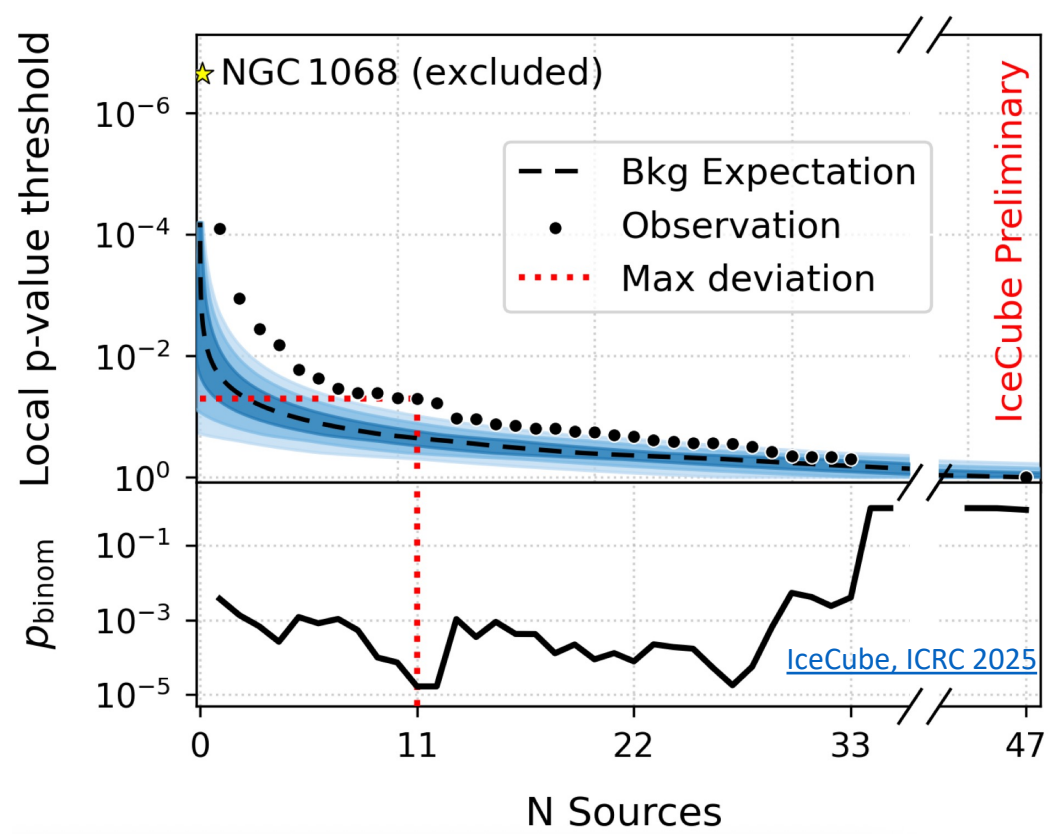


- Number of known neutrino sources increased by $\infty\%$ in last eight years
- ... but these comprise only a small fraction of the diffuse flux

Ensemble searches beginning to unveil neutrino sources



3.0 σ observation of 13 X-ray bright Seyferts
First observation in Southern sky



3.3 σ observation of 11 X-ray bright AGN
New sources in Northern sky

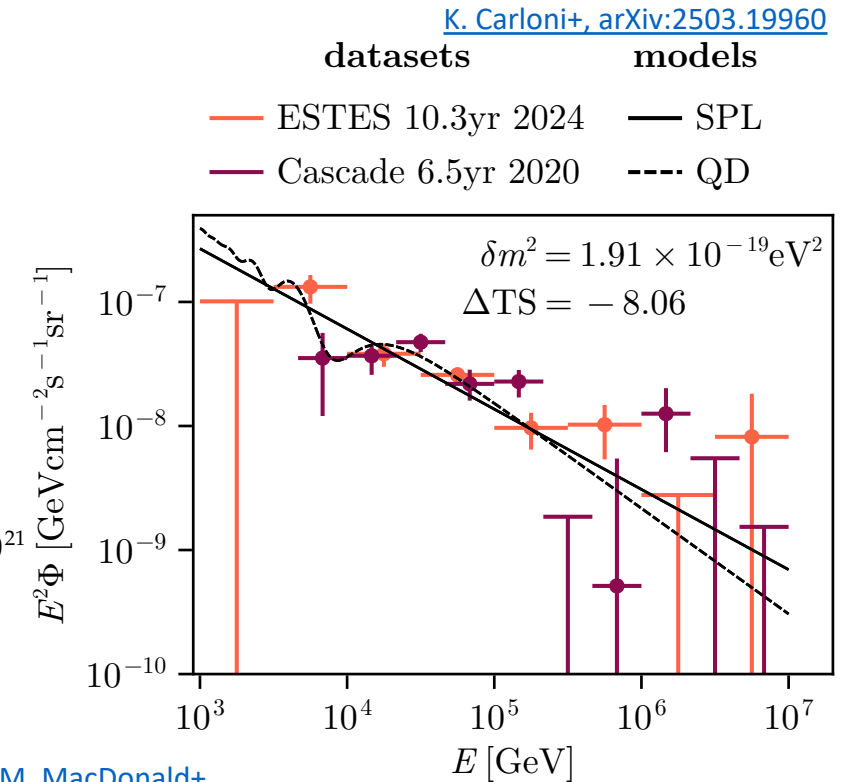
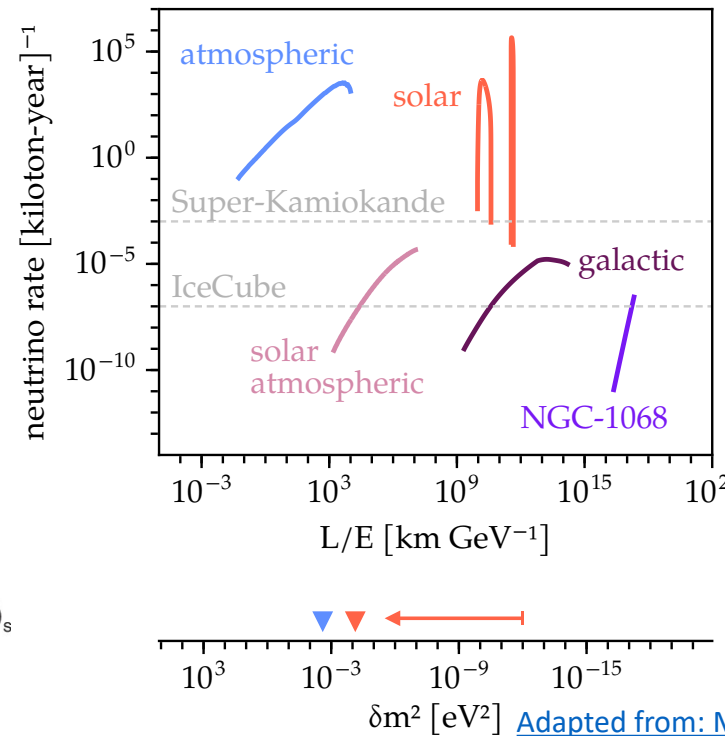
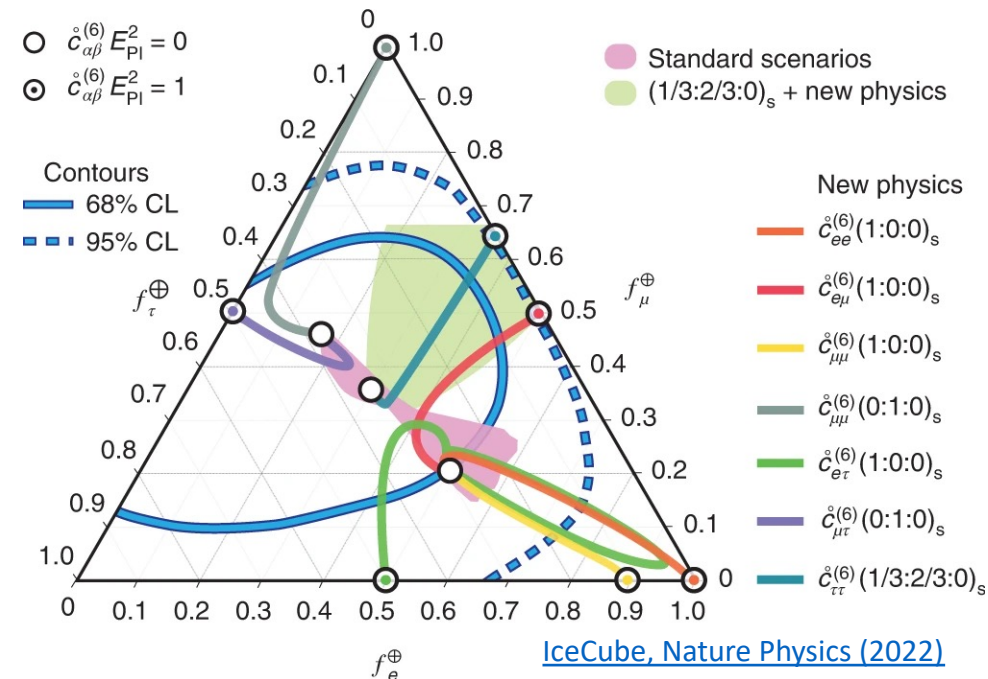


Can also probe BSM physics

Astrophysical neutrinos travel over great distances with enormous energies

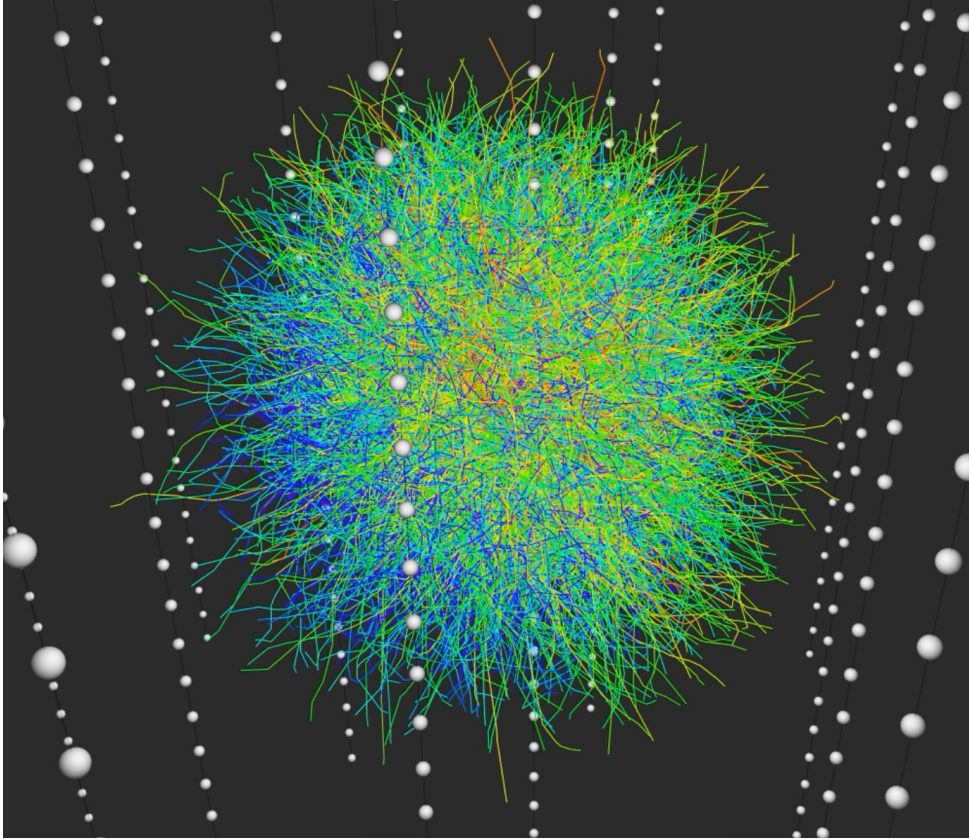
Extreme distances
compound minute effects

And extreme energies open up new oscillation space
Ex: Quasi-Dirac ν : $\delta m^2 = 1.9 \times 10^{-19} \text{ eV}^2$ preferred at 2.8σ



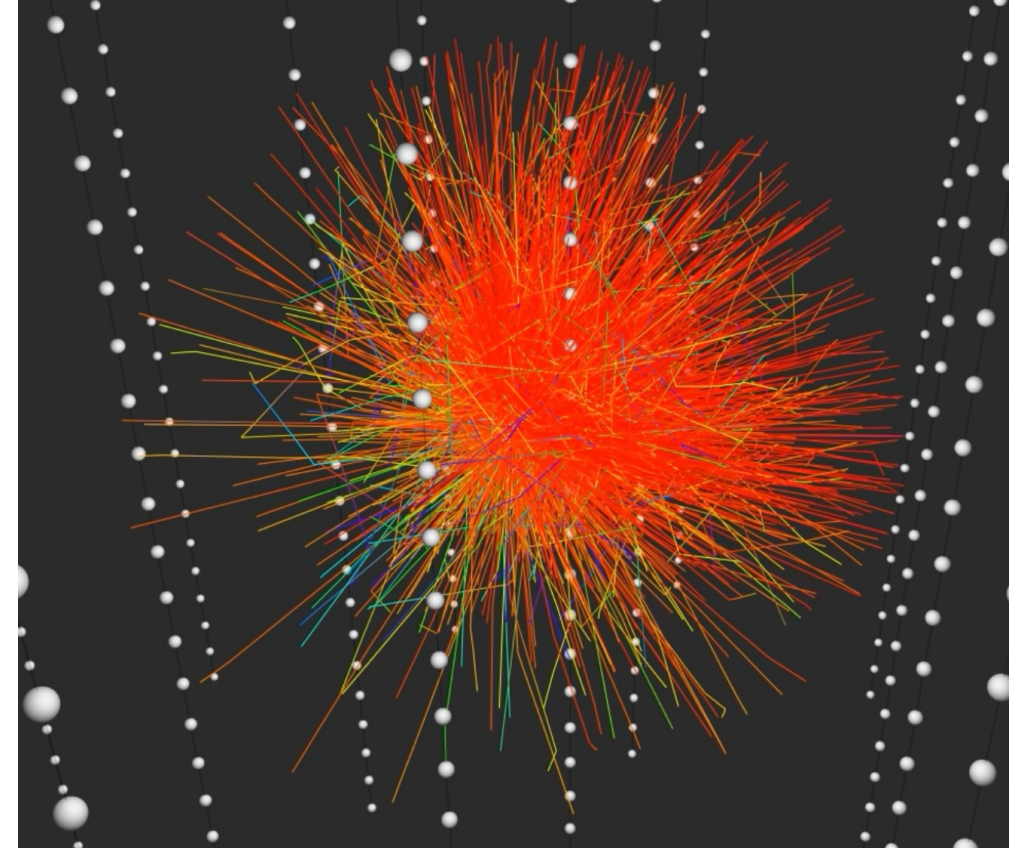
Ice & water detectors have different advantages

10 TeV in ice



Short scattering length
Long absorption length

10 TeV in water



Long scattering length
Short absorption length