Multimessenger Astrophysics and Particle Physics Opportunities With Neutrino Detectors

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ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

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RESEARCH CORPORATION for SCIENCE ADVANCEMENT

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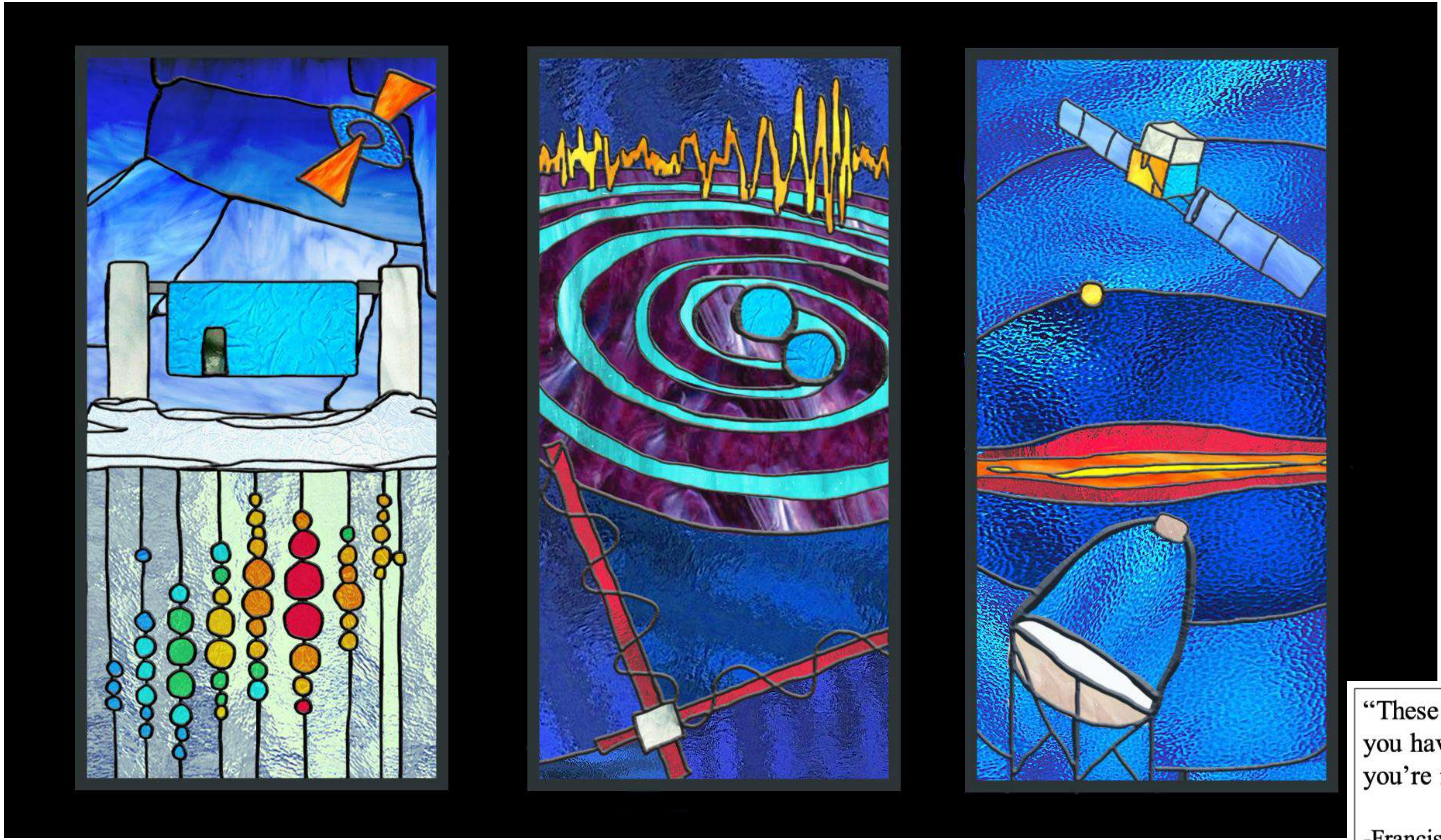
Neutrino Scattering: Theory, Experiment, Phenomenology
Institute of Theoretical Physics, Chinese Academy of Sciences

How does the Universe look in neutrinos?



> "These **sources** are complicated… Unless you have many ways to ***look*** at them, you're not going to figure them out"
>
> -Francis Halzen on Multimessenger Astronomy Scientific American

Echoed by Max Fried, DPF-Pheno2024

How do high-energy neutrinos behave?

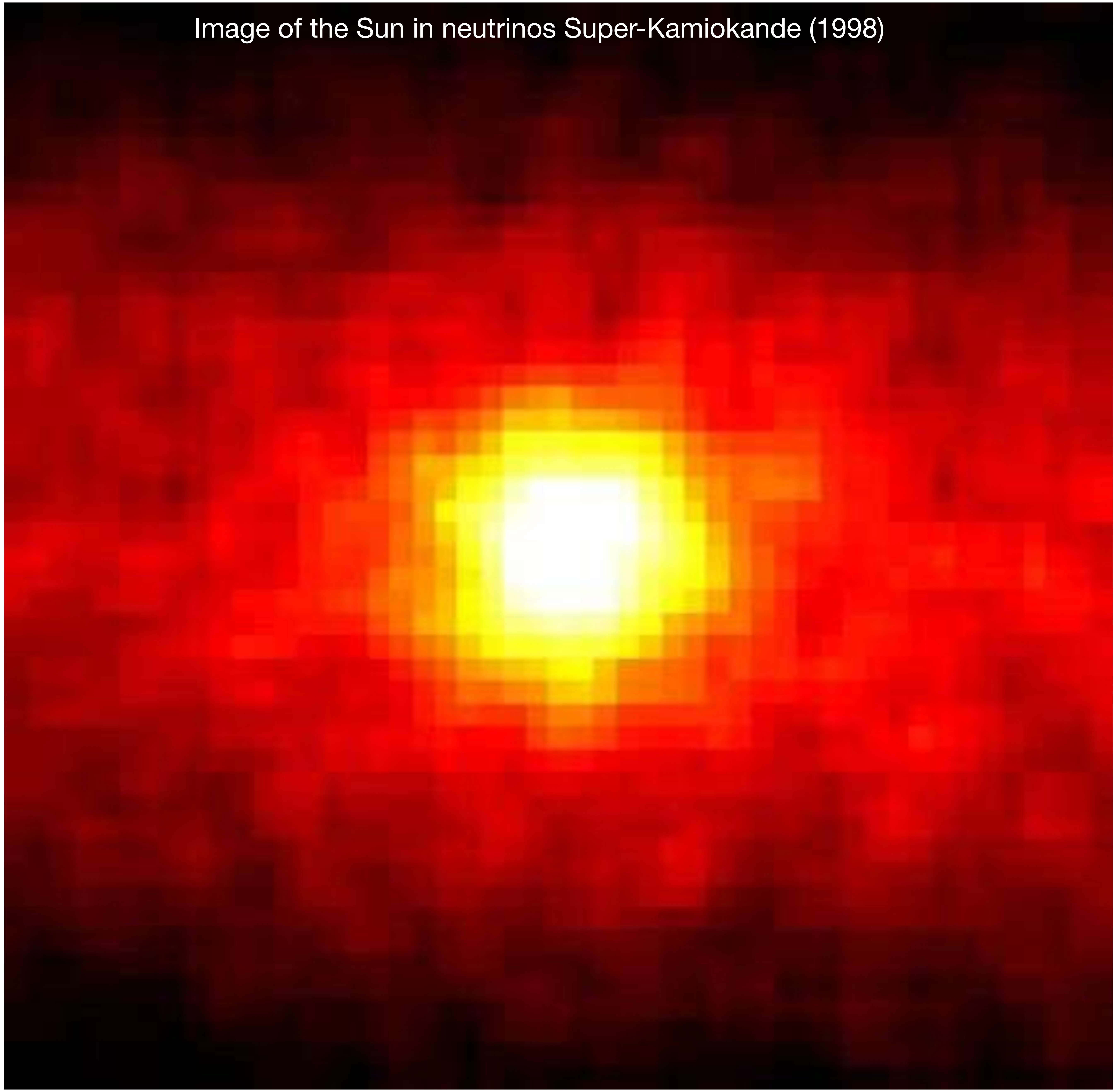
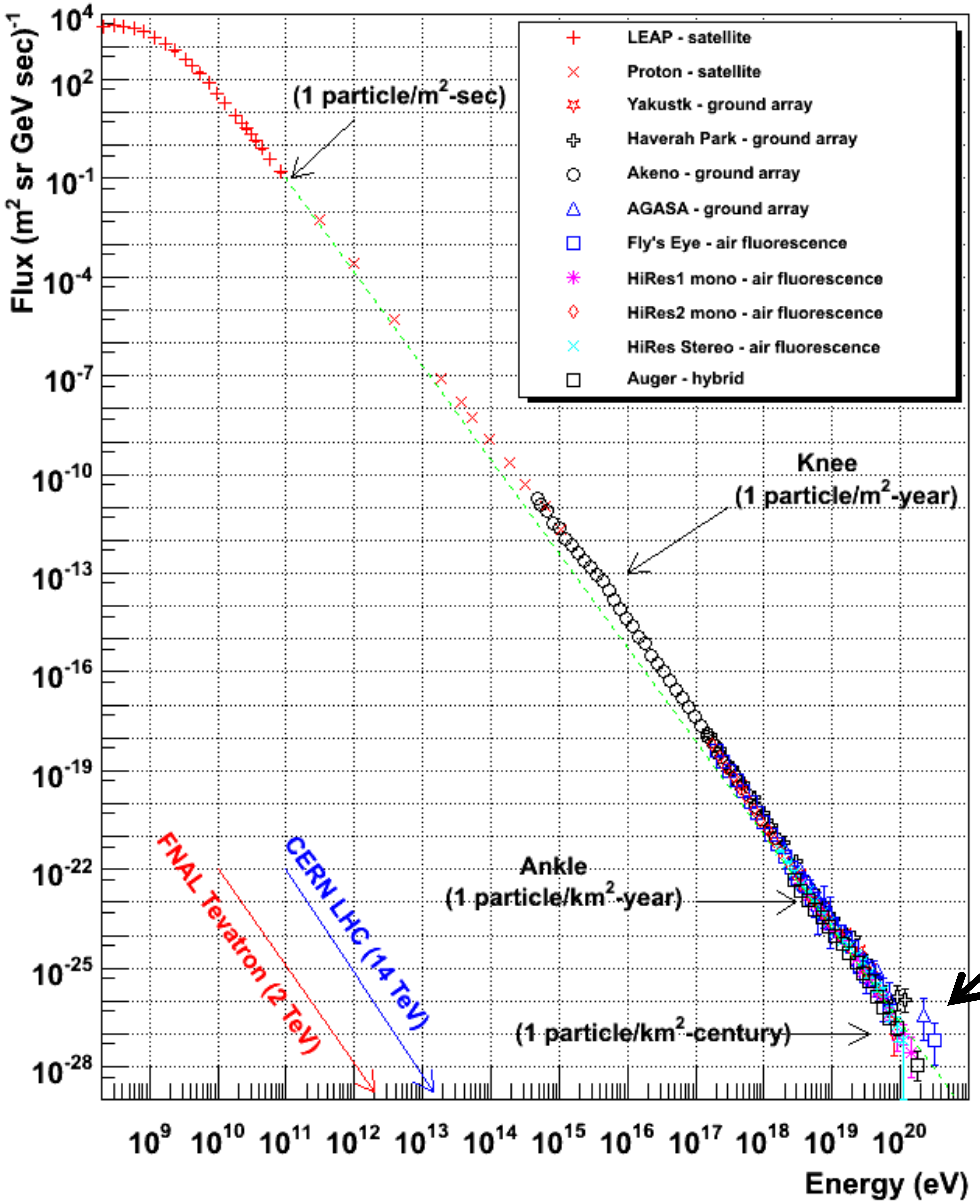


Image of the Sun in neutrinos Super-Kamiokande (1998)

Outline for the rest of this talk

1. **Neutrino astrophysics is multi-messenger astrophysics**
2. Most significant observations in neutrino astrophysics
3. New opportunities for particle physics
4. Future detectors & new ideas

origin of cosmic rays: oldest problem in astroparticle physics

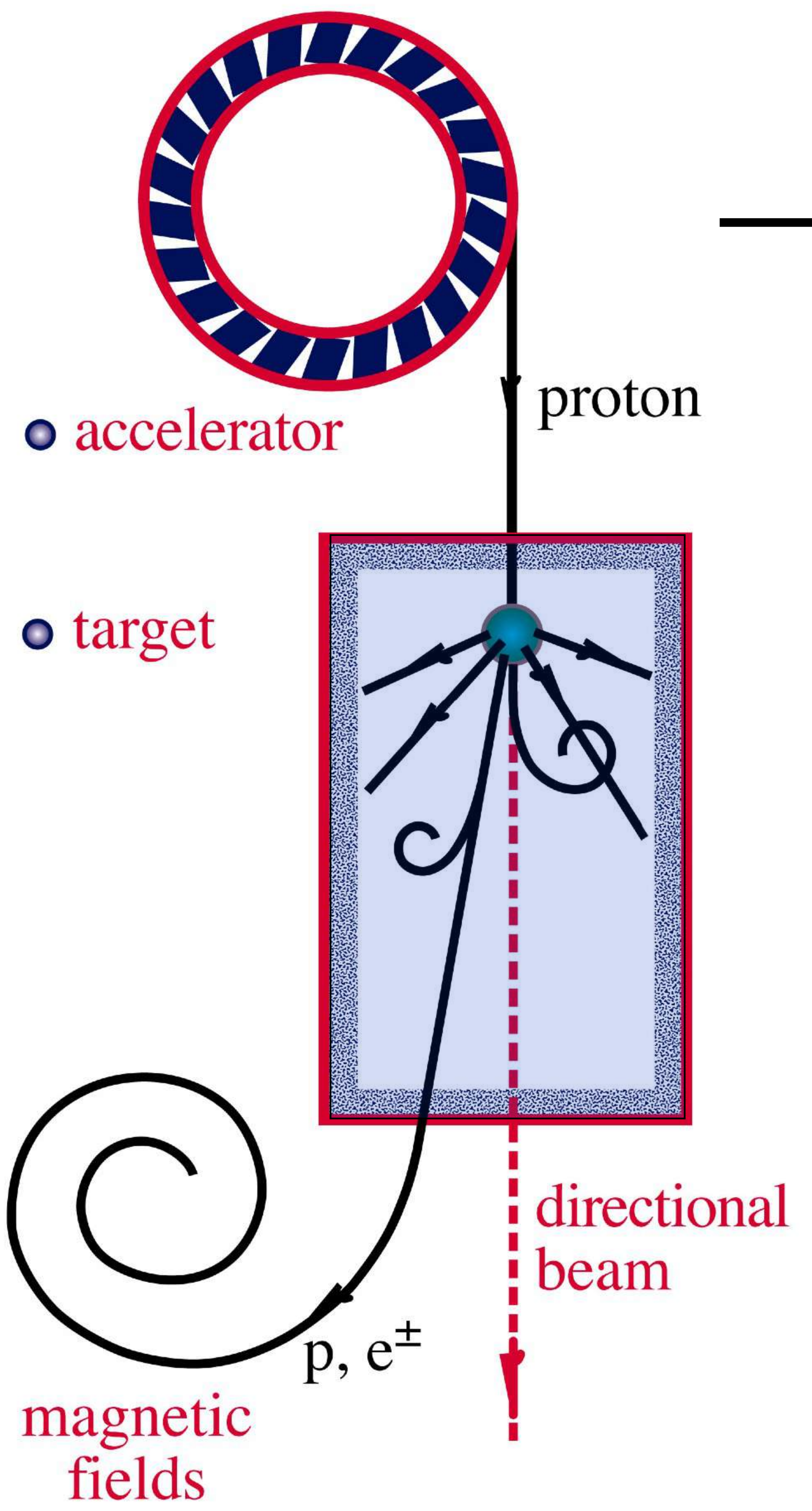


cosmic-ray challenge

both the energy of the particles and the *luminosity* of the accelerators are large

gravitational energy from collapsing stars is converted into particle acceleration?

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

nearby radiation

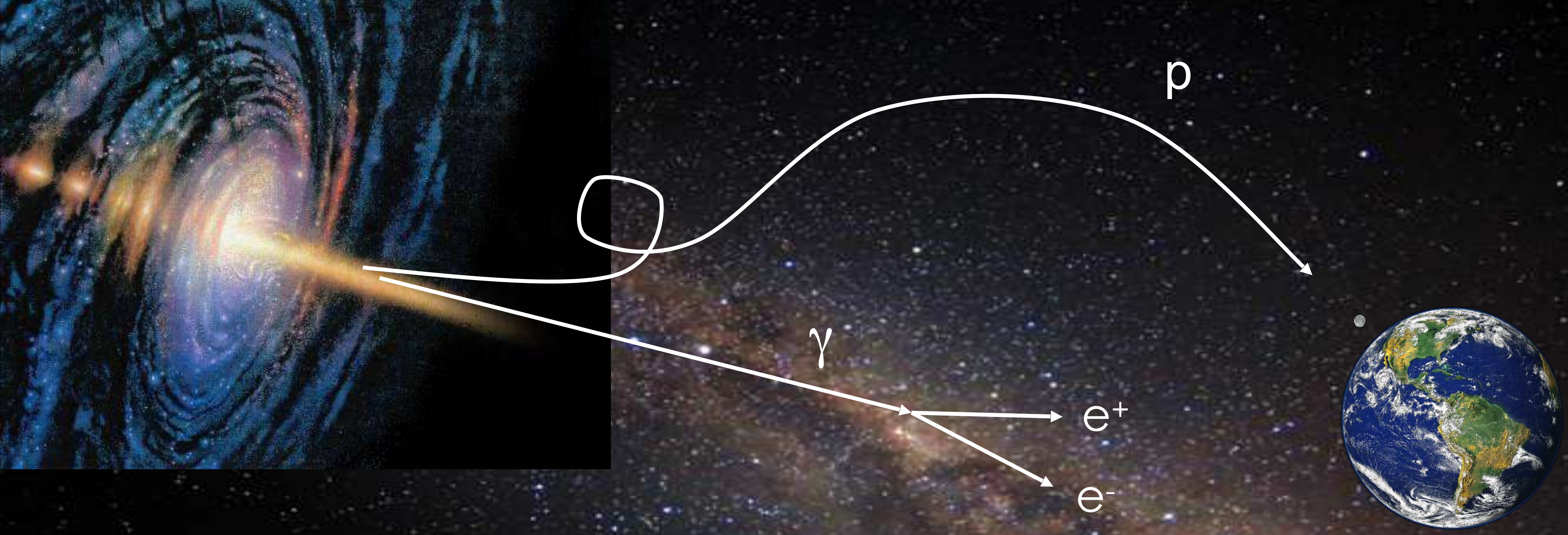
$$p + \gamma \rightarrow n + \pi^+$$

~ cosmic ray + neutrino

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

~ cosmic ray + gamma

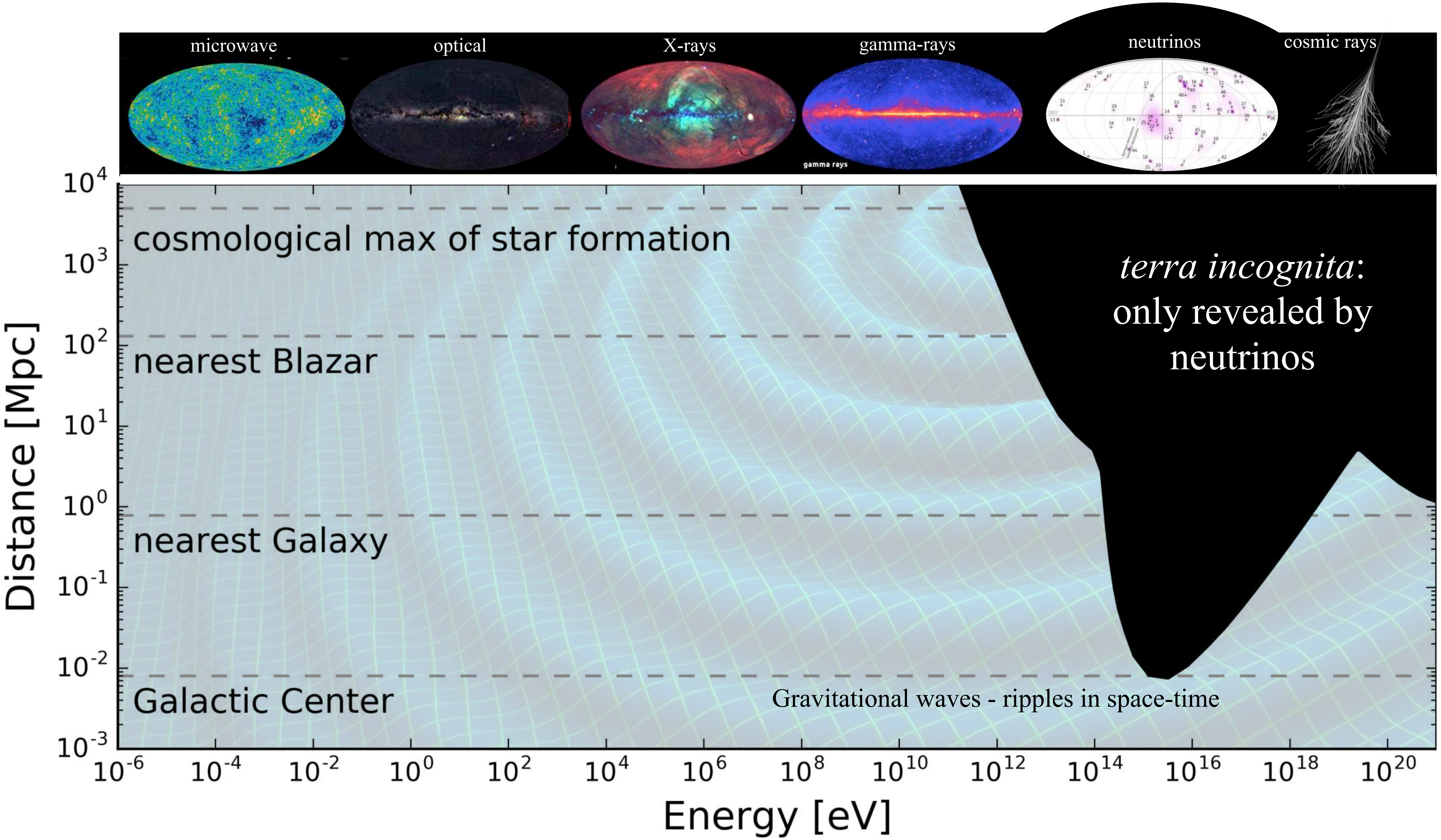
The opaque Universe



$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

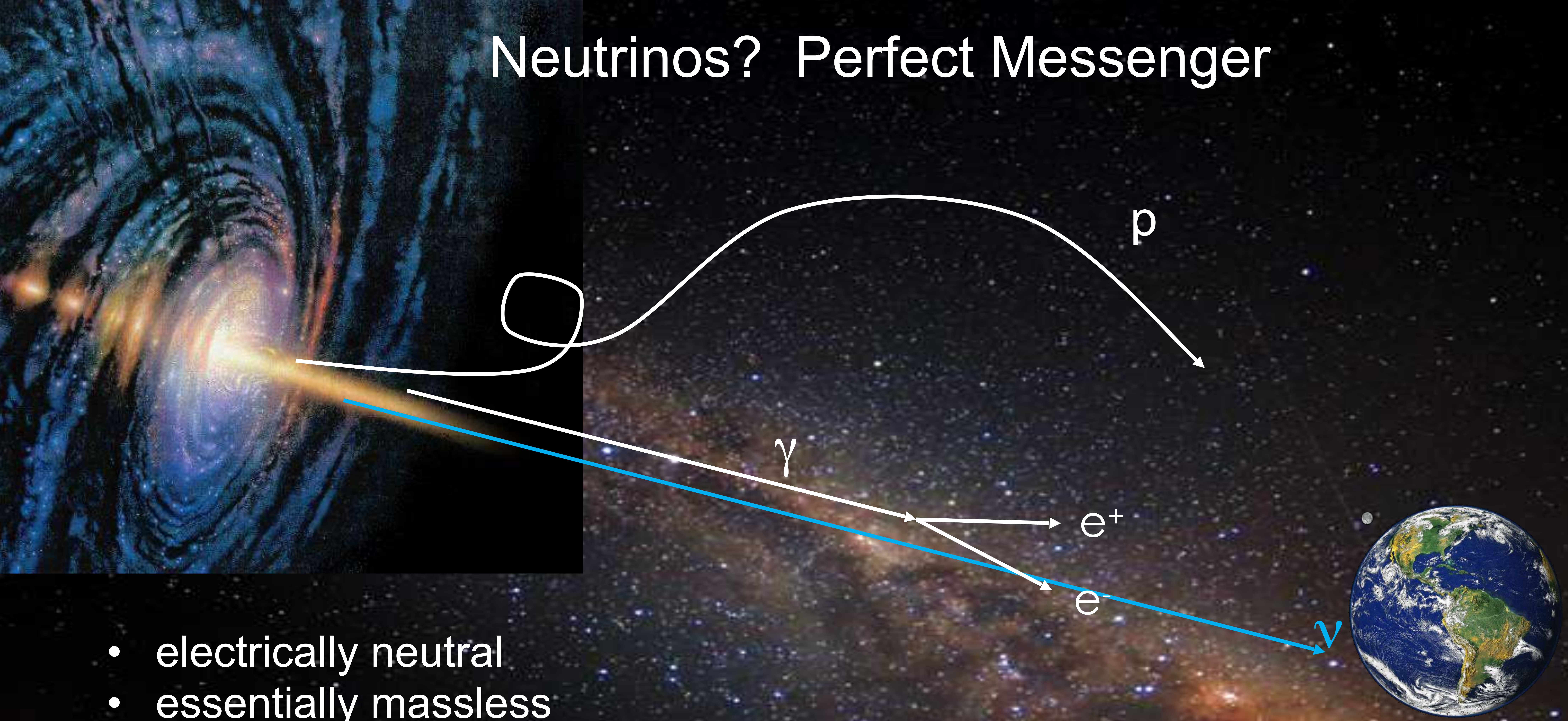
PeV photons interact with microwave photons (411/cm^3)
before reaching our telescopes
enter: neutrinos

highest energy "radiation" from the Universe: neutrinos and cosmic rays



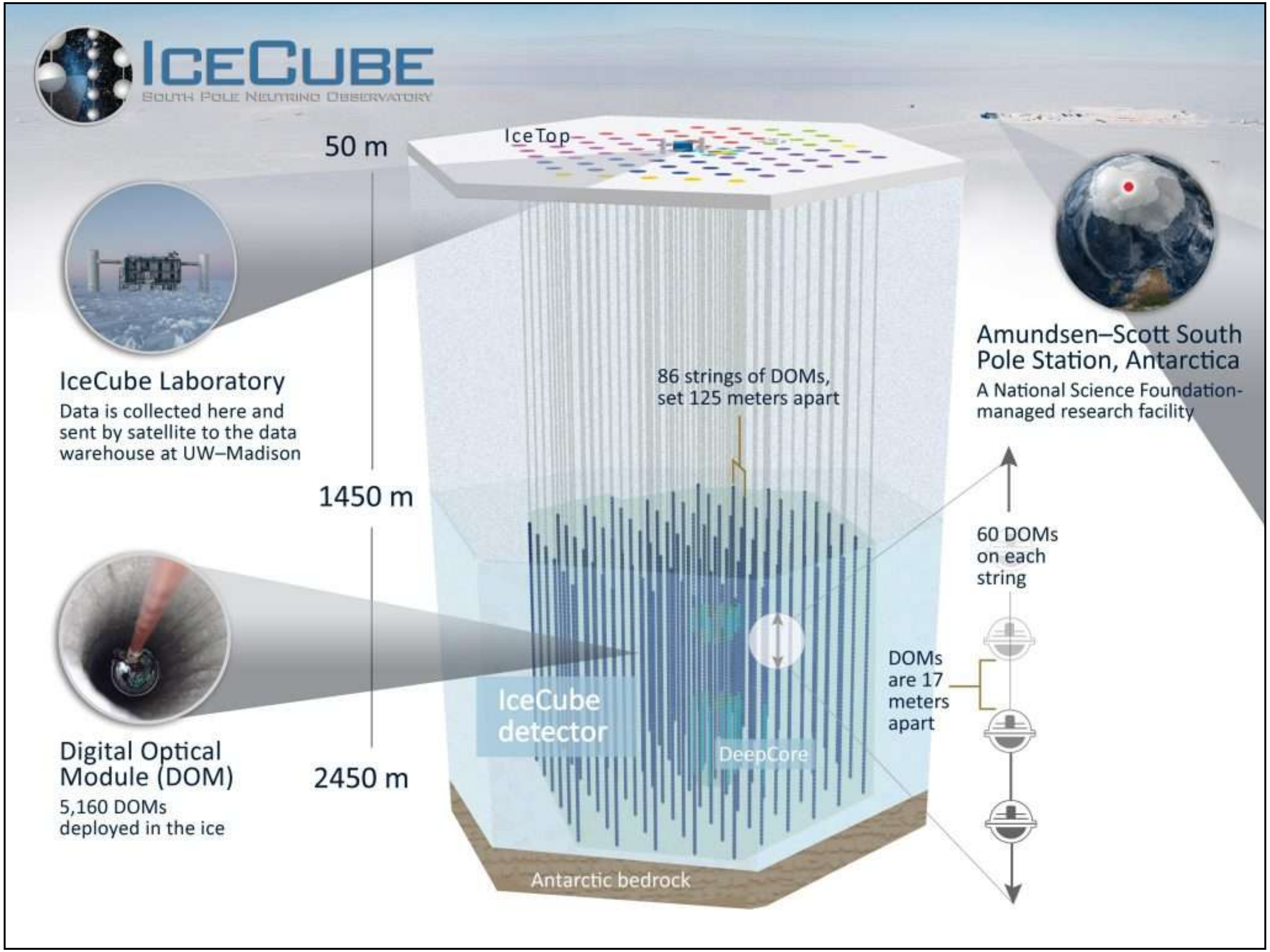
Universe is opaque above ~100 TeV energy

Neutrinos? Perfect Messenger



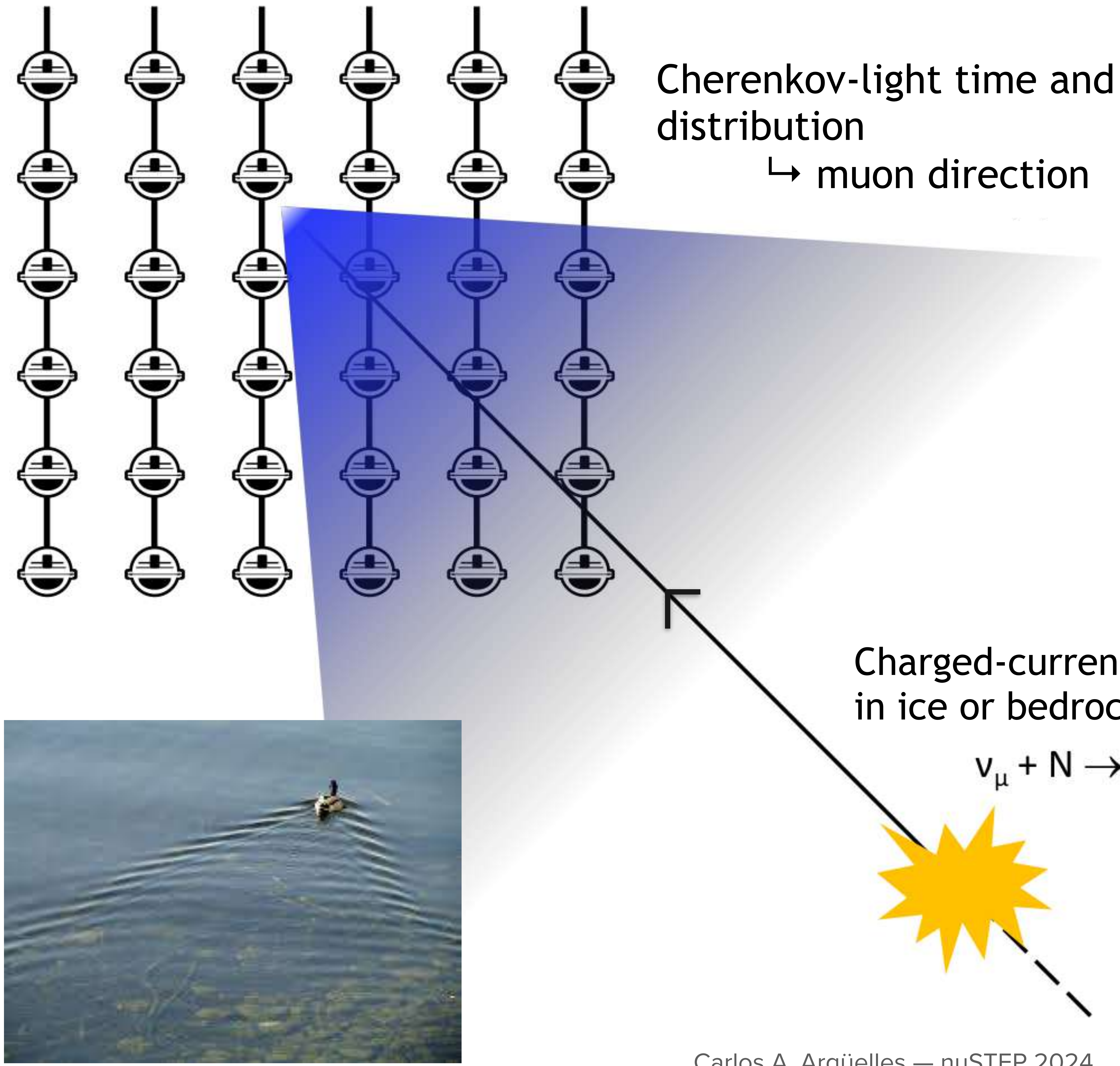
- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but **difficult** to detect



A cubic-kilometer of clear ice instrumented with photo sensors.

~1 Gigaton target mass for neutrinos to interact.



Cherenkov-light time and spatial distribution

↳ muon direction

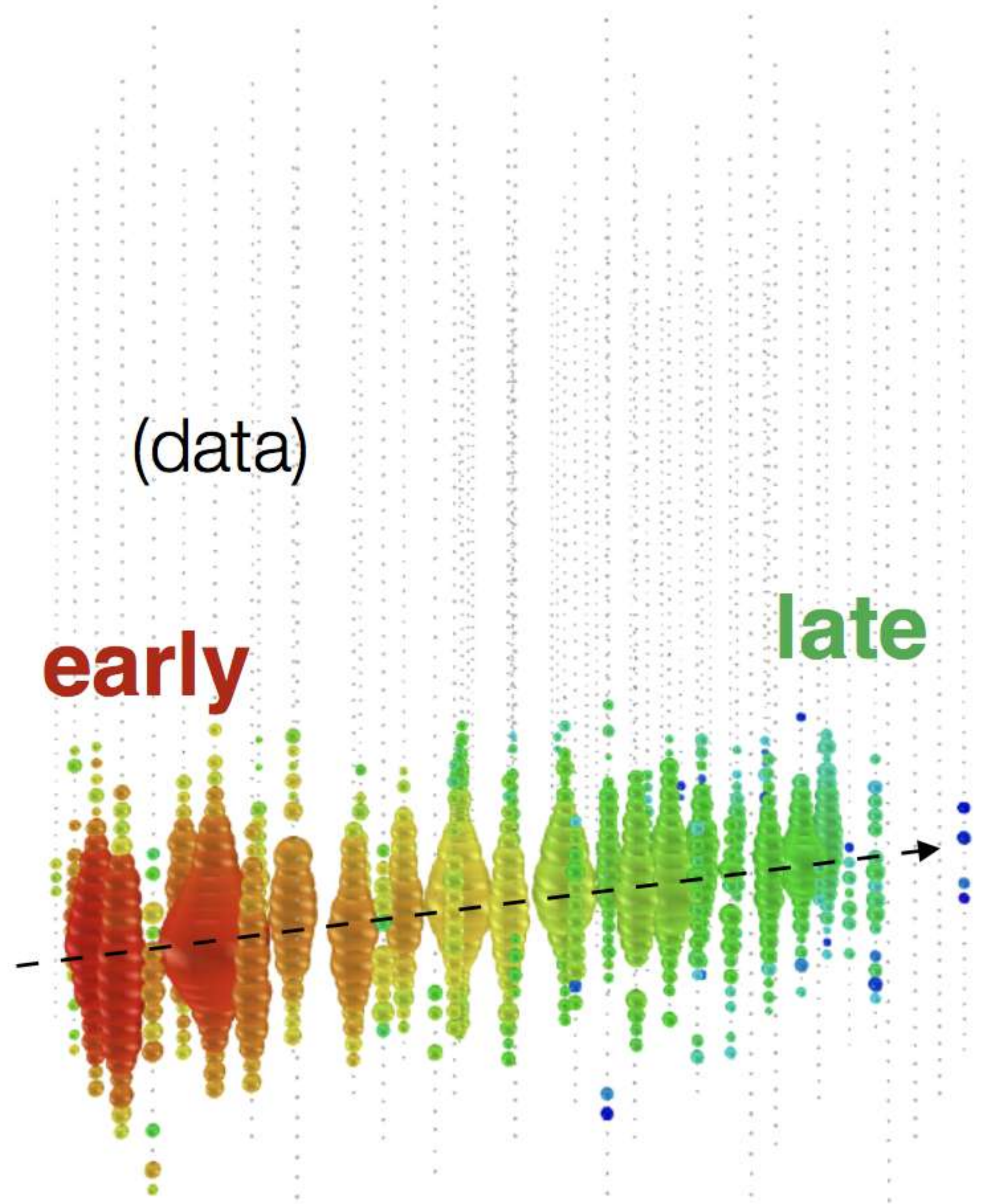
Charged-current interaction in ice or bedrock

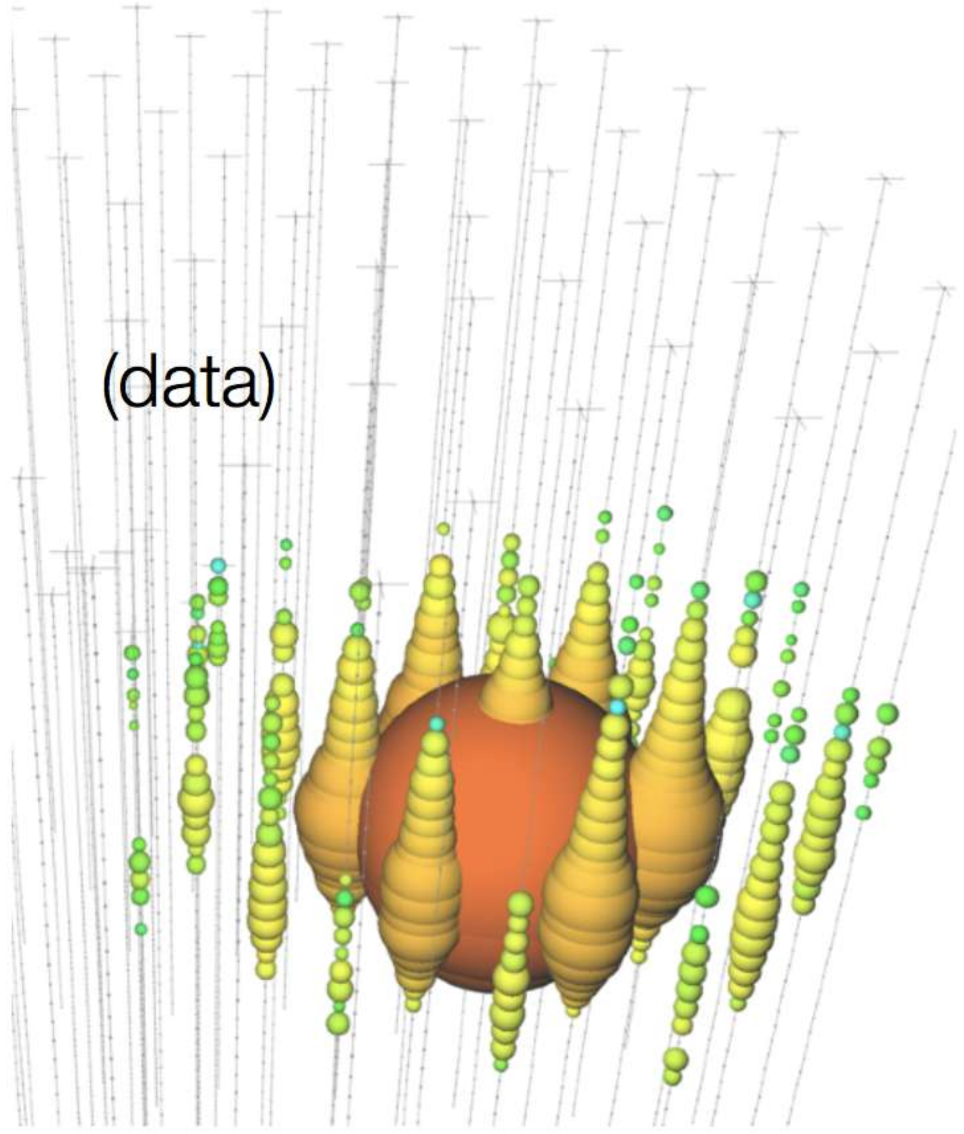
$\nu_\mu + N \rightarrow \mu + X$

Principle detection mechanism of neutrino telescopes is Cherenkov light.

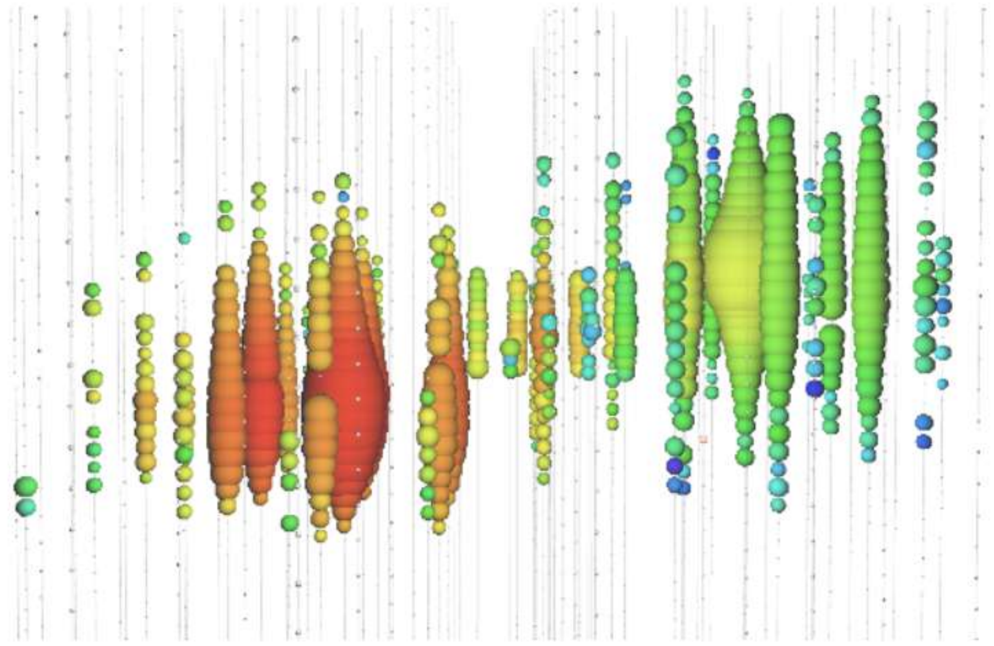
All event morphologies

Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ





(simulation)



Up-going track	Isolated energy deposition (cascade) with no track	Double cascade
Factor of ~ 2 energy resolution < 1 degree angular resolution	15% deposited energy resolution 10 degree angular resolution (above 100 TeV)	(resolvable above ~ 100 TeV deposited energy)

Neutrino telescopes can identify tau neutrinos on an *event by event* basis.

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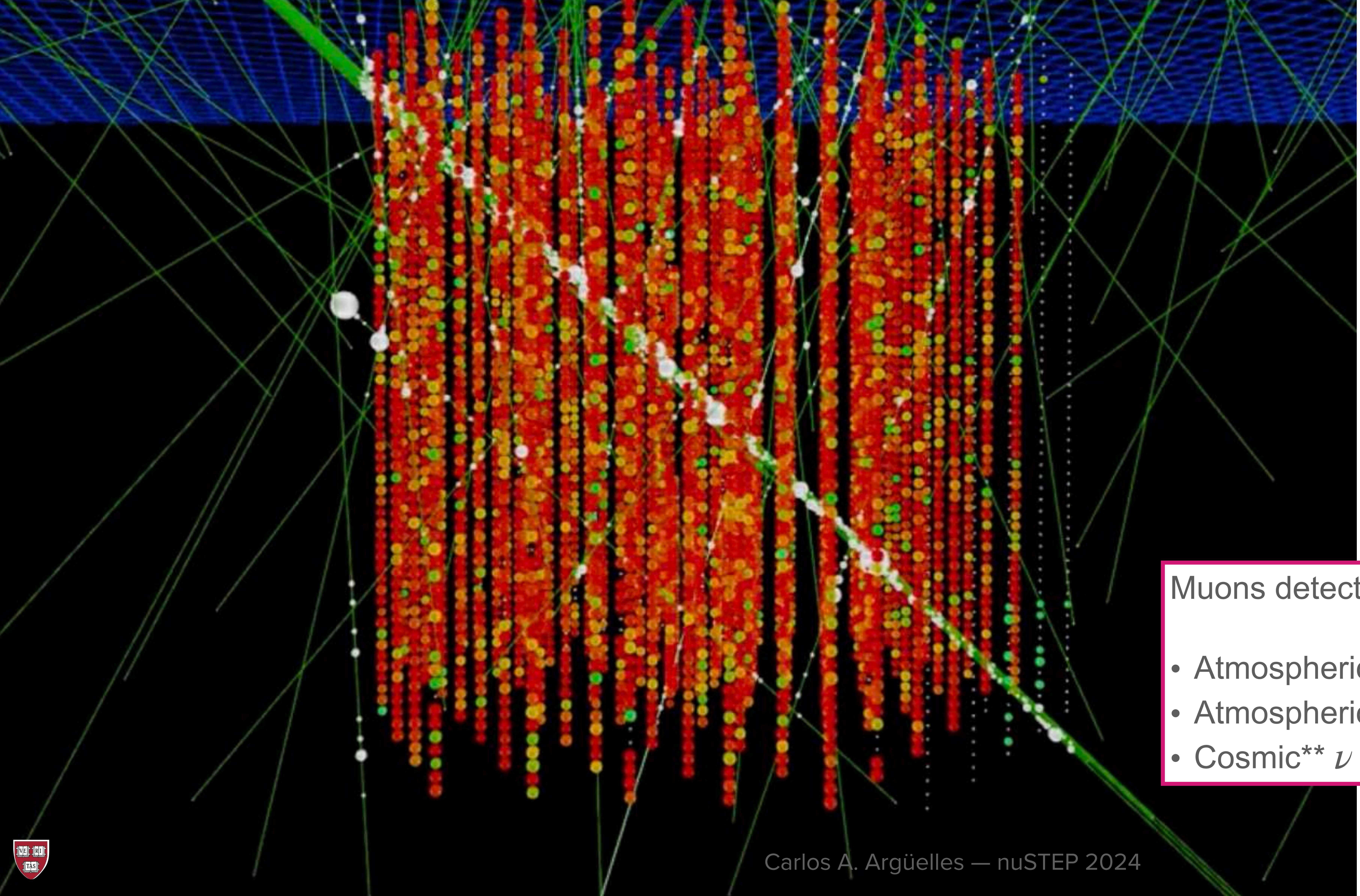
10 msec of IceCube data

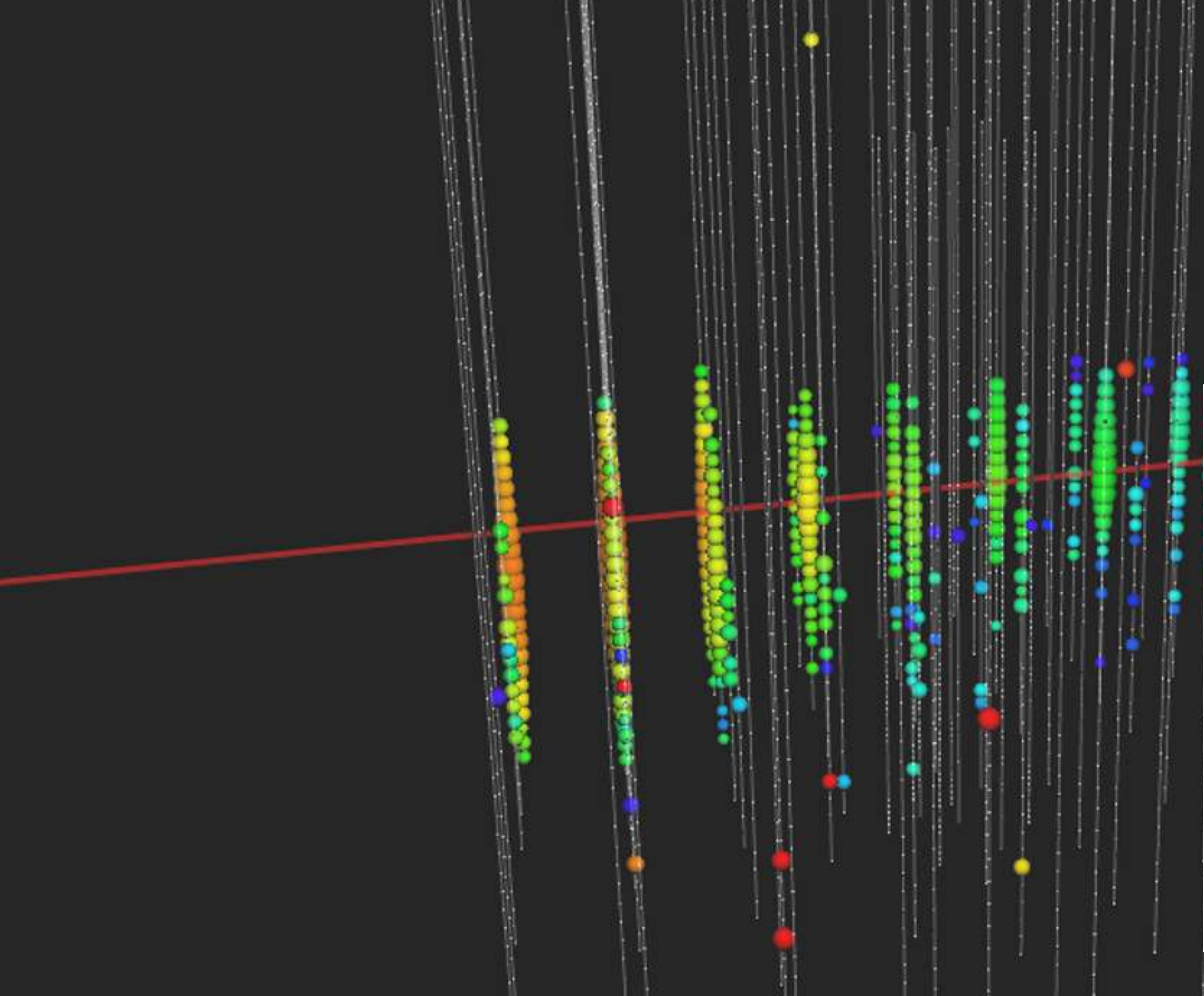


Muons detected per year:

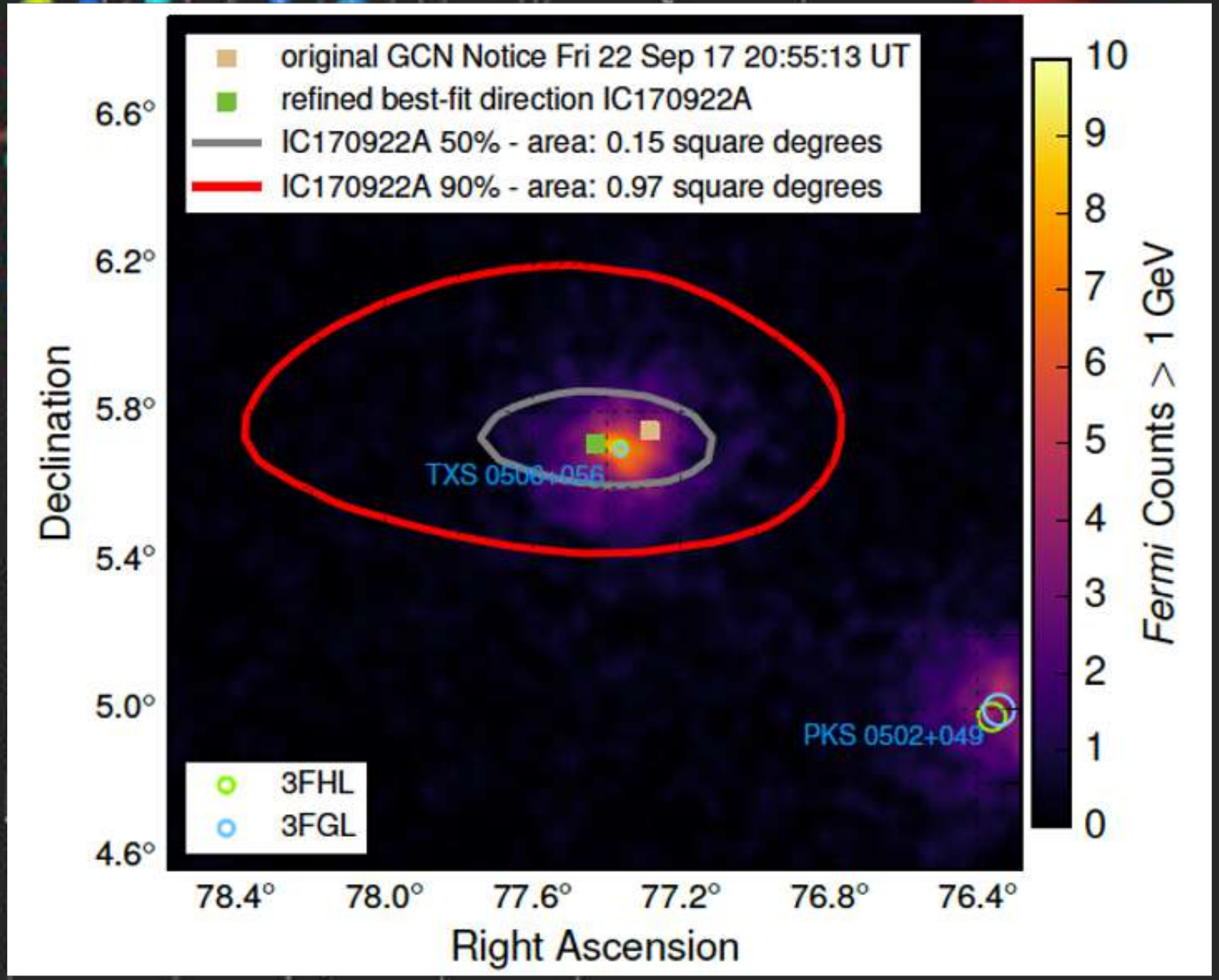
- Atmospheric $\mu \sim 10^{11}$ (3000 per second)
- Atmospheric* $\nu \to \mu \sim 10^5$ (1 every 6 minutes)
- Cosmic** $\nu \to \mu \sim 10^2$


IceCube 170922

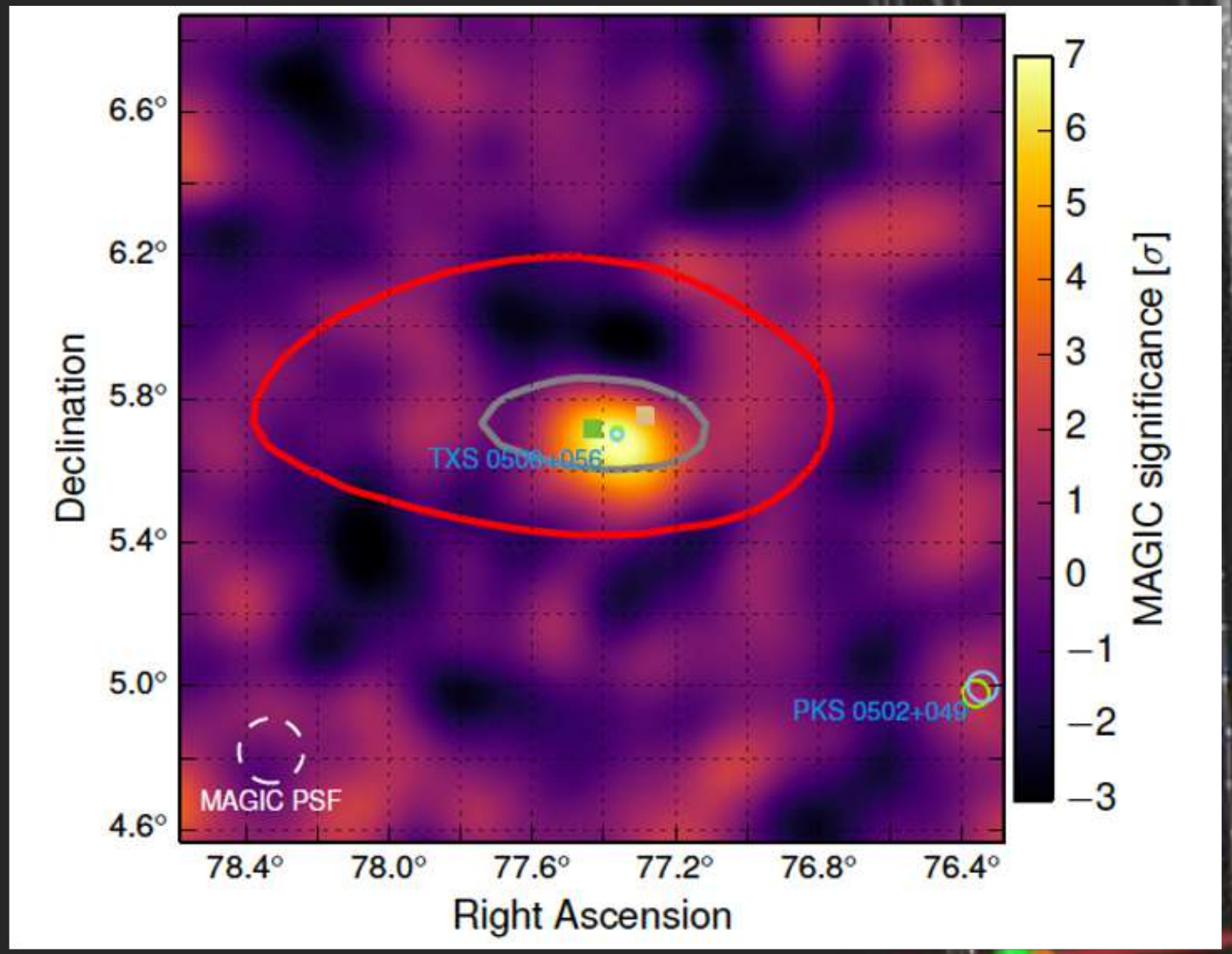
IceCube 170922



Fermi detects a flaring blazar within 0.1°

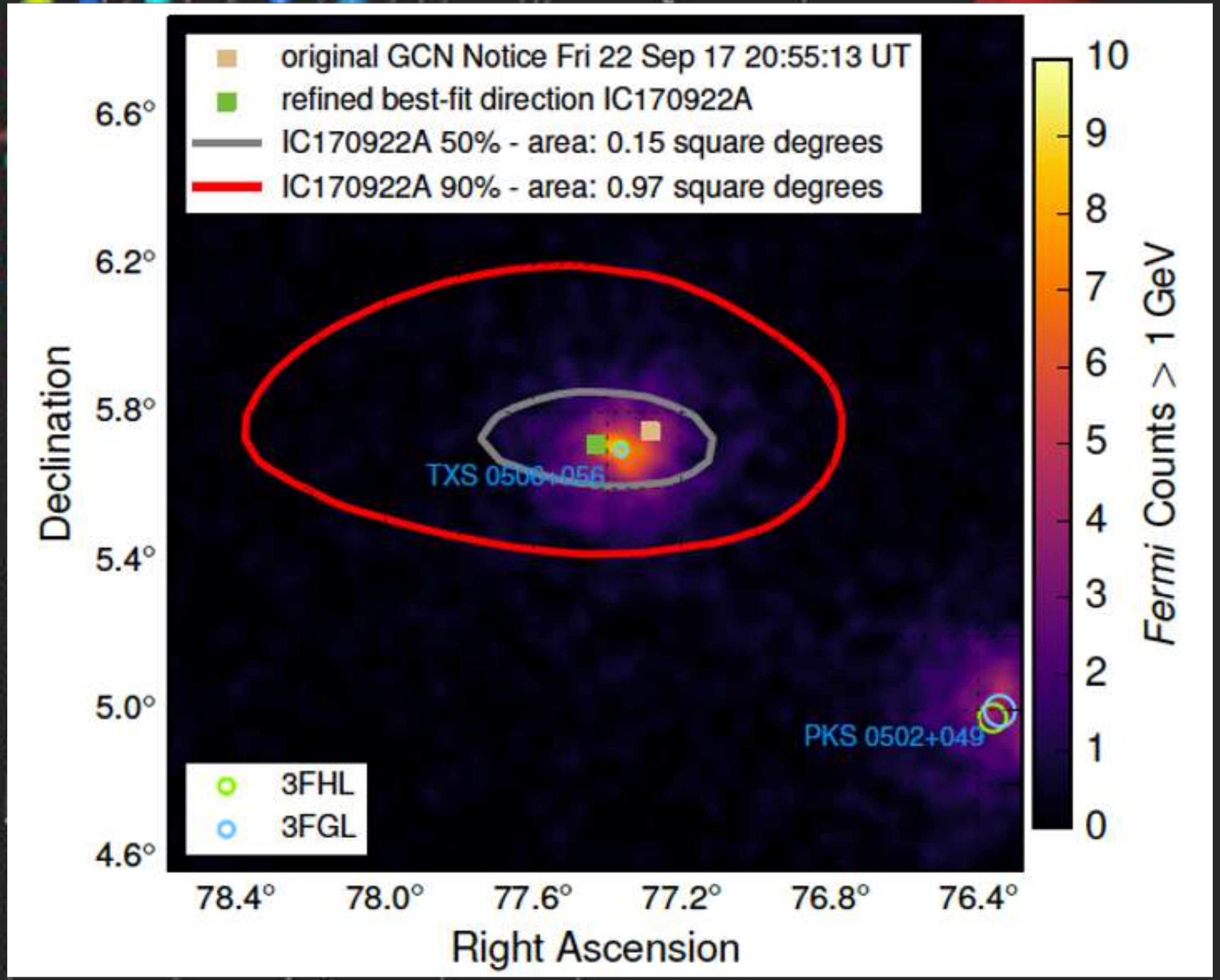


IceCube 170922



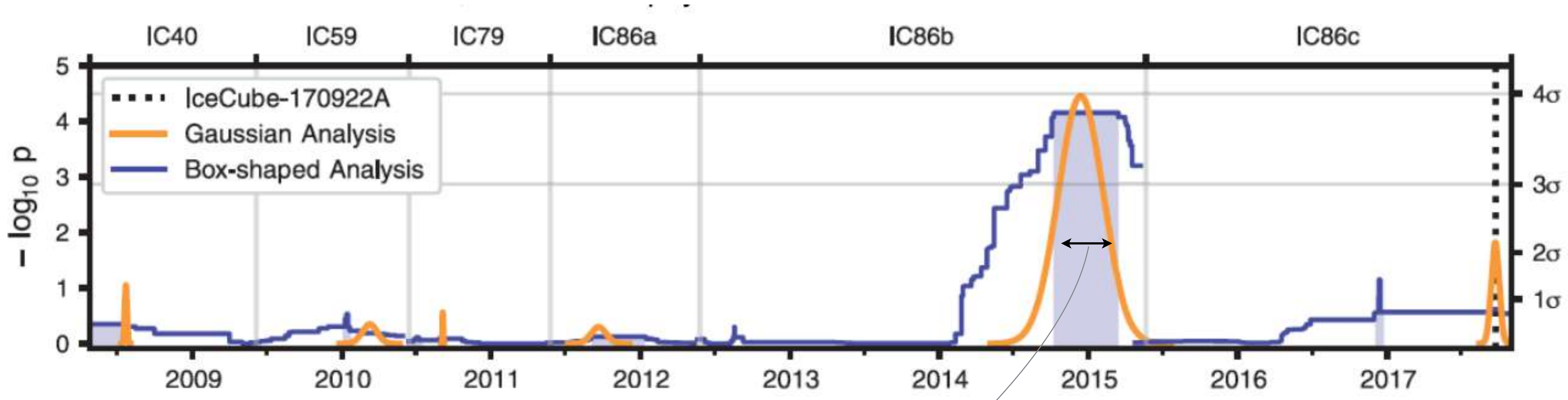
MAGIC
detects emission of
> 100 GeV gammas

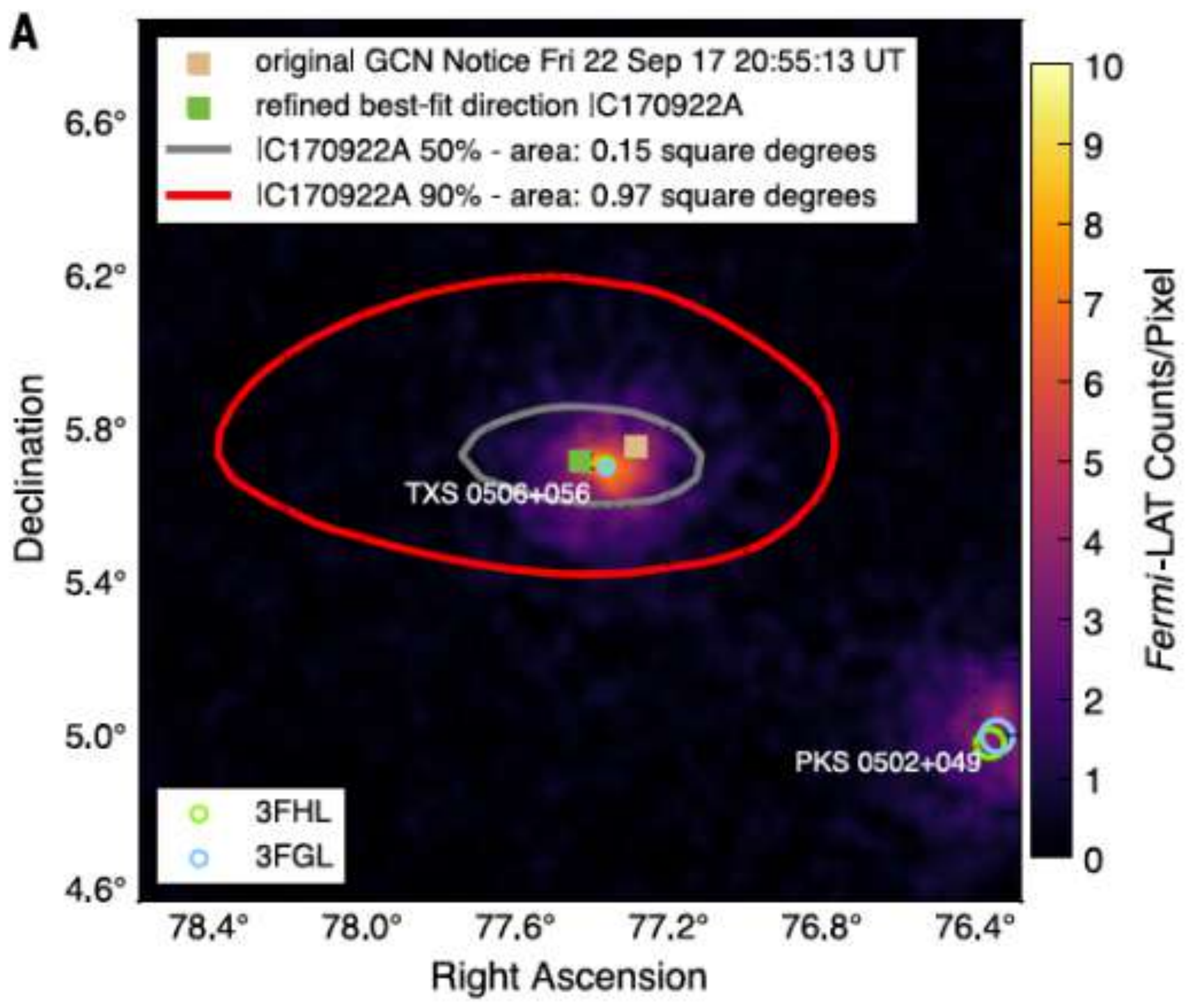
Fermi
detects a flaring
blazar within 0.1°



Follow-up detections of IC170922 based on public telegrams

Looking at the archival data in the TXS 0506+056 direction





$$T_W = 110^{+35}_{-24} \text{ days}$$

$$\Phi_{100} = \left(1.6^{+0.7}_{-0.6}\right) \times 10^{-15} \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$$

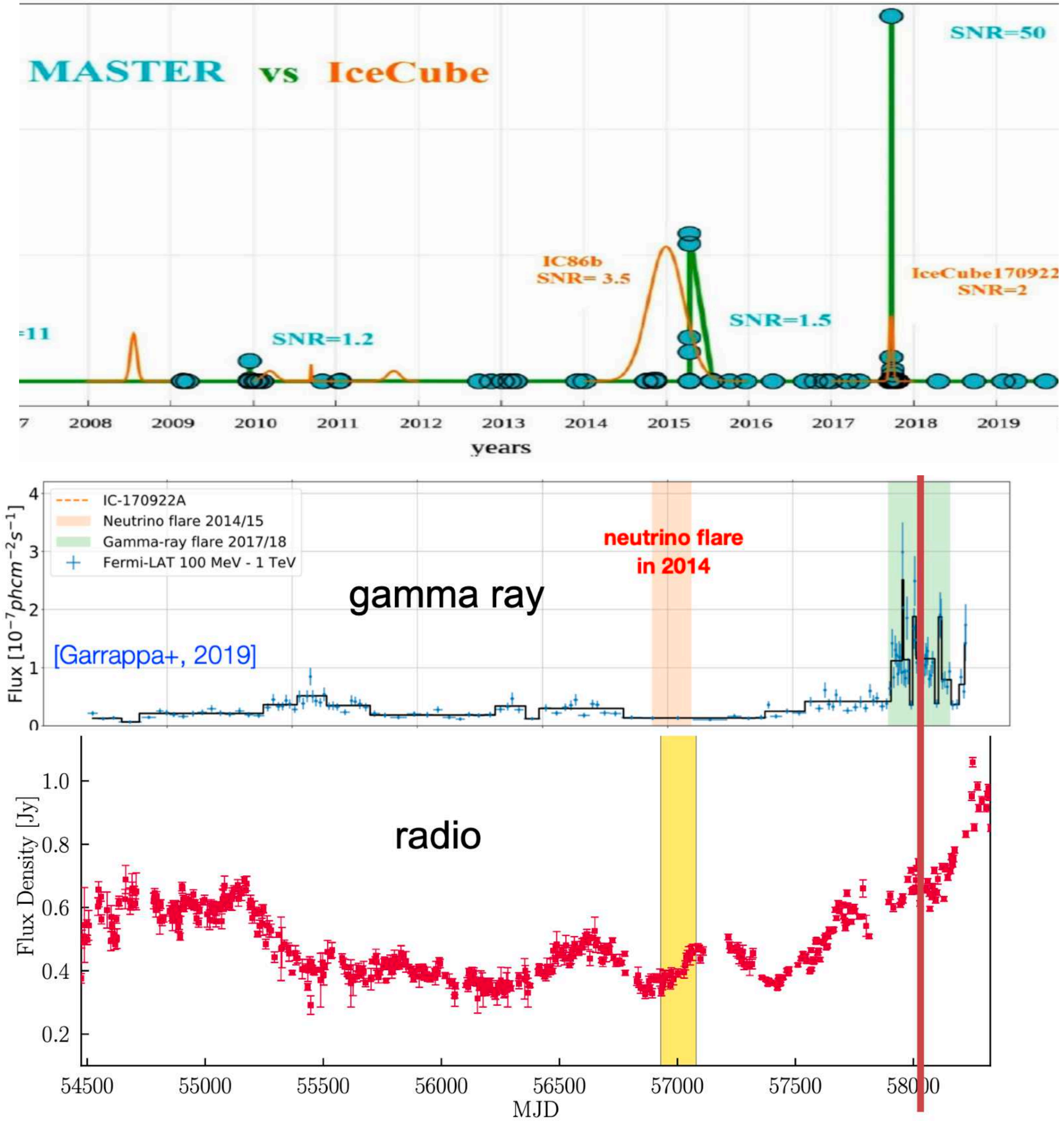
13±5 signal events rejecting background hypothesis at 3.5σ

No significant gamma-ray emission at flaring time!

E. Kun, I. Bartos, J. B. Tjus et al 2009.09792

2014 Neutrino Flare From TXS 0506+056

- Enhancement is seen around IC170922A in gamma-rays and radio, and a drop in optical.
- Neutrino flare in 2014-2015 is correlated with enhancement in radio and drop in optical flux, but *no change in gamma-rays.*



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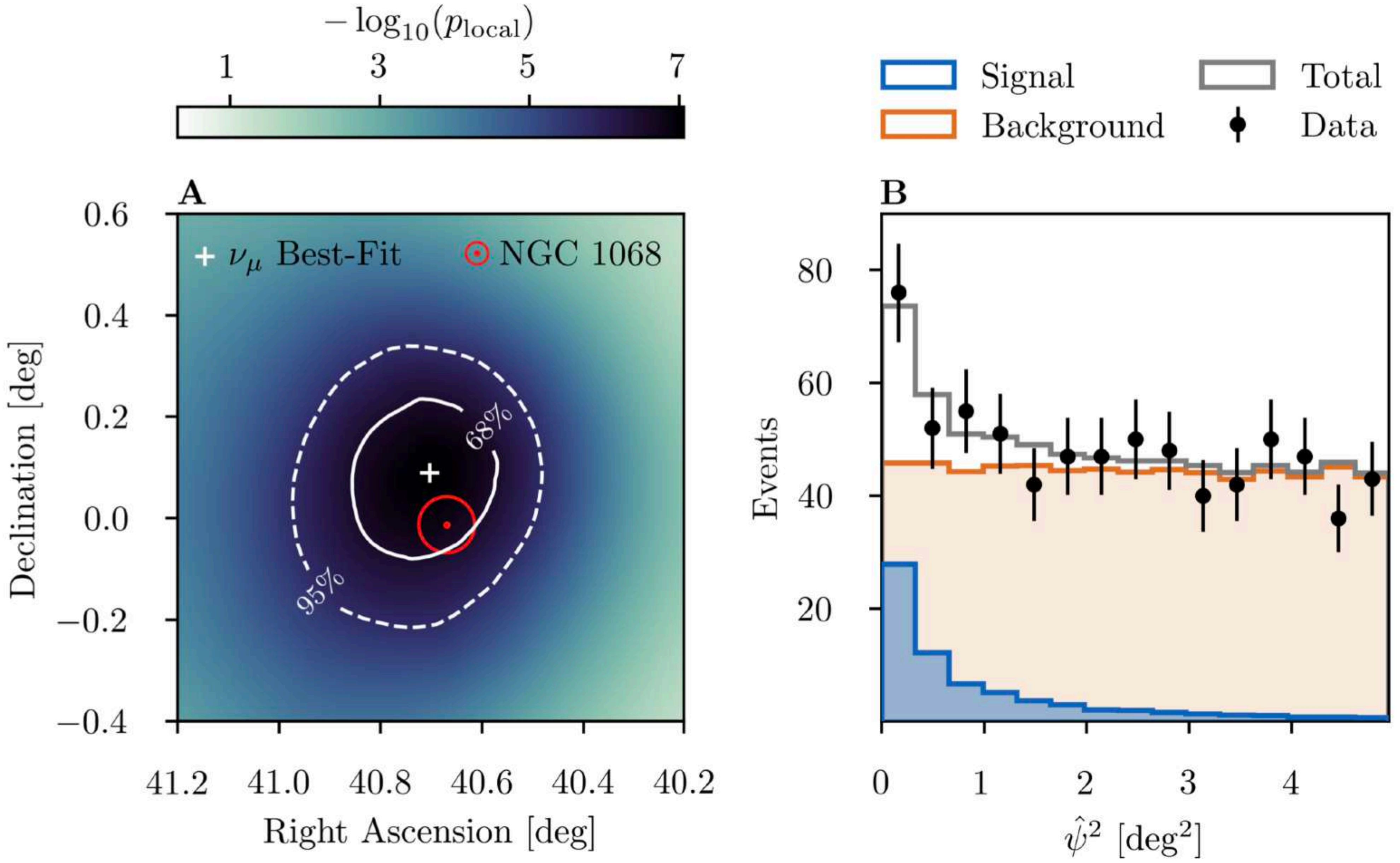
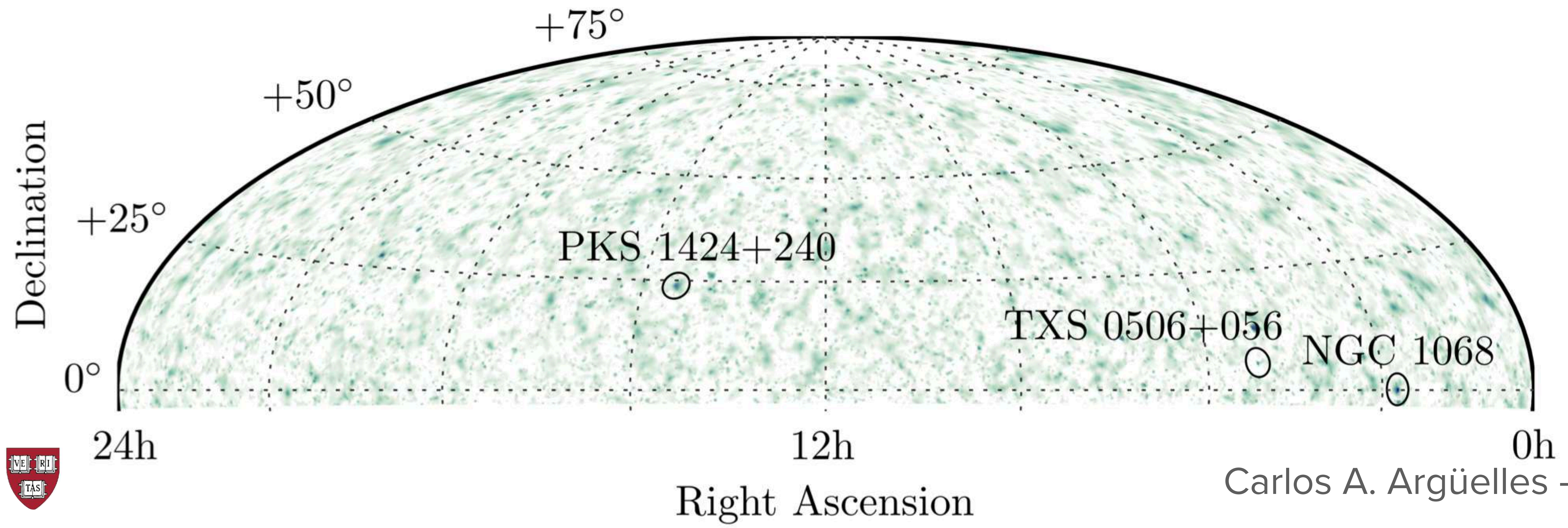
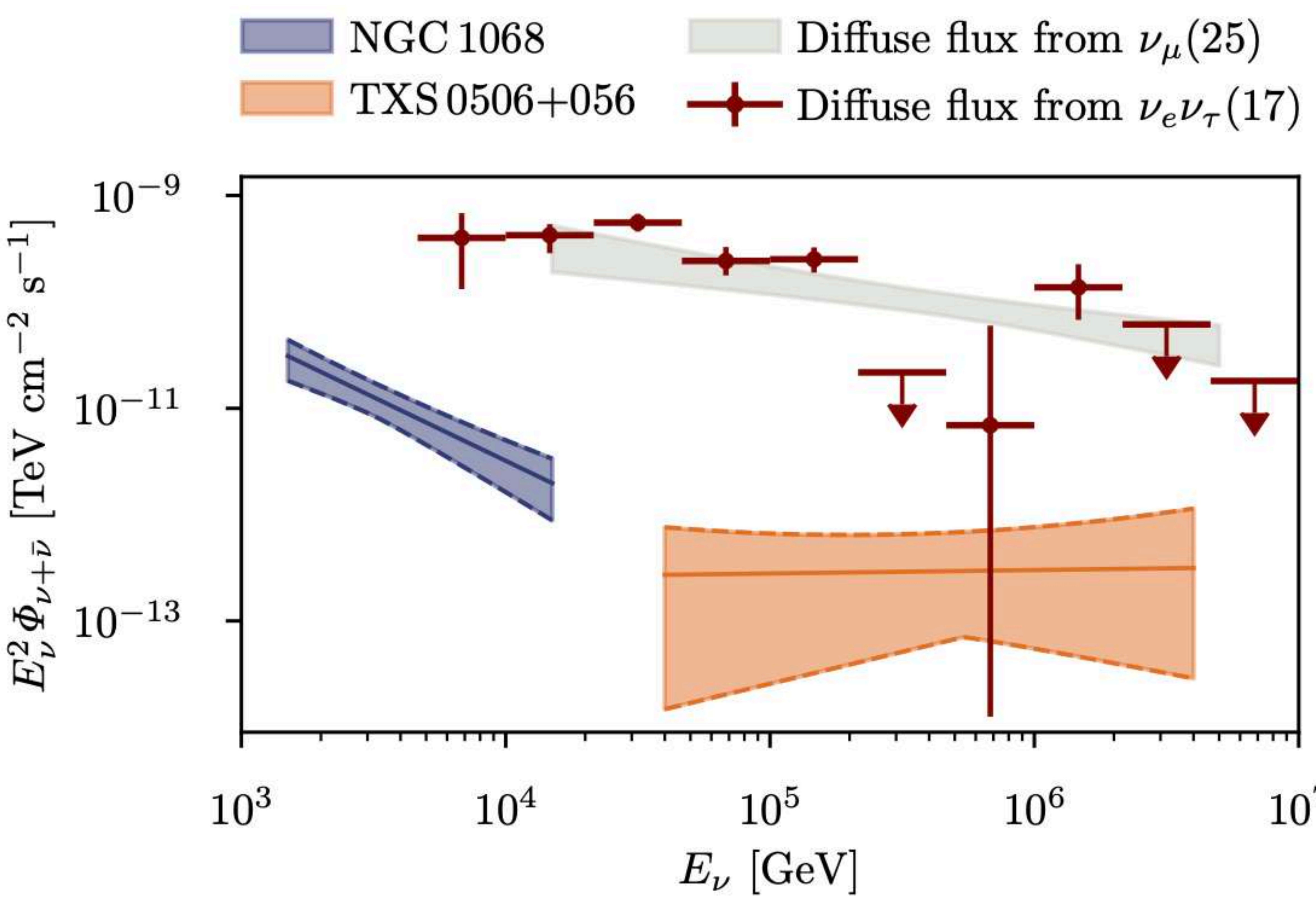
RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068



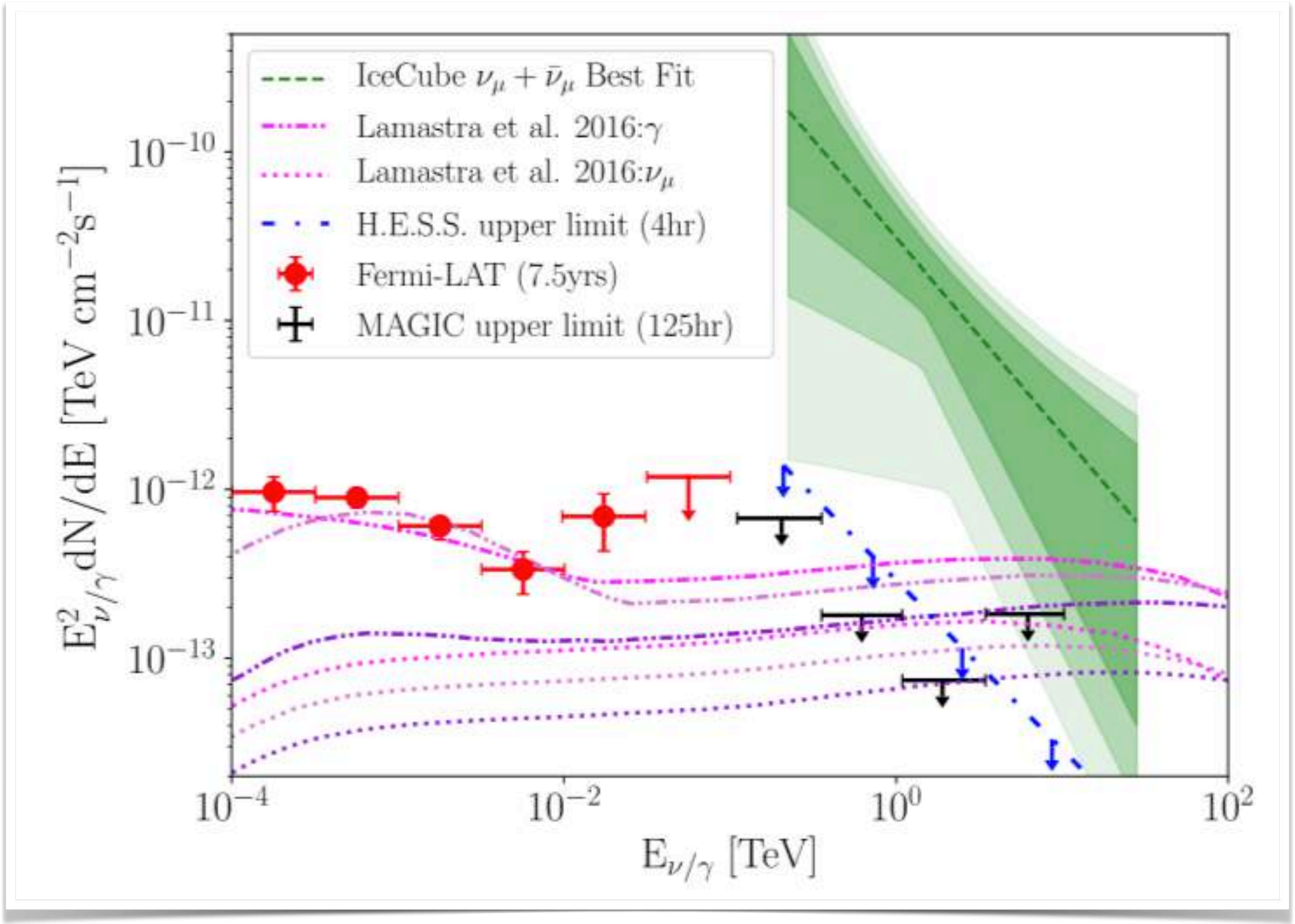




Gamma-ray's and Neutrinos From NGC 1068

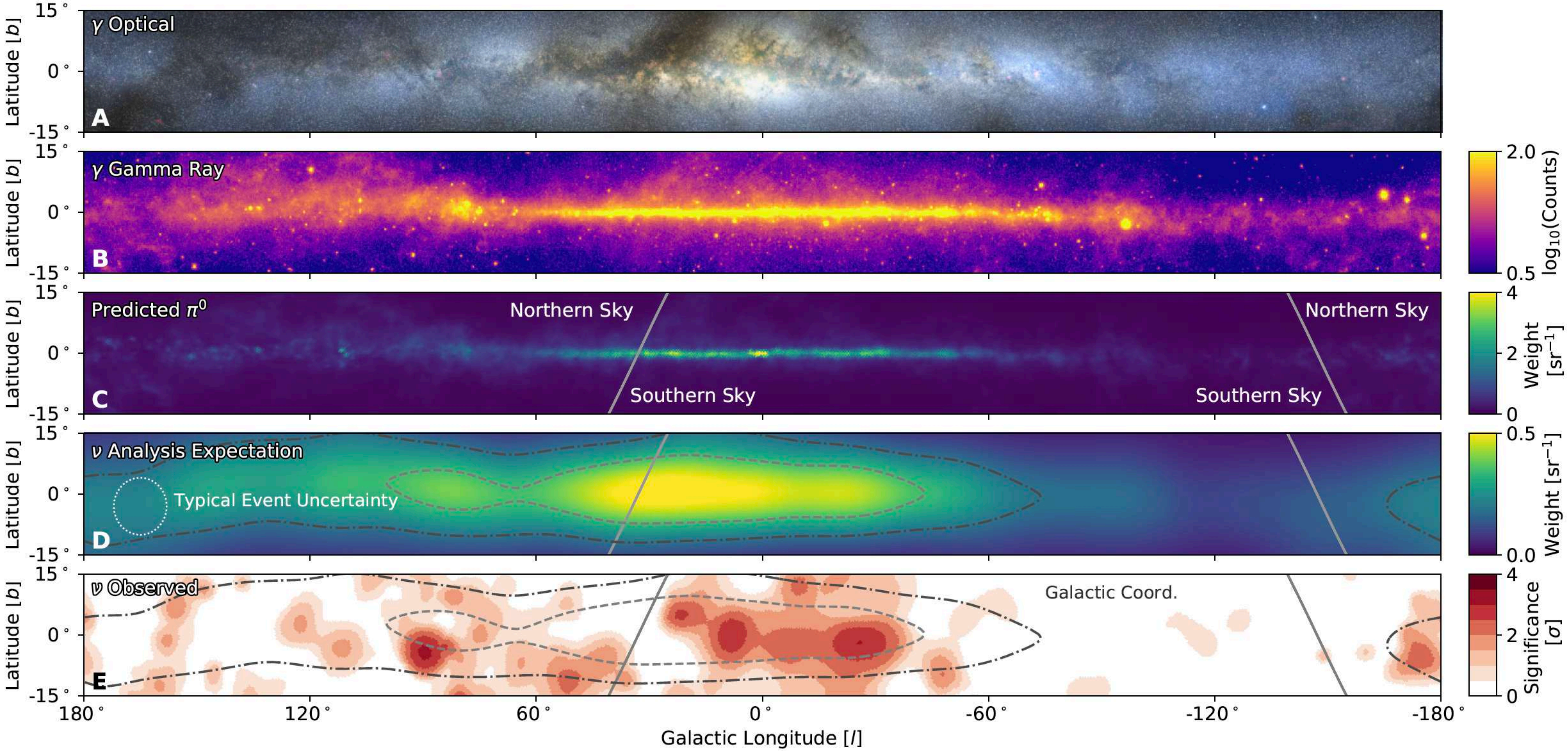
$$\tau_{\gamma\gamma} \propto \frac{\sigma_{\gamma\gamma}}{\sigma_{p\gamma}} \tau_{p\gamma}$$

the gamma rays that accompany the neutrinos lose energy in the source



Neutrinos from Our Galaxy

IceCube Collaboration, Science, 2023



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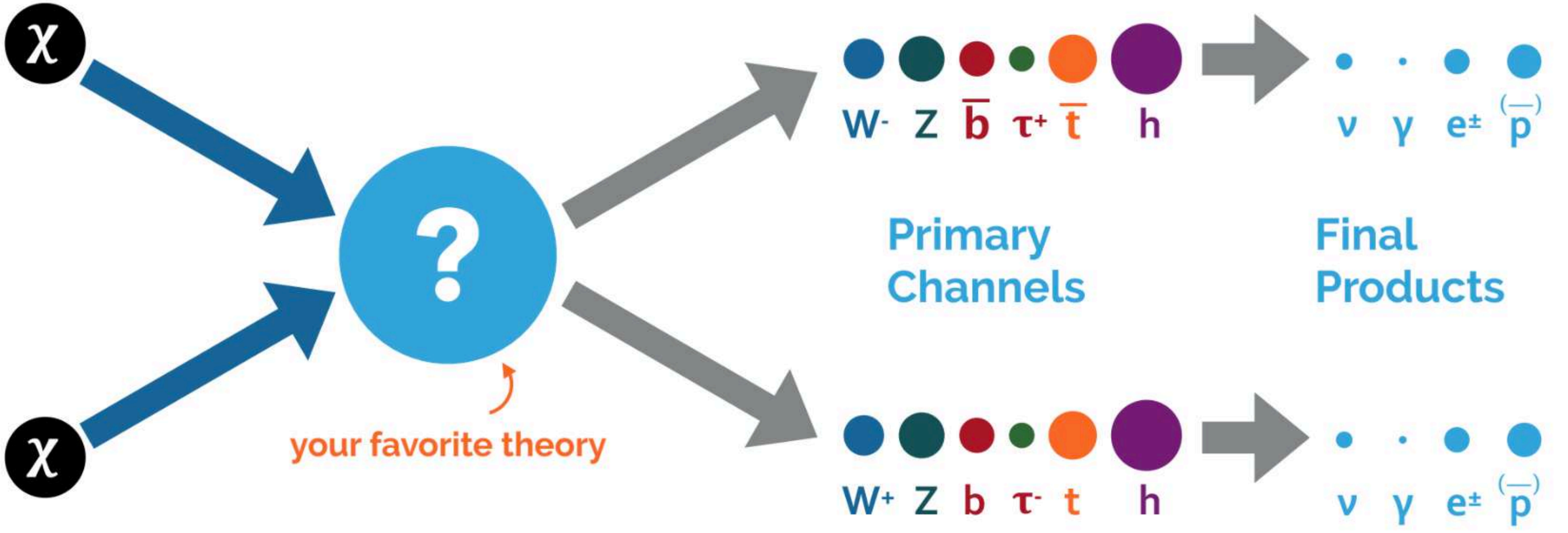
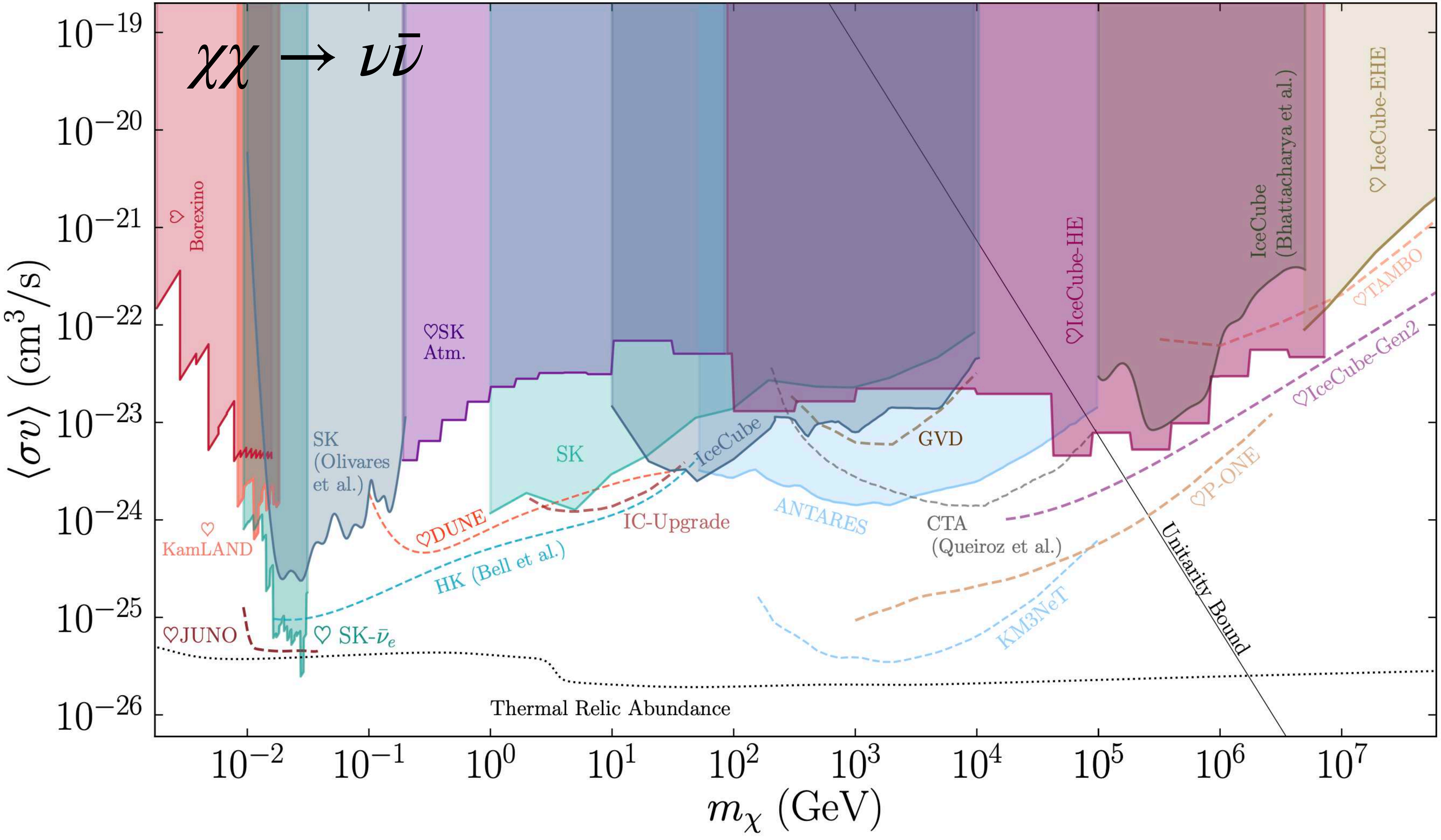
Dark matter annihilation



IceCube Collaboration 2205.12950.
See also CA, H. Dujmovic arXiv 1907.11193, Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

Dark matter annihilation to neutrino: a largely unexplored frontier

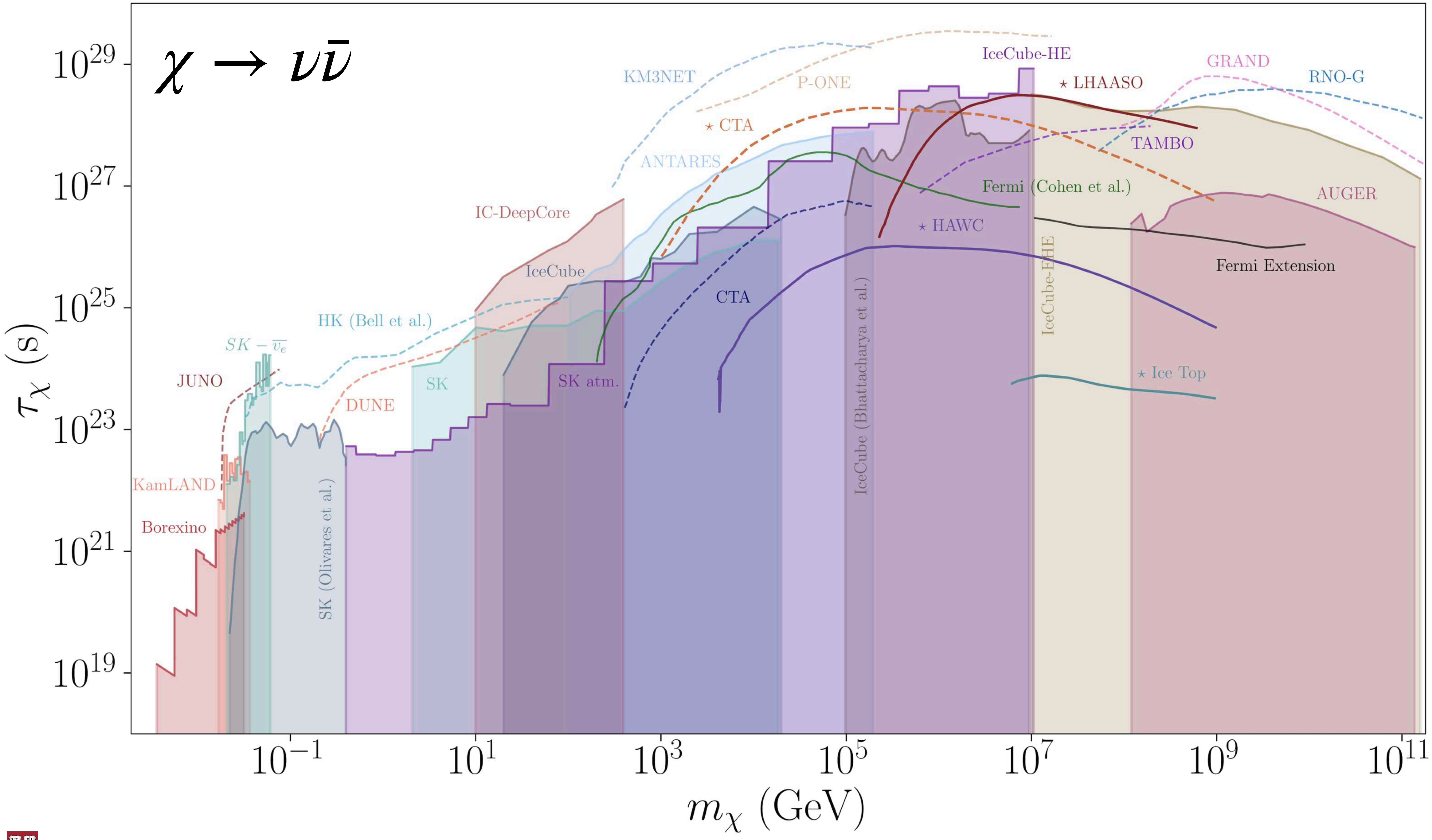


CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;

See also Beacom et al. *PRL 99: 231301, 2007*.

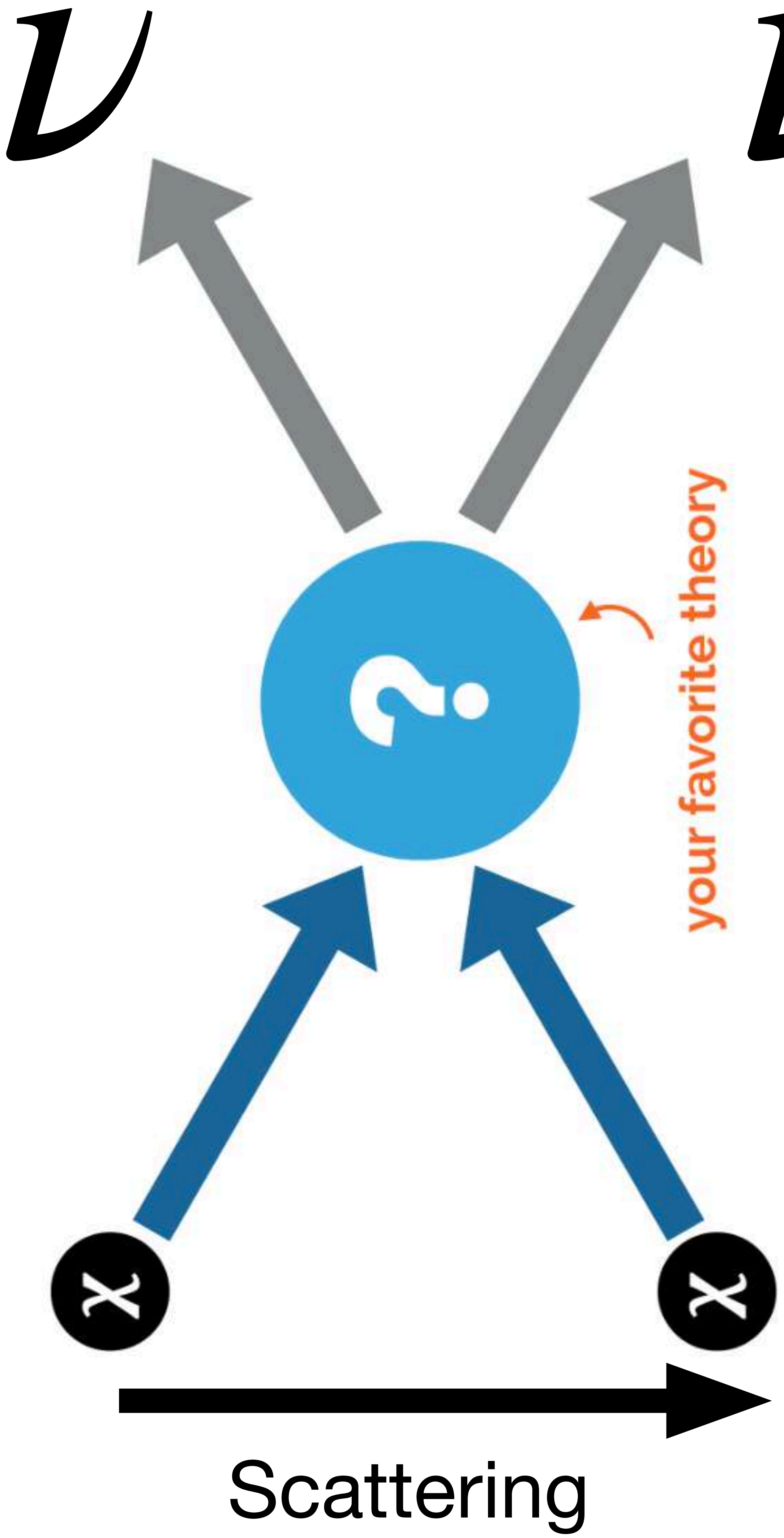
See also CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White (arXiv:2210.01303) for a recent review focused on dark matter decay

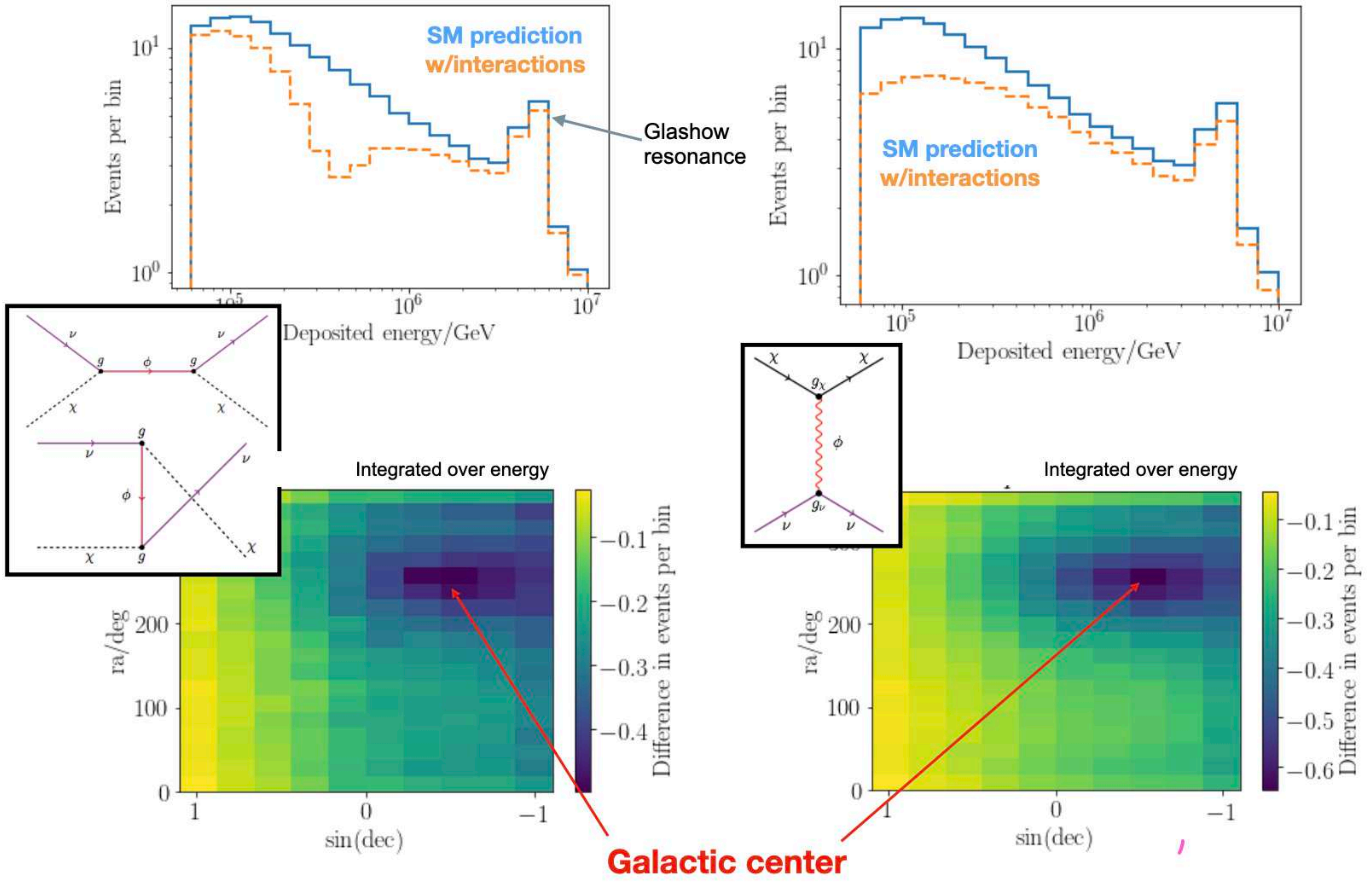
And many more measurements ...



CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White arXiv:2210.01303

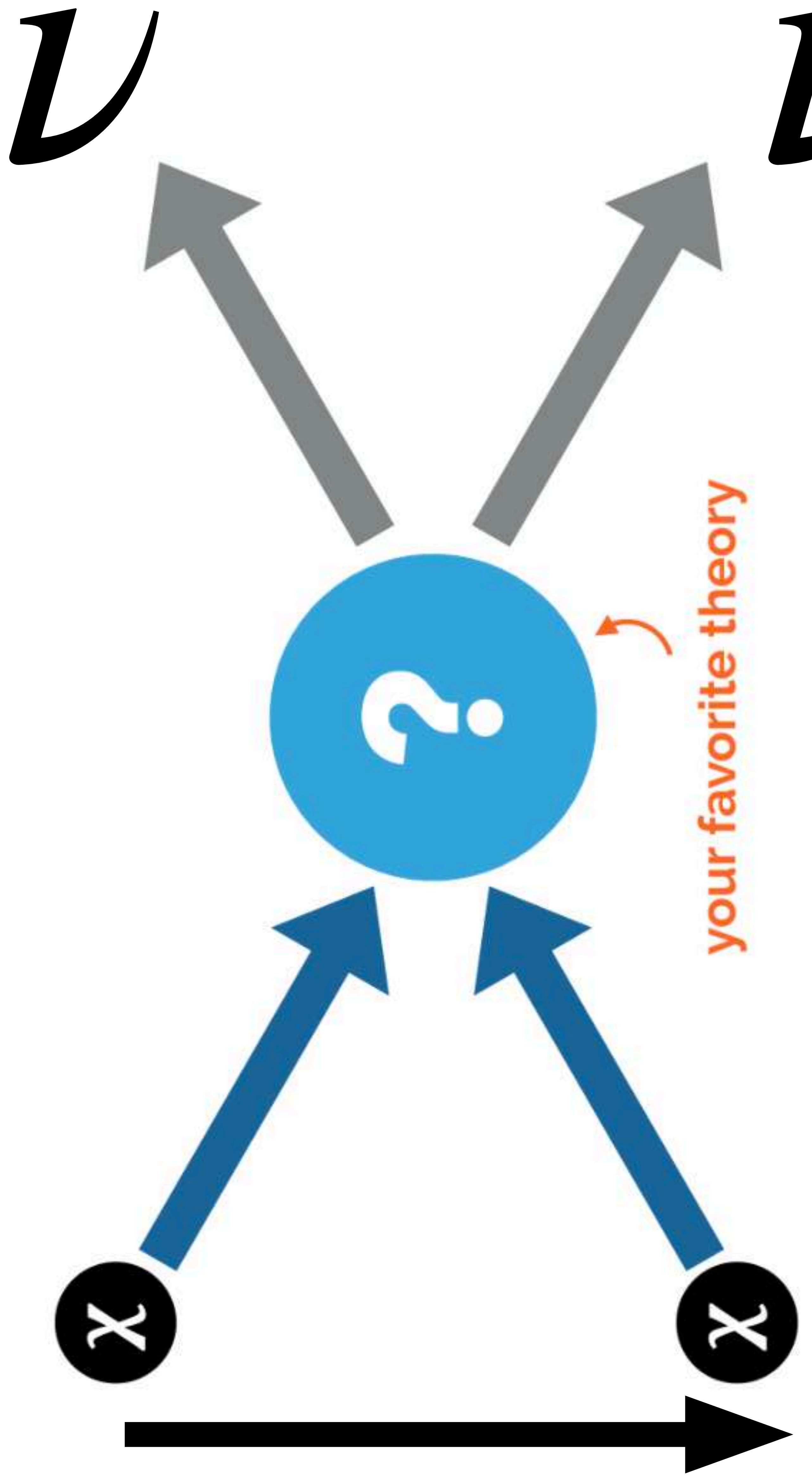
Dark matter scattering with neutrinos



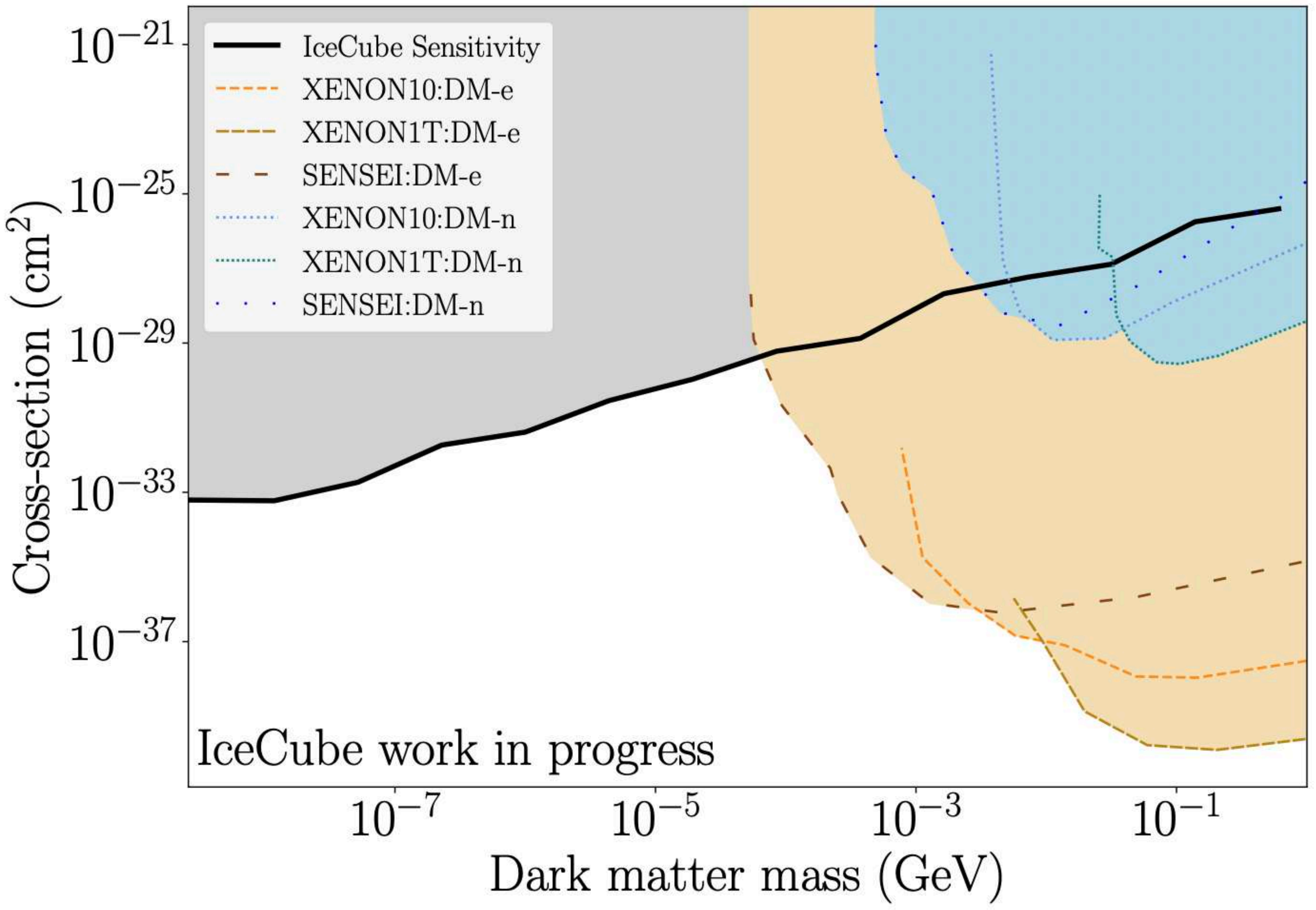


Constrainst comparable to cosmology

Dark matter scattering with neutrinos



Scattering



Constrainst comparable to cosmology

What is the nature of neutrino mass?

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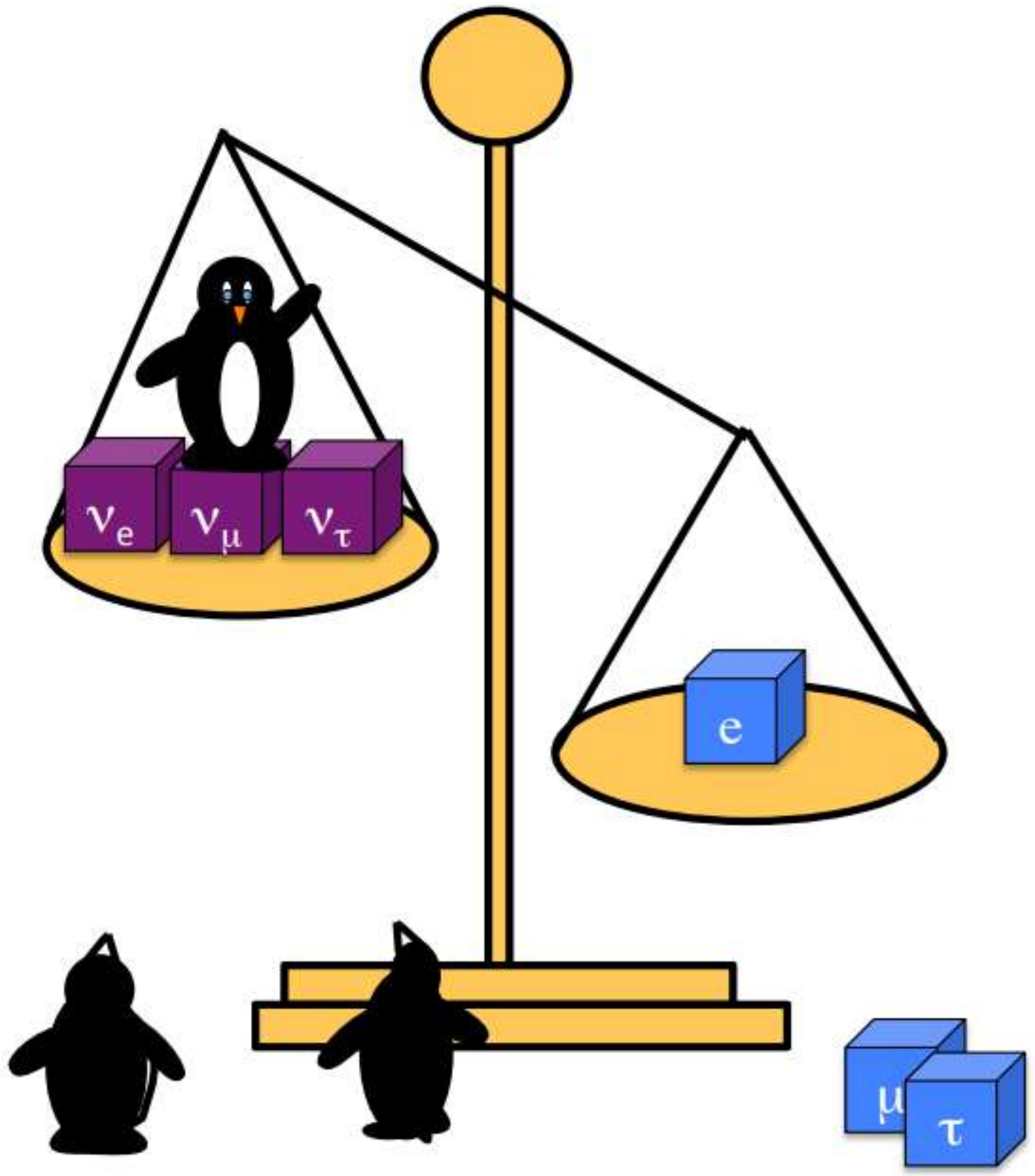
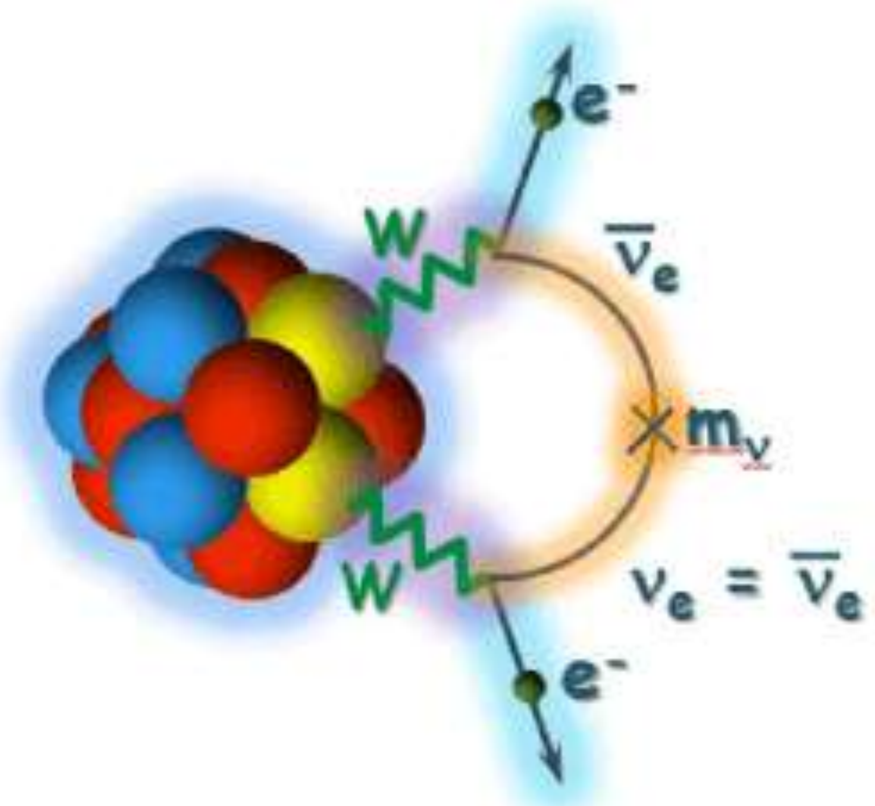
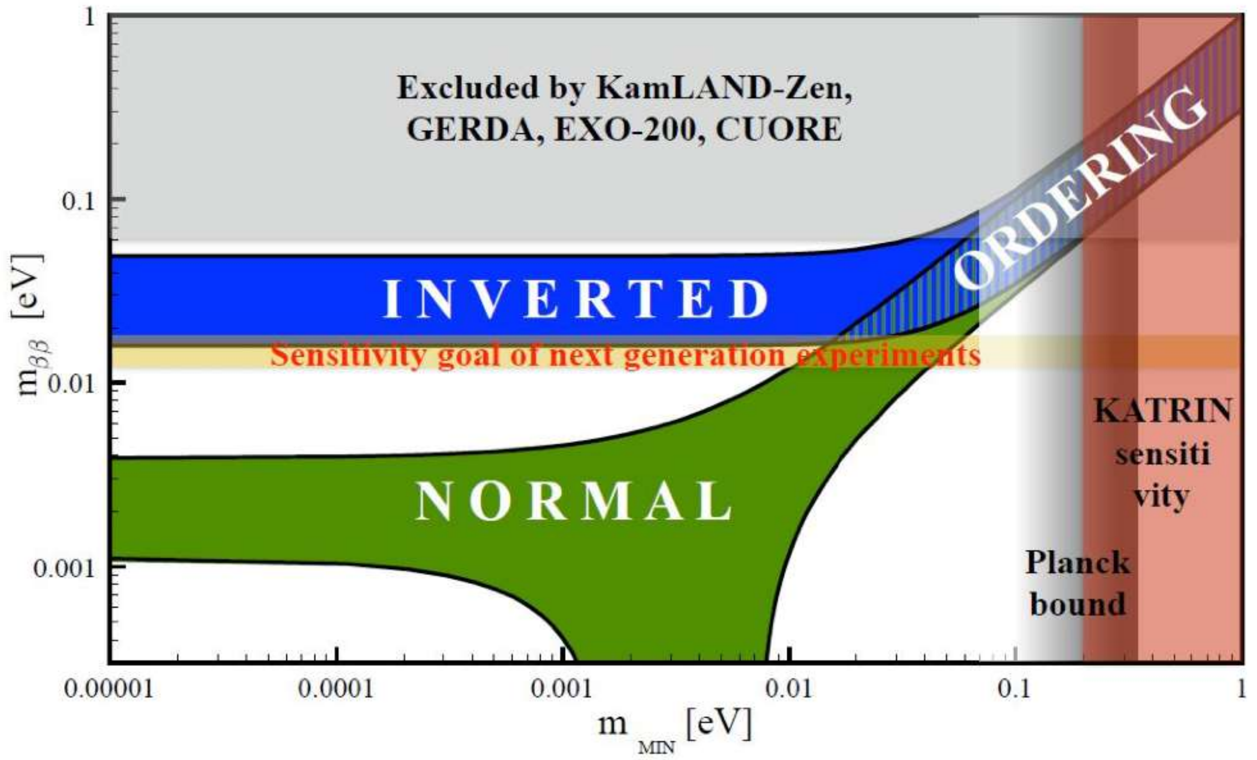




Neutrinoless double beta decay



If exactly Dirac: combine measurements from Cosmology or direct neutrino mass measurements and neutrinoless double beta decay.

If Quasi-Dirac: ultra long-baseline neutrino oscillation measurements

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Quasi-Dirac Neutrino Model

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737
Beacom et al, 2003 (arXiv:hep-ph/0307151
Shoemaker & Murase, 2015 (arXiv:1512.07228)
Esmaili, 2012

$$L_{\text{mass}} = \frac{1}{2}\Psi_L^\dagger C M \Psi_L \qquad \Psi_L = \begin{pmatrix} \nu_{\alpha L} \\ (\nu_{\alpha R})^c \end{pmatrix}$$

$$M = \begin{pmatrix} 0_3 & M_D \\ M_D & M_R \end{pmatrix}$$

Expected to be the dominant contribution if neutrinos are Dirac-like

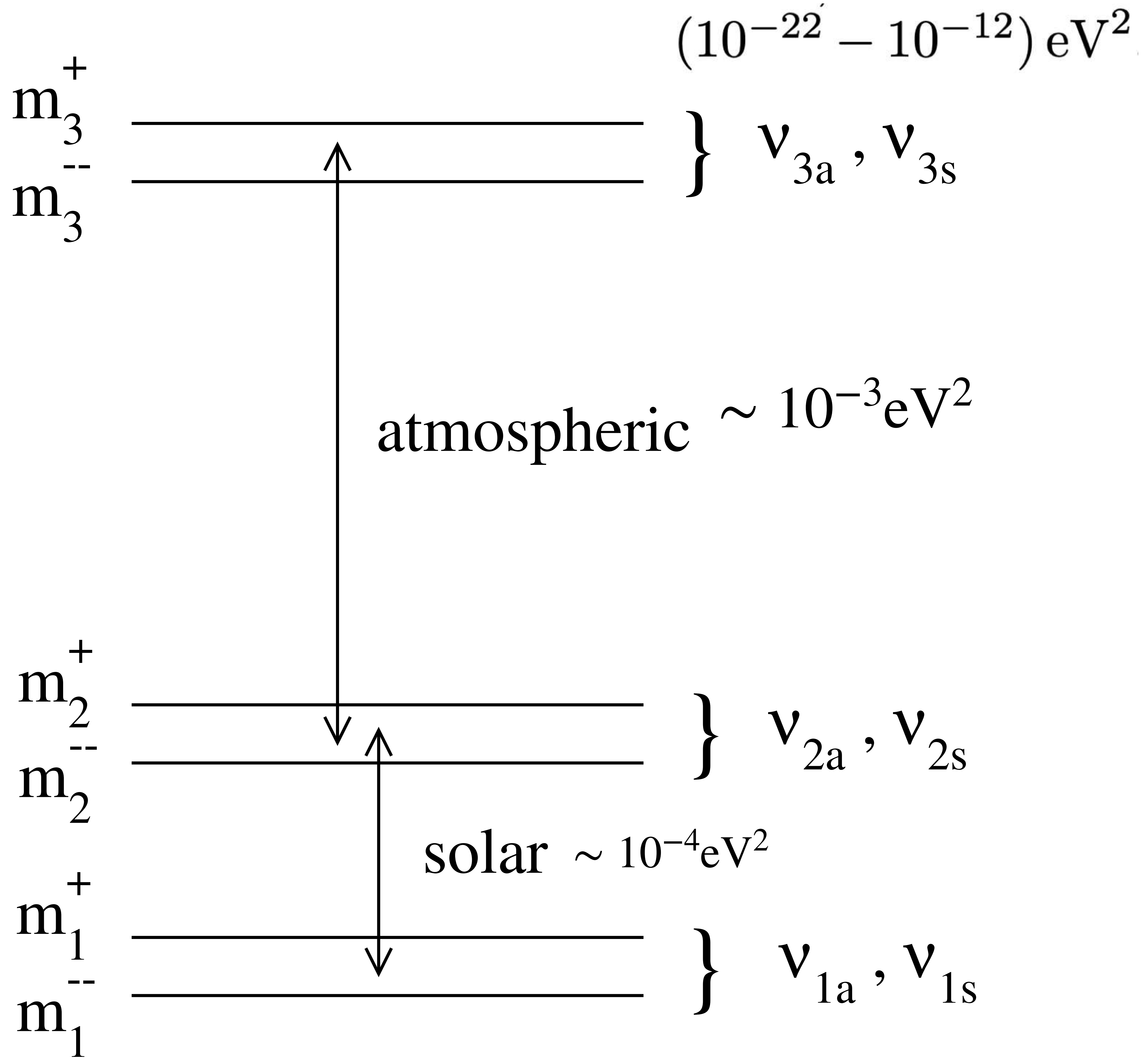
Lepton-number breking term.

Dirac neutrinos: $M_R = 0$
See-saw scenario: $M_R \gg M_D$
Quasi-Dirac scenario: $M_R \ll M_D$

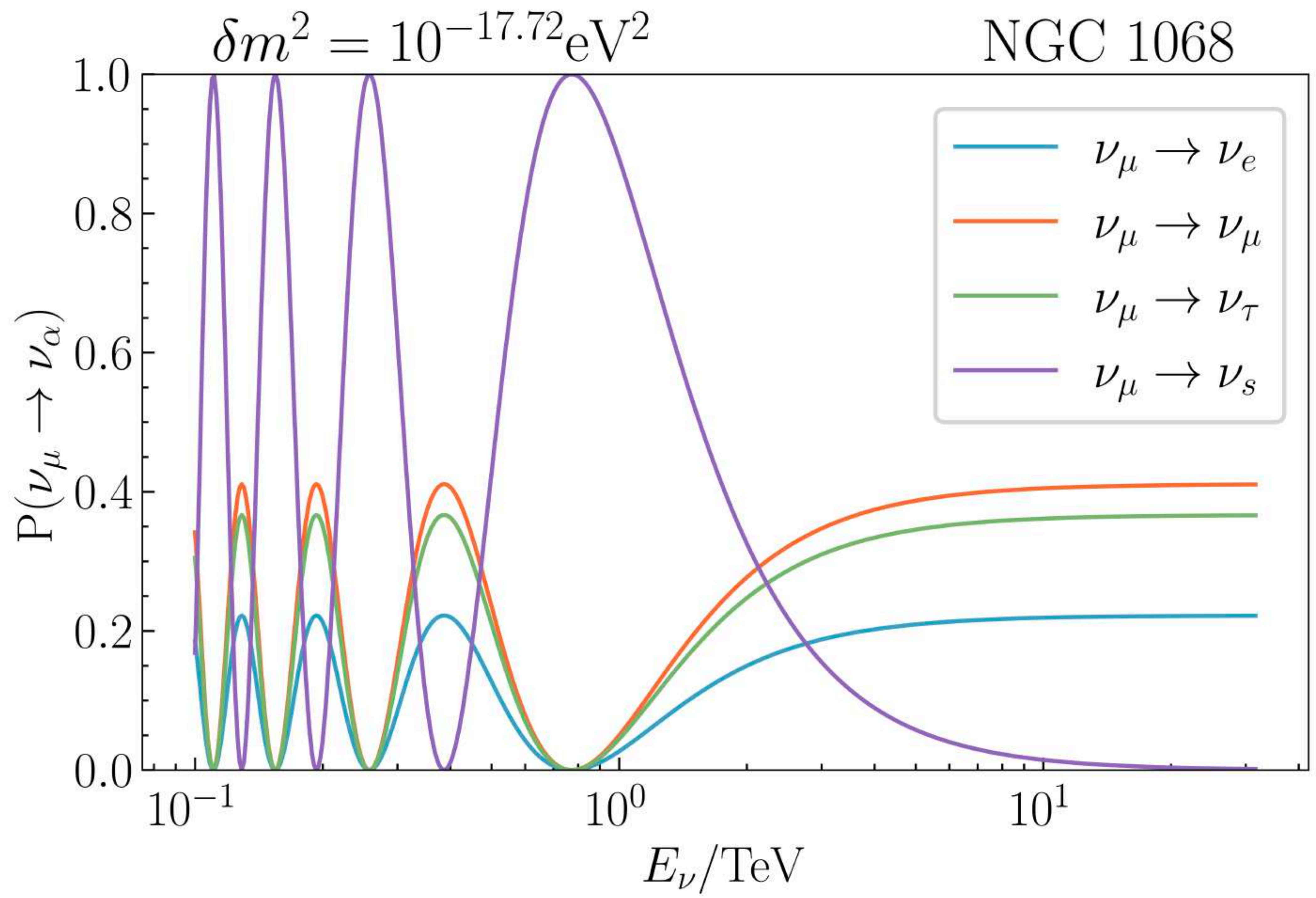
J. W. Valle Phys.Rev.D 28 (1983) 540

Oscillations With Quasi-Dirac Neutrinos

Beacom et al, 2003 (arXiv:hep-ph/0307151
Shoemaker & Murase, 2015 (arXiv:1512.07228)
Esmaili, 2012



$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\rm eff}}{2E_\nu}\right)\right]$$

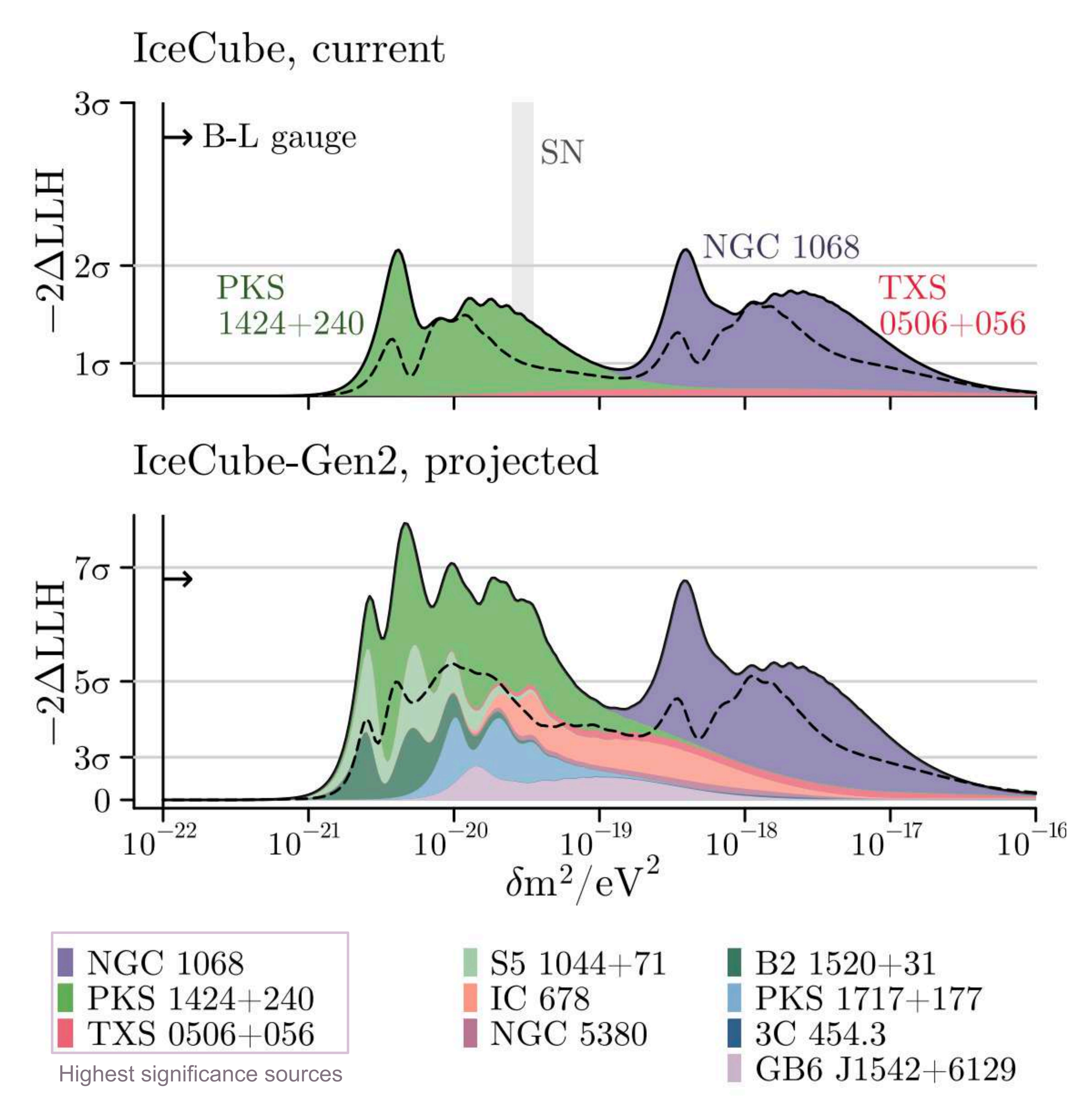


Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

Neutrino Oscillations At Cosmic Scales

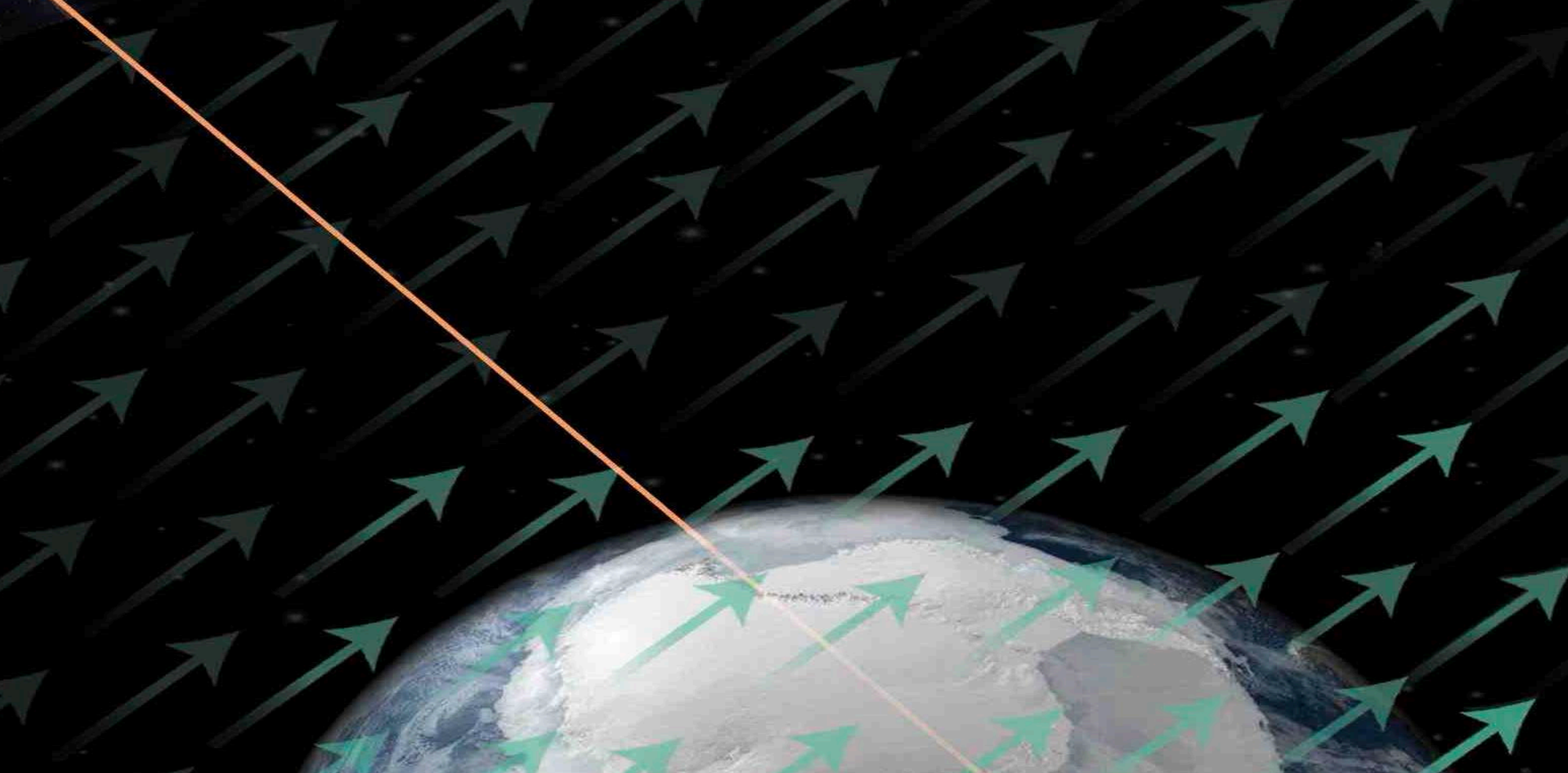
Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

Neutrino Oscillations At Cosmic Scales



Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

Search for Lorentz Violation via Flavor Morphing



As neutrinos travel from their far away source they can interact with fields in space.

Example: spontaneous Lorentz violation.

Effects expected at the Planck Scale.

Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

Trajectories in the flavor triangle in the presence of Lorentz Violation (LV)

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger$$

Dimension

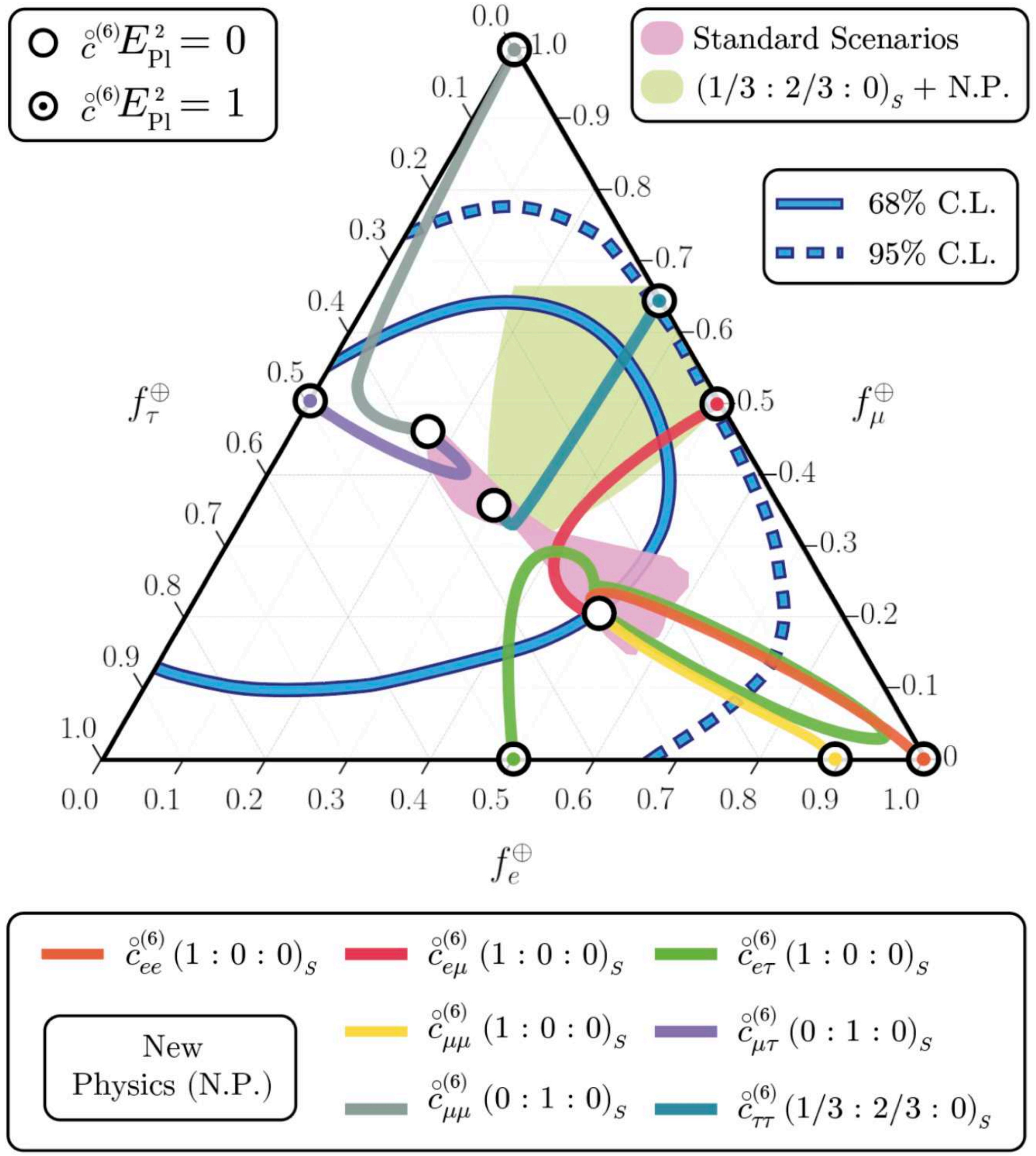
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

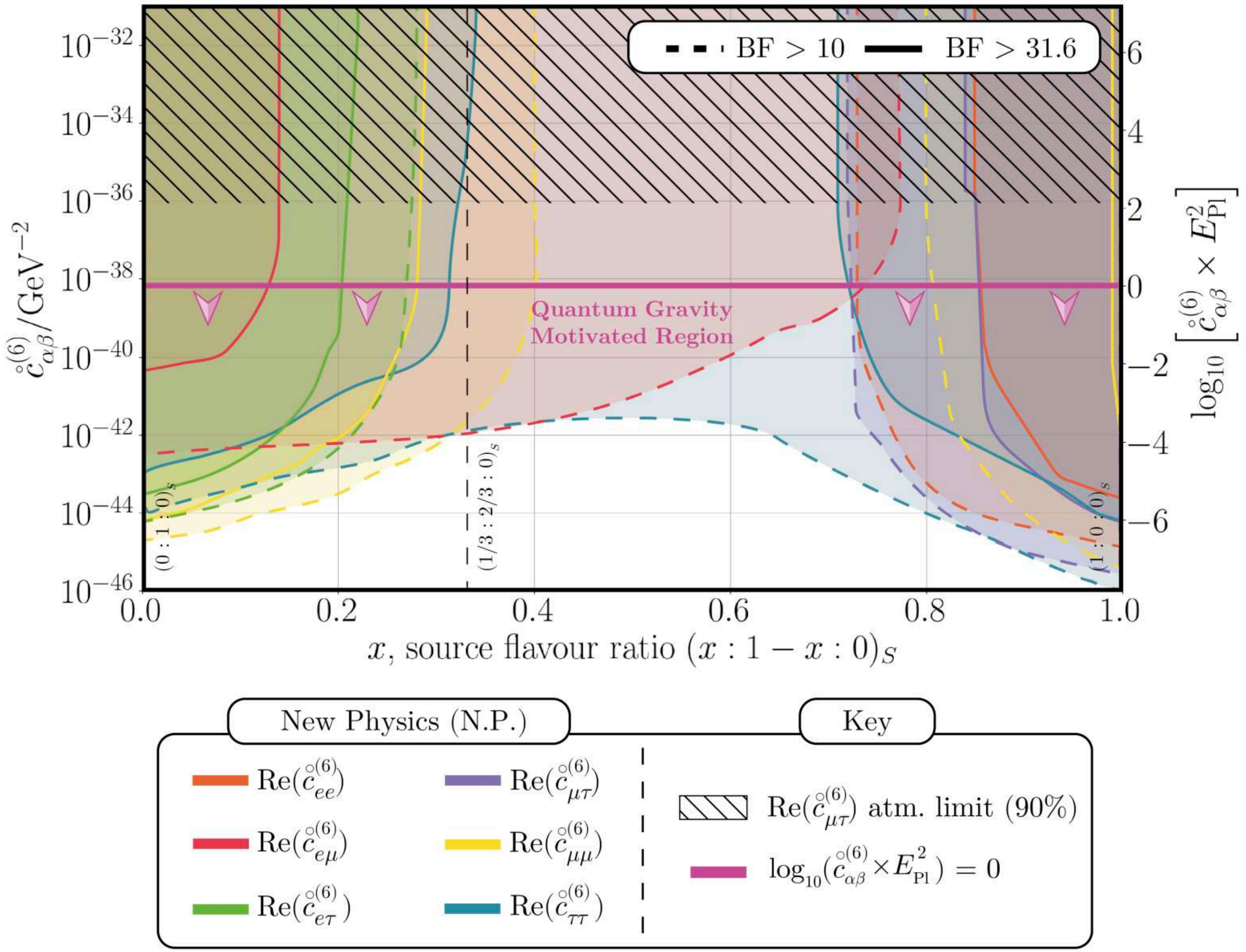
$(0:1:0)$ neutron

$(1:0:0)$ muon-damped



IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

Results on high-dimensional LV operators



IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

Constraints of neutrino flavor transition can be interpreted in various models

Model	Limits
IceCube Lorentz violation limit	$\mathring{a}^{(3)}_{\tau\tau} < 2 \times 10^{-26}$GeV
Dark matter potential	$V_{\tau\tau} < 2 \times 10^{-26}$GeV
Dark matter effective Fermi coupling	$G'_F < 10^{-13}$GeV$^{-2}(m_\phi/10^{-20}$eV$)$
Dark matter non-standard interaction	$\epsilon_{\tau\tau} < 8 \times 10^{-9}(m_\phi/10^{-20}eV)$
Vector dark matter coupling	$g_{\tau\tau} < 3 \times 10^{-33}(m_\phi/10^{-20}eV)$
Axion dark matter coupling	$g_{a\tau\tau} < 3 \times 10^{-13}$eV^{-1}

CA, Farrag, Katori arXiv:2404.10926

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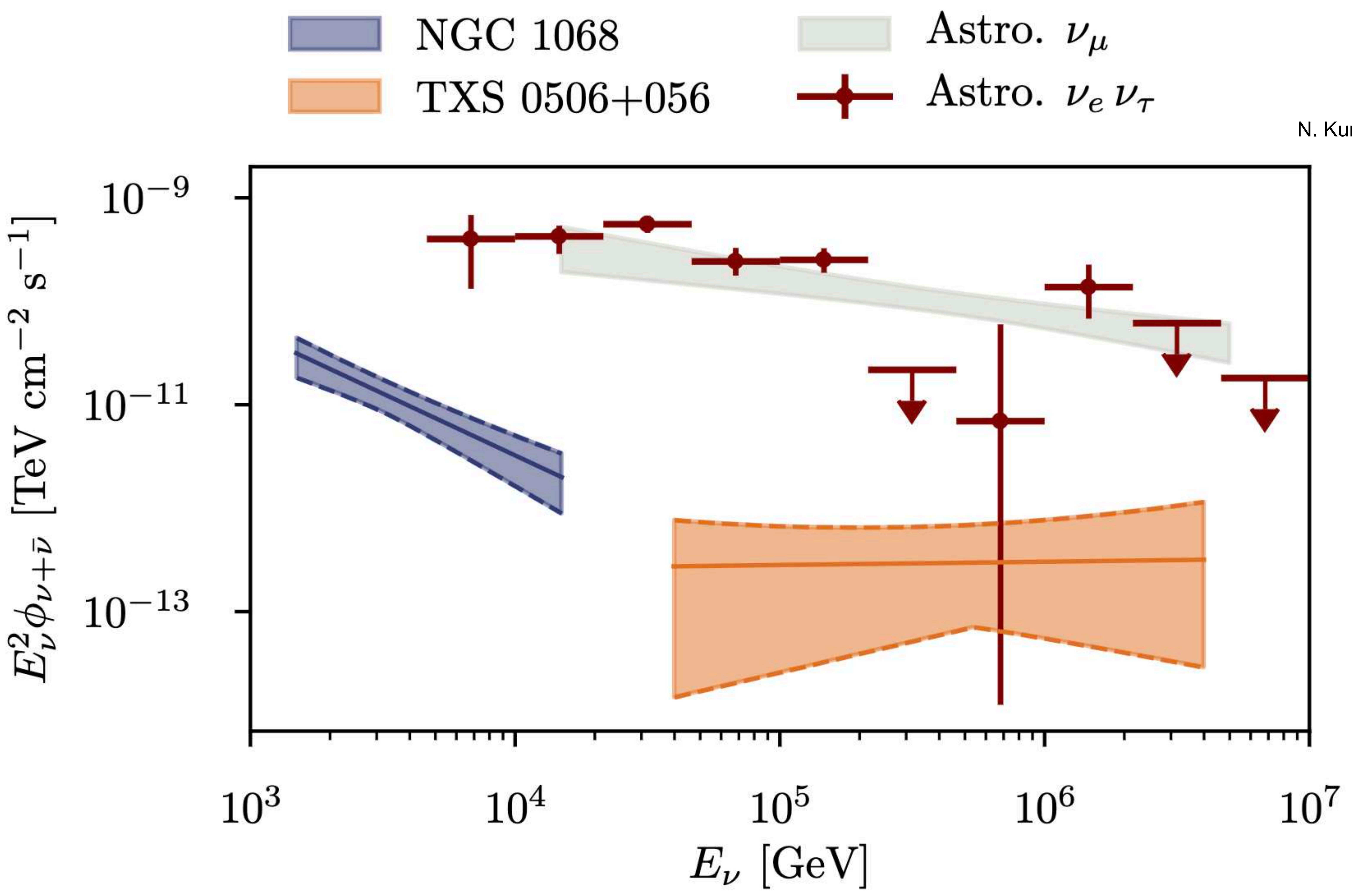
Big Question:
Where are these neutrinos coming from?

IceCube Collaboration, Science, 2022
N. Kurahashi ICRC204 for the IceCube Collaboration



HYPER K

P-ONE

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ICECUBE GEN2

JEM-EUSO

Many Neutrino Telescopes On Our Way

BAIKAL-GVD

GRAND

TRIDENT
海 | 铃 | 计 | 划

TAMBO

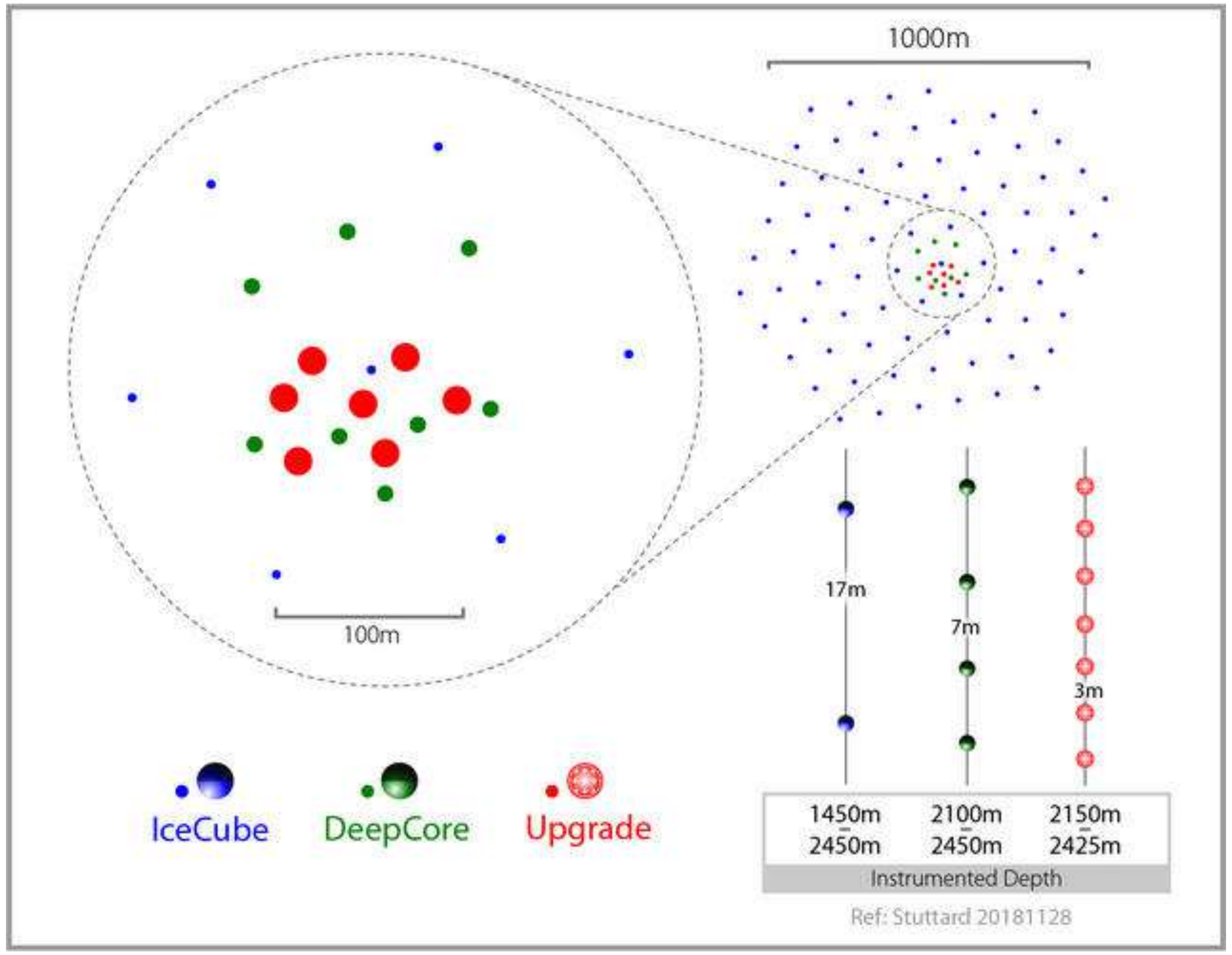
KM3NeT

POEMMA

Non-exhaustive list

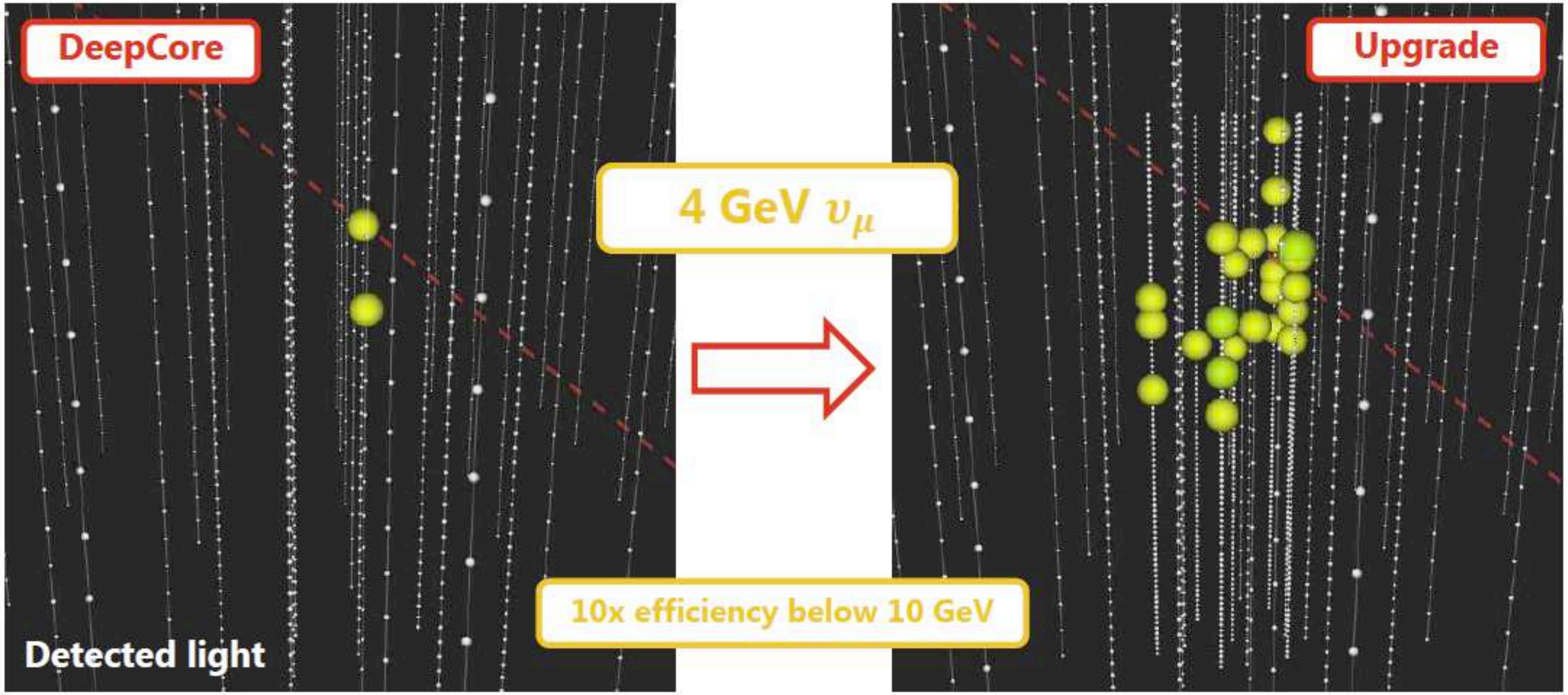
IceCube is growing:
The Upgrades

Phase 1: 7 new, high-precision strings in
the central, densely instrumented region.
Funded, installation in 2025.



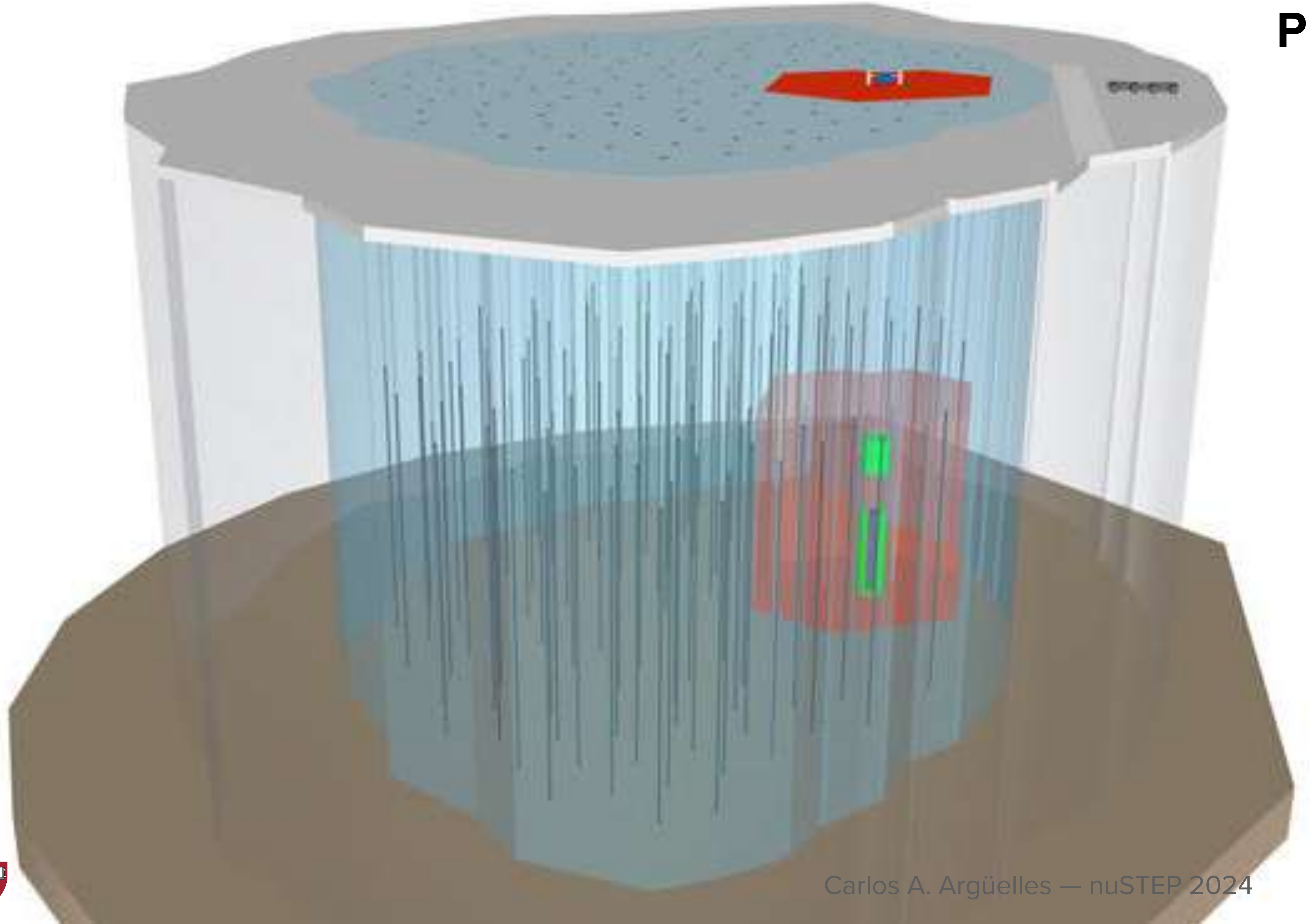
New detector technologies.
Better low energy reconstruction.
Improved flavor identification.

Improved light-collection for low-energy events



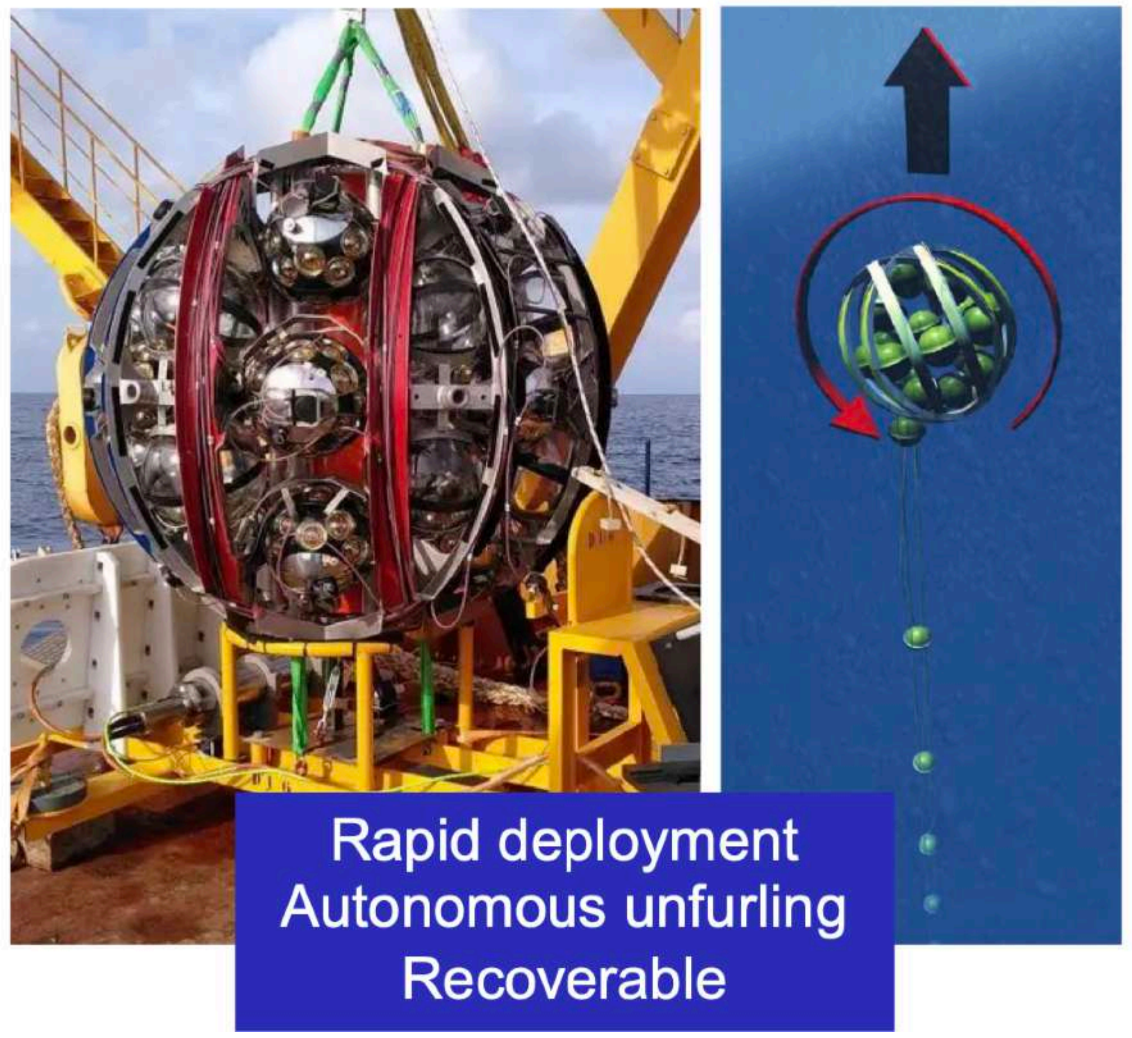
*DeepCore (shown on the left) is the current low-energy extension of IceCube

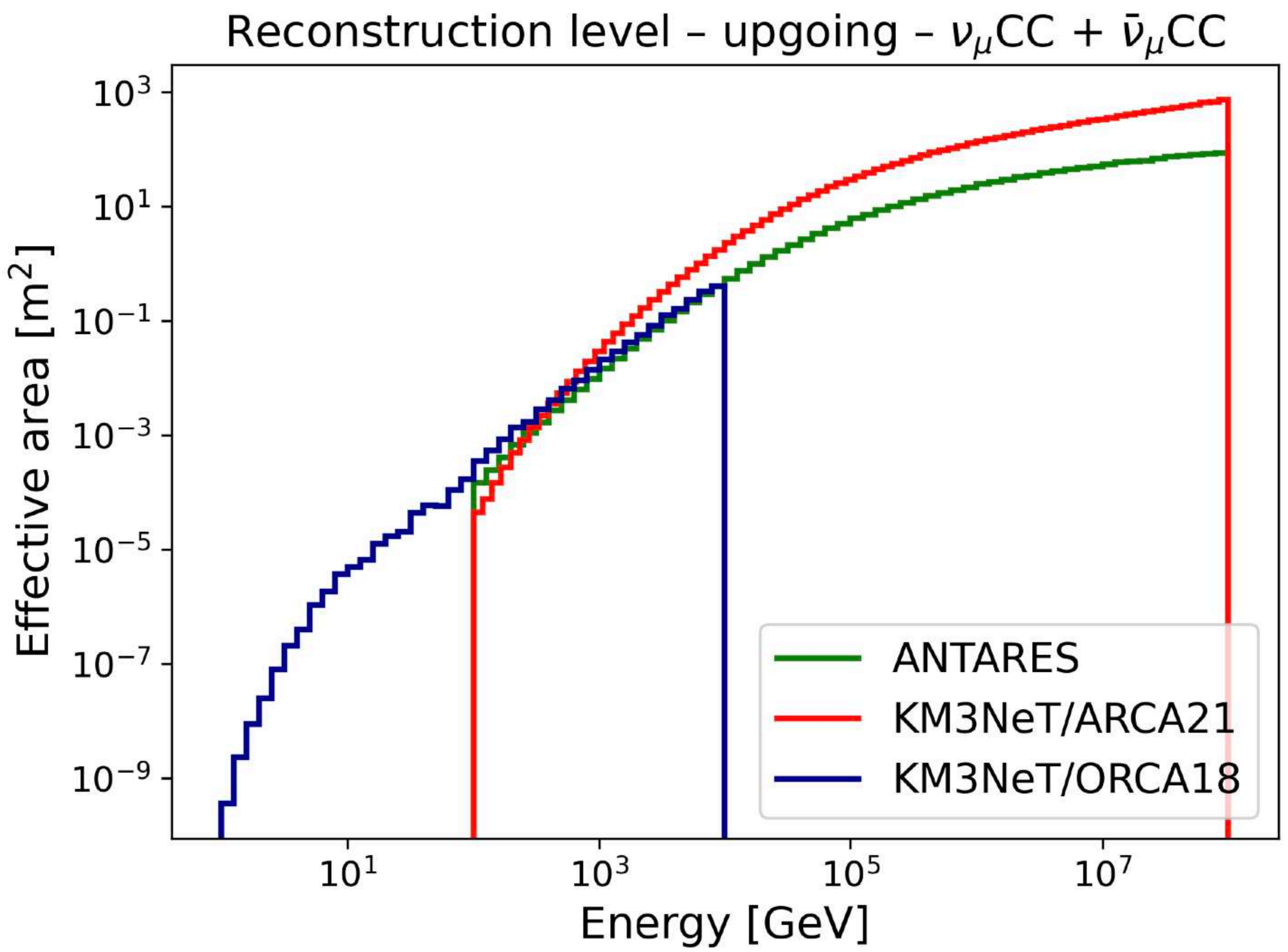
IceCube is growing: The Upgrades

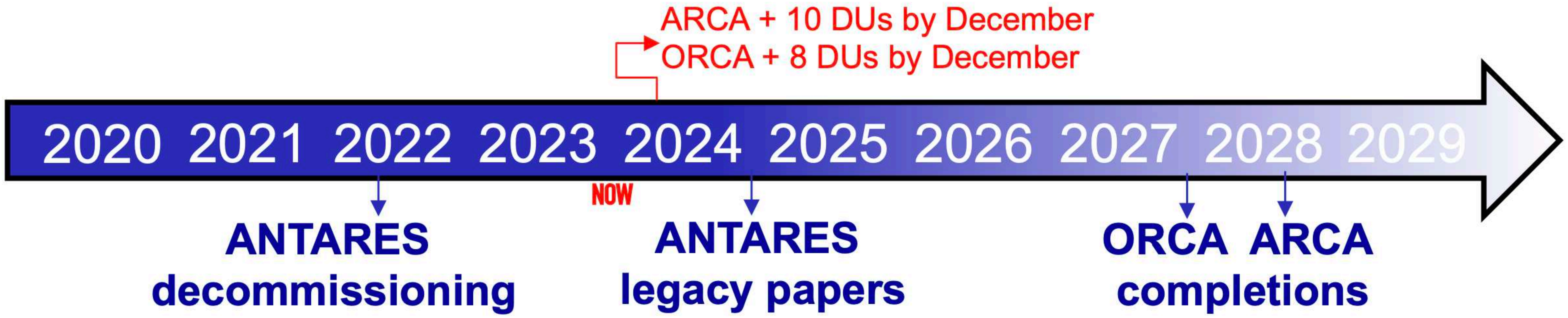


Phase 2: x10 the volume
of present IceCube,
plus additional detectors.

Next Neutrino Telescope: KM3NeT

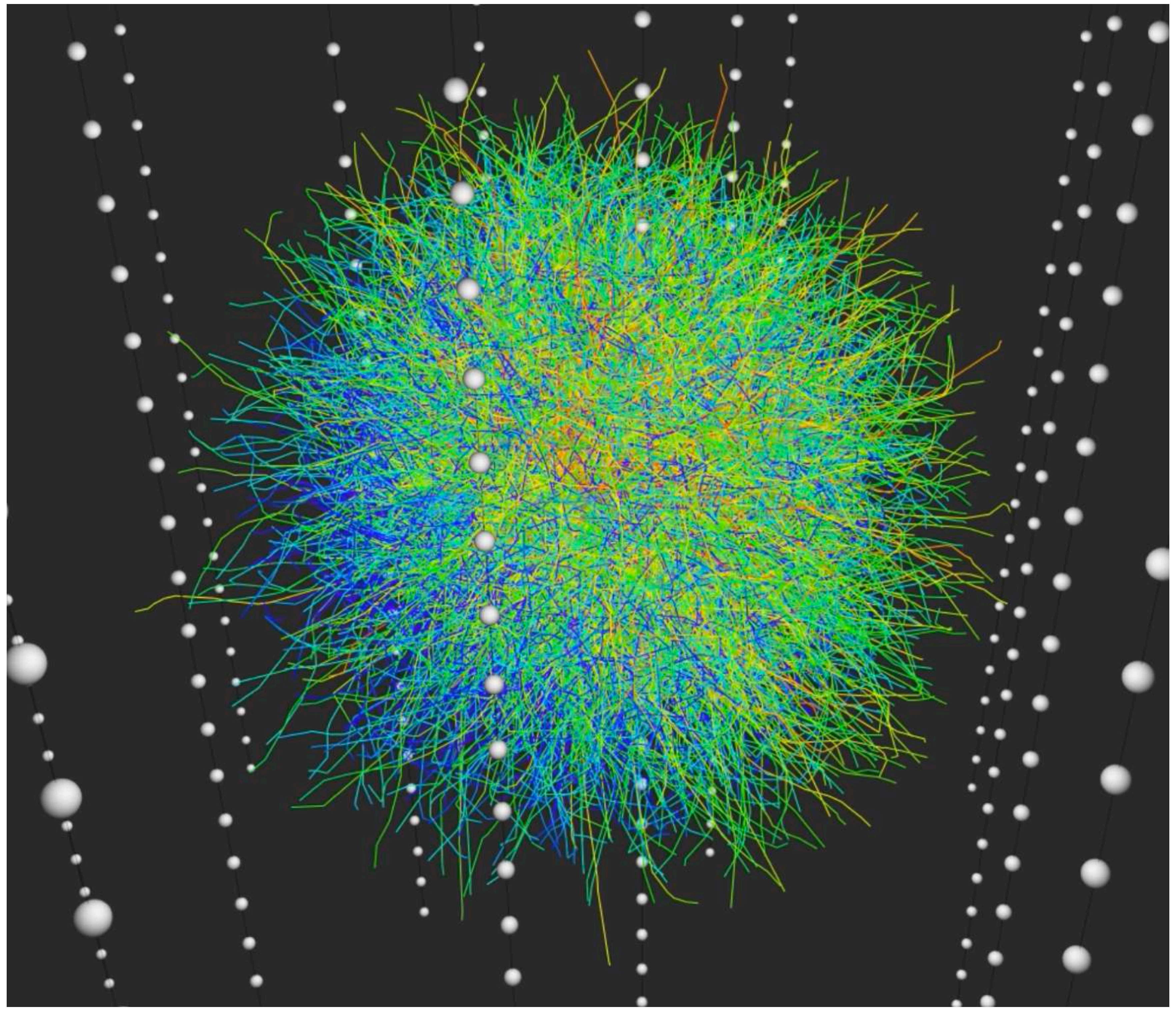




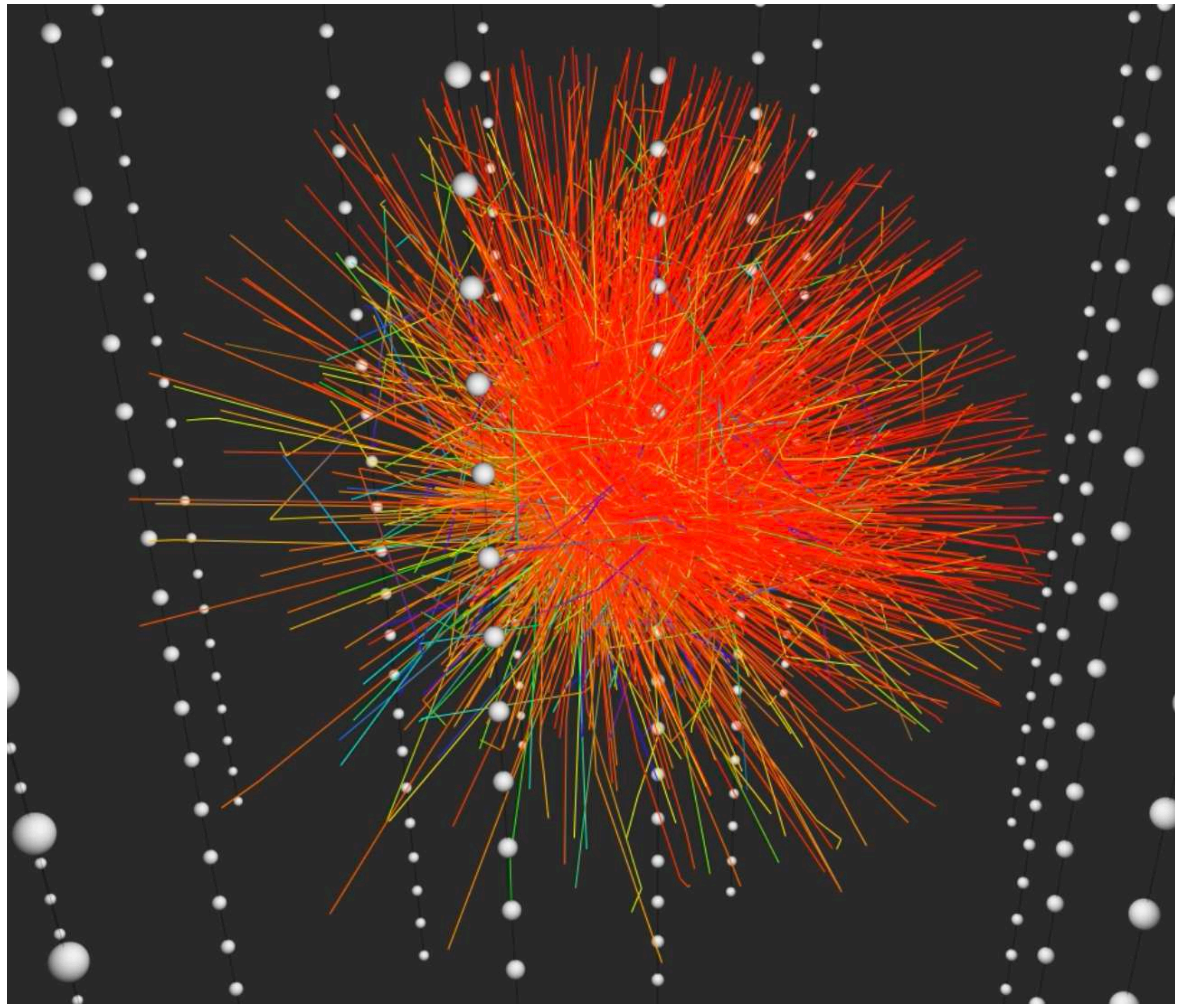


(Adapted from a slide courtesy of Antoine Koushner)

Cascade in Water and Ice Compared



10 TeV in ice



10 TeV in water

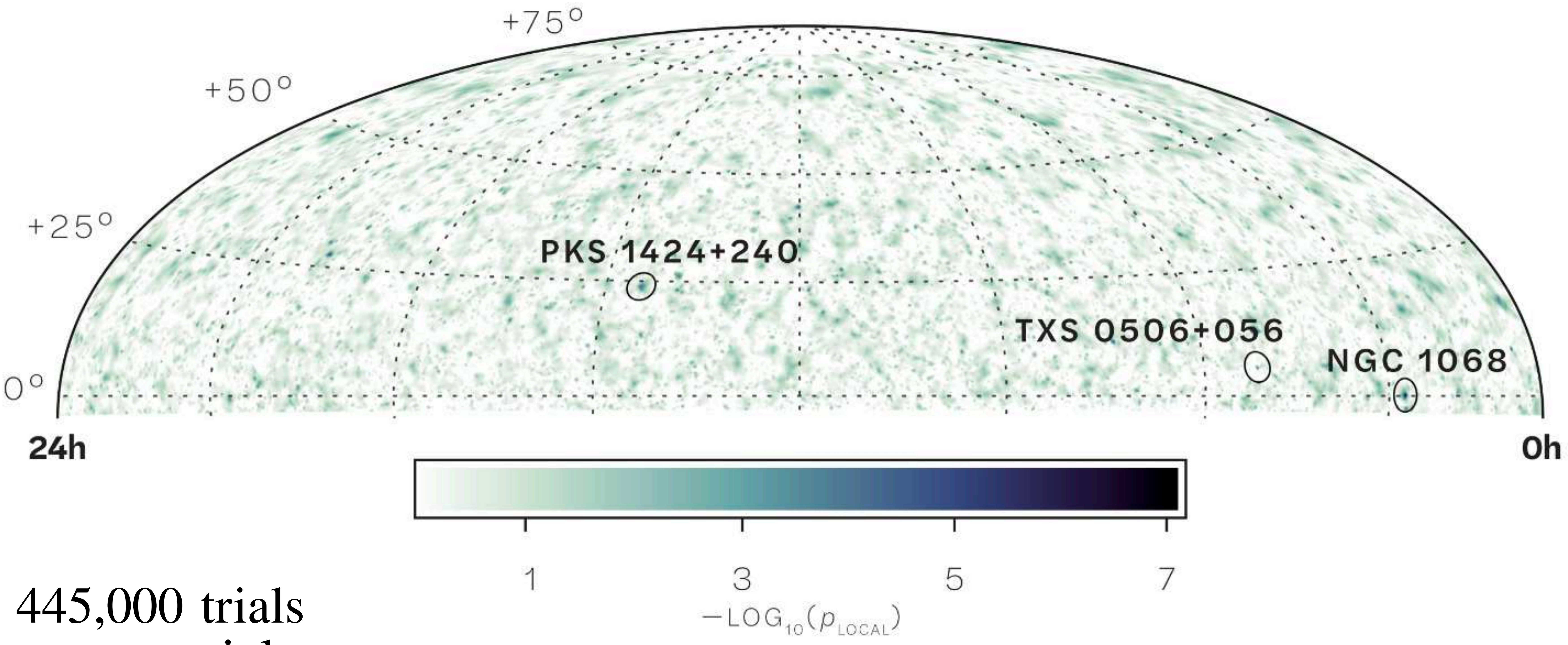
Water detectors are expected to have better particle identification capability.

All is that is very good, but …
why we can’t find the sources right now?

Why we can't find the sources right now?

Trials and tribulations

Test type	Pre-trial p-value (p_{local})	Post-trial p-value (p_{global})
Northern Hemisphere scan	5.0×10^{-8} ($5.3\,\sigma$)	2.2×10^{-2} ($2.0\,\sigma$)



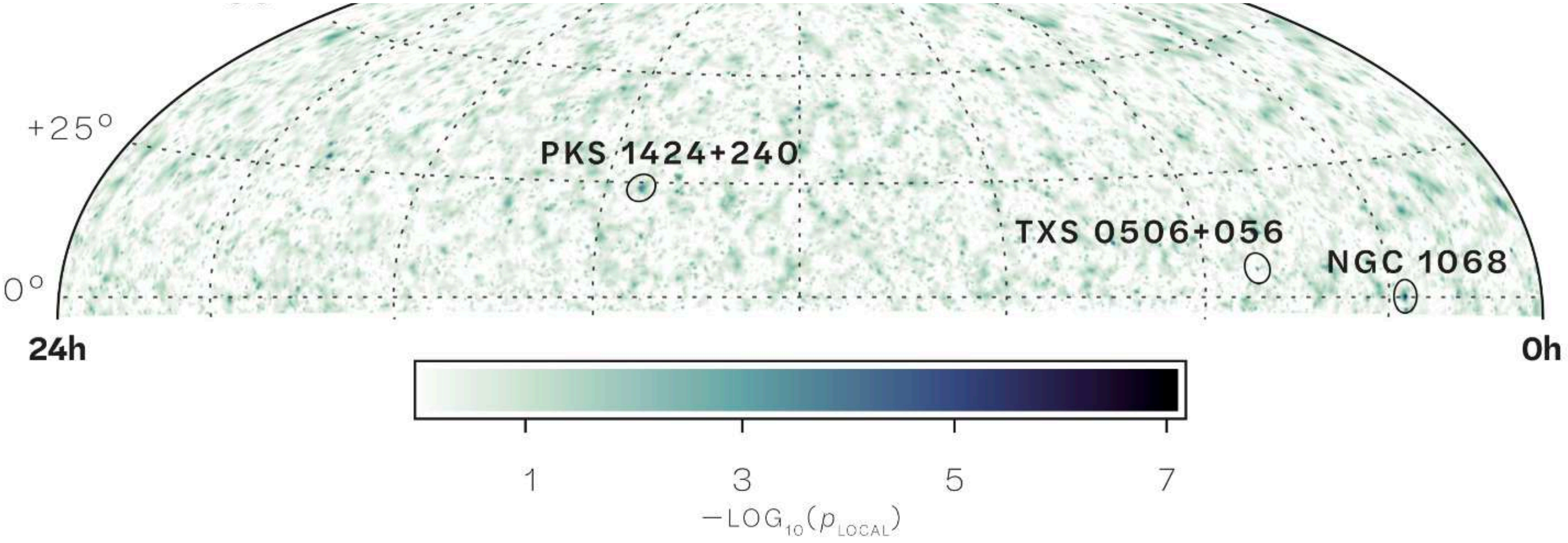
$$\sim 445{,}000 \text{ trials}$$

$$\implies \; 19.8 \frac{\text{trials}}{\circ^2}$$

Why we can't find the sources right now?

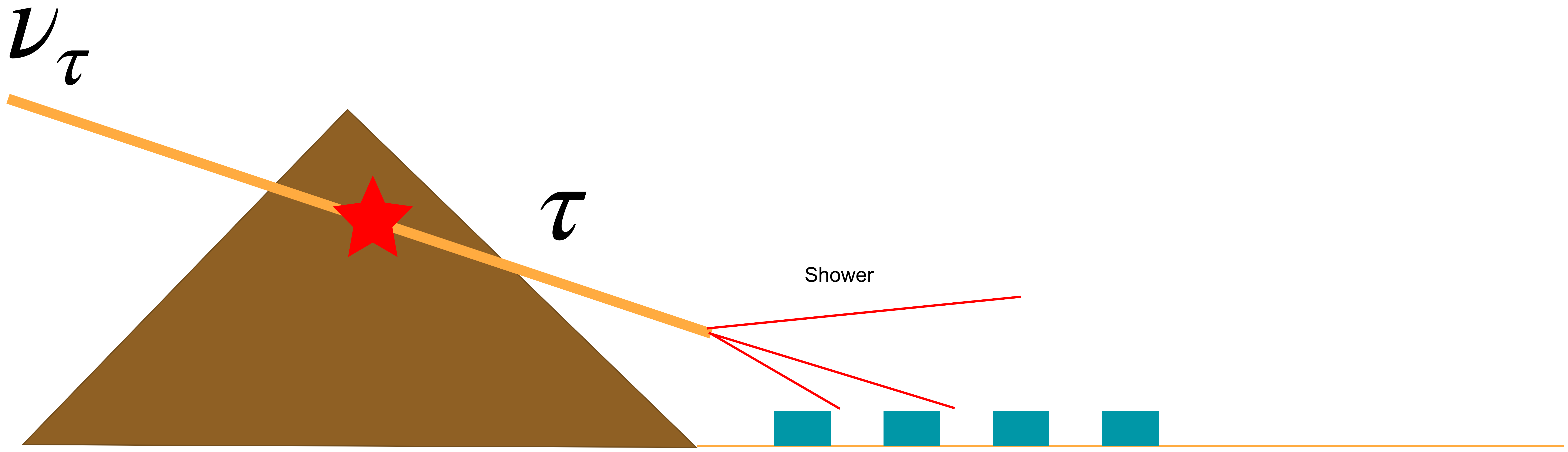
Trials and tribulations

Test type	Pre-trial p-value (p_{local})	Post-trial p-value (p_{global})
Northern Hemisphere scan	5.0×10^{-8} ($5.3\,\sigma$)	2.2×10^{-2} ($2.0\,\sigma$)
List of candidate sources, single test	1.0×10^{-7} ($5.2\,\sigma$)	1.1×10^{-5} ($4.2\,\sigma$)
List of candidate sources, binomial test	4.6×10^{-6} ($4.4\,\sigma$)	3.4×10^{-4} ($3.4\,\sigma$)



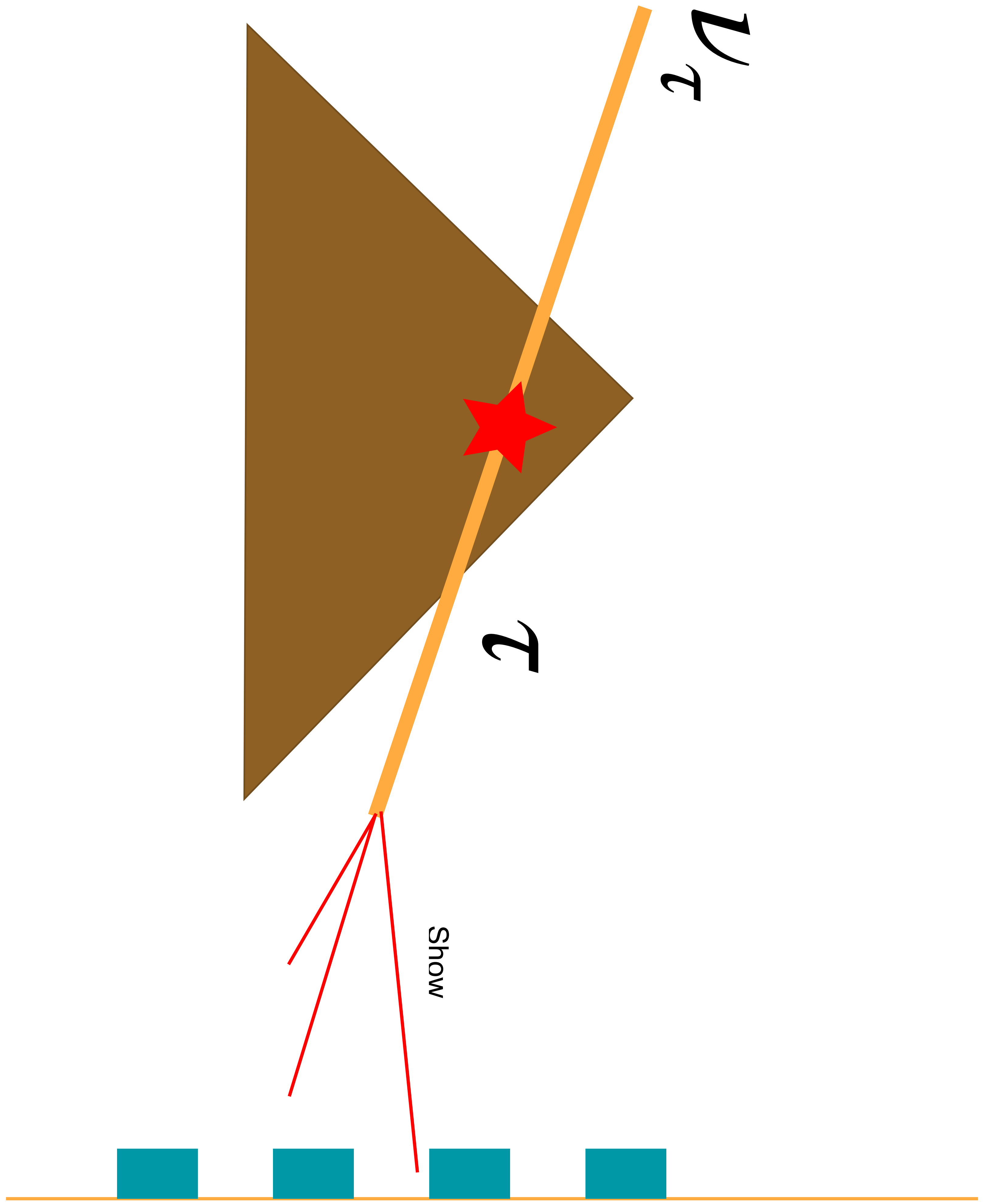
If you know where to look, bright sources are currently detectable

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection
This would be a more ideal scenario, but can't put mountain over detector

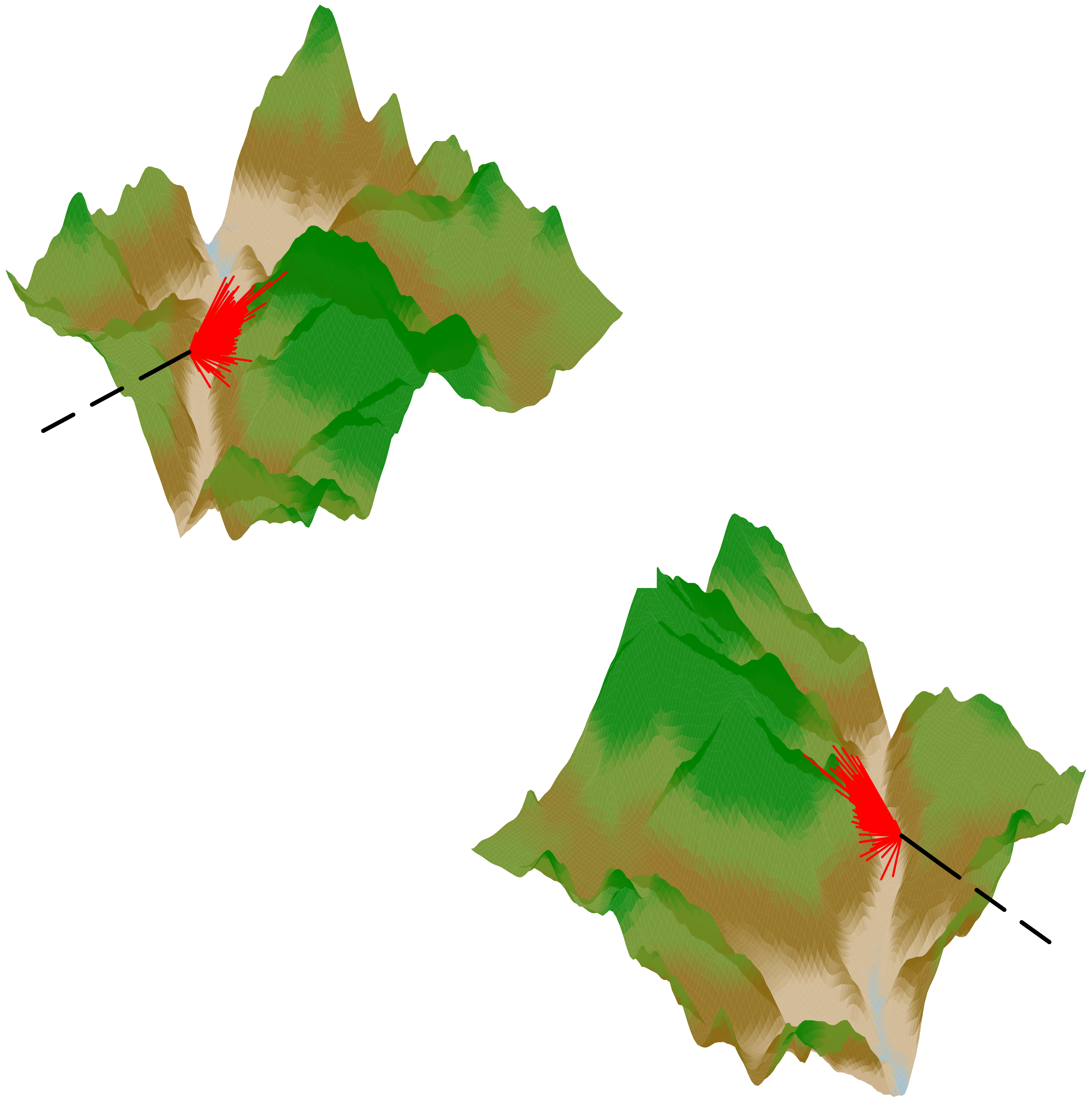
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

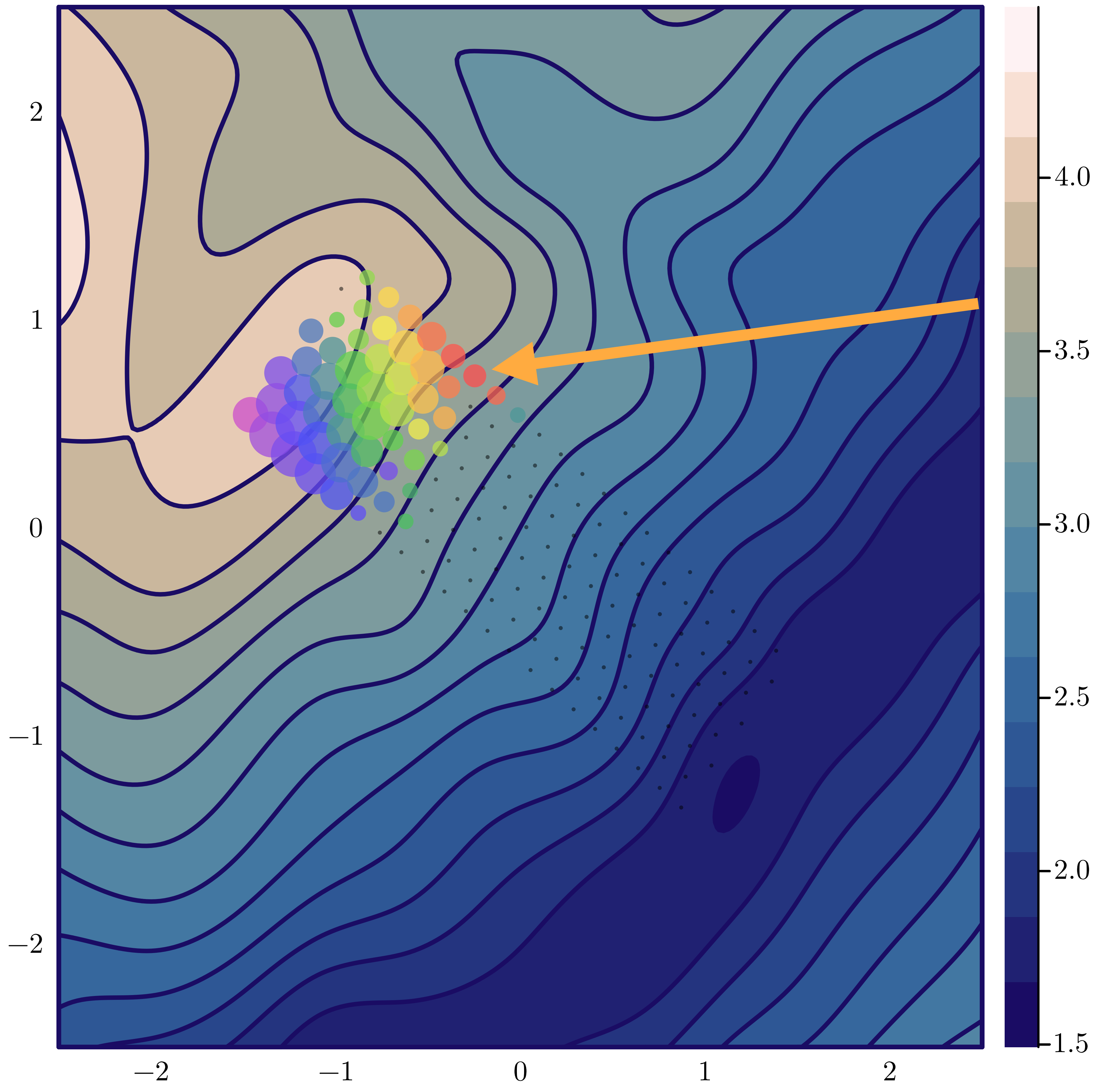
W. Thompson ICRC2024 (arXiv:2308.09753)

*TAMBO means rest place, house or inn in Quechua.

We went to Peru earlier last year and found a location for the experiment!
First prototype detectors are expected to be deployed this summer.

How would these events look like?

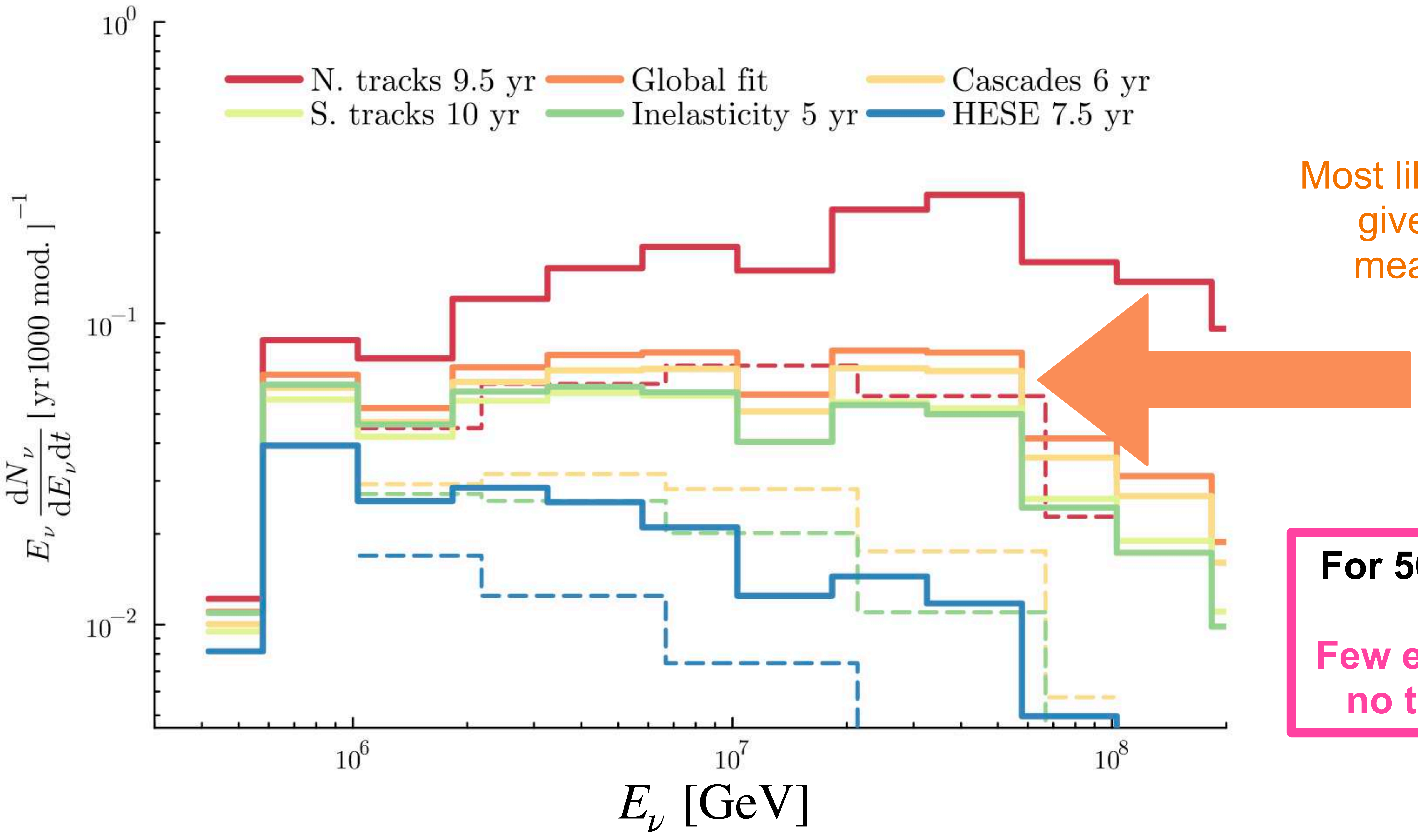




Figures possible by the amazing simulation work done by Jeff Lazar, Pavel Zhelnin, and William Thompson

Expected rates at TAMBO given unknown-origin IceCube flux

J. Lazar, P. Zhelnin, W. Thompson for the TAMBO Collabotion (2024, to arXiv)



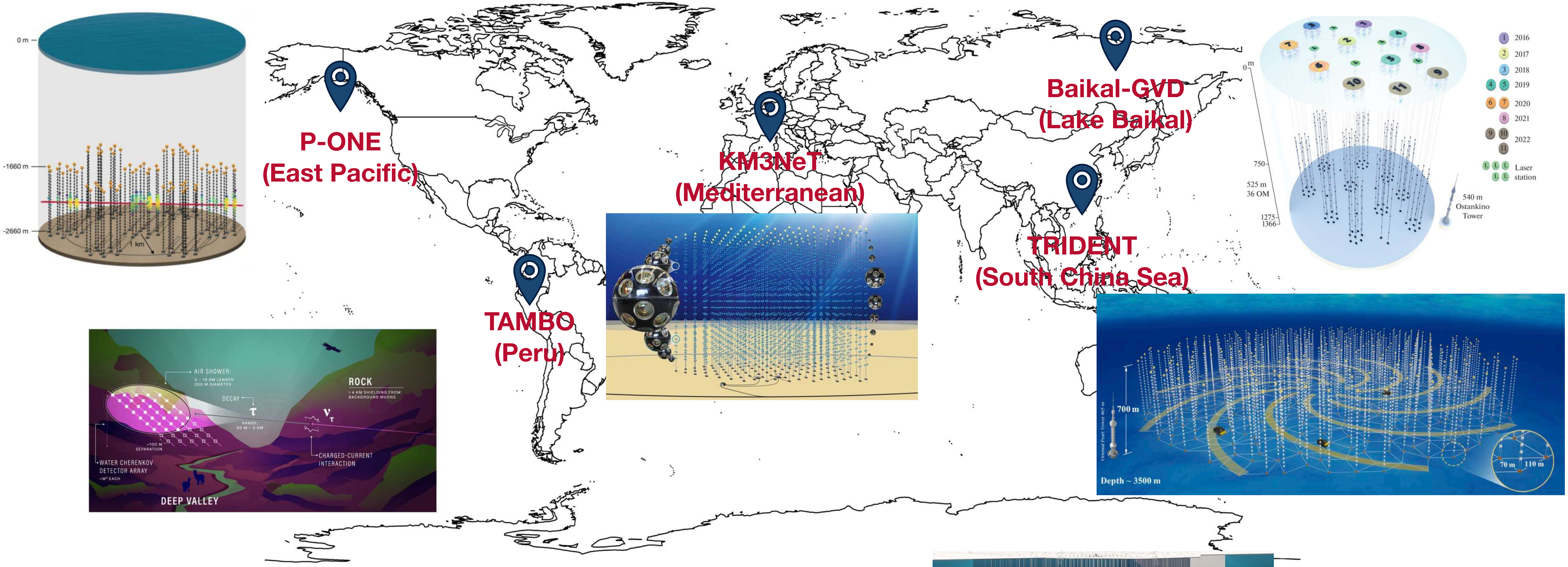
Most likely event rate given IceCube measuremetns

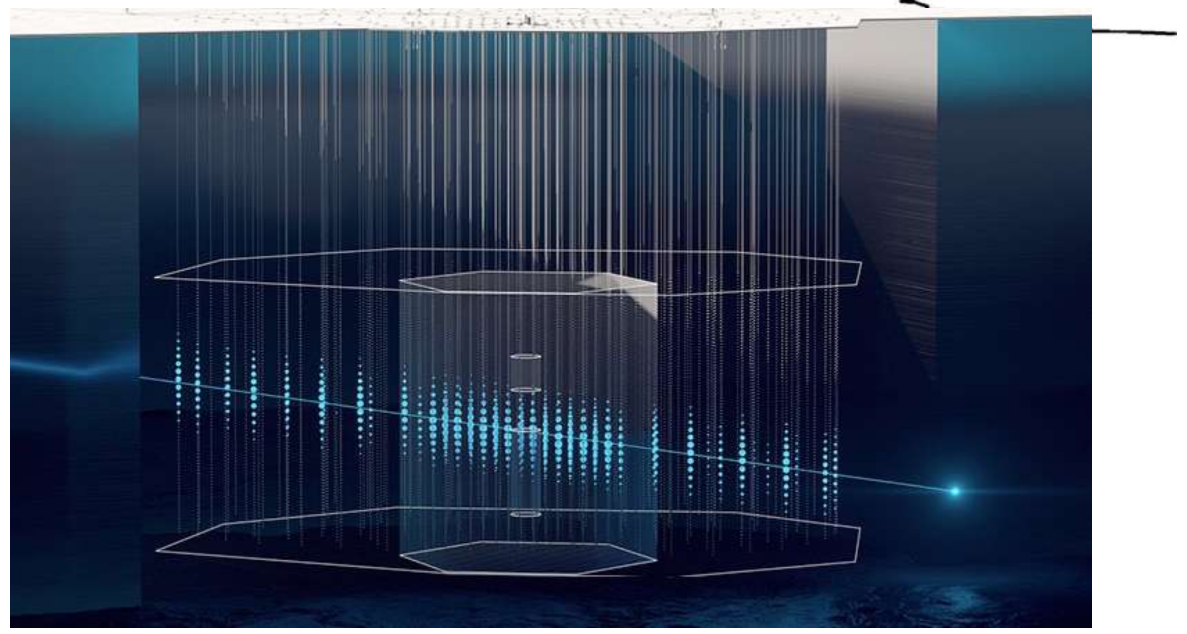
For 5000 sensors we expect a couple of events every year.

Few events, but every event points to a source: no trial factor in a IceCube/KM3NeT follow up

Towards a *Joint* Global Neutrino Telescope

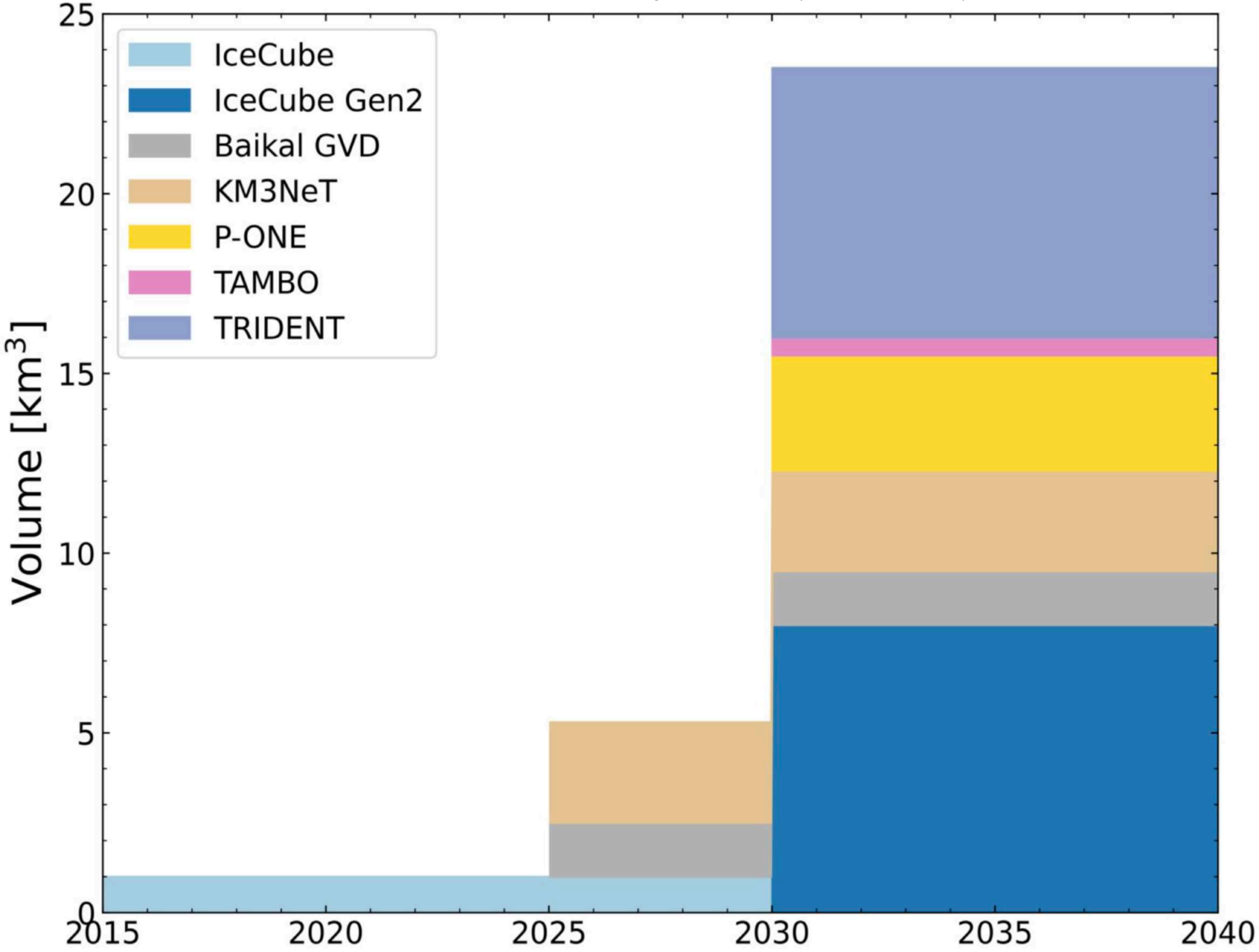
(Diagram courtesy of Qinrui Liu)





Many neutrino telescopes on similar energy ranges and with complementary capabilities under construction/planning

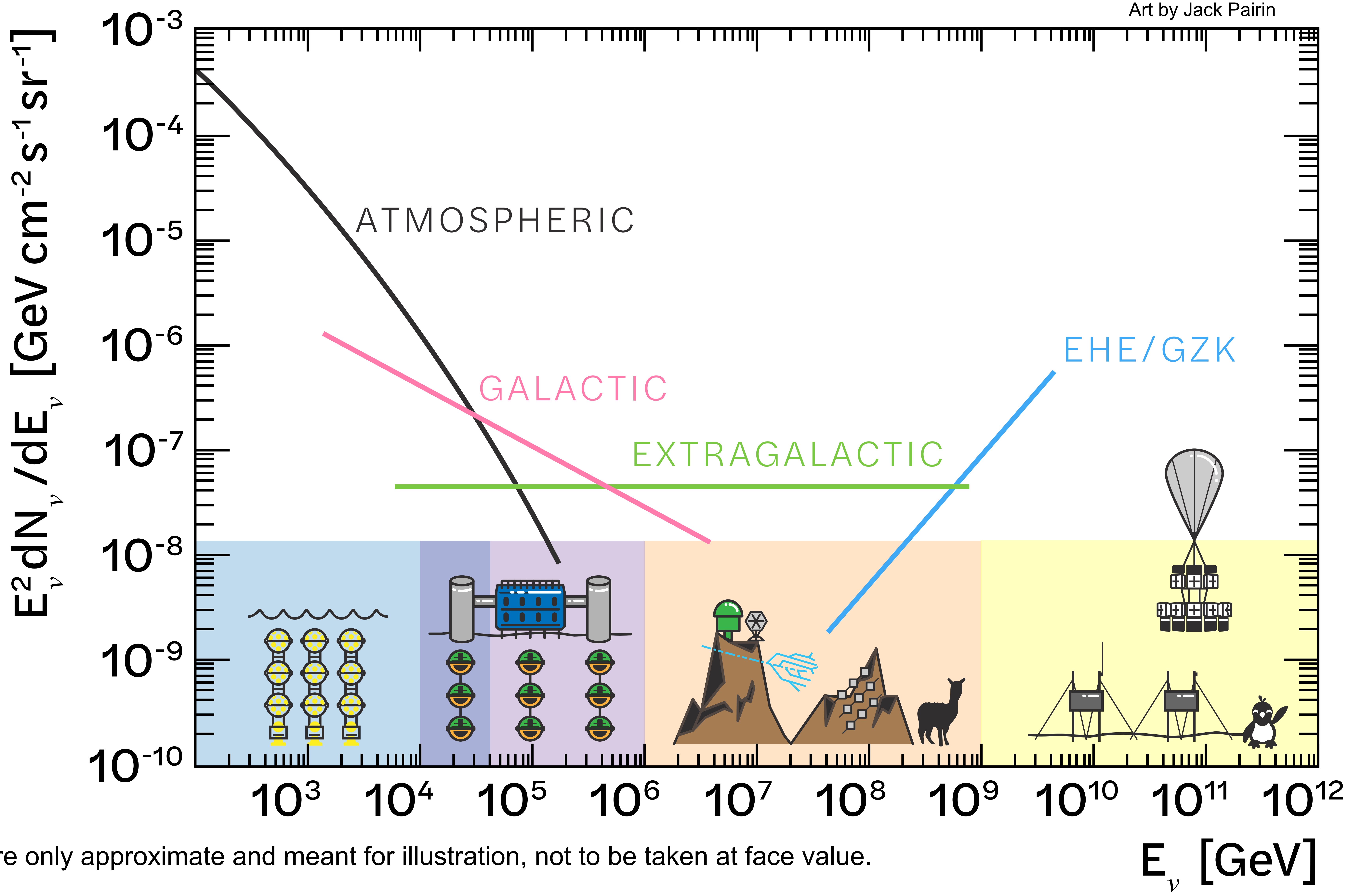
Q. Liu, F. G. Fiorillo, CA, M. Bustamante, N. Song, A. C. Vincent (arXiv:2312.07649)



Neutrino astronomy has started with first high-significance sources. Exponentially growing field expected.

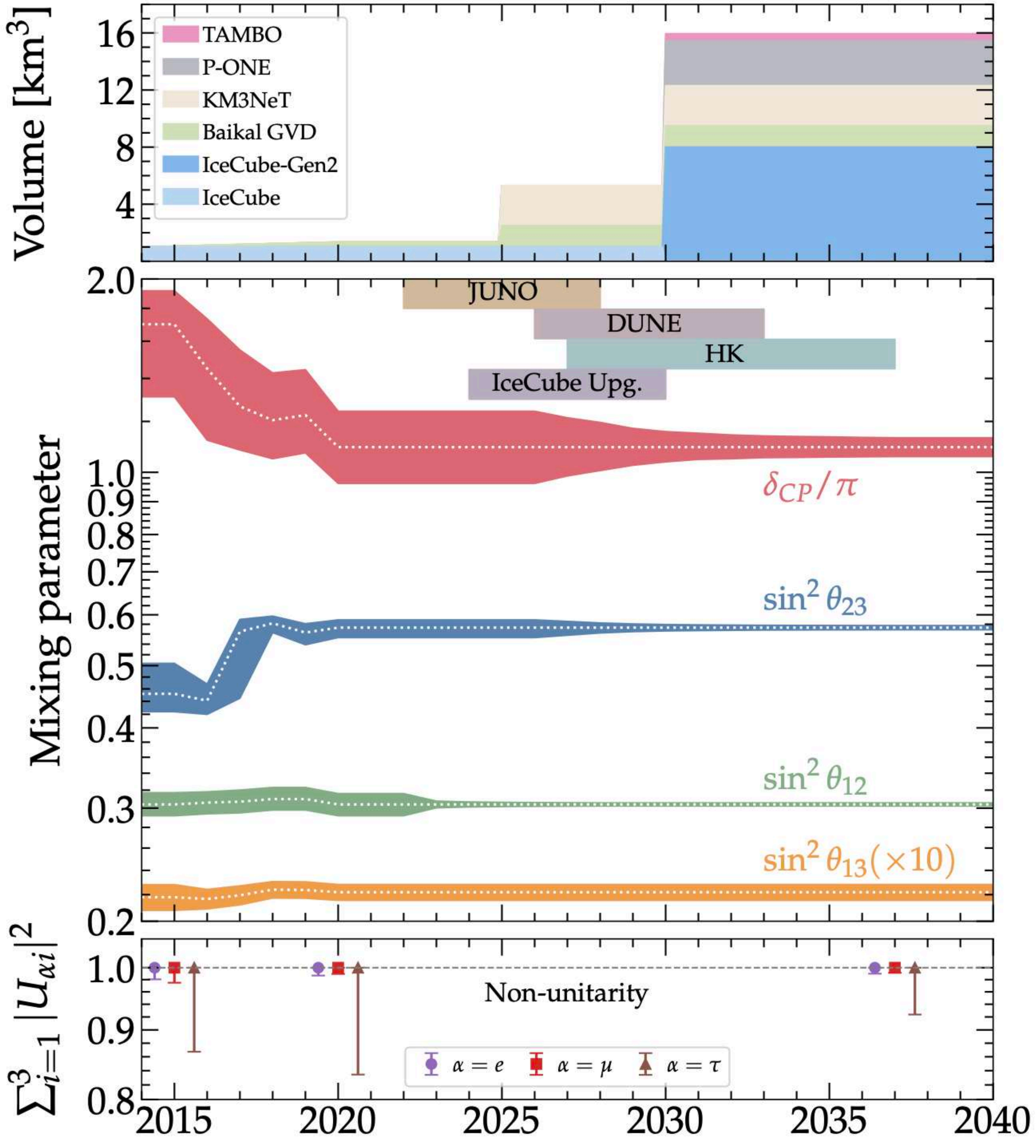
Specialized Neutrino Telescopes

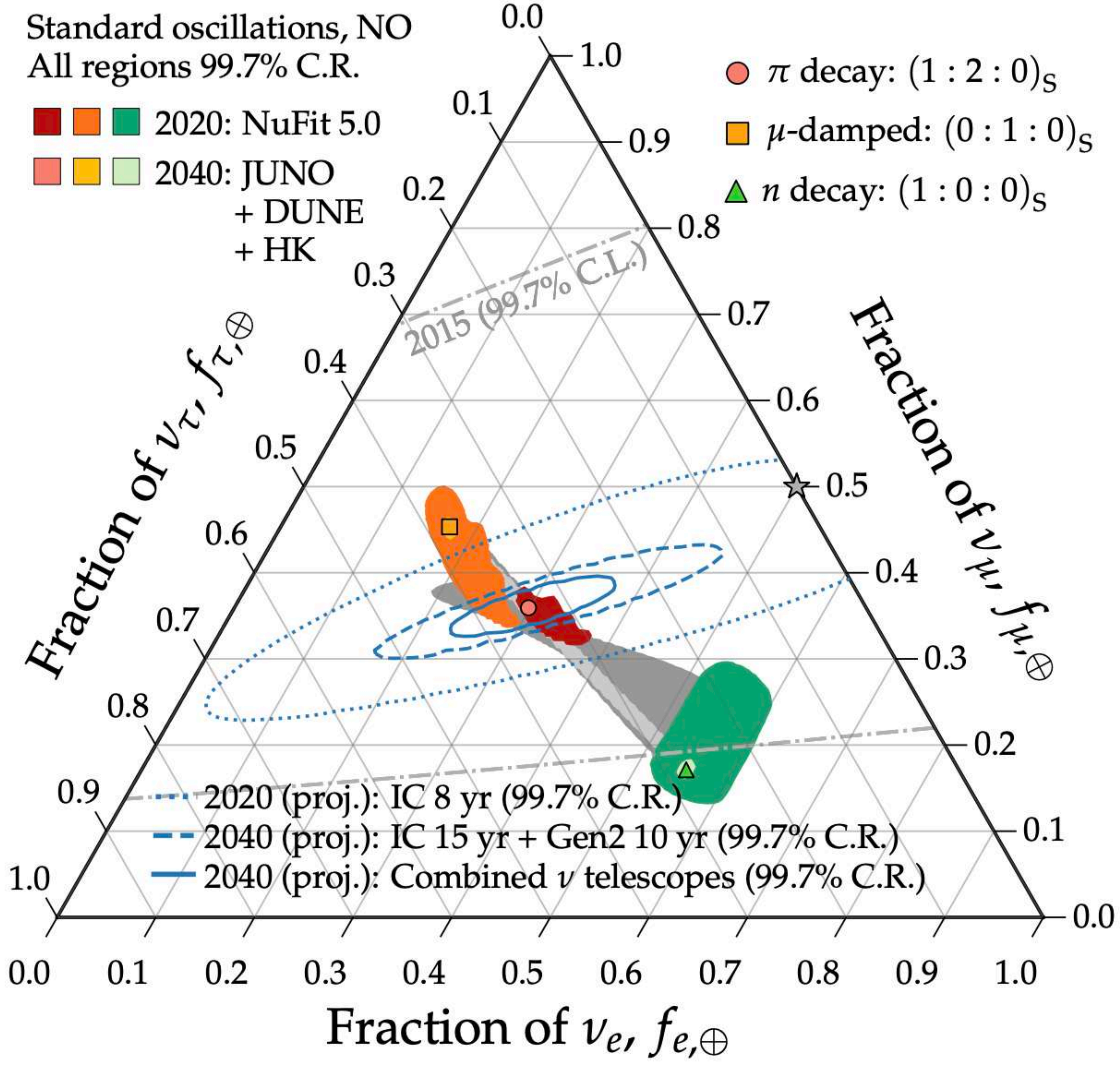
Argüelles, Kurahashi, and Halzen (2024, to arXiv))
Art by Jack Pairin



*Energy ranges here are only approximate and meant for illustration, not to be taken at face value.

The Power of *Collaboration*: Flavor measurements





N. Song, S. Li, CA, M. Bustamante, A. Vincent (arXiv:2012.12893)

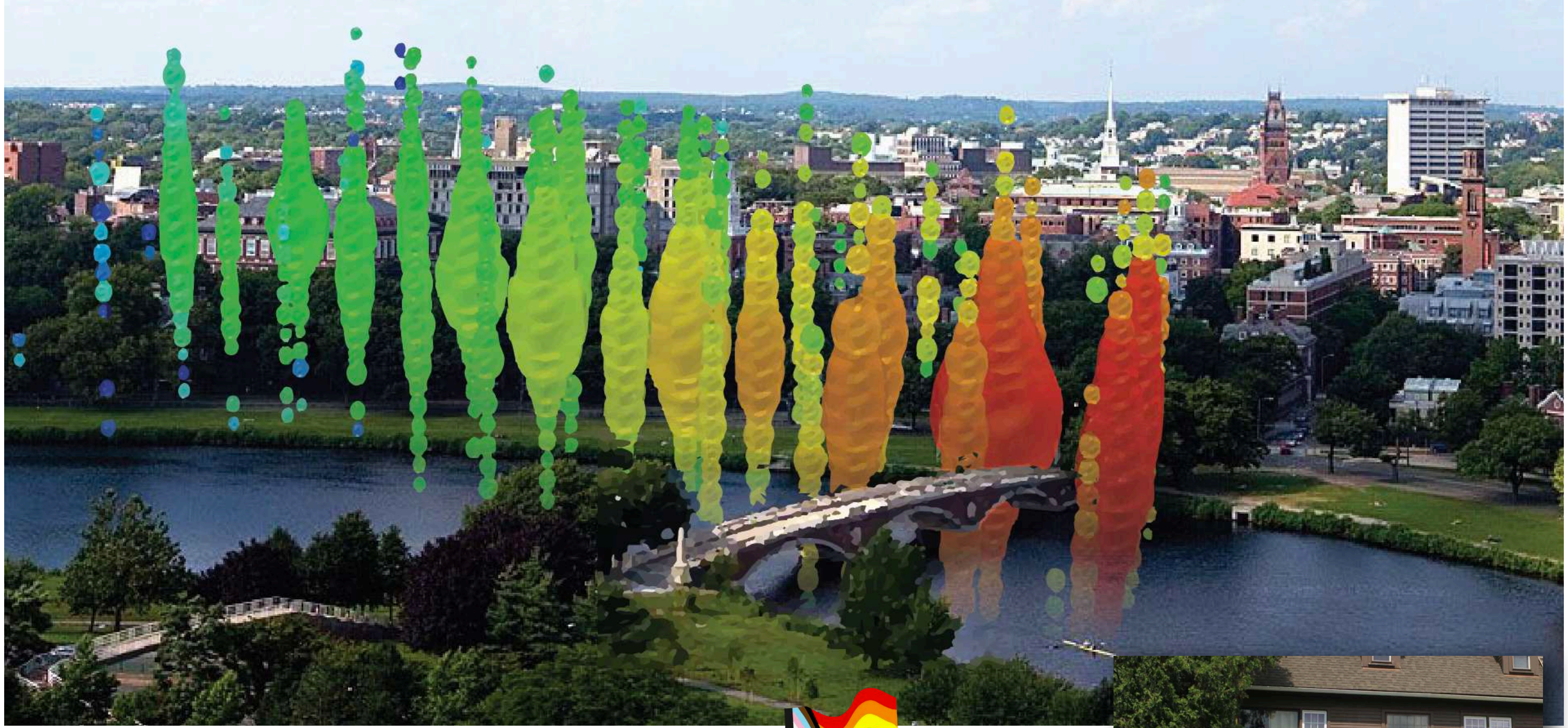
Conclusion

We live in exciting times for particle astrophysics

- First astrophysical neutrino sources are appearing.
- IceCube is able to observe neutrinos from all flavors.
- Neutrino interferometry is a powerful tool to measure tiny effects.

We also have great opportunities for the future

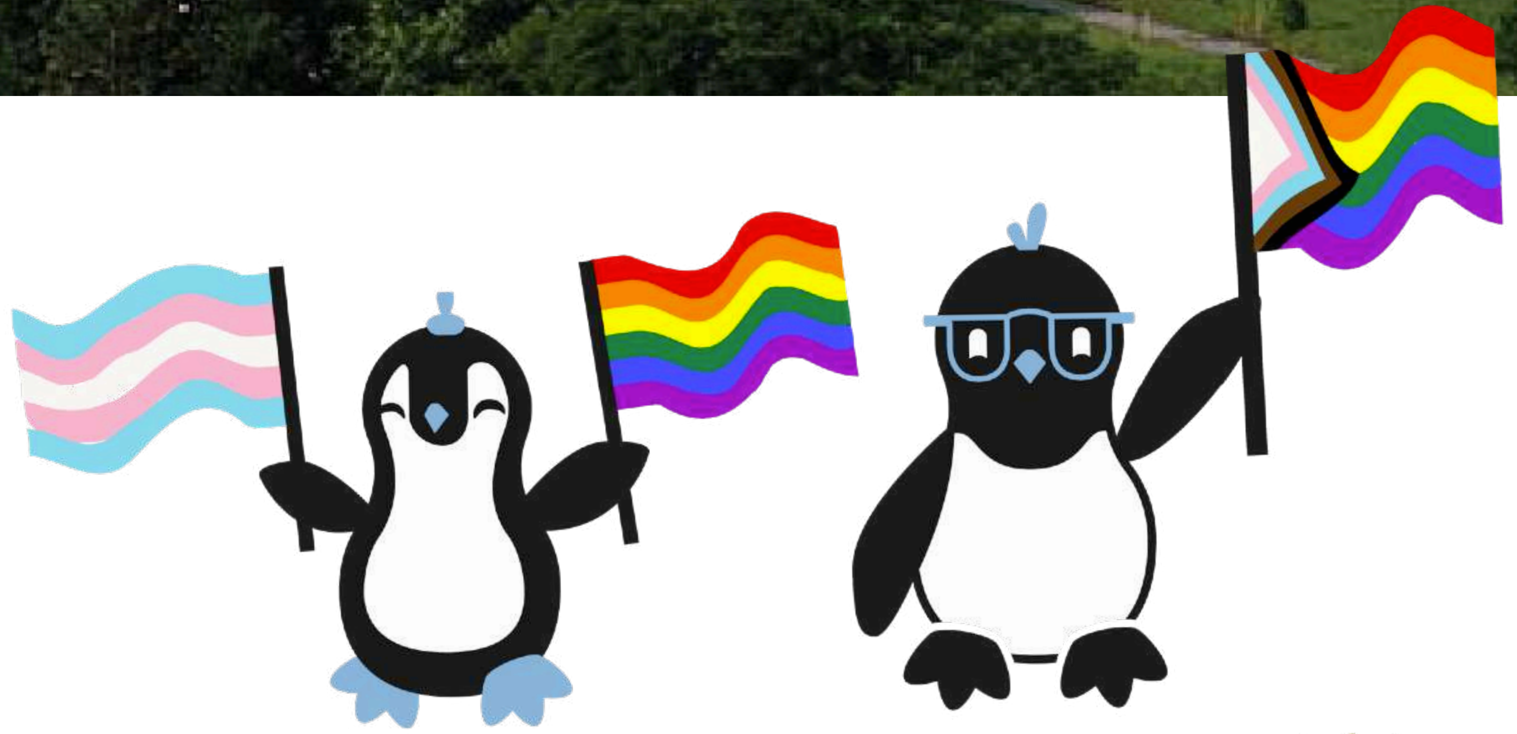
- With IceCube we have a rich data set for continuing searches
- With the Upgrade we will have great new precision
- More neutrino telescopes: more data!
- Diversified neutrino telescope portafolio opens new opportunities for discovery



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

KM3NeT

TAMBO



Thanks!

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