New Physics With (high-energy) Neutrinos From The Sky

Carlos Argüelles

Invisible Workshop, Bologna, Italy, Jul. 1st, 2024

HARVARD UNIVERSITY

The NSF Institute for Artificial Intelligence and Fundamental Interactions

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

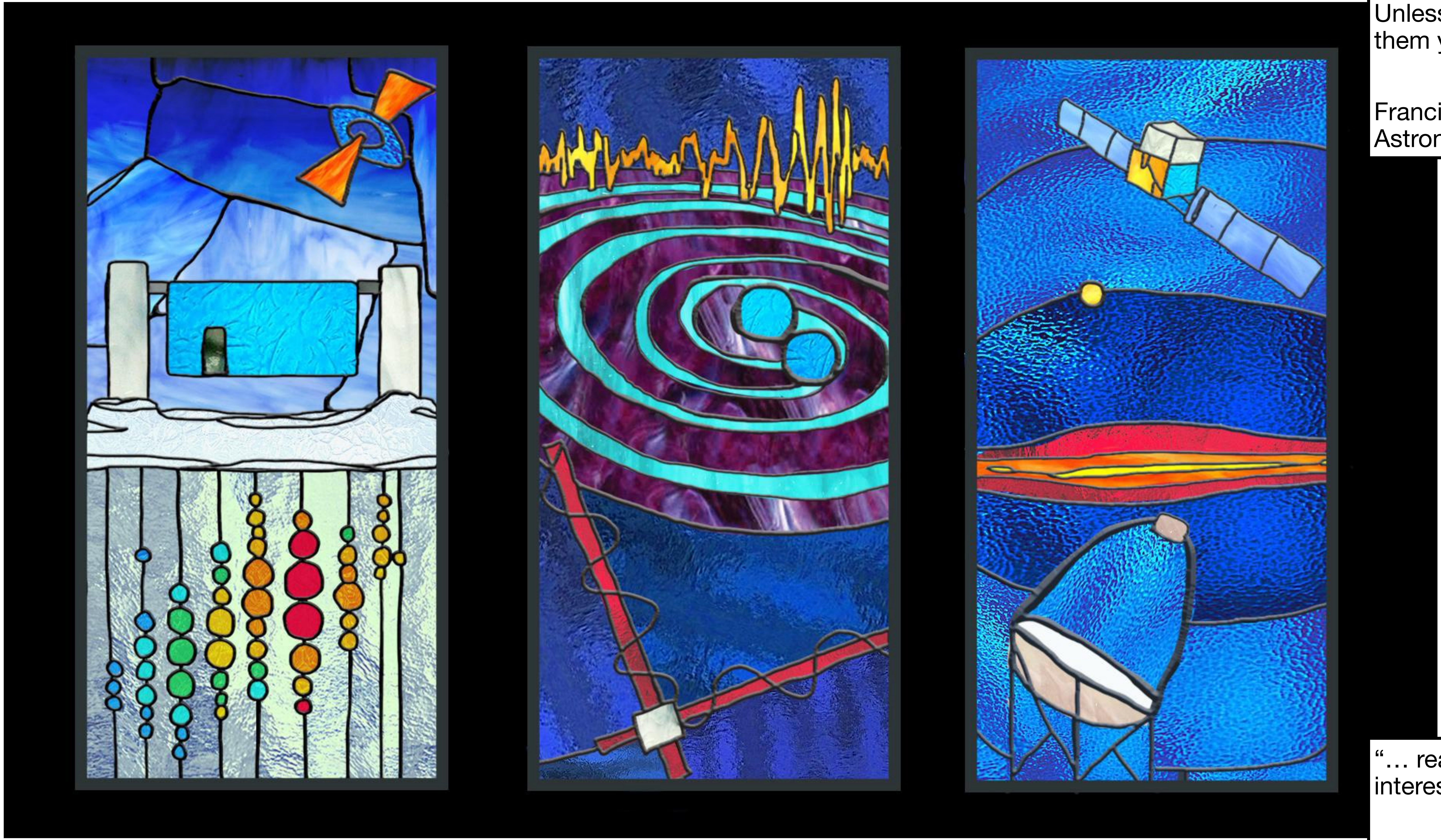
NSF

RESEARCH CORPORATION for SCIENCE ADVANCEMENT

the David & Lucile Packard FOUNDATION

CIFAR

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*

See CA, Kurahashi, and Halzen (arXiv:2405.17623)

"… reality may avoid the obligation to be interesting, but hypotheses may not."

Jorge Luis Borges, *La Brújula y la Muerte*

How do high-energy neutrinos behave?

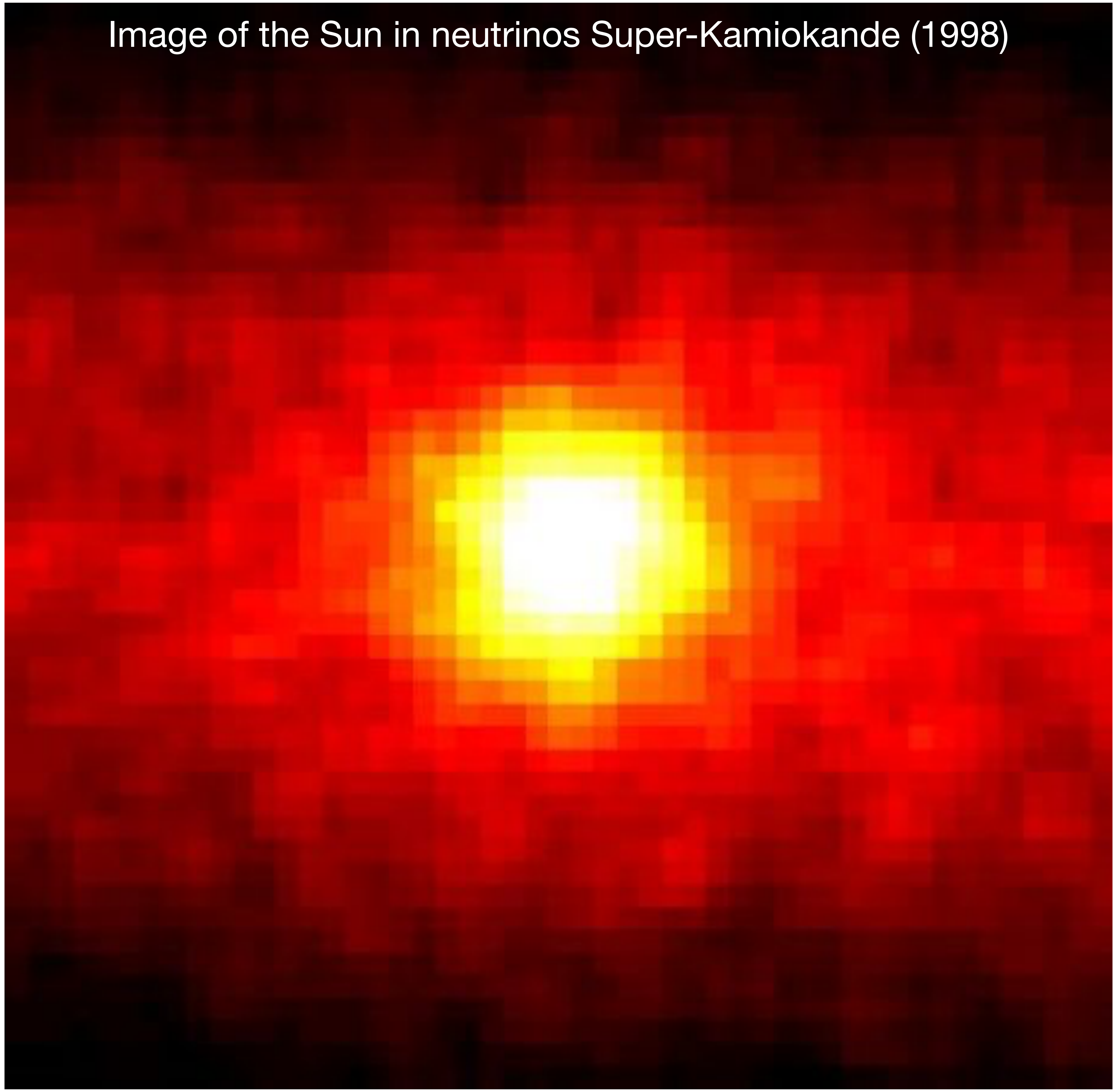
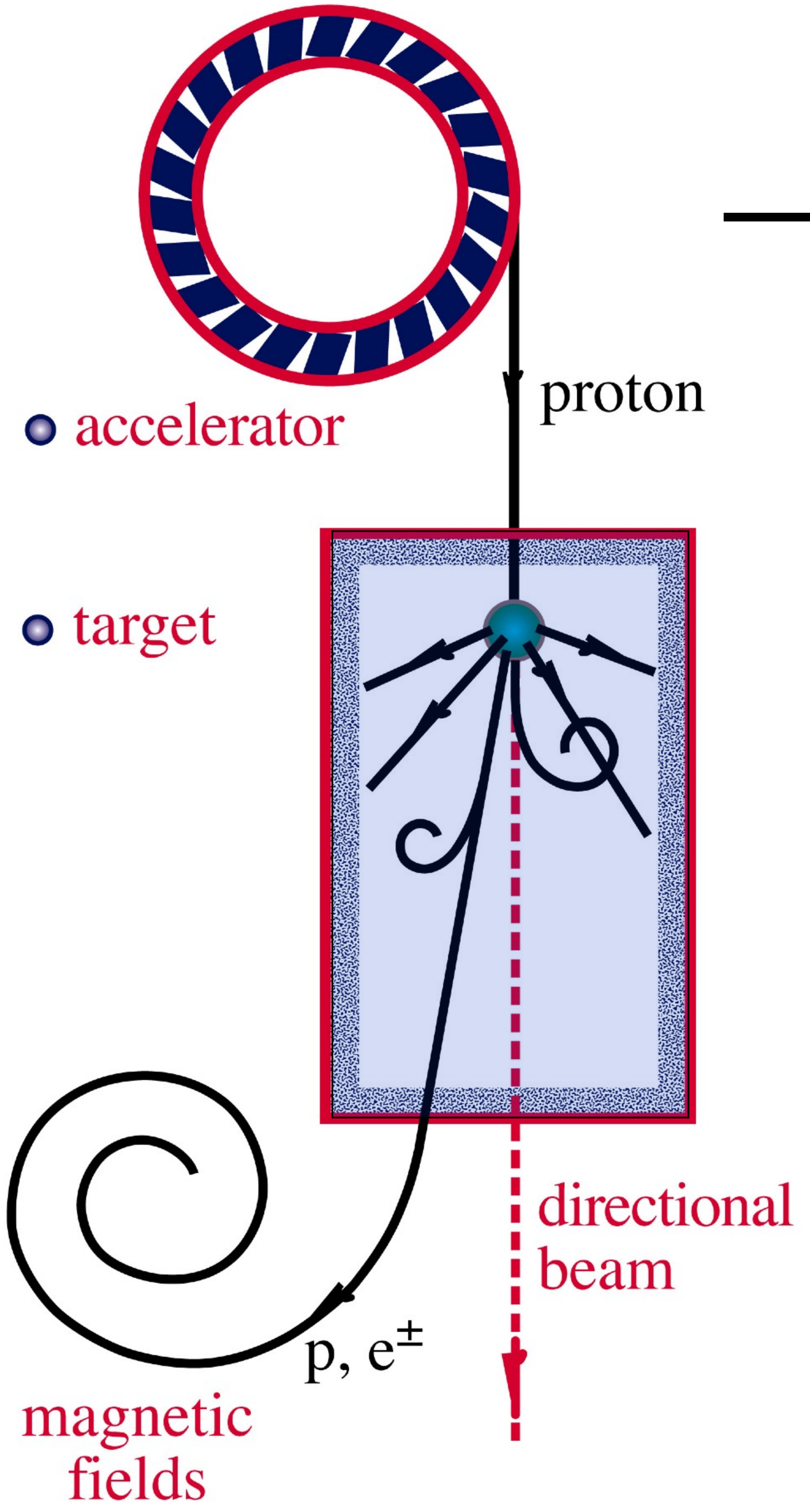


Image of the Sun in neutrinos Super-Kamiokande (1998)

Outline for the rest of this talk

1. **Neutrino astrophysics and IceCube**
2. Most significant observations in neutrino astrophysics
3. New opportunities for particle physics
4. Future detectors & new ideas

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

supermassive black hole

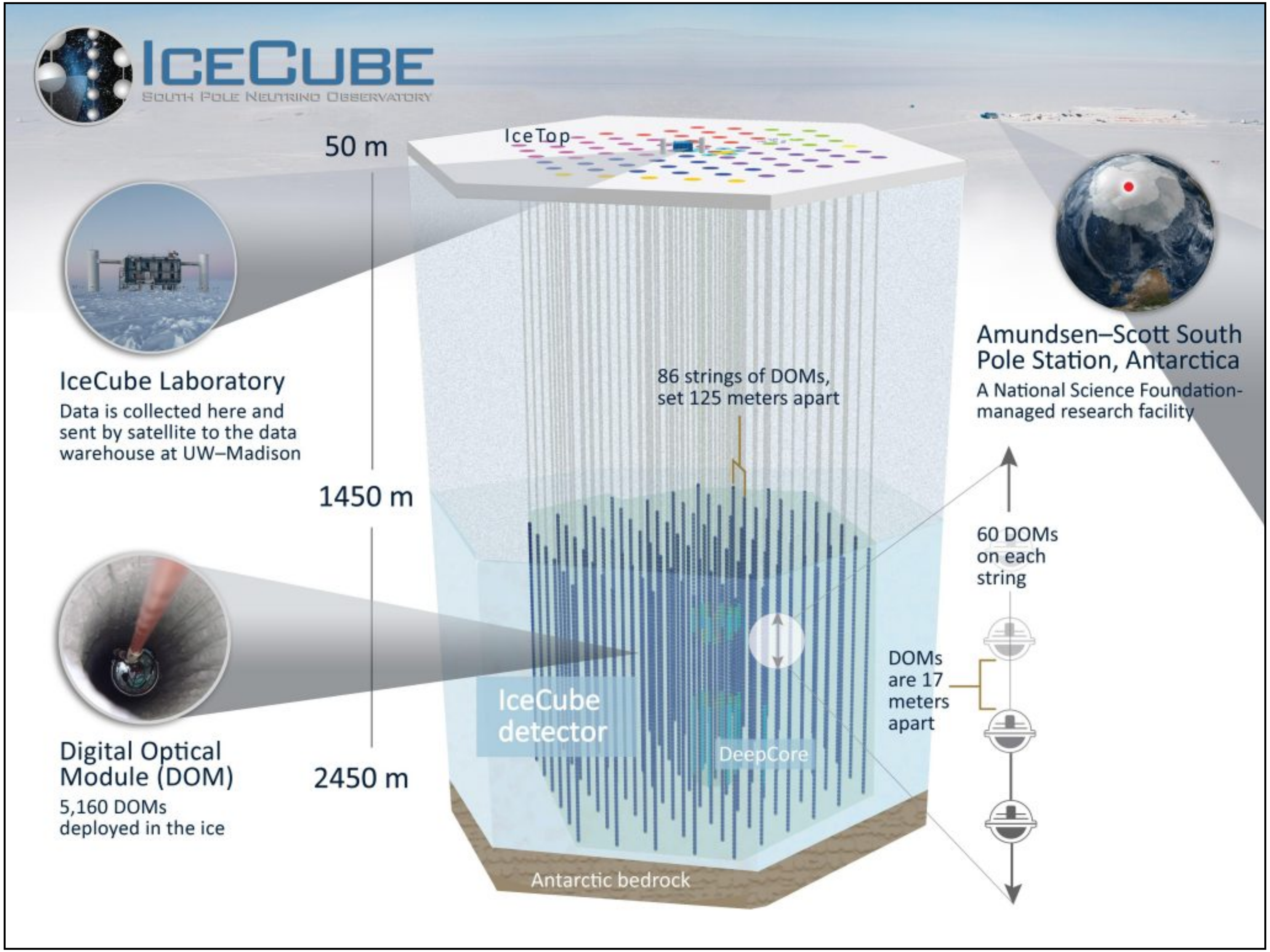
nearby radiation

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

~ cosmic ray + neutrino

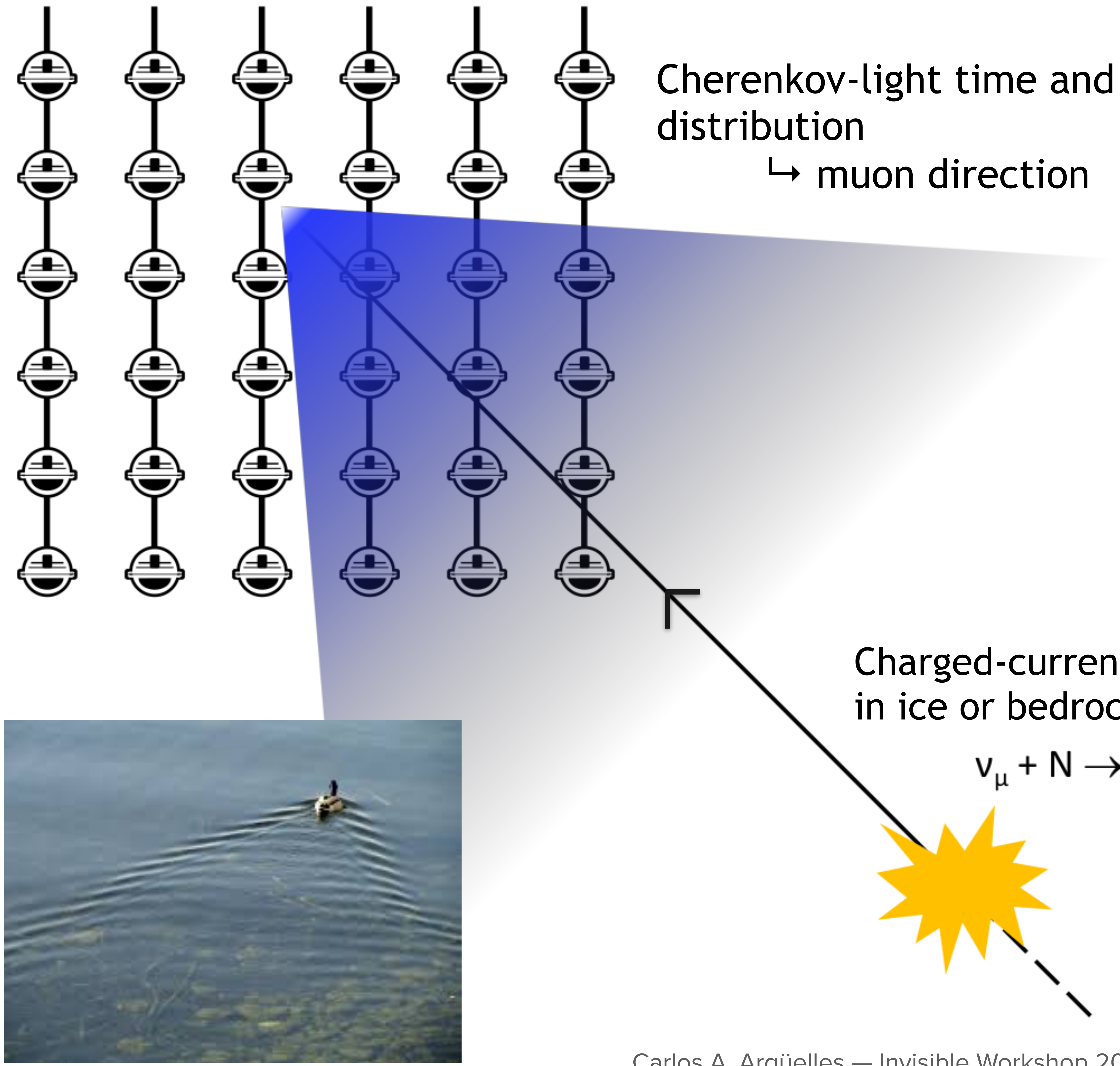
$\rightarrow p + \pi^0$

~ cosmic ray + gamma



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

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

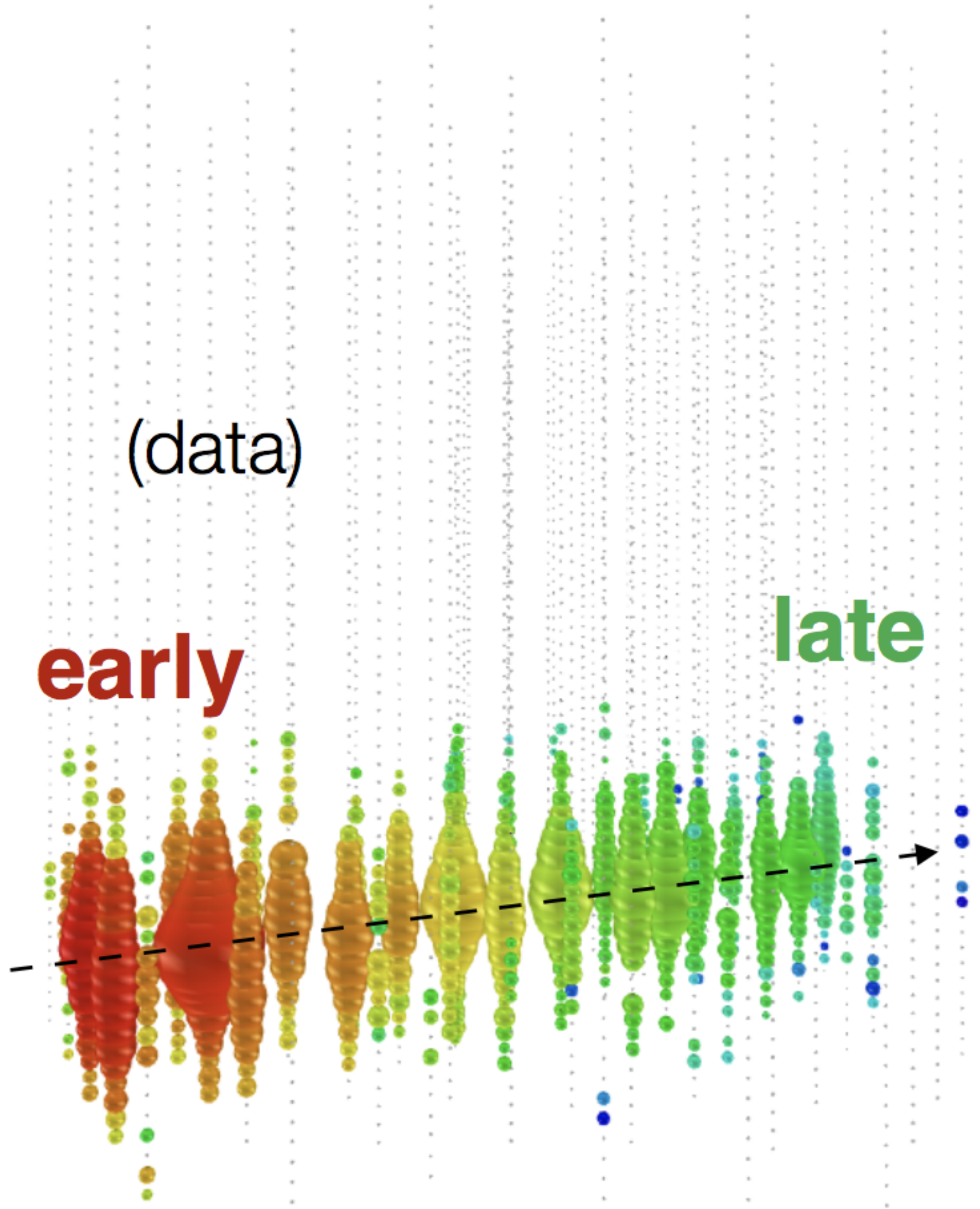
Principle detection mechanism of neutrino telescopes is Cherenkov light.


deg
wn, max E(GeV) == 1206.72
nown, max E(GeV) == 1.42

All event morphologies

Charged-current ν_μ

(data)

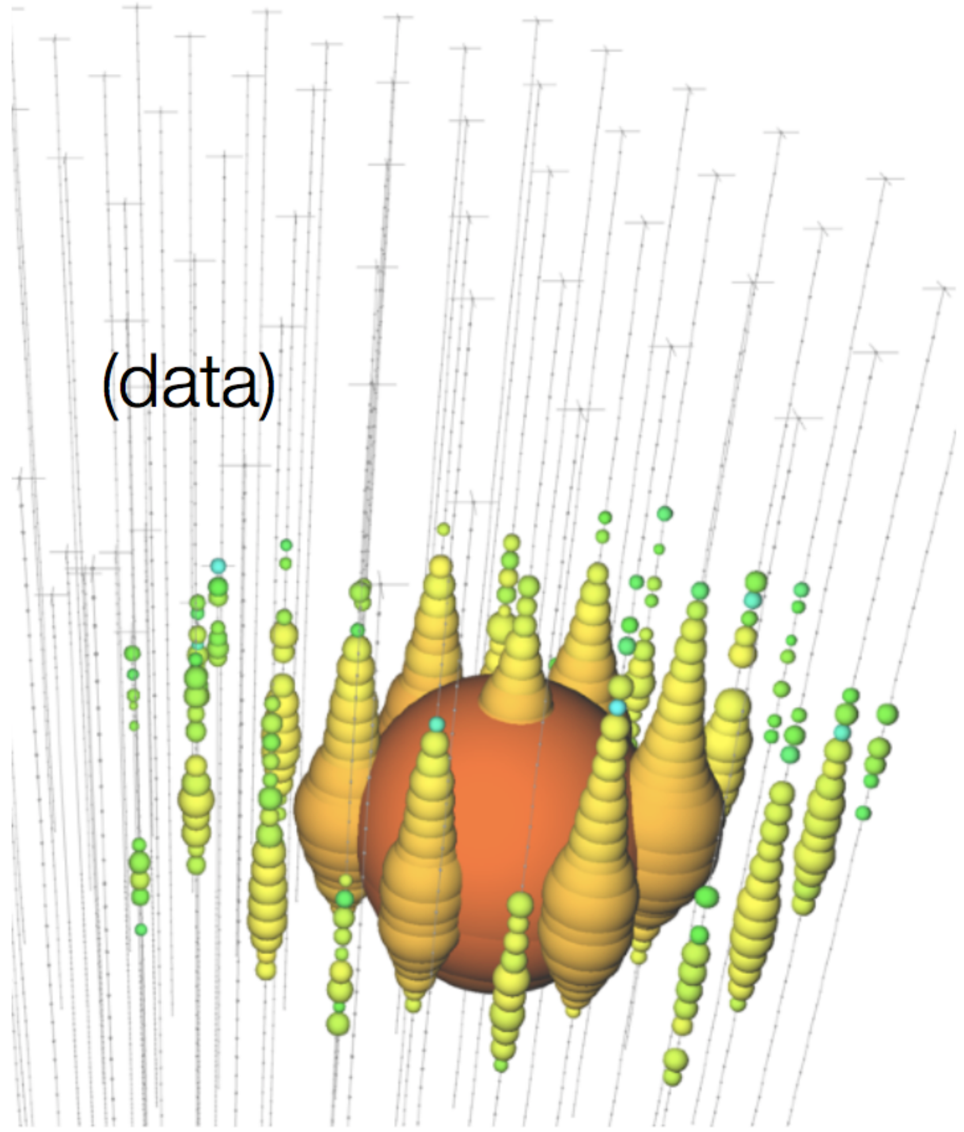


Up-going track

Factor of ~ 2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

(data)

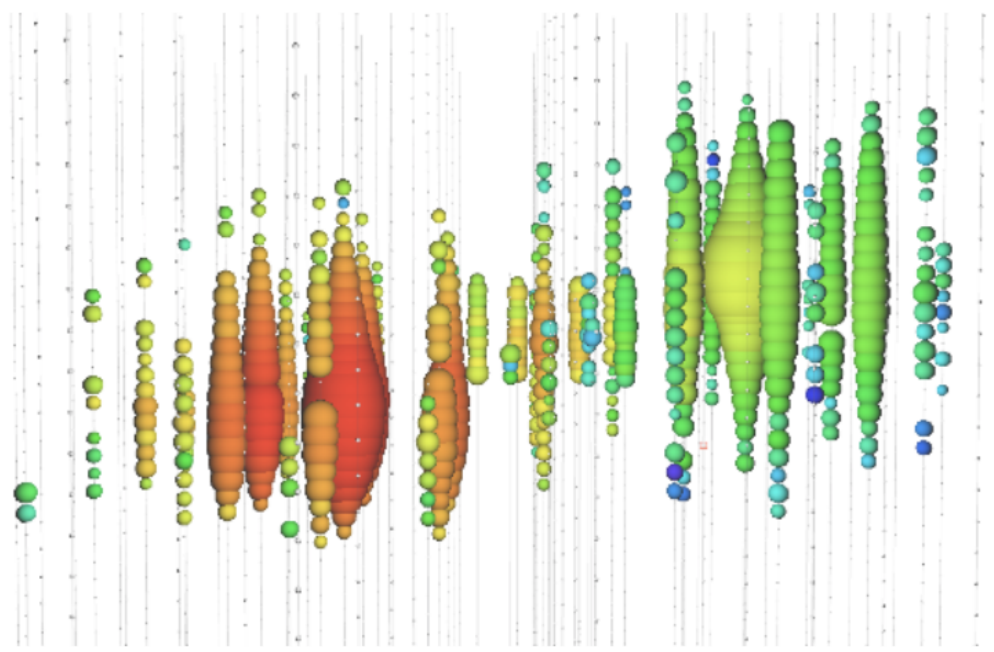


Isolated energy deposition (cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

Charged-current ν_τ

(simulation)

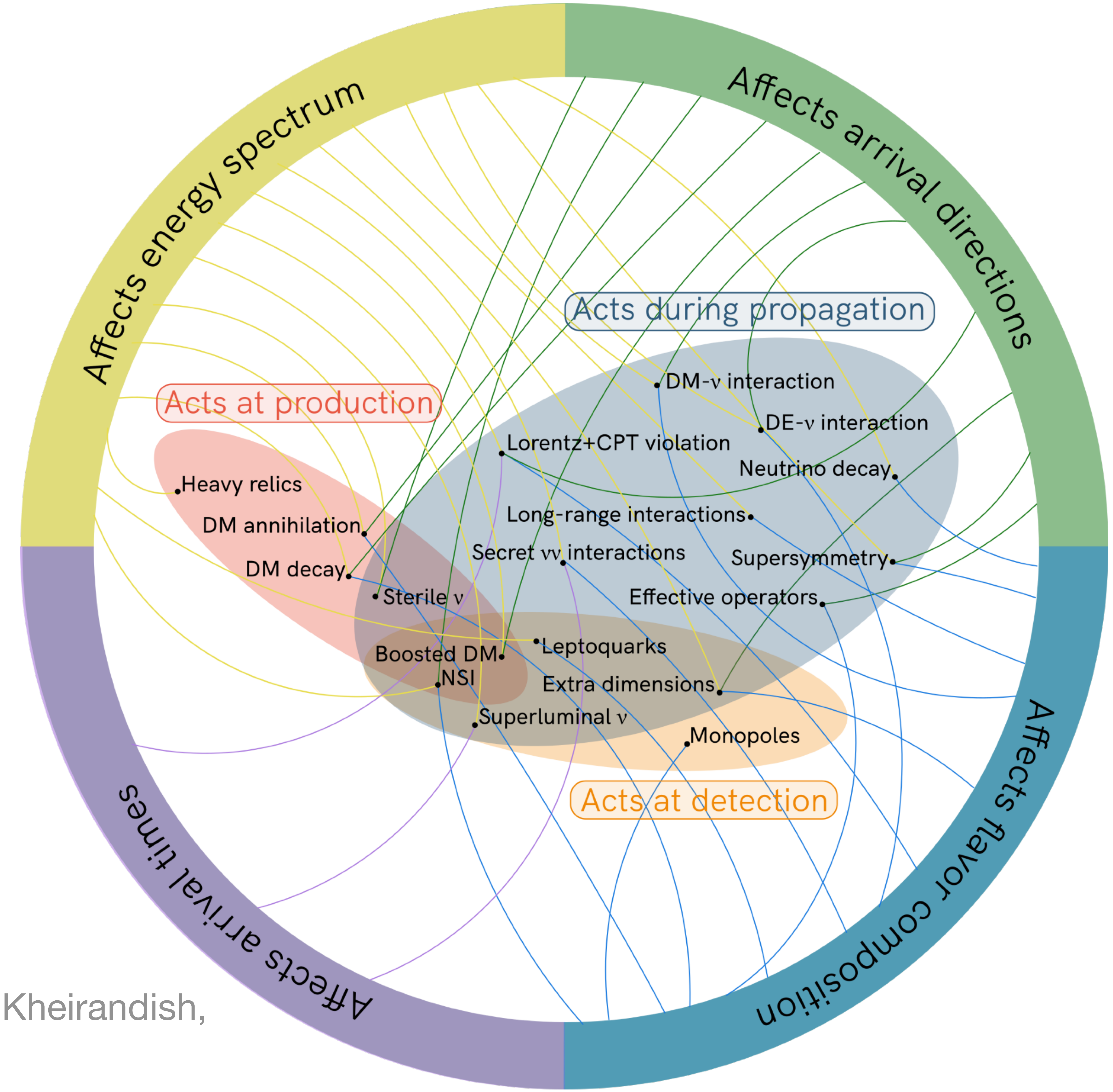


Double cascade

(resolvable above ~ 100 TeV deposited energy)

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

Observables and Models

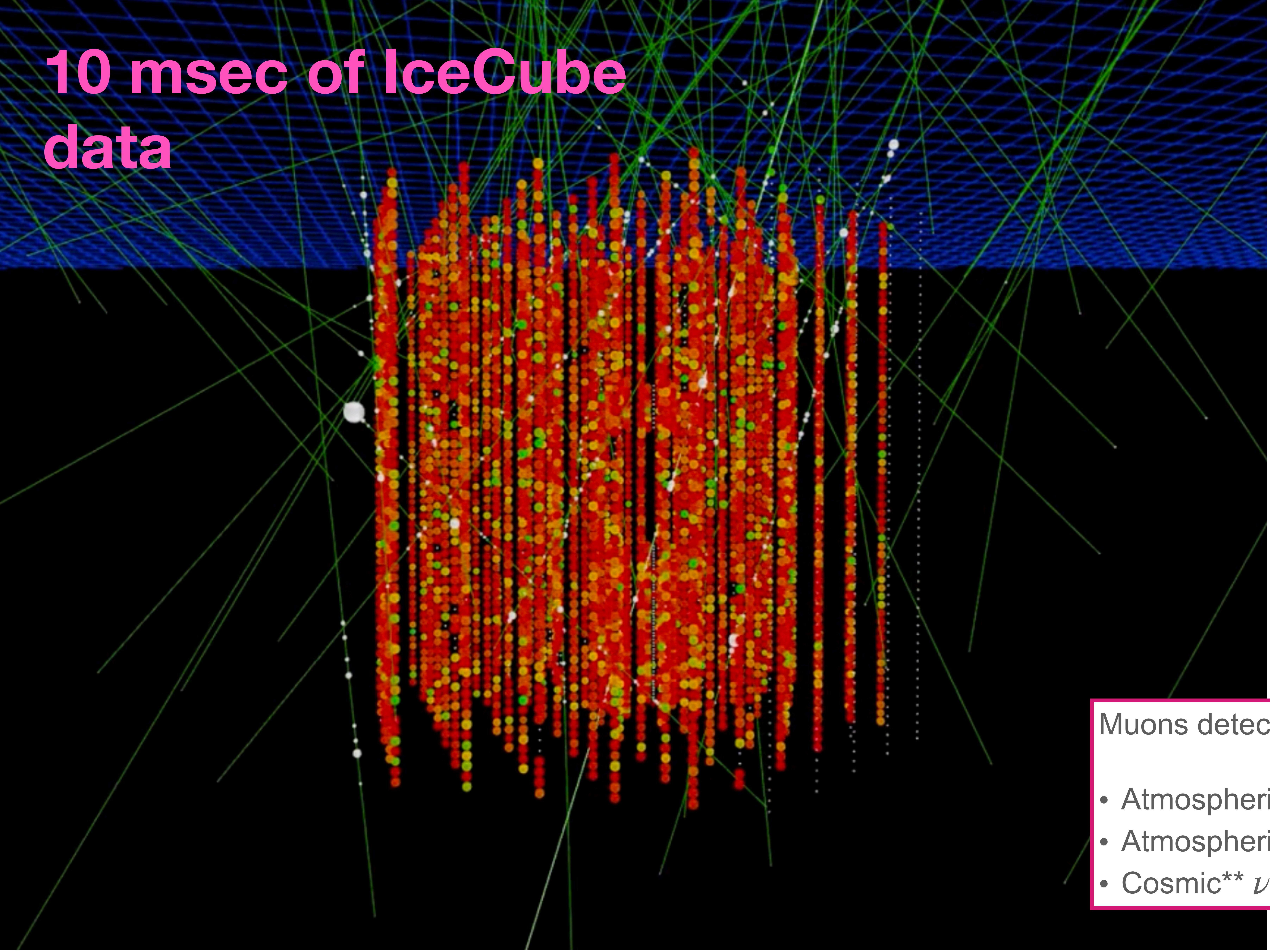


More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Outline for the rest of this talk

1. Neutrino astrophysics and IceCube
2. **Most significant observations in neutrino astrophysics**
3. New opportunities for particle physics
4. Future detectors & new ideas

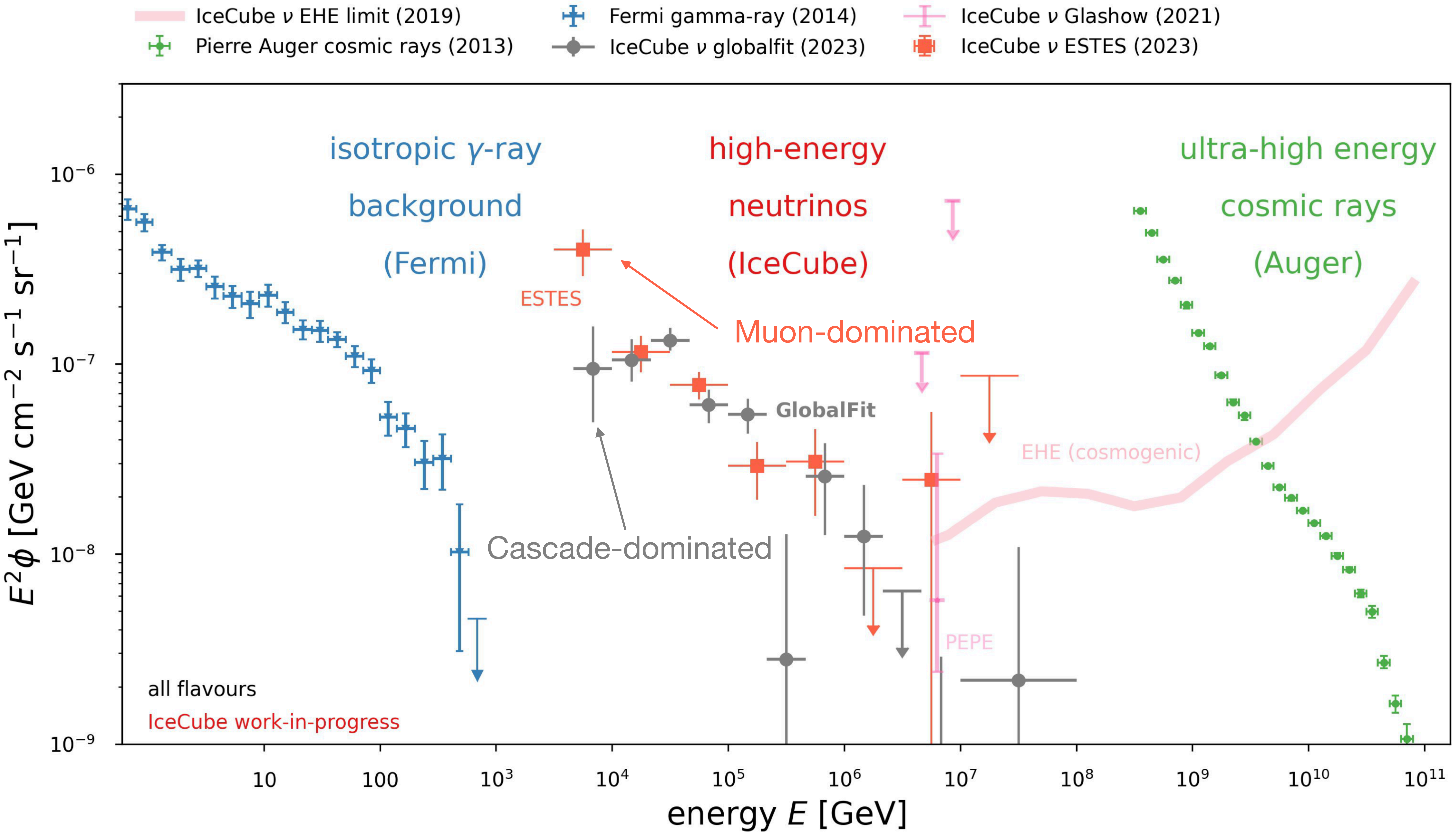
10 msec of IceCube data



Muons detected per year:

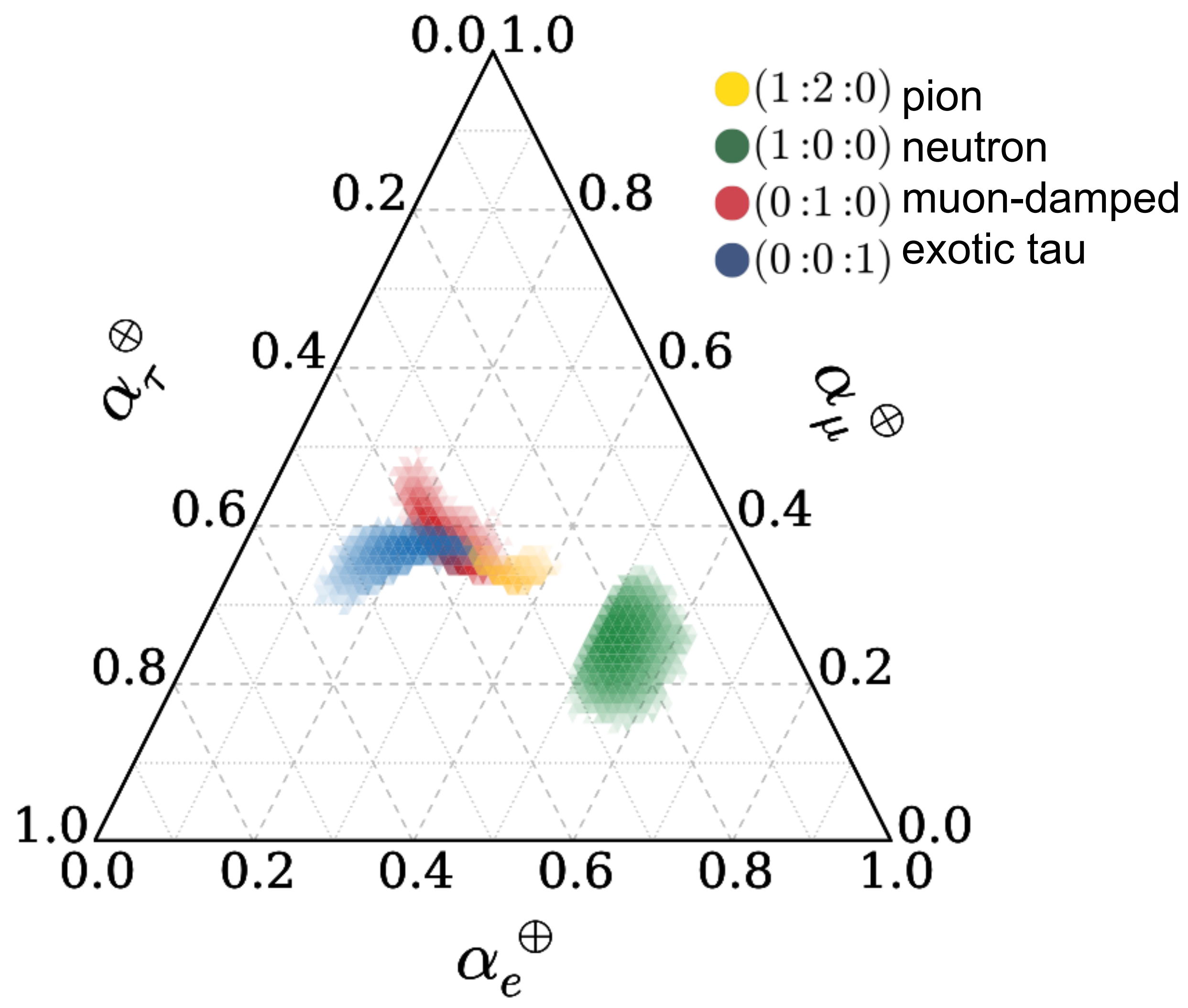
- Atmospheric $\mu \sim 10^{11}$ (3000 per second)
- Atmospheric* $\nu \to \mu \sim 10^{5}$ (1 every 6 minutes)
- Cosmic** $\nu \to \mu \sim 10^{2}$

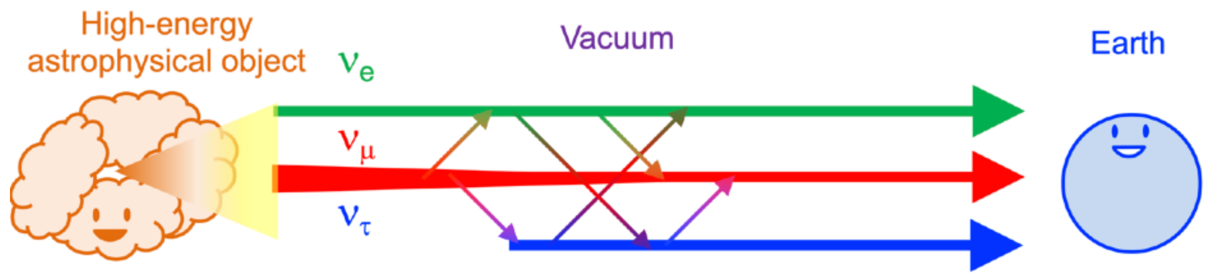
Diffuse Measurement of the Neutrino Sky



L. Lu PoS(ICRC2023)1188

CA, T. Katori, J. Salvado
(Phys. Rev. Lett. **115**, 161303)



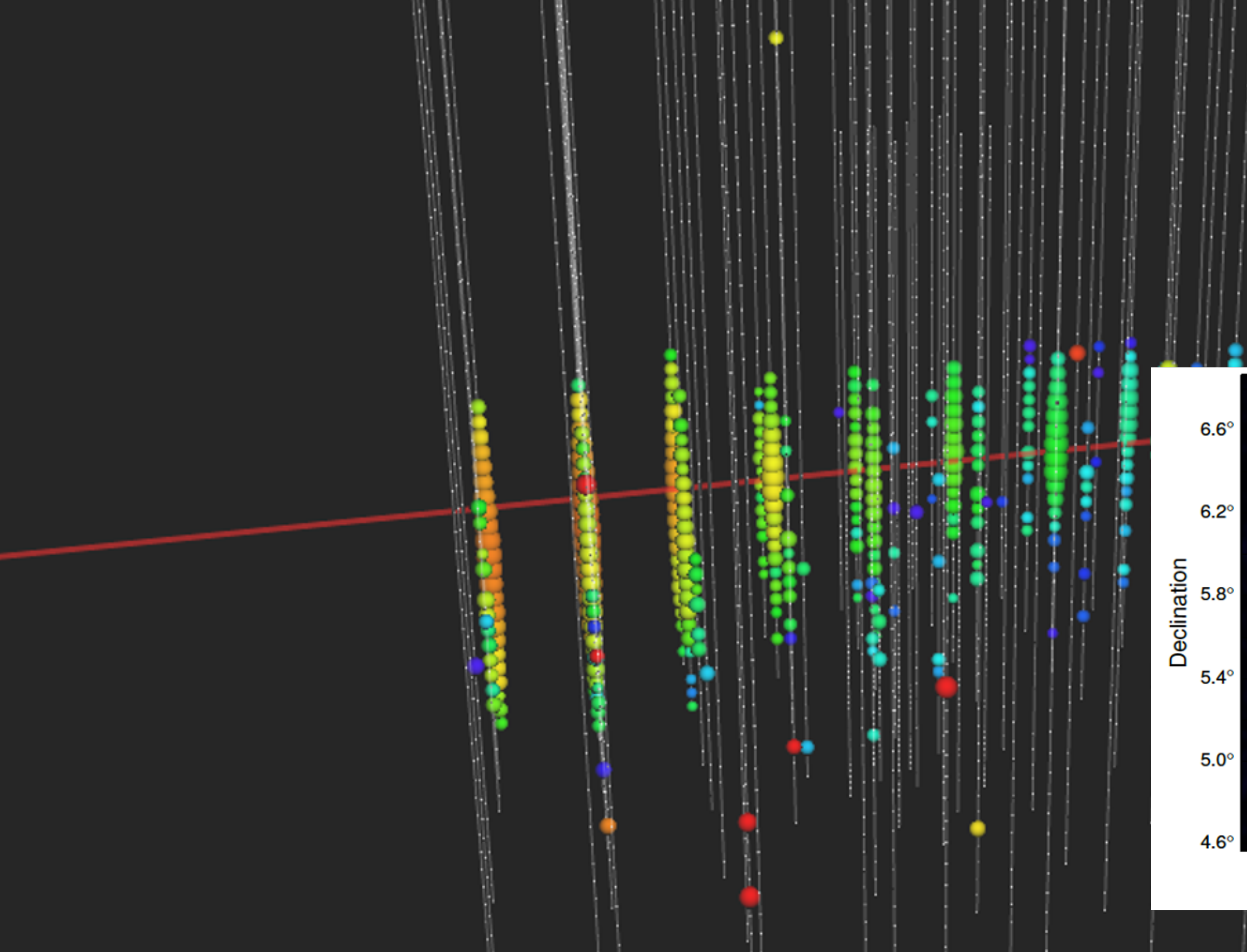


See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

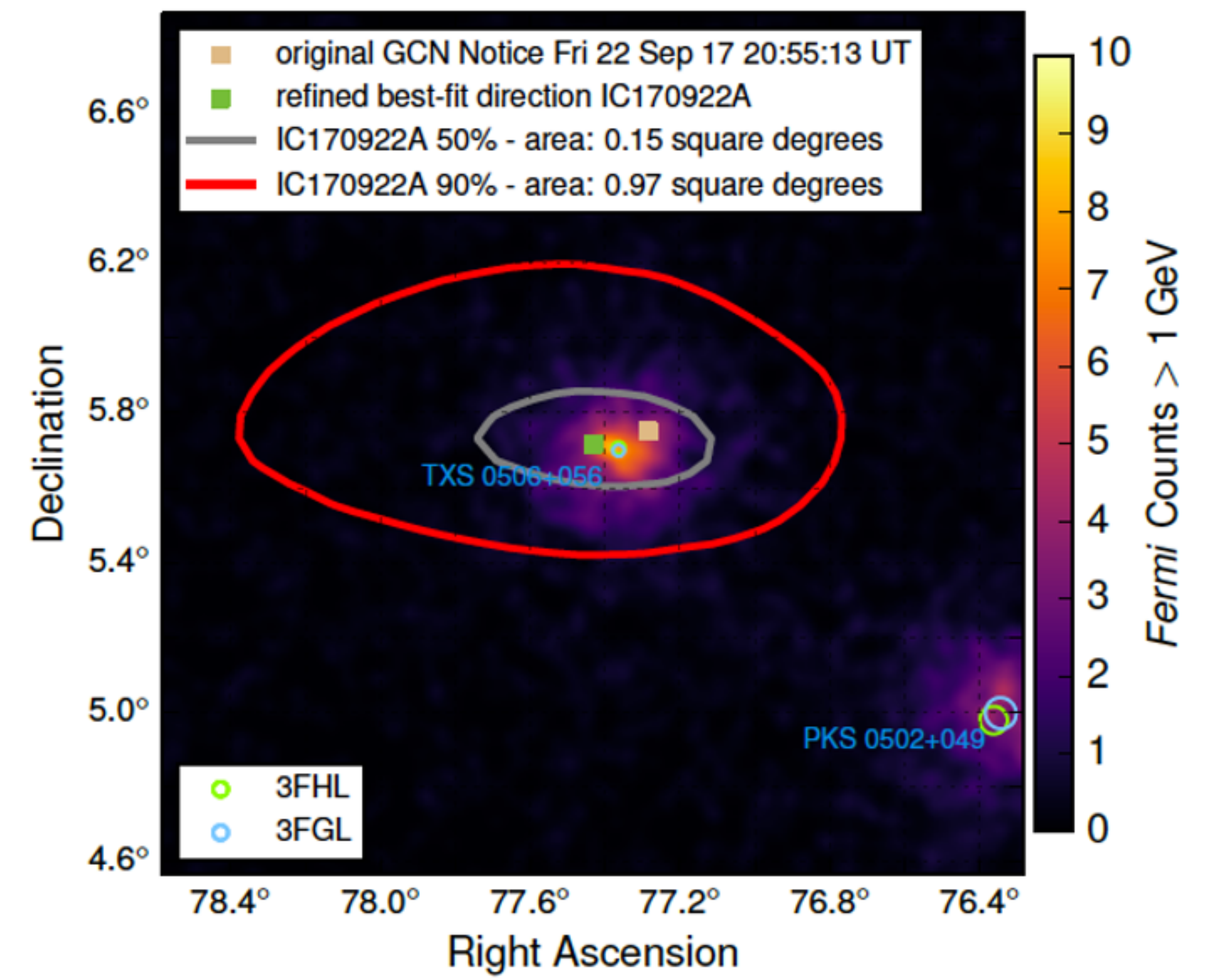
See more details in J. Lazar talk (Tuesday)


IceCube 170922

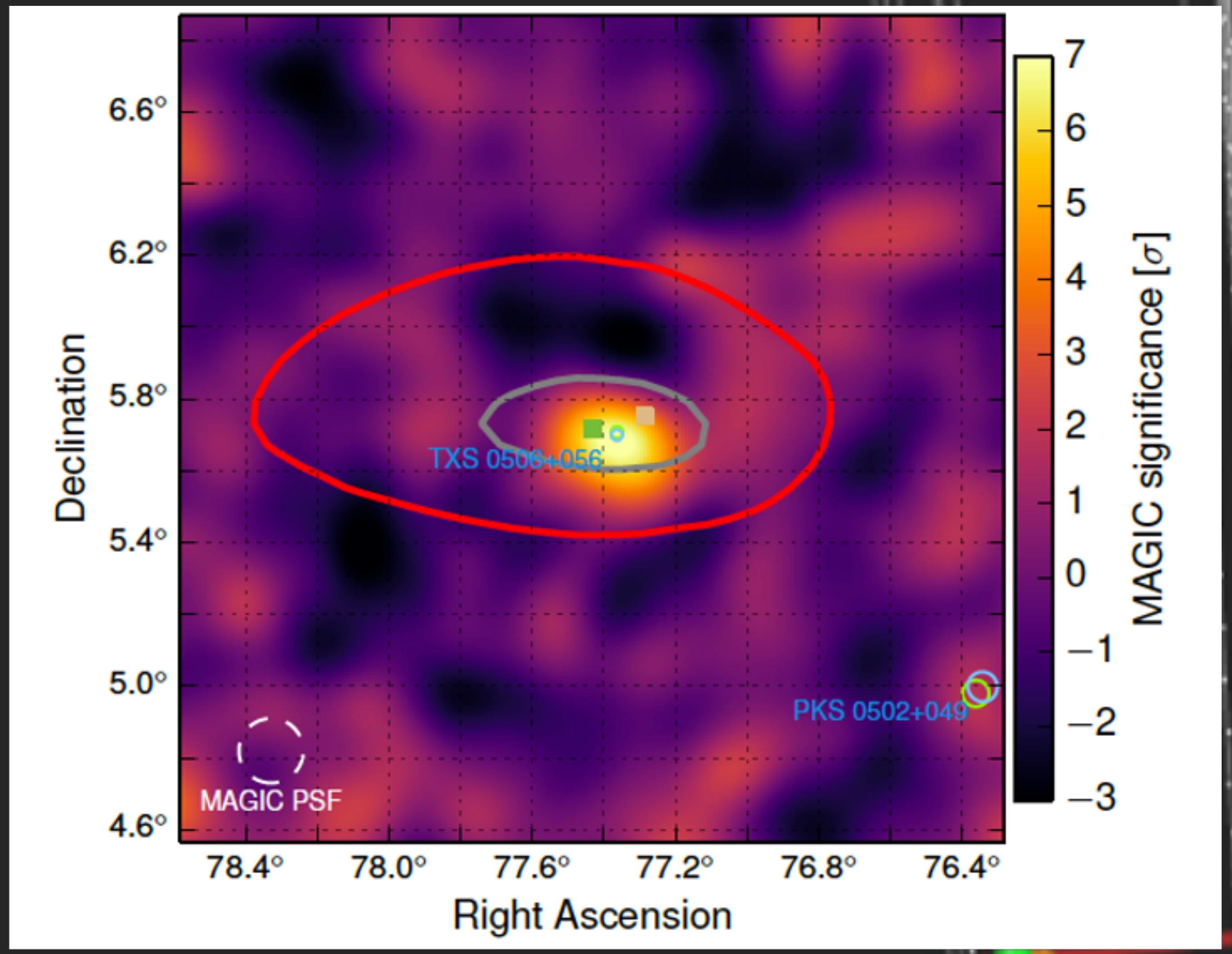
IceCube 170922



Fermi
detects a flaring
blazar within 0.1°

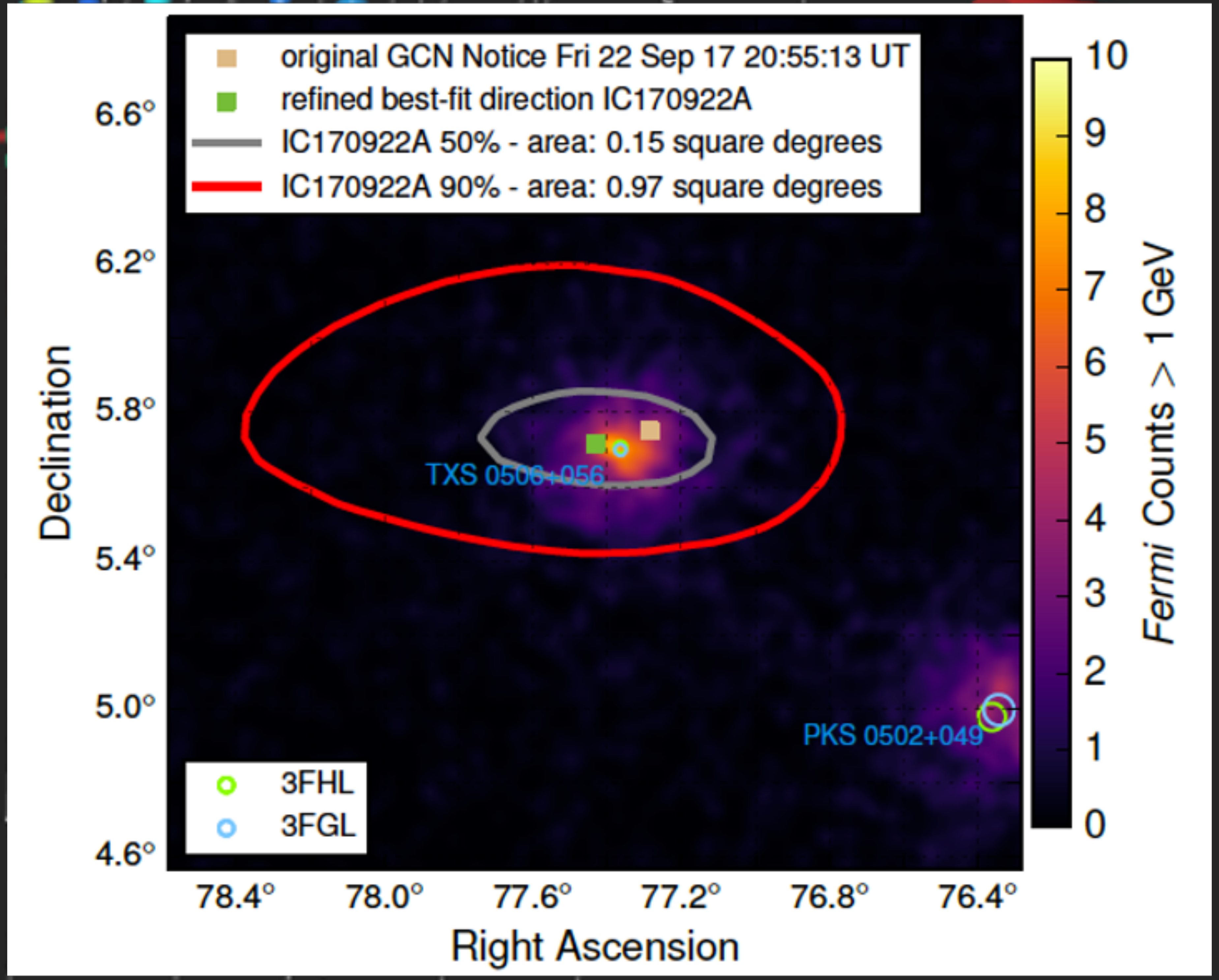


IceCube 170922

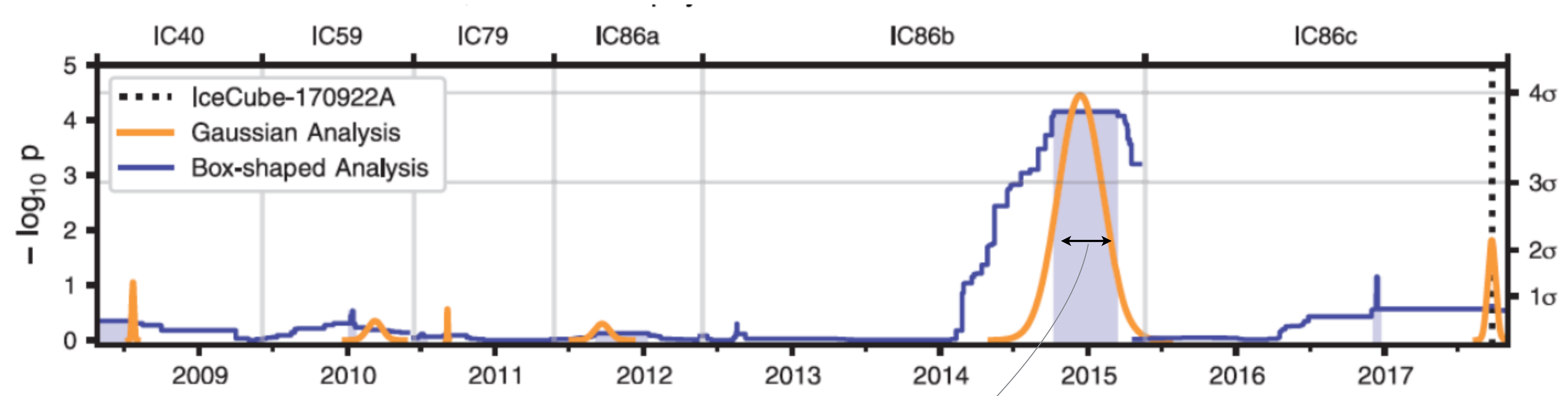


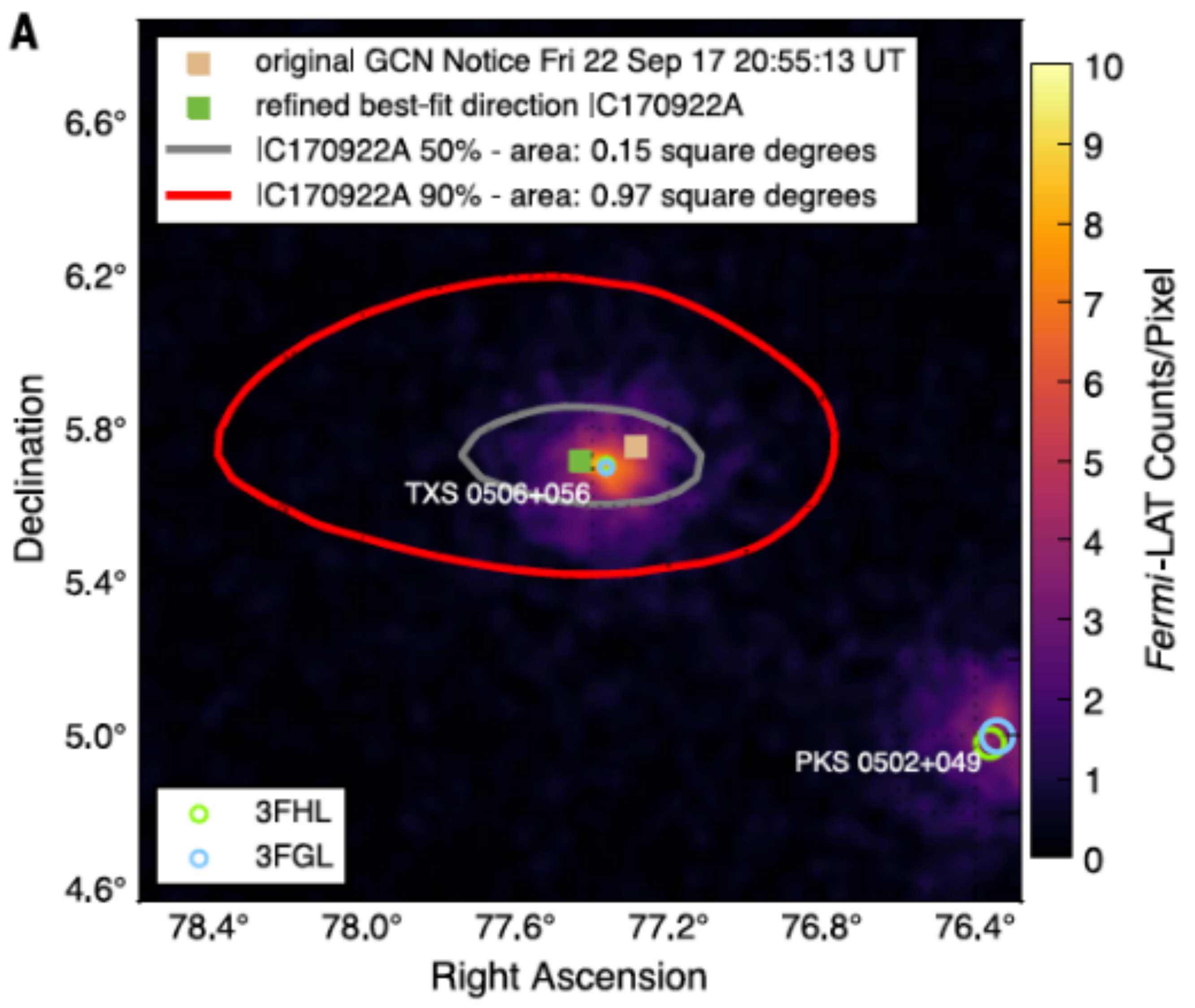
MAGIC
detects emission of
> 100 GeV gammas

Fermi
detects a flaring
blazar within 0.1°



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 earlier flaring time!

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

Gamma-neutrino anti-correlation?

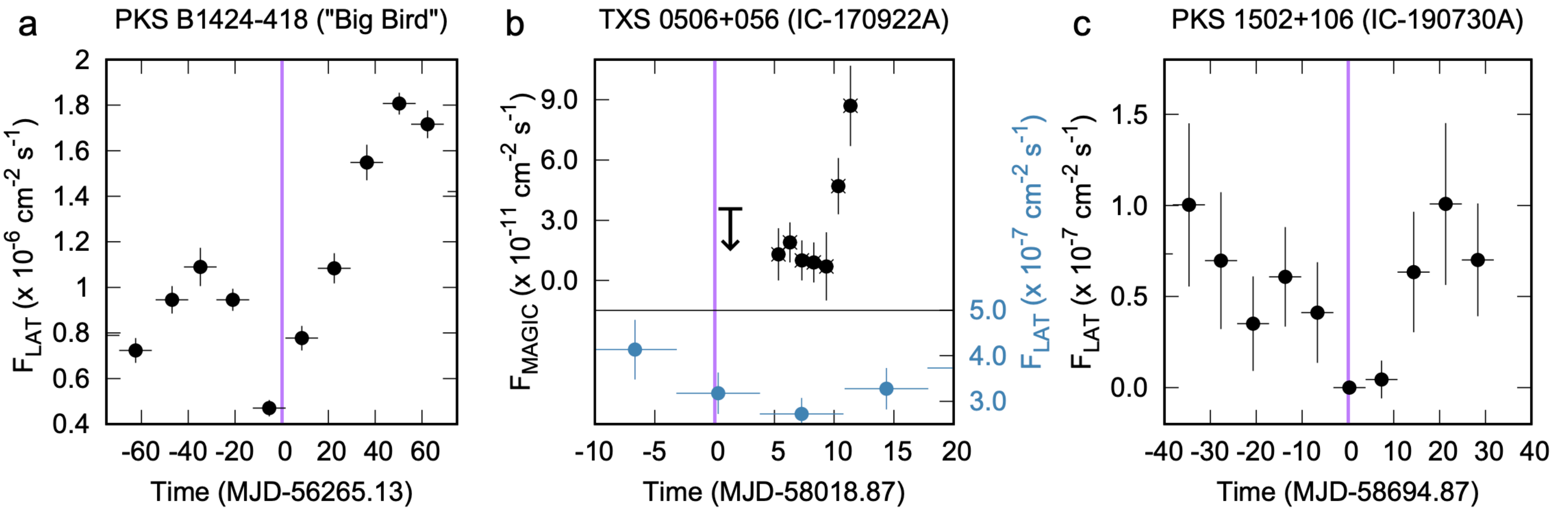


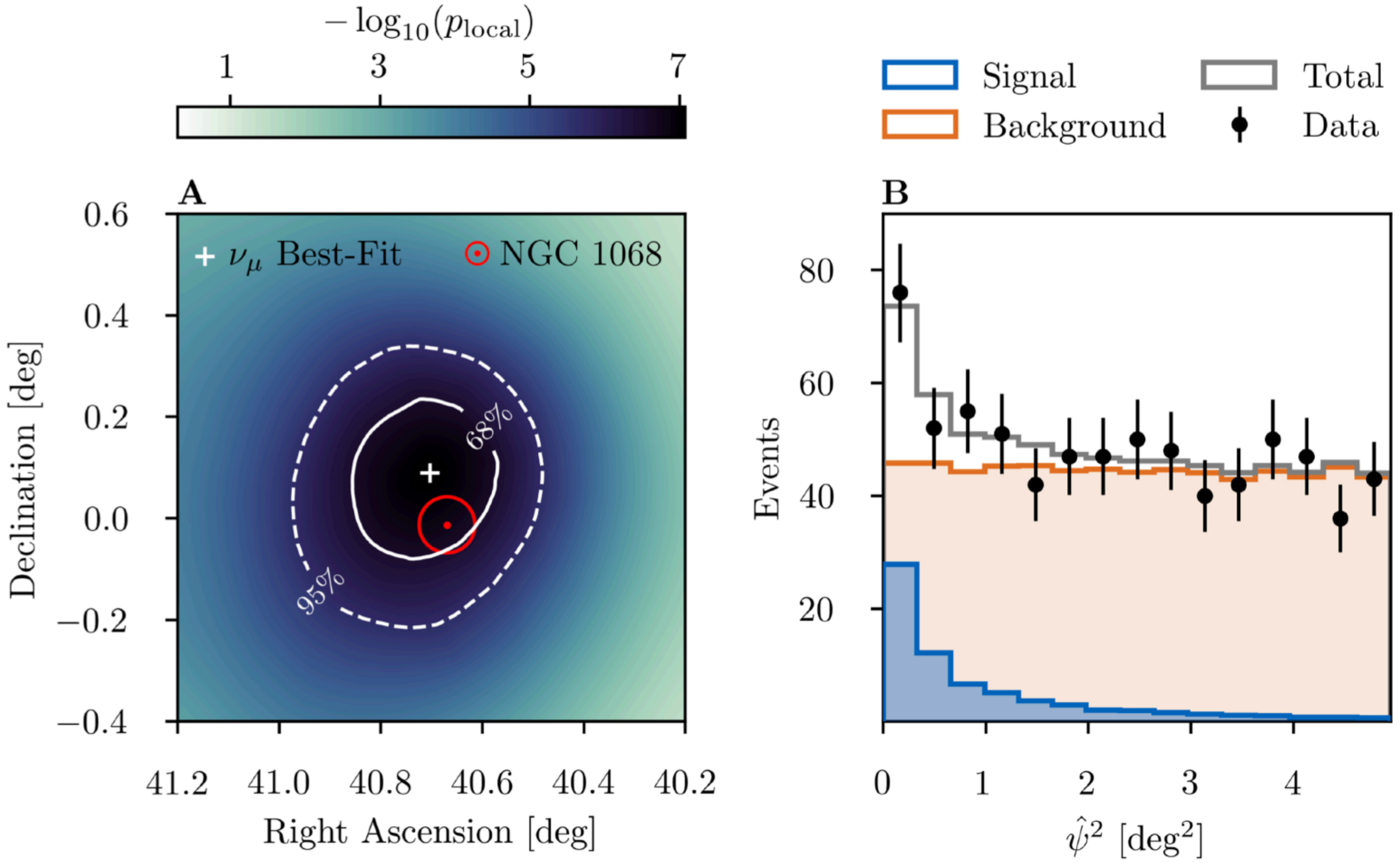
Figure 3. γ-ray light curves for three blazars with coincident high-energy neutrinos. a: PKS B1424-418 as mea-

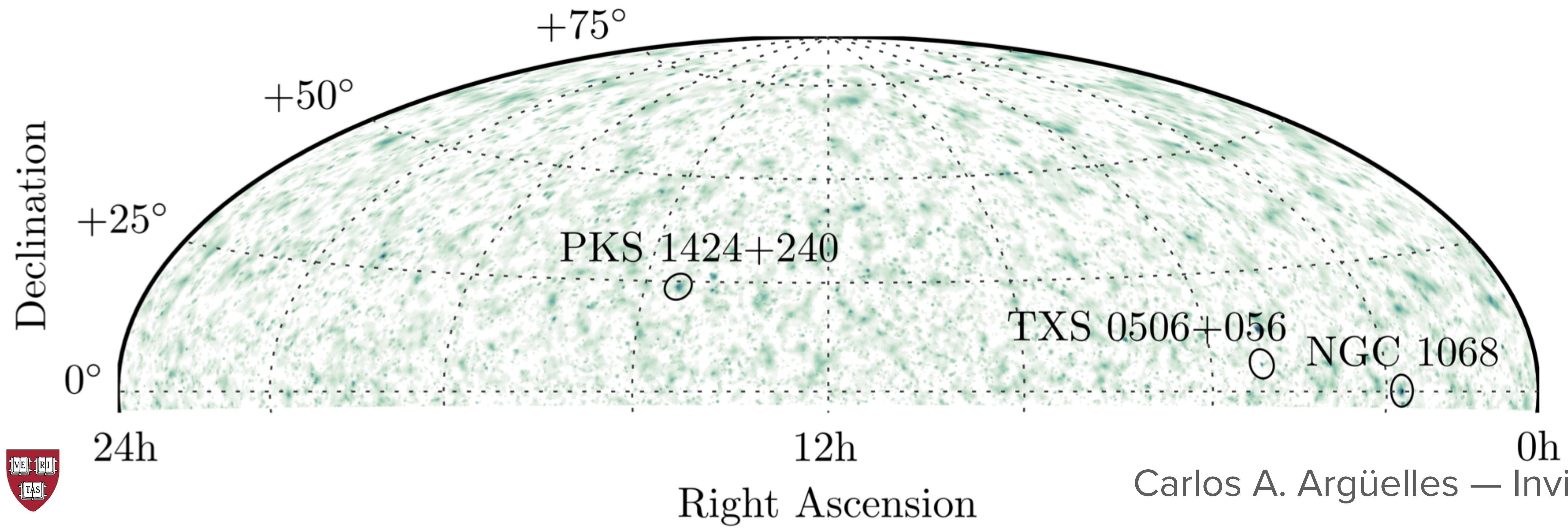
E. Kun, I. Bartos, J. B. Tjus et al 2009.09792

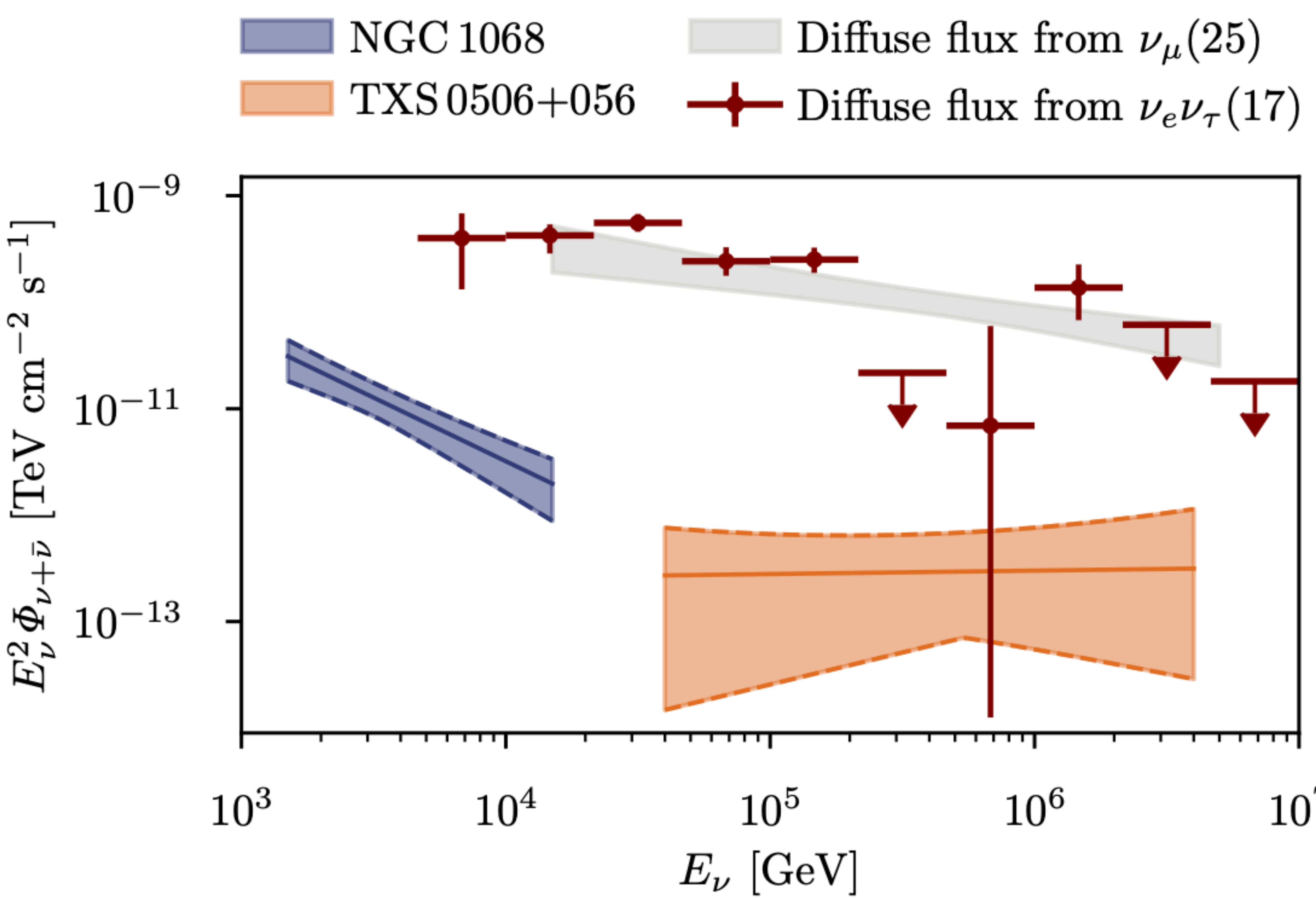
The gamma-ray correlation is not so direct/obvious

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068





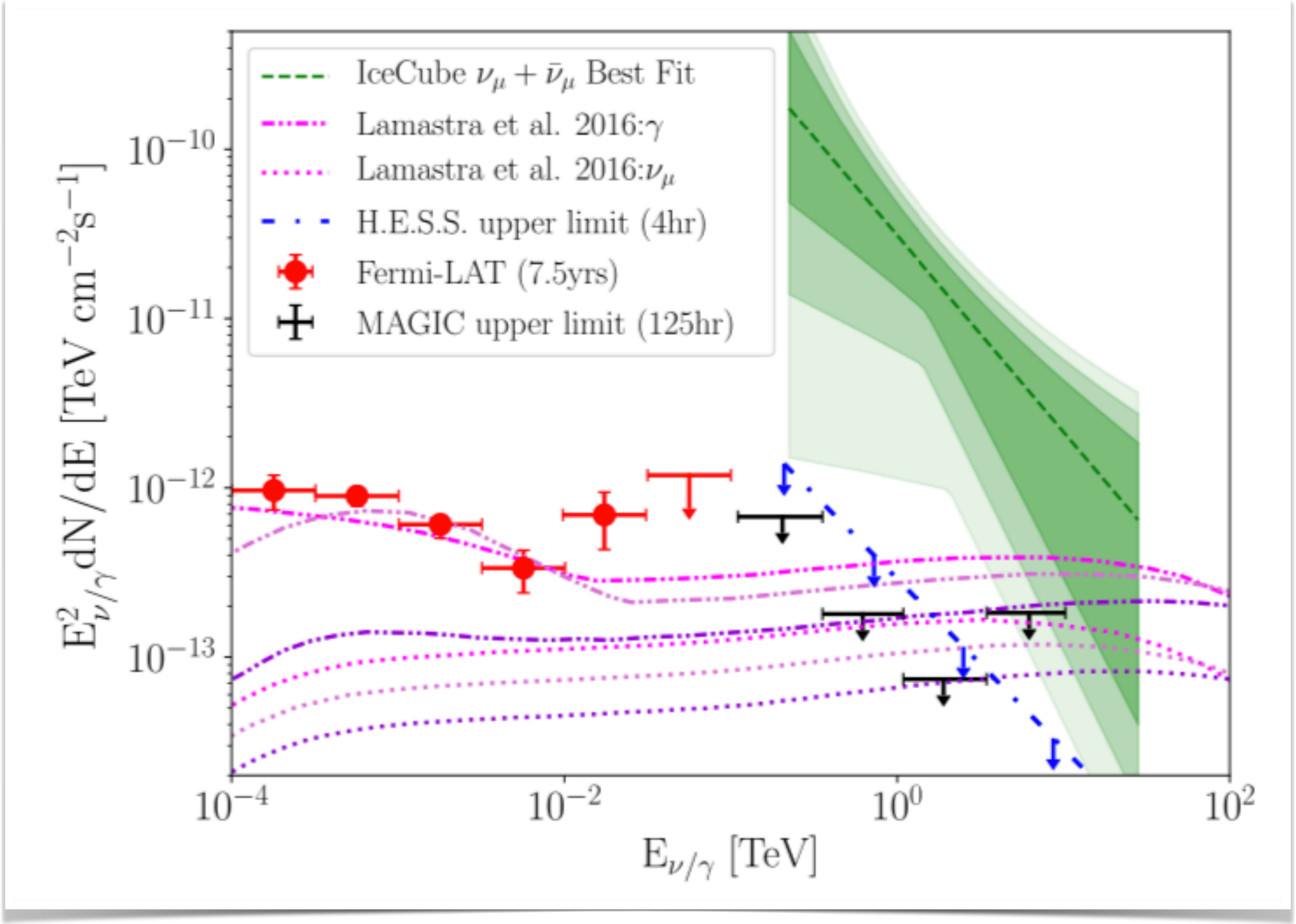


See more details in J. Lazar talk (Tuesday)

Gamma-ray's and Neutrinos From NGC 1068

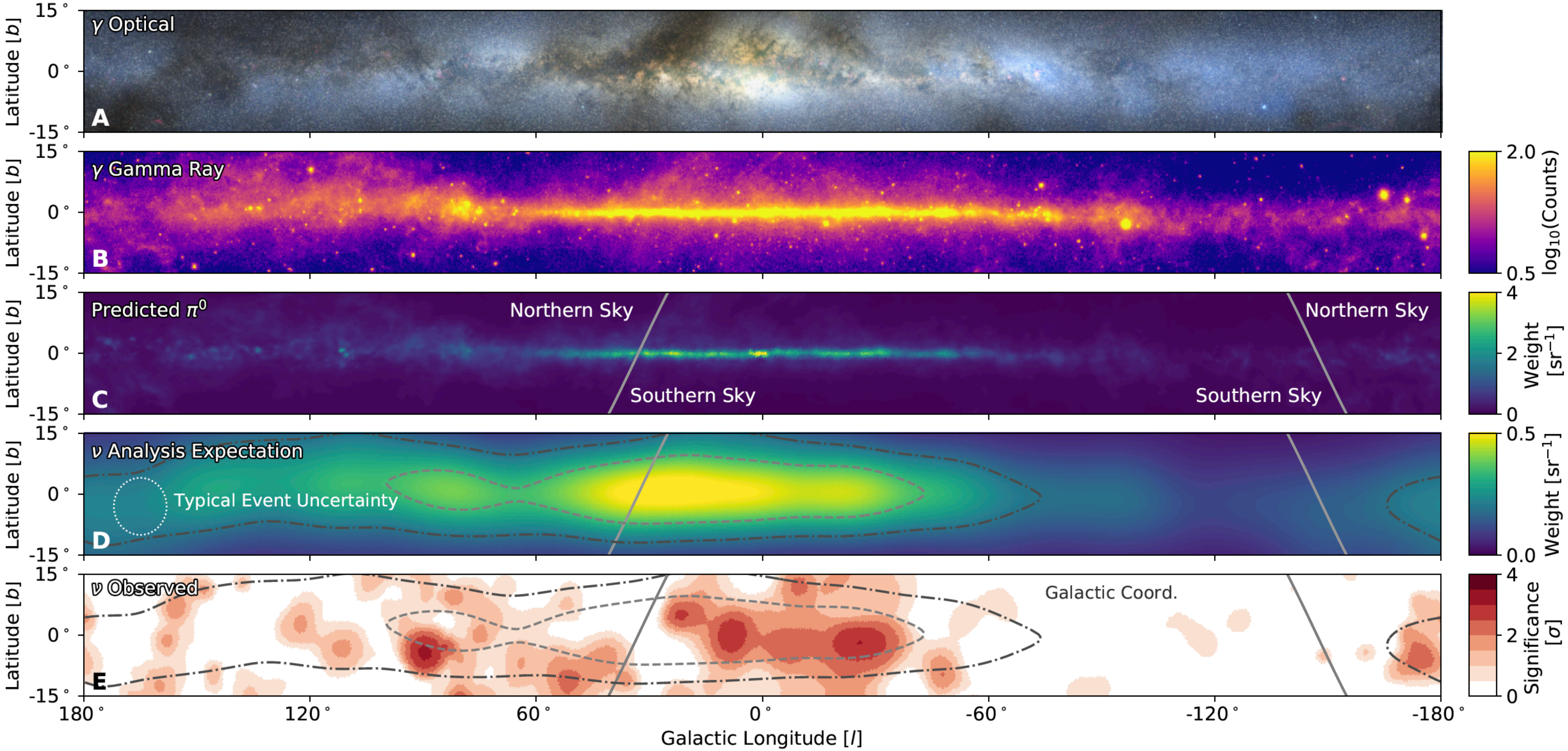
$$\tau_{\gamma\gamma} \propto \frac{\sigma_{\gamma\gamma}}{\sigma_{p\gamma}} \tau_{p\gamma}$$

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



Neutrinos from Our Galaxy

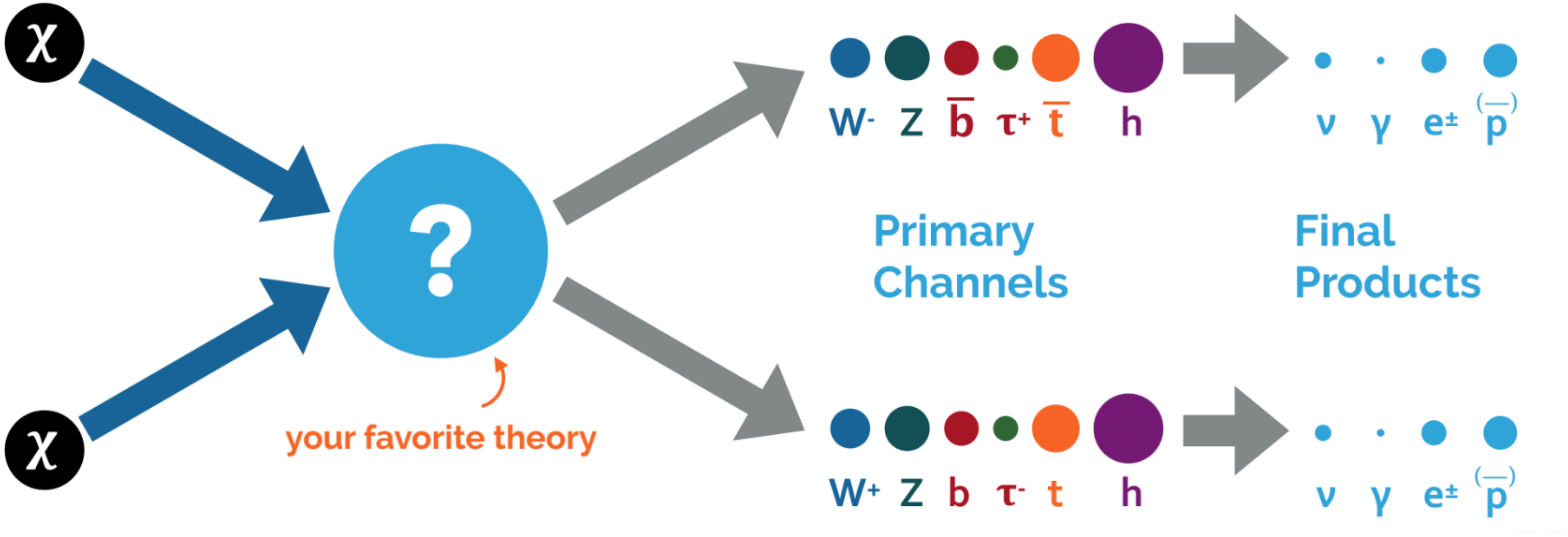
IceCube Collaboration, Science, 2023



Outline for the rest of this talk

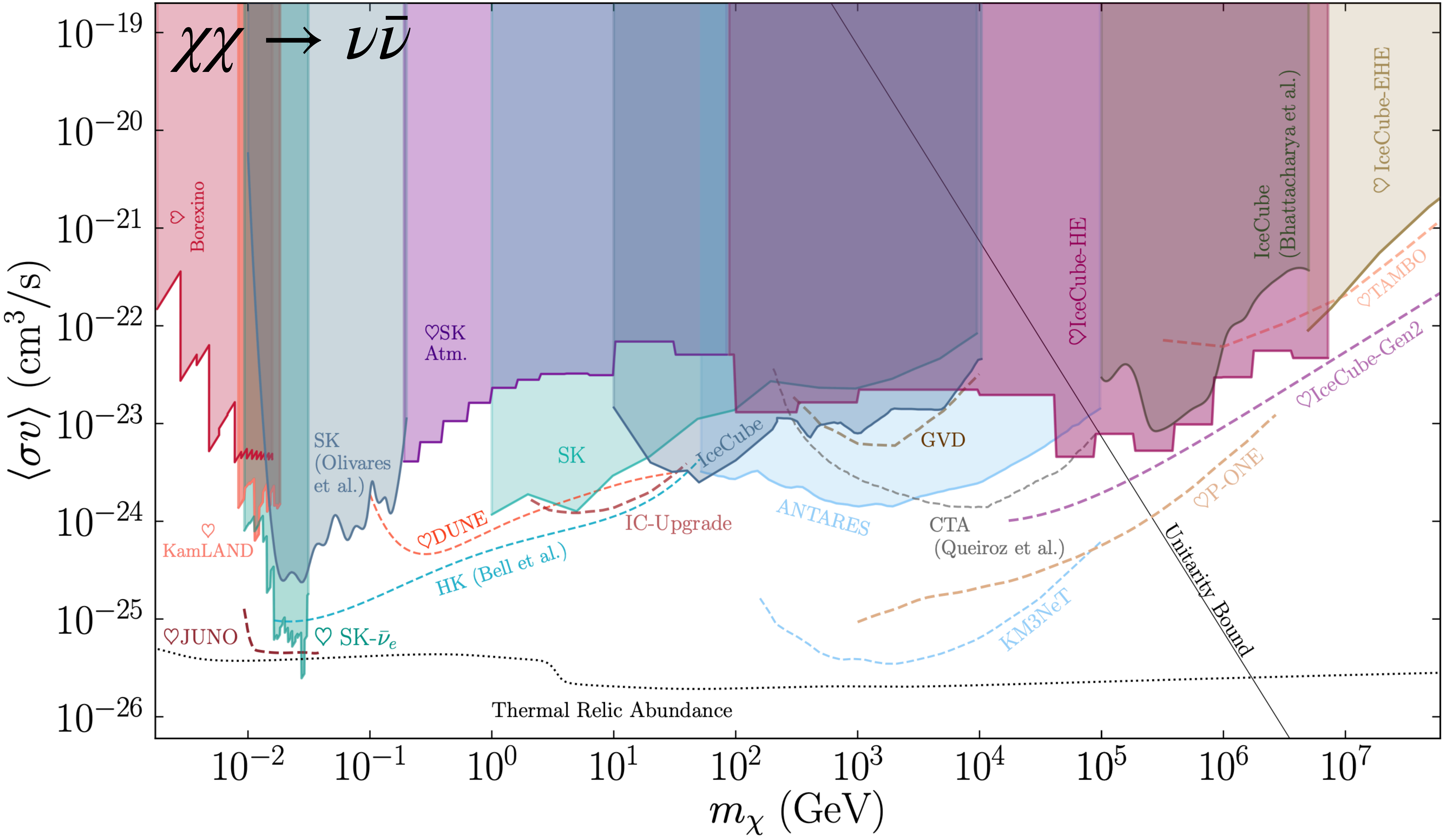
1. Neutrino astrophysics and IceCube
2. Most significant observations in neutrino astrophysics
3. **New opportunities for particle physics**
4. Future detectors & new ideas

Dark matter annihilation



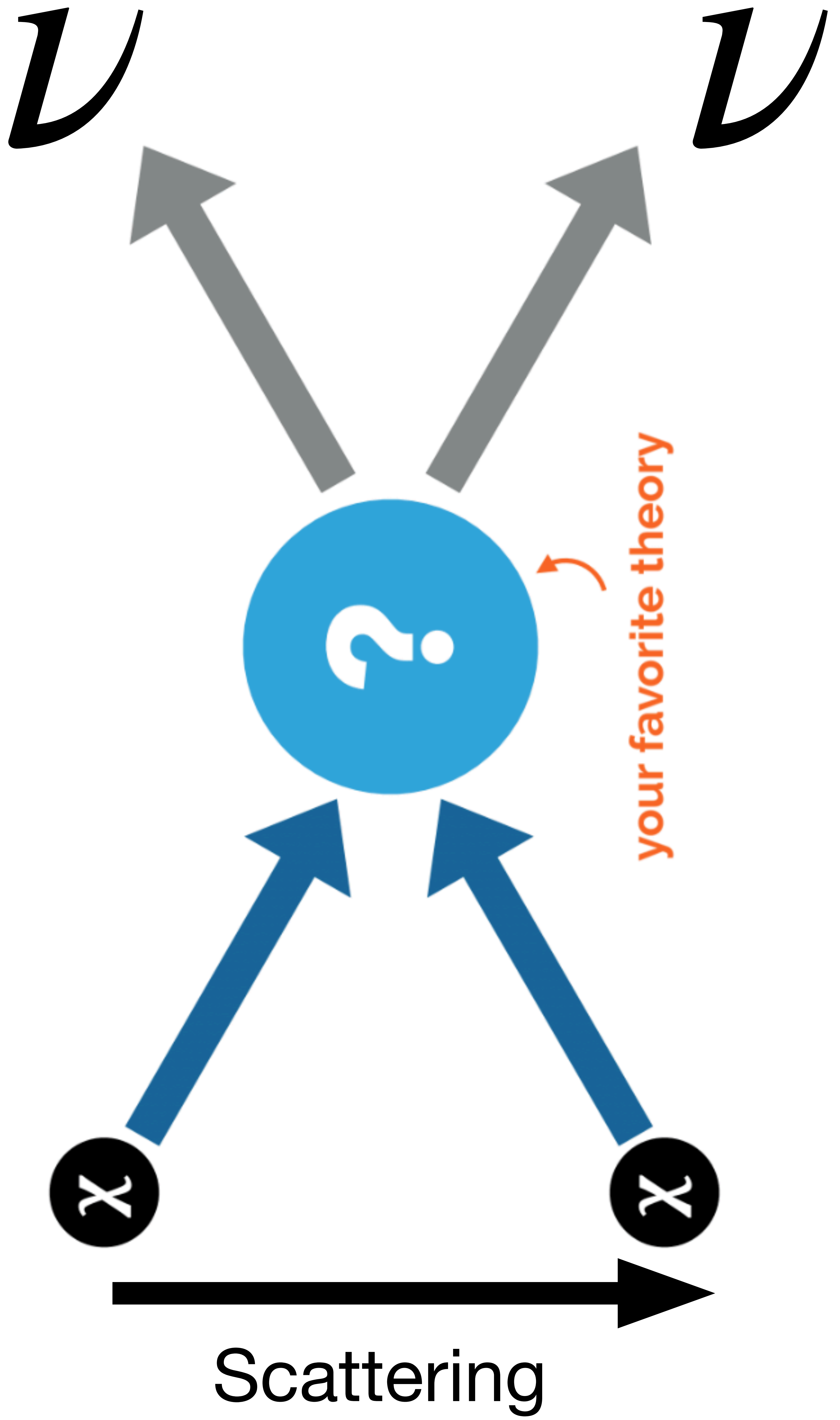
IceCube Collaboration 2205.12950.
See also CA, H. Dujmovic arXiv 1907.11193, Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

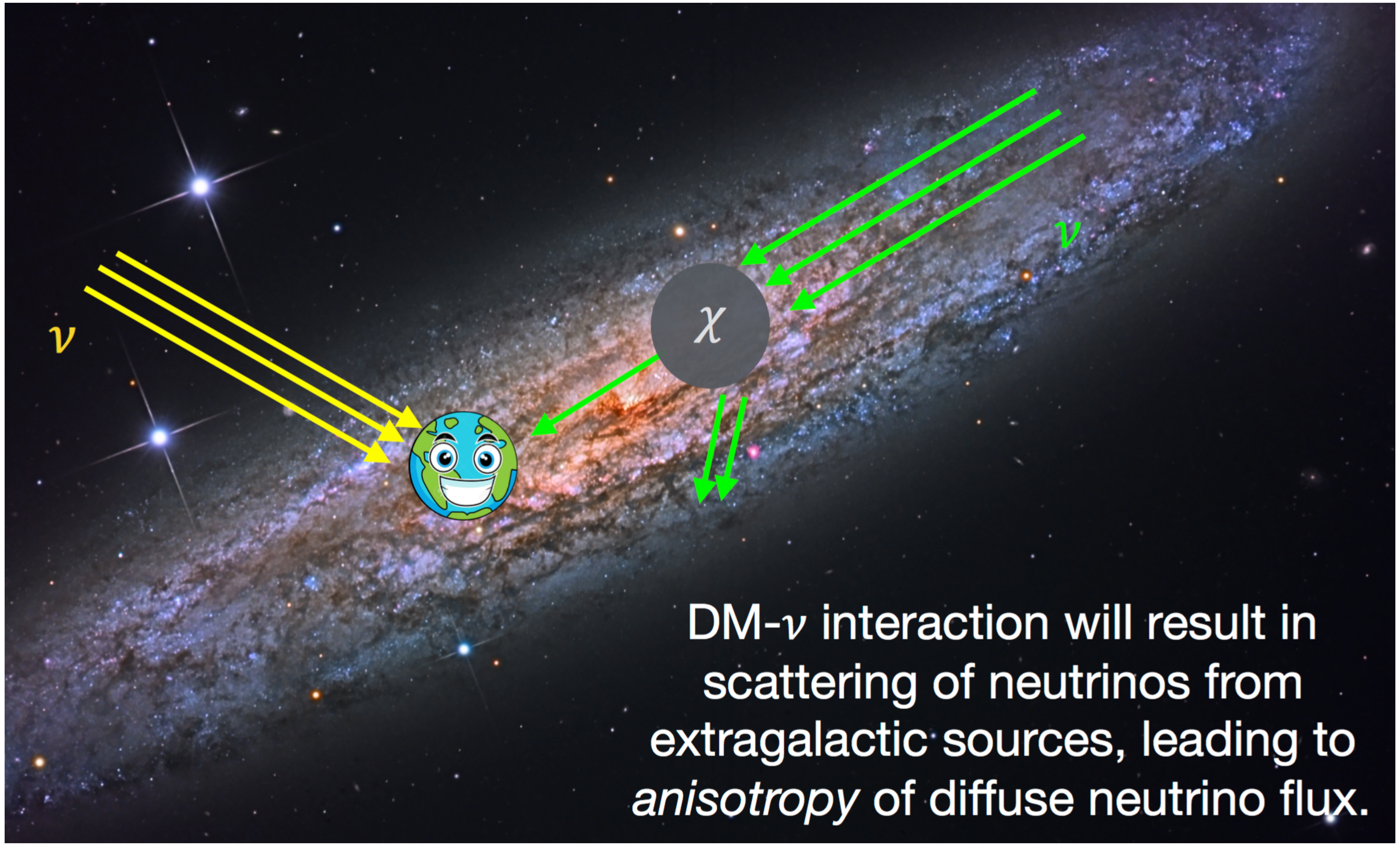
Dark matter annihilation to neutrino: a largely unexplored frontier



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

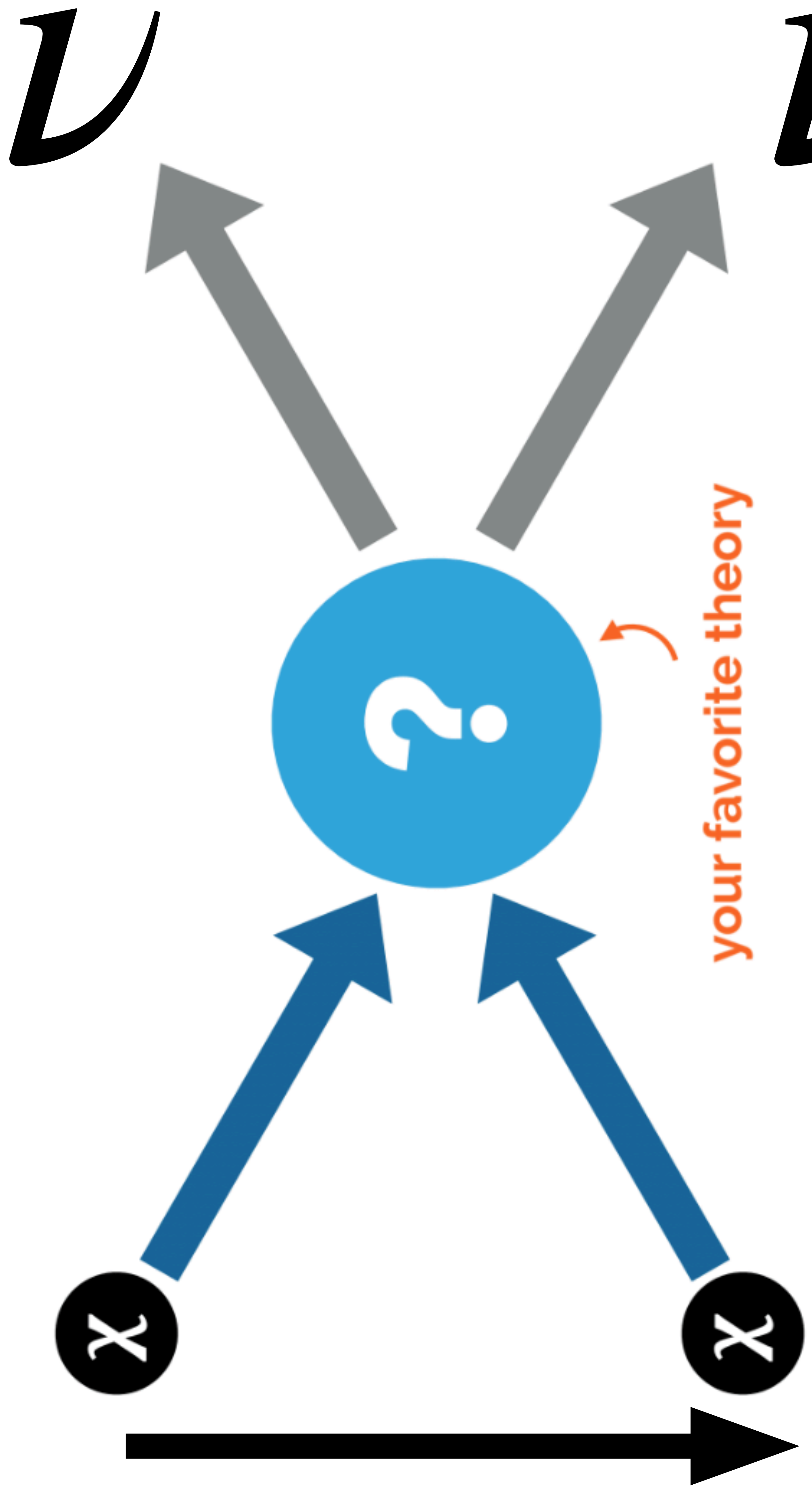
Dark matter scattering with neutrinos





CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

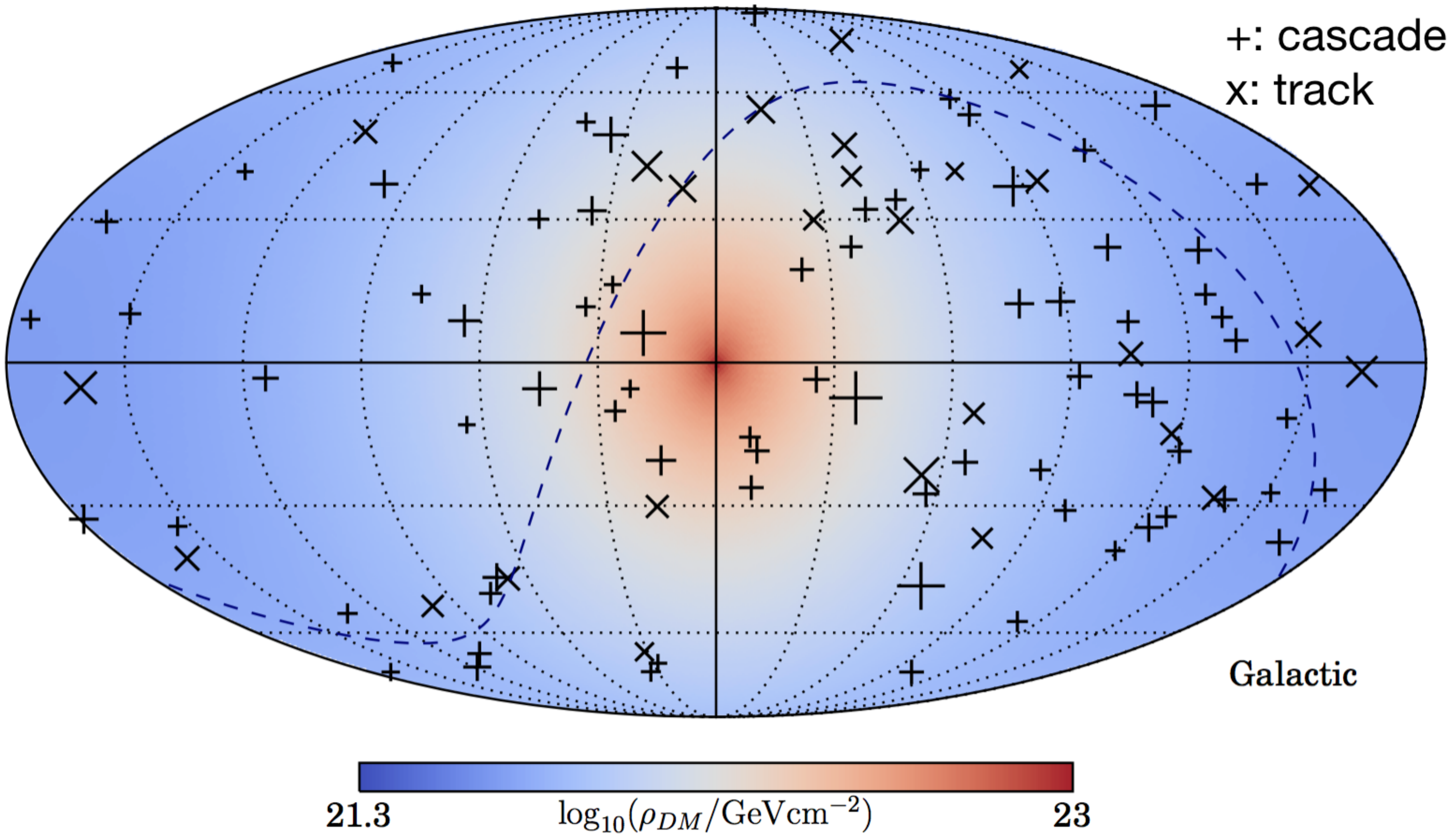
Dark matter scattering with neutrinos



Scattering

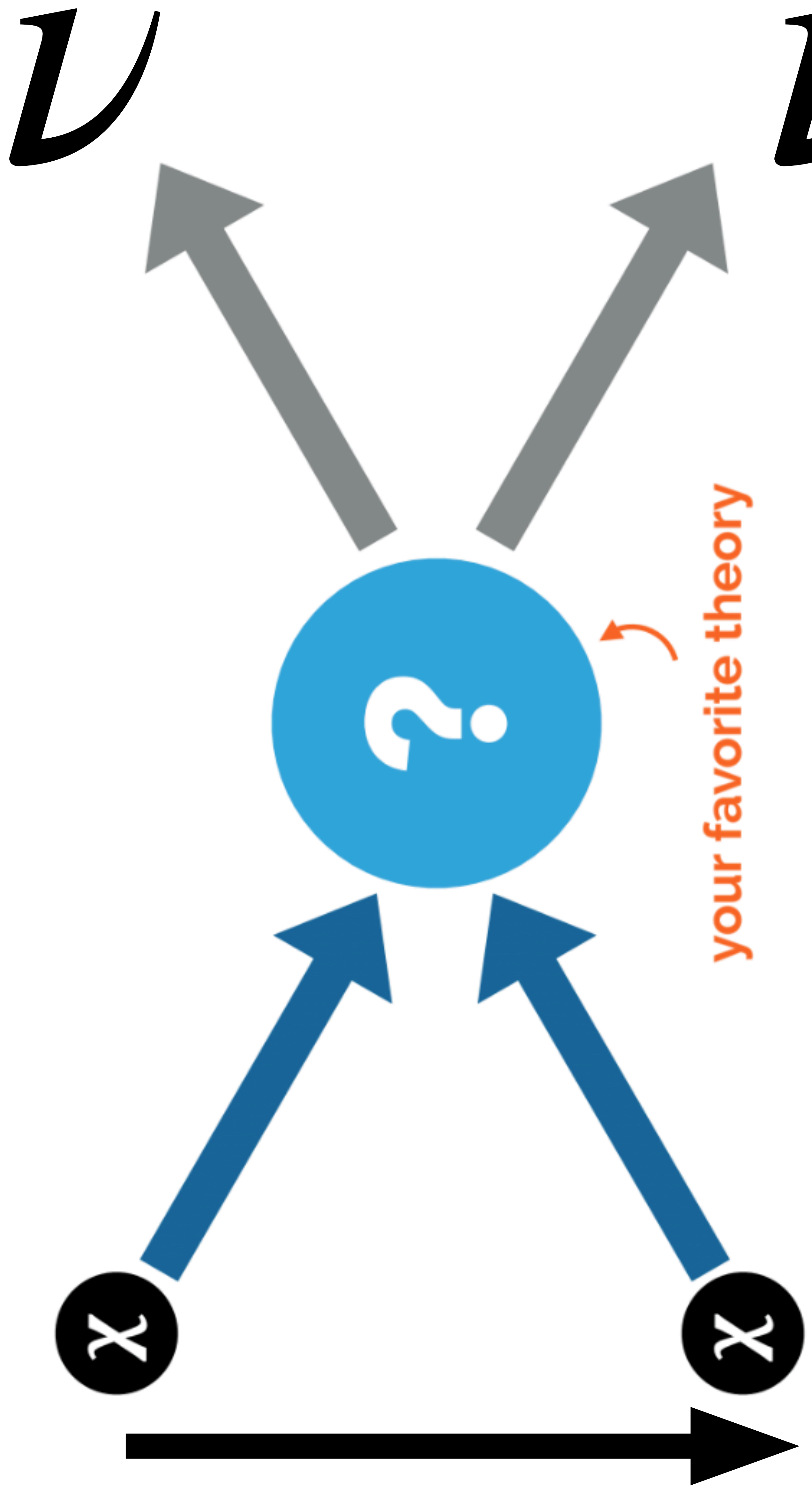
IceCube Collaboration, arXiv:2205.12950

HESE: high-energy starting events

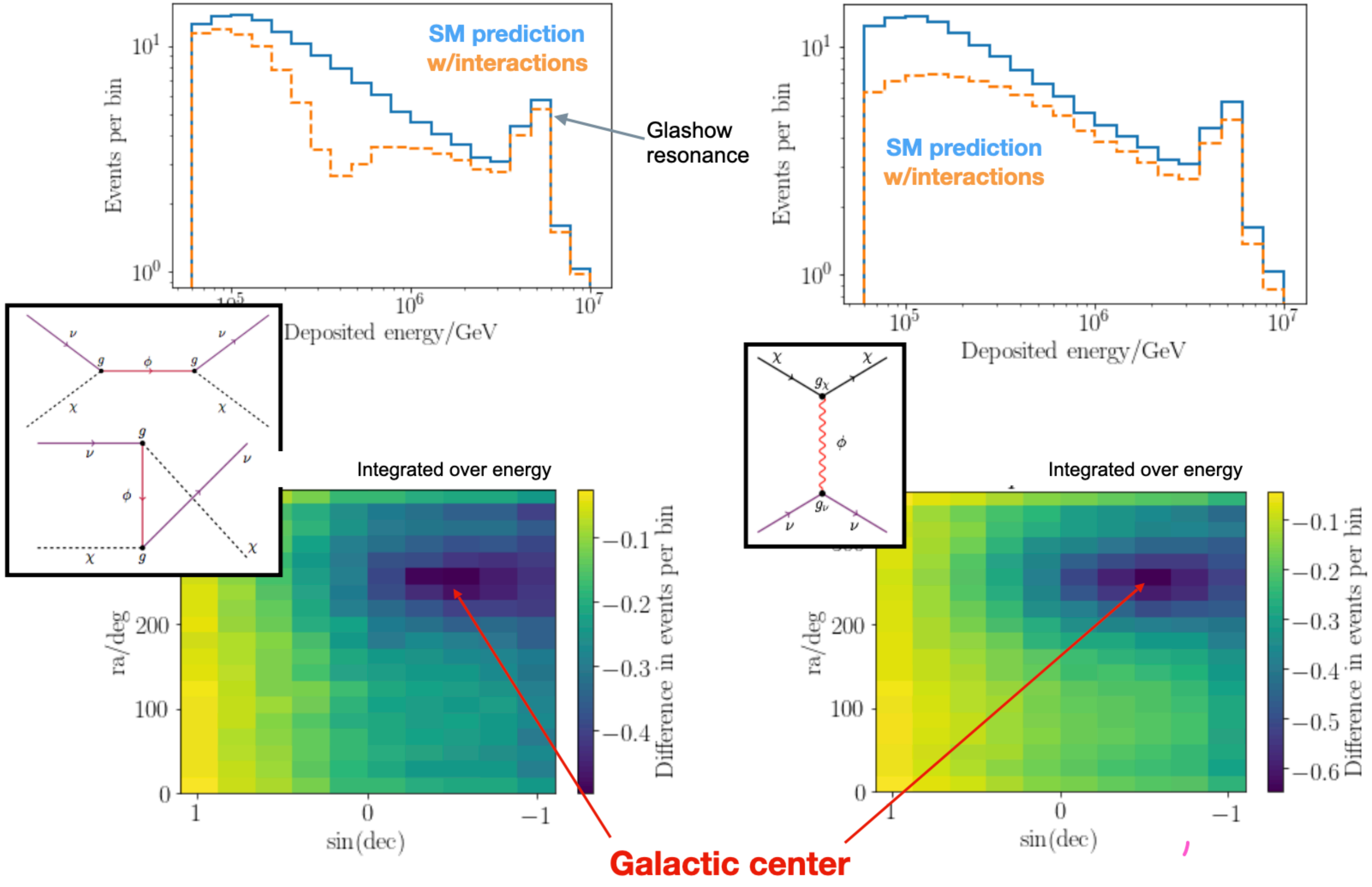


CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

Dark matter scattering with neutrinos



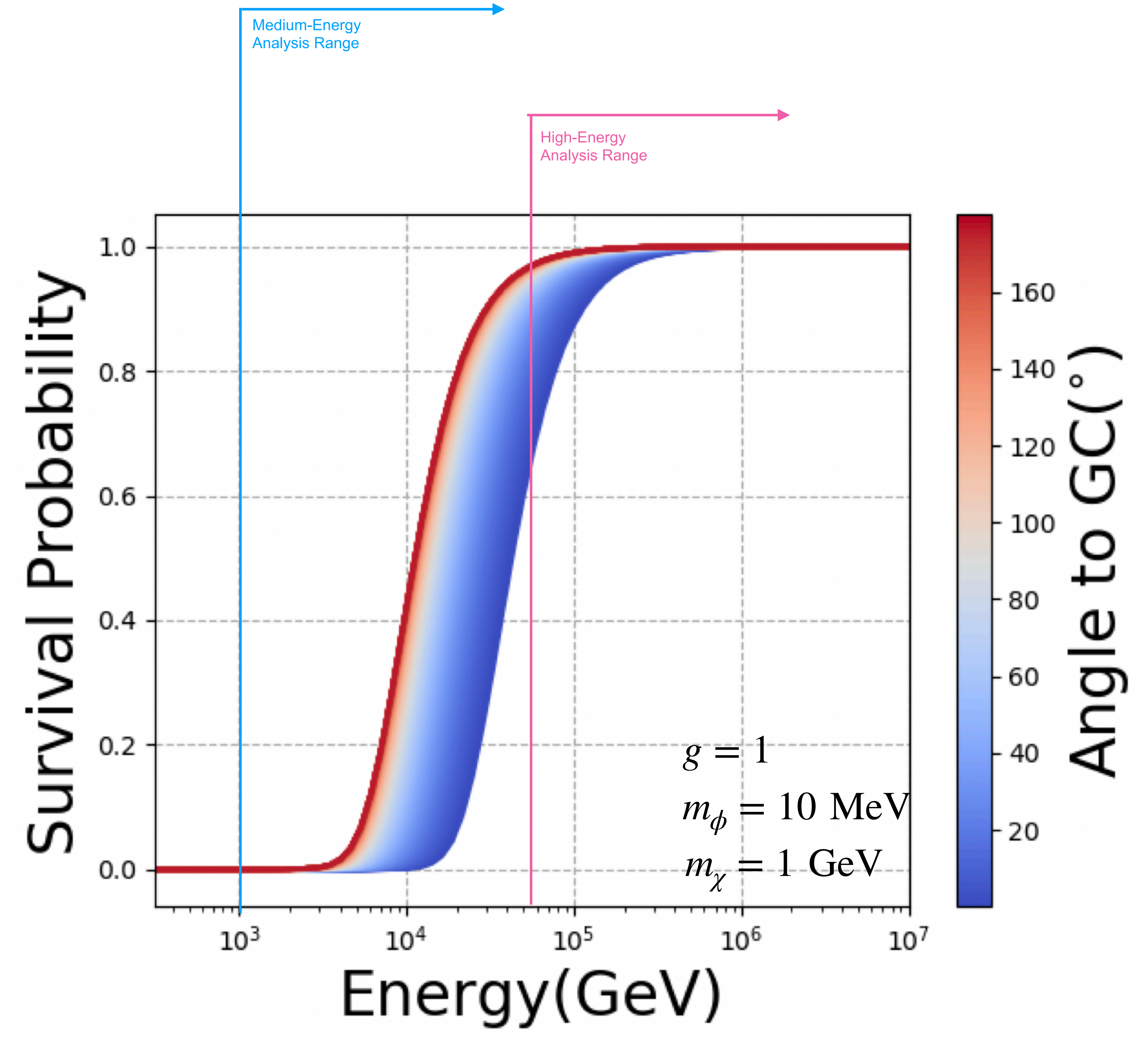
Scattering



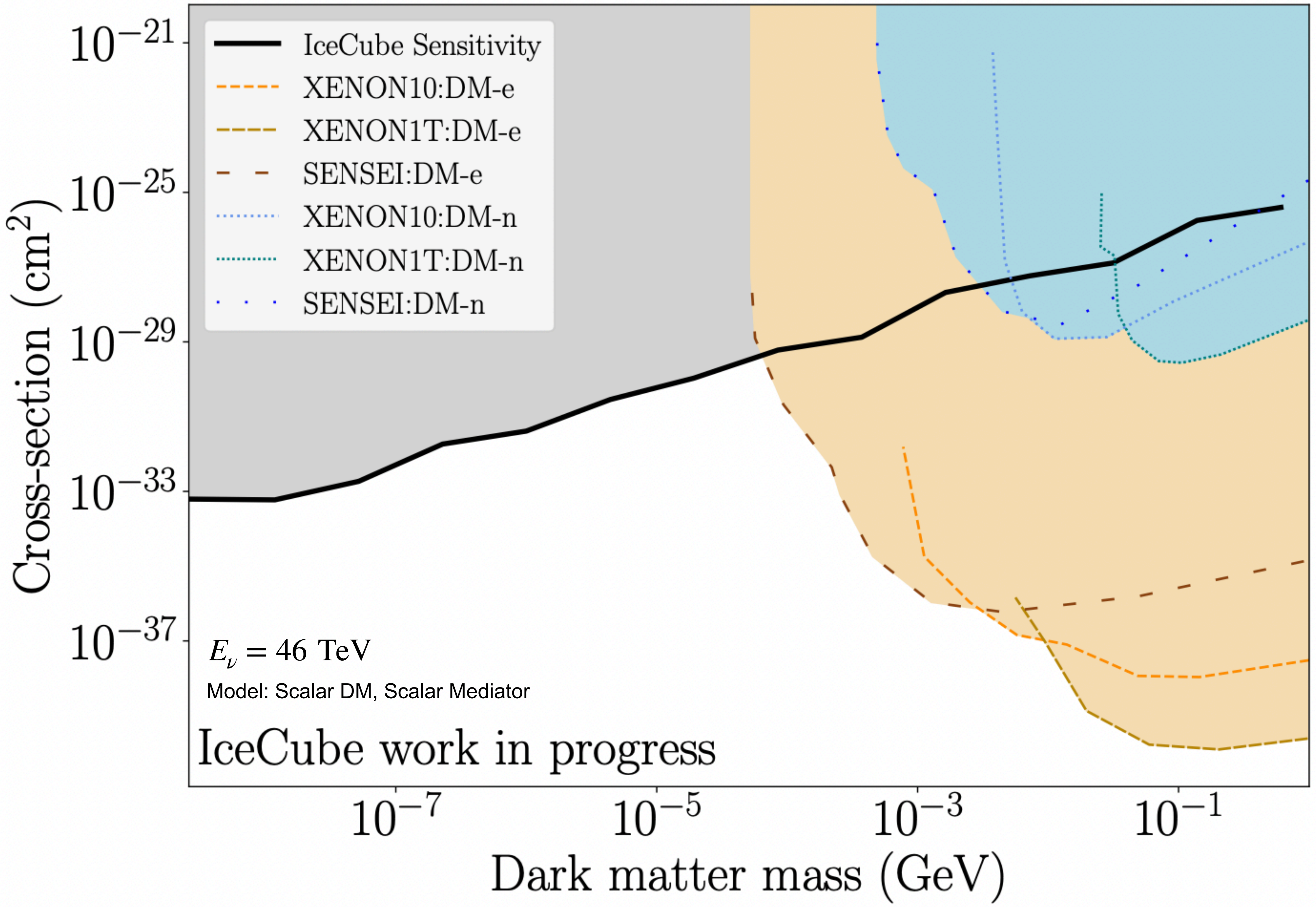
Constraints comparable to cosmology

Dark matter scattering with neutrinos: new analysis!

Work by Diya Delgado



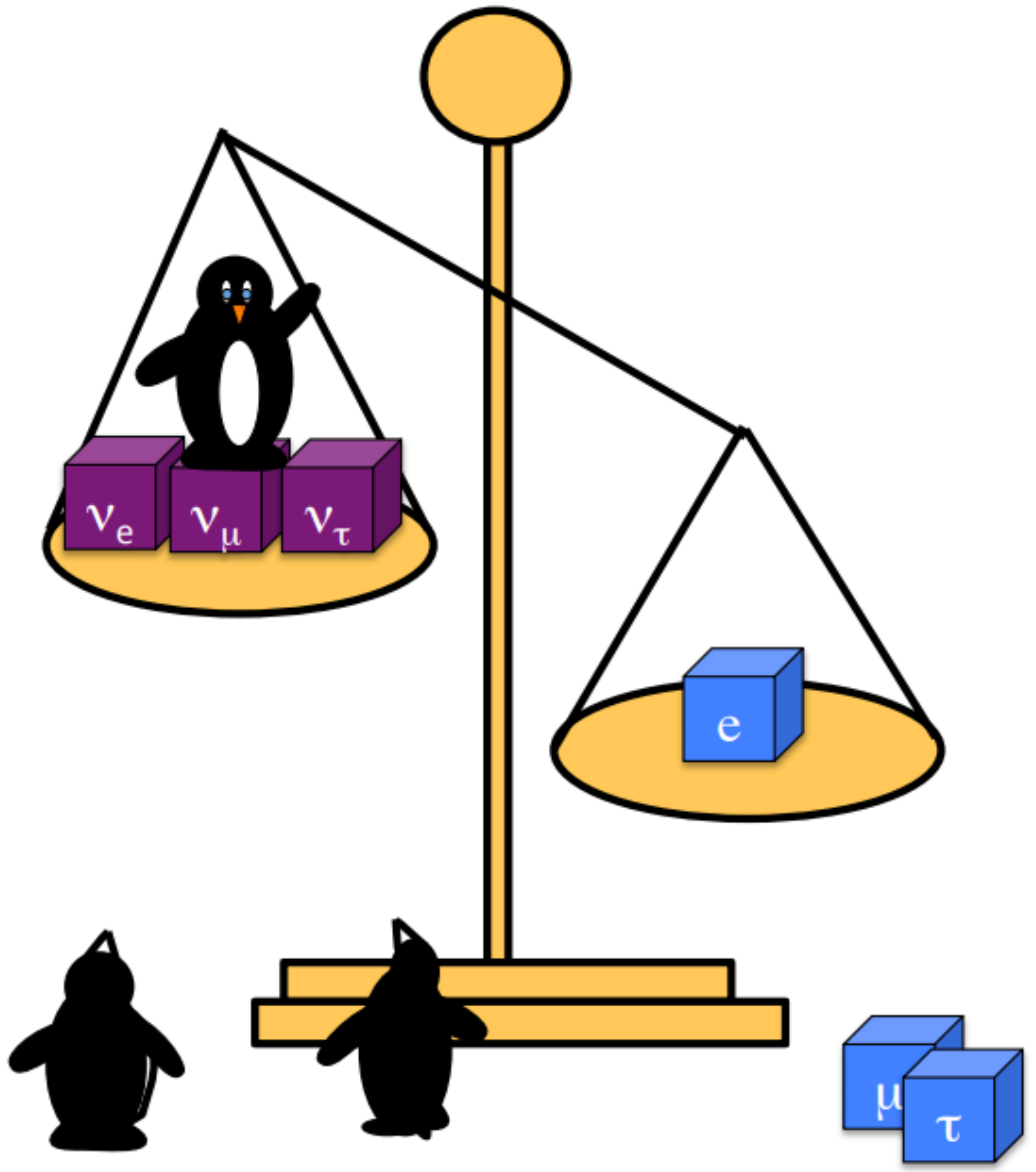
A. McMullen, A. Vincent, CA, A. Schneider arXiv:2107.11491



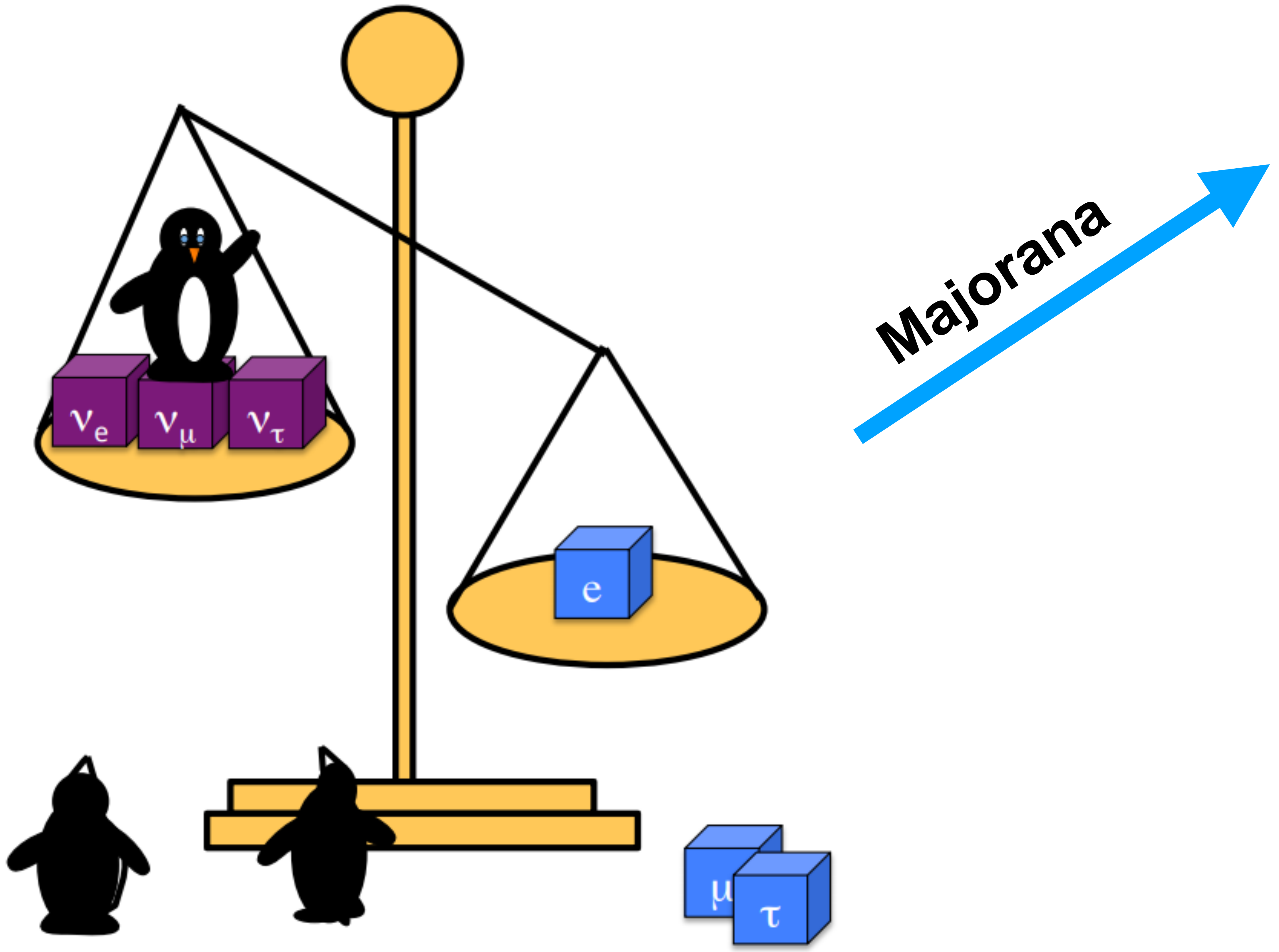
Larger sample sizes data sets yet to be used for these searches.
Only IceCube's High-Energy Starting Events used so far.

What is the nature of neutrino mass?

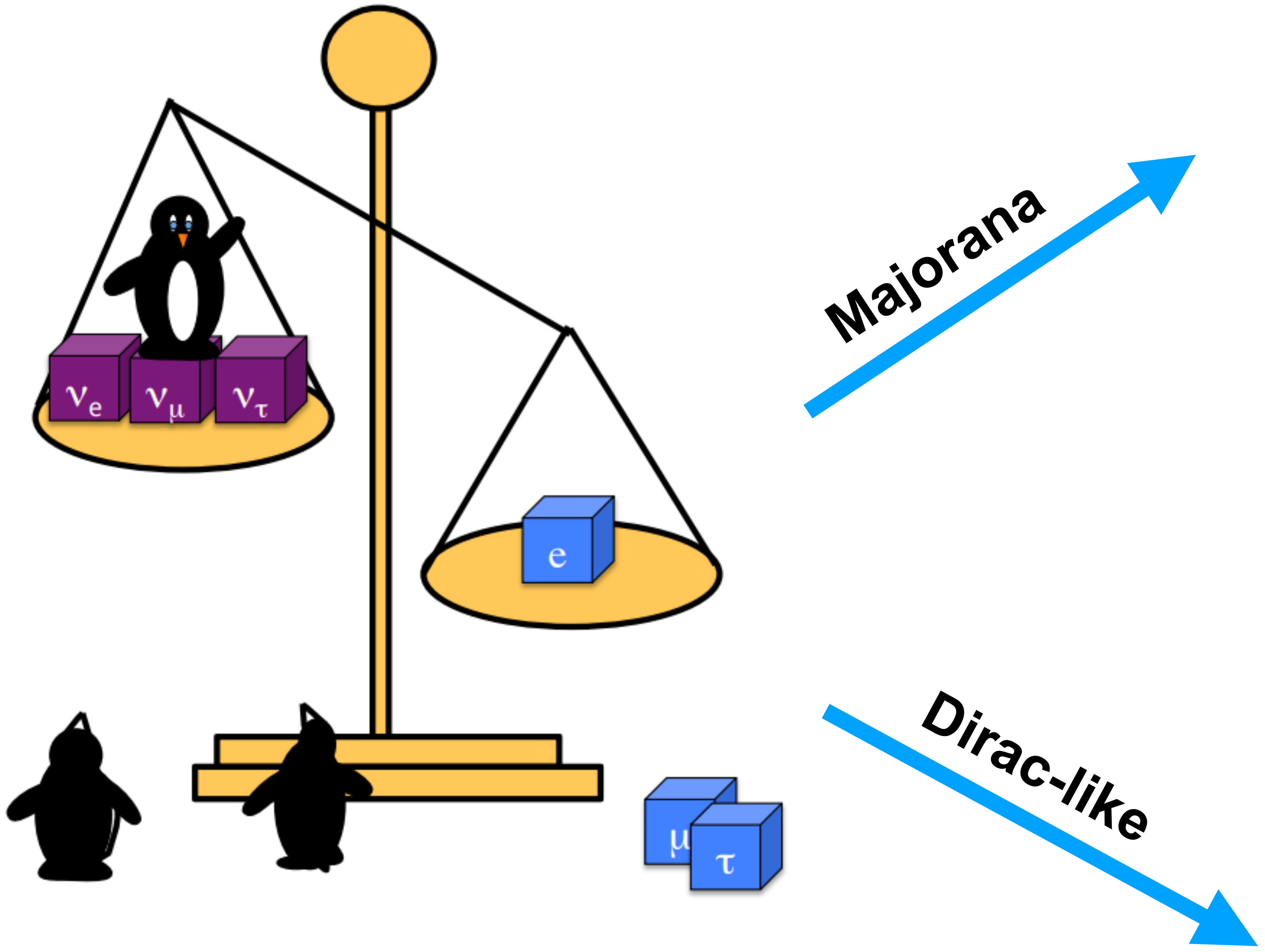
What is the nature of neutrino mass?



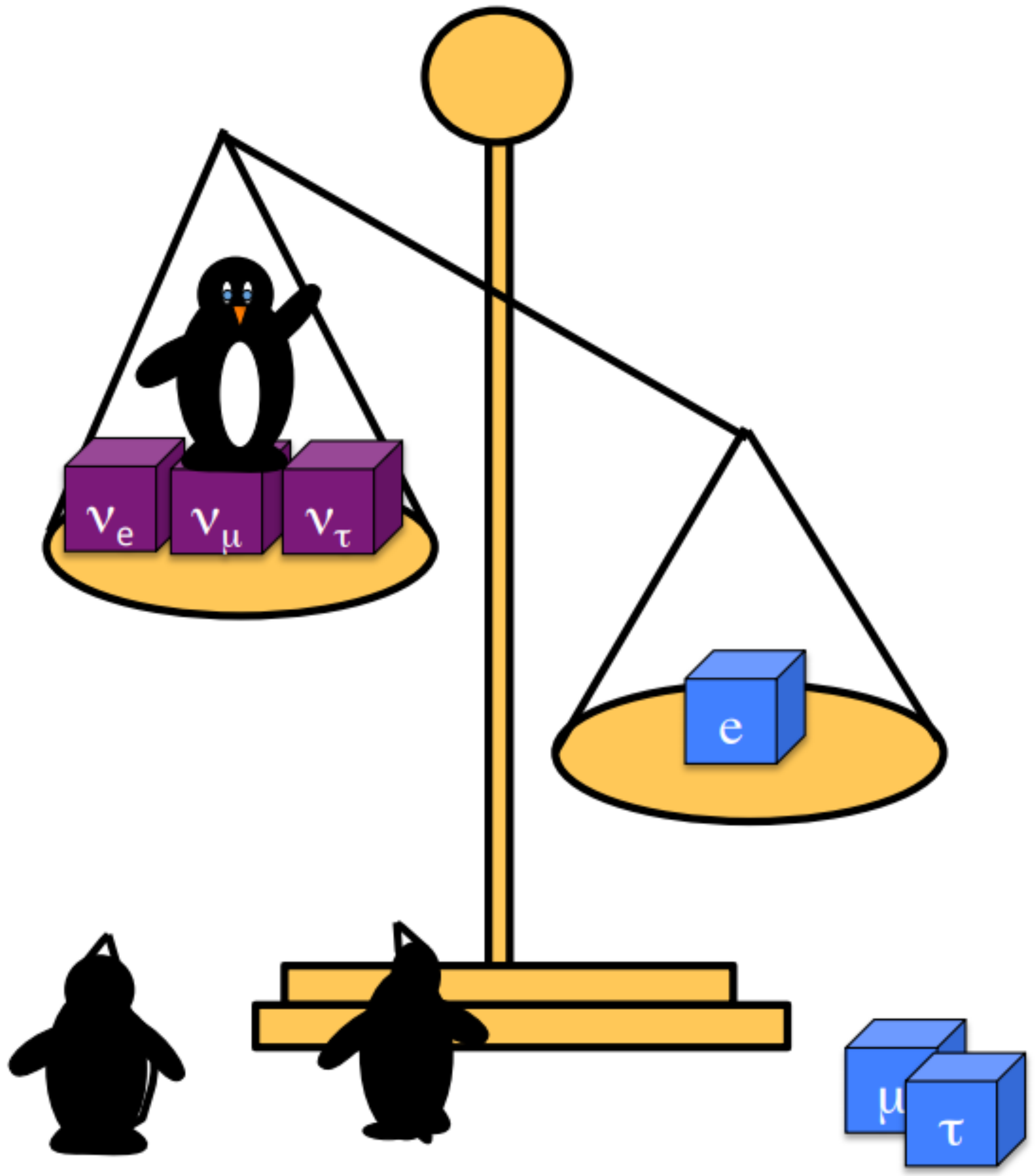
What is the nature of neutrino mass?



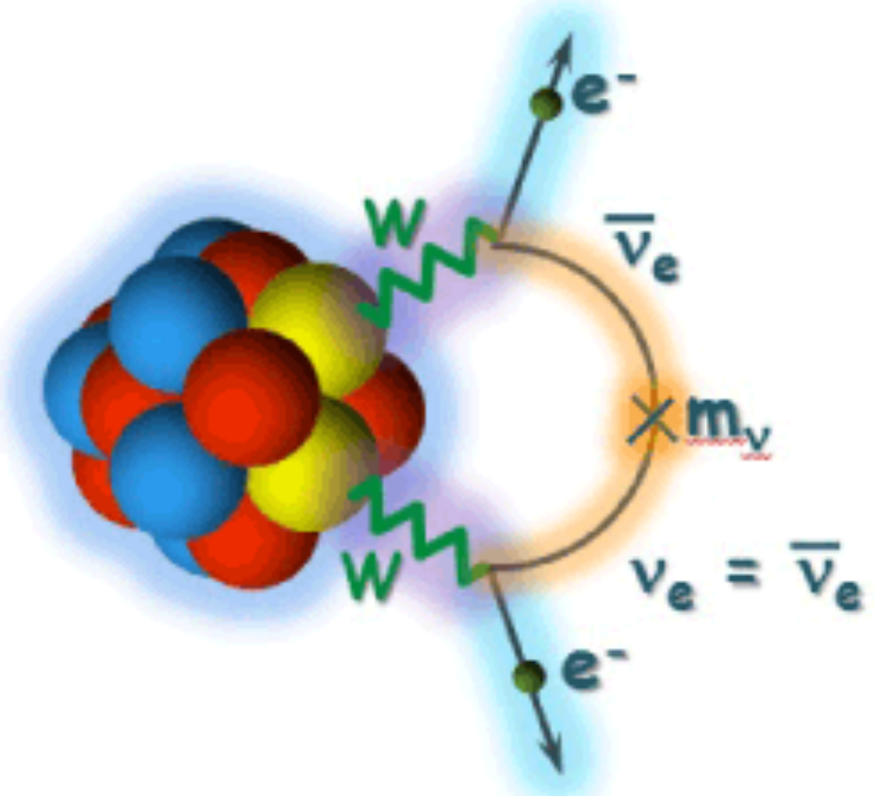
What is the nature of neutrino mass?



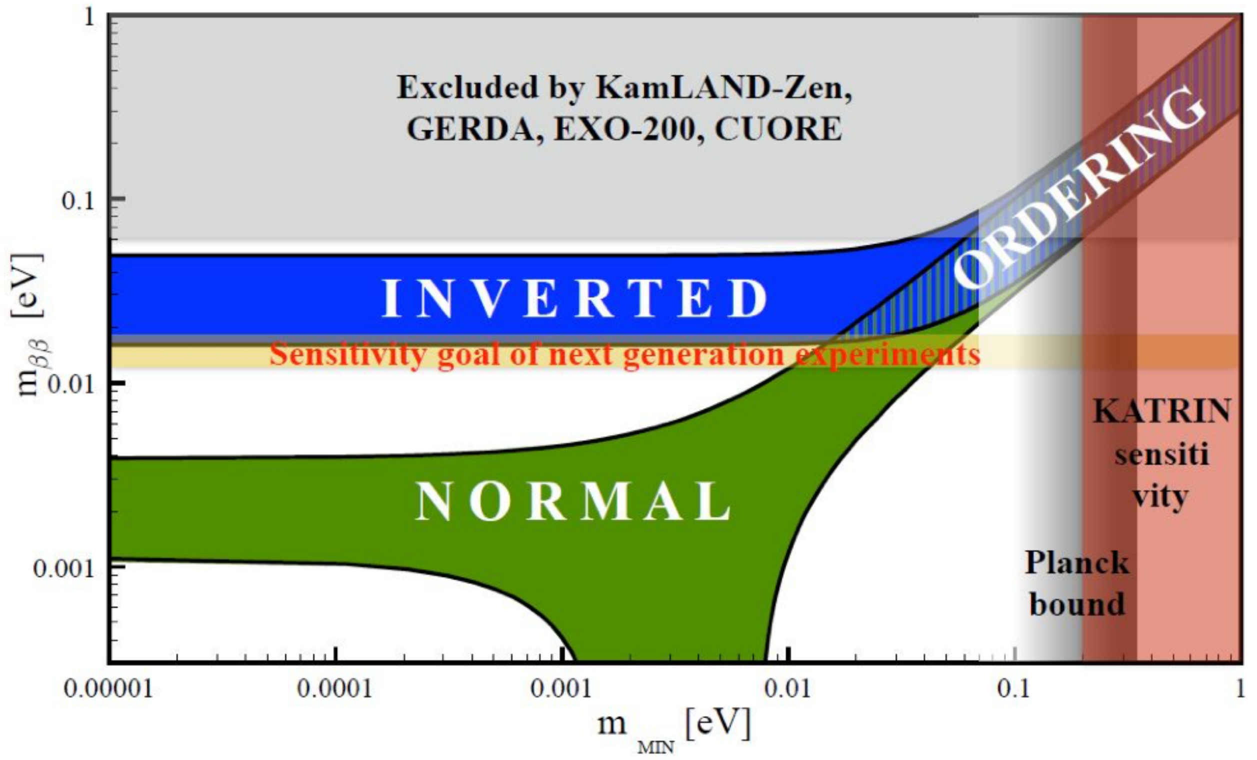
What is the nature of neutrino mass?



Majorana

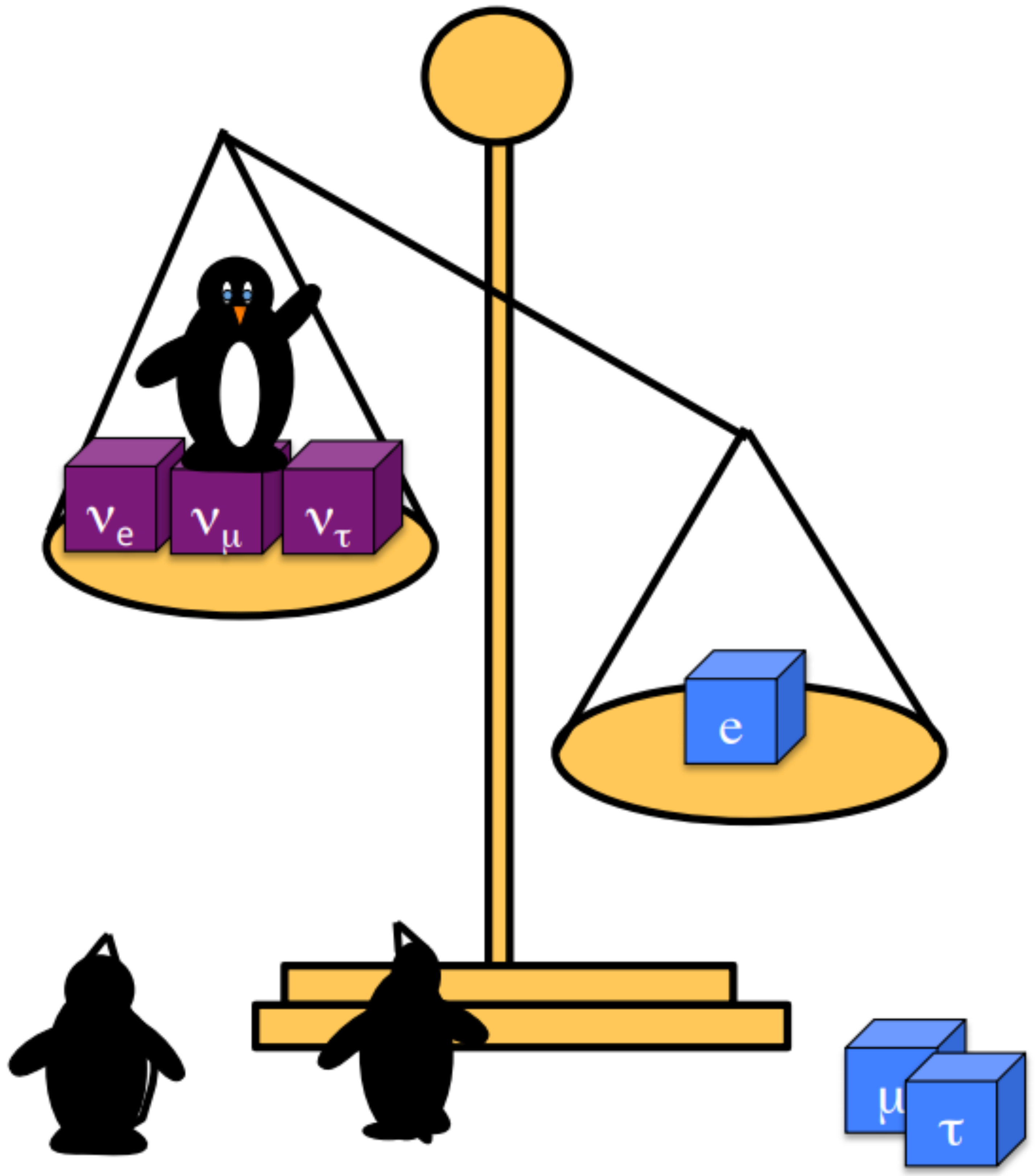


Neutrinoless
double beta decay

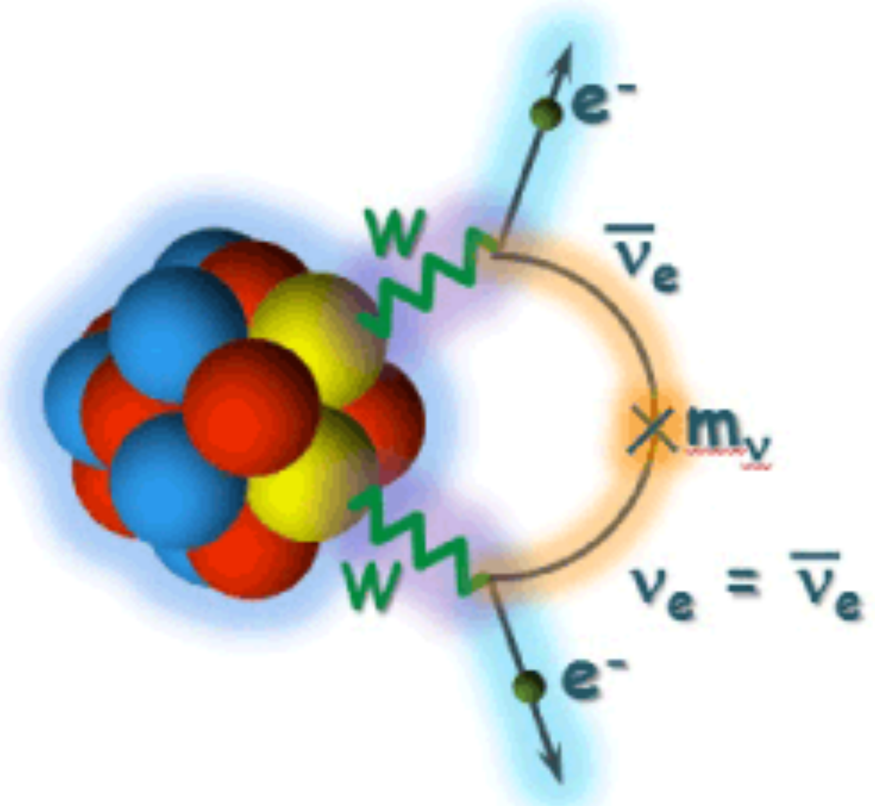


Dirac-like

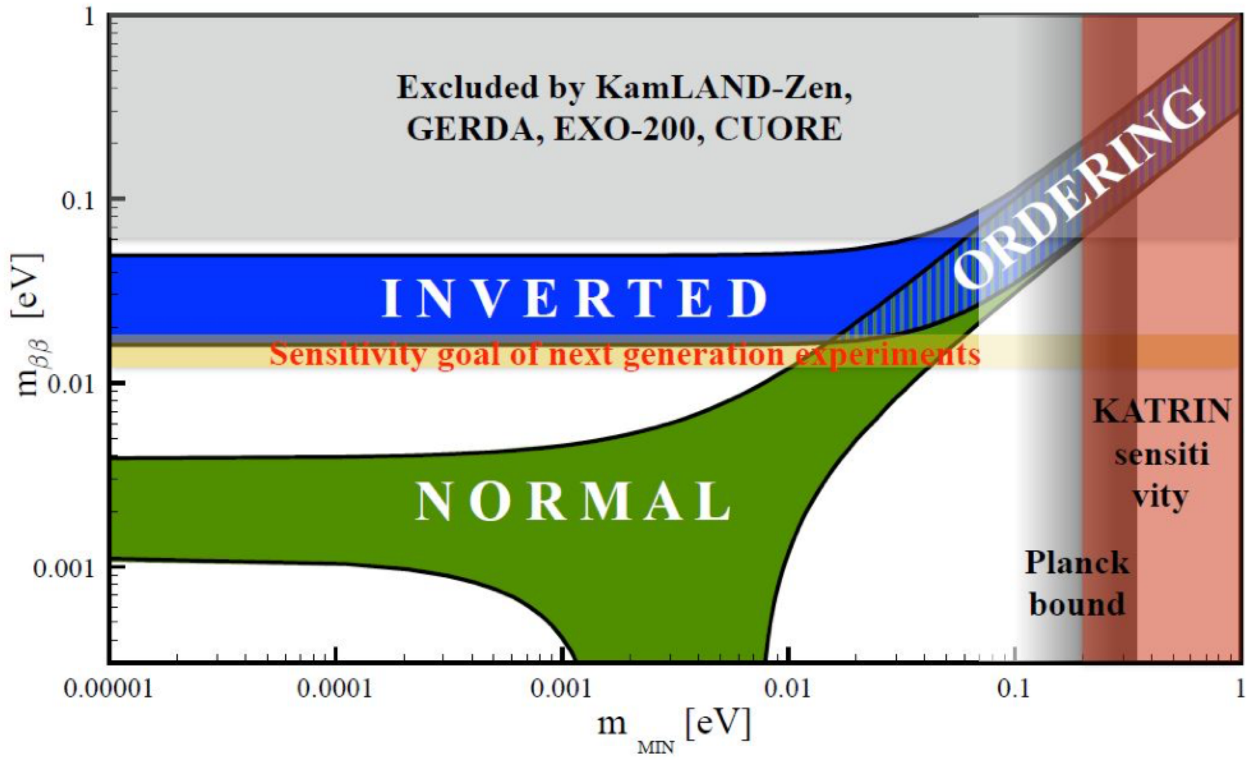
What is the nature of neutrino mass?



Majorana



Neutrinoless double beta decay



Dirac-like

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

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

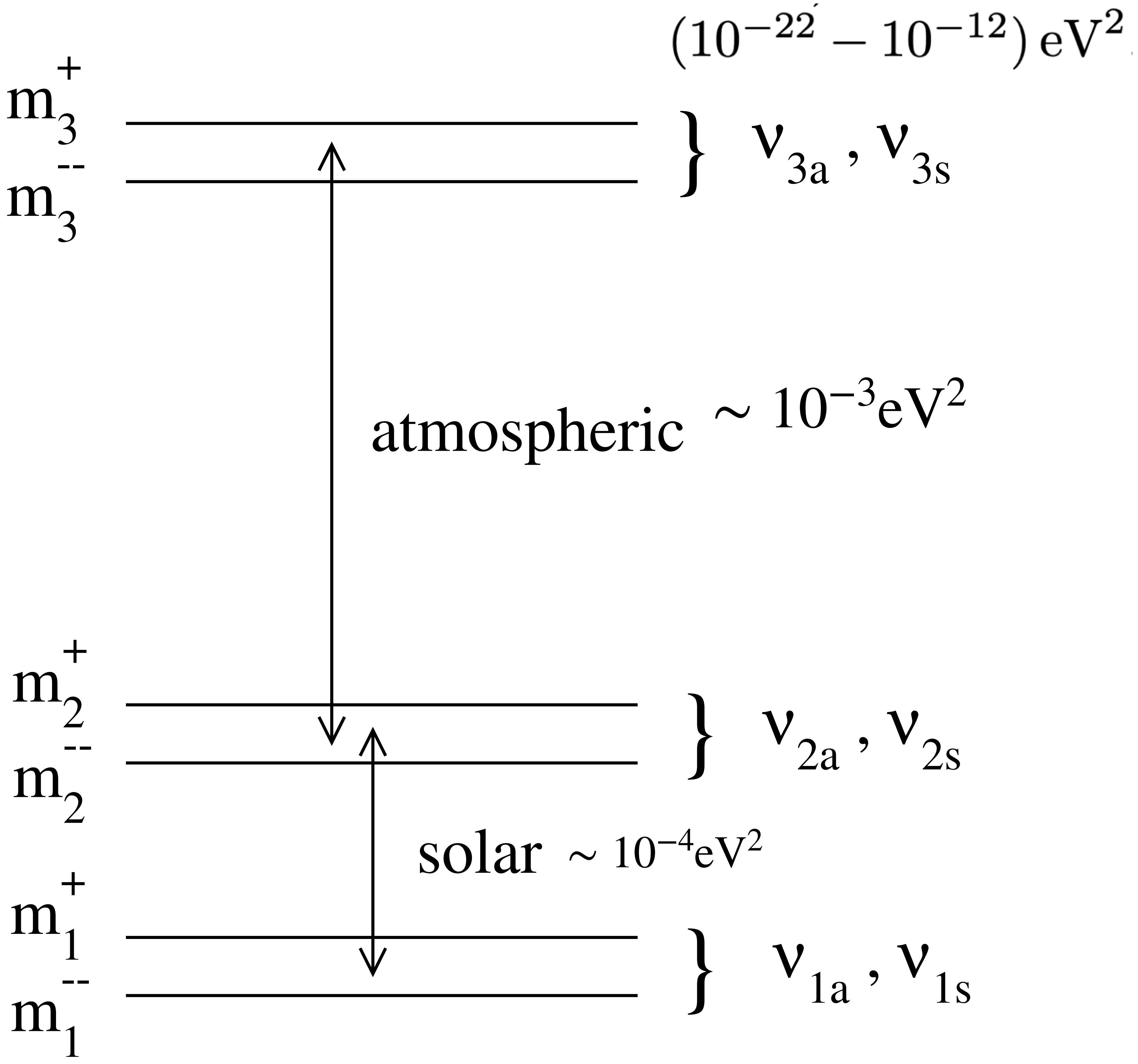
Lepton-number breking term.

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
…

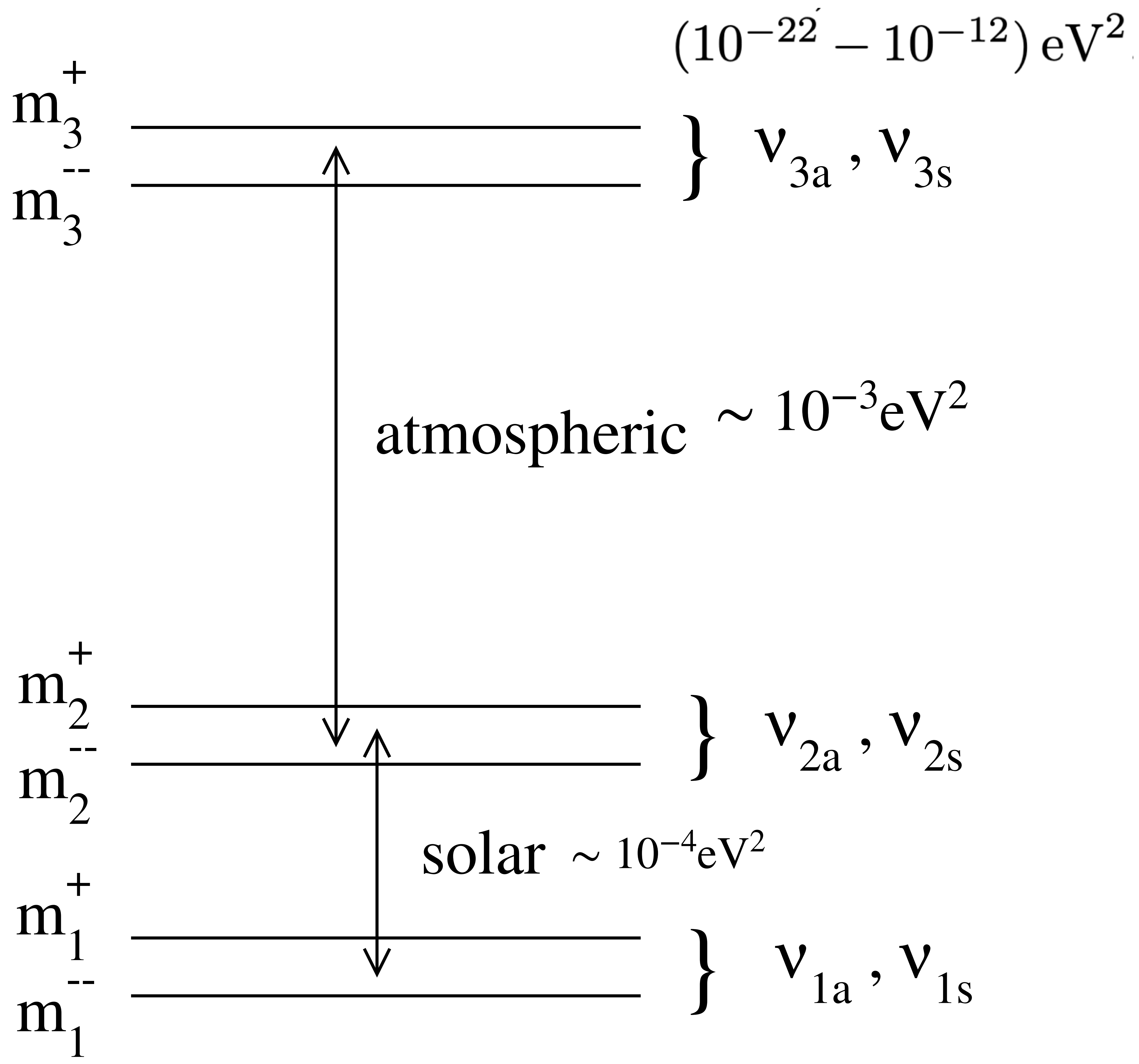
Oscillations With Quasi-Dirac Neutrinos

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

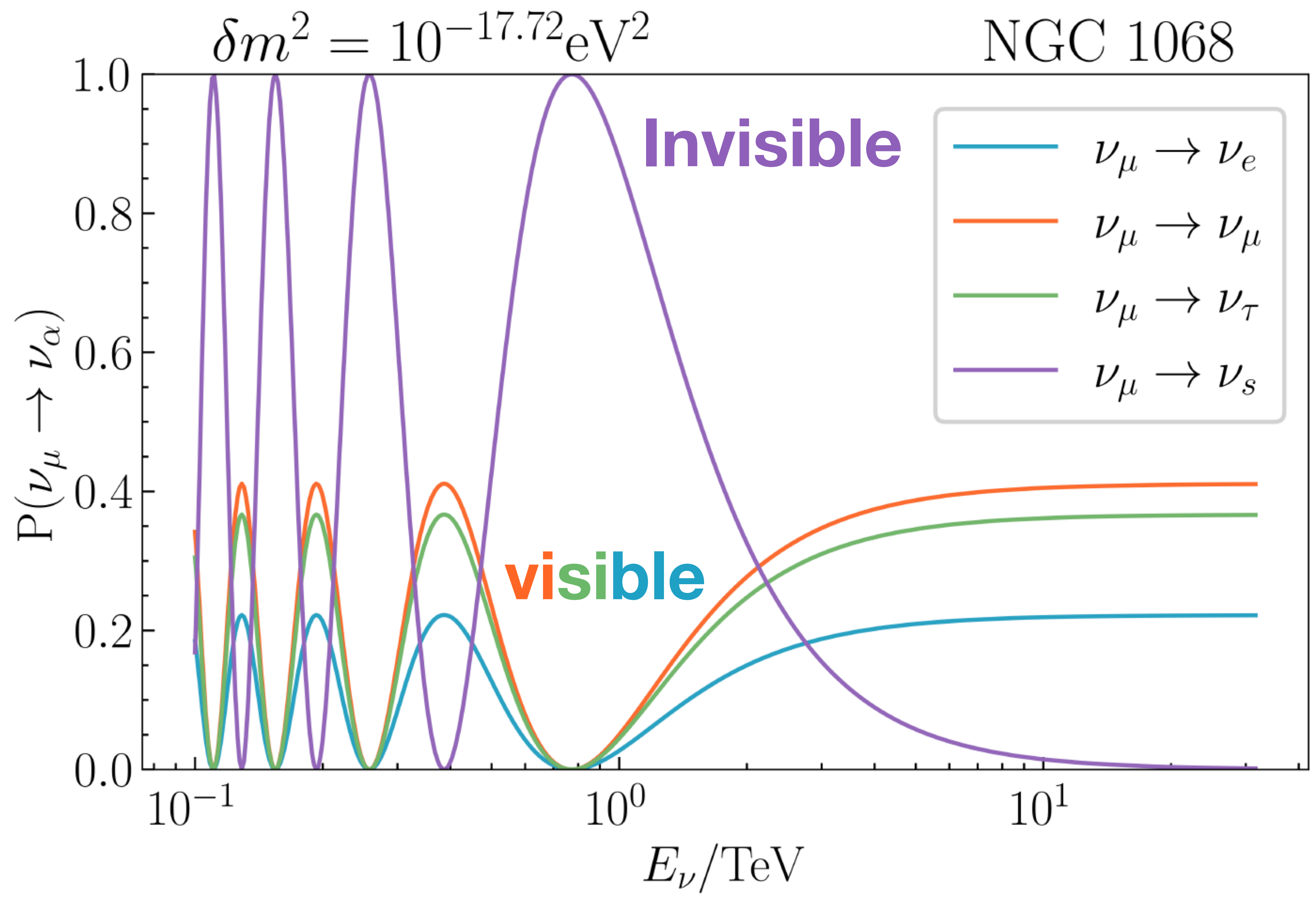


Oscillations With Quasi-Dirac Neutrinos

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

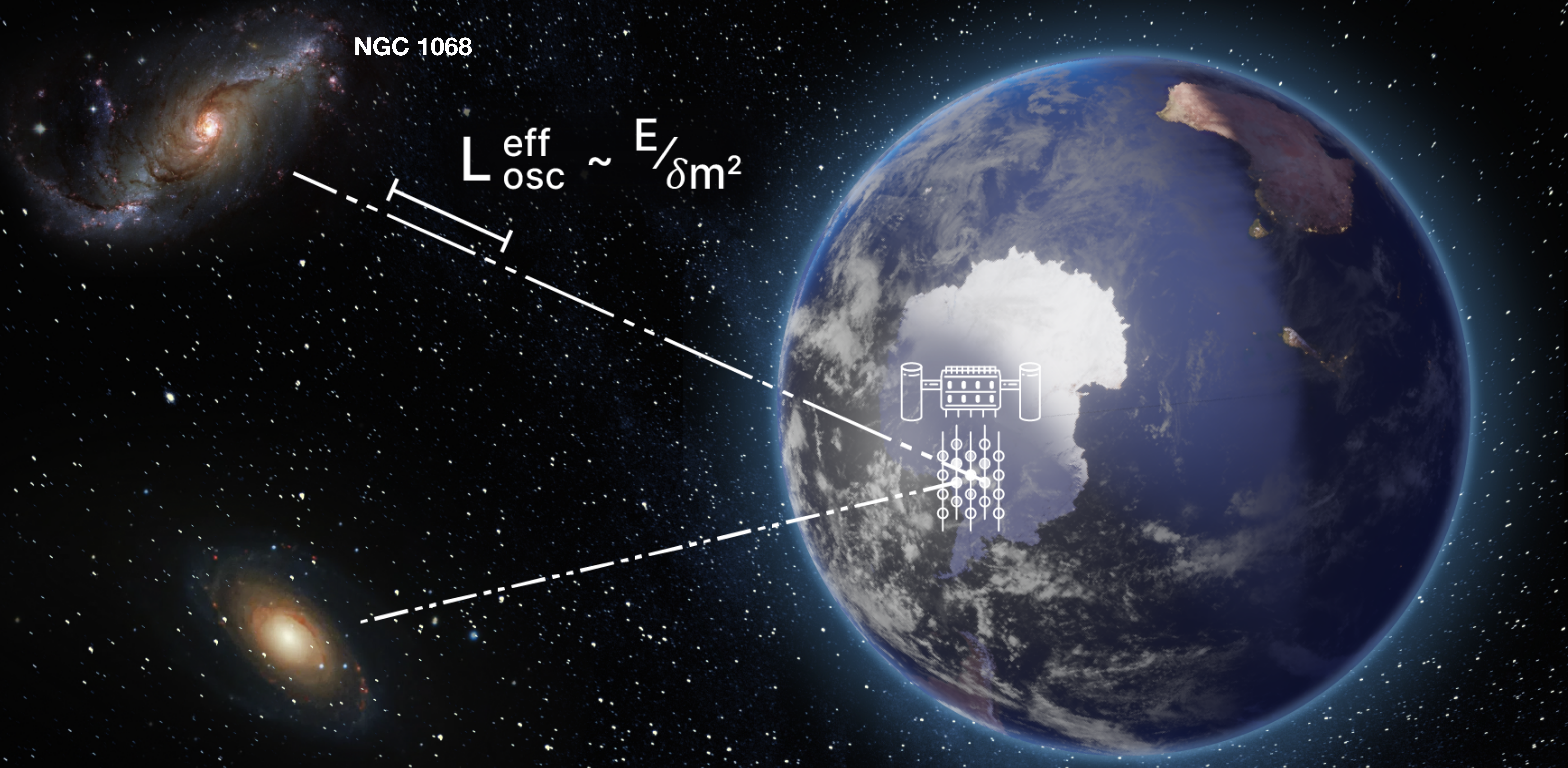


$$P_{\alpha\beta} = \frac{1}{2}\sum_{j=1}^{3} |U_{\beta j}|^2 |U_{\alpha j}|^2 \left[1 + \cos\left(\frac{\delta m_j^2 L_{\rm eff}}{2E_\nu}\right)\right]$$



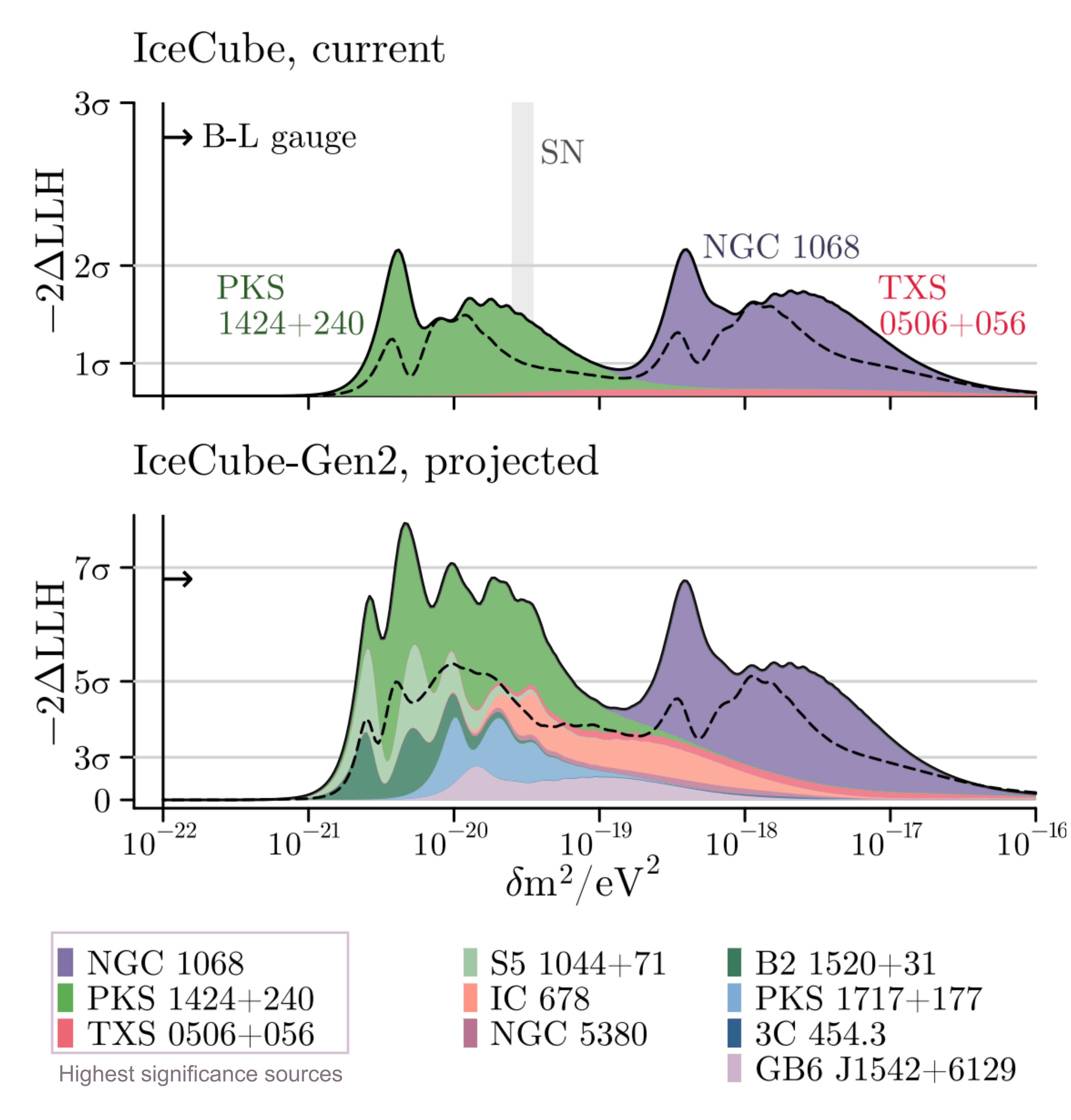
Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

Neutrino Oscillations At Cosmic Scales



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

Neutrino Oscillations At Cosmic Scales



Work by Kiara Carloni and Ivan Martinez-Soler

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

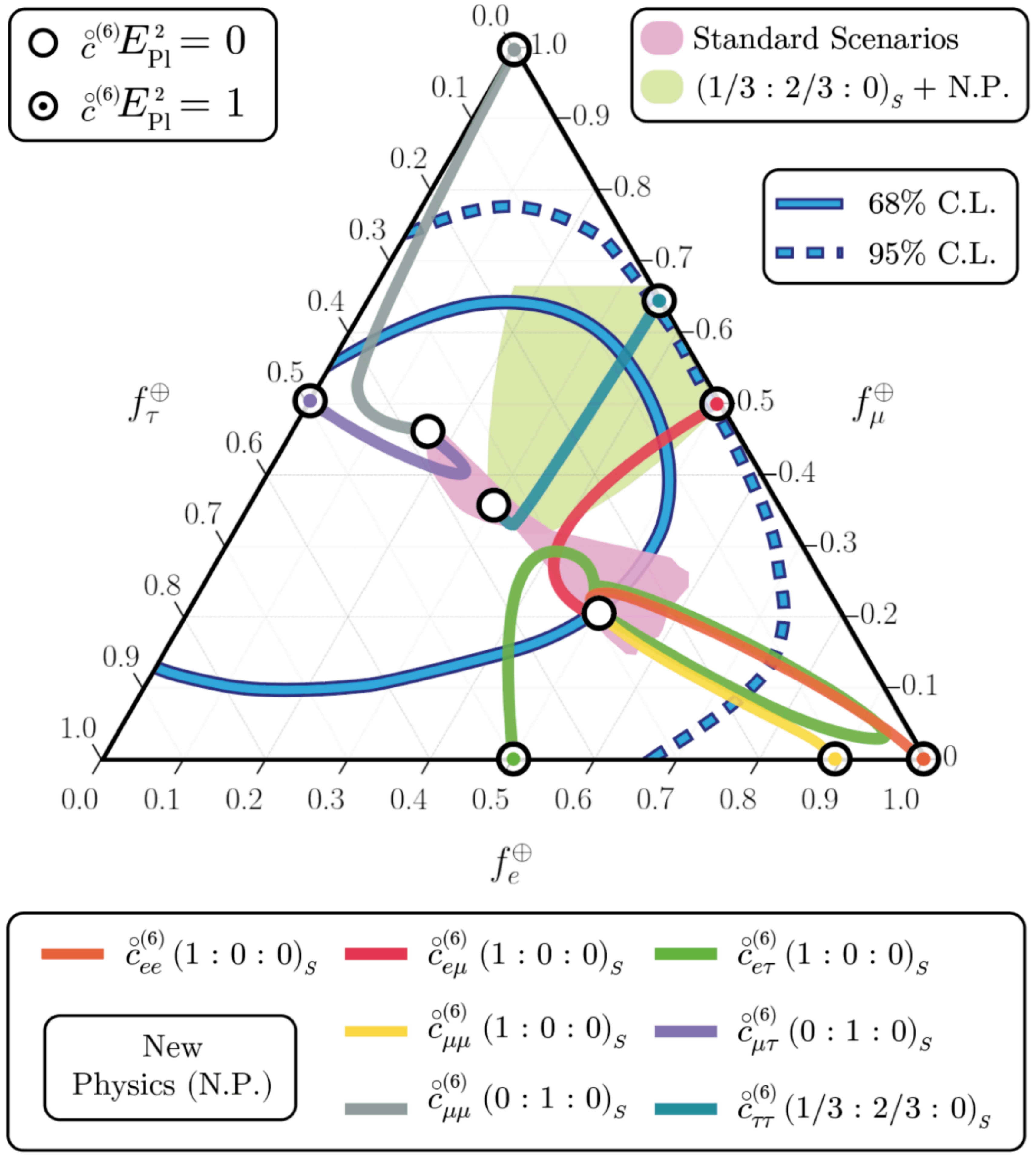
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

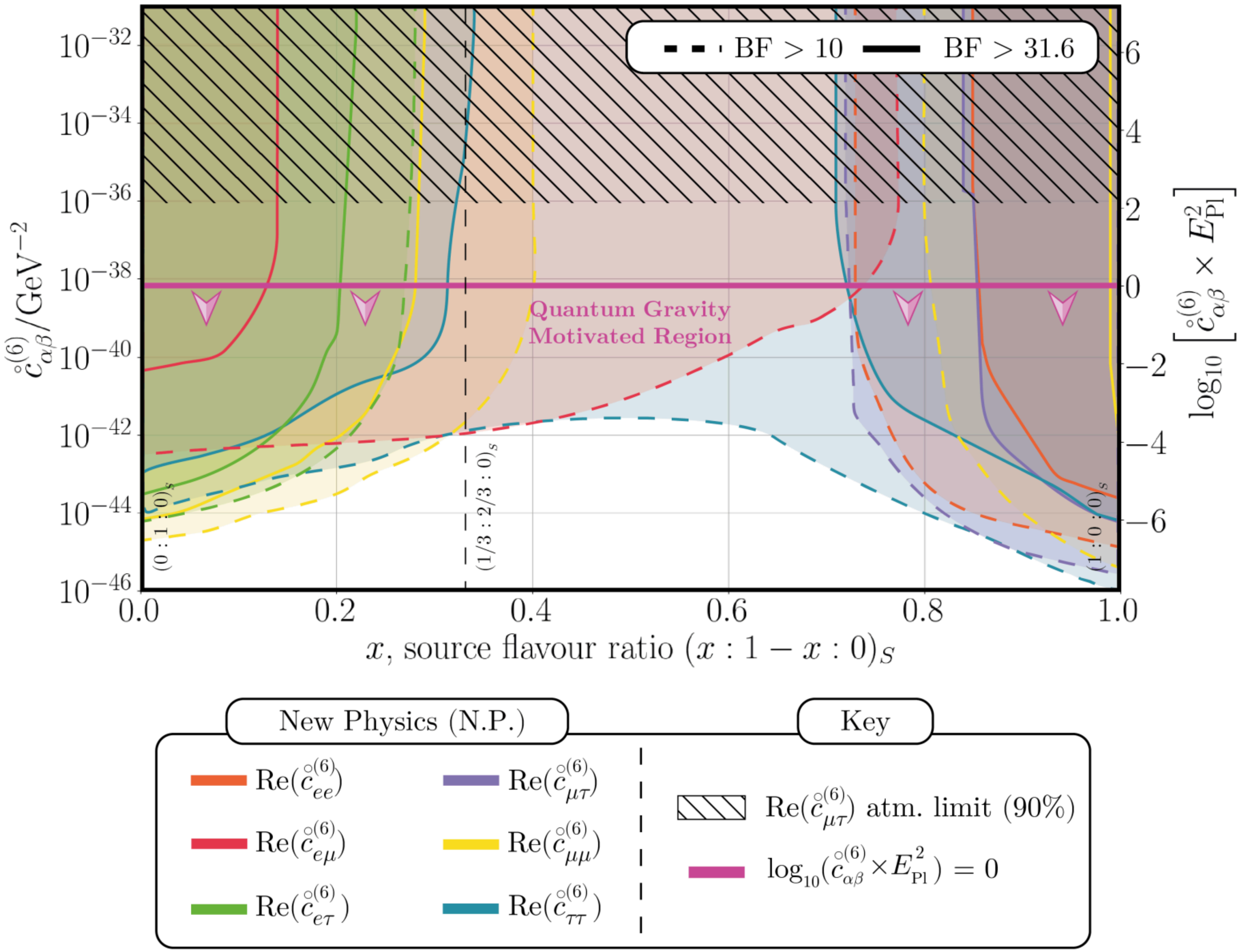
$(0:1:0)$ neutron

$(1:0:0)$ 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

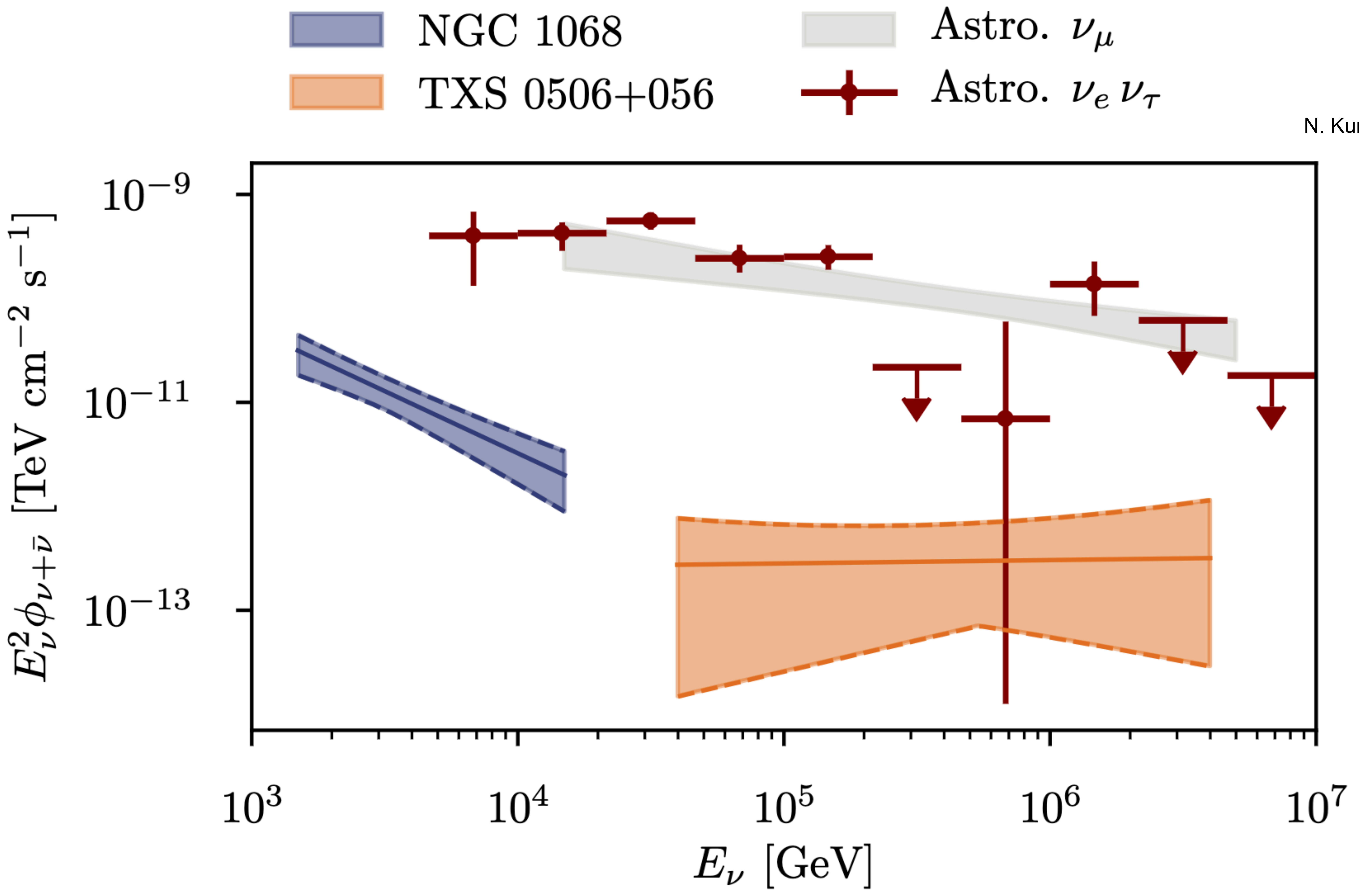
Model	Limits
IceCube Lorentz violation limit	$\mathring{a}^{(3)}_{\tau\tau} < 2 \times 10^{-26}\mathrm{GeV}$
Dark matter potential	$V_{\tau\tau} < 2 \times 10^{-26}\mathrm{GeV}$
Dark matter effective Fermi coupling	$G'_F < 10^{-13}\mathrm{GeV}^{-2}(m_\phi/10^{-20}\mathrm{eV})$
Dark matter non-standard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

CA, Farrag, Katori arXiv:2404.10926

Outline for the rest of this talk

1. Neutrino astrophysics and IceCube
2. Most significant observations in neutrino astrophysics
3. New opportunities for particle physics
4. **Future detectors & new ideas**

Big Question:
Where are these neutrinos coming from?



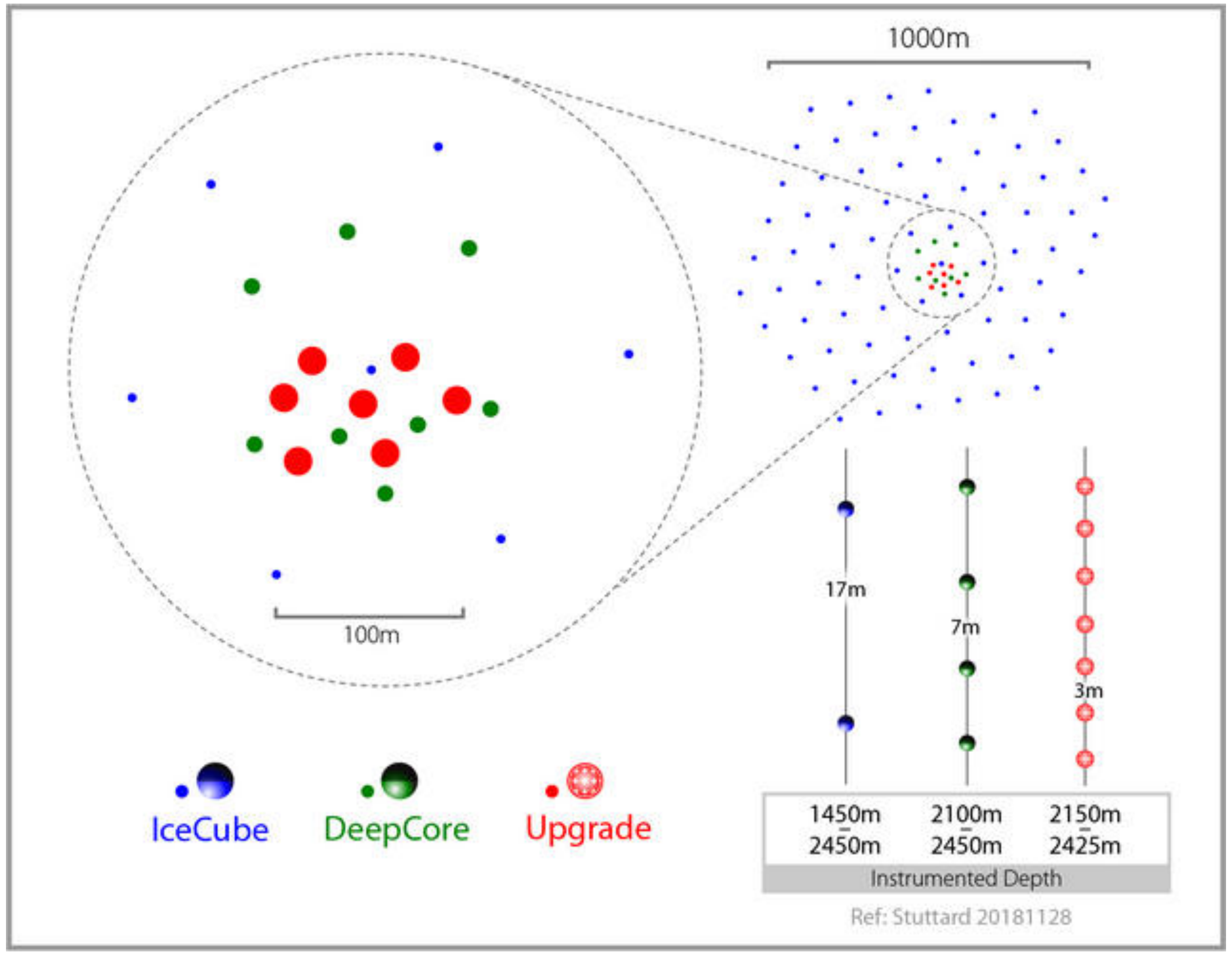
IceCube Collaboration, Science, 2022
N. Kurahashi ICRC204 for the IceCube Collaboration

Many Neutrino Telescopes On Our Way

Non-exhaustive list

IceCube is growing: The Upgrades

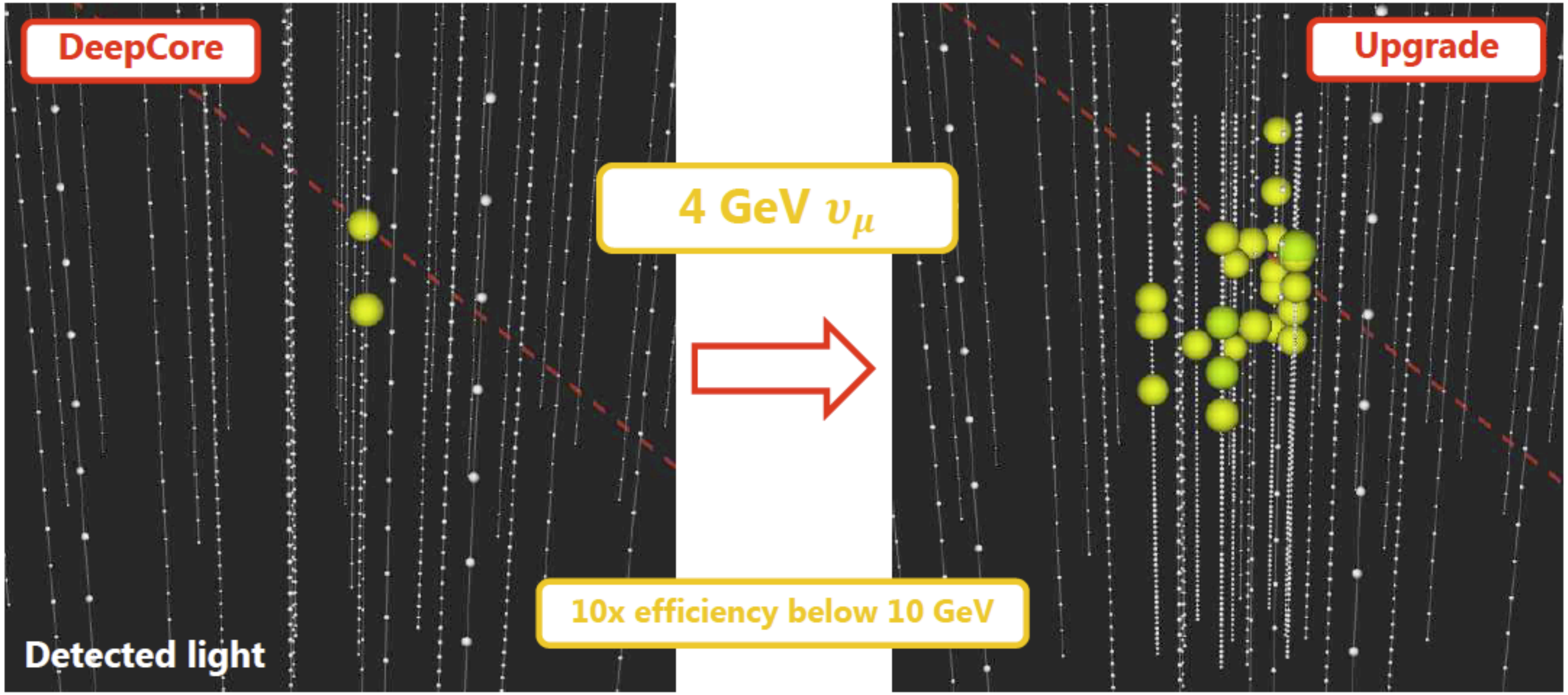
Phase 1: 7 new, high-precision strings in the central, densely instrumented region. Funded, installation in 2025.



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

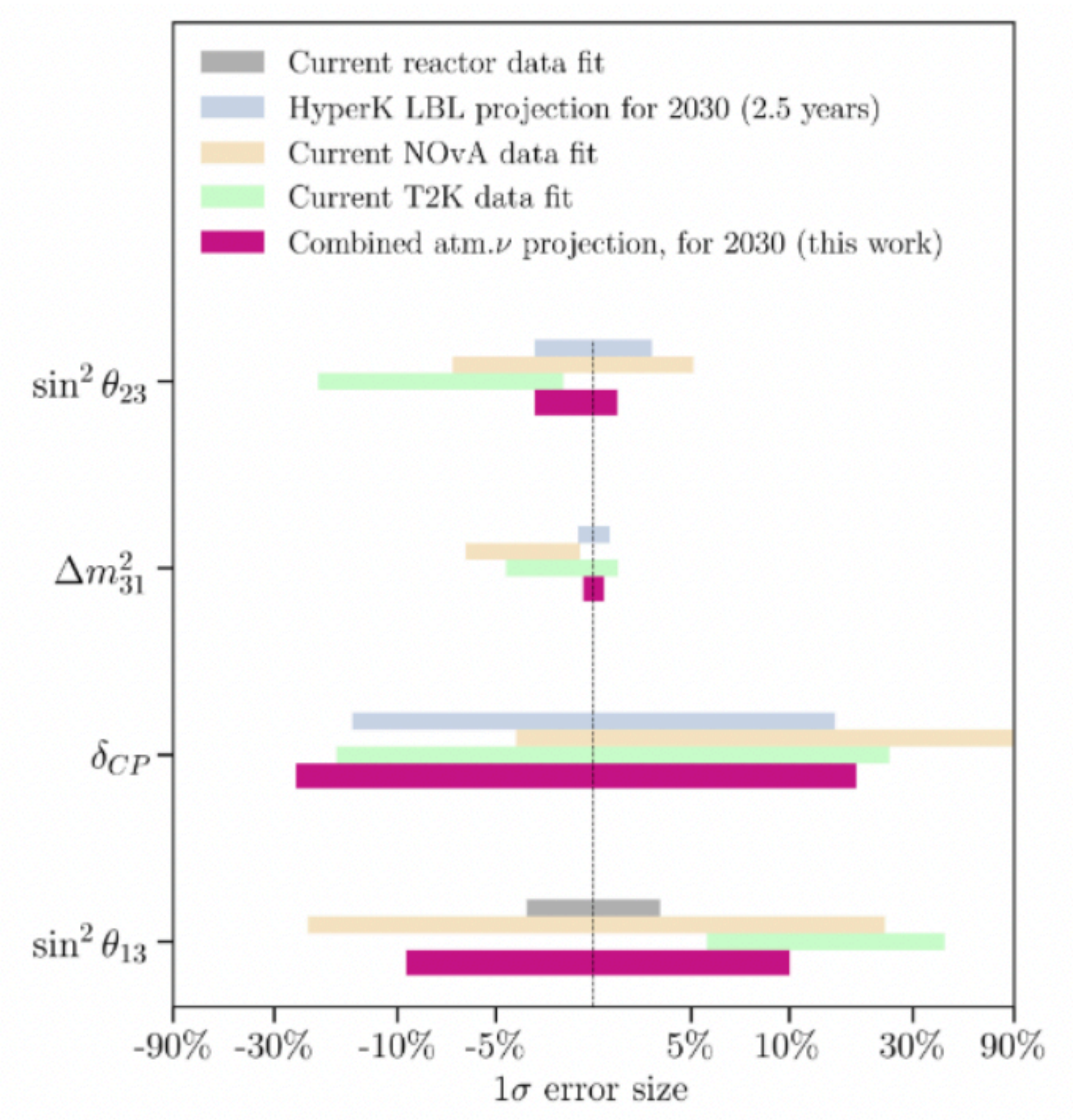
See more details in J. Lazar talk (Tuesday)

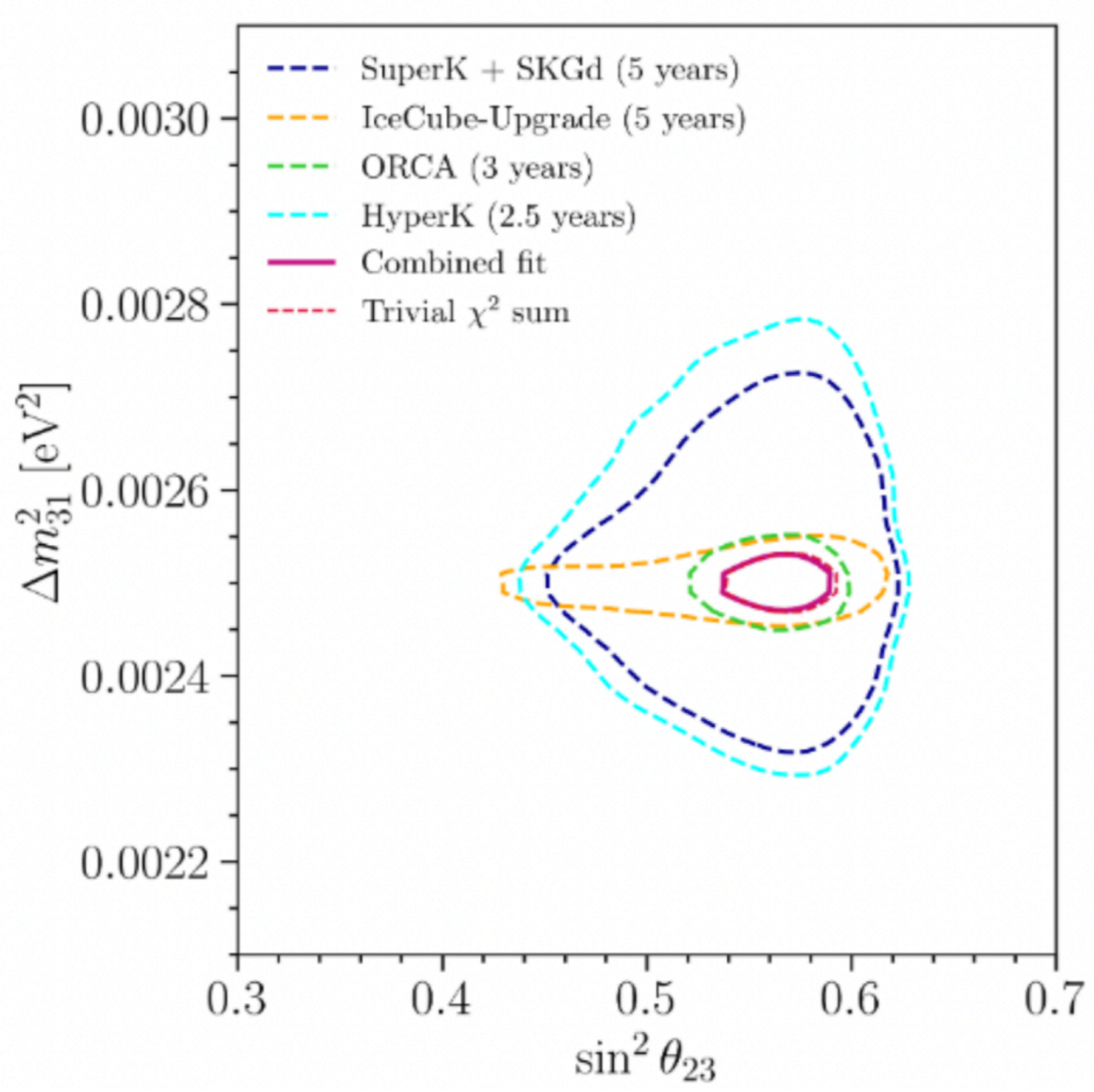
Improved light-collection for low-energy events

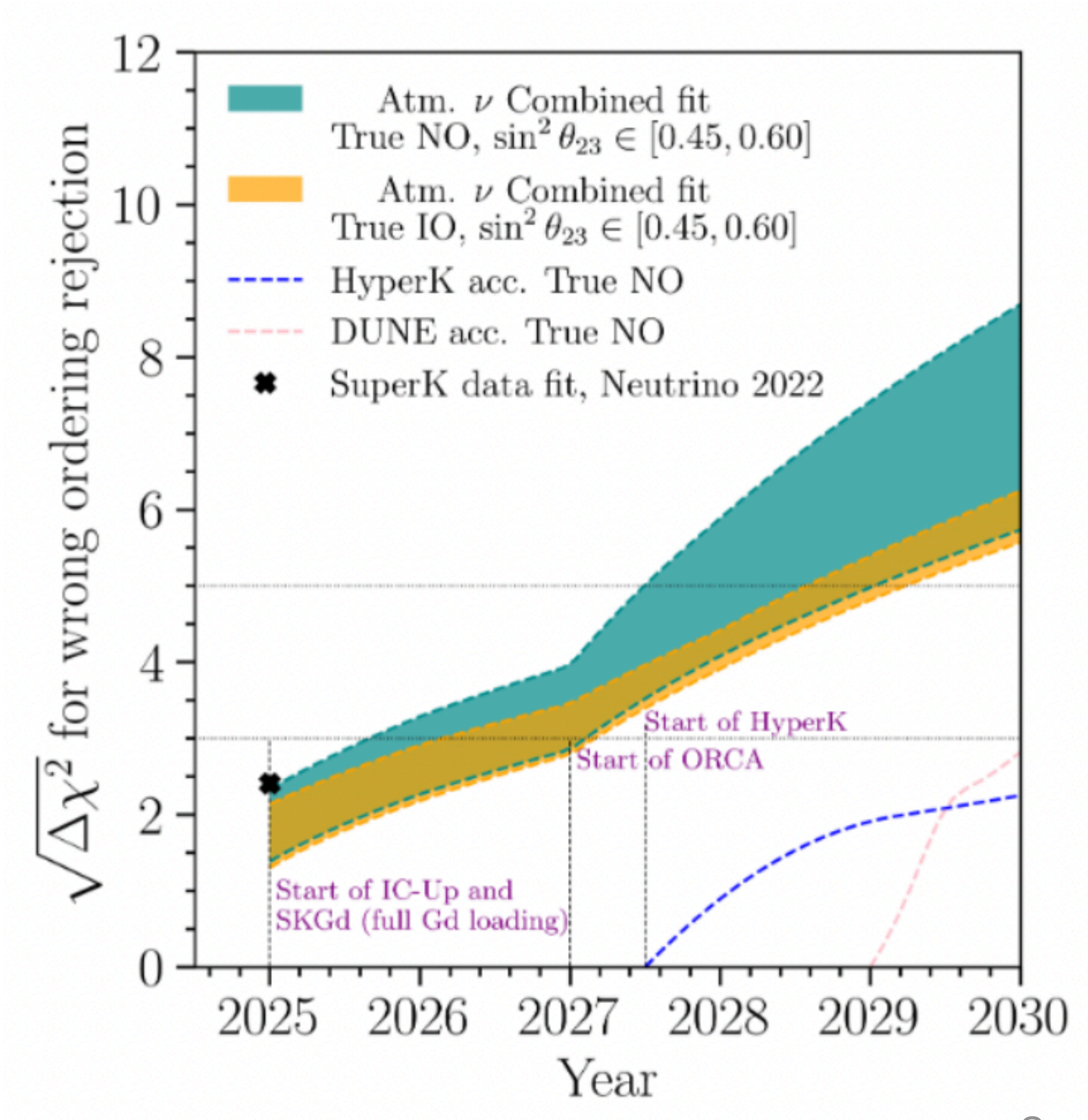


*DeepCore (shown on the left) is the current low-energy extension of IceCube

Near-term atmospheric neutrinos together





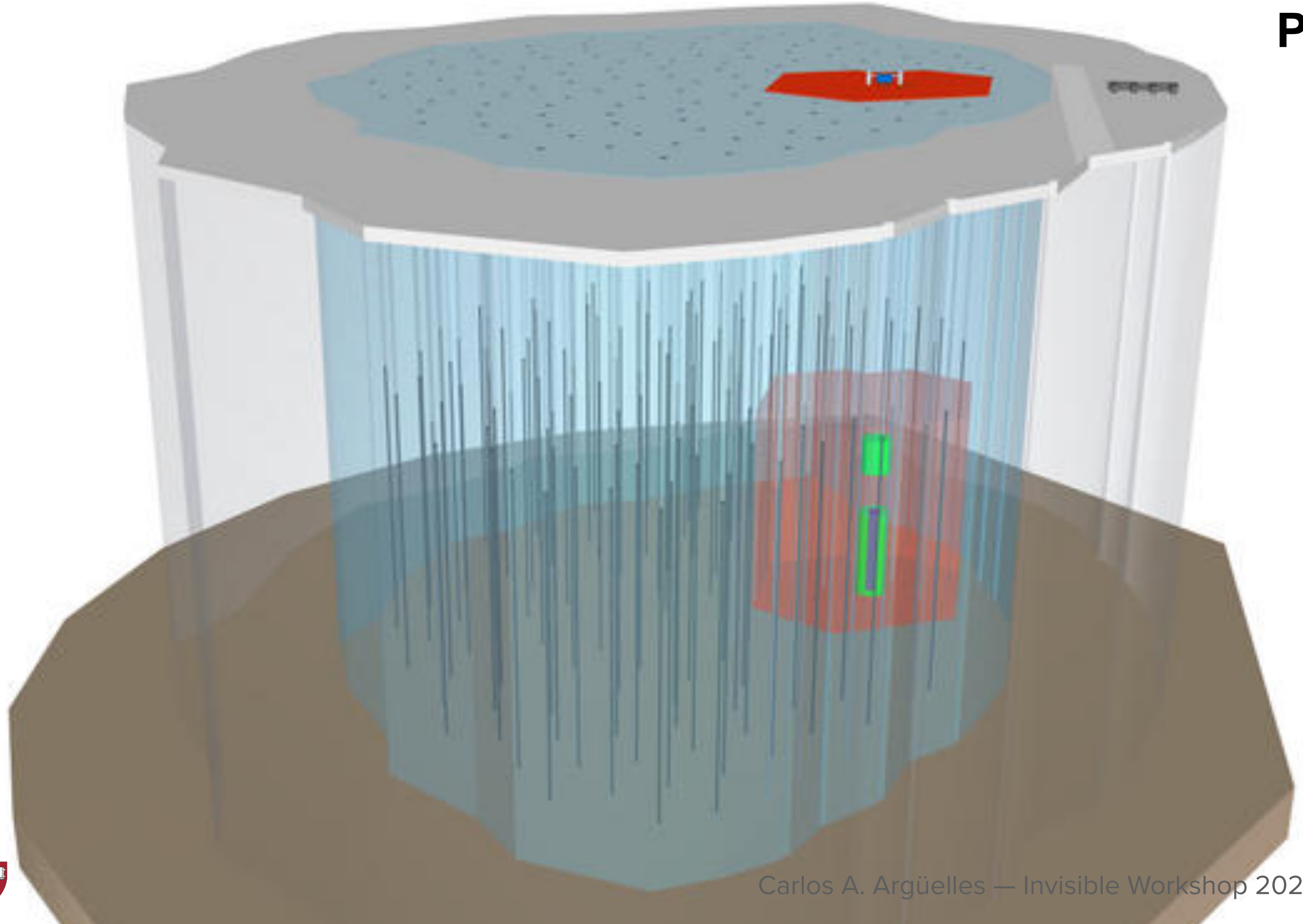


CA, P. Fernández, I. Martínez-Soler, and M. Jin, PRX 13 041055

See also Giner-Olavarrieta, Jin, CA, Fernandez, Martínez-Soler (2402.13308)

See also talks earlier by S. Parke and S. Petcov

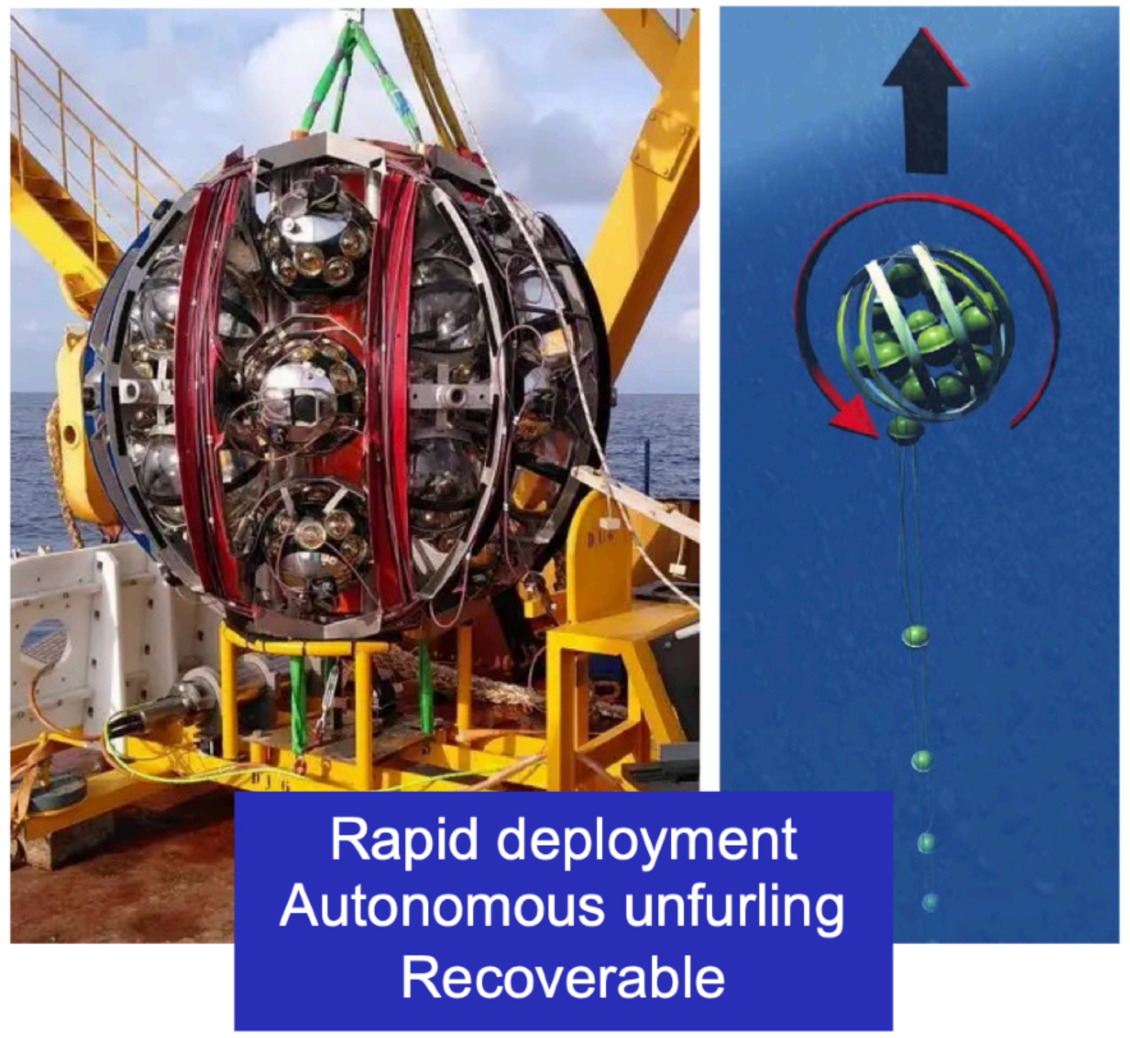
IceCube is growing: The Upgrades

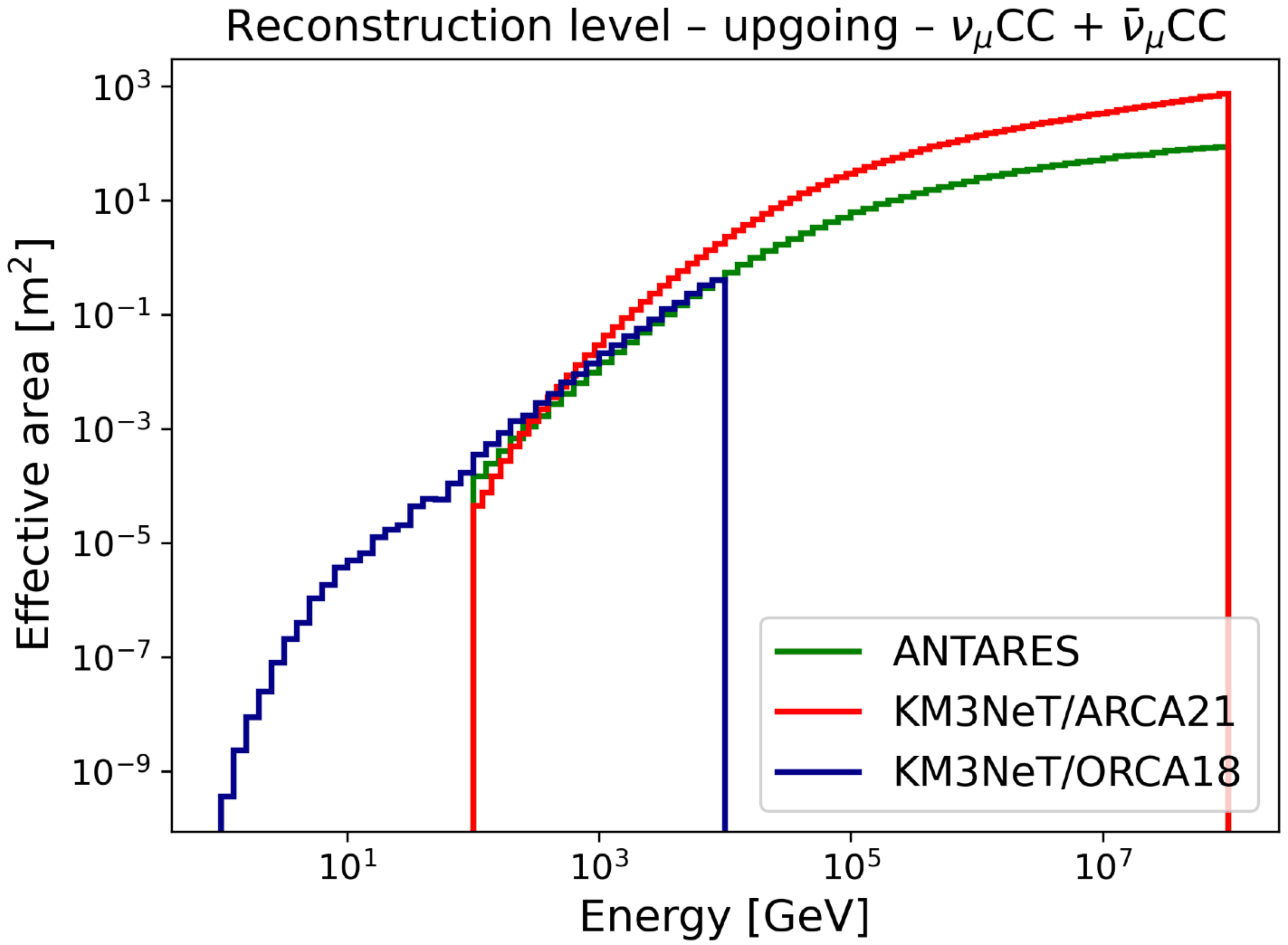


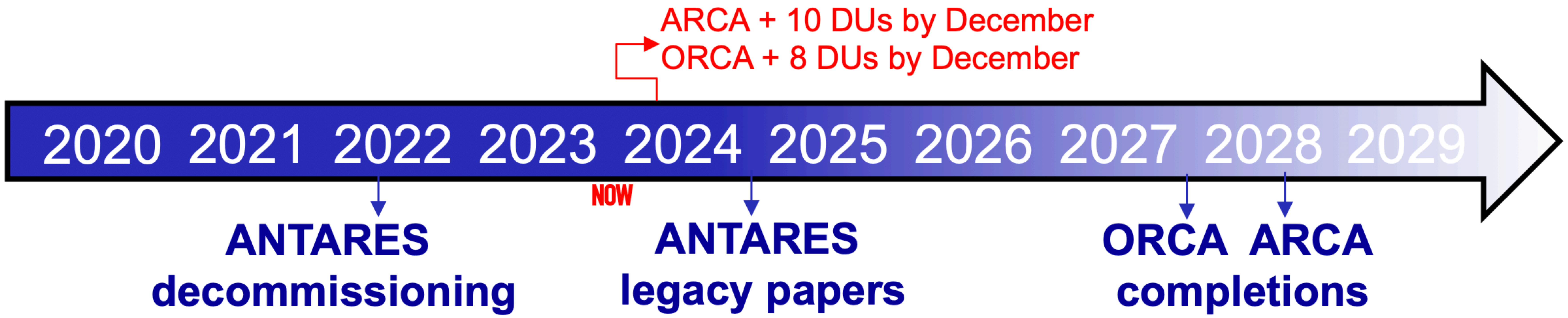
Phase 2: x10 the volume of present IceCube, plus additional detectors.

See more details in J. Lazar talk (Tuesday)

Next Neutrino Telescope: KM3NeT

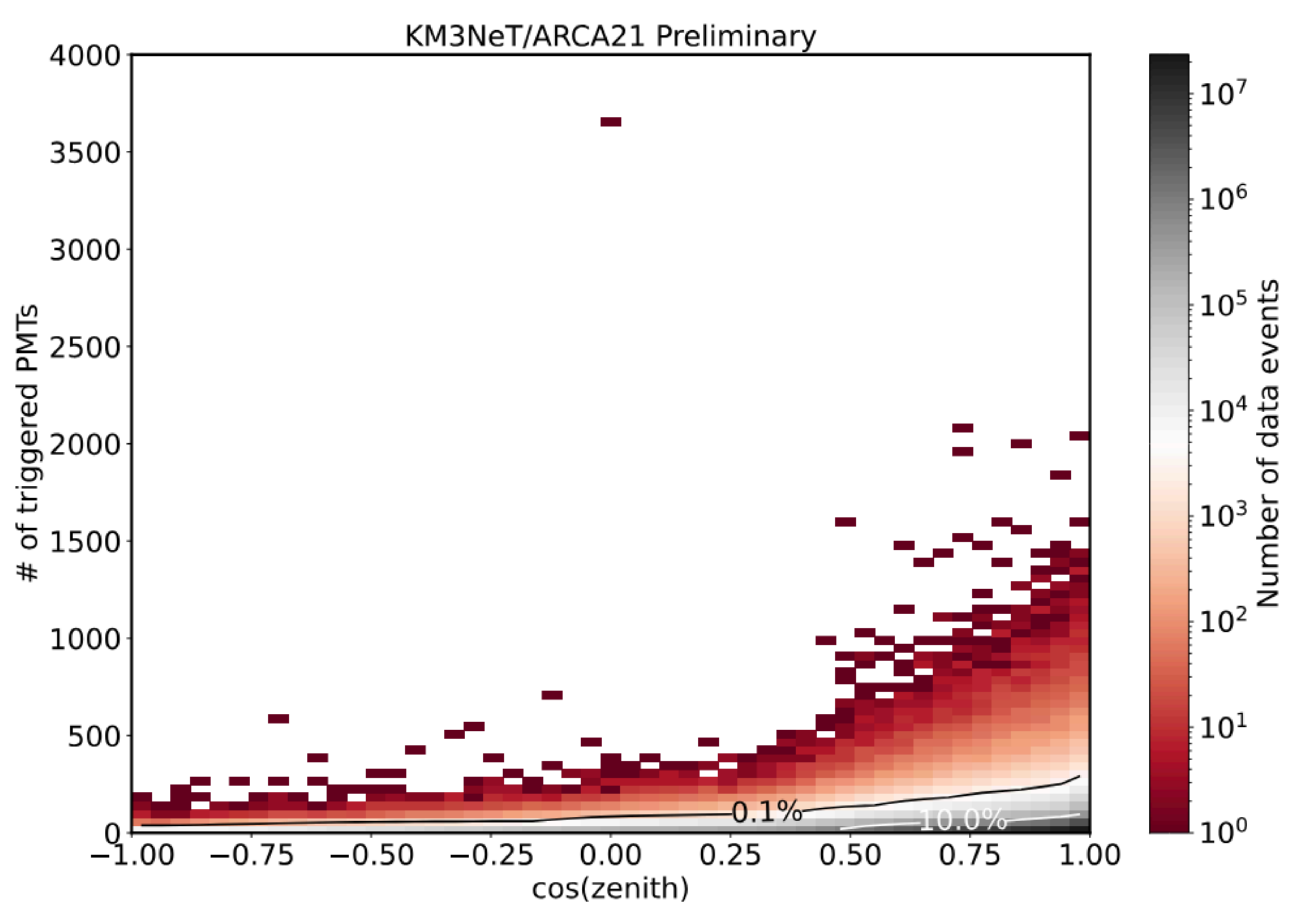


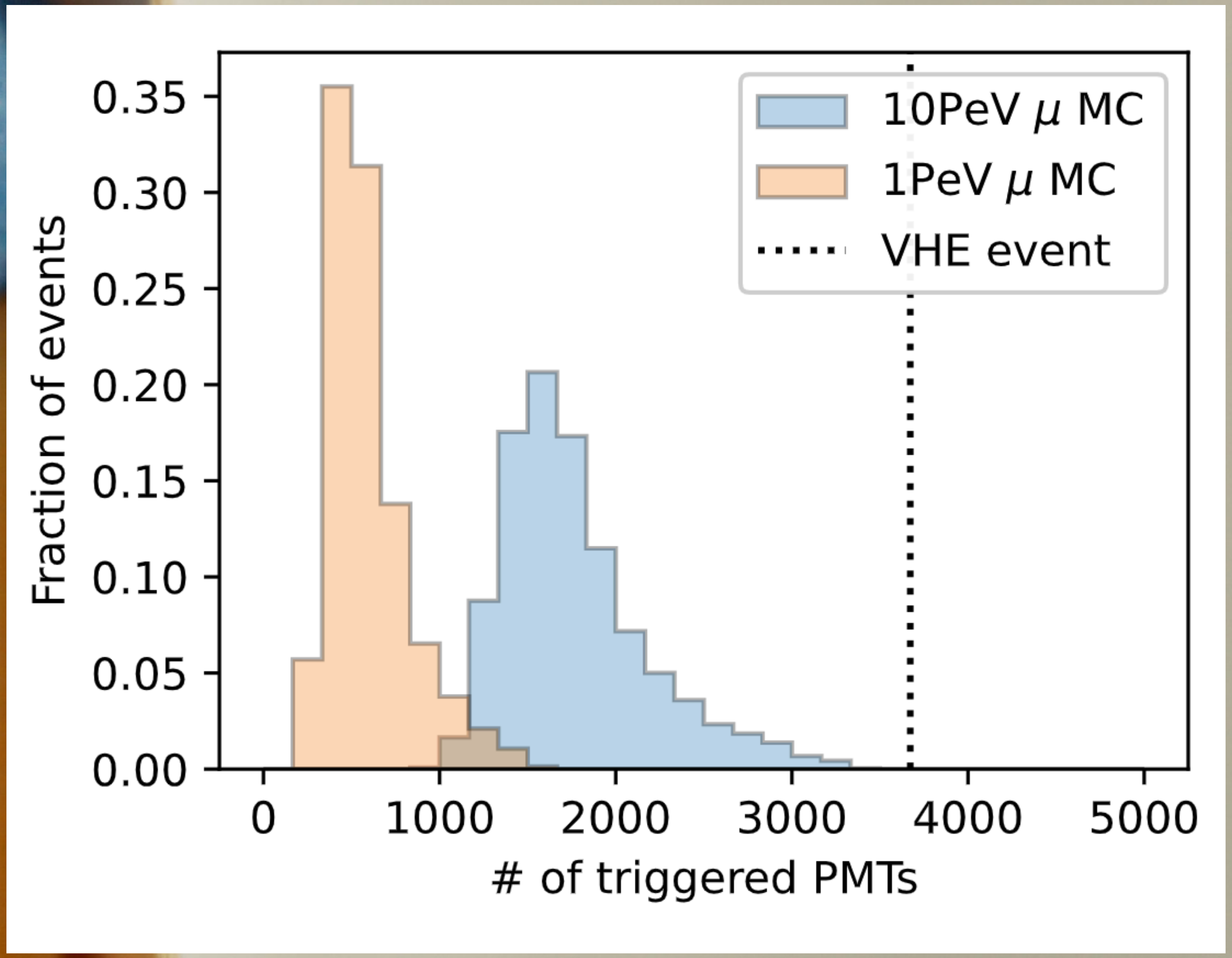




(Adapted from a slide courtesy of Antoine Koushner)

KM3NeT see first nu-light?





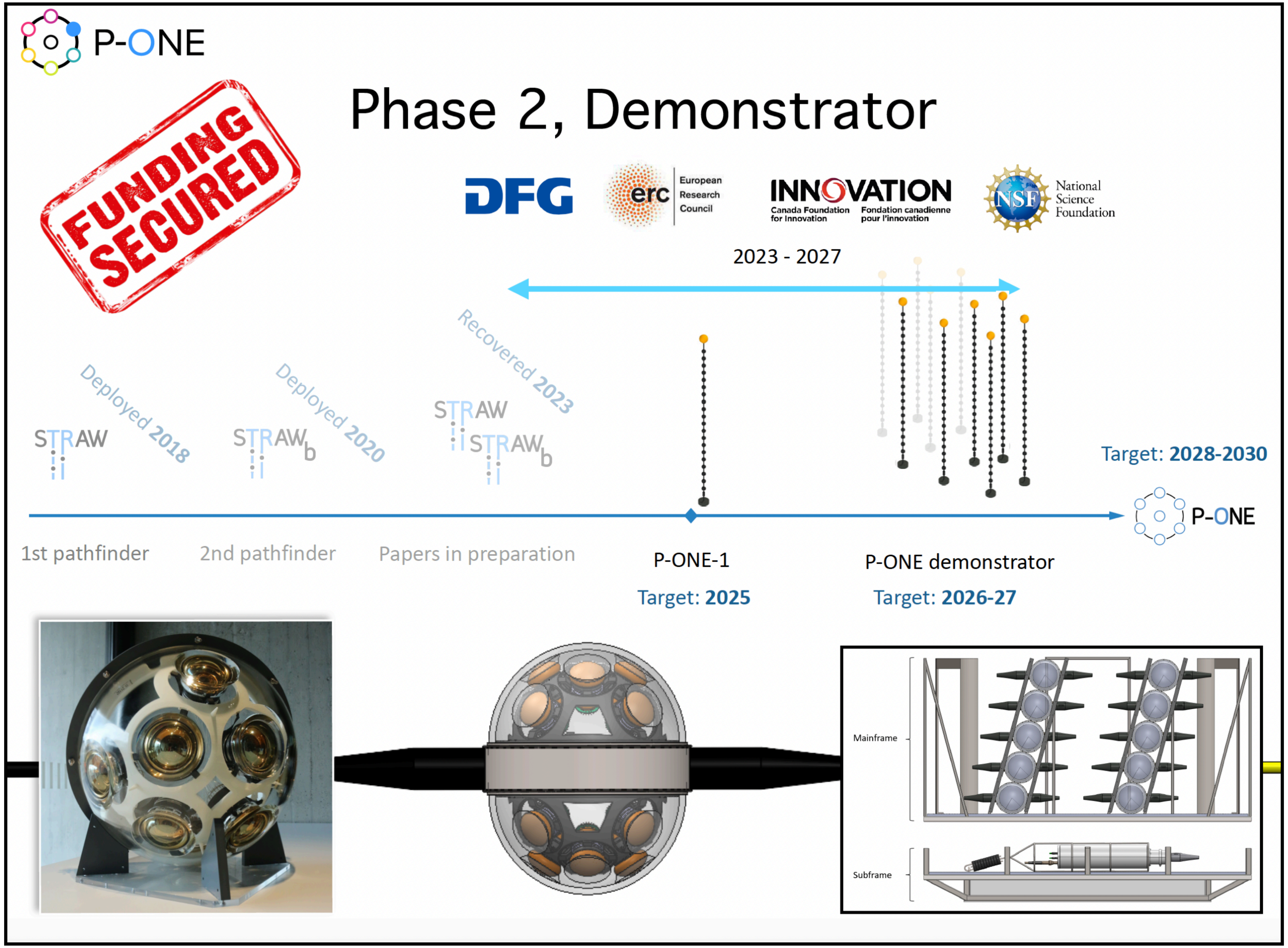
…DEVELOPING STORY…

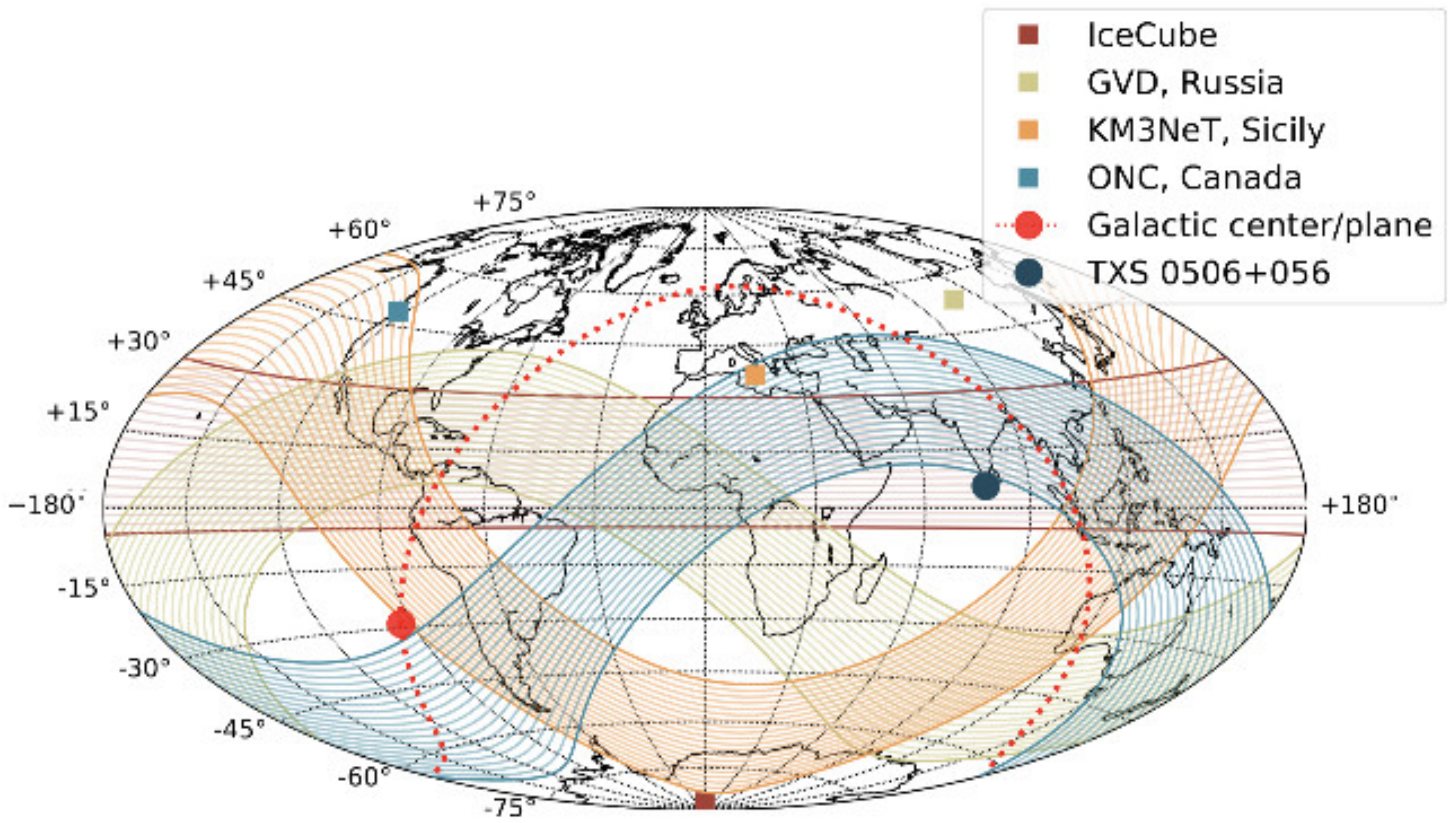
Muons simulated at 10 PeValmost never generate this much light

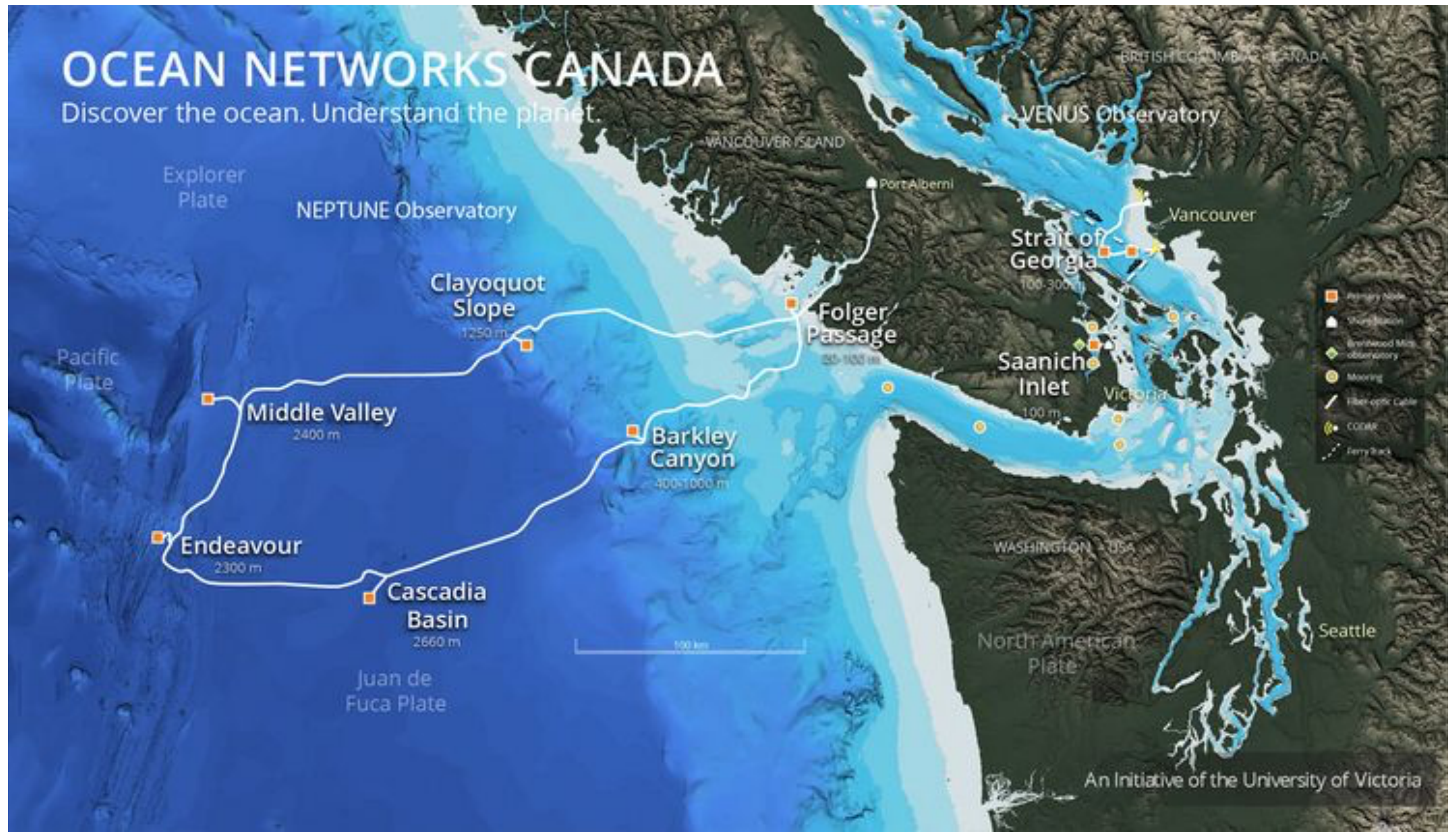
–Likely multiple 10's of PeV!!!

See more details in J. Lazar talk (Tuesday)

Future, Water Neutrino Telescope: P-ONE

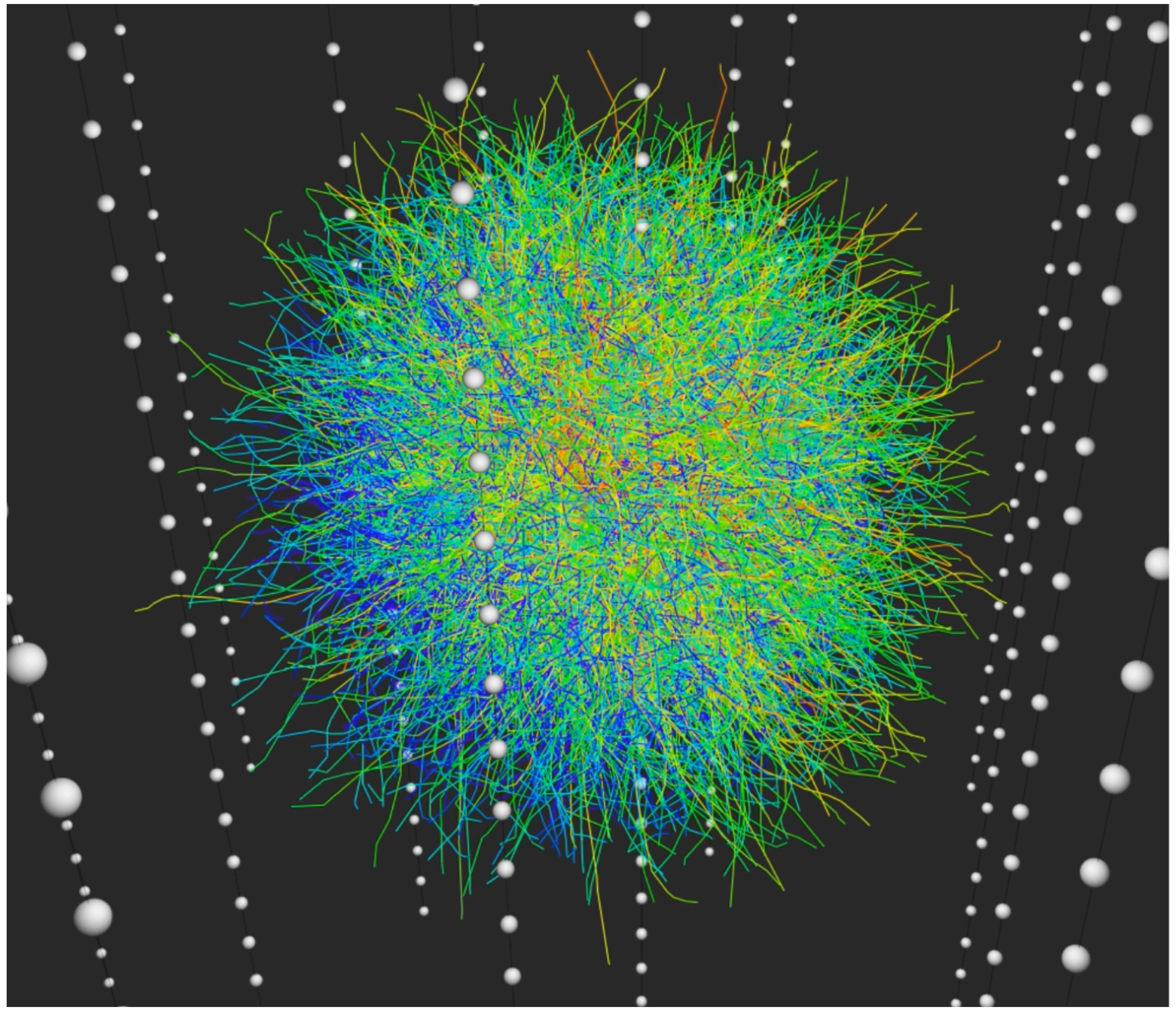




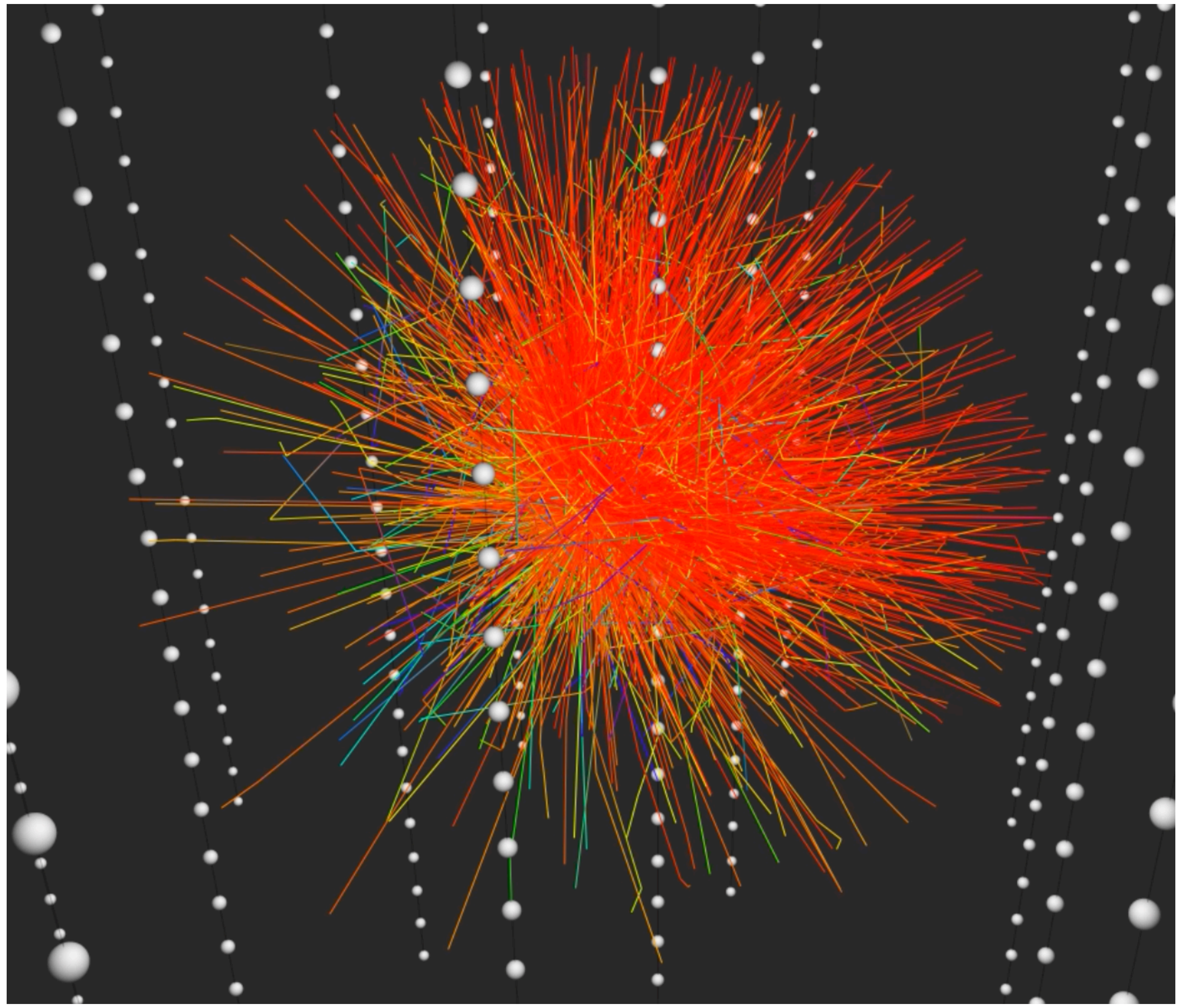


(Adapted from a slide courtesy of Elisa Resconi)

Cascade in Water and Ice Compared



10 TeV in ice



10 TeV in water

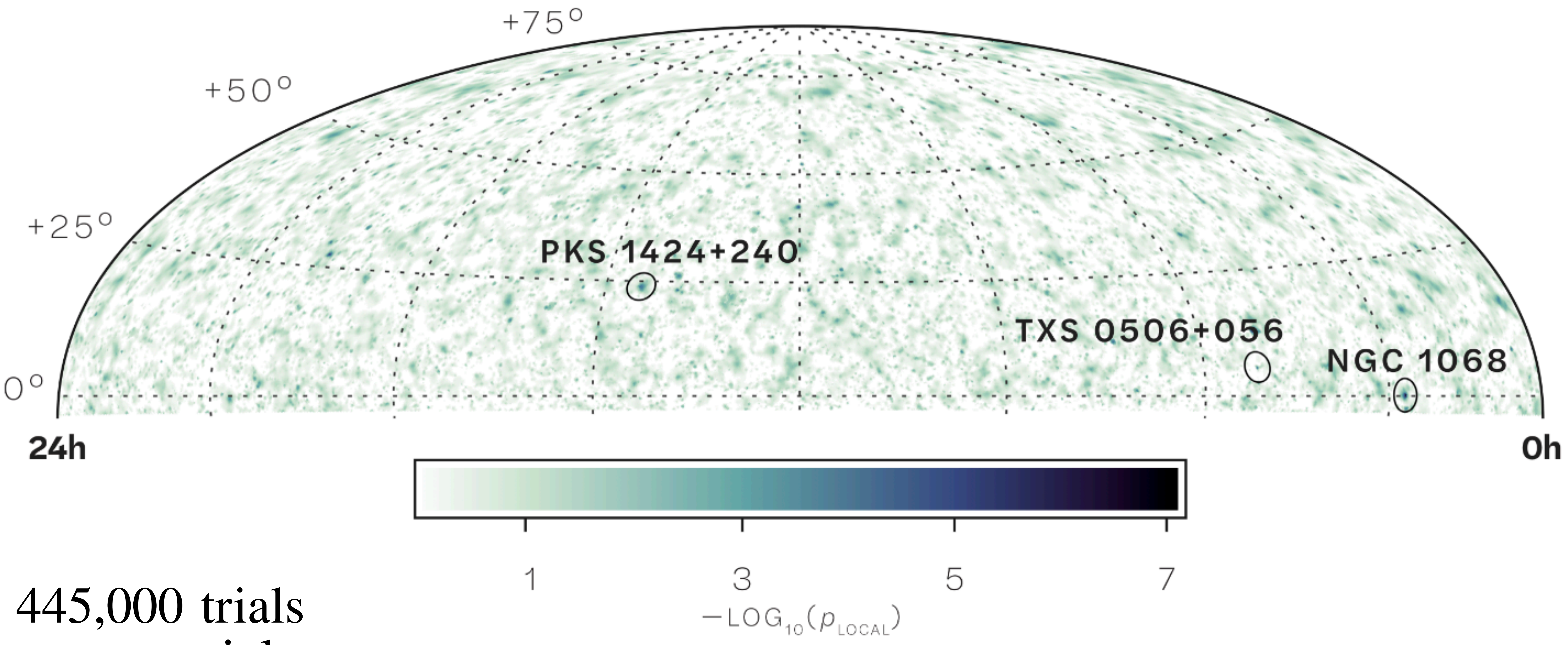
Water detectors are expected to have better particle identification capability.

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} ($2.0\,\sigma$)



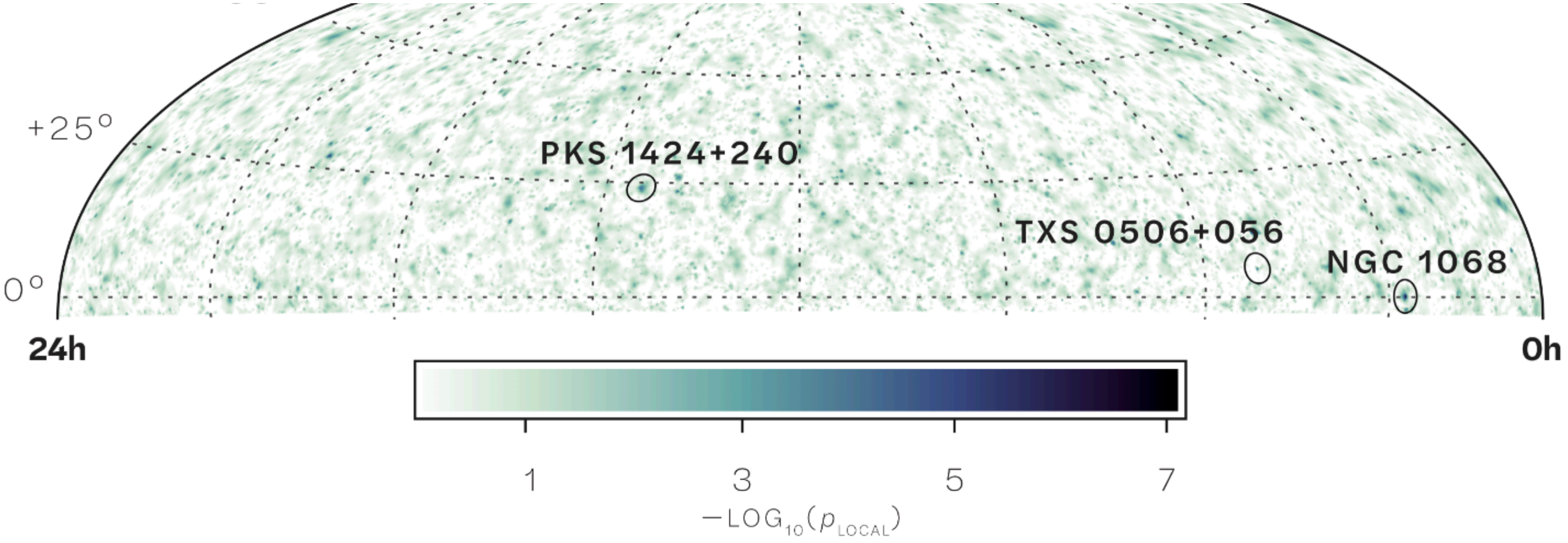
$\sim 445{,}000$ trials

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

Why we can't find the sources right now?

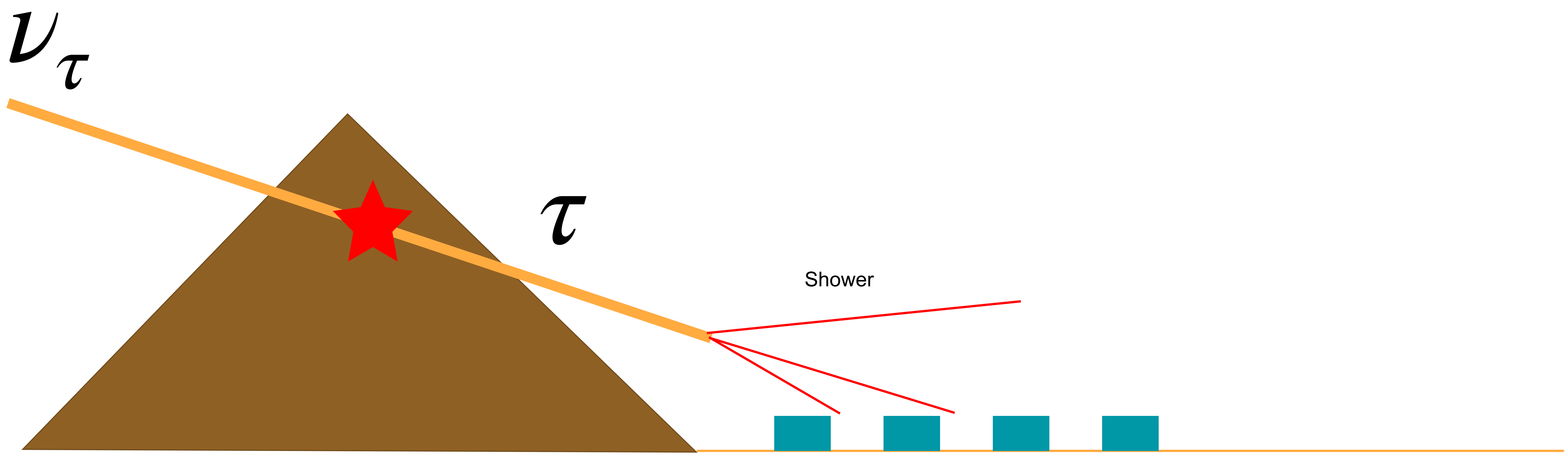
Trials and tribulations

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} ($3.4\,\sigma$)



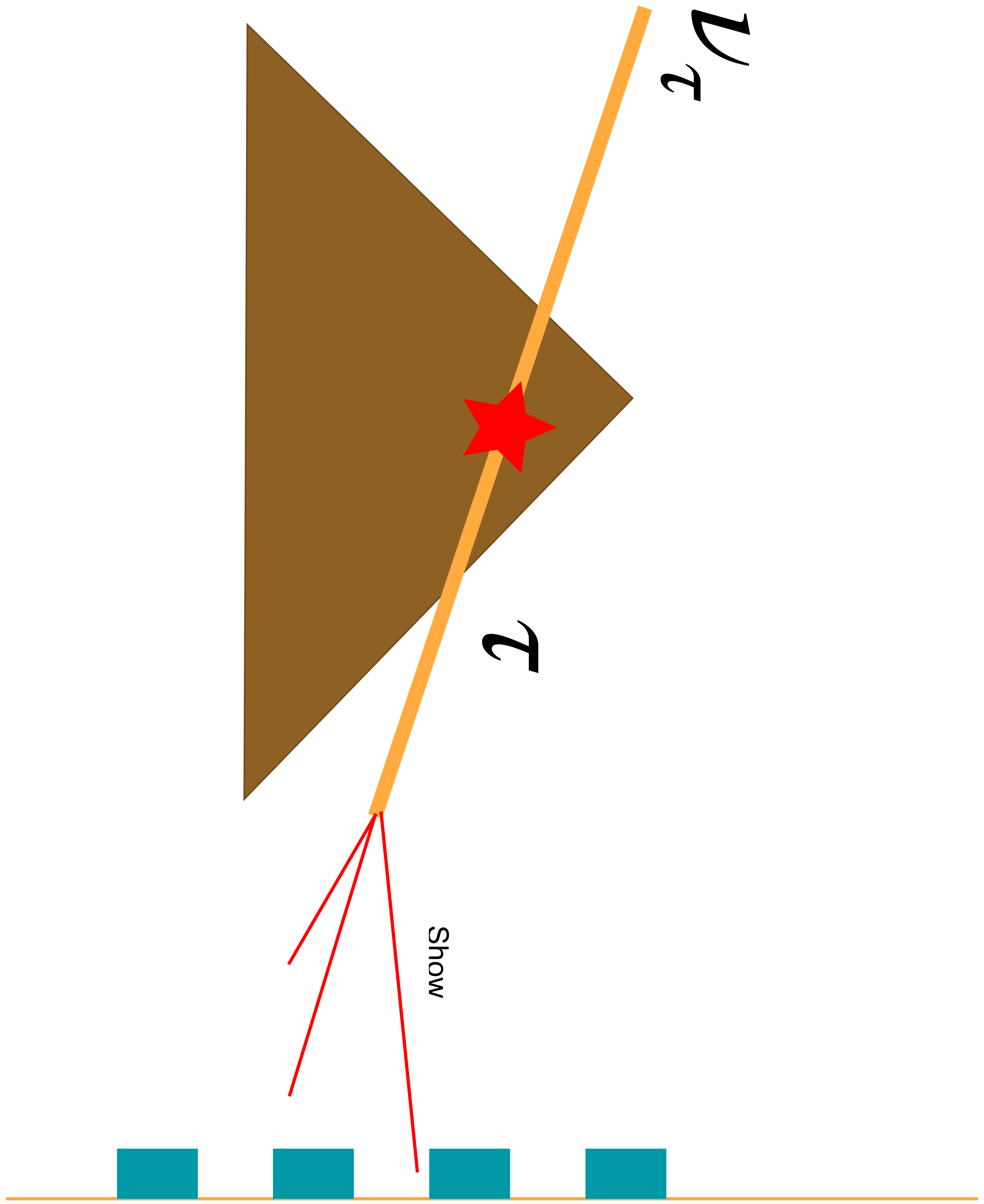
If you know where to look, bright sources are currently detectable

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

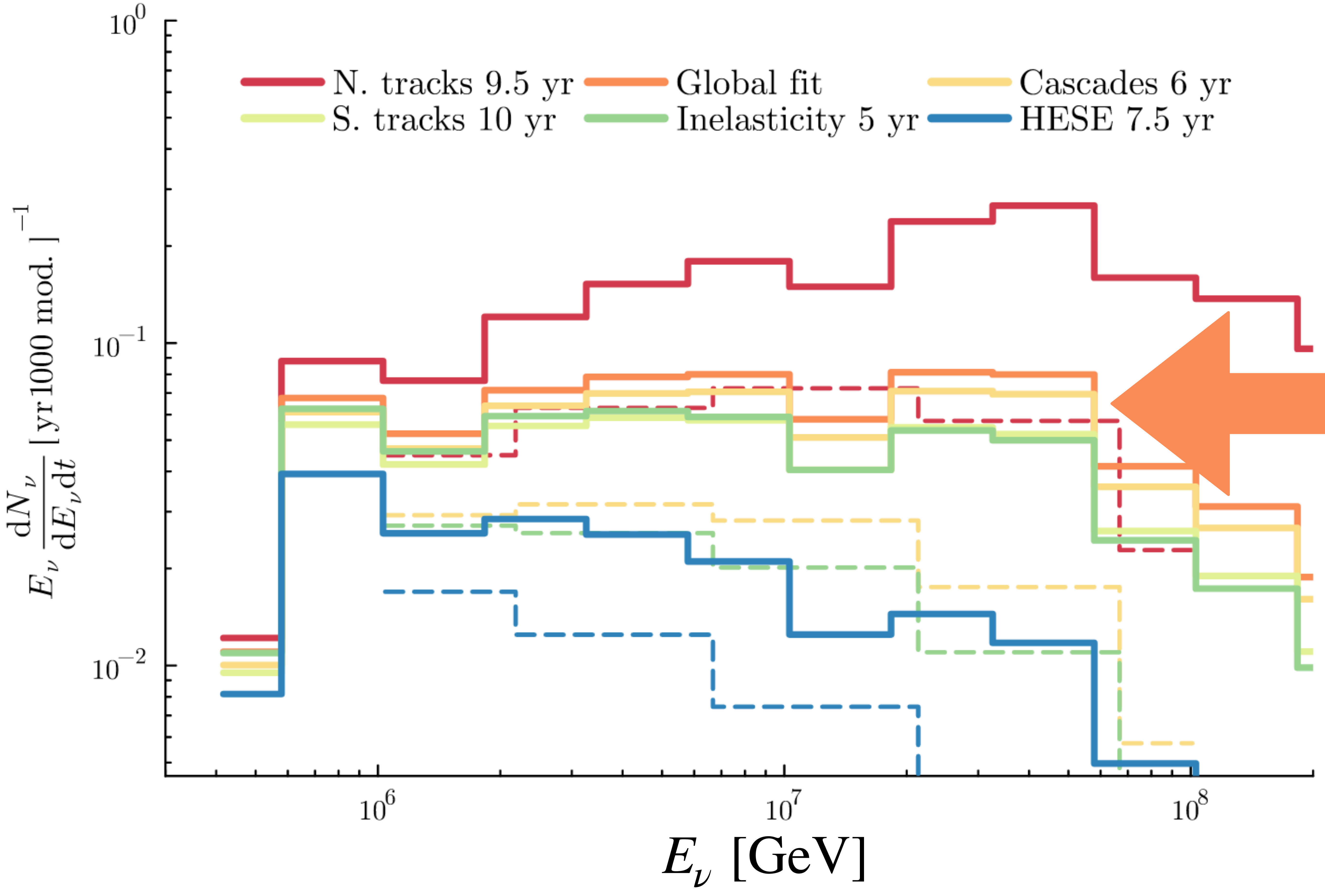
W. Thompson ICRC2024 (arXiv:2308.09753)

*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.

Expected rates at TAMBO given unknown-origin IceCube flux

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

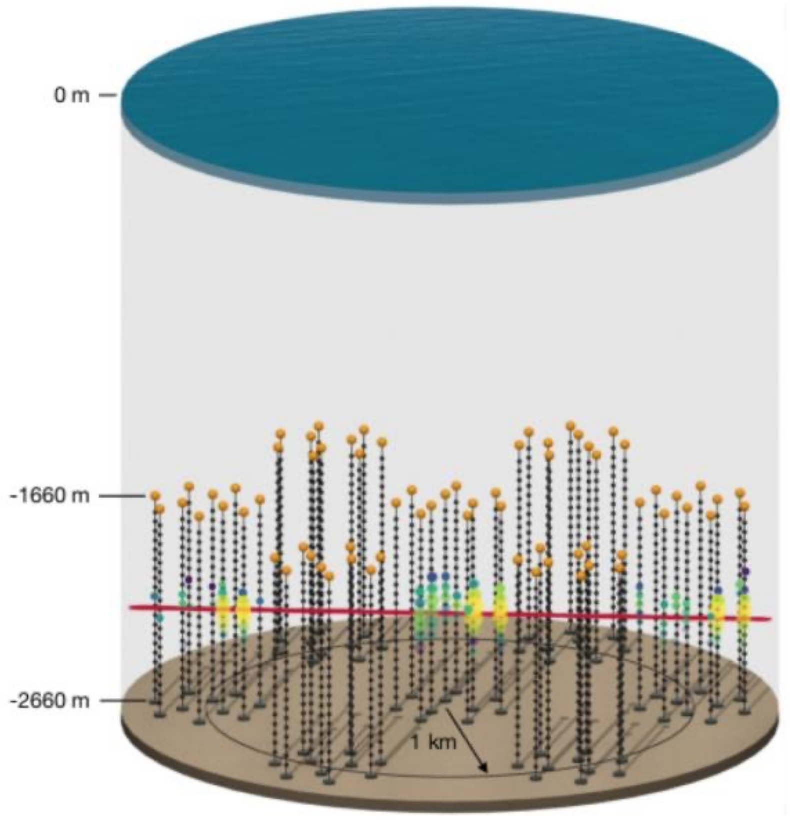


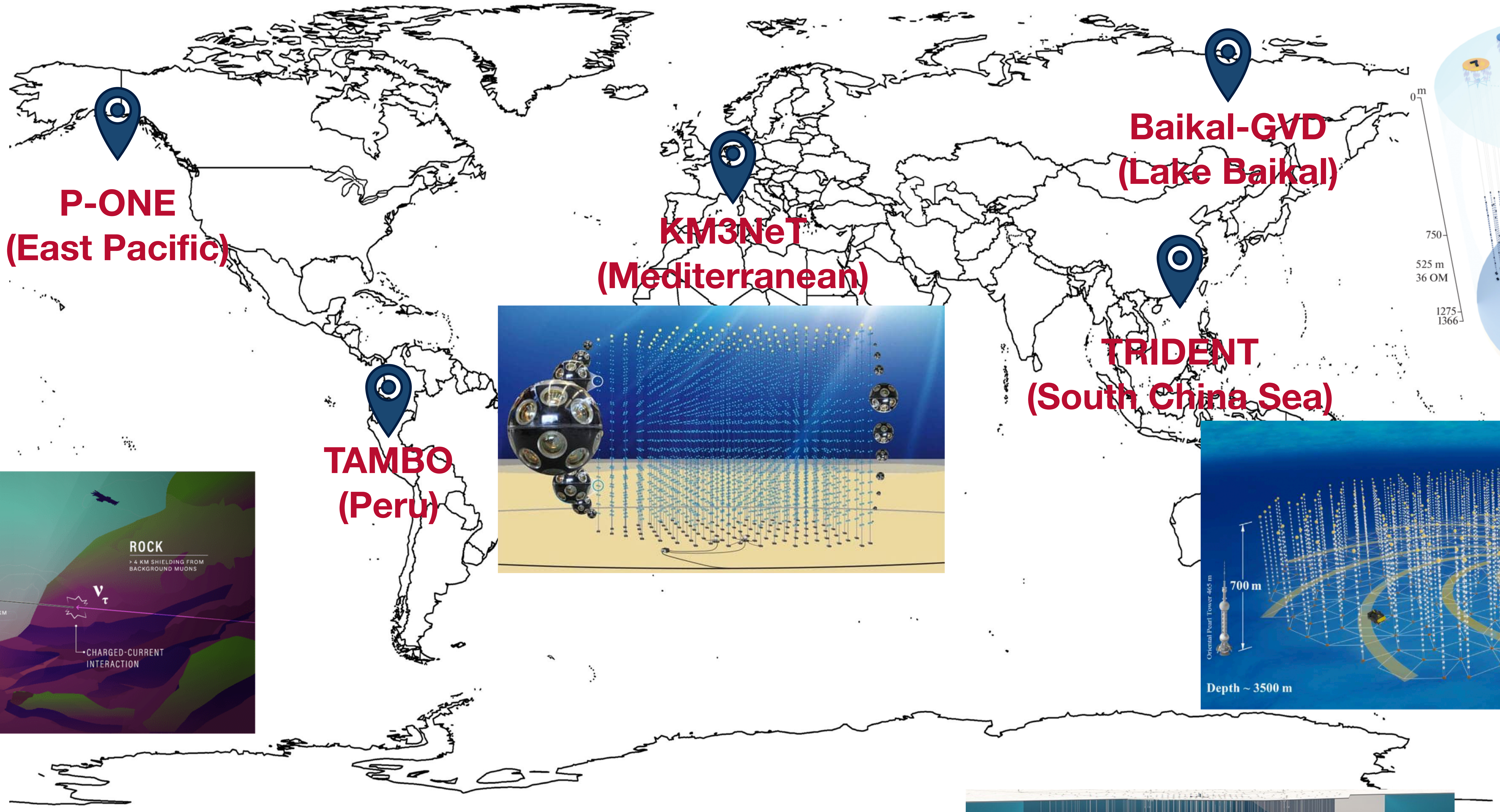
Most likely event rate given IceCube measuremetns

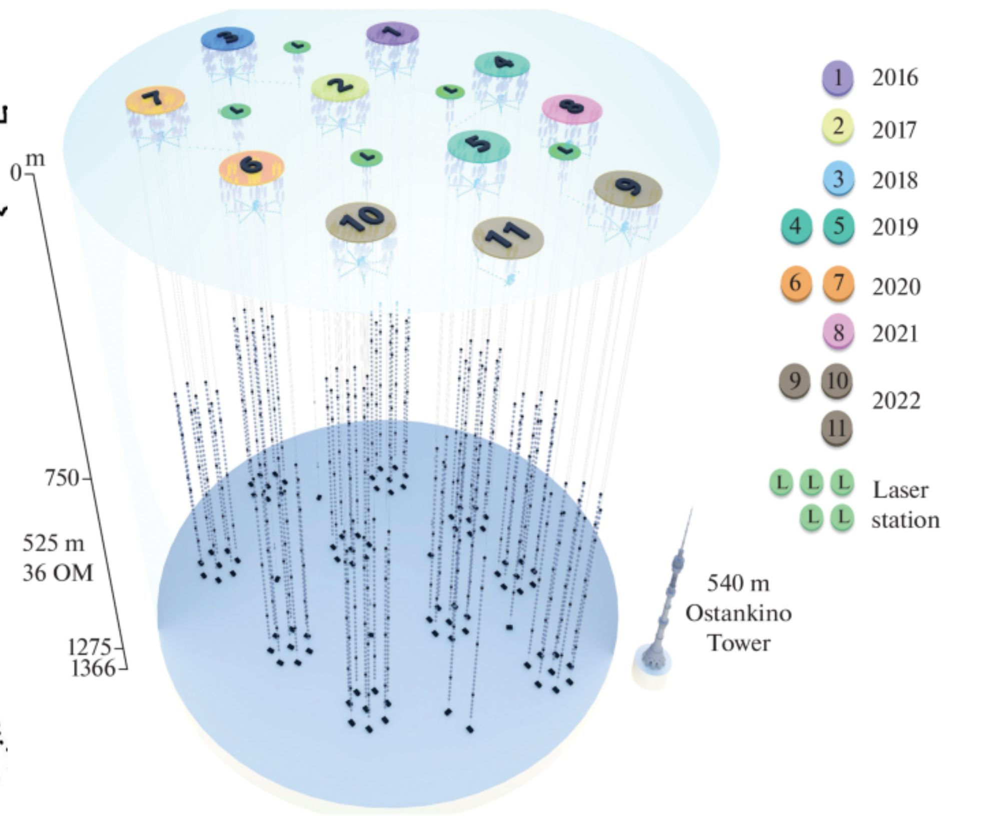
For 5000 sensors we expect a couple of events every year.
Few events, but every event points to a source: no trial factor in a IceCube/KM3NeT follow up

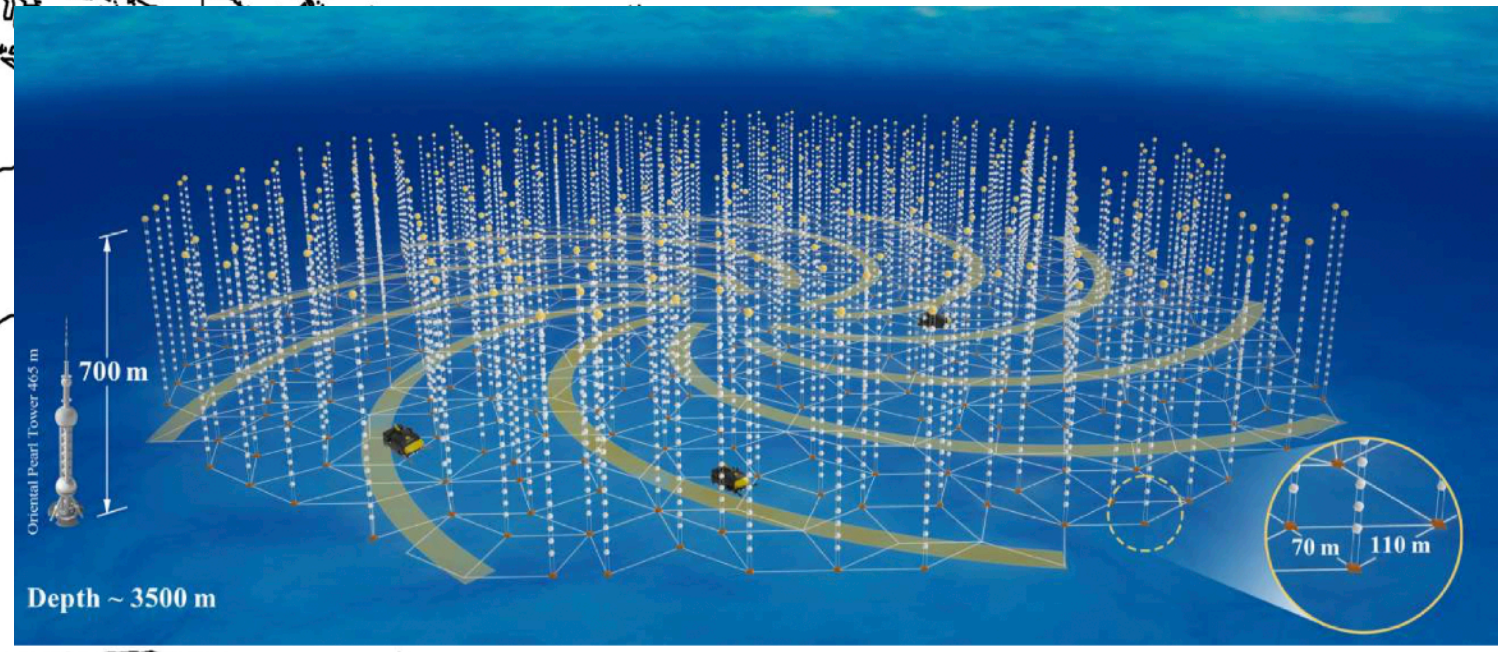
Towards a *Joint* Global Neutrino Telescope

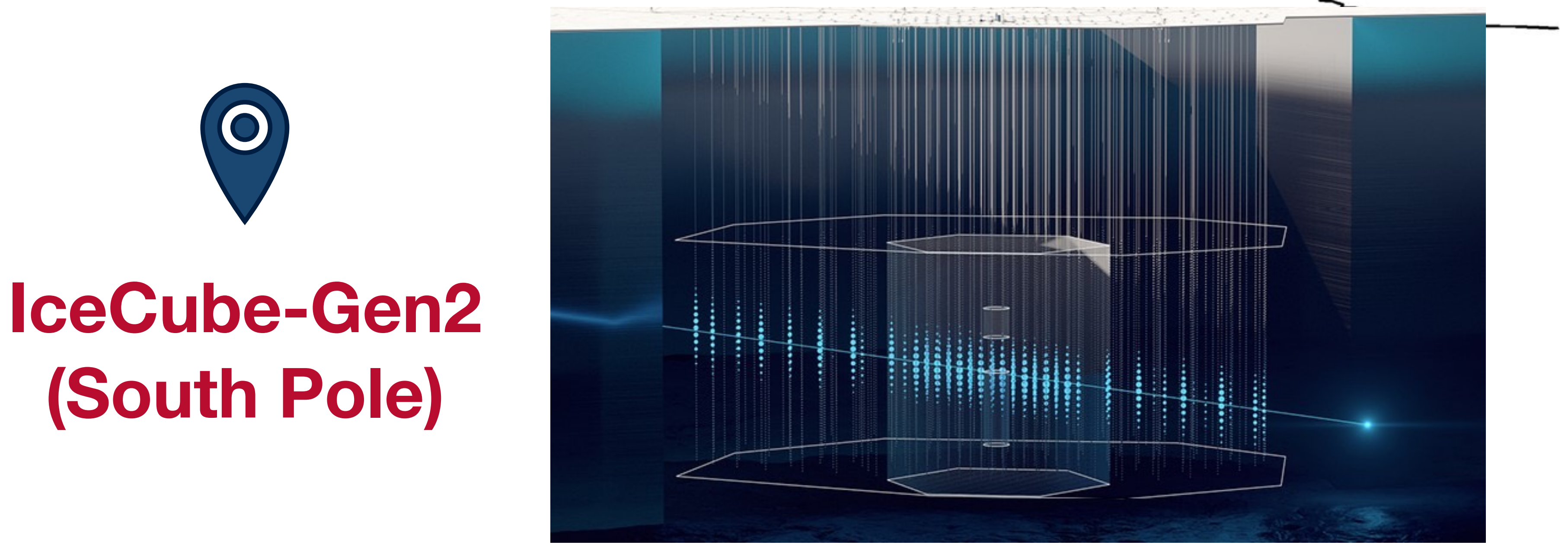
(Diagram courtesy of Qinrui Liu)





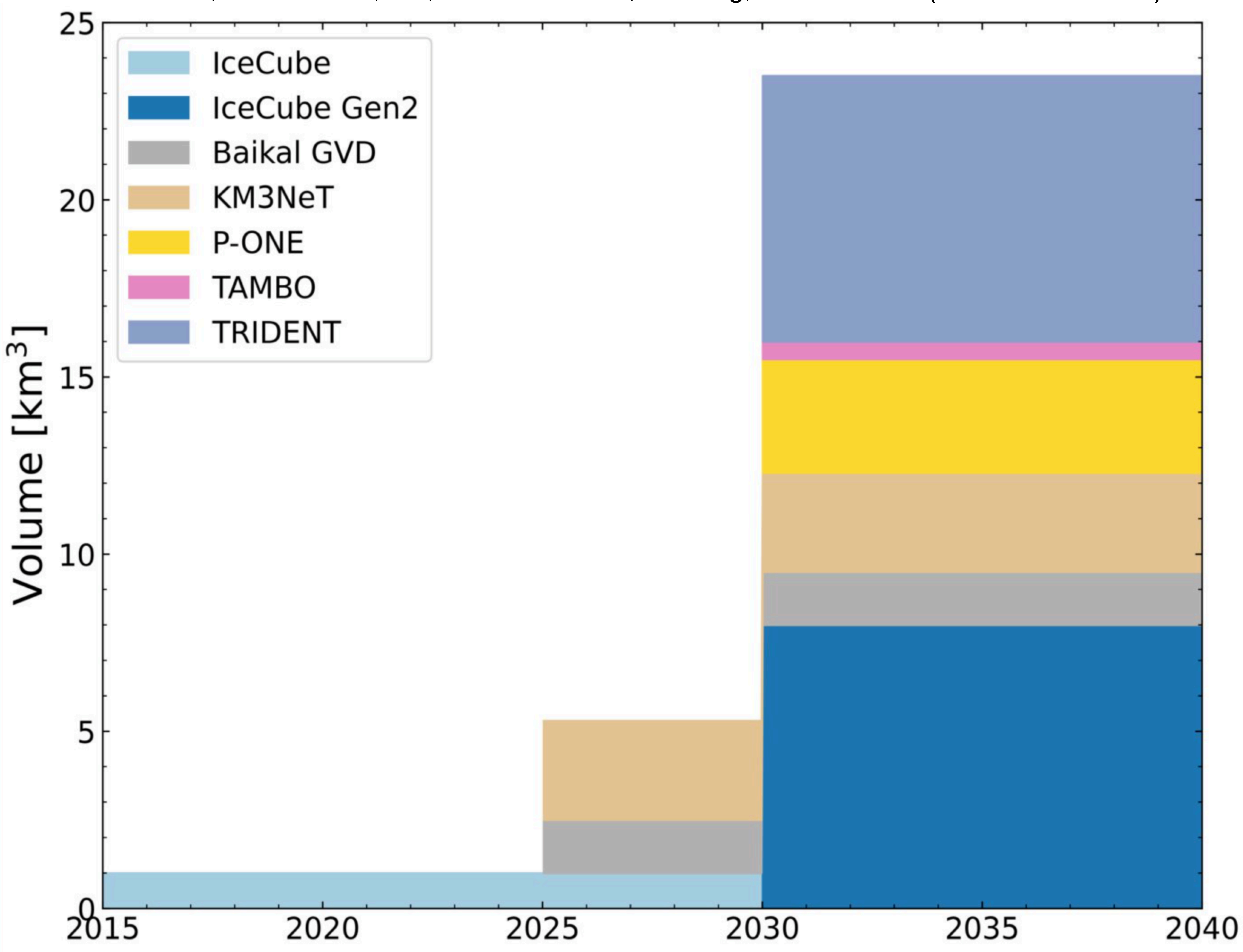






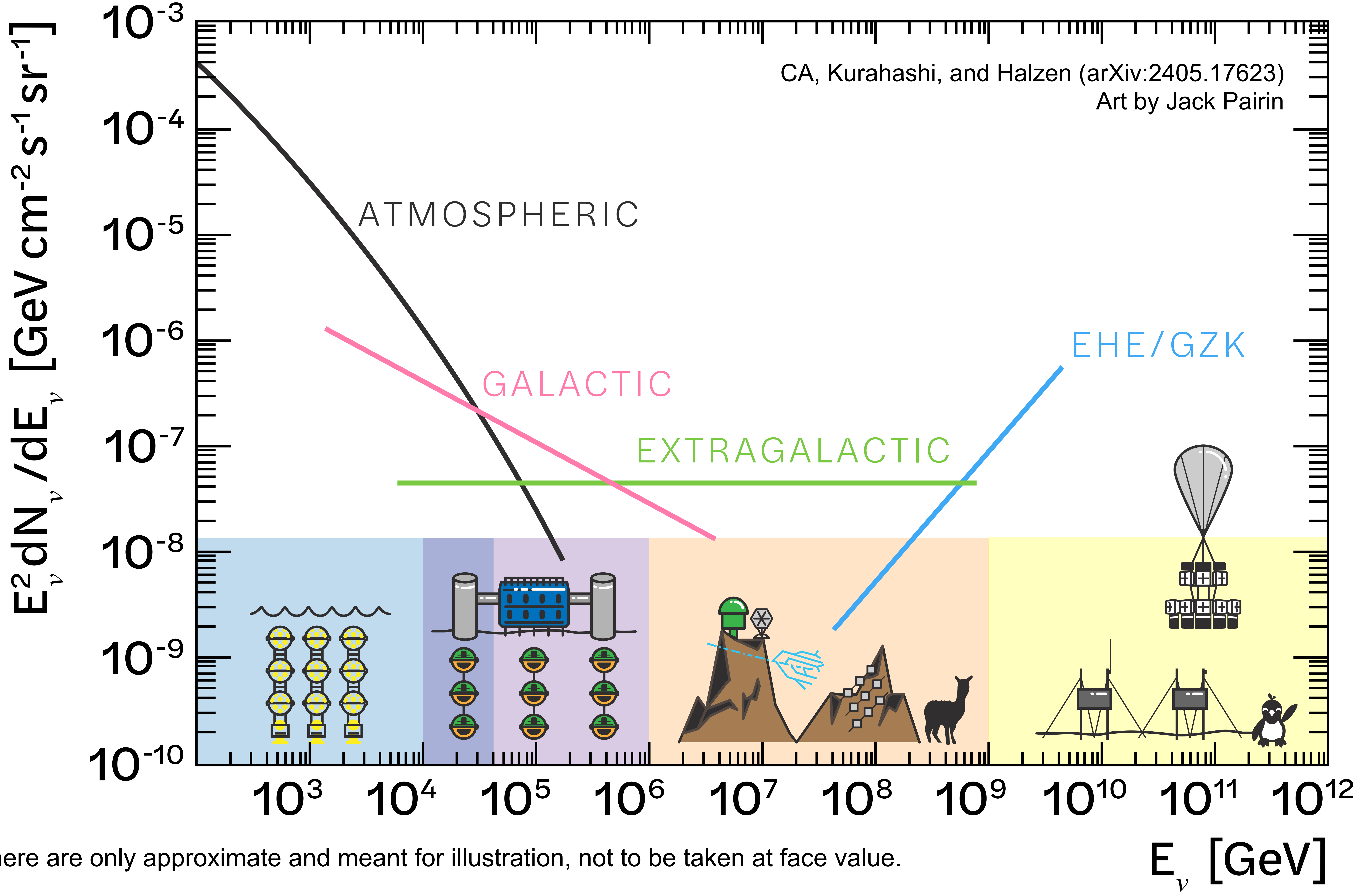
Many neutrino telescopes on similar energy ranges and with complementary capabilities under construction/planning

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



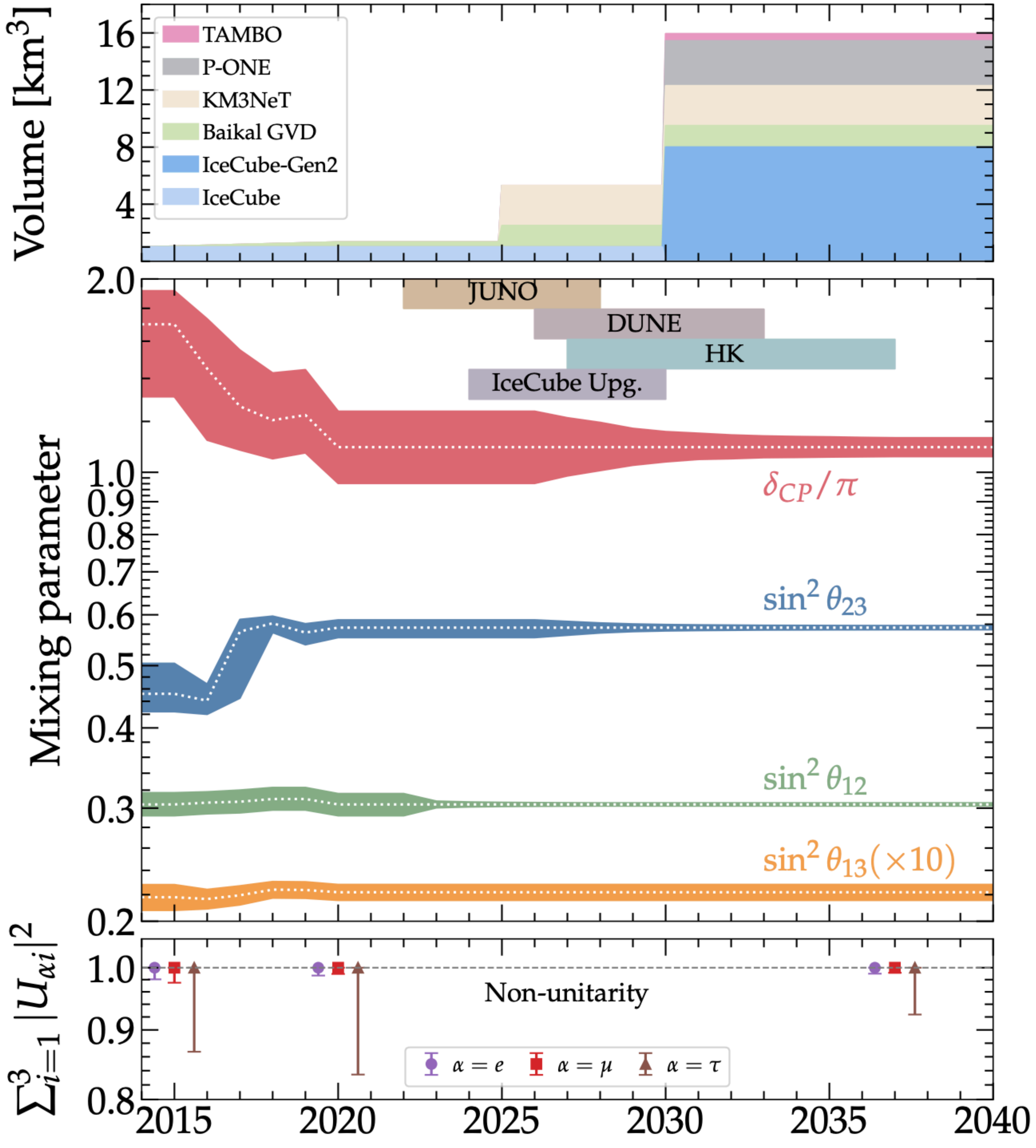
Neutrino astronomy has started with first high-significance sources.
Exponentially growing field expected.

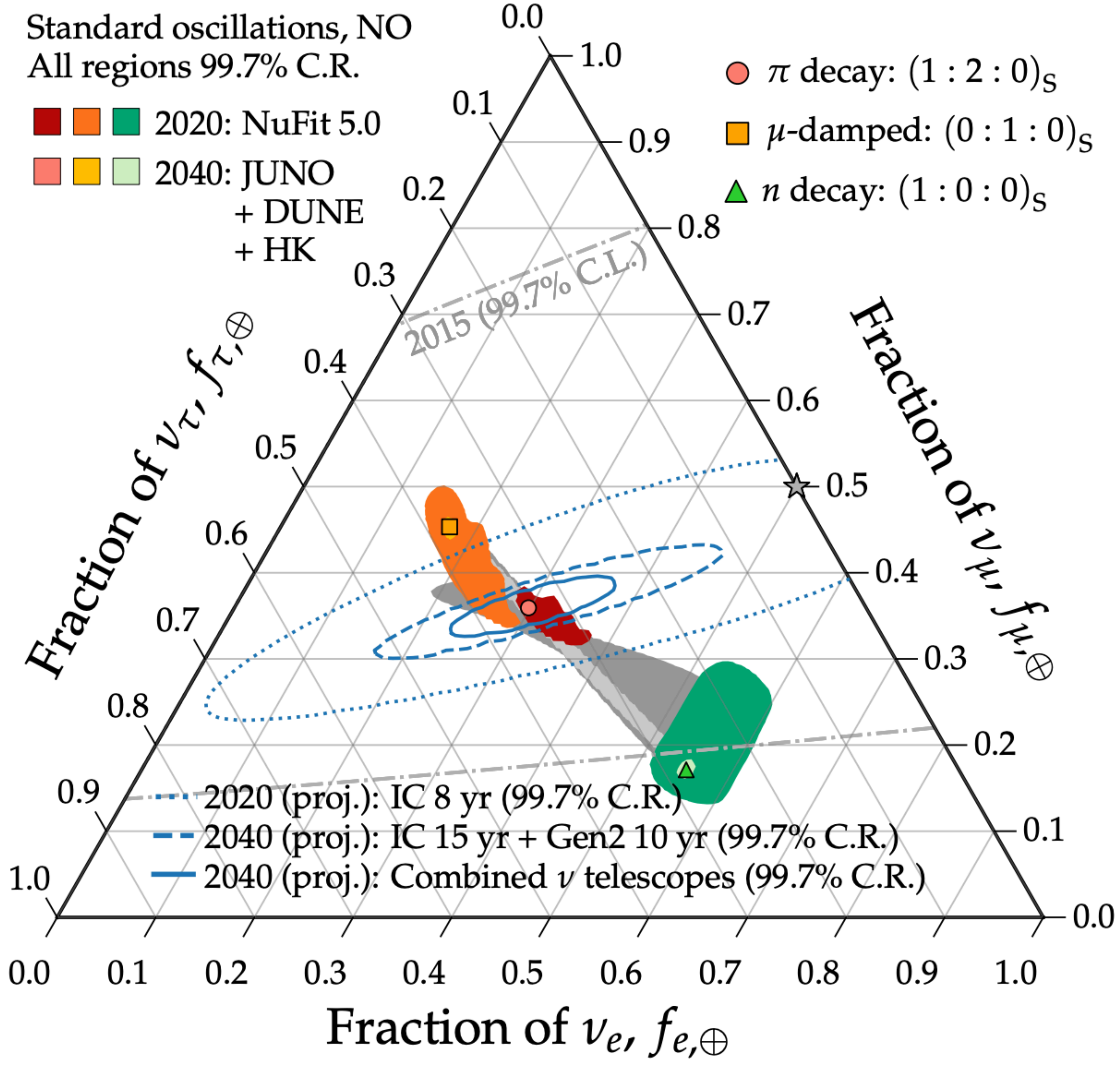
Specialized Neutrino Telescopes



*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.

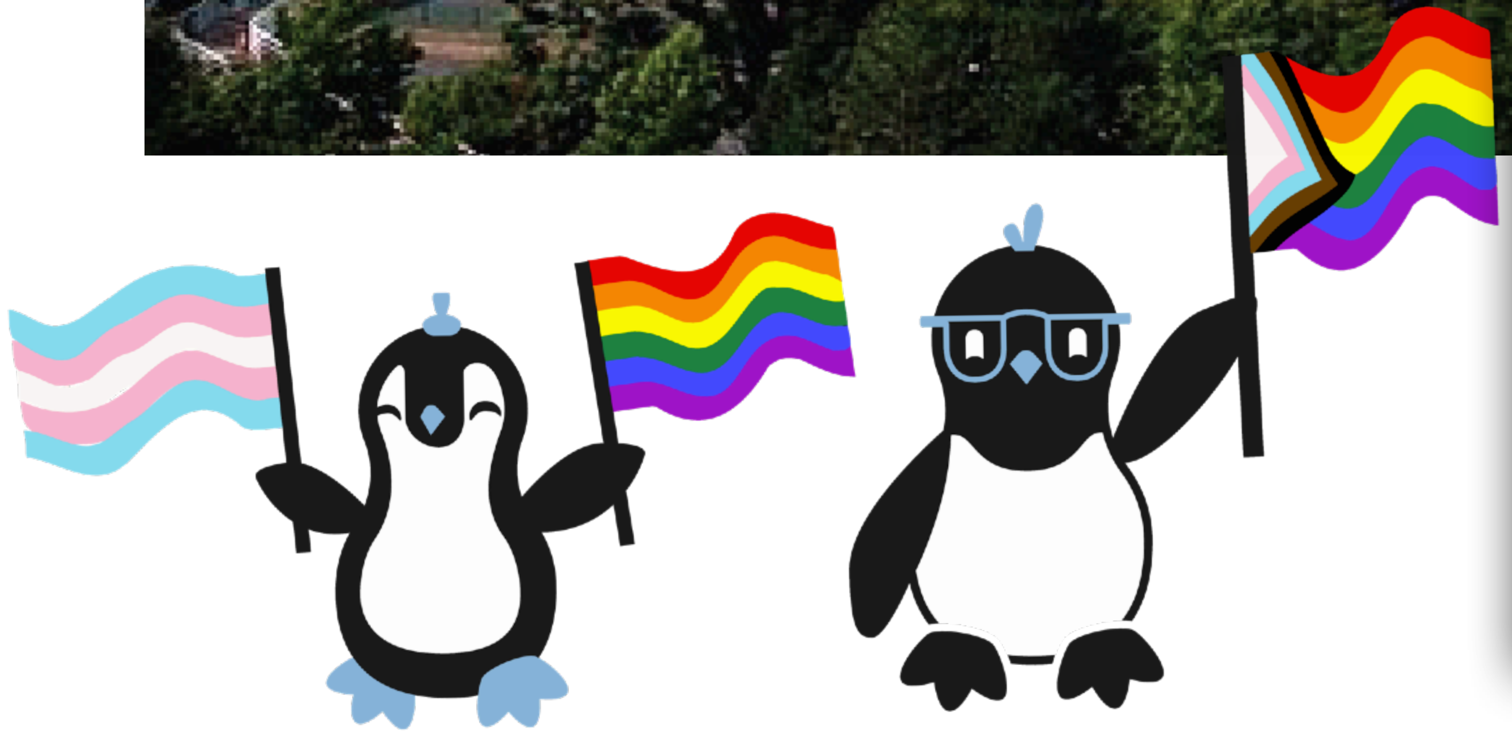
We also have great opportunities for the future

- 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!

The NSF Institute for Artificial Intelligence and Fundamental Interactions

NSF

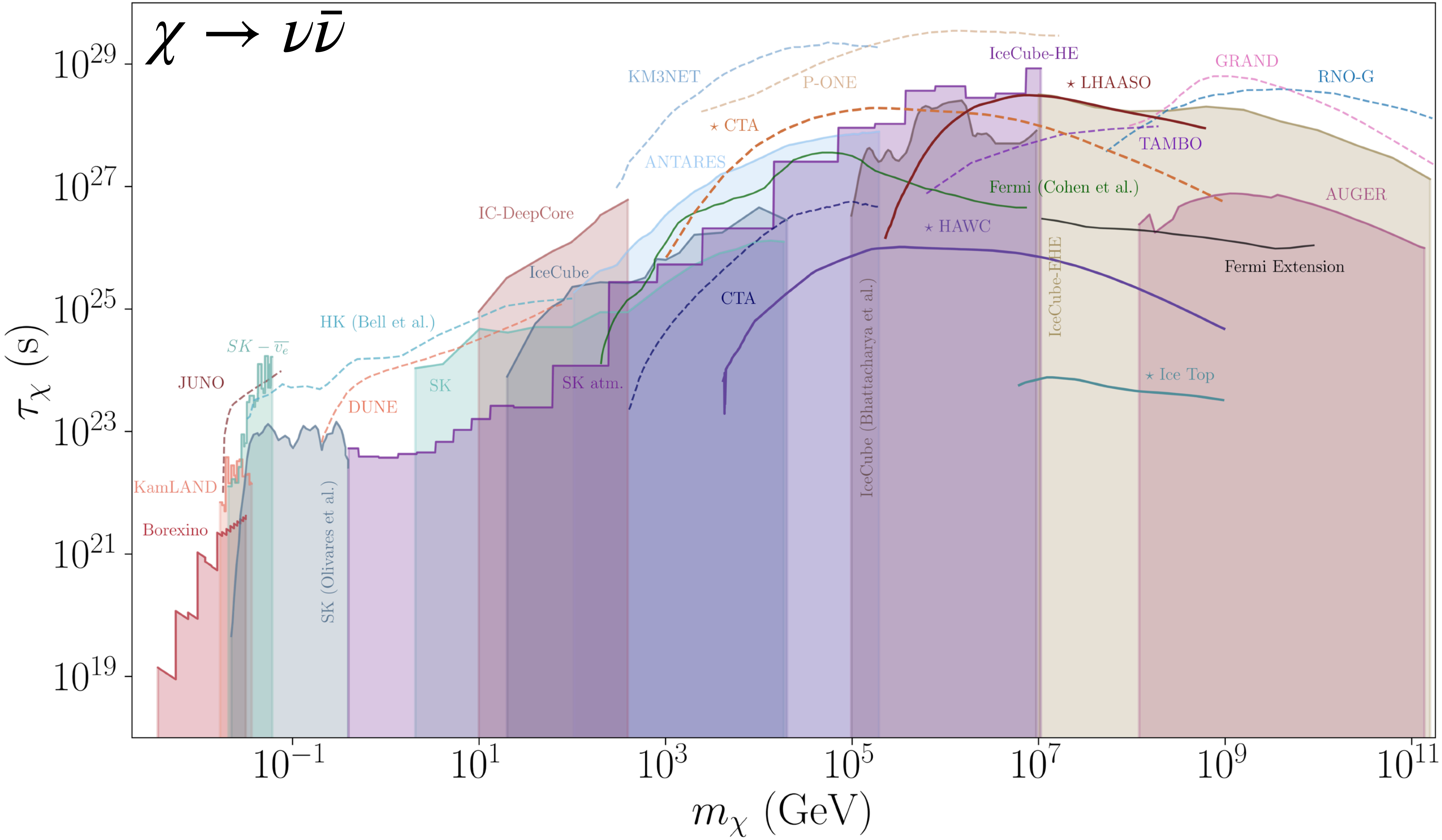
RESEARCH CORPORATION for SCIENCE ADVANCEMENT

the David & Lucile Packard FOUNDATION

CIFAR

Bonus slides

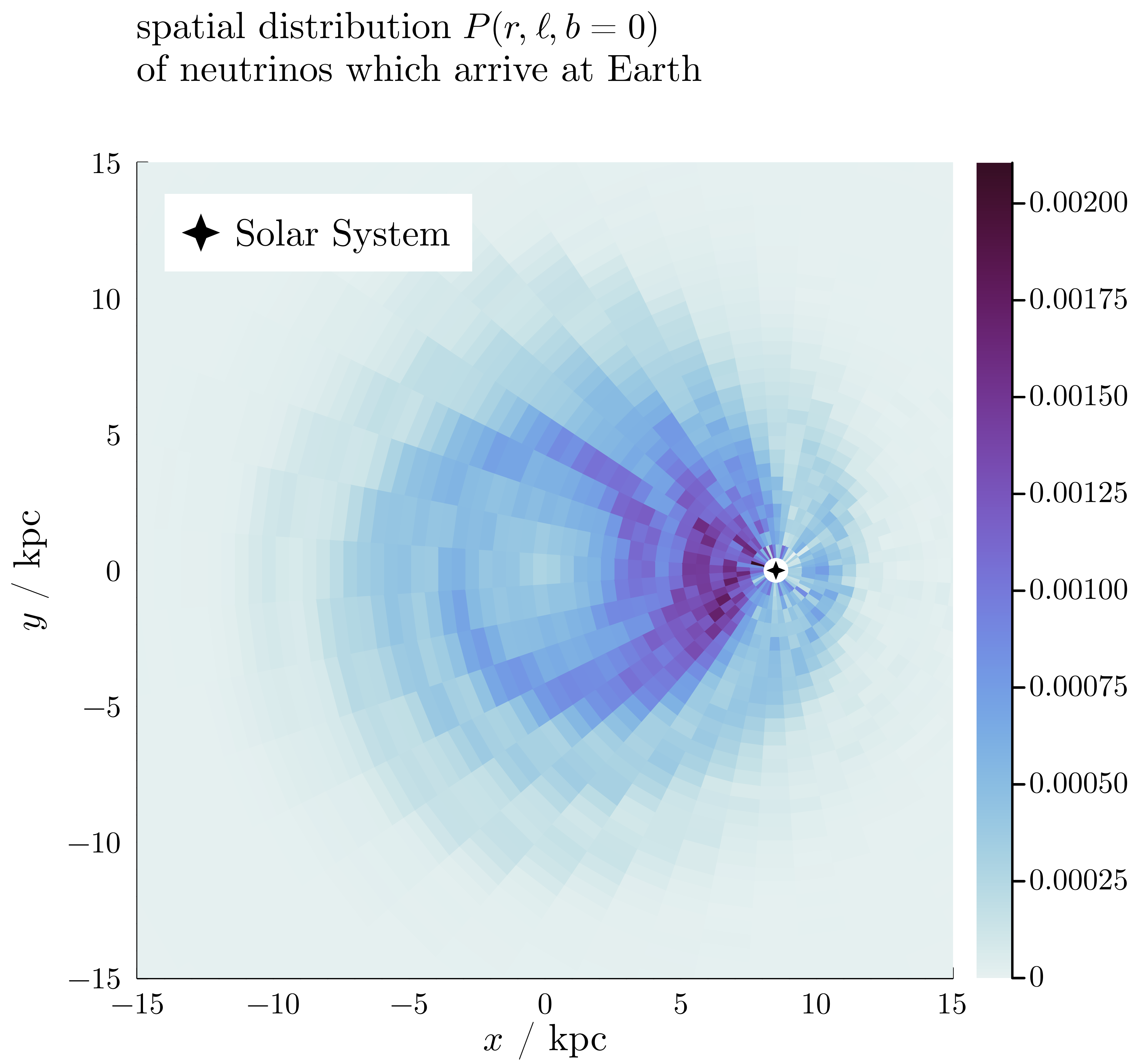
Dark Matter Decay To Neutrinos

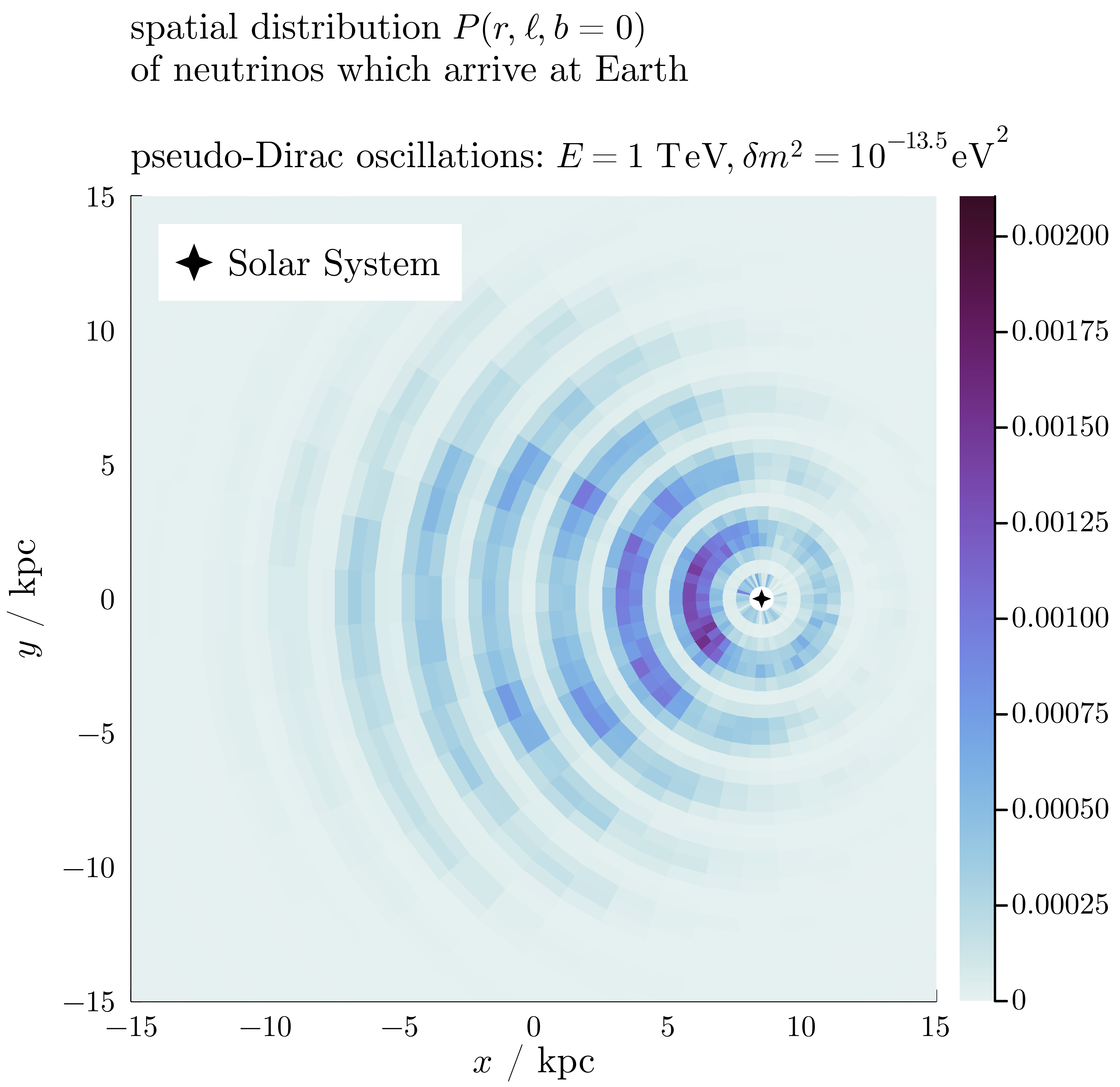


CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White arXiv:2210.01303

Work by Diya Delgado

Quasi-Dirac Oscillations and Galactic Neutrinos

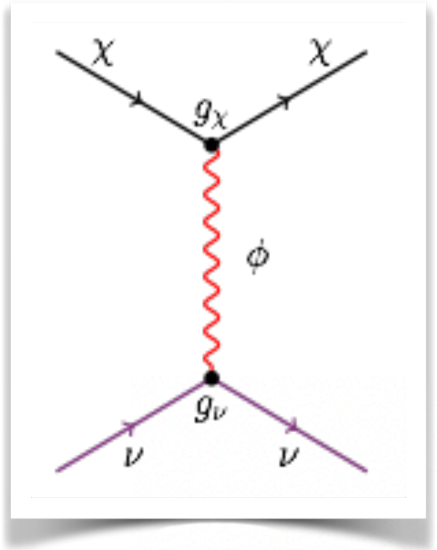




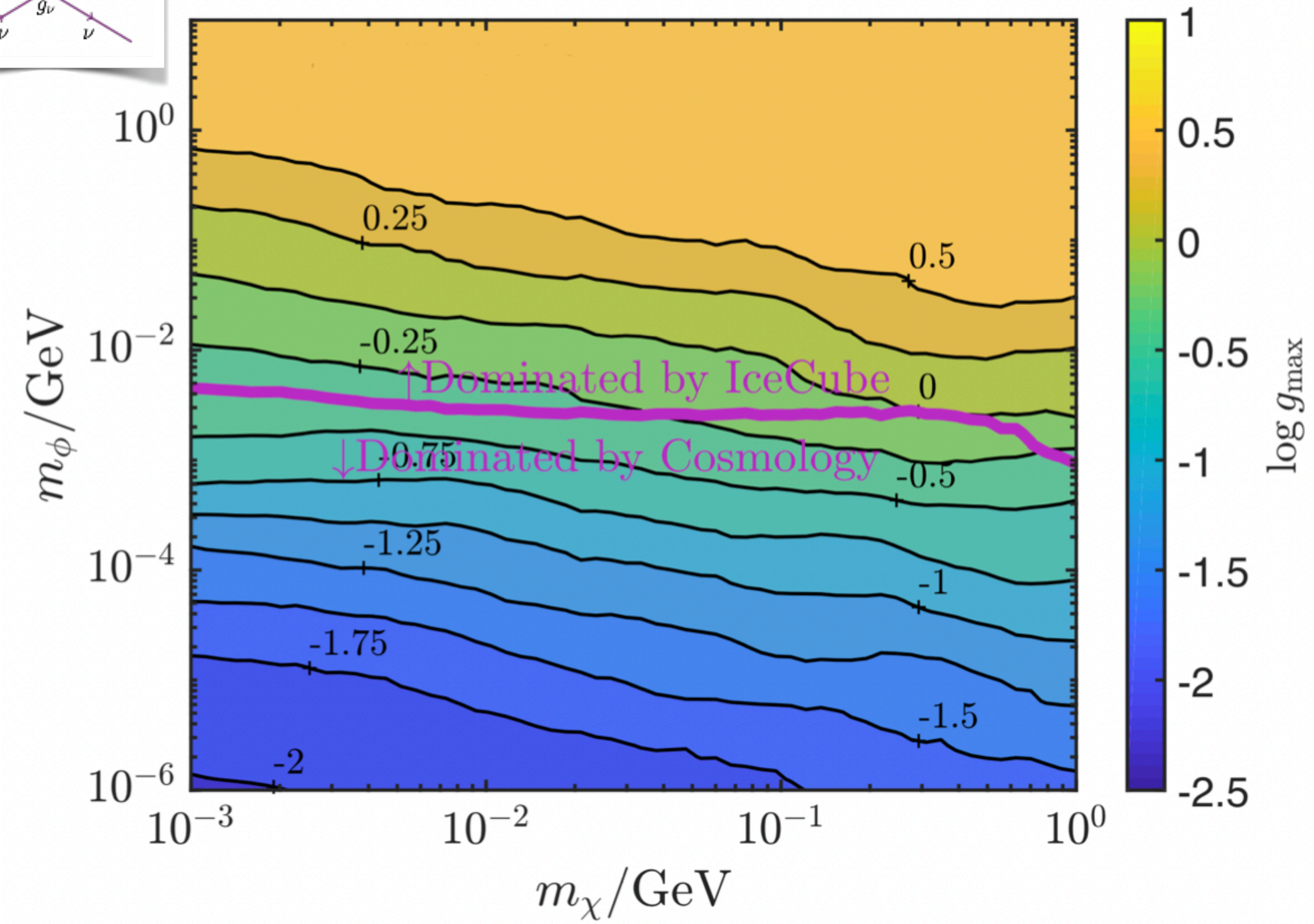
Pseudo-Dirac neutrinos can produce oscillations on galactic neutrinos for mass-squared-differences around $10^{-13.5}\mathrm{eV}^2$!

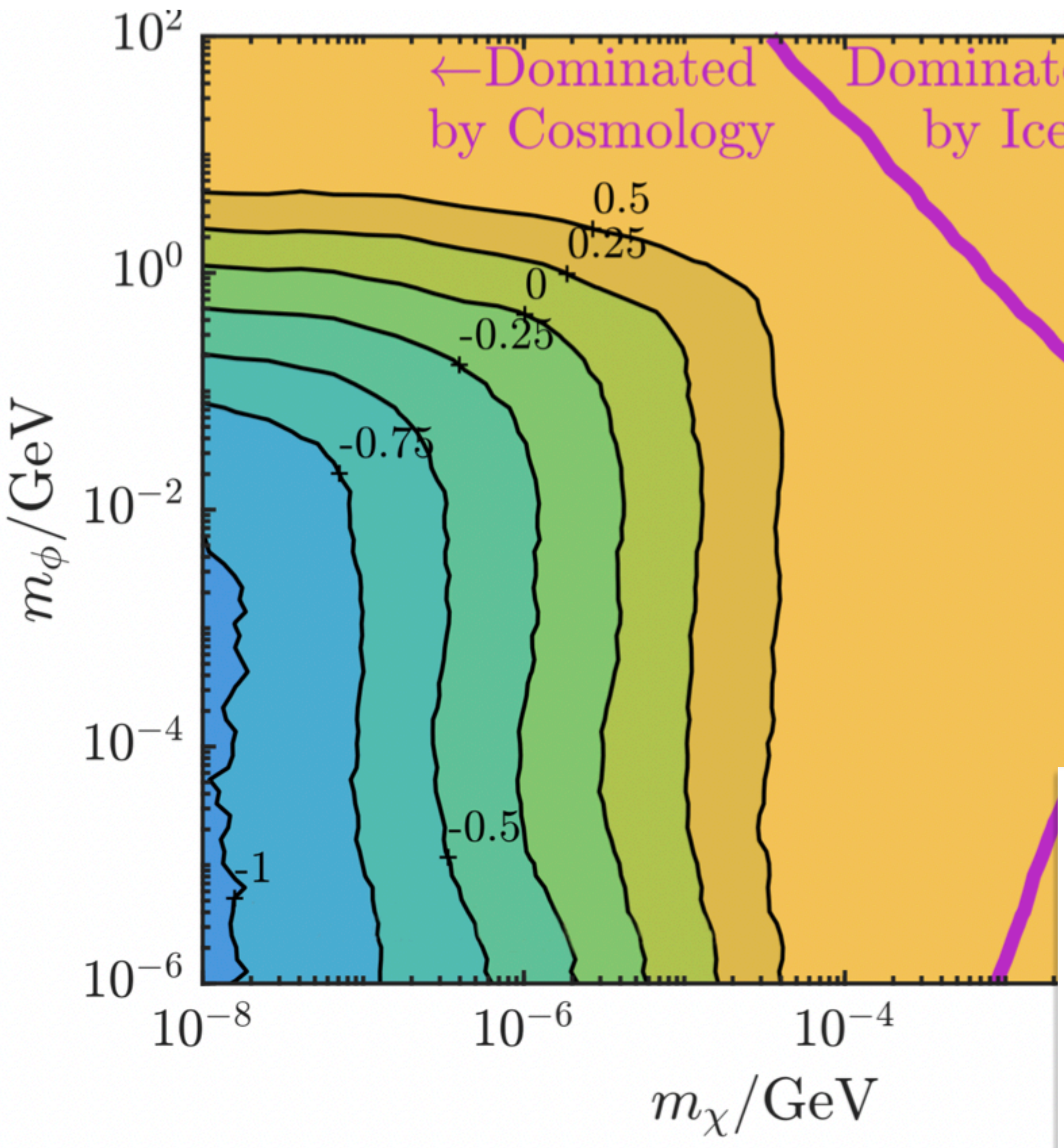
M. McDonald, K. Carloni, R. Alves, CA, and I. Martínez-Soler to appear

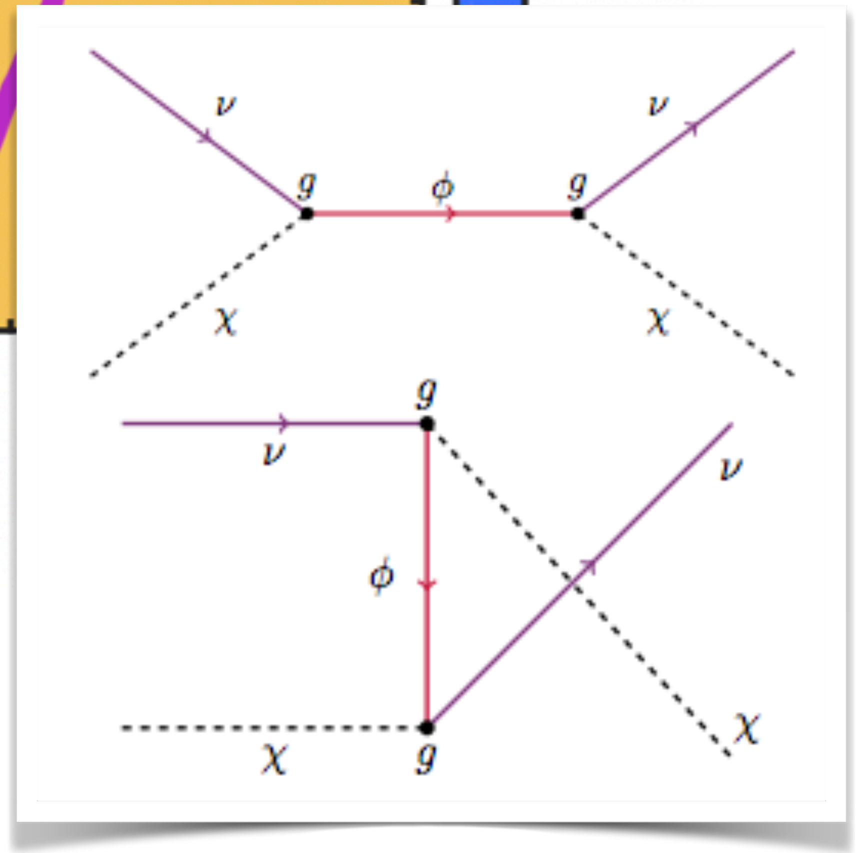
Constrains on Dark Matter Neutrino Scattering



IceCube Collaboration, arXiv:2205.12950



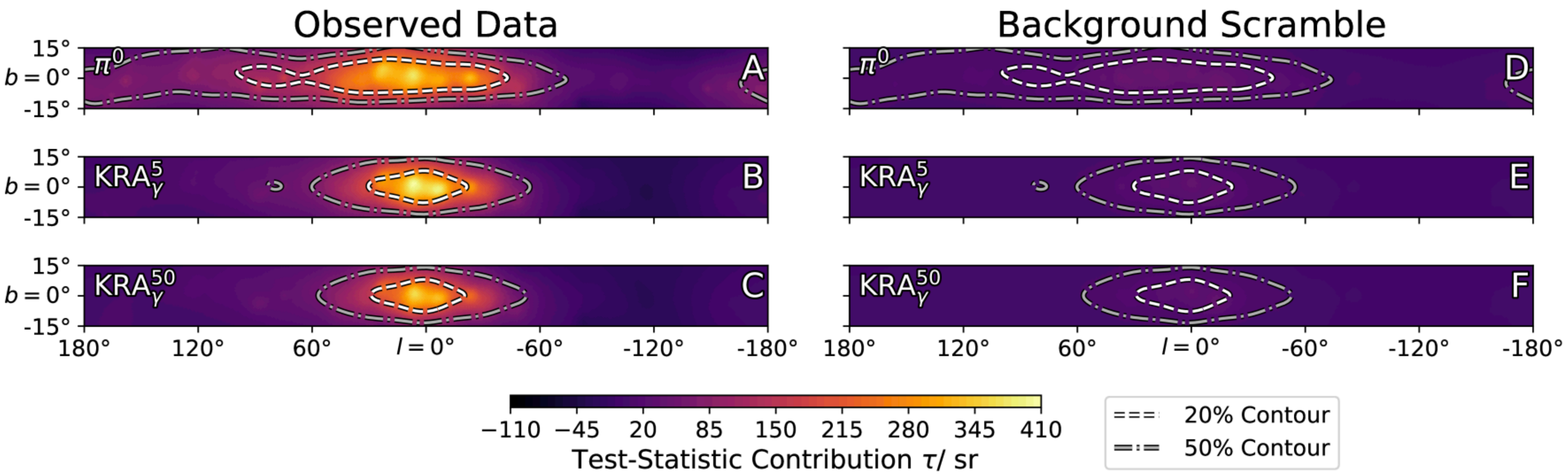




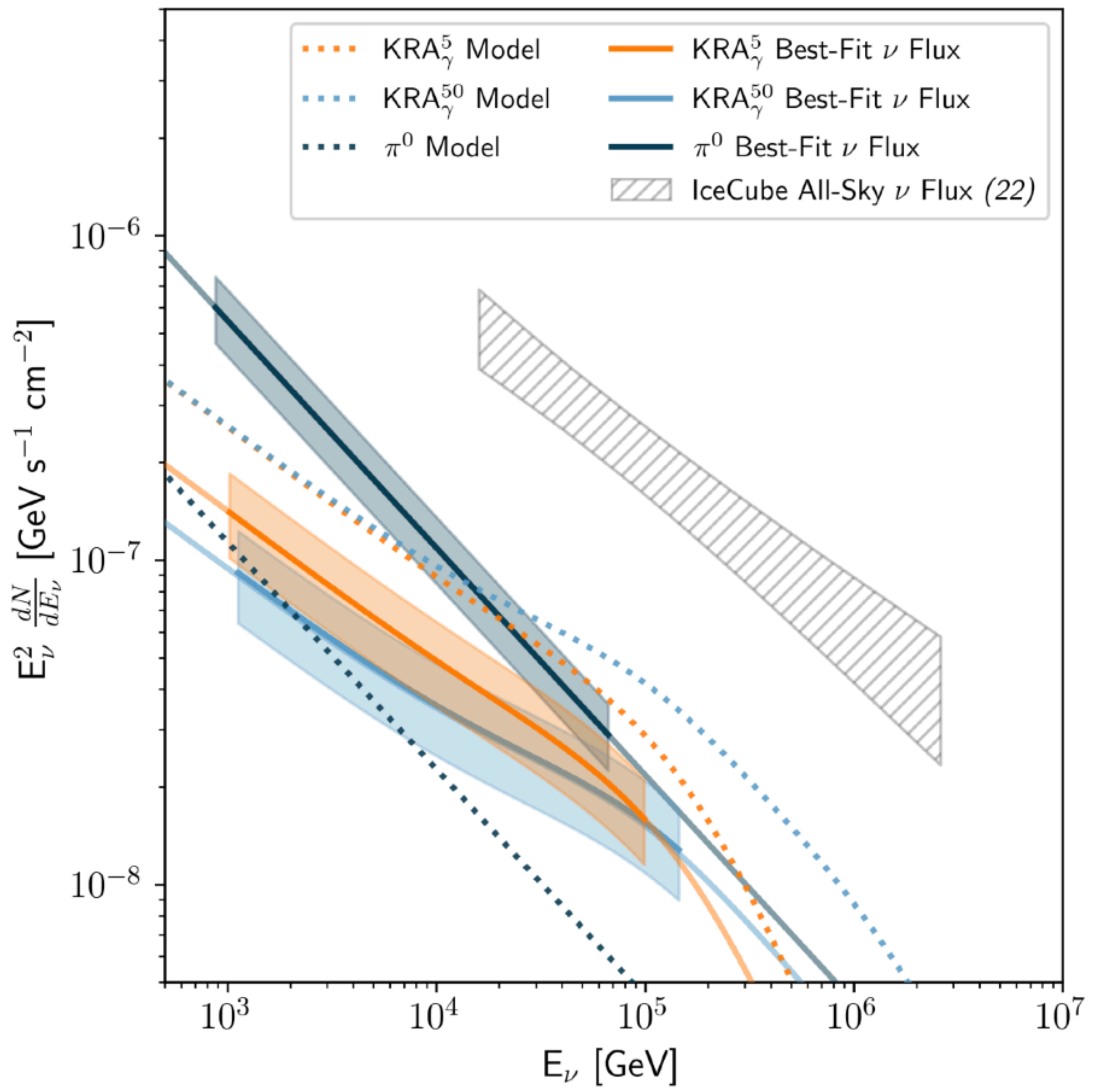
Color scale is the maximum allowed coupling.

Cosmological bounds using Large Scale Structure from Escudero et al 2016

S. Sclafani PoS(ICRC2023)1108

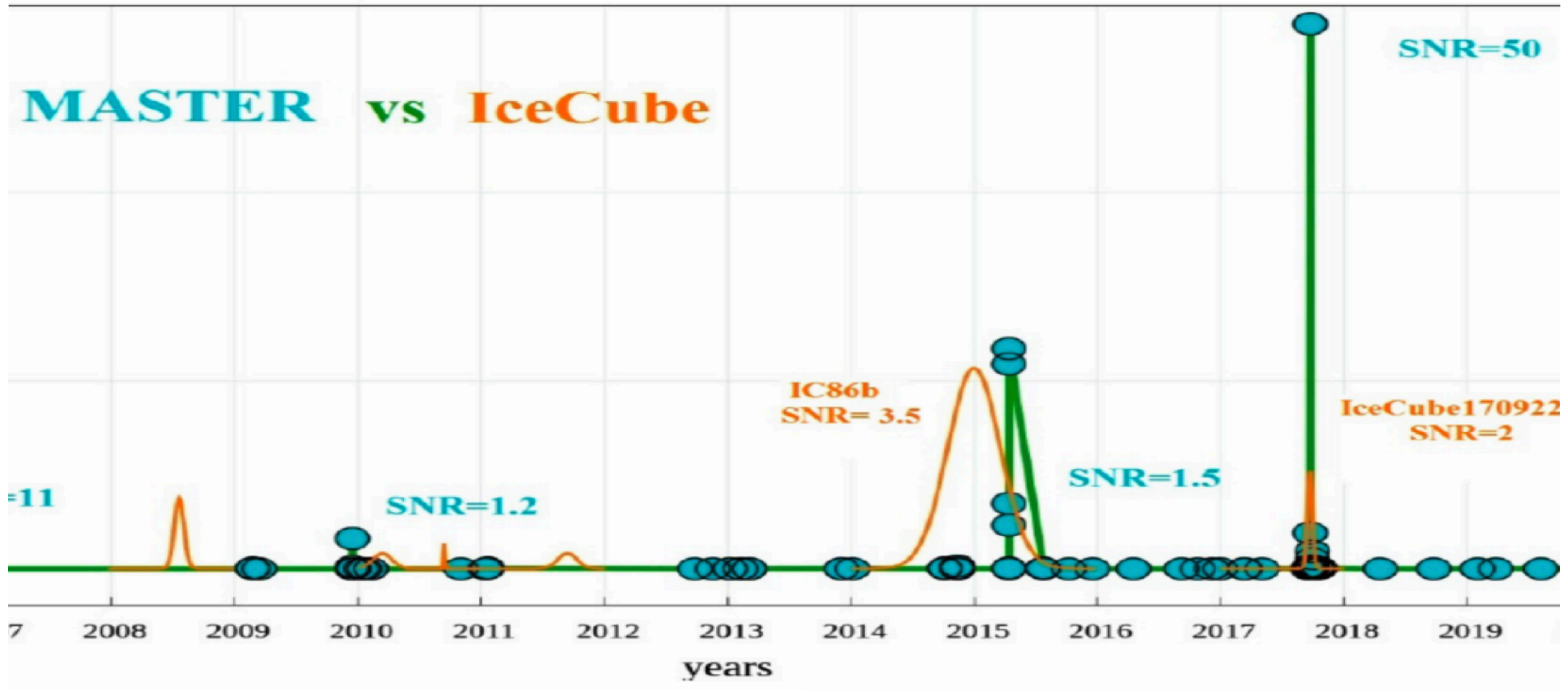


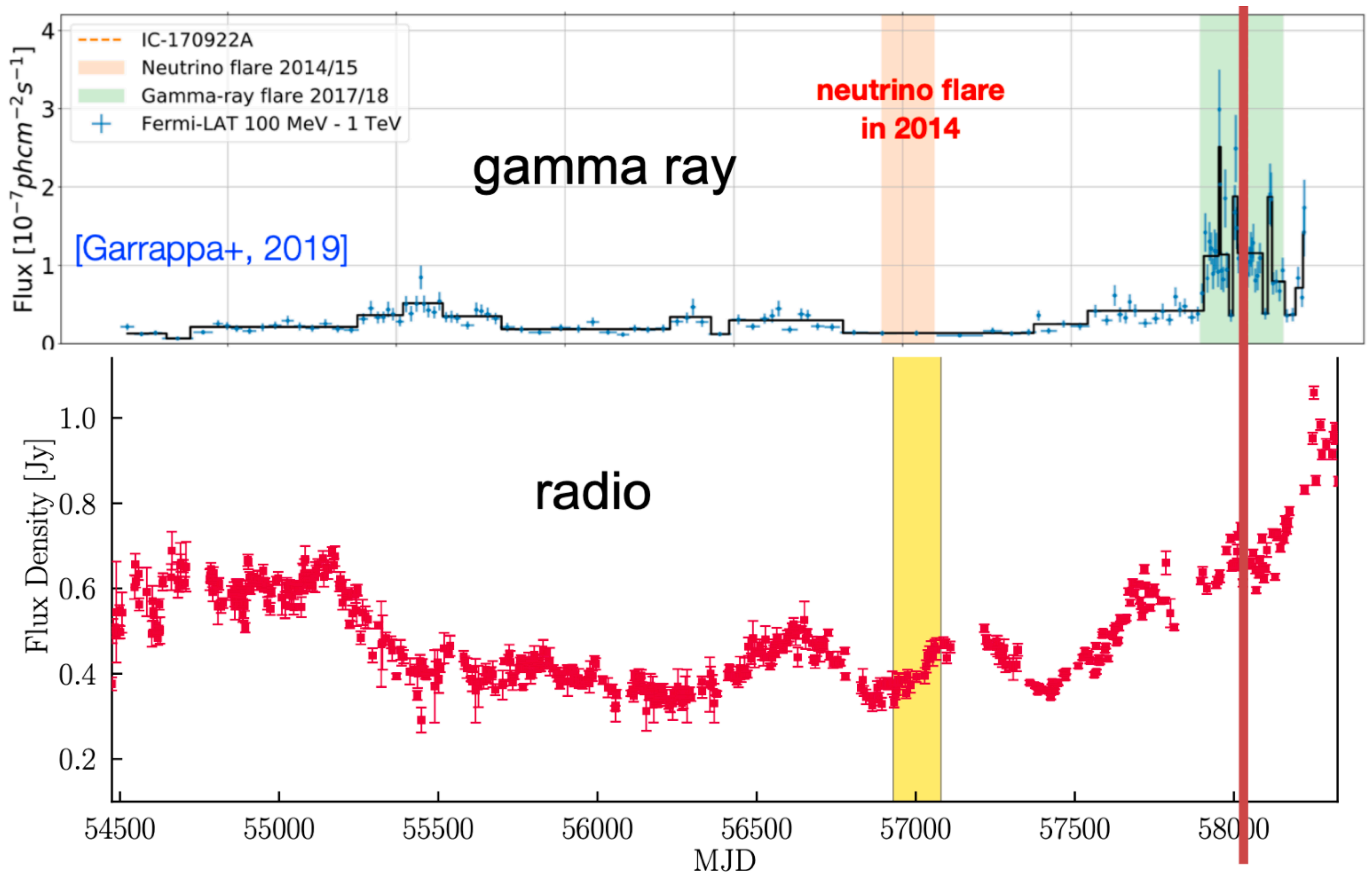
Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	



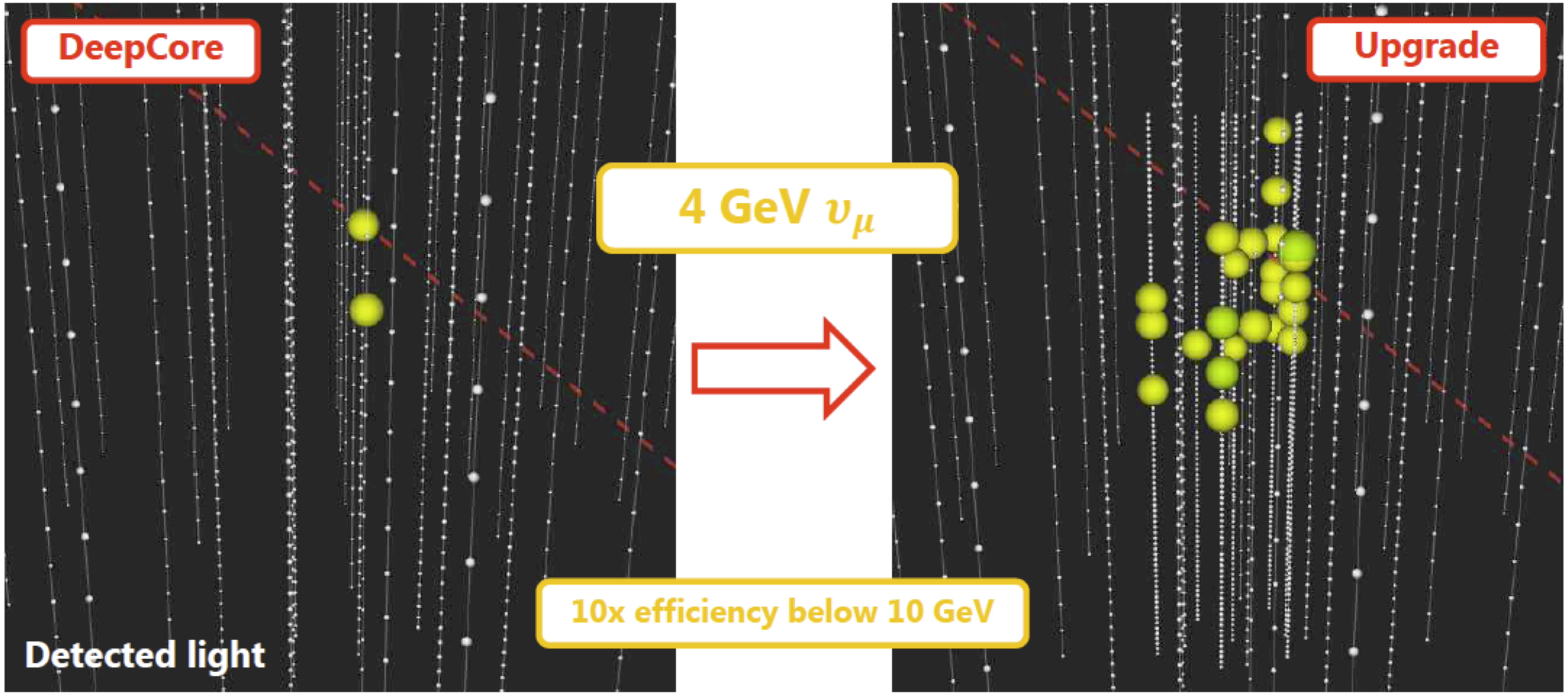
2014 Neutrino Flare From TXS 0506+056

- 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.*



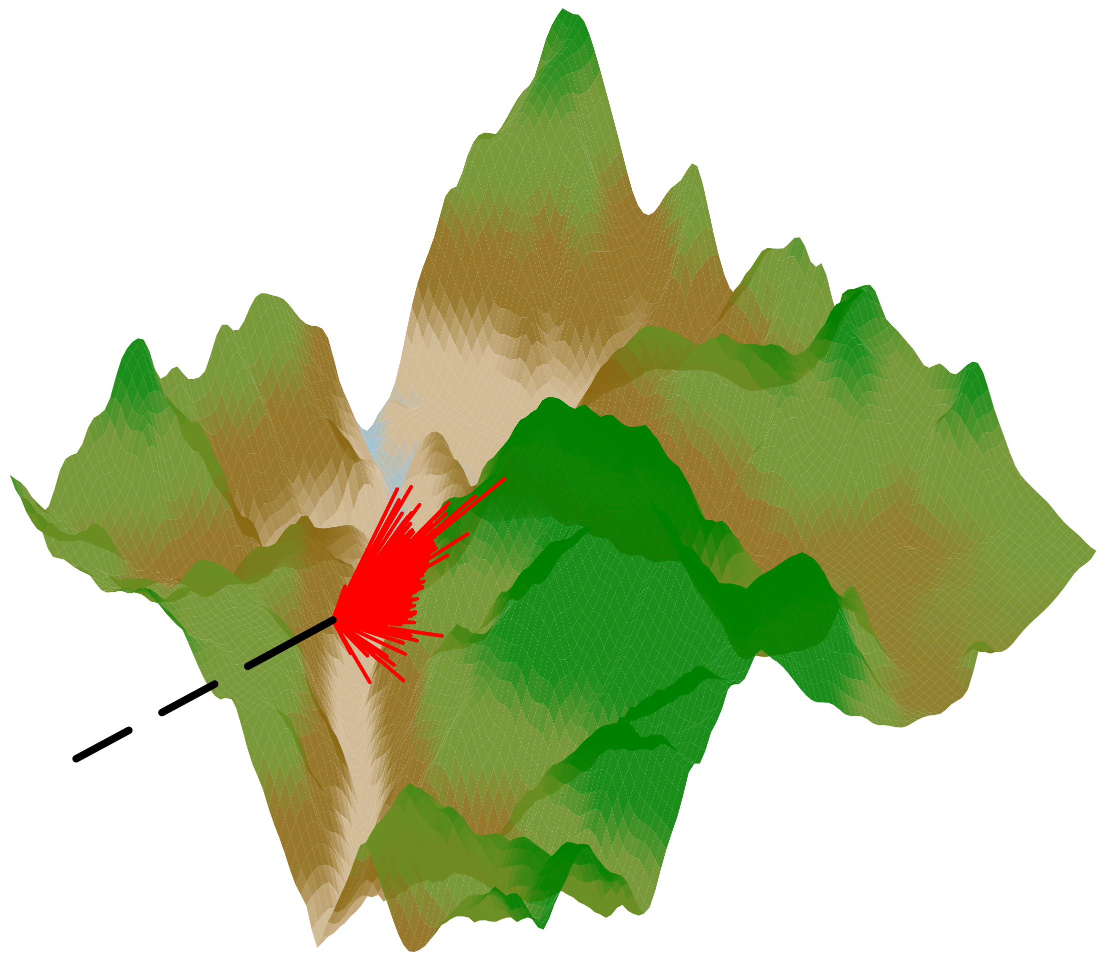


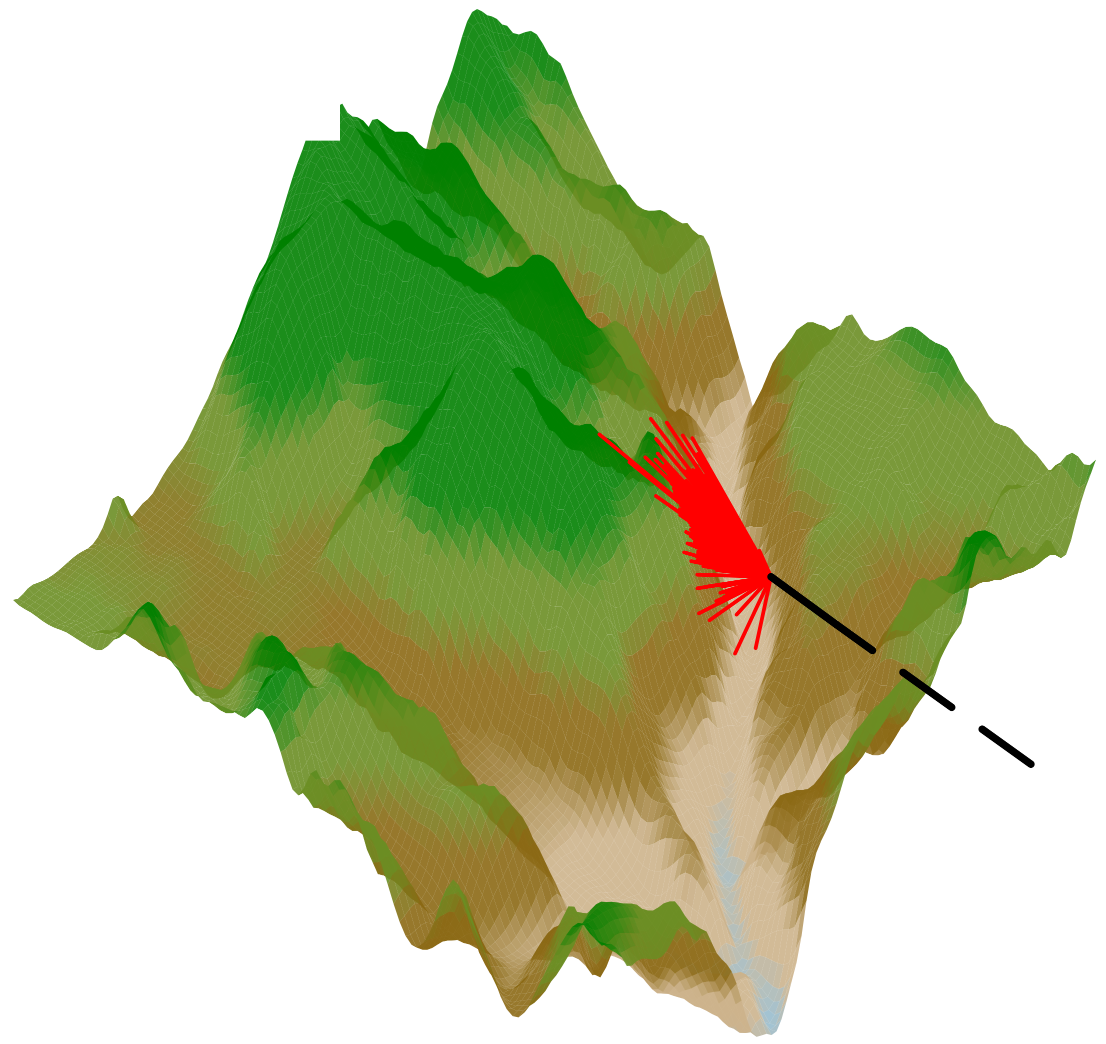
Improved light-collection for low-energy events

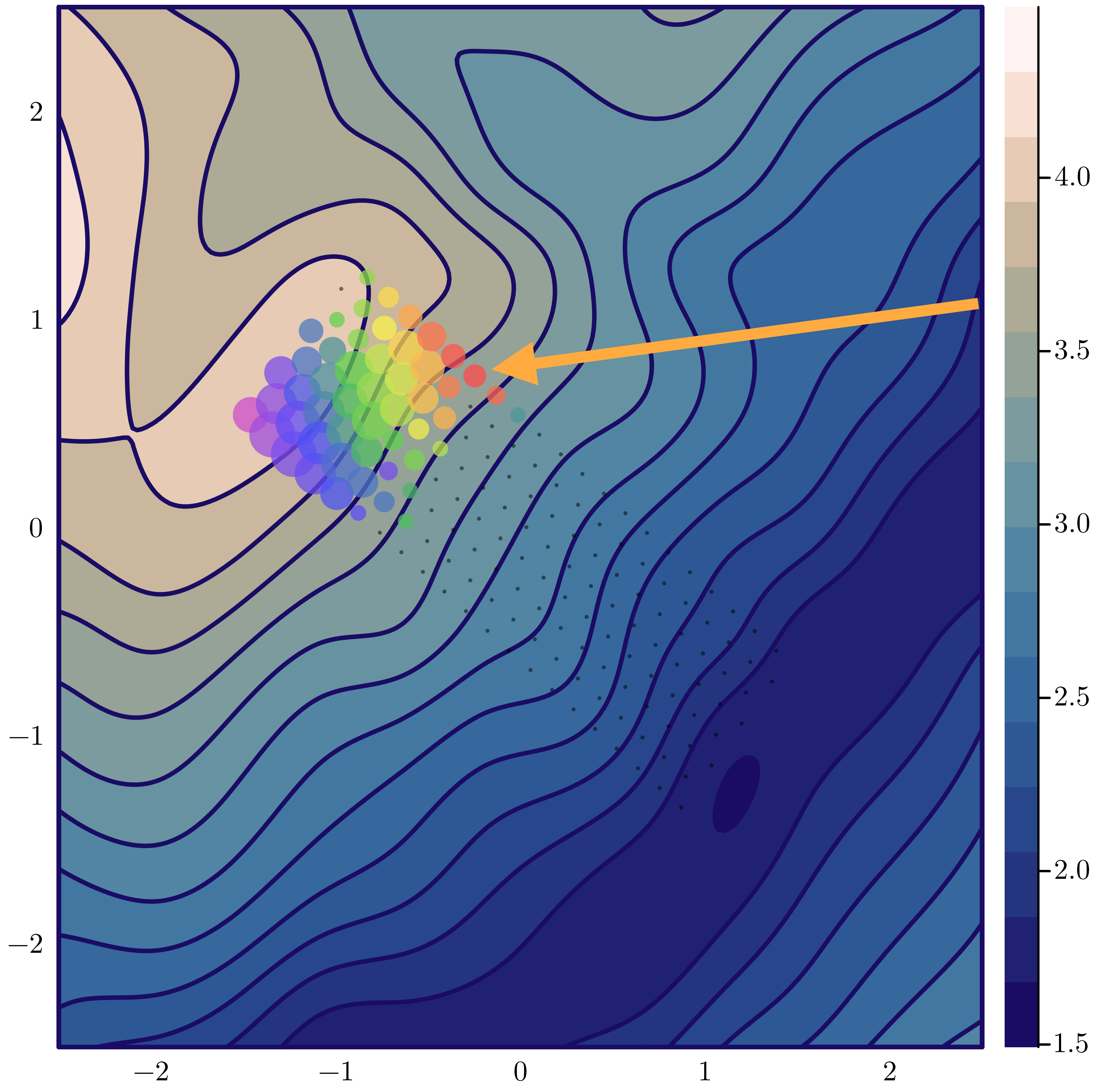


*DeepCore (shown on the left) is the current low-energy extension of IceCube

How would these events look like?

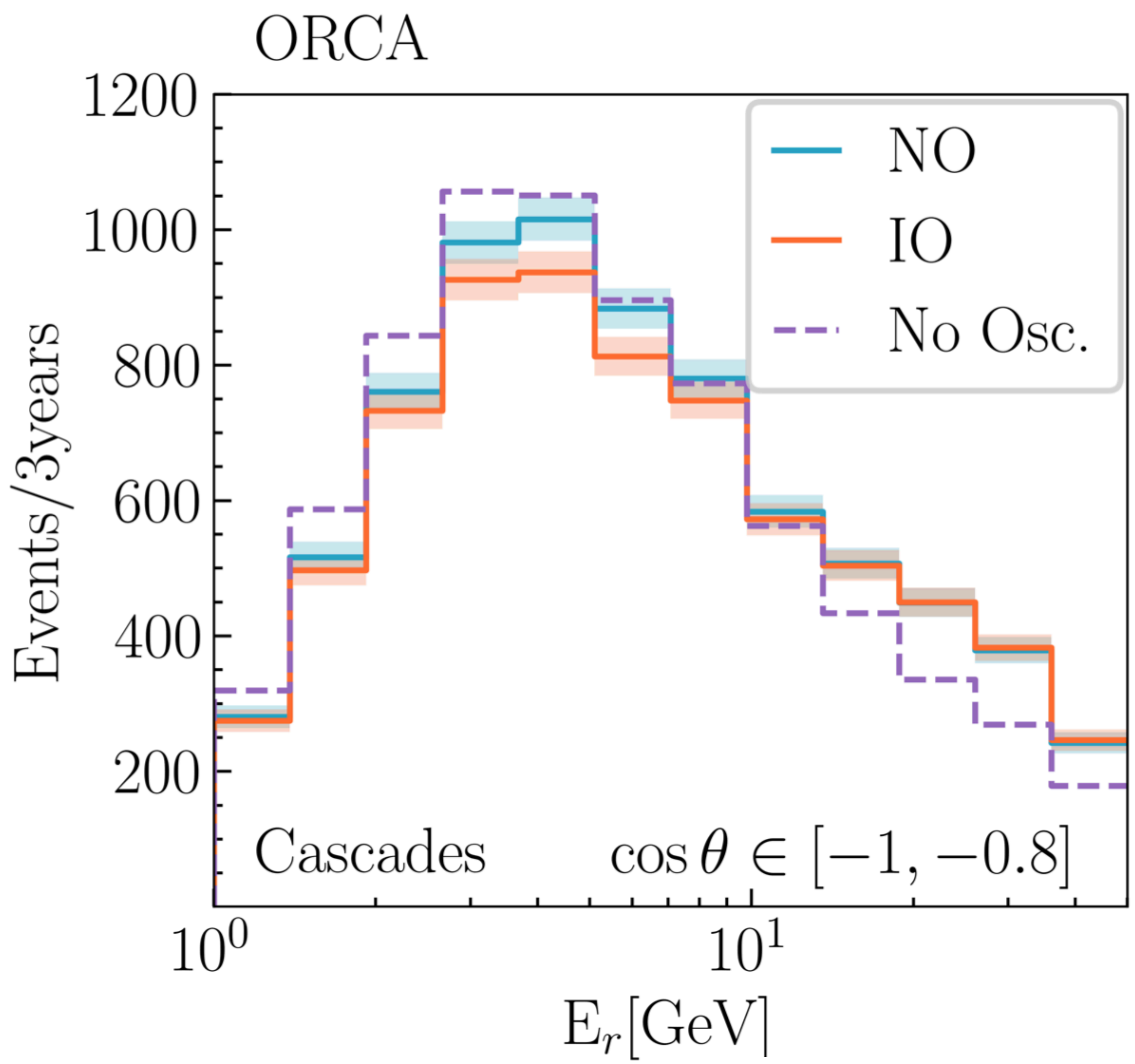


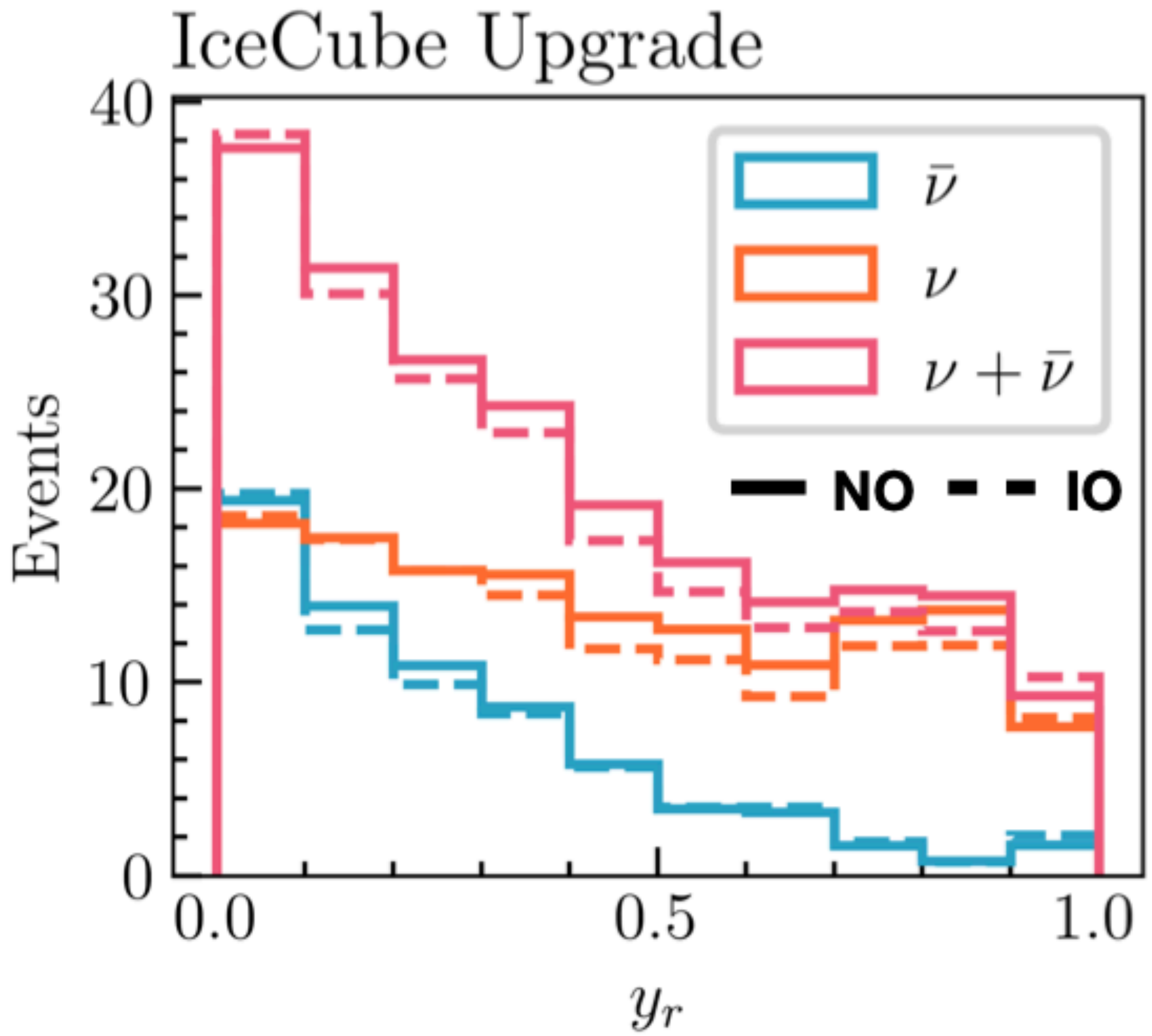




Figures possible by the amazing simulation work done by Jeff Lazar, Pavel Zhelnin, and William Thompson

Atmospheric neutrino distributions





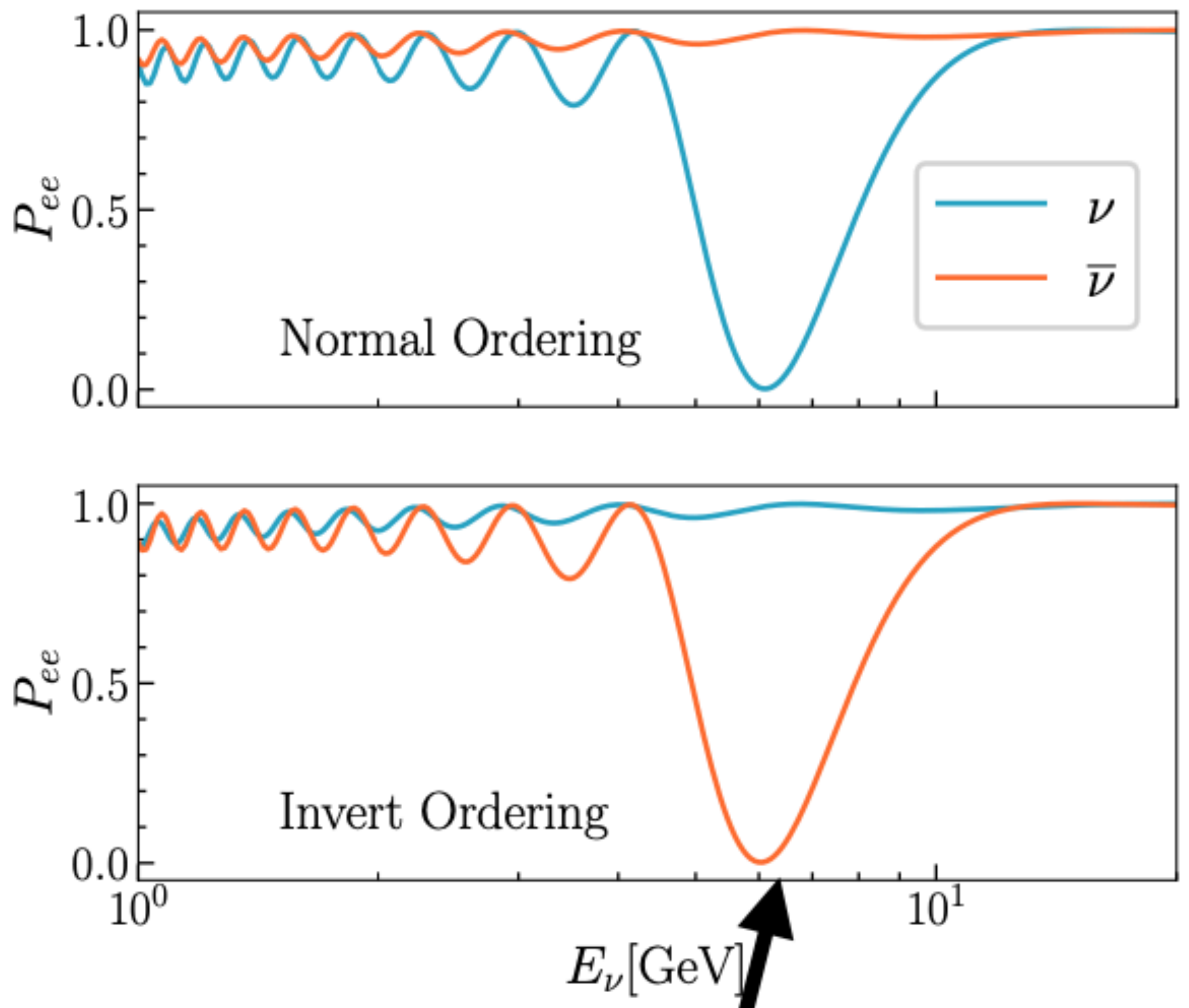
The **sensitivity** to the ordering is dominated by the cascades crossing the core in IC-upgrade and ORCA around the GeV.

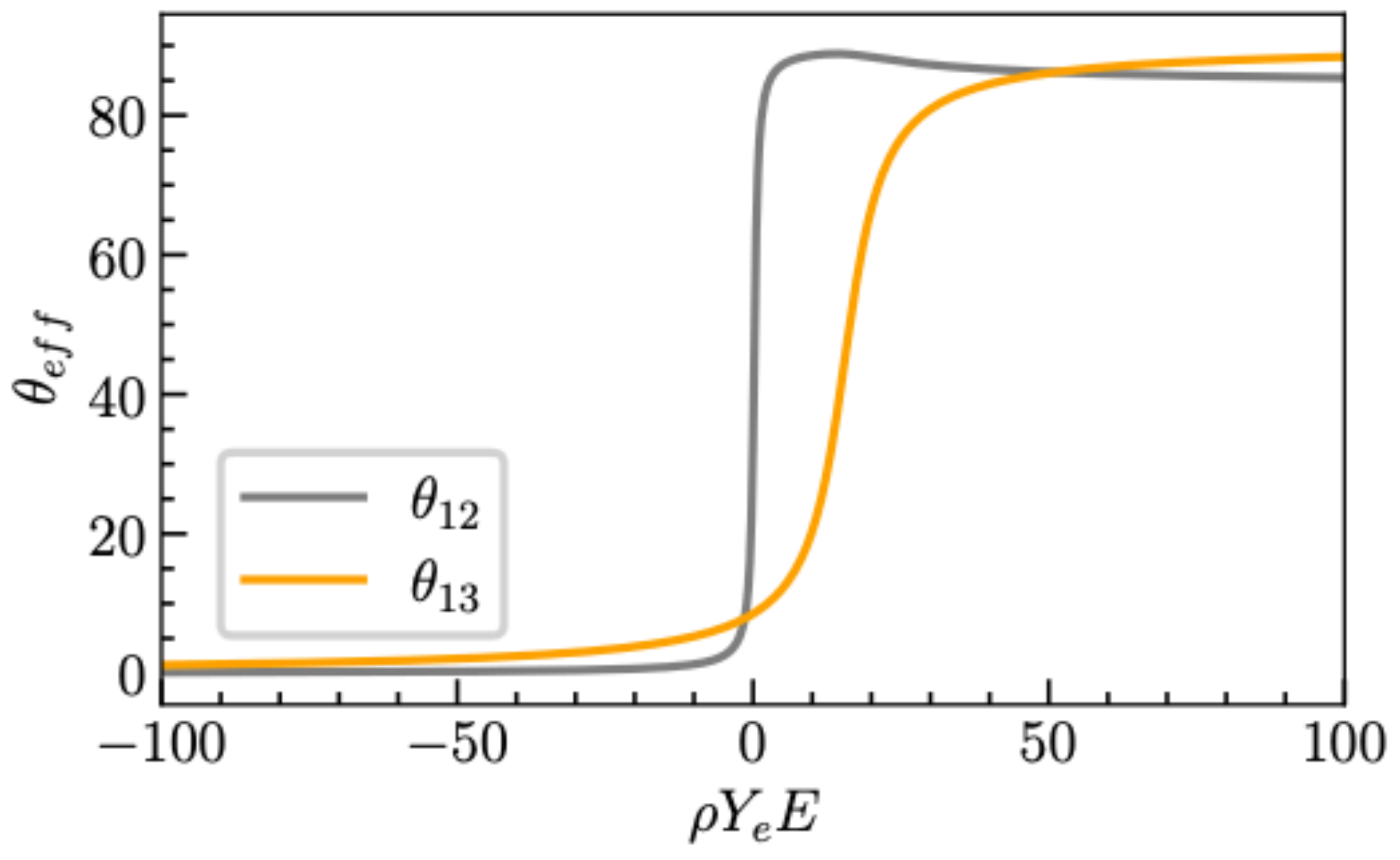
Atmospheric neutrino oscillation probabilities

Multi-GeV

At the **GeV scale**, trajectories crossing the mantle experience an **MSW** resonance, making neutrinos sensitive to the **mass ordering**:

- The matter effect enhances the oscillation of neutrinos (anti-neutrinos) for NO (IO)





The enhancement of θ_{13}^{eff} lead to a deep in P_{ee} for ν ($\overline{\nu}$) for NO (IO)

Palomares-Ruiz and Petcov, NPB 712 (2005)
Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

Ivan Martinez-Soler (IPPP) 11 Neutrino2024