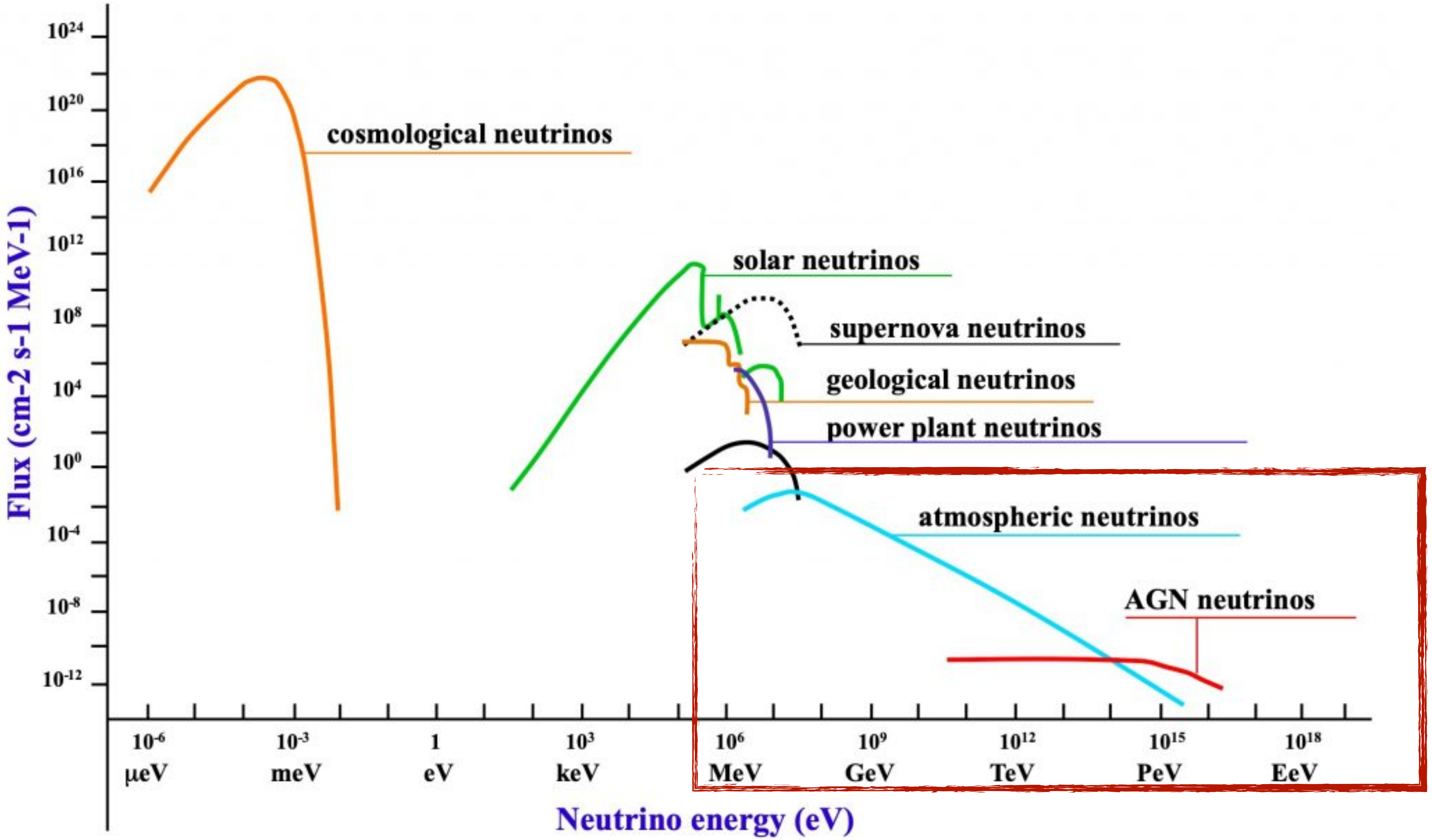
New-ν searches with IceCube

New-ν Physics: From Colliders to Cosmology

Ivan Martinez Soler

High-Energy Neutrinos

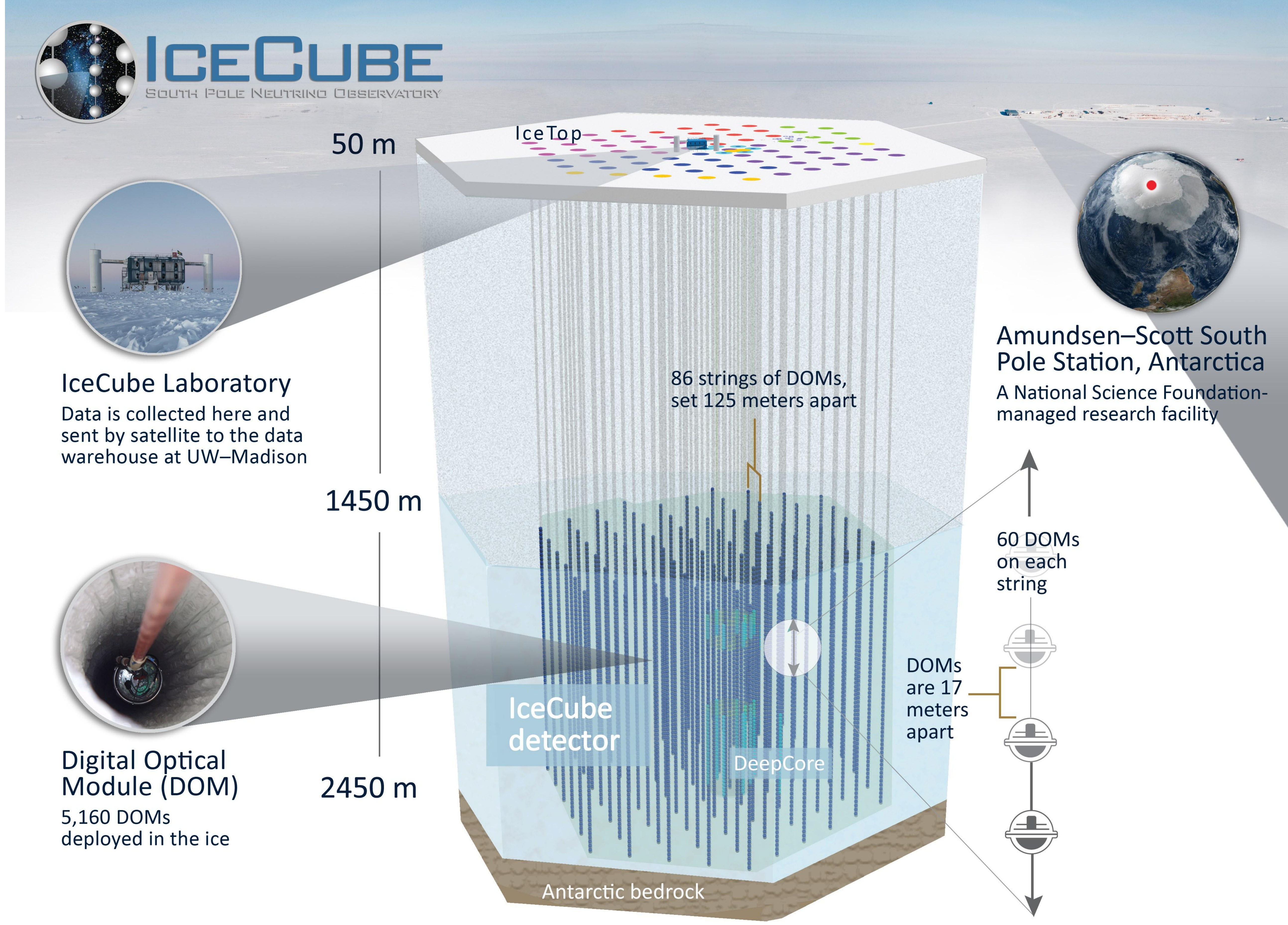
We focus on the high-energy part of the flux, which is very small and therefore requires large detectors



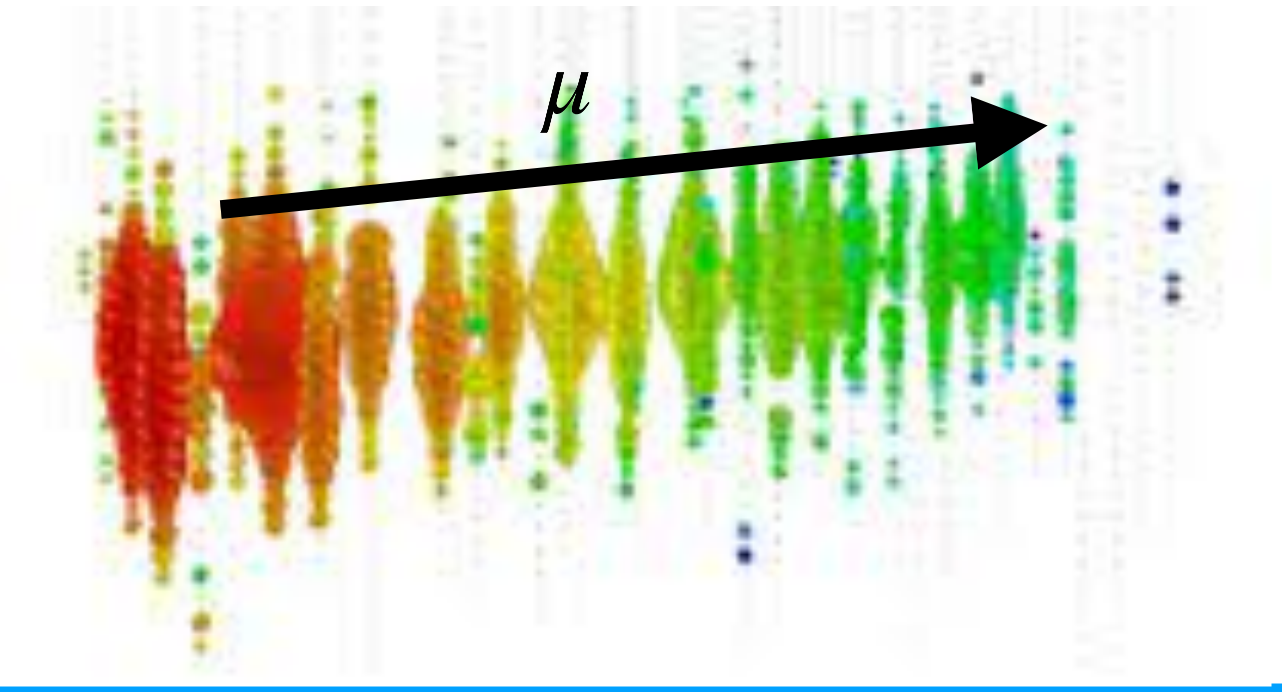
IceCube

IceCube is a neutrino telescope in the south pole.

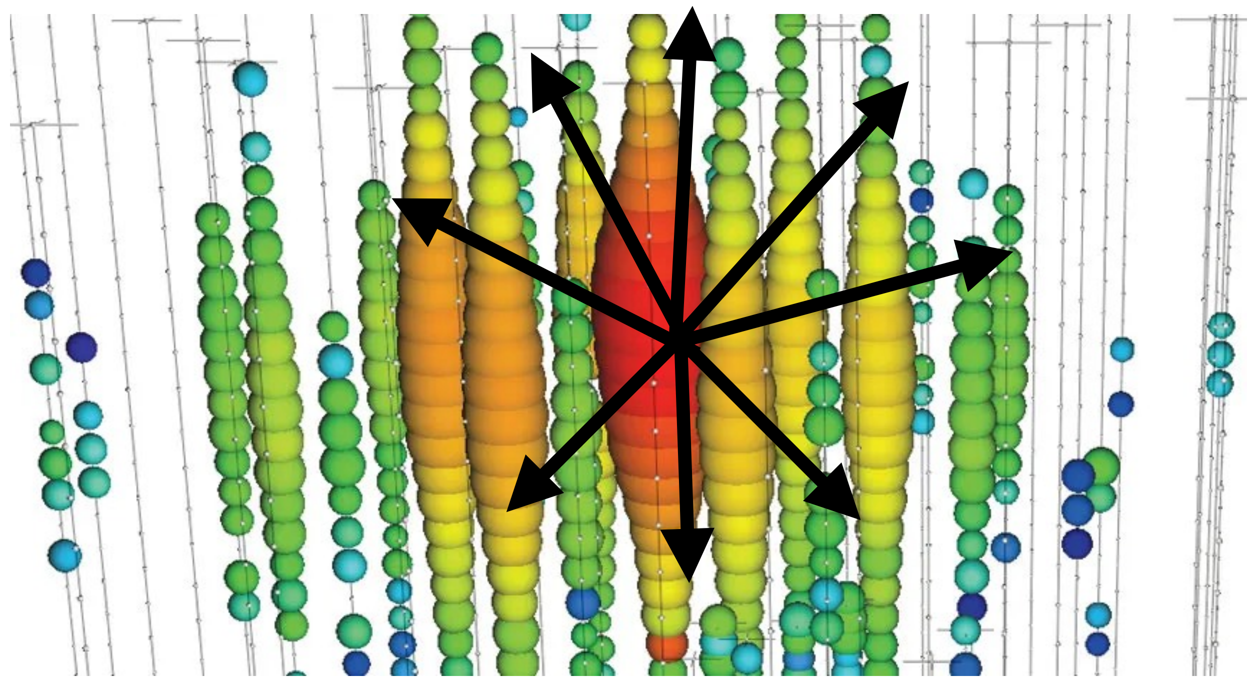
- $\sim 1\mathrm{km}^3$ ice Cherenkov
- Contains 5160 DOMs
- 86 strings
- Approximately ~2 km below the surface
- IceTop
- The main background is muons from cosmic-rays.
- Three-different event topologies



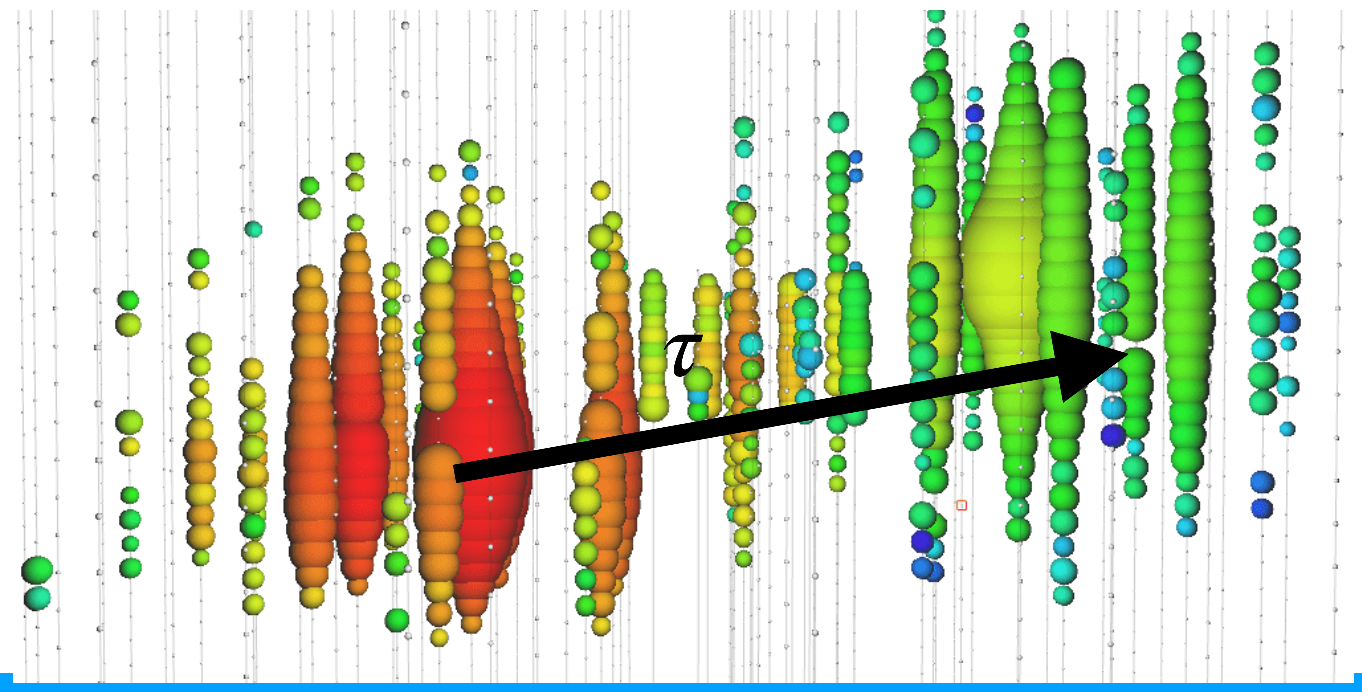
Tracks



Cascades



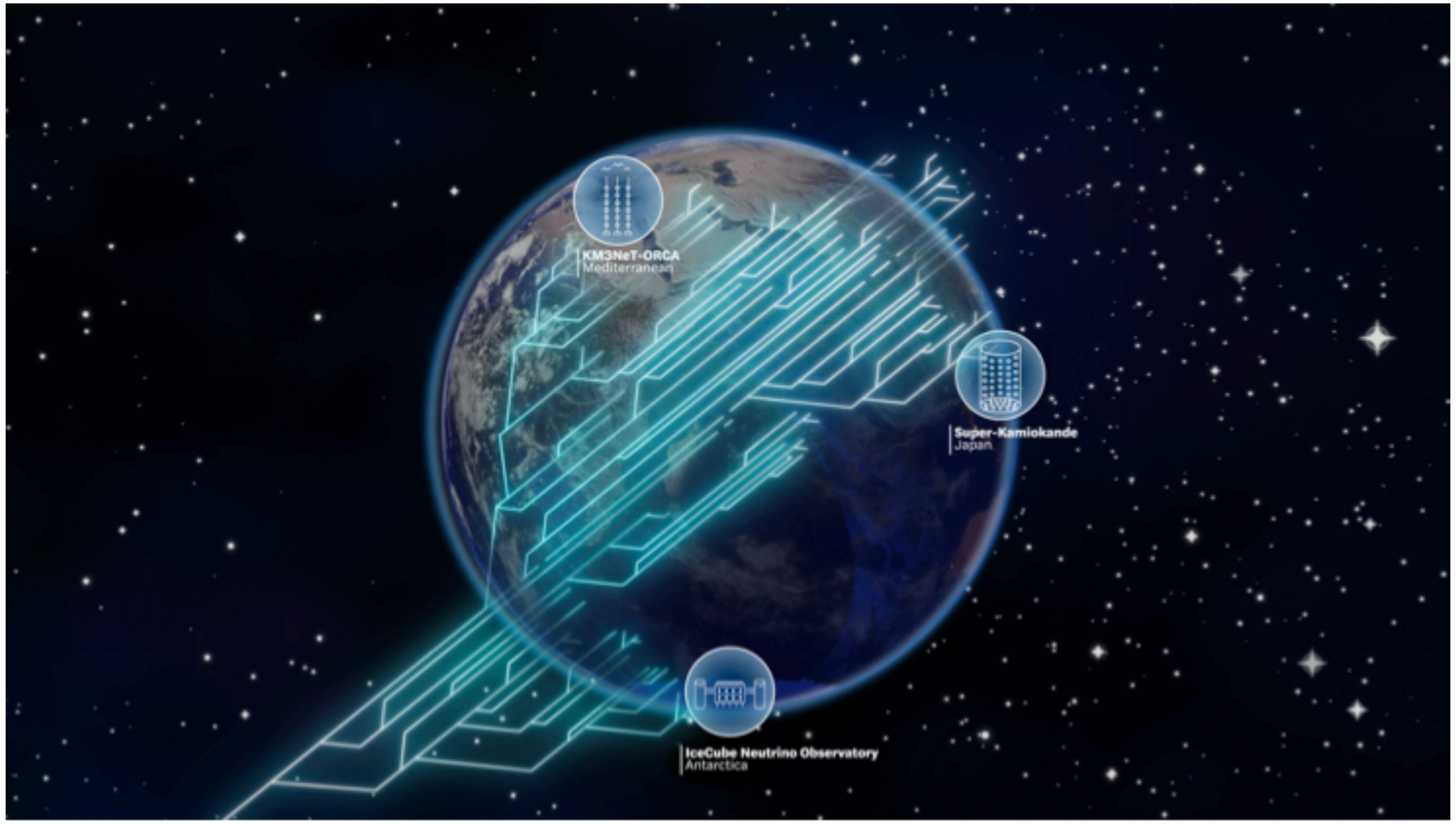
Double-Bangs

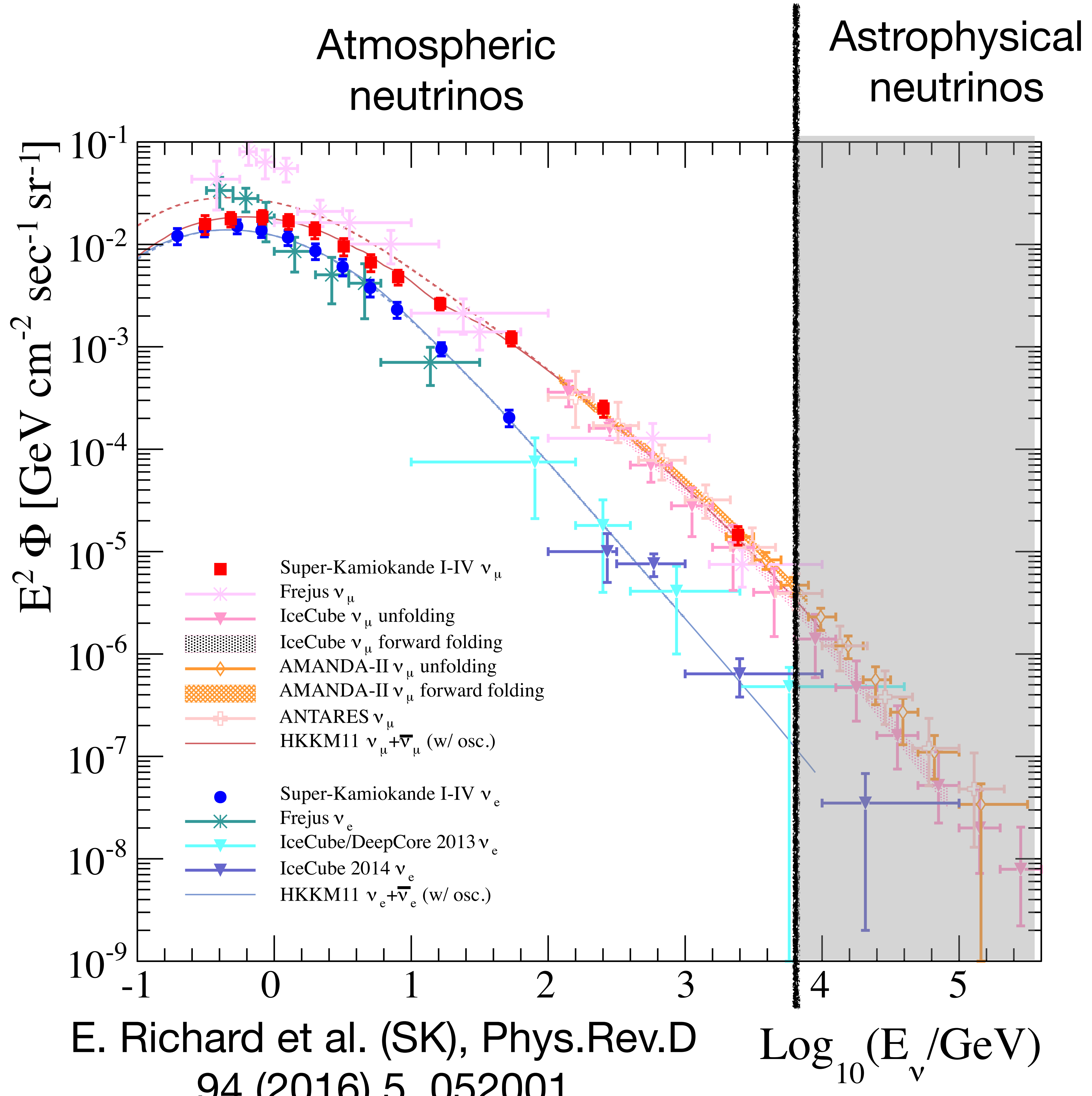


Atmospheric neutrinos

The low-energy flux reaching neutrino telescopes is primarily dominated by the atmospheric neutrinos

Atmospheric neutrinos are created in the collision of cosmic rays with the atmospheric nuclei



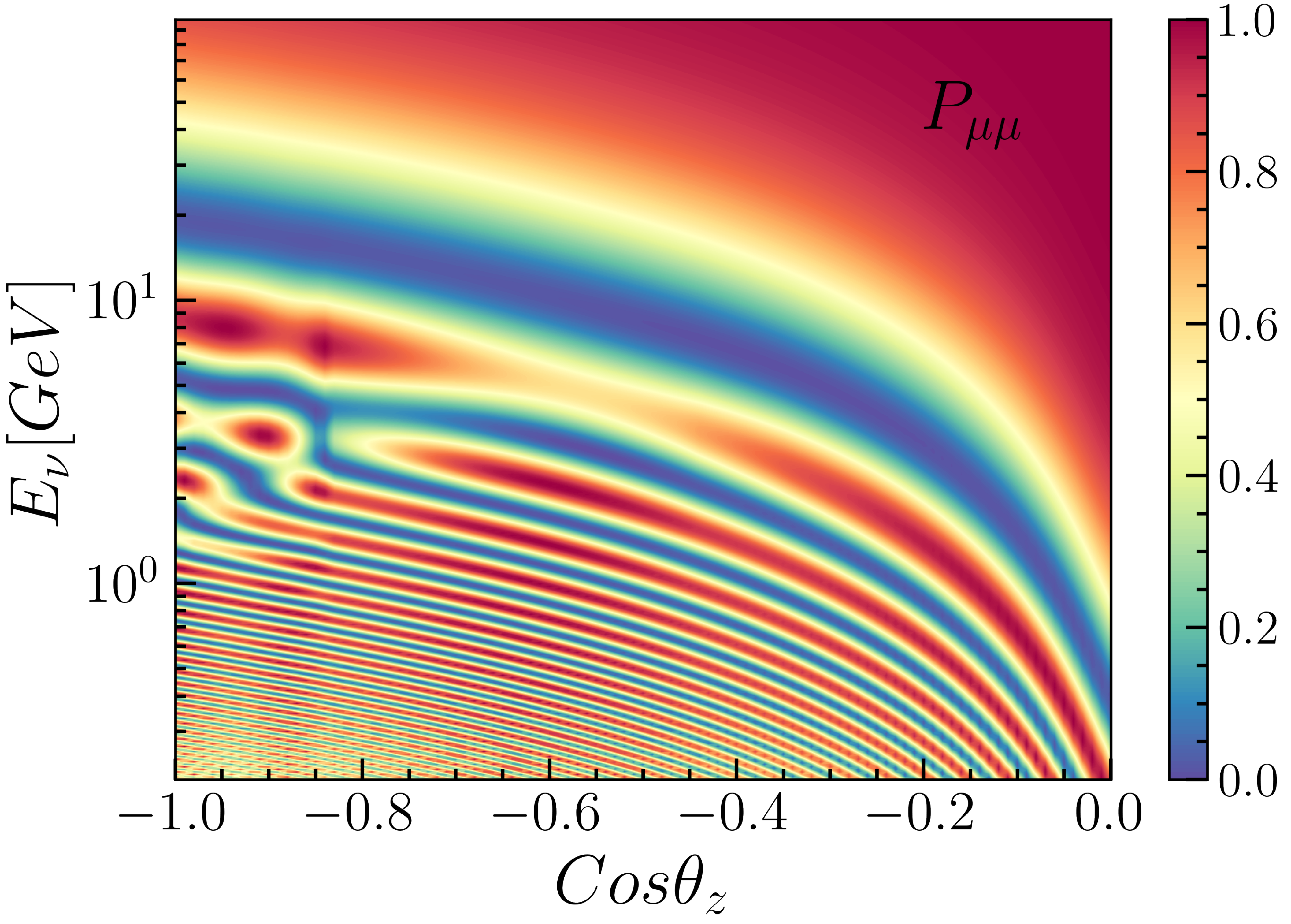


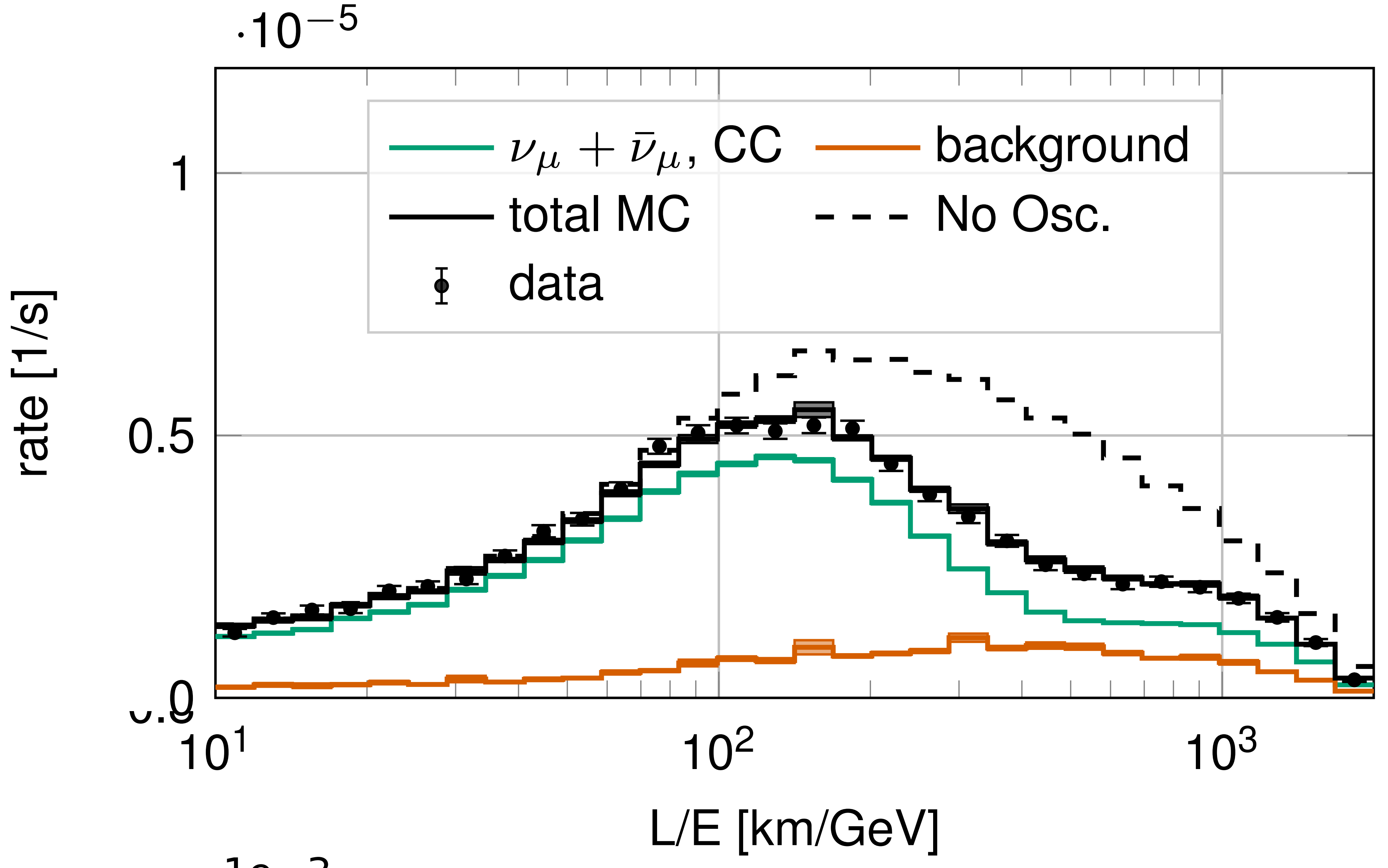
E. Richard et al. (SK), Phys.Rev.D 94 (2016) 5, 052001

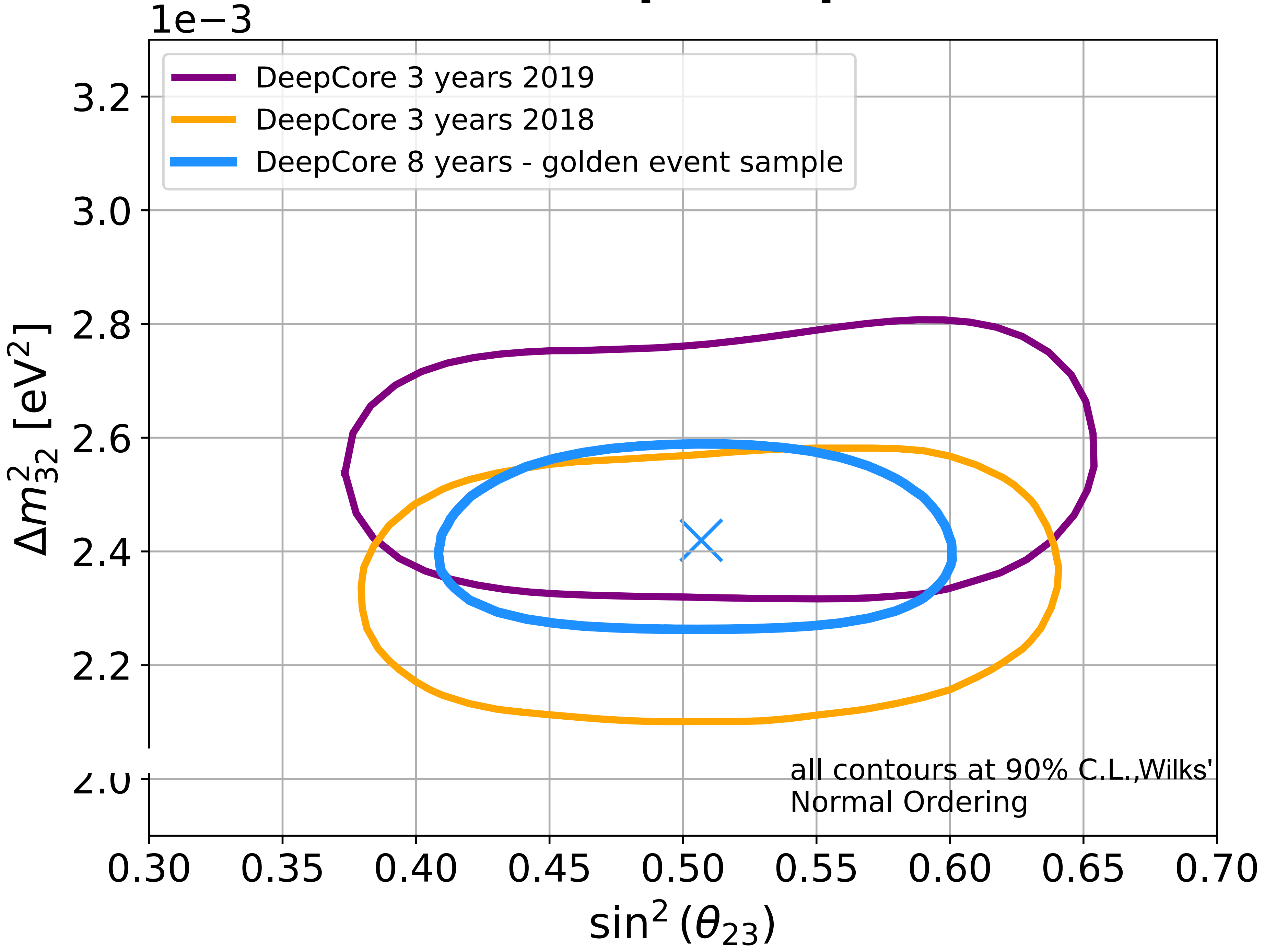
Flavor Oscillations

Measuring the **flavor composition** of the flux passing through the Earth enables the determination of neutrino **oscillation parameters**

$$P_{\alpha\beta} = \sum_{i,j} U_{\alpha i} U^*_{\beta j} U^*_{\alpha j} U_{\beta i} e^{-\frac{i\Delta m^2_{ij} L}{2E}}$$





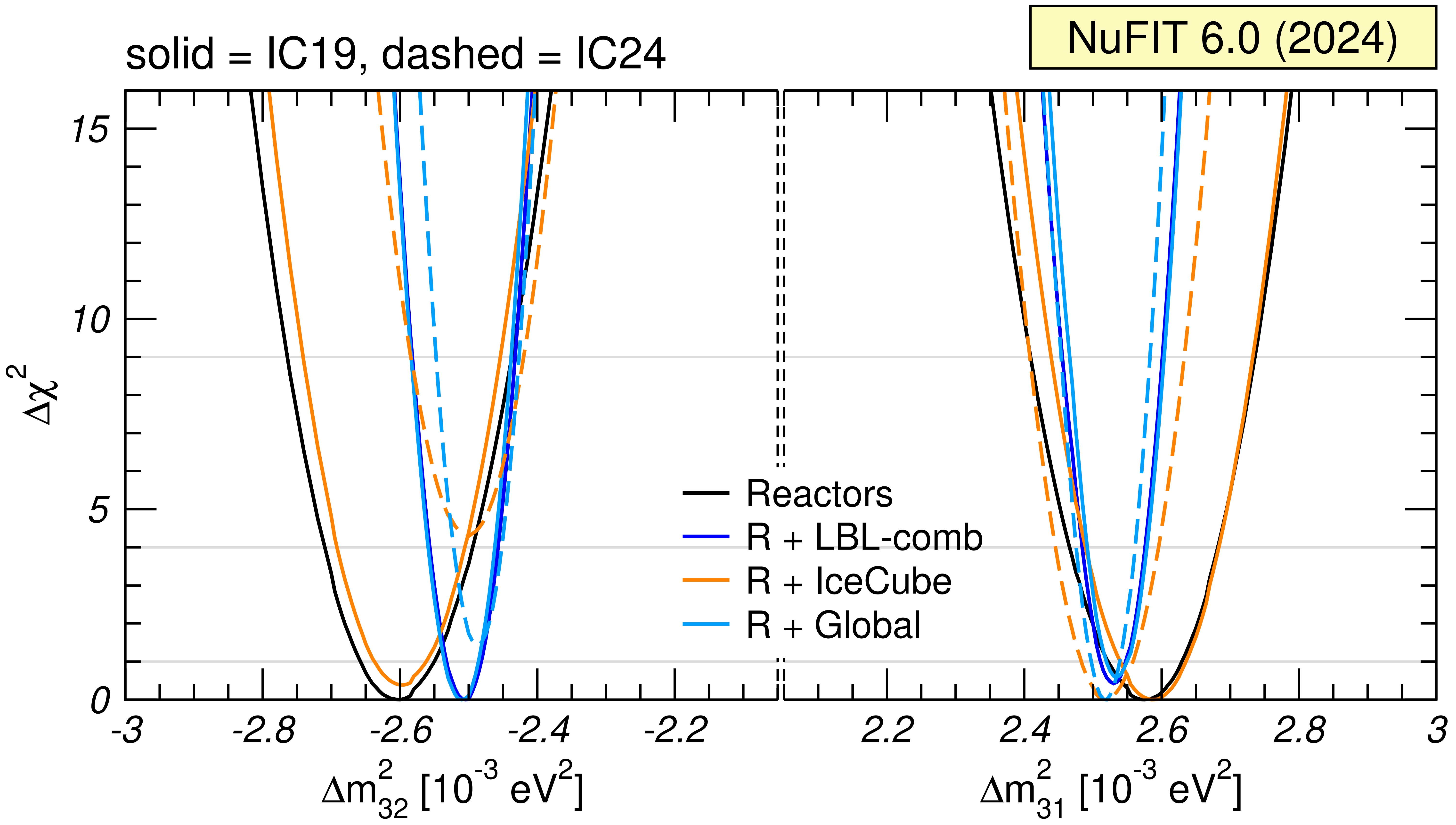


Abbasi et al. (IceCube), PRD 108 (2023)
Abbasi et al. (IceCube), arXiv: 2405.02163

Flavor Oscillations: Mass Ordering

Combining IC measurements with other oscillation experiments we get sensitivity over unconstrained parameters

- Combining **IC24+Reactors**, we get a preference for NO of $\Delta\chi^2 \sim 4.5$
- **Super-Kamiokande** alone shows a preference for NO of $\Delta\chi^2 \sim 4.5$
- **Combining IC+SK+global fit** results in a preference for NO of $\Delta\chi^2 \sim 6.1$



Quantum Decoherence

In case there is new dissipative effects, the flavor oscillation get dumps

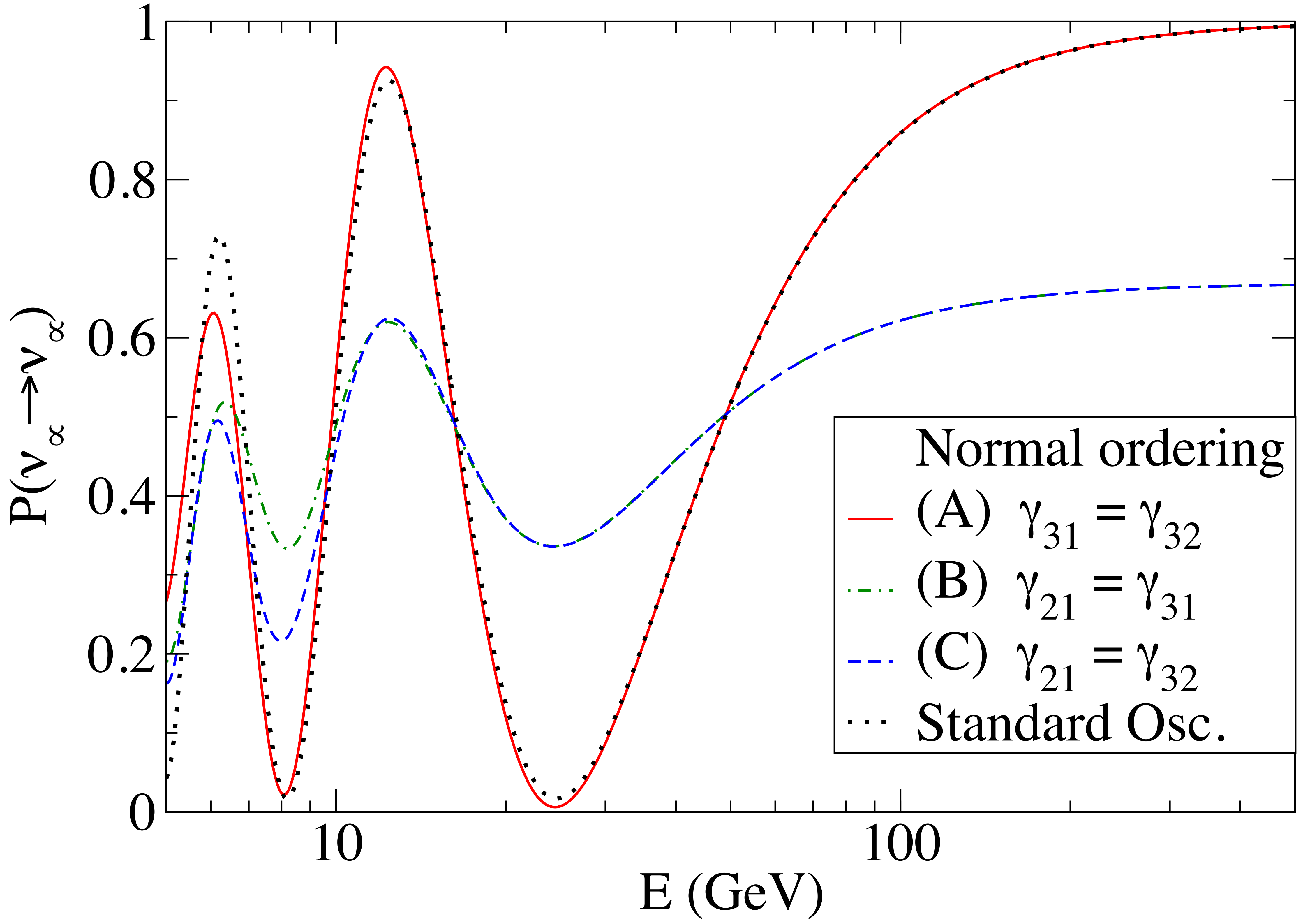
$$\frac{d\rho}{dt} = -i\left[H,\rho\right] - \mathscr{D}\left[\rho\right]$$

Standard evolution

Dissipative effects

Considering unitarity and energy conservation

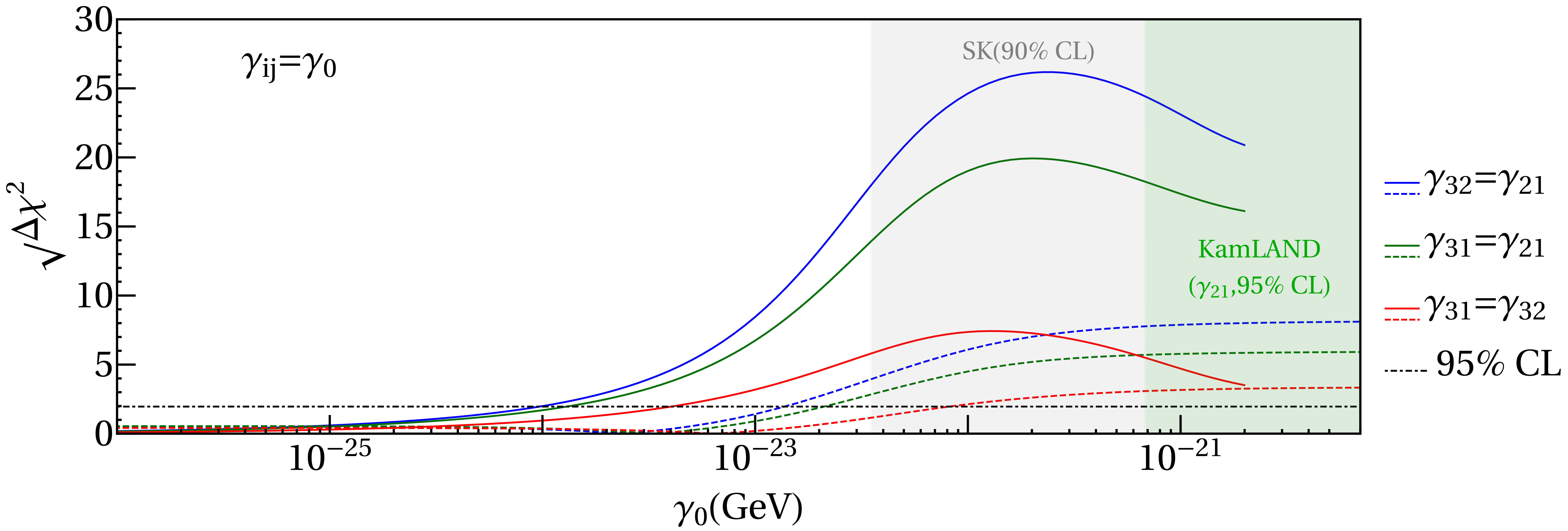
$$P_{\alpha\beta} = \sum_{i,j} U_{\alpha i}U^*_{\beta j}U^*_{\alpha j}U_{\beta i}e^{-\gamma_{ij}L + \frac{i\Delta m^2_{ij}L}{2E}}$$



P Coloma, J López-Pavón, IMS, H. Nunokawa, EPJC 78

Quantum Decoherence

By studying how the dissipative effects affect the propagation of atmospheric neutrinos, we analyzed the IceCube data



P Coloma, J López-Pavón, IMS, H. Nunokawa, EPJC 78

Heavy sterile neutrino

To explain the origin of the neutrino masses, the SM can be considered as a low energy effective model

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{\mathscr{L}_{d=5}}{\Lambda} + \cdots$$

- At d=5, we have the Weinberg operator

See Steve King, Thomas Schwetz-Manglod, Richard Ruiz, Arsenii Titov, Jacobo López-Pavón

Type-I seesaw:

- Introduce right-handed neutrinos
- Allow L number violation

$$\mathscr{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N}^c_R N_R + h.c.$$

- For $M_R >> v$

$$m_\nu \sim \frac{Y^\dagger_\nu Y_\nu v^2}{M_R} \qquad m_N \approx M_R + \mathcal{O}\left(m_\nu\right)$$

- Neutrino masses can be smaller than other fermion masses
- Heavy neutrinos can hardly be tested
- There are other scenarios where the Majorana mass can take smaller values

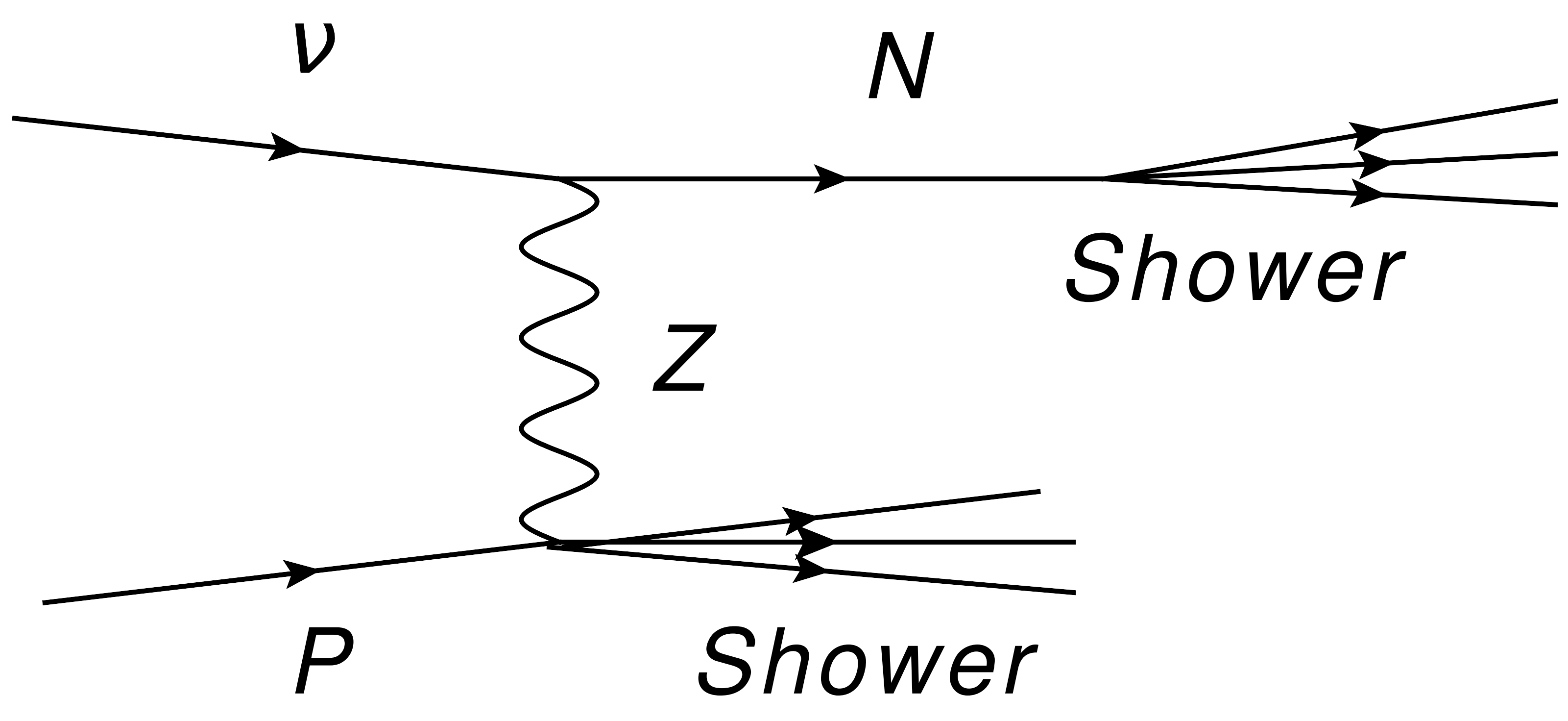
Heavy sterile neutrino

In the presence of N_R, the flavor states can be written as a superposition of massive states as

$$\nu_{\alpha L} = \sum U_{\alpha m} \nu_{mL} + U_{\alpha 4} N_{4L}$$

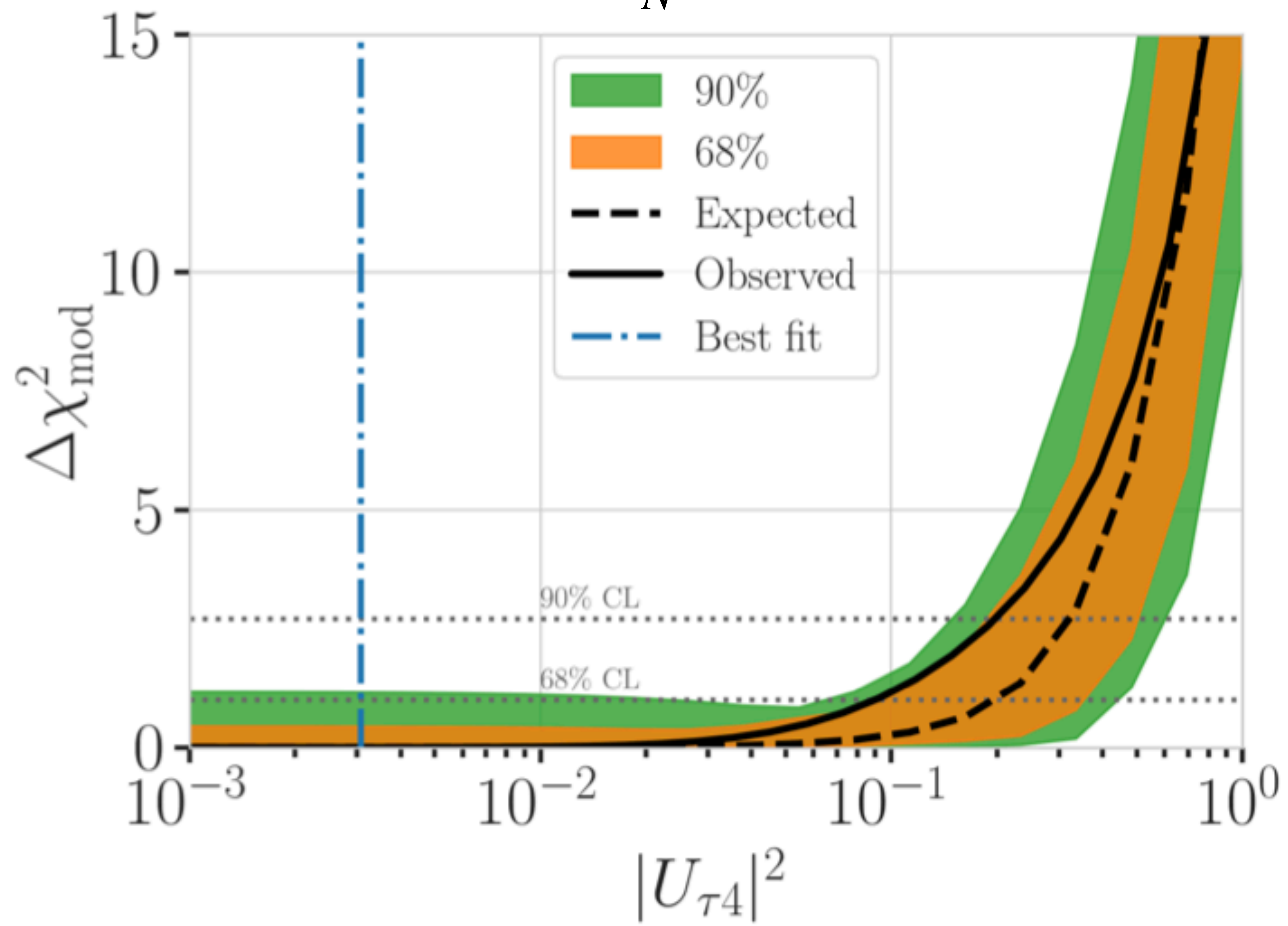
We can look for HNLs using **double bang signals**

$$\nu + N \rightarrow N_4 + \text{shower}$$
$$N_4 \rightarrow \nu + \text{signal}$$



P. Coloma, P.A.N. Machado, IMS, I.M.Shoemaker, PRL 119 (2017)

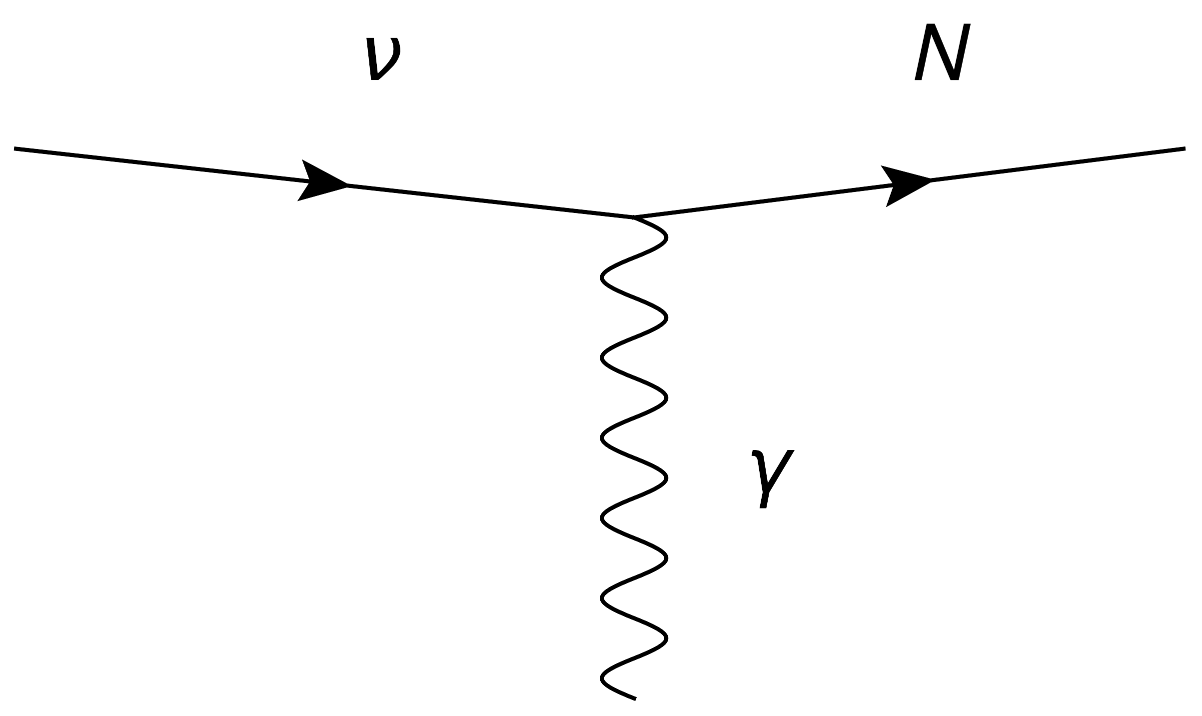
$m_N = 0.3$GeV



Abbasi et al. (IceCube), arXiv:2502.09454

Transition Magnetic Moment

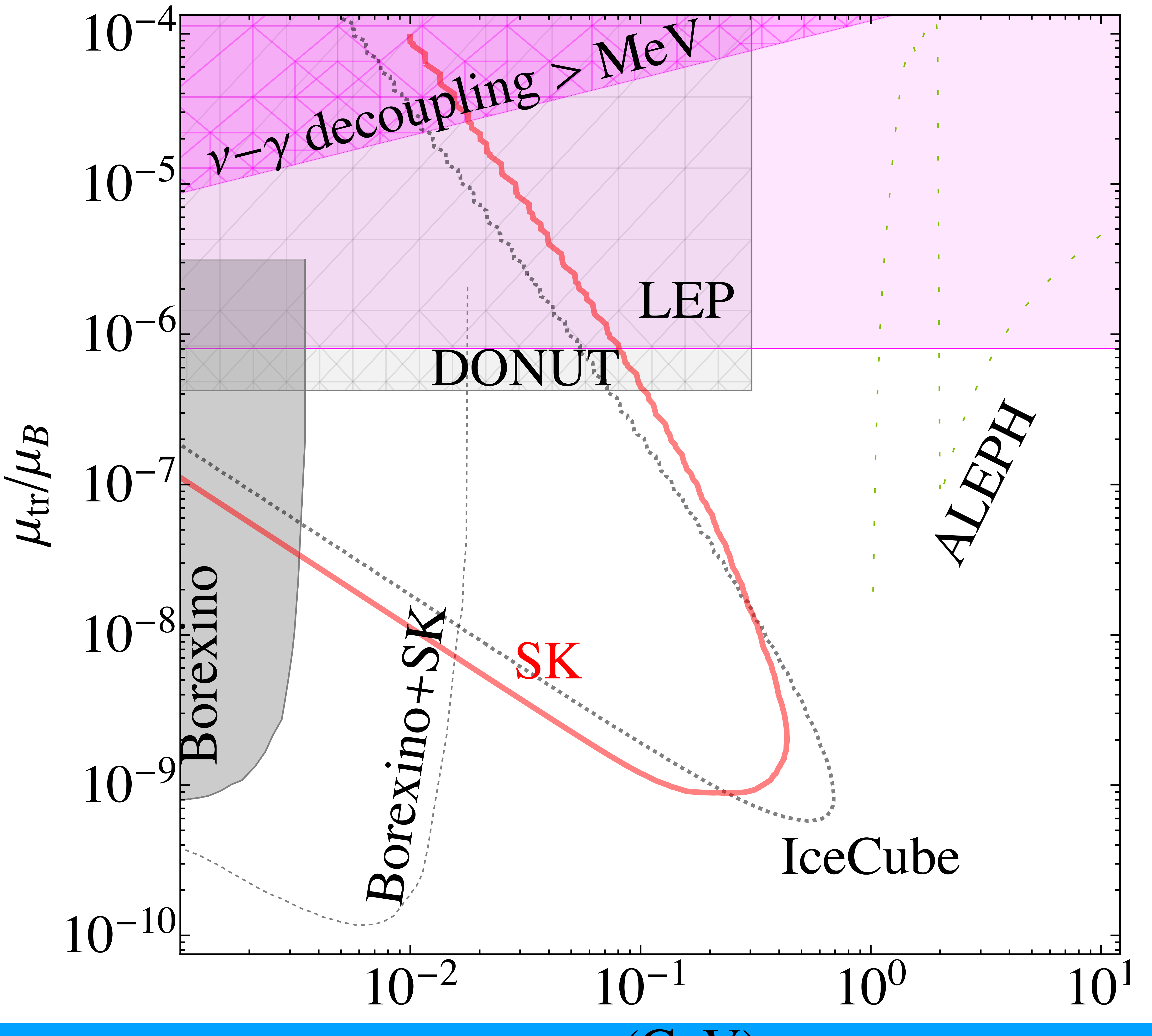
Active and HNL states may be coupled via a **transition dipole moment**



$$\mathscr{L} \supset -\mu_\nu \bar{N}_4 \sigma_{\mu\nu} P_L \nu_\alpha F^{\mu\nu}$$

We are going to consider that both the HNL production and decay are given by the dipole moments ($N \to \nu_i \gamma$)

$$\Gamma = \frac{\mu_\nu^2 M_4^3}{4\pi}$$



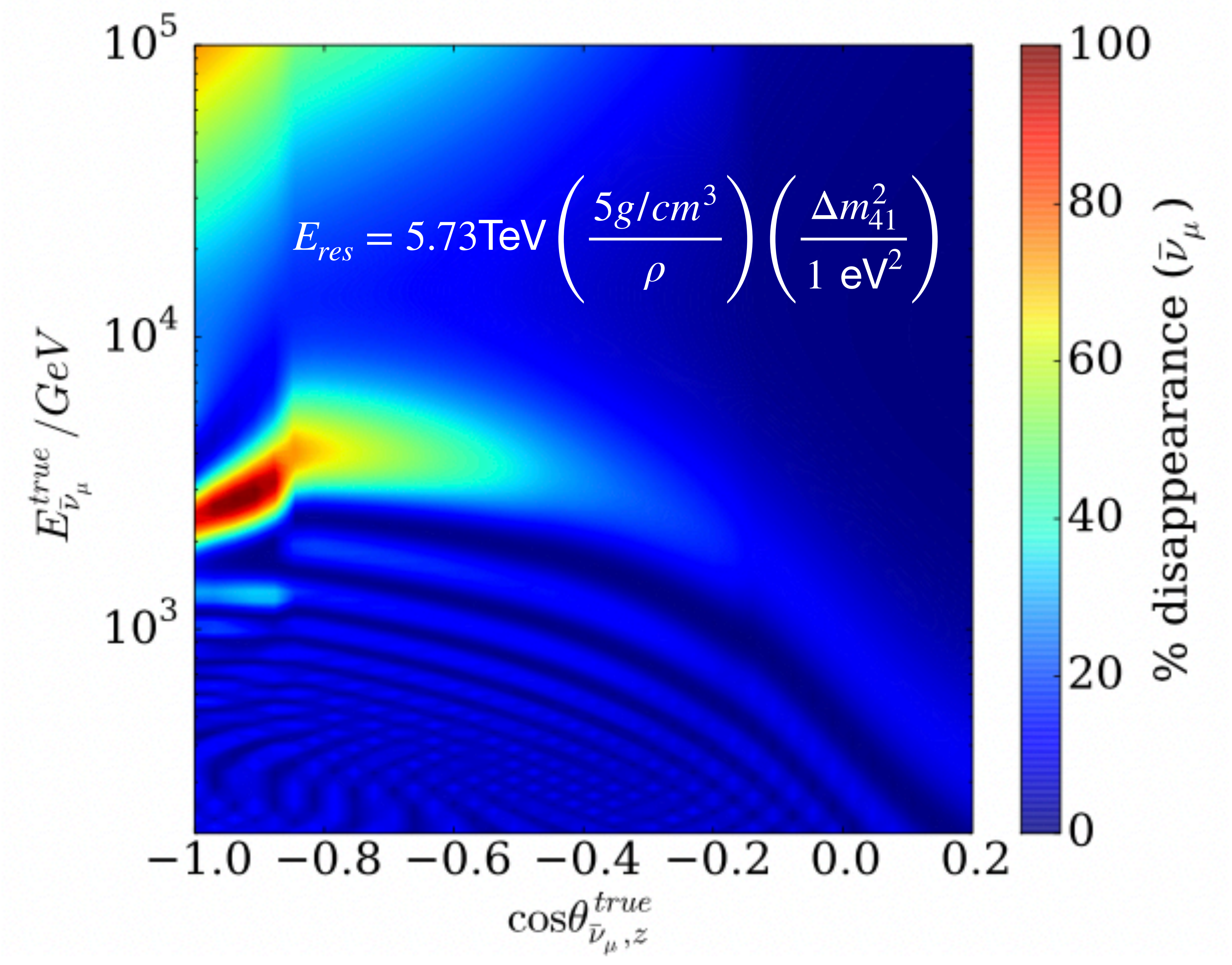
P. Coloma, P.A.N. Machado, IMS, I.M.Shoemaker, PRL119 (2017)

M. Atkinson, P. Coloma, IMS, Noemi Rocco, I.M. Shoemaker, JHEP 04 (2022) 174

Light-Sterile Neutrinos

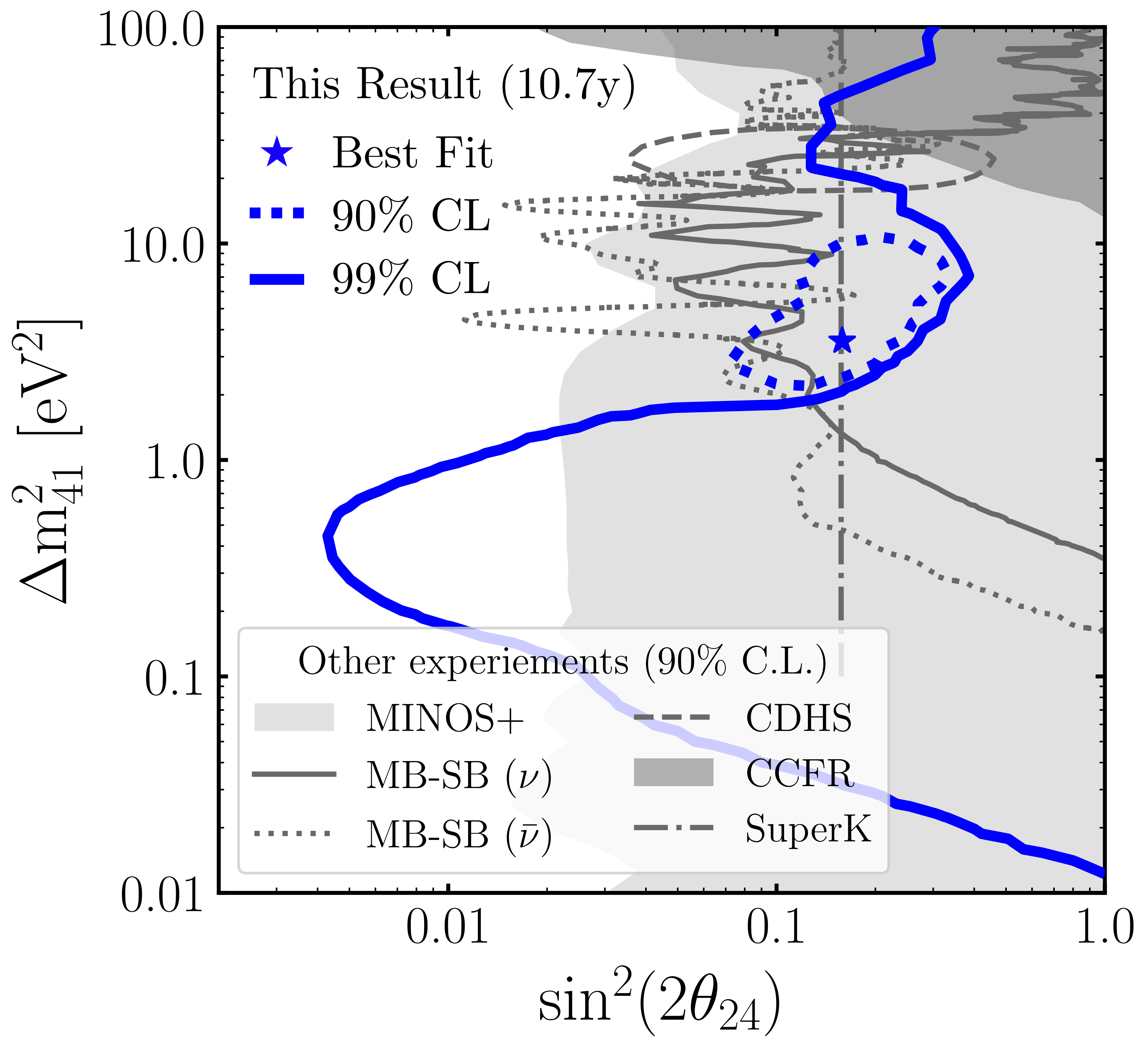
See Thomas Schwetz-Mangold, Claudio Silva

eV sterile neutrinos lead to a disappearance in the atmospheric muon neutrino flux at the TeV scale



There is a slight preference for sterile neutrinos, which is in tension with other measurements

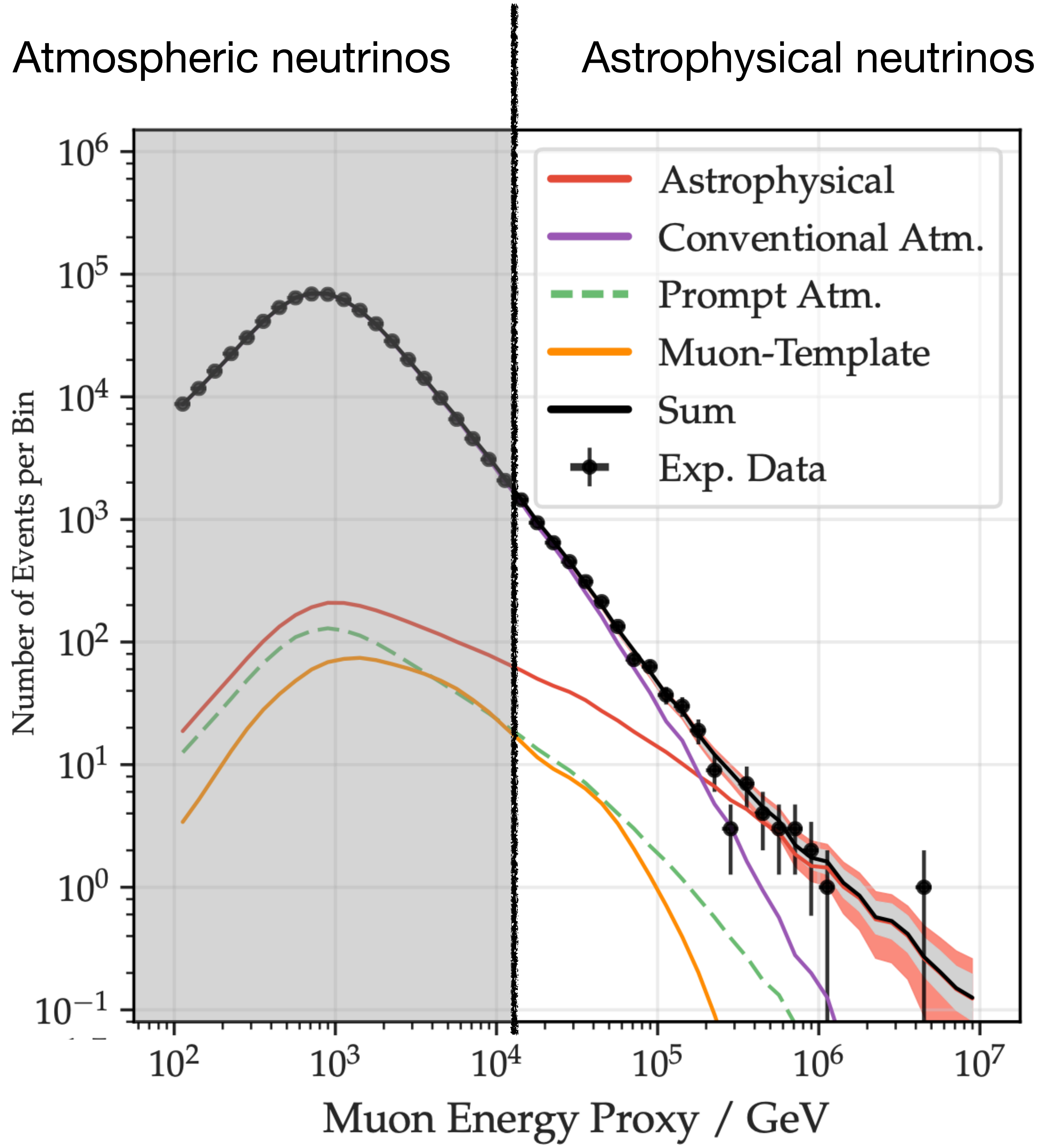
$P_{\mu\mu} < 1$



Abbasi et al. (IceCube), arXiv: 2405.08070

Astrophysical neutrinos

At energies above ~10 TeV, the flux reaching the Neutrino Telescopes is dominated by astrophysical sources.

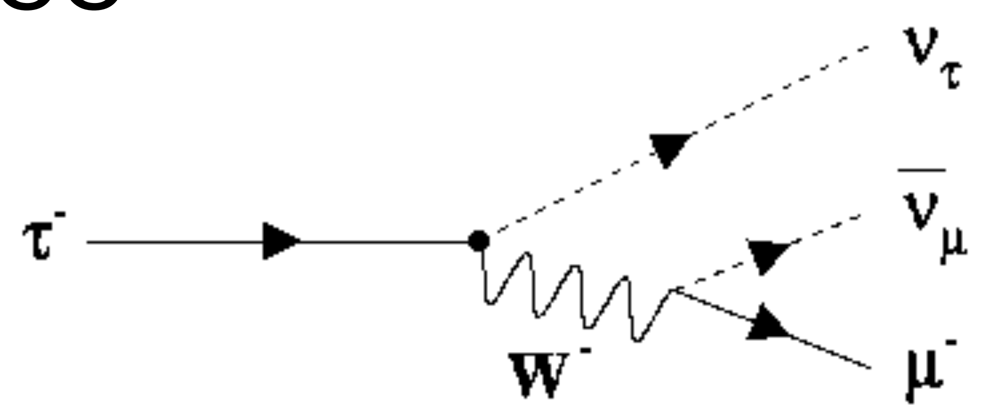


R. Abbasi, et al. (IceCube), Astrophys.J. 928 (2022) 1, 50

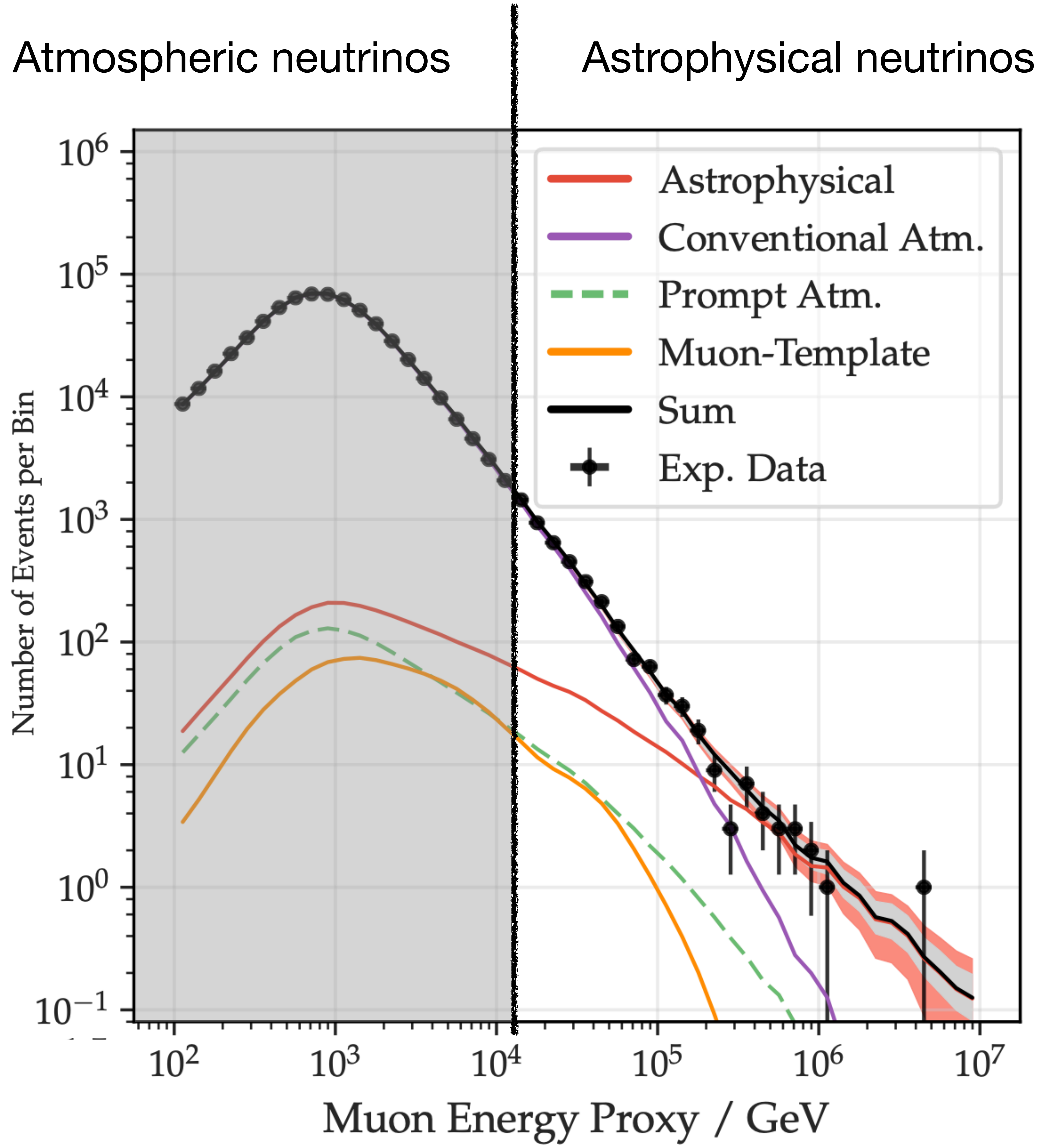
Through-going Muons

IceCube has measured the astrophysical muon-neutrino flux

- It includes both starting and through-going samples.
- The measurement is dominated by ν_μ CC, with a small contribution from ν_τ CC



- To minimize the background, only up-going events have been considered ($\theta_{zenith} > 85^\circ$)
- The energy range considered is 15 TeV to 5 PeV

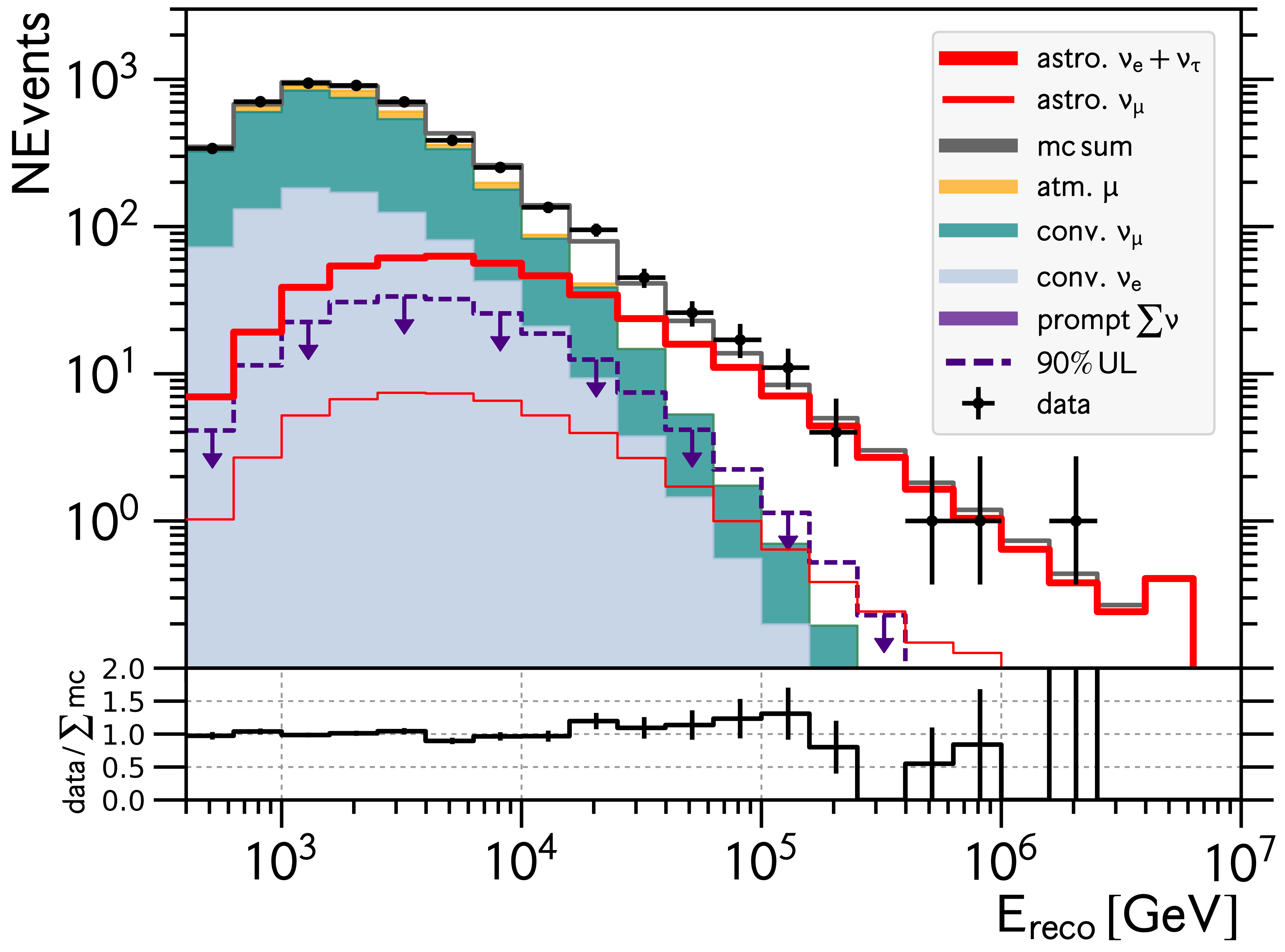


R. Abbasi, et al. (IceCube), Astrophys.J. 928 (2022) 1, 50

Electron and Tau Neutrinos

IceCube has searched for astrophysical events using cascades

- This analysis is dominated by ν_e and ν_τ
- The astrophysical neutrino flux at Earth assumes an equal number of neutrinos and anti-neutrinos, with an equal flavor composition
- The energy range considered spans from 16 TeV to 2.6 PeV
- Cascades from all the sky are included.



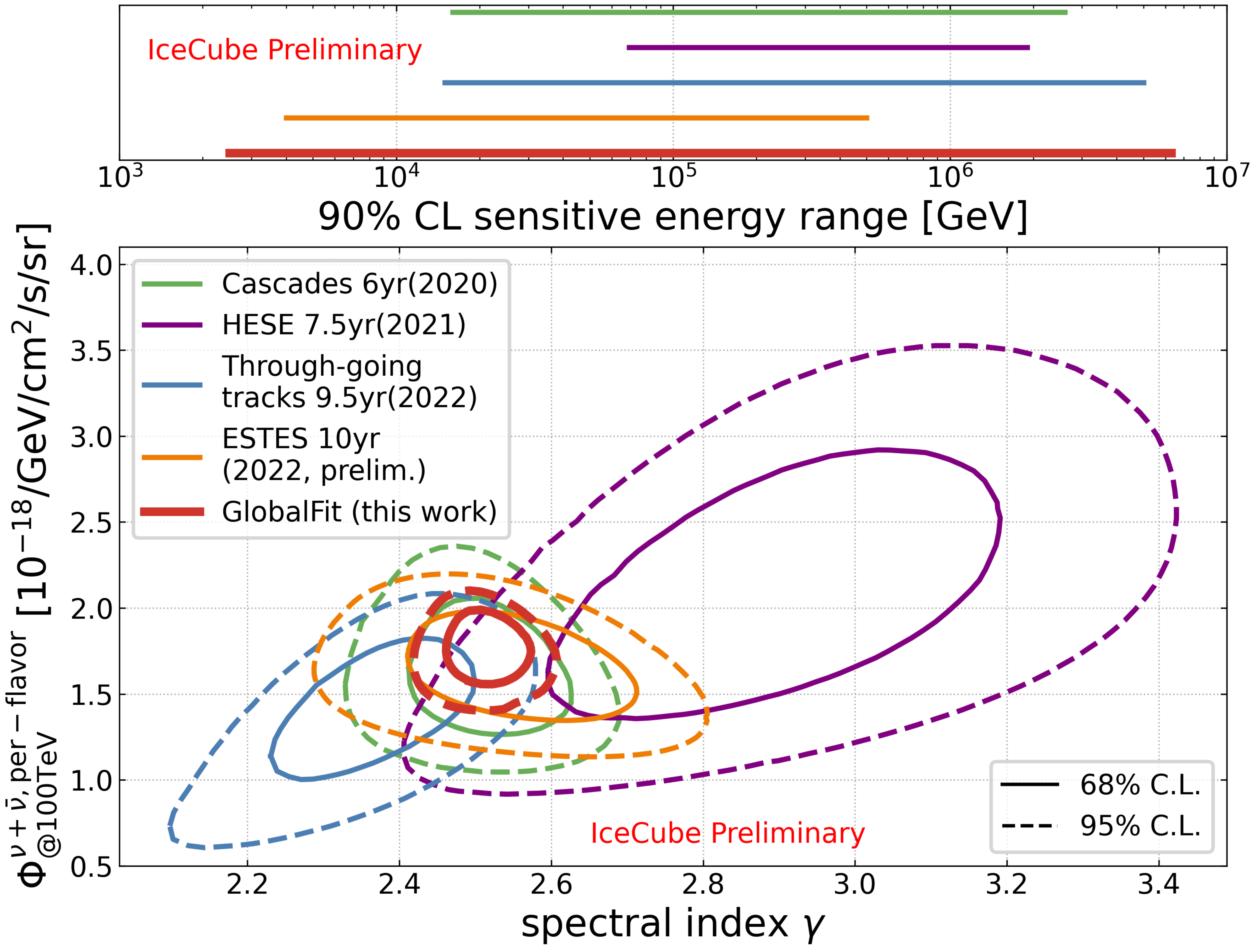
M.G. Aartsen, et al. (IceCube), PRL 125 (2020)

Combined Analysis

Tracks and cascades represent two independent data samples that can be combined into a global determination of the astrophysical flux

Assuming the astrophysical flux follows a power law

$$\phi_\nu(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\gamma}$$

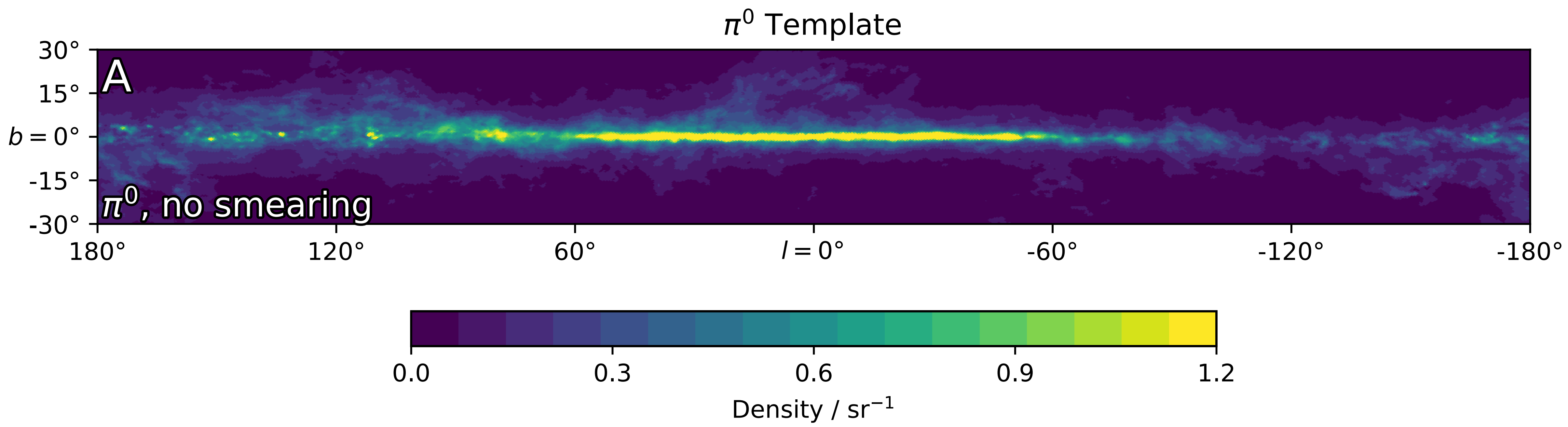


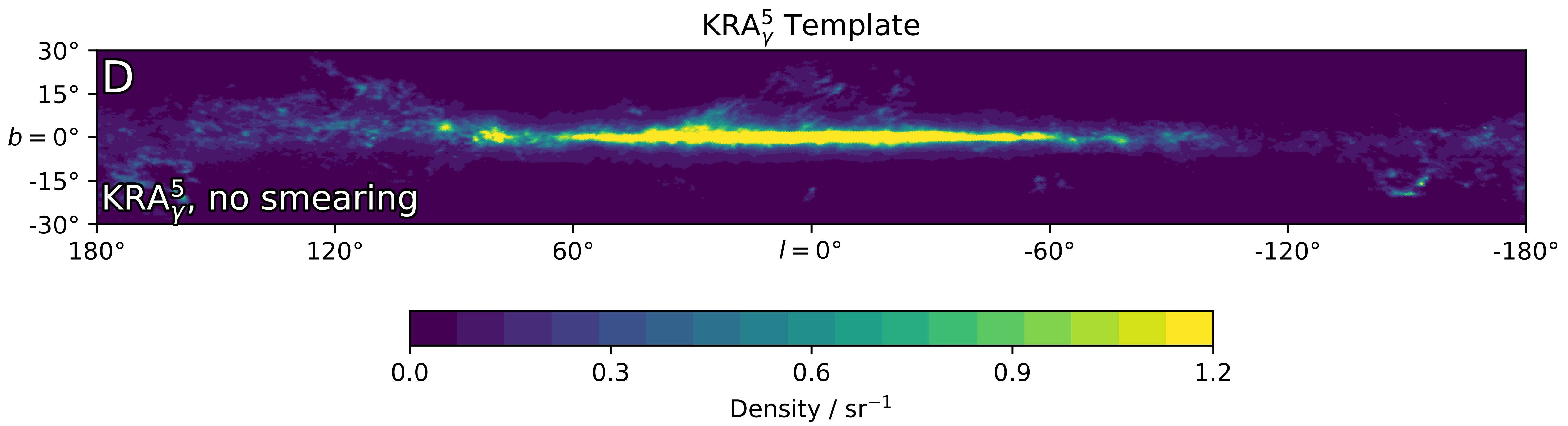
R. Naab, E. Ganster and Z. Zhang (IceCube), PoS(ICRC2023) 1064

Where Do Neutrinos Come From?

Galactic Plane

- The highest neutrino production in the galaxy is expected near the Galactic Center
- Three models of Galactic diffuse neutrino emission have been considered, differing in energy spectrum and emission location.



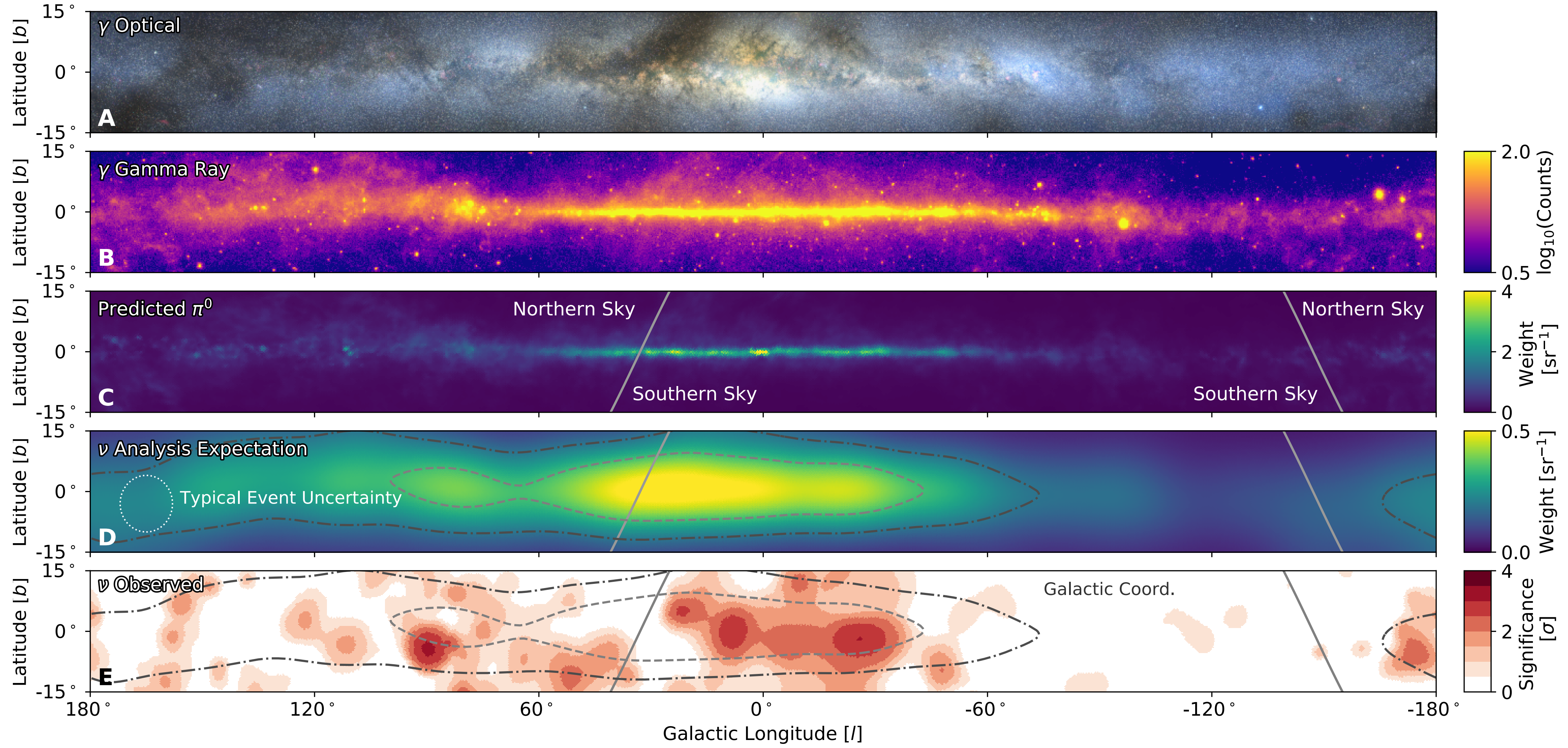


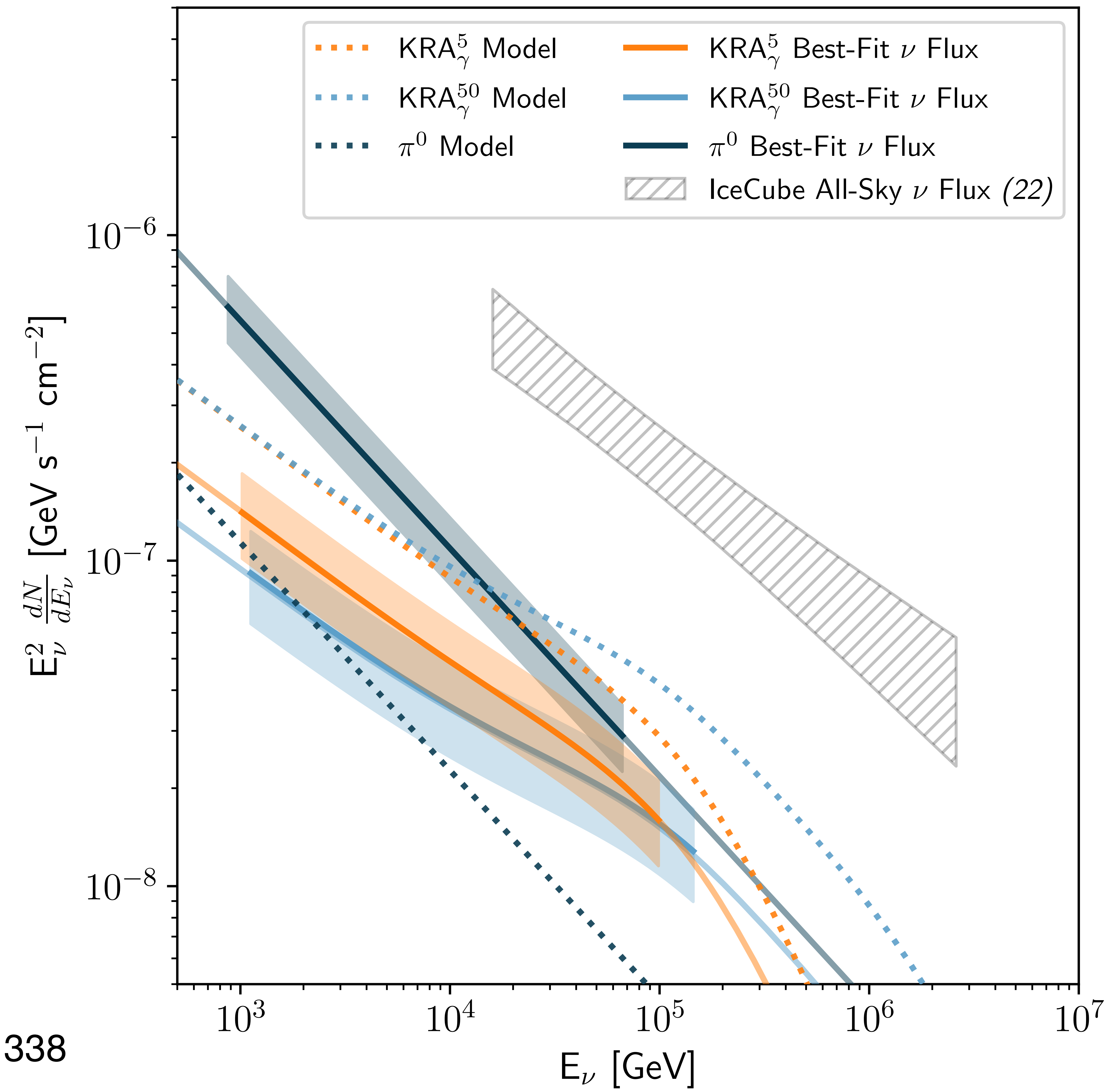
IceCube, Science 380 (2023) 1338

Galactic Plane

- Neutrino emission from the Galactic Plane is found at 4.5σ

- The flux from the galactic plane will contribute between 6-13% to the diffuse flux at 30TeV



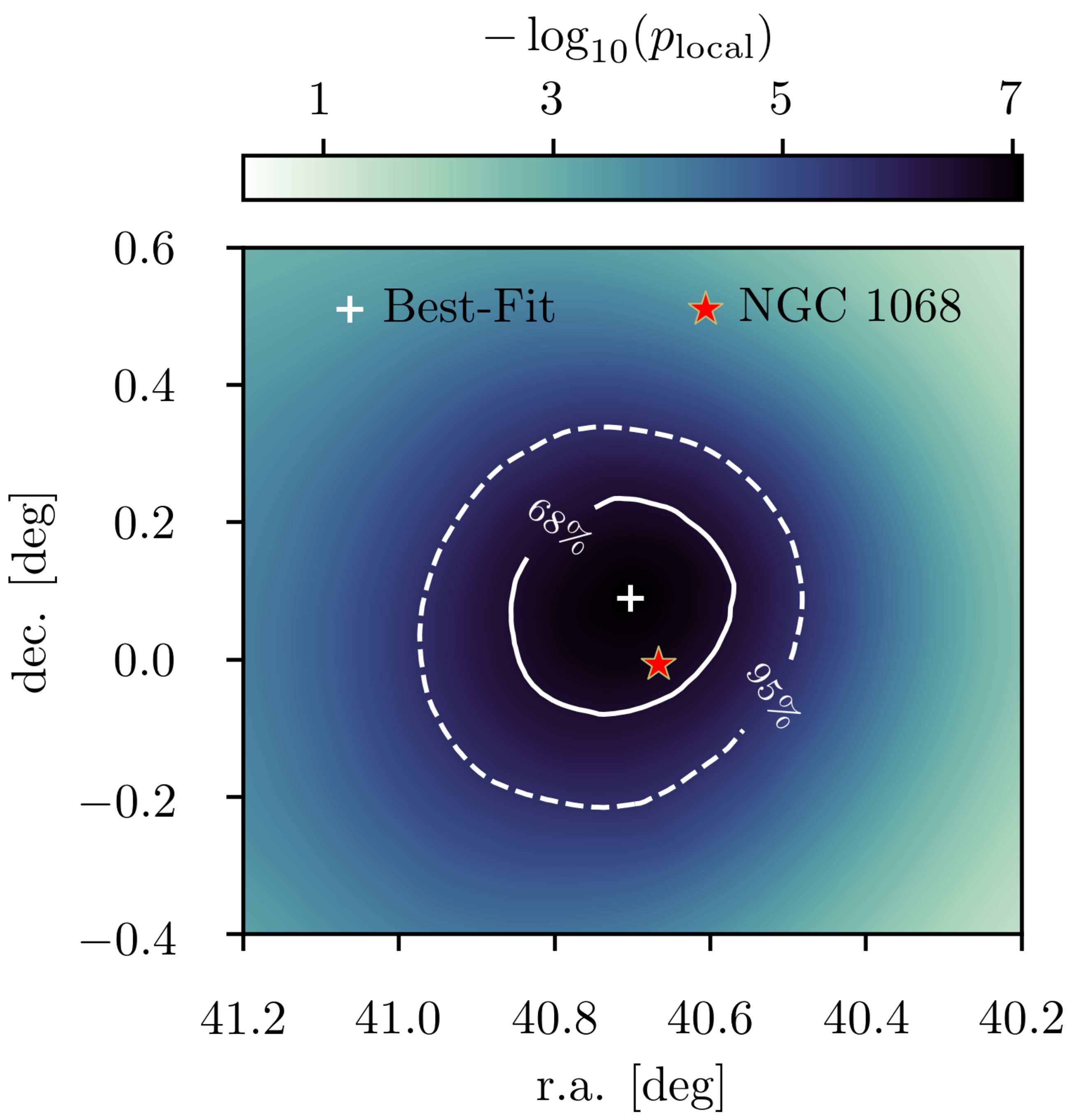


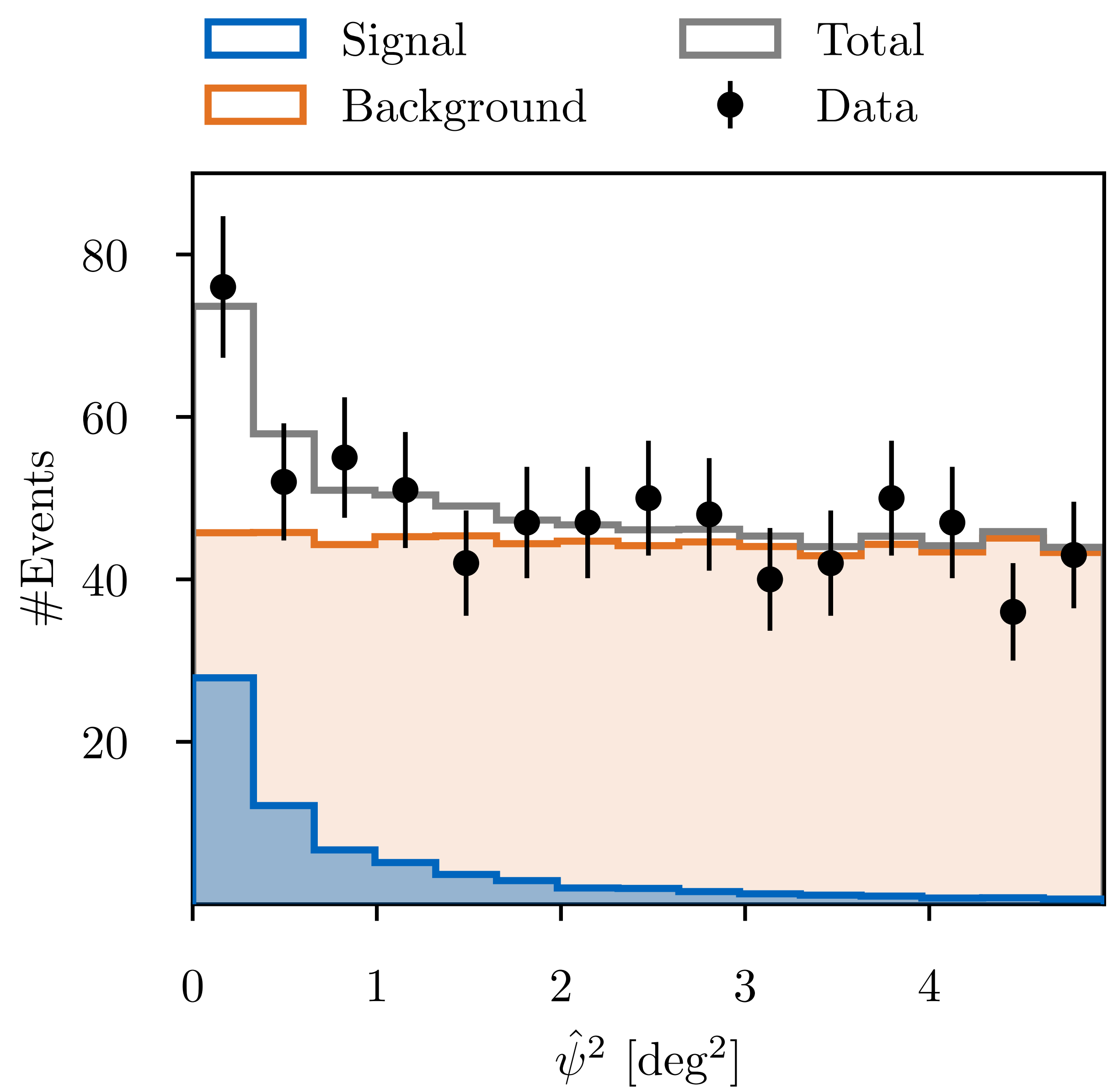
IceCube, Science 380 (2023) 1338

Point Sources

The most significant source observed by IceCube is **NGC 1068** with a significance of 4.2σ

- The analysis is optimized for searching tracks from the Northern Hemisphere
- The analysis assumes a single power law finding a preference for $\gamma = 3.2 \pm 0.2$ and an excess of 79^{+22}_{-20} events
- Most of the events have energies between 1.5TeV and 15TeV





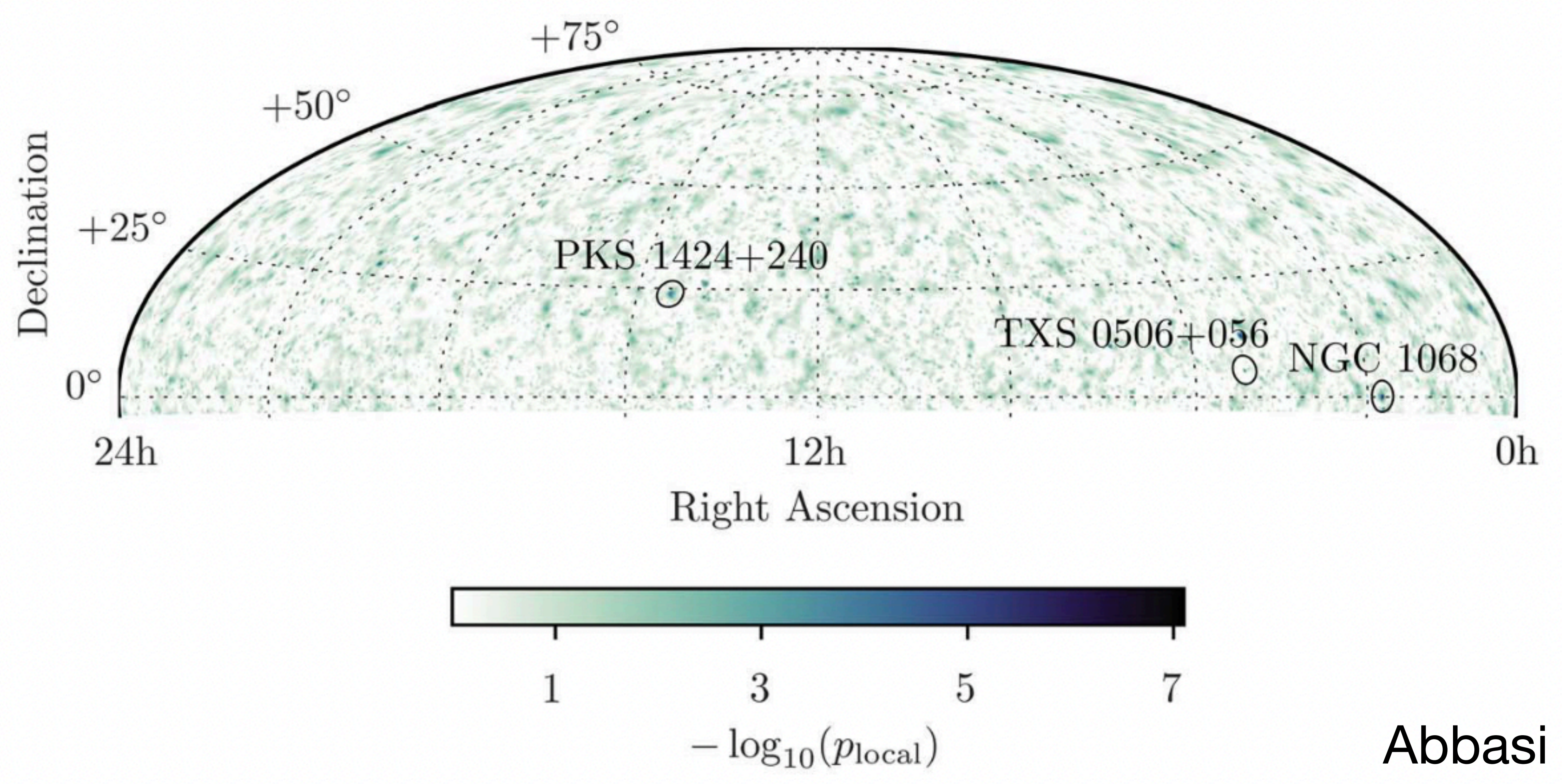
Abbasi et al. (IceCube) Science 378, 538 (2022)

Point Sources

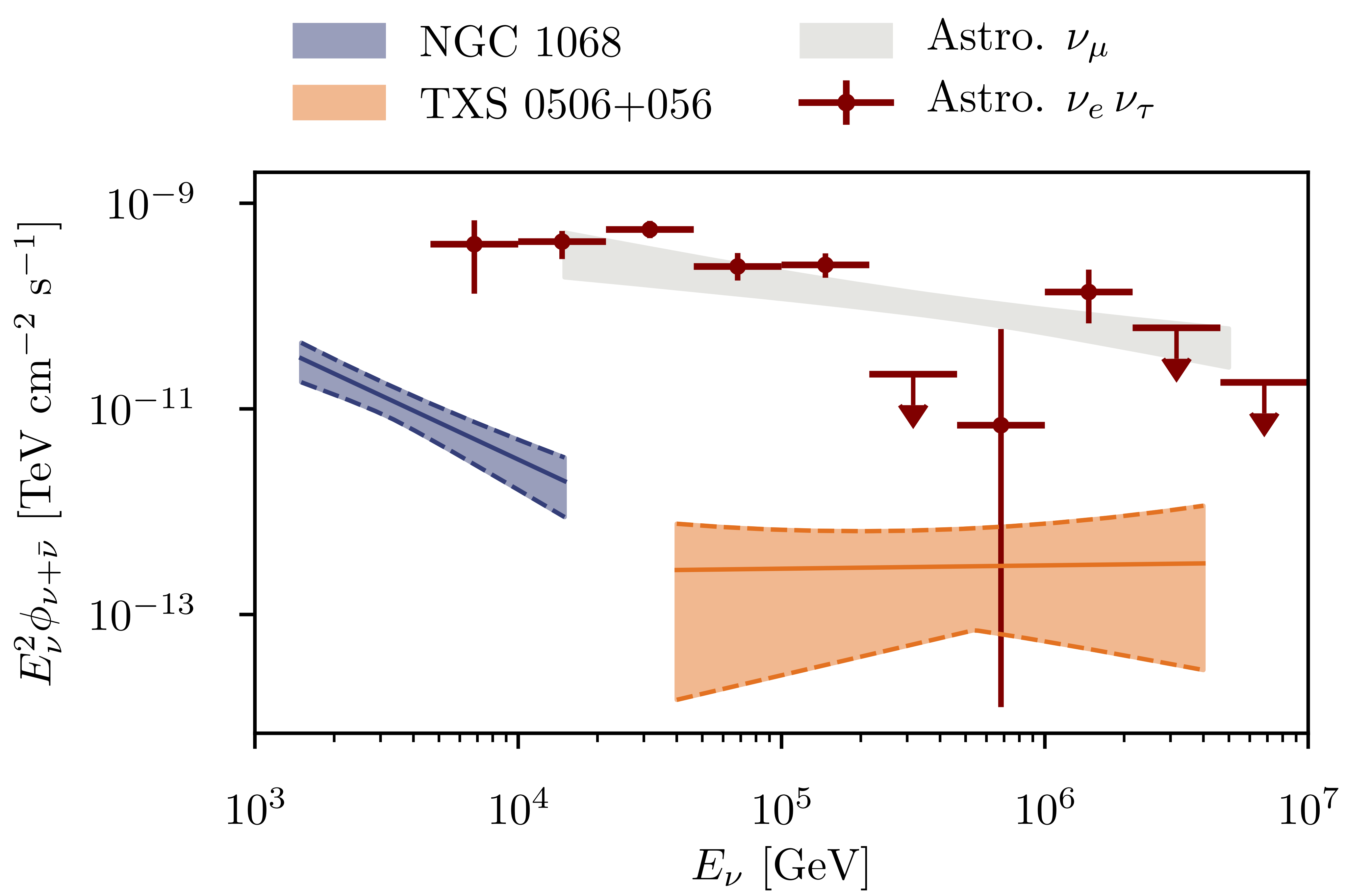
Beyond NGC 1068, IceCube has identified more candidate sources

The most significant point sources

Source	$-\log_{10} p$	$\hat{\gamma}$	z
NGC 1068	7.0	3.2	0.0038
PKS 1424+240	4.0	3.5	0.6047
TXS 0506+056	3.6	2.0	0.3365



These sources contribute no more than $\sim 1\,\%$ to the total diffuse flux measured.



Abbasi et al. (IceCube) Science 378, 538 (2022)

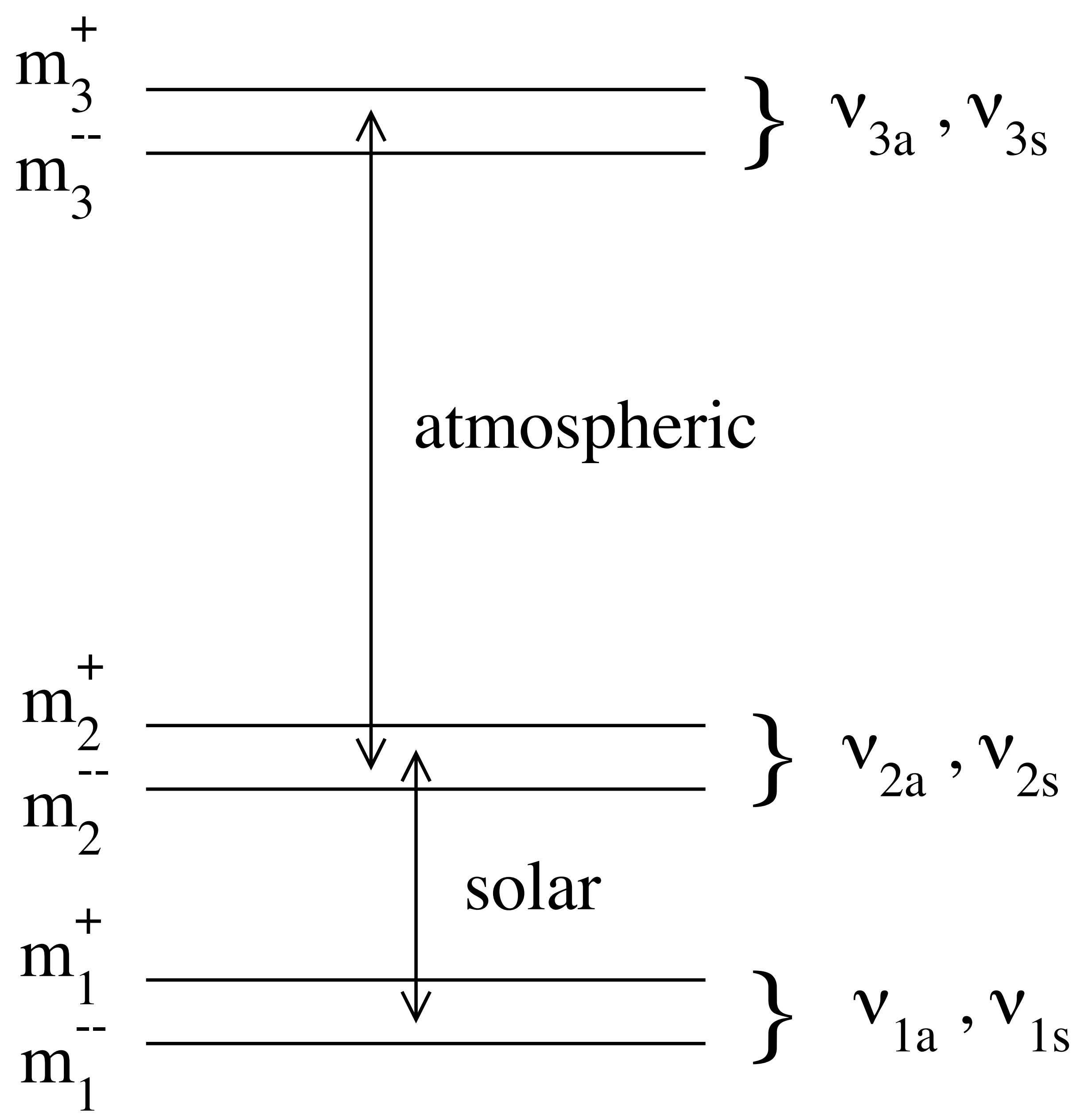
Pseudo-Dirac neutrinos

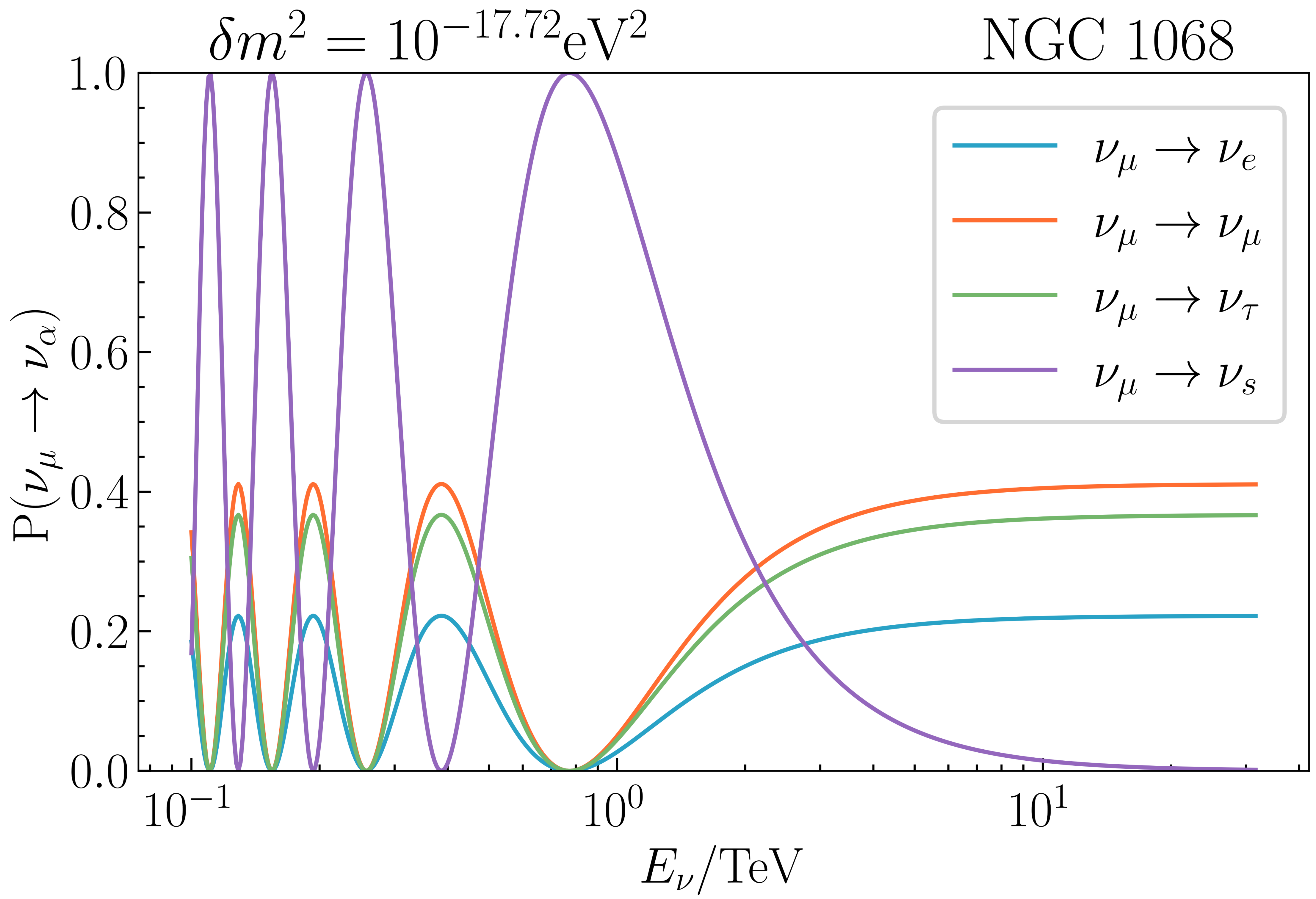
In the scenario where $M_R << M_D$ the active neutrinos can be written as a superposition of two massive states

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j}(\nu_{js} + i\,\nu_{ja})$$

$$m_{ks}^2 = m_k^2 + \frac{1}{2}\delta m_k^2$$

$$m_{ka}^2 = m_k^2 - \frac{1}{2}\delta m_k^2$$

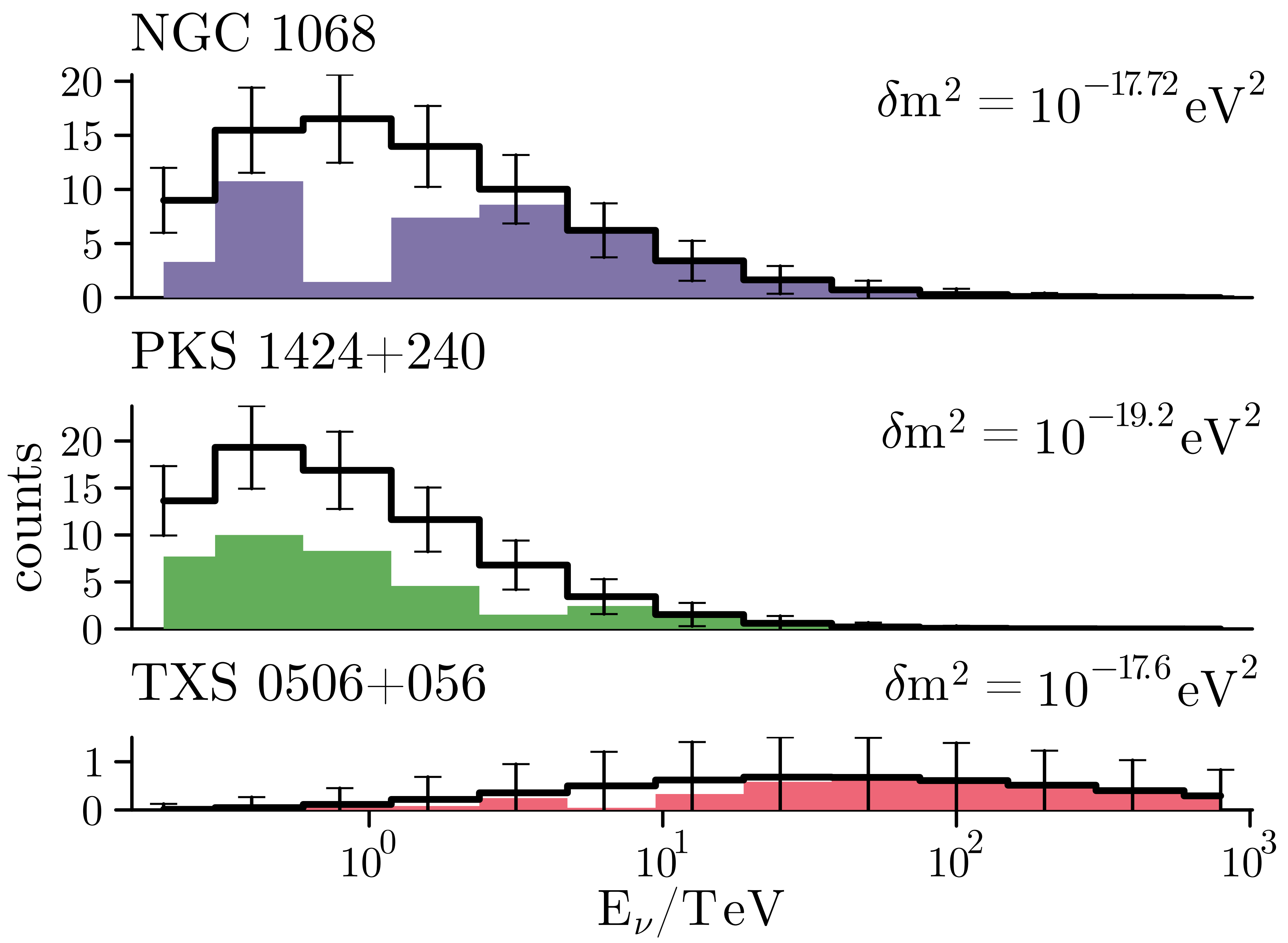




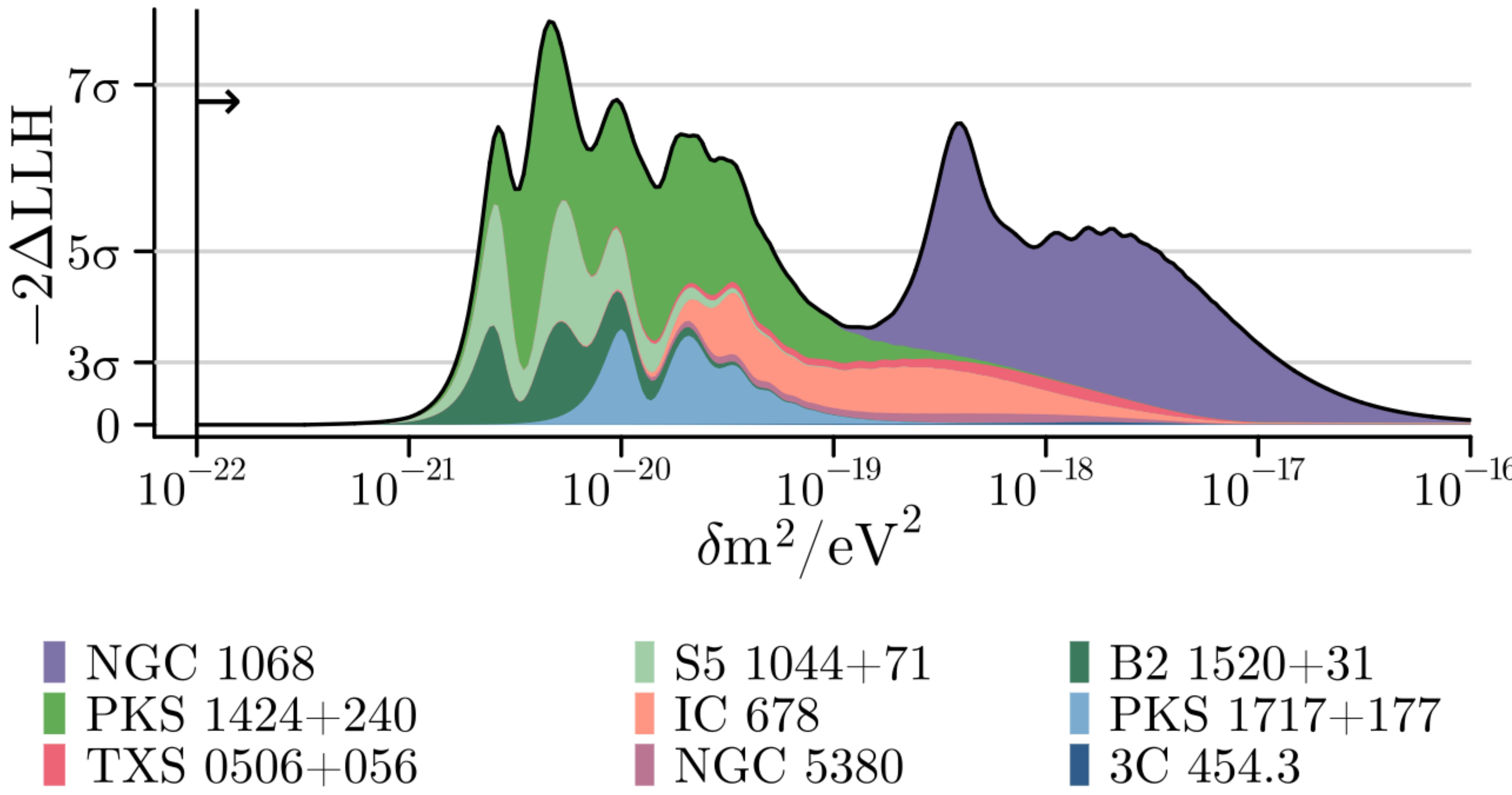
Pseudo-Dirac neutrinos

In this analysis, we consider the most significant candidate sources observed by IceCube

A dip in the neutrino spectra of several sources will robustly indicate this scenario.



The pseudo-Dirac scenario can be explored with a high significance by combining several sources.



Carloni, Martinez-Soler, Arguelles, Babu, Bhupal, PRD 109 (2024) L051702

Conclusions

- **Neutrino telescopes** can provide valuable information about the **neutrino properties.**

- By measuring of the atmospheric neutrino flux, **neutrino telescopes** will contribute to some of the open questions in neutrino physics: the **mass ordering.**

- **Atmospheric** neutrinos can also be used to search for **BSM signals**: quantum decoherence, HNLs…

- Neutrino telescopes have also been able to identify some sources of **astrophysical neutrinos.**

- Considering the most significant point sources, we explored the sensitivity to the **pseudo-Dirac scenario,** finding that $10^{-21}\text{eV}^2 < \delta m^2 < 10^{-16}\text{eV}^2$ can be explored with more than 3σ significance.

Thanks!