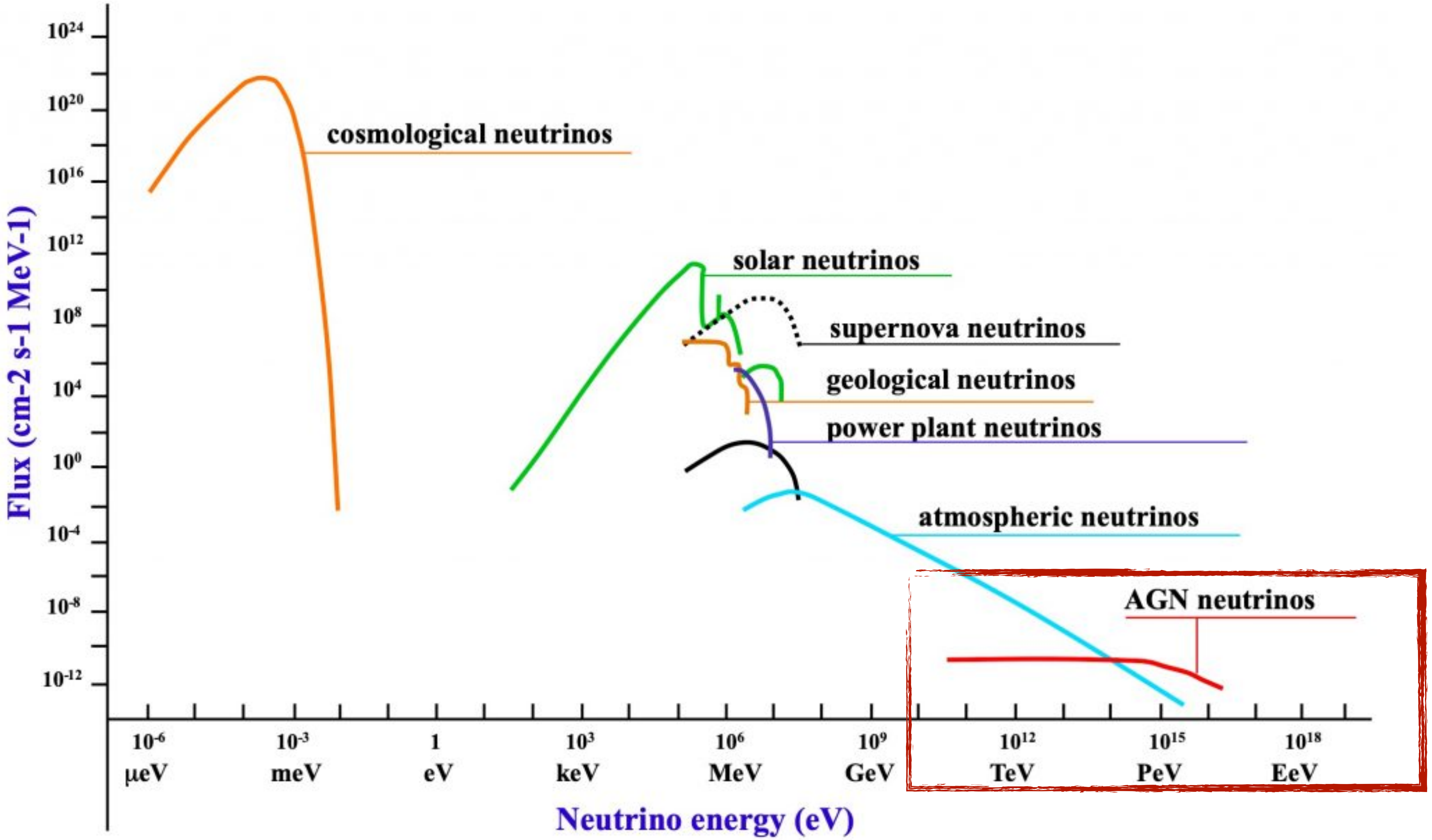
Unraveling Neutrino Properties with Neutrino Telescopes

Ivan Martinez Soler

High-Energy Neutrinos

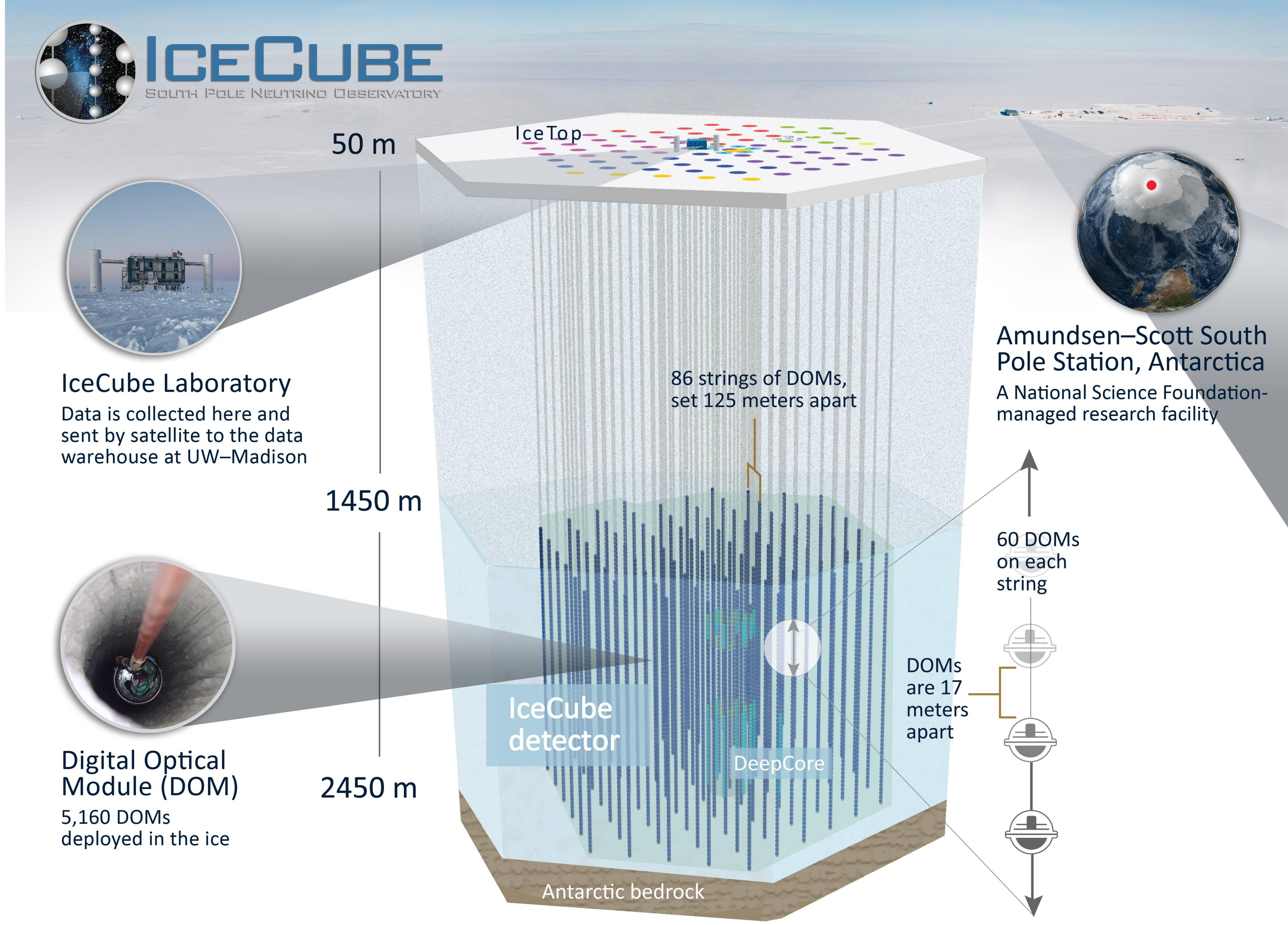
We focus on the high-energy part of the flux, which is very small and therefore requires large detectors



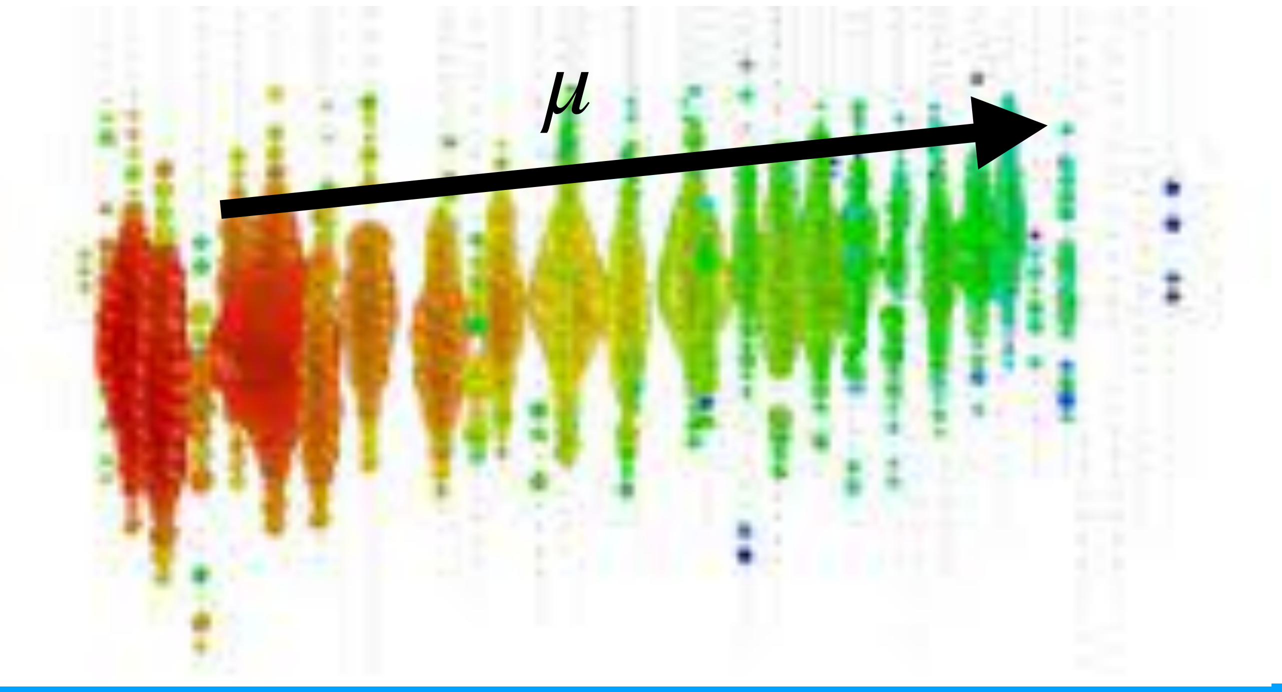
IceCube

IceCube is a neutrino telescope in the south pole.

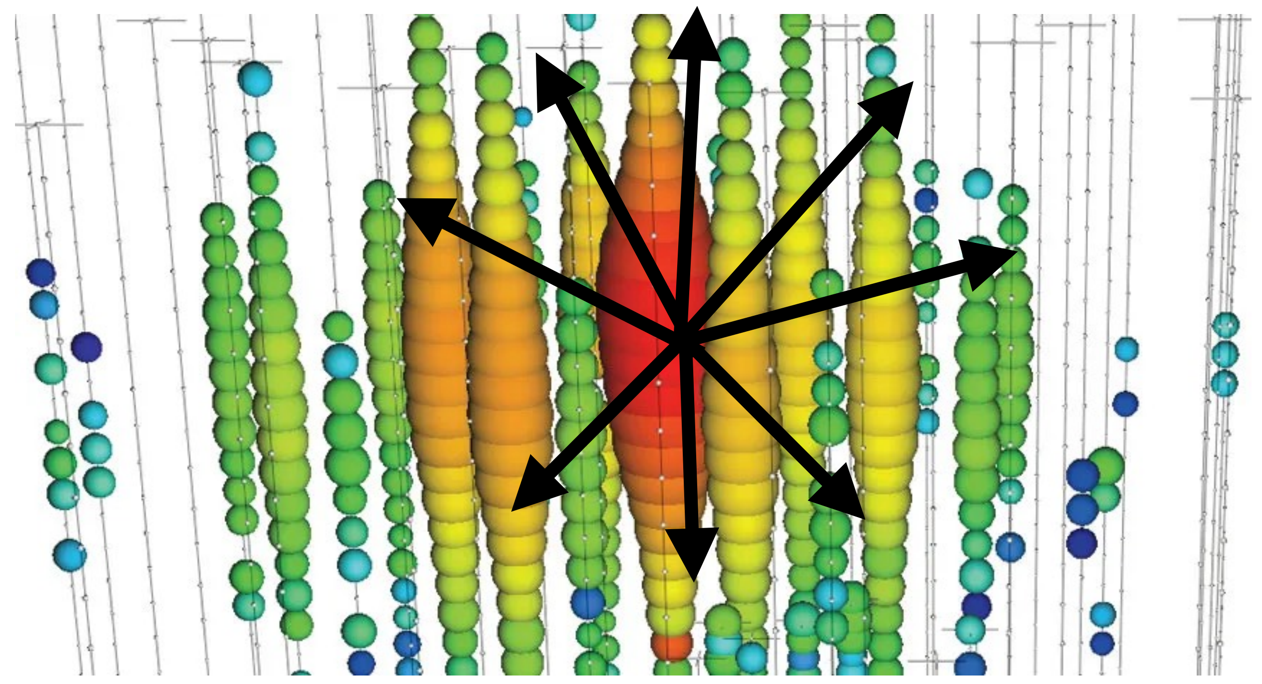
- $\sim 1\text{km}^3$ ice Cherenkov
- Contains 5160 DOMs
- 86 strings
- Approximately ~2 km below the surface
- IceTop
- The main background is muons from cosmic-rays.
- Three-different event topologies



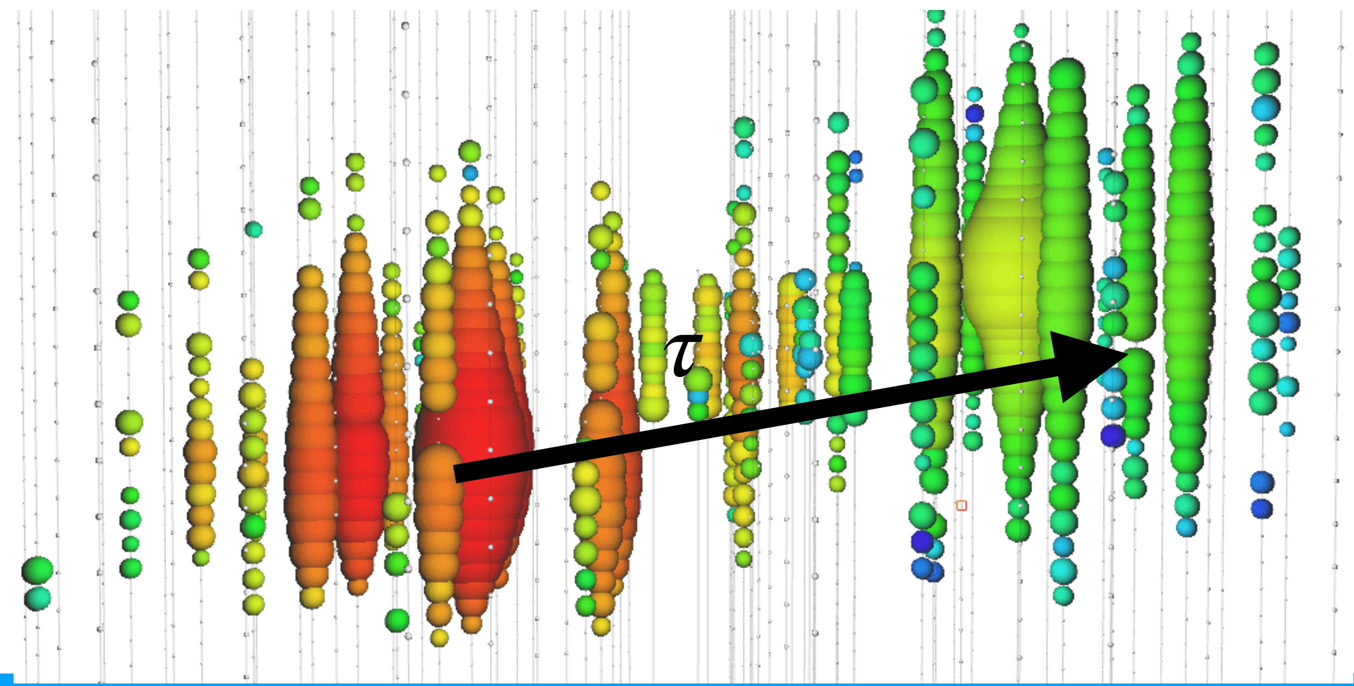
Tracks



Cascades



Double-Bangs

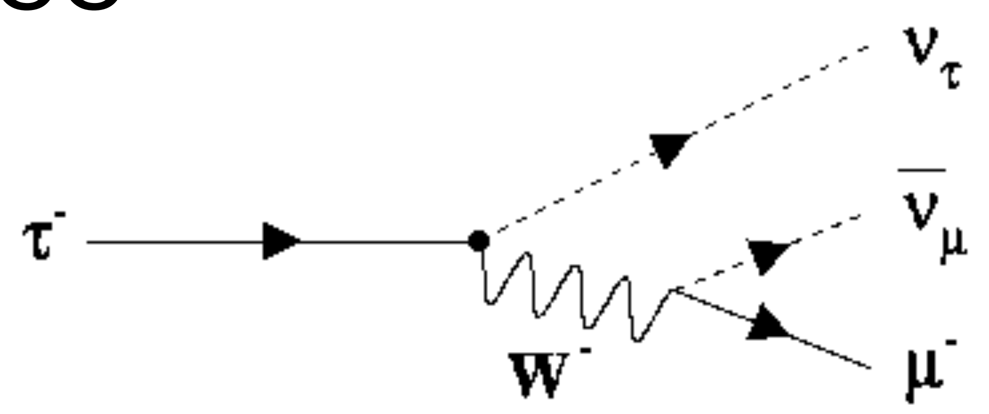


Through-going Muons

IceCube has measured the astrophysical muon-neutrino flux

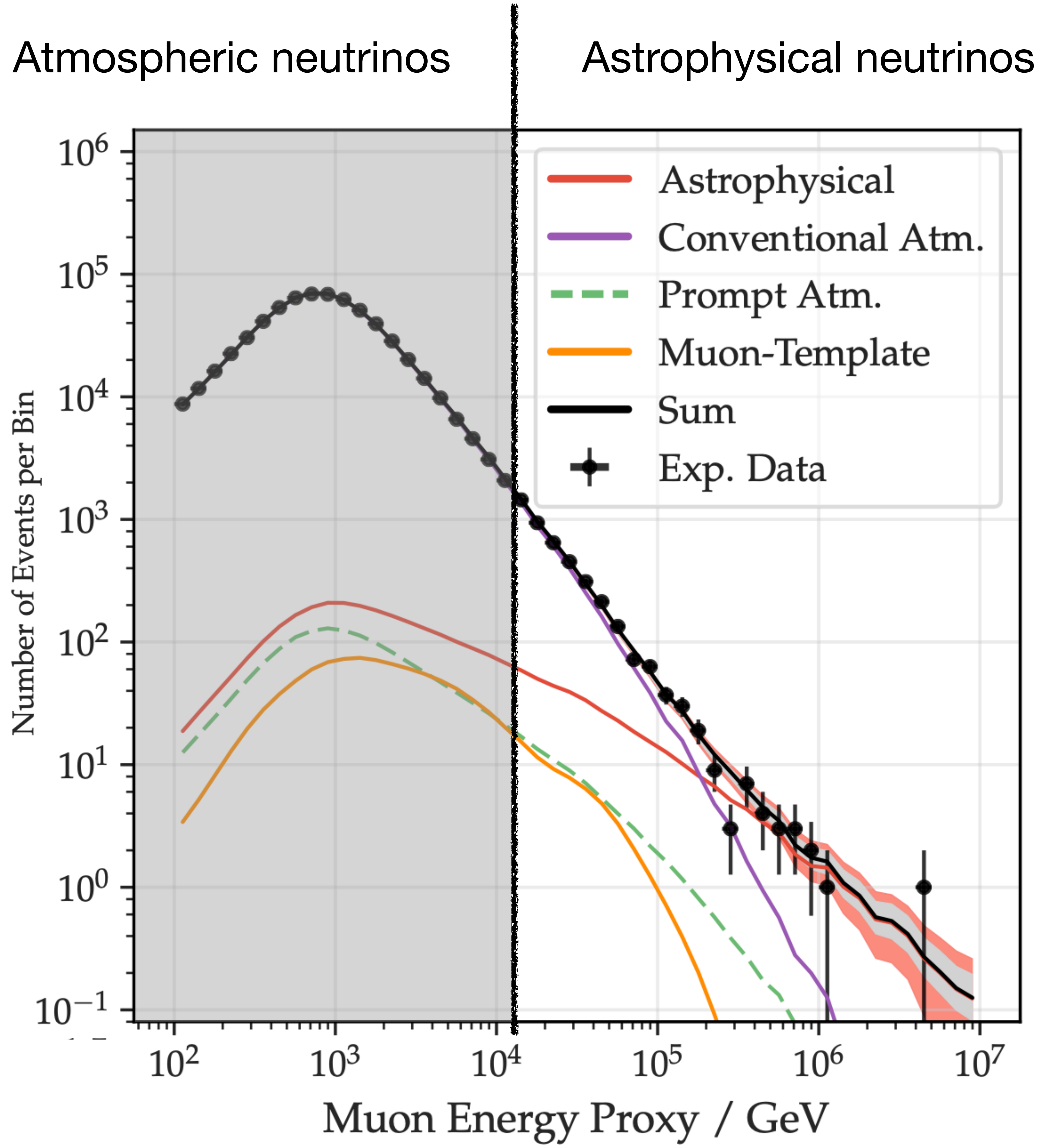
- It includes both starting and through-going samples.

- 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 ($\theta_{zenith} > 85°$)

- The energy range considered is 15 TeV to 5 PeV

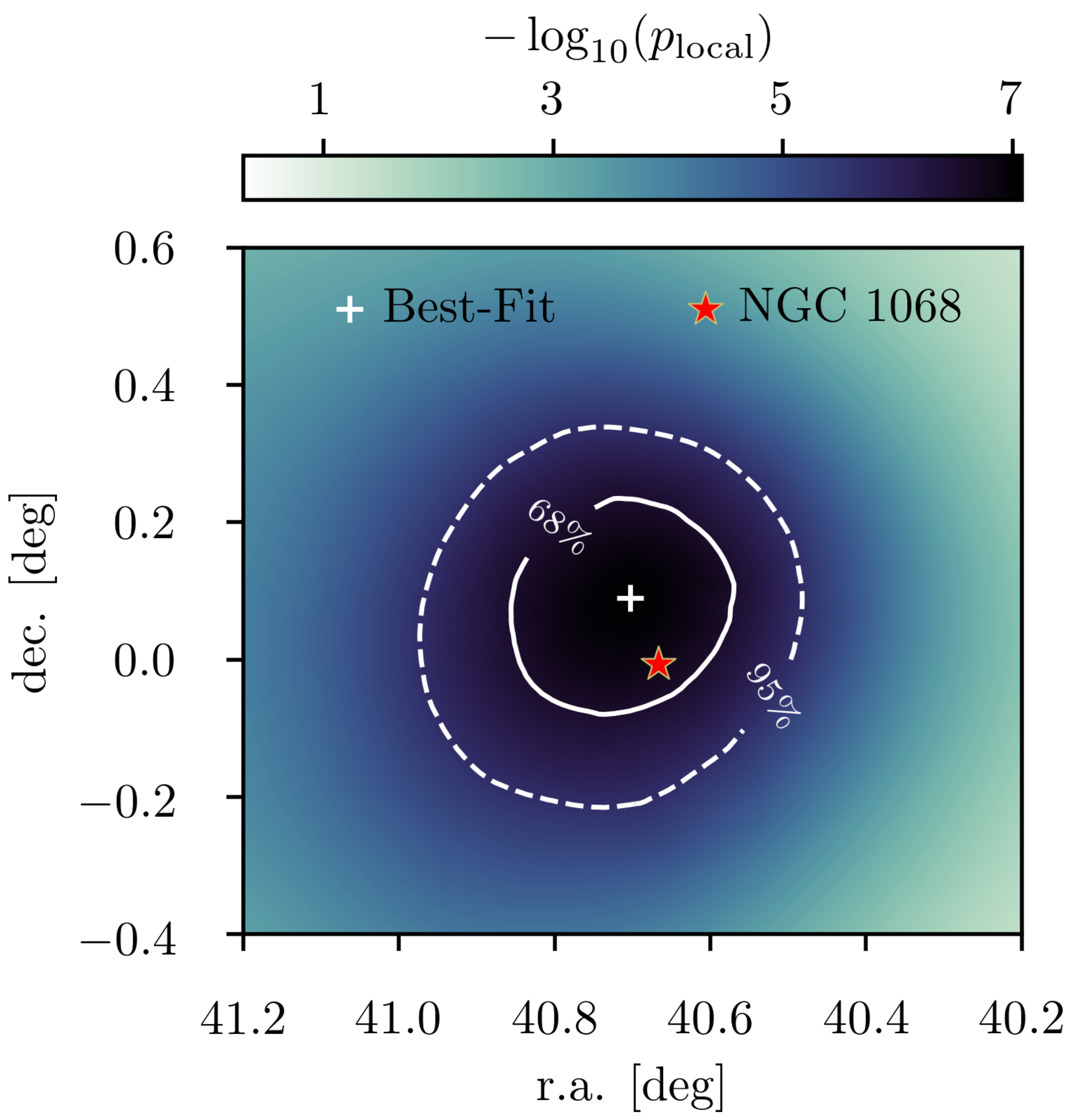


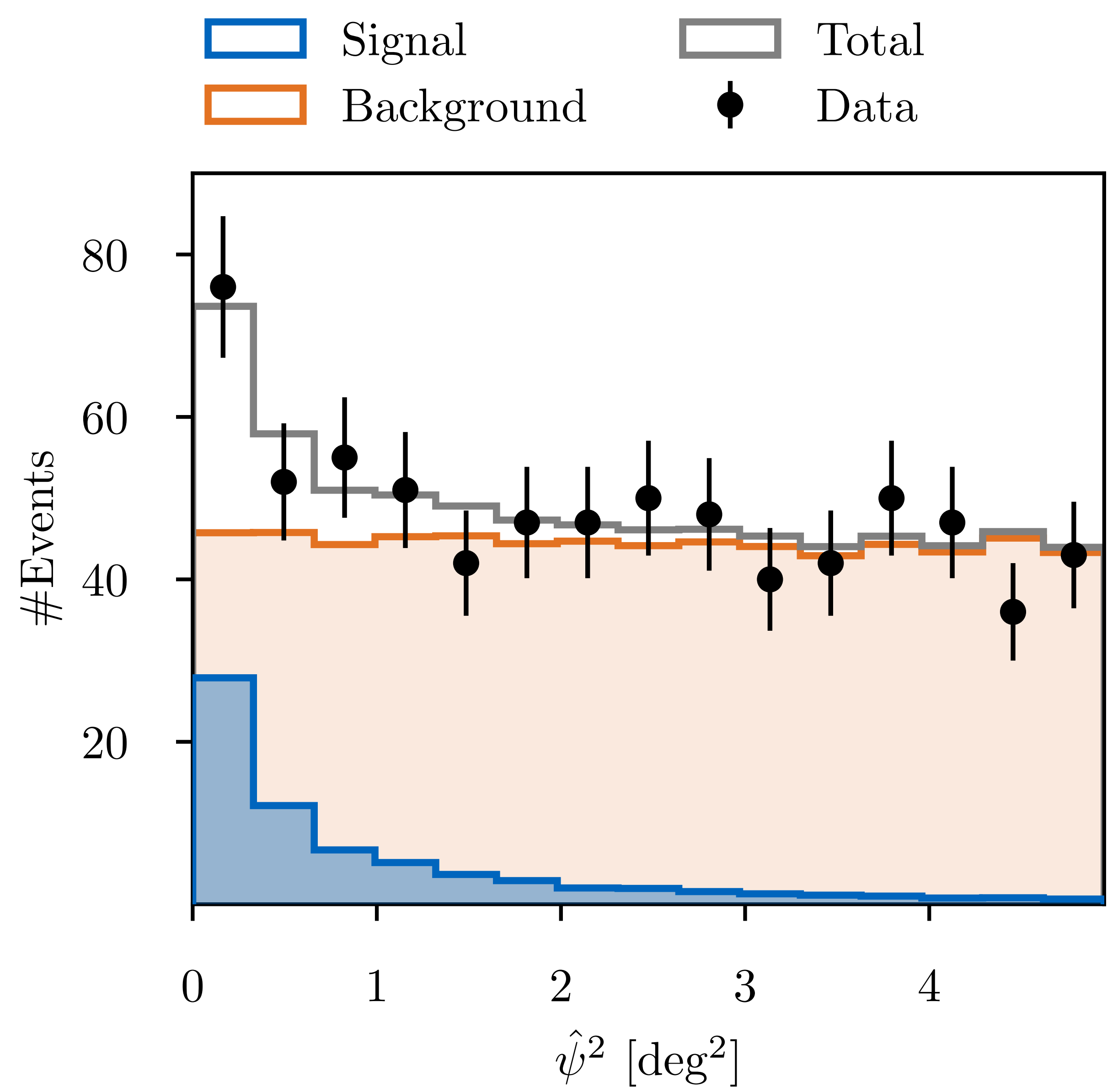
R. Abbasi, et al. (IceCube), Astrophys.J. 928 (2022) 1, 50

Point Sources

Further away from our galaxy, 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





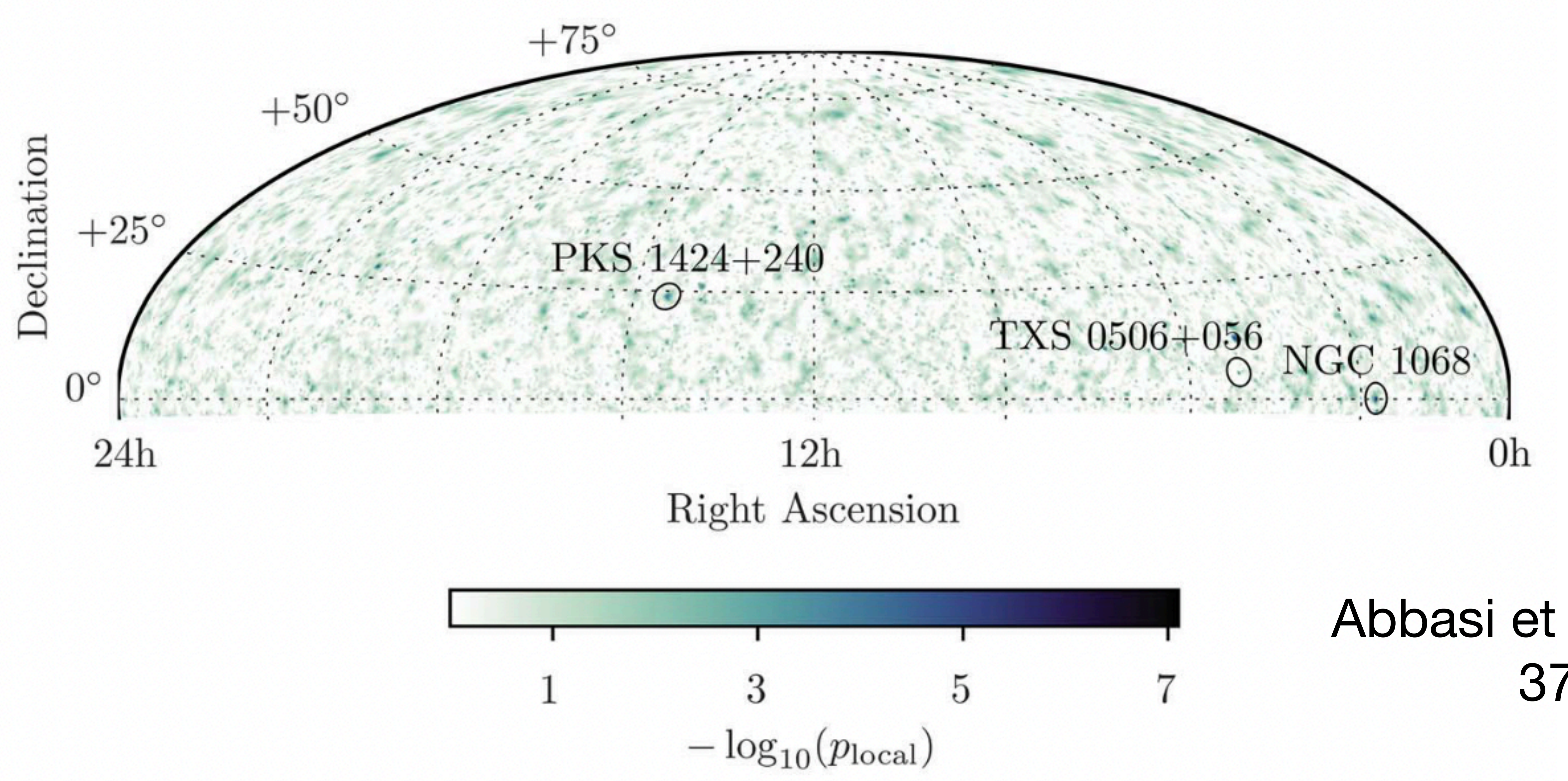
Abbasi et al. (IceCube) Science 378, 538 (2022)

Point Sources

Beyond NGC 1068, IceCube has identified more candidate sources

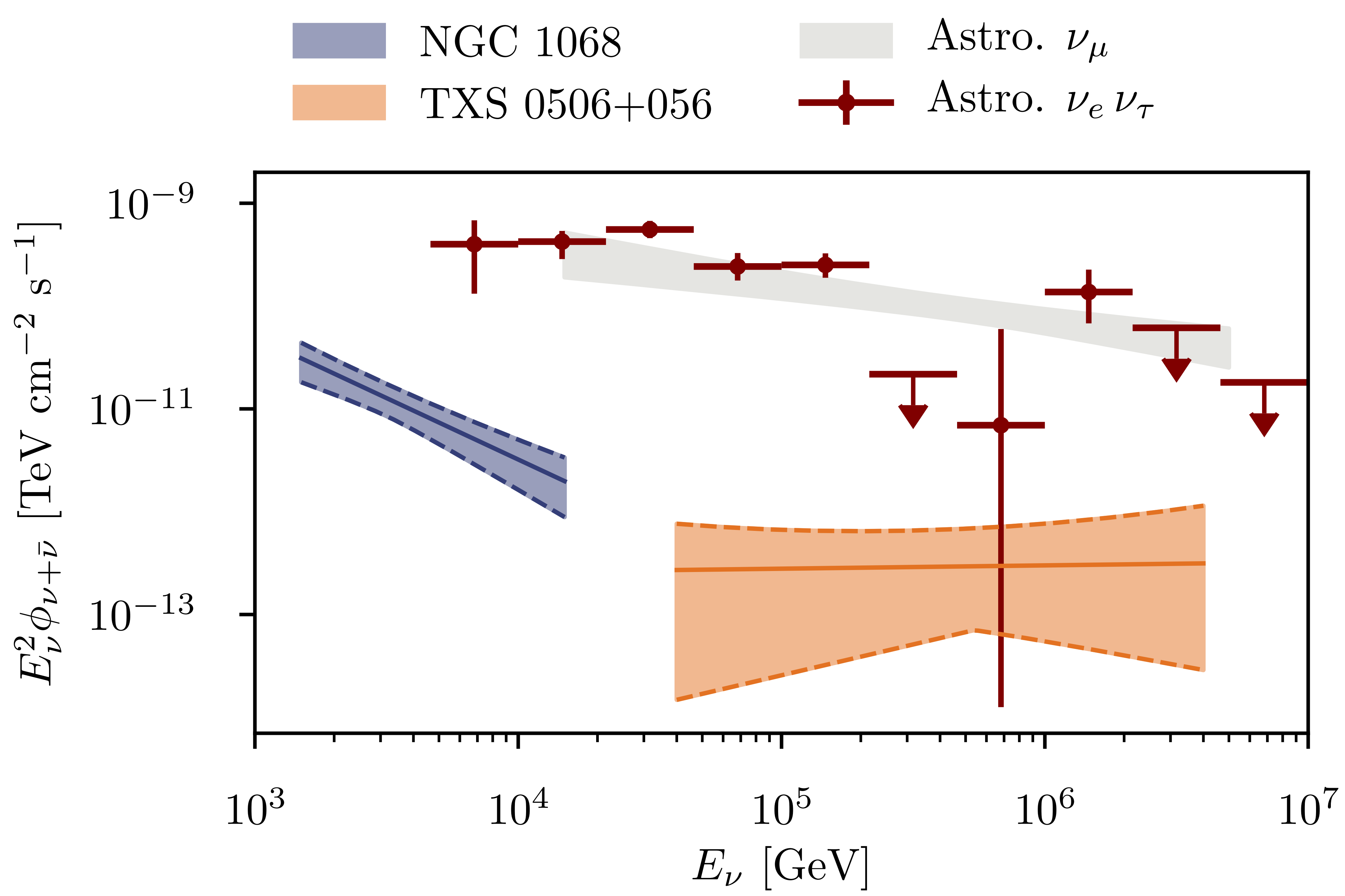
The most significant point sources

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



Abbasi et al. (IceCub
378, 538 (202

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



Knowing the energy, flavor, and travel distance of these neutrinos opens up the possibility to explore their fundamental properties

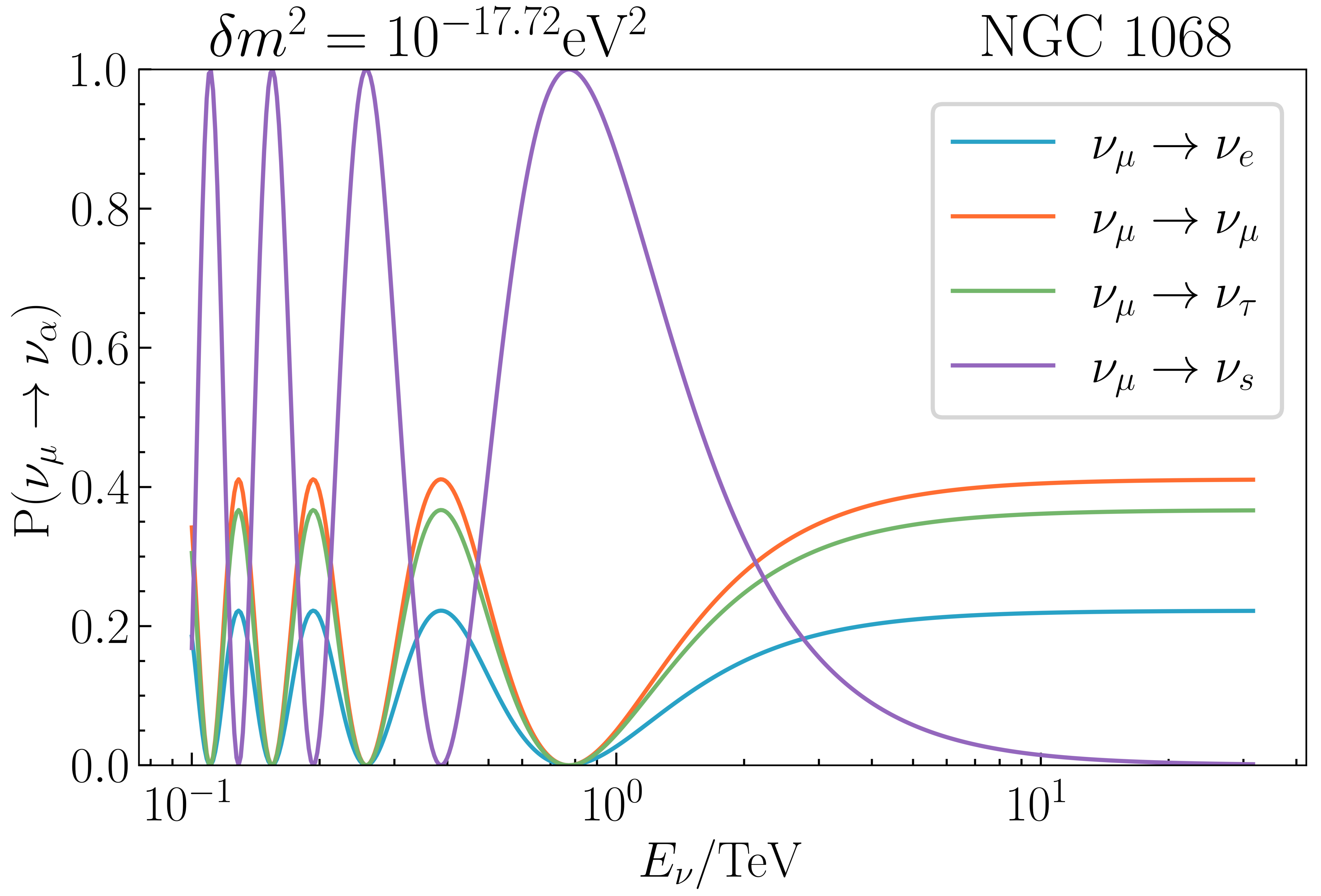
Pseudo-Dirac neutrinos

To explain the origin of the neutrino masses, the SM can be extended by adding right-handed neutrinos

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

In case that the Majorana mass is smaller than the Dirac mass term

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j} (\nu_{js} + i \nu_{ja}) \qquad \delta m^2 \sim M_D M_R$$

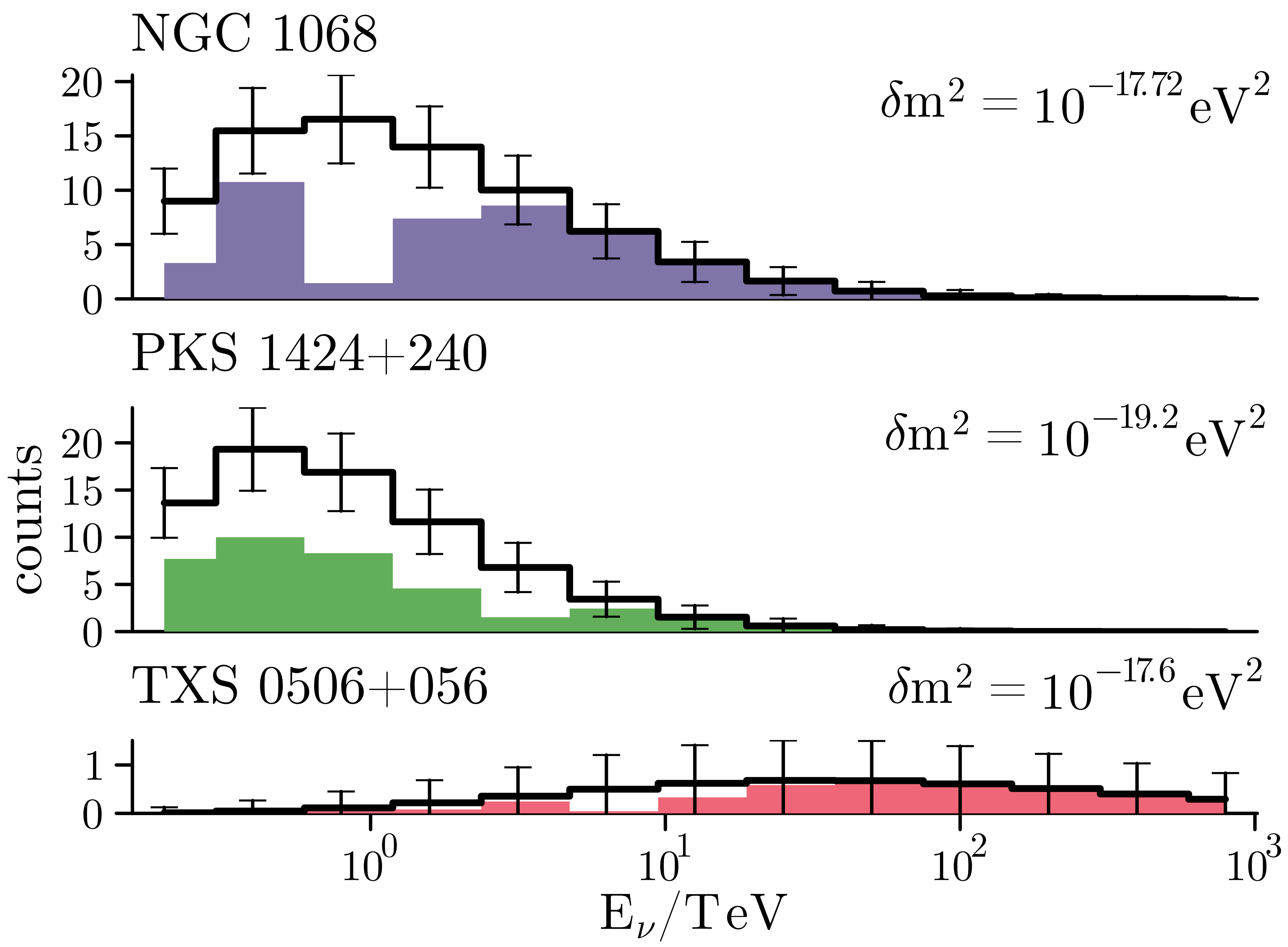


An oscillation between active and sterile neutrinos could happen over astrophysical scales

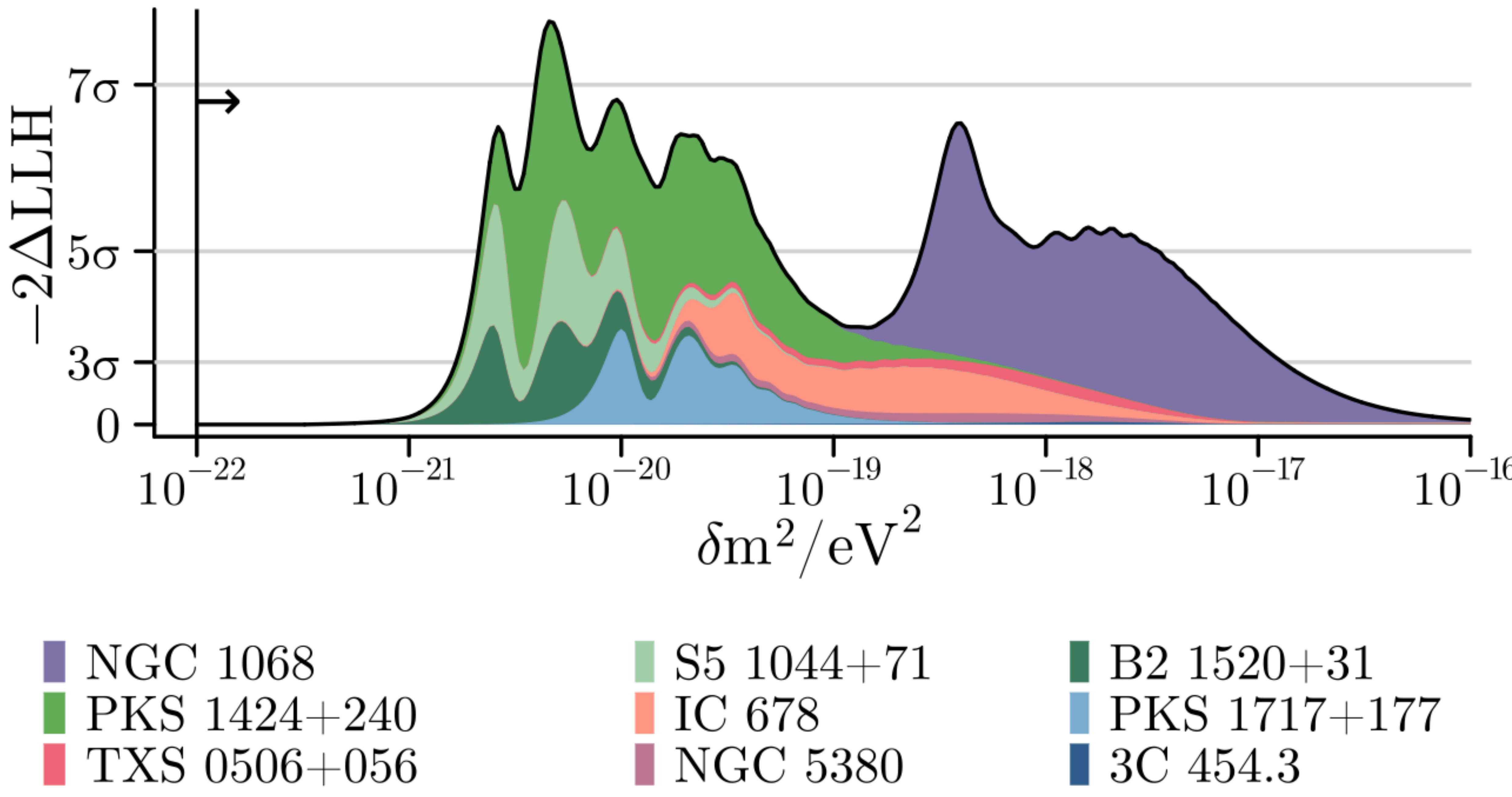
Pseudo-Dirac neutrinos

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.



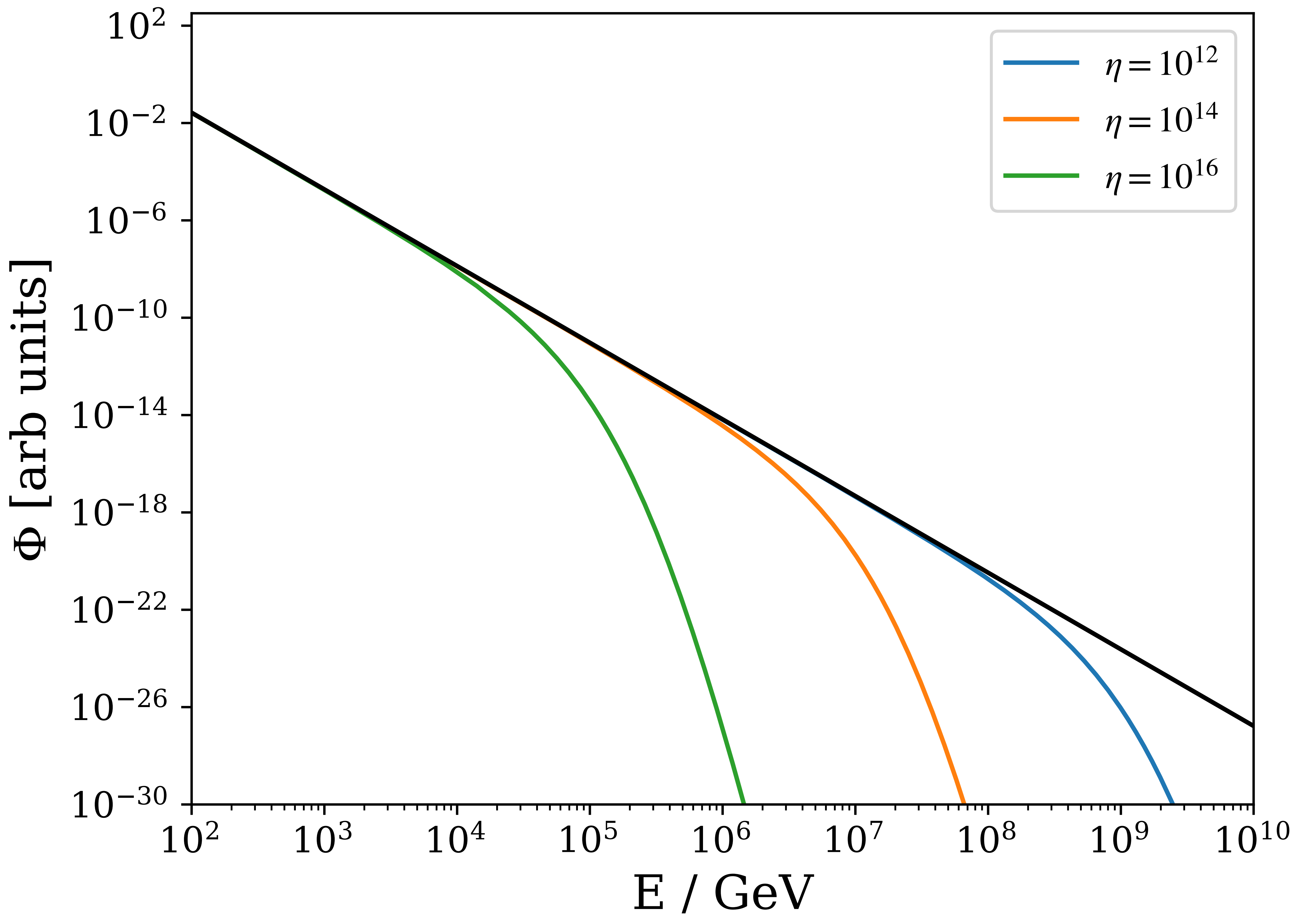
Carloni, Martinez-Soler, Arguelles, Babu, Bhupal, PRD 109 (2024) L051702

Astrophysical Neutrinos and CνB

On their way to the Earth, astrophysical neutrinos must pass through a large flux of CνB neutrinos

In case of large overdensities of the CνB, astrophysical neutrinos can interact with it

- The scattering with the CvB suppresses the astrophysical neutrino flux
- Considering only the SM, large overdensities are needed



Jack Franklin, IMS Yuber F. Perez-Gonzalez, and Jessica Turner, PLB 867 (2025)

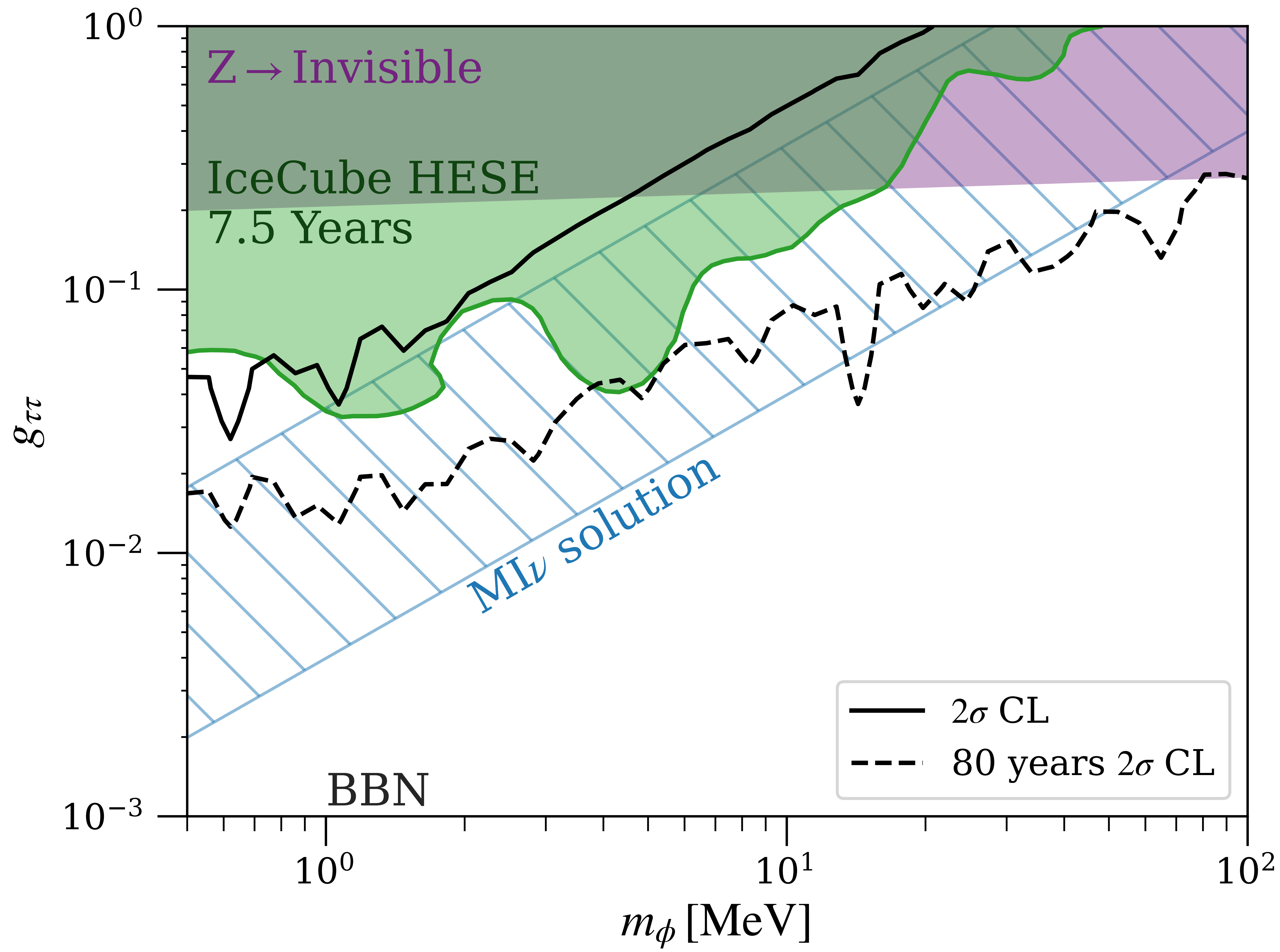
Astrophysical Neutrinos and CνB

In the case of neutrinos-non standard interactions, the astrophysical neutrino flux will also be suppressed

Considering a scalar interaction between the neutrinos

$$\mathscr{L} \supset \frac{1}{2} g_{\alpha\beta} \phi \nu_\alpha \nu_\beta$$

- The coupling between ν_τ can alleviate the H_0 tension
- Gen2 will be able to probe a large phase space

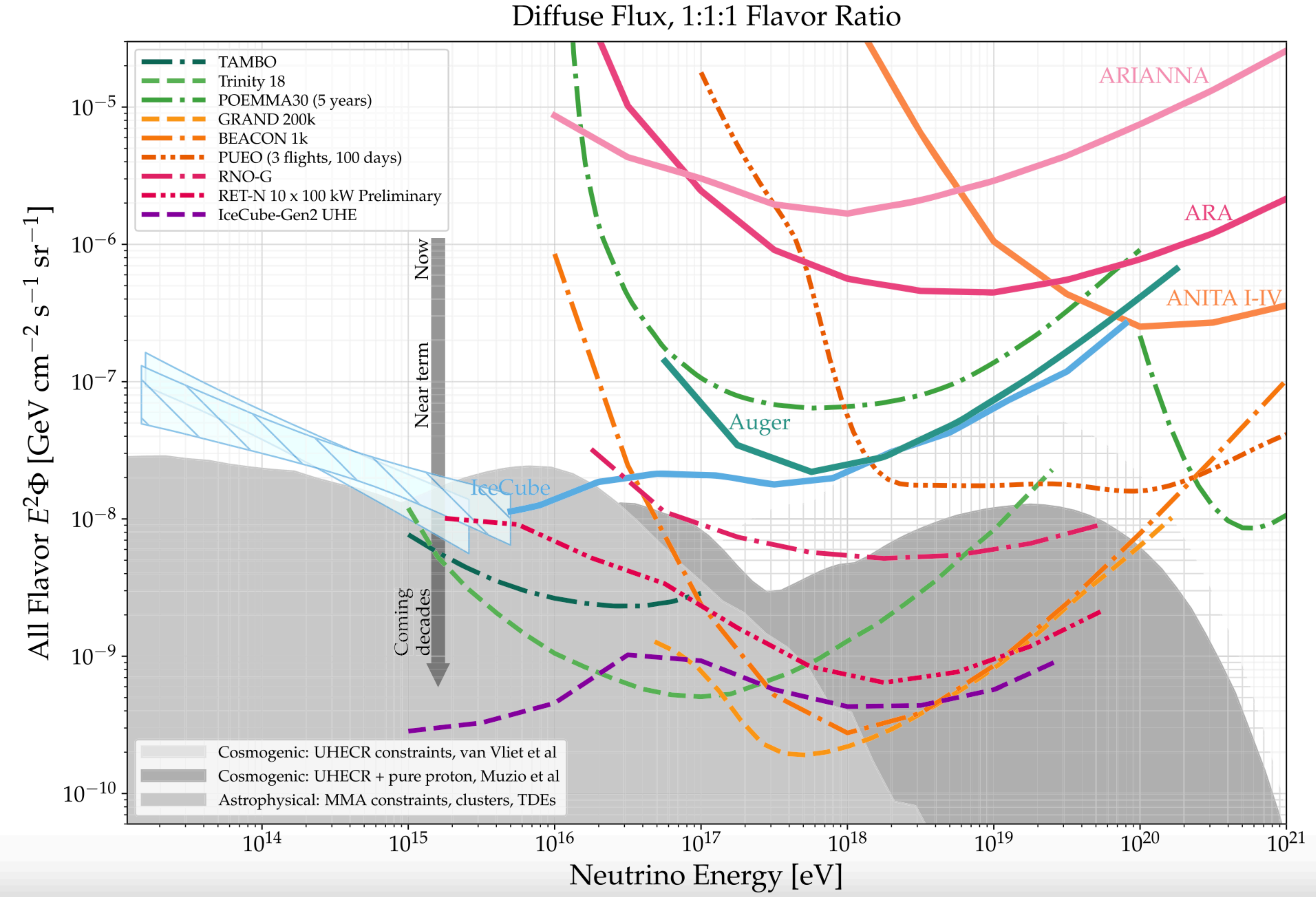


Jack Franklin, IMS, Yuber F. Perez-Gonzalez, and Jessica Turner, PLB 867 (2025)

Beyond the PeV Scale

Several experiments are already looking for GZK neutrinos or they will do it in the near future.

- At the EeV scale, neutrinos are expected from cosmic rays (CRs) interaction with CMB photons (GZK neutrinos)
- IceCube/Gen-2, Trinity, ANITA/PUEO, …
- Many of these experiments are not underground



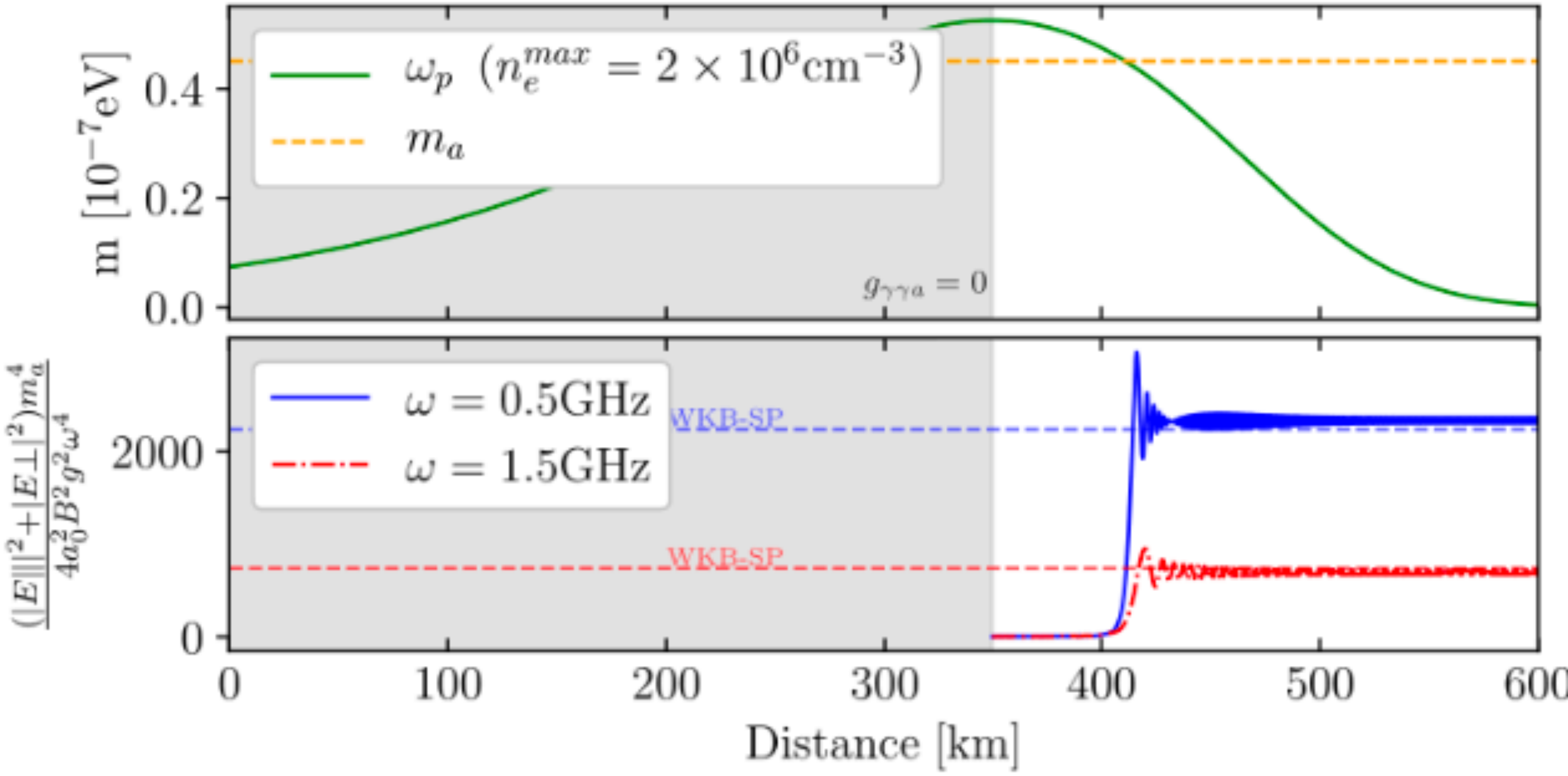
Snowmass 2021

ALPs

Axions were proposed to address the strong CP problem, but they can solve various other questions in physics

$$\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

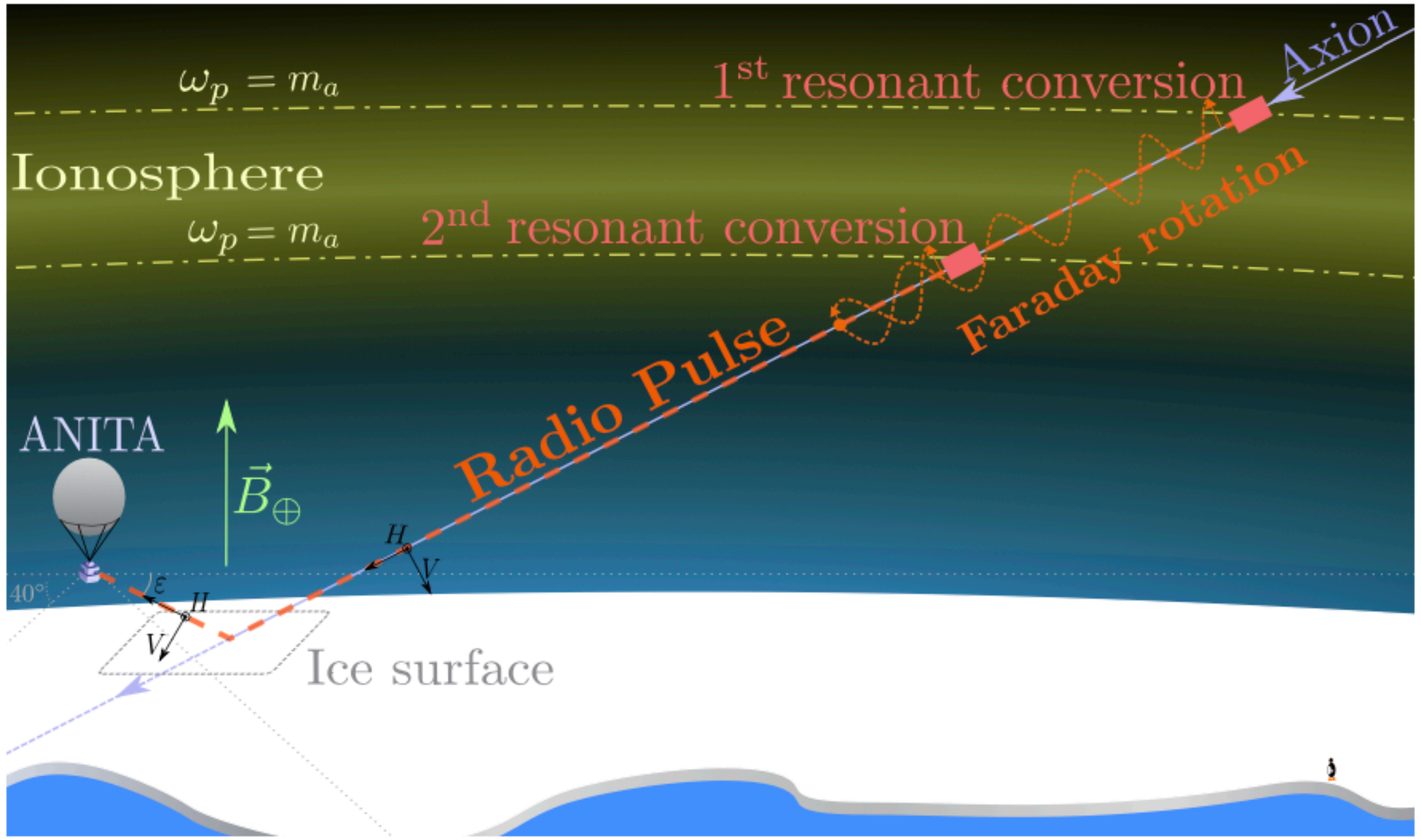
In the presence of a magnetic field (B), axions can undergo a resonant conversion into photons when the plasma frequency matches the axion mass.



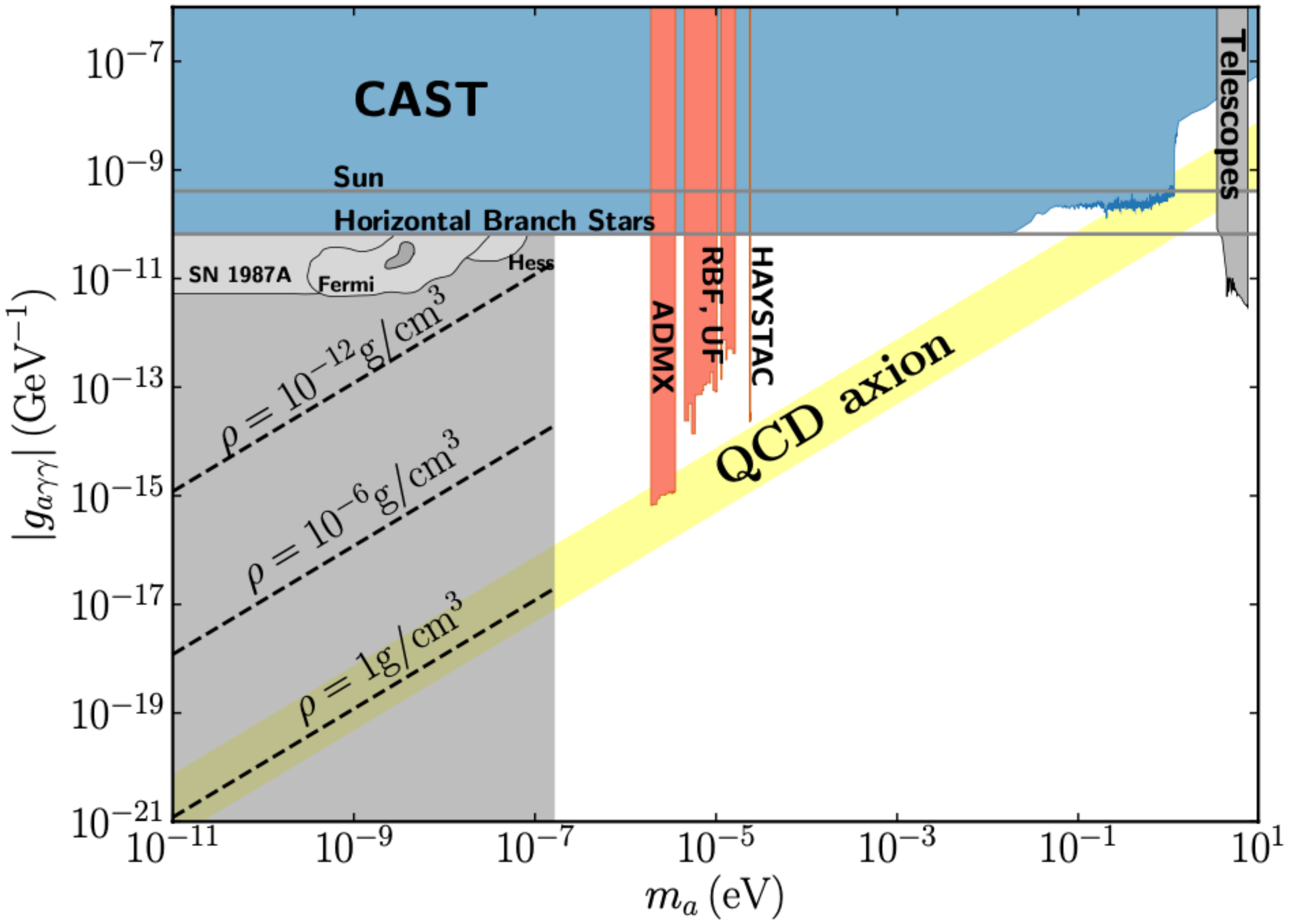
I Esteban, J Lopez-Pavon, IMS, J Salvado, EPJC 80 (2020) 3, 259

ALPs

The interaction of an axion flux with $B_\oplus$ can generate a polarized radio pulse



Range of masses and couplings that can explain the two anomalous events observed by ANITA



I Esteban, J Lopez-Pavon, IMS, J Salvado, EPJC 80 (2020) 3, 259

Conclusions

- **Neutrino telescopes** have already detected astrophysical neutrinos, and these measurements can provide valuable insights into **neutrino properties.**

- To fully extract information about neutrinos, we need to consider all available observables, such as **energy, travel distance, and flavor.**

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

- The **vast distances** covered by these neutrinos opens up the possiblity to search for NSI

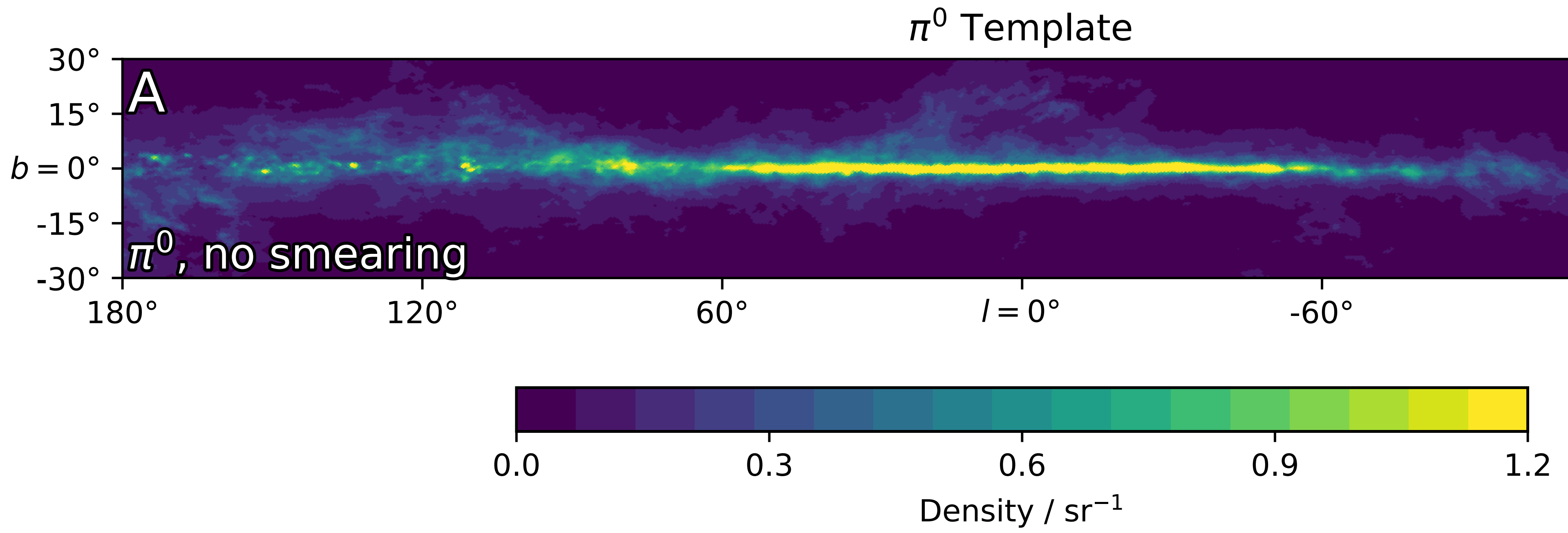
- Beyond neutrinos, neutrino telescopes can also be used to search for other BSM scenarios such as ALPs, among others.

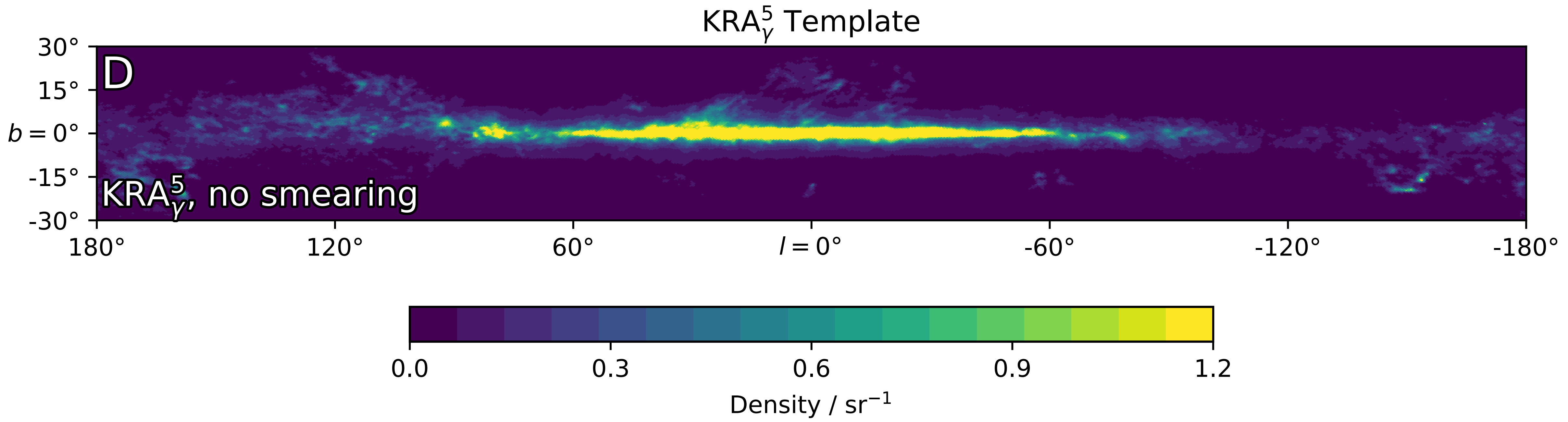
Thanks!

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.





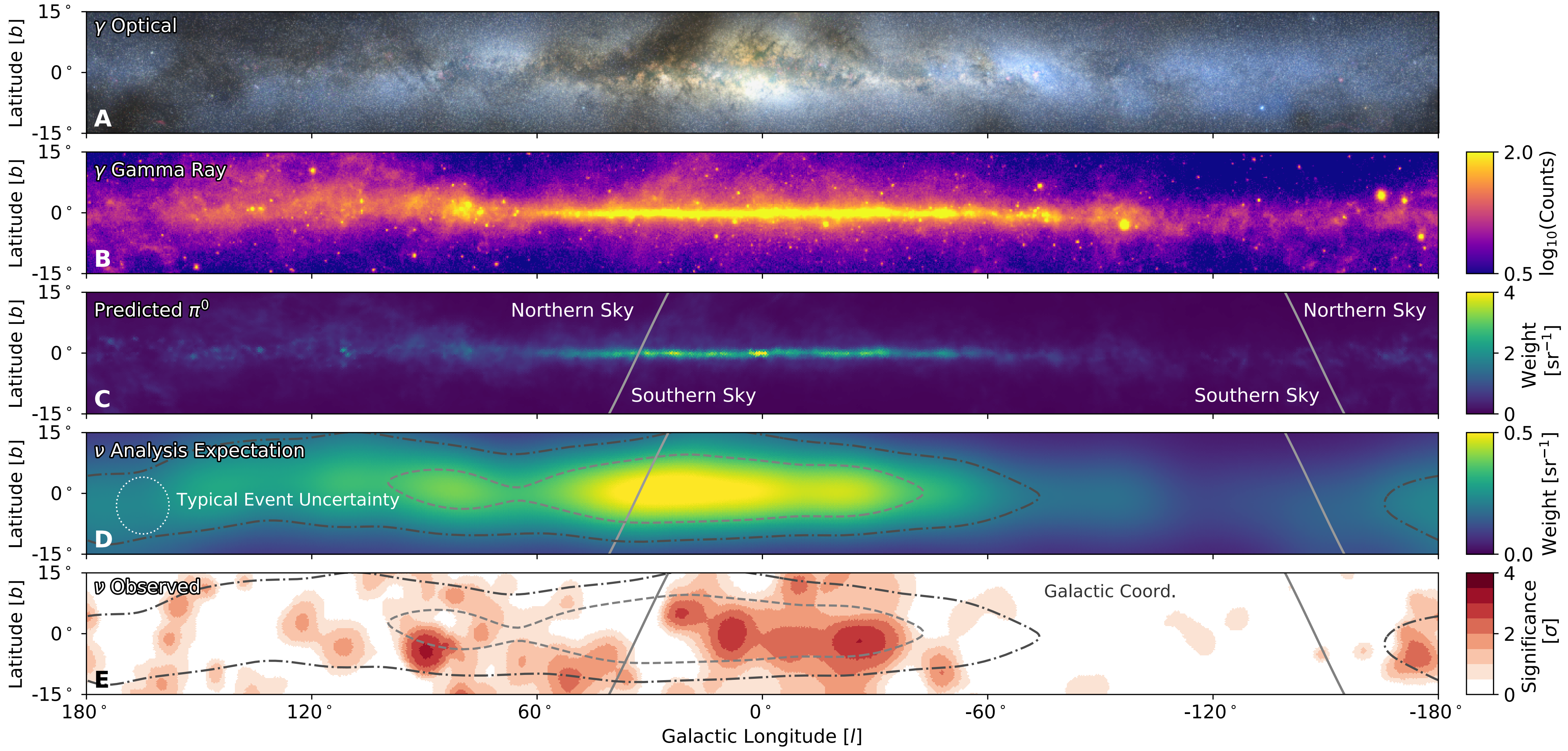
IceCube, Science 380 (2023) 1338

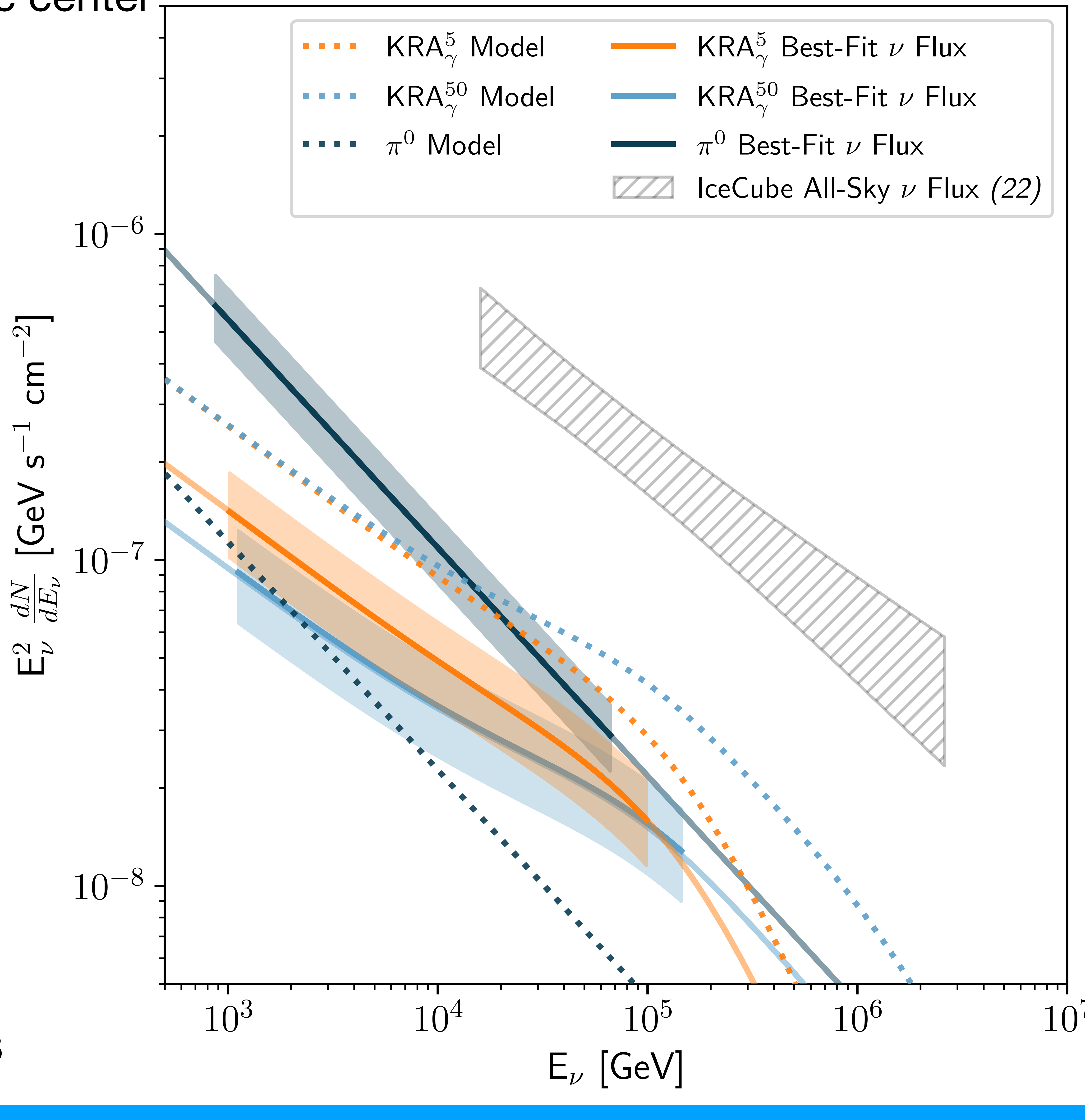
Galactic Plane

In our galaxy, the highest emission is expected near to the galactic center

- 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

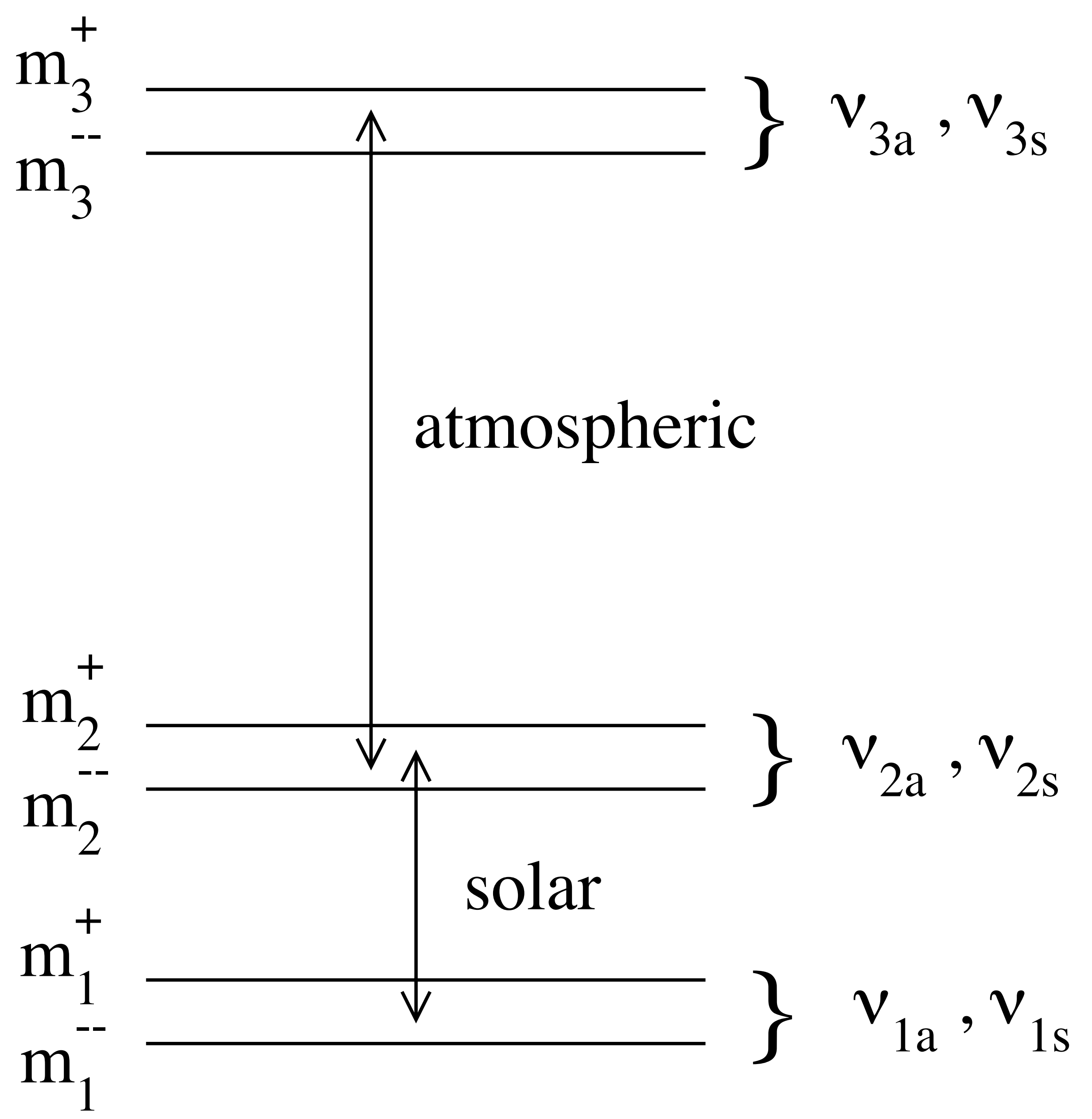
Pseudo-Dirac neutrinos

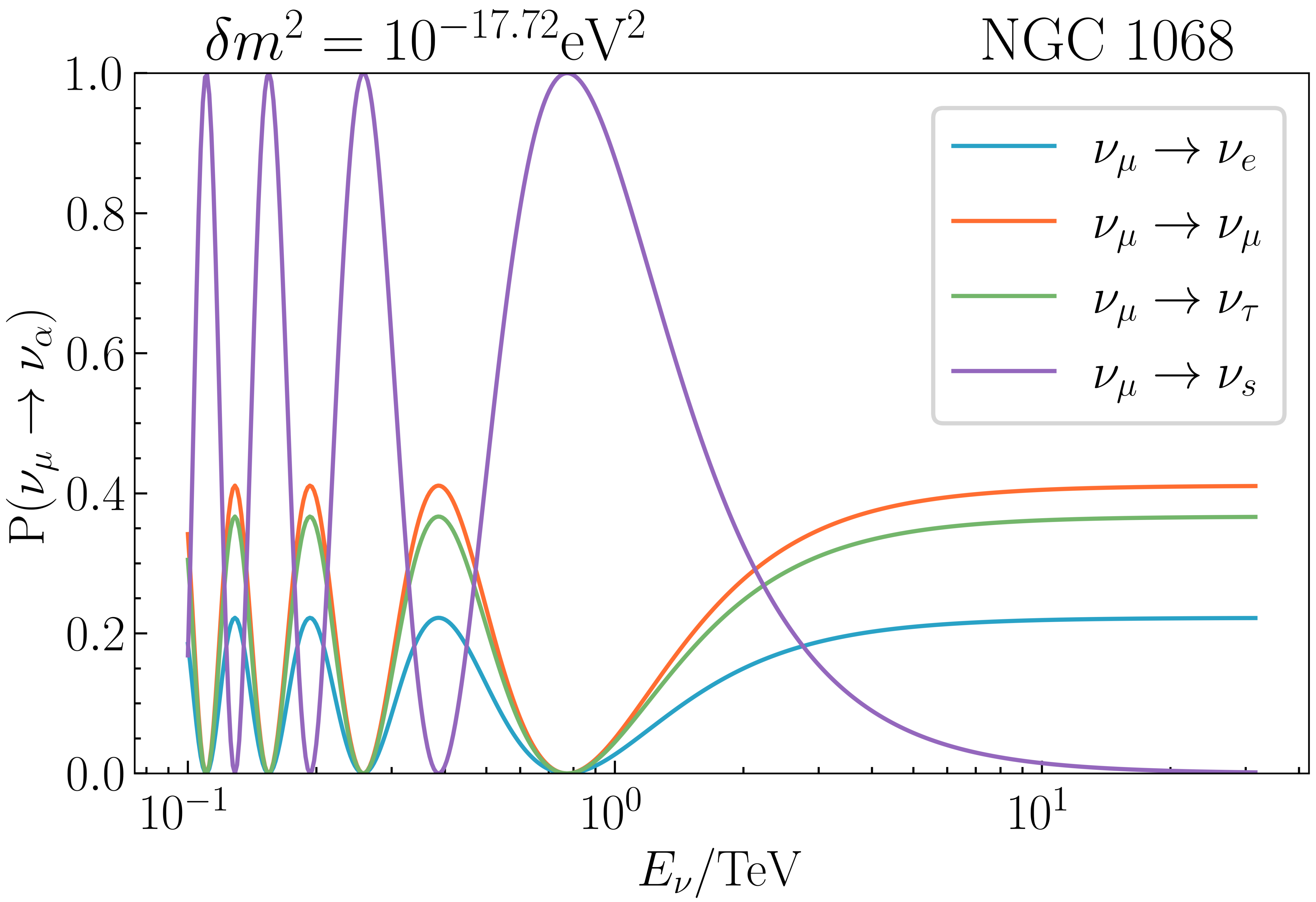
In the scenario where $M_R << M_D$ the active neutrinos can be written as a superposition of two massive states

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

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

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





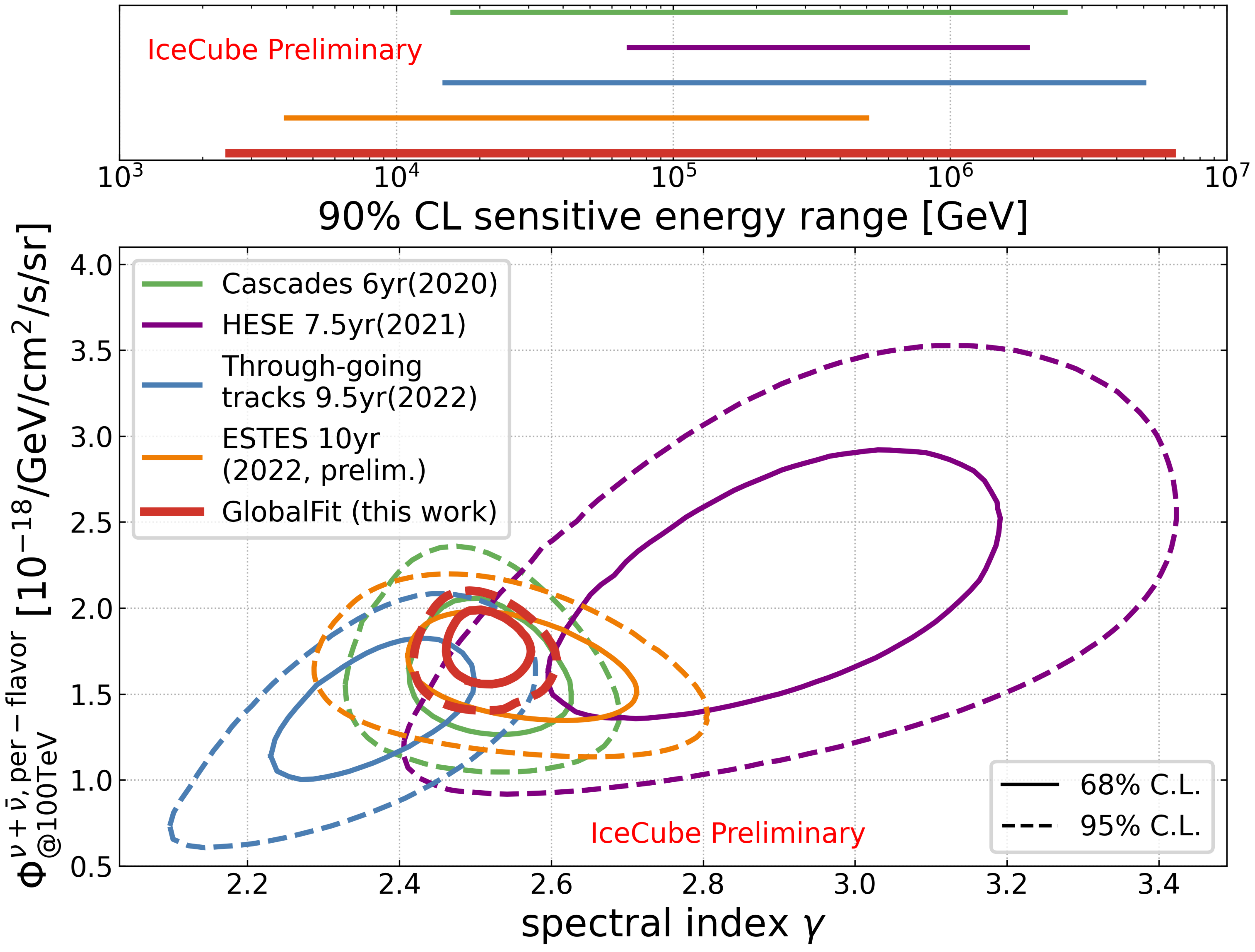
Ivan Martinez-Soler (IPPP)

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

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

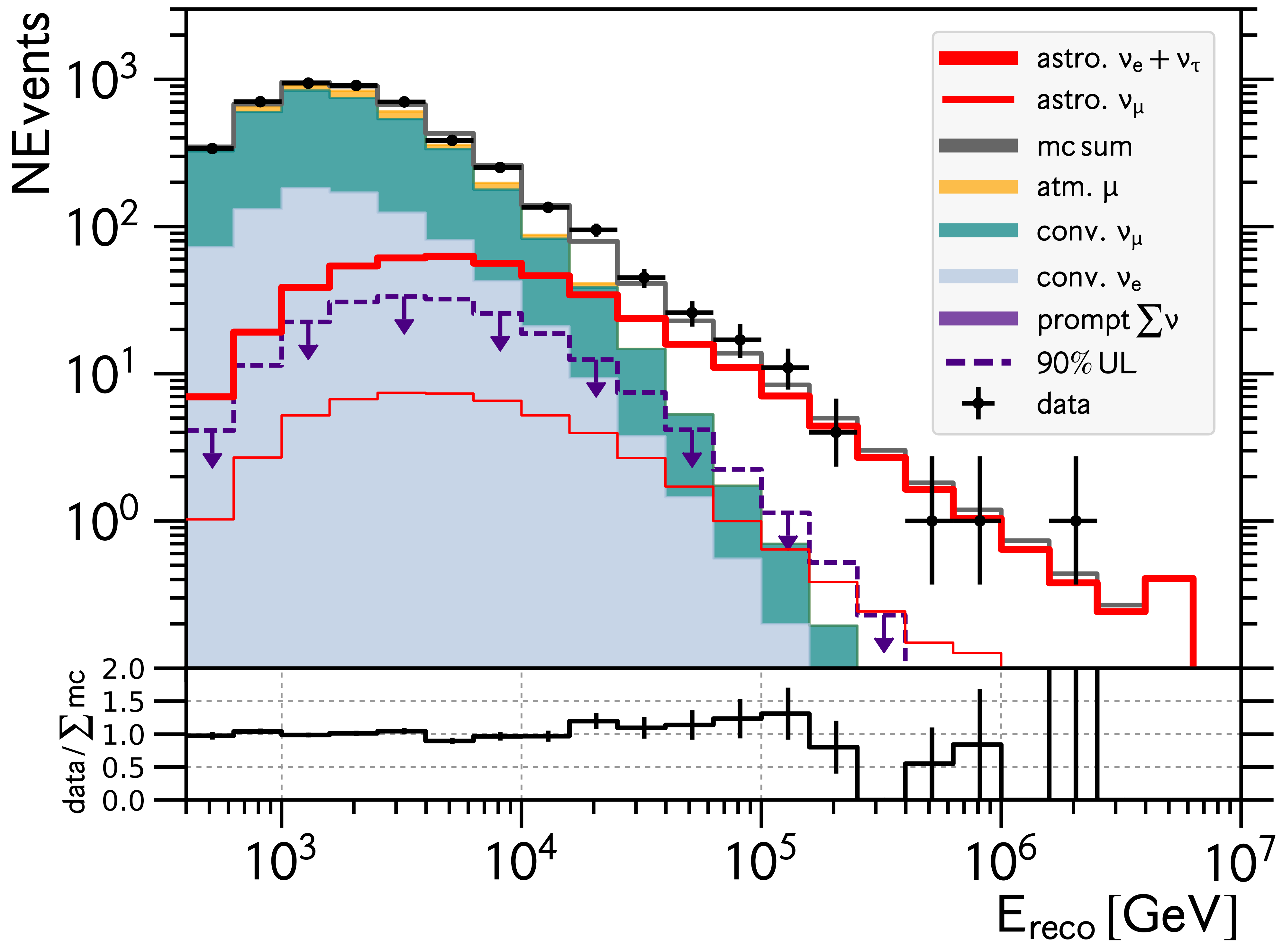


R. Naab, E. Ganster and Z. Zhang (IceCube), PoS(ICRC2023) 1064

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)