

TeVPa, August 31th, 2026

Signatures of Quasi-Dirac Neutrinos in Neutrino Telescopes

Carlos Argüelles

In collaboration with Rafael Alves Batista, K. S. Babu, P.S. Bhupal, Kiara Carloni, Sudip Jana, Miller MacDonald, Ivan Martínez-Soler, Yago Porto

Based on *Phys.Rev.D* 109 (2024) L051702, *Phys.Rev.D* 113 (2026) 11, 115004, and arXiv:2512.10744



HARVARD
UNIVERSITY



The NSF Institute for
Artificial Intelligence and
Fundamental Interactions



**JOHN
TEMPLETON**
FOUNDATION

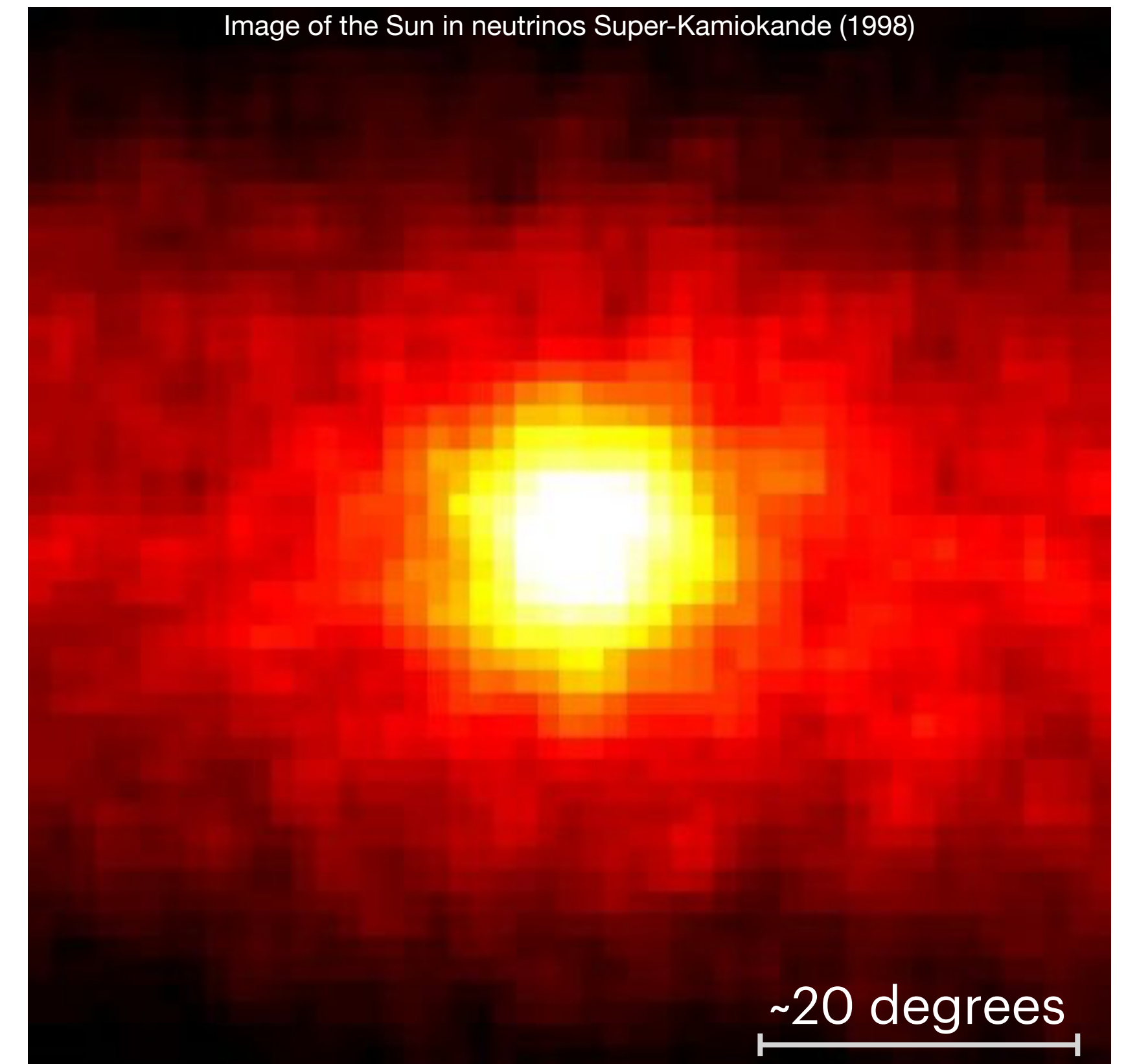
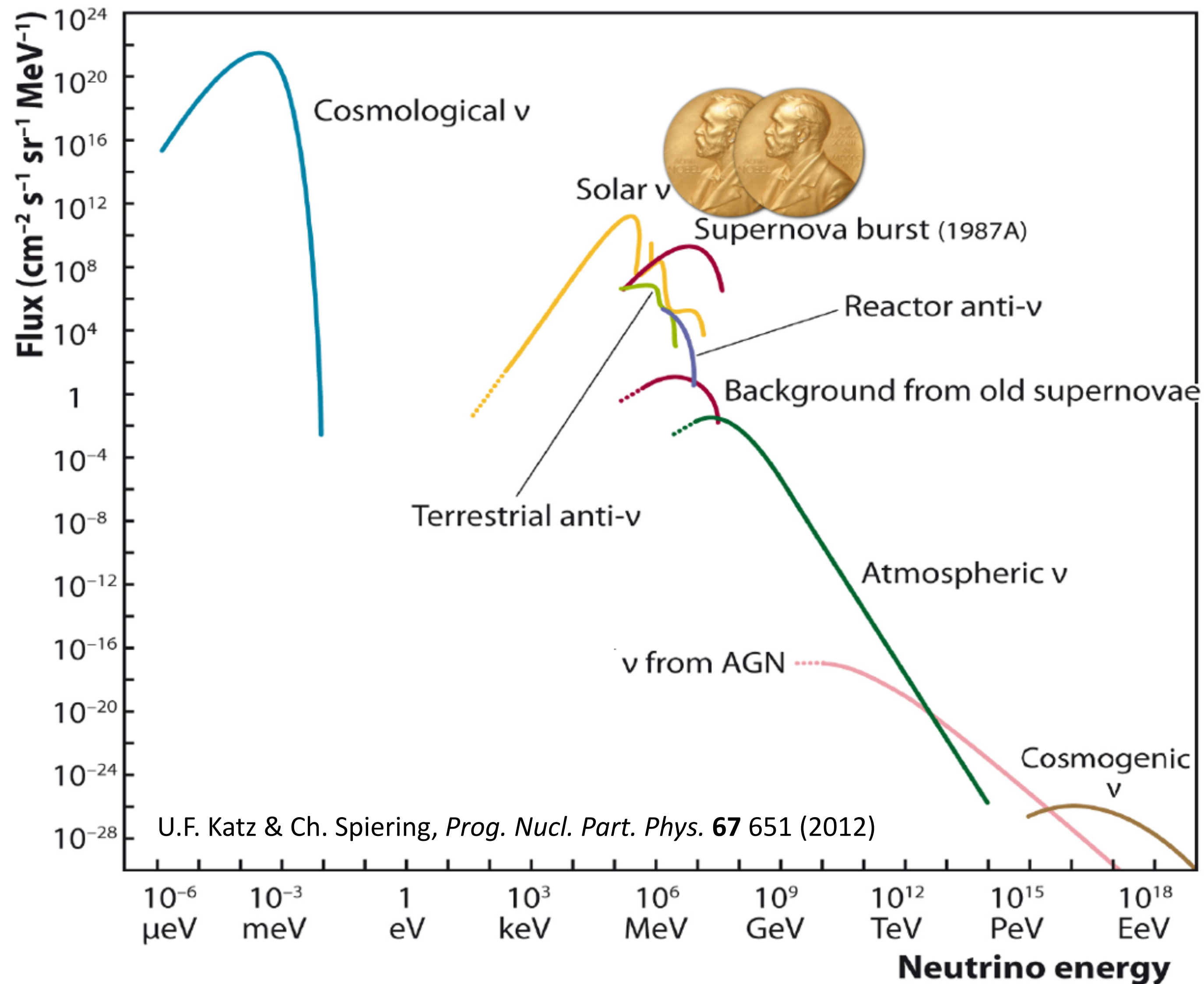


RESEARCH CORPORATION
for SCIENCE ADVANCEMENT

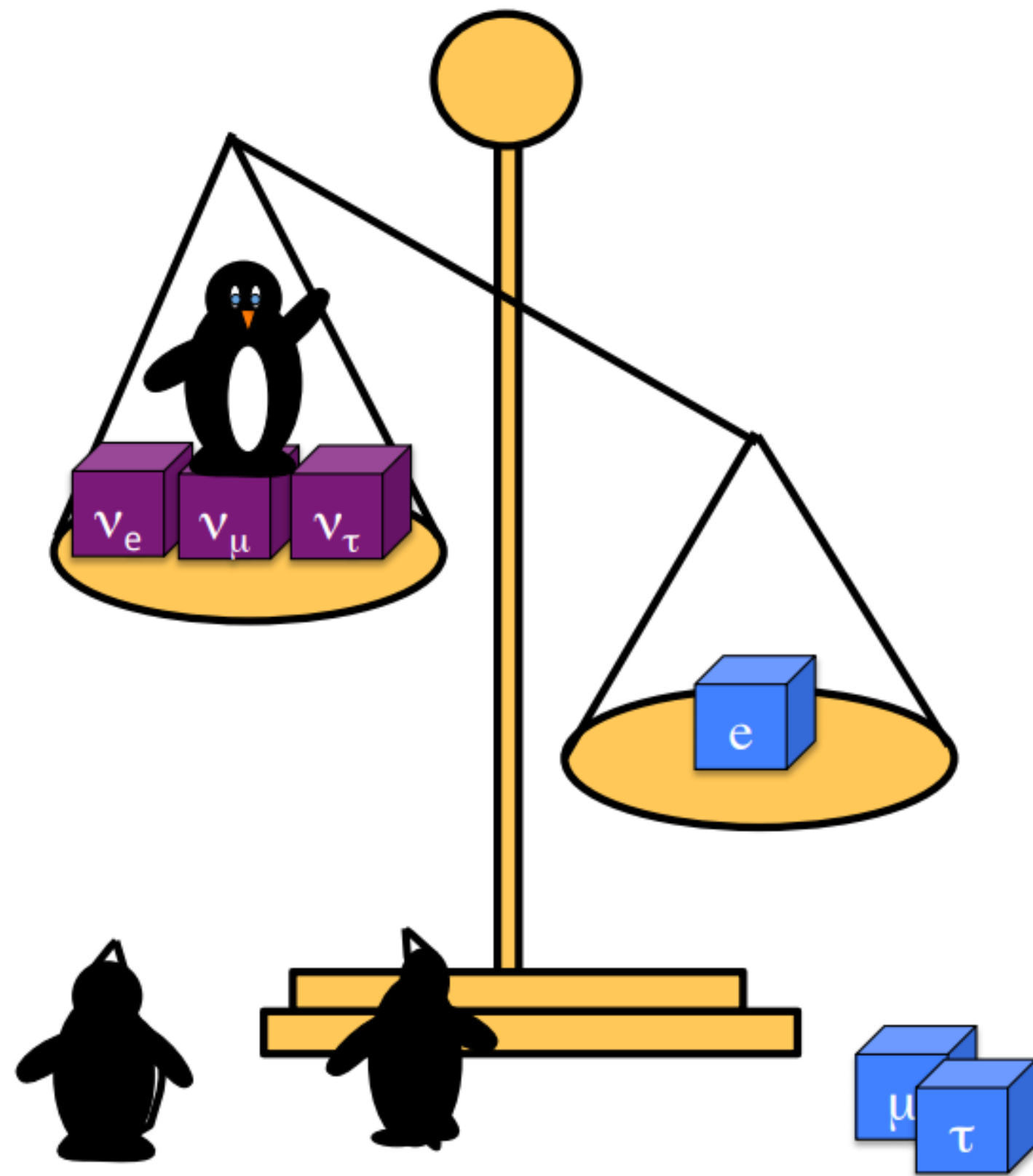


the David
& Lucile **Packard**
FOUNDATION

The nature of neutrino masses is one of the biggest problems in particle physics.



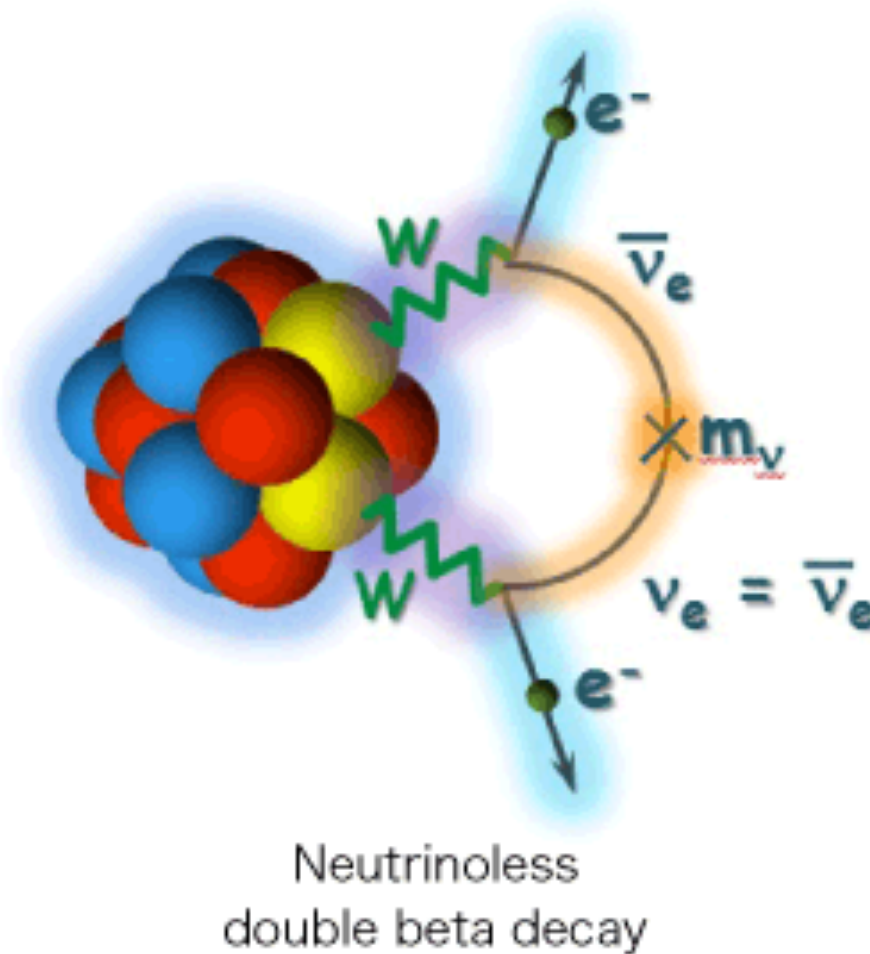
What is the origin of neutrino mass?



Arkani-Hamed et al, 2007
Ooguri & Vafa, 2017
Hamada & Shiu, 2017
Gonzalo, Ibañez, Valenzuela, 2021
Vafa, 2024

Majorana

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

Neutrino
telescopes!

Theory of neutrino masses

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

$$2\mathcal{L}_{\text{mass}} = m_D \overline{N}_R \nu_L + m_D \overline{\nu}_L^C N_R^C + m_R \overline{N}_R^C N_R + \text{h.c.}$$

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

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

Lepton-number breaking
term.

Dirac neutrinos: $M_R = 0$

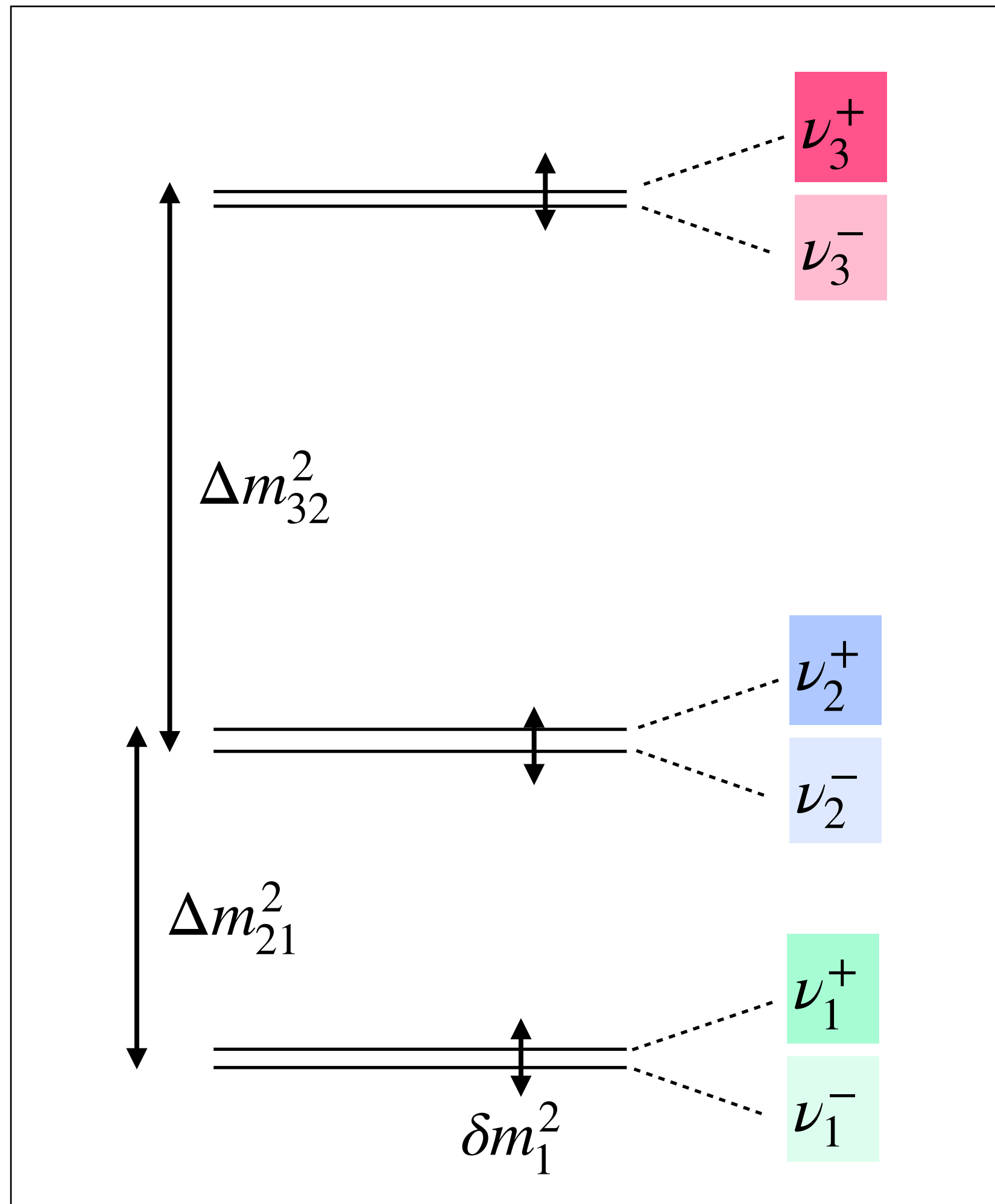
See-saw scenario: $M_R \gg M_D$

Quasi-Dirac scenario: $M_R \ll M_D$

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

Dirac See Saw Scenario: Z. K. Silagadze, *Phys. Atom. Nucl.* 60, 272 (1997); A. S. Joshipura, S. Mohanty, and S. Pakvasa *Phys. Rev. D* 89, 033003 (2014); P.-H. Gu and H.-J. He *JCAP* 12, 010; E. Ma and R. Srivastava *Phys. Lett. B* 741, 217 (2015); J. W. F. Valle and C. A. Vaquera-Araujo *Phys. Lett. B* 755, 363 (2016); S. Centelles Chuliá, R. Srivastava, and J. W. F. Valle *Phys. Rev. D* 98, 035009 (2018); Z. G. Berezhiani and R. N. Mohapatra, *Phys. Rev. D* 52, 6607 (1995), ...

Neutrino hyper-fine mass structure



Hyperfine splitting:

$$\delta m_j^2 \sim 10^{-22} - 10^{-12} \text{eV}^2$$

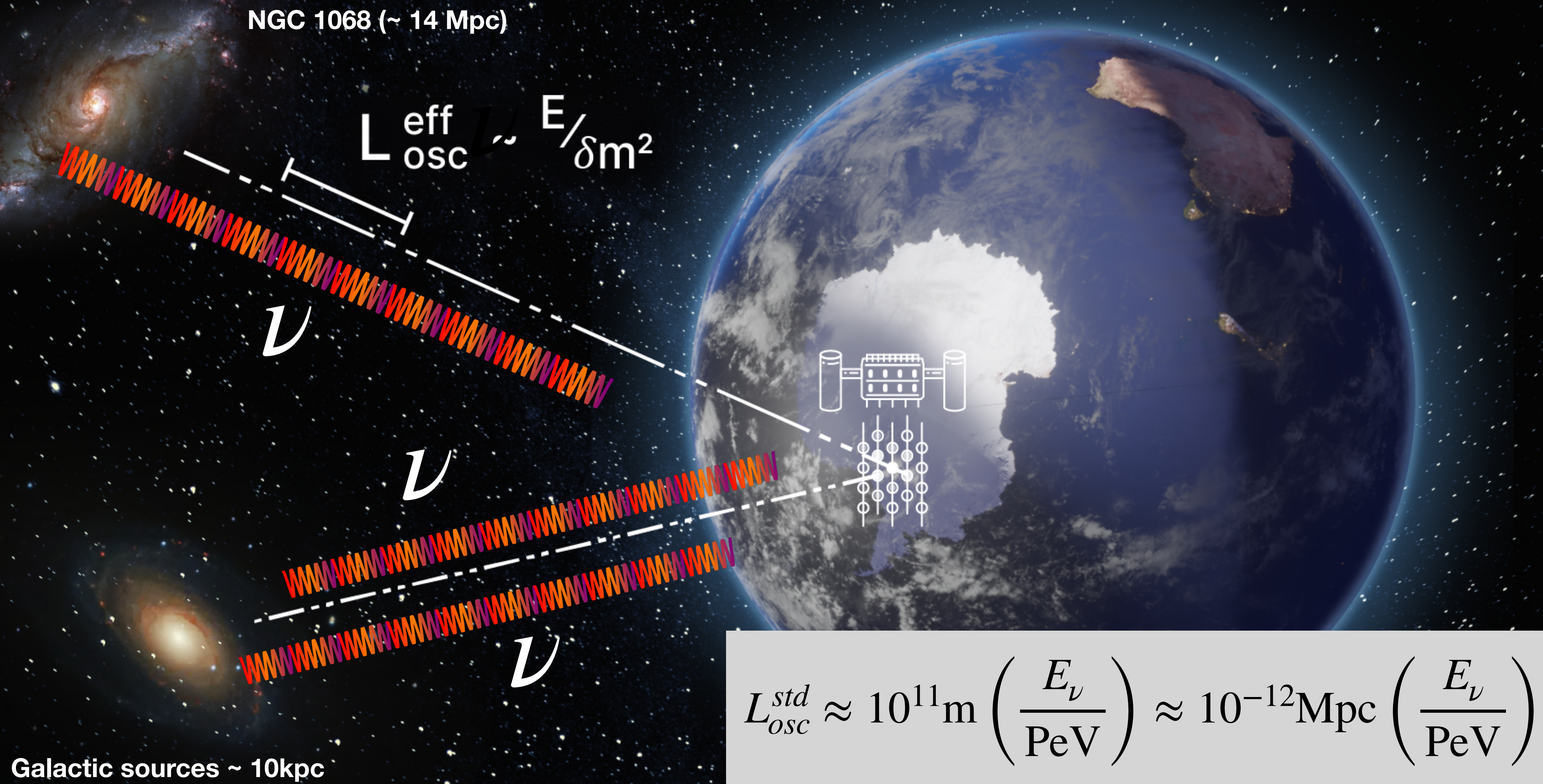
Oscillations from active to sterile neutrinos

$$|\nu_j^\pm\rangle = \begin{array}{cc} \text{active} & \text{sterile} \\ \hline \text{dark bar} & \text{light bar} \end{array}$$

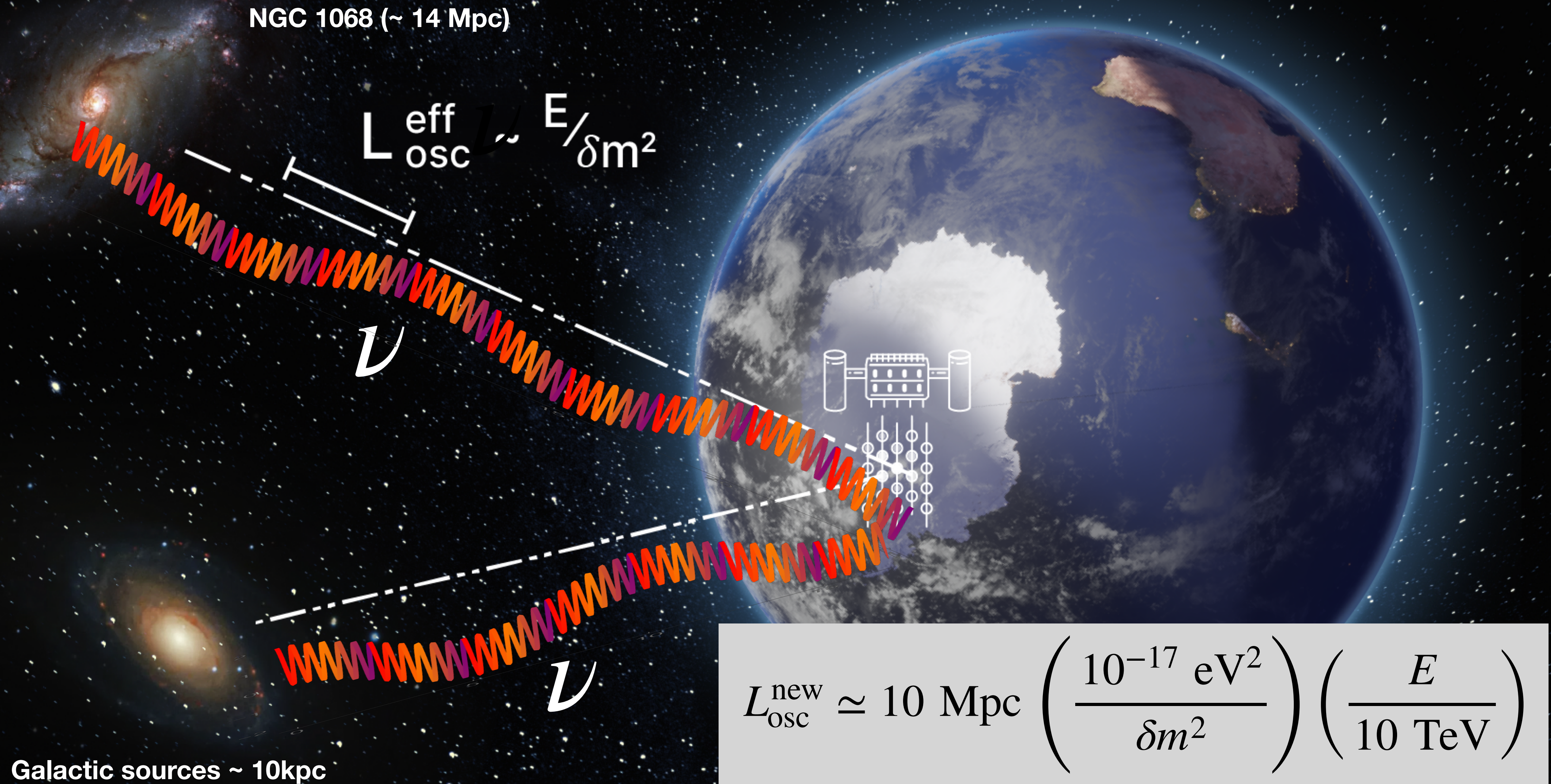
J. W. Valle Phys.Rev.D 28 (1983) 540

Dirac See Saw Scenario: Z. K. Silagadze, *Phys. Atom. Nucl.* 60, 272 (1997); A. S. Joshipura, S. Mohanty, and S. Pakvasa *Phys. Rev. D* 89, 033003 (2014); P.-H. Gu and H.-J. He JCAP 12, 010; E. Ma and R. Srivastava *Phys. Lett. B* 741, 217 (2015); J. W. F. Valle and C. A. Vaquera-Araujo *Phys. Lett. B* 755, 363 (2016); S. Centelles Chuli'á, R. Srivastava, and J. W. F. Valle *Phys. Rev. D* 98, 035009 (2018); Z. G. Berezhiani and R. N. Mohapatra, *Phys. Rev. D* 52, 6607 (1995), ...

Oscillation from astrophysical sources

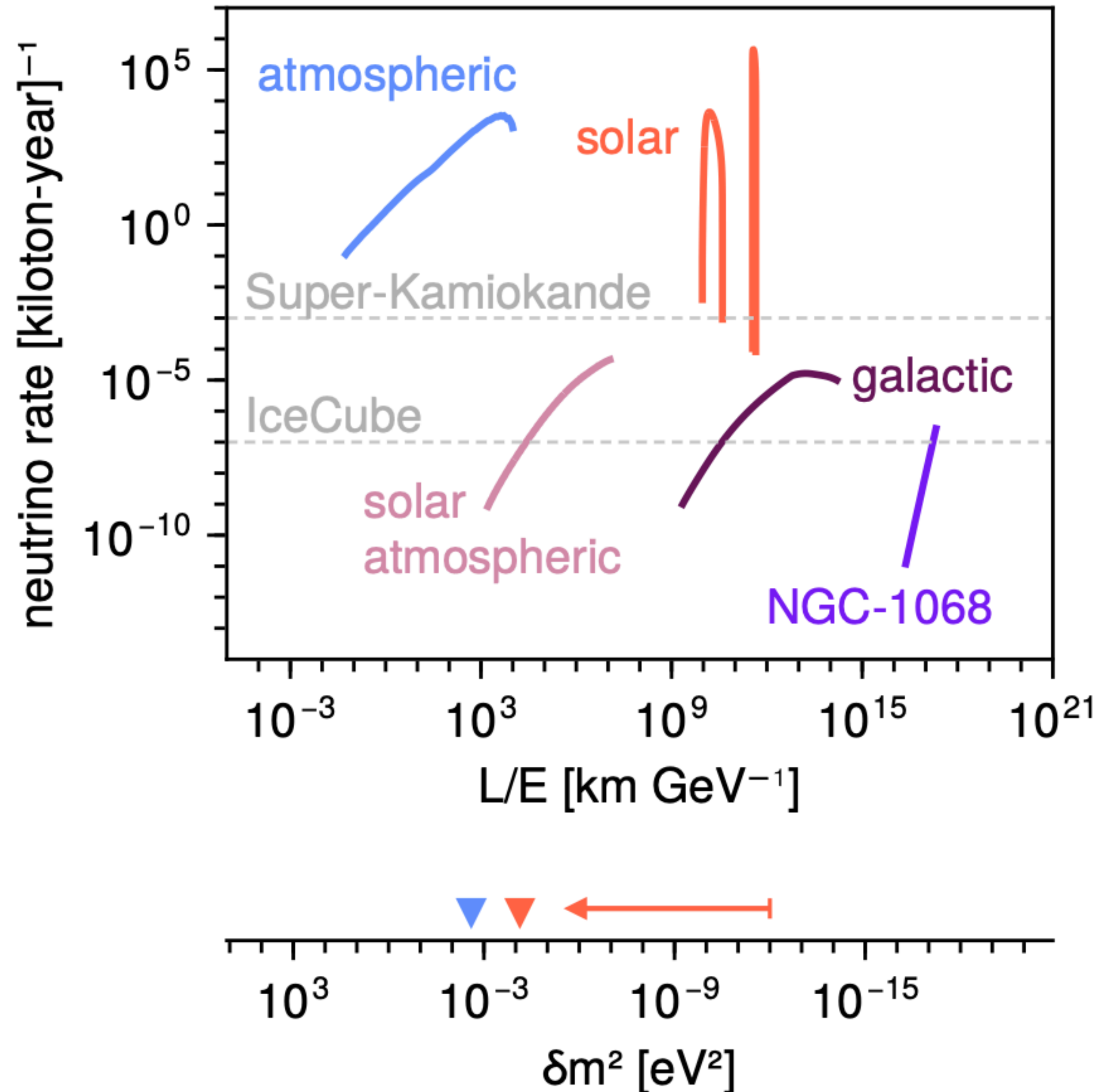


Oscillations in the presence of hyper-fine splittings



Relevant Oscillation scales

M. MacDonald, K. Carloni, CA, I. Martínez-Soler, R. Alves Batista (arXiv:2512.10744)



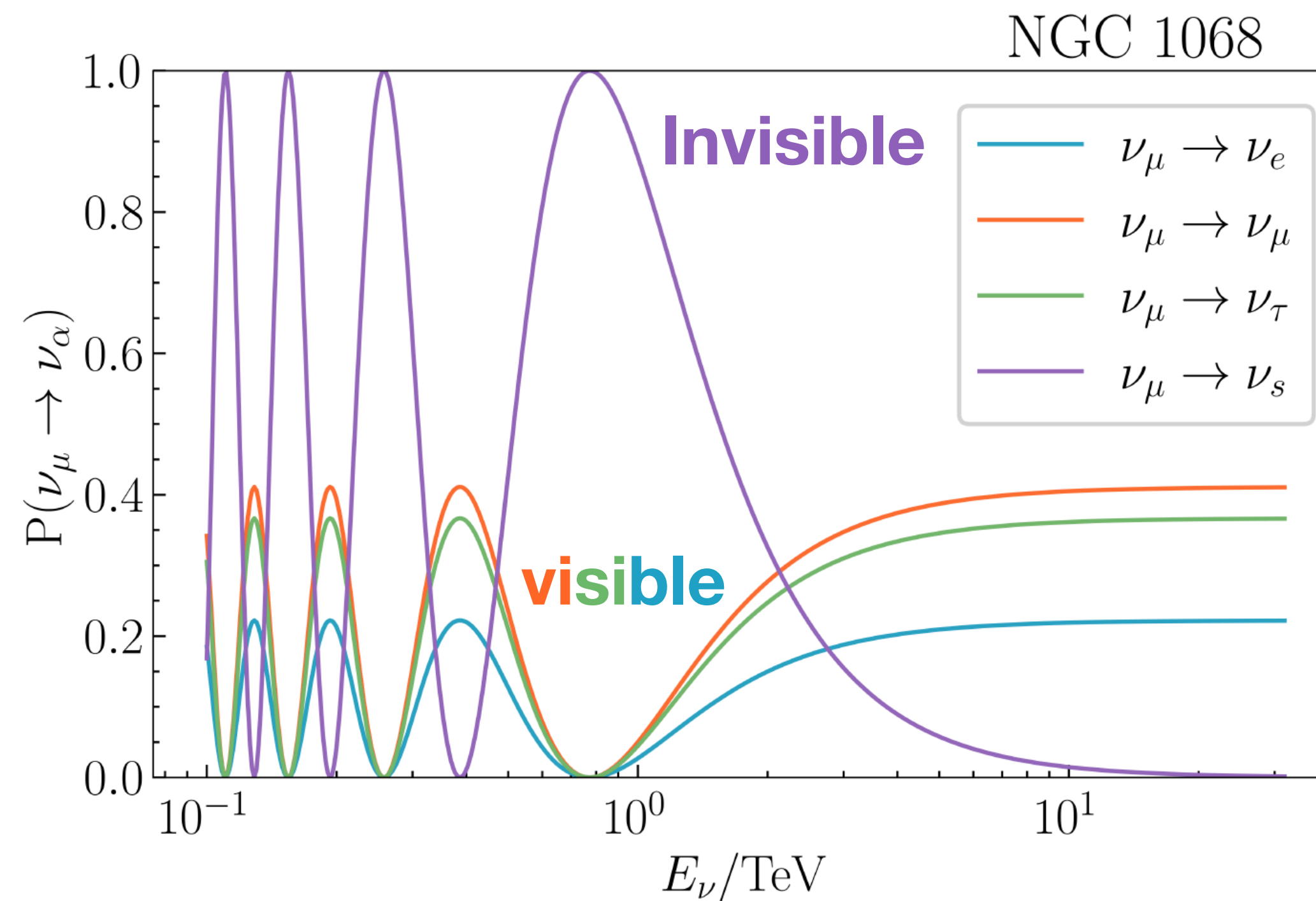
- L/E ratio defines the relevant mass-square difference.
- Three **high-energy** astrophysical sources:
 - **Point sources**
 - **Galactic** **This talk**
 - **Diffuse**
- Cosmogenic (L. P. S. Leal, et al. arXiv:2504.10576)
- Three **low-energy** astrophysical sources:
 - Solar (de Gouvêa et.al. 0906.1611, Donini et.al. 1106.0064, Ansarifard & Farzan 2211.09105, ...)
 - DSNB (M. MacDonald et al, 2409.16367, ...)
 - SN1987A (I. Martinez-Soler et al., 2105.12736, ...)

Oscillations observable in spectra of sources

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

$L \sim 14 \text{ Mpc}$

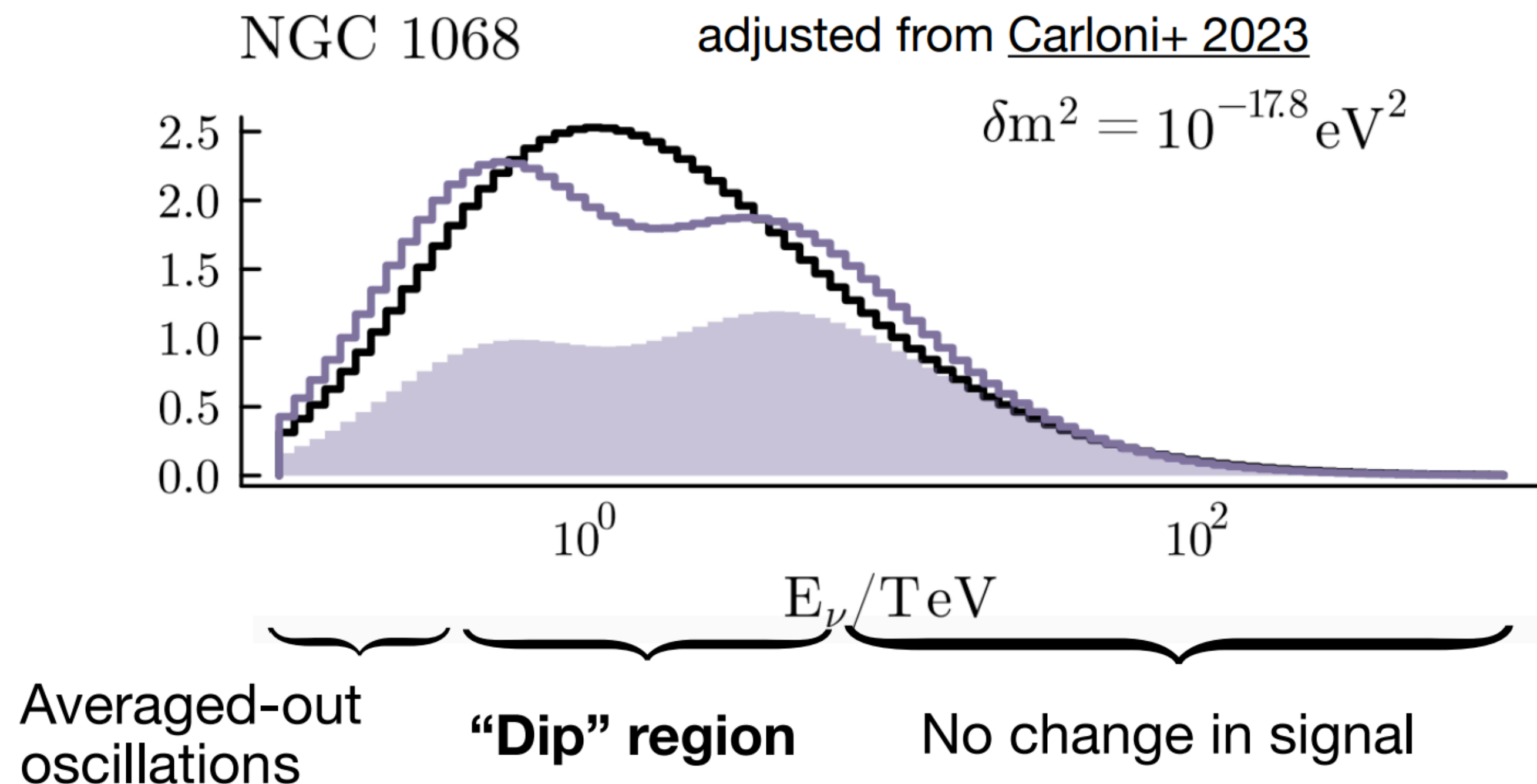
$\delta m^2 \sim 10^{-18} \text{ eV}^2$



Carlioni, Martínez-Soler, CA, Babu, Bhupal Dev *Phys.Rev.D* 109 (2024) L051702

Observable Oscillation Signatures

$$P_{\alpha\beta} = \frac{1}{2} \sum_{k=1}^3 |U_{\beta k}^* U_{\alpha k}|^2 \left[1 + \cos \left(\frac{\delta m_k^2 L_{\text{eff}}}{2E} \right) \right]$$



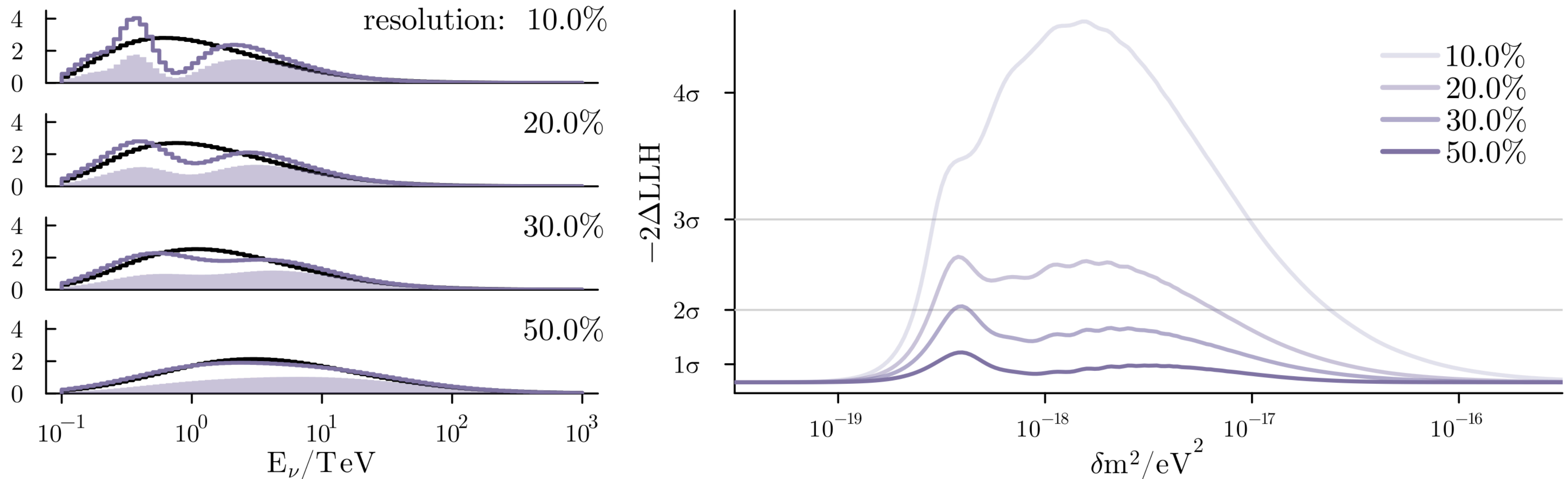
- Individual source flux uncertainties are large
- Energy resolution for muons is poor resulting in diminished signatures.

Solid: SM, Shaded: QD prediction with nominal astro model, Purple: QD with tuned astro model.

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev, *Phys. Rev. D.* 109, L051702 (2024)

Observable Oscillation Signatures

NGC 1068 and other extragalactic sources detected with uncontained muons. Energy resolution is poor for these events.

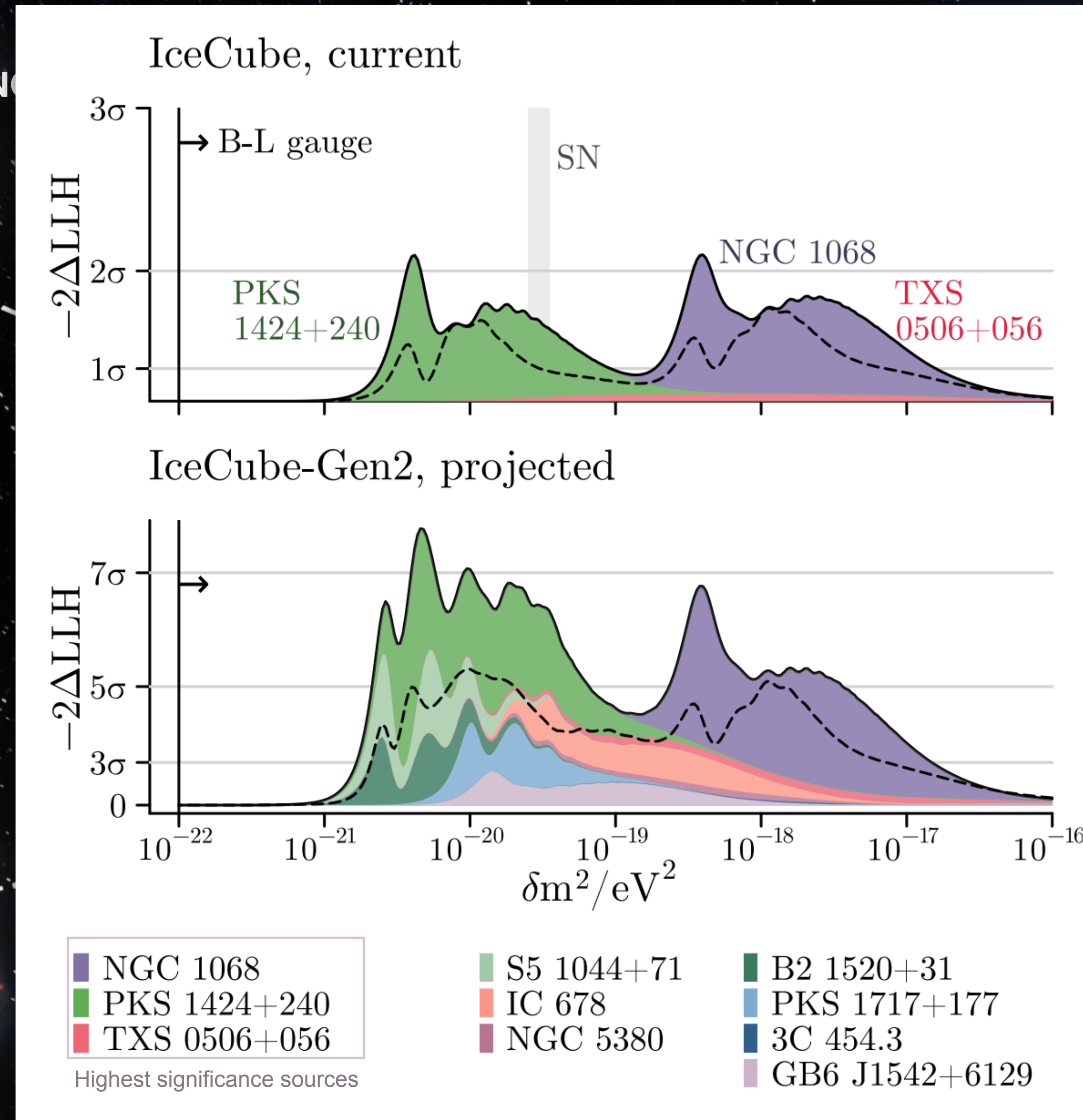


Solid: SM, Shaded: QD prediction with nominal astro model, Purple: QD with tuned astro model.

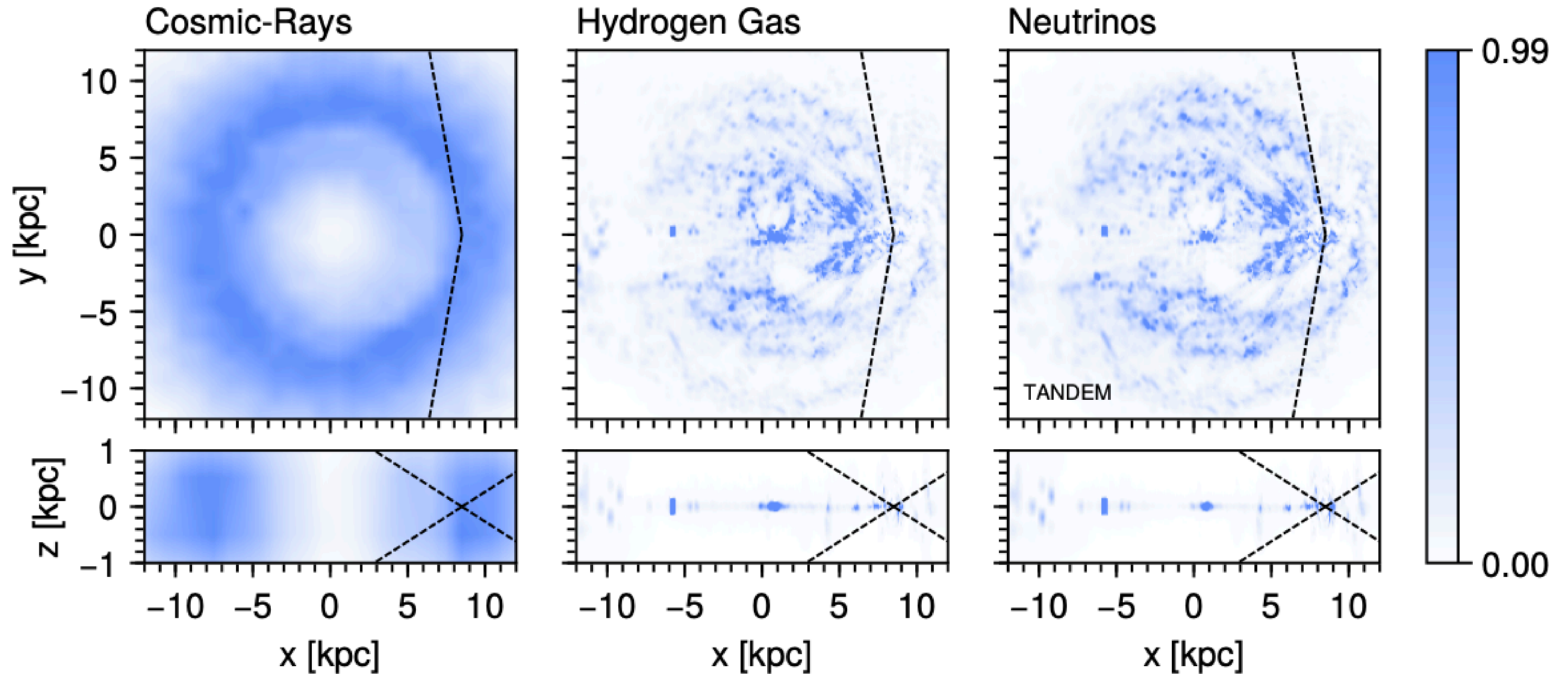
Carlioni, Martínez-Soler, CA, Babu, Bhupal Dev, *Phys. Rev. D.* 109, L051702 (2024)

Carlos A. Argüelles — TeVPa, August, 2026

Sensitivity to hyper-fine splittings with extragalactic sources

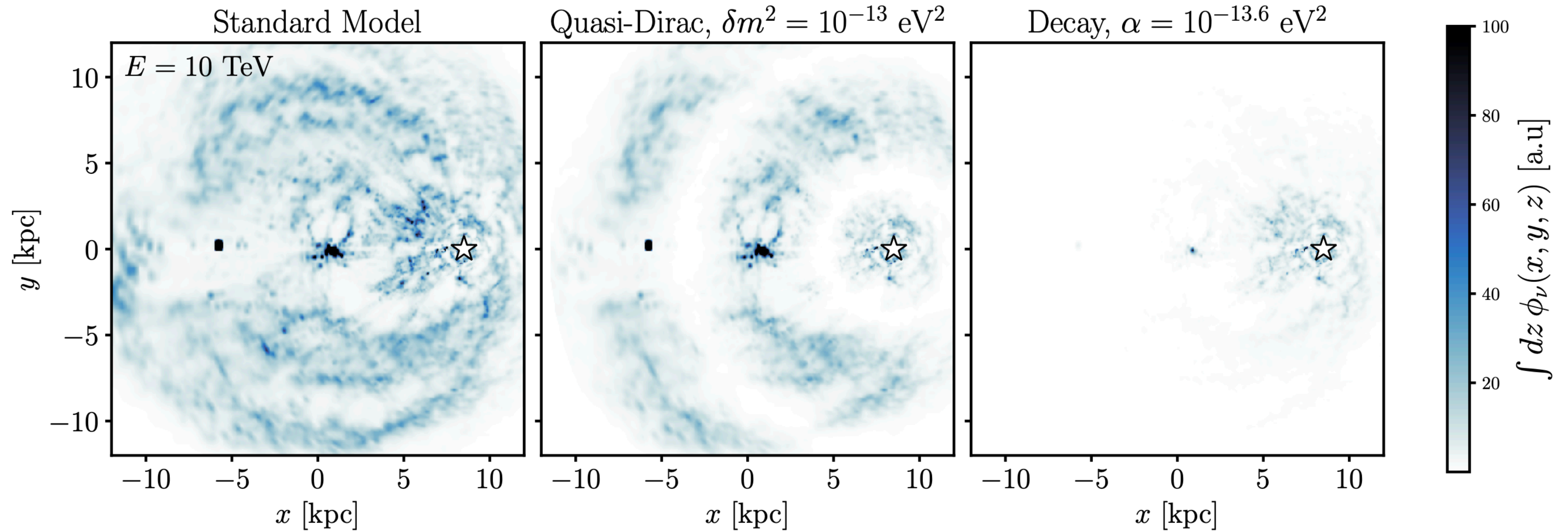


Neutrino emission in our galaxy



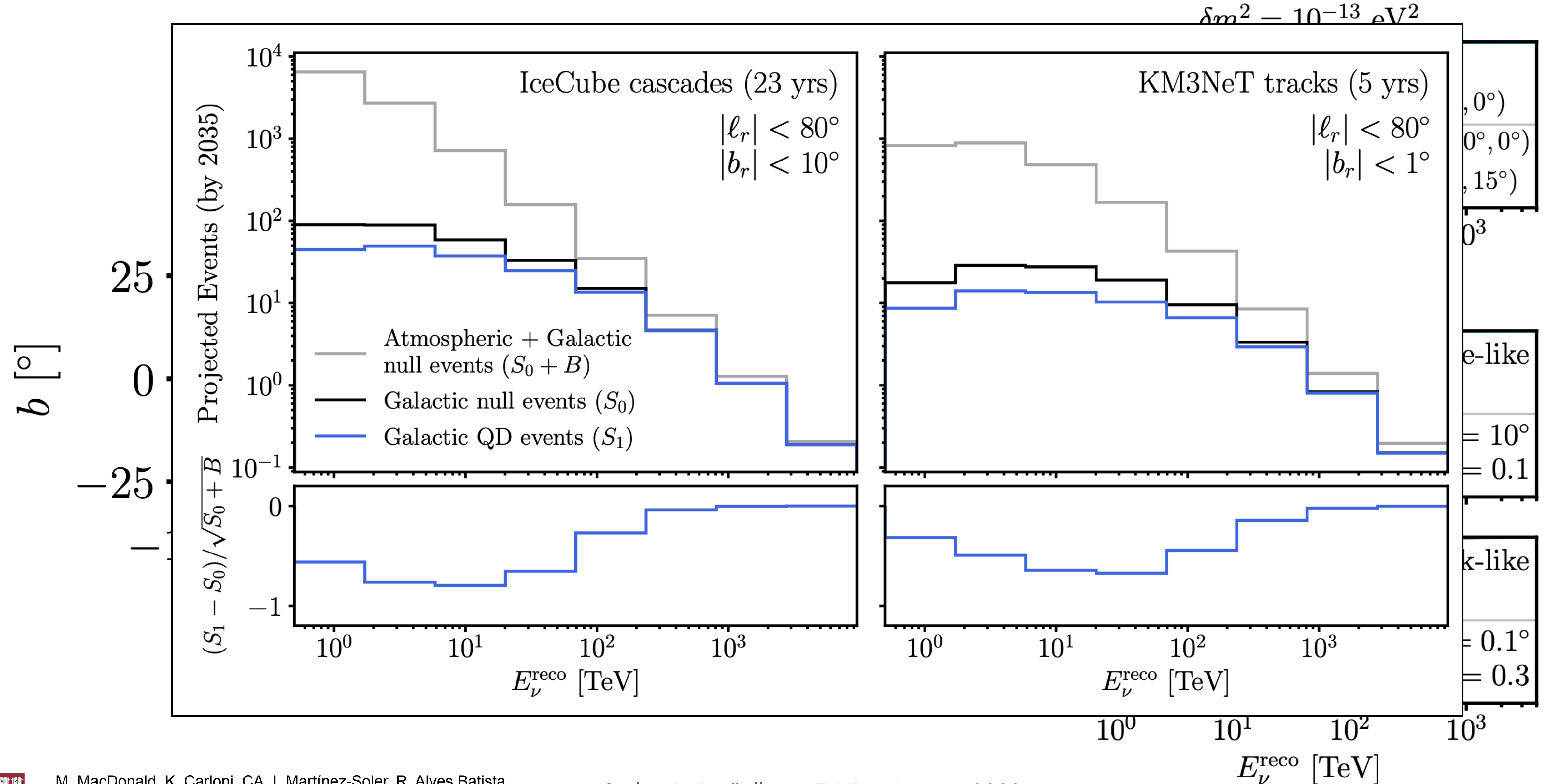
M. MacDonald, K. Carloni, CA, I. Martínez-Soler, R. Alves Batista (to appear soon)!

Effect of oscillations in galactic neutrino distributions

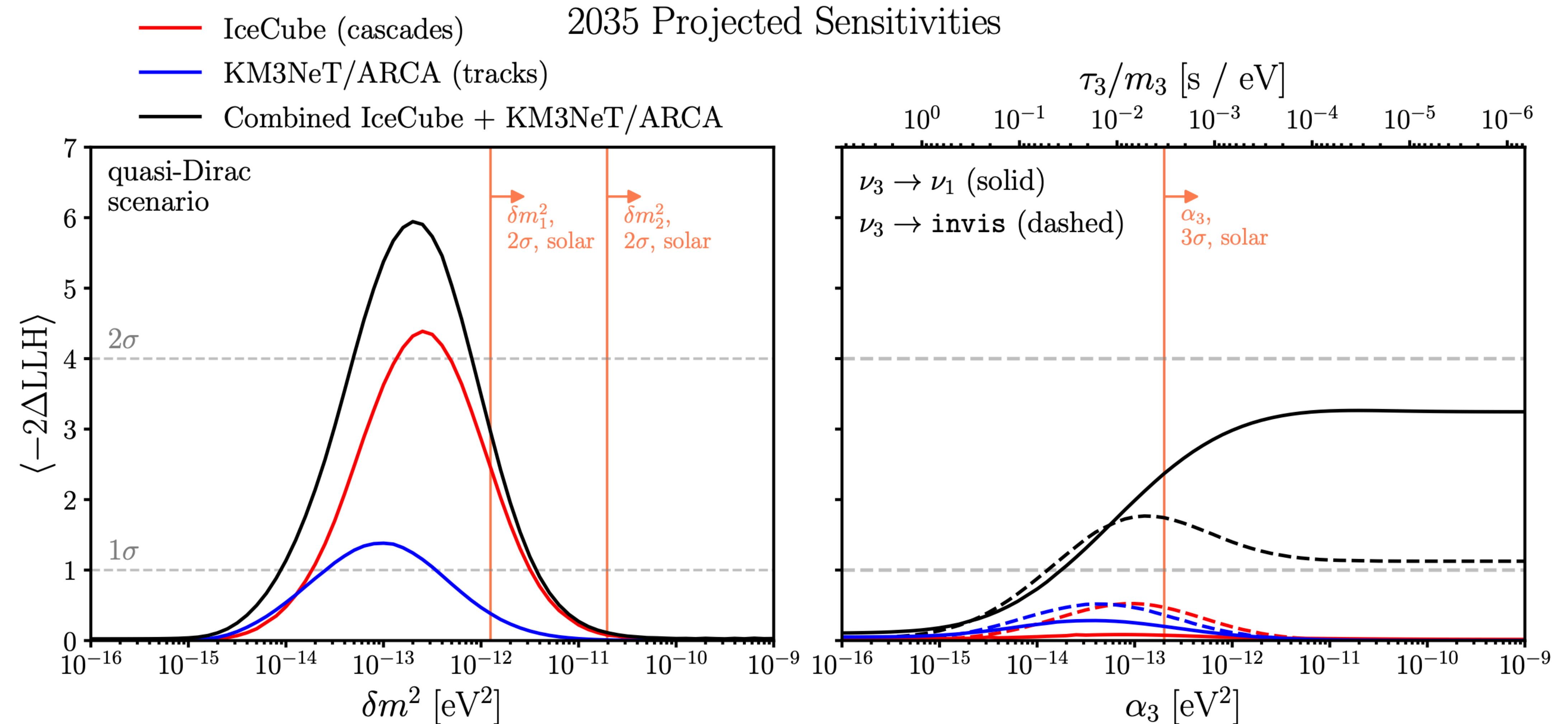


M. MacDonald, K. Carloni, CA, I. Martínez-Soler, R. Alves Batista (arXiv:2512.10744)

Observable distributions of galactic neutrino oscillations



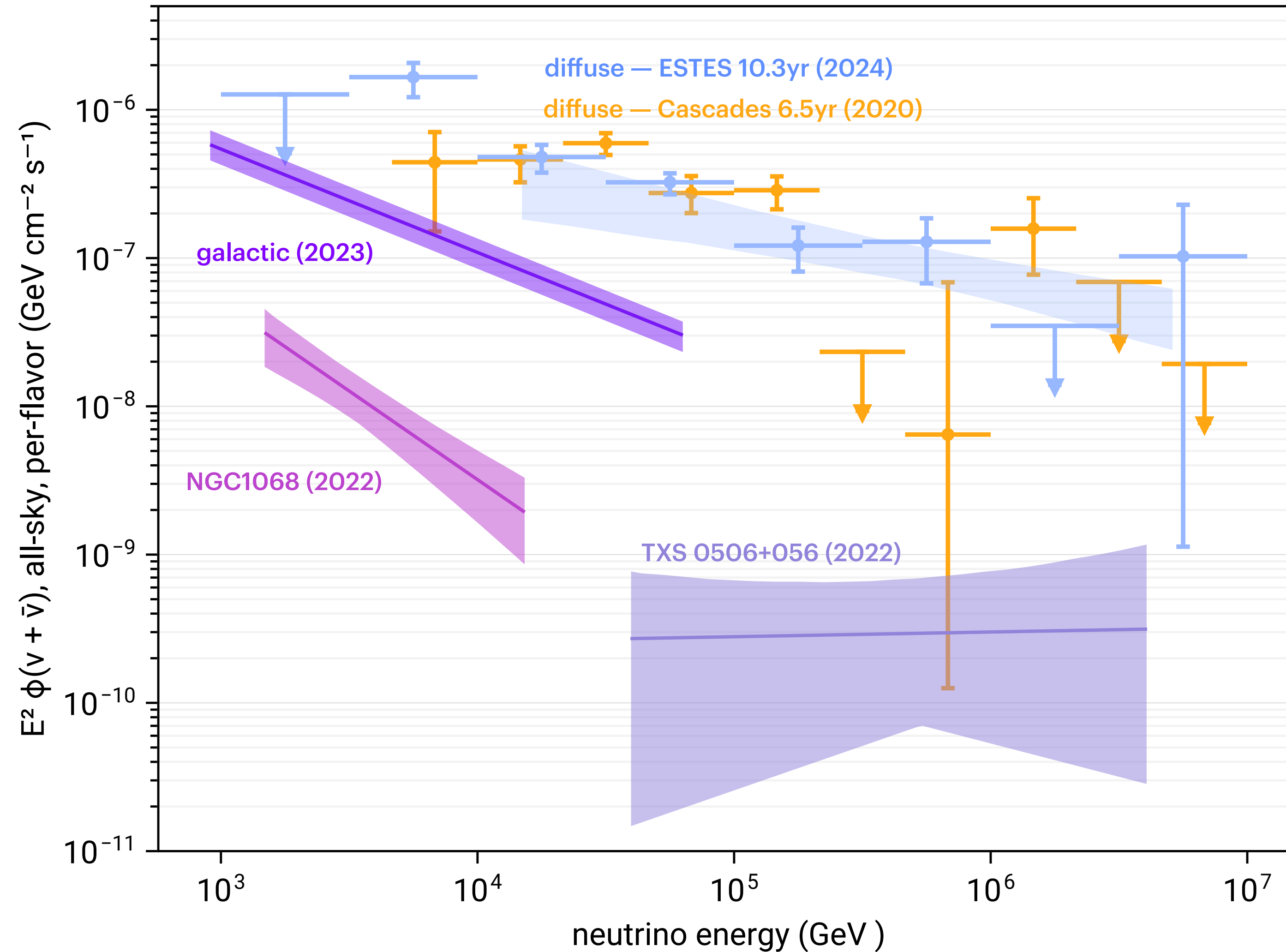
Observable distributions of galactic neutrino oscillations



Given that the oscillation length is comparable to the source size, oscillation sensitivity is suppressed.

On going IceCube analysis, expected to have ~ 2 sigma sensitivity.

What about the all-sky, unassociated neutrinos?



re-plotted from:

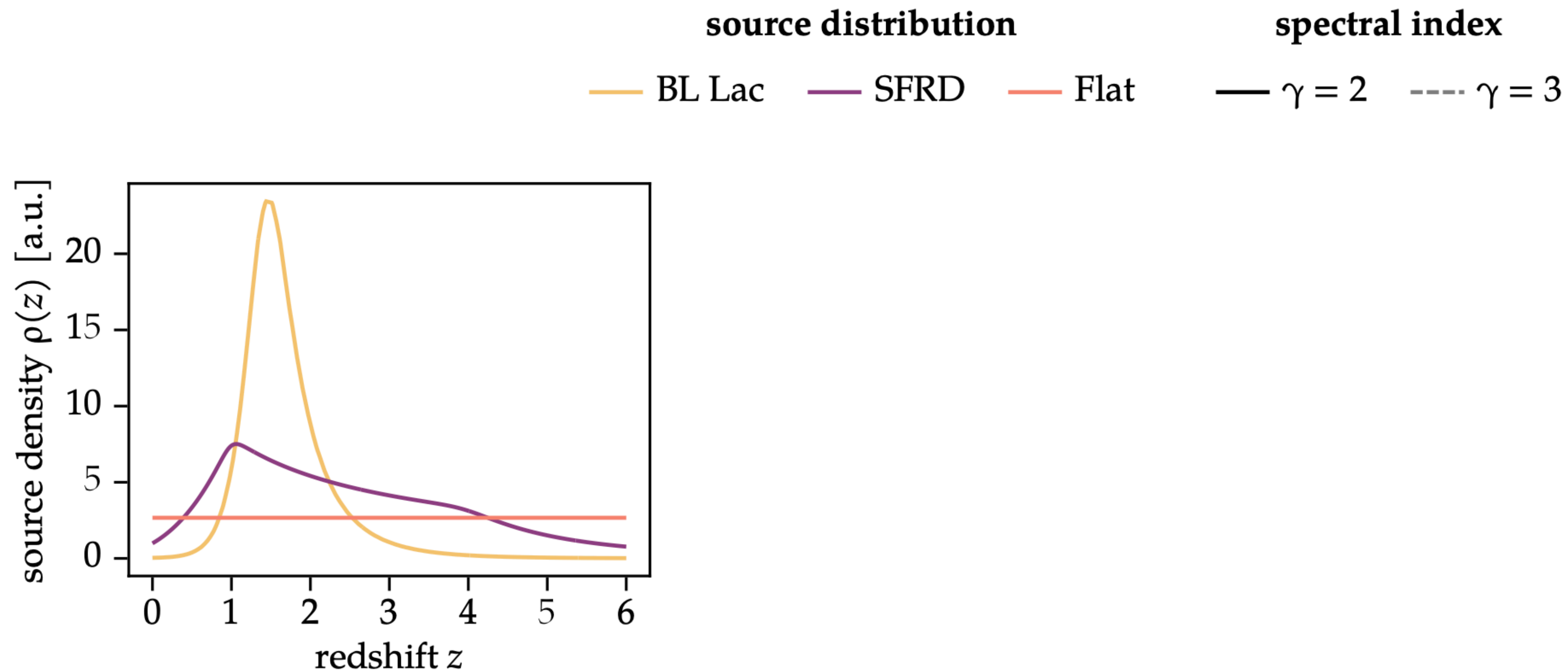
1. IceCube Collaboration, 2001.09520
2. IceCube Collaboration, 2402.18026

Sources are very stat.
limited

What about all of those
“diffuse neutrinos”?

K. Carloni, J. Porto, CA, B. Dev, S. Jana (arXiv:2503.19960, *Phys.Rev.D* 113 (2026) 11, 115004)

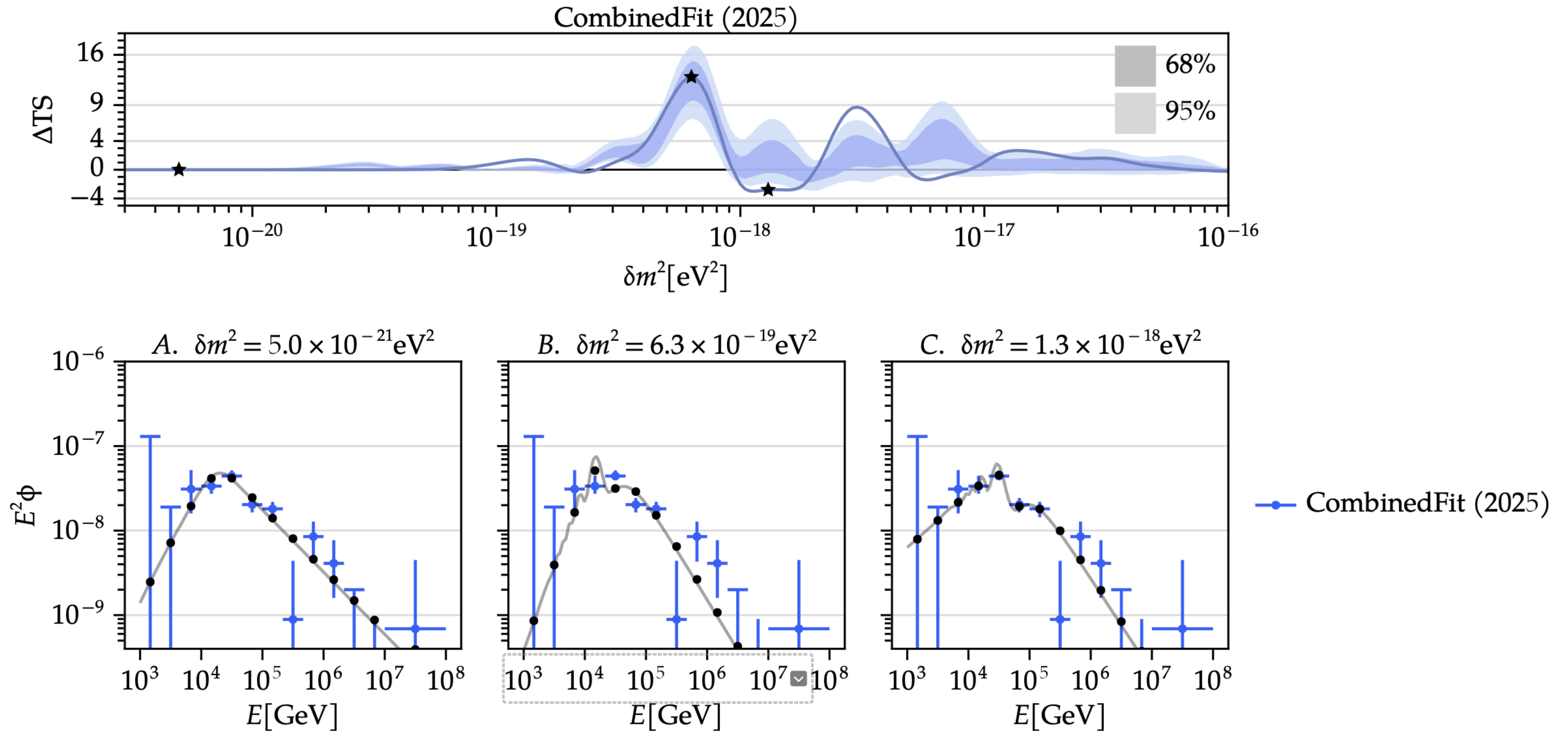
Astrophysical neutrino cosmic distribution



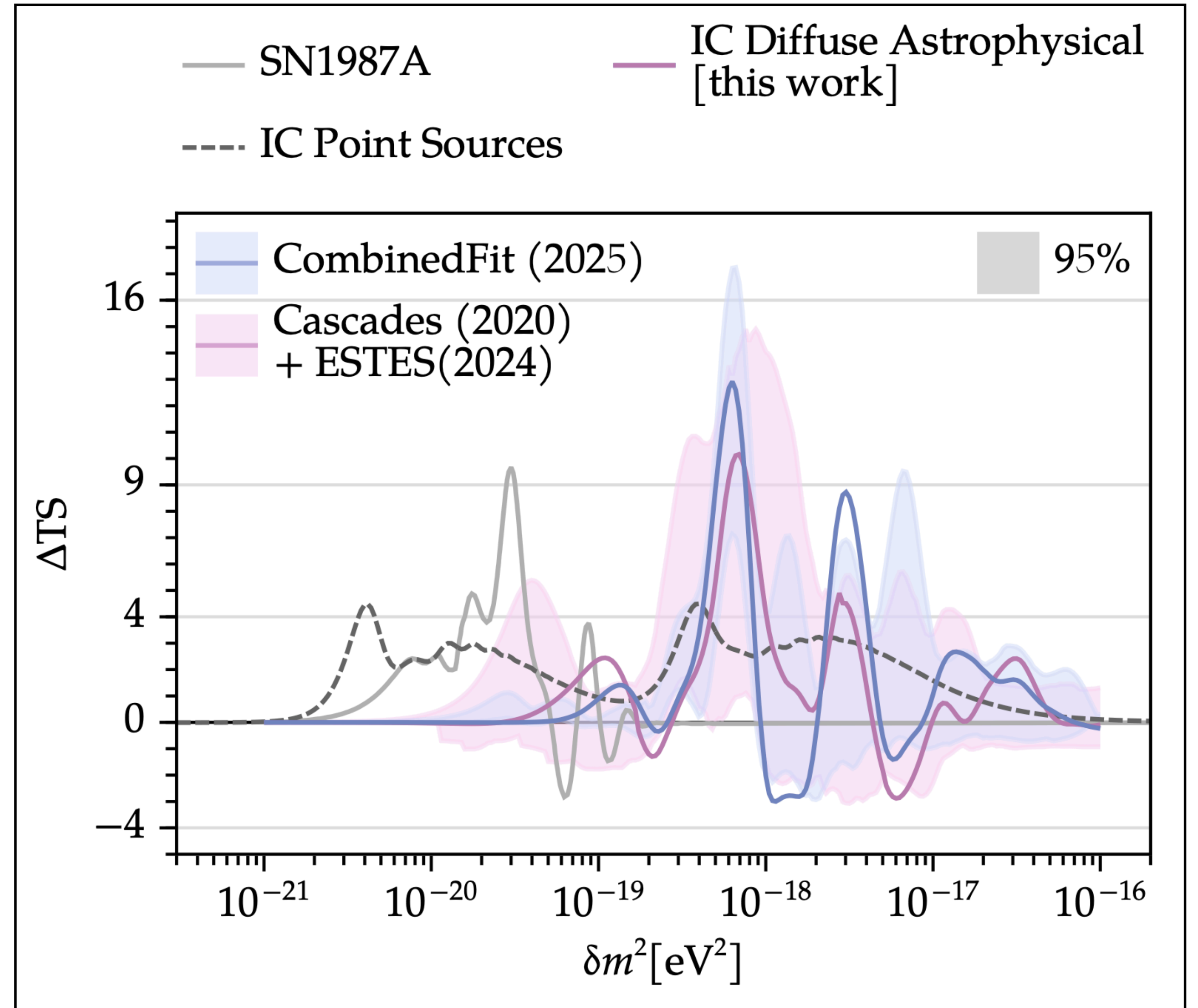
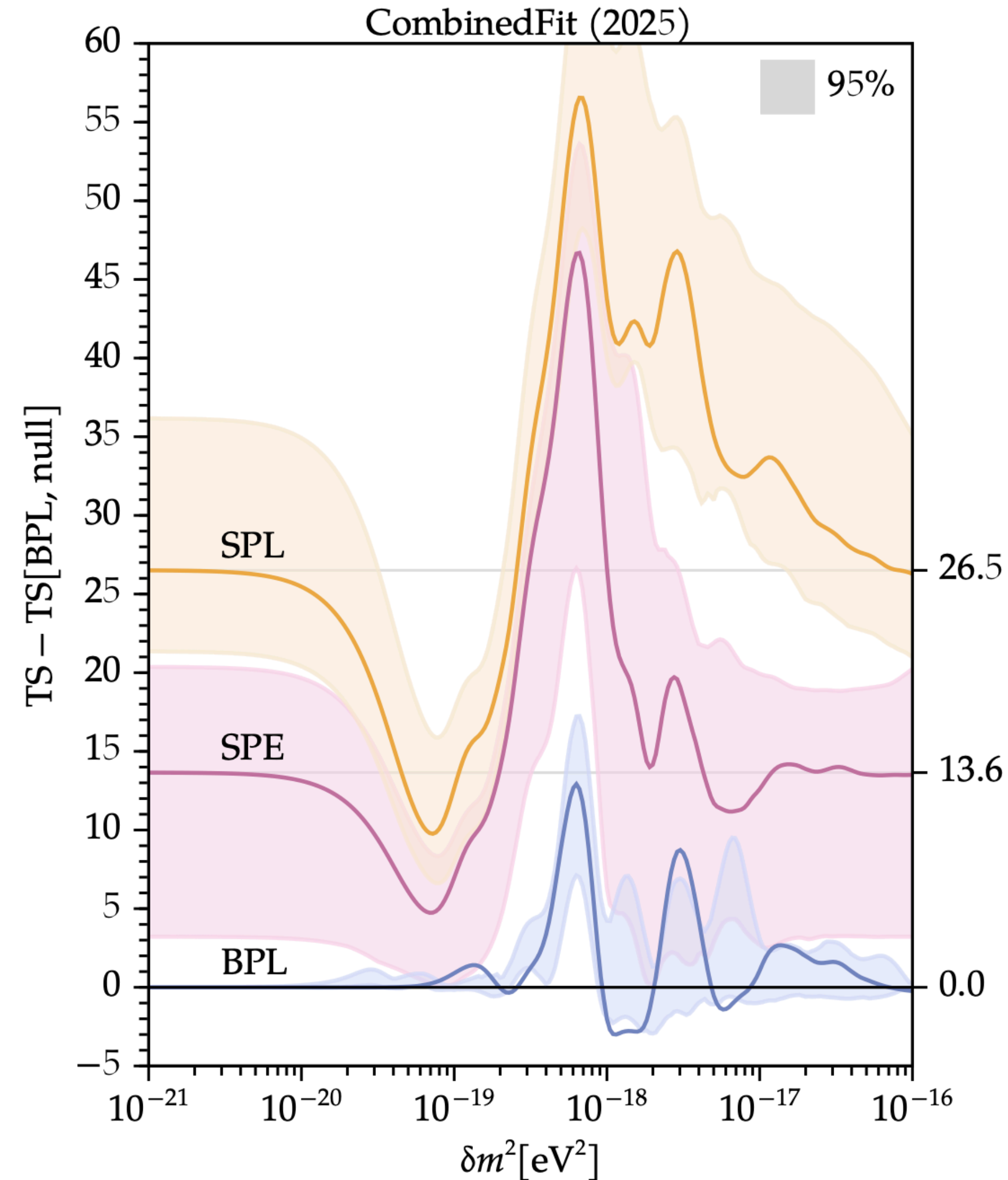
See Capel et al. *Phys. Rev. D* 101, 123017 (2020)

K. M. Groth and M. Ahlers *Phys. Rev. D* 111, 103052 (2025) for source distribution inference

Fit to the all-sky neutrino data



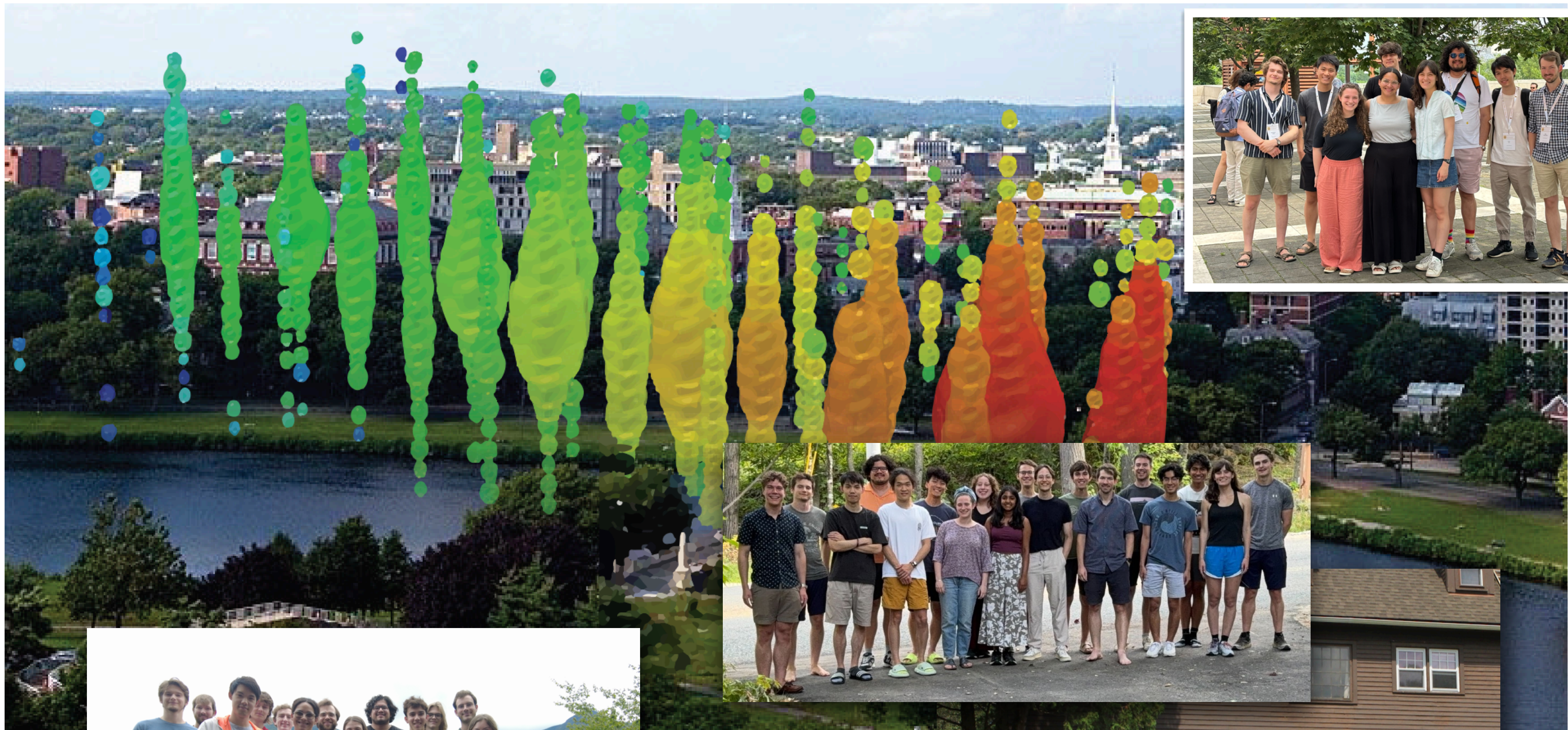
New Constraints on Hyper-fine Splittings



Take-home message

- ❖ Astrophysical neutrinos could give us evidence for Dirac-like neutrinos.
- ❖ Galactic neutrinos offer the possibility to study ultra-long-baseline oscillation physics.
- ❖ We set new constraints on the neutrino hyperfine splitting using diffuse neutrino measurements.





CIFAR



Thanks!



Carlos A. Argüelles — TeVPa, August, 2026

Comparing Flux Measurements with Model Expectations

- Assume all sources have the same emission spectrum ϕ_0 , which can be a single power law, power law with a cutoff, or a broken power law
 - Perform a likelihood fit to the IceCube flux measurements
 - Marginalize over all emission spectrum parameters
 - Will show results for IceCube “CombinedFit”
- IceCube Collaboration, 2507.22234

Our total diffuse flux, including QD oscillations, is given by:

$$\Phi_{\beta}(E) = \int dz \sum_{\alpha} P_{\alpha\beta}^{QD}(E, L_{\text{eff}}(z)) \times f_{\alpha} \times \phi_0(E(1+z)) \times \frac{\rho(z)}{H(z)}$$

$P_{\alpha\beta}^{QD}$ = oscillation probability

f_{α} = initial flavor fraction

ϕ_0 = emission spectrum

$\rho(z)$ = redshift evolution of source population

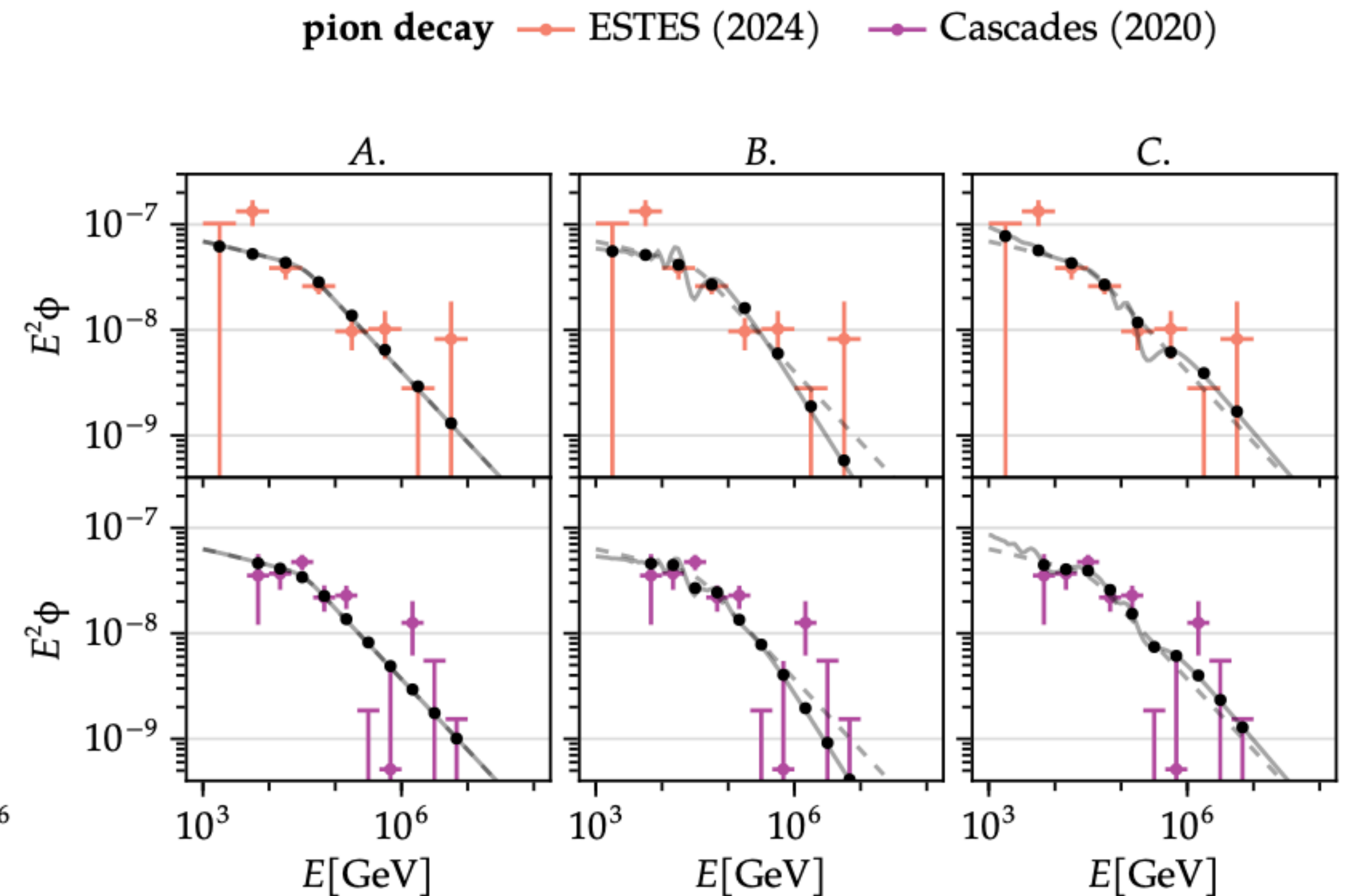
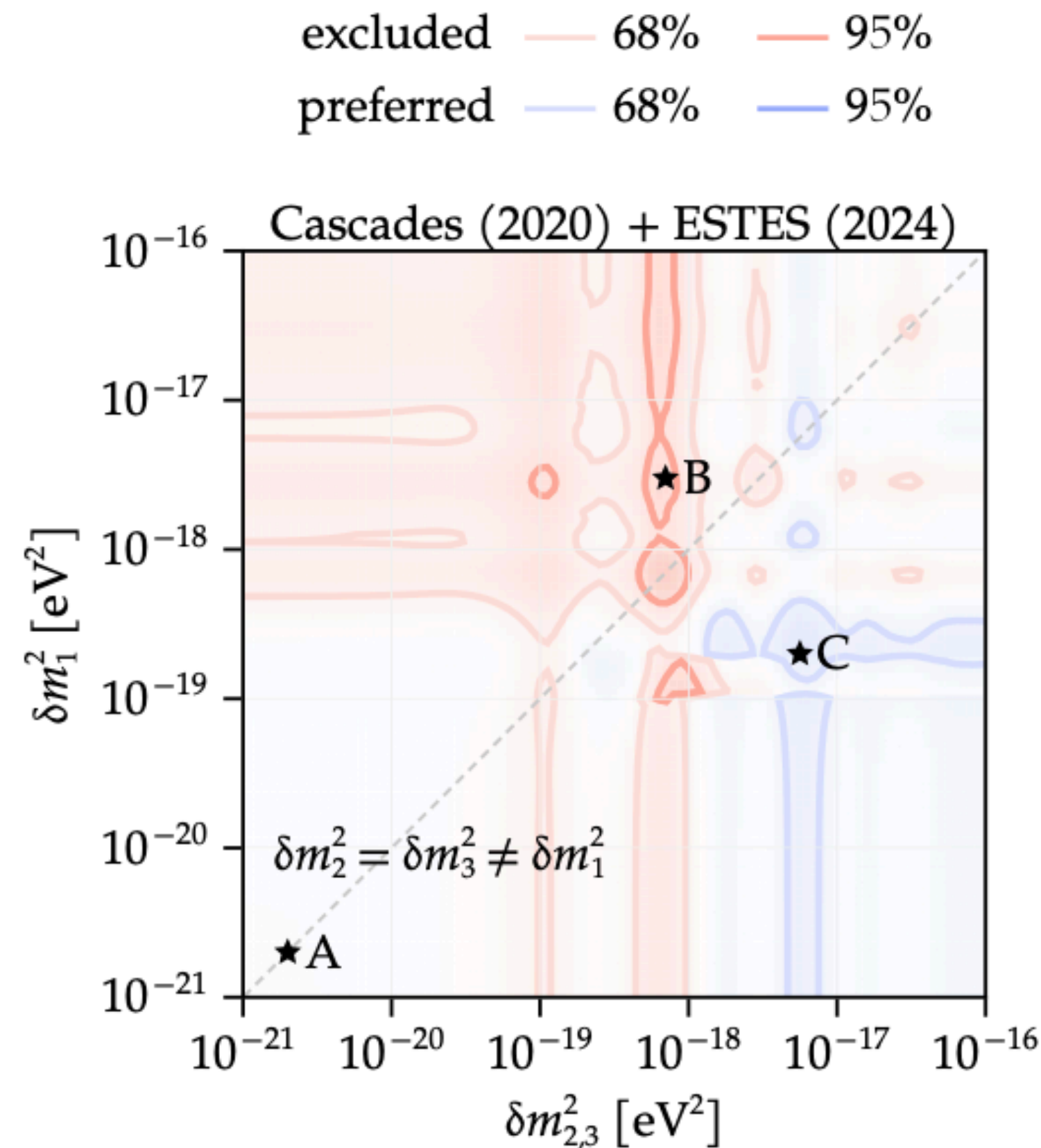
$$L_{\text{eff}}(z) = \int_0^z \frac{dz'}{H(z')(1+z')^2}$$

Possibility of Flavor Effects

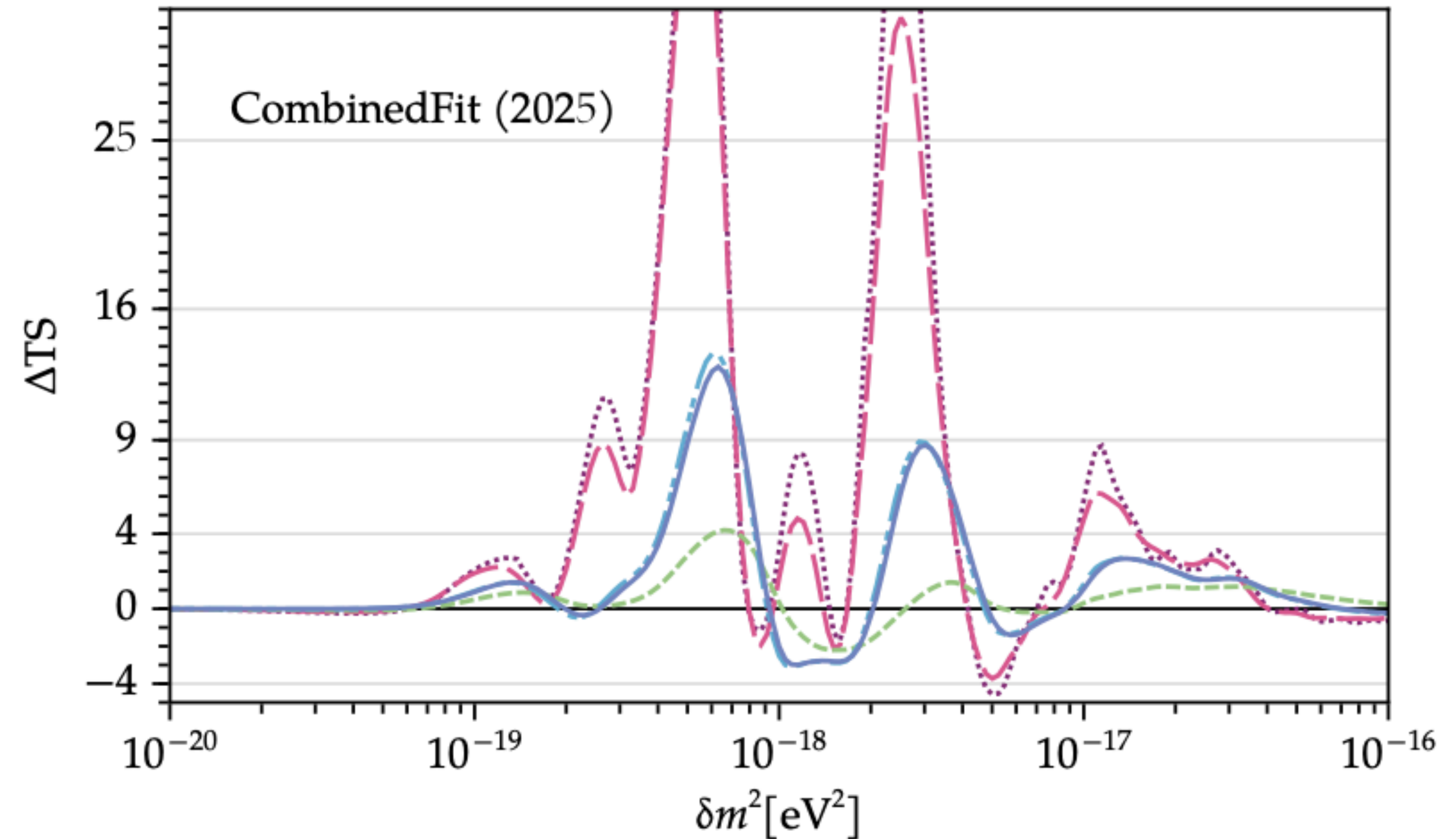
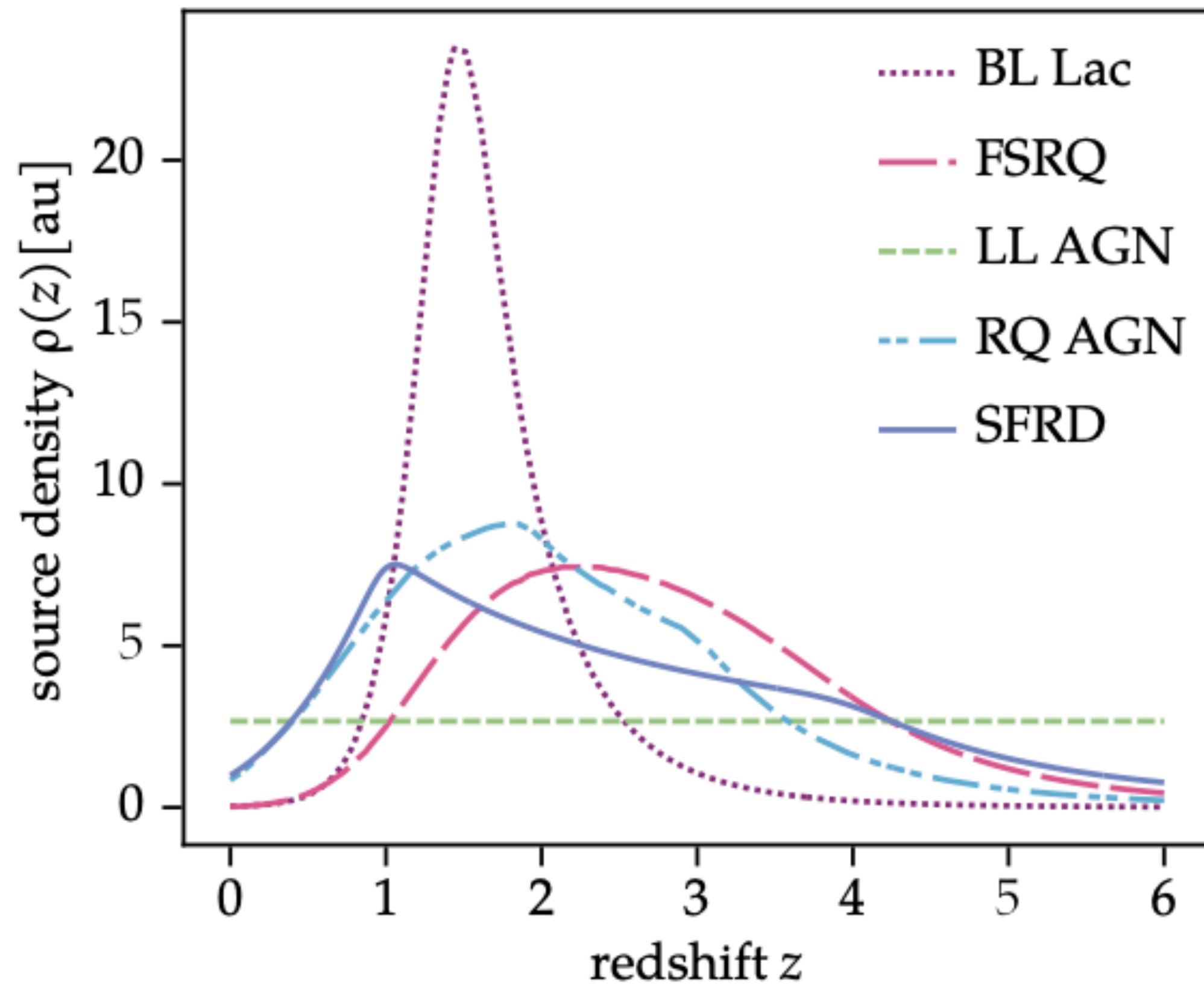
In prior slides, we have assumed that $\delta m_i^2 = \delta m^2$ if we allow for different hyperfine splitting, then we also get flavor dependency.

CombinedFit sample fit is not separated by flavors.

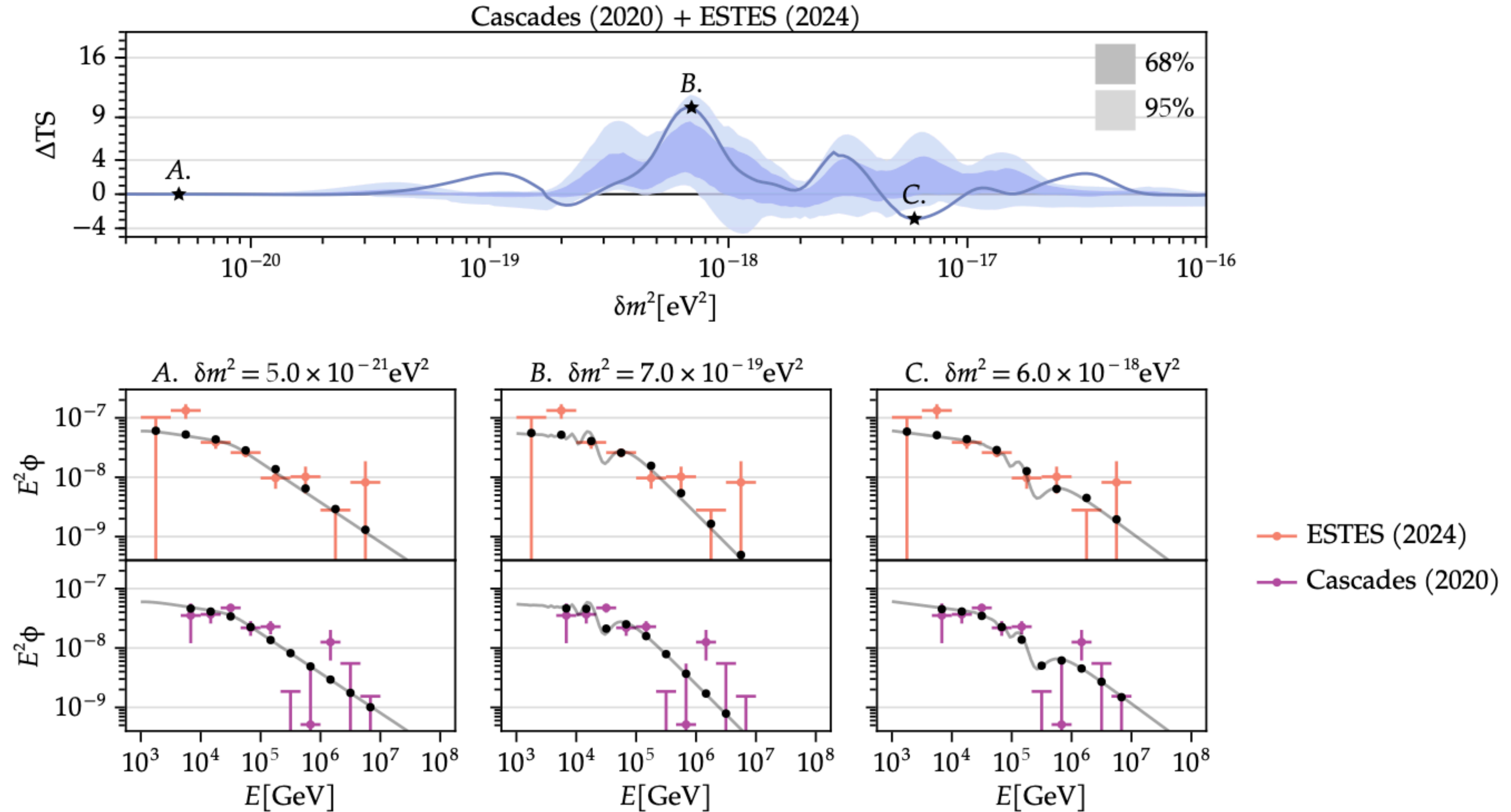
We study ESTES+Cascade samples.



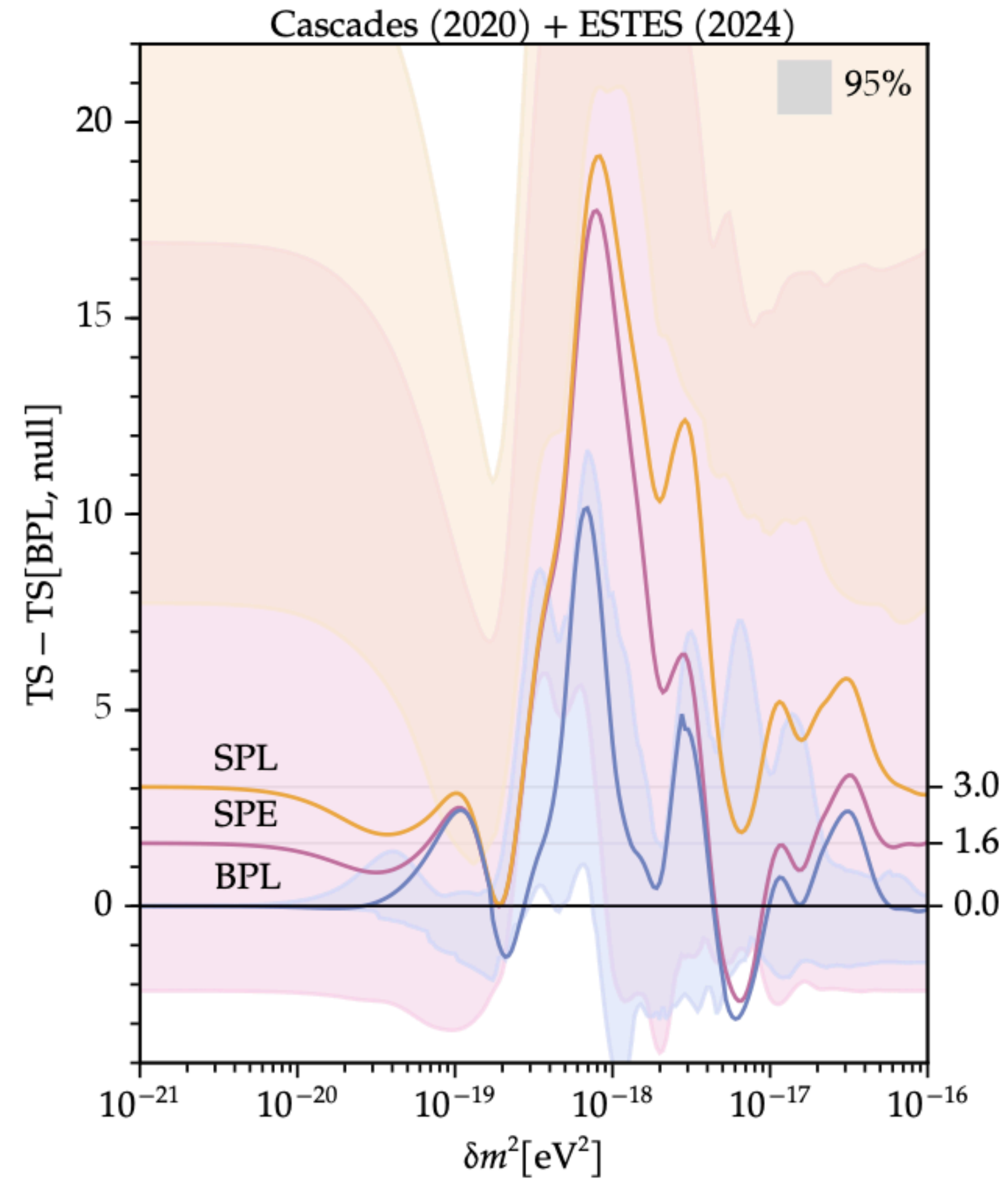
Effect of spatial distribution on quasi-Dirac neutrino constraints



Fit using Cascade + ESTES



Fit using Cascade + ESTES



Neutrino coherence

$$L_{\text{coh}} = \frac{4\sqrt{2}E^2}{|\delta m_k^2|} \sigma_x$$
$$\approx 18 \text{ Gpc} \left(\frac{E}{10 \text{ TeV}} \right)^2 \left(\frac{10^{-19} \text{ eV}^2}{\delta m_k^2} \right) \left(\frac{\sigma_x}{10^{-19} \text{ m}} \right)$$