Signatures of quasi-Dirac neutrinos in the high-energy astrophysical neutrino flux

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Carloni, Porto, Argüelles, Dev, Jana, 2503.19960v2

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TeVPA
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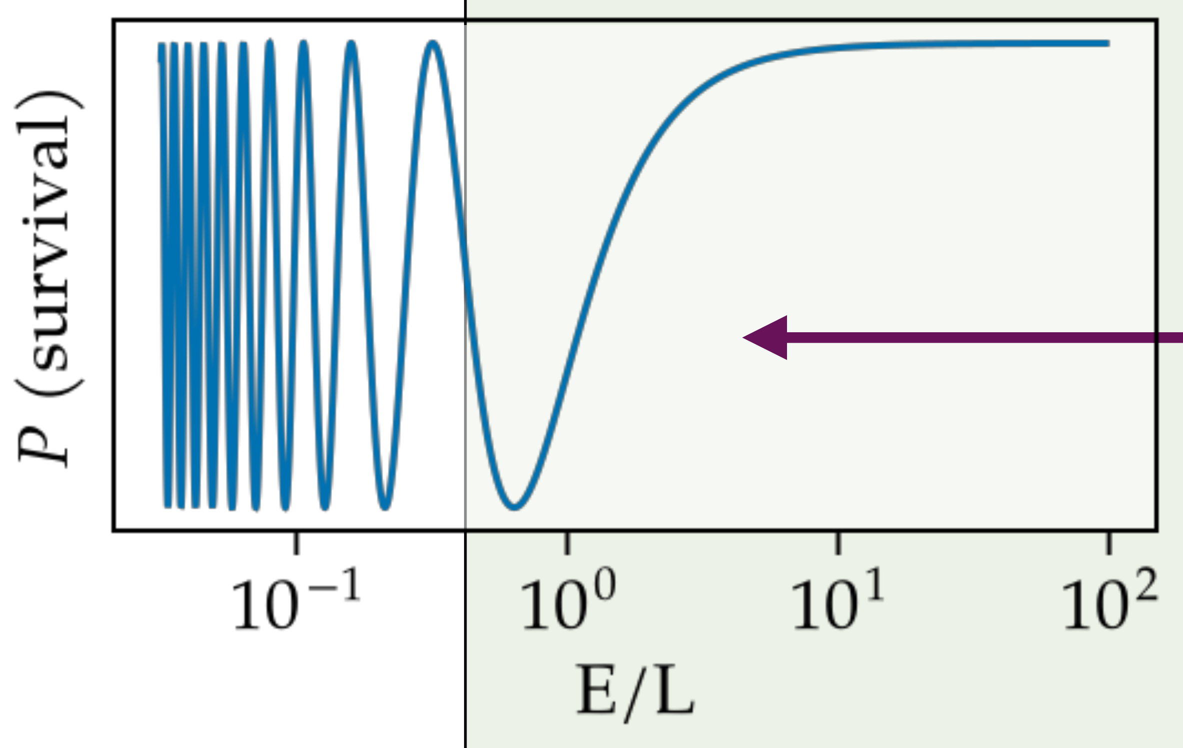
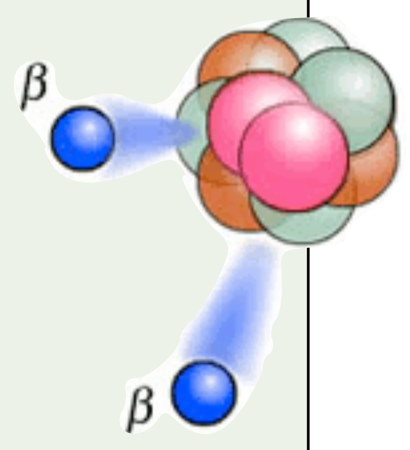
The interplay between the Dirac and Majorana terms produces a wide variety of phenomena:

$$\mathscr{L}_{\nu-\mathrm{mass}} = -\underbrace{m_D \bar{\nu}_R \nu_L}_{\text{Dirac term}} + \underbrace{m_R \nu_R^T C^\dagger \nu_R}_{\text{Majorana term}} + \mathrm{H.c.}$$

exactly Dirac! — more Majorana ⟶ — exactly Majorana!

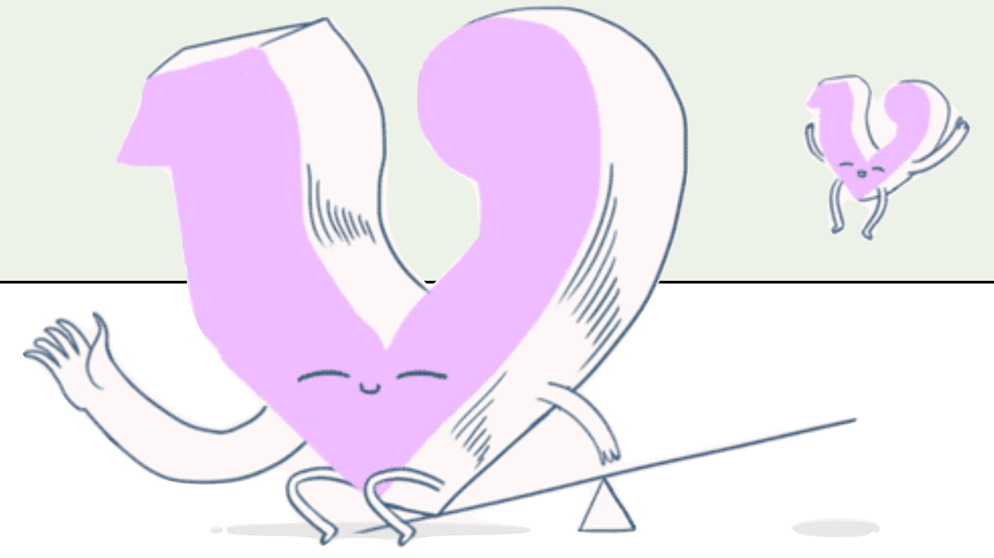


oscillations into light steriles



neutrino-less double beta decay

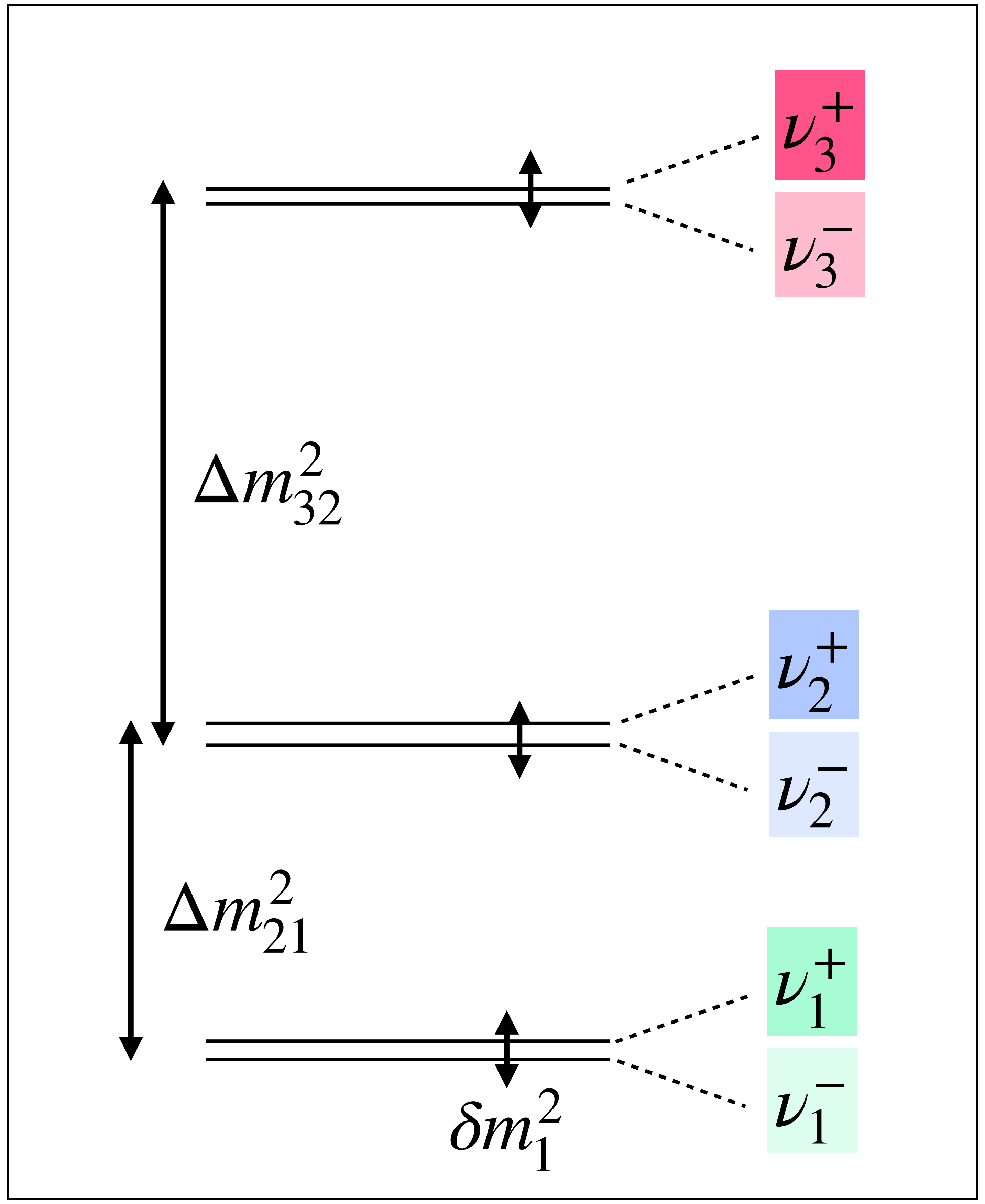
see-saw mechanism
(heavy neutral leptons)



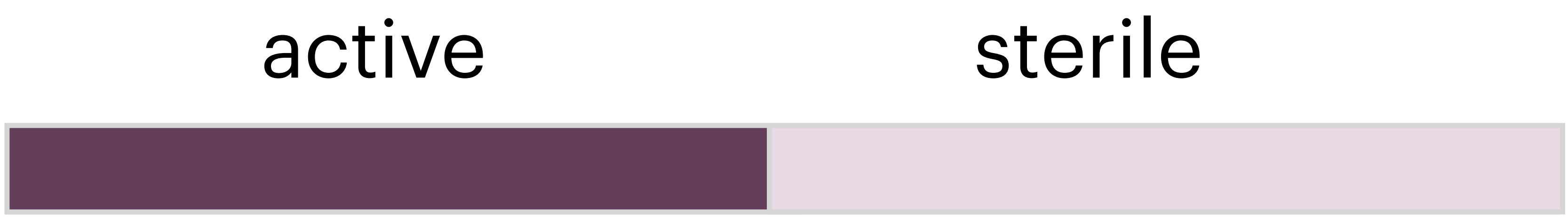
quasi-Dirac neutrinos*

*also known as pseudo-Dirac

In the quasi-Dirac limit $m_D \gg m_R$, we expect three sets of "hyper finely" split neutrino mass eigenstates:



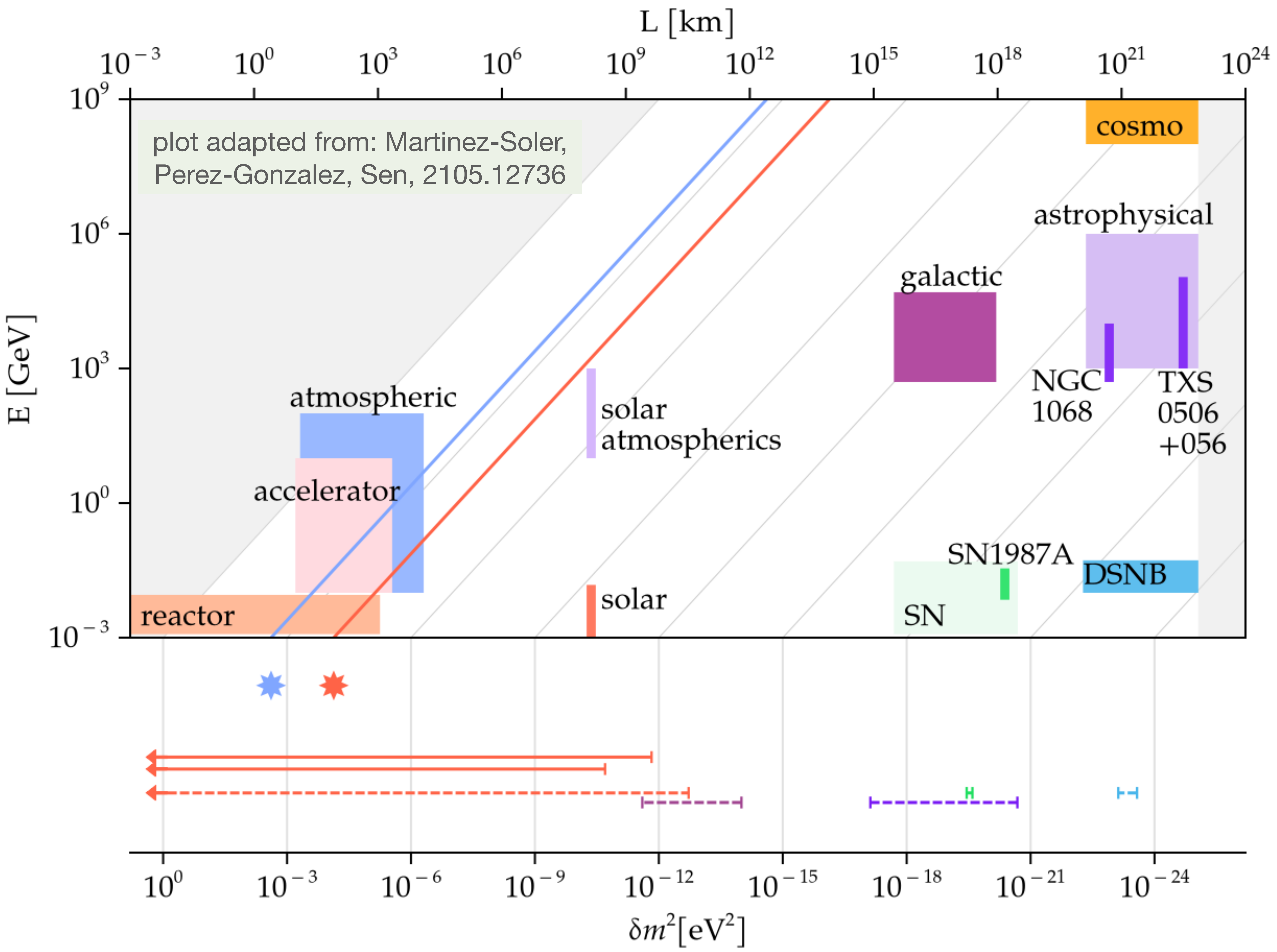
Each of these mass states are 50-50 mixes of "active" neutrinos $\{\nu_e, \nu_\mu, \nu_\tau\}$ and undetectable "steriles":

$|\nu_j^\pm\rangle =$


The hyperfine mass differences δm^2 would produce an oscillatory disappearance signal on very, very long baselines.

$$P^{QD}_{\alpha\to\beta} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \cos^2\left(\frac{\delta m_j^2 L}{4E}\right)$$

Wolfenstein (NPB '81); Petcov (PLB '82); Valle, Singer (PRD '83)



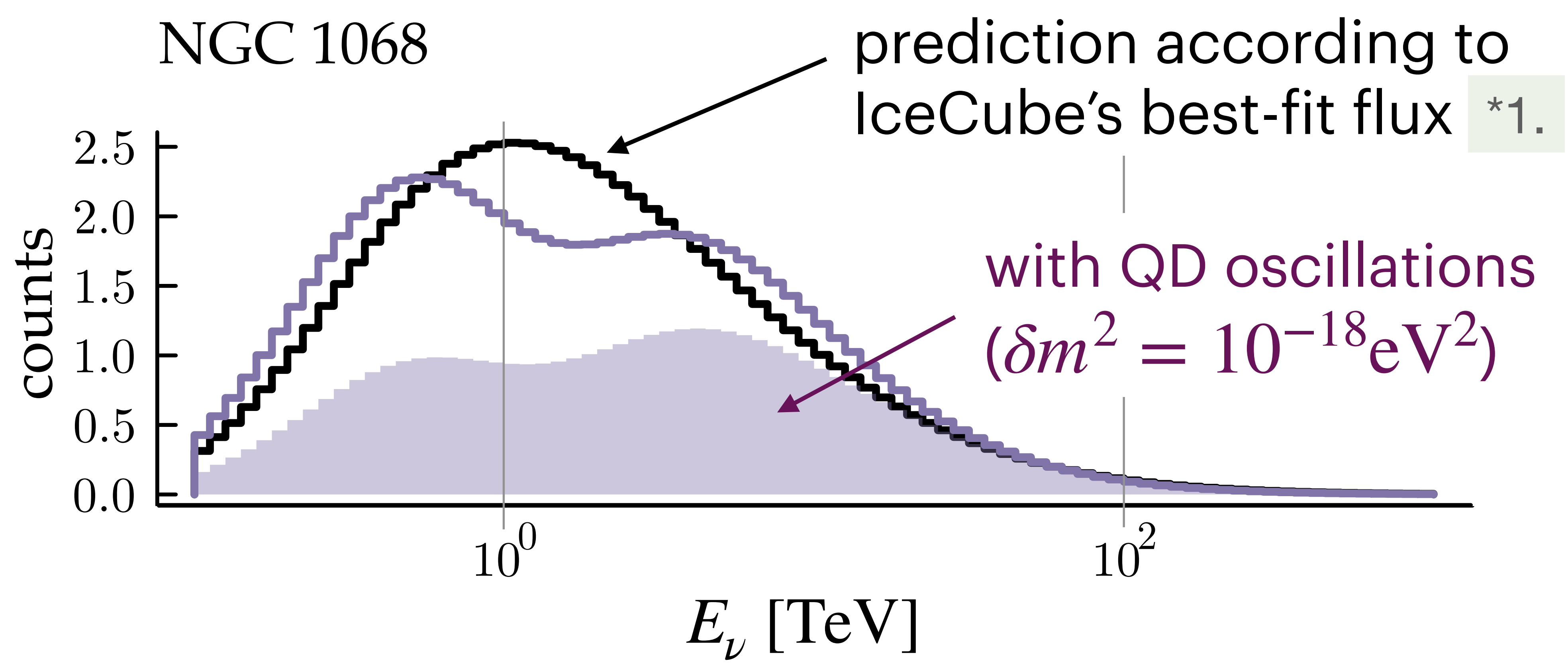
Beacom, Bell, Hooper, Learned, Pakvasa, Weiler, 0307151;

We need "extra-terrestrial" neutrinos to probe Quasi-Dirac models!

Solar:	Ansarifard, Farzan, 2211.09105 Franklin, Perez-Gonzalez, Turner, 2304.05418
SN1987A:	Martinez-Soler, Perez-Gonzalez, Sen, 2105.12736
DSNB:	de Gouvêa, Martinez-Soler, Perez-Gonzalez, Sen, 2007.13748
Cosmo-genic:	Leal, Naredo-Tuero, Funchal, 2504.10576
Galactic:	MacDonald, KC, Argüelles, Batista, Martinez-Soler (ICRC 2025)
Astro point sources:	KC, Martinez-Soler, Argüelles, Babu, Dev, 2212.00737

Previous work: QD sensitivity using point sources

The QD signature is an oscillation-induced disappearance dip:



Sensitivities from multiple sources can be directly stacked.

1. IceCube Collaboration, 2211.09972

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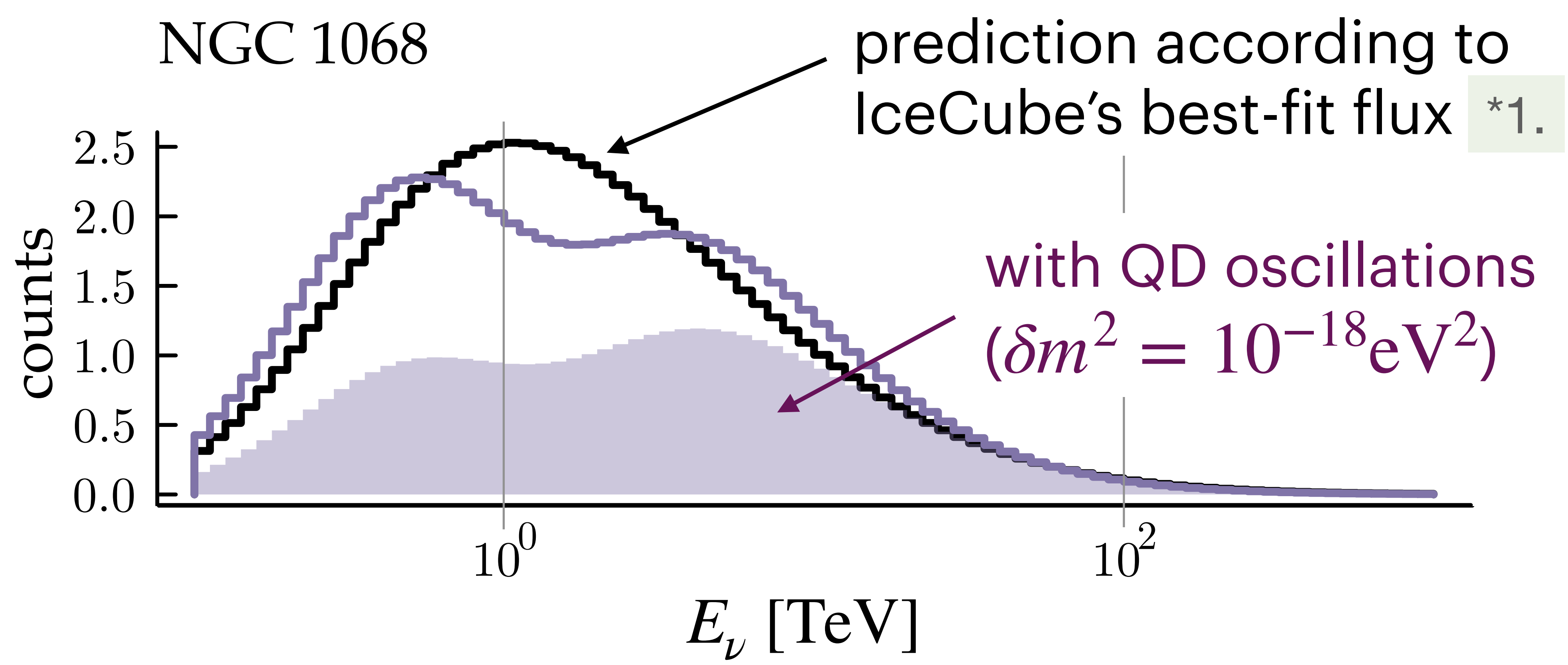

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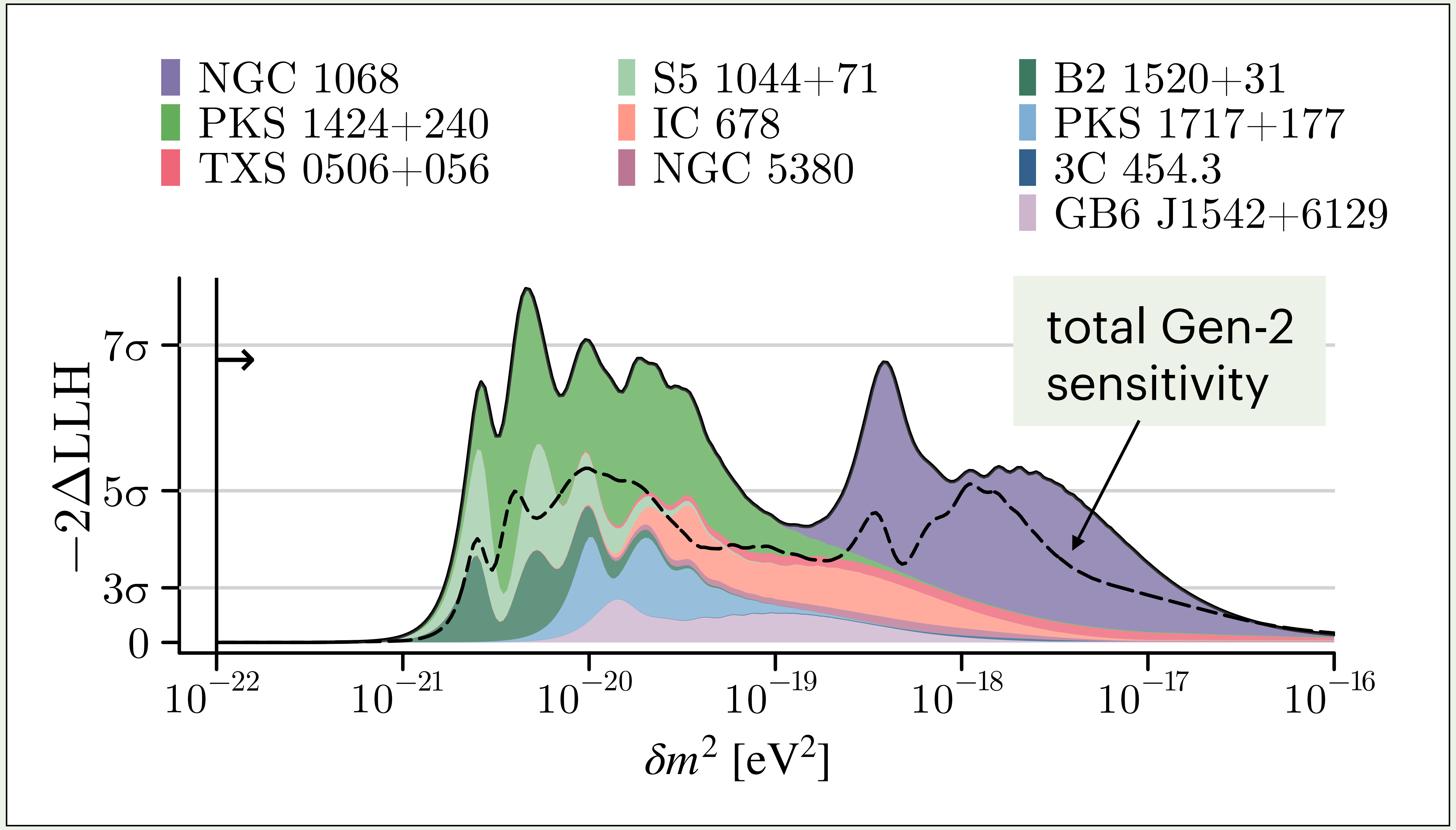
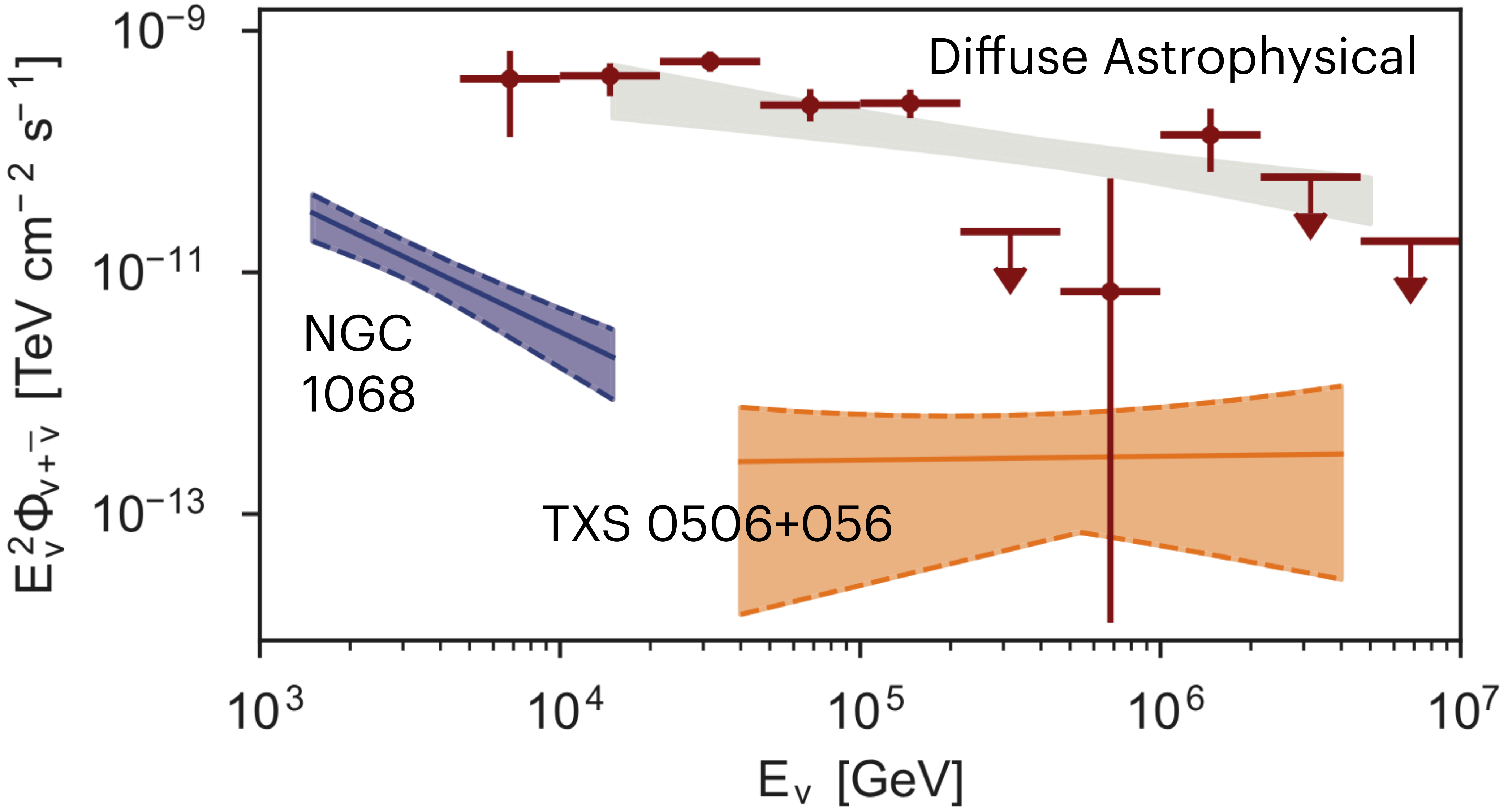


We found that the sensitivity is limited by:

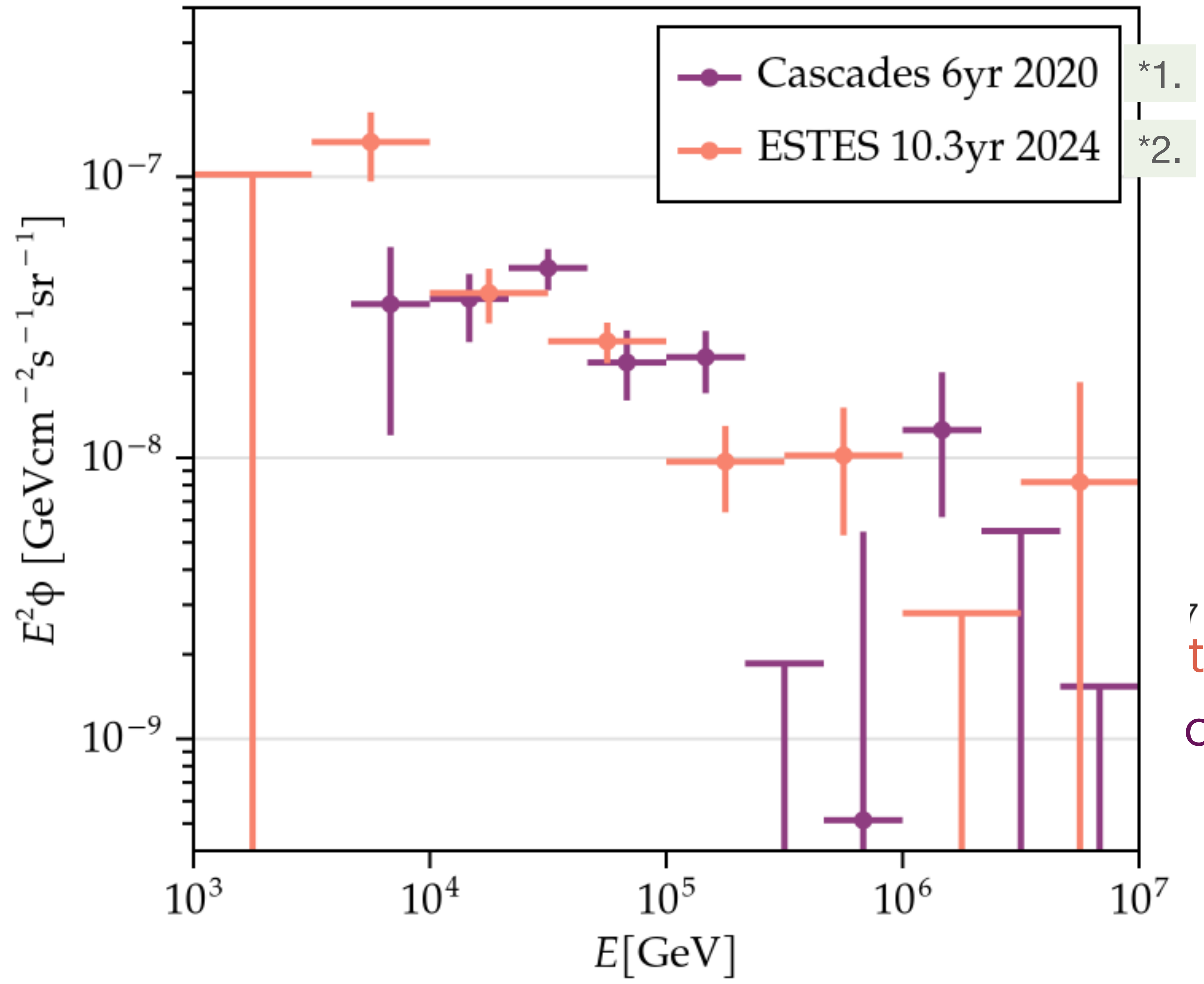
- poor energy resolution (~30% in $\log_{10} E$)
- need to marginalize over unknown spectra
- limited statistics (<100 events per source)

1. IceCube Collaboration, 2211.09972

IceCube Collaboration, 2211.09972



The total astrophysical flux is much larger and better characterized than that of individual sources...



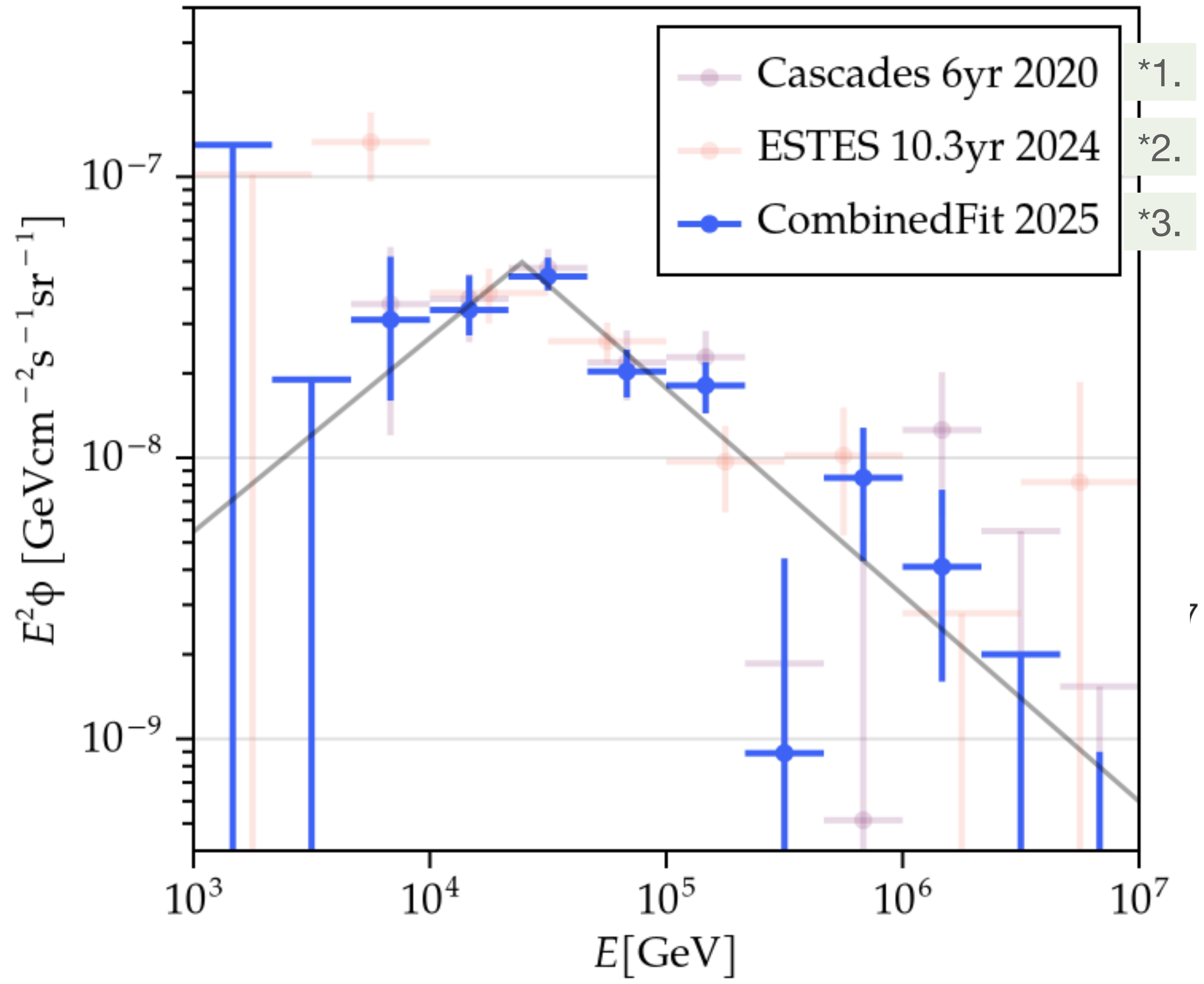
re-plotted from:
1. IceCube Collaboration, 2001.09520
2. IceCube Collaboration, 2402.18026

The total astrophysical flux is much larger and better characterized than that of individual sources...

...and has been measured in multiple flavor combinations.

tracks = ν_μ dominated

cascades = all-flavor



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1. IceCube Collaboration, 2001.09520
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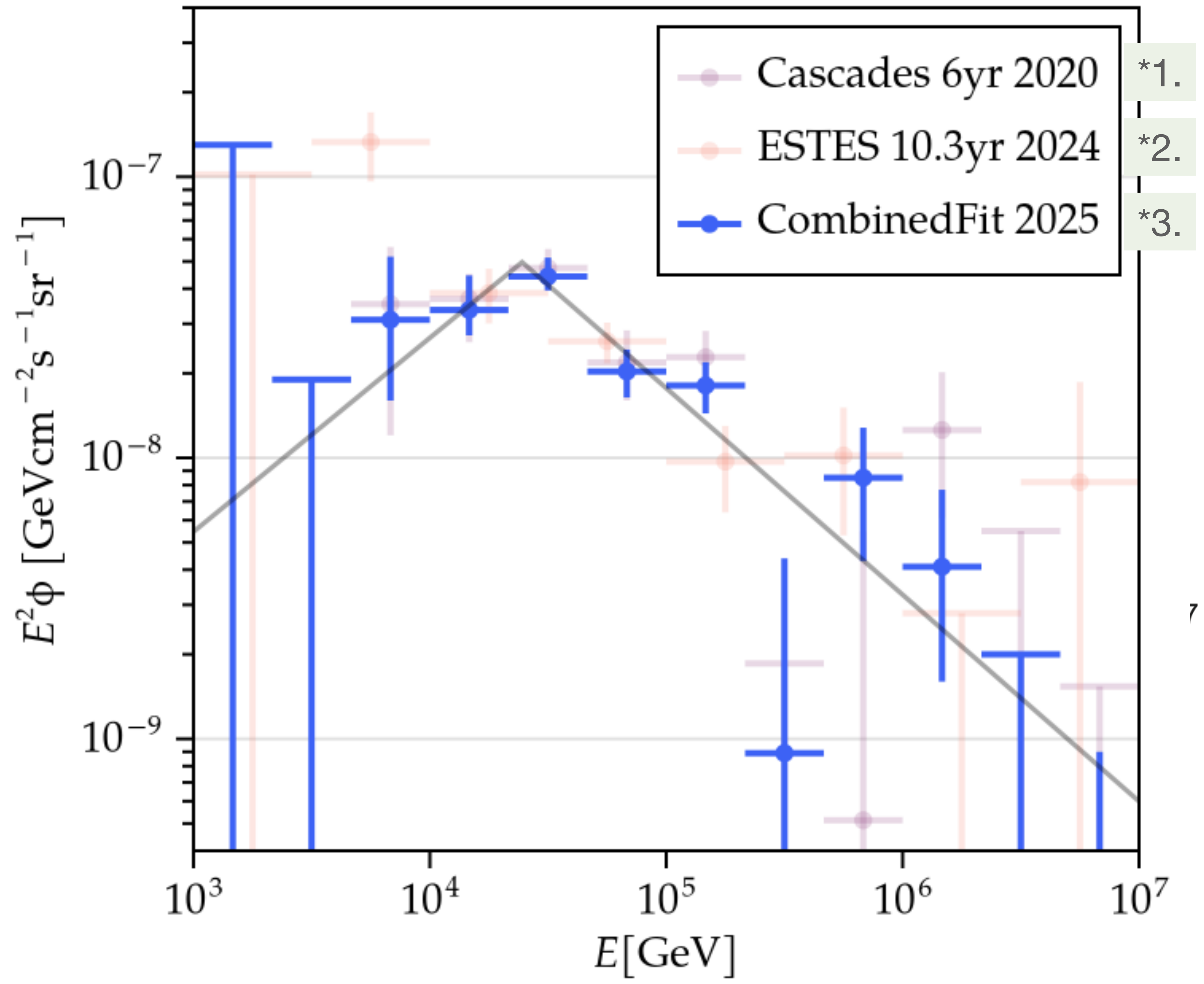
3. IceCube Collaboration, 2507.22234

The total astrophysical flux is much larger and better characterized than that of individual sources…

…and has been measured in multiple flavor combinations.

The most recent IceCube analyses found a >4σ preference for a break around 30TeV!



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The most recent IceCube analyses found a $>4\sigma$ preference for a break around 30TeV!

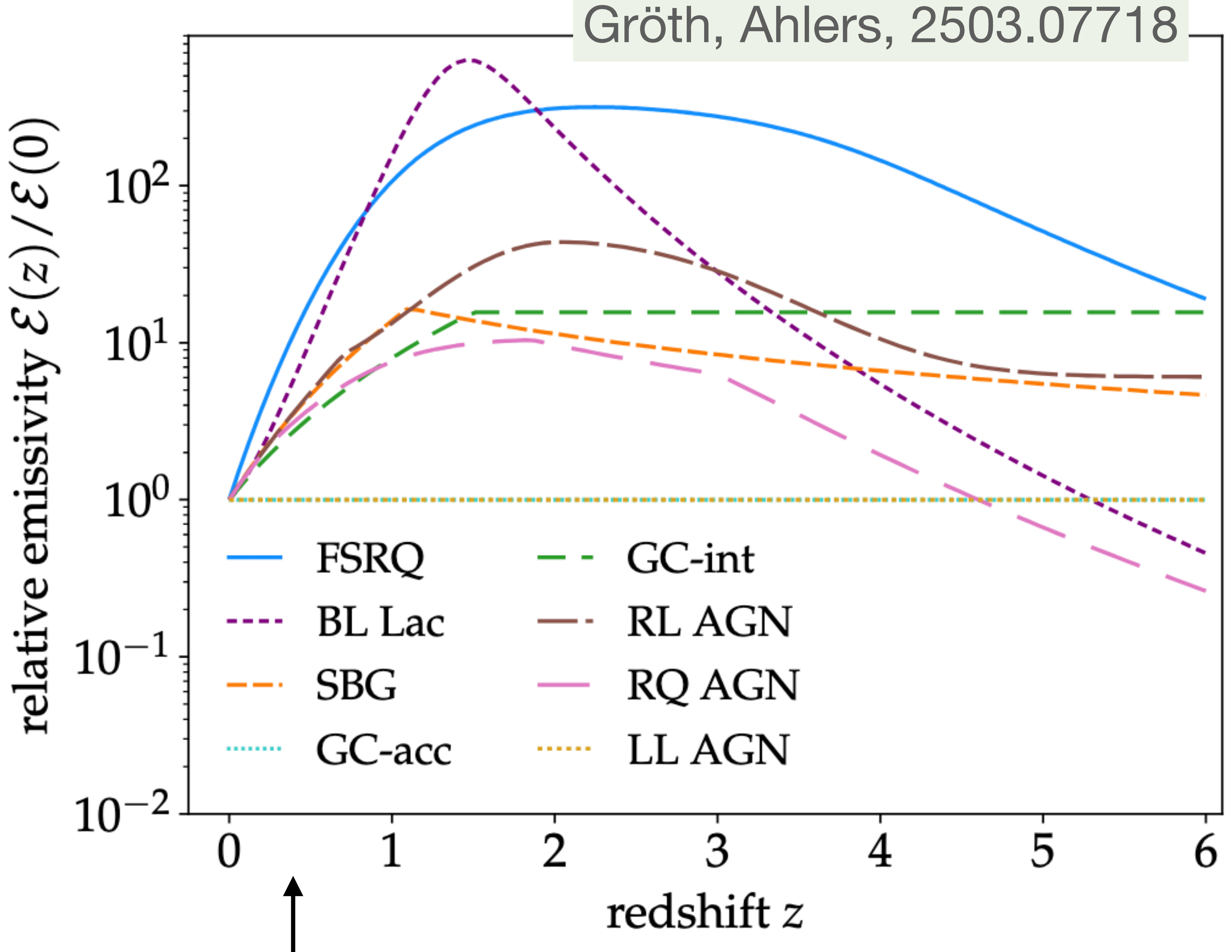
Can we use IceCube's diffuse flux measurements to constrain QD parameter space?

=> How is the total source population distributed across the universe?

In our study, we

- Consider multiple physical evolution functions $\rho(z)$

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



Scale as $(1+z)^m$ at small z, for $m = 0, 3, 5$

Note:
Capel, Mortlock, Finley (2022) found that IceCube's non-observation of point sources requires sources to be very dim and dense if you assume flat evolution.

Capel, Mortlock, Finley, 2005.02395

In our study, we

- Consider multiple physical evolution functions $\rho(z)$
- Assume all sources have the same emission spectrum $\phi_0(z)$, which can be a single power law, power law with a cutoff, or a broken power law

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

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

$P^{QD}_{\alpha\beta}$ = oscillation probability

f_α = initial flavor fraction

ϕ_0 = emission spectrum

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

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- Perform a likelihood fit to the IceCube flux measurements

- Marginalize over all emission spectrum parameters

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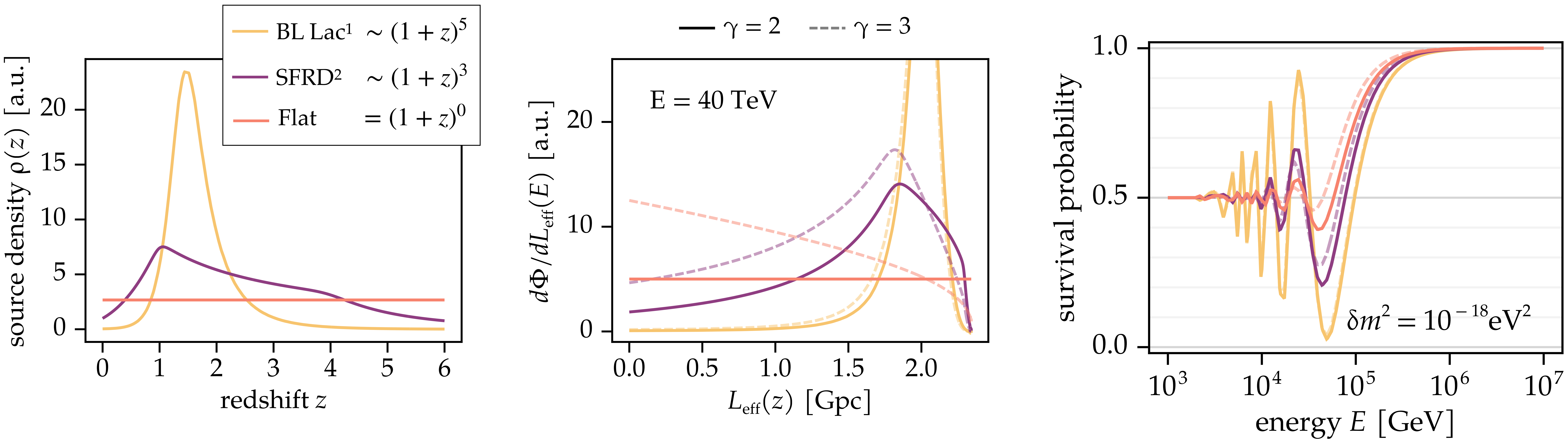
$$L_{\text{eff}}(z) = \int_0^z \frac{dz'}{H(z')(1+z')^2}$$

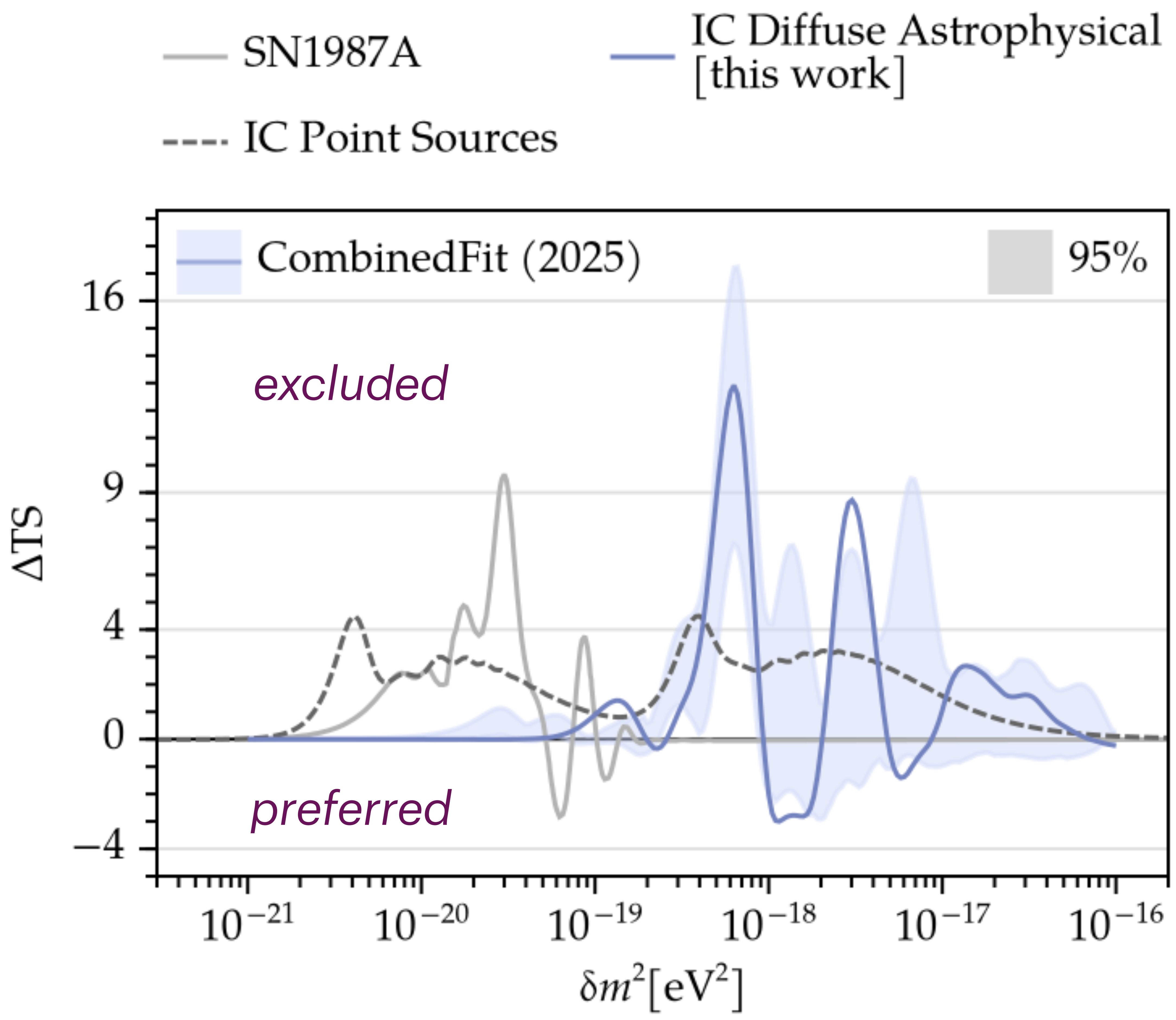
After integrating over all sources, we find that the QD disappearance dip remains resolvable!



1. Gröth, Ahlers, 2503.07718
2. Elías-Chávez, Martínez, 2503.07718

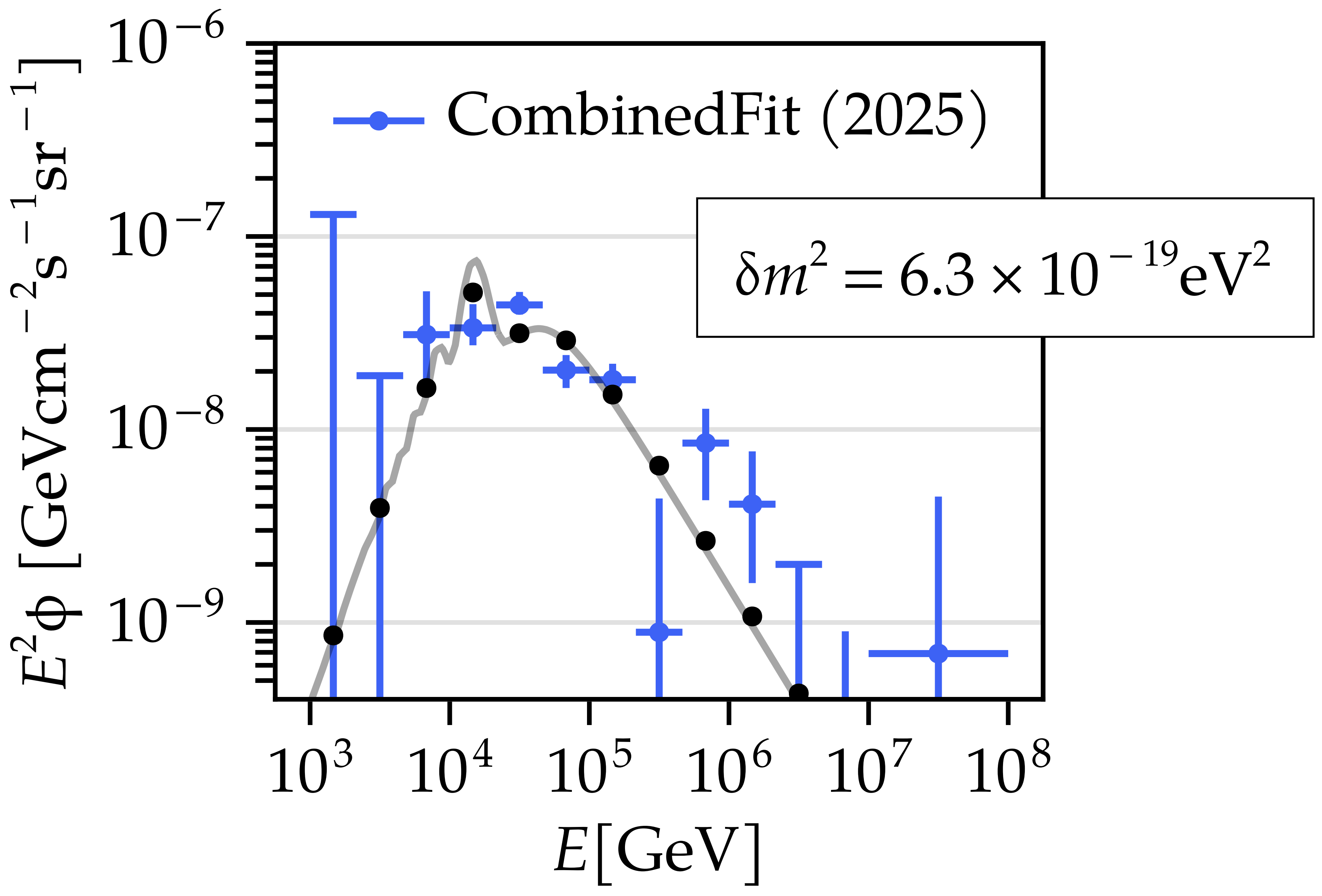
Results (1): Assuming equal squared-mass differences, $\delta m_k^2 = \delta m^2$

For our main result, we use a source evolution following the SFRD and emission given by a broken power law.



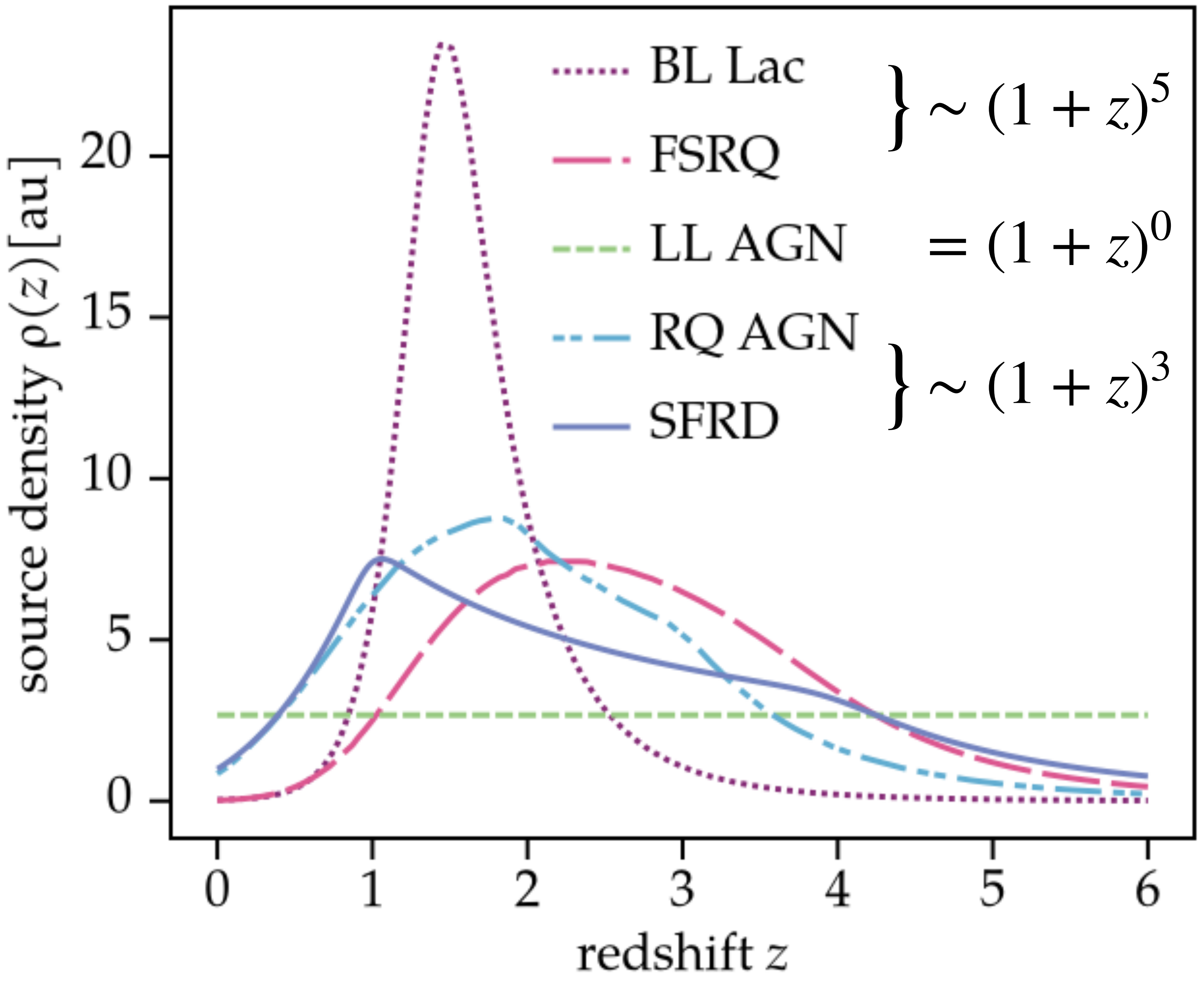
We find no preference for a QD hypothesis.

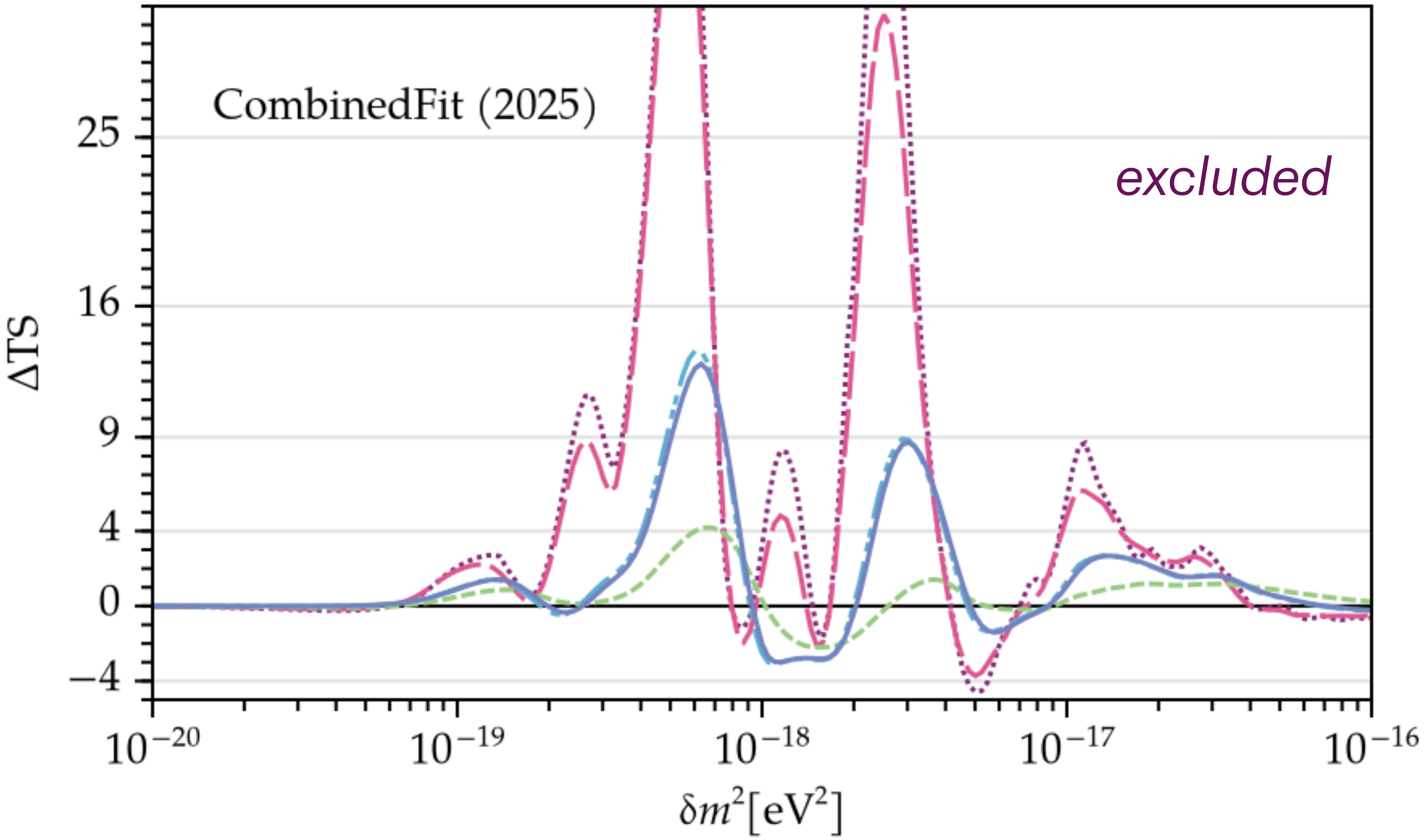
We constrain $\delta m^2 \in [5 - 7.5] \times 10^{-18}\ \mathrm{eV}^2$ at 3σ, driven by incompatibility at the break around 30TeV:



Results (1): Assuming equal squared-mass differences, $\delta m_k^2 = \delta m^2$

The significance of our constraints depend strongly on the scaling of the source evolution $\rho(z)$:

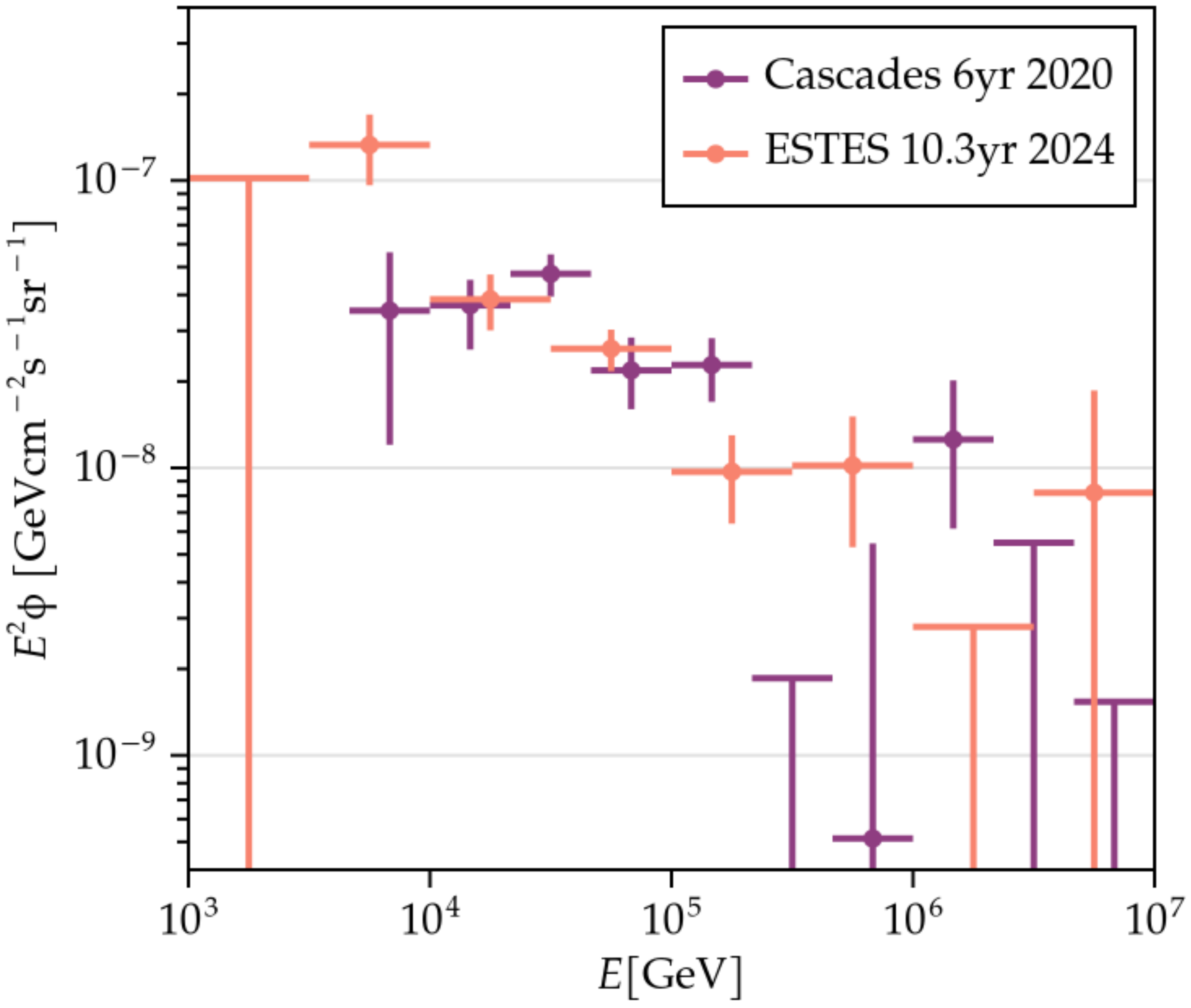




Redshift evolution models taken from: Gröth, Ahlers, 2503.07718; Elías-Chávez, Martínez, 2503.07718

Results (2): Assuming two distinct squared-mass differences => flavor-dependent effects

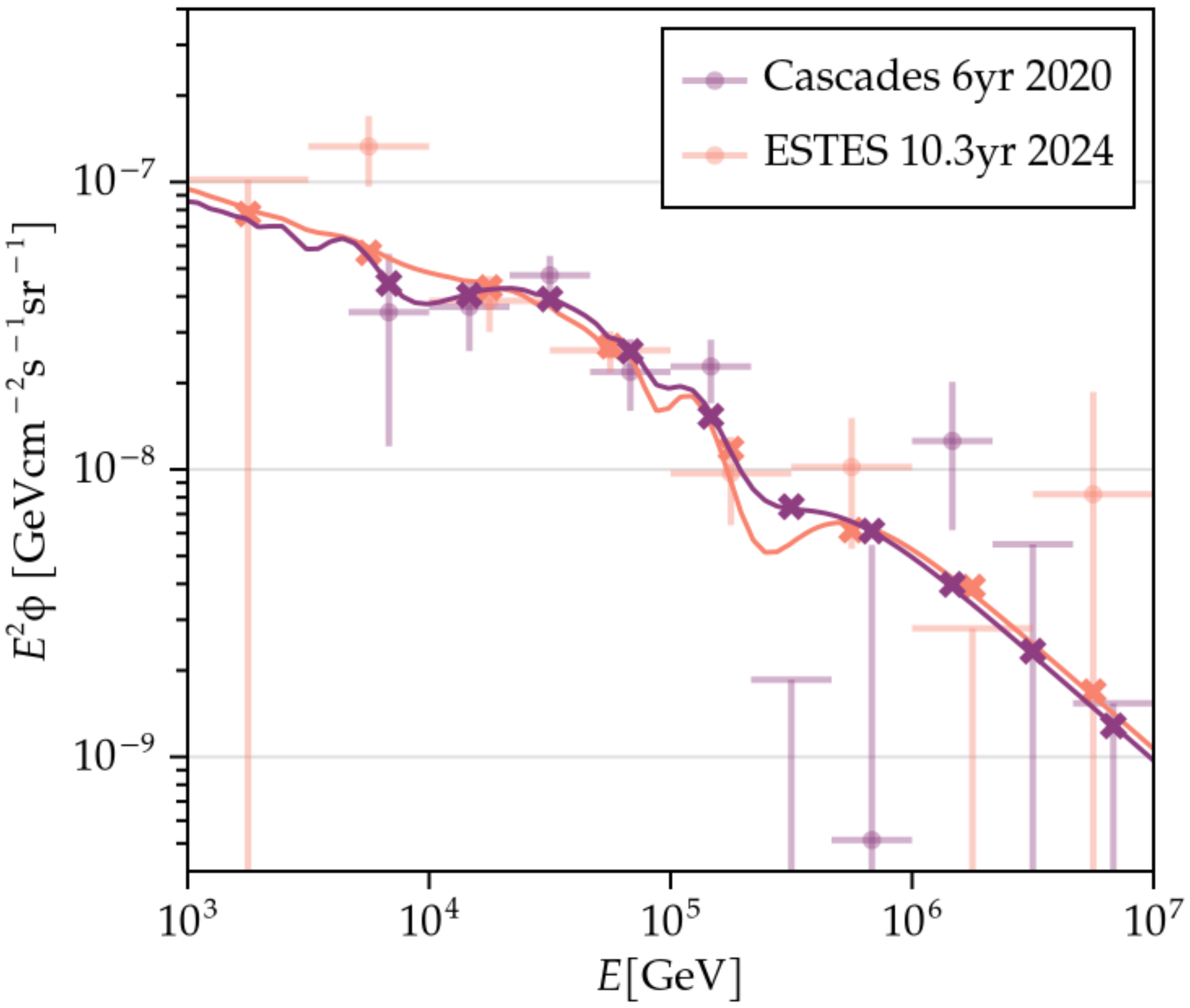
QD oscillations caused by δm_1^2 disproportionately affect cascades, while those caused by δm_3^2 disproportionately affect tracks.



Results (2): Assuming two distinct squared-mass differences => flavor-dependent effects

QD oscillations caused by δm_1^2 disproportionately affect cascades, while those caused by δm_3^2 disproportionately affect tracks.

However, we find this additional flexibility does not significantly improve the joint fit (1.4σ)



Conclusions:

- The effects of extremely long baseline quasi-Dirac oscillations are resolvable in the total astrophysical ν flux

- We set constraints on $\delta m^2 \in [5, 7.5] \times 10^{-18}\ \mathrm{eV}^2$

Prospects:

- IceCube's diffuse flux measurements are continuously improving
  - better control of systematics

- Our understanding of what astrophysical objects produce neutrinos is improving!
  - => better characterize source population distribution and emission spectra

¡Gracias!

Sample(s)	Redshift dist. $\rho(z)$	3σ region(s) [eV^2]
`CombinedFit`	SFRD [55]	$(5.0 - 7.5) \times 10^{-19}$
`Cascades` + `ESTES`	SFRD [55]	$(5.9 - 7.9) \times 10^{-19}$
`CombinedFit`	BL Lac [56]	$(2.4 - 3.0), (3.5 - 7.2), (18 - 35) \times 10^{-19}$
`CombinedFit`	FSRQ [56]	$(3.5 - 7.2), (19 - 35) \times 10^{-19}$
`CombinedFit`	LL AGN [56]	
`CombinedFit`	RQ AGN [56]	$(4.9 - 7.5) \times 10^{-19}$

TABLE I. ***Limits on the squared-mass difference.***. These results assume the source emission spectrum is a broken power-law (BPL).

Sample(s)	Flux Model ϕ	$\delta m^2[\mathrm{eV}^2]$	TS	dof	p-value
`CombinedFit`					
	SPL	*null*	35.67	11	0.02%
	SPL	7.2×10^{-20}	18.93	10	4.11%
	SPE	*null*	22.82	10	1.14%
	SPE	6.9×10^{-20}	13.91	9	12.57%
	BPL	*null*	9.17	9	42.20%
	BPL	1.2×10^{-18}	6.17	8	62.84%
`Cascades + ESTES`					
	SPL	*null*	28.10	16	3.07%
	SPL	1.9×10^{-19}	25.10	15	4.87%
	SPE	*null*	26.67	15	3.16%
	SPE	6.3×10^{-18}	22.64	14	6.63%
	BPL	*null*	25.06	14	3.39%
	BPL	6.0×10^{-18}	22.18	13	5.26%

TABLE II. ***Best fit parameters, for each combination of IceCube results used, assuming a single mass-squared difference δm^2.*** These results use the SFRD [55] for the source redshift distribution $\rho(z)$.

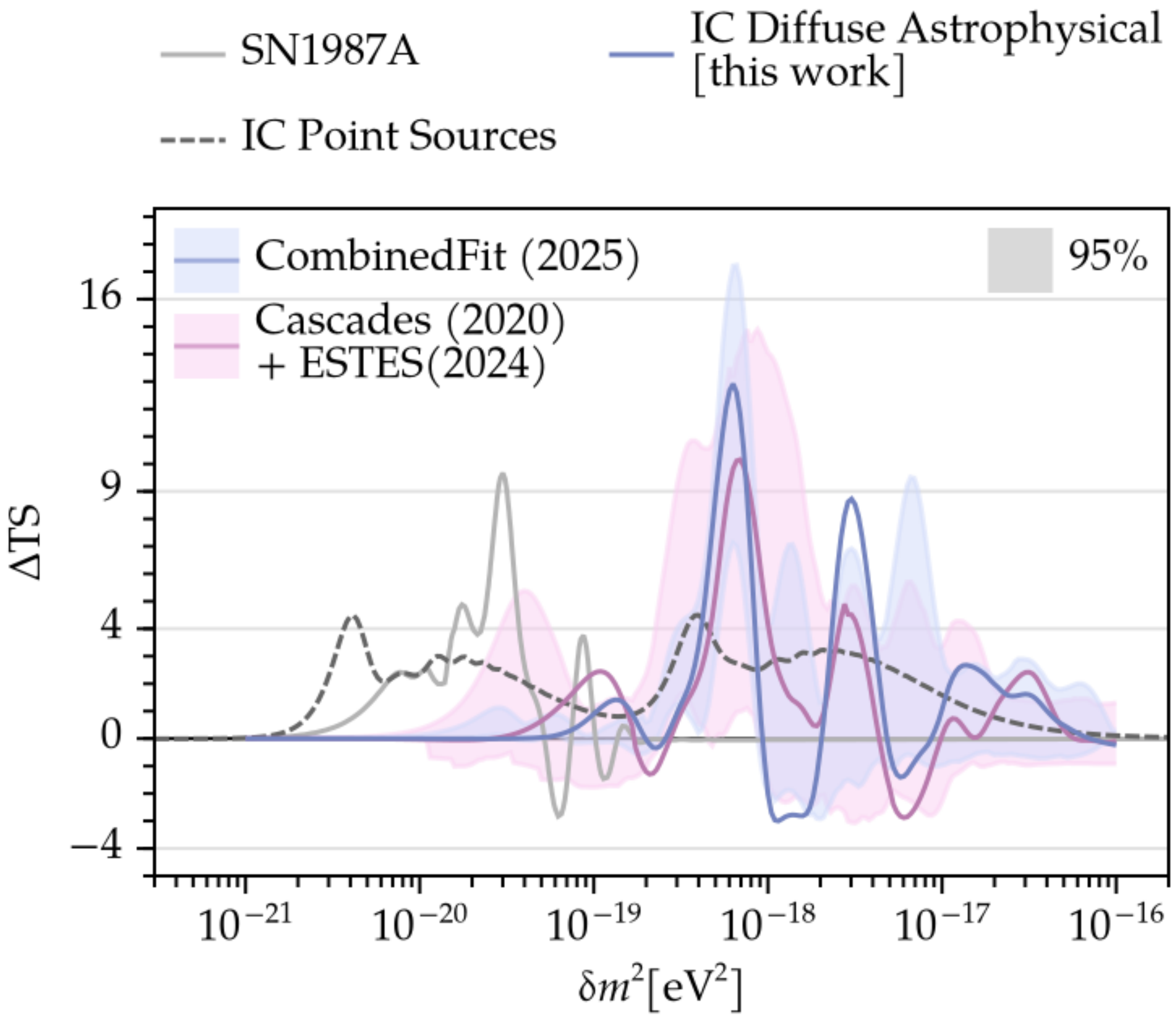
Flavor Ratio		Flux Model ϕ	$\delta m_1^2[\mathrm{eV}^2]$	$\delta m_2^2[\mathrm{eV}^2]$	$\delta m_3^2[\mathrm{eV}^2]$	TS	dof	p-value
Pion decay	(1,2,0)	BPL	*null*	*null*	*null*	25.06	14	3.39%
Muon-damped	(0,1,0)	BPL	*null*	*null*	*null*	32.52	14	0.34%
Neutron dom.	(1,0,0)	BPL	*null*	*null*	*null*	33.35	14	0.26%
Pion decay	(1,2,0)	BPL	2.0×10^{-19}	5.6×10^{-18}	$= \delta m_2^2$	20.00	12	6.71%
Muon-damped	(0,1,0)	BPL	2.5×10^{-20}	$= \delta m_1^2$	5.6×10^{-18}	27.12	12	0.74%
Neutron dom.	(1,0,0)	BPL	6.3×10^{-18}	1.0×10^{-21}	$= \delta m_2^2$	25.63	12	1.21%

TABLE III. ***Best fit parameters for fits assuming two distinct mass-squared differences.*** These results are based on the combined `Cascades` and `ESTES` flux points, and use the SFRD [55] for the source redshift distribution $\rho(z)$.

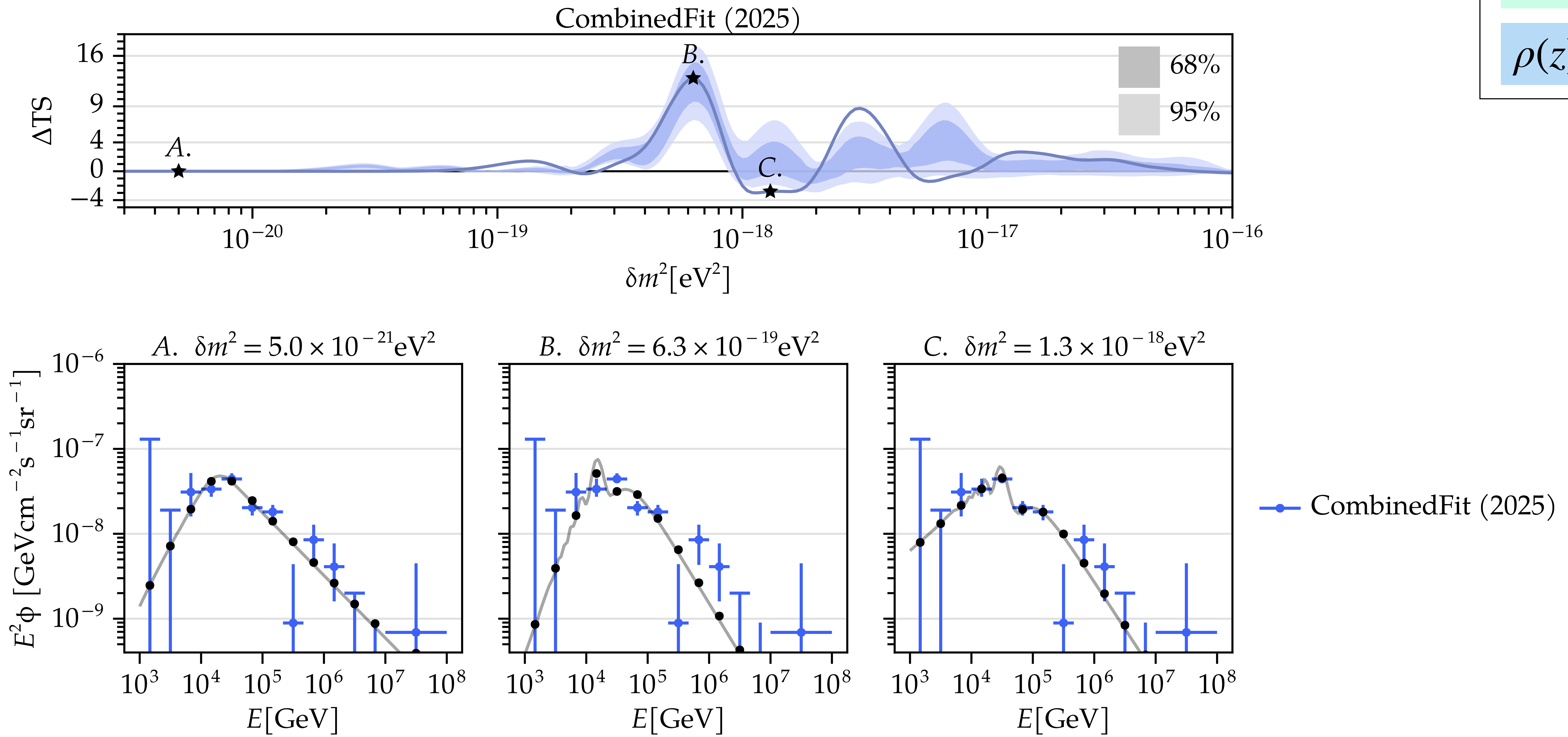
f_α = pion decay

ϕ_0 = BPL

$\rho(z)$ ~ SFRD



Constraints based on the *CombinedFit* measurements are consistent with those using *Cascades* and *ESTES*.



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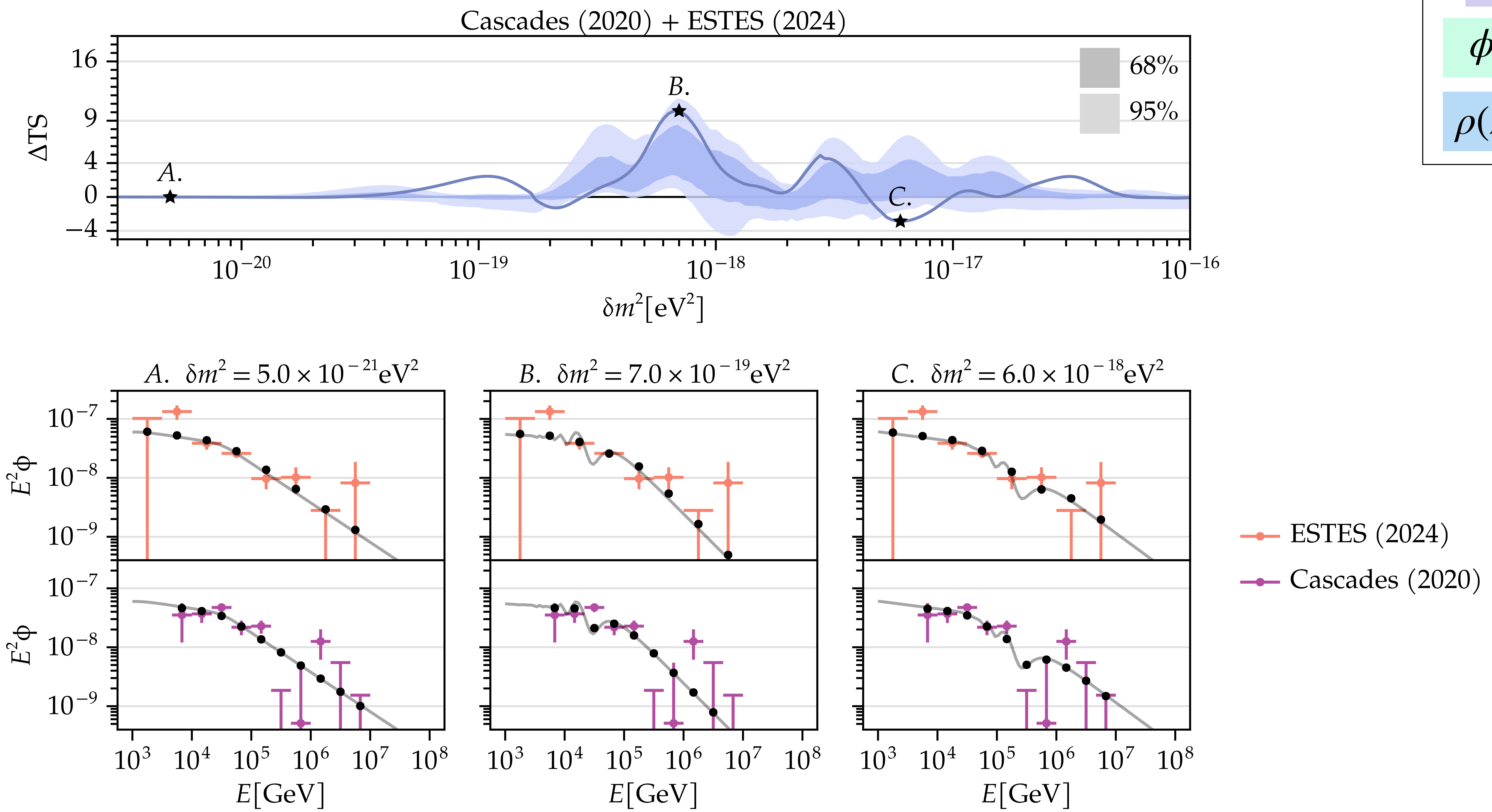

f_α	= pion decay
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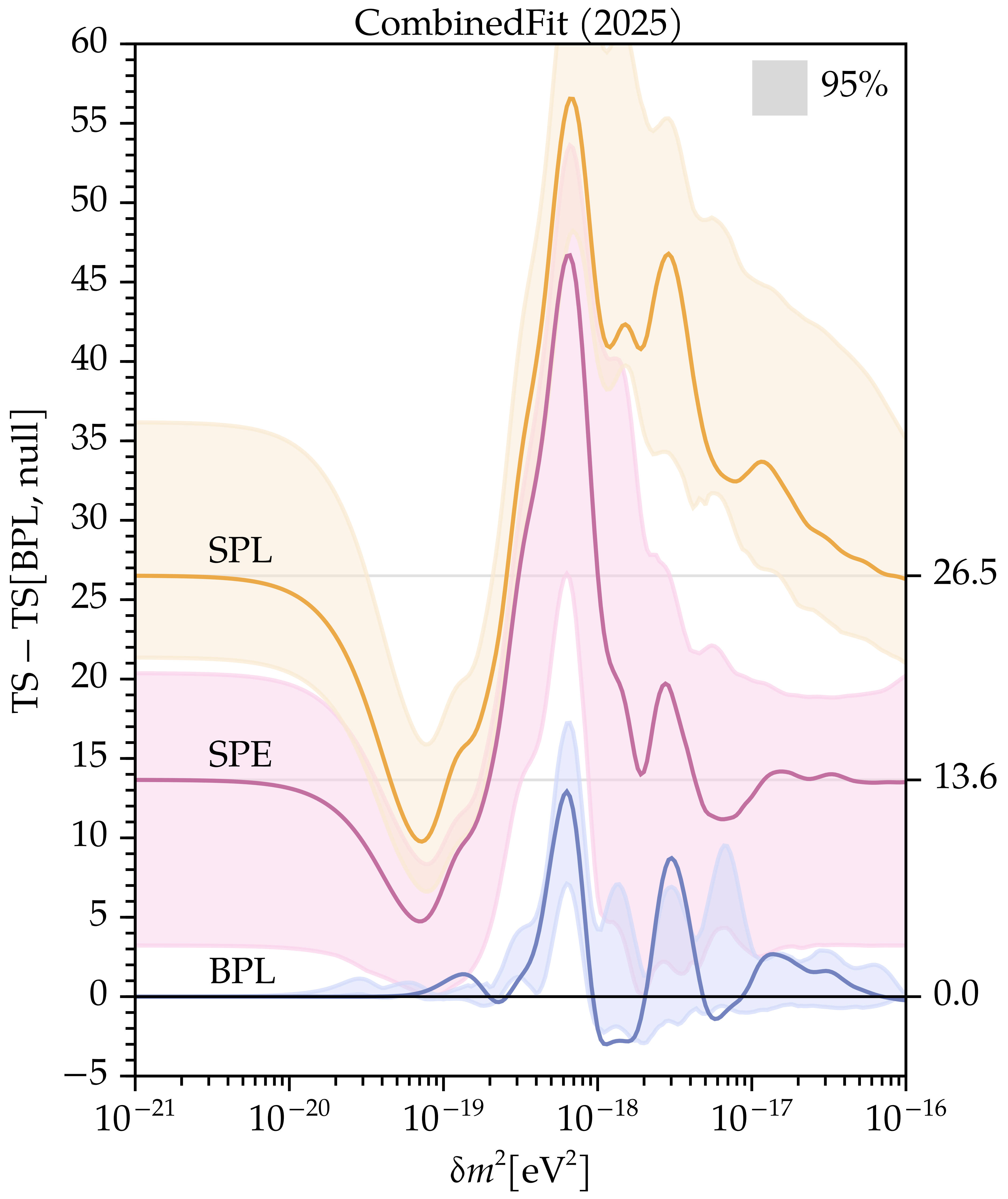
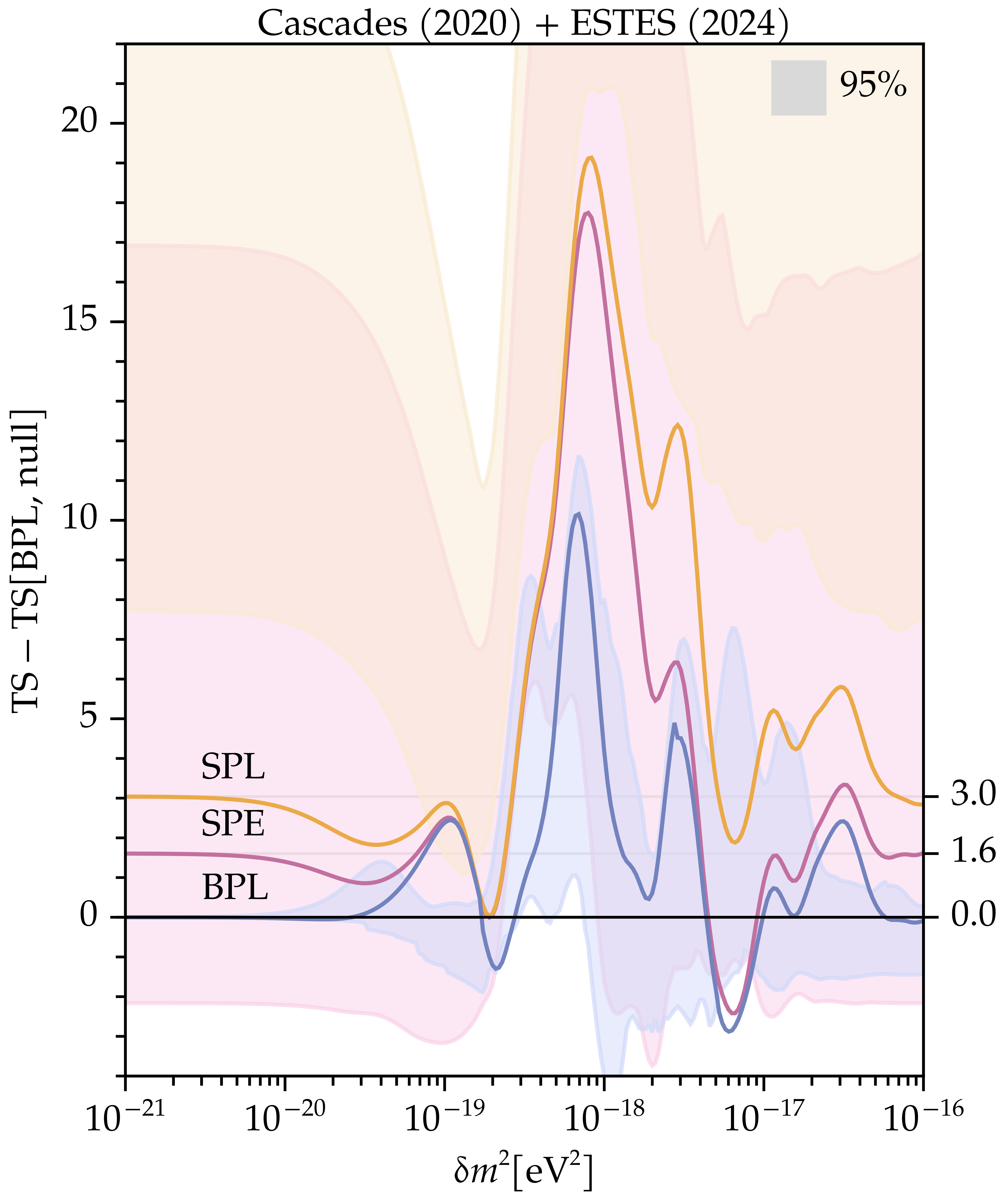

CombinedFit (2025)
95%
SPL
SPE
BPL
26.5
13.6
0.0
TS − TS[BPL, null]
δm²[eV²]

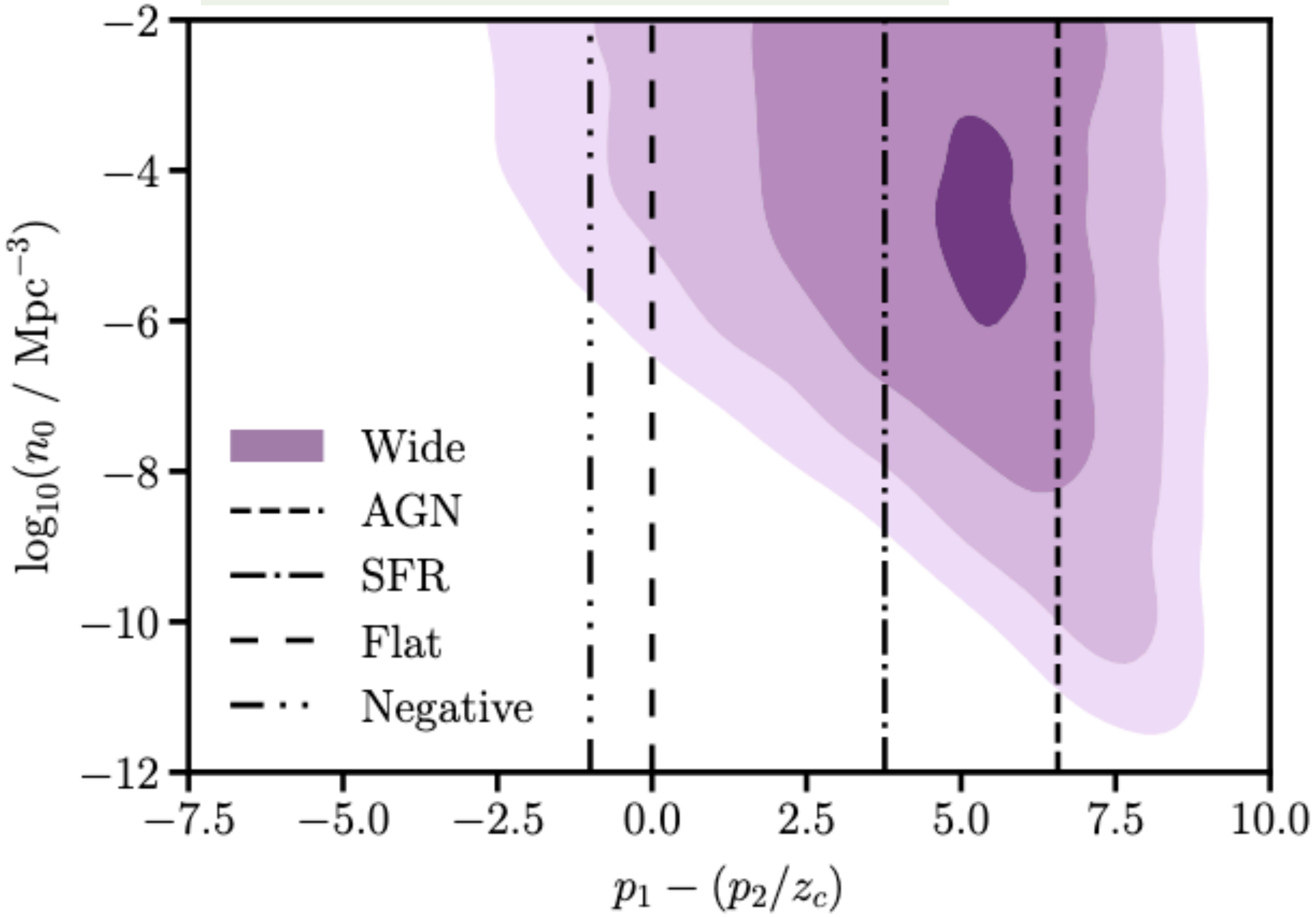

Cascades (2020) + ESTES (2024)
95%
SPL
SPE
BPL
3.0
1.6
0.0
TS − TS[BPL, null]
δm²[eV²]

Fit	Sample	Flux Model				
		SPL	γ	ϕ_0		
IceCube	`Cascades`		$2.53^{+0.07}_{-0.07}$	$1.66^{+0.25}_{-0.27}$		
This work	`Cascades`		2.41	1.95		
IceCube	`ESTES`		$2.58^{+0.1}_{-0.09}$	$1.68^{+0.19}_{-0.22}$		
This work	`ESTES`		2.57	1.60		
IceCube	`CombinedFit`		$2.52^{+0.036}_{-0.038}$	$1.8^{+0.13}_{-0.16}$		
This work	`CombinedFit`		2.35	1.83		
		SPE	γ	ϕ_0	$\log_{10} E_{\rm cut}$	
IceCube	`Cascades`		$2.45^{+0.09}_{-0.11}$	$1.83^{+0.37}_{-0.31}$	$6.4^{+0.9}_{-0.4}$	
This work	`Cascades`		2.30	2.41	6.29	
IceCube	`CombinedFit`		$2.386^{+0.081}_{-0.09}$	$2.2^{+0.3}_{-0.25}$	$6.15^{+0.37}_{-0.24}$	
This work	`CombinedFit`		2.19	2.40	5.99	
		BPL	ϕ_0	$\log_{10} E_{\rm break}$	γ_1	γ_2
IceCube	`Cascades`		$1.71^{+0.65}_{-0.29}$	$4.6^{+0.5}_{-0.2}$	$2.11^{+0.29}_{-0.67}$	$2.75^{+0.29}_{-0.14}$
This work	`Cascades`		2.15	4.42	1.52	2.67
IceCube	`ESTES`		$1.70^{+0.19}_{-0.22}$	4.36	$2.79^{+0.3}_{-0.5}$	$2.52^{+0.1}_{-0.09}$
This work	`ESTES`		1.51	4.67	2.46	2.72
IceCube	`CombinedFit`		$1.77^{+0.19}_{-0.18}$	$4.39^{+0.1}_{-0.1}$	$1.31^{+0.51}_{-1.3}$	$2.735^{+0.067}_{-0.075}$
This work	`CombinedFit`		1.75	4.36	1.25	2.74

SUPPL. TABLE IV. ***Compatibility with IceCube results*** Best-fit parameters obtain in our analysis compared with IceCube published values and their uncertainties.

The non-observation of point sources requires sources to be very dim and dense if you assume flat evolution
— see Capel et. al. (2017).

Capel, Mortlock, Finley, 2005.02395



How do neutrinos acquire mass?

We could write down a Yukawa coupling to a right-handed neutrino…

$$\mathscr{L}_{\nu-\text{mass}} = -m_D \bar{\nu}_R \nu_L + m_R \nu_R^T C^\dagger \nu_R + \text{H.c.}$$
$$= N_L^T C^\dagger \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix} N_L$$

In the QD limit, $m_D \gg m_R$, the 1-dimensional eigensystem is:

$$\begin{bmatrix} \nu_L \\ \nu_R^C \end{bmatrix} = R_\theta \begin{bmatrix} \nu^+ \\ \nu^- \end{bmatrix}$$

$m_\pm = m_D(1 \pm m_R/m_D)$ **tiny mass-squared difference**

$\tan 2\theta = 2m_D/m_R \gg 1$ **maximal mixing**

The 3D system is approximately equal to three copies of the 1D system; the mixing between mass generations (PMNS) are unchanged!

QD-nos undergo very long baseline oscillations between the sterile and active states:

$$P_{\alpha \to \beta} = \left| \hat{V} \exp(i\hat{M}^2/2Et)\hat{V}^\dagger \right|^2_{\beta\alpha}$$

$$= \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \cos^2\left(\delta m_j^2 L/4E\right) + \sum_{i>j} \mathrm{Re}\left[\exp[i\Delta m_{ij}^2 L/2E] \times \ldots\right]$$

Quasi-Dirac oscillations are not washed out by extragalactic baselines.
This is because the coherence length is

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

Therefore, for benchmark values of 10 TeV and $\delta m_k^2 = 10^{-19}\text{eV}^2$, the coherence length is comparable to the radius of the observable universe, even for wavepacket sizes $\sigma_x \sim 10^{-19}\text{m}$, orders of magnitude smaller than the smallest wave packets typically considered.