Searching for quasi-Dirac oscillations in the high-energy astrophysical neutrino flux

Kiara Carloni, Harvard University

KC, Martinez-Soler, Argüelles, Babu, Dev, PRD 109, L051702 (2024)

KC, Porto, Argüelles, Dev, Jana, 2503.19960

MacDonald, KC, Argüelles, Alves-Batista, Martinez-Soler (to appear)

How do neutrinos get their mass?
Are they their own antiparticle?

If (undetected) right-handed neutrinos exist,
then neutrinos can get their mass similarly to how charged leptons do…

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Dirac term Majorana term

Modified from Symmetry Magazine (2015)

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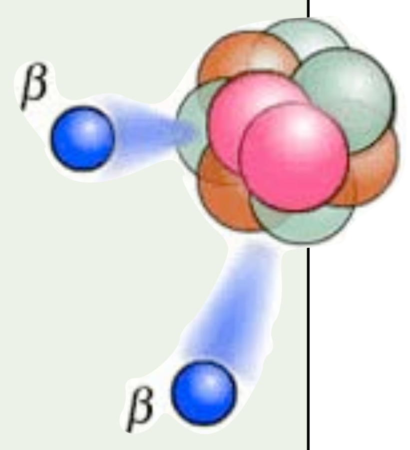
exactly Dirac!

more Majorana ⟶

neutrino-less double beta decay



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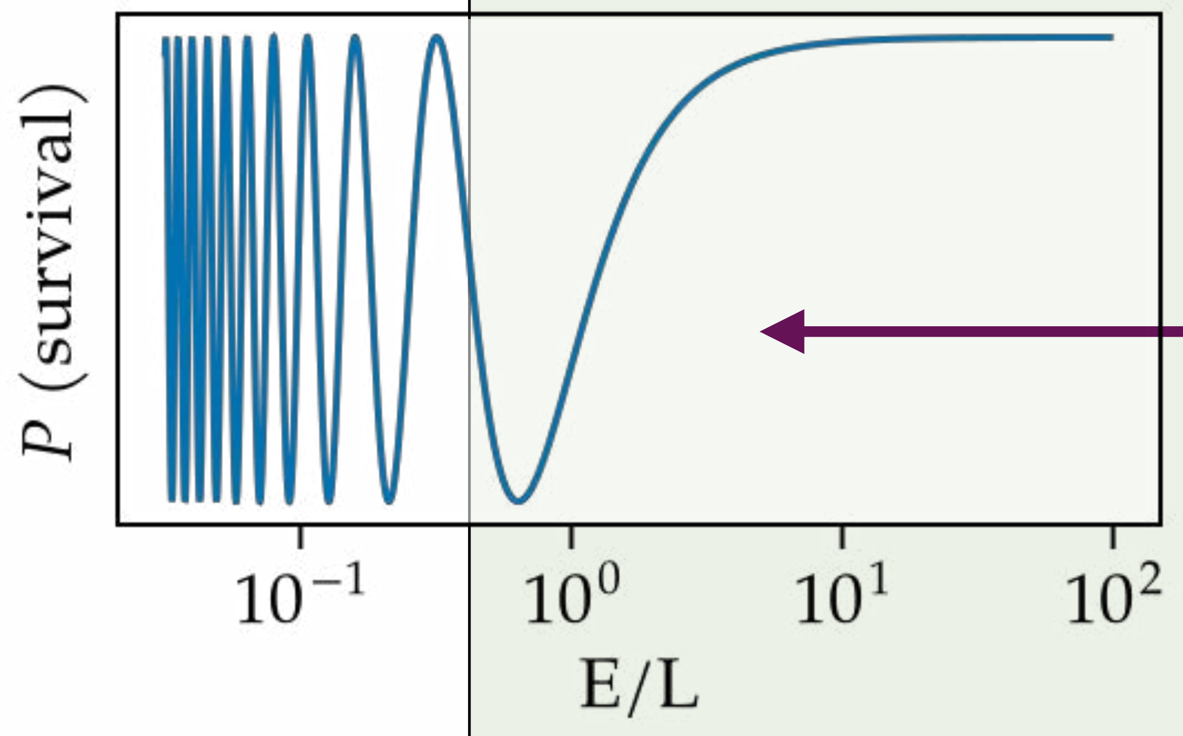

see-saw mechanism
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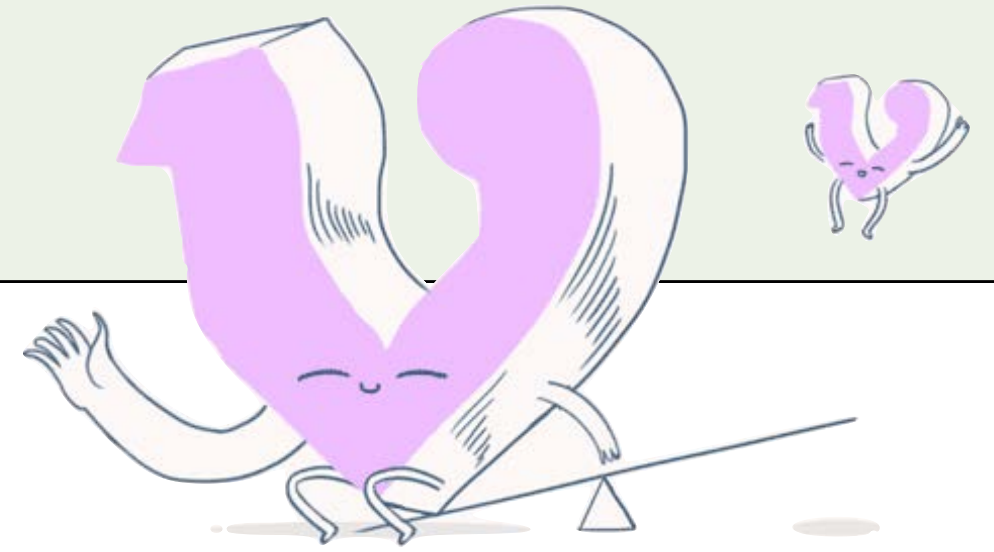
quasi-Dirac neutrinos*



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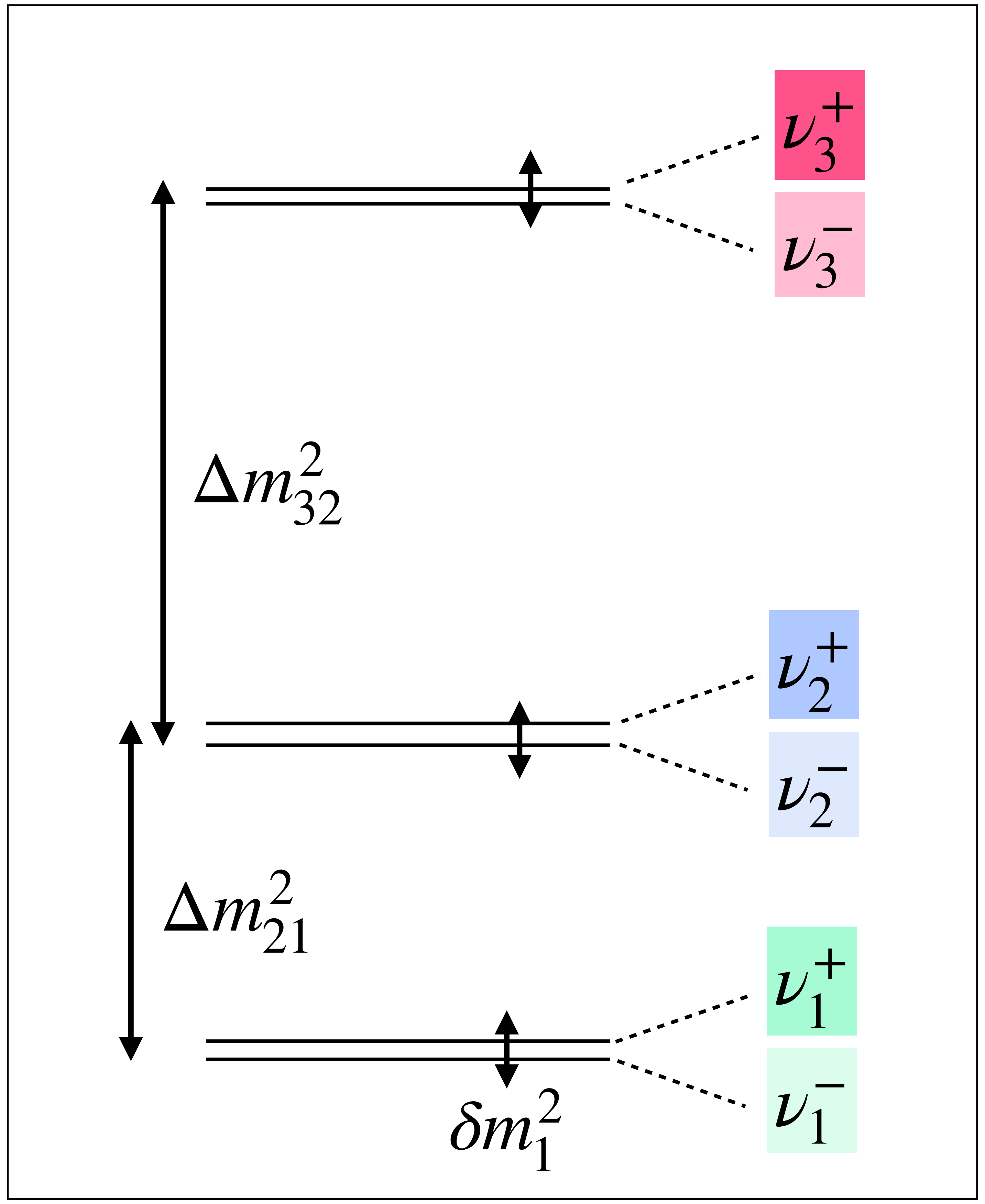

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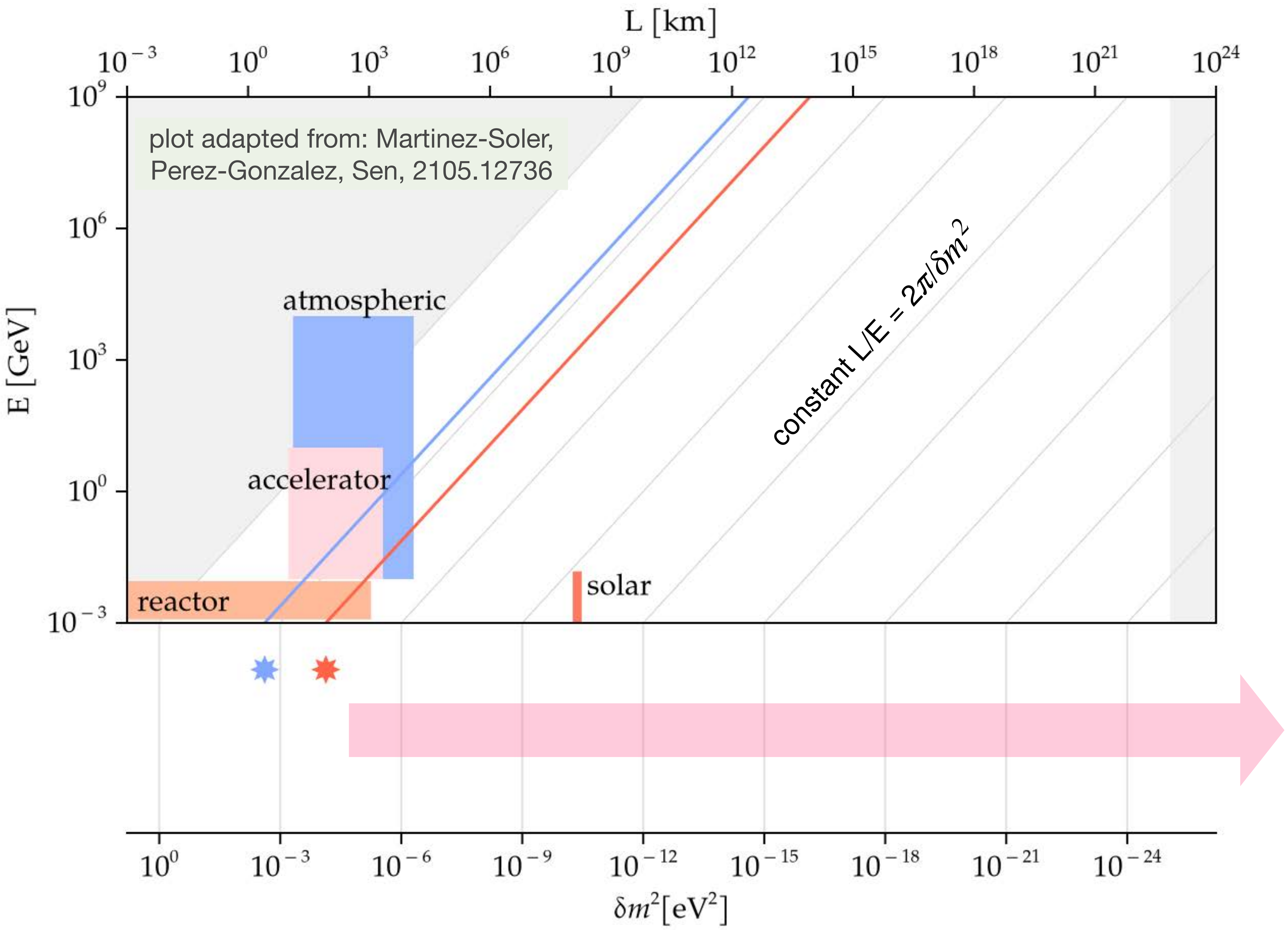

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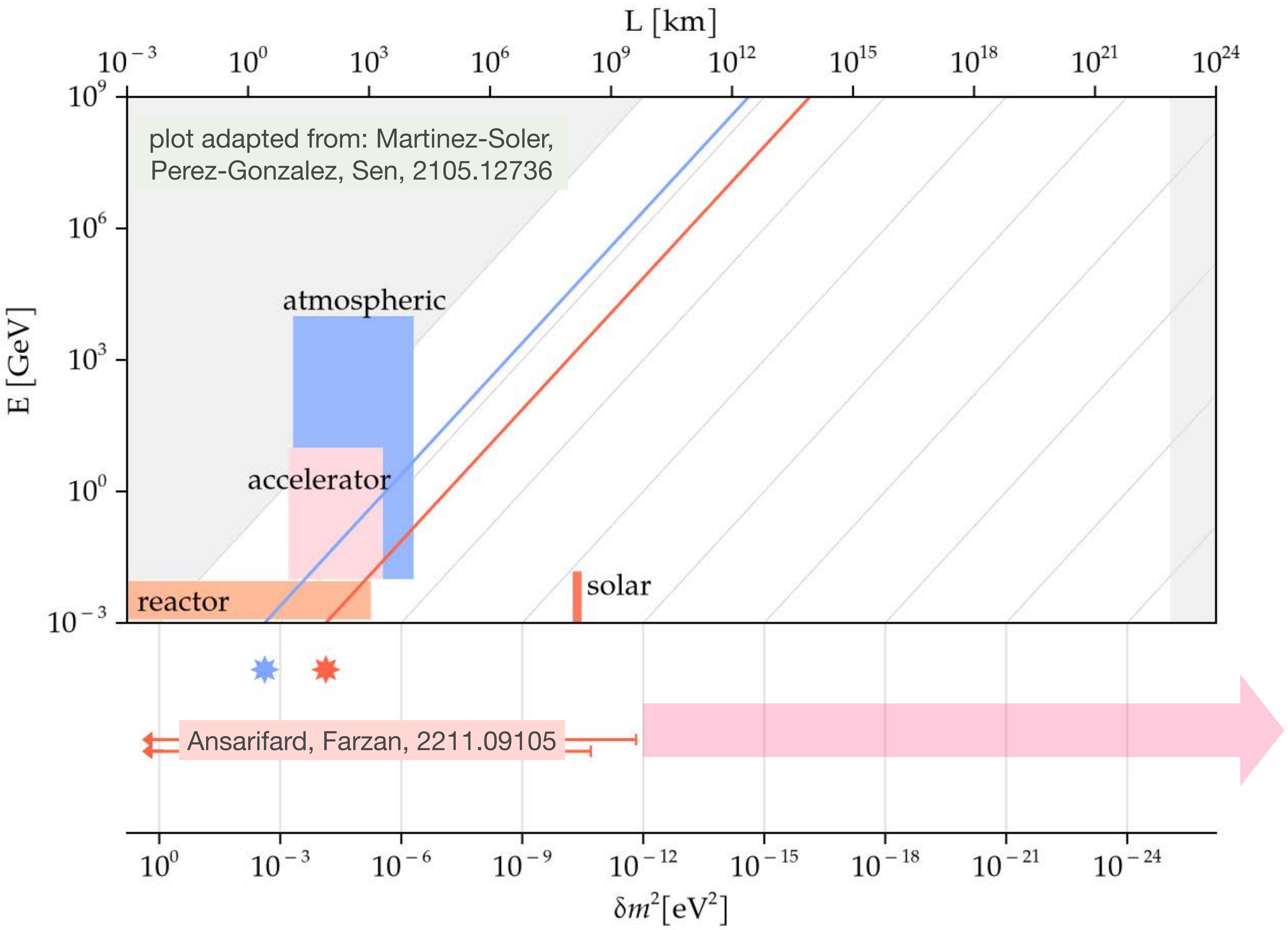

Solar: Ansarifard, Farzan, 2211.09105

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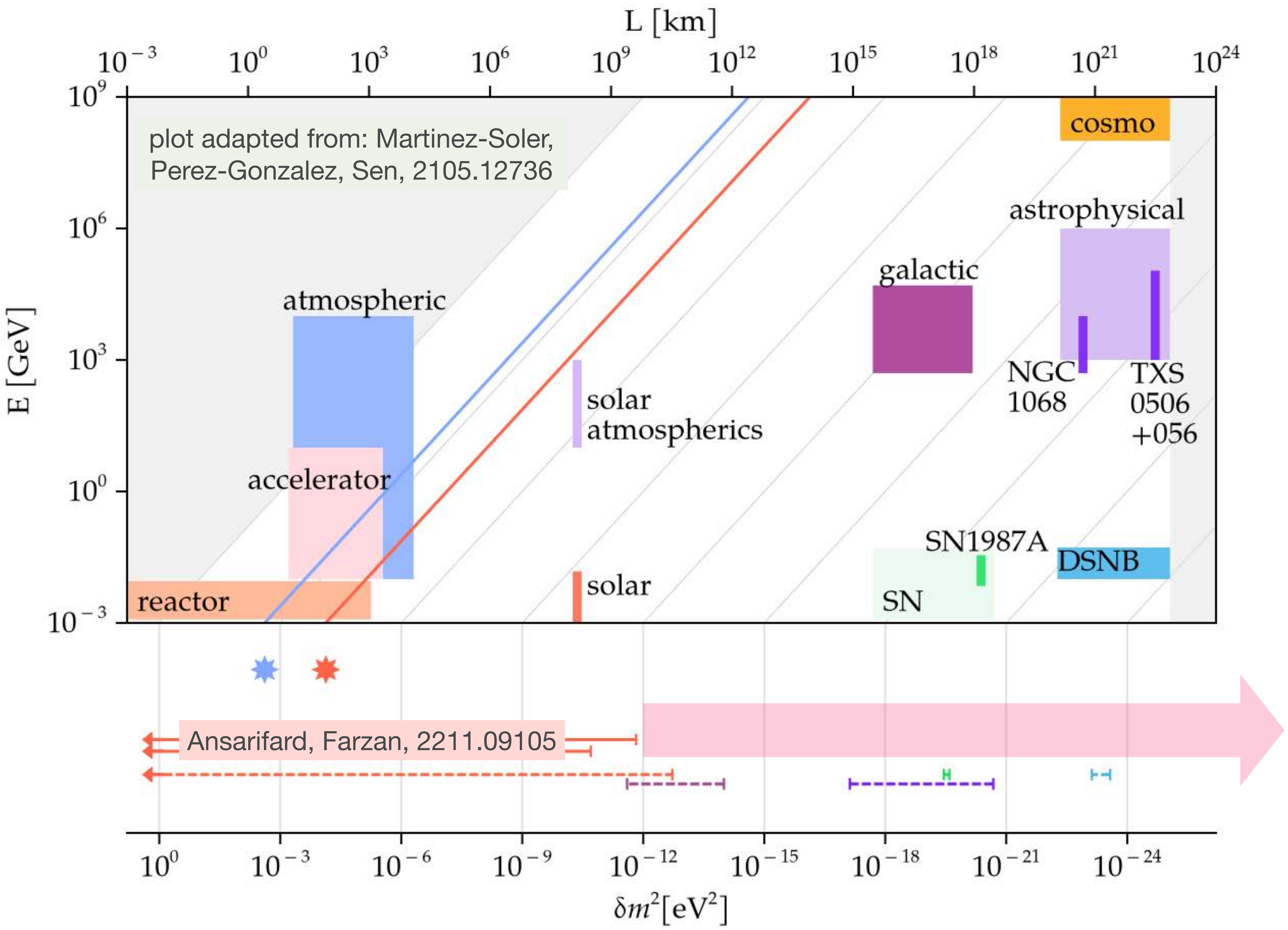

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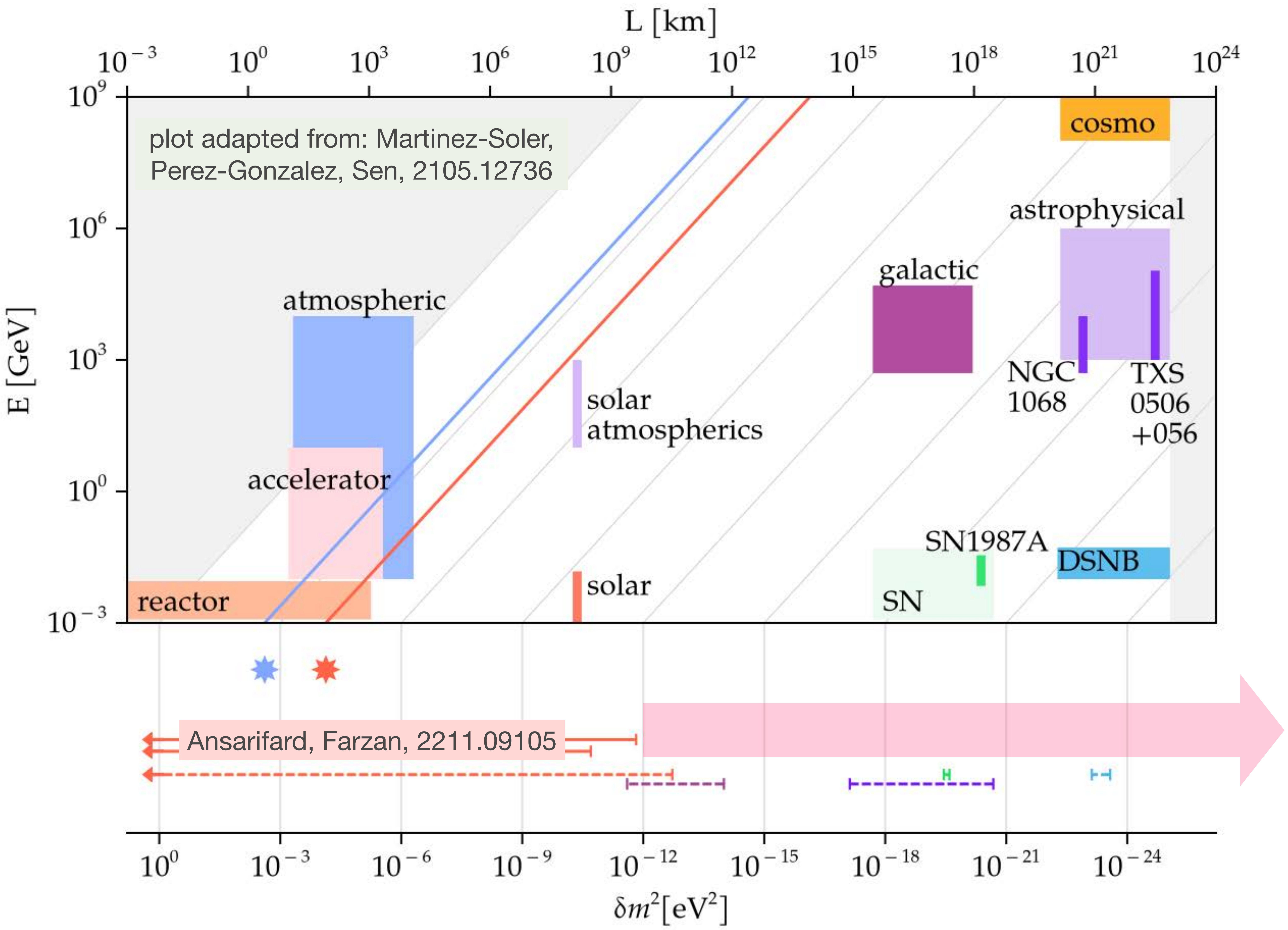

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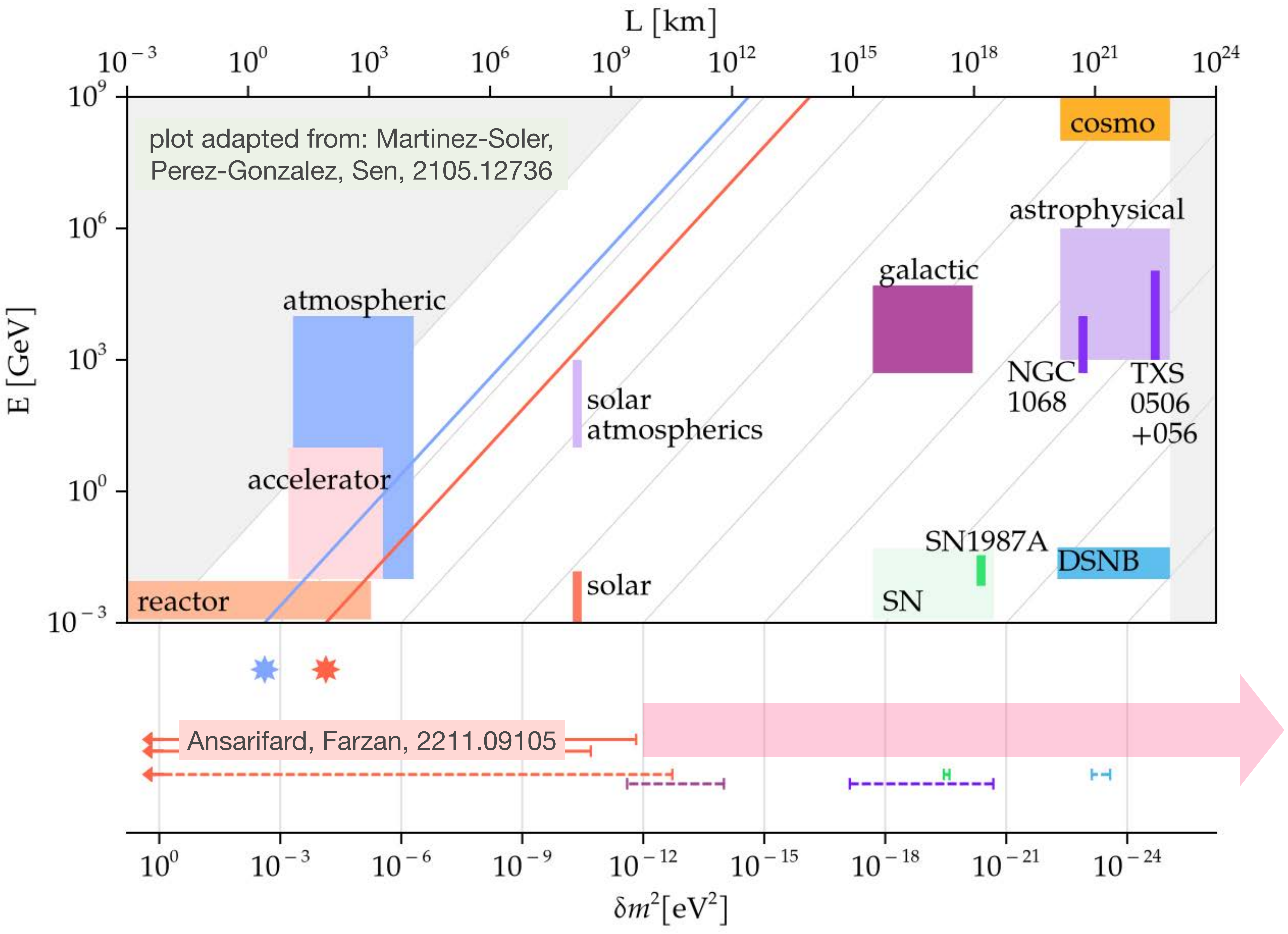

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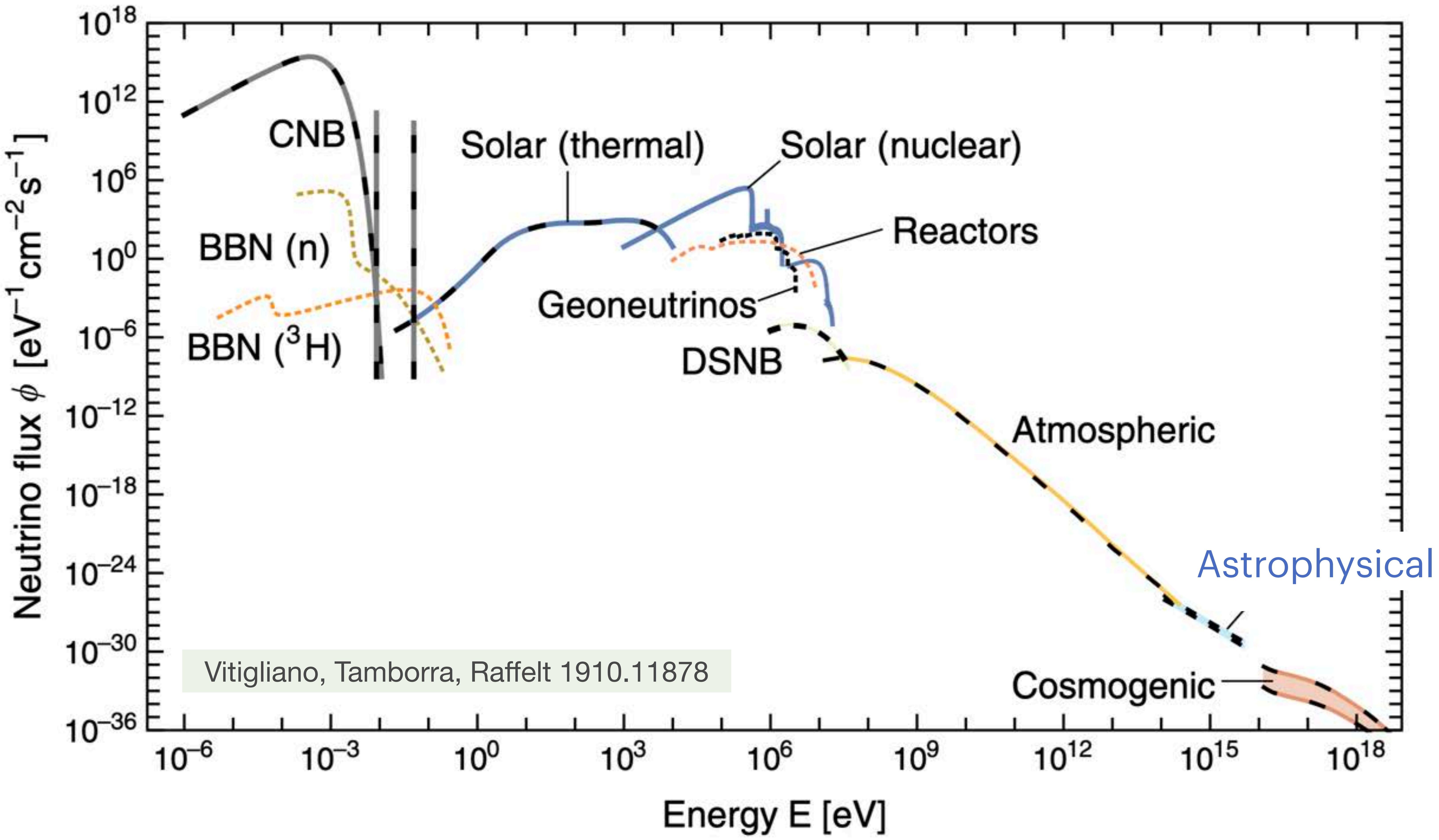

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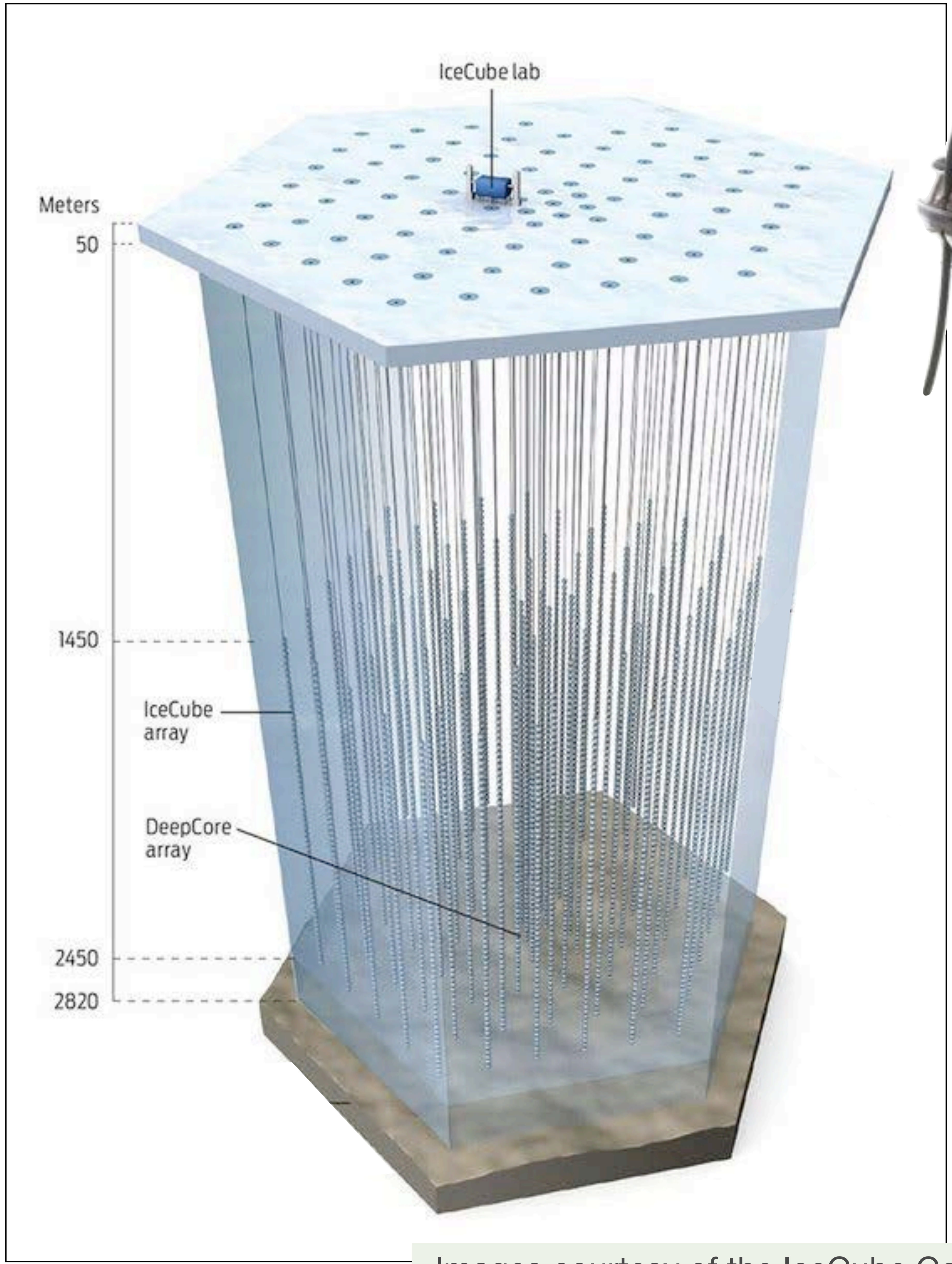

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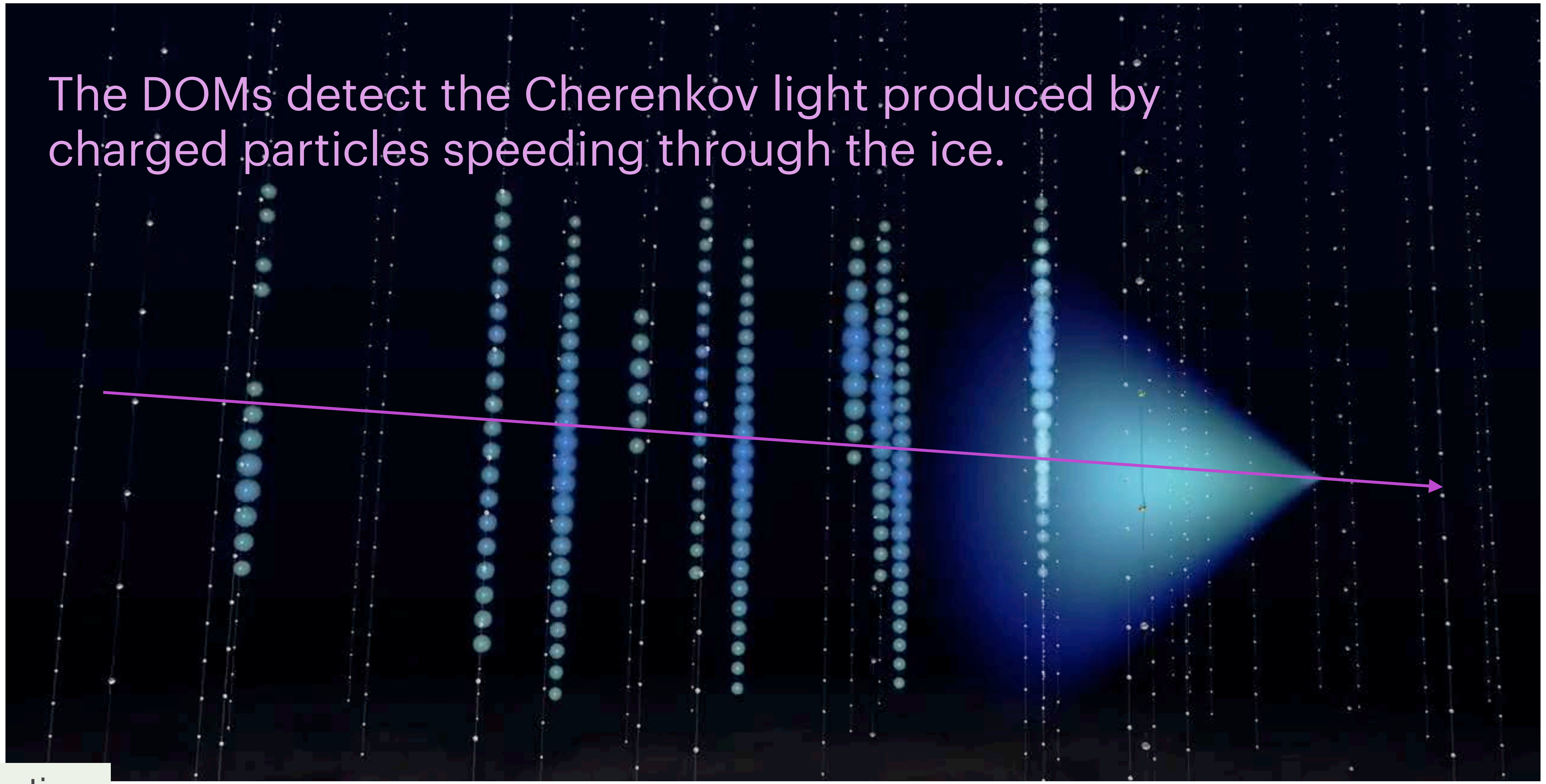

Images courtesy of the IceCube Collaboration

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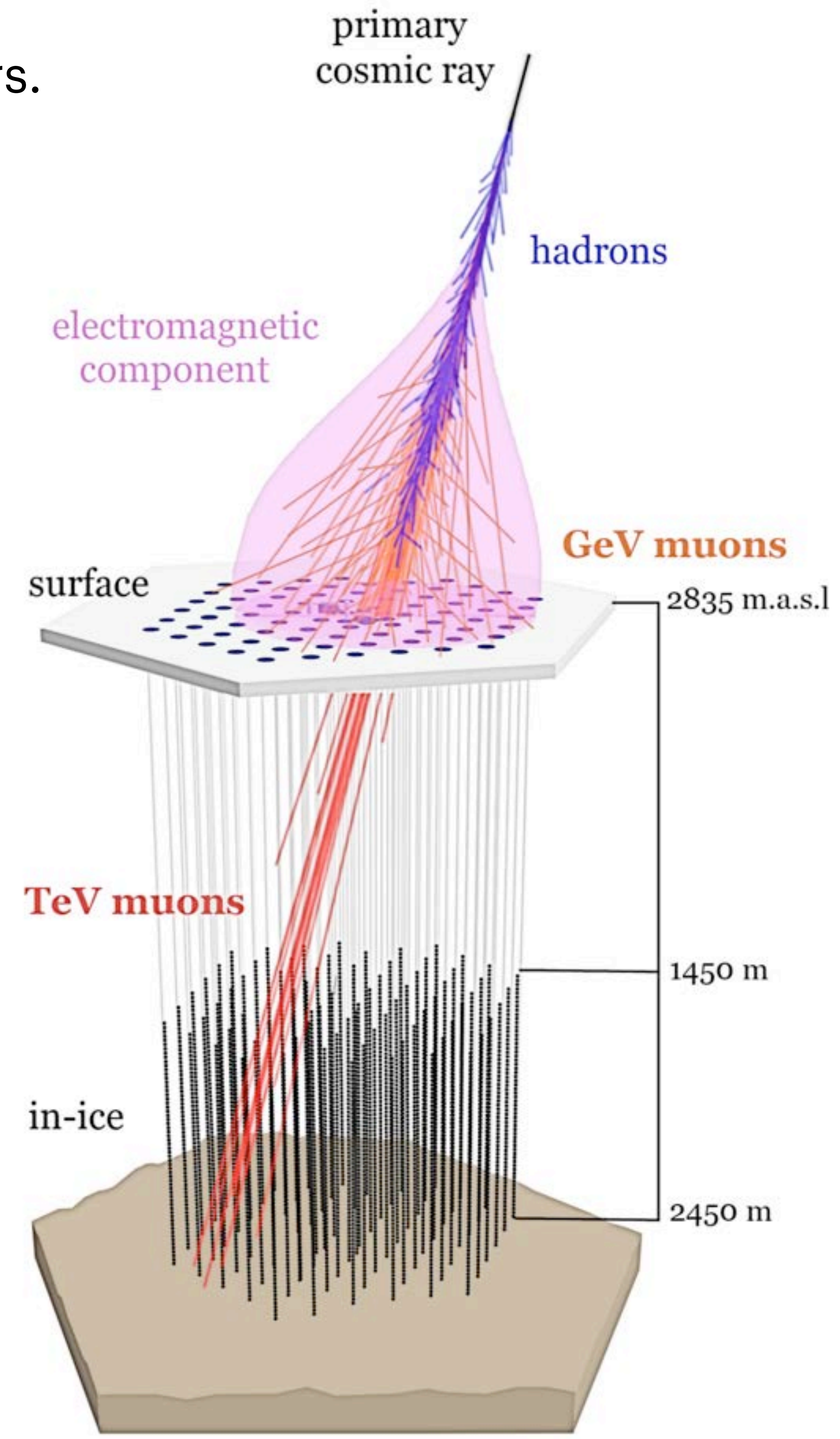

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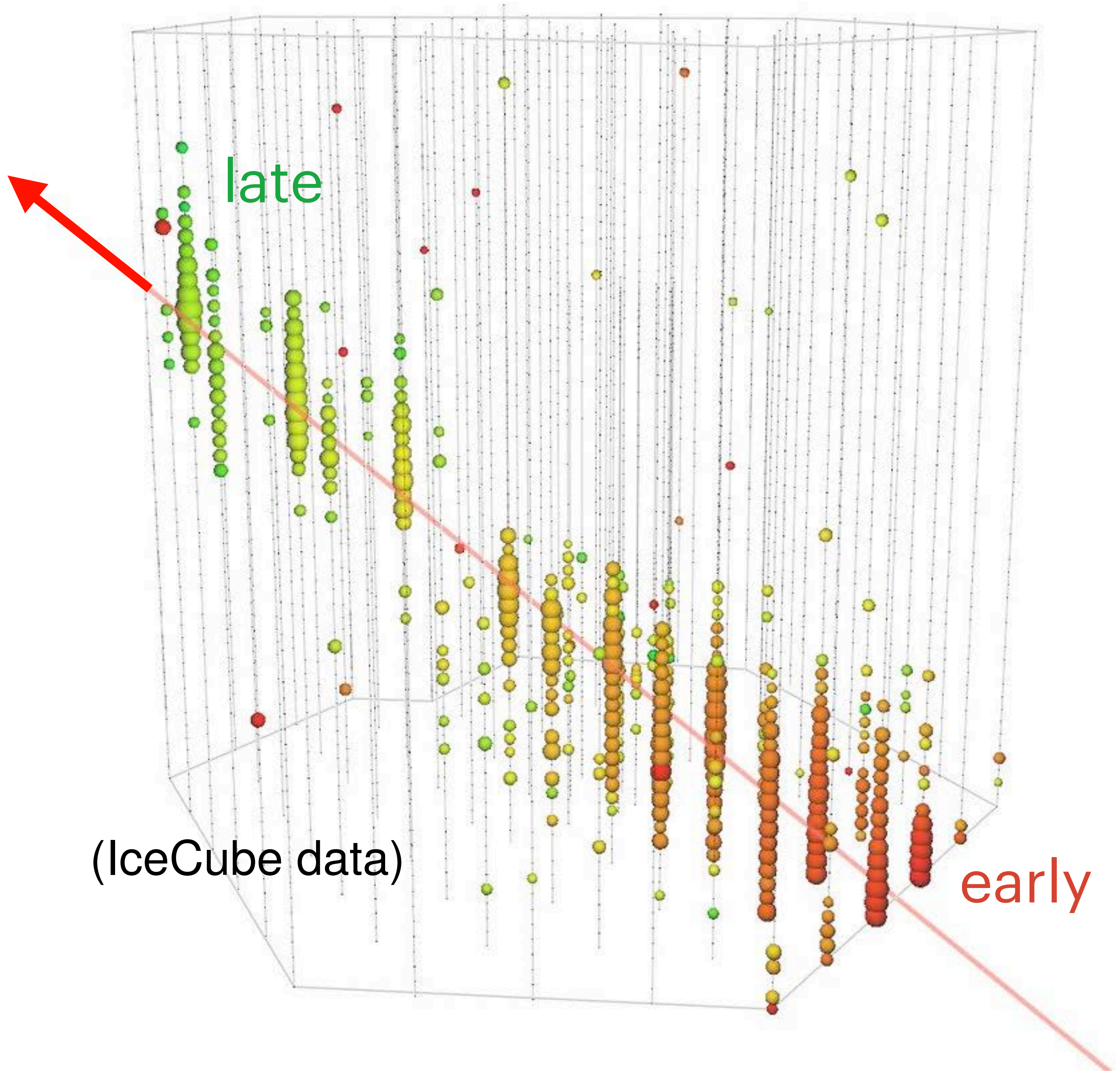

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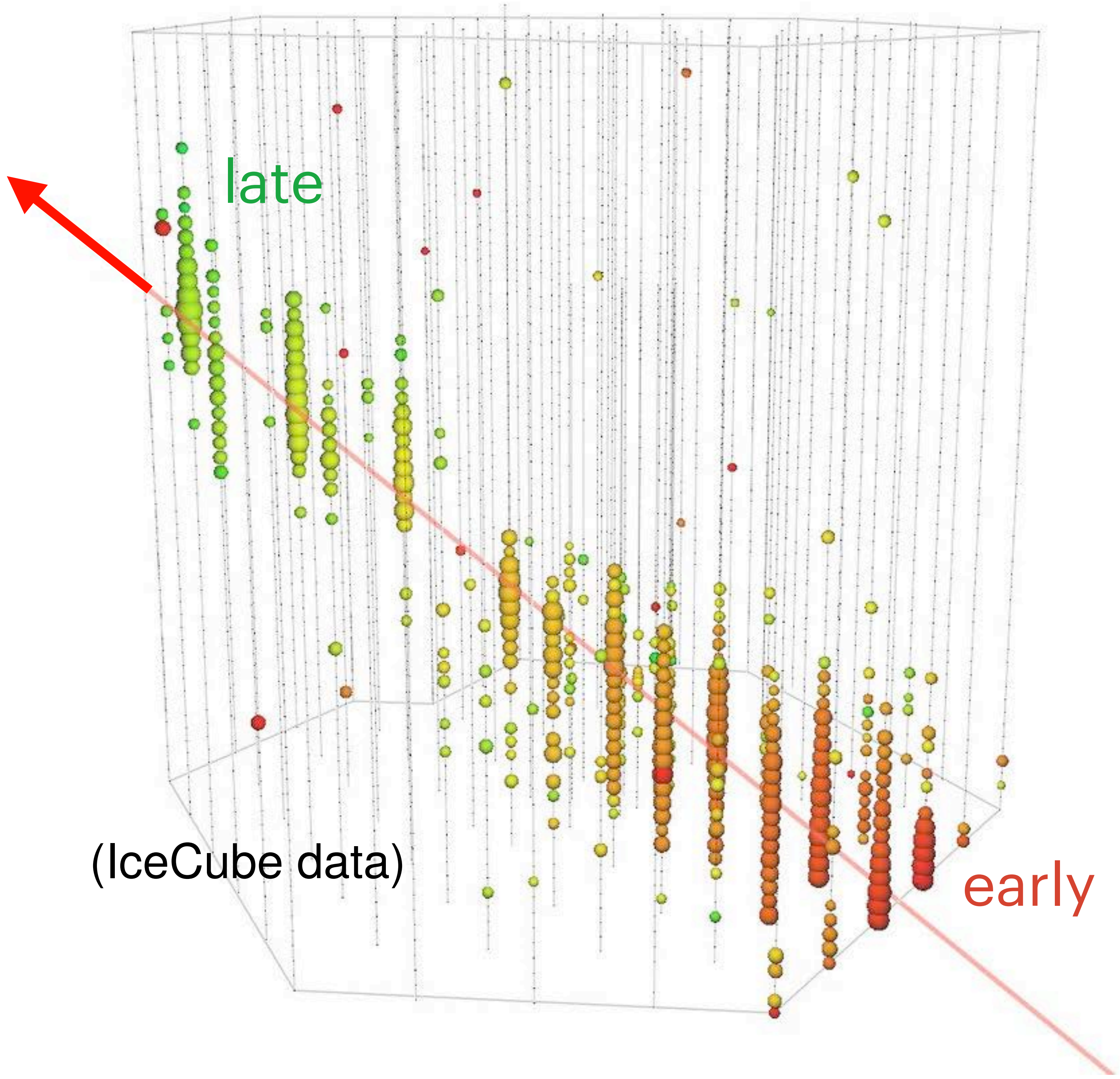

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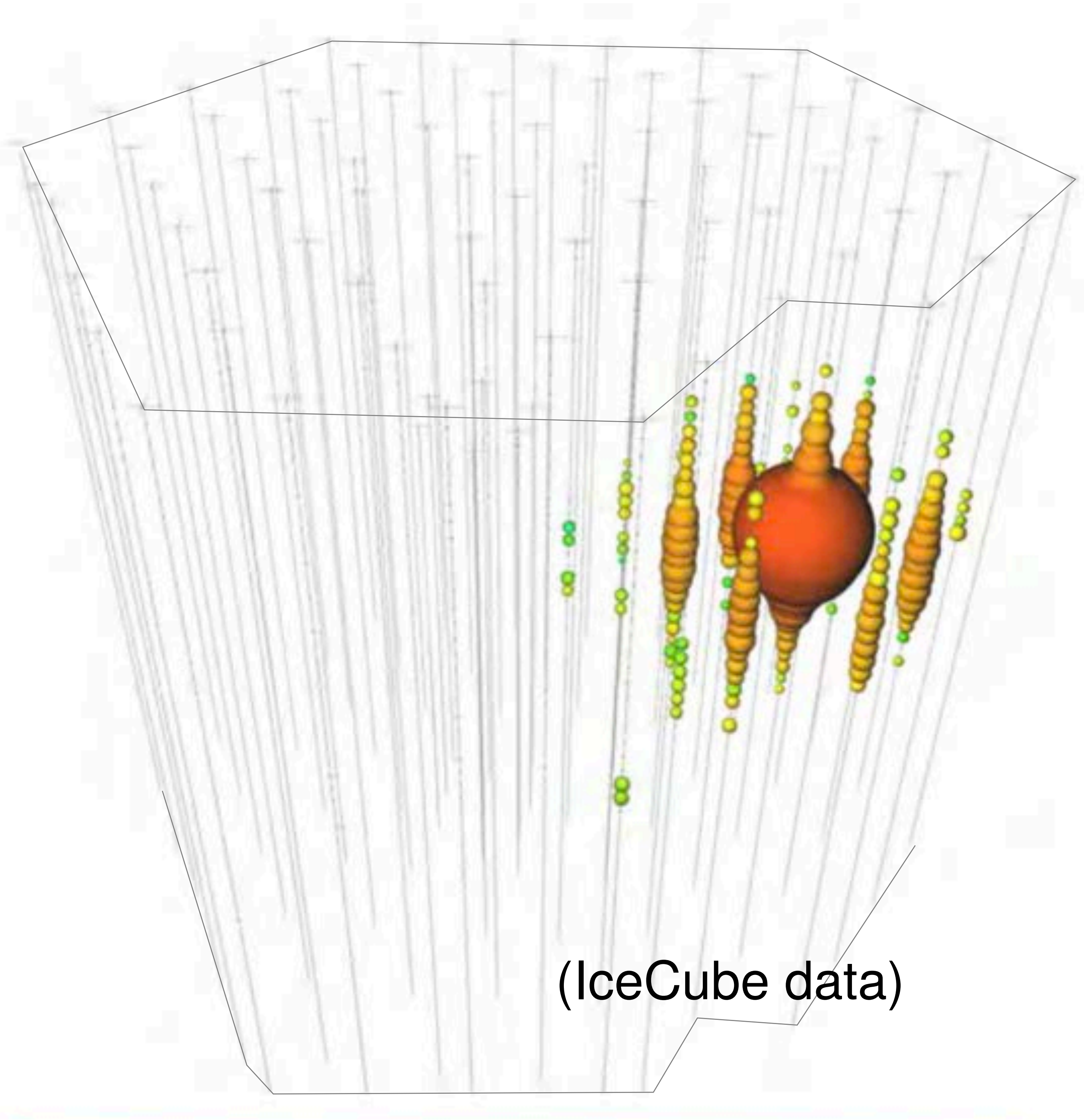

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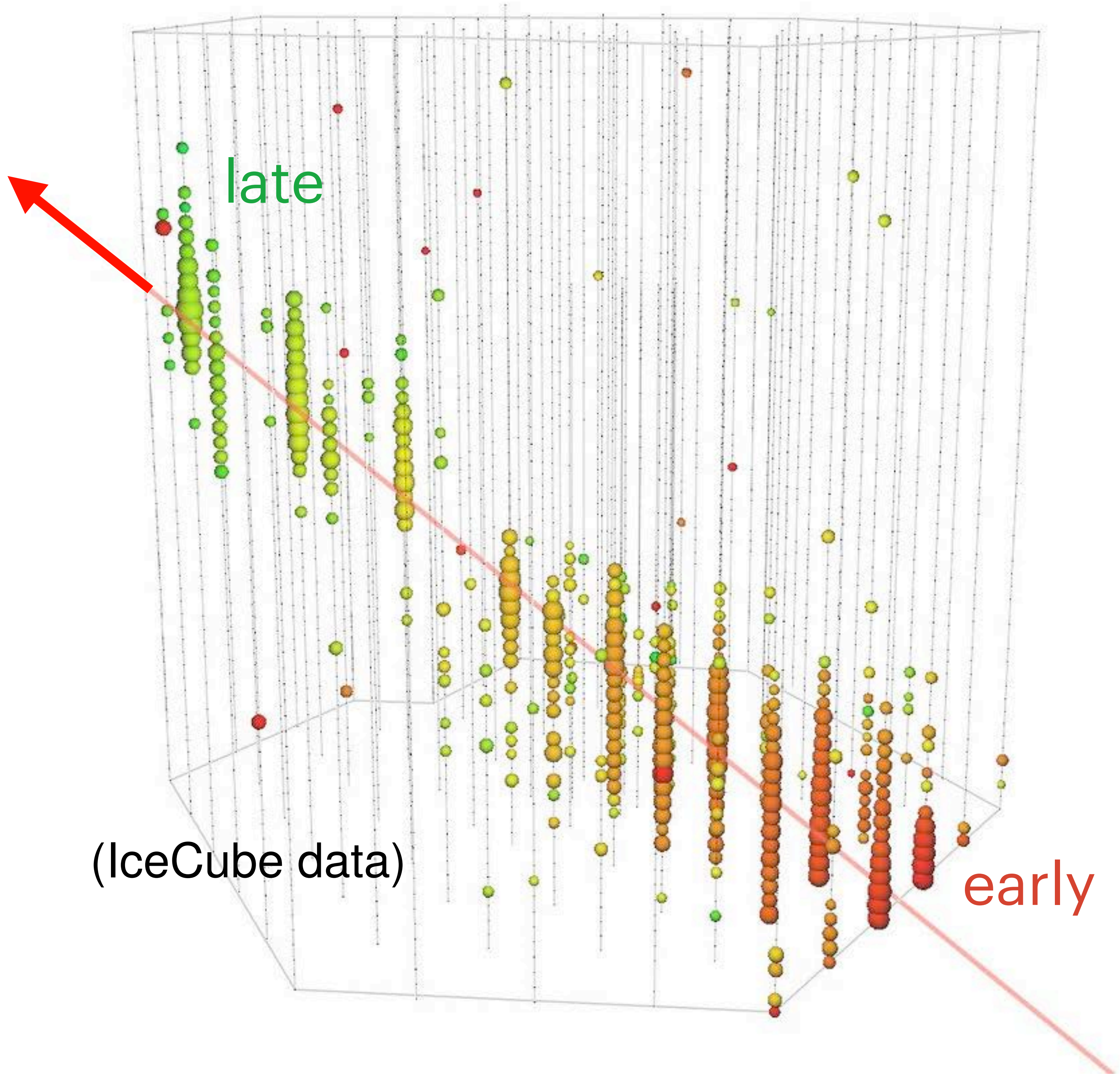

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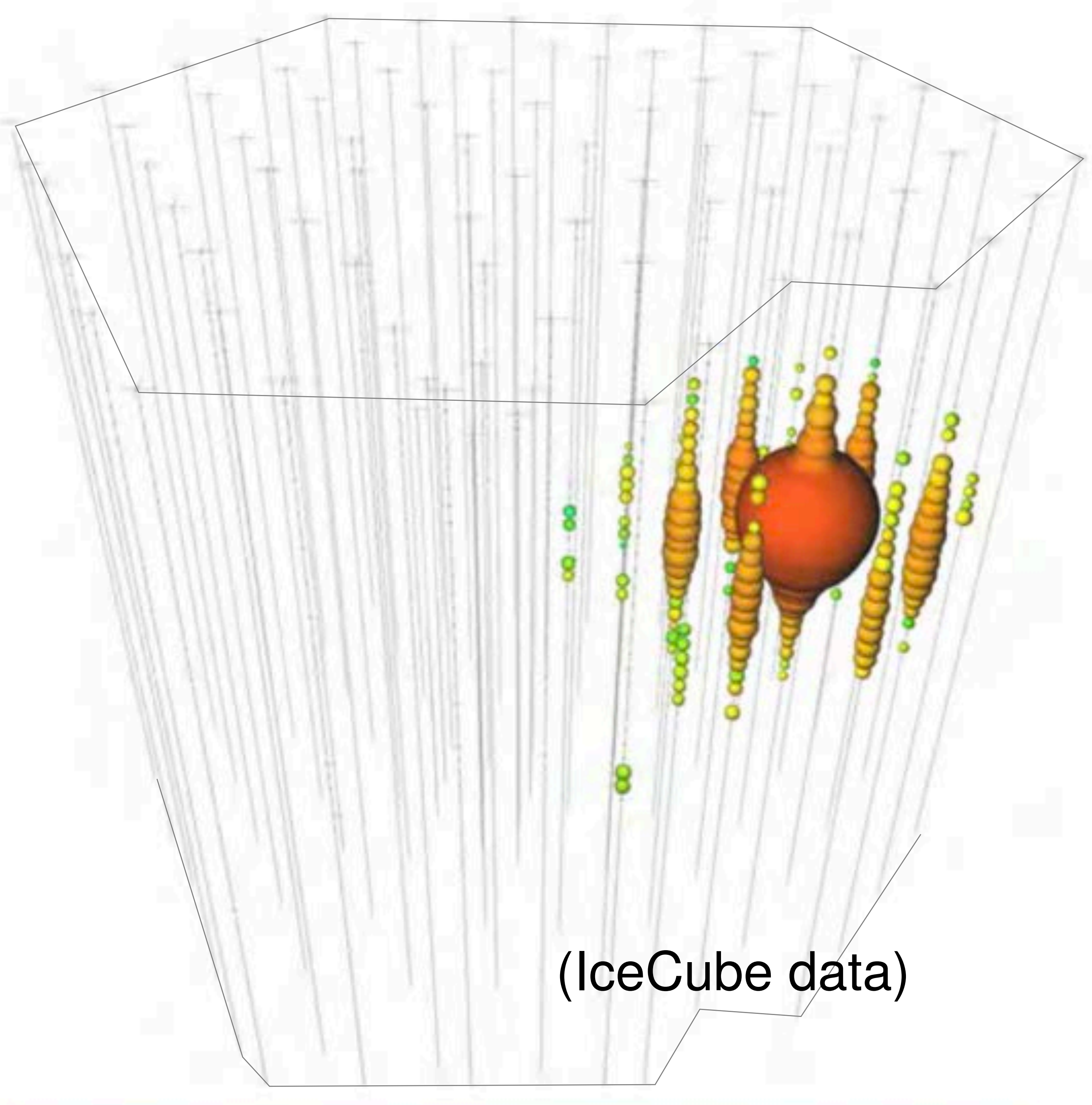

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- $\lesssim 1°$ angular resolution
- $\simeq$30% log-energy resolution
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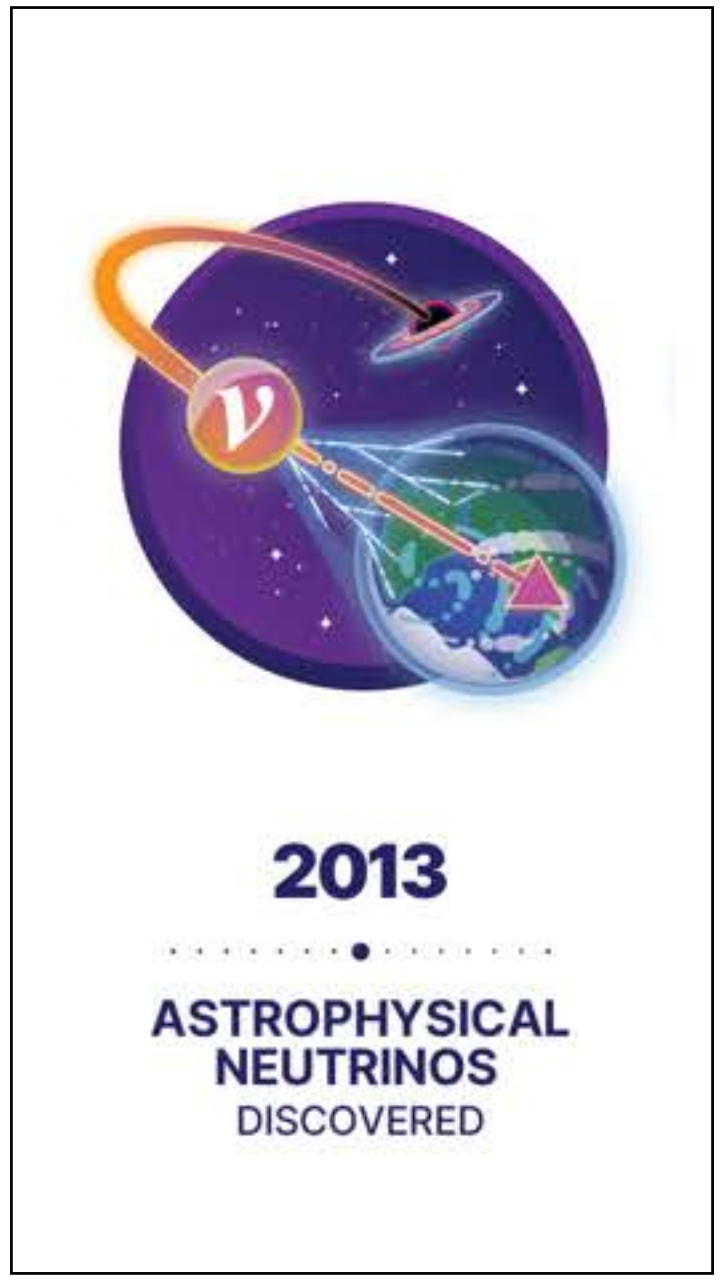
IceCube has identified multiple populations of astrophysical neutrinos…

…which we can use to constrain QD models!



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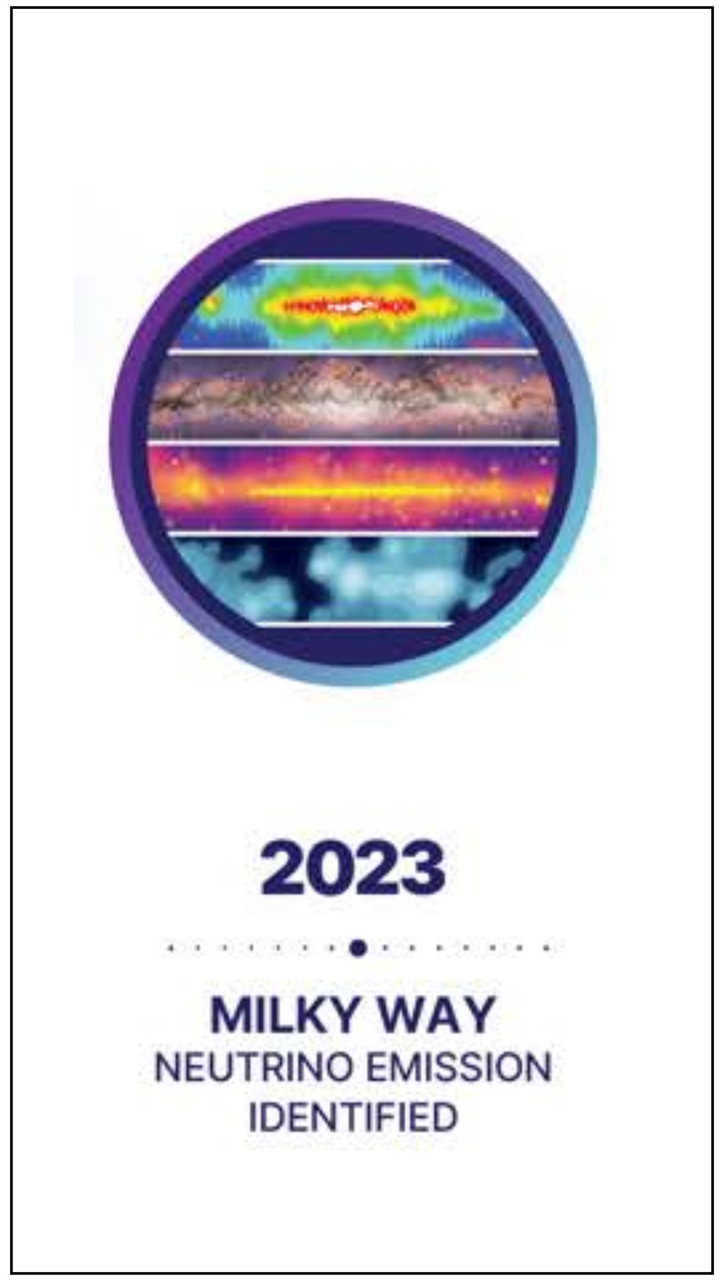

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HARVARD UNIVERSITY

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Integrating Discovery and Education to Advance Science

AsYmmetry
Essential Asymmetries of Nature

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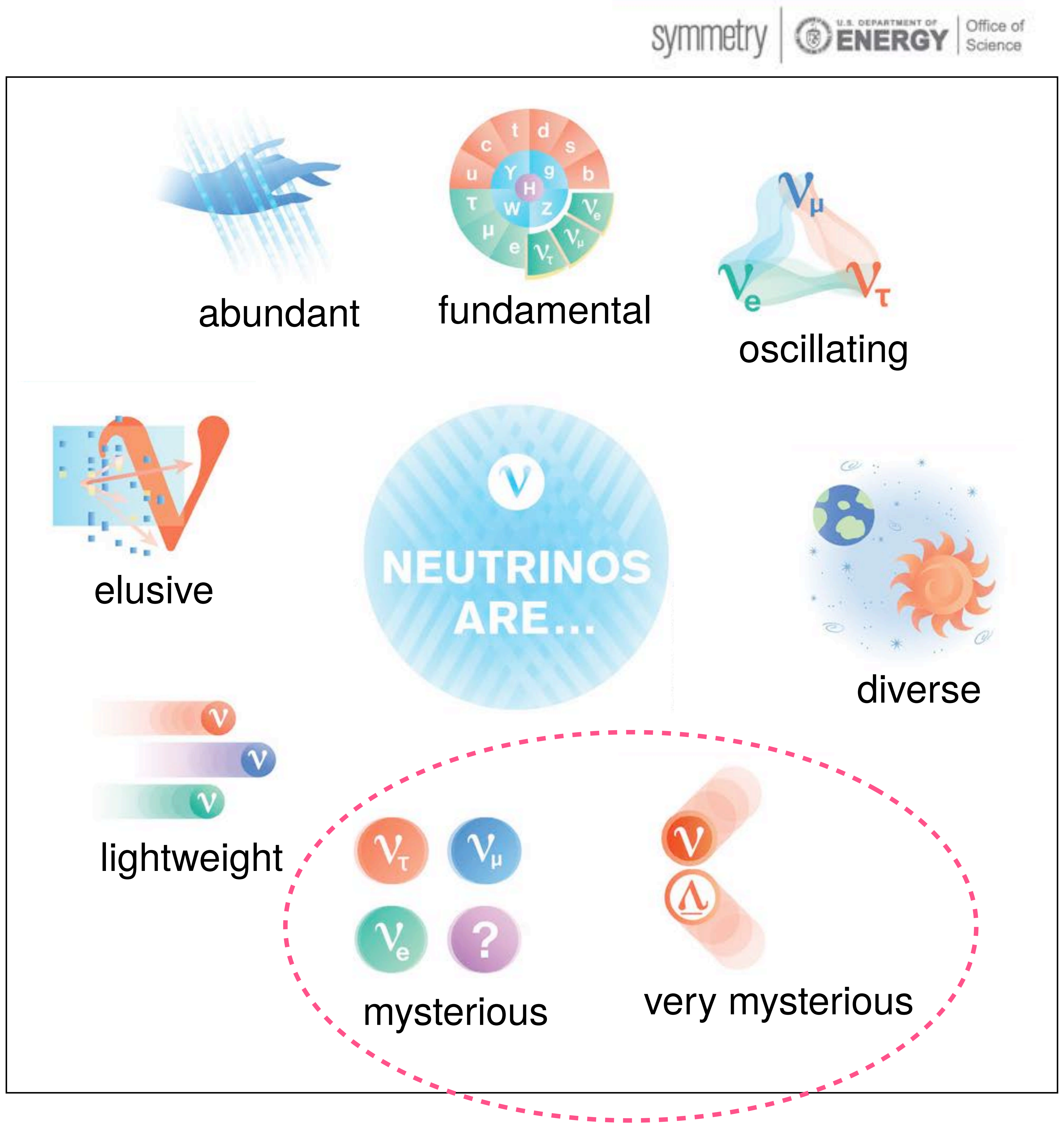

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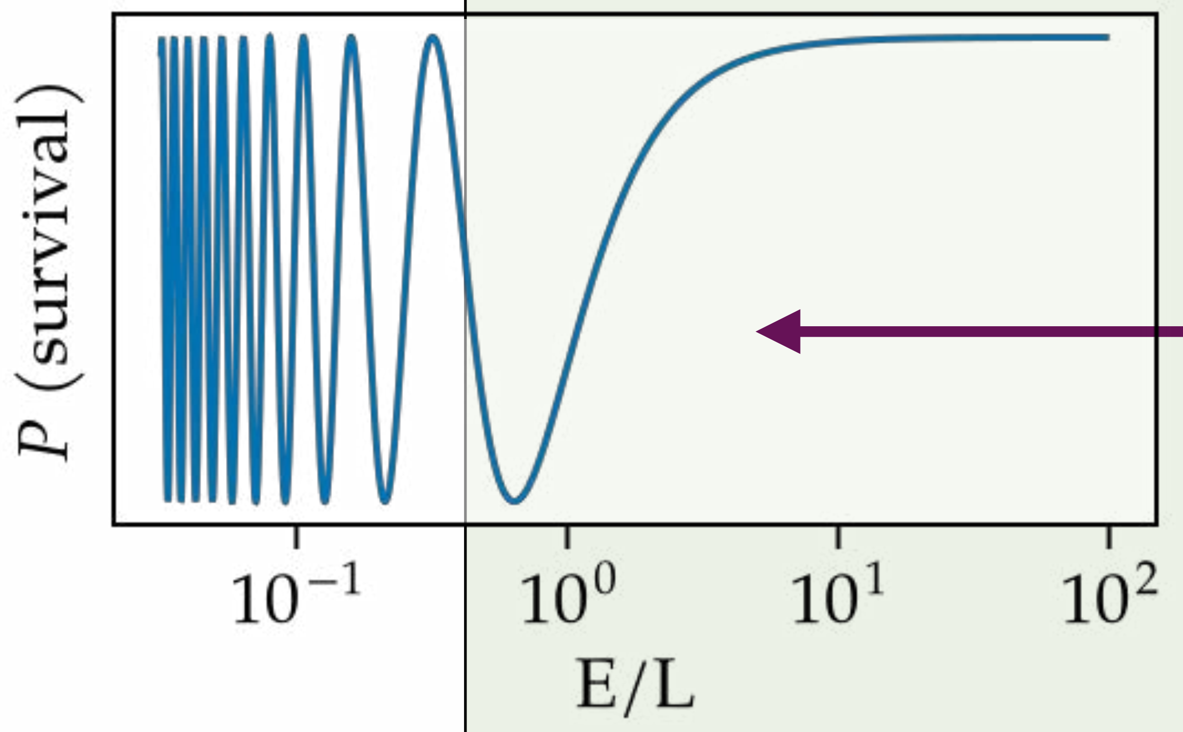

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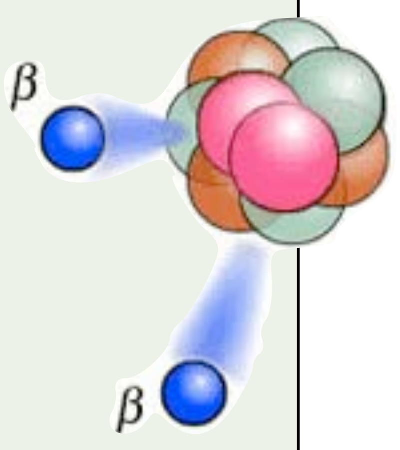

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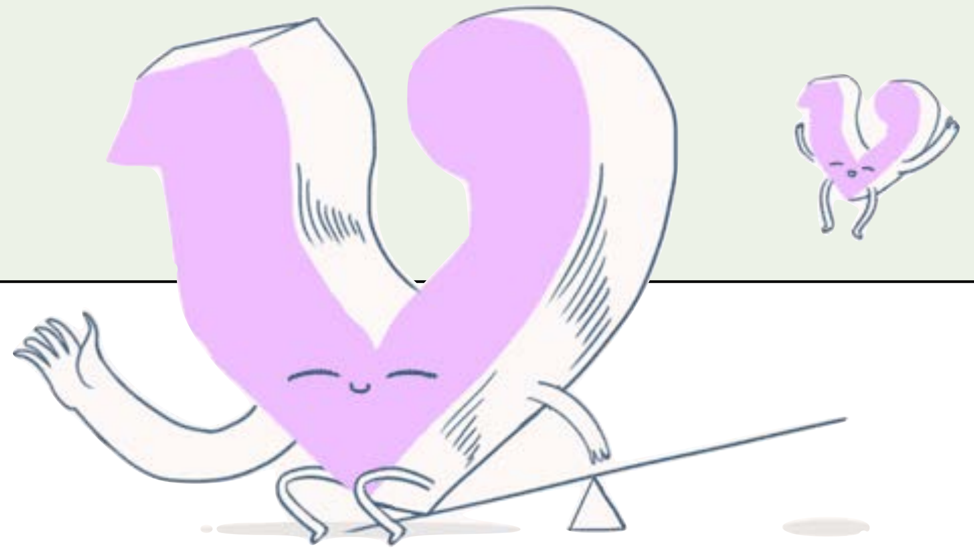

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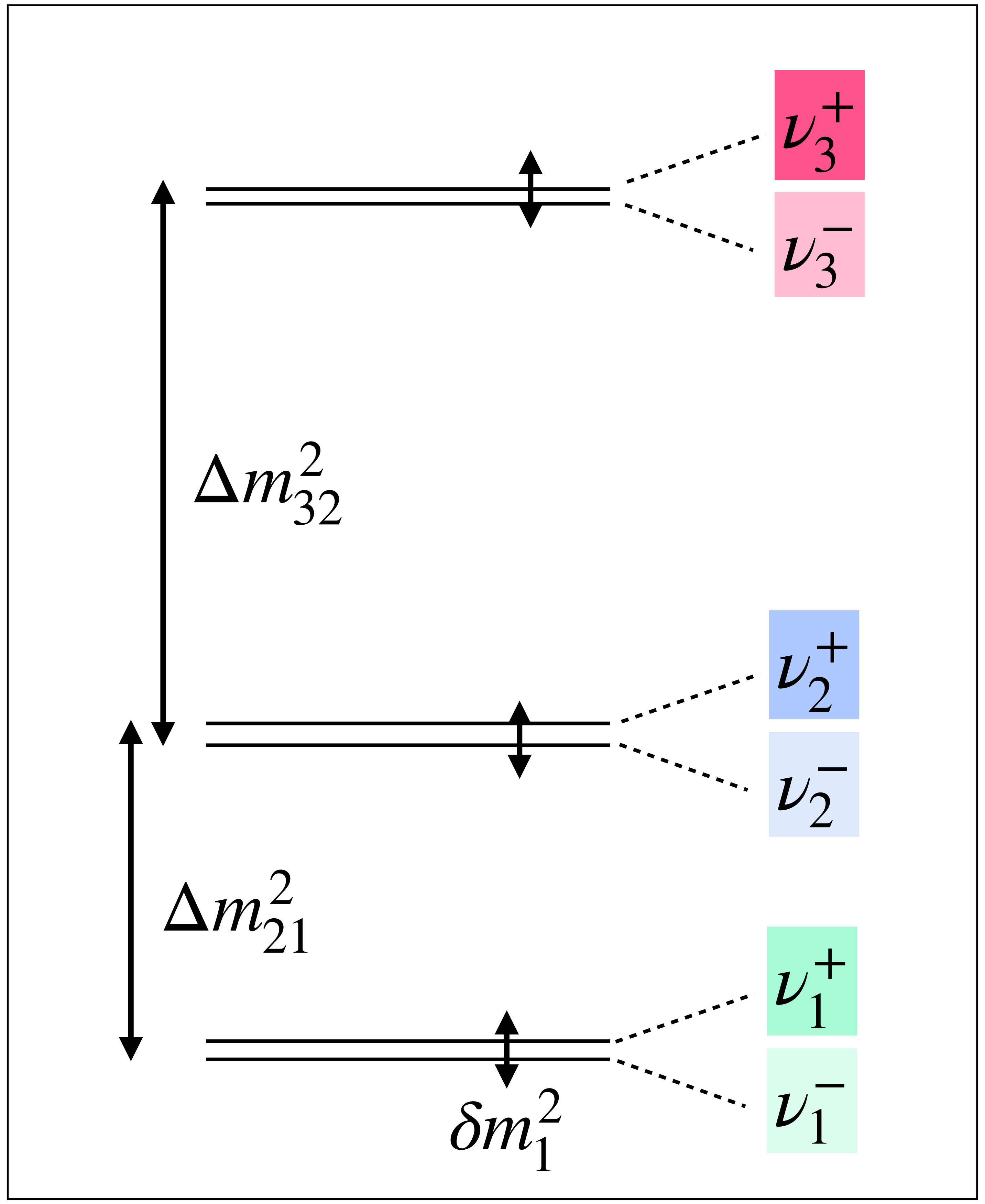

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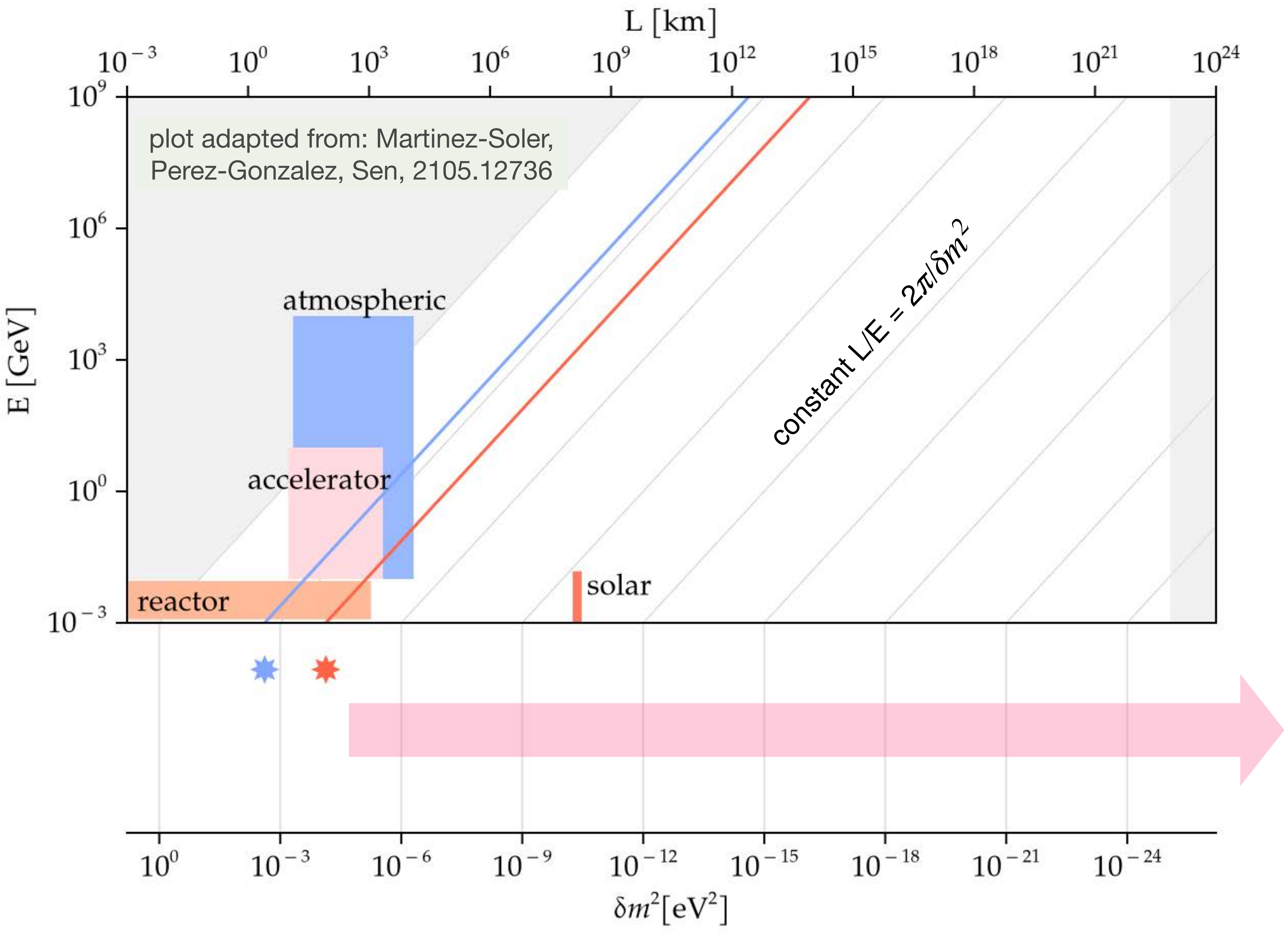

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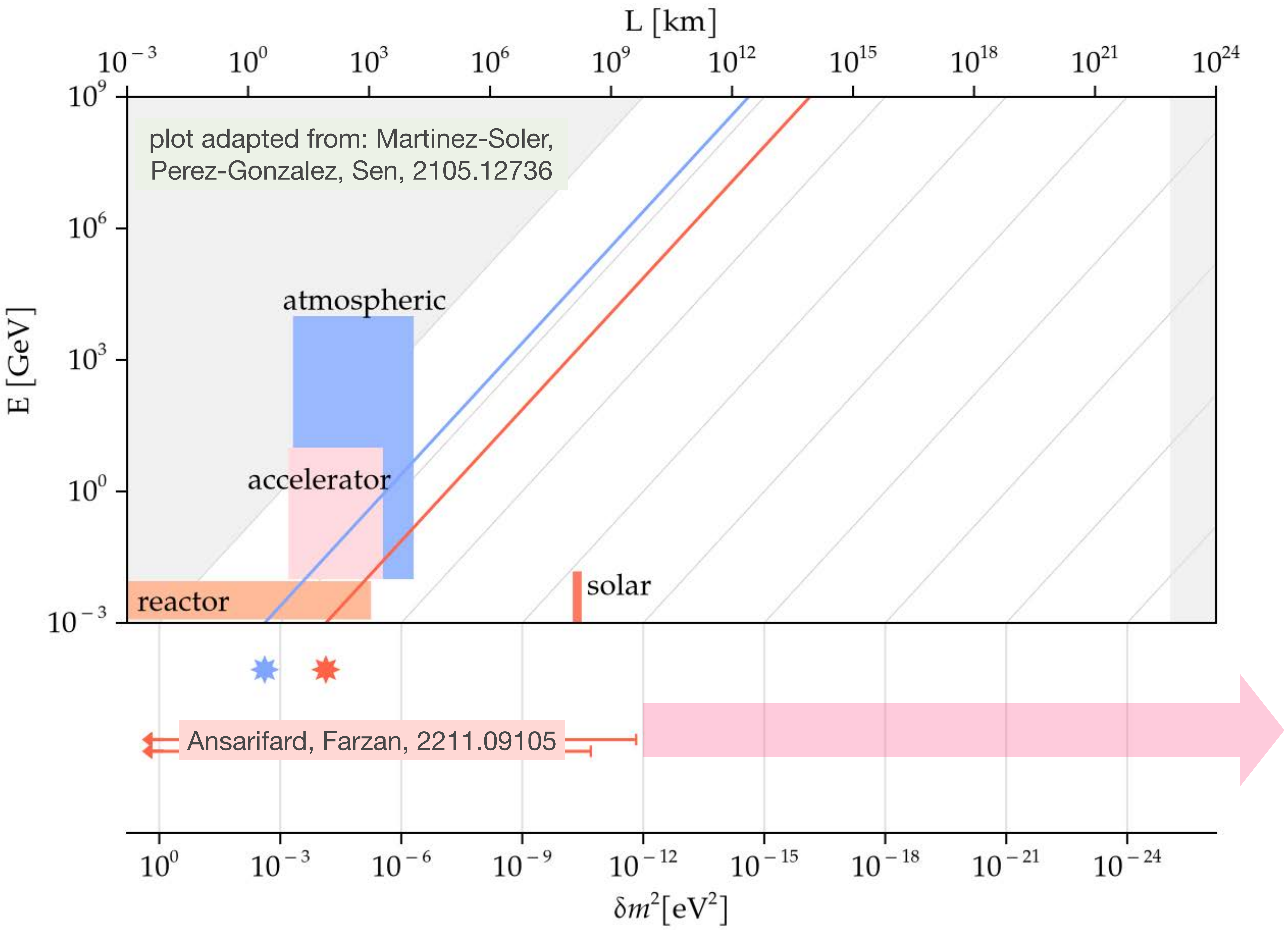

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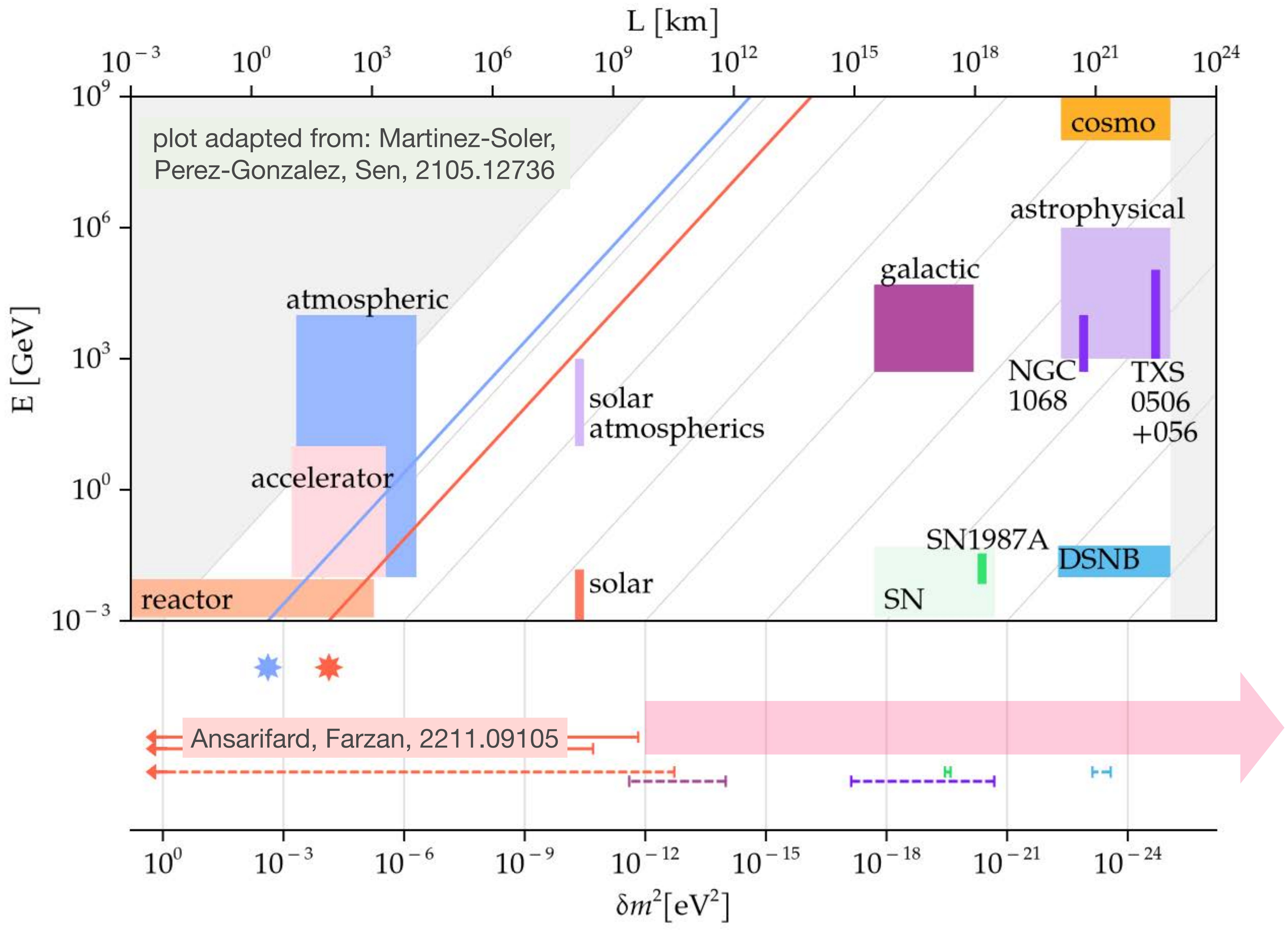

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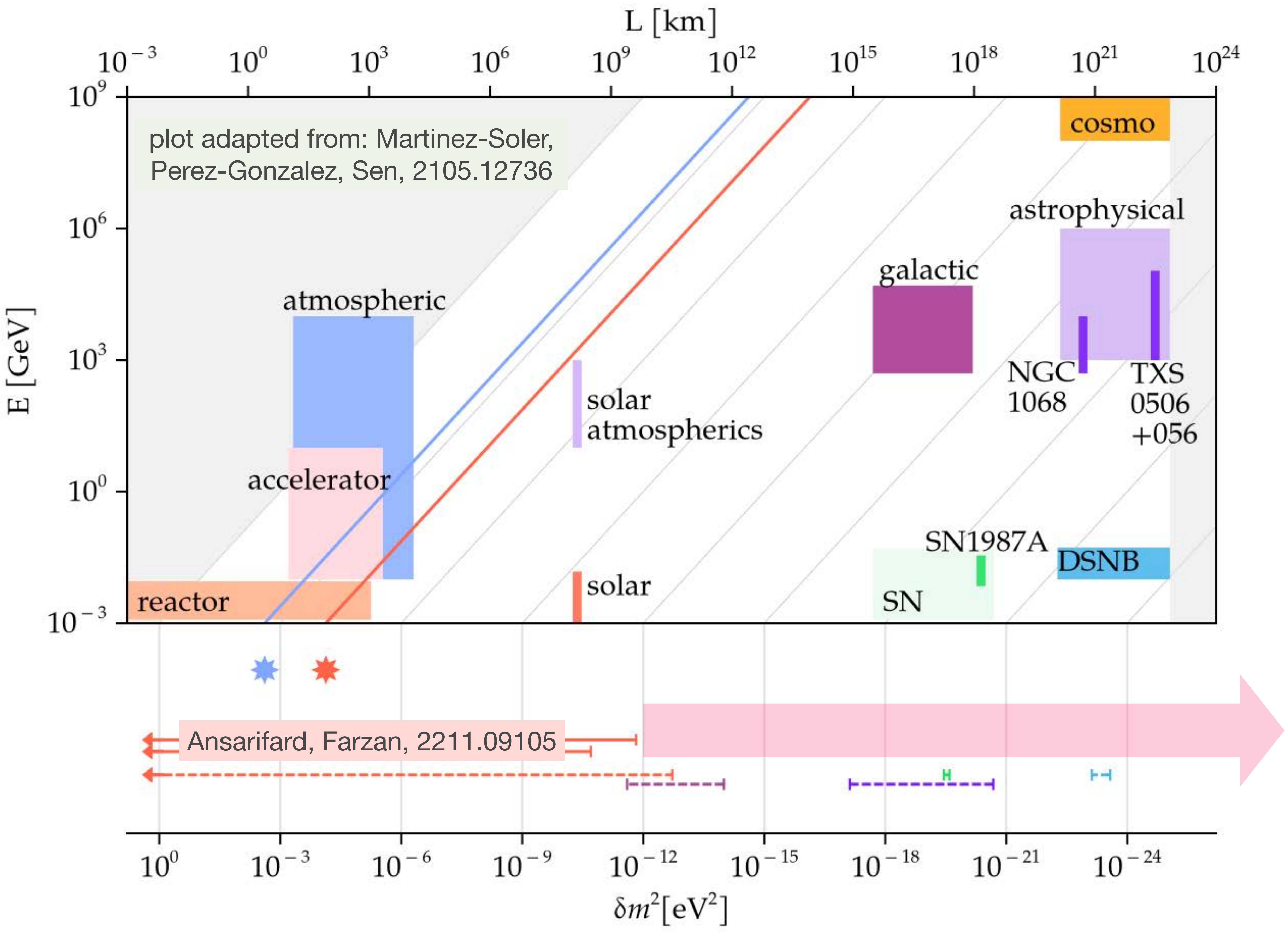

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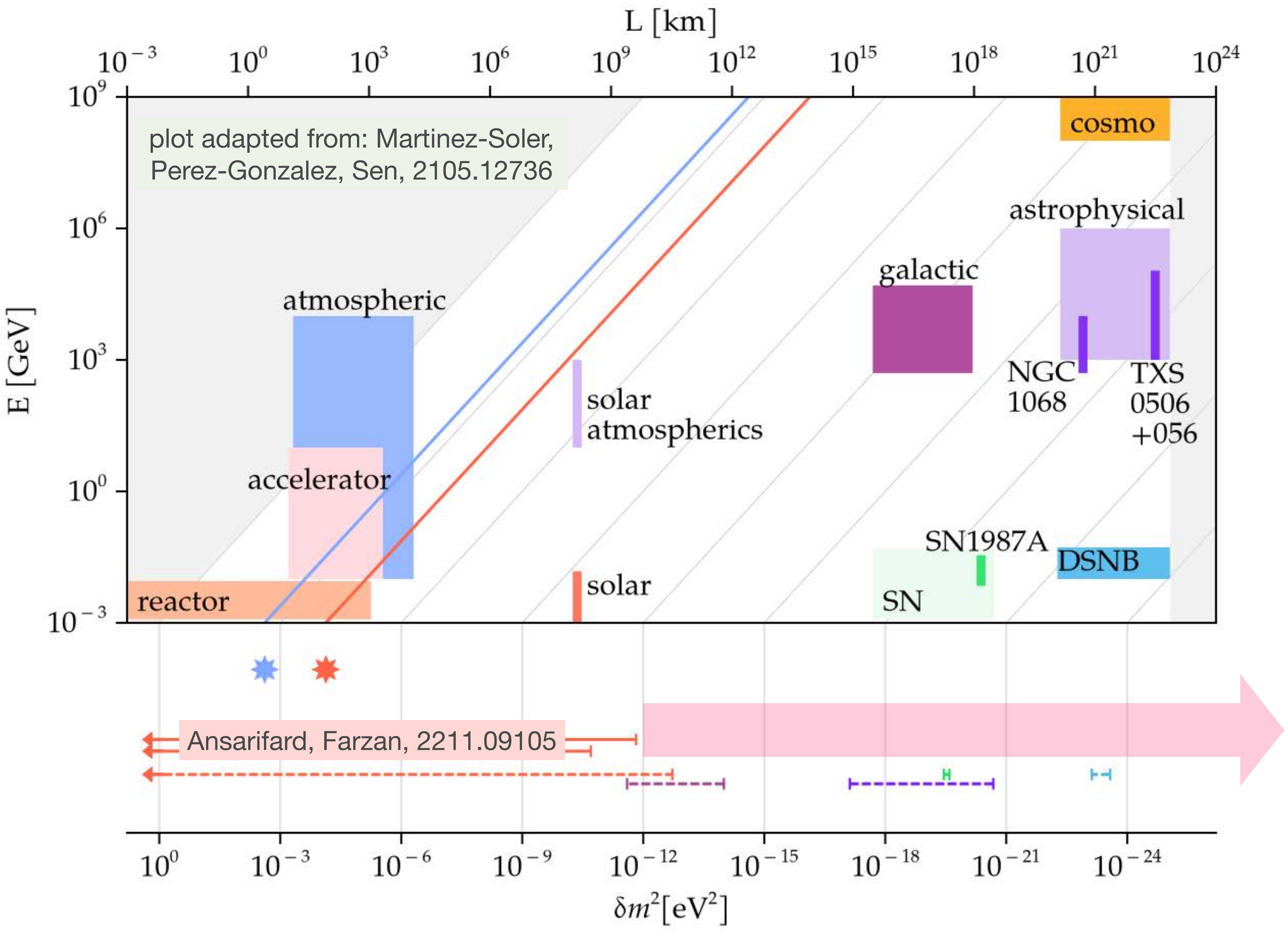

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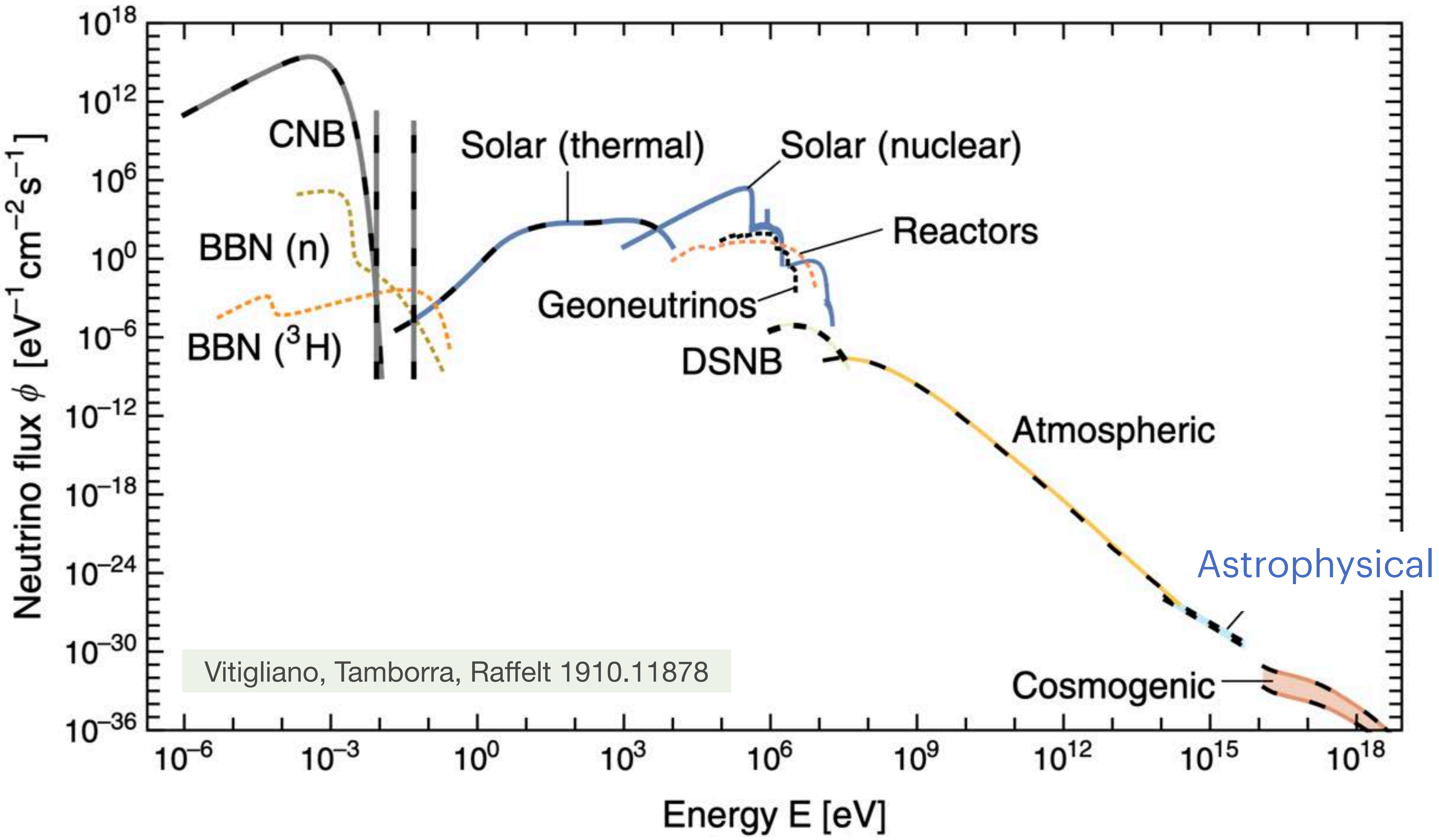

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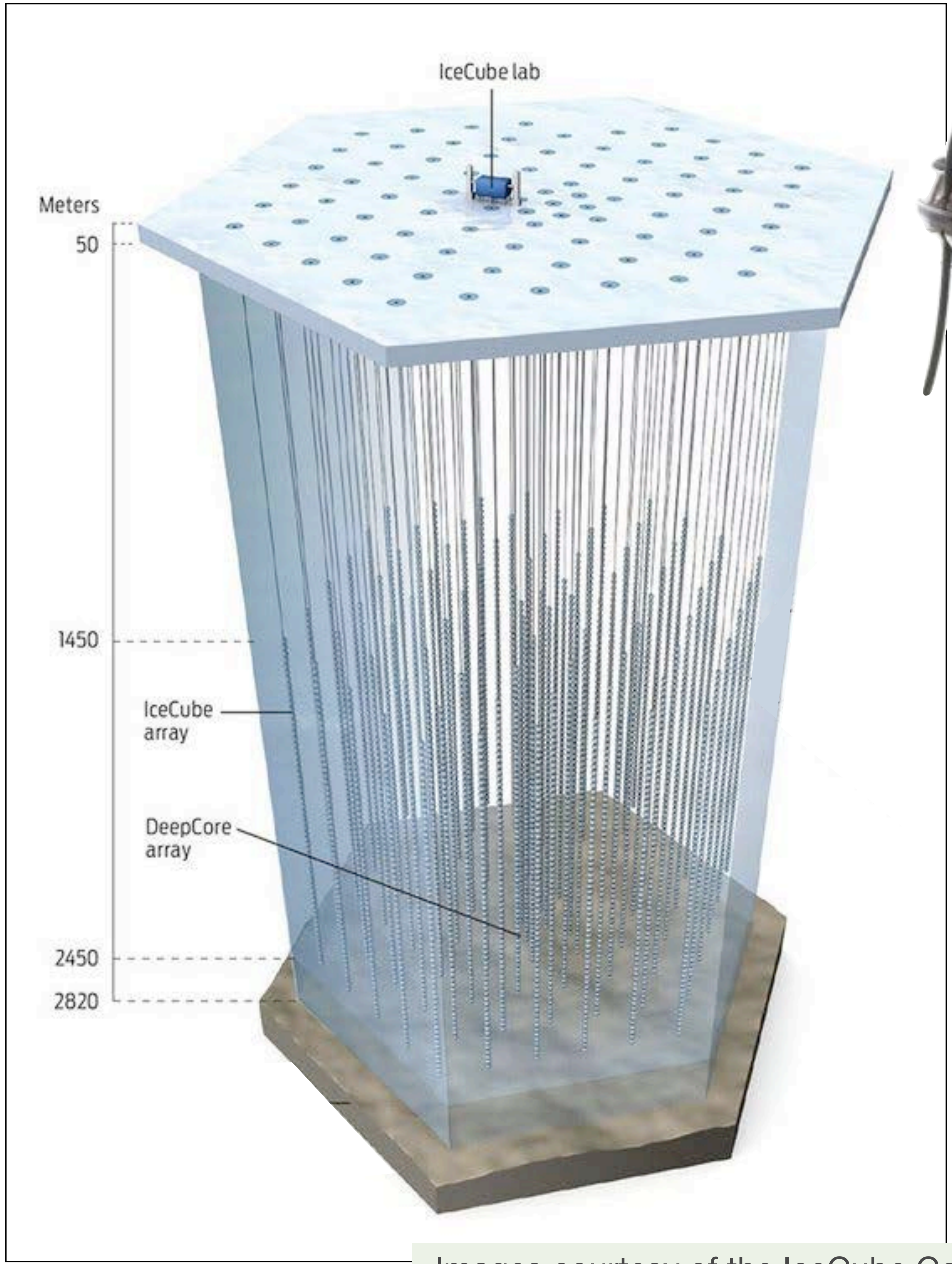

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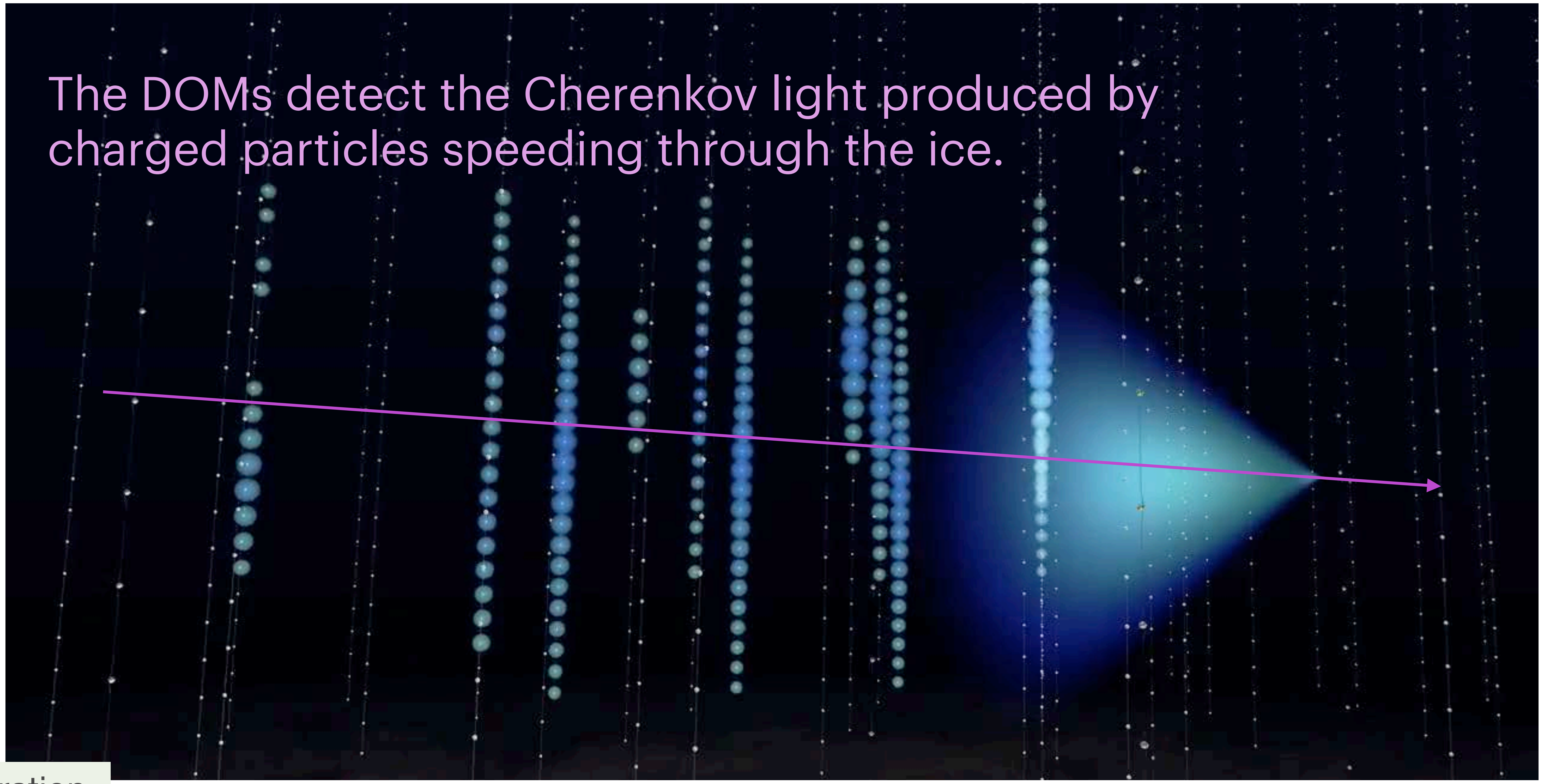

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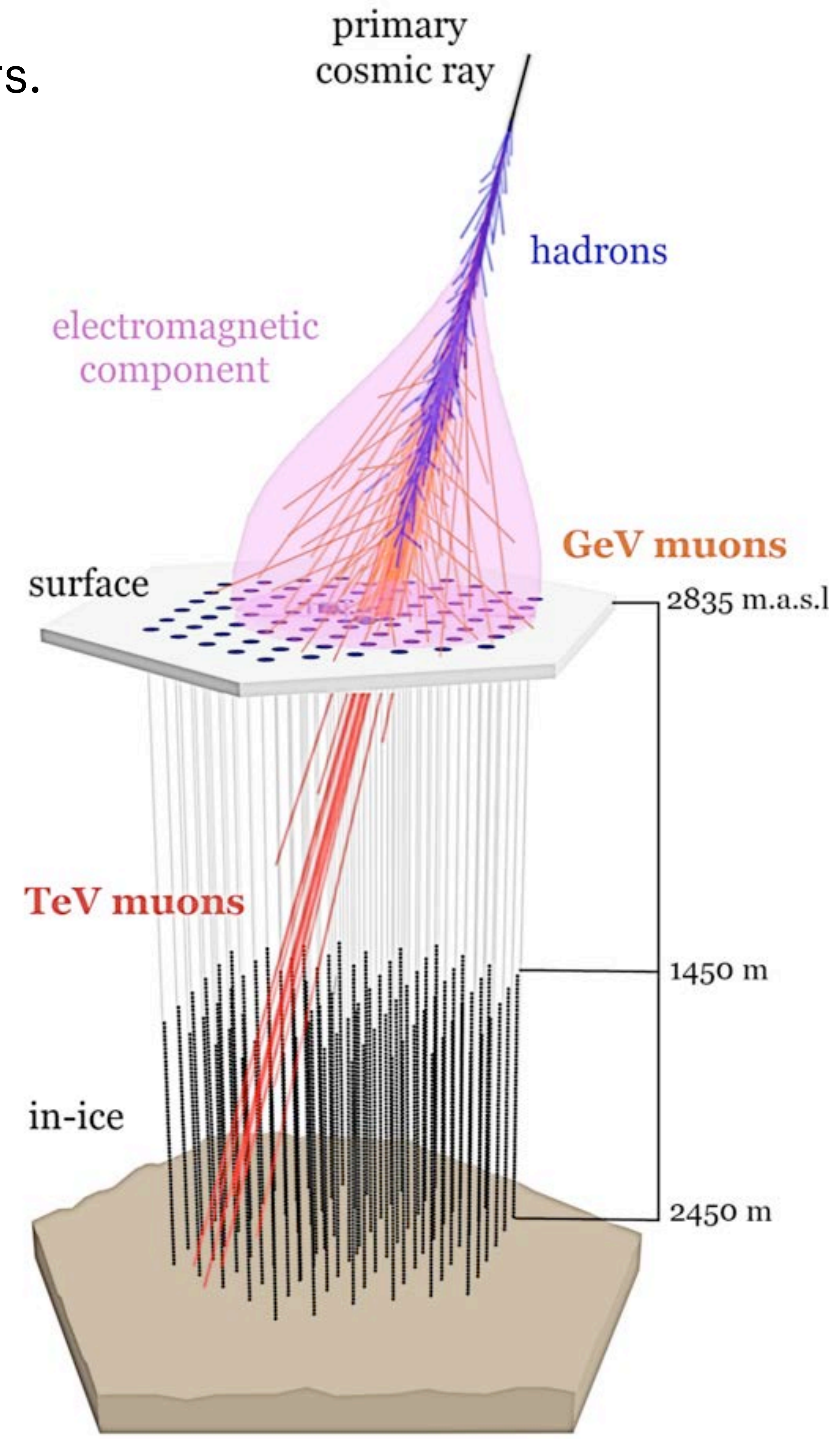

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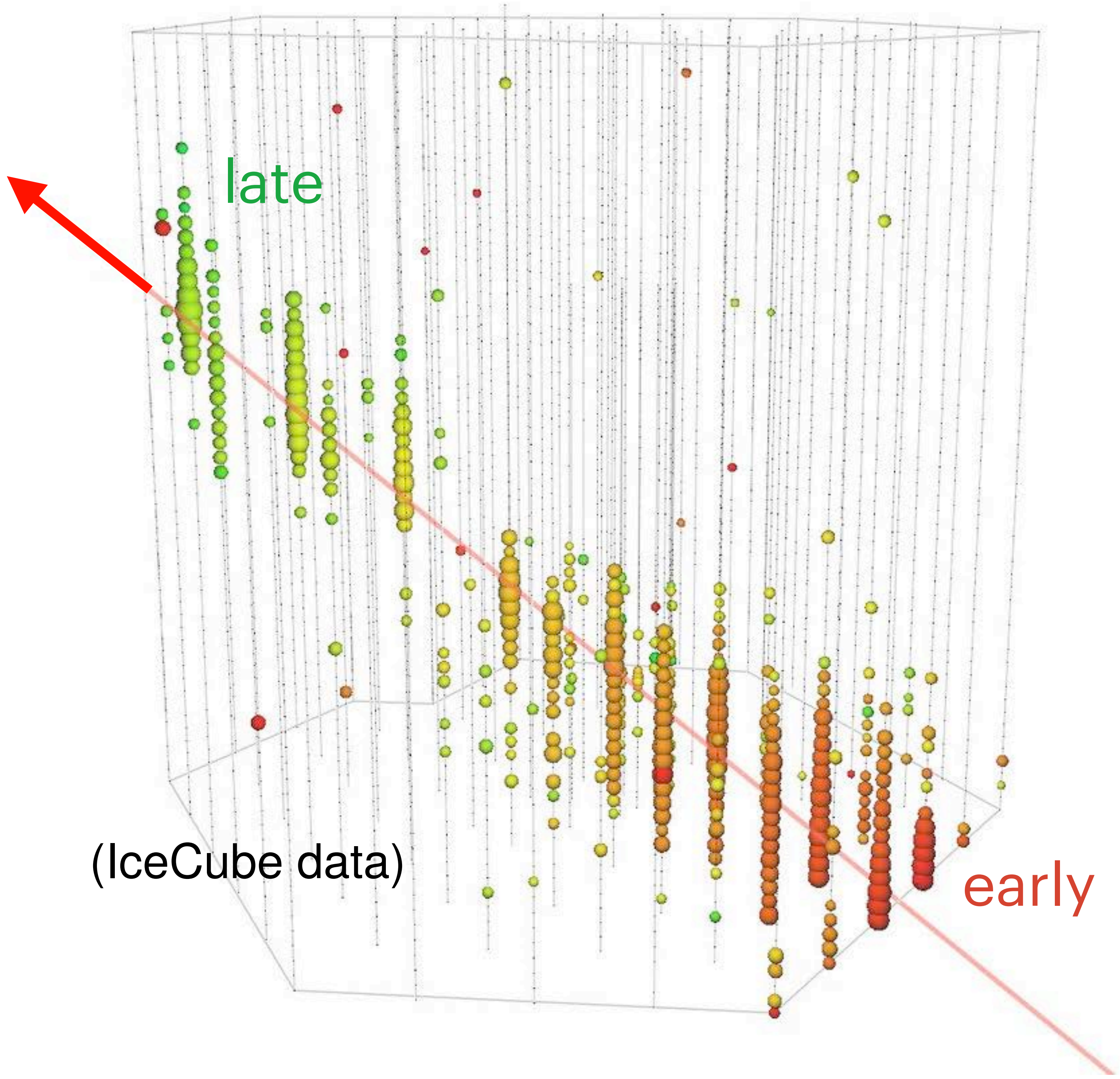

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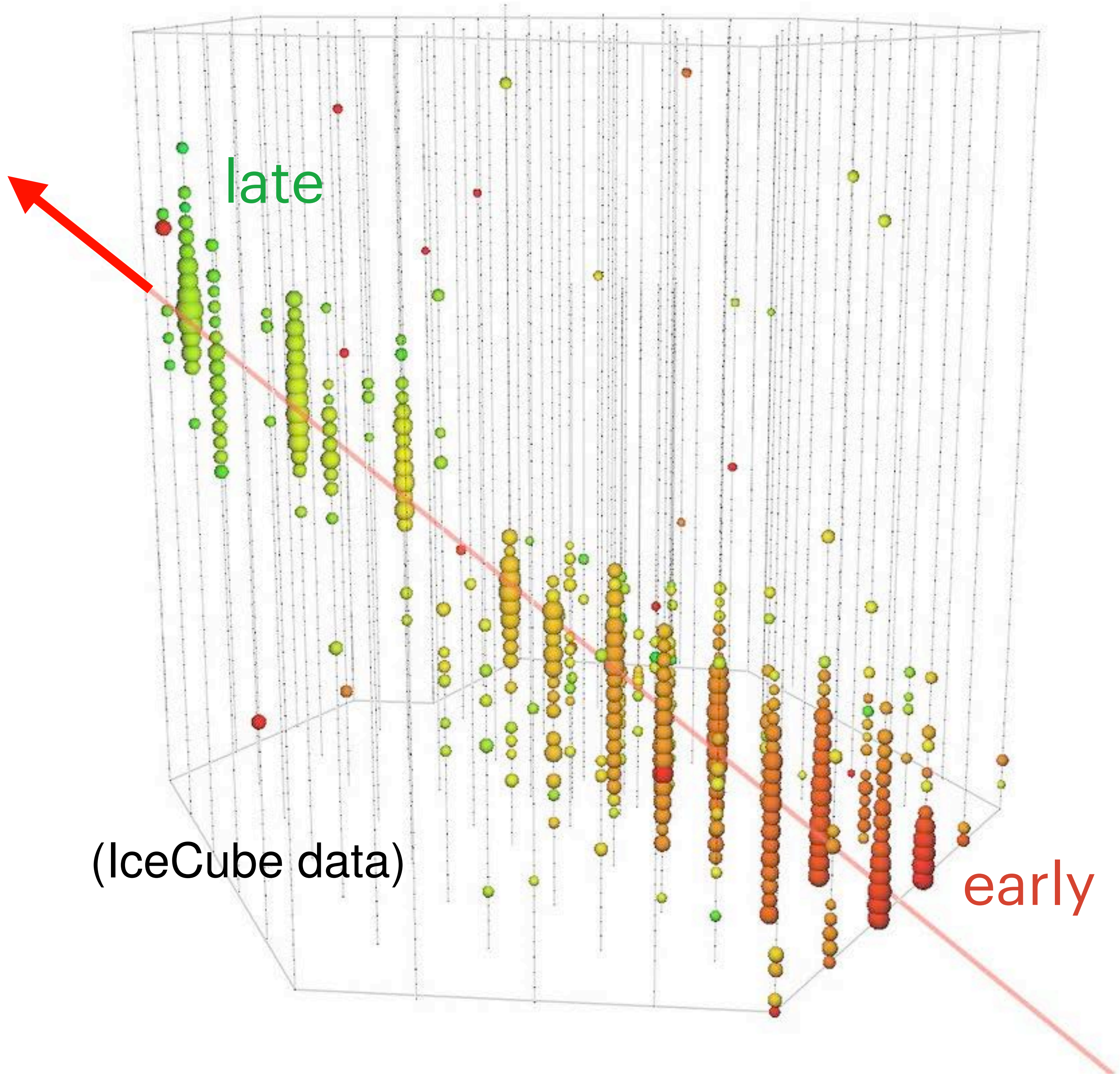

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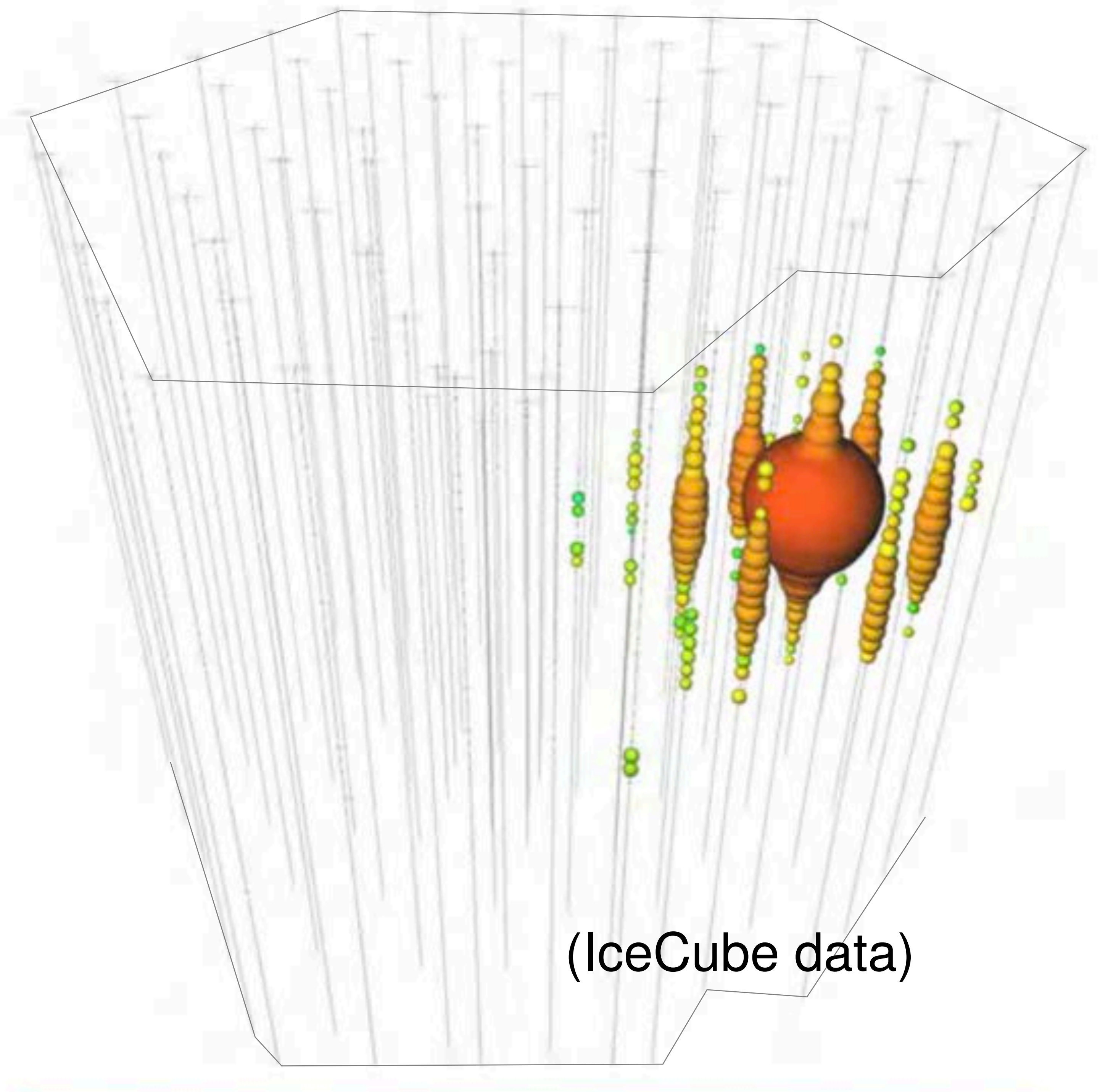
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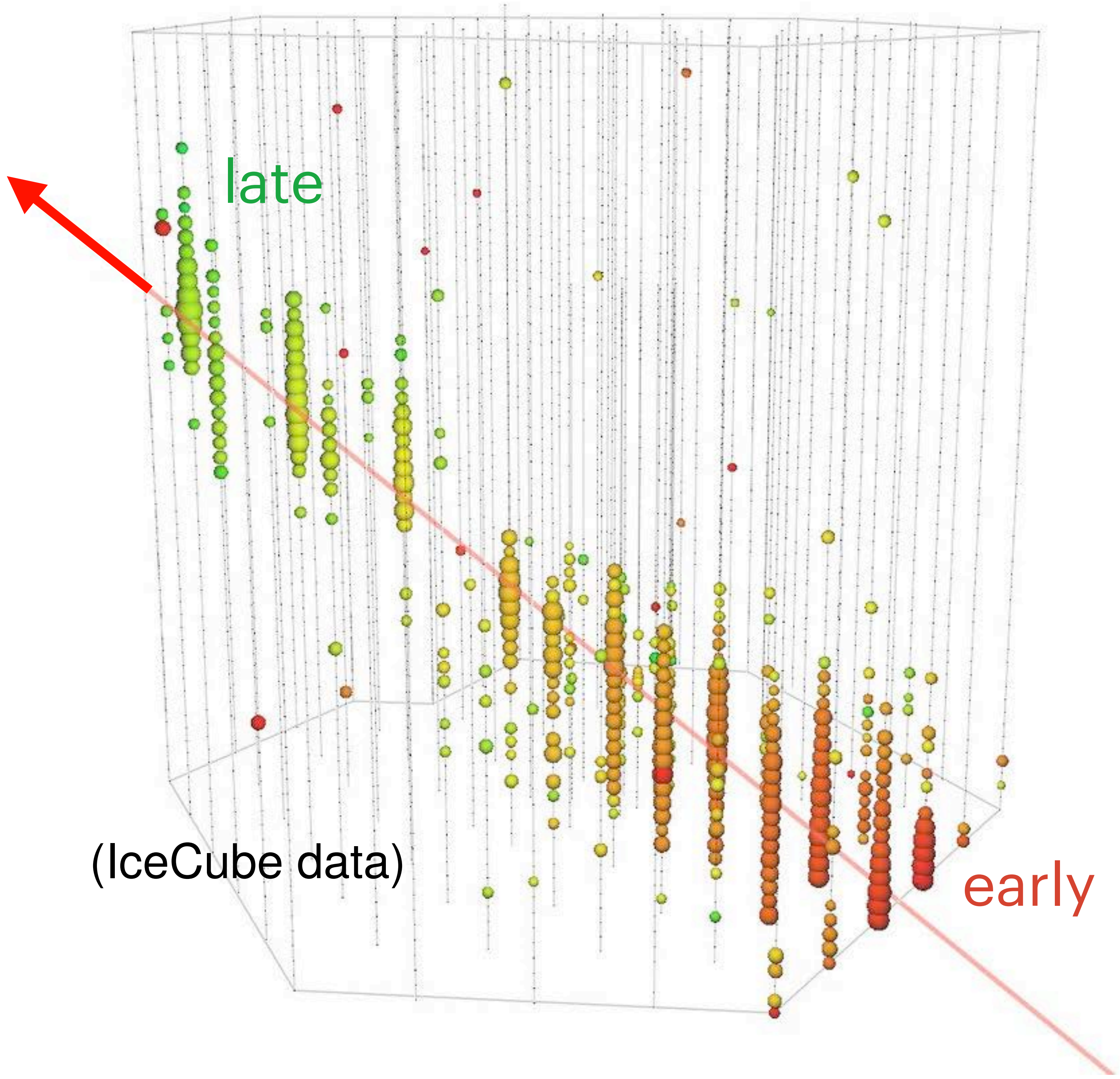

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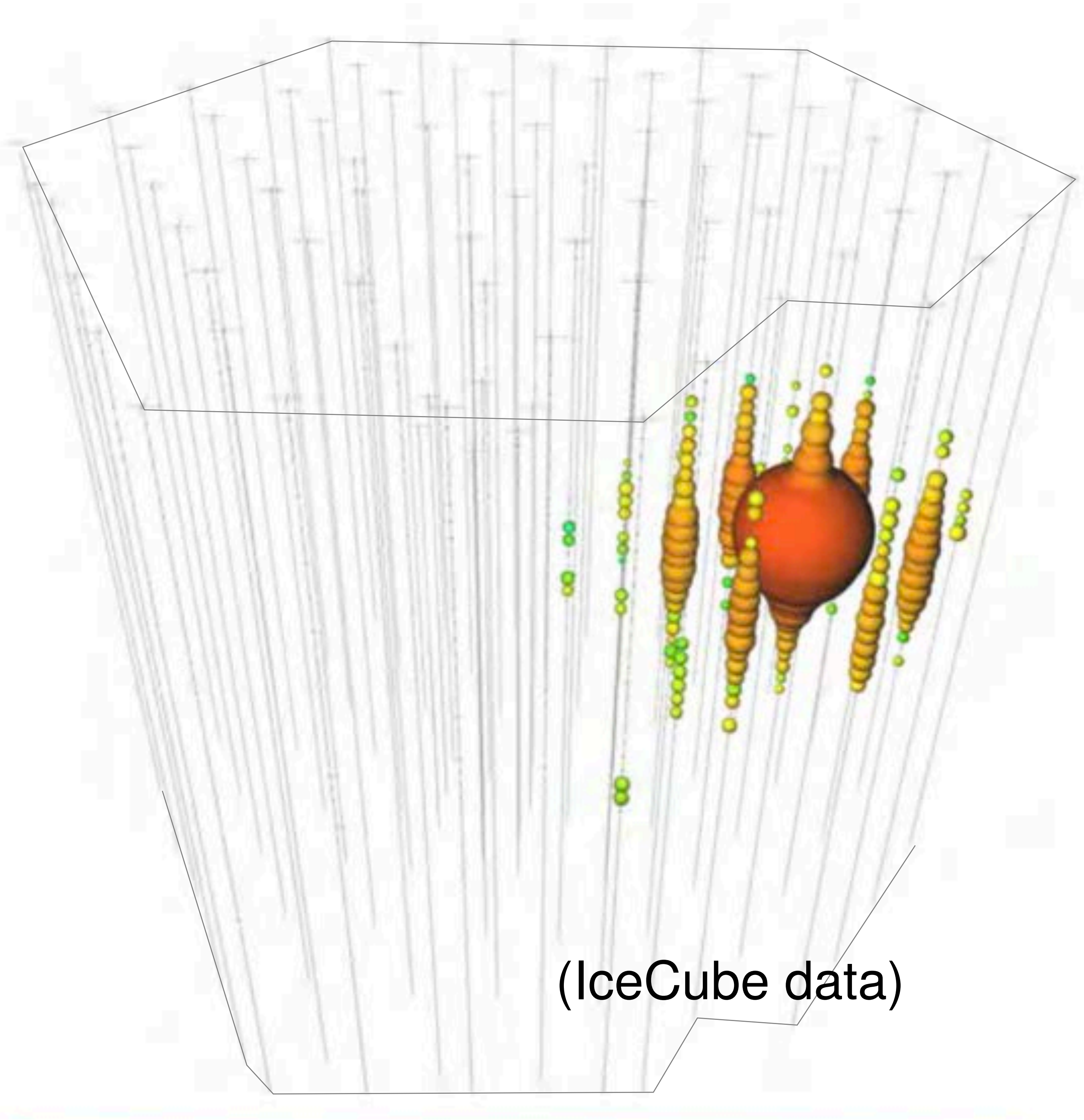

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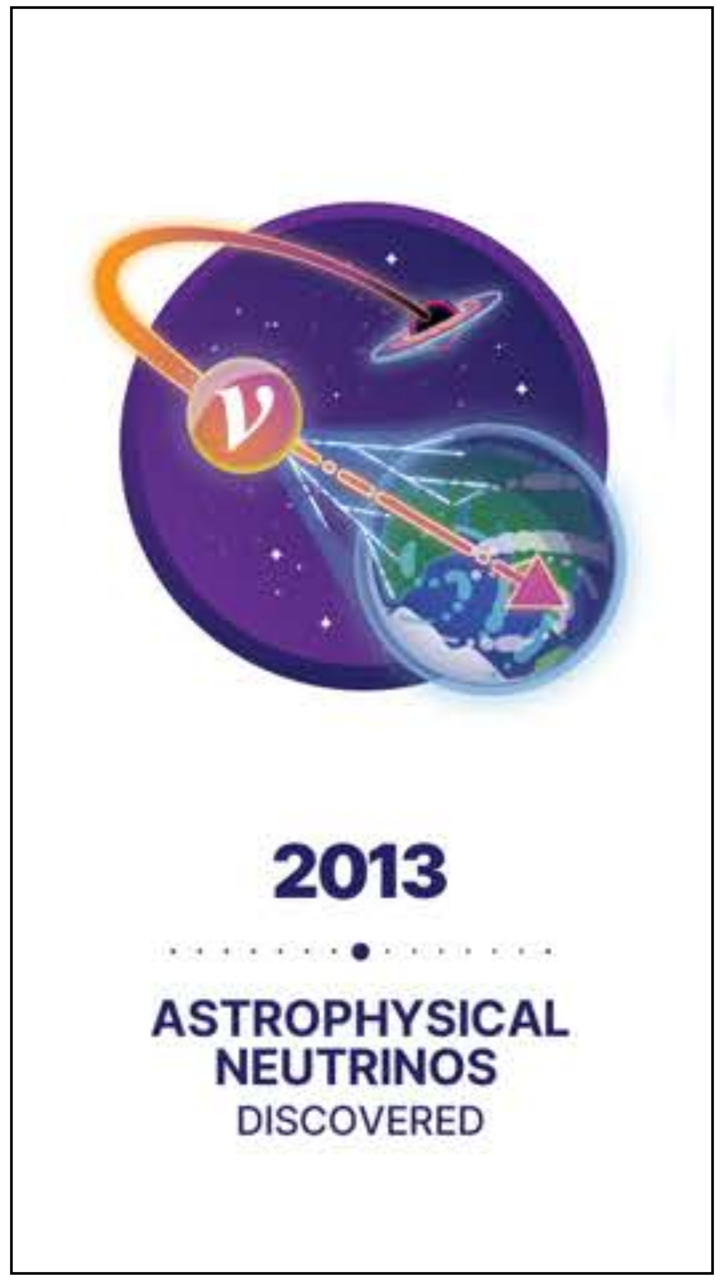

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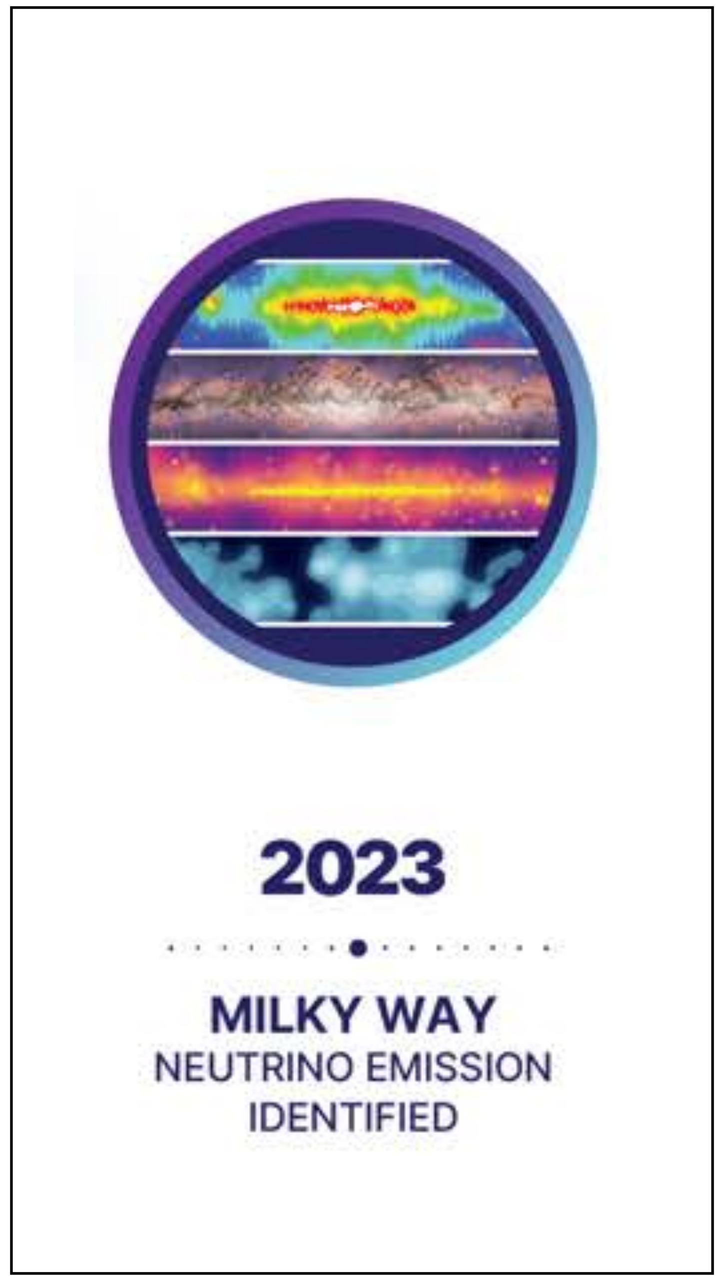

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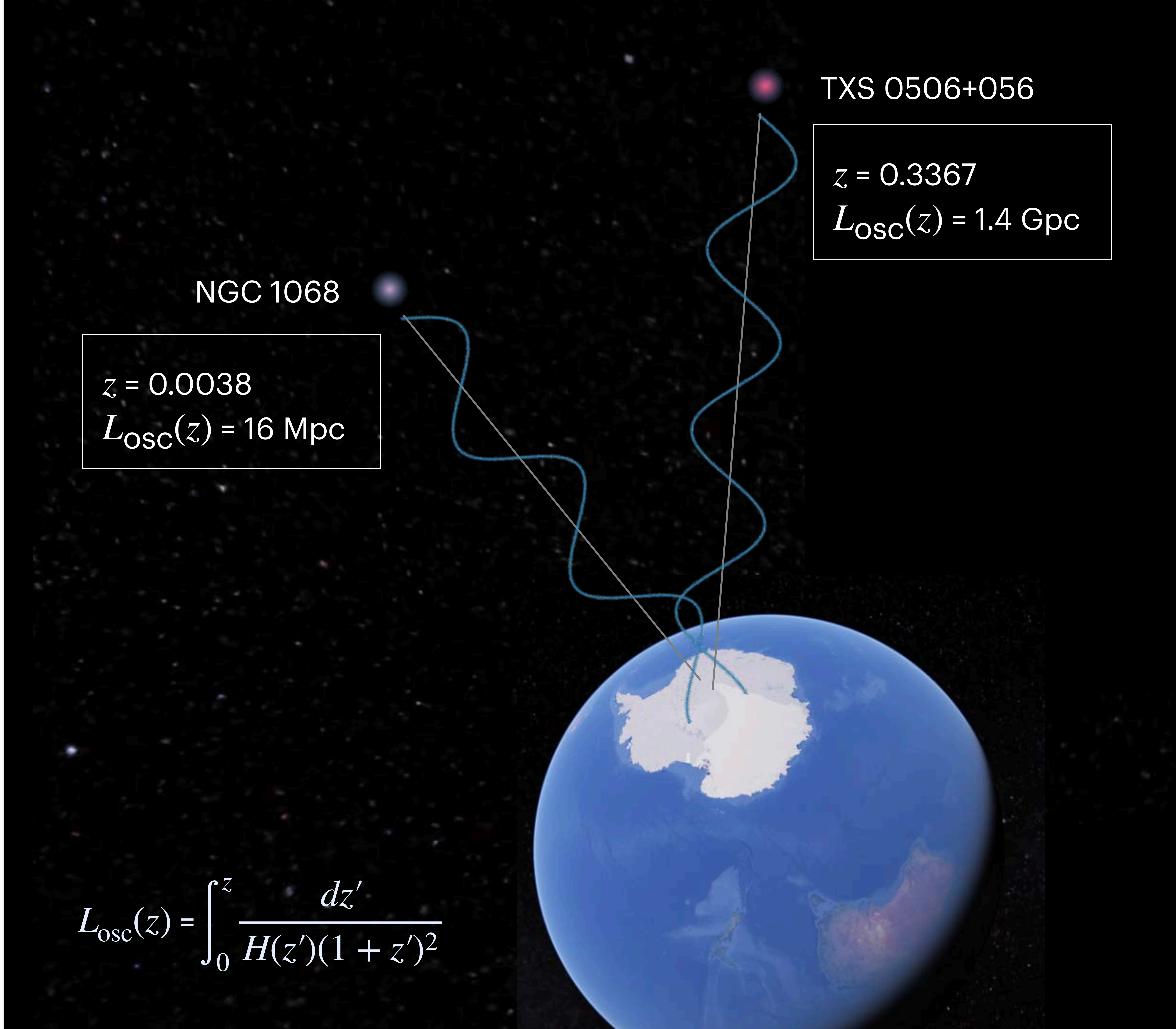
How well can we constrain QD models with a population of neutrino "point sources"?

Each point source emits neutrinos from a fixed distance L.

If neutrinos are QD, a fraction will disappear into sterile states, leaving fewer detectable neutrinos:

$$P_{\text{surv}}(E) = \cos^2(\delta m^2 L/4E)$$



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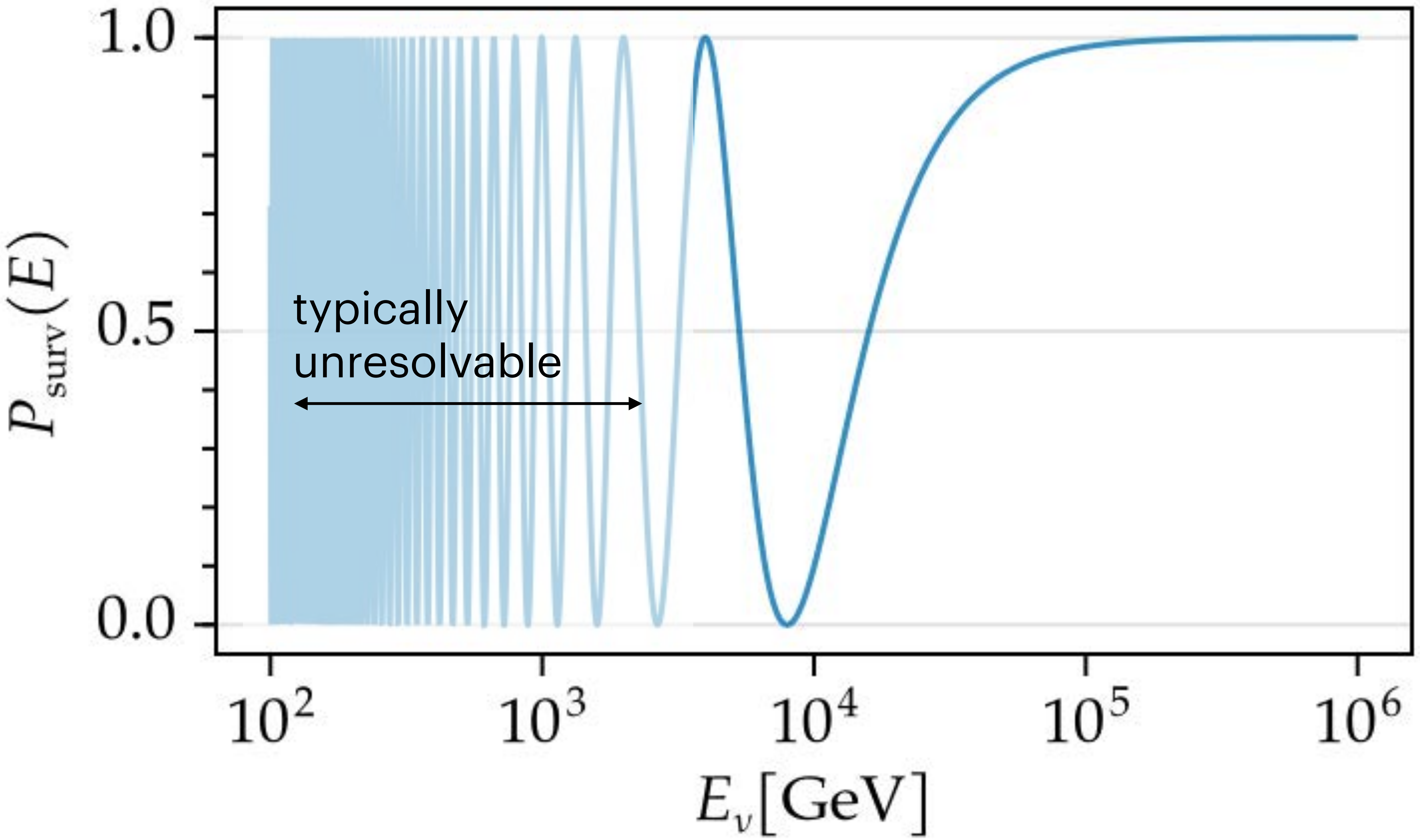
$$P_{\rm surv}(E) = \cos^2(\delta m^2 L/4E)$$

The QD signature is thus an oscillation-induced disappearance dip in energy.

$L = 16\,{\rm Mpc}$,
$\delta m^2 = 5 \times 10^{-18}\,{\rm eV}^2$



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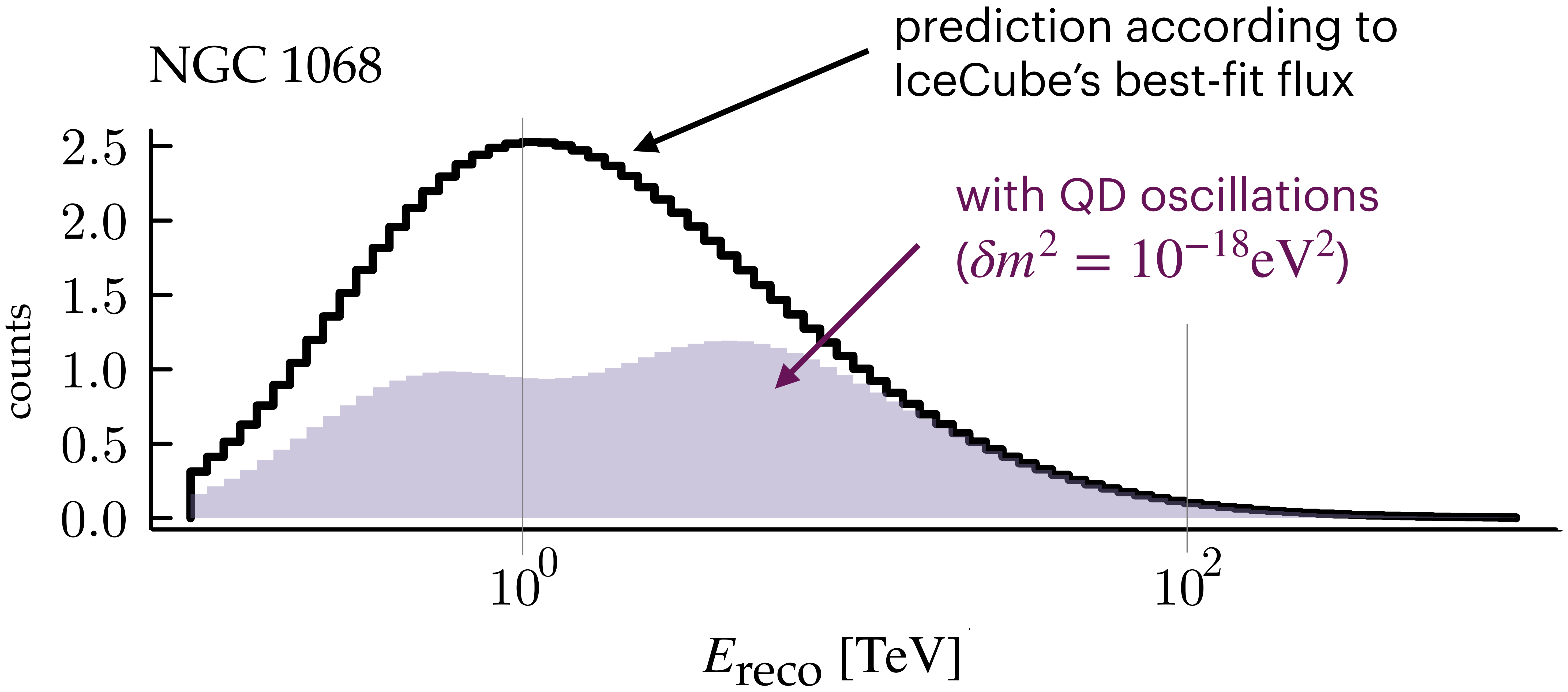

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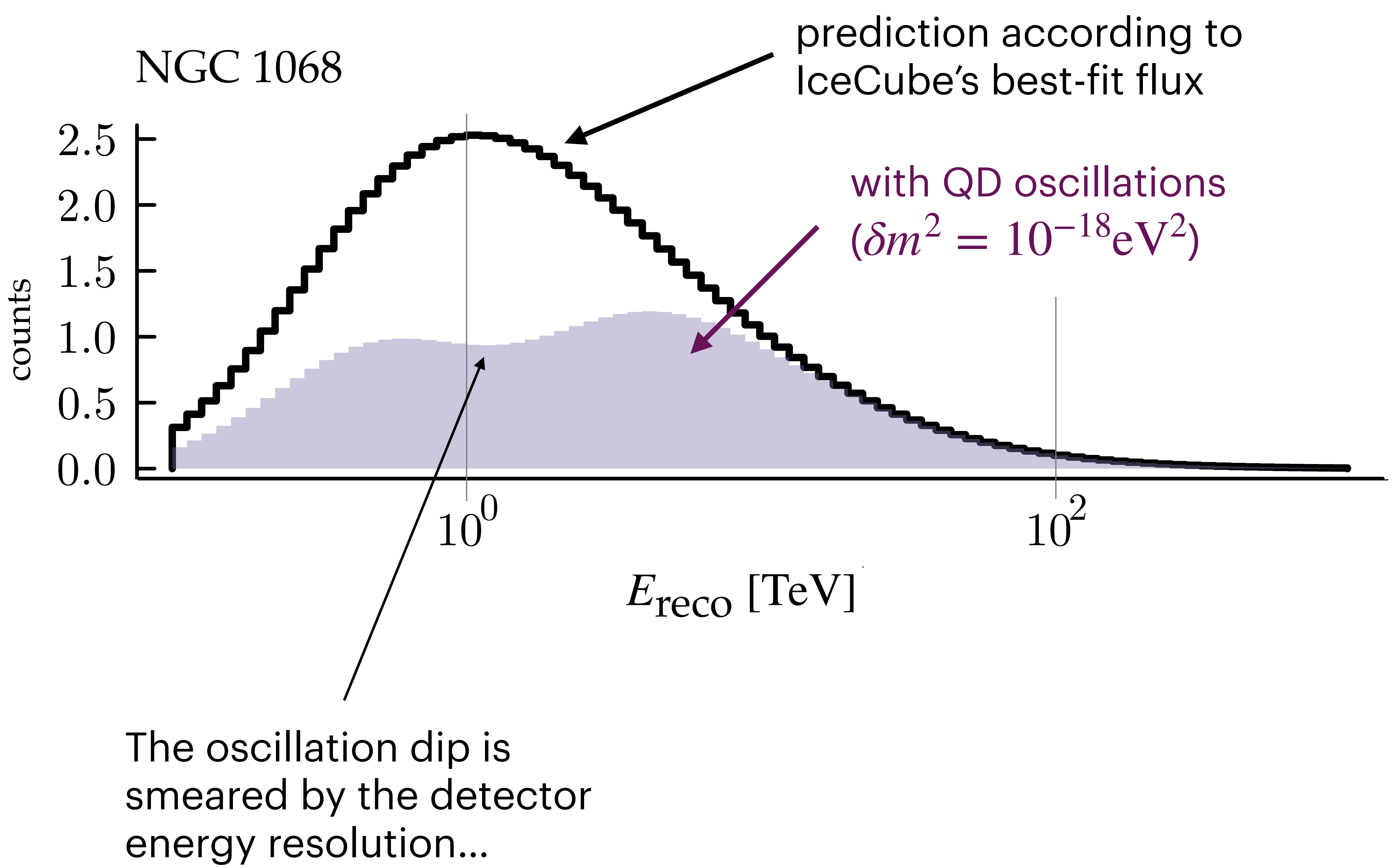

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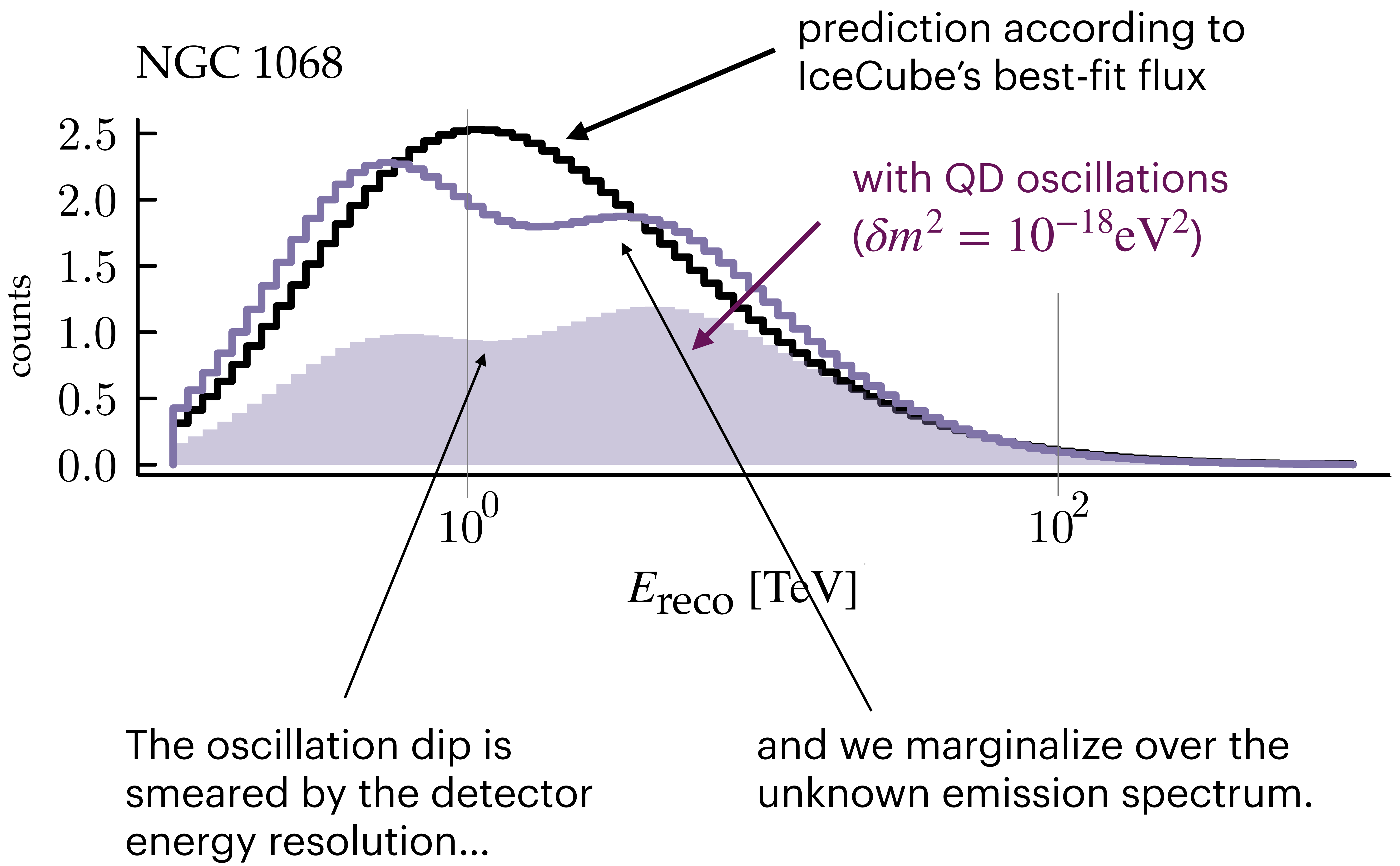

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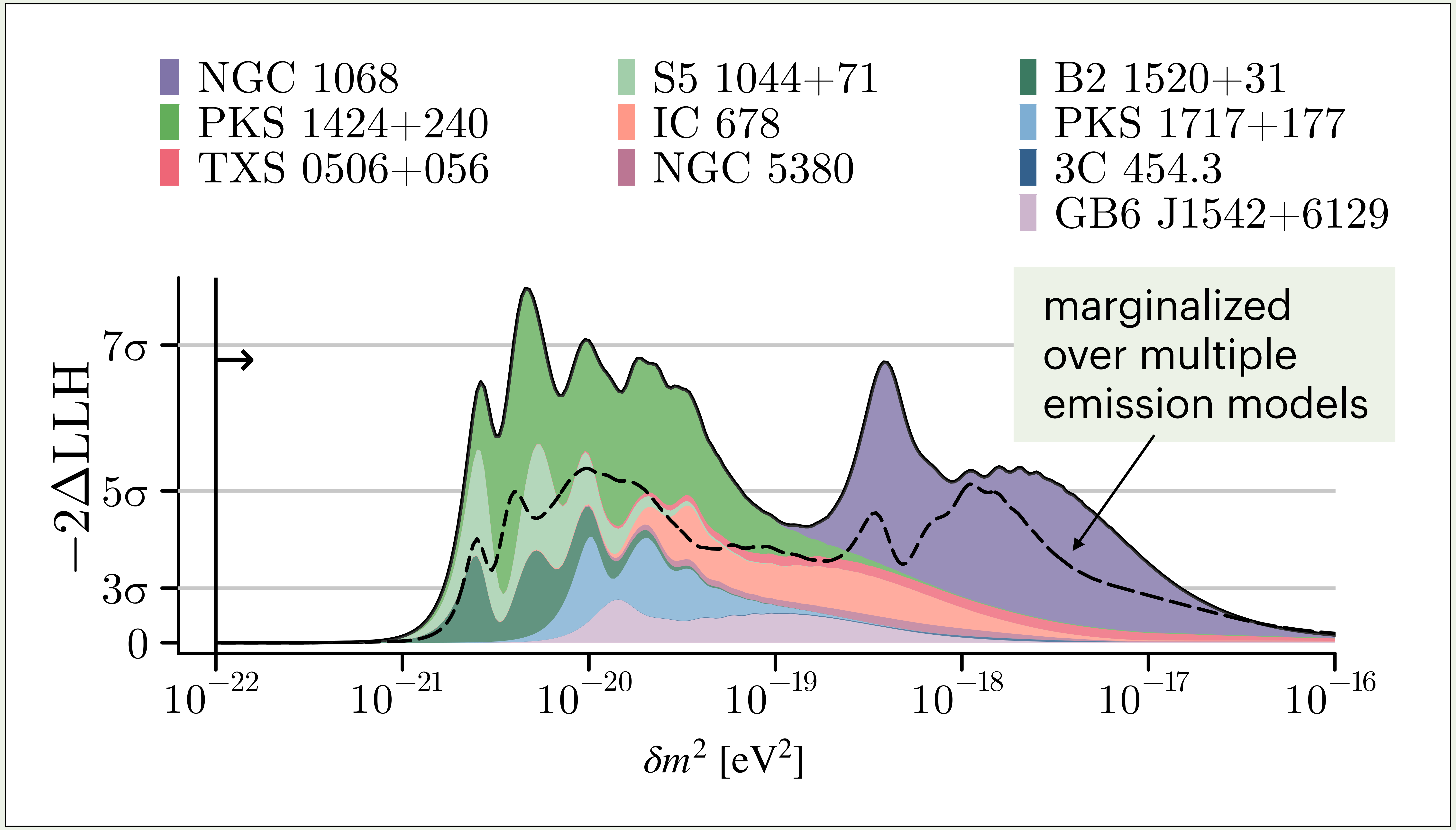
Since each point source is independent, their contributions stack!

We project the sensitivity of IceCube-Gen2:



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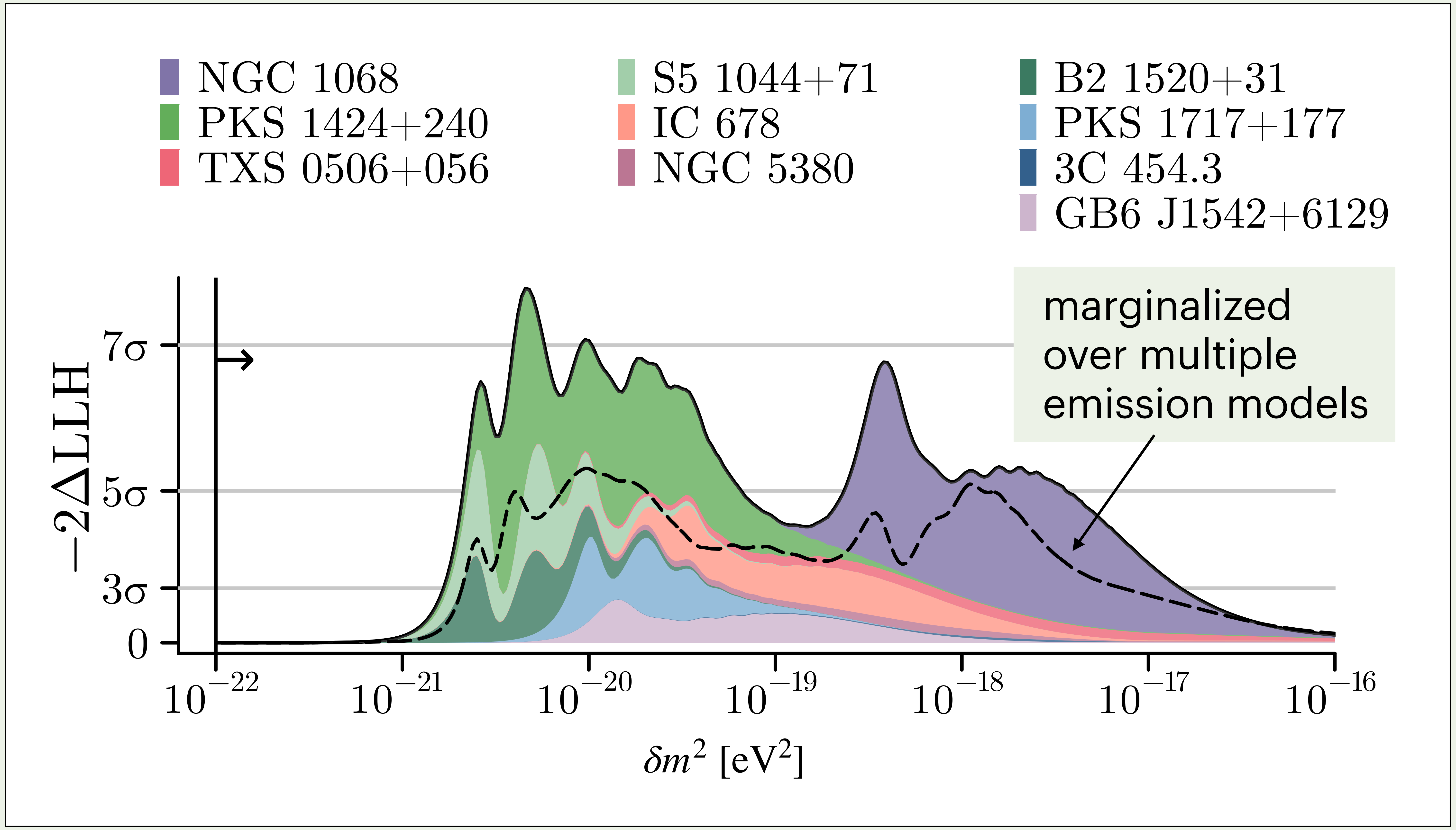
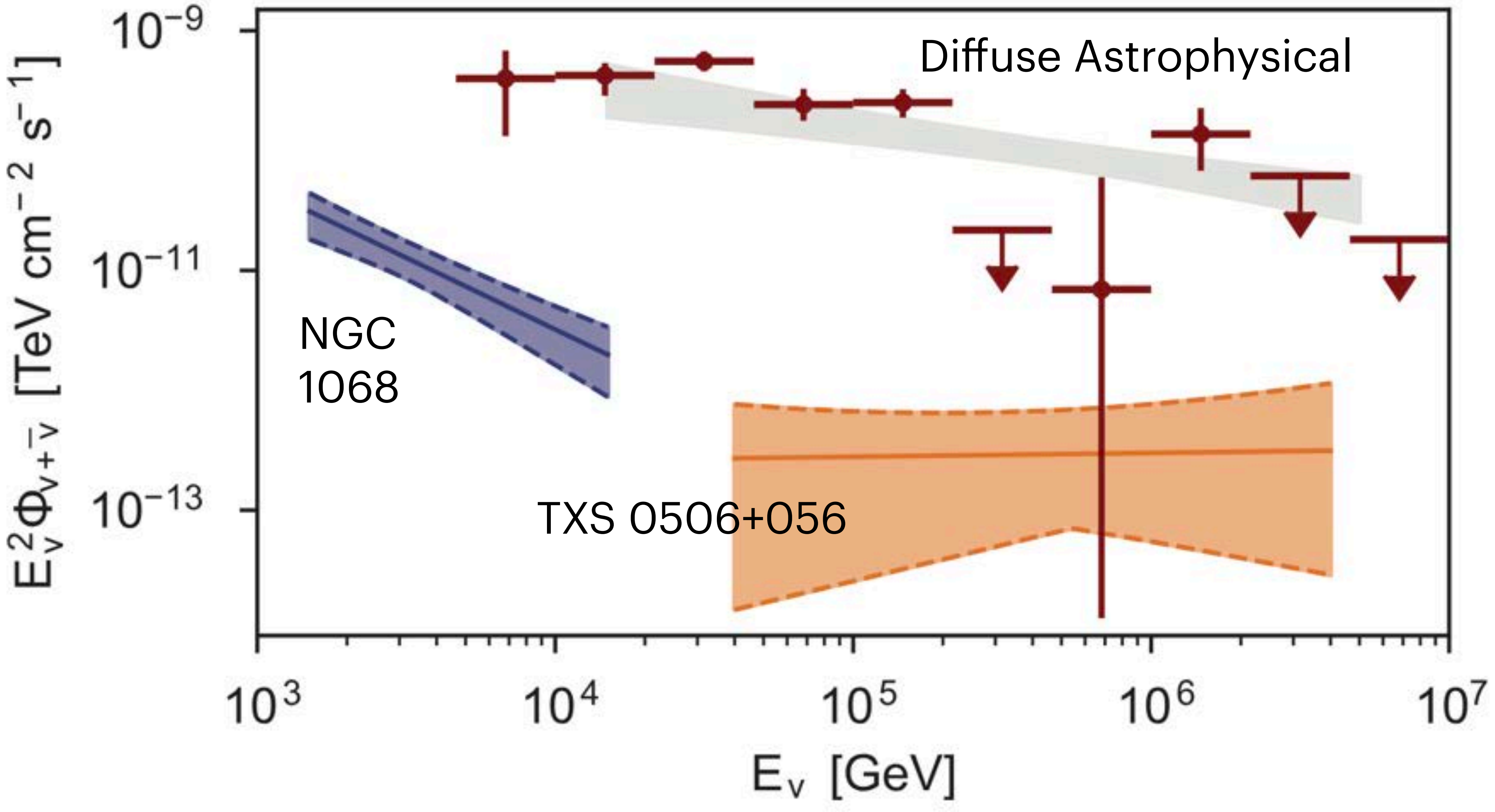


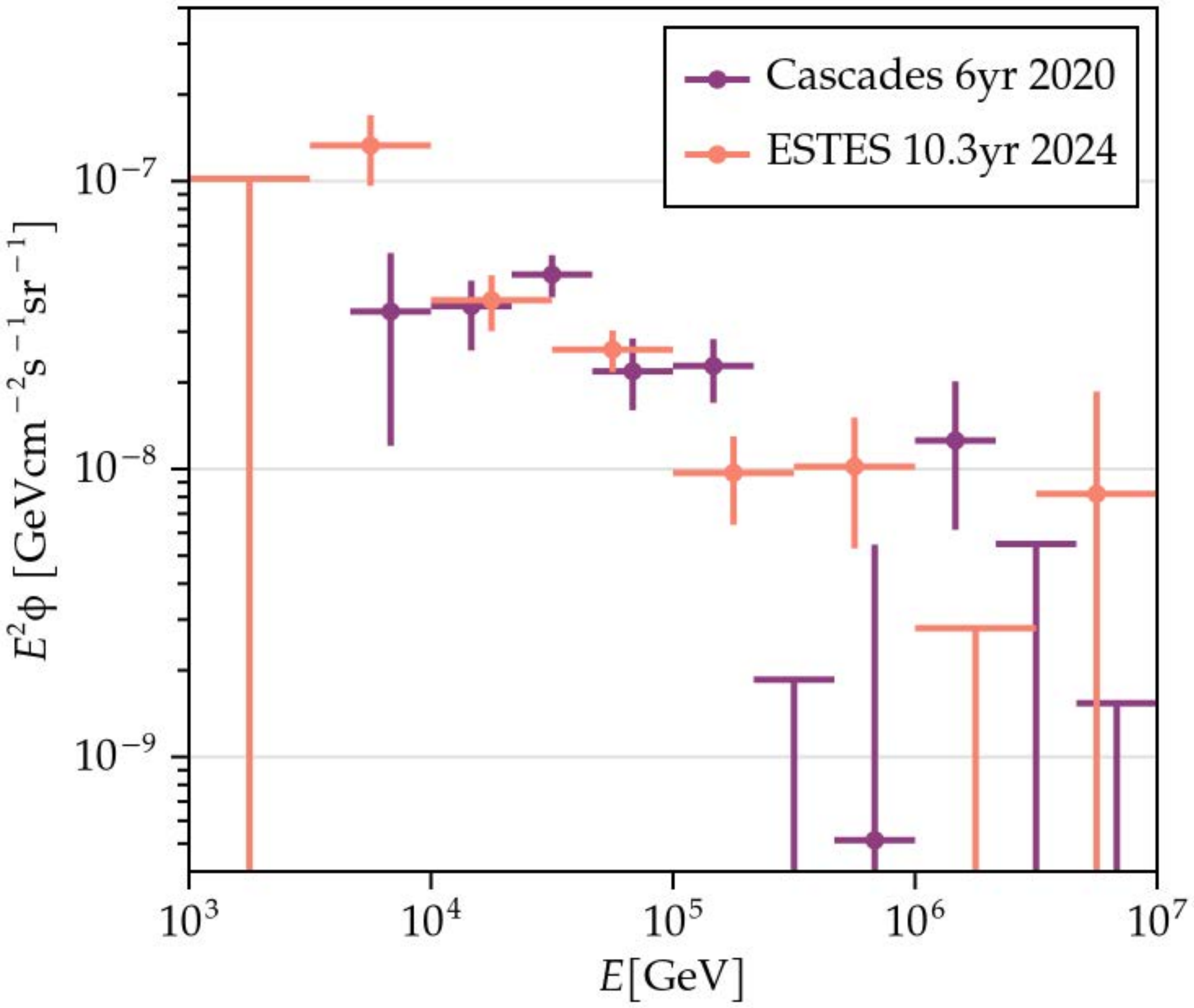
Our current sensitivity is limited by:

- poor energy resolution
- need to marginalize over unknown emission spectra
- few sources / limited statistics

IceCube Collaboration, 2211.09972



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

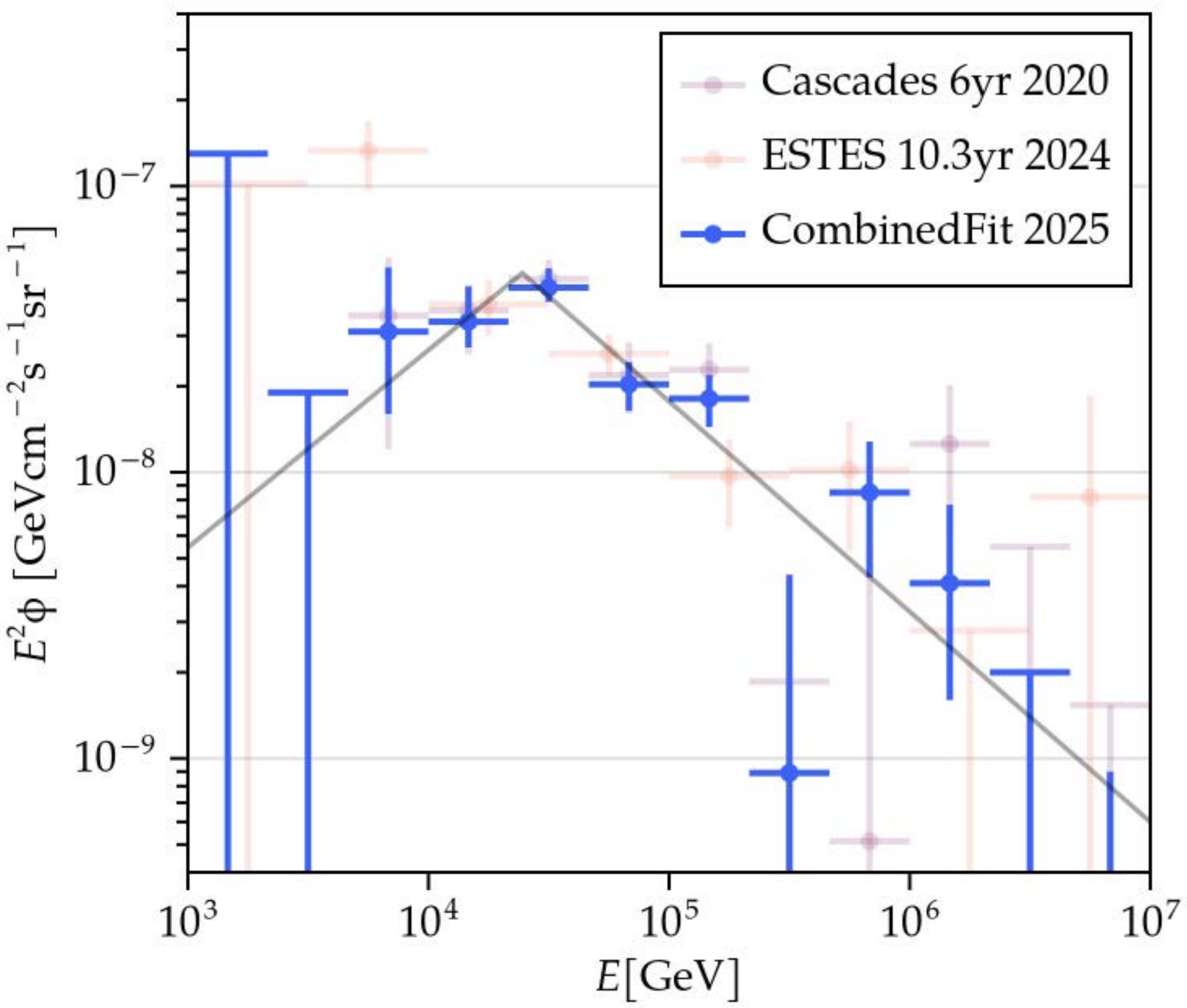


adapted from:
1. IceCube Collaboration, 2001.09520
2. IceCube Collaboration, 2402.18026

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



tracks + cascades

adapted from:
1. IceCube Collaboration, 2001.09520
2. IceCube Collaboration, 2402.18026
3. IceCube Collaboration, 2507.22234

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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!

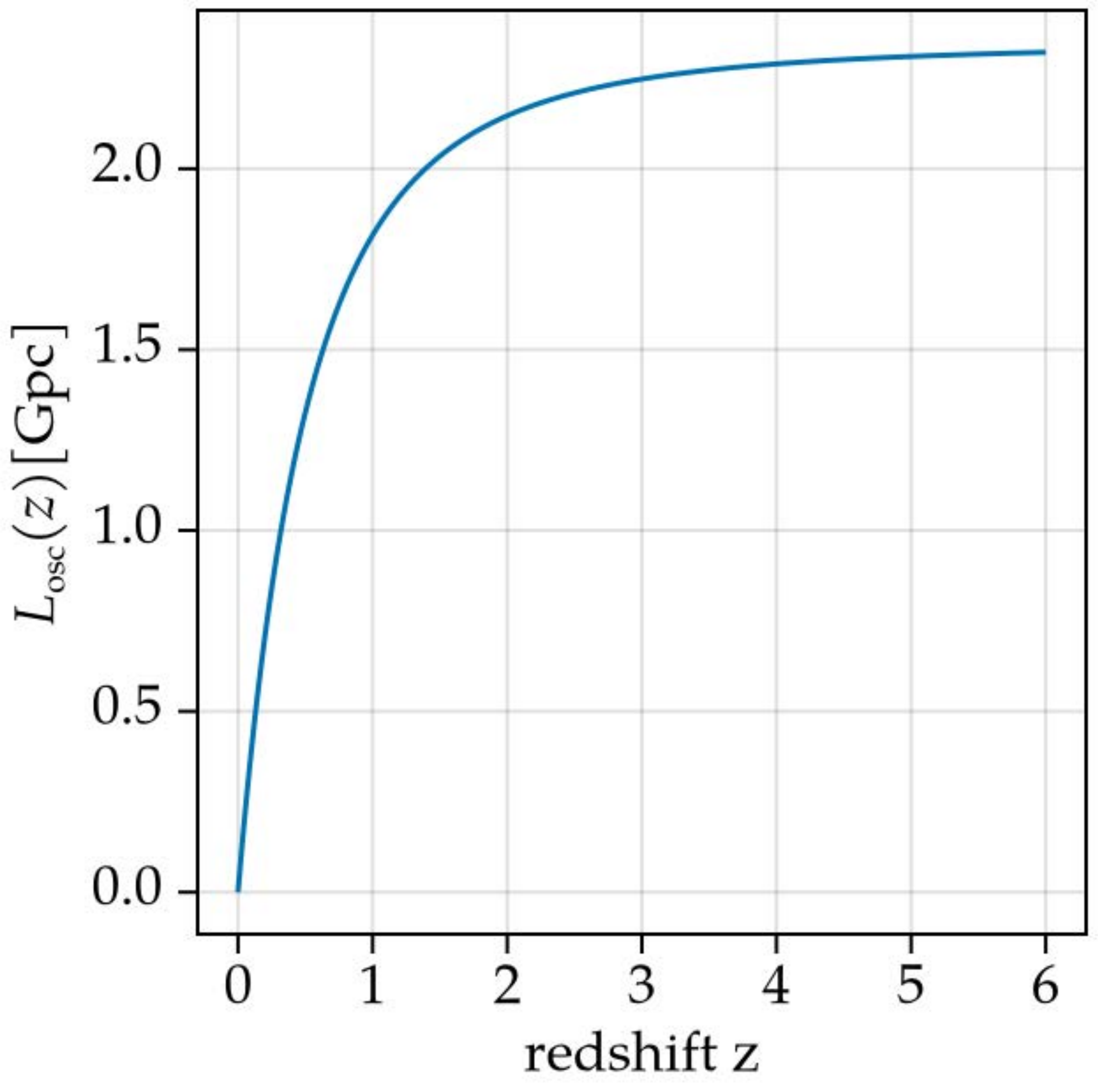
Can we use IceCube's diffuse flux measurements to constrain QD parameter space?

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



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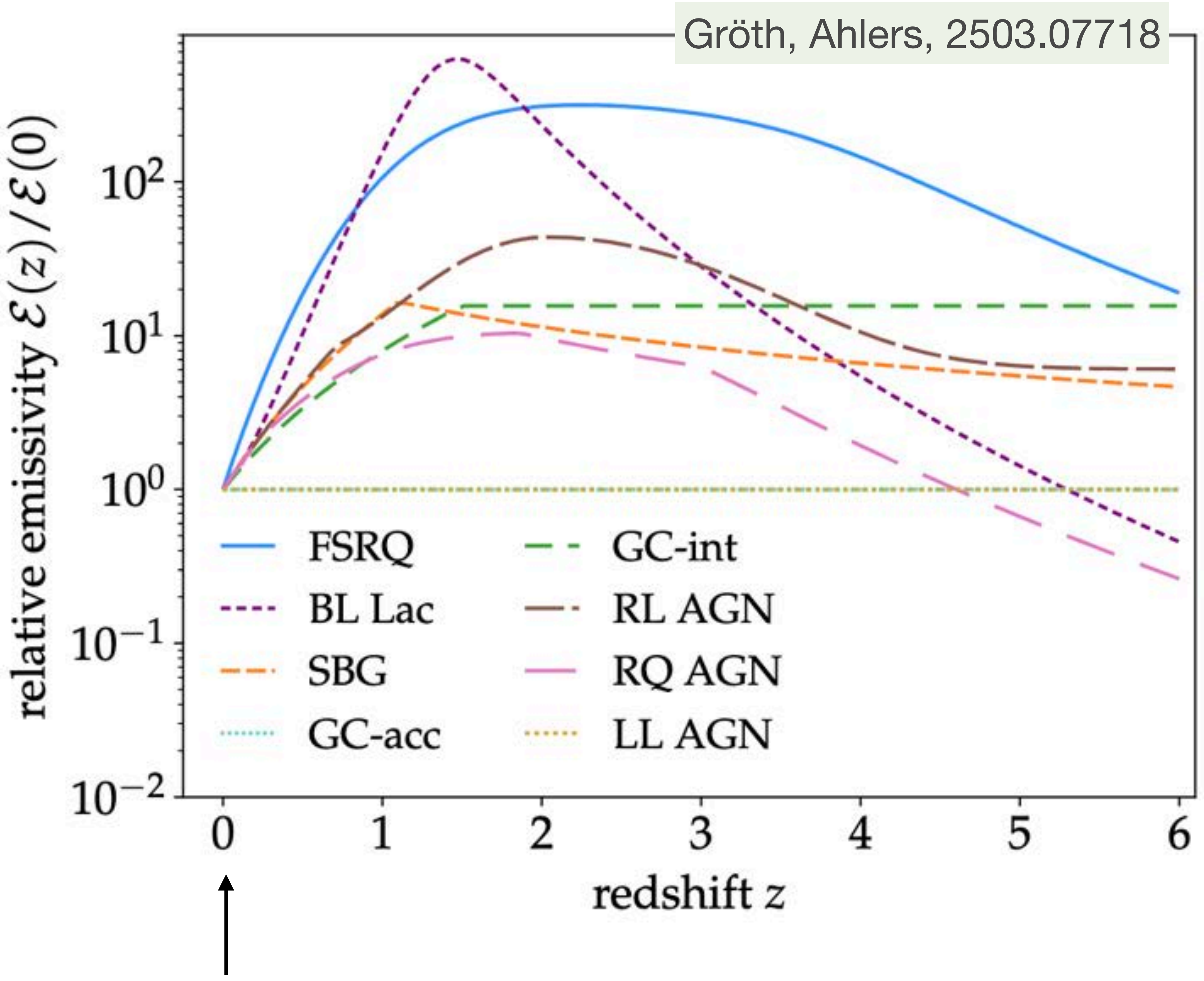

Scale as $(1+z)^m$ at small z, for $m = 0, 3, 5$

In our study, we

- Consider multiple physical evolution functions $\rho(z)$
- Assume all sources have the same emission spectrum $\phi_0(E_z)$, 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:

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

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

f_α = initial flavor fraction

ϕ_0 = emission spectrum

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

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- Consider multiple physical evolution functions $\rho(z)$
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- Perform a likelihood fit to the IceCube flux measurements
- Marginalize over all emission spectrum parameters

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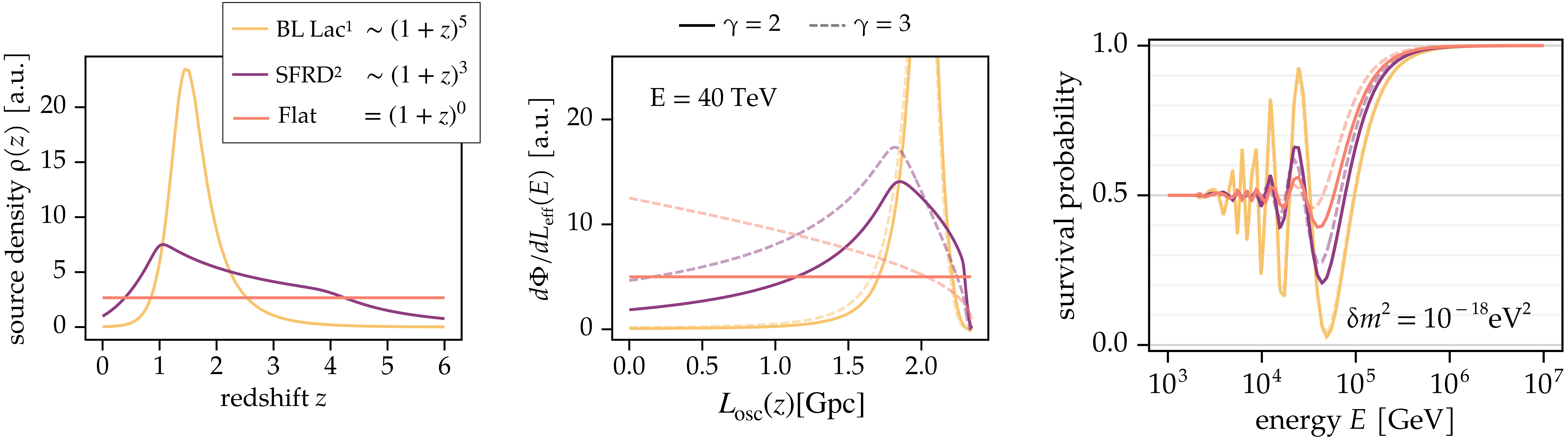
After integrating over all sources, we find that the QD disappearance dip remains resolvable!



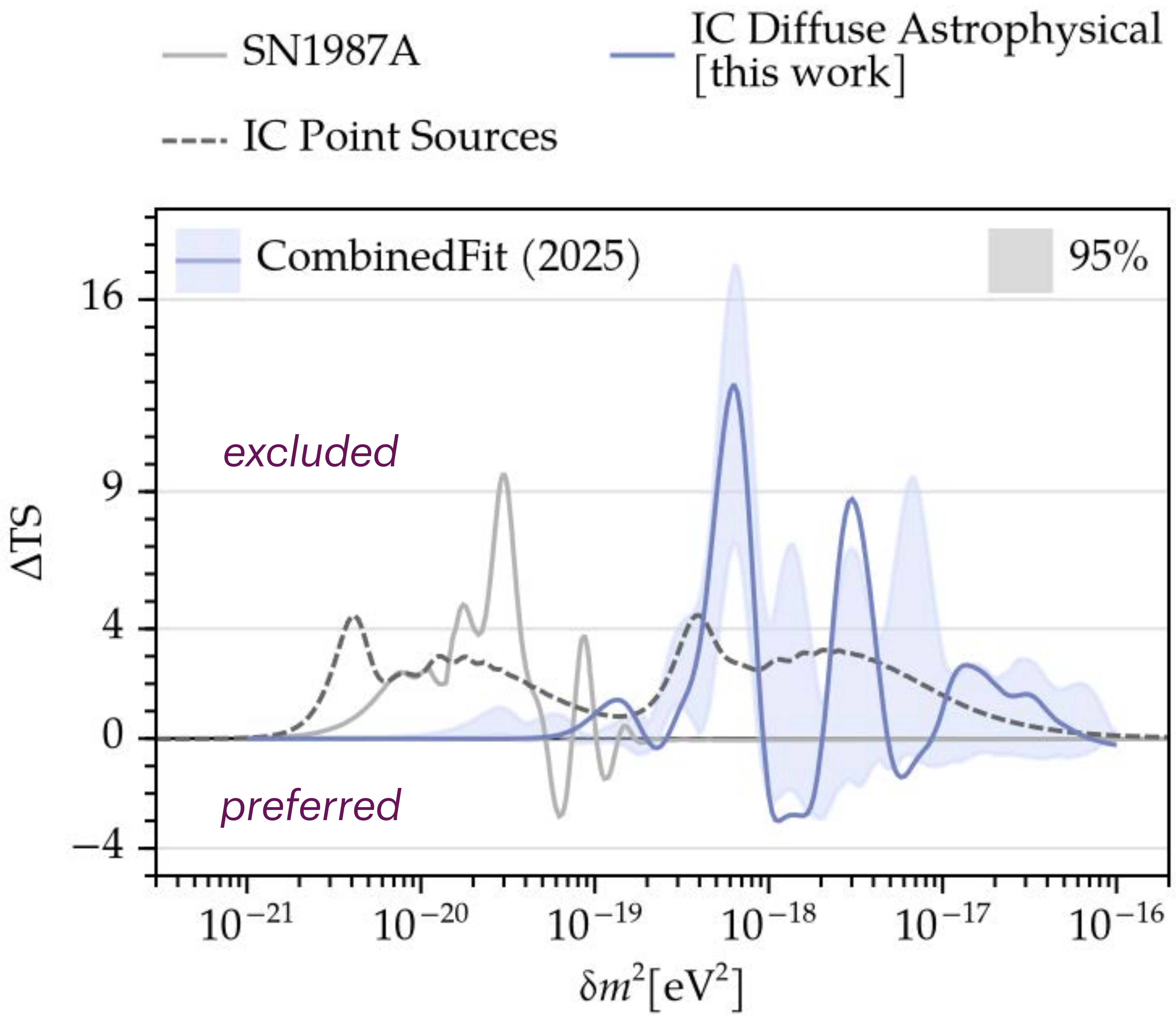
1. Gröth, Ahlers, 2503.07718
2. Elías-Chávez, Martínez, 2503.07718

We consider two scenarios for our results:

1. All generations have equal hyperfine splittings, $\delta m_k^2 = \delta m^2 \forall k$.

2. There are two distinct splittings, producing flavor-dependent as well as energy-dependent disappearance effects.

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



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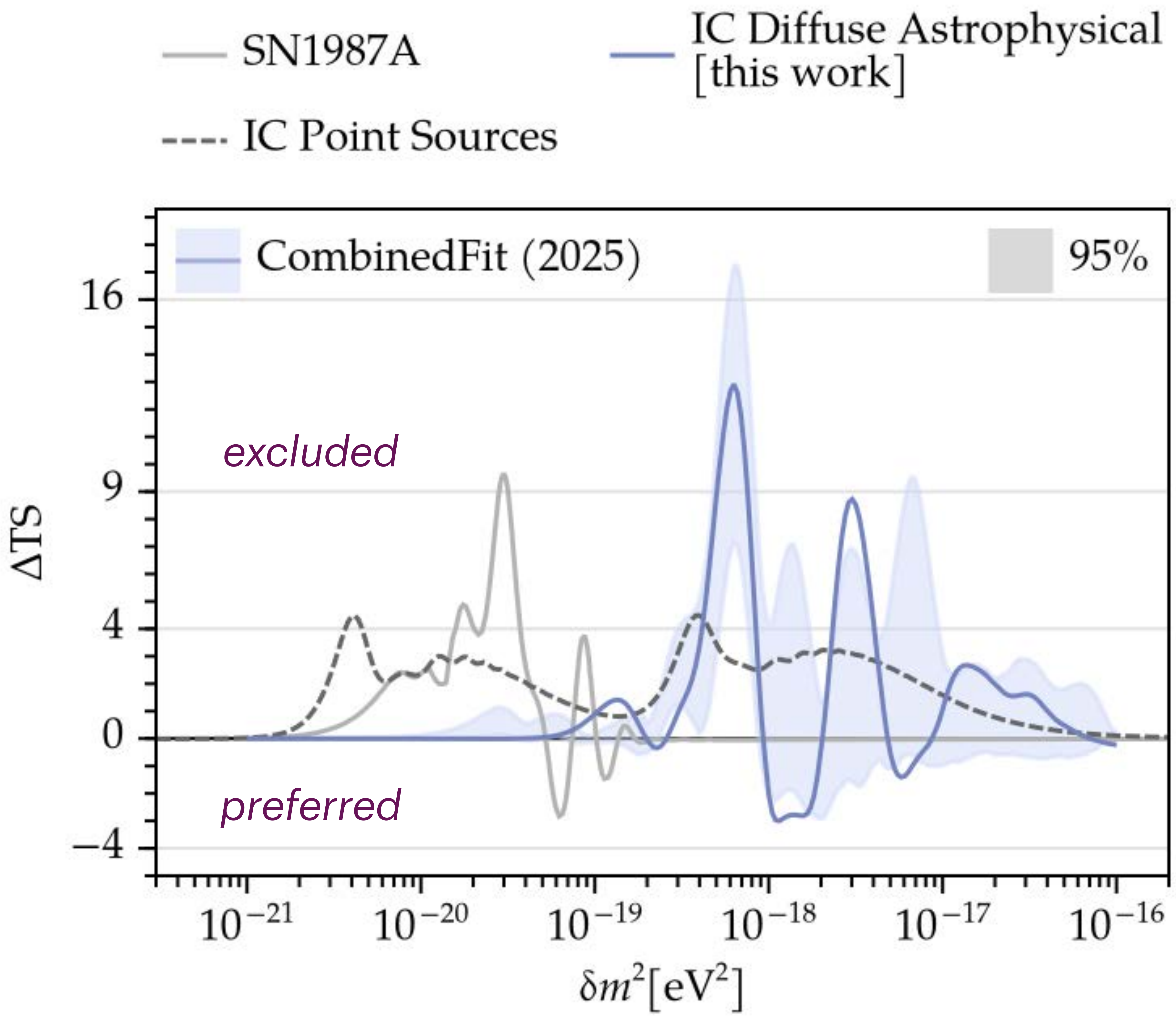

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We find no preference for a QD hypothesis.

We constrain

$\delta m^2 \in [5 - 7.5] \times 10^{-19}\ \mathrm{eV}^2$

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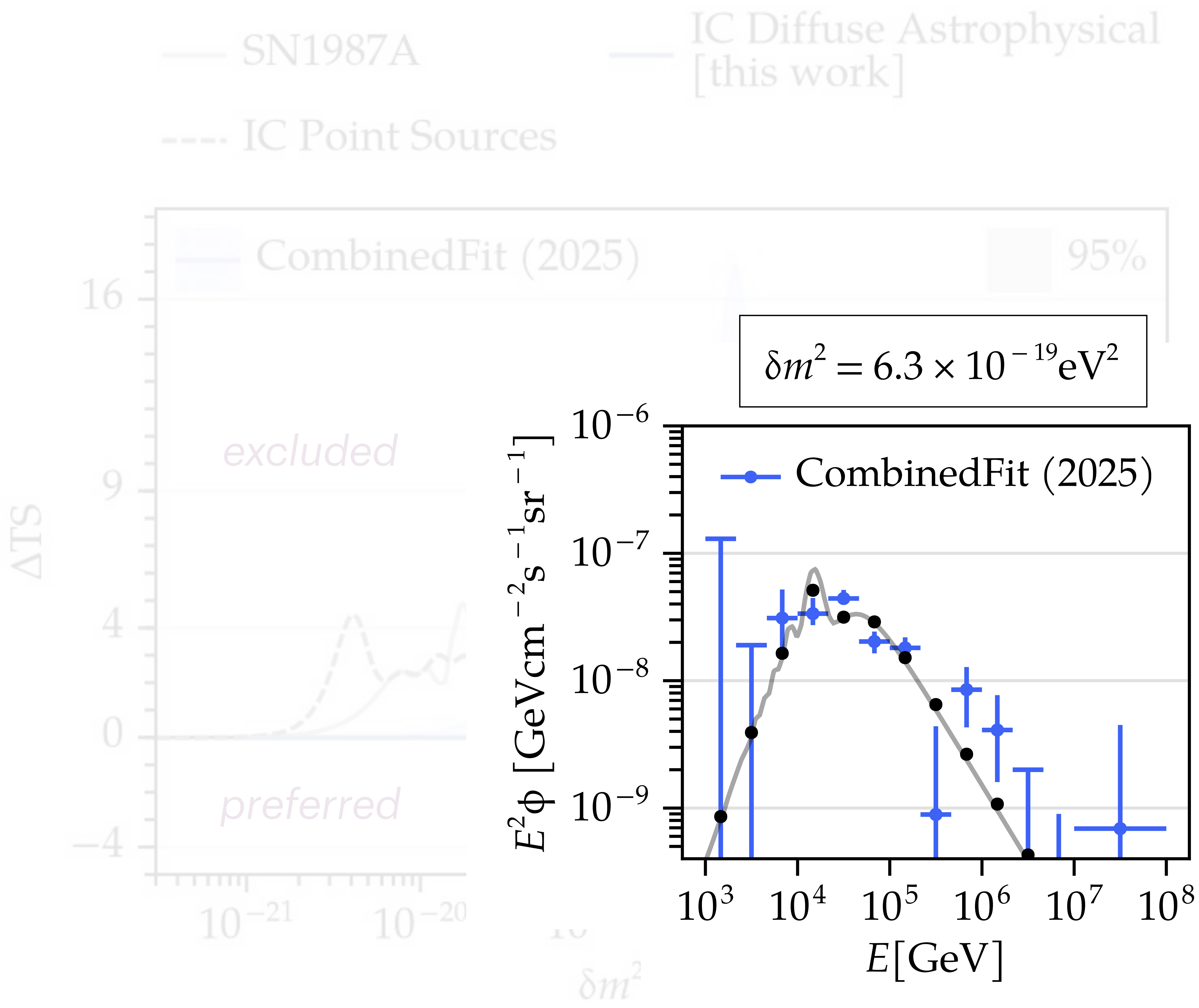

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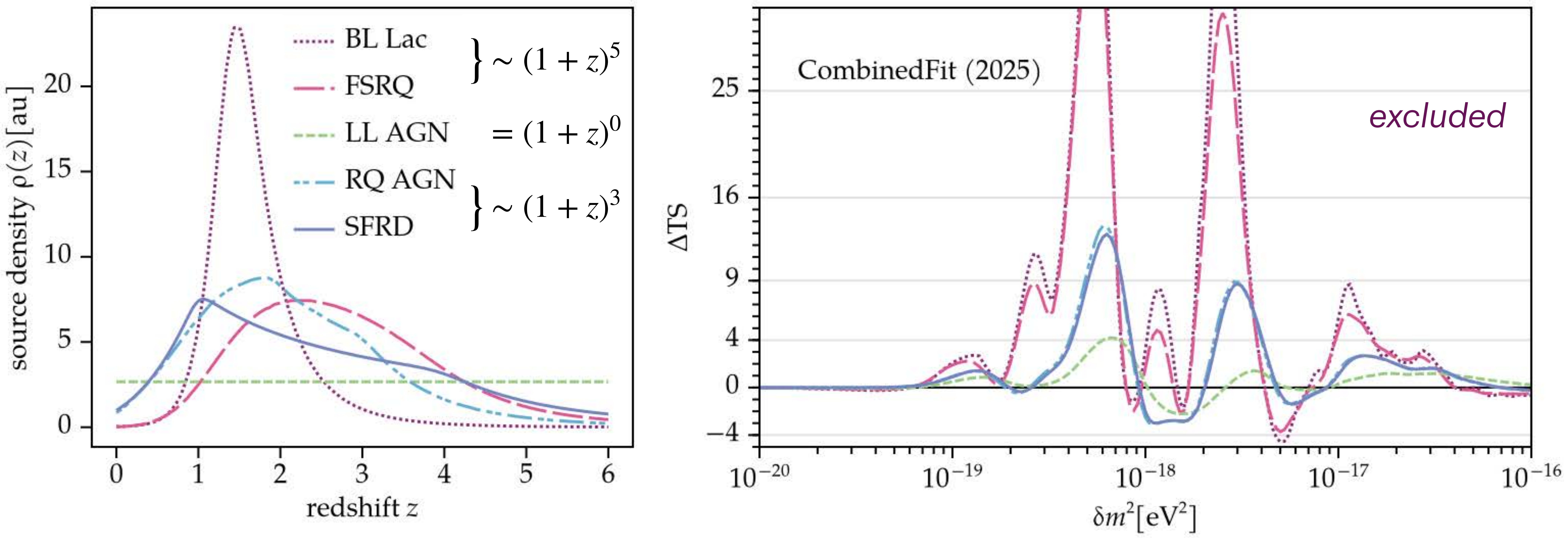
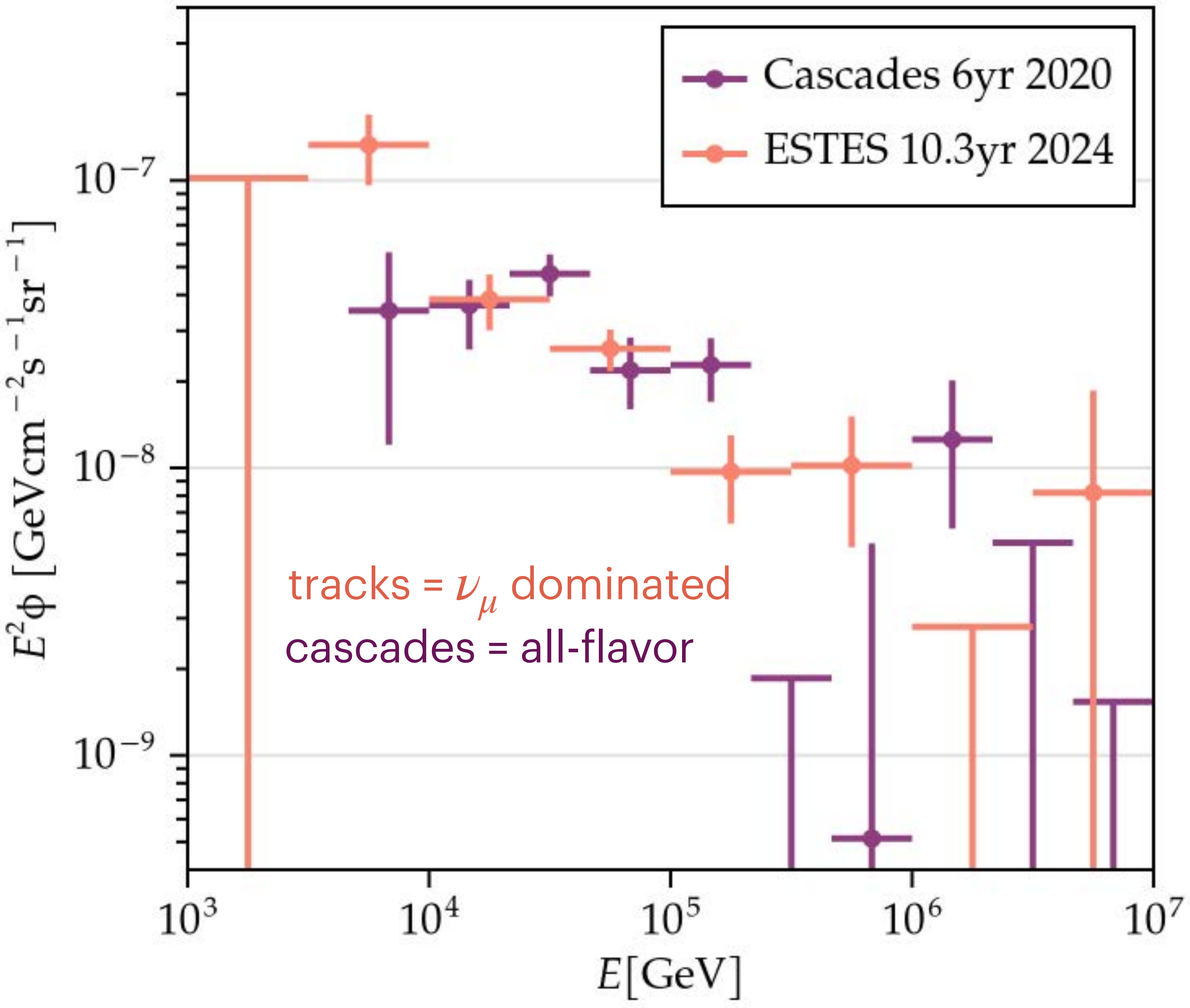
The significance of our constraints depend strongly on the scaling of the source evolution $\rho(z)$:



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

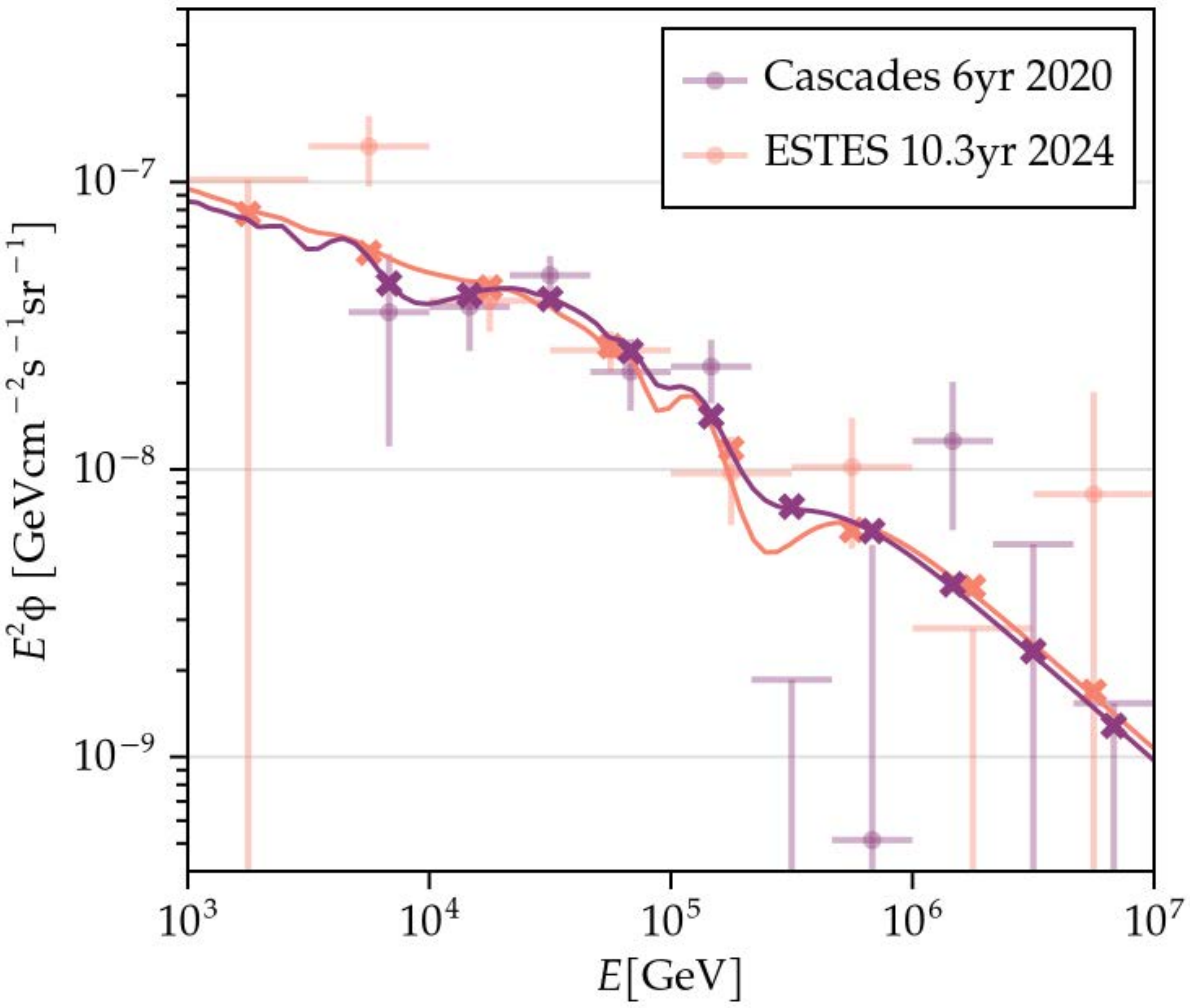
QD oscillations caused by δm_1^2 disproportionately affect cascades, while those caused by δm_3^2 disproportionately affect tracks.



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

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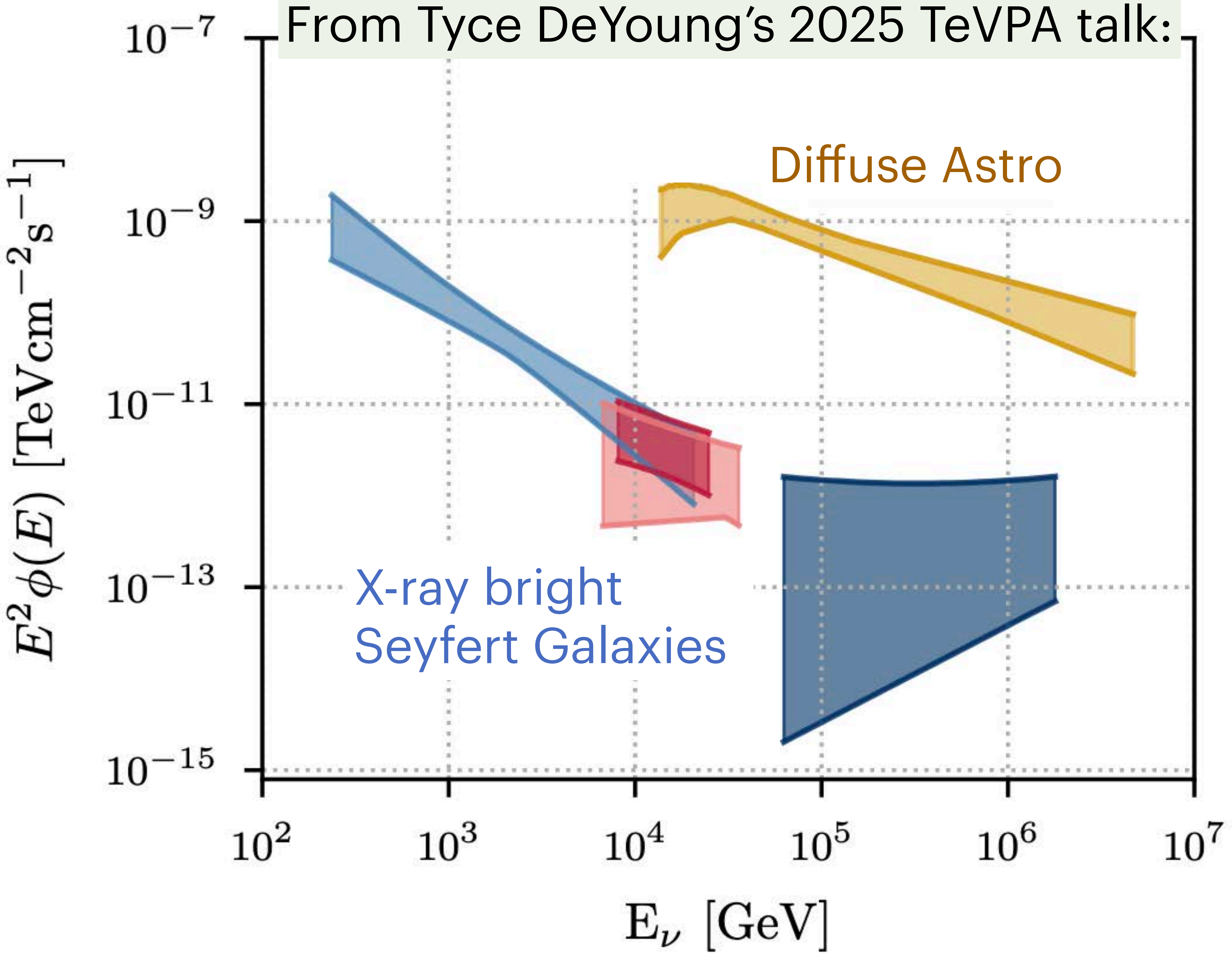
Prospects:

- IceCube's diffuse flux measurements are continuously improving
  - better control of systematics at low energies
- Our understanding of what astrophysical objects produce neutrinos is improving!
  - => better characterize source population distribution and emission spectra

From Tyce DeYoung's 2025 TeVPA talk:



Outline for the rest of this talk:

1. What are quasi-Dirac neutrinos?
2. How has IceCube detected astrophysical neutrinos?
3. Searches using extragalactic sources
4. **Searches using galactic sources**
5. Bonus

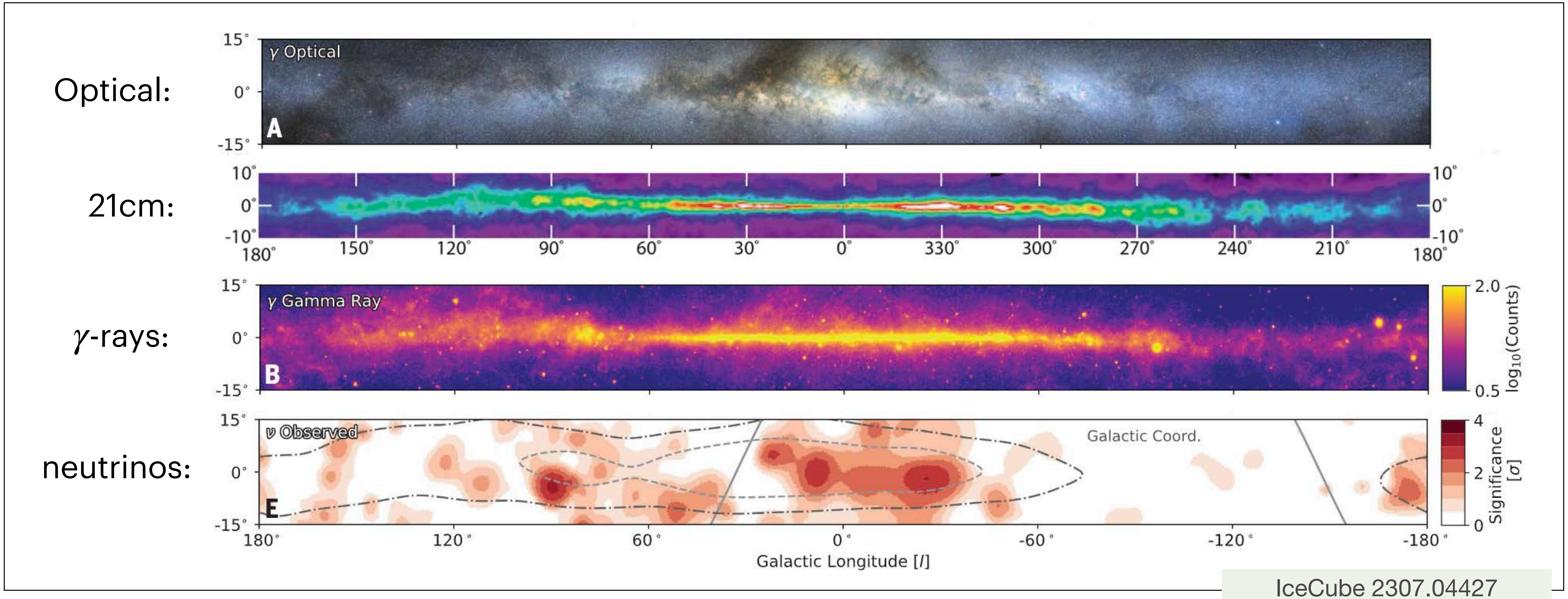
MacDonald, **KC**, Argüelles, Alves-Batista, Martinez-Soler (to appear)

IceCube has reported the observation of our Milky Way in neutrinos at ~~4.5σ~~ 5.7σ!

How well can we constrain QD models with galactic neutrinos?

There are 2 big advantages to galactic QD searches:

1. We've observed the Milky Way in many messengers:



IceCube 2307.04427
21cm line from NASA's multiwavelength Milky Way

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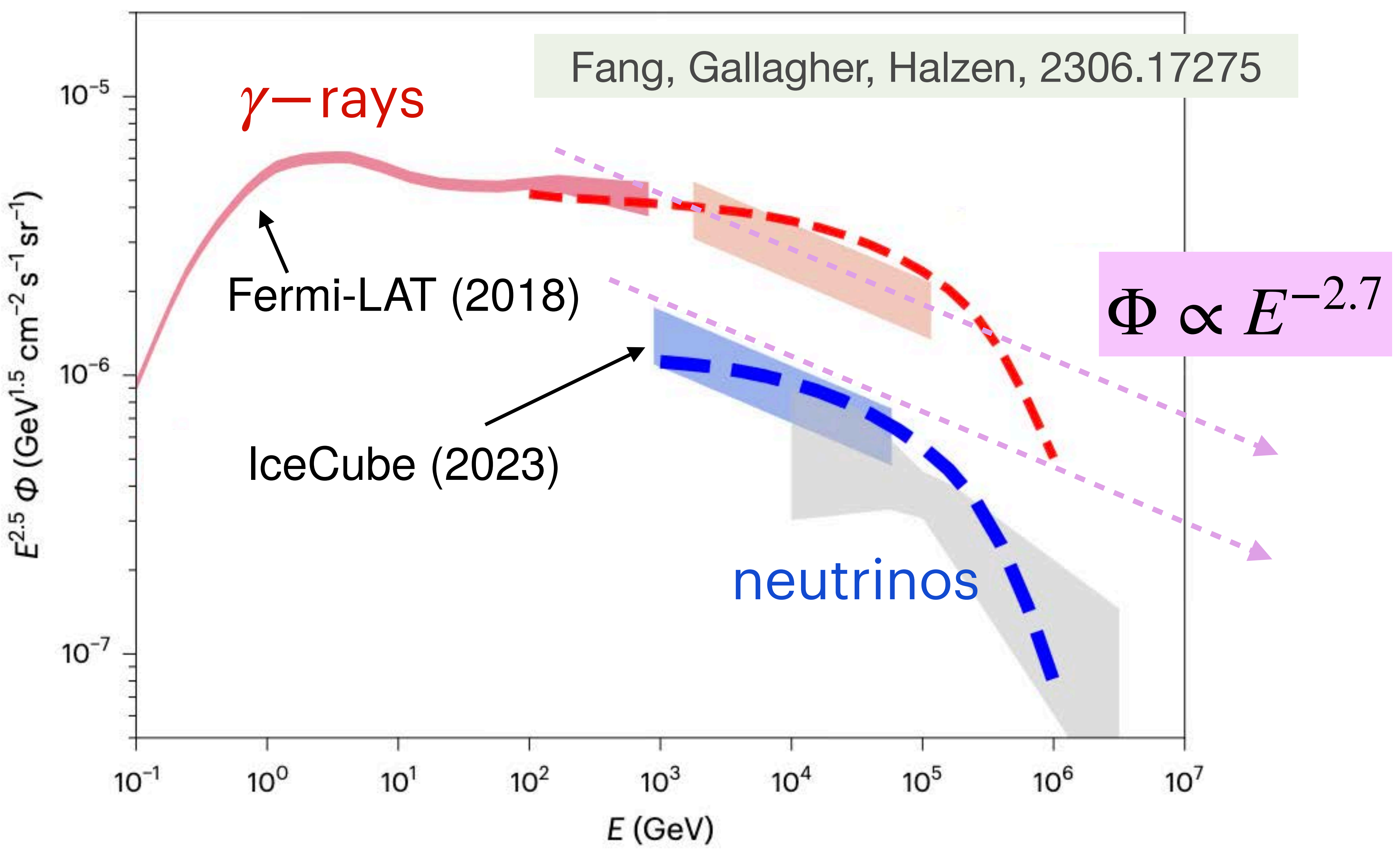

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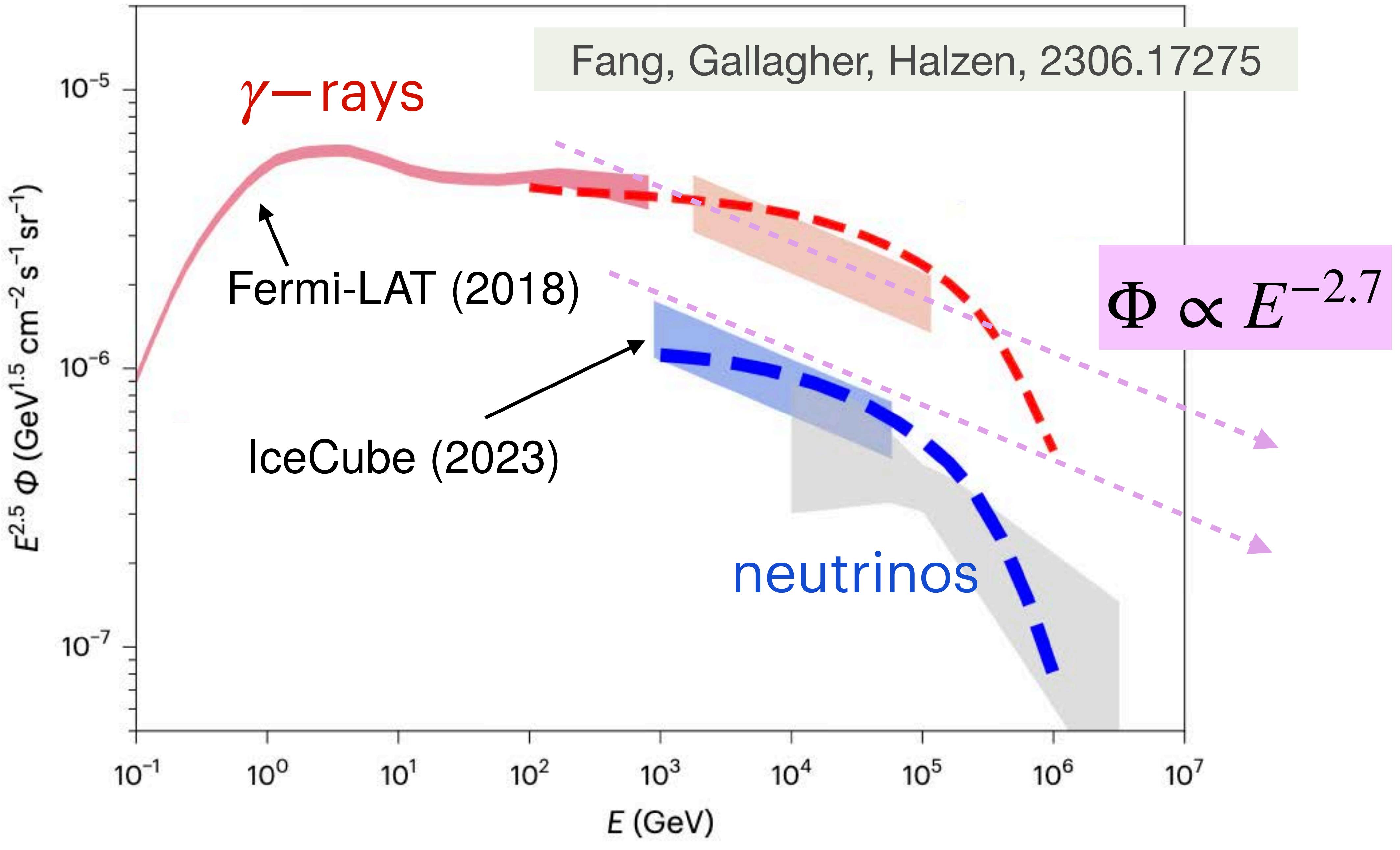

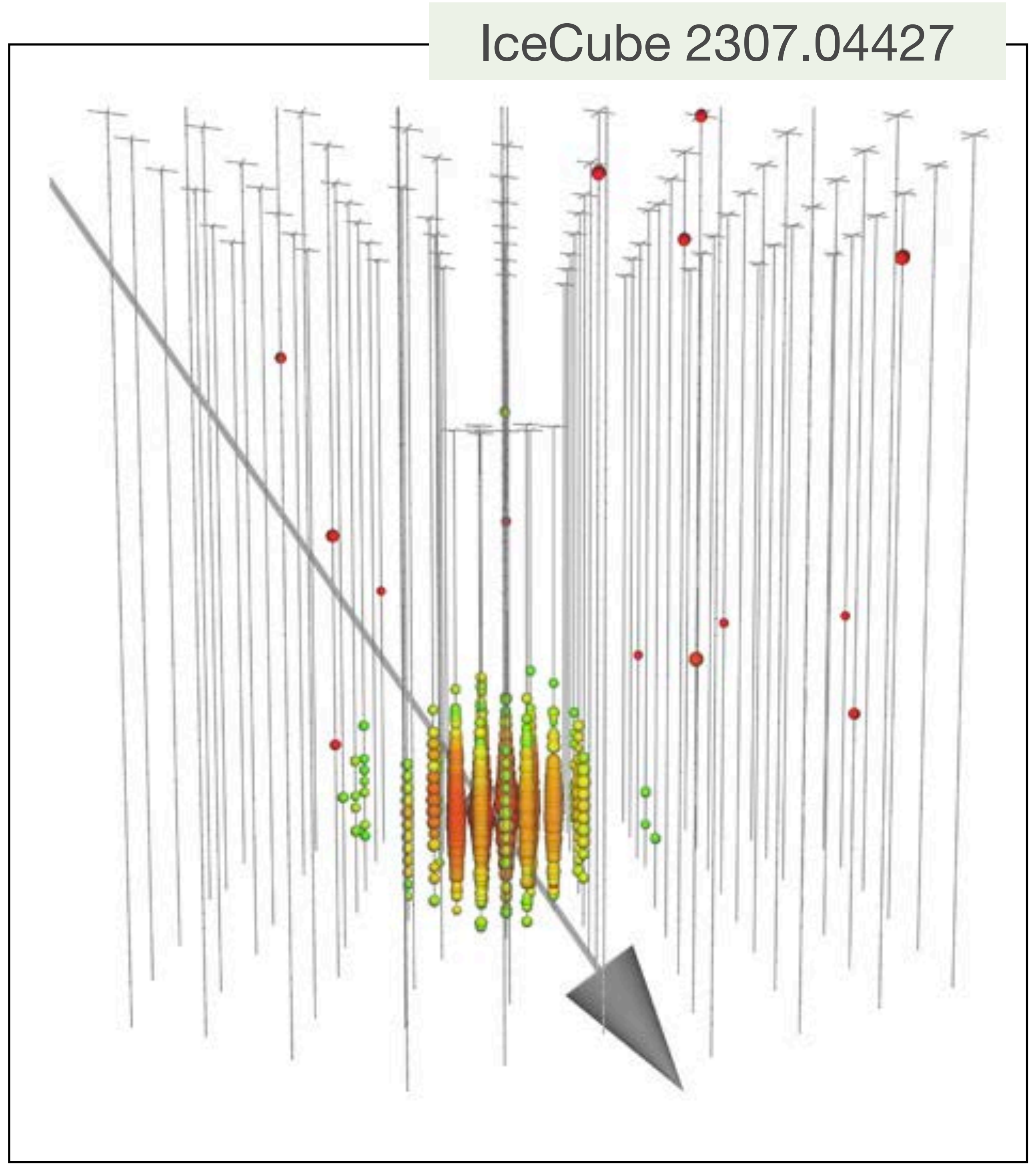

2. IceCube detected the Milky Way in cascades, which have much better energy resolution!

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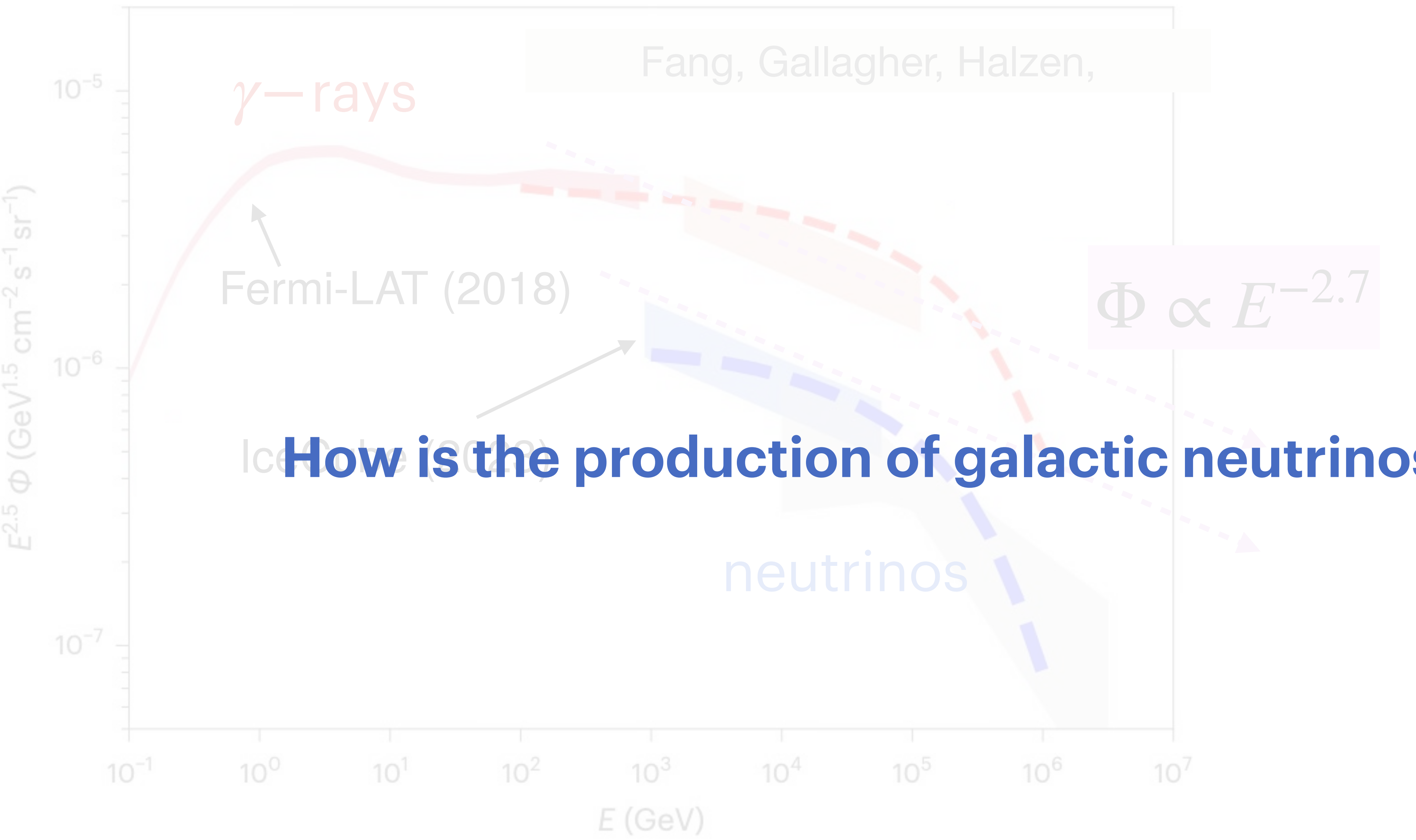
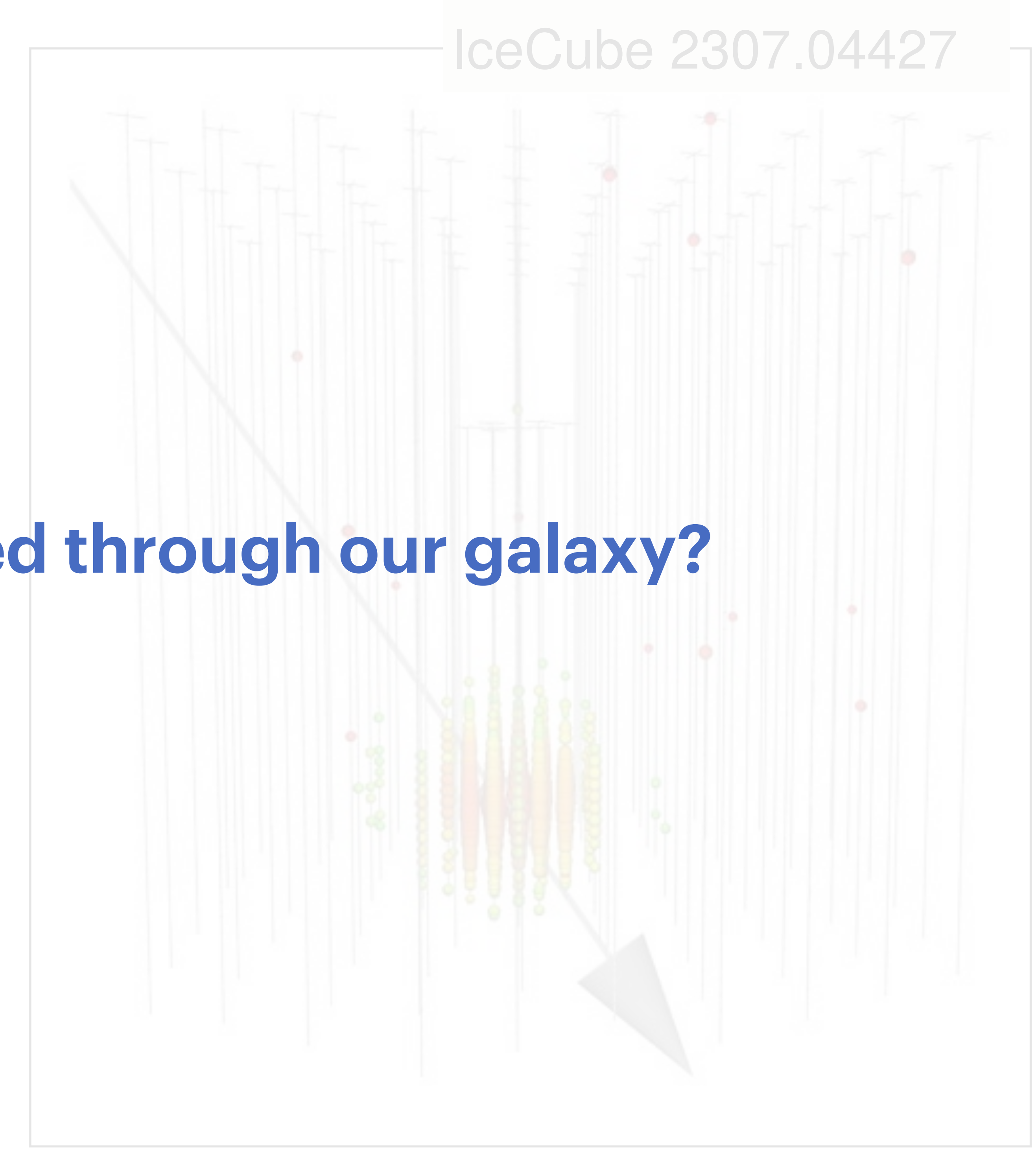
1. Because we've observed the Milky Way in many messengers…
   we have a much better understanding of the neutrino production spectrum.



How is the production of galactic neutrinos distributed through our galaxy?



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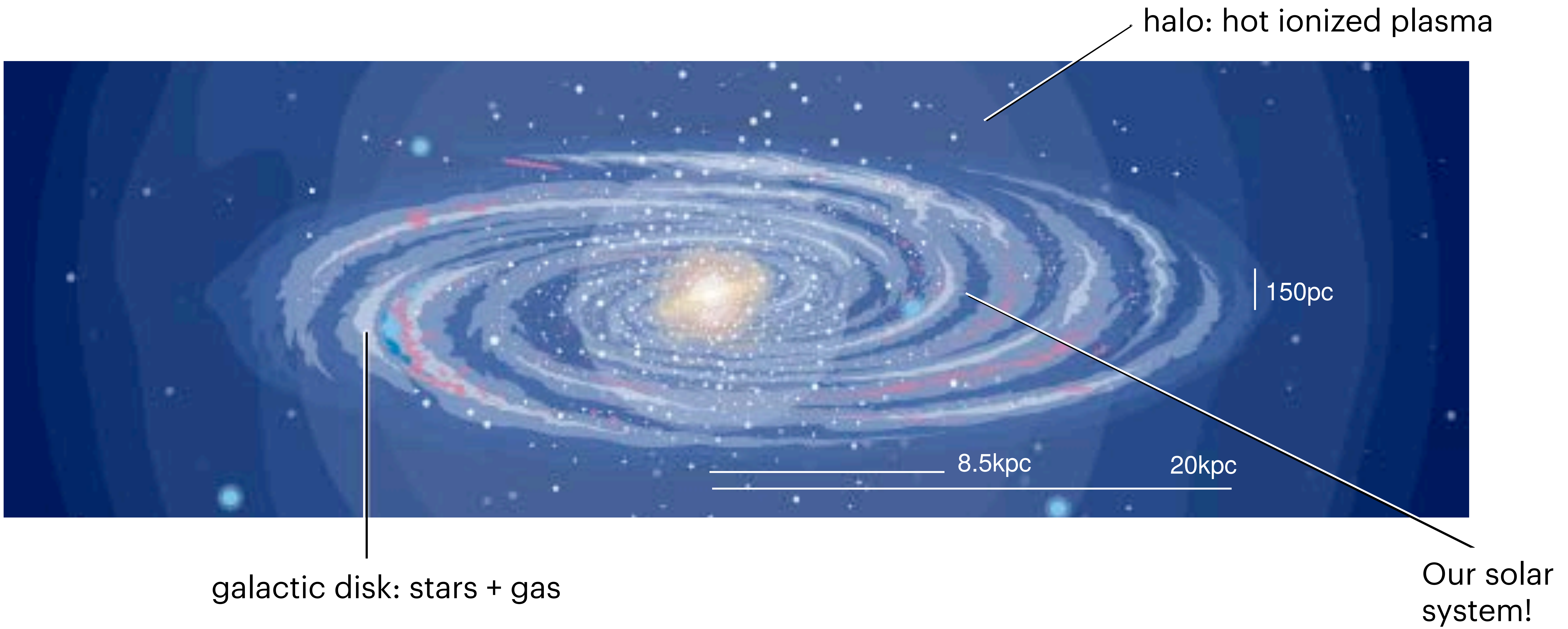
Galactic neutrinos are primarily produced in cosmic ray - gas collisions within the galactic disk:



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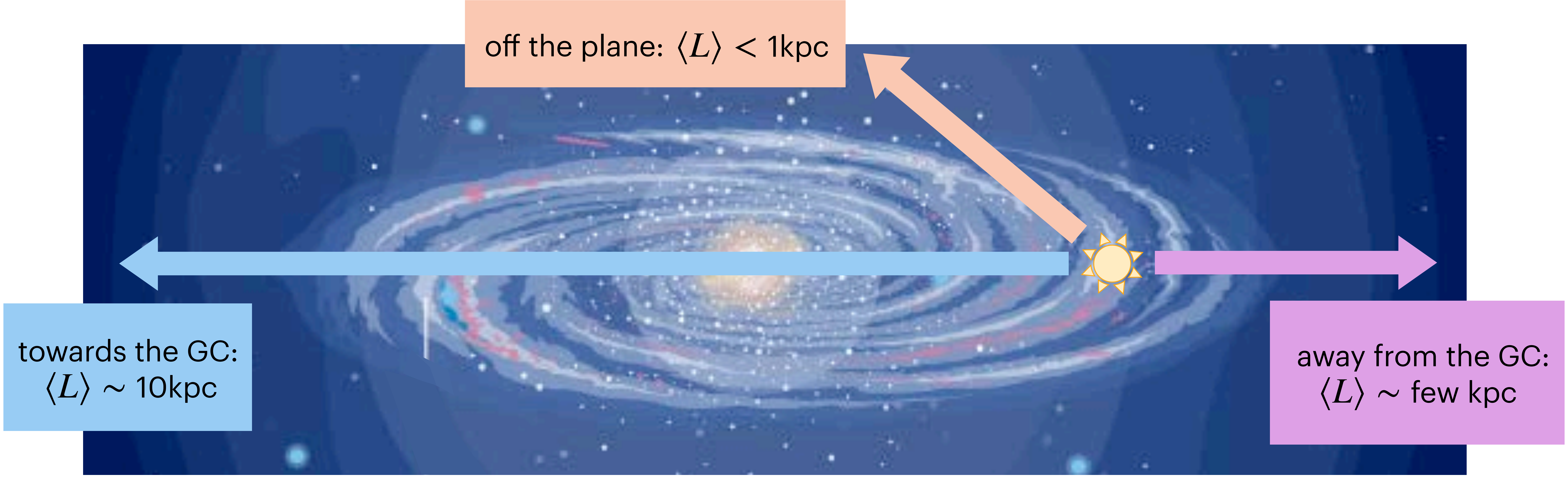

The geometry of the disk implies that the neutrino travel distance L depends strongly on which direction it's coming from.

We created a suite of models for the neutrino spatial distribution (TANDEM) based on the products of CR and gas maps:

neutrino $\simeq$ cosmic rays $\times$ gas

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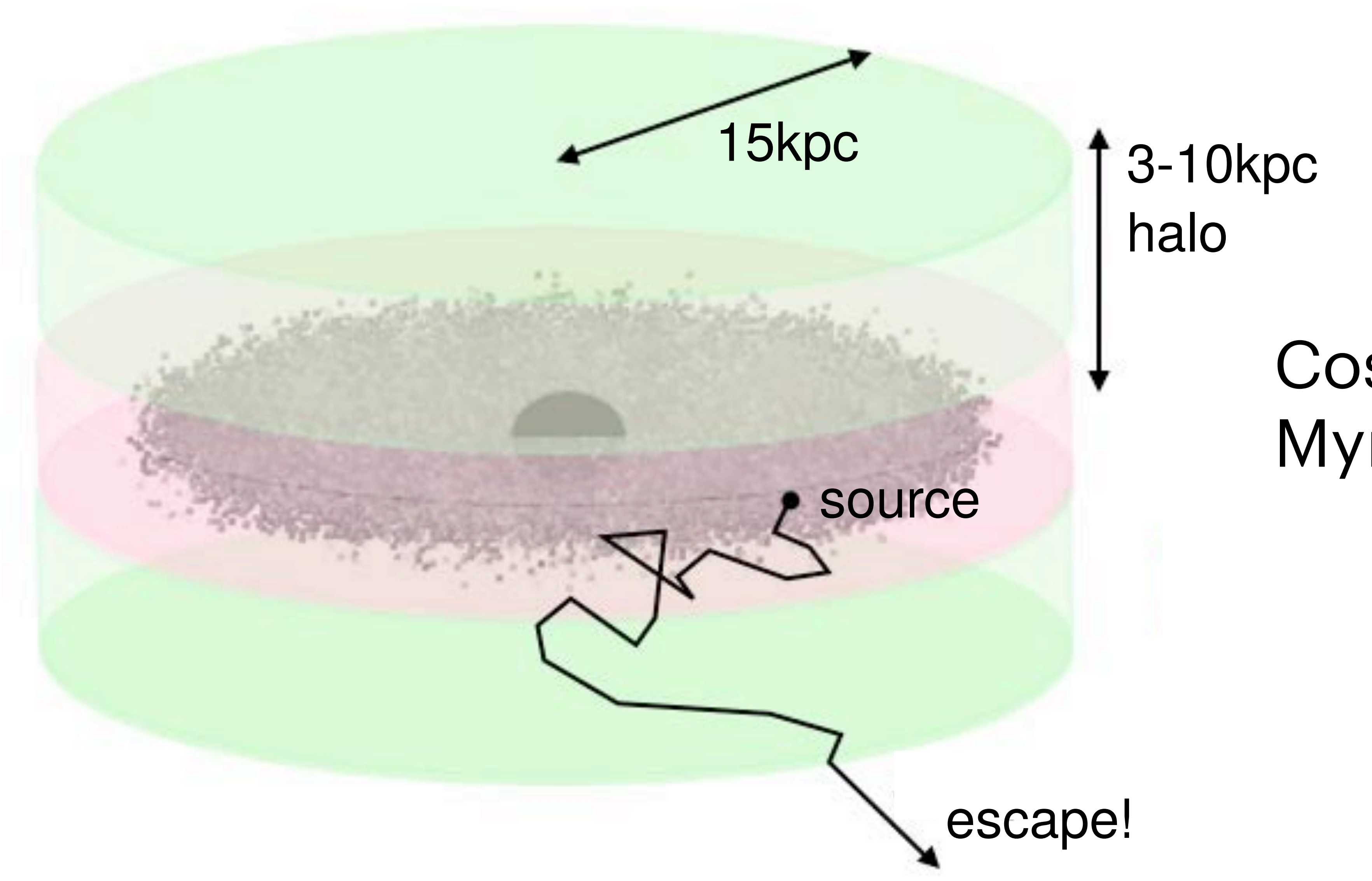

Cosmic Rays diffuse for many Myrs in a halo around our galaxy…

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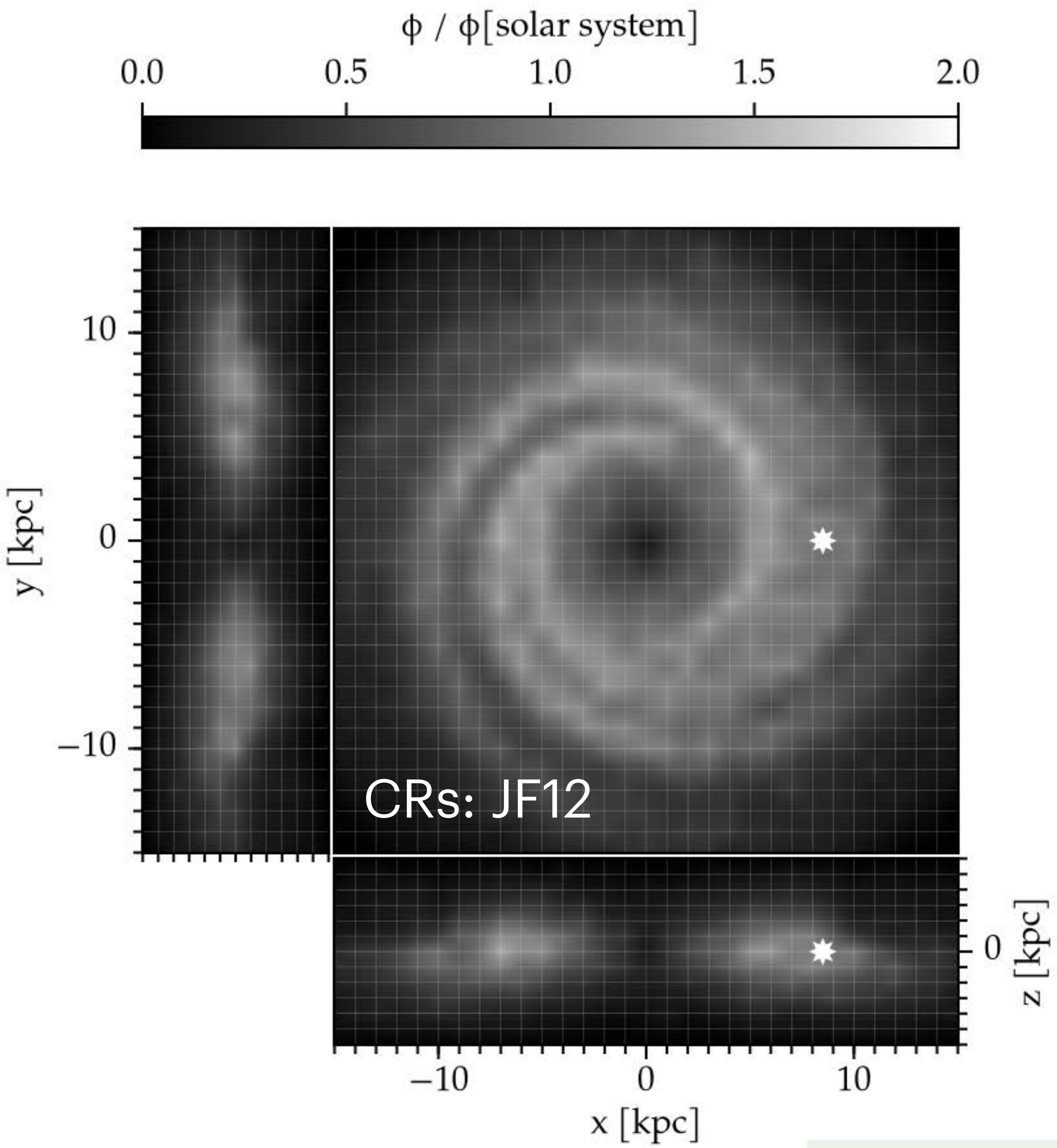

Cosmic Rays diffuse for many Myrs in a halo around our galaxy...

We simulate CR transport under different magnetic field models using **CRPropa**.

CRPropa3.2: Batista et. al. 2208.00107

Magnetic field from: Jansson, Farrar, 1210.7820

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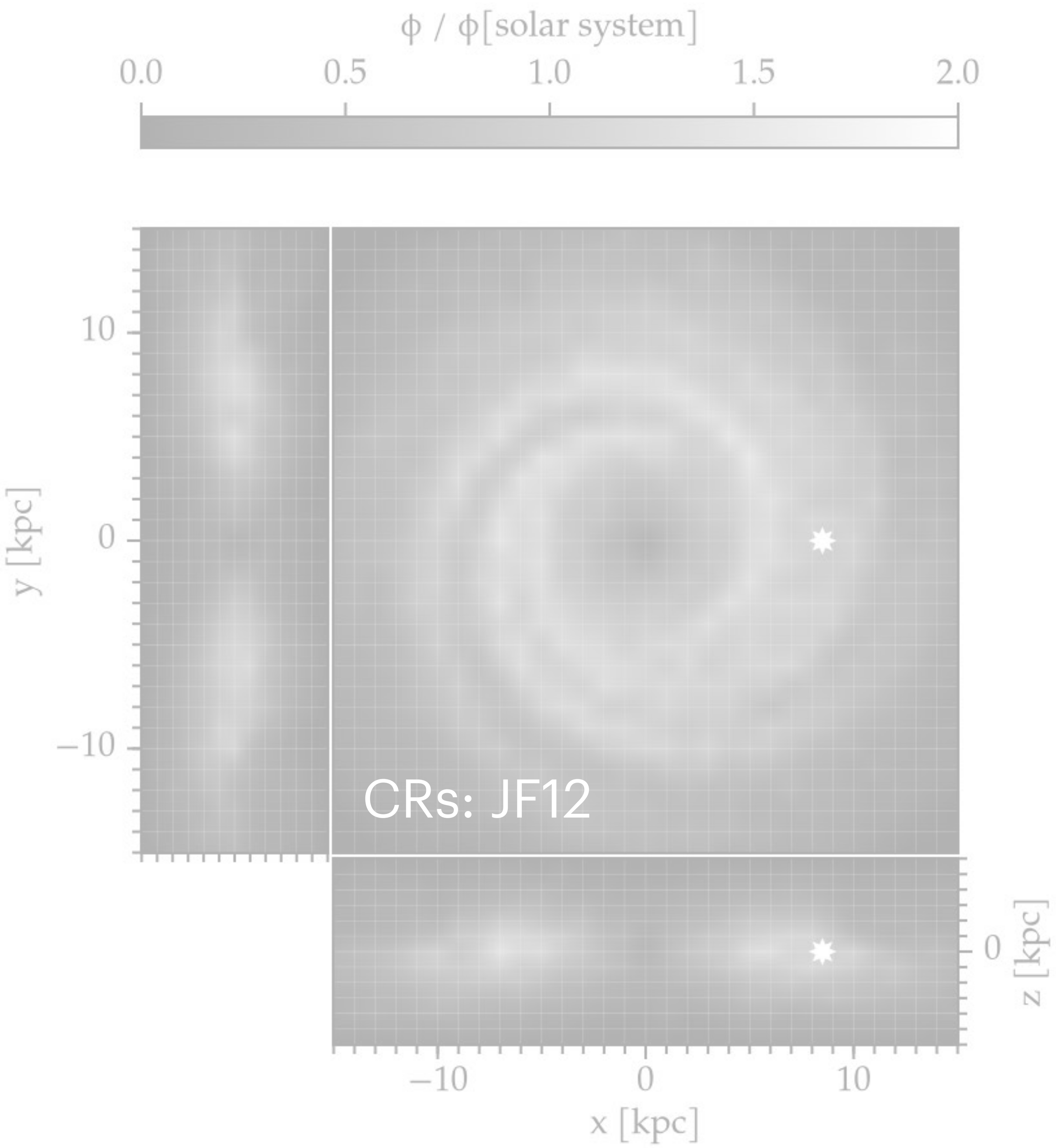
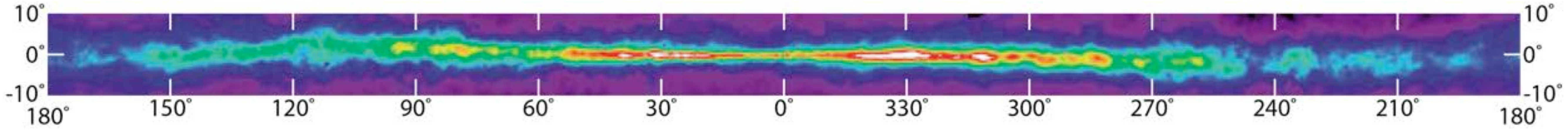
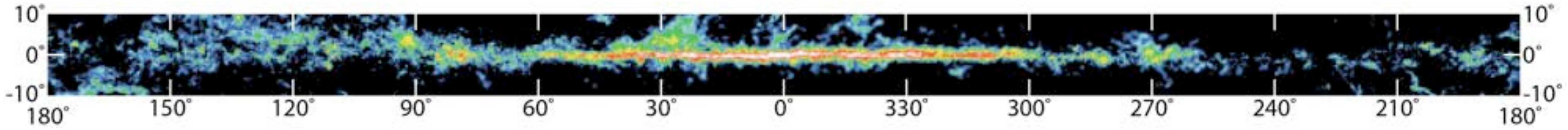


The spatial distribution of H_I and H_2 gas can be reconstructed from redshifted emission lines by assuming a galactic rotation curve.

21cm:



CO:



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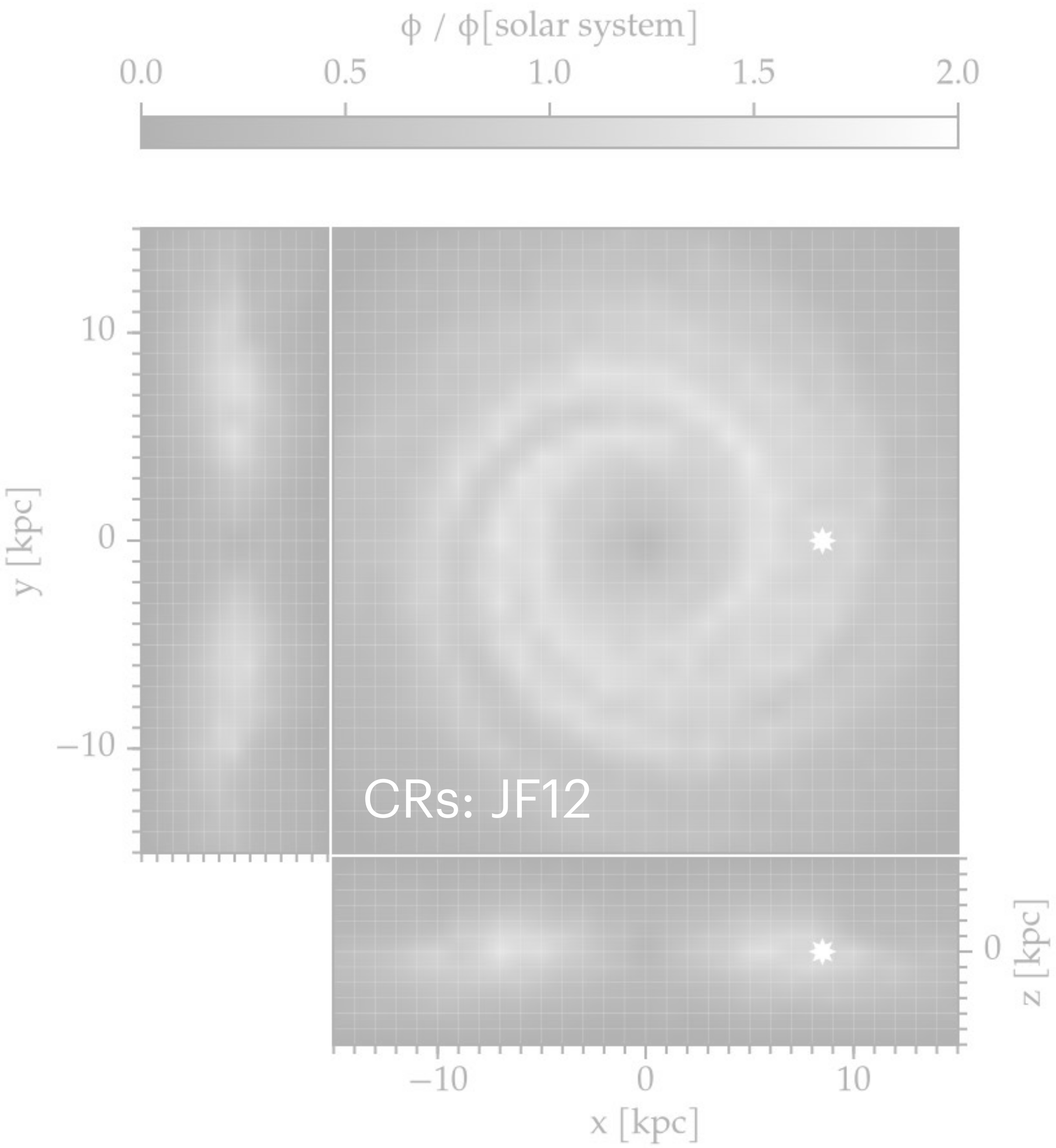

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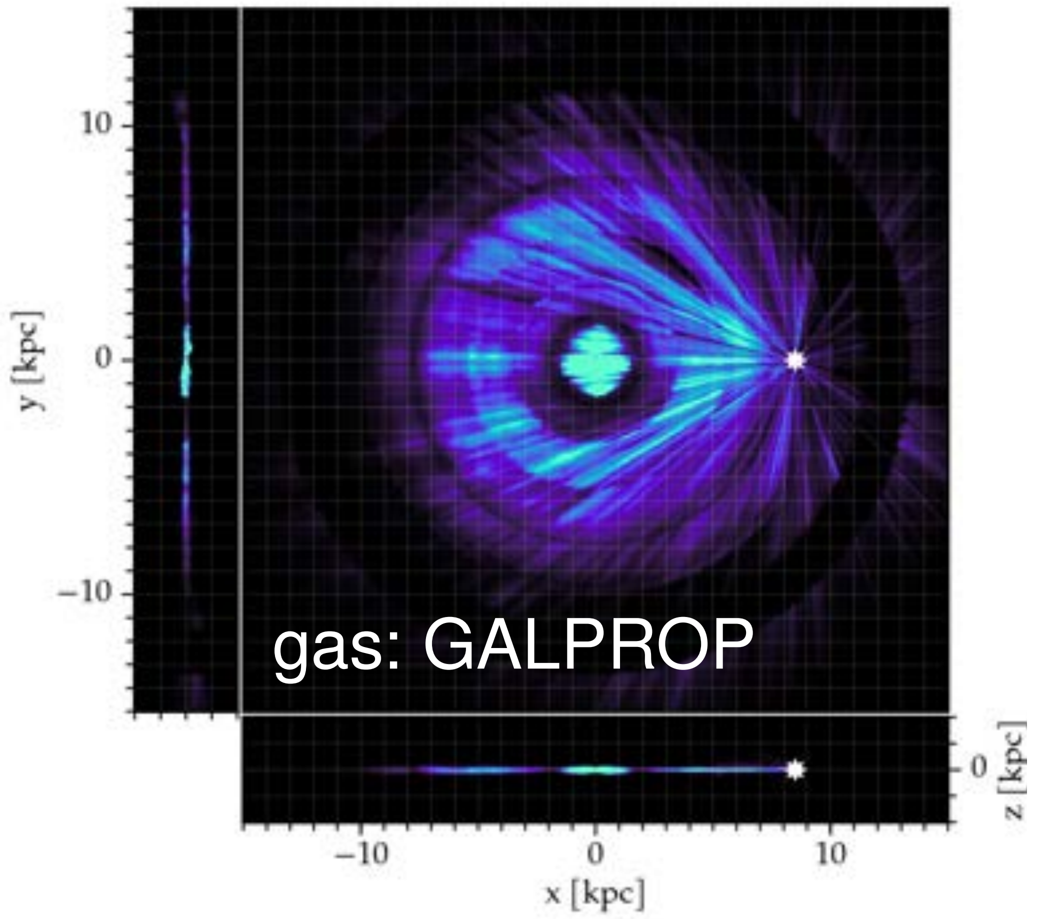
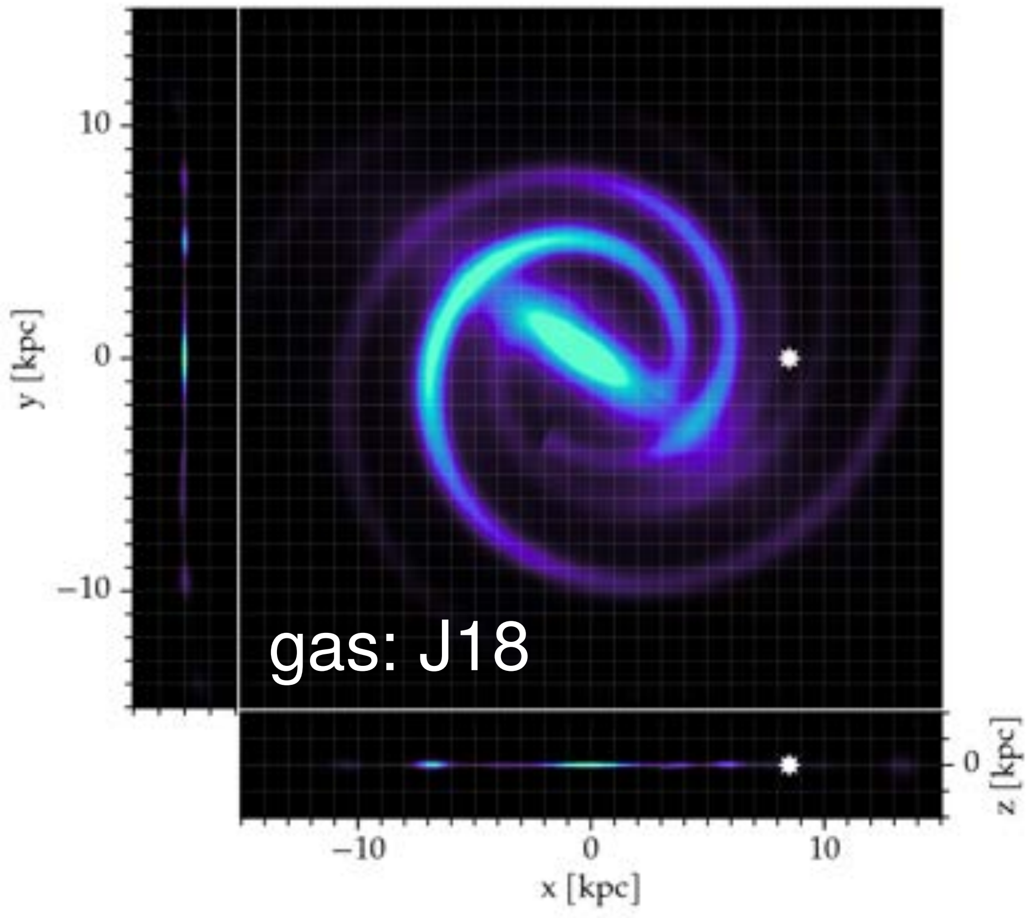
We compiled multiple models:



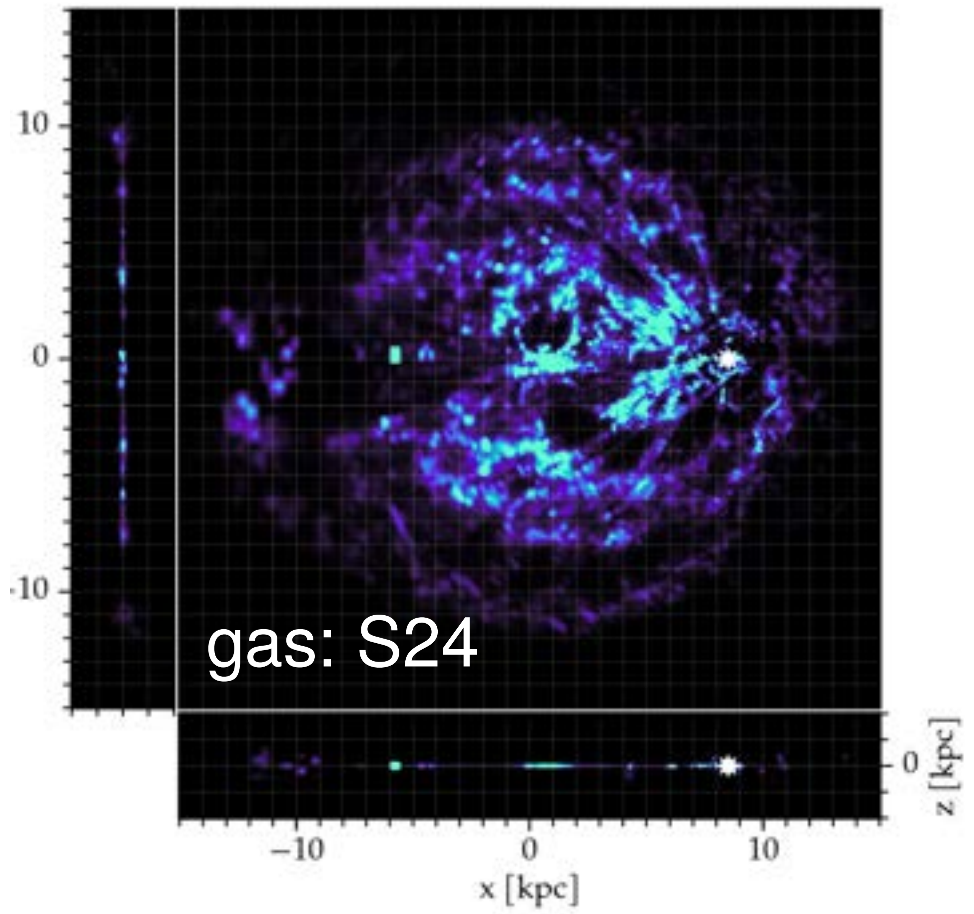
Ring-based assignment

Fermi-LAT collaboration, 1202.4039



Analytic model fit

Fermi-LAT collaboration, 1202.4039



Bayesian Inference

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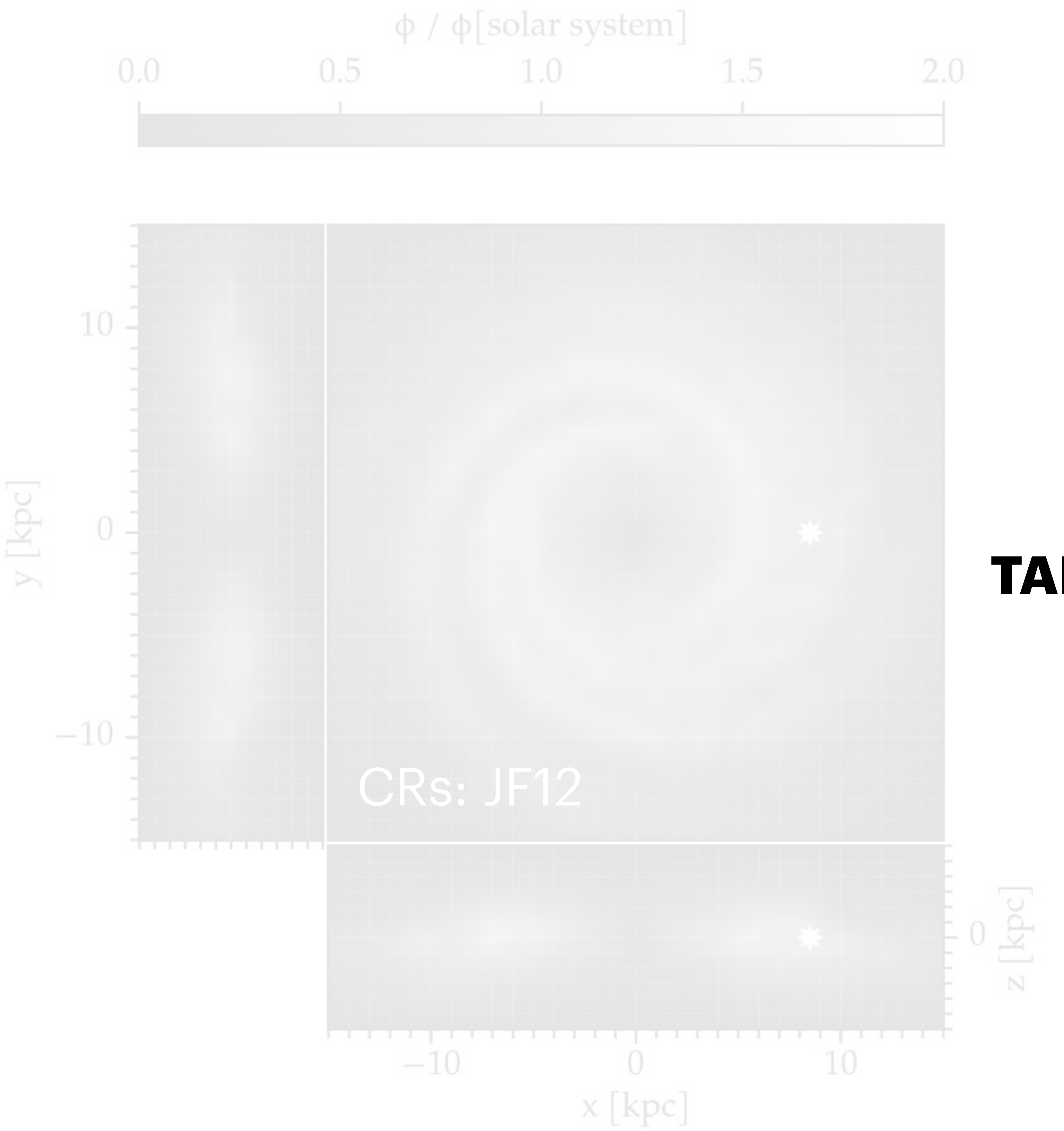

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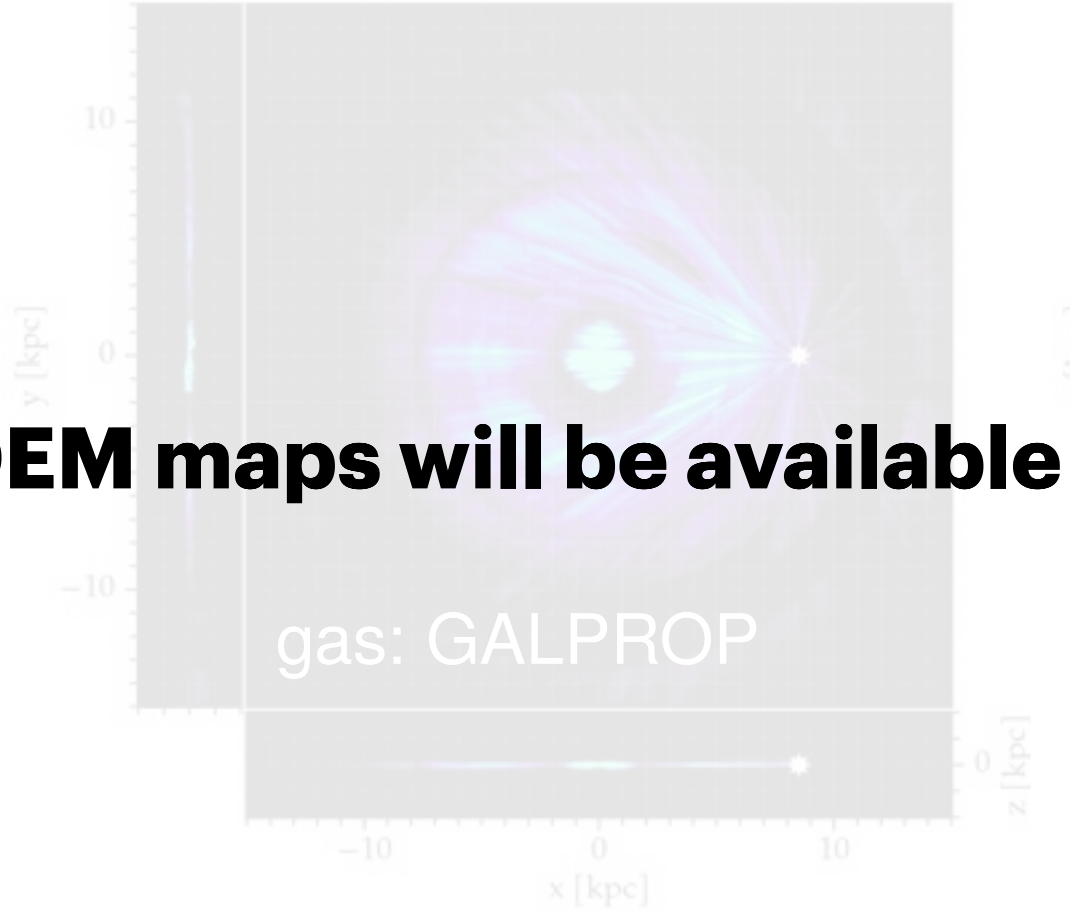

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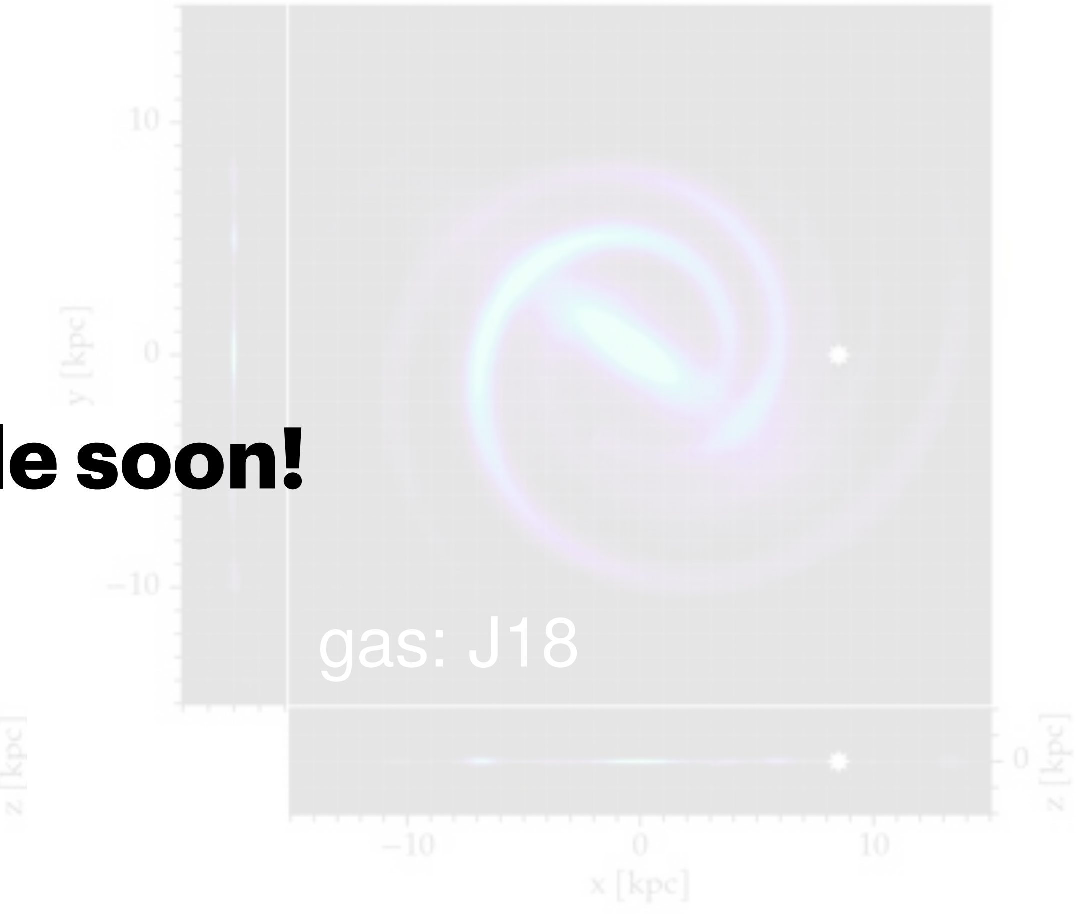


Analytic model fit

Fermi-LAT collaboration, 1202.4039

Bayesian Inference

TANDEM maps will be available soon!

In our study, we

- create a suite of models for the neutrino spatial distribution ("TANDEM")
- model the distribution of galactic events at IceCube (cascades) and KM3Net (tracks)
- model atmospheric neutrino backgrounds at each experiment
- perform a binned likelihood ratio test, marginalizing over the galactic flux normalization.

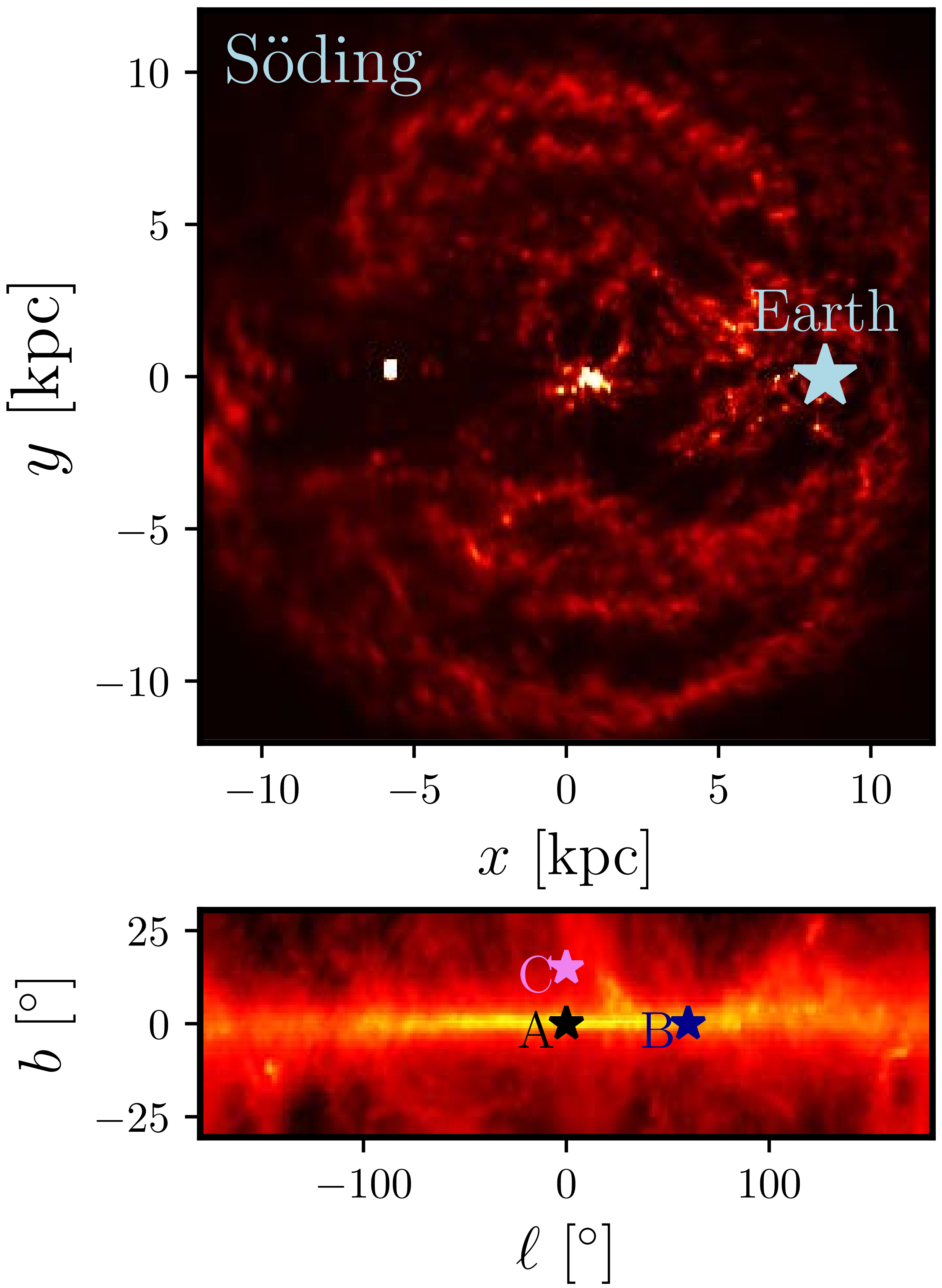
use each experiment's
- effective area
- PSF
- energy resolution

- using H3a_SYBYLL23C
- included the self-veto via `NuVeto`

spectral index assumed fixed at $\gamma = 2.7$

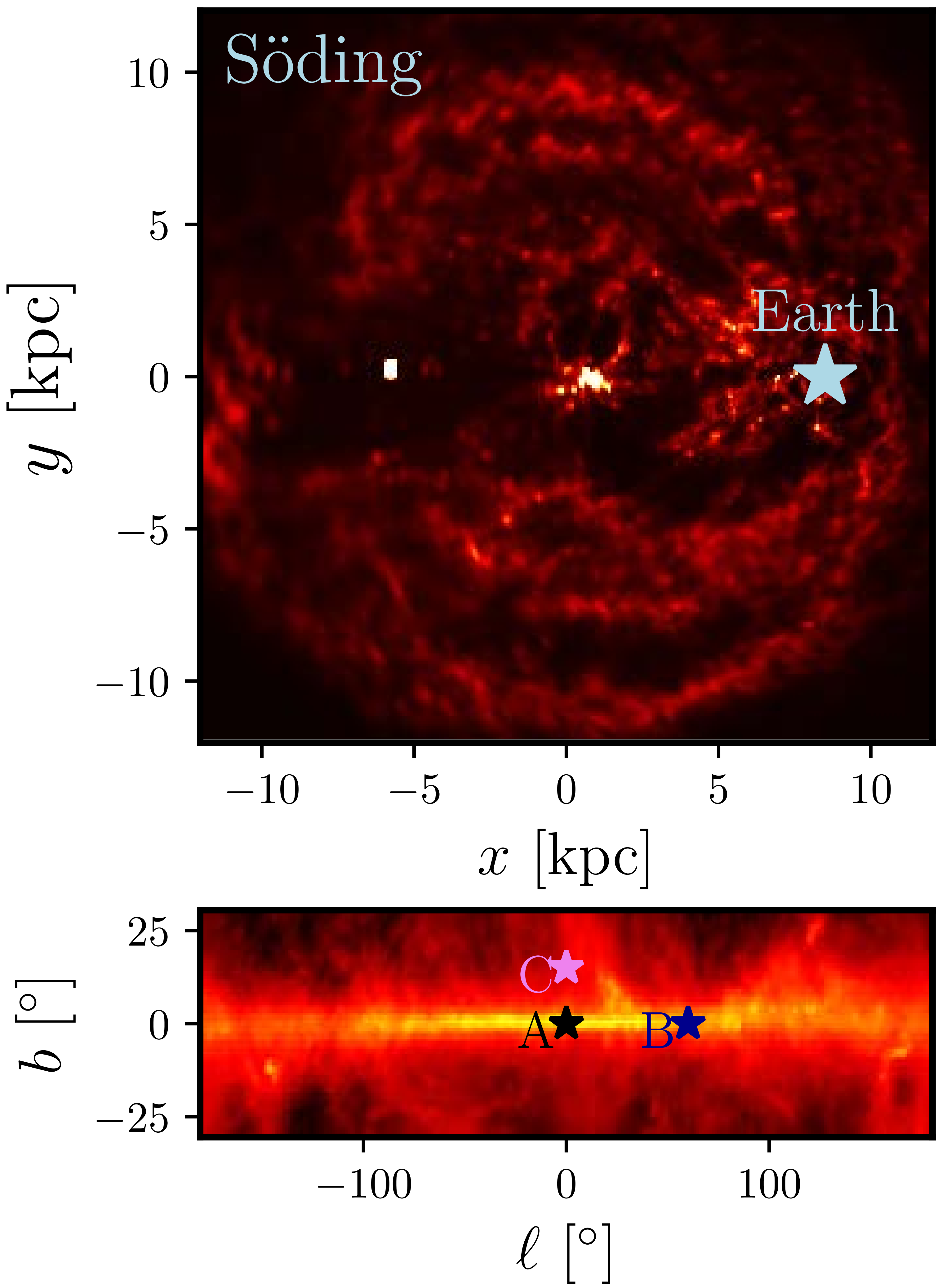
Miller Macdonald, Harvard College undergraduate

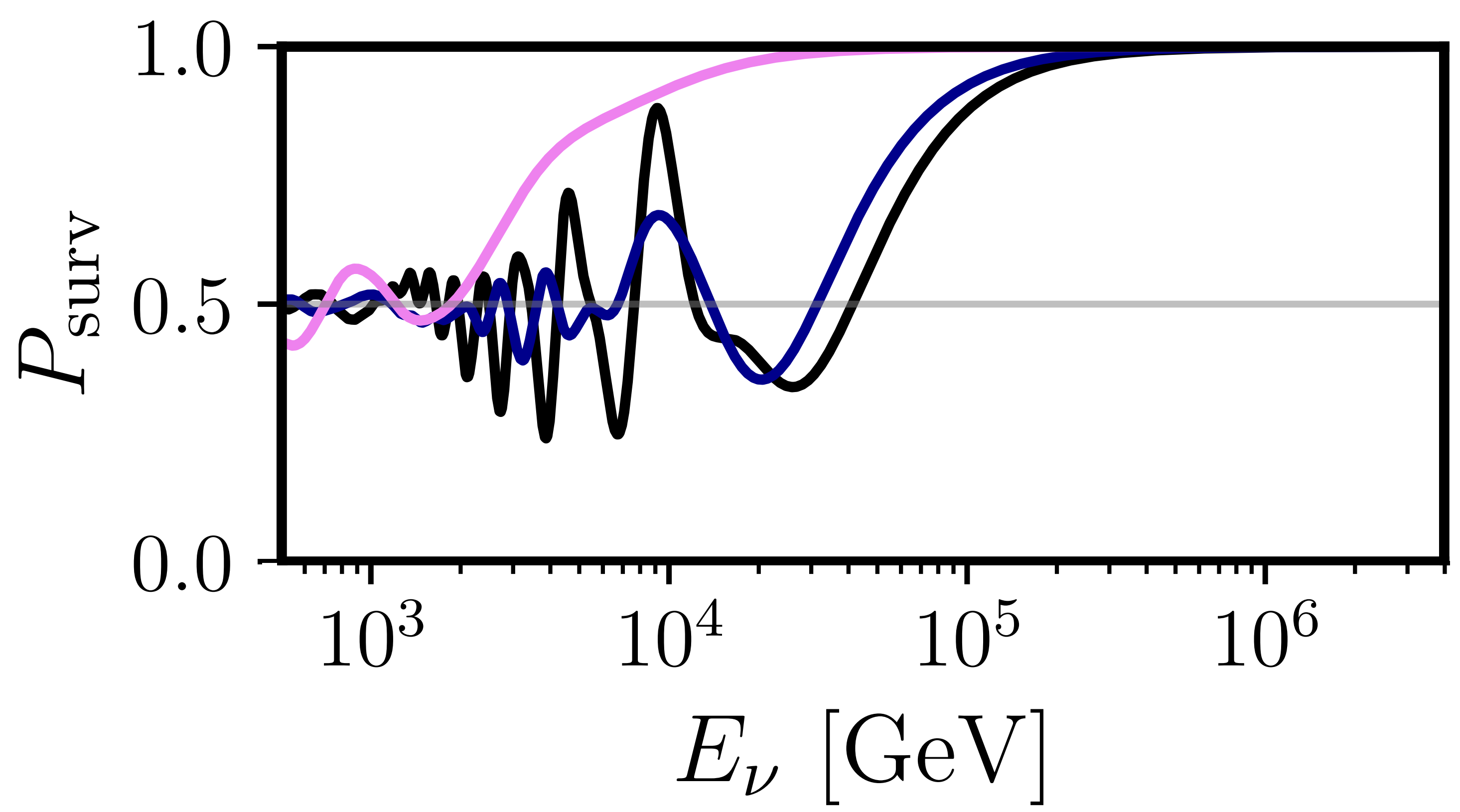
This is an example neutrino spatial distribution:



MacDonald, **KC**, Argüelles, Alves-Batista, Martinez-Soler (to appear)

As expected, the survival probability is strongly dependent on the neutrino's direction.





Perfect resolution

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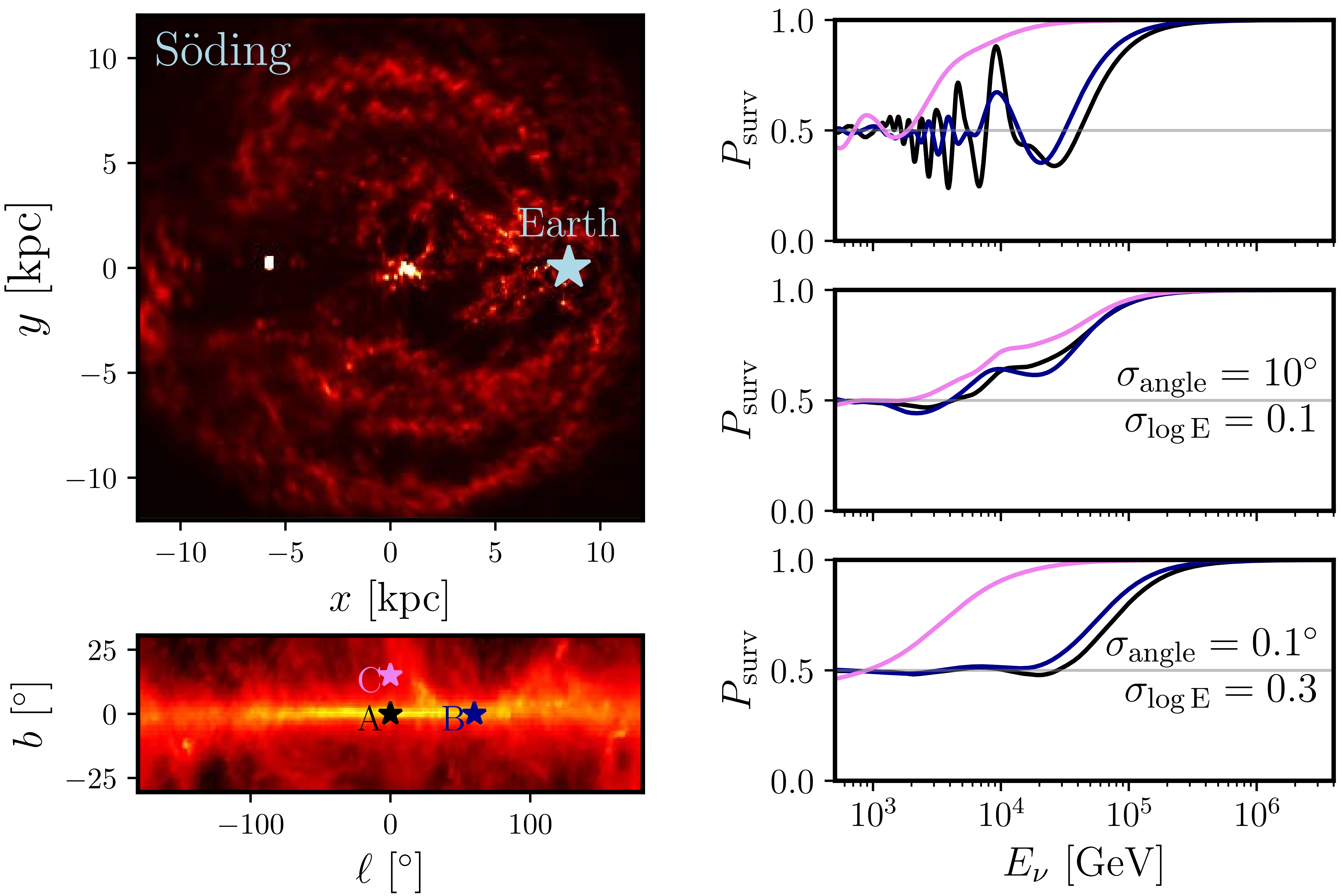


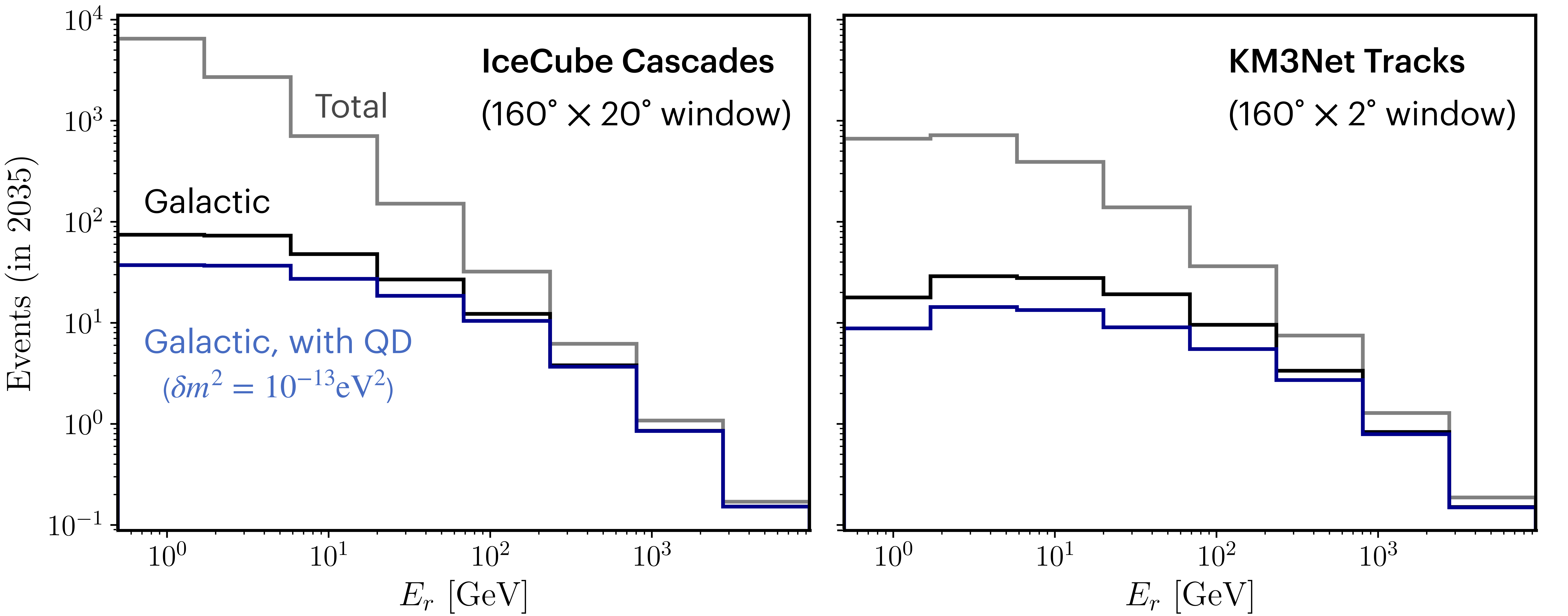
Perfect resolution

Cascade-like

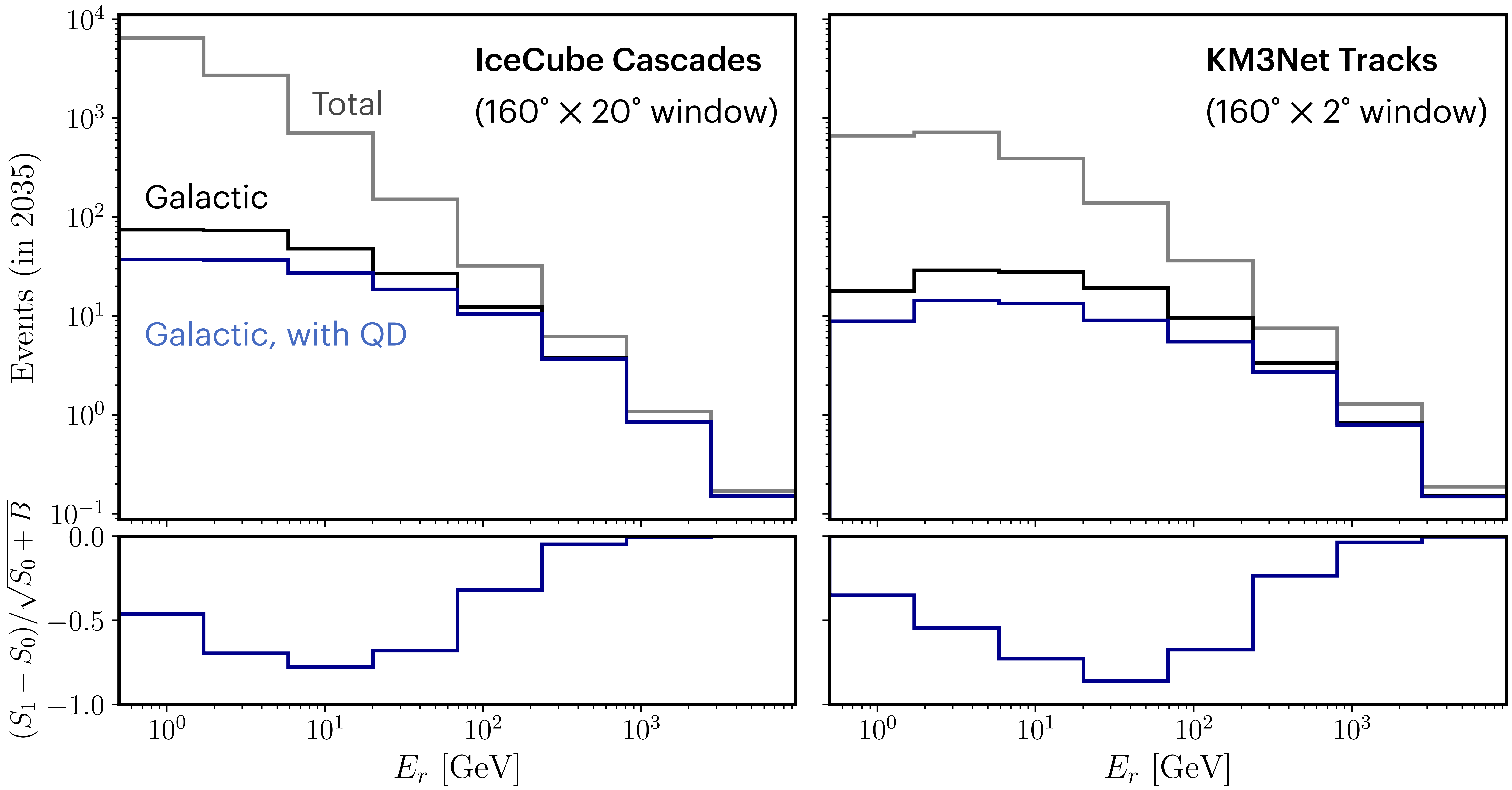
Track-like

MacDonald, **KC**, Argüelles, Alves-Batista, Martinez-Soler (to appear)

We find that the galactic QD disappearance effect is smeared out, making it difficult to pick out over background fluctuations.



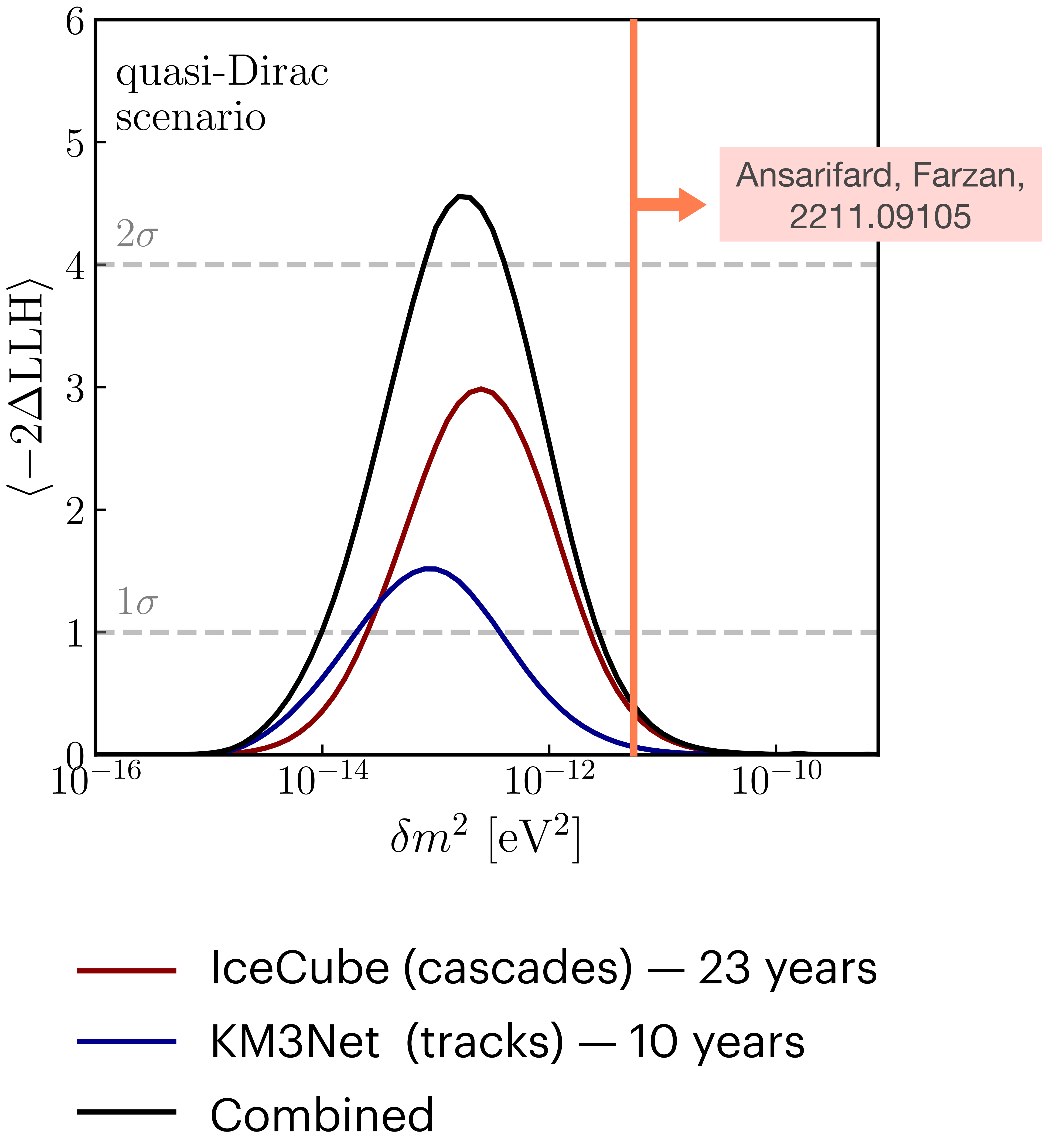
We find that the galactic QD disappearance effect is smeared out, making it difficult to pick out over background fluctuations.



MacDonald, **KC**, Argüelles, Alves-Batista, Martinez-Soler (to appear)

Results: Projected 2035 sensitivity of IceCube + KM3Net

The combination of the two experiments will be sensitive to $\delta m^2 \in$ [0.76, 4] $\times 10^{-13}$eV^2 at the 2σ level.



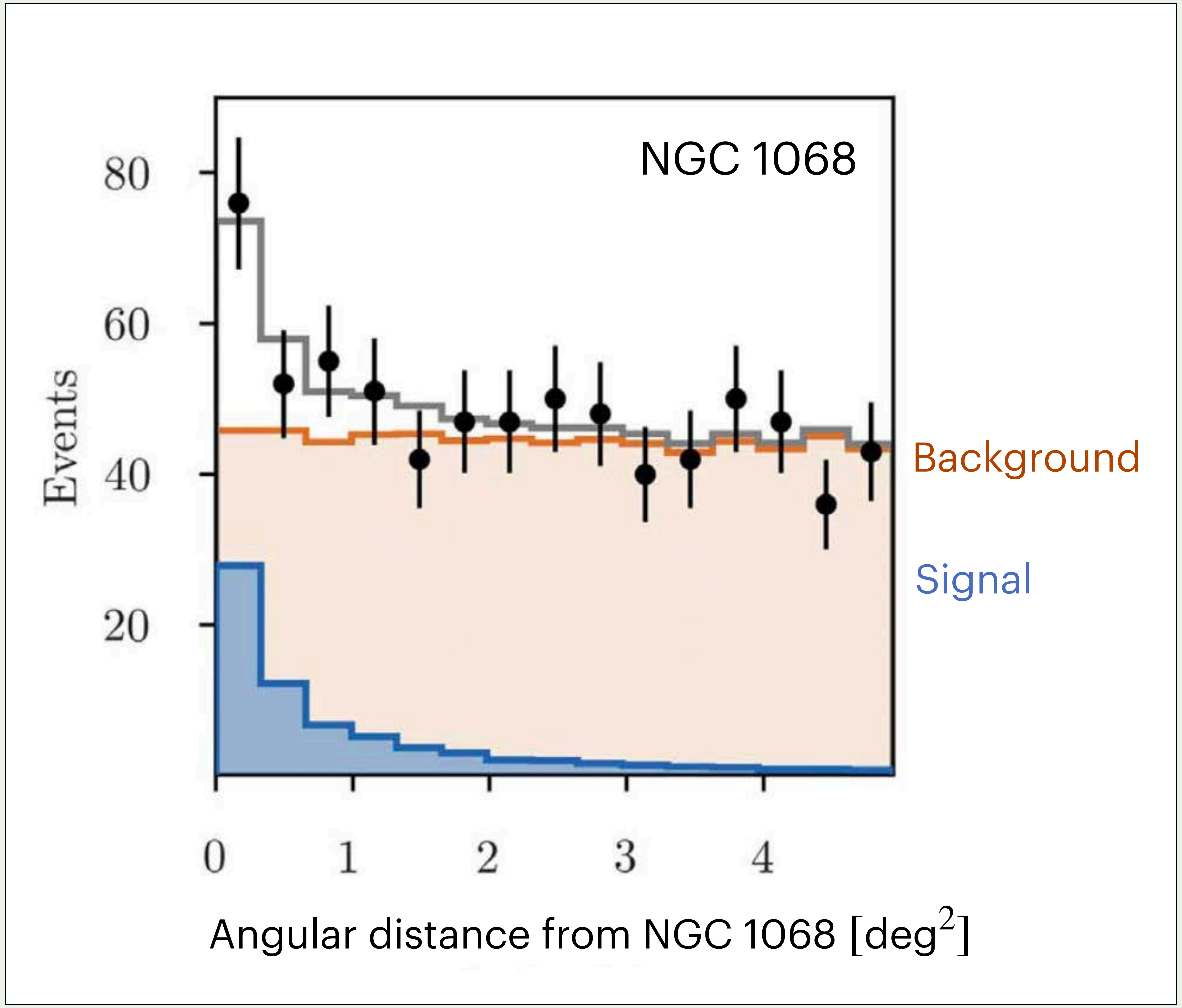
Prospects:

This comparatively poor sensitivity could be improved if we can:

- constrain the normalization of the galactic flux to within 50%
- use a data selection with both good energy and angular resolution

Outline for the rest of this talk:

1. What are quasi-Dirac neutrinos?
2. How has IceCube detected astrophysical neutrinos?
3. Searches using extragalactic sources
4. Searches using galactic sources
5. **Bonus: Muon Tagging in the IceCube Upgrade!**

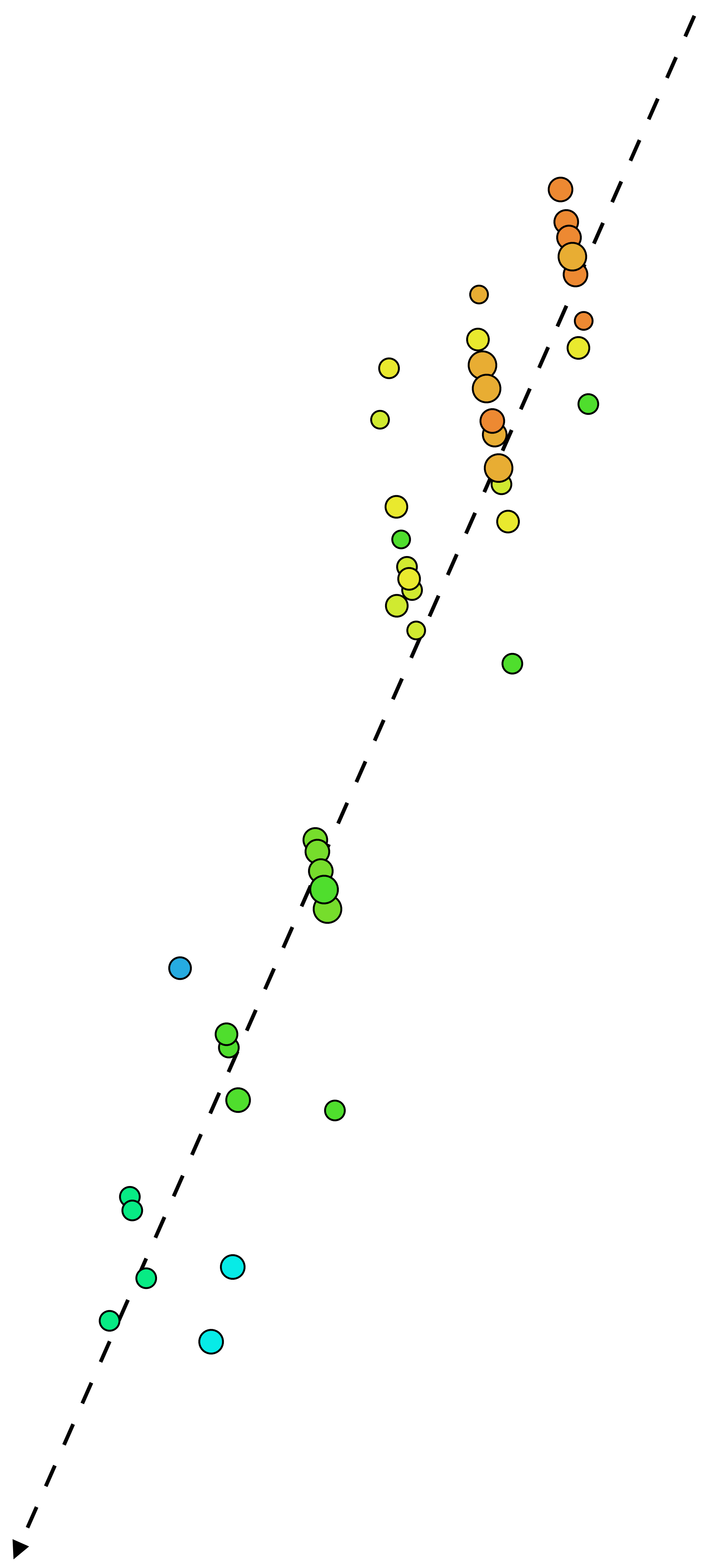


IceCube Collaboration, 2211.09972

NGC 1068's optical size is 0.1°.

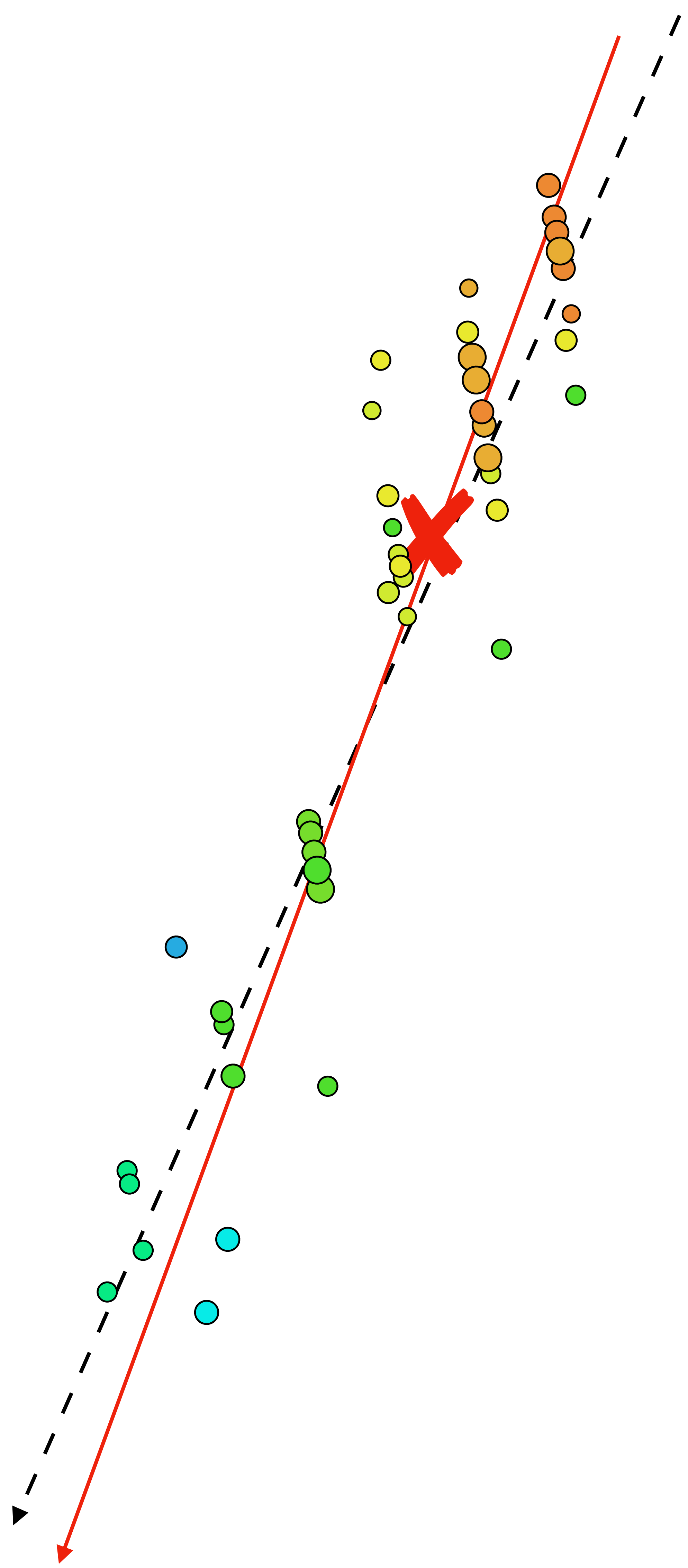
The actual width of the signal distribution is set by the experimental angular resolution.

Better angular resolution => more sources!



For tracks, directional reconstruction means fitting a line to the pattern of light deposition.

This is a five-dimensional problem: two angles + three coordinates.



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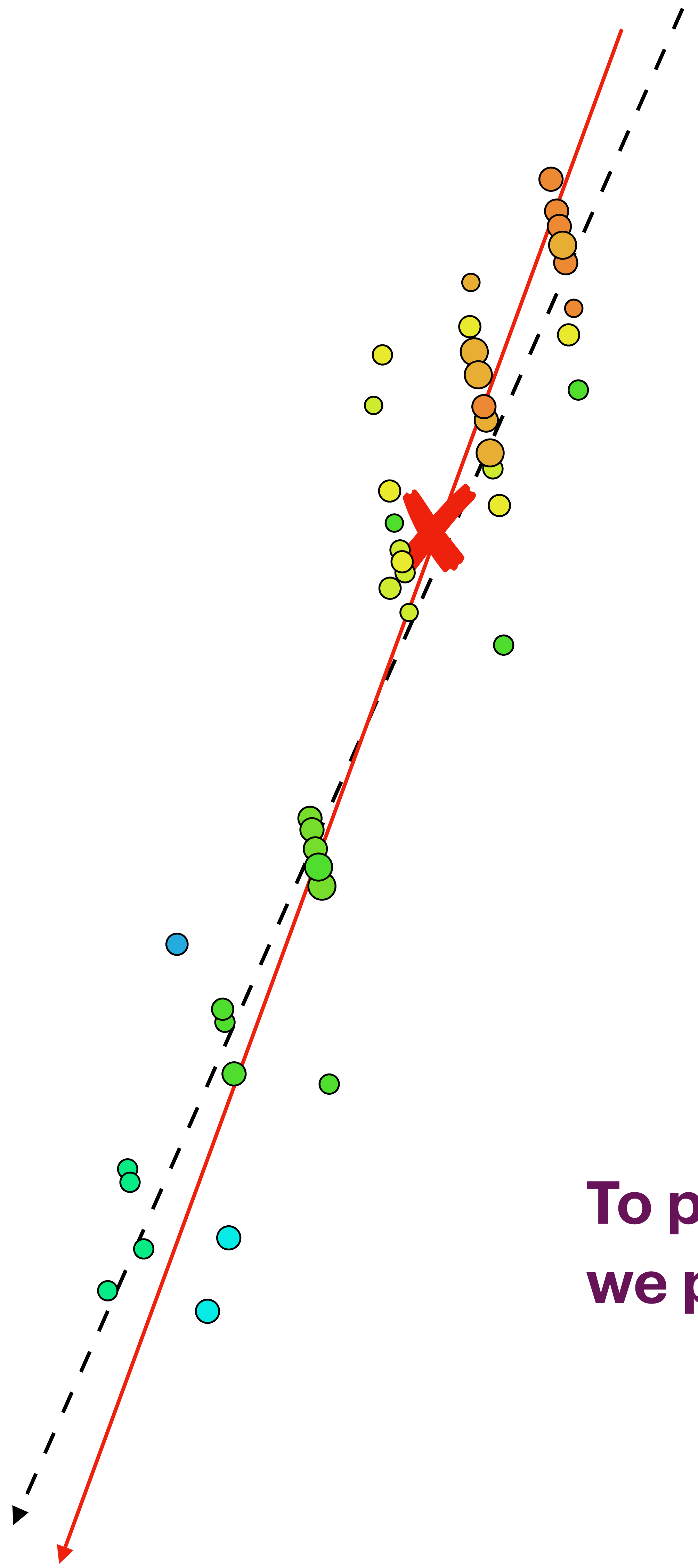
If we could tag a muon that passed through a particular "pivot point," then we'd only need to fit two angles.

This is a significantly easier problem!



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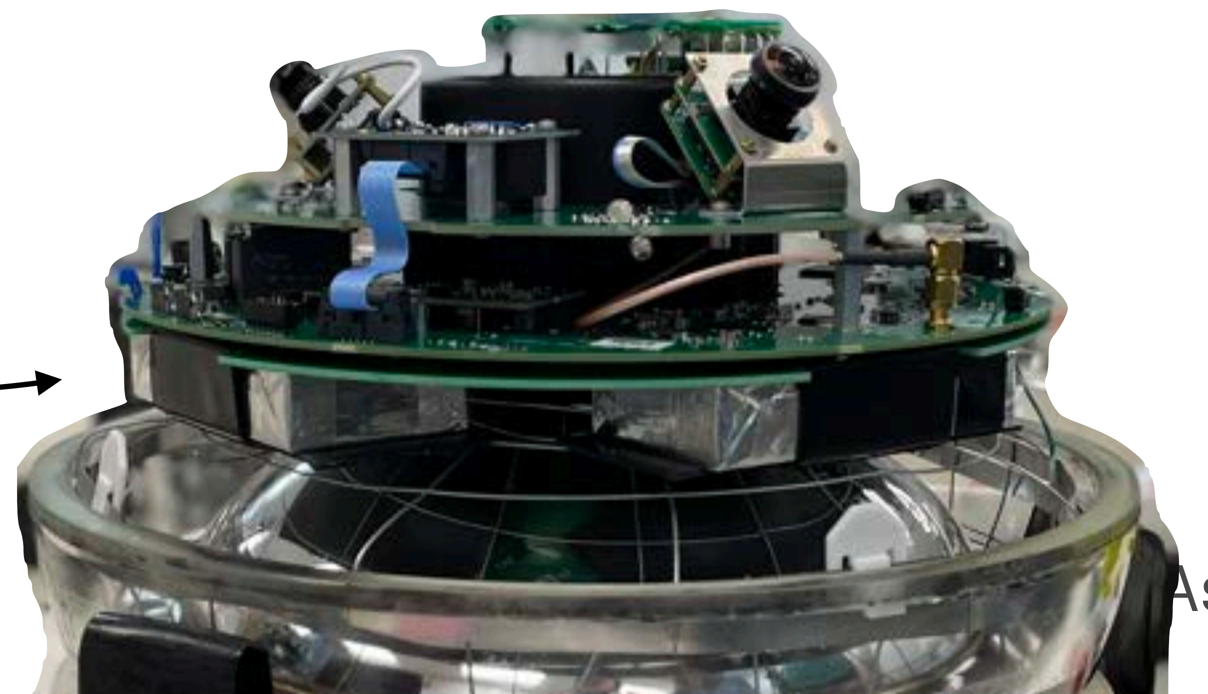
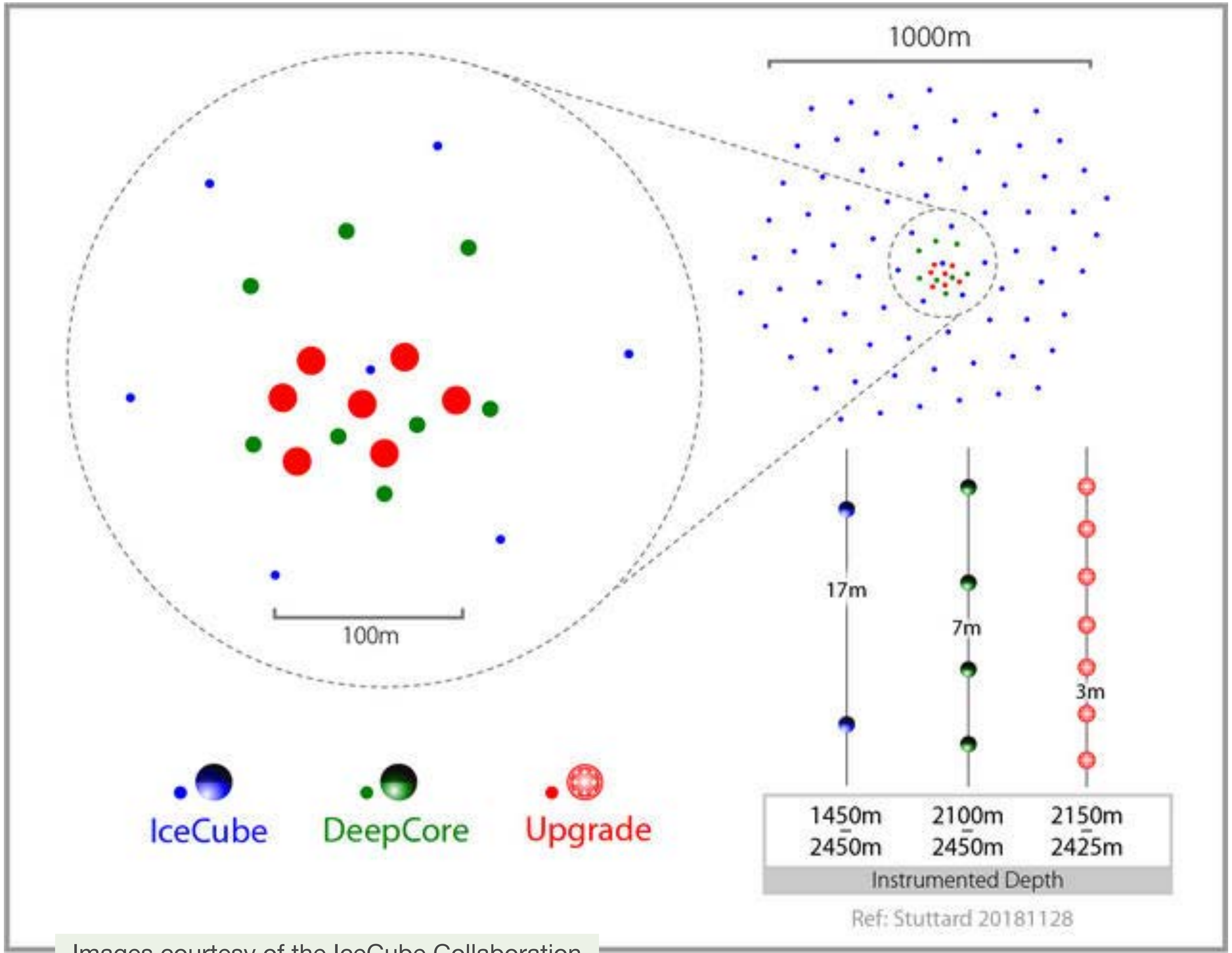
If we could tag a muon that passed through a particular “pivot point,” then we'd only need to fit two angles.

This is a significantly easier problem!

To produce a dataset of well-reconstructed “standard arrows,” we put “muon taggers” into some of the DOMs going in to the IceCube upgrade!



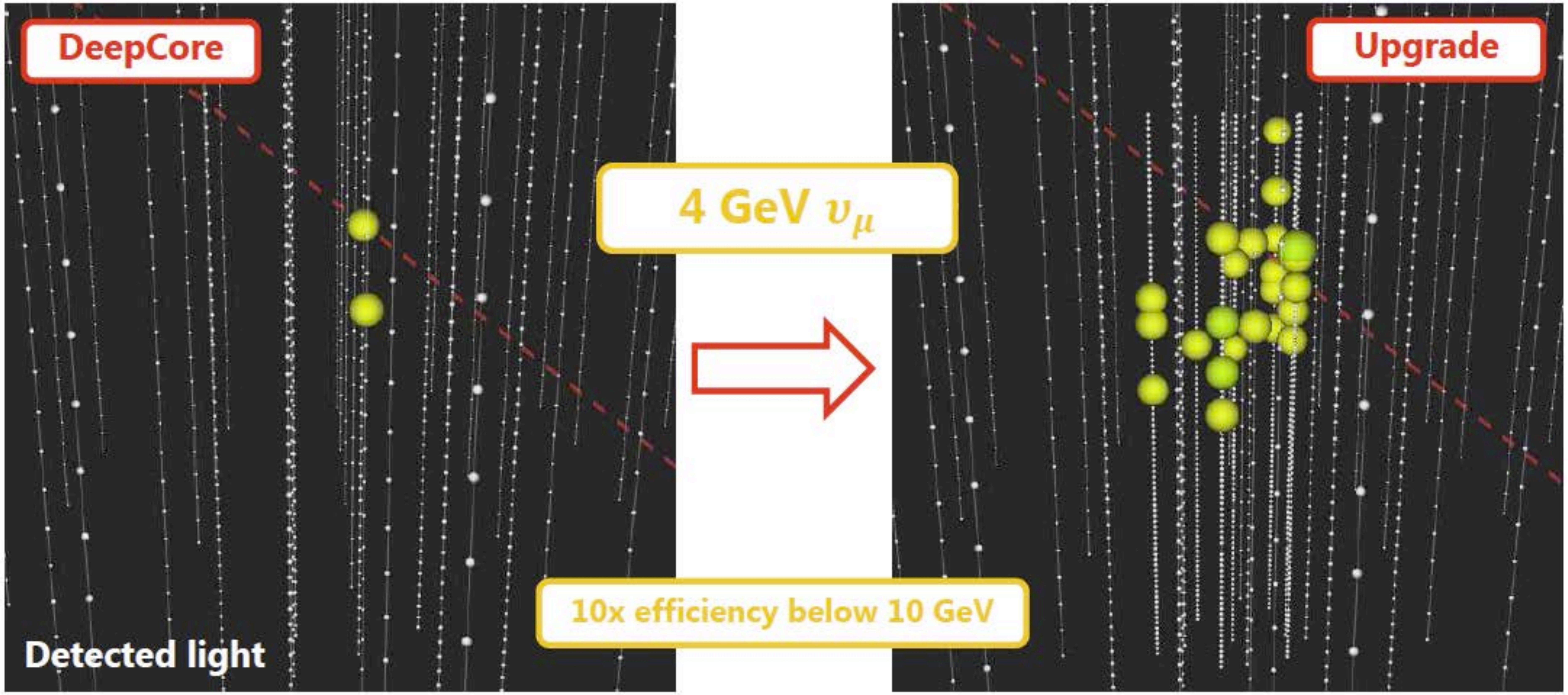


Images courtesy of the IceCube Collaboration

The IceCube Upgrade will:

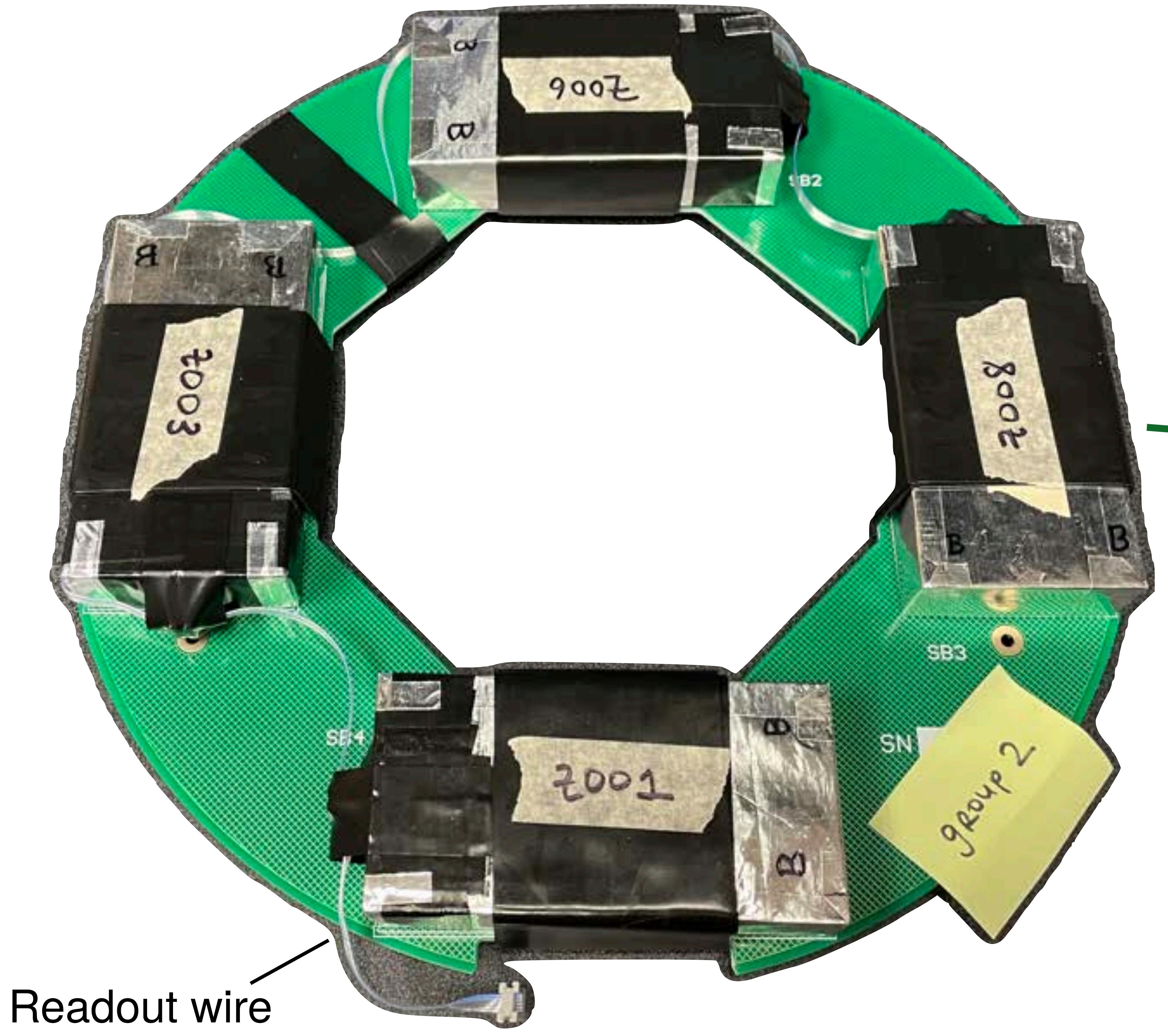
- significantly enhance world-leading low-energy oscillation physics
- significantly improve our detector characterization

The IceCube Upgrade will significantly enhance the sensitivity to few GeV-scale neutrinos:

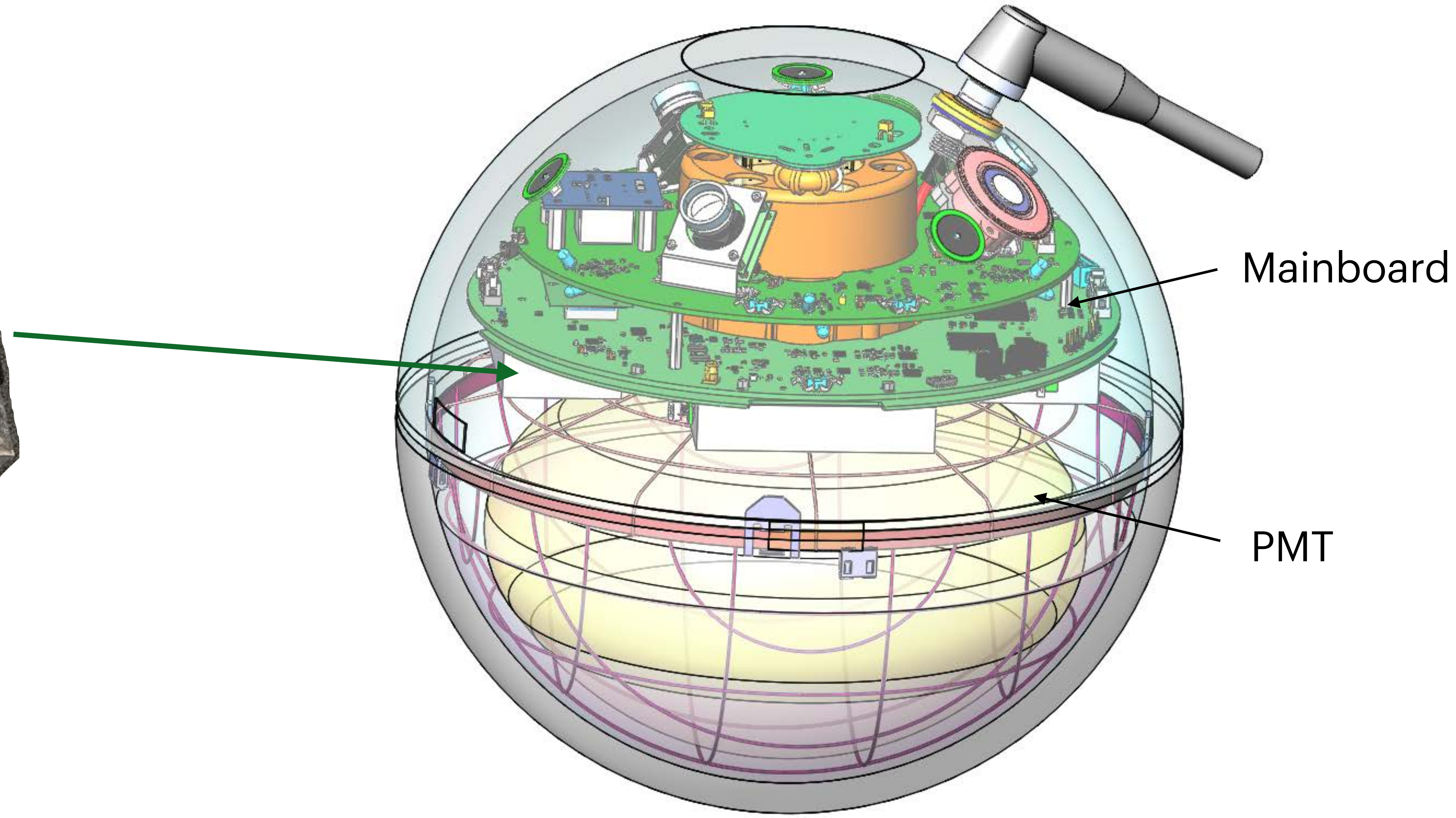


Images courtesy of the IceCube Collaboration

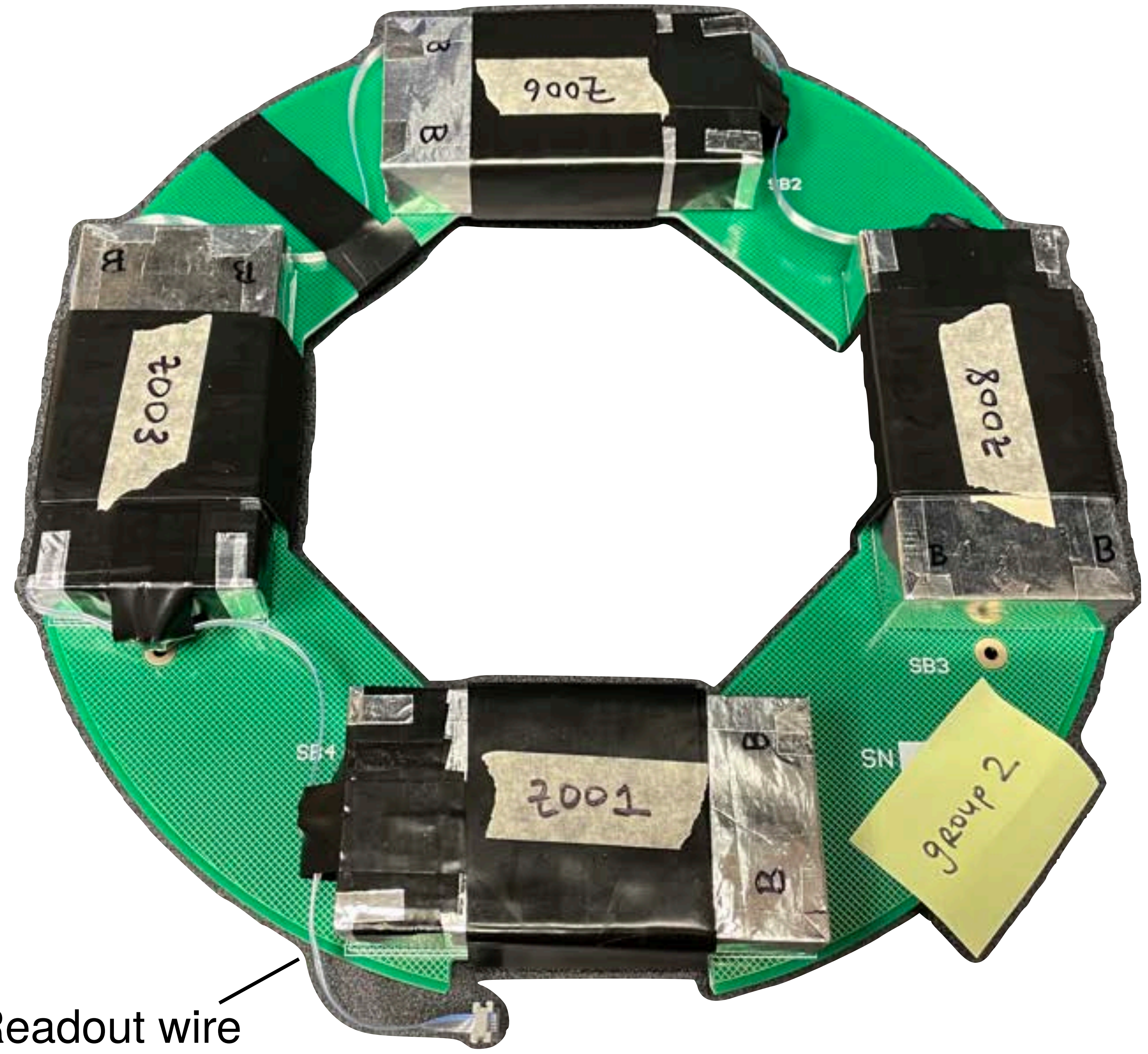
We deployed muon taggers (MTAs) in 21 “Precision” DOMs, which will go into the ice this winter.



Muon Tagger Array



The MTA is composed of 4 blocks of 2cm thick plastic scintillator, wired in parallel to a SiPM:



Muon Tagger Array

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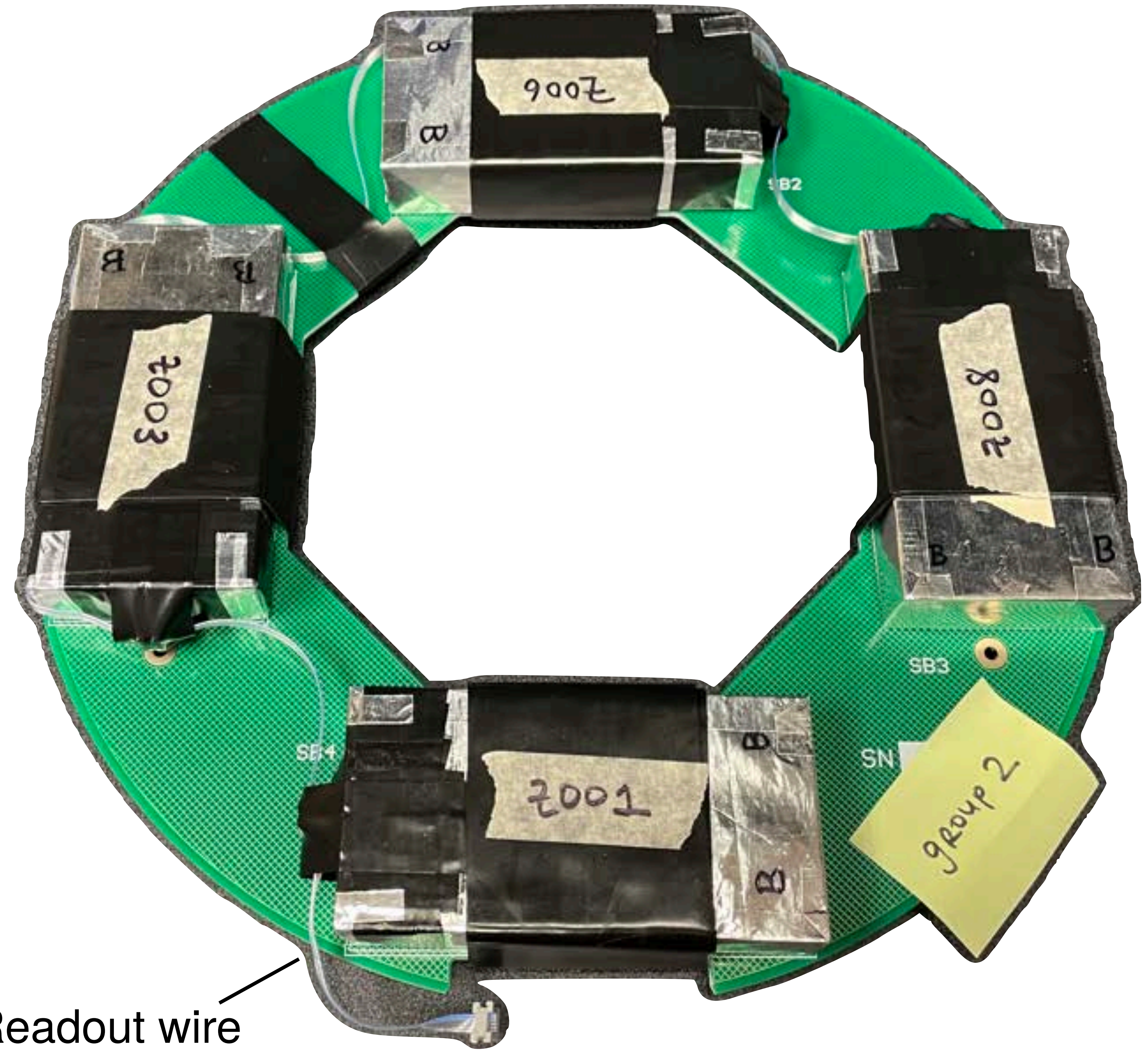
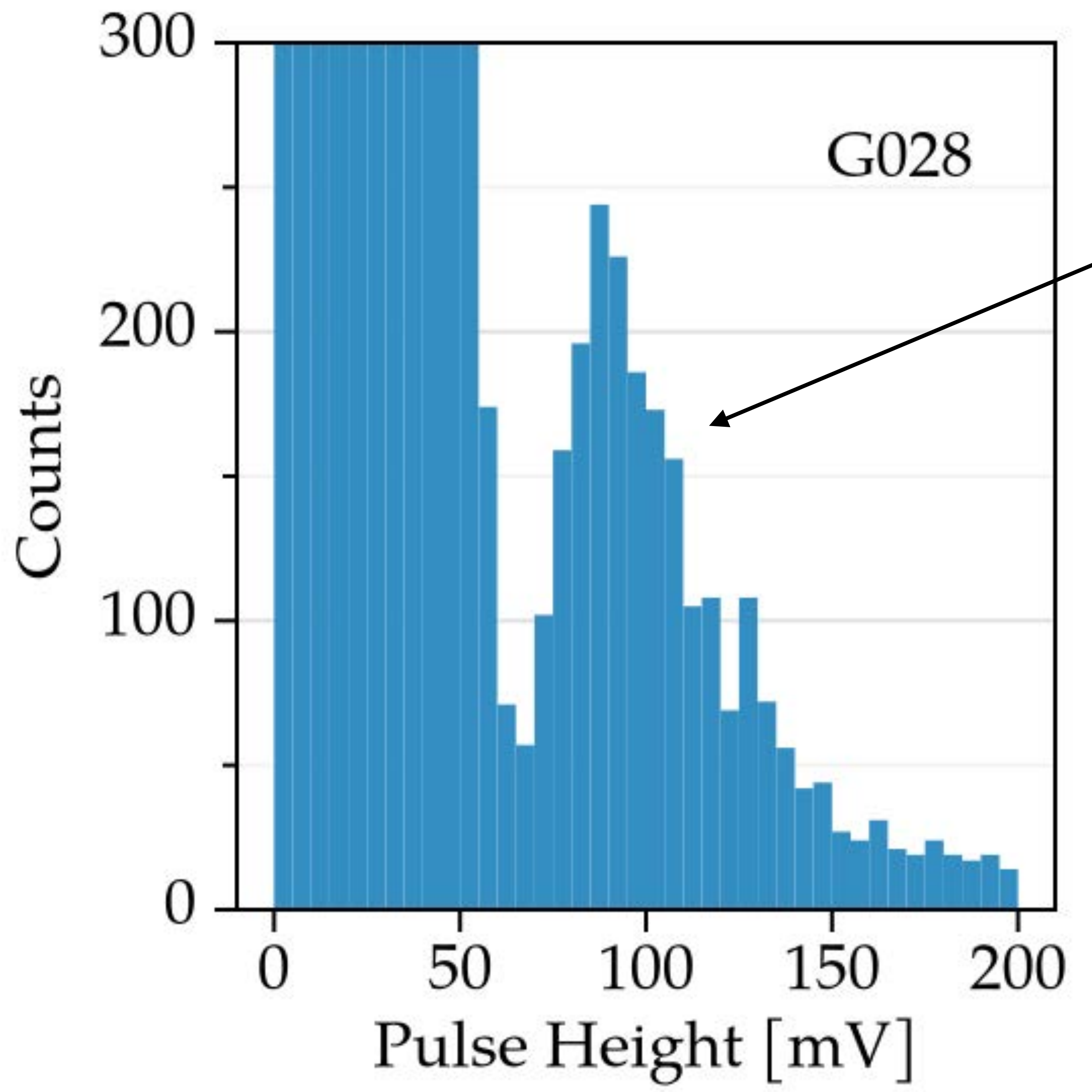


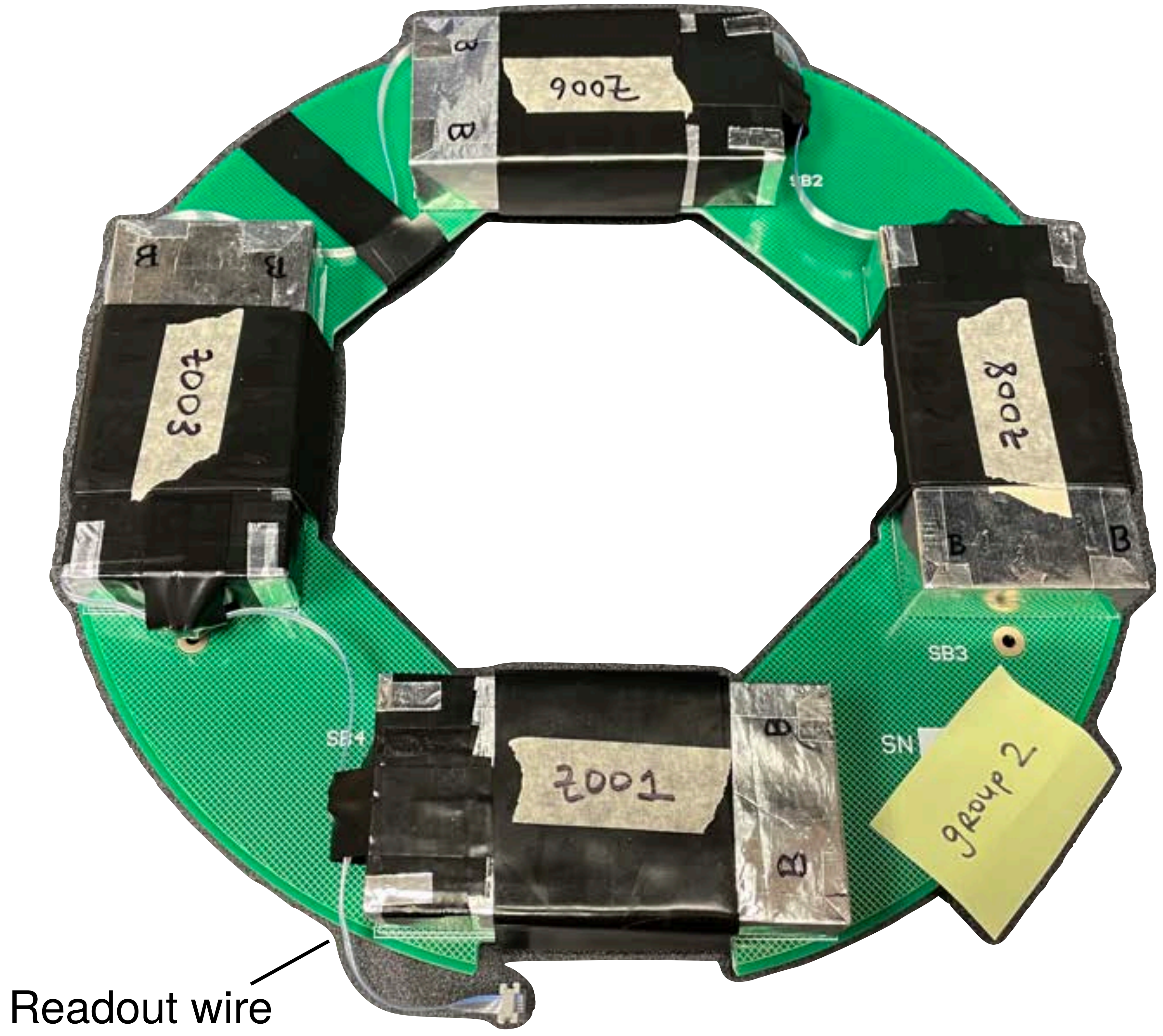
Muon Tagger Array

A minimum ionizing muon deposits about 4MeV as it passes through the scintillator block.

This results in a clean muon signature:



Lab measurement @Harvard.



Muon Tagger Array

We expect to detect about 22k muons / year with the 21 MTAs!

With this dataset of standard arrows, we can:

- test data-driven machine learning methods
- improve reconstruction of low-energy muons
- perform calibration studies

In the long term, the MTA will improve angular resolution => help discover more sources!

Conclusions:

- Whether neutrinos are Majorana or Dirac is one of the biggest outstanding problems in neutrino physics.
- If lepton number is nearly conserved, neutrinos may be quasi-Dirac!

- We can constrain QD models by looking for disappearance signatures in the spectra of astrophysical neutrinos.
- Currently, the most promising search strategy is to use the total diffuse flux.

- Understanding the SM emission physics will improve our ability to constrain BSM oscillation physics.

- Muon taggers can help improve the angular reconstruction of next-generation neutrino telescopes, and thus help discover more sources.

Thank you!

Back-up material:

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]	$(4.9 - 7.5) \times 10^{-19}$

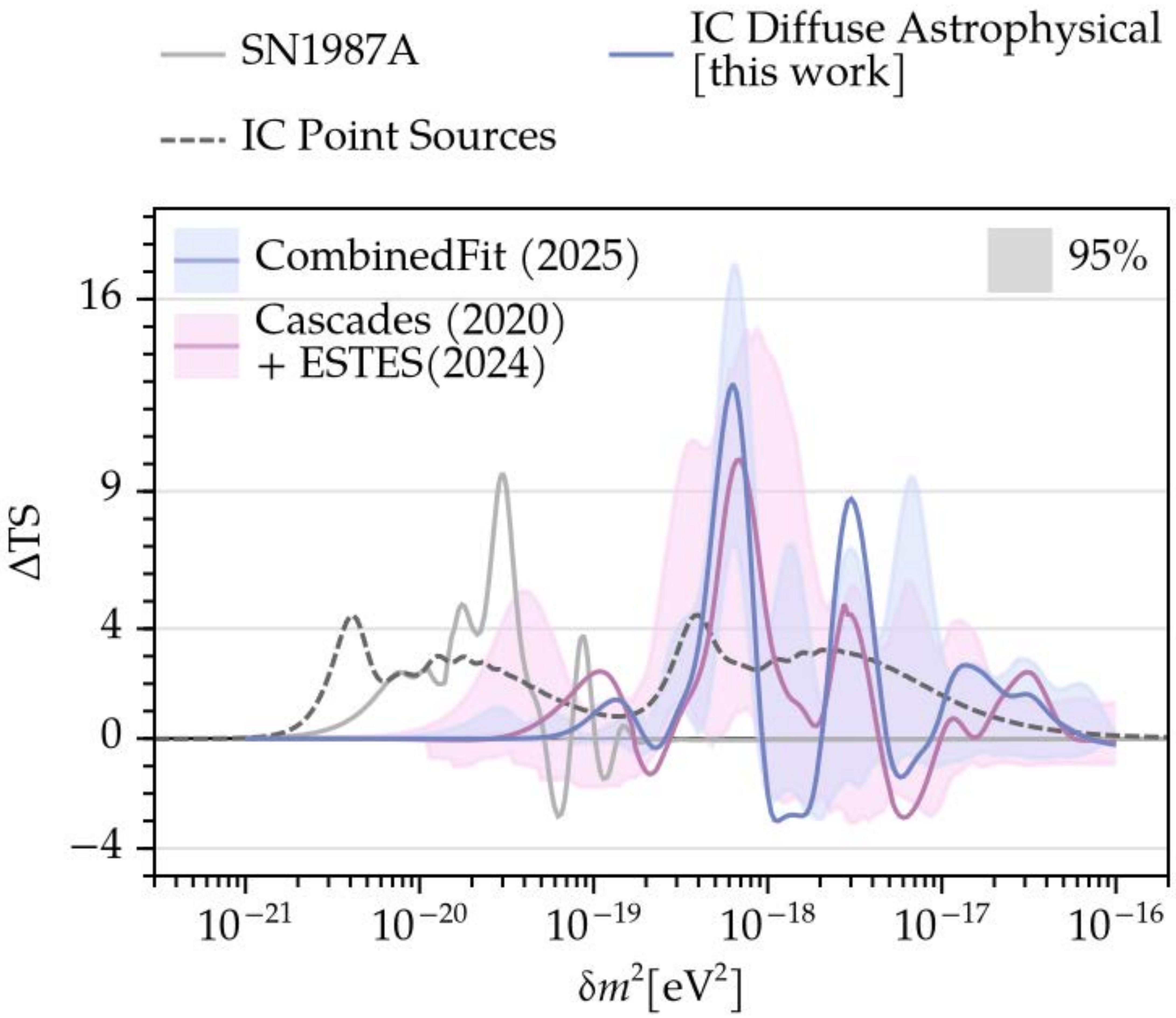
TABLE I. ***Limits on the squared-mass difference.***. These results assume the source emission spectrum is a broken power-law (BPL).

Sample(s)	Flux Model ϕ	$\delta m^2[\text{eV}^2]$	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 $\rho(z)$.

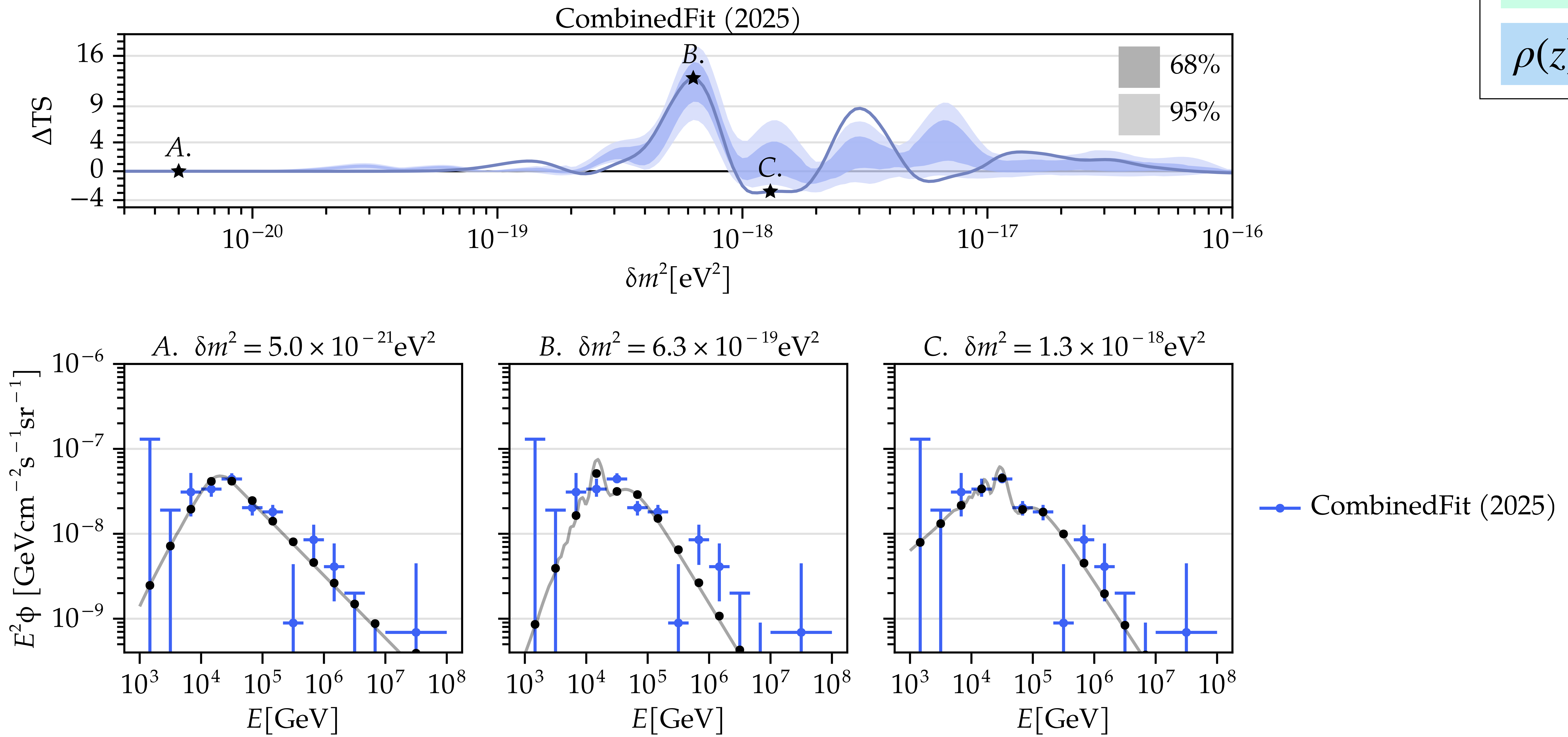
Flavor Ratio		Flux Model ϕ	$\delta m_1^2[\mathrm{eV}^2]$	$\delta m_2^2[\mathrm{eV}^2]$	$\delta m_3^2[\mathrm{eV}^2]$	TS	dof	p-value
Pion decay	(1,2,0)	BPL	*null*	*null*	*null*	25.06	14	3.39%
Muon-damped	(0,1,0)	BPL	*null*	*null*	*null*	32.52	14	0.34%
Neutron dom.	(1,0,0)	BPL	*null*	*null*	*null*	33.35	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 $\rho(z)$.

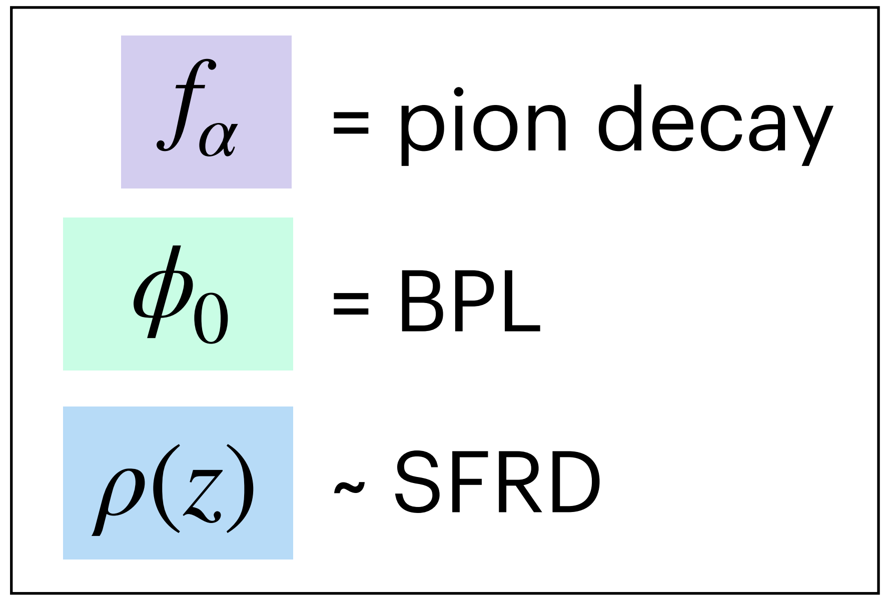


f_α = pion decay
ϕ_0 = BPL
$\rho(z)$ ~ SFRD

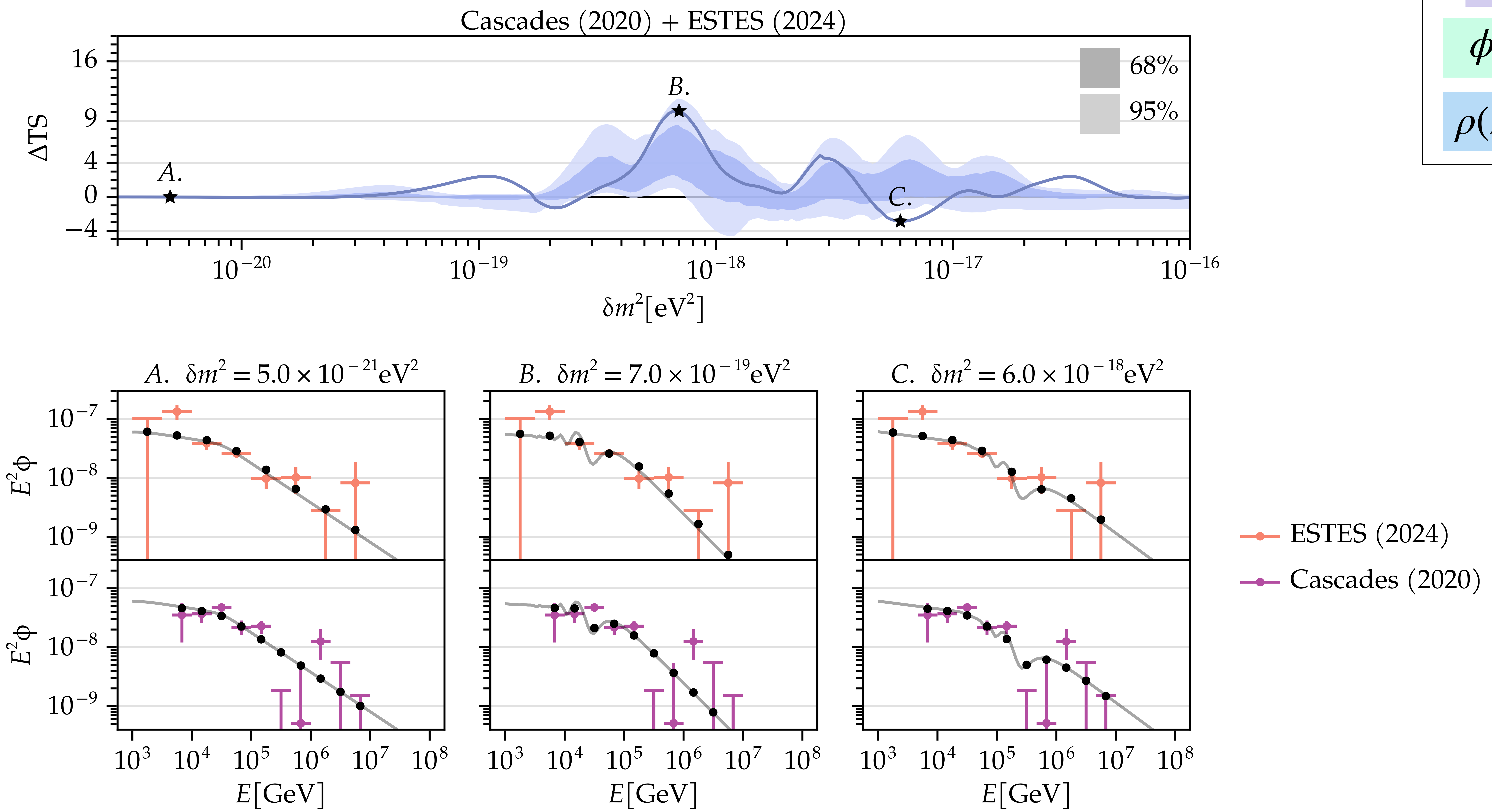
Constraints based on the *CombinedFit* measurements are consistent with those using *Cascades* and *ESTES*.

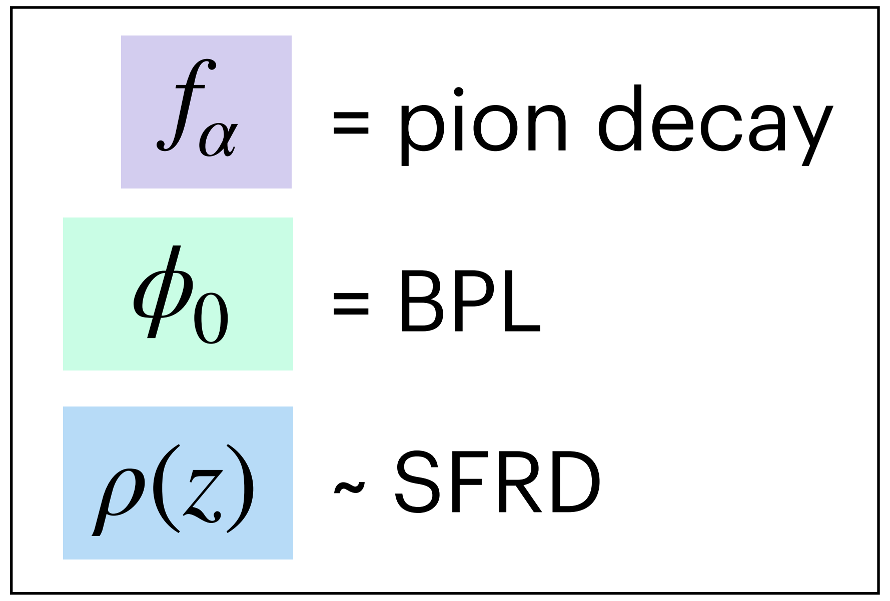


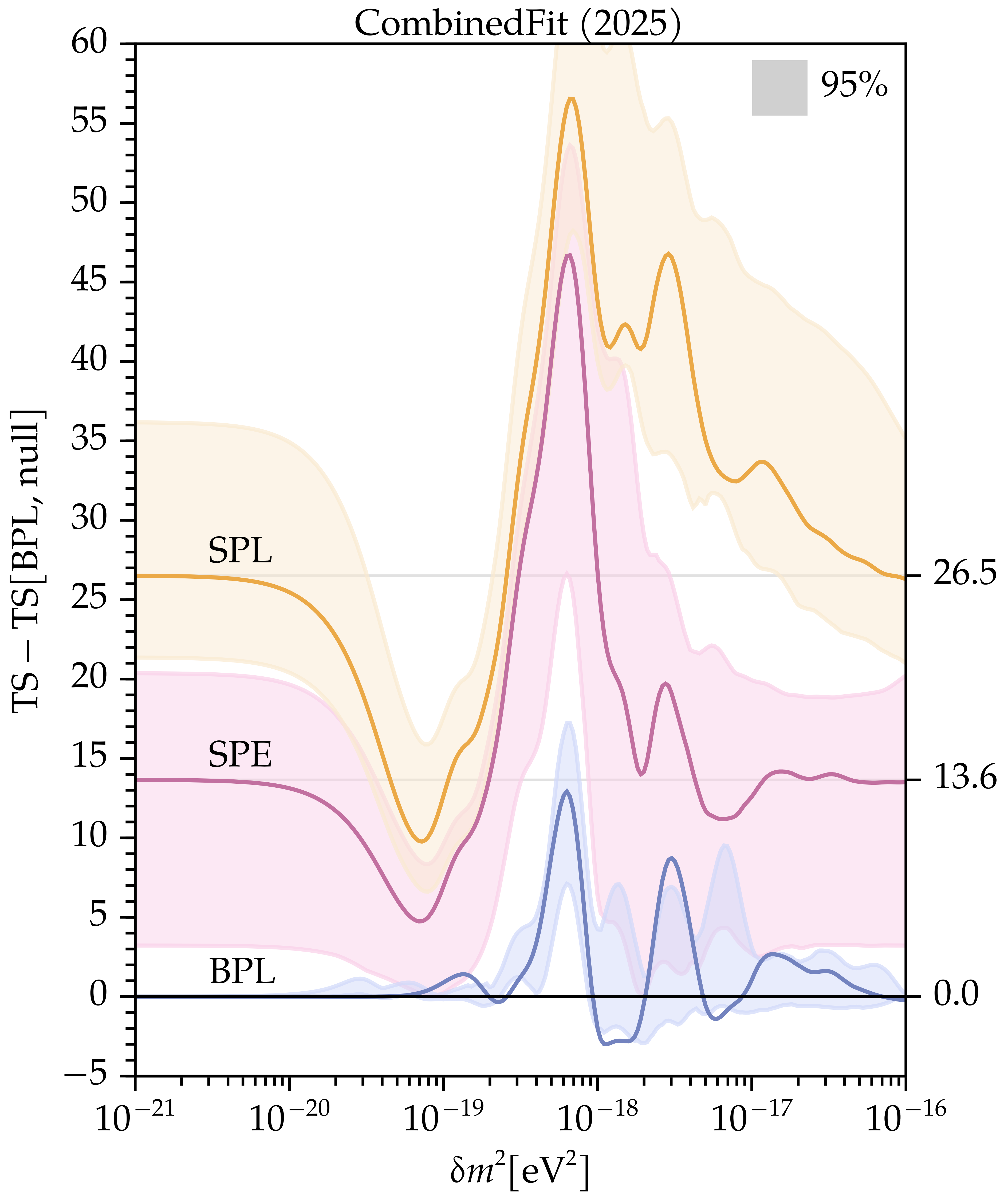
CombinedFit (2025)
ΔTS
16
9
4
0
−4
A.
B.
C.
68%
95%
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
$\delta m^2[\mathrm{eV}^2]$
$A.\ \delta m^2 = 5.0 \times 10^{-21}\mathrm{eV}^2$
$B.\ \delta m^2 = 6.3 \times 10^{-19}\mathrm{eV}^2$
$C.\ \delta m^2 = 1.3 \times 10^{-18}\mathrm{eV}^2$
$E^2\phi\ [\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}]$
$E[\mathrm{GeV}]$
CombinedFit (2025)

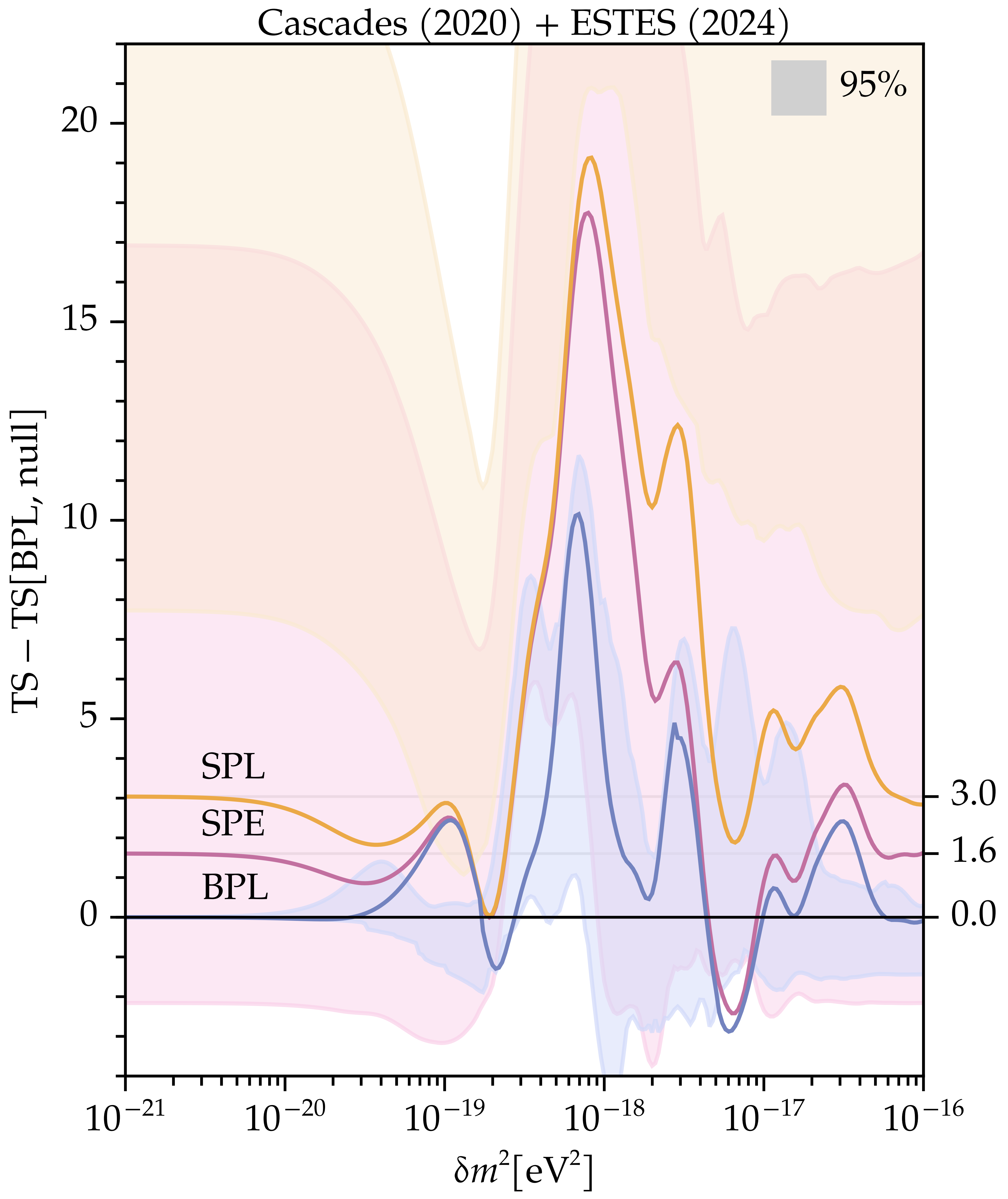


f_α = pion decay
ϕ_0 = BPL
$\rho(z)$ ~ SFRD


Cascades (2020) + ESTES (2024)
68%
95%
ΔTS
A.
B.
C.
δm²[eV²]
A. δm² = 5.0 × 10⁻²¹eV²
B. δm² = 7.0 × 10⁻¹⁹eV²
C. δm² = 6.0 × 10⁻¹⁸eV²
E²Φ
E[GeV]
ESTES (2024)
Cascades (2020)


f_α = pion decay
ϕ_0 = BPL
$\rho(z)$ ~ SFRD


CombinedFit (2025)
95%
SPL
SPE
BPL
26.5
13.6
0.0
TS − TS[BPL, null]
δm²[eV²]
60
55
50
45
40
35
30
25
20
15
10
5
0
−5
10^−21
10^−20
10^−19
10^−18
10^−17
10^−16

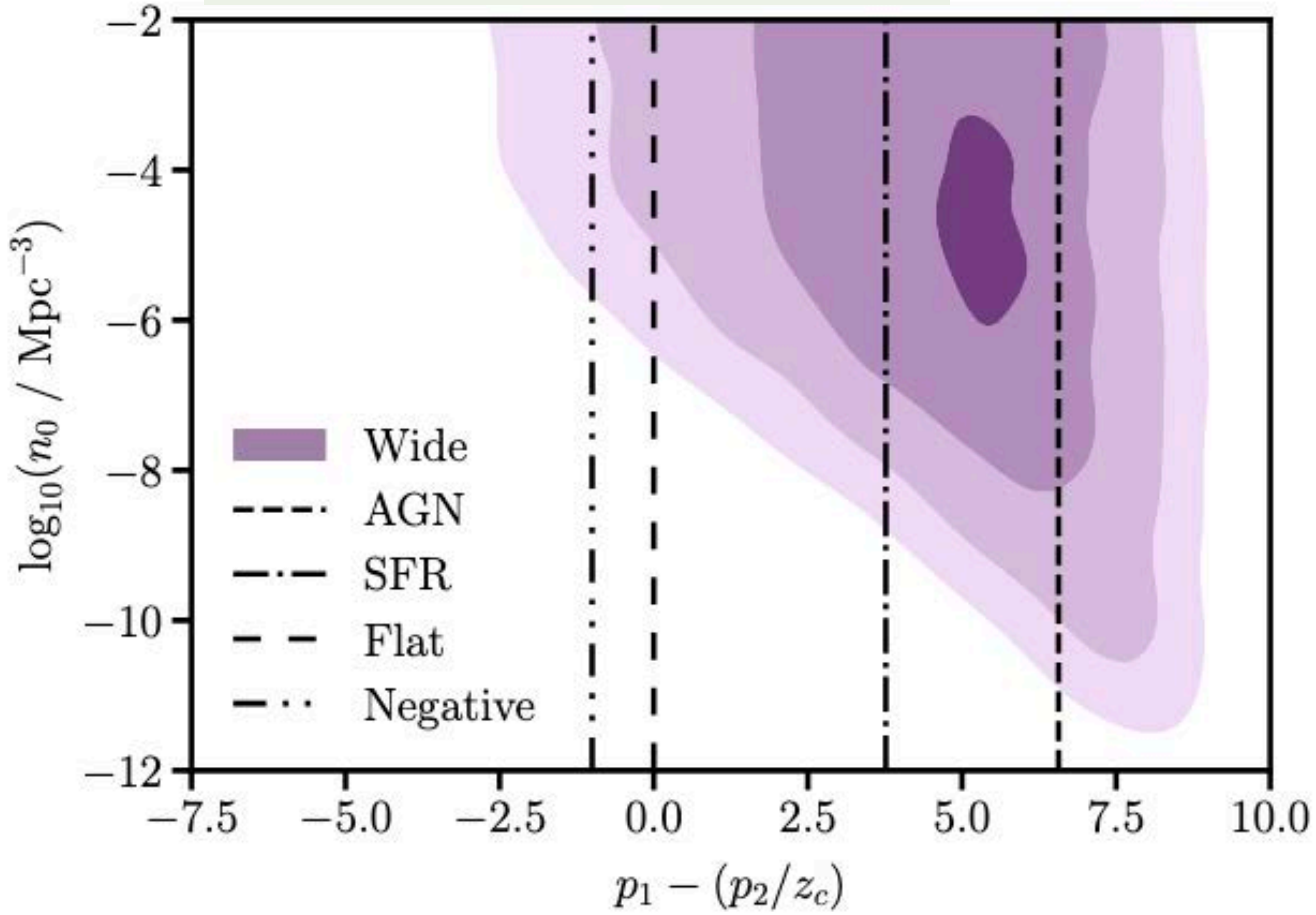

Cascades (2020) + ESTES (2024)
95%
SPL
SPE
BPL
3.0
1.6
0.0
TS − TS[BPL, null]
δm²[eV²]
20
15
10
5
0
10^−21
10^−20
10^−19
10^−18
10^−17
10^−16

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:

$$\begin{bmatrix} \nu_L \\ \nu_R^C \end{bmatrix} = R_\theta \begin{bmatrix} \nu^+ \\ \nu^- \end{bmatrix} \qquad m_\pm = m_D(1 \pm m_R/m_D) \quad \textbf{tiny mass-squared difference}$$
$$\tan 2\theta = 2m_D/m_R \gg 1 \qquad \textbf{maximal mixing}$$

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:

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

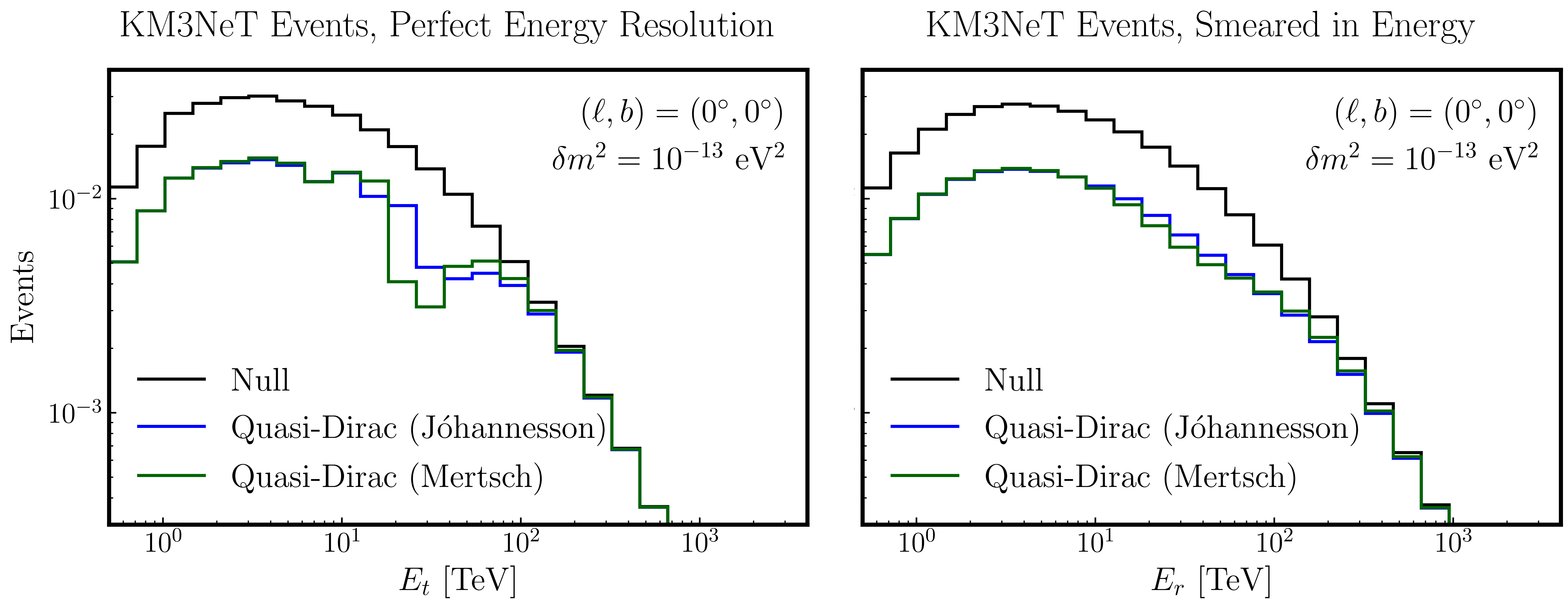
$$= \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \cos^2\left(\delta m_j^2 L/4E\right) + \sum_{i>j} \mathrm{Re}\left[\exp[i\Delta m_{ij}^2 L/2E] \times \ldots\right]$$

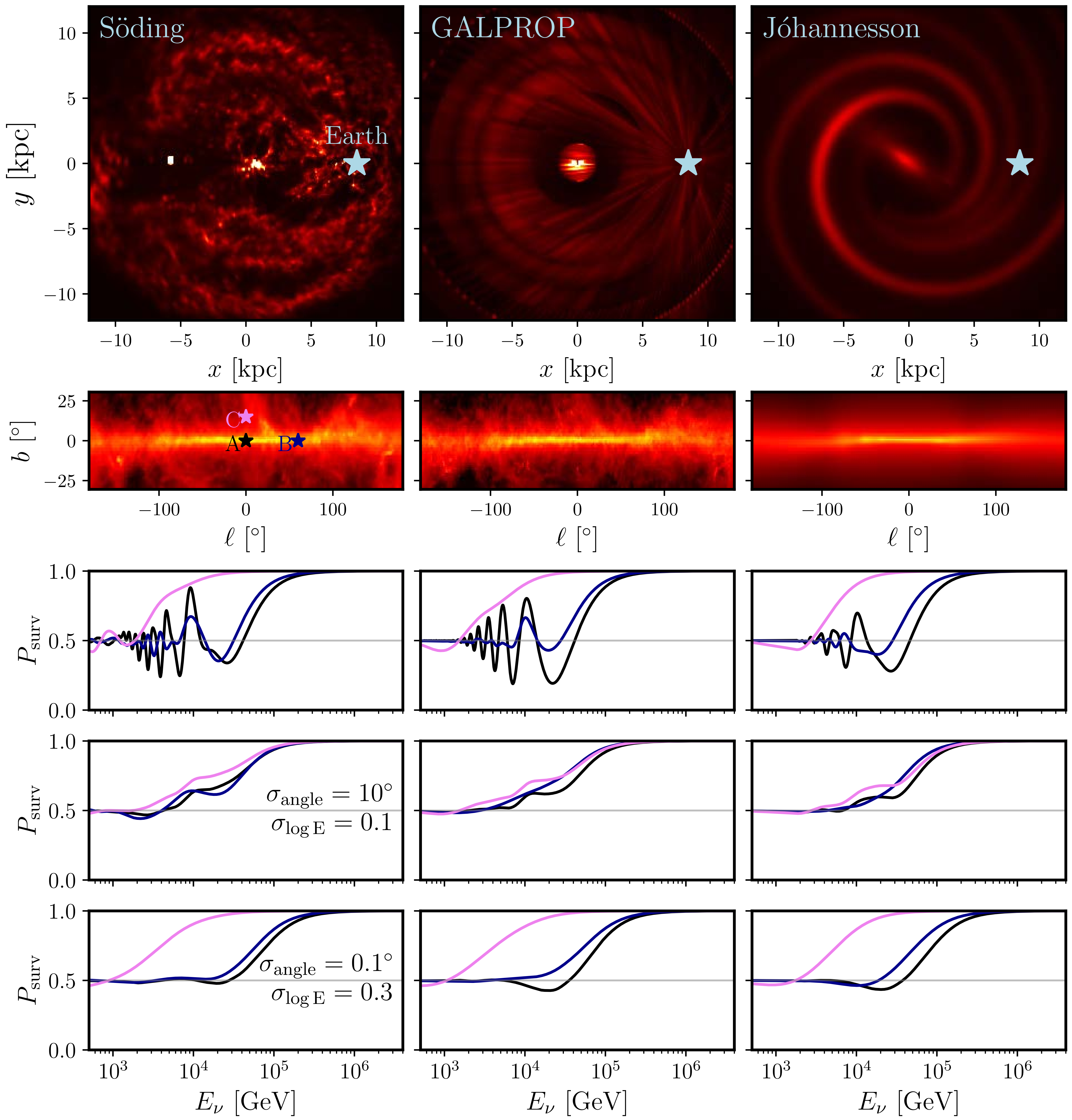
Quasi-Dirac oscillations are not washed out by extragalactic baselines.
This is because the coherence length is

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

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.

Differences in oscillation pattern become negligible after accounting for energy resolution:

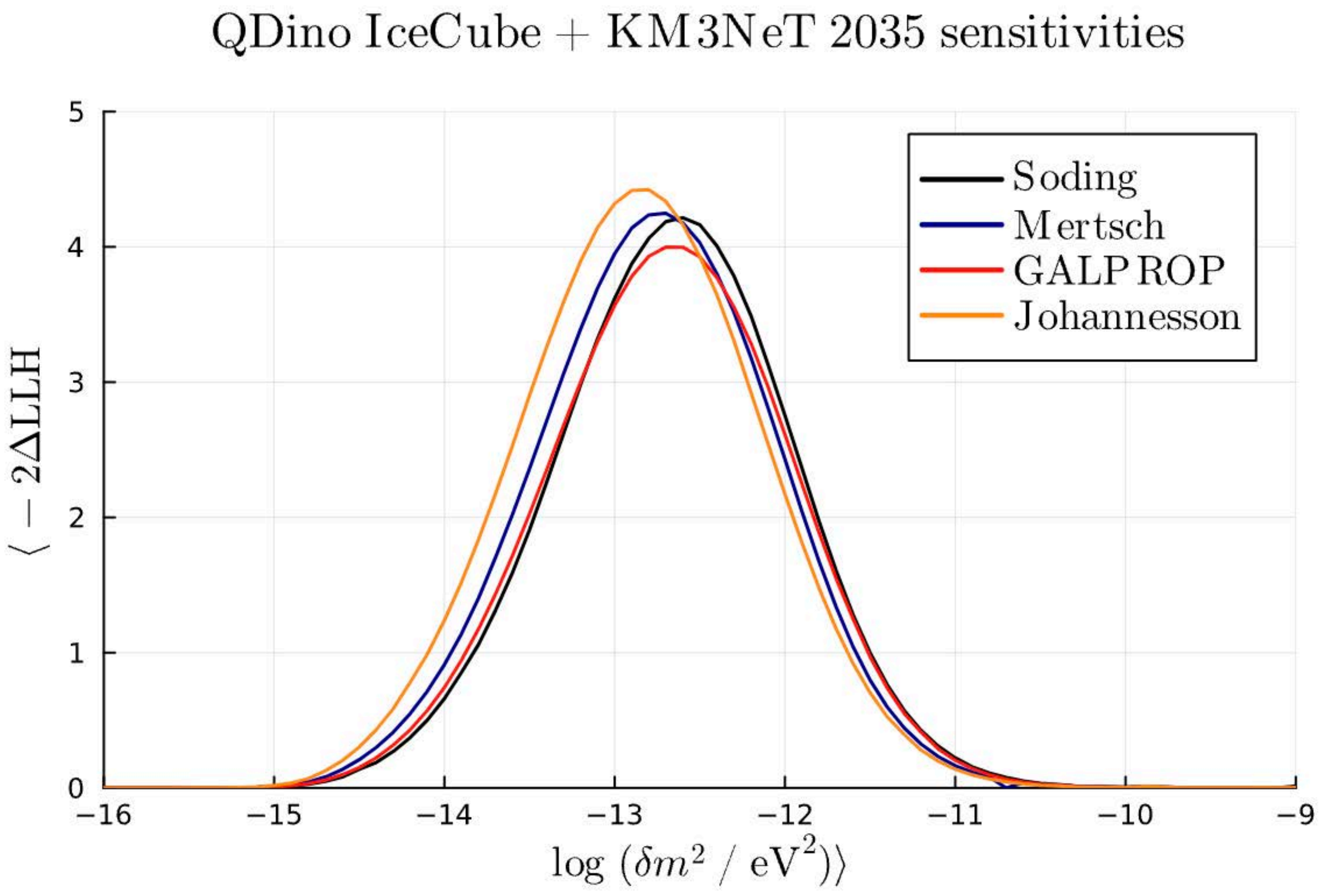




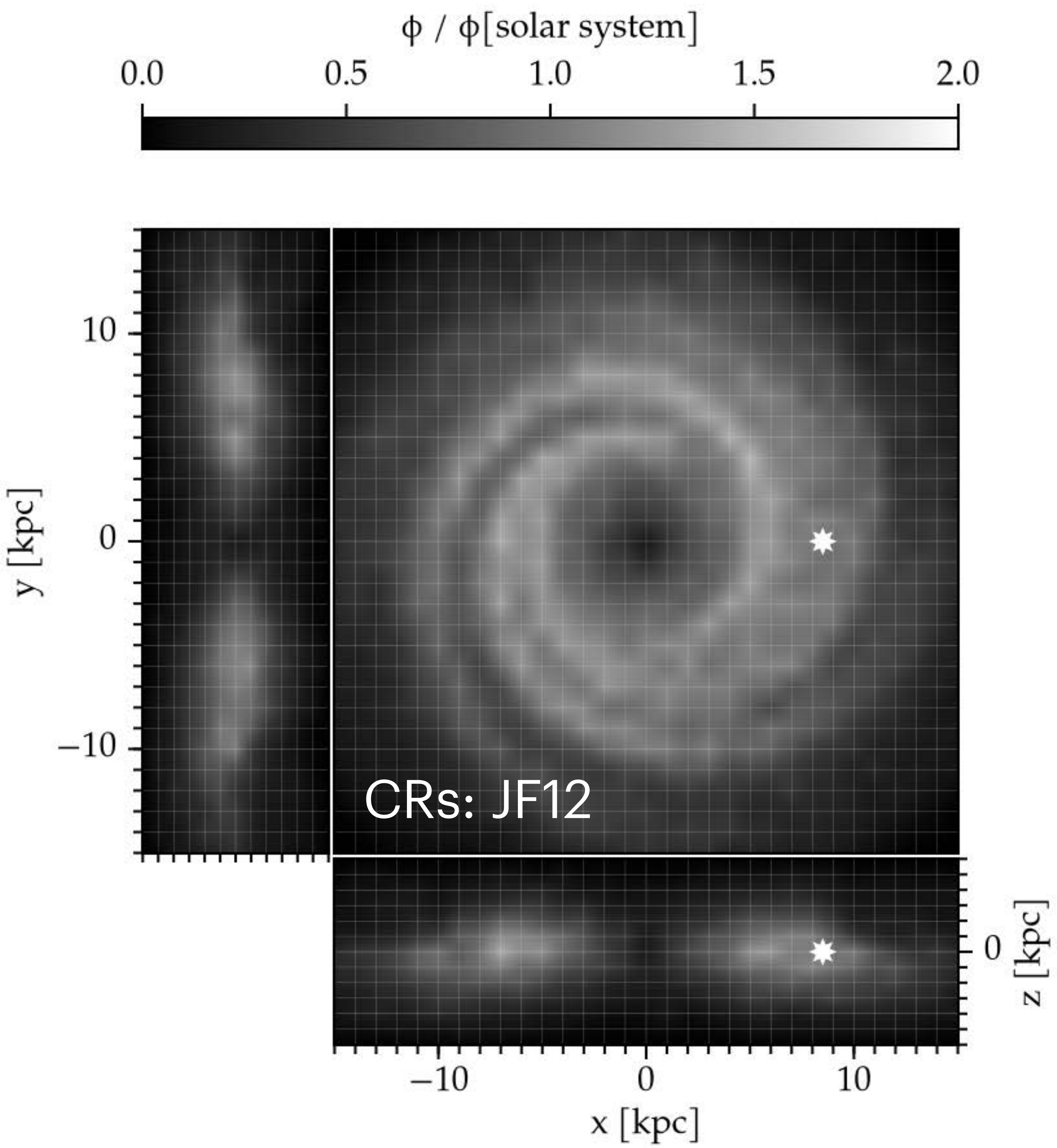
Perfect Resolution

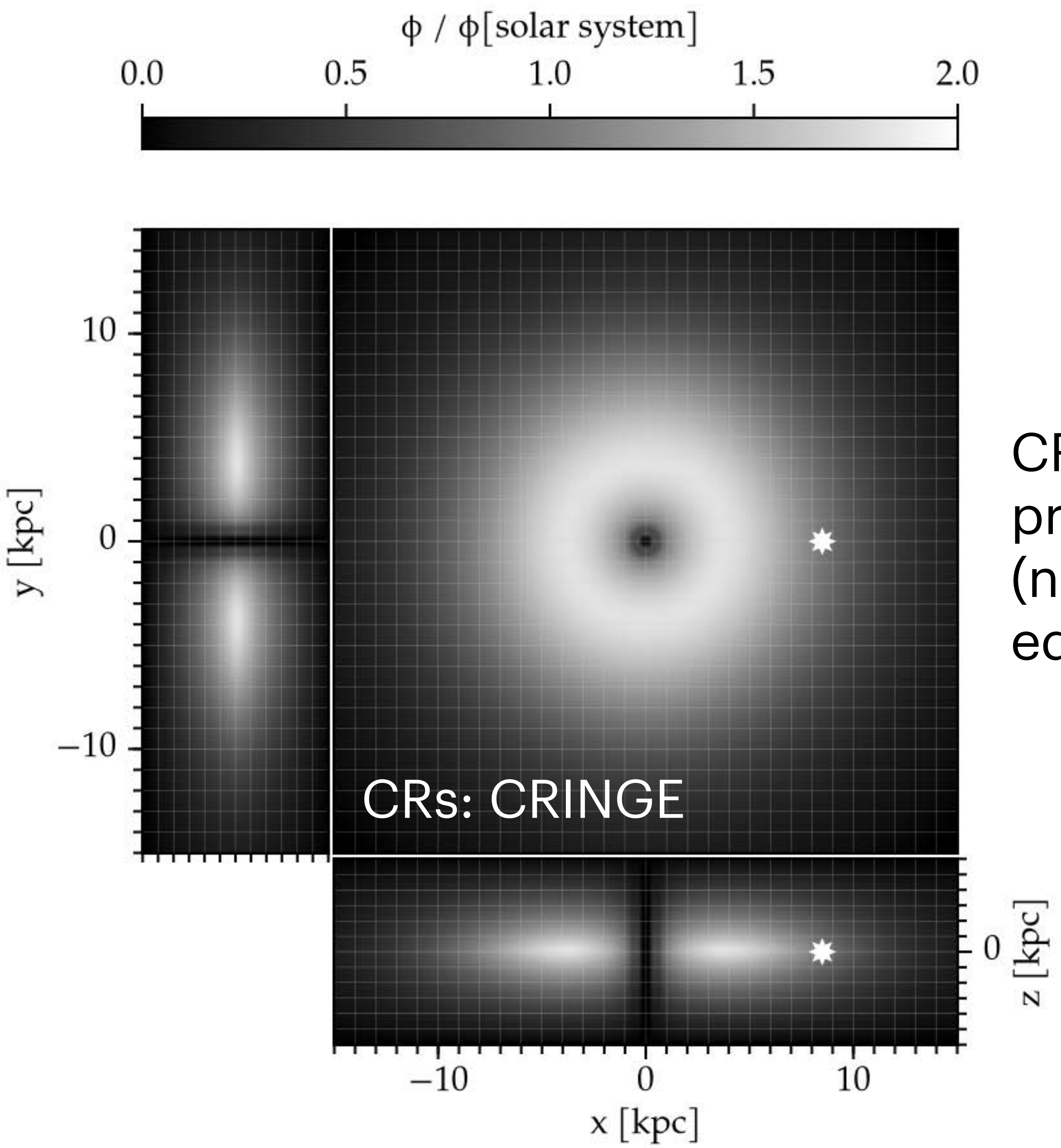
Cascade-like Resolution

Track-like Resolution



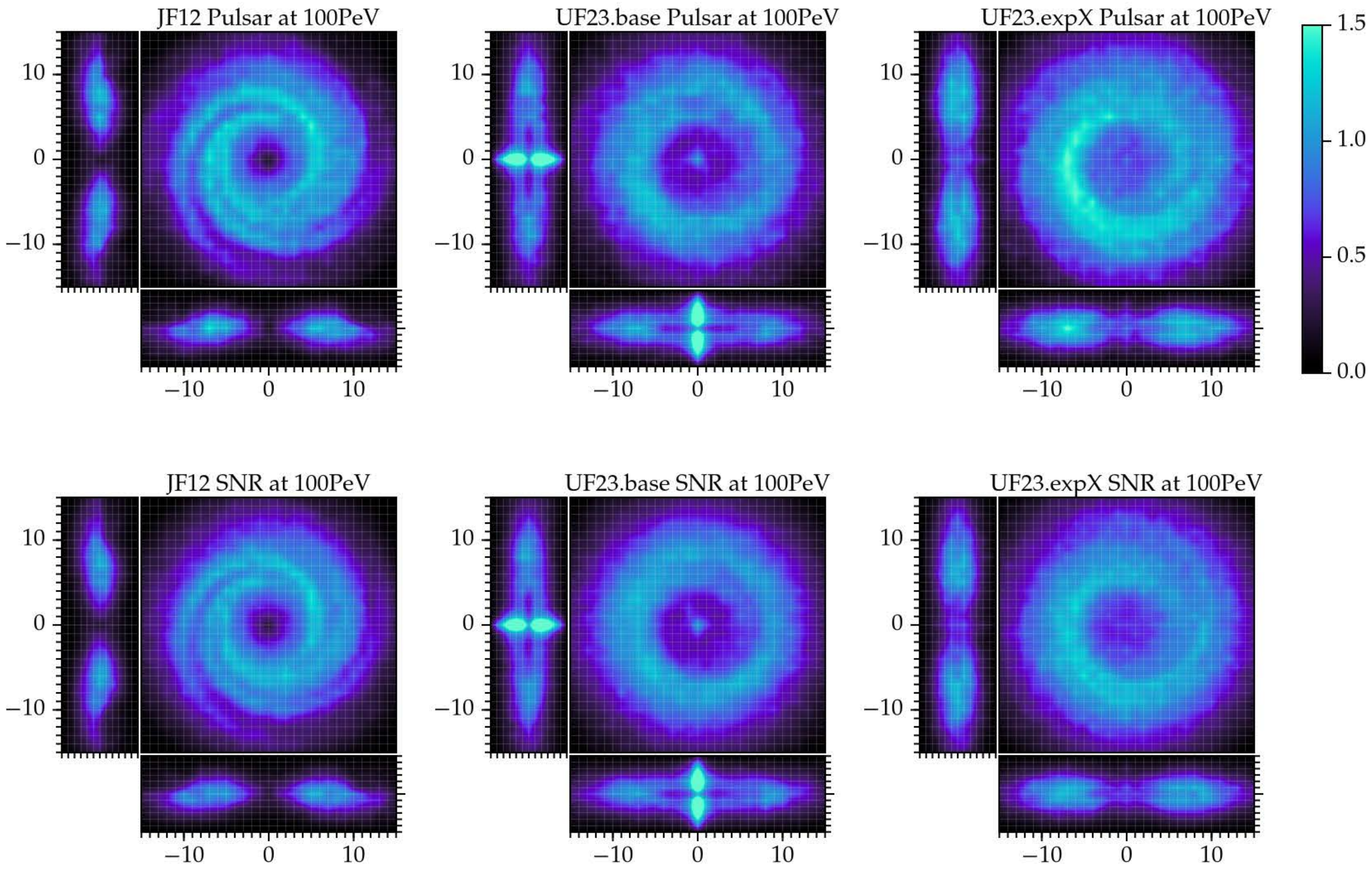
Changing gas models => slight difference in baselines





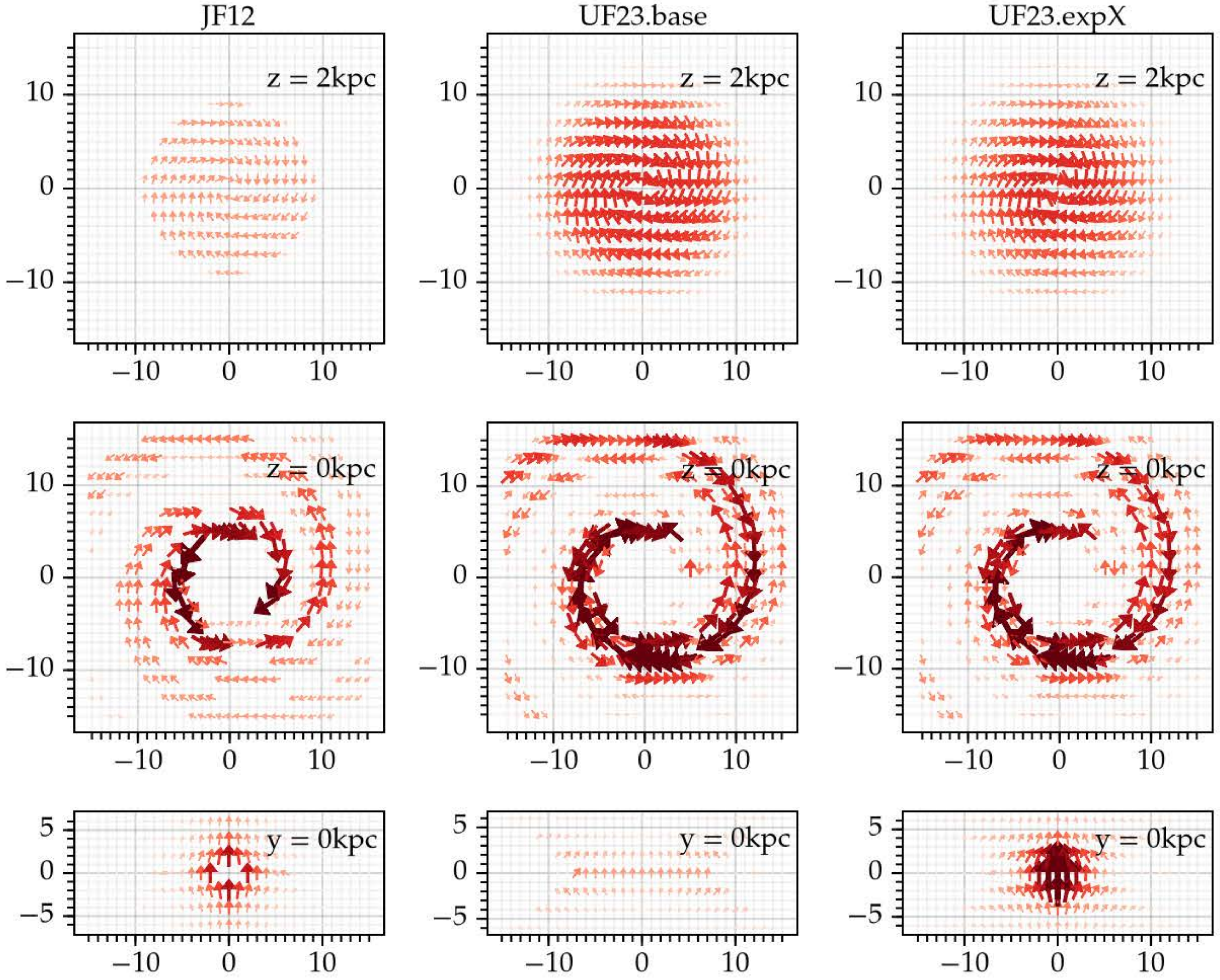
CR proton distribution produced using DRAGON (numerical transport equation solver)

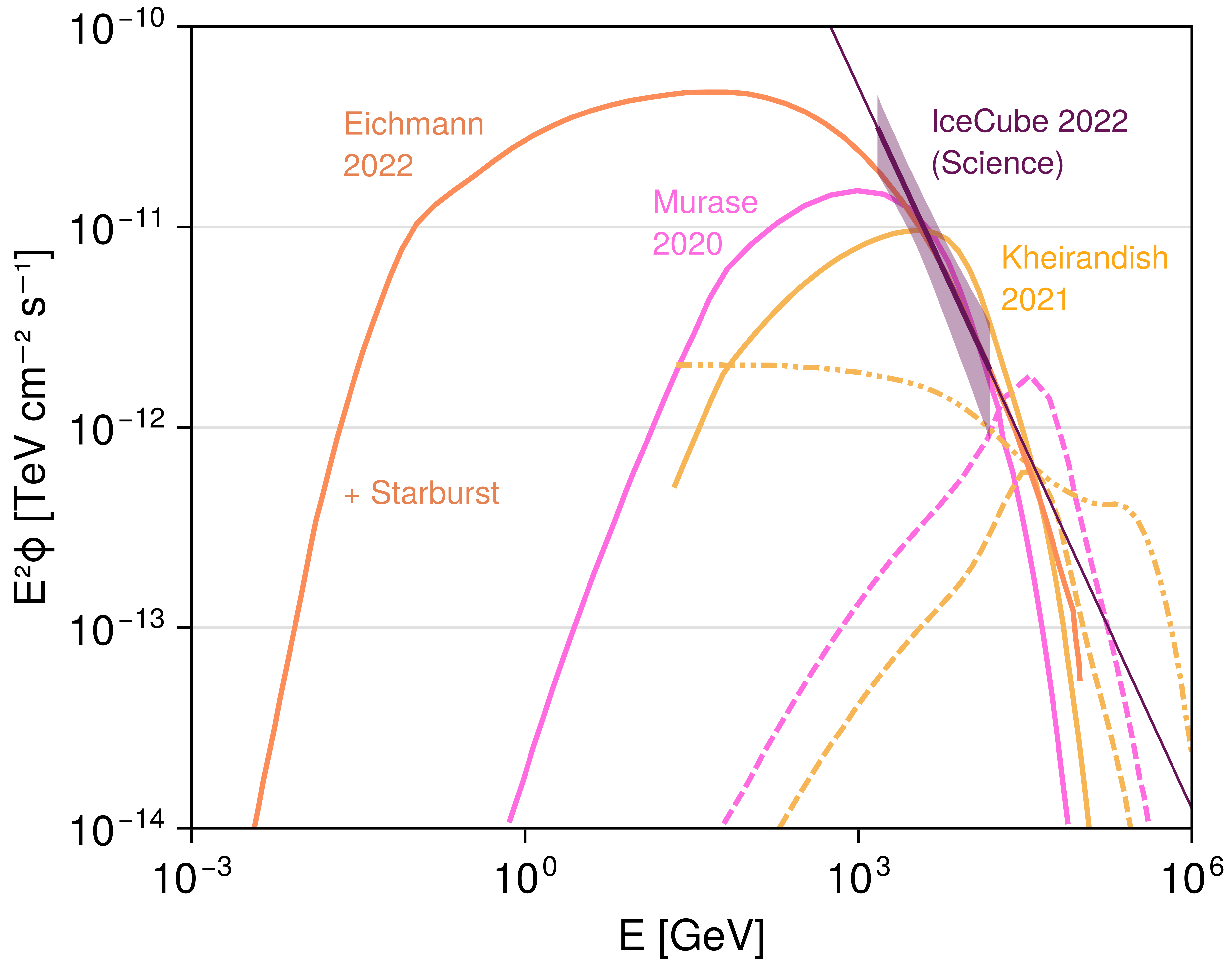
Different B-field models
=> qualitative differences
in CR distributions



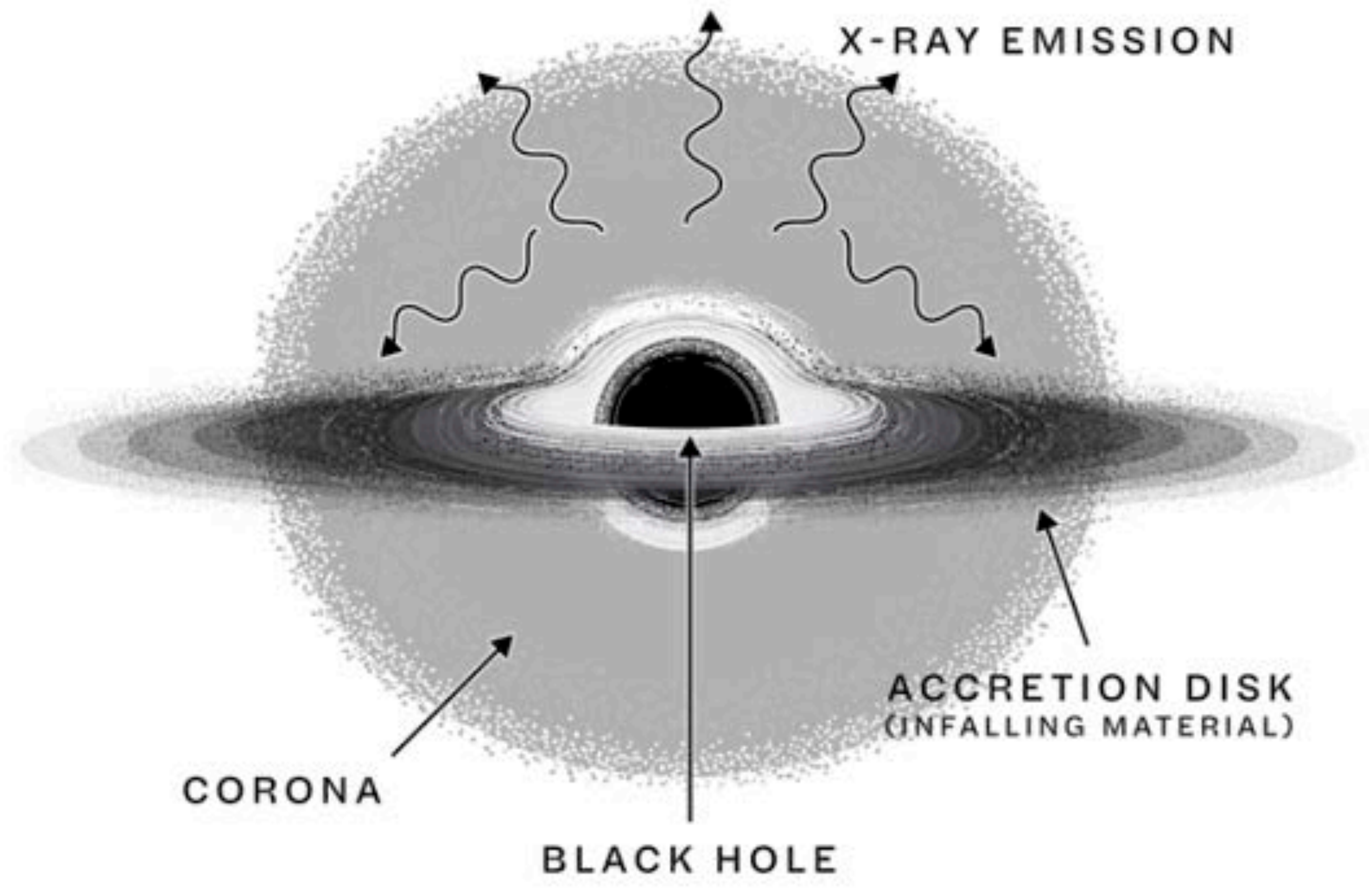
Cosmic rays primarily escape vertically out of the disk into the halo;

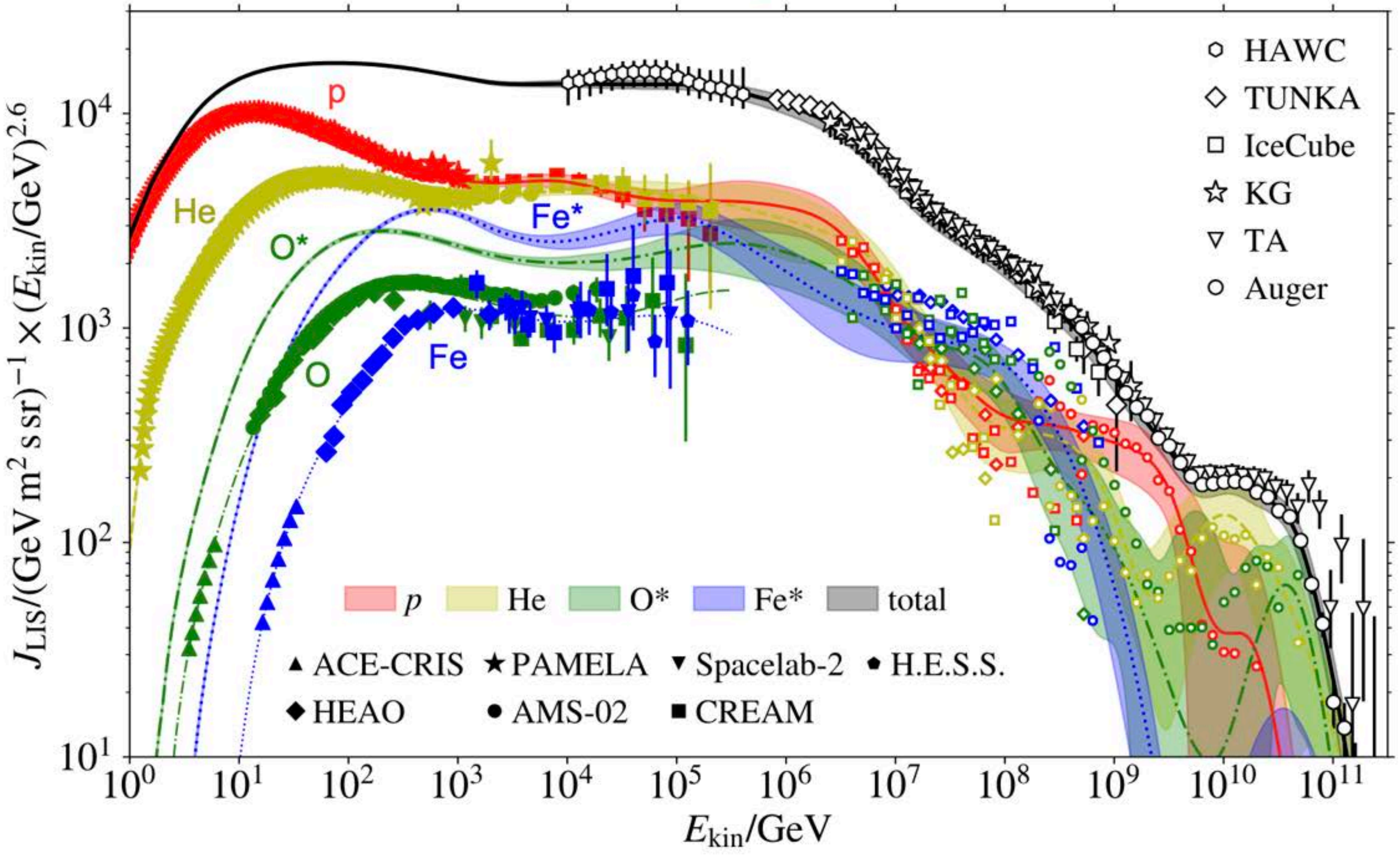
the strength of the B_z component seems to strongly affect the efficiency of vertical diffusion





Disk - Corona model:
predicts X-ray and neutrino emission from Seyferts

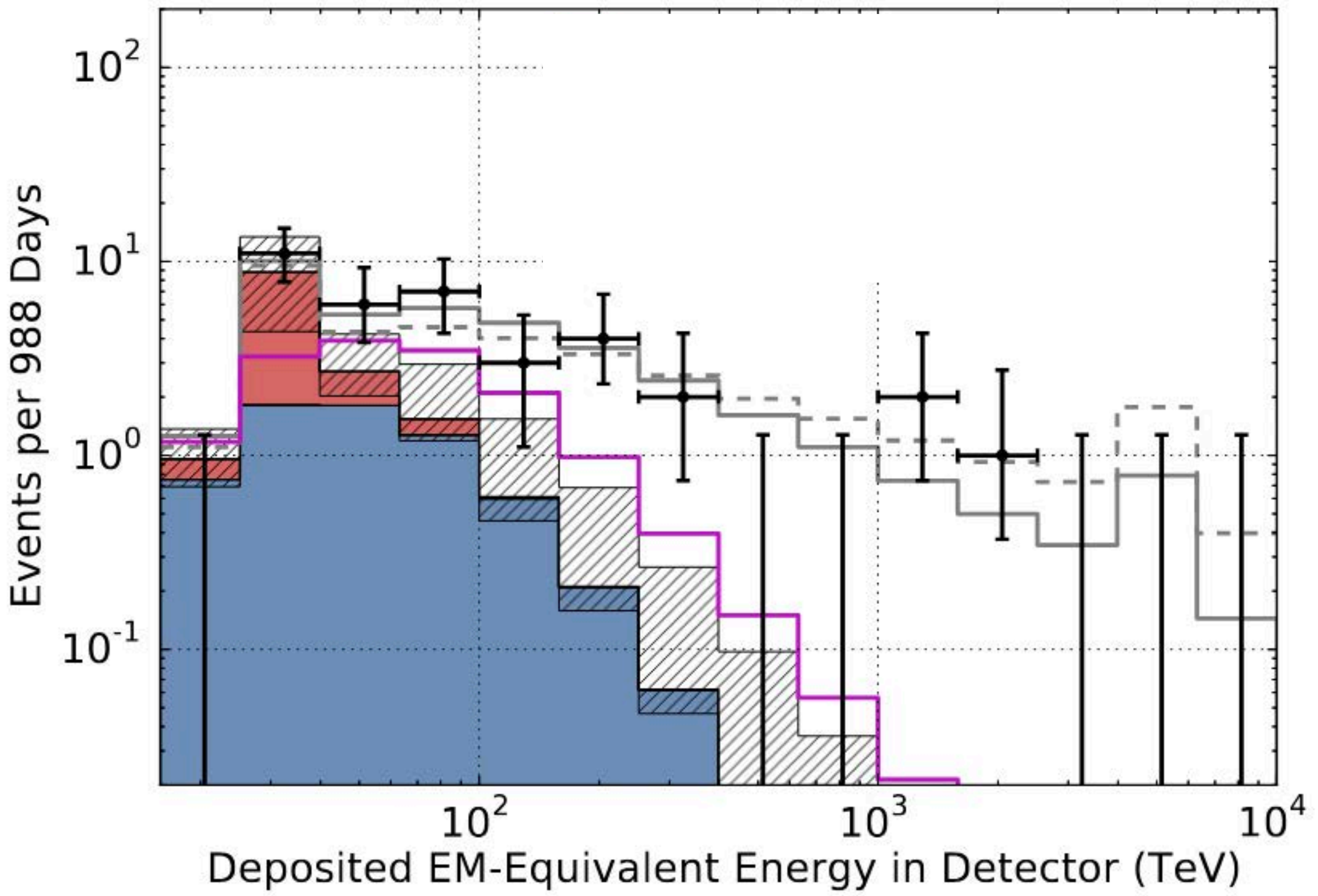




Dembinski at UHECR 2018,
based on:
Data-driven model of the cosmic-ray flux and composition from 10 GeV to 10^11 GeV, 2017

In 2014, IceCube discovered the “diffuse” astrophysical flux of neutrinos

which emerges over atmospheric backgrounds at high energies > 100TeV



downgoing atmospheric neutrinos are reduced a bit more by the self-veto effect