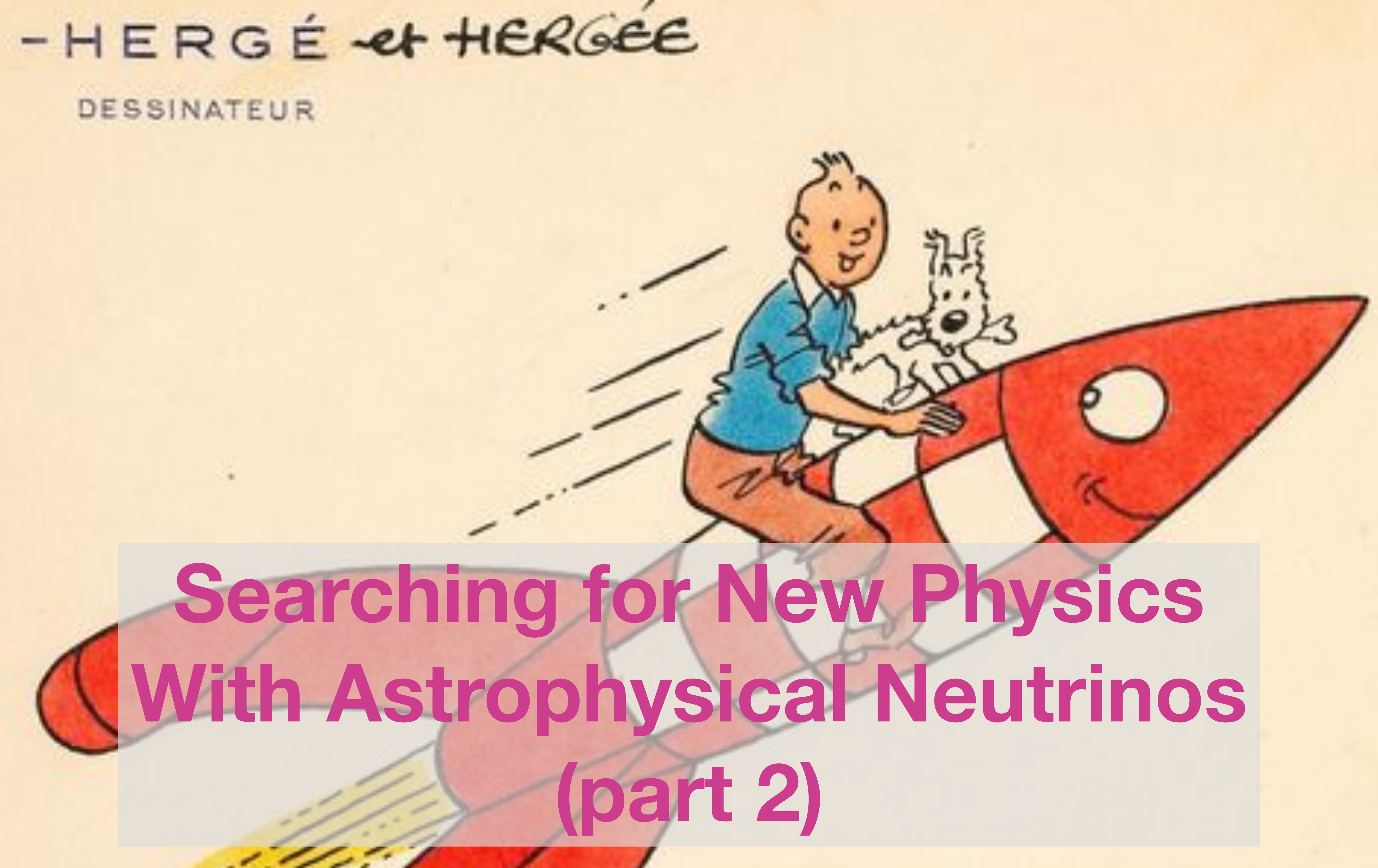


Searching for New Physics With Astrophysical Neutrinos (part 2)

Carlos Argüelles (they/them)*

HARVARD UNIVERSITY

Alfred P. Sloan FOUNDATION

CR-N-MME 2022
Louvain, Belgium
Dec. 02, 2022

*Disclaimer:This talk is not on behalf of the IceCube Collaboration. Opinions/ideas/mistakes are mine.

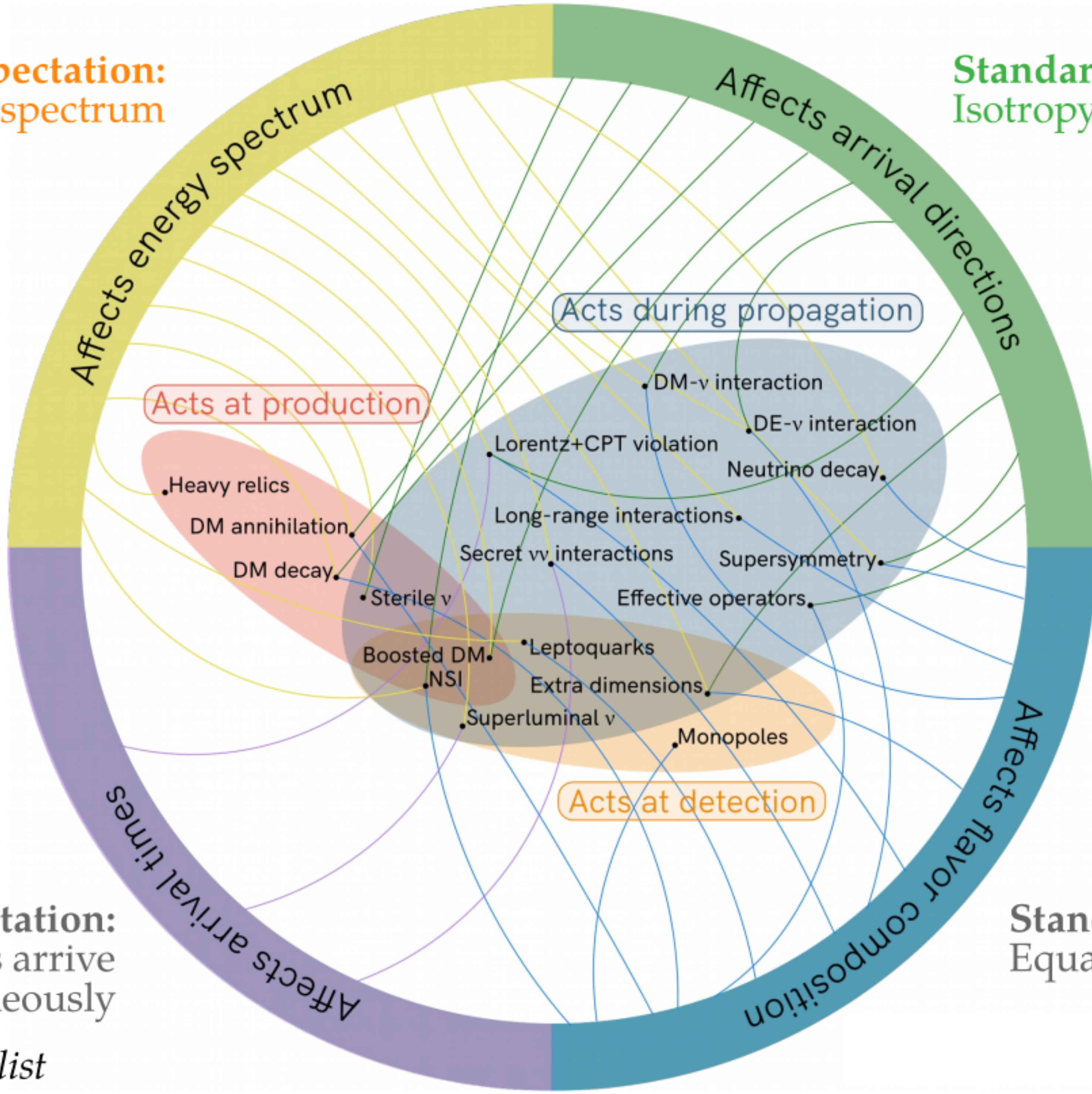
Why High-Energy Neutrinos?

$$\sigma \sim G_F^2 s$$

Extreme long baselines

Observing neutrinos
from uncharted territories

Landscape of New Physics That We can Explore



Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

See CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvado, and Vincent arXiv:1907.08690 for more details

Stops

- A new frontier in the search for dark matter
- Using the flavor of neutrinos to find new physics
- New physics with new sources
- Anomalies and new physics at PeV-EeV

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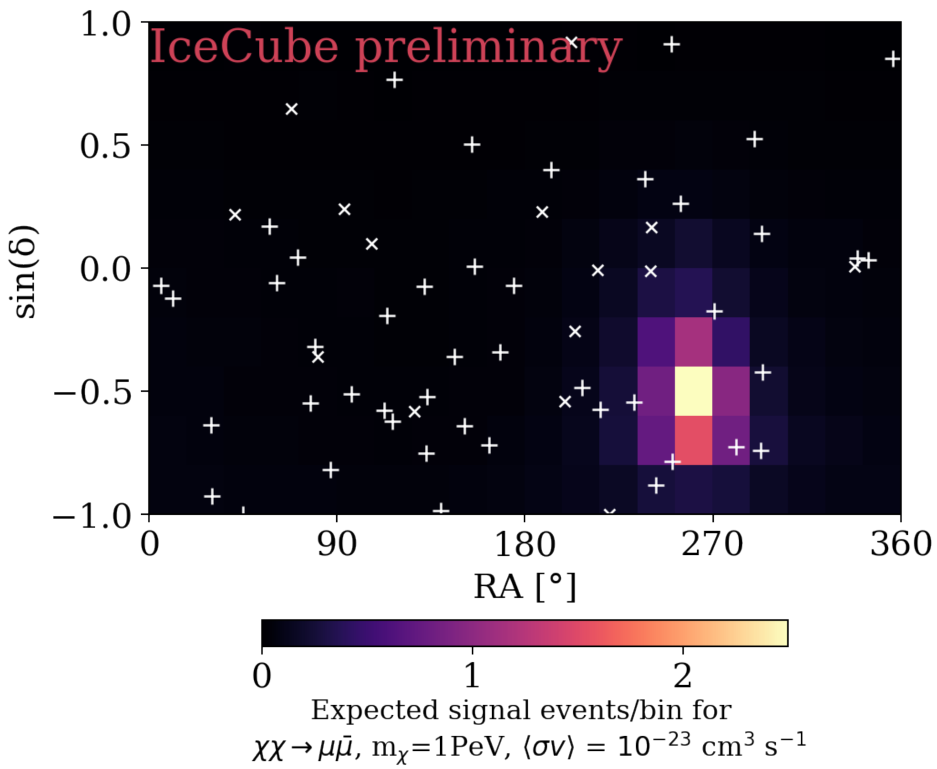
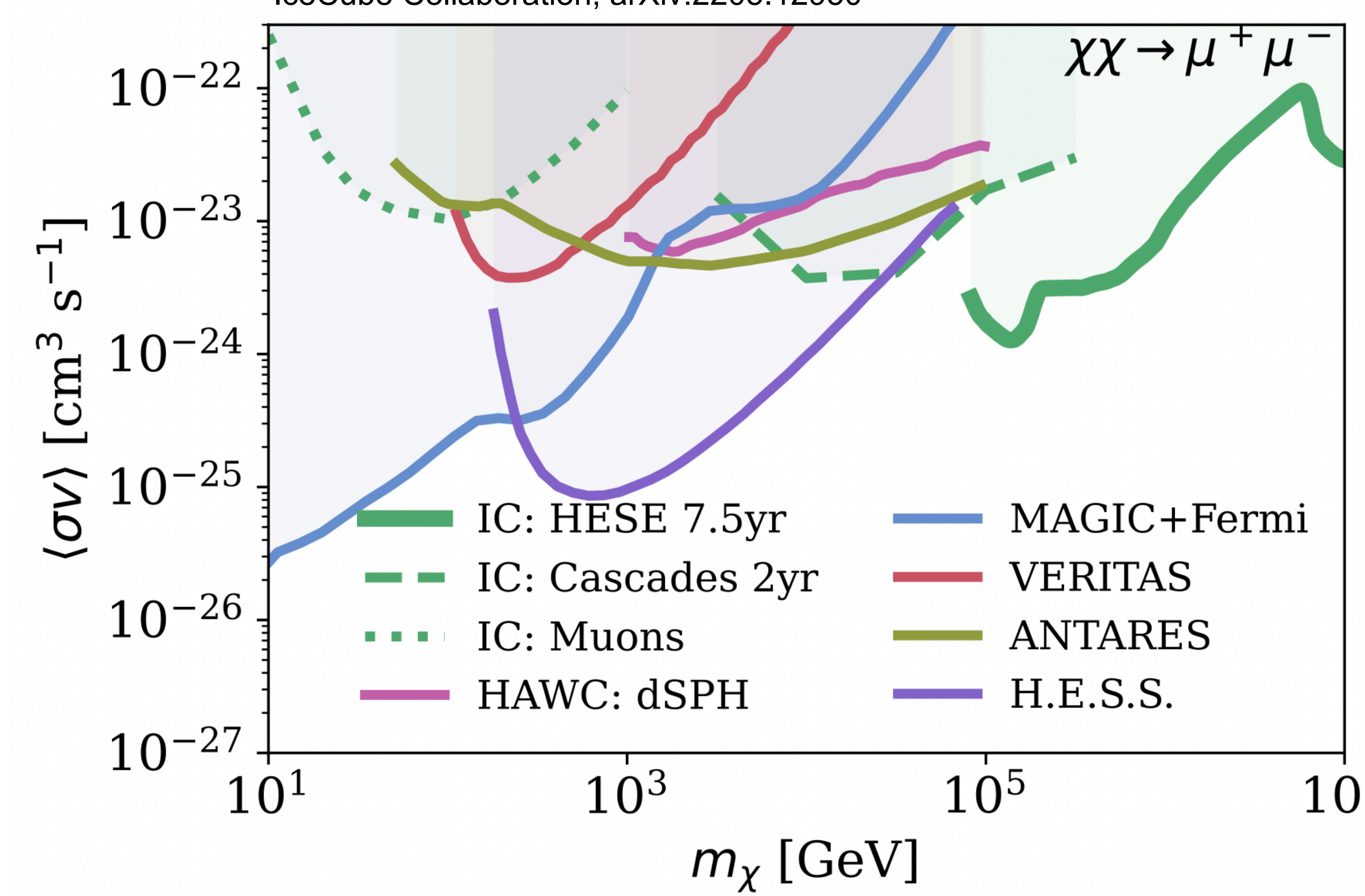
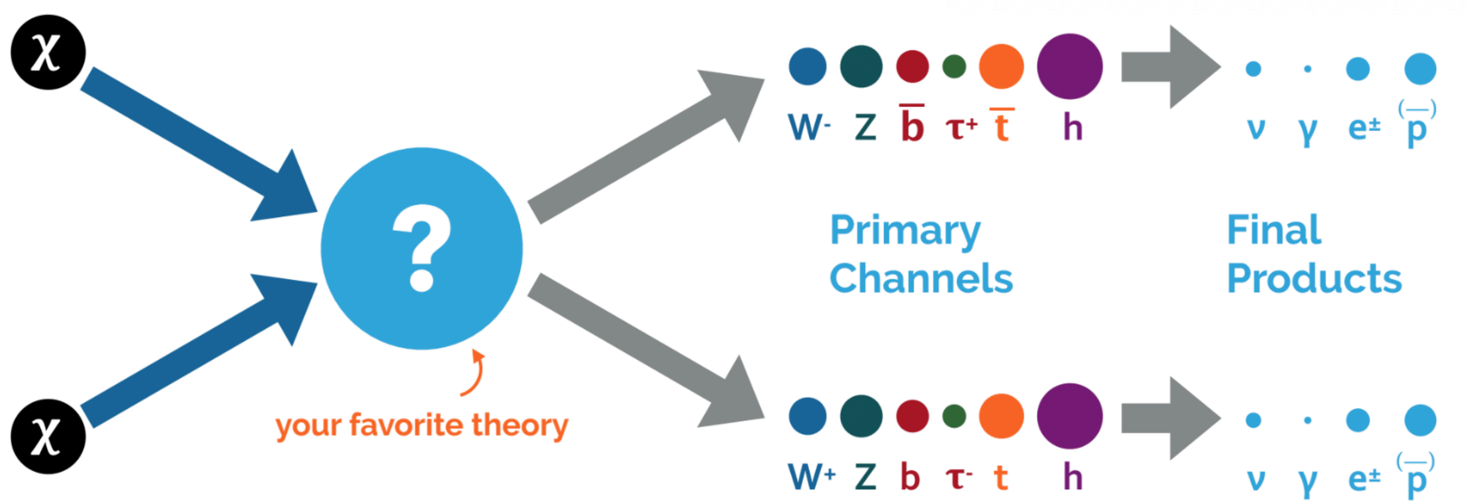
Dark matter annihilation



IceCube Collaboration, arXiv:2205.12950

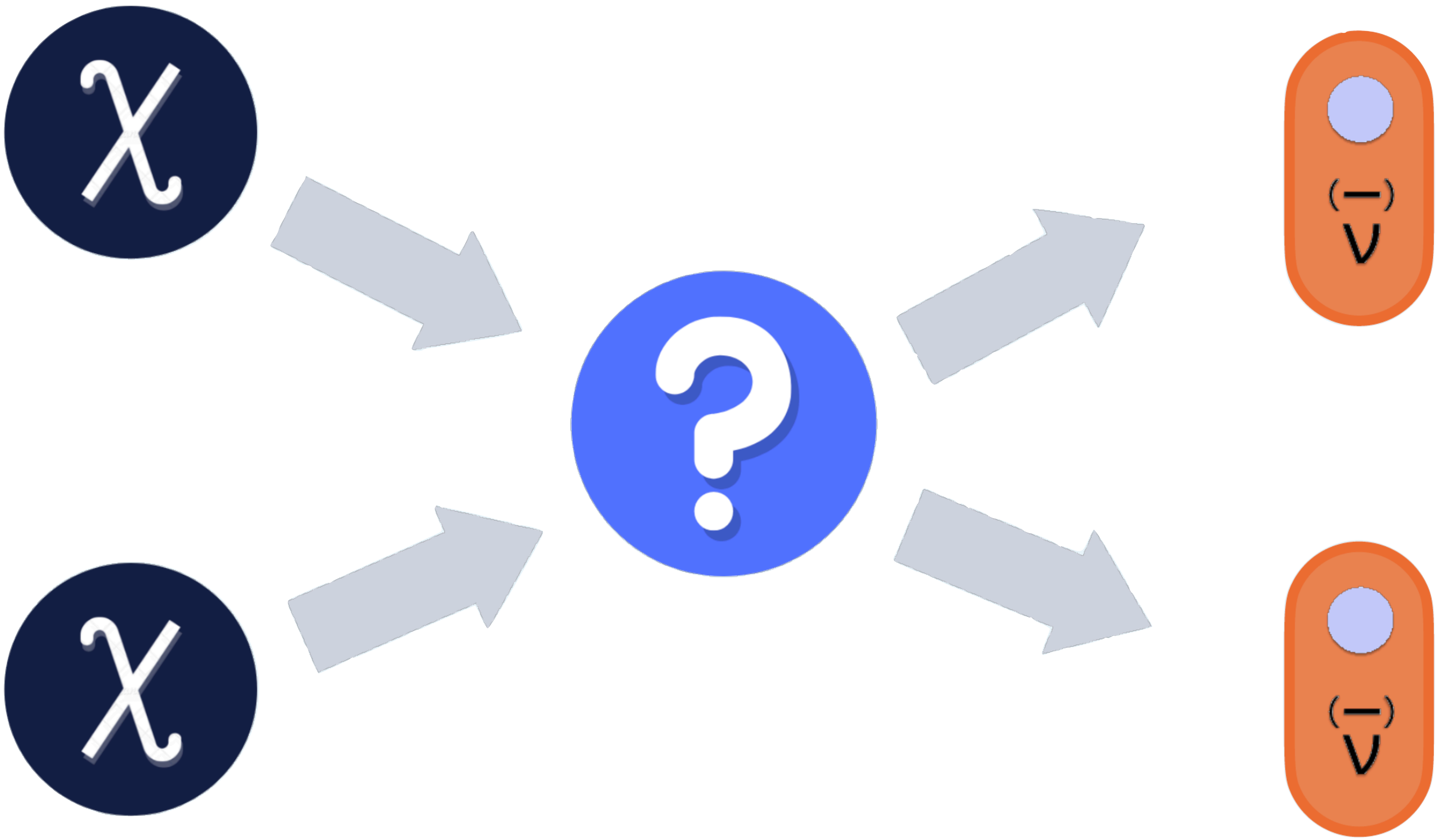




IceCube Collaboration 2205.12950.

See also CA, H. Dujmovic arXiv 1907.11193, Dekker et al 1910.12917; Chianese et al. 1907.11222; Sui & Bhupal Dev 1804.04919; Feldstein et al 1303.7320; Murase et al 1503.04663, Murase & Beacom 1206.2595 …

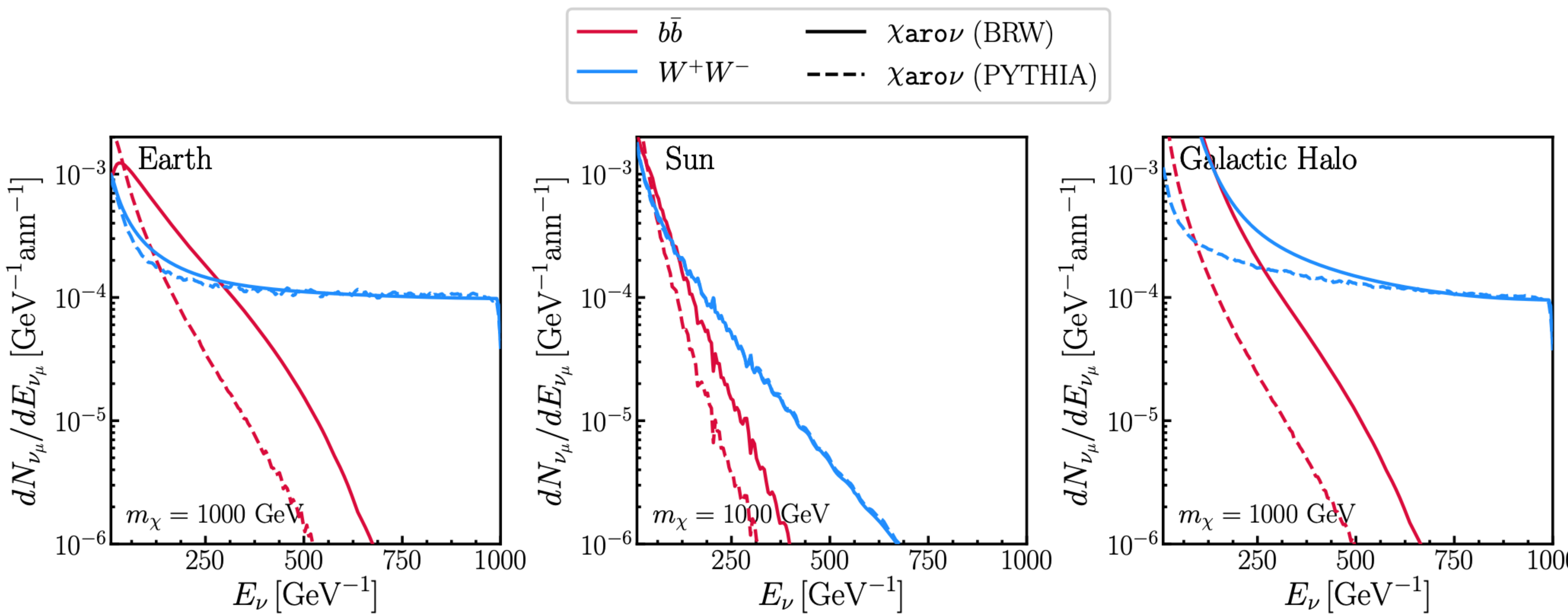
WIMP Miracle:
The final frontier



To rule out the WIMP miracle in a "model independent way"
one needs to constraint all SM annihilation channels.

For good limits, we need good predictions!

https://github.com/IceCubeOpenSource/charon

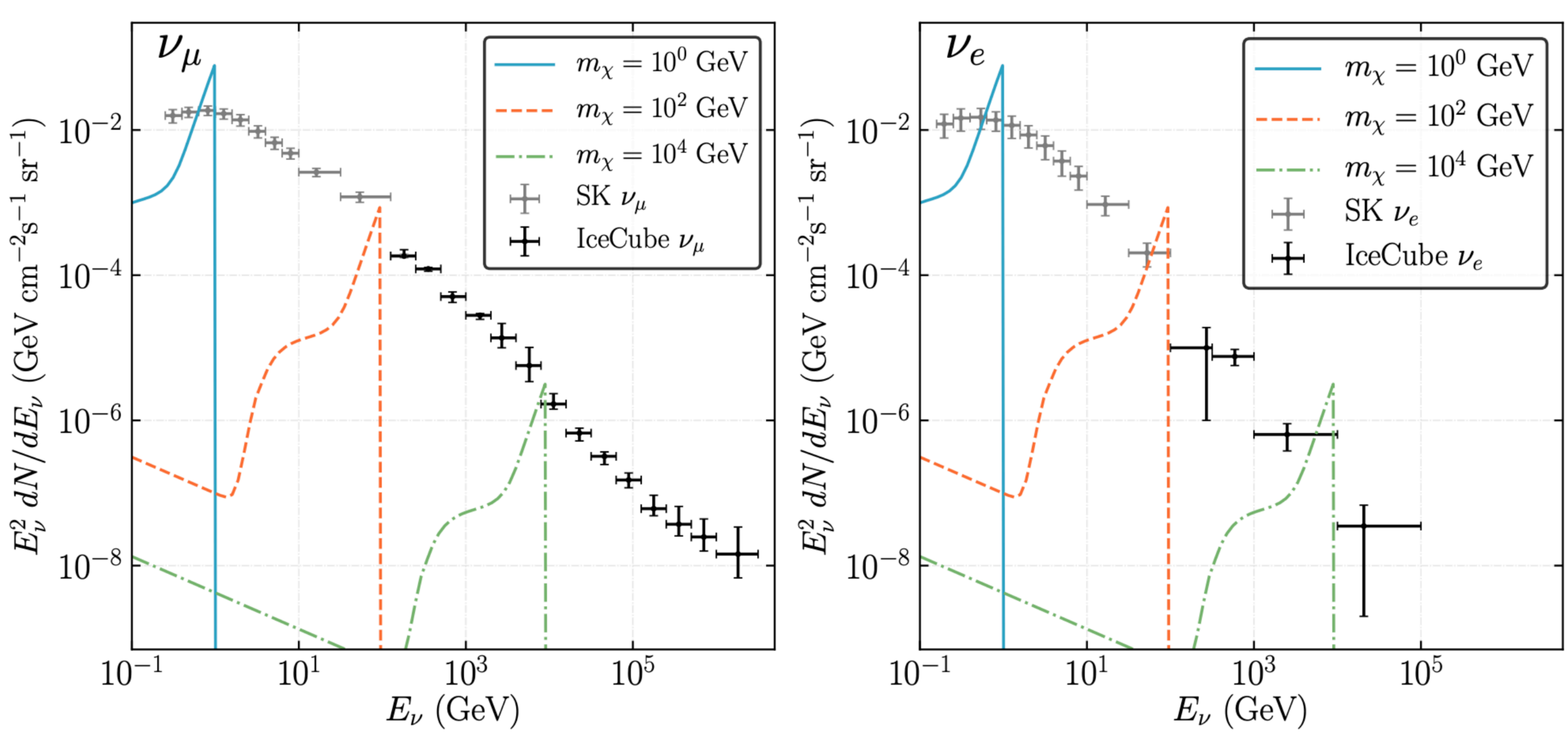


IceCube results with updated calculations to appear soon!

Q. Liu & J. Lazar *et al* 2007.15010

Bauer, Rodd & Webber *et al* 2007.15001

Background agnostic constraints on Dark matter making neutrinos



ARGÜELLES, ET AL., REV. MOD. PHYS. 93, ARXIV:1912.09486

Background Agnostic $\Rightarrow \mathscr{L} = \begin{cases} \mathbb{P}(d\,|\,\mu) & (d < \mu), \\ 1 & (d \geq \mu) \end{cases}$

RICHARD, F., ET AL. (SUPER-KAMIOKANDE) PHYS. REV. D94 (5), 052001

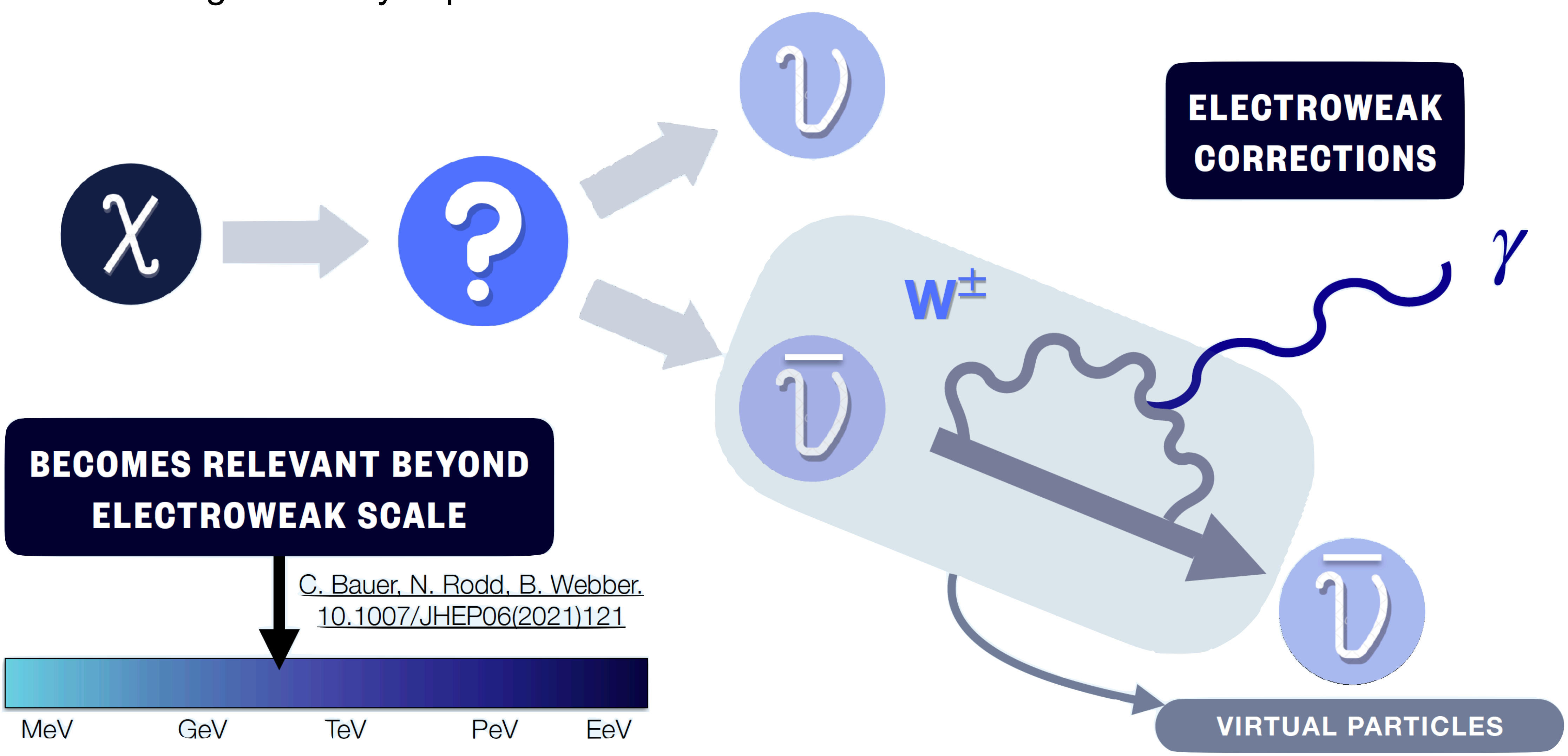
AARTSEN, M. G., ET AL. (ICECUBE) (2015B), PHYS. REV. D91, 122004

Flux of neutrinos from dark matter cannot overshoot measurements of the integrated neutrino flux.

$10^{-1} - 10^{2}$	Fermi-LAT [63]	γ
$10^{3} - 10^{9}$	*CTA* [64]	γ
$10^{4} - 10^{9}$	HAWC [65]	γ
$10^{5} - 10^{9}$	LHAASO [66]	γ
$10^{6} - 10^{9}$	IceTop [67]	γ
$10^{7} - 2 \times 10^{9}$	KASCADE [68]	γ
$10^{8} - 2 \times 10^{10}$	CASA-MIA [69]	γ
$10^{9} - 2 \times 10^{12}$	EAS-MSU [70]	γ
$10^{11.5} - 10^{14}$	TA-SD [71]	γ
$> 10^{12}$	Auger-SD [72]	γ

Gamma-ray experiments will have correlated signals

I will discuss these gamma-ray experiments too!



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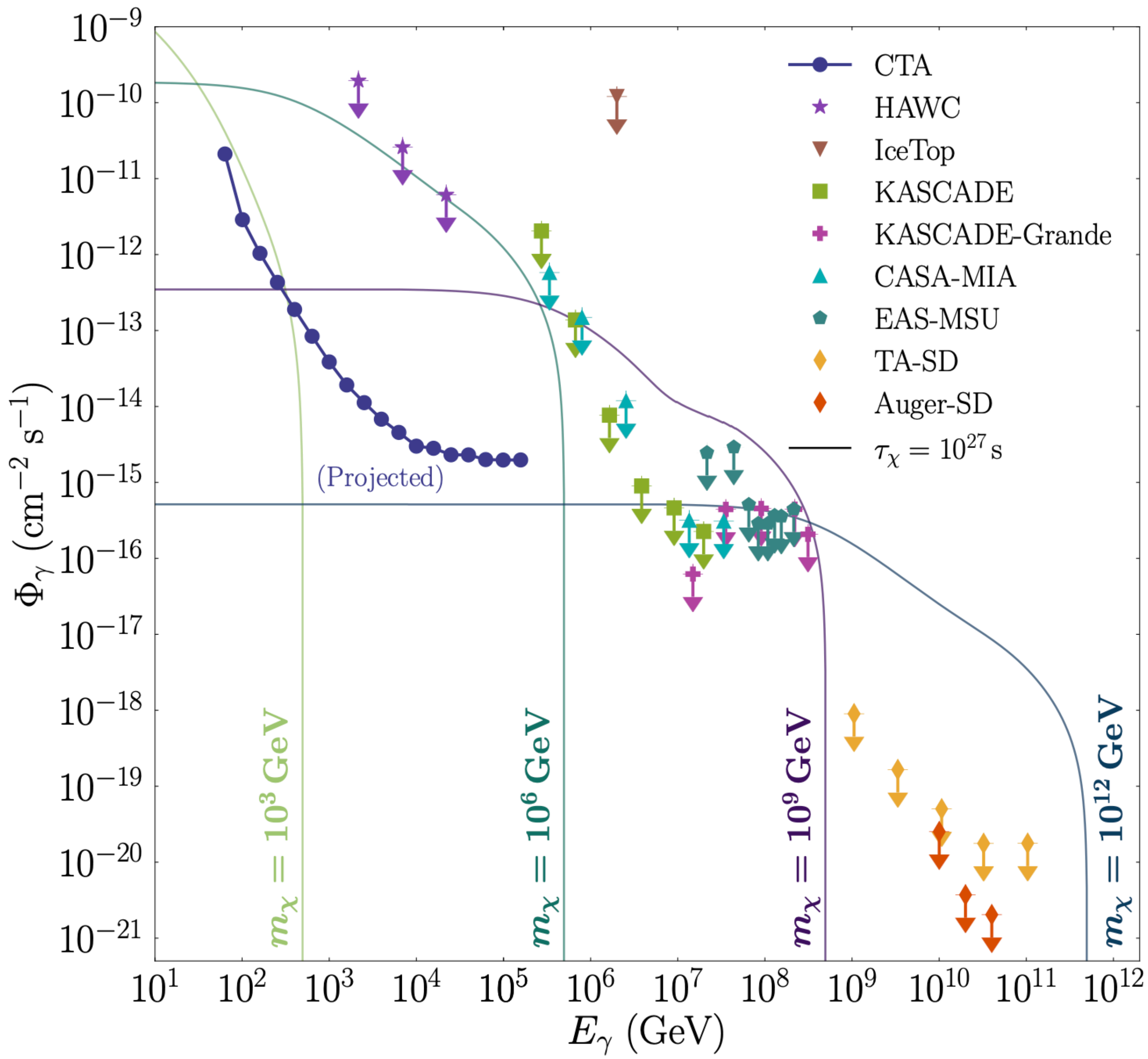
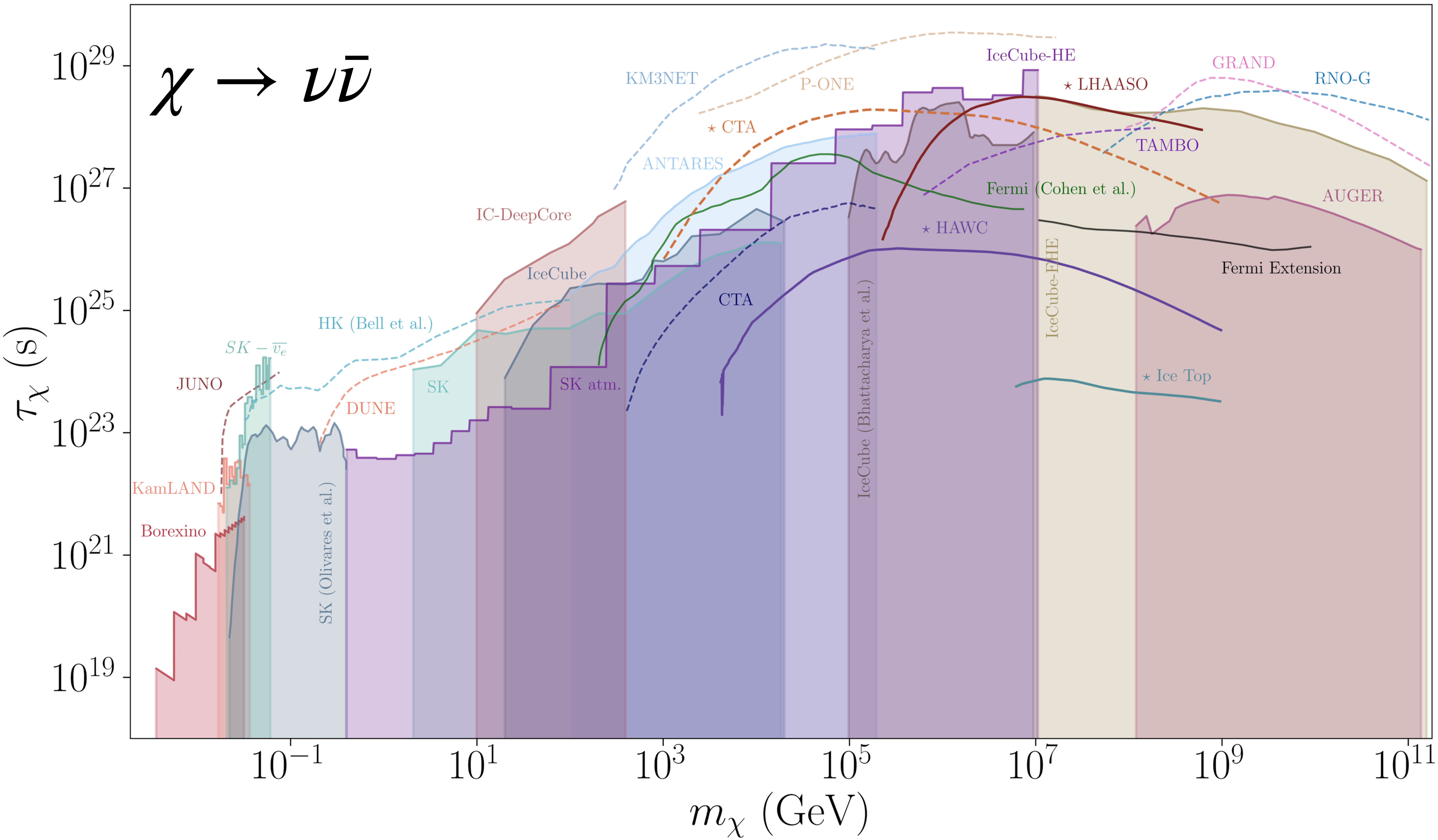


Associated gamma-ray flux should also not overshoot constraints

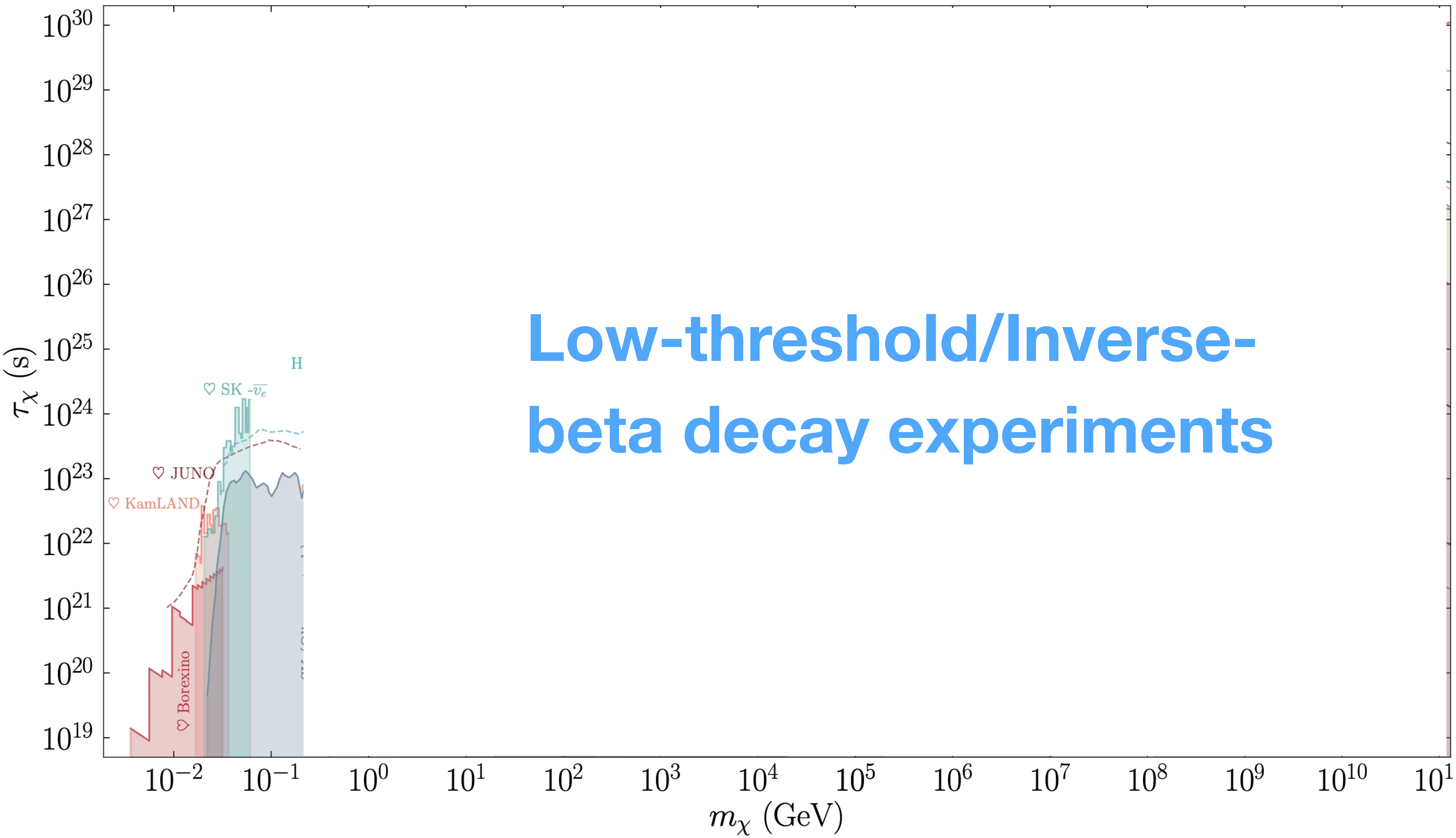
CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

And many more measurements ...



CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

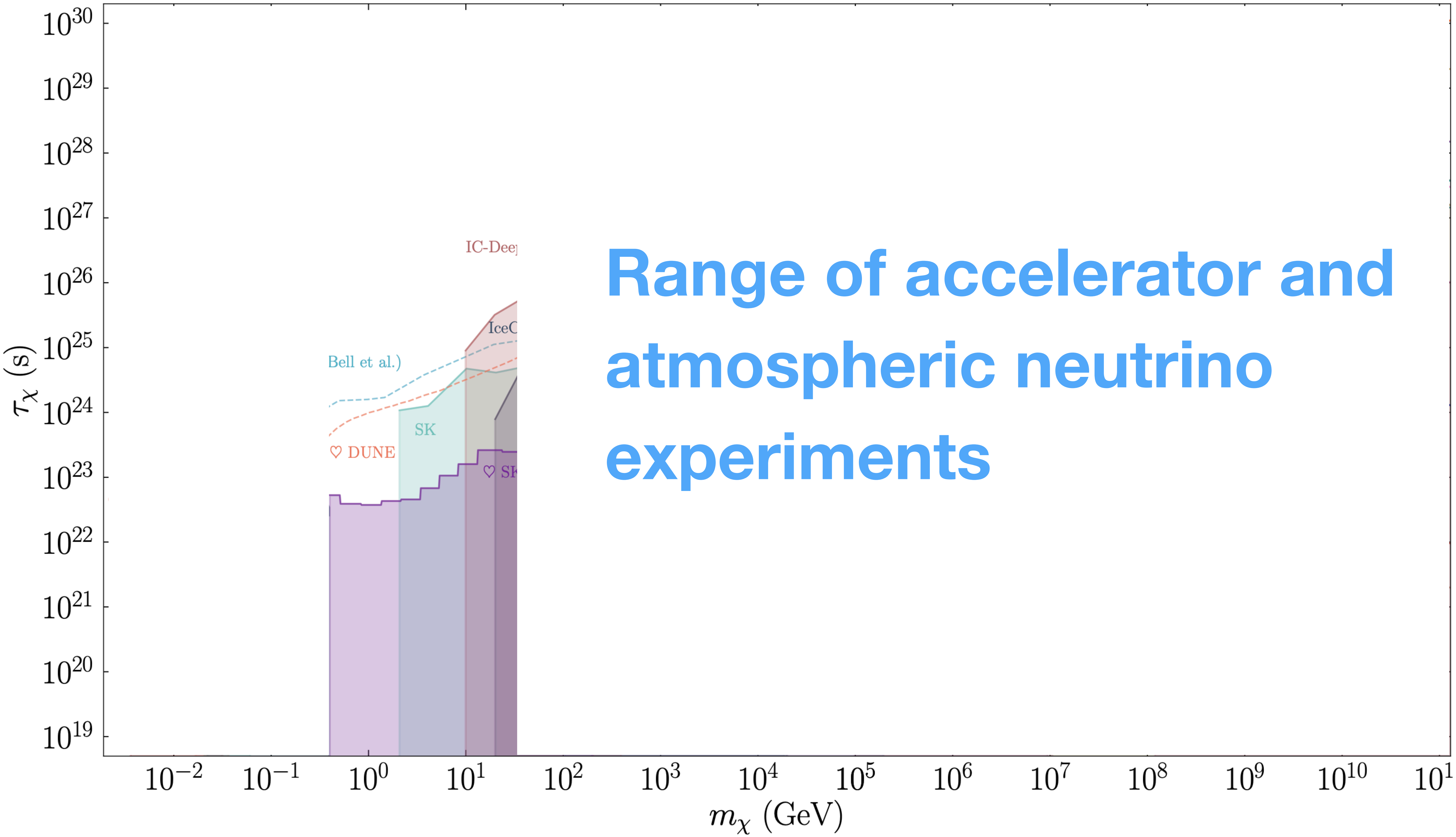
Constraints on dark matter decay to neutrinos



Low-threshold/Inverse-beta decay experiments

CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

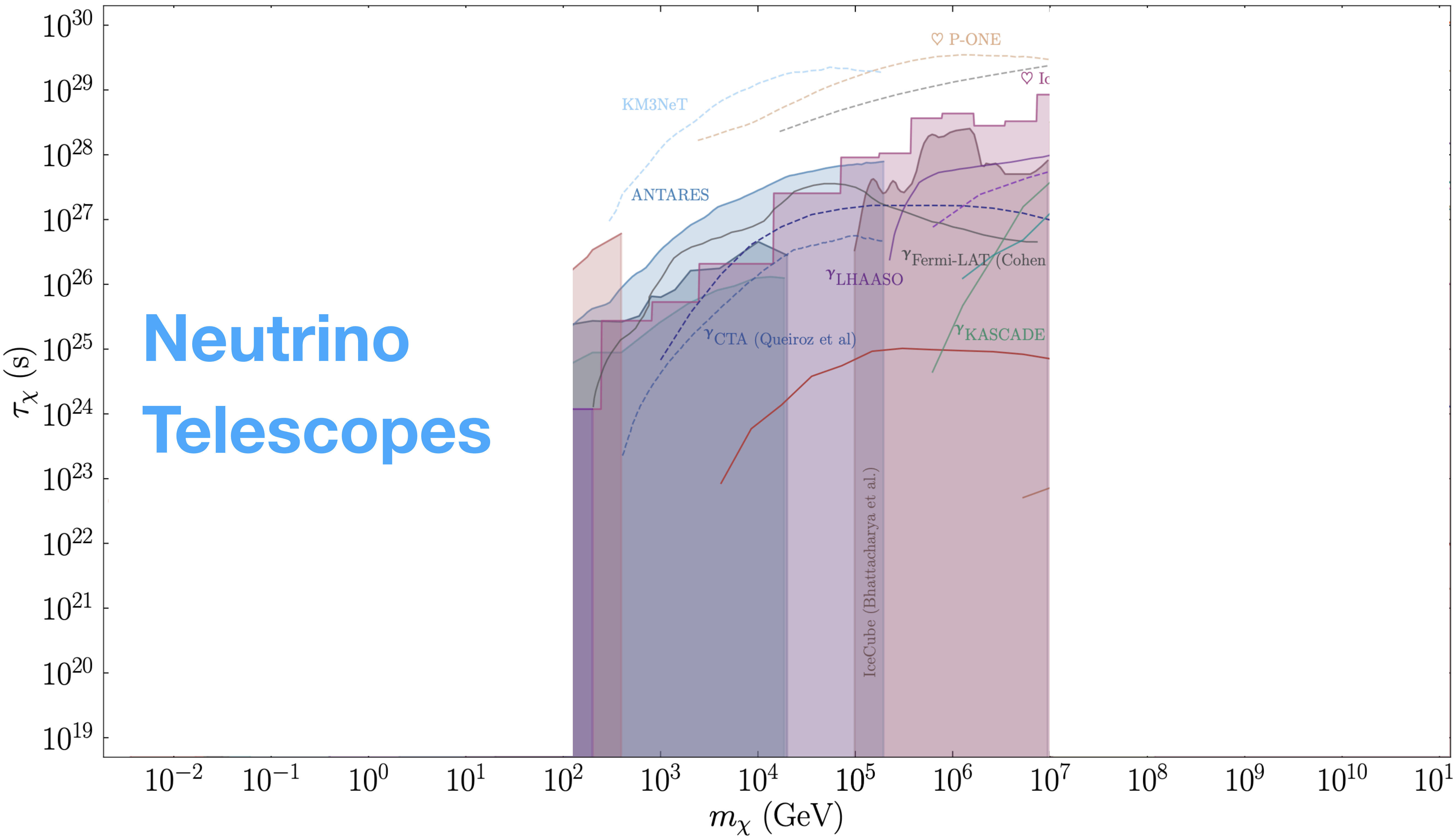
Constraints on dark matter decay to neutrinos



Range of accelerator and atmospheric neutrino experiments

CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

Constraints on dark matter decay to neutrinos



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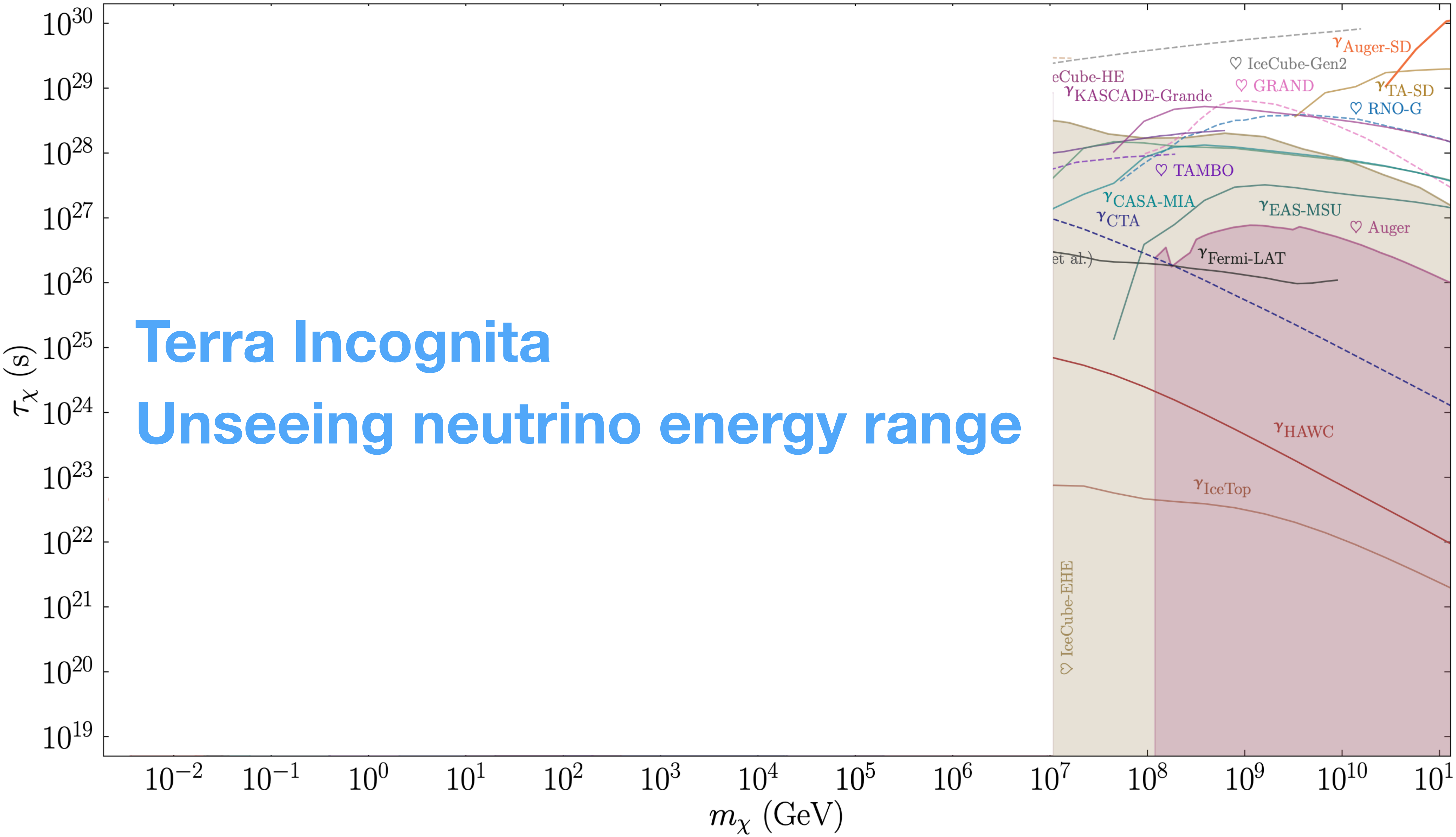

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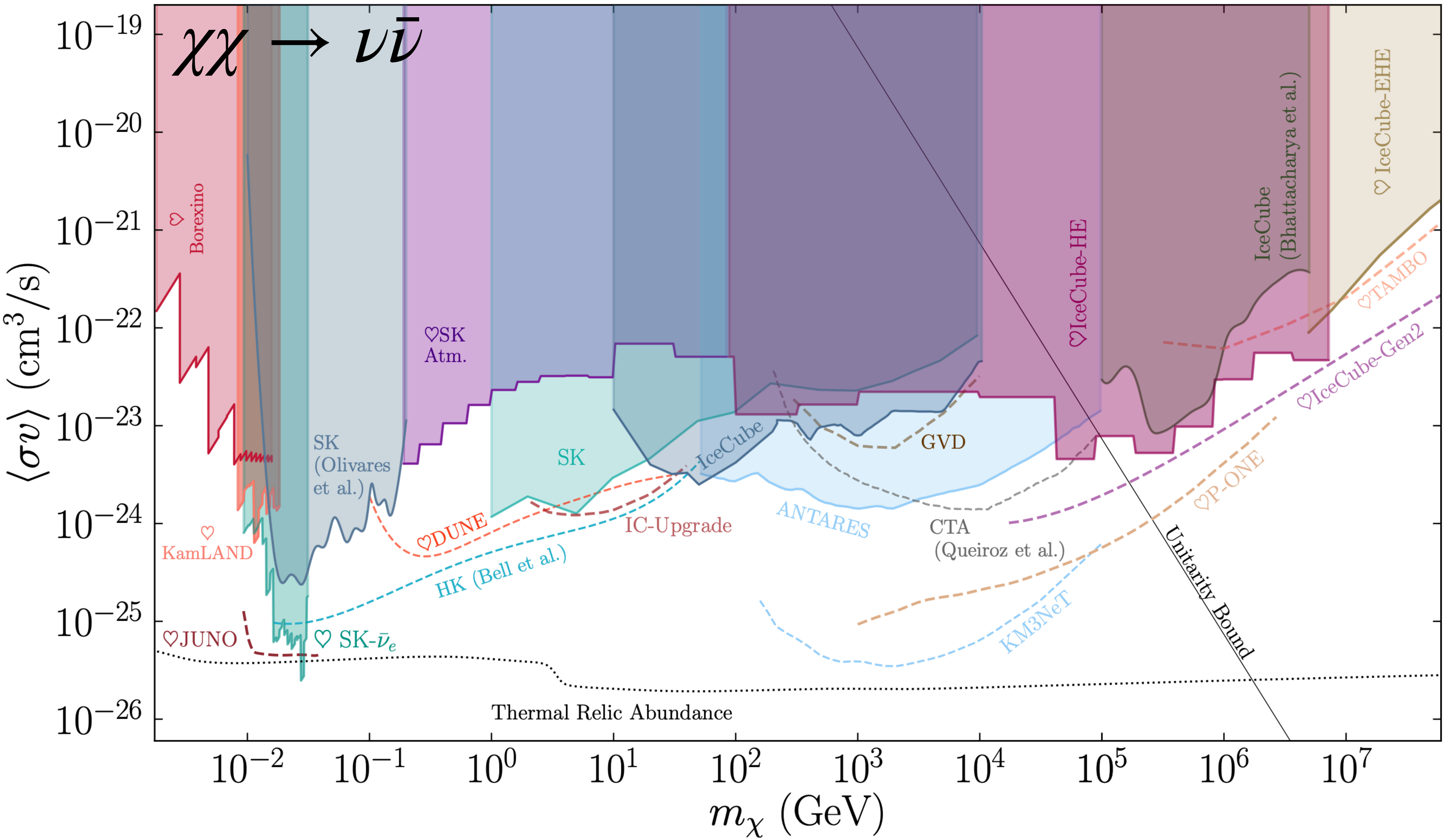
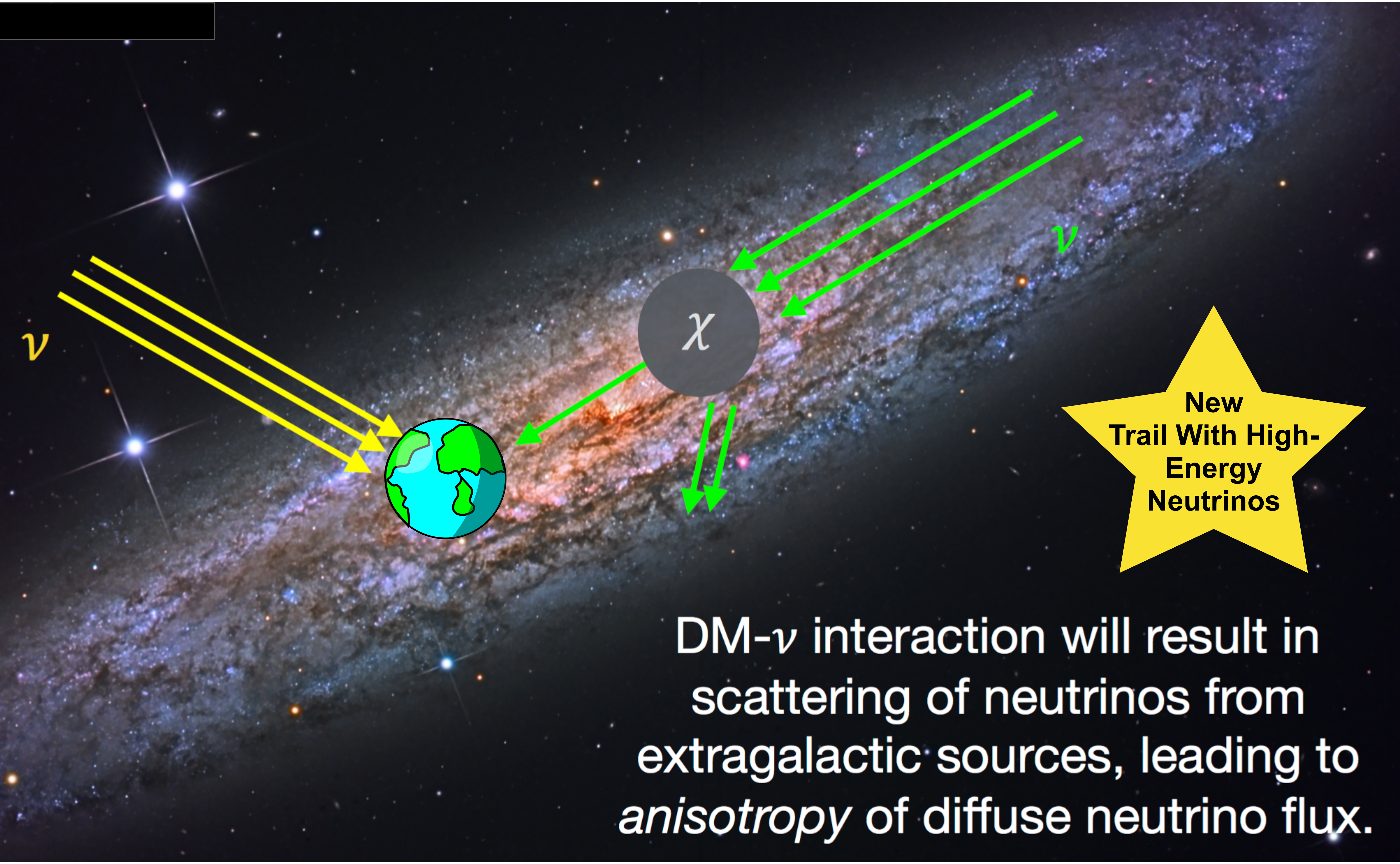


CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;

See also Beacom et al. *PRL 99: 231301, 2007.*

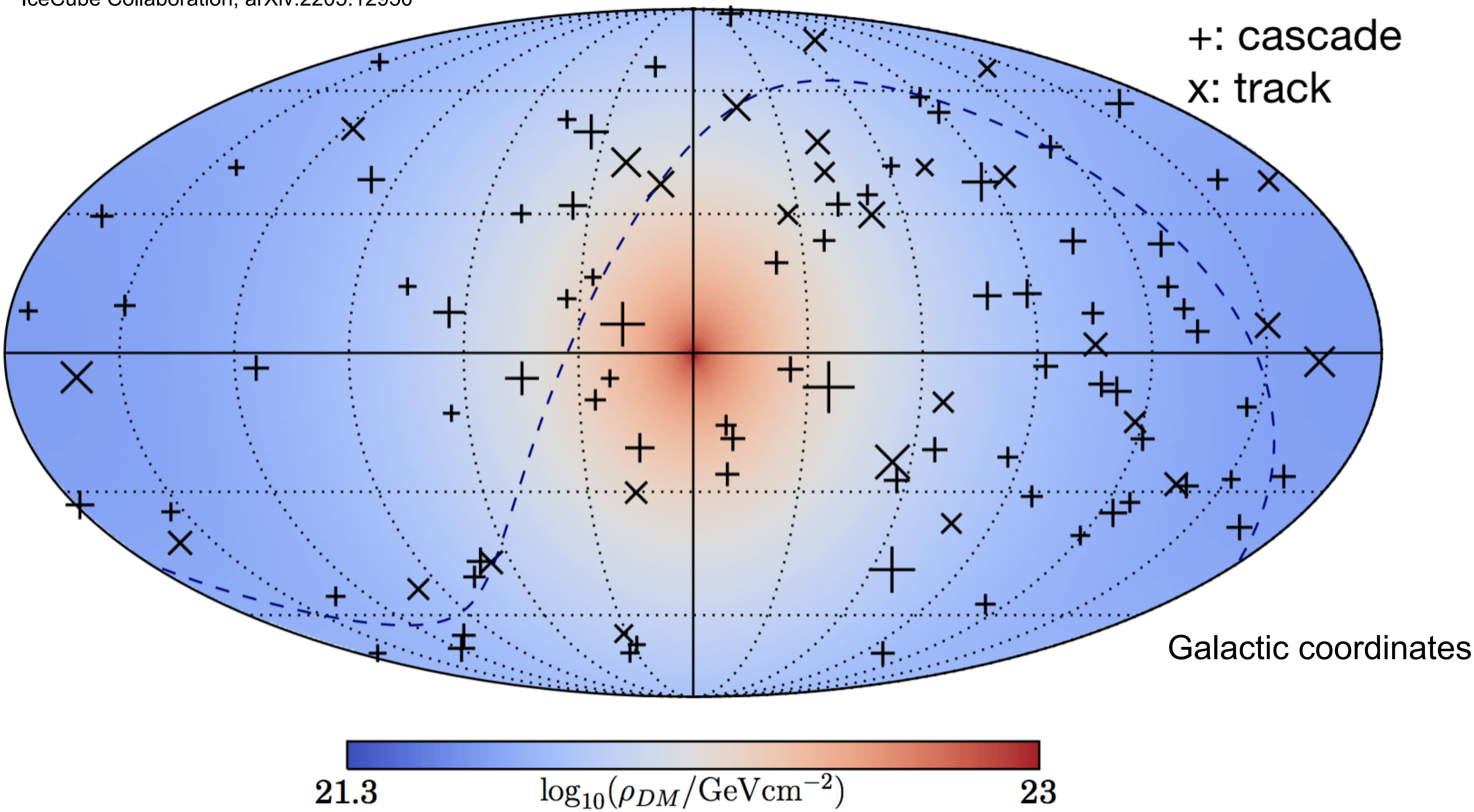
Dark matter neutrino incoherent **scattering**



CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

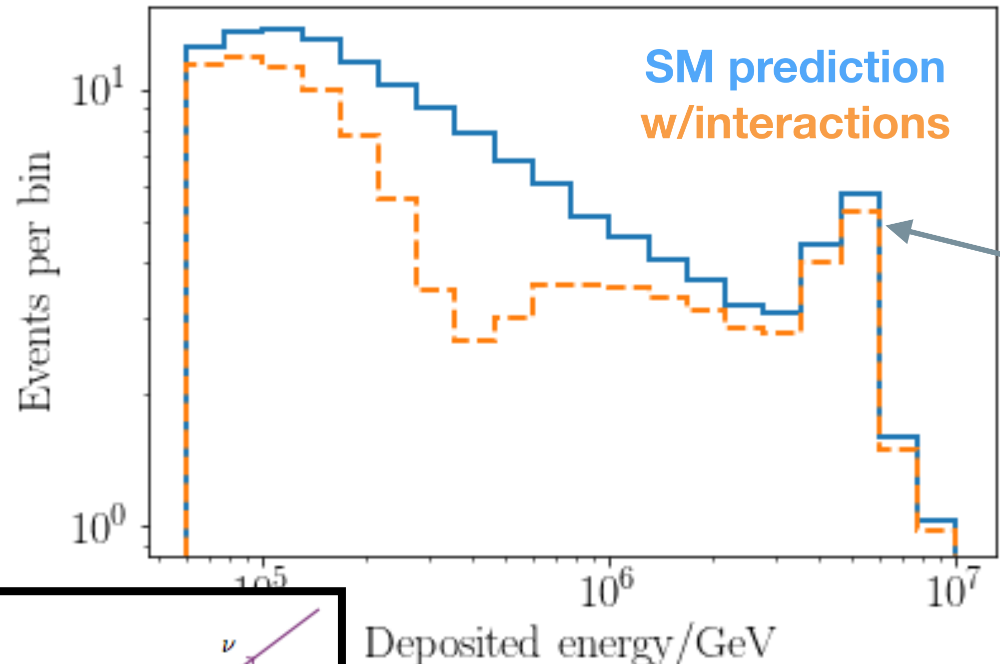
HESE Neutrino Skymap

HESE: high-energy starting events
IceCube Collaboration, arXiv:2205.12950

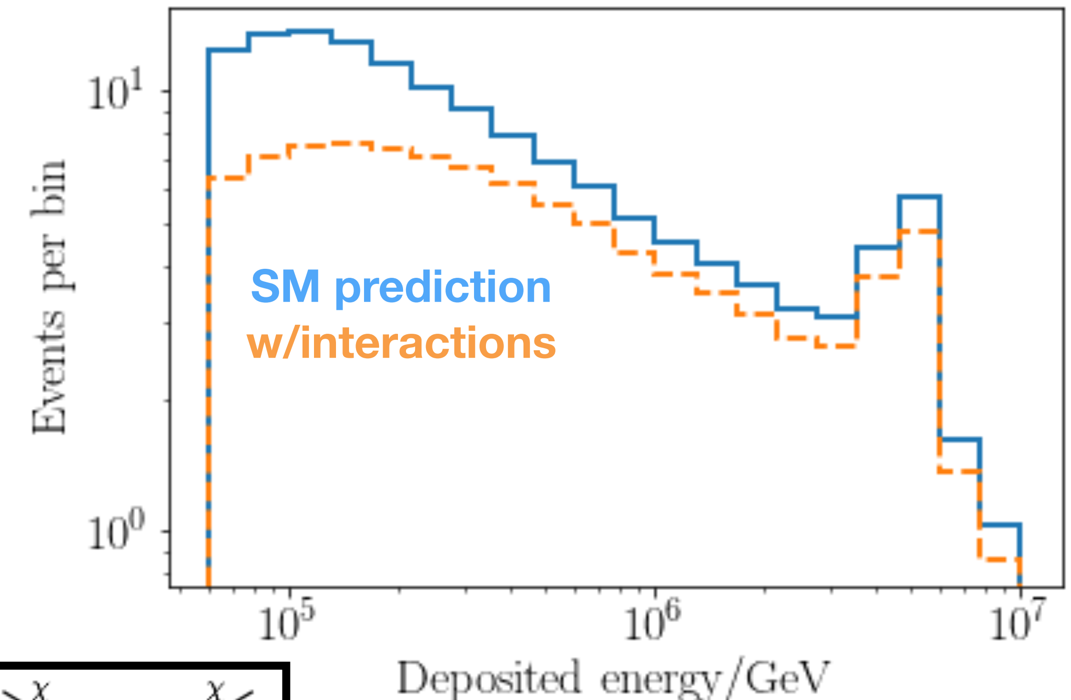


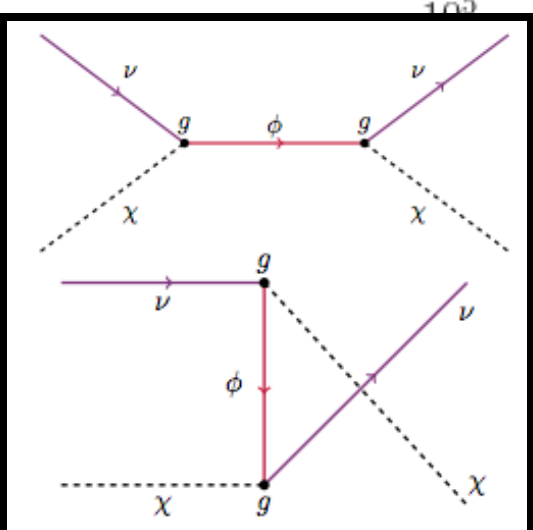
Events are compatible with an isotropic distribution: found no signal!

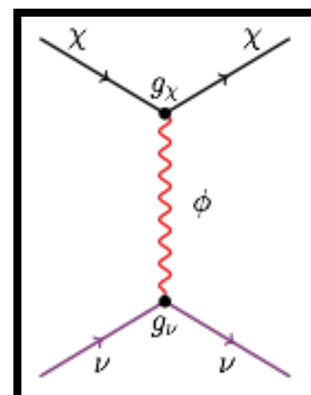
Also include effects in energy and direction

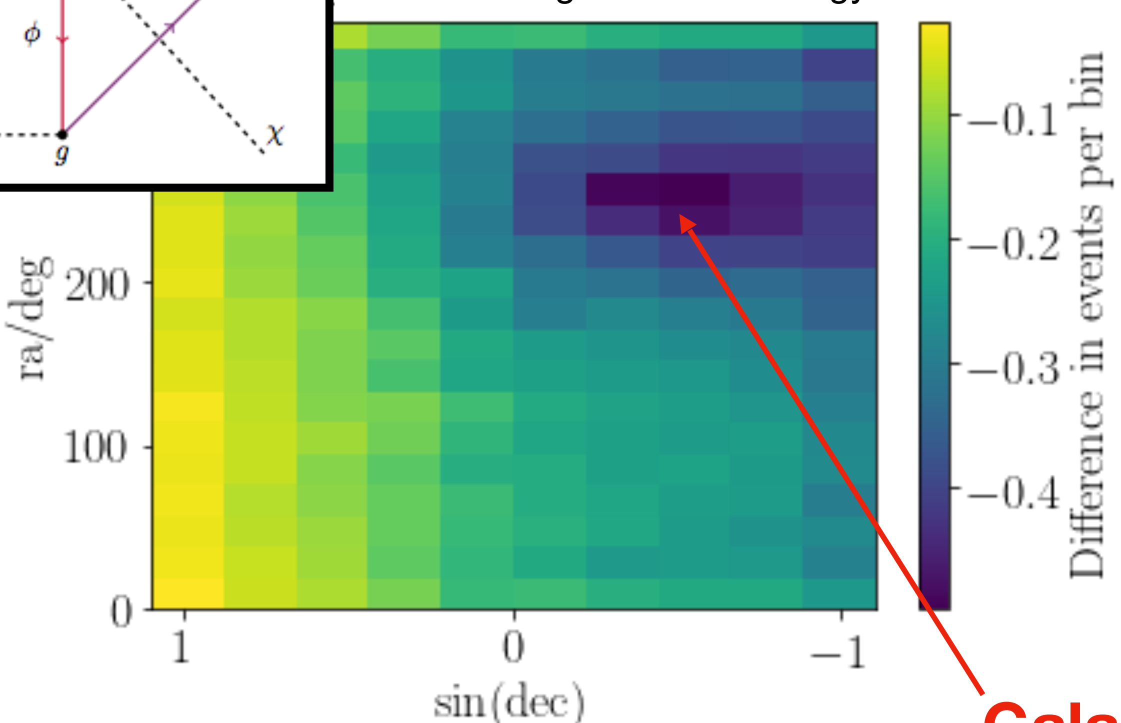


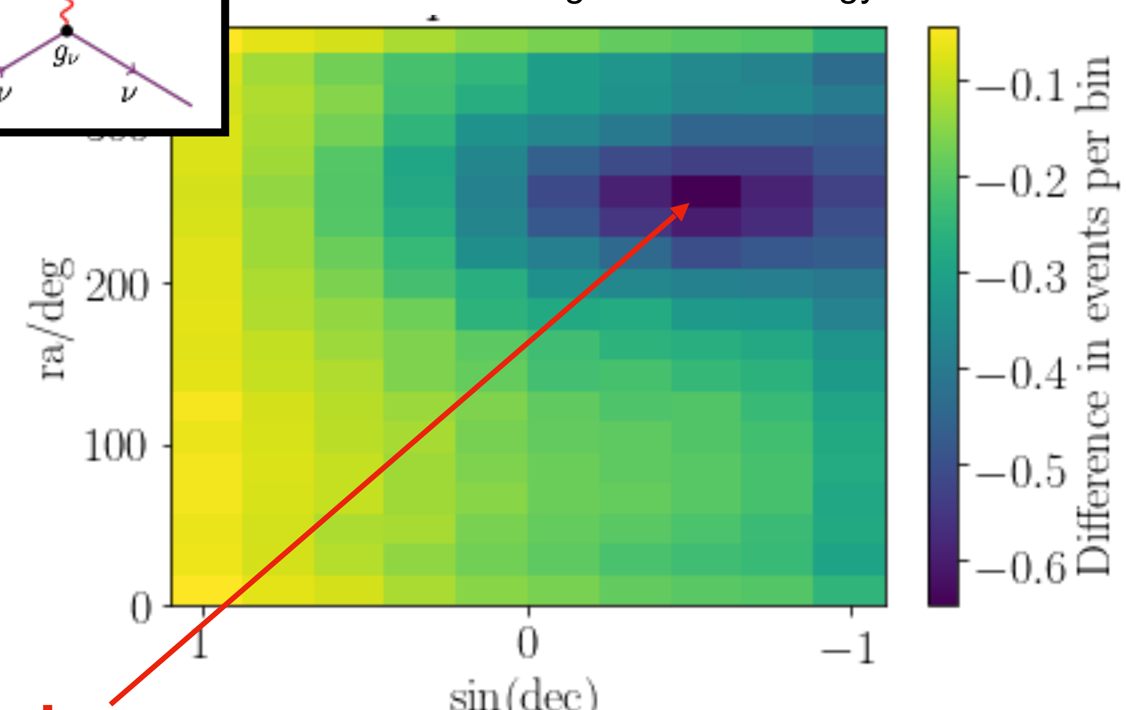
Glashow resonance





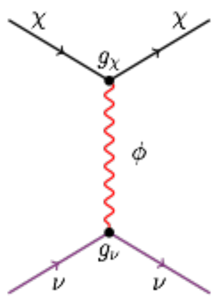




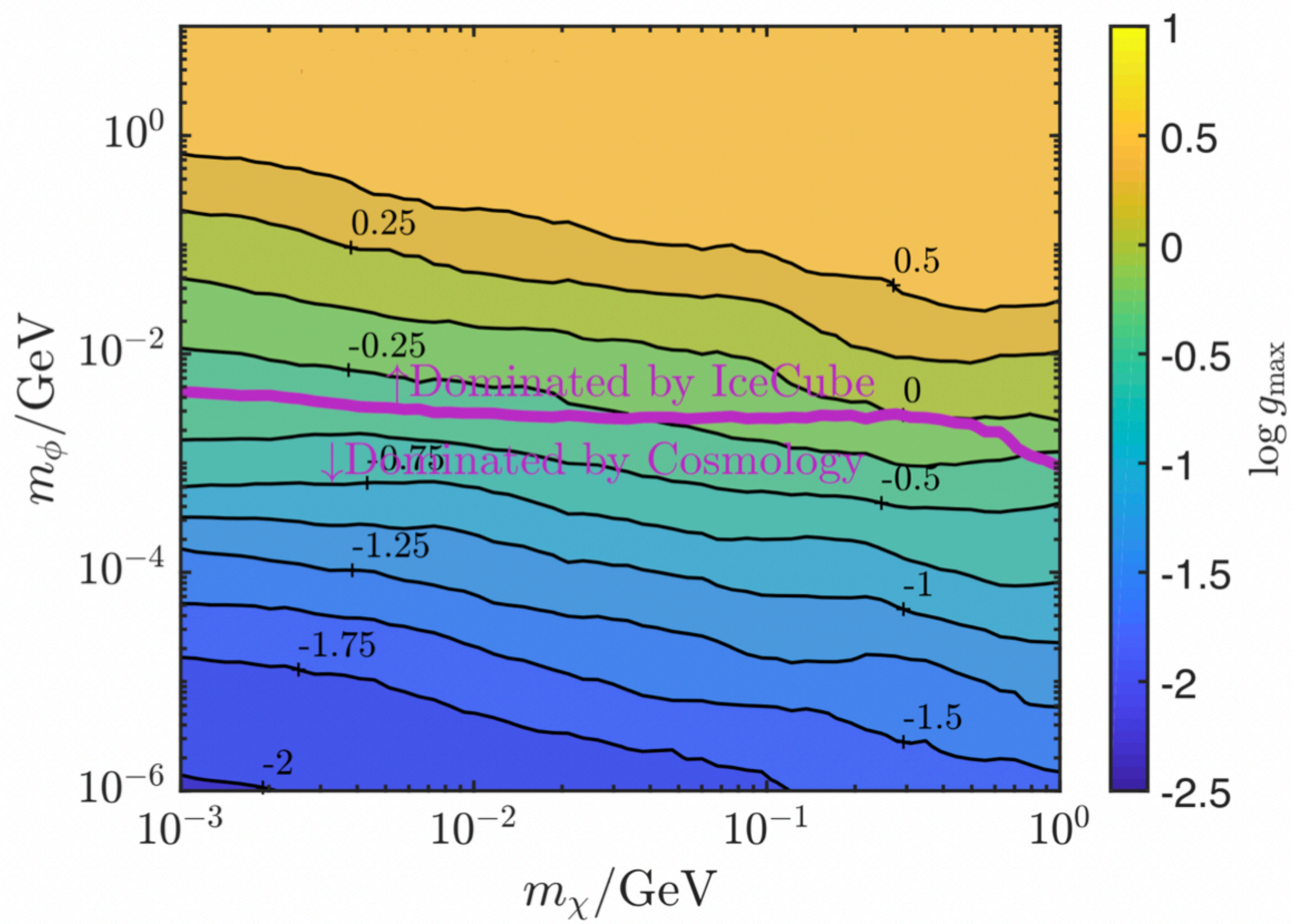


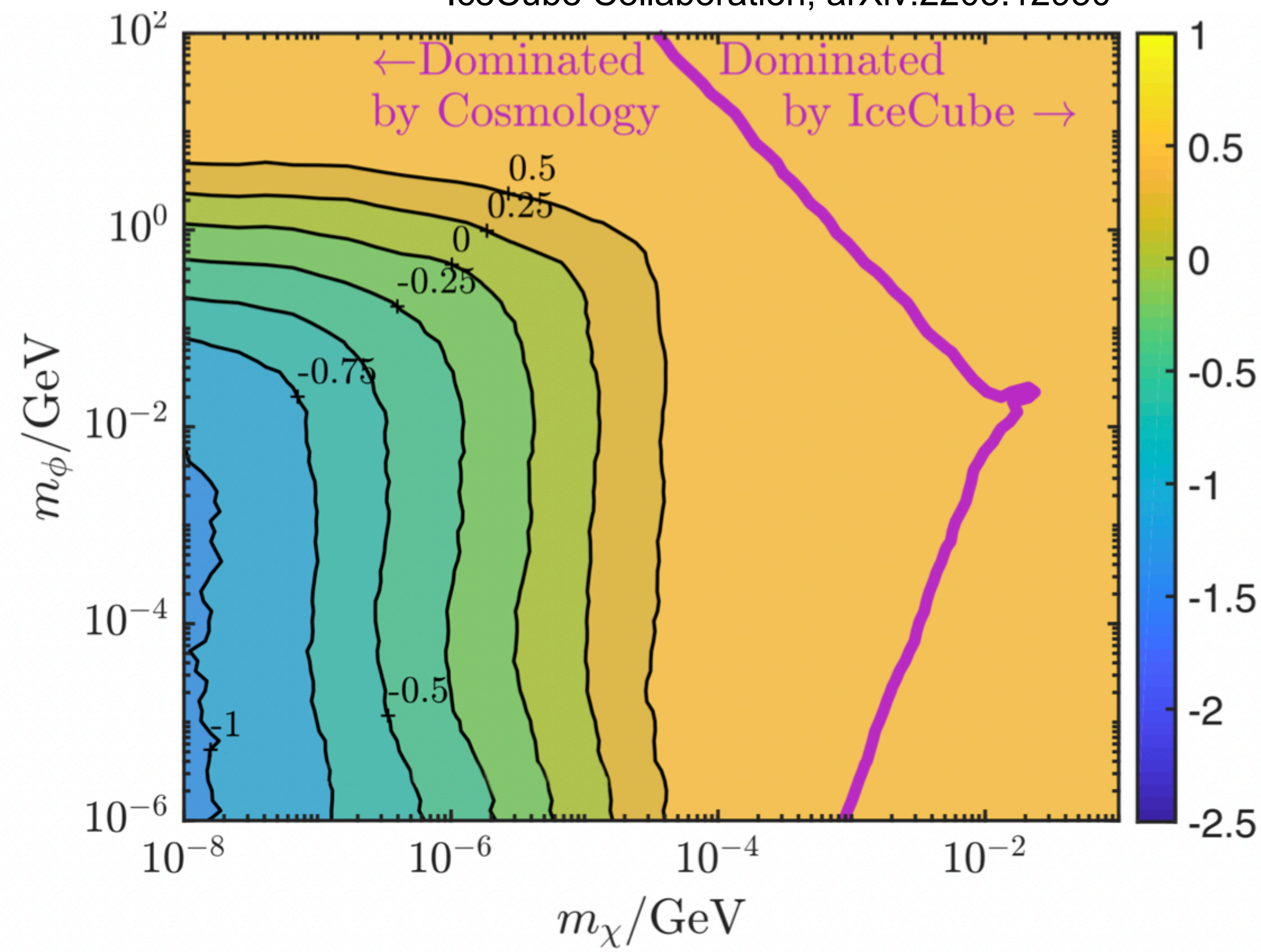
Galactic center

New constraints on neutrino-dark matter interactions



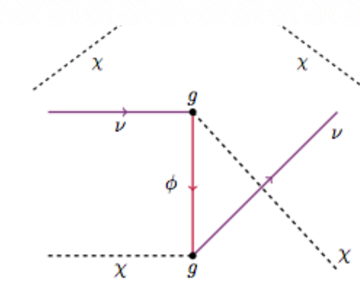
IceCube Collaboration, arXiv:2205.12950



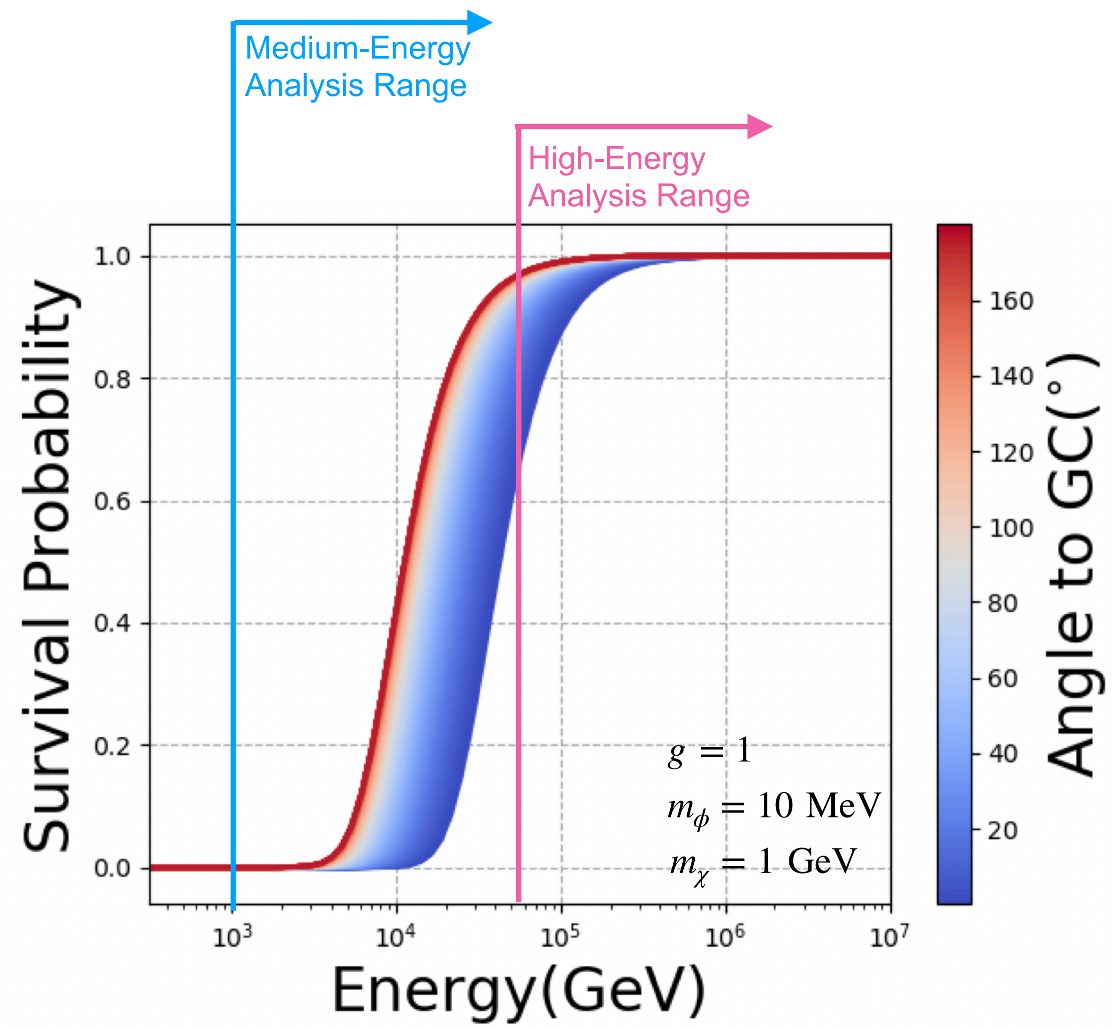


Color scale is the maximum allowed coupling.

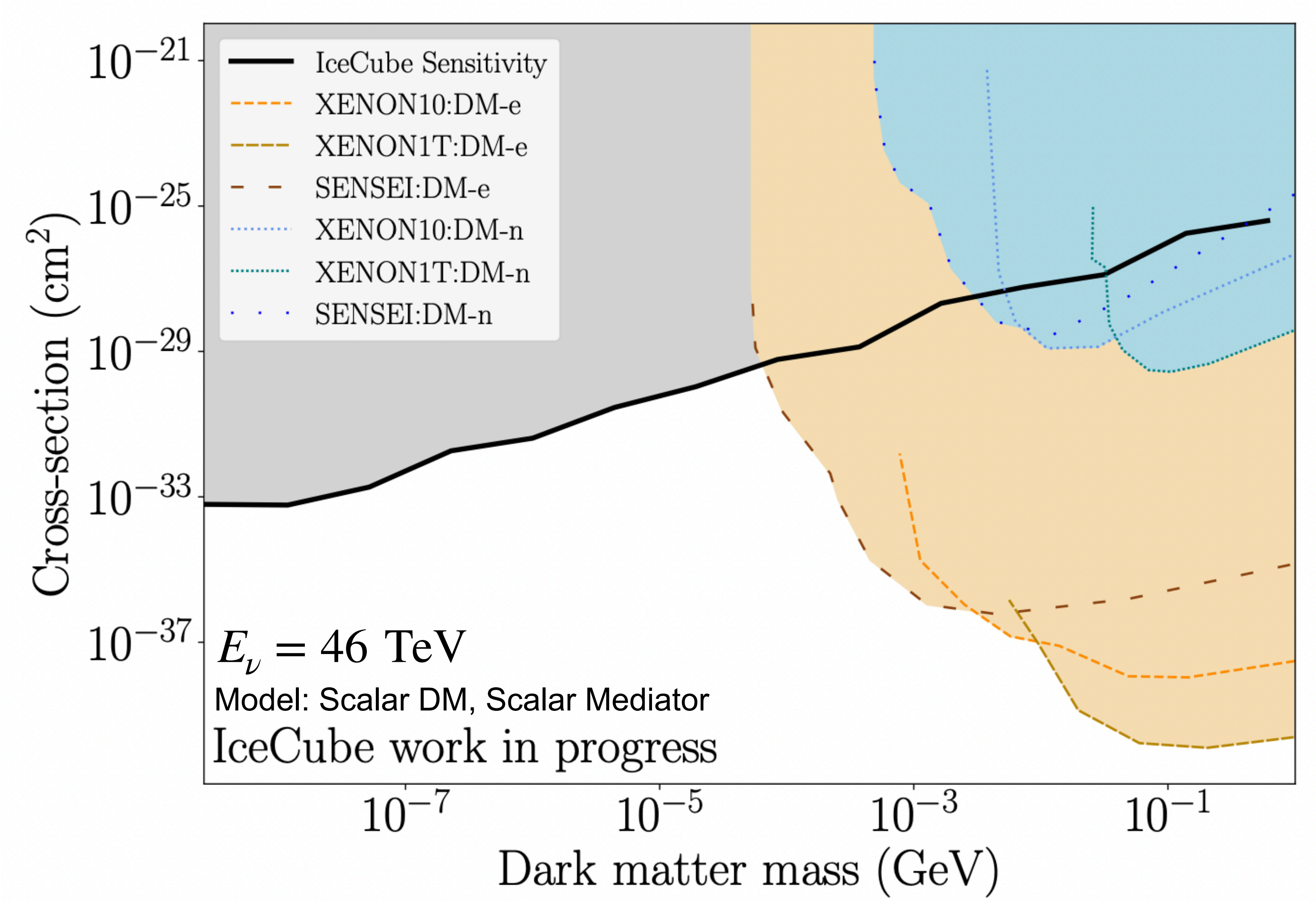
Cosmological bounds using Large Scale Structure from Escudero et al 2016



Second Generation Analyses Using Medium-Energy Starting Events



A. McMullen, A. Vincent, CA, A. Schneider arXiv:2107.11491

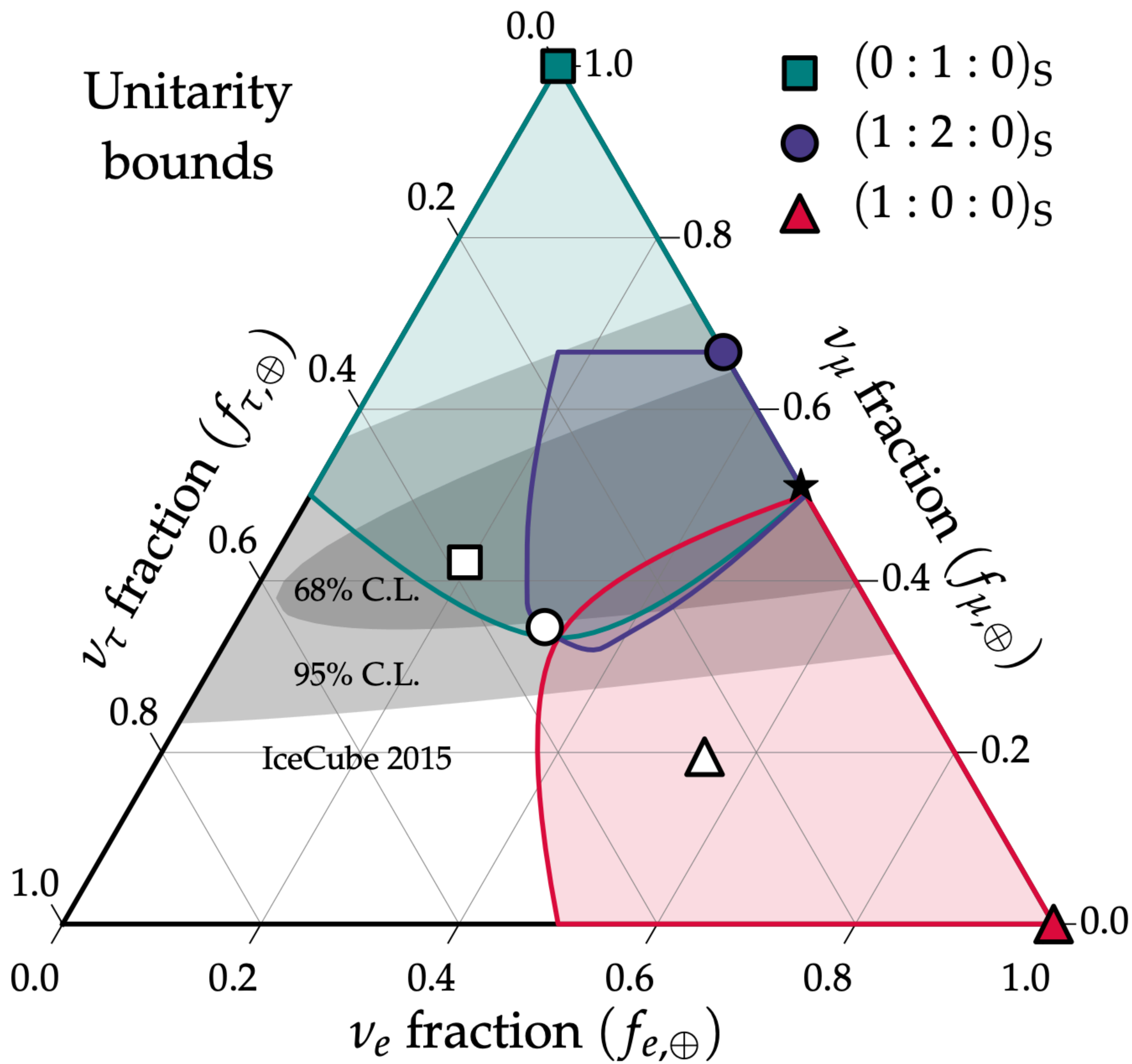


Larger sample sizes data sets yet to be used for these searches.
Only IceCube's High-Energy Starting Events used so far.

Stops

- A new frontier in the search for dark matter
- Using the flavor of neutrinos to find new physics
- New physics with new sources
- Anomalies and new physics at PeV-EeV

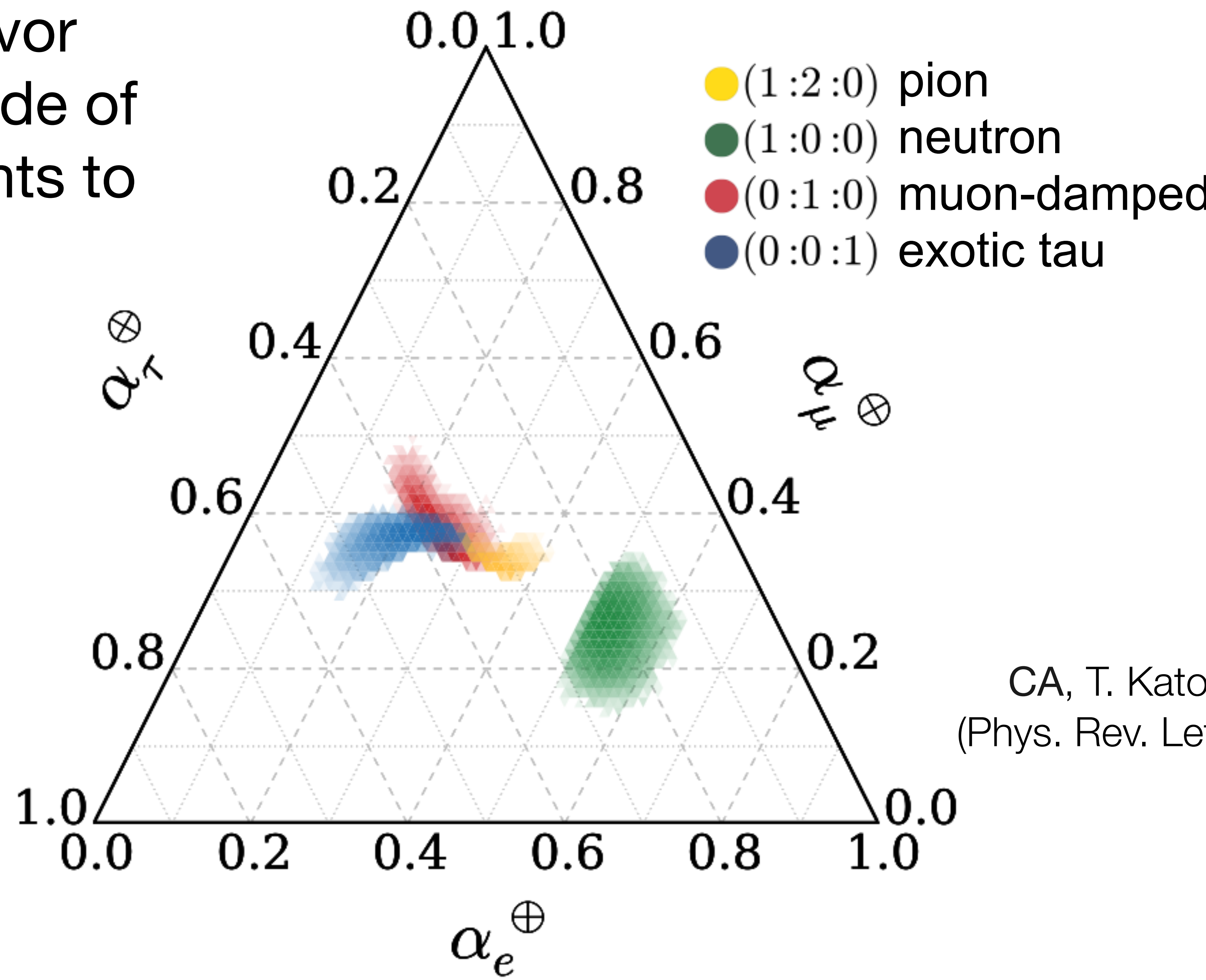
Unitarity



Ahlers, Bustamante, and Mu arXiv:1810.00893

After oscillations where will the different sources end up?

Measuring a flavor composition outside of these regions points to new physics!

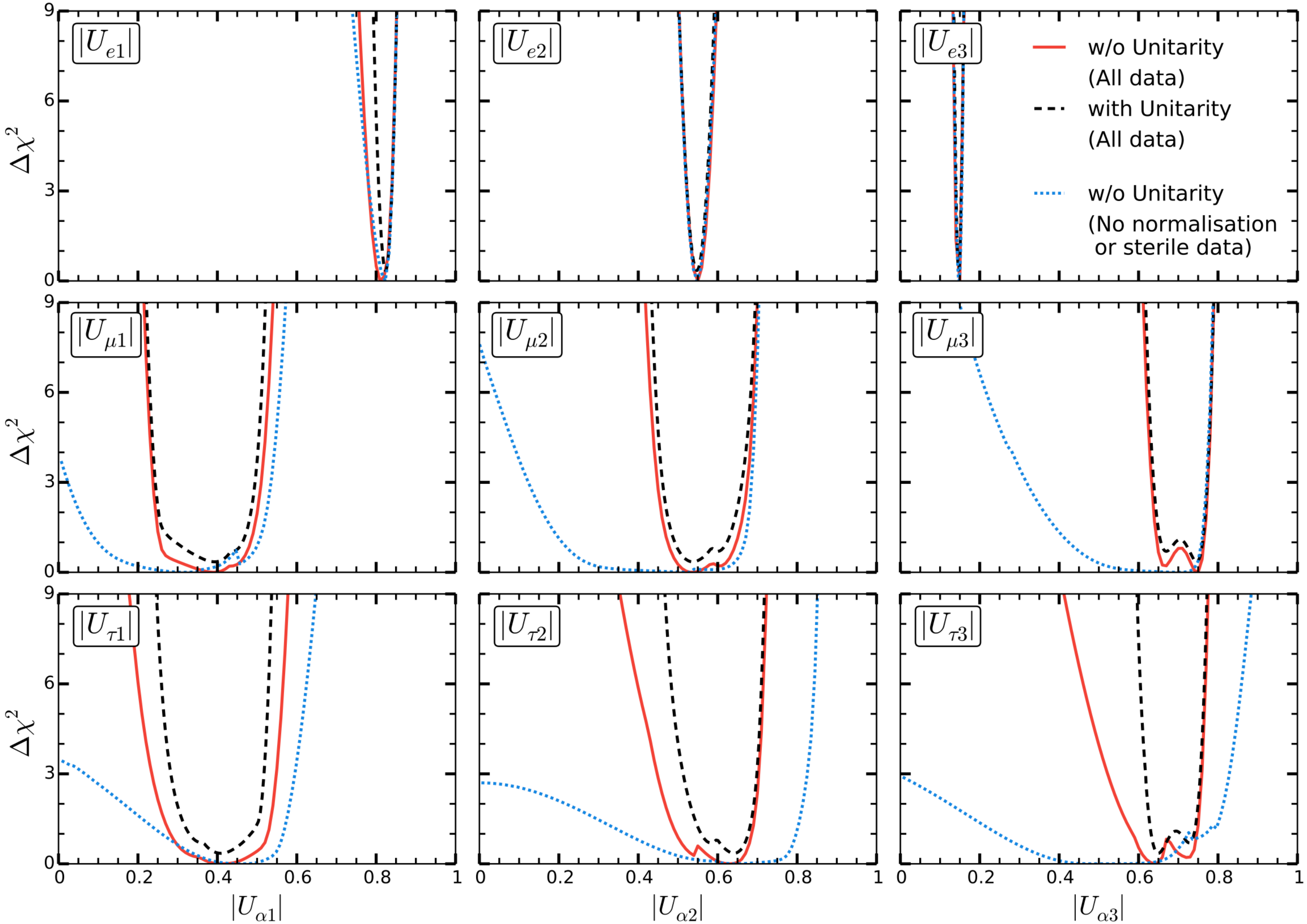


CA, T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

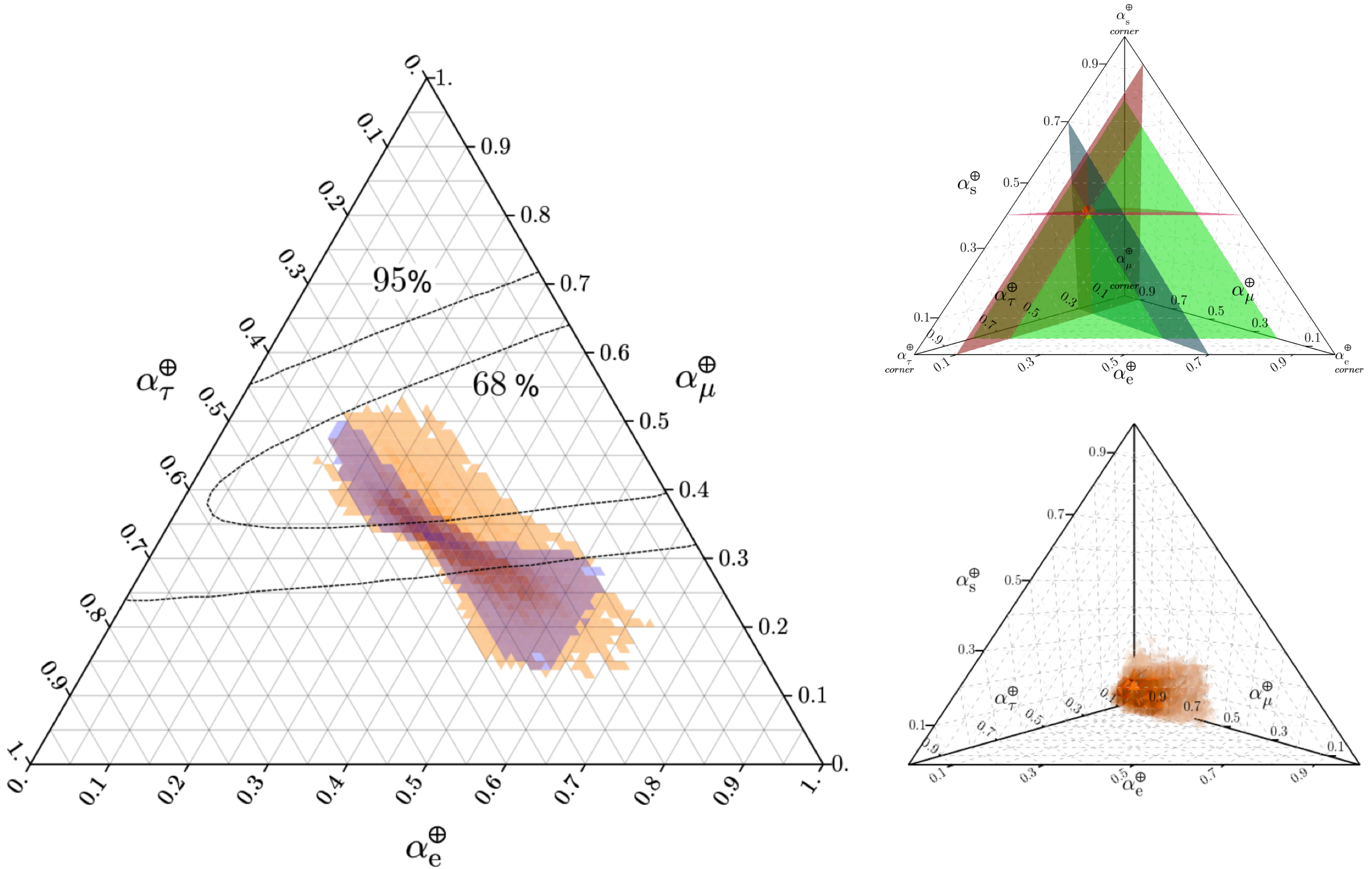
See also Bustamante et al. PRL 115, 161302 (2015); Rasmussen et al. 1707.07684; Palomares-Ruiz 1411.2998; Palladino et al 1502.02923; Bustamante et al 1610.02096; Brdar et al. 1611.04598; Farzan & Palomares-Ruiz 1810.00892; CA et al. 1909.05341; Learned & Pakvasa hep-ph/9405296 ..

Non-unitarity

Parke & Ross-Lonergan 1508.05095



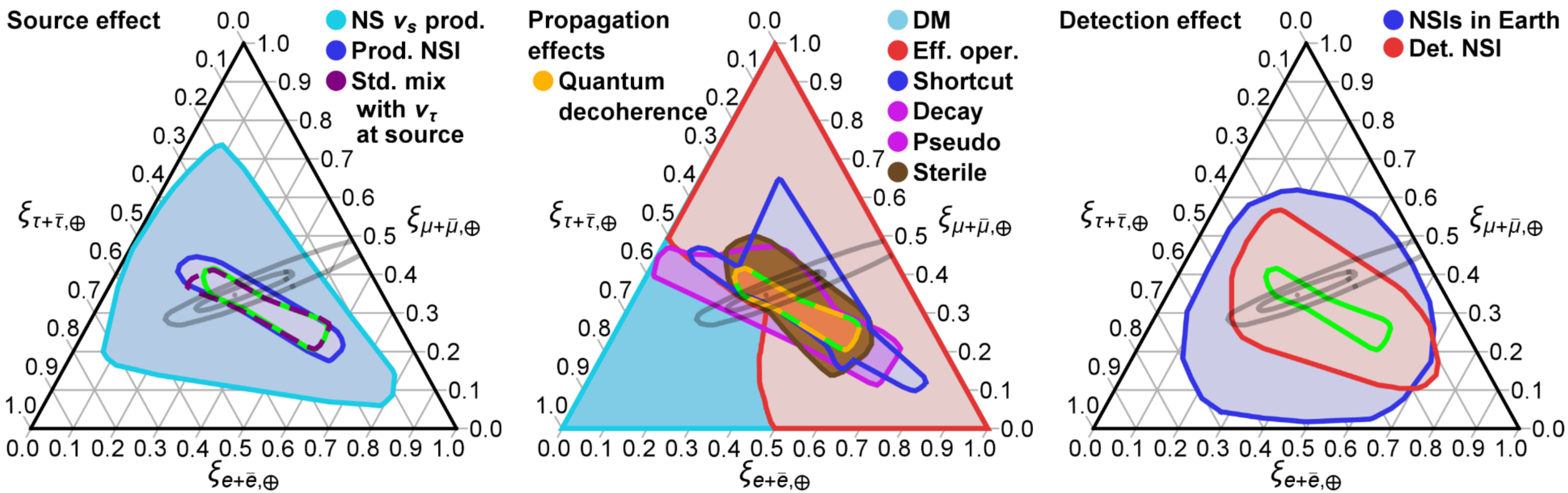
Non-unitarity



CA, Farrag, Katori, Khandelwal, Mandalia, Salvado arXiv:1909.05341

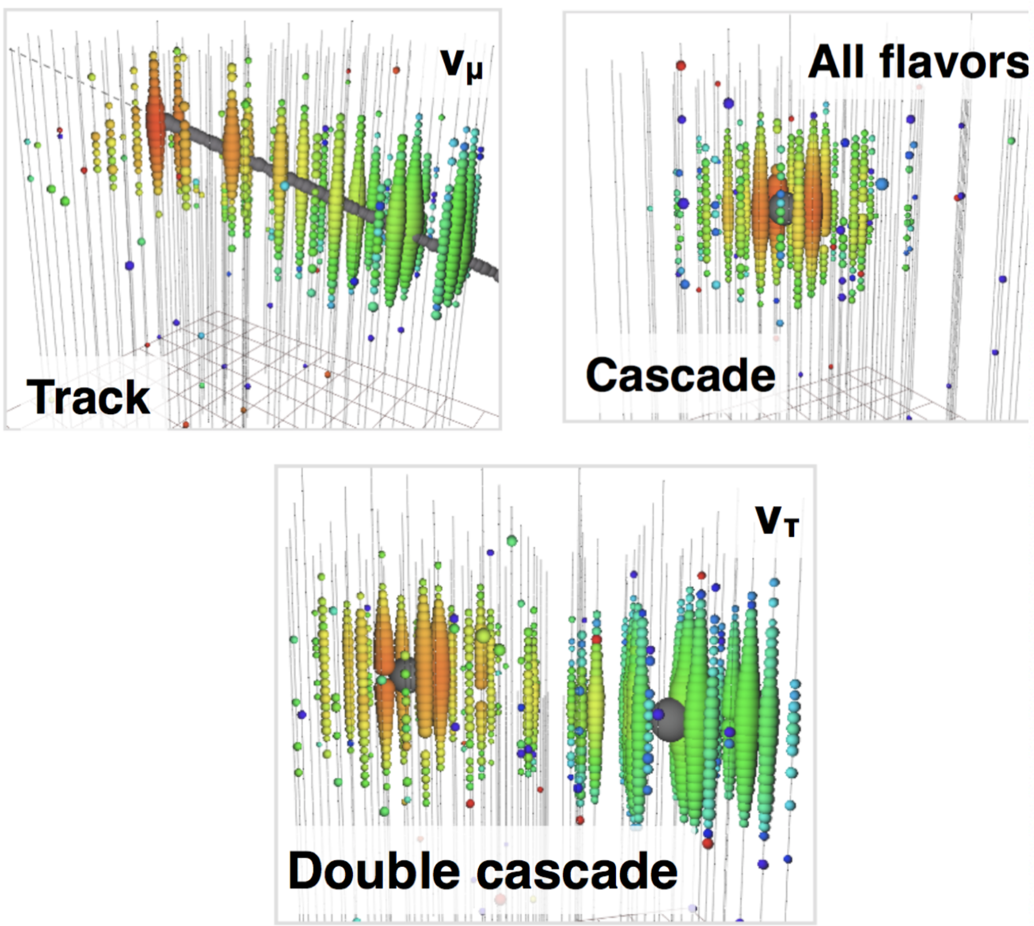
Other New Physics Effects on the Flavor Triangle

Rasmussen et al arXiv:1707.07684

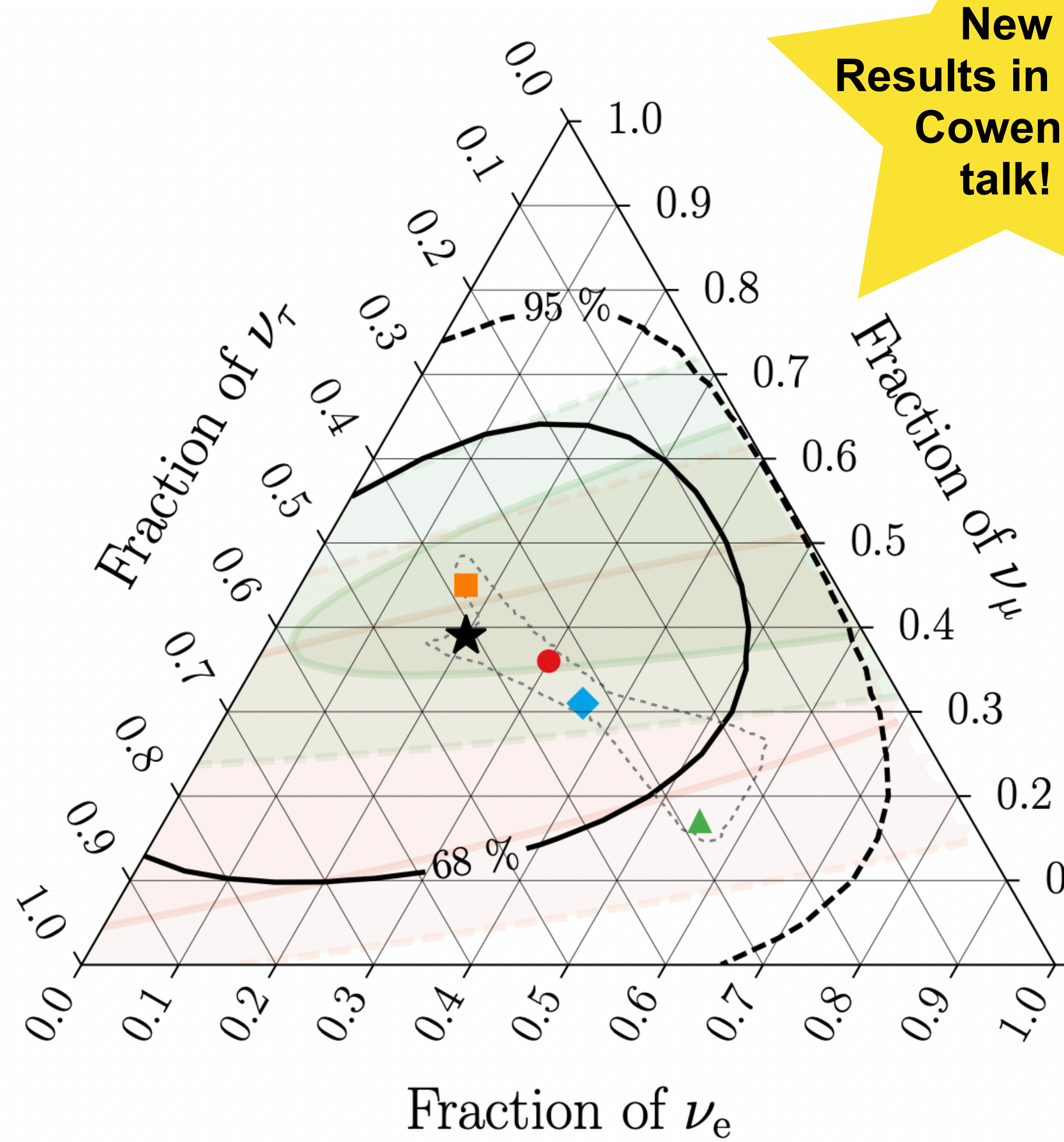


Learned & Pakvasa arXiv:hep-ph/9405296, Mena et al arXiv:1404.0017, CA et al arXiv:1506.02043, Bustamante et al arXiv:1506.02645, Brdar et al arXiv:1611.04598, Gonzalez-Garcia et al arXiv:1605.08055, Rasmussen et al arXiv:1707.07684, Etc

High-Energy Starting Event Flavor Measurement



New Results in Doug Cowen's talk!



—	HESE with ternary topology ID
★	Best fit: 0.20 : 0.39 : 0.42
(green)	Global Fit (IceCube, APJ 2015)
(pink)	Inelasticity (IceCube, PRD 2019)
·······	3ν-mixing 3σ allowed region

$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:	
■	0:1:0 → 0.17 : 0.45 : 0.37
●	1:2:0 → 0.30 : 0.36 : 0.34
▲	1:0:0 → 0.55 : 0.17 : 0.28
◆	1:1:0 → 0.36 : 0.31 : 0.33

IceCube Collaboration arXiv:2011.03561

Search for Lorentz Violation via Flavor Morphing

As neutrinos travel from their far away source they can interact with a Lorentz violating field.

Effects expected at the Planck Scale.

Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

Trajectories in the flavor triangle in the presence of Lorentz Violation (LV)

$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U}_d O_d \tilde{U}_d^\dagger$$

Dimension

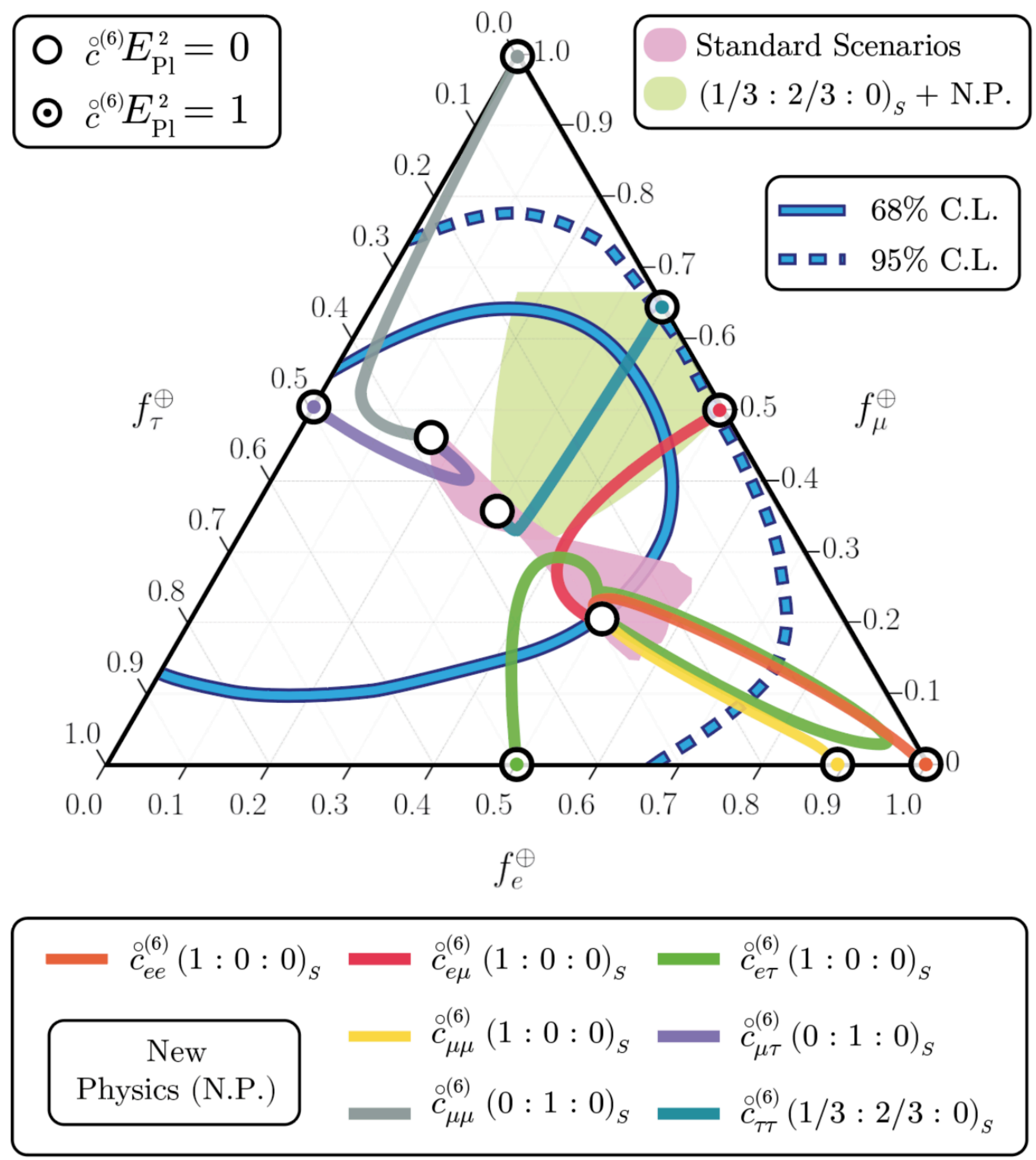
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

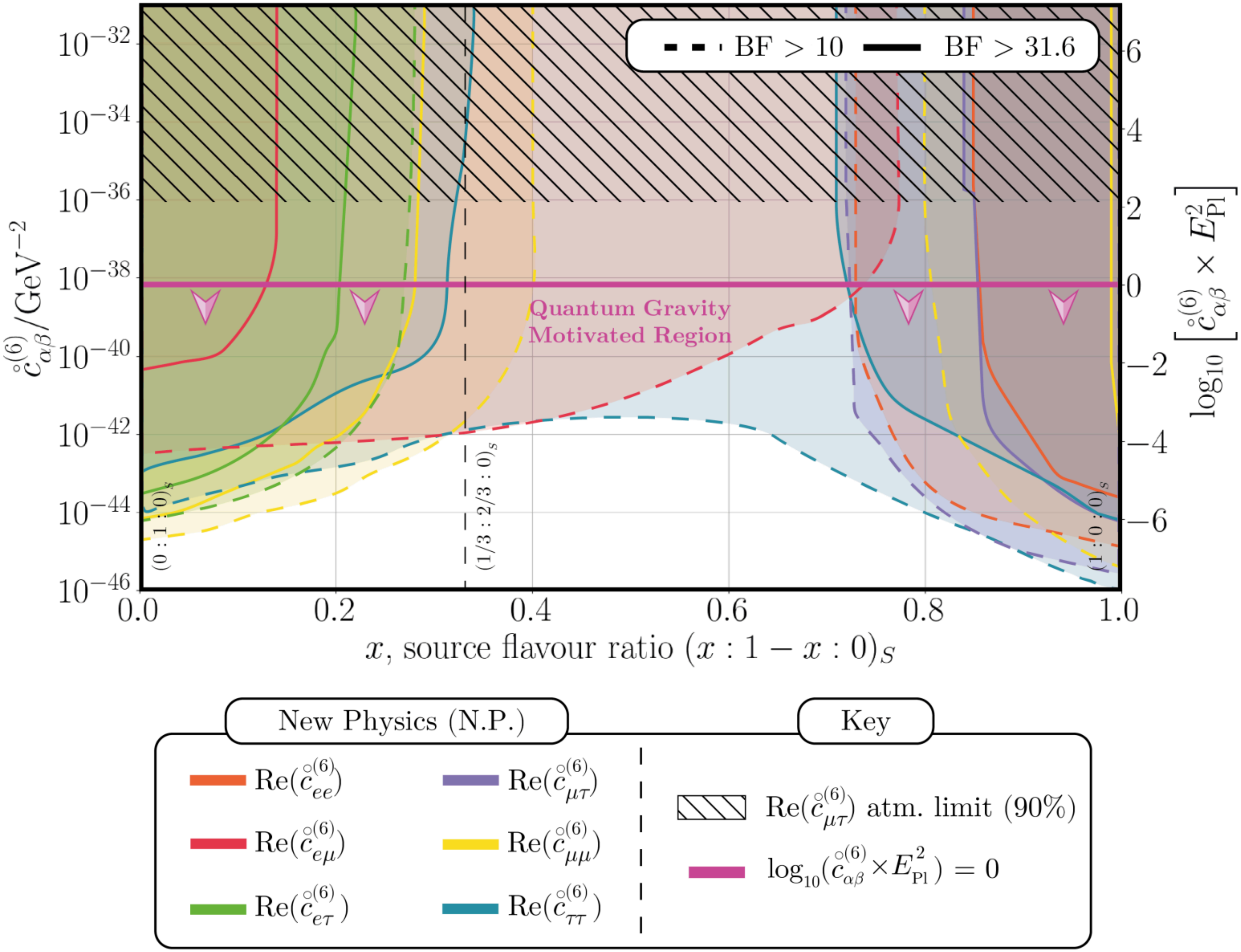
$(0:1:0)$ neutron

$(1:0:0)$ muon-damped



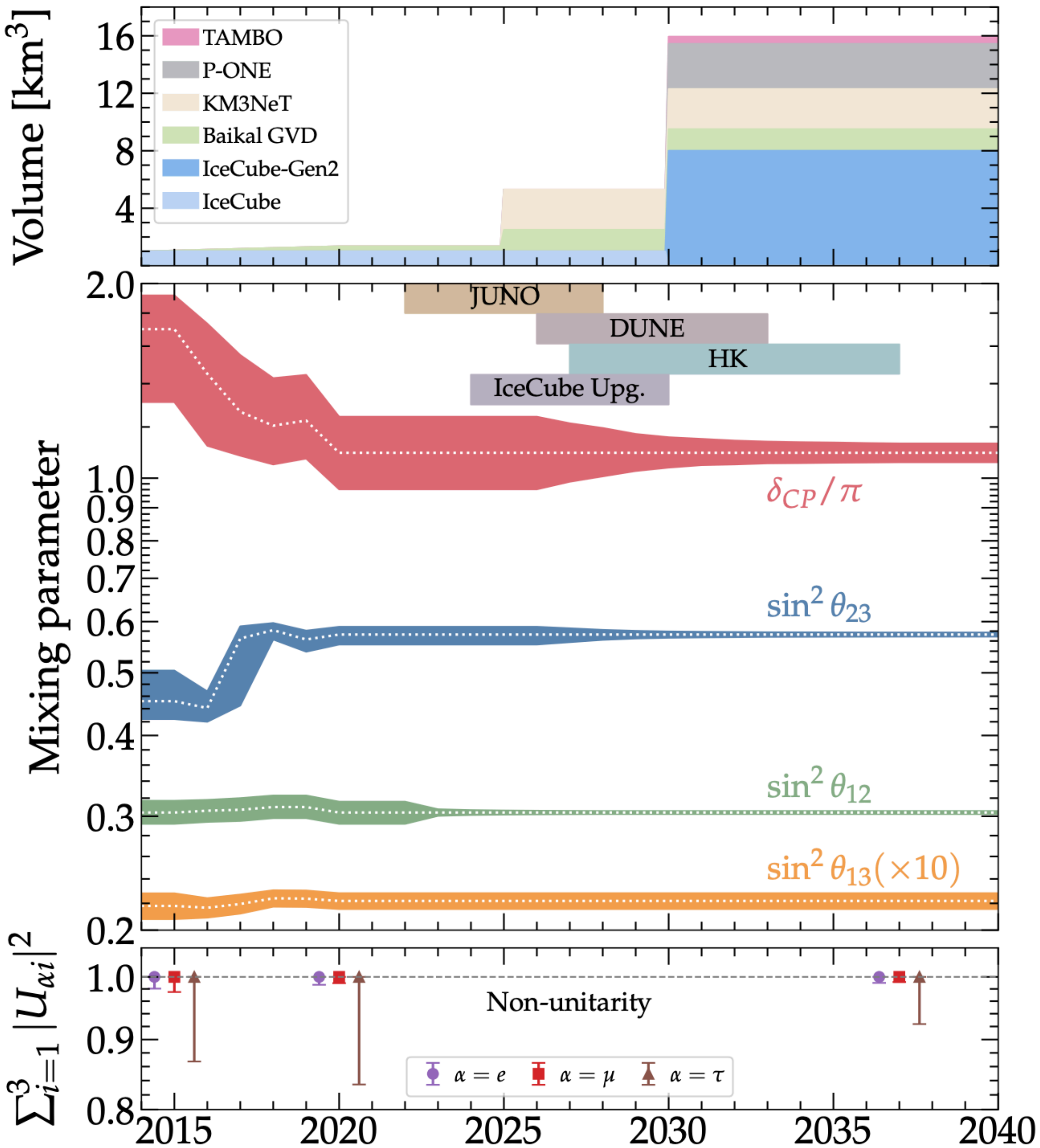
IceCube collaboration arXiv:2111.04654

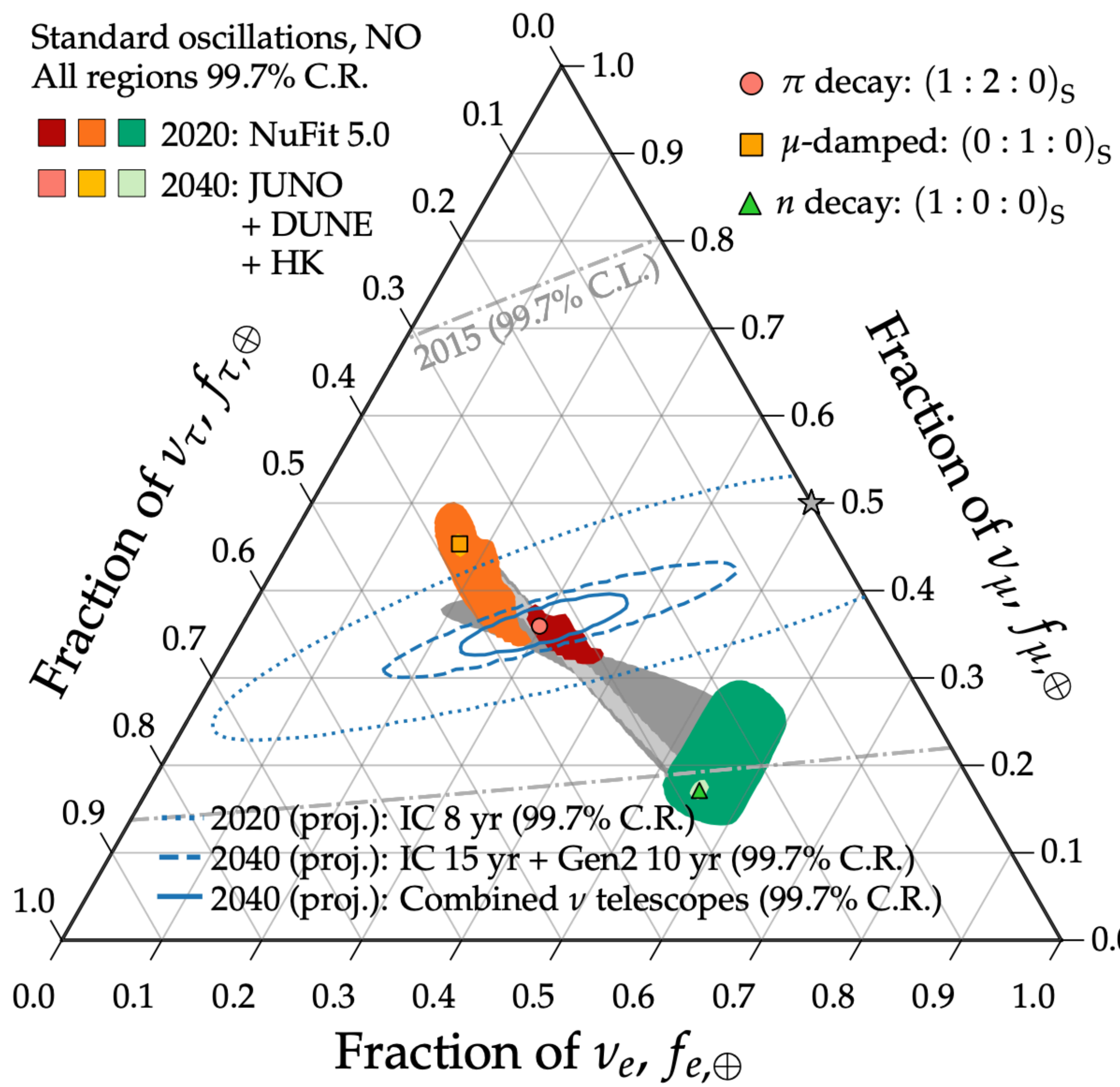
Results on high-dimensional LV operators



IceCube collaboration arXiv:2111.04654

Projected Upgrade Flavor Measurement





N. Song, S. Li, CA, M. Bustamante, A. Vincent (arXiv:2012.12893)

Stops

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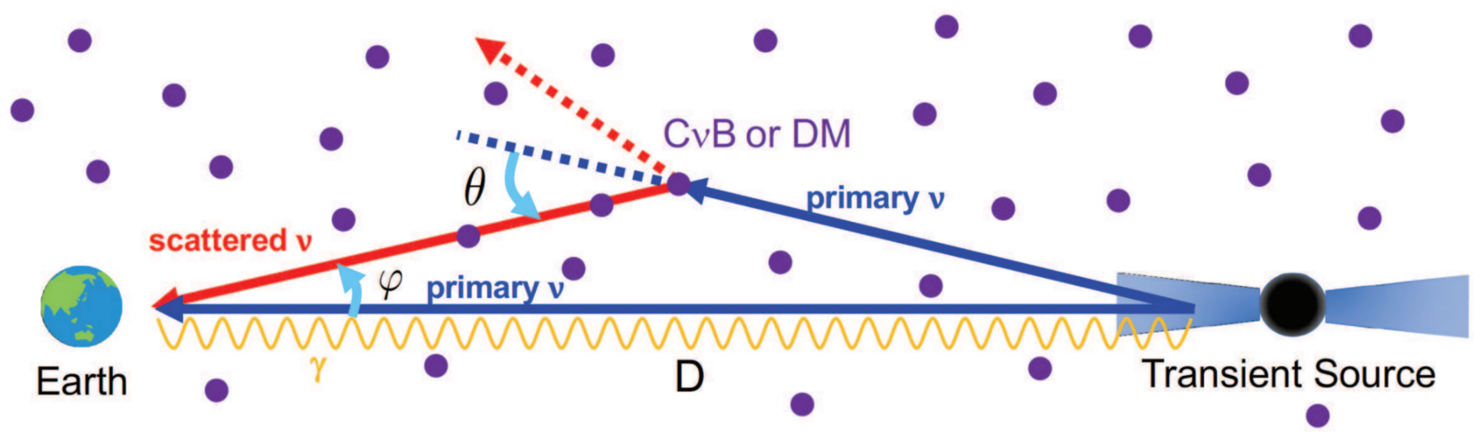
Neutrino Time of Flight

Dark Matter-neutrino interactions
Murase & Shoemaker arXiv:1903.08607

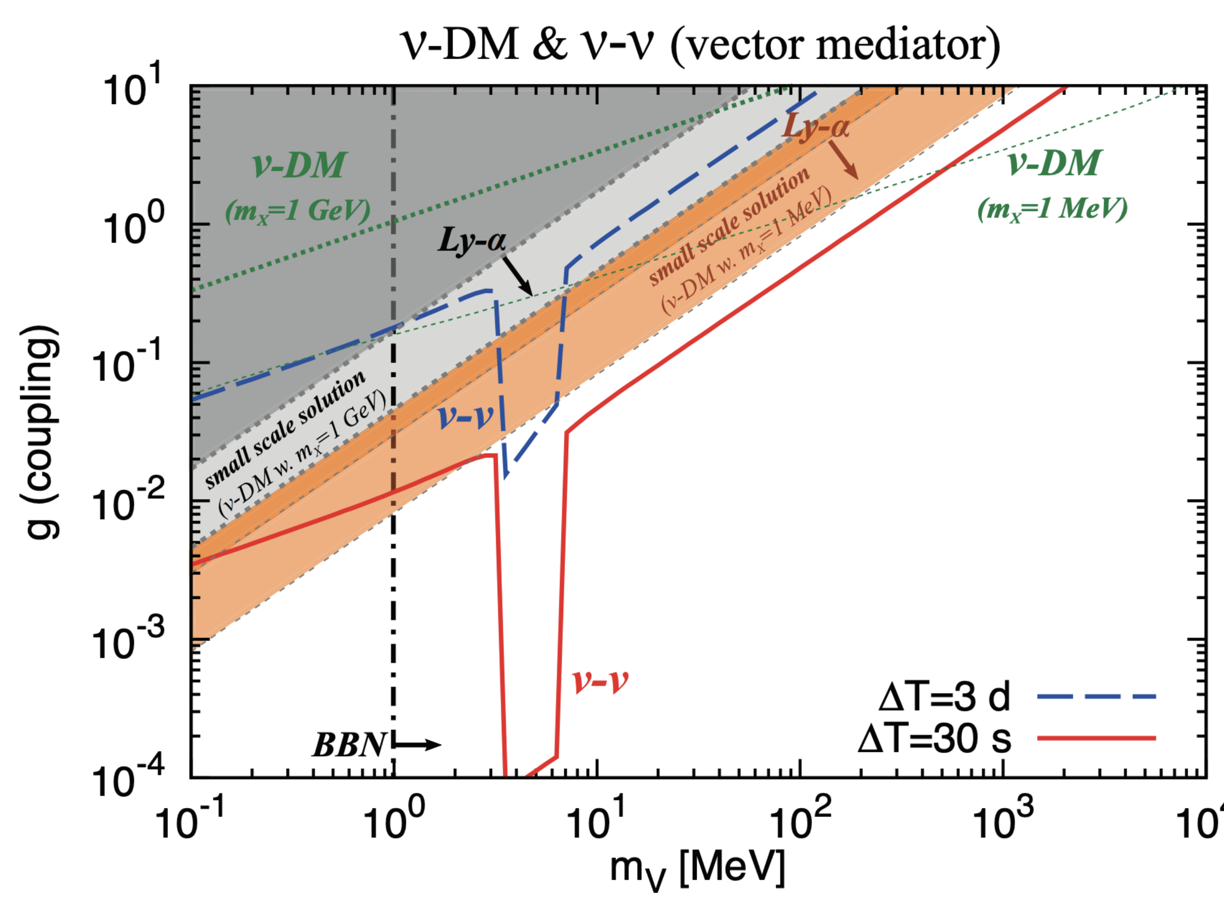
Time-of-flight constraints rely on assumption of flare emission window. Handle with care.



$$v(E) = c\left[1 - s_{\rm n}\frac{n+1}{2}\left(\frac{E}{E_{\rm LV,n}}\right)^n\right]$$

$$(\Delta v_{\nu\gamma}/c)_{TXS} \sim 10^{-11}$$

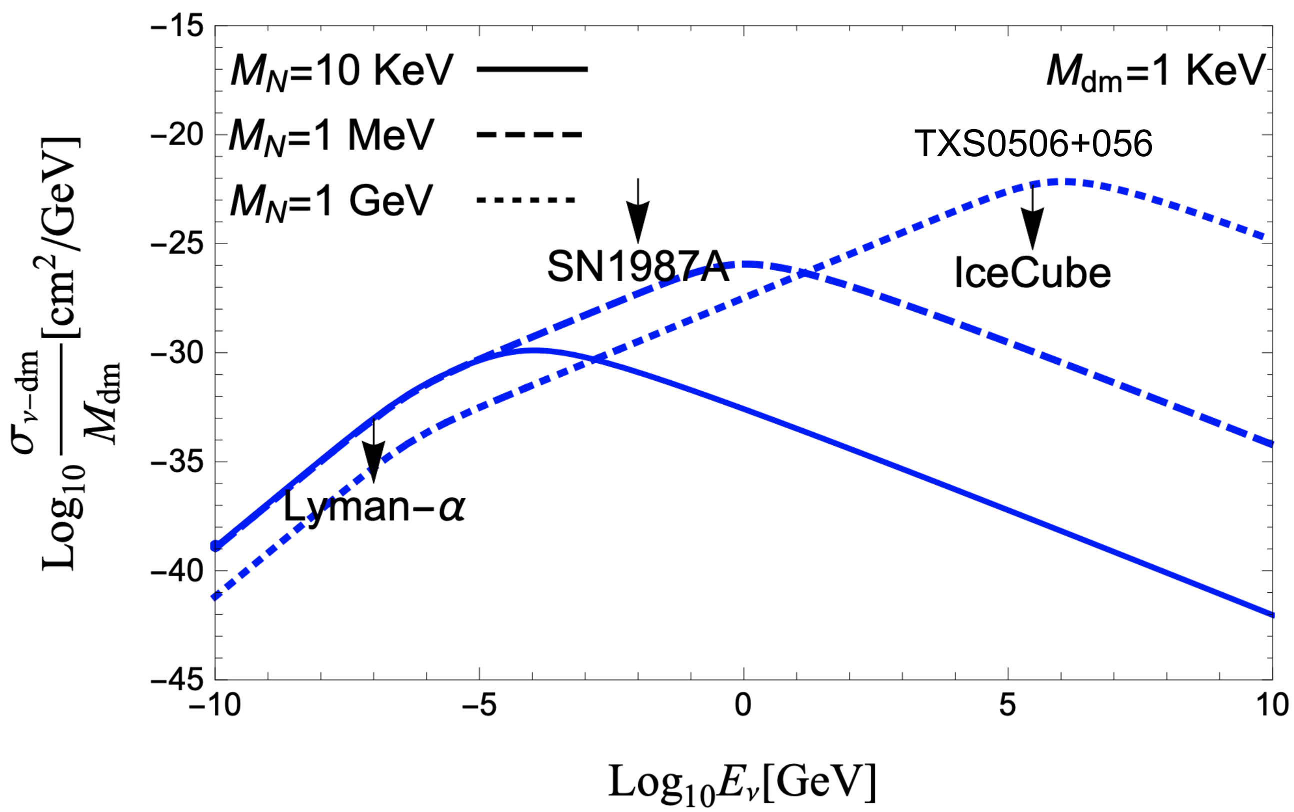
$$(\Delta v_{\nu\gamma}/c)_{SN1987A} \sim 3 \cdot 10^{-9}$$



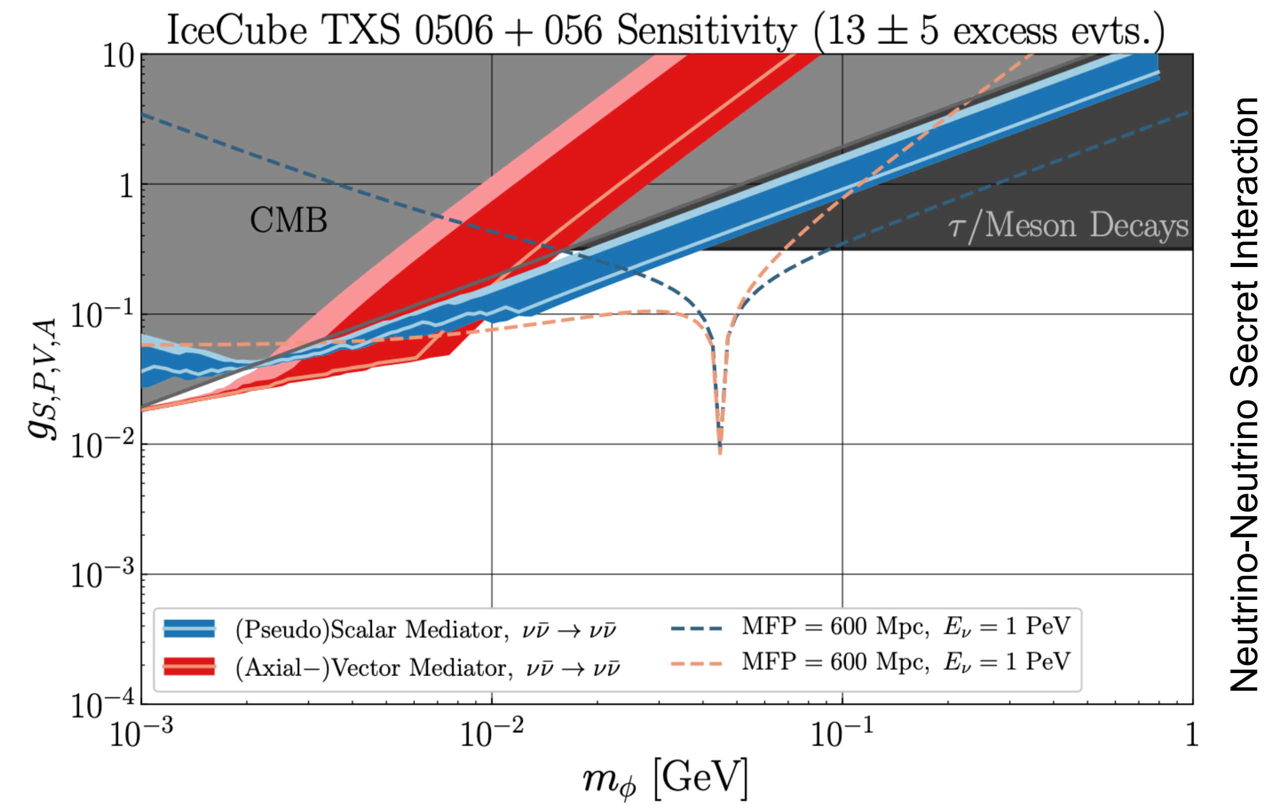
Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

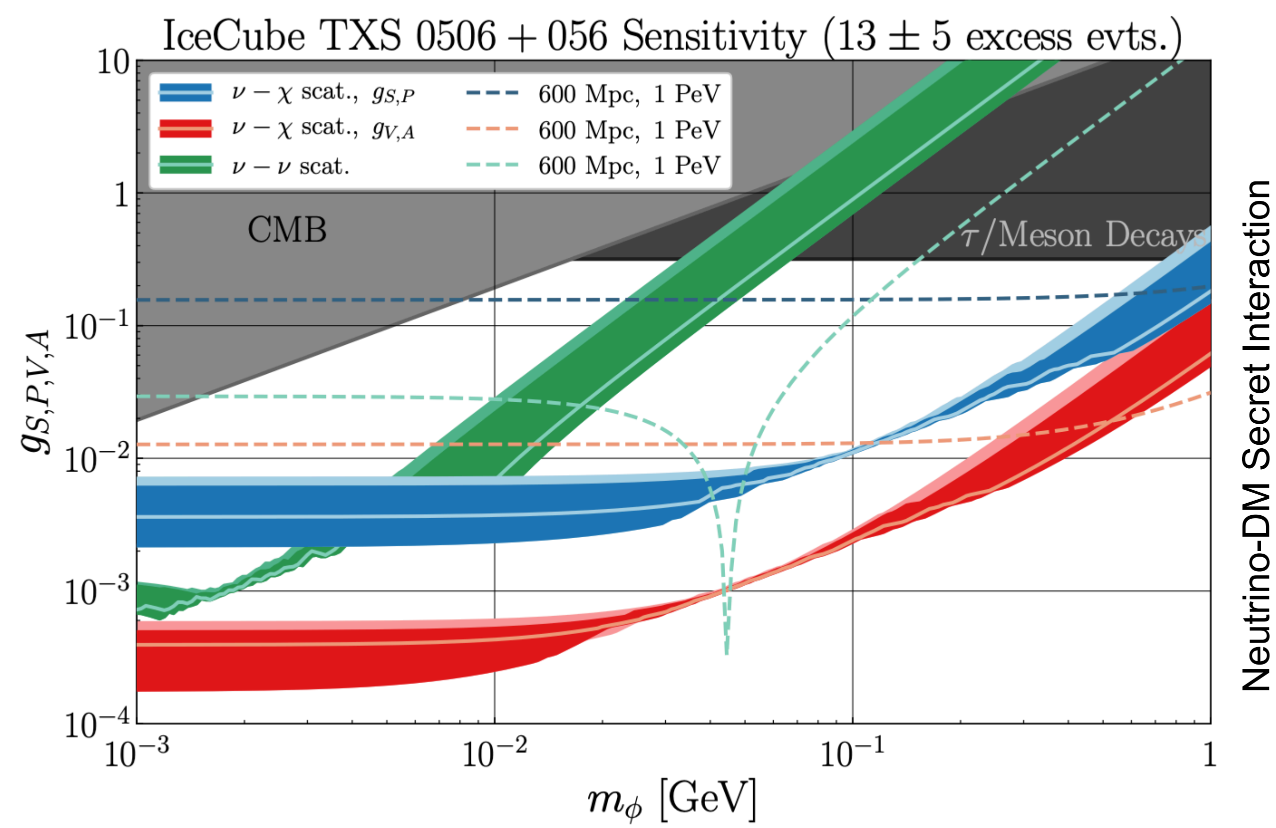
Opacity to Individual Sources

Choi et al. arXiv:1903.03302



Kelly et al arXiv:1808.02889



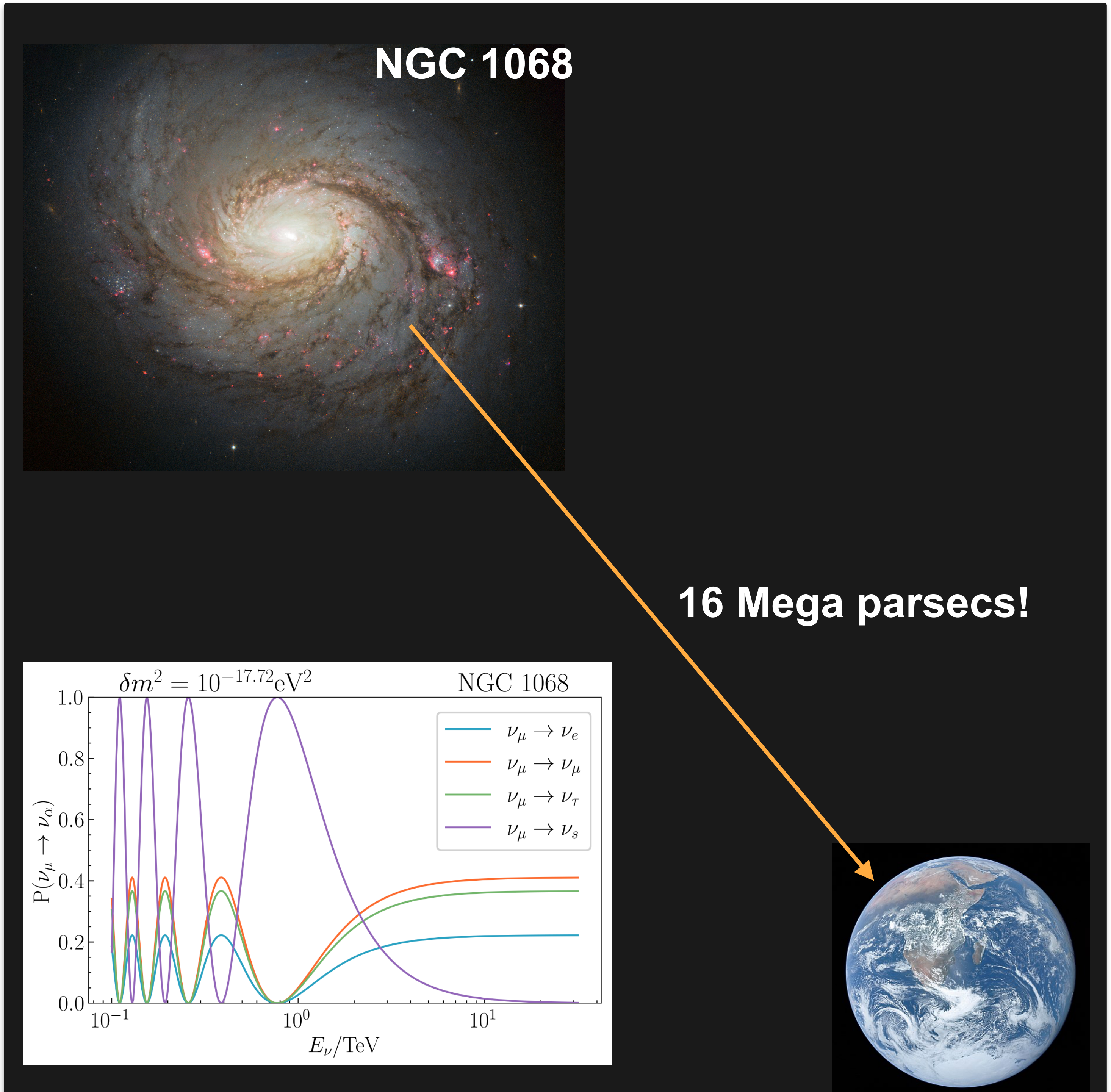


Opacity constraints rely on assumptions on the intrinsic source luminocity. Handle with care.

dark matter-neutrino couplings
CA et al. arXiv:1703.00451
Kelly et al arXiv:1808.02889
Choi et al. arXiv:1903.03302

neutrino-neutrino couplings
Kelly et al arXiv:1808.02889
CA et al. arXiv:2009.05201
Carpio et al. arXiv:2104.15136

Neutrino Oscillations At Cosmic Scales



$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

If B-L is a good symmetry that's spontaneously broken.
Gauging B-L and breaking it spontaneously, we would get:

$$(10^{-22} - 10^{-12})\,\text{eV}^2$$

Pseudo-Dirac Neutrino Mass Structure

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

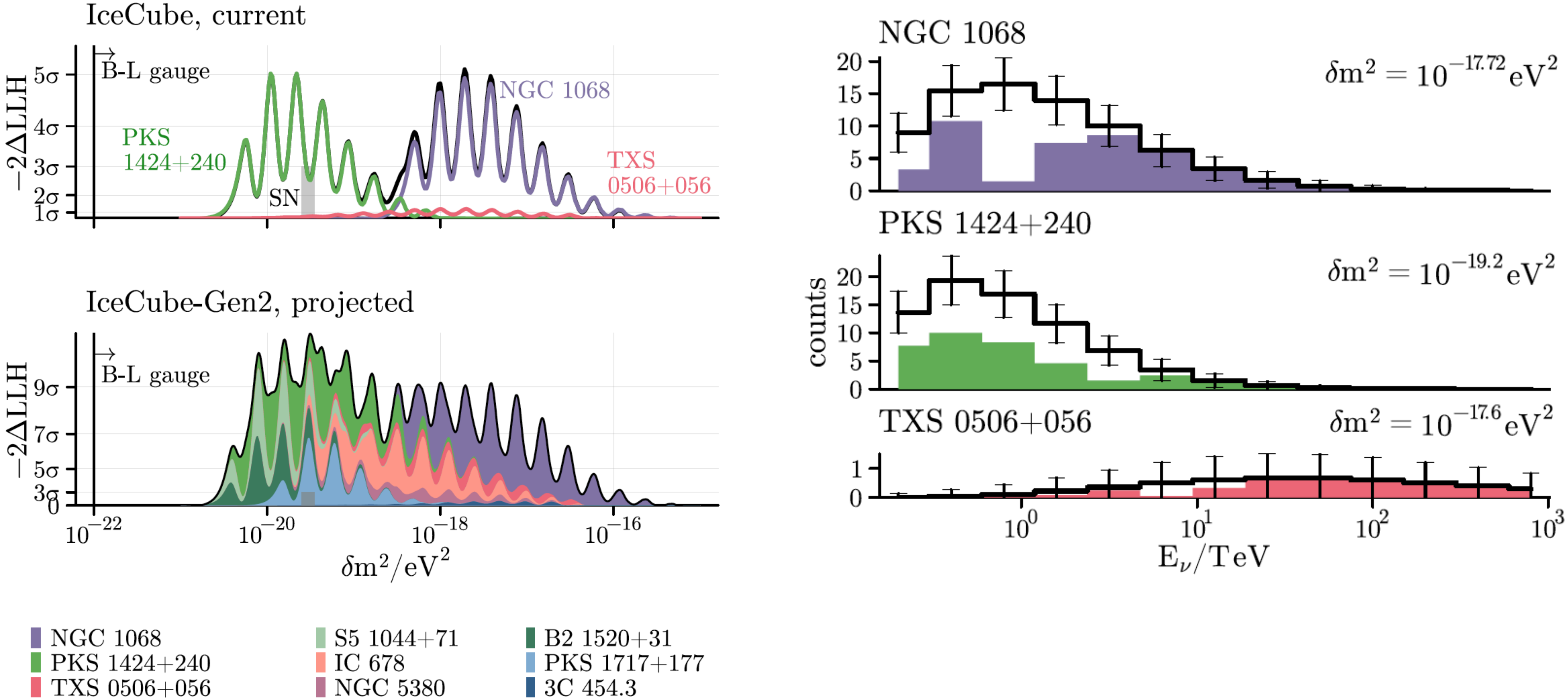
Probing Pseudo-Dirac Neutrinos with Astrophysical Sources at IceCube

2212.00737

Kiara Carloni,[1,*] Ivan Martínez-Soler,[1,†] Carlos A. Argüelles,[1,‡] K. S. Babu,[2,§] and P. S. Bhupal Dev[3,¶]

See also Rink & Sen arXiv:2211.16520

Neutrino Oscillations At Cosmic Scales



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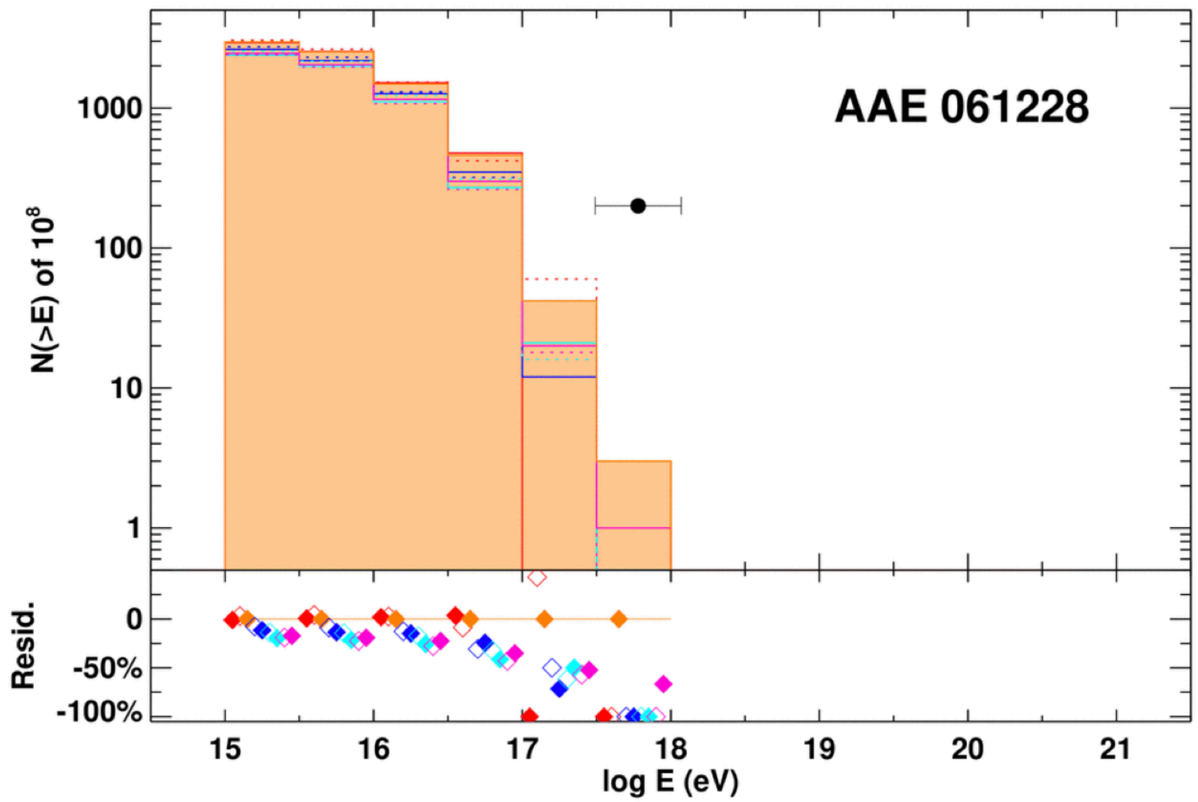
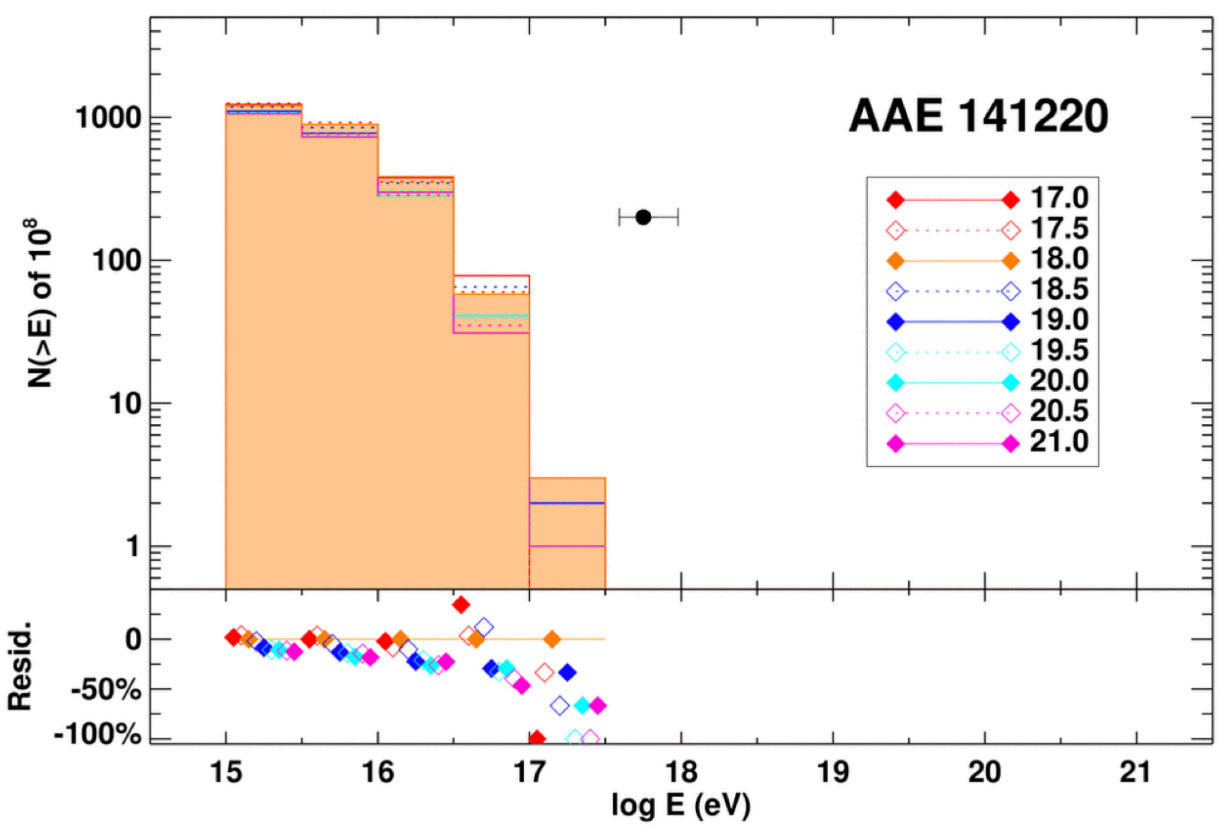
Stops

- A new frontier in the search for dark matter
- Using the flavor of neutrinos to find new physics
- New physics with new sources
- Anomalies and new physics at PeV-EeV

Unusual things

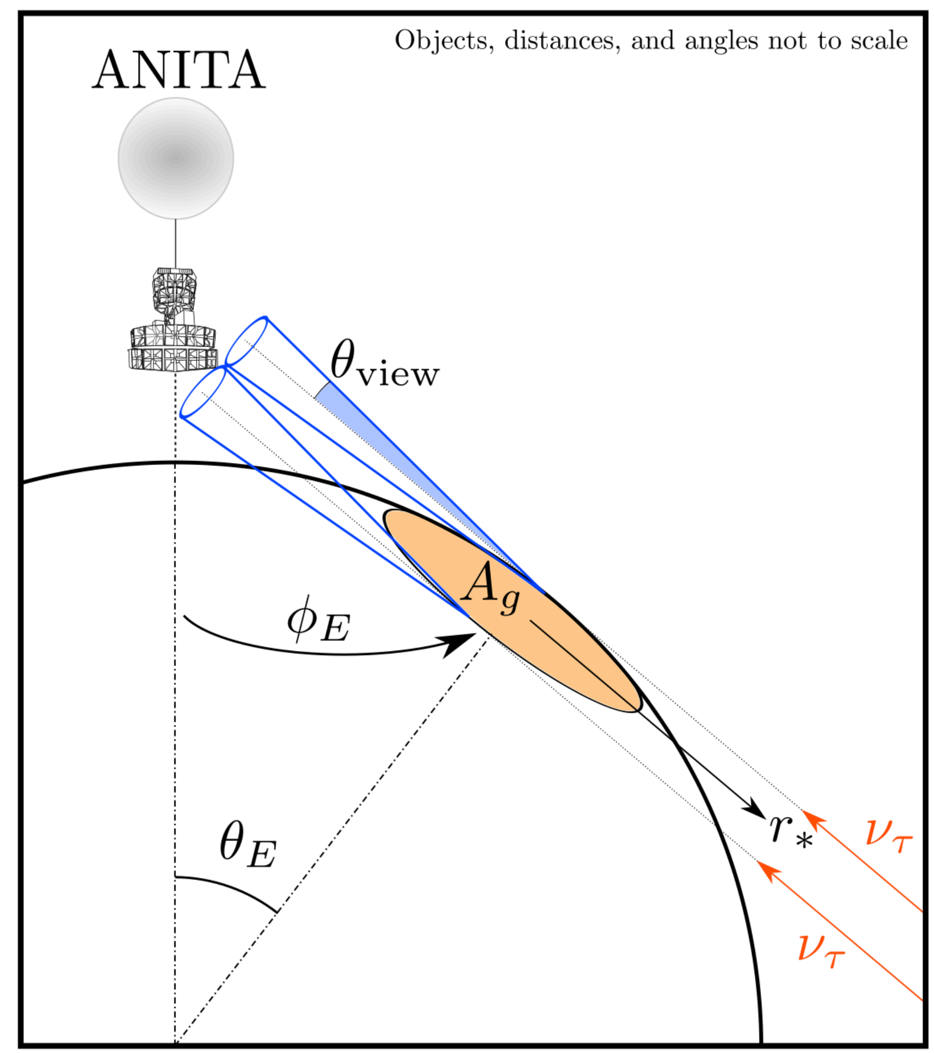
Fox et al arXiv:1809.09615





ANITA Collaboration arXiv:1803.05088

event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[(1)]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4\pm0.3°, 159.62\pm0.7°$	$-35.0\pm0.3°, 61.41\pm0.7°$
RA, Dec[(2)]	282.14064, +20.33043	50.78203, +38.65498
E_{shower}[(3)]	0.6 ± 0.4 EeV	$0.56^{+0.3}_{-0.2}$ EeV

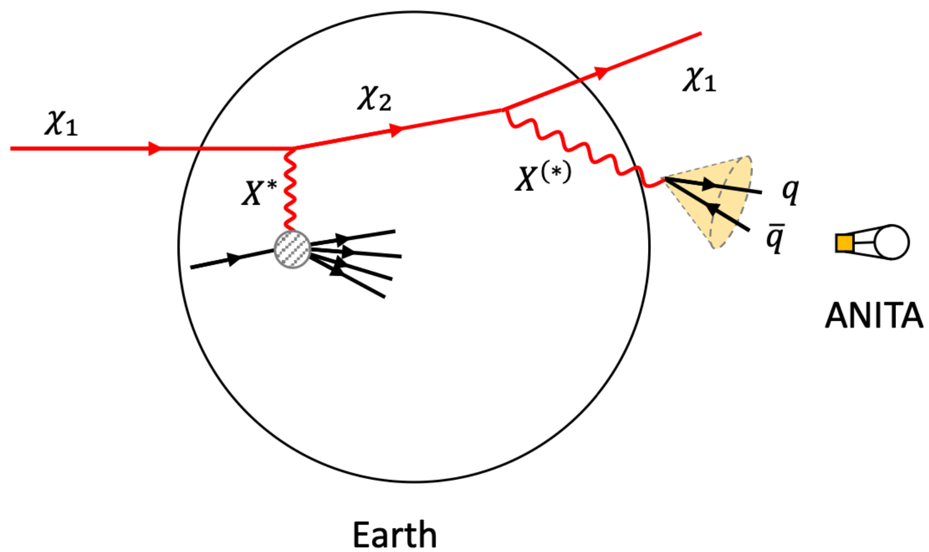


See also ANITA Coll. arXiv:2112.07069 for ANITA-IV results.
Four additional interesting events observed.

Unusual things

Explaining the ANITA Anomaly with Inelastic Boosted Dark Matter

Lucien Heurtier,[1,*] Doojin Kim,[1,†] Jong-Chul Park,[2,‡] and Seodong Shin[3,§]
[1]*Department of Physics, University of Arizona, Tucson, AZ 85721, USA*
[2]*Department of Physics, Chungnam National University, Daejeon 34134, Republic of Korea*
[3]*Department of Physics & IPAP, Yonsei University, Seoul 03722, Republic of Korea*



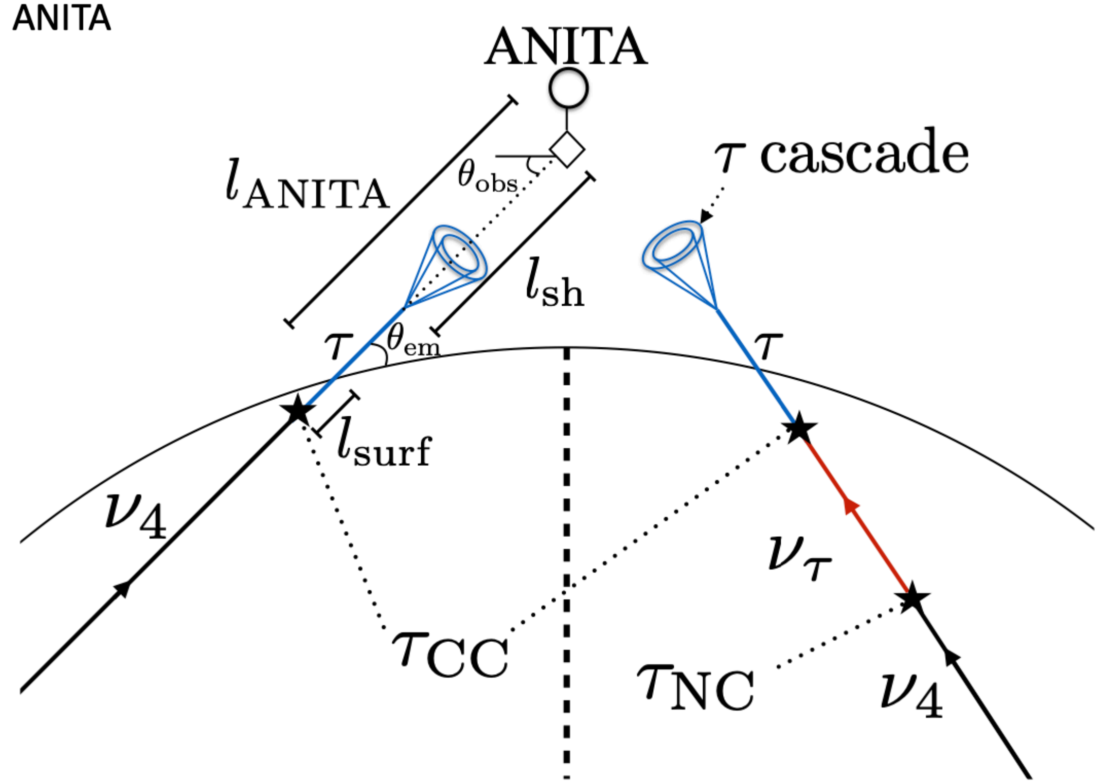
Looking at the Axionic Dark Sector with ANITA

I. Esteban[a,1], J. Lopez-Pavon[b,2], I. Martinez-Soler[c,3,4,5], J. Salvado[d,1]

See also …

Reflections On the Anomalous ANITA Events: The Antarctic Subsurface as a Possible Explanation

Ian M. Shoemaker,[1] Alexander Kusenko,[2,3] Peter Kuipers Munneke,[4] Andrew Romero-Wolf,[5] Dustin M. Schroeder,[6] and Martin J. Siegert[7]

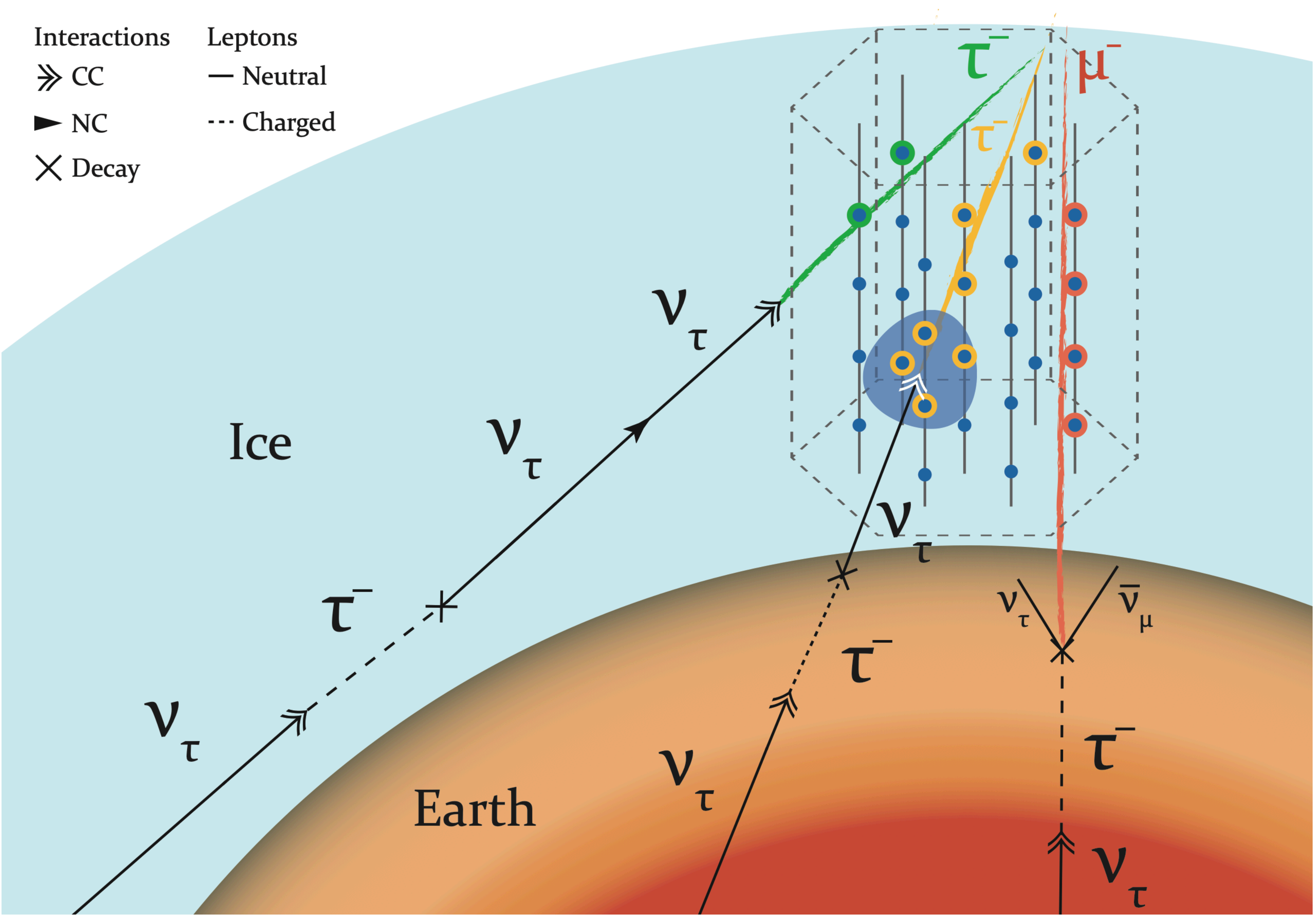


A Sterile Neutrino Origin for the Upward Directed Cosmic Ray Showers Detected by ANITA

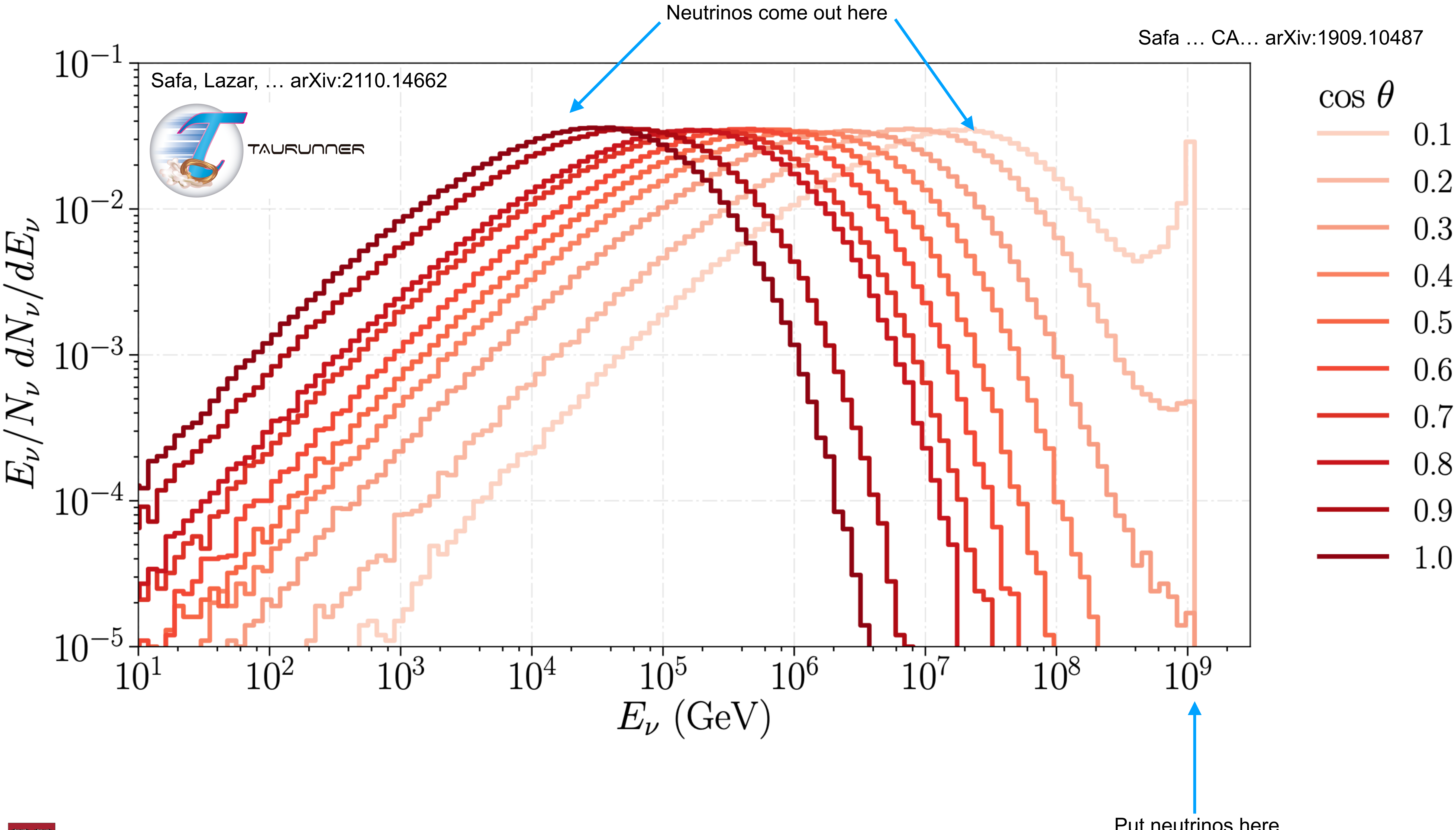
John F. Cherry[1] and Ian M. Shoemaker[1]
[1]*Department of Physics, University of South Dakota, Vermillion, SD 57069, USA*[*]
(Dated: 8-23-2018)

Tau Regeneration

Safa … CA… arXiv:1909.10487

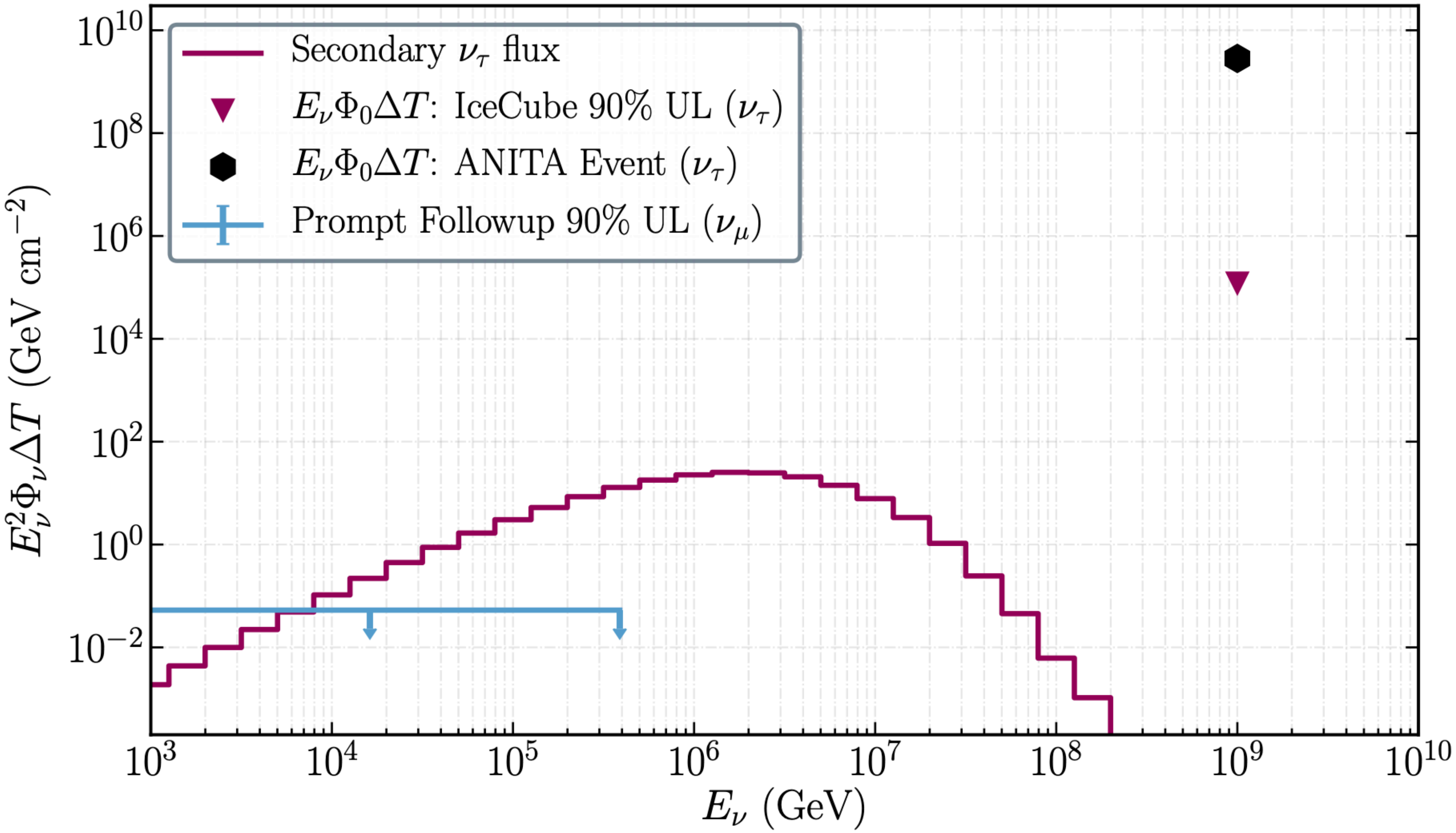


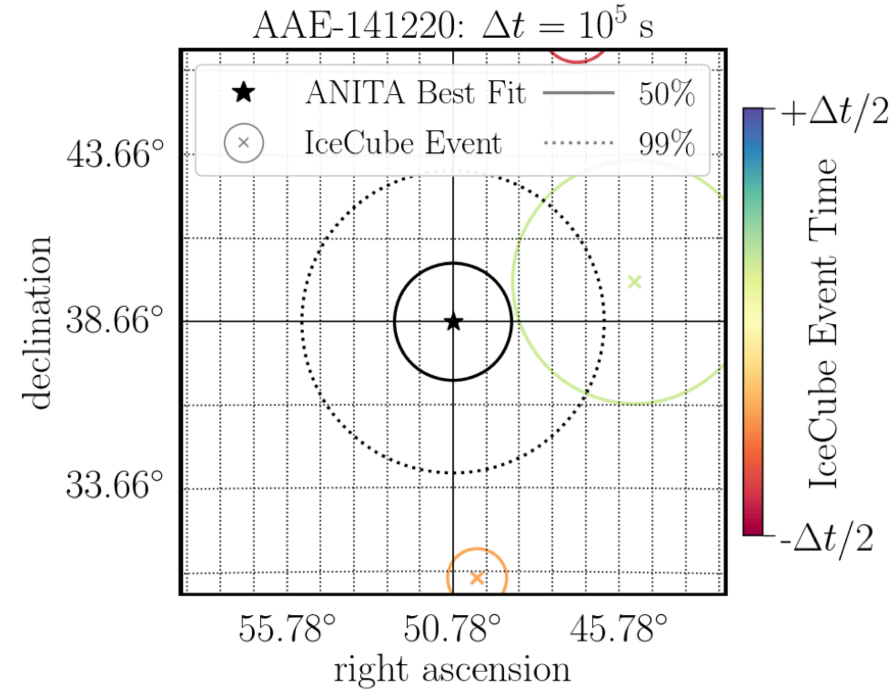
Intimate connection between PeV and ZeV energies

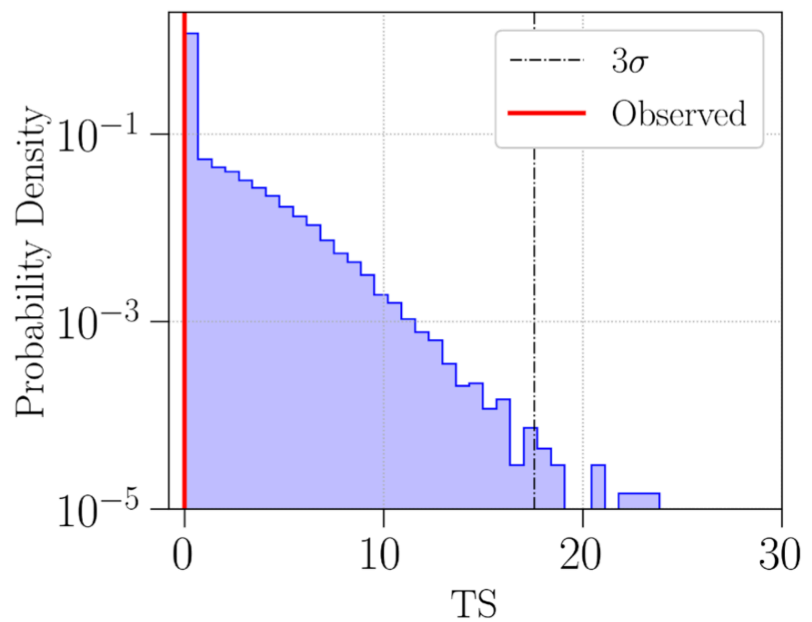


Get code here:
https://github.com/icecube/TauRunner

Ruling out ANITA Neutrino Interpretation

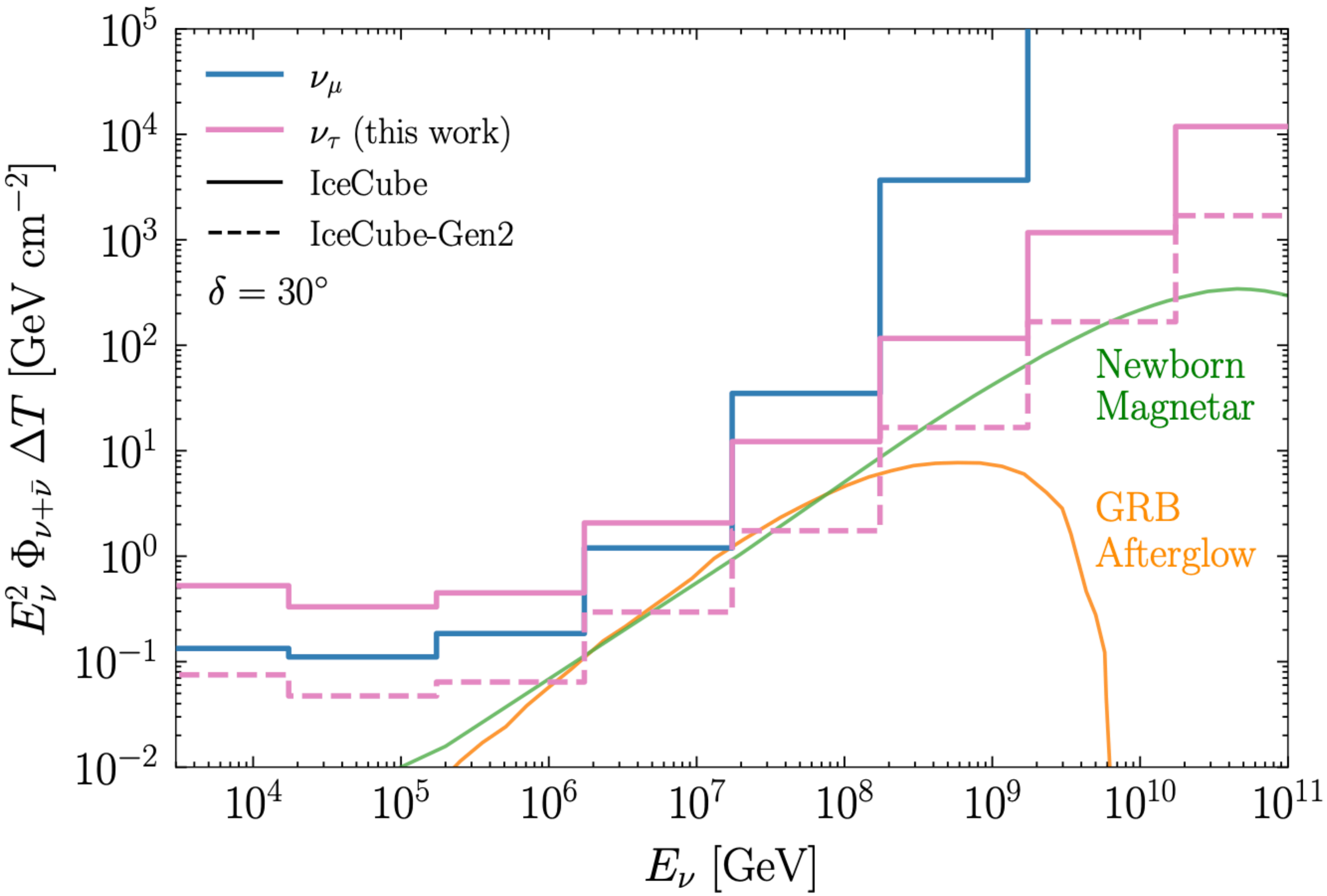


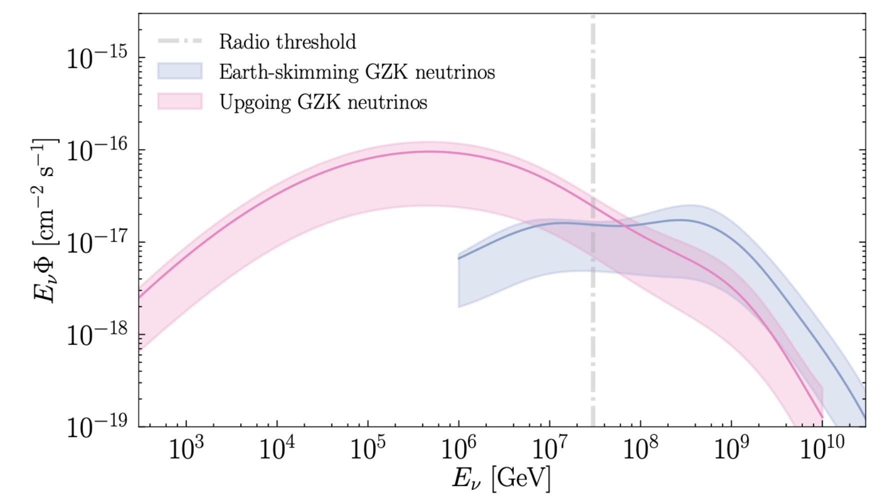




IceCube Collaboration arXiv:2001.01737

Constraints on EeV Fluxes From PeV Measurements





PeV Tau Neutrinos to Unveil Ultra-High-Energy Sources

Carlos A. Argüelles,[1,*] Francis Halzen,[2,†] Ali Kheirandish,[3,‡] and Ibrahim Safa[1,2,§]

arXiv:2203.13827

Take home message

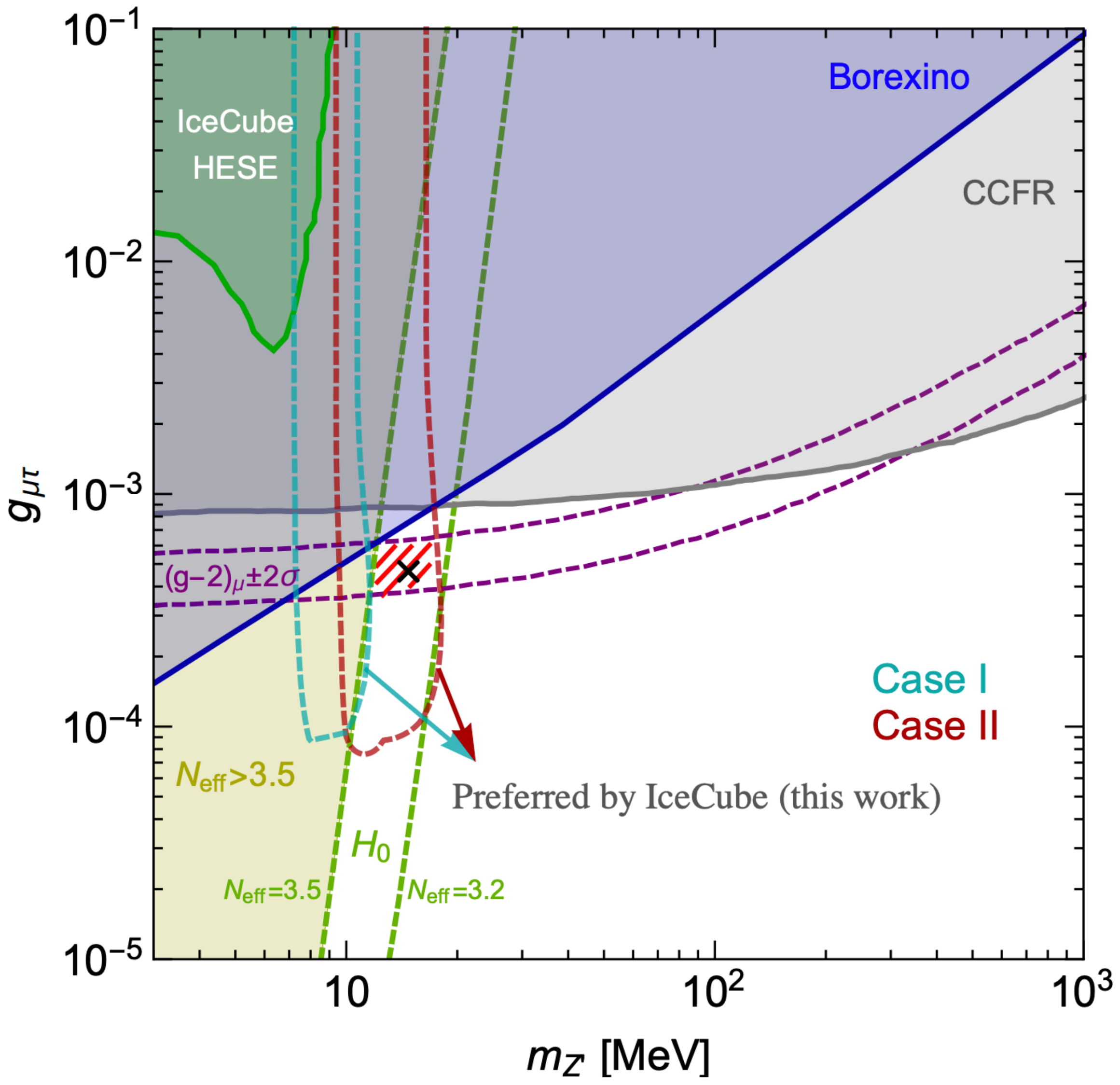
- We live in interesting times! Nu-probes are available and old puzzles remain!
- Astrophysical neutrinos provide new ways to search for dark matter.
- The flavor of astrophysical neutrinos is a powerful probe of new physics.
- Observation of sources open the possibility to study oscillation physics at new, uncharted scales

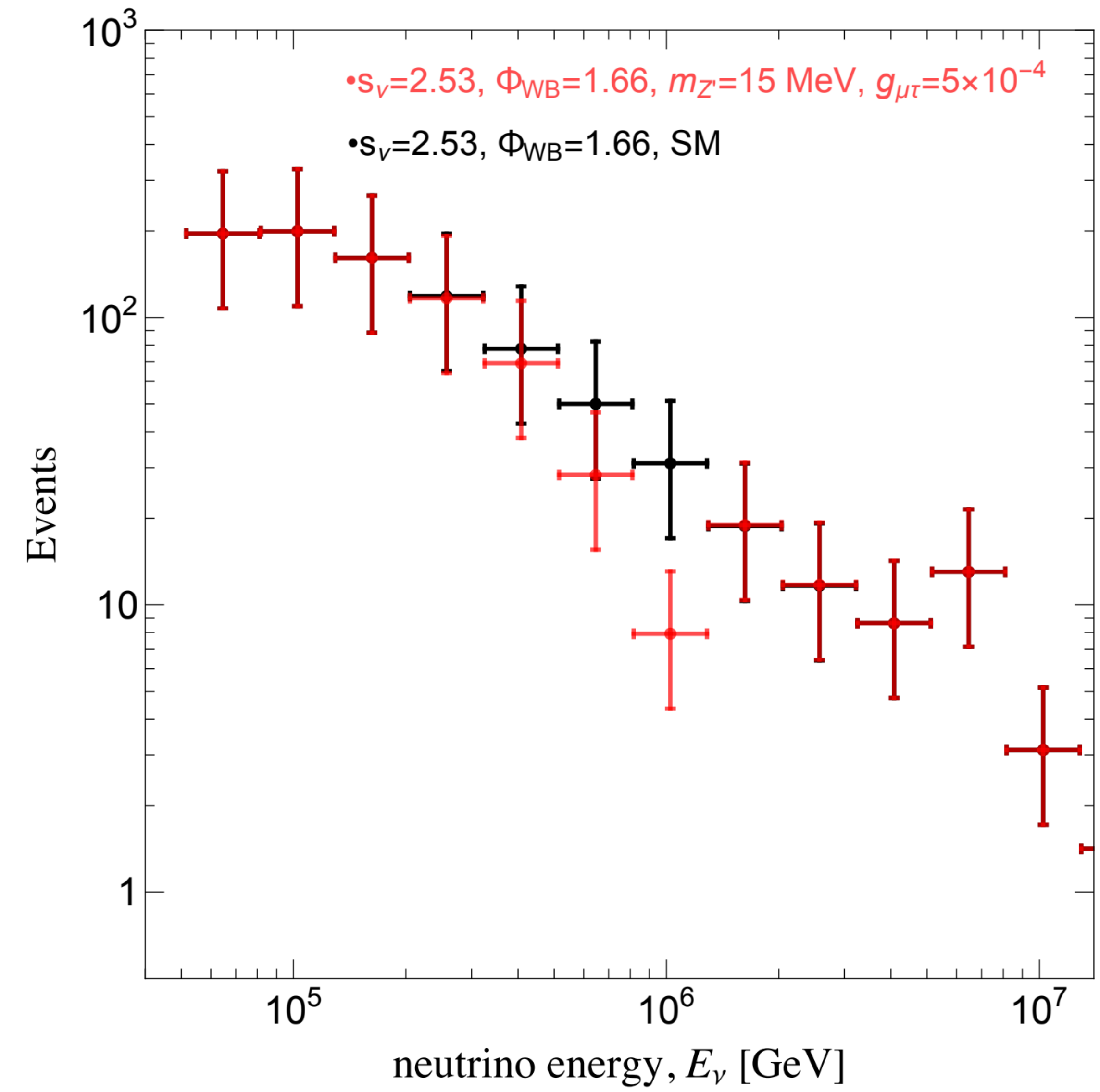
May your chosen trail lead you to new physics!

Thank you!

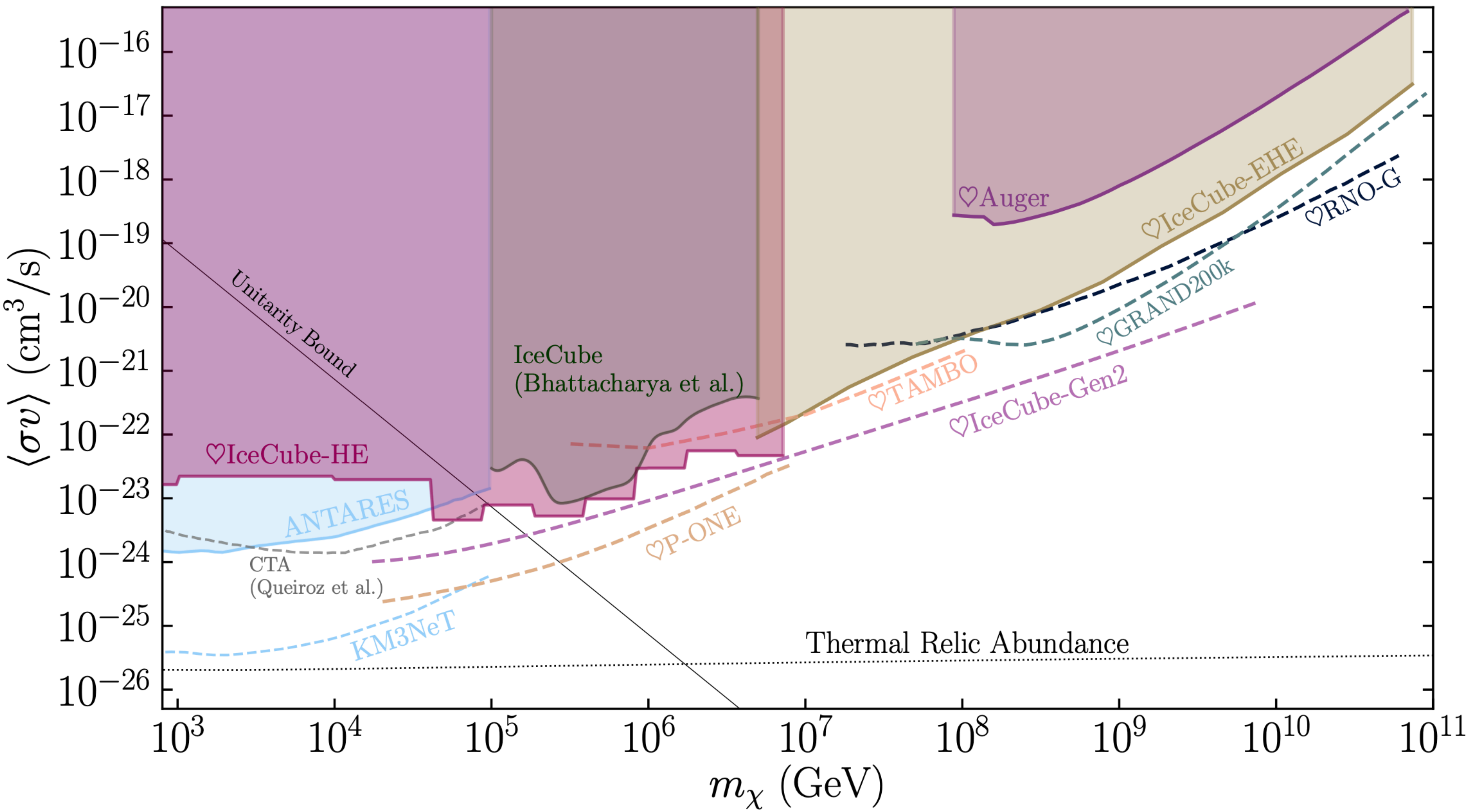
Bonus slides

Carpio et al. arXiv:2104.15136



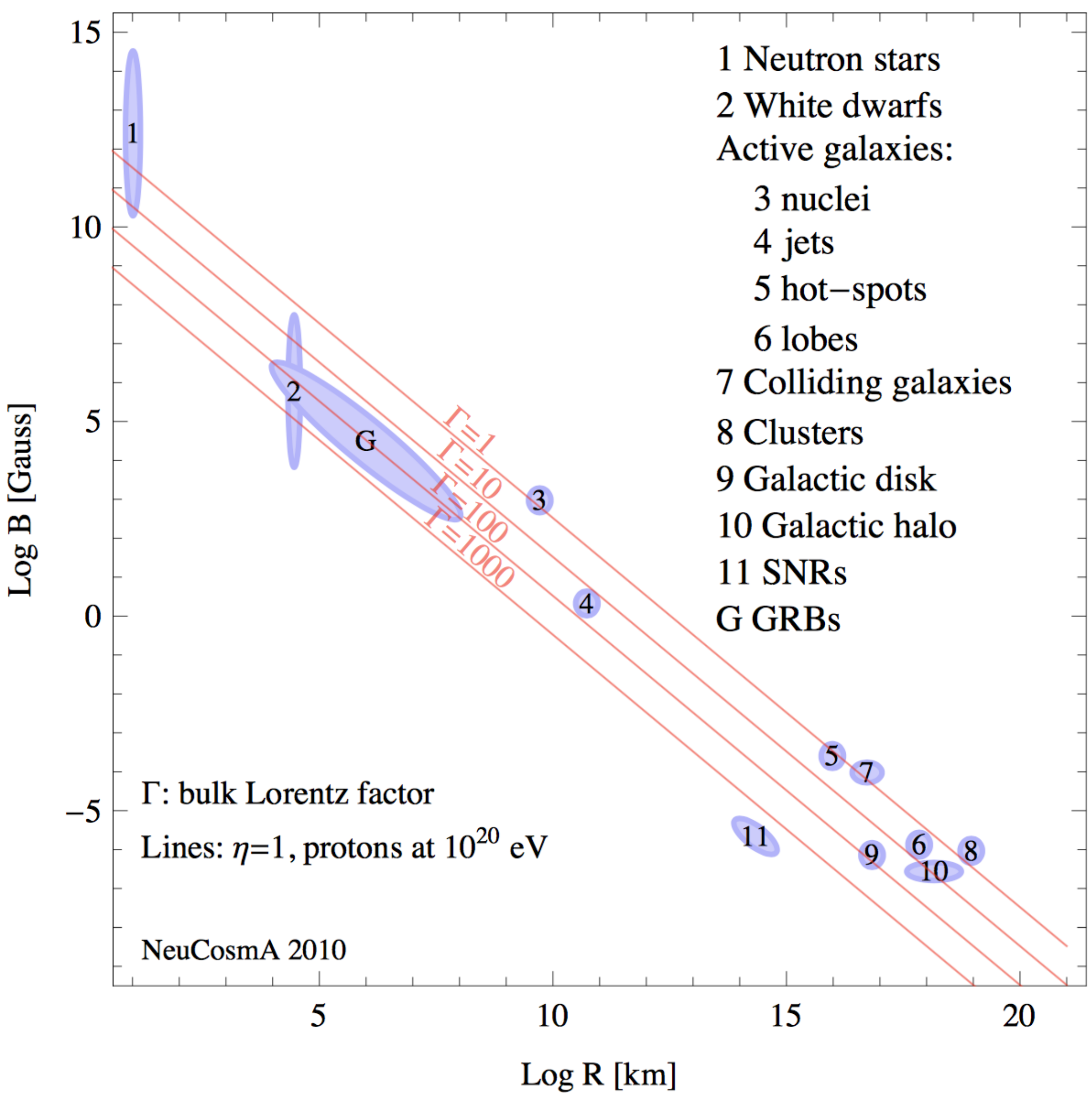


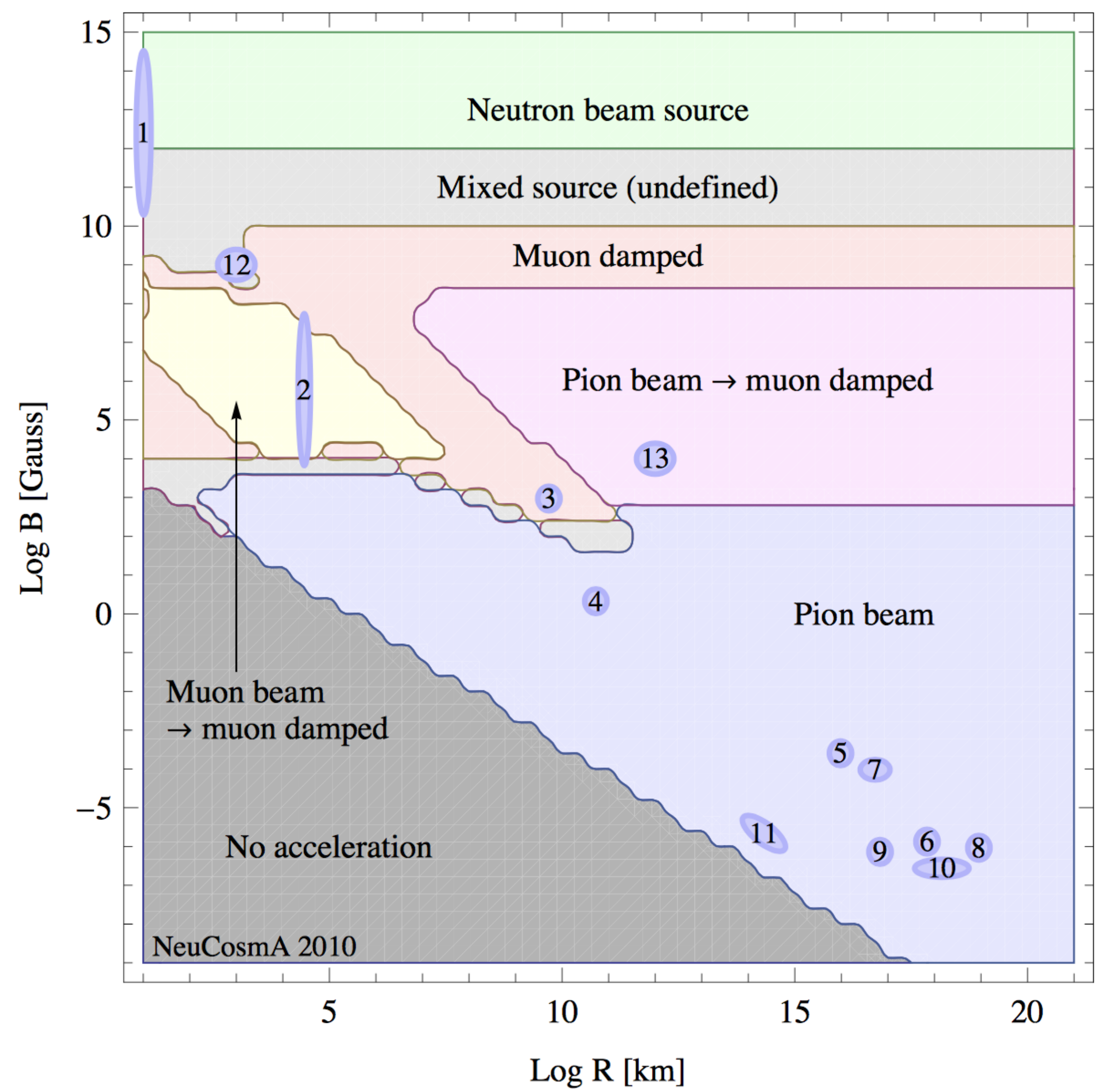
Next Generation Dark Matter Searches



CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;
See also Beacom et al. *PRL 99: 231301, 2007*.

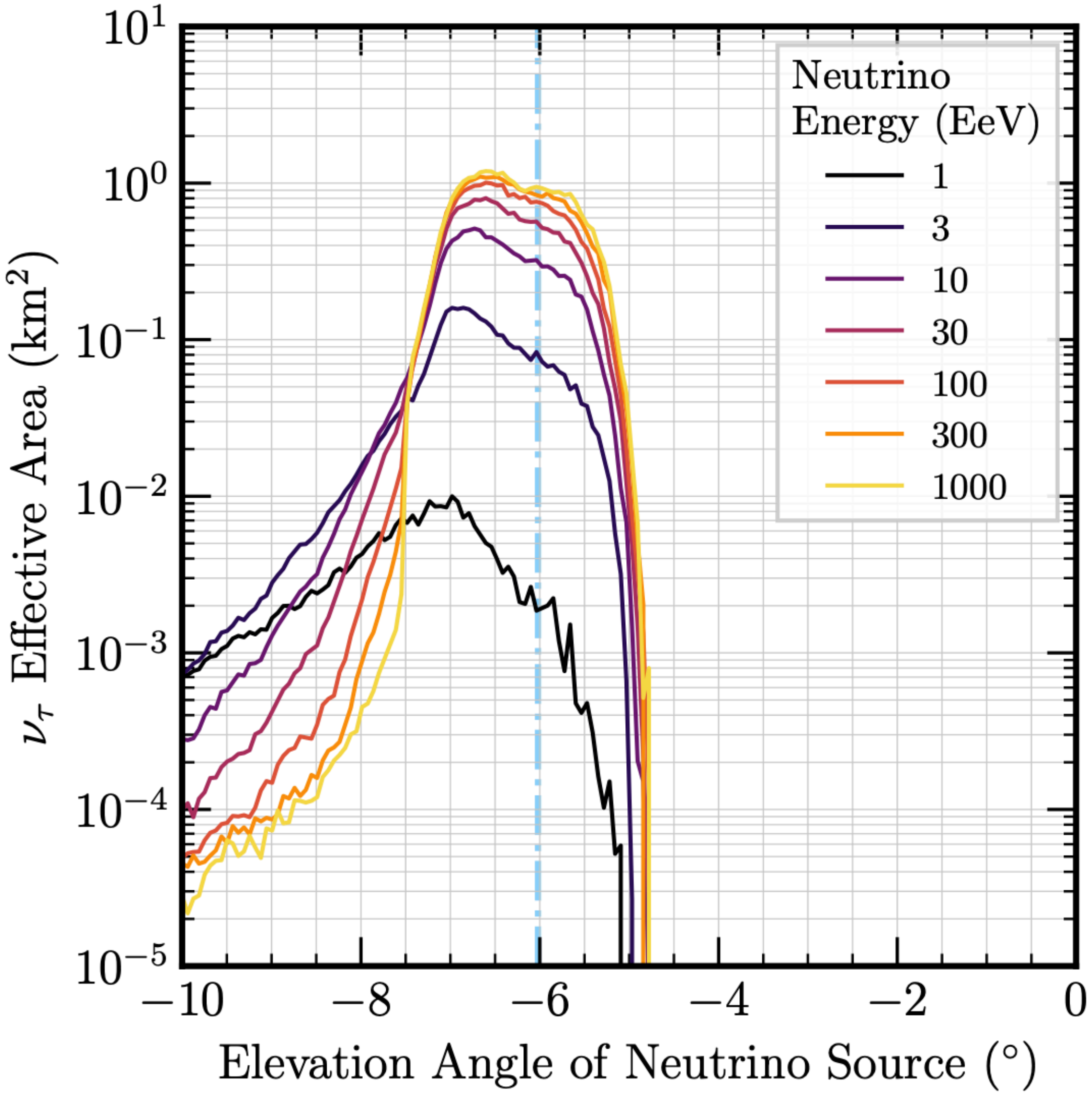
Sources of Astrophysical Neutrinos

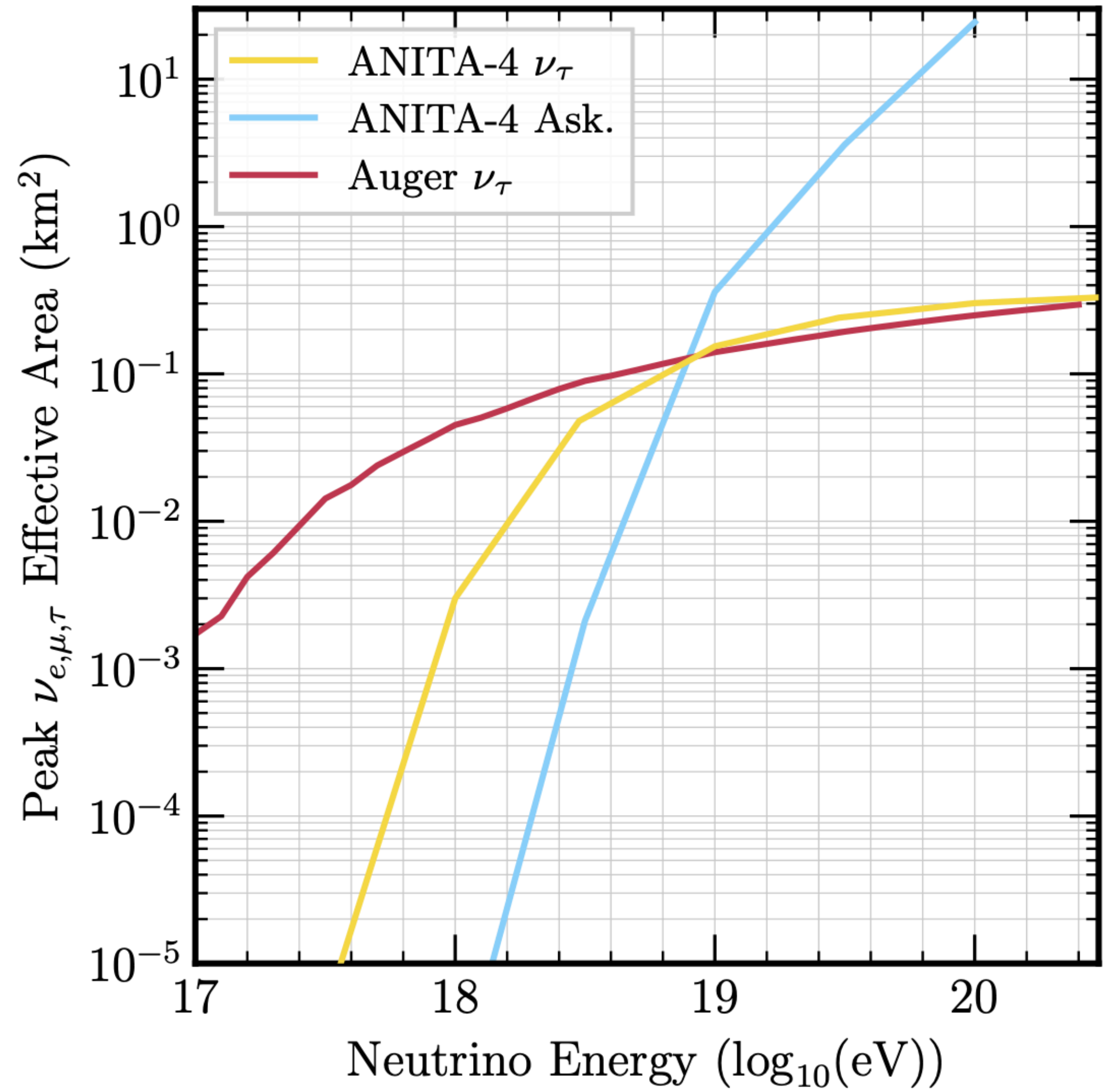




(arXiv:1007:0006)

ANITA-IV





Event	$E_{\nu,\gamma=-1}$ (EeV)	$E_{\nu,\gamma=-2}$ (EeV)	$E_{\nu,\gamma=-3}$ (EeV)
4098827	$49.8^{+80.3}_{-37.7}$	$12.5^{+29.9}_{-7.4}$	$5.2^{+6.0}_{-2.5}$
19848917	$31.9^{+76.0}_{-24.5}$	$5.2^{+11.0}_{-2.9}$	$2.6^{+3.1}_{-1.1}$
50549772	$45.4^{+83.4}_{-34.4}$	$8.8^{+19.5}_{-4.9}$	$4.3^{+4.8}_{-2.1}$
72164985	$60.3^{+88.9}_{-38.2}$	$15.1^{+27.3}_{-7.6}$	$8.9^{+10.5}_{-4.5}$