Neutrino Telescopes:
A New Trail to Find New Physics

Carlos Argüelles

Cosmic-ray and Neutrinos in the Multi-messenger Era, Dec. 12th, 2024

HARVARD UNIVERSITY
The NSF Institute for Artificial Intelligence and Fundamental Interactions
ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
NSF
RESEARCH CORPORATION for SCIENCE ADVANCEMENT
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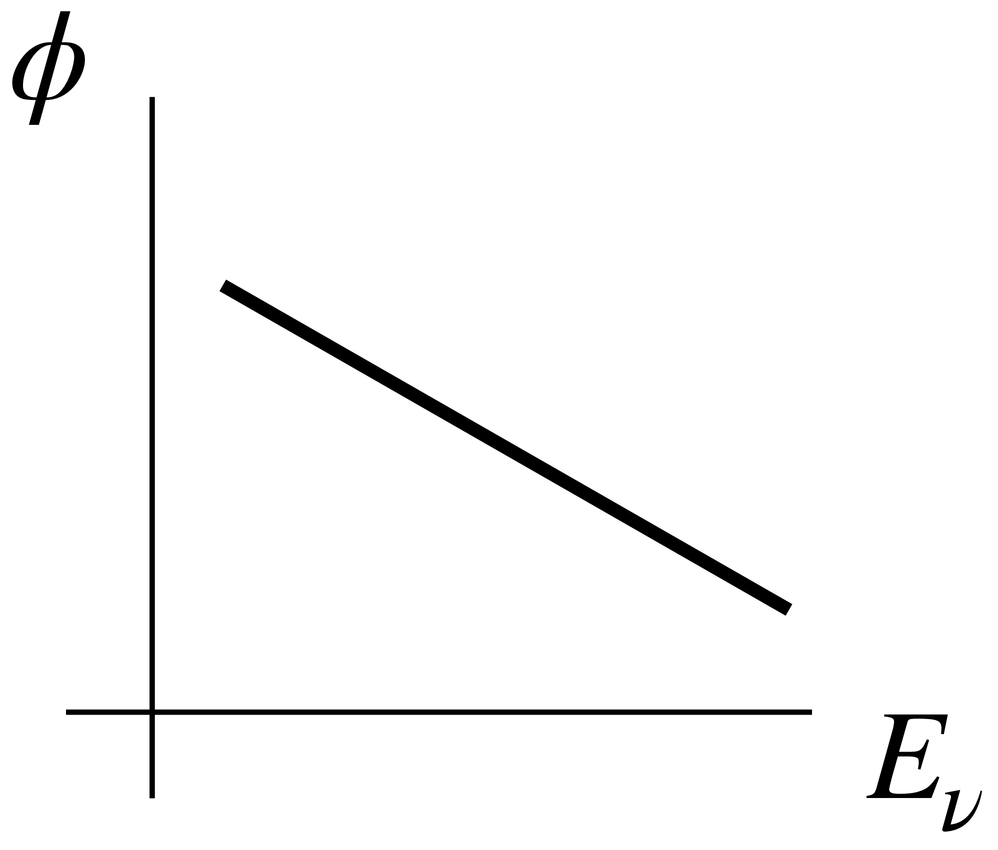
Why High-Energy Neutrinos?

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

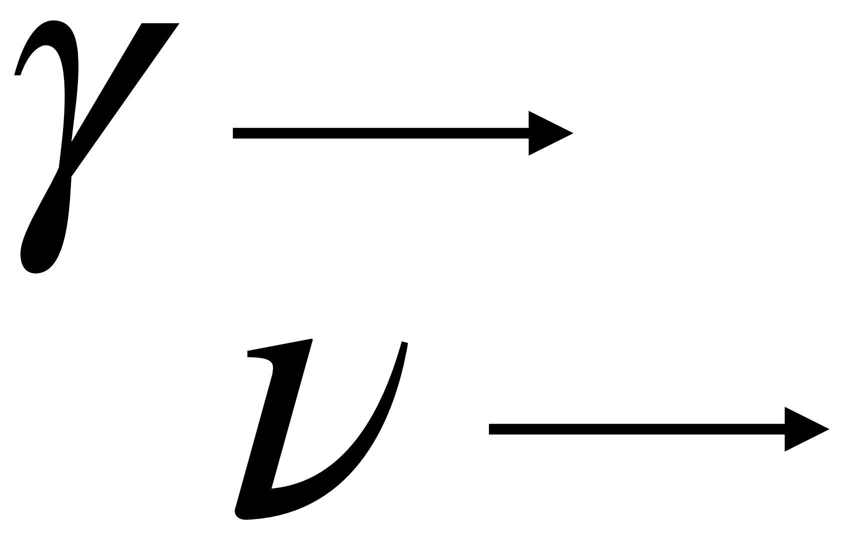
Extreme long baselines

Observing neutrinos
from uncharted territories

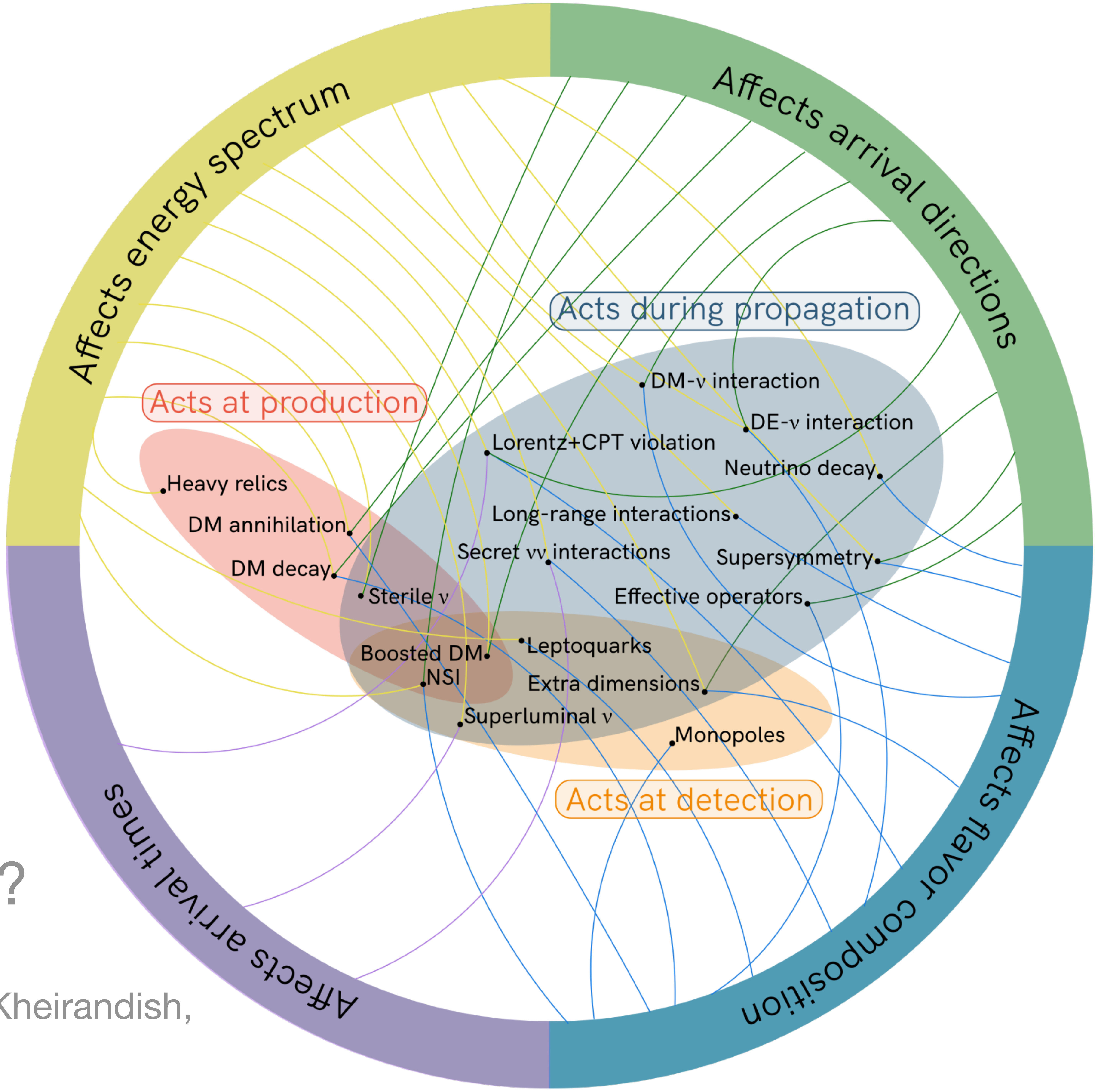
Observables and Models

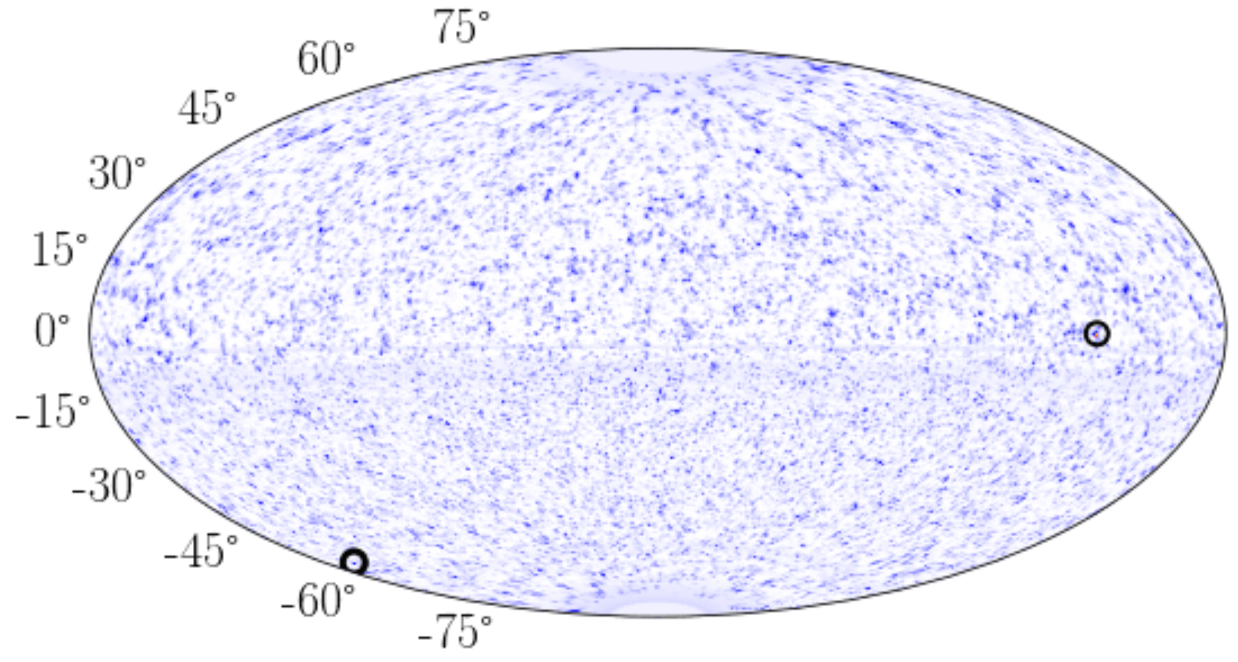


SM: power-law?

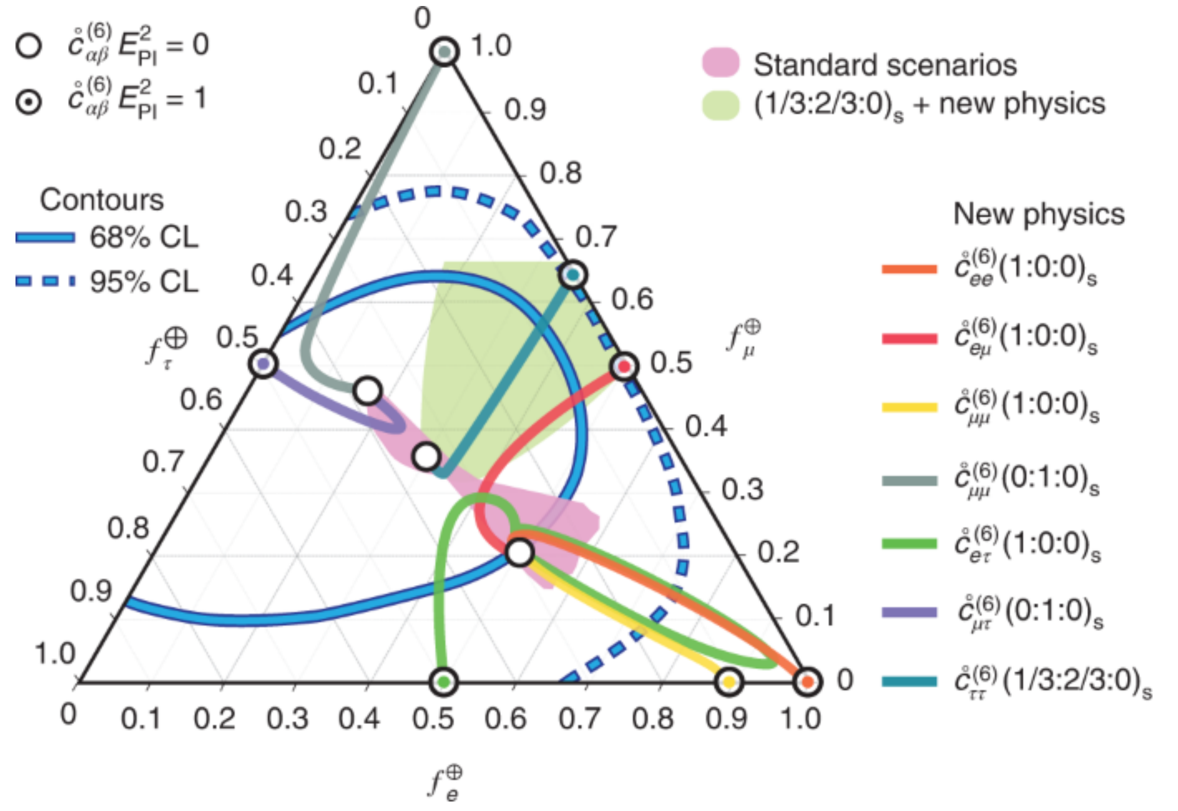


SM: Equal arrival time?





SM: Isotropic?



SM: Equal flavors

More: 1907.08690 CA, Bustamante, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Stops

1. A new frontier in the search for dark matter
2. Using the flavor of neutrinos to find new physics
3. New physics with new sources
4. Future detectors and new ideas

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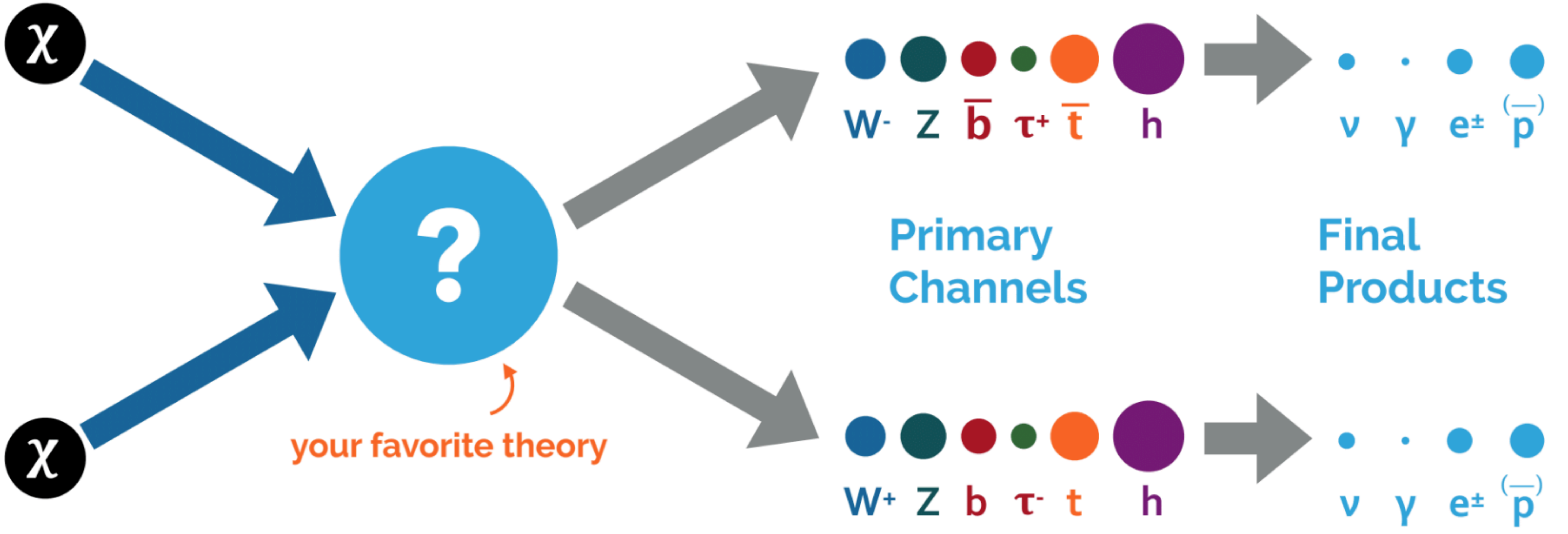
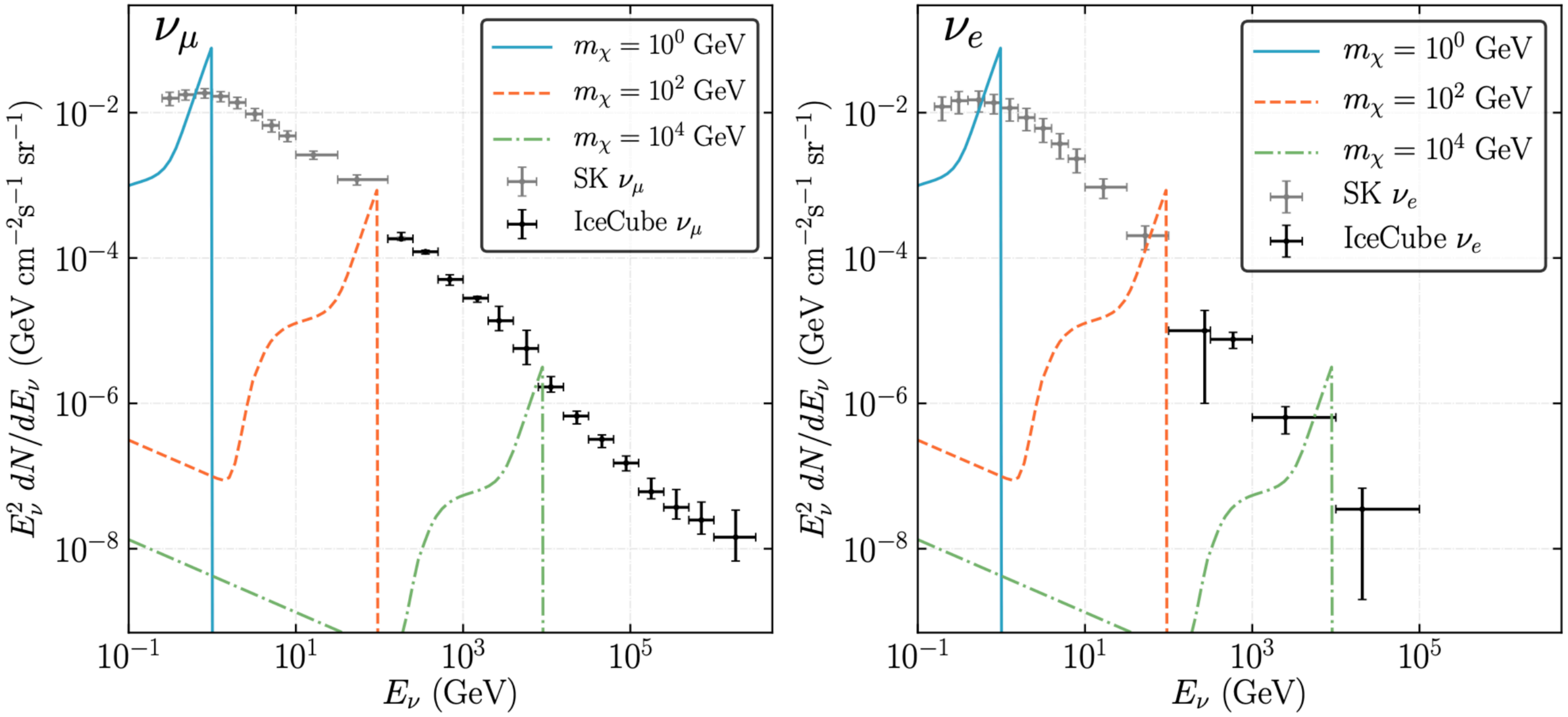
Dark matter annihilation



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 …

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

Background agnostic constraints on Dark matter making neutrinos



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

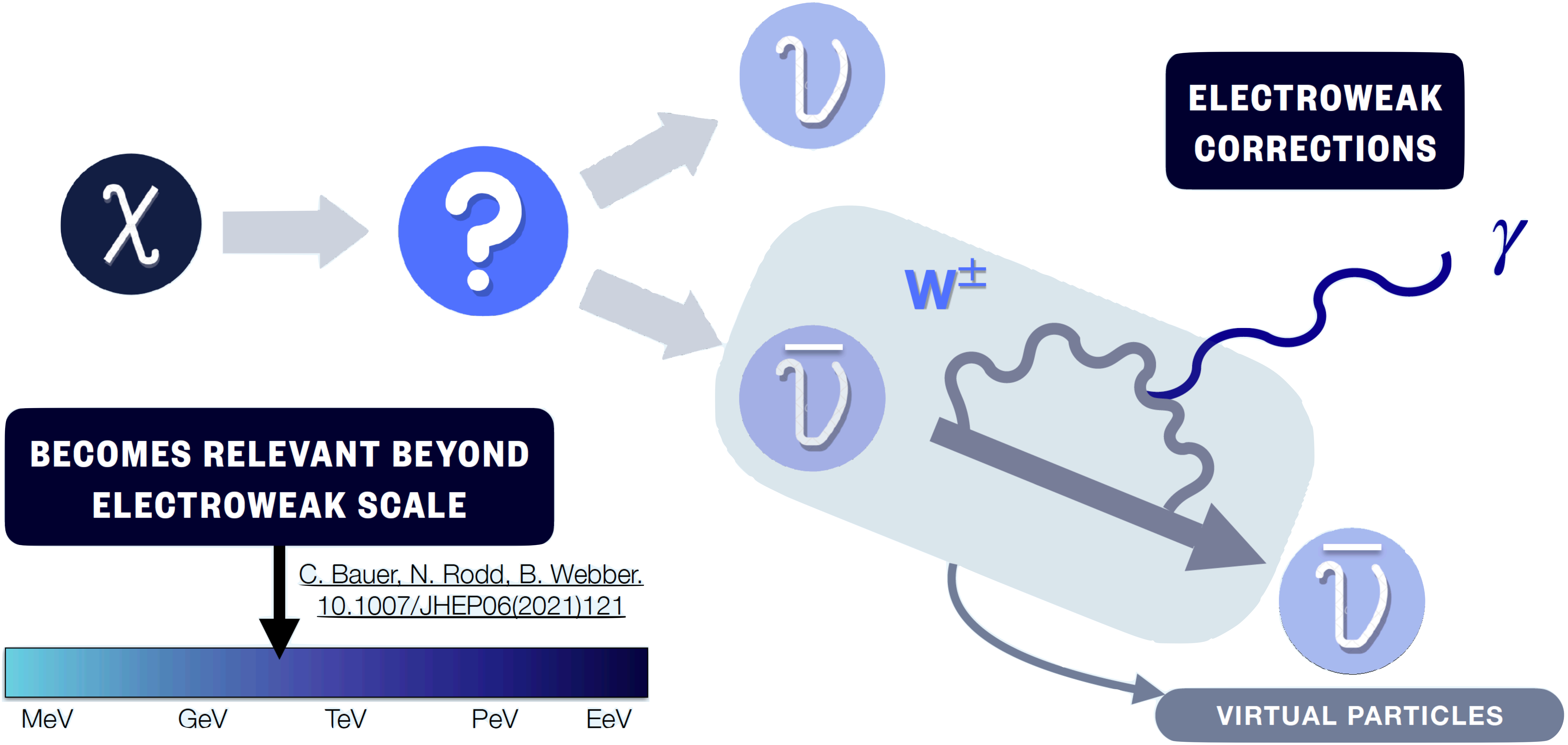
Background Agnostic $\Rightarrow \mathscr{L} = \begin{cases} \mathbb{P}(d\,|\,\mu) & (d < \mu), \\ 1 & (d \geq \mu) \end{cases}$

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.

Gamma-ray experiments will have correlated signals



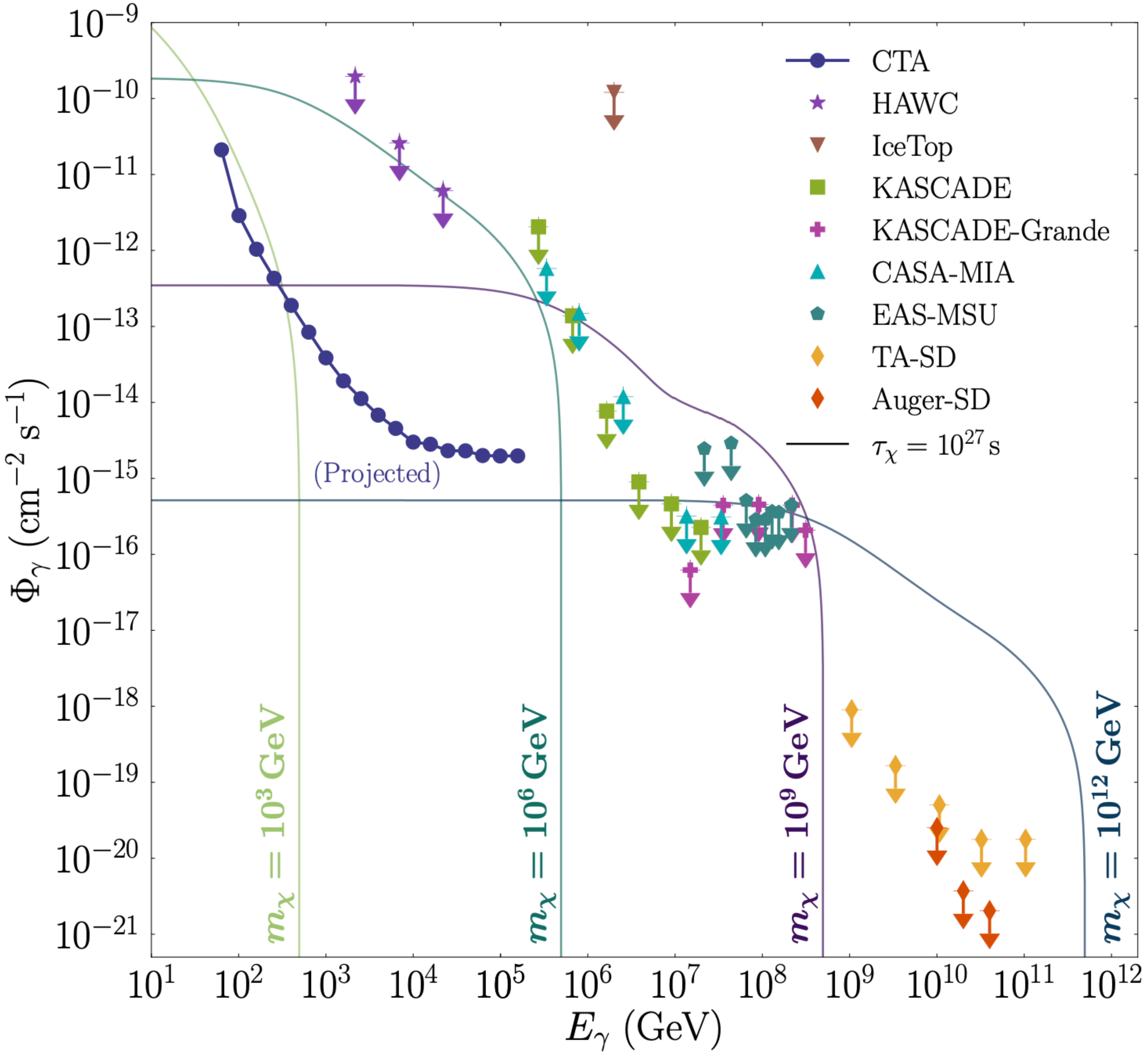
C. Bauer, N. Rodd, B. Webber. 10.1007/JHEP06(2021)121

The energy-scale in this process is set by the DM mass, which can be above EWSB, where bosons are massless.

Background agnostic constraints on Dark matter making neutrinos

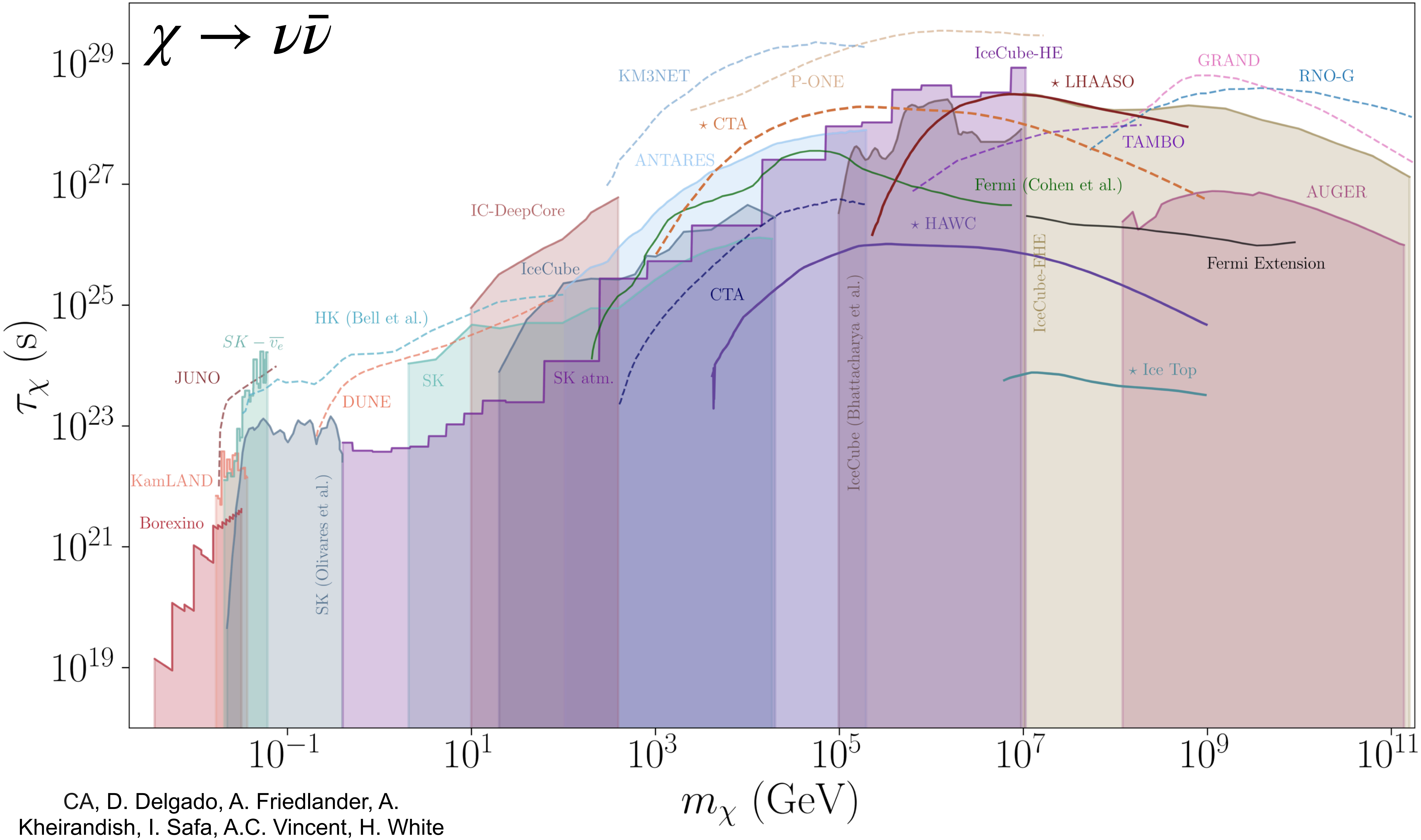
$10^{-1} - 10^{2}$	Fermi-LAT [63]
$10^{3} - 10^{9}$	*CTA* [64]
$10^{4} - 10^{9}$	HAWC [65]
$10^{5} - 10^{9}$	LHAASO [66]
$10^{6} - 10^{9}$	IceTop [67]
$10^{7} - 2 \times 10^{9}$	KASCADE [68]
$10^{8} - 2 \times 10^{10}$	CASA-MIA [69]
$10^{9} - 2 \times 10^{12}$	EAS-MSU [70]
$10^{11.5} - 10^{14}$	TA-SD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

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 …



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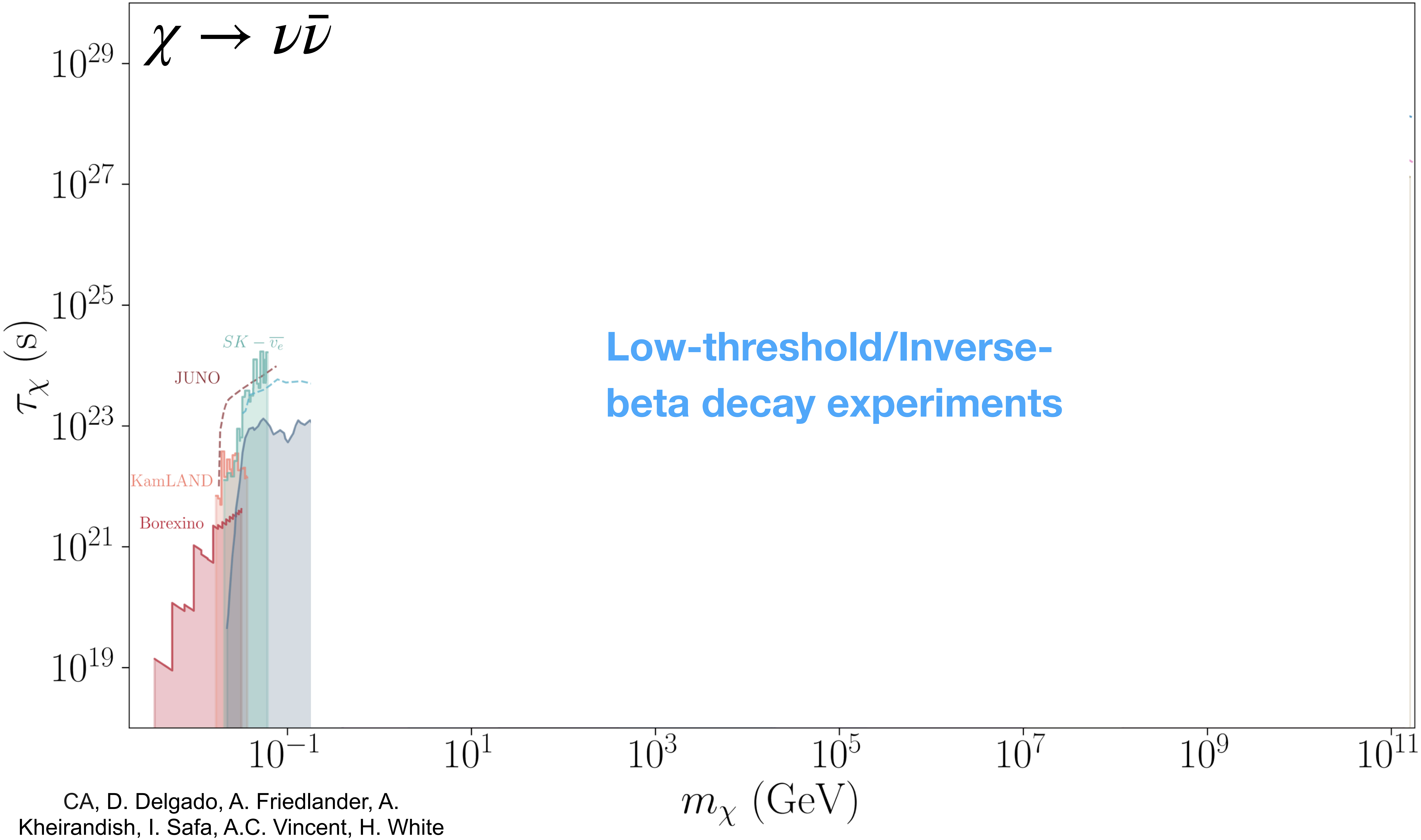
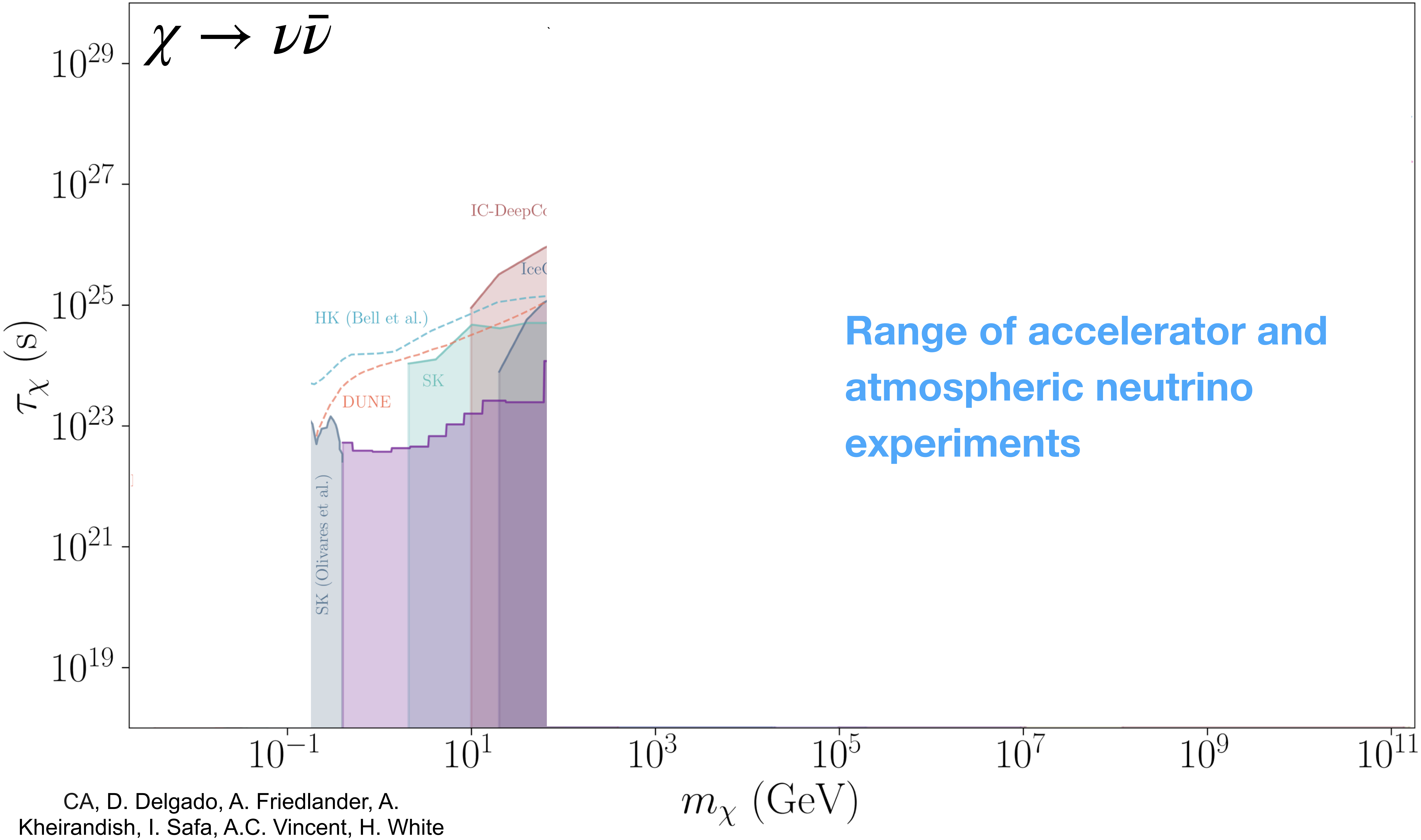


Low-threshold/Inverse-beta decay experiments

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

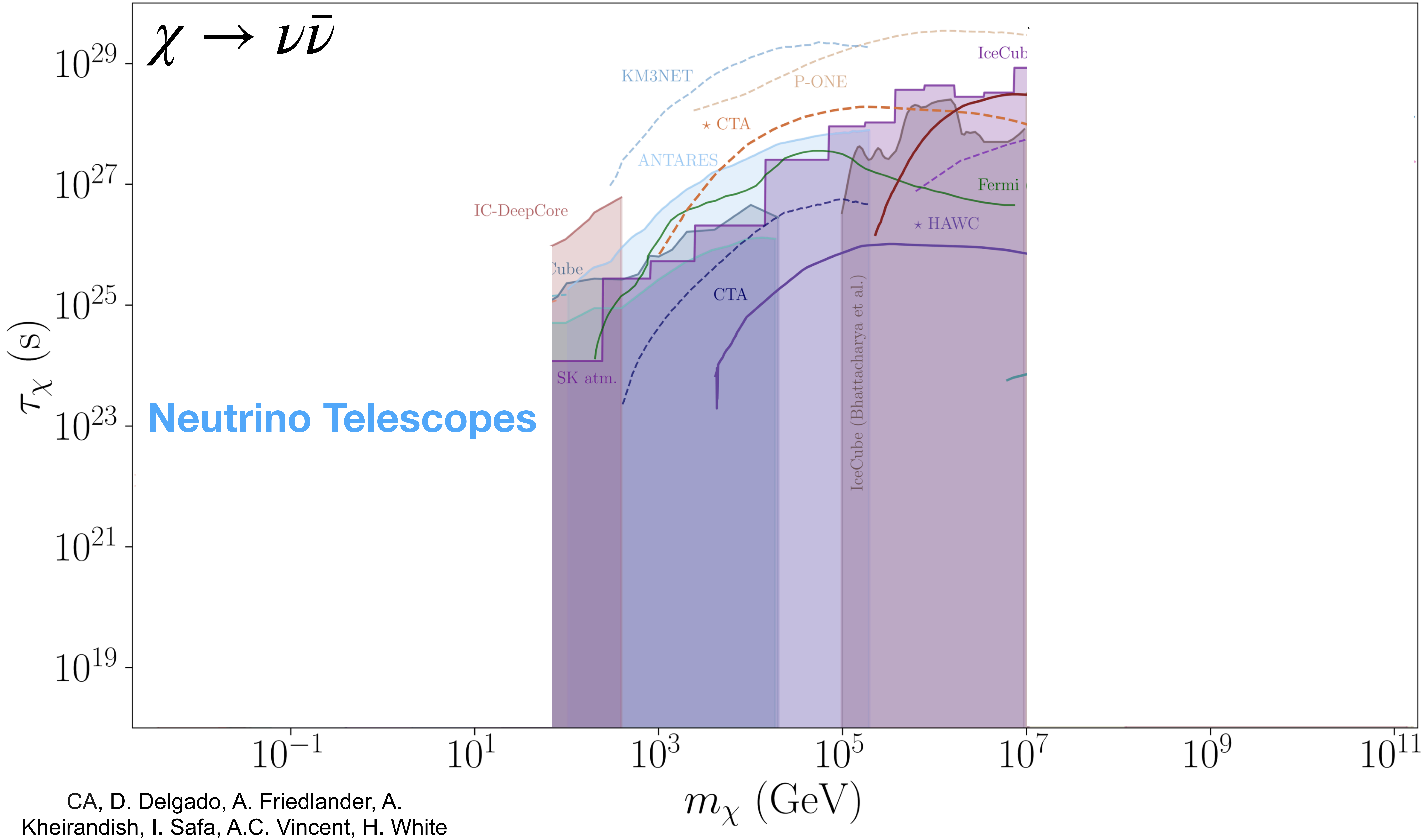
And many more measurements …



Range of accelerator and atmospheric neutrino experiments

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

And many more measurements …



Neutrino Telescopes

CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White
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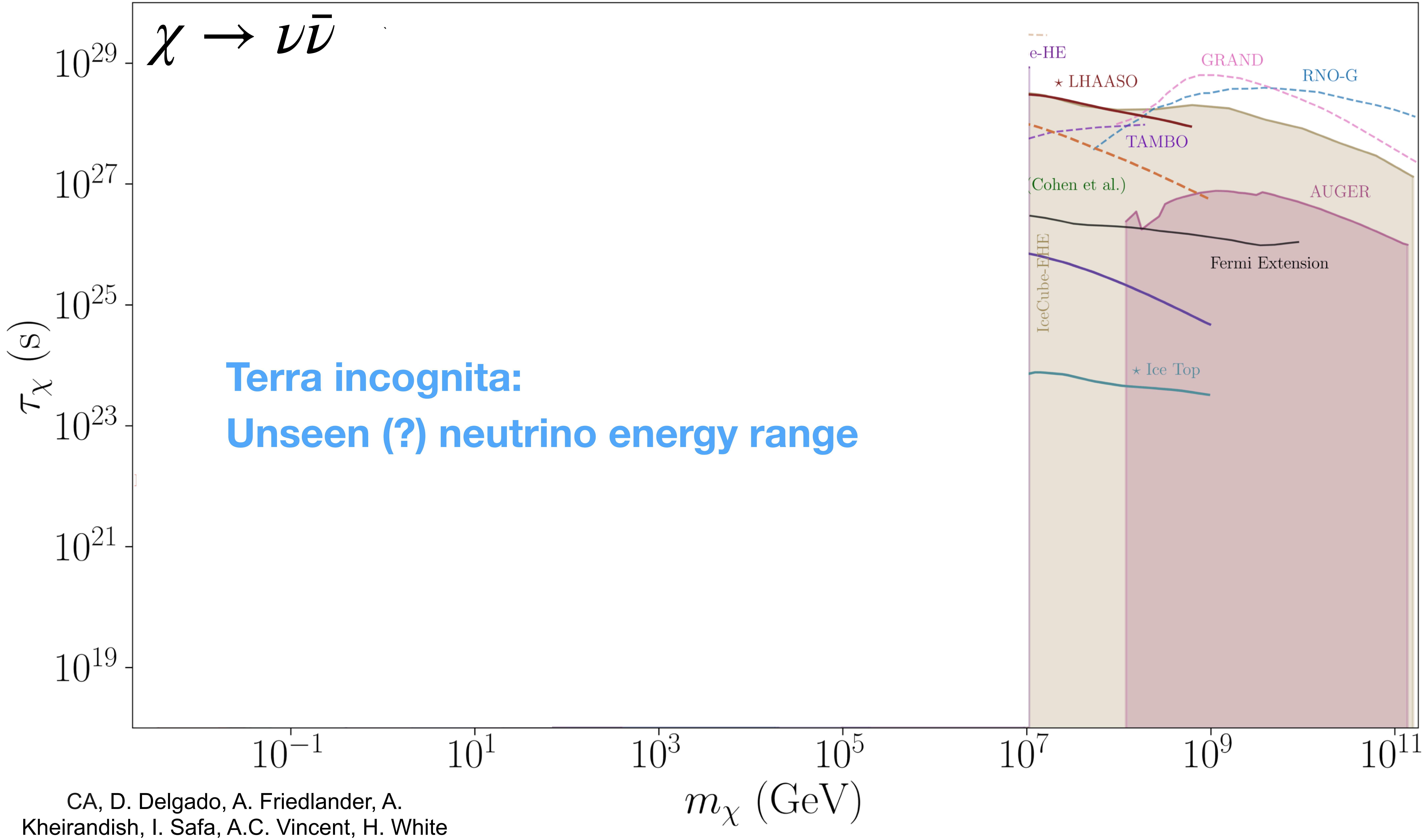
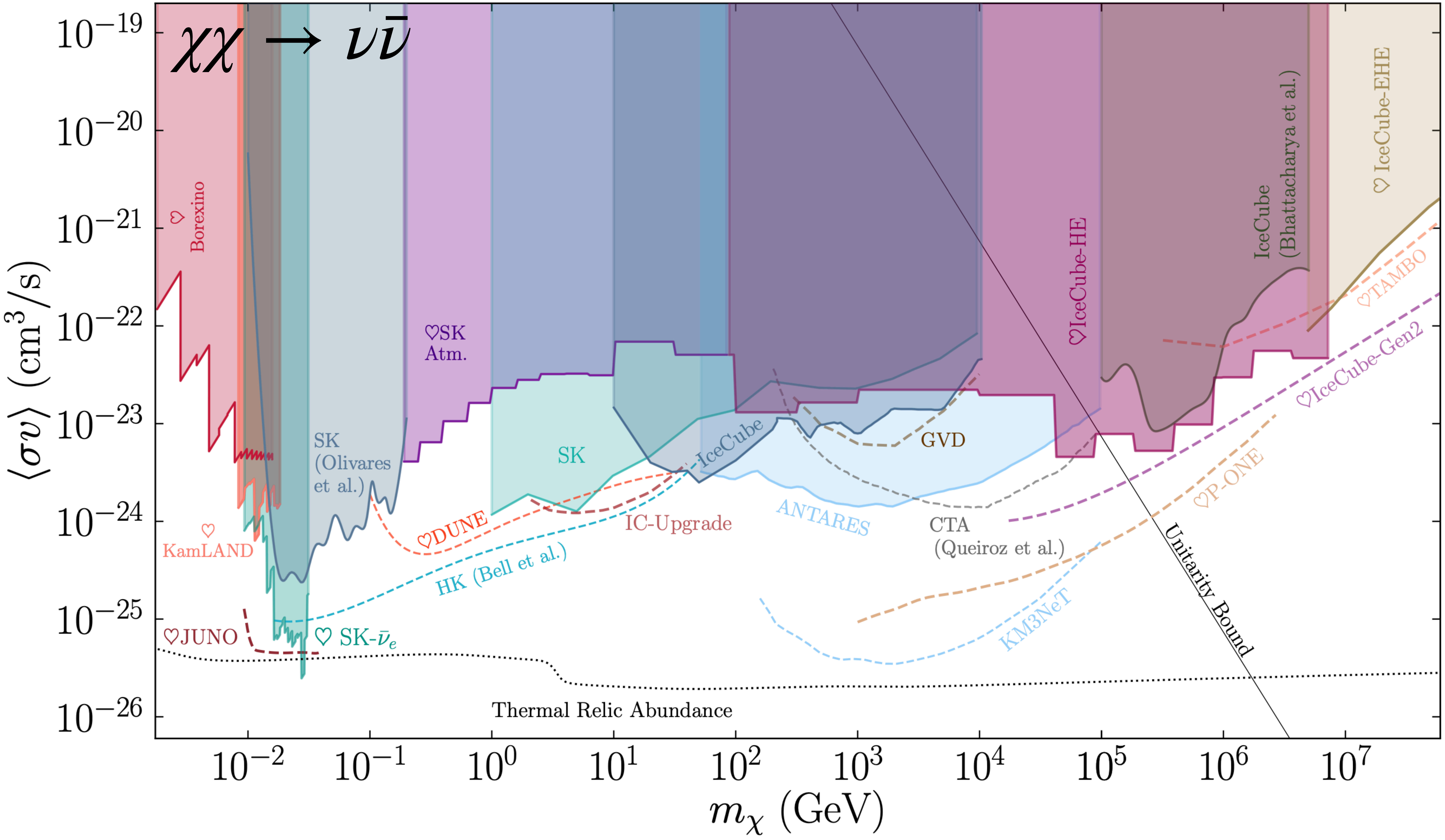
And many more measurements …



Terra incognita:
Unseen (?) neutrino energy range

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

Dark matter annihilation to neutrino: a largely unexplored frontier

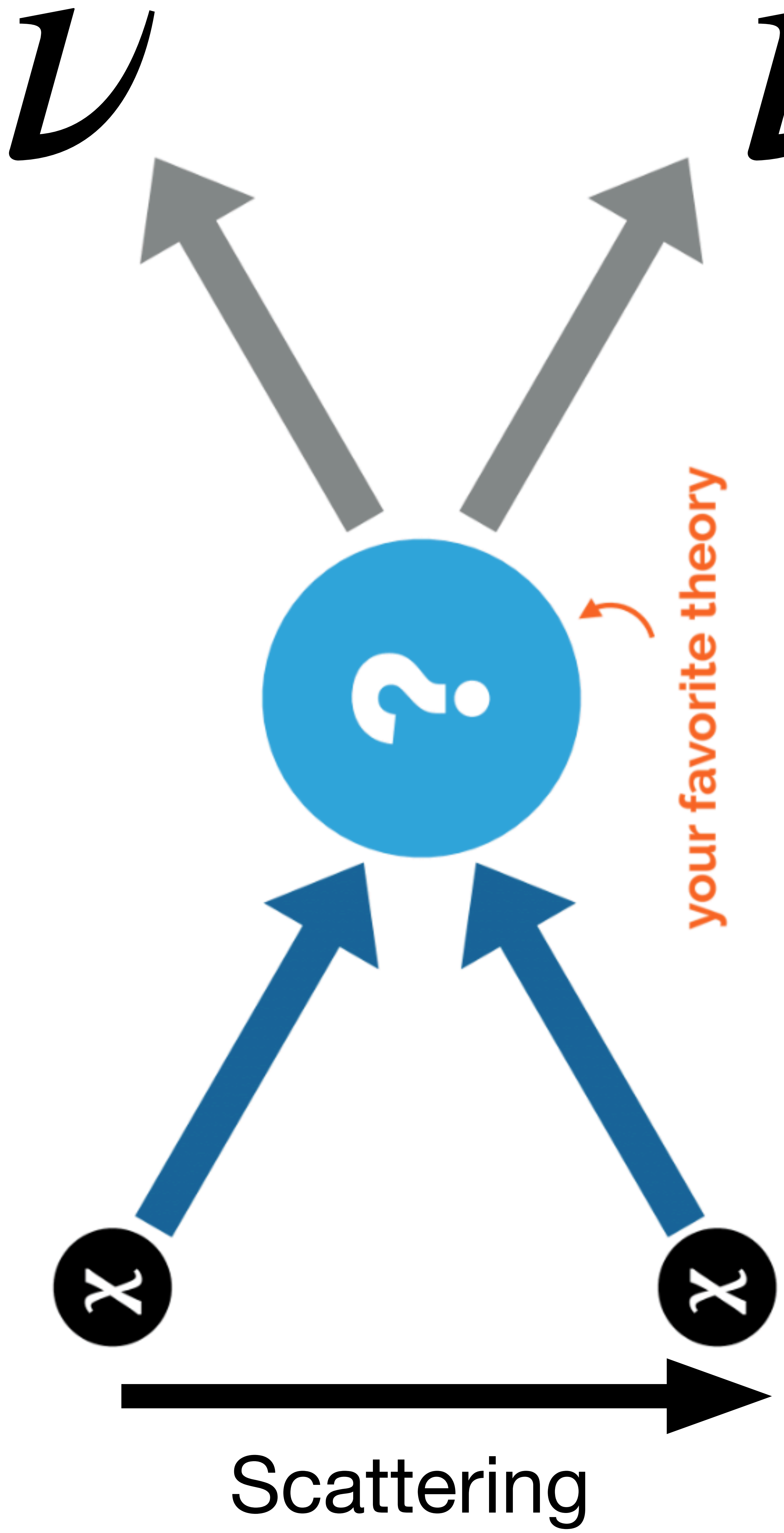


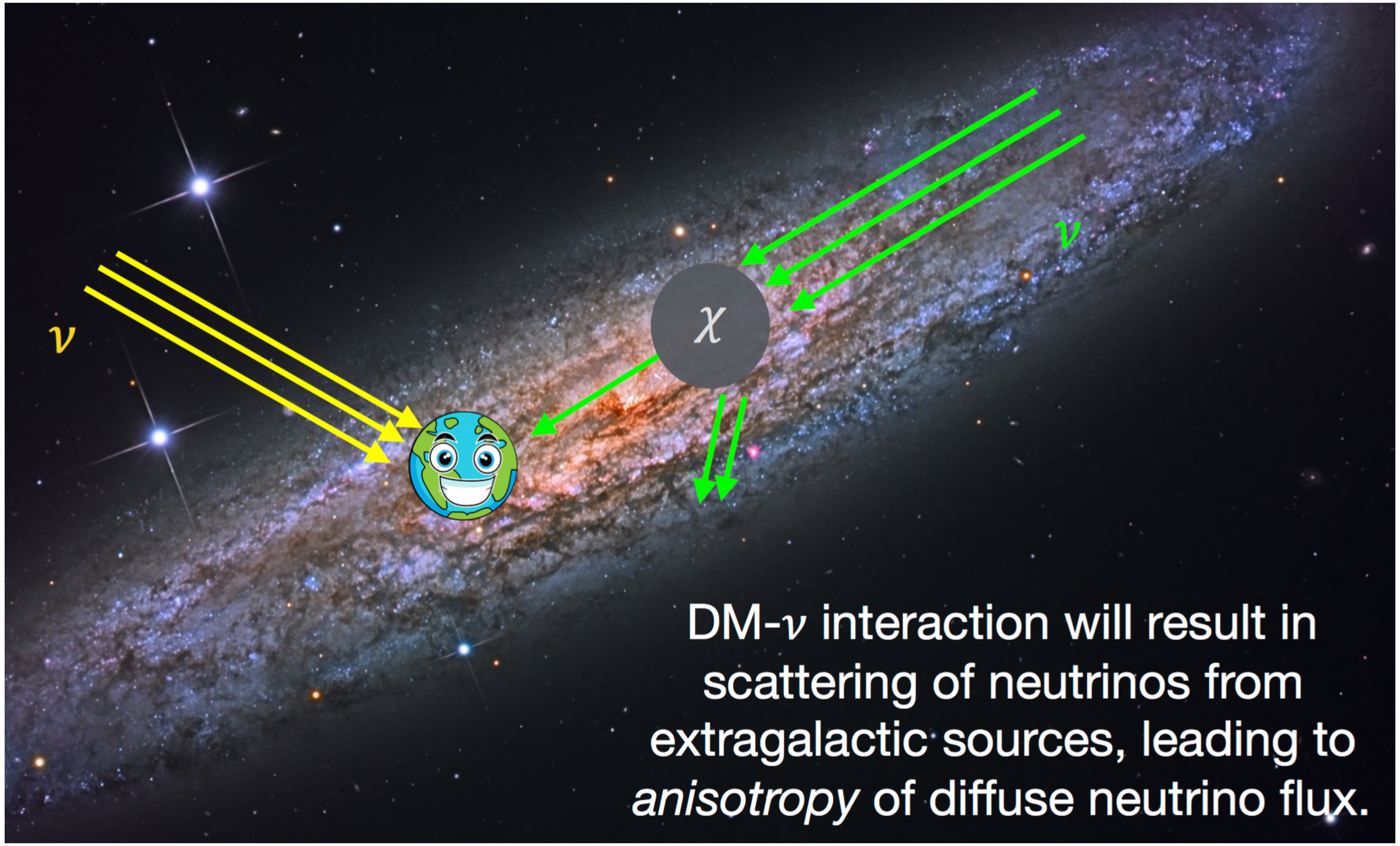
CA, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa, A.C. Vincent *Rev. Mod. Phys. 93, 35007 (2021)*;

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

See also CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White (arXiv:2210.01303) for a recent review focused on dark matter decay

Dark matter scattering with neutrinos

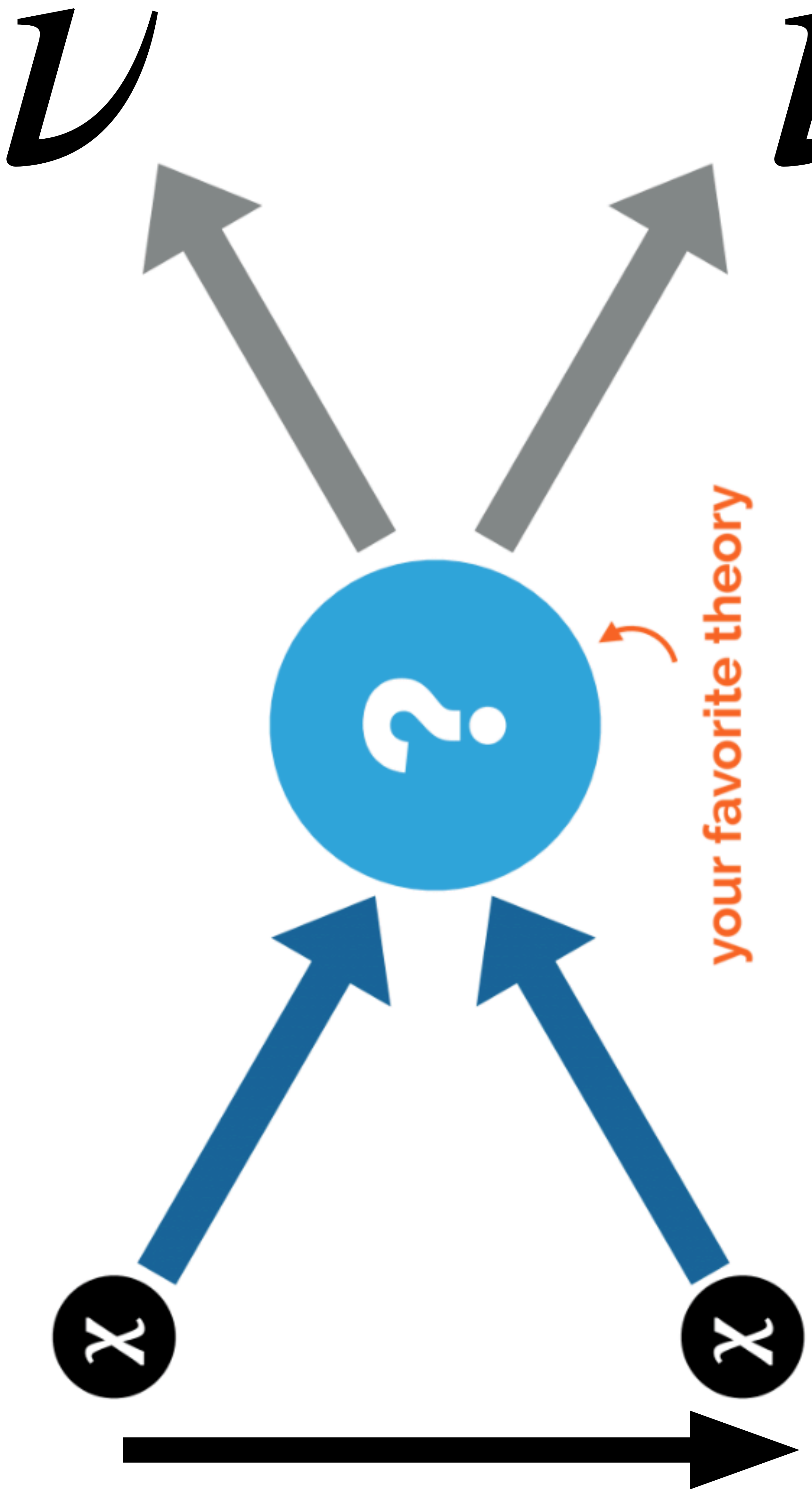




DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to *anisotropy* of diffuse neutrino flux.

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

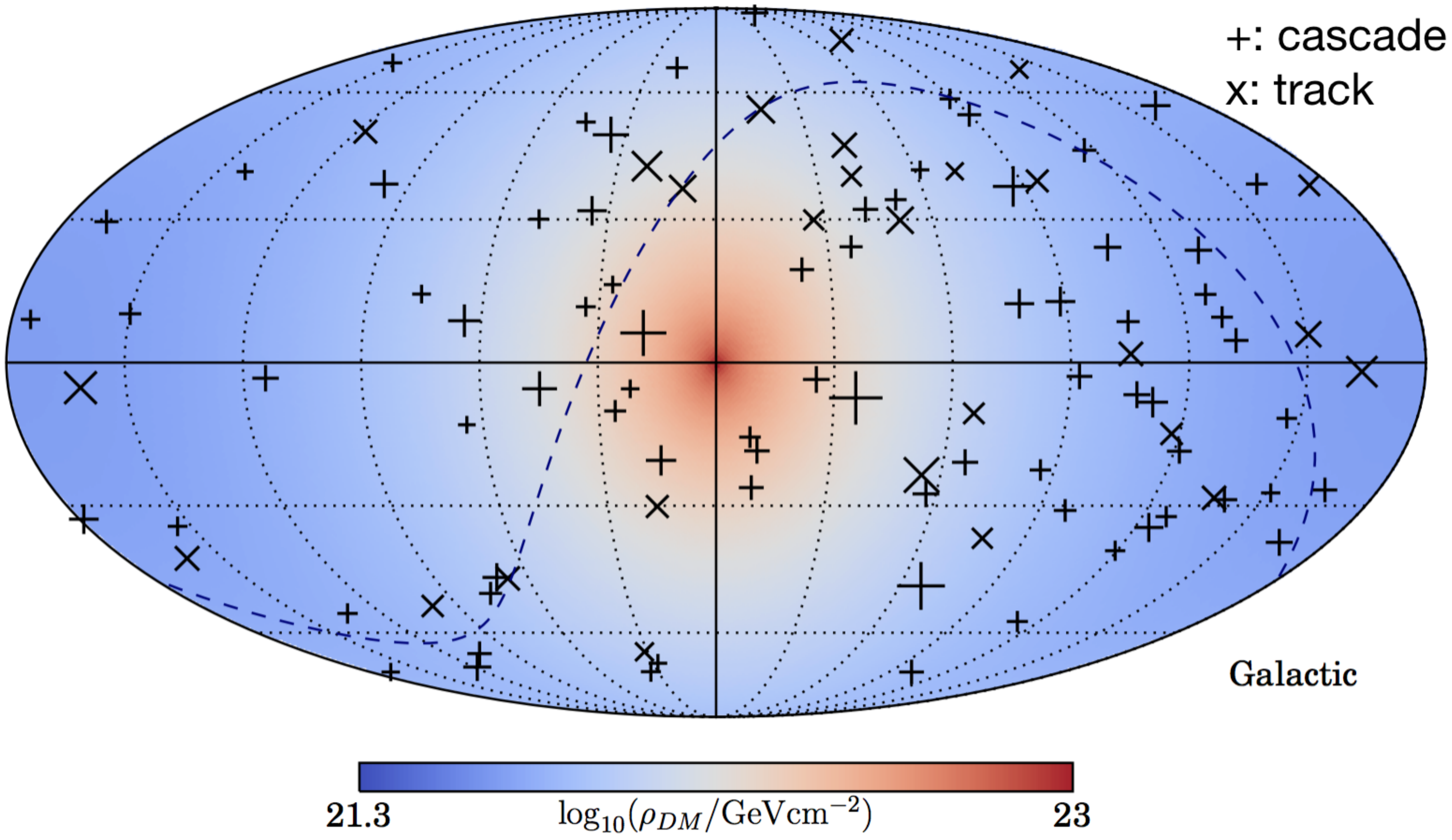
Dark matter scattering with neutrinos



Scattering

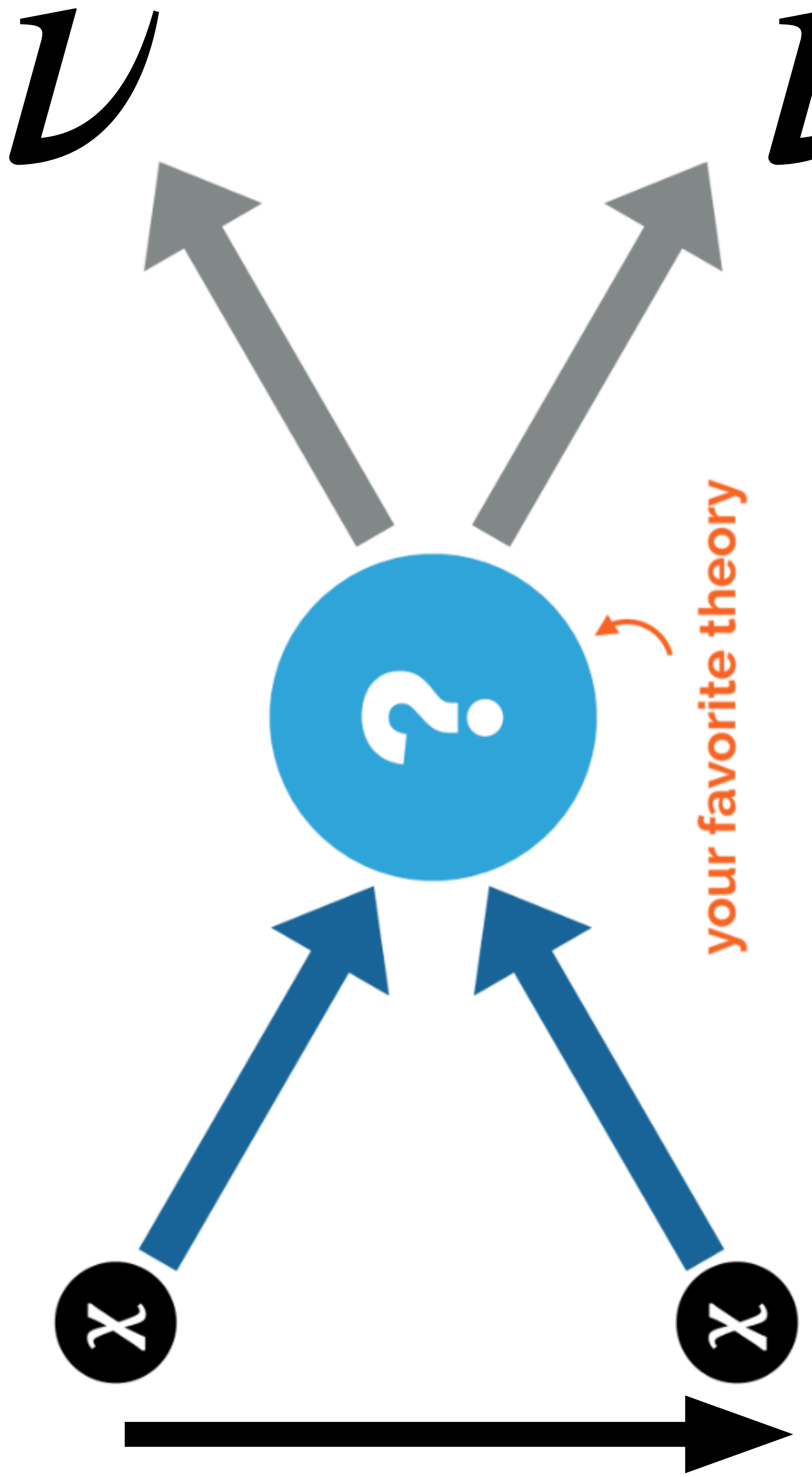
IceCube Collaboration, arXiv:2205.12950

HESE: high-energy starting events



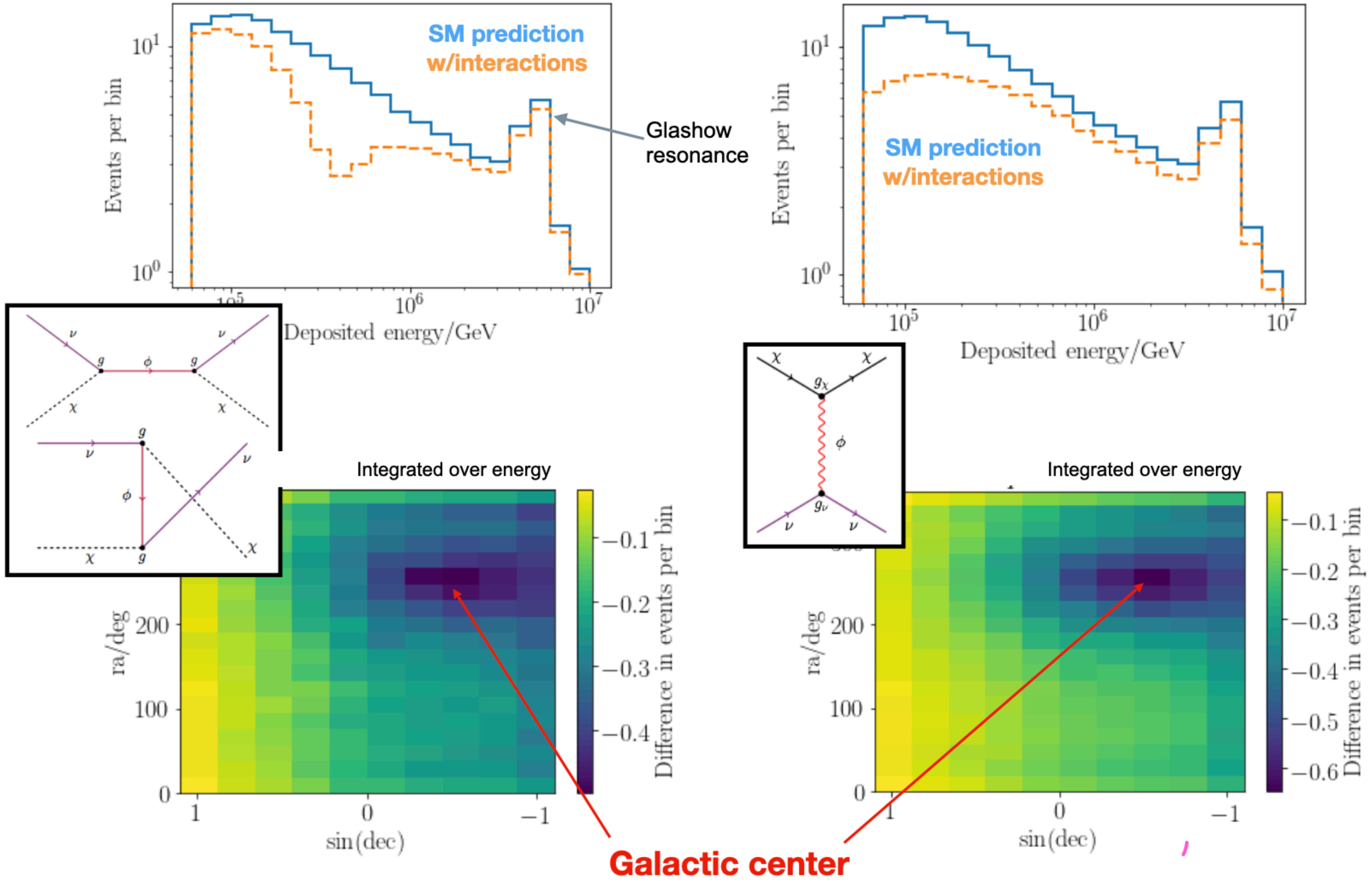
CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

Dark matter scattering with neutrinos



Scattering

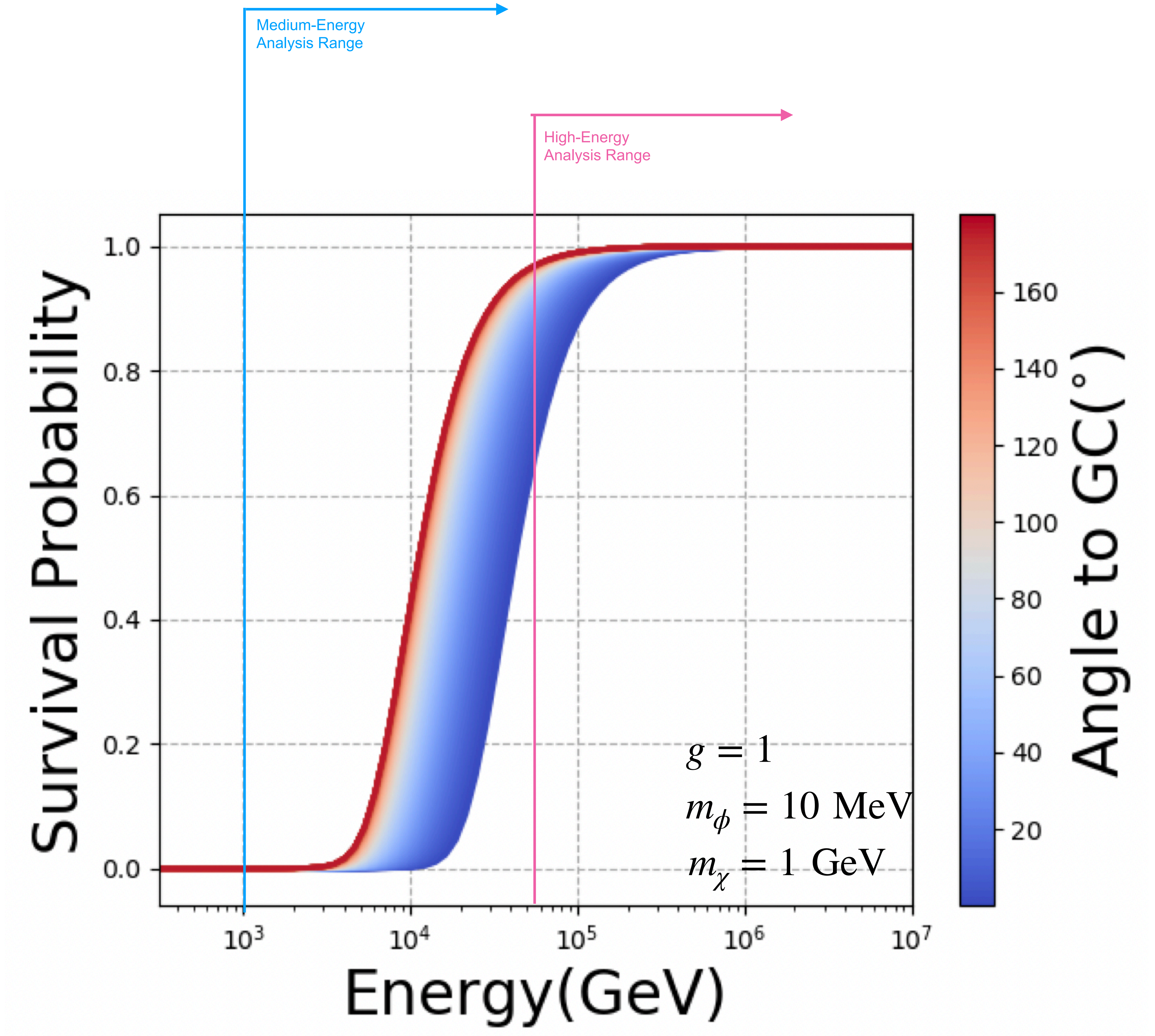
$E_\nu > 60$ TeV



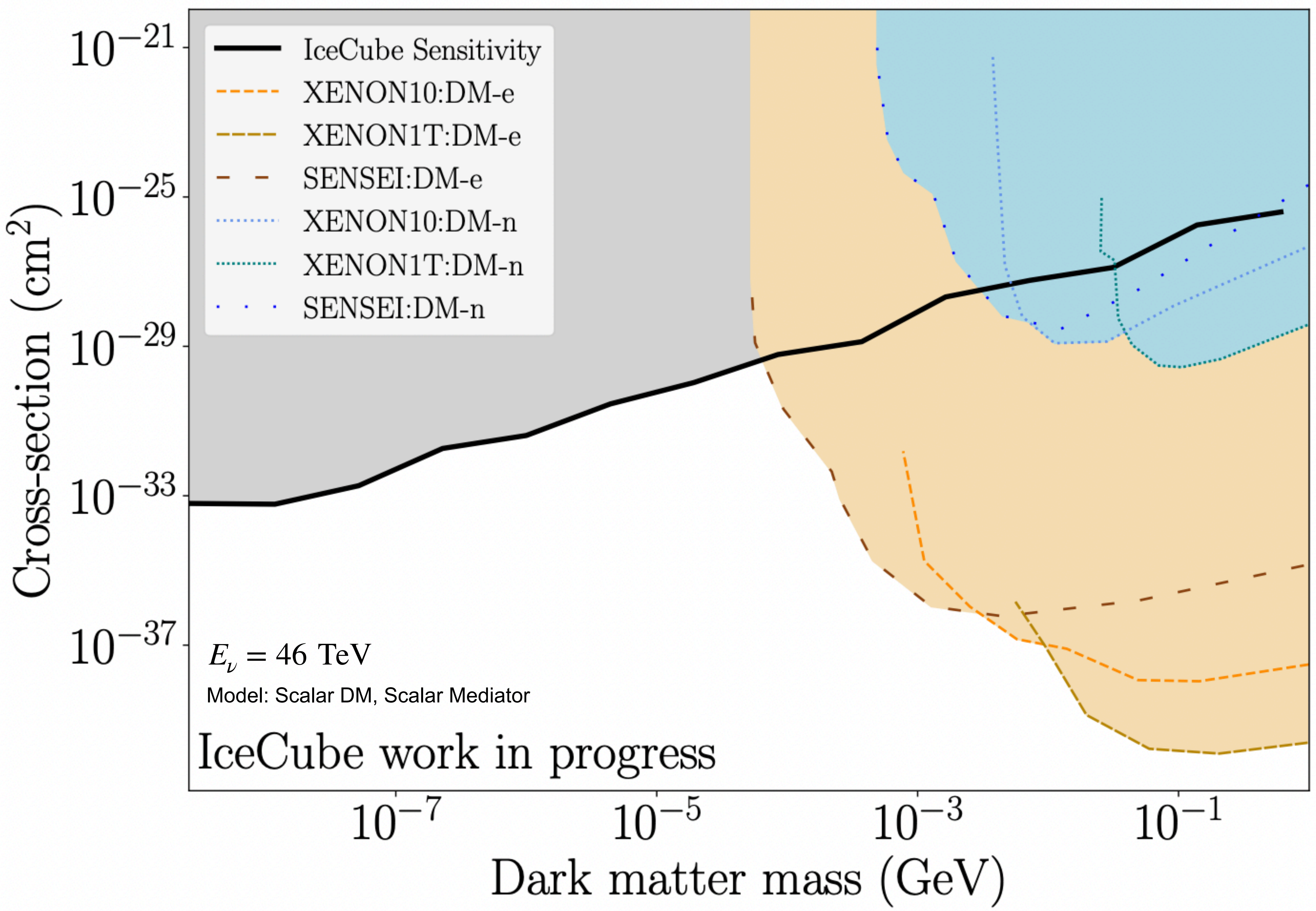
Constraints comparable to cosmology

Dark matter scattering with neutrinos: new analysis!

Work by Diya Delgado



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

1. A new frontier in the search for dark matter
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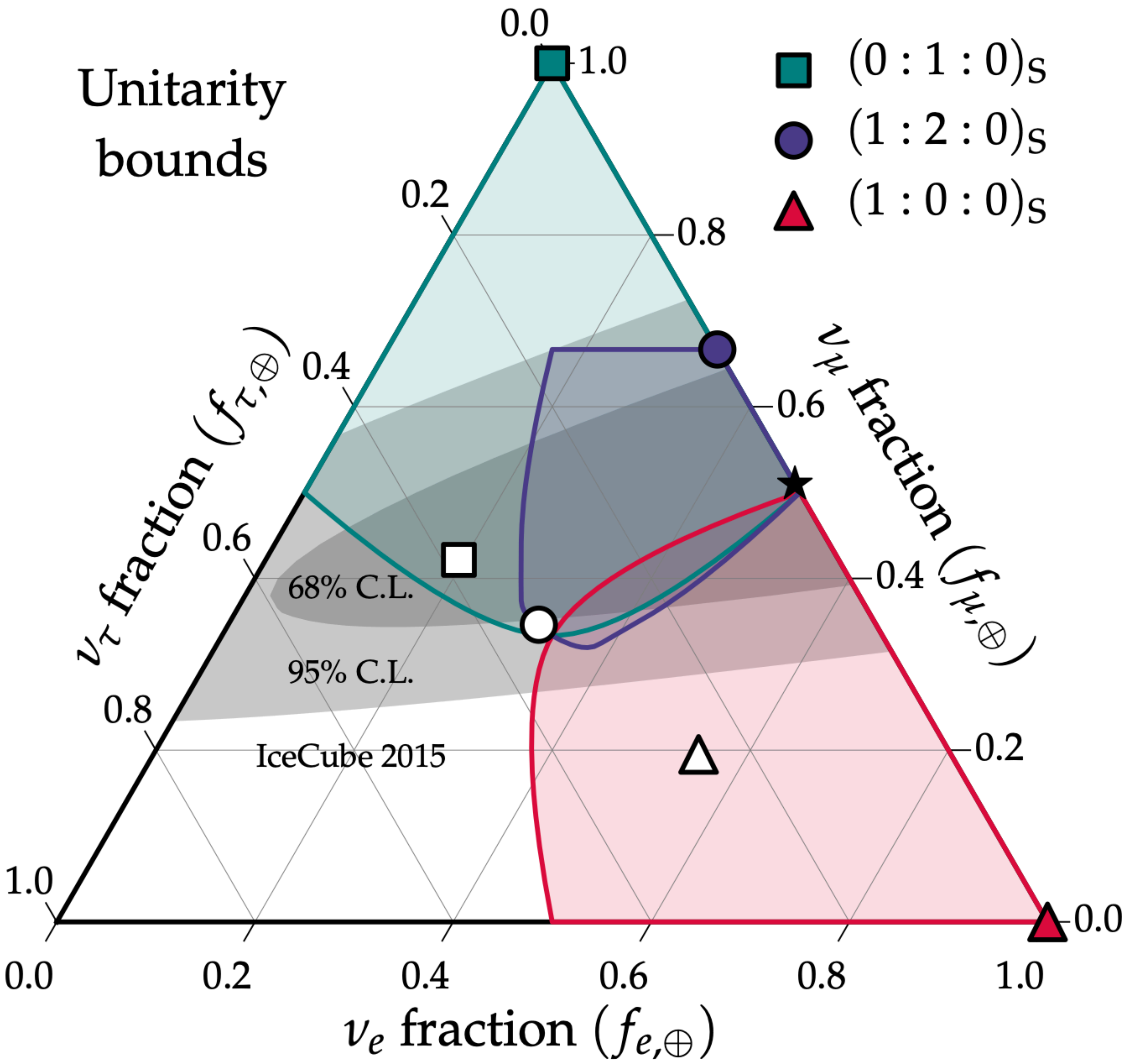
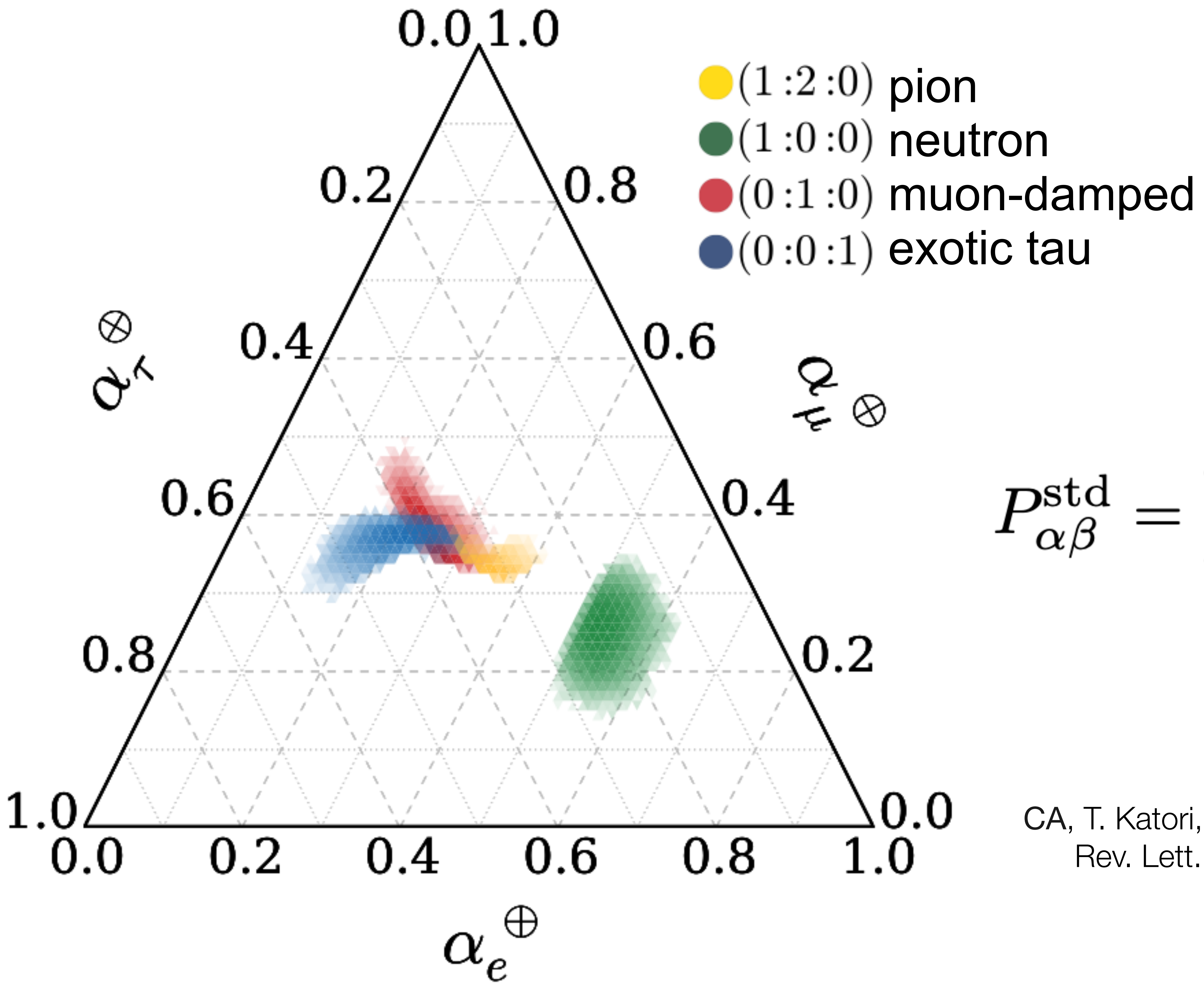
Unitarity



Ahlers, Bustamante, and Mu arXiv:1810.00893

After oscillations where will the difference sources end up?

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



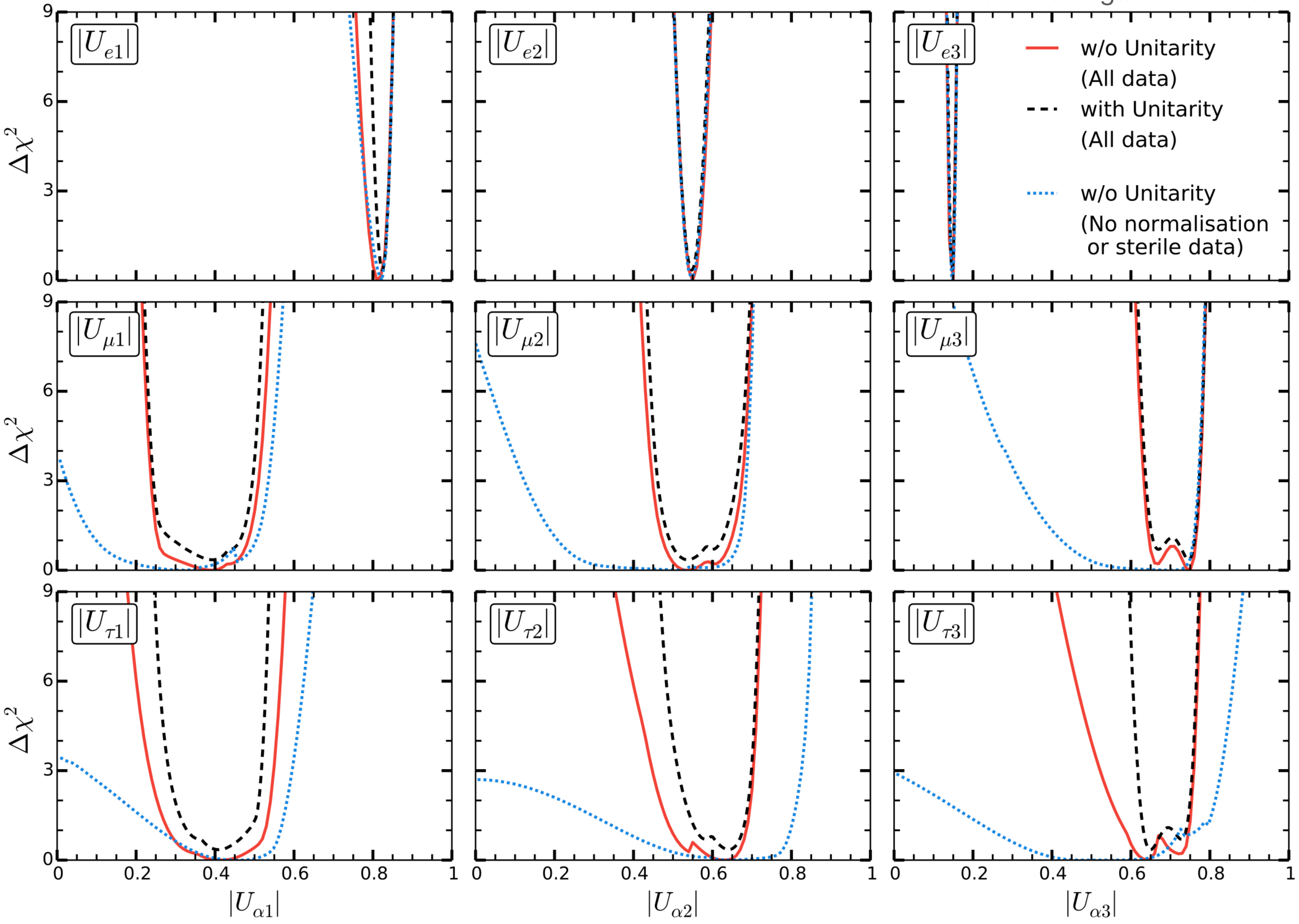
$$P^{\rm std}_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

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

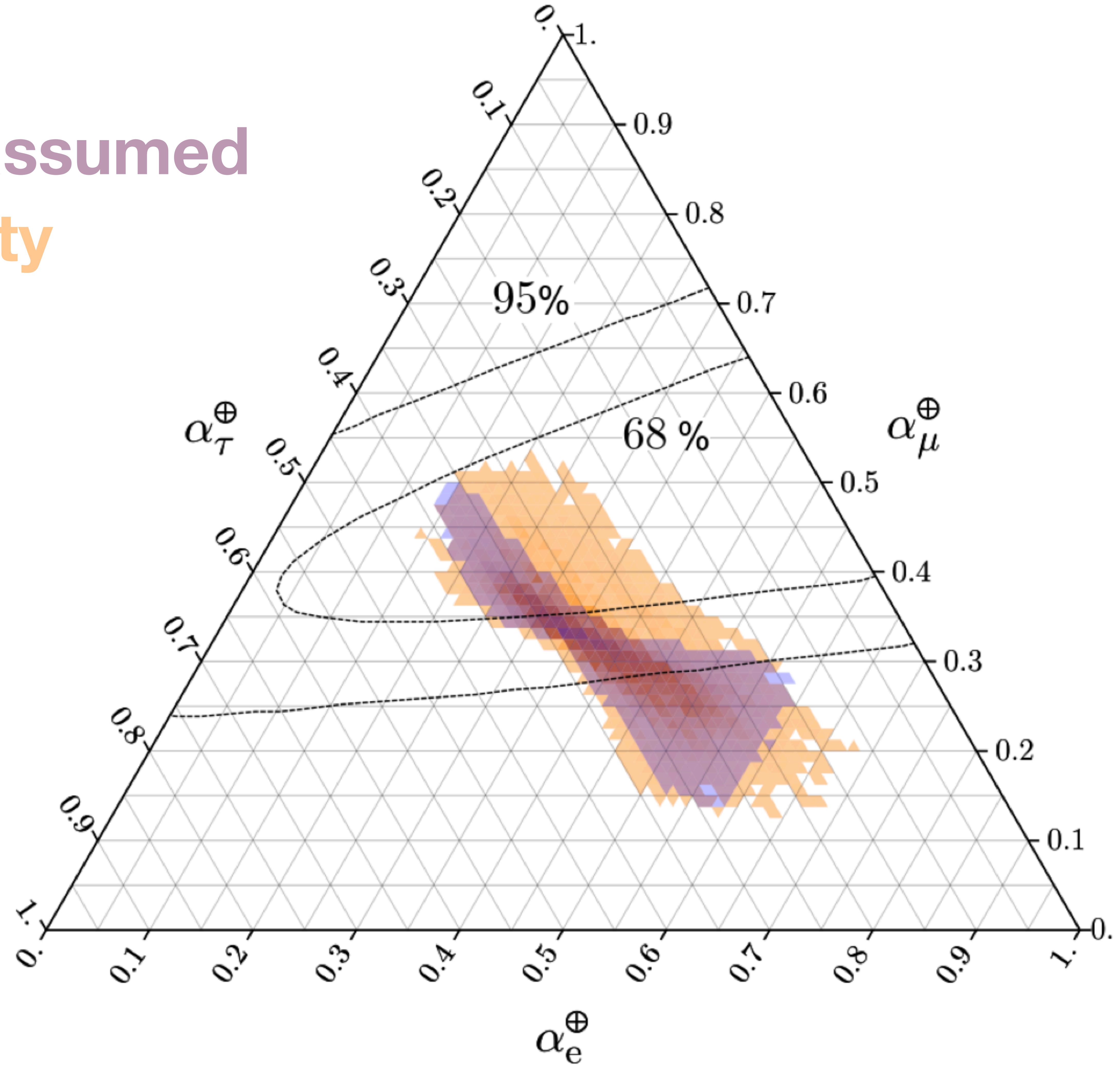


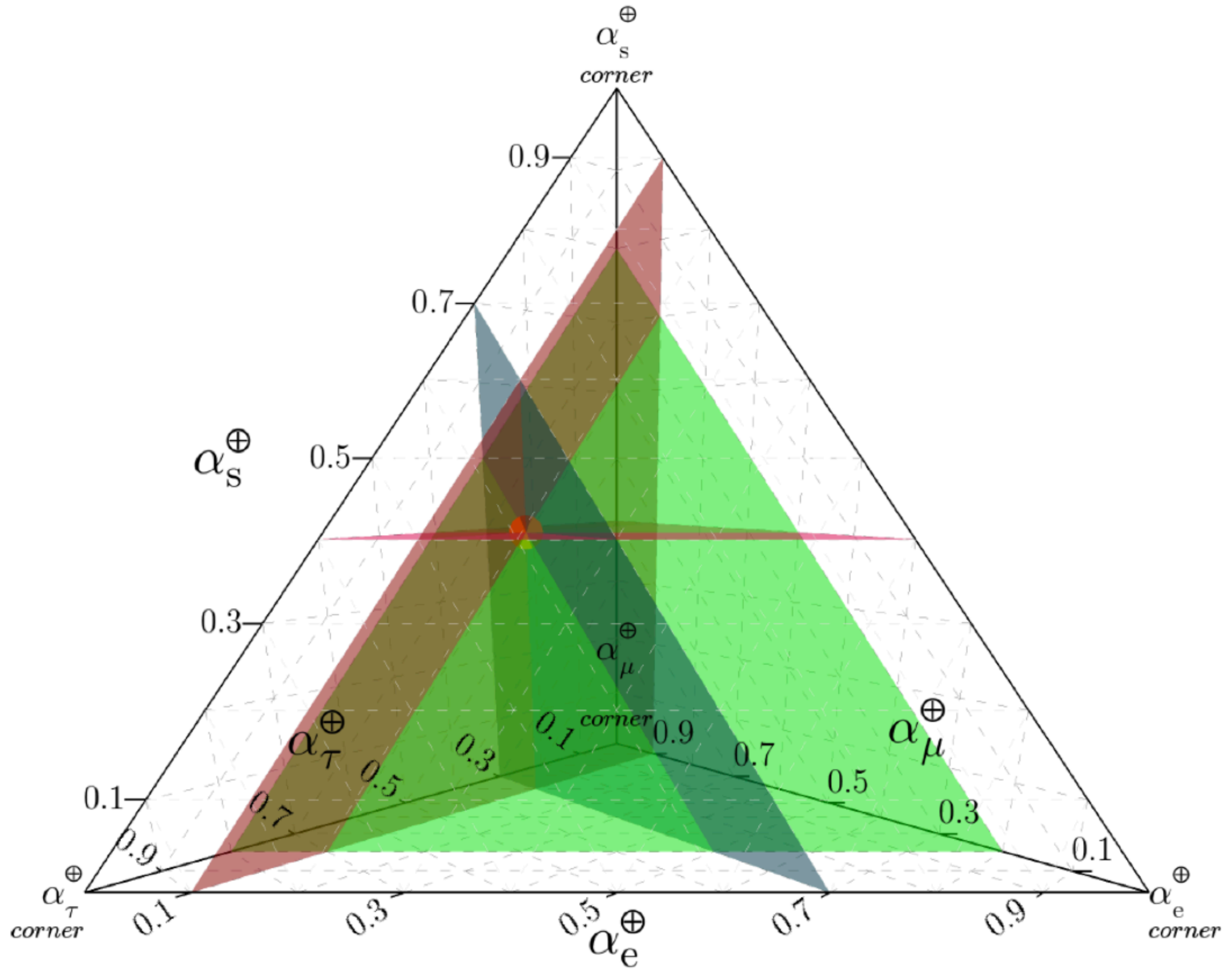
Tau-row largerly unconstrainted without unitarity assumption

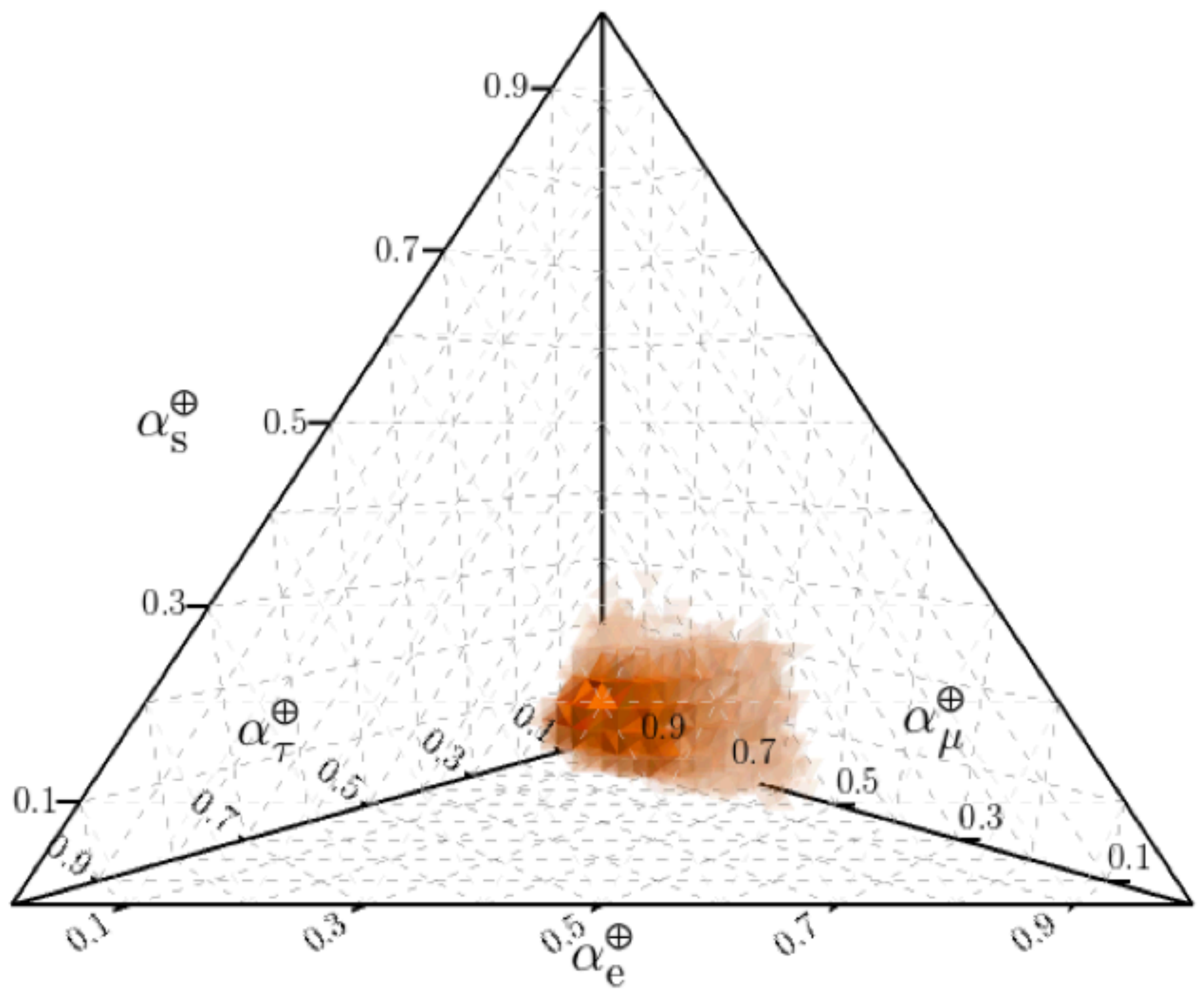
Non-unitarity

Unitarity assumed

No-unitarity



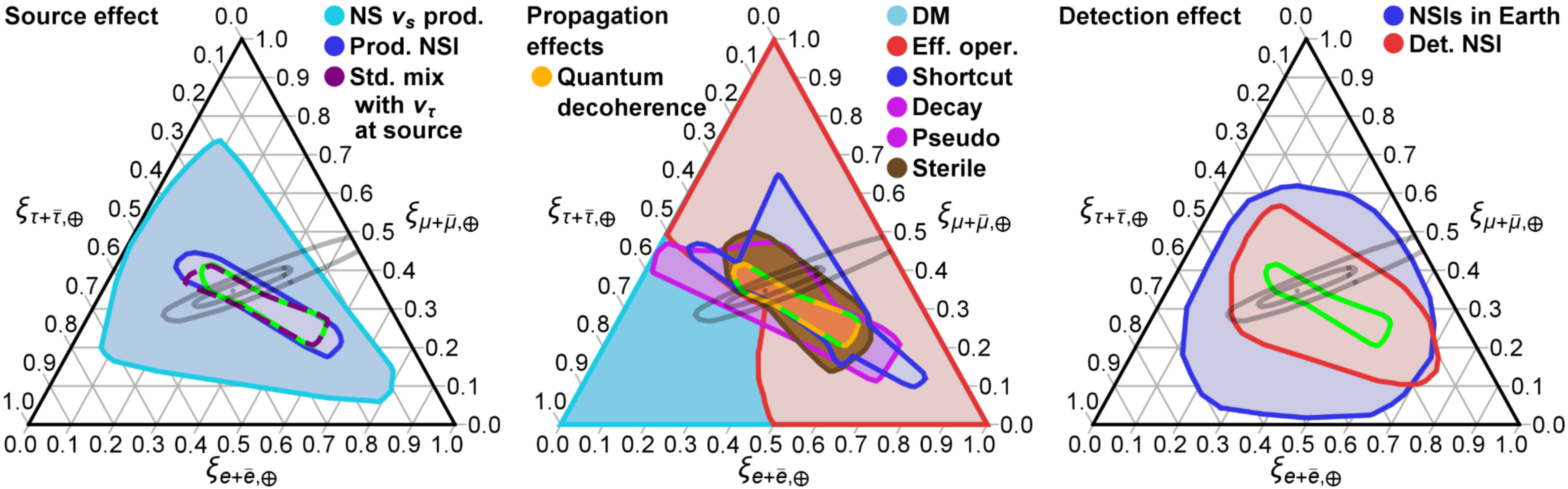




CA, Farrag, Katori, Khandelwal, Mandalia, Salvado arXiv:1909.05341

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

Search for Lorentz Violation via Flavor Morphing

As neutrinos travel from their far away source they can interact with fields in space.

Example: spontaneous Lorentz violation.

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)

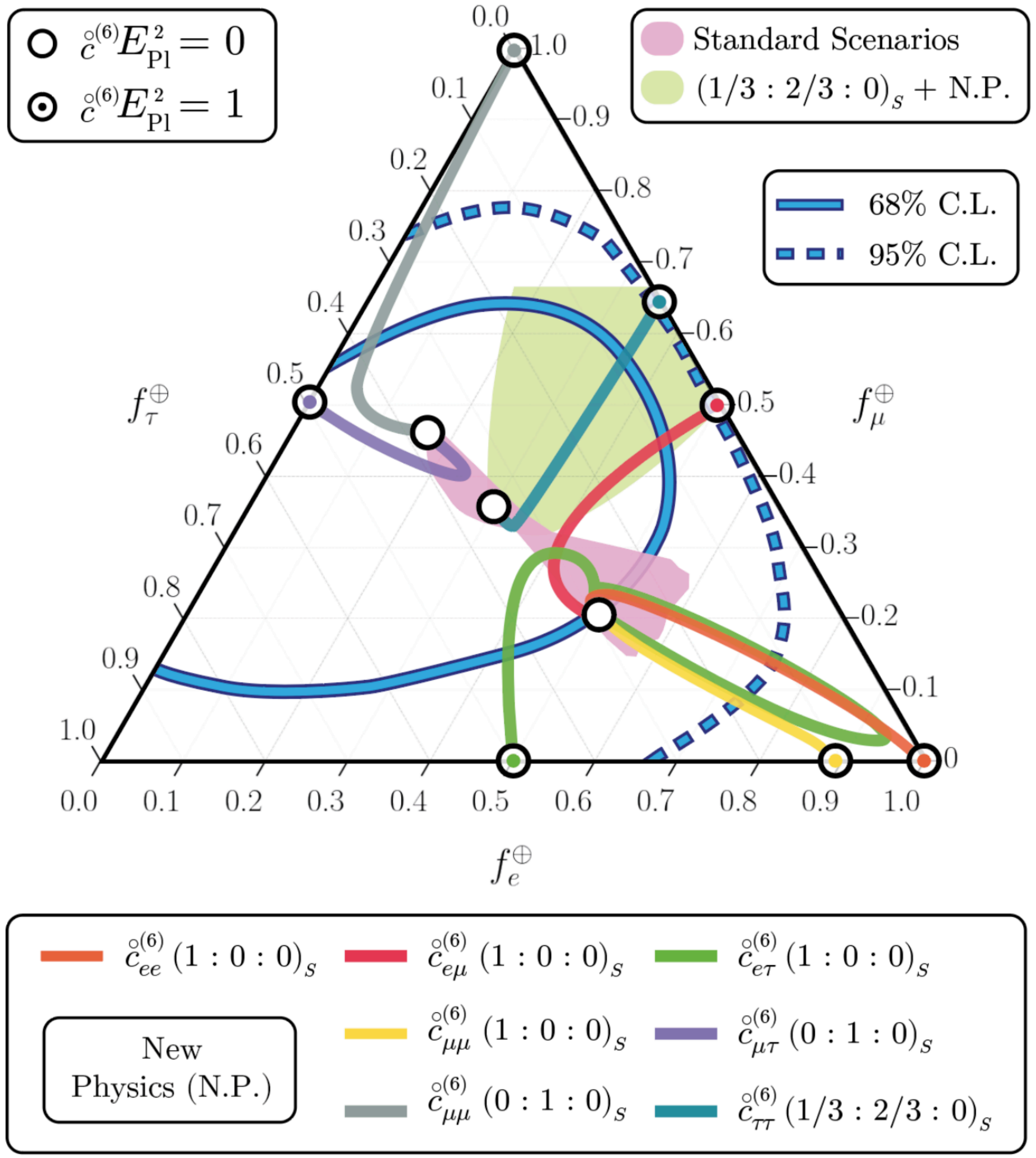
New Physics Terms

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

Standard Mixing

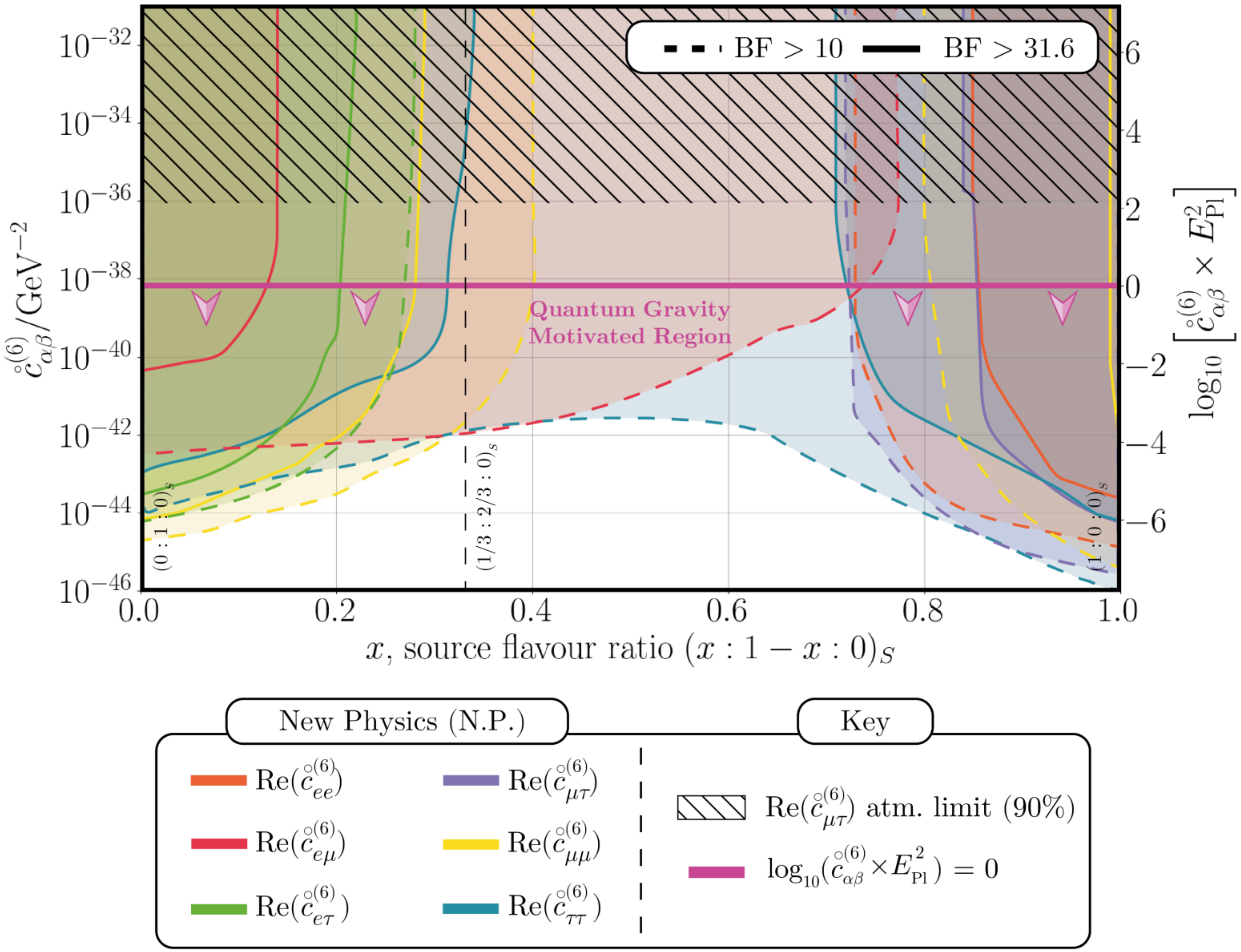
$(1:2:0)$ pion
$(0:1:0)$ neutron
$(1:0:0)$ muon-damped

$$O_d^{e\mu} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



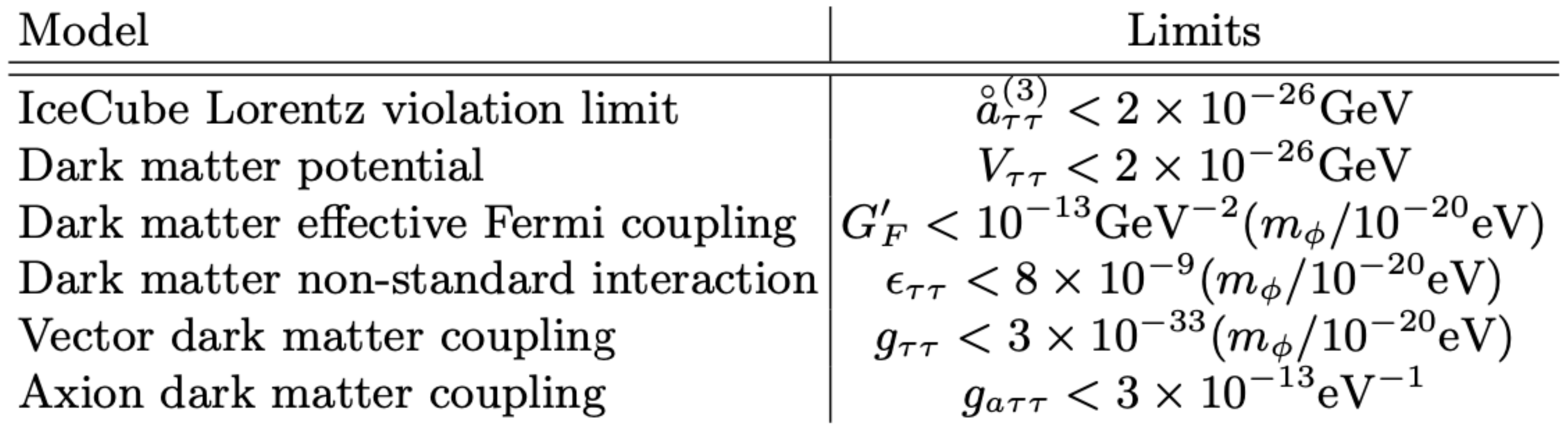
IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

Results on high-dimensional LV operators



IceCube collaboration *Nature Physics* (2022) arXiv:2111.04654

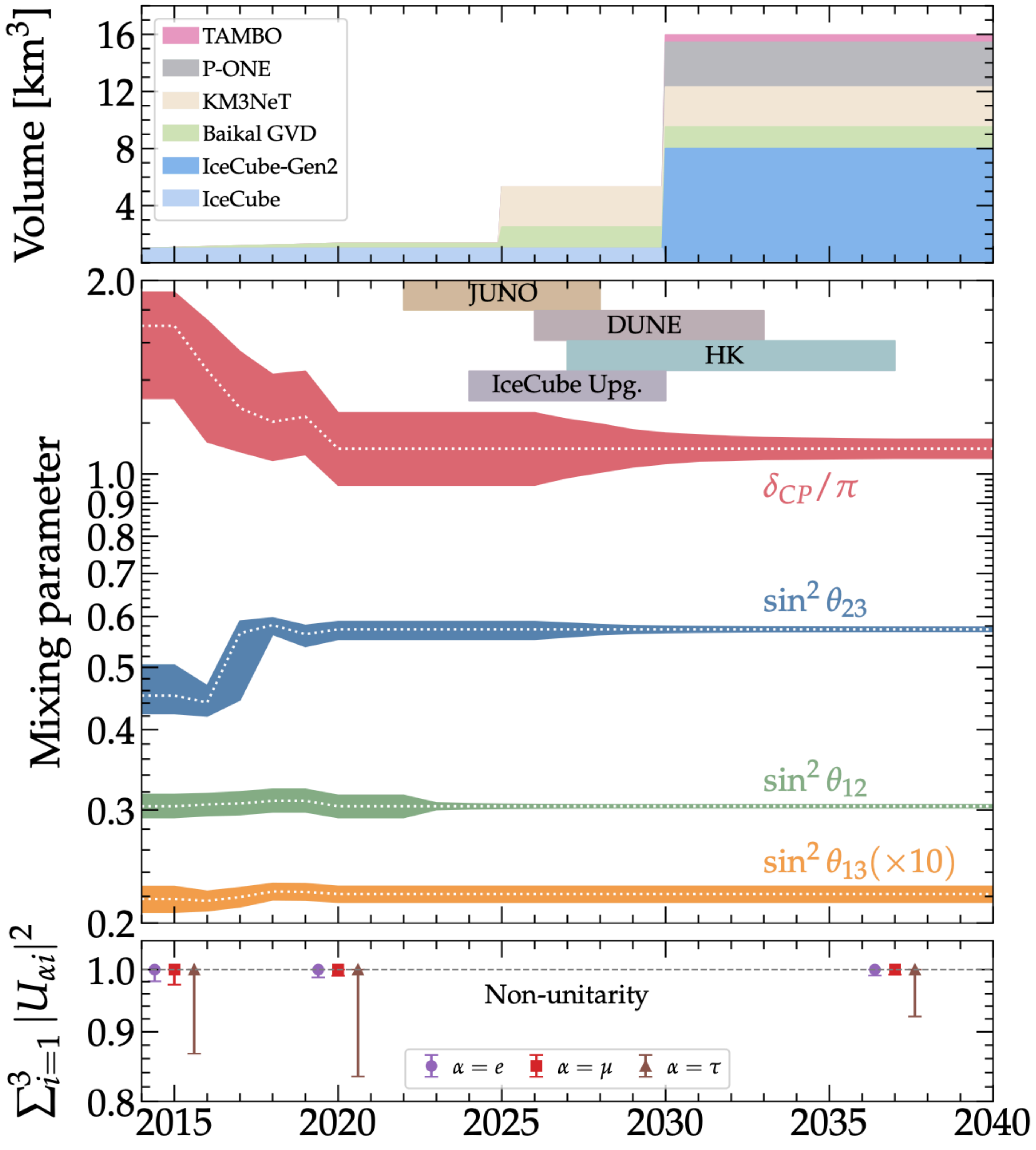
Constraints of neutrino flavor transition can be interpreted in various models

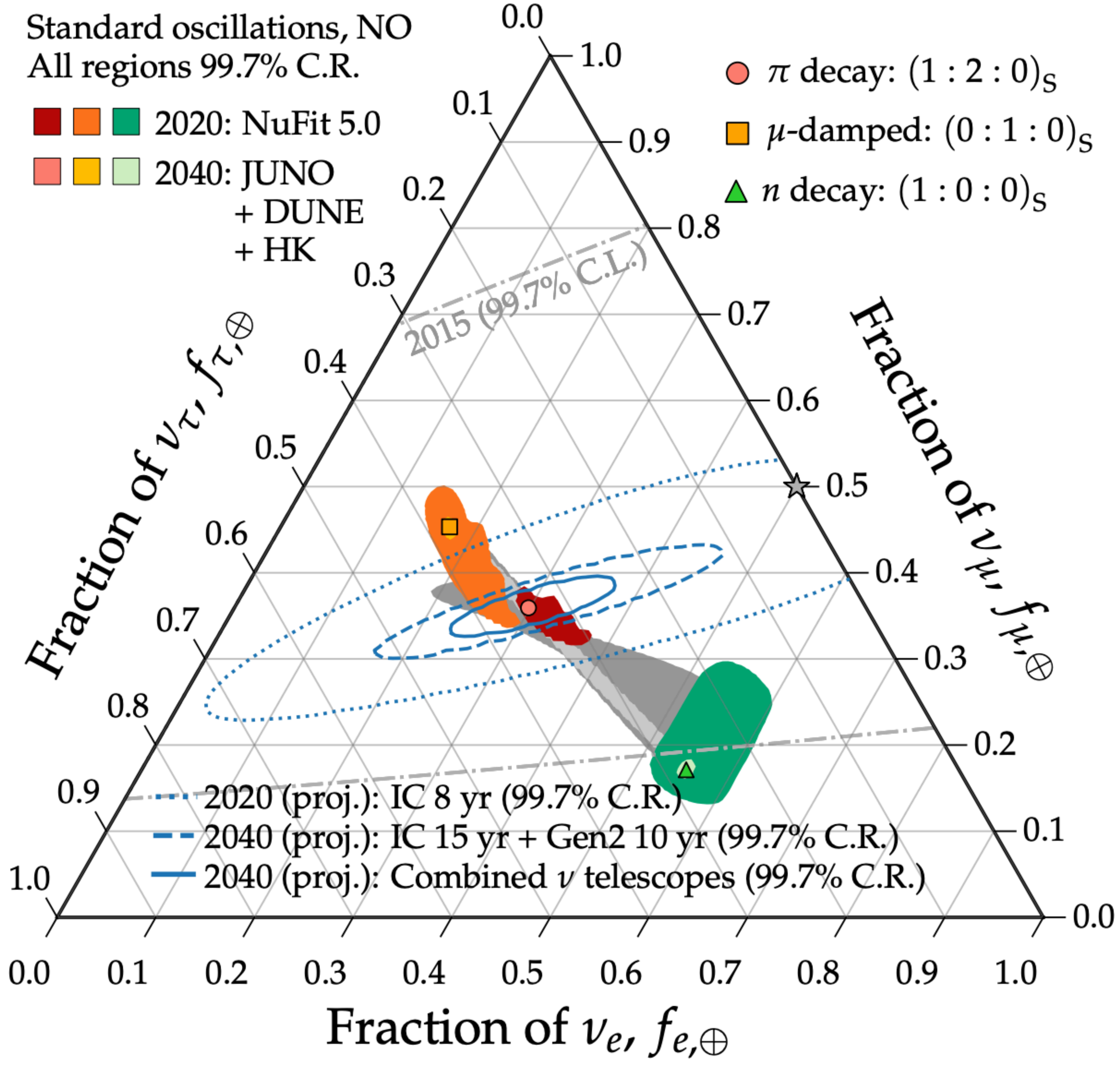


Model	Limits
IceCube Lorentz violation limit	$\mathring{a}^{(3)}_{\tau\tau} < 2 \times 10^{-26}\mathrm{GeV}$
Dark matter potential	$V_{\tau\tau} < 2 \times 10^{-26}\mathrm{GeV}$
Dark matter effective Fermi coupling	$G'_F < 10^{-13}\mathrm{GeV}^{-2}(m_\phi/10^{-20}\mathrm{eV})$
Dark matter non-standard interaction	$\epsilon_{\tau\tau} < 8 \times 10^{-9}(m_\phi/10^{-20}\mathrm{eV})$
Vector dark matter coupling	$g_{\tau\tau} < 3 \times 10^{-33}(m_\phi/10^{-20}\mathrm{eV})$
Axion dark matter coupling	$g_{a\tau\tau} < 3 \times 10^{-13}\mathrm{eV}^{-1}$

CA, Farrag, Katori arXiv:2404.10926

Future of Flavor Measurements and Synergies With Earth-bound experiments





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

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Neutrino Time of Flight

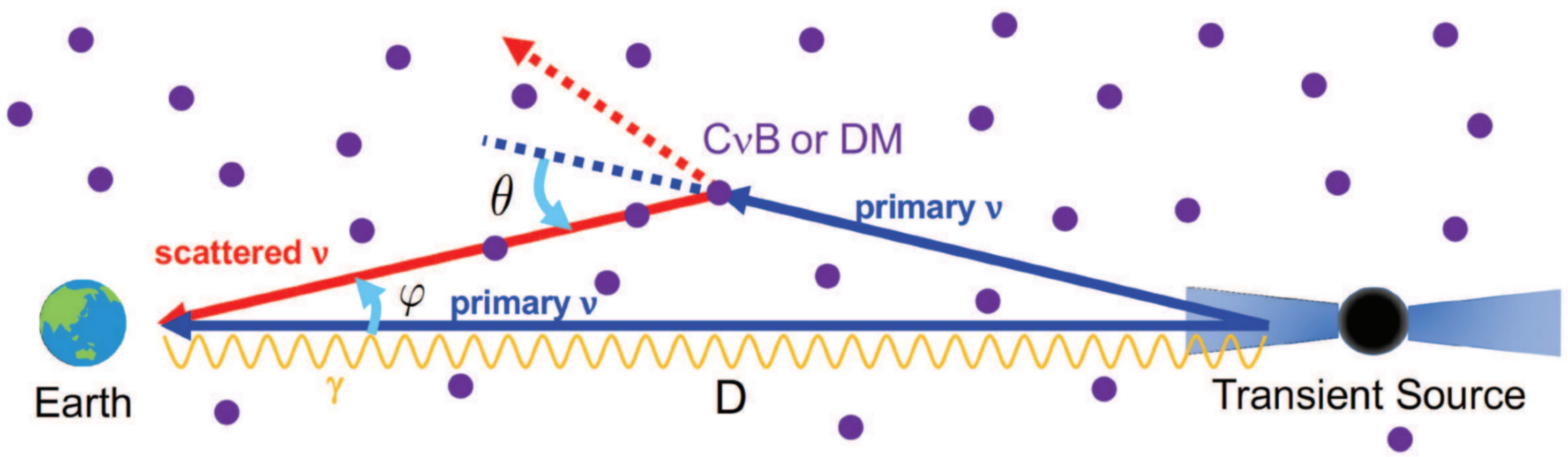
Dark Matter-neutrino interactions
Murase & Shoemaker
arXiv:1903.08607

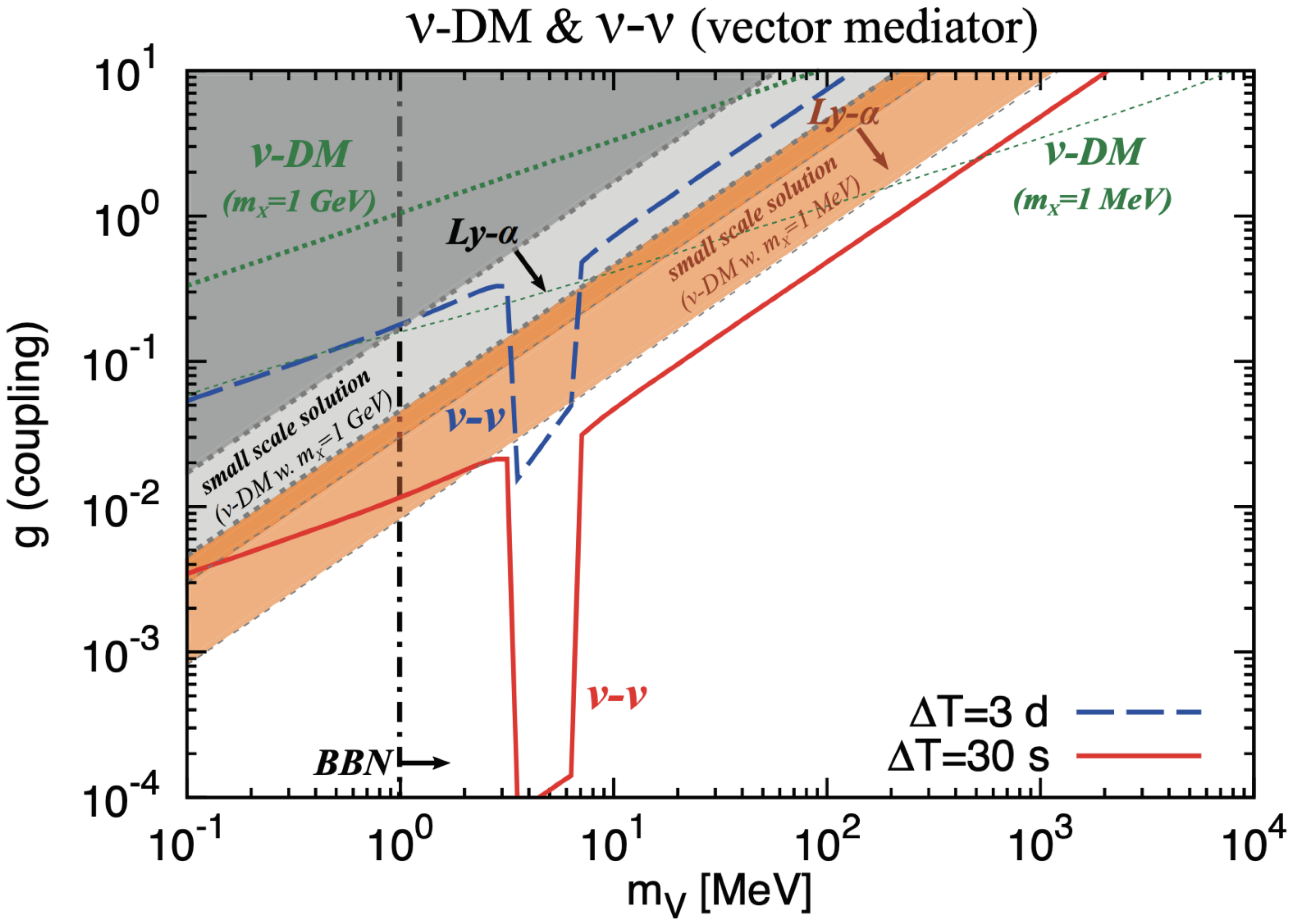
Time-of-flight constraints rely on assumption of flare emission window. Handle with care.

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

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

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

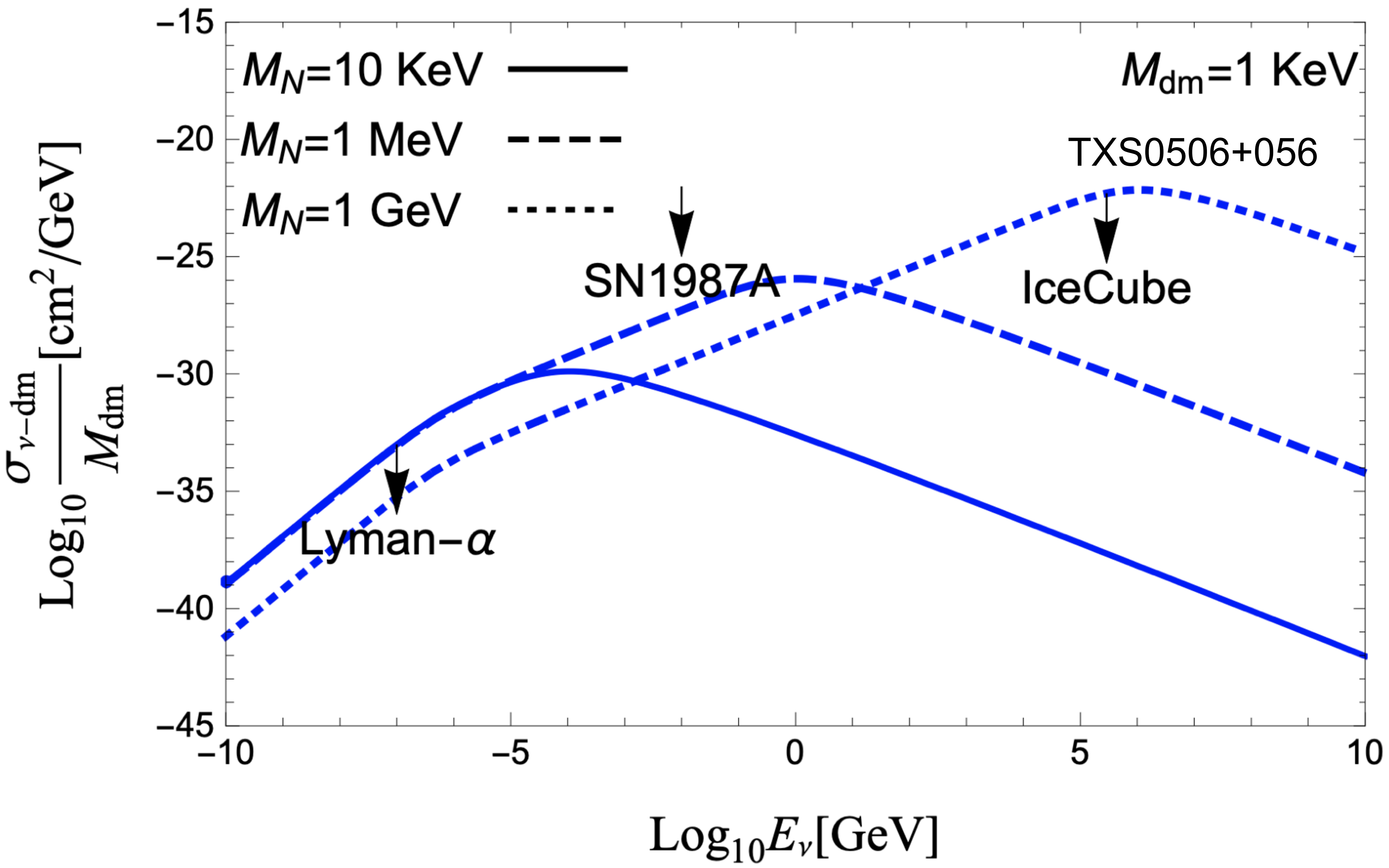




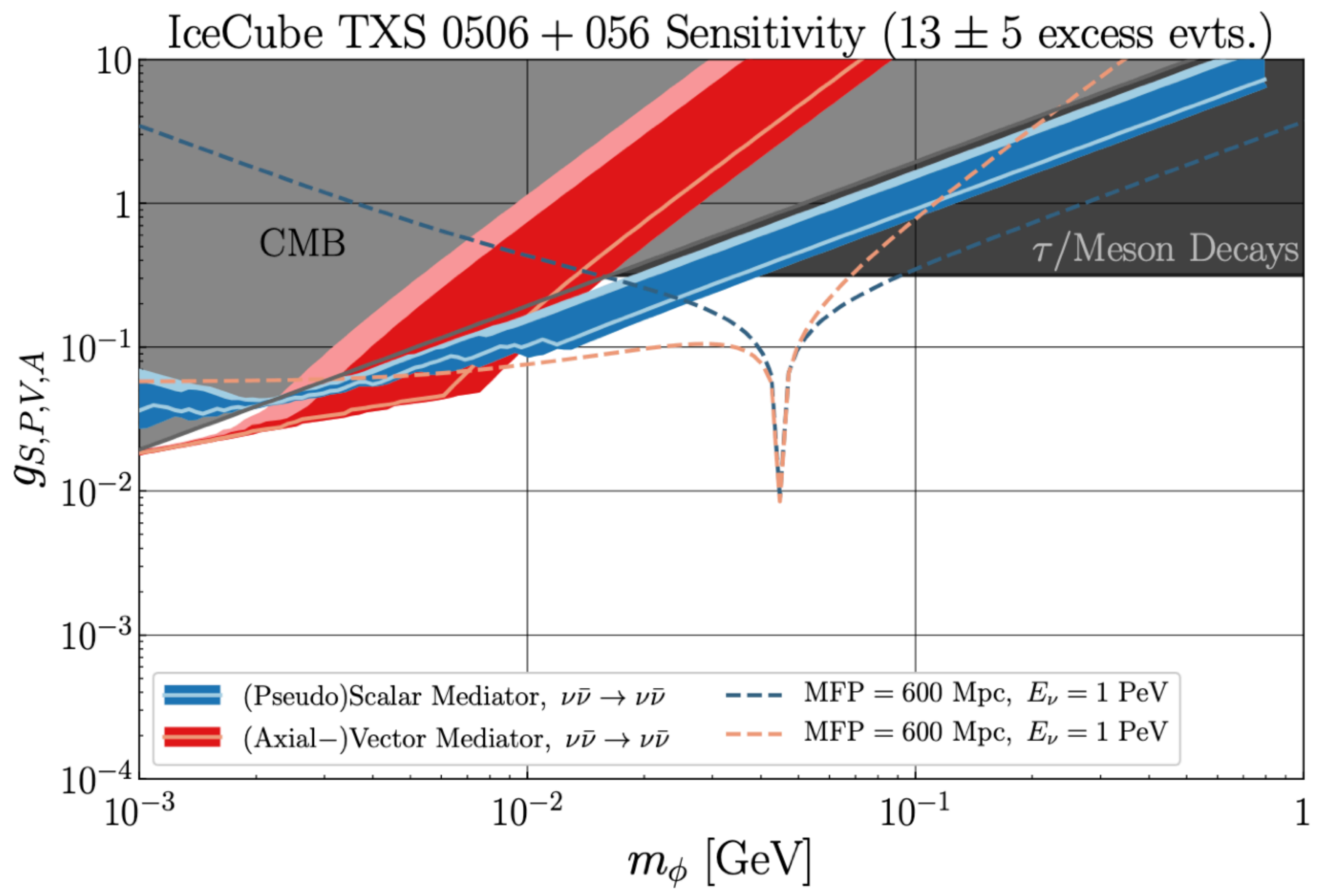
Space-time effects
J. Ellis et al arXiv:1807.051550
K. Wang et al. arXiv:2009.05201
Zhang & Ma arXiv:1406.4568

Opacity in Individual Sources

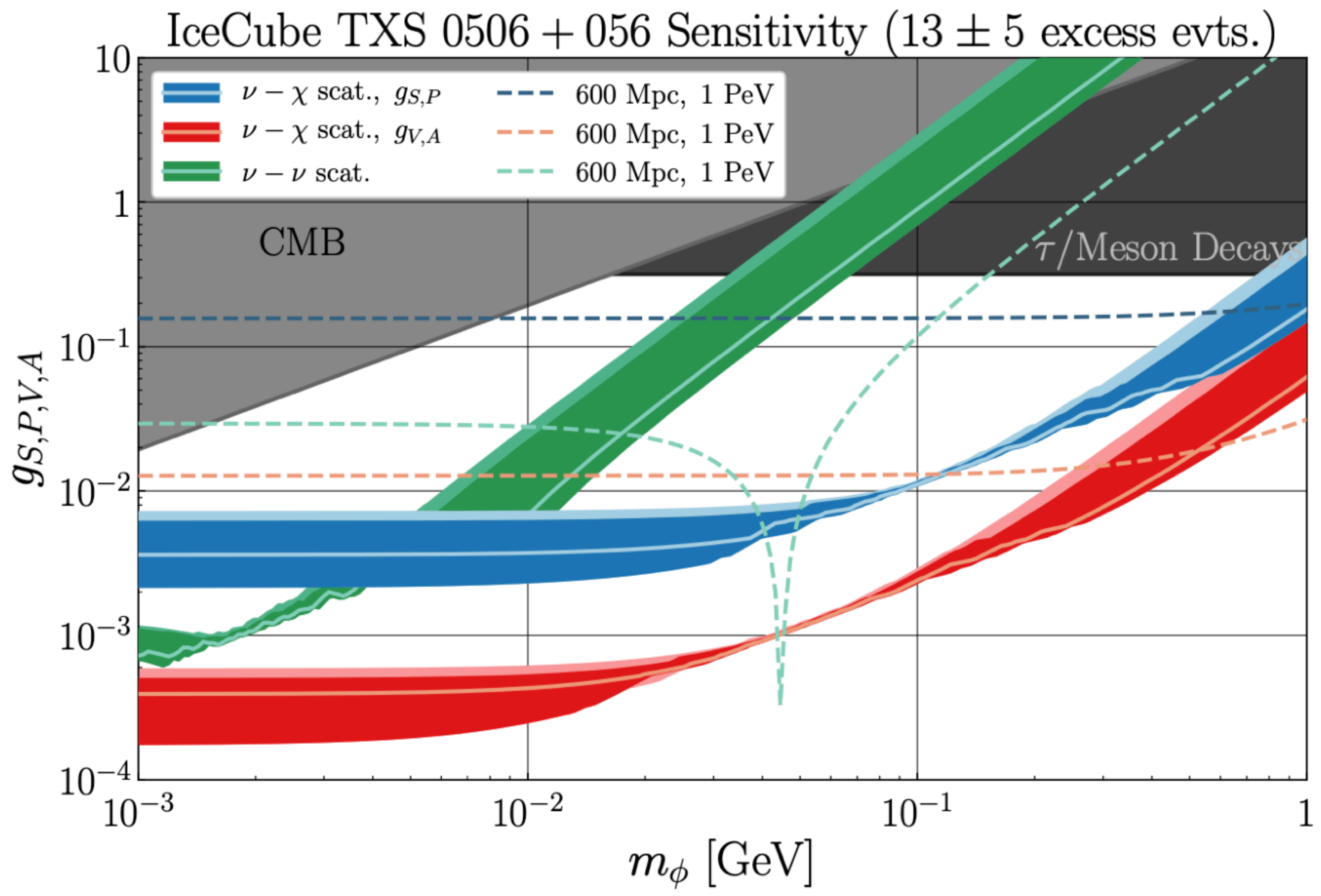
Choi et al. arXiv:1903.03302



Kelly et al arXiv:1808.02889



Neutrino-Neutrino Secret Interaction



Neutrino-DM Secret Interaction

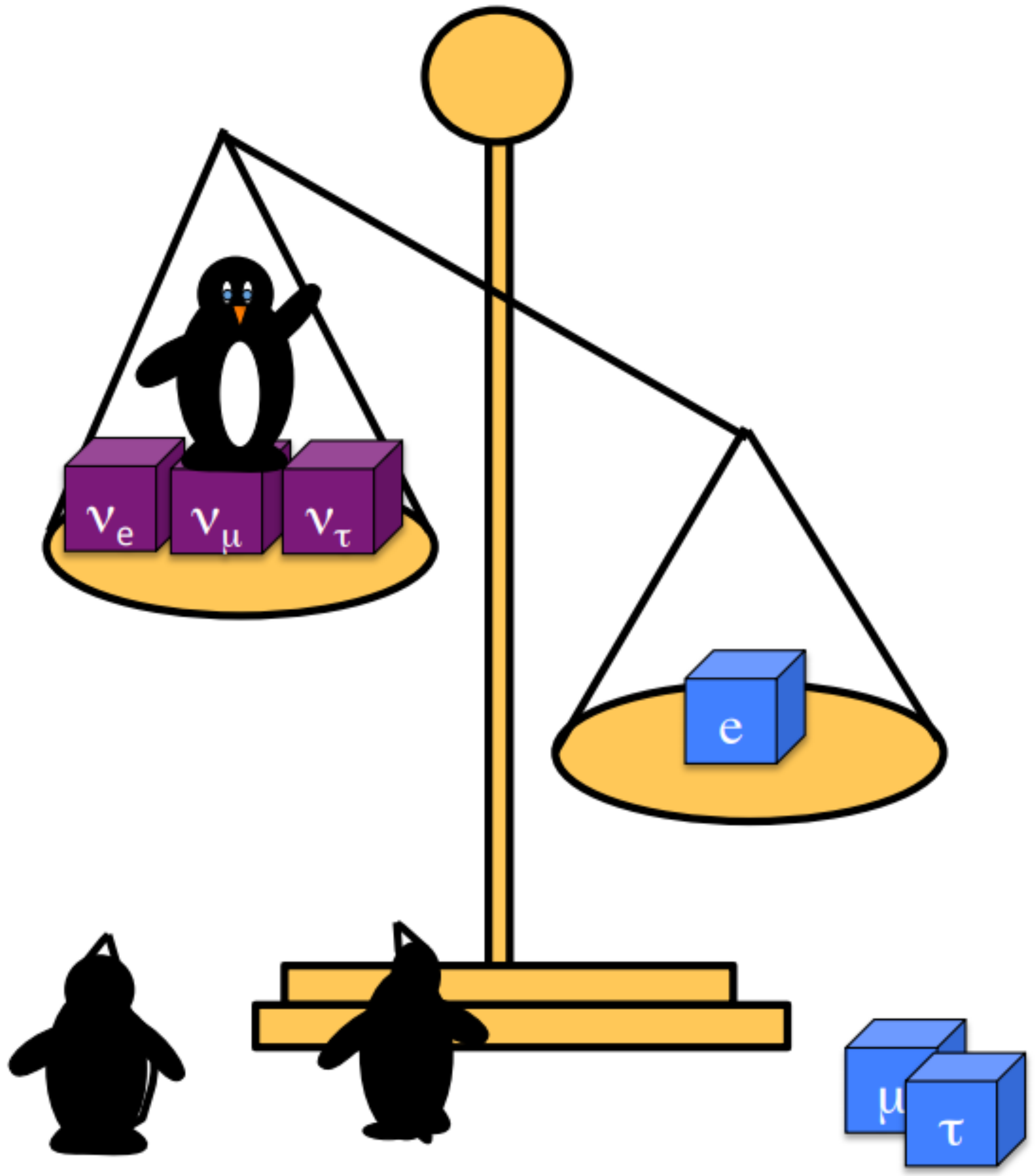
Opacity constraints rely on assumptions on the intrinsic source luminocity. Handle with care.

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

<u>neutrino-neutrino couplings</u>
Kelly et al arXiv:1808.02889
CA et al. arXiv:2009.05201
Carpio et al. arXiv:2104.15136

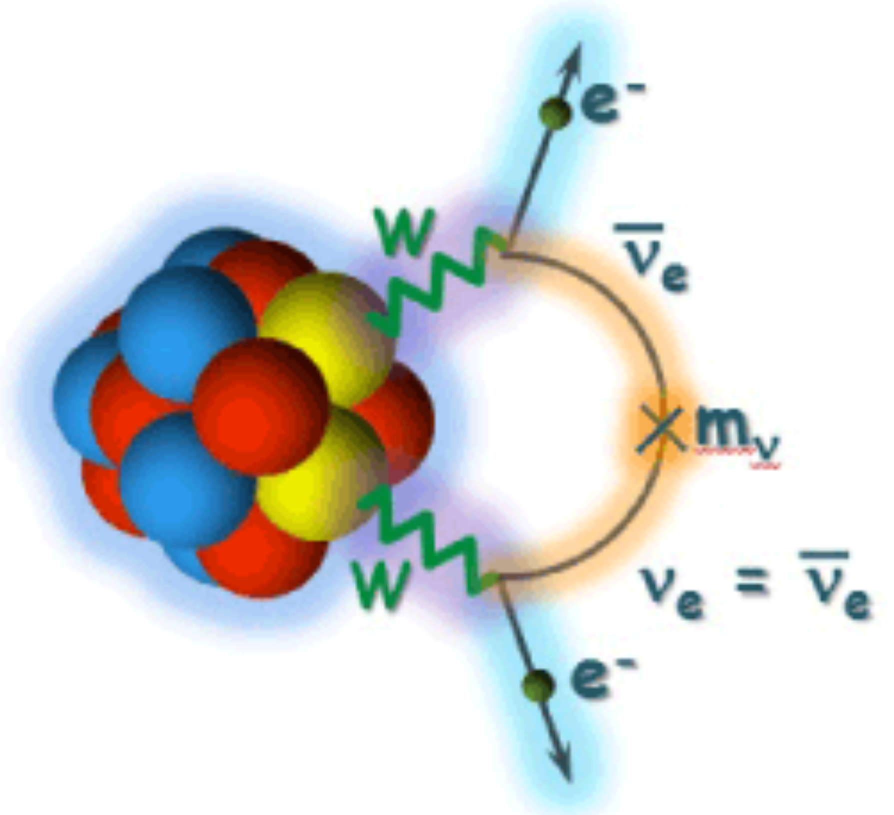
What is the nature of neutrino mass?

What is the nature of neutrino mass?

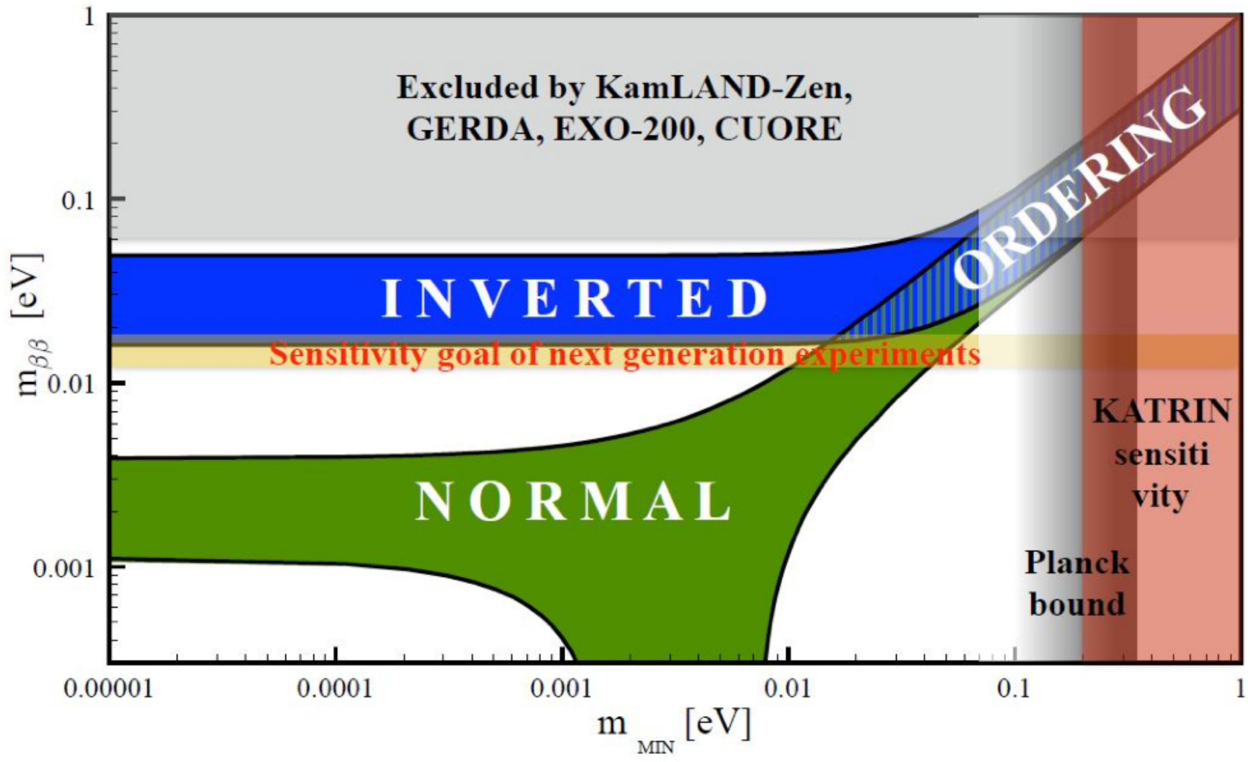


Arkani-Hamed et al, 2007
Ooguri & Vafa, 2017
Gonzalo, Ibañez, Valenzuela, 2021
Vafa, 2024

Majorana



Neutrinoless
double beta decay



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

Quasi-Dirac Neutrino Model

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737
Beacom et al, 2003 (arXiv:hep-ph/0307151
Shoemaker & Murase, 2015 (arXiv:1512.07228)
Esmaili, 2012

$$L_{\text{mass}} = \frac{1}{2}\Psi_L^{\dagger} C M \Psi_L \qquad \Psi_L = \begin{pmatrix} \nu_{\alpha L} \\ (\nu_{\alpha R})^c \end{pmatrix}$$

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

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

Lepton-number breking term.

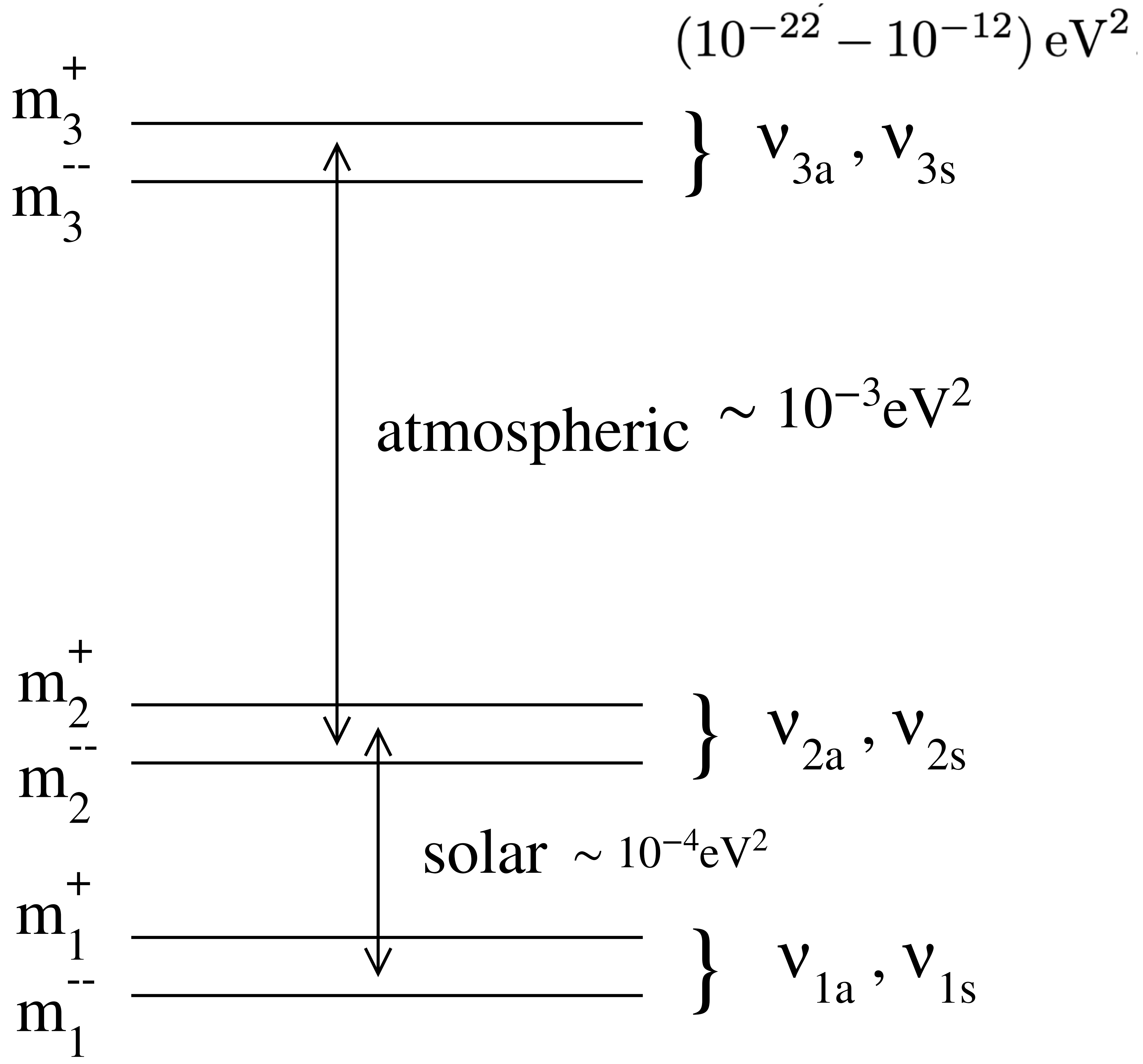
Dirac neutrinos: $M_R = 0$
See-saw scenario: $M_R \gg M_D$
Quasi-Dirac scenario: $M_R \ll M_D$

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

Oscillations With Quasi-Dirac Neutrinos

See also Esmaili arXiv:0909.5410, Esmaili & Farzan arXiv:1208.6012,
Rink & Sen arXiv:2211.16520

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



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

m_3^+, m_3^{--} $\}$ ν_{3a}, ν_{3s}

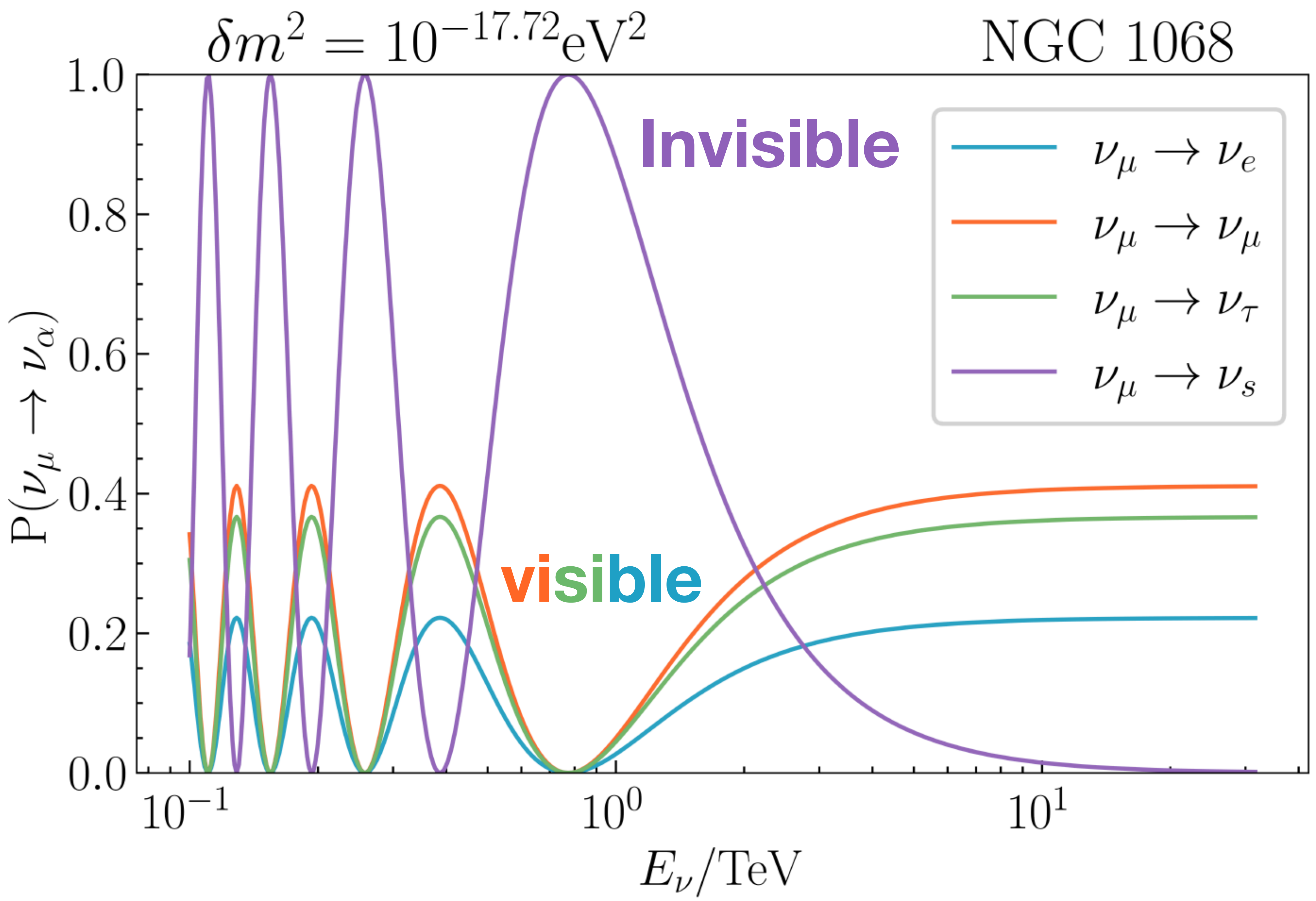
atmospheric $\sim 10^{-3}\mathrm{eV}^2$

m_2^+, m_2^{--} $\}$ ν_{2a}, ν_{2s}

solar $\sim 10^{-4}\mathrm{eV}^2$

m_1^+, m_1^{--} $\}$ ν_{1a}, ν_{1s}

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



Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

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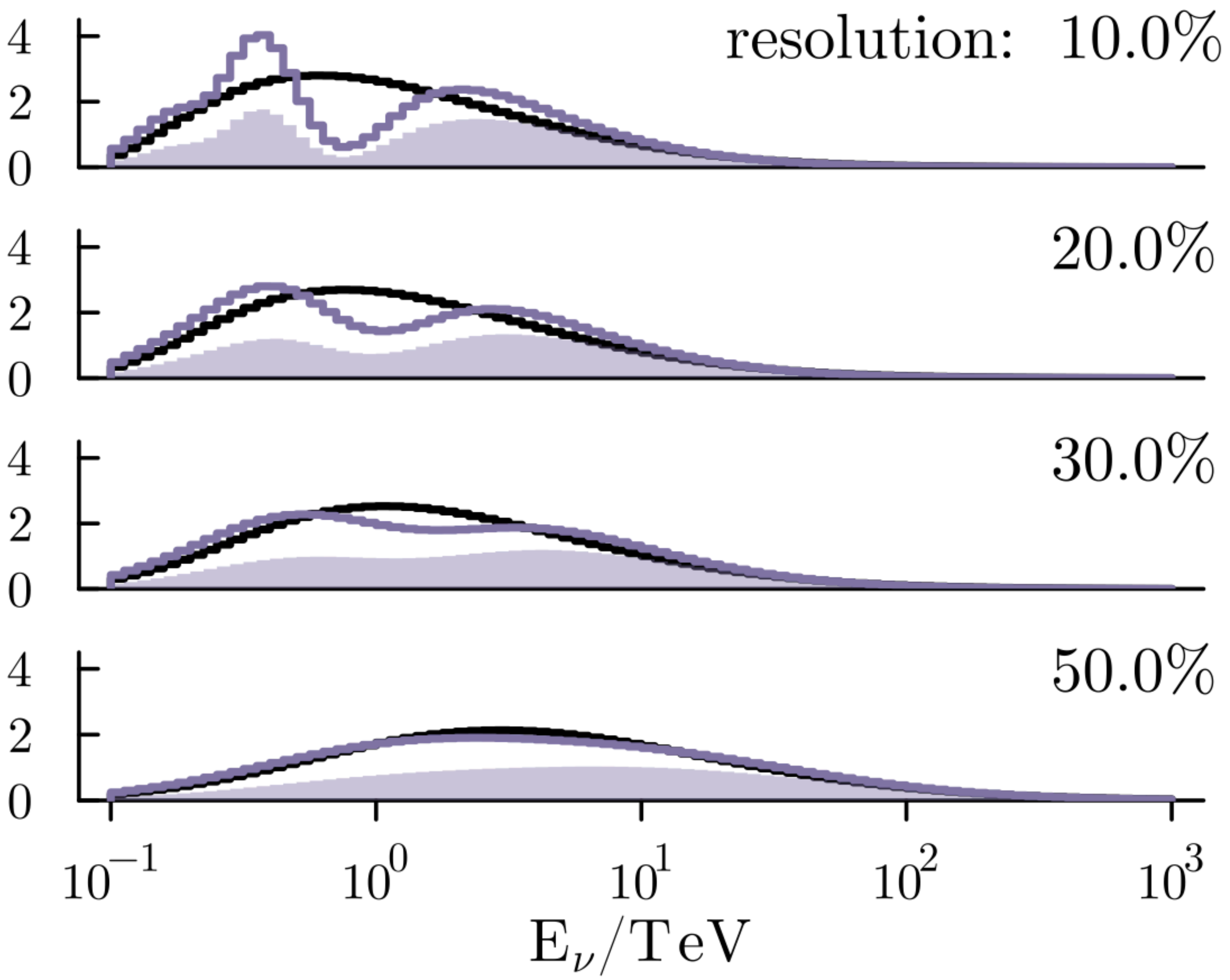

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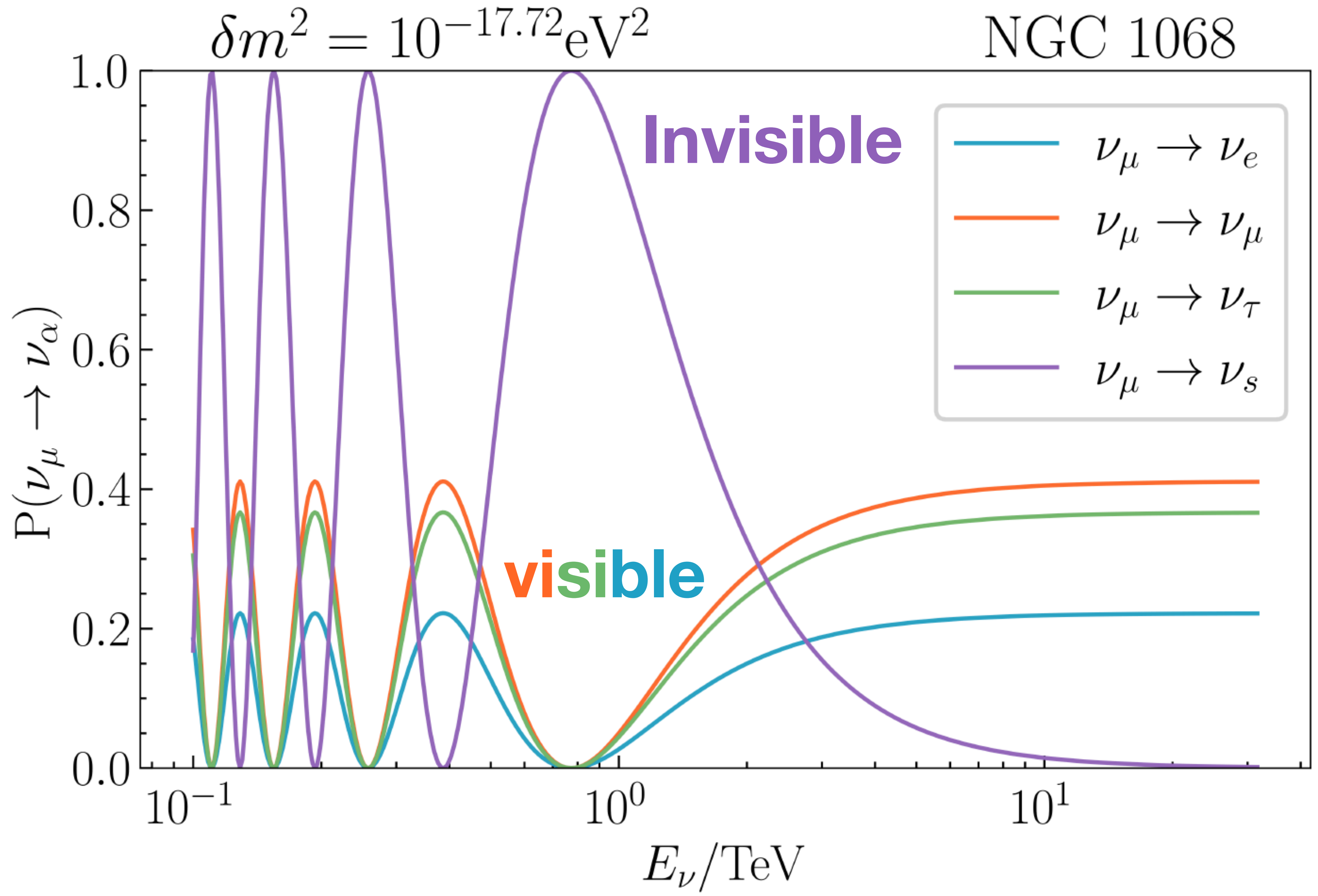
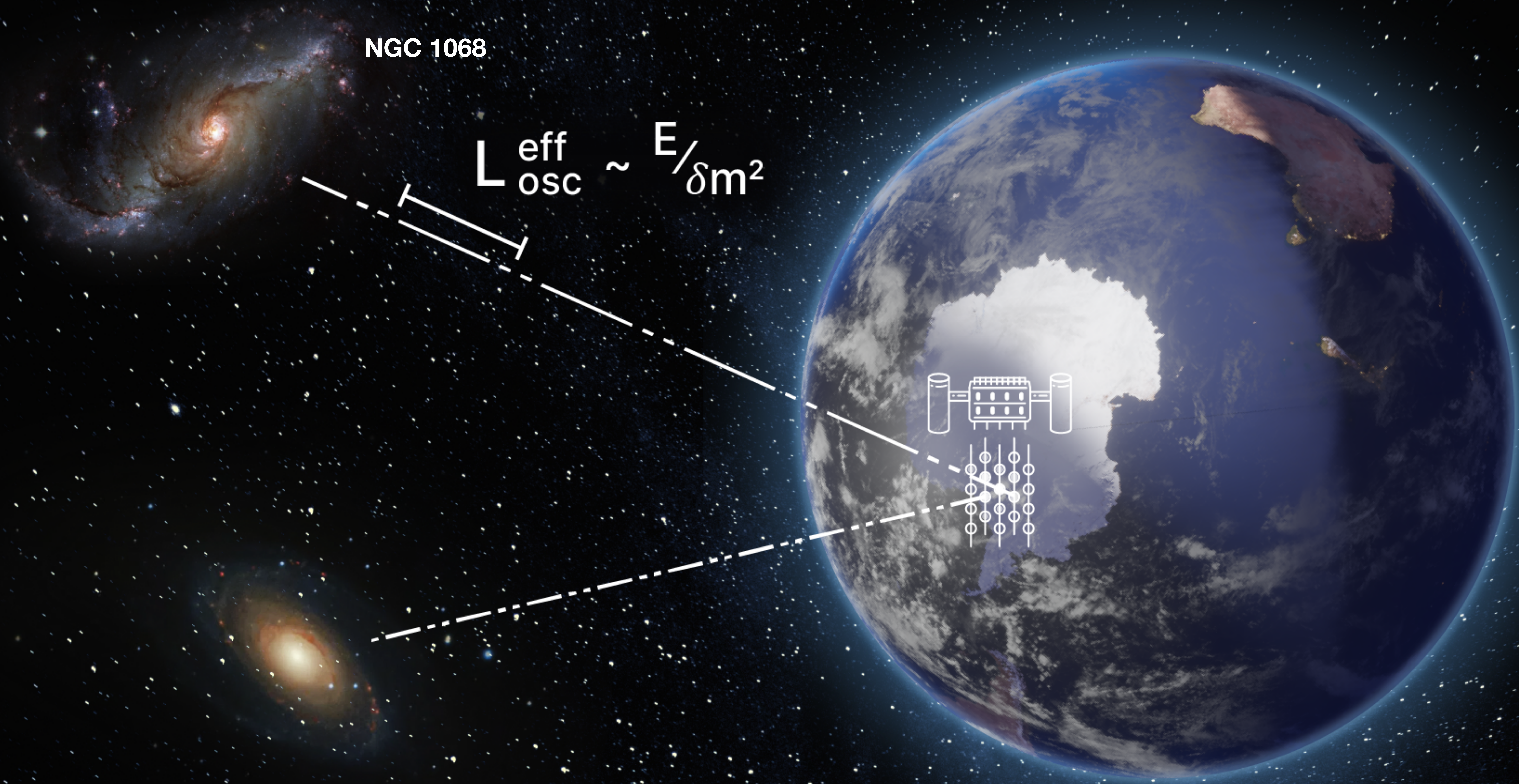


Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

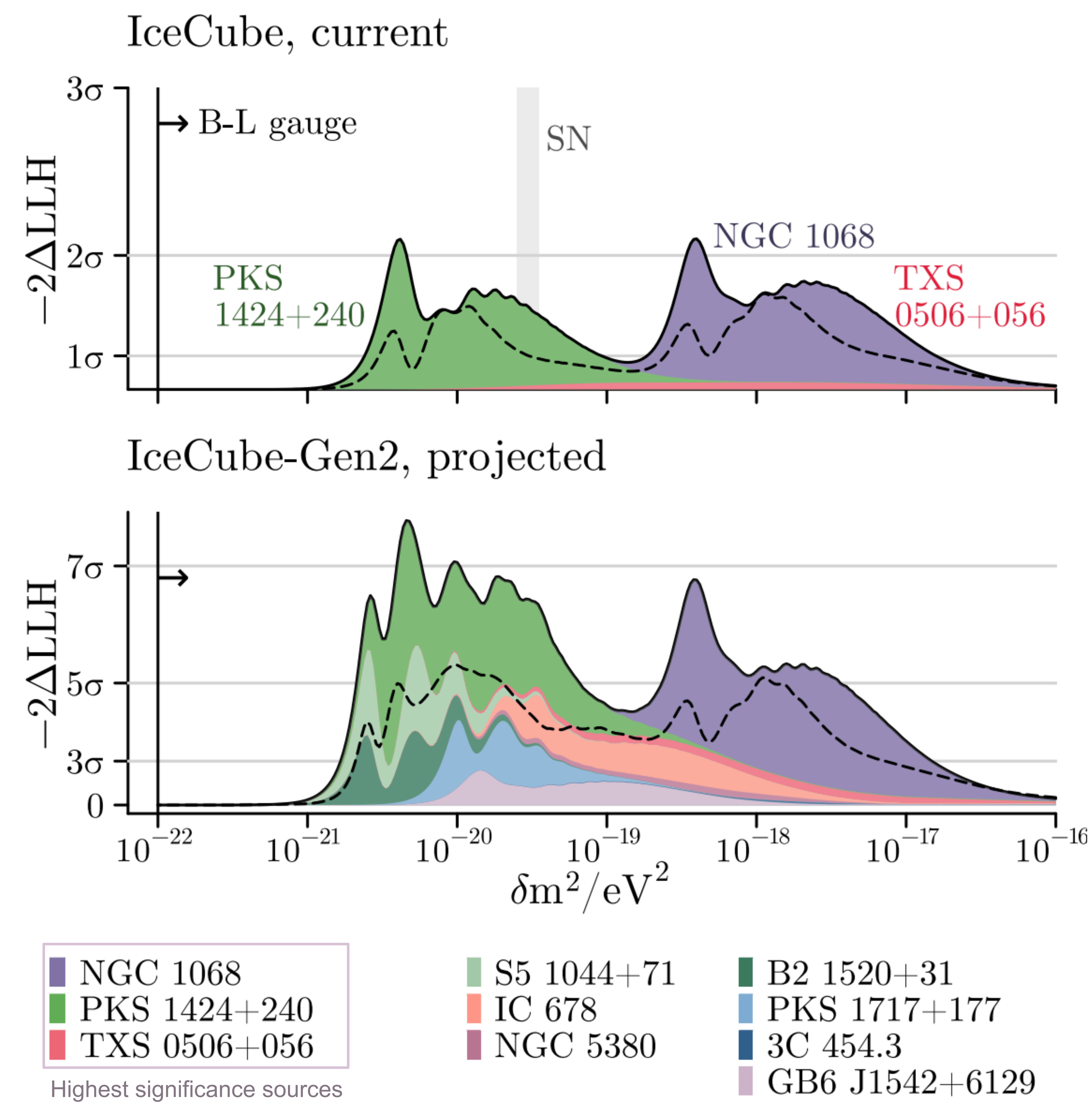
Neutrino Oscillations At Cosmic Scales



$$L_{osc}^{eff} \sim E/\delta m^2$$

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

Neutrino Oscillations At Cosmic Scales

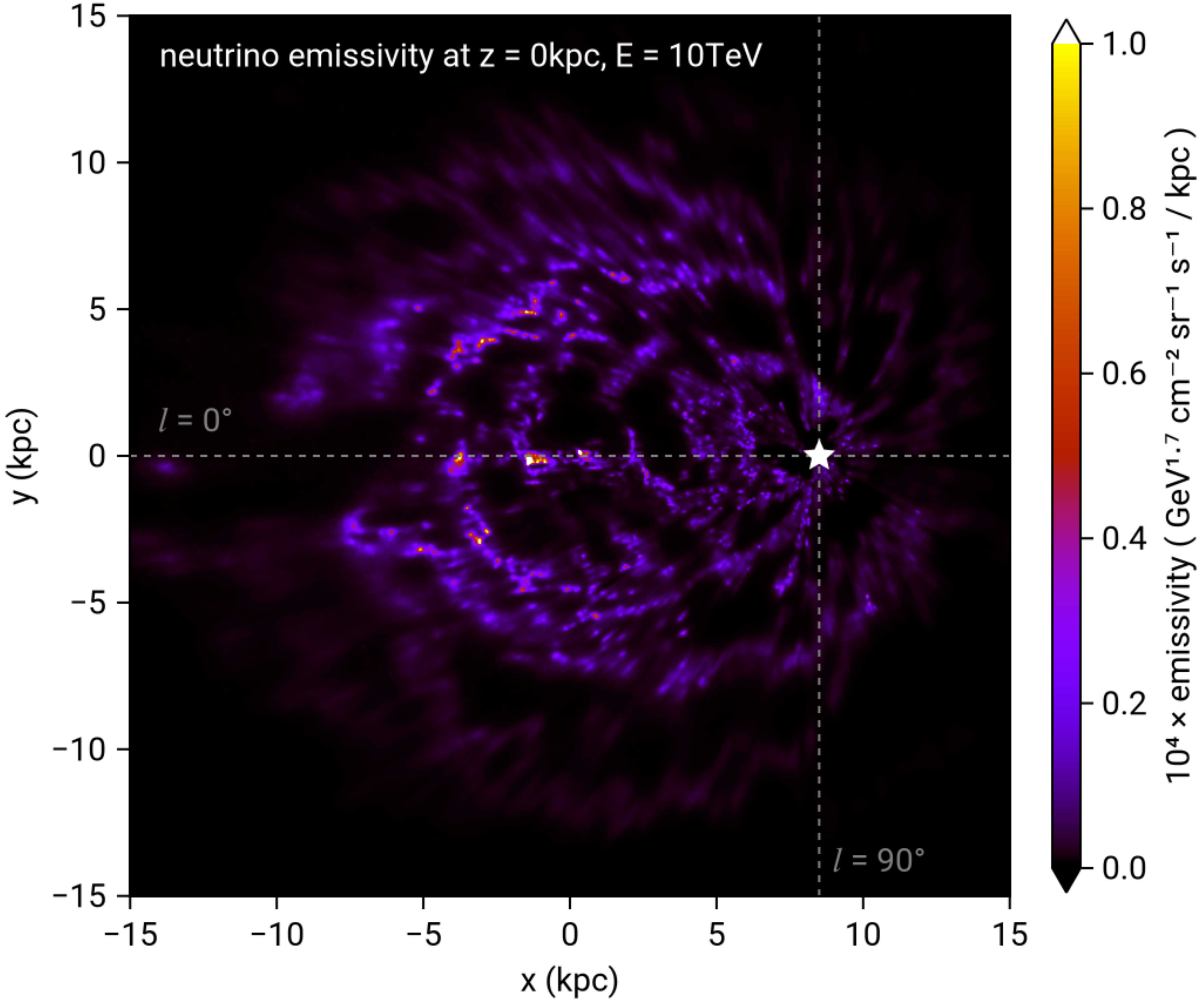


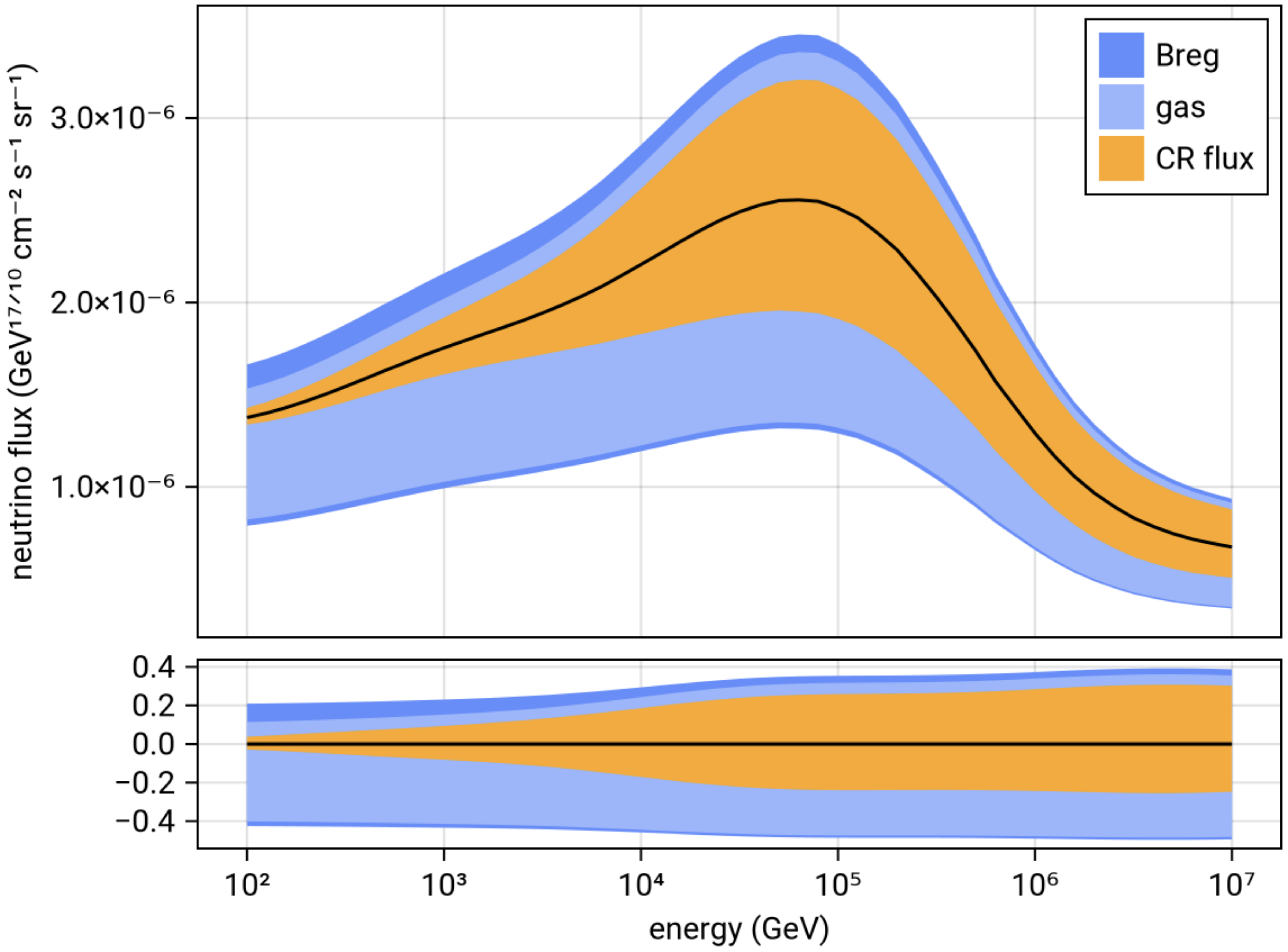
Work by Kiara Carloni and Ivan Martinez-Soler

Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737
See also Rink & Sen arXiv:2211.16520

Quasi-Dirac Oscillations and Galactic Neutrinos

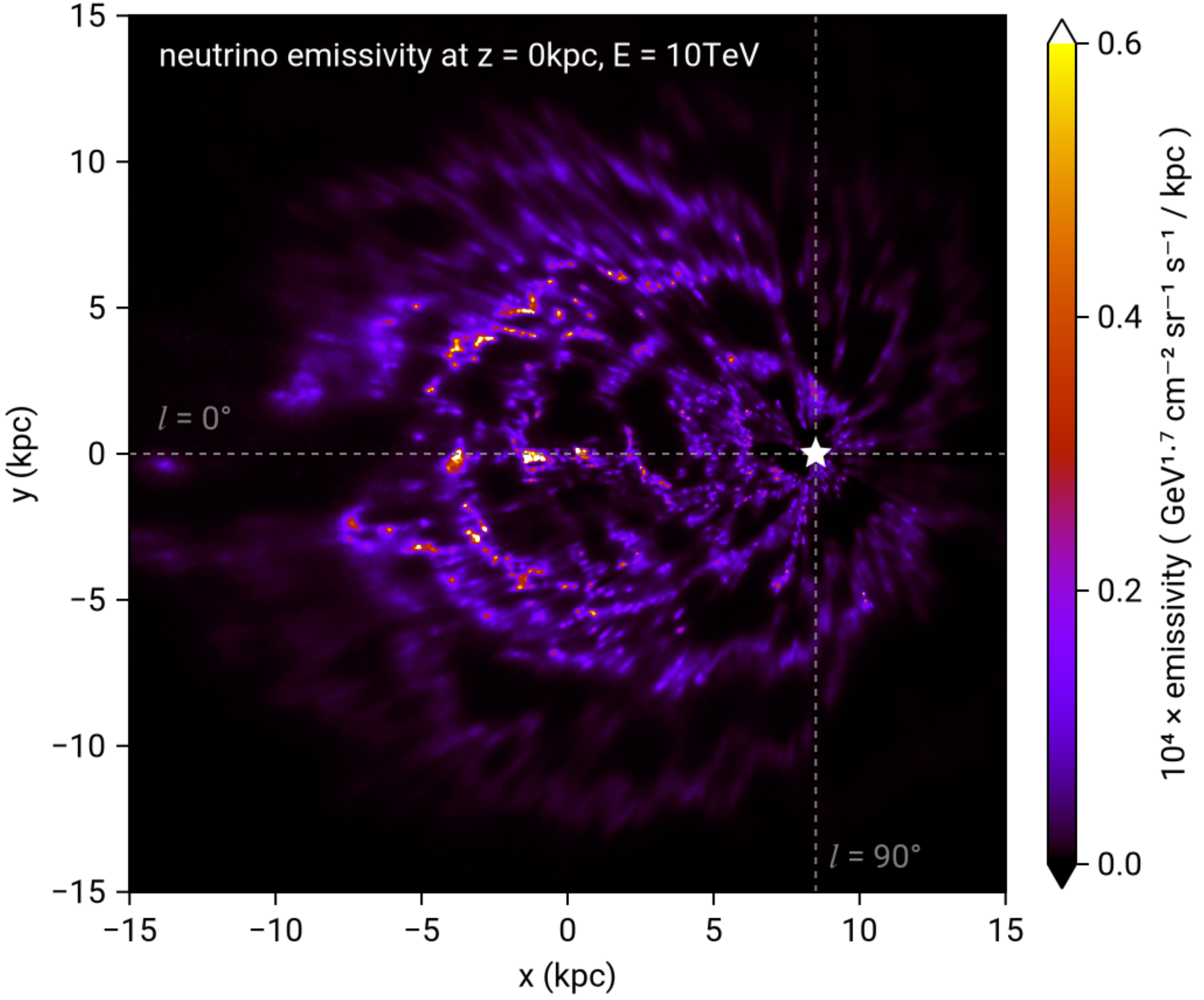
TANDEM:
New model for neutrino emission of the galaxy using *CR-Propa*



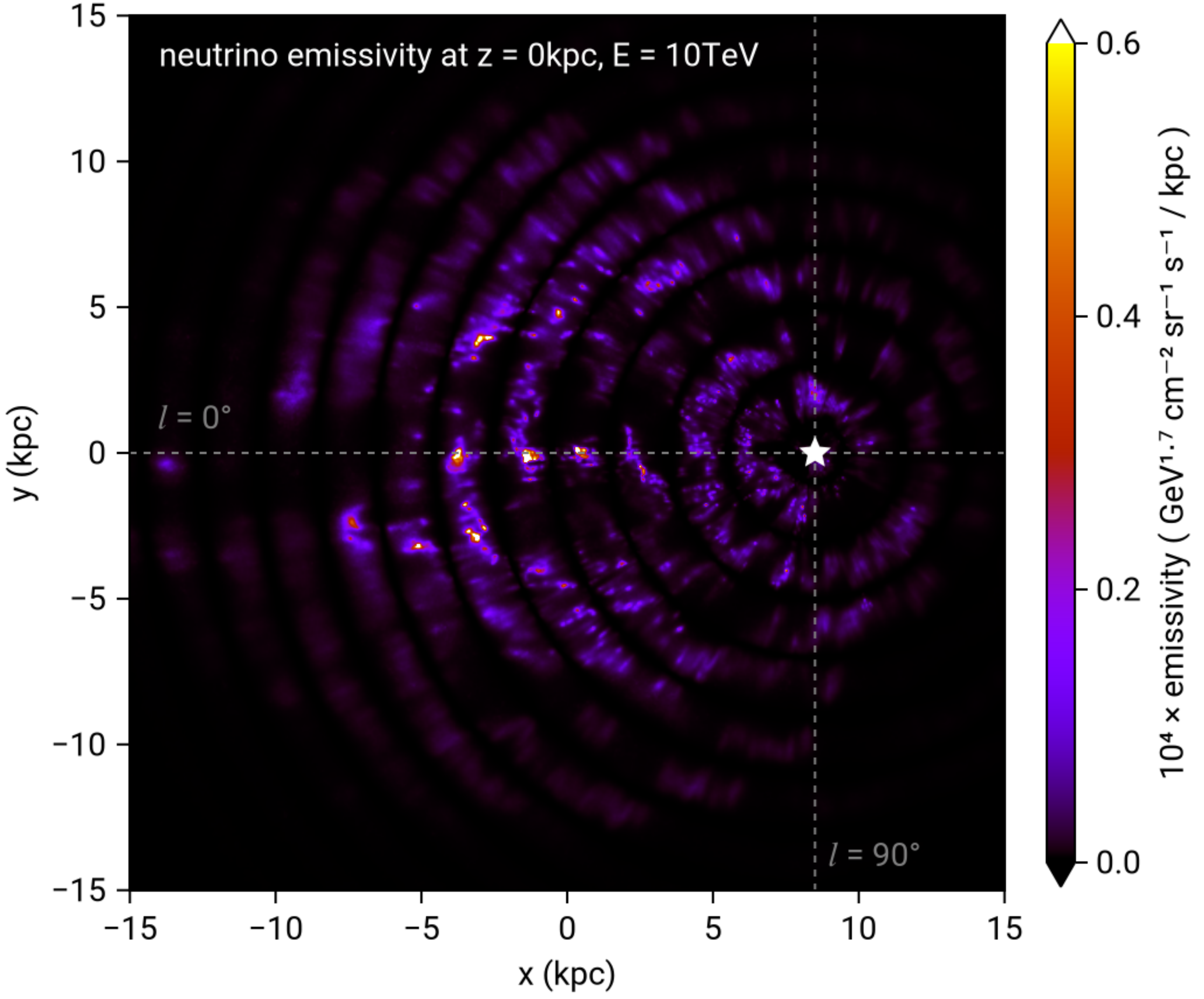


K. Carloni, M. McDonald, R. Alves, CA, and I. Martínez-Soler to appear

Quasi-Dirac Oscillations and Galactic Neutrinos



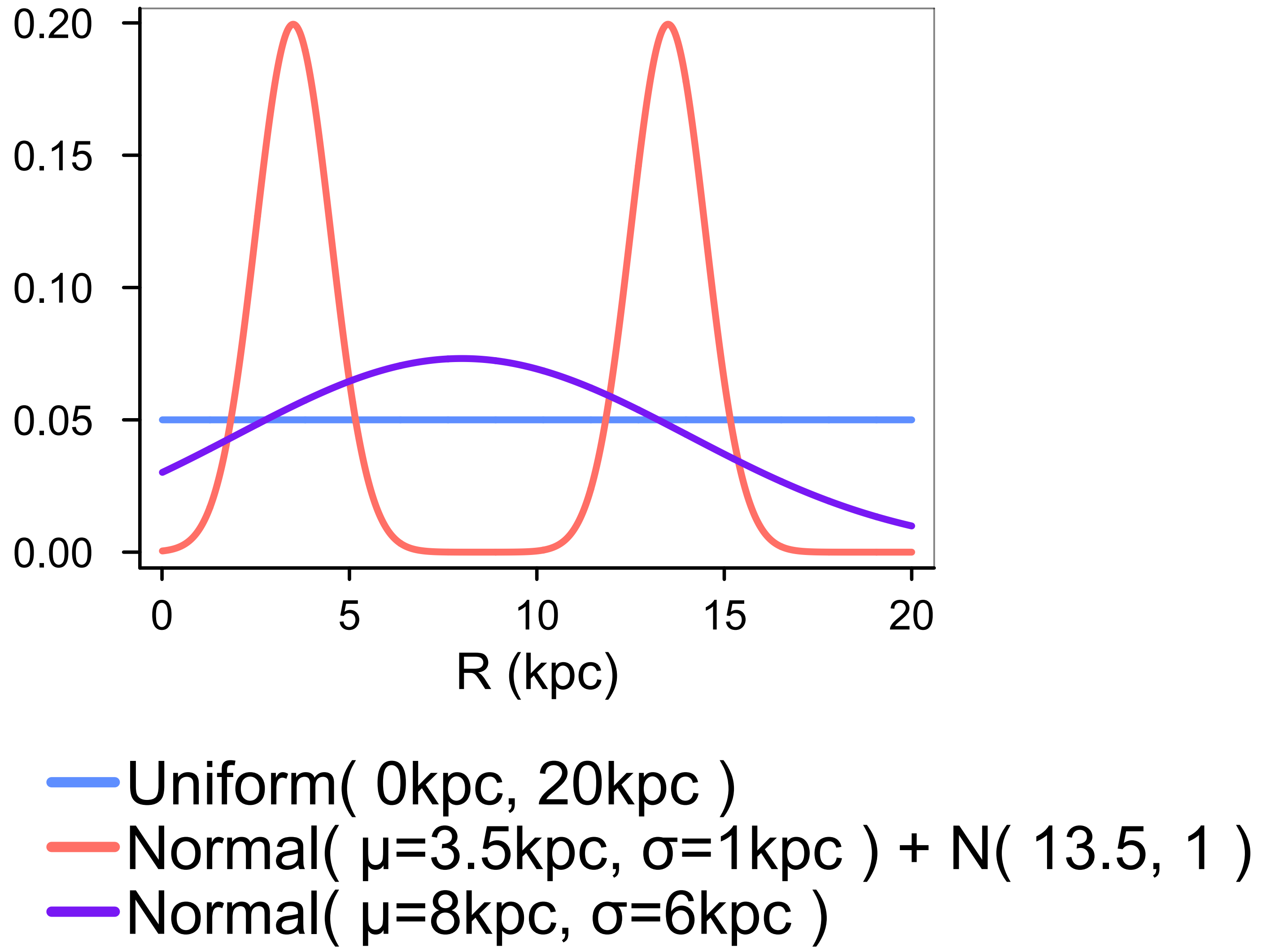
$\delta m^2 = 10^{-13} \mathrm{eV}^2$



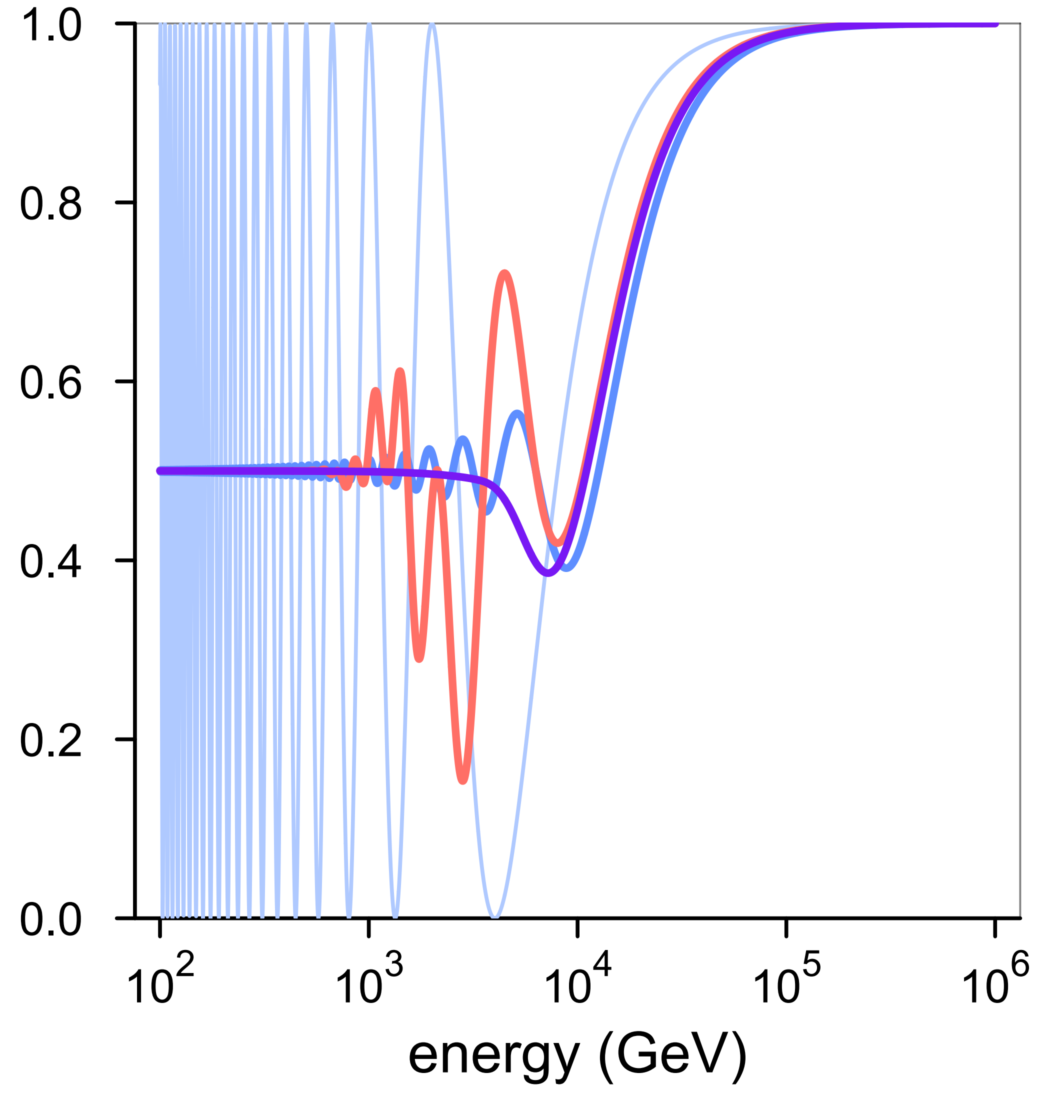
K. Carloni, M. McDonald, R. Alves, CA, and I. Martínez-Soler to appear

What are we actually sensitive to?

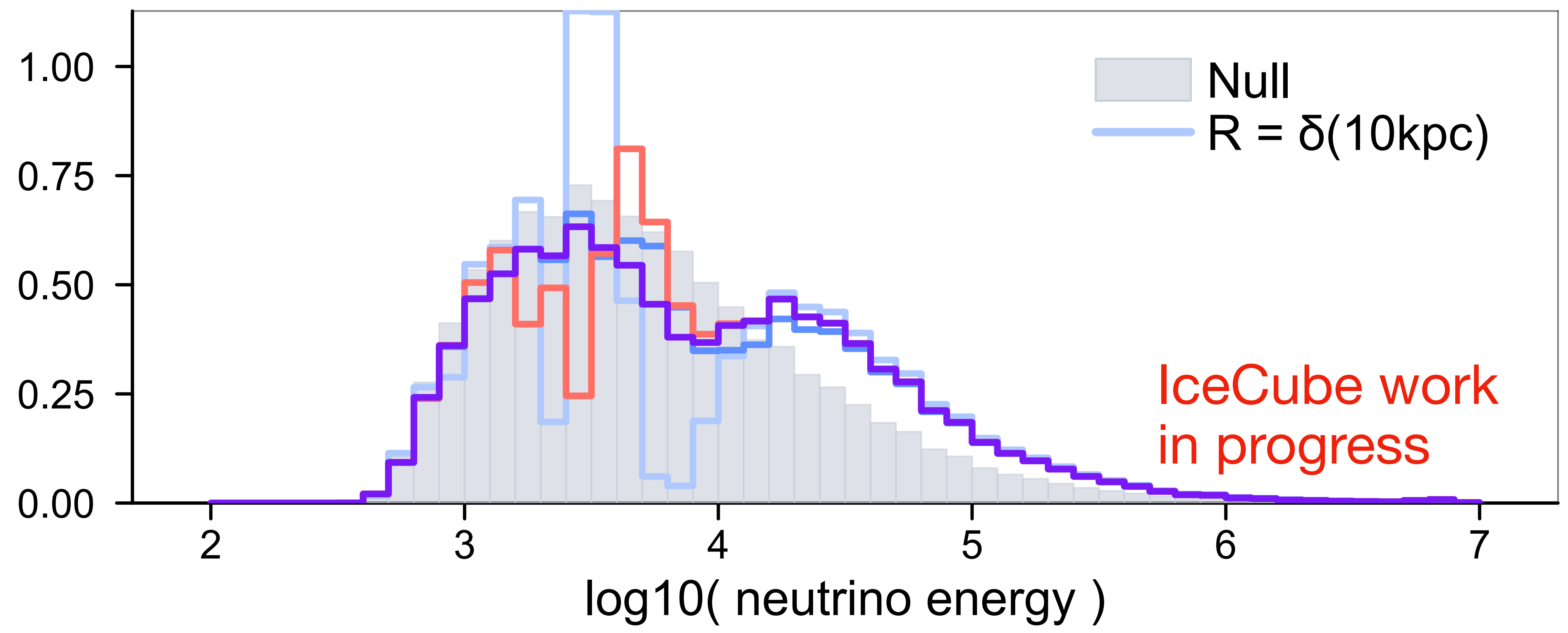
1. Ansatz R-distribution



2. Oscillations in energy

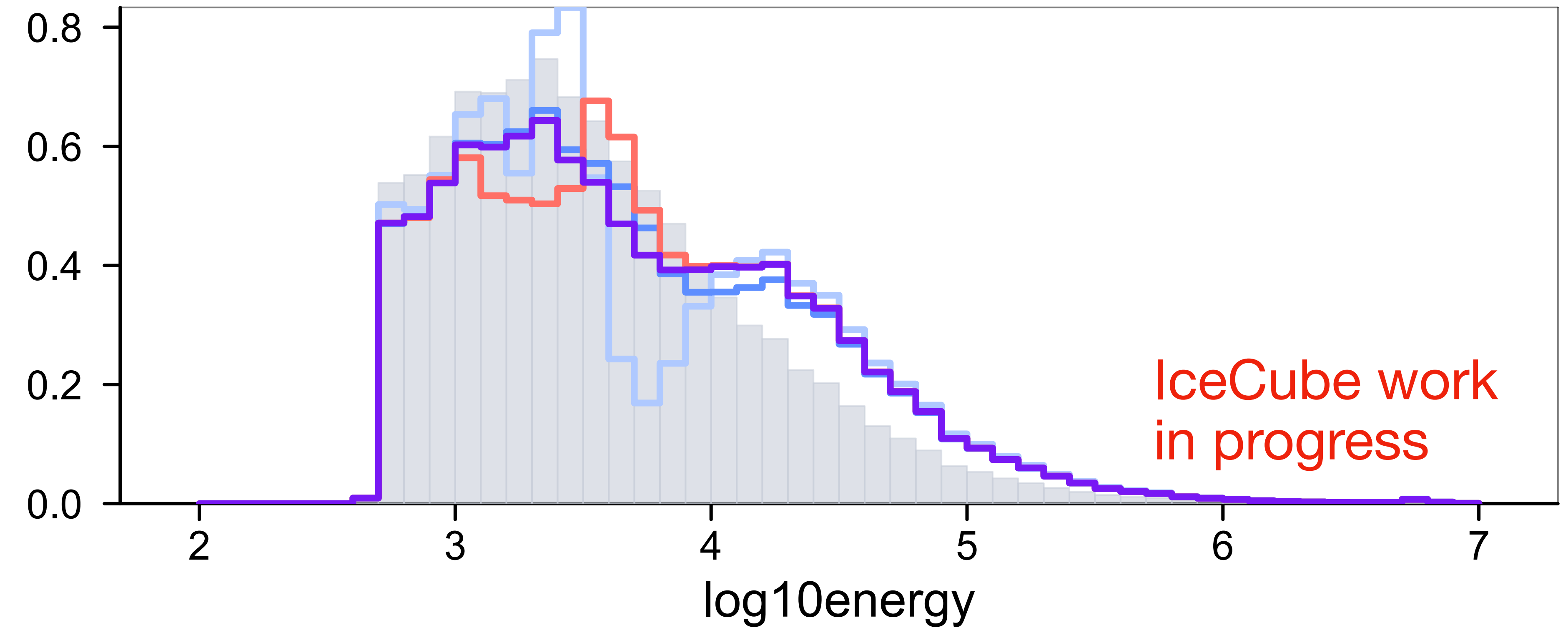


3. Signal PDFs in true energy



IceCube work in progress

4. Signal PDFs in reco energy



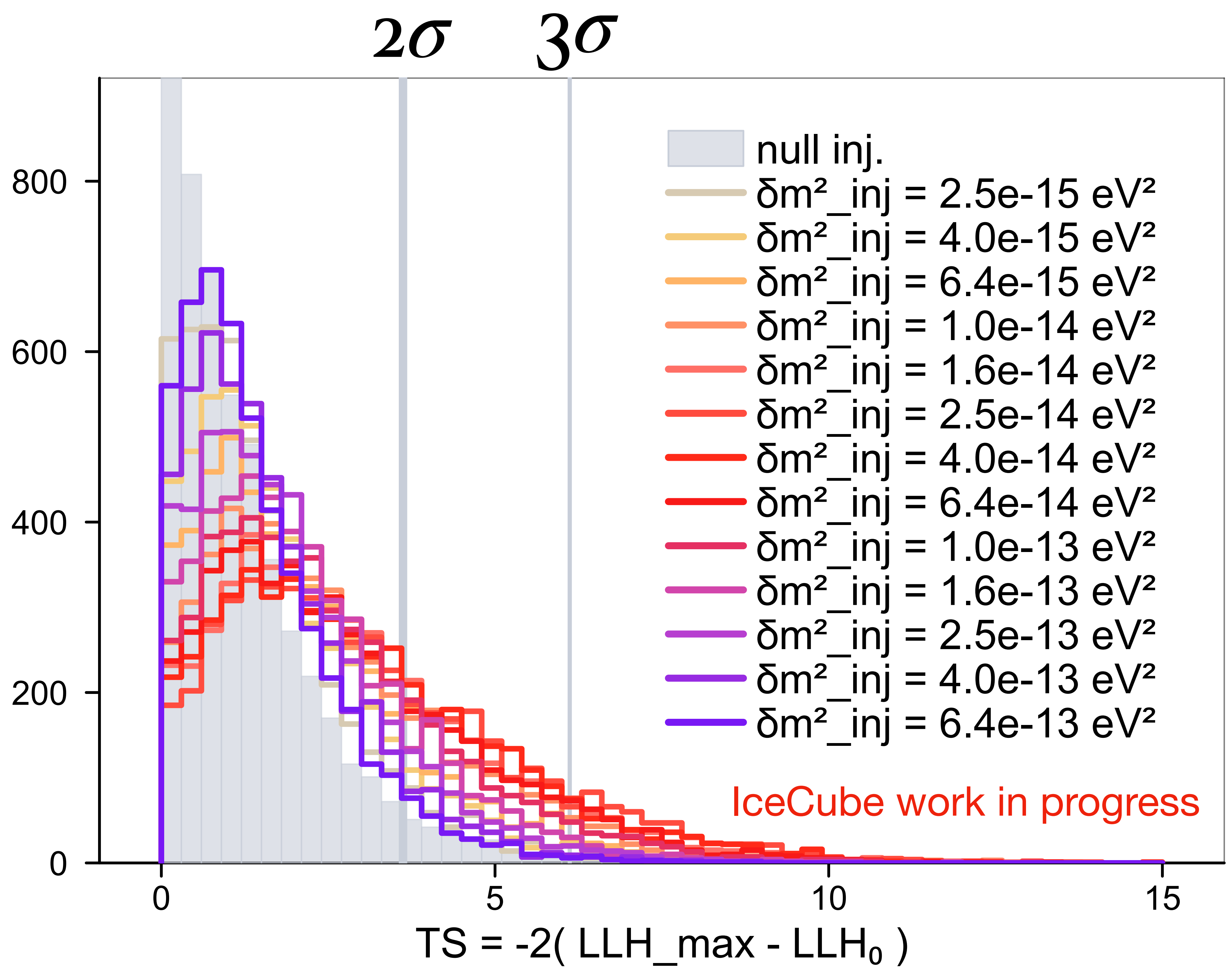
IceCube work in progress

significant unknowns → begin with 'worst case'

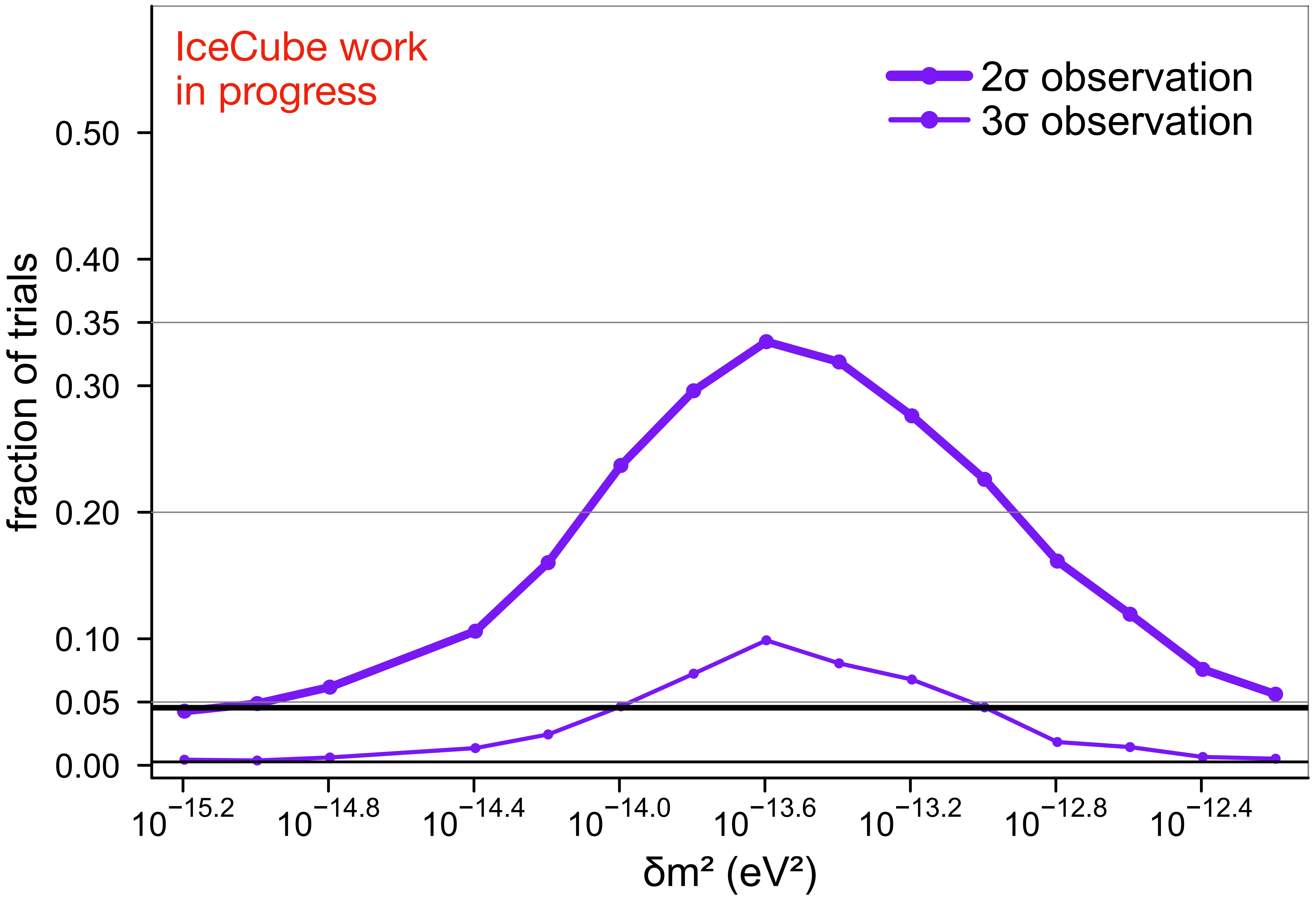
Work by Kiara Carloni (kcarloni@g.harvard.edu)

What are we actually sensitive to?

If neutrinos are QD with some δm^2, how often would we reject the null at x certainty?



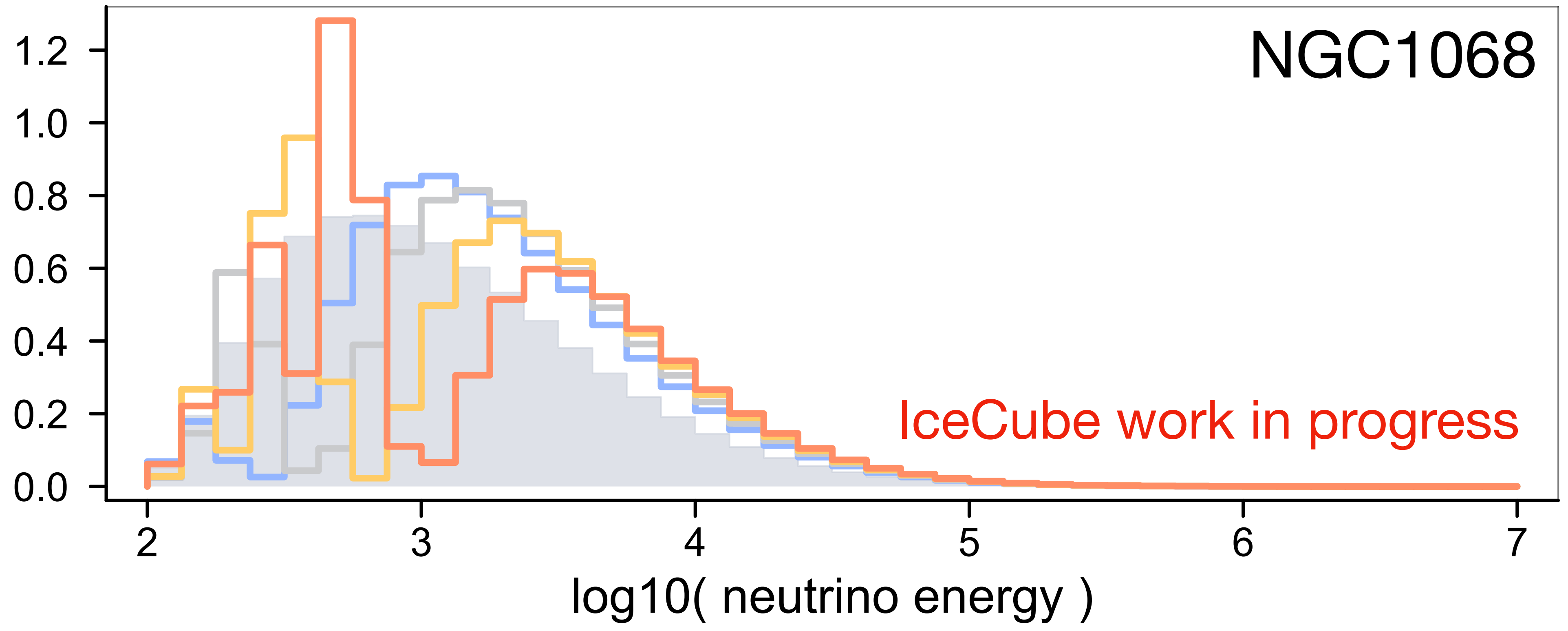
if neutrinos are QD with given δm^2:

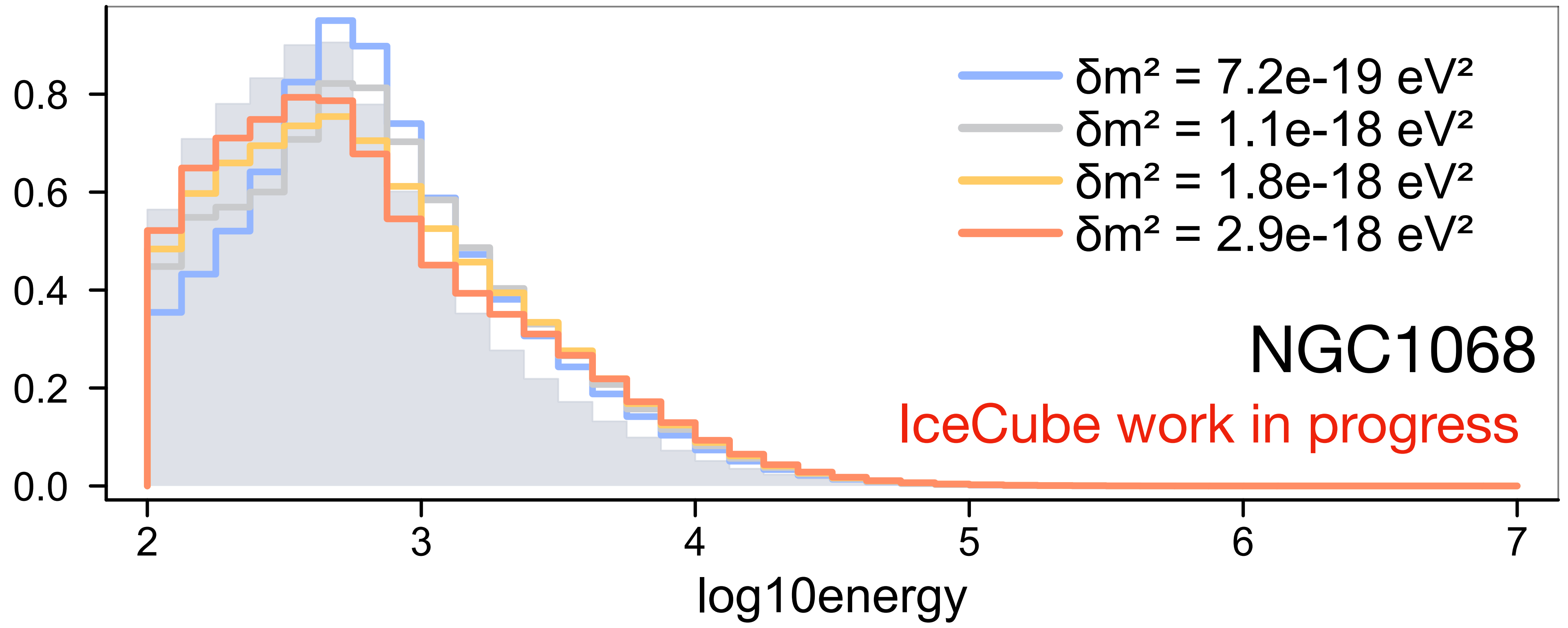


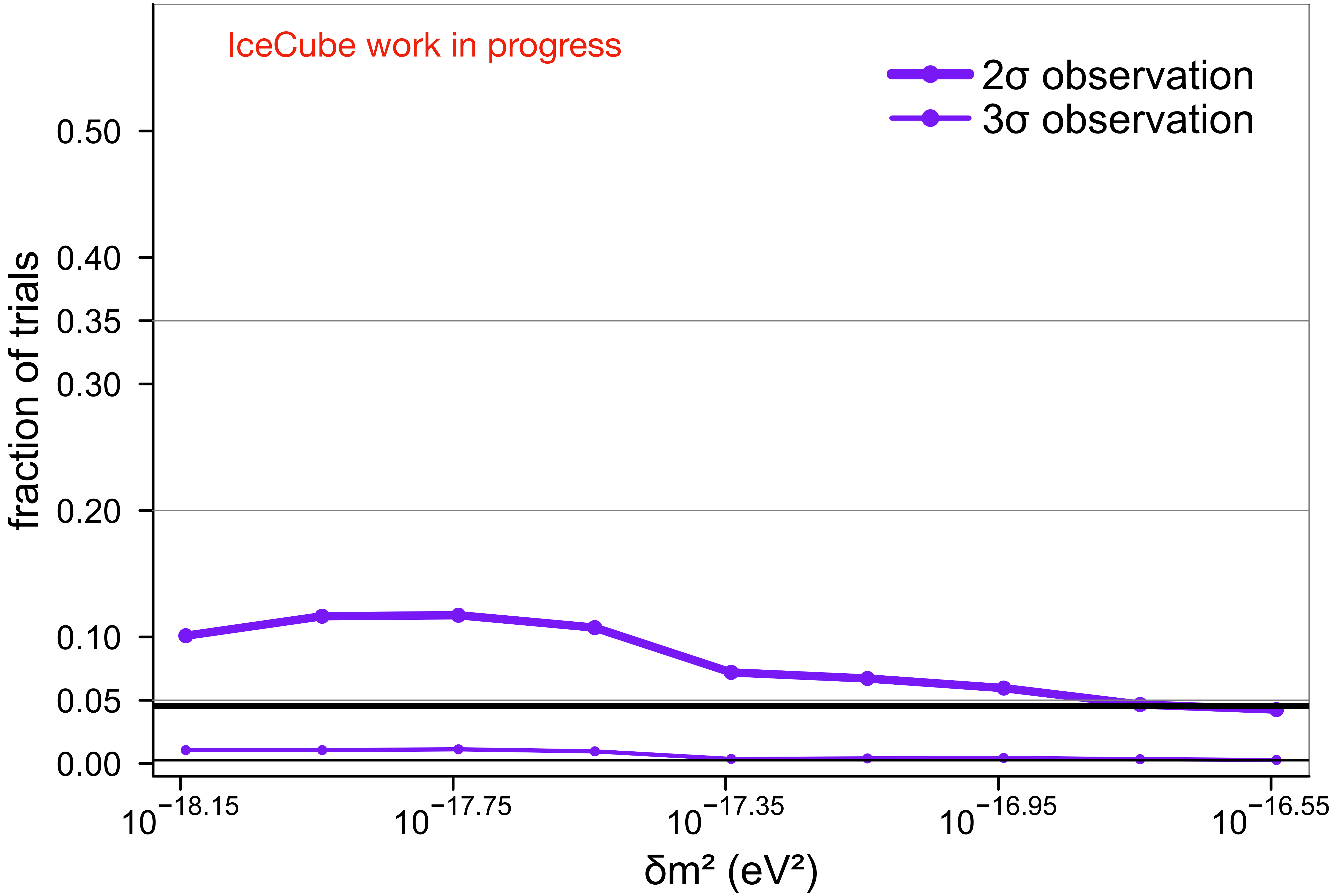
We cover new parameter space never explored before.

What about the sources?

! Recent claims using IceCube Public Data (arXiv:2211.16520v2, arXiv:2406.06476v2) find TS ~ 4 and place strong constraints.







Current single-source sensitivity, should not, on average place constraints due to non-Wilksian nature of TS distribution.

Stops

1. A new frontier in the search for dark matter
2. Using the flavor of neutrinos to find new physics
3. New physics with new sources
4. **Future detectors and new ideas**

HYPER K

P-ONE

RNO-G

ICECUBE GEN2

JEM-EUSO

Many Neutrino Telescopes On Our Way

BAIKAL-GVD

GRAND

TRIDENT
海 | 铃 | 计 | 划

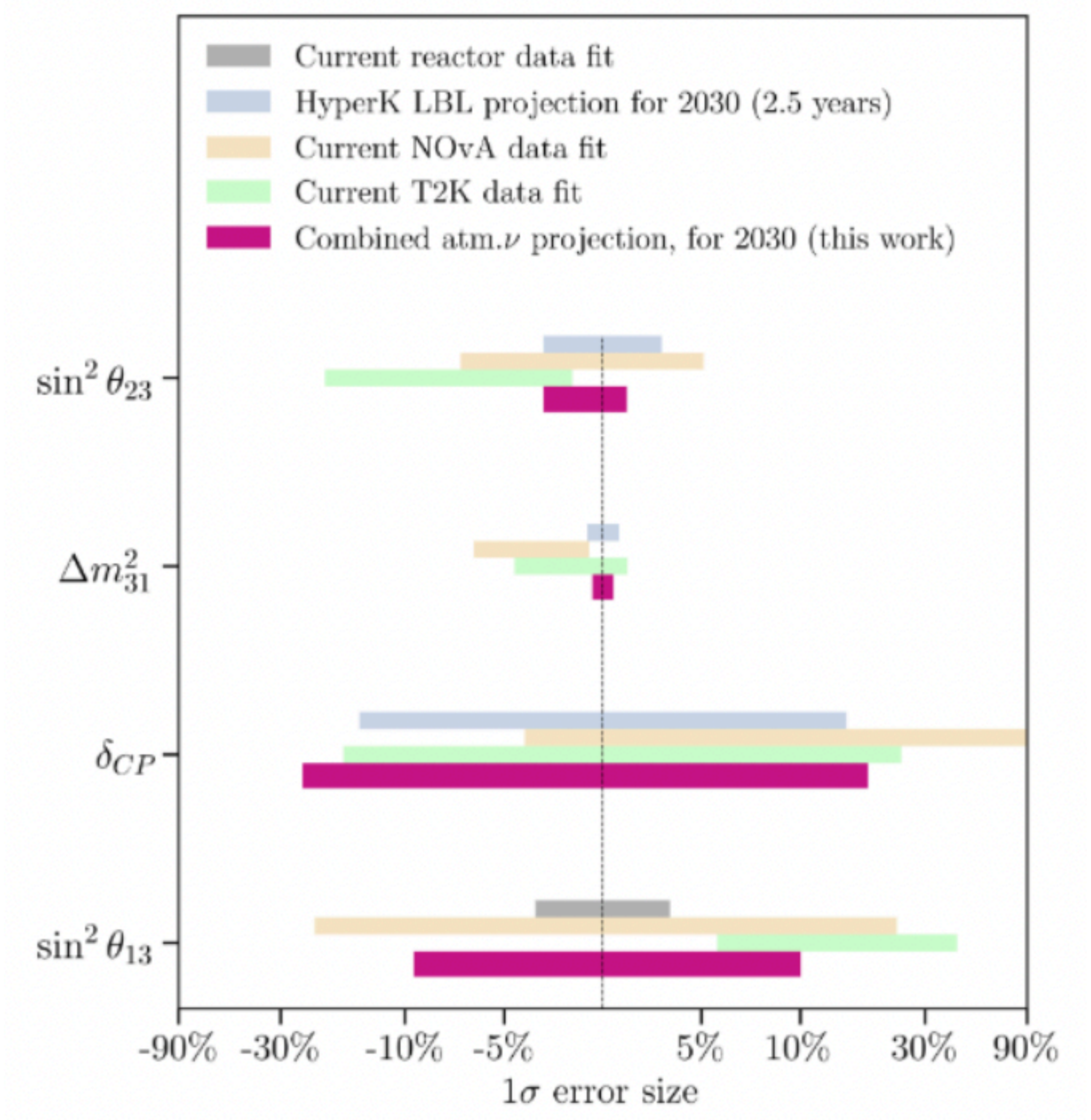
TAMBO

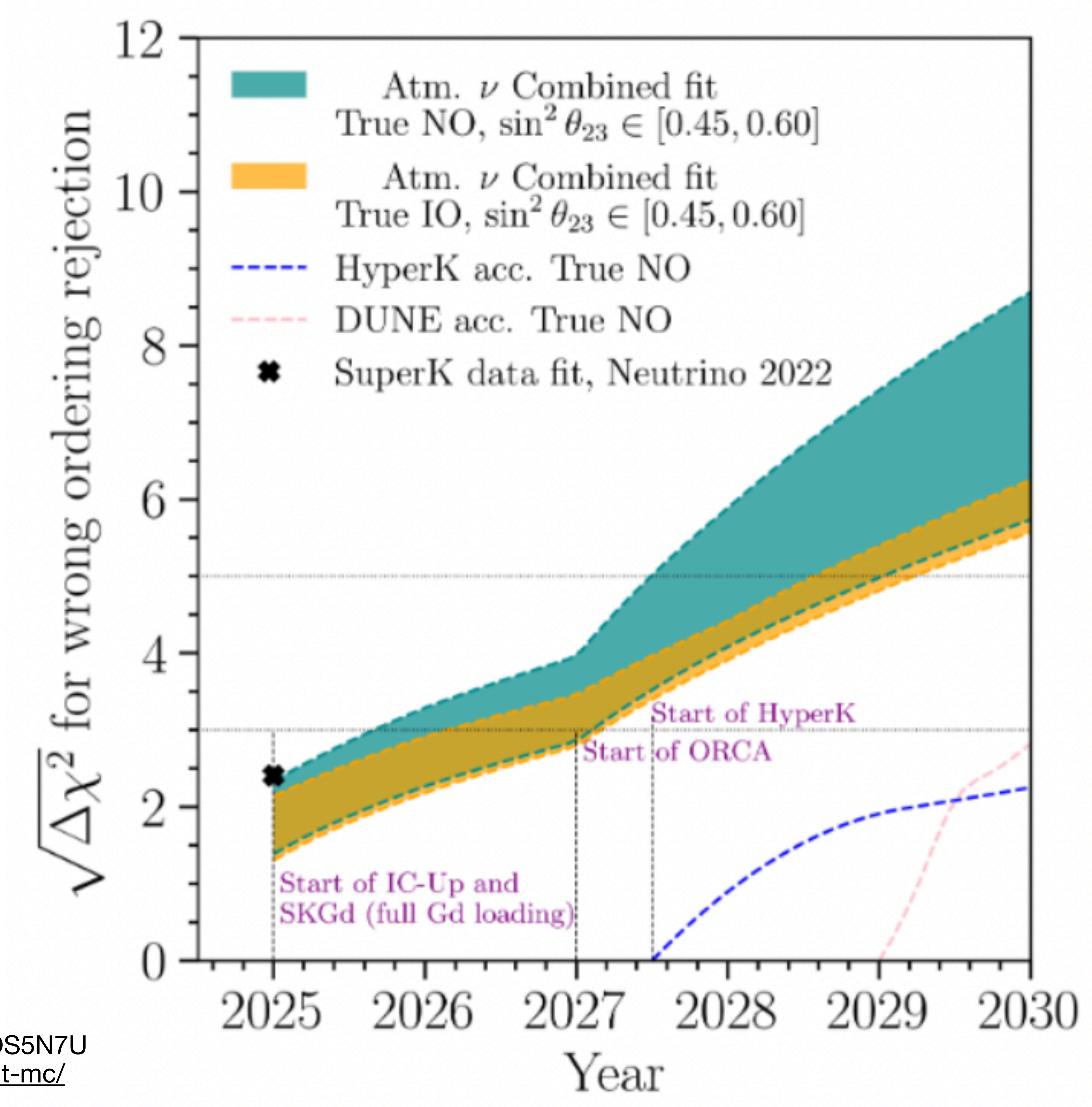
KM3NeT

POEMMA

Non-exhaustive list

Near-term atmospheric neutrinos *together*





CA, P. Fernández, I. Martínez-Soler, and M. Jin, PRX 13 041055

See also Giner-Olavarrieta, Jin, CA, Fernandez, Martínez-Soler (2402.13308)

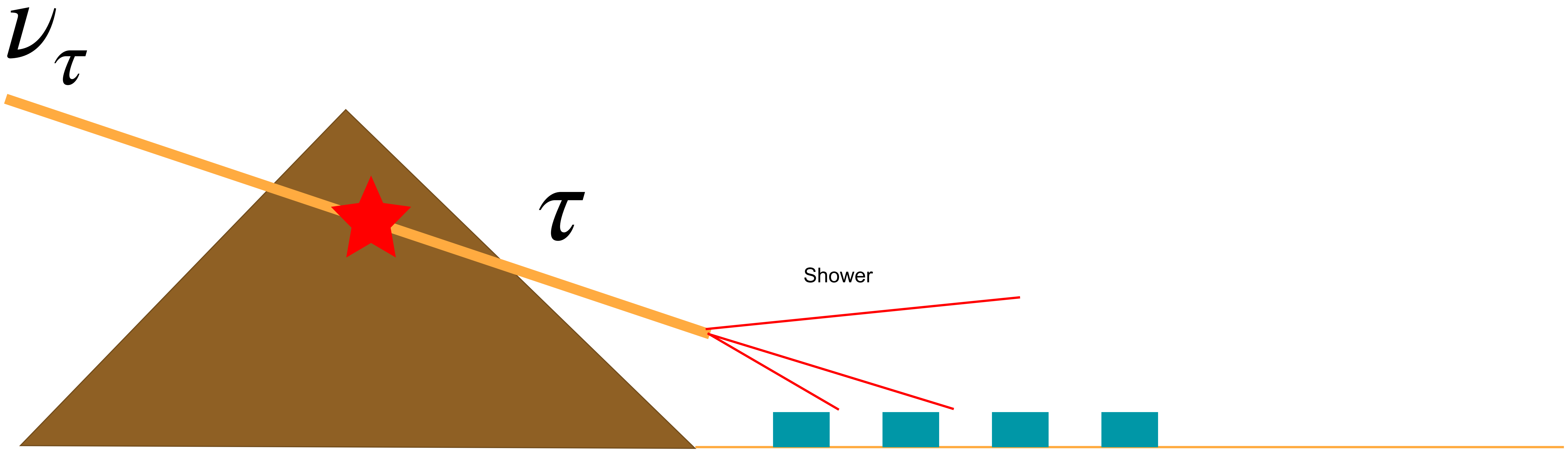
Reprodusability:

MC: https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/ OS5N7U
Instructions: https://github.com/Harvard-Neutrino/atmospheric-neutrino-experiment-mc/
Code:https://github.com/Harvard-Neutrino/AtmNuCombination

Flavor is a very powerful observable

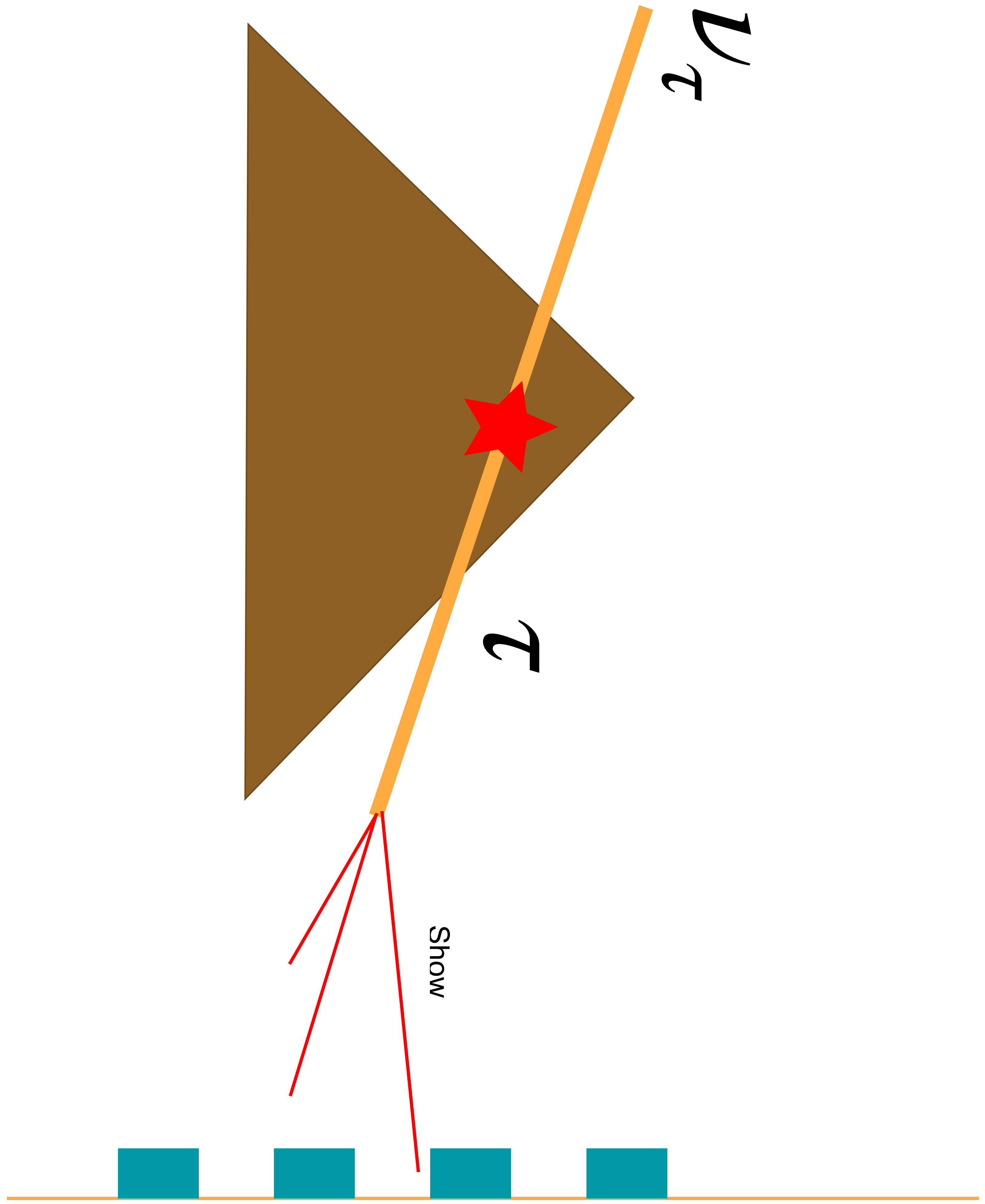
Tau neutrinos are the least observed neutrino flavor

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection
This would be a more ideal scenario, but can’t put mountain over detector

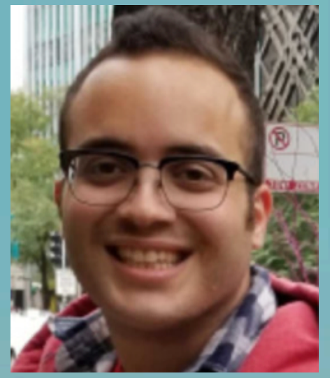
Pavel Zhelnin

William Thomson

Diya Delgado

Jeffrey Lazar

Ibrahim Safa



And many others …

AIR SHOWER:

3 – 10 KM LENGTH
200 M DIAMETER

ROCK

> 4 KM SHIELDING FROM
BACKGROUND MUONS

DECAY

τ

ν_τ

RANGE:
50 M – 5 KM

~100 M
SEPARATION

WATER CHERENKOV
DETECTOR ARRAY

~M³ EACH

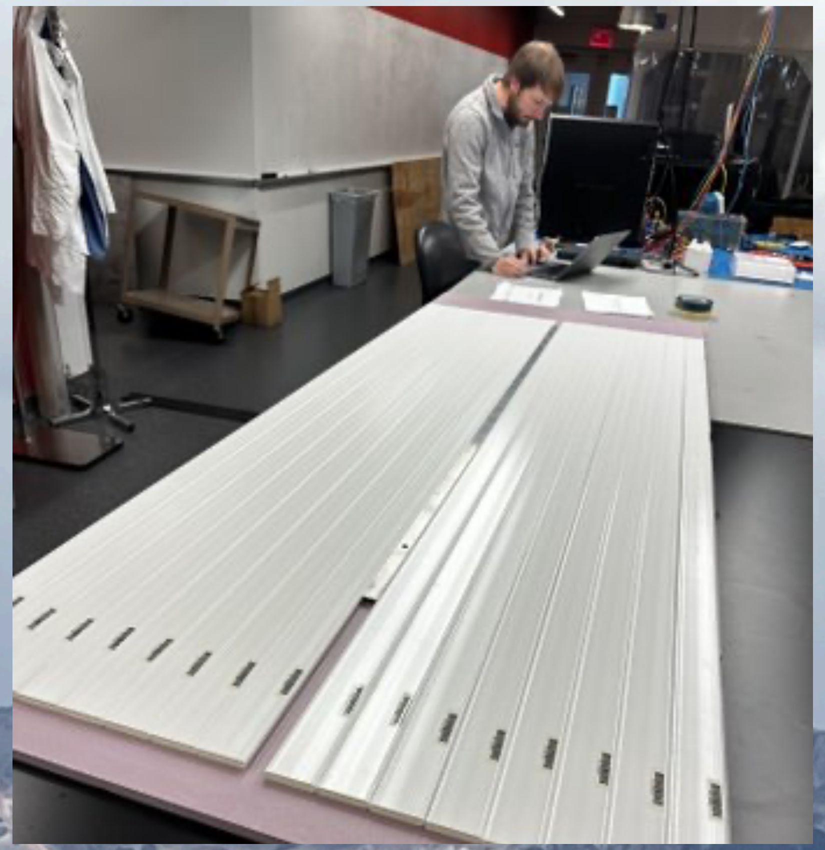
CHARGED-CURRENT
INTERACTION

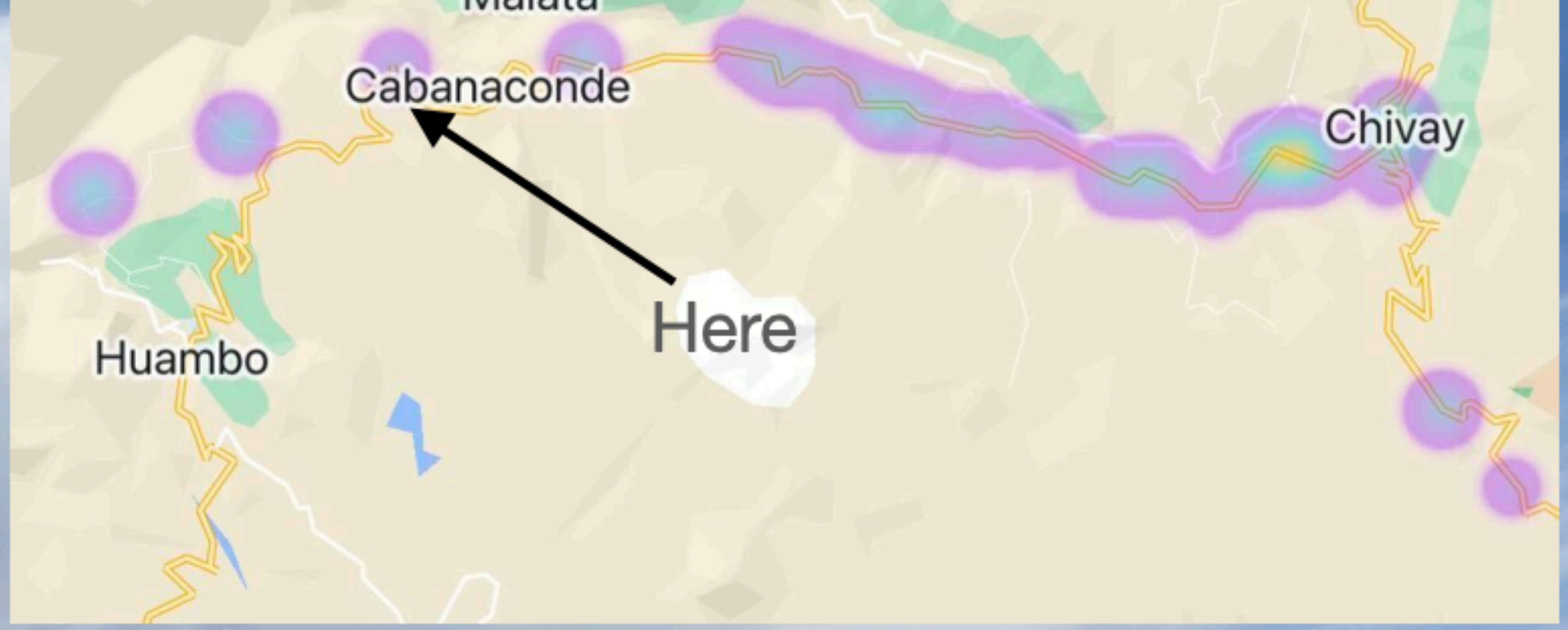
DEEP VALLEY

TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

W. Thompson ICRC2024 (arXiv:2308.09753)

*TAMBO means rest place, house or inn in Quechua.



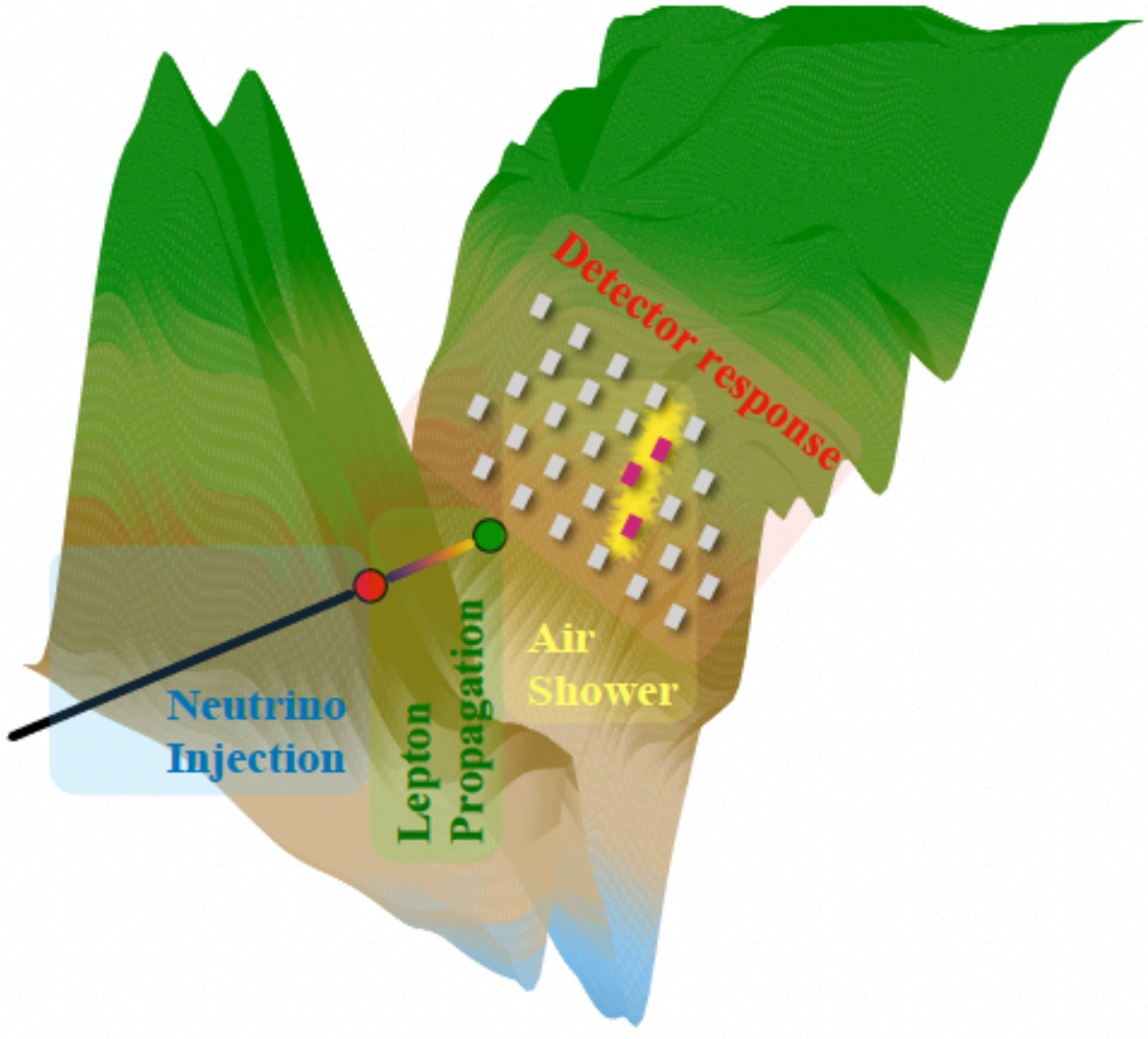


TAMBO

We went to Peru in 2022 and found a location for the experiment!
First prototype detectors are expected to be deployed next summer.

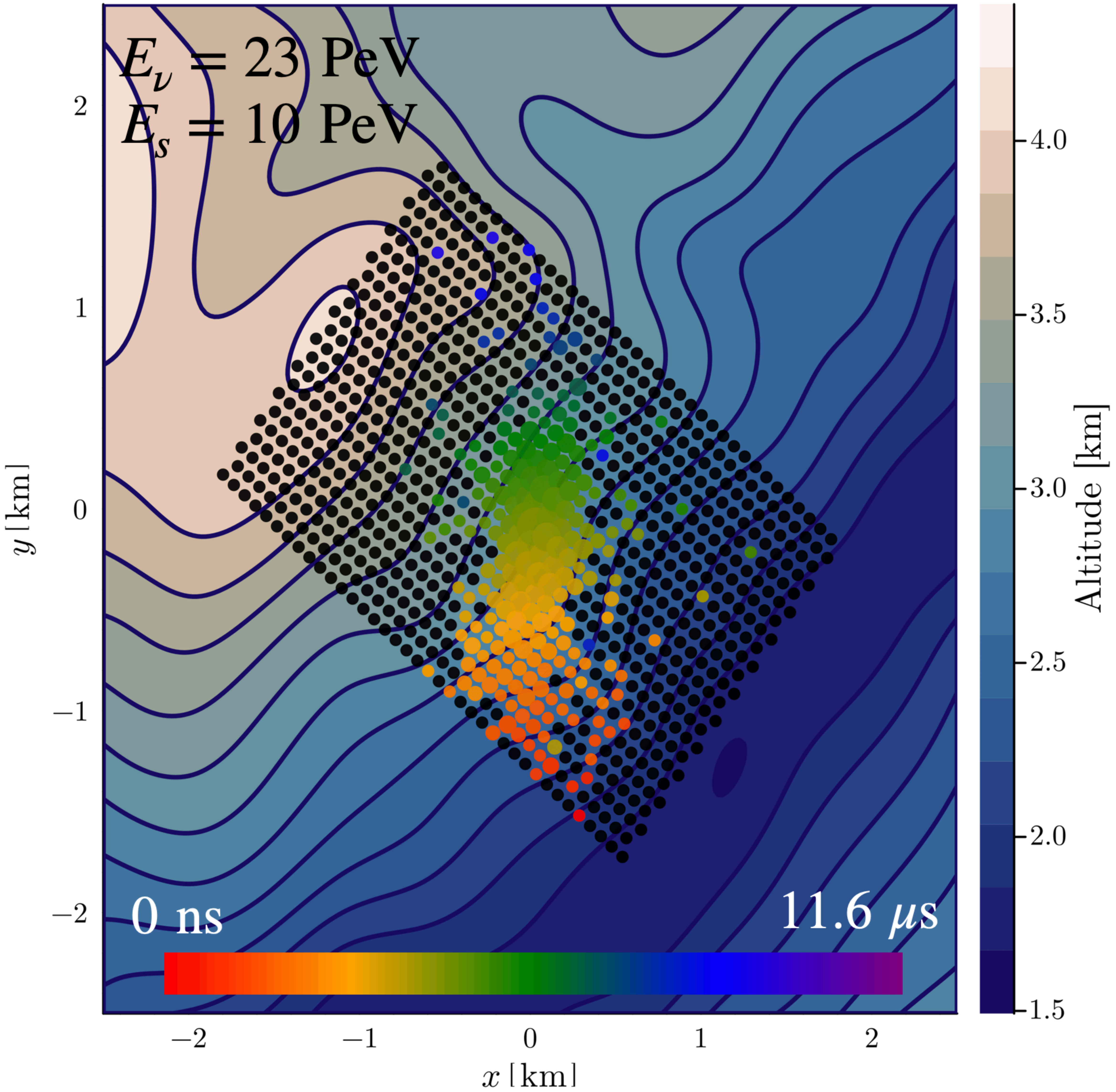
TAMBO Simulation

*simulation of air-showers using **CORSIKA8**



TAMBOSim

J. Lazar, P. Zhelnin, W. Thompson for the TAMBO Collabotion (2024, to arXiv)

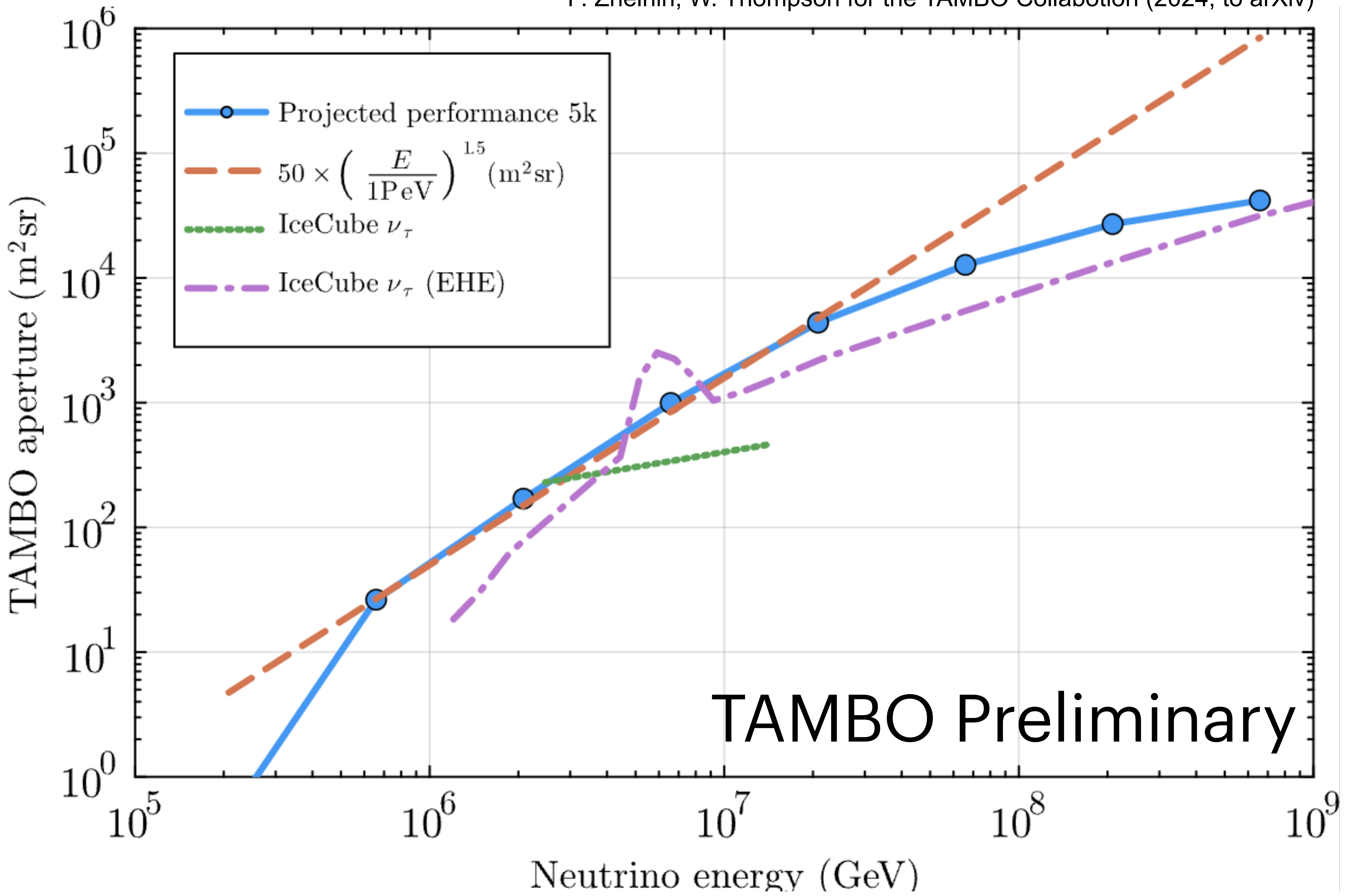


TAMBO Simulation

Design goal: Aim to go as low as possible in energy: 1 PeV to 100 PeV range

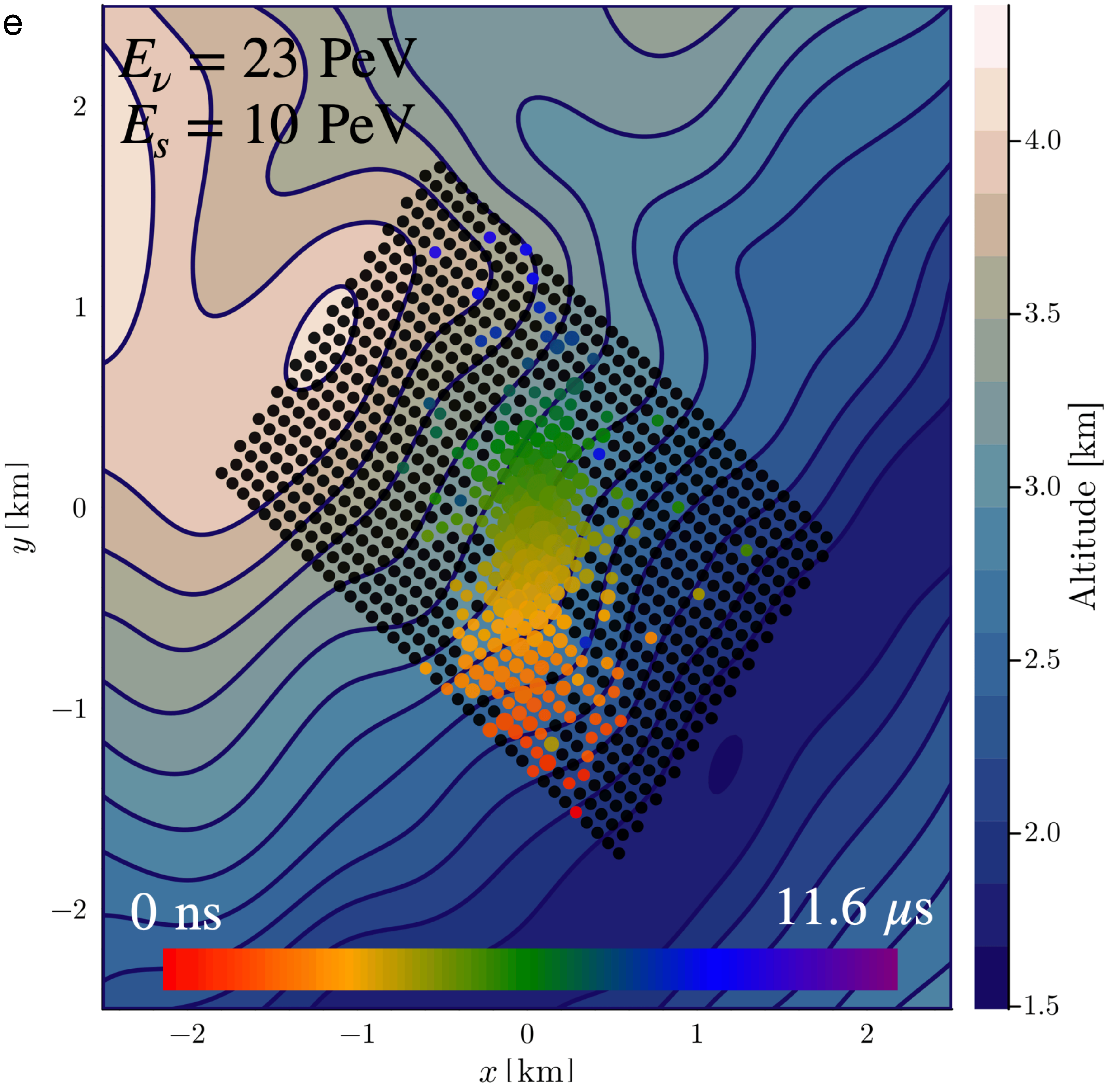
(*glashow contribution not included yet)

P. Zhelnin, W. Thompson for the TAMBO Collabotion (2024, to arXiv)

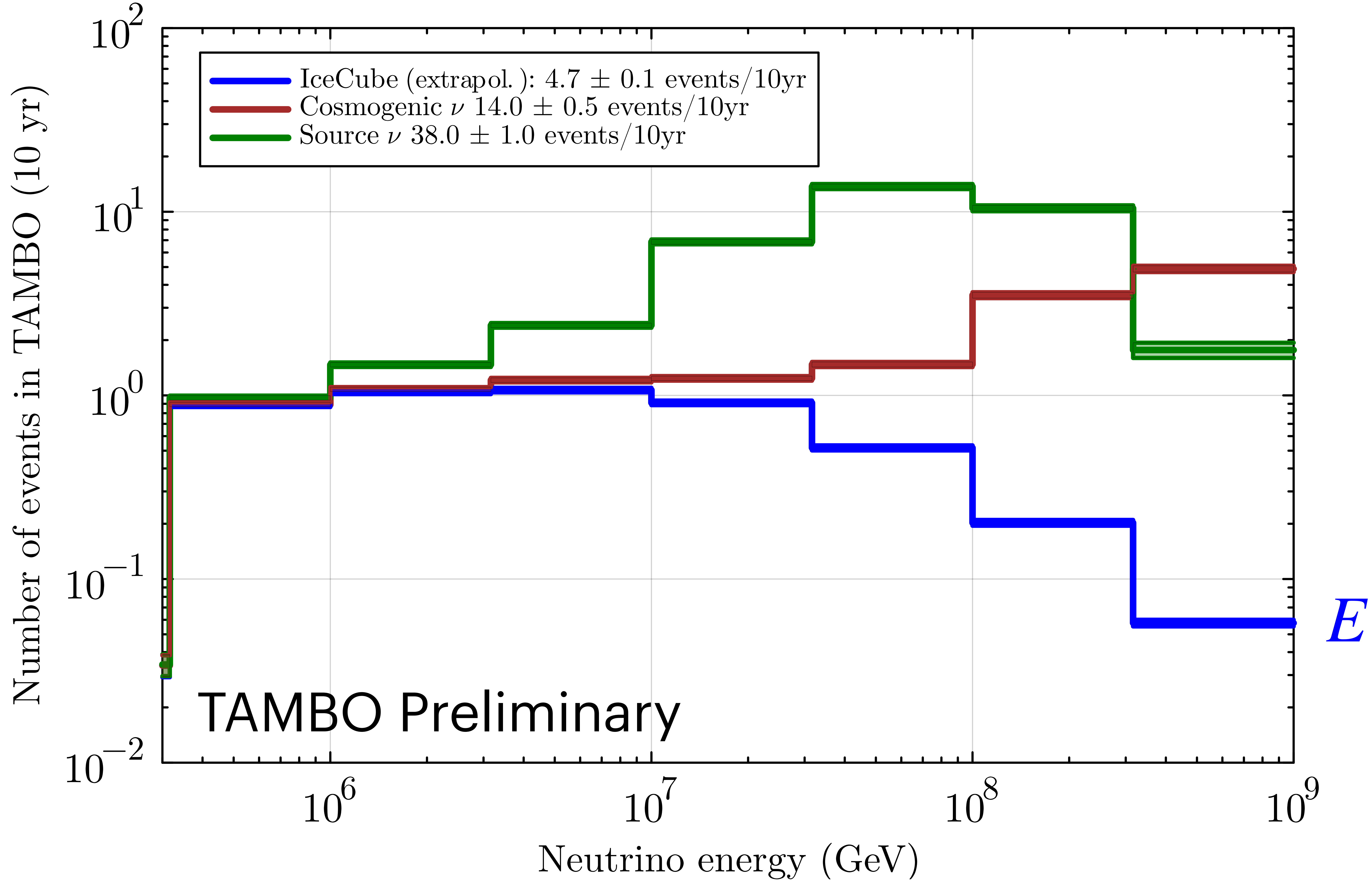


With ~ 5000 modules we hace IceCube-EHE comparable or greater effective areas

J. Lazar, P. Zhelnin, W. Thompson for the TAMBO Collabotion (2024, to arXiv)



Expected rates at TAMBO given unknown-origin IceCube flux



Cosmogenic ν
(Bergman & Van Vliet)

AGN source polulation
(Rodriguez et al. AGN)

$E^{-2.5}$ **IceCube extrapolation**

For 5000 sensors we expect events every other year.
Few events, but high-purity
Good for IceCube/KM3NeT follow up

Towards a *Joint* Global Neutrino Telescope

BAIKAL-GVD
WATER CHERENKOV
0.4km^3

KM3NeT
ORCA
ARCA
WATER CHERENKOV
ORCA: 0.0067km^3
ARCA: 1km^3

GRAND
RADIO DETECTORS

TRIDENT
海 | 铃 | 计 | 划
WATER CHERENKOV
8km^3

NEON
WATER CHERENKOV
30km^3

HUNT
WATER CHERENKOV
30km^3

P-ONE
WATER CHERENKOV
1km^3

Trinity
AIR CHERENKOV

RNO-G
RADIO DETECTORS

BEACON
RADIO INTERFEROMETRY

TAMBO
PARTICLE DETECTORS

PIERRE AUGER OBSERVATORY
PARTICLE DETECTORS

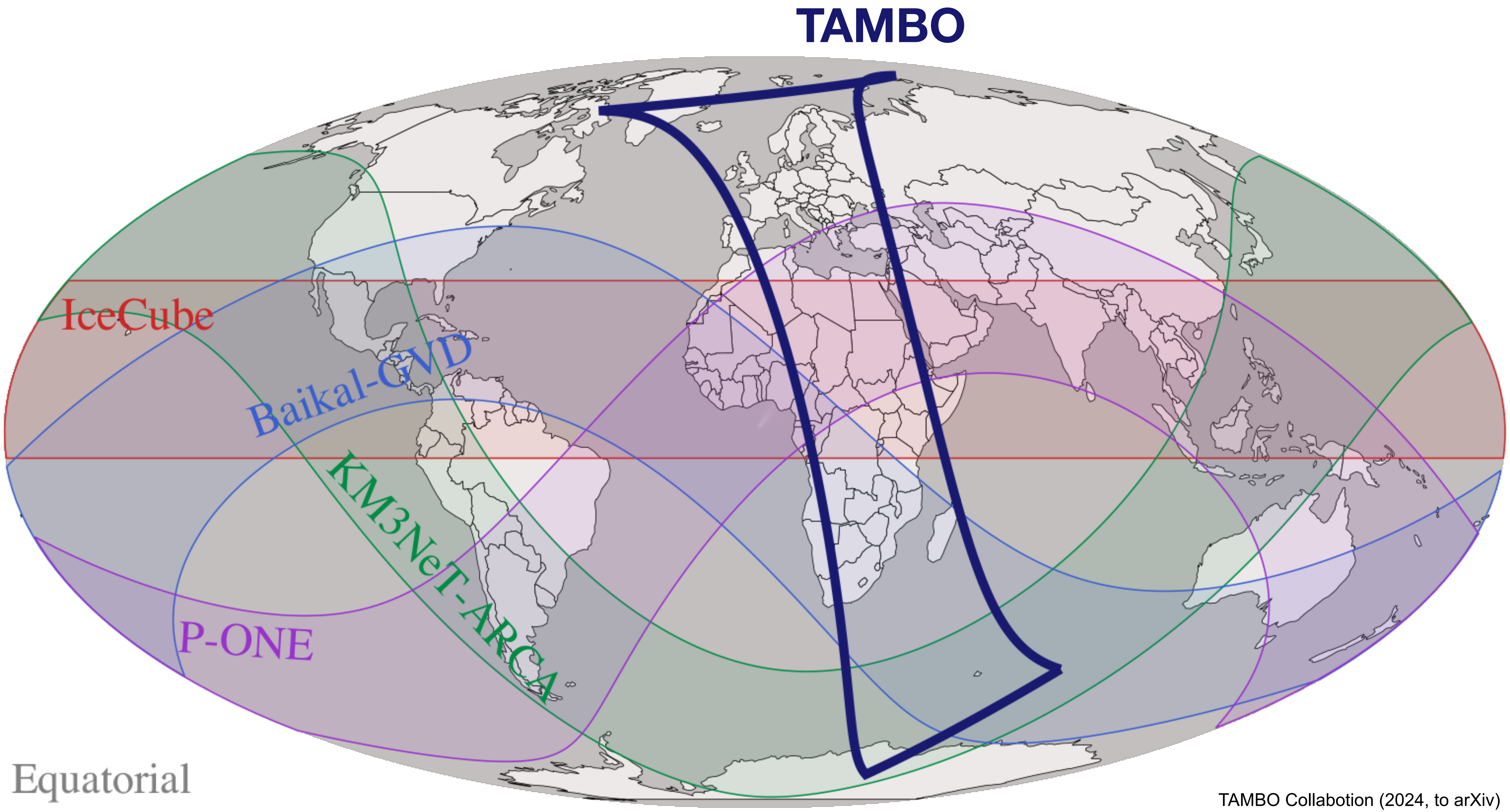
ICECUBE NEUTRINO OBSERVATORY
ICE CHERENKOV
1km^3

ICECUBE GEN2
ICE CHERENKOV
8km^3

NOTE
PROJECTS MARKED IN BLUE ARE COMPLETE OR UNDER CONSTRUCTION.
PROJECTS MARKED IN WHITE ARE PROPOSED.

EARTH MAP TEXTURE CREDIT: VIDEO COPILOT

Towards a *Joint* Global Neutrino Telescope



TAMBO Collabotion (2024, to arXiv)

Conclusion

We live in exciting times for particle astrophysics

- First astrophysical neutrino sources are appearing.
- IceCube is able to observe neutrinos from all flavors.
- Neutrino interferometry is a powerful tool to measure tiny effects.

We also have great opportunities for the future

- With IceCube we have a rich data set for continuing searches
- With the Upgrade we will have great new precision
- More neutrino telescopes: more data!
- Diversified neutrino telescope portafolio opens new opportunities for discovery

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

KM3NeT

TAMBO

CIFAR

Thanks!

The NSF Institute for Artificial Intelligence and Fundamental Interactions

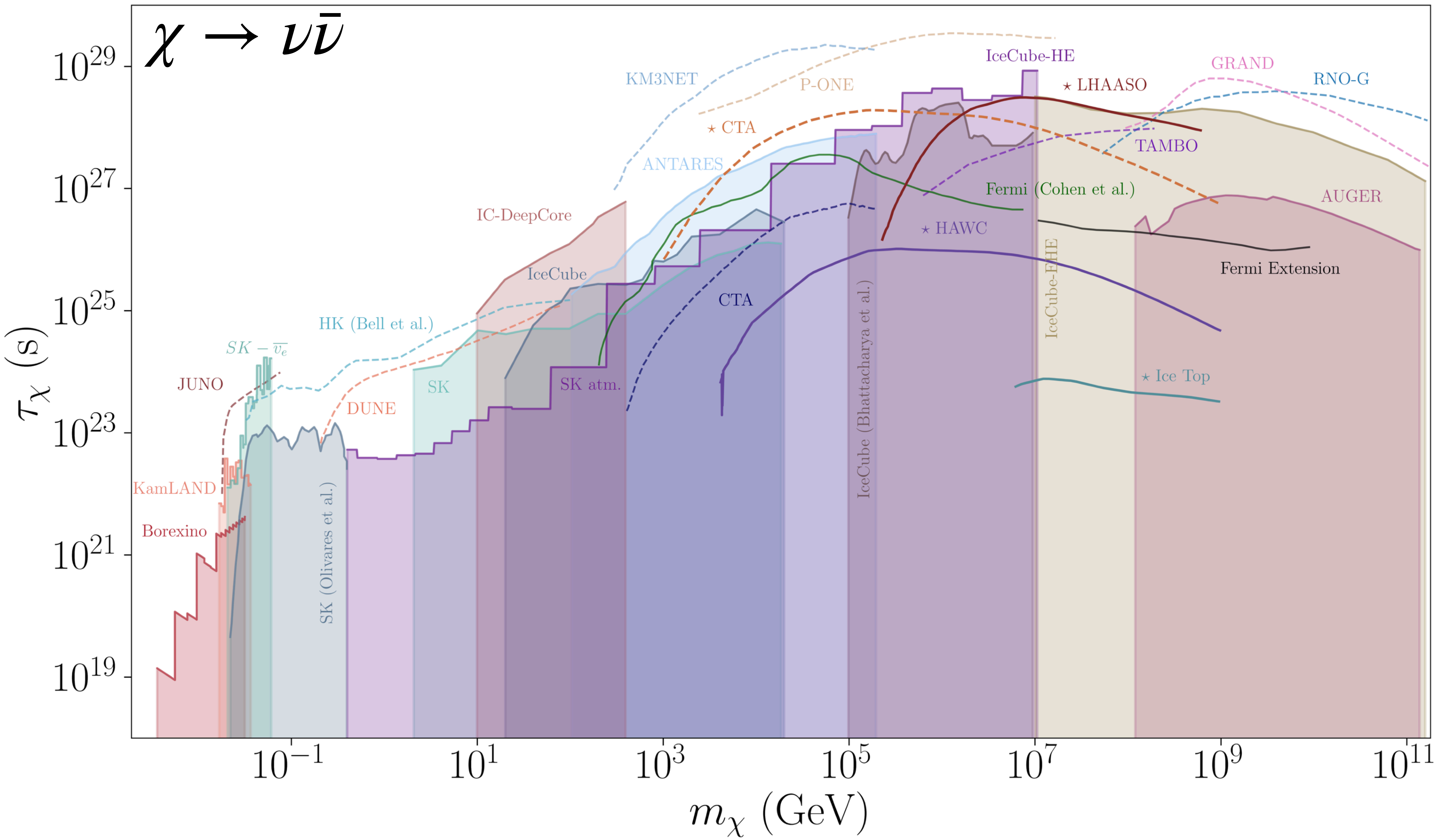
NSF

RESEARCH CORPORATION for SCIENCE ADVANCEMENT

the David & Lucile Packard FOUNDATION

Bonus slides

Dark Matter Decay To Neutrinos

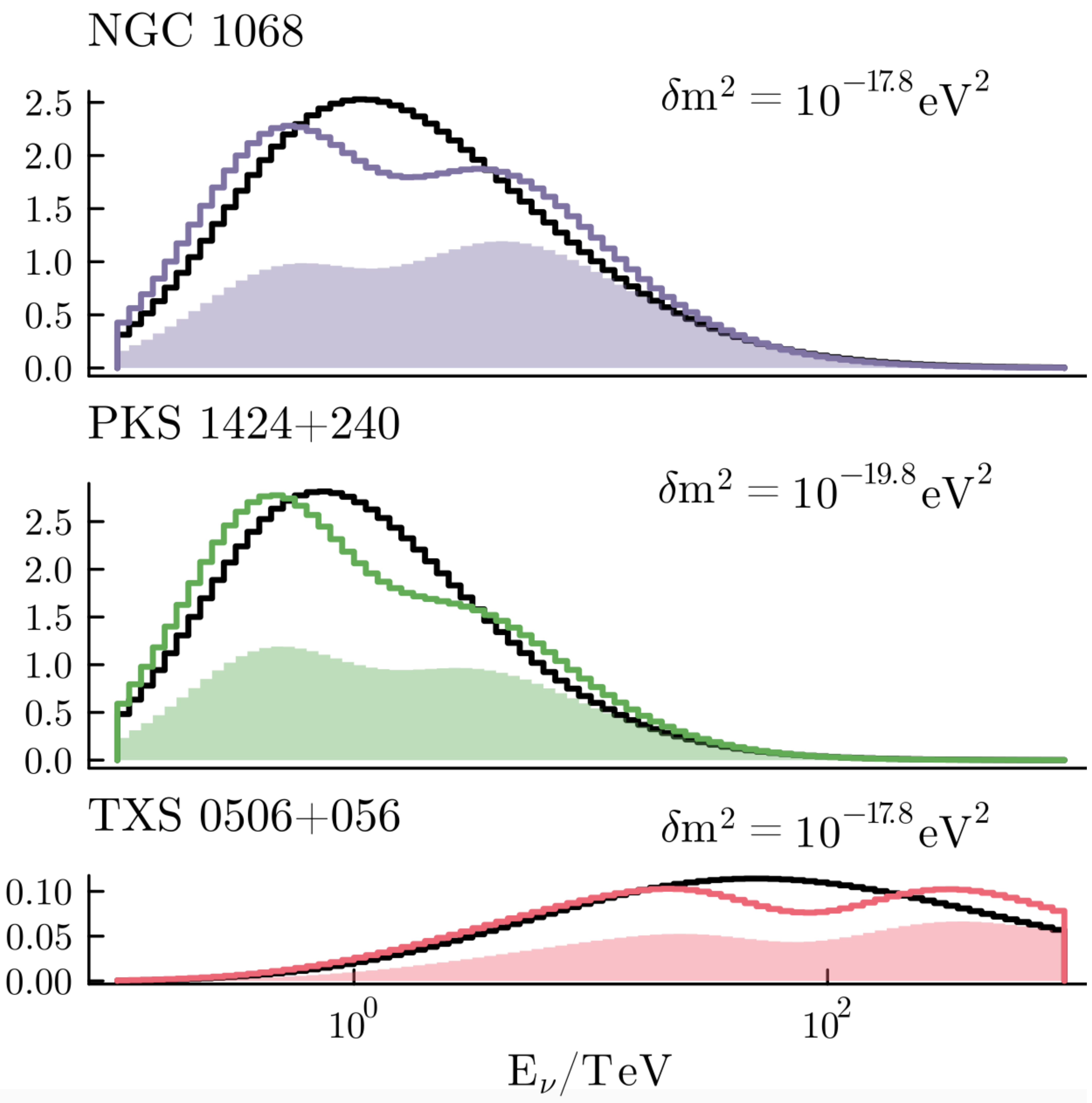


CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White arXiv:2210.01303

Work by Diya Delgado

Quasi Dirac Bonus

See also Esmaili arXiv:0909.5410, Esmaili & Farzan arXiv:1208.6012,
Rink & Sen arXiv:2211.16520



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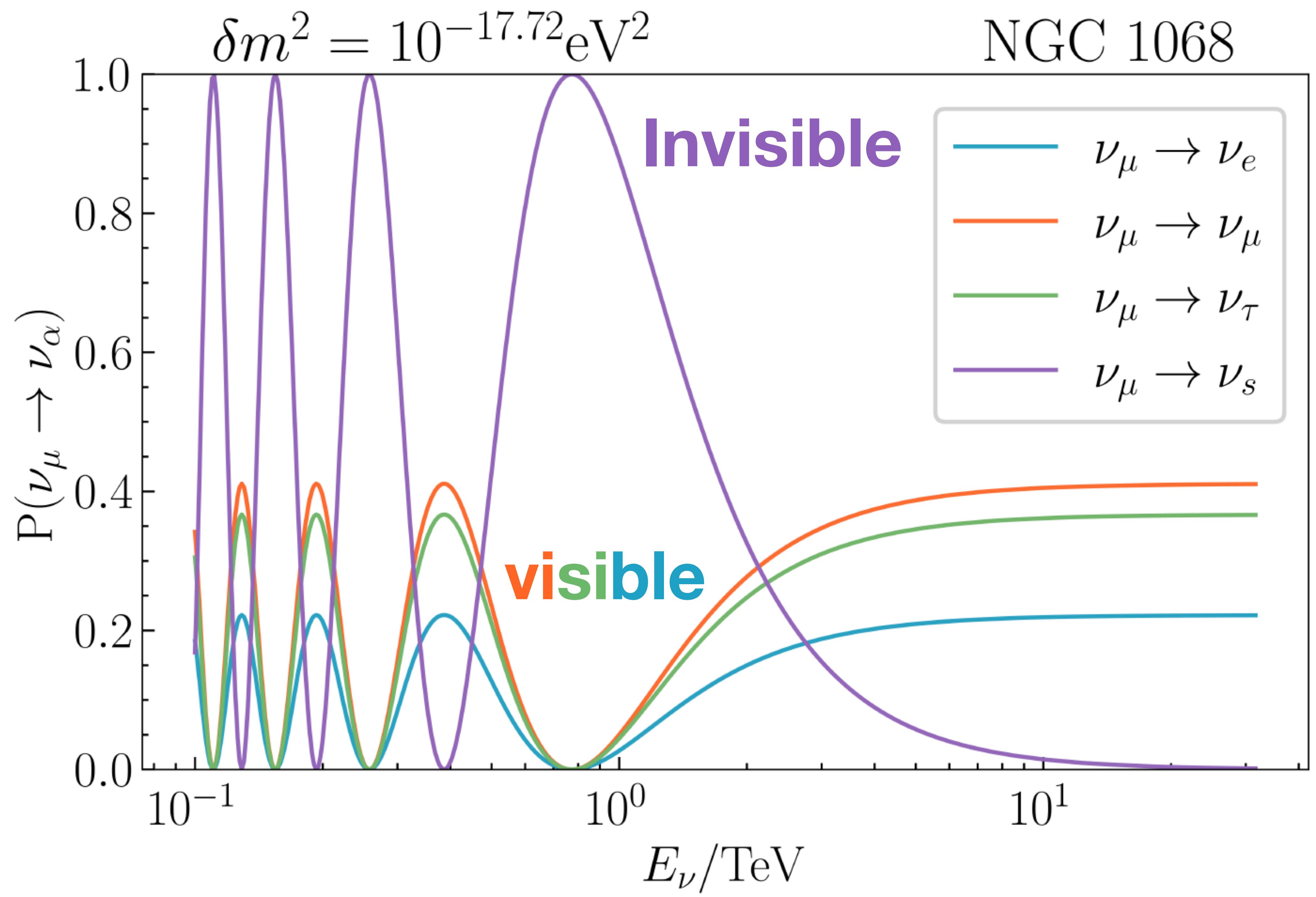
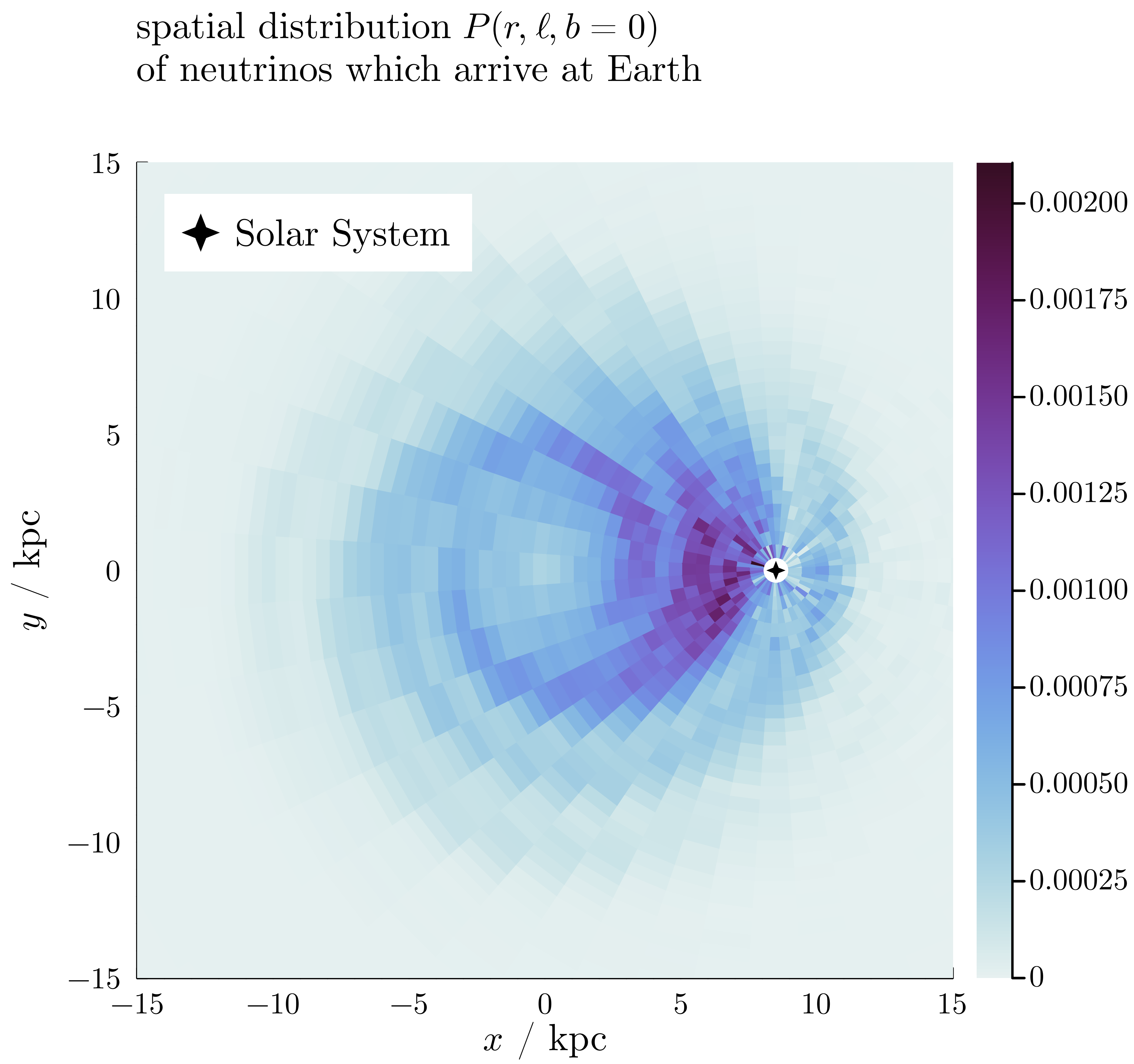
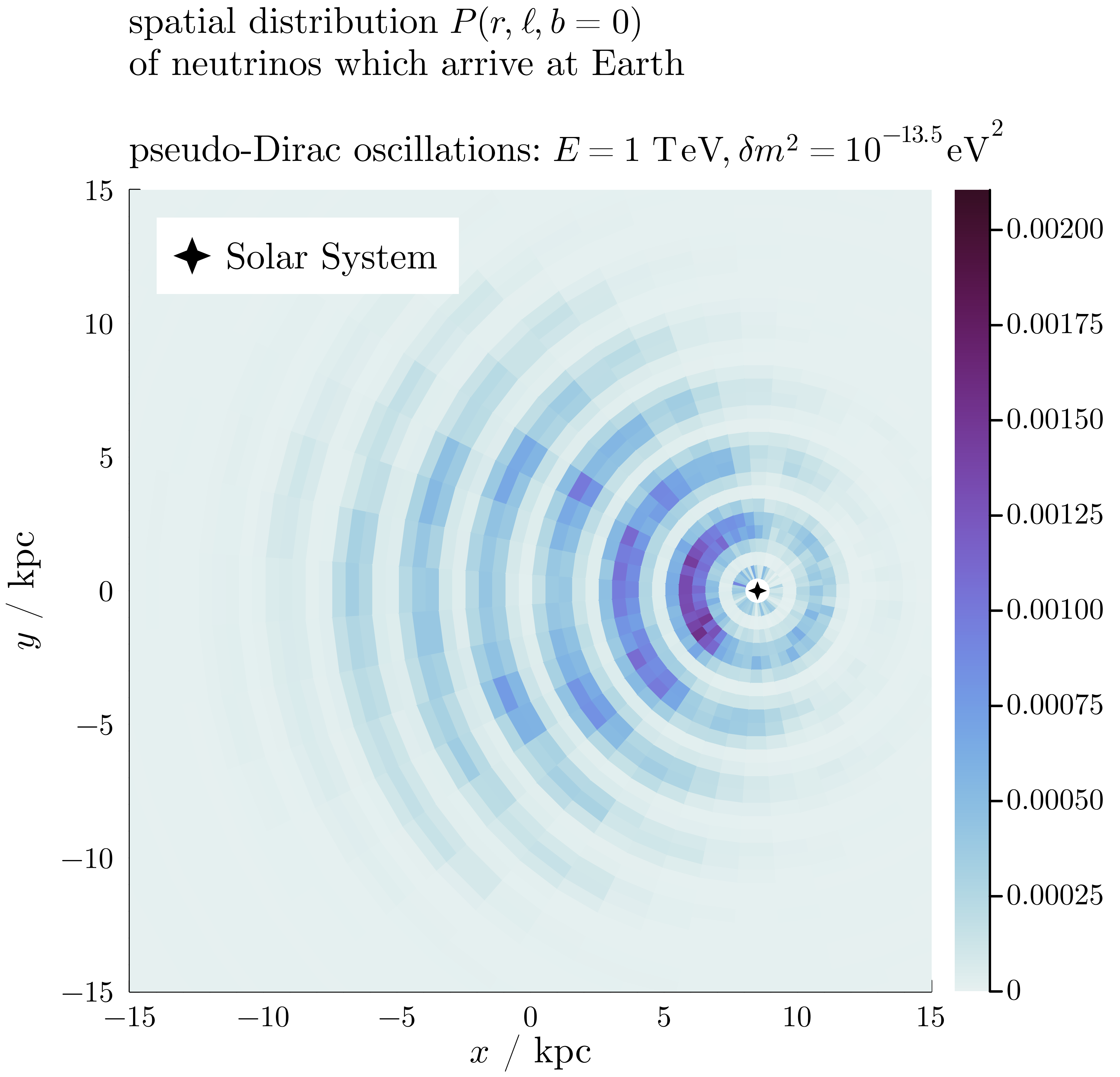


Carloni, Martínez-Soler, CA, Babu, Bhupal Dev arXiv:2212.00737

Quasi-Dirac Oscillations and Galactic Neutrinos

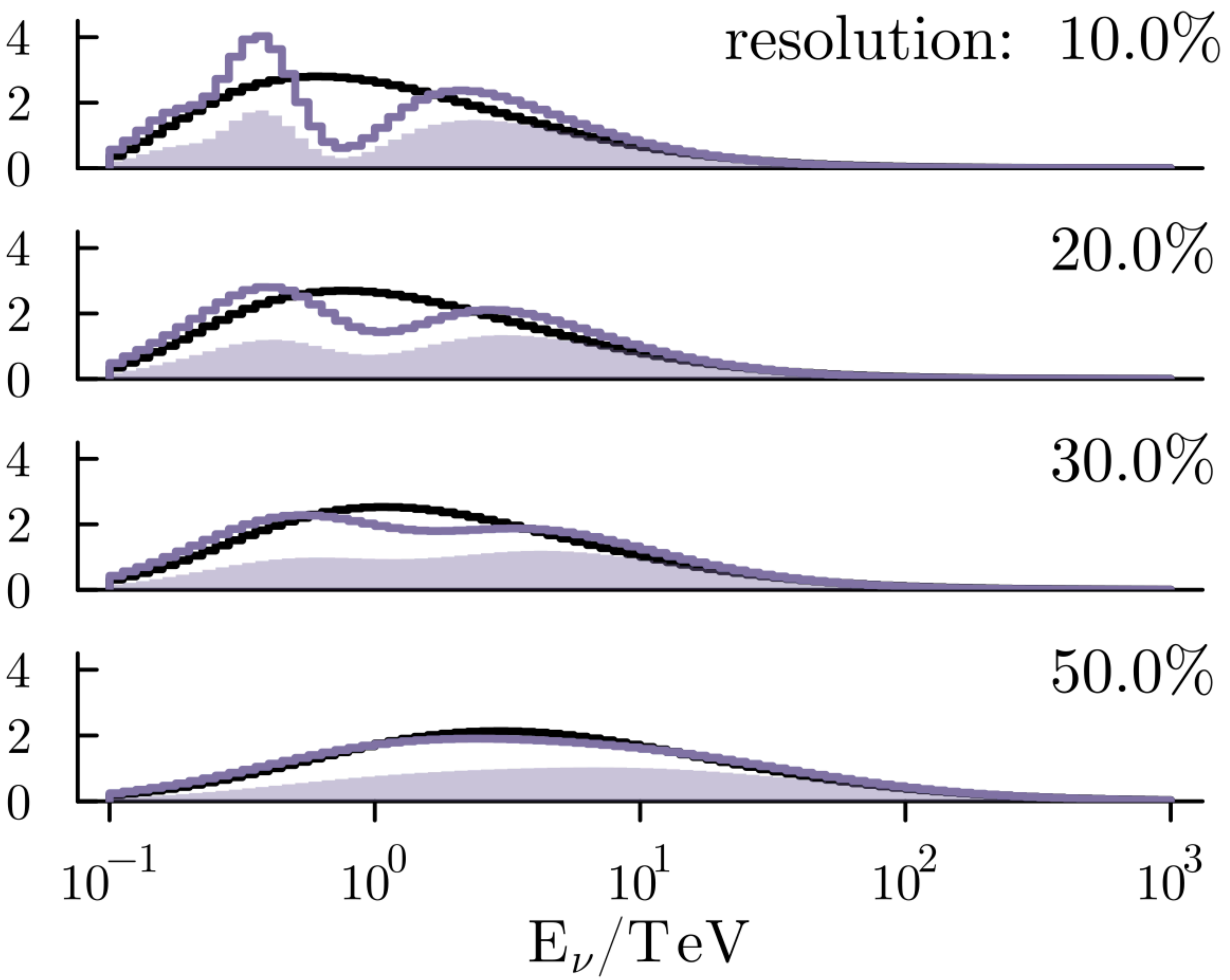


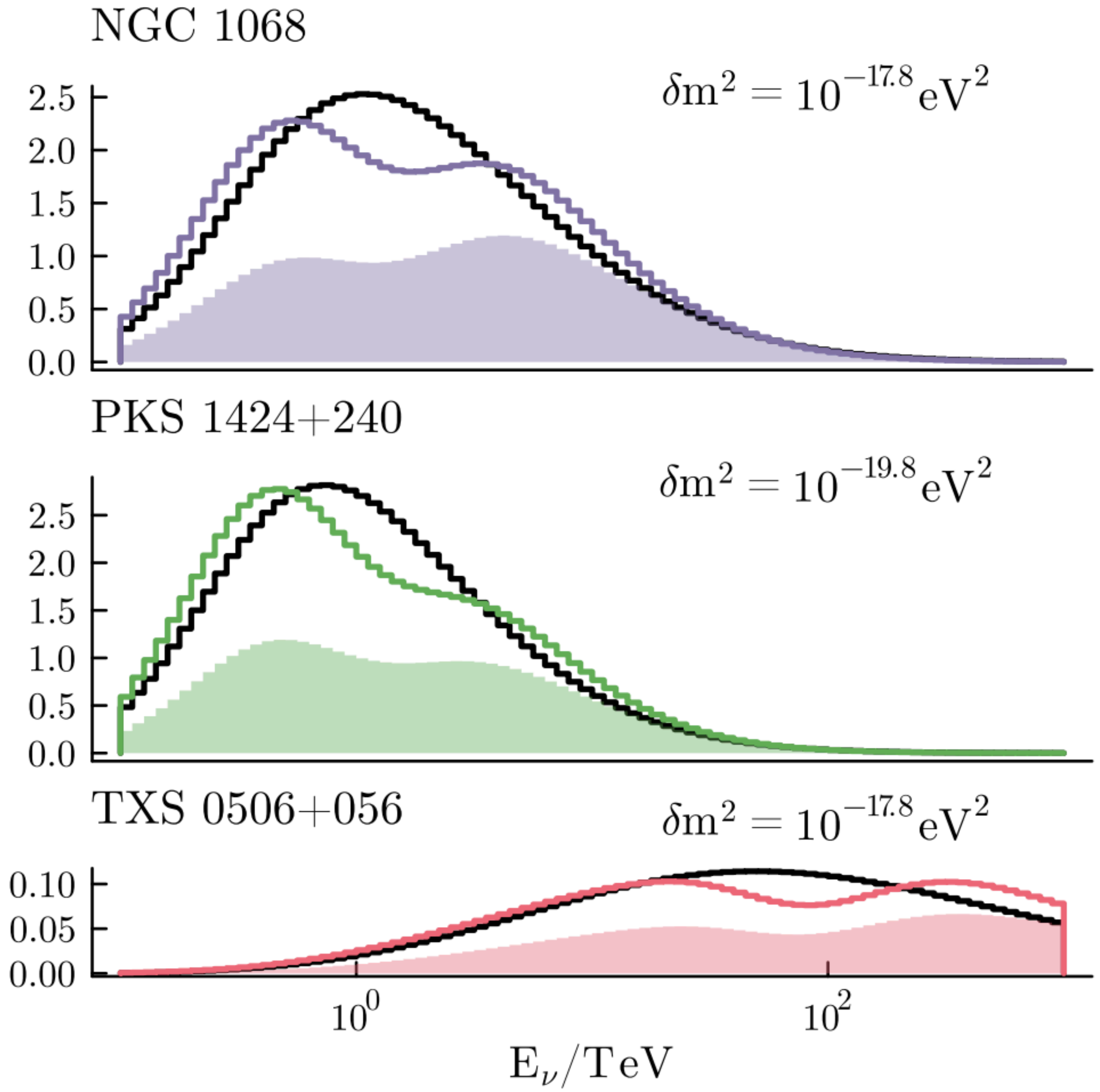


Pseudo-Dirac neutrinos can produce oscillations on
galactic neutrinos for mass-squared-differences around $10^{-13.5}\mathrm{eV}^2$!

M. McDonald, K. Carloni, R. Alves, CA, and I. Martínez-Soler to appear

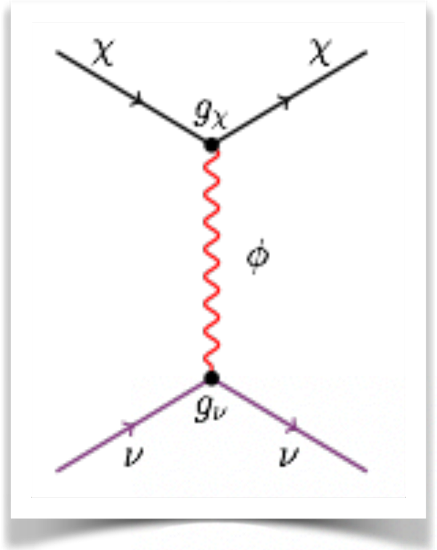
Challenges in Quasi-Dirac Neutrino Searches



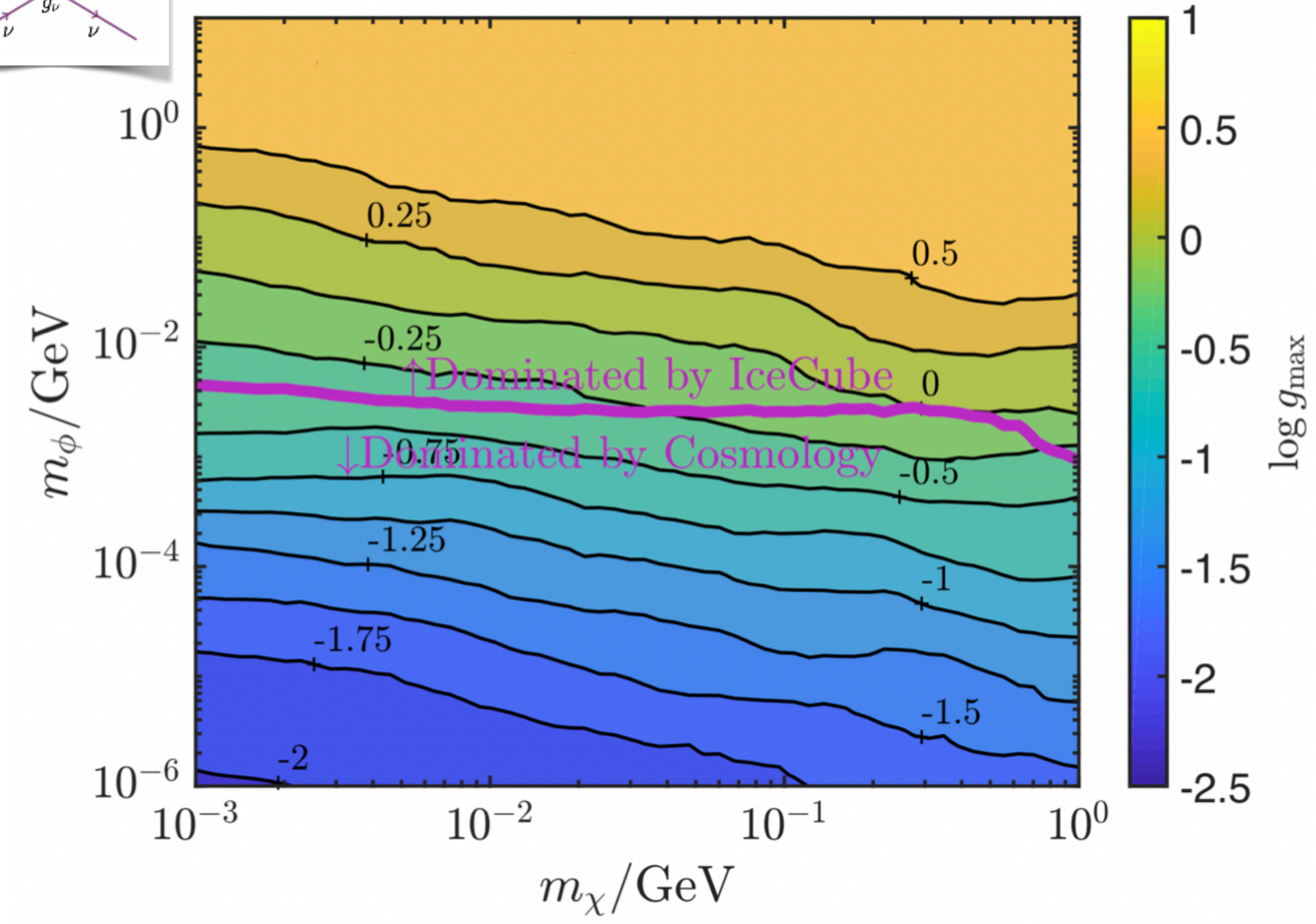


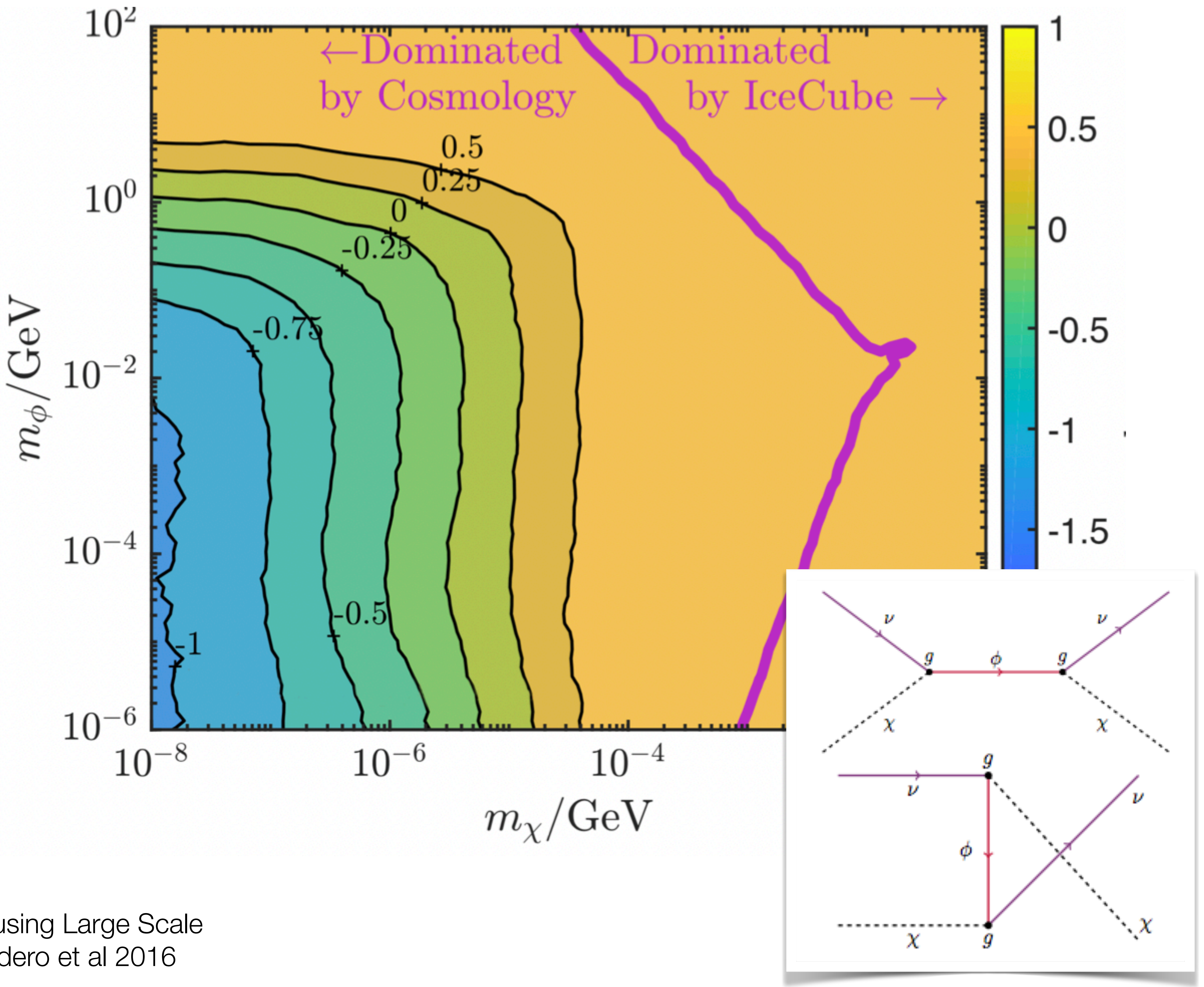
K. Carloni, I. Martínez-Soler, CA, KS Babu, PS Bhupal Dev arXiv:2212.00737

Constrains on Dark Matter Neutrino Scattering



IceCube Collaboration, arXiv:2205.12950

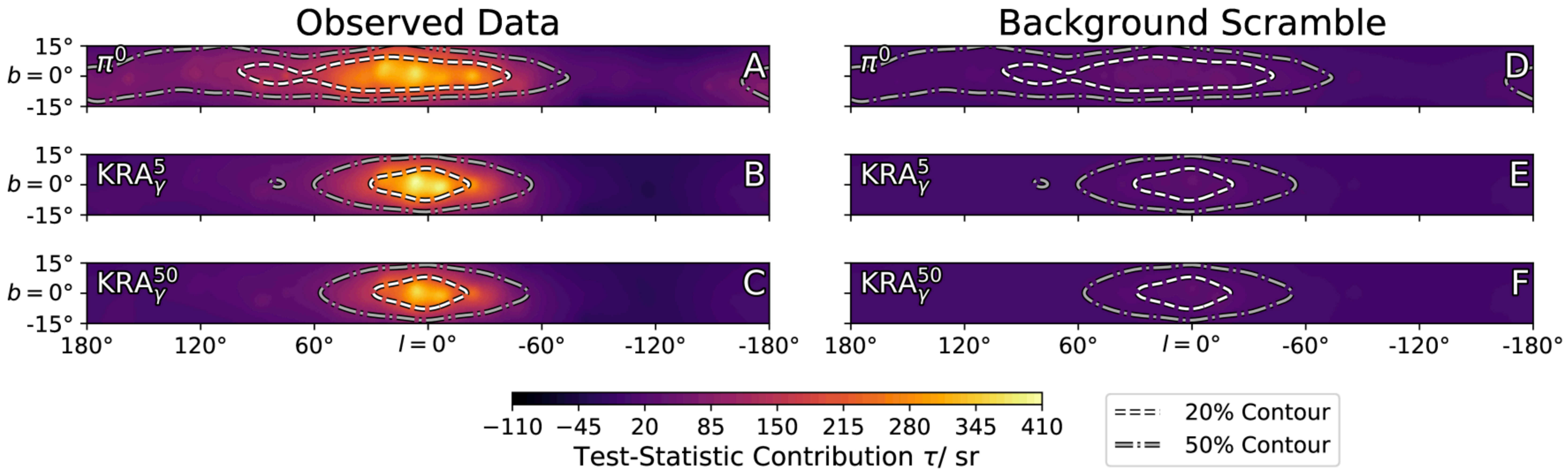


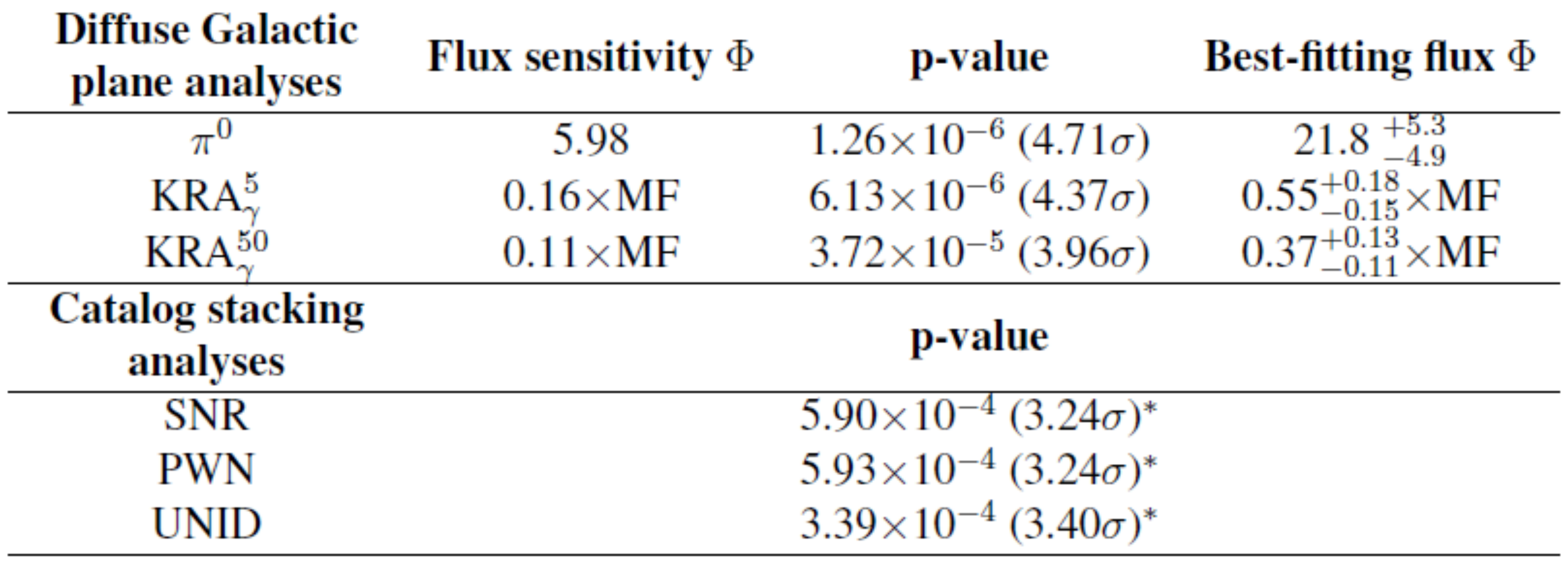


Color scale is the maximum allowed coupling.

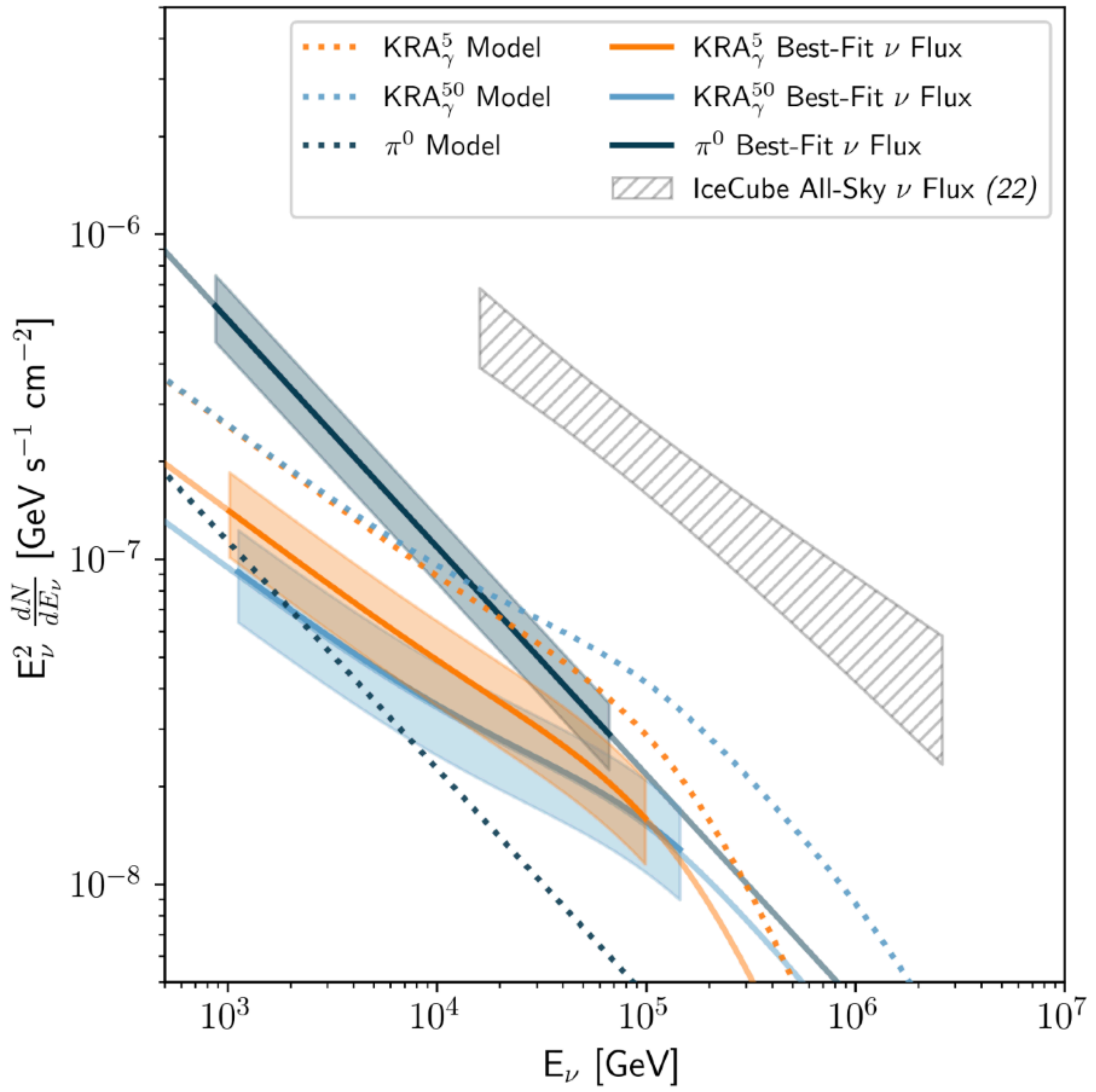
Cosmological bounds using Large Scale Structure from Escudero et al 2016

S. Sclafani PoS(ICRC2023)1108

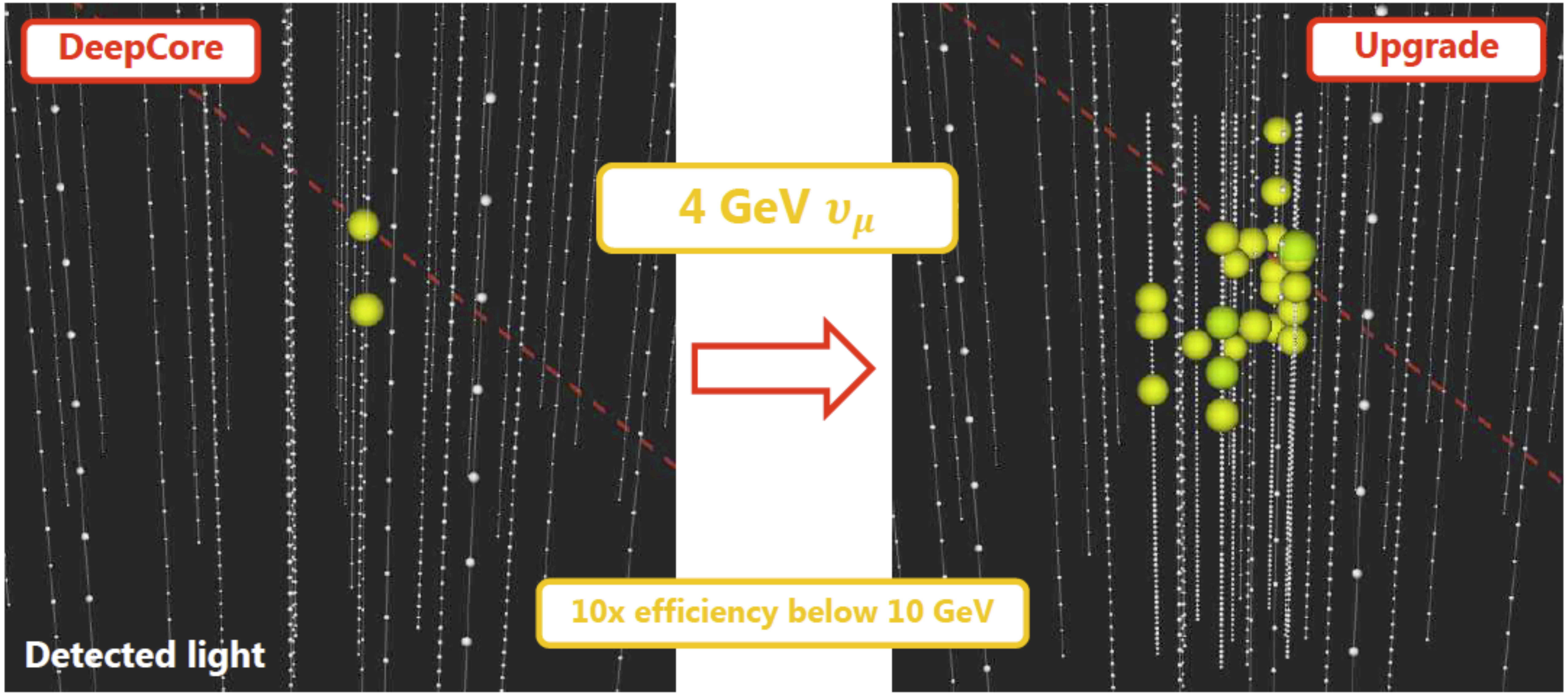




Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA_γ^{50}	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} $(3.24\sigma)^*$	
PWN		5.93×10^{-4} $(3.24\sigma)^*$	
UNID		3.39×10^{-4} $(3.40\sigma)^*$	

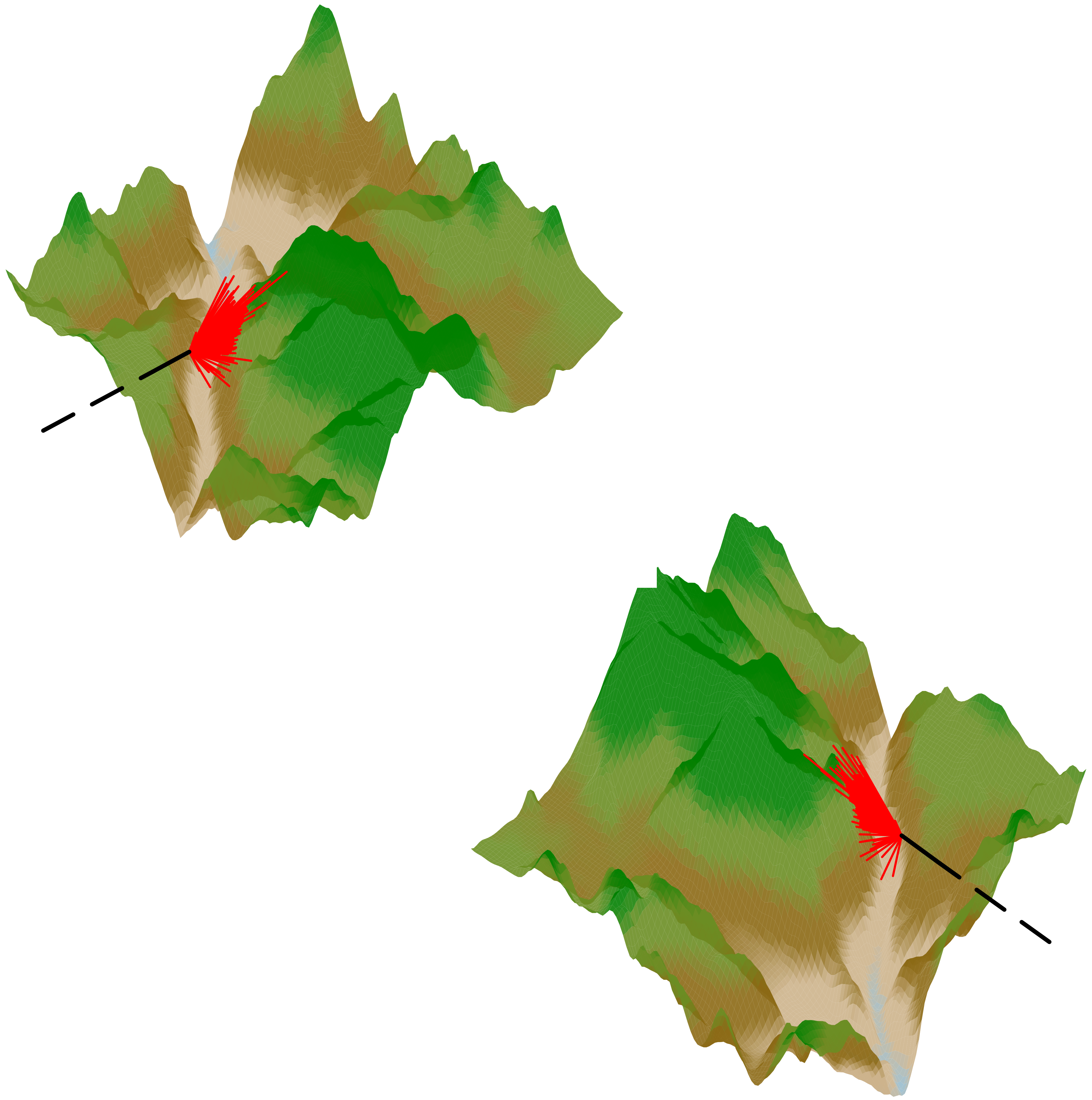


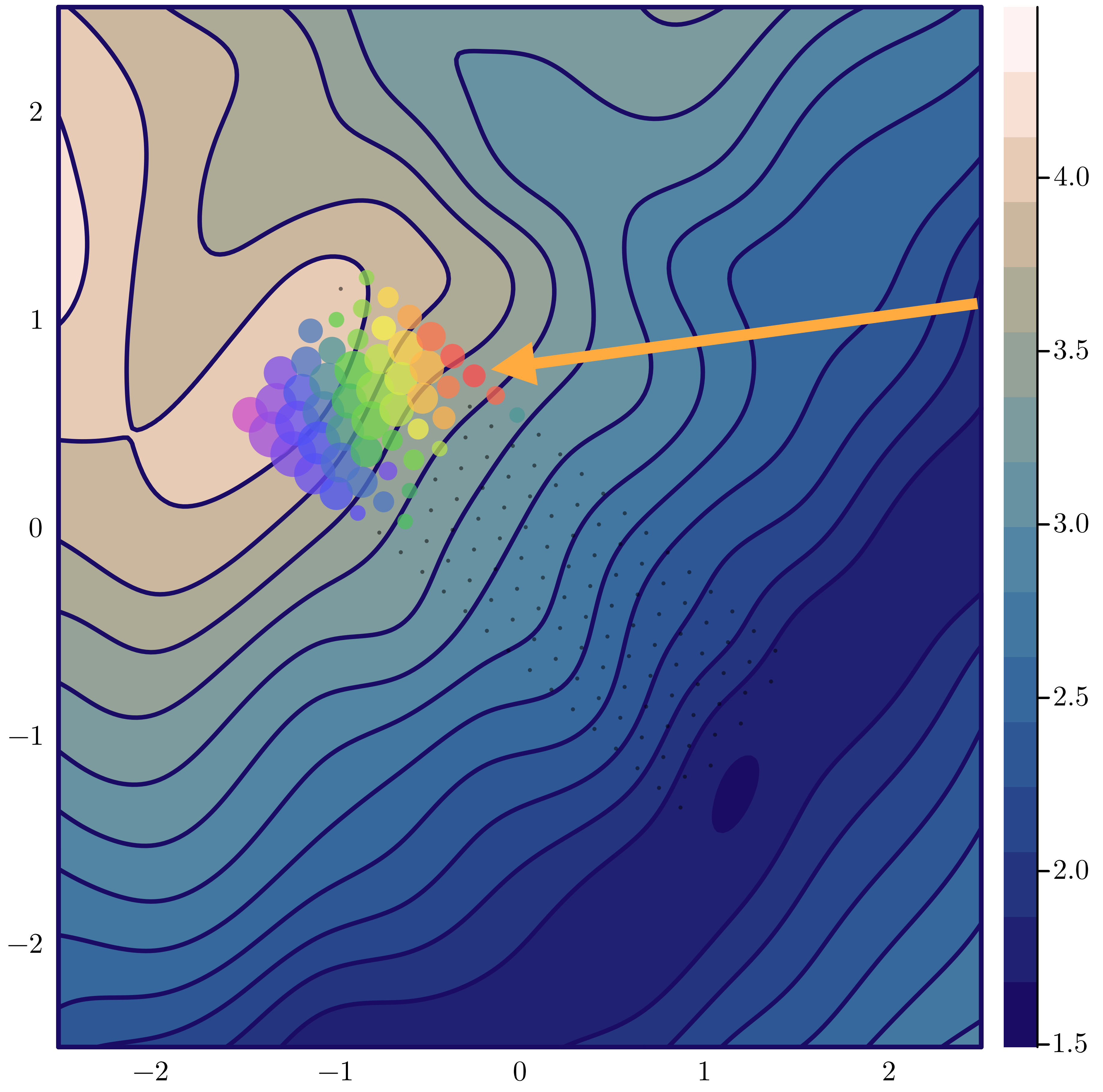
Improved light-collection for low-energy events



*DeepCore (shown on the left) is the current low-energy extension of IceCube

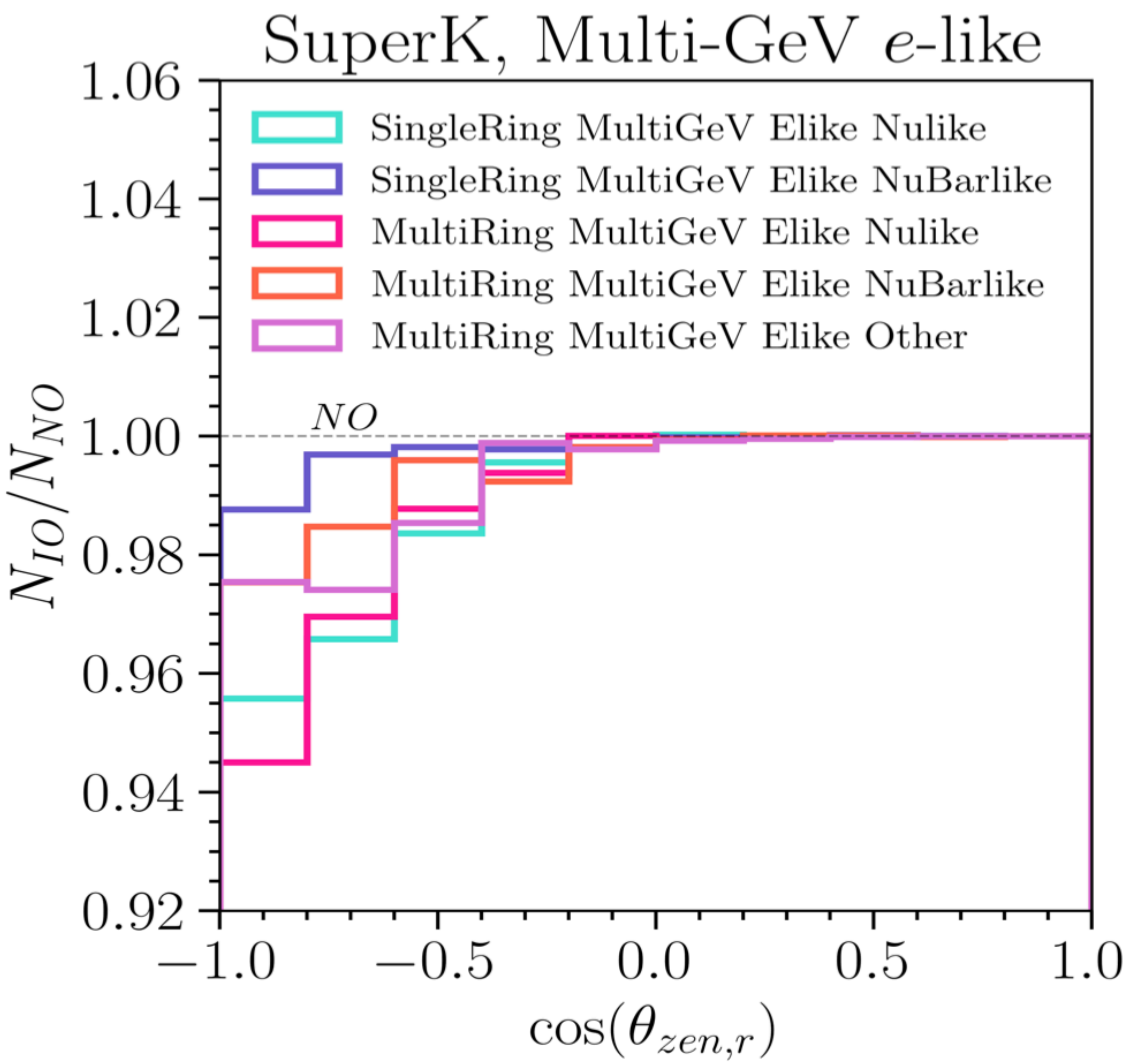
How would these events look like?

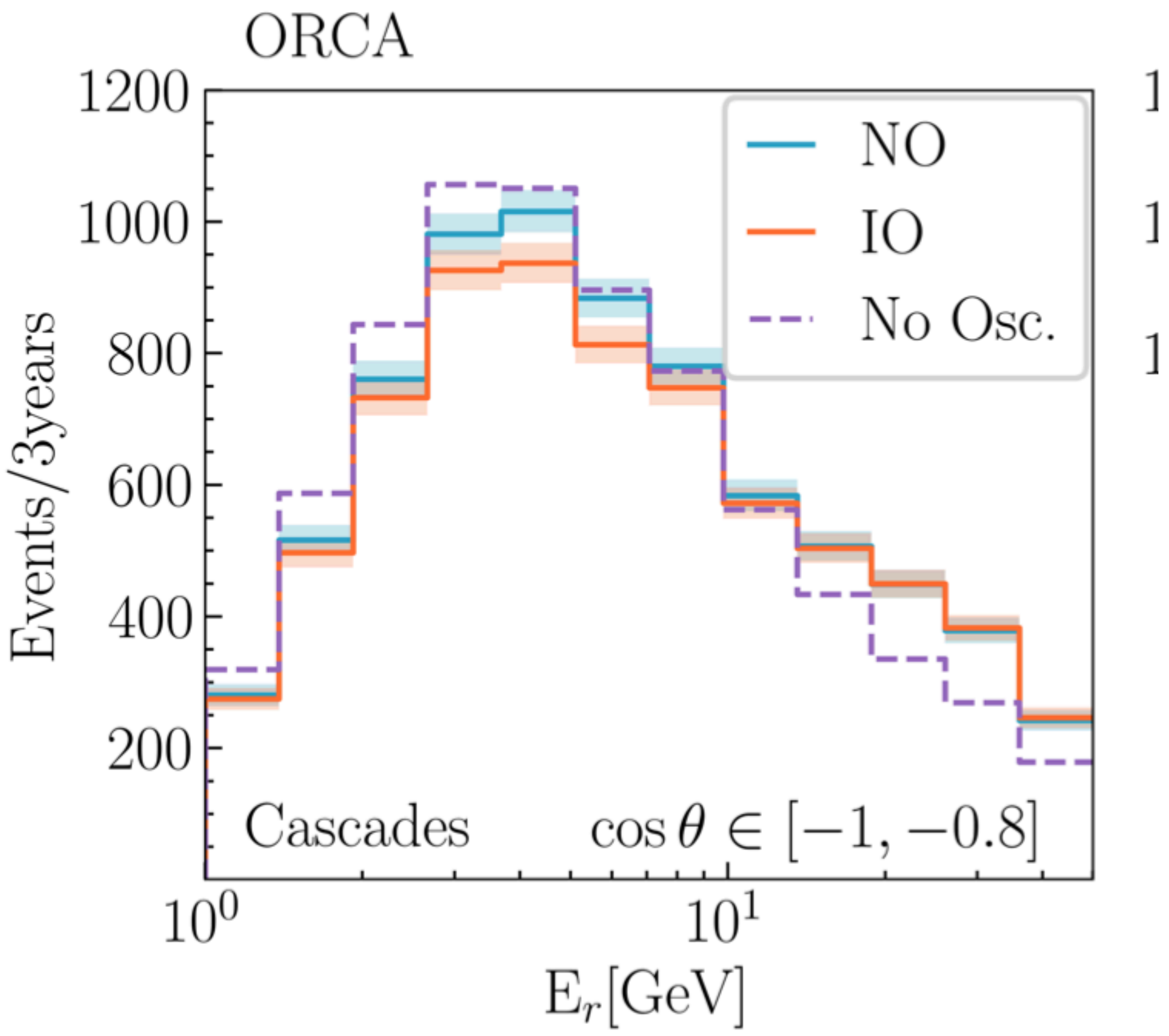




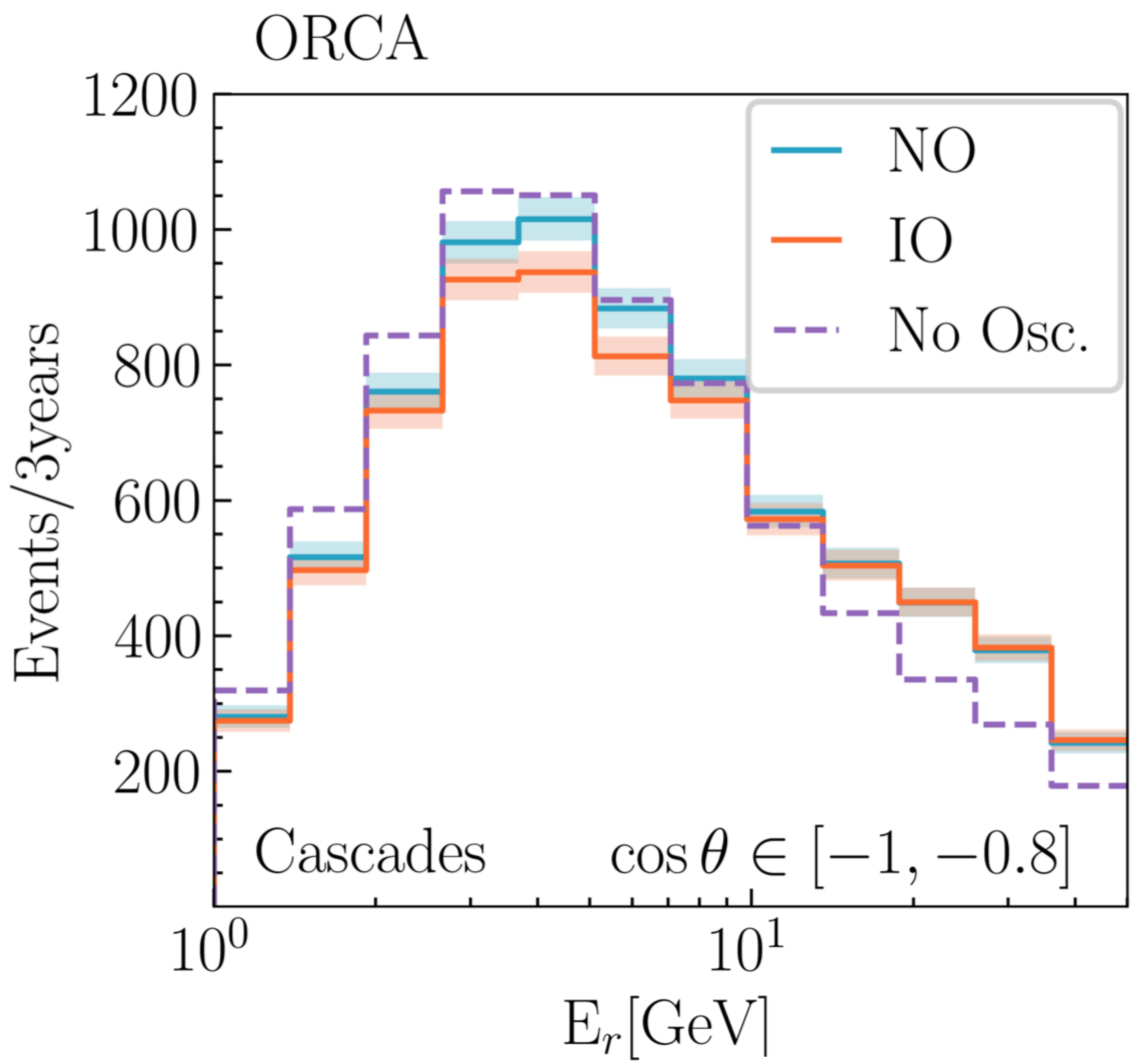
Figures possible by the amazing simulation work done by Jeff Lazar, Pavel Zhelnin, and William Thompson

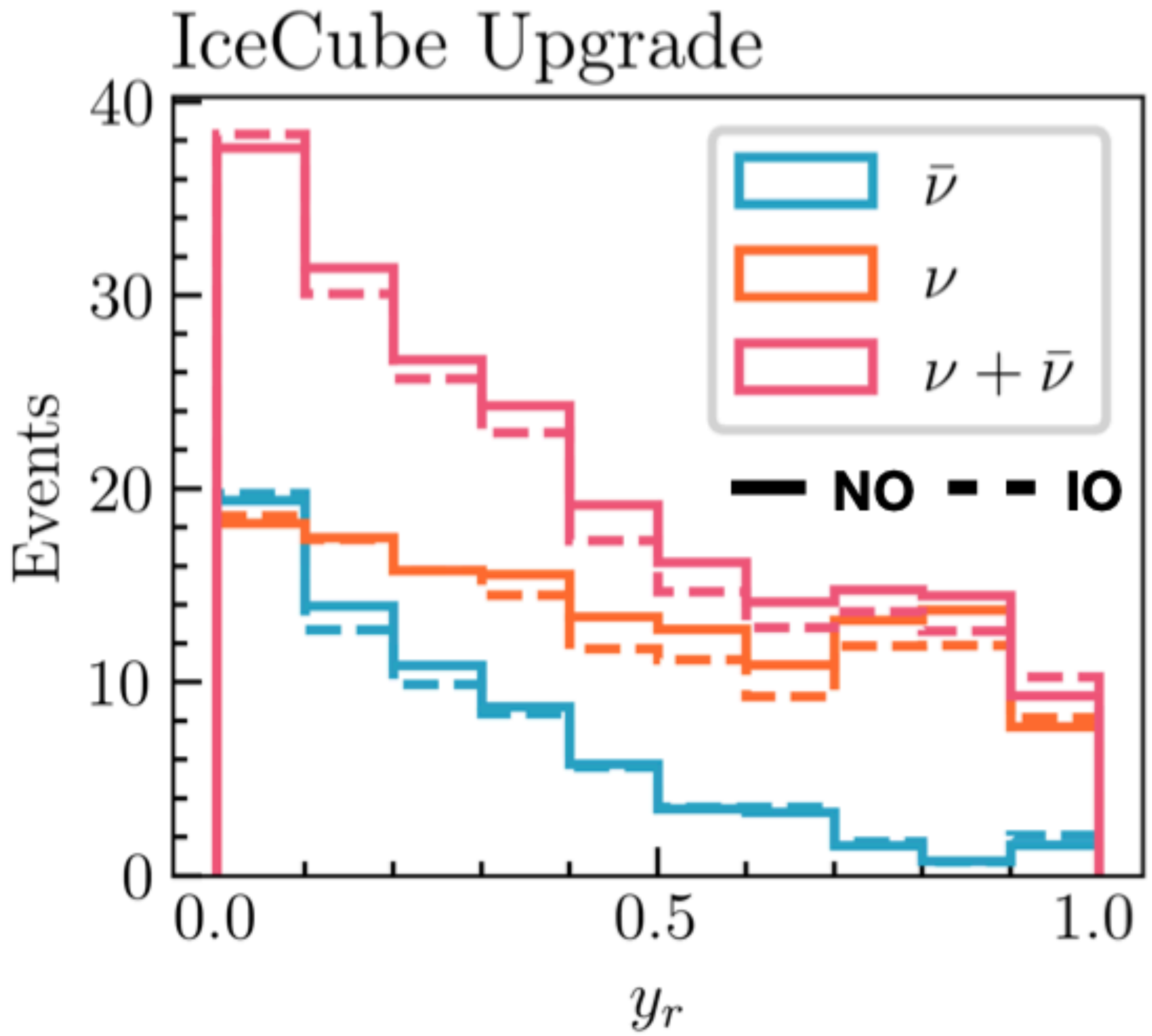
Atmospheric neutrino distributions





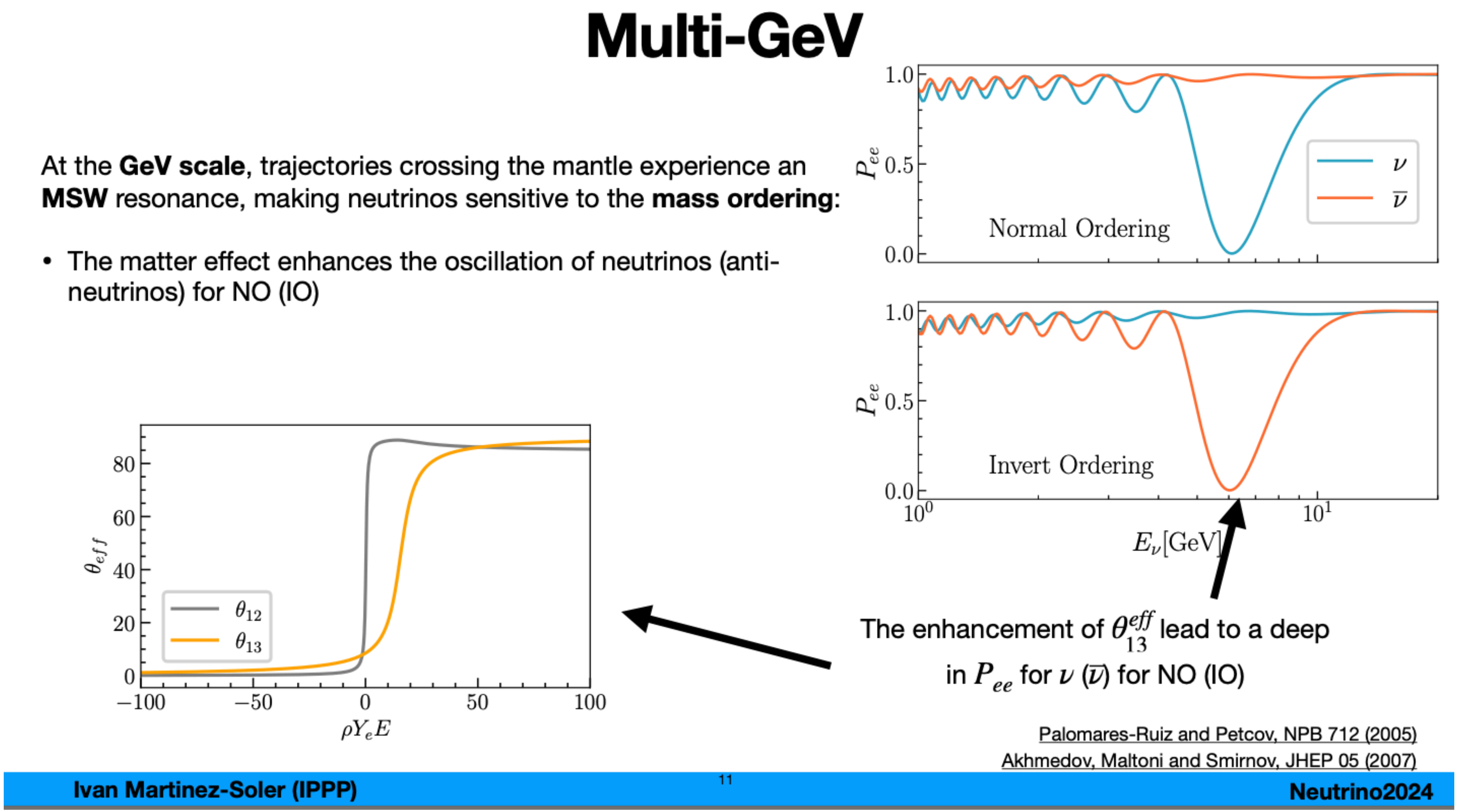
Atmospheric neutrino distributions





The **sensitivity** to the ordering is dominated by the cascades crossing the core in IC-upgrade and ORCA around the GeV.

Atmospheric neutrino oscillation probabilities



Multi-GeV

At the **GeV scale**, trajectories crossing the mantle experience an **MSW** resonance, making neutrinos sensitive to the **mass ordering**:

- The matter effect enhances the oscillation of neutrinos (anti-neutrinos) for NO (IO)

The enhancement of θ_{13}^{eff} lead to a deep in P_{ee} for ν ($\overline{\nu}$) for NO (IO)

Palomares-Ruiz and Petcov, NPB 712 (2005)

Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

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