Do dark matter and neutrinos talk to each other?

Based on arXiv:1912.09486, 2205.12950, and 2210.01303

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HARVARD UNIVERSITY

Dark Interactions
Nov. 16, 2022

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

Why Search For Dark Matter With Neutrinos?

Neutrinos present BSM properties (mass)

Neutral particles allow
for direct coupling to DM

The final frontier for indirect searches

Stops

- Neutrino detectors and fluxes
- Searching for an excess of neutrinos
- Searching for a deficit of neutrinos
- Searching for a strange neutrino flavor effects
- How do we move forward?

Stops

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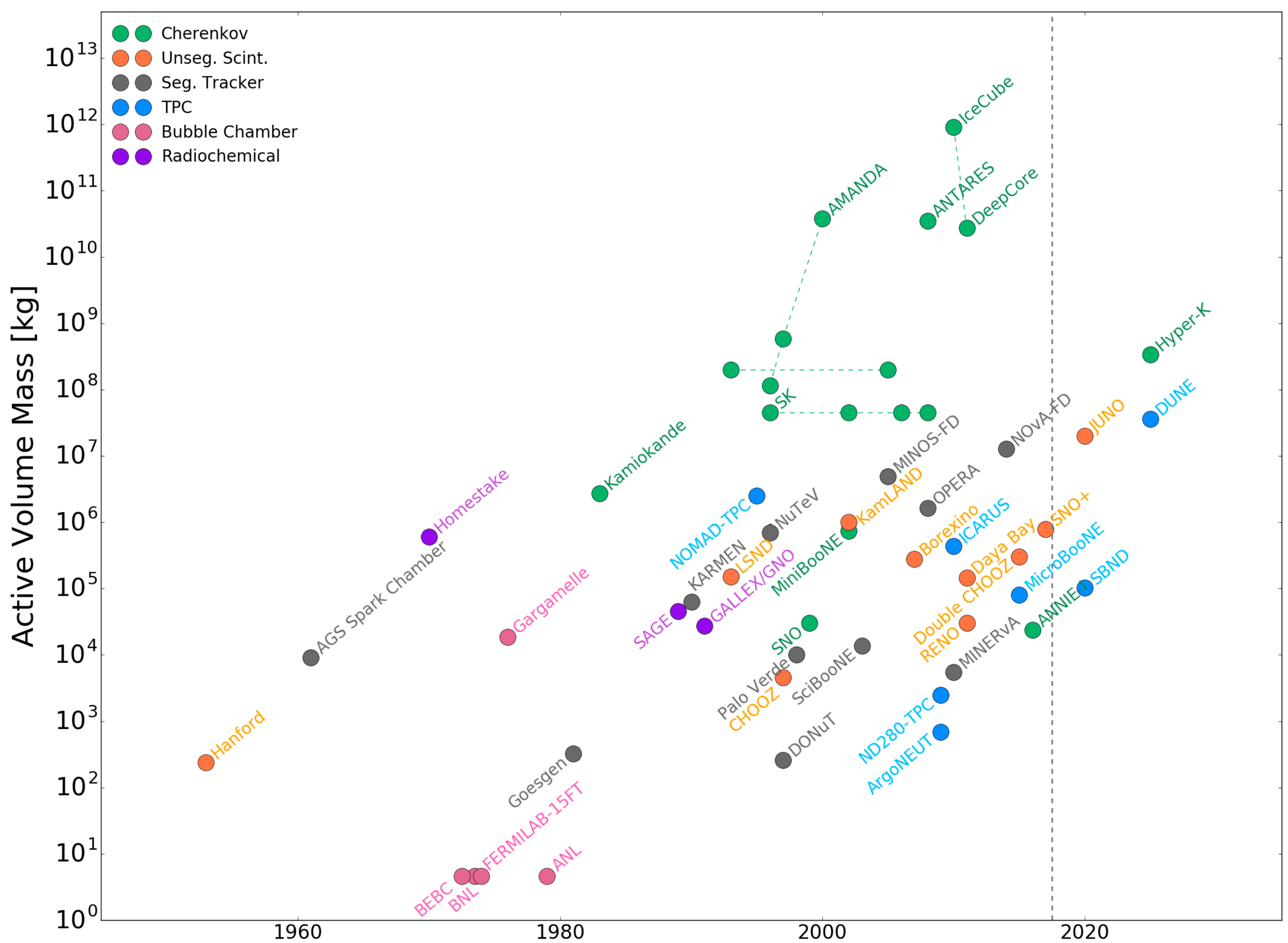
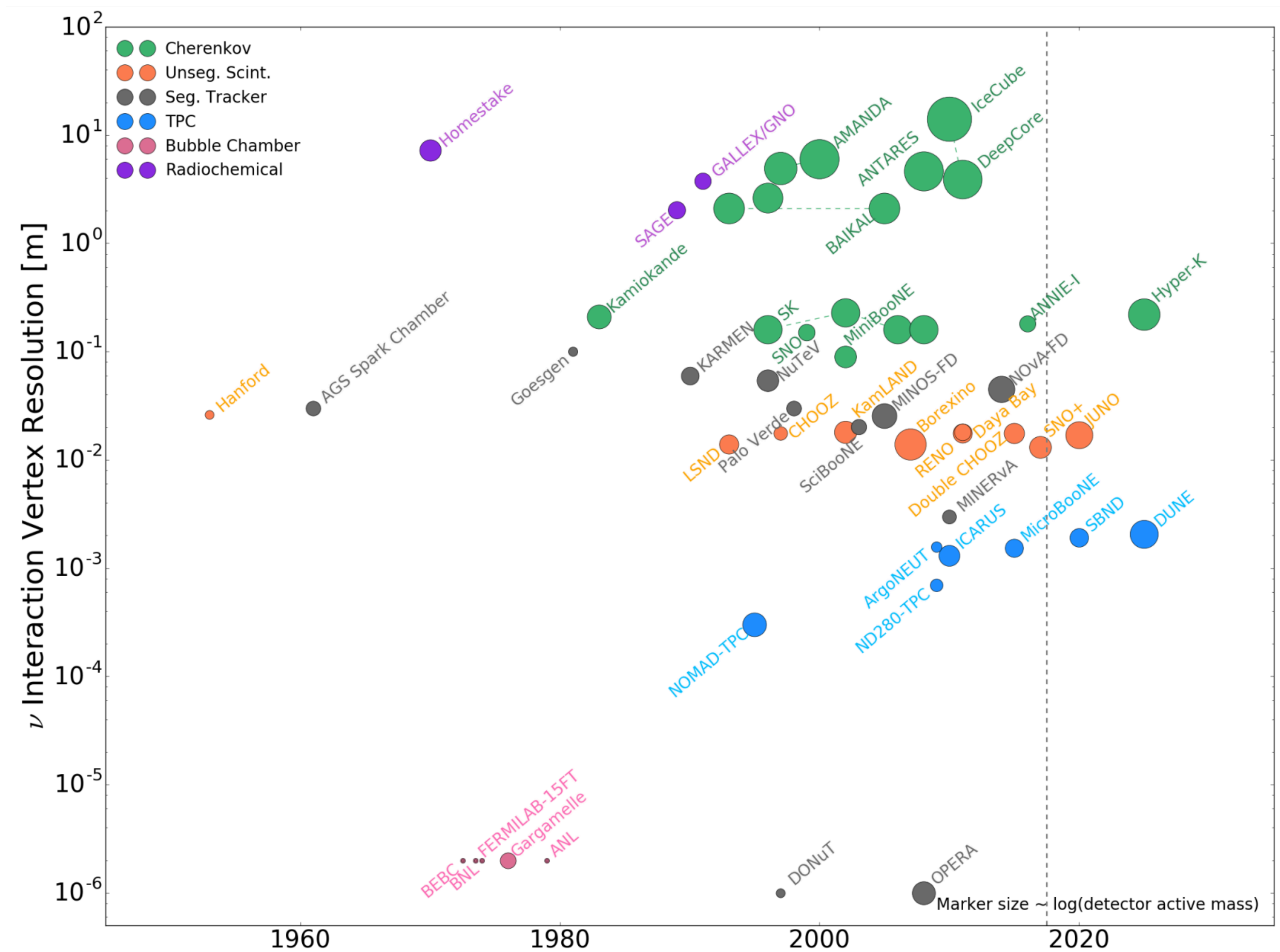
Neutrino detectors through the decades

Multiple different detection technologies to hunt for neutrinos. Different pros and cons.





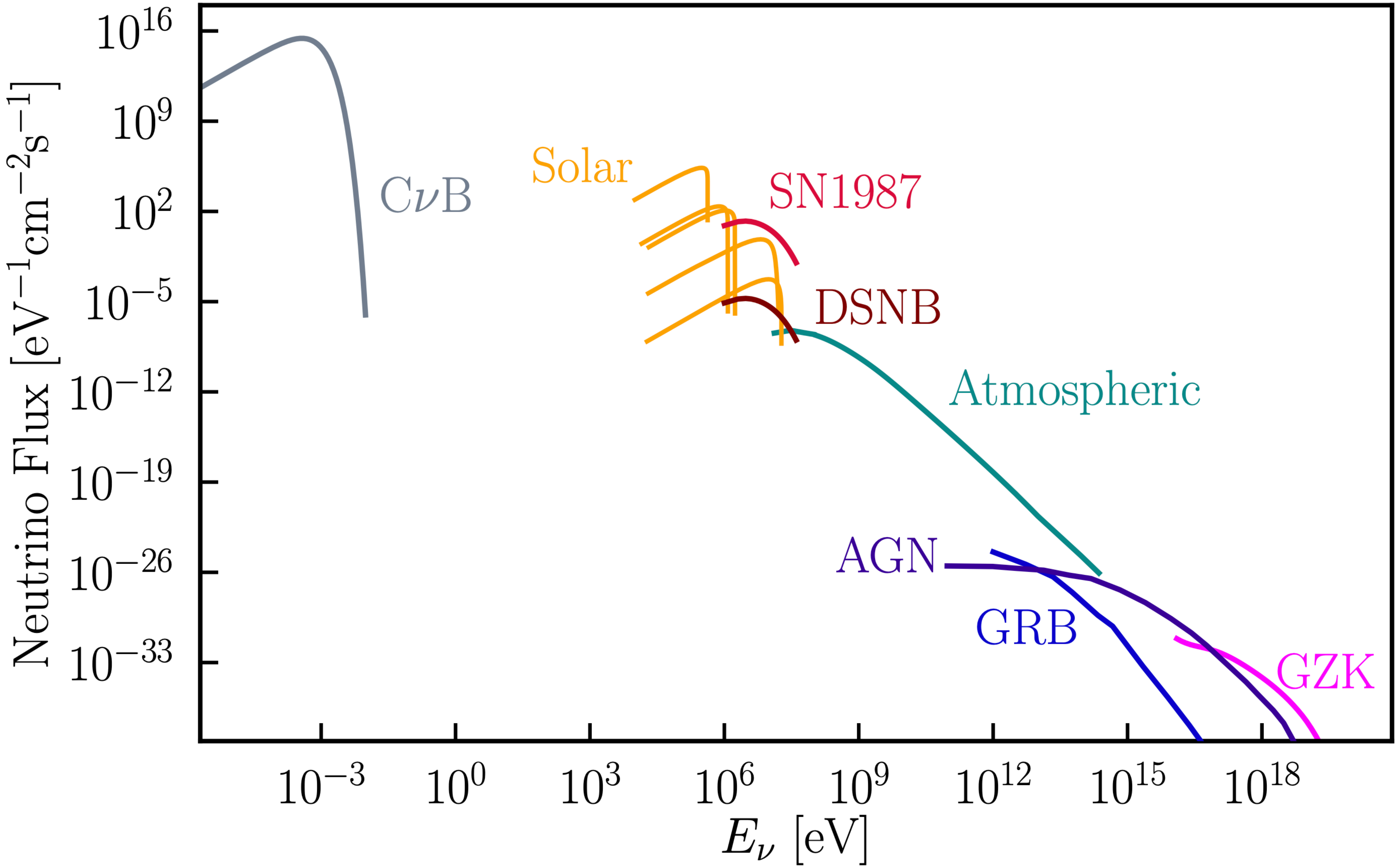
Size ~ statistics

Precision ~ particle id, background rejections

ARGÜELLES ET AL., IOP 23, ARXIV:1907.08311

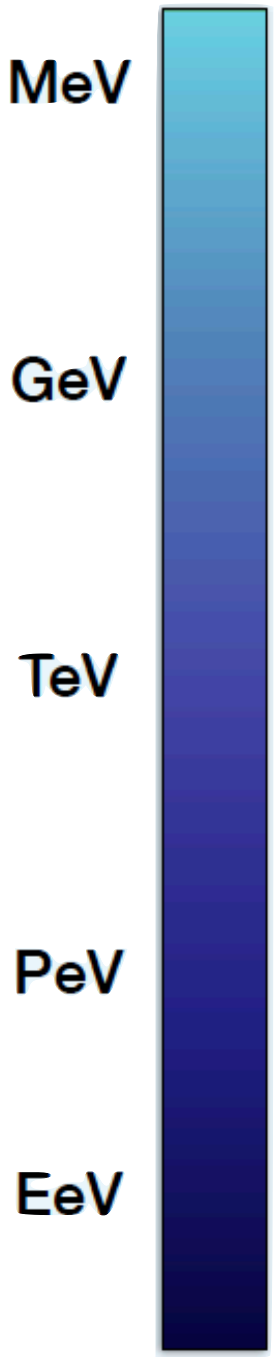
“Background/Foreground” neutrino fluxes

Depending on the technology we maybe able to reduce these backgrounds from DM-induced neutrinos.
For example the Sun only produces neutrinos so antineutrino searches remove this foreground.



HALZEN, F. AND KHEIRANDISH, A. ARXIV:2202.00694

Neutrino experiments I will discuss in this talk



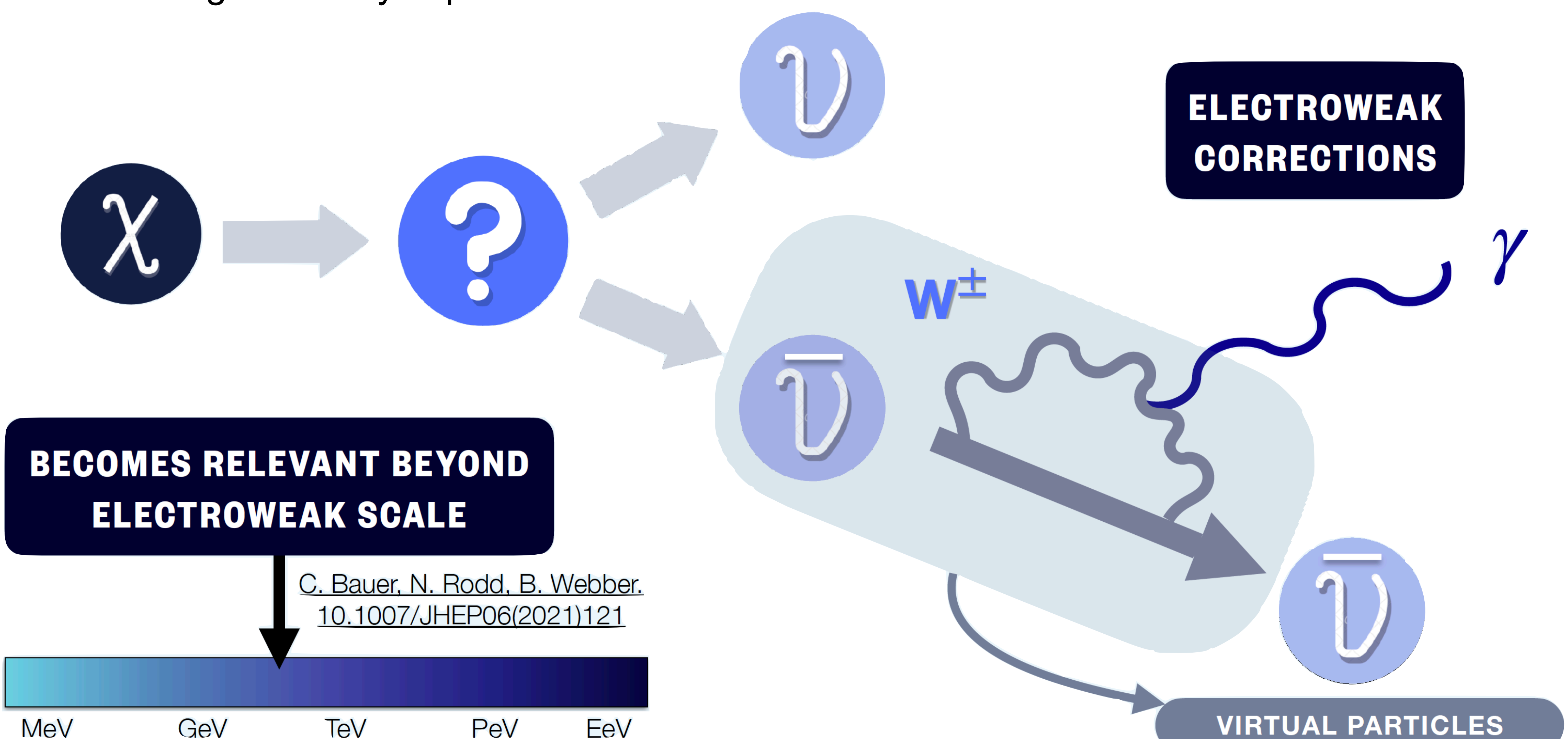
Energy Range	Experimental Analysis	Directionality	Detected Flavor
2.5 – 15 MeV	Borexino (Bellini *et al.*, 2011)	×	$\bar{\nu}_e$ (IBD)
8.3 – 18.3 MeV	KamLAND (Gando *et al.*, 2012)	✓	$\bar{\nu}_e$ (IBD)
10 – 40 MeV	JUNO (An *et al.*, 2016)	✓	$\bar{\nu}_e$ (IBD)
15 – 10^3 MeV	SK (Olivares-Del Campo *et al.*, 2018a)	×	$\bar{\nu}_e$ (IBD)
	DARWIN (McKeen and Raj, 2018)	×	All Flavors (Coherent)
0.1 – 30 GeV	DUNE (Abi *et al.*, 2020b) HK (Olivares-Del Campo *et al.*, 2018b)	×	$\nu_e, \bar{\nu}_e, \nu_\tau, \bar{\nu}_\tau$ (CC)
1 – 10^4 GeV	SK (Abe *et al.*, 2020; Frankiewicz, 2015)	✓	All Flavors
20 – 10^4 GeV	IceCube (Aartsen *et al.*, 2016a)	✓	All Flavors
50 – 10^5 GeV	ANTARES (Adrian-Martinez *et al.*, 2015)	✓	ν_μ, $\bar{\nu}_\mu$ (CC)
0.2 – 100 TeV	CTA (Queiroz *et al.*, 2016)	✓	All Flavors (Bremsstrahlung)
10 – 10^4 GeV	IC-Upgrade (Baur, 2019)	✓	All Flavors
$>$ 10 PeV	IC Gen-2 (Aartsen *et al.*, 2014b)	✓	All Flavors
10 – 10^4 TeV	KM3Net (Adrian-Martinez *et al.*, 2016)	✓	All Flavors
1 – 100 PeV	TAMBO (Wissel *et al.*, 2019)	✓	ν_τ, $\bar{\nu}_\tau$ (CC)
$>$ 100 PeV	GRAND (Alvarez-Muniz *et al.*, 2018)	✓	ν_τ, $\bar{\nu}_\tau$ (CC)

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

$10^{-1} - 10^{2}$	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!



Stops

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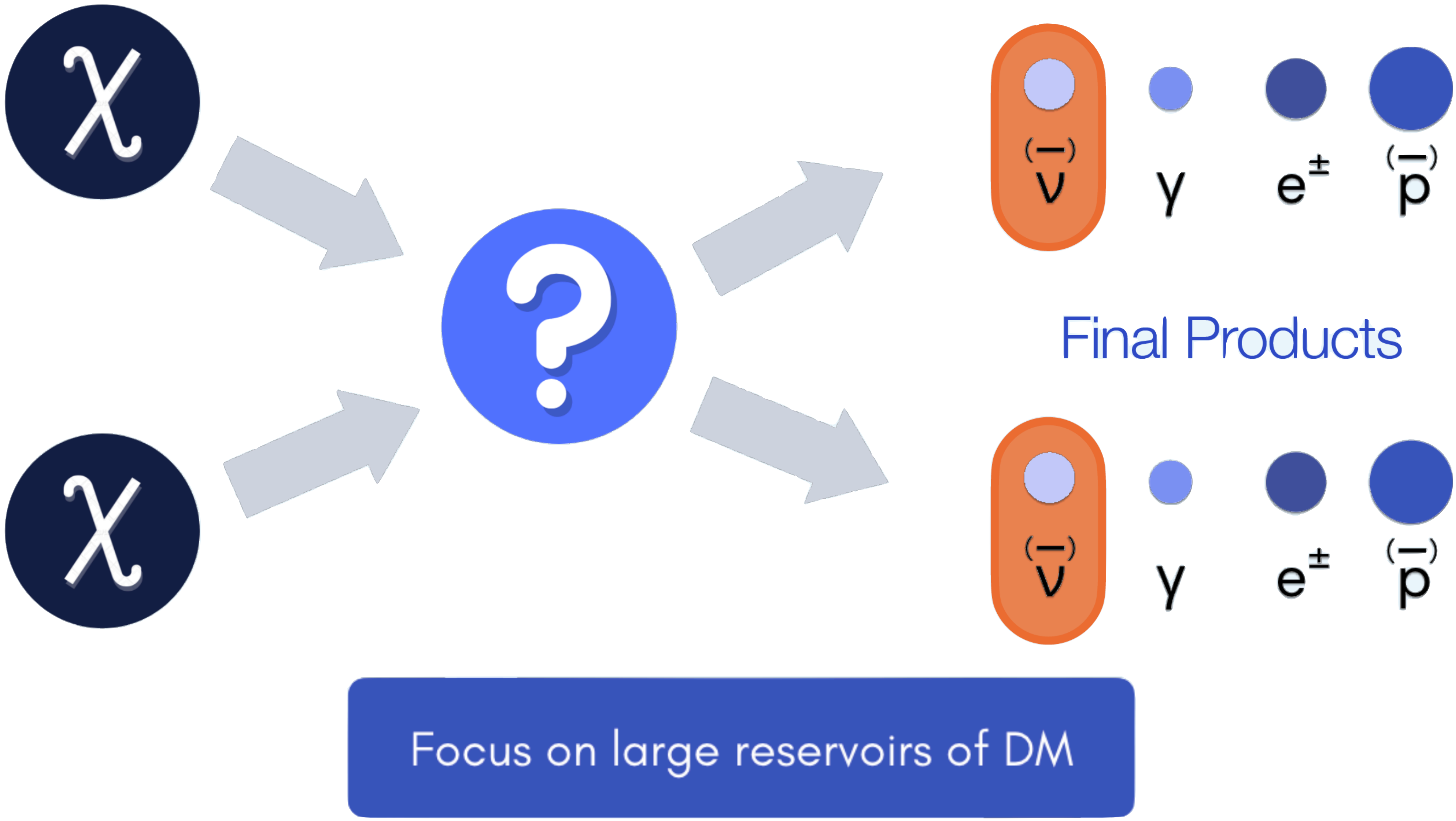
- **Searching for an excess of neutrinos**
- Searching for a deficit of neutrinos
- Searching for a strange neutrino flavor effects
- How do we move forward?

Indirect Detection



In this talk I will only focus on dark matter decaying or annihilating directly to neutrinos

Recipe to obtain the neutrino flux

Decay

$$\frac{d\Phi^{*}_{\nu/\gamma}}{dE} = \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi}\frac{dN_{\nu/\gamma}}{dE} \; D(\Omega, x)$$

* Divided by 3 in the case of all neutrino flavors.

Particle Physics | **Astro-physical**

τ_χ **DM decay lifetime**

$$\frac{dN_\nu}{dE} = \delta\left(\frac{m_\chi}{2} - E_\nu\right)$$

Neutrino Production Spectrum for Direct Decay of DM to neutrinos*

* with gamma-ray production becomes more complicated due to electroweak corrections.

$$D = \int d\Omega \int_{l.o.s.} \rho_\chi(x)\, dx$$

D factor: 3D integral over the sky solid angle and line of sight

Dark Matter density: NFW Profile

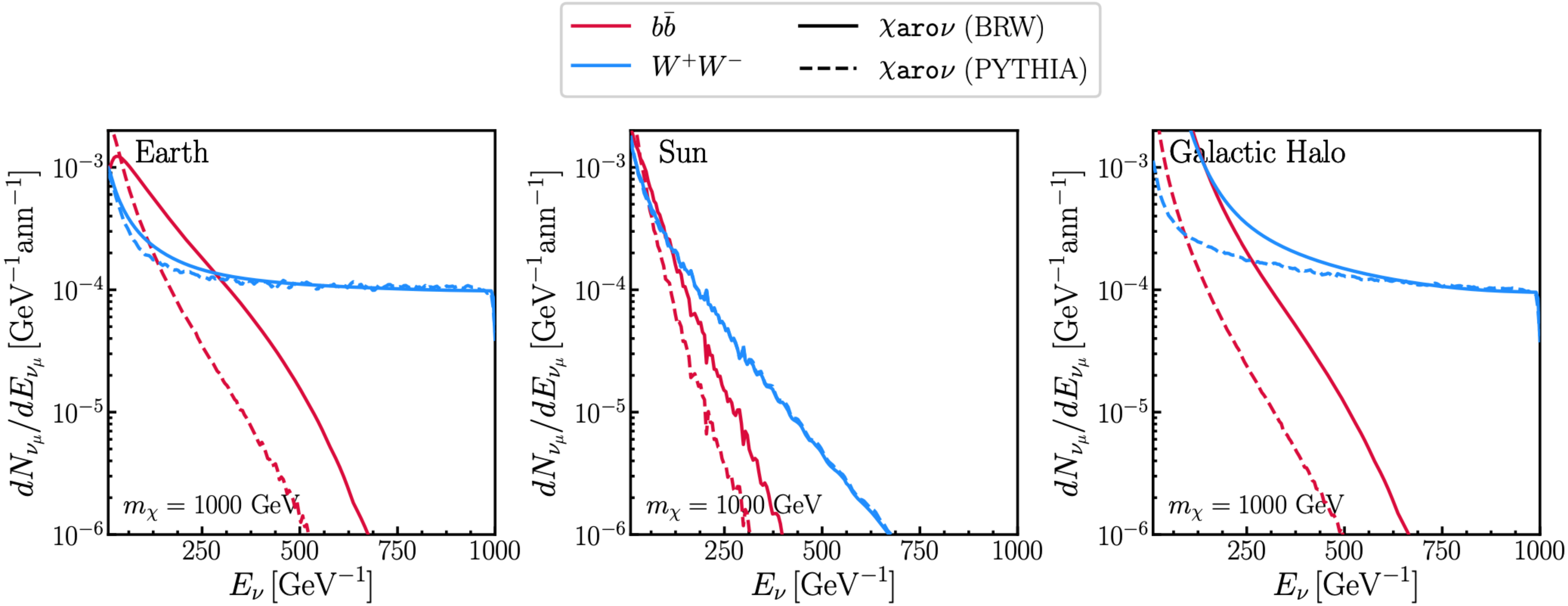
$$\rho_\chi = \frac{2^{3-\gamma}\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \frac{r}{r_s}\right)^{3-\gamma}}$$

NAVARRO, ET AL. ASTROPHYS.J. 462, ARXIV:ASTRO-PH/9508025

Similar in the case of annihilation. Will discuss this later.

For good limits, we need good predictions!

https://github.com/IceCubeOpenSource/charon

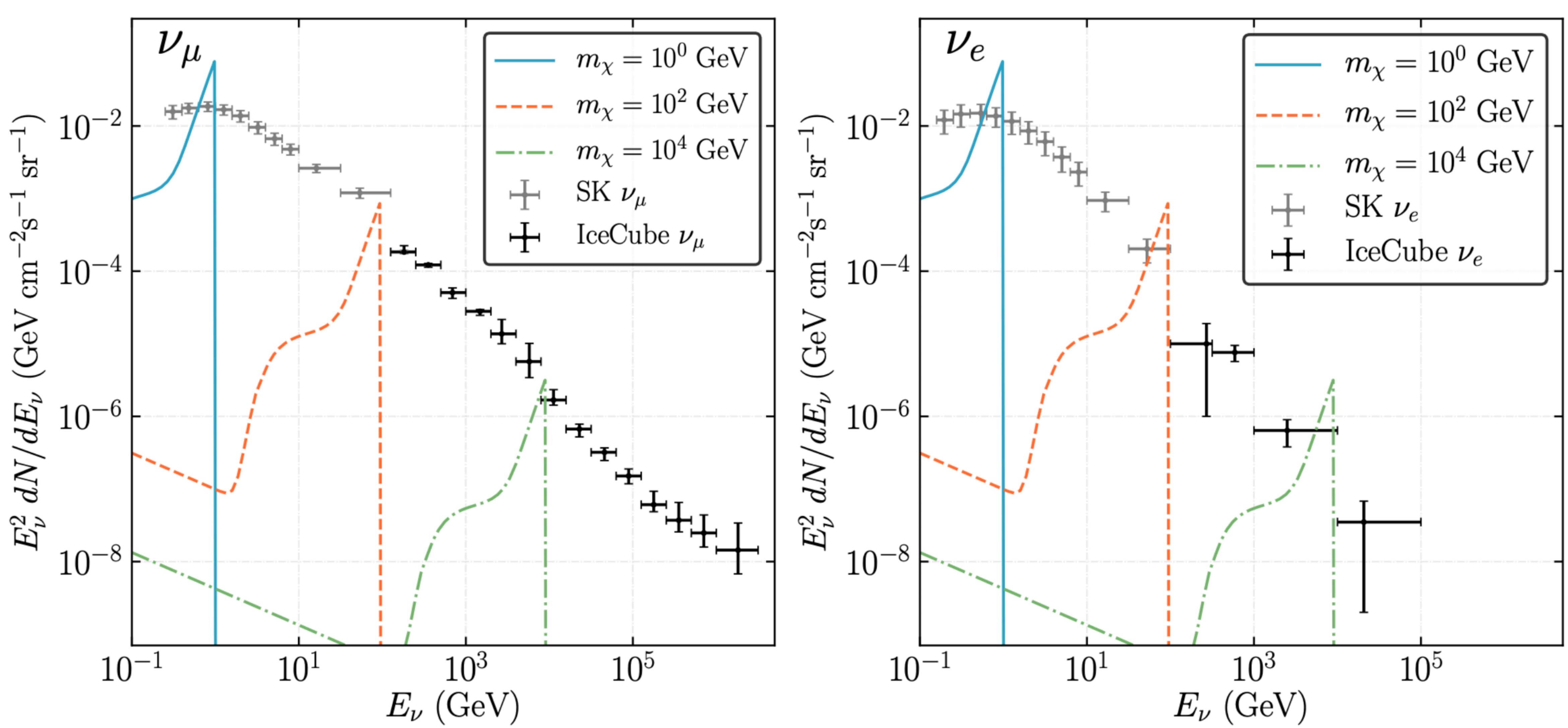


IceCube results with updated calculations to appear soon!

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.

Background agnostic constraints on Dark matter making neutrinos

$10^{-1} - 10^{2}$	Fermi-LAT [63]
$10^{3} - 10^{9}$	*CTA* [64]
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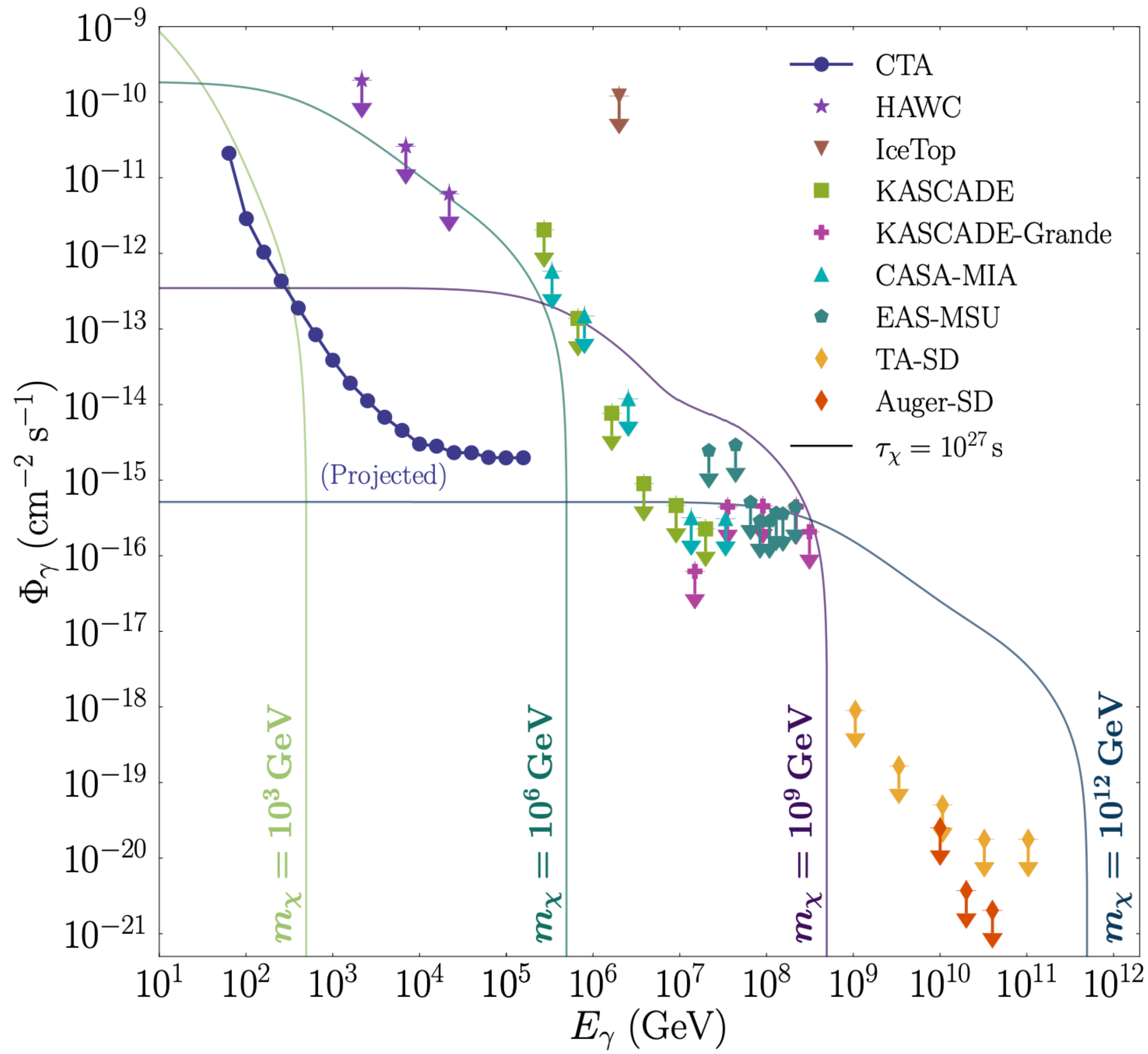
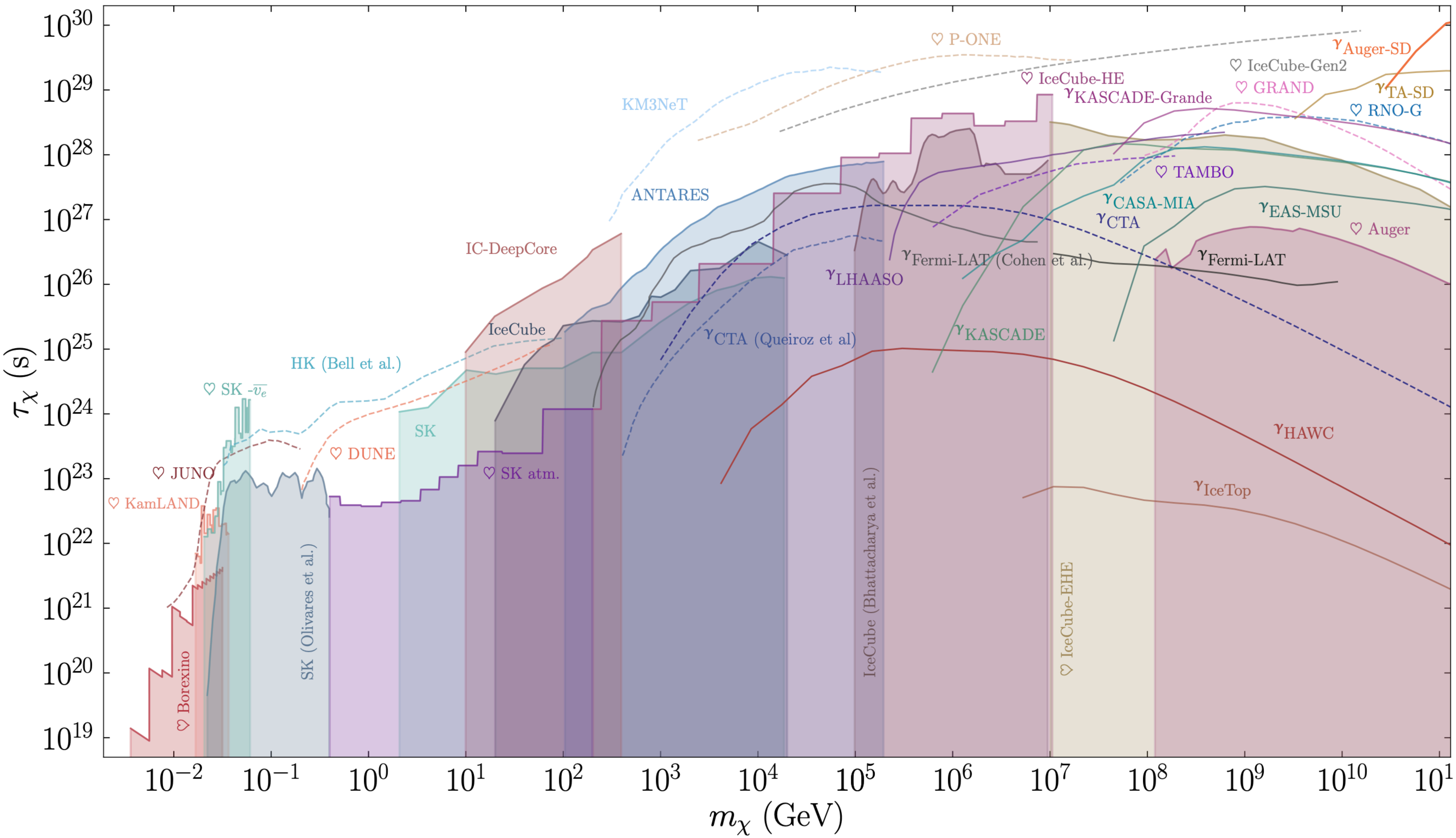


Associated gamma-ray flux should also not overshoot constraints

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

Constraints on dark matter decay to neutrinos



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

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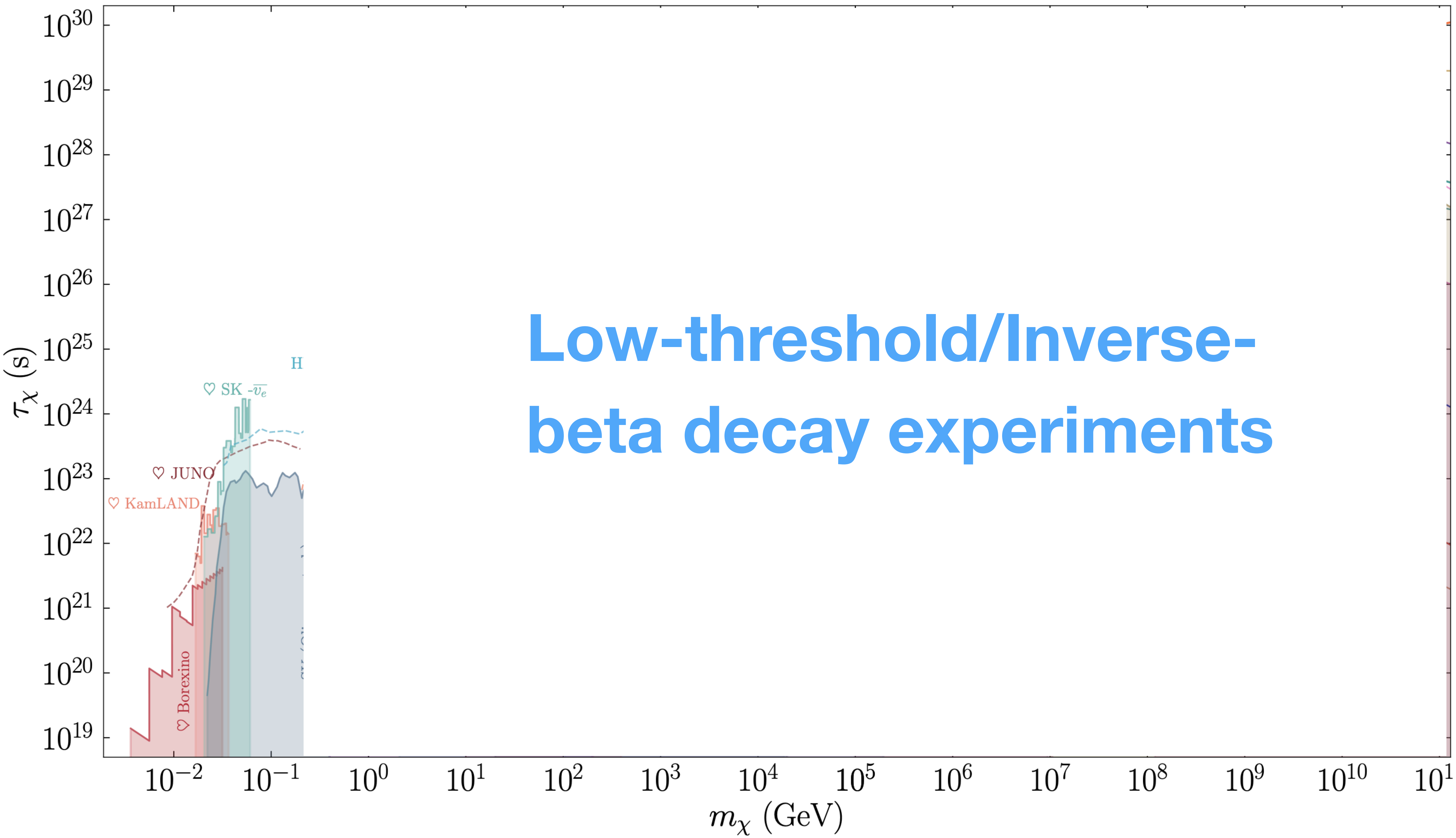

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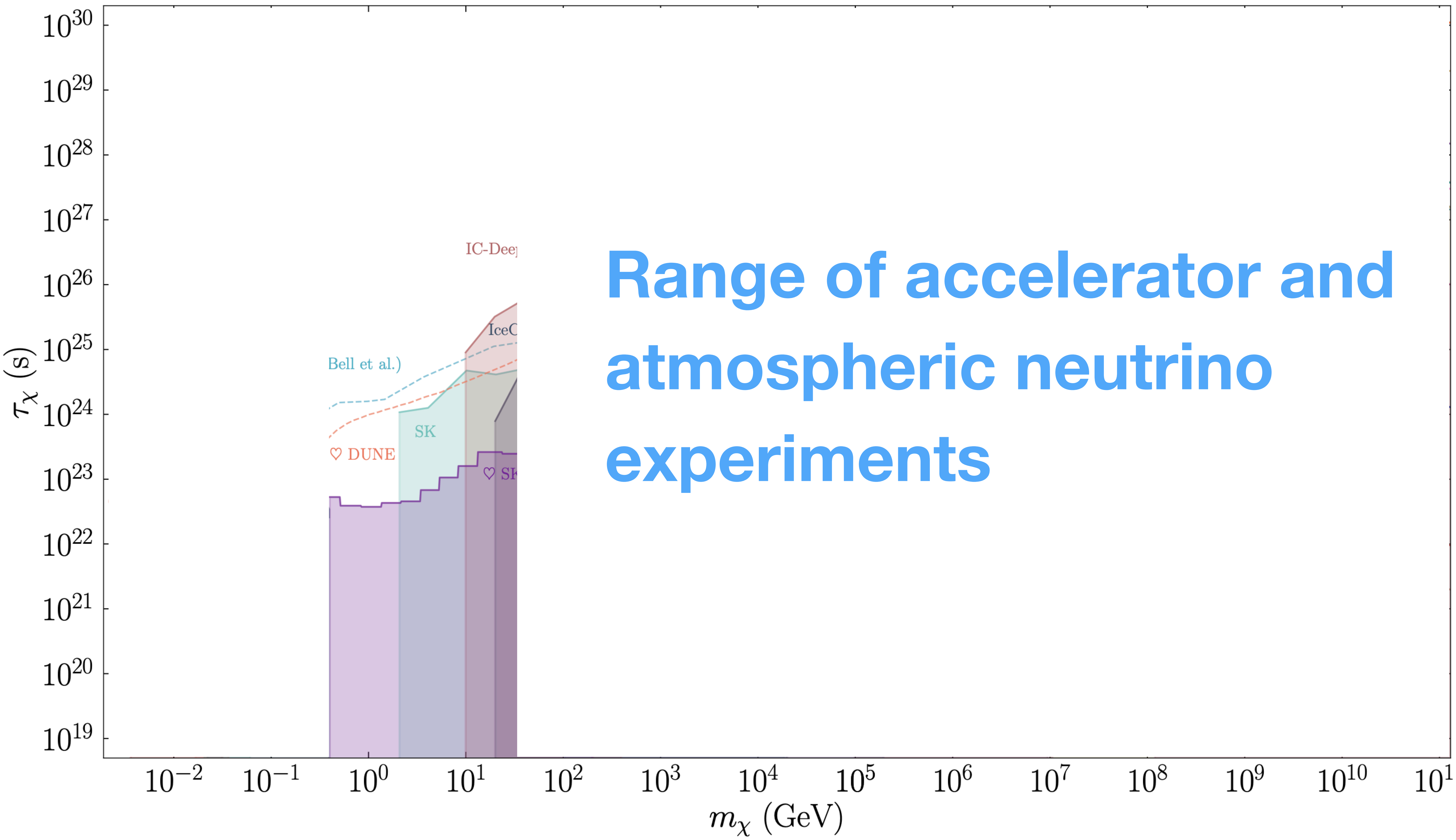
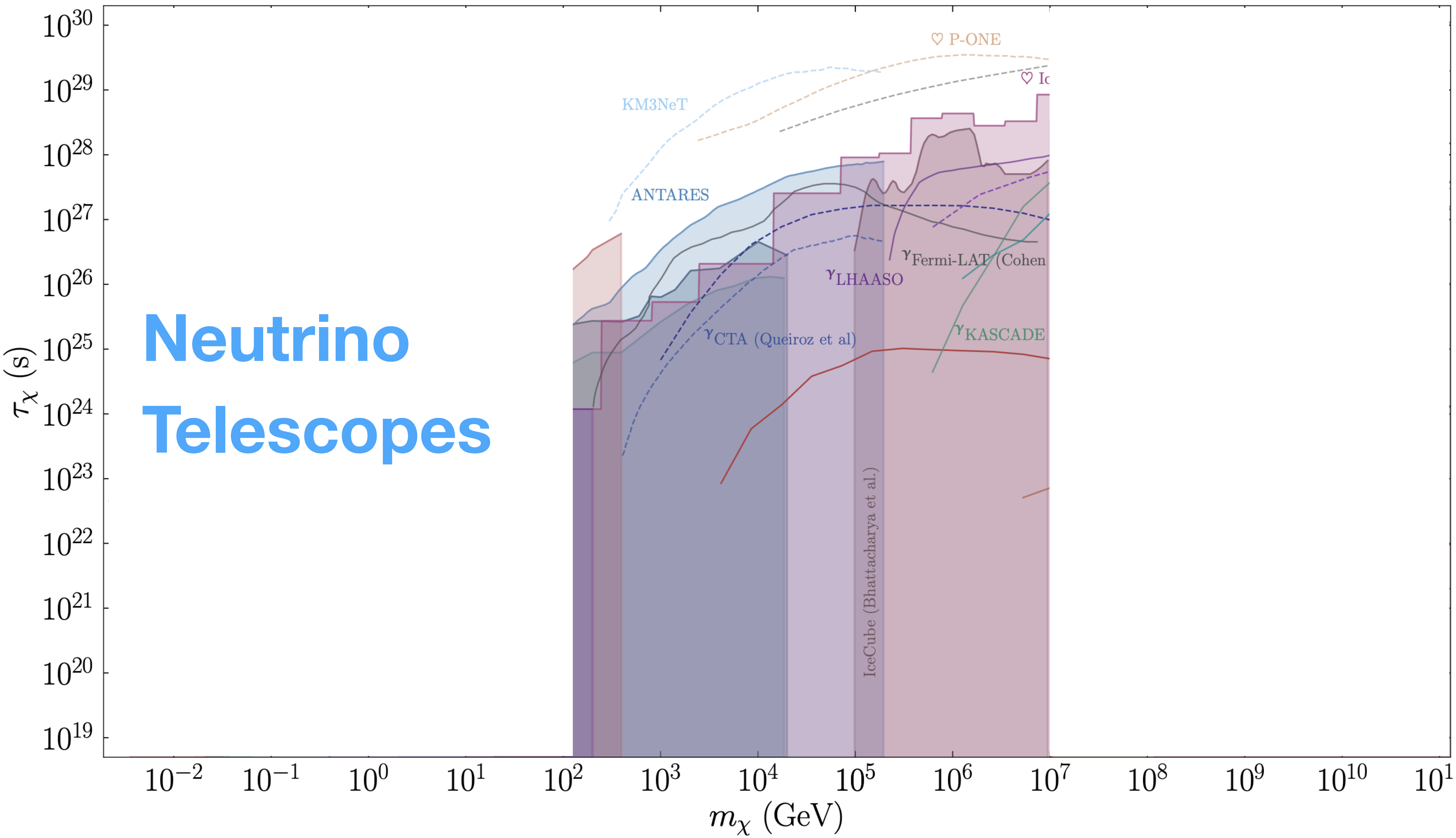


Range of accelerator and atmospheric neutrino experiments

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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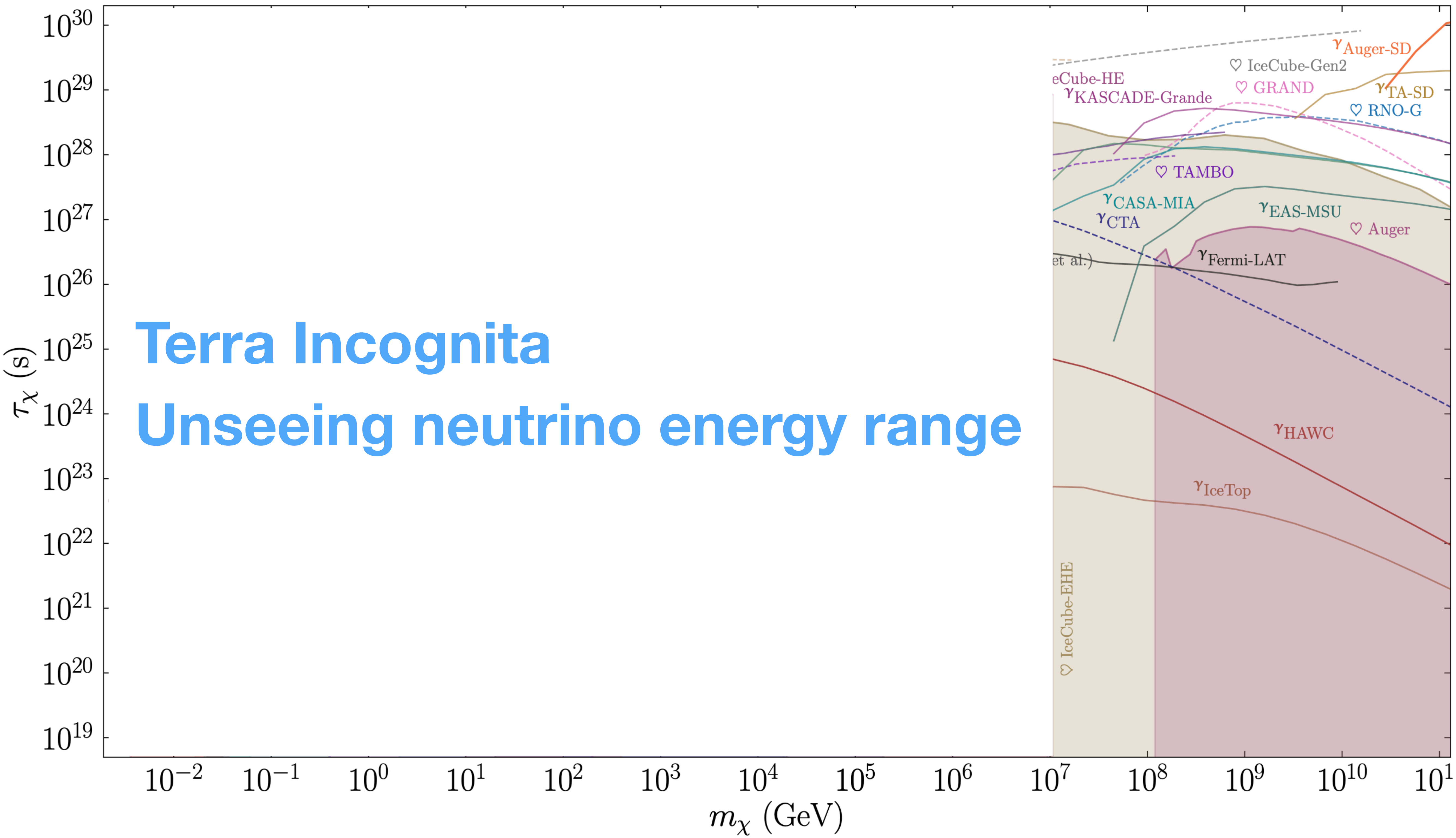
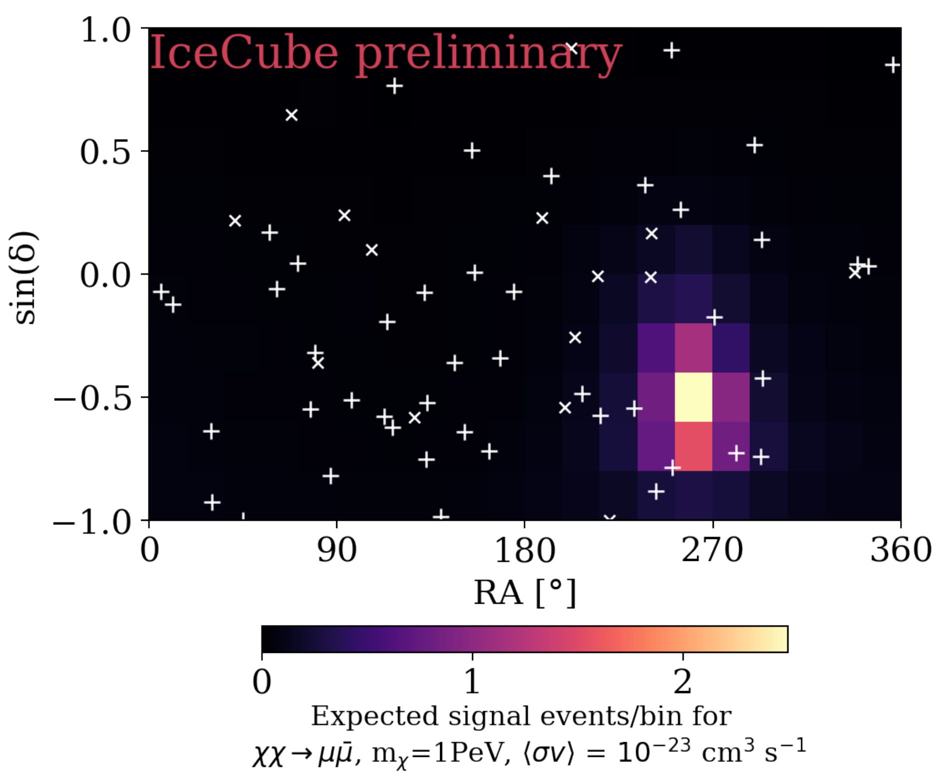
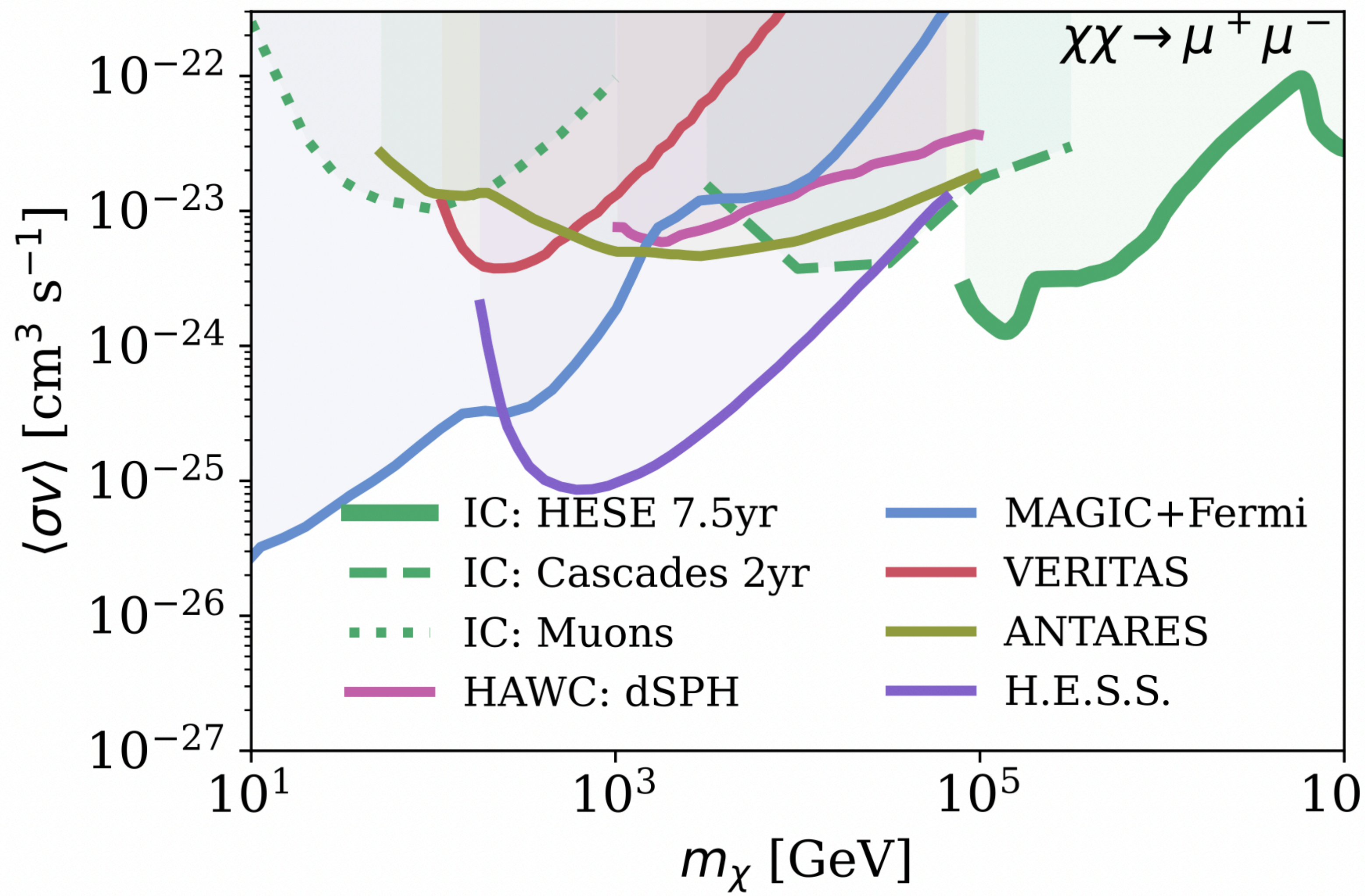


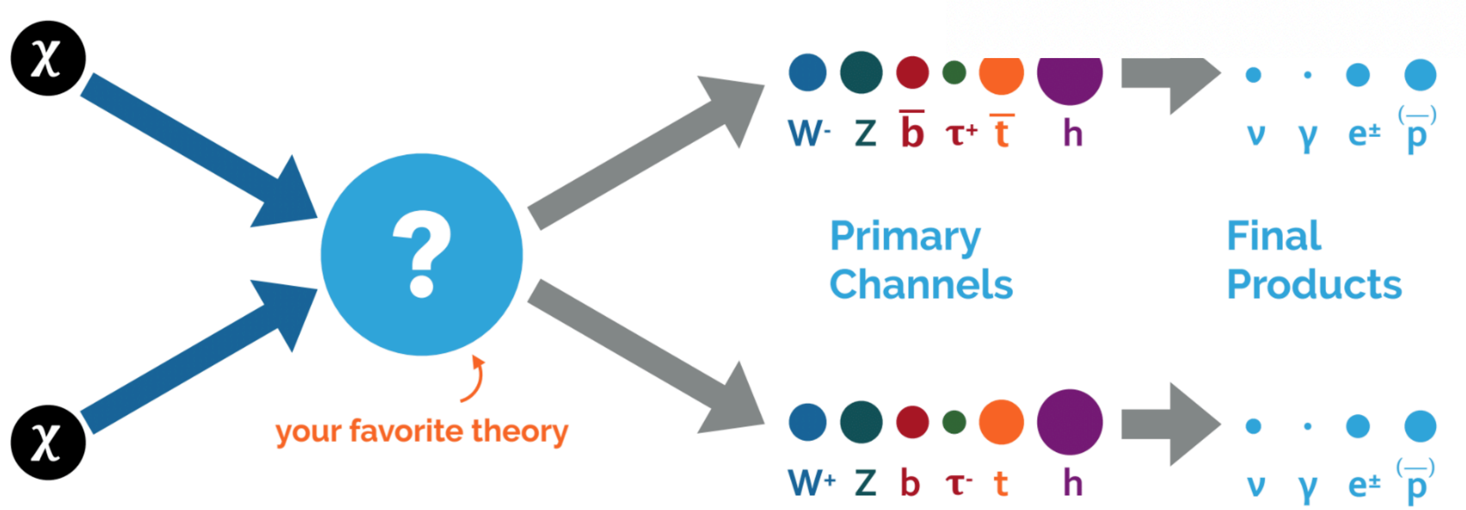
CA, D. Delgado, A. Friedlander, A. Kheirandish, I. Safa, A.C. Vincent, H. White *arXiv:2210.01303*

Background informed constraints on Dark matter annihilation



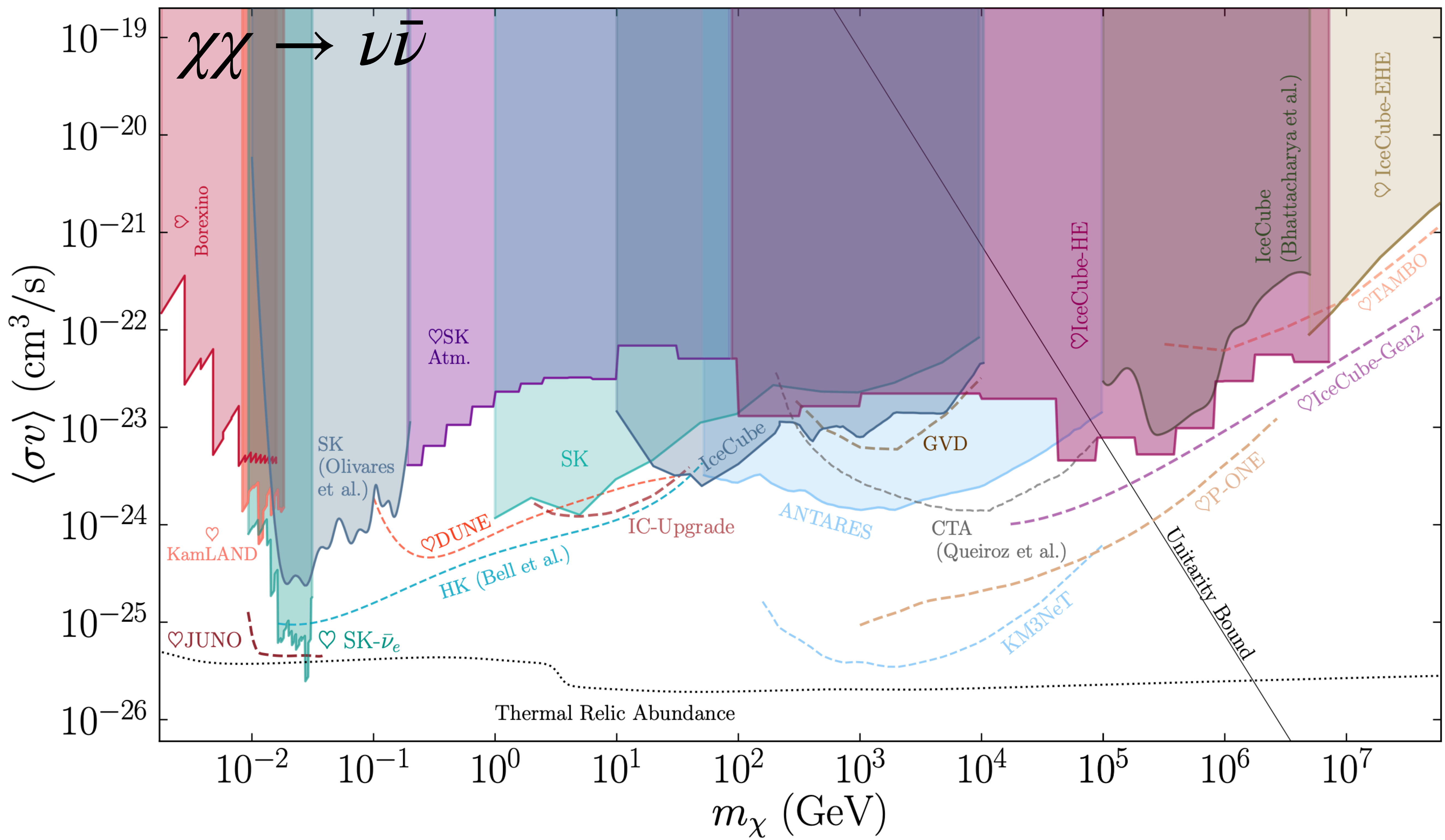
IceCube Collaboration, arXiv:2205.12950





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 …

Constraints on dark matter annihilation to neutrinos



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.*

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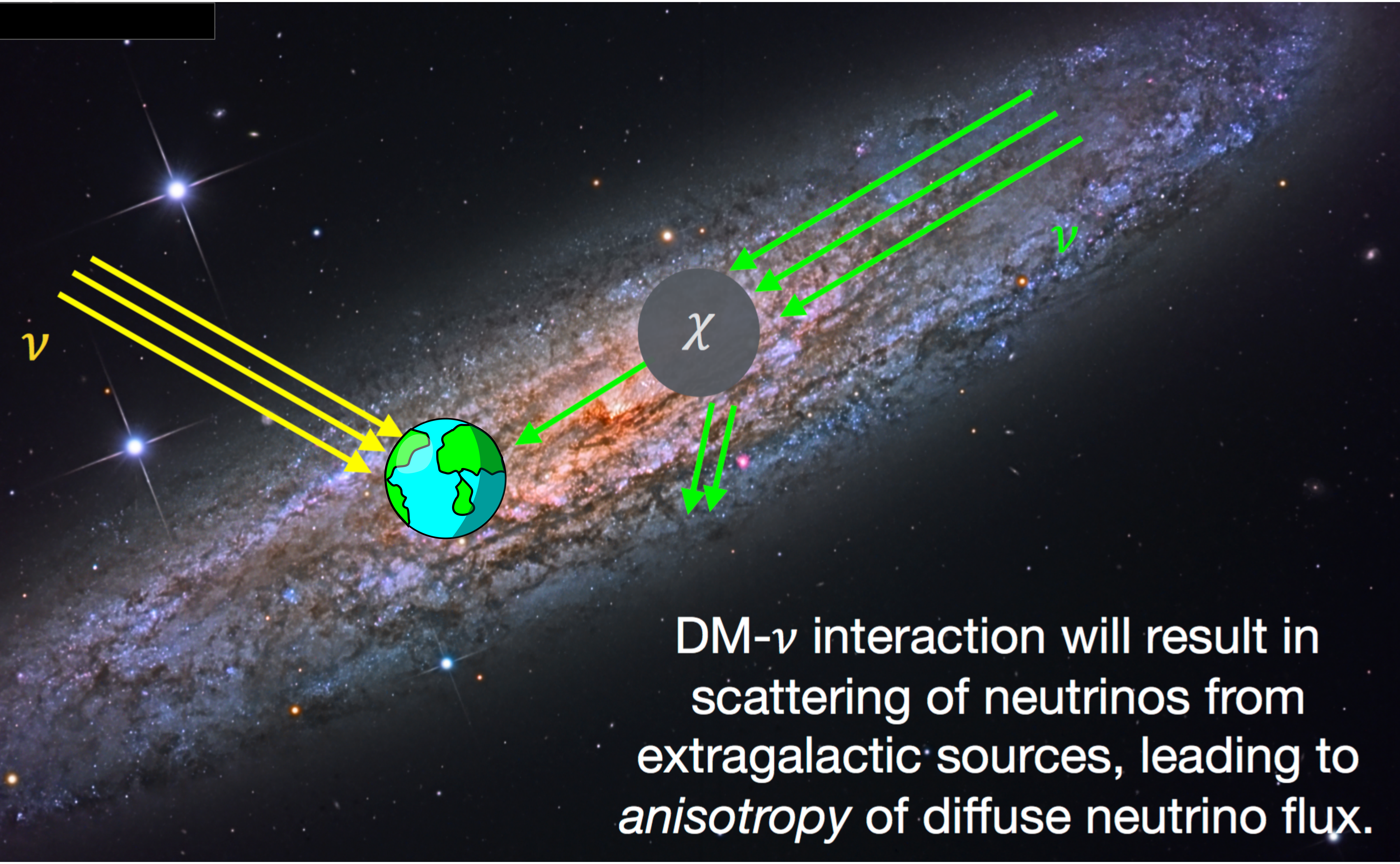
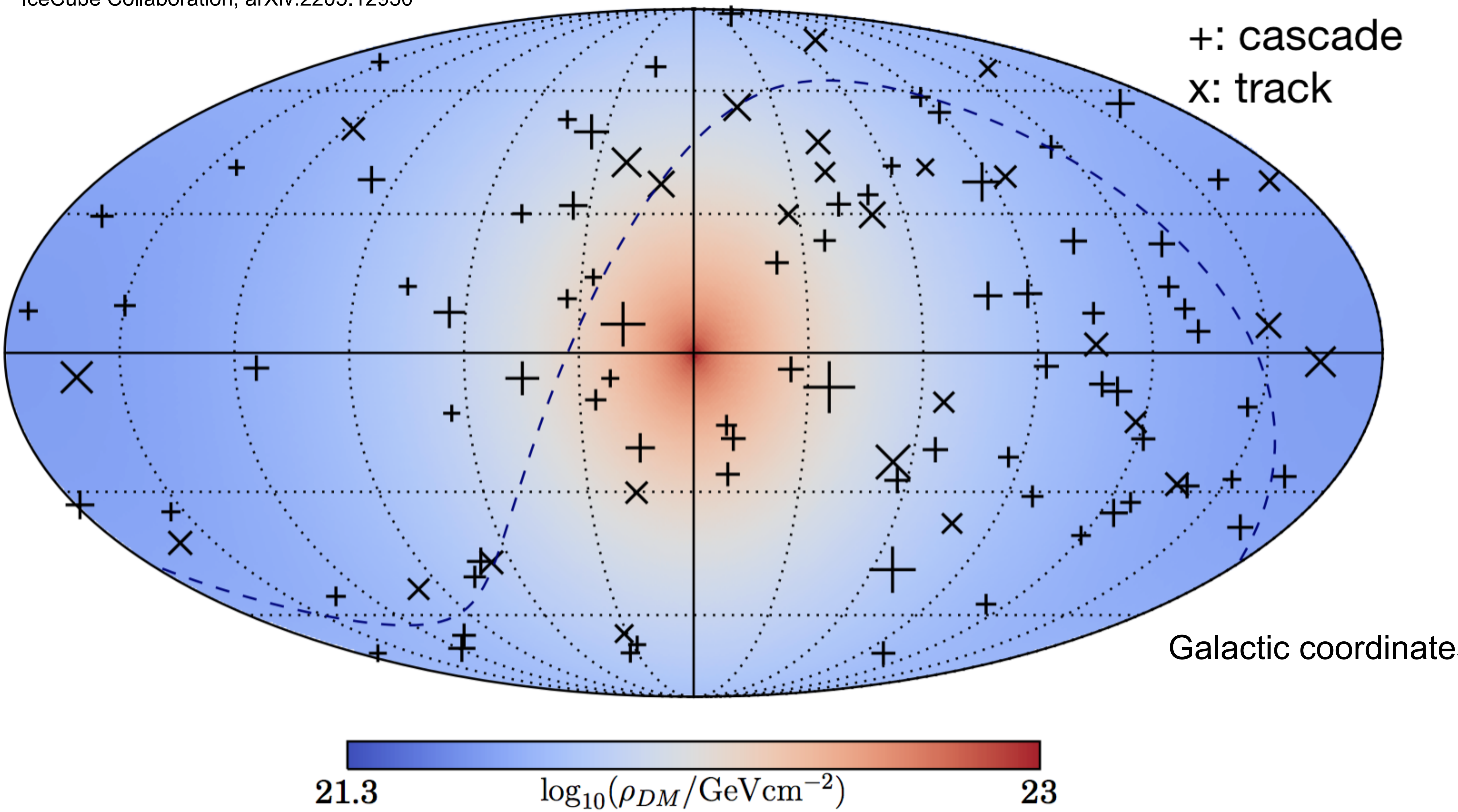
Dark matter neutrino incoherent scattering



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

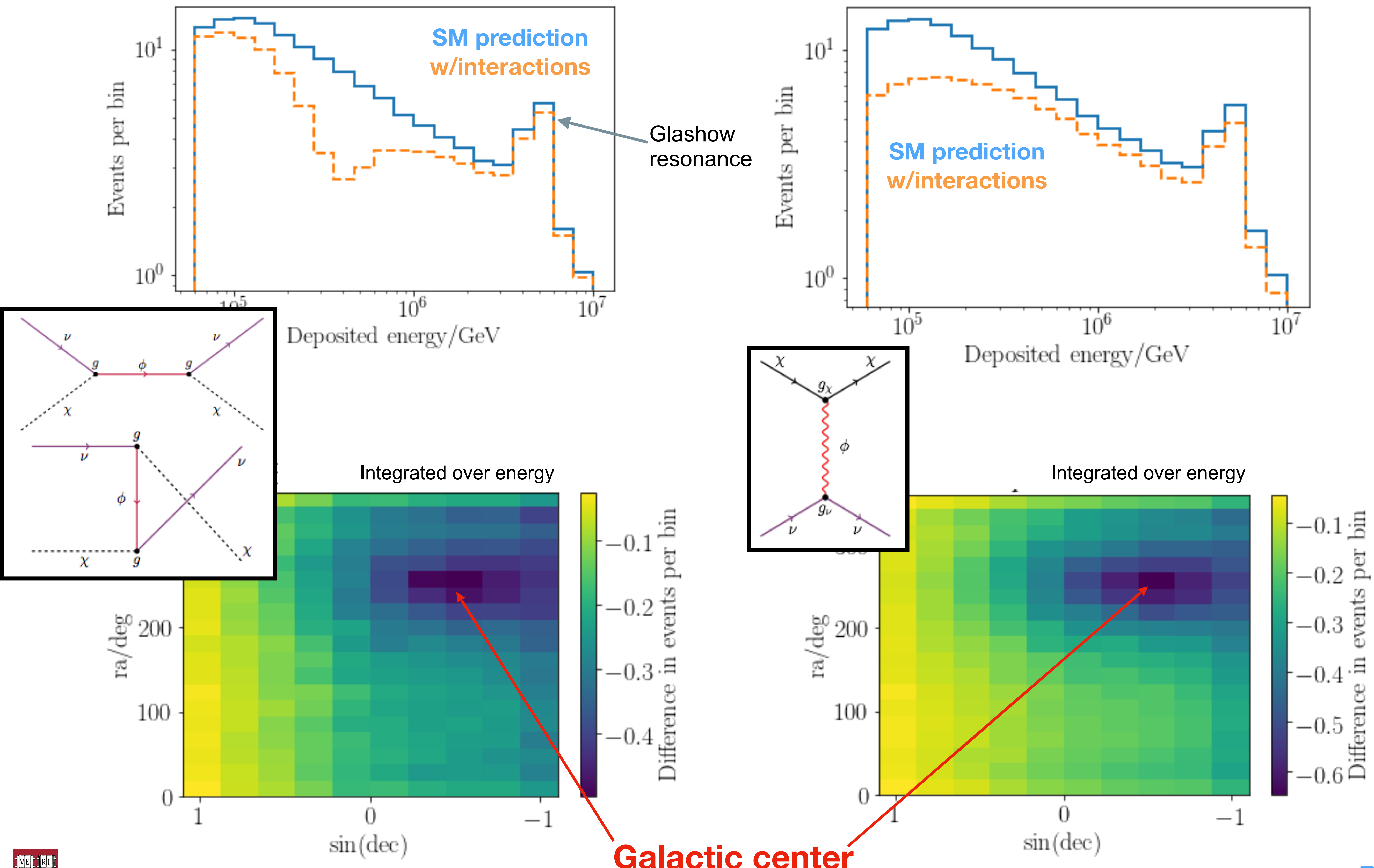
HESE Neutrino Skymap

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

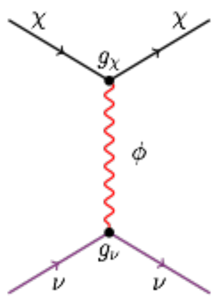


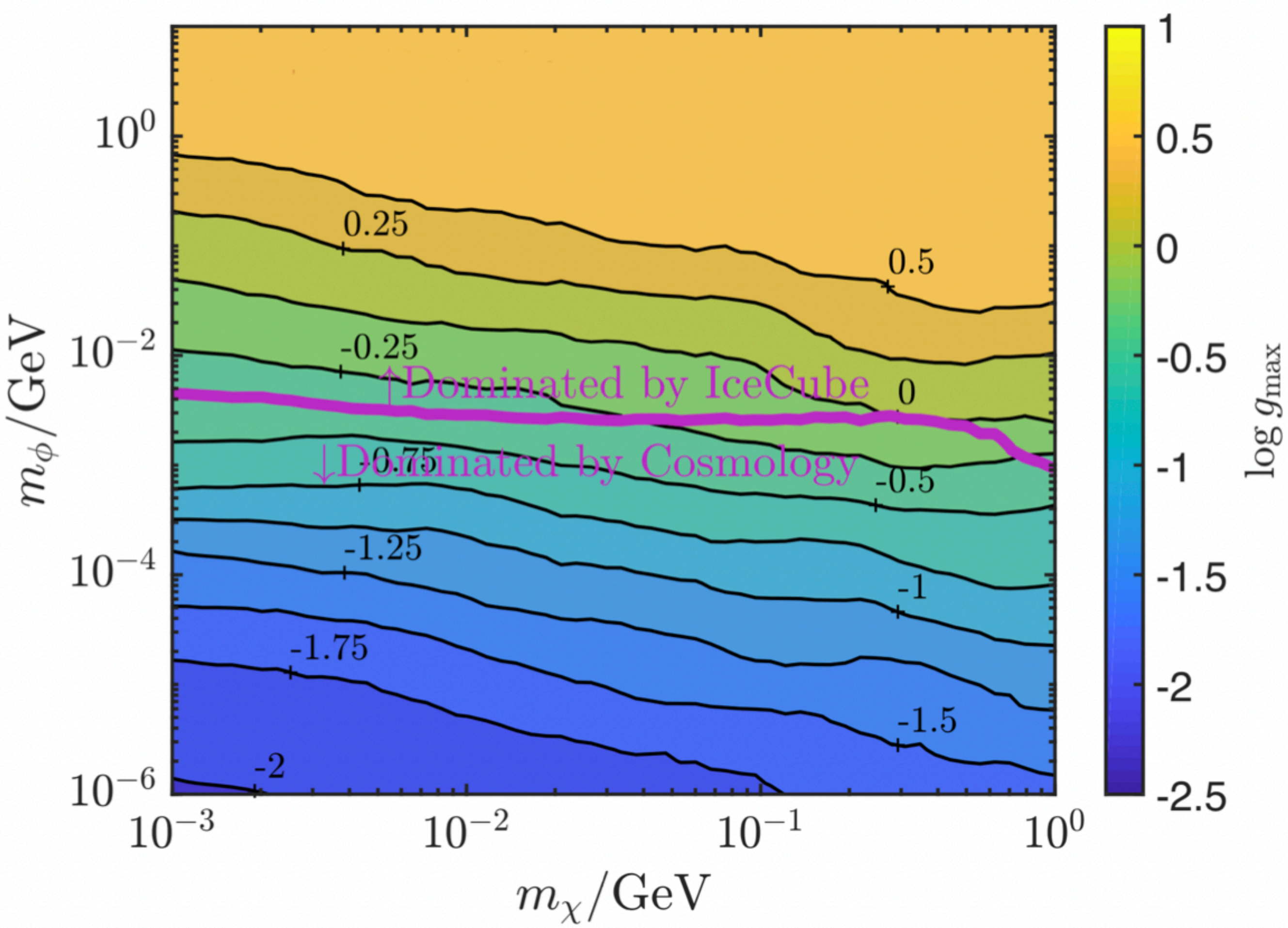
Events are compatible with an isotropic distribution: found no signal!

Also include effects in energy and direction

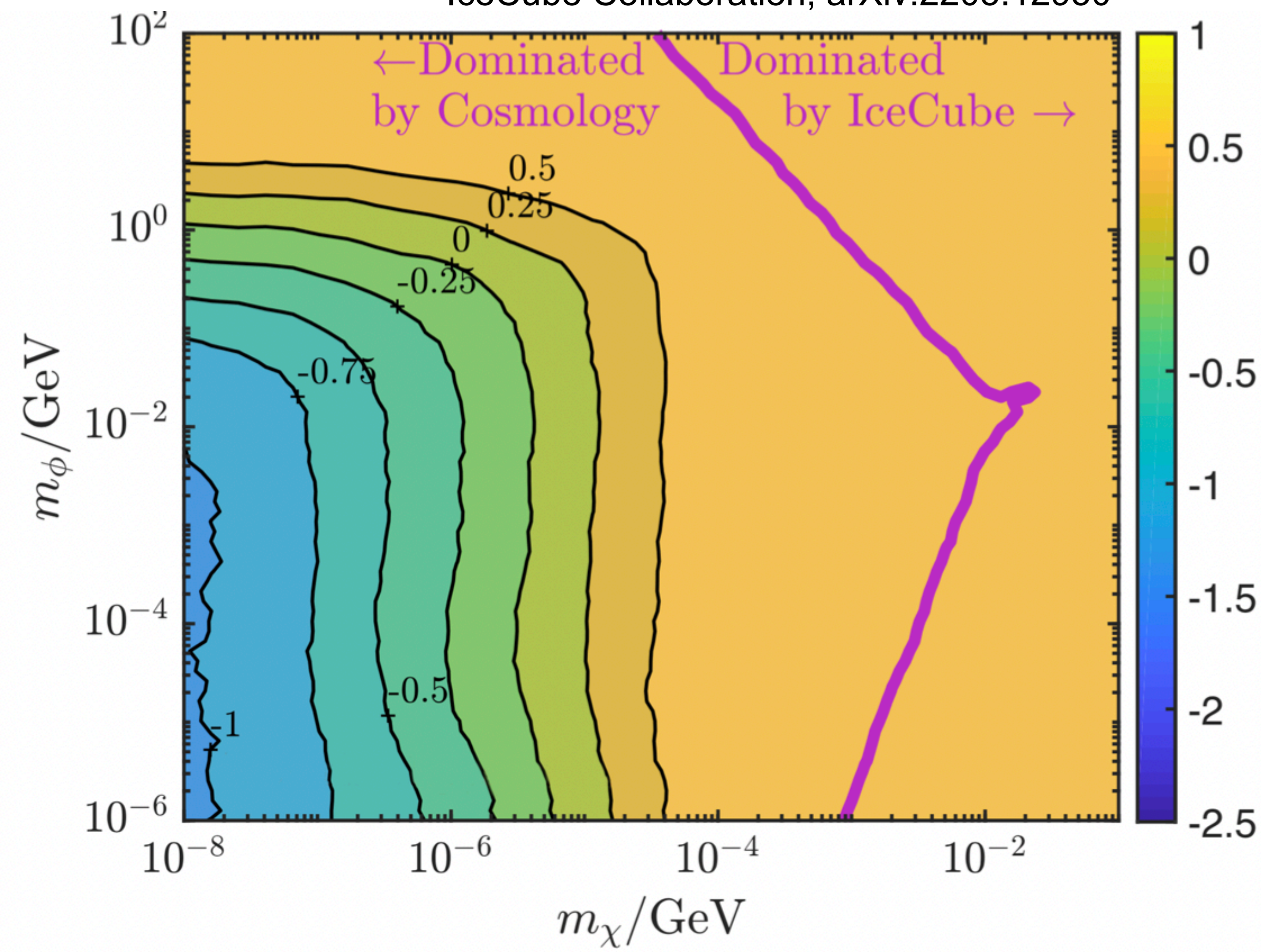


New constraints on neutrino-dark matter interactions



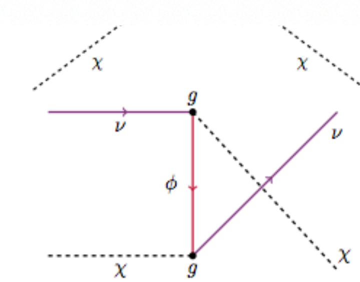


IceCube Collaboration, arXiv:2205.12950

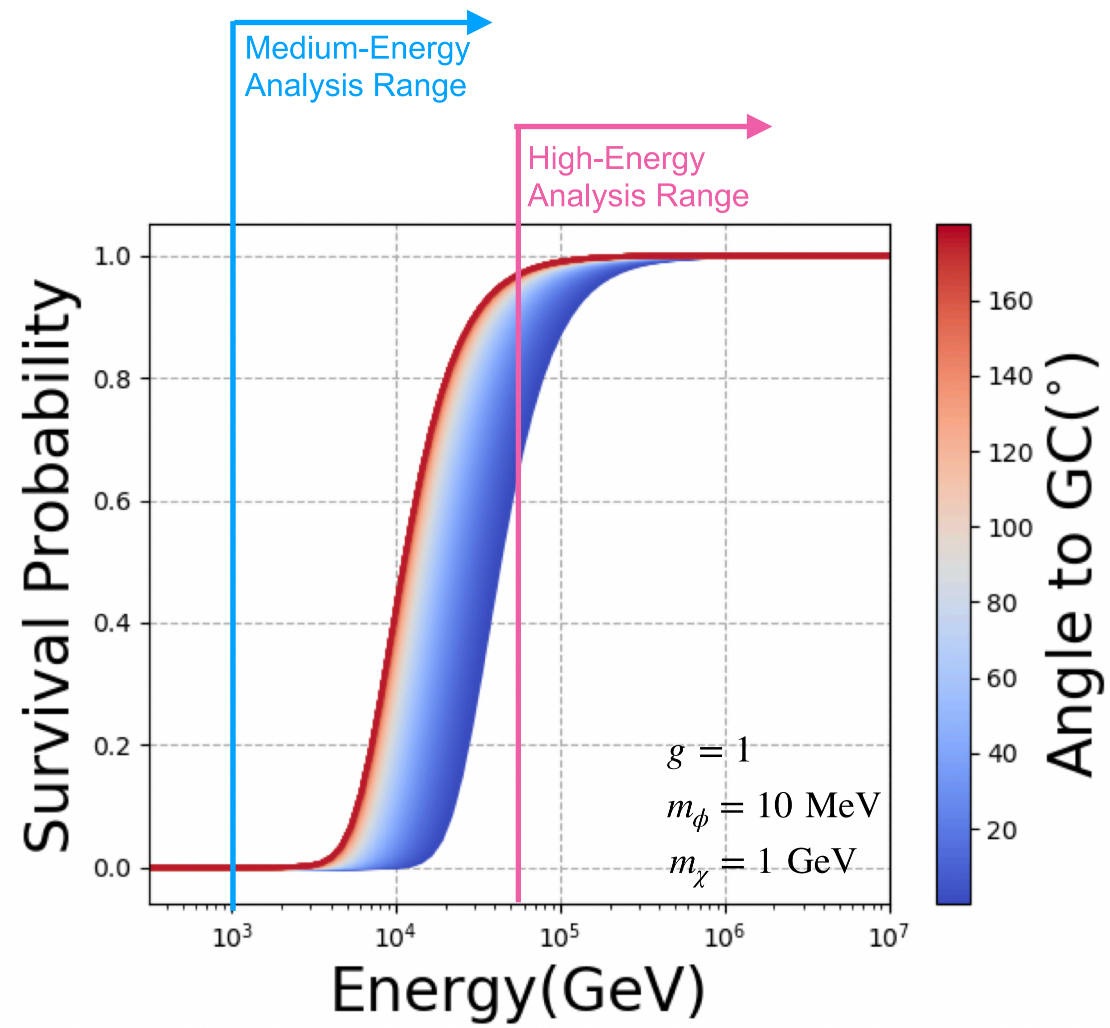


Color scale is the maximum allowed coupling.

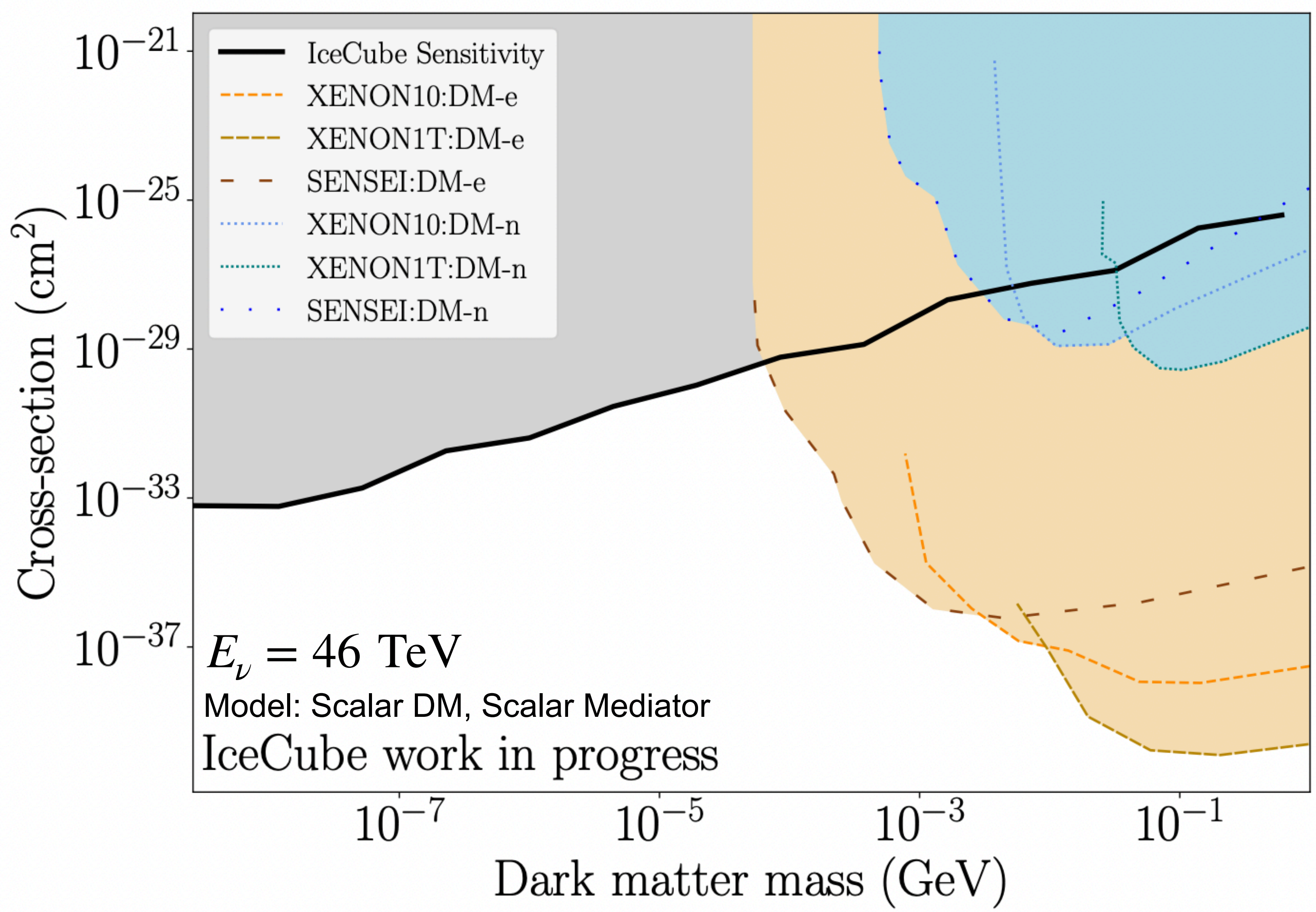
Cosmological bounds using Large Scale Structure from Escudero et al 2016



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.

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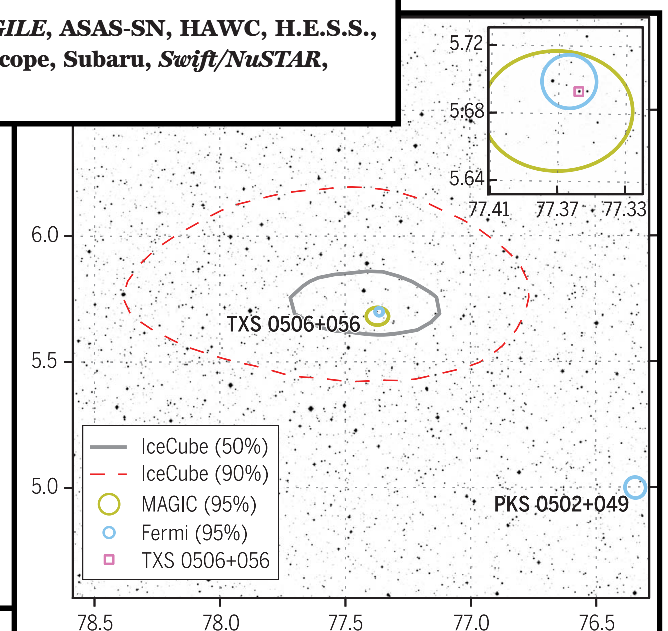
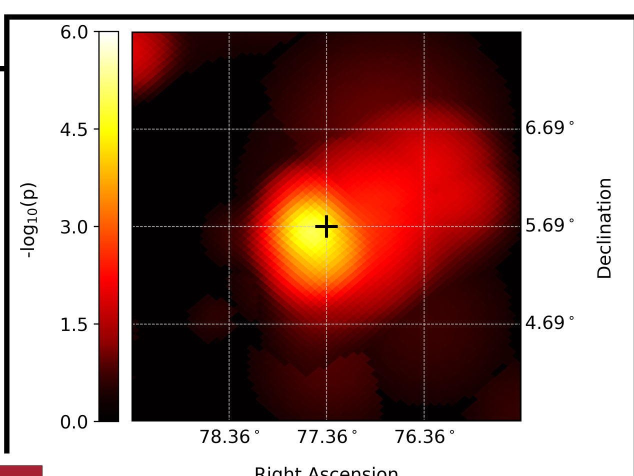
Neutrinos From Cosmic Beam dump
Blazar: TXS 0506+056

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams*†



Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert



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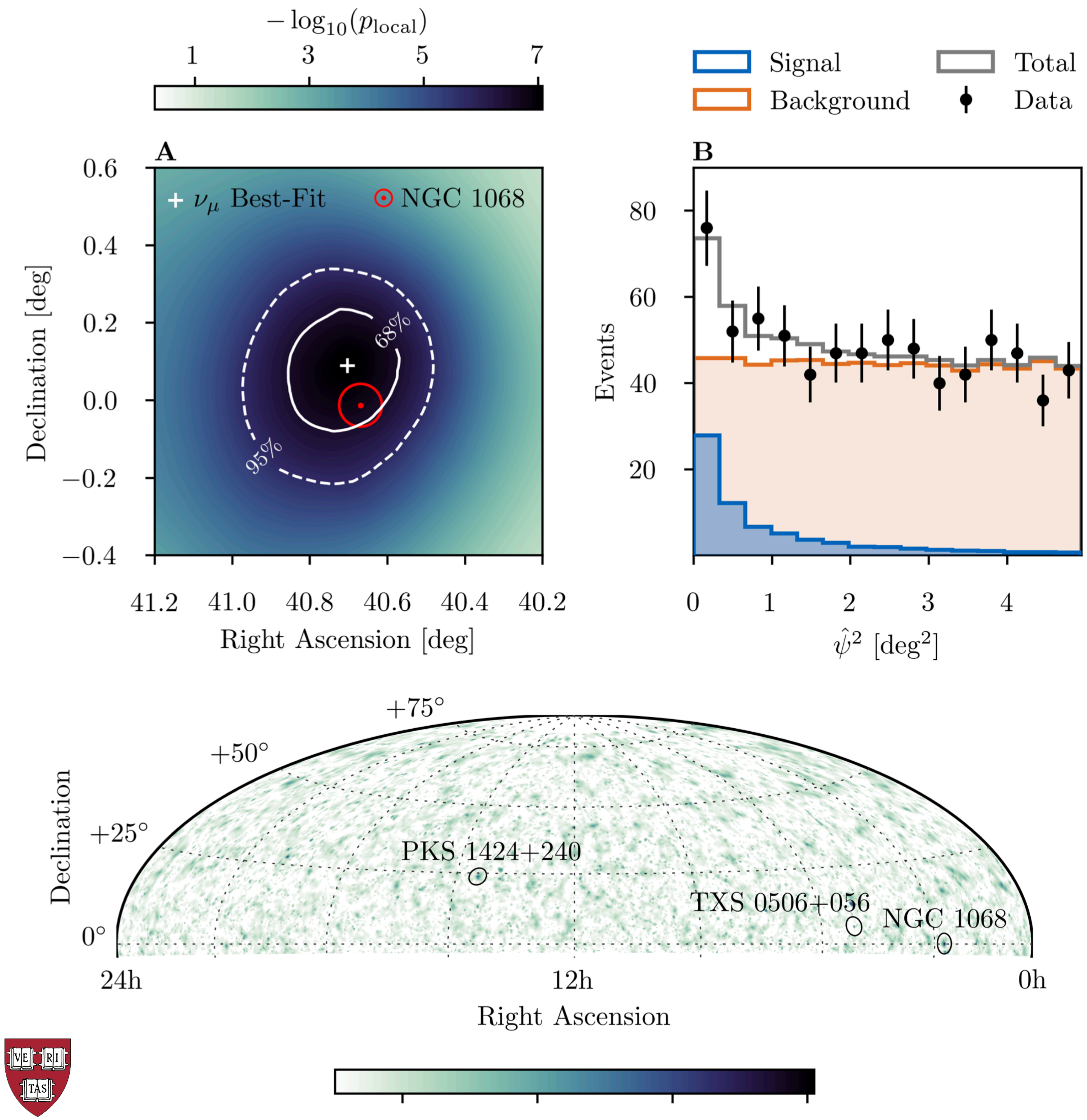
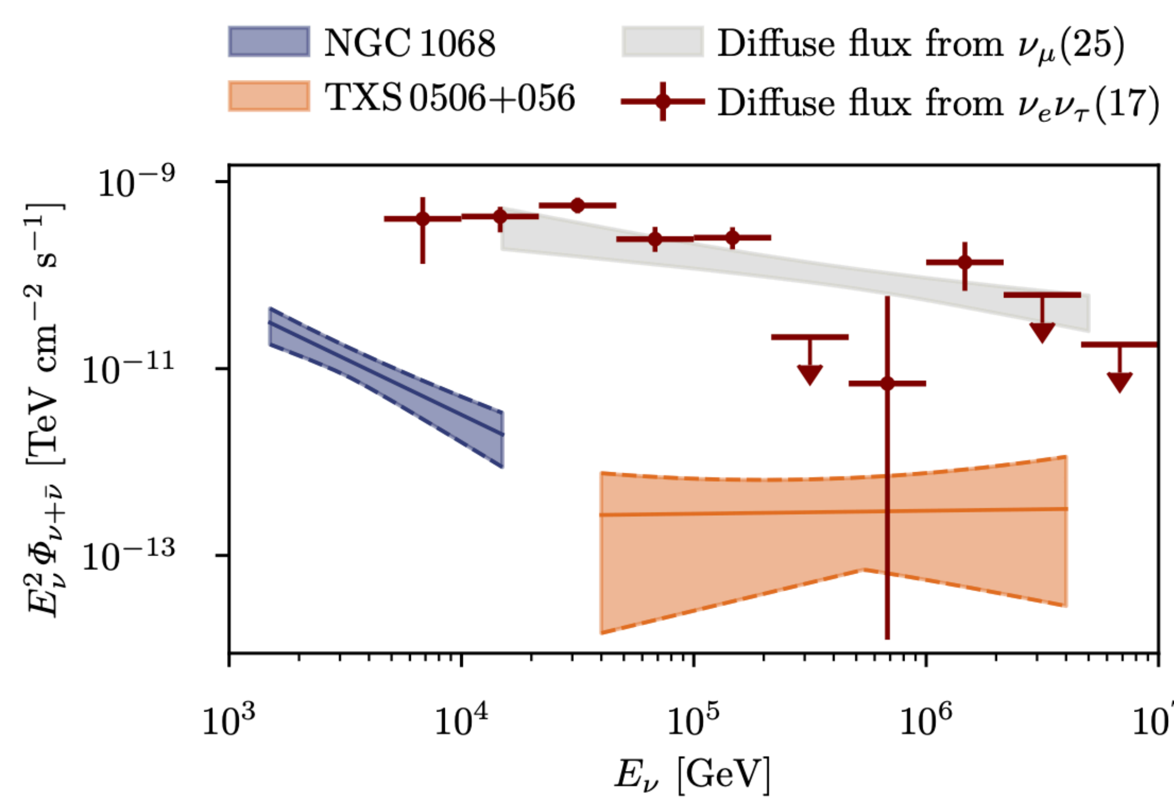
RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Evidence for neutrino emission from the nearby active galaxy NGC 1068



Breaking news! NGC1068 is a high-energy neutrino source

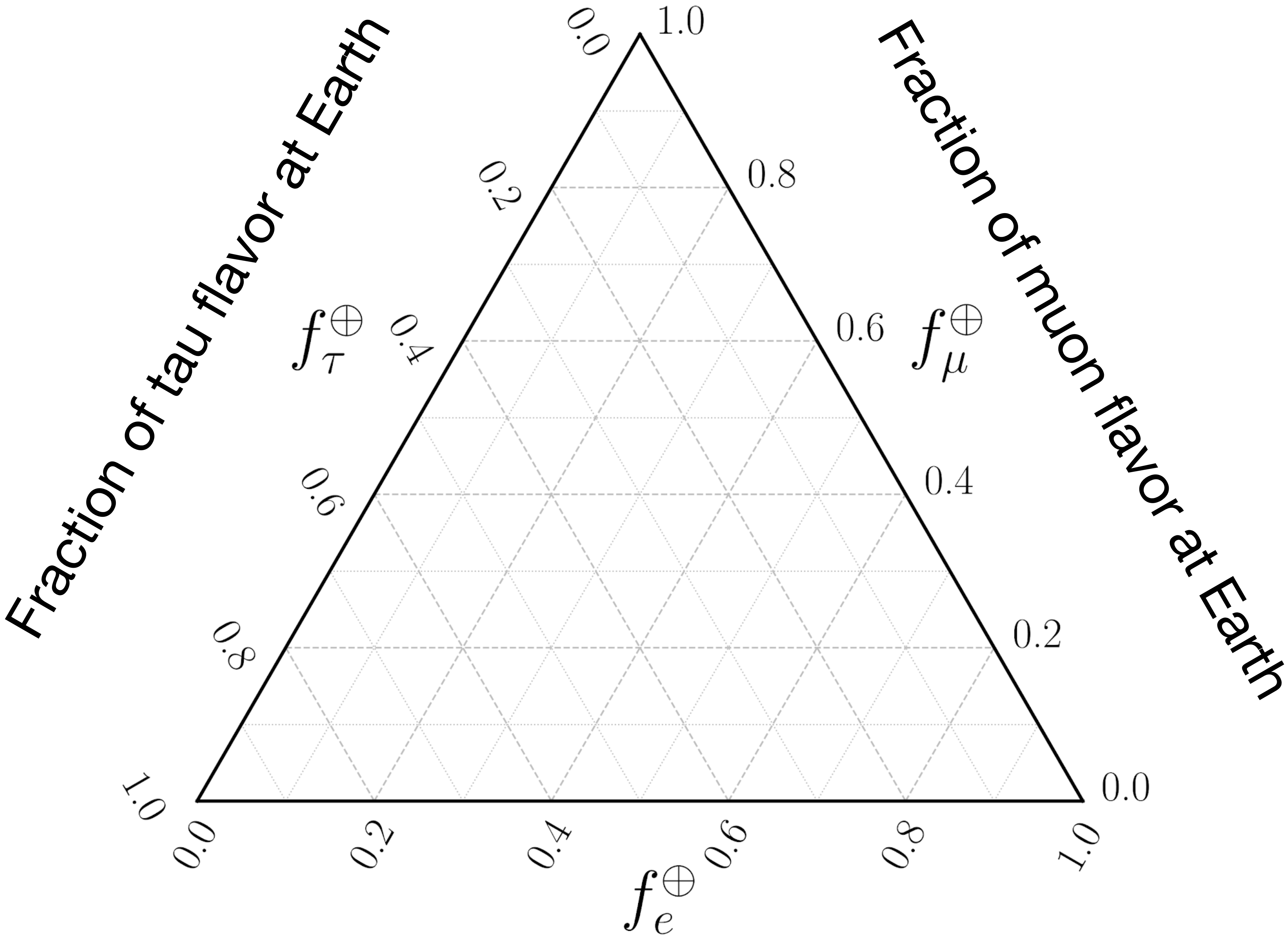


Flavor composition @ source

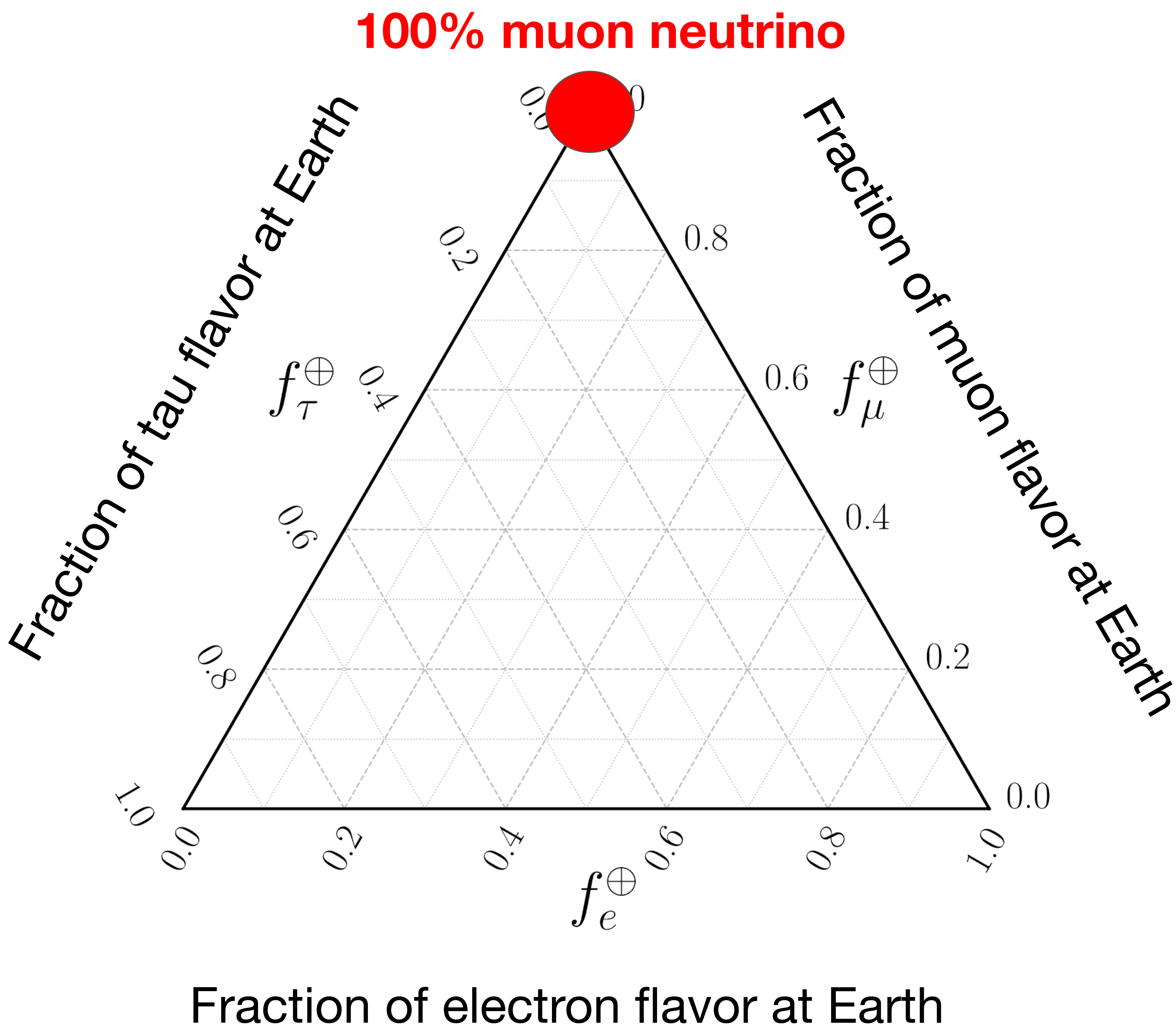
(GRBs, AGNs, blazars, pulsars…) $(\alpha_e : \alpha_\mu : \alpha_\tau)$

Pion	$\pi^+ \to \mu^+ + \nu_\mu$ $\downarrow$ $\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$	(1:2:0)
Muon-damped	$\pi^+ \to \mu^+ + \nu_\mu$ (μ^+ crossed out)	(0:1:0)
Neutron	$n \to p + e^- + \bar{\nu}_e$	(1:0:0)

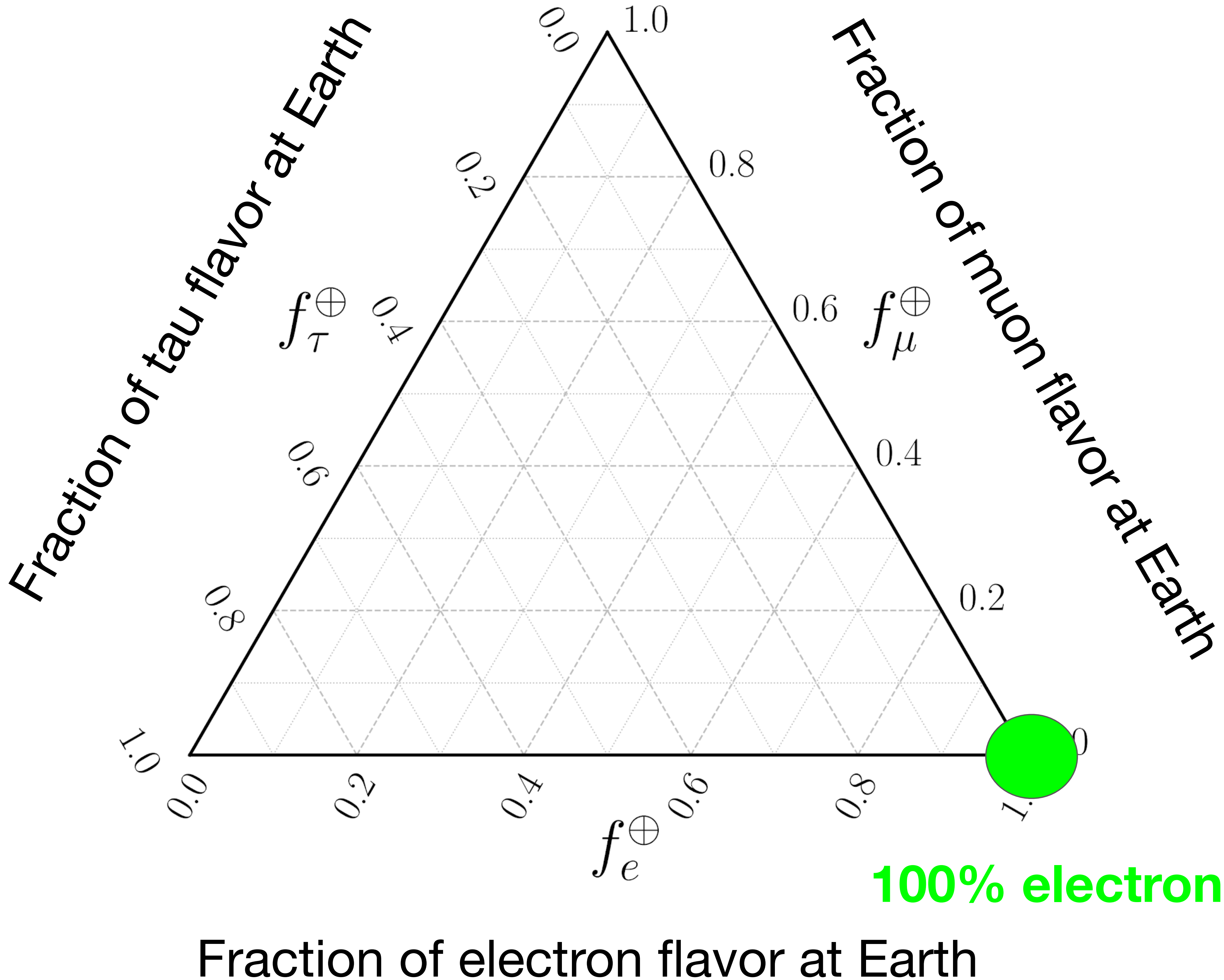
The flavor triangle



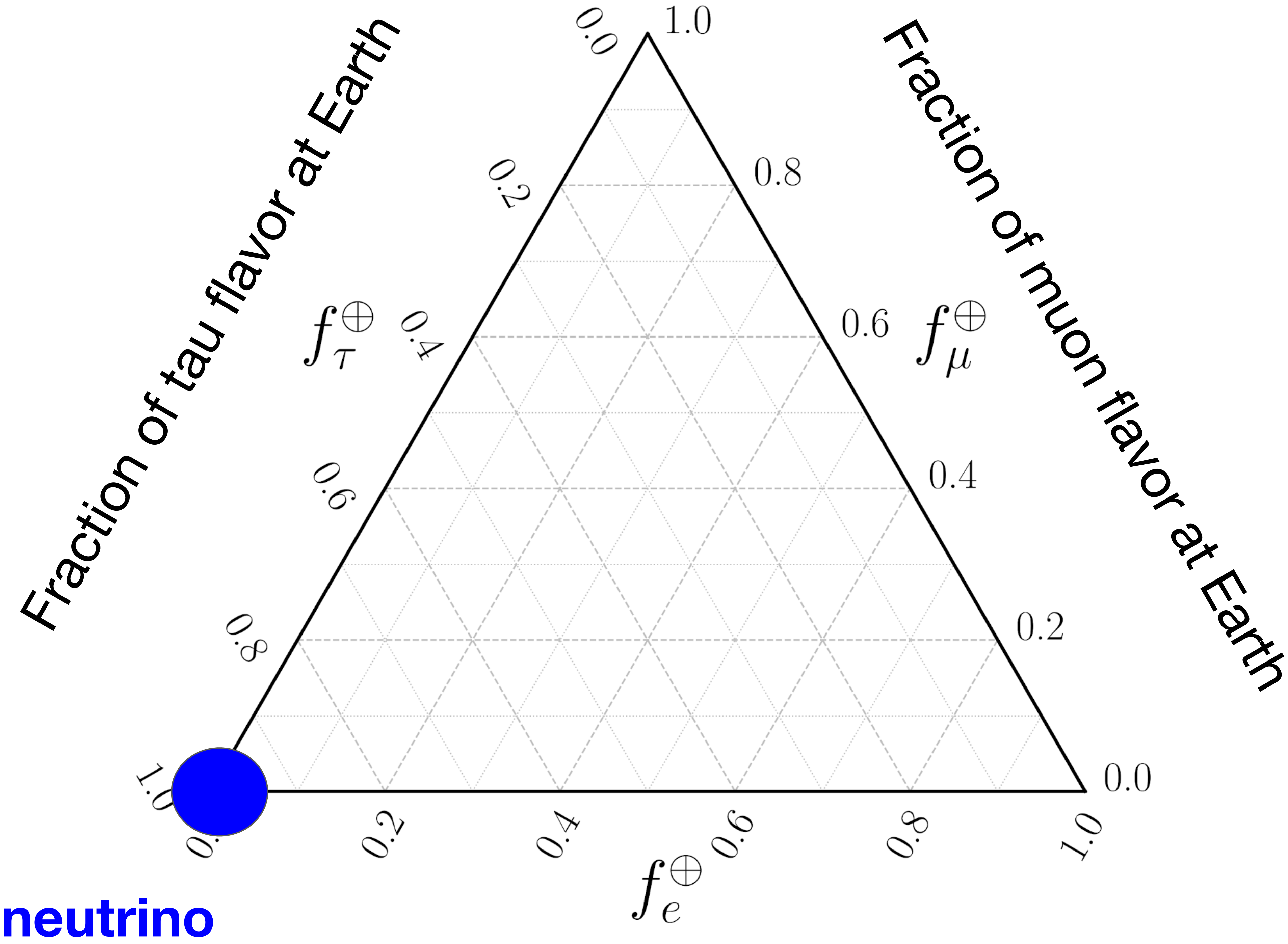
The flavor triangle



The flavor triangle

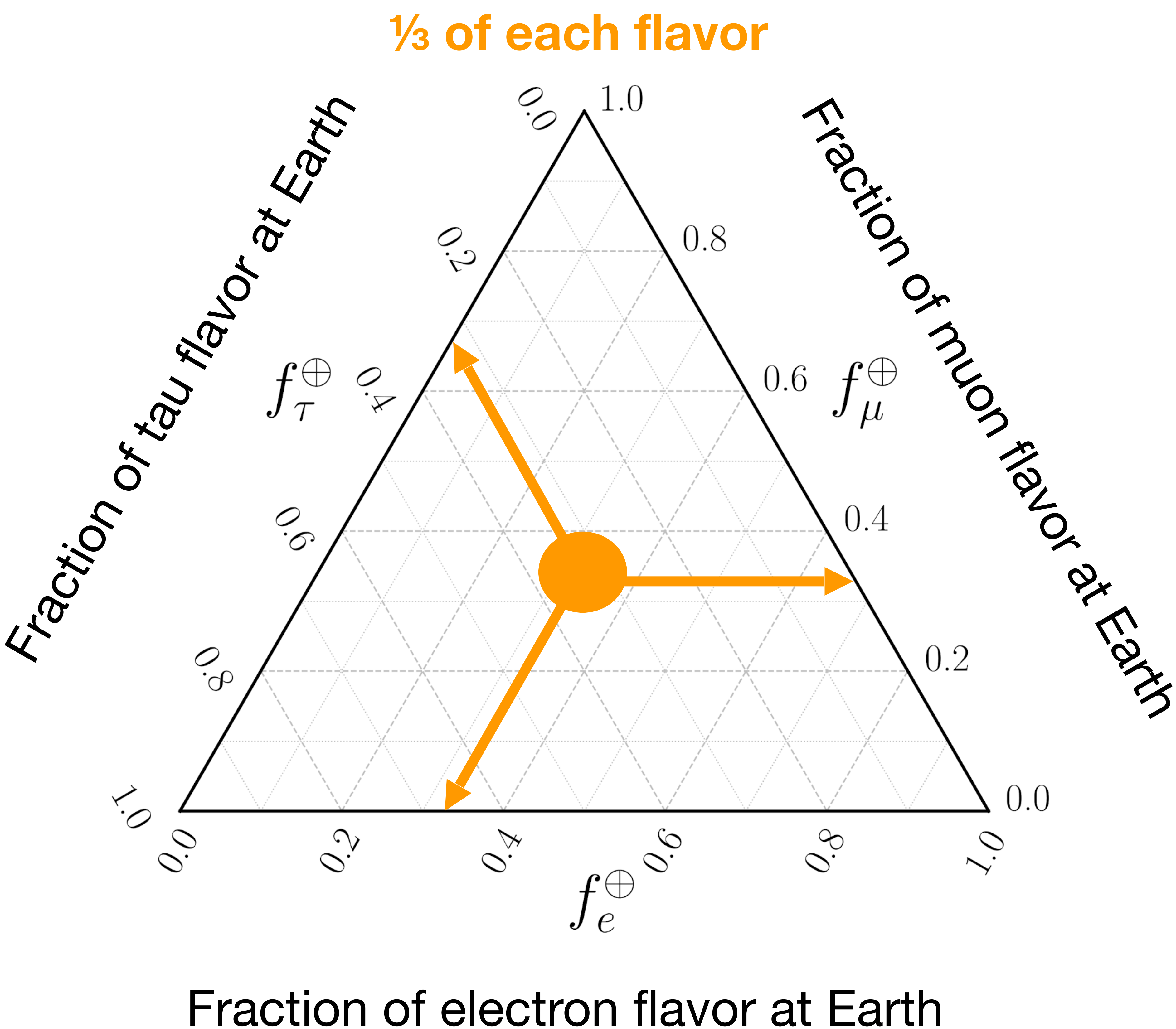


The flavor triangle



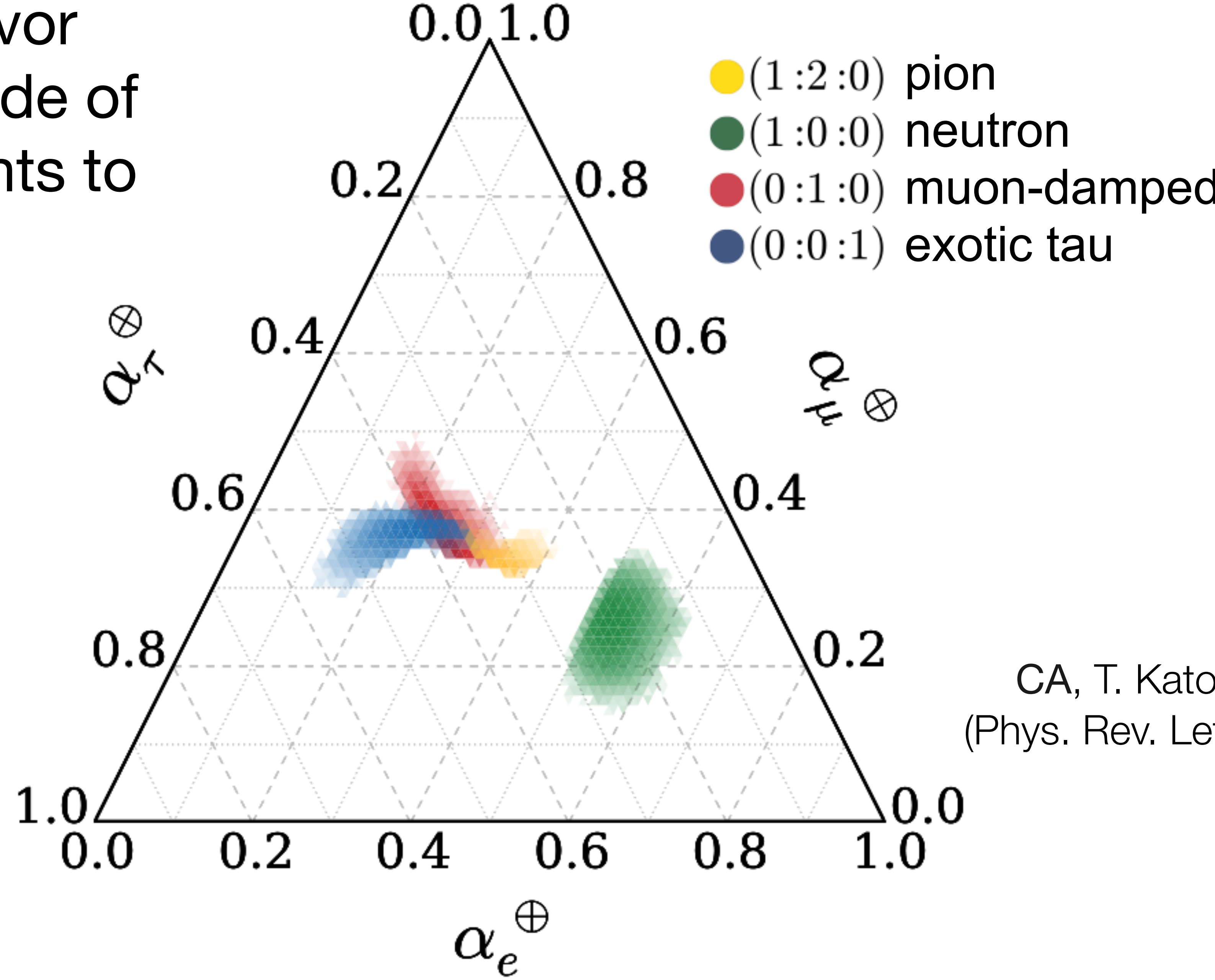
100% tau neutrino

The flavor triangle



After oscillations where will the different sources end up?

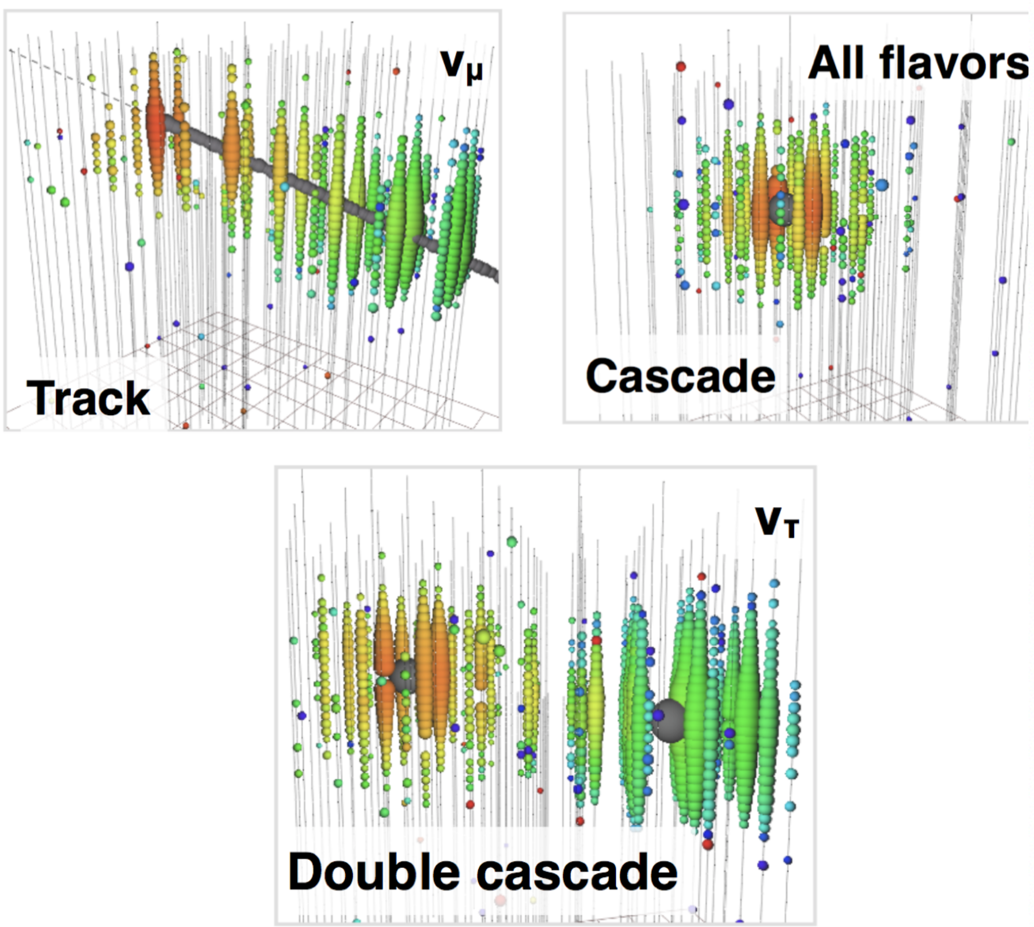
Measuring a flavor composition outside of these regions points to new physics!

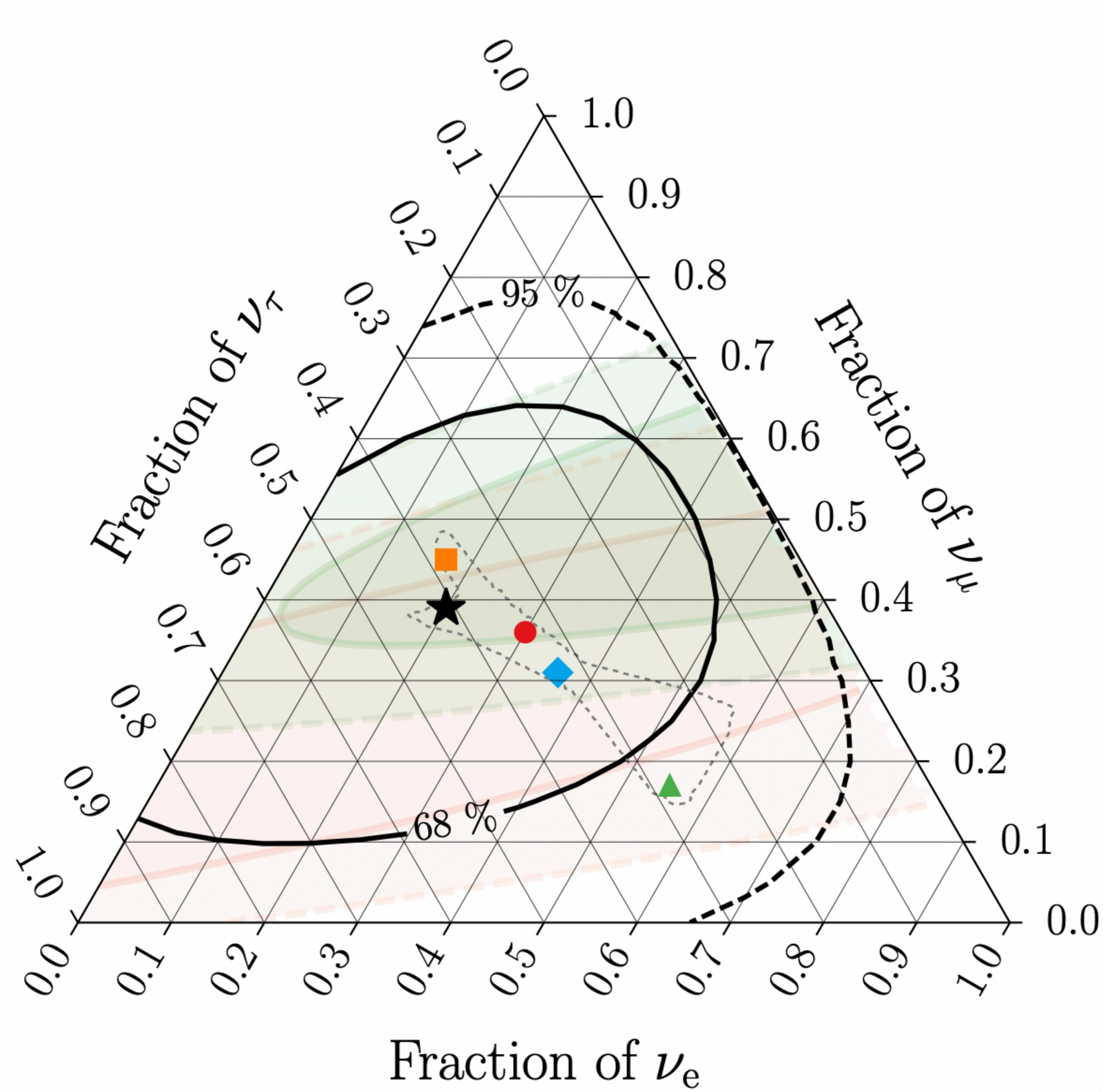


CA, T. Katori, J. Salvado (Phys. Rev. Lett. **115**, 161303)

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 ..

Latest astrophysical neutrino flavor measurement





— HESE with ternary topology ID
★ Best fit: 0.20 : 0.39 : 0.42
Global Fit (IceCube, APJ 2015)
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 Secret Interactions via Flavor Morphing

As neutrinos travel from their far away source they can interact with dark matter along the way.

Trajectories in the Flavor Triangle In the Presence of Secret Interactions

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

Dimension

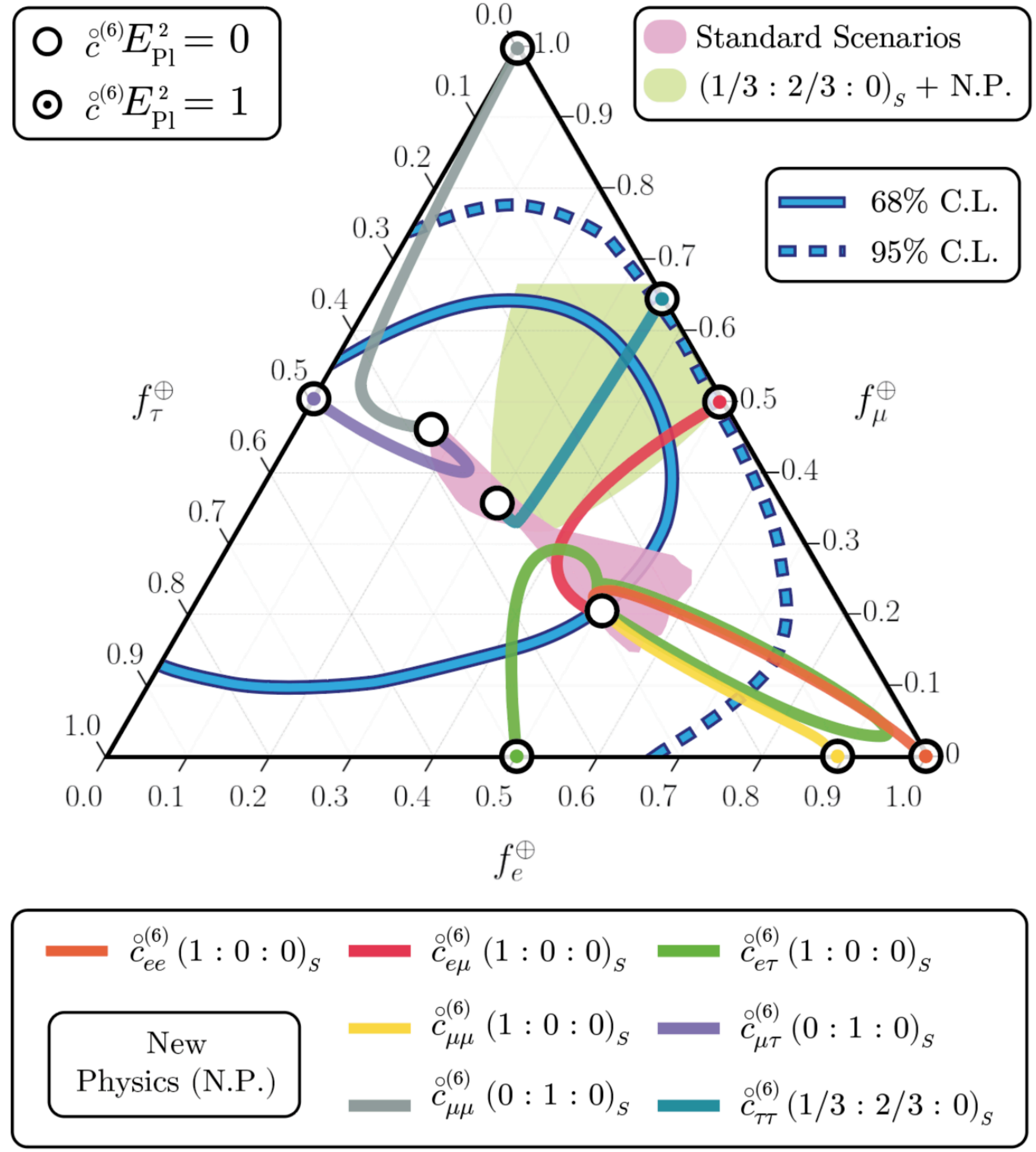
Standard Mixing

New Physics Terms

$(1:2:0)$ pion

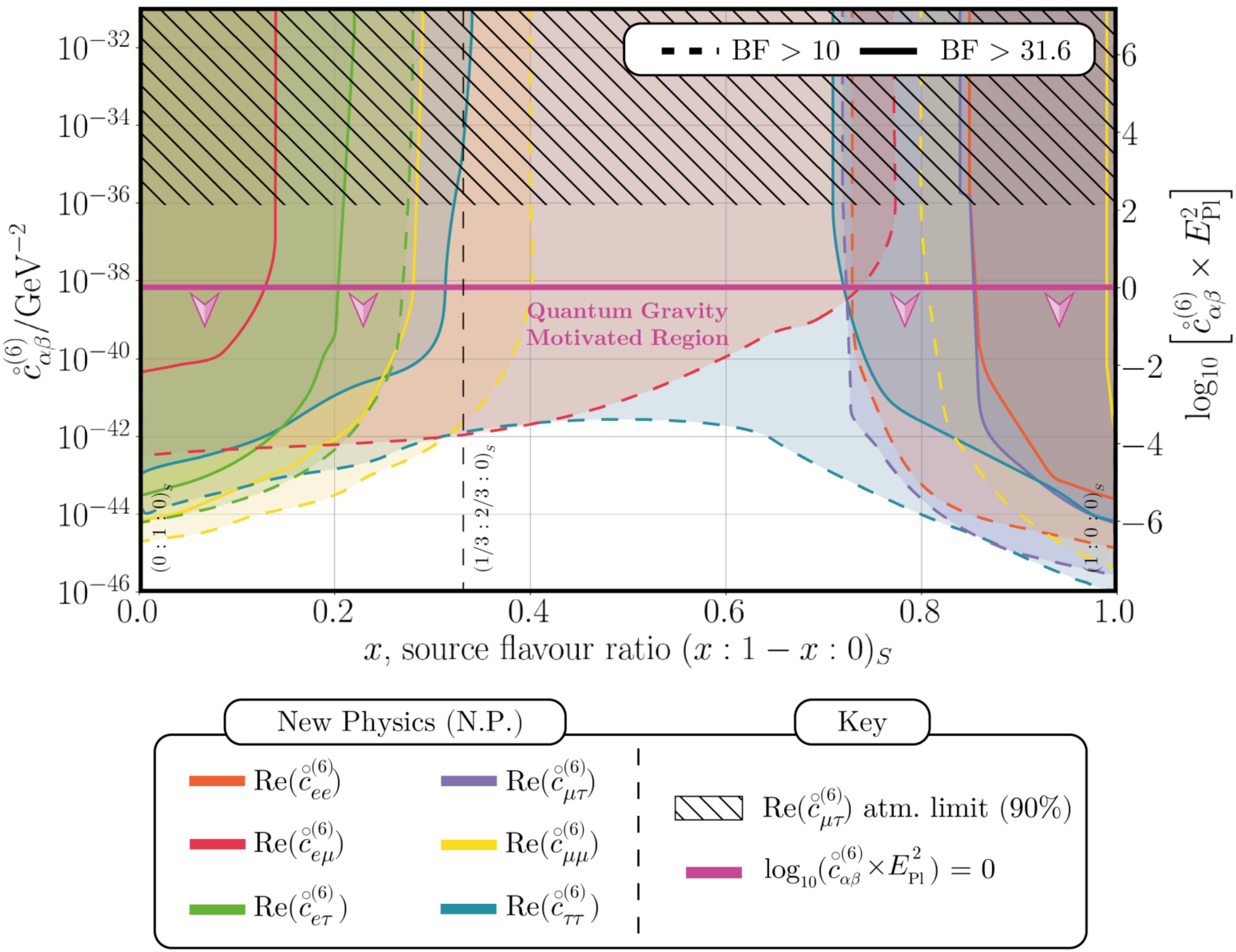
$(0:1:0)$ neutron

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



IceCube collaboration arXiv:2111.04654

Results for high-dimensional operators



IceCube collaboration arXiv:2111.04654

Coherent Dark Matter Scattering

Standard term — New physics term

$$H = \boxed{\frac{1}{2E} U M^2 U^\dagger} + \boxed{V_{\mathrm{new\ \ physics}}}$$

$V_{e\tau} < 10^{-27}\mathrm{GeV}$

(0:1:0) source

$V_{\mu\tau} < 10^{-28}\mathrm{GeV}$

(1:0:0) source

Coherent scattering with dark cosmic background

Our analysis is performed by introducing *effective terms*, which can be due to other new physics.

$$V_D \sim G_D N_D$$

$$G_D \sim \frac{g_d^2}{M_D^2}$$

Caveat: need to know neutrino source initial flavor composition to get robust bounds with current limits.

de Salas, et al. Phys. Rev. D94 (2016) 123001

Capozzi et al. 1804.05117

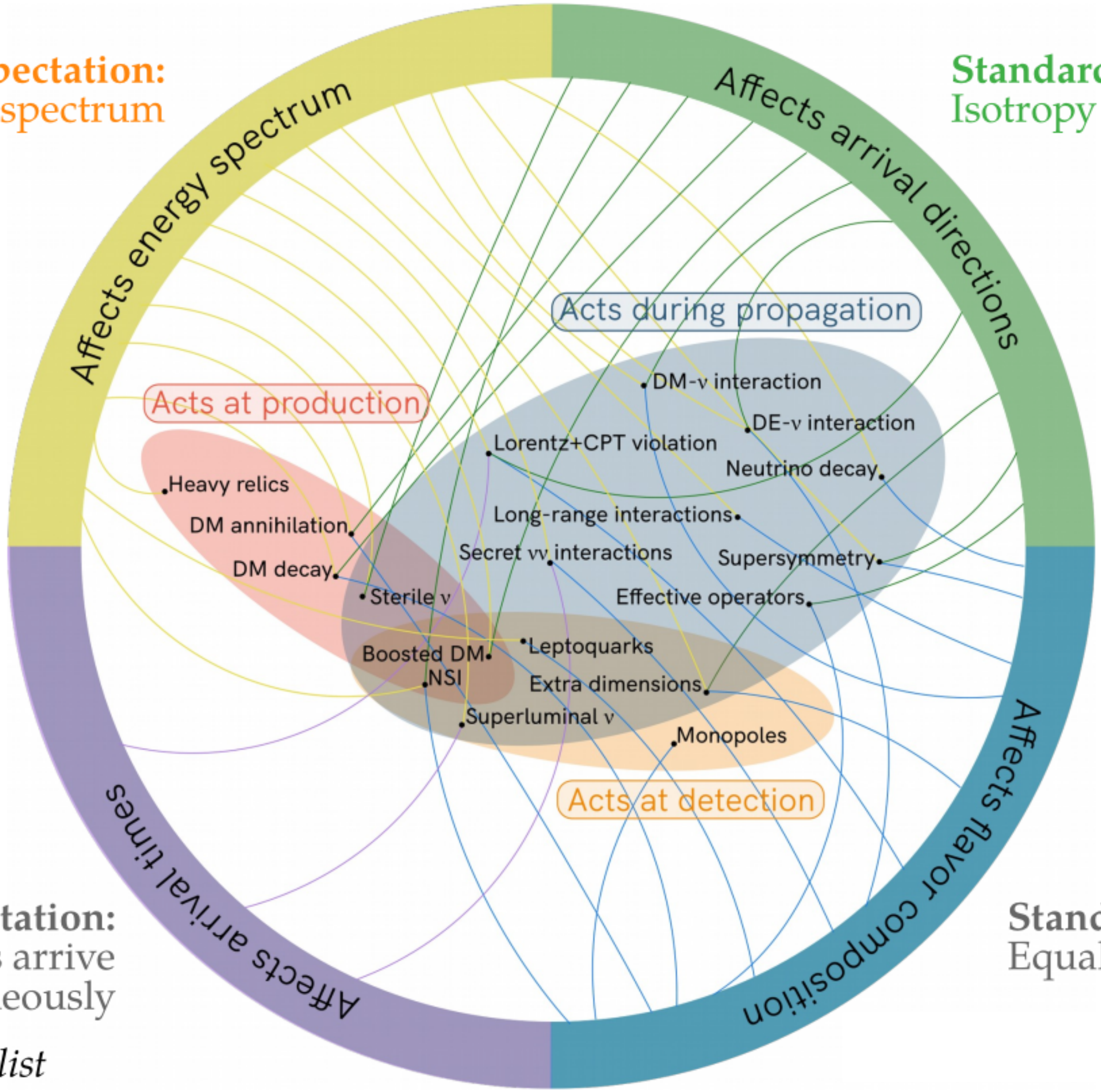
Stops

- Neutrino detectors and fluxes
- Searching for an excess of neutrinos
- Searching for a deficit of neutrinos
- Searching for a strange neutrino flavor effects
- **How do we move forward?**

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

HYPER K

P-ONE

RNO-G

ICECUBE GEN2

JEM-EUSO

Many Neutrino Telescopes On Our Way

BAIKAL-GVD

KM3NeT

TRIDENT 海 | 铃 | 计 | 划

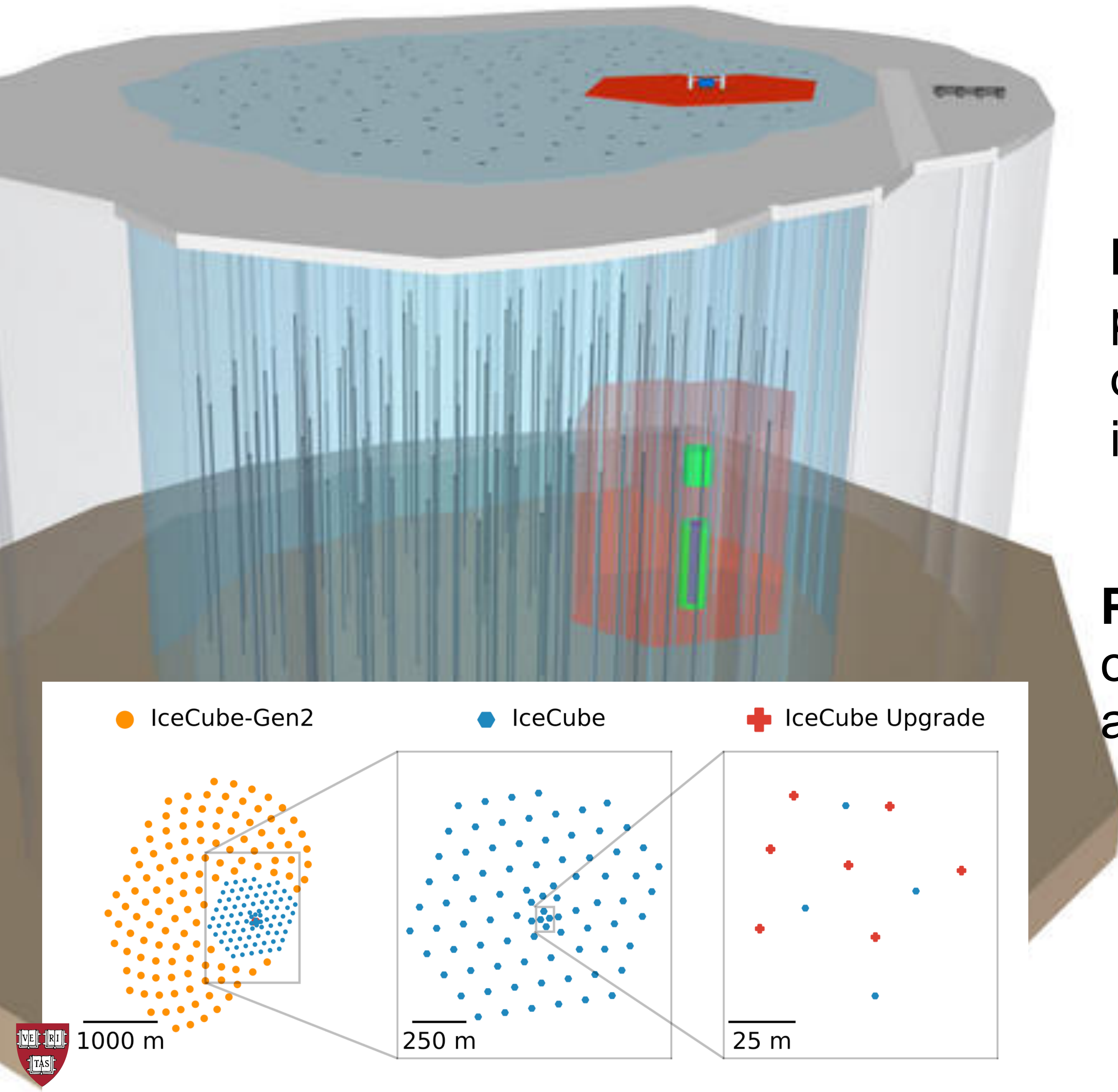
GRAND

POEMMA

νTAMBO

Non-exhaustive list

The IceCube Upgrades!



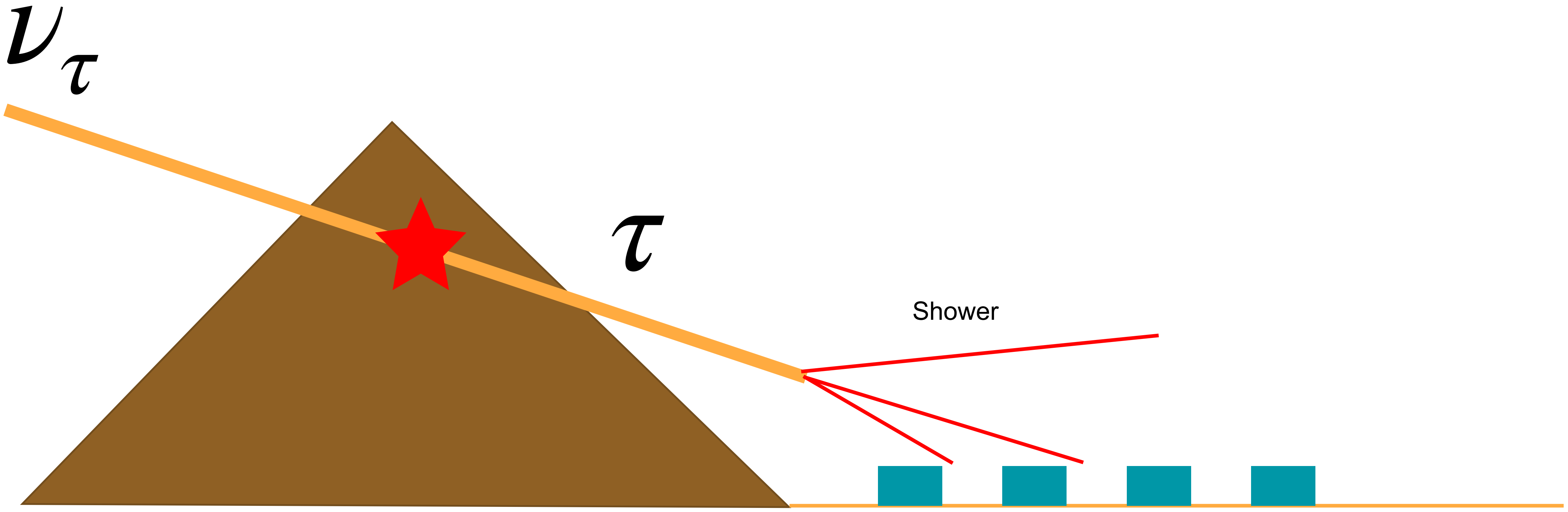
See talk by Jason Koskinen this week!

Phase 1: 7 new, high-precision strings in the central, densely instrumented region.

Phase 2: x10 the volume of present IceCube, plus additional detectors.

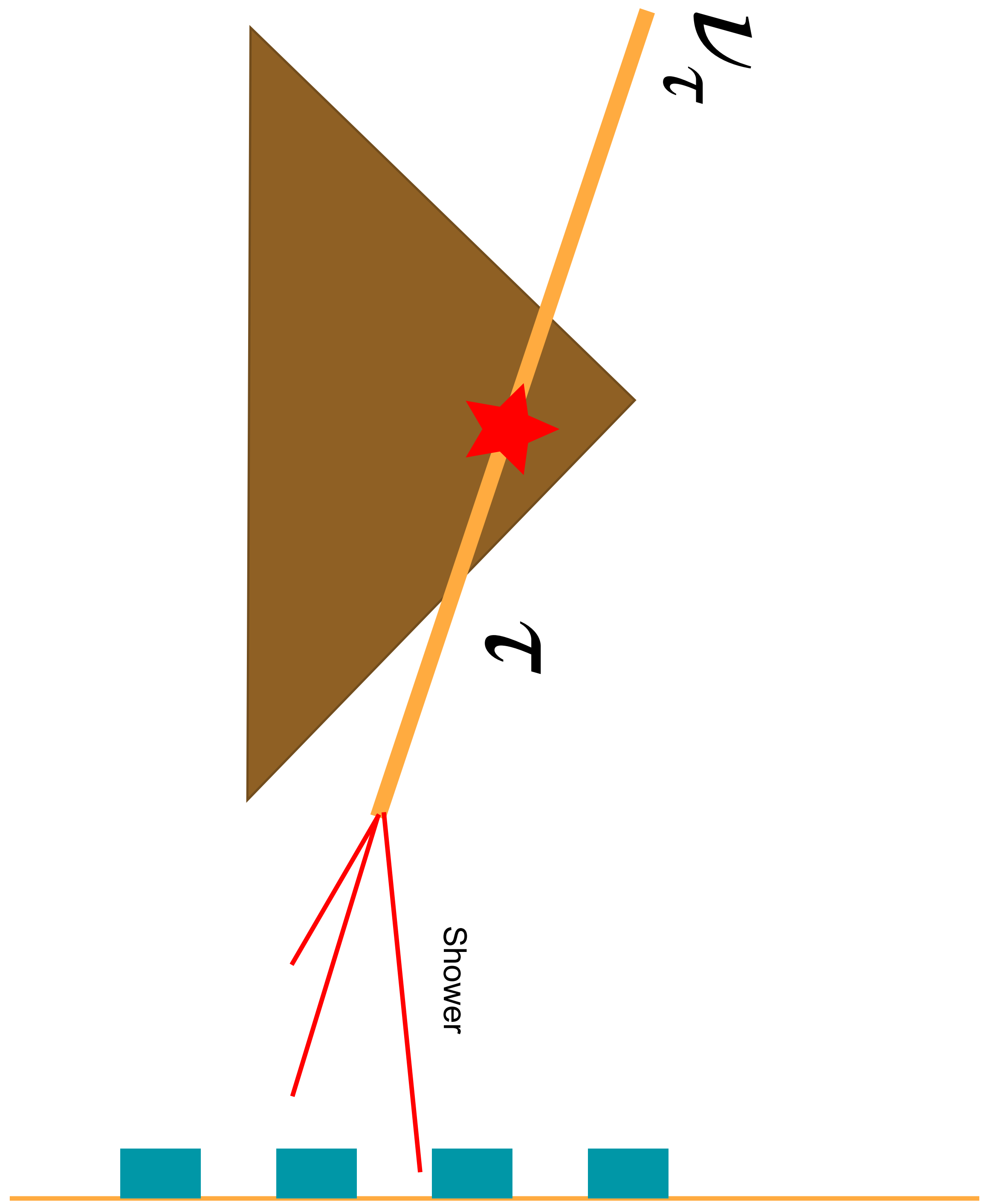
See talk by Lu Lu!

Thinking about Earth-skimming neutrino detectors



The geometry here is key for the acceptance of neutrino detection

Thinking about Earth-skimming neutrino detectors

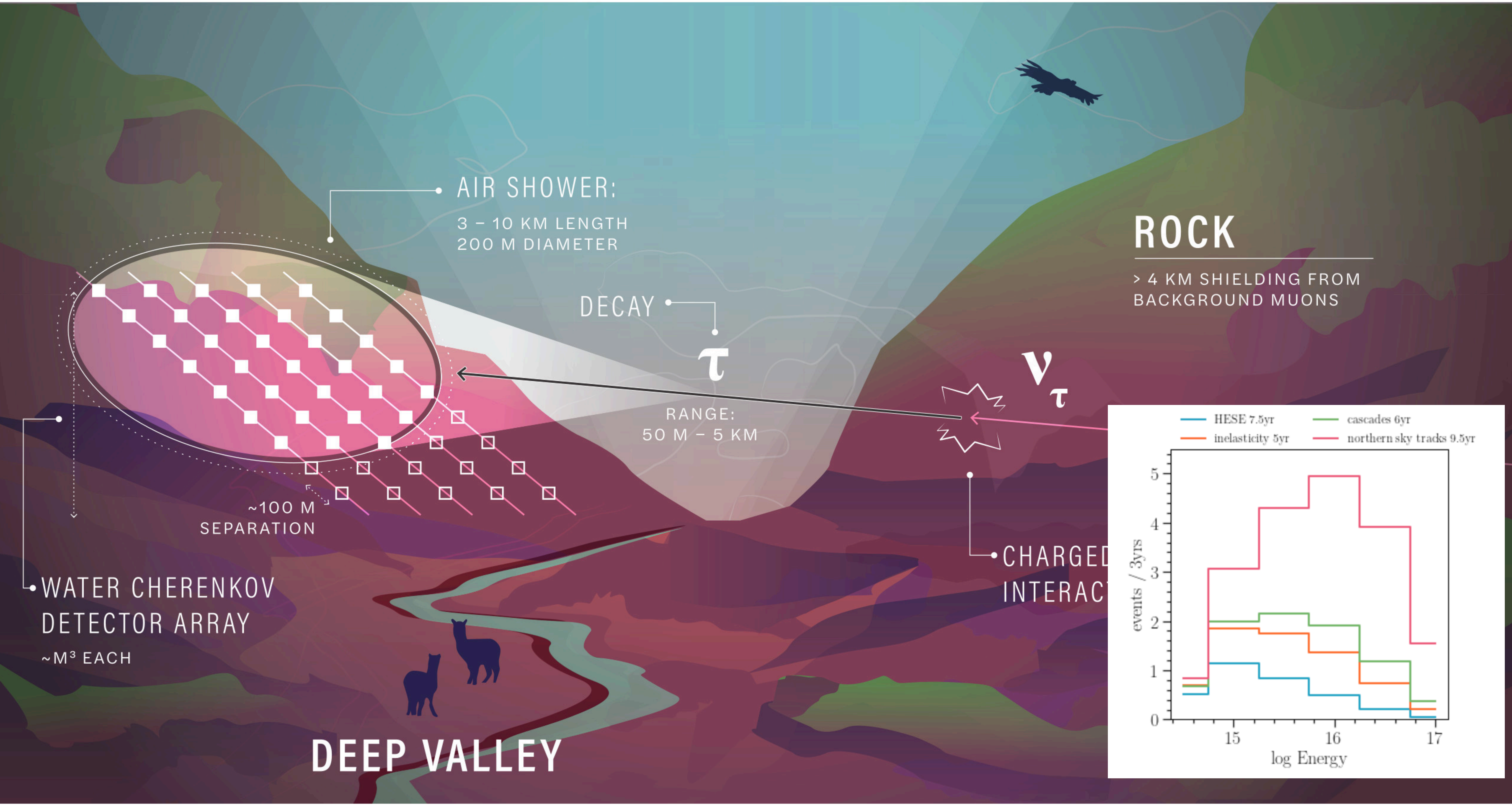


The geometry here is key for the acceptance of neutrino detection

This would be a more ideal scenario, but can’t put mountain over detector

See talk by Pavel Zhelnin this afternoon for new ideas on tau neutrinos

TAMBO

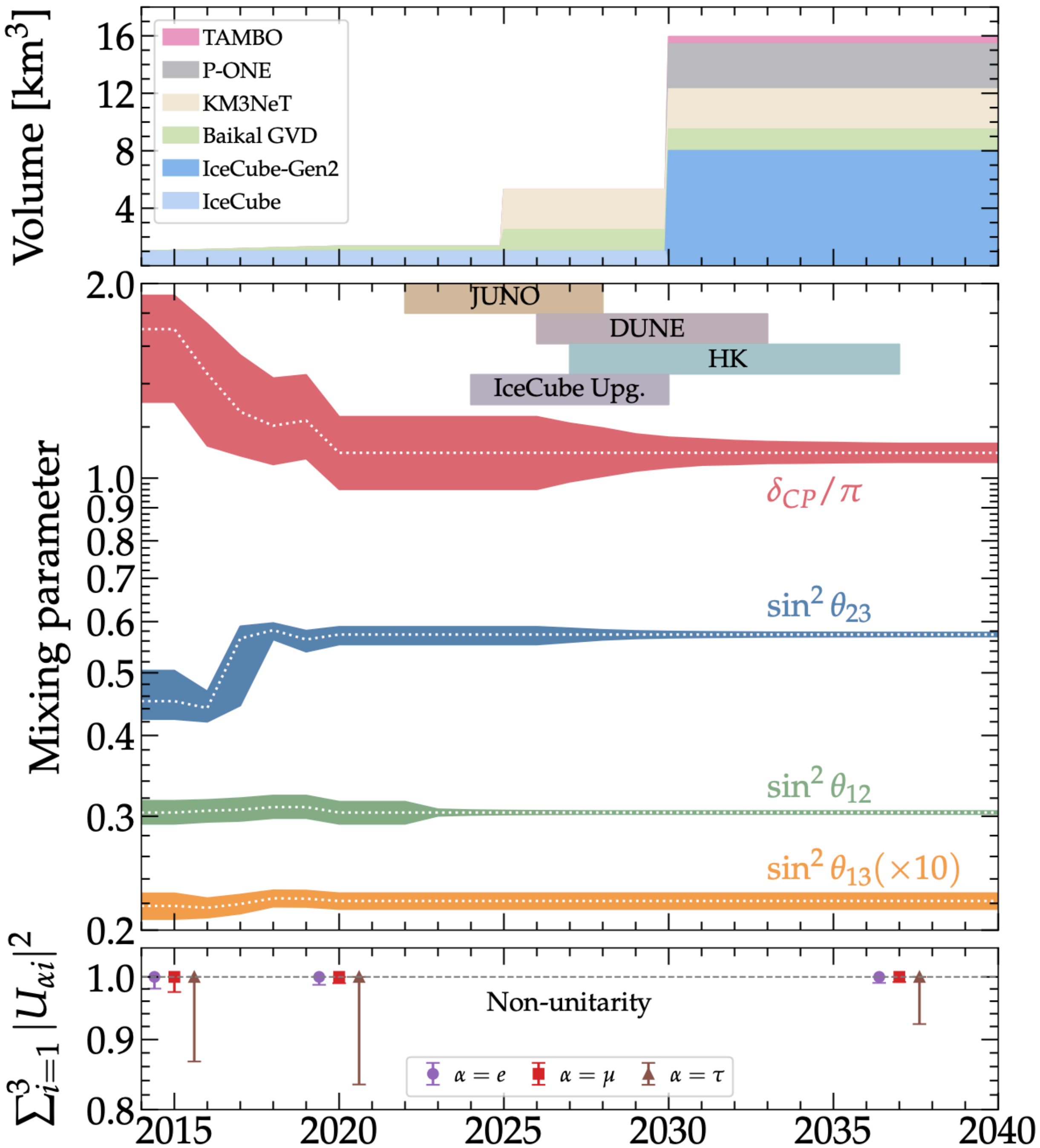


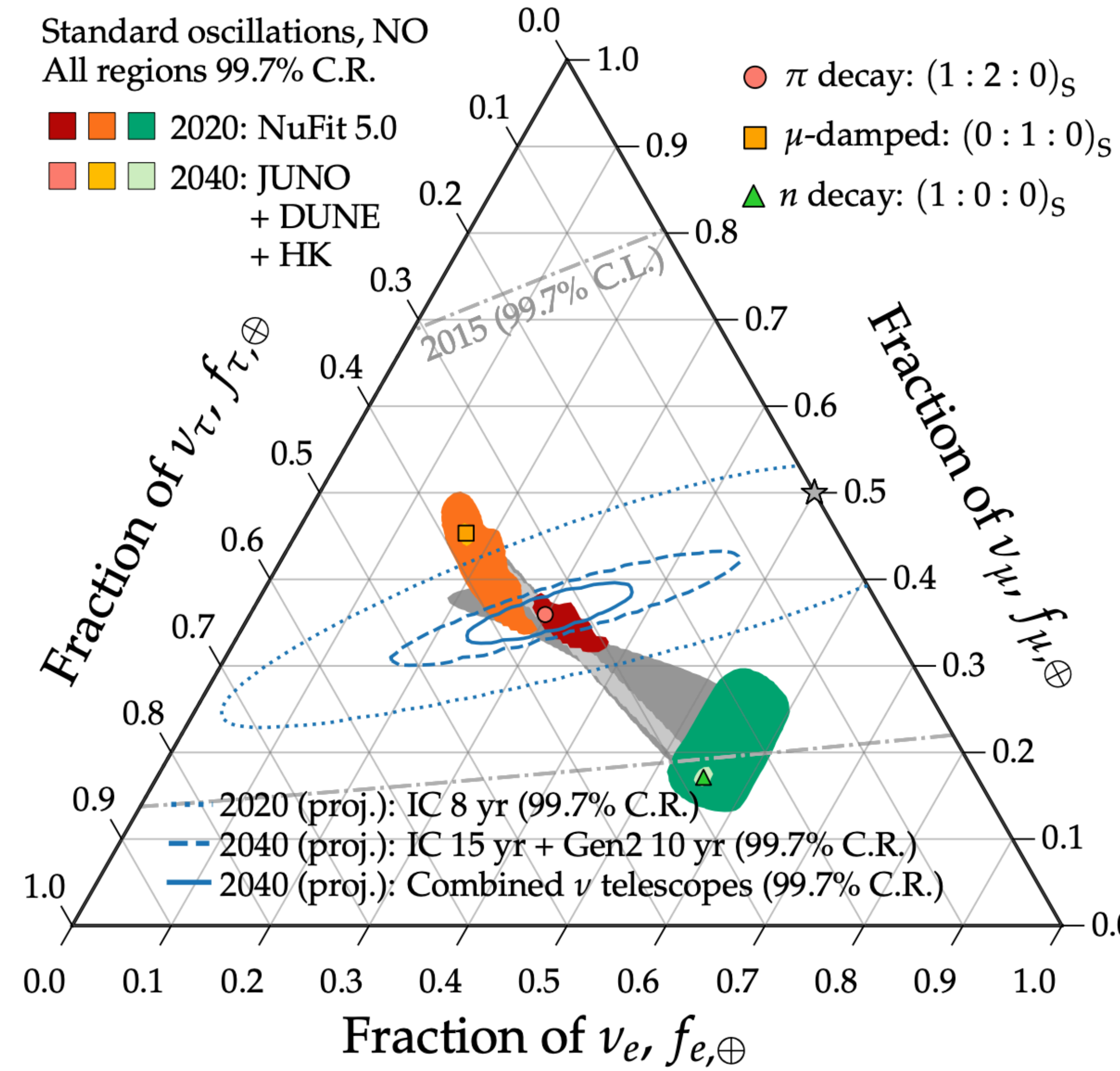
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

Romero-Wolf *et al* https://arxiv.org/abs/2002.06475

*TAMBO means house or inn in Quechua.

Projected Upgrade Flavor Measurement





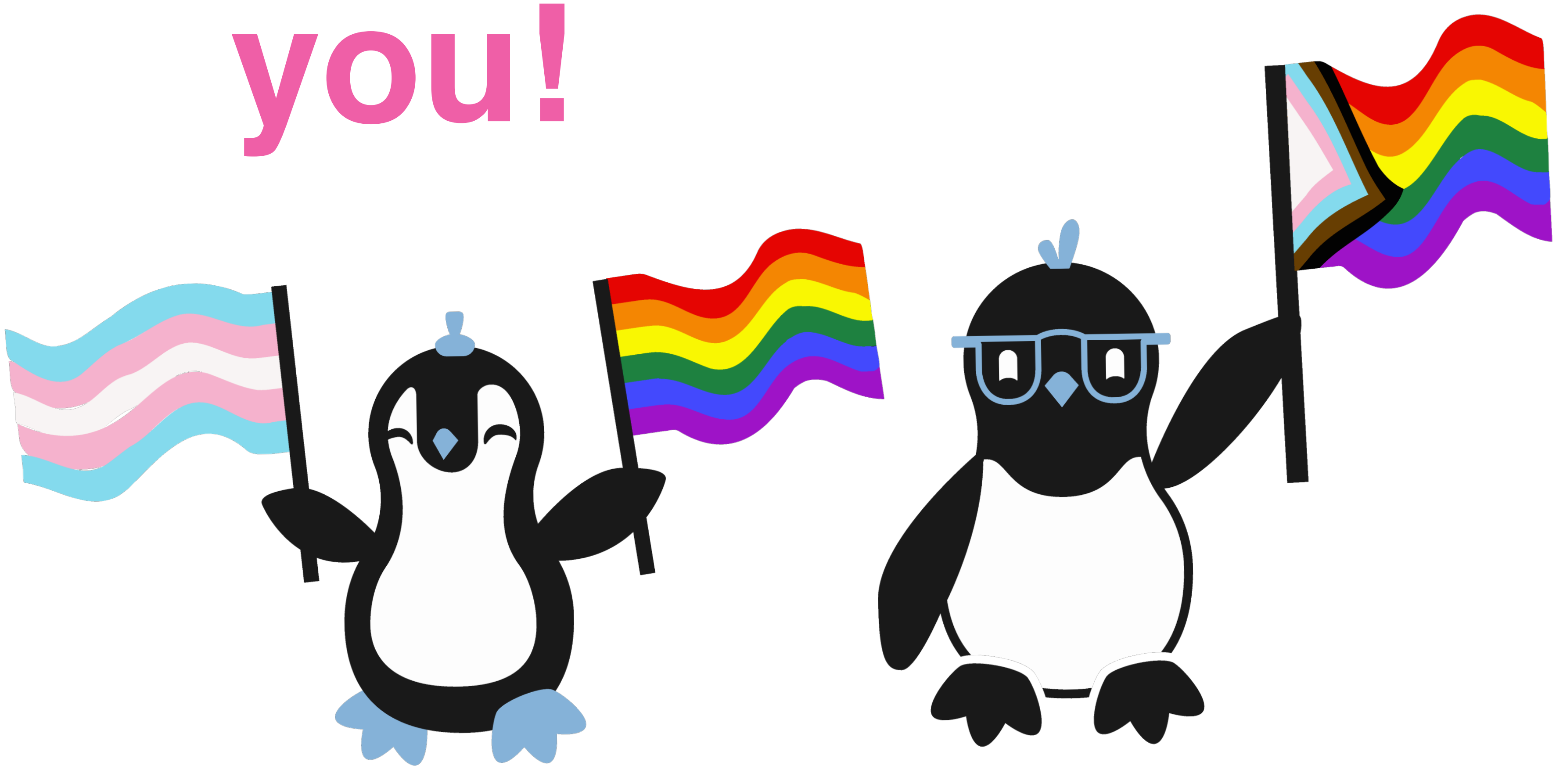
N. Song, S. Li, CA, M. Bustamante, A. Vincent (arXiv:2012.12893)

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.
- ❖The future is bright in neutrino telescopes: new detectors and technologies ahead!

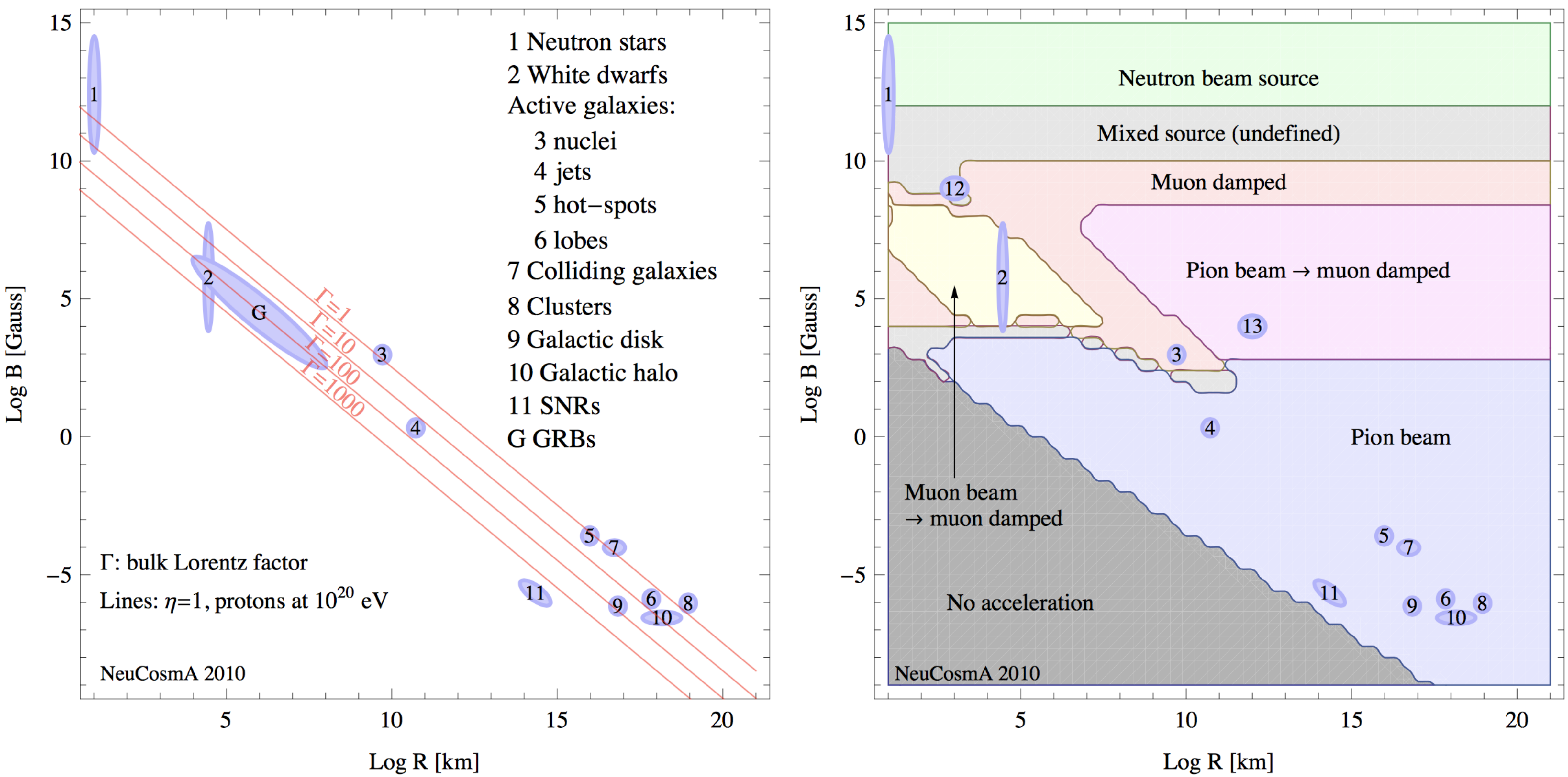
May your chosen trail lead you to new physics!

Thank you!



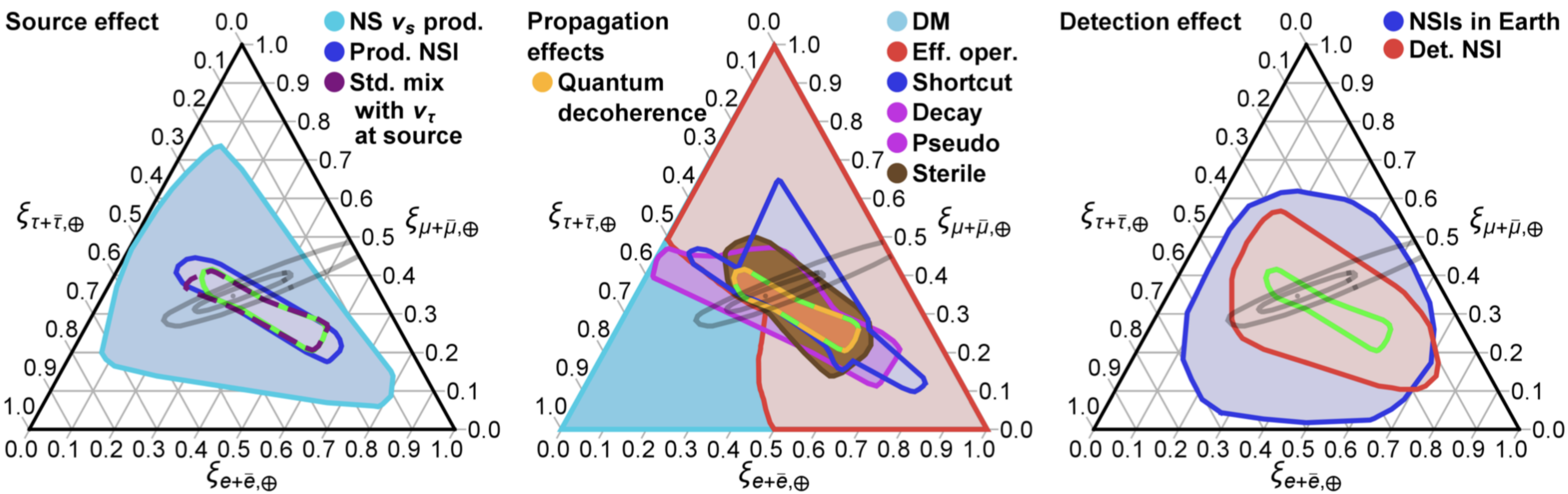
Bonus slides

Sources of Astrophysical Neutrinos



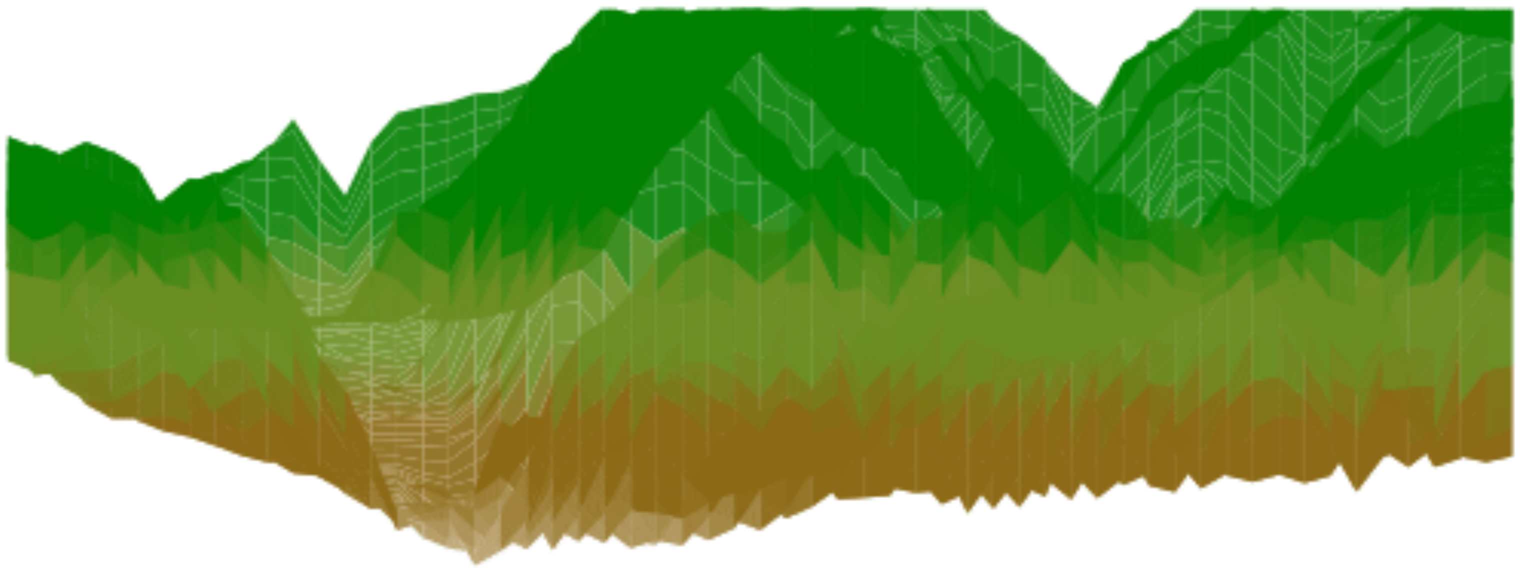
(arXiv:1007:0006)

New Physics In Astrophysical Neutrino Flavor



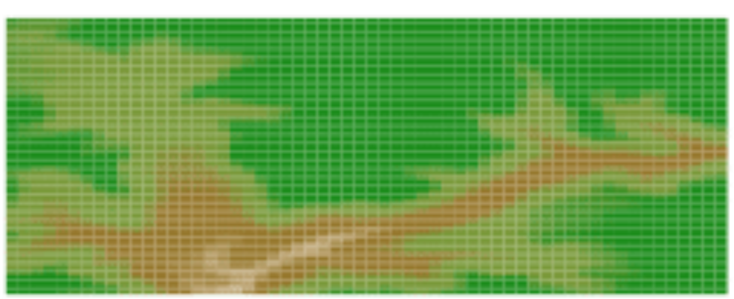
Rasmussen et al Phys. Rev. D 96, 083018 (2017) arXiv:1707.07684

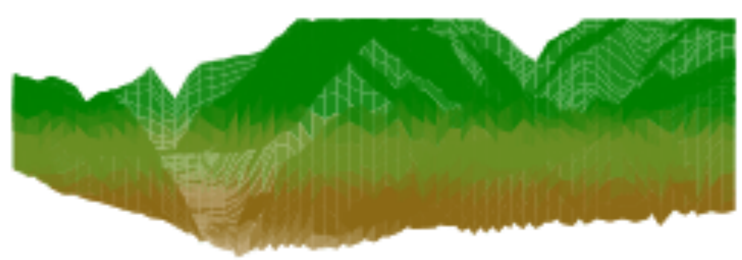
Currently working on simulation with detailed geography of the Colca valley



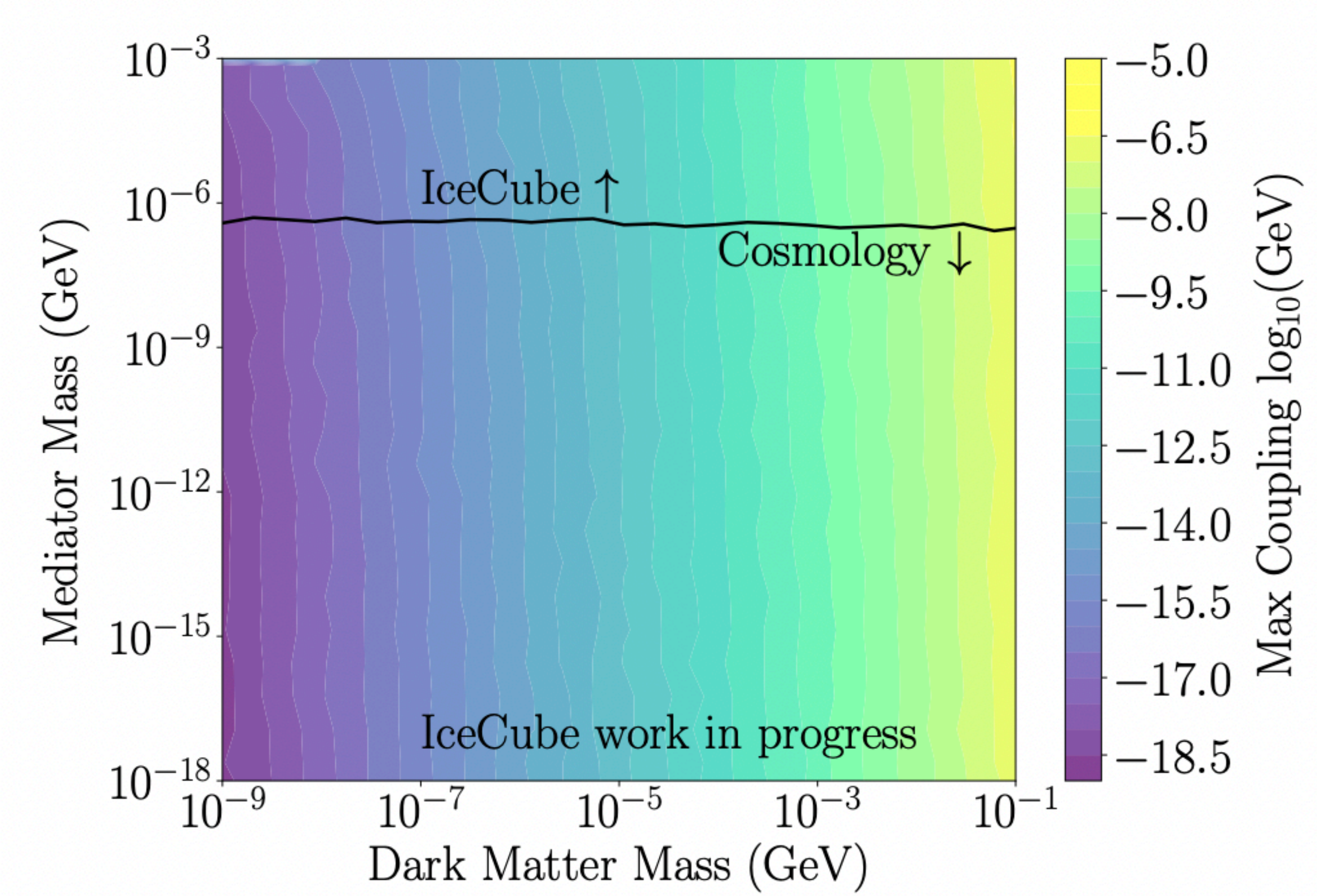
TAURUNNER

- Initial simulation of ν_τ in Colca valley is complete
- Working on connecting to CORSIKA to simulate air shower
- TauRunner will serve as neutrino injector
- All being written in Julia

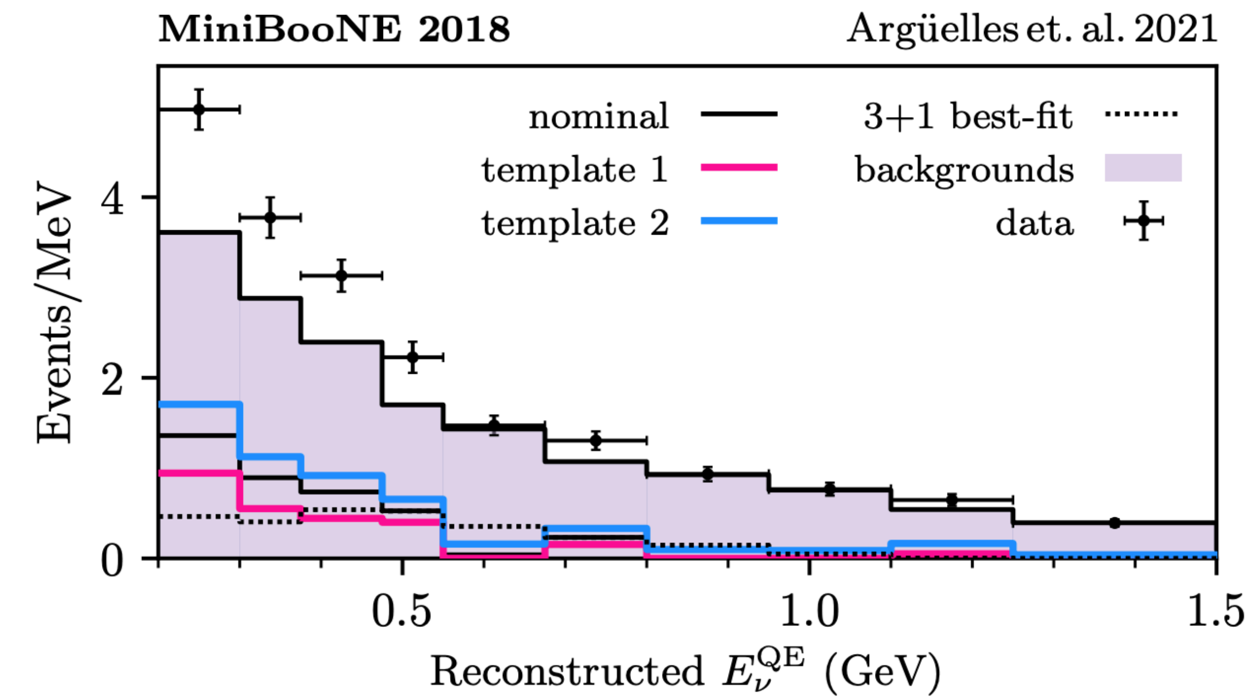


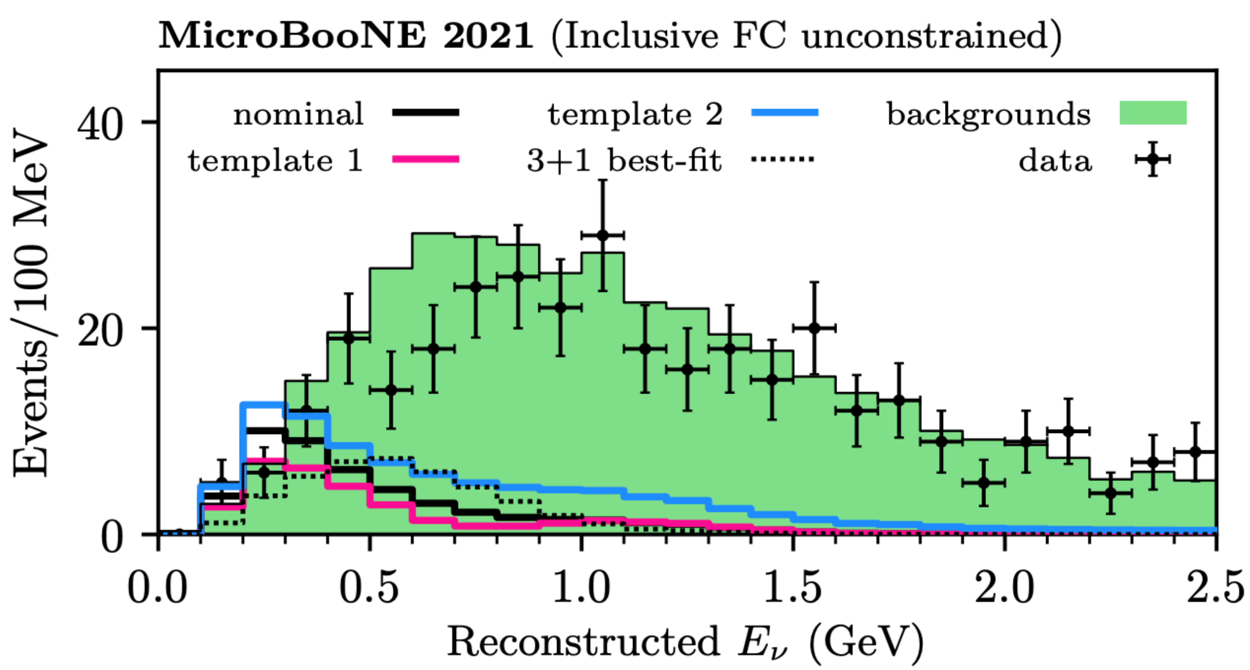


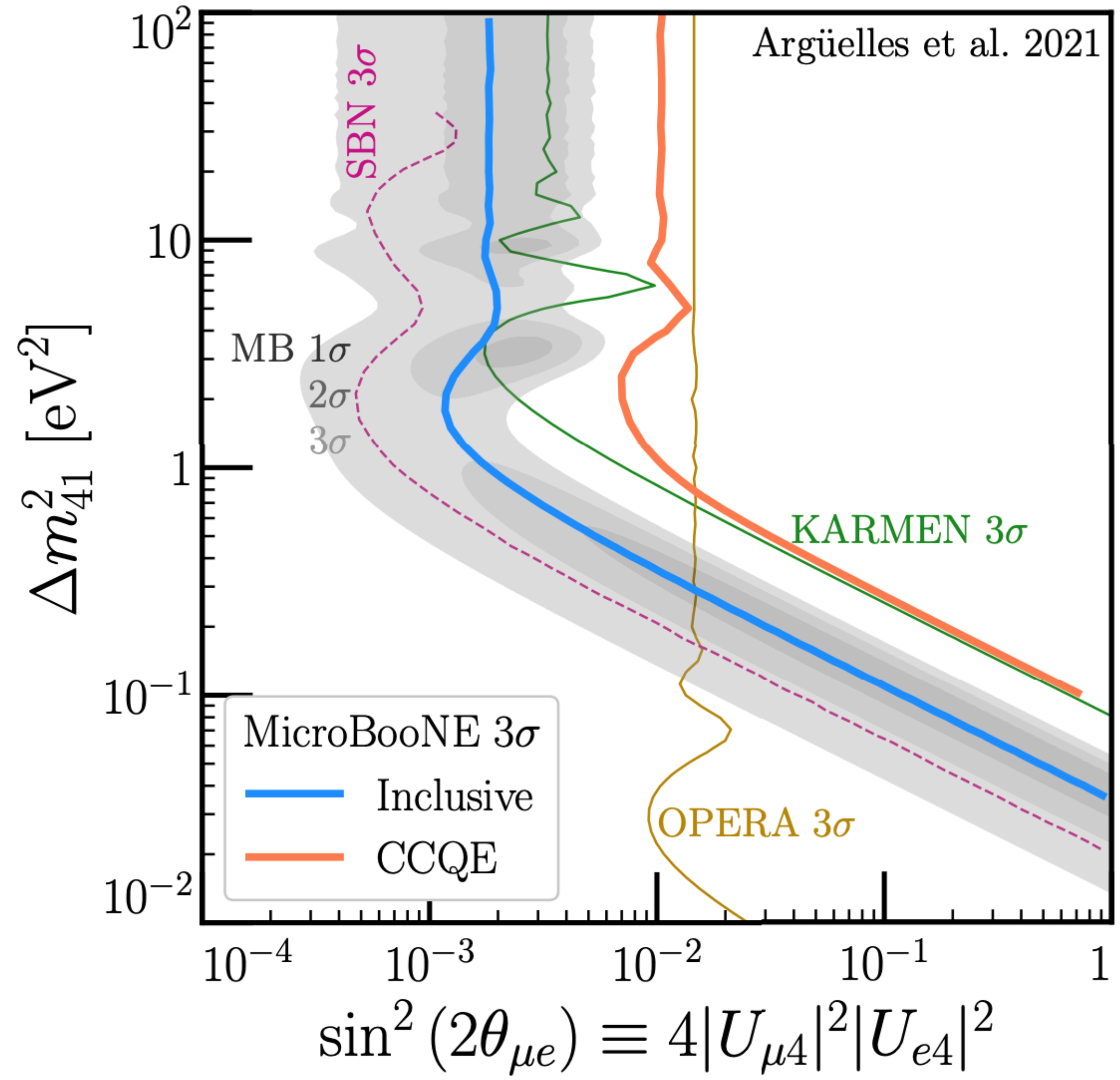
Second Generation Analyses Using Medium-Energy Starting Events



Constraints from $\nu_\mu \to \nu_e / \nu_e \to \nu_e$ searches on 3+1 with MicroBooNE?







MicroBooNE collaboration arXiv:2110.14054,2110.13978,2110.14080

CA, I. Esteban, M. Hostert, K.J. Kelly, J. Kopp, P.A.N. Machado, I. Martinez-Soler, Y. F. Perez-Gonzalez, arXiv:2111.10359