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High-Energy Neutrinos as Probes of New Physics

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Pennsylvania State University

Connecting high-energy astroparticle physics for origins of cosmic rays & future perspectives

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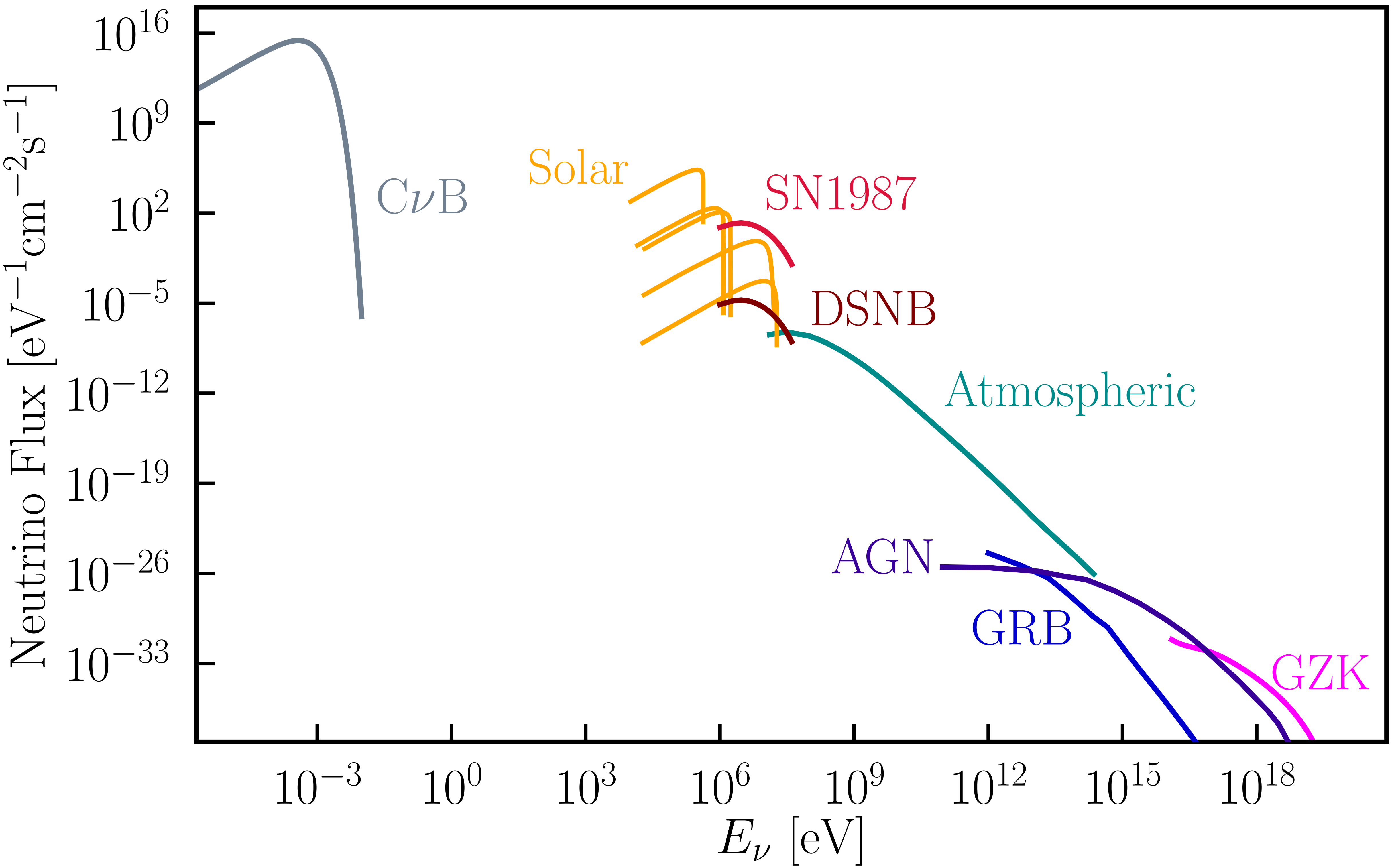
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, Japan

The Universe in Neutrinos



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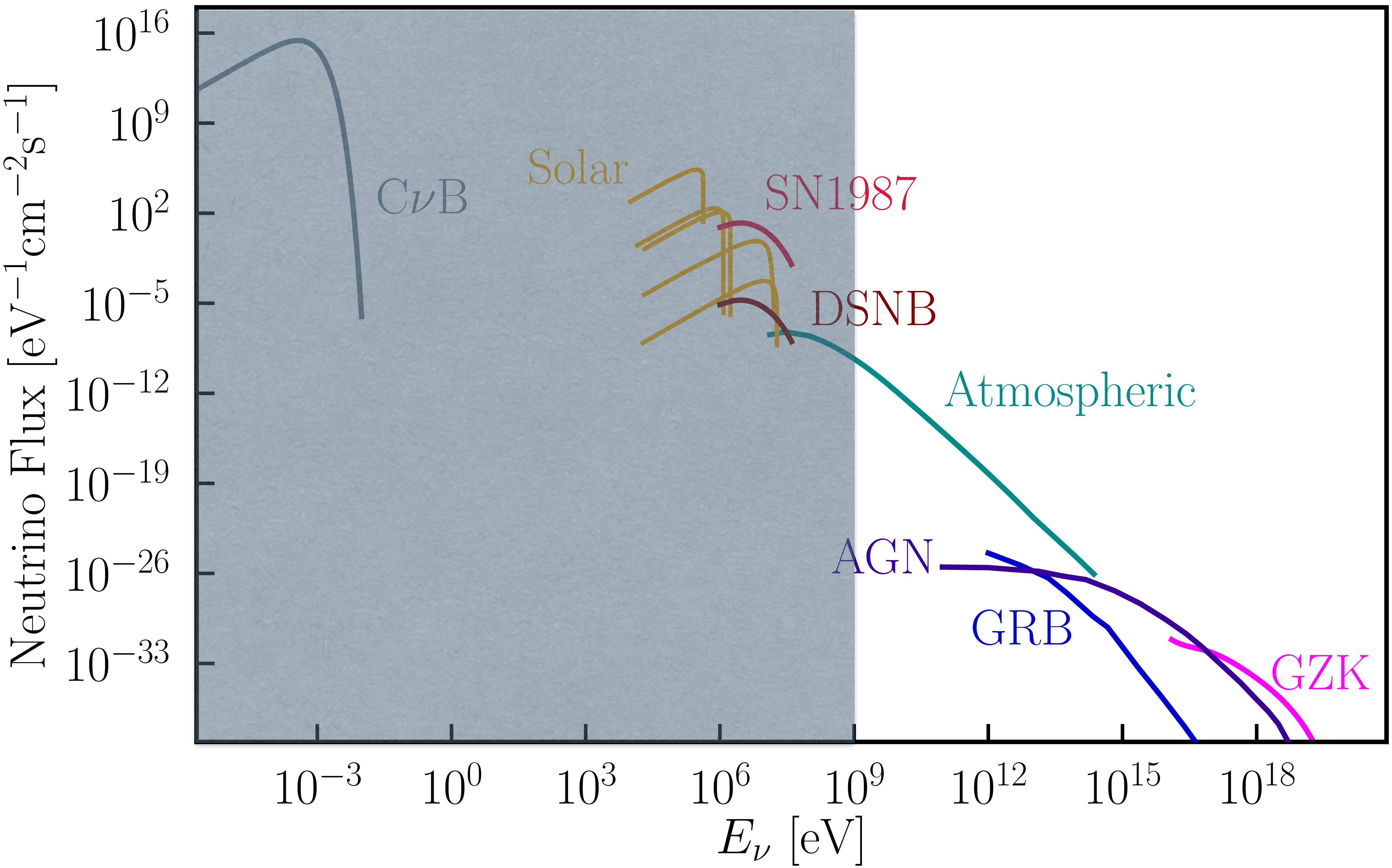

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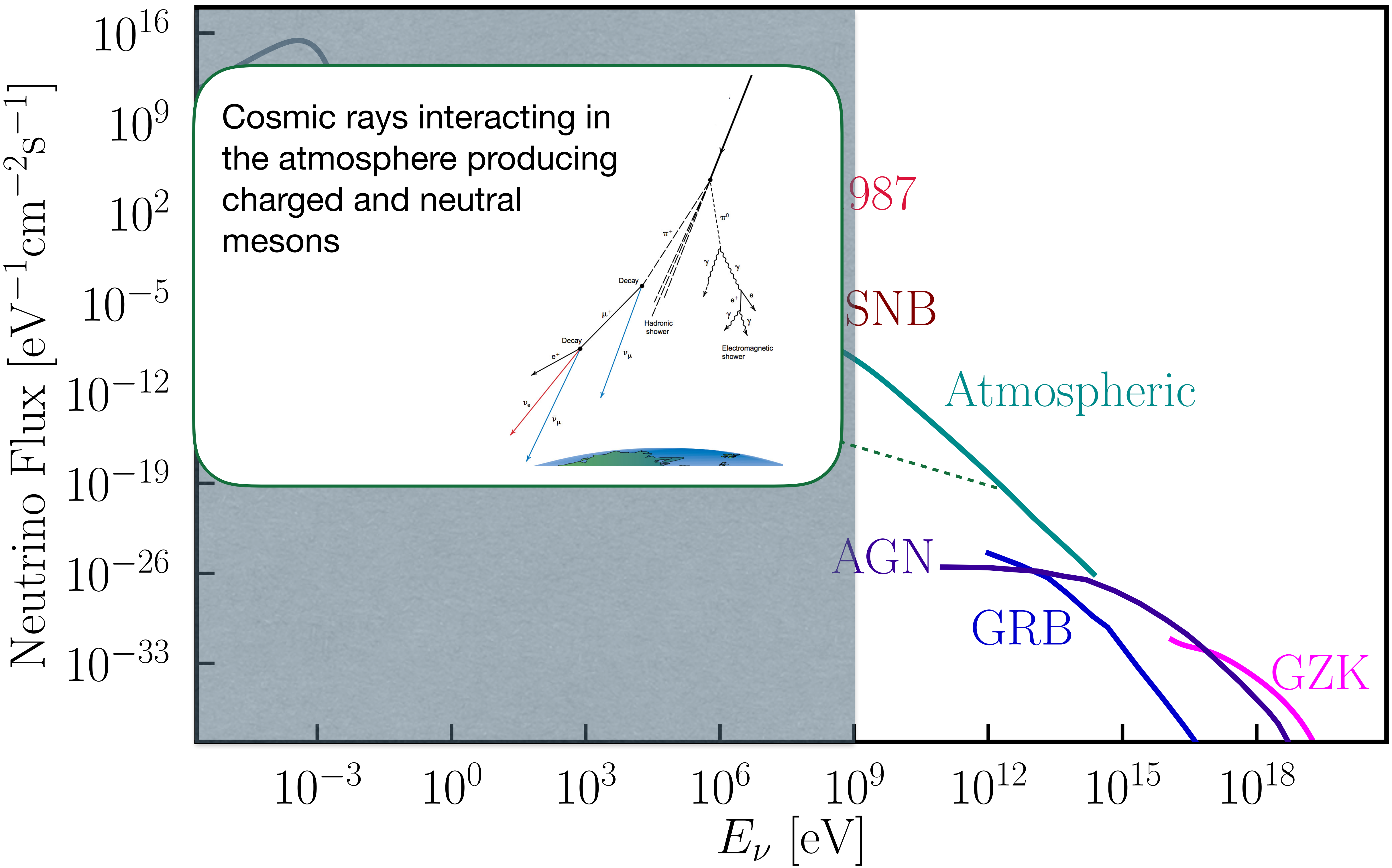

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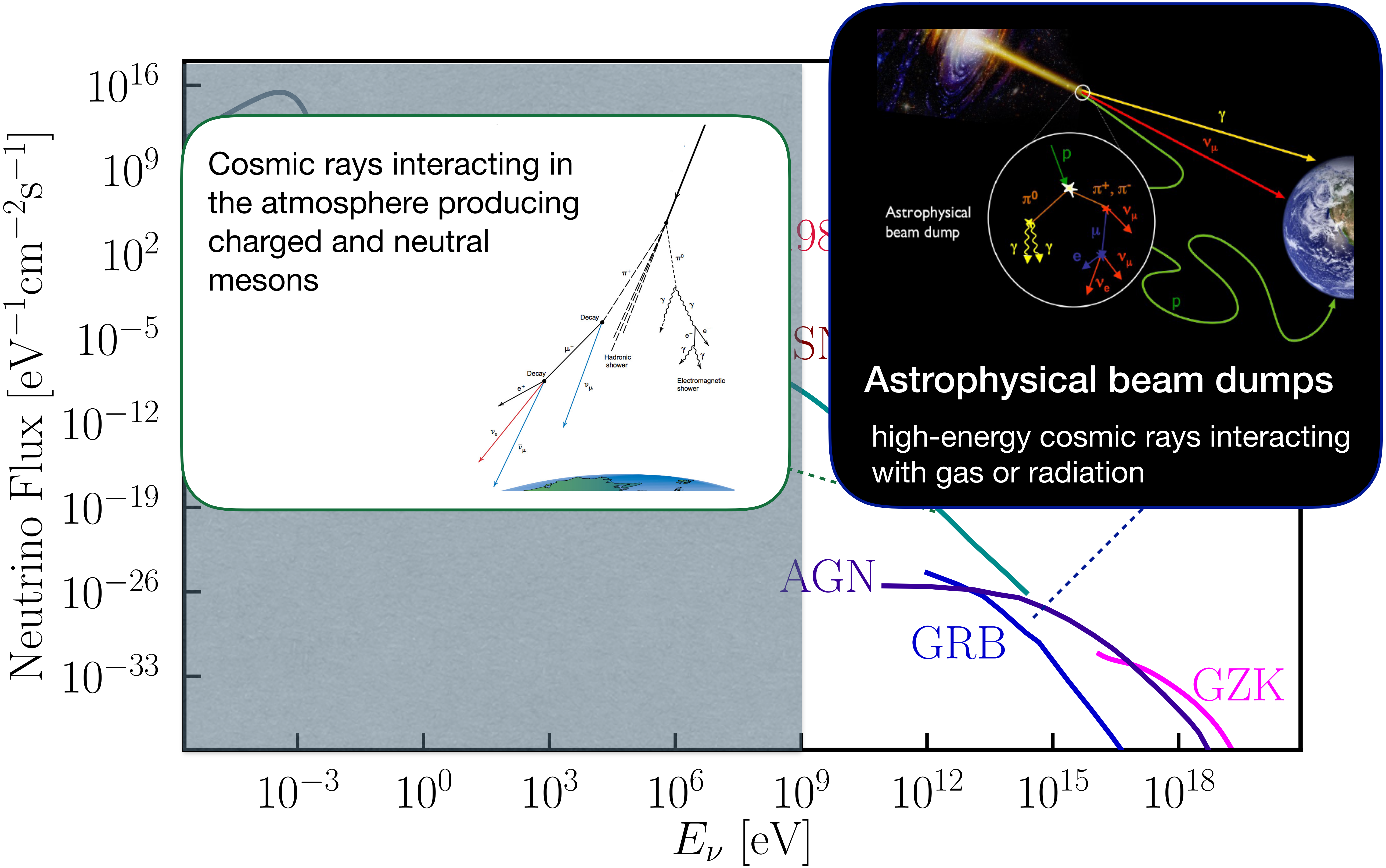

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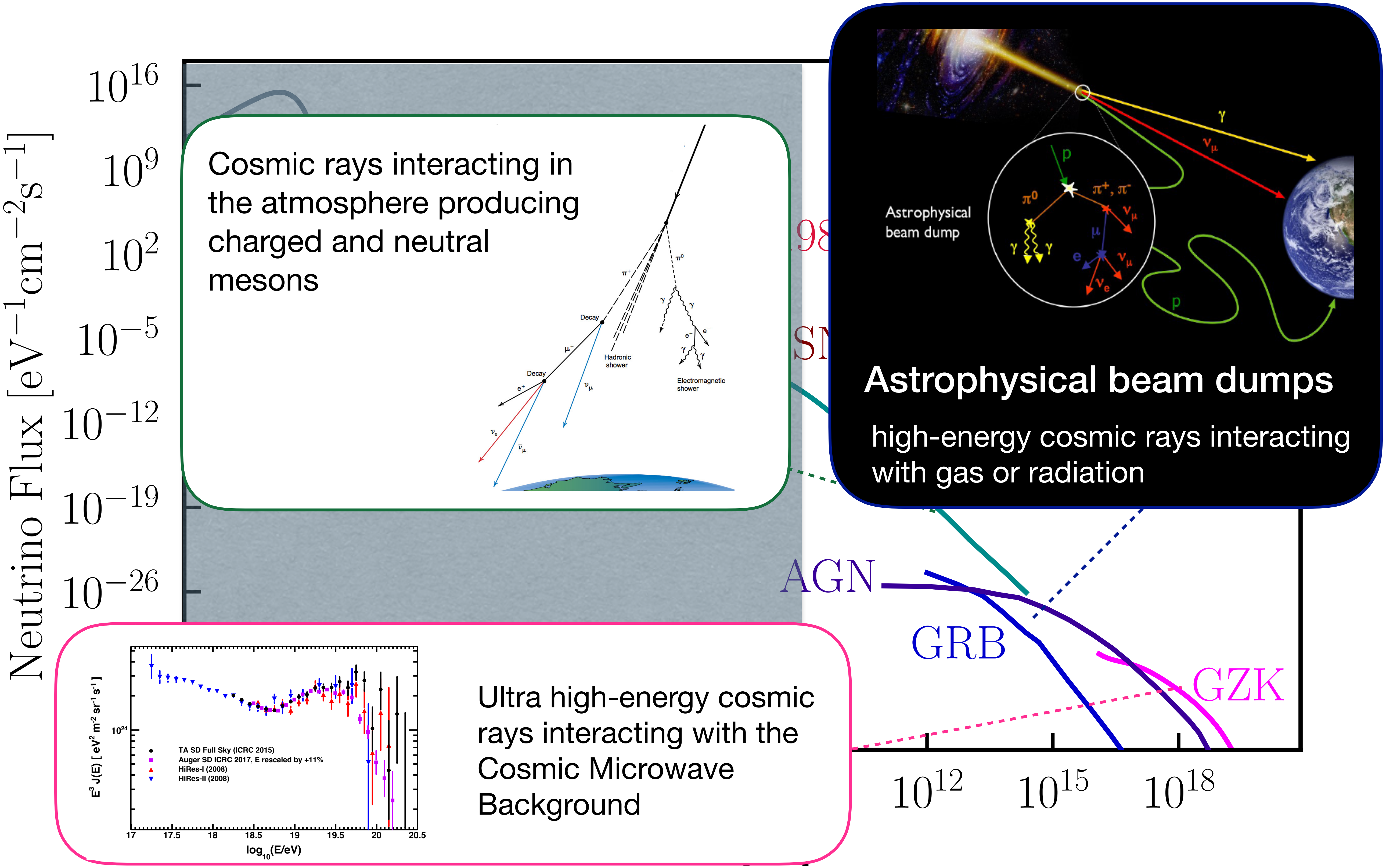

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5. It comes *for free* from natural sources

High-Energy Neutrino Observables

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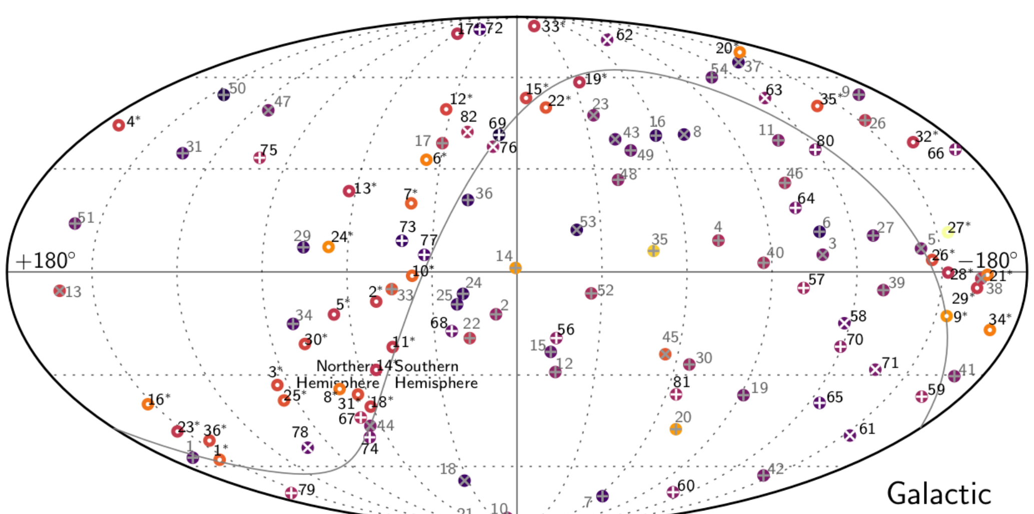
Direction & Time



IceCube Preliminary

High-Energy Neutrino Observables

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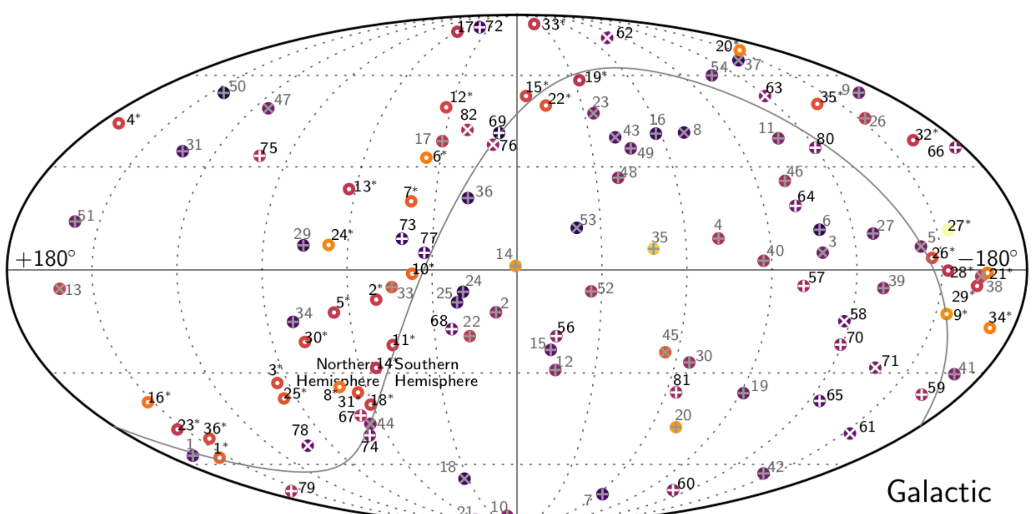

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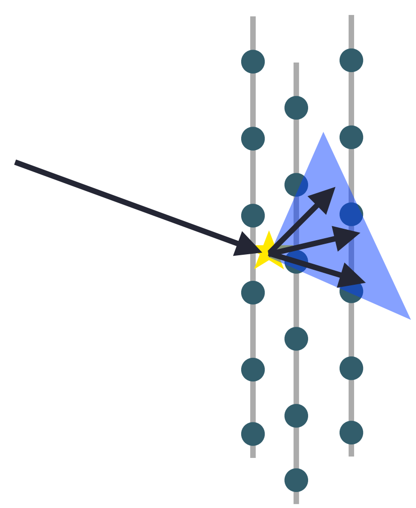
Neutrino energy

Deposited EM-equivalent



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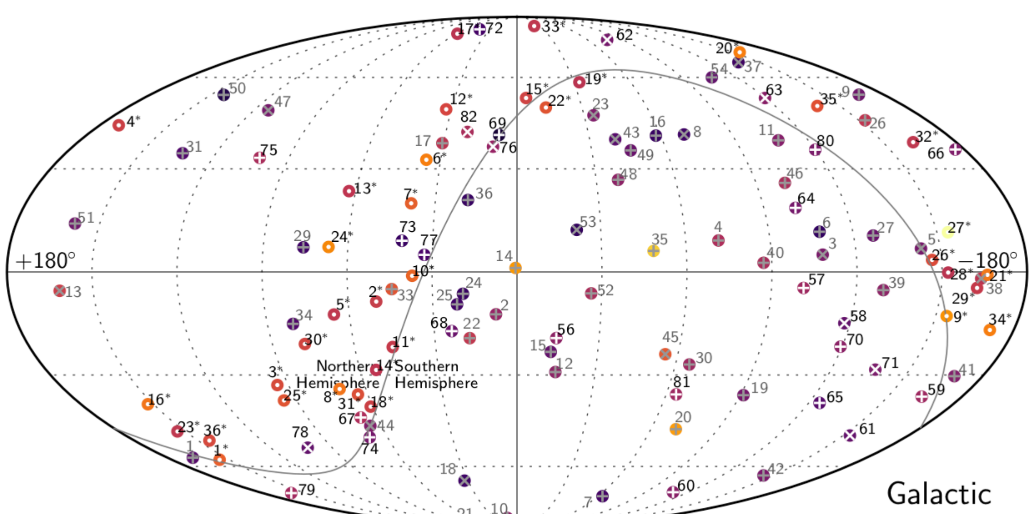

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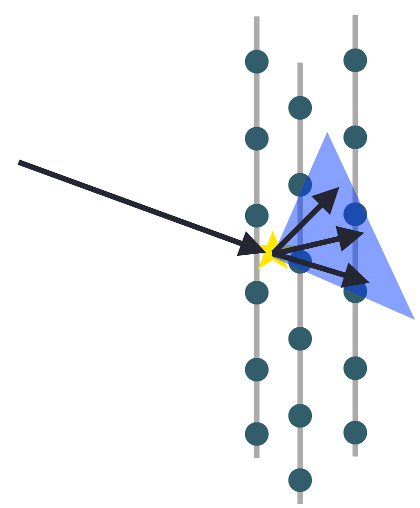
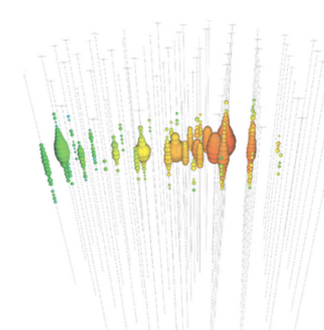
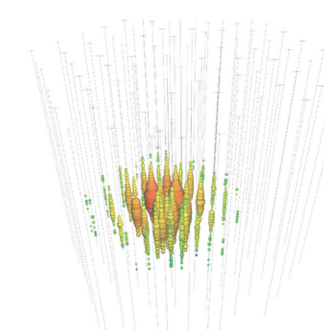


Flavour (e, μ, τ)

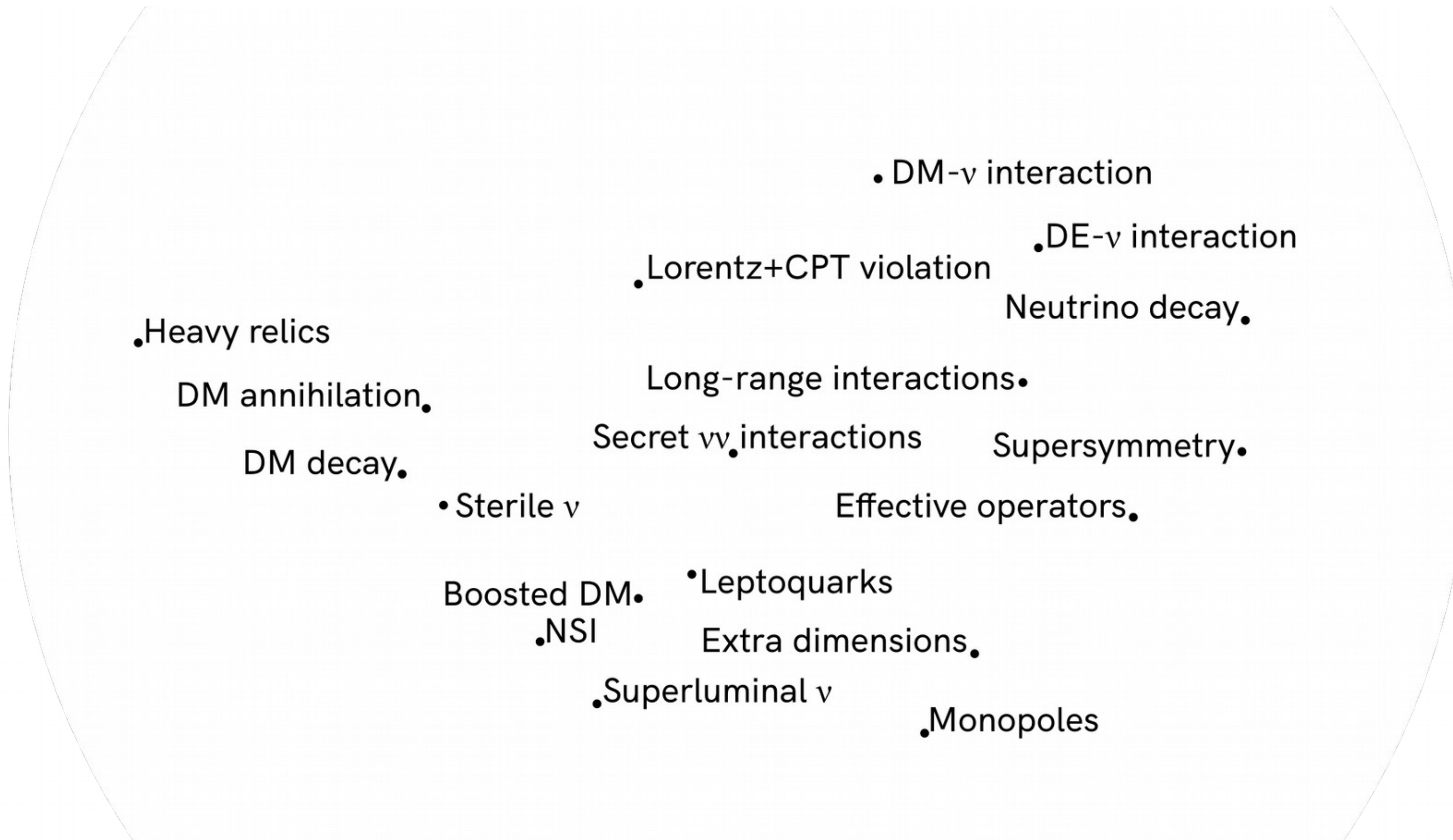
Topology



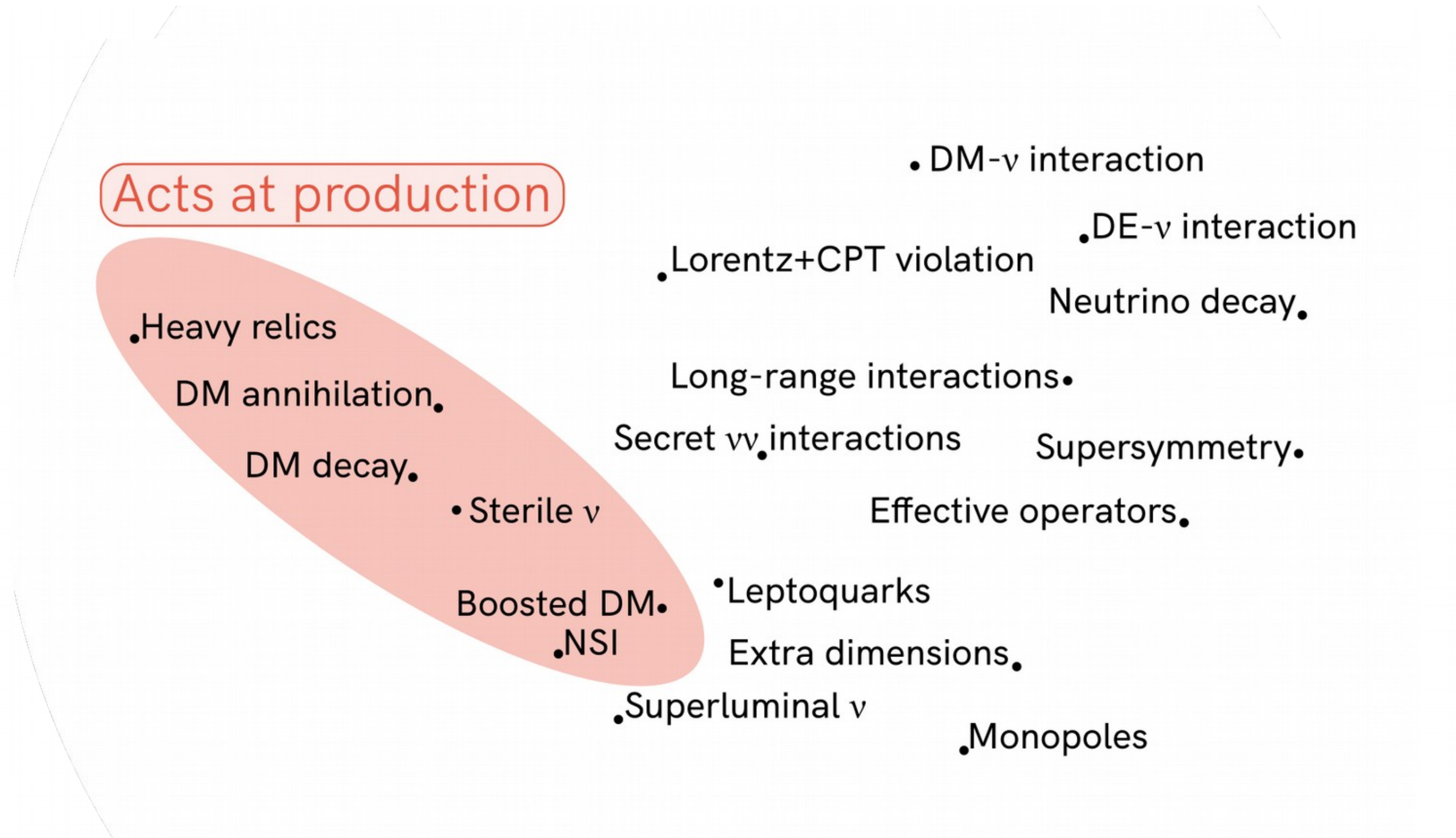
muon track



shower



Argüelles, Bustamante, **AK,** Palomares-Ruis, Vincent, 2019



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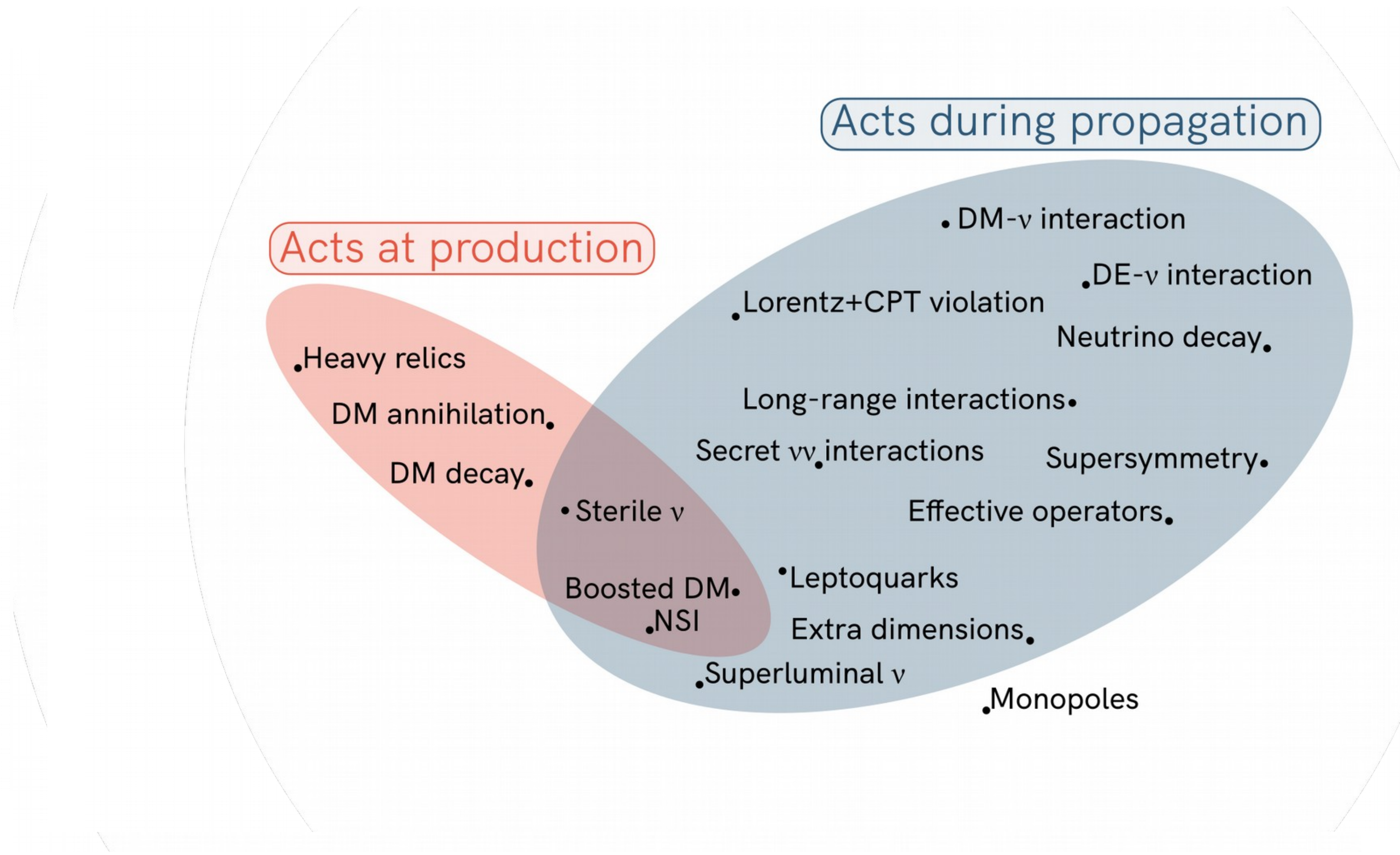

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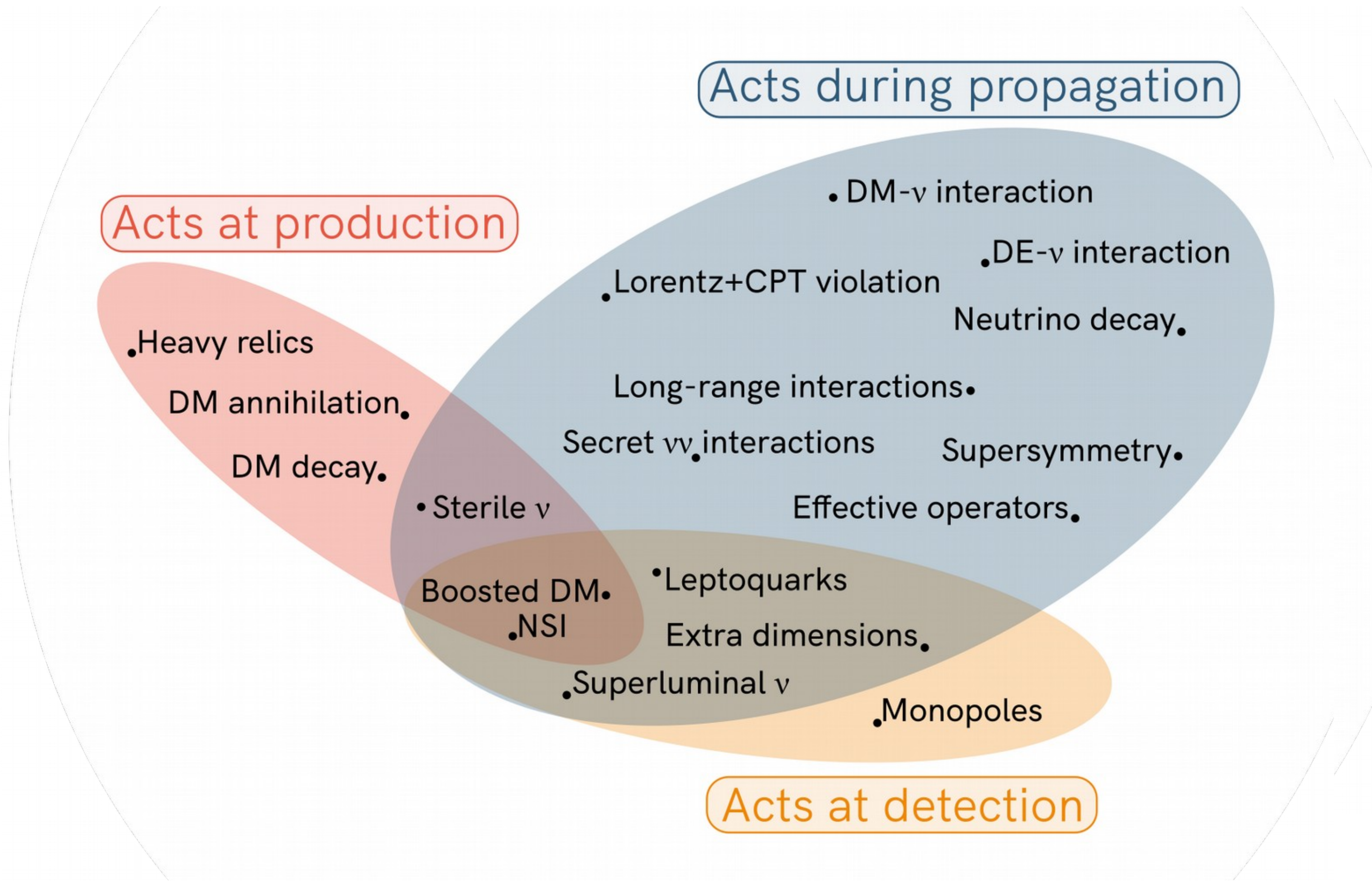

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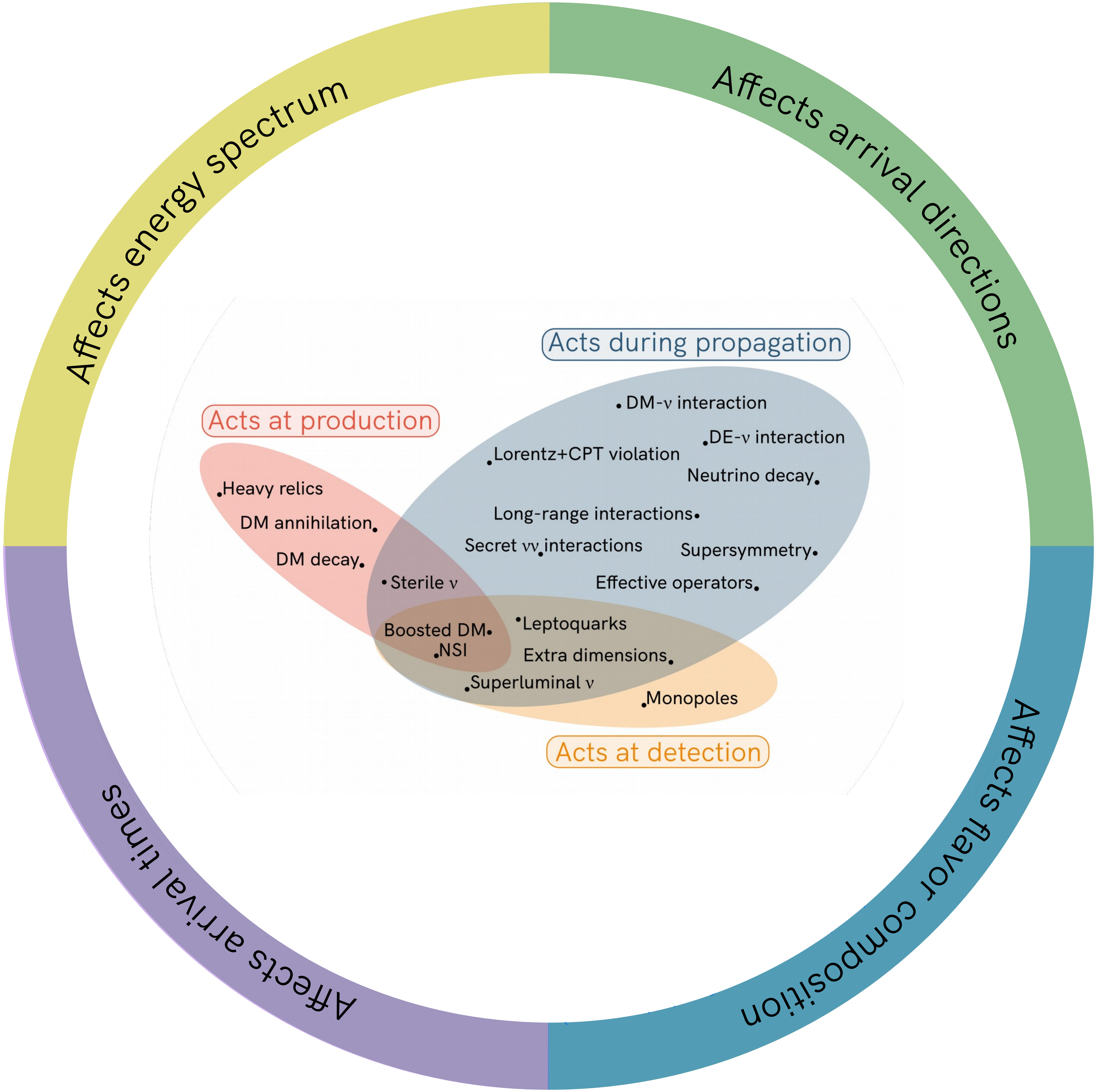

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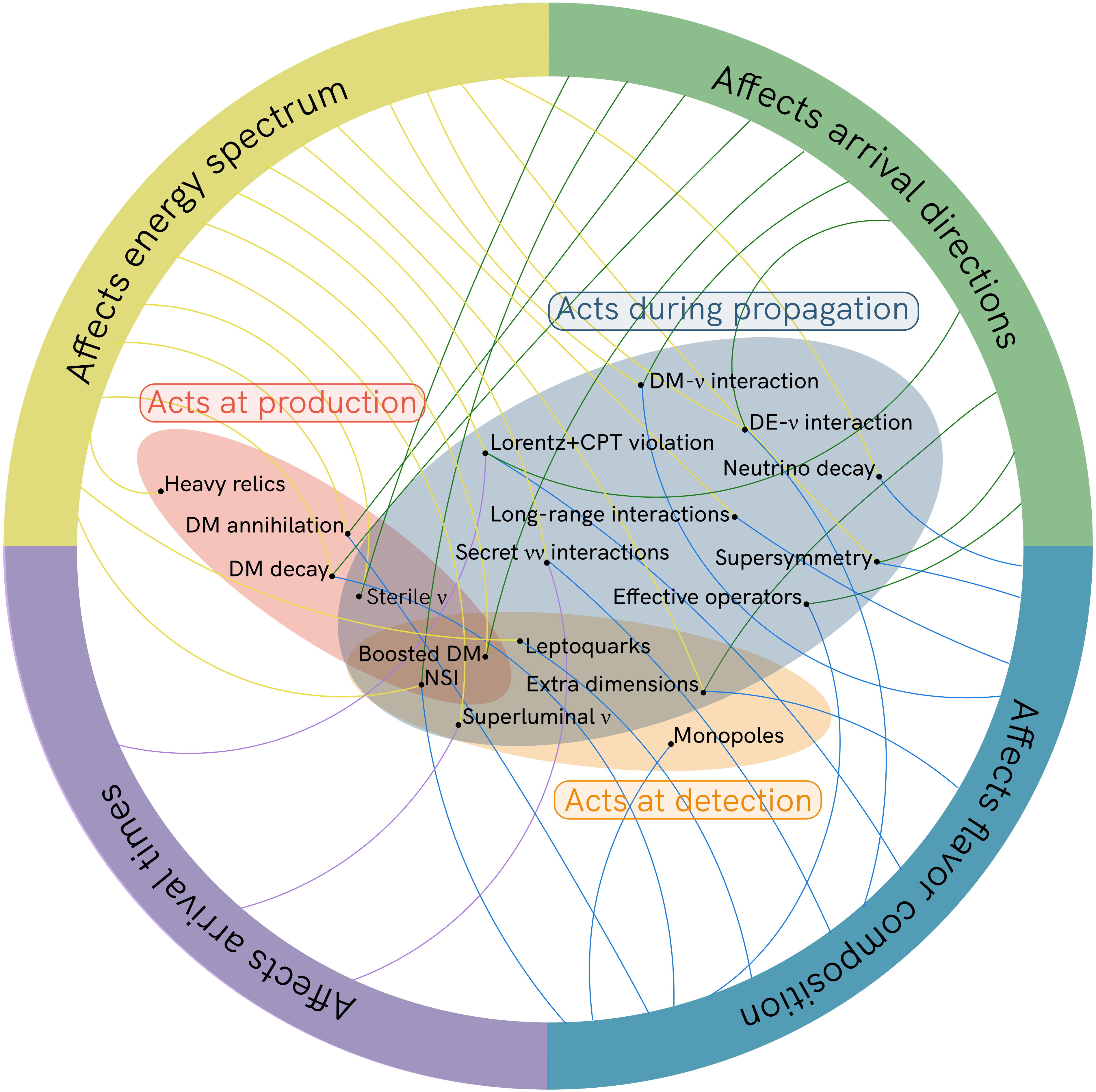

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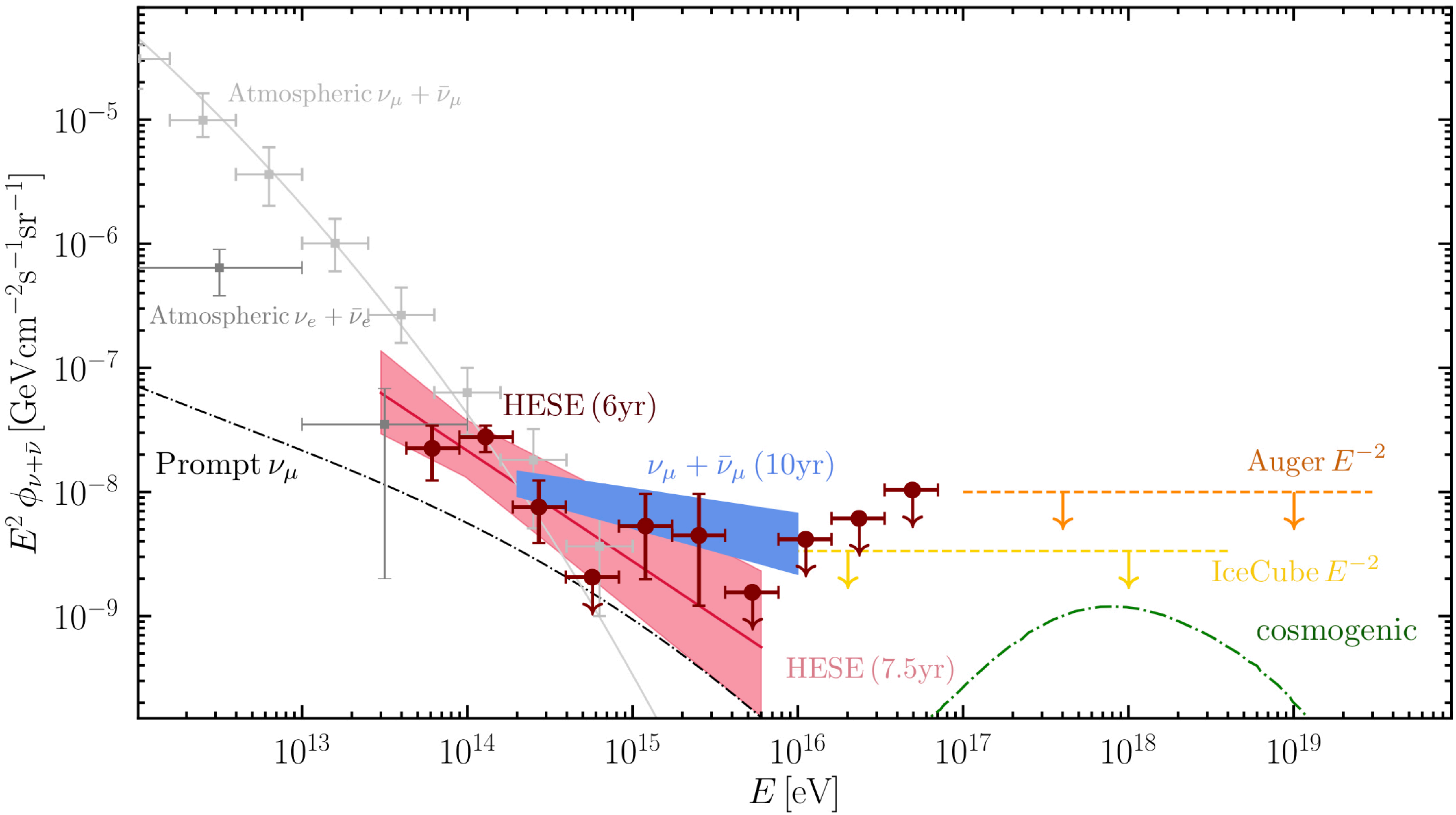
New Physics Search with HE Neutrinos

Where it happens

What it changes

	At source	During propagation
Energy		Lorentz violation
Direction	DM annihilation, DM-ν interaction	New ν-N, DM-ν interactions, Lorentz violation
Topology / flavor	DM-ν interaction	DM-ν interaction, Lorentz violation
Time		Lorentz violation, Neutrino echoes

High-Energy Neutrino Flux



Features in high-energy neutrino flux can reveal new physics phenomena.
The upper limits on yet to be seen fluxes impose limits on BSM scenarios.

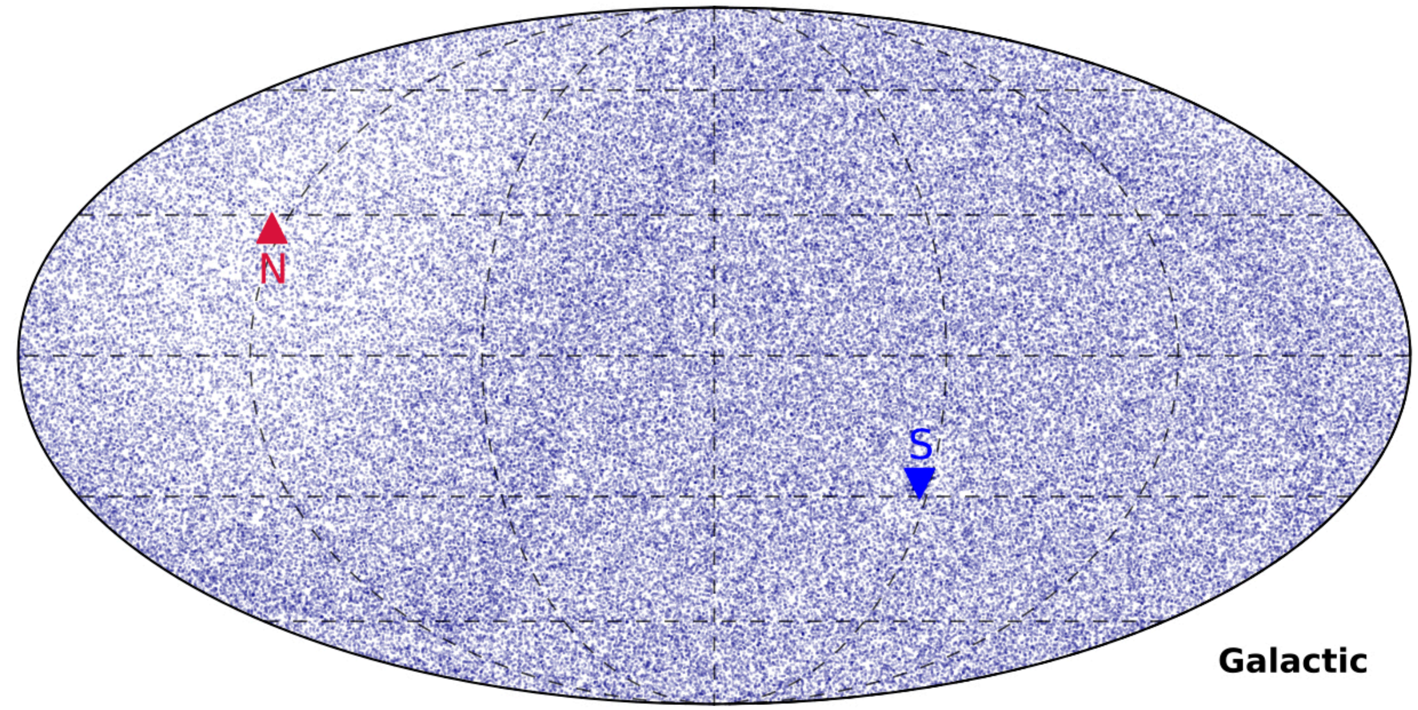
Spatial Distribution

The spatial and temporal distribution of high-energy neutrinos offer opportunities for BSM searches.

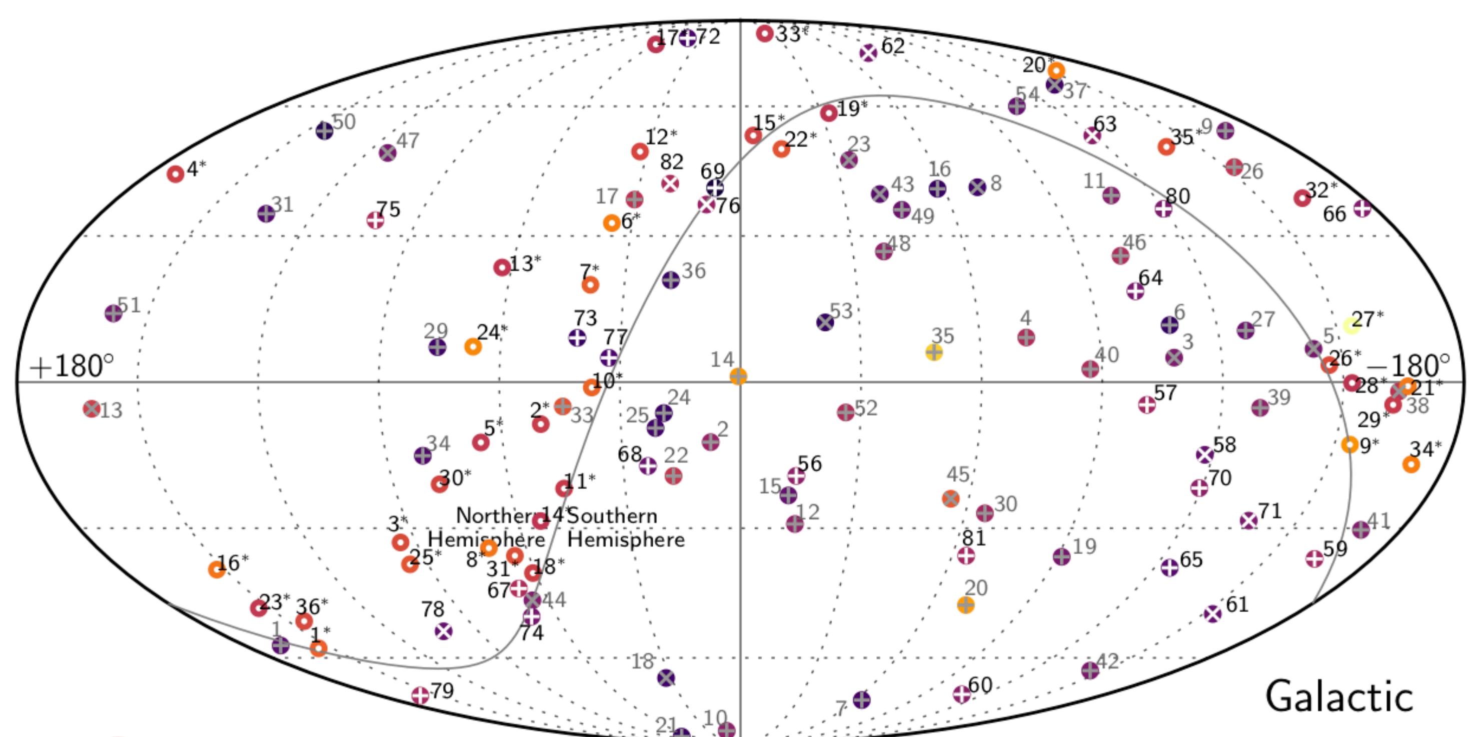
The atmospheric flux is expected to be isotropic.

In an extragalactic isotropic distribution of cosmic neutrinos, BSM scenarios can create altered spatial distribution.

Identification of sources of high-energy cosmic neutrinos, especially transients, offers opportunity of searching for time-induced BSM features.



138322 neutrino candidates in one year
dominated by atmospheric flux



IceCube Preliminary

Arrival Direction of the Highest Energy Neutrinos

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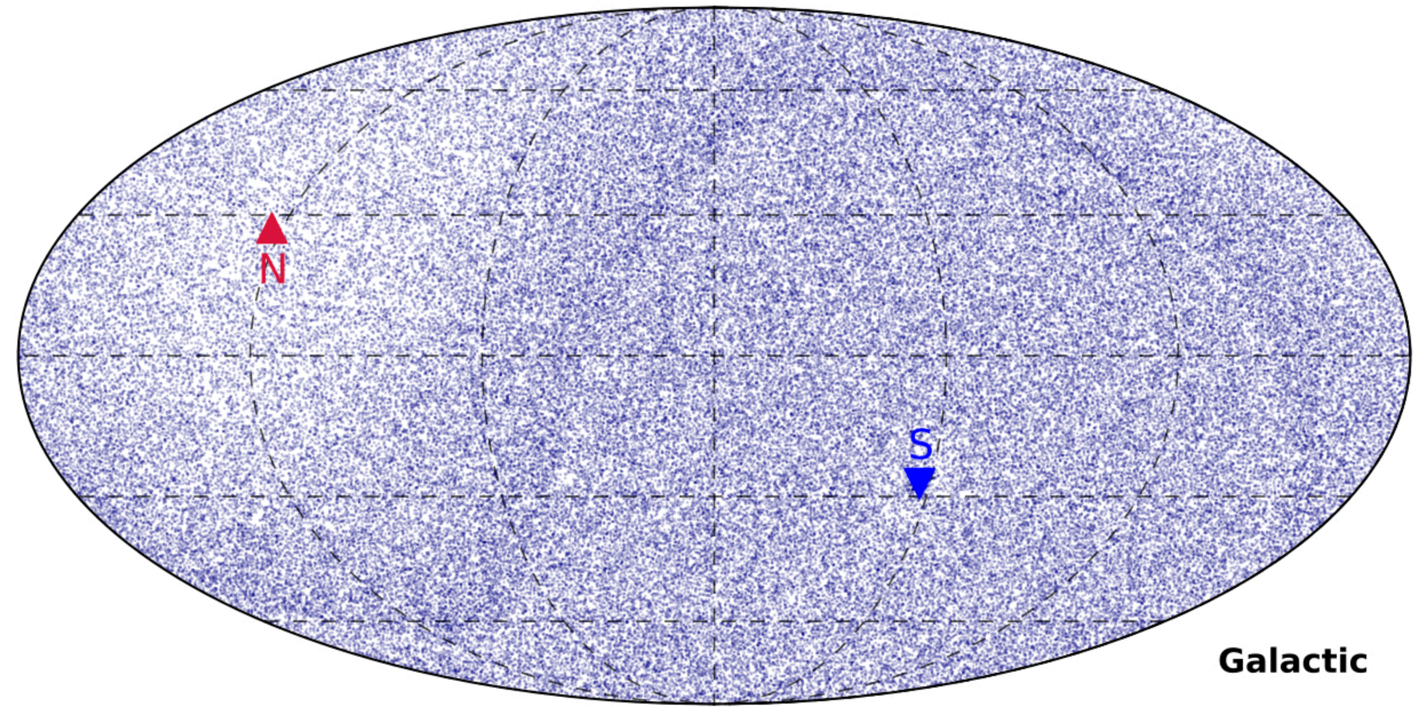

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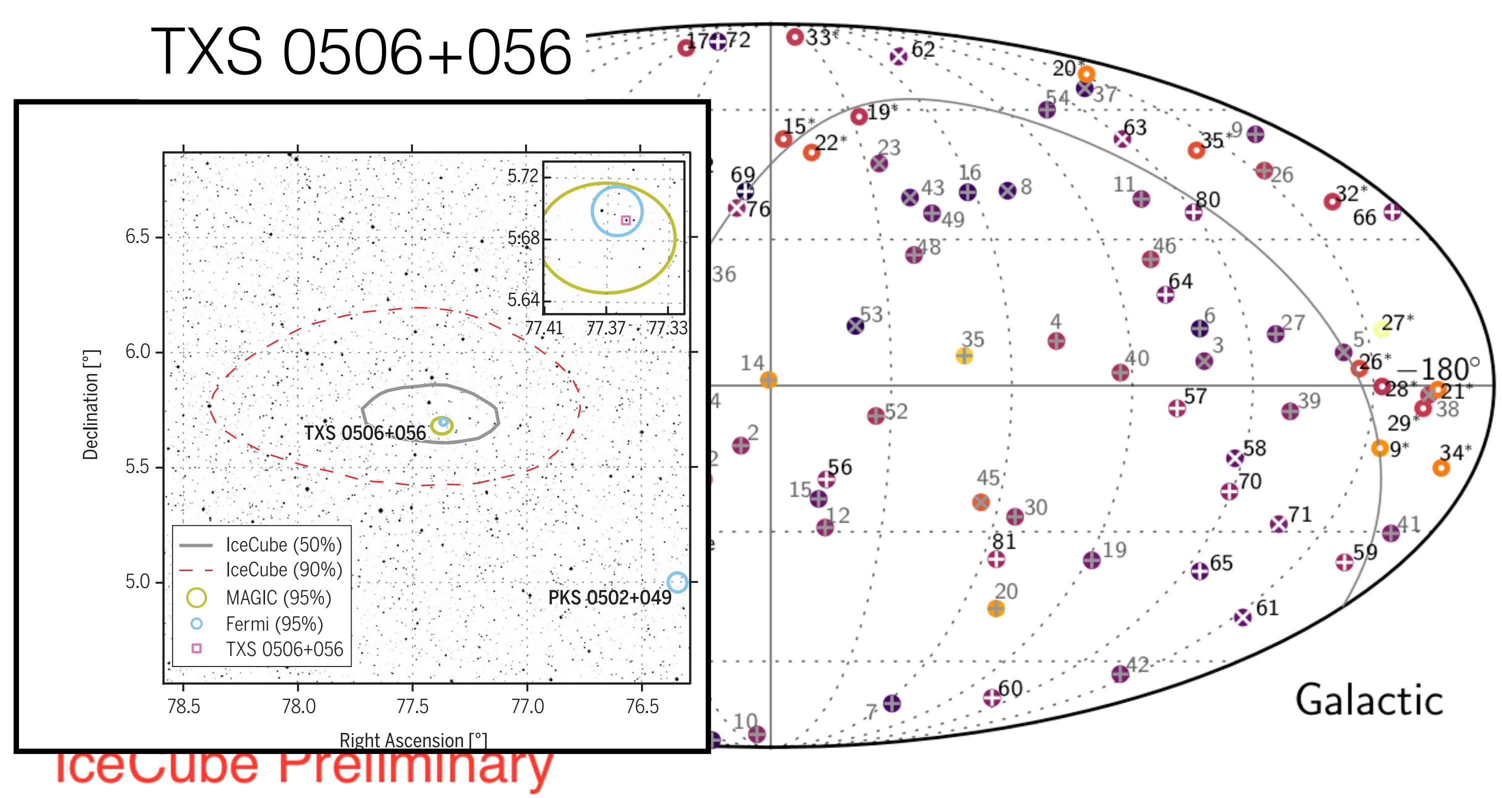

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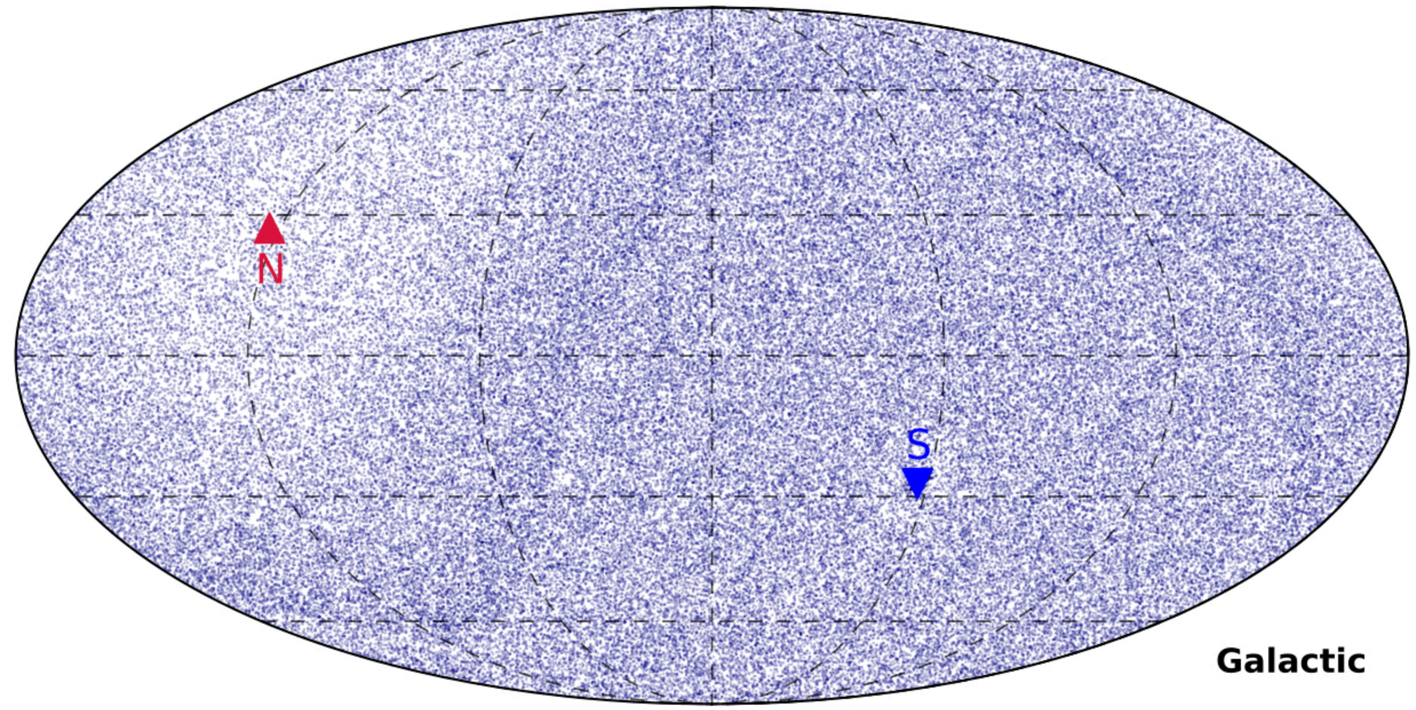

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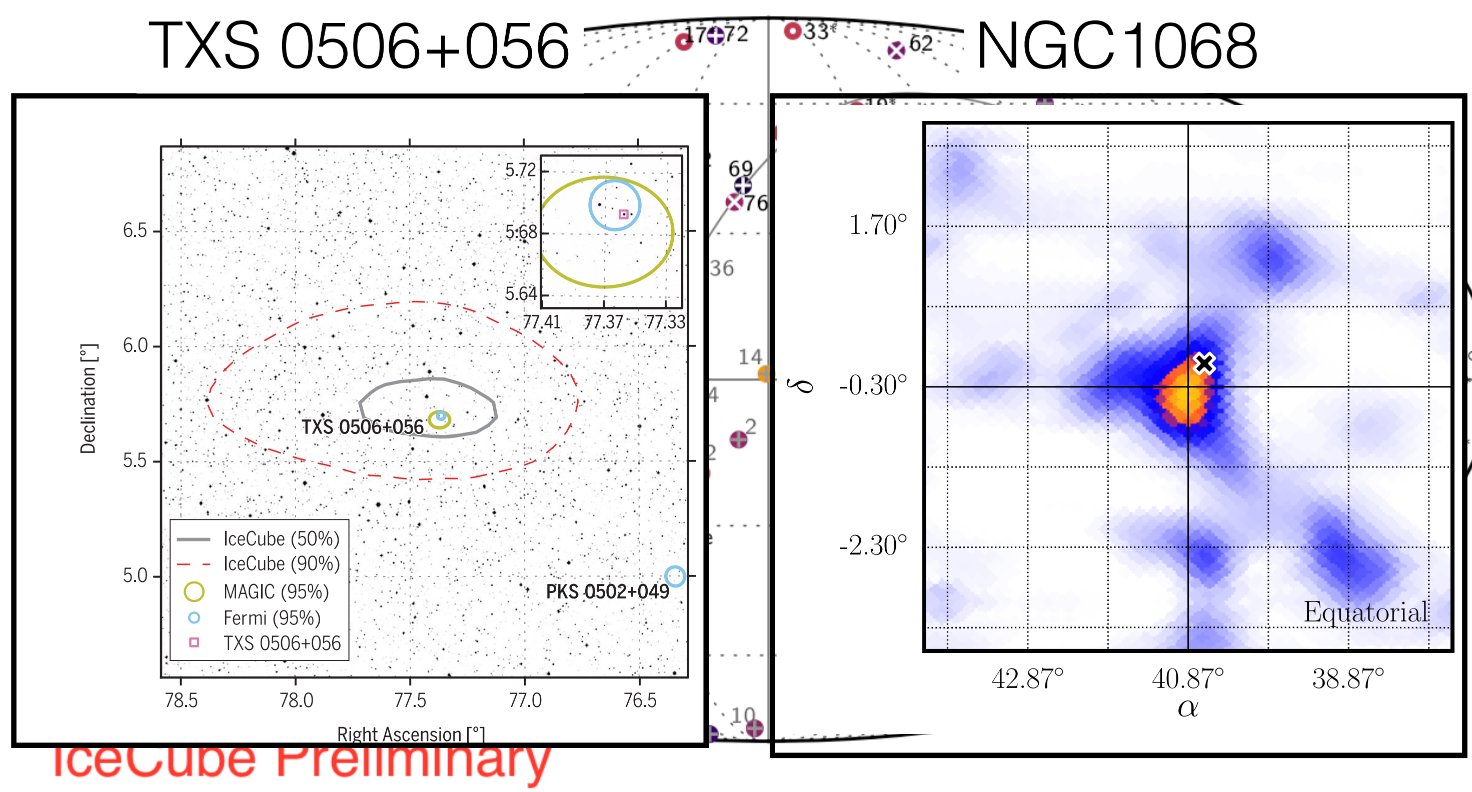
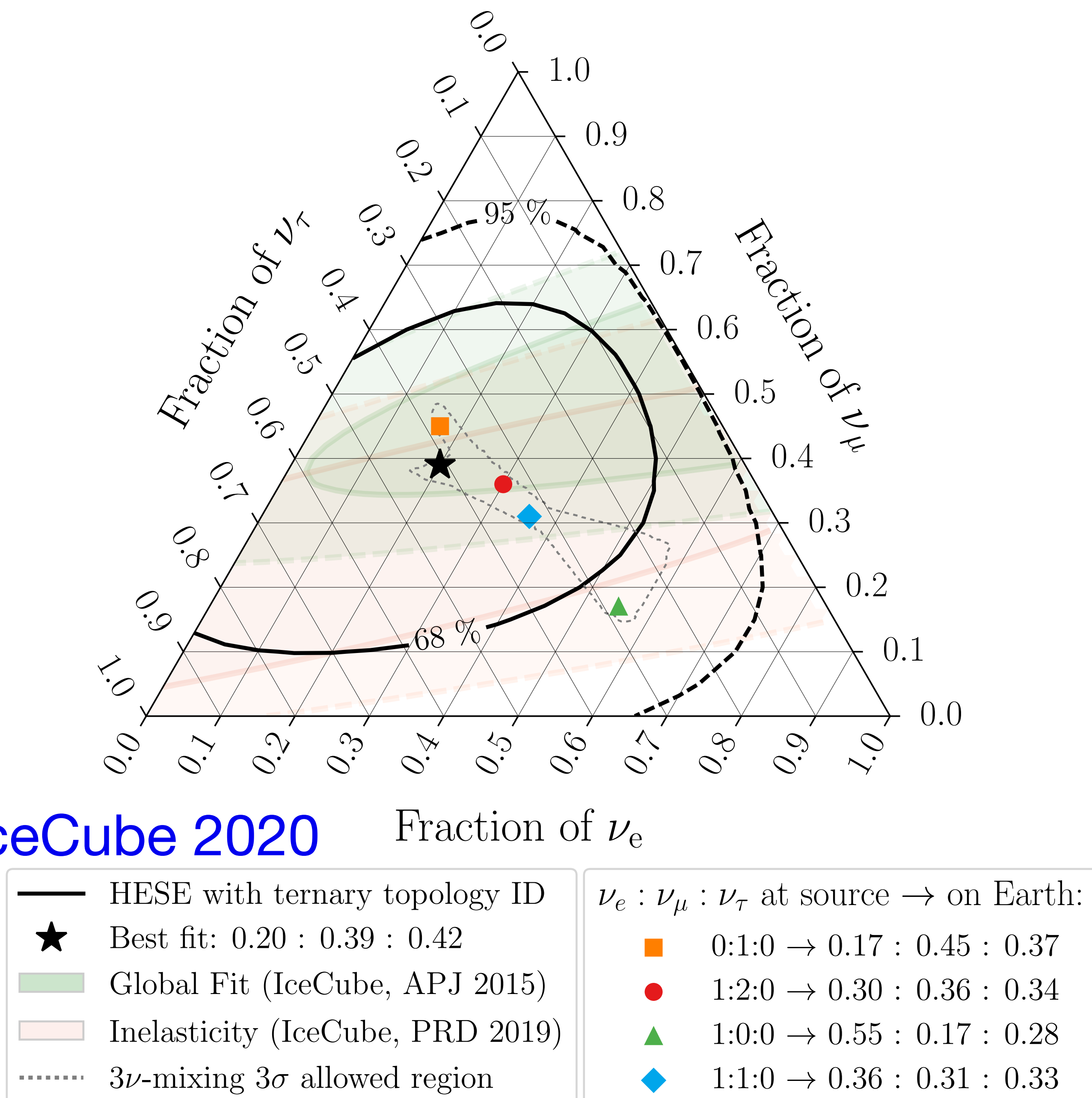


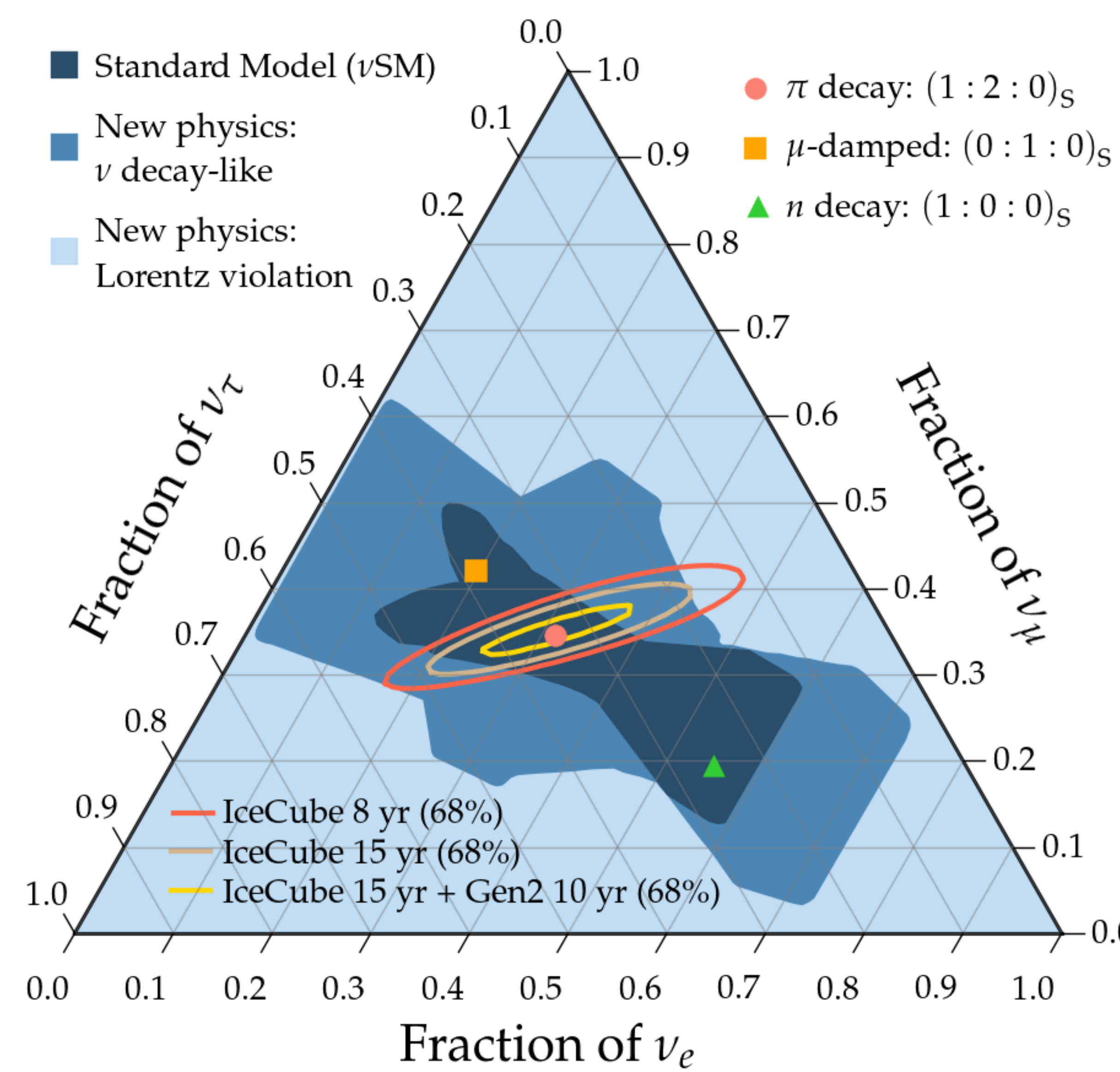
Arrival Direction of the Highest Energy Neutrinos

Flavor Composition

- Standard Expectation: equal proportion of each flavor
- Flavor composition compatible with equal proportion of each flavor.
- **Any deviation from the equal proportion indicate new physics!**



IceCube 2020



IceCube Gen-2 2020

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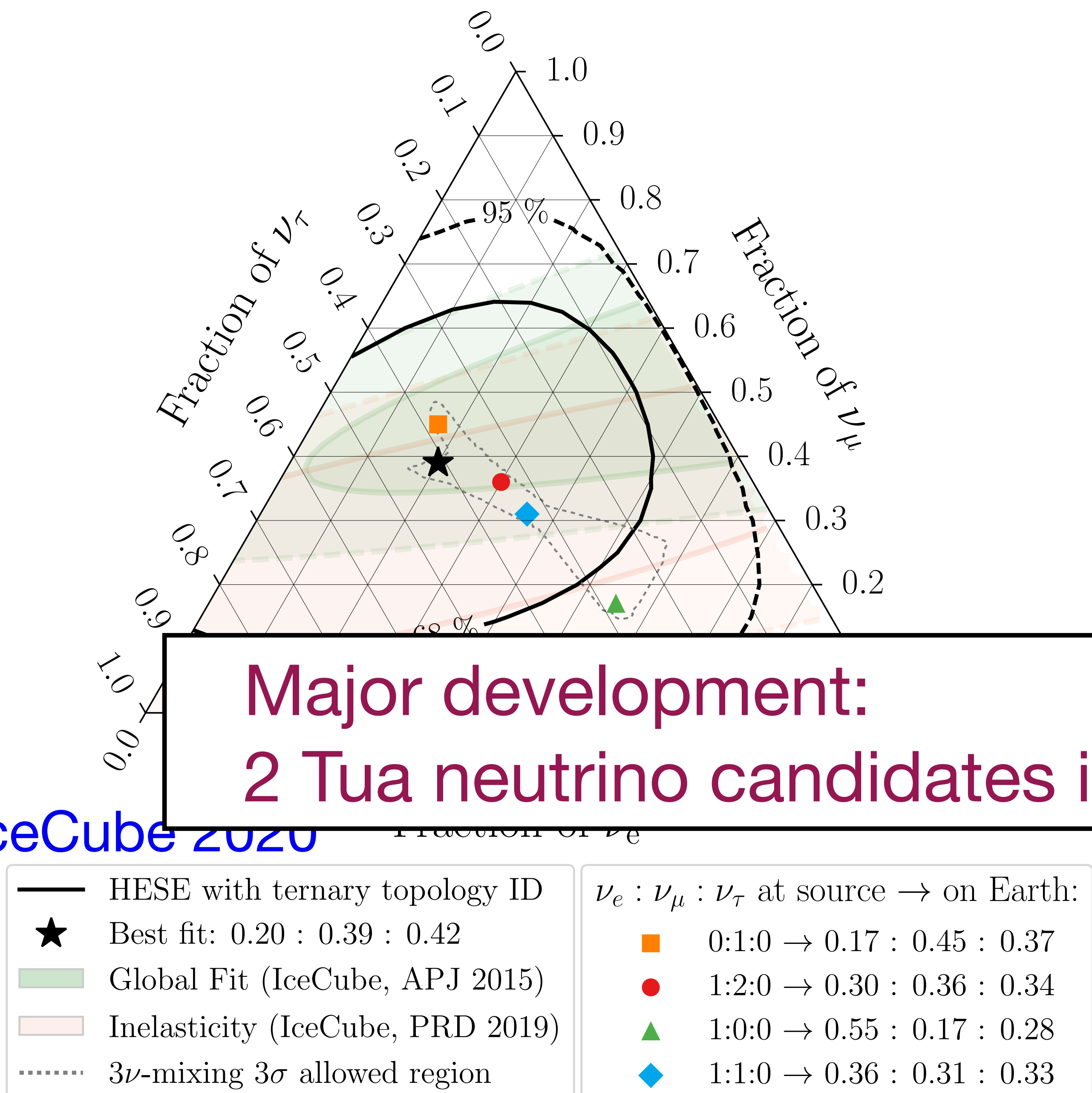
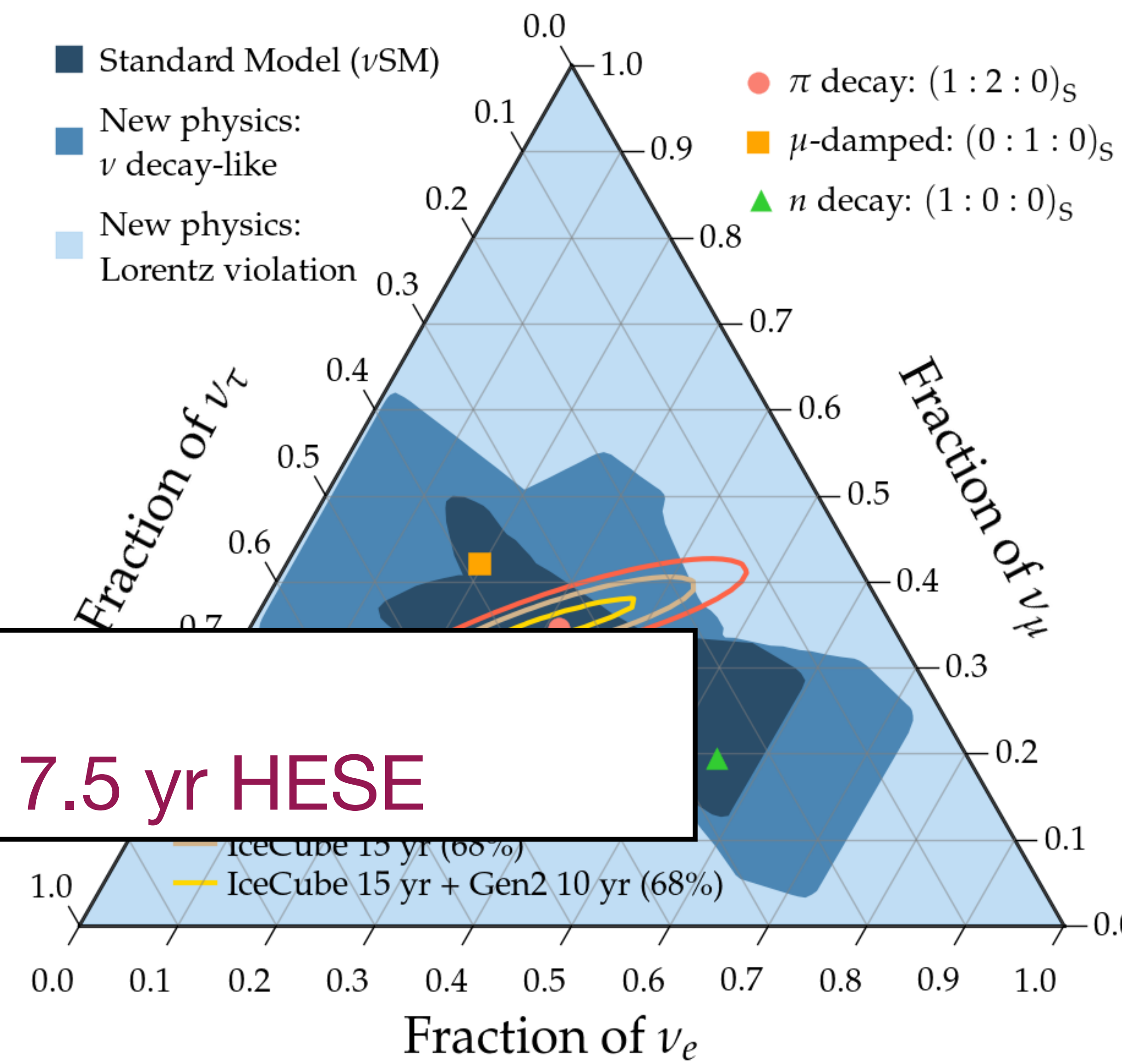


IceCube 2020

Major development:
2 Tua neutrino candidates in 7.5 yr HESE



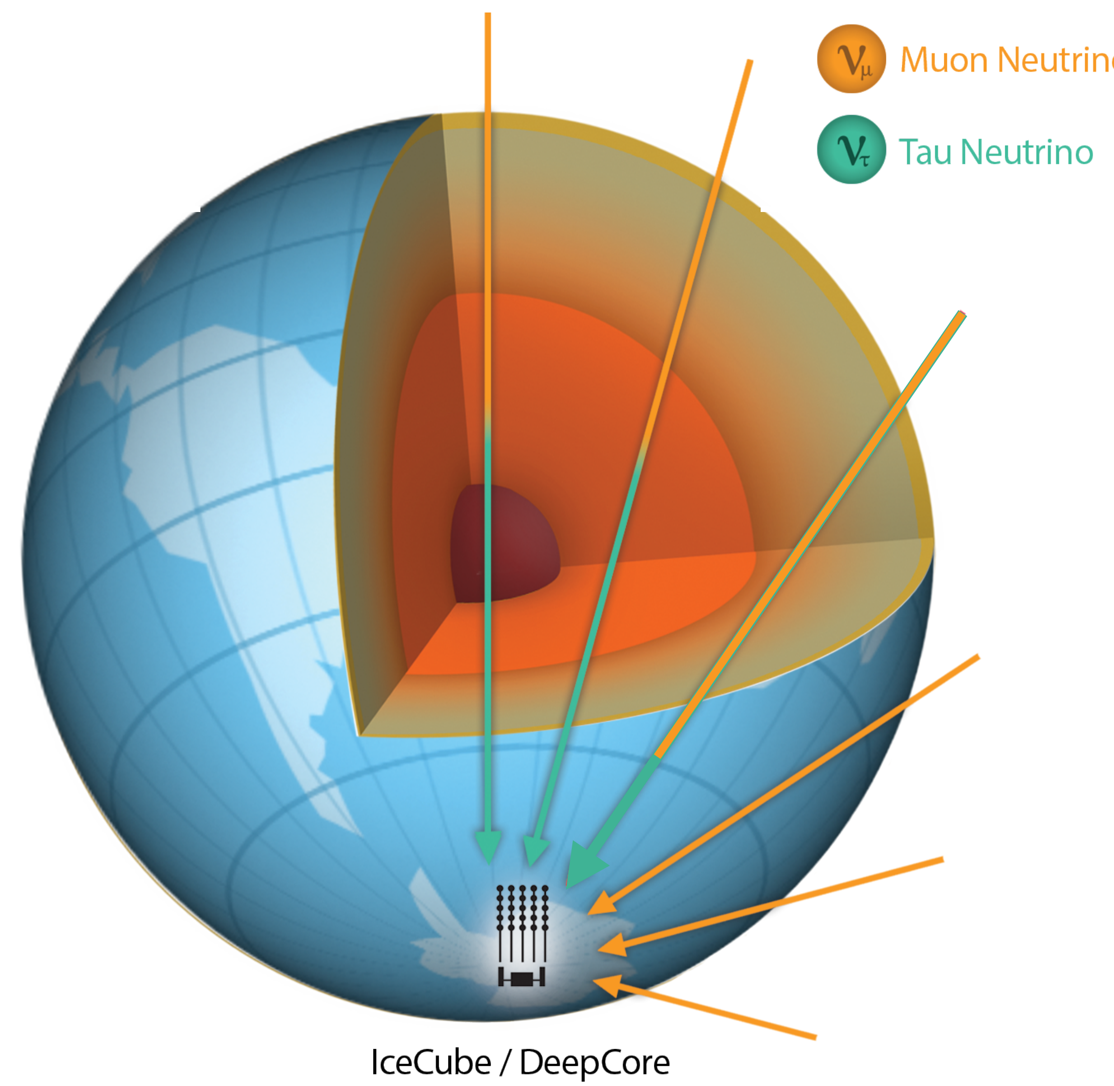
IceCube Gen-2 2020

Lorentz Violation in Neutrino Sector

Lorentz symmetry is a fundamental space-time symmetry underlying the Standard Model of particle physics and gravity. Violation motivated by the unifying theories.

Neutrino oscillation is a natural interferometer.

Looking for anomalous flavor changing effects caused by **Lorentz violation that would modify the energy and zenith angle distribution** of observed atmospheric neutrinos.



$$H \sim \frac{m^2}{2E} + \sum_3 E^{d-3}(\mathring{a}^{(d)} - \mathring{c}^{(d)}) \longrightarrow P(\nu_\mu \to \nu_\tau) = f(m^2, E, L, c^{(d)})$$

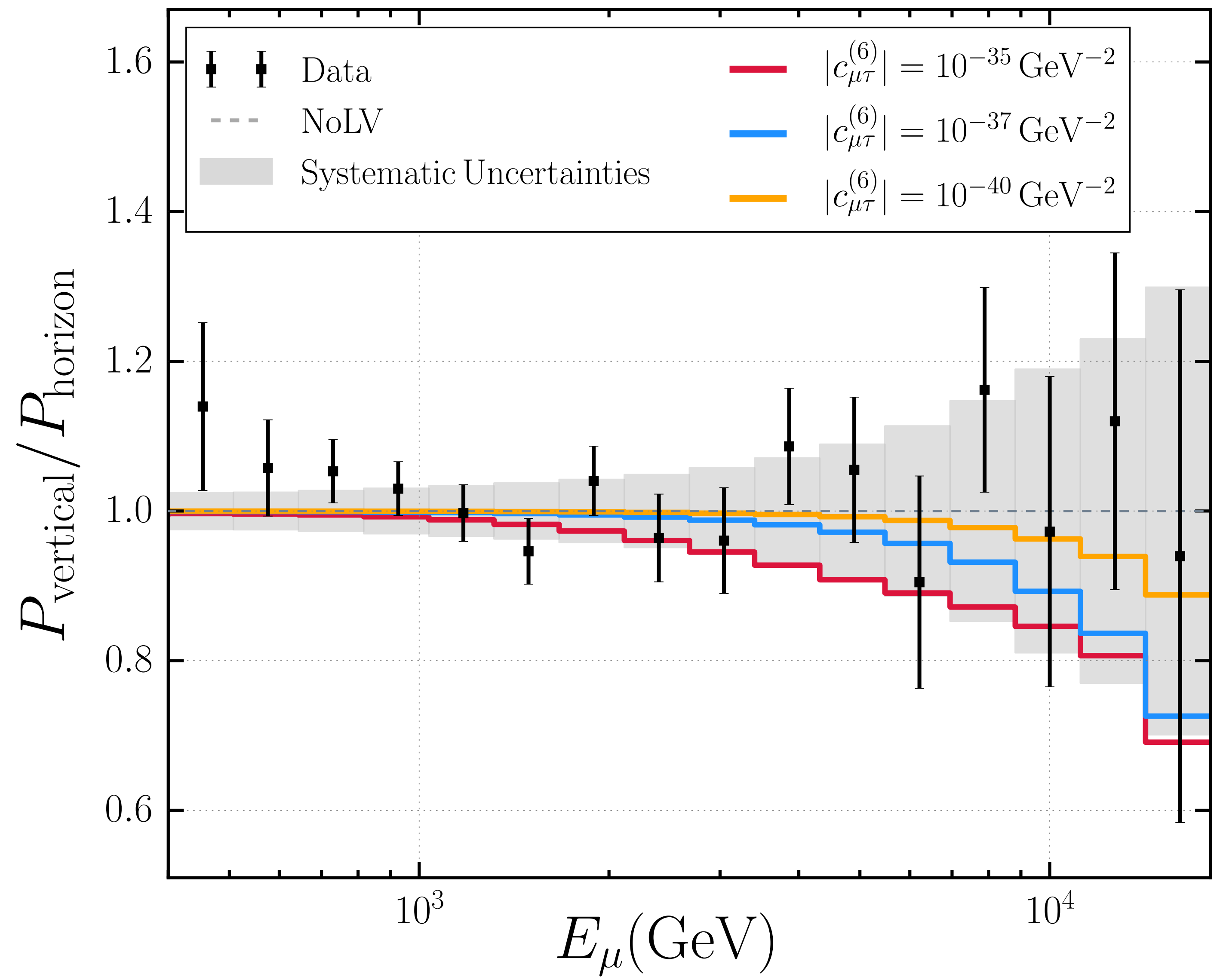
Distortion of the Events

Oscillation probability depends on the energy and baseline (direction).

Lorentz violation will ***distort*** the expected number of neutrinos in different energy and direction with respect to Standard Model expectation.

$$P_{\mathrm{h/v}} = \frac{N_\nu(\mathrm{h/v}|\mathrm{LV})}{N_\nu(\mathrm{h/v}|\mathrm{no\,LV})}$$

IceCube, Nature Phys 2018



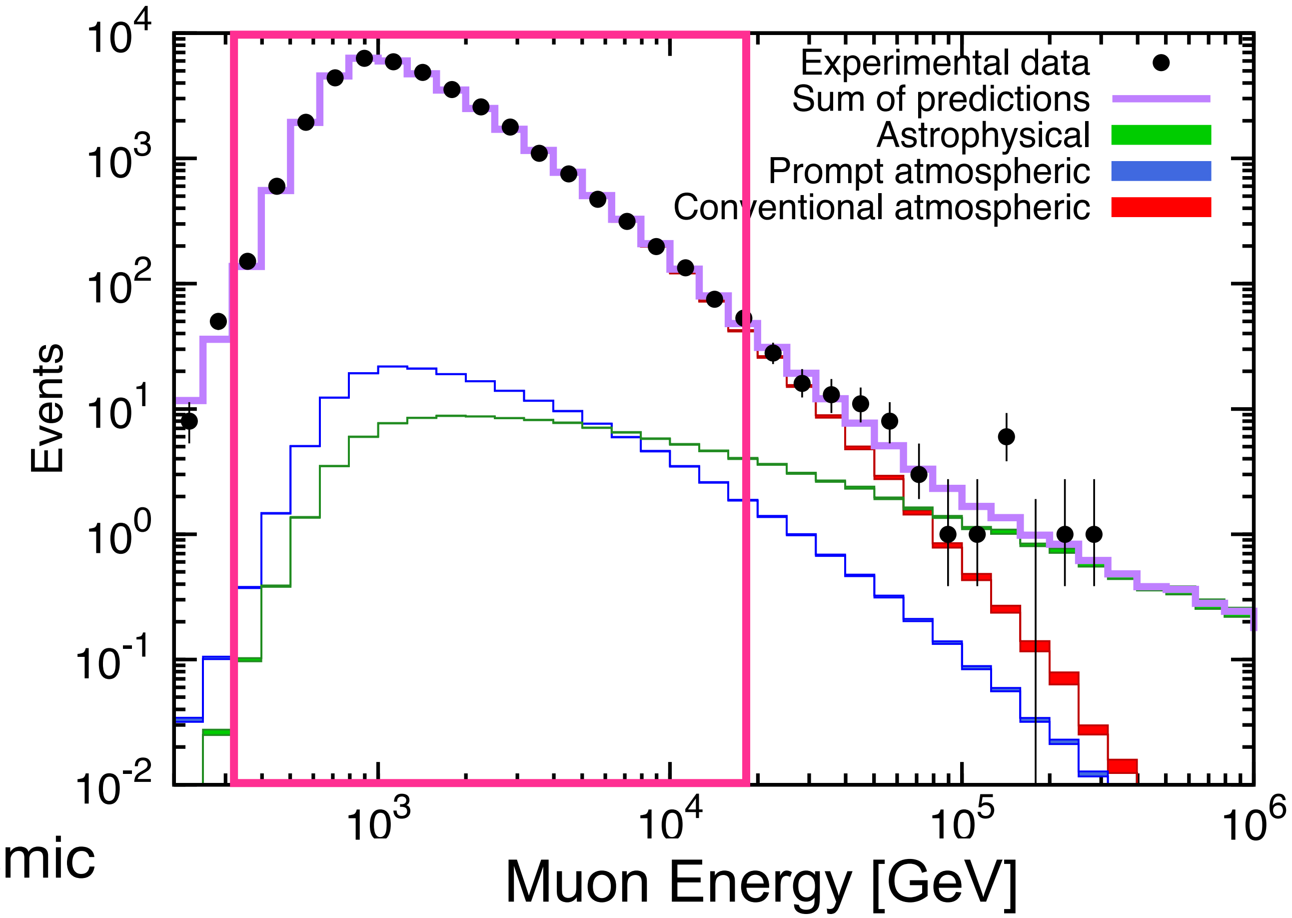
horizontal: cos(zenith) > -0.6
vertical: cos(zenith) < -0.6

Analysis Specifications

Binned Likelihood analysis of conventional atmospheric neutrinos:

data

- data binned in zenith angle & energy
- 2 years of IceCube through-going muons
- energy range: 400 GeV - 18 TeV



simulation

- Atmospheric neutrinos from MCEq
- Simple power law for cosmic neutrinos
- DIS cross section from CSS

systematics

- flux normalization: conventional, prompt, astrophysical
- spectral index: primary cosmic rays and cosmic neutrinos
- pion/kaon ratio for conventional flux
- Ice model
- DOM efficiency

→ Perform fit for 3 LV parameters:

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots$$

$$\begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

Constraining LV parameters

No evidence found for violation of the Lorentz and CPT invariance.

➡ constraints on LV parameters:

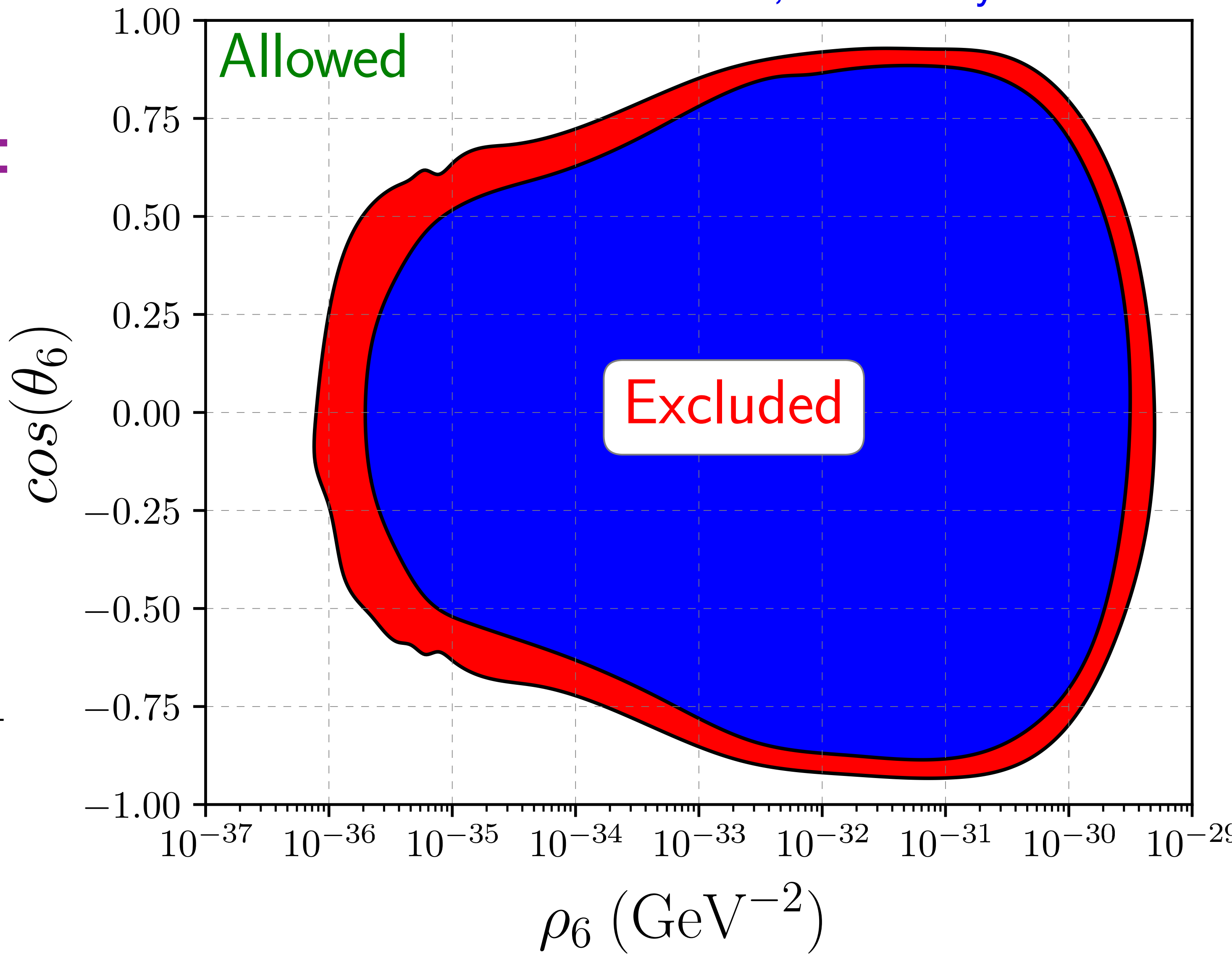
$$\begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

Re-parameterization:

$$\rho_6 \equiv \sqrt{(\mathring{c}^{(6)}_{\mu\mu})^2 + \mathrm{Re}\,(\mathring{c}^{(6)}_{\mu\tau})^2 + \mathrm{Im}\,(\mathring{c}^{(6)}_{\mu\tau})^2}$$

$$\cos\theta_6 \equiv \mathring{c}^{(6)}_{\mu\mu}/\rho_6$$

IceCube, NaturePhysics 2018



90% (99%) confidence levels exclusion regions

Constraining LV parameters

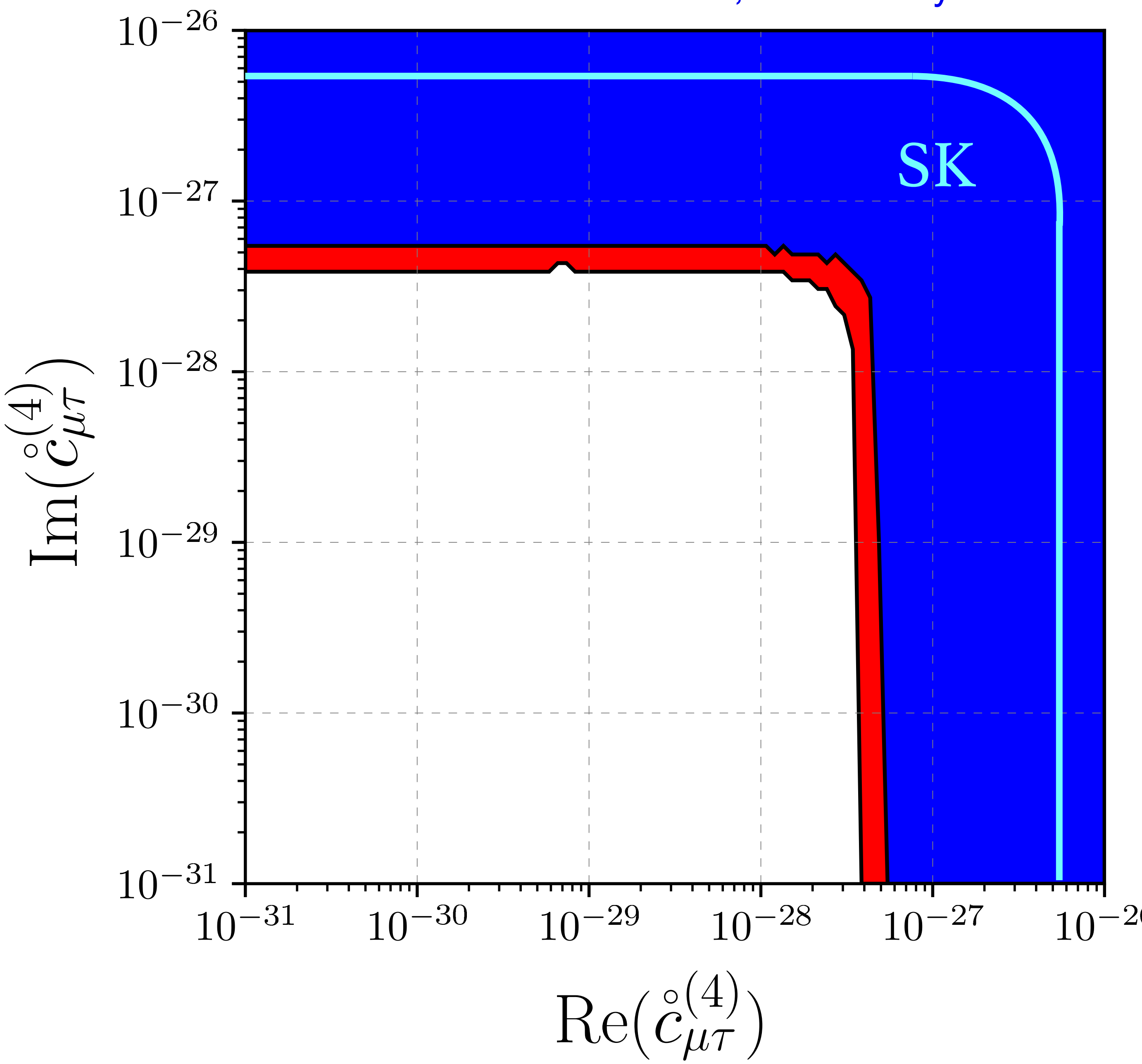
No evidence found for violation of the Lorentz and CPT invariance.

→ constraints on LV parameters

Setting diagonal terms to zero (similar to SK)

$$\mathring{c}^{(4)} = \begin{pmatrix} 0 & \mathring{c}^{(4)}_{\mu\tau} \\ \mathring{c}^{(4)*}_{\mu\tau} & 0 \end{pmatrix}$$

IceCube, Nature Phys. 2018



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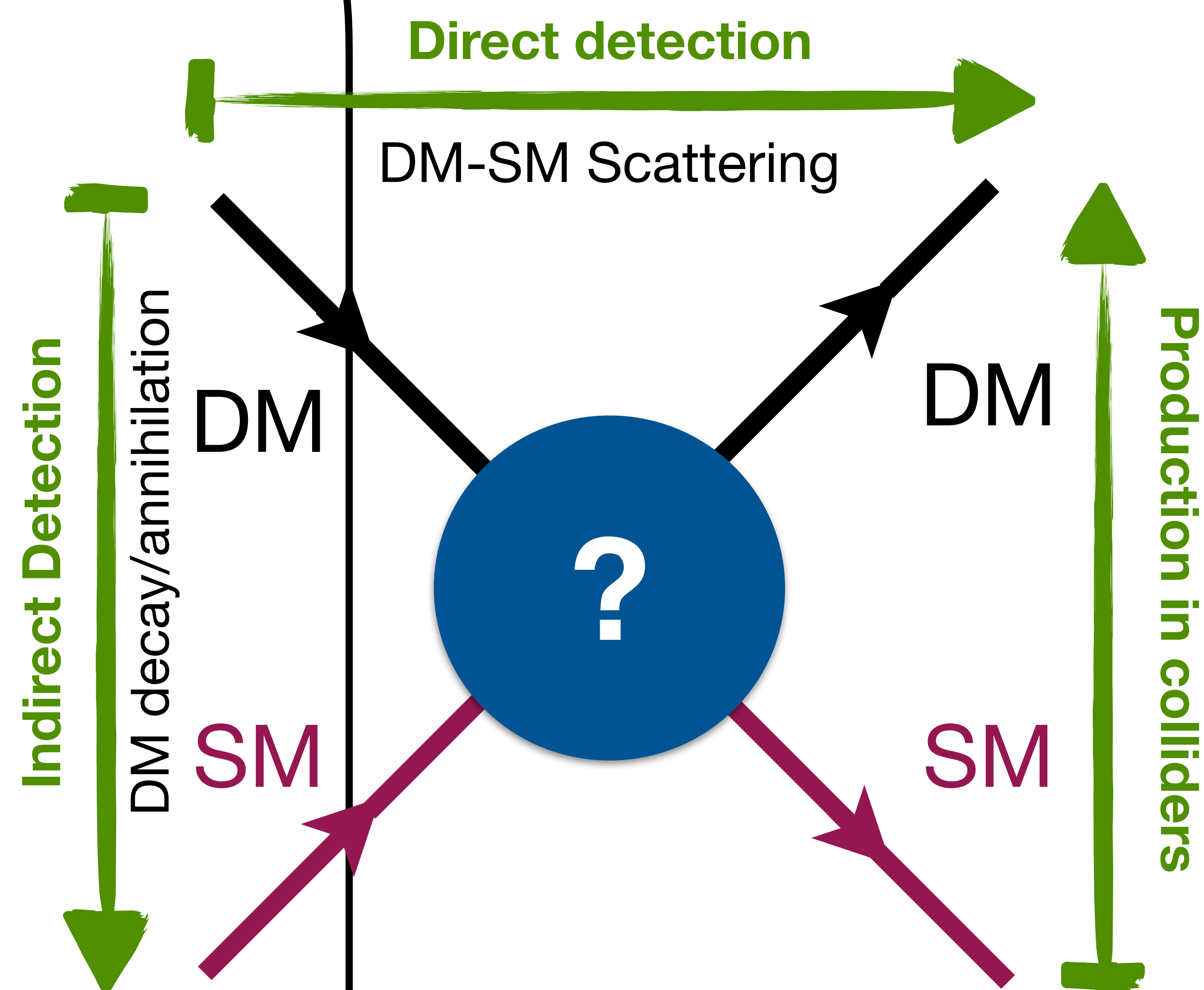
Neutrino portal to Dark Matter

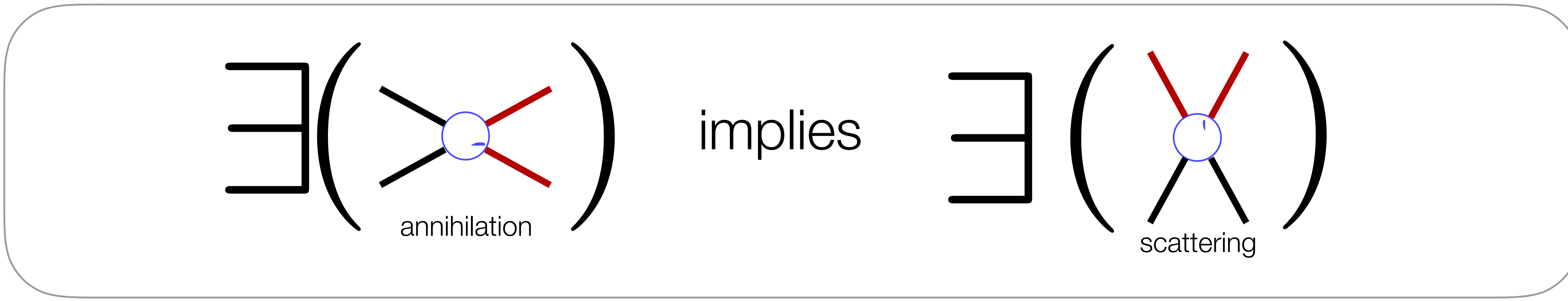
Indirect dark matter signatures in the neutrino sector:

- Features in geo, solar, atmospheric, and cosmic neutrino spectra
- Anisotropies in high-energy neutrinos due to DM-Neutrino interaction.
- Features in the diffuse SN neutrino background.

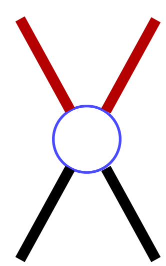


Dark Matter-Neutrino Interaction?

DM annihilation near Weak Scale: *WIMP Miracle*



if —— = quarks, then

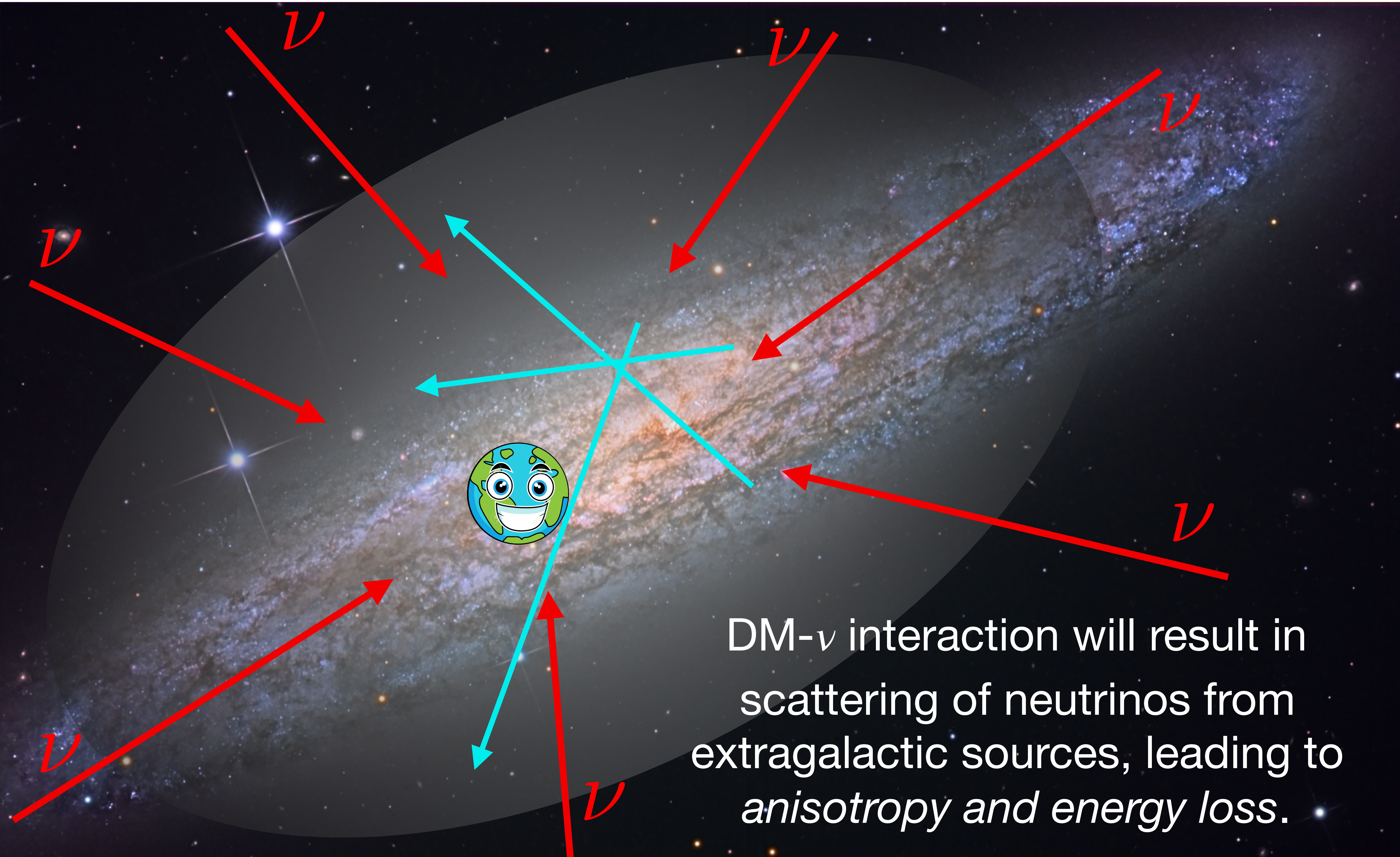


= direct detection
(LUX, LZ, SuperCDMS, …)

But if —— too light, or ? does not talk to quarks, then
—— could be neutrinos

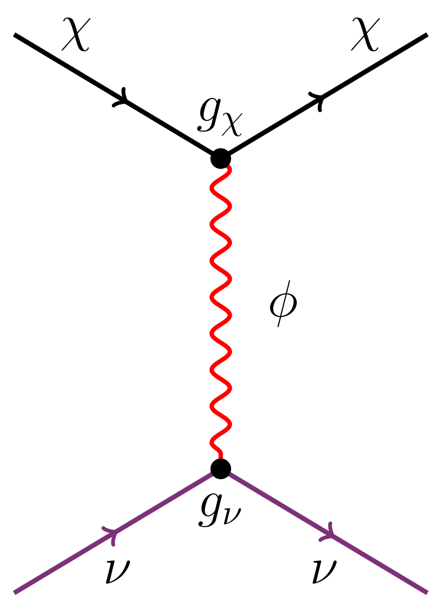
[Boehm+ 01, 02, 05, 14—Bertschinger+ 06— Mangano+ 06—Serra+ 10—Wilkinson+ 14
—van den Aarssen+ 12—Farzan+ 14—Cherry+ 14—Bertoni+ 15—Chewtschenko+ 15]

DM density is largest in center of the Galaxy.

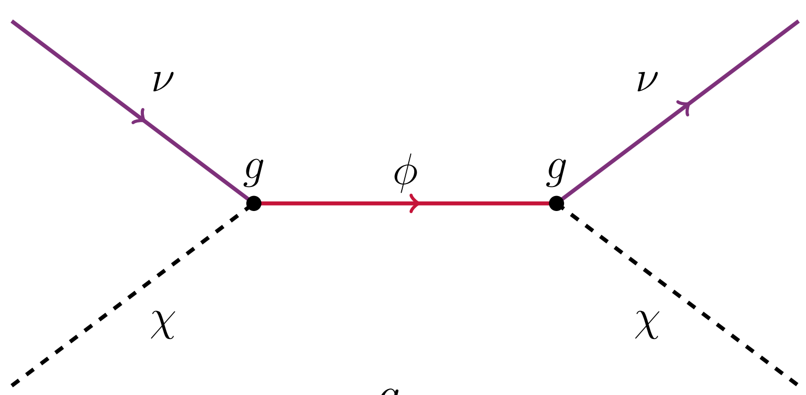


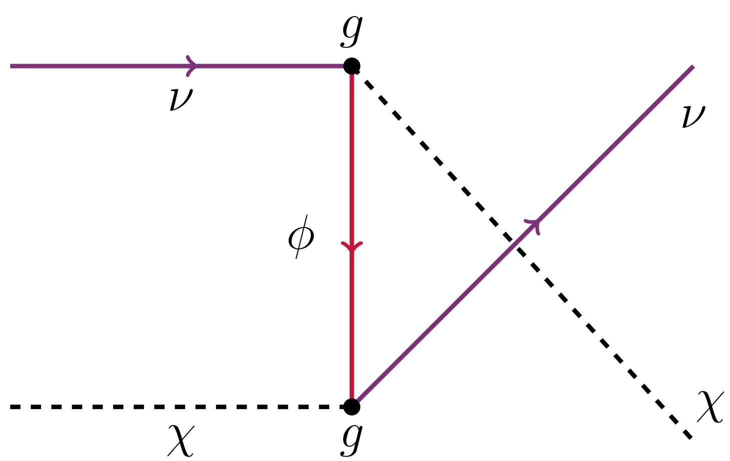
DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to *anisotropy and energy loss*.

Two fiducial simplified models



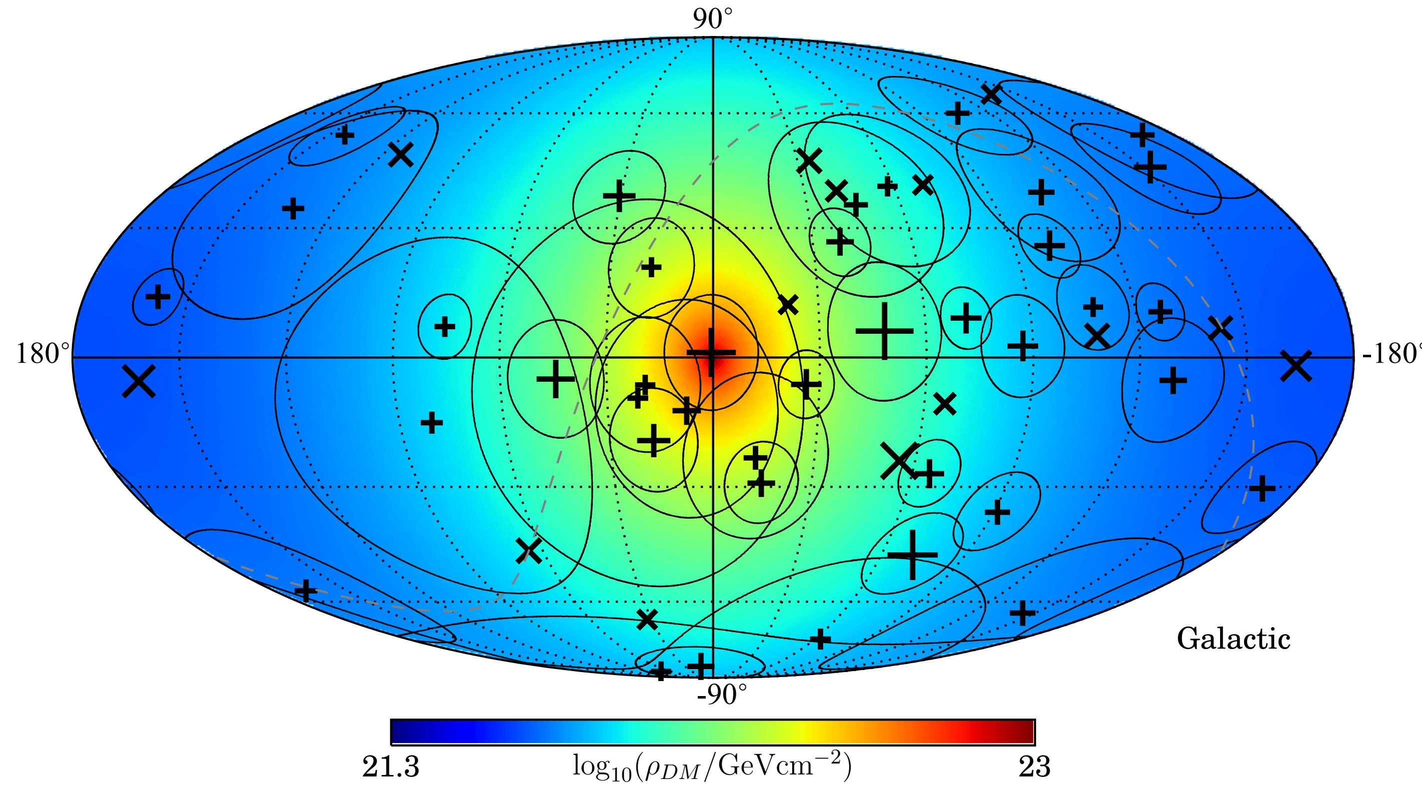
Fermion DM, **vector mediator**:
similar to a leptophillic Z’ model
Scales strongly with *E*





Scalar DM, **fermionic mediator**:
e.g. sneutrino dark matter,
neutralino mediator.
Resonant behaviour (s-channel)

Dark matter column density* seen from Earth



* *Einasto*

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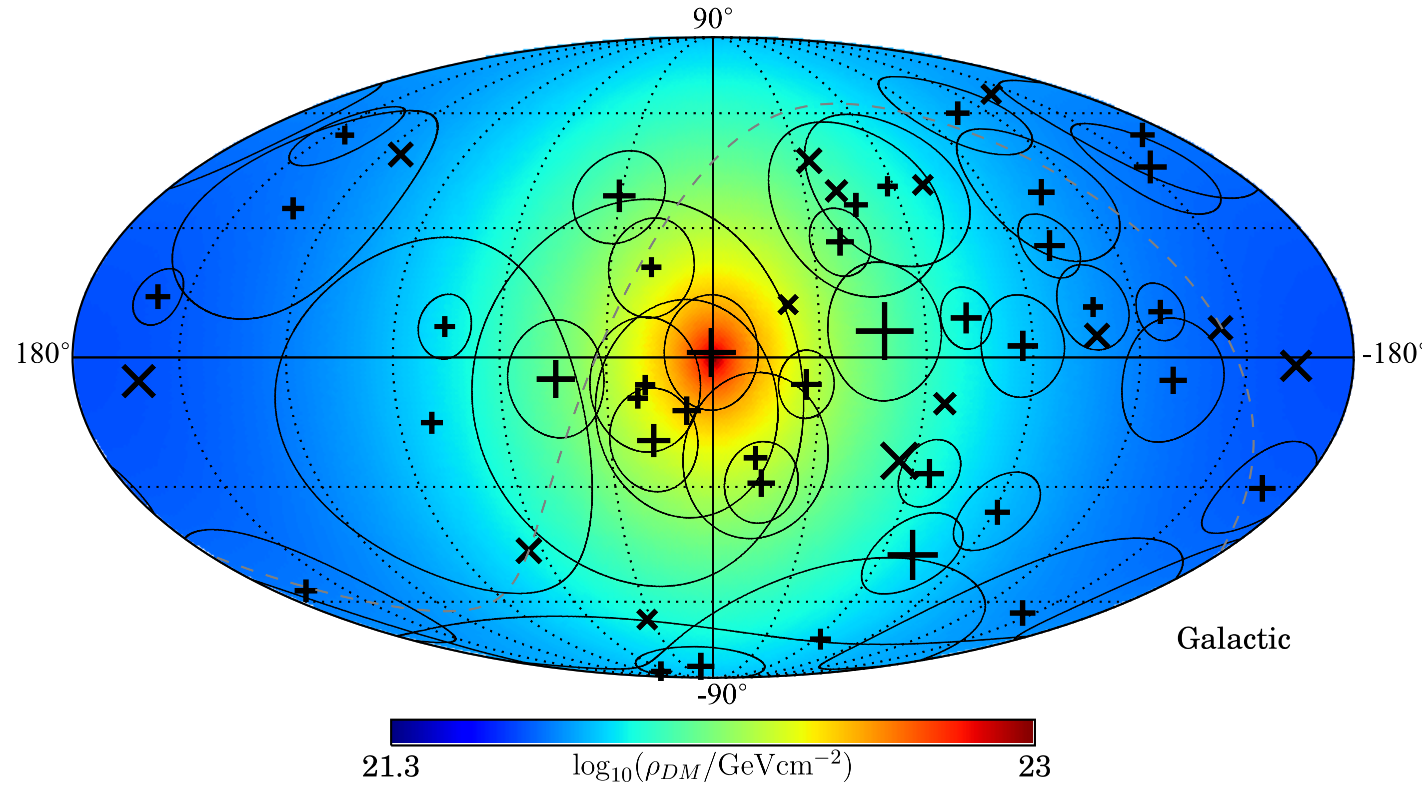

Simulation including effects of detector, Earth

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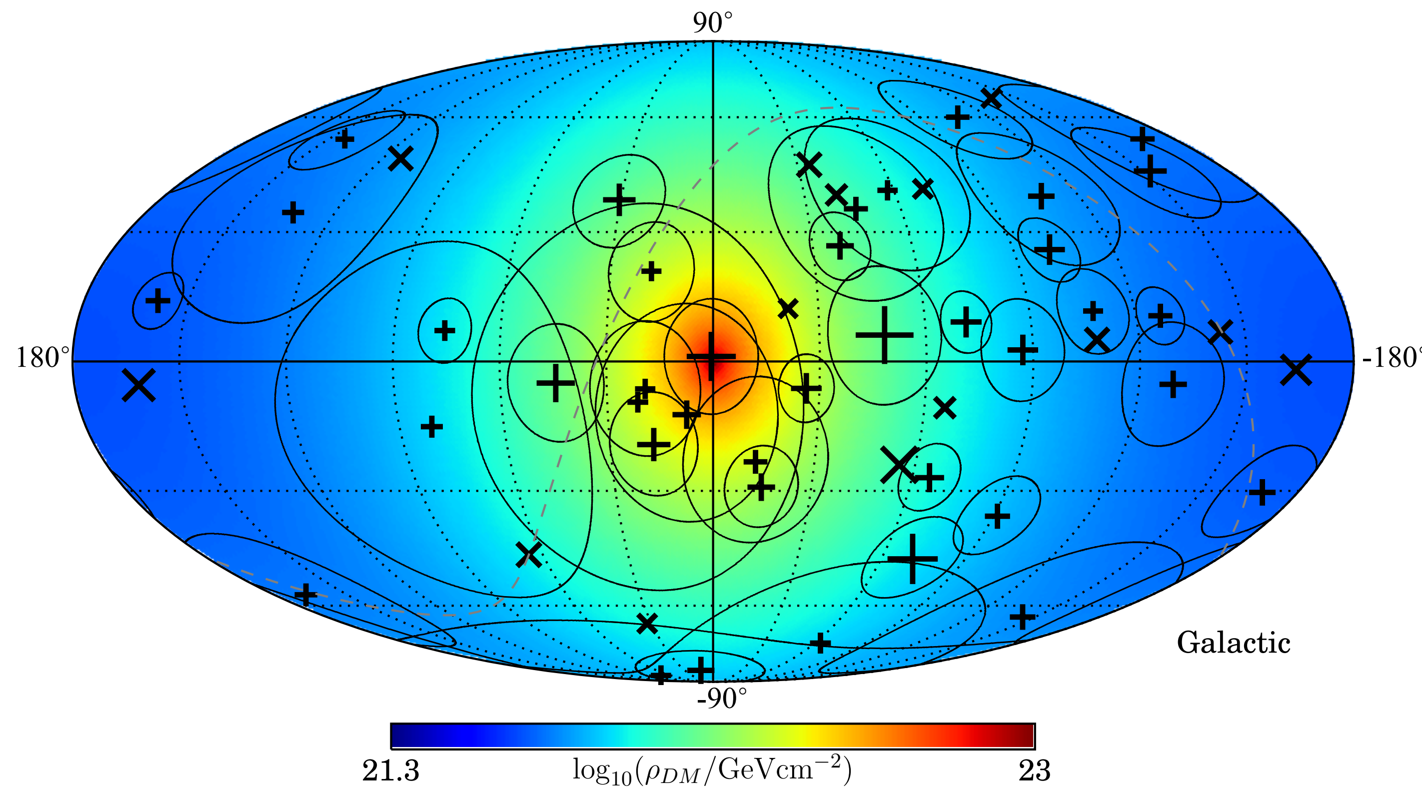

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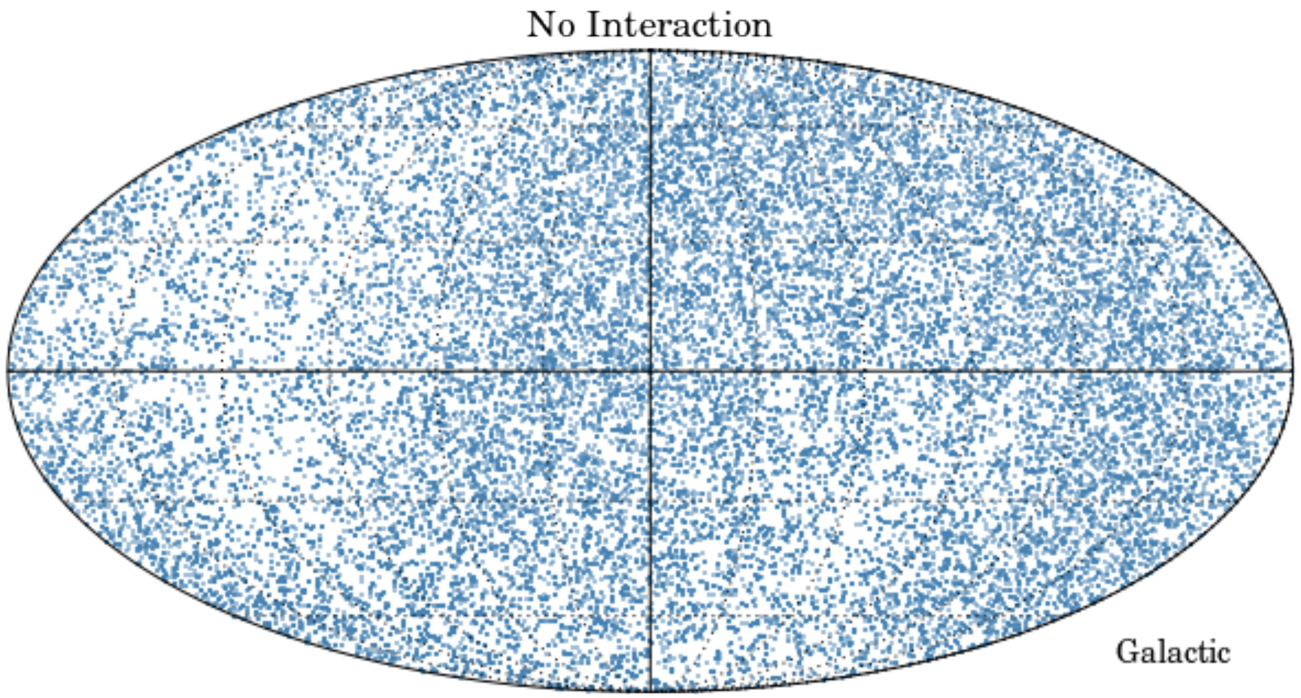

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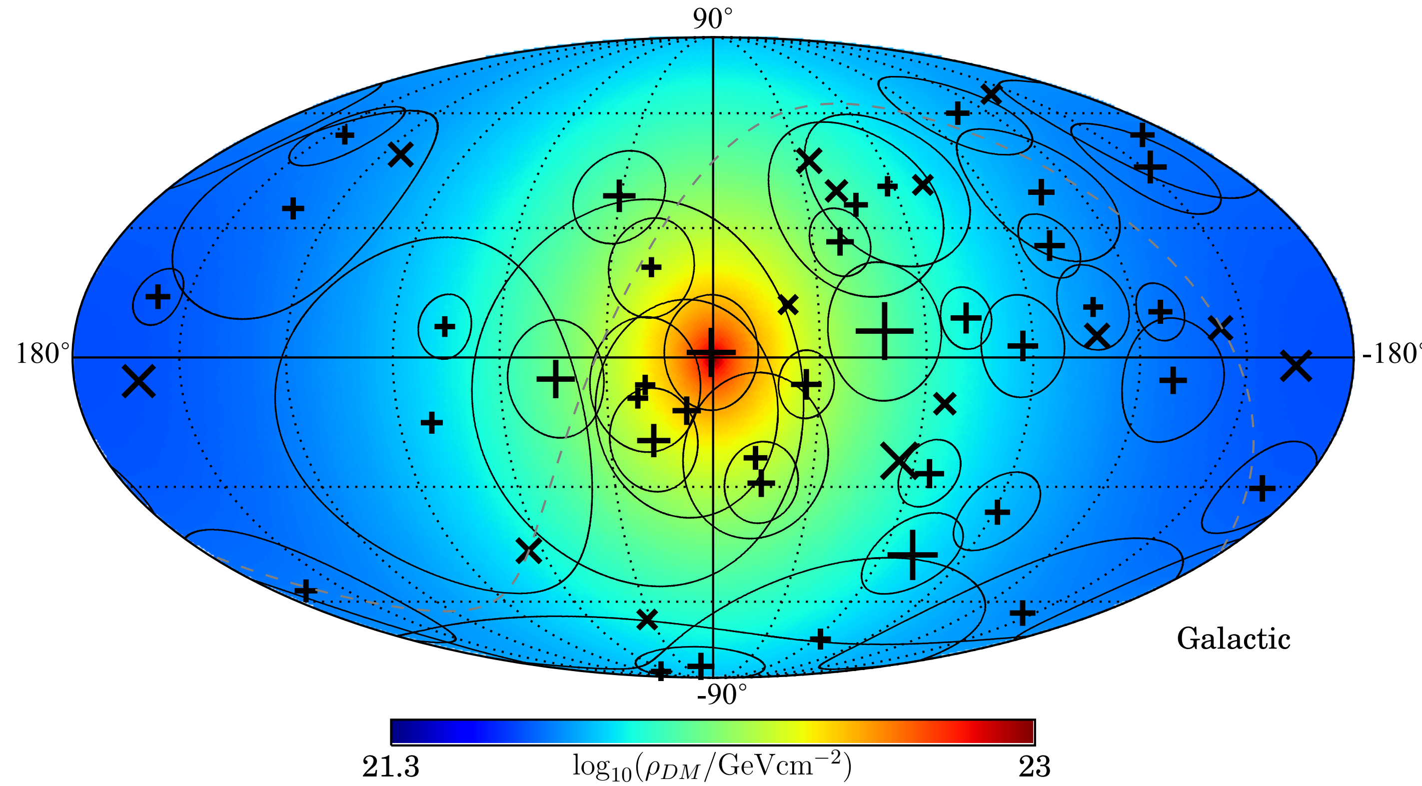

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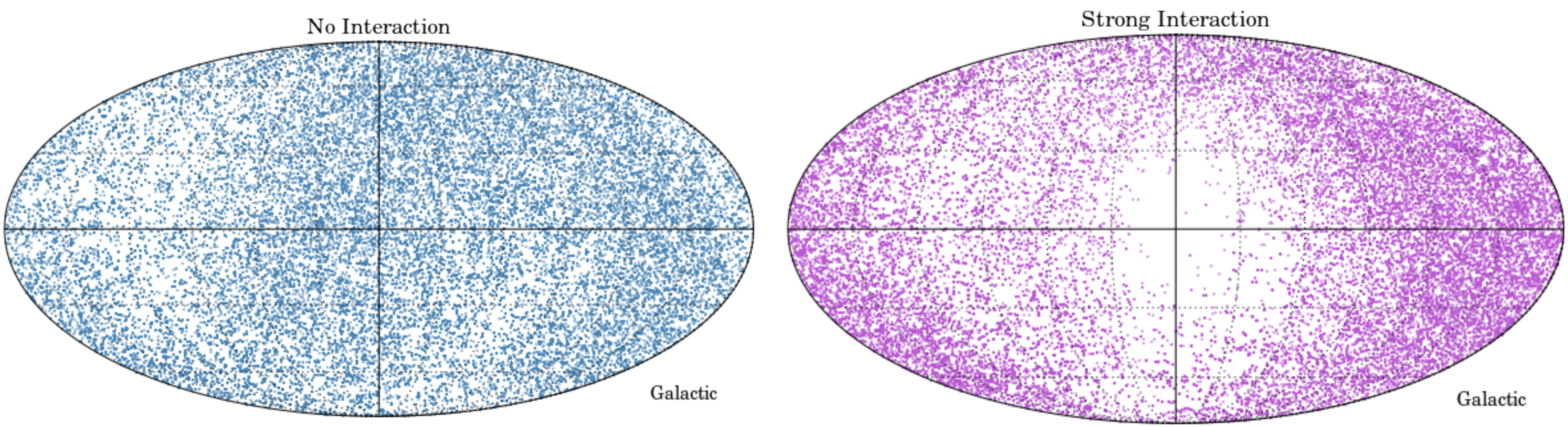
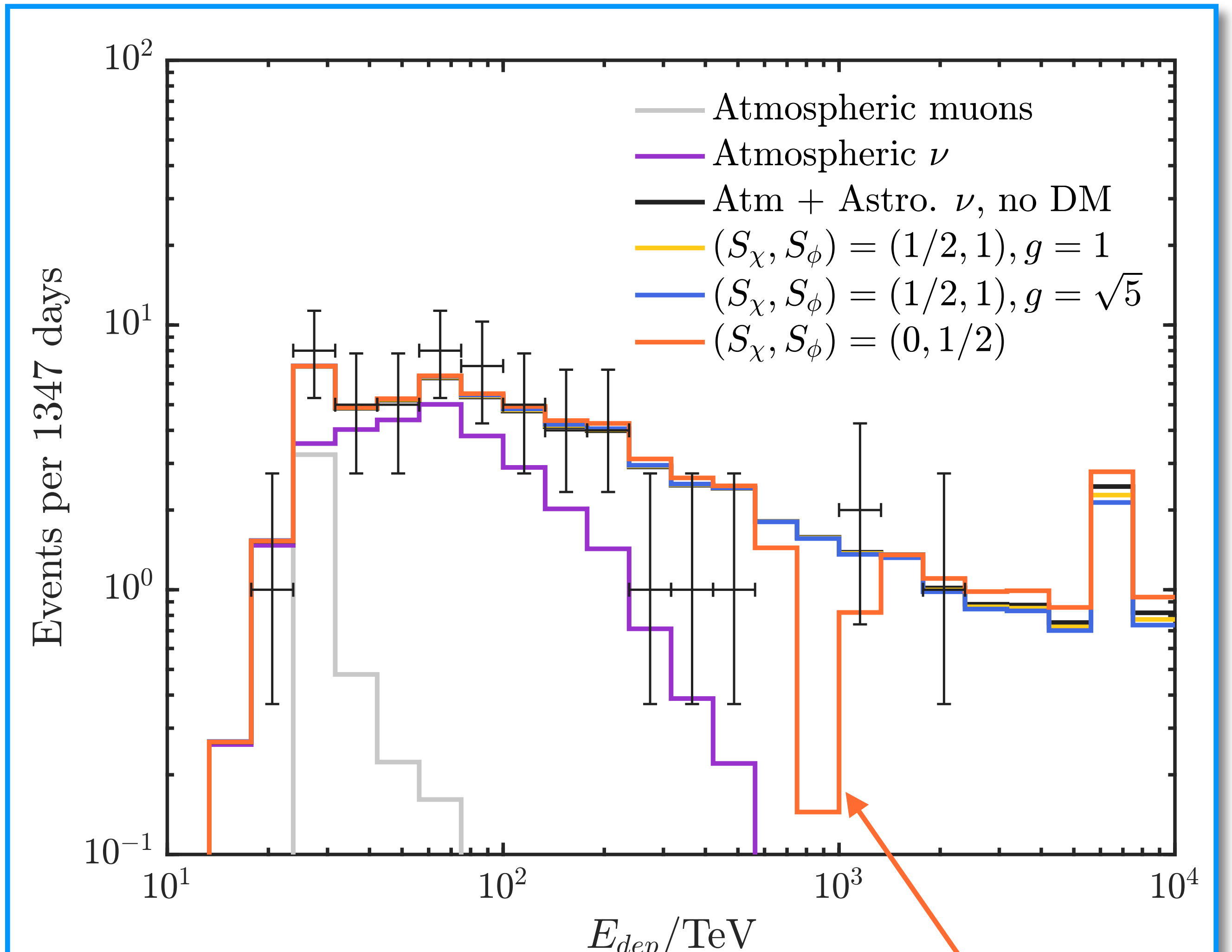


* *Einasto*

Energy & Morphology

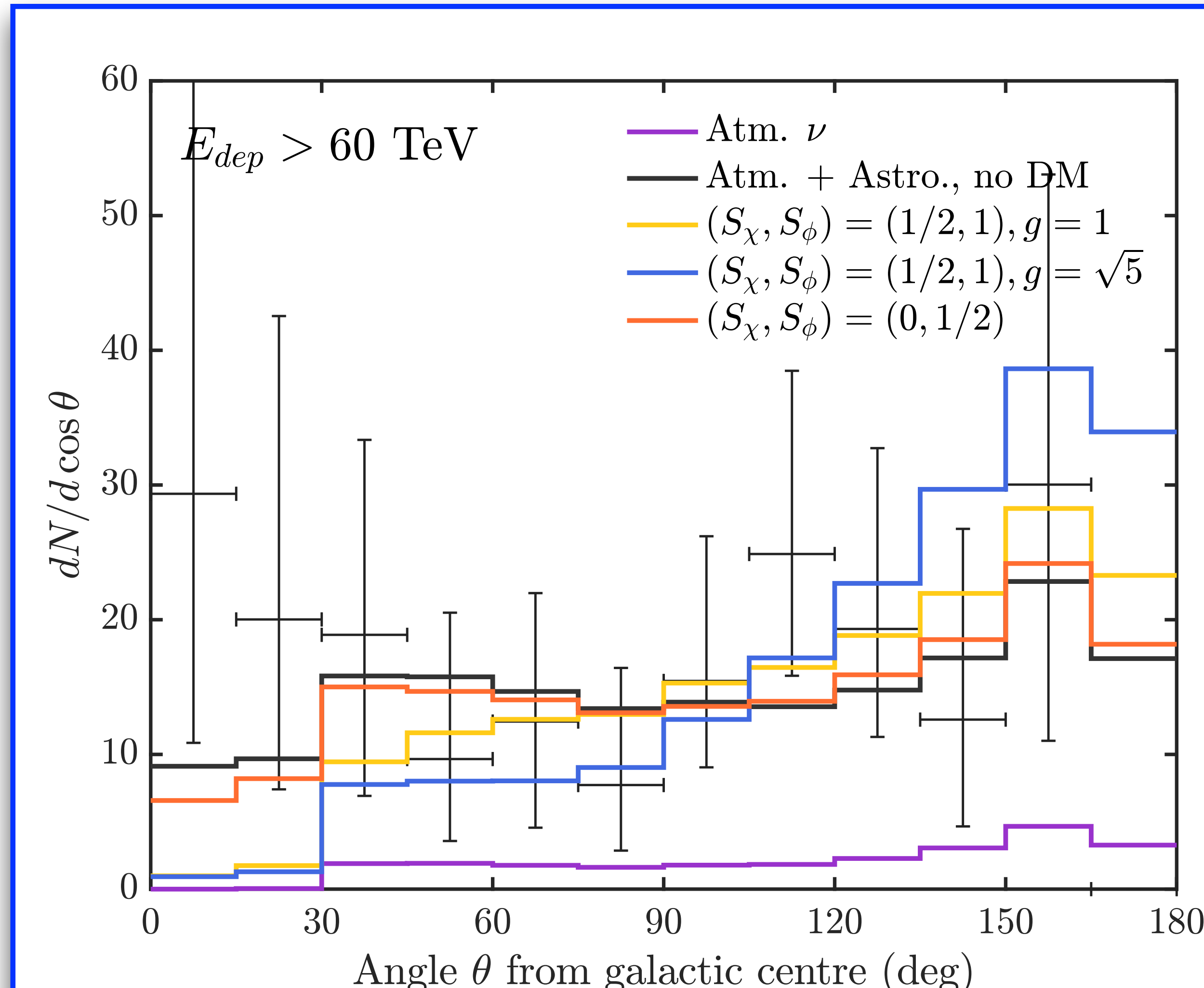
Energy Distribution



Resonance @ 810 TeV

Neutrino-DM interactions creates features in the energy spectrum (e.g. Dips, cut-off, softening)

Angular Distribution

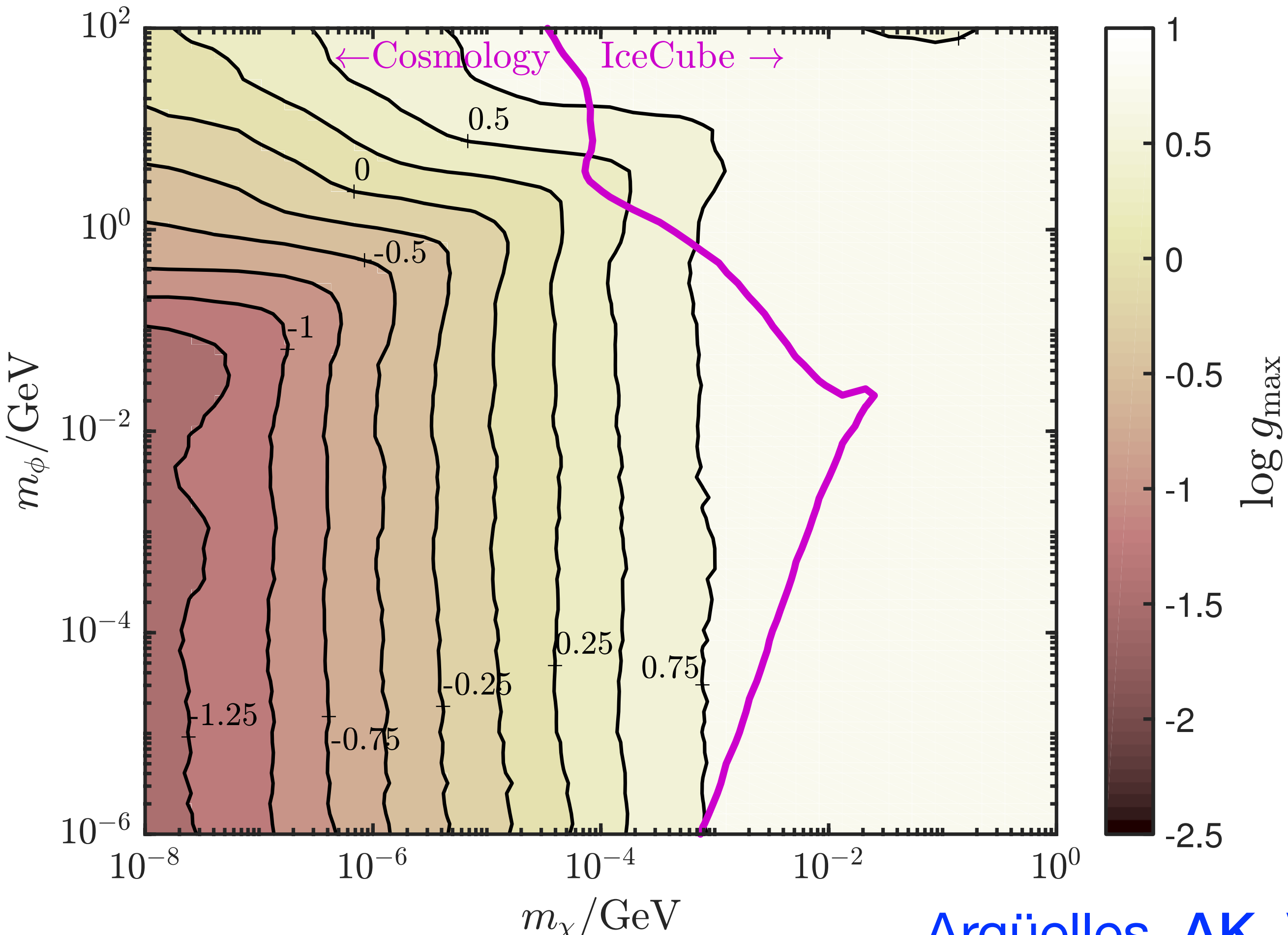


IceCube HESE

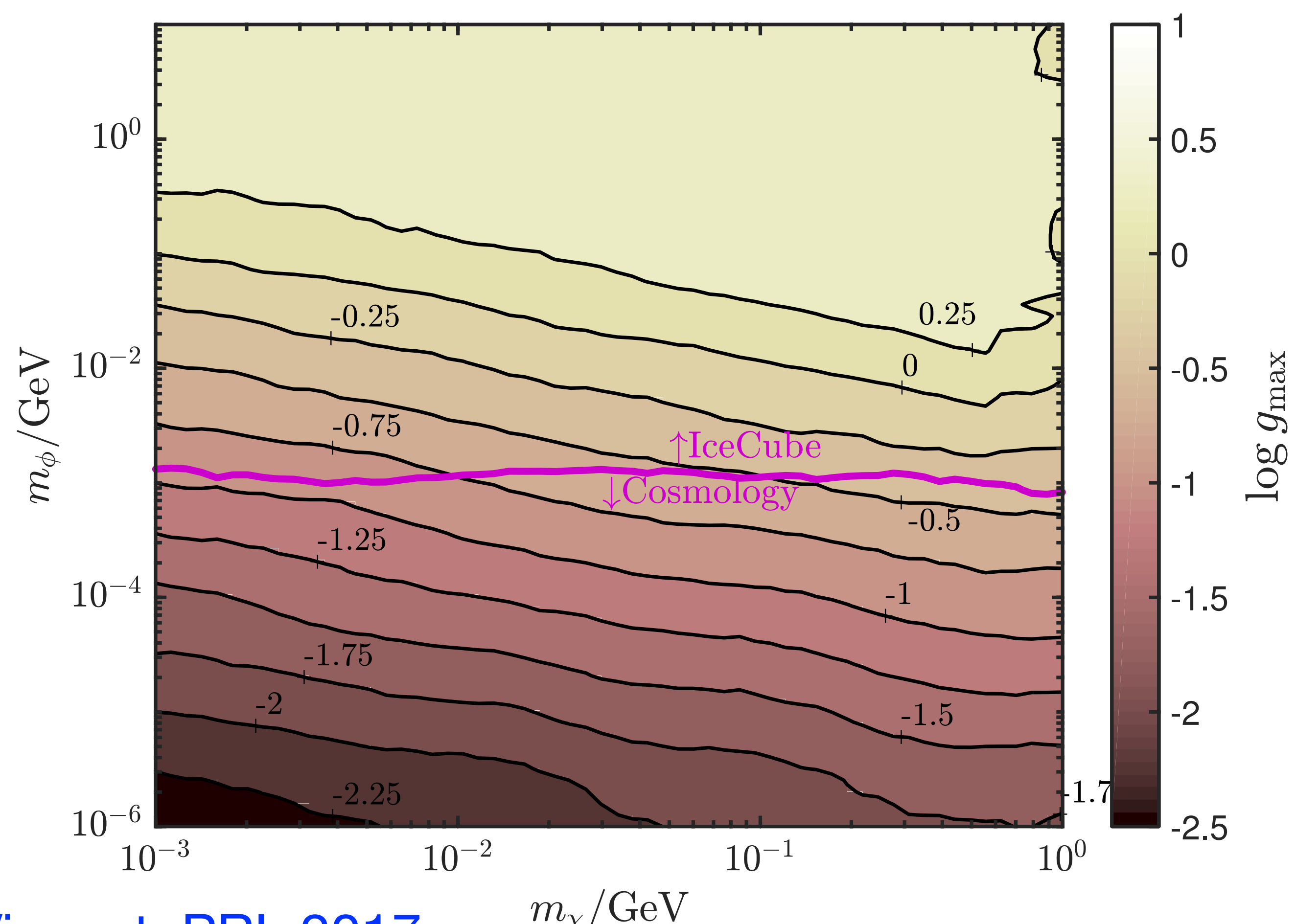
Neutrino-DM interaction leads to the deficit towards Galactic center

Constraints on DM-Nu Interaction

Scalar DM
Fermionic Mediator



Fermionic DM
Vector Mediator



Argüelles, **AK**, Vincent, PRL 2017

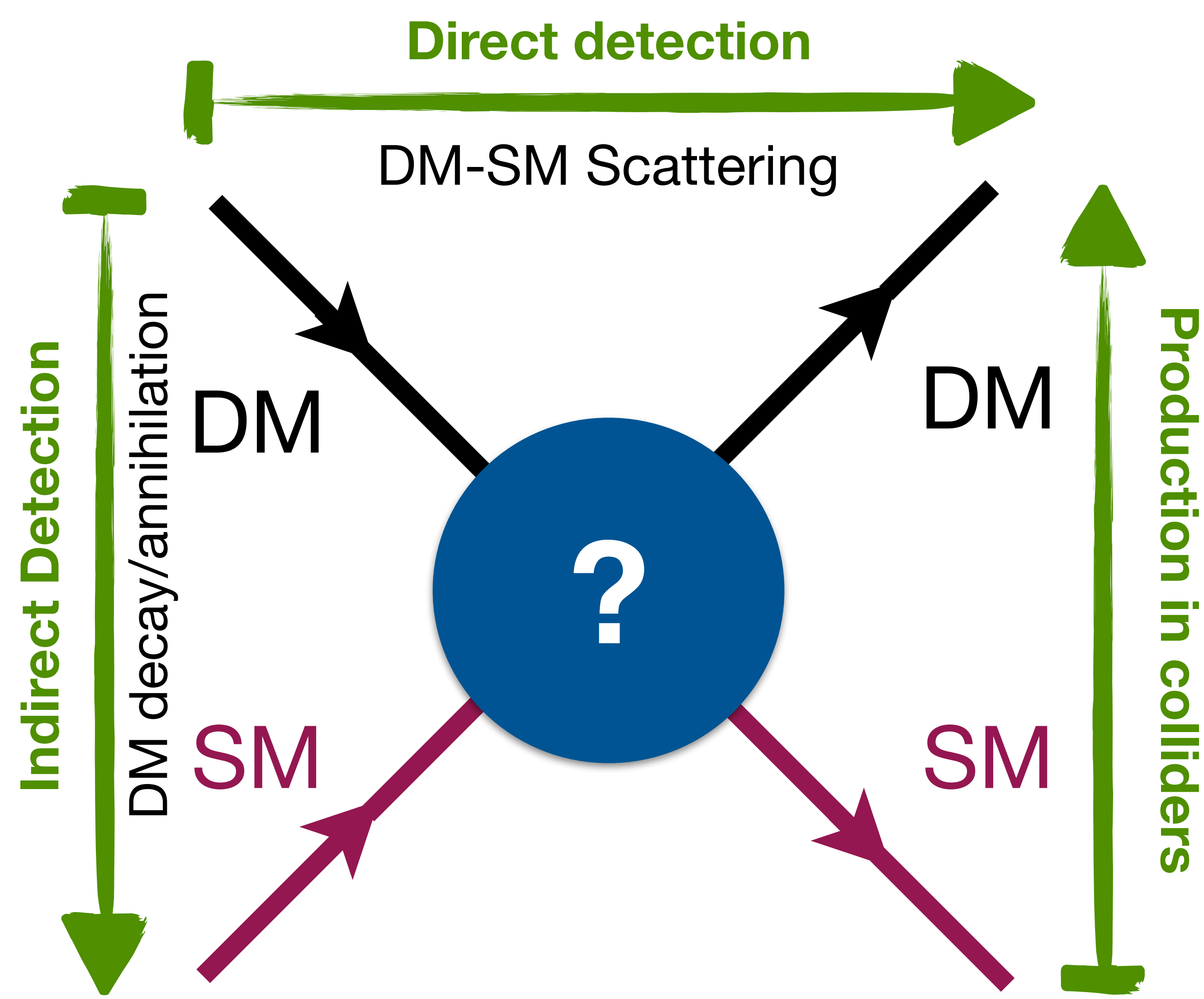
Competitive limits compared to cosmological constraints!

DM Annihilation to Neutrinos

- What is dark matter (DM)?
- What SM particles does DM interact with?
- How does it interact?

Thermal production of WIMPs in early Universe implies possible ongoing self-annihilation of DM.

Strongest constraints are in place from the absence of any signal in X-ray & gamma-rays from the Milky Way.



Neutrino portal: *the most invisible channel*, hardest to detect, difficult to rule out!

DM Annihilation to Neutrinos

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Galactic component

Flux of neutrinos from dark matter annihilation in the Milky Way:

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thermally averaged DM annihilation cross section

The neutrino production spectrum for direct annihilation of DM to neutrinos

$$= \delta(m_\chi - E_\nu)$$

J-facror: 3d integral over the target solid angle in the sky and the line of sight

$$J \equiv \int d\Omega \int_{\text{l.o.s.}} \rho_\chi^2(x) dx,$$

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Extragalactic component

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$$\frac{d\Phi_\nu}{dE} = \frac{c}{4\pi} \frac{\Omega_{DM}^2 \rho_{crit}^2 \langle \sigma v \rangle}{2m_x^2} \int_0^{z_{up}} dz \frac{\big(1 + G(z)\big)(1+z)^3}{H(z)} \frac{dN_\nu(E')}{dE}$$

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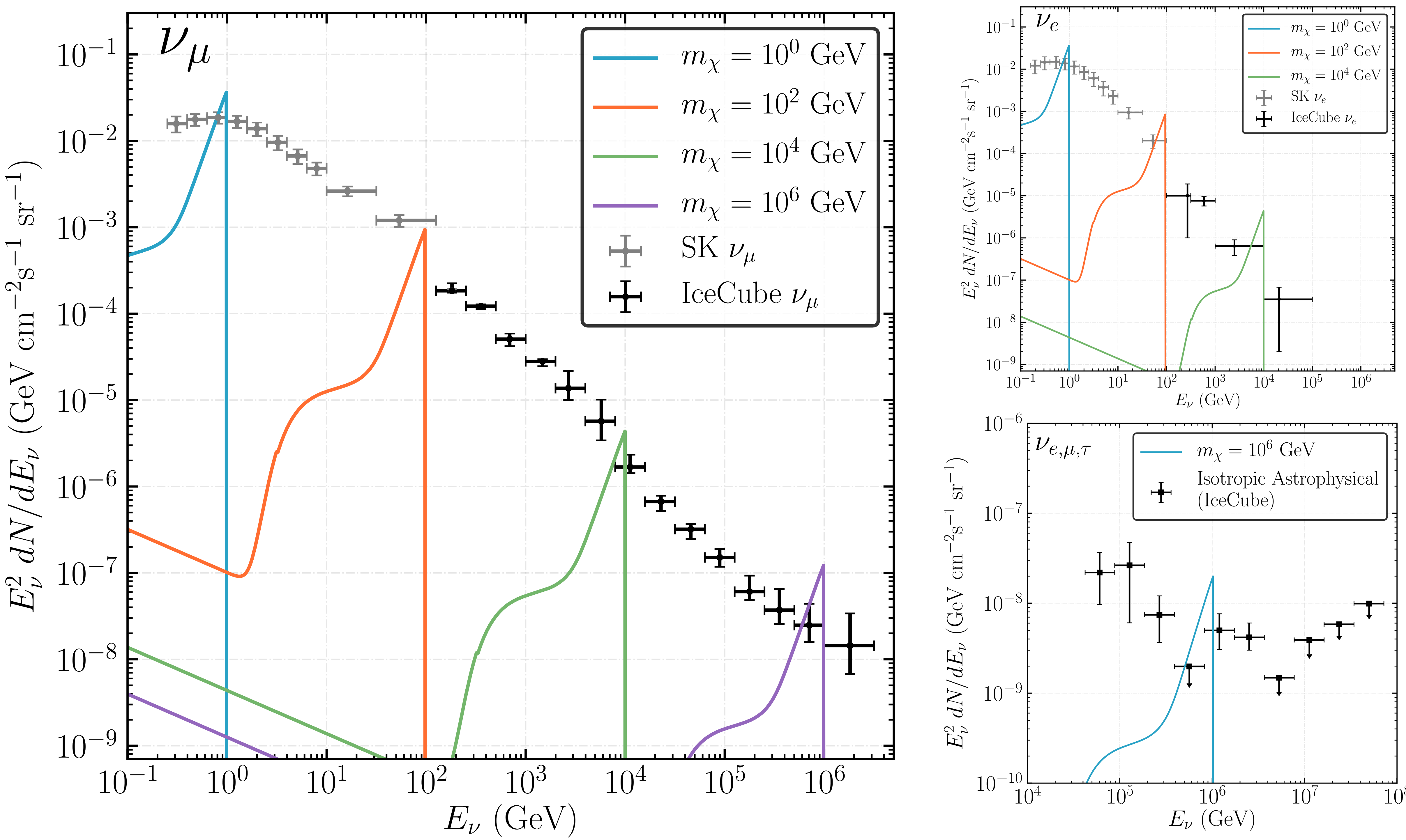
An isotropic neutrino signal is also expected from DM annihilation in every other halo in the universe:

Production spectrum $\frac{2}{3E}\delta\left[z-\left(\frac{m_\chi}{E}-1\right)\right]$

Halo boost

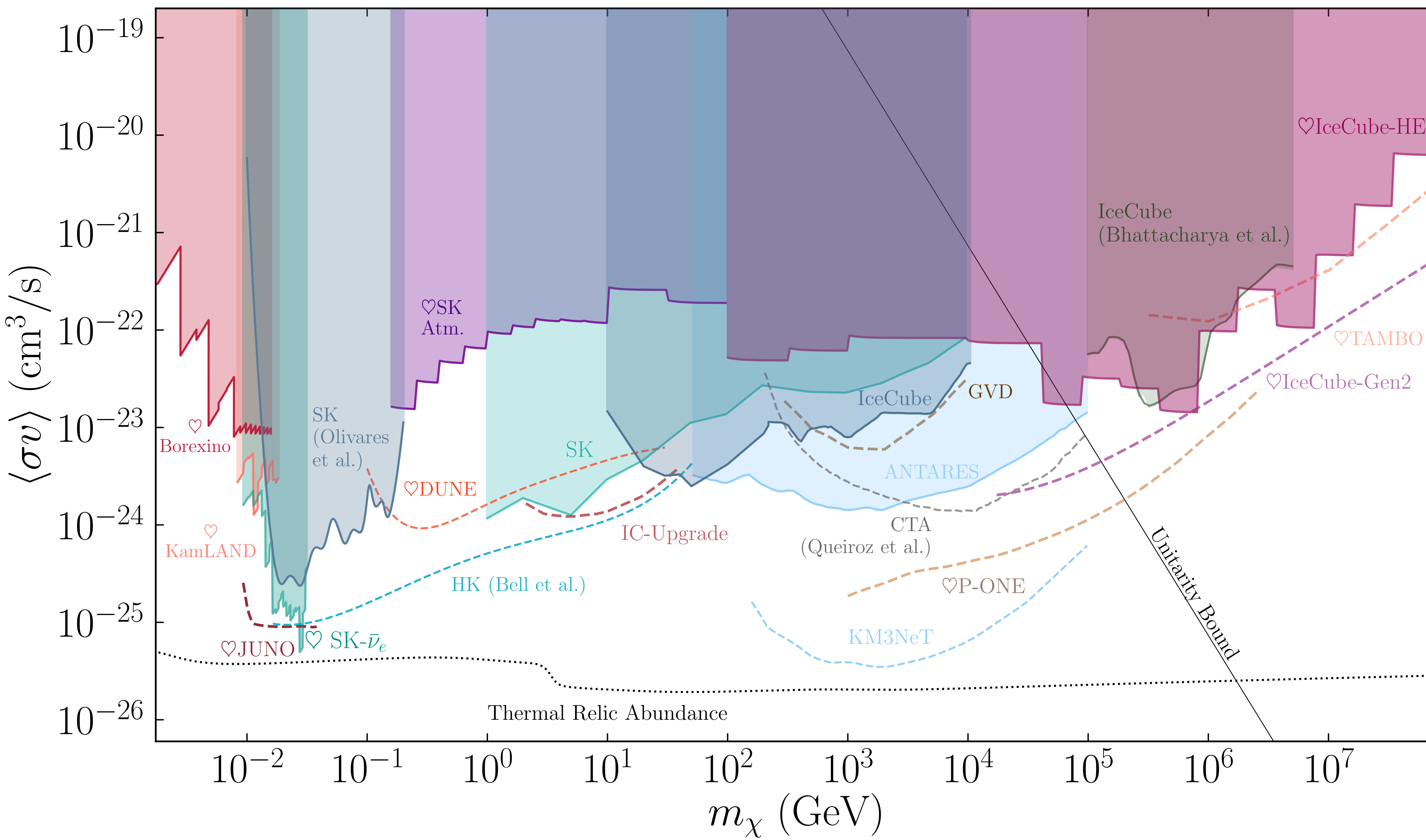
$$\frac{d\Phi_\nu}{dE} = \frac{c}{4\pi}\frac{\Omega_{DM}^2\rho_{crit}^2\langle\sigma v\rangle}{2m_\chi^2}\int_0^{z_{up}} dz\frac{\left(1+G(z)\right)(1+z)^3}{H(z)}\frac{dN_\nu(E')}{dE}$$

Neutrinos Signal from DM Annihilation



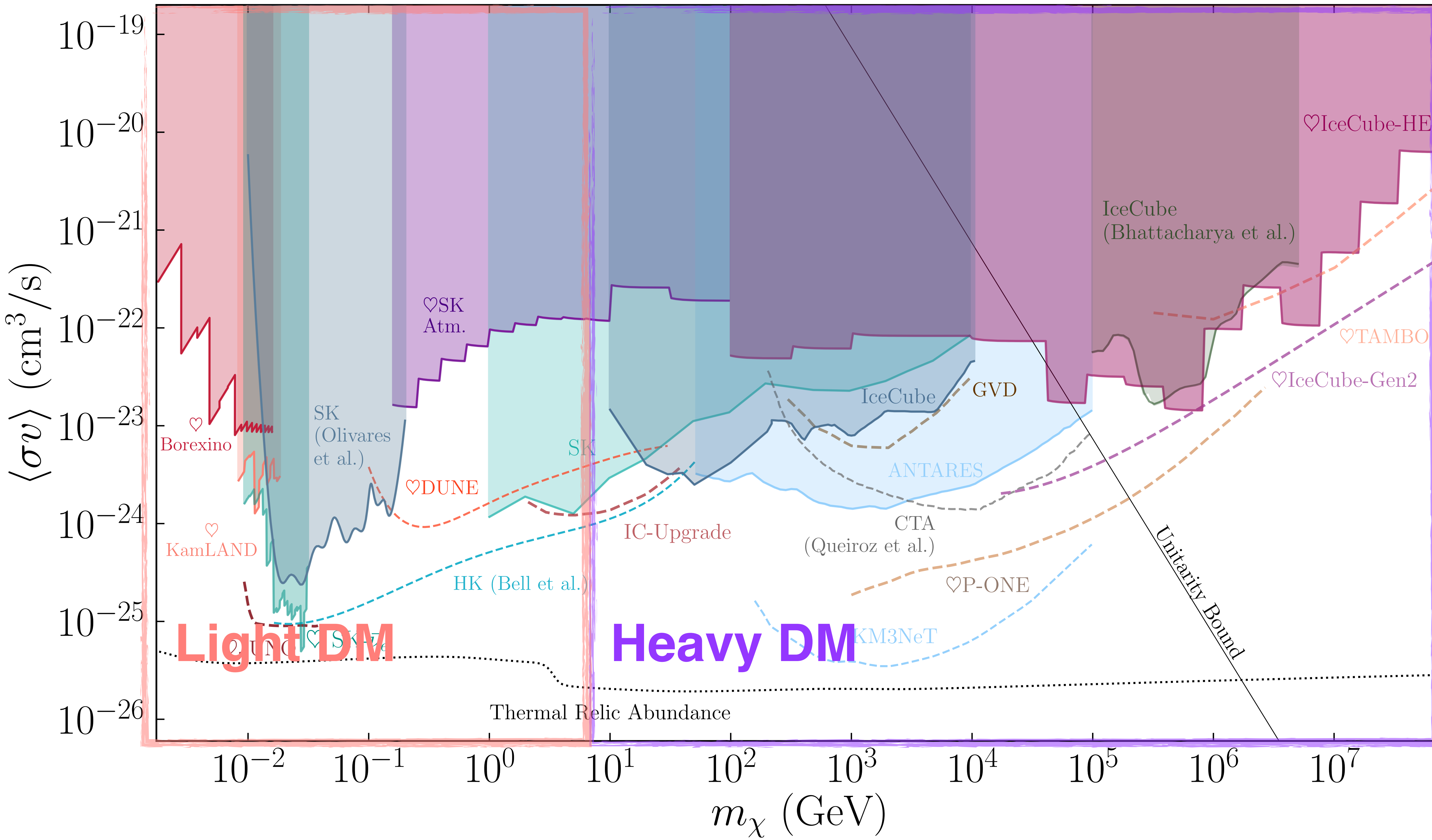
Direct DM annihilation to neutrinos would create spikes in atmospheric and cosmic neutrino flux

Constraining the DM parameter space

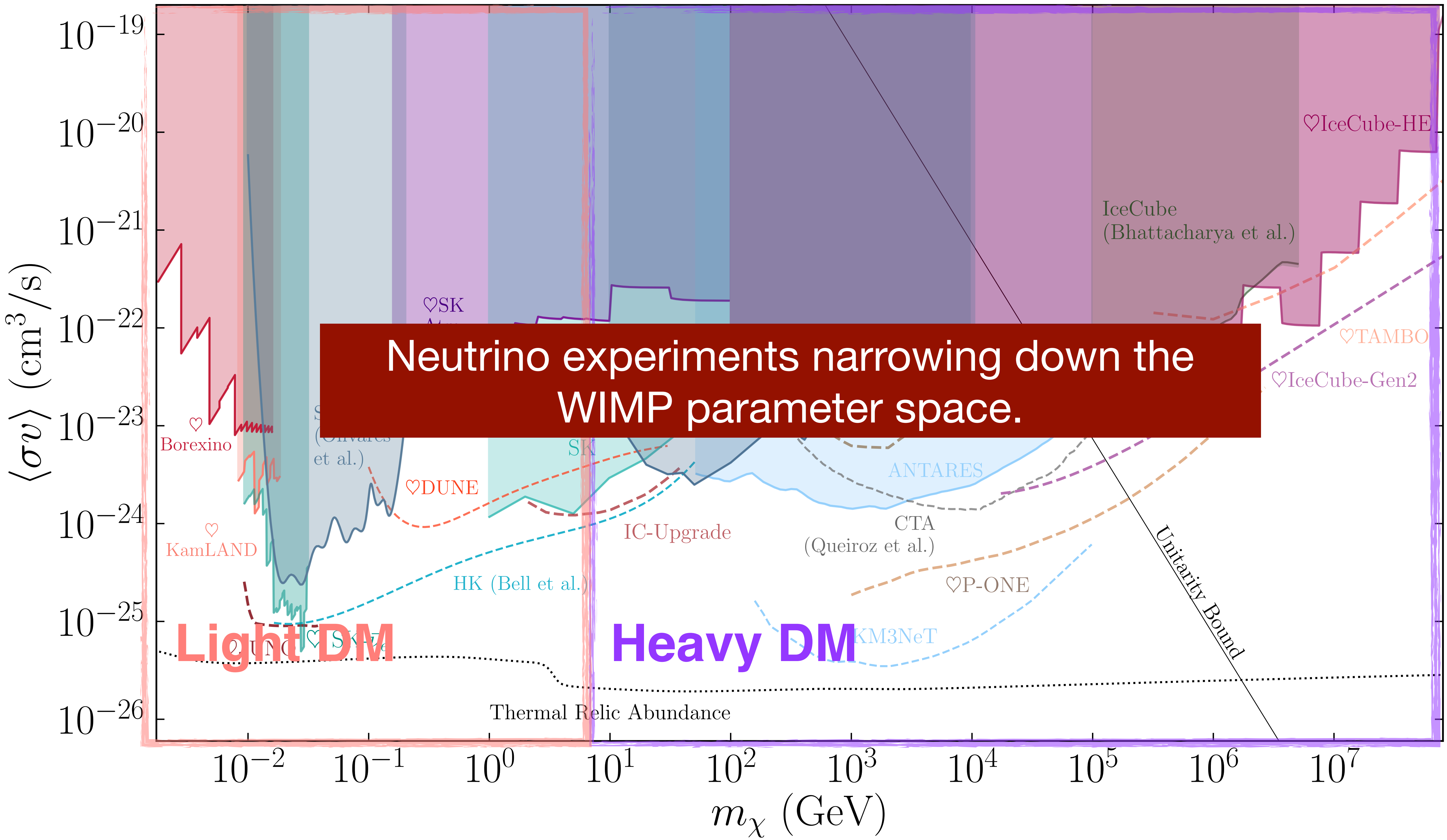


Argüelles, Diaz, **AK**, Safa, Olivares-Del-Campo, Vincent, 1912.09486

Constraining the DM parameter space

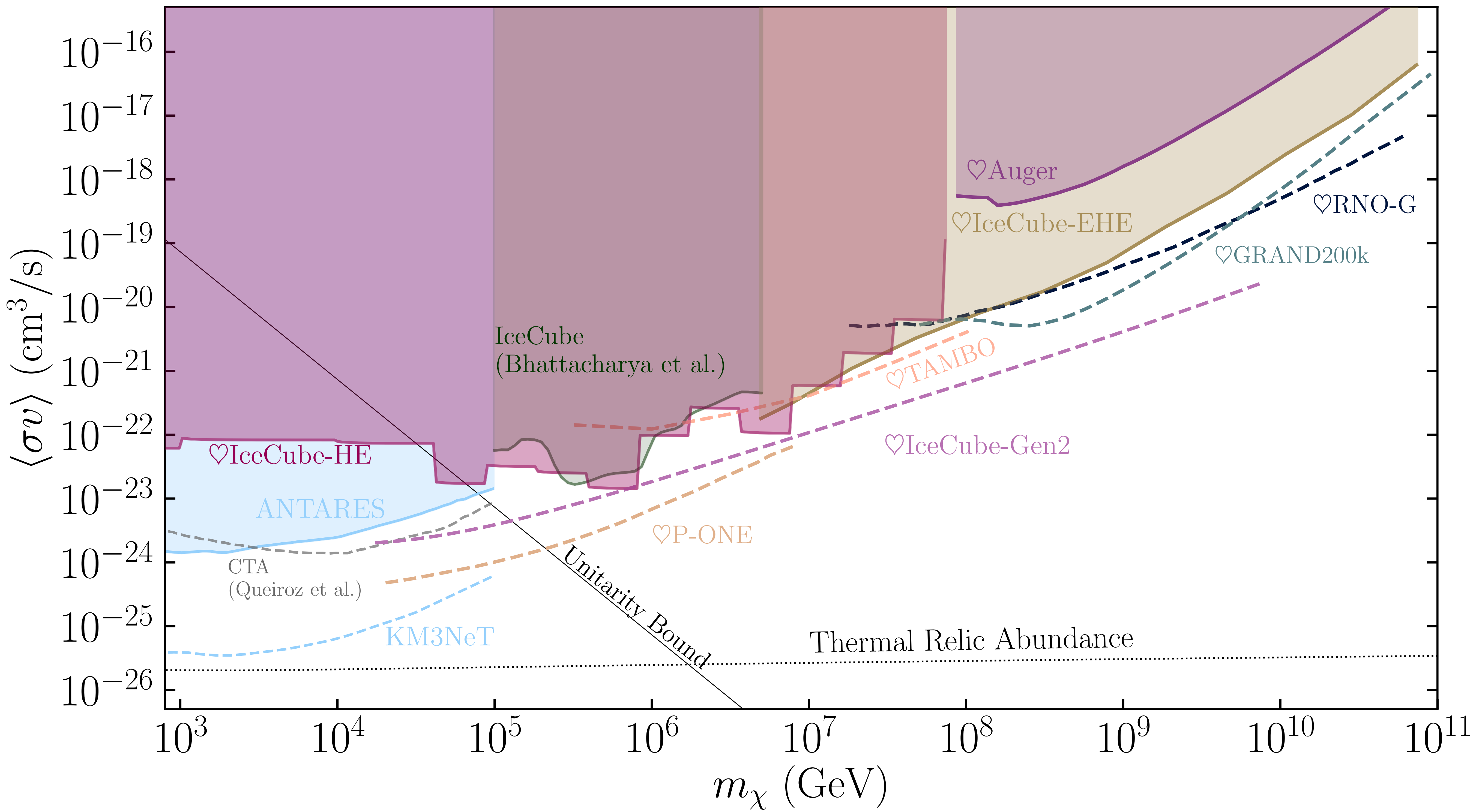


Constraining the DM parameter space



Argüelles, Diaz, **AK**, Safa, Olivares-Del-Campo, Vincent, 1912.09486

Constraining the DM parameter space
‣ High Mass (only accessible to neutrinos)



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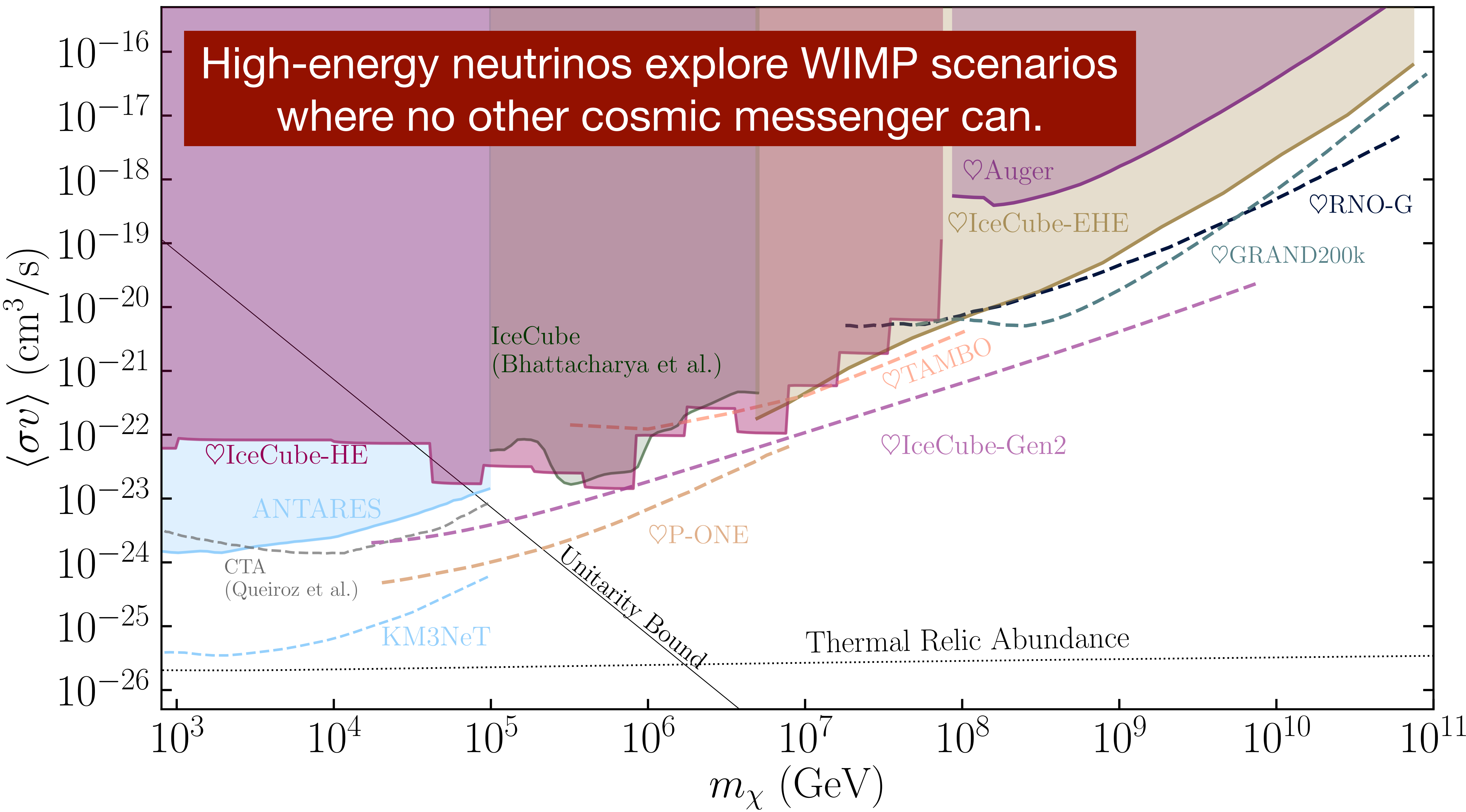
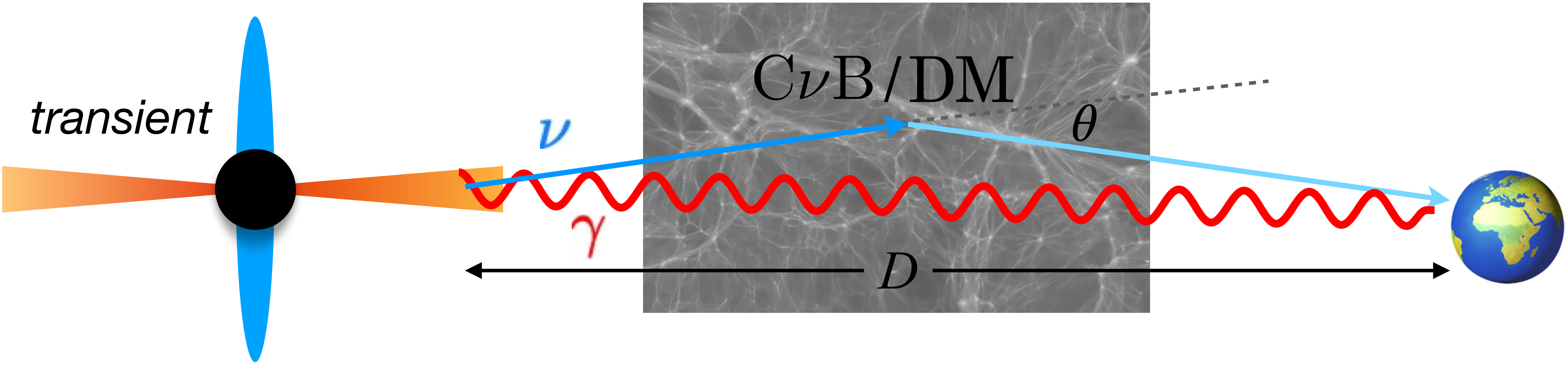


Argüelles, Diaz, **AK**, Safa, Olivares-Del-Campo, Vincent, 1912.09486

BSM induced time delay

Identification of the origin of cosmic neutrinos offer new avenues to probe for new physics.

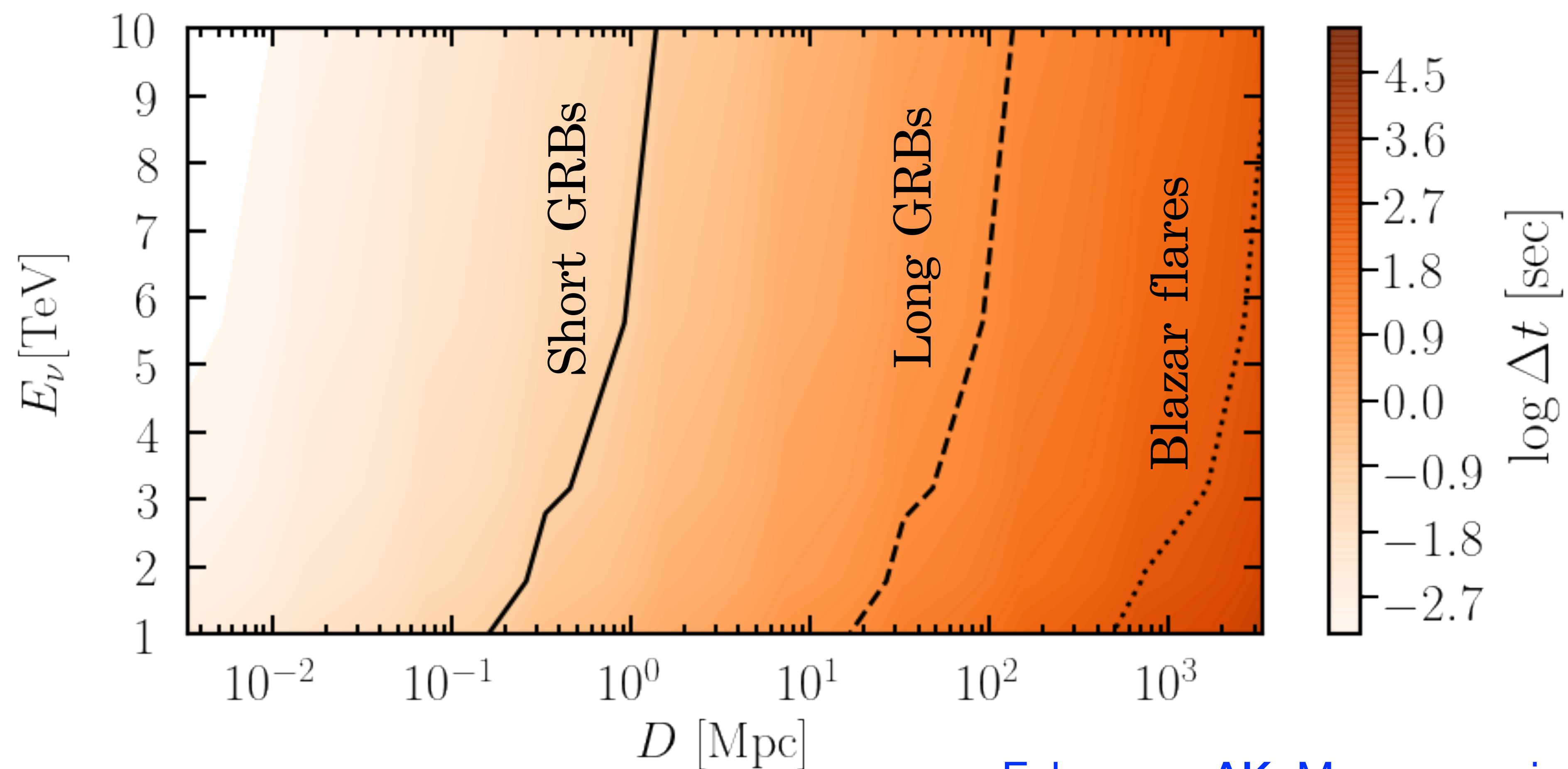
Transients offer exploring the delay induced by neutrino secret interactions.



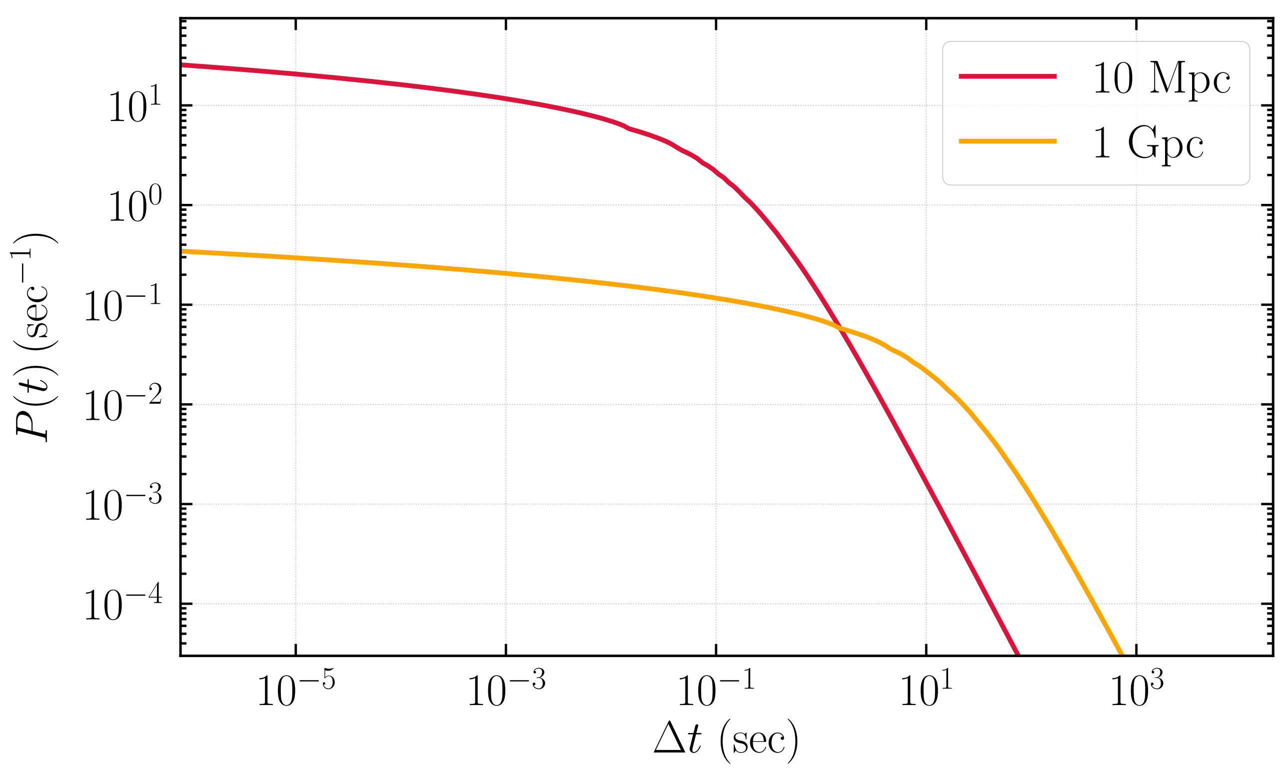
The time difference can be estimated by evaluating the extra distance neutrino has to travel.

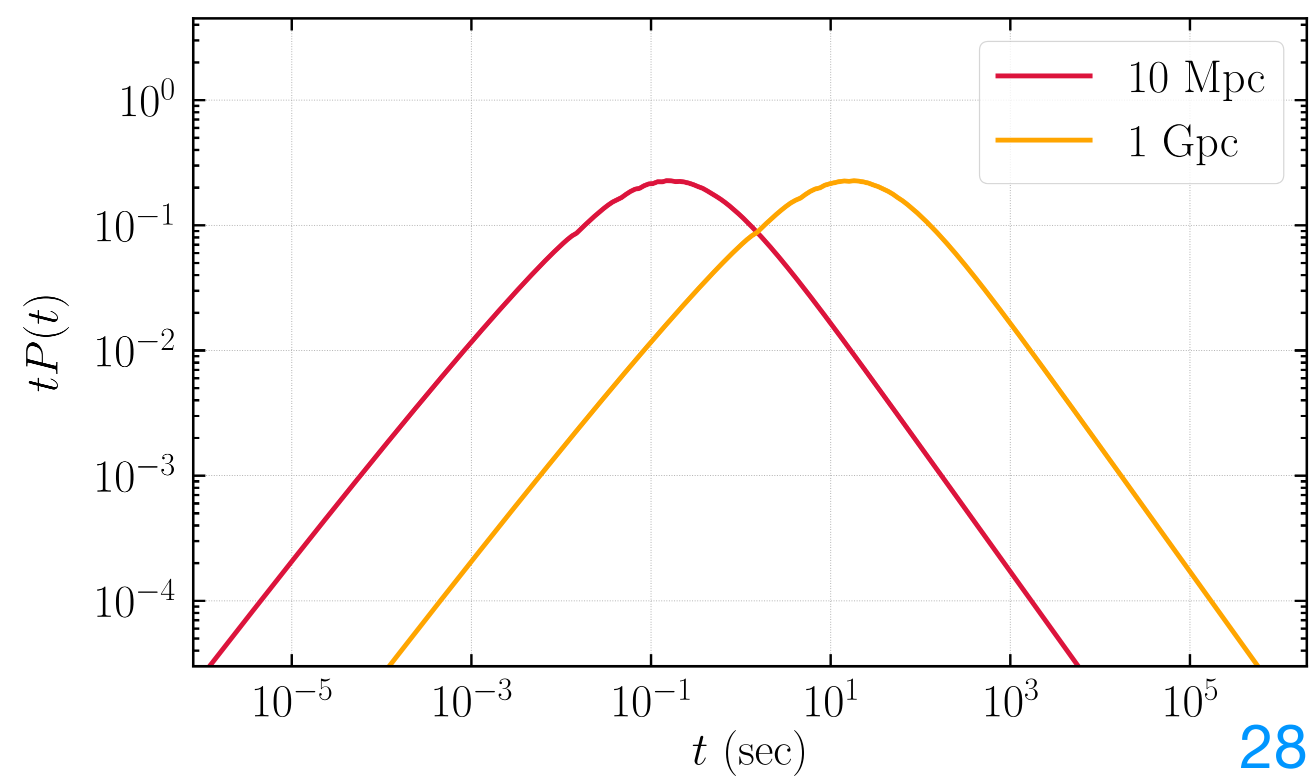
$$t \approx \frac{1}{2}\frac{\langle\theta^2\rangle}{4} D \simeq 77\ \mathrm{s} \left(\frac{D}{3\ \mathrm{Gpc}}\right)\left(\frac{C}{0.6}\right)^2\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

Delay induced by Secret Neutrino Interaction



Eskenasy, **AK**, Murase, arxiv:2020.xxxx

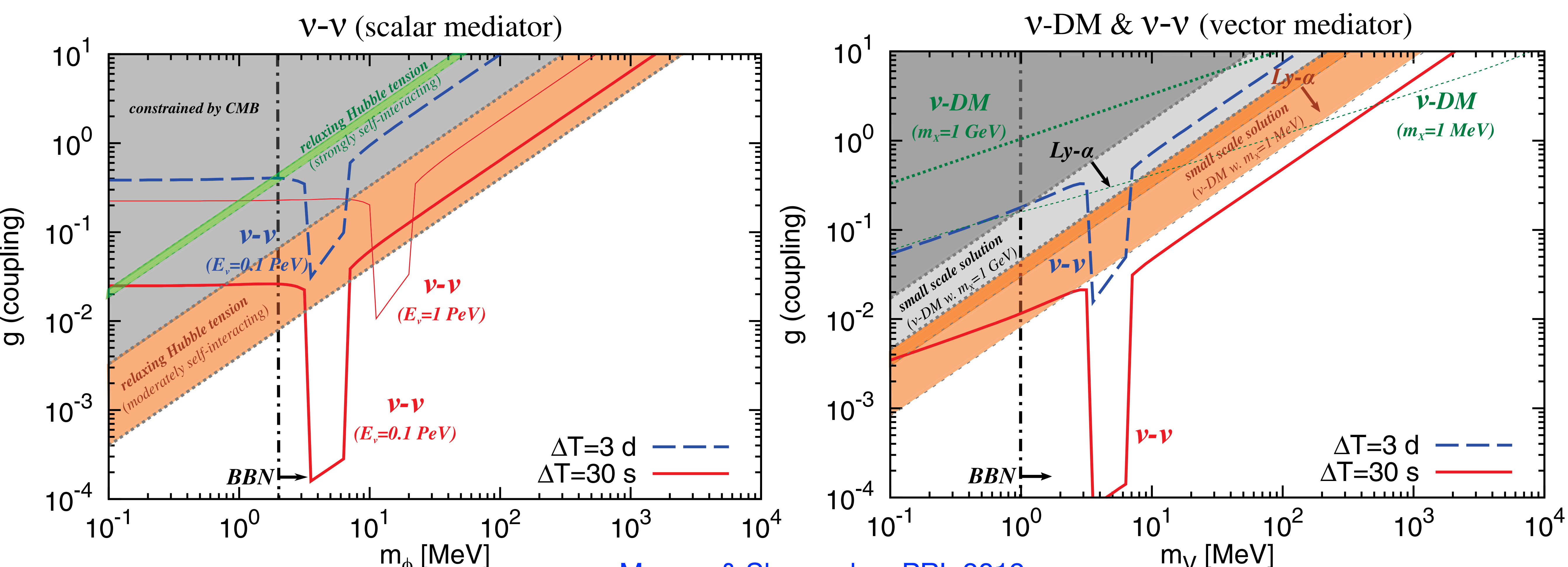




In the absence of delay

Absence of time-delay in a multi messenger observation of a transient will provide upper limit on the strength of neutrino secret interactions:

$$\sigma_{\nu\nu} \leq \frac{2.3}{N_{\text{sig}} n_\nu D}$$



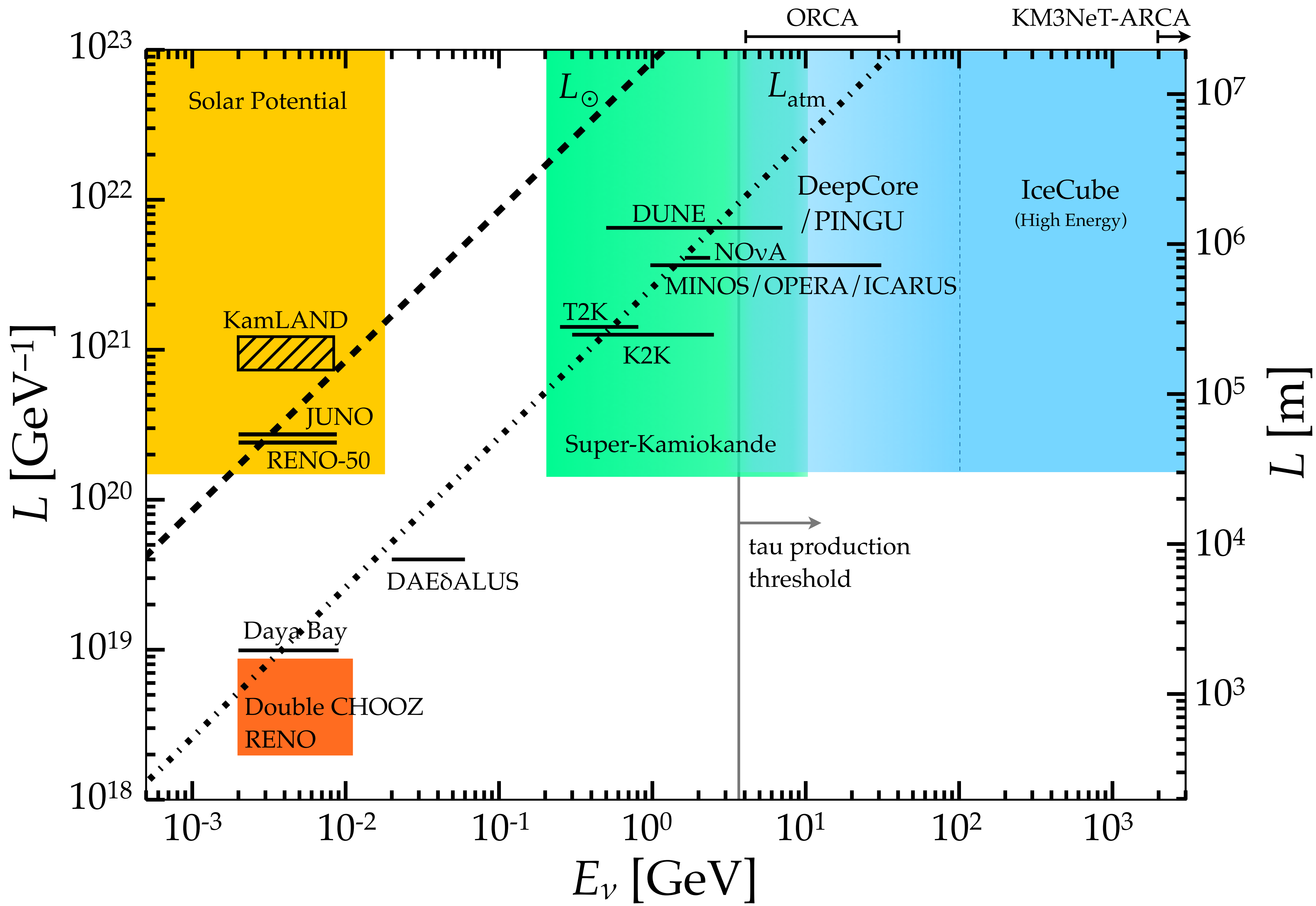
Murase & Shoemaker, PRL 2019

Summary

- High-energy neutrinos can expose the footprints of the physics beyond the Standard Model and provide an insight unattainable by any other sectors.
- High-energy neutrinos are at the intersection of particle physics, astrophysics, and cosmology, presenting an unprecedented opportunity to probe new physics.
- Neutrinos could present the key portal from Standard Model to the dark sector.
- Future neutrino experiments will be closing in on the parameter space of direct dark matter annihilation to neutrinos.

Thanks!

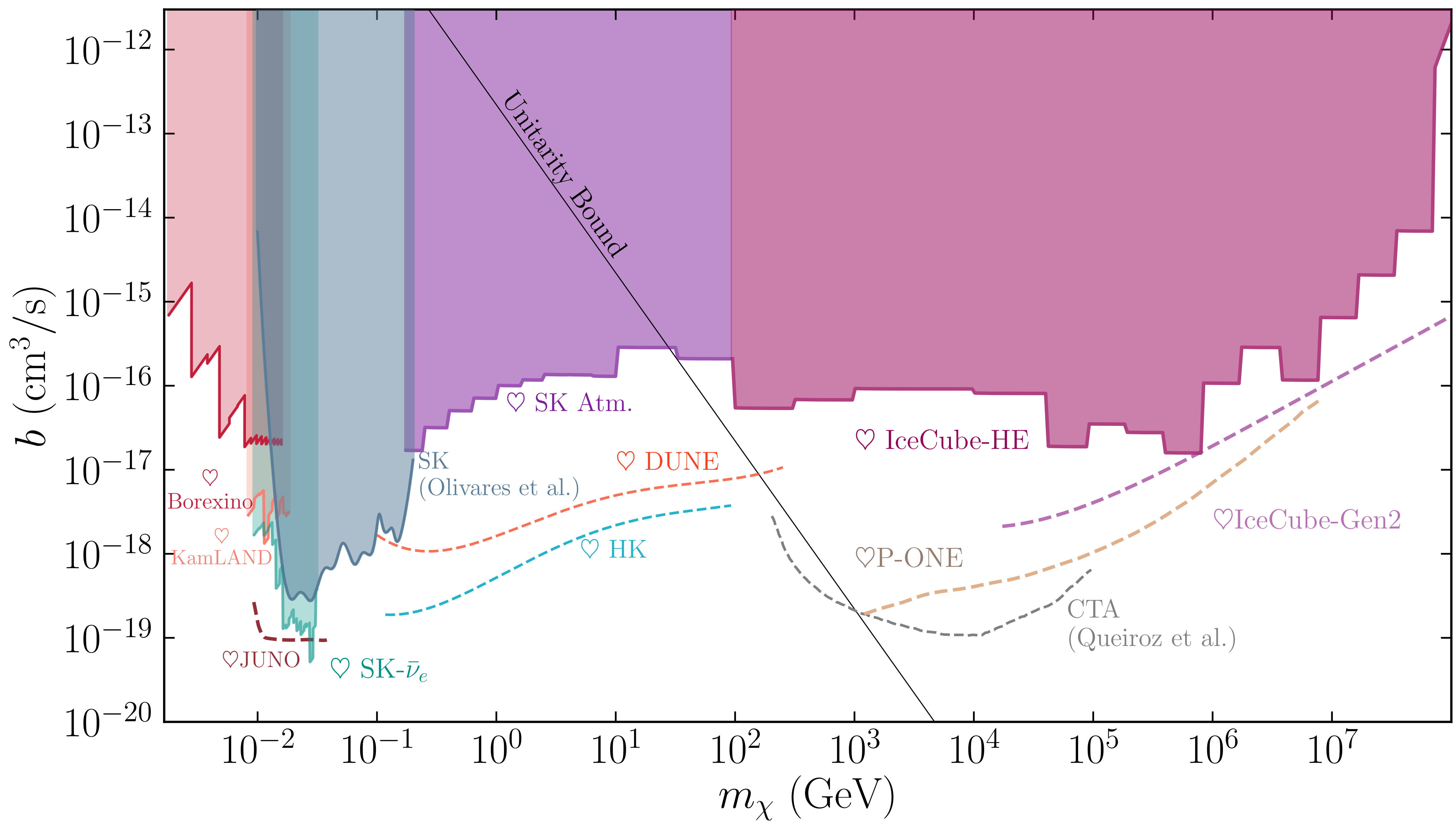
Back up Slides



IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments – essential for constraining new physics

Constraining the DM parameter space

‣ p-wave $< \sigma v >= b(v/c)^2$



Constraining the DM parameter space

▸ d-wave $<\sigma v> = d(v/c)^4$