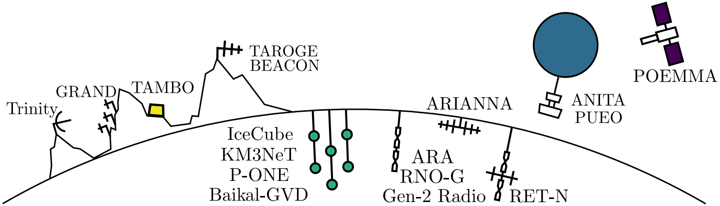
Neutrino telescopes: lessons on particle physics and astrophysics



Ivan Esteban

5th June 2026

EHU
EHU Quantum Center

Introduction

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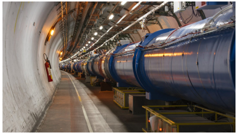
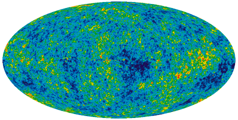
Fundamental physics has made significant progress by going for extremes

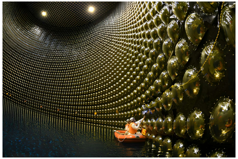
- The highest energies



- The largest distances



- The most quiet environments



High-energy neutrinos

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When talking about neutrinos, high-energy astrophysical neutrinos *(IceCube)* are definitely an extreme.

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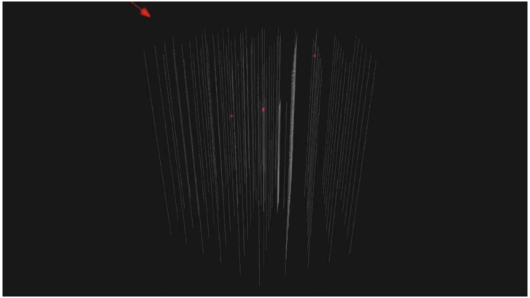

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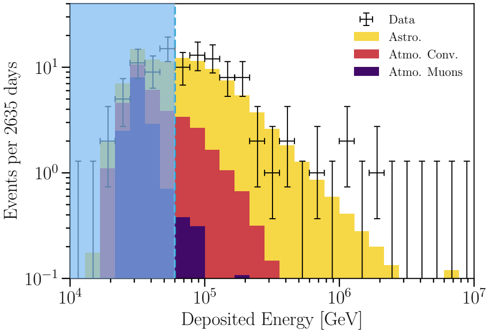
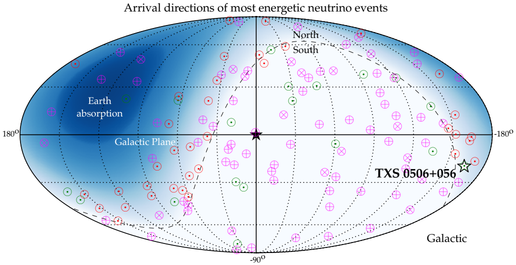


IceCube HESE, 2011.03545



Astro2020, 1903.04334

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Where do they come from?

- Isotropic $\Rightarrow$ **extragalactic** (neutrinos travel *without deflection*)
- Very high energies $\Rightarrow$ naturally produced with **hadronic cosmic rays**

(Magnetic fields, shock waves... naturally present in supernovae or supermassive black holes)

$$p + \gamma_{\rm bkg} \Rightarrow \Delta^+ \Rightarrow n + \pi^+$$

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \Rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \Rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

(Also $p + p$ and other nuclear interactions)

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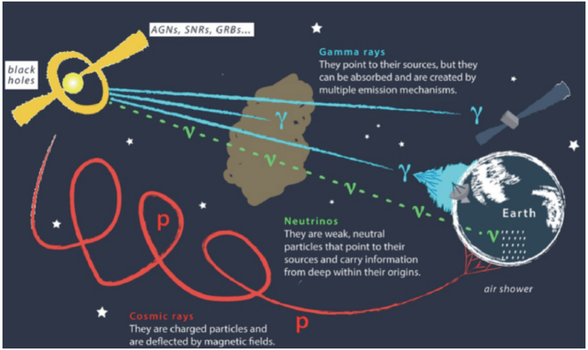
Learning about sources

Neutrino telescopes have the potential to bring **direct, clean information on cosmic-ray acceleration sites!**



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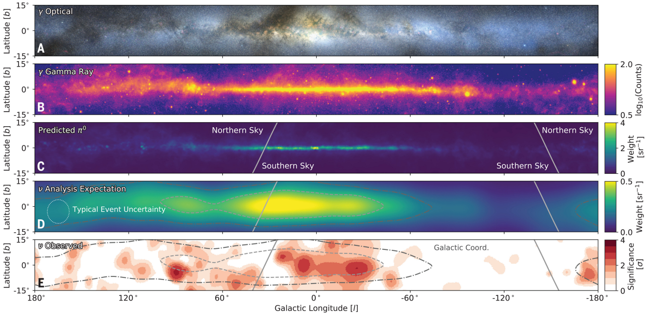
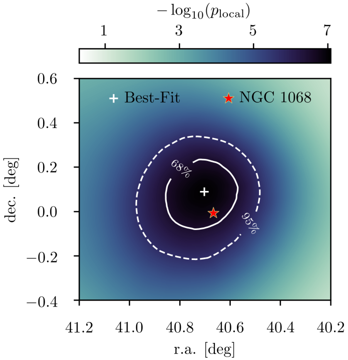
Some successes in astrophysics





Milky Way
arXiv:2307.04427

NGC 1068 (supermassive black hole)
arXiv:2211.09972

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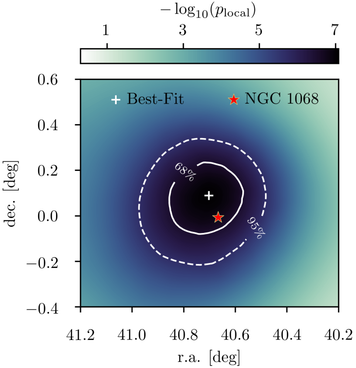
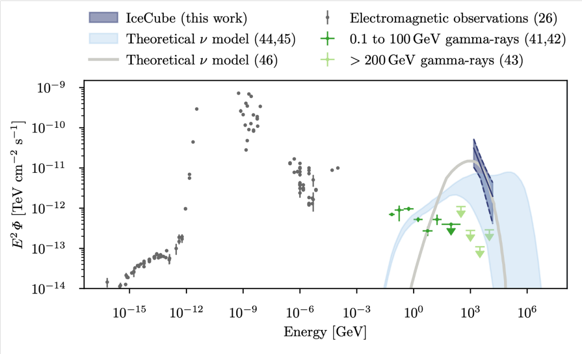
Learning about sources: “dark” sources

NGC1068: no γ rays. . .





are neutrino sources dark (in TeV-γ rays)?

High-energy neutrinos

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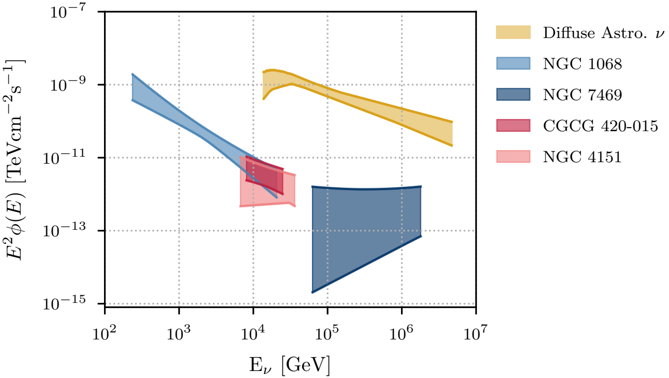
Learning about sources: "dark" sources



IceCube: 2510.13403

Recent evidence for neutrino emission from X-ray-bright AGN.

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Learning about sources: "dark" sources

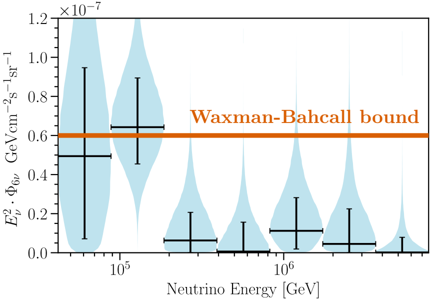
Seems to be consistent with order-of-magnitude estimations. . .

High Energy Neutrinos from Astrophysical Sources: An Upper Bound

Eli Waxman and John Bahcall

We show that cosmic-ray observations set a model-independent upper bound of $E_\nu^2\Phi_\nu < 2\times10^{-8}\mathrm{GeV/cm^2\,s\,sr}$ to the intensity of high-energy neutrinos produced by photo-meson (or p-p) interactions in sources of size not much larger than the proton photo-meson (or p-p) mean-free-path. This bound applies, in particular, to neutrino production by either

Waxman, Bahcall; 1998



(The Waxman-Bahcall bound is optimistic: it assumes many sources at high redshift, proton-dominated cosmic rays, and $\mathcal{O}(1)$ conversion of proton energy into neutrinos.)

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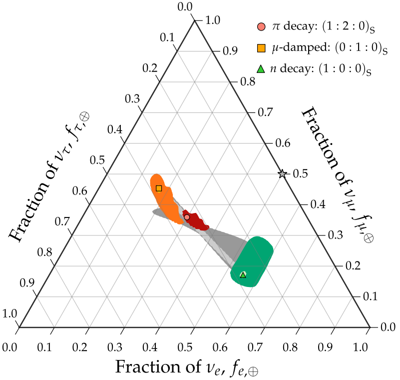
Learning about sources: flavor

Determining neutrino flavor can identify the production mechanism

$$\pi \Rightarrow \nu_\mu + \mu \Rightarrow \nu_\mu + \nu_\mu + \nu_e + e$$

$$\pi \Rightarrow \nu_\mu + \mu$$

$$n \Rightarrow p + e + \nu_e$$



Song et al, 2012.12893

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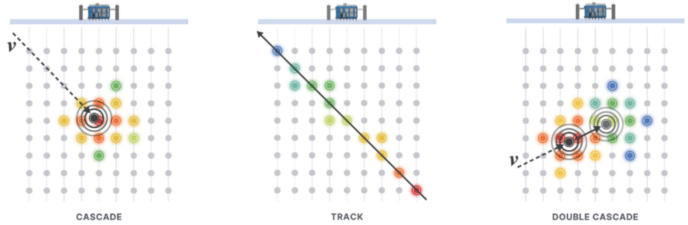
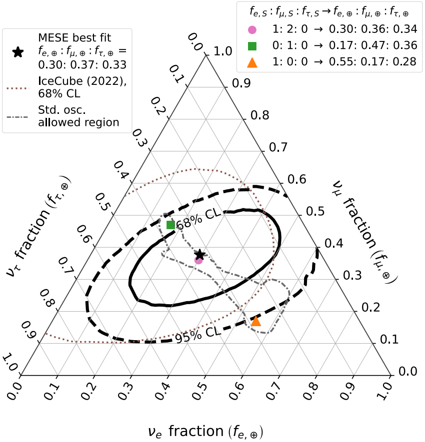
Learning about sources: flavor





IceCube: 2510.24957

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Learning particle physics

How can we learn particle physics if the details of sources and production mechanisms are unknown?

Neutrino interactions within the Standard Model are weak.

The flux should be

$\Rightarrow$ *(Mostly) extragalactic*: largely isotropic.

$\Rightarrow$ *Propagate without attenuation*: comparable to production rates.

$\Rightarrow$ *Flavor can be well-predicted*: with a known flavor structure.

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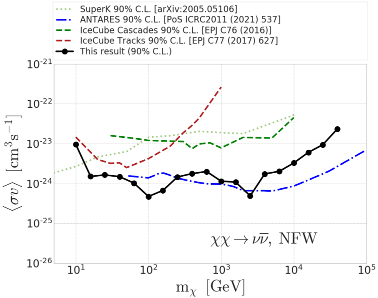
Some successes in particle physics

Dark Matter



IceCube collaboration, 2303.13663

One can look for a (monochromatic) flux from the galactic center

High-energy neutrinos

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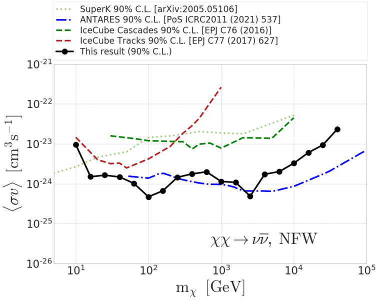
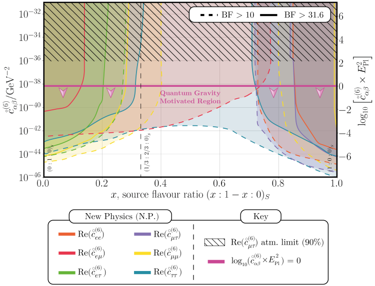
Some successes in particle physics

Dark Matter



IceCube collaboration, 2303.13663

Lorentz Invariance Violation (*flavor*)



IceCube collaboration, 2111.04654

Neutrinos should change flavor in a well-defined way.

One can also look for pulse distortions, see 2408.15949; or for exponential attenuation, see 2605.13955.

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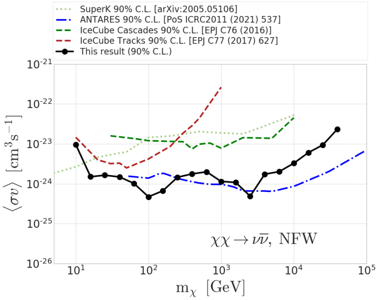
Some successes in particle physics

Dark Matter



IceCube collaboration, 2303.13663

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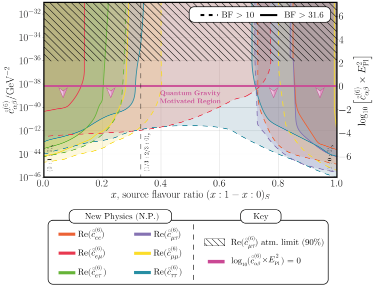
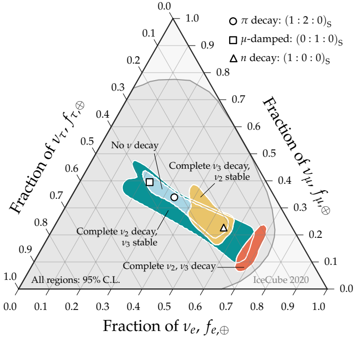


IceCube collaboration, 2111.04654

Neutrino decay (*flavor*)



Valera, Fiorillo, IE, Bustamante, 2405.14826

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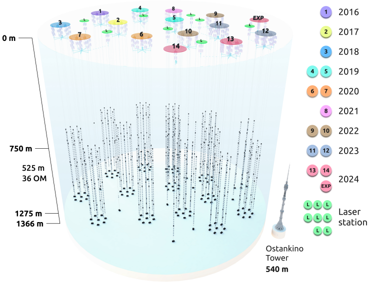
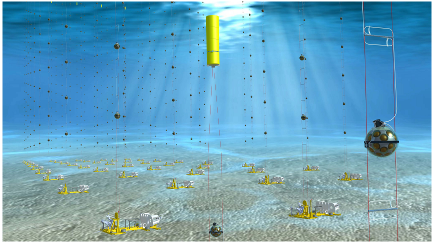
The future is bright





Baikal-GVD, 2412.00164. $\mathcal{O}(0.6\,\mathrm{km}^3)$, 3σ hint.

KM3NET, $\mathcal{O}(0.2\,\mathrm{km}^3)$, analysis underway.

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The future is bright

- Not in the South Pole $\Rightarrow$ better view of the Galactic Center!
  - Astrophysics (e.g., Milky Way emission)
  - Fundamental Physics (e.g., Dark Matter)
- Water $\Rightarrow$ angular resolution!
  - Astrophysics (e.g., point sources)
  - Fundamental Physics (e.g., neutrino decay from point sources)

UHE neutrinos

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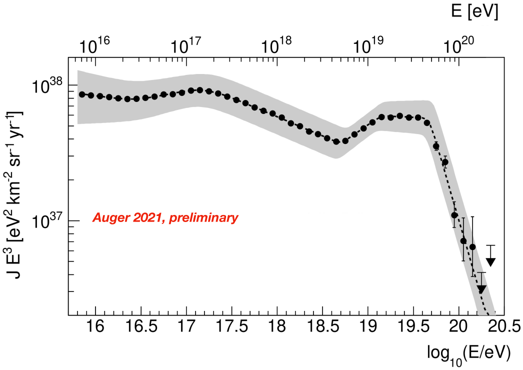
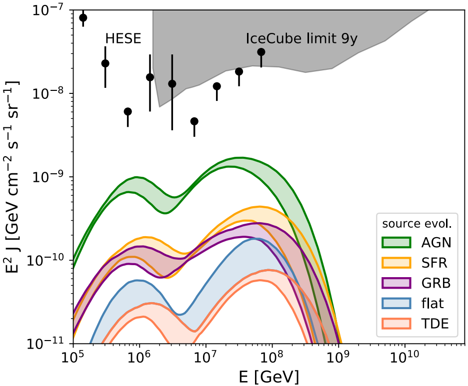
How to get them

Ultra-high energy proton flux ⇒ **Ultra-High Energy neutrino flux**



Auger, ICRC2021



Heinze et al, 1901.03338

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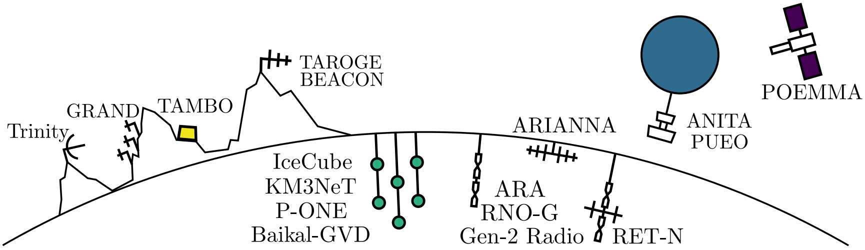
Overall view



Esteban, Prohira, Beacom, 2205.09763

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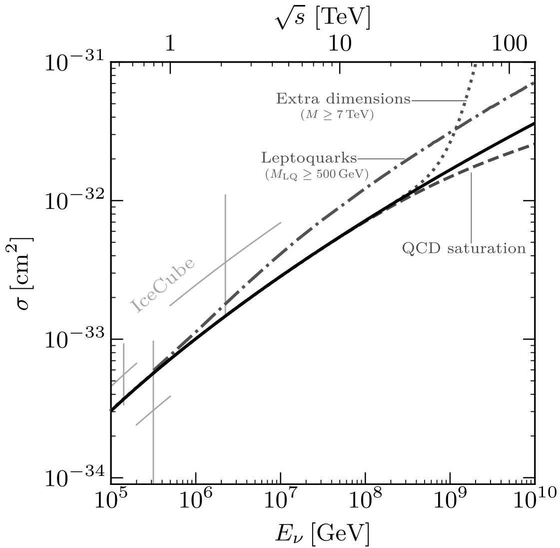
Physics opportunities: cross section

- UHE regime,
  $E_\nu \sim 10^7$–$10^{10}\,\mathrm{GeV}$.
- When they hit a nucleon in our detector,
  $\sqrt{s} = \sqrt{2E_\nu m_\mathrm{N}} \sim$ 5–100 TeV
  beyond collider reach!



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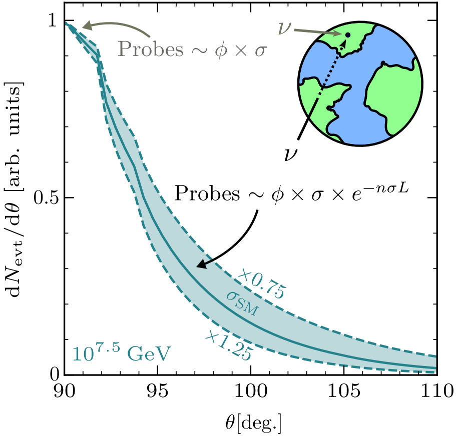
Physics opportunities: cross section

- $\sigma \sim 10^{-32}\,\mathrm{cm}^2$;
  $\lambda \sim \frac{1}{n\sigma} \sim 1000\,\mathrm{km}$!
- Neutrinos get attenuated by Earth with a **characteristic scale set by $\boldsymbol{\sigma}$**.
  Model-independent handle!
- Even few events at the tail contain a lot of information.
  We don't need huge statistics!

Kusenko & Weiler, 2002; Anchordoqui et al, 2002; Jain et al, 2002; Hooper, 2002 . . .



Esteban, Prohira, Beacom, 2205.09763

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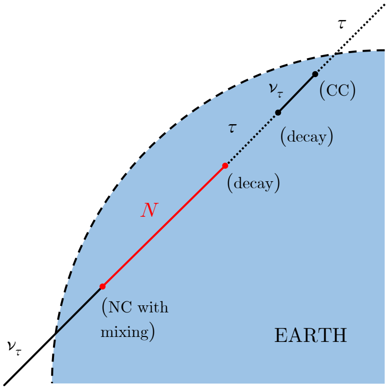
Physics opportunities: anomalous angular distributions

Heighton, Heurtier, Spannowsky, 2303.11352

There should be no Earth-traversing neutrinos



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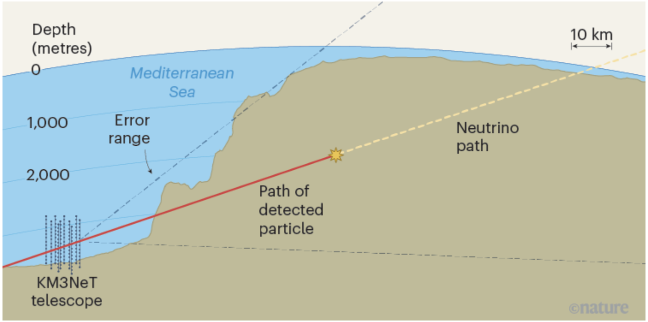
Are we there? KM3NET



UHE neutrinos

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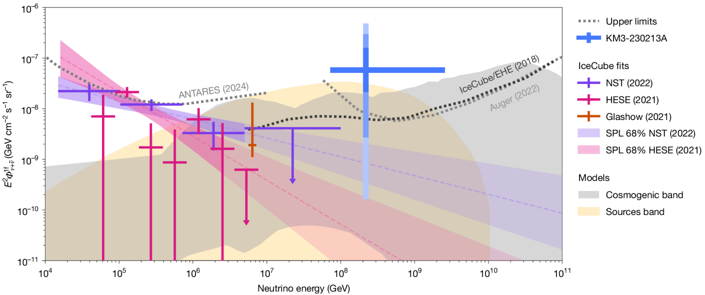

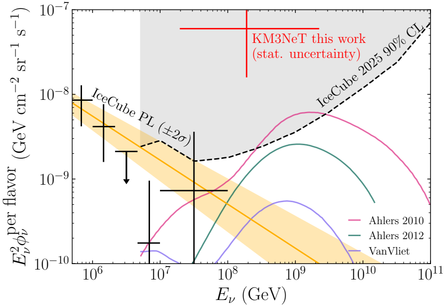

$\sim 3\sigma$ tension, arXiv:2502.08173 (old IceCube limits)

Li et al, arXiv:2502.04508
$> 3\sigma$ unless the source is transient

Can already be used to derive limits on attenuation! (E.g., 2508.02869)

Summary and conclusions

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- We have detected the **highest-energy**, **highest-distance** neutrinos.
  - Great astrophysics (cosmic accelerators)
  - Great particle physics (Dark Matter, Lorentz Invariance, Neutrino Decay ...)

  That are still being understood: stay tuned for **more sources** and **more statistics**.
  It will get better (e.g., Baikal-GVD, KM3NET).

- There should be an even-higher-energy flux!

- Stay tuned for the first events within $\sim$ decade! Or now?