Two topics: neutrinos in multi-messenger and in BSM astrophysics

Hallsie Reno (University of Iowa)

International Neutrino Summer School

UCSB

July 8-9, 2026

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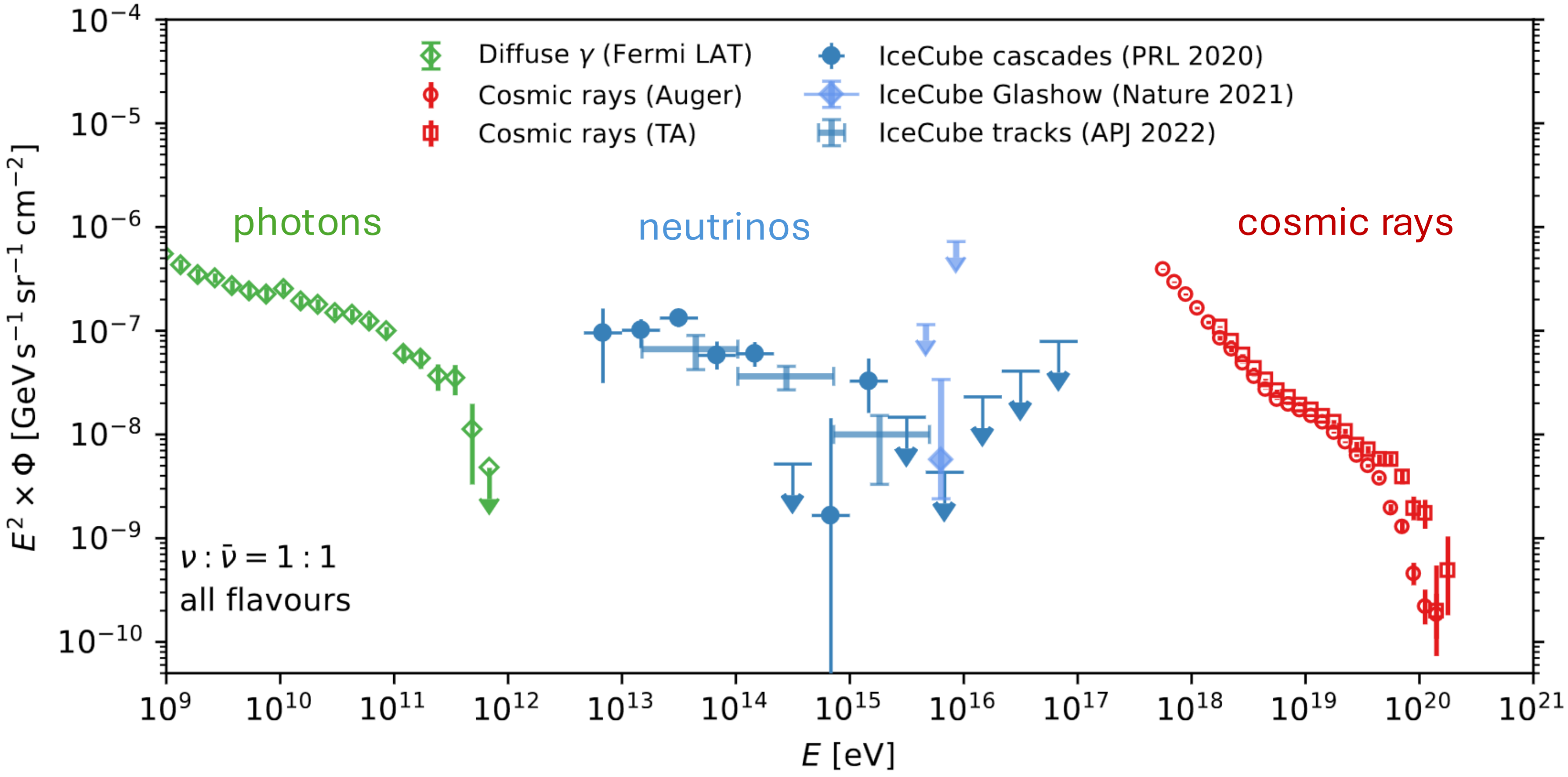
Today

Neutrinos in multi-messenger and BSM astrophysics

- Multi-messenger connections: **cosmic rays and neutrinos**, **neutrinos and photons**, gravitational waves
- Some **BSM neutrino** physics examples with astrophysical neutrinos

Multimessenger connection

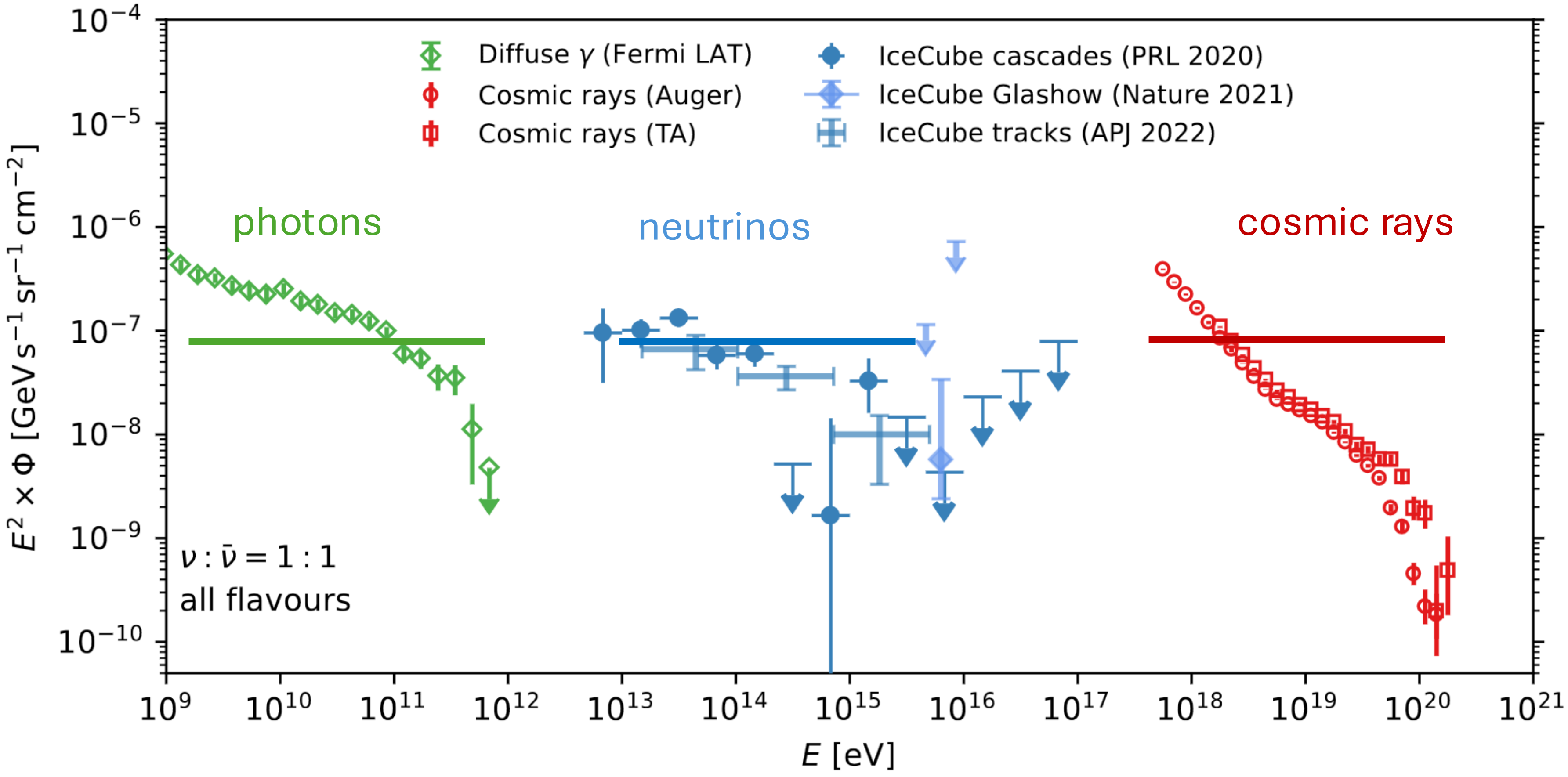
Connections between neutrinos, photons and cosmic rays:



Snowmass white paper: *Ackermann*+, JHEAp 36 (2022) 55-110 https://arxiv.org/pdf/2203.08096

Multimessenger connection

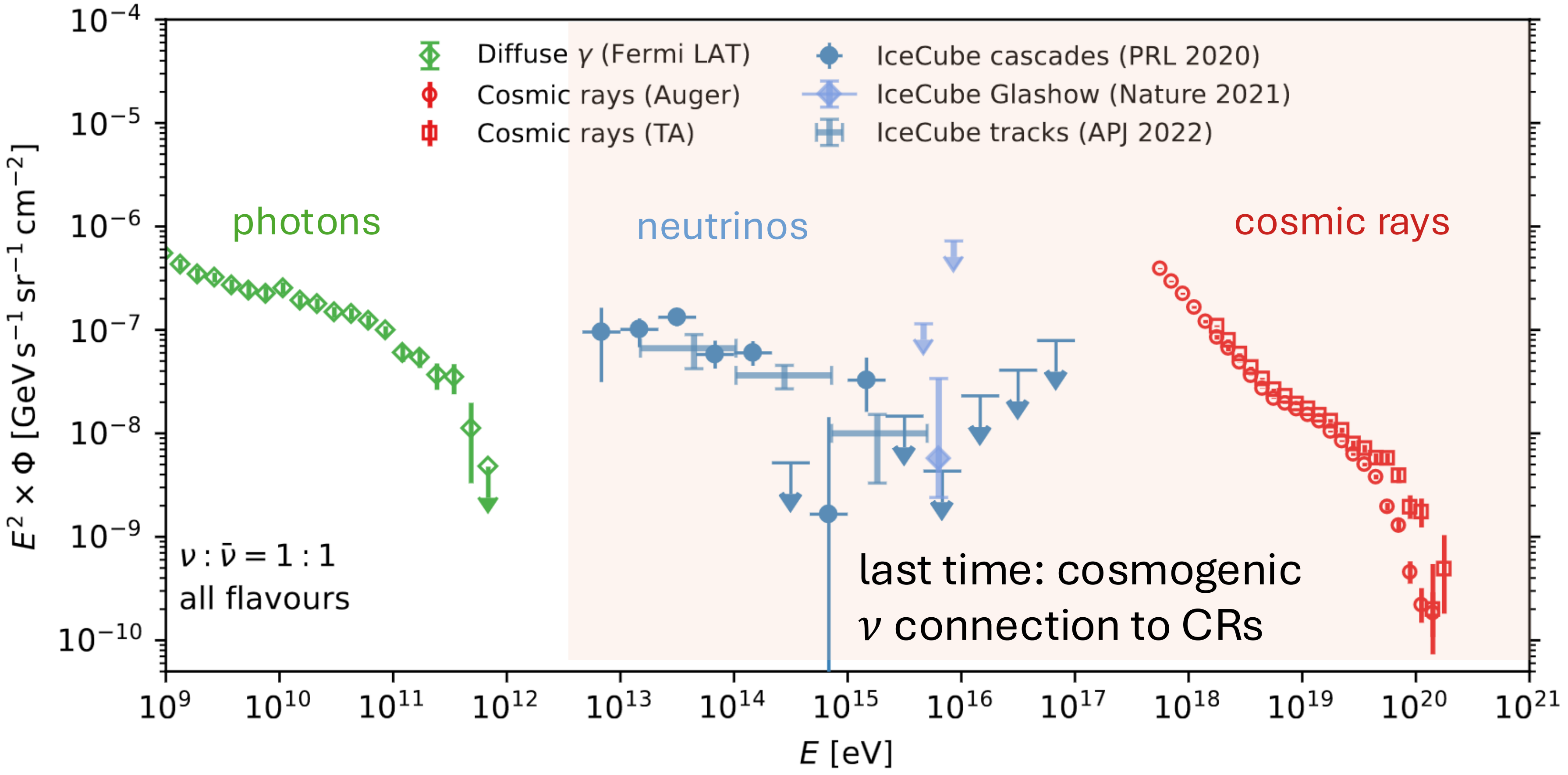
$$E\frac{dN}{d\log(E)} \text{ vs } \log(E)$$



Snowmass white paper: *Ackermann*+, JHEAp 36 (2022) 55-110 https://arxiv.org/pdf/2203.08096

Multimessenger connection

Connections between neutrinos, photons and cosmic rays:



Snowmass white paper: *Ackermann+*, JHEAp 36 (2022) 55-110 https://arxiv.org/pdf/2203.08096

Part 1: multi-messenger particle astrophysics

- More on connections between cosmic ray fluxes and neutrino fluxes from sources.
  - The “Waxman-Bahcall bound”
- Cosmic rays – neutrinos – photons
  - Cosmogenic neutrinos and associated photons (all from cosmic ray interactions with background radiation in transit to Earth.
  - Neutrinos and photons produced by cosmic ray interactions in sources.

Neutrinos & cosmic rays 1

Hooper, *Particle Cosmology and Astrophysics*

Ahlers and Halzen, Prog. Theor. Exp. Phys. 12A105 (2017)

We have seen this before:

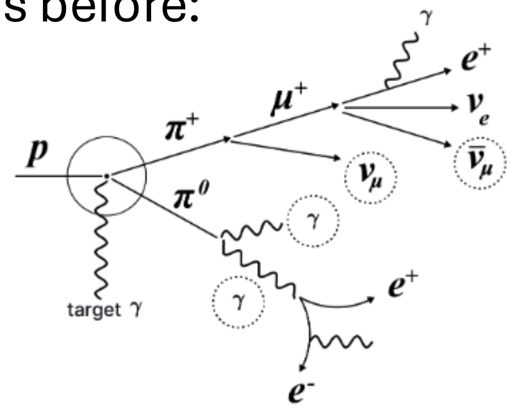


Fig. from Arguelles et al, PRX 15 (2025) 030501

(say)

$$p\gamma \to \Delta^+ \to \begin{matrix} n\pi^+ \\ p\pi^0 \end{matrix}$$

$$\pi^+ \to \mu^+ \nu_\mu$$

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

$$E_\nu \sim E_\pi/4$$

Now relation between energy in cosmic rays and in neutrinos that come from sources of cosmic rays (not CR propagation through CMB). Energy arguments starting with the cosmic ray production rate to get "Waxman-Bahcall bound":

$$Q_N = \frac{\#N}{GeV \cdot sec}$$

energetic cosmic ray (N) production rate

Produce pions with efficiency factor ϵ_π for cosmic ray energy conversion to charged pions:

$$k_\pi = \frac{E_\pi}{E_N} \simeq \frac{1}{5}$$

$$E_\pi^2 Q_{\pi\pm} \simeq \epsilon_\pi\ f_{\pi\pm}[E_N^2 Q_N(E_N)]_{E_N = E_\pi/k_\pi}$$

$$f_{\pi\pm} = N_{\pi\pm}/N_\pi$$

Neutrino (all-flavor) production rate related to the pion production rate:

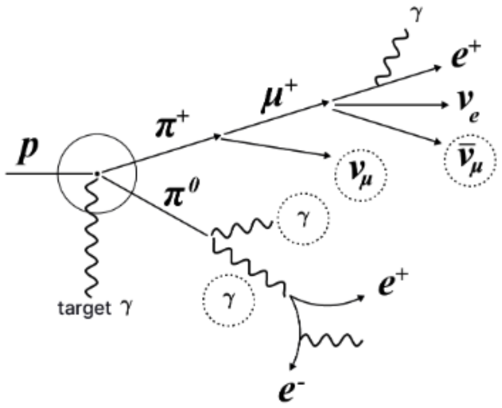
$$E_\nu Q_\nu \simeq\ 3[E_\pi Q_{\pi\pm}(E_\pi)]_{E_\pi = E_\nu/f_\nu}$$

$$f_\nu = \frac{E_\nu}{E_\pi} \simeq \frac{1}{4}$$

Neutrinos & cosmic rays 2

Hooper, *Particle Cosmology and Astrophysics*

Ahlers and Halzen, Prog. Theor. Exp. Phys. 12A105 (2017)



Take the neutrino production at the source, sum over all sources for all times (redshifts):

$$E_\nu^2 \phi_\nu \simeq \frac{3}{4\pi}\int \left.\frac{E_N^2 Q_N}{V}\right|_{z=0} f(z)\, \epsilon_\pi\, f_{\pi\pm}\, f_\nu\, \frac{dt}{dz}\, dz (1+z)^{-1}$$

$\frac{E_N^2 Q_N}{V} \simeq 10^{44}$ erg/Mpc^{-3}yr^{-1}

energy in CRs now | source evolution | cosmic evolution

$$\frac{dt}{dz} = -[H(z)(1+z)]^{-1}$$

High-energy neutrinos from astrophysical sources: An Upper bound #5

Eli Waxman (Princeton, Inst. Advanced Study), John N. Bahcall (Princeton, Inst. Advanced Study) (Jul, 1998)

Published in: *Phys.Rev.D* 59 (1999) 023002 • e-Print: hep-ph/9807282 [hep-ph]

pdf DOI cite claim reference search 1,195 citations

Neutrinos & cosmic rays 3

$$E_\nu^2\phi_\nu \simeq \frac{3}{4\pi}\int \frac{E_N^2 Q_N}{V}\Big|_{z=0} f(z)\,\epsilon_\pi\, f_{\pi\pm}\, f_\nu\, \frac{dt}{dz}\,dz(1+z)^{-1}$$

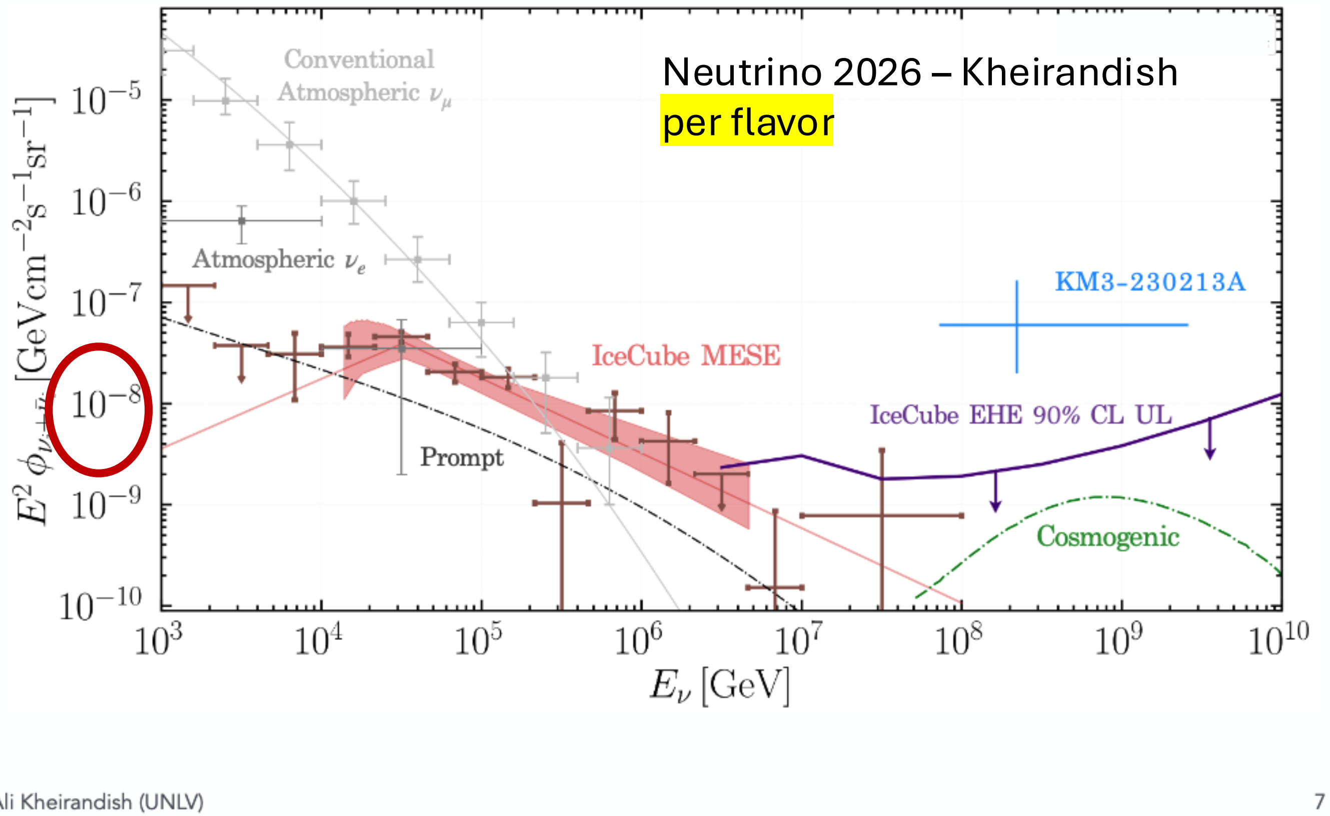
$$\simeq 6\times 10^{-8}\,\frac{\epsilon_\pi}{1}\cdot\frac{f_{\pi\pm}}{0.5}\cdot\frac{f_\nu}{0.25}\cdot\xi \quad \text{GeV/cm2/s/sr}$$

all flavors

"Waxman-Bahcall bound" for $\epsilon_\pi = 1$.

- $\xi \sim 1-6$ accounts for source evolution
- assumes E^{-2} CR flux at source
- assumes pure proton
- assumes magnetic fields don't change the flux of observed extragalactic CRs

Reference point on y-axis:
10^{-8}
This scale, with km-cubed detector gives events on 1 year time-scale.



Neutrinos & cosmic rays 4

”Bounds” → “Landmarks” because of dependence on assumptions.

Murase & Beacom, PRD 81 (2010) 123001
Muzio, Eur Phys J Spec Top 234 (2025) 234

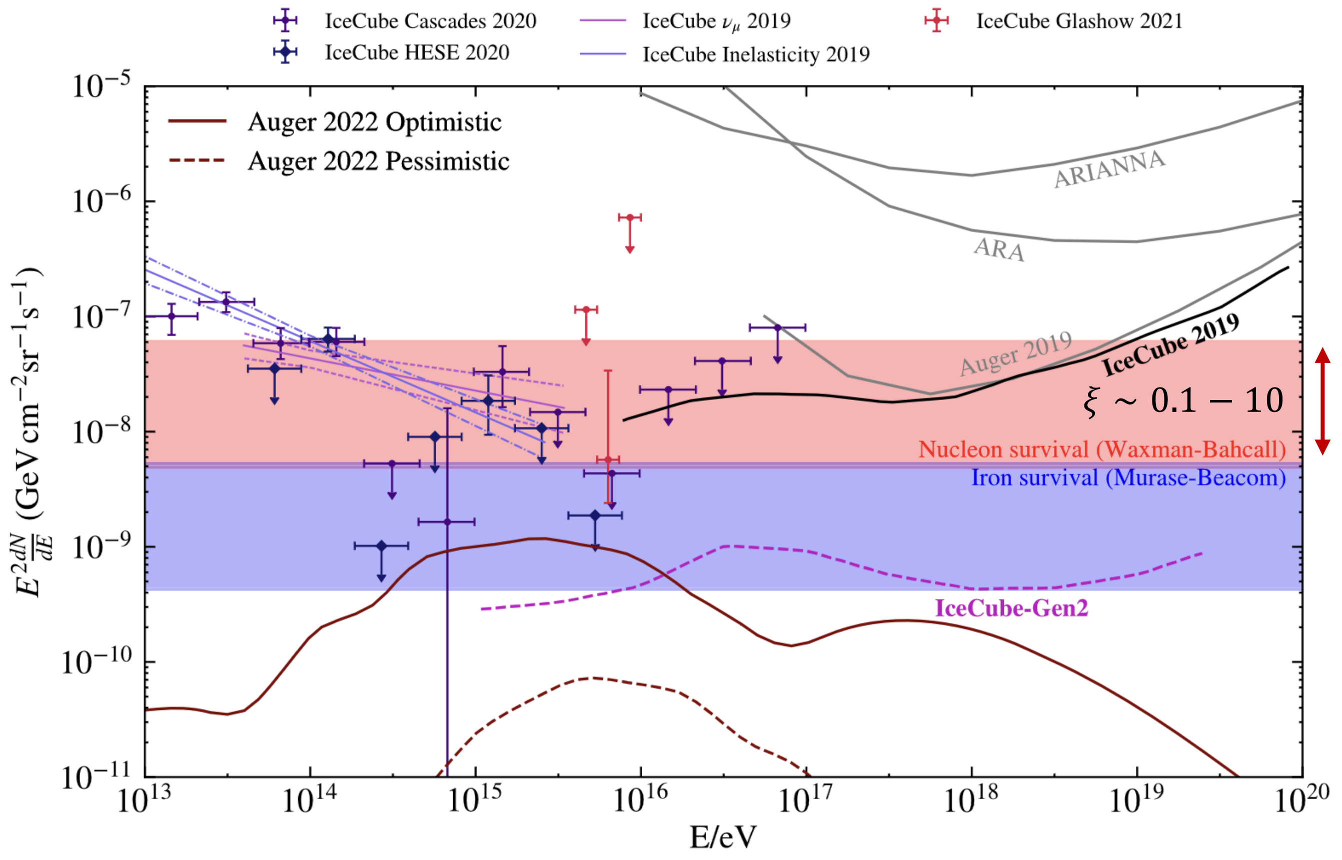


Fig. from Muzio, Eur Phys J Spec Top 234 (2025) 234

- Photodisintegration of nuclei more important than pion production in sources, so lower range of upper bounds.
- Optimistic & pessimistic ”neutrino floor” refer to source evolution for cosmogenic neutrinos based on Auger flux.
- Assume that cosmic rays can emerge from sources to come to Earth – none are reprocessed to lower energies after (maybe copious) neutrino production.

Neutrinos & photons & cosmic rays

At production: $$E_\nu^2\, Q_{\nu_i}(E_\nu) \simeq \frac{f_{\pi\pm}}{4(1-f_{\pi\pm})}\left[E_\gamma{}^2 Q_\gamma\left(E_\gamma\right)\right]_{E_\gamma = 2E_\nu}$$

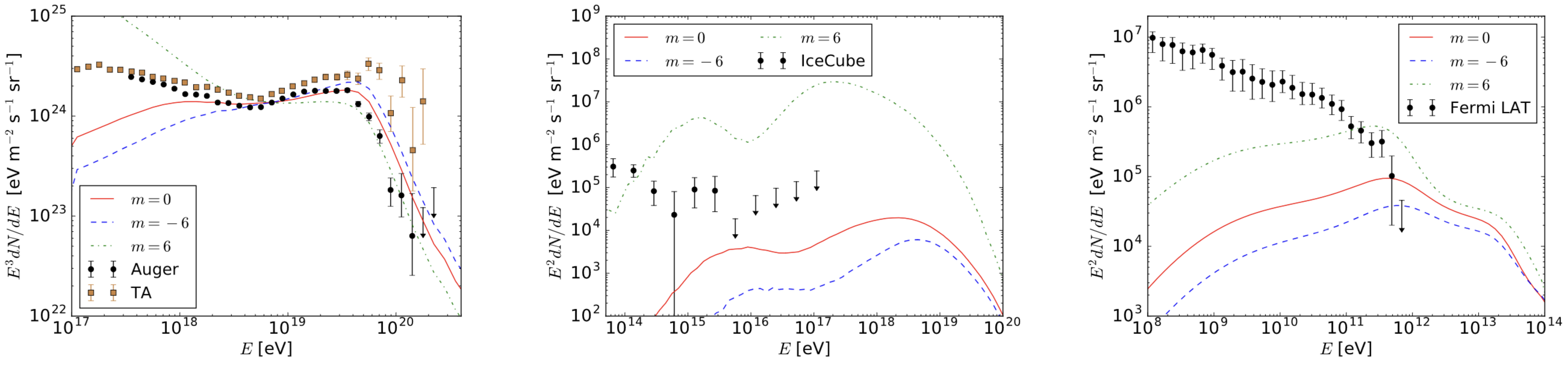
ratio of charged to neutral pions, and $\frac{1}{4} = \frac{E_\nu}{E_\gamma} \cdot \frac{2\,\gamma}{4\,\nu}$

Cosmogenic neutrino flux and cosmogenic photon flux from CR scattering with background photons.

Ahlers and Halzen, Prog. Theor. Exp. Phys. 12A105 (2017)

Cosmic rays, neutrinos & photons (cosmogenic)

cosmogenic neutrinos and photons



(a) Cosmic rays (b) Neutrinos (c) Photons

Figs from van Vliet et al, 1609.03336

all proton, E_{cut}=200 EeV, $\alpha = 2.5$, z_{max}=6

Diffuse gamma-ray flux constrains parameters as well – here source evolution $S(z) = (1+z)^m, m = 6$ is bad in far right plot!

Neutrinos & photons & cosmic rays

At production, per flavor: $$E_\nu^2\, Q_{\nu_i}(E_\nu) \simeq \frac{f_{\pi\pm}}{4(1-f_{\pi\pm})}\left[E_\gamma^{\,2} Q_\gamma\left(E_\gamma\right)\right]_{E_\gamma=2E_\nu}$$

ratio of charged to neutral pions, and $\frac{1}{4} = \frac{E_\nu}{E_\gamma} \cdot \frac{2\,\gamma}{4\,\nu}$

Cosmogenic neutrino flux and cosmogenic photon flux from CR scattering with background photons.

Within sources:

- There is an additional energy dependence of the photon targets for $p\gamma$ and $\gamma\gamma$interactions.
- Photons may not get out of the source

Ahlers and Halzen, Prog. Theor. Exp. Phys. 12A105 (2017)

Example of neutrinos & photons (diffuse astrophysical)

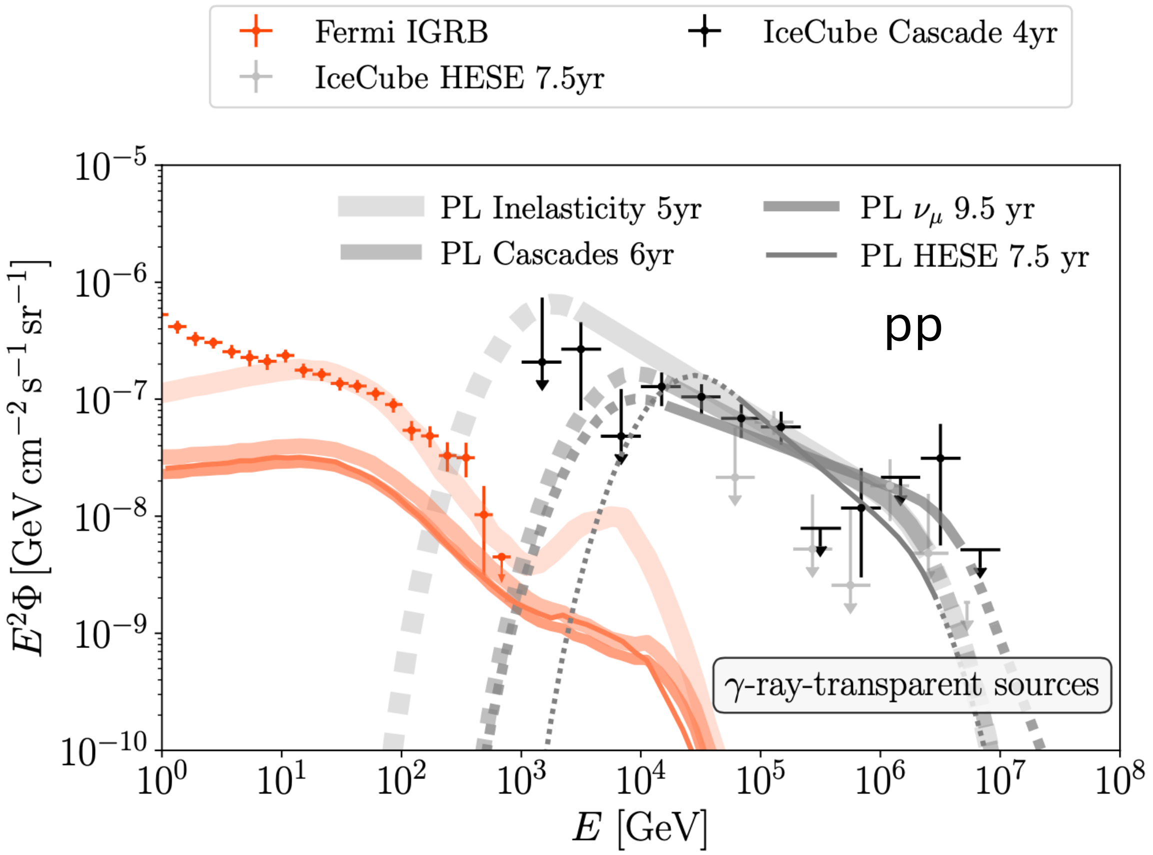


Fig. from Fang et al, Ap J 933 (2022) 190, see also Arguelles et al, 2405.17623, *Phys.Rev.X* 15 (2025) 3, 030501

- dashes show extrapolations below IceCube measured region
- use relation between photon and neutrino fluxes from sources, **no photon attenuation in sources**
- include star formation rate
- propagate photons through background
- little to no room to accommodate photon production not associated with neutrinos
  - gamma-ray transparent sources unlikely to dominate neutrino sources
  - look for lower energy photons from these sources

Fermi data may include unresolved sources at the 60% level.

Example of neutrinos & photons (diffuse astrophysical)

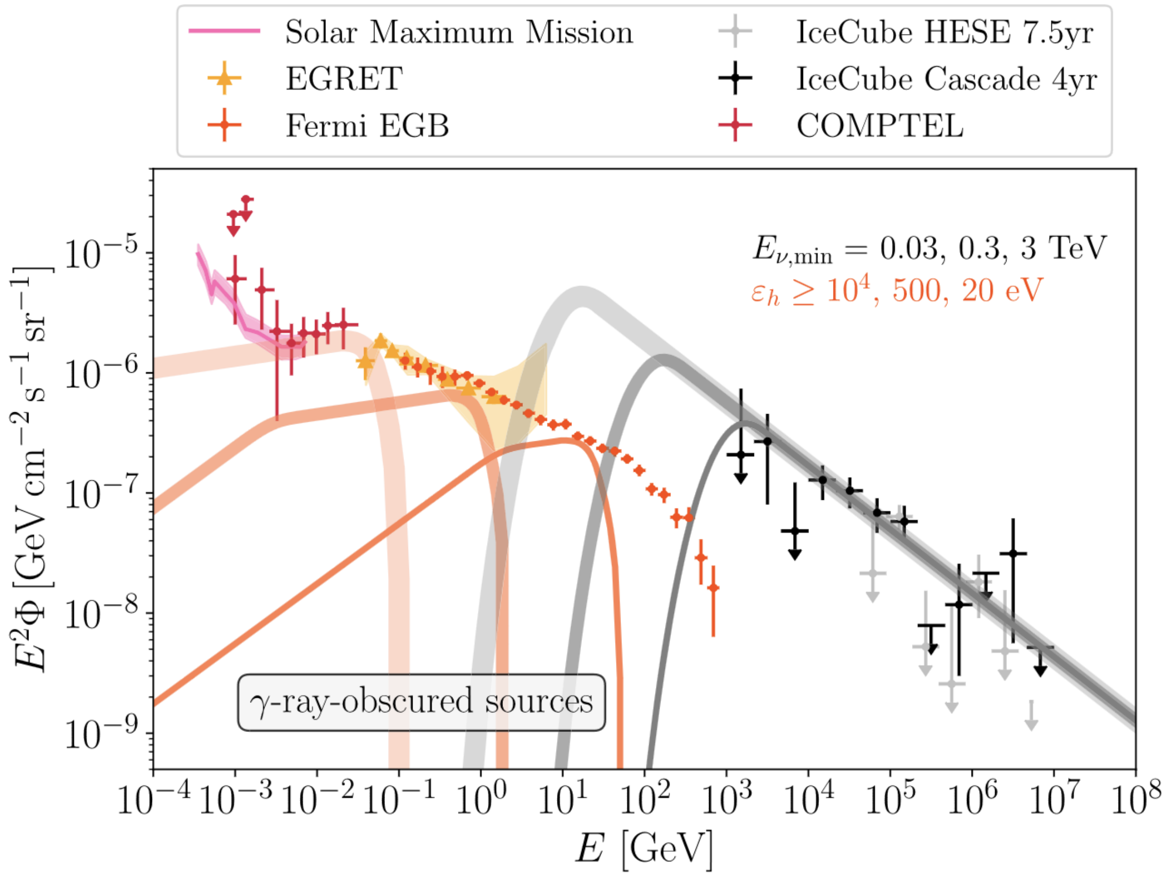


Fig. from Fang+, Ap J 933 (2022) 190

In **gamma-ray obscured sources**, gamma rays cascade to the MeV-GeV range at Earth.

- Look for neutrino sources in coincident with MeV-GeV electromagnetic signals?

Gamma-ray obscured – $p\gamma$ & $\gamma\gamma$

ϵ_h is highest energy of γ –ray attenuating radiation field, adjusted to have diffuse photon flux satisfy observational limits.

These authors conclude: γ –ray obscured sources are most likely the bright neutrino sources. Look for MeV-GeV photons from these sources.

Multi-messenger transient sources

Pointing and timing are goals.

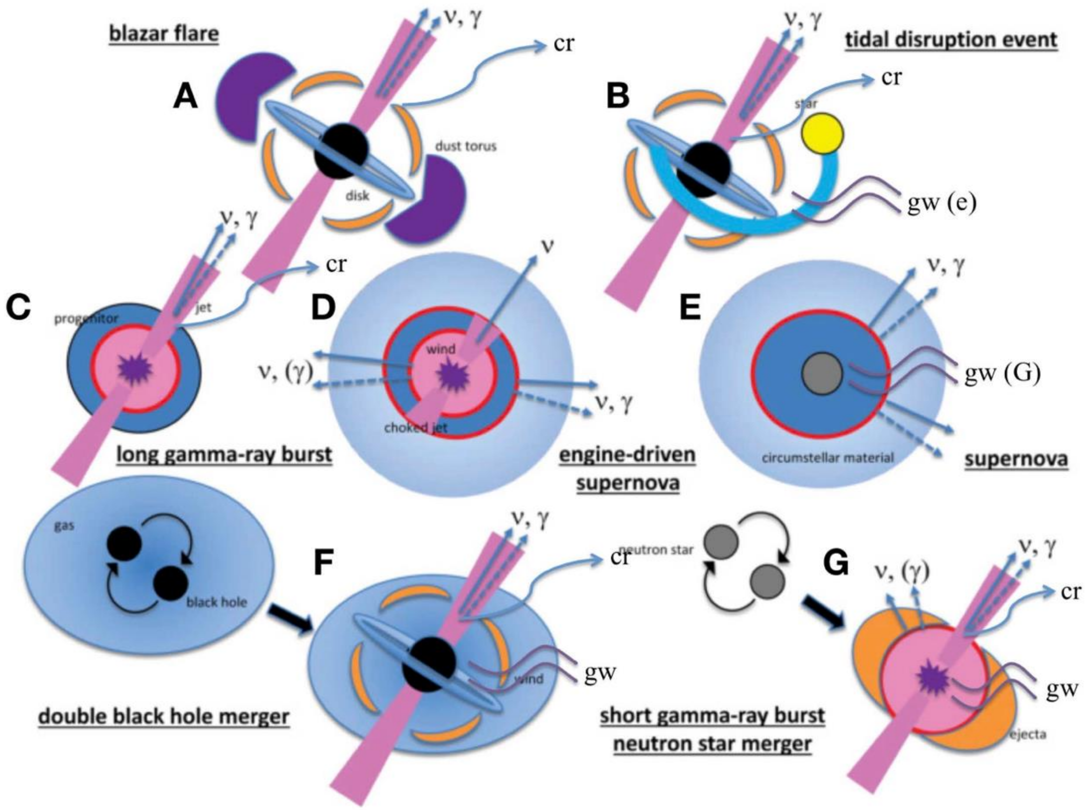


Fig. from Meszaros+, Nature Rev.Phys. 1 (2019) 585

Alert network.

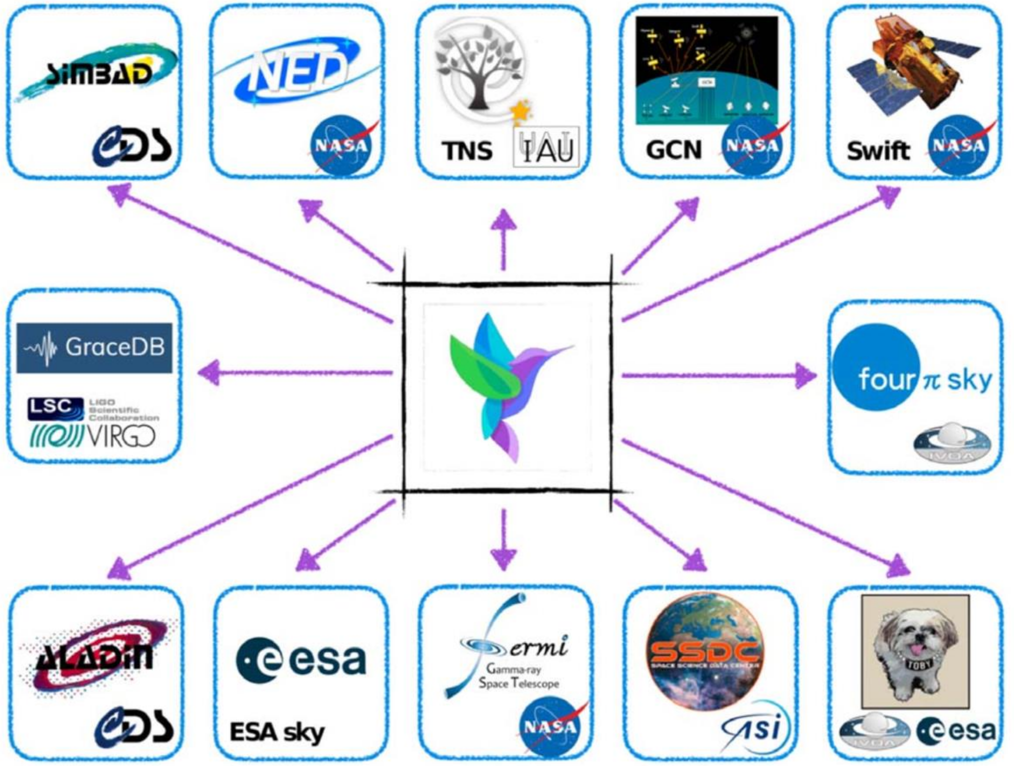


Figure 7. Astro-COLIBRI provides direct links to dedicated services and websites. See Table 3 for details.

Fig. from Reichherzer+, Ap J Supp S 256 (2021) 5
https://www.astro-colibri.com/

Part 2: BSM physics with cosmic neutrinos*

Some options:

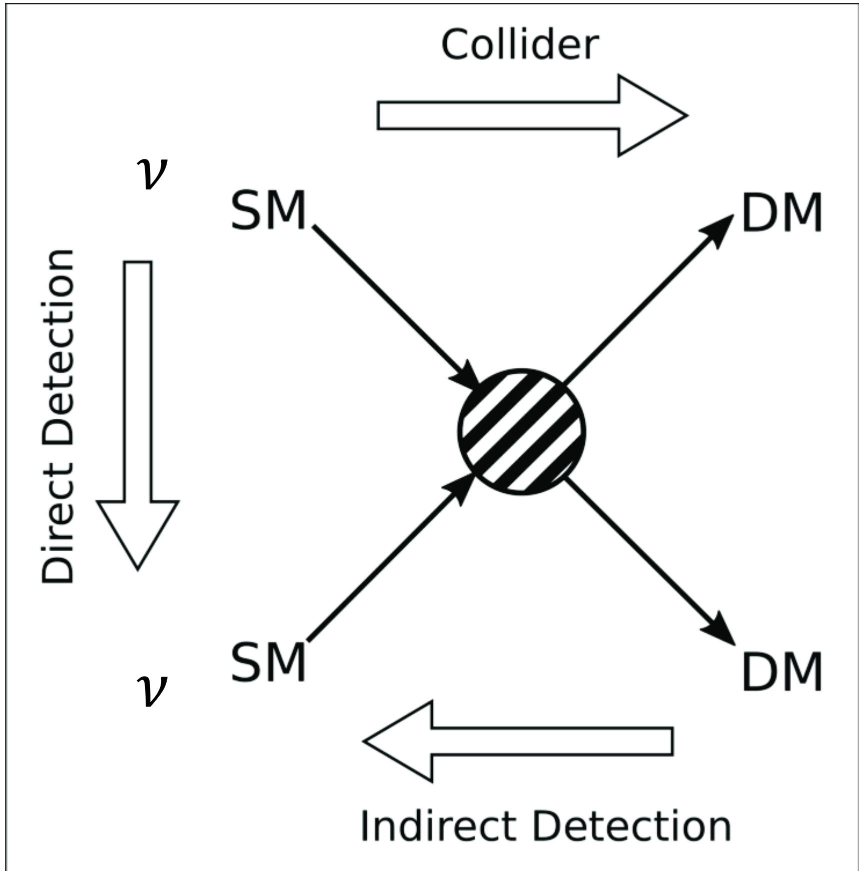
- Use BSM physics to create neutrinos (say, dark matter annihilation/decay).
- Use BSM physics to change how neutrinos propagate to Earth & flavor ratios.
- Use BSM physics to change how neutrinos are detected (say, attenuation in Earth).
- Use BSM physics to make “neutrino-like” particles.

Some motivations for BSM speculations:
ANITA anomalous events
KM3NeT events

*idiosyncratic tour

- Use BSM physics to create neutrinos (say, dark matter annihilation/decay).

Dark matter – indirect detection with neutrinos



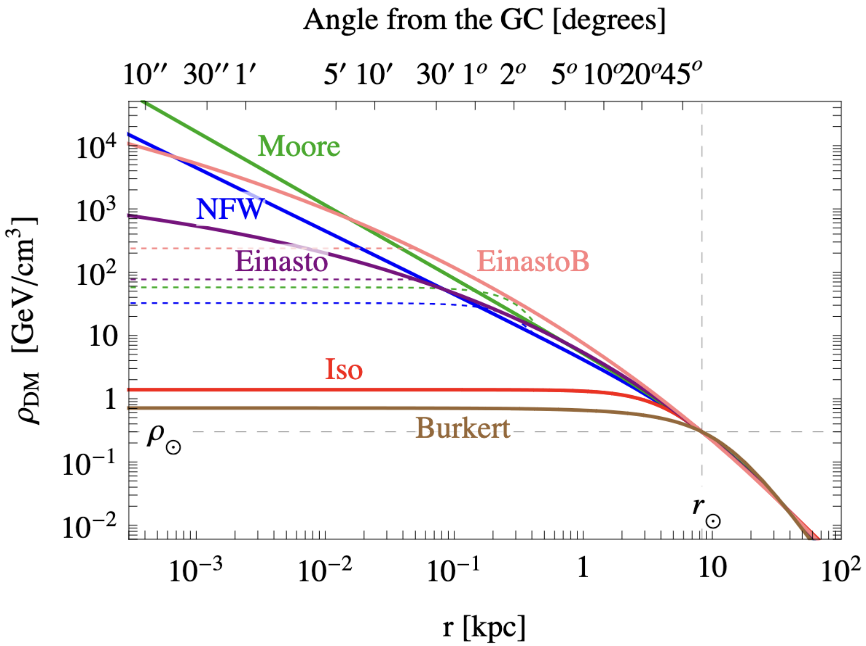
J-factor:

$$J \equiv \int d\Omega \int_{\mathrm{LOS}} \rho_\chi^2(x)dx.$$

From the Milky Way:

$$\frac{dN_i}{dAdtdE_i} = \frac{d\Phi_i}{dE_i} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_{\mathrm{DM}}^2}\frac{dN_i}{dE_i} \times \int_\Omega \int_{l.o.s.} \rho_{\mathrm{DM}}^2(r)drd\Omega$$

involves the thermally averaged DM-DM cross section*v_{rel}



DM density as function of distance from the Galactic Center.

Fig. from Perez de los Heros, 2008.11561

Aside: ν & $\bar{\nu}$

[CC ratio: pQCD/pdf extrapolations]

Low energy:

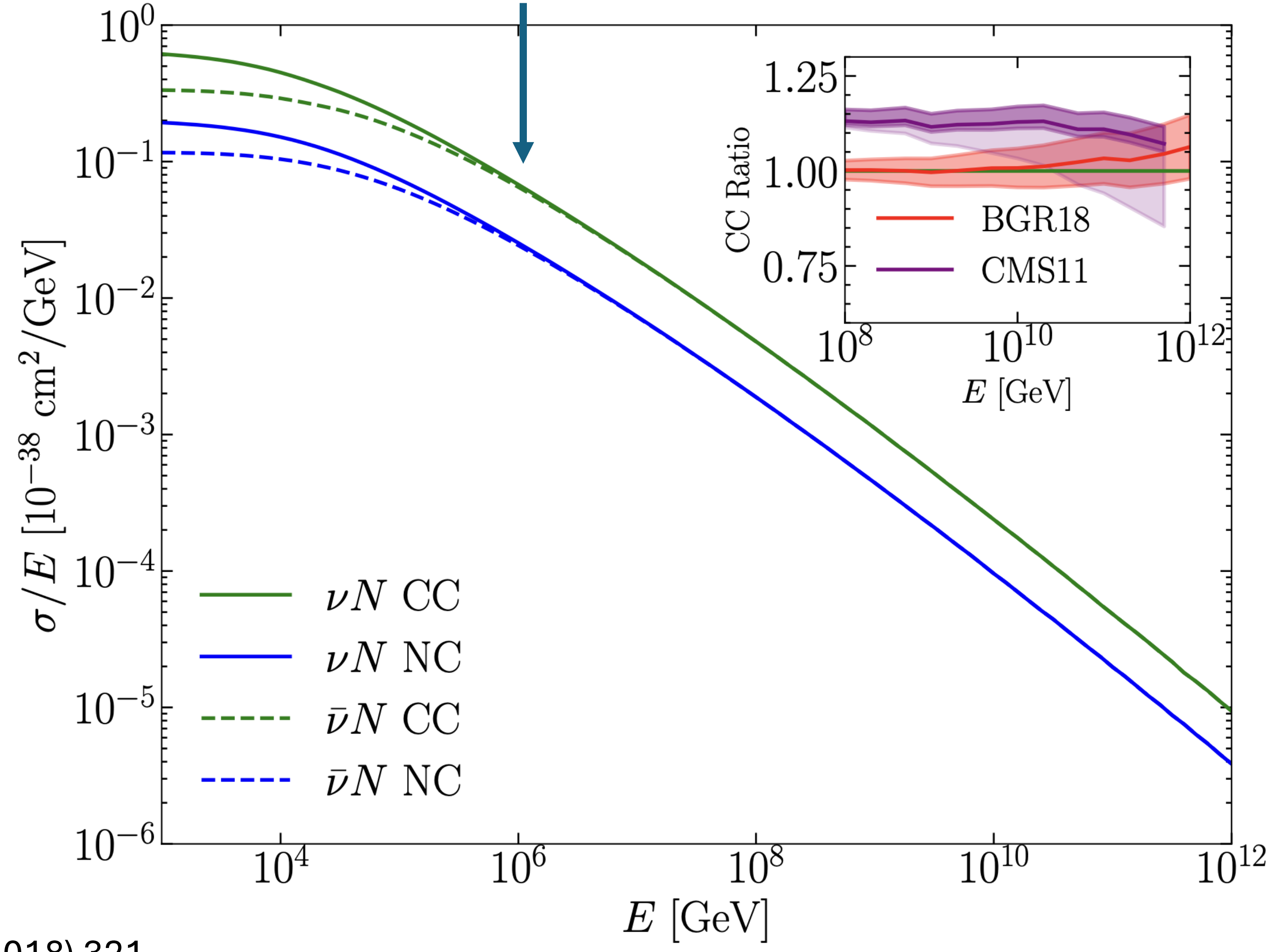
$\sigma \sim E$

High energy:

$\sigma_{\nu N} \sim E^{0.3}$

"sea quark dominated"

$\sigma_{\nu N} \simeq \sigma_{\bar{\nu} N}$



BGR = Ball+, Eur. Phys. J. C 78 (2018) 321
CMS = Cooper-Sarkar, JHEP 08 (2011) 042

MHR, Ann Rev 73 (2023) 1

Dark matter – indirect detection with neutrinos from our galaxy

J-factor:

$$J \equiv \int d\Omega \int_{\rm LOS} \rho_\chi^2(x)dx.$$

From the Milky Way:

$$\frac{dN_i}{dAdtdE_i} = \frac{d\Phi_i}{dE_i} = \frac{1}{4\pi}\frac{\langle\sigma_{\rm A}v\rangle}{2m_{\rm DM}^2}\frac{dN_i}{dE_i} \times \int_\Omega \int_{l.o.s.} \rho_{DM}^2(r)drd\Omega$$

Annihilation rate per unit volume = $\dfrac{\langle\sigma_A v\rangle\rho_\chi^2}{m_\chi^2}$

Annihilation at rest (approx): $\dfrac{dN_i}{dE_i} = \dfrac{2}{3}\delta(E_i - M_\chi)$

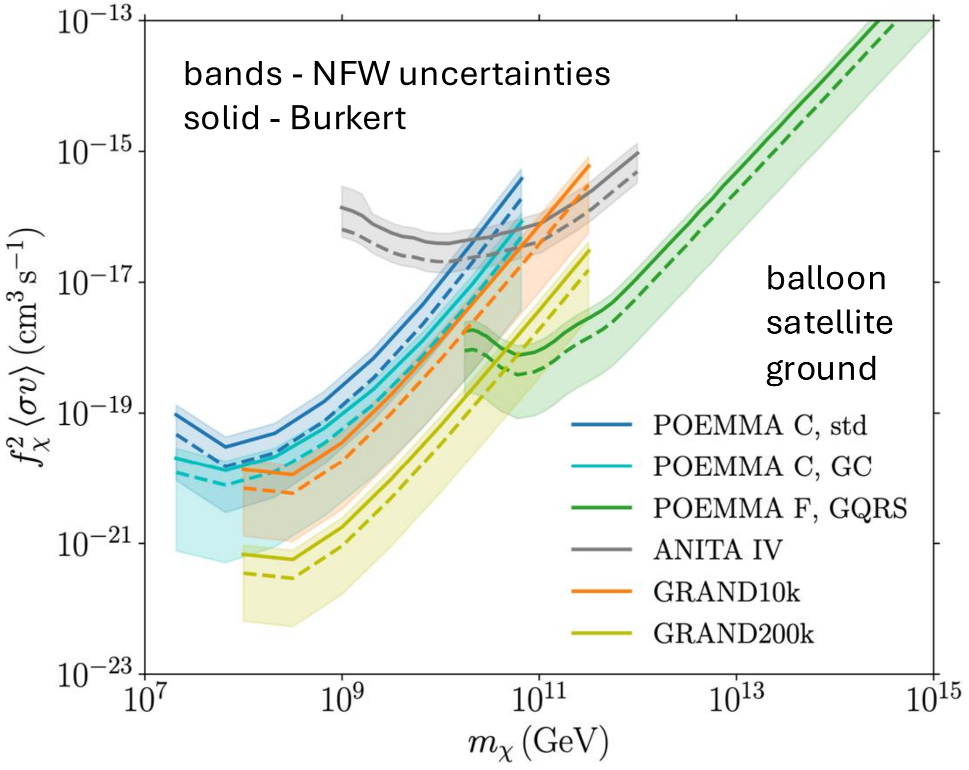
2 neutrinos from each annihilation

Example of constraints from future (and past) detectors

Fig. from *Guepin*+, PRD 104 (2021) 083002

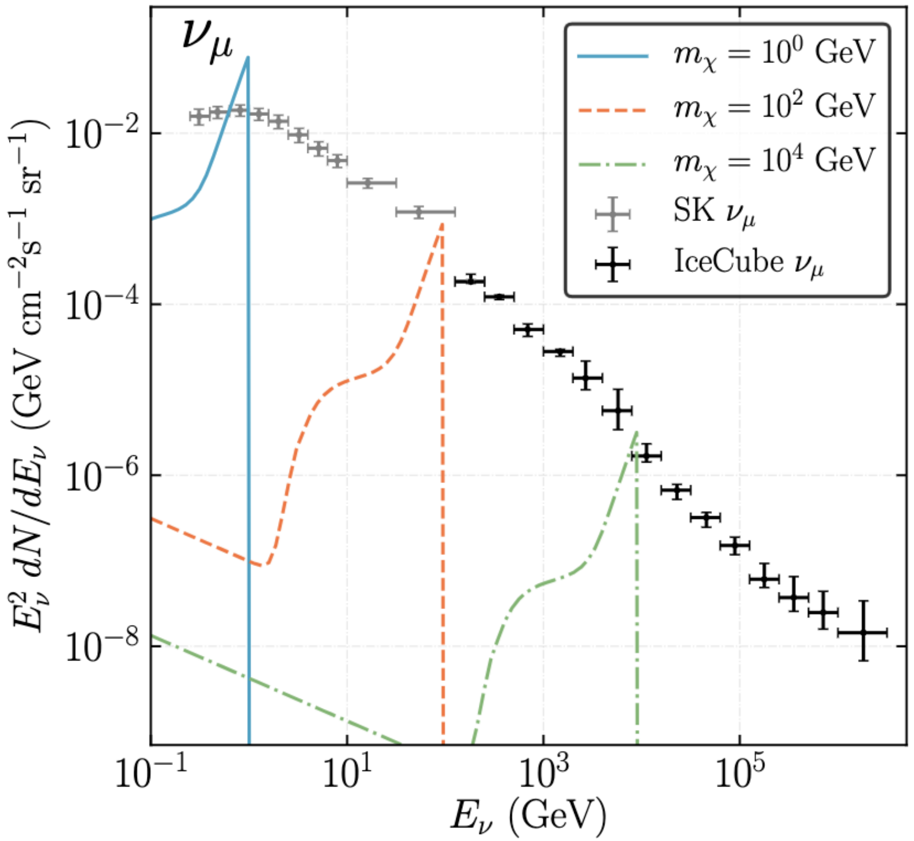
$DM = \chi \to f_\chi = 1$ below:

Assumed Majorana, another factor of 1/2 for Dirac.

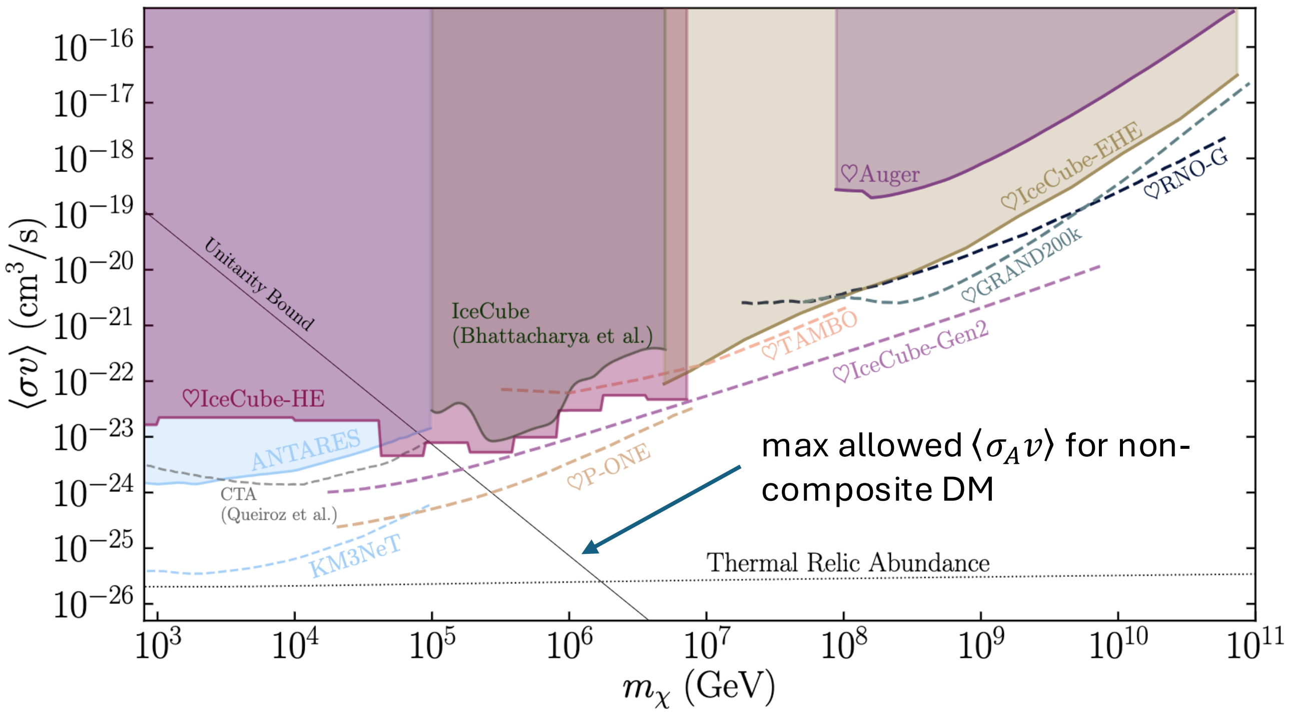


Extragalactic dark matter annihilation to neutrinos

assume limiting $\langle \sigma v \rangle$



Evolution over redshift (DM density effects). Dashed curves, projected limits.



Figs. from Arguelles+, Rev Mod Phys 93 (2002) 035007
See Beacom, Bell, Mack, PRL 99 (2007) 231301

See Smirnov & Beacom PRD 100 (2019) 043029 for unitarity discussion.

Extragalactic dark matter decay to neutrinos

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

D-factor, like the J-factor, but for decays

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\frac{1}{3}\frac{dN_\nu}{dE_\nu}D(\Omega)$$

Now the constraint is on the lifetime.

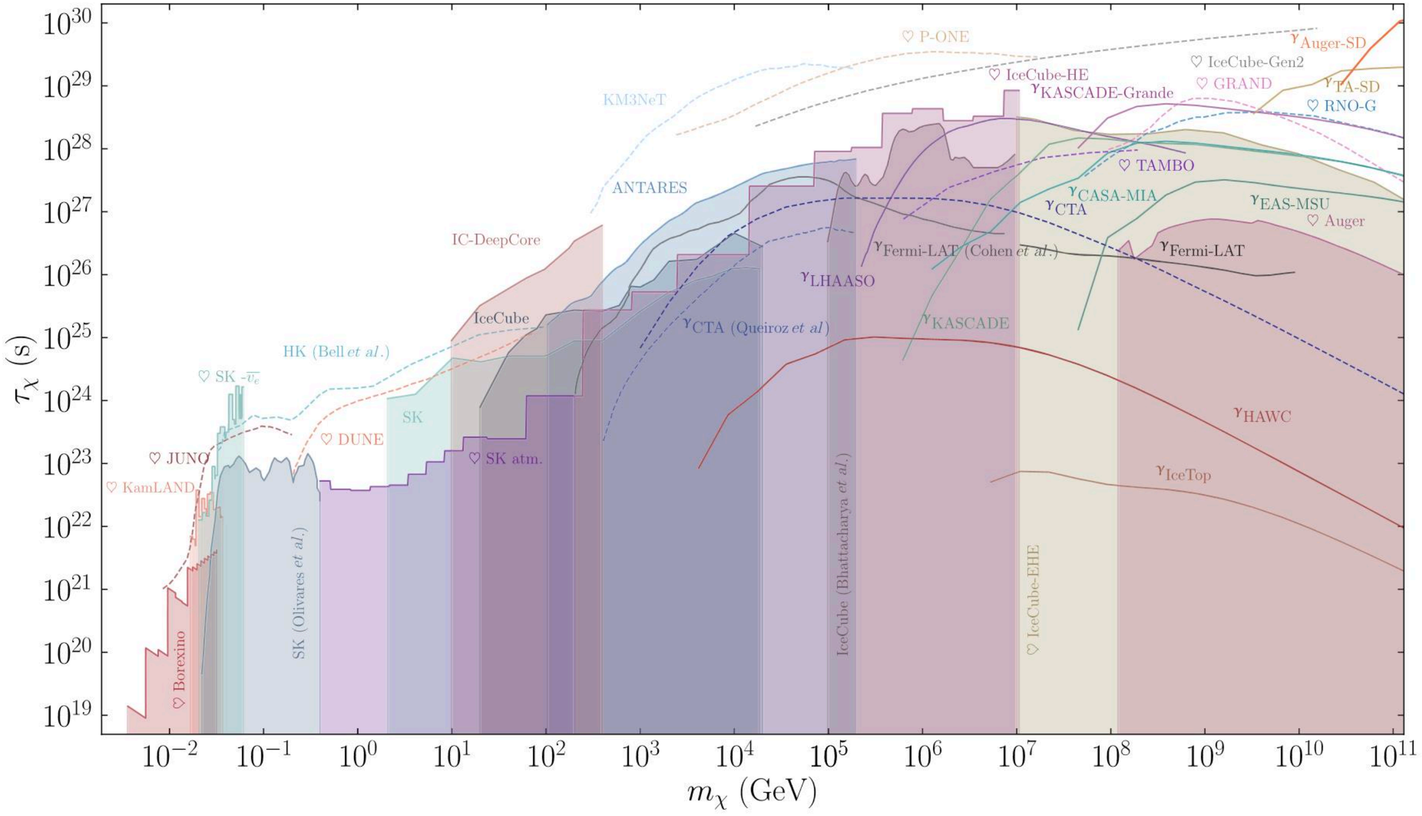
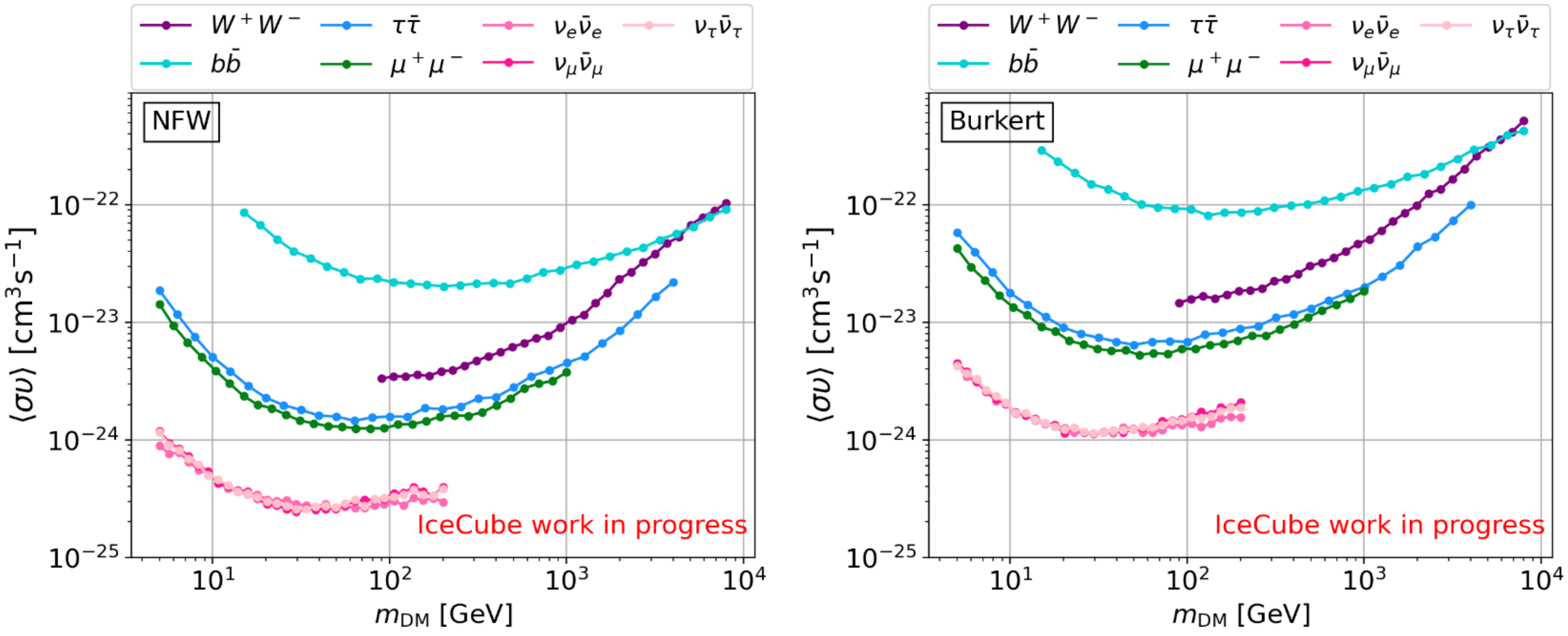


Fig. from Arguelles+, PRD 108 (2023) 123021

Dark matter annihilations to … neutrinos

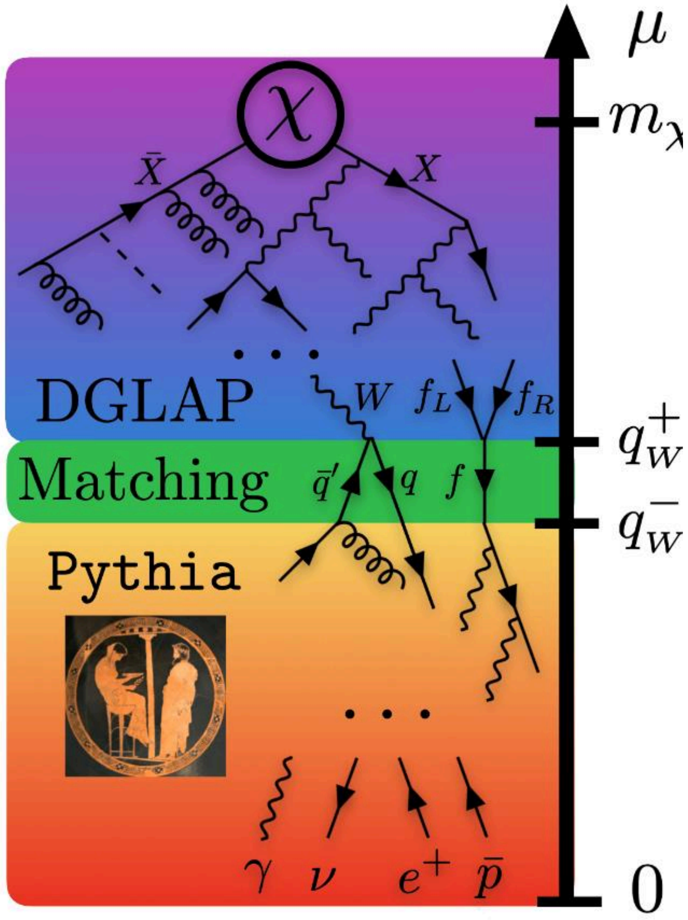
Dark matter annihilation or decay to particles that decay to neutrinos

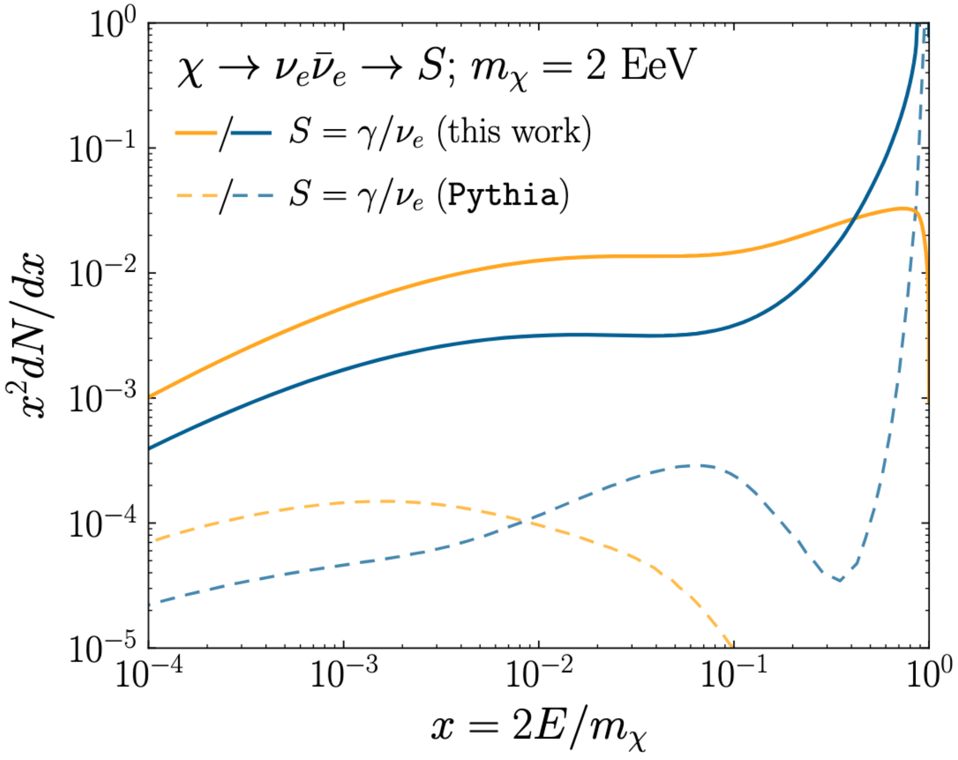


IceCube, https://arxiv.org/pdf/2308.06729

Here, for DM in the Galactic center.
Can also look at the Sun, in the Earth
(capture and annihilation not likely in equilibrium in the Earth).

Super-heavy dark matter – showering





Particle showering for SHDM – neutrino channel gives photons, too!

We are back to multi-messenger.

1 EeV = 10^9 GeV

Bauer, Rodd & Webber, JHEP 06 (2021) 121

https://github.com/nickrodd/HDMSpectra

- Use BSM physics to change how neutrinos propagate to Earth & flavor ratios.

Attenuate neutrino flux with BSM

Esteban et al, 2605.13955

"Model independent" approach – parameterize τ

$$\phi_i = \int_{z_{\min}}^{\infty} \frac{dz}{4\pi H(z)} \mathcal{I}_i((1+z)E, z) e^{-\tau(E,z)}$$

$$\tau(E,z) \equiv \int_0^z \frac{dz'}{H(z')(1+z')} \Gamma_i((1+z')E)$$

$$\Gamma_i(E) = \gamma_0 \left(\frac{E}{E_0}\right)^n$$

Strategy, use energy arguments:

- Take a generous Waxman-Bahcall bound/landmark as unattenuated flux.
- Require that losses don't take the flux below the IceCube measurements.

Highly constraining (exponential!)

See also Esteban, Ibarra, 2508.02869

Esteban et al, 2605.13955

	$\gamma_0^{\max}$ (GeV)				
	Only ν attenuation			All particle attenuation	
n	SN1987A [37](90%CL)	This work (SFR)	This work (BL-Lac)	This work (SFR)	This work (BL-Lac)
2	2.3–3.2 $\times 10^{-34}$	1.4×10^{-53}	1.7×10^{-52}	3.5×10^{-51}	4.5×10^{-51}
1	1.5–1.8 $\times 10^{-35}$	1.1×10^{-47}	9.9×10^{-47}	1.2×10^{-44}	1.3×10^{-44}
0	3.1–5.0 $\times 10^{-37}$	1.6×10^{-42}	7.7×10^{-42}	6.6×10^{-38}	8.3×10^{-38}
-1	3.2–5.5 $\times 10^{-39}$	2.0×10^{-37}	7.6×10^{-37}	1.7×10^{-33}	1.8×10^{-33}
-2	3.1–6.4 $\times 10^{-41}$	2.6×10^{-32}	8.4×10^{-32}	6.4×10^{-29}	6.7×10^{-29}

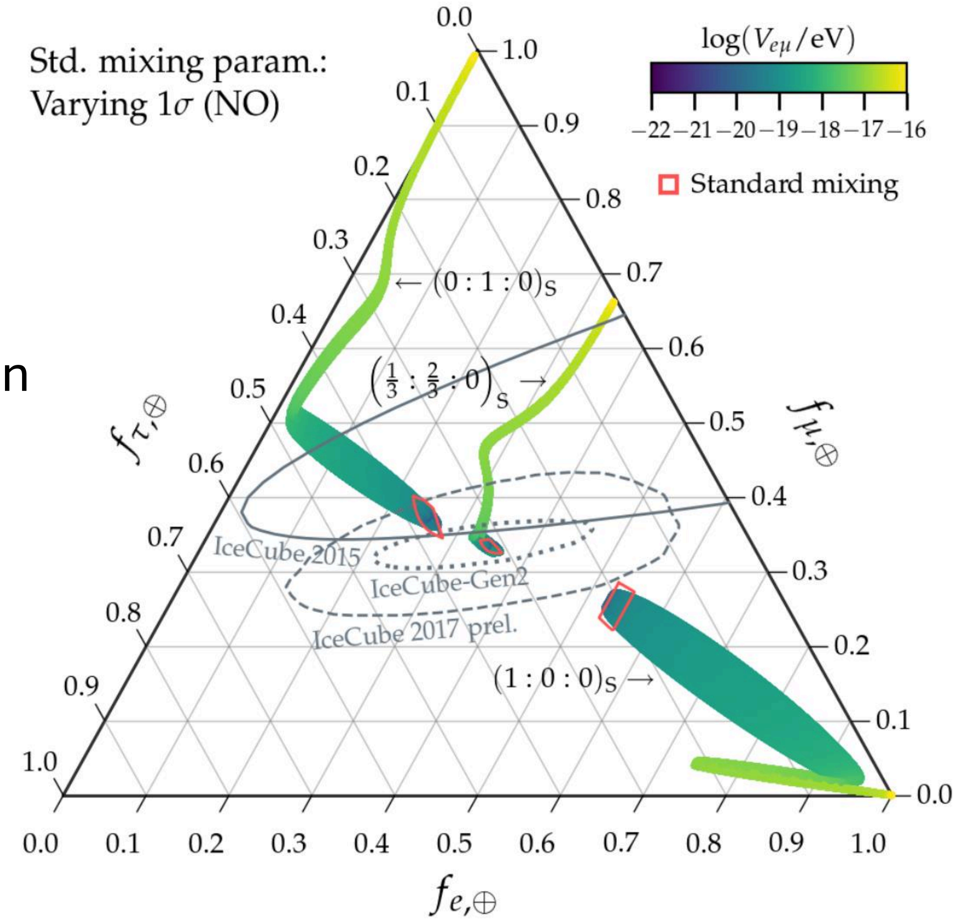
Use BSM physics to change how neutrinos propagate to Earth & flavor ratios.

Change effective favor mixings with BSM - example

Bustamante & Agarwalla, PRL 122 (2019) 061103

Introduce very light neutral vector boson that violates L_e and L_μ, but not $L_e - L_\mu$.

- Flavor non-diagonal neutral current scattering.
- New interactions give a long-range potential given electron density and very light masses.
- Flavor oscillations to Earth are distorted by new interactions (matter potential with electron densities) .
- Show results for neutrino energy of 100 TeV, location on triangle determined by how big is the BSM matter potential (see colors).



ANITA anomalous events

- Use BSM physics to change how neutrinos are detected (say, attenuation in Earth).

Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA #1

ANITA Collaboration • P.W. Gorham (Hawaii U.) et al. (Mar 14, 2018)

Published in: *Phys.Rev.Lett.* 121 (2018) 16, 161102 • e-Print: 1803.05088 [astro-ph.HE]

pdf DOI cite claim reference search 175 citations

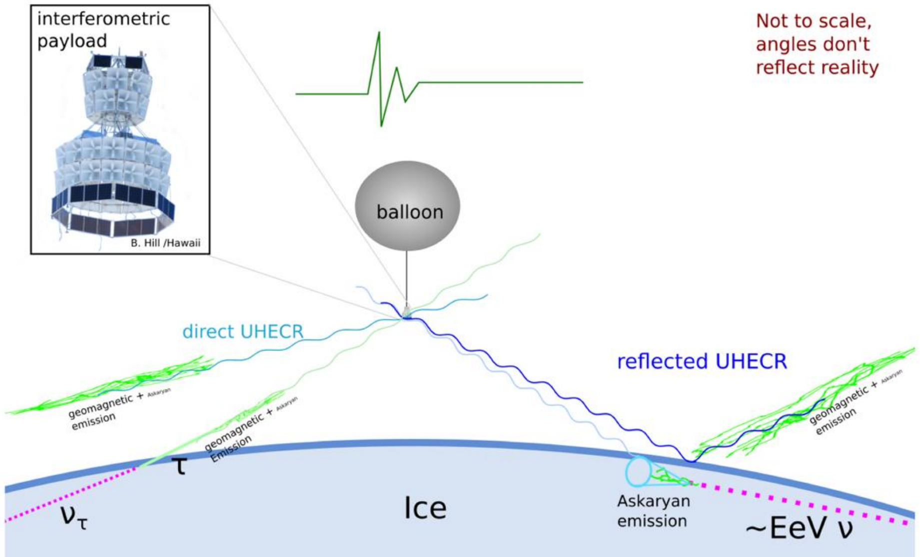


Fig from https://www.hep.ucl.ac.uk/uhen/anita/

The ANITA detection concepts, figure from ***Cosmin Deaconu.***

- Two anomalous events, from detector at angles -27 deg and -35 deg, energy range ~0.5×10^9 GeV.
- Limb of the Earth ~ -6 deg.

Polarization consistent with up-going air shower (like what could be initiated by tau neutrino to tau, tau makes air shower), not consistent with reflected cosmic ray events.

We await PUEO results.

ANITA anomalous events

Tau neutrinos regenerate, are these events just SM nu-tau events?

Tau exit probability on a log plot, fixed incident neutrino energy:

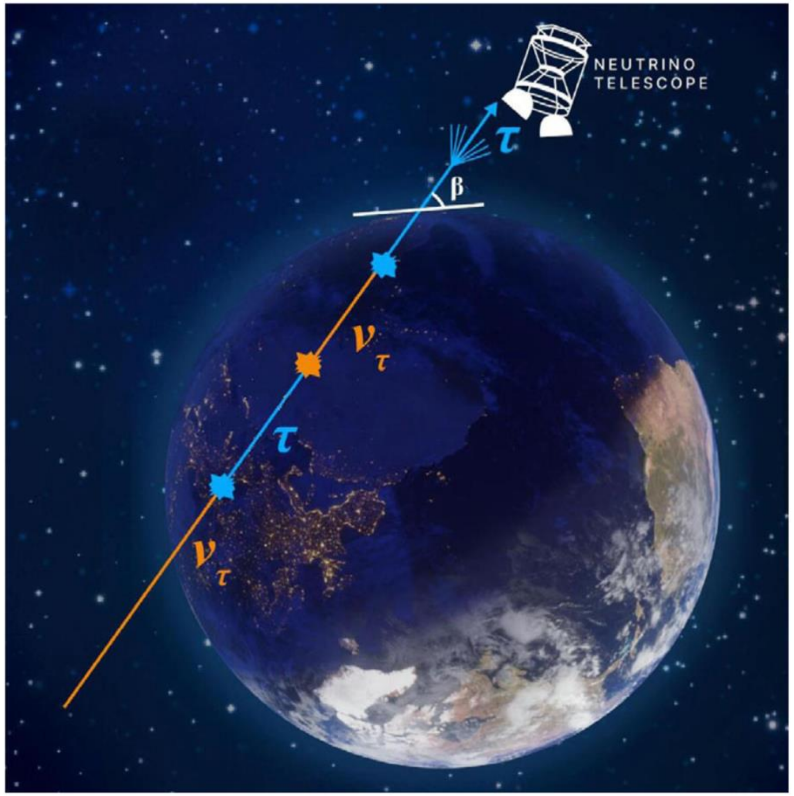
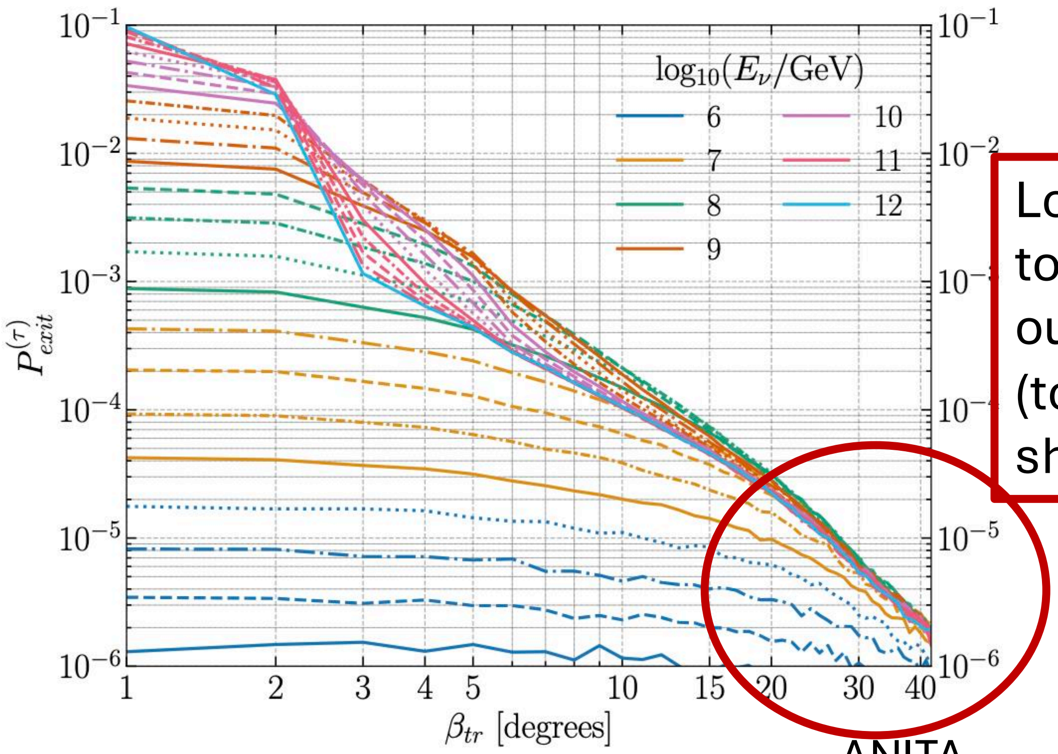


Fig. from *Arguelles*+, PRD 107 (2023) 033009



Low probability to tau to make it out of the Earth (to start air shower).

ANITA angles -27 & -35 deg

Fig. from *Garg*+, JCAP 01 (2023) 041
https://github.com/NuSpaceSim/nupyprop

ANITA anomalous events

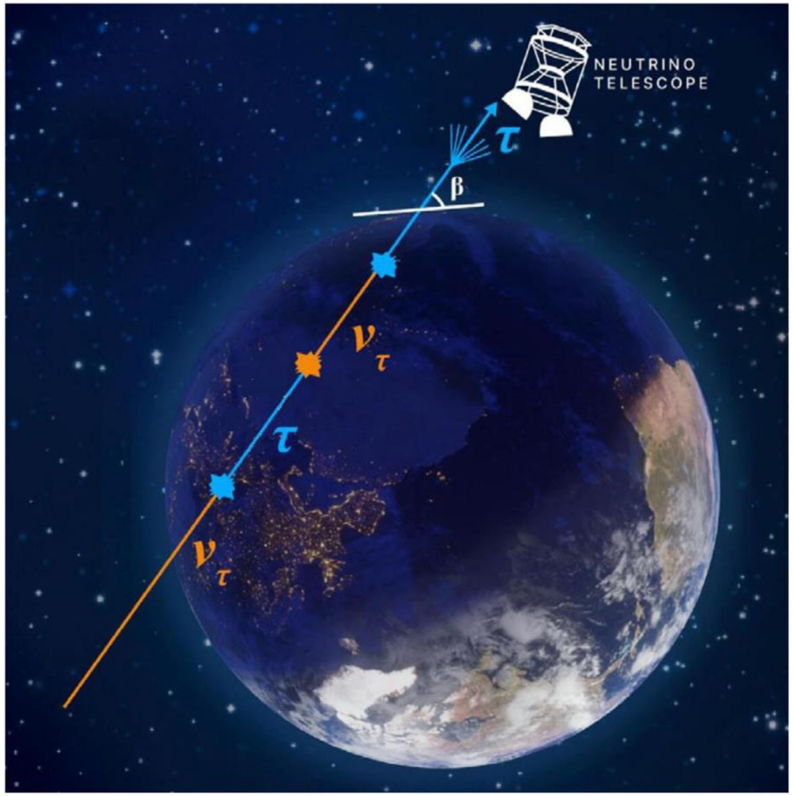


Fig. from *Arguelles*+, PRD 107 (2023) 033009

Tau neutrinos regenerate, are these events just SM nu-tau events?

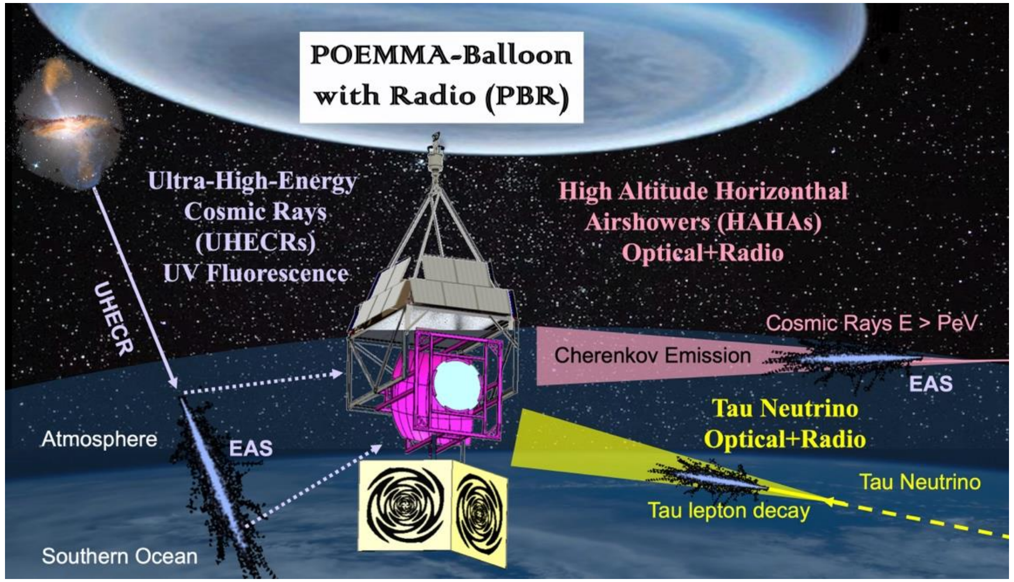
No, even with accounting for tau neutrino regeneration, these large exit angles have very low probability of generating events for standard model neutrino interactions..

Chipman+, PRD 100 (2019) 063011
Romero-Wolf et al, PRD 99 (2019) 063011

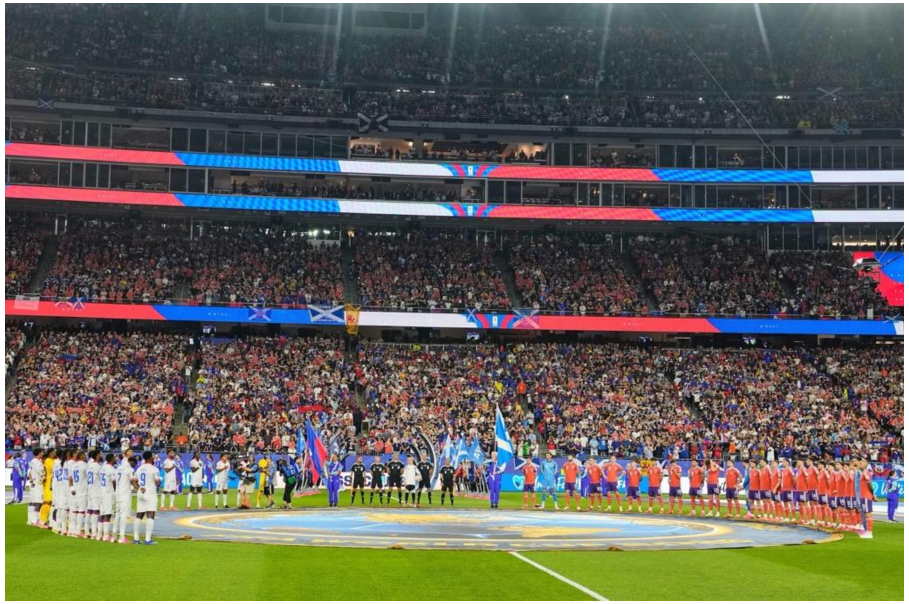
SpaceSim

Garg+, JCAP 01 (2023) 041
https://github.com/NuSpaceSim/nupyprop

Aside – EUSO-SPB2 and PBR

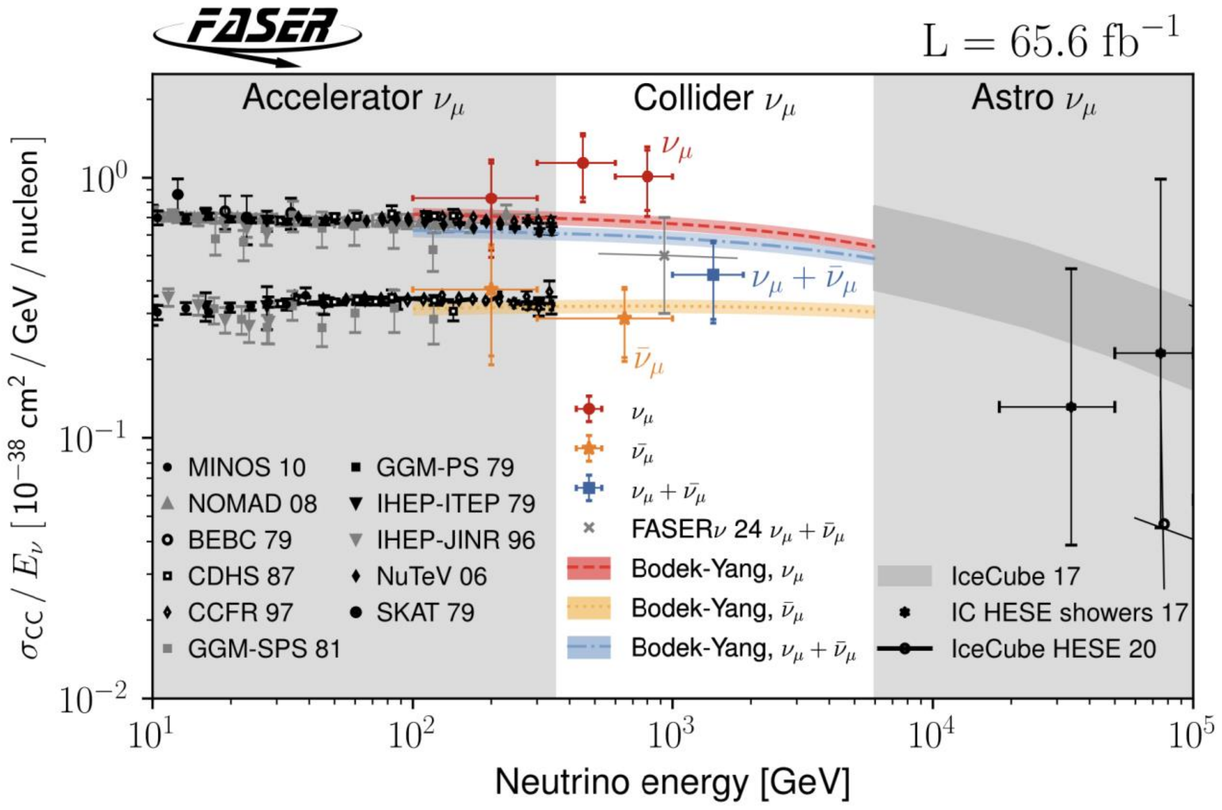


Balloon at float inflates to the size of a football field/soccer pitch!

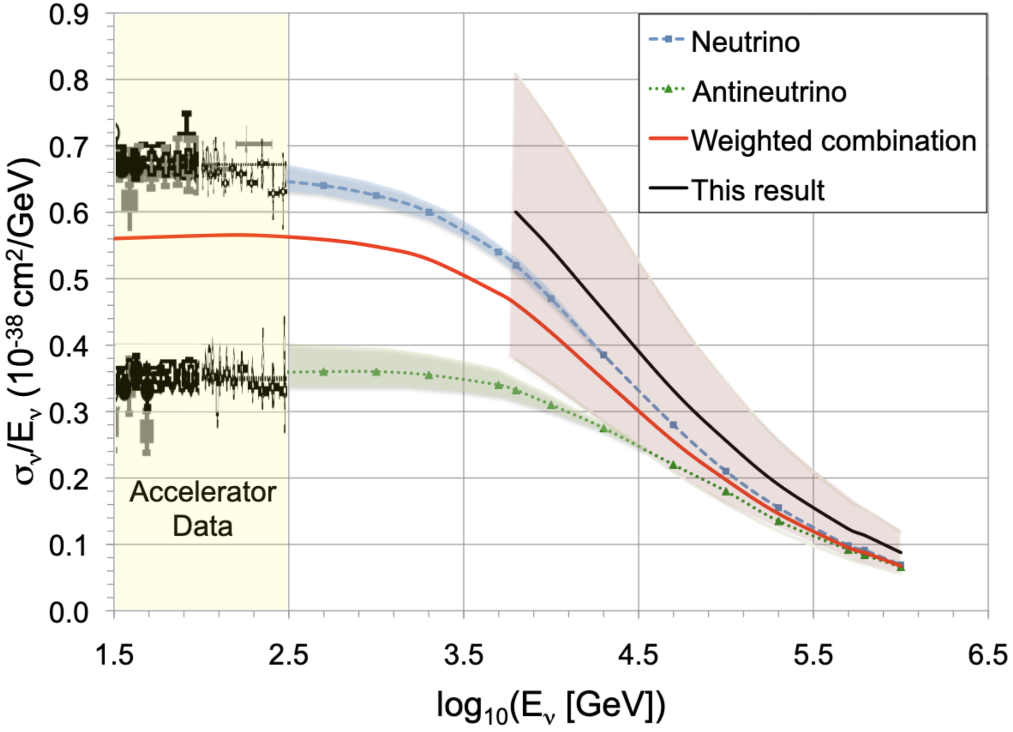


One science goal – search for skimming tau neutrinos.

Aside – neutrino DIS cross section measurements



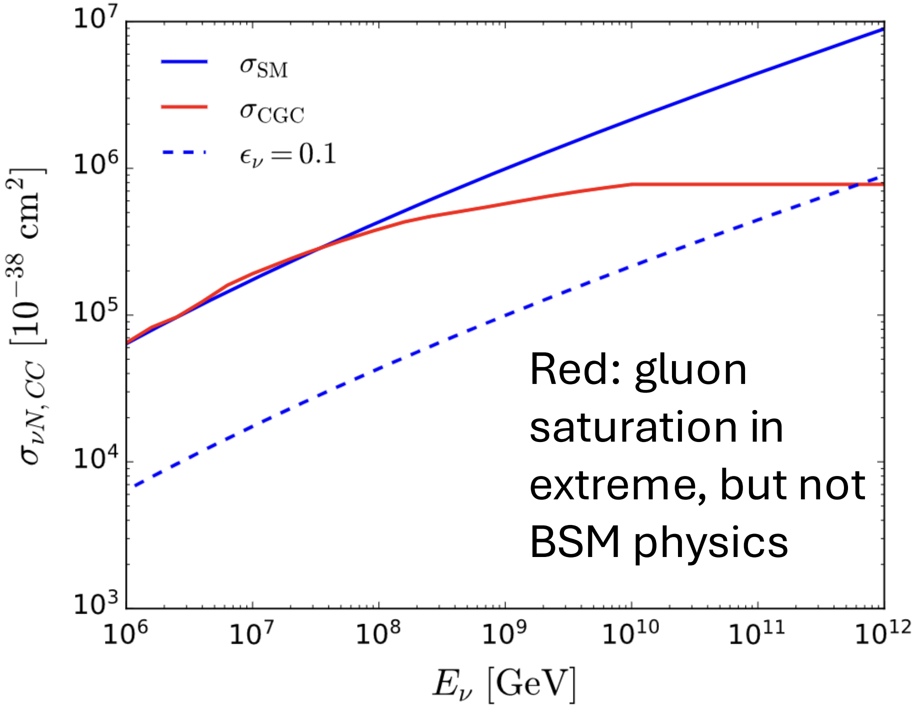
Abraham+ (FASER), PRL 134 (2025) 211801

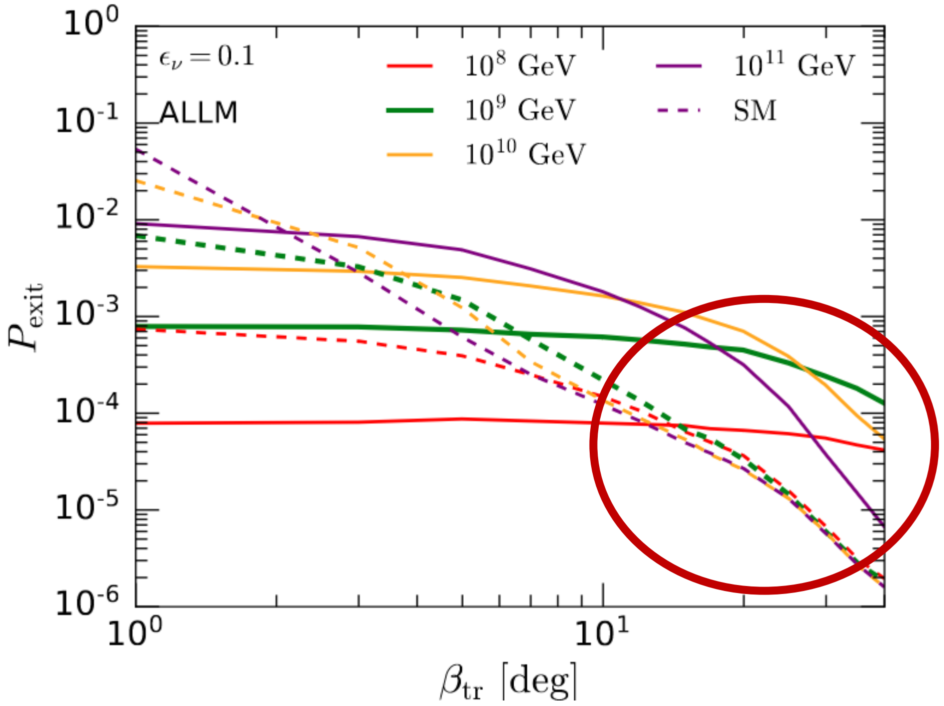


Aartsen+ (ICECUBE), Nature 551 (2017) 596

ANITA anomalous events – change ν attenuation

red cross section: doesn't change SM conclusion



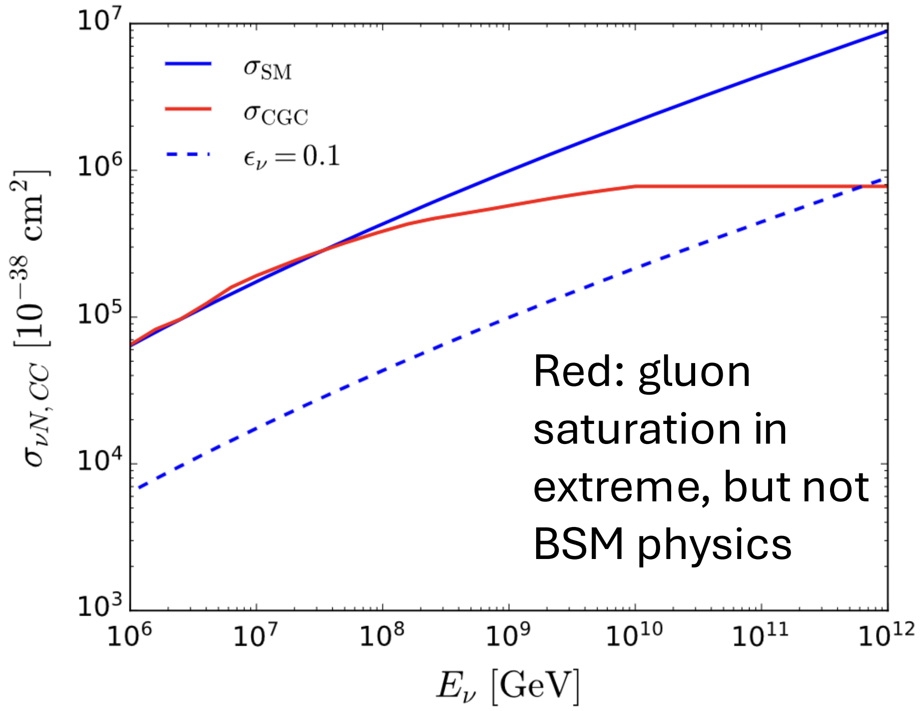


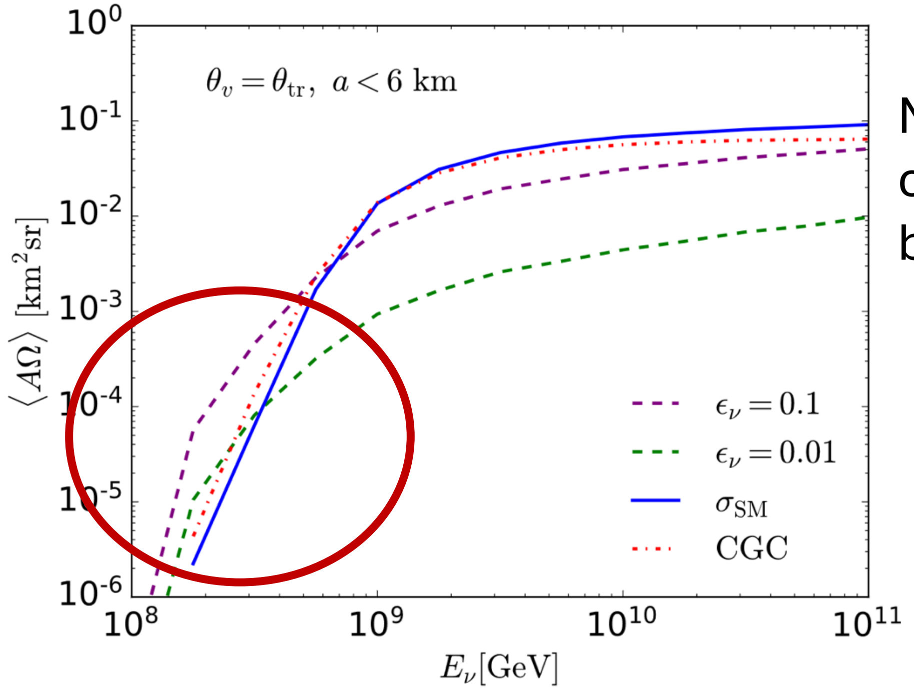
Blue dashed – suppress SM cross section by 0.1
"boosted" sterile neutrino, dark particle with suppressed cross section

You can get enhanced tau exit probabilities at large angles with suppressed cross sections.

ANITA anomalous events – change ν attenuation

red cross section: doesn't change SM conclusion





Multi-instrument constraints can't be satisfied.

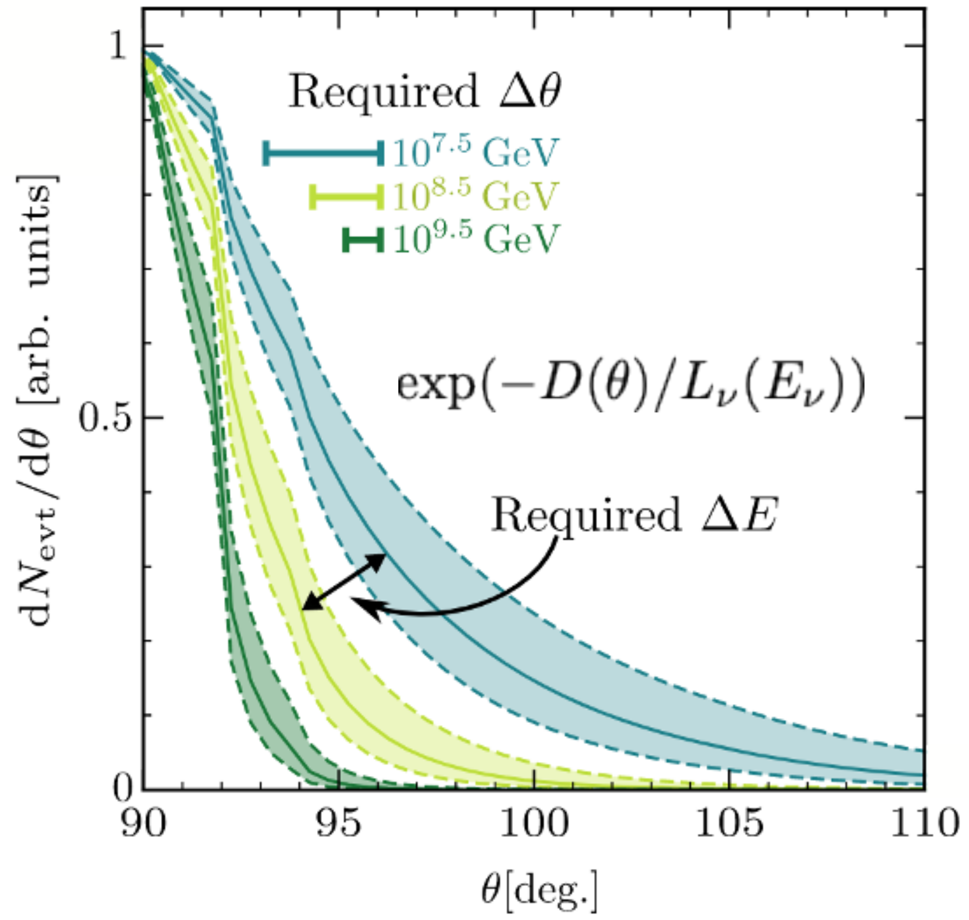
Blue dashed – suppress SM cross section by 0.1 "boosted" sterile neutrino, dark particle with suppressed cross section

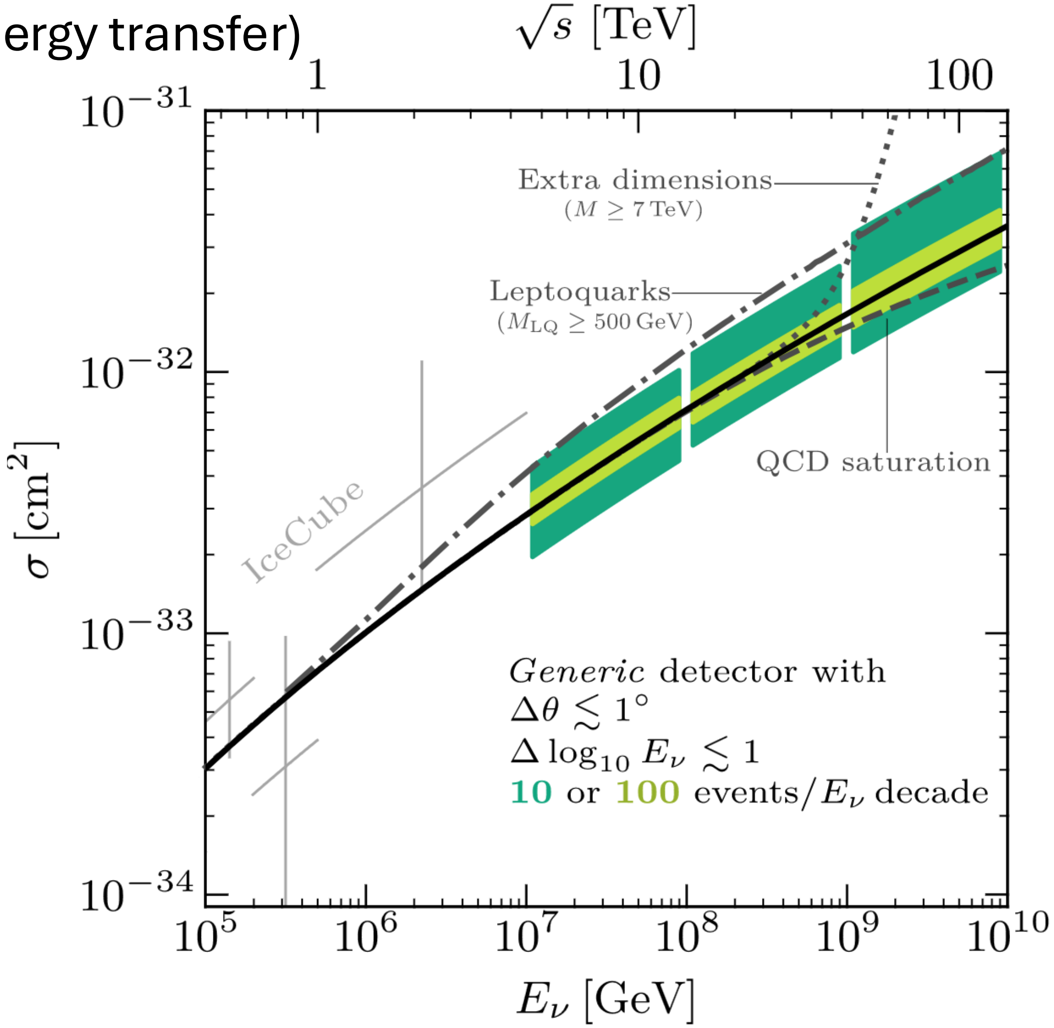
You can get enhanced effective apertures, but the corresponding effective aperture at IceCube will also be large.

Aside - cross sections again

Esteban, Prohira, Beacom, PRD 106 (2022) 023021

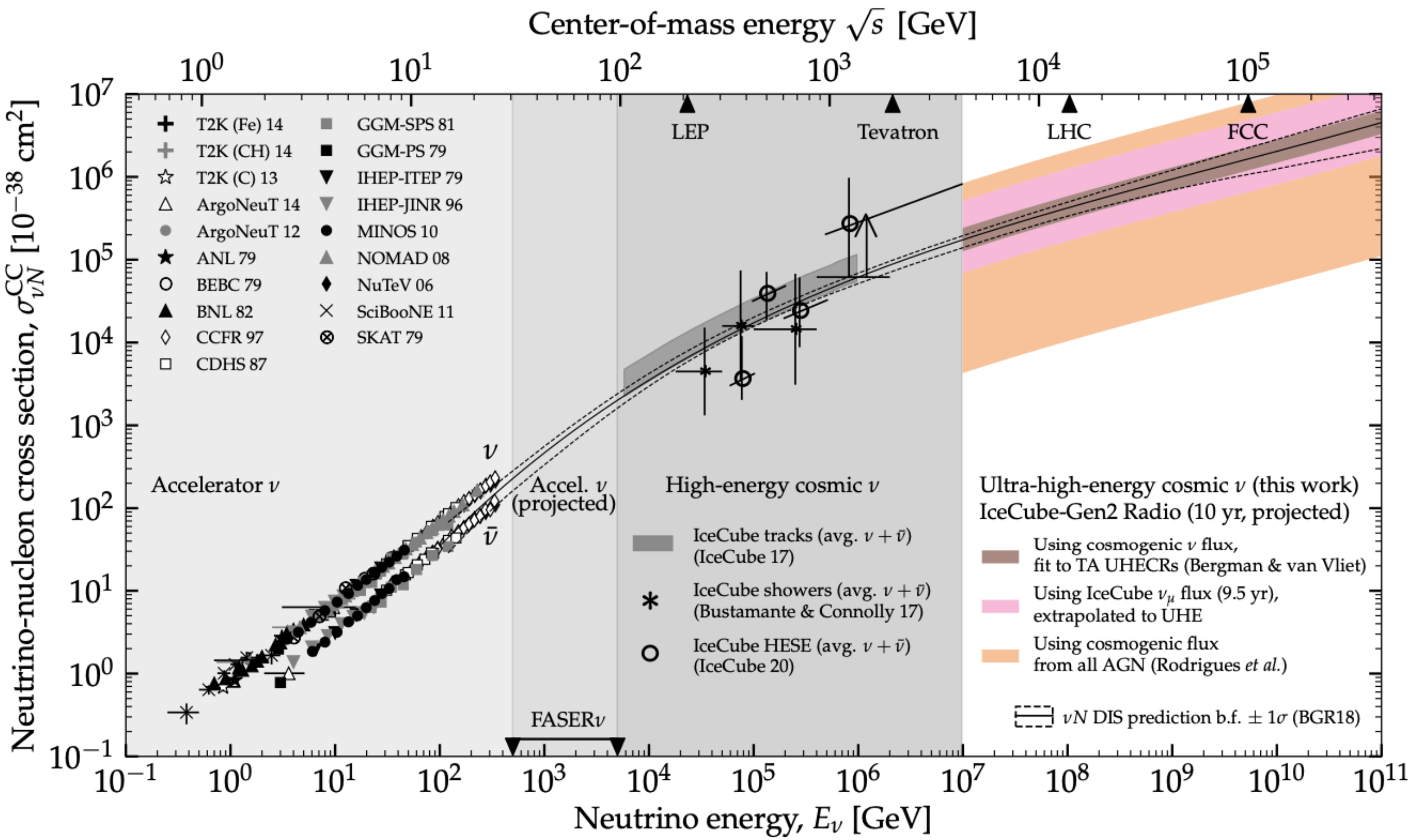
(assume SM inelasticity – e.g., $\nu_\mu \to \mu$ energy transfer)





Cross sections again

Valera, Bustamante, Glaser, JHEP 06 (2022) 105



Here with specific flux assumptions instead of # of events.

Fluxes will be low, generally will need multiple detectors.

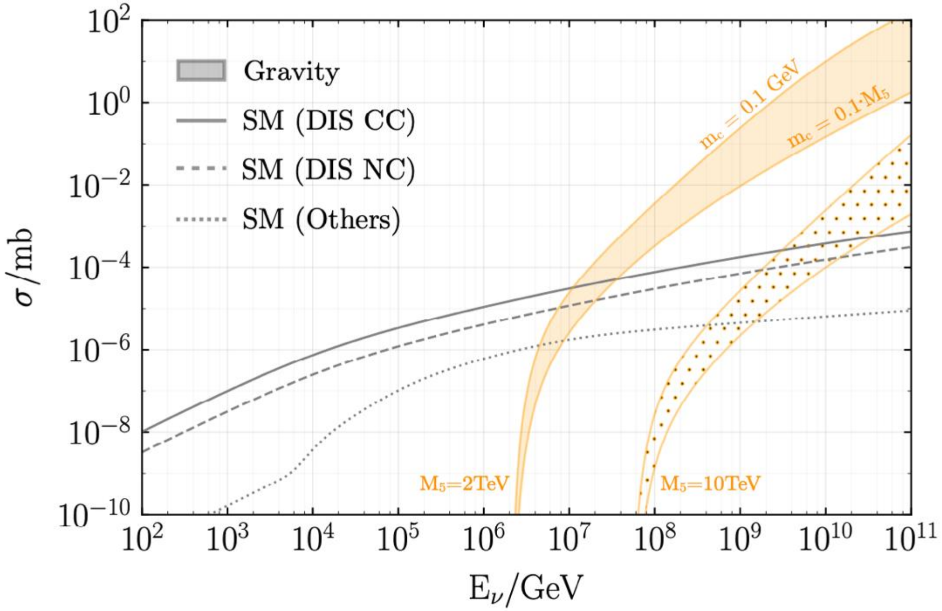
$$\exp(-D(\theta)/L_\nu(E_\nu))$$

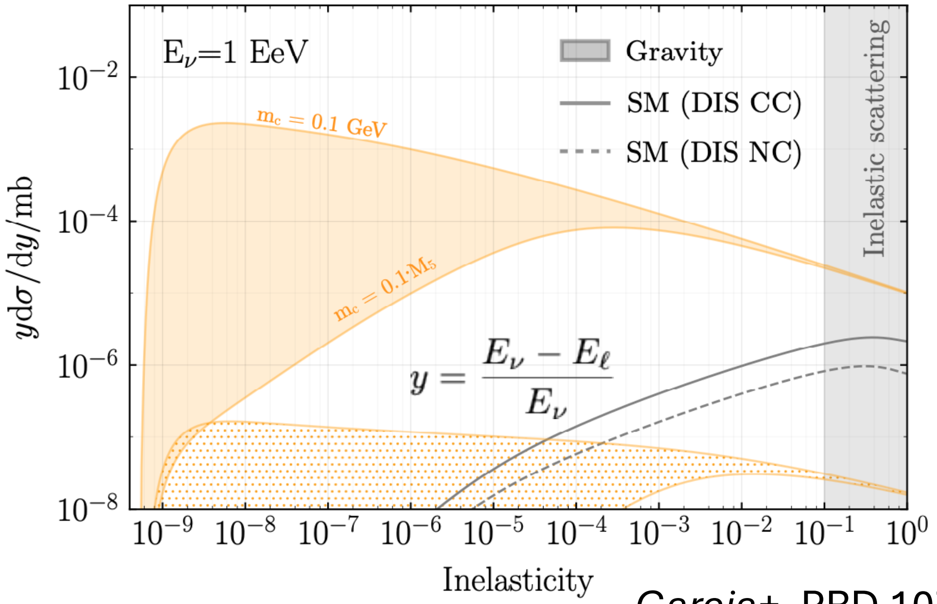
Ultimately, need global monitoring, multiple detectors.

See, e.g., Schumacher+, Phys.Rev.*D* 112 (2025) 083027

BSM physics – neutrino cross section caution

- TeV scale extra dimensions can enhance the neutrino cross section, but may do this through mostly elastic scattering, so don't affect attenuation of the neutrino flux in the "standard way."
- (Cross section measurements discussed above rely on SM $d\sigma/dy$. distributions.)
- Flux uncertainties would make it very difficult to distinguish SM and BSM cross sections through number of events, however, angular distributions and number of triggered stations @IceCube Gen2 radio (multiple small energy bursts) may help.





$M_5 = 2,\ 10$ TeV

m_c first KK excitation

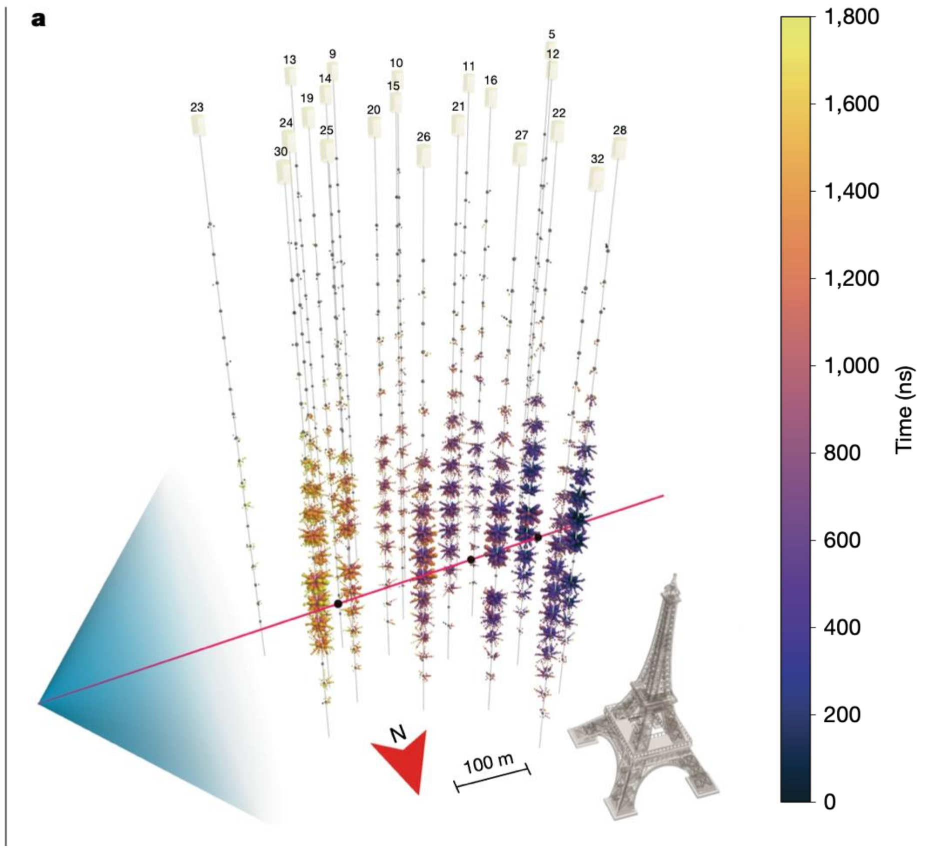
Garcia+, PRD 107 (2023) 033009

An invitation to BSM speculations:

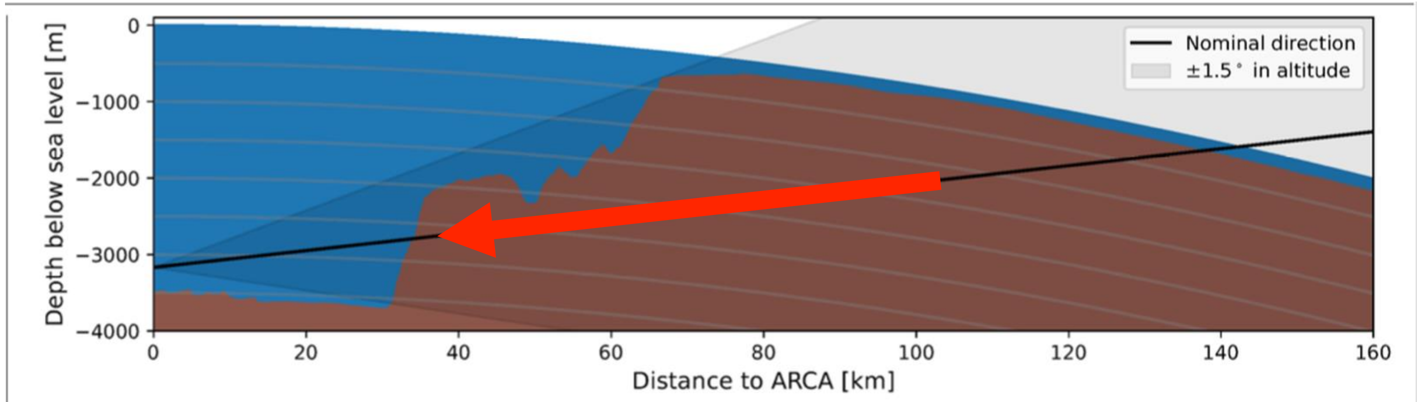
The KM3NeT event:

$$E_\mu = 120^{+110}_{-60}\,\mathrm{PeV},\ E_\nu = 72\,\mathrm{PeV} - 2.6\,\mathrm{EeV}$$

(90% CL)

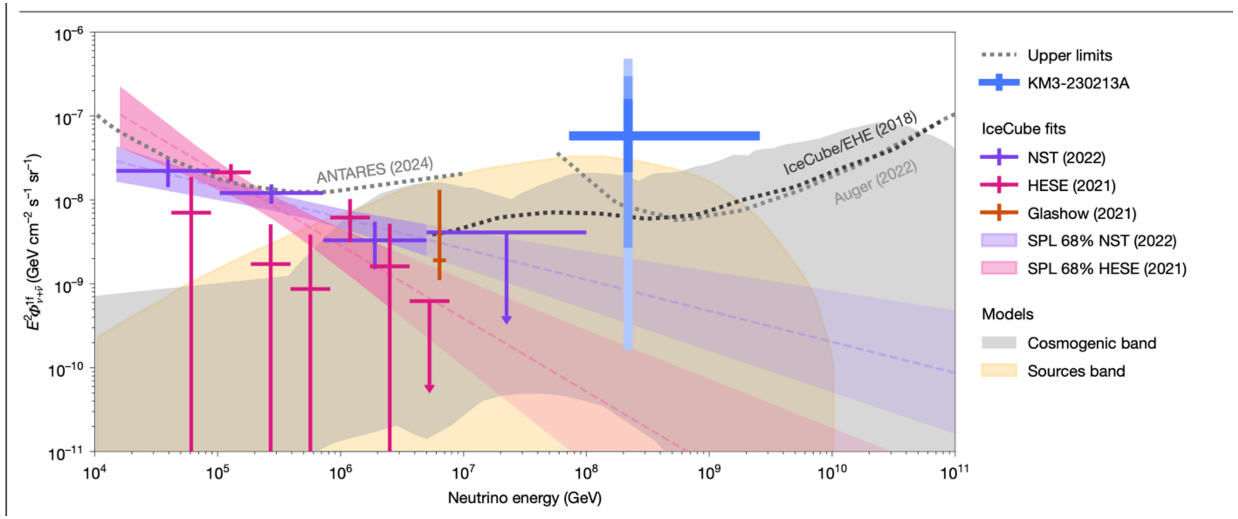


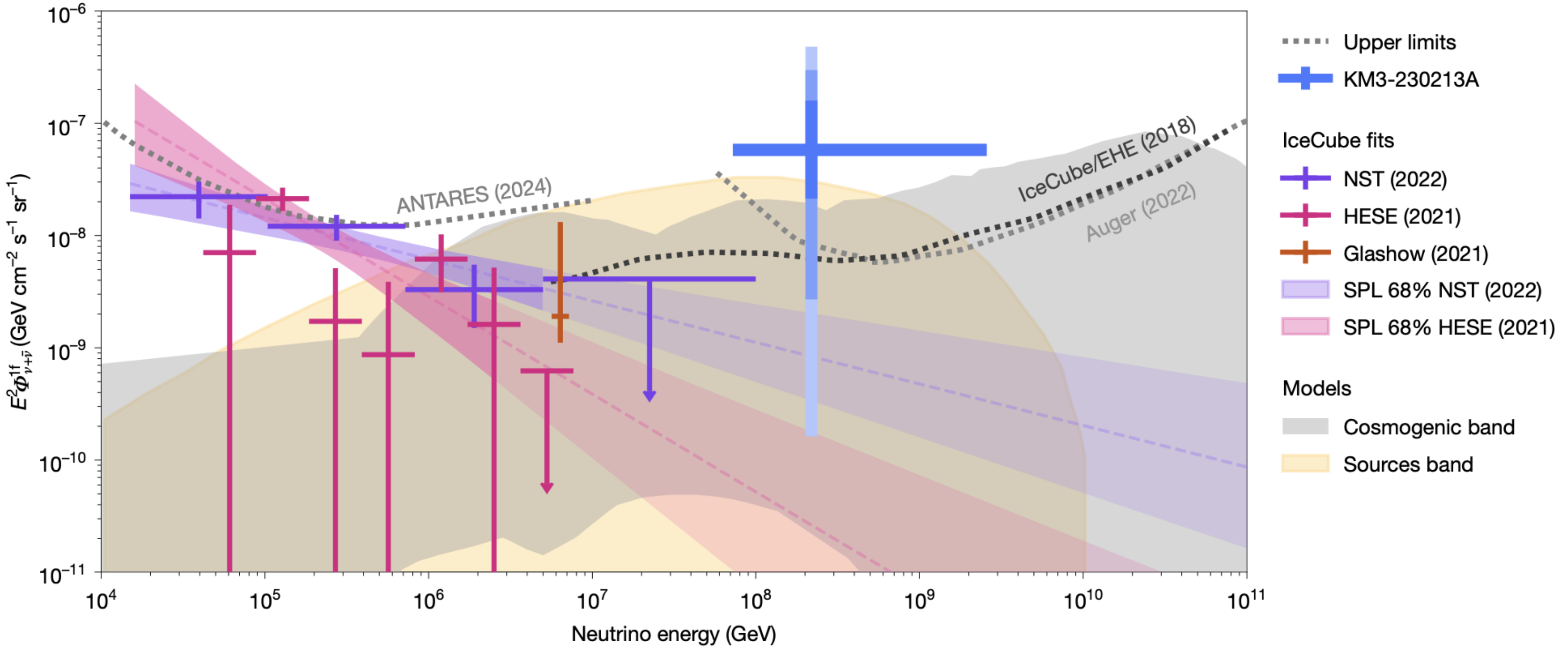
KM3NeT, Nature 638 (2025) 376



Extended Data Fig. 4 | Illustration of the topography. Using bathymetric data from EMODnet[90], a sectional view along the incoming direction and position of the event is shown, with the sea shown in blue and the seabed and the rock beneath in brown. The *x* axis indicates the total distance from the ARCA site and the *y* axis and grey lines represent the depth with respect to the sea level. The shaded area shows the effect of a variation of ±1.5° in the direction reconstruction, corresponding to the 68% error region from the evaluation of systematic uncertainties.

KM3-230213A 21 lines 287.4 days



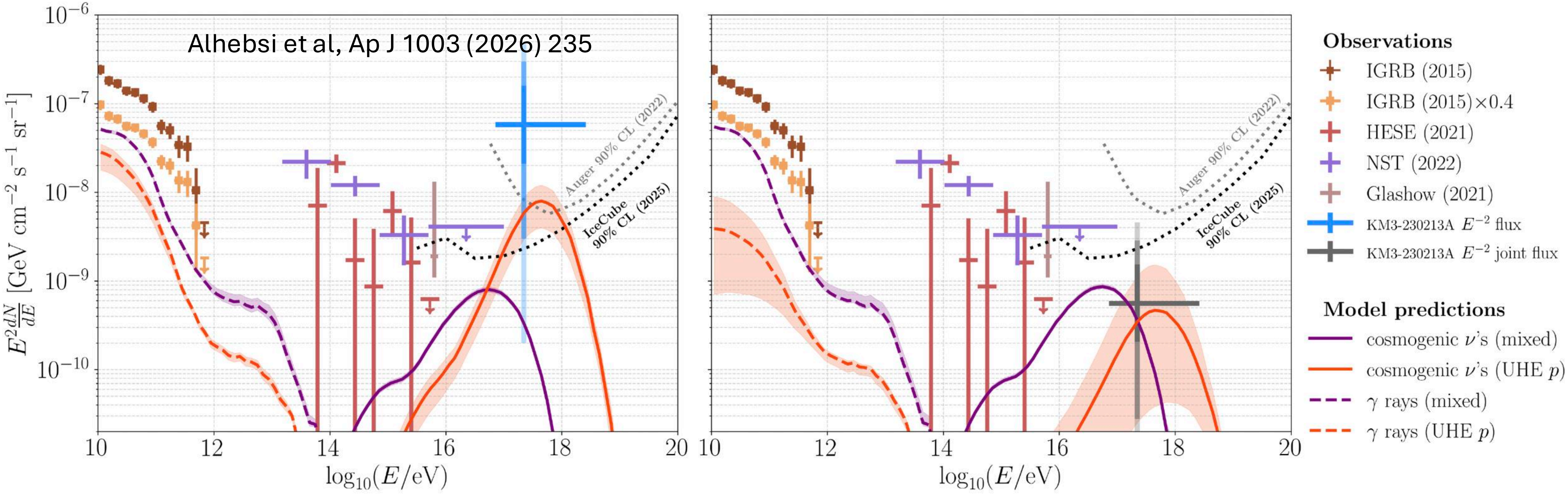


$$E_\mu = 120^{+110}_{-60}\mathrm{PeV} E_\nu = 72\mathrm{PeV} - 2.6\mathrm{EeV}$$

See Yuan, Lu, HiHEP 1 (2025) 2, 19 for discussion.

- Standalone flux value from KM3NeT is high!
- Why no IceCube, Auger observation?
- Could this be something other than a neutrino?

Aside – SM (not BSM) example of cosmogenic neutrinos & photons with KM3Net result



per flavor neutrinos, mixed composition (purple) and proton (orange)
Left: KM3NeT flux – alone, Right: joint fit flux

conclusion, about 20% protons in CRs at 1 EeV, could be strong proton evolution.

Best fit parameters to accommodate KM3NeT

Alhebsi et al, Ap J 1003 (2026) 235

$$J_{\rm inj}(E) = J_0 \sum_A f_A \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{Z_A R_{\rm max}}\right).$$

$$S(z) = \begin{cases} (1+z)^m & \text{for } m \leqslant 0 \text{ and } z \leqslant z_{\rm max} \\ (1+z)^m & \text{for } m > 0 \text{ and } z \leqslant z_0 \\ (1+z_0)^m & \text{for } m > 0 \text{ and } z_0 < z \leqslant z_{\rm max} \\ 0 & \text{for } z > z_{\rm max}. \end{cases}$$

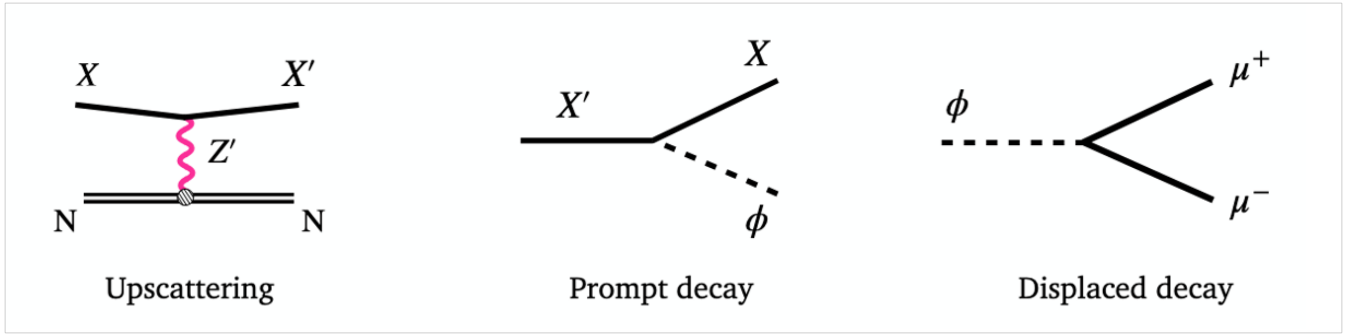
Table 1
The 68% CL Intervals around the Best-fit Parameters

Best Fit	KM3NeT-only	Joint
Mixed-composition population		
γ	$-2.77^{+0.11}_{-0.11}$	$-2.78^{+0.13}_{-0.13}$
$R_{\rm max}$ (EV)	$1.23^{+0.03}_{-0.03}$	$1.24^{+0.03}_{-0.04}$
m	$3.9^{+0.1}_{-0.1}$	$4.0^{+0.1}_{-0.1}$
$f^R_{\rm H}$ (%)	$0.2^{+6.8}_{-0.2}$	$0.3^{+9.5}_{-0.3}$
$f^R_{\rm He}$ (%)	$50.5^{+5.1}_{-5.2}$	$47.0^{+2.6}_{-5.1}$
$f^R_{\rm N}$ (%)	$41.9^{+5.5}_{-5.5}$	$45.4^{+5.5}_{-6.5}$
$f^R_{\rm Si}$ (%)	$7.0^{+0.7}_{-0.9}$	$7.0^{+0.7}_{-1.5}$
$f^R_{\rm Fe}$ (%)	$0.39^{+0.26}_{-0.15}$	$0.43^{+0.25}_{-0.16}$
Pure-proton population		
γ^p	$-1.66^{+1.18}_{-1.34}*$	$-0.05^{+0.66}_{-0.88}$
$R^p_{\rm max}$ (EV)	$7.18^{+2.82}_{-1.96}$	$10.01^{+2.95}_{-2.30}$
m^p	$6.1^{+0.5}_{-0.9}$	$2.5^{+1.6}_{-3.7}$
$f^{\rm obs}_p$(20 EeV) (%)	$20.3^{+1.6}_{-1.4}$	$19.4^{+1.4}_{-1.3}$
$D/N_{\rm dof}$	155.4/51	165.2/55

Note. The number of degrees of freedom are $N_{\rm dof,CR} = 49$ and $N_{\rm dof,UHE\ \nu} = 2$ from the two Poissonian distributions inside and outside the energy range of KM3-230213A. Confidence intervals that touch the boundaries of the parameter space are indicated by an asterisk.

BSM "neutrino-like" physics

- Use BSM physics to make "neutrino-like" particles.



Farzan & Hostert, JHEP 10 (2025) 208

Hot dark matter χ:

$$\chi A \to \ldots \to \chi \mu^+ \mu^- A$$

KM3NeT distance - 147 km

IceCube distance - 14 km

Solution: $\chi \to \phi \to \ell^+ \ell^-$

$$\gamma c \tau_\phi \sim 100\text{km}\left(\frac{E_\phi}{100\text{PeV}}\right)$$

$$E_\phi = E_{\mu^+} + E_{\mu^-} \sim E_{\text{KM3NeTevt}}$$

Muon pair combined gives KM3NeT event.

No decay of ϕ in short distance to IceCube!

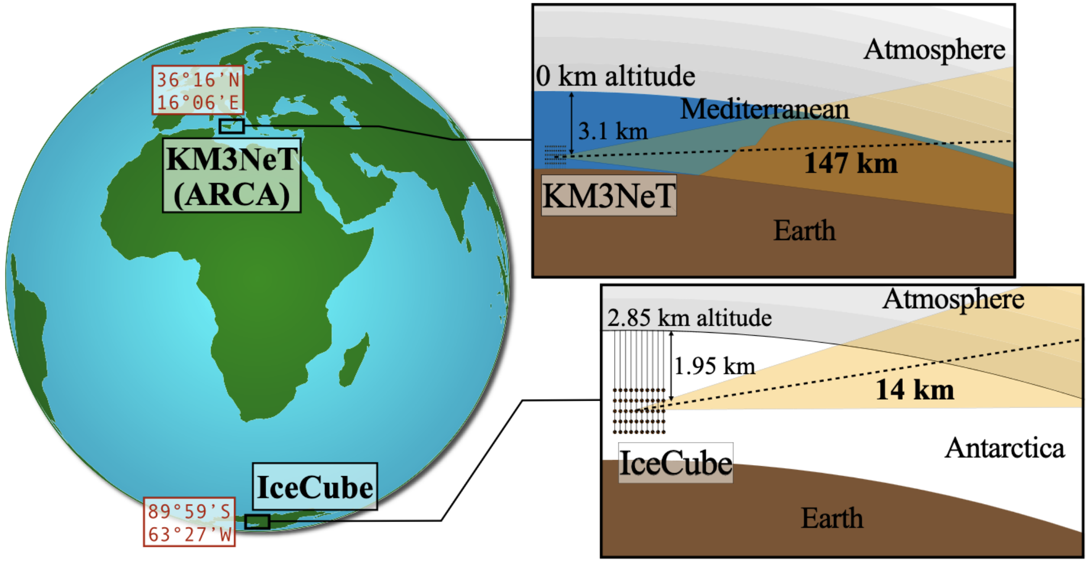
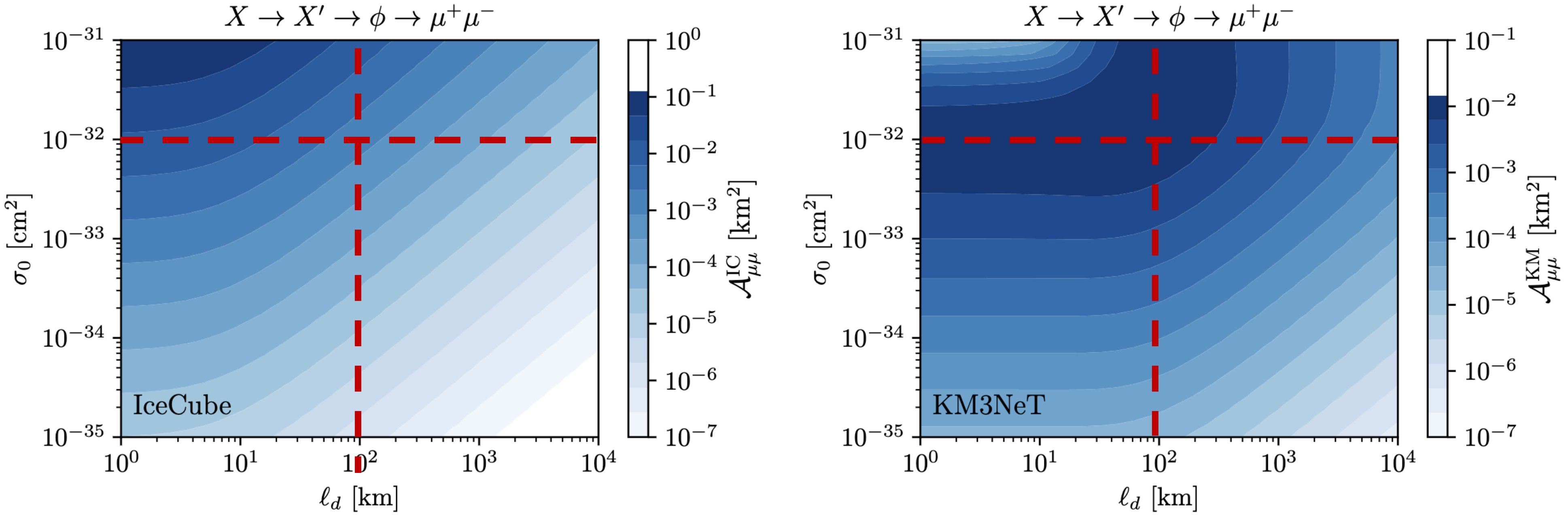


Fig. from Brdar & Chattopadhyay, PRL 136 (2026) 081001

BSM “neutrino-like” physics

Farzan & Hostert, JHEP 10 (2025) 208



Can get better sensitivity of KM3NeT than for IceCube for a transient source in this location (even an order of magnitude).

Many other speculations.

Final remarks – need multi-messenger/multi-detector

- Simplified picture: pp (atmosphere, in sources), $p\gamma$ (in sources, in transit) produce pions which lead to neutrinos.
- $\pi^{\pm} \rightarrow \nu's, \pi^0 \rightarrow \gamma\gamma$ lead to relations between ϕ_ν, ϕ_γ at the point of production.
  - Photons and cosmic rays (CRs) propagate, and spectra change due to transit.
- Neutrino fluxes/fluences (and associated photon, CRs) requirements include information about acceleration (spectrum, cutoff) of CRs in sources, target γ in sources. The evolution of sources as function of time (redshift) needed for the diffuse neutrino flux.
  - Very efficient neutrino production may impact escape of HE CRs and photons – multi-messenger observations will be key to understanding sources. Simple models (one-zone) of source production may not work. Trend: gamma-ray opaque neutrino source models.
  - CR nuclei propagate differently than CR protons; it is still and active area of research to understand CR composition – trend to heavy, but a component could still be protons.
- BSM physics can introduce new neutrino fluxes, neutrino-like particles, modify neutrino cross sections, …. The UHE access that neutrino telescopes have can constrain parameter space in ways that human-made neutrino sources cannot.