Connections between neutrino interaction physics and astrophysics/astroparticle physics

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NuSTEC Summer School

CERN

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Plan for lectures

- Neutrino cross sections: DIS and extrapolation to ultrahigh energies (UHE)
- Glashow resonance, subleading contributions
- Neutrino detection: across the energies

- Atmospheric neutrinos
- Astrophysical neutrinos: diffuse neutrino flux and transient sources
- Cosmogenic neutrinos: diffuse neutrino flux from cosmic rays in transit through Universe
- Some BSM physics examples with astrophysical neutrinos

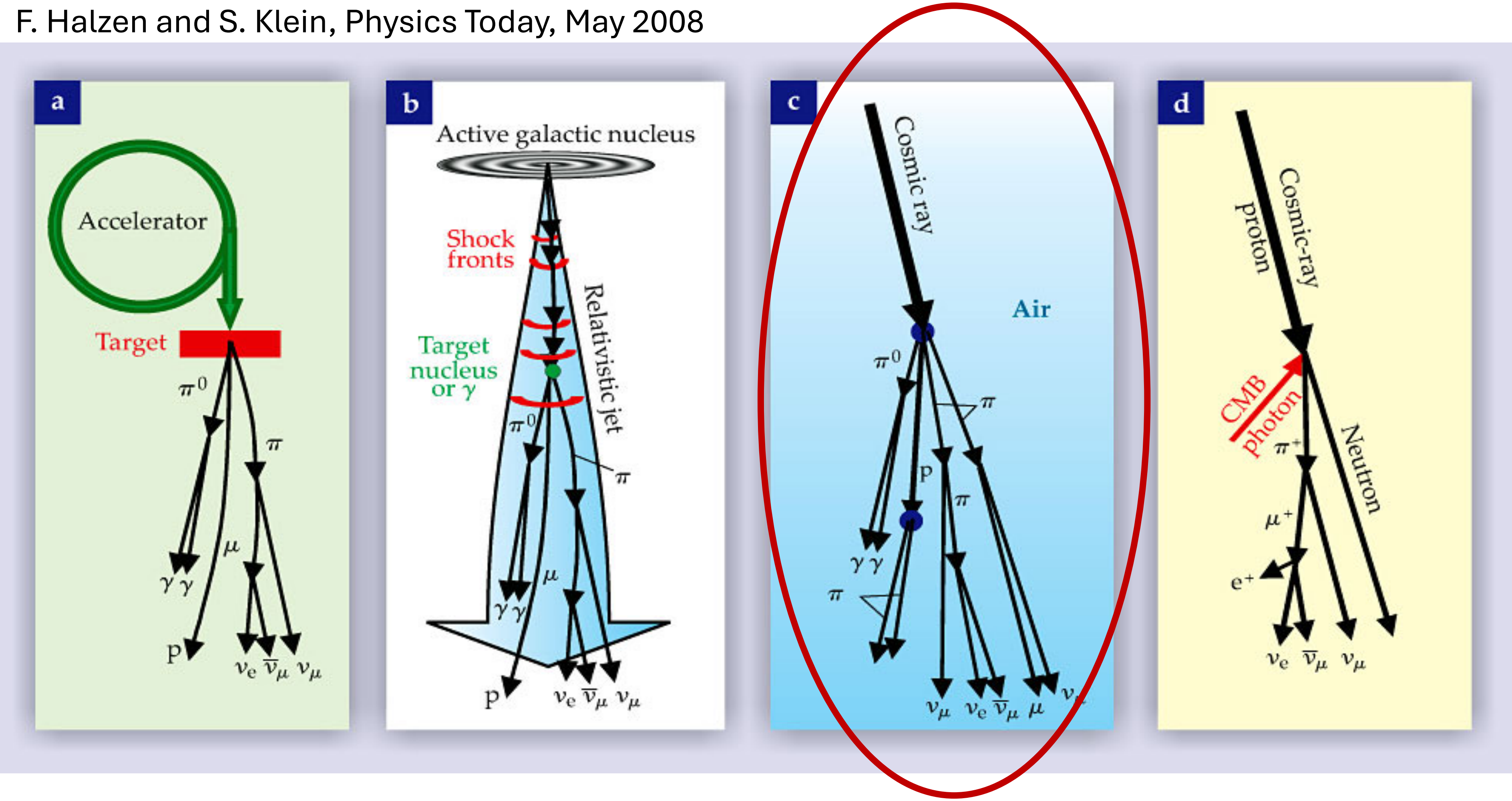
Atmospheric neutrinos

References

- Lipari, Lepton spectra in the earth's atmosphere, Astropart.Phys. 1 (1993) 195
- Gaisser, Engel & Resconi, Cosmic Rays and Particle Physics : 2nd Edition
- Conventional flux, for example:
  - Gaisser & Honda, Flux of atmospheric neutrinos, Ann.Rev.Nucl.Part.Sci. 52 (2002) 153
  - Fedynitch et al., Hadronic interaction model sibyll 2.3c and inclusive lepton fluxes, PRD 100 (2019) 103018
- Prompt flux, for example:
  - Bhattacharya et al., Prompt atmospheric neutrino fluxes: perturbative QCD models and nuclear effects, JHEP 11 (2016) 167
  - Gauld et al., The prompt atmospheric neutrino flux in the light of LHCb, JHEP 02 (2016) 130
  - Zenaiev et al, Improved constraints on parton distributions using LHCb, ALICE and HERA heavy-flavour measurements and implications for the predictions for prompt atmospheric-neutrino fluxes, JHEP 04 (2020) 118

Neutrino production

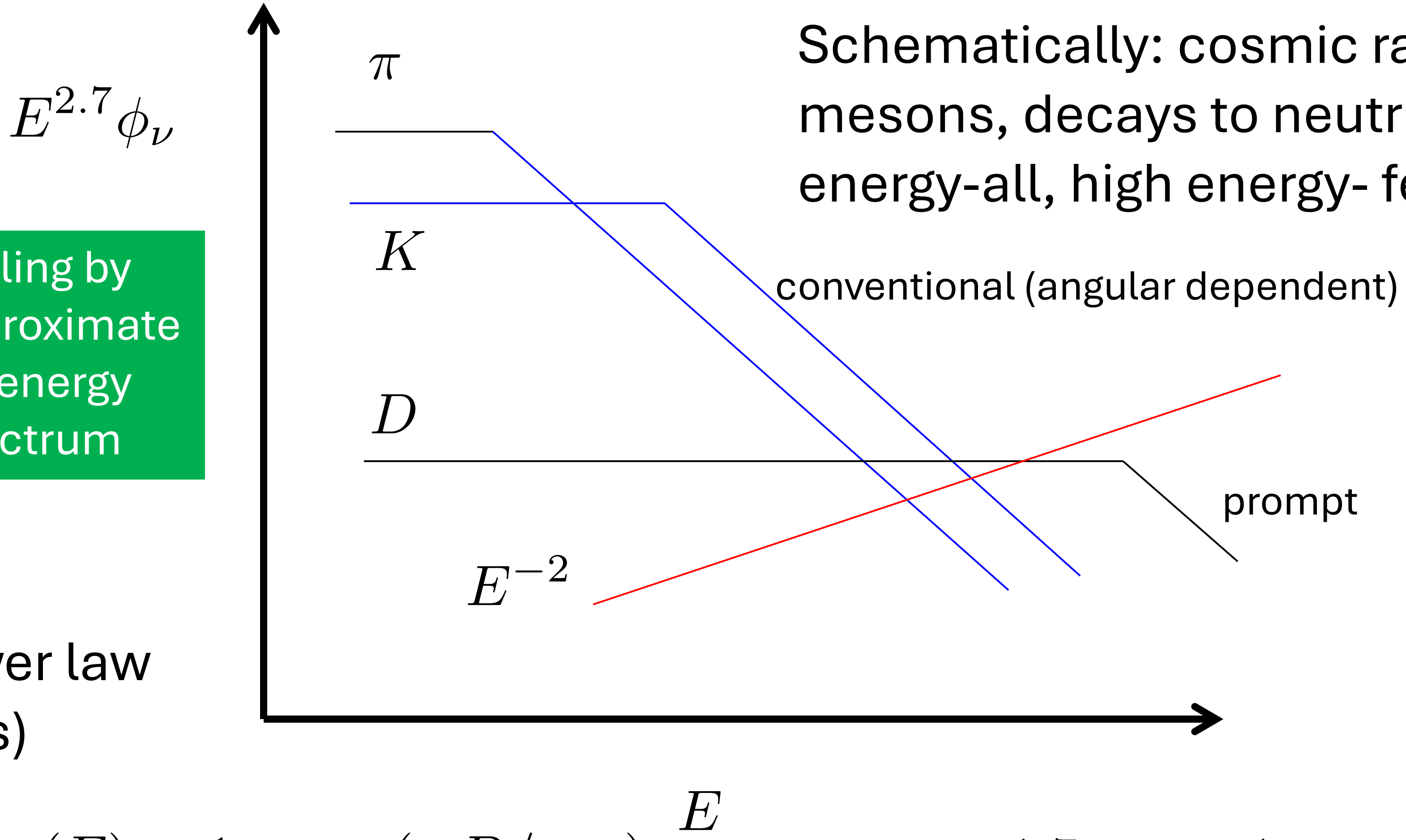
F. Halzen and S. Klein, Physics Today, May 2008



Same production mechanism for accelerator beams, inside astrophysical objects, in the atmosphere, and for the cosmogenic neutrino flux.

Atmospheric lepton fluxes

Schematically: cosmic rays produce mesons, decays to neutrino (low energy-all, high energy- few)



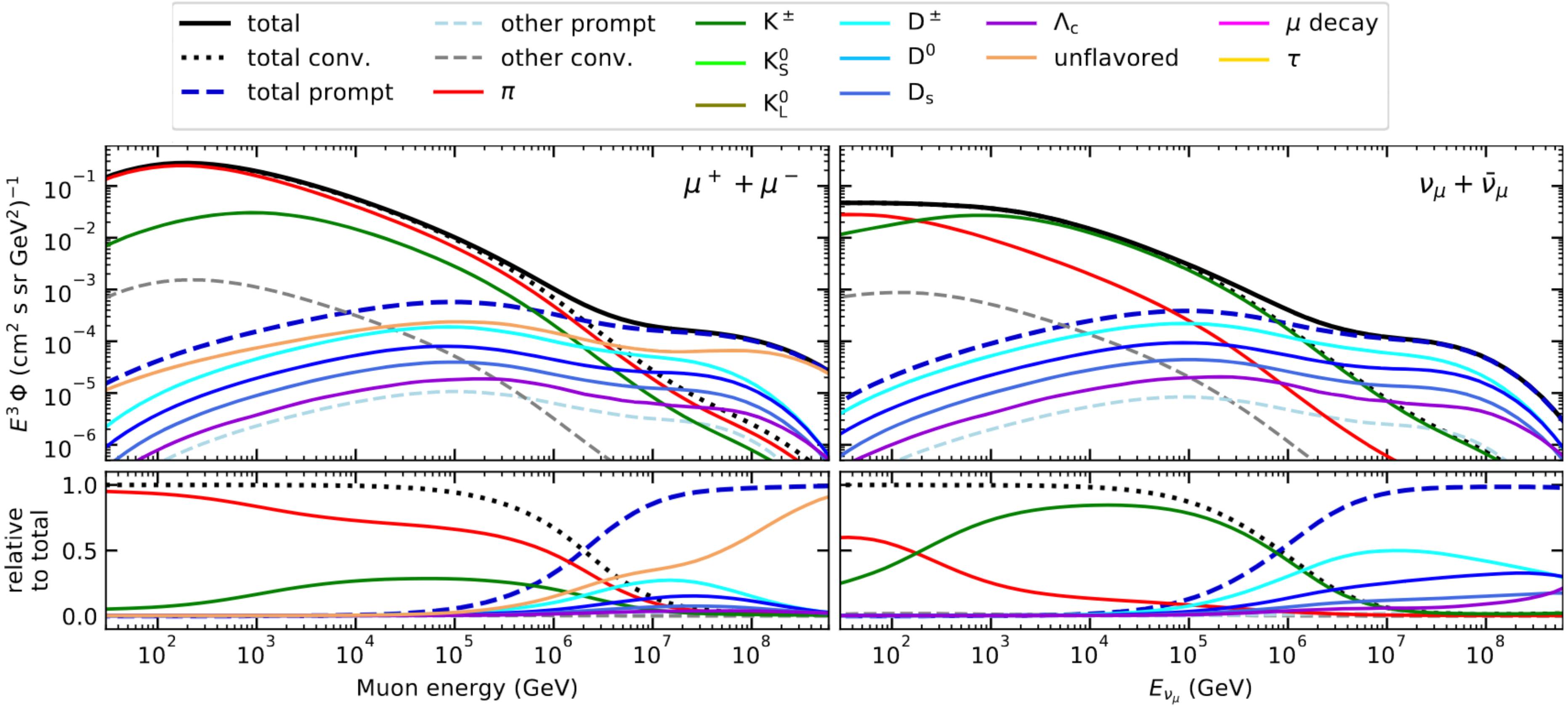
Scaling by approximate CR energy spectrum

BPL=broken power law (for comparisons)

$$P_{decay}(E) = 1 - \exp(-D/\gamma c\tau) \simeq D/\gamma c\tau = E_c/E$$

$$\phi \sim \frac{1.7}{E_{\mathrm{GeV}}^{2.7}} \frac{1}{\mathrm{cm^2\,s\,sr\,GeV}}$$

Example atmospheric flux calculation



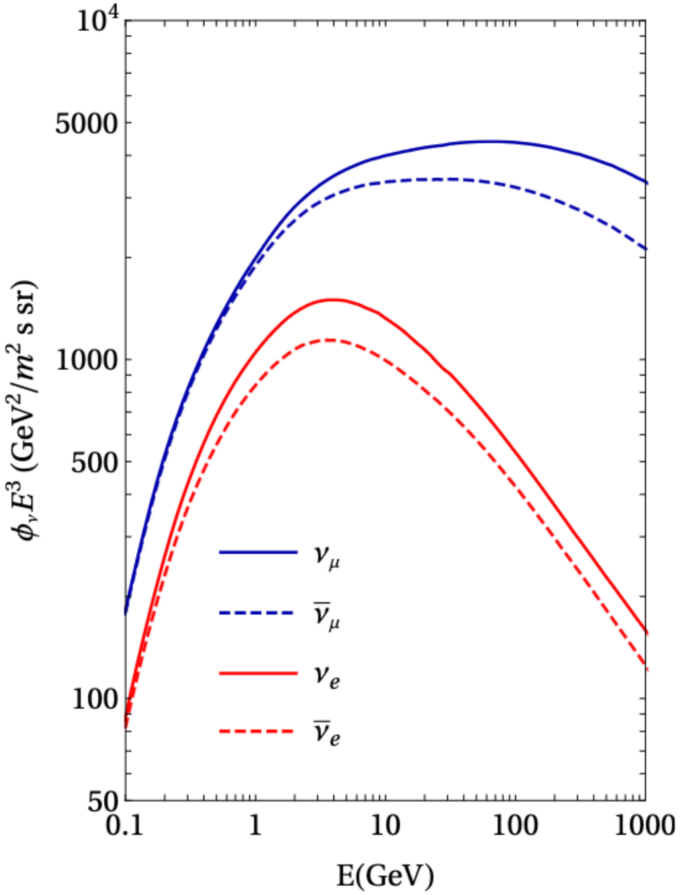
Fedynitch et al, PRD 100 (2019) 103018

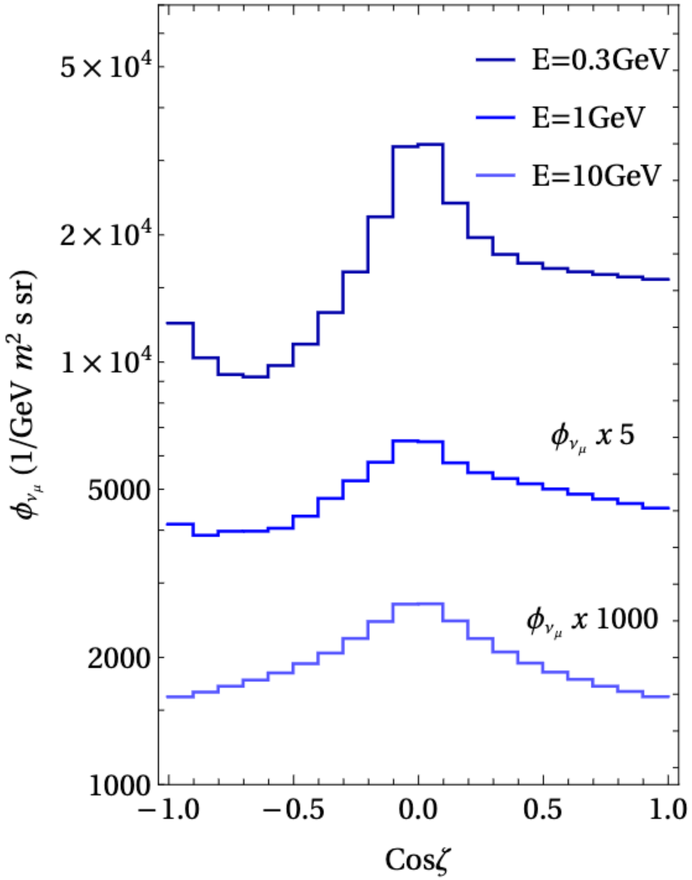
Atmospheric neutrino flux

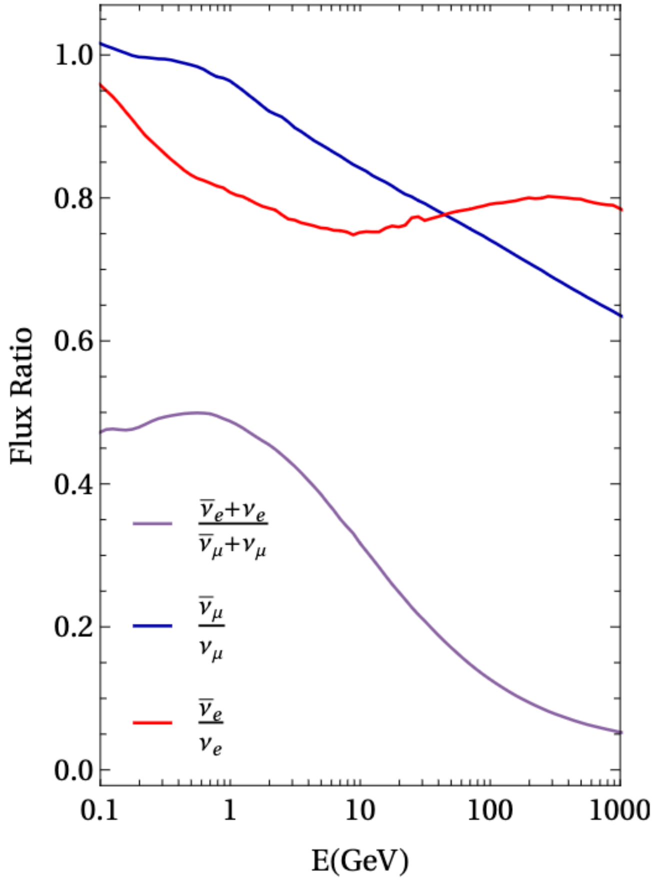
cosmic rays have positive charge

- magnetic field effect
- column depth of atmosphere

high energy muons don't decay

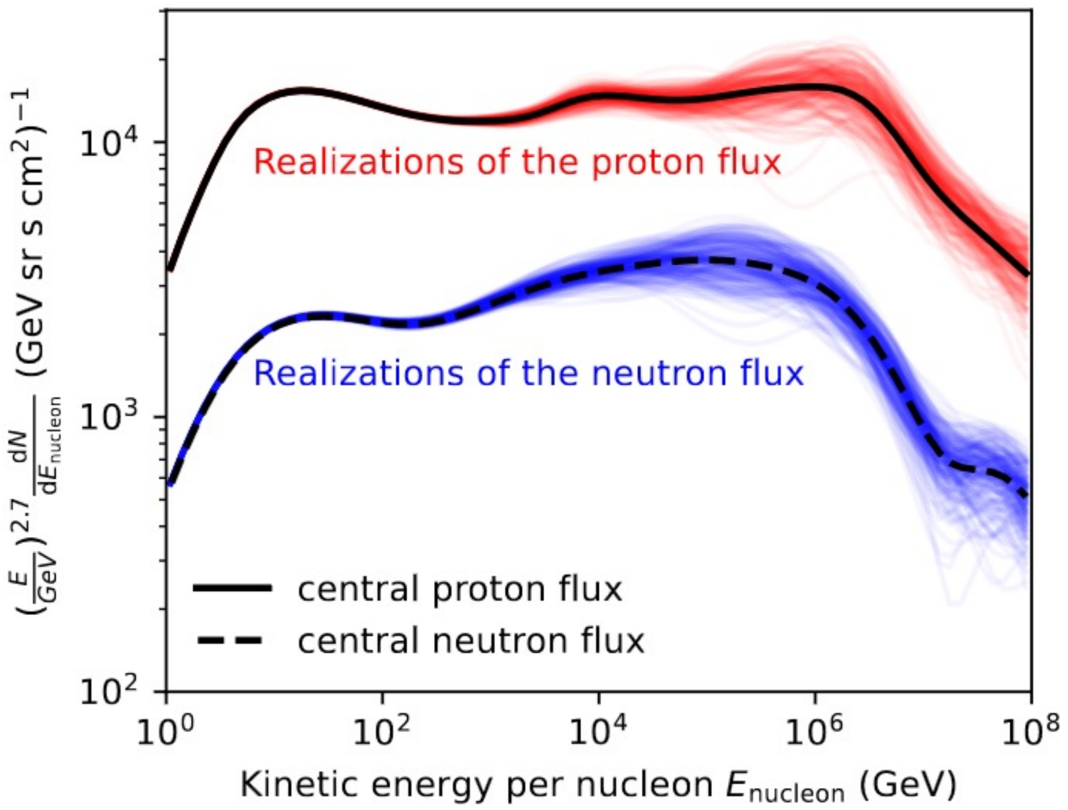






Kelly et al, JHEP 05 (2022) 187. Atm neutrino oscillations not important above ~50 GeV. Ask Kevin about Earth tomography.

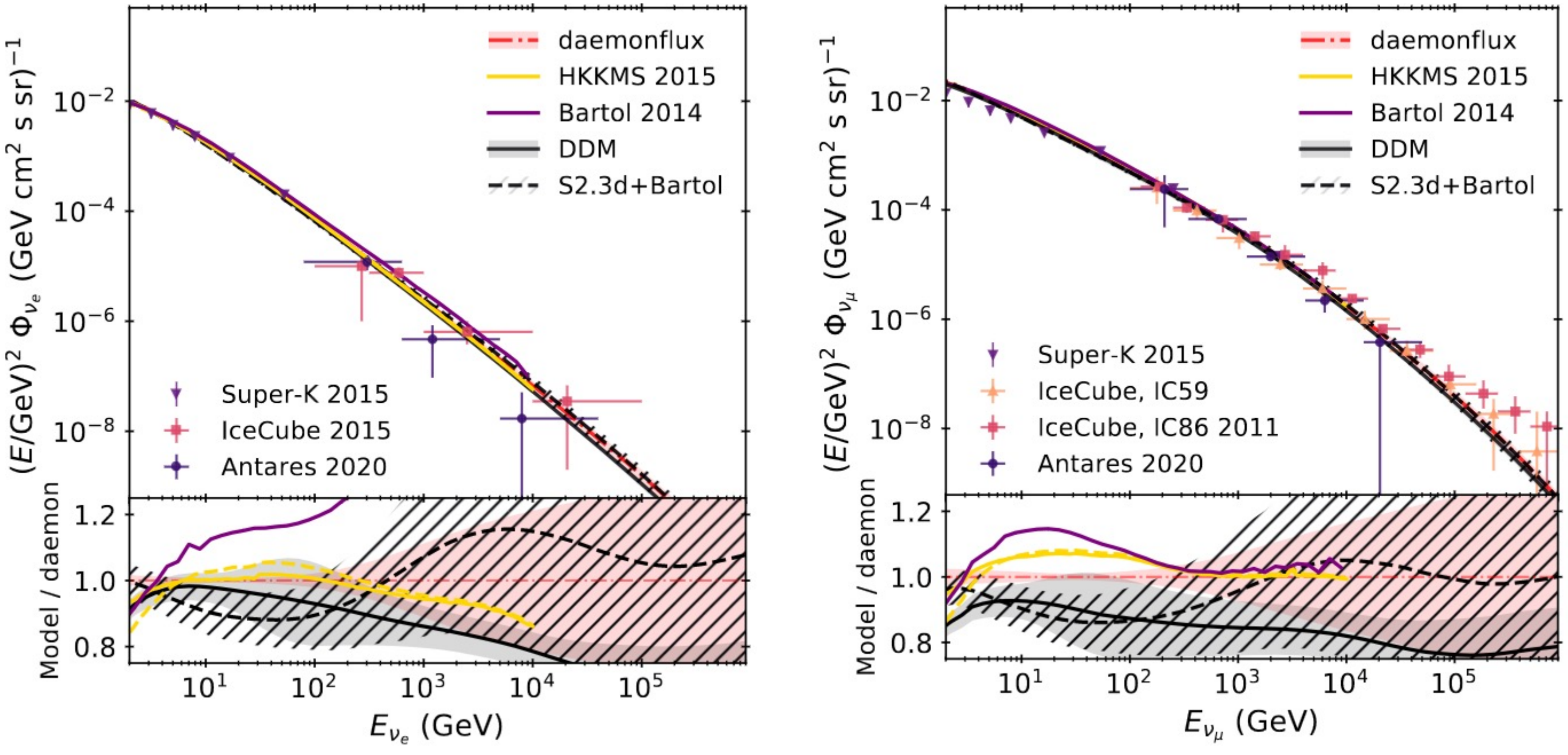
Atmospheric flux uncertainties



Yanez & Fedynitch, PRD 107 (2023) 123037, PoS (ICRC2023) 1215.

- Cosmic ray spectrum and composition. Here, per nucleon, primarily from p and He.
- Light meson production, forward production – cross sections and energy distributions, limited range of lab energies in experiments.
- Traditional uncertainties from measurements: e.g., Barr+, PRD 74 (2006) 094009, 15%-30% uncertainties in $\nu_\mu, \bar{\nu}_\mu$ flux normalizations for $E \sim 0.1 -$ 100 GeV, smaller uncertainties in ratios.

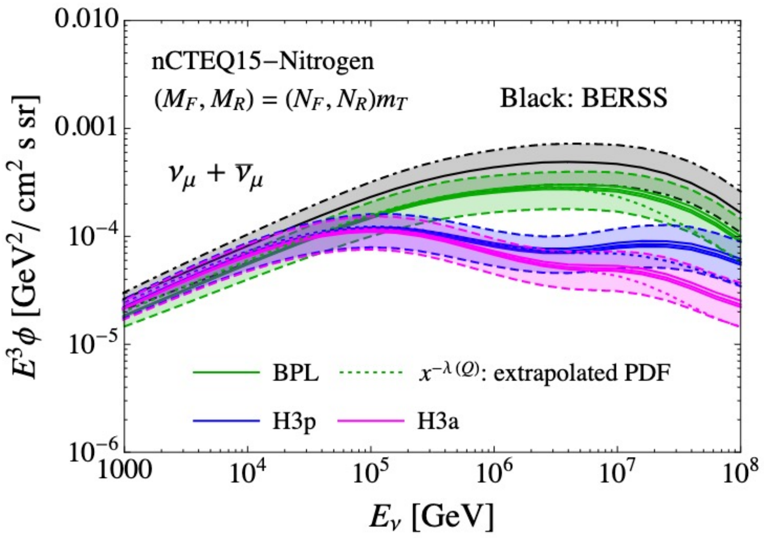
Atmospheric fluxes

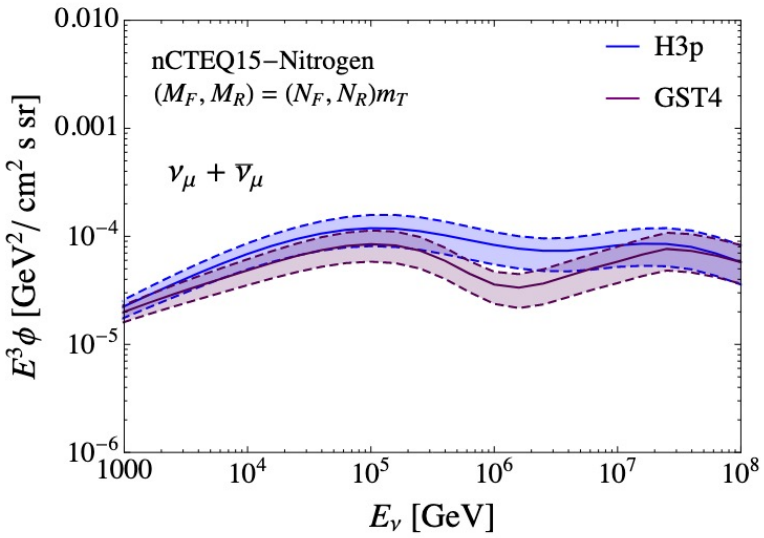


Yanez & Fedynitch, PRD 107 (2023) 123037, PoS (ICRC2023) 1215.

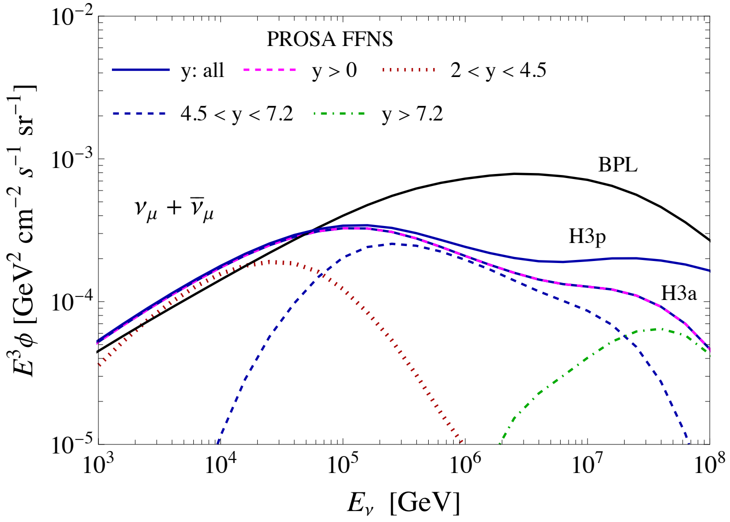
- Yanez & Fedynitch use correlations between atmospheric muon and neutrino fluxes: daemonflux
- Note shaded red uncertainties below 100 GeV are small.

High energy atmospheric lepton fluxes





LHC connection: different y-axis scale

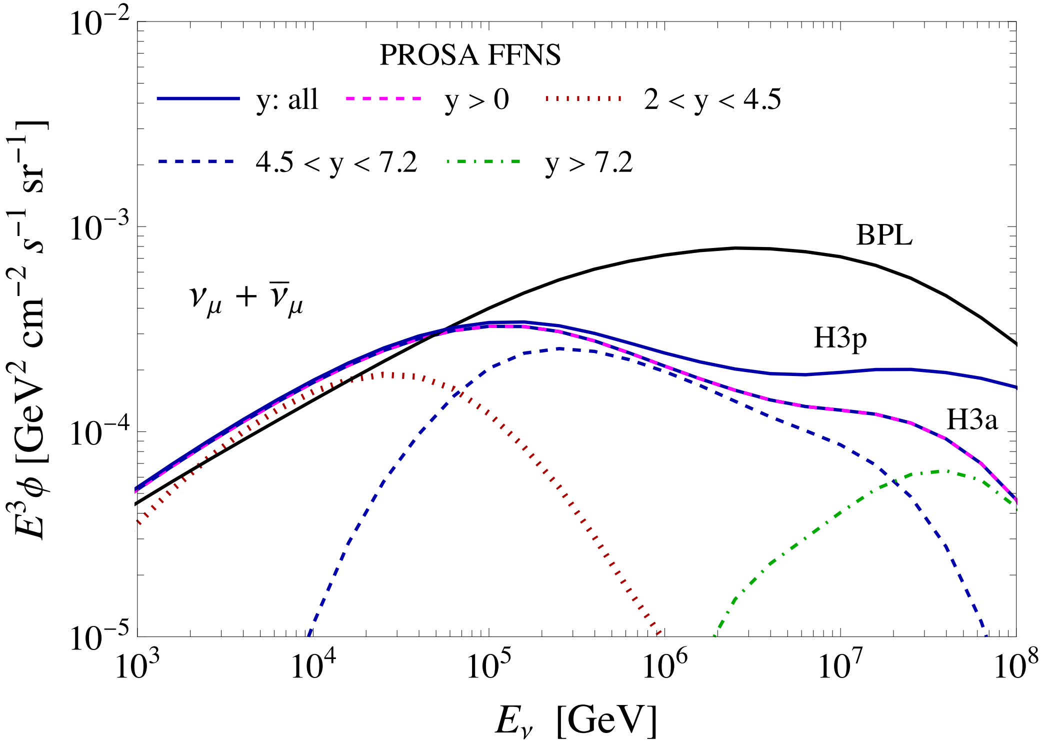


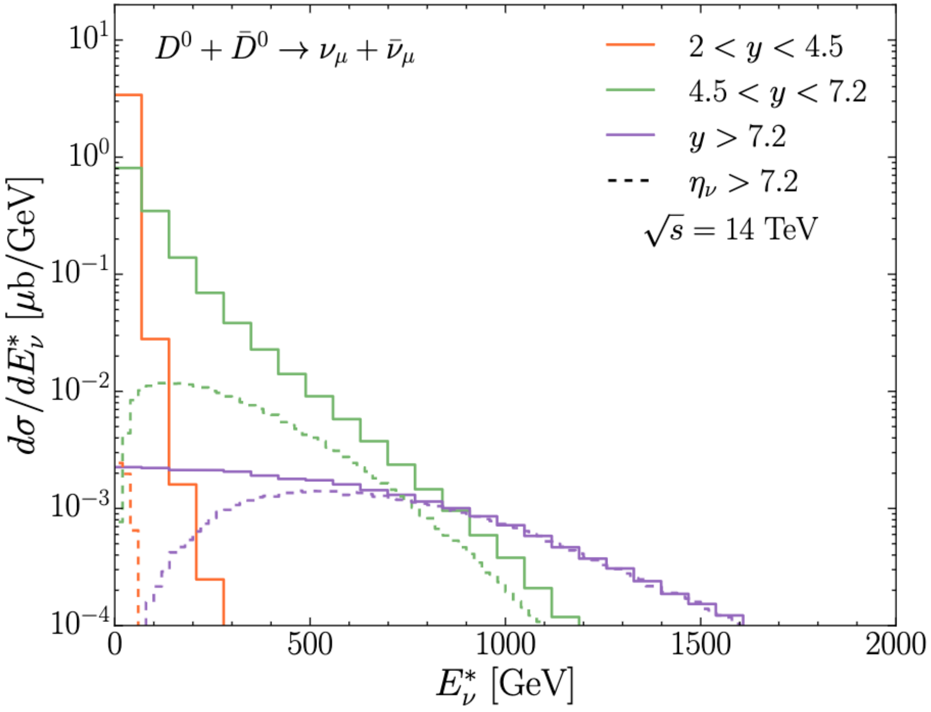
Forward production of charm is dominant contribution. Theoretical uncertainties are large. Interesting connection to forward production of charm & Forward Physics Facility.

Example, Bhattacharya …MHR… et al., JHEP 11 (2016) 167. FPF connection: Bai …MHR…et al, JHEP 10 (2023) 142

Atmospheric neutrinos & FPF

- histograms: neutrinos from charm y ranges
- dashed show distributions that go into the detectors

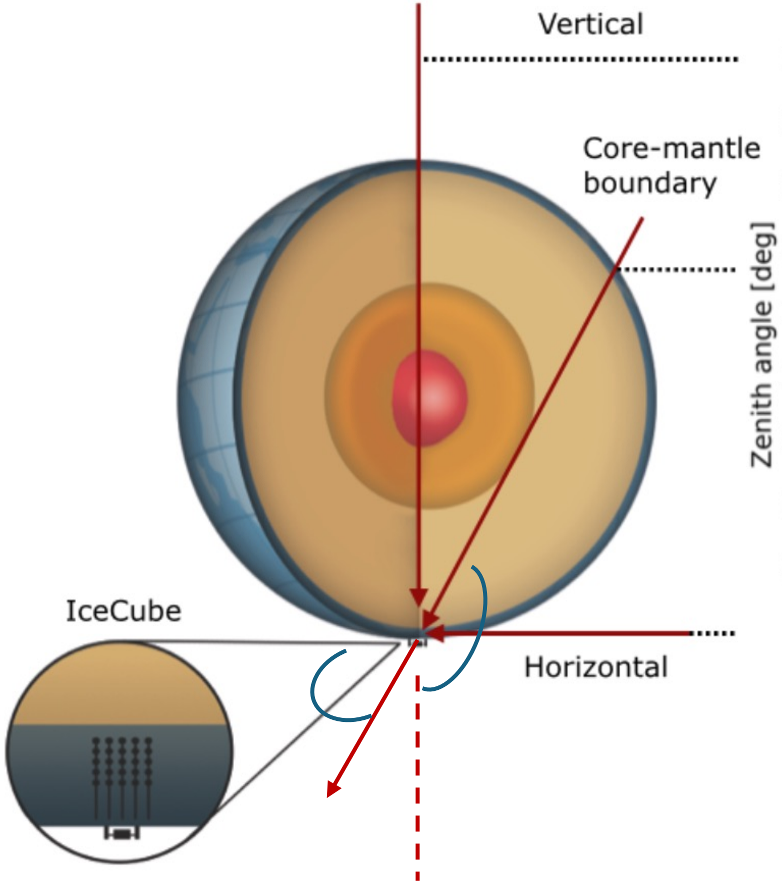


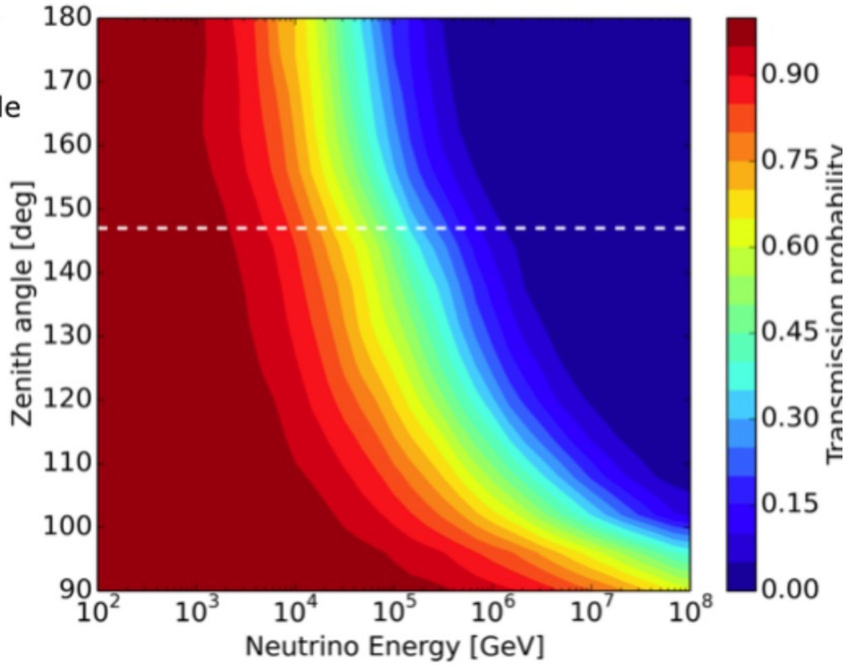


middle contribution in left plot corresponds to green dashed distribution in FPF plot

: Bai …MHR…et al, JHEP 10 (2023) 142

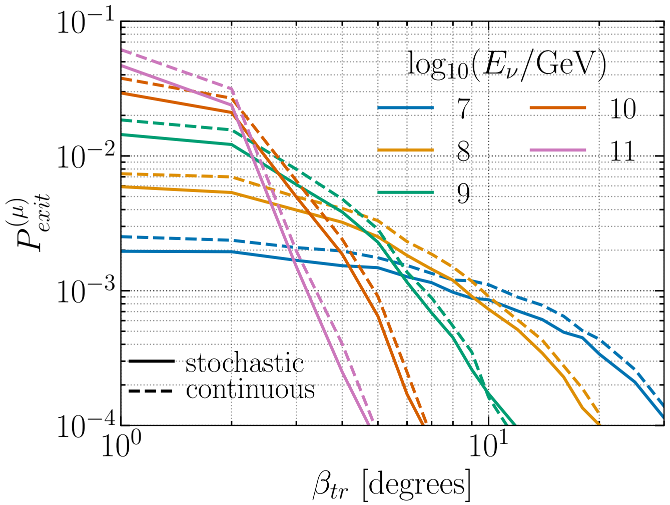
Neutrino cross section measurement





IceCube, *Nature* 551 (2017) 596-600

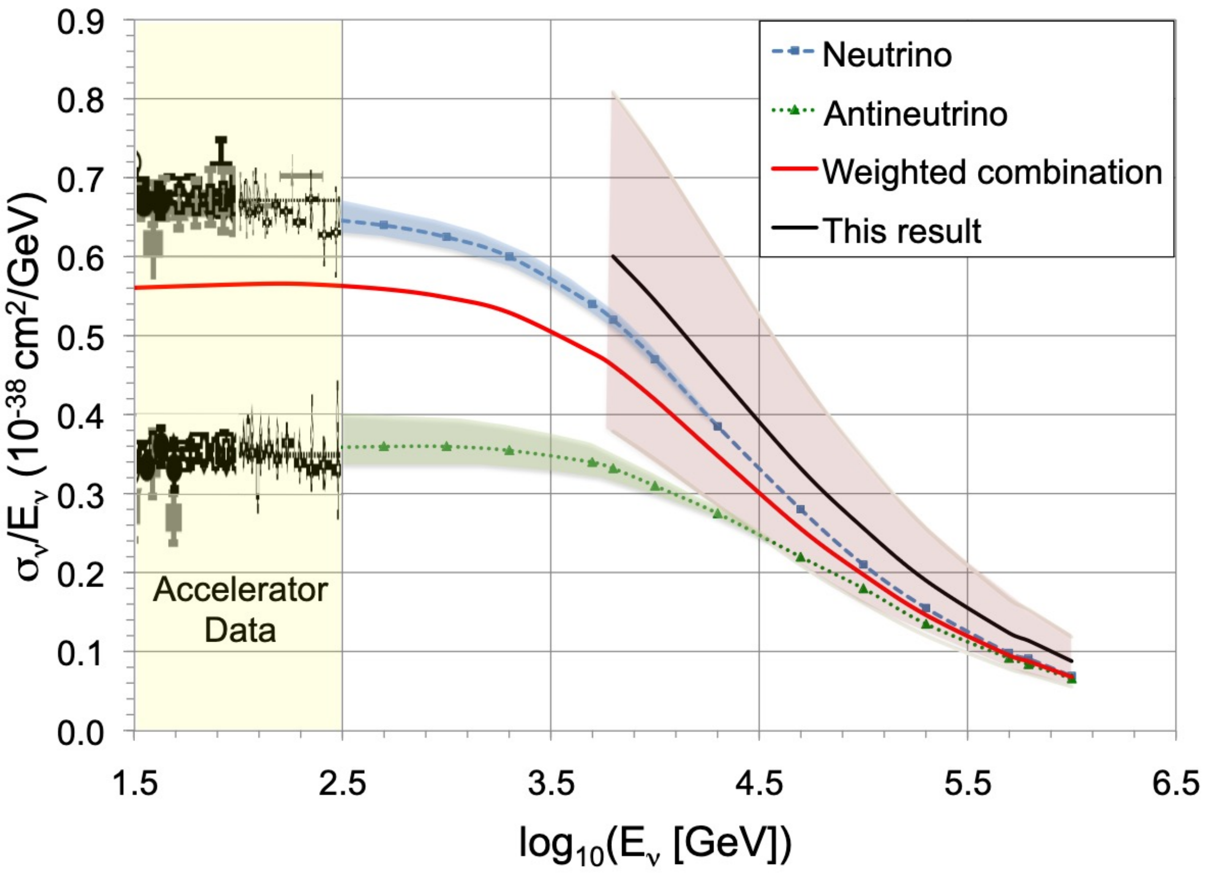
Upward-going neutrino induced muons for this measurement.



$E_\mu > 10^3$ GeV

Diksha Garg …MHR… et al JCAP01 (2023) 041

Neutrino cross section measurement

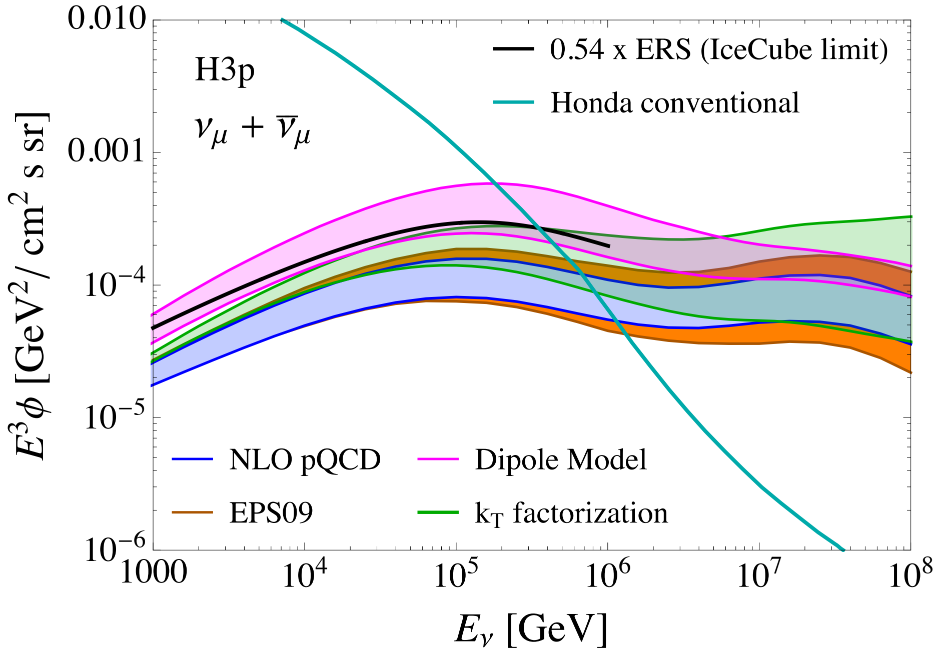


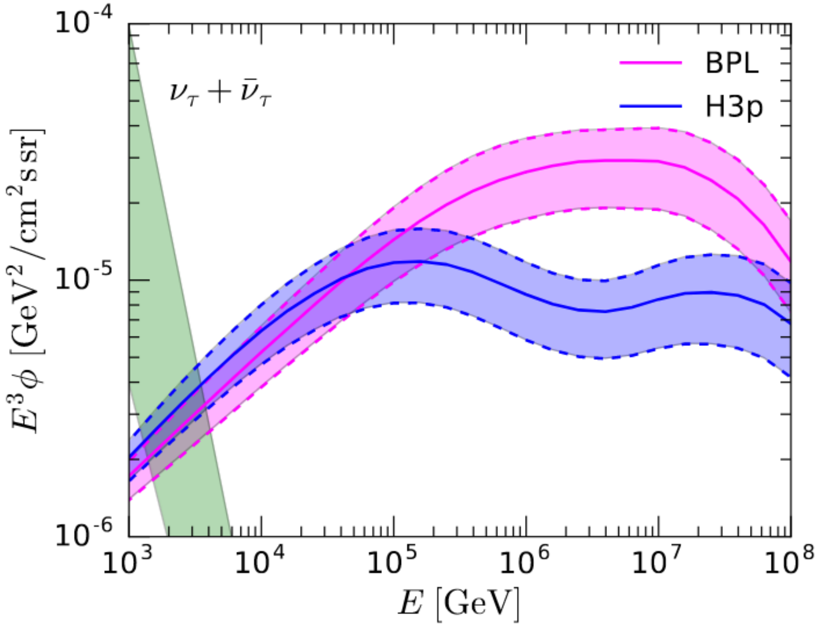
IceCube, *Nature* 551 (2017) 596-600

- Will improve statistics.
- Uncertainties include ice model and neutrino fluxes.

Tau neutrino flux

Note different scales for different flavors!





For tau neutrinos: D_s

Interesting connection to forward production of charm & Forward Physics Facility.

Example, Bhattacharya ...MHR... et al., JHEP 11 (2016) 167. FPF connection: Bai ...MHR...et al, JHEP 10 (2023) 142

Astrophysical neutrinos

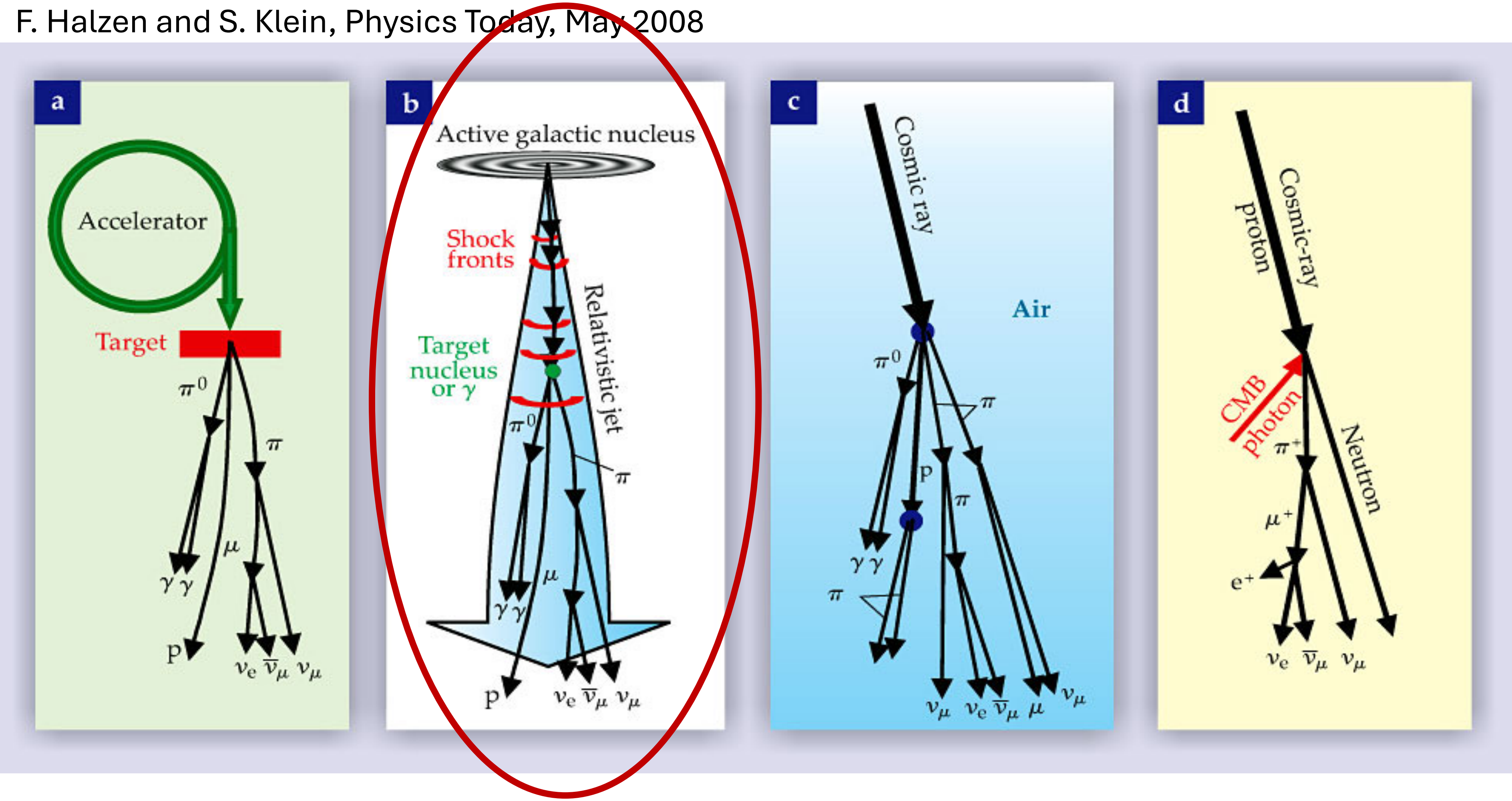
References

Referencing here more reviews, overviews rather than individual papers. Lots of reviews, e.g.,:

- Kurahashi, Murase, Santander, "High-Energy Extragalactic Neutrino Astrophysics," Ann Rev Nucl Part Sci, 2203.11936;
- Winter, "Sources of high-energy astrophysical neutrinos," 2402.19314;
- Ahlers & Halzen, "IceCube: neutrinos and multimessenger astronomy," Prog. Theor. Exp. Phys. (2017) 12A105

Neutrino production

F. Halzen and S. Klein, Physics Today, May 2008



Same production mechanism for accelerator beams, inside astrophysical objects, in the atmosphere, and for the cosmogenic neutrino flux.

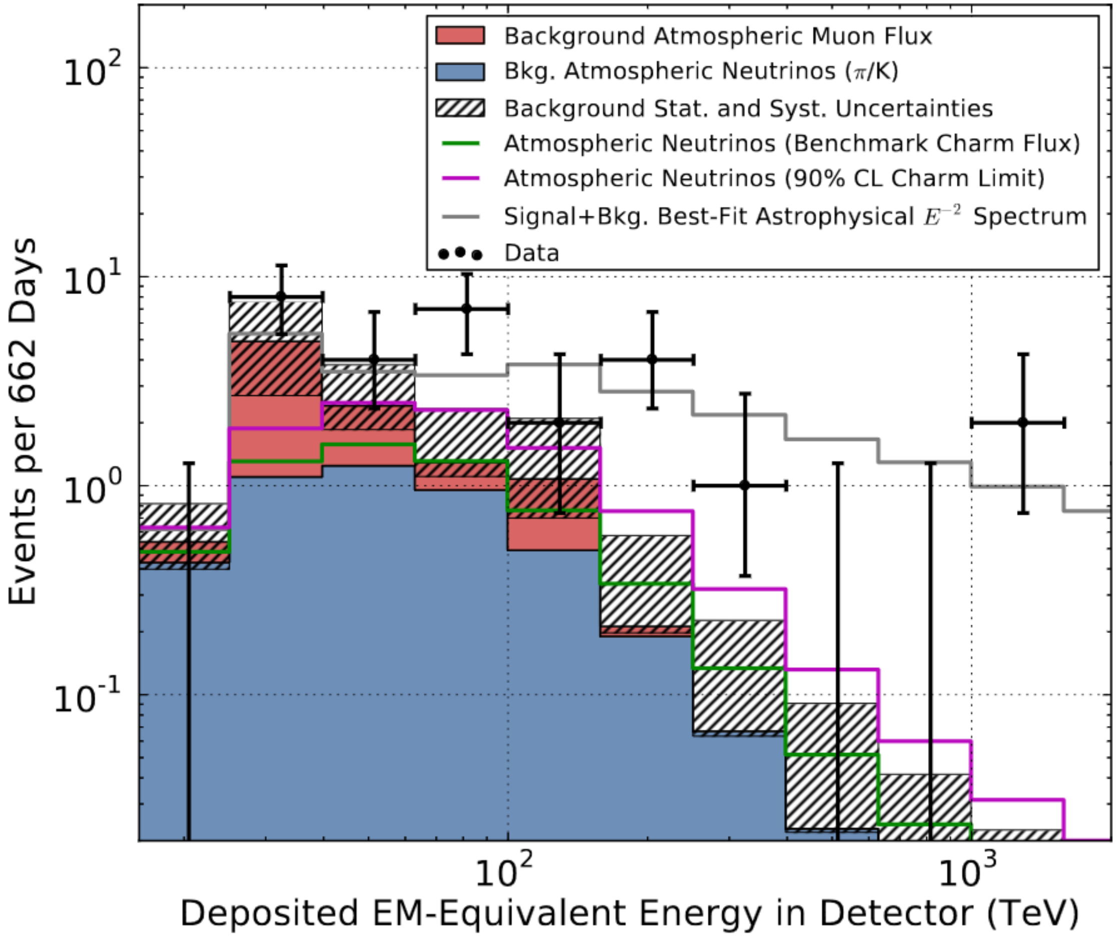
Astrophysical neutrinos

- Sources (point sources of neutrinos)
  - A few sources plus the Milky Way
- Diffuse flux (sum over all neutrino sources over all time)
  - First evidence from IceCube in 2013

Per flavor, for deposited energy 60 TeV – 2 PeV:

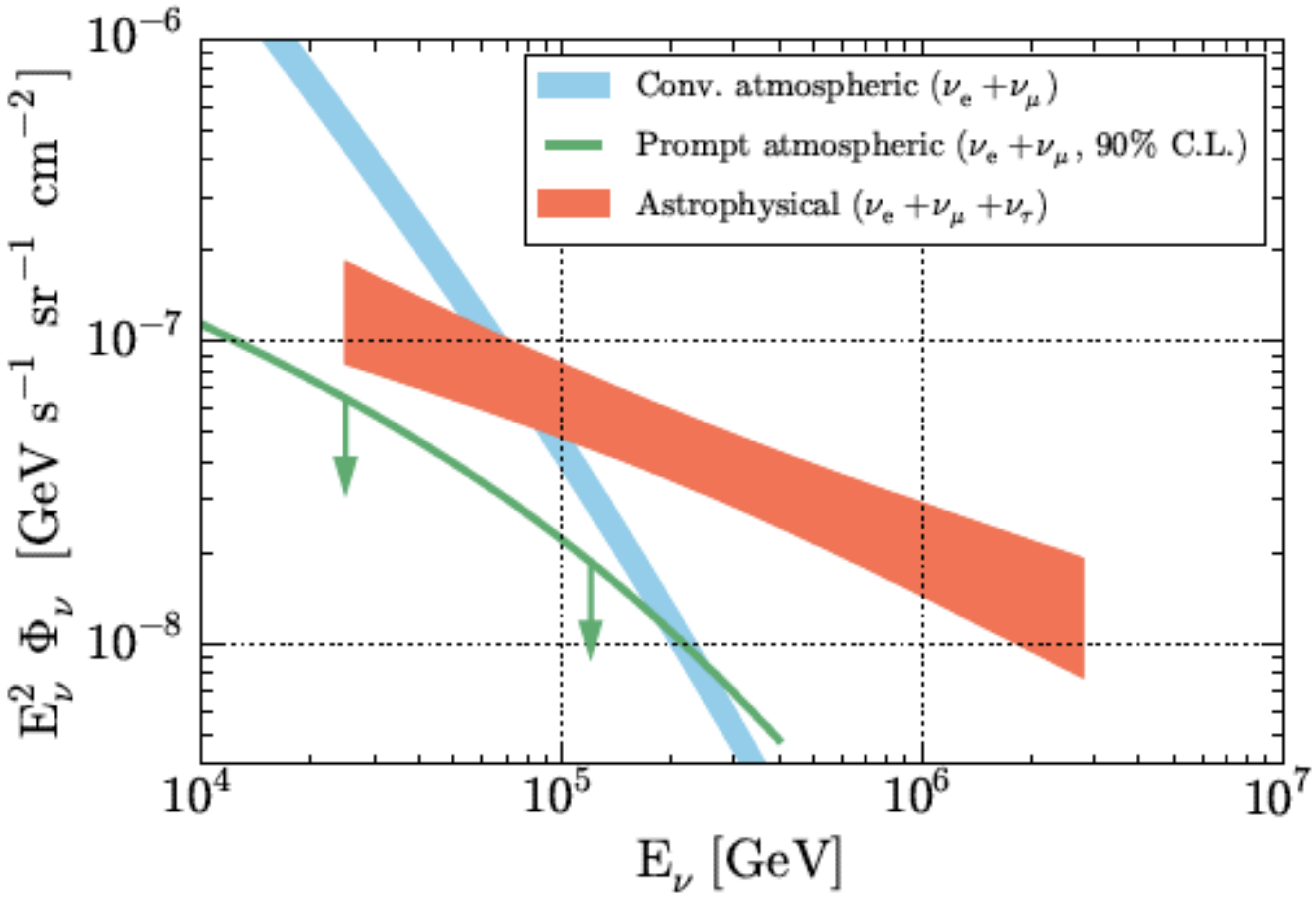
$$E^2\Phi(E) = (1.2\pm0.4)\cdot10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

<u>Start here with the diffuse flux.</u>



IceCube, Science 342 (2013) 1242856

IceCube best fit to single power law



IceCube, Astrophys.J. 809 (2015) 1, arXiv:1507.03991

Pay attention to:

- energy scaling
- overall normalization
- sum of flavors or single flavor

Conventional (from $\pi^\pm, K$) and prompt (from charm) atmospheric neutrino fluxes, then transition to astrophysical flux.

Generic astrophysical sources of neutrinos

Neutrinos can come from pp or $p\gamma$ interactions: produce $\pi^{\pm}$ (and π^0).
Charged pion (and muon) decays yield neutrinos, neutral pions yield photons.
To first approximation at the source:

$$E_\nu^2 \phi_\nu \sim E_\gamma^2 \phi_\gamma$$

and these fluxes are also related to the cosmic ray flux at the source.
Caveats:

- Gamma rays scatter with CMB and extragalactic background photons to degrade their energies.
- There is an additional energy dependence of the photon targets for $p\gamma$ interactions.
- Photons may not get out of the source, and maybe not cosmic rays.

Classic "bound": diffuse flux limits
cosmic ray proton interactions with photons in sources

- Waxman-Bahcall (PRD 59 (1999)) upper "bound" on diffuse neutrino flux. Relies on energy rate of production of cosmic rays.
- Cosmic ray spectrum produced at the source scale like: $\sim E_p^{-2}$
- Neutrino flux should scale like $\sim E_\nu^{-2}$
- Focus on $p\gamma$ neutrino production. Maximum neutrino intensity, neglect evolution and redshift dependence of sources, assuming source size is shorter than photon-meson mean free path (protons get out), is proportional to cosmic ray flux at sources:

$$E^2\Phi_\nu < 2 \times 10^{-8}\,\frac{\mathrm{GeV}}{\mathrm{cm^2\,s\,sr}}$$

- Assumptions include: semi-transparent sources, spectral index = 2 for CR at source and magnetic fields don't change observed spectrum.

Classic “bound”: diffuse flux limits

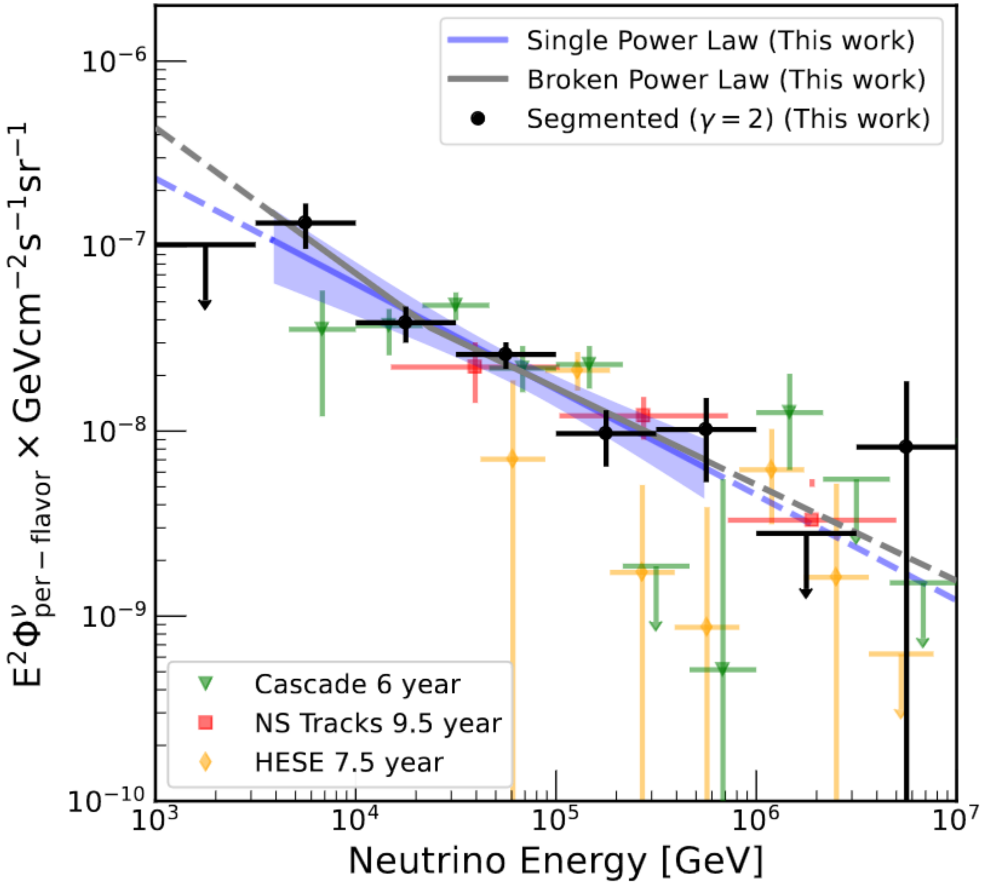
cosmic ray proton interactions with photons in sources

- Waxman-Bahcall bound: reference scale of neutrino flux.

$$E^2\Phi_\nu < 2 \times 10^{-8}\,\frac{\mathrm{GeV}}{\mathrm{cm}^2\mathrm{s}\,\mathrm{sr}}$$

- This is the scale we used to estimate that we need a km^3 size detector for the diffuse astrophysical neutrino flux detection.

IceCube diffuse flux measurements



Single power law:

$$\Phi^{Total}_{Astro} = \phi^{\mathrm{per-flavor}}_{\mathrm{Astro}} \times \left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma} \times C_0$$

$$C_0 = 3 \times 10^{-18} \times \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

where,

$$\phi^{\mathrm{per-flavor}}_{\mathrm{Astro}} = 1.68^{+0.19}_{-0.22}, \quad \gamma = 2.58^{+0.10}_{-0.09}$$

Broken power law:

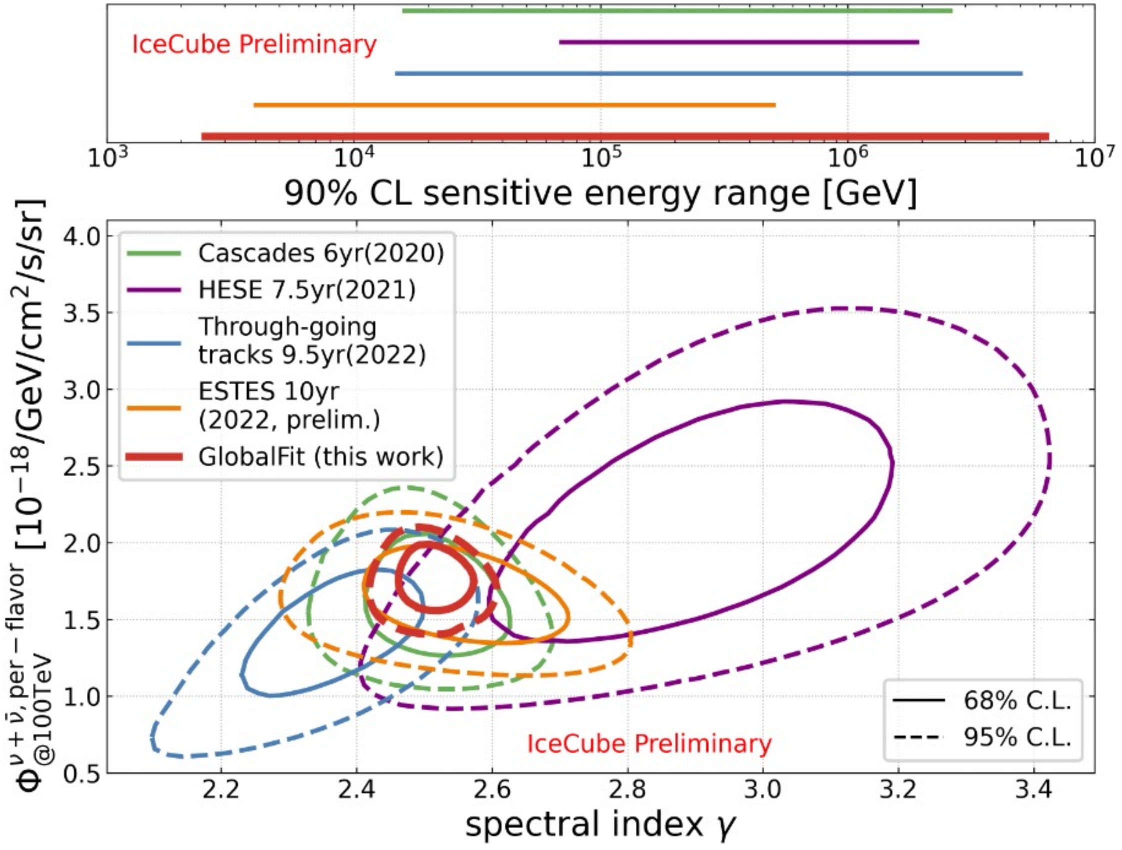
$$\phi^{\mathrm{Astro}}_{\mathrm{per-flavor}} = 1.7^{+0.19}_{-0.22}, \quad log_{10}\left(\frac{E_{\mathrm{break}}}{1\mathrm{GeV}}\right) \sim 4.36,$$

$$\gamma_1 = 2.79^{+0.30}_{-0.50}, \quad \gamma_2 = 2.52^{+0.10}_{-0.09}.$$

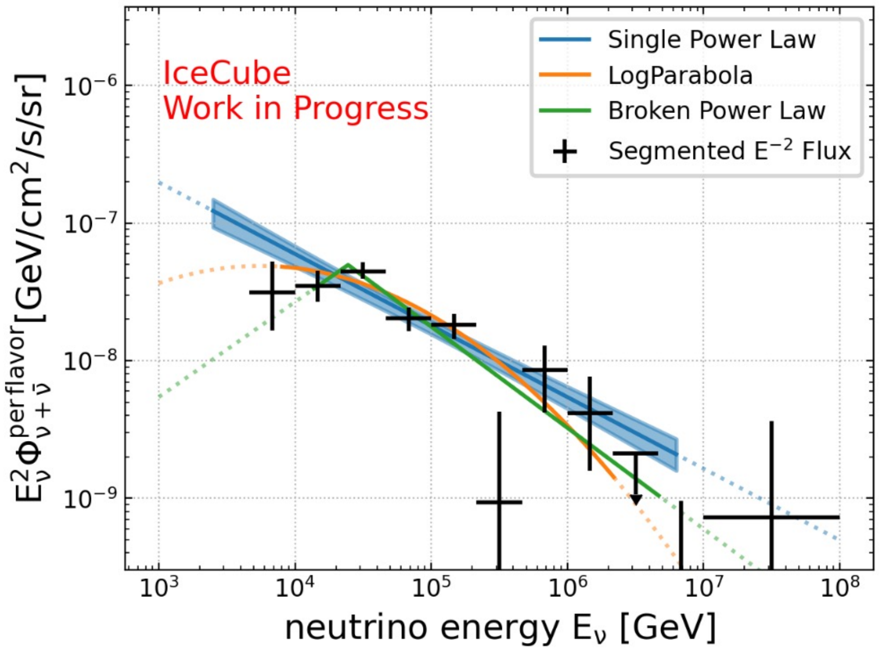
IceCube, https://arxiv.org/pdf/2402.18026

Neutrino spectral index and normalization

First guess was γ=2, not so here:



$$\Phi_{\nu+\bar{\nu}} = \frac{\mathrm{y-axis\ val} \times 10^{-18}}{\mathrm{GeV\,cm^2\,s\,sr}} \left(\frac{100\ \mathrm{TeV}}{E_\nu}\right)^{-\gamma}$$



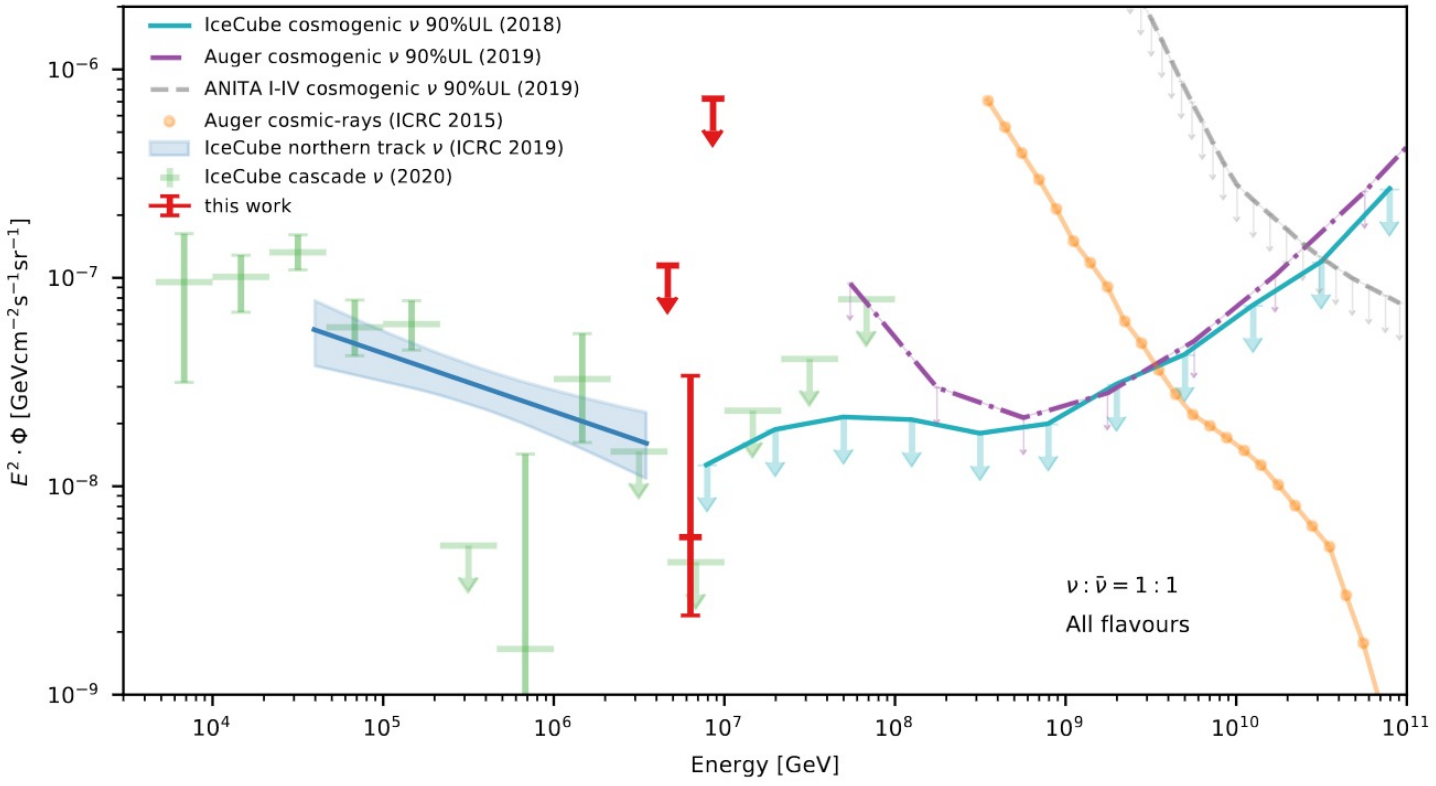
IceCube, ICRC2023 Proceedings, https://arxiv.org/pdf/2308.00191

per flavor here

Glashow resonance

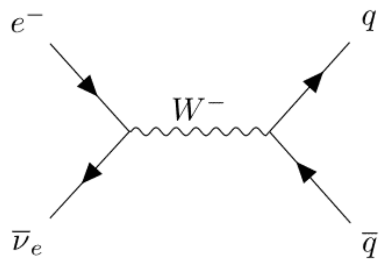
$$\bar{\nu}_e + e \to W^-$$

$$\sigma(s) = 24\pi\Gamma_W^2 \cdot B_{W^- \to \bar{\nu}_e + e^-} \frac{s/M_W^2}{(s - M_W^2)^2 + \Gamma_W^2 M_W^2}$$



$$2m_e E_{\bar{\nu}_e} = M_W^2 \to E_{\bar{\nu}_e} = 6.3 \text{ PeV}$$

shower energy 6.05 ± 0.72 PeV



IceCube, Nature 591, 220-224 (2021)

Diffuse flux limits (now and future)

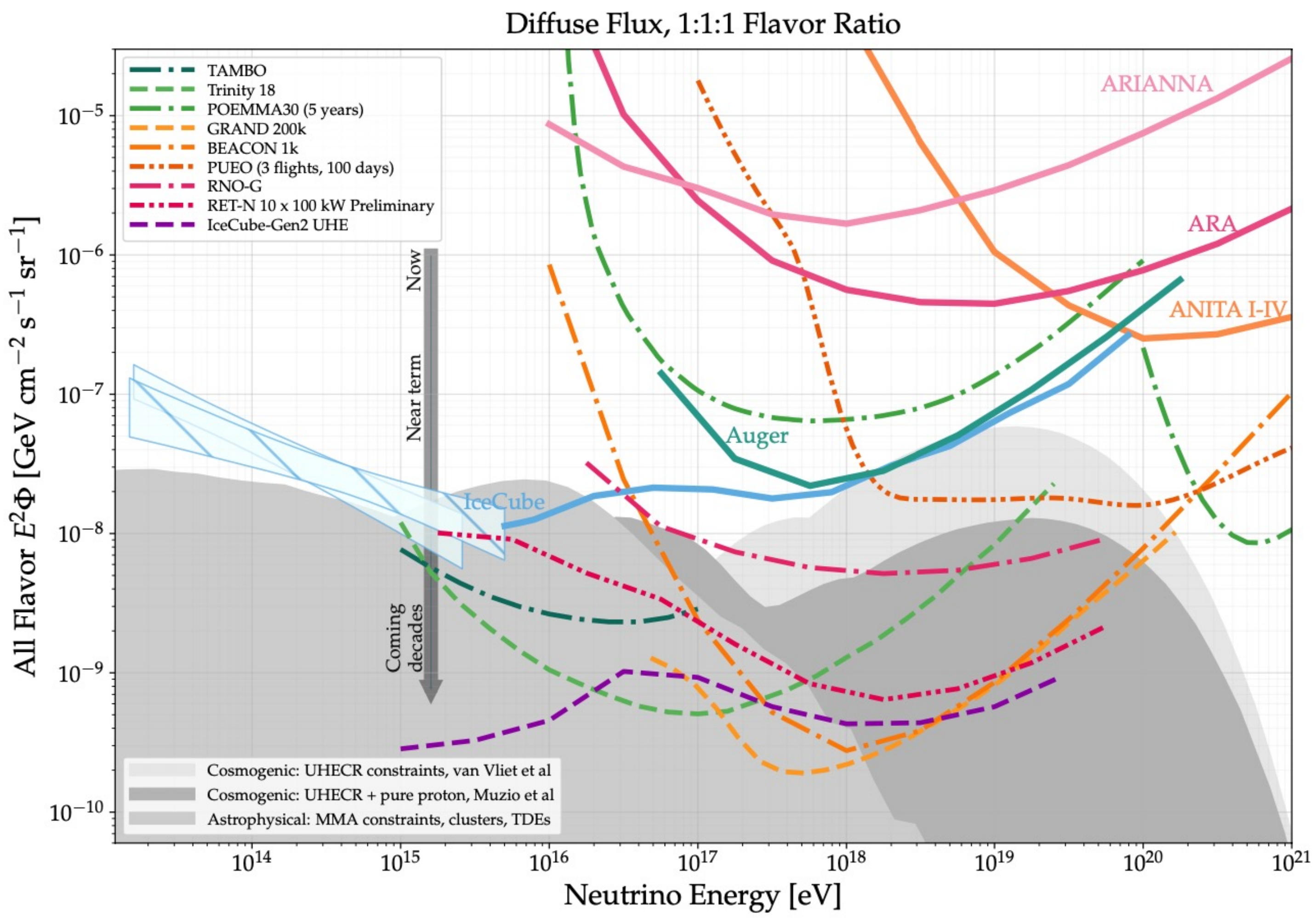


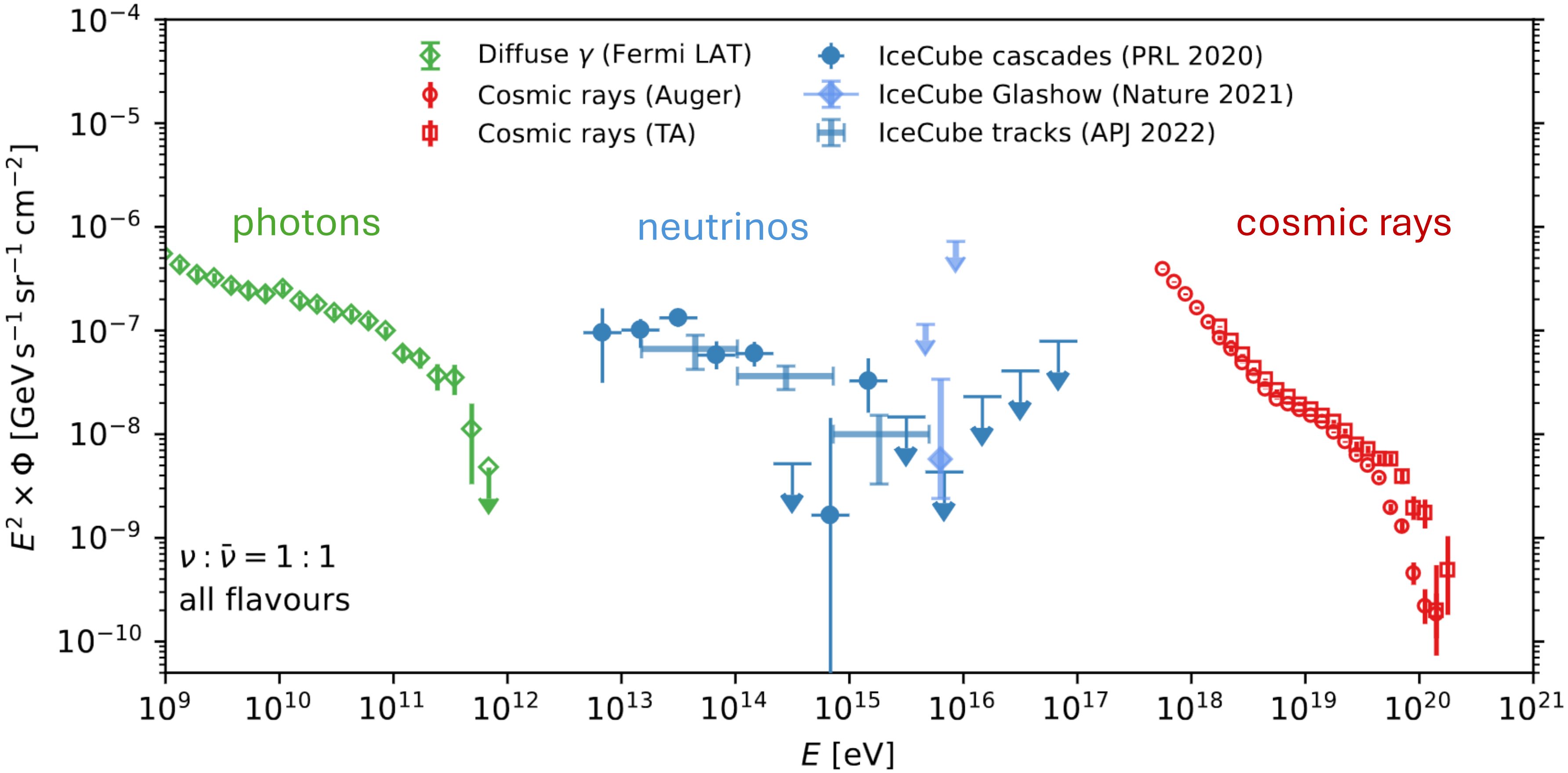
Fig. from Ackermann ...MHR... et al., JHEAp 36 (2022) 55

More about flavor soon.

More about higher energies soon.

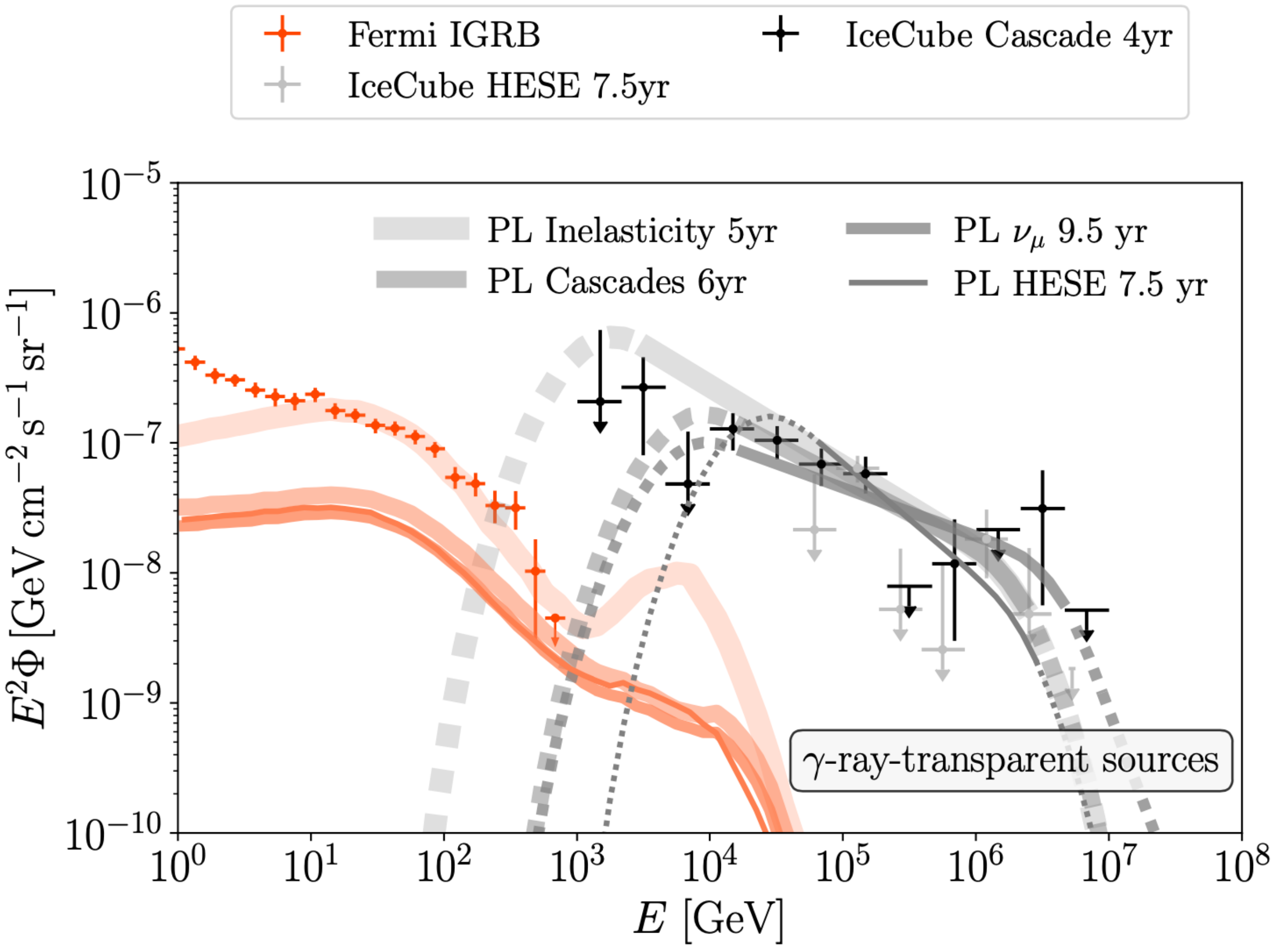
Multimessenger connection

Look at connections between neutrino and photons:



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

Example of a multimessenger picture



Arguelles et al, 2405.17623

- dashes show extrapolations below IceCube measured region
- put in simple relation between photon and neutrino fluxes from 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

Neutrino flavor dependence

Neutrino oscillations over astronomical distances, neglect CP violation:

$$P(\nu_\alpha \to \nu_\beta) \simeq \delta_{\alpha\beta} - 4 \sum_{i>j} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2 \Delta_{ij}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Over astronomical distances, and using unitarity

$$\sin^2 \Delta_{ij} \to \frac{1}{2}, \; P(\nu_\alpha \to \nu_\beta) \to \sum_i U_{\alpha_i}^2 U_{\beta i}^2$$

$$\theta_{23} \sim 45^\circ, \; \theta_{12} \sim 34^\circ$$

Source & Earth flavor ratios:

$$(\nu_e : \nu_\mu : \nu_\tau)_S = (1:2:0)$$

$$(\nu_e : \nu_\mu : \nu_\tau)_E = (1:1:1)$$

Flavor fraction at Earth, from fraction at source:

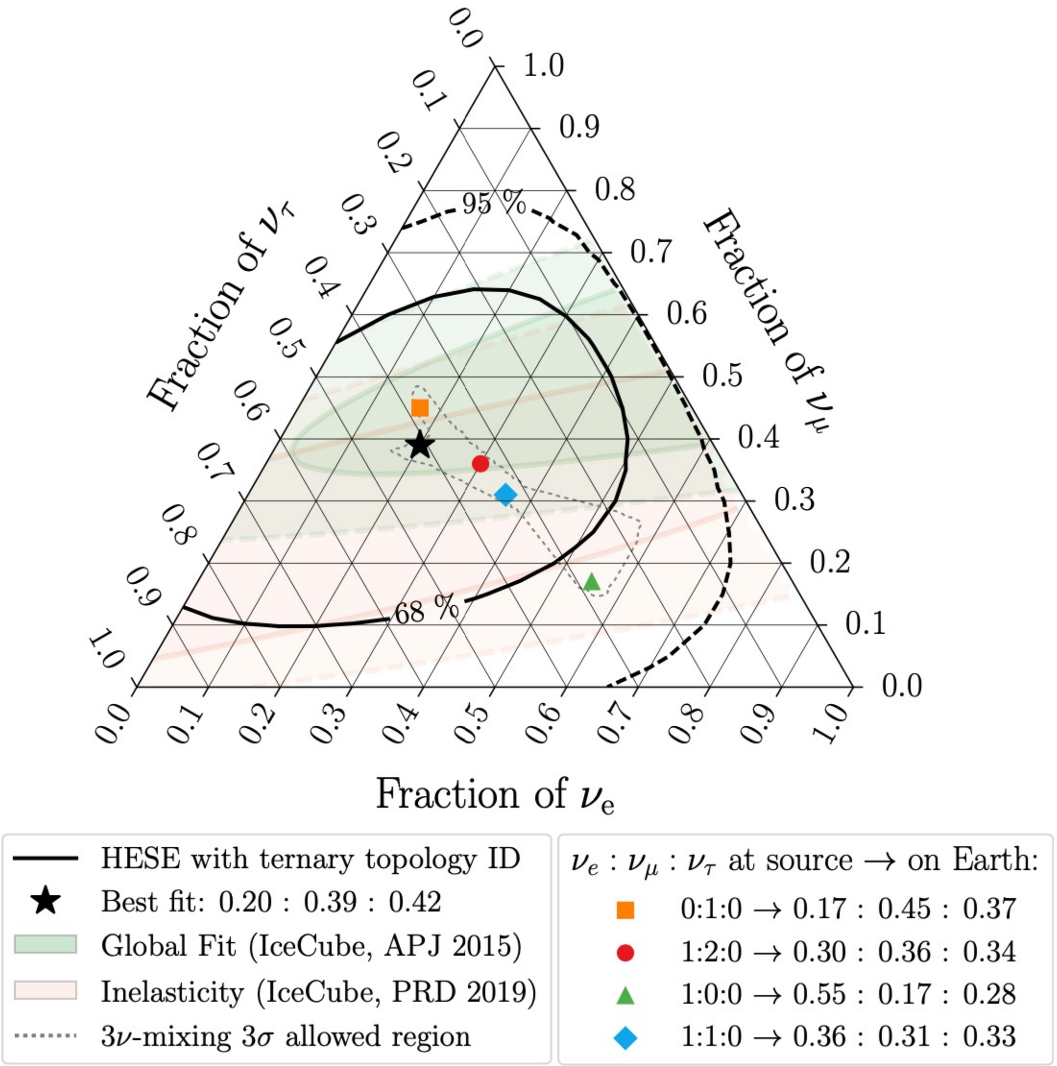
$$f_{\beta,E} = \sum_\alpha P(\nu_\alpha \to \nu_\beta) f_{\alpha,S}$$

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

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

IceCube flavor results

IceCube, Eur.Phys.J.C 82 (2022) 1031



Projected improvements of IceCube measurements and of oscillation parameters

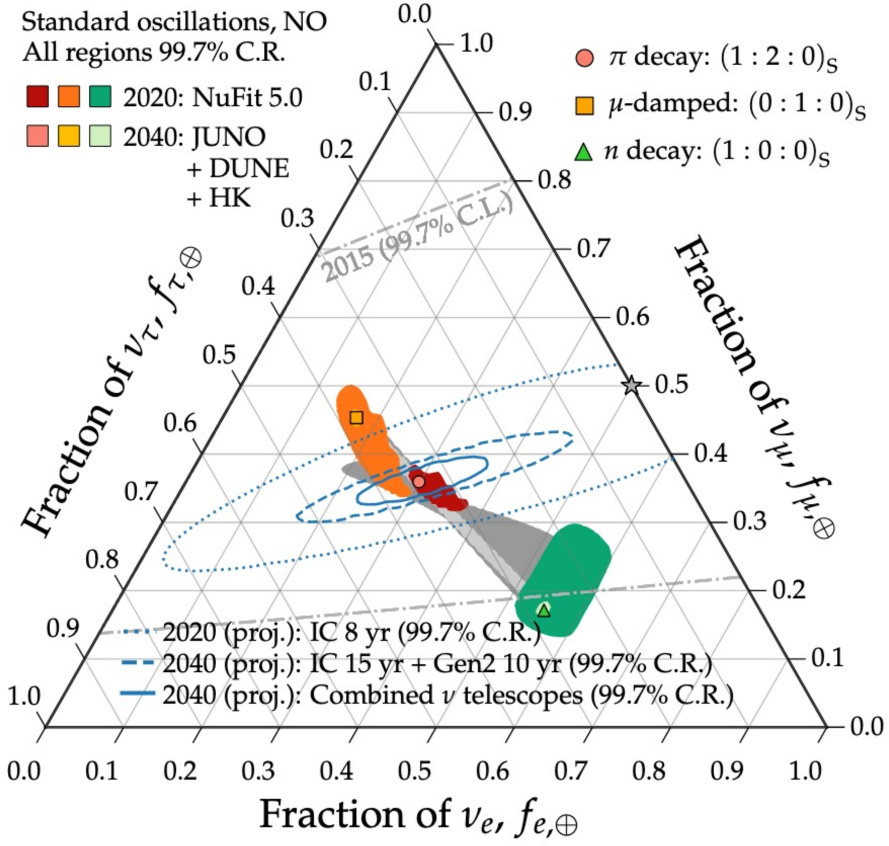


Fig. from Song et al, JCAP 04 (2021) 054

Point sources

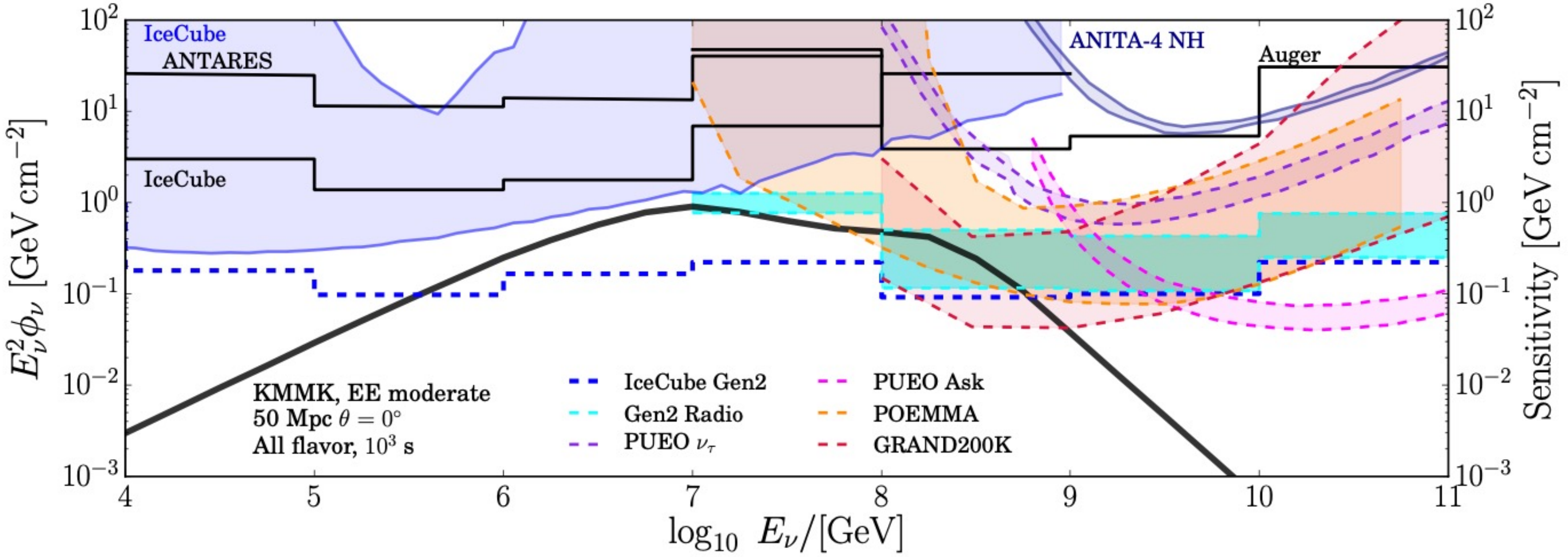


Fig. from Ackermann …MHR… et al., JHEAp 36 (2022) 55

- KMMK = Kimura, Murase, Meszaros, Kiuchi, ApJ 848 (2017) L4 for short gamma ray burst
- limit histograms for ± 500 s around GW170817 to show potential sensitivity

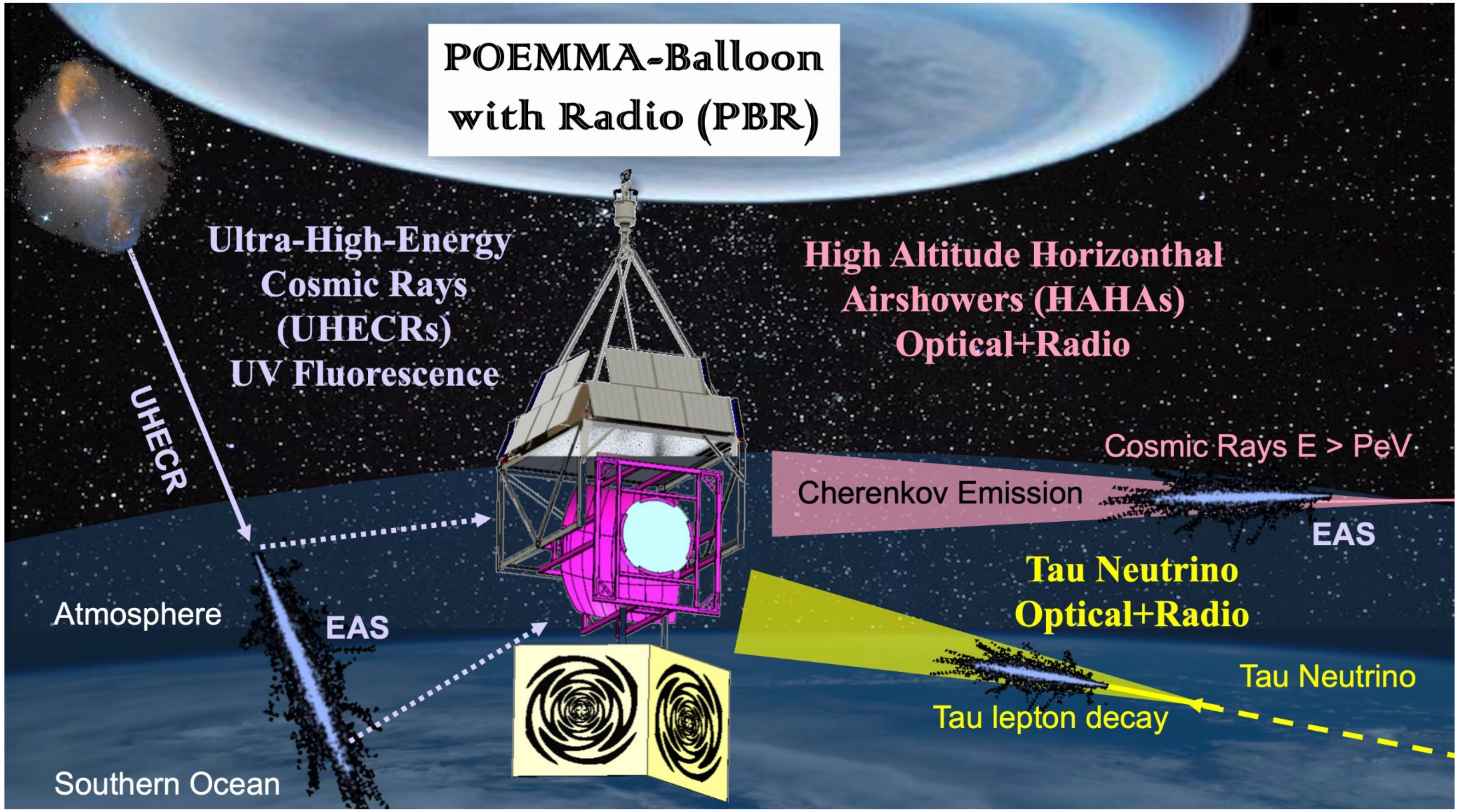
Detection goal: neutrinos, coincident detection of neutrinos with gamma rays.

Success: TXS 0506+056 flaring blazar

Also source association with NGC 1068

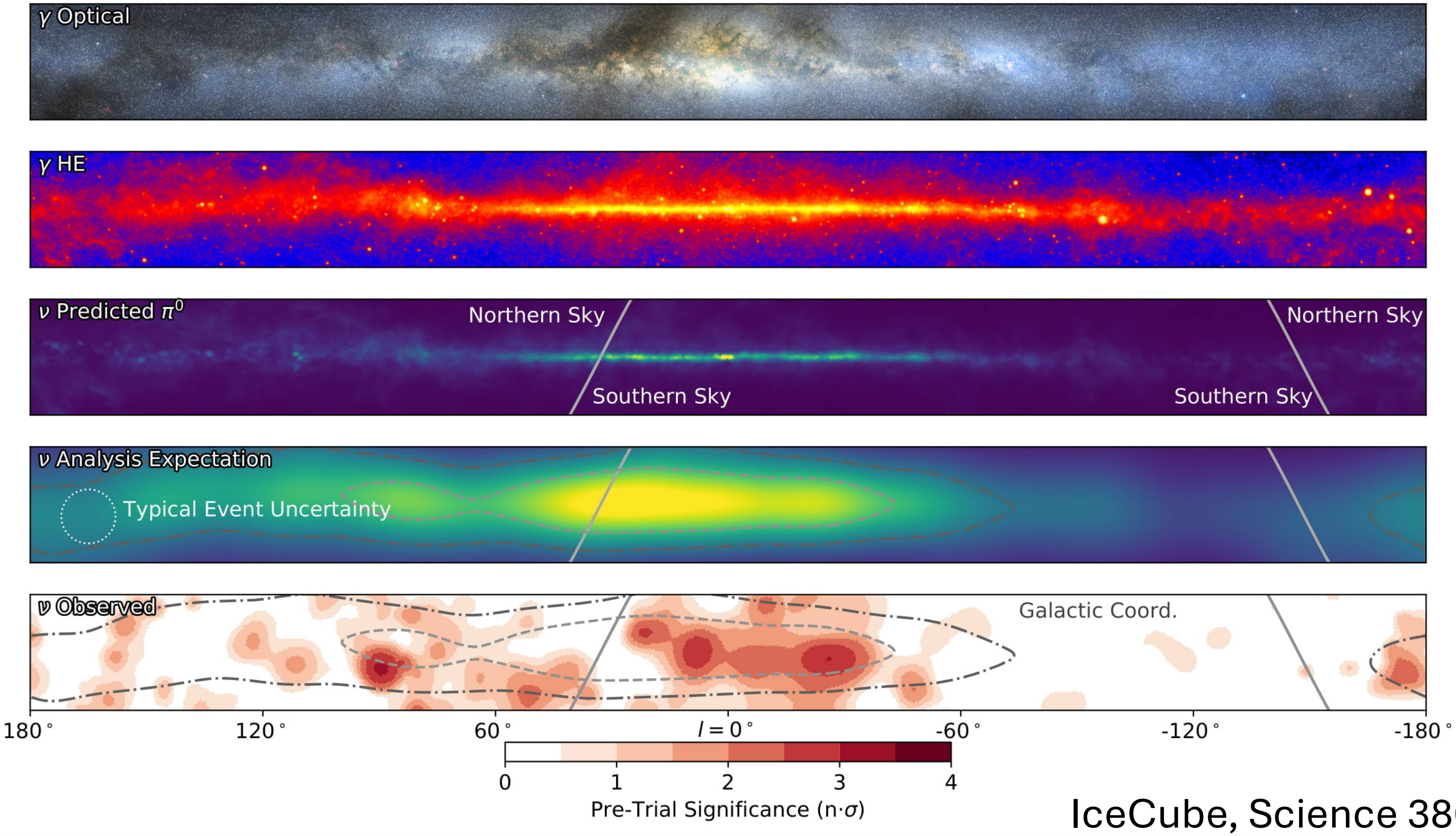
ASIDE

Auxiliary observations at UHE – cosmic rays



Different view of extensive air shower development from 33 km altitude.

Neutrinos from galactic plane

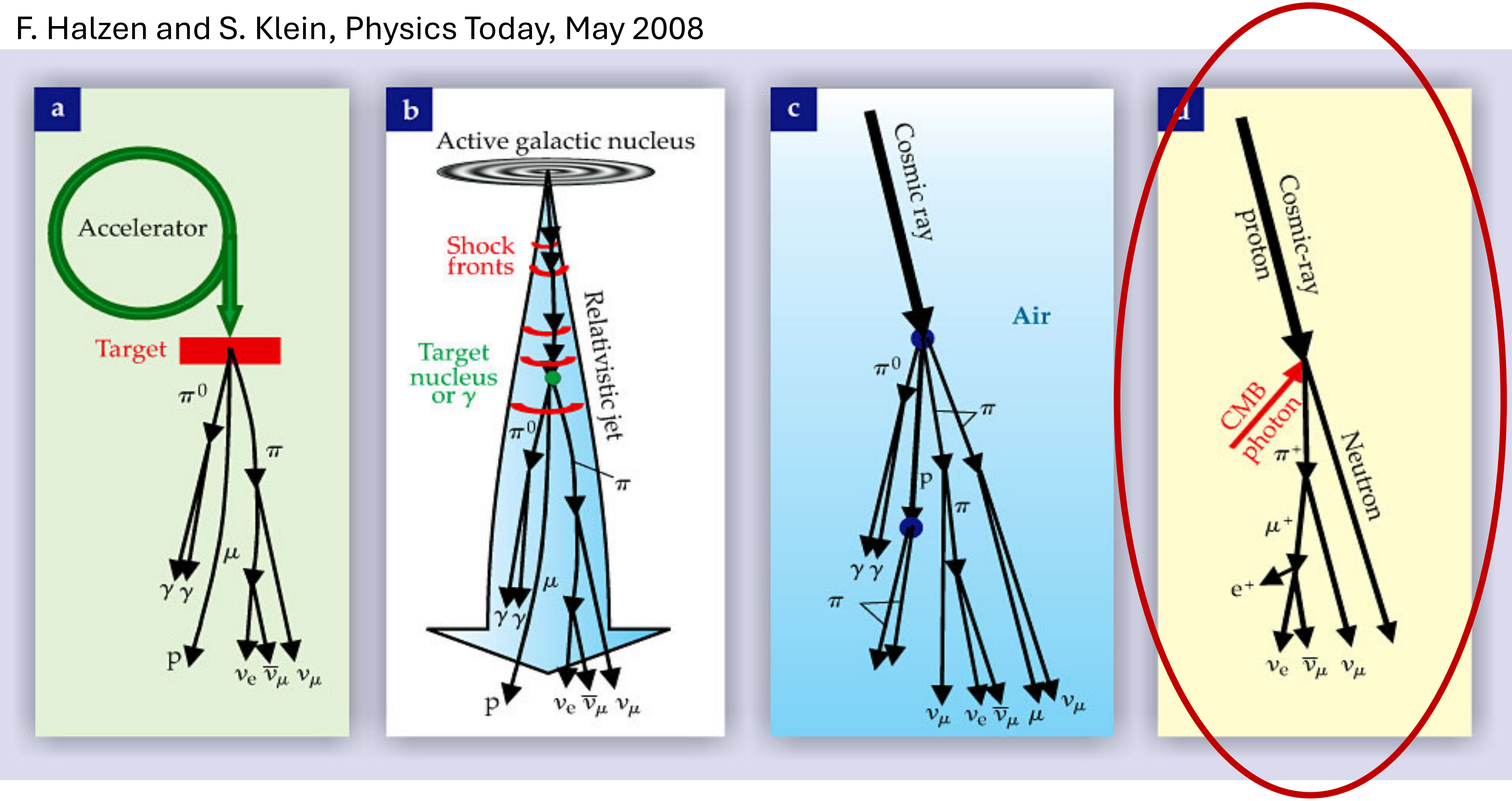


IceCube, Science 380 (2023) 1338

Cosmogenic neutrinos

Neutrino production

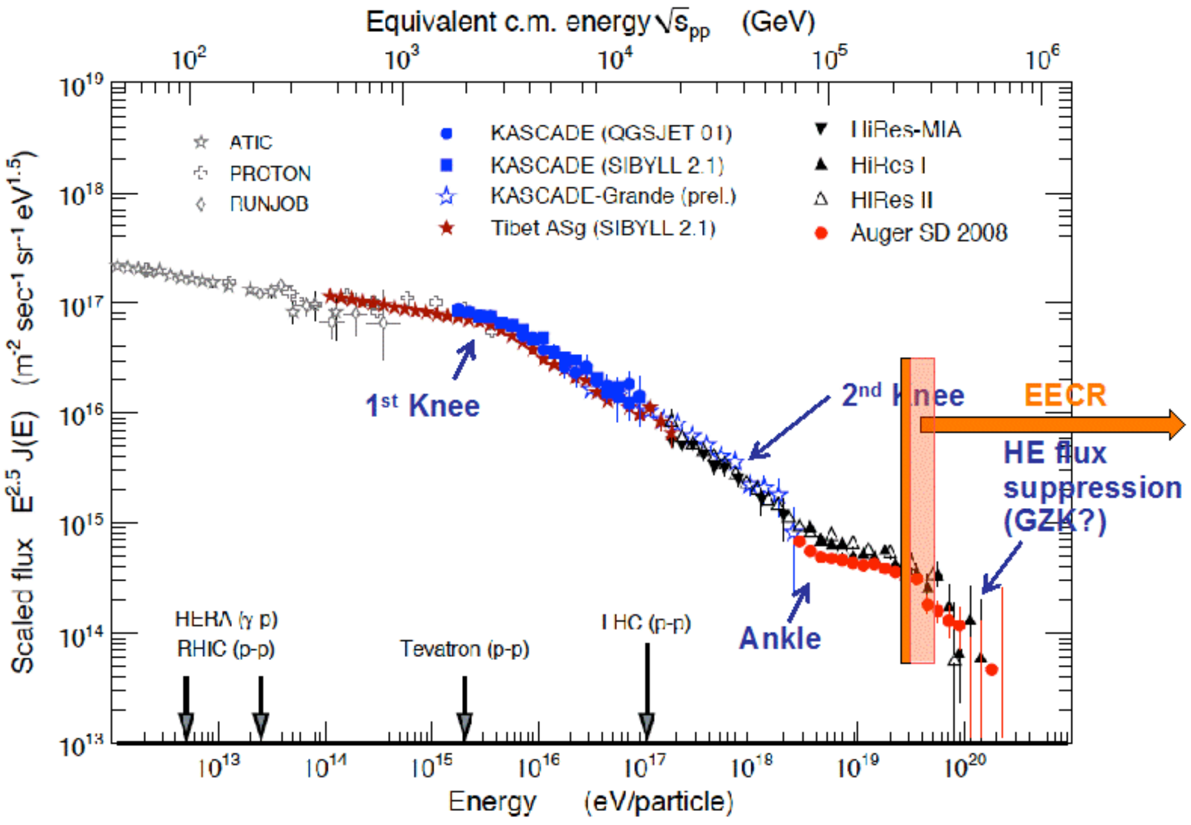
F. Halzen and S. Klein, Physics Today, May 2008



Same production mechanism for accelerator beams, inside astrophysical objects, in the atmosphere, and for the cosmogenic neutrino flux.

Cosmic rays – cut-off at highest energies

UHE or EE region



http://www1.na.infn.it/wsubnucl/cosm/JemEuso/physics.html

Cosmogenic neutrinos – Greisen Zatsepin Kuzmin (GZK) cutoff

Key process: $p\gamma \to \Delta \to n\pi^+$ $p\gamma \to \Delta \to p\pi^0$

Target 3K photons have energy: $8.6 \times 10^{-5}\ \mathrm{eV}/K \times 3K = 2.6 \times 10^{-4}\ \mathrm{eV}$

proton- 3K photon interactions:

$$\begin{aligned} s_{p\gamma} &\simeq (E_\gamma + E_p)^2 - (p_\gamma - p_p)^2 \\ &\simeq 4E_\gamma E_p = 10^{-12}\ \mathrm{GeV}^2\ E_p/\mathrm{GeV} \end{aligned}$$

Need $s_{p\gamma} \simeq m_\Delta^2$. Note, there is a distribution of photons, also other energies from stellar sources, etc. so it is not a sharp threshold.

Cosmogenic neutrino flux predictions, some of the variables

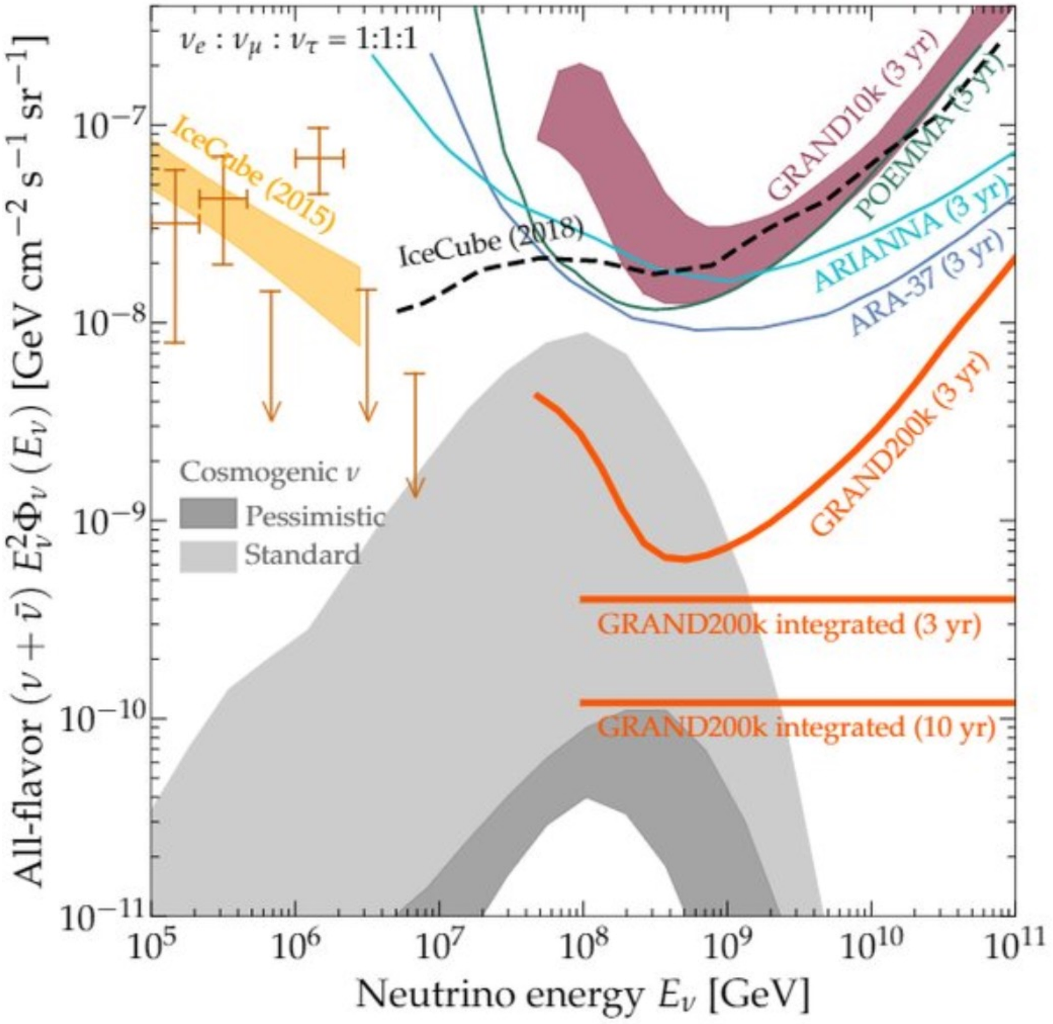
Cosmogenic neutrinos come from decays:

$$p\gamma \to \Delta \to n\pi^+$$

pion decays
muon decays
neutron decays

- What is the spectrum and composition of ultrahigh energy cosmic rays? What is the cutoff energy of cosmic ray sources?
- What is the cosmic ray source evolution rate/star formation rate?
- At what energy is the transition from galactic to extragalactic cosmic rays in the flux?

Cosmogenic neutrino flux



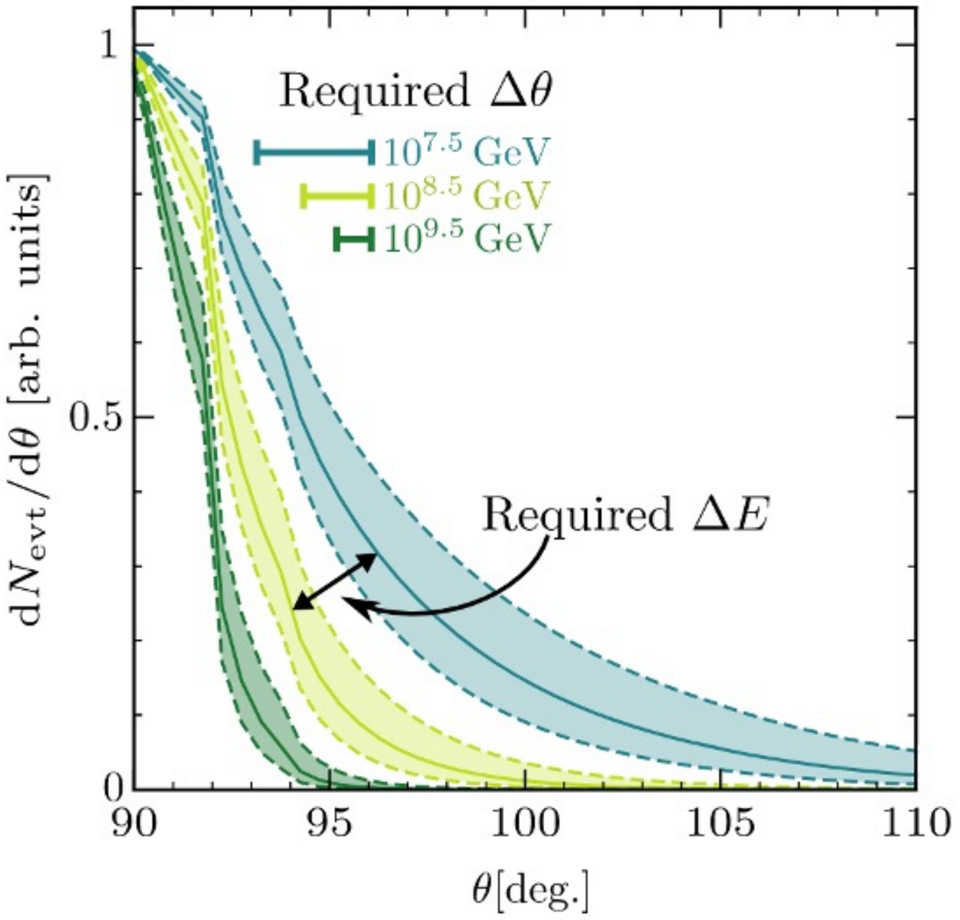
Guaranteed flux, but not guaranteed to be large.

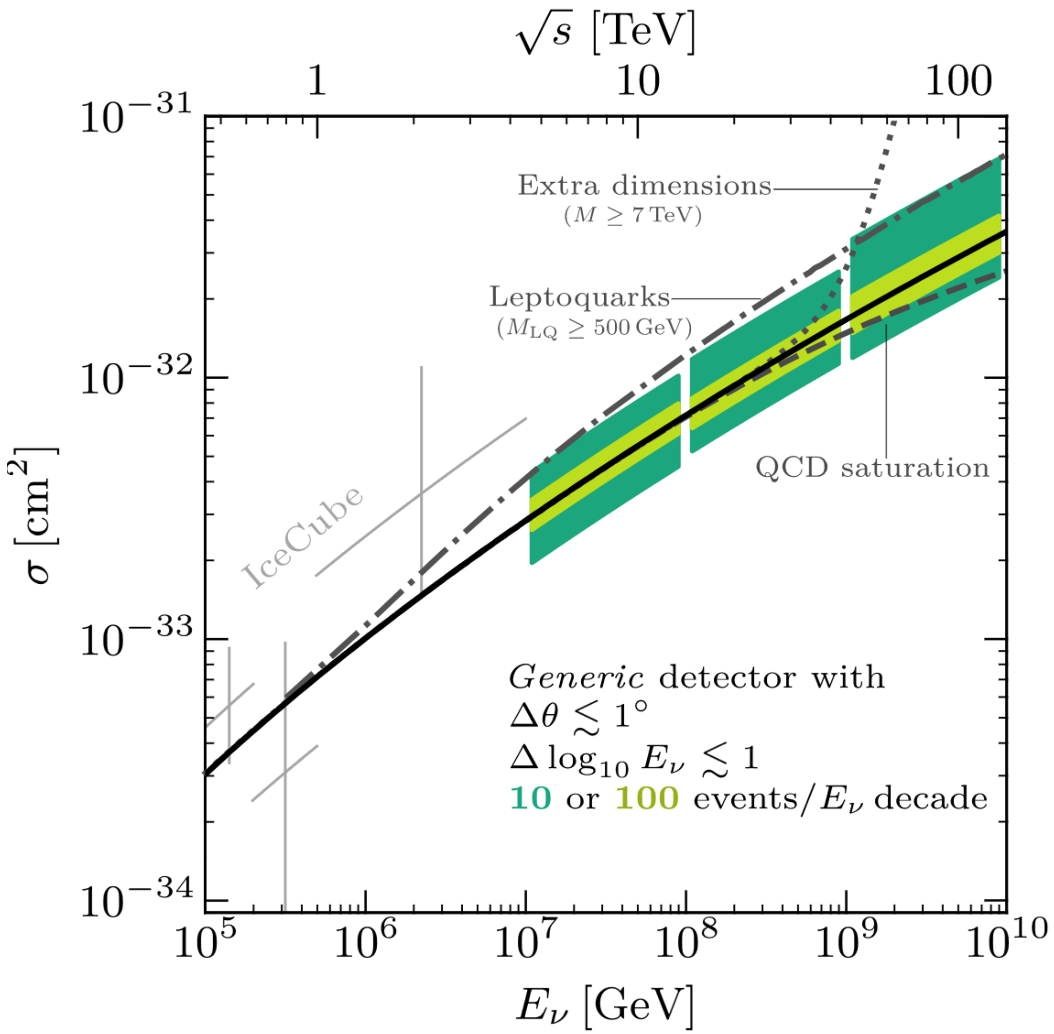
Require that your model matches the measured UHE cosmic ray flux.

Fig. from GRAND, SciPost Phys. Proc. 10, 027 (2022), Alves Batista et al, JCAP (2019) 002

Cross sections

Esteban, Prohira, Beacom, PRD 106 (2022) 023021
See also Valera, Bustamante, Glaser,JHEP 06 (2022) 105





Beyond Standard Model physics with cosmic neutrinos

a short idiosyncratic tour

ANITA anomalous events

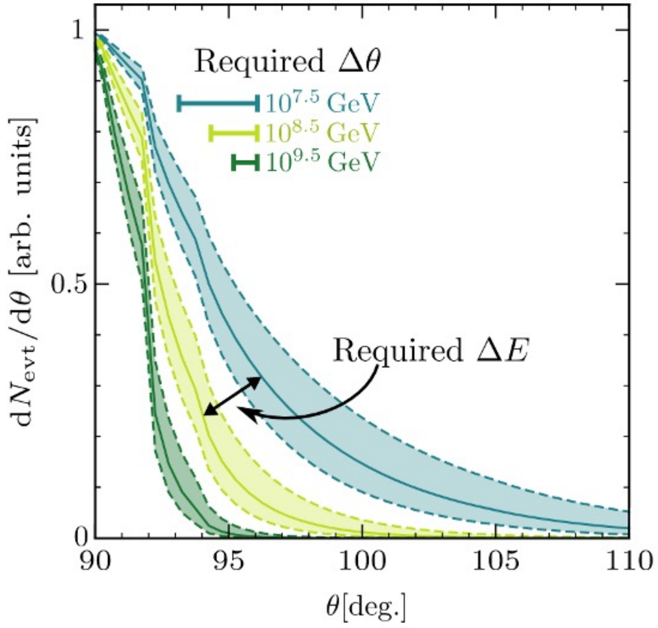
Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA #1

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]

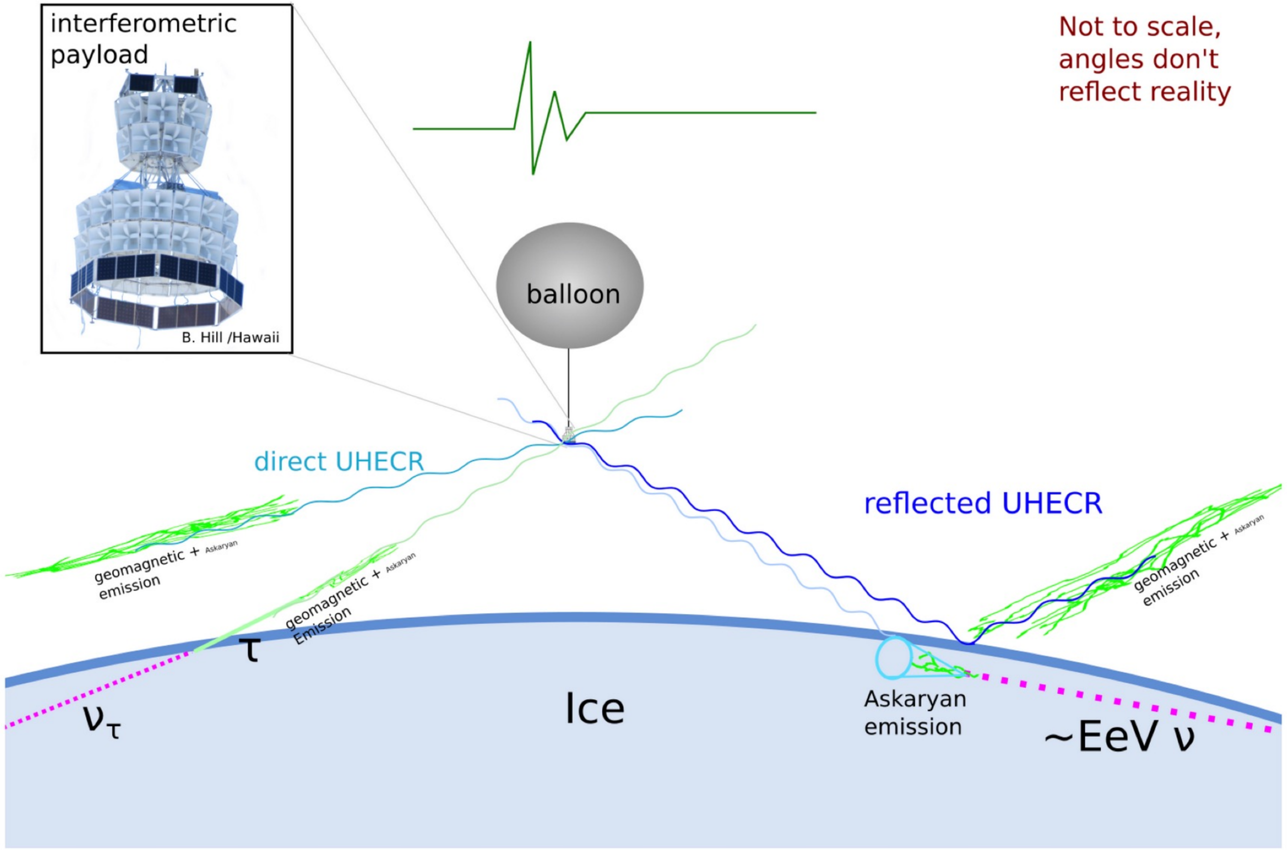
pdf   DOI   cite   claim   reference search   146 citations

Esteban et al, PRD 106 (2022) 023021



- Two anomalous events, from detector at angles 117 deg and 125 deg.
- Consistent with up-going air showers/geomagnetic radio signal (not reflected down-going CR-induced air showers).
- Inconsistent with neutrino flux attenuation in the Earth.
- Invites BSM physics explanation, but none convincing so far. Concordance between experiments required.

ANITA experiment – 4 flights



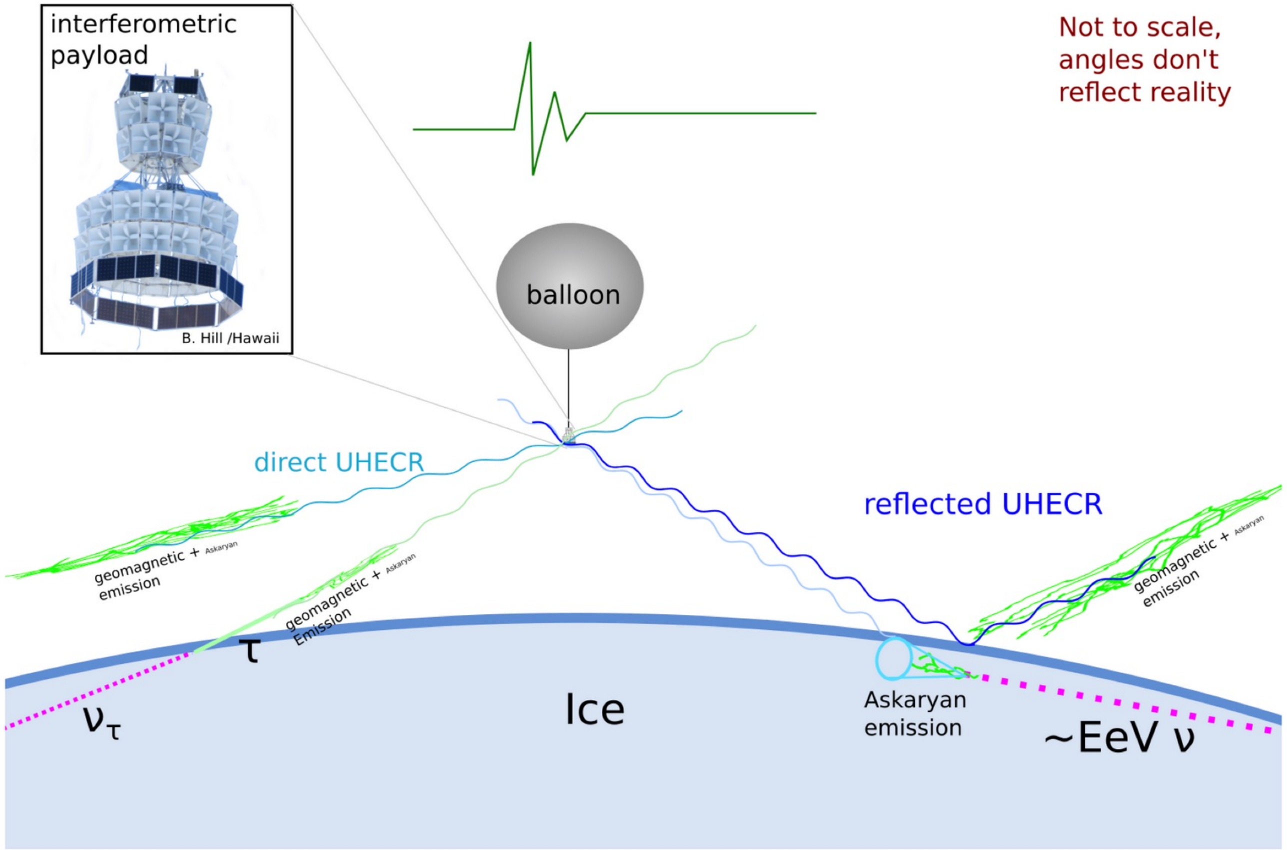
*The ANITA detection concepts, figure from **Cosmin Deaconu**.*

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

- radio detection
- polarization of anomalous signals suggested up-going air showers (geomagnetic origin), not reflected or refracted radio signals

ANITA experiment – 4 flights

ANITA, PRL126, 071103 (2021)



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

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

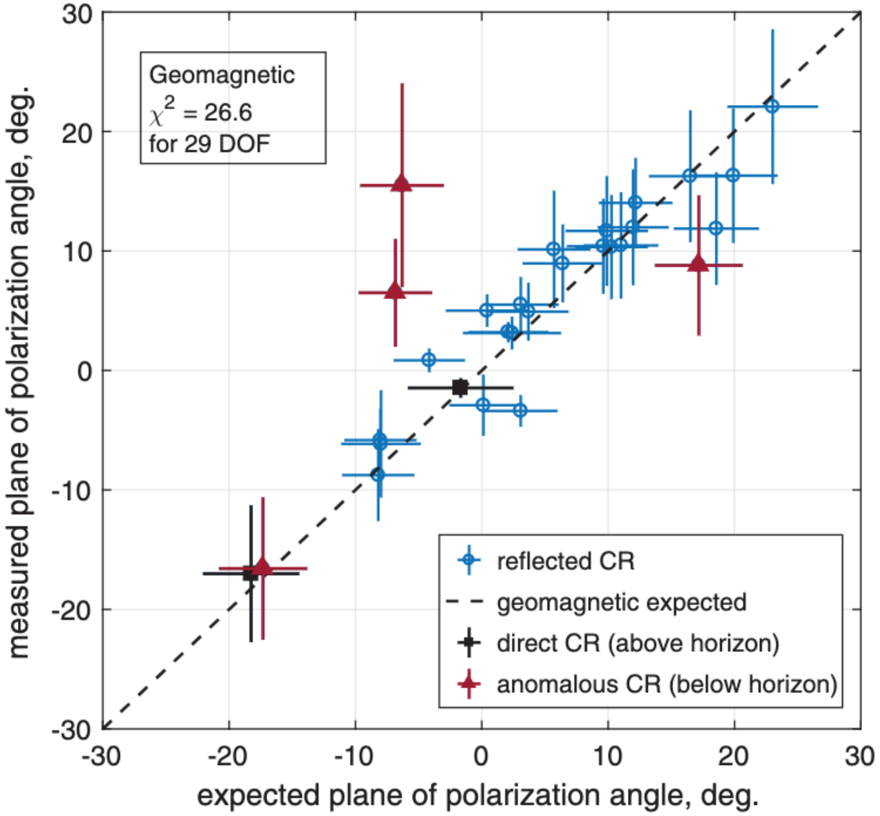
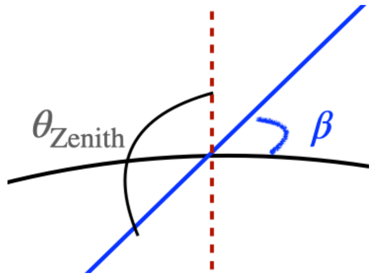


FIG. 2. Top: ANITA-IV flight path and location of payload and apparent event source location and ice surface elevation above sea level for each of the 29 events in the final CR sample. Bottom: Geomagnetic correlation of 29 candidate events revealed in our CR analysis.

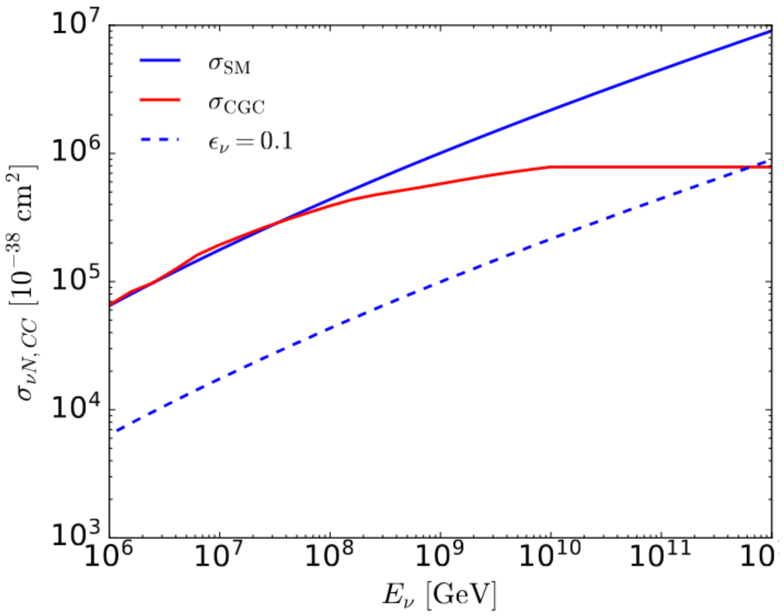
ANITA anomalous events BSM example



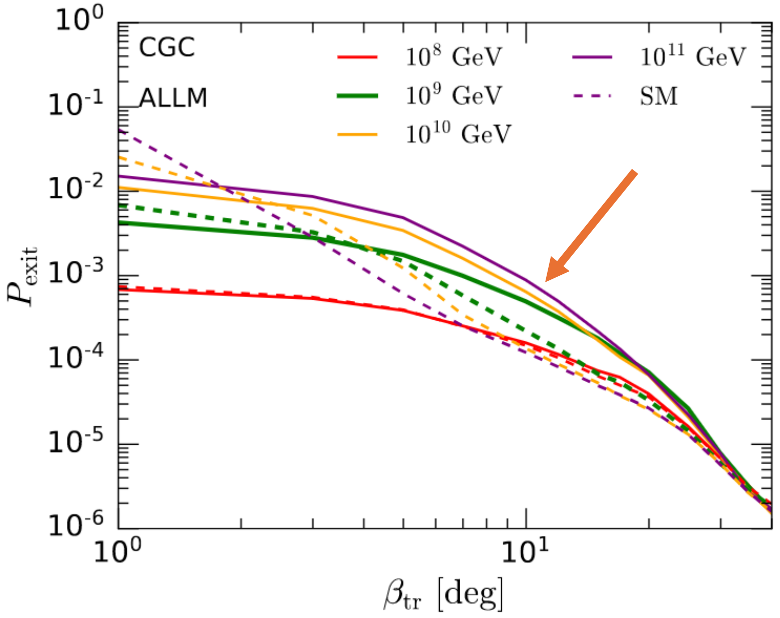
1. Check that tau neutrino to tau upward air showers don't work

   Chipman ...MHR... et al, PRD 100 (2019) 063011. See also Romero-Wolf et al, PRD 99 (2019) 063011

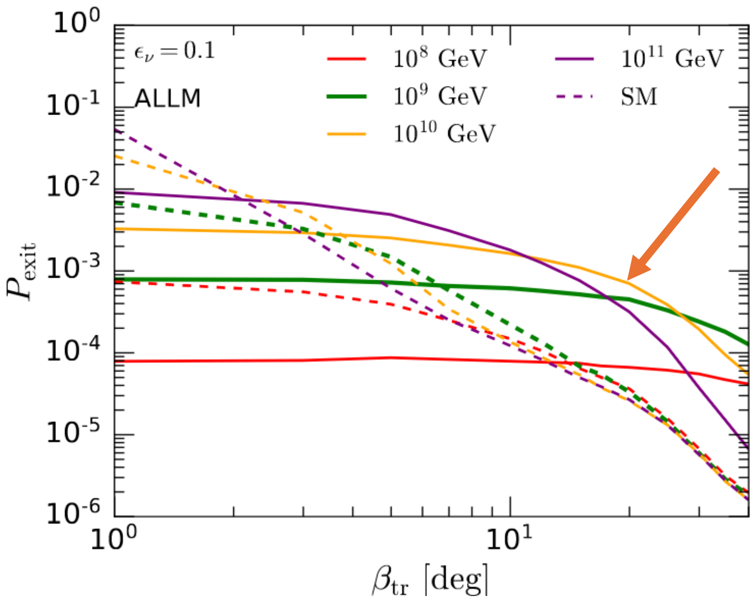
2. Change the cross section to try to avoid attenuation at observed angles.



sterile neutrinos that couple to taus



some, but not much enhancement



enhanced large angle contribution

ANITA anomalous events BSM example

1. Check that tau neutrino to tau upward air showers don't work

   Chipman ...MHR... et al, PRD 100 (2019) 063011. See also Romero-Wolf et al, PRD 99 (2019) 063011

2. Change the cross section to try to avoid attenuation at observed angles.
3. Assess how angular dependence affects the event rate in ANITA angular range, and at other angles.

   Enhanced special ANITA events mean even more events closer to the horizon.

4. Check implications for other experiments.

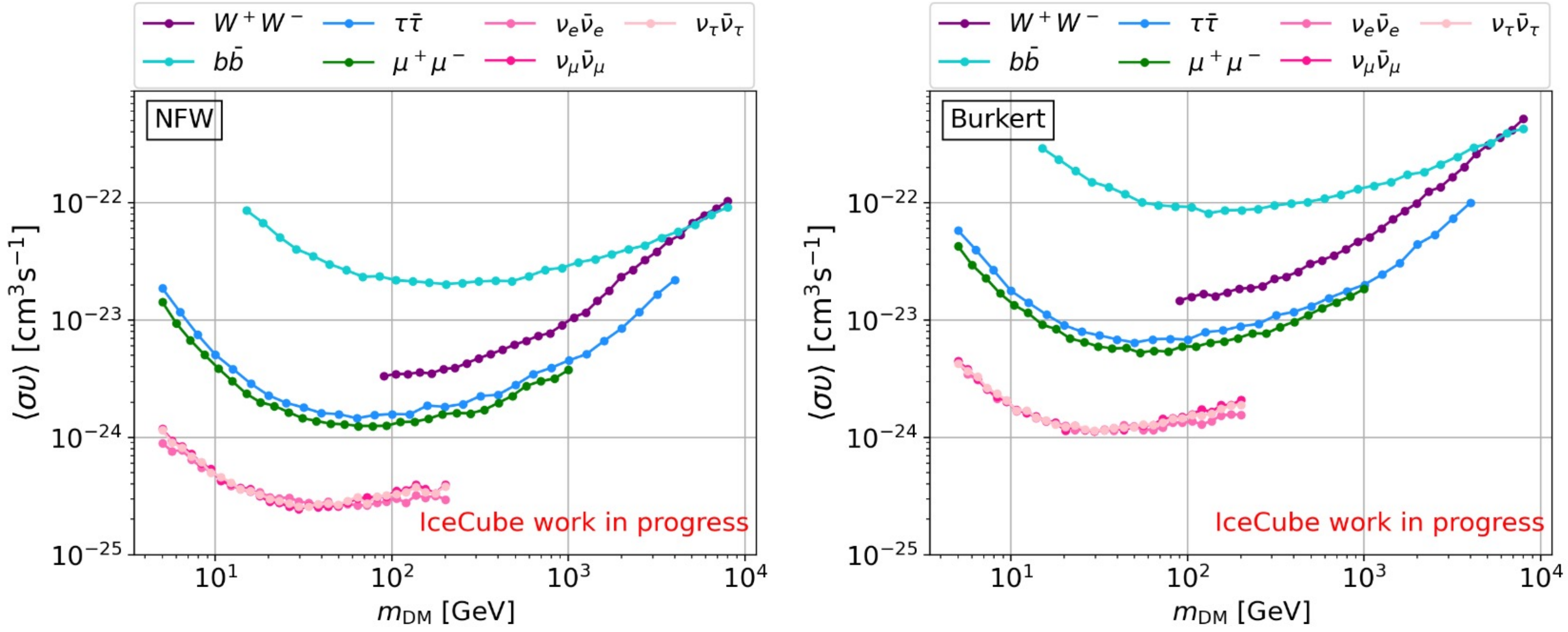
   Inconsistent with Pierre Auger Observatory limits.

5. Triage – maybe they come from a mono-energetic source: superheavy dark matter decays to sterile neutrinos that couple to taus. However, if they explain ANITA events, limits are in contradiction with IceCube limits.

   See also Hooper et al, PRD 100 (2019) 043019.

Some BSM signals with neutrinos

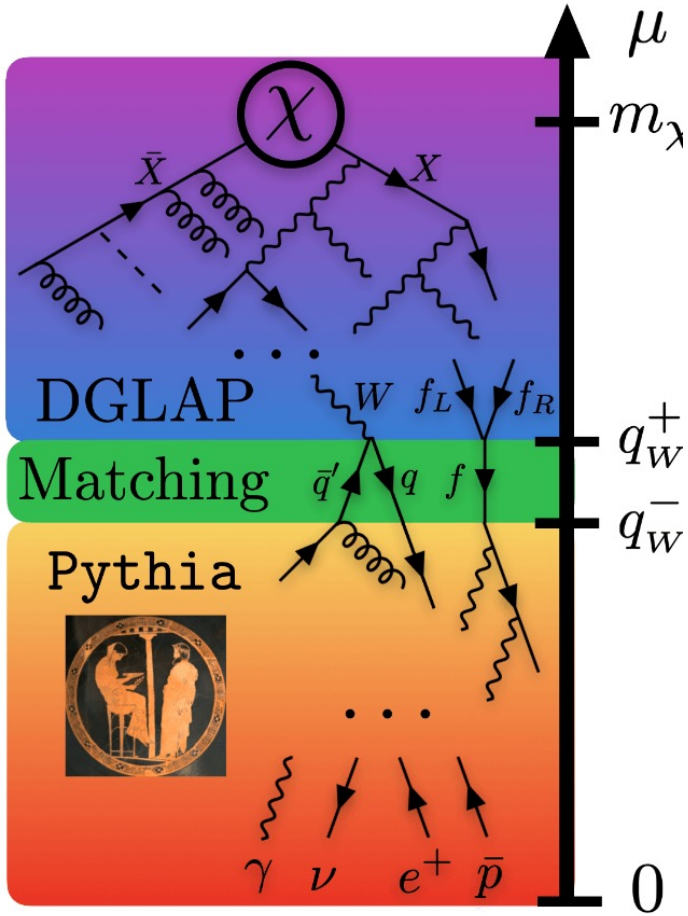
1. Dark matter annihilations or decays to $\bar{\nu}\nu$
2. Dark matter annihilation or decay to particles that decay to neutrinos

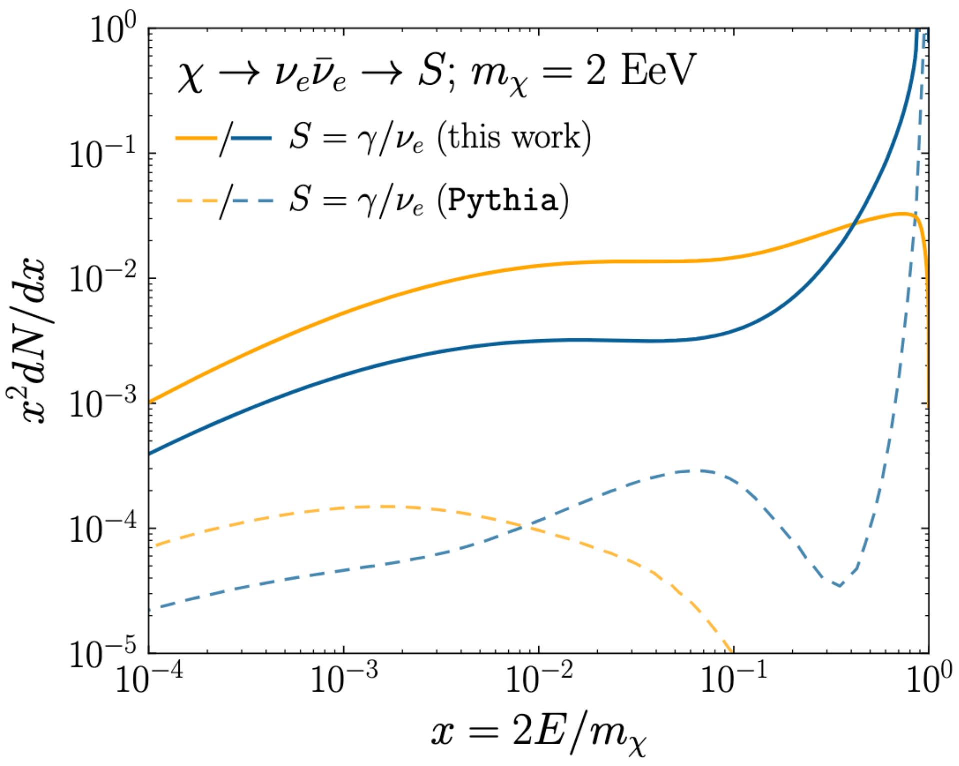


IceCube, https://arxiv.org/pdf/2308.06729

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!

1 EeV = 10^9 GeV

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

https://github.com/nickrodd/HDMSpectra

Some BSM signals with neutrinos

3. Neutrino interactions with dark matter.

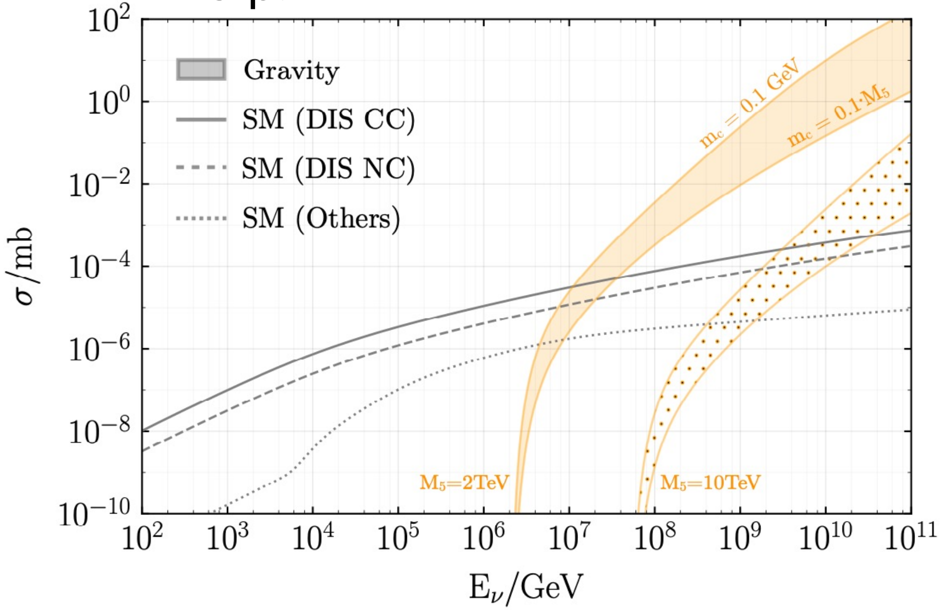
Cosmological constraints.

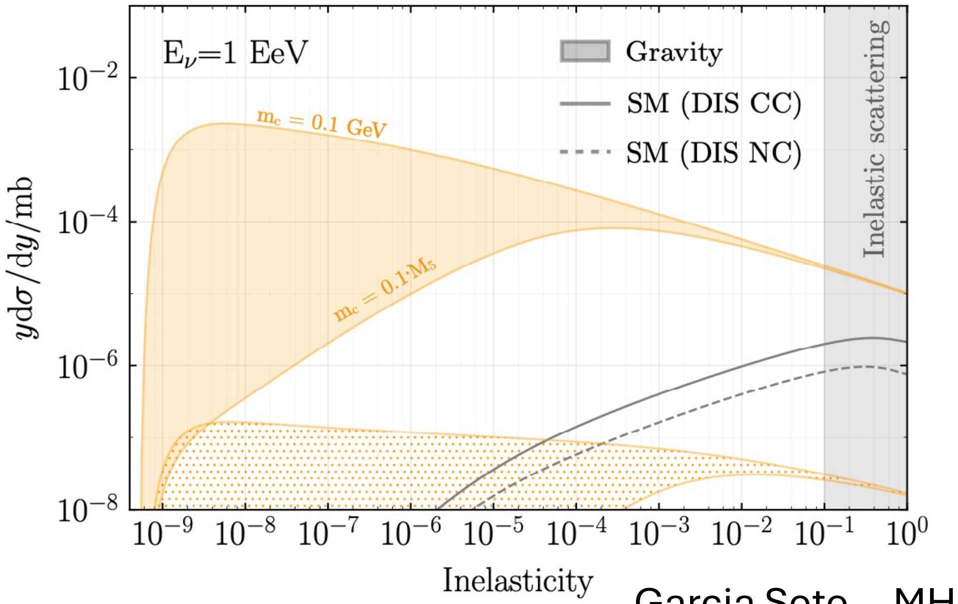
Can also look at supernova neutrinos.

4. Neutrino interactions with the cosmic neutrino background.
5. Enhanced neutrino cross sections with nucleons.

BSM physics – neutrino cross section example

- TeV scale extra dimensions can enhance the neutrino cross section, but may do this through mostly elastic scattering.
- (Cross section measurements discussed above rely on SM $d\sigma/dy$. distributions.)
- Flux uncertainties 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 help.





Garcia Soto …MHR… et al, PRD 107 (2023) 033009

Some BSM signals with neutrinos

3. Neutrino interactions with dark matter.

Cosmological constraints.

Can also look at supernova neutrinos.

4. Neutrino interactions with the cosmic neutrino background.

5. Enhanced neutrino cross sections with nucleons.

6. BSM particles that mimic signals of neutrino interactions in ice or water or the atmosphere.

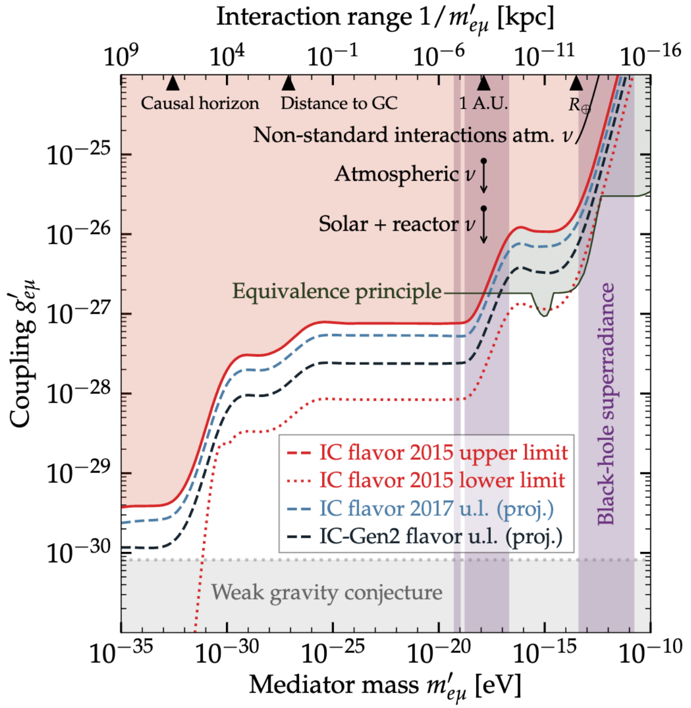
- Ask Kevin Kelly about milli-charged particles in IceCube! Arguelles, Kelly & Munoz Albornoz, JHEP 11 (2021) 099
- Staus look like lower-energy muons.

7. Introduce new interactions that change effective mixing angle to change flavor ratios.

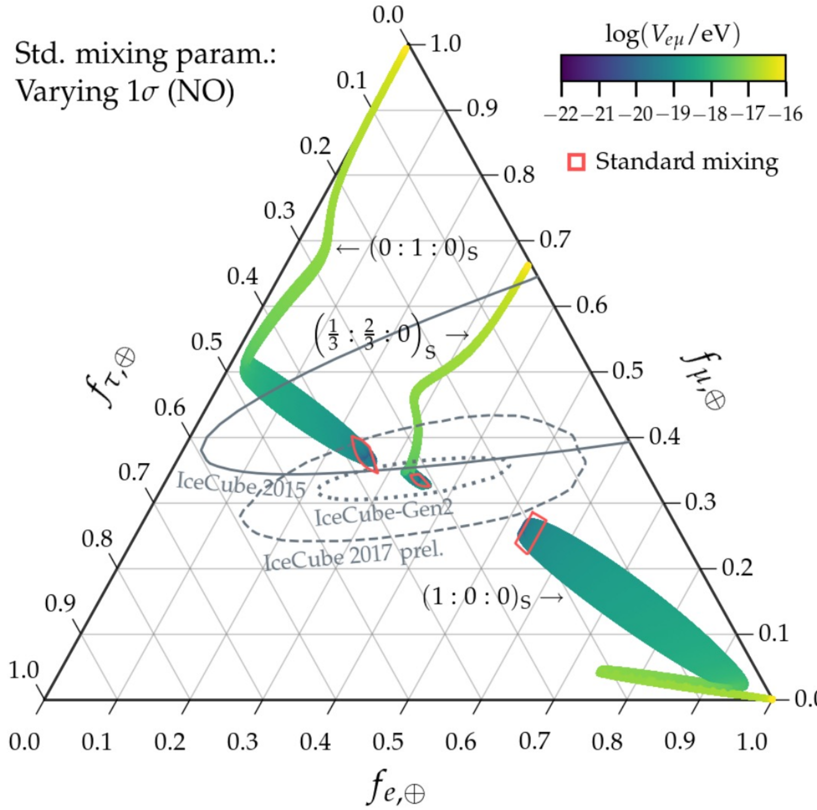
Neutrino flavor ratio example

Bustamante & Agarwalla, PRL 122 (2019) 061103

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



- New interactions give a long range potential given electron density and very light masses.
- Flavor oscillations to Earth are distorted.



Homework

(See slide 29). Using the 3x3 unitary PMNS matrix, neglect CP violation and θ_{13}, estimate the neutrino flavor composition at Earth is the composition at the astrophysical source is 100% tau neutrinos.

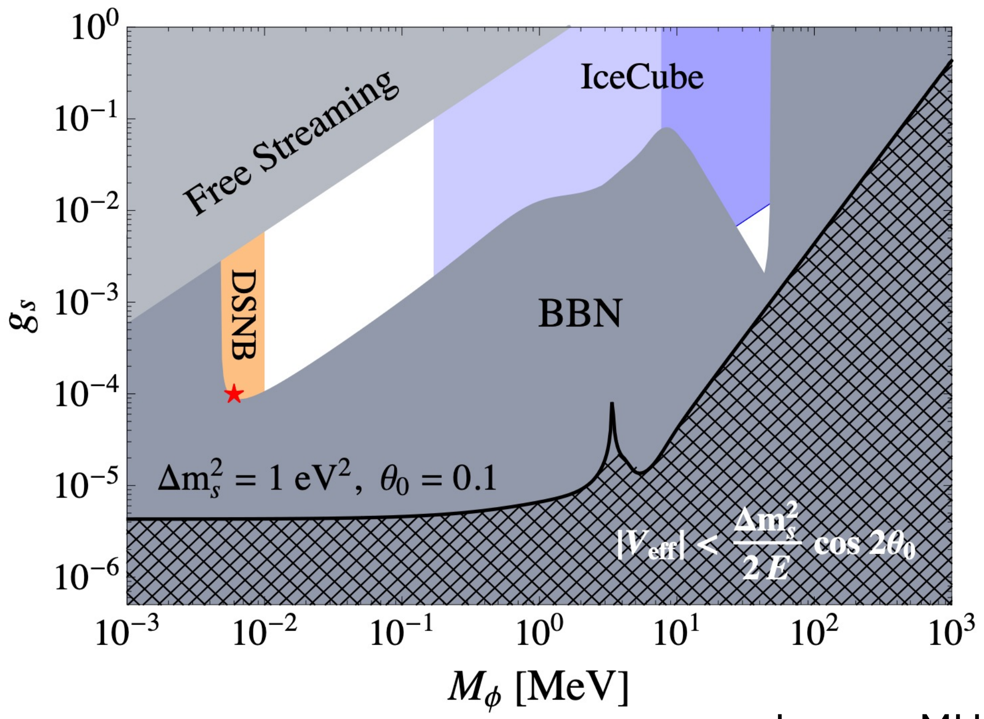
Can you derive for $P(\nu_\alpha \to \nu_\beta)$ in the CP conserving limit?

$$\sin^2 \Delta_{ij} \to \frac{1}{2}, \; P(\nu_\alpha \to \nu_\beta) \to \sum_i U^2_{\alpha_i} U^2_{\beta i}$$

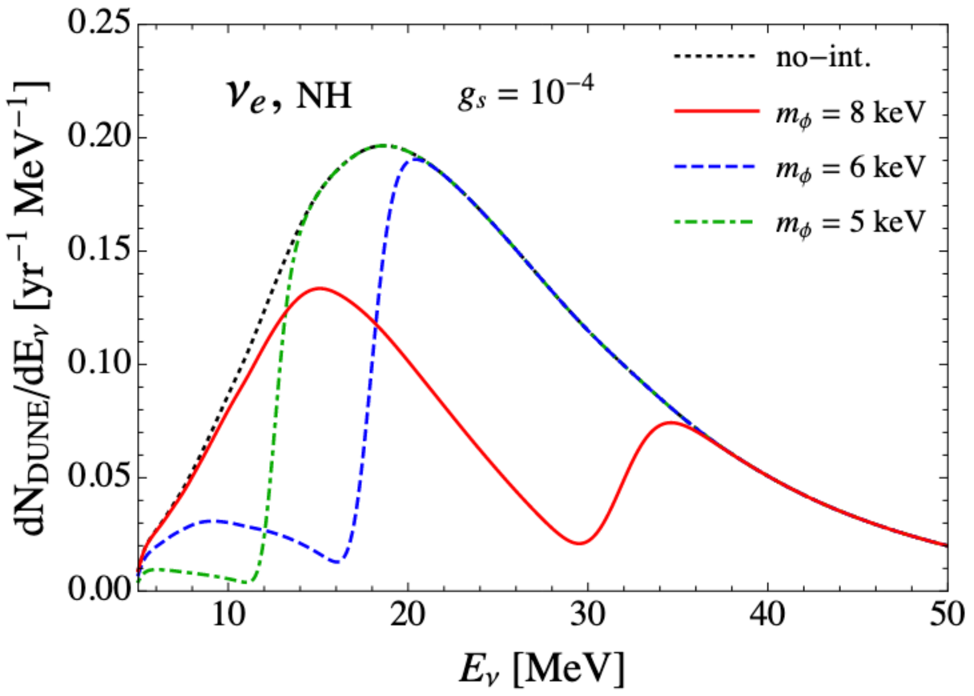
Backup slides

Supernova neutrinos

Introduce eV scale sterile neutrino that mixes with active neutrinos and new gauge boson that interacts with sterile neutrino.

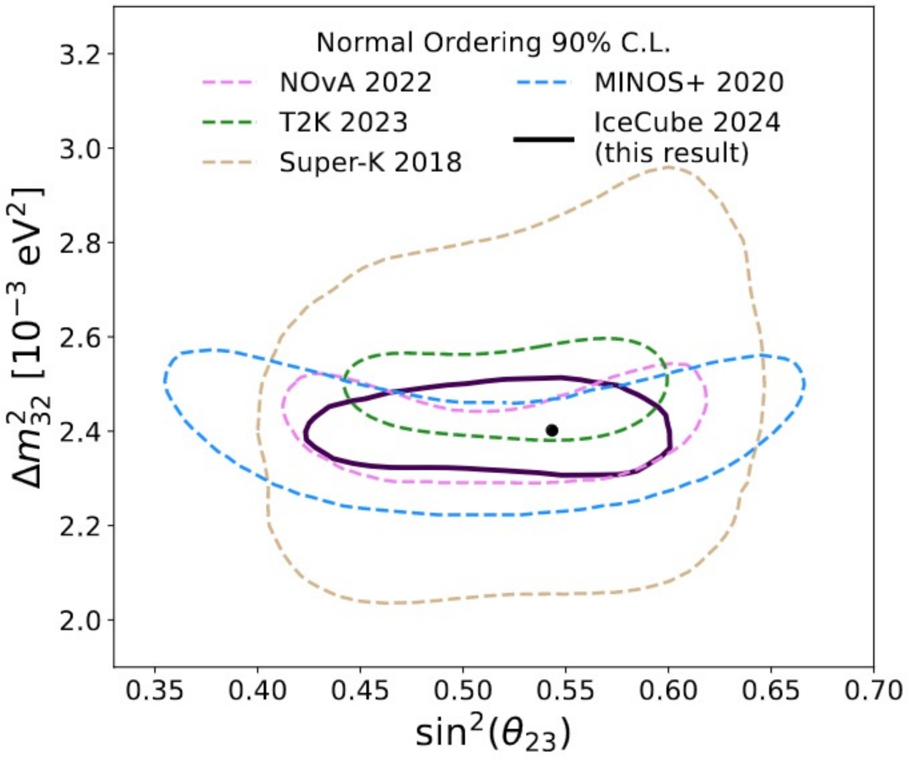


scattering of DSNB with relic sterile neutrino background, detection in 40 kton LAr



Jeong …MHR…et al, JCAP 06 (2018) 019

Neutrino oscillations



IceCube, https://arxiv.org/pdf/2405.02163

- Look for track-like events (muons) in DeepCore subdetector of IceCube.
- Muon neutrino disappearance measurement for reconstructed energies between 5-100 GeV.