Theory/modeling of cosmic rays and atmospheric neutrinos

Brookhaven National Laboratory

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Cosmic rays

- Discovery in 1912 by Victor Hess (balloon ride to almost 30,000 feet!)
- "Natural accelerators" enabled particle discoveries: positron, muon, pion, kaon.
- Incredible energy range, up to 320 ± 90 EeV (1 EeV $= 10^9$ GeV).

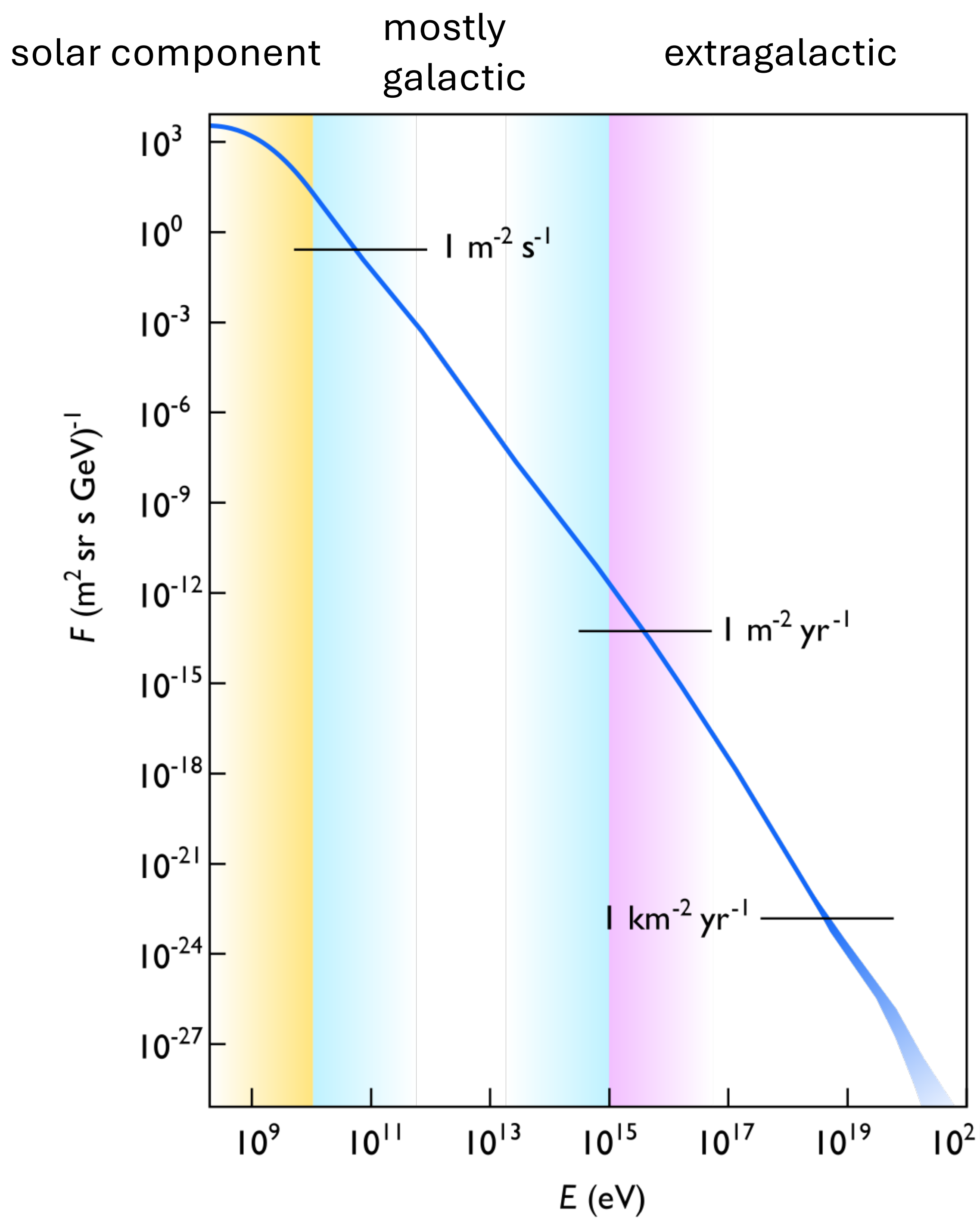


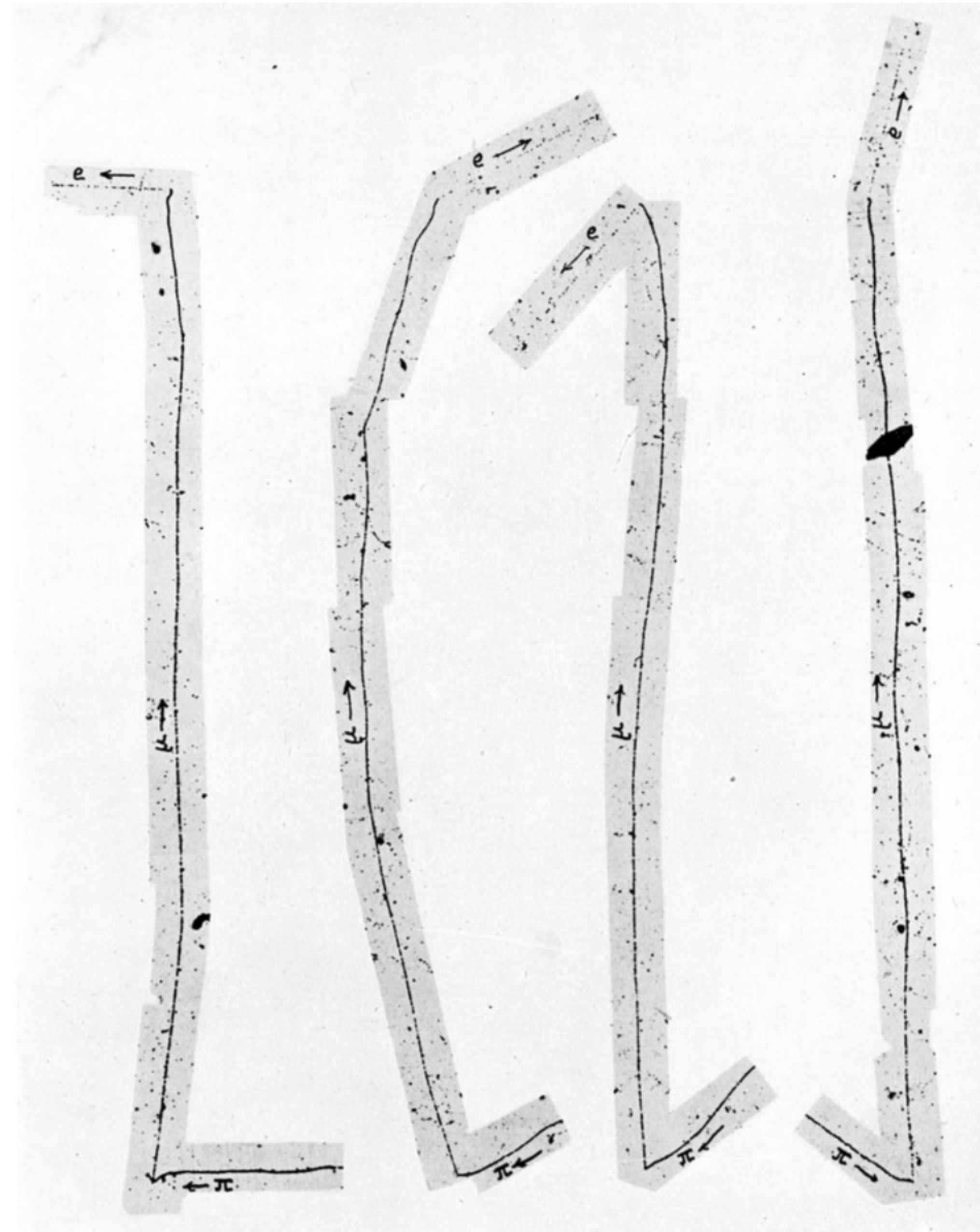
Fig. by Lefebre, after Sword and De Angellis
https://en.wikipedia.org/wiki/Cosmic_ray

Pions from cosmic rays

Cosmic ray interaction with emulsion plates to produce pions – discovered in 1947. Pions and other light & heavy hadrons continue to be of interest.

Fig. 4. A team of emulsion microscopists working at the Brazilian Center for Physics Research at Rio de Janeiro (ca. 1960). Powell's method of work was emulated by Lattes and colleagues in Brazil. Credit: Centro Brasileiro de Pesquisas Físicas/Ministério da Ciência, Tecnologia e Inovação.

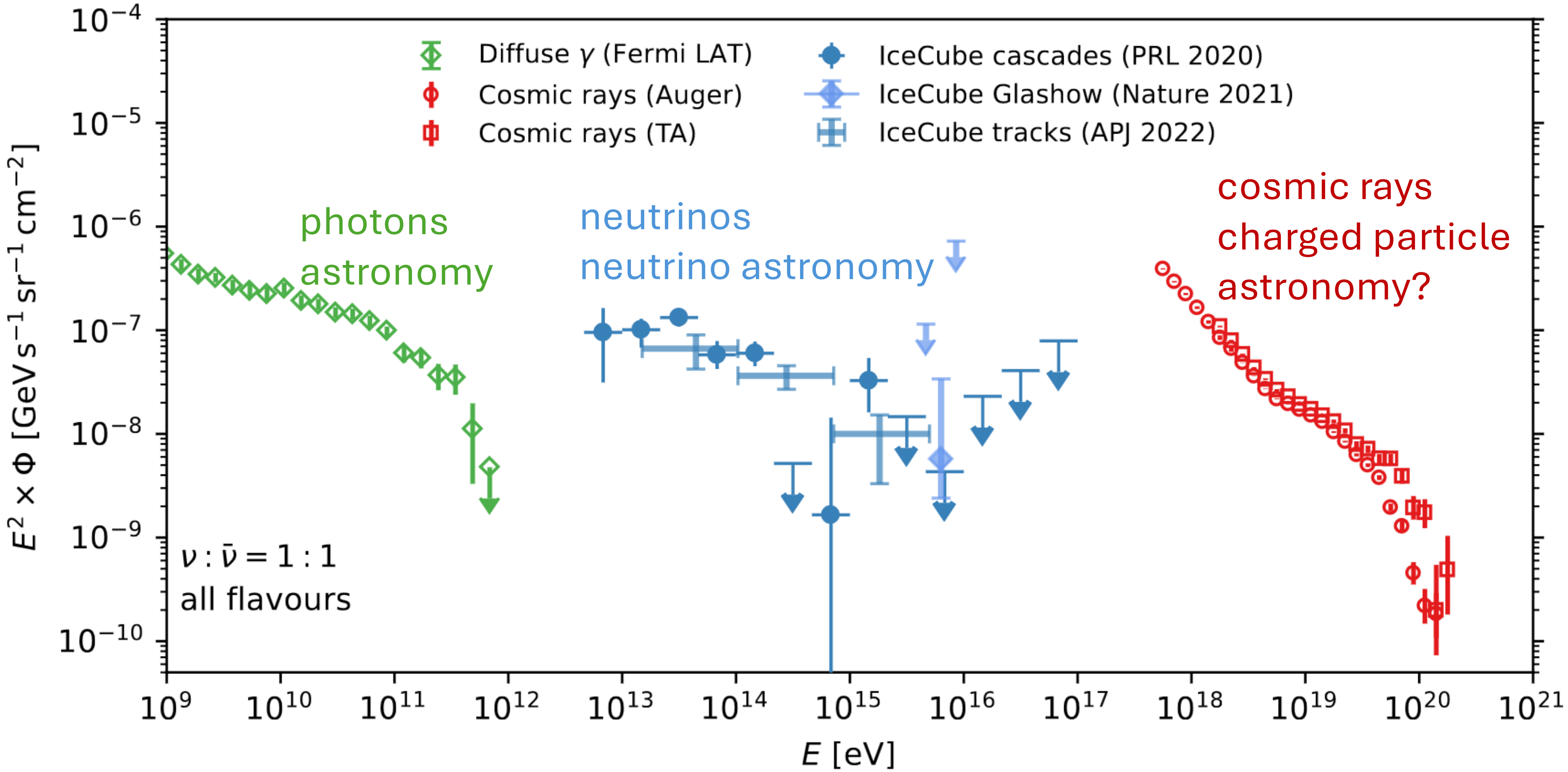
Vieira & Videira, Phys. Perspct. 16 (2014) 3



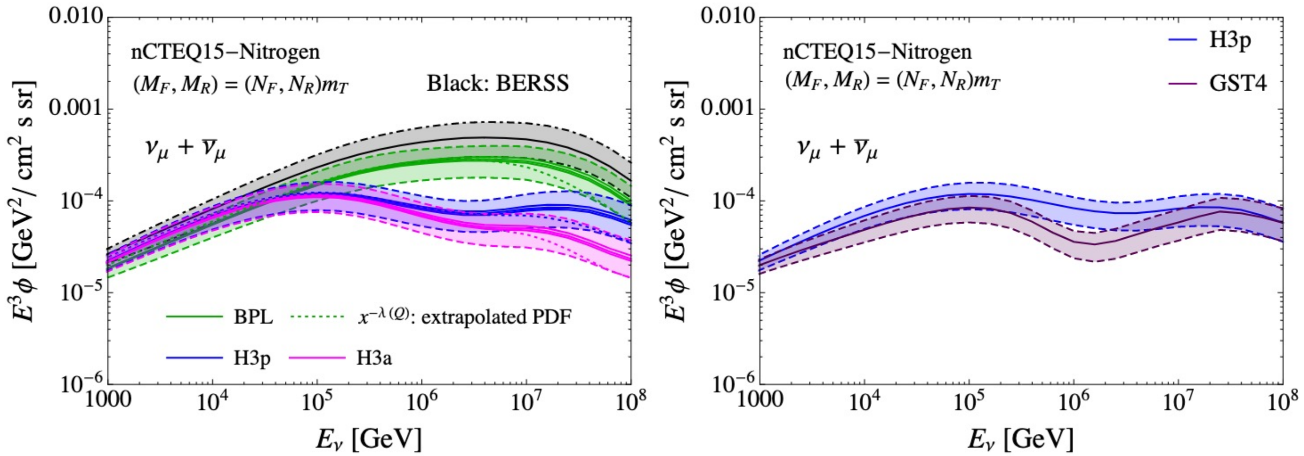
C F Powell (1950) Rep. Prog. Phys. 13 350

Multimessenger connection

One goal: understand connections between photons, neutrinos and cosmic rays

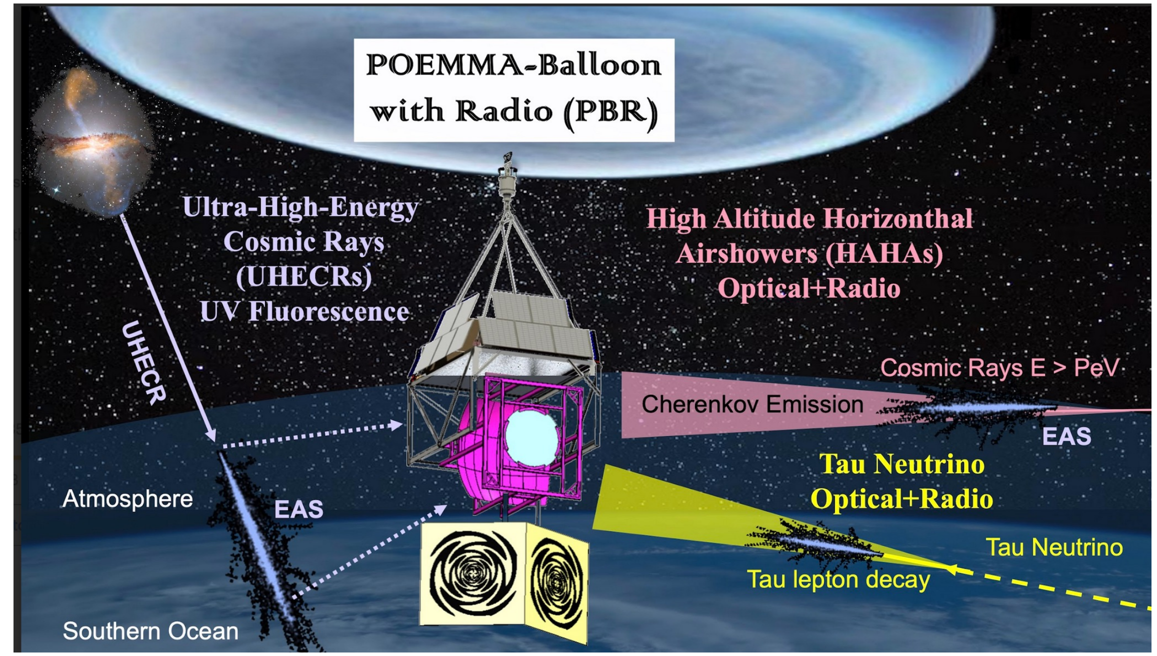


Snowmass white paper: Ackermann …MHR… et al., JHEAp 36 (2022) 55-110
https://arxiv.org/pdf/2203.08096

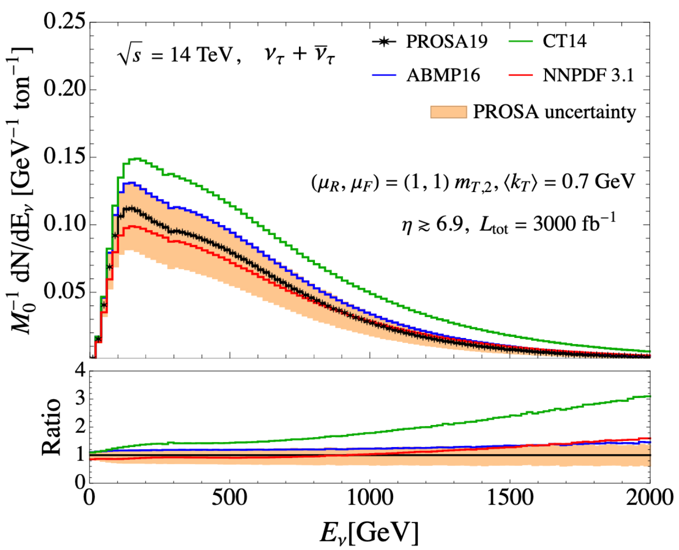


prompt atmospheric neutrinos from charm, background to astrophysical neutrinos

new project

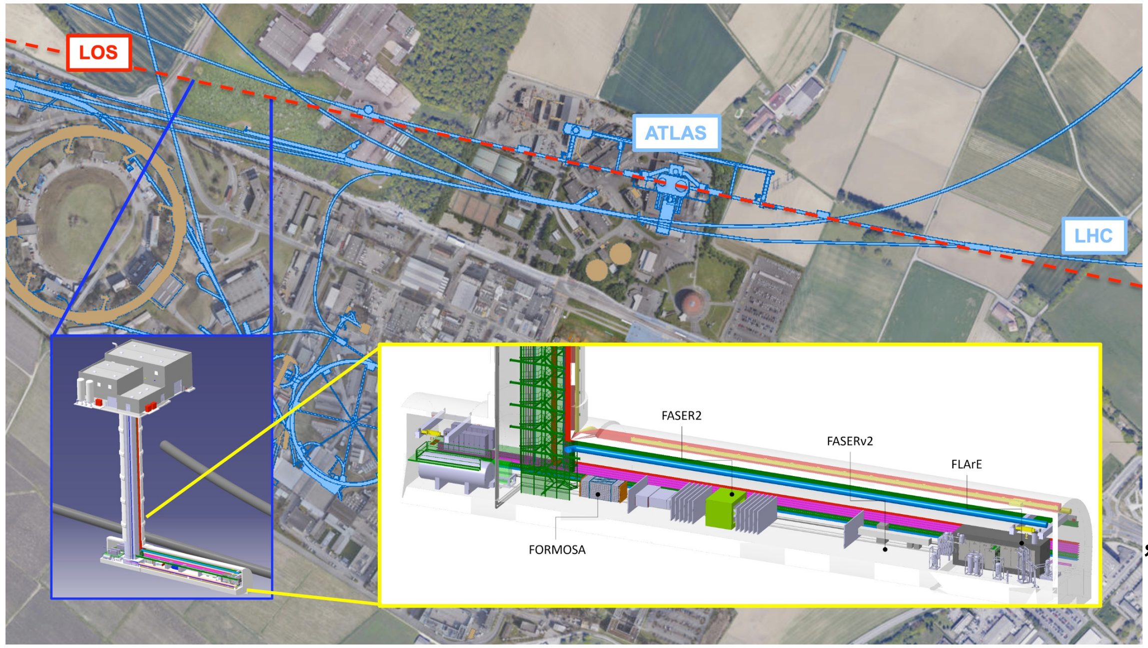


tau neutrino CC events at an FPF experiment



EUSO-SPB2 (launch in May 2023, about 2 nights of data)

My connections ....



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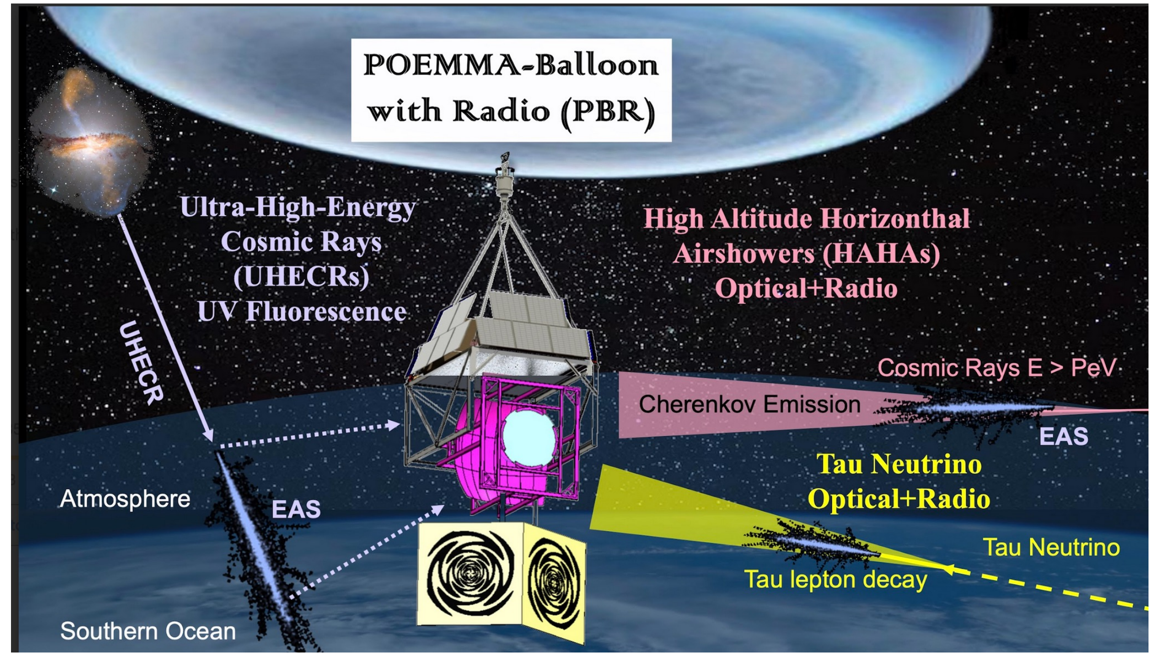
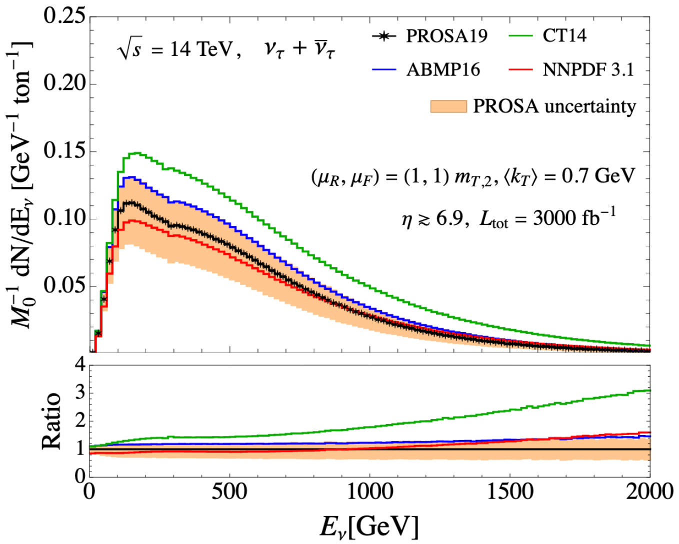
new project



tau neutrino CC events
at an FPF experiment



EUSO-SPB2 (launch in May 2023, about 2 nights of data)

My connections ....

Plan

Cosmic rays – spectrum, composition (indirect measurement from air showers)
- Modeling of muon number

Atmospheric neutrino (and muon) fluxes – spectrum
- Role of forward physics
- Cosmic ray composition
- Connection to Forward Physics Facility physics

Neutrino cross sections from UHE neutrinos (time permitting)
- In part, back to air showers (tau decays in the atmosphere)

Cosmic rays

- Peak of the cosmic ray spectrum at about 0.3 GeV energy.
- Rapidly falling flux as energy increases: larger and larger detectors required.
- Low energy detection: direct detection; High energy detection: indirect detection from extensive air showers (EAS).

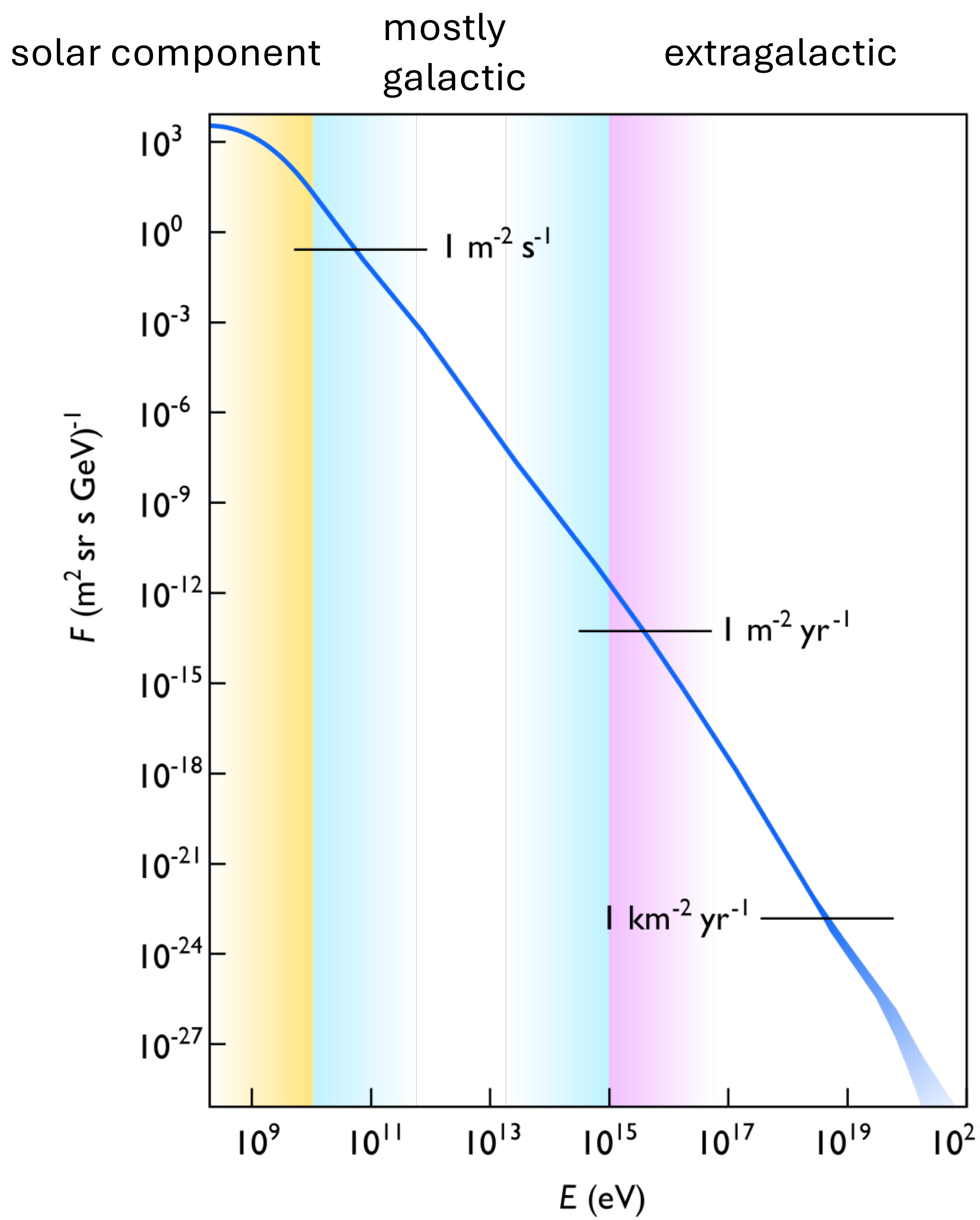
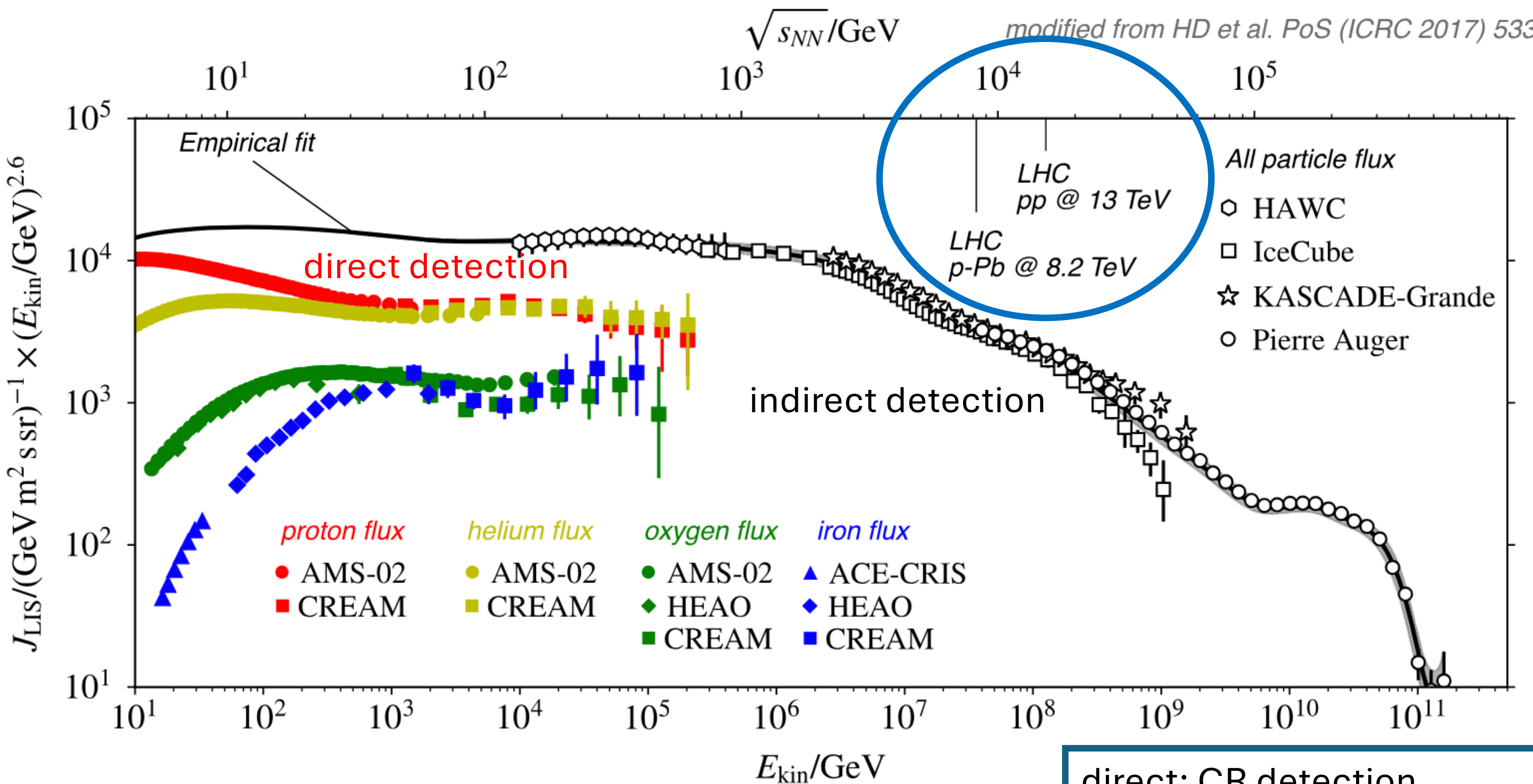


Fig. by Lefebre, after Sword and De Angellis
https://en.wikipedia.org/wiki/Cosmic_ray

Energy scaled cosmic ray flux ($E^{2.6}$)

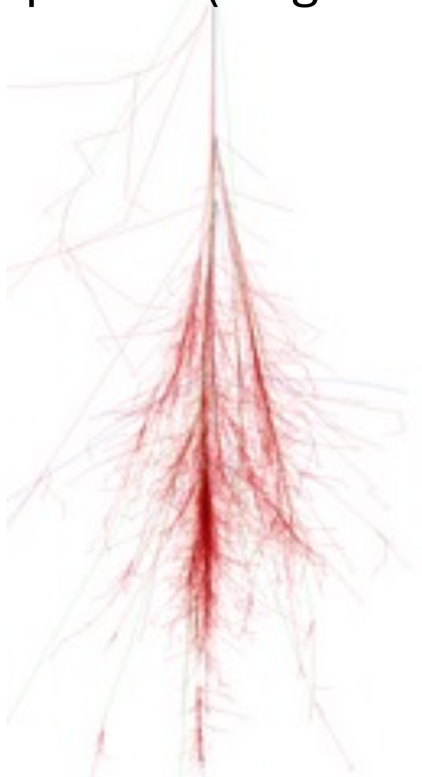


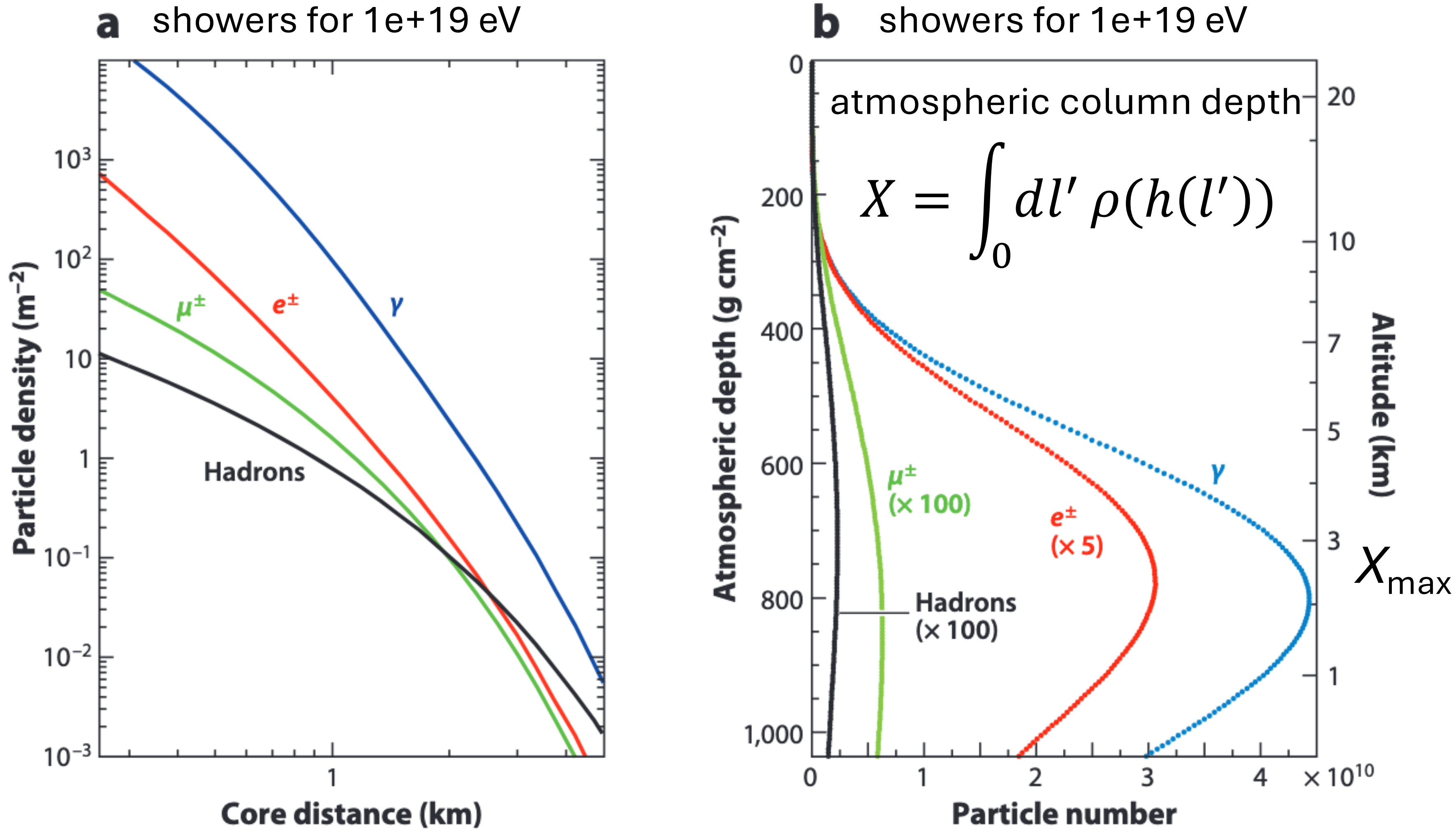
Albrecht et al, Astrophys. and Space Sci (2022) 367: 27

direct: CR detection
indirect: detection of showers they make

Indirect detection from extensive air showers

- Air fluorescence from EM component (isotropic)
- Muons from hadronic component (on ground)

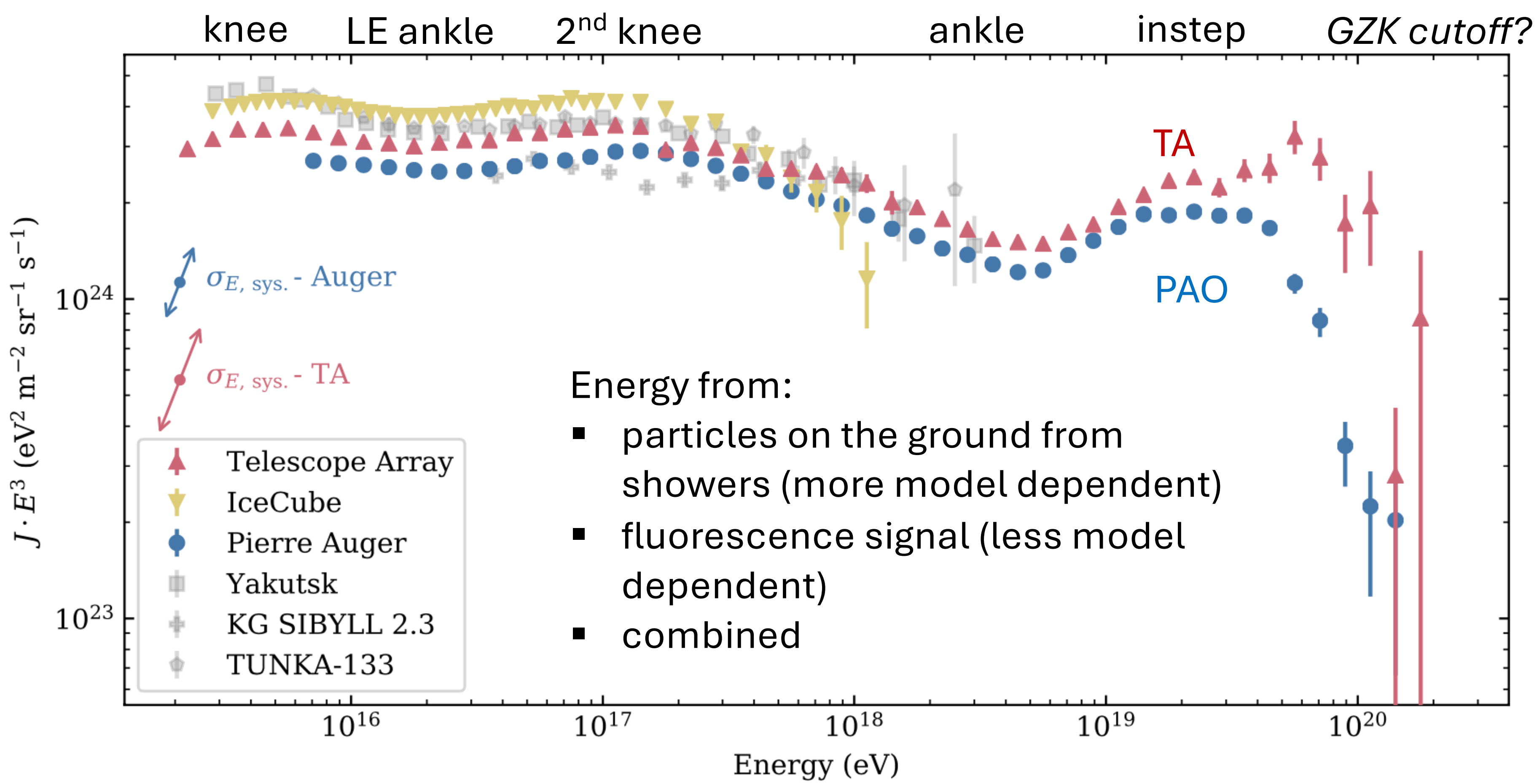




https://www.iap.kit.edu/corsika/

Engel, Heck & Pierog, Ann Rev Nucl Part Sci 61 (2011) 467

Energy scaled cosmic ray flux (E^3)



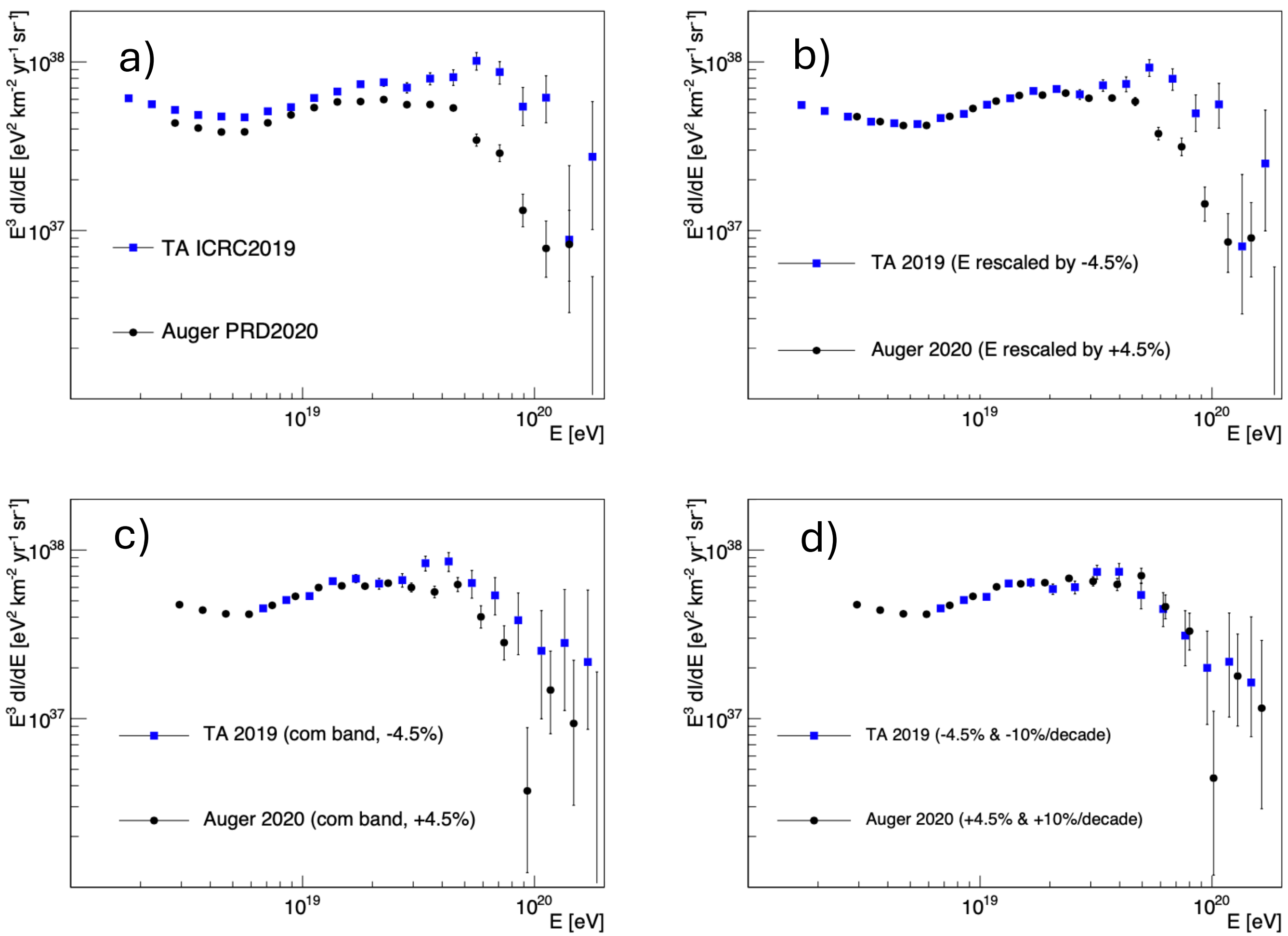
Energy from:

- particles on the ground from showers (more model dependent)
- fluorescence signal (less model dependent)
- combined

Coleman et al, Snowmass White Paper, arXiv:2205.05845

CR spectra from TA and PAO

TA and PAO: different translations of shower to primary CR energy, also declination dependence.



a) High energy comparison.
b) Energy rescaling by $\pm 4.5\%$.

c) Energy rescaling and common band $\delta = -15.7^o$ to 24.8^o.
d) Common band, energy rescaling and energy dependent shift of $\pm\, 10\% \times \log_{10}(E/10^{19}\ eV)$.

Coleman et al, Snowmass White Paper, arXiv:2205.05845;
TA & PAO, PoS ICRC 2021 (2021) 337

CR spectrum/Greisen Zatsepin Kuzmin (GZK) cutoff

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

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:

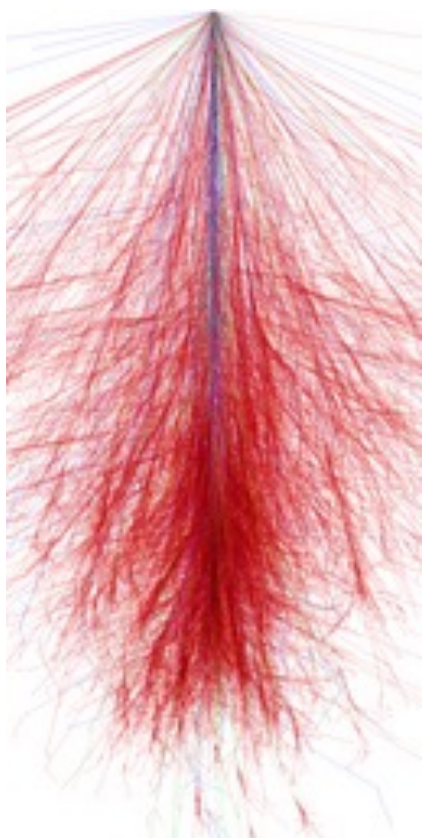
$$\begin{aligned} s_{p\gamma} &\simeq (E_\gamma + E_p)^2 - (p_\gamma - p_p)^2 \\ &\simeq 4E_\gamma E_p = 10^{-12}\ \mathrm{GeV}^2\ E_p/\mathrm{GeV} \end{aligned}$$

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

Guaranteed source of neutrinos at the highest energies if cutoff due to GZK. Normalization of the neutrino flux has uncertainties. (Guaranteed flux, but not guaranteed to be large.)

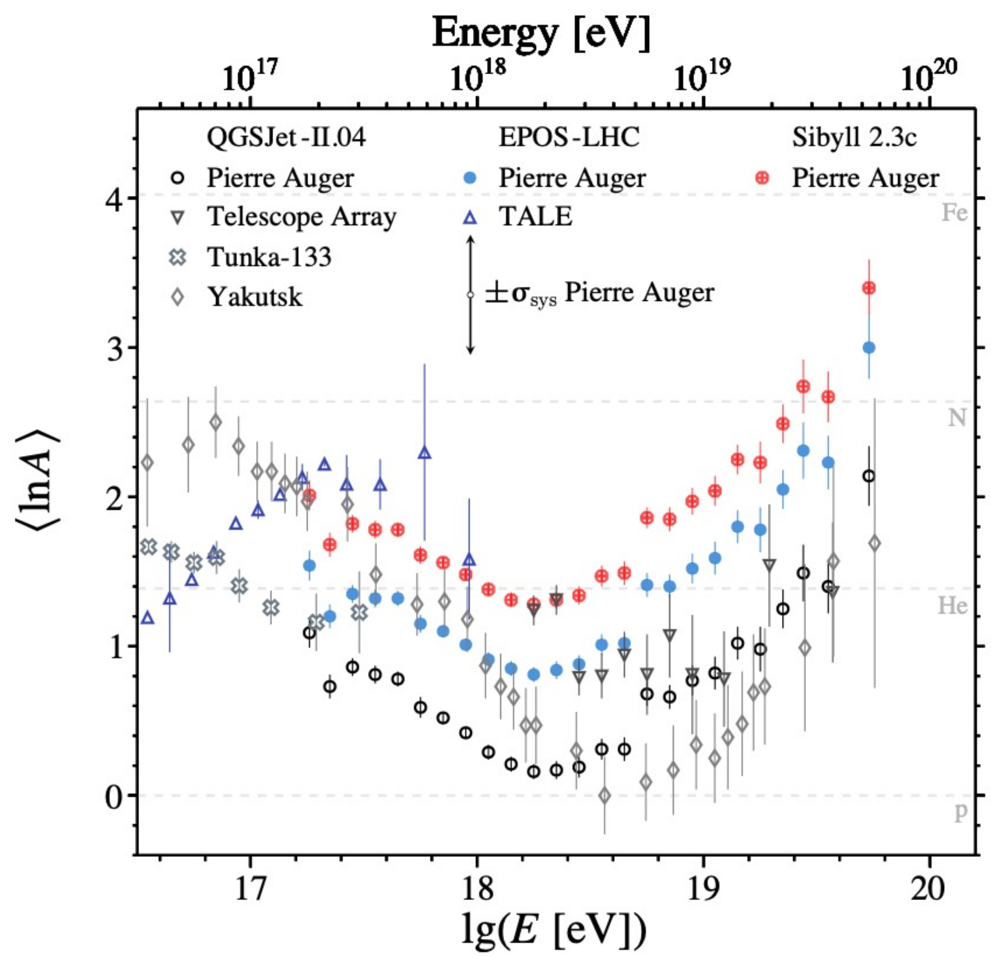
Cosmic ray composition: $\langle \ln A \rangle$

proton induced air shower



iron induced air shower

https://www.iap.kit.edu/corsika/



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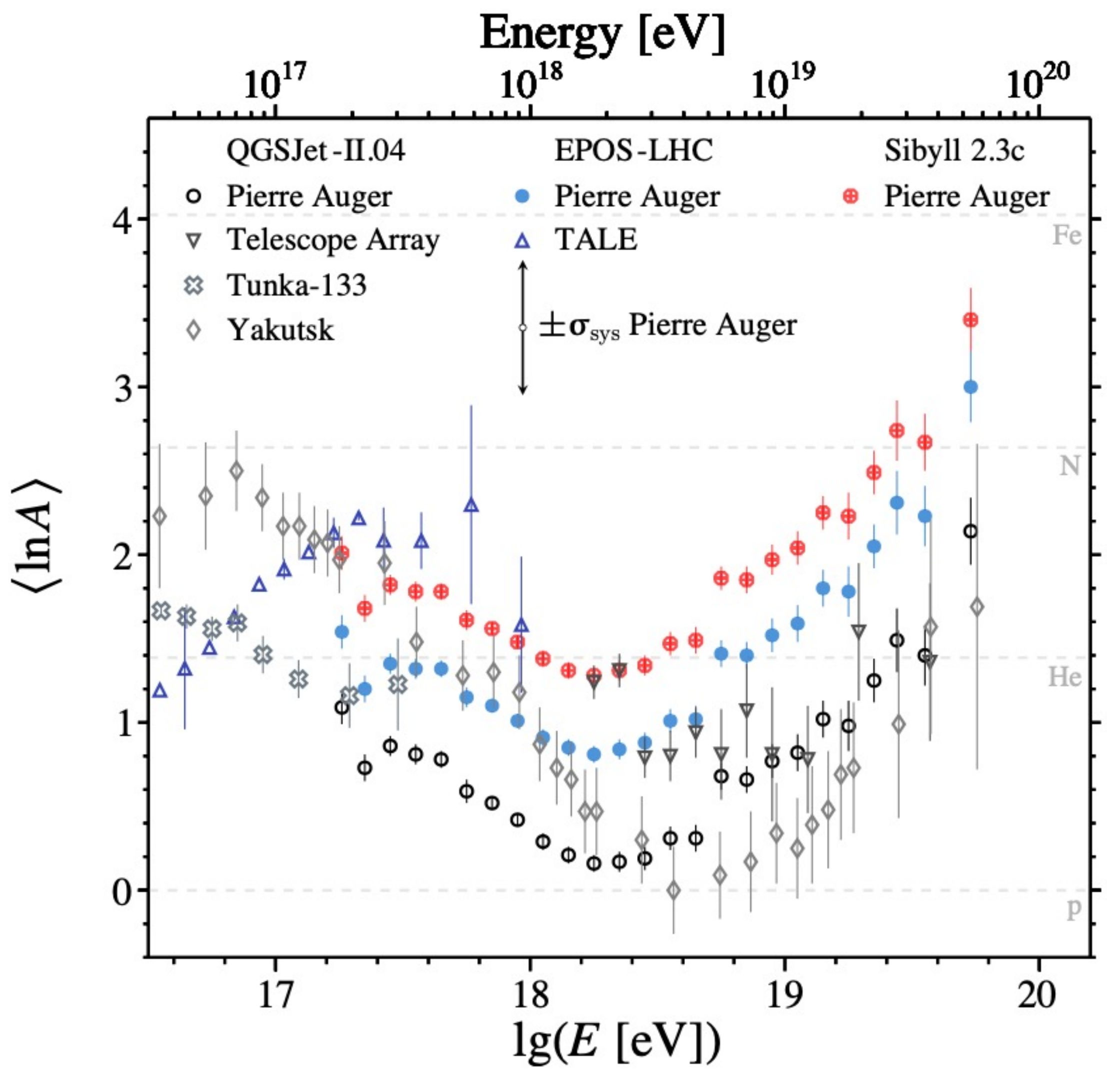
Cosmic ray composition : $\langle \ln A \rangle$

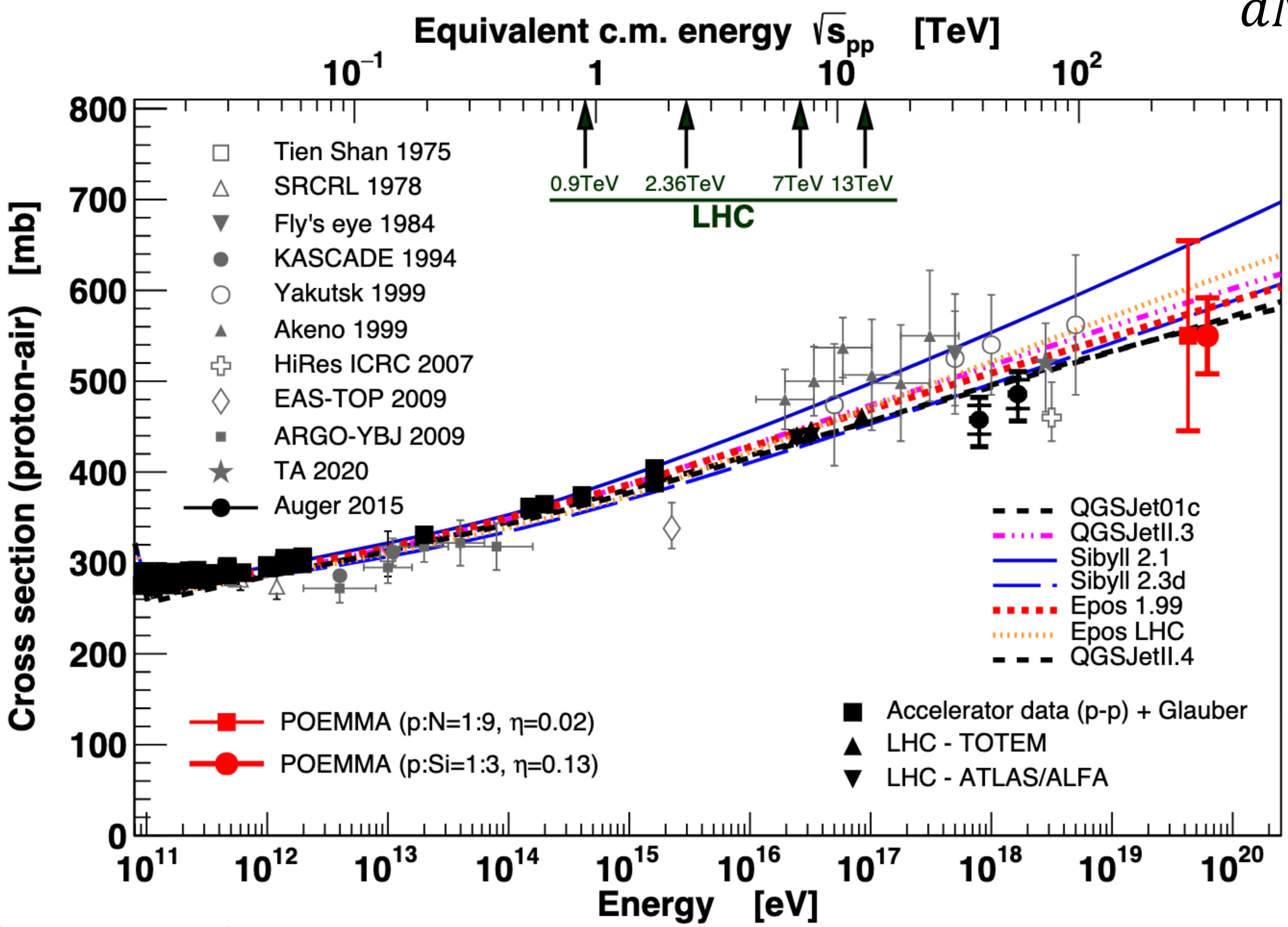


- Composition as function of energy could help distinguish between cosmic ray sources.
- Composition from showers: X_{max} and particles on the ground
- Hadronic interaction model of showers – strong dependence (but mostly common energy dependence – the curves are mostly parallel), e.g. Auger with 3 different shower models.

Coleman et al, Snowmass White Paper, arXiv:2205.05845

Proton-air cross sections

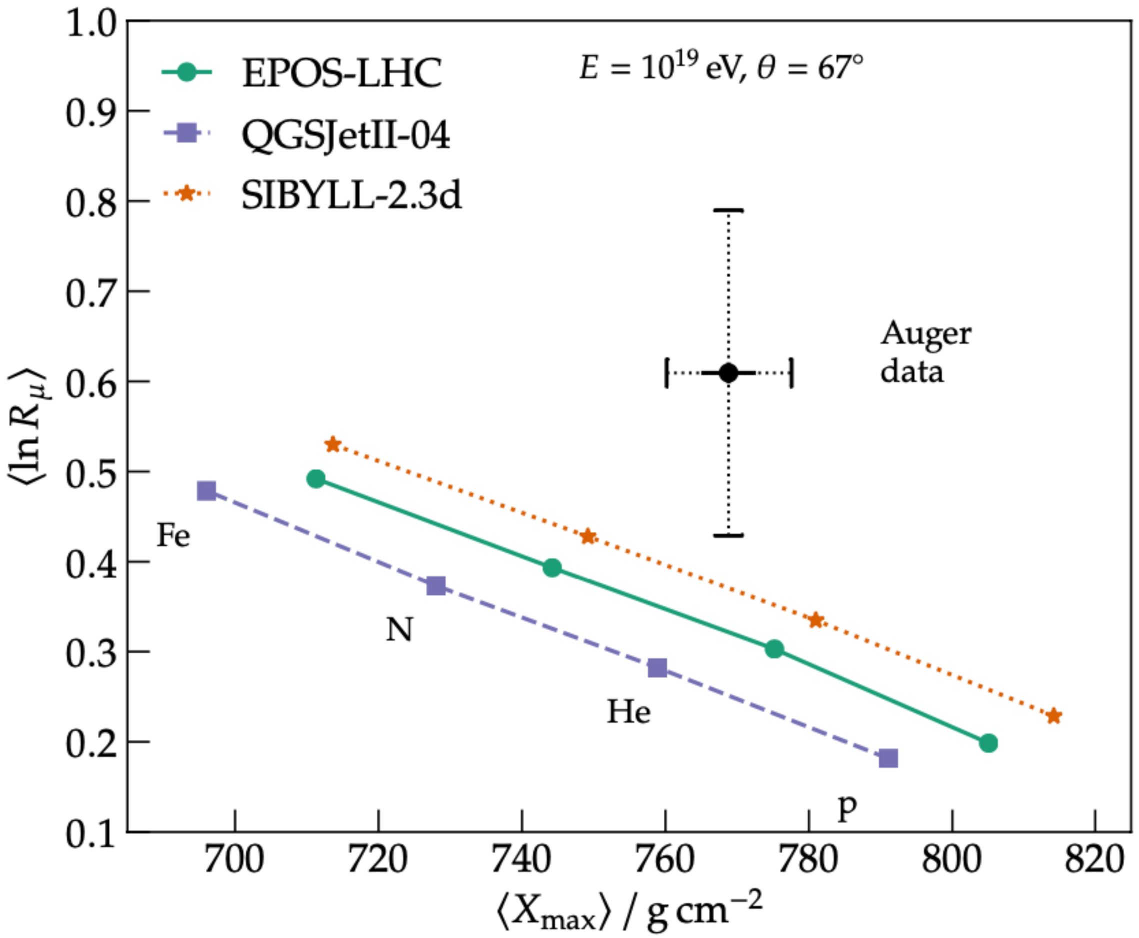
$$dN/dX_{\max} \sim \exp(-X_{\max}/\Lambda_\eta)$$



Olinto et al, JCAP 06 (2021) 007

- Protons traverse greater X than nuclei.
- Focus on the tail of the $X_{\max}$ distribution.
- η is related to the fraction of the most penetrating events, comprised of protons.
- Results depend on contamination of heavier nuclei in the tail.

Muon puzzle



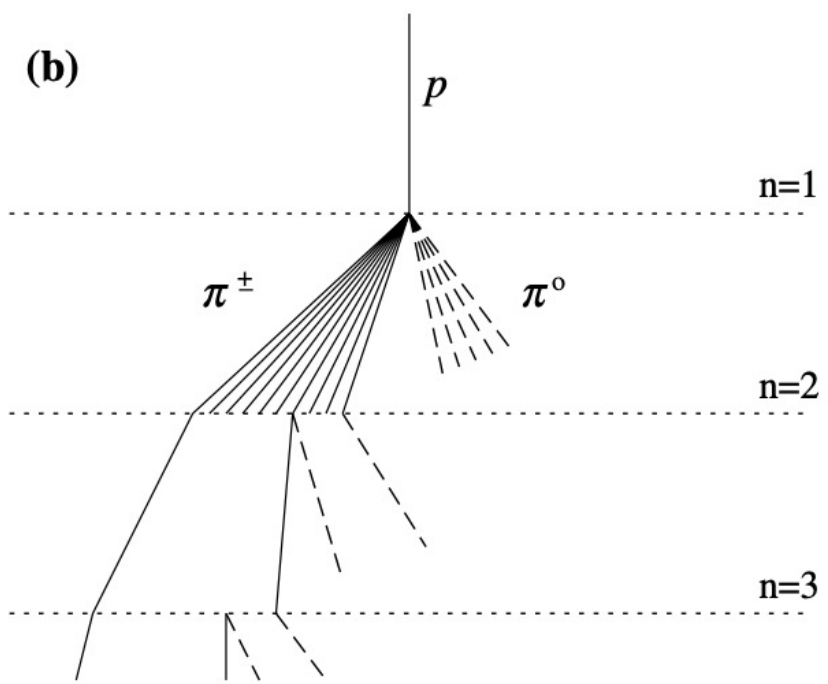
PAO collab., PRL 126 (2021) 152002

- Example of discrepancy between simulations and measurements of muons on the ground.
  - *Puzzle*: There are fewer muons in simulations than actually measured.
- Example of composition dependence.
- Example of MC simulation dependence.

R_μ is scaled muon number

R_μ = 1 when $N_\mu = 1.455\ 10^7$

Muon puzzle, simplified



Heitler-Matthews simplified model.
Fig. from Matthews, Astropart. Phys. 22 (2005) 387

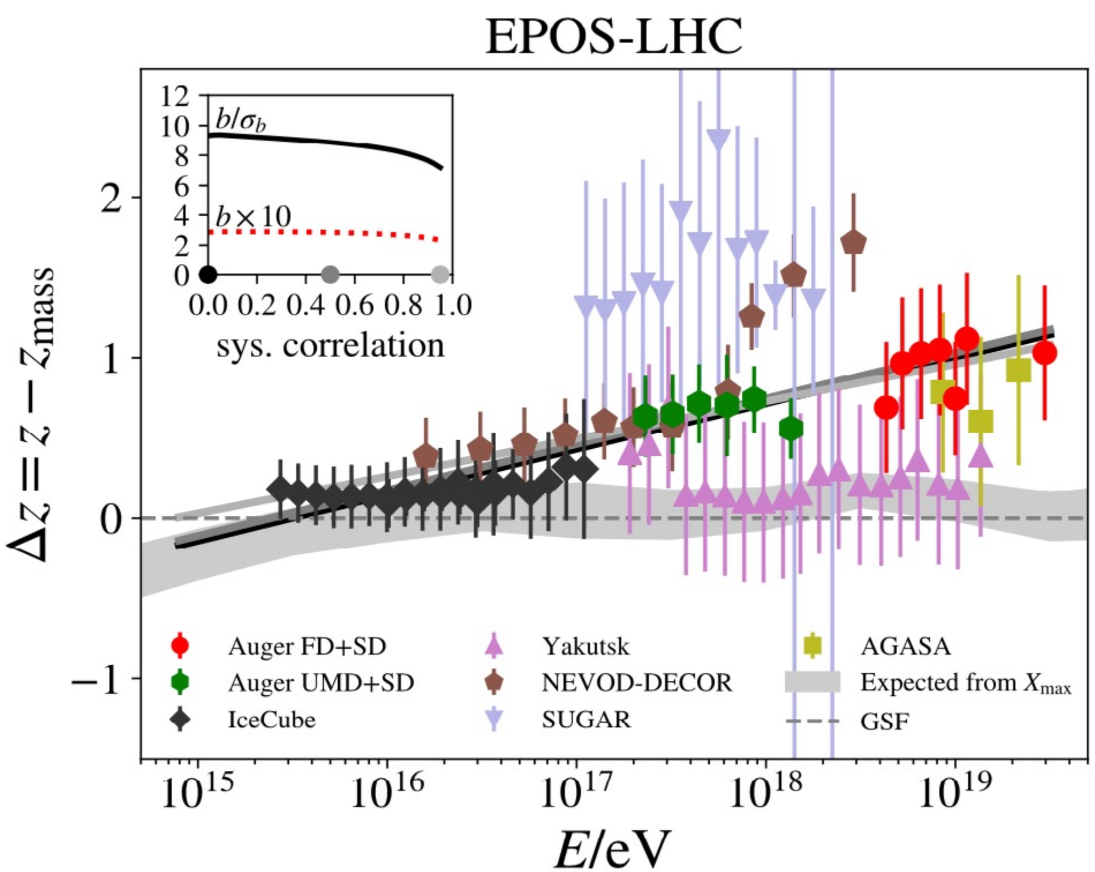
Superposition model: (A,E) replaced by A x (1,E/A).
Muons come from charged pions.

Muon number sensitive to
- particle multiplicity as a function of energy,
- fraction of charged pions produced (or fraction of neutral pions produced),
- CR composition.

Muon puzzle: too many neutral pions in simulations relative to charged pions (in this simplified version).

Muon puzzle

Δz~1 means ~40% muon deficit



Soldin, PoS ICRC2021 (2021) 349

Albrecht et al, Astrophys. and Space Sci (2022) 367: 27

$$z = \frac{\overbrace{\ln\langle N_\mu\rangle}^{\text{measured}} - \overbrace{\ln\langle N_\mu\rangle_p}^{\text{simulated}}}{\underbrace{\ln\langle N_\mu\rangle_{\mathrm{Fe}}}_{\text{simulated}} - \underbrace{\ln\langle N_\mu\rangle_p}_{\text{simulated}}}$$

WHISP Group (Working group on Hadronic Interactions and Shower Physics) – eliminate experimental variations as much as possible

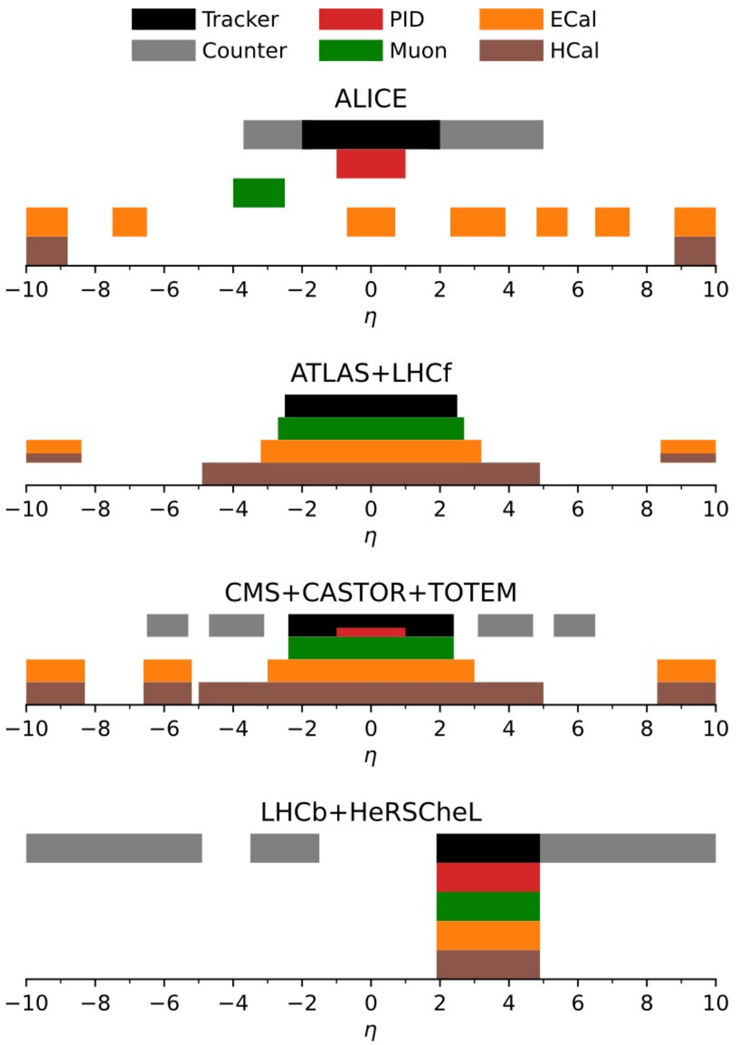
- adjust energy scale offsets per CR flux
- take composition from X_{max} measurement (z_{mass})
- shower simulation dependent, but same trend
- LHC energies relevant

Muon puzzle, theory & simulations

- More muons if there is a decrease to the energy fraction carried by neutral pions.
- Energy dependent: NN CoM energy greater than ~8 TeV.
- Can't be a rare process, difficult to solve only in the 1st interaction. Likely from multiple stages in the shower cascade.
- Enhance strangeness, baryons in forward production at high energies for A_1-A_2 collisions? Proposals include:
  - Quark gluon plasma (relevant here?)
  - Color glass condensate
  - Color string effects in high multiplicity events

See Albrecht et al, Astrophys. and Space Sci (2022) 367: 27 and references therein for discussion.

Muon puzzle, experiments



LHC experiments:

- enhanced with forward detectors (TOTEM, CASTOR, LHCf, HeRSCheL)
- ion beams, gas targets (SMOG, SMOG2)
- multiple measurements to understand inelastic cross section, hadronic/EM energy flow, multiplicity, etc.

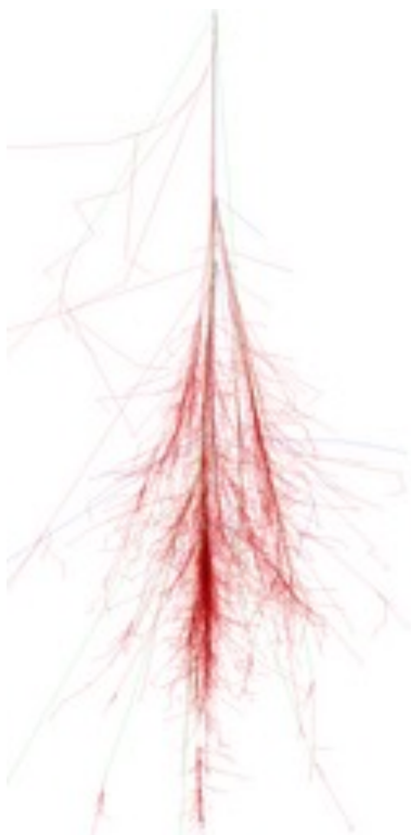
Fixed target experiments:

- NA61/SHINE proton and carbon targets (lower energies)
- Forward Physics Facility experiments – neutrino flux depends on pions, kaons, heavy flavor production and decays.

Albrecht et al, Astrophys. and Space Sci (2022) 367: 27, see also Feng et al, J.Phys.G 50 (2023) 030501

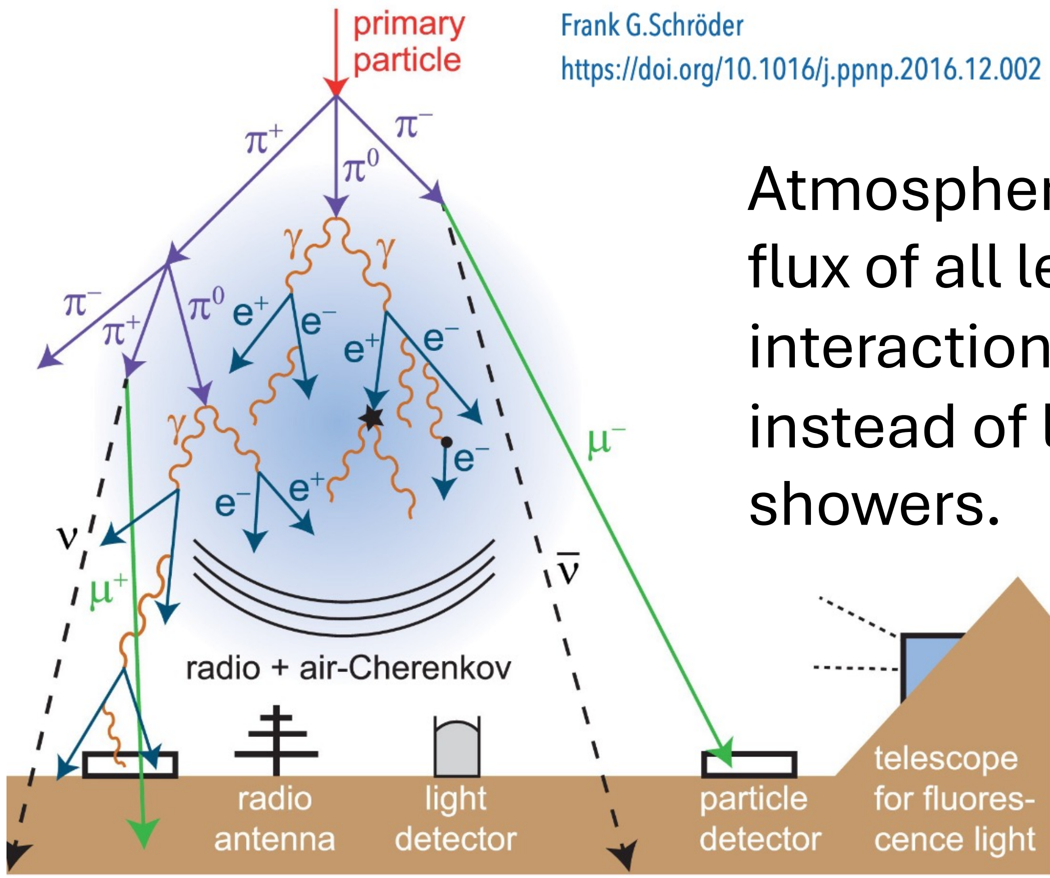
Atmospheric lepton fluxes

Cosmic ray interactions in the atmosphere make muons and neutrinos.



One incident CR energy, muons at the ground.

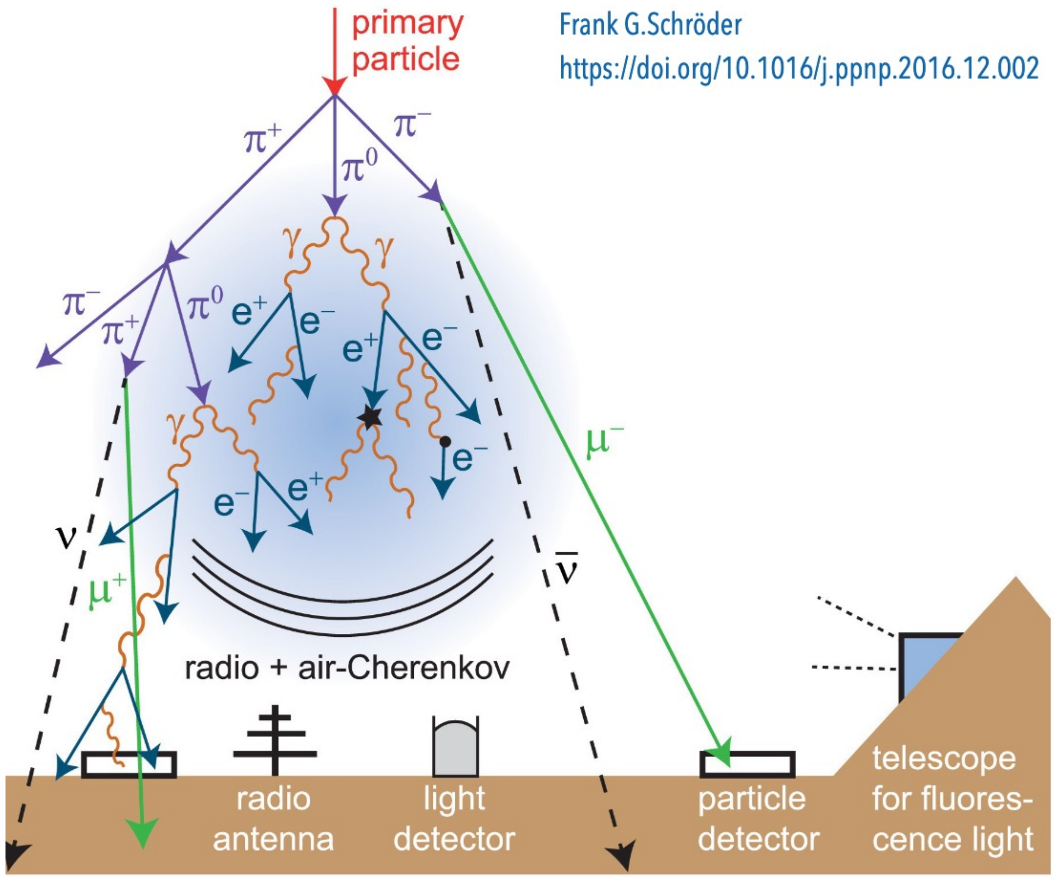
Frank G.Schröder
https://doi.org/10.1016/j.ppnp.2016.12.002



Many interactions, spectrum of CRs, consider lepton energy spectrum at the ground.

Atmospheric lepton flux: consider flux of all leptons from CR interaction in the atmosphere instead of looking at individual showers.

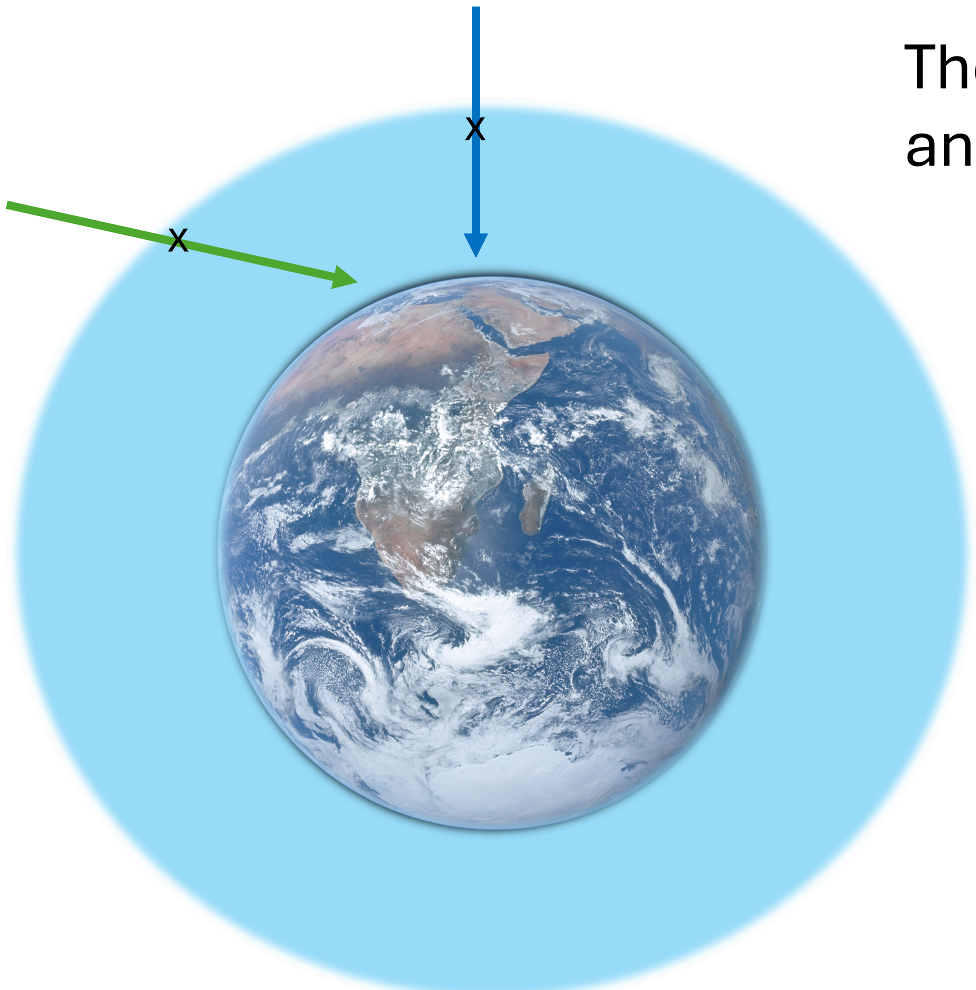
Atmospheric lepton fluxes



Flux evaluation relies on:

- model of the atmosphere
- cosmic ray flux (spectrum and composition)
- hadronic interaction cross sections
- energy distribution of produced hadrons at forward angles
- hadron decays to leptons
- for muons, EM energy loss

Atmospheric lepton fluxes



The atmospheric lepton flux (at Earth) depends on energy, angle:

$$X = \int_0 dl'\, \rho(h(l'))$$

Coupled cascade equations:

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{\mathrm{dec}}} + \sum S(k \to j)$$

Production or decay:

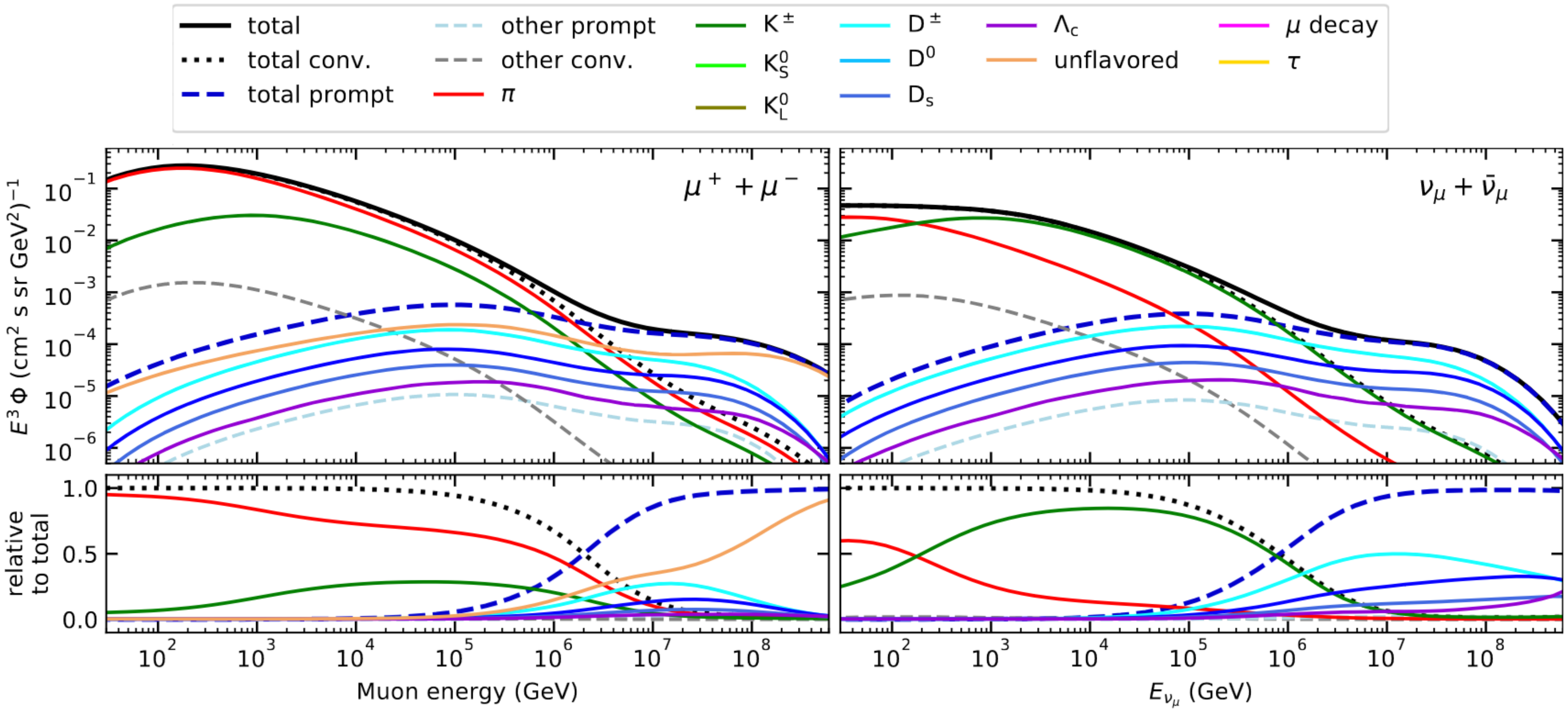
$$S(k \to j) = \int_E^\infty dE' \frac{\phi_k(E')}{\lambda_k(E')} \frac{dn(k \to j; E',\ E)}{dE}$$

$j = N, \pi, K, D, \ldots, \nu_\mu, \nu_e, \mu$ (also need EM loss term)

tothemoon.ser.asu.edu/gallery/Apollo/17/

Energy scaled atmospheric flux (E^3)

Example: - MCEQ

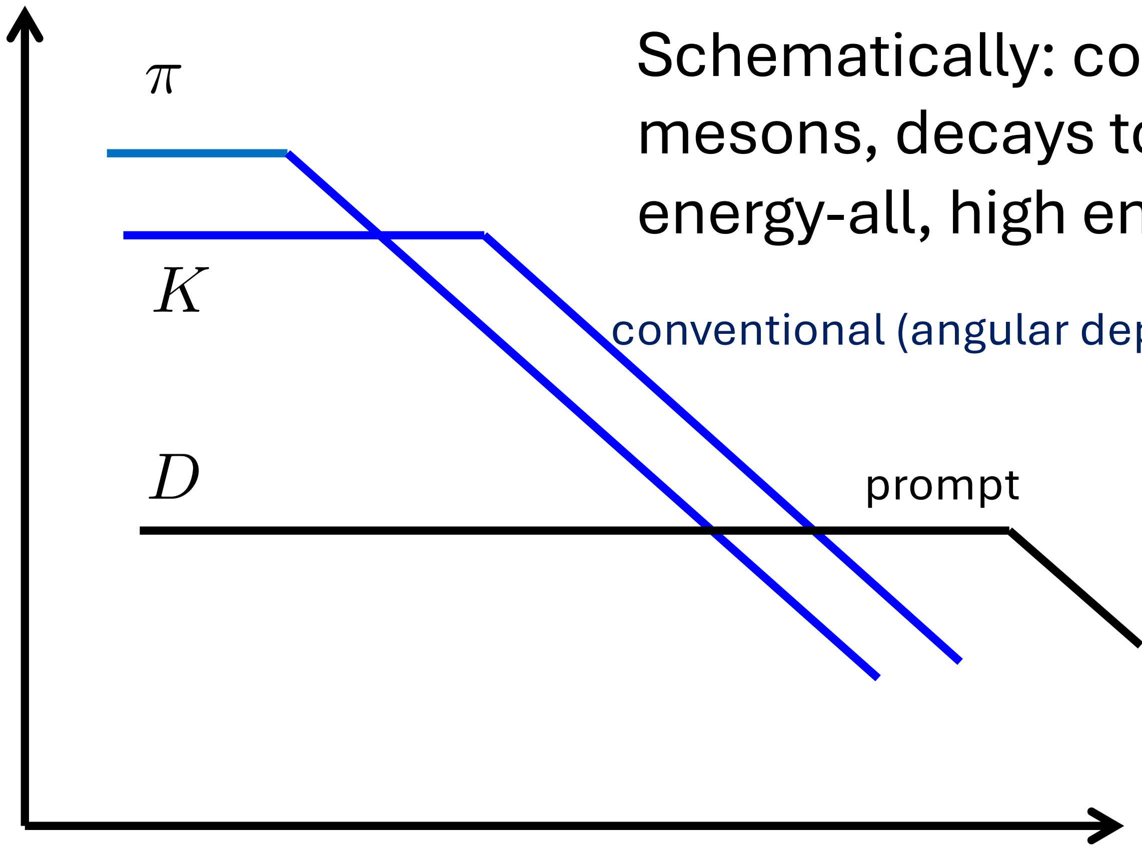


Fedynitch et al, PRD 100 (2019) 103018

Atmospheric lepton fluxes (schematically)

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

Scaling by approximate CR energy spectrum

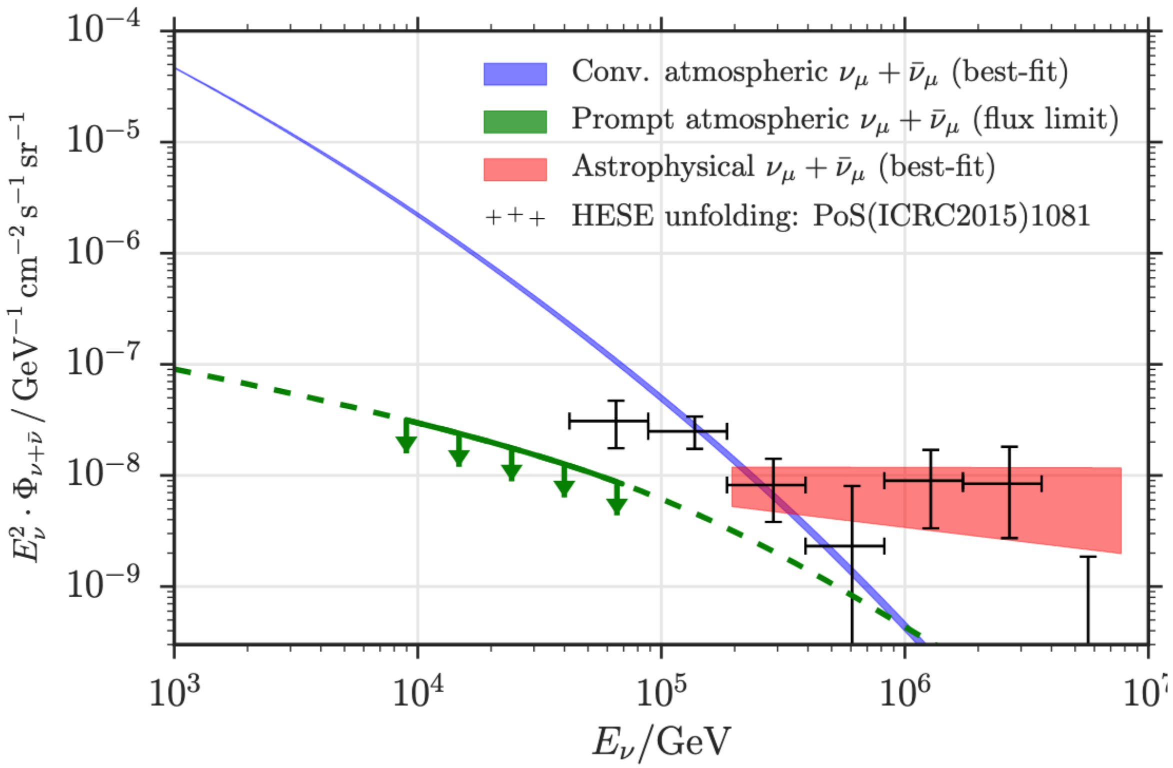


Something about IceCube.

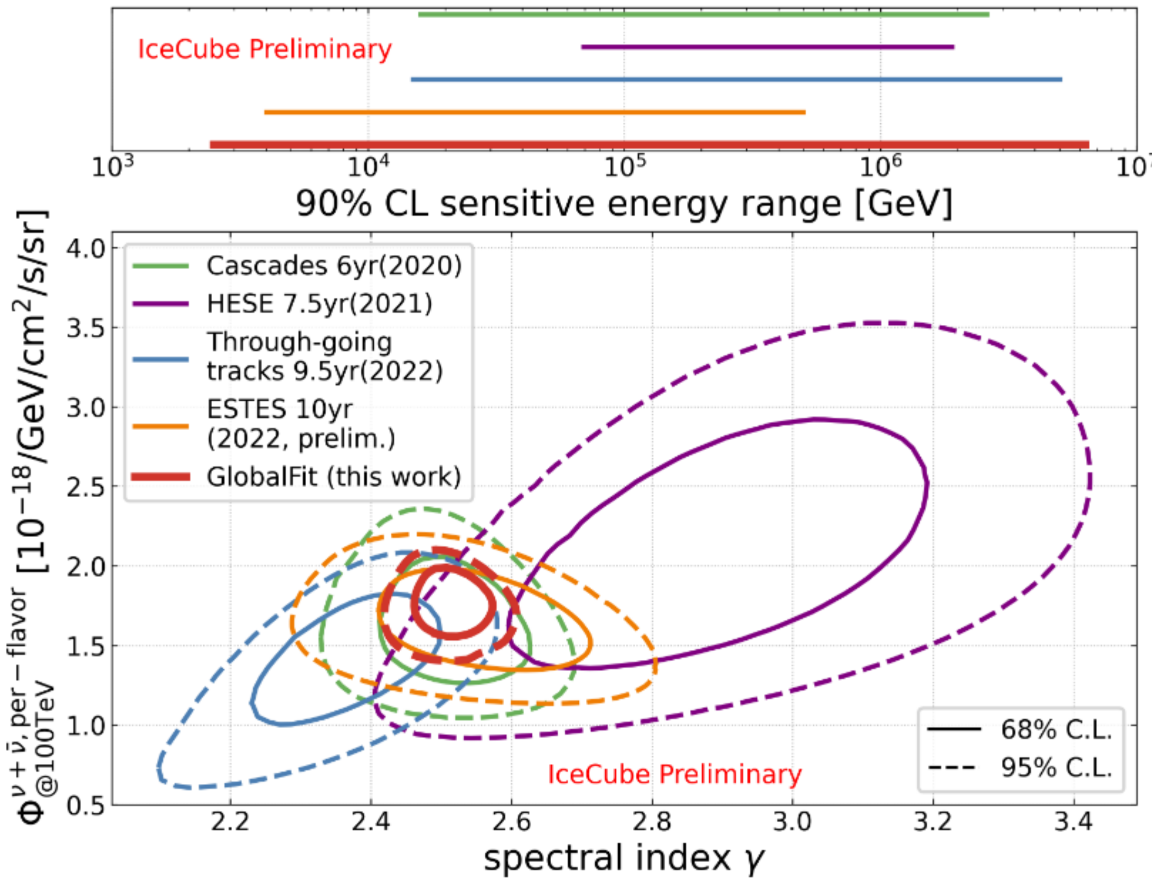
$$P_{decay}(E) = 1 - \exp(-D/\gamma c\tau)$$
$$\simeq D/\gamma c\tau = E_c/E$$

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

Atmospheric neutrinos fluxes & IceCube

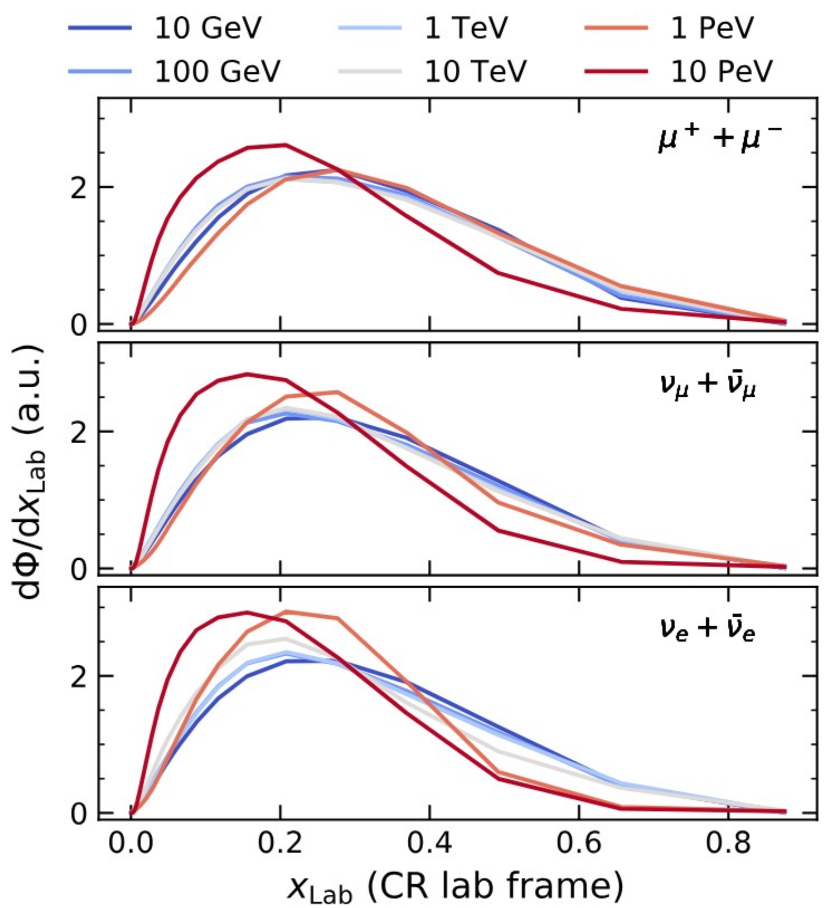


IceCube, Astrophys.J. 833 (2016) 3



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

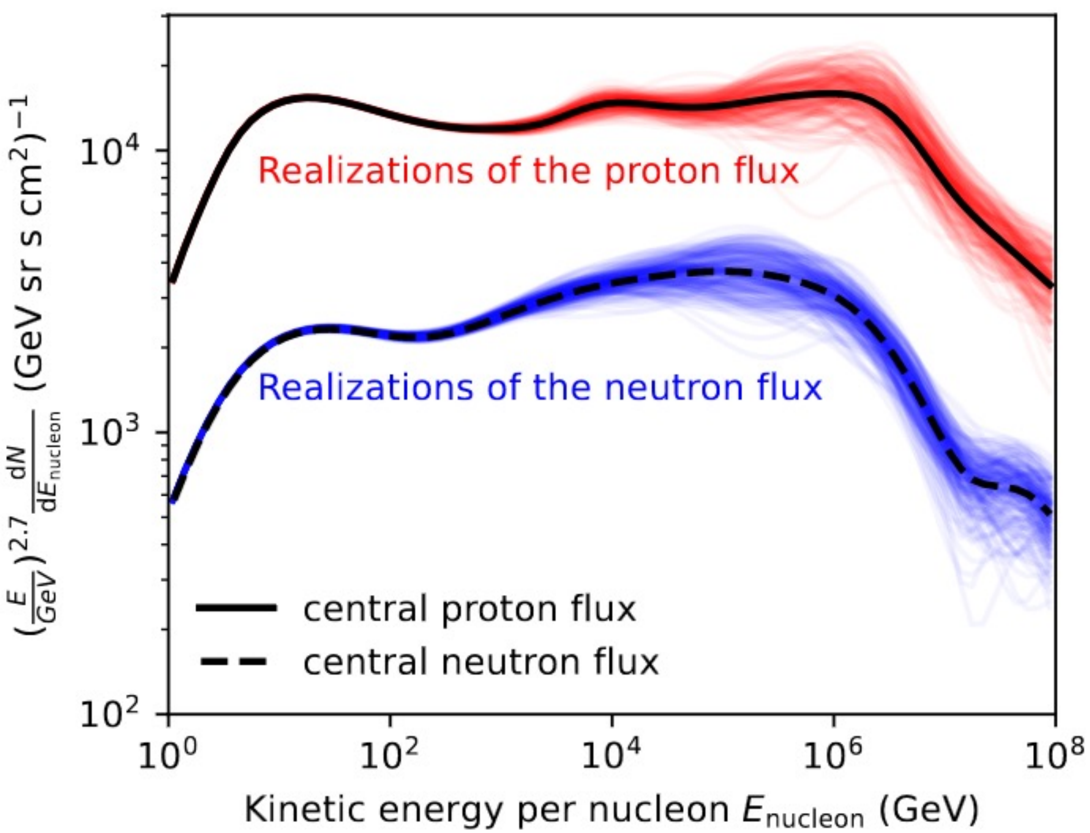
Particle physics - forward phase space



Fedynitch et al, PRD 100 (2019) 103018

- Probability distribution functions in $x_{Lab} = E_\pi / E_{CR}$ for vertical lepton flux at fixed energies ($E_{CR} \sim 10\ E_\mu$).
- Inclusive lepton fluxes, given CR spectrum, results less sensitive to secondary interactions than the number of muons at the ground from an individual shower.
- Input meson production at forward angles (large x_{Lab}).
- Leading particles important for charge ratios, too.

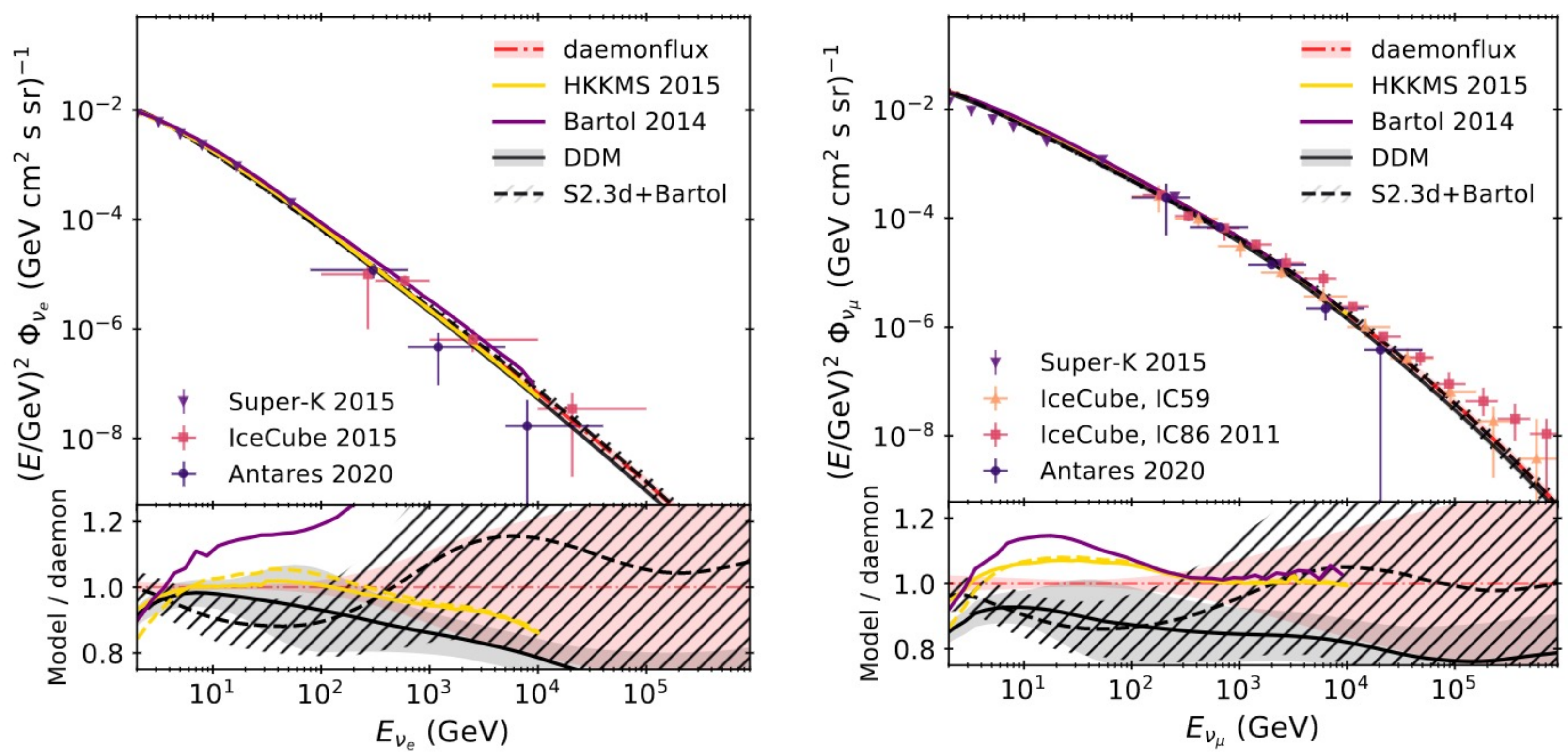
Atmospheric flux uncertainties



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: 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 flux ratios.

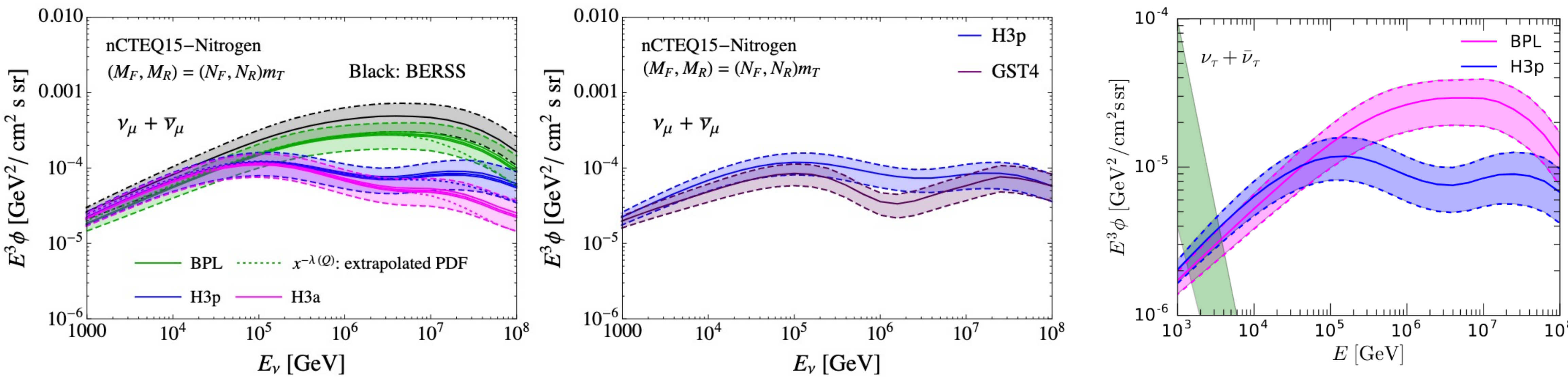
Atmospheric fluxes



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. Very good!
- More uncertainties at higher energies, especially heavy flavor.

High energy atmospheric lepton fluxes



Forward production of charm is dominant contribution. For tau neutrinos: D_s .
Interesting connection to forward production of charm & Forward Physics Facility.

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

High energy atmospheric lepton fluxes

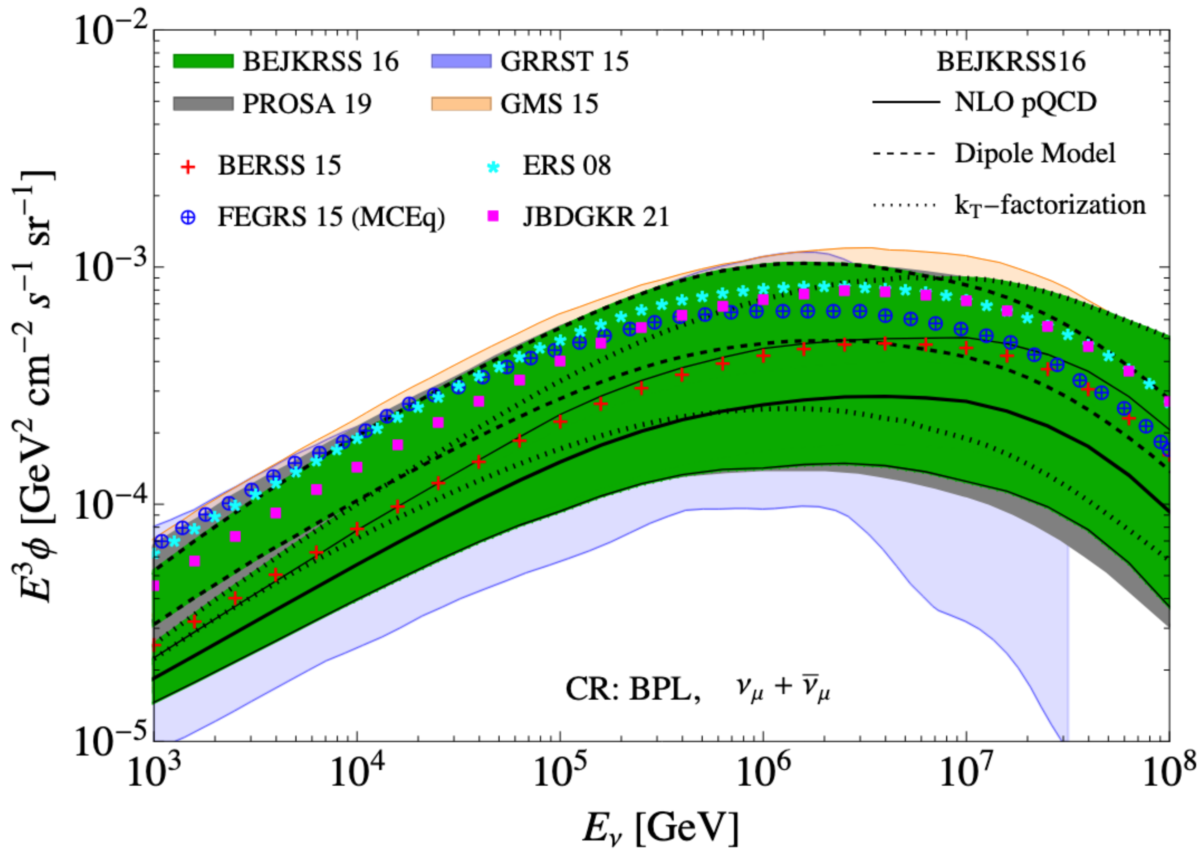


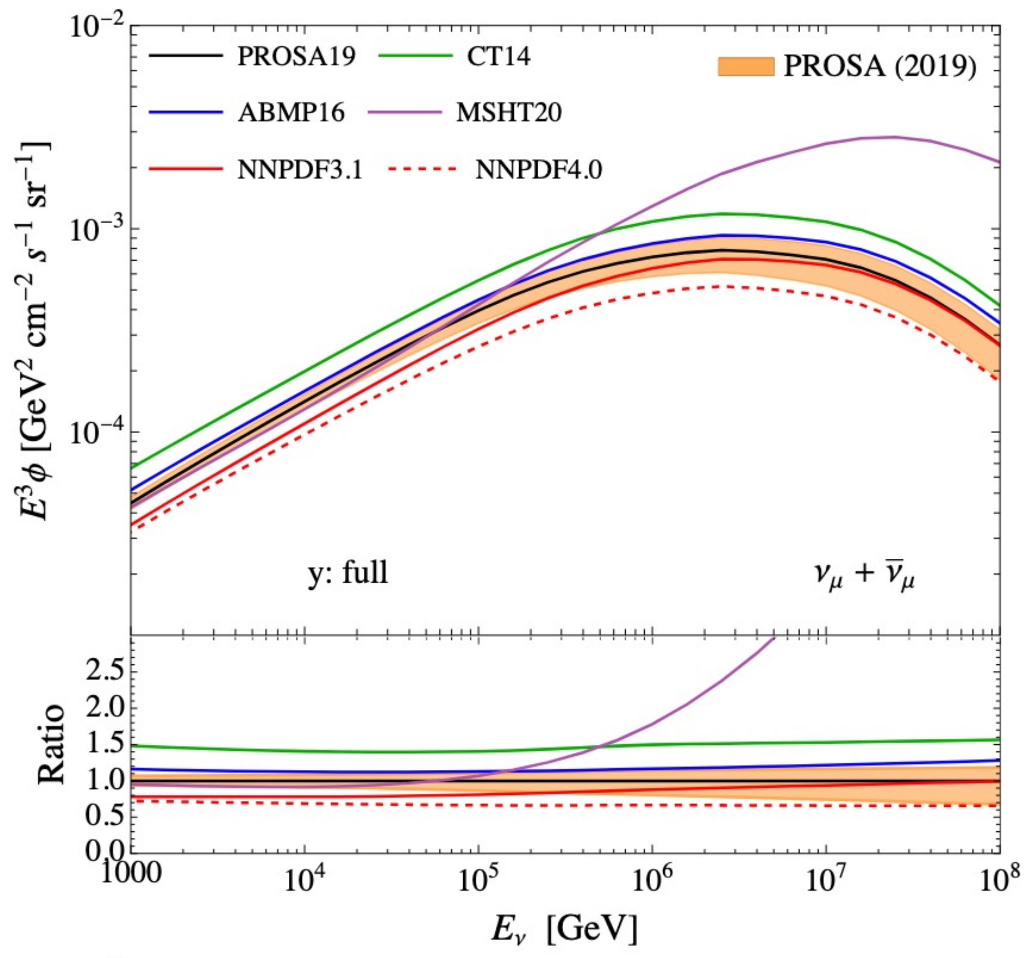
Fig. from Zenaiev et al, JHEP 04, 118 (2020)

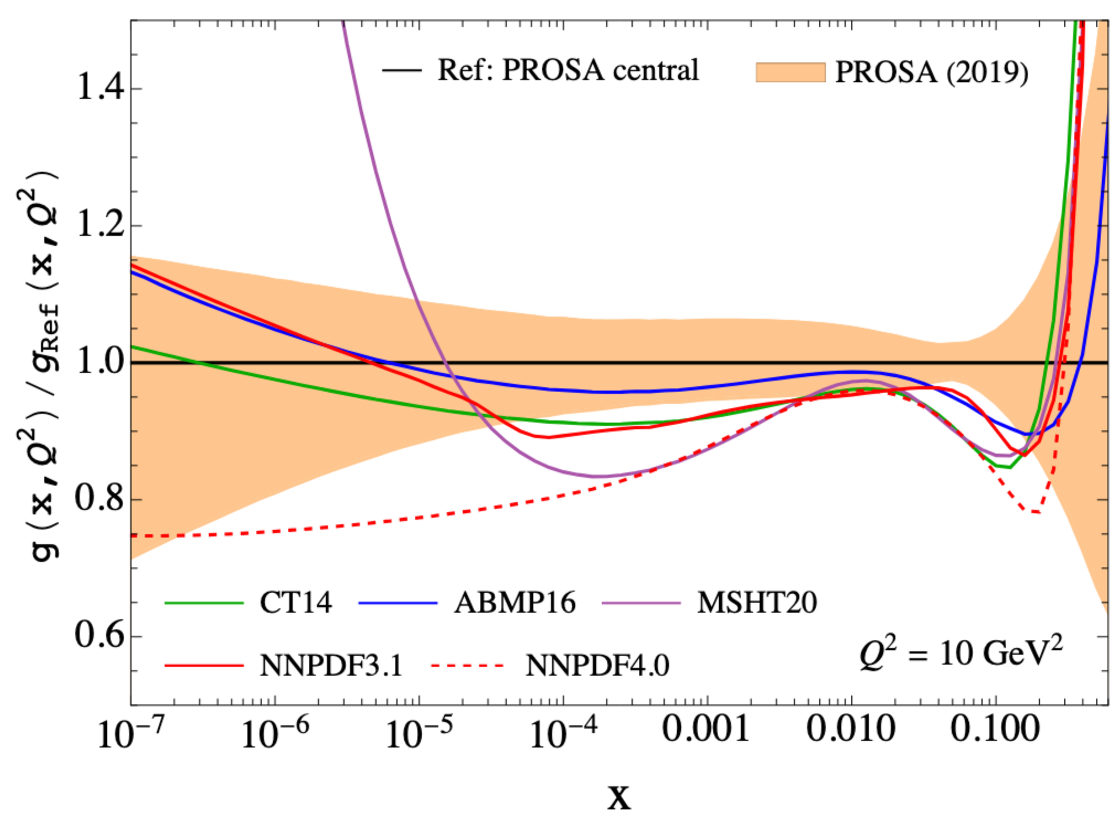
- small-x physics/approaches
- parton distribution functions
- scale variations
- charm mass
- nuclear effects

Comparison with LHCb results to anchor predictions

- transverse momentum effects
- fragmentation

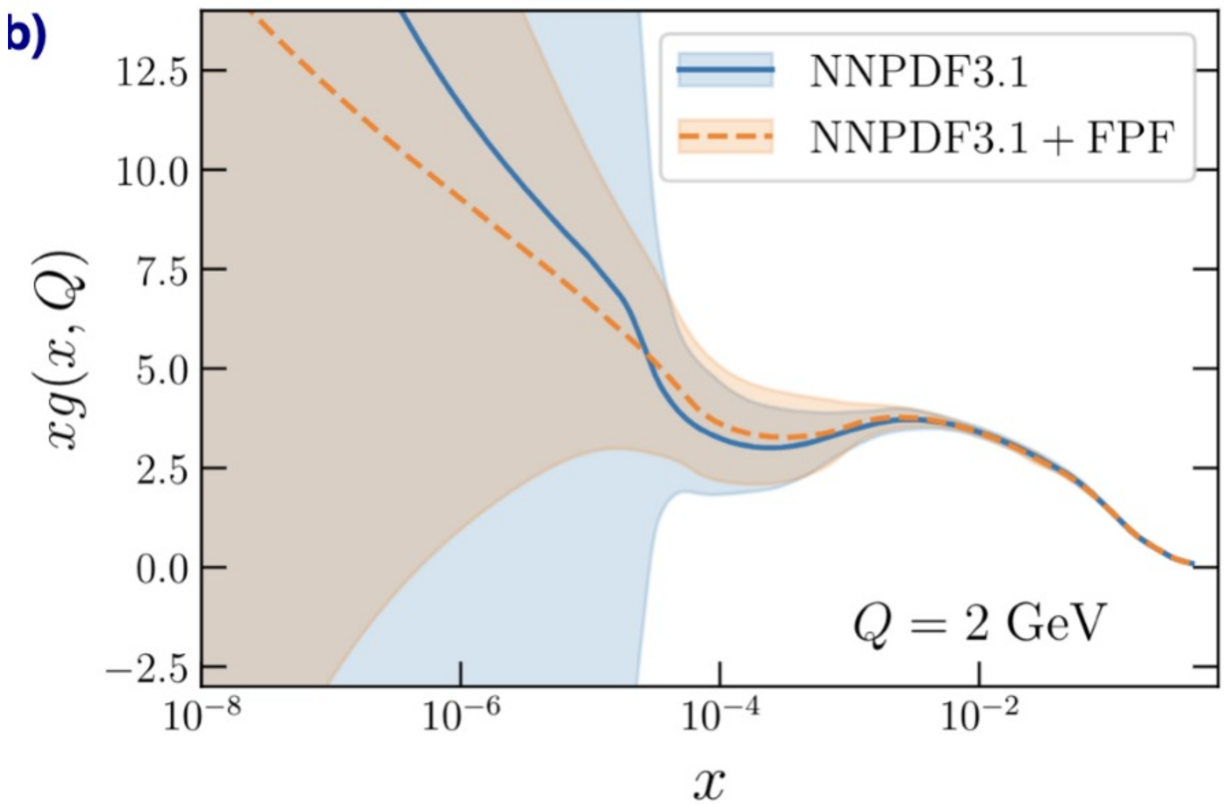
Prompt atmospheric lepton fluxes: parton distribution function (PDF) uncertainties





Bai, Diwan, …MHR…et al, JHEP 10 (2023) 142

FPF projected reduction of PDF uncertainties

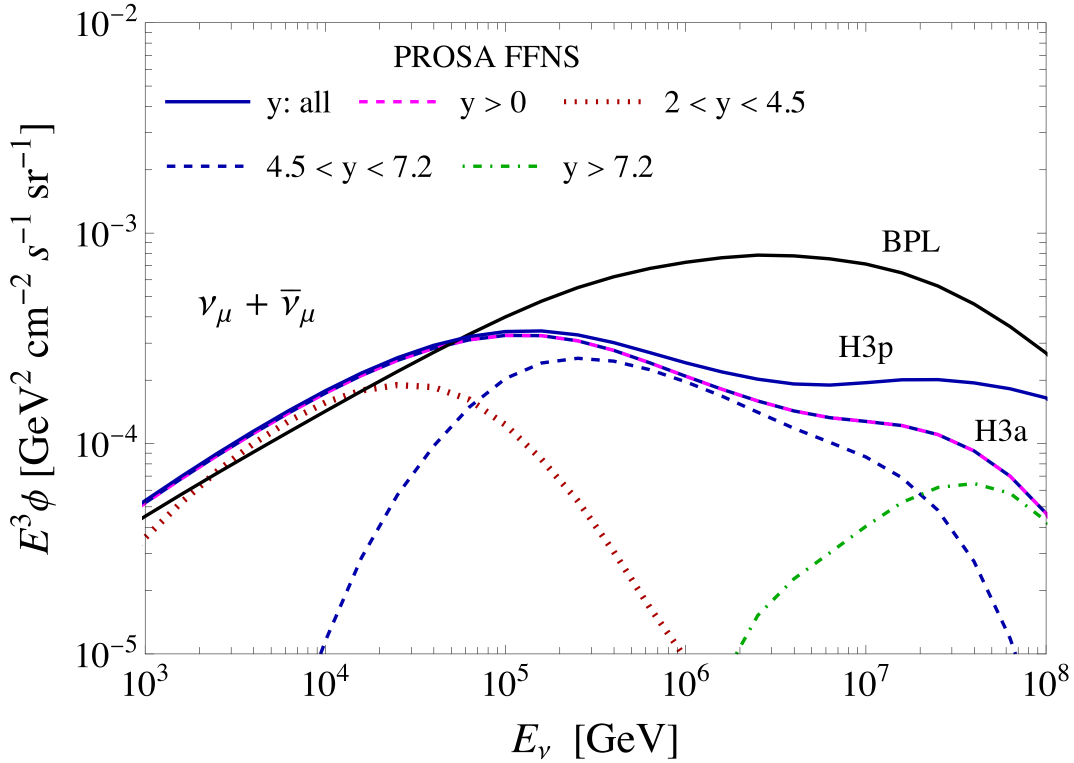


Rojo, https://arxiv.org/pdf/2407.06731

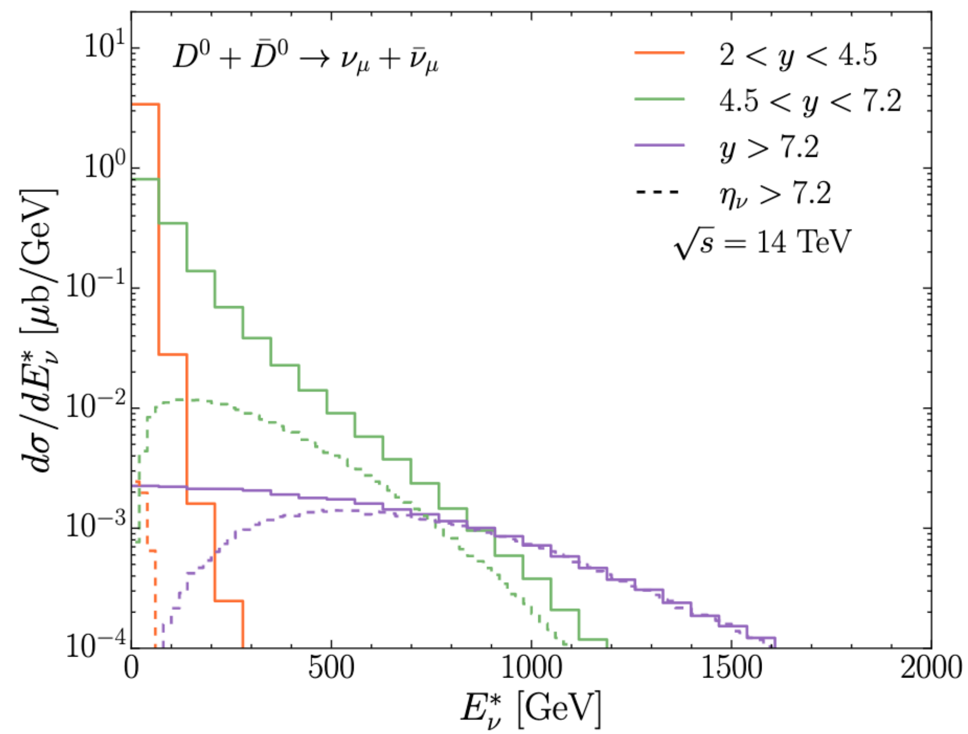
Improved PDF uncertainties will improve prompt atmospheric lepton flux error bands (somewhat).

Forward production of charm at the FPF and in the atmosphere (and their neutrinos)

prompt atmospheric neutrino flux



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

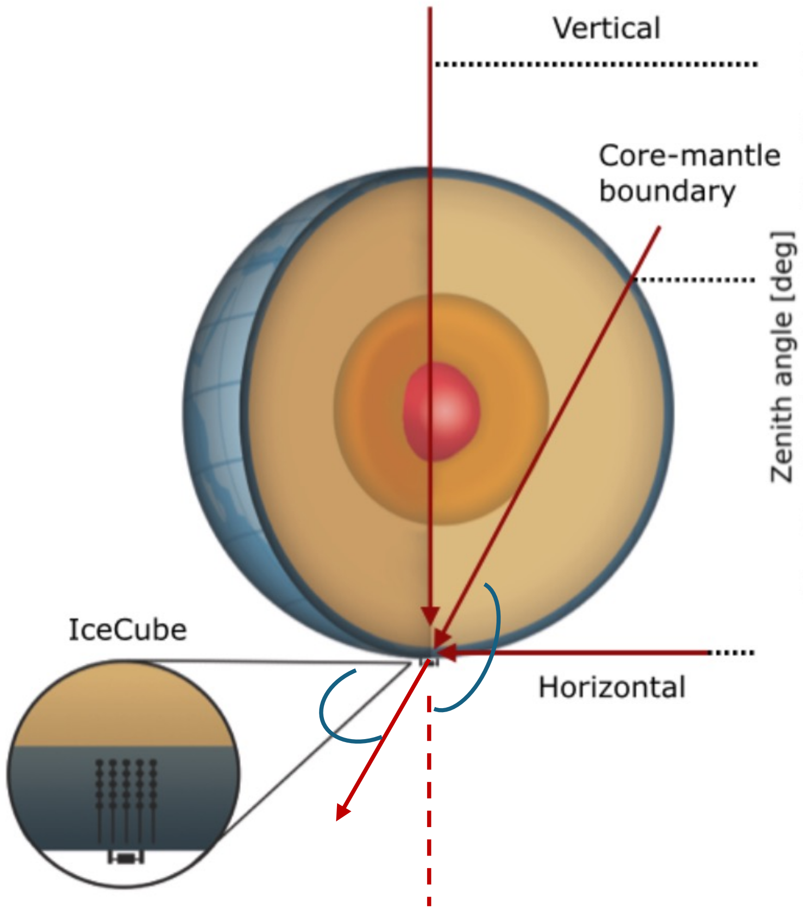


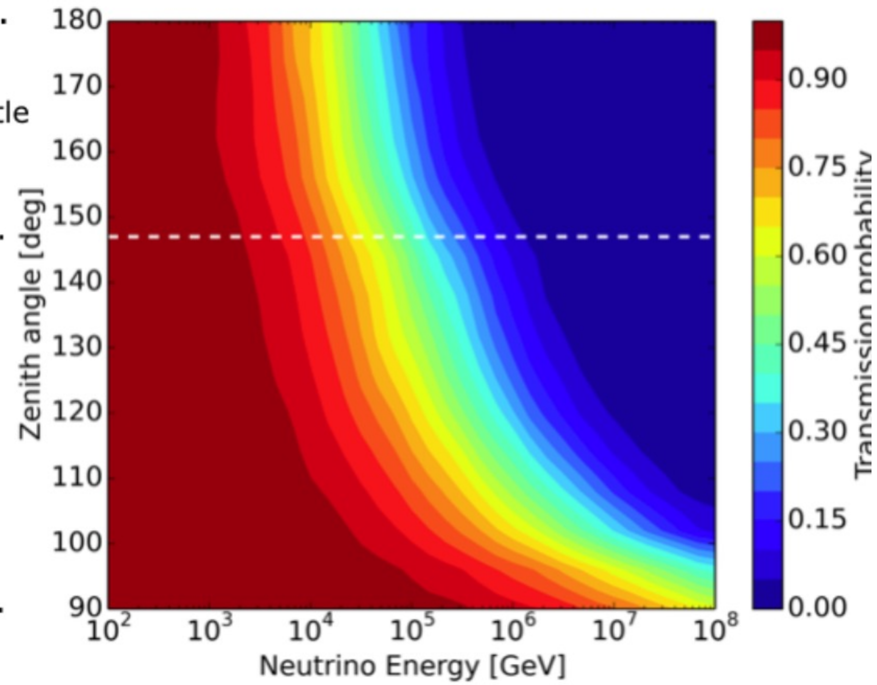
middle contribution in left plot corresponds to green dashed distribution in FPF plot

Bai, Diwan, ...MHR...et al, JHEP 10 (2023) 142

Neutrino cross section measurements

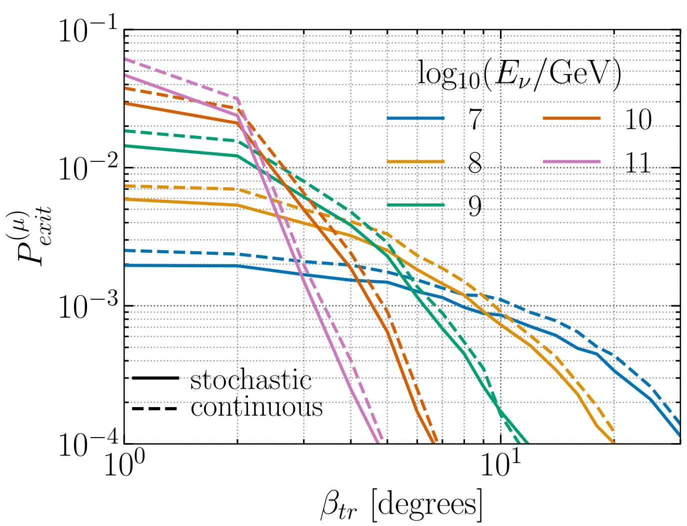
Atmospheric, then astrophysical neutrinos





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

Upward-going neutrino induced muons for this measurement.

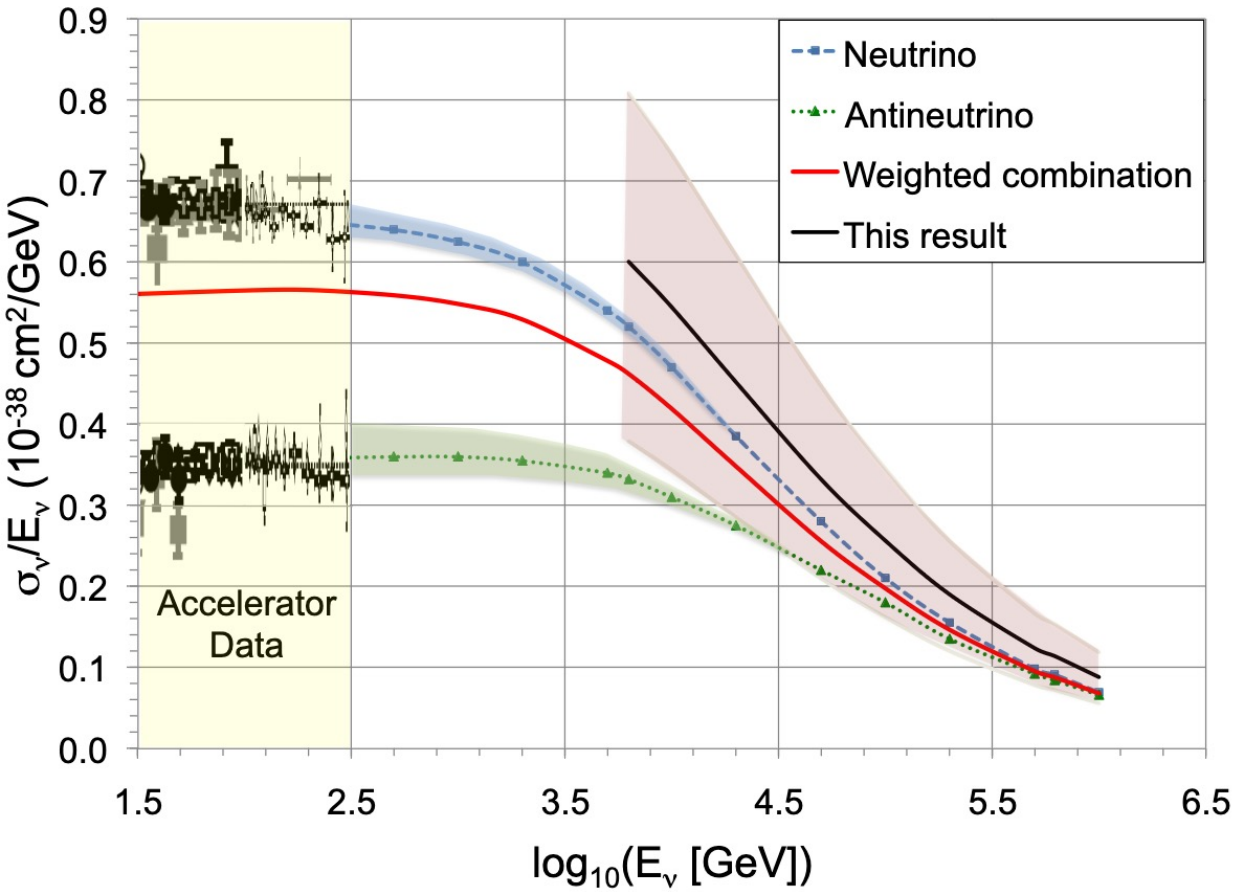


$E_\mu > 10^3$ GeV

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

Attenuation of neutrino flux as function of angle (Earth column depth).

Neutrino cross section measurement



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

- Relies on neutrino flux attenuation in the Earth.
- Will improve statistics.
- Uncertainties include ice model and neutrino fluxes.

Higher energy cross section measurements: Earth as a neutrino converter

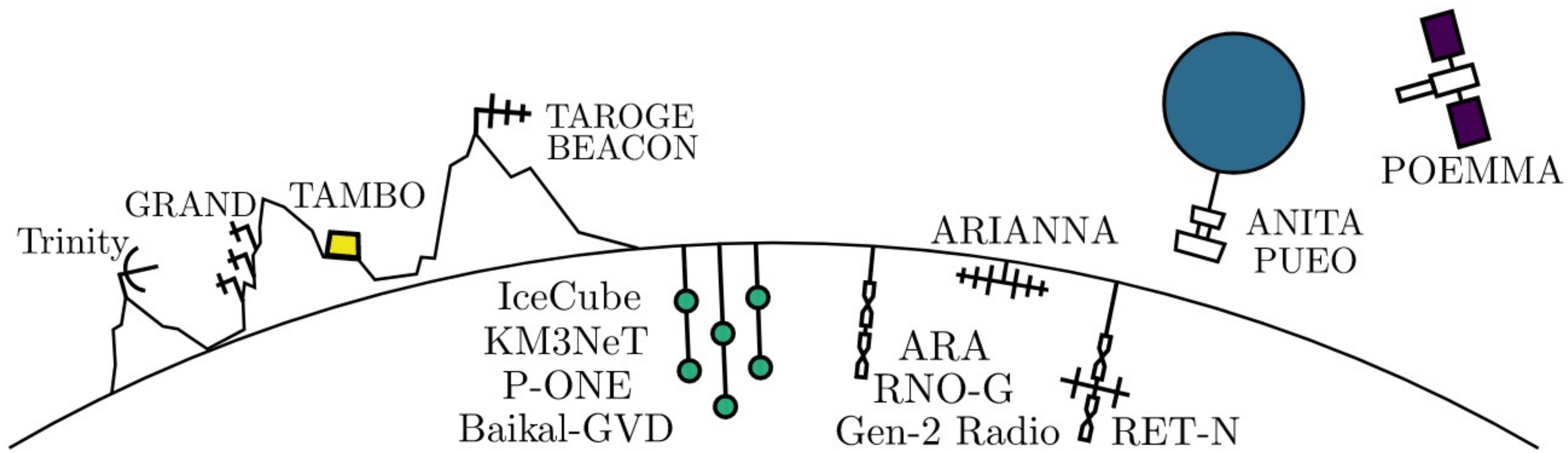
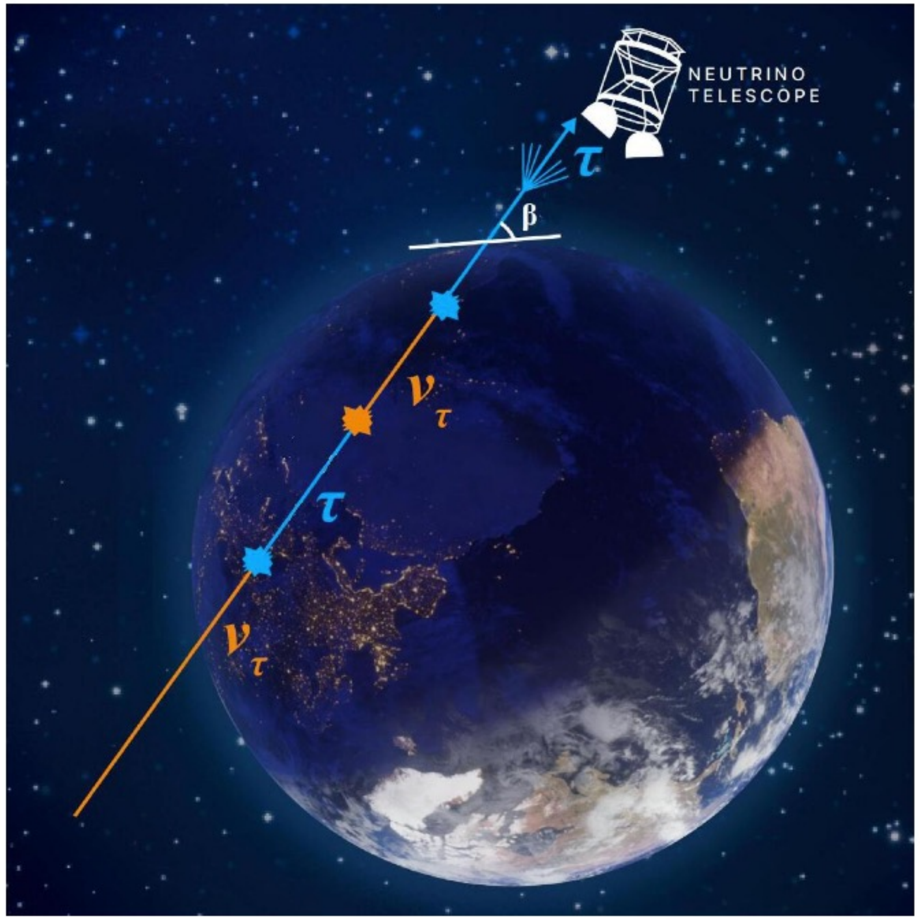


FIG. 2. Proposed strategies to detect UHE neutrinos. *The variety guarantees complementary physics opportunities.*

Fig. from Esteban et al., PRD 106 (2022) 023021
See also Ackerman et al, JHEAp 36 (2022) 55 (Snowmass White Paper)

E.g., up-going air showers from τ decays



Arguelles et al, PRD 106 (2022) 043008

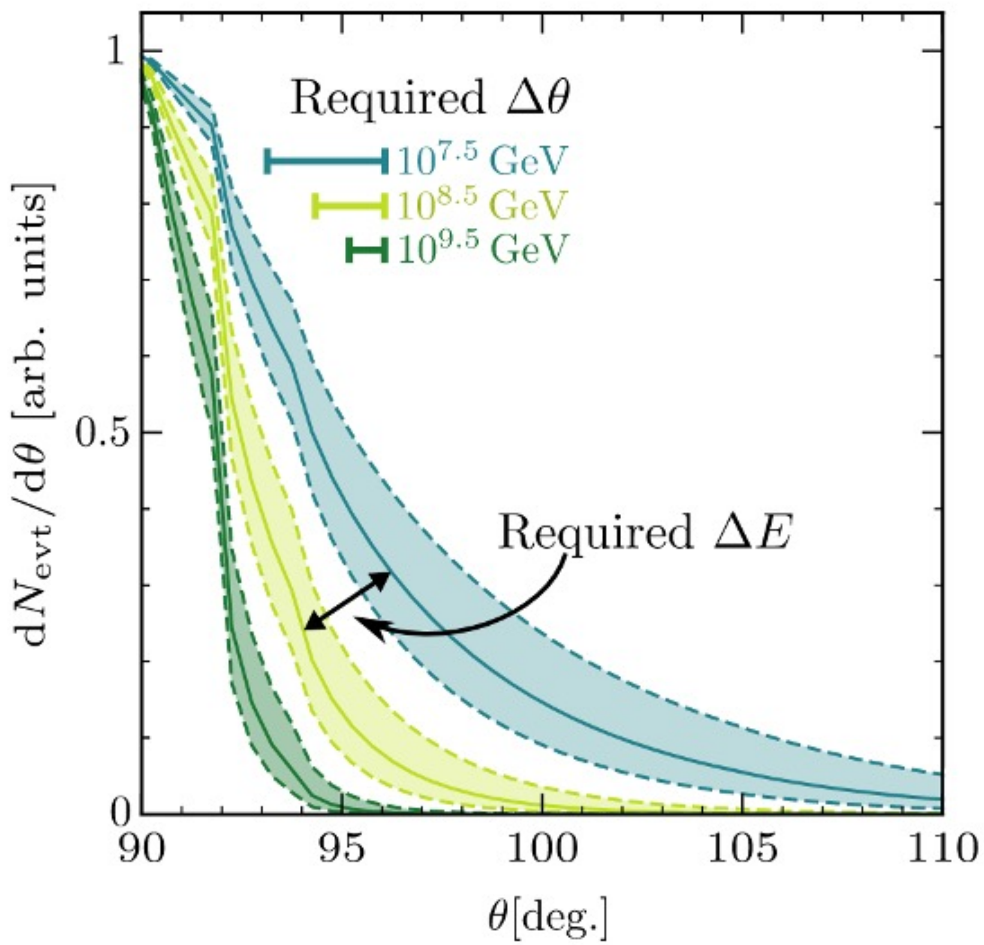
Showers “from neutrinos,” detection by optical Cherenkov signal.
Hadrons from tau decays initiate showers.

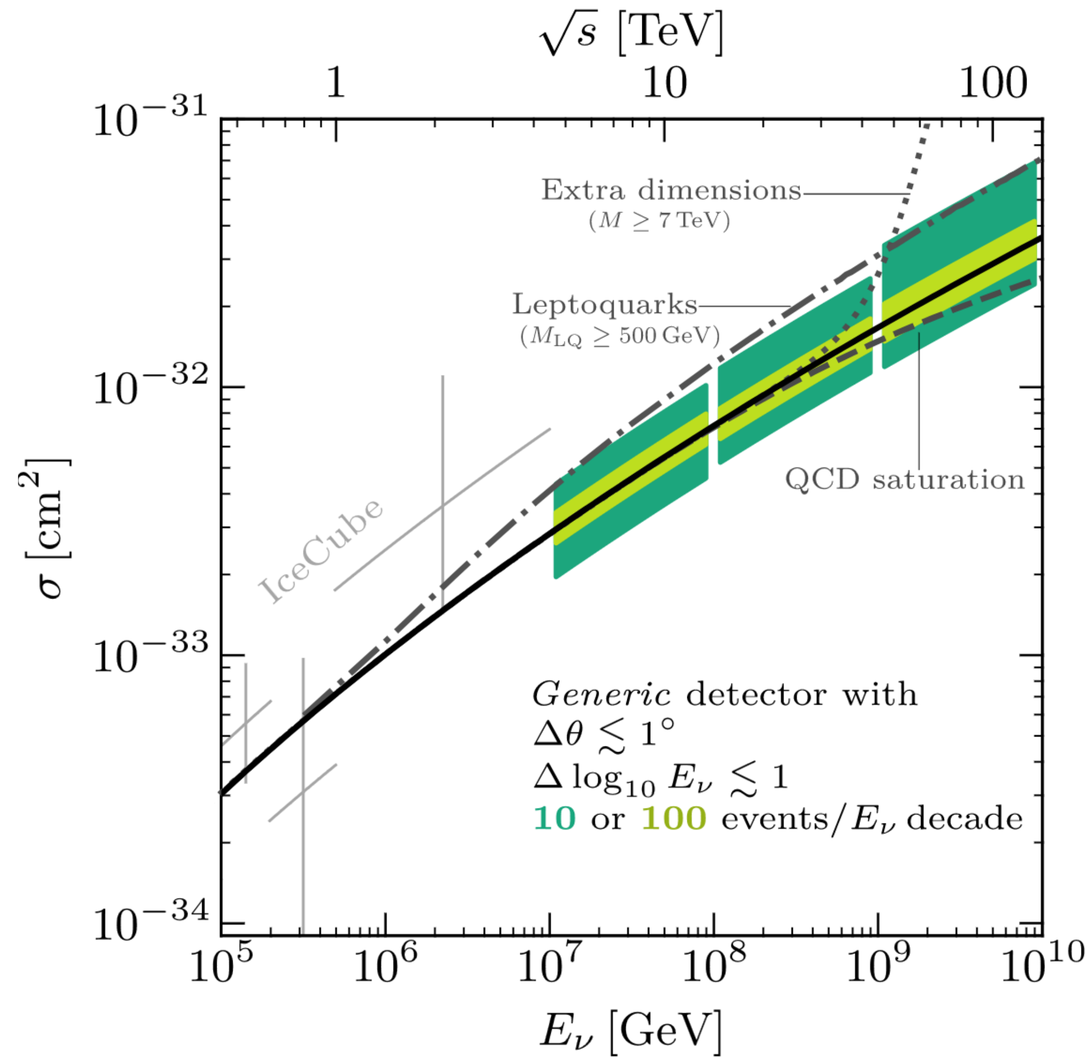
- POEMMA (satellites) would have Cherenkov and fluorescence telescopes.
- PBR (balloon) will develop technical readiness for satellite (plus has radio detection).

POEMMA: see Olinto et al, JCAP 06 (2021) 007

Cross sections

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





Final remarks

- Cosmic ray physics is “old” particle physics, but still highly relevant as detectors push sensitivities to higher energies.
- Neutrinos and cosmic rays are related: astrophysical neutrinos and cosmic rays come from the same accelerators. (For another talk.)
- Direct connection between cosmic rays and atmospheric lepton fluxes.
- Interpretation of cosmic ray EAS events require understanding of high energy hadronic interactions in regions of phase space complementary to focus of many HEP experiments.
- Future measurements of forward neutrinos (from forward pions, kaons, heavy flavor) from Forward Physics Facility experiments (like FLArE) would inform air shower modeling – help in understanding highest energy events.