Astrophysical neutrinos: from pions to diffuse neutrino fluxes

Hallsie Reno (University of Iowa)

International Neutrino Summer School

UCSB

July 8-9, 2026

Work supported in part by the US DOE.

Who am I?

I’m a neutrino phenomenologist interested in neutrino astroparticle physics, neutrino interactions and BSM physics with neutrino (and neutrino-like) signals, including UHE cross section, prompt neutrinos, and tau leptons.

Professor at the University of Iowa, advisor of Laksha Pradip Das who is here!

Also a member of the EUSO-SPB2 and POEMMA Balloon-with-Radio (PBR) balloon mission collaborations and the nuSpaceSim Collaboration (simulation software).

exa zetta

TeV=10^{12}, PeV = 10^{15}, EeV = 10^{18}, ZeV = 10^{21}

38 orders of magnitude

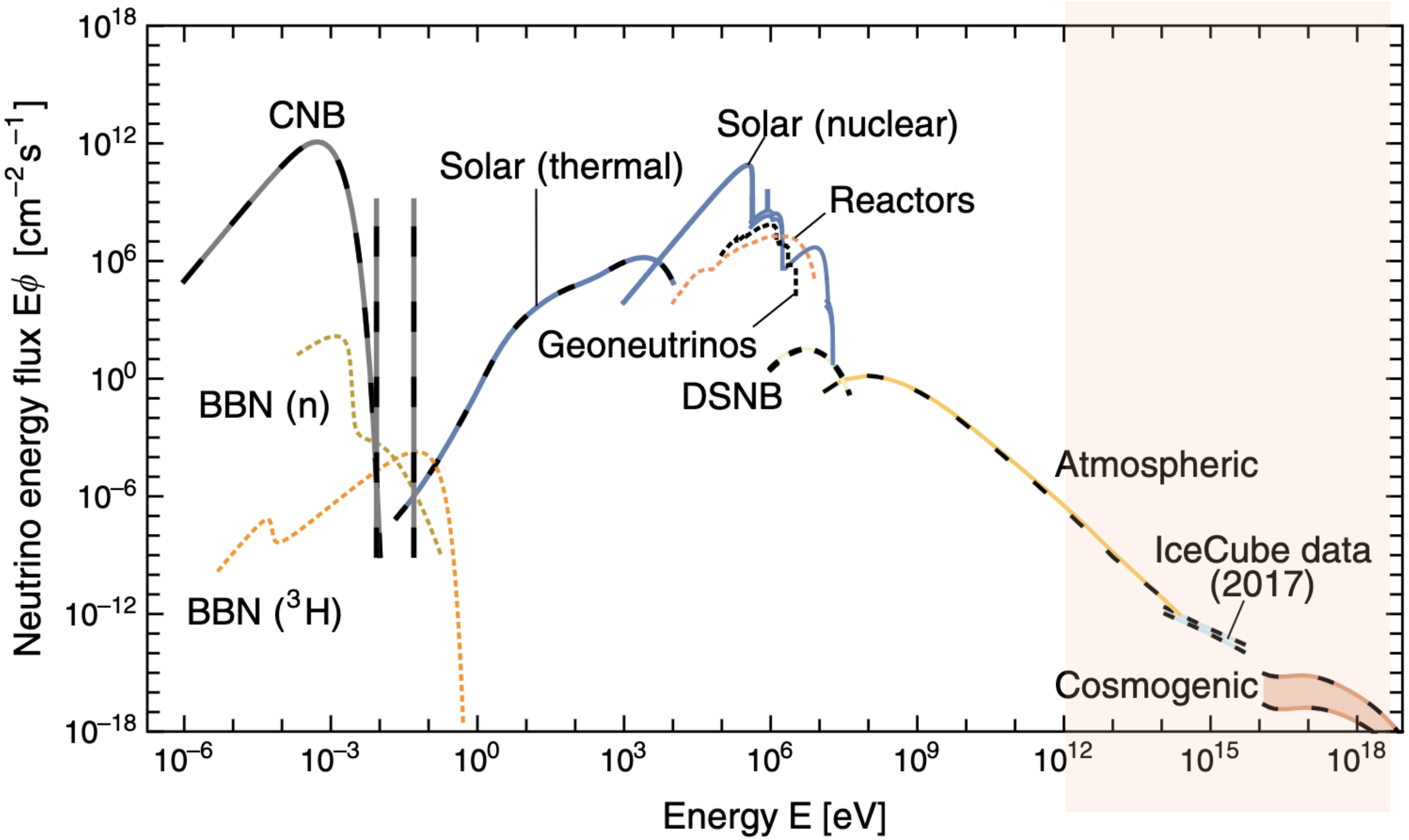
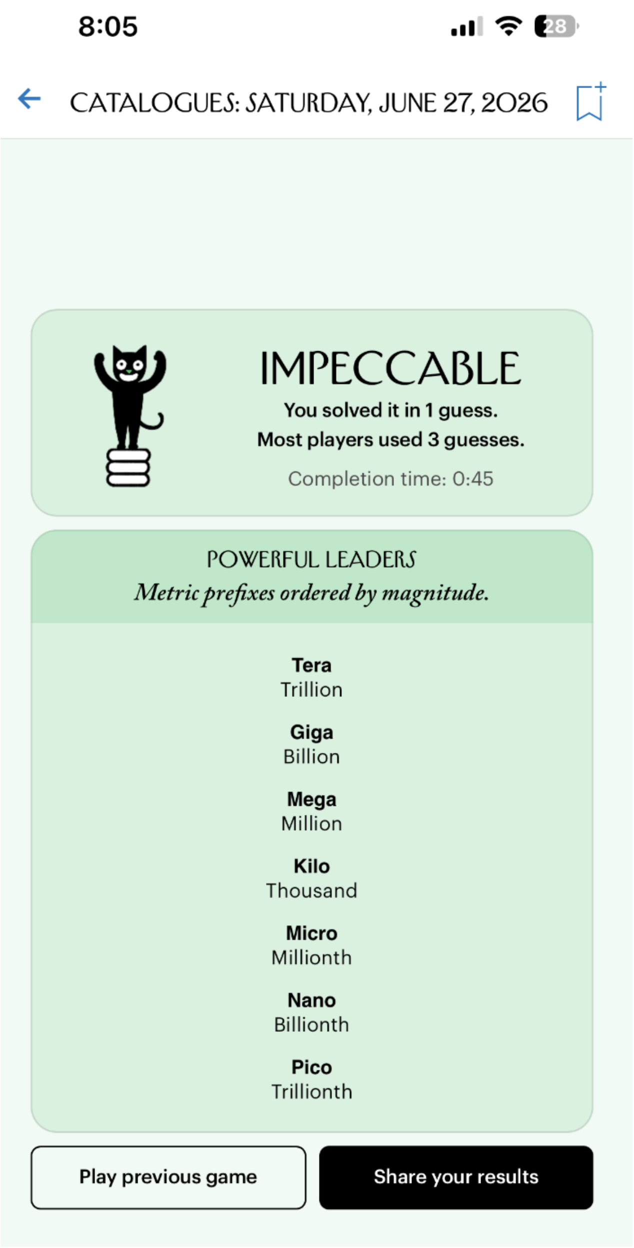


Fig. from Vitagliano et al, Rev Mod Phys 92 (2020) 045006



Plan for lectures

See also Laura Fields's lecture 1, Lu Lu's lectures

- **(Mostly diffuse) neutrino fluxes**
  - **Atmospheric neutrinos** – what we can learn from atmospheric neutrinos to carry over to astrophysical neutrino sources (compare & contrast)
  - **Astrophysical neutrinos**: diffuse neutrino flux and transient sources
  - **Cosmogenic neutrinos**: diffuse neutrino flux from cosmic rays in transit through Universe

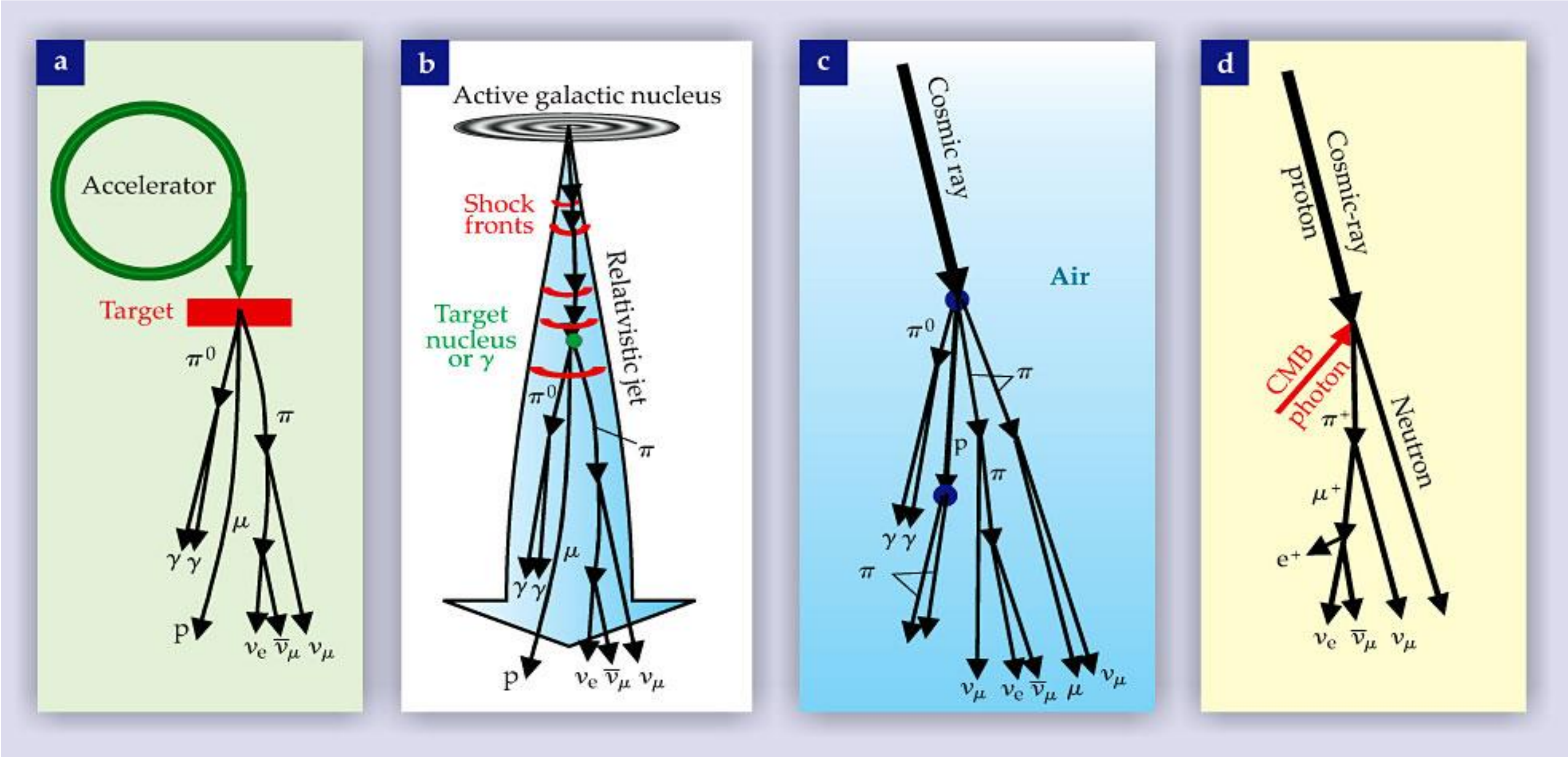
---

- **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

Neutrino production from pions (and other hadrons)

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

CMB=cosmic microwave bkgd



accelerator beams

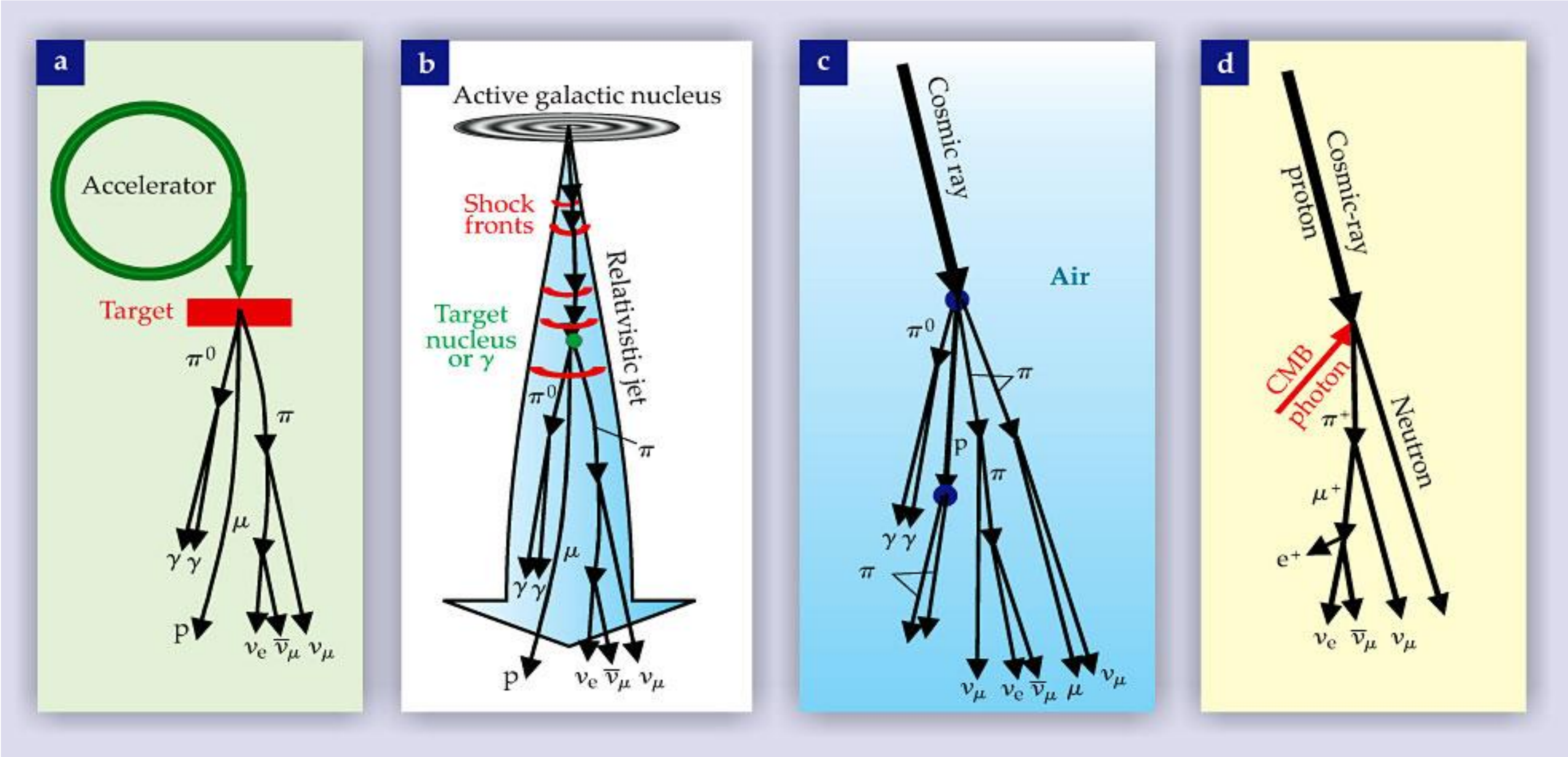
cosmic accelerators

cosmic rays (air targets)

cosmic rays (CMB targets)

Neutrino production

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



Laura Fields

← Lu Lu – detection →

Atmospheric neutrinos

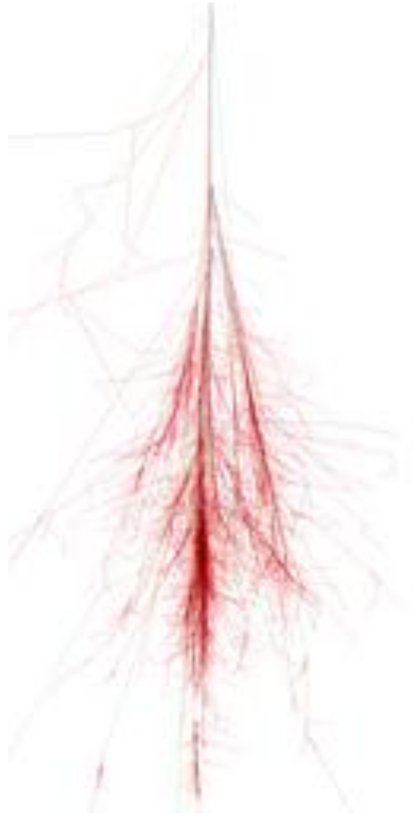
A familiar case to start.

A few of many references

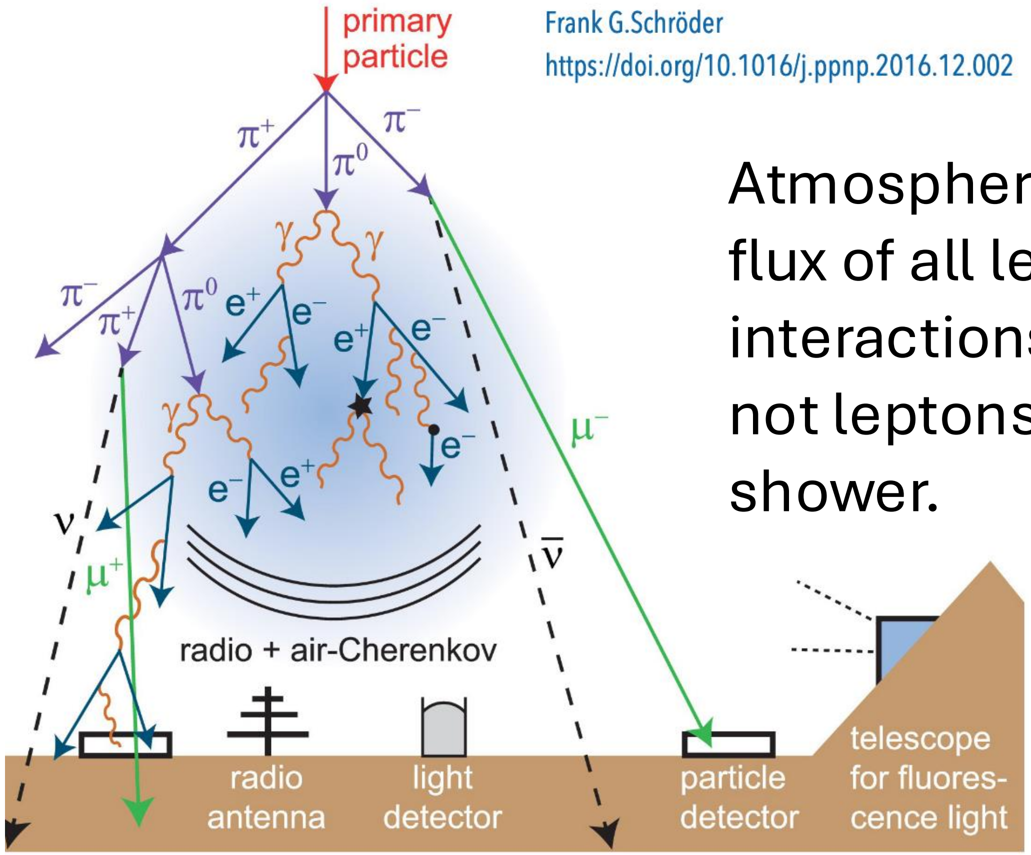
- ✓ Lipari, Lepton spectra in the earth's atmosphere, Astropart.Phys. 1 (1993) 195
- ✓ Thunman et al., Charm production and high energy atmospheric muon and neutrino fluxes , Astropart. Phys. 5 (1996) 309
- ✓ Gaisser, Engel & Resconi, Cosmic Rays and Particle Physics : 2nd Edition
- Conventional flux, for example:
  - Gaisser & Honda, Flux of atmospheric neutrinos, Ann.Rev.Nucl.Part.Sci. 52 (2002) 153
  - Fedynitch+, Hadronic interaction model sibyll 2.3c and inclusive lepton fluxes, PRD 100 (2019) 103018
- Prompt flux, for example:
  - *Bhattacharya*+, Prompt atmospheric neutrino fluxes: perturbative QCD models and nuclear effects, JHEP 11 (2016) 167
  - Gauld+, The prompt atmospheric neutrino flux in the light of LHCb, JHEP 02 (2016) 130
  - Zenaiev+, 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

Atmospheric lepton fluxes

Cosmic rays interact with the atmosphere make to make muons and neutrinos, etc.



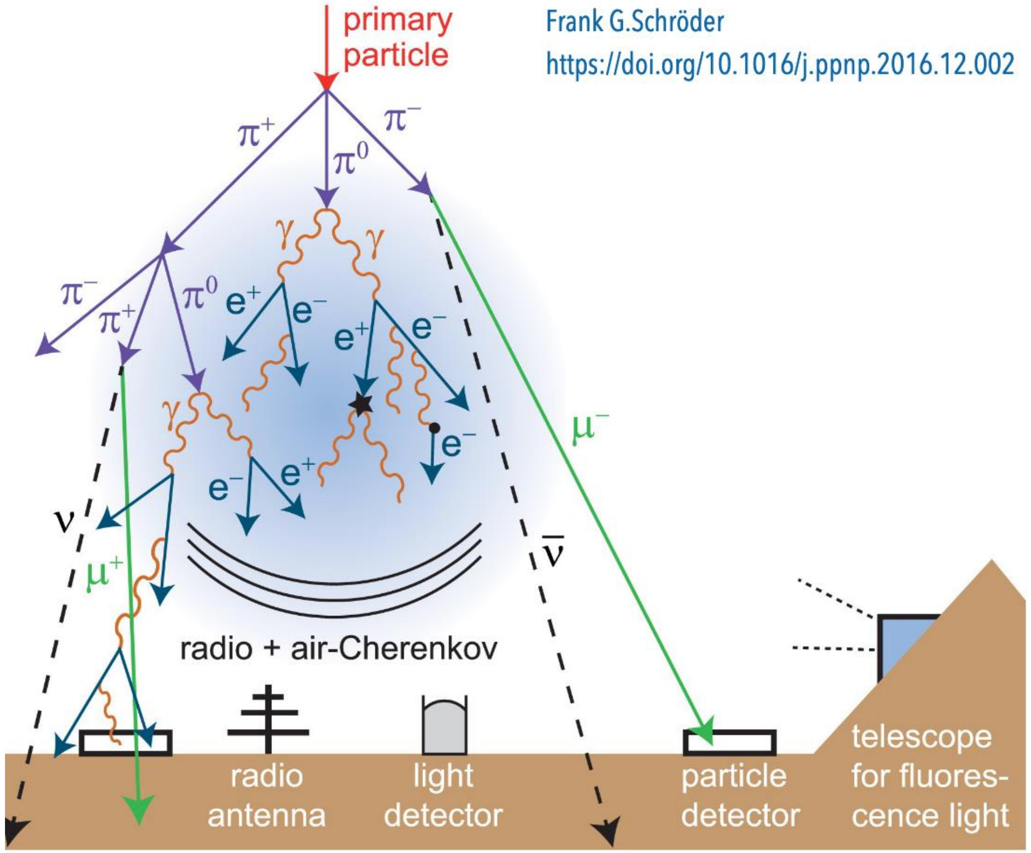
One incident cosmic ray produces an air shower.



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

Atmospheric lepton flux: consider flux of all leptons from cosmic ray interactions in the atmosphere, not leptons from one individual air shower.

Atmospheric lepton fluxes



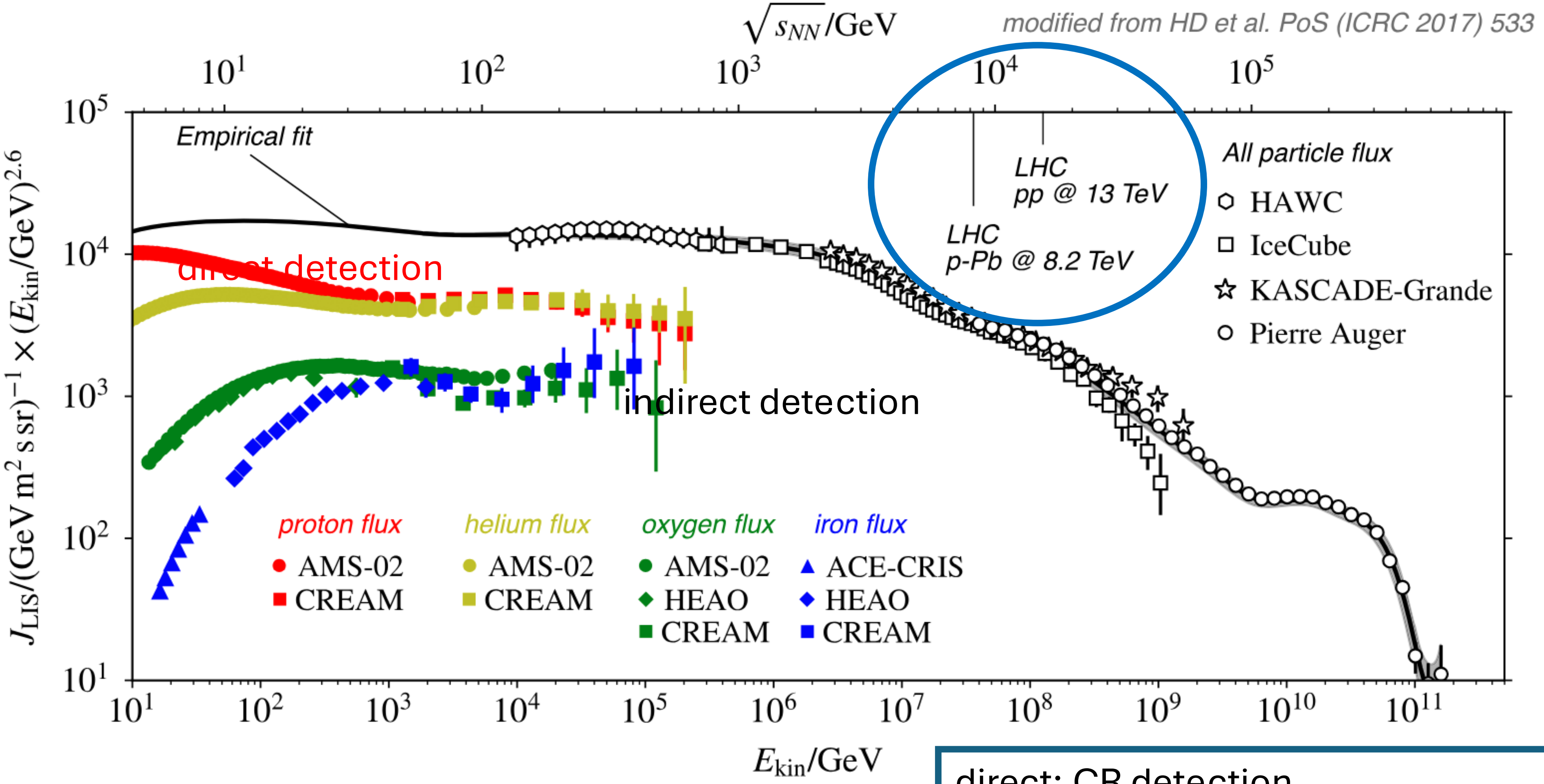
Atmospheric lepton flux evaluation relies on:

- **incident beam**: cosmic ray flux (spectrum and composition)
- **targets**: model of the atmosphere, here air nuclei (hadrons)
- **beam-target interaction cross sections**: related to σ_{pp}
- **differential energy distribution:** outgoing hadron energies, especially mesons
- **reinteractions**: hadronic interactions, muon electromagnetic energy loss
- **decays**: to leptons, here μ, ν_i
- **propagation**: (trivial at high energy, no mixing)

Cosmic ray flux ($E^{2.6}$ scaling)

- **incident beam:** cosmic ray flux (spectrum and composition)

Scaling by approximate CR energy spectrum



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

direct: CR detection
indirect: detection of showers they make

Cosmic ray composition

- **incident beam:** cosmic ray flux (spectrum and composition)

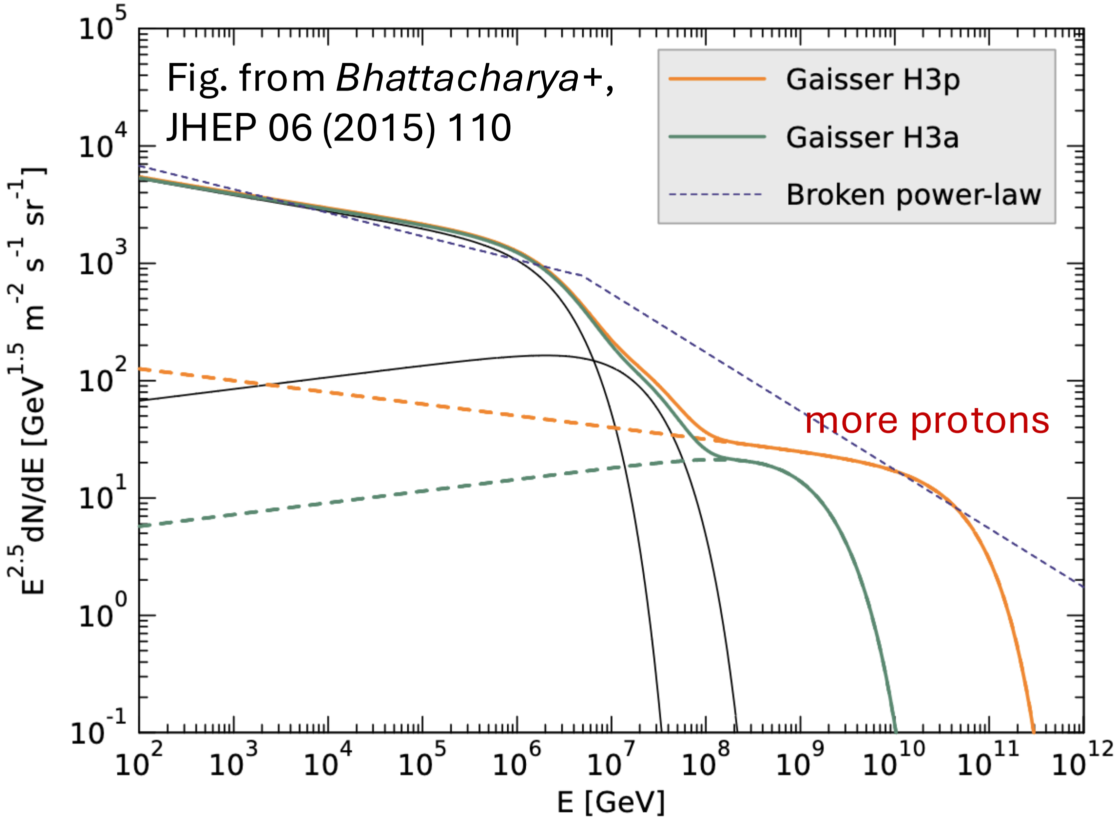
Cosmic ray particle flux (previous slide)

$$\phi_A = \frac{\#}{\mathrm{GeV\,cm^2 s\,sr}} = \frac{dN}{dE_A\, da\, dt\, d\Omega}$$

Cosmic ray nucleon flux

$$\phi_N = A\phi_A(E_A = AE_N)\frac{dE_A}{dE_N}$$
$$= A^2\phi_A(E_A = AE_N)$$

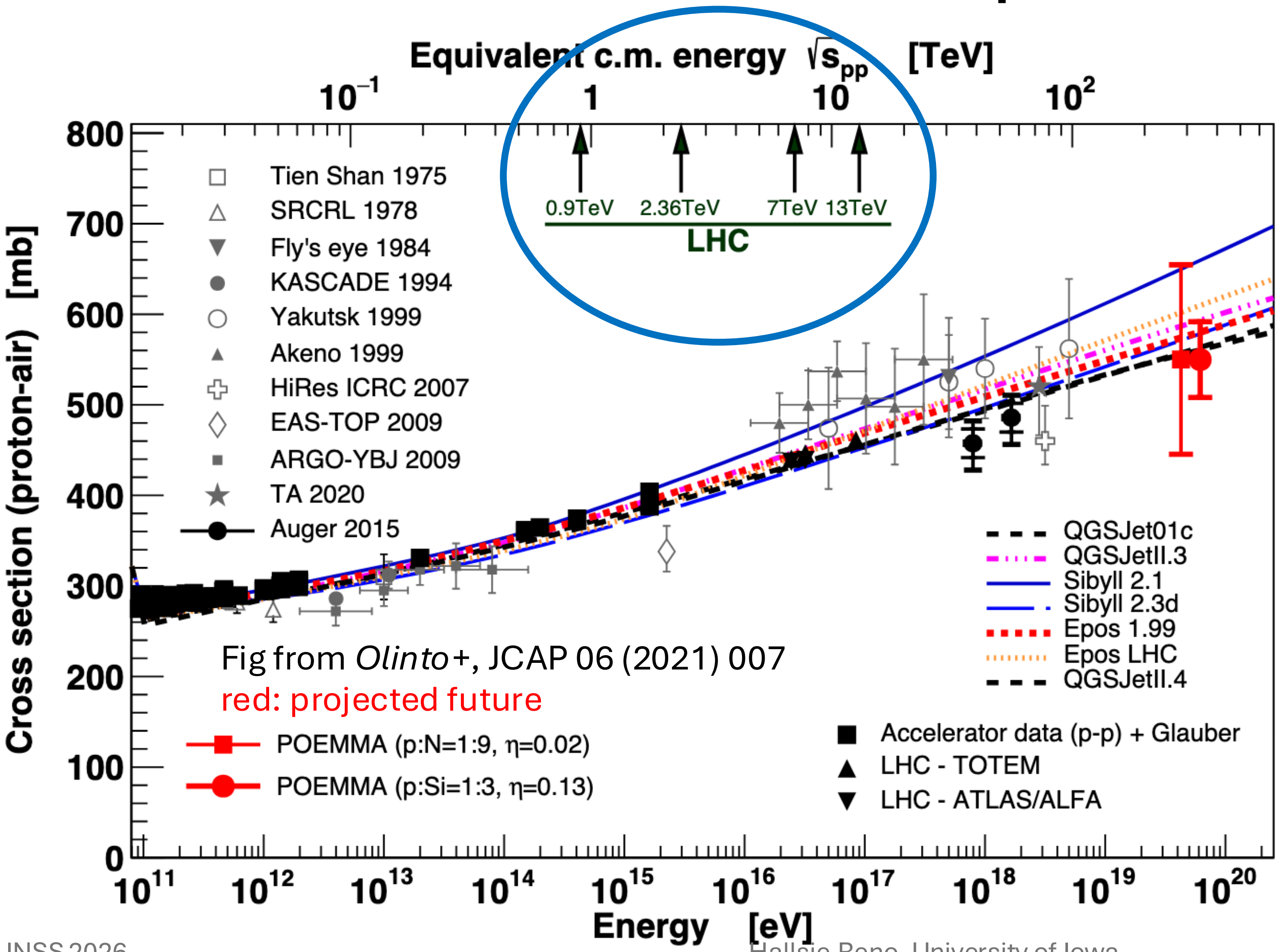
(superposition approximation)



- Broken power law, for apples-to-apples comparisons.
- Clear high energy dependence on composition (more later, not settled).

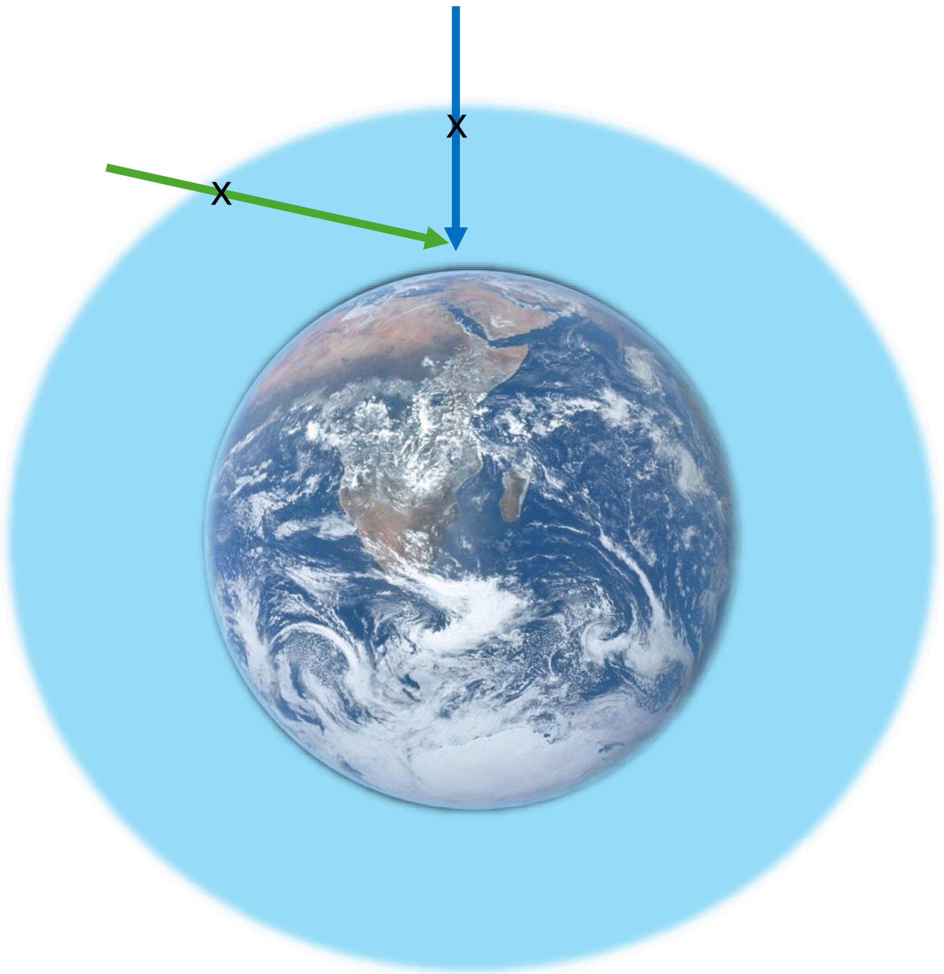
Interaction cross sections: proton-air

- **beam-target interaction cross sections**: related to σ_{pp}



- The proton-air cross section is weakly dependent on energy.
  - log scale in energy
  - linear scale for σ
- At high energies, σ must be extrapolated.

Cascade equations



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

- **differential energy distribution:** outgoing hadron energies, especially mesons
- **reinteractions**: hadronic interactions, muon electromagnetic energy loss
- **decays**: to leptons, here μ, ν_i

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

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

Coupled cascade equations:

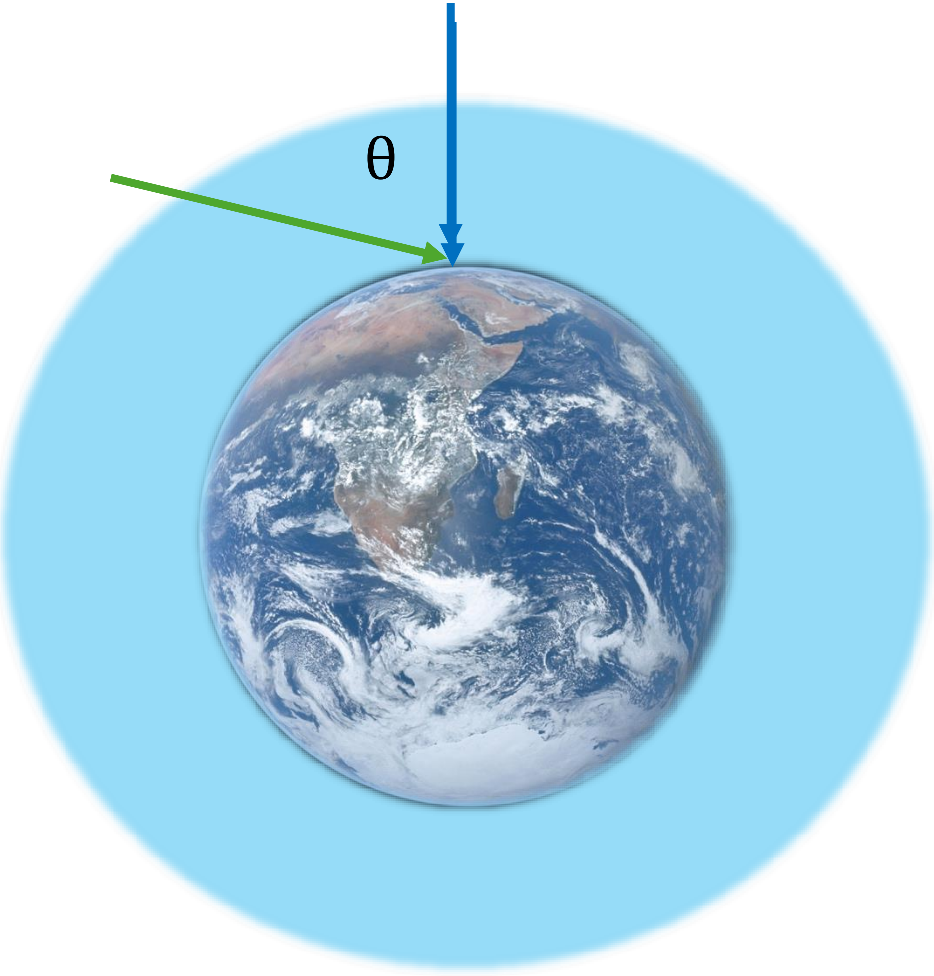
$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_j} - \frac{\phi_j}{\lambda_j^{\rm dec}} + \sum S(k \to j)$$

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)

Column depth X



$$X = \int_0 dl' \, \rho(h(l')) \qquad [\mathrm{g/cm^2}]$$

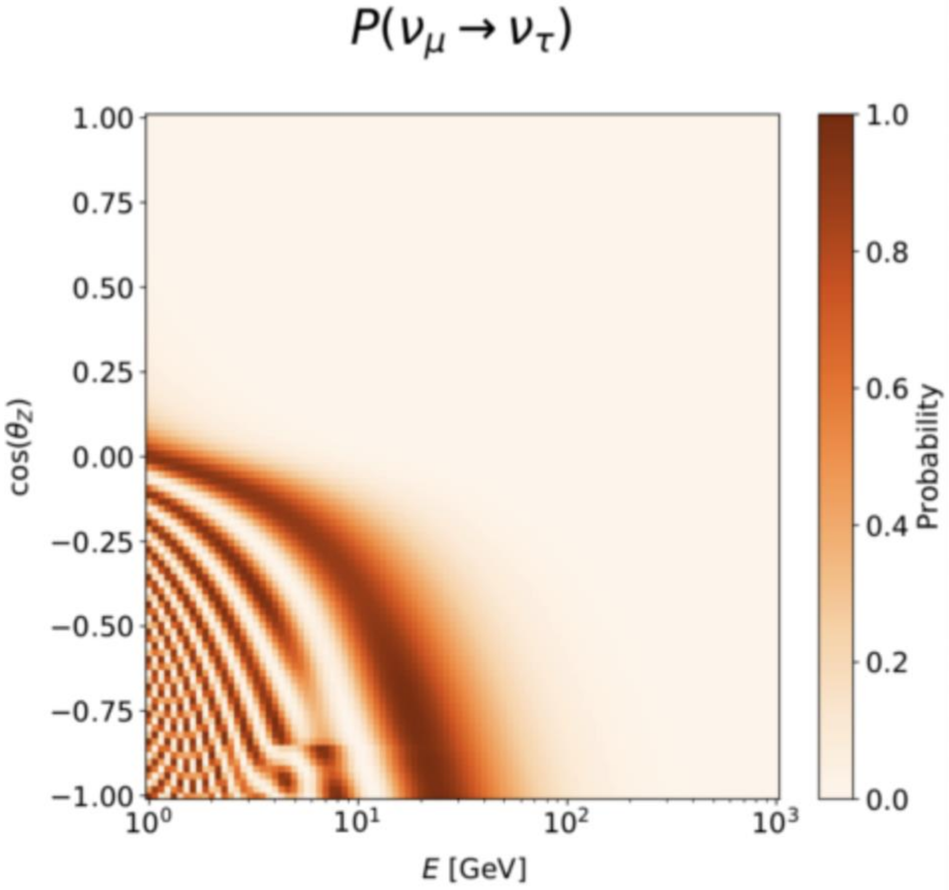
Two simple cases:

constant density, $X = \rho_0 L$
exponential density, $\rho = \rho_0 \exp[-(h/h_0)]$,
vertical: $X = \rho_0 h_0$
at angle: $X = \rho_0 h_0 / cos\theta$ (approx.)

Convention:

1 $\mathrm{g/cm^2}$ = 1 cm.w.e. (cm water equivalent)
10^5 $\mathrm{g/cm^2}$ = 1 km.w.e.

Neutrino propagation



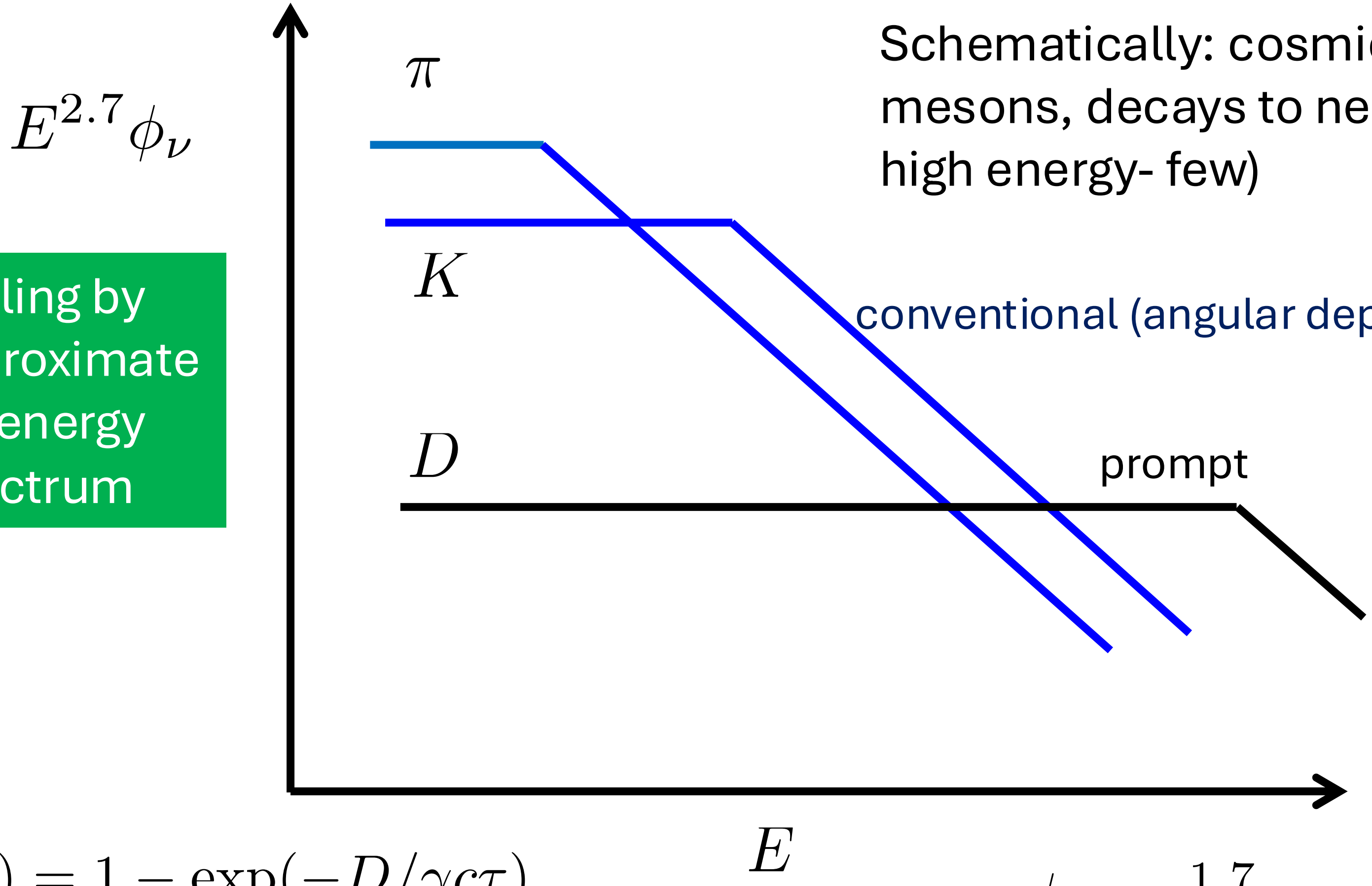
https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/neutrino-oscillation/

Example for propagation in the atmosphere:

$$\frac{\Delta m^2/\mathrm{eV}^2 \cdot L/\mathrm{km}}{E/\mathrm{GeV}} \lesssim \frac{10^{-3} \cdot (15 - 60)}{10^3}$$

We will consider energies above 1 TeV.

Atmospheric neutrino fluxes (schematically)



Scaling by approximate CR energy spectrum

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

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

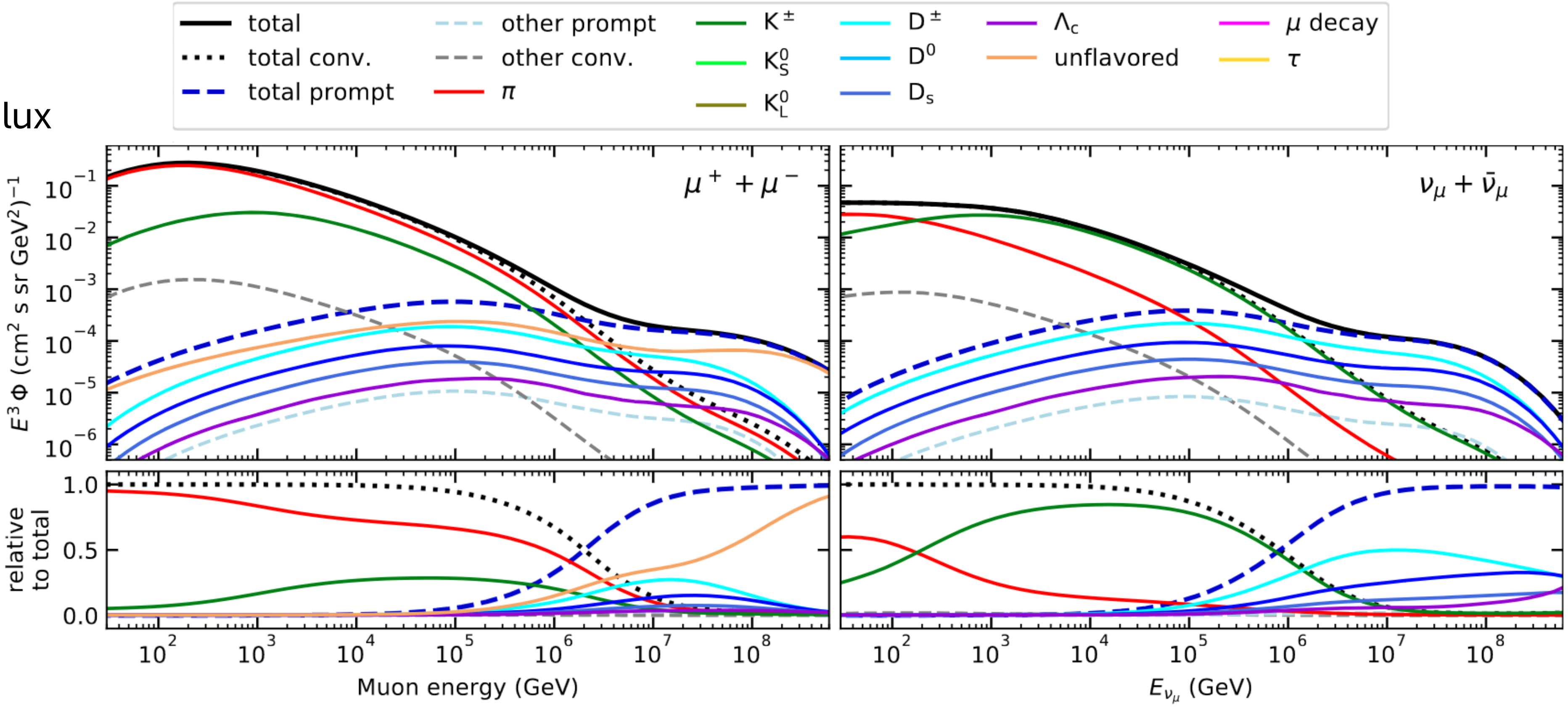
$$\phi \sim \frac{1.7}{E_{\rm GeV}^{2.7}} \frac{1}{\rm cm^2\,s\,sr\,GeV}$$

Energy scaled atmospheric flux (E^3)

Lots of hadronic physics modeling/parameterization/ Monte Carlo goes into these predictions. This figure uses Sibyll2.3.

Example: - MCEq https://github.com/mceq-project/MCEq.git

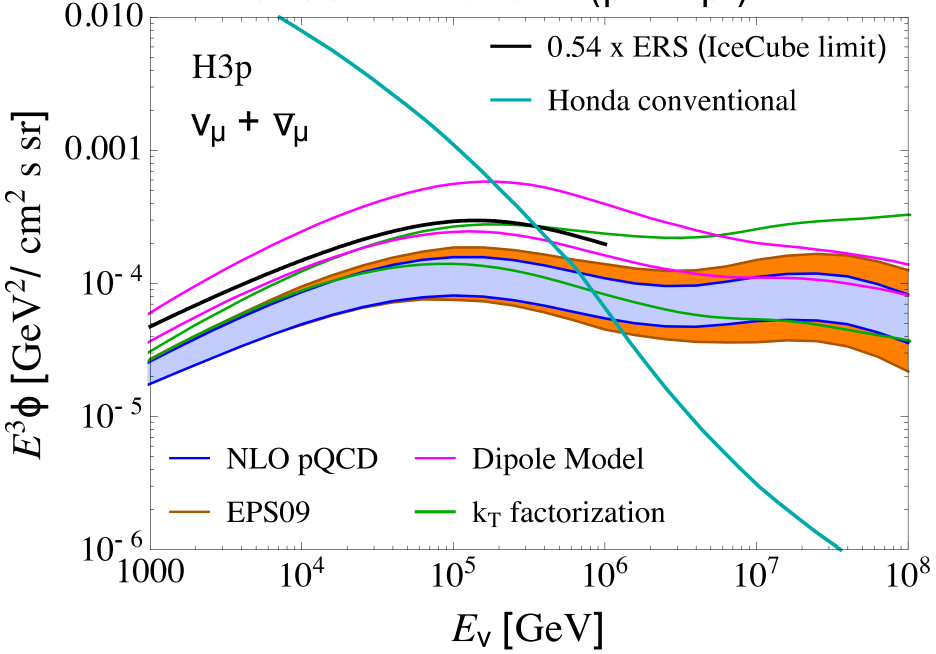
- atm muon flux similar, but more pion dominated



Fedynitch+, PRD 100 (2019) 103018

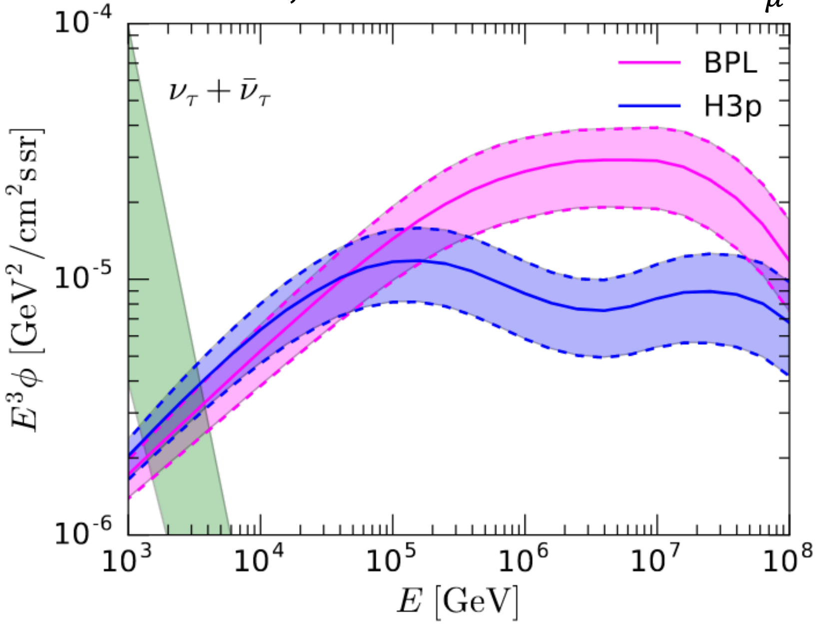
Tau neutrino flux

Bands: from charm (prompt)



Note different scales for different flavors!

Green, oscillated conventional ν_μ



For tau neutrinos: $D_s \to \tau\nu_\tau$ (also for accelerator beams)

Interesting connection to forward production of charm & forward physics, future (?) Forward Physics Facility at CERN.

Example, *Bhattacharya*+, JHEP 11 (2016) 167. FPF connection: *Bai*+, JHEP 10 (2023) 142
FPF neutrinos in *Feng*+, J.Phys.G 50 (2023) 030501

Aside – neutrinos @ LHC Run 3

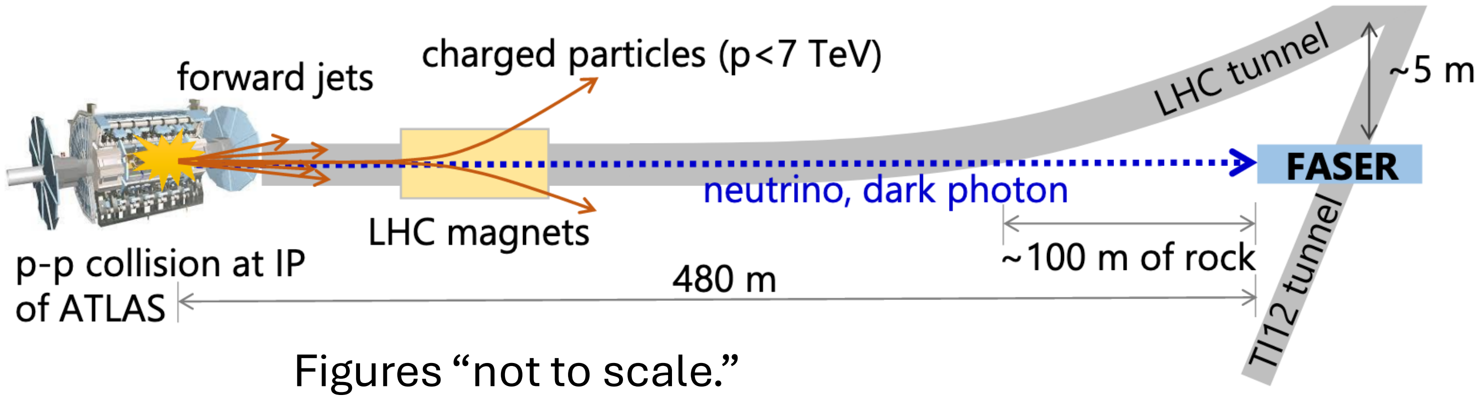
Laura Fields's lecture from last week.

Both experiments installed, in T12 and T18 existing injector tunnels on either side of the ATLAS IP.

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

θ	η
0°	∞
0.1°	7.04

FASERν

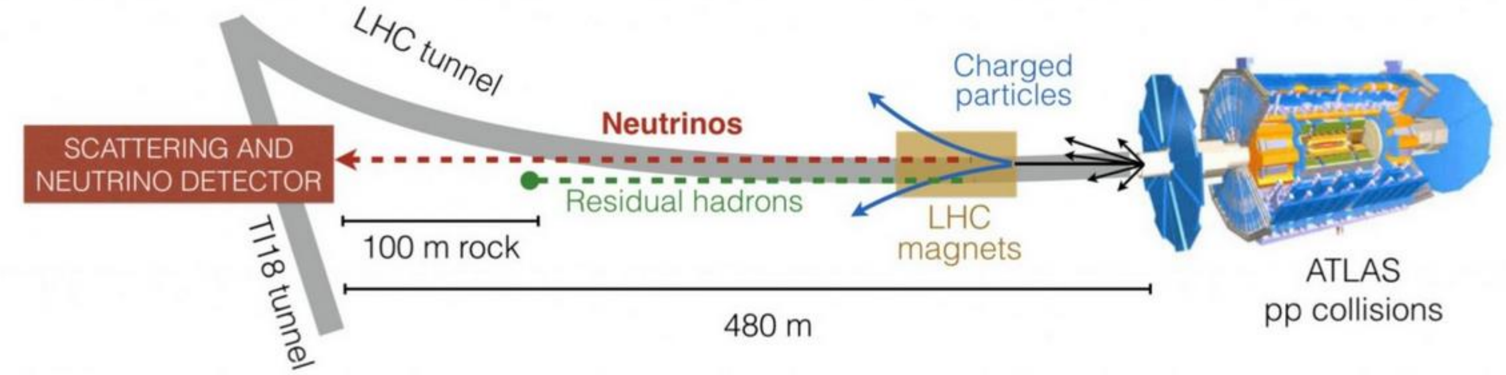


Figures "not to scale."

FASERν 1.2 ton, 25 cm x 25cm

on axis, $\eta > 8.5$

SND@LHC



https://www.epfl.ch/labs/lphe/en/4266-2/

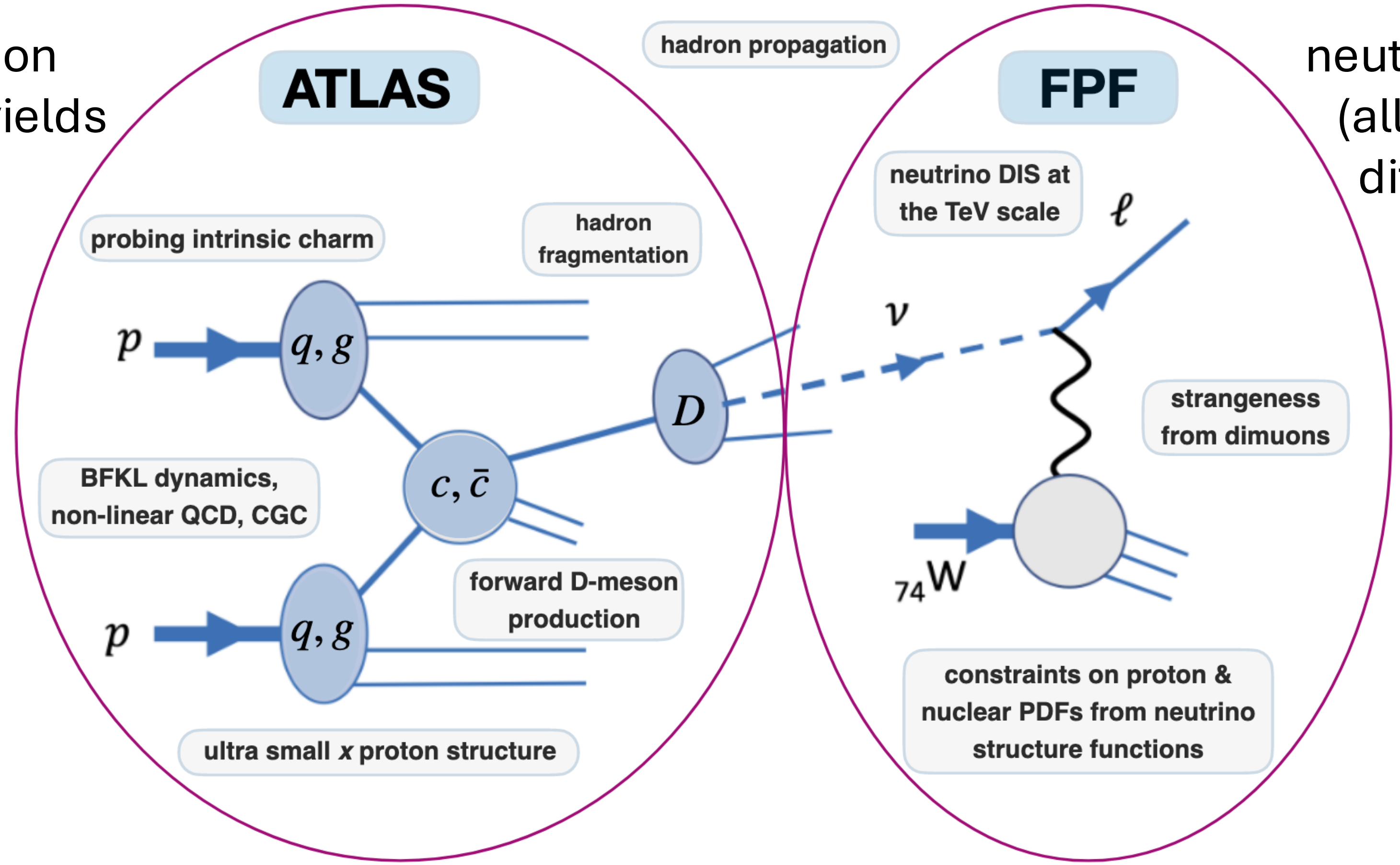
SND@LHC 800 kg, 39 cm x 39 cm

off axis, $8.5 > \eta > 7$

150 fb^{-1}

Aside - collider neutrinos: pp and νA collisions

hadron production that ultimately yields neutrinos of all 3 flavors

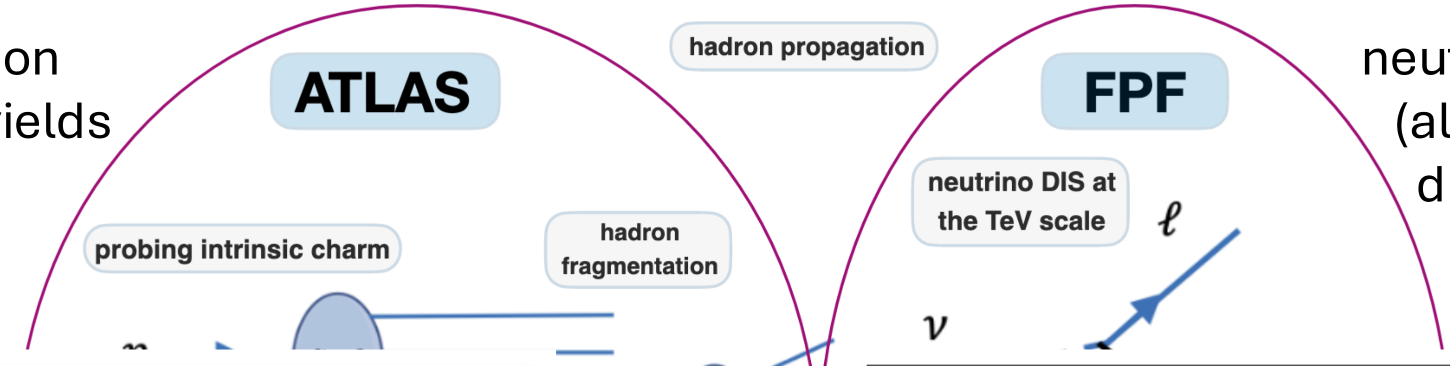


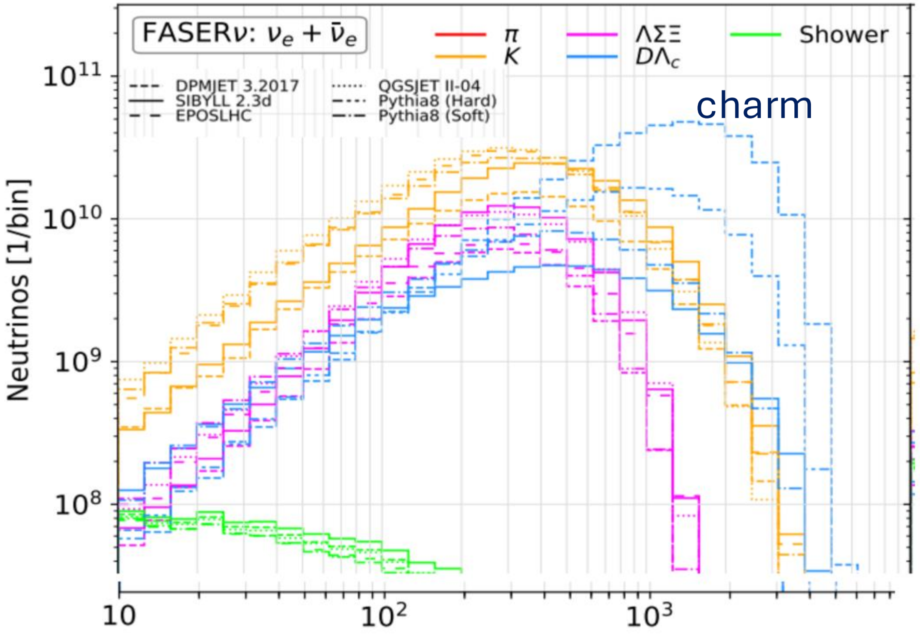
neutrino interactions (all 3 flavors, from different hadron sources) on nuclear targets

FPF neutrinos in *Feng*+, J.Phys.G 50 (2023) 030501

Aside - collider neutrinos: pp and νA collisions

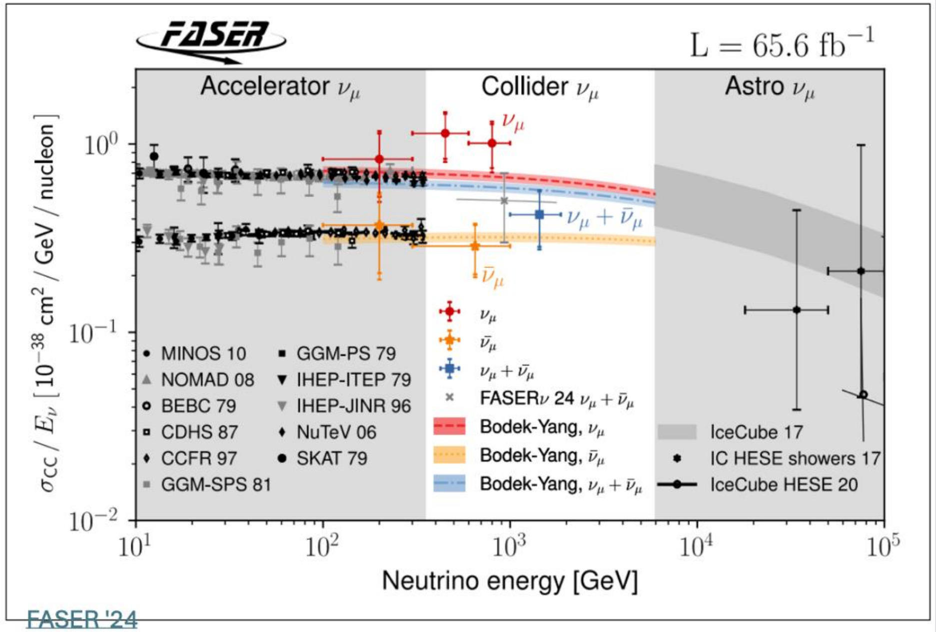
hadron production
that ultimately yields
neutrinos
of all 3 flavors





neutrino
(all 3 fl
differe
sources) on
nuclear targets

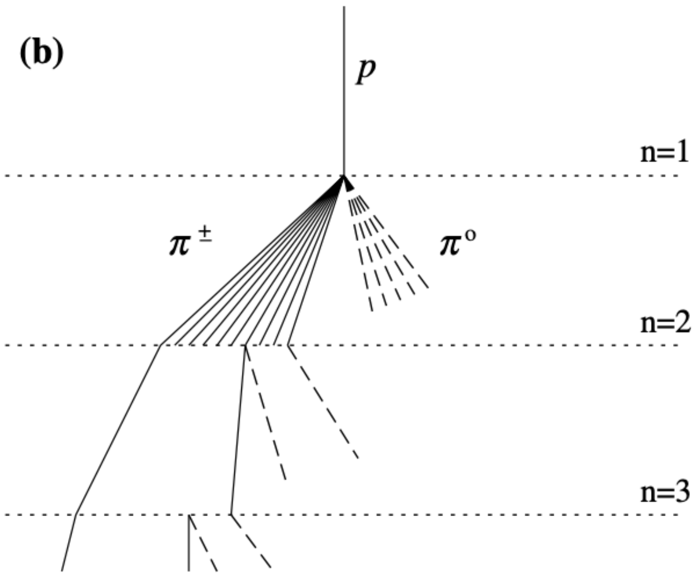
Laura Fields's & Teppei Katori's lectures from last week.



FASER '24

Feng+,
23) 030501

Aside #2: muon puzzle – low energy muons at the ground from a single shower



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

vertical proton induced showers for 1e+19 eV

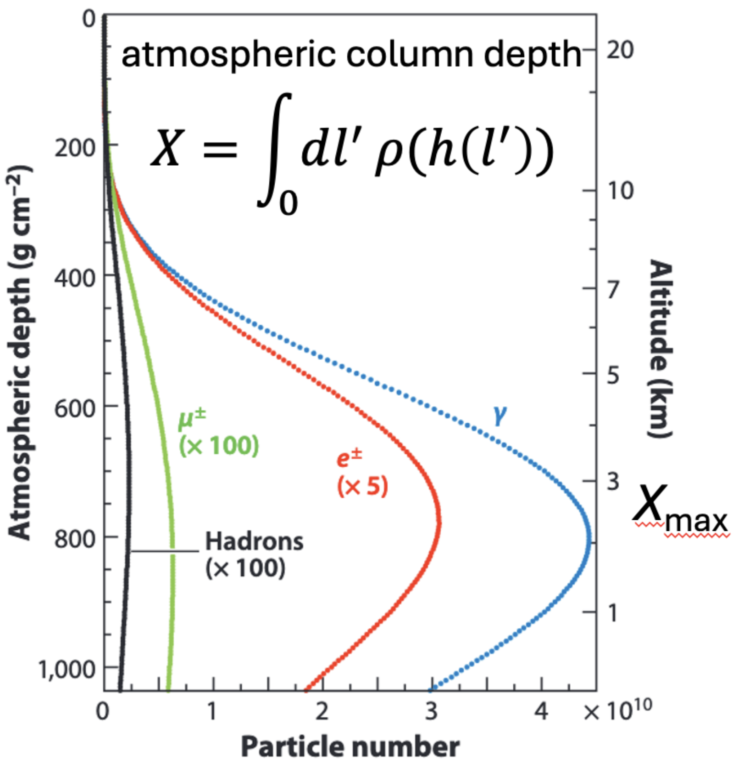


Fig. from Engel, Heck & Pierog, Ann Rev Nucl Part Sci 61 (2011) 467

Muon number sensitive to

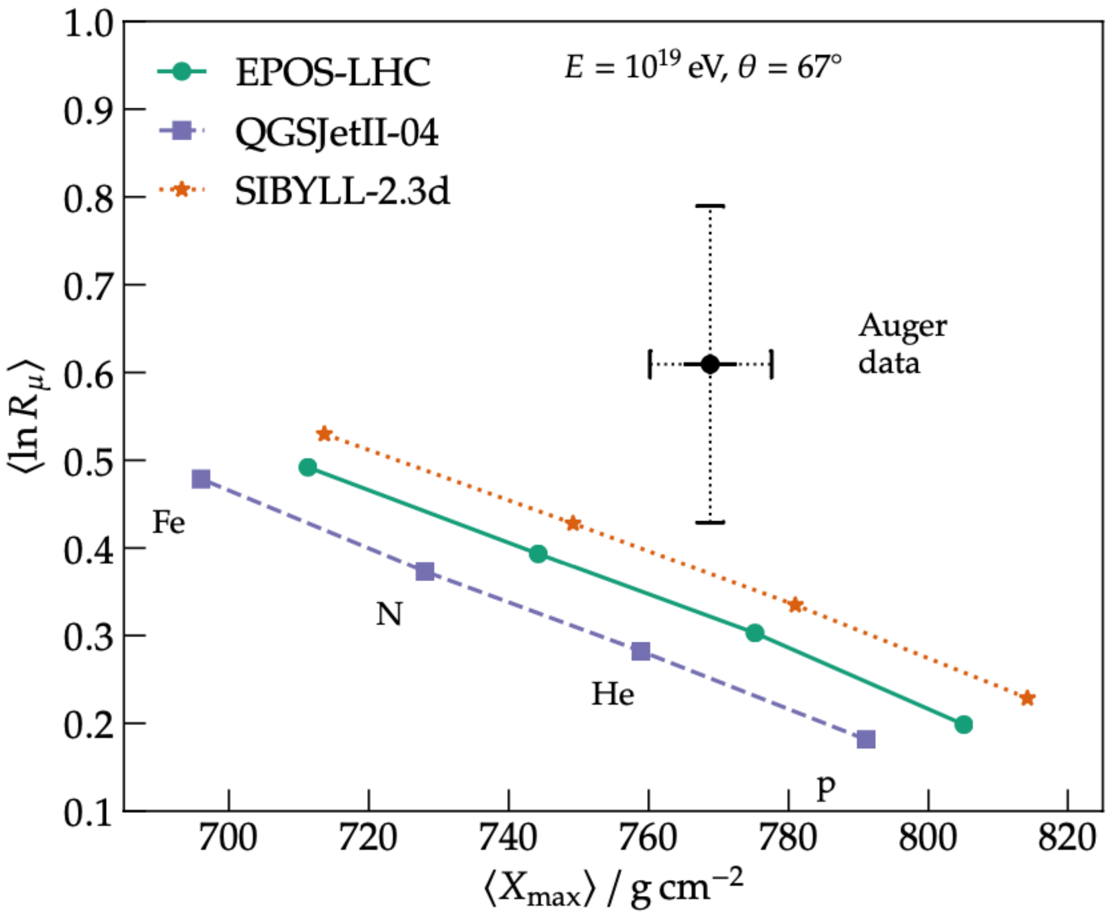
- particle multiplicity as a function of energy,
- fraction of charged pions produced (or fraction of neutral pions produced),
- CR composition.

Muon puzzle: too many neutral pions in simulations relative to charged pions (in this simplified version), not enough muons.

Average muon energy on the ground: ~ a few GeV

Aside #2-muon puzzle

This is not directly related to the atmospheric muon flux because this is *all* muons, not just the leading muons.



Pierre Auger Observatory 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 ($E_\mu >$ 0.3 GeV)
- Example of composition dependence (muon number and X_{max} dependence).
- Example of MC simulation dependence.

R_μ is scaled muon number

R_μ = 1 when $N_\mu = 1.455\ 10^7$

High energy astrophysical neutrinos

- diffuse flux (all sources from all times)
- individual point sources of 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
- Vitagliano+, “Grand unified neutrino spectrum at Earth: Sources and spectral components,” Rev Mod Phys 92 (2020) 045006
- Guepin, Kotera, Oikonomou, “High-energy neutrino transients and the future of multi-messenger astronomy,” Nature Rev.Phys. 7 (2025) 126, 2207.12206
- *Ackerman*+, “High-energy and ultra-high-energy neutrinos: A Snowmass white paper,” JHEAp 36 (2022) 55

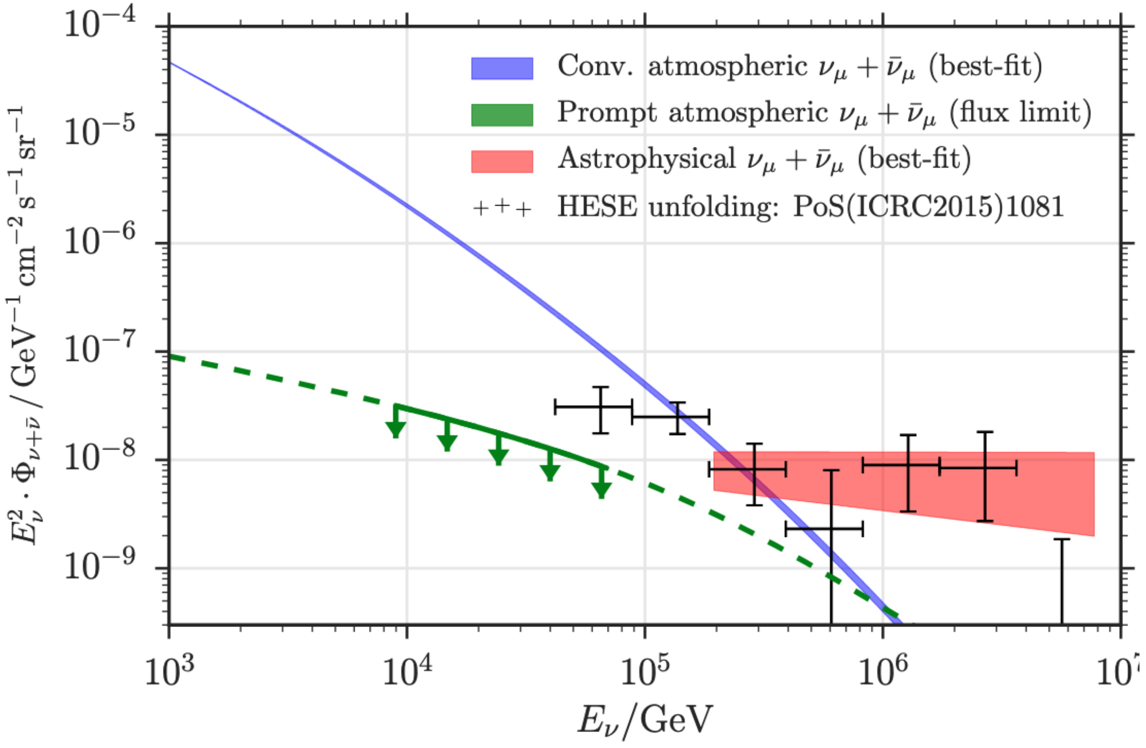
More about cosmic rays, e.g.:

Coleman+, “Ultra high energy cosmic rays The intersection of the Cosmic and Energy Frontiers,” Astropart Phys 149 (2023) 102819

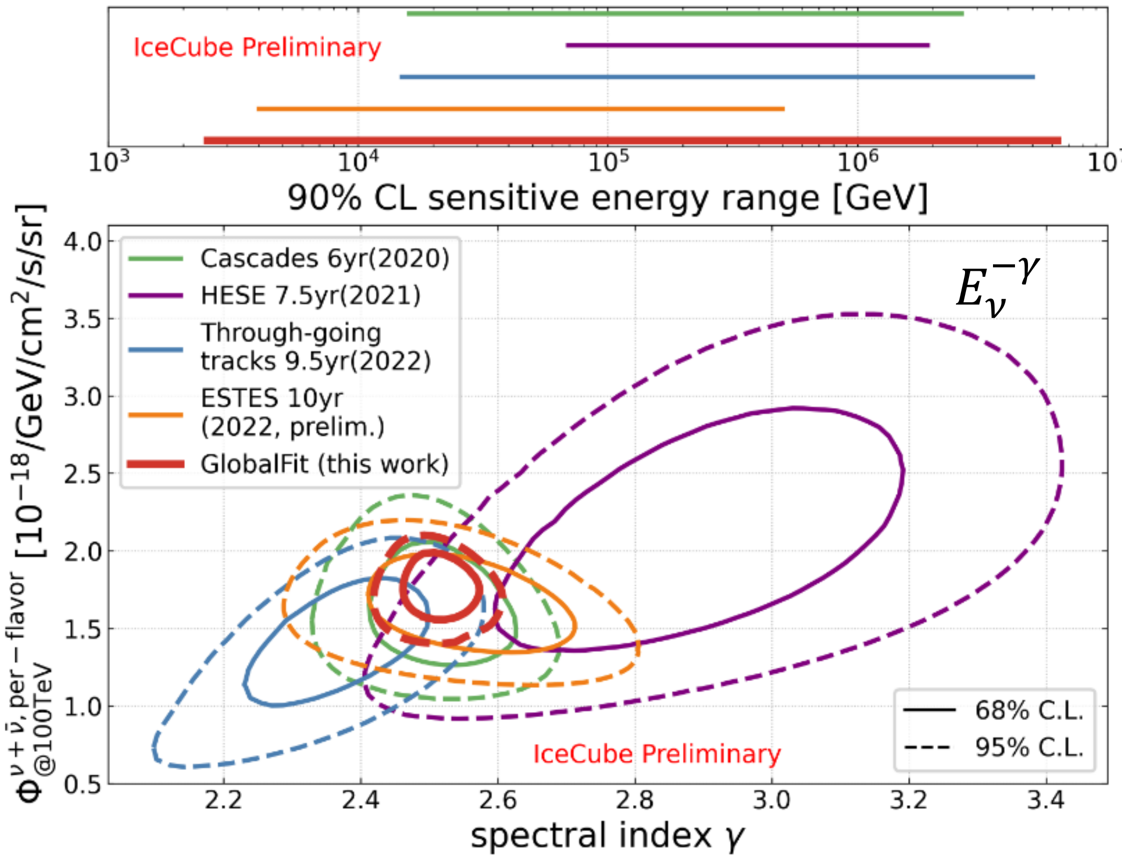
Old figures, more from Lu Lu tomorrow.

Diffuse neutrinos fluxes

Atmospheric transitions to astrophysical flux: different spectrum, isotropic.



IceCube, Astrophys.J. 833 (2016) 3



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

High energy astrophysical neutrinos

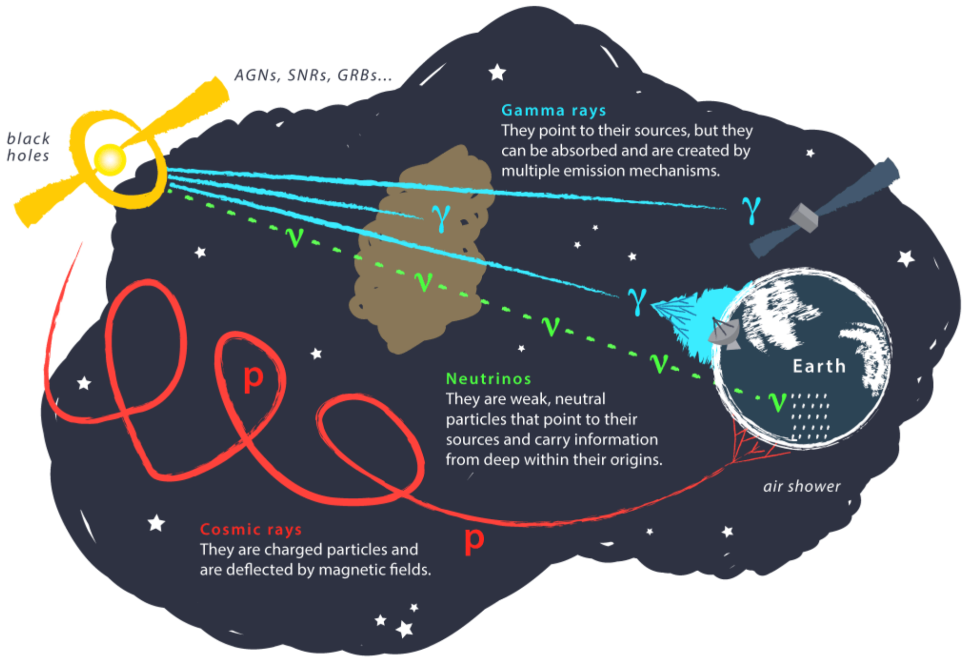
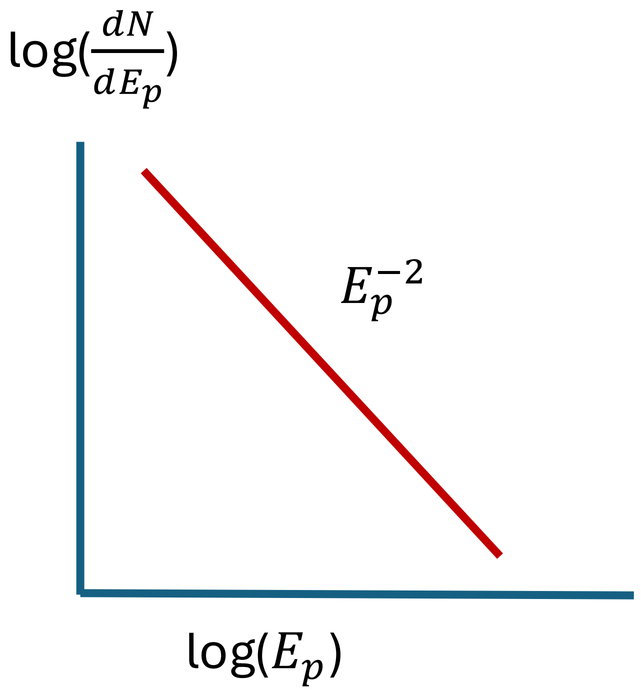


Fig. from IceCube/WIPAC

- **incident beam**: cosmic rays (lets call them protons) in the acceleration environment
- **targets**: photons and cold nucleons
- **beam-target interaction cross sections**: related to $\sigma_{p\gamma}$ and σ_{pp}
- **differential energy distribution:** outgoing hadron energies, especially mesons
- **reinteractions/cooling**: interactions, energy loss
- **decays**: eventually to ν_i
- **propagation:** to Earth, cosmic distances

Neutrinos are unattenuated, point back to sources, will reveal sites of acceleration of highest energy cosmic rays.

High energy astrophysical neutrinos

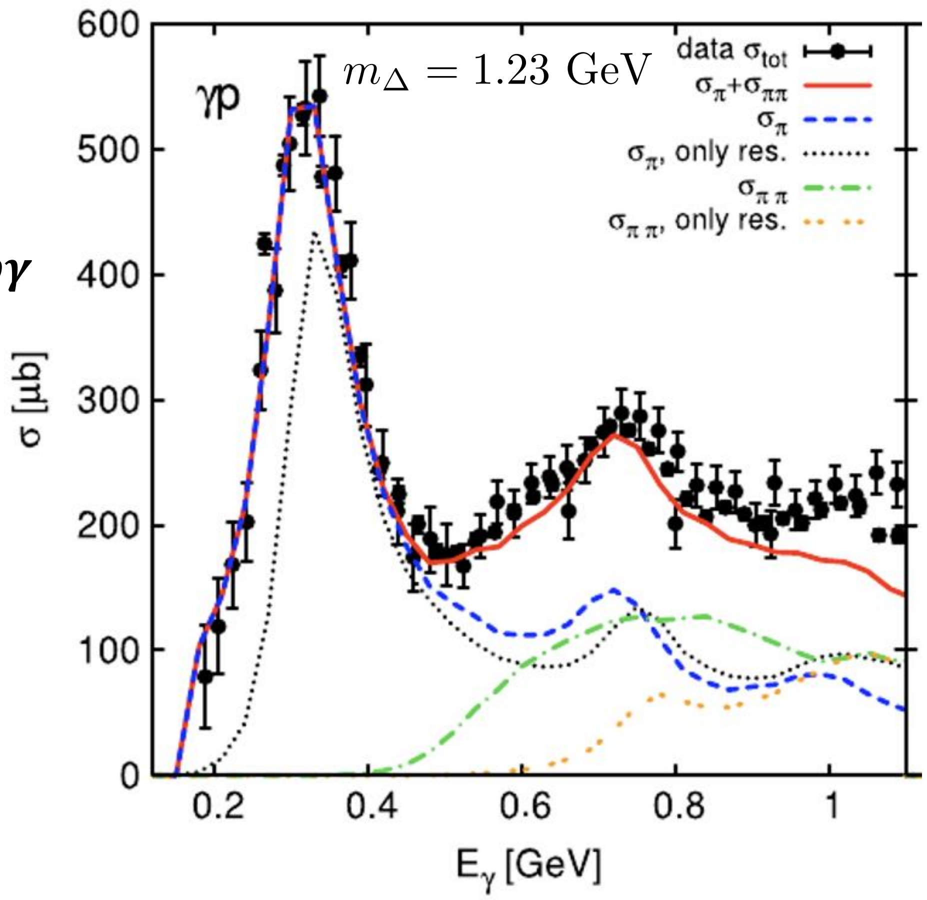


Simplest Fermi-shock acceleration.
Diffusion through magnetic fields to Earth steepens the cosmic ray spectrum.

- **incident beam**: cosmic rays (lets call them protons) in the acceleration environment
- **targets**: photons and cold nucleons
- **beam-target interaction cross sections**: related to $\sigma_{p\gamma}$ and σ_{pp}
- **differential energy distribution:** outgoing hadron energies, especially mesons
- **reinteractions/cooling**: hadronic interactions, energy loss
- **decays**: eventually to ν_i
- **propagation to Earth**: cosmic distances

High energy astrophysical neutrinos

$\boldsymbol{\sigma_{p\gamma}}$



Lalakulich & Mosel, arXiv:1303.6677, see also SOPHIA MC code

- **incident beam**: cosmic rays (lets call them protons) in the acceleration environment
- **targets**: photons and cold nucleons
- **beam-target interaction cross sections**: related to $\boldsymbol{\sigma_{p\gamma}}$ and σ_{pp}
- **differential energy distribution:** outgoing hadron energies, especially mesons
- **reinteractions/cooling**: hadronic interactions, energy loss
- **decays**: eventually to ν_i
- **propagation to Earth**: cosmic distances

Energy distribution of target photons affects eventual spectrum of neutrinos.

High energy astrophysical neutrinos

(say)

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

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

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

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

(We will return to $\pi^0 \to \gamma\gamma, E_\gamma \sim E_\pi/2$)

not a Feynman diagram

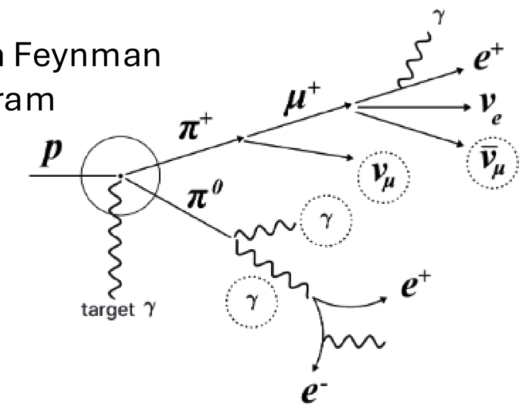
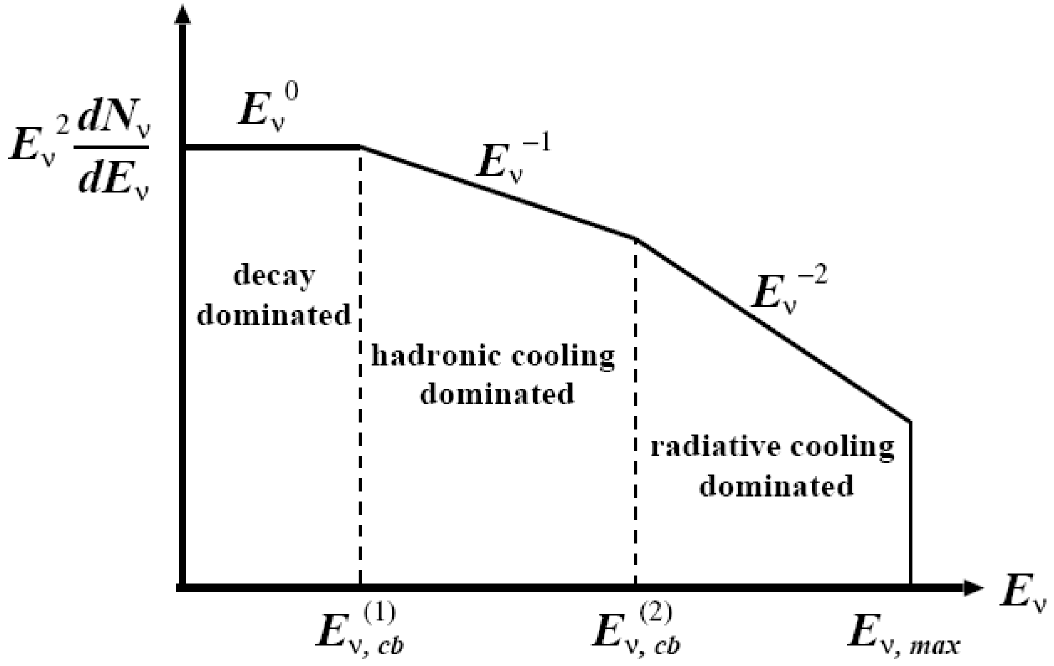


Fig. from Arguelles+, PRX 15 (2025) 030501

- **incident beam**: cosmic rays (lets call them protons) in the acceleration environment
- **targets**: photons and cold nucleons
- **beam-target interaction cross sections**: related to $\sigma_{p\gamma}$ and σ_{pp}
- **differential energy distribution:** outgoing hadron energies, especially mesons
- **reinteractions/cooling**: hadronic interactions, energy loss
- **decays**: eventually to ν_i
- **propagation to Earth**: cosmic distances

More details about energy distributions: Gaisser's book, Kelner+, PRD 74 (2006) 034018, PRD 82 (2010) 099901.

High energy astrophysical neutrinos



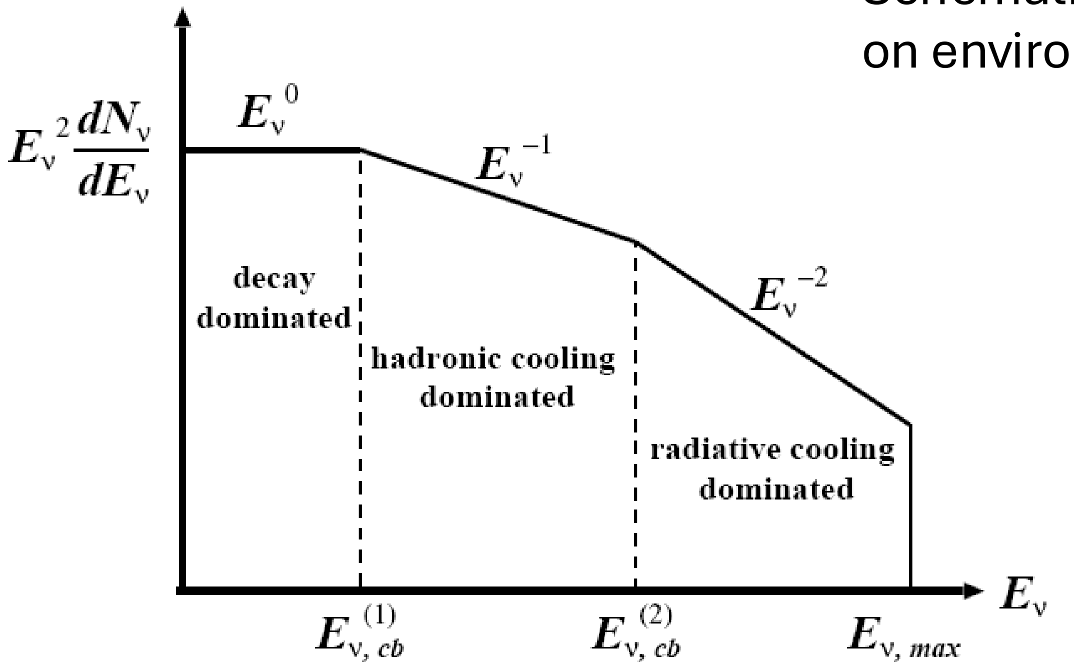
Schematic energy dependence, Fig. from Ando & Beacom PRL 95 (2005).

- **incident beam**: cosmic rays (lets call them protons) in the acceleration environment
- **targets**: photons and cold nucleons
- **beam-target interaction cross sections**: related to $\sigma_{p\gamma}$ and σ_{pp}
- **differential energy distribution:** outgoing hadron energies, especially mesons
- **reinteractions/cooling**: hadronic interactions, energy loss
- **decays**: eventually to ν_i
- **propagation to Earth**: cosmic distances

Here, assuming cosmic ray spectrum of E^{-2}.
Next slide for energy discussion.

High energy astrophysical neutrinos

Schematic/simplified source modeling. Spectral breaks depend on environment, e.g., photon densities, energies, magnetic fields.



Schematic energy dependence, Fig. from Ando & Beacom PRL 95 (2005).

- **decay dominated:** neutrino energy scales like proton energy (think atmospheric neutrinos, pions decay right away!) No time to interact or lose energy.
- **hadronic cooling dominated**: related to $\frac{t_{cool}}{t_{decay}} < 1, t_{decay} = \gamma c\tau = Ec\tau/m$ contributes extra E^{-1} since hadronic cooling time ~ energy independent.
- **radiative cooling dominated:** contributes extra E^{-2} since radiative cooling time (inverse Compton, synchrotron) ~ E^{-1}.

Neutrino flavor dependence

Neutrino oscillations over astronomical distances, neglect CP violation:

$$P(\nu_\alpha \to \nu_\beta) \simeq \delta_{\alpha\beta} - 4\sum_{i>j} U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j}\sin^2\Delta_{ij} \qquad \Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Over astronomical distances, and using unitarity (here approx. real)

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

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

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:

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

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

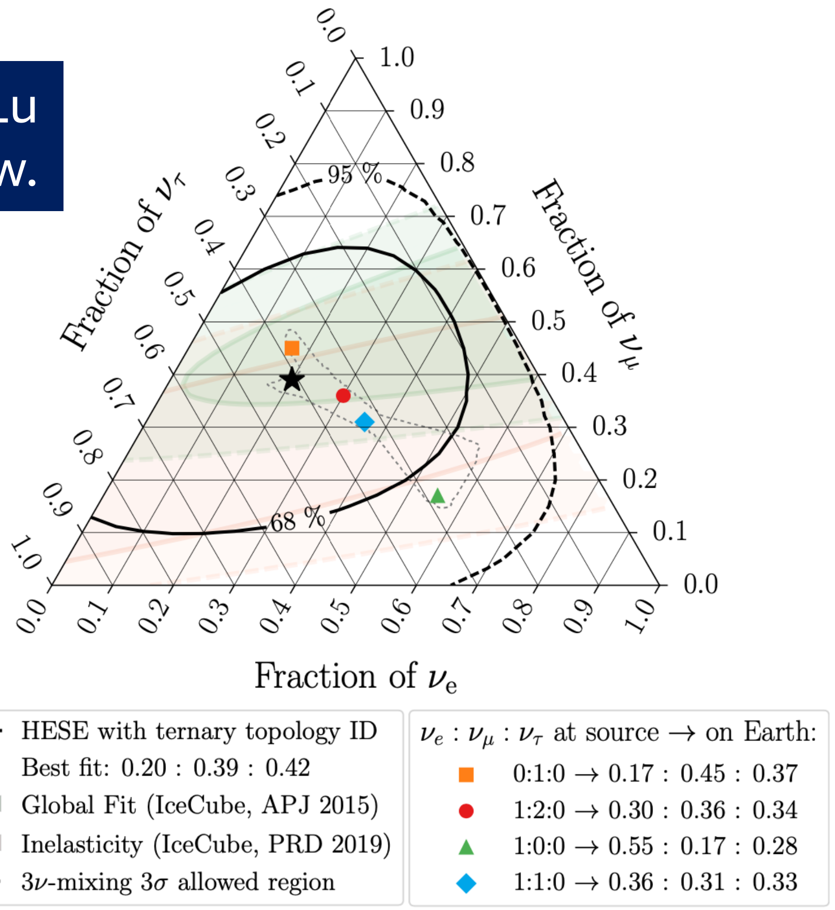
$$\mu^+ \to \bar{\nu}_\mu\, e^+\, \nu_e$$

IceCube flavor results

- **propagation to Earth**: cosmic distances

More from Lu Lu tomorrow.

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



Projected improvements of IceCube measurements and of oscillation parameters

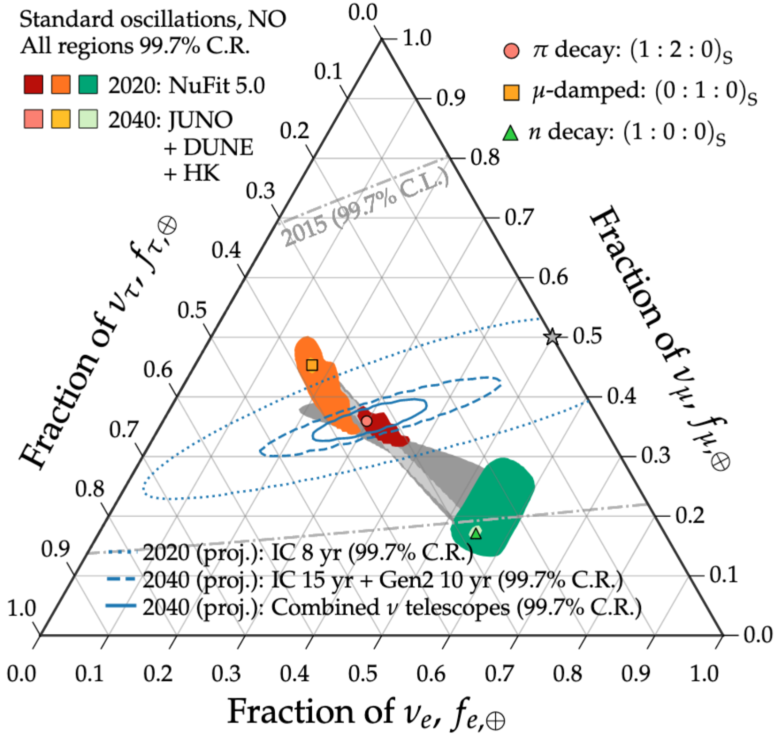


Fig. from Song+, JCAP 04 (2021) 054

Diffuse flux from all sources/all times

$$\phi_\nu \simeq \frac{1}{4\pi}\int R(z)\,\frac{dN\big(E'=E(1+z)\big)}{dE'}\,(1+z)\frac{dt}{dz}dz$$

rate density of sources (uncertain)

$$R(z) = \frac{\#}{yr\cdot Gpc^3}$$

cosmic evolution

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

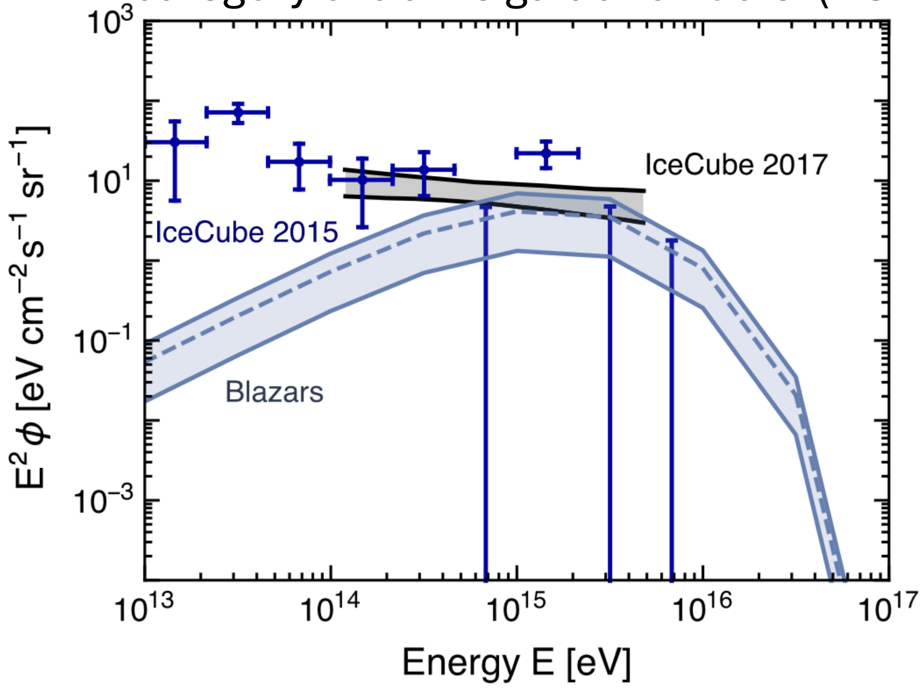
redshift of energy

$$E' = E(1+z)$$

- In general, proton-proton or p-γ or both?
- injection spectra model (source) dependent:

$$\frac{dN\big(E'=E(1+z)\big)}{dE'}$$

Example: blazar sources,
category of active galactic nuclei (AGN)



per flavor

Vitagliano+, Rev Mod Phys 92 (2020) 045006, Palladino+, Ap J 871 (2019) 41

Diffuse flux predictions, some examples

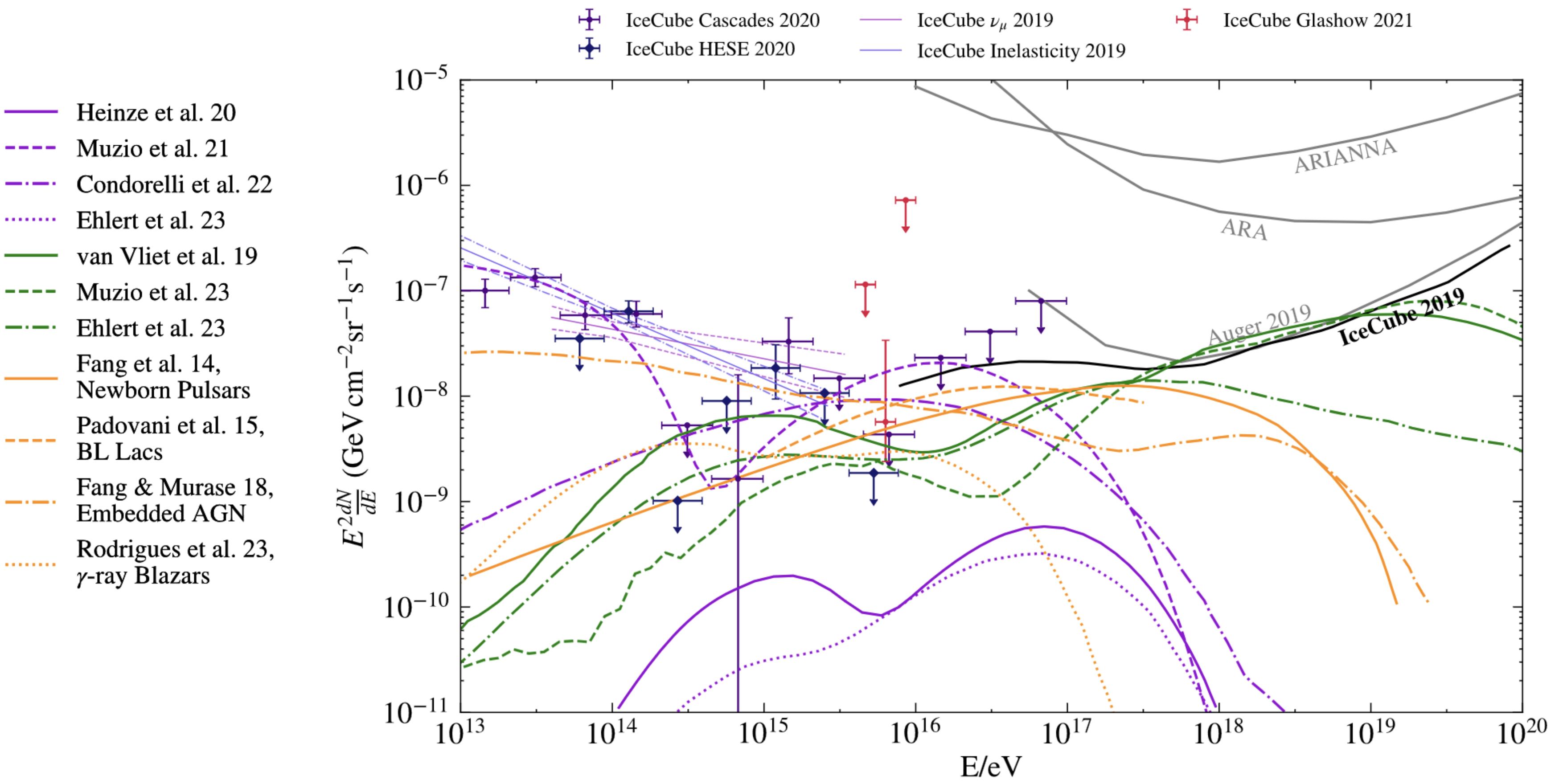


Fig. from Muzio, Eur Phys J Spec Top 234 (2025) 234

Different approaches:

- phenomenological approach tied to CRs observed (purple) [more on this soon]
- phenonomenological + HE protons in CR composition (green)
- modeling particular sources (orange)

Some candidate source classes for diffuse ν

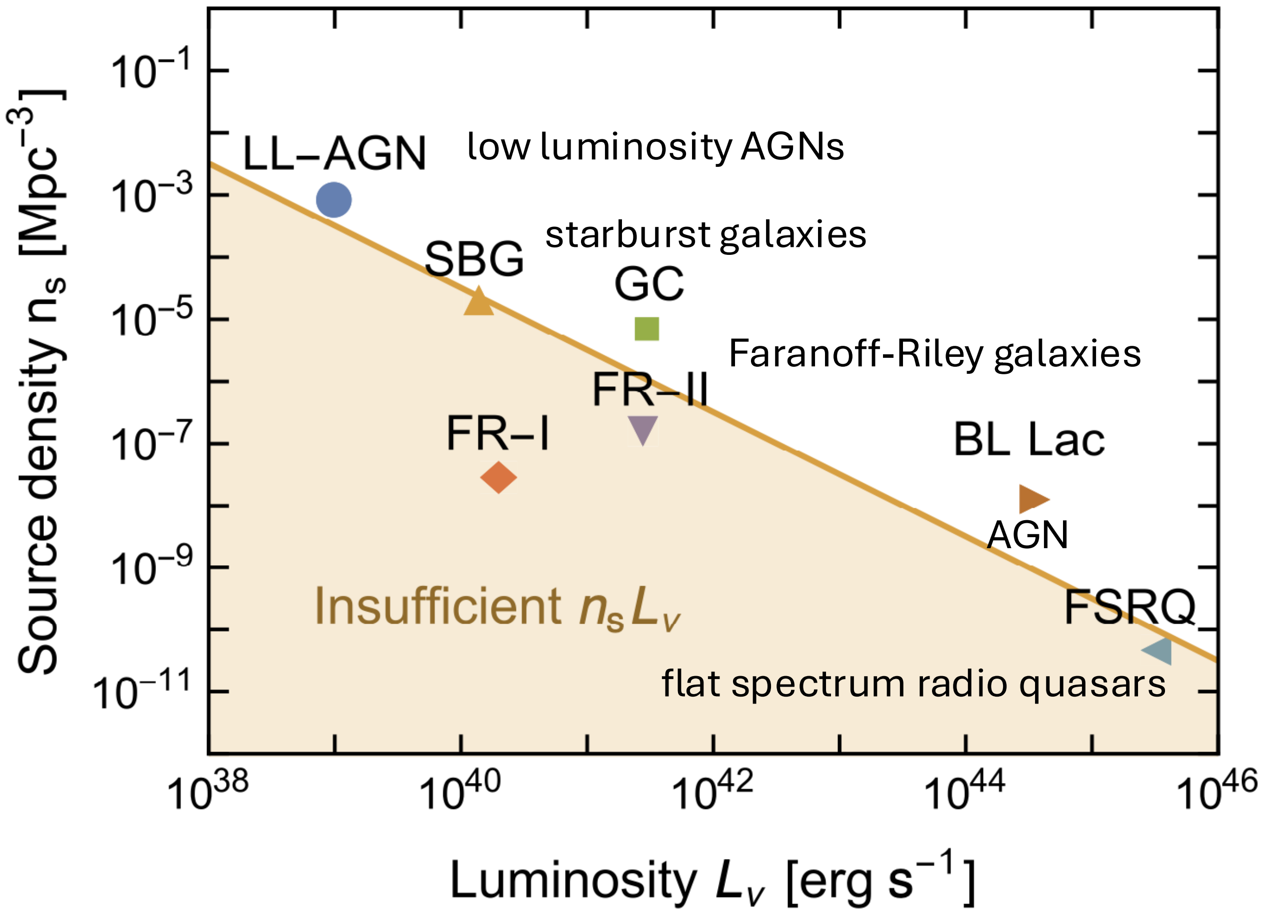
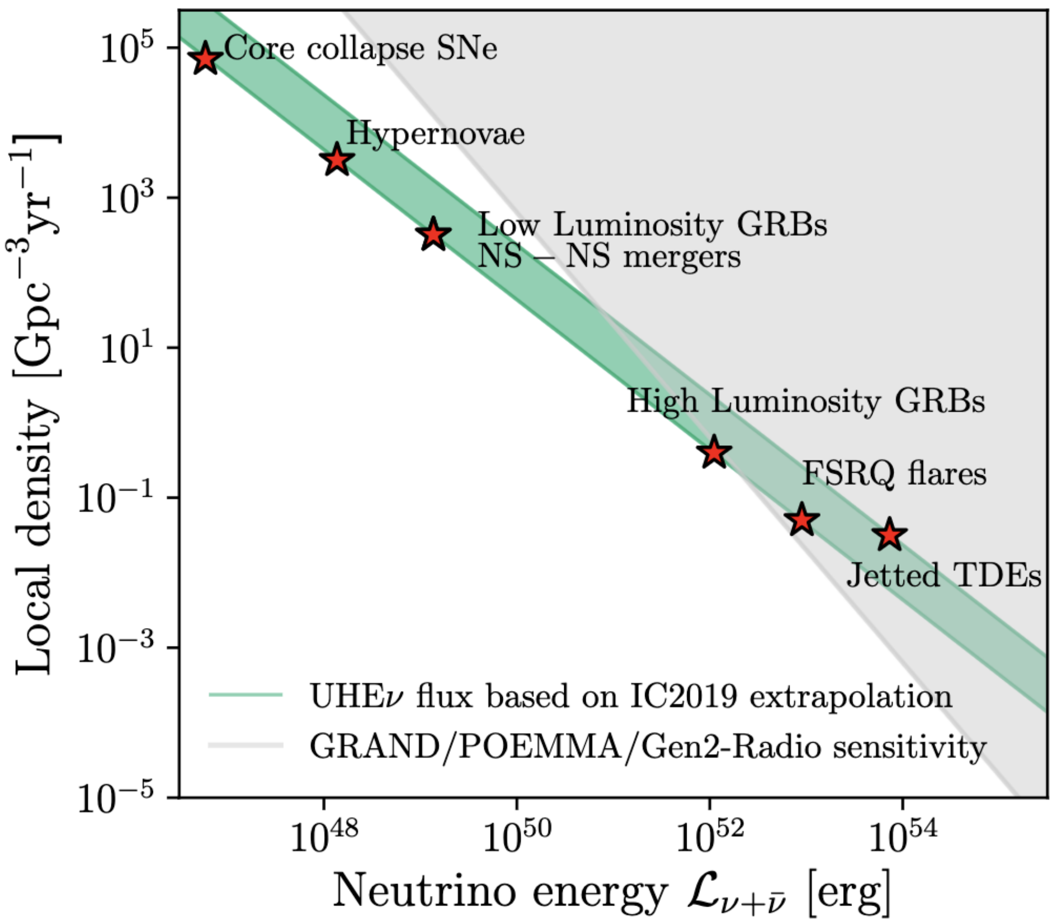


Fig. from Vitagliano+, Rev Mod Phys 92 (2020) 045006

Need enough luminous sources to inject the measured diffuse astrophysical neutrino flux measured by IceCube.

Faranoff-Riley galaxies: radio loud active galaxies, type II – high luminosity
BL Lac: variable extragalactic AGN with beaming to us

Transient neutrino source candidates



Another compilation, here for neutrino burst candidates.

Green: compatible with observed diffuse flux, uncertainty band from source evolution
Grey: will be constrained by upcoming detectors

Fig. from Guepin, Kotera, Oikonomou, 2207.12205

Need good cosmic ray accelerators with relativistic outflows, sufficient targets (photons or protons) for pion production.

Transient neutrino source - γ-ray burst example

1 erg = 625 GeV

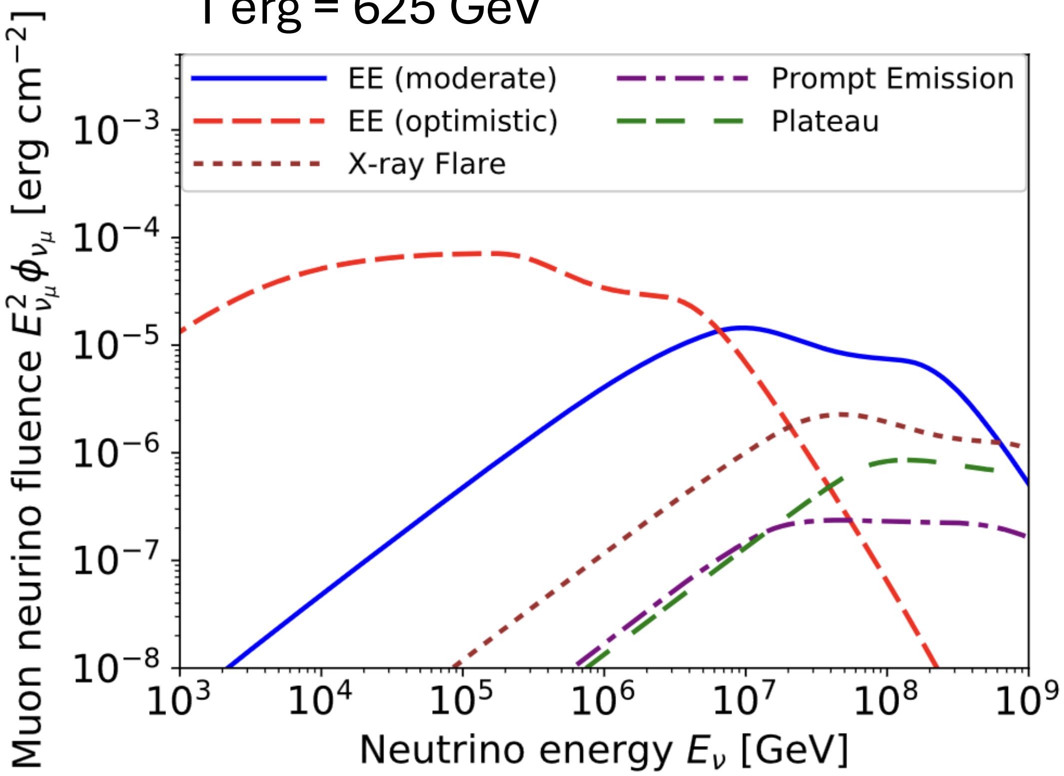


Figure 1. Neutrino fluences from the EE-mod, EE-opt, prompt emission, flare, and plateau for $d_L = 300$ Mpc.

An often-cited example for gamma ray bursts from Kimura, Murase, Meszaros, Kiuchi (KMMK), Ap J Lett 848 (2017) L4.

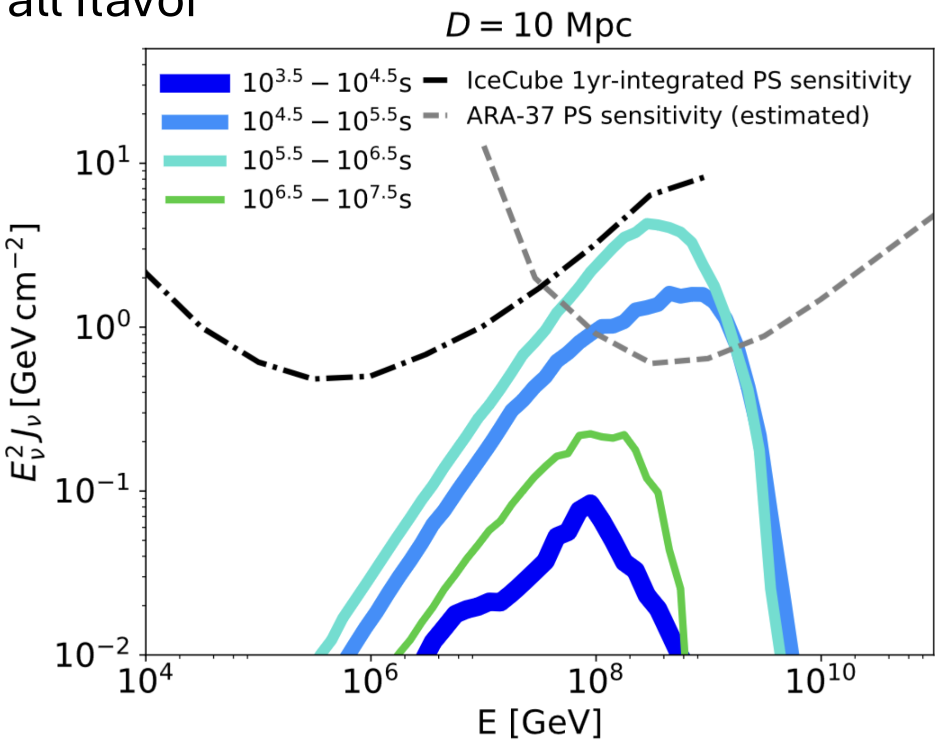
- Range of different inputs, for different phases of the burst.
- EE = extended emission, different configurations.

Short GRBs due to binary system mergers.

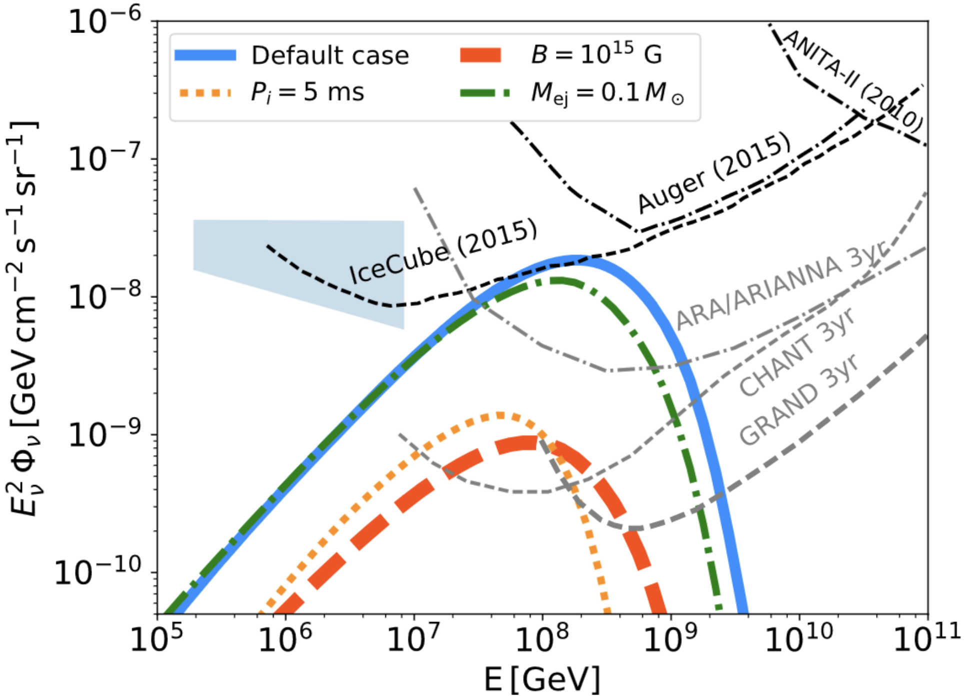
- Prompt – 10 ms to a few s
- EE – 10-100's s
- plateau – post merger 1000's s

Binary neutron star merger to magnetar example

all flavor



all flavor diffuse



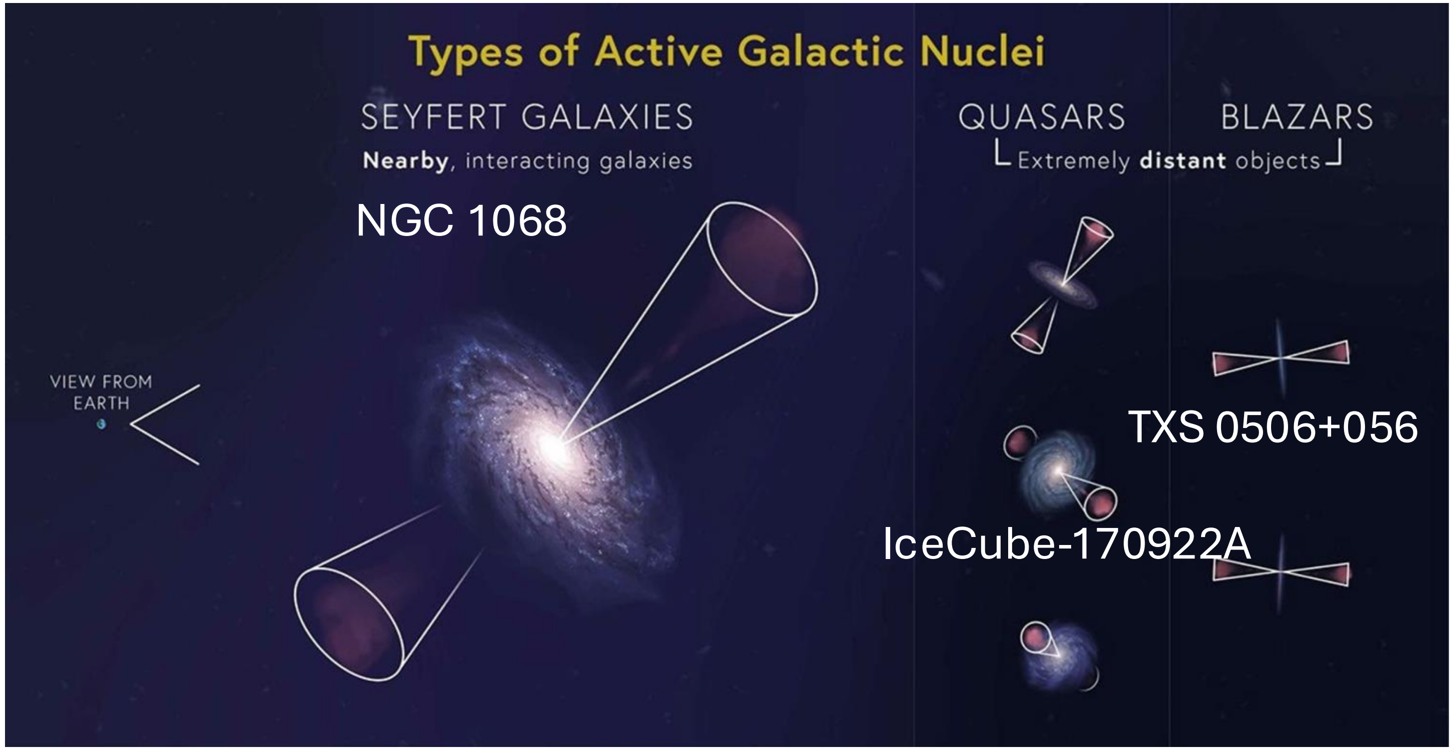
Point source neutrino fluence from ms magnetar formed by BNS merger. Energy and time domain predictions.

Figs. from Fang & Metzger, 849 (2017) 153

Two sources with neutrino event association

More from Lu Lu tomorrow.

Seyfert galaxies: jet quiet, X-ray sources, expect pp and pγ.



https://science.nasa.gov/mission/webb/science-overview/science-explainers/what-are-active-galactic-nuclei/

Active galactic nuclei (AGN) powered by super-massive black hole cores, $M > 10^5 M_\odot$.

Blazars – bright in gamma rays

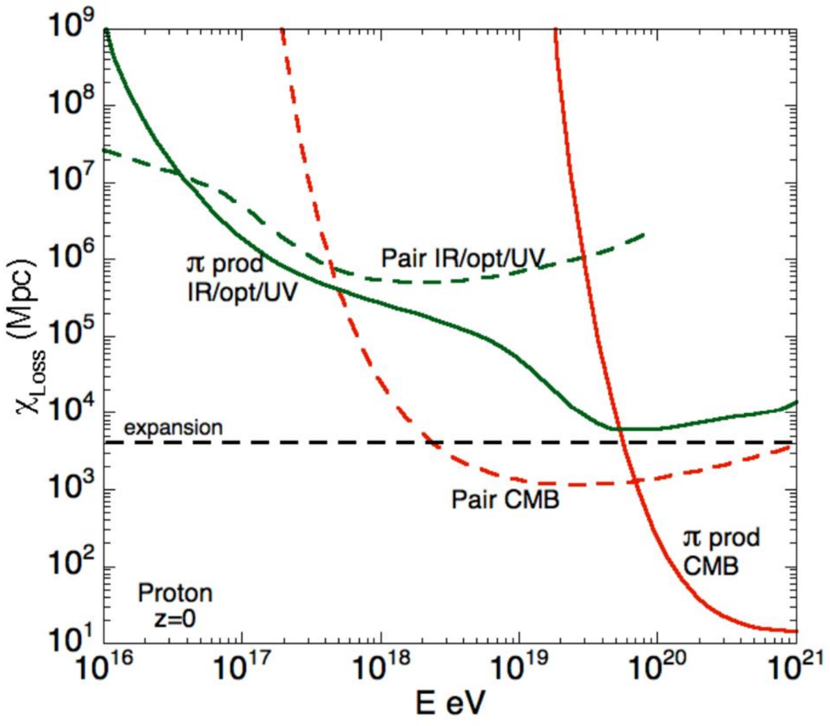
- Multi-messenger approach- neutrinos and photons- more tomorrow.
- Many model are constrained to require at least two zones, more complicated modeling.

Cosmogenic neutrinos

Cosmic rays – cut-off at highest energies

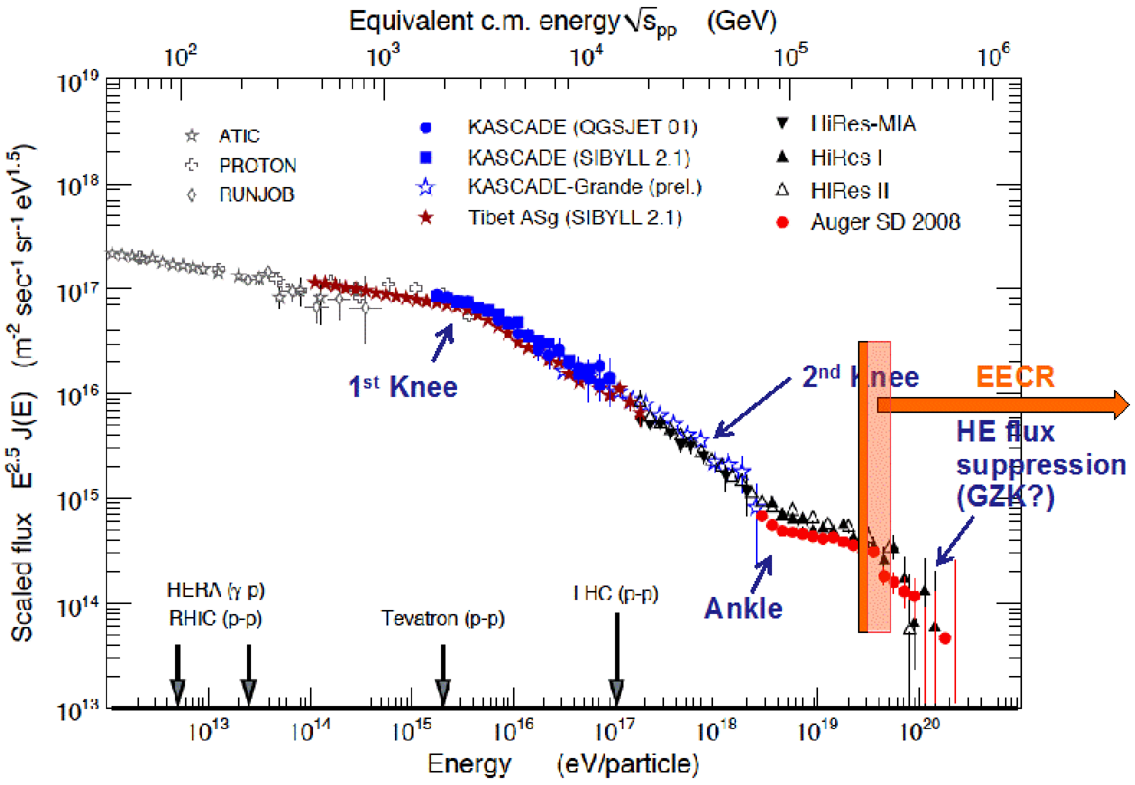
GZK cutoff- CR scattering from from cosmic background radiation.

UHE or EE region



Energy loss length of protons

Allard, Astropart.Phys. 39-40 (2012) 33-43



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 photon energies, also other energies from stellar sources (previous slide), so it is not a sharp threshold.

Cosmogenic neutrino flux predictions, some of the variables

Cosmogenic neutrinos come from decays:

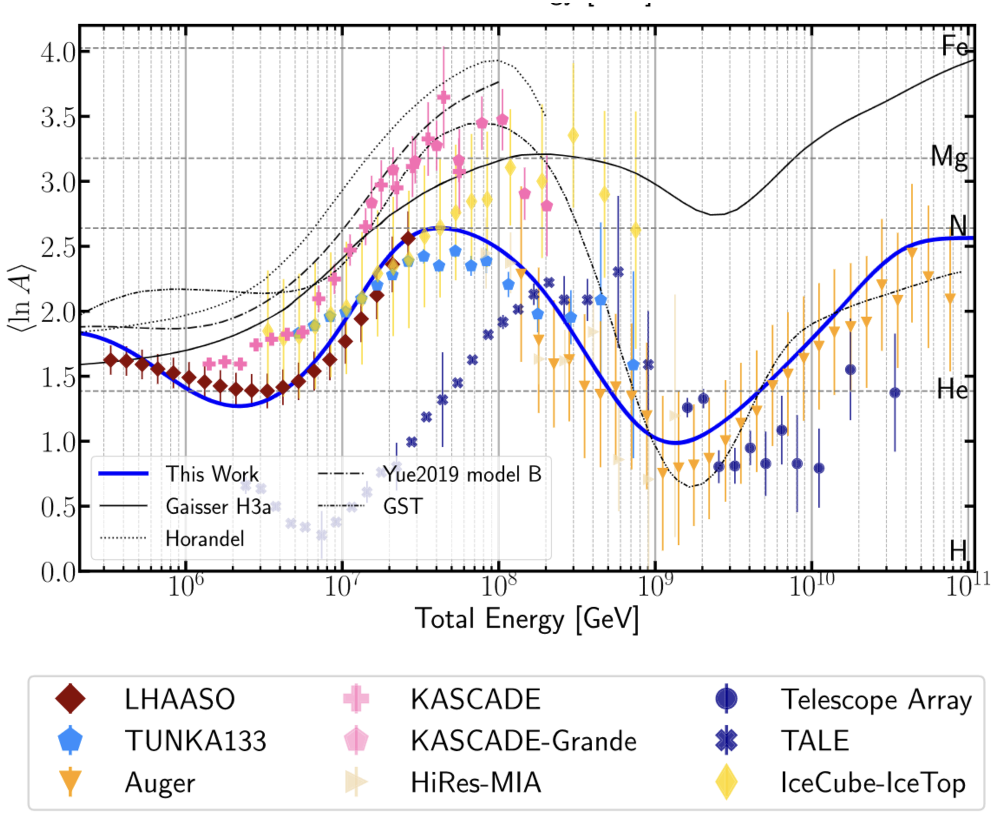
$$p\gamma \to \Delta \to n\pi^+$$

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 themselves?
- What is the cosmic ray source evolution rate?
- At what energy is the transition from galactic to extragalactic cosmic rays in the flux?

Cosmogenic neutrinos - composition

Diffuse multi-messenger approach: match CR fluxes and composition at Earth, then see what are the “secondary” neutrinos from the propagation.



Lv+, Ap. J. 979 (2025) 225

- We are not completely sure about “chemical” composition.
- Auger – heavier, TA – lighter

Example, van Vliet et al, ICRC2017 1707.04511

- injection spectrum $\frac{dN}{dE} \propto \left(\frac{E}{E_0}\right)^{-\alpha} \exp\left(-\frac{E}{ZR_{\rm cut}e}\right)$

$$R_{\rm cut} = E_{\rm cut}/Ze$$

- model of extragalactic background light (EBL)
- source evolution model, e.g., $(1+z)^m$
- propagate using CRPropa code
- normalize Earth flux to Auger CR flux

Rigidity cut

Definition of rigidity

$$R = \frac{pc}{Ze}$$

Larmor radius in magnetic field

$$r_\perp = \frac{p_\perp}{qB} < r_{\rm source}$$

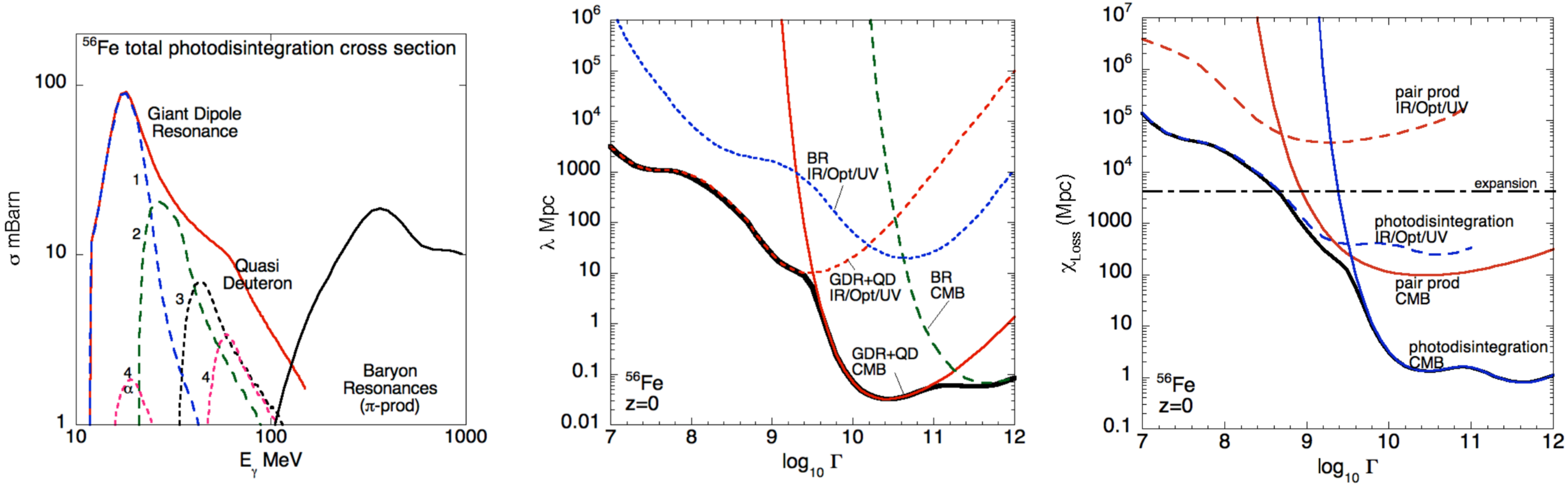
For a given B, $r_\perp < r_{source}$ can be translated to $R < R_{\max}$.

cut=max

charge dependent maximum energy $E_{\max} = R_{max} \cdot Ze$

Cosmic ray nuclei - propagation

Γ is Lorentz factor of outflow of source

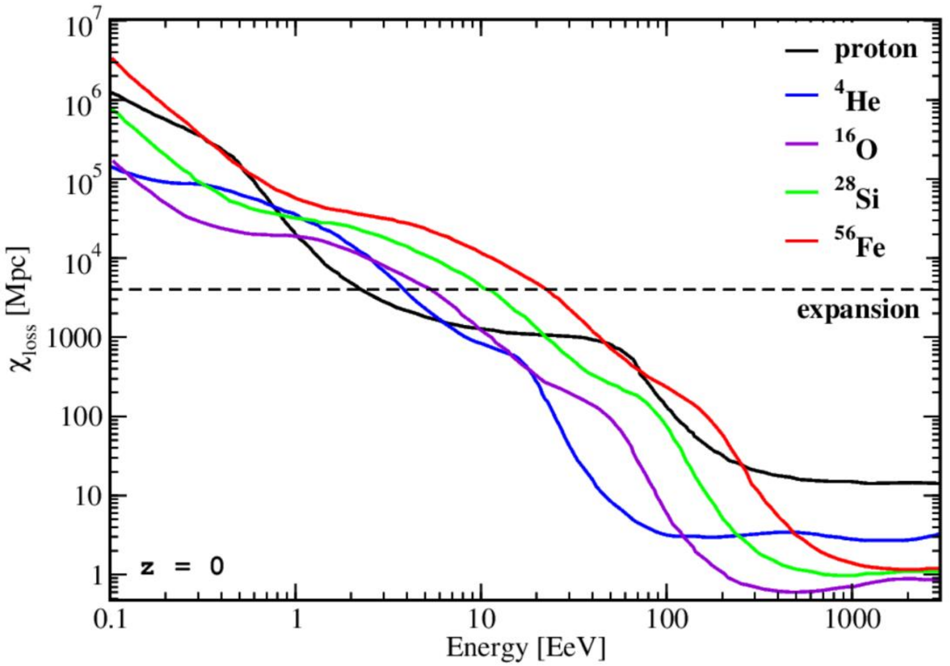


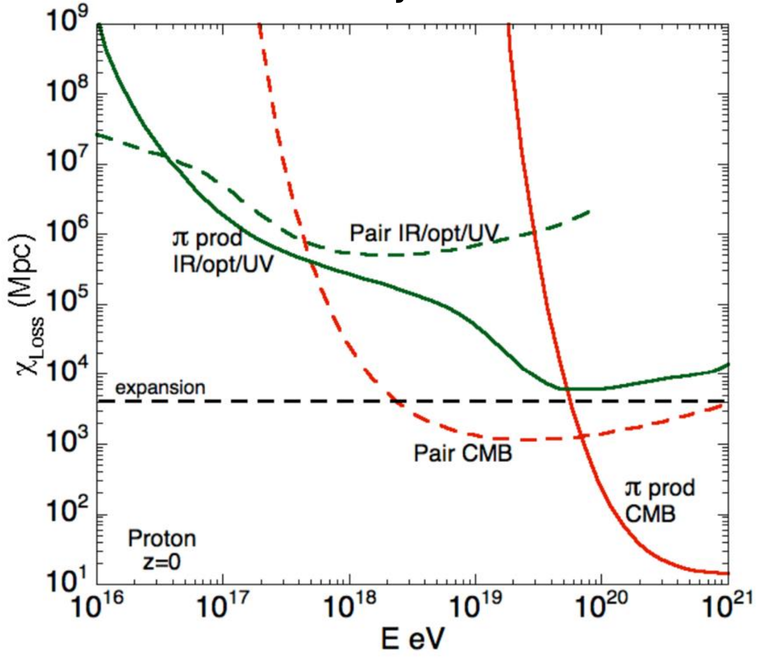
Photodisintegration cross section, iron mean free path for photodisintegration (distance between collisions), and attenuation length (scattering, disintegration).

Figs. from Allard, Astropart.Phys. 39-40 (2012) 33-43

Cosmic ray nuclei - propagation

note different y axis scales



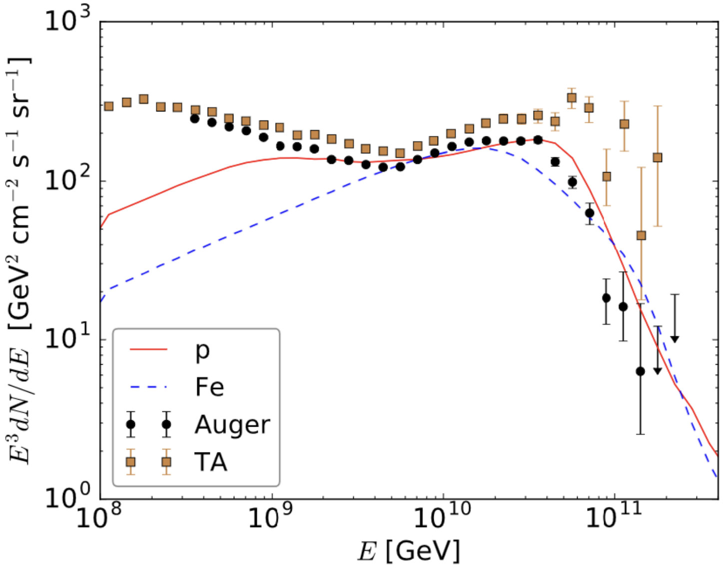


Nuclear attenuation lengths (scattering, disintegration).

Proton attenuation length.

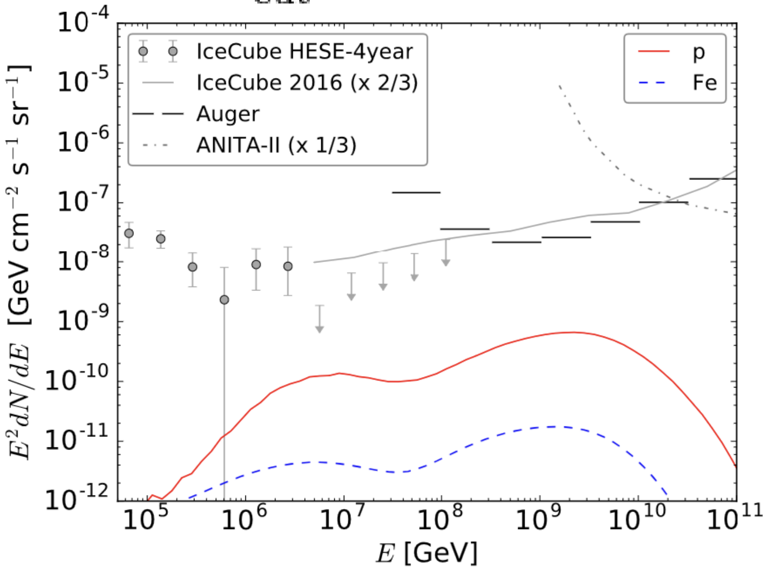
Figs. from Allard, Astropart.Phys. 39-40 (2012) 33-43 and
Leigui de Oliveira, Costa, *PoS* ICRC2019 (2020) 330

Cosmogenic neutrinos – step-by-step – Fe & p

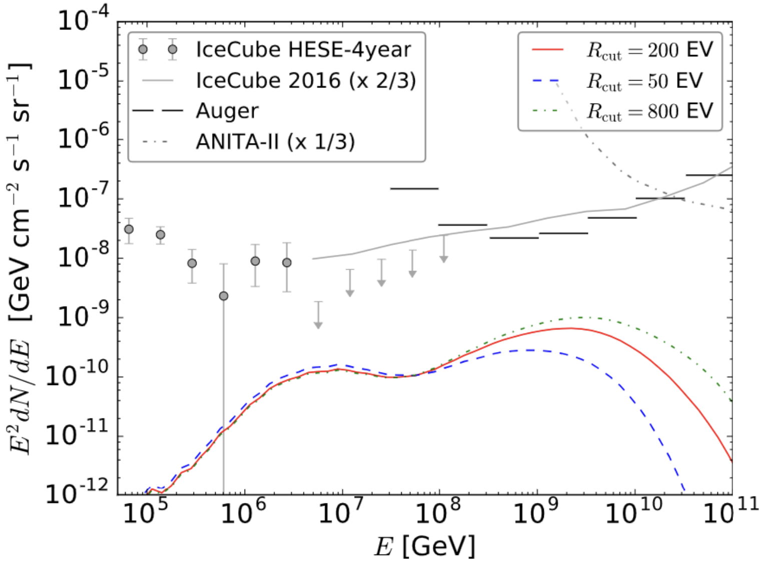


(a) Cosmic rays

$R_{\rm cut} = 200$ EV



(b) Neutrinos



(b) Neutrinos

Figs from van Vliet et al, ICRC2017 1707.04511

composition

single flavor

$R_{\rm cut}$, pure proton

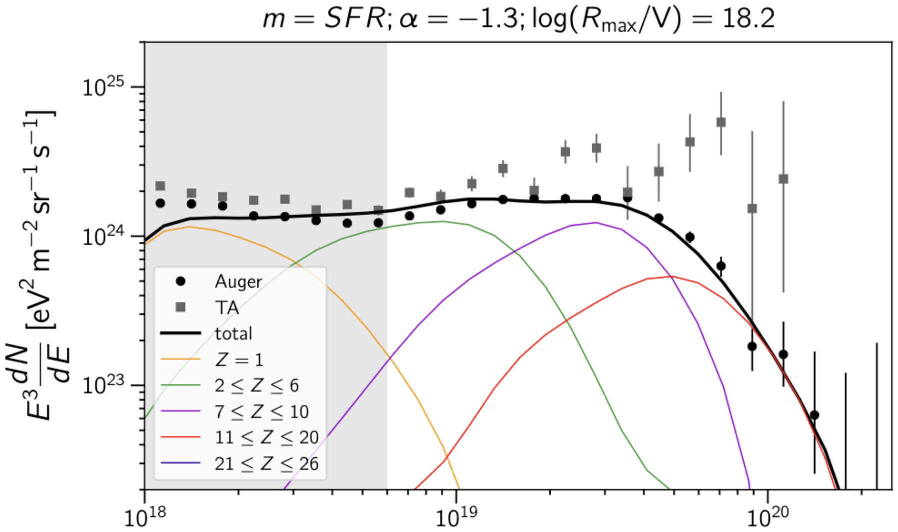
(max energy)

m=0, normalized to E=$10^{9.85}$ GeV, $\alpha = 2.5$

Isotropic, identical sources homogeneously distributed.

Not a great agreement with the cosmic ray features.

Cosmogenic neutrinos – example with more comprehensive variations



Compare CRPropa result with Auger spectrum and composition a la Auger, using:

$$J(E) = J_0 \sum_j f_j E^{-\alpha} \begin{cases} 1 & \text{if } Z_j R_{\max} > E \\ \exp\left(1 - \frac{E}{Z R_{\max}}\right) & \text{if } Z_j R_{\max} \leq E \end{cases}$$

with spectral index α.

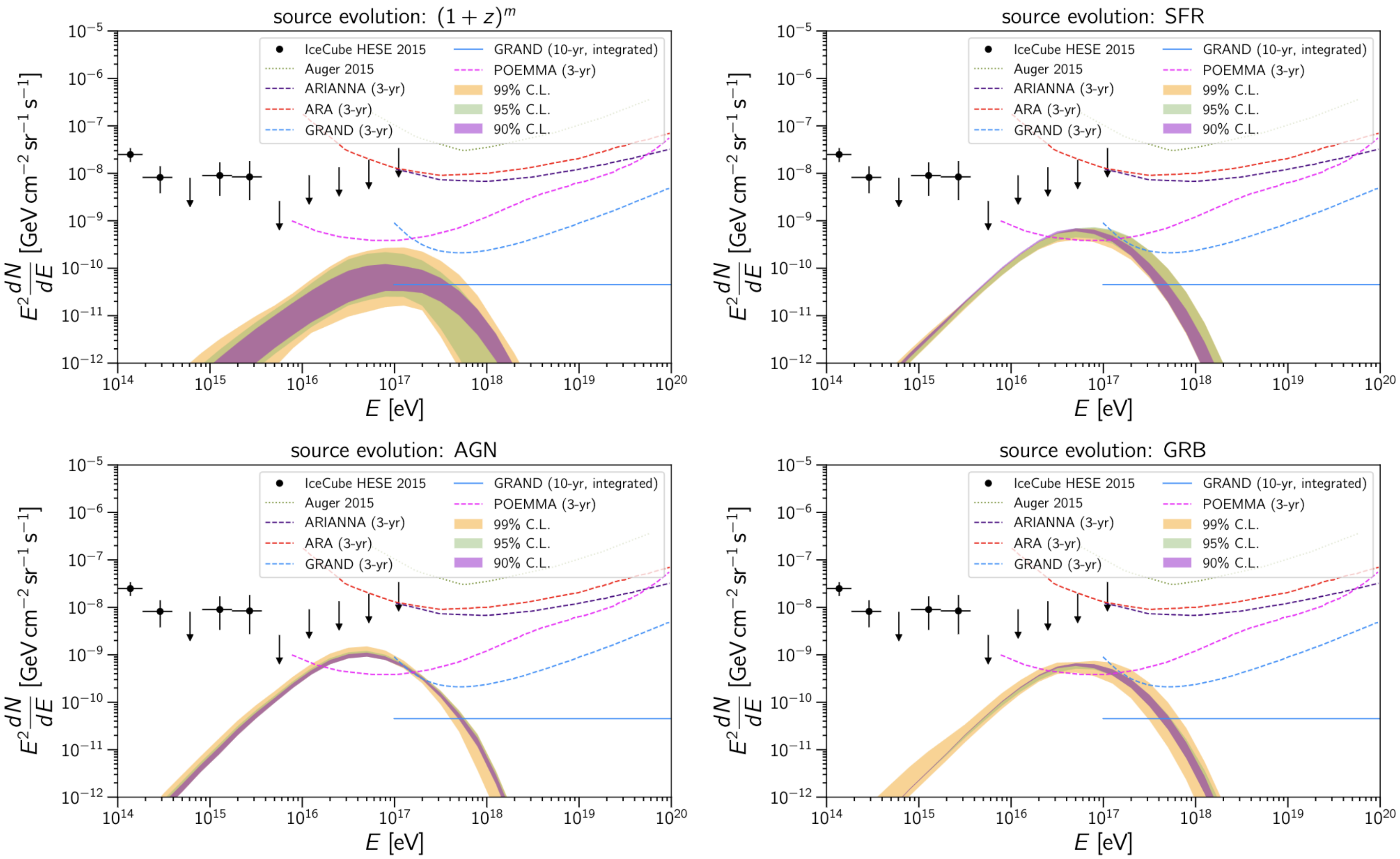
Alves Batista et al, JCAP (2019) 002

m	α	$\log(\frac{R_{max}}{V})$	f_H	f_{He}	f_N	f_{Si}	f_{Fe}	χ^2_{comp}	χ^2_{spec}	χ^2
-1.6	+1.0	18.7	0.0003	0.0101	0.8906	0.0990	0.0	161.1	17.6	178.7
SFR	-1.3	18.2	0.1628	0.8046	0.0309	0.0018	0.0	184.4	19.9	204.3
AGN	-1.0	18.2	0.8716	0.0778	0.0469	0.0038	0.0	224.9	33.1	258.0
GRB	-1.5	18.2	0.5876	0.3973	0.0147	0.0004	0.0	170.8	20.1	190.9

Table 1. Best-fit parameters for specific spectral indices.

Table has different CR source evolution assumptions.

Cosmogenic neutrinos



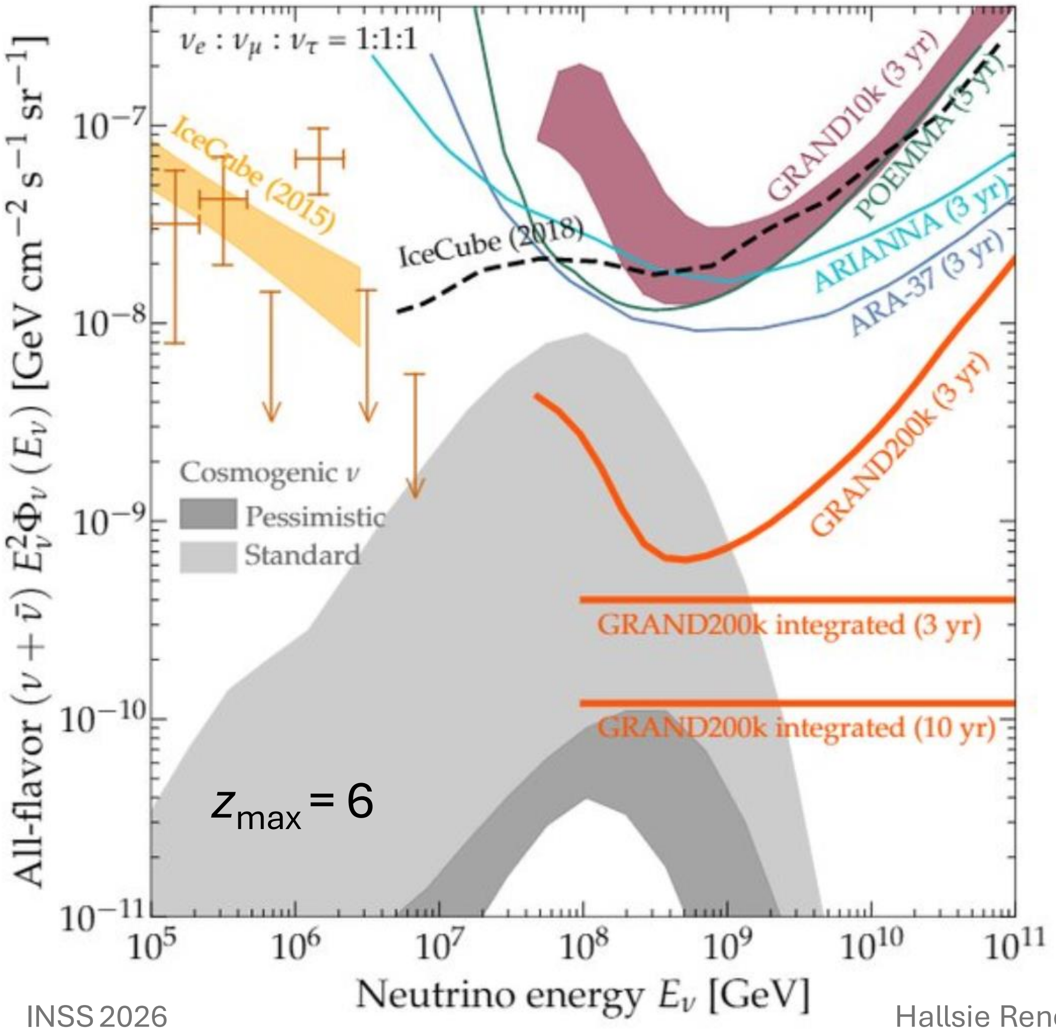
Alves Batista et al, JCAP (2019) 002

All flavor, CR best fits with different source evolution assumptions, z_{max}=5.

Depends on:

- spectral index
- max energy
- composition
- luminosity
- evolution

Cosmogenic neutrino flux



Guaranteed flux, but not guaranteed to be large.

Fig. from GRAND, SciPost Phys. Proc. 10, 027 (2022), Alves Batista et al, JCAP (2019) 002, $z_{max} = 6$

Next time

- **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