Diffuse Astrophysical Neutrinos: The Multi-Messenger Landscape and Neutrino Production

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PC: Martin Wolf, IceCube/NSF

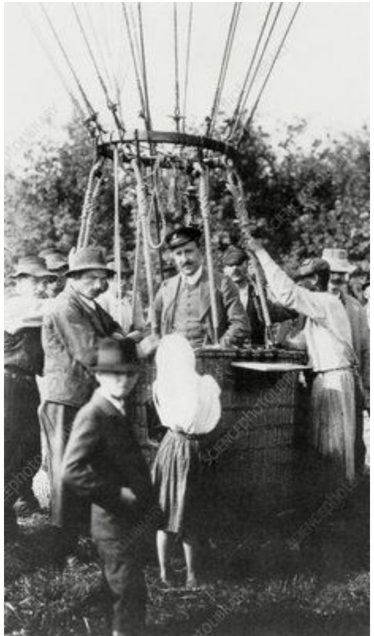
Outline

- **Neutrinos and Cosmic Rays**
- Neutrino Production Mechanisms
- Neutrino Source Models
- Searches for astrophysical neutrinos
- Outlook

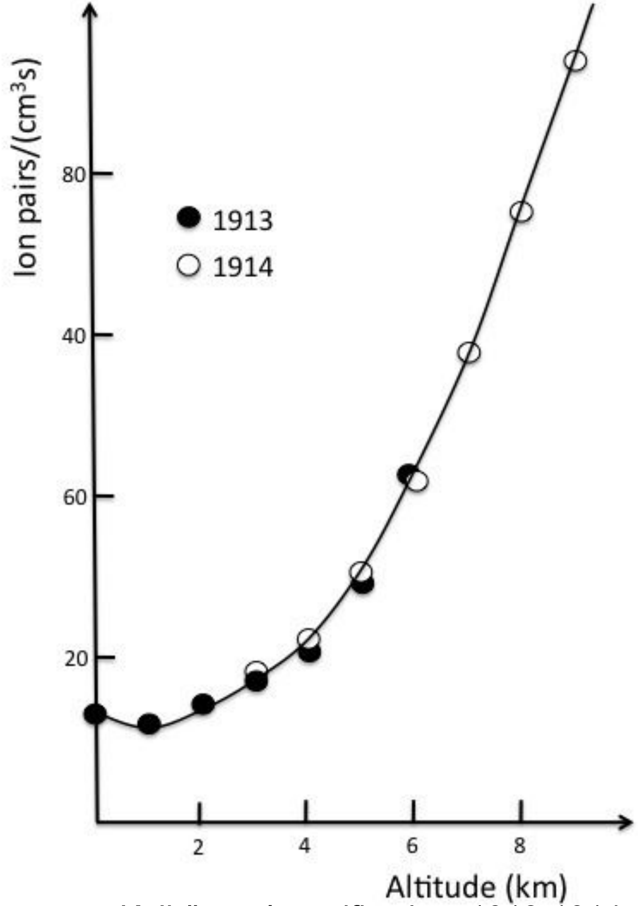
What Are Cosmic Rays?

- Ionized nuclei from space

- First studied by Victor Hess, who found the charged background radiation increased with altitude
  → originates above the atmosphere



Victor Hess, 1912
Wikimedia Commons

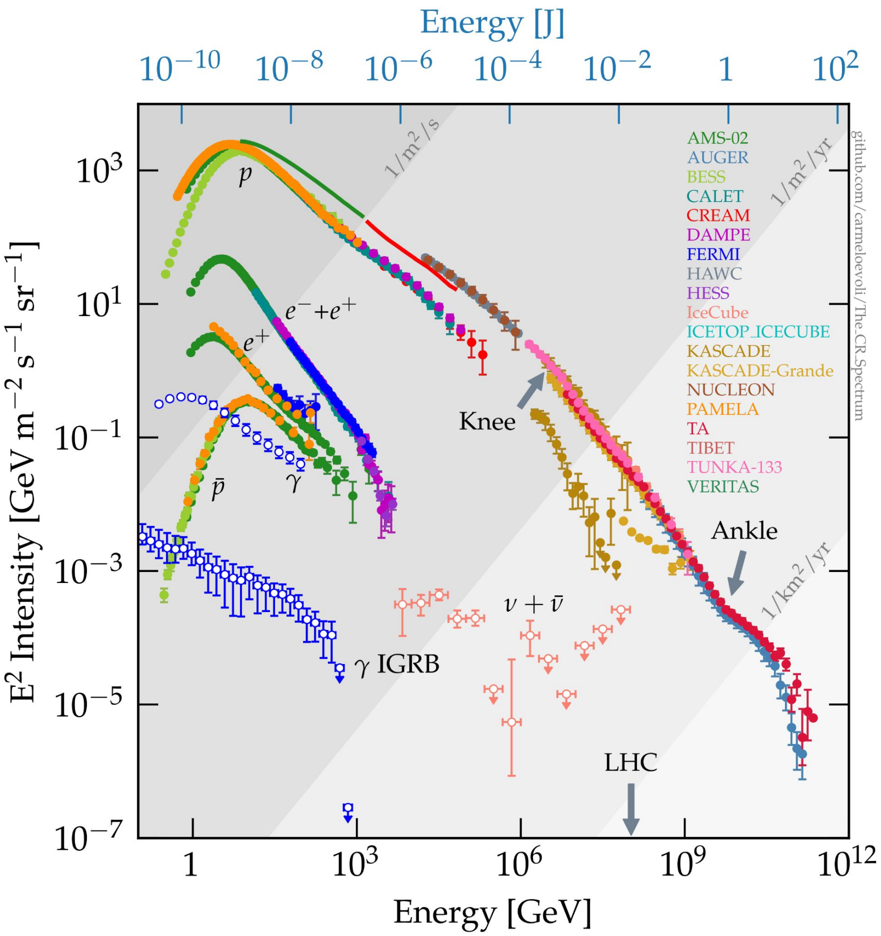


Kolhörster's verification, 1913-1914
Wikimedia Commons

Properties of Cosmic Rays

What we know:

- Charged particles from space
- The spectrum is a **power law** following $E^{-2.7}$ up to the 'knee', softening to ~E^{-3}, before hardening again at the 'ankle'
- Above ~50 EeV, the flux of charged particles is suppressed due to resonant interaction with the cosmic microwave background, known as the GZK cutoff



Swordy Plot
Evoli, C. 2020

Properties of Cosmic Rays

What we don’t:

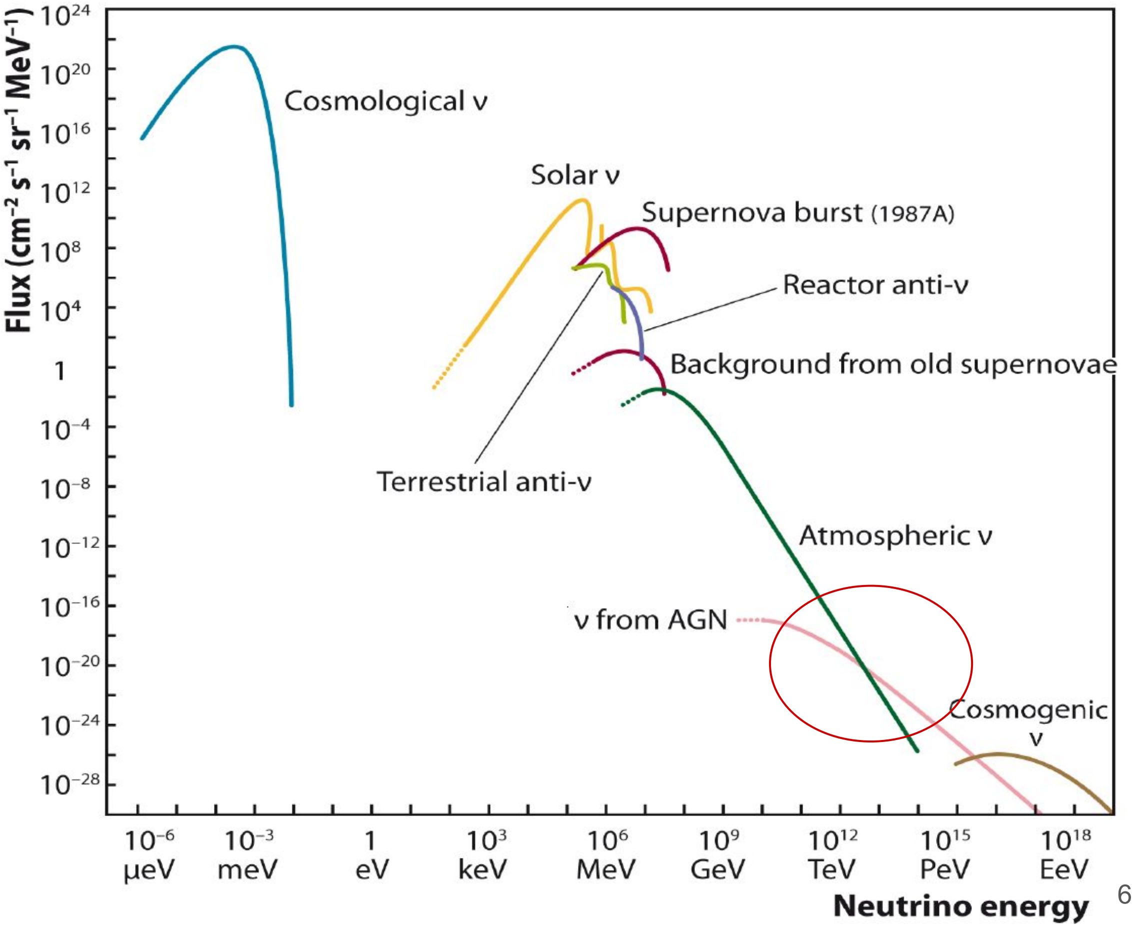
- Where are the highest energy cosmic rays produced?
  - As charged particles, they are deflected by cosmic magnetic fields as they travel

- How are they accelerated?
  - We know that their energies are high enough to preclude confinement in galactic magnetic fields

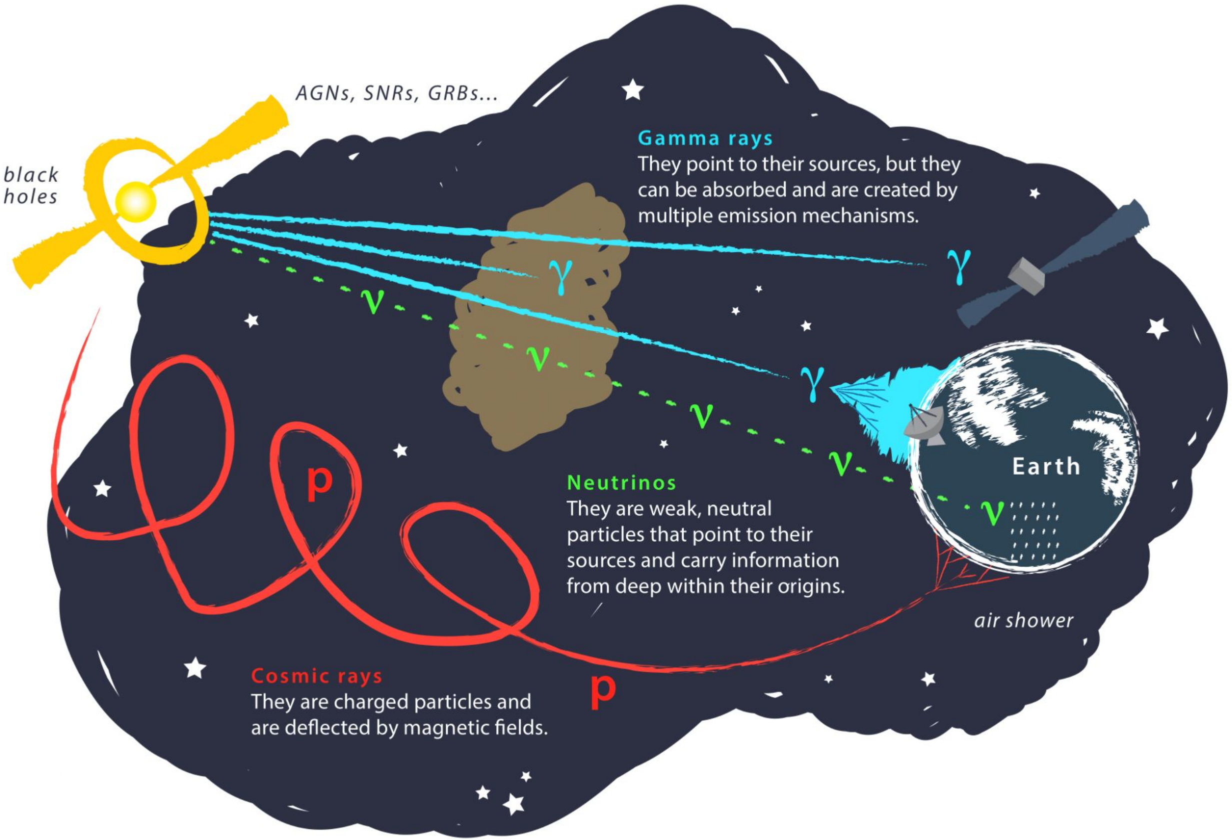
- What causes the ‘knee’ and ‘ankle’ features?
  - The ‘knee’ is a spectral softening (steepening) observed at 3 PeV.
  - A further steepening is observed at around 100 PeV, known as the ‘second knee’, followed by the ‘ankle’ a hardening around 10 EeV.
  - hypothesized to be caused by a composition dependent transition from galactic cosmic rays to extragalactic cosmic rays

Neutrino Sources

- Neutrino spectra cover multiple orders of magnitude, from a plethora of sources
- Diffuse cosmic neutrino analyses focus on characteristics of astrophysical neutrino flux in the TeV-PeV range
- Isotropic nature indicates extragalactic origin, possibly from sites of cosmic ray acceleration



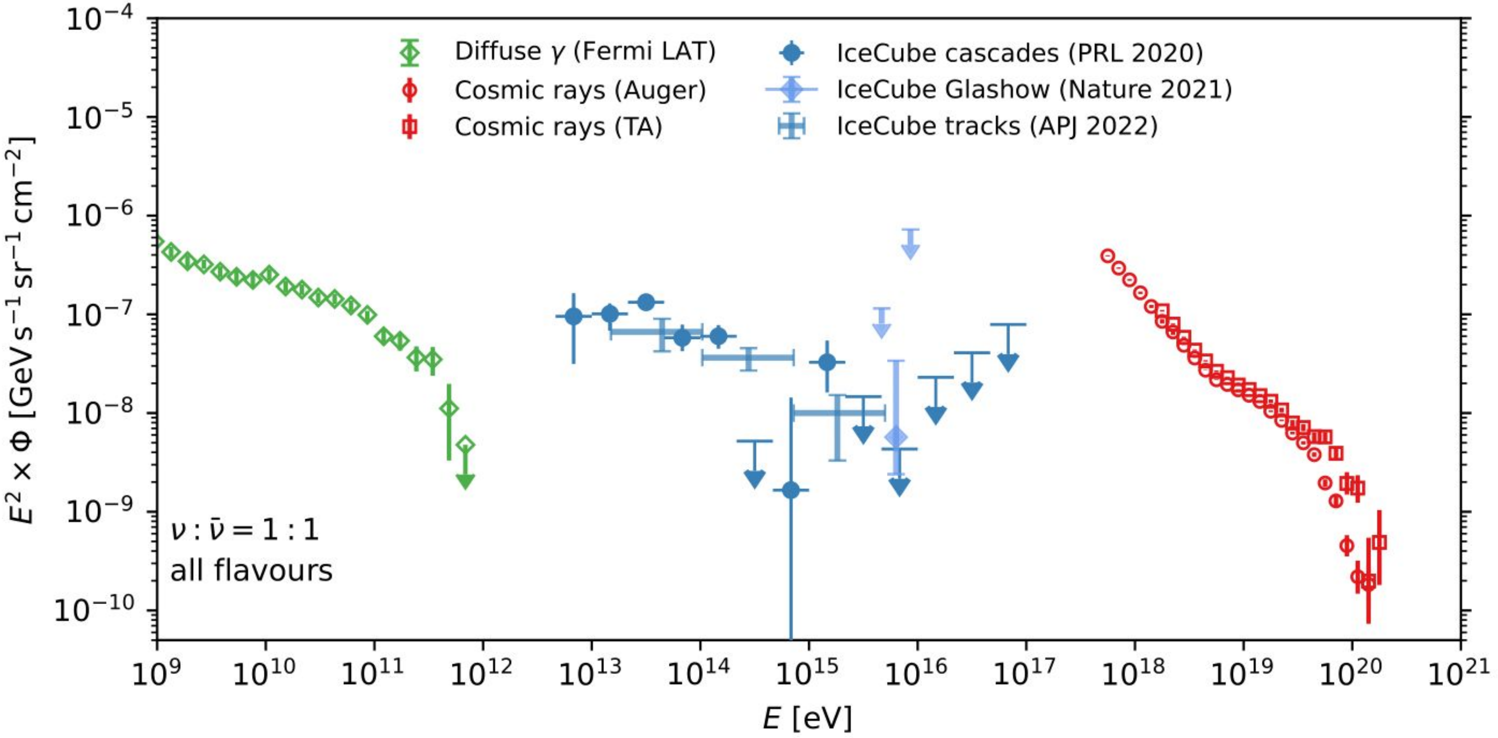
Cosmic Messengers



J. Aguilar and J. Yang for the IceCube Collaboration

Multimessenger Astronomy

Energy density of high energy neutrinos similar to γ-ray flux, and Ultra High Energy Cosmic Rays (UHECRs)



Ackermann, M., et al. Journal of high energy astrophysics 36 (2022)

The connection between cosmic messengers

- Production of neutrinos from charged pion decay linked to gamma-ray photons from neutral pion decay
- Assuming cosmic rays produce neutrinos, a calorimetric bound exists on the maximum flux of high energy neutrinos (Waxman-Bahcall limit)
- Cosmogenic neutrinos arise from cosmic ray interactions with the CMB

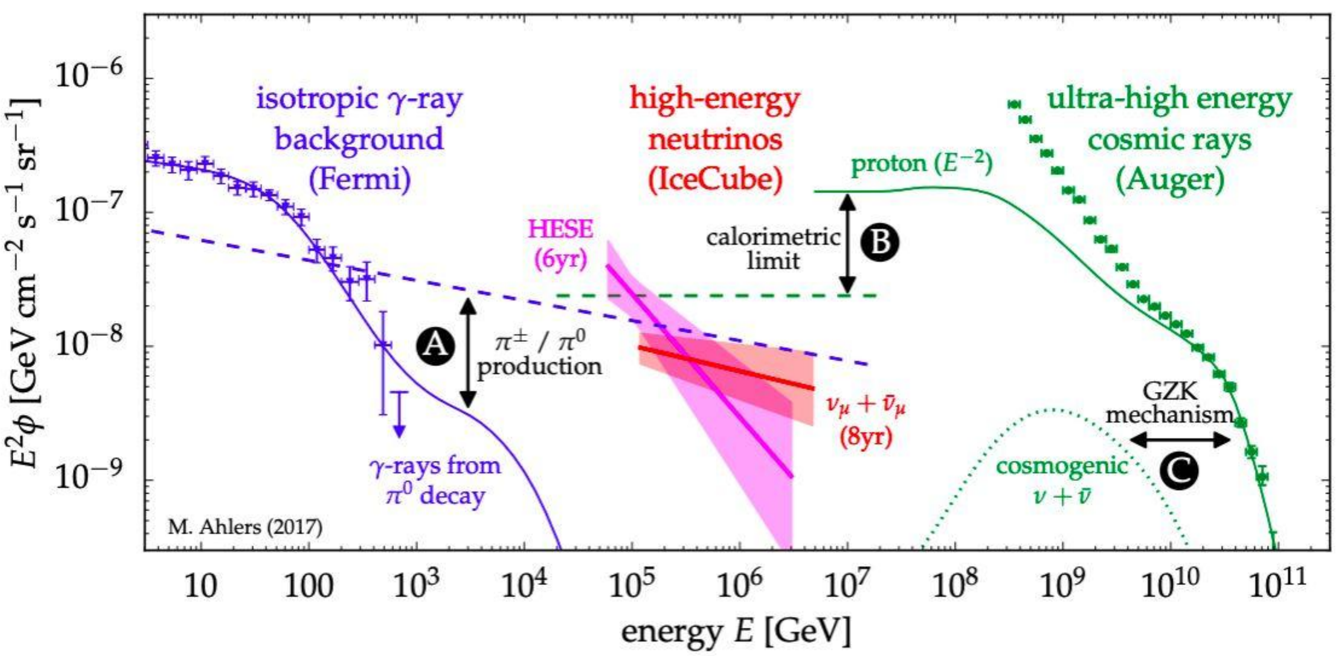


Fig: Ahlers, M., & Halzen, F. (2018). Progress in Particle and Nuclear Physics, 102, 73-88.

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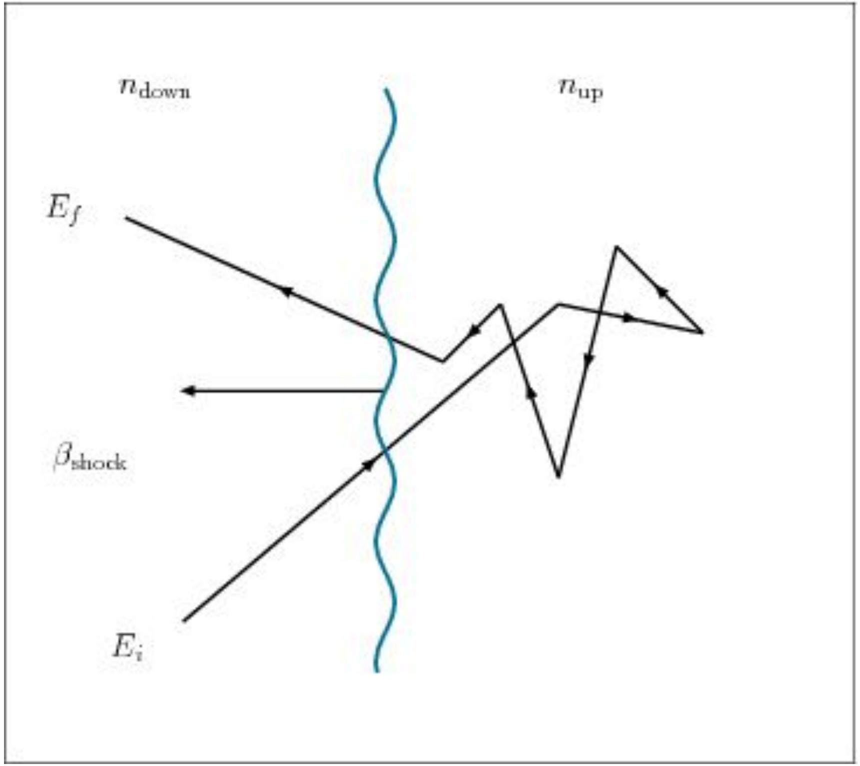
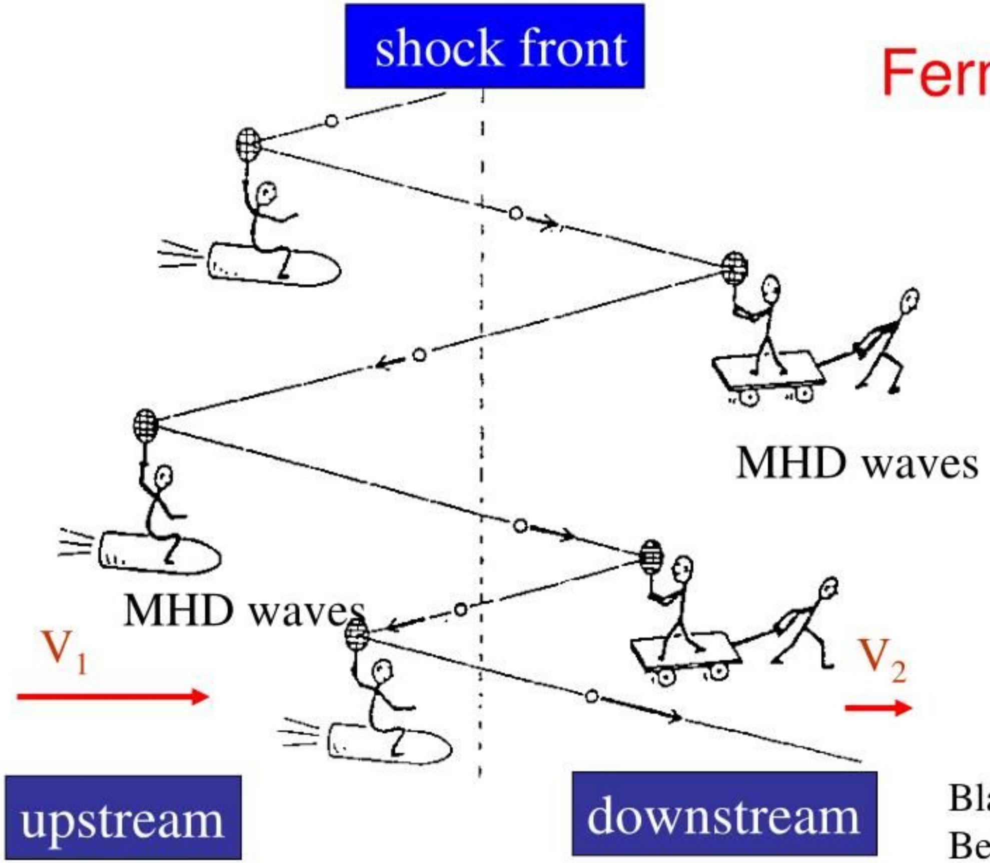
Fermi Acceleration of Cosmic Rays

- Can explain how protons and nuclei are accelerated to high energies
- First order: Accelerates particles by crossing back and forth over a shock boundary
- Second order: Accelerates particles by scattering off plasma clouds
- Results in a **power law energy distribution** as seen in the cosmic rays
- Requires a magnetic field to confine the particles to the acceleration region



Diffusive Shock Acceleration

Fermi Model



$$N(E) \propto E^{-s},$$

$$s = \frac{r+2}{r-1} \Rightarrow 2$$

Blandford & Ostriker, 1978
Bell 1978

Cartoon by M Hoshino, 2011

How does this give us a power law?

- Consider an iterative acceleration where a particle of energy E_0 increases its energy by $\Delta E = \epsilon E$ per cycle, and has a probability of escape from the acceleration region P_{esc}

- Then, after n cycles

$$E_n = E_0(1+\epsilon)^n$$

$$N(>E_n) \propto \sum^{\infty}(1-P_{\rm esc})^n = \frac{(1-P_{\rm esc})^n}{P_{\rm esc}}$$

$$N(>E_n) \propto \frac{(1-P_{\rm esc})^{ln(\frac{E_n}{E_0})/ln(1+\epsilon)}}{P_{\rm esc}}$$

$$= \frac{1}{P_{\rm esc}}(\frac{E_n}{E_0})^{ln(1-P_{\rm esc})/ln(1+\epsilon)}$$

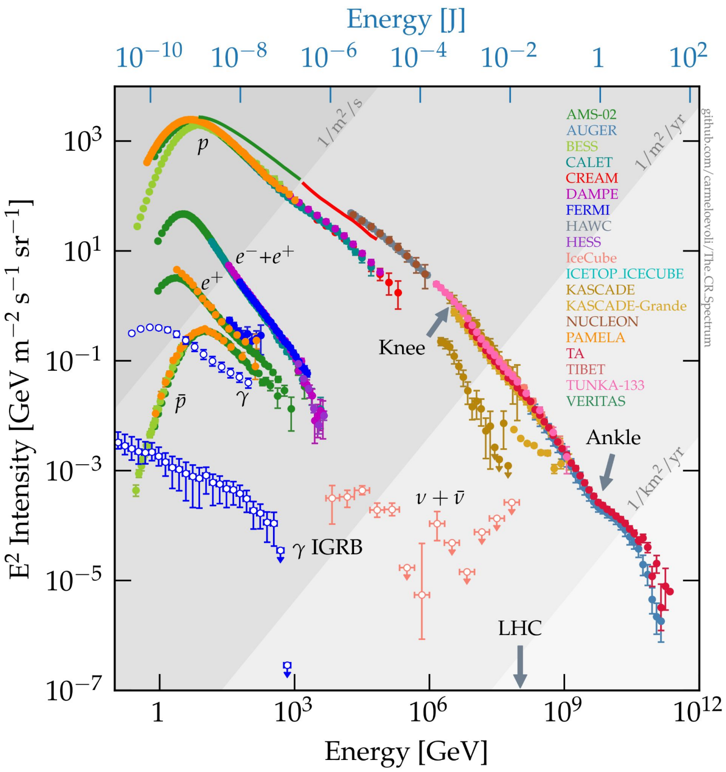
$$\sim \frac{1}{P_{\rm esc}}(\frac{E_n}{E_0})^{-\frac{P_{\rm esc}}{\epsilon}}$$

Astrophysical Neutrinos

Interactions create pions and kaons, which decay into neutrinos and gamma rays

How are neutrinos produced from cosmic rays?

- Accelerated cosmic rays interact with photons in the ambient radiation field (p-γ interaction), or with protons in a gaseous environment (p-p interaction)
- In p-p interactions, pions are produced even at GeV proton energies, and inherit the power law spectrum of their parents.
- When the p-γ interaction is considered, the production of pions has a sharp resonance at the Δ+ mass of 1232 MeV.



How are neutrinos produced from cosmic rays?

- The major channels through which neutrinos are produced at cosmic accelerators are through the weak decays of pions and kaons

- The leptonic decay products carry on average 25% of the energy of the parent pion, translating to about 5% of parent proton energy

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})(\ 100\%)$$

$$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})(\ 63.5\%)$$

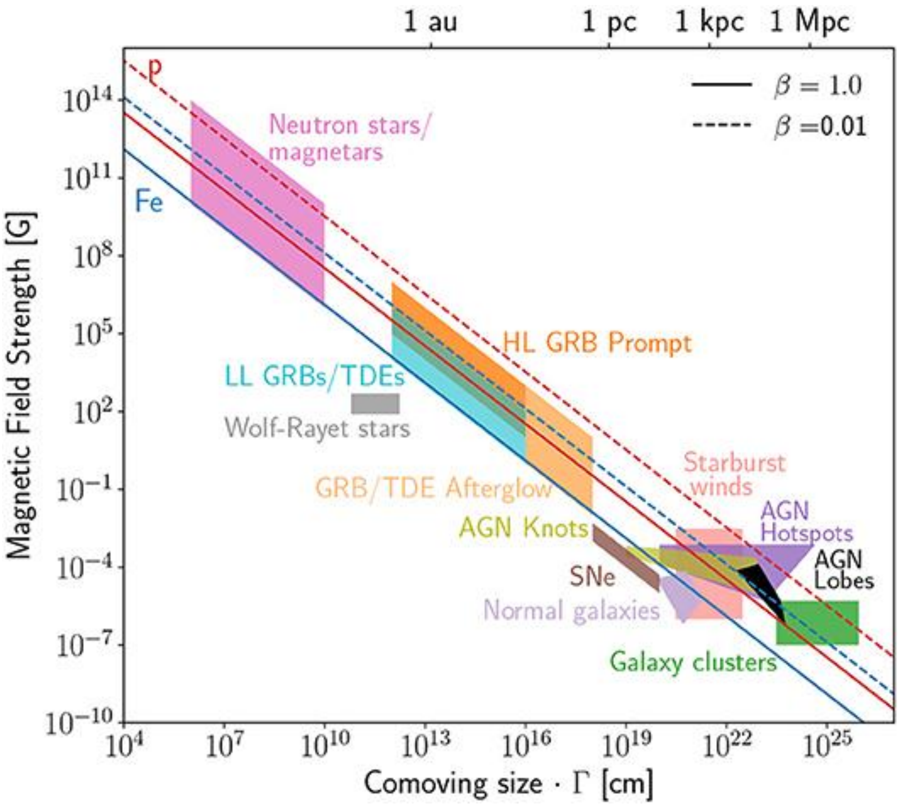
$$K_{L} \rightarrow \pi^{\pm} + e^{\pm} + \nu_{e}(\bar{\nu}_{e})(\ 38.7\%)$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

Characteristics of cosmic accelerators

- If we define the escape probability in terms of the characteristic periods of the acceleration and escape phenomena, T_{acc} and T_{esc} , we may define $P_{esc} = T_{acc}/T_{esc}$
- An accelerator with a certain characteristic T_{acc} must have an upper bound on the energy to which it can accelerate particles
- This also imposes a bound on the confinement volume of an accelerator. If the gyroradius of a particle exceeds the radius of the accelerator, it is no longer confined (**Hillas** criterion)

A Hillas Plot



Alves Batista, R., et al,, 2019. Open questions in cosmic-ray research at ultrahigh energies. *Frontiers in Astronomy and Space Sciences*, *6*, p.23.

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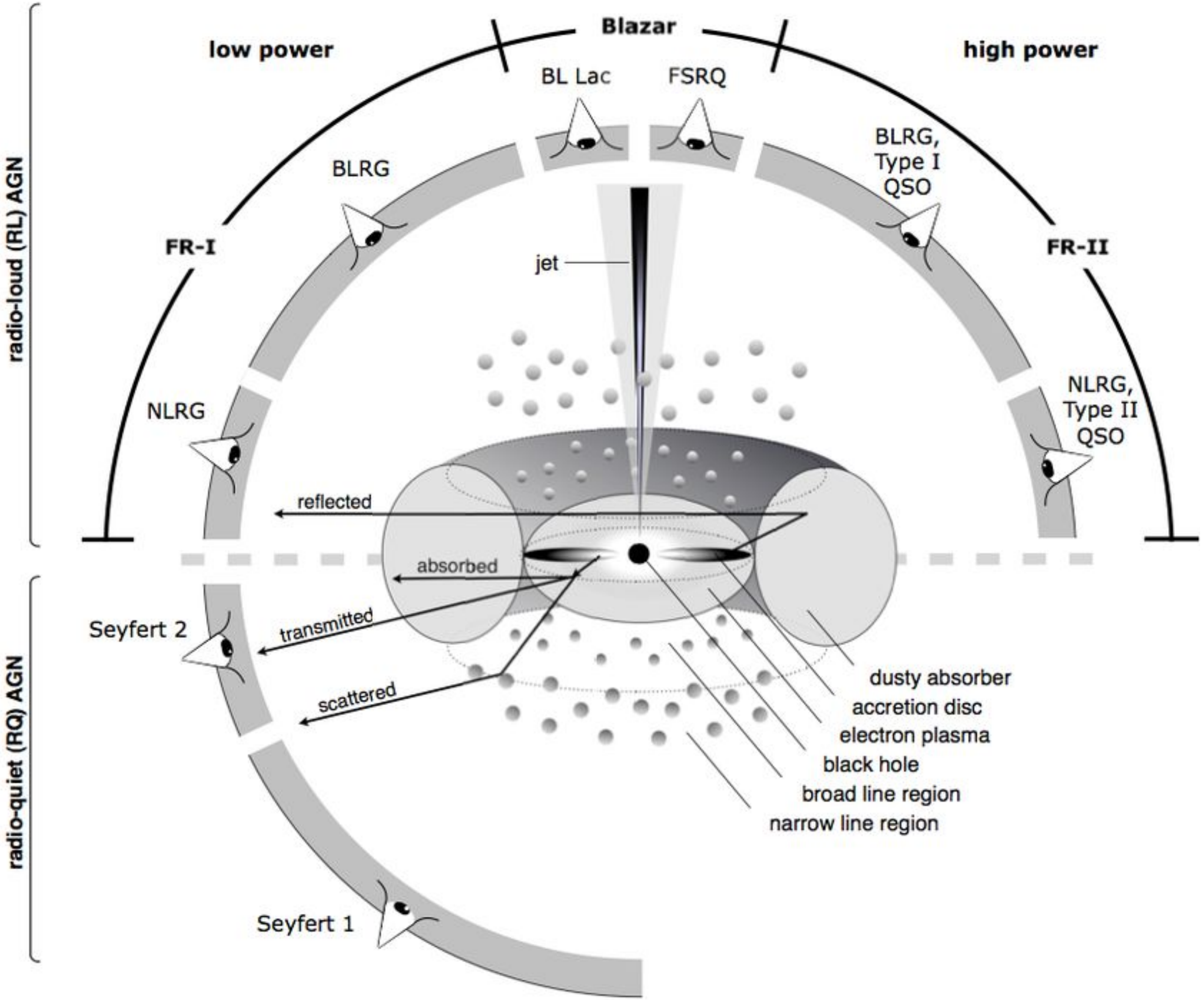
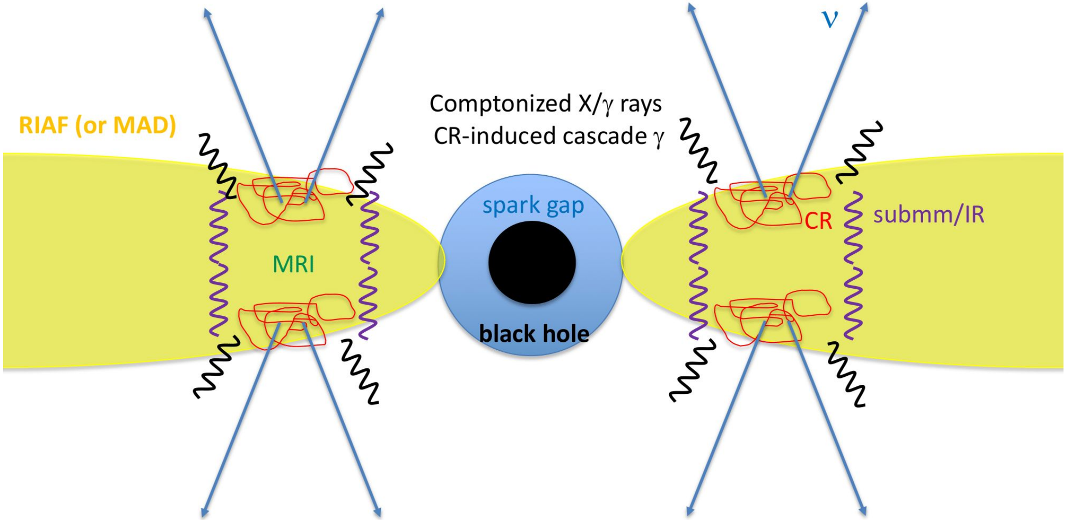
AGN Classification



Ref: V. Beckmann and C. Shrader.
Active Galactic Nuclei.

Neutrino Production from AGNs: Disks

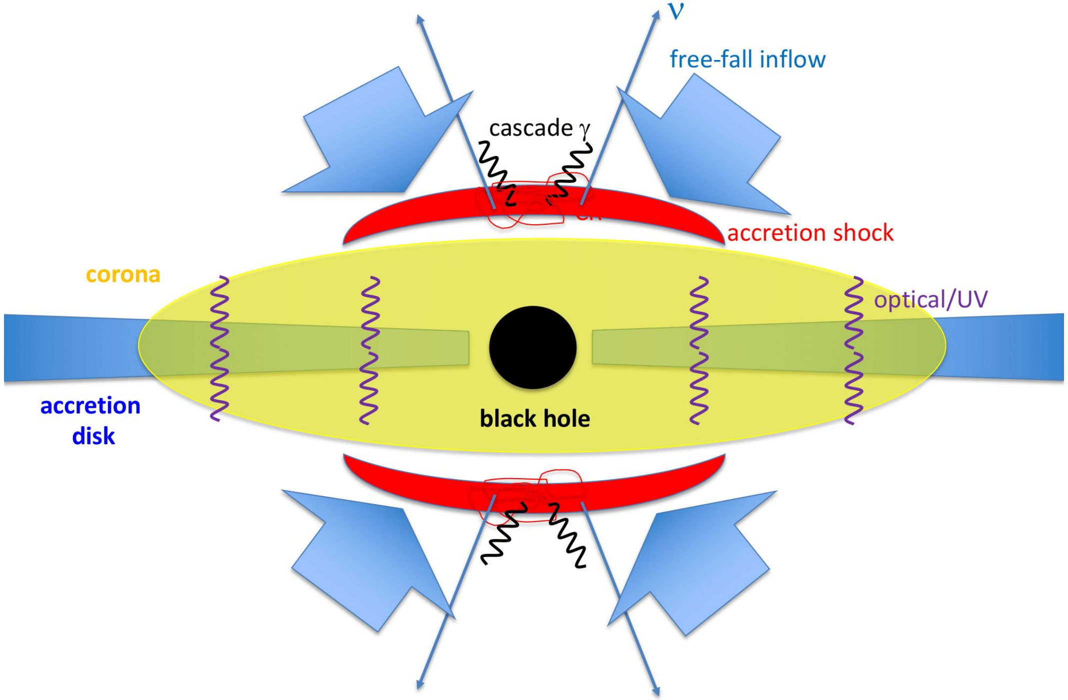
- Infalling matter heats up disk which radiates in UV/X-ray spectrum
- In low luminosity radiatively inefficient disks, protons can be accelerated by mag. reconnections/MHD turbulence
- They interact with disk gas emitting pions



Ref: K. Murase and F. W. Stecker. "High-energy neutrinos from active galactic nuclei." In The Encyclopedia of Cosmology: Set 2: Frontiers in Cosmology Volume 2 Neutrino Physics and Astrophysics, pp. 483-540. 2024.

Neutrino Production from AGNs: Accretion Shock

- Accretion shock created by infalling matter accelerates protons
- Disk produces thermal UV photons (10 eV), with X-ray radiation in the corona
- Calorimetric photomeson production expected to emit PeV neutrinos
- Gamma rays created from Comptonized disk photon



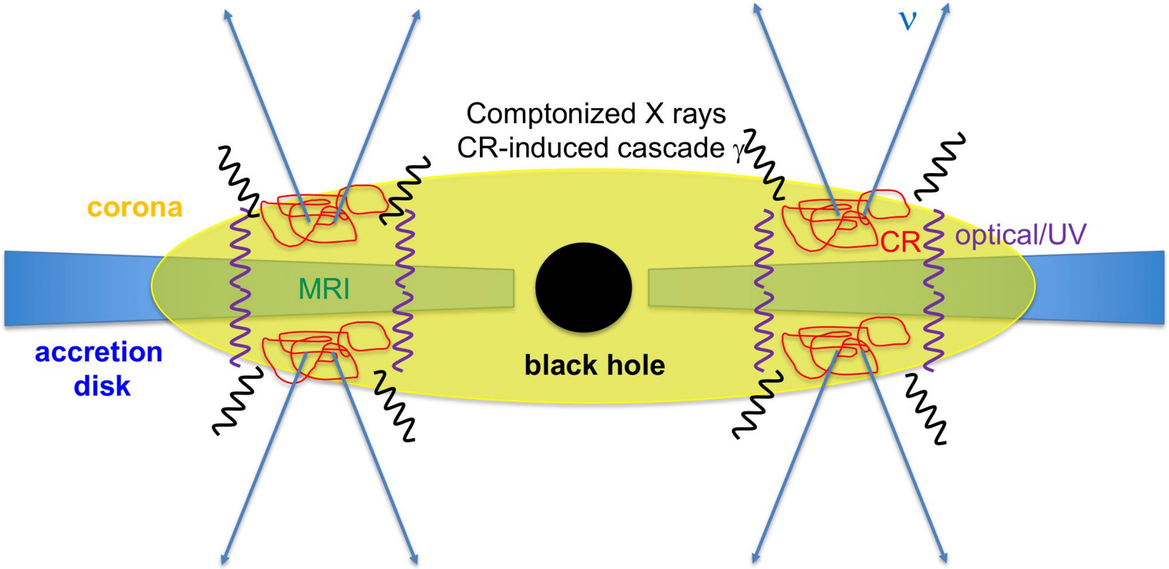
Ref: K. Murase and F. W. Stecker. "High-energy neutrinos from active galactic nuclei." In The Encyclopedia of Cosmology: Set 2: Frontiers in Cosmology Volume 2 Neutrino Physics and Astrophysics, pp. 483-540. 2024.

Neutrino Production from AGNs: Magnetized Corona

- Stochastic proton acceleration in magnetized corona

- Efficient p-p interactions expected in corona

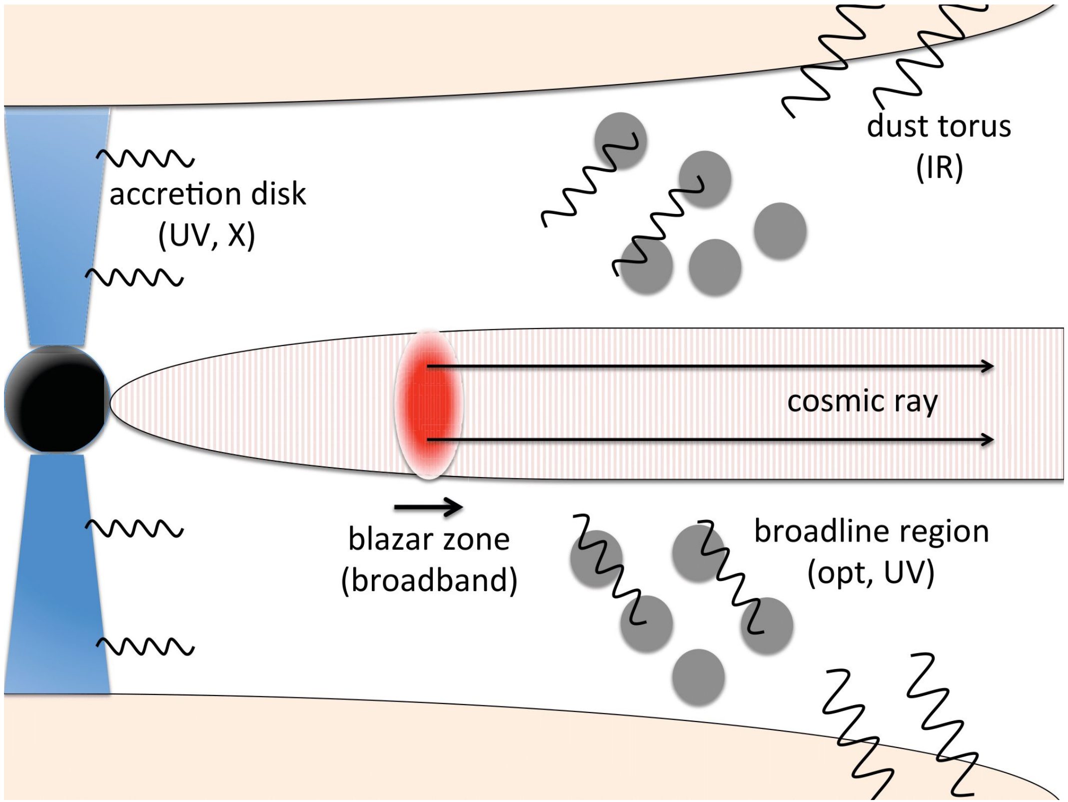
- Predicts 10-100 TeV neutrino emission



Ref: K. Murase and F. W. Stecker. "High-energy neutrinos from active galactic nuclei." In The Encyclopedia of Cosmology: Set 2: Frontiers in Cosmology Volume 2 Neutrino Physics and Astrophysics, pp. 483-540. 2024.

Neutrino Production from Blazars: Jets

- Acceleration by shocks or by magnetic reconnections
- Photopion production with electron synchrotron photons
- Observed blazar flux unlikely to be dominant contribution to IceCube diffuse flux



Ref: K. Murase and F. W. Stecker. "High-energy neutrinos from active galactic nuclei." In The Encyclopedia of Cosmology: Set 2: Frontiers in Cosmology Volume 2 Neutrino Physics and Astrophysics, pp. 483-540. 2024.

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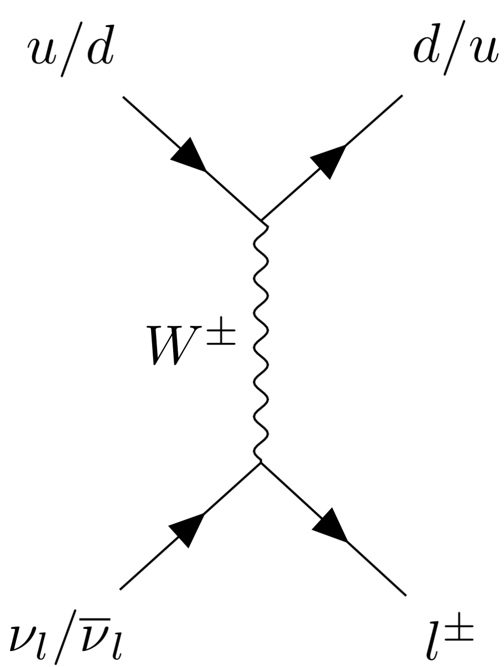
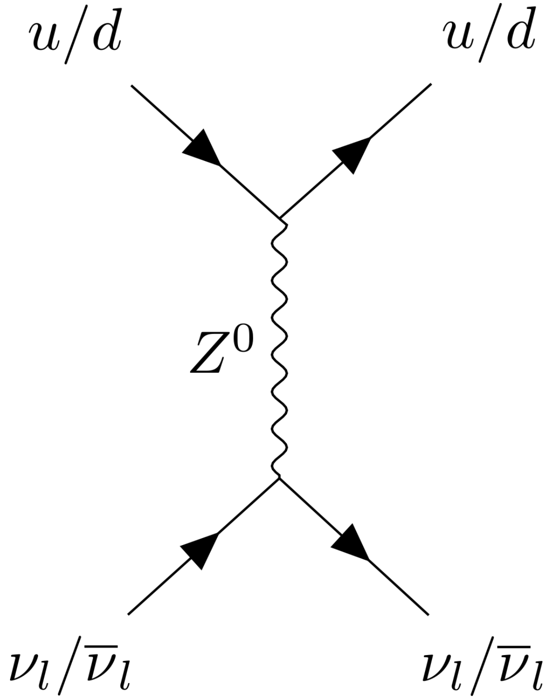
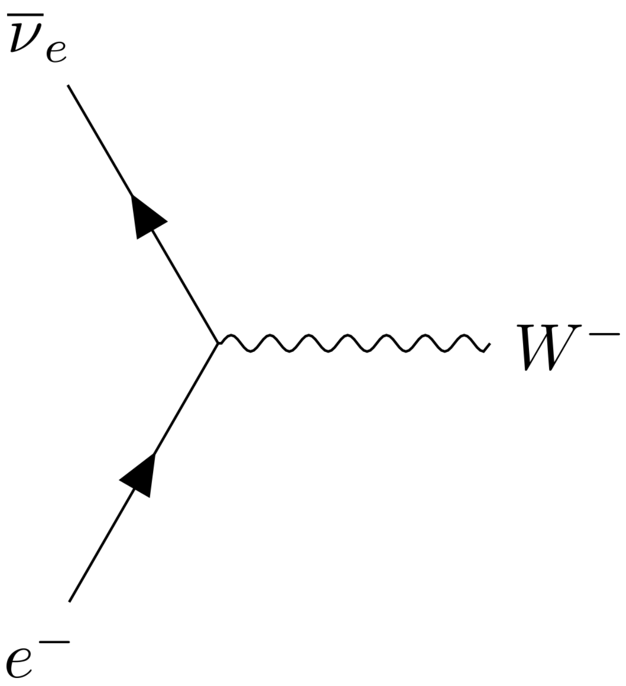
Neutrino Interaction Channels



Charged current interactions yield an outgoing charged lepton and a hadronic shower



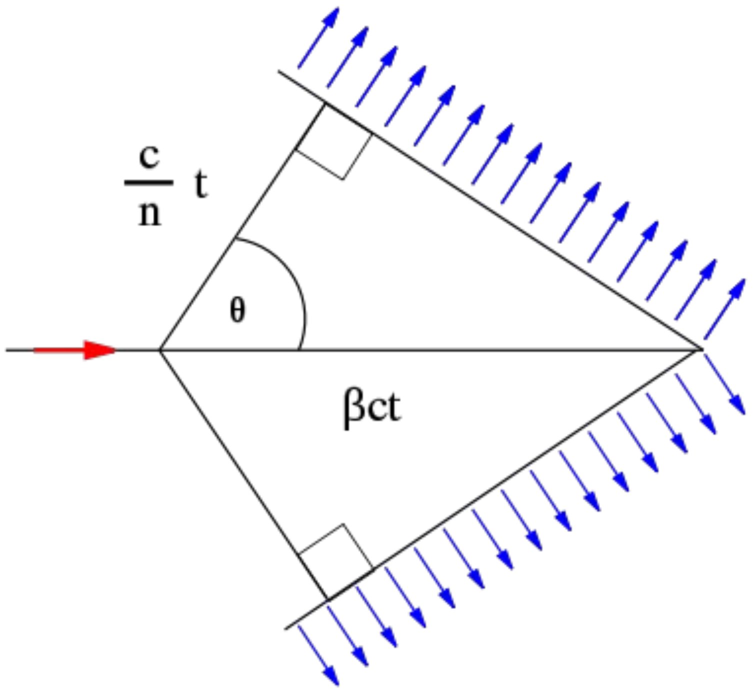
Neutral current interactions have an outgoing scattered hadron and neutrino



Glashow Resonance interactions yield an on-shell W^- boson, which subsequently decays

Observing neutrino interactions via the Cherenkov effect

- **Charged particles deposit energy** as they travel through matter
- When charged particles travel faster than the speed of light in a medium, they emit Cherenkov radiation
- A **cone of light is formed** determined by Cherenkov angle, θ_C
- Cherenkov light collected by DOM photomultiplier tubes (PMTs), which convert the optical signal to an amplified electrical signal

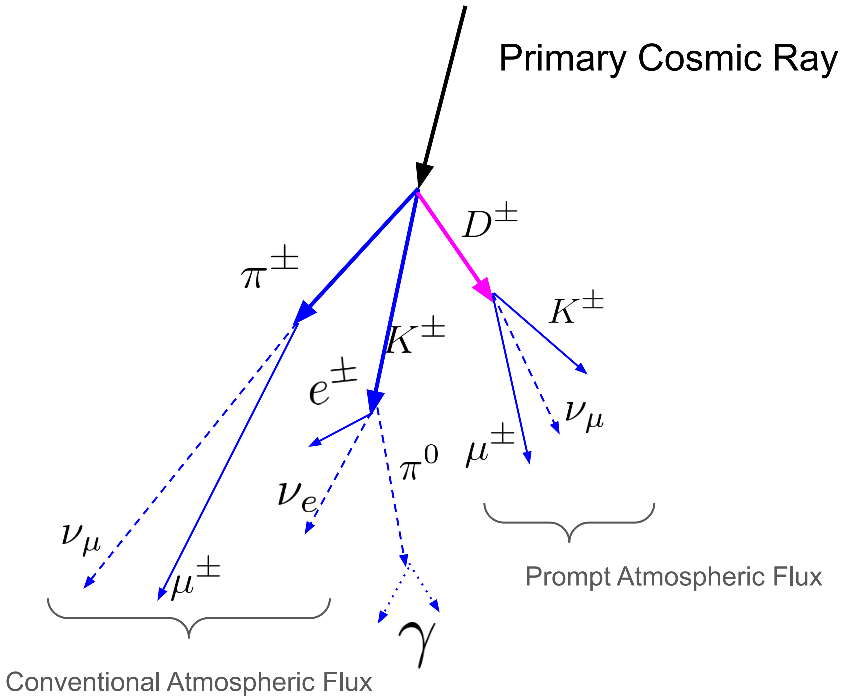


In ice: $\theta_C = 40.2°$

Wikimedia Commons

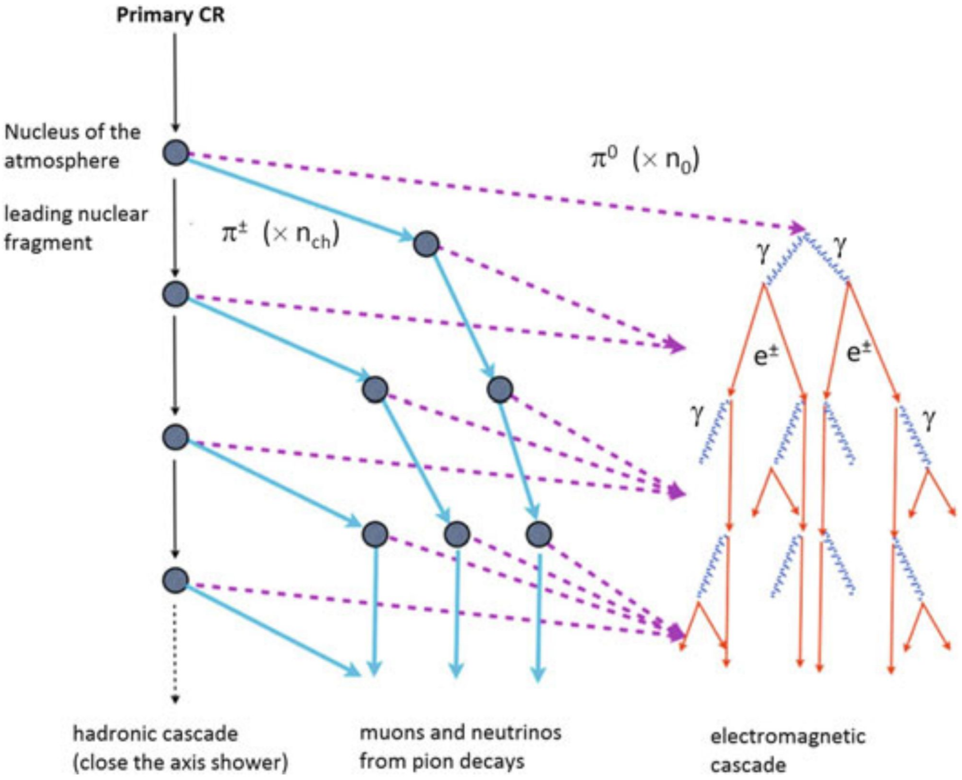
Atmospheric Background

- Main background from atmospheric muons
- Neutrinos also produced in atmospheric cosmic rays interactions.
- Conventional flux from pion/kaon decay follows ~$E^{-3.7}$
- Prompt contribution from charmed meson decay- follows ~$E^{-2.7}$



Air Shower Development

- Charged pion decay to muons and muon neutrinos
- Bulk of atm. neutrino production at high energy from $K^{\pm}$ decay
- Electron neutrinos primarily arise from 3 body kaon decay
- Isotropic prompt flux predicted from D meson decay



Di Sciascio, G. (2022). *Applied Sciences*, *12*(2), 705.

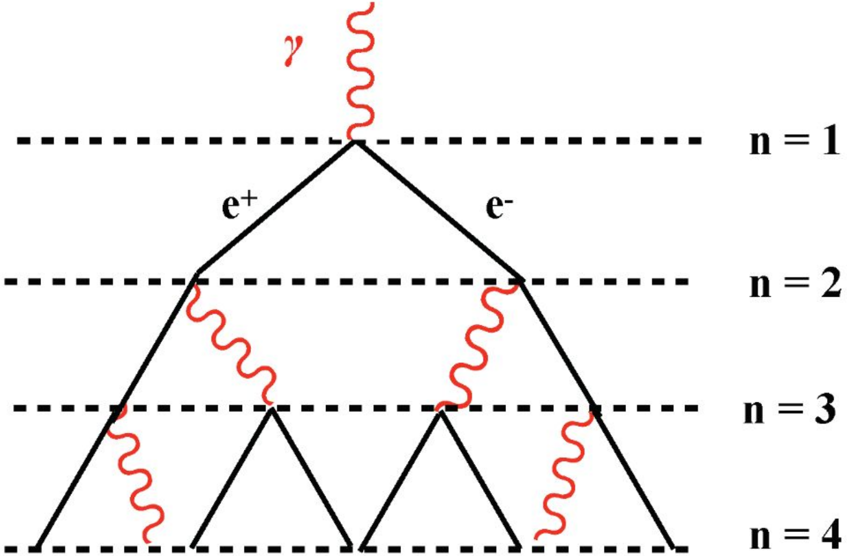
Electromagnetic Cascade Development

- Cascade develops via Bethe-Heitler pair production and electron bremsstrahlung

- Shower maximum when particle energy < E_c , at depth $\log_2(E_0/E_c)$

- $N(>E)=(E_0/E)/\ln 2$

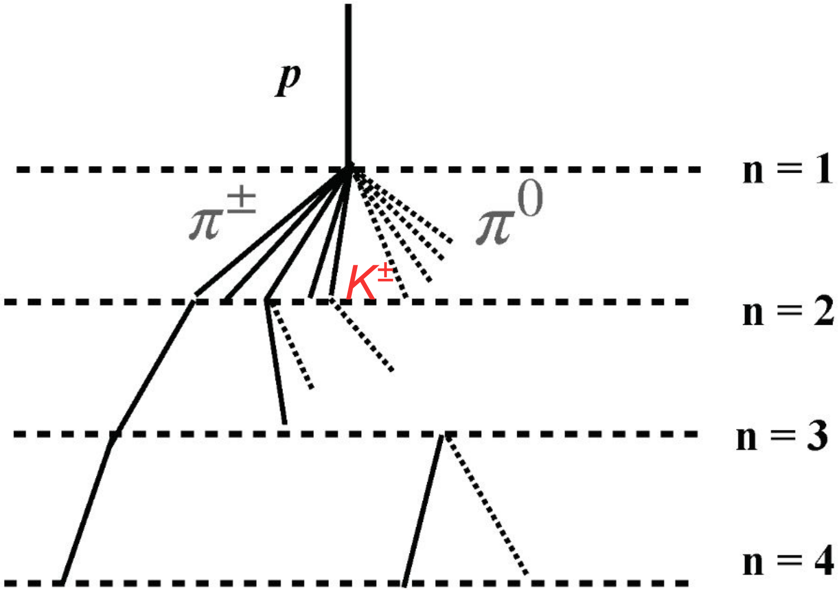
- Beyond shower maximum, particles lose energy via ionization losses
  $L \propto E_0/E_c$



Di Sciascio, G. (2022). *Applied Sciences*, *12*(2), 705.

Hadronic Cascade Development

- EM component develops from neutral pion decay (shorter absorption length) -> more π^0 at higher energies
- Assuming $N_{\pi\pm}:N_{\pi 0}$=2:1, share of parent energy in hadronic component= ⅔=> $E_{had}=(⅔)^n\ E_{primary}$
- Interactions continue until pions and kaons reach critical energy, and then decay into muons when the decay length < interaction length

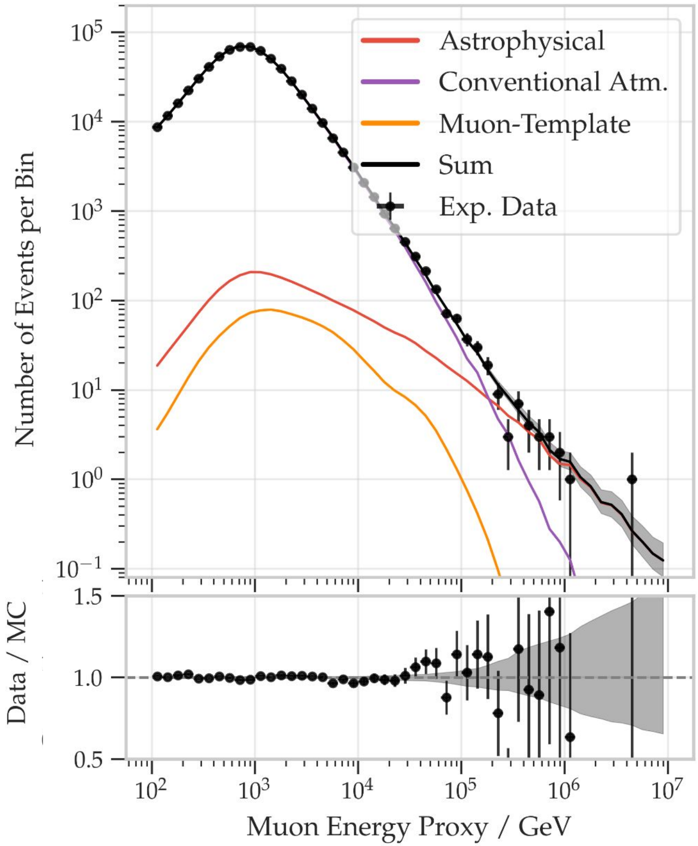


Di Sciascio, G. (2022). *Applied Sciences*, *12*(2), 705.

Atmospheric Neutrino Spectrum

- As conventional neutrinos are produced by the decay of pions produced in cosmic ray air showers, they follow a spectrum one unit steeper than the parent cosmic ray spectrum $\sim E^{-3.7}$

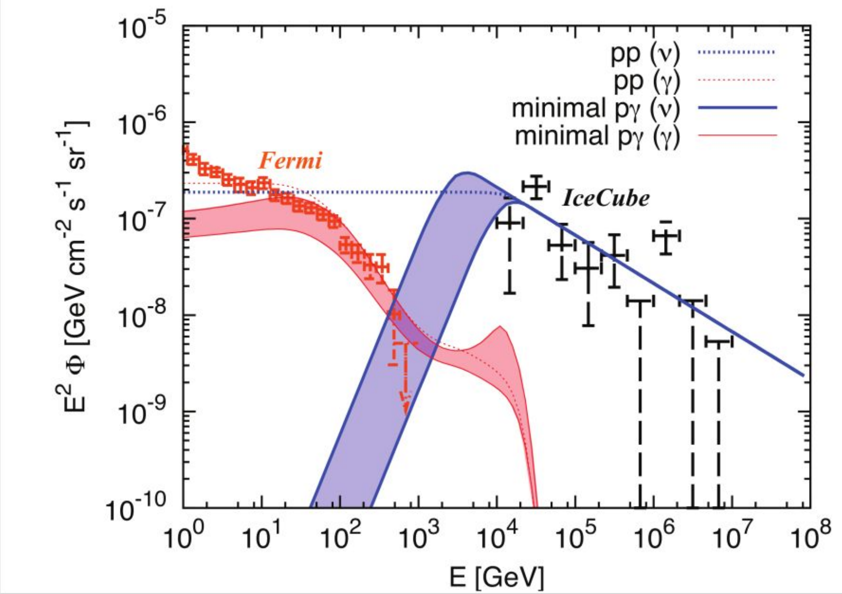
- The neutrino spectrum at Earth is therefore dominated by atmospheric neutrinos upto ~100 TeV, at which point astrophysical neutrinos predominate



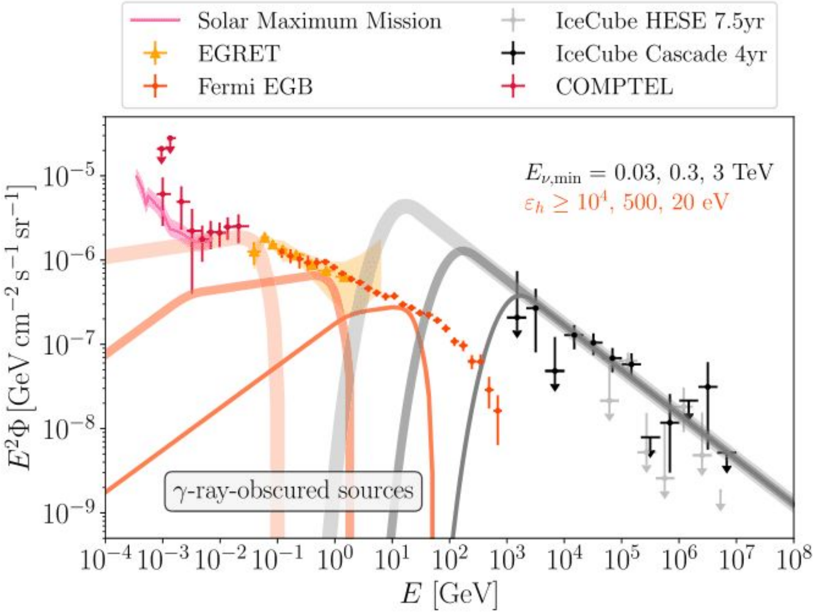
The energy distribution of upgoing tracks for the period 2010-18
The Astrophysical Journal 928.1 (2022): 50

Cosmic ray accelerator dynamics

- Extrapolation of SPL model overestimates γ-ray flux
- Low-energy cutoff may indicate sensitivity to p-p vs p-γ neutrino emission
- Neutrino energy constrains photon field at source, could indicate correlation with MeV/X-ray bright objects



Murase et al Phys. Rev. Lett. 116, 071101

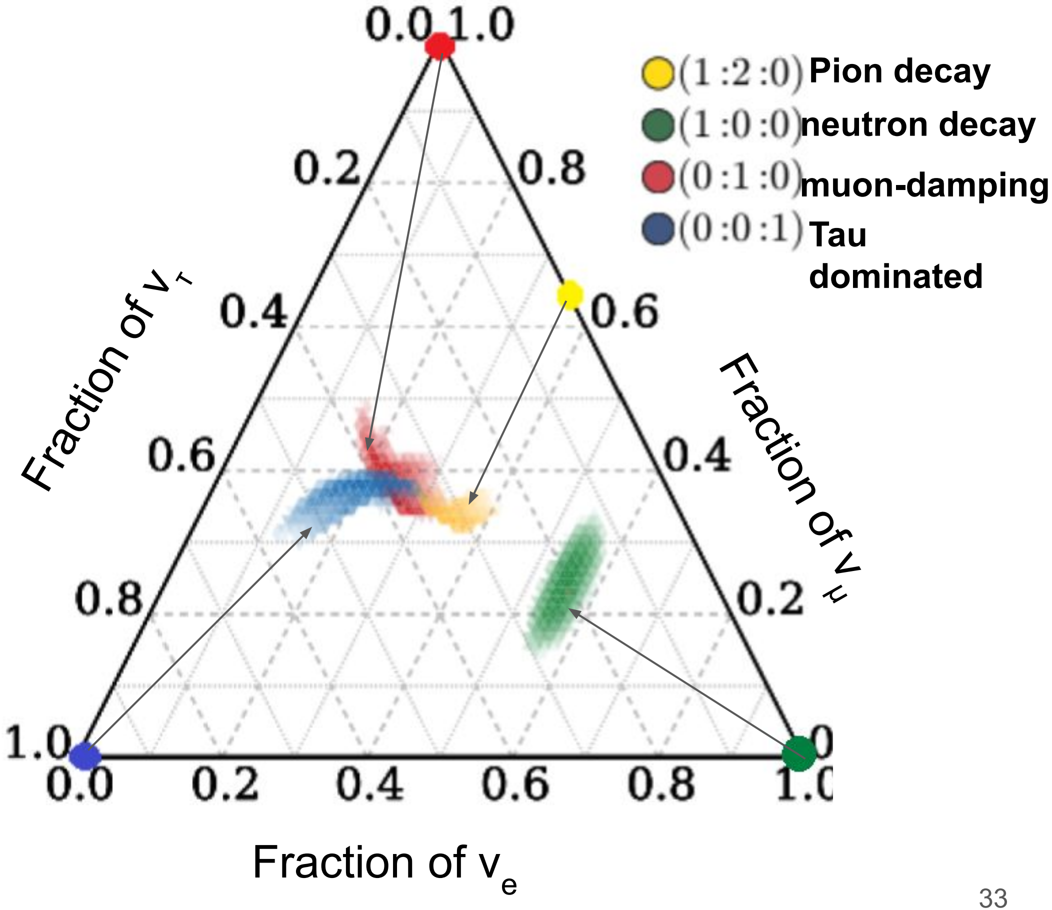


Fang et al 2022 ApJ 933 190

Neutrino Flavor Studies

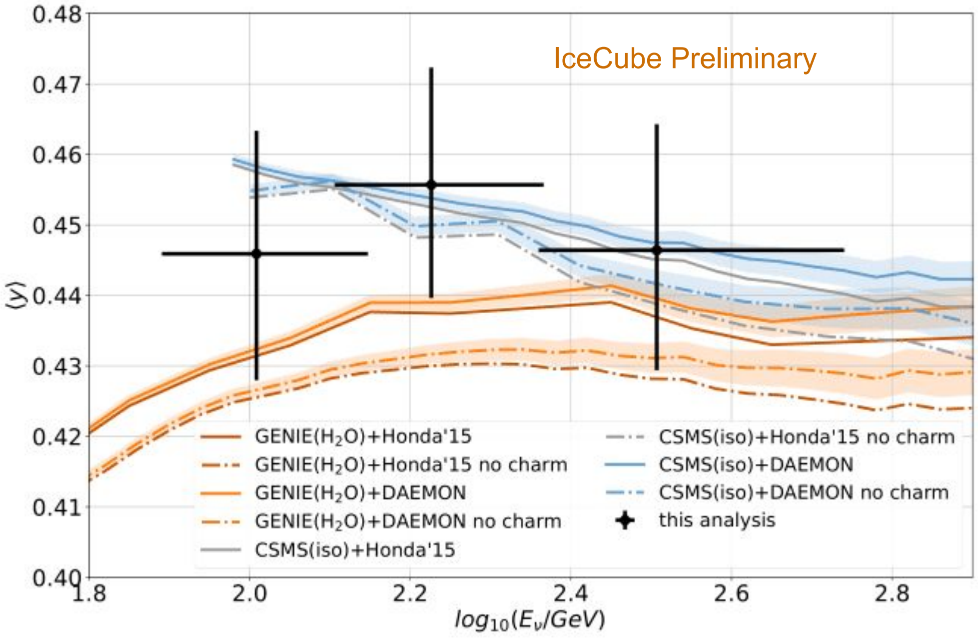
- With tracks, cascades and tau discrimination, we can study the flavour composition of cosmic neutrinos.

- These observations help constrain the source production mechanisms and possible new physics



Deep Inelastic Scattering Inelasticity measurements

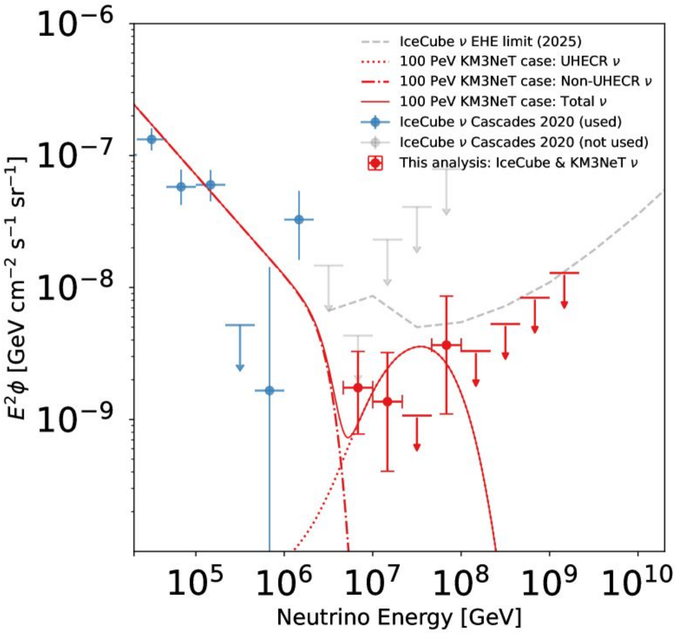
- Inelasticity measurements from 80-560 GeV
- Use atmospheric muon neutrinos
- Upcoming IceCube Upgrade expected to extend threshold below 80 GeV

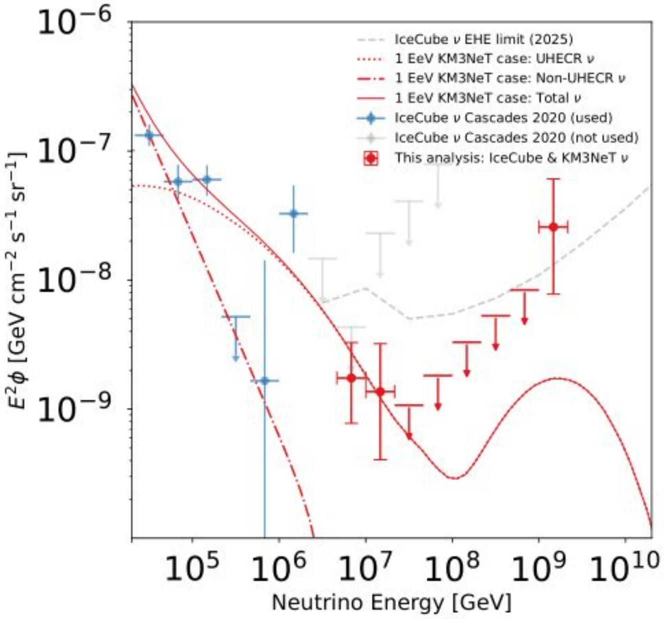


arxiv

PeV neutrino flux

- KM3NeT recently observed a neutrino of energy 220^{+570}_{-110} PeV.
- In conjunction with IceCube events observed >5 PeV (including IC190331), could indicate origin from UHECR-photon interactions





Muzio et al arXiv:2502.06944 (2025)

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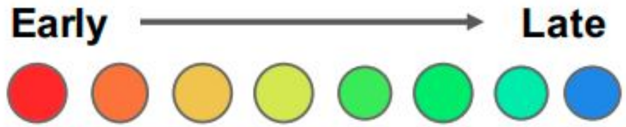
Summary

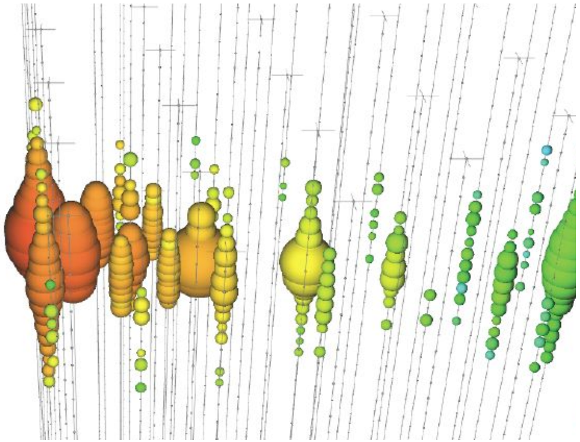
- We have characterized the different neutrino populations across the energy spectrum, from MeV (Supernovae) to PeV+ (Astrophysical/GZK).
- Astrophysical neutrinos in the TeV range primarily originate from the interactions of cosmic rays with either matter or radiation fields
- The spectra of astrophysical neutrinos reveals many characteristics of their origins at cosmic ray accelerators
- We now turn our attention to techniques used in the search for astrophysical neutrinos

Backup

IceCube Event Morphologies



Tracks (Data)

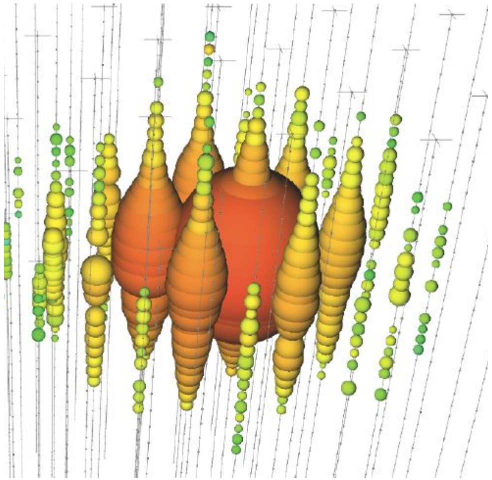


$$\nu_\mu + \mathrm{X} \rightarrow \mu^- + \mathrm{Hadrons}$$

$$\text{Energy Res.} : 0.3 \text{ in } \mathrm{Log}\frac{\mathrm{E}}{\mathrm{TeV}}$$

$$\text{Angular Res.} : 0.3^\circ$$

Cascades (Data)

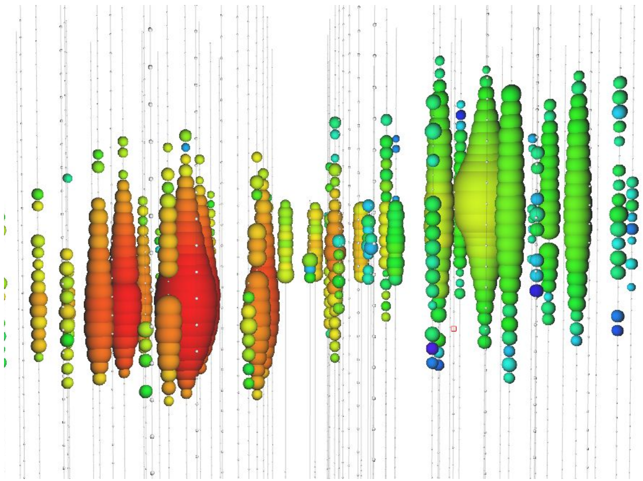


$$\nu_e + \mathrm{X} \rightarrow e^- + \mathrm{Hadrons}$$
$$\nu_l + \mathrm{X} \rightarrow \nu_l + \mathrm{Hadrons}$$

$$\text{Energy Res.} : 8\%@100\mathrm{TeV}$$

$$\text{Angular Res.} : 4^\circ$$

Double Cascade (Simulated)



$$\nu_\tau + \mathrm{X} \rightarrow \tau^- + \mathrm{Hadrons}$$
$$\tau^- \rightarrow \nu_\tau + \ldots$$

$$\text{Decay Length} : 50\mathrm{m/PeV}$$

Ref.