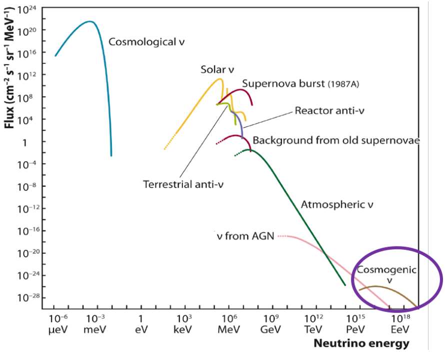
Ultra-High Energy Neutrinos (UHE-νs), part I: Origins and Importance

Jorge Torres

Connolly's Group Meeting

What are UHE-νs

- νs with energies of 10^{17} eV and above.
- Also called "cosmogenic neutrinos".
- Flux is very small: tens of billions $cm^{-2}s^{-1}$ (solar) vs $< 1km^{-2}yr^{-1}$ (cosmogenic)
- Produced by interactions of UHE cosmic rays (UHECRs) and CMB-γ. $\leftarrow$ GZK-mechanism.



The GZK-Mechanism

- GZK=Greisen-Zatsepin-Kuzmin.
- Only charged pion decays produce UHE-neutrinos.
- $\approx \frac{1}{3} E_{\text{UHECR}}$ transferred to ν.
- These are the ν that we want to detect.
- What about the UHECRs?

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \nu_\mu + \mu^+$$

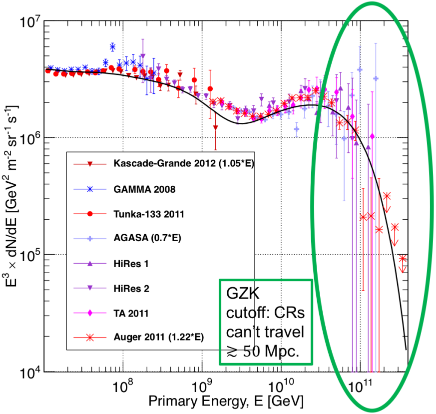
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Each carries $\sim 10\%$ of the proton energy

UHE-Cosmic Rays

- Main ingredient for the GZK-mechanism.
- We don't know much about them:
  - Origin? SNR, AGN, GRB?
  - Composition? Protons, heavy nuclei?
  - Acceleration and emission?
- Constrained to a ~50 Mpc radius.
- Deflected by magnetic fields.



Gaisser, Stanev, Tilav, 2013.

How do UHECRs shape the ν-flux?

1. Mass composition
   - photo-hadronic ($p\gamma$) interactions significantly suppressed for heavy-nuclei, also different energy loss mechanisms. Heavier CRs make less ν.
2. Evolution of CR sources
   - At higher redshifts, $\bar{E}_{\text{CMB}}$ is higher. More sources at high redshift result in more ν.
3. Source's maximum CR energy
   - More UHECRs produced by the source→ more GZK neutrinos.
4. Other factors.

Thus, measure UHE-ν flux to rule out scenarios...or to find the right one!

Why to study UHE-neutrinos?

- Neutrino astronomy and astrophysics.
- To probe particle physics

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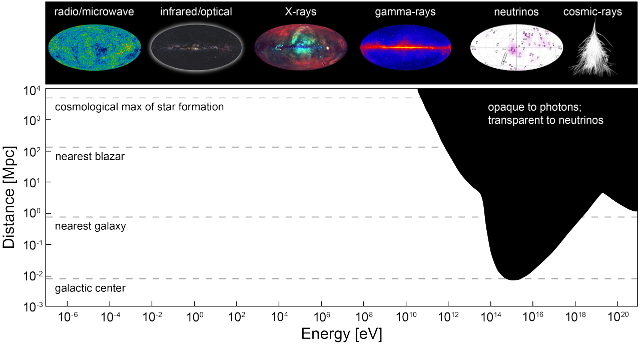
- Neutrino astronomy and astrophysics.
- To probe particle physics
- Exotic physics (Talk by Hannah)

Neutrino Astronomy and astrophysics

- Exploration of extragalactic high-energy universe (>TeV) challenging:
  - Gamma rays highly attenuated by diffuse light sources ($\gamma\gamma \rightarrow e^{+}e^{-}$)
  - Cosmic rays (CRs) deflected by magnetic fields and confined to ~ 50 Mpc[1] due to GZK-interactions.
- Solution: use neutrinos.



Credits: The IceCube Collaboration

Neutrino Astronomy and astrophysics

- Neutrinos as cosmic messengers: undeflected and almost non-interacting.
- Point back to the source: identification of UHECRs sources.
- ν-flux measurement will help with elucidating origin and composition of UHECRs

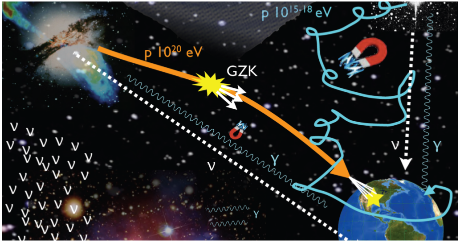
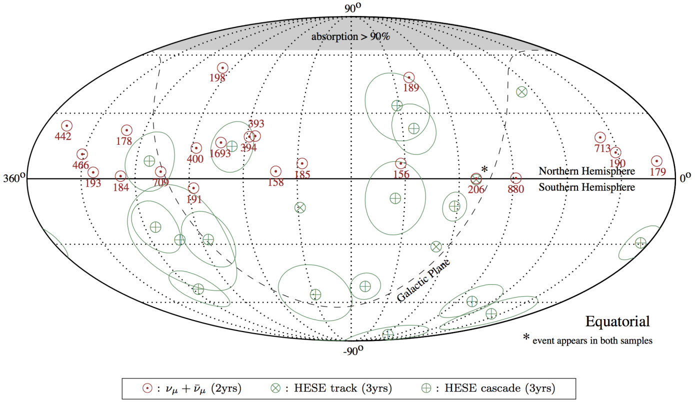


Image Credits: N. Charis

Neutrino Astronomy

Neutrino astronomy began with IceCube. We haven't seen any UHE-ν, though!



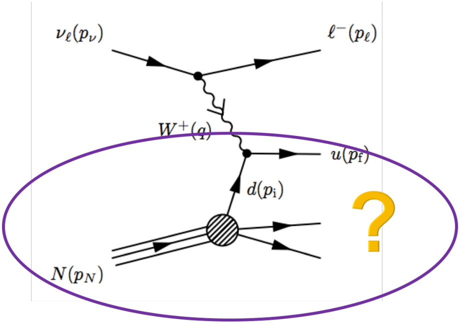
Credits: The IceCube Collaboration. Red circles show where neutrinos came from. The number indicates their energy in TeV.

Probing particle physics with UHE-ν

- Neutrinos can interact with atomic nuclei (quarks, for high-energy neutrinos).
- Small knowledge at HE due to limited accelerator energy.
- At very high energies,

$$\sqrt{s} \approx \sqrt{2E_\nu m_p} \approx 45\,\text{TeV}$$

  for $\nu - N$ interaction and $E_\nu = 10^{18}$ eV.
- Higher than the LHC (14 TeV).
- Some goals:
  - Measure cross section.
  - Test unprobed nucleon structure ($\lambda \propto \frac{1}{p}$).



Deep Inelastic Scattering (DIS). Giunti and Kim, Fundamentals of Neutrino Physics and Astrophysics.

Several things can be done, but...

neutrinos barely interact and the flux is very small

- In fact, we expect to detect a few/year.

Radio-detection is a young technique that can potentially discover the most energetic neutrinos...Part II.

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