Cosmogenic neutrinos and gamma-rays and the redshift evolution of UHECR sources

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[1]Now at DESY, Zeuthen, Germany
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Outline

1. Ultra-high-energy cosmic rays
   - Propagation through intergalactic space
   - The secondary particles produced
   - Open questions
2. Multi-messenger studies
   - Experimental limits on EeV fluxes and measured GeV–PeV fluxes
   - Simulated expected neutrino and γ-ray fluxes in various scenarios
3. Conclusions

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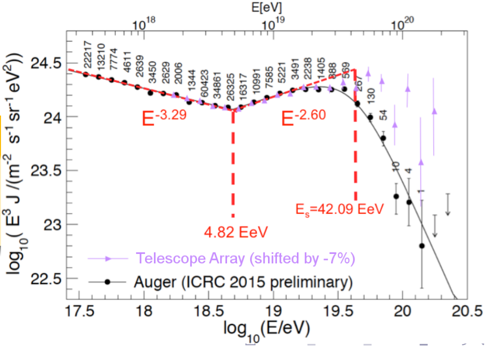
Ultra-high-energy cosmic rays

- Ultra-high-energy cosmic rays (UHECRs) are particles of extraterrestrial origin with energy above 10^{18} eV.
- They are protons and possibly other atomic nuclei, with stringent upper limits on the fraction of photons and neutrinos.
- Their origin is unknown, but most likey extragalactic (at least at the highest energies).

UHECR energy spectrum

At $E \approx 5$ EeV: ankle

At $E \approx 40$ EeV: cutoff



Processes affecting UHECR propagation

During their trip to Earth, extragalactic cosmic rays can:

- lose energy adiabatically due to the expansion of the universe (redshift);
- interact with background photons:

Relevant backgrounds (ϵ = photon energy in lab frame)

$\epsilon \lesssim 3$ meV (MW): cosmic microwave background (CMB)

1 meV $\lesssim \epsilon \lesssim 10$ eV (IR to UV): extragalactic background light (EBL)

Main processes (ϵ' = photon energy in nucleus rest frame)

$\epsilon' \gtrsim 1$ MeV: pair production, $N + \gamma \to N + \mathrm{e}^+ + \mathrm{e}^-$

$\epsilon' \gtrsim 8$ MeV: disintegration, e.g. $Z^A + \gamma \to Z^{A-1} + \mathrm{n}$

$\epsilon' \gtrsim 150$ MeV: pion production, e.g. $\mathrm{p} + \gamma \to \mathrm{p} + \pi^0$

- be deflected by intergalactic and galactic magnetic fields.

Pion production

$$p + \gamma \to p + \pi^0, \quad n + \gamma \to n + \pi^0, \quad p + \gamma \to n + \pi^+, \quad n + \gamma \to p + \pi^-$$

- Affects nucleons with:
  - $E \gtrsim 40$ EeV (CMB photons; $\lambda \sim 10$ Mpc $\to$ GZK cutoff);
  - $E \gtrsim 4$ EeV (EBL photons; $\lambda \sim$ a few Gpc $\to$ minor impact on proton fluxes but potentially lots of secondaries).
- Subsequently:
  - $\pi^0 \to \gamma + \gamma$, each with $\sim 10\%$ of initial nucleon energy
  - $\pi^+ \to \mu^+ + \nu_\mu$
    $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$, each with $\sim 5\%$ of initial nucleon energy
  - $n \to p + e^- + \bar{\nu}_e$, each with $\sim 0.05\%$ of initial nucleon energy
- The neutrinos can reach Earth (with $E \sim$ a few PeV – a few EeV) without further interacting, even from $z \sim 10$.
- The photons will undergo $\gamma + \gamma_{\text{CBM,URB}} \to e^+ + e^-$ within ~ 1 Mpc, initiating EM cascades of (eventually) $\lesssim 1$ TeV photons.

Photodisintegration

$$^{A}Z + \gamma \to {}^{A-1}Z + \mathrm{n}, \qquad {}^{A}Z + \gamma \to {}^{A-1}(Z-1) + \mathrm{p},$$

$$^{A}Z + \gamma \to {}^{A-4}(Z-2) + {}^{4}\mathrm{He}, \qquad \text{and various combinations thereof}$$

- Affects nuclei with:
  - $E/A \gtrsim 2$ EeV (CMB photons; $\lambda \sim$ few Mpc $\to$ "GZK" or "GR" cutoff);
  - $E/A \gtrsim 0.2$ EeV (EBL photons; $\lambda \sim 100$ Mpc).
- Important effects on energy spectrum and mass composition of UHE nuclei, but few direct multi-messenger implications
- (Energy of beta-decay neutrinos $\lesssim 1$ PeV, subdominant w.r.t. those from EBL pion production)

Pair production

$$N + \gamma \to N + \mathrm{e}^+ + \mathrm{e}^-$$

- Affects protons and nuclei with:
  - $E/A \gtrsim 0.2$ EeV (CMB photons; $\lambda \sim 1$ Mpc).
- Electrons with $E \sim$ a few PeV, undergo inverse Compton scattering/synchrotron ratiation initiating EM cascades of (eventually) $\lesssim 1$ TeV photons.
- The shape of the energy spectrum of cascade photons at Earth doesn't depend on the initial photon/electron energy (e.g. cascades from ten 1 PeV electrons same as from one 10 PeV electron), only on the redshift of the production point.

Open questions

- Where and how are UHECRs accelerated?
- Why the ankle?
  - Pair production dip?
  - Superposition of two populations?
  - Something else?
- Why the cutoff?
  - Effects of propagation?
  - Maximum acceleration rigidity?
  - Both?
- Mass composition at the highest energies:
  - Protons?
  - Medium/heavy nuclei?
  - Both?

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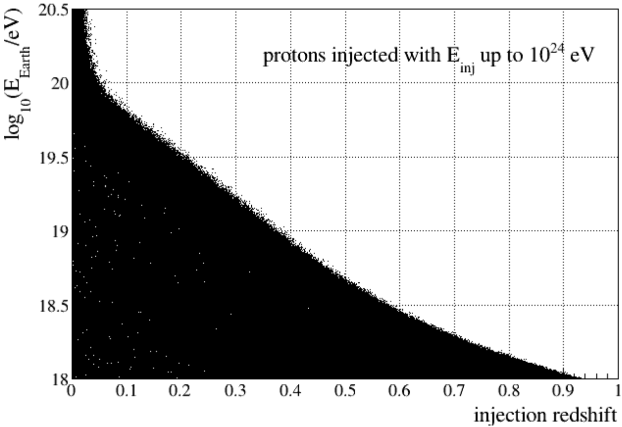
Why multi-messenger?

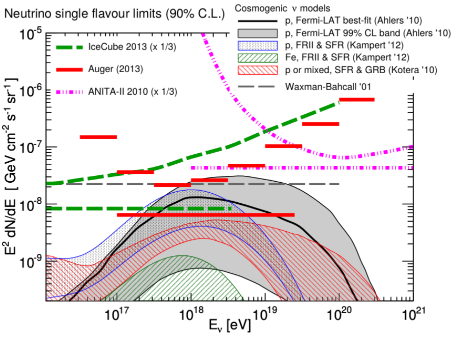
- No matter how much energy they start with, no protons or nuclei from $z > 1$ will reach Earth with $E > 1$ EeV



- All information about sources at $z > 1$ is lost.

Why multi-messenger?

- Neutrinos can reach Earth no matter how far away they originated.
  - Their flux also depends on the emissivity of sources at high z.
- Also, charged cosmic rays are deflected by magnetic fields (possibly by several tens of degrees), whereas neutral particles arrive to us straight from their production point.
  - Cascades broadened by magnetic fields, but still centered around production point
- In principle, neutrinos carry more information than cascade gamma rays, but they are harder to detect.



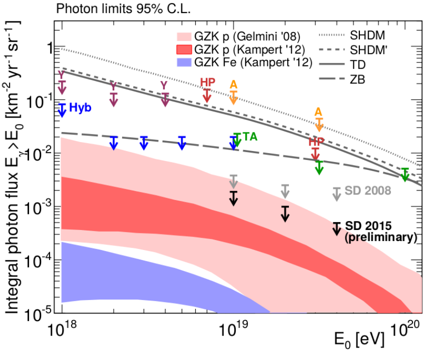


Figure: Limits on EeV neutrino and gamma-ray fluxes and various model predictions, from C. Bleve [Auger Collab.], PoS(ICRC2015)1103

Measurements of PeV neutrinos and TeV gamma rays

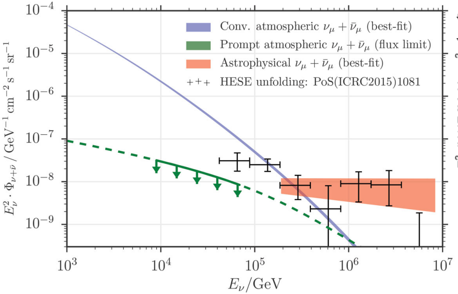


Figure: Astrophysical neutrinos detected by IceCube, from `arXiv:1607.08006`

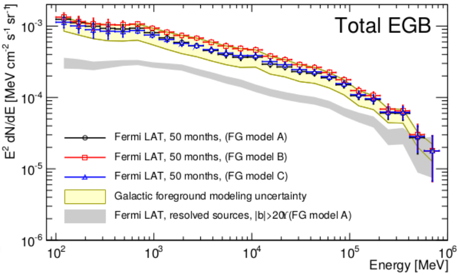


Figure: Gamma-ray background detected by Fermi-LAT, from `arXiv:1410.3696`

Our Monte Carlo simulation code

SimProp v2r0: only photodisintegration treated stochastically
(25 Oct 2011, `arXiv:1204.2970`)

SimProp v2r1: pion production on the CMB also treated stochastically
(07 Feb 2013, `arXiv:1307.3895`)

SimProp v2r2: pion production on the EBL also treated stochastically
(06 May 2015, `arXiv:1505.01347`)

SimProp v2r3: photodisintegration also ejecting alpha particles
(03 Feb 2016, `arXiv:1602.01239`)

SimProp v2r4: secondary electrons/positrons from pair production, so that cascades can be computed with external tools e.g. ELMAG (coming soon)

Available upon request to:

- `SimProp-dev@aquila.infn.it`

Cosmogenic neutrinos in “dip-model” scenario

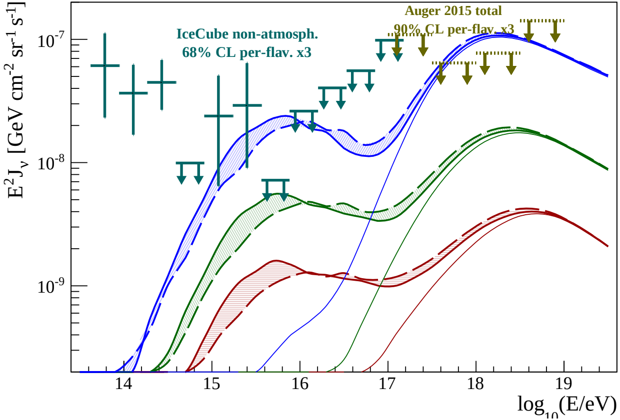


Figure: Neutrino fluxes simulated with *SimProp* v2r2 in proton-only scenario, assuming **constant**, **SFR**, **AGN** source emissivity evolution, from `arXiv:1505.04020`

Cosmogenic neutrinos in “two-component” scenario

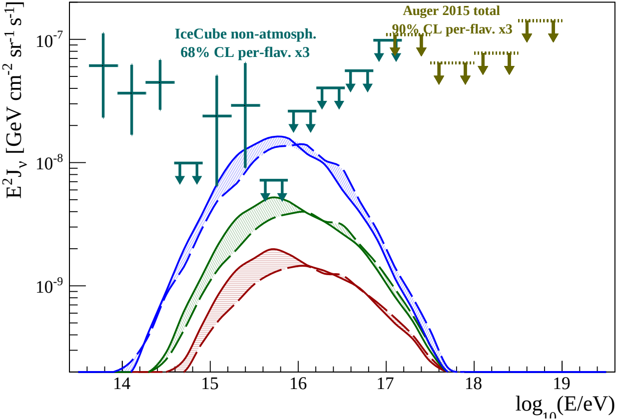


Figure: Neutrino fluxes simulated with *SimProp* v2r2 in high-metallicity scenario, assuming **constant**, **SFR**, **AGN** source emissivity evolution, from `arXiv:1505.04020`

Gamma-ray background from cascades

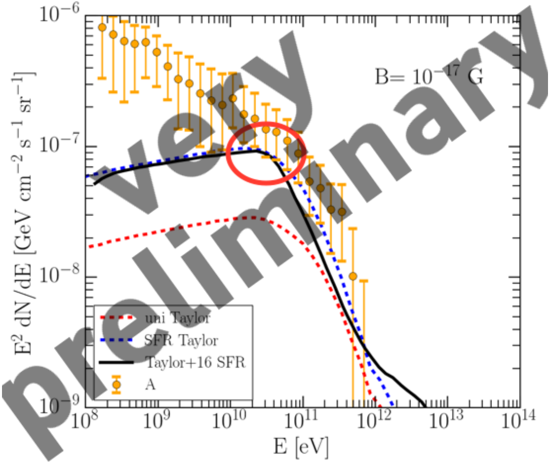


Figure: Gamma-ray cascades simulated with *SimProp* v2r4 + ELMAG and data from Fermi-LAT on diffuse gamma-ray background

- Mostly coming from 1–4 EeV CRs, which everybody agrees are mostly protons
- More stringent limit than from IceCube neutrinos
- See also
  - R.-Y. Liu et al., `arXiv:1603.03323`
  - O. Kalashev, `arXiv:1608.07530`

Outline

Conclusions

- "Top-down" models as the source of most UHECRs below 100 EeV have been ruled out for quite a long time now.
- EeV neutrinos only produced if there are protons among highest-energy CRs
- Cosmogenic neutrino fluxes at all energies strongly dependent on UHECR source emissivity evolution
  - We can already rule out models with source emissivity too strongly increasing with redshift (decreasing with time).
- Same applies to gamma-ray fluxes — the interpretation is more complicated, but the limits we can put on source emissivity are more stringent.