Interaction of ultra-high-energy cosmic rays with cosmic background photons

Armando di Matteo

armando.dimatteo@aquila.infn.it

INFN and Department of Physical and Chemical Sciences, University of L'Aquila, L'Aquila, Italy

International School of Space Science, L'Aquila, 22–26 April 2014

Ultra-high-energy cosmic rays

- **Cosmic rays** are high-energy particles (mainly protons and nuclei) arriving to Earth from outer space.
- Cosmic rays with energy above 10^{18} eV are known as **ultra-high-energy cosmic rays** (UHECRs).
- UHECRs have been detected with energies up to 3×10^{20} eV (50 J).
- The origin of UHECRs is still unknown, but the most energetic ones are most likely extragalactic.

Detection of UHECRs

- UHECRs too rare for direct detection (a few per km^2 per century)
- When a UHECR interacts with a molecule in the atmosphere, it initiates a particle cascade known as an **extensive air shower**.
- Showers can be detected by arrays of particle detectors on the ground and/or (during clear moonless nights) by telescopes detecting fluorescence light.
- Largest currently active experiments:
  - **Pierre Auger Observatory** (Argentina): 1660 surface detectors over 3000 km^2 area + 27 telescopes
  - **Telescope Array** (Utah): 507 surface detectors over 700 km^2 area + 38 telescopes
- Shower-to-shower fluctuations, low statistics, poor knowledge of shower physics $\rightarrow$ large statistical and systematic uncertainties

The observed cosmic ray spectrum at Earth

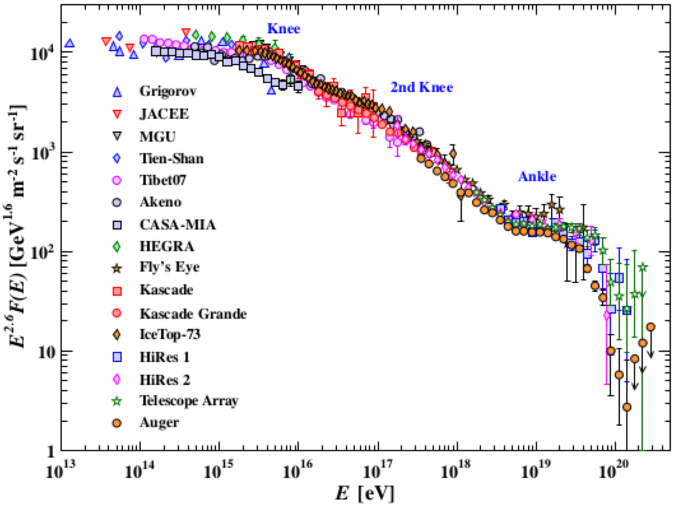


Figure: Energy spectrum of cosmic rays at Earth, multiplied by $E^{2.6}$ (from the *Review of Particle Physics*)

Interaction with CMB photons

- Ultra-high-energy protons and nuclei travelling through intergalactic space can interact with CMB photons producing new particles, e.g.
  - **Pair production**: $\mathrm{p} + \gamma \to \mathrm{p} + \mathrm{e}^+ + \mathrm{e}^-$;
  - **Pion production**: $\mathrm{p} + \gamma \to \mathrm{p} + \pi^0$ or $\mathrm{p} + \gamma \to \mathrm{n} + \pi^+$.
- These processes (especially pion production) cause protons to lose part of their energy, modifying their energy spectrum.
- In particular, no proton originating more than 50 Mpc away should reach Earth with $E > 10^{19.5}$ eV.
- This is known as the **Greisen–Zatsepin–Kuzmin** (GZK) **limit**.
- Ultra-high-energy nuclei can also undergo **photodisintegration** (both on CMB and on IR/opt/UV intergalactic background light):
  - $(A, Z) + \gamma \to (A - 1, Z - 1) + \mathrm{p}$
  - $(A, Z) + \gamma \to (A - 1, Z) + \mathrm{n}$
  - $(A, Z) + \gamma \to (A - 2, Z - 1) + \mathrm{p} + \mathrm{n}$, etc.

Other effects of propagation

- All particles travelling cosmological distances lose energy due to the expansion of the Universe.
- Charged particles may be deflected by intergalactic magnetic fields.

All these effects can be taken into account by Monte Carlo simulations (e.g. *SimProp* or CRPRopa) or analytic approximations, to compute expected UHECR fluxes at Earth according to a given model of sources and cosmology.

Effects on the UHECR energy spectrum

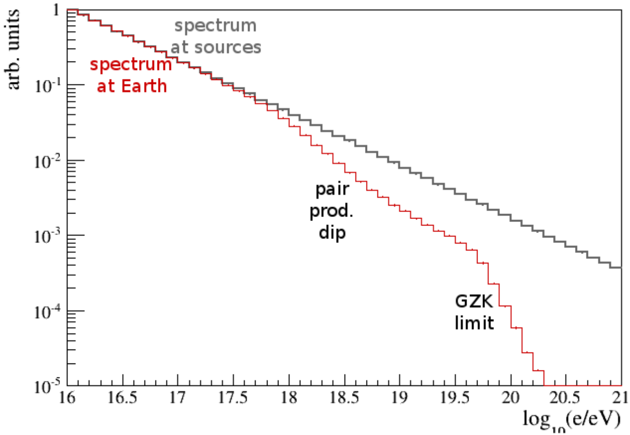


Figure: Energy spectrum of UHECRs at Earth, multiplied by E^2, assuming homogeneously distributed proton sources with power-law spectrum $\propto E^{-2.7}$ and no magnetic fields, computed via *SimProp* Monte Carlo simulations

Experimental data on the end of the UHECR spectrum

- Recent UHECR experiments indeed see a flux suppression:

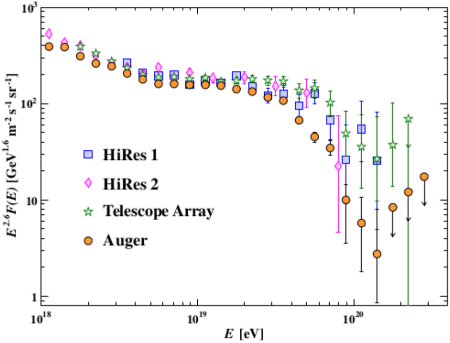


Figure: Energy spectrum of UHECRs, multiplied by $E^{2.6}$ (from the *Review of Particle Physics*)

- They agree within their systematic uncertainties ($\approx 15\%$).
- Is this actually the GZK effect?

What is the mass composition of UHECRs?

- It is impossible to measure the mass of individual UHECRs on an event-by-event basis.
- Their mass composition is estimated from the distributions of observables such as $X_{\max}$ (atmospheric depth where the number of particles in the shower is largest) via hadronic interaction models, which need to rely on extrapolations because UHECR–air collisions are much more energetic than LHC ones $\to$ large systematic uncertainties
- Also, $X_{\max}$ can only be measured by fluorescence detectors $\to$ low statistics
- Auger data suggest heavier nuclei (e.g. C, N, O) at the highest energies, but Telescope Array data are compatible with a proton-dominated composition at all energies.

Experimental data on the mass of UHECRs

$\langle \ln A \rangle$ as a function of E from Auger data

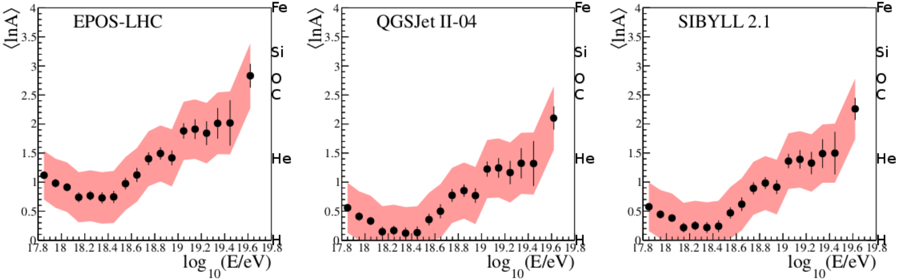


Figure: Average logarithmic mass of UHECRs from Auger measurements interpreted using various hadronic models (from `arXiv:1307.5059`)

Experimental data on the mass of UHECRs

$\sigma^2(\ln A)$ as a function of E from Auger data

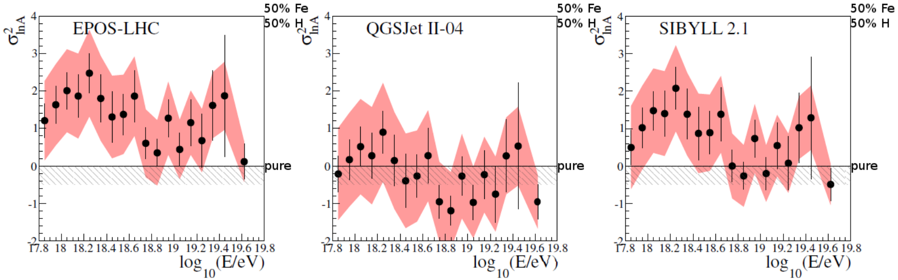
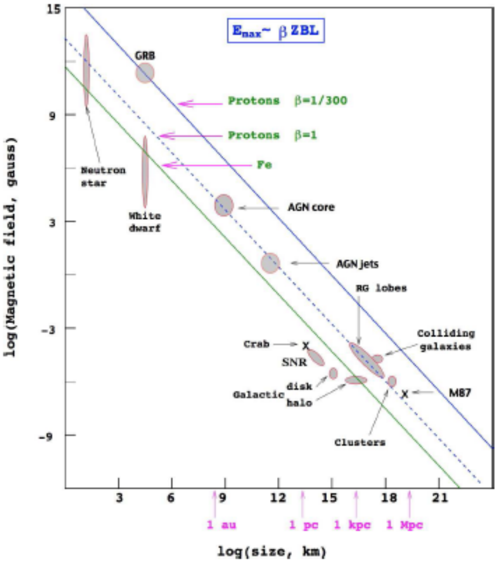


Figure: Variance of logarithmic mass of UHECRs from Auger measurements interpreted using various hadronic models (from `arXiv:1307.5059`)

Effect on the interpretation of the cutoff

- For a nucleus with mass number A, the energy threshold for pion production is A times that for protons, but photodisintegration is also possible.
- If Auger is right, the observed cut-off is at a lower energy-per-nucleon than expected.
- Maybe the sources themselves have an energy cutoff around here?
- If UHECRs are accelerated electromagnetically (most likely), there is a cutoff $E_{\text{max}} \propto Z$.

The Hillas plot



- The maximum acceleration energy of a source is proportional its size and magnetic field strength.
- Nuclei with electric charge Z can only be accelerated to energies above E by sources above the corresponding line in the **Hillas plot**.

Some models of UHECR sources

Extragalactic, protons-only

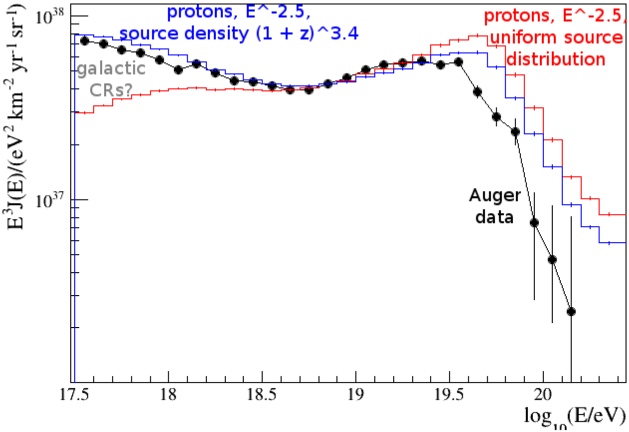


Figure: UHECR fluxes at Earth assuming two proton-only, power-law-spectrum source models, computed with *SimProp*

Some models of UHECR sources

Mixed composition, rigidity-dependent cutoff

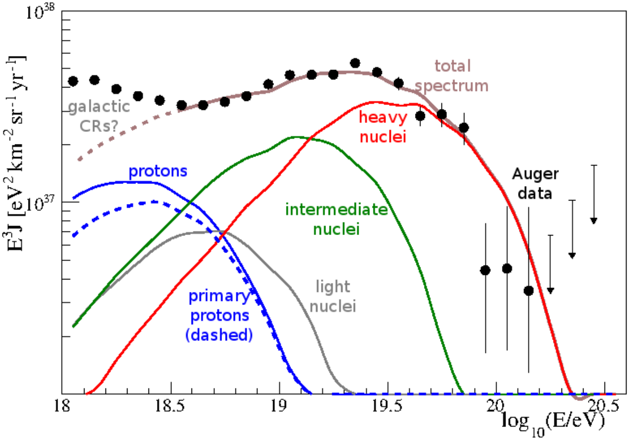


Figure: UHECR fluxes at Earth assuming sources with a mixed mass composition, spectrum $\propto E^{-1.55}$, and exponential cutoff above $E_{\max} = 10^{19.9} \frac{Z}{26}$ eV (from `arXiv:1307.3895`)

Cosmogenic neutrinos

- When charged pions are produced ($p + \gamma \to n + \pi^+$) they decay into neutrinos:
  - $\pi^+ \to \mu^+ + \nu_\mu$
  - $\mu^+ \to e^+ + \overline{\nu}_\mu + \nu_e$
- Each neutrino carries a few per cent of the initial nucleon energy, i.e. $\approx 10^{18}$ eV.
- These neutrinos can reach Earth unaffected by propagation, and be detected by experiments such as Auger or IceCube.
- No neutrinos with $E \gg 10^{15}$ eV have been detected so far.
- Neutrinos are also produced in beta decay (e.g. $n \to p + e^- + \overline{\nu}_e$) but are much less energetic.

Expected fluxes of cosmogenic neutrinos

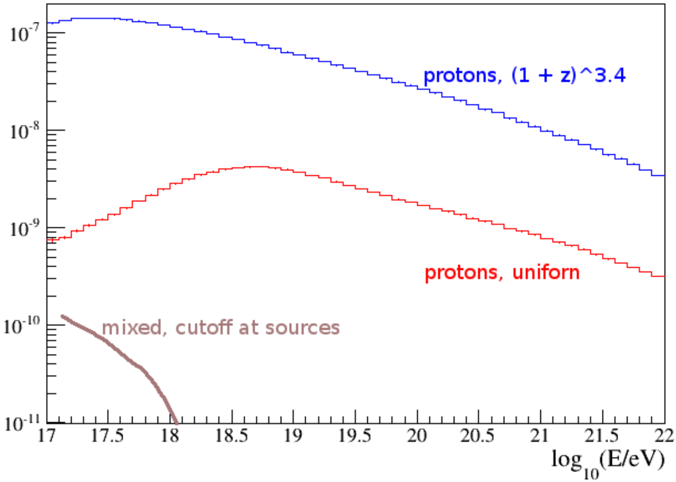


Figure: Expected fluxes of cosmogenic neutrinos, multiplied by E^2, in GeV cm^{-2} s^{-1} sr^{-1}

Current experimental upper limits

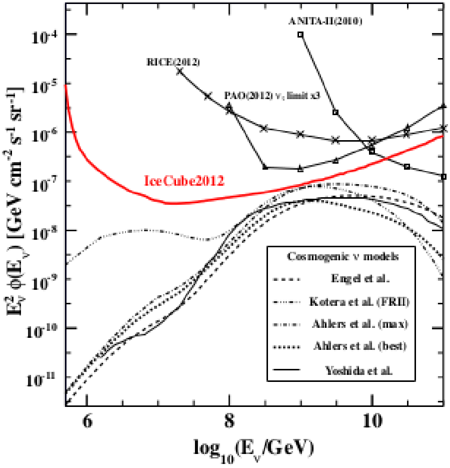


Figure: Upper limits of cosmogenic neutrino fluxes from IceCube and other experiments (from `arXiv:1310.5477`)

Expected future sensitivity

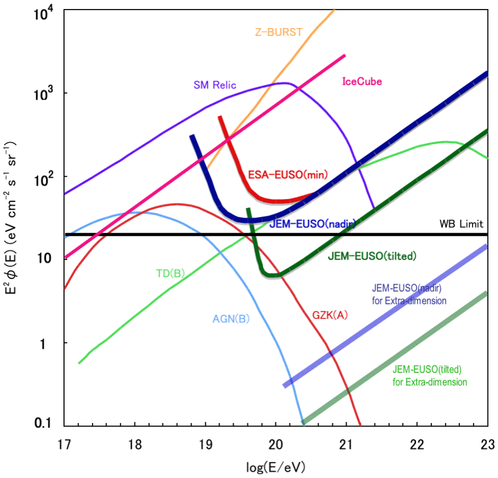


Figure: Expected sensitivity to cosmogenic neutrino fluxes of JEM-EUSO (from `http://jemeuso.riken.jp/en/about6.html`)

Conclusion

- Experimental upper limits to cosmogenic neutrino fluxes already rule out some of the parameter space of models where the observed UHECR cutoff is due to the GZK limit.
- Future experiments with greater sensitivities will be able to corroborate some such models or rule them out entirely.
- Conversely, models where the UHECR cutoff is the maximum acceleration rigidity predict much lower neutrino fluxes, which we would not be able to detect in a very long time.