The UHECR source evolution and high-energy neutrinos and γ-rays

R. Aloisio,[1,2] D. Boncioli,[3] A. di Matteo,[4] S. Petrera[1,2] and F. Salamida[5,2]

[1]GSSI, L'Aquila, Italy [2]INFN LNGS, Assergi, Italy [3]DESY, Zeuthen, Germany [4]ULB, Brussels, Belgium
[5]Department of Physical and Chemical Sciences, University of L'Aquila, L'Aquila, Italy

armando.di.matteo@ulb.ac.be

Ultra-high-energy cosmic rays (UHECRs)

- Energies up to a few $100\ \mathrm{EeV} = 10^{20}\ \mathrm{eV} \approx 16\ \mathrm{J}$
- Protons and/or other nuclei (strong limits on photon and neutrino fractions)
- Origin unknown, most likely extragalactic

Phenomena in UHECR propagation

- Adiabatic energy loss due to the expansion of the Universe (redshift)
- Interactions with
  - cosmic microwave background (CMB) $\epsilon \lesssim 3\ \mathrm{meV}$
  - extragalactic background light (EBL) $1\ \mathrm{meV} \lesssim \epsilon \lesssim 10\ \mathrm{eV}$

  $\to$ production of secondary particles (protons, neutrinos, photons)
- Deflections by intergalactic and galactic magnetic fields

Interactions with background photons

Pair photoproduction $\epsilon' \gtrsim 1\ \mathrm{MeV}$

- $\mathrm{p} + \gamma \to \mathrm{p} + \mathrm{e}^+ + \mathrm{e}^-$ (each e with $\sim 0.05\%$ of p energy)
- (also with other nuclei)

Photodisintegration $\epsilon' \gtrsim 8\ \mathrm{MeV}$

- ${}^{A}Z + \gamma \to {}^{A-1}Z + \mathrm{n}$
- ${}^{A}Z + \gamma \to {}^{A-1}(Z-1) + \mathrm{p}$ (each n, p with $1/A$ of nucleus energy)
- ${}^{A}Z + \gamma \to {}^{A-2}(Z-1) + \mathrm{p} + \mathrm{n}$, ${}^{A}Z + \gamma \to {}^{A-4}(Z-2) + {}^{4}\mathrm{He}$, etc.

Lighter nuclei $\to$ shorter interaction lengths

Pion photoproduction $\epsilon' \gtrsim 150\ \mathrm{MeV}$

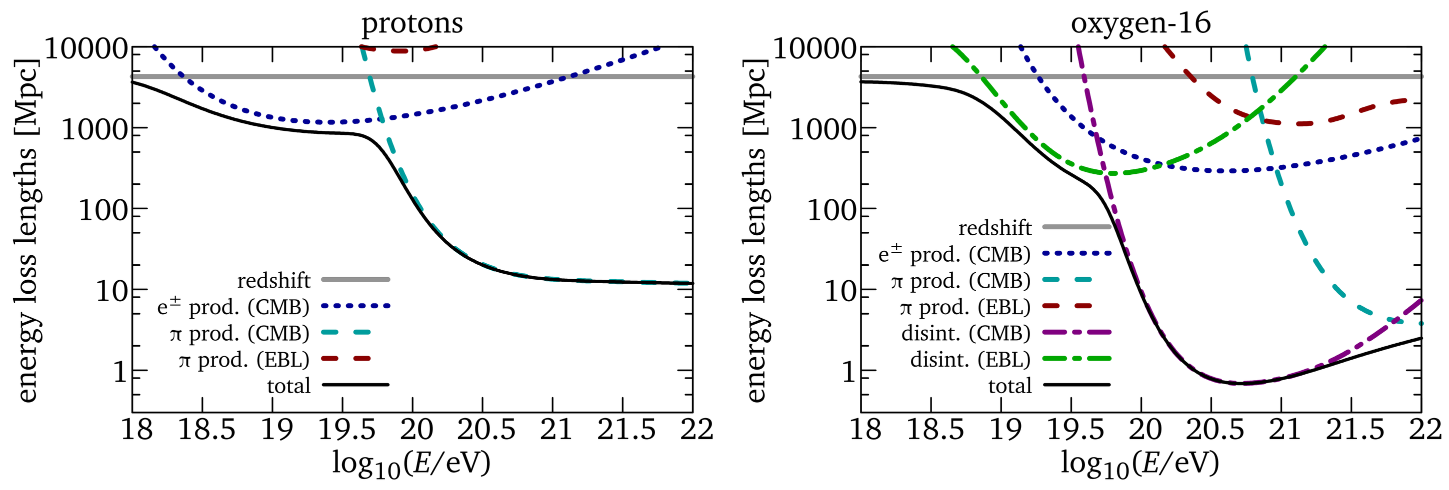
- $\mathrm{p} + \gamma \to \mathrm{n} + \pi^+$

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

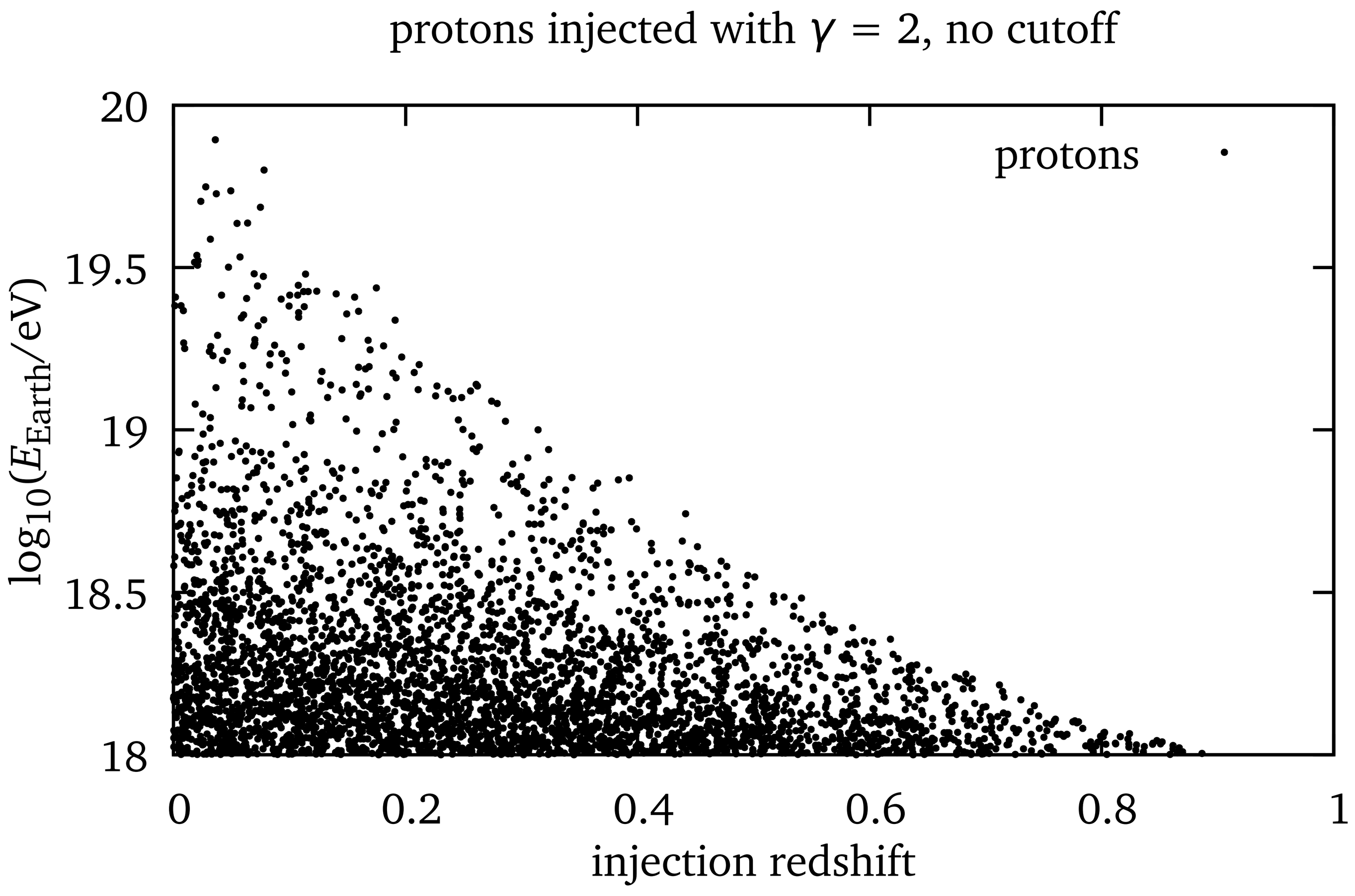
  $\mu^+ \to \mathrm{e}^+ + \bar{\nu}_\mu + \nu_\mathrm{e}$ (each e, ν with $\sim 5\%$ of p energy)

  $\mathrm{n} \to \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ (each e, ν with $\sim 0.04\%$ of p energy)
- $\mathrm{p} + \gamma \to \mathrm{p} + \pi^0$

  $\pi^0 \to \gamma + \gamma$ (each γ with $\sim 10\%$ of p energy)
- (also $\mathrm{n} + \gamma \to \mathrm{p} + \pi^-$, $\mathrm{n} + \gamma \to \mathrm{n} + \pi^0$, also with p, n within nuclei)



The GZK horizon



All info about sources at $z > 1$ is lost, if we look at protons/nuclei alone!
(possible magnetic suppressions and/or Galactic CR admixture below 10^{18} eV)

The secondaries

- Electrons and photons produced with $E \sim$ a few EeV (π prod. on CMB) / a few PeV (π prod. on EBL / $\mathrm{e}^\pm$ prod.), initiate electromagnetic cascades
  - Shape of cascade spectrum at Earth independent of initial energy [1]
- Neutrinos produced with $E \sim$ a few EeV (CMB) / a few PeV (EBL), unaffected by propagation (except for flavour oscillations and redshift)
- Neutrinos carry more information, but harder to detect

A multi-messenger approach can give info about distant UHECR sources

Results from *SimProp* [2] Monte Carlo

We considered three models of UHECR source emissivity evolution:

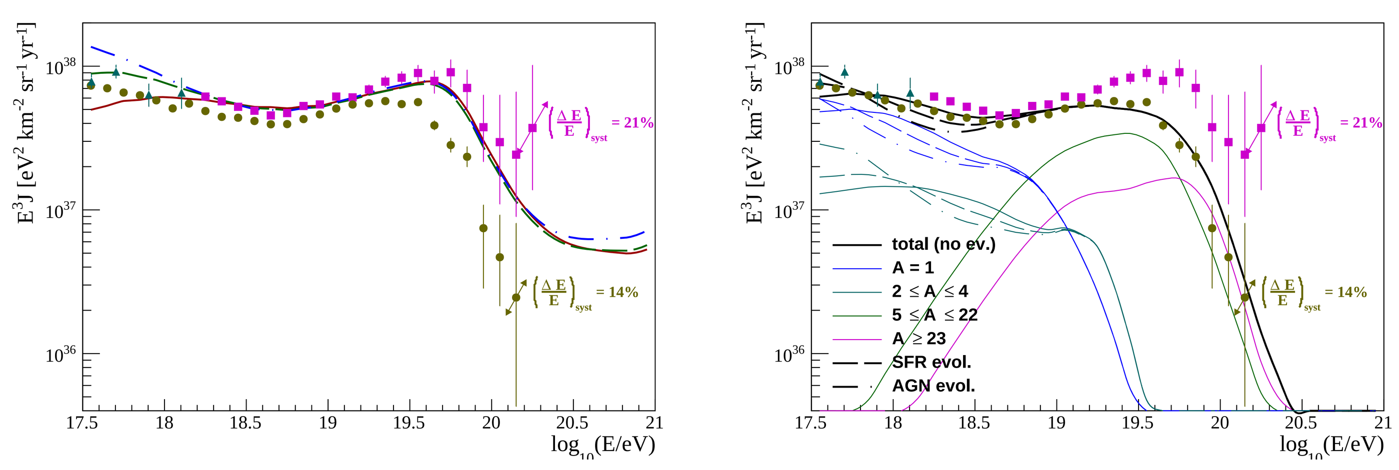
$$\mathcal{L}_\mathrm{uni} = \text{const.} \qquad \mathcal{L}_\mathrm{SFR} \propto \begin{cases} (1+z)^{3.4}, & z \le 1 \\ (1+z)^{-0.3}, & 1 \le z \le 4 \\ (1+z)^{-3.5}, & z \ge 4 \end{cases} \qquad \mathcal{L}_\mathrm{AGN} \propto \begin{cases} (1+z)^{5.0}, & z \le 1.7 \\ \text{const.}, & 1.7 \le z \le 2.7 \\ 10^{-z}, & z \ge 2.7 \end{cases}$$

and two models for the UHECR source spectrum and composition:

"dip model"	mixed composition model "soft sources"	mixed composition model "hard sources"
100% p	75% p, 25% He	35% p, 30% He, 25% N, 10% Si
$\gamma = \begin{cases} 2.6, & \mathcal{L}_\mathrm{uni} \\ 2.5, & \mathcal{L}_\mathrm{SFR} \\ 2.4, & \mathcal{L}_\mathrm{AGN} \end{cases}$	$\gamma = \begin{cases} 2.6, & \mathcal{L}_\mathrm{uni} \\ 2.5, & \mathcal{L}_\mathrm{SFR} \\ 2.4, & \mathcal{L}_\mathrm{AGN} \end{cases}$	$\gamma = 1.0$, no source evolution
$E_\mathrm{cut} = 10^{22}$ eV	$E_\mathrm{cut} = 2Z \times 10^{18}$ eV	$E_\mathrm{cut} = 6Z \times 10^{18}$ eV

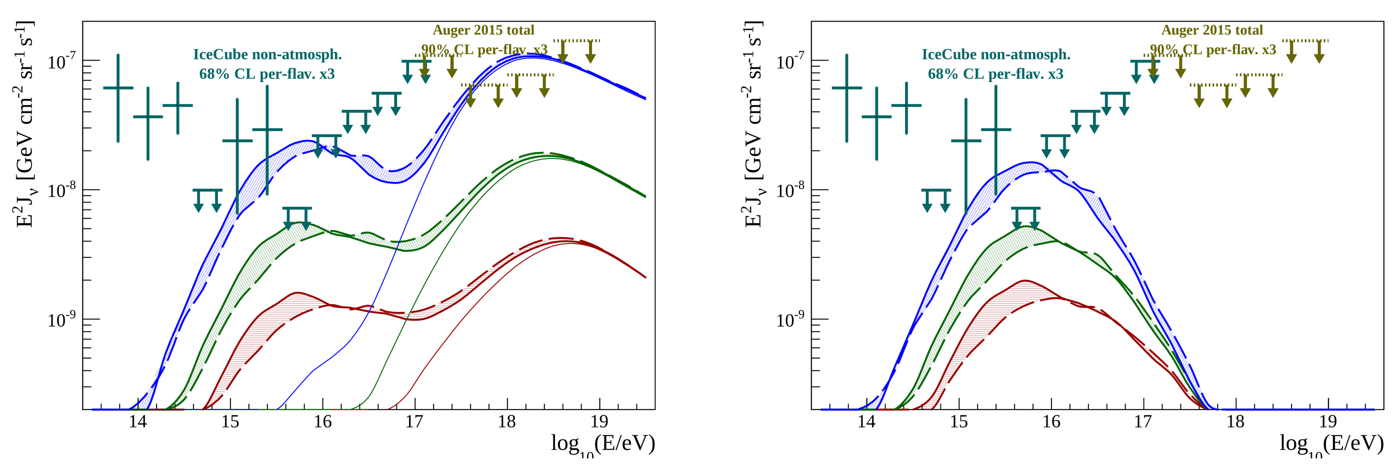
(fractions at 10^{18} eV; $Q_\mathrm{inj}(E) \propto (E/E_0)^{-\gamma} \exp(-E/E_\mathrm{cut})$)

The resulting UHECR fluxes above 10^{18} eV are very similar:

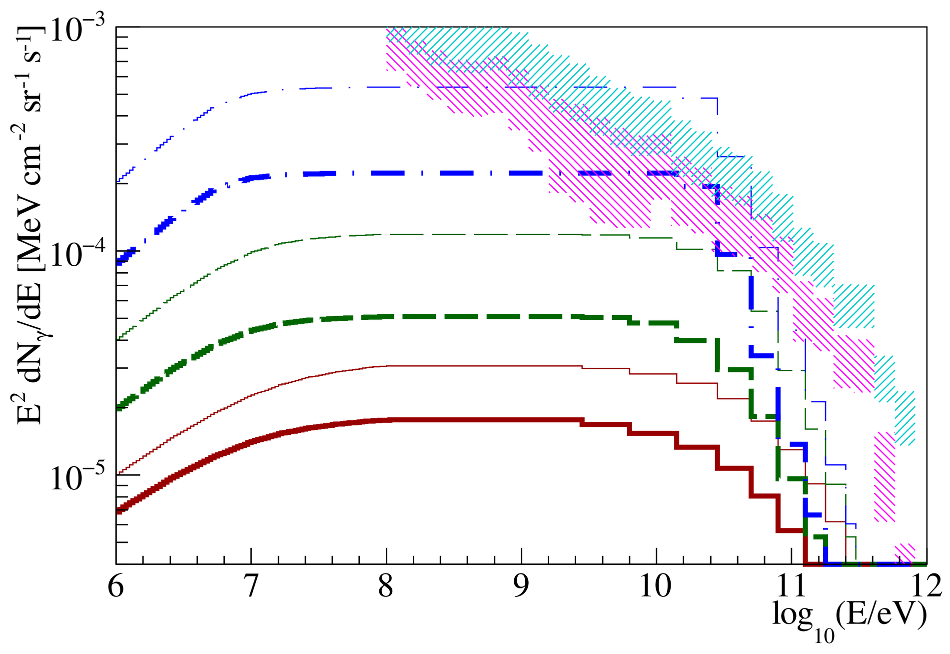


(from Ref. [3])

But the predictions for neutrino and γ-ray fluxes are rather different:



(from Ref. [3])



(from Ref. [2], using cascade development model from Ref. [1])

References

[1] V. Berezinsky and O. Kalashev, *Phys. Rev.* **D94** (2016) 023007, [1603.03989].
[2] R. Aloisio et al., *submitted to JCAP* (2017), [1705.03729].
[3] R. Aloisio et al., *JCAP* **1510** (2015) 006, [1505.04020].