Predicting the UHE photon flux from GZK-interactions of hadronic cosmic rays using CRPropa 3

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UNIVERSITÄT SIEGEN

ONLINE ICRC 2021 THE ASTROPARTICLE PHYSICS CONFERENCE Berlin | Germany

37th International Cosmic Ray Conference 12–23 July 2021

Take-Home Message

- The **origin of the spectral cut-off** of ultra-high-energy (UHE) cosmic rays (CRs) can be tested by searching for a diffuse flux of **UHE photons**.
- Recent results by the Pierre Auger Collaboration give **detailed estimates for CR spectrum and composition at the sources**.
- **Updated model predictions for the flux of UHE photons** from Greisen-Zatsepin-Kuzmin (GZK) interactions of charged cosmic rays with the cosmic microwave background are derived here taking into account latest results of the Pierre Auger Collaboration.

Introduction

- The Pierre Auger Observatory [1] reports a **suppression of CR flux** beyond 50 EeV [2].
- Possible **explanations**:
  - Maximum energy of the **sources**?
  - **Propagation effect**? ⇒ **GZK interactions** [4] with the CMB:

$$p+\gamma_{\mathrm{CMB}} \to \Delta^+(1232) \to \begin{cases} p+\pi^0 \\ n+\pi^+. \end{cases}$$

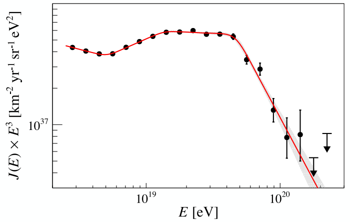

Figure 1: Measurements of the differential energy spectrum published by the Pierre Auger Collaboration [2].

- The GZK hypothesis can be tested by **searching for UHE photons** (decay products of neutral pions).
- **No UHE photons detected** so far.
- **Upper limits on UHE photons** could be placed by various experiments
- Most stringent constraints are placed by the **Pierre Auger Observatory** (c.f. [5] and references therein).
- **Integral photon flux constrained** to $\lesssim 3\times10^{-2}\,\mathrm{km^{-2}sr^{-1}y^{-1}}$ above $10^{18}\,\mathrm{eV}$ ($\lesssim 2\times10^{-3}\,\mathrm{km^{-2}sr^{-1}y^{-1}}$ above $10^{19}\,\mathrm{eV}$).
- **Model predictions** are needed in order to interpret these upper limits.

Simulation Setup with CRPropa 3

- **CRPropa 3**: simulation framework for studying galactic and extragalactic propagation of cosmic rays [6].
- Recent results by the Pierre Auger Collaboration suggest a **mixed composition** of primary cosmic rays at the sources [7].

  ⇒ Three **source scenarios** fit the Auger data (see Tab. 1).

  ⇒ 7 fit parameters: **spectral index** α, **rigidity cut-off** $R_{\text{cut-off}}$, **5 fractions of elemental classes**.

Parameter	α	$\log_{10}(R_{\text{cut-off}}/eV)$	$f_{\mathrm{H}}(\%)$	$f_{\mathrm{He}}(\%)$	$f_{\mathrm{N}}(\%)$	$f_{\mathrm{Si}}(\%)$	$f_{\mathrm{Fe}}(\%)$
Scenario 1	0.96	18.68	0.0	67.3	28.1	4.6	0.0
Scenario 2	2.04	19.88	0.0	0.0	79.8	20.2	0.0
Scenario 3	1.22	18.72	6.4	46.7	37.5	9.4	0.0

Table 1: The three source scenarios that are favored by the data of the Pierre Auger Observatory [7].

- Spectral distribution at the source:

$$\frac{\mathrm{d}N_A}{\mathrm{d}E} \propto f_A E^{-\alpha} \begin{cases} 1 & (E < Z_A R_{\text{cut-off}}) \\ \exp\left(1-\frac{E}{Z_A R_{\text{cut-off}}}\right) & (E > Z_A R_{\text{cut-off}}) \end{cases}$$

- Use **"Auger composition"** scenarios as **initial conditions to simulate CR propagation**.
- Further **boundary conditions**:
  - Isotropic source distribution between 4 Mpc and 2800 Mpc.
  - Source distribution follows redshift evolution of star formation rate $\rho(z) = (1+z)^{3.4}$ [9, 10].
  - Uniform perpendicular magnetic field of 1 nG.
- All **standard interaction processes** considered (e.g. photodisintegraion, pairproduction etc.)
- Interactions with CMB, universal radio background and infrared background light.
- Simulation of **secondary photons down to $10^{15.8}$ eV**.
- All-particle flux on earth **normalized to the differential CR spectrum** above 10^{19} eV as measured by the Pierre Auger Observatory (see Fig. 1).

Results

- **Integral flux of photons** above $10^{15.8}\,\mathrm{eV}$ for three source scenarios (Fig. 2):

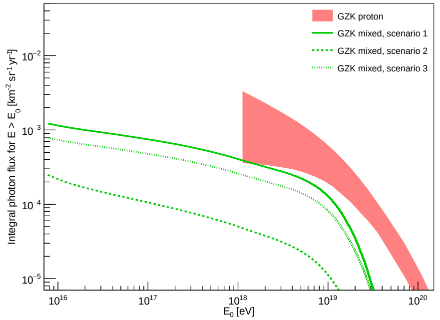

Figure 2: Green lines show the resulting integral photon flux predictions for the initial cosmic ray scenarios as proposed by the scenario 1 (solid) scenario 2 (dashed) and scenario 3 (dotted). The shaded region marks the photon flux that has been predicted in a previous study [13].

- No relevant contribution to photon flux from **primary cosmic rays below 10^{18} eV**.
- Scenario 1 (c.f. Tab. 1) leads to the **highest photon flux predictions**.
- Total photon yield **mainly determined by spectral index**.
- GZK photon predictions that are favored by Auger data are **driven by elements in the mass range of helium and nitrogen**.
- Mixed compositions may lead to **higher photon fluxes than a pure protons**, depending on the spectral distribution.
- "Auger composition" scenarios lead to **considerably lower photon flux** than derived in [13] for pure protons.
  Main reasons:
  - Lower cut-off energy (by ~ 1.5 orders of magnitude).
  - Improvements to photonpion production cross section in CRPropa 3.

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