Constraining Primary Composition and Evolution of Ultra-High Cosmic Rays Sources Using Secondary Signals

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Abstract
The measurements of Ultra-High Energy Cosmic Rays (UHECR) composition based on the observation of extensive air shower properties suffer from huge systematic errors. We show that the primary UHECR mass composition and/or evolution of sources may be constrained by the study of secondary ν and γ fluxes, produced via UHECR attenuation in intergalactic space. We use the recent measurement of the isotropic γ–ray background (IGRB) by Fermi LAT and present limits on astrophysical neutrino flux above 10 PeV to derive the constraints. We also calculate the minimal expected diffuse γ–ray flux produced by UHECR interactions with an interstellar photon background.

Introduction

The Fermi LAT Collaboration [2] has presented their measurement of the IGRB within an unprecedentedly wide energy range up to 820 GeV based on 50 months of observations at Galactic latitude (b) $|b| > 20$. The IGRB spectrum can be well described over nearly four decades in energy by a power law with exponential cut-off, having a spectral index of 2.3 and a break energy of about 0.3 TeV. The origin of IGRB is not fully understood. However, it has been demonstrated recently [4] that unresolved point γ–ray sources, such as Active Galactic Nuclei or Star Forming Galaxies may account for up to 100% of IGRB flux and at least 86% of integral isotropic flux above 50 GeV. This leaves little space for other possible contributions, such as the electromagnetic cascades produced by UHECR interactions. UHECR existence has been confirmed experimentally and therefore the guaranteed minimal contribution to the IGRB from UHECR must exist. We obtain constraints imposed by the IGRB measurement on UHECR source models and calculate minimal expected cascade γ–ray flux, originated from UHECR interactions with the interstellar photon background. The constraints obtained appear to be more restrictive the these based on GZK neutrino nonobservation [1].

Main Objectives

1. Constrain UHECR origin models assuming primary proton composition by comparison of the secondary diffuse γ-ray and neutrino flux, originated from interaction of cosmic rays with intergalactic photon background, with the recent observations.
2. Calculate minimal contribution of UHECR sources to diffuse γ-ray background.

Methods

Using numerical code [5] we fit the observed UHECR spectrum assuming simple phenomenological model with homogeneously distributed proton emitting sources and power-law generation spectrum

$$Q_p(E,z) \propto (1+z)^3 H(z) \left(\frac{E}{E_0}\right)^{-p}, \quad E \in [E_{\min}, E_{\max}], \tag{1}$$

For the evolution term $H(z)$ we either use general form

$$H(z) = H(0)(1+z)^m \quad \text{for } 0 \le z \le z_{\max}, \tag{2}$$

or assume some source specific form e.g. star formation rate (SFR), AGN, etc.

We calculate secondary flux of γ–rays, electrons and neutrinos, produced in the following interactions of UHECR with CMB and extragalactic background light (EBL) photons:

$$p + \gamma_{\text{CMB,EBL}} \to e^+ + e^- + p. \tag{3}$$

and

$$N + \gamma_{\text{CMB}} \to \pi^{\pm,0} + N', \tag{4}$$

We then follow the development of the electromagnetic cascades, initiated by γ, $e^\pm$ and driven by the chain of inverse Compton scattering of electrons

$$e^\pm + \gamma_{\text{CMB}} \to e^\pm + \gamma, \tag{5}$$

and pair production by high energy photons on the background photons

$$\gamma + \gamma_{\text{CMB,EBL}} \to e^+ + e^- \tag{6}$$

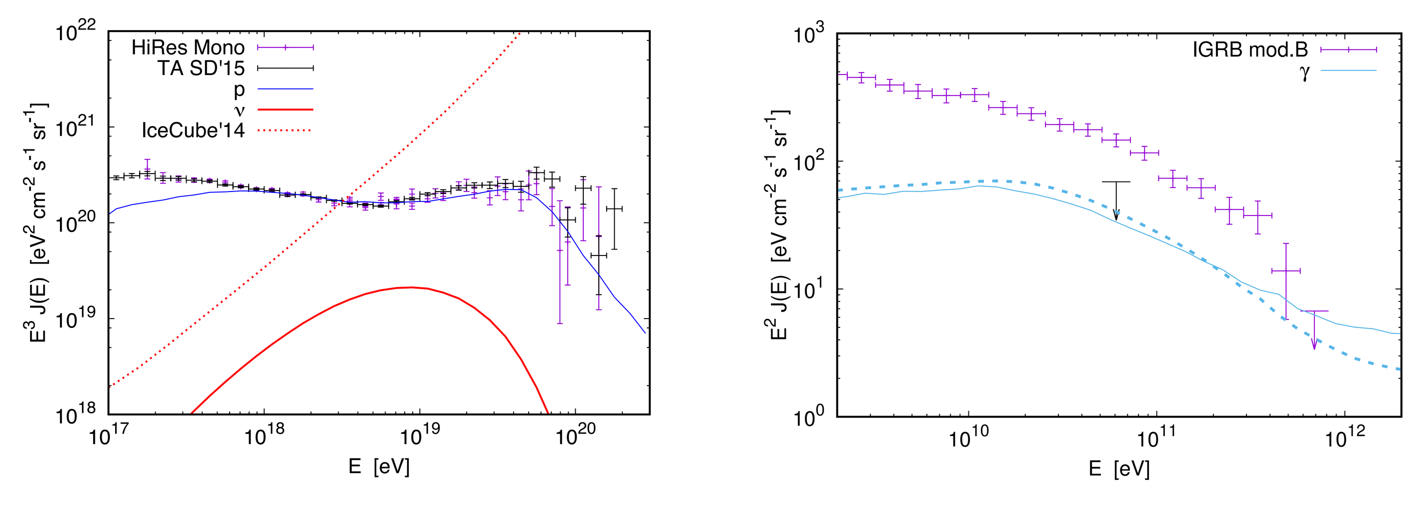

Figure 1: p,ν (left) and γ (right) spectra in the sample model with $p = 2.6$, $m = 1$, $E_{\max} = 10^{2.5}$ EeV and $E_{\min} = 0.1$EeV and two models of EBL as in Ref. [3]

p	m	$z_{\max}$	η_γ [A]	η_γ [B]	η_γ [C]	$\bar{N}_\nu$
2.6	1	5	0.92 - 1.40	0.61 - 0.94	0.73 - 1.11	0.78
2.6	1	1	0.90 - 1.38	0.60 - 0.93	0.71 - 1.10	0.31
2.5	2	5	1.02 - 1.60	0.68 - 1.07	0.81 - 1.26	2.24
2.5	2	1	0.99 - 1.57	0.66 - 1.05	0.79 - 1.24	0.48
2.4	SFR	5	1.16 - 1.88	0.78 - 1.26	0.92 - 1.49	2.28
2.3	5	1	1.29 - 2.23	0.87 - 1.49	1.02 - 1.76	1.72
2.2	6	1	1.42 - 2.52	0.95 - 1.69	1.17 - 2.00	2.88
2.2	5	0.7	1.30 - 2.15	0.87 - 1.44	1.03 - 1.70	0.99
2.2	6	0.7	1.35 - 2.31	0.91 - 1.55	1.07 - 1.83	1.19

Table 1: Relative UHECR contribution to IGRB at cut-off region η_γ obtained assuming galactic γ-ray foreground models A, B or C for several representative proton source models fitting TA spectrum. The models with $\eta_\gamma > 1$ are in conflict with Fermi LAT data even disregarding contribution of unresolved point γ–sources. Also shown the expectation value of the neutrino events $\bar{N}_\nu$ with energy $E_\nu > 10$ PeV assuming IceCube 7 year exposure from Fig.1 of Ref. [1]. Models with $\bar{N}_\nu > 2.3$ have Poisson probability less than 10%. The range of η_γ was obtained for EBL models as in Ref. [3].

Accounting for the minimal contribution of unresolved point γ-sources

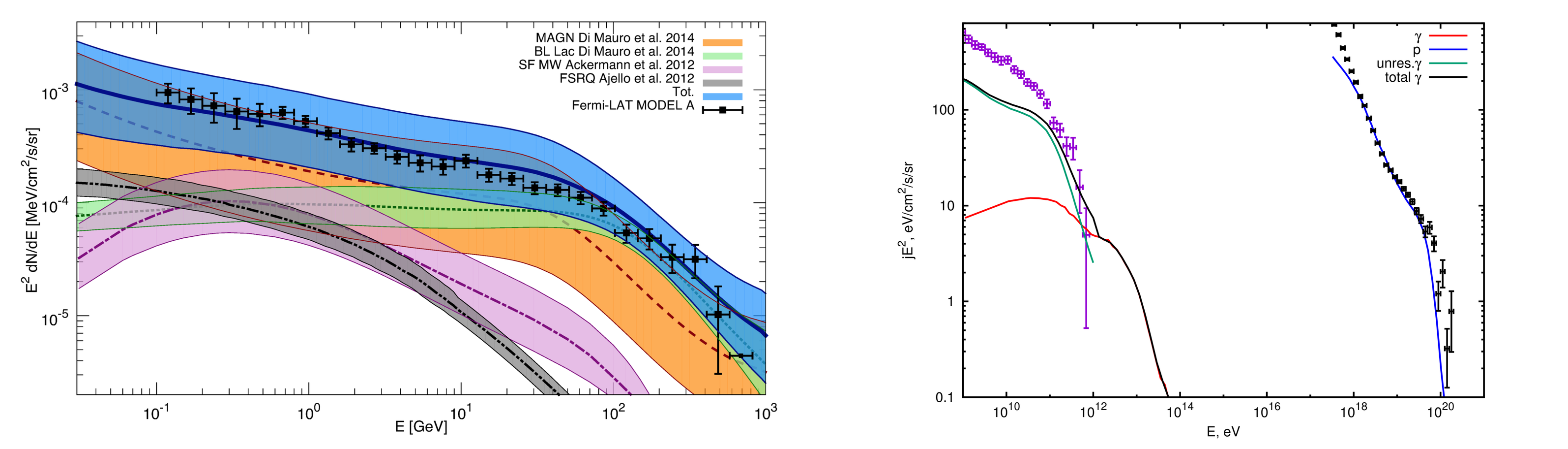

Figure 2: Contribution of unresolved point γ–sources to IGRB following Ref. [4] (left), secondary γ in UHECR model with $\frac{d\Phi}{dE} \propto E^{-2.6}$ compared to minimal flux from unresolved point γ–sources (right)

To build *conservative* limit on pure proton source models we

- use simple phenominological source model (1)
- don't require perfect UHECR spectrum fit
- choose EBL minimizing secondary γ flux
- for each m in physically motivated range we find p providing best fit (see Figure 3)
- calculate secondary γ ray flux and compare it to IGRB
  $\chi^2_{IGRB} \equiv \sum_{\Phi_\gamma(E_i) > \Phi_{\max}(E_i)} \frac{(\Phi_\gamma(E_i) - \Phi_{\max}(E_i))^2}{\sigma_i^2}$
  taking into account minimal contribution to IGRB from unresolved sources (see Figure 2)
  $\Phi_{\max} = \Phi_{\max,\text{IGRB}} - \Phi_{\min,\text{astro}}$
- consider influence of systematic uncertainty in UHECR energy scale (20%) and IGRB determination (use model B for galactic foreground γ)

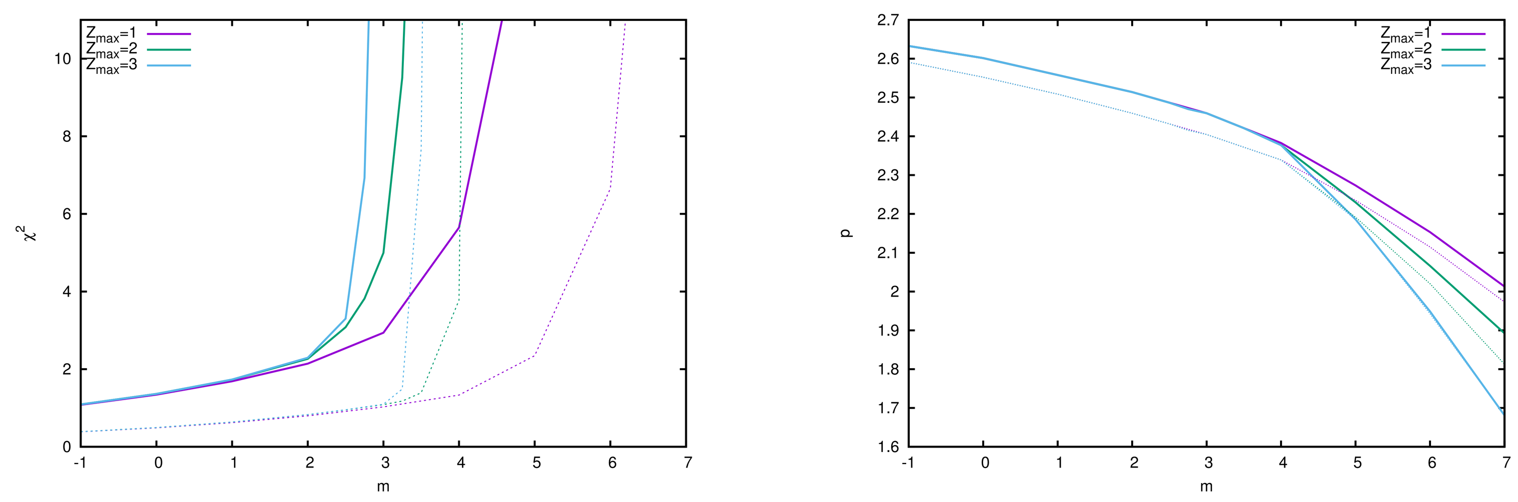

Figure 3: $\chi^2_{IGRB}(m)$ (left) and the essential best fit parameters (right) p(m) for $E_{\max} = 10^{2.5}$ EeV and $E_{\min} = 0.1$EeV. Solid lines were built using original Telescope Array energy spectrum and dottted lines were built using the spectrum with energy scale shifted by 20% towards lower energies.

Minimal UHECR contribution to IGRB

To obtain minimal UHECR contribution to IGRB we

- fit proton component of UHECR measured by Pierre Auger Observatory
- assume negative evolution (BLLacs) and low $E_{\max} = 40$ EeV

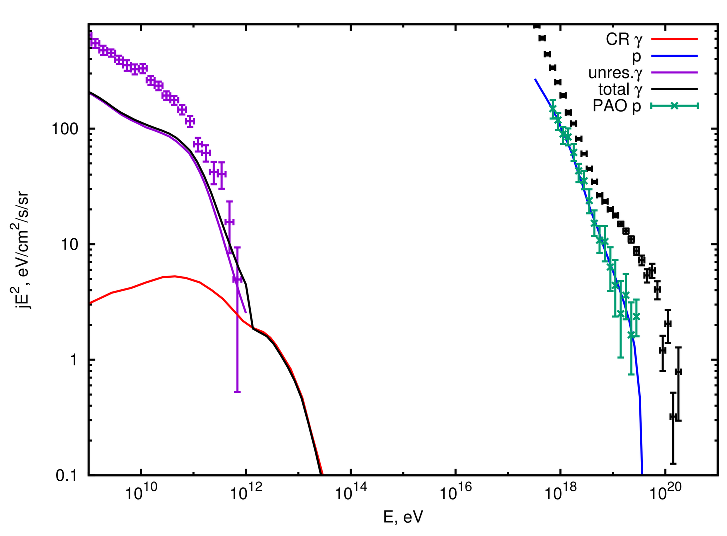

Figure 4: Minimal contribution of UHECR to IGRB

Conclusions

- Pure proton source models under pressure. Substantial contribution of nuclei or flat/negative evolution is required $m \lesssim 3$.
- Minimal contribution to IGRB from UHECR is not negligible and may be comparable to the flux from unresolved point γ-sources at IGRB cut-off region.

References

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