



## Constraints on secondary 10-100 EeV gamma ray flux in the minimal bottom-up model of Ultra High Energy Cosmic Rays.

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**Abstract:** In a recently proposed model the cosmic rays spectrum at energies above EeV can be fitted with a minimal number of unknown parameters assuming that the extragalactic cosmic rays are only protons with a power law source spectrum [1]. Within this minimal model, after fitting the observed HiRes spectrum with four parameters (proton injection spectrum power law index, maximum energy, minimum distance to sources and evolution parameter) we compute the flux of ultra-high energy photons due to photon-pion production and e+e- pair production by protons for several radio background models and a range of average extragalactic magnetic fields.

The “ankle” in the Ultra-high Energy Cosmic Ray (UHECR) spectrum can be interpreted as an absorption “dip” at energies  $E = 3 - 10$  EeV [1], due to the propagation of extragalactic protons over large distances in the cosmic microwave background (CMB) [2]. This would agree with the indication of a transition from heavy to light primary nuclei observed by the HiRes collaboration at energies close to  $5 \times 10^{17}$  eV [3]. In this case the UHECR HiRes spectrum [4], in which the GZK cutoff [5] is present, can be fitted with a minimal number of unknown parameters assuming the extragalactic cosmic rays are only protons with a power law source spectrum  $\sim E^{-\alpha}$  with  $\alpha \simeq 2.6$  [1]. This is a minimal model of UHECR.

The GZK process produces pions. From the decay of  $\pi^0$  we obtain photons, which we call “GZK photons”. Previously we studied in detail the GZK photon flux dependence on different unknown parameters of the source spectrum and distribution and the intervening cosmological backgrounds [6]. Below we briefly discuss the perspectives for photon detection in the minimal UHECR model (for more details see Ref. [7]).

We use a numerical code developed in Ref. [8, 6] to compute the flux of GZK photons produced by a homogeneous distribution of sources emitting originally only protons. This is the same numerical code as in Ref. [6], with a few modifications described in details in ref. [7]. As it is usual, we take the spectrum of an individual UHECR source to be of the form:

$$F(E) = f E^{-\alpha} \Theta(E_{\max} - E) \quad (1)$$

where  $f$  provides the flux normalization,  $\alpha$  is the spectral index and  $E_{\max}$  is the maximum energy to which protons can be accelerated at the source. The source density is defined by

$$n(z) = n_0(1+z)^{3+m} \Theta(z_{\max} - z) \vartheta(z - z_{\min}), \quad (2)$$

where  $m$  parameterizes the source density evolution ( $m = 0$  corresponds to non-evolving sources with constant density per comoving volume) and  $z_{\min}$  and  $z_{\max}$  are respectively the redshifts of the closest and most distant sources. Sources with  $z > 2$  have a negligible contribution to the UHECR flux above  $10^{18}$  eV. The value of  $z_{\min}$  is connected to the density of sources and influences strongly the

shape of the “bump” produced by the pile-up of protons which loose energy in the GZK cutoff and the strength of the GZK suppression [10, 11, 12]. Here we fix  $z_{\max} = 3$  and consider three values for  $z_{\min}$ , namely 0, 0.005 and 0.01 in Eq. (2).

The main energy loss mechanism for photons with  $E > 10^{19}$  eV is pair production on the radio background and cascade electron and positrons losses in the Extra Galactic Magnetic Fields (EGMF). Here we assume either the minimal intervening radio background of Clark *et al.* [13]) and EGMF  $B = 10^{-11}$  G or the largest radio background of Protheroe and Biermann [14]) and EGMF  $B = 10^{-9}$  G, and many different source models.

We consider many different proton spectra resulting from changing the slope  $\alpha$  and the maximum energy  $E_{\max}$  in Eq. 1 within the ranges  $2.3 \leq \alpha \leq 2.8$  and  $1.6 \times 10^{20} \text{eV} \leq E_{\max} \leq 1.28 \times 10^{21}$  eV and the source evolution parameter  $m$  in Eq.(2) within the range  $-2 \leq m \leq 3$ . We fit the observed spectrum UHECR [4] at energies  $E \geq 2$  EeV with these models, which requires a steeply falling source proton spectra with  $\alpha \geq 2.3$ . For such injected proton spectra the GZK photons reaching us are subdominant at all energies. Details of the fitting procedure can be found in Ref. [7].

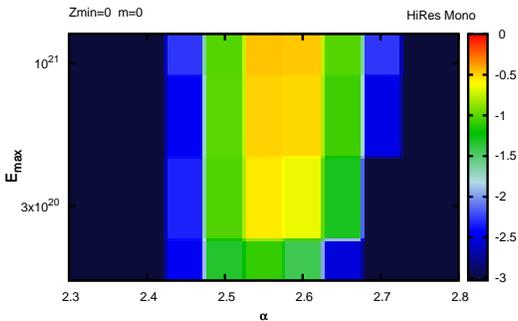


Figure 1: Consistency level of the predicted UHECR proton flux with HiRes data at  $E > 2$  EeV as function of  $E_{\max}$  and  $\alpha$  for  $m = 0$  and continuous distribution of sources. Color coded logarithmic  $p$ -value scale, from best ( $p = 1$ ) to worse ( $p$  close to zero).

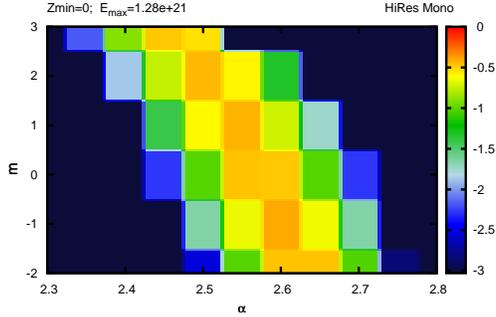


Figure 2: Consistency level of the predicted UHECR proton flux with HiRes data at  $E > 2$  EeV as function of  $m$  and  $\alpha$  for  $E_{\max} = 10^{21}$  eV and a continuous distribution of sources. Color coded logarithmic  $p$ -value scale, from best ( $p = 1$ ) to worse ( $p$  close to zero).

In Fig. 1 and Fig. 2 we show the logarithm of the  $p$ -value in a color coded scale, from best ( $p = 1$ ) to worse ( $p$  close to zero), which measures the consistency level of the predicted UHECR proton flux with the HiRes data, for different parameter ranges.

We can see from the figures that fitting the UHECR data at 2 EeV and above, requires the initial proton spectrum to be relatively hard, with  $\alpha = 2.50 - 2.65$  in Eq.(1). Fig. 1 shows that this range does not depend strongly on  $E_{\max}$  for a continuous distribution of sources. In Ref. [7] it is shown that if instead there are no sources within a distance of 50 Mpc, i.e. if  $z_{\min} = 0.01$ , the HiRes observed spectrum is not fitted as well anymore, and a relatively high maximum energy  $E = 10^{21}$  eV is required for a reasonable fit.

The low energy part of the predicted spectrum depends mostly on the power law index  $\alpha$  and source evolution index  $m$ . In Fig. 2 we show the goodness of fit  $p$ -value as function of  $m$  and  $\alpha$  for  $E_{\max} = 10^{21}$  eV for  $z_{\min} = 0$ . This figure clearly shows the degeneracy between the parameters  $m$  and  $\alpha$ : as  $m$  increases from  $-2$  to  $3$  the value of  $\alpha$  of the best fits decreases from  $\simeq 2.6 - 2.7$  to  $\simeq 2.4 - 2.5$ .

Let us now discuss the secondary photon fluxes. The main difference between the min-

imal model we are concentrating on here and other models (see Ref. [6]) is that in the minimal model one fits the UHECR data with extragalactic protons from low energies  $E > 2$  EeV, what requires a hard spectrum with index  $\alpha > 2.4$  (see Figs. 1 and 2). In this case, as mentioned above, the GZK photon flux is always sub-dominant, at all energies.

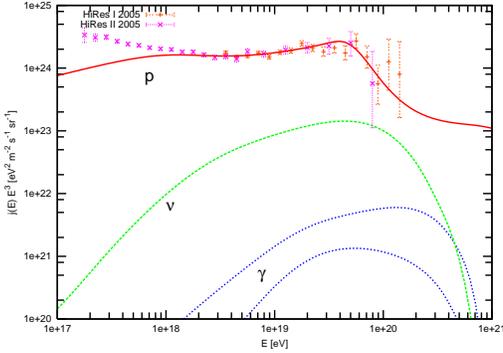


Figure 3: Proton, GZK photon and cosmogenic neutrino spectra for the model with  $m = 0$ ,  $z_{min} = 0$ ,  $E_{max} = 10^{21}$  eV and  $\alpha = 2.55$ . The upper photon line is for minimal radio background and  $B_{EGMF} = 10^{-11}$  G, while the lower photon line for maximal radio background  $B_{EGMF} = 10^{-9}$  G.

As an example, in Fig. 3 we show the possible range of GZK photon fluxes for the same proton spectrum. Here we do not deal with neutrinos in any detail, but just to compare the photon and neutrino fluxes produced in the same GZK processes, in Fig. 3 we also plotted the cosmogenic neutrino flux per flavor for the same model. Even if the neutrino flux is much higher than the photon flux, its detection may be even more difficult due to the strongly reduced probability of neutrinos to produce air-showers.

In Fig. 3 one can see that the best energy range to find GZK photons is  $E = 5 - 20$  EeV. At higher energies, the small event statistics will not allow to find a 1% fraction of photons in the UHECR flux, while at lower energies the photon fraction is strongly reduced.

In Fig. 4 we show the GZK photon fraction given in percentage of the integrated UHECR

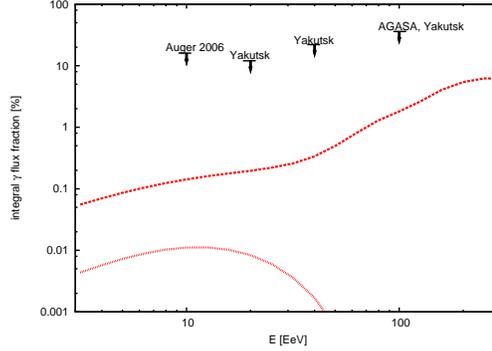


Figure 4: Maximum and minimum GZK photon fractions given in percentages of the integrated flux above the energy  $E$  as function  $E$  for maximum source proton energy  $E_{max} = 10^{21}$  eV. Present limits on photon fraction from Auger [20], Yakutsk [21] and combined AGASA/Yakutsk [22] data are also shown.

flux above the energy  $E$  as function of  $E$ , for the whole parameter space we consider (i.e. maximum source proton energy  $1.6 \times 10^{20} \text{ eV} \leq E_{max} \leq 1.28 \times 10^{21}$  eV, source evolution parameter  $-2 \leq m \leq 3$ , power law index  $2.3 \leq \alpha \leq 2.9$  and minimum redshift of the sources  $0 \leq z_{min} \leq 0.01$ ). Present limits on the photon fraction from Auger [20], Yakutsk [21] and combined AGASA/Yakutsk [22] data are also shown in the figure. It is clear that, contrary to the case of top-down models (which are restricted already by present bounds on the GZK-photon fraction [6]) the present limits are well above the expected the GZK photon fraction in the minimal UHECR model by a factor of 10 to 100 depending on the energy (see Fig. 4). The detection of GZK photons in this model will remain as a task for the future.

We find that the expected photon fraction of the integrated flux above  $E = 10$  EeV in the minimal UHECR models, is  $10^{-4}$  to  $10^{-3}$  independently of the unknown

The South site of the Pierre Auger Observatory after several years of data taking will probably be able to reach a photon fraction sensitivity of the order of  $10^{-3}$  in the integrated flux close to  $E = 10$  EeV. As can be seen in Fig. 4 this is the level of the largest GZK photon frac-

tion expected in the minimal UHECR model. Larger future observatories like Auger North plus South [23] and EUSO [24] could probe lower photon fractions if they are able to collect statistics a factor of 5-10 larger than Auger South and have thresholds around  $1 - 2 \times 10^{19}$  eV (provided these experiments are sensitive to photon primaries).

We have assumed that the sources emit only protons, however our predictions for GZK photon fractions shown in Fig. 4 would not change too much if nuclei primaries were present too, as assumed in the so called “mixed models” [25]. The reason is that even in mixed models, primary protons dominate the UHECR flux at high energies  $E > 50$  EeV, i.e. in the energy region where the primary protons produce secondary GZK photons.

As a final remark let us mention that even if the GZK photon fluxes considered here are very small, much larger fluxes are possible in more general models, which are not restricted by the condition that all the UHECR spectrum from energies  $2 \times 10^{18}$  eV to the largest is explained with extragalactic protons [6].

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