Single source scenario describing the very end of the cosmic-ray energy spectrum

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ABSTRACT

The energy spectrum of cosmic rays is steeply falling with a suppression of the flux at the highest energies caused by energy losses during propagation or by reaching the maximum power of cosmic accelerators. The energy spectrum at the highest energies is currently measured with high precision by two experiments, Telescope Array in the Northern hemisphere and the Pierre Auger Observatory in the Southern hemisphere. In our work, we study the possibility of explaining the shape of the energy spectrum above $10^{19.5}$ eV measured by the Pierre Auger Observatory with a single (dominant) source. Using numerical simulations in CRPropa 3 of cosmic ray propagation in the Universe we show possible features of such a single source that would be able to create a shape of the energy spectrum compatible with the measurement including limitations on the source distance, spectral index and mass composition.

1. SIMULATIONS

- 1D propagation of particles from a source to the Earth in CRPropa 3 [1]
- Interactions of cosmic rays with CMB and EBL background
  - Photo-pion production
  - Electron pair production
  - Photodisintegration
  - \+ nuclear decay and redshift energy losses
- Four primary particles: H, He, N, Fe
- Power-law energy spectrum with minimal energy $\log_{10}(^{E_{\min}}/_{\mathrm{eV}}) = 19.5$ and maximum rigidity $\log_{10}(^{R_{\max}}/_{\mathrm{V}}) = 20.5$

SOURCE FEATURES

- Energy spectrum: power-law with rigidity dependent exponential cutoff, $\log_{10}(R_{\mathrm{cut}}/\mathrm{V}) = 18.5 - 20.5$ with step of 0.1

$$\frac{dN}{dE} \propto E^{-\gamma} f_{\mathrm{cut}} \qquad f_{\mathrm{cut}} = \begin{cases} 1 & \text{, for } E < eZR_{\mathrm{cut}} \\ \exp\left(1 - \dfrac{E}{ZR_{\mathrm{cut}}}\right) & \text{, for } E > eZR_{\mathrm{cut}} \end{cases}$$

- Source distance from 3 Mpc to 100 Mpc with step of 1 Mpc up to 20 Mpc and step of 10 Mpc further of
- Spectral indices $\gamma = 1.0 - 3.0$ with step of 0.5
- Composition mixes on the source with step of 10% in primary fractions

2. COMPARISON OF MC WITH DATA

- Simulated energy spectrum for different source features is compared with the spectrum measured by the Pierre Auger Observatory [2] above $10^{19.5}$ eV
- Good agreement between the two spectra is defined with two conditions
  1. $\chi^2/\mathrm{ndf} \leq 2$
  2. Non-zero simulated flux of particles in all energy bins containing measured events

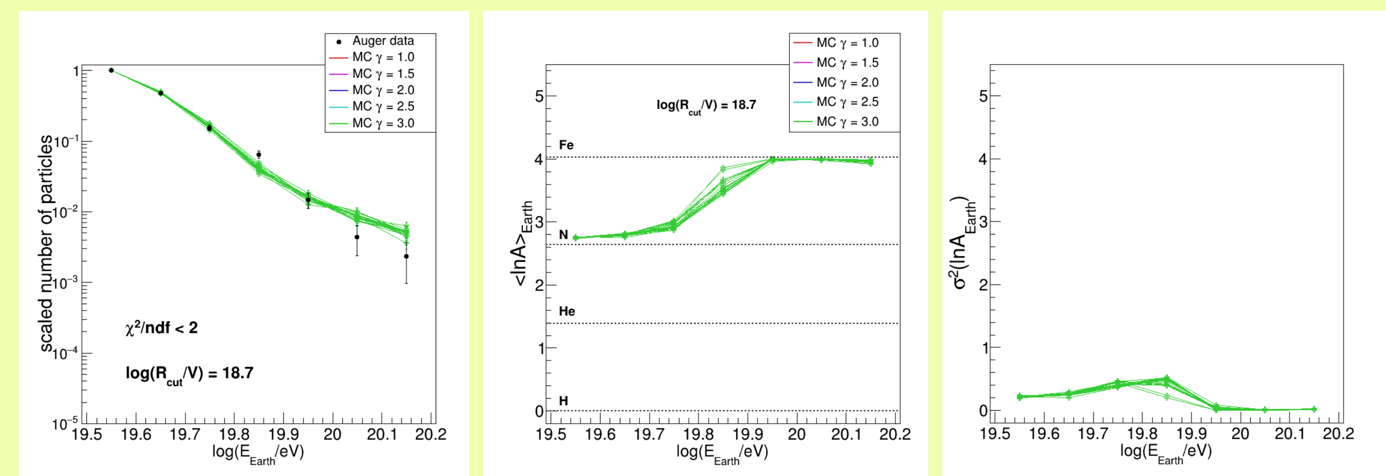

Figure 1: Energy spectrum (left), mean lnA evolution with energy (middle) and evolution of variance of lnA with energy (right) for cutoff rigidity of the source $\log_{10}(^{R_{\mathrm{cut}}}/_{\mathrm{V}}) = 18.7$. All solutions found are for sources within 20 Mpc.

- Additional assumptions on mass composition based on measurements by the Pierre Auger Observatory [3-5]
  1. $\langle \ln A \rangle \gtrsim 2.6$, e.i. heavier than nitrogen
  2. $\sigma^2(\ln A) \leq 0.5$, e.i. low mixing of particles

3. RESULTS

- Comparing the energy spectrum only, we get large set of possible single source features across all values of R_{cut} and spectral indices γ
- Different mass compositions of CRs on the Earth above $E = 10^{19.5}$ eV
  - Light composition $\langle \ln A \rangle < \ln 4$ for $\log_{10}(R_{\mathrm{cut}}/\mathrm{V}) = 19.0 - 20.5$
  - Heavy composition $\langle \ln A \rangle > \ln 14$ for $\log_{10}(R_{\mathrm{cut}}/\mathrm{V}) = 18.5 - 19.4$
- Number of possible solutions decreases rapidly applying additional conditions on mass composition $\langle \ln A \rangle \gtrsim 2.6$ and $\sigma^2(\ln A) \leq 0.5$
- Solutions remaining for sources with
  - Distance $D \leq 20$ Mpc
  - Rigidity cutoff $\log_{10}(R_{\mathrm{cut}}/\mathrm{V}) \leq 19.3$
  - Spectral index $\gamma \approx 3$

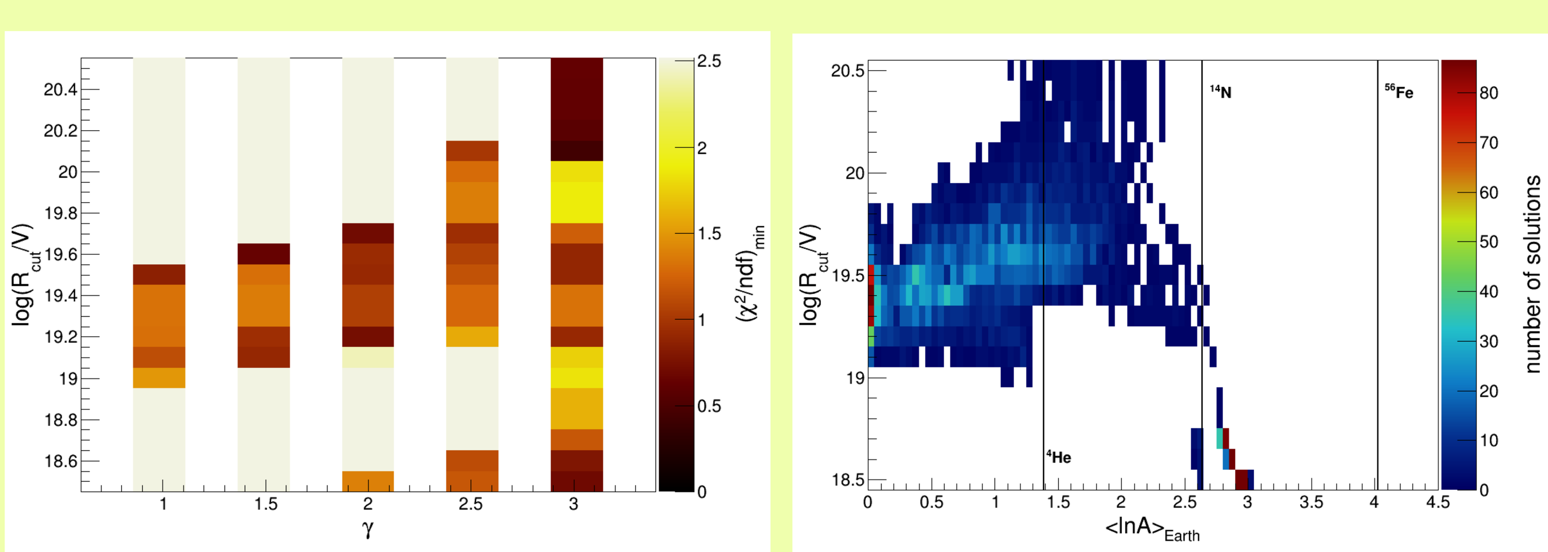

Figure 2: (left) Minimal value of χ^2/ndf found for different combinations of R_{cut} and γ. (right) Number of solutions for different values of R_{cut} with respect to mean mass composition on the Earth.

$\langle \ln A \rangle \gtrsim 2.6$
$\sigma^2(\ln A) \leq 0.5$

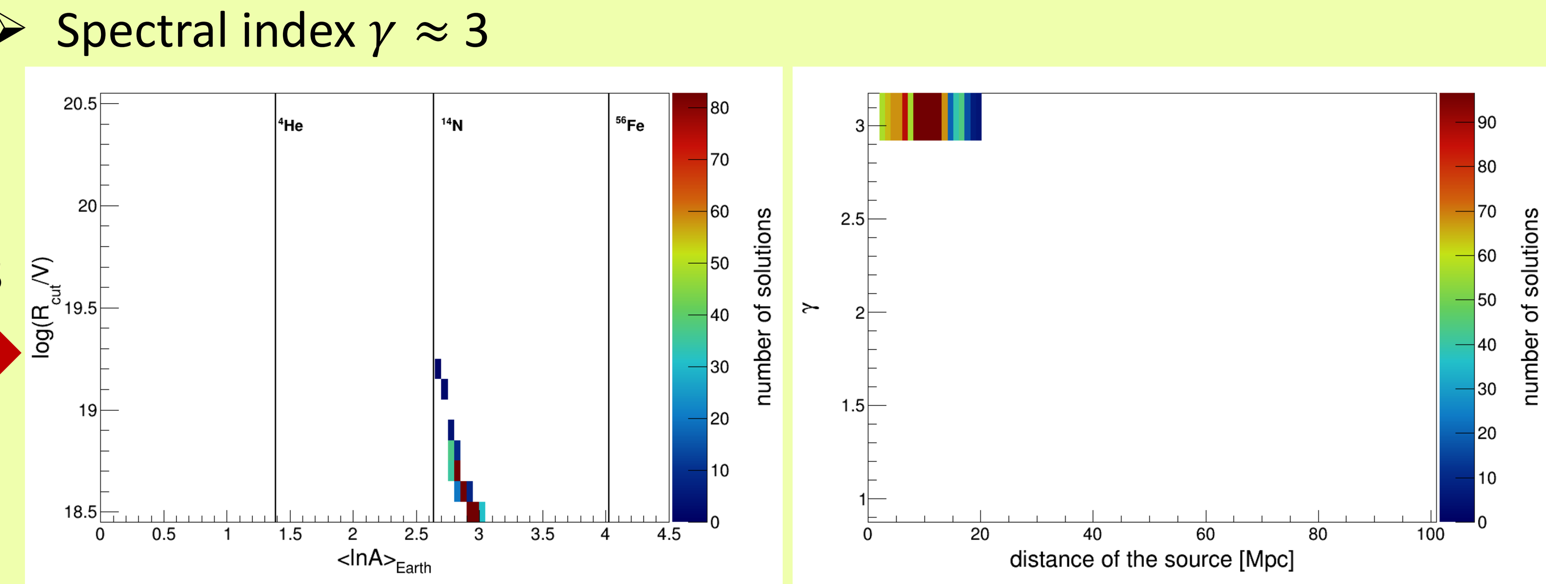

Figure 3: Number of solutions for different R_{cut} values with respect to mass composition on the Earth (left) and different spectral indices with respect to source distance (right) after applying additional mass composition cuts.

4. CONCLUSIONS

We find it is possible to describe the shape of the energy spectrum of cosmic rays measured by the Pierre Auger Observatory above $10^{19.5}$ eV by a single source with various source features in R_{cut}, γ and mass composition mix. When applying additional conditions on the mass composition on the Earth (heavy with low mixing) we restrict the number of possible solutions and find that such a source needs to be within 20 Mpc from the Earth, with rigidity cutoff $\log_{10}(R_{\mathrm{cut}}/\mathrm{V}) \leq 19.3$ and spectral index $\gamma \approx 3$.

References

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[2] The Pierre Auger Collaboration, *Phys. Rev. D* **102** (2020) 062005.
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[5] J. Vicha, ISVHE-CRI (2022), arXiv:2209.00744.

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