Features of a single source describing the very end of the energy spectrum of cosmic rays

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Outline

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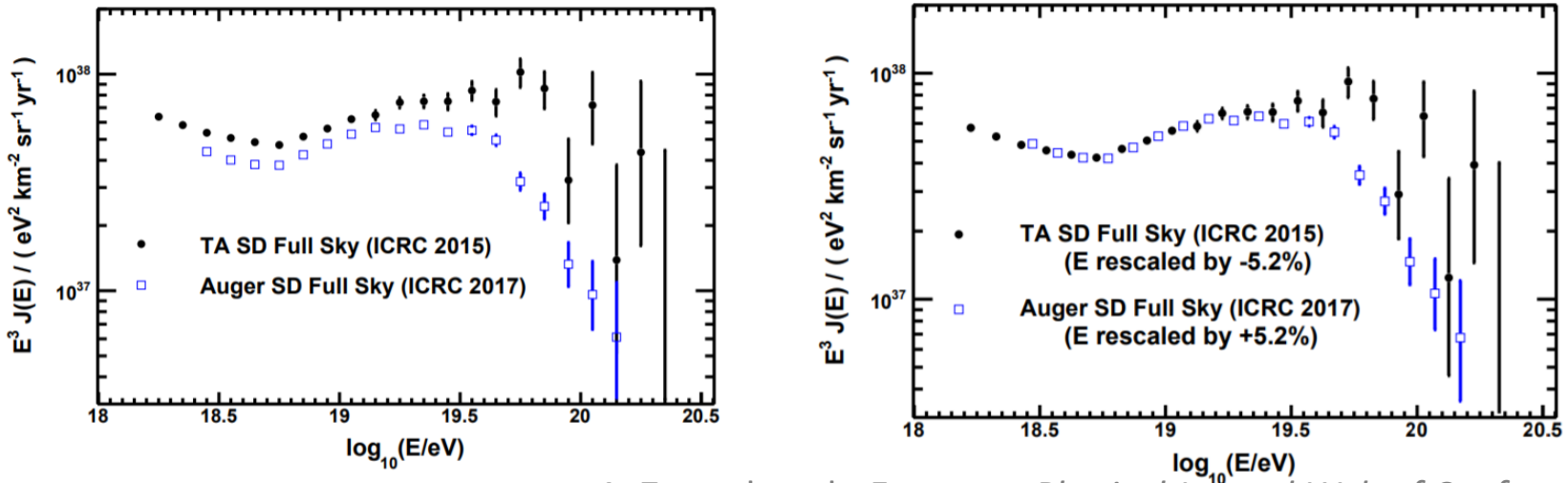
- Simulations of cosmic-ray propagation
- Comparison of simulations and measurement
- Results
  - Possible rigidity cutoff of the source and other features
  - Mass composition on the Earth at the highest energies
  - Anisotropies in arrival directions for single source scenario
- Summary

Motivation

- Different suppression of the flux of cosmic rays at the highest energies measured by the Pierre Auger Observatory and Telescope Array



A. Zayyad et al., *European Physical Journal Web of Conferences* **210** (2019) 01002

- Possibility of observing different (dominant) sources on the Northern and Southern hemisphere
- In this work we start with the southern hemisphere, Pierre Auger Observatory provides open data of tabulated energy spectrum

Is it possible to explain the shape of the end of energy spectrum by a **single (dominant) source**? What properties should such a source have?

Simulations of cosmic-ray propagation

- Cosmic-ray propagation simulated in one-dimensional mode of CRPropa 3
- Four types of primary particles: H, He, N, Fe with power-law energy spectrum with minimal energy $\log_{10}(E/eV) = 19.5$ and maximum rigidity $\log_{10}(R/V) = 20.5$
- 10,000 simulated particles for each primary

SOURCE PARAMETERS

- Source distance (3-100) Mpc – step of 1 Mpc up to 10 Mpc, step of 10 Mpc further of
- Composition mixes on the source with step of 10% in relative abundance of each of the simulated components
- Different spectral indices of the source:

$$\gamma = 1.0, \gamma = 1.5, \gamma = 2.0, \gamma = 2.5, \gamma = 3.0$$

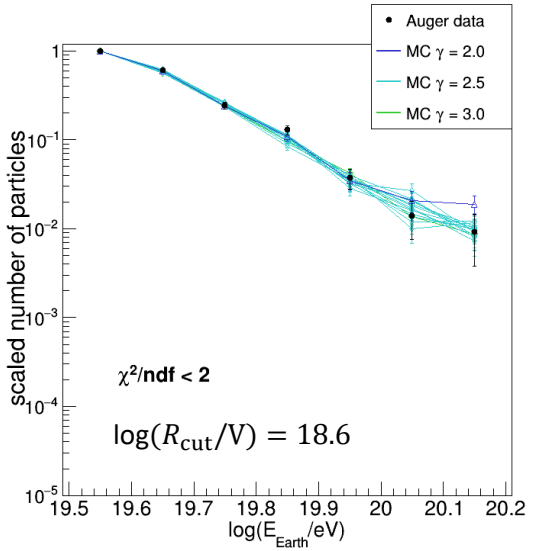
- Broken power-law with exponential rigidity cutoff with $\log_{10}(R_{\mathrm{cut}}/\mathrm{V}) = 18.5 - 20.5$

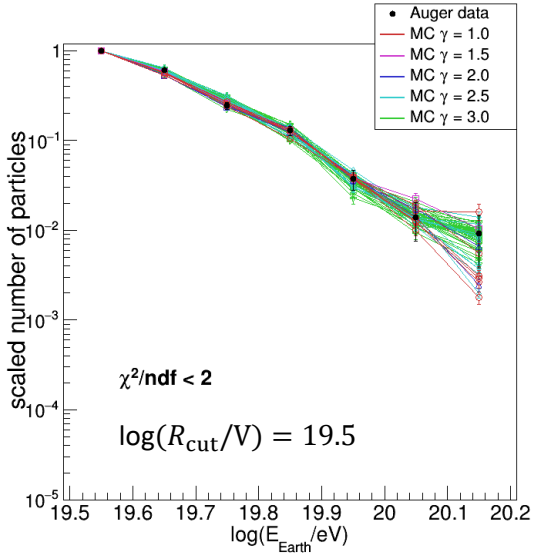
$$\frac{\mathrm{d}N}{\mathrm{d}E} = E^{-\gamma} f_{\mathrm{cut}} \qquad f_{cut} = \begin{cases} 1 & E < eZR_{\mathrm{cut}} \\ \exp\left(1 - \frac{E}{ZR_{\mathrm{cut}}}\right) & E > eZR_{\mathrm{cut}} \end{cases}$$

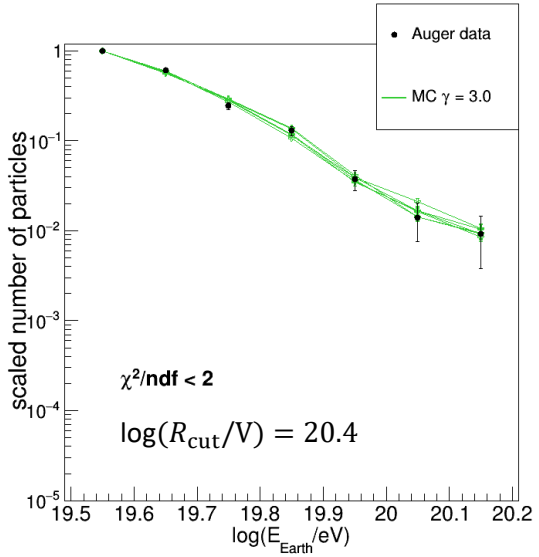
Comparison of simulations with measurement

- We take values of the flux of cosmic rays at the highest energies from measurements by the Pierre Auger Observatory The Pierre Auger Collaboration, *Phys. Rev. D* **102** (2020) 062005
- Simulated energy spectrum for different source features is compared with the measured spectrum above $10^{19.5}$ eV

→ good agreement defined with condition $\chi^2/ndf < 2$ + non-zero simulated flux of particles in all energy bins containing measured events



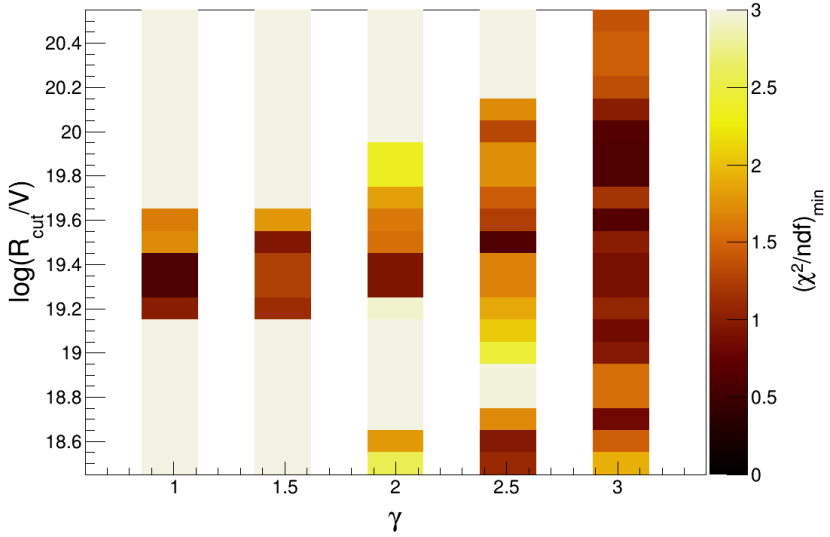


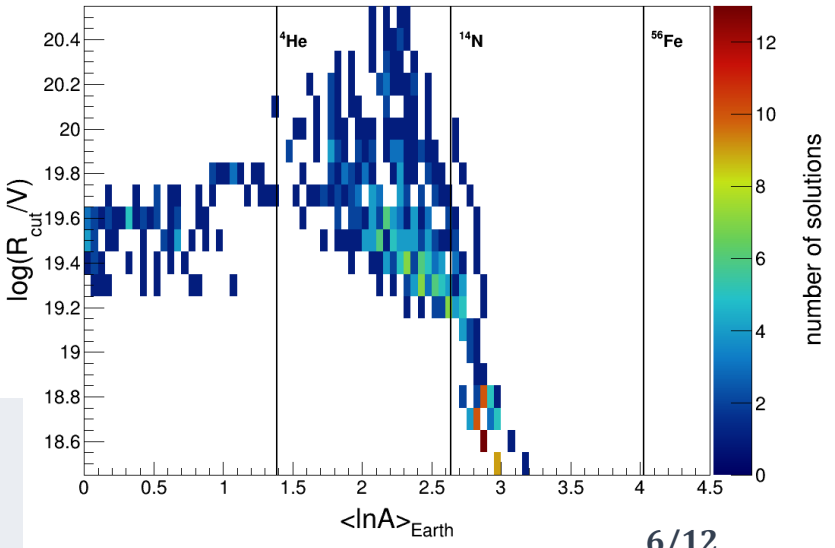


log(*E*/eV)	$J\ [\mathrm{km^{-2}yr^{-1}sr^{-1}eV^{-1}}]$
19.55	$1.252^{+0.052}_{-0.050} \cdot 10^{-21}$
19.65	$5.98^{+0.32}_{-0.31} \cdot 10^{-22}$
19.75	$1.93^{+0.17}_{-0.15} \cdot 10^{-22}$
19.85	$8.10^{+0.99}_{-0.88} \cdot 10^{-23}$
19.95	$1.86^{+0.46}_{-0.38} \cdot 10^{-23}$
20.05	$5.5^{+2.5}_{-1.8} \cdot 10^{-24}$
20.15	$2.9^{+1.7}_{-1.2} \cdot 10^{-24}$

Source features describing the energy spectrum

- Scan of the energy spectra produced by sources with different distances, composition mixes, γ and R_{cut}
- Possible solutions found across all investigated R_{cut} values
- Sources with spectral indices $\gamma = 1.0, \gamma = 1.5$ describe energy spectrum well in a narrow band of rigidity cutoff (19.2-19.6)
- All sources producing compatible energy spectrum with measurement are within 50 Mpc from Earth
- Different possible mass compositions of CRs on the Earth above $E = 10^{19.5}$ eV
  - Light composition ($\langle \ln A \rangle < \ln 4$) for $\log_{10}(R_{\mathrm{cut}}/V) = 19.3 - 19.8$
  - Heavy composition ($\langle \ln A \rangle > \ln 14$) for $\log_{10}(R_{\mathrm{cut}}/V) = 18.5 - 20.0$

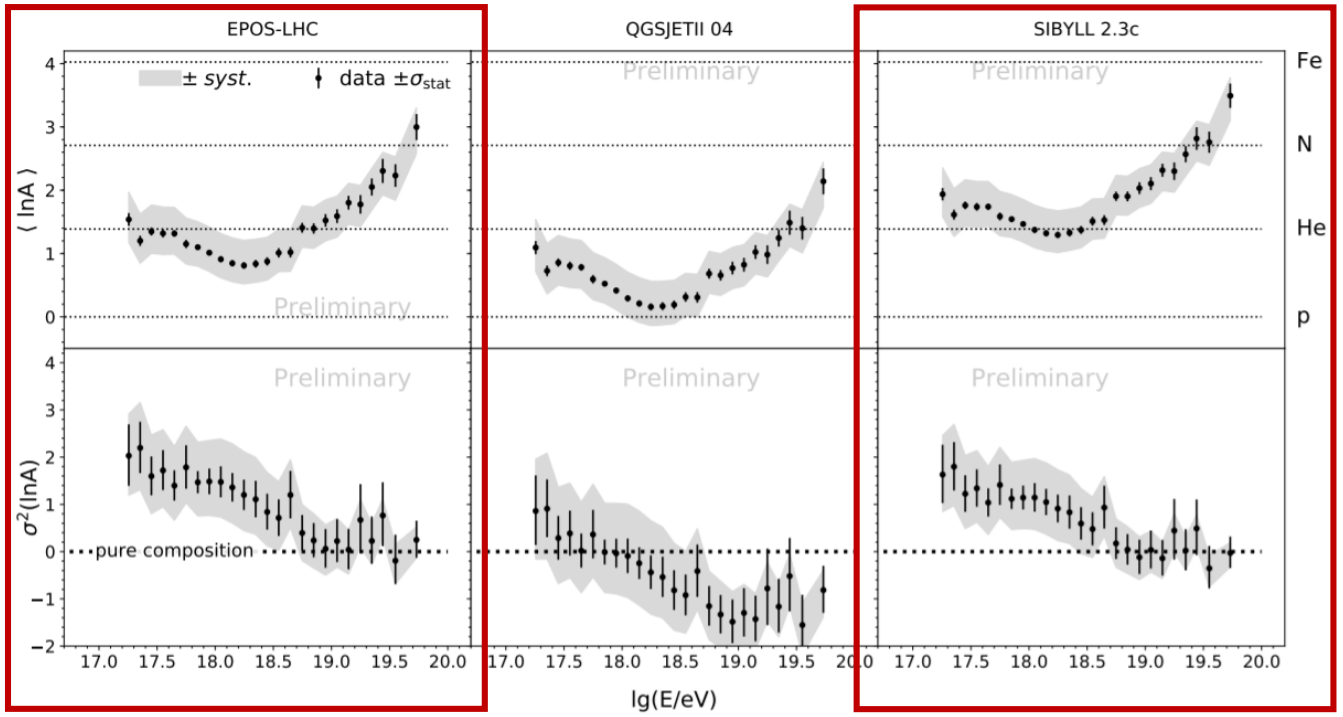


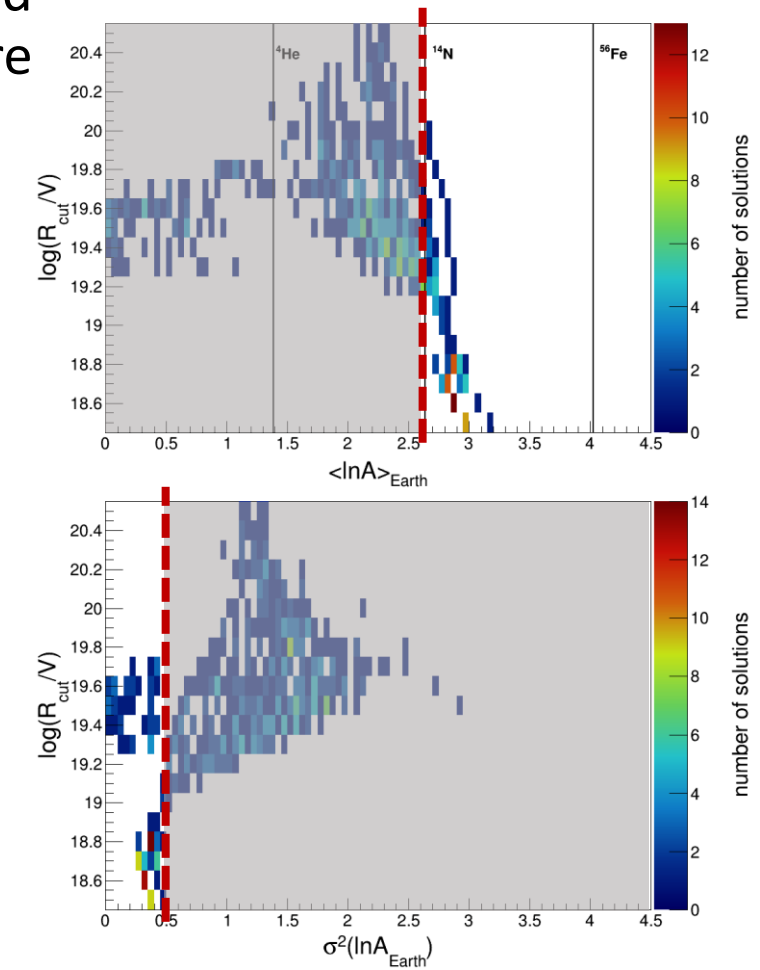


Is it possible to narrow down the possible source features using additional conditions based on measured data?

Additional conditions on mass composition

- X_{max} measurements and Delta method suggest heavy composition of the CRs at the highest energies on the Earth (A. Yushkov, *PoS(ICRC2019)*482, C. J. T. Peixoto, *PoS(ICRC19)*440)
- Interpretation of measured data with EPOS-LHC and Sybill 2.3c might indicate $\langle \ln A \rangle$ heavier than pure nitrogen and $\sigma^2(\ln A) \leq 0.5$ at the highest energies

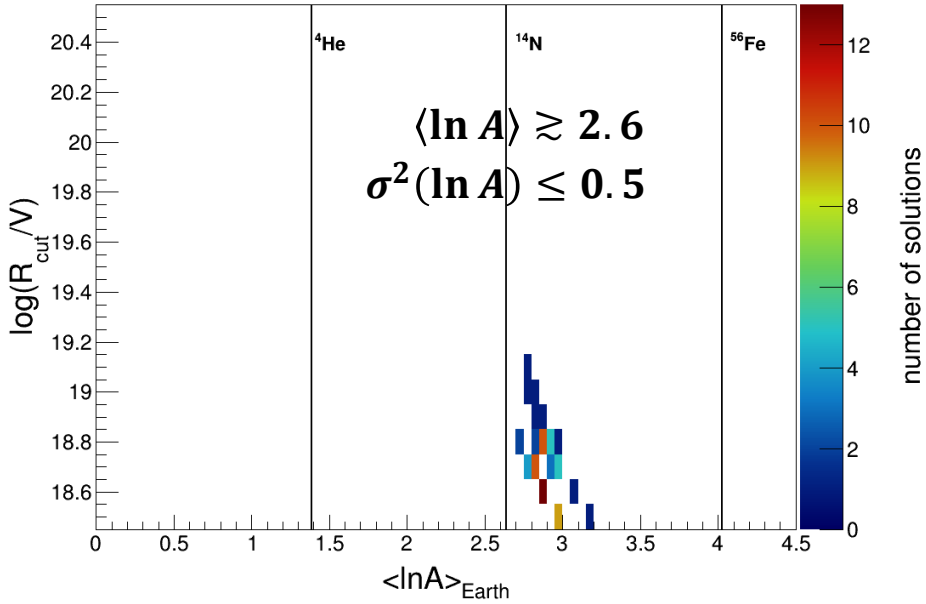


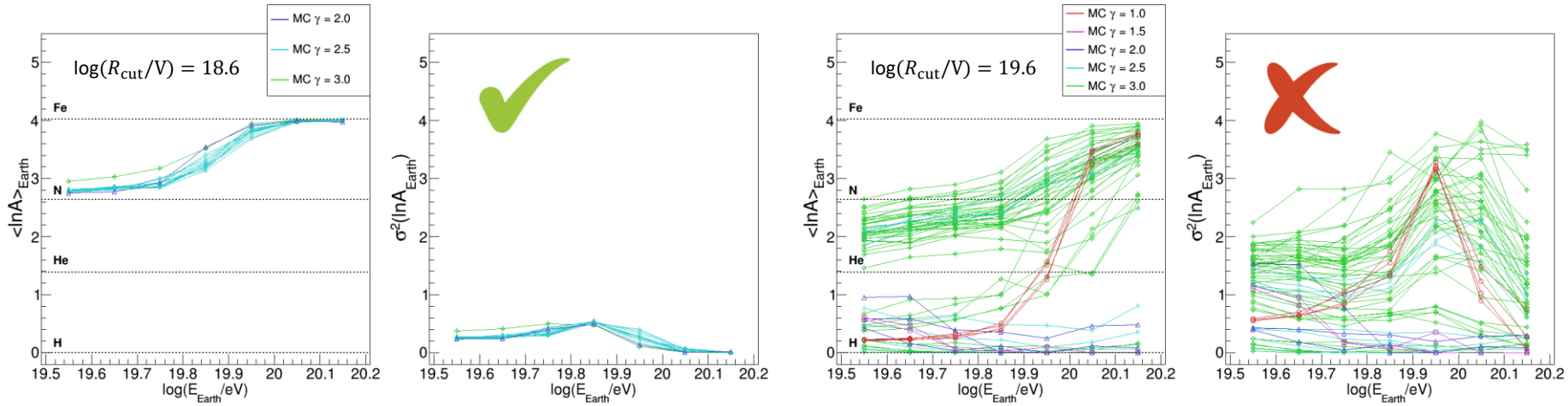


A. Yushkov, *PoS(ICRC2019)* **358** (2019) 482

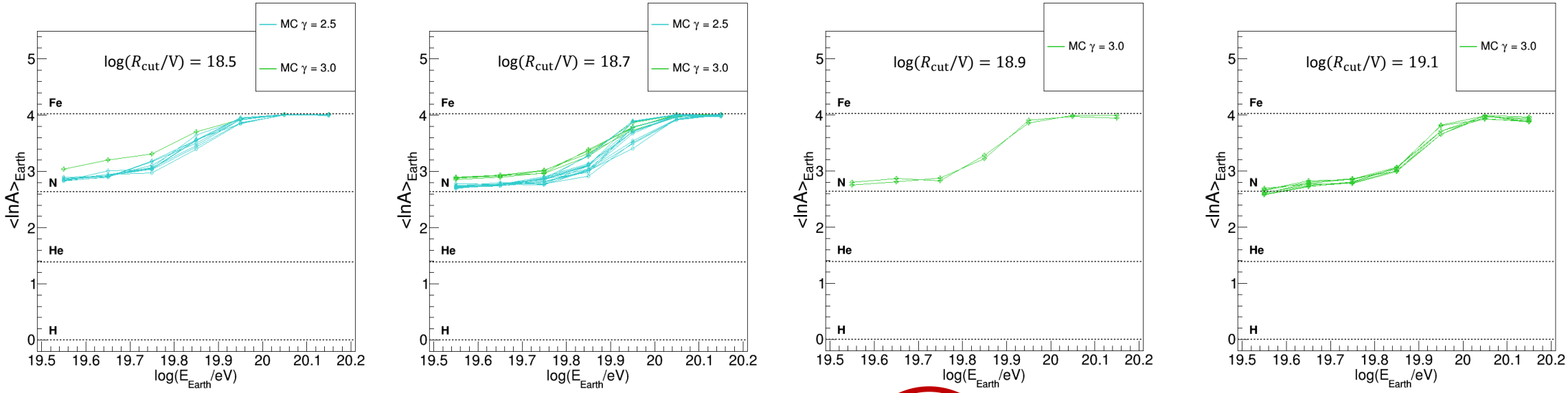
Source features satisfying composition condition

- Additional conditions on mass composition on the Earth limit the possible source features
- Sources with low cutoff rigidity $\log(R_{cut}/V) < 19.2$ and spectral index $\gamma \gtrsim 2.0$ can describe well both the shape of the energy spectrum and the composition measurements
- Low R_{cut} is needed to suppress light elements in the mass composition

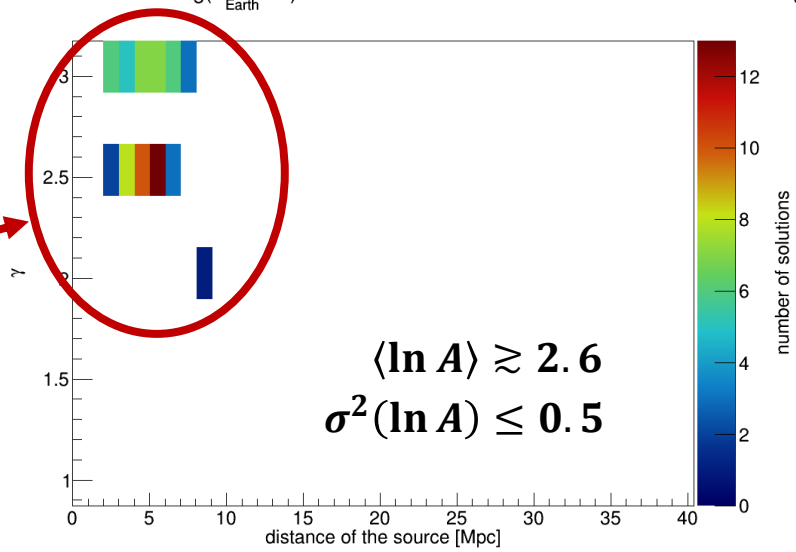




Source features satisfying composition condition

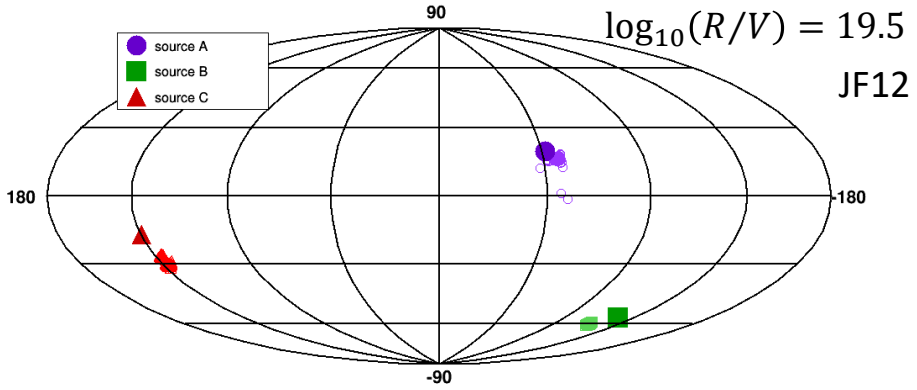


- Similar evolution of $\langle \ln A \rangle$ on the Earth with energy for all possible R_{cut} values
- For all possible solutions the source is within 10 Mpc from the Earth

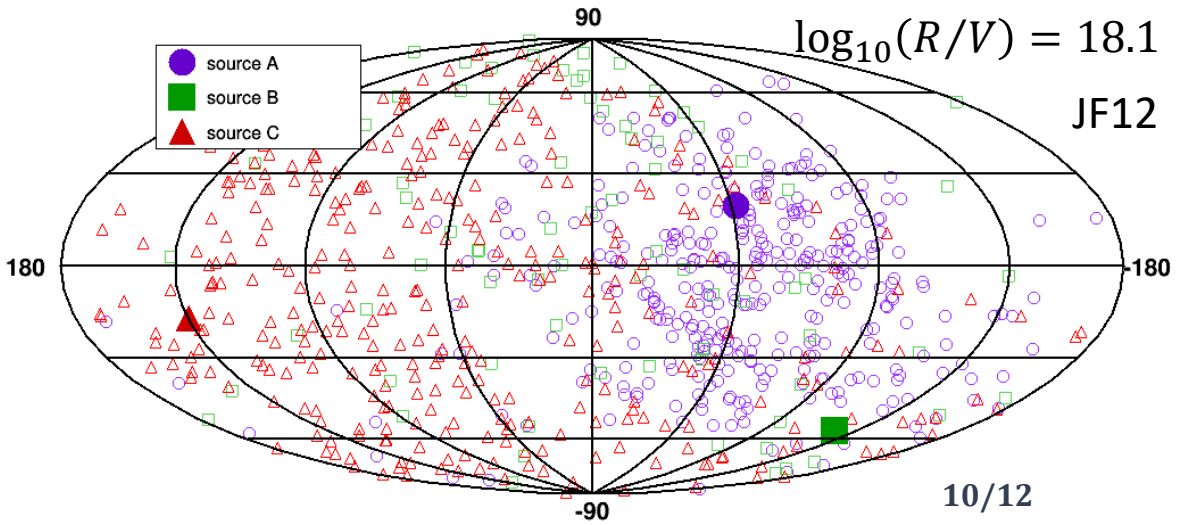


Single source and anisotropies in arrival directions

- Single source emitting protons at the highest energies might cause strong anisotropies in arrival directions on the Earth – not observed
- Arrival directions depend on the rigidity of these CRs
- Galactic magnetic field smears the arrival directions of CRs into a very large area even at the highest energies for heavy primaries



Fe primary: $E = 10^{19.5}$ eV → $R \sim 10^{18.1}$ V



- Information about the source position is lost during propagation in the GMF

Summary

- Can we describe the very end of CR energy spectrum by a single source?
- It is possible to describe the shape of the energy spectrum for various source features in R_{cut}, γ and mass composition mix
- All sources producing the energy spectrum well within 50 Mpc to the Earth

- Additional conditions on mass composition on the Earth

  $\rightarrow \langle \ln A \rangle \gtrsim 2.64$ (nitrogen) and $\sigma^2(\ln A) \leq 0.5$

  - Source rigidity cutoff $\log_{10}(R_{\mathrm{cut}}/\mathrm{V}) < 19.2$
  - Source spectral index $\gamma \gtrsim 2.0$
  - Source distance within 10 Mpc

Thank you for your attention

References

[1] T. AbuZayyad, O. Deligny, D. Ikeda, D., et al., *European Physical Journal Web of Conferences* **210** (2019) 01002 https://www.epj-conferences.org/epjconf_uhecr18_01002

[2] A. Yushkov, *PoS(ICRC2019)* **358** (2019) 482 https://pos.sissa.it/358/482/pdf

[3] C. J. T. Peixoto, *PoS(ICRC2019)* **358** (2019) 440 https://pos.sissa.it/358/440/pdf

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