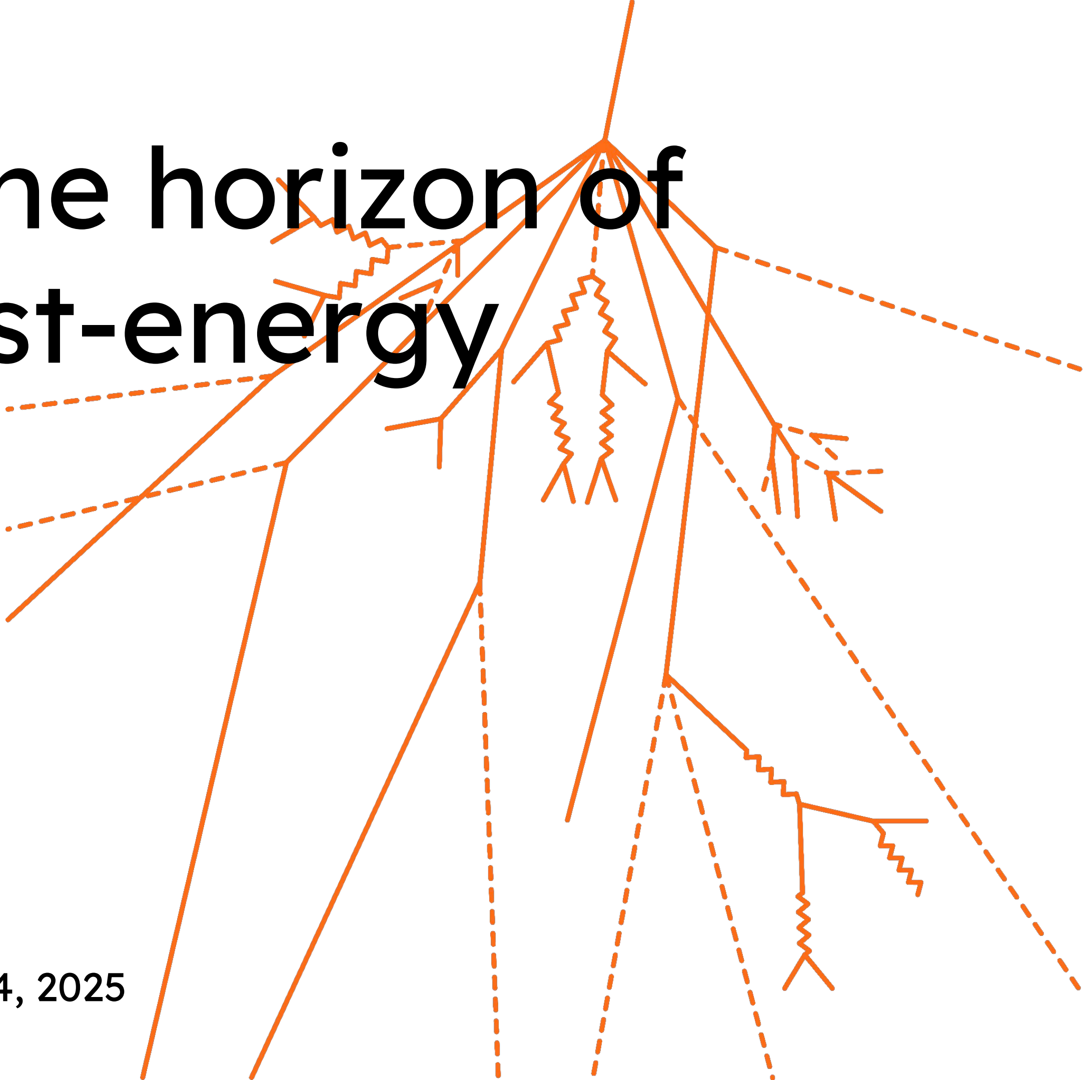
Determining the horizon of Auger’s highest-energy events



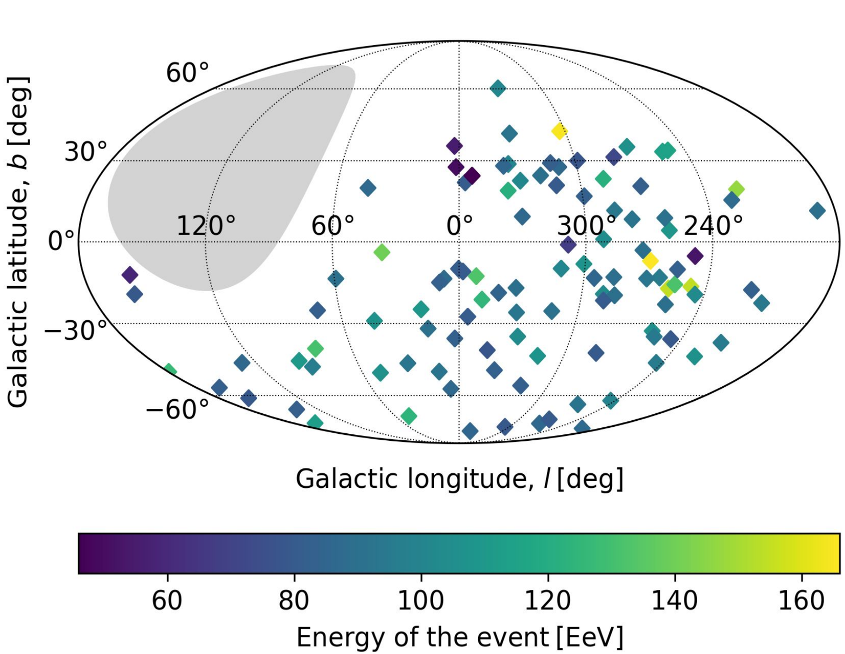
Luciana Andrade Dourado | February 04, 2025

Current status of Auger's highest-energy events

- The Pierre Auger Collaboration (2023) publicly published *a catalog of its 108 highest-energy events*, ranging from 46 to 166 EeV.

- An analysis searching for the sources of the *four highest-energy events* from this catalog was conducted in the GAP2024_011 by M. Unger and G. Farrar.

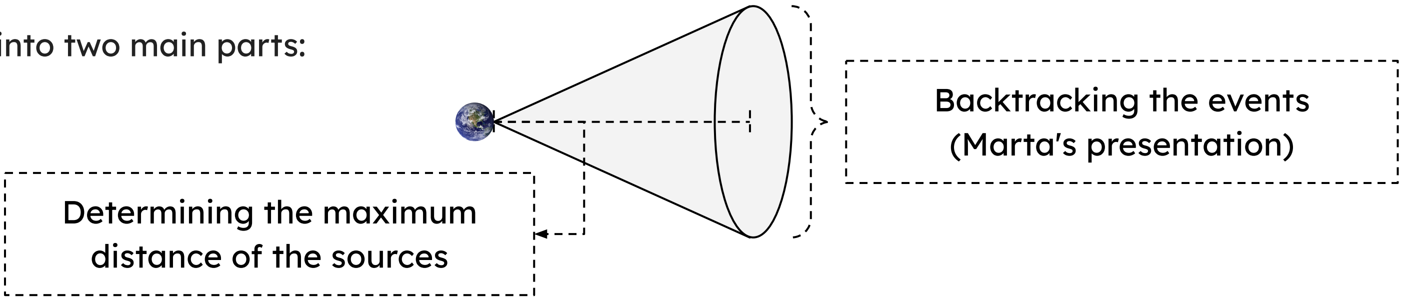
- The GAP2024_011 was performed by *defining a region of the universe from which these events could originate*. The following assumptions were made:
  - Fixed definition of the horizon;
  - Injection of iron at the sources with an energy distribution given by:
  - No extragalactic magnetic fields.



$$Q(E_s) = Q_0 \left(\frac{E_s}{10^{18}\,\mathrm{eV}}\right)^{-1} e^{-E_s/(26\times 10^{18.6}\,\mathrm{eV})}$$

Our work on Auger's highest-energy events

- A work in progress with Marta Bianciotto, Denise Boncioli, Antonella Castellina, Armando di Matteo, Carmelo Evoli, and Francesco Salamida.
- The work is divided into two main parts:



- We aim to expand on the work already conducted in that GAP Note by *including more events from the catalog and taking into account all significant uncertainties.* Among these uncertainties, we have:
  - The definition of the horizon;
  - The energy measurements;
  - The spectral parameters at the sources, including the particle species injected;
  - The extragalactic magnetic fields;
  - The cross-section models.

Horizon definitions in the market

Unger & Farrar (2024) (UF24, “Amaterasu paper”) + GAP2024_011

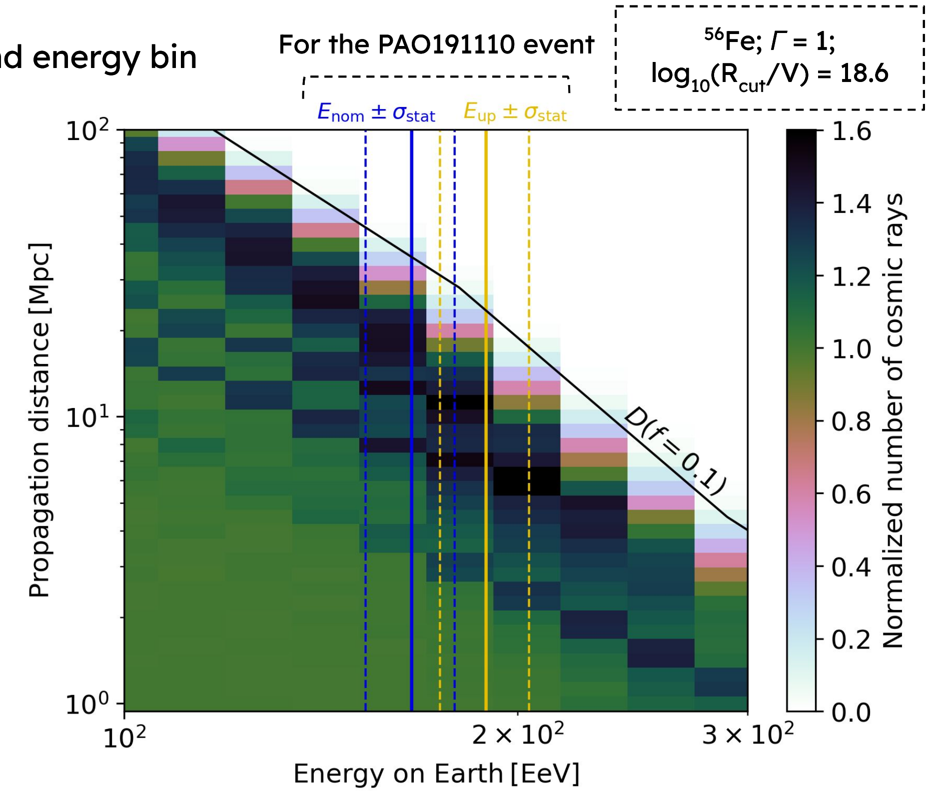
Globus, Fedynitch & Blandford (2023) (GFB23)

Harari, Mollerach & Roulet (2006) (HMR06)

UF24 definition

- Normalized number of cosmic rays per distance and energy bin

$$f_{\text{att}} = \frac{\overbrace{n(D)}^{\text{Spectrum from a given distance } D}}{\underbrace{n(0)}_{\text{Spectrum without energy losses or at the sources}}}$$



- To define the horizon, it's necessary to set a threshold for the attenuation factor
- In the case of the right graph, the horizon (*black line*) corresponding to an attenuation factor of 10 is shown

GFB23 definition

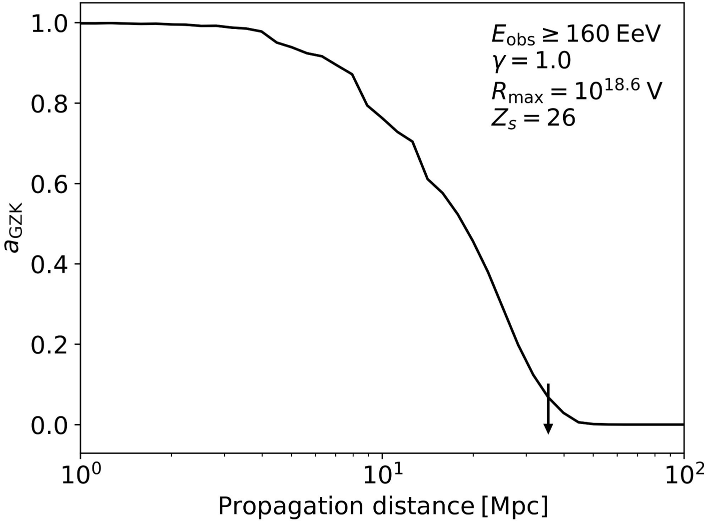
- Loss of number, a_{GZK}

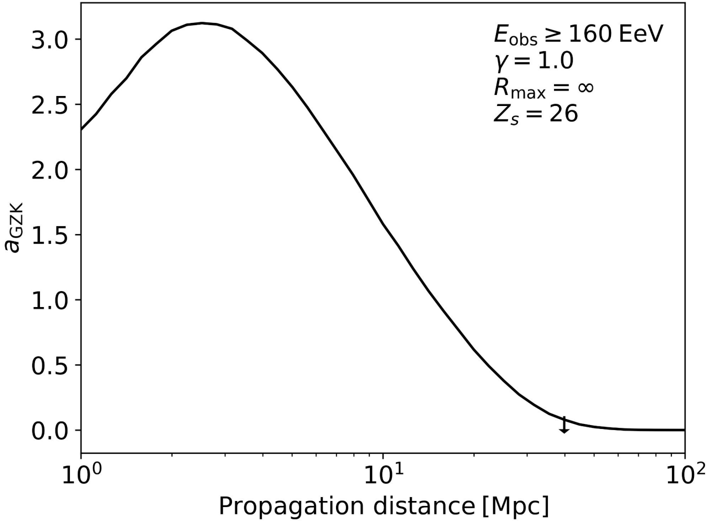
Spectrum from a given distance d_s

$$a_{\rm GZK}(A_s, d_s, E_{s,\max}, \gamma | A_{\rm obs}, E_{\rm obs}) = \frac{\sum_{A_i \leq A_s} \int_{E_{\rm obs}}^{\infty} \overbrace{dE \frac{dT_{A_i}}{dE}(d_s, \gamma, E_{s,\max})}^{\text{Spectrum from a given distance } d_s}}{\int_{E_{\rm obs}}^{\infty} \underbrace{dE_s \frac{dN}{dE_s}(E_s, E_{s,\max})}_{\text{Spectrum at the sources}}}$$

- Threshold on the a_{GZK} value to define the horizon

Spectrum at the sources





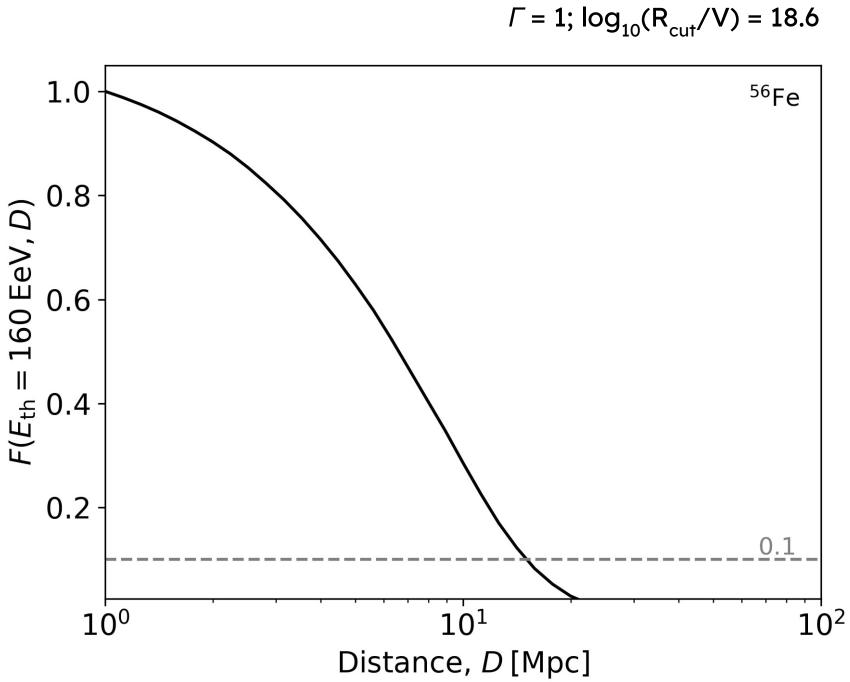
Extrapolating the source parameters too much can lead to *values greater than 1* for a_{GZK}

HMR06 definition

The fraction of particles above the observed energy on Earth

$$F(E_{\mathrm{th}}, D) = \frac{\int_D^{\infty} dx\, A(E_{\mathrm{th}}, x)}{\int_0^{\infty} dx\, A(E_{\mathrm{th}}, x)}$$

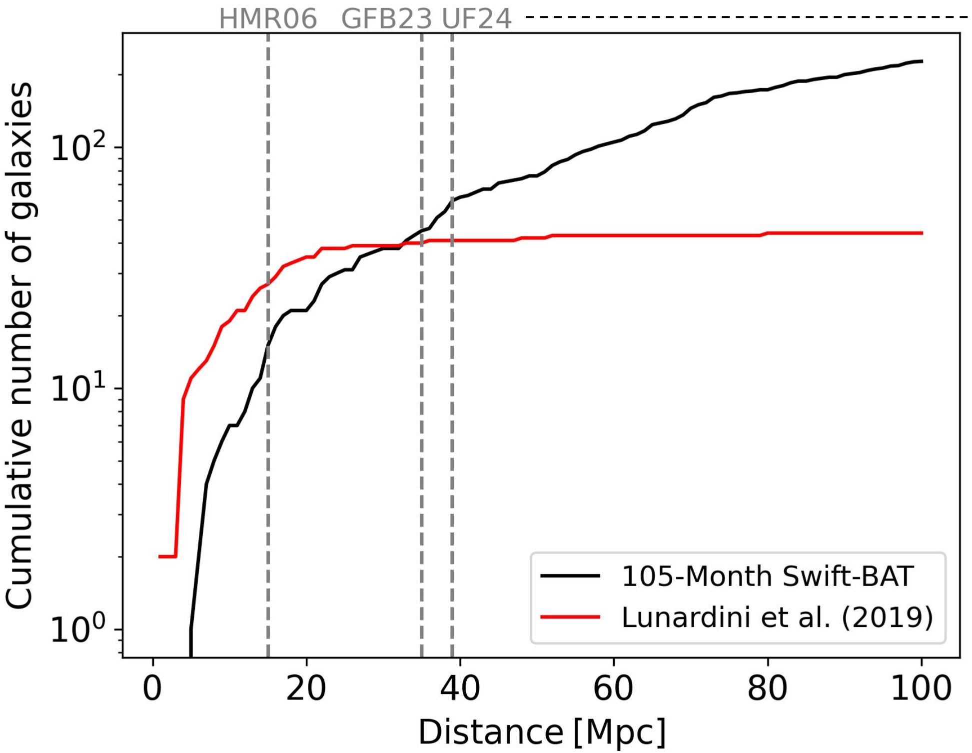
- This definition only depends on the spectrum on Earth
- By definition, this fraction *F* always has values smaller than 1
- As before, a threshold value must be defined for this fraction *F* to determine the horizon



This method significantly reduces the particle horizon from 39 Mpc and 35 Mpc for the UF24 and GFR23 definitions, respectively, to 15 Mpc for HMR06 at an energy of 160 EeV

Comparisons with galaxy catalogs

- Without considering the deflections by the Galactic magnetic fields, only the definition of the horizon can impact the number of source candidates for a given event



For a 160 EeV particle

Number of galaxies (< *D*)

	HMR06	GFB23	UF24
Lunardini	27	45	54
Swift-BAT	15	40	41

Comparisons with my implementation (UF24)

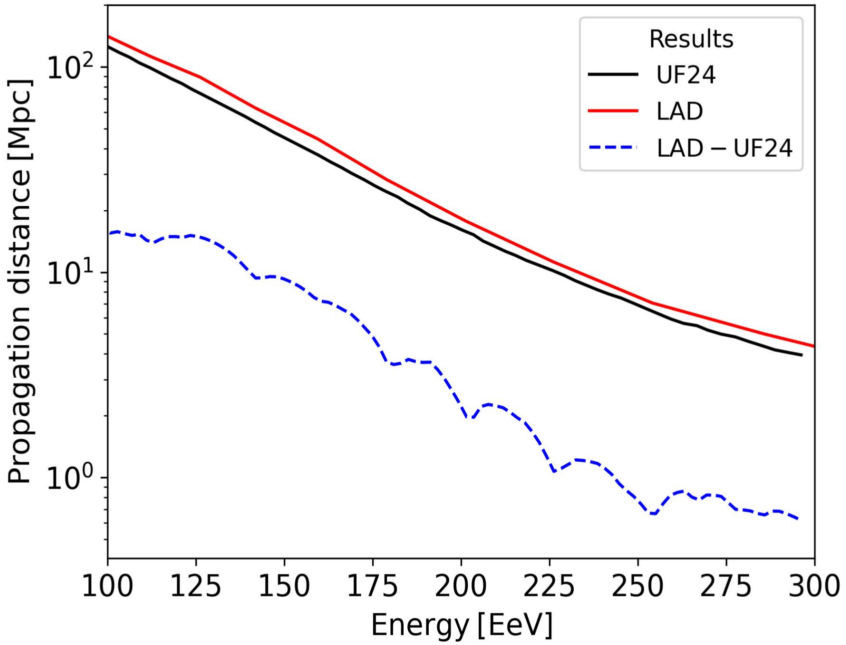
- Direct comparisons between the results for the horizon in the aforementioned papers and my implementation were conducted as follows.

- In the case of UF24, there is only one curve to compare with. This curve corresponds to the injection of iron, a spectral index of -1, and a rigidity cutoff of $10^{18.6}$ V.

- Both results were obtained using CRPropa, but with different versions.

- The difference increases as the energy decreases.

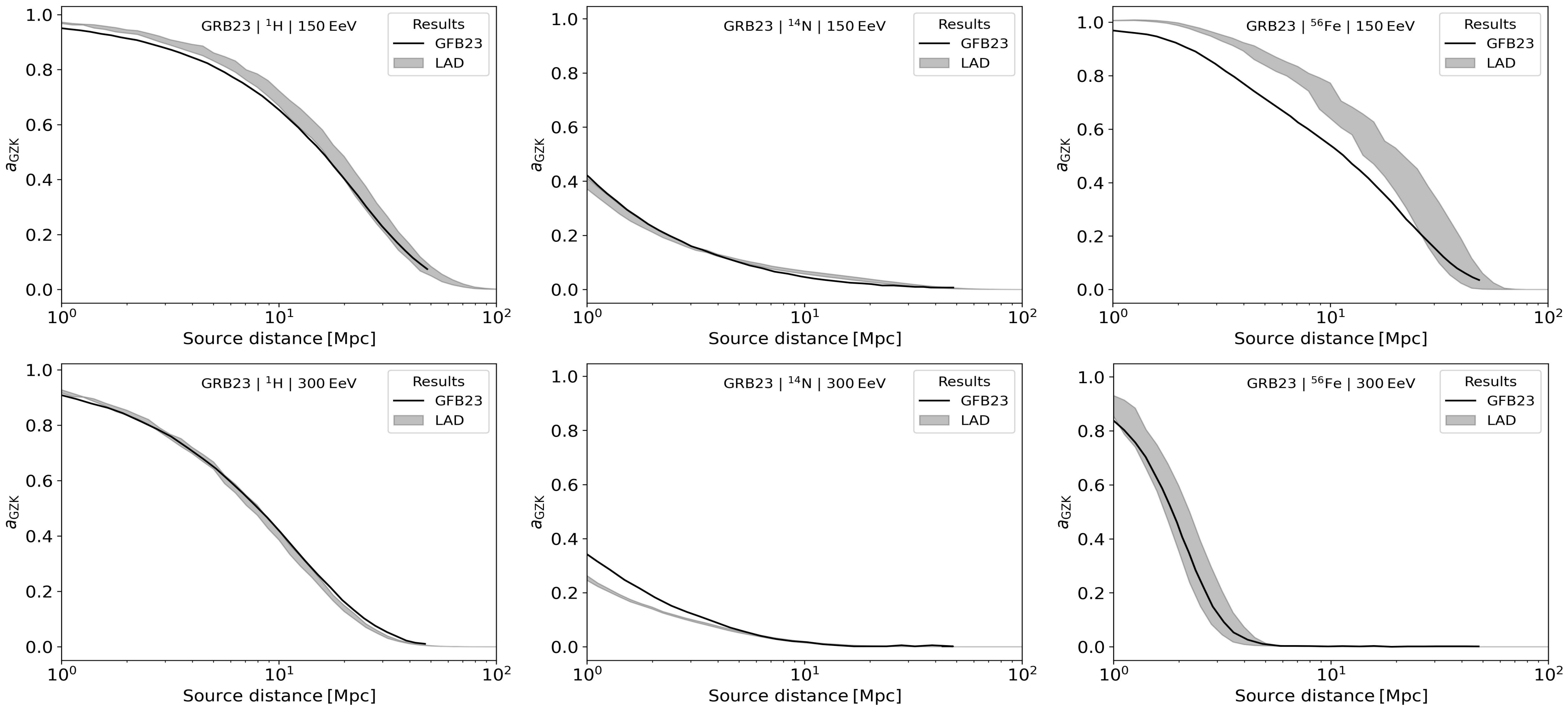
- Although an overall agreement can be observed, the difference can become significant in the studies we are conducting (~10 Mpc)



Comparisons with my implementation (GFB23)

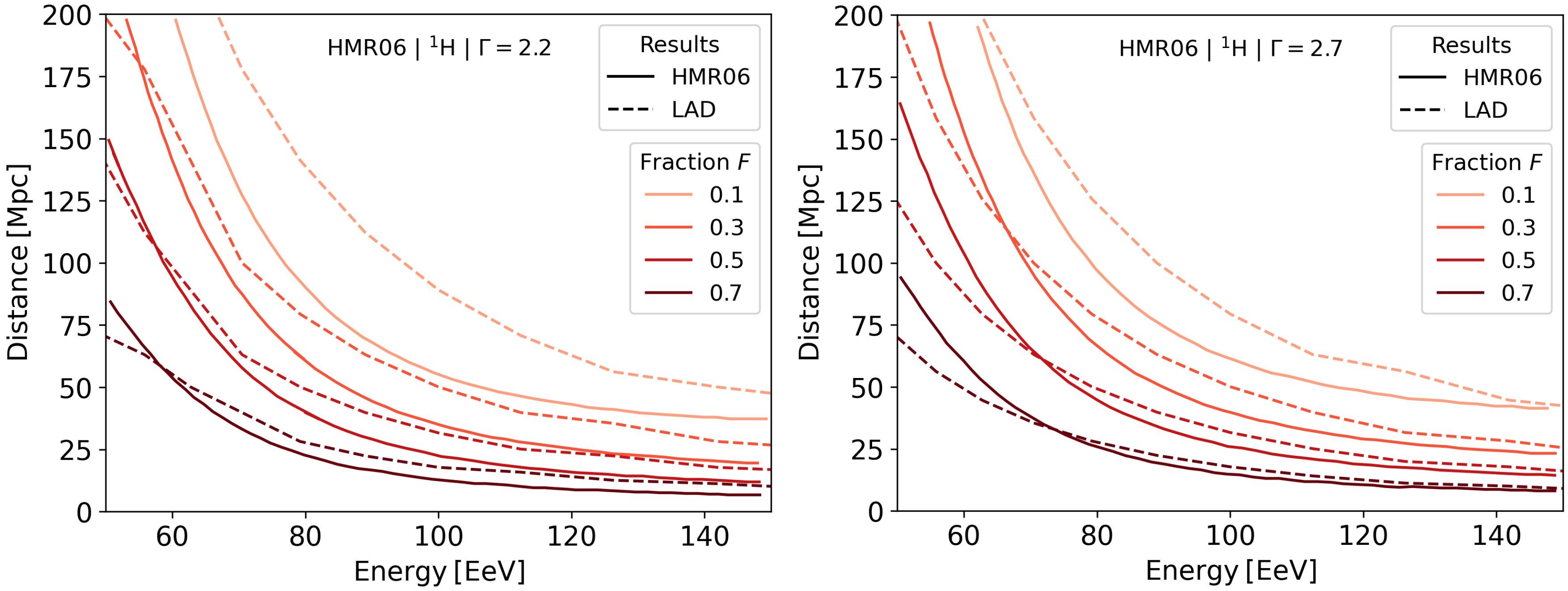
- For GBF23, we don't have the propagation distance as a function of the particle's energy, which would be our final goal, only the a_{GZK}.
- The propagation of particles in the GFB23 paper was performed using the PRINCE code (Heinze et al., 2019), whereas I performed the propagation using CRPropa 3.1.6.

Comparisons with my implementation (GFB23)



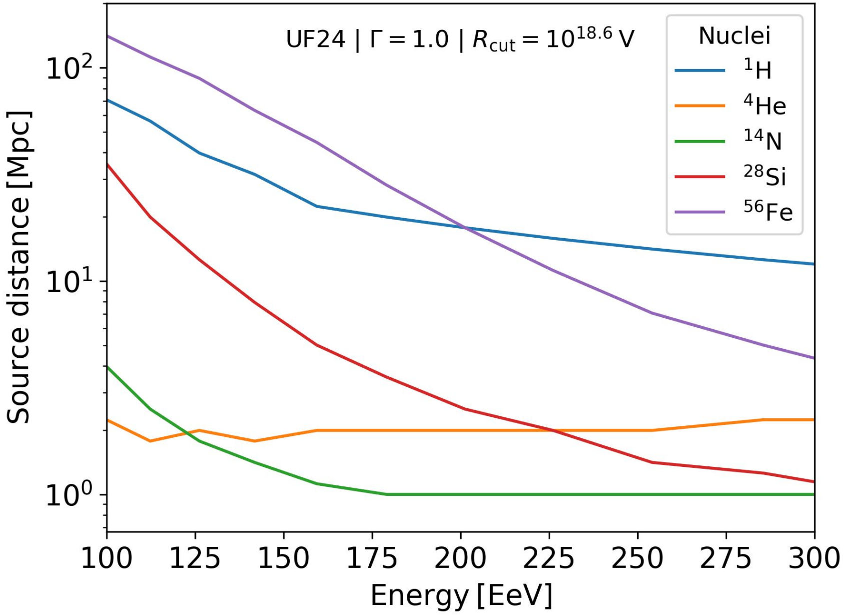
Comparisons with my implementation (HMR06)

- The most significant difference with my implementation is in the HMR06 definition.
- In the HMR06 paper, an analytical procedure was adopted to determine the horizon for protons.
- The differences in the results are under investigation.



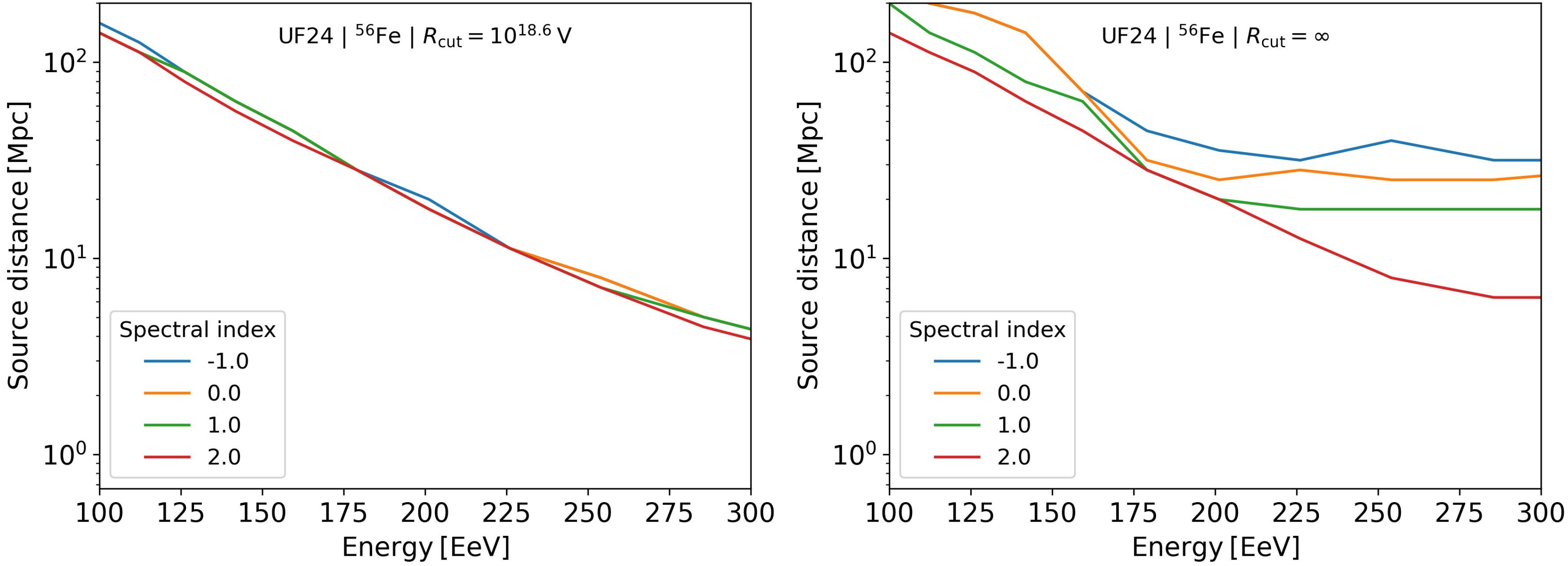
Comparison of the distinct mass compositions

- Using my implementation of the UF24 definition, we changed the injected particle to observe the differences.
- For Auger events above 100 EeV, iron provides the largest source distance, i.e., a broader distance range, if we aim to define the volume of the universe from which these events originate.



Comparison of the distinct spectral indices

- Using my implementation of the UF24 definition, we changed the spectral indices several times for two cases: with and without an exponential rigidity cutoff.
- The behavior of the horizon is very similar for all spectral indices in the case with an exponential rigidity cutoff.

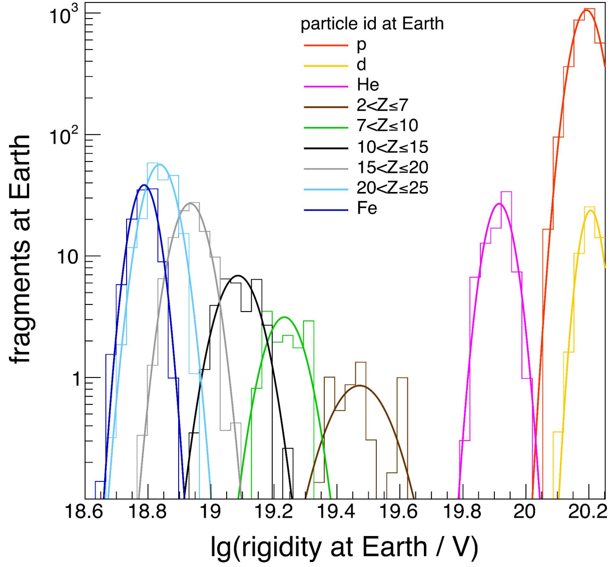


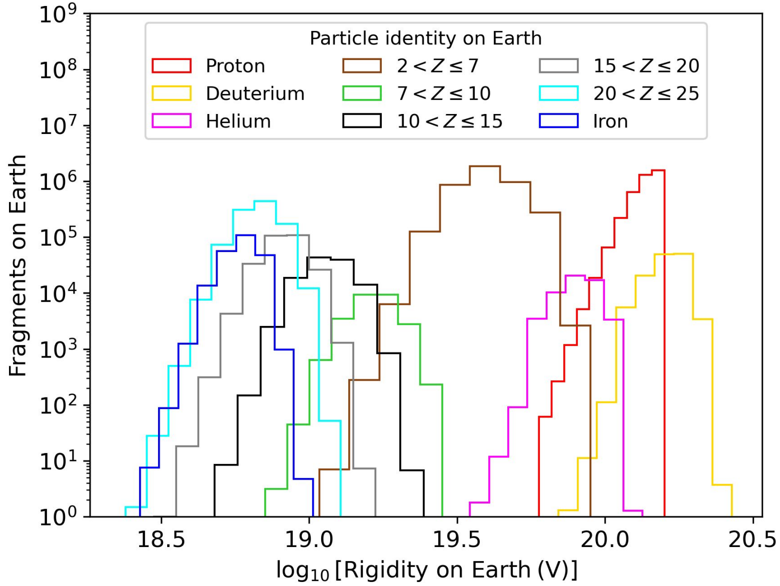
Rigidity distribution on Earth

Without the rigidity cutoff weight

- Important for backtracking the particles through the Galactic magnetic fields

Unger & Farrar (2024) | arXiv:2312.13273





Probably caused by ≠ versions of CRPropa, which include ≠ photodisintegration models

An excess of particles in the group with 2 < Z < 7

Summary

- We analyzed three distinct definitions of the horizon for a particle.
- For the search of the sources of the highest-energy events, it's crucial to obtain:
  - The maximum source distance to constrain candidate sources in galaxy catalogs
  - The expected particle rigidity on Earth for backtracking through the GMF

Inputs for Marta's work

- The uncertainties of both pieces of information come from:
  - The definition of the horizon;
  - The energy measurements;
  - The spectral parameters at the sources, including the particle species injected;
  - The extragalactic magnetic fields;
  - The cross-section models.
- Therefore, to try to access the origin of the highest-energy events, we should account for all these uncertainties.