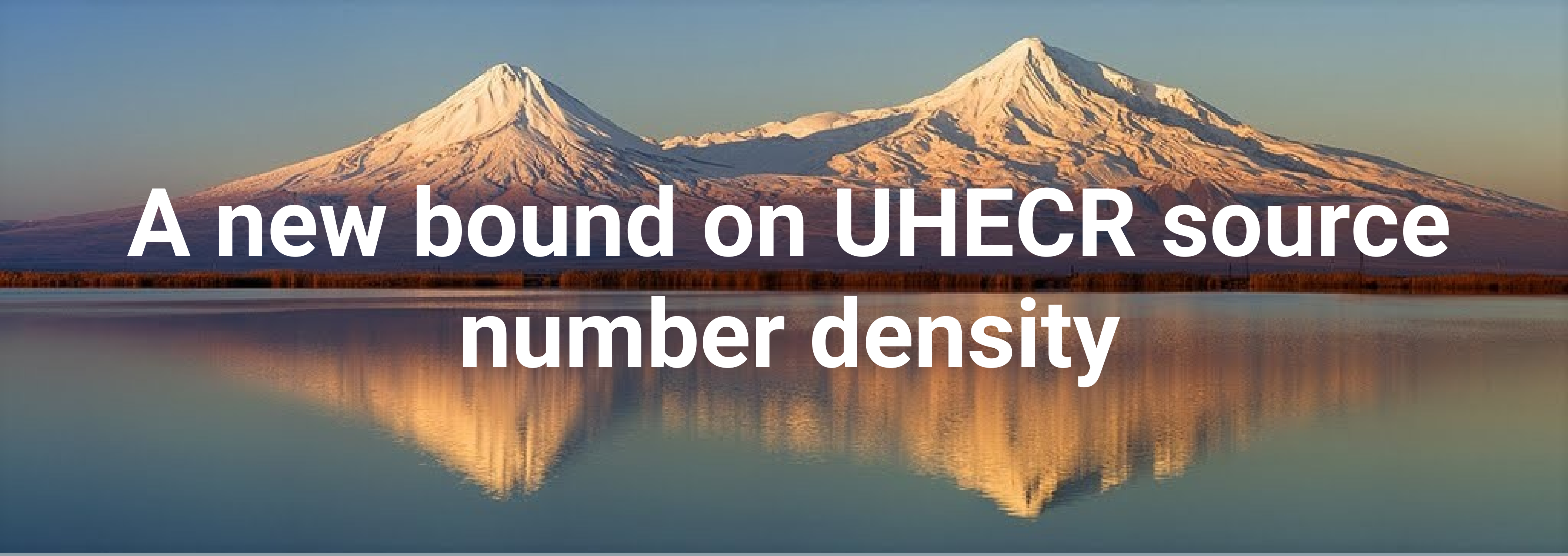

A new bound on UHECR source number density

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Rubakov Memorial Conference
Yerevan, 04.10.23

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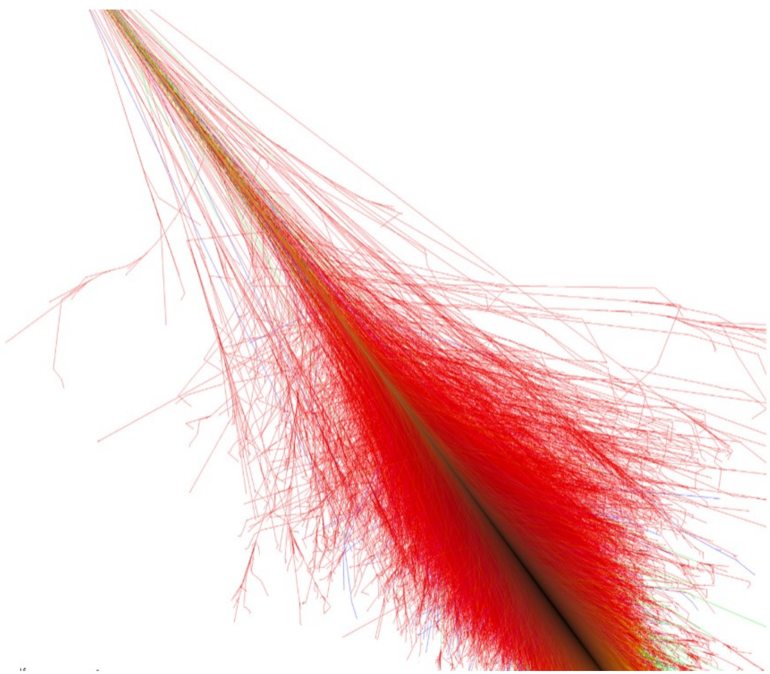
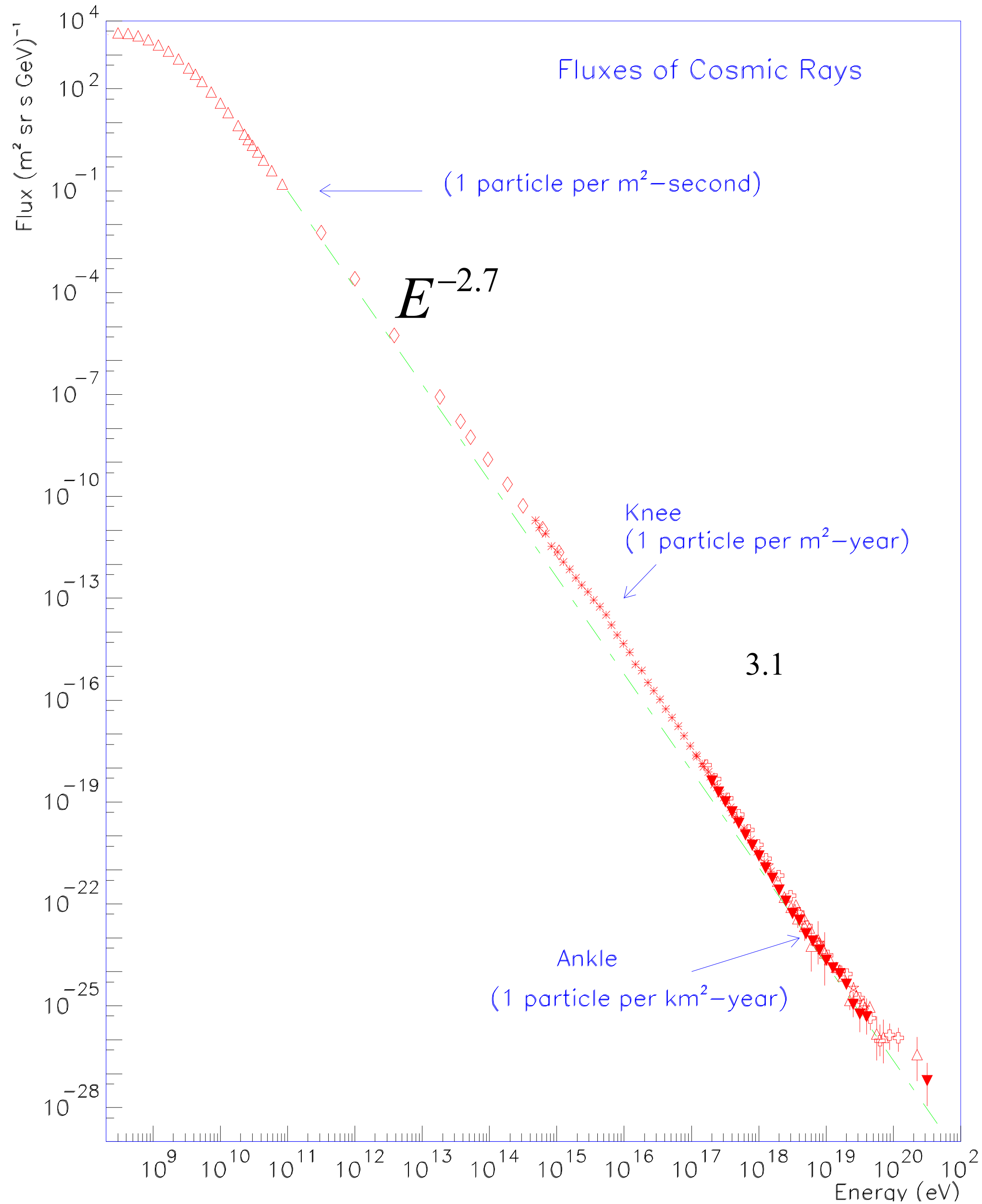
Outline

- Ultra-high energy cosmic rays
- Problems with UHECR sources identification
- Existing constraints on sources number density
- High energy event detected by the Telescope Array experiment
- Scenarios of the event origin and constraints for sources

Ultra-high energy cosmic rays

- Charged particles with E > 10^{18} eV
- Flux < 1 $km^{-2}yr^{-1}sr^{-1}$
- Steeply falling spectrum
- Origin still unknown (extragalactic)
- Detecting via showers of charged particles in atmosphere





What are UHECR sources?

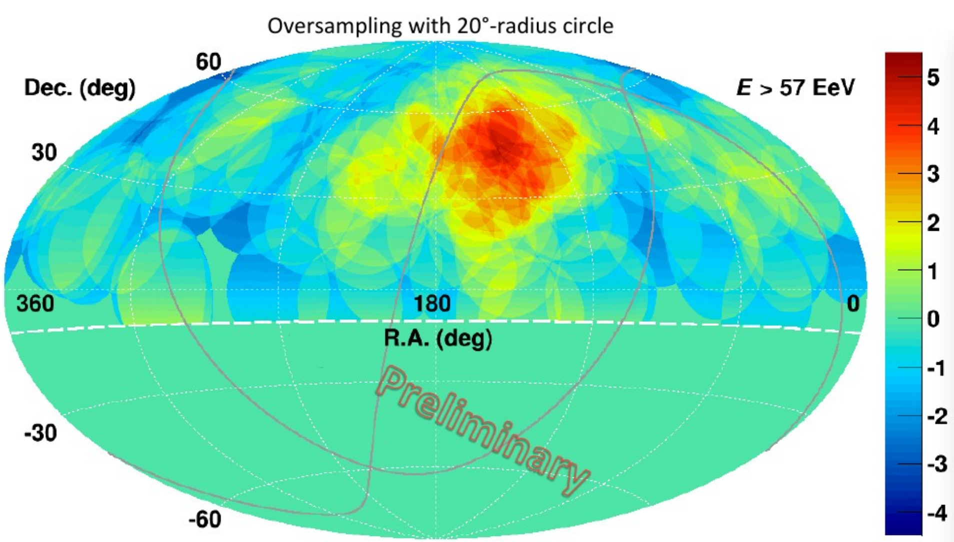
- Arrival directions are measured with **good precision** (~1°)

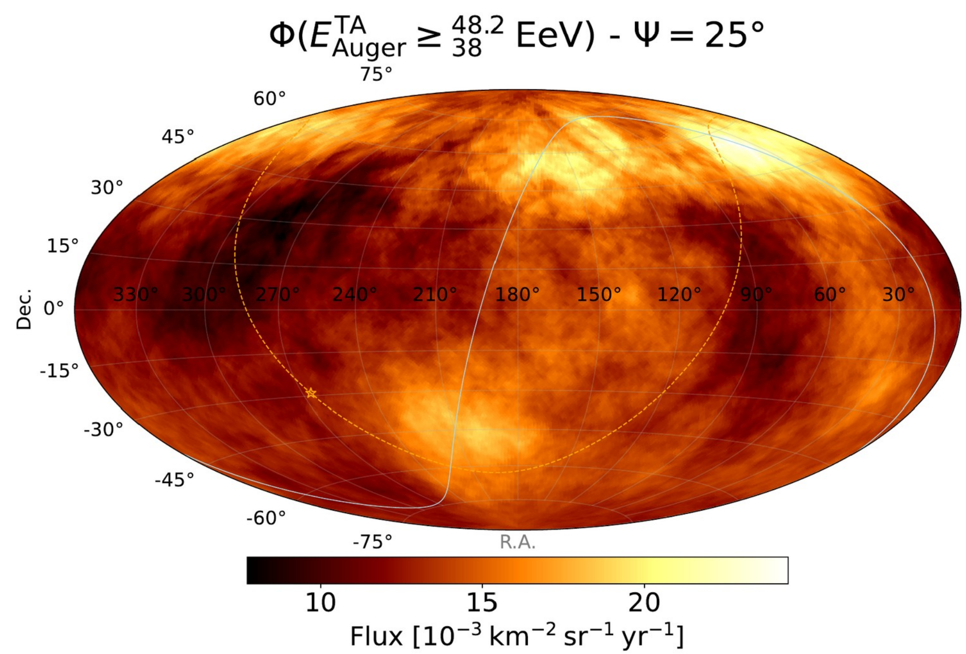
But

- UHECR deflections from their sources directions are uncertain:
- Uncertain galactic and extragalactic magnetic fields
- Uncertain mass (and charge) composition of UHECR

Achievements

- Overdensities of the UHECR flux observed (TA 2014, Auger 2022) → Hard to correlate with a specific source
- Correlations of UHECRs with SBG and AGN source classes (Auger 2018, Auger + TA 2021) → Only ~10% of the flux is correlated → Hard to interpret unambiguously (Auger + TA 2023)





What are UHECR sources?

- If it is difficult to find the UHECR sources let's constrain their number density at least
- This would allow us to exclude some candidate source classes

- Strategy:
  - Take some anisotropic observable,
  - Simulate it for various source scenarios
  - Compare with what we have in data
- Example:
  - Autocorrelation function of UHECR directions distribution (Auger 2013)

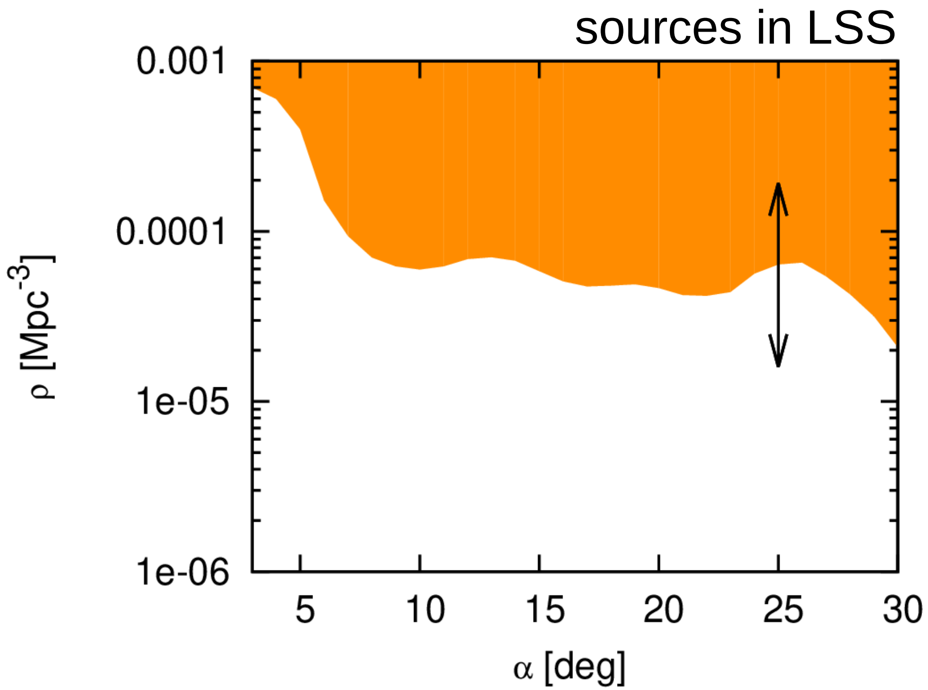
$$n(\alpha) = \sum_{i=2}^{N} \sum_{j=1}^{i-1} \Theta(\alpha - \alpha_{ij}), \text{ where } \alpha \text{ is a separation angle between two events}$$

$\rho > 2 \cdot 10^{-5}\ \mathrm{Mpc}^{-3}$ for injected nuclei with $Z<14$ ($\alpha = 30°$)

$\rho > 6 \cdot 10^{-5}\ \mathrm{Mpc}^{-3}$ for injected nuclei with $Z<6$ ($\alpha = 10°$)

$\rho > 7 \cdot 10^{-4}\ \mathrm{Mpc}^{-3}$ for injected p ($\alpha = 3°$)

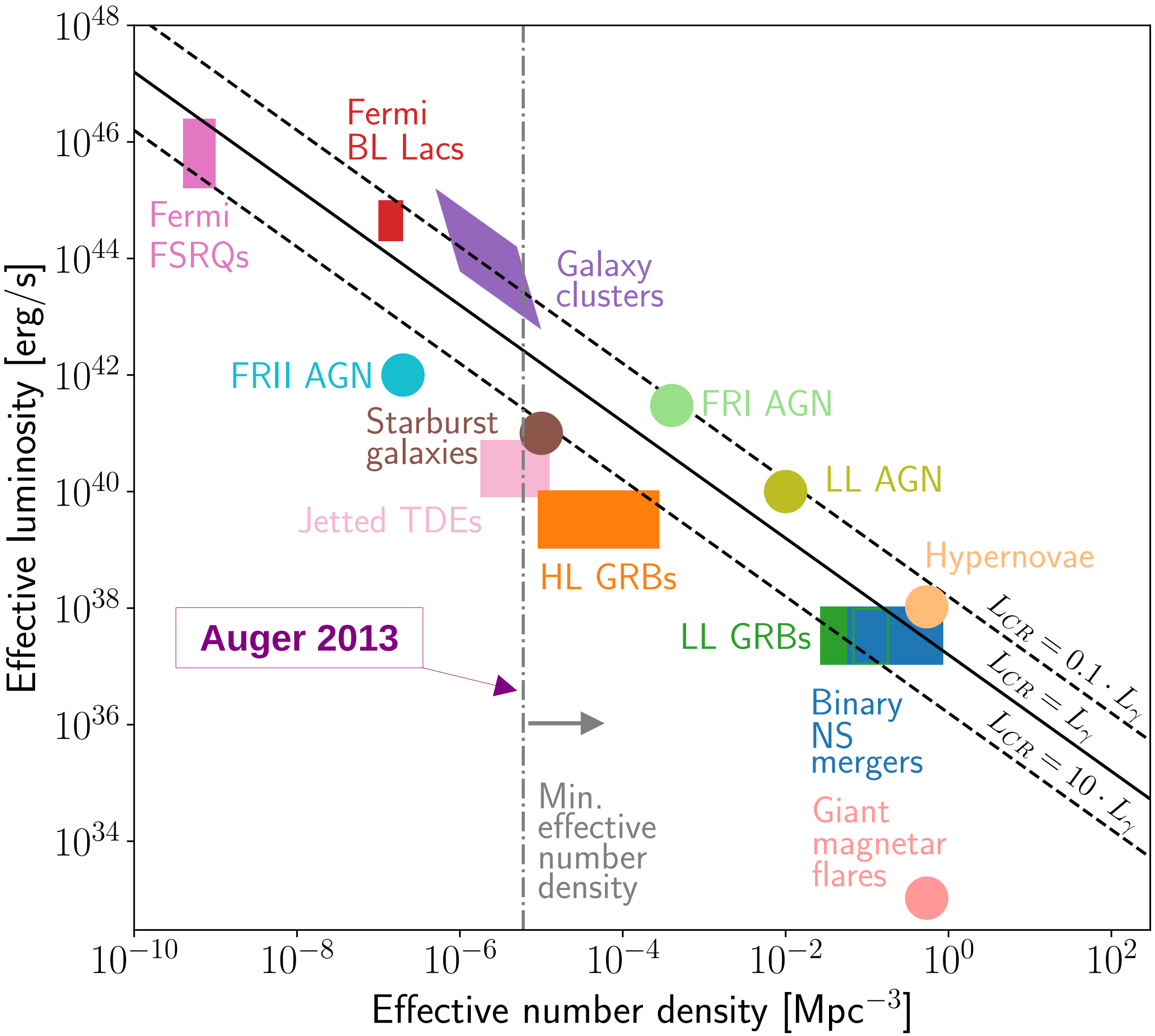
Sources injecting something heavier than Si are not bound by these constraints!



Constraints on UHECR sources: interpretation for source classes

Knowing a source luminosity budget and a number density of sources we can disfavor some source classes:

- Constraints from total photon luminosity
  - Hint: we need to know the dominant photon frequency band and the ratio of CR/photon fluxes
- Constraints on number density
  - Hint: depend on CR deflections



from Alves Batista et al., 2019

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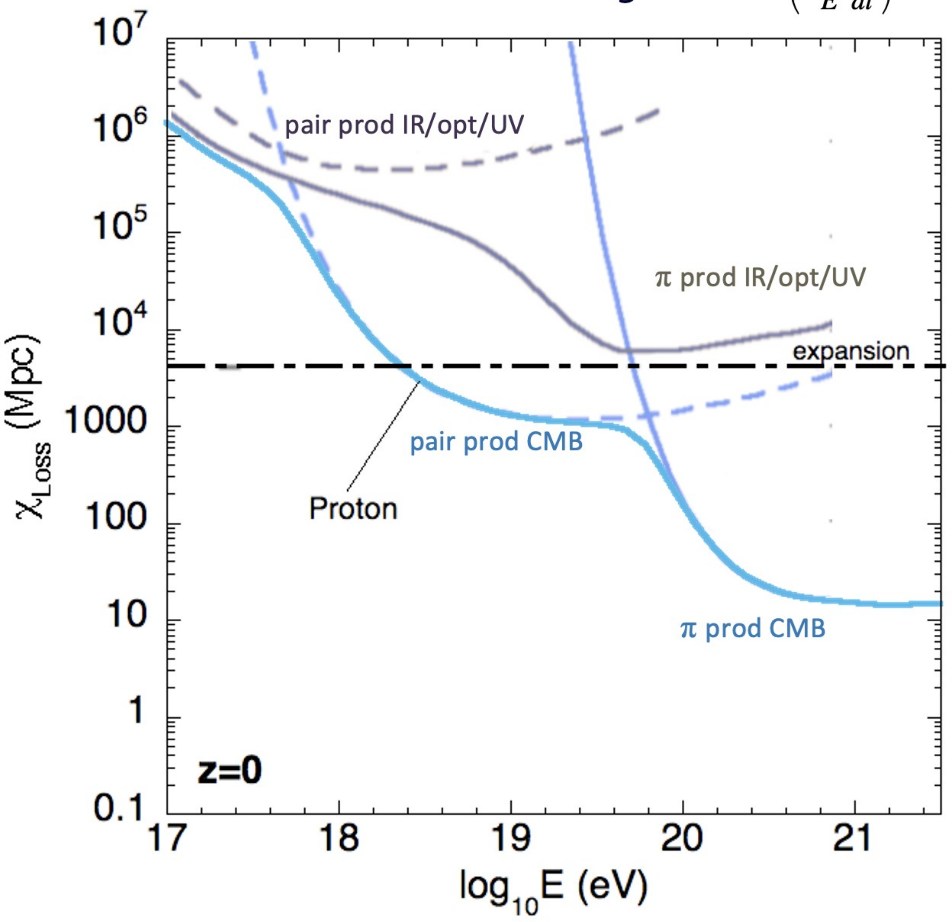
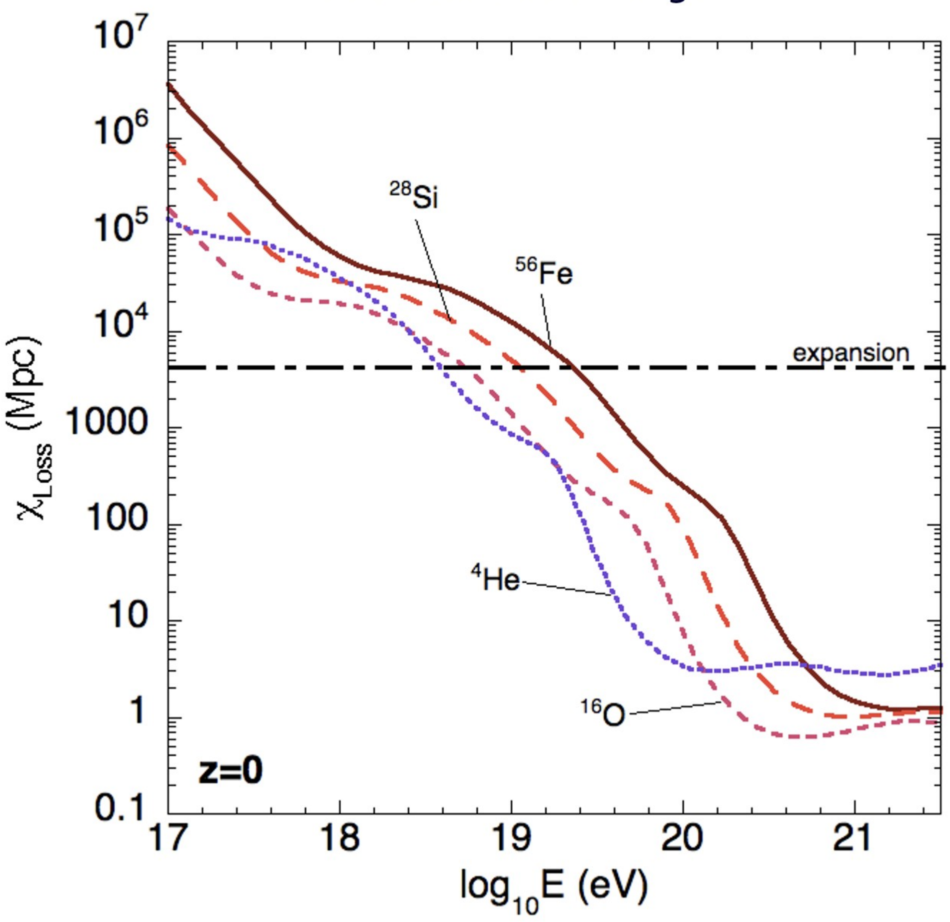
Another idea: constraints from attenuation of highest energy CRs

Proton attenuation length $\chi_{loss} = c\left(-\frac{1}{E}\frac{dE}{dt}\right)^{-1}$



nuclei attenuation length



If there is a CR with very high $E_{detected}$ – its source should be close enough

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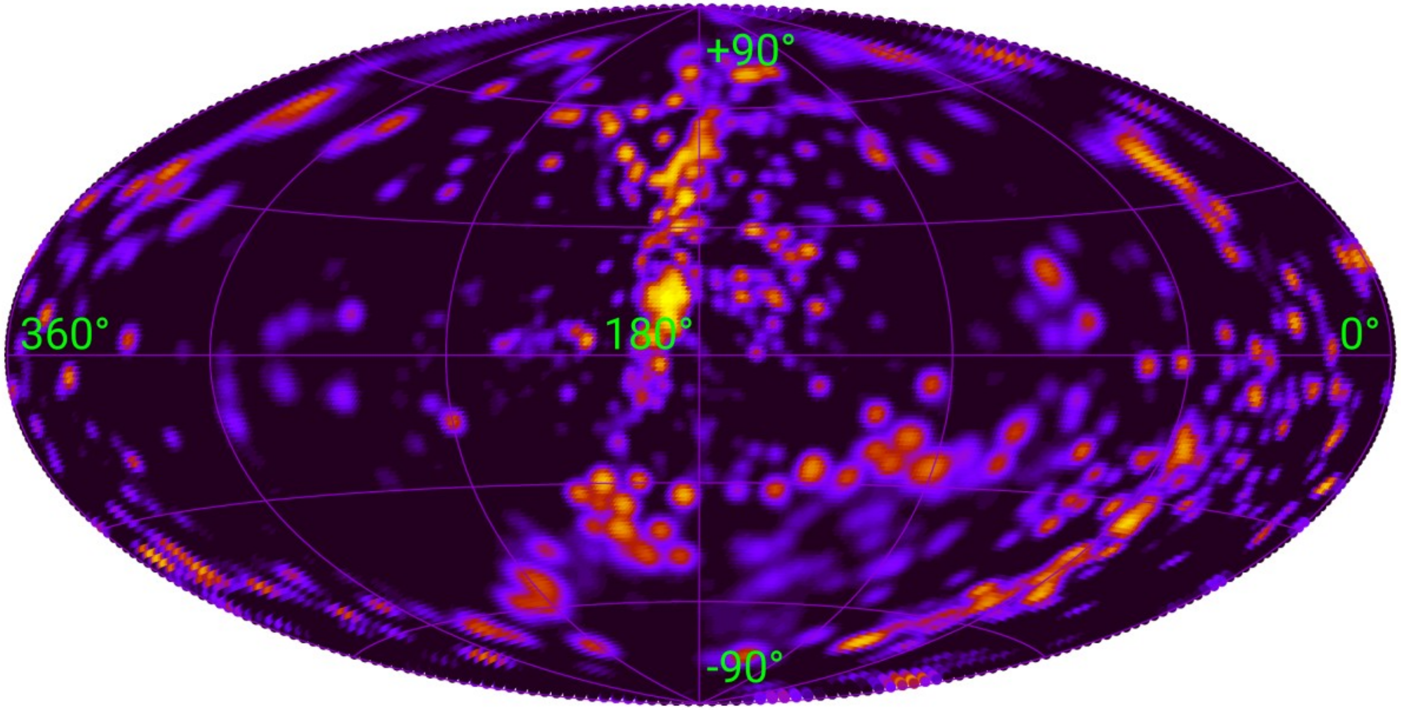
Constraints from attenuation of UHECRs: hints

We can constrain the distance to the source by analyzing the CR propagation

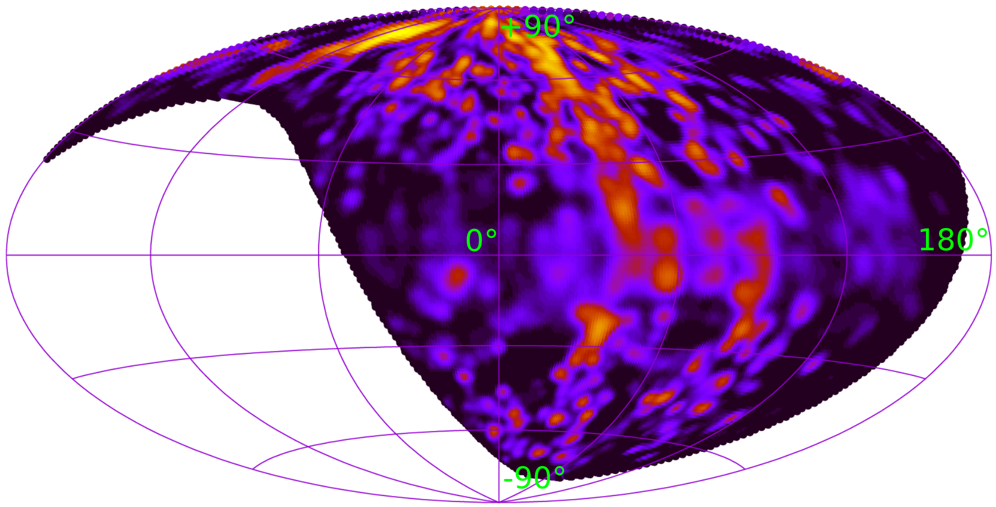
- Value of $E_{detected}$ affects result much
- Detected particle type effect is even larger
- Idea: constrain the particle type by looking for event correlation with all possible sources (LSS)



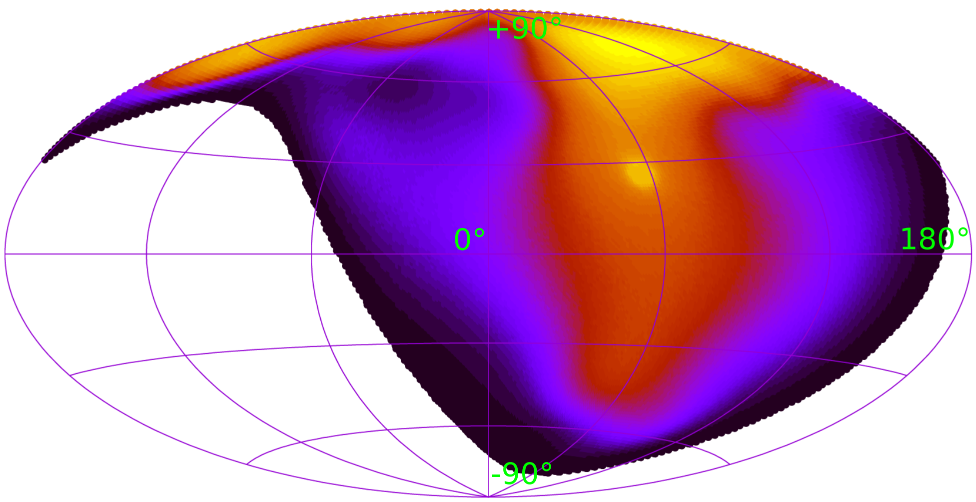
Maps of expected UHECR sources: details

- Sources in LSS: 2MRS catalog from 5 Mpc up to 250 Mpc ($\rho \sim 10^{-2}$ Mpc^{-3})
- Properly attenuated protons or nuclei
- Injection spectrum: separate best fit (SimProp 2.4) to observed spectrum for each primary
- EGMF deflections: either no deflections or maximum possible deflections
- GMF deflections:
  - Backtracking in JF'12 or PT'11 model for regular field
  - PTU'13 fit for b-dependent gaussian smearing for random field
- Angular resolution: additional 1° uniform smearing

Proton map at E = 100 EeV

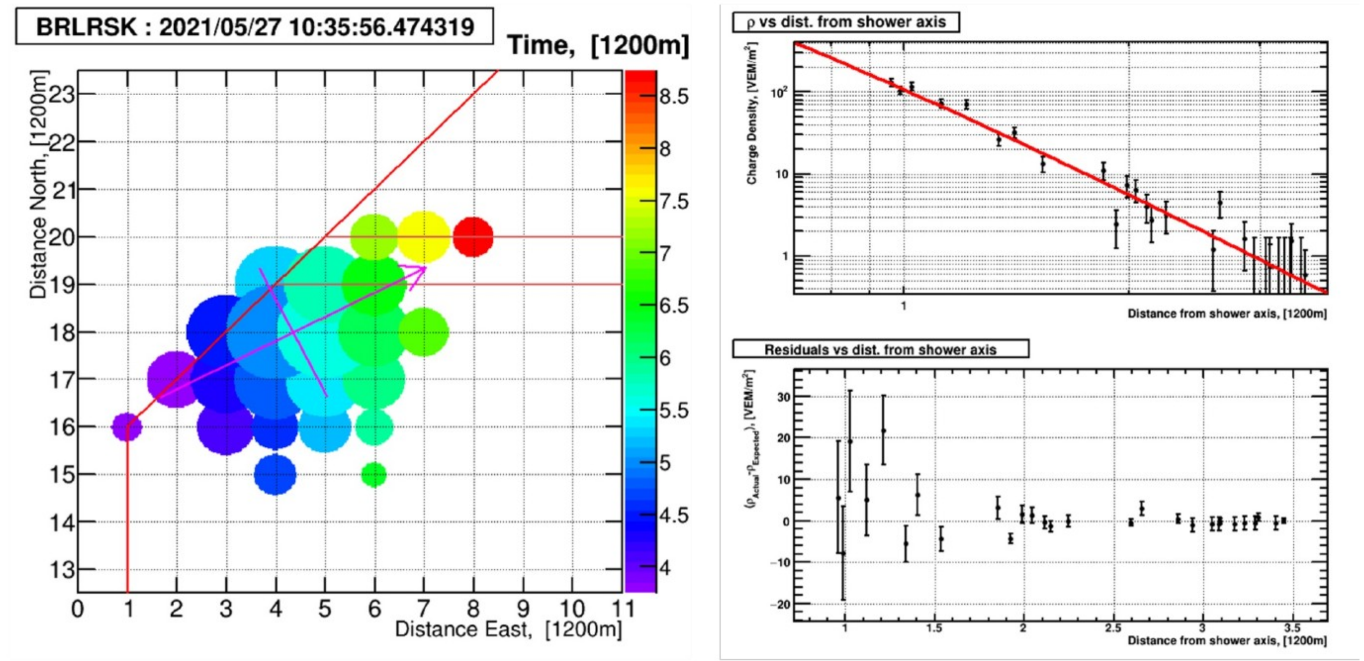


Iron map at E = 100 EeV



TA observed a highest energy event at 27 of May 2021

Figure 5.8: **Left:** SD display of the highest energy event seen by TA, at $10^{20.4}$ eV. The circle size represents the SD integrated signal, while the color represents the relative time. The shower core and direction are shown by the cross. **Right:** The longitudinal profile of the event. The two counters closest to the core of the shower were saturated and are not included. The value of $S(800)$ is $530\,\mathrm{VEM/m^2}$.



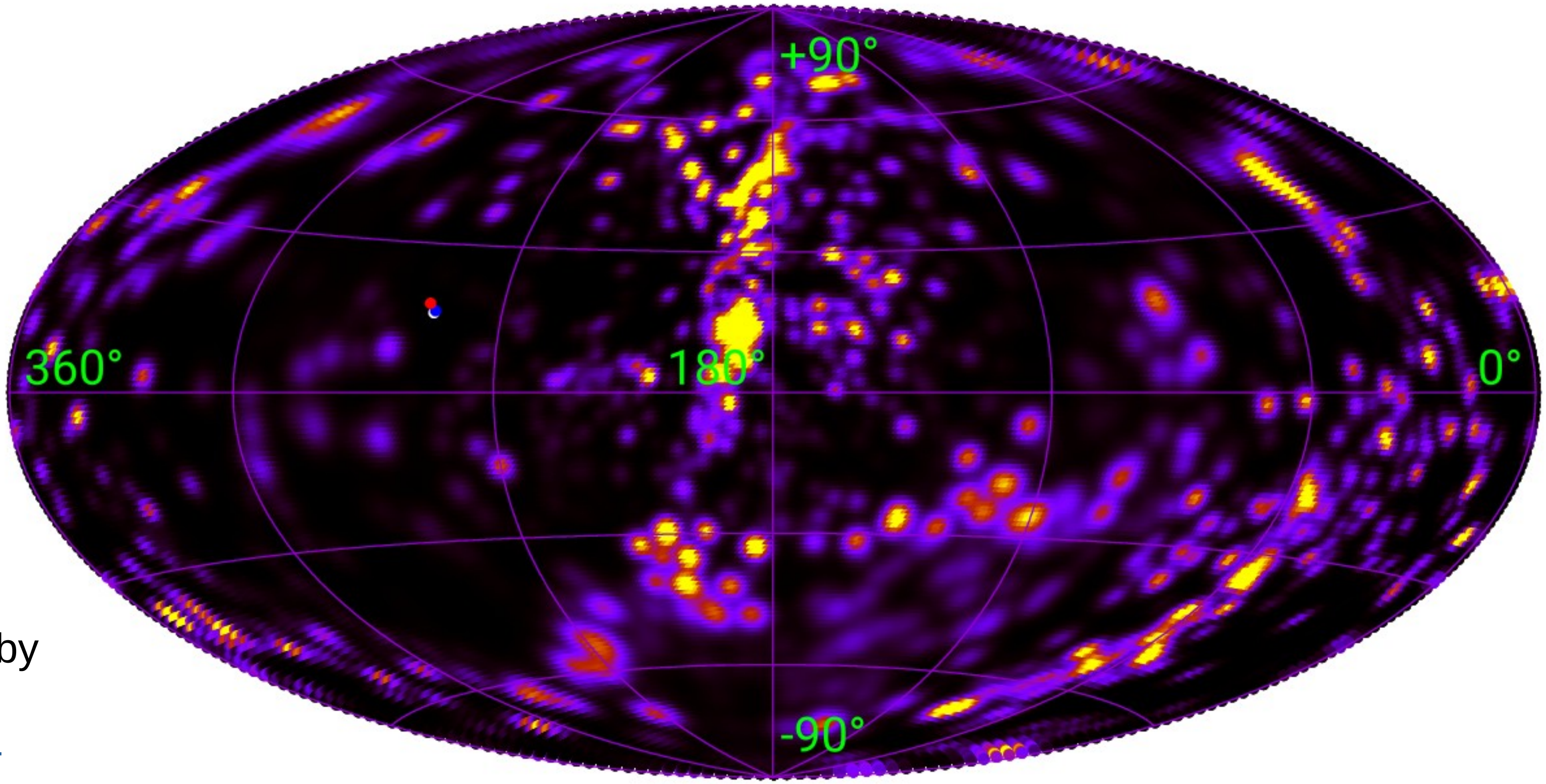
$$E = 244 \pm 29(\mathrm{stat.})^{+51}_{-76}(\mathrm{syst.})\mathrm{EeV}$$

Snowmass 2021 whitepaper, arXiv:2205.05845, to be published

Correlation with sources, proton scenario

We can constrain the distance to the source by analyzing the CR propagation

- Idea: constrain the particle type by looking for correlation with all possible sources (LSS)
- Basic scenario: E = 244 EeV, no deflections in EGMF
- The relative expected flux at the event direction is less than 1% → proton scenario is disfavored

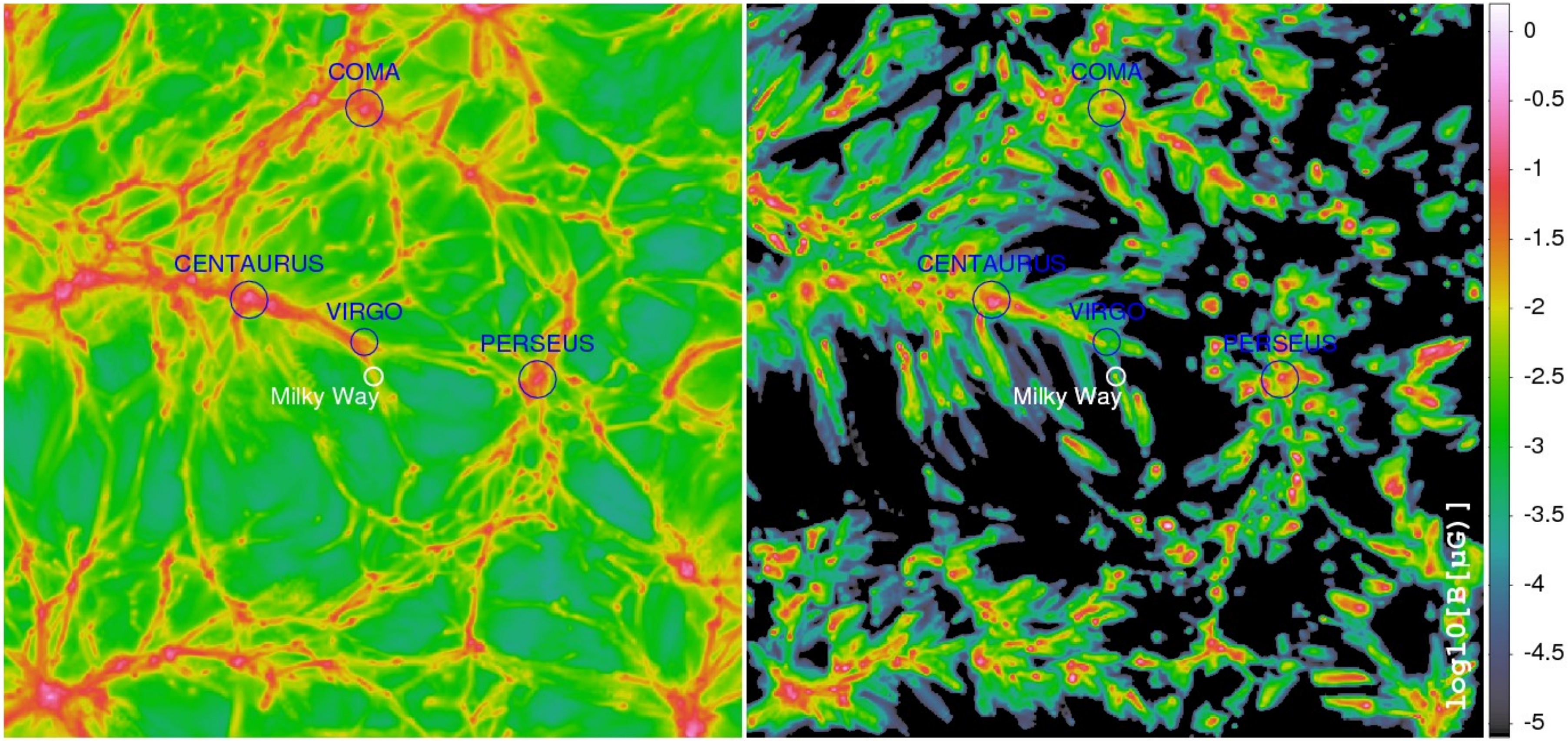


Red: event deflected by reg. GMF JF'12
Blue: reg. GMF PT'11

Impact of extragalactic magnetic fields

- Global field in LSS voids (IGMF) and field in local extragalactic structures
- Two possible origins: primordial or astrophysical
- Experimental constraints: $B_{IGMF} < 1.7$ nG with correlation length $\lambda_{IGMF} \sim 1$ Mpc
- Deflections in the largest (from simulations) local EGMF is subdominant for our setup
- Model the deflections as an additional uniform smearing of the sources

Simulations from: Hackstein et al., MNRAS 475 (2018) 2519



Primordial EGMF

Astrophysical EGMF

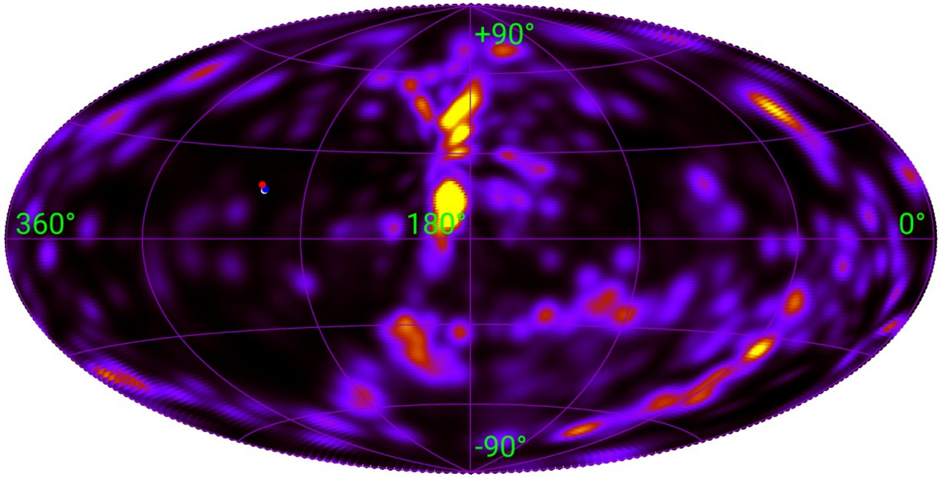
Correlation with sources, proton scenario: uncertainties

We can constrain the distance to the source by analyzing the CR propagation

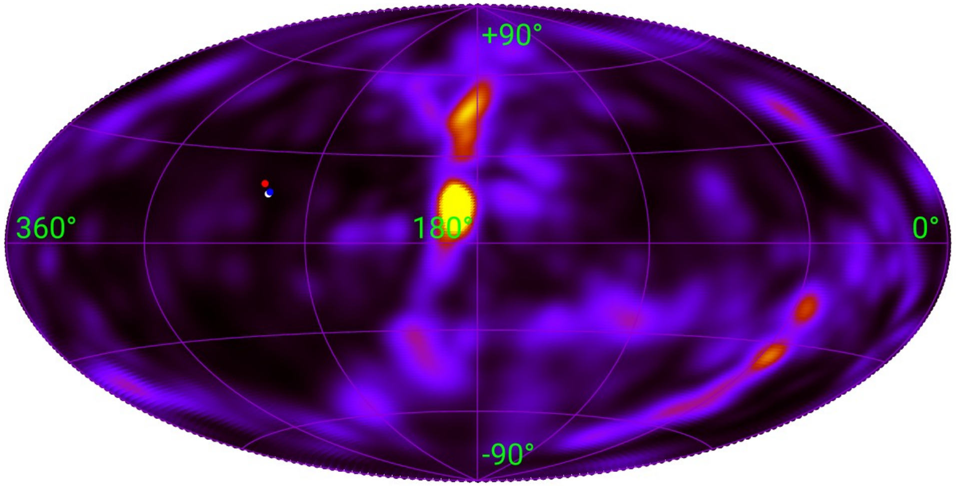
- Scenario Ia: E = 244 EeV, extreme EGMF
- Scenario Ib: $E = E_{detected}$ - 2σ (stat.) - (sys.) = 135 EeV, extreme EGMF

The relative expected flux at the event direction is less than 1% in both cases → proton scenario is disfavored even with uncertainties! → The event should be a nucleus!

E = 244 EeV, EGMF



E = 135 EeV, EGMF

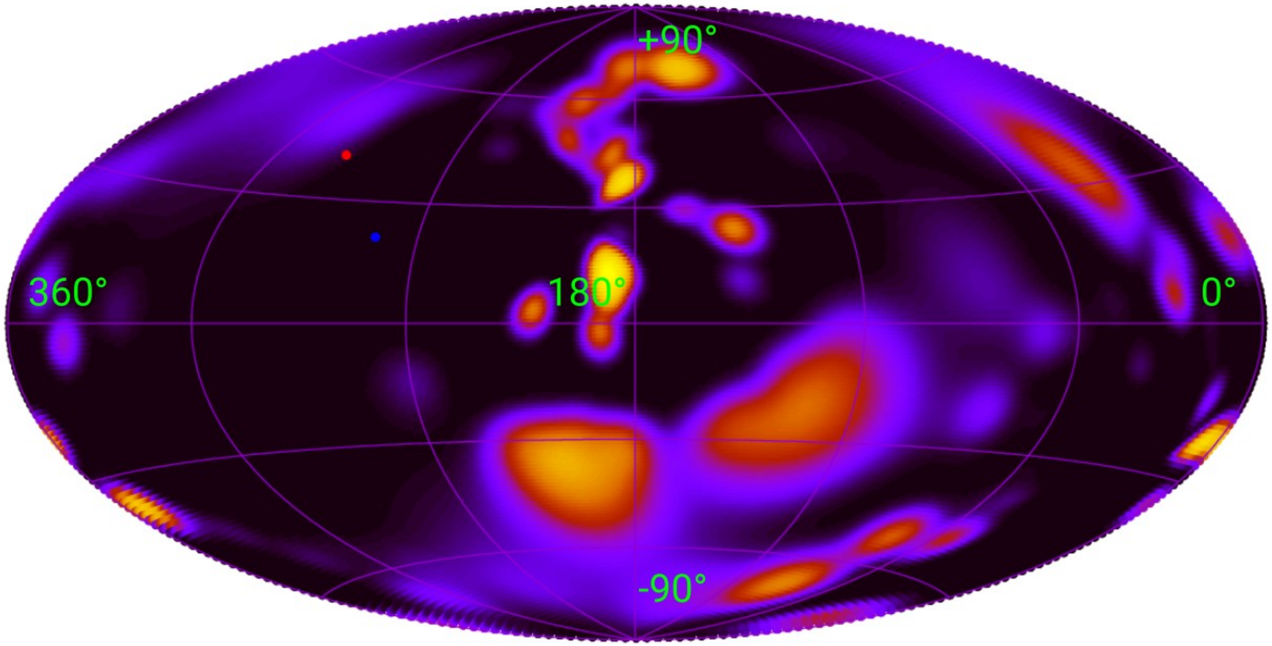


Correlation with sources, nucleus scenario

Simulate various nuclei propagation for various distances to the source: a cascade of secondary particles is formed due to primary spallation on a cosmic background radiation

Which Z nucleus should have, to correlate with LSS with at least 5% probability?
(we want to set constraints with 95% C.L.)

E = 244 EeV, P (Z = 15), no EGMF



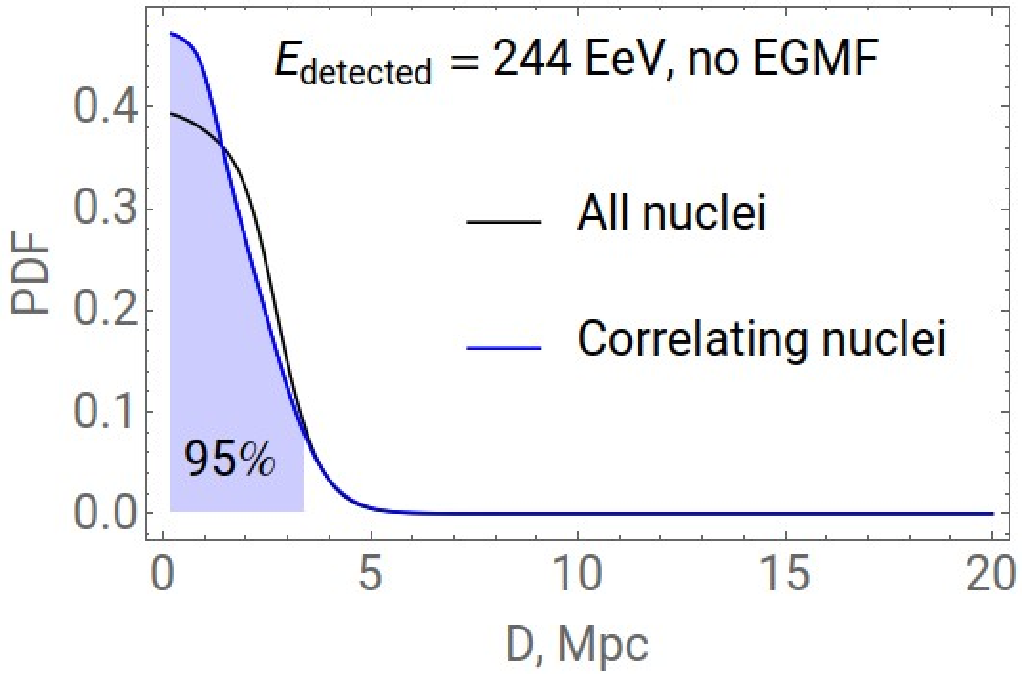
Correlation with sources, nucleus scenario

How to constrain the distance to the closest source?

- Lightest LSS-correlating nucleus is P ($Z = 15$)
- Conservatively assume that source emits Fe (the least attenuated nucleus)
- Consider the detected flux of all nuclei with $Z > 15$ and $E > 244$ EeV as a function of the distance to the source D
- Interpret it as a probability:
  - Flux injected uniformly at all $D < 100$ Mpc: $F_{tot} = F(D<100\ \mathrm{Mpc})$
  - Probability to have a source within D_0: $p(D_0) = F(D<D_0)/F_{tot}$
  - To have 95% C.L. constraints on D_0 we require $p(D_0) > 0.95$

In basic scenario ($E = 244$ EeV, no EGMF) the source should be not farther than 3.4 Mpc!

(Conservatively: $D < 5$ Mpc, as a threshold of our source catalog)



simulations with TransportCR code (Kalashev & Kido 2014)

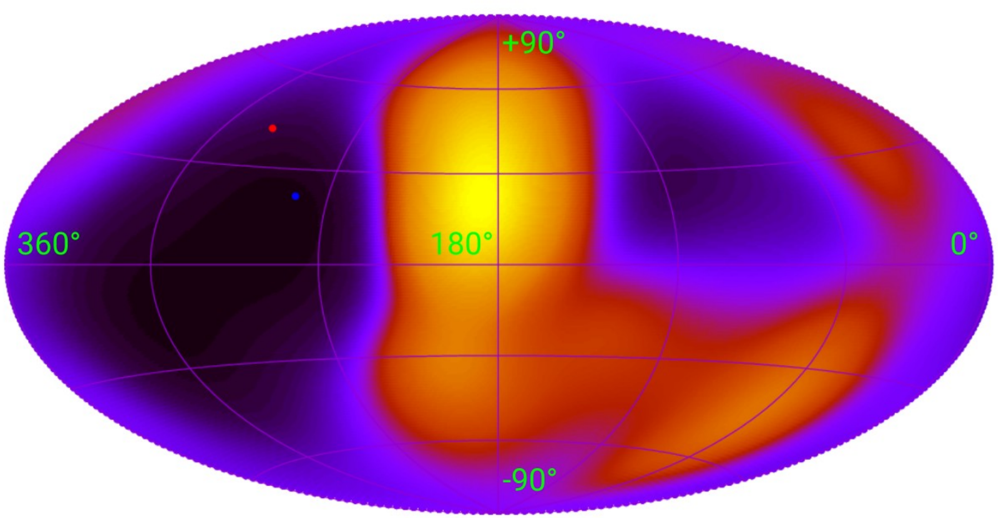
Correlation with sources, nucleus scenario: uncertainties

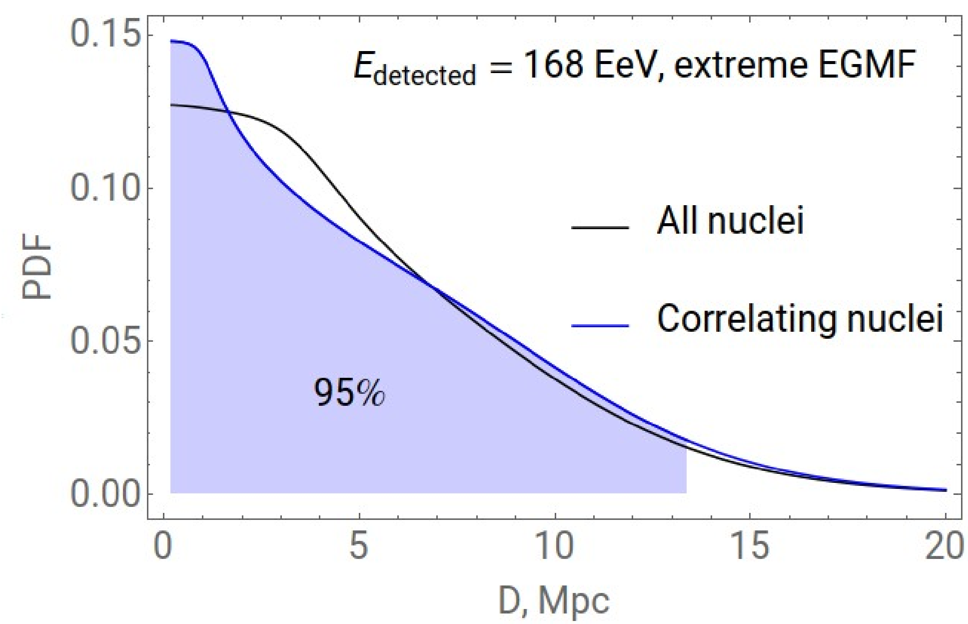
Take into account energy uncertainty and possible EGMF

For $E = E_{detected}$ - (sys.) = 168 EeV and with extreme EGMF the lightest correlated nucleus is S (Z=16)

Constrain the distance with the same procedure: D < 13.4 Mpc

E = 168 EeV, S (Z = 16), extreme EGMF





Constraints on the sources number density

Now we have the constraints on the distance to the closest source: $D < 5.0^{+8.0}_{-0.0}\ \mathrm{Mpc}$
(the lower uncertainty is absent because of the catalog threshold)

We need to translate this into constraint on the UHECR source number density ρ

Assume the sources are distributed in the Universe according to Poisson distribution:

$$p(\rho, N) = \frac{e^{-\rho V}(\rho V)^N}{N!}$$

N is a number of sources inside the volume V

To get 95% C.L. constraints on ρ we simulate the number of source distribution realizations and require to have at least on source in $V = 4/3\ \pi\ D^3$ in at least 5% of realizations

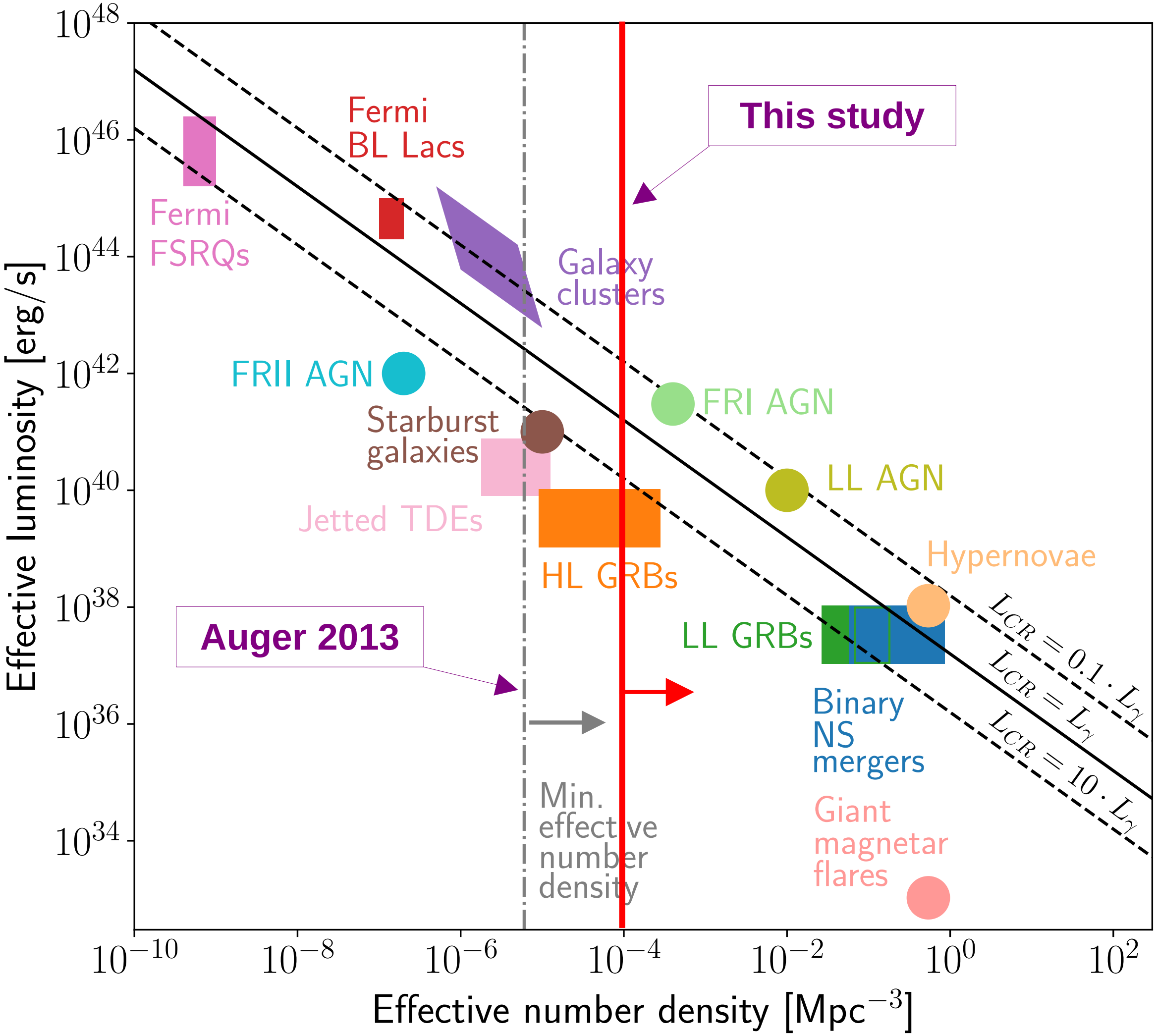
Then for basic nucleus scenario: $D < 5.0$ Mpc → $\rho > 1.0 \cdot 10^{-4}\ \mathrm{Mpc}^{-3}$

For nucleus scenario with uncertainties: $D < 13.4$ Mpc → $\rho > 5.2 \cdot 10^{-6}\ \mathrm{Mpc}^{-3}$

Results vs source classes

The constraint for the number density of UHECR **sources that emit heavy nuclei** is **set for the first time**!

Our constraint disfavors Starburst Galaxies, Jetted Tidal Disruption Events and Galaxy Clusters as the main sources of UHECRs



from Alves Batista et al., 2019

Conclusions

- We proposed a new method to constrain UHECR sources number density from UHECR events of extremely high energy
- Such an event was detected by Telescope Array
- The event cannot be a proton because of the lack of correlation with any possible source
- We obtained the strongest up to date constraint on a number density of UHECR sources: $\boldsymbol{\rho > 1.0 \cdot 10^{-4}}$ **Mpc^{-3}**
- The constraint for the number density of UHECR sources that emit heavy nuclei is set for the first time
- The constraints also disfavors SBGs, Jetted TDEs and Galaxy Clusters as the main sources of UHECR

Thank you!