

Ближкий источник космических лучей ультравысоких энергий

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[arXiv:2311.14628]

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ФИАН, Москва, 02.07.24

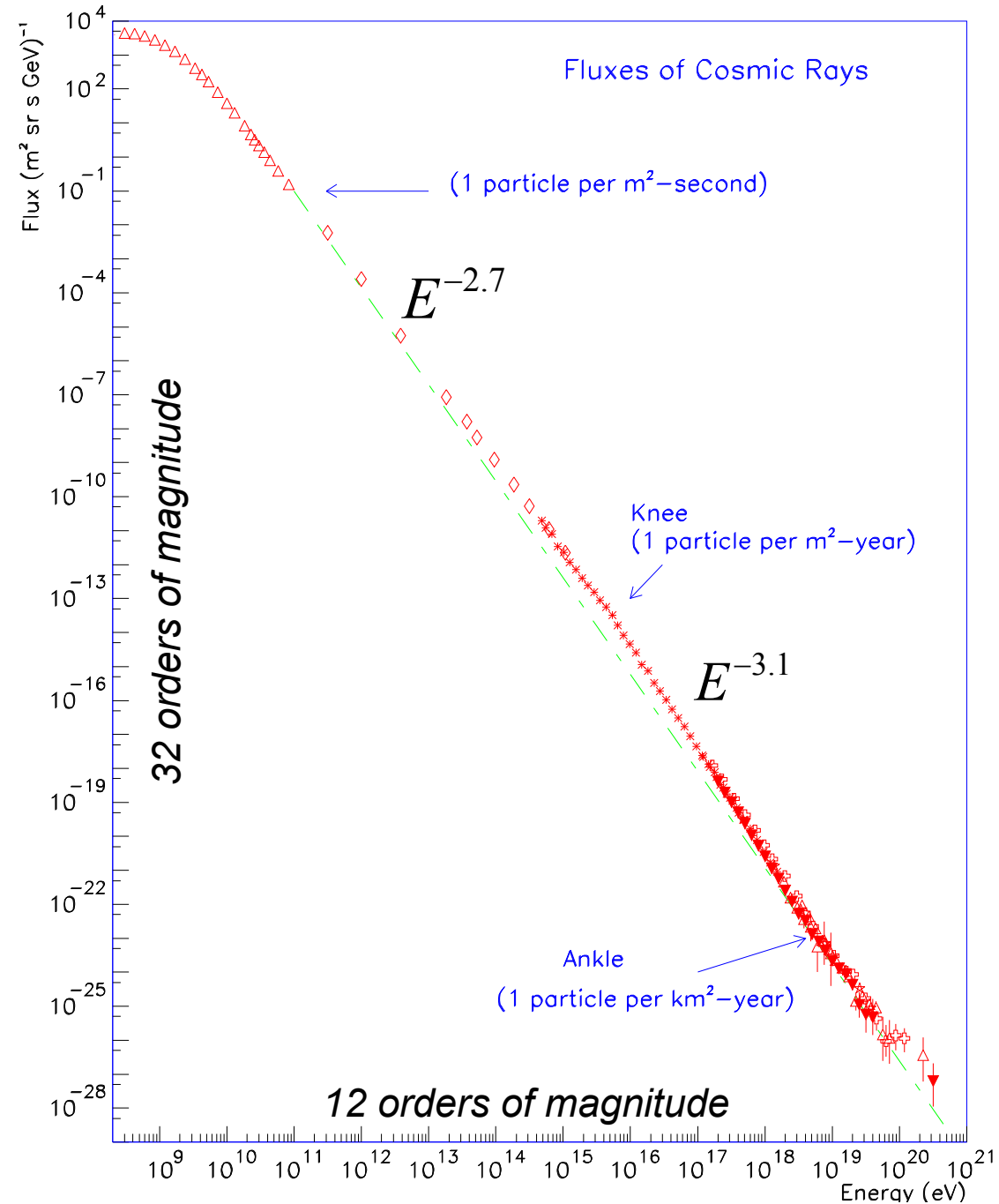
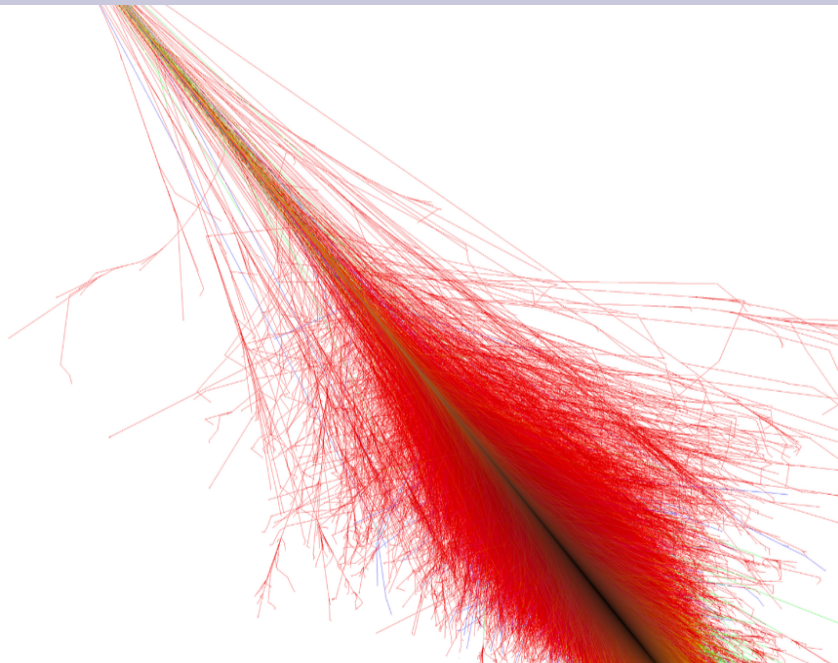


Outline

- 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 $< 1 \text{ km}^{-2}\text{yr}^{-1}\text{sr}^{-1}$
- Steeply falling spectrum
- Origin still unknown (extragalactic)
- Detecting via showers of charged particles in atmosphere

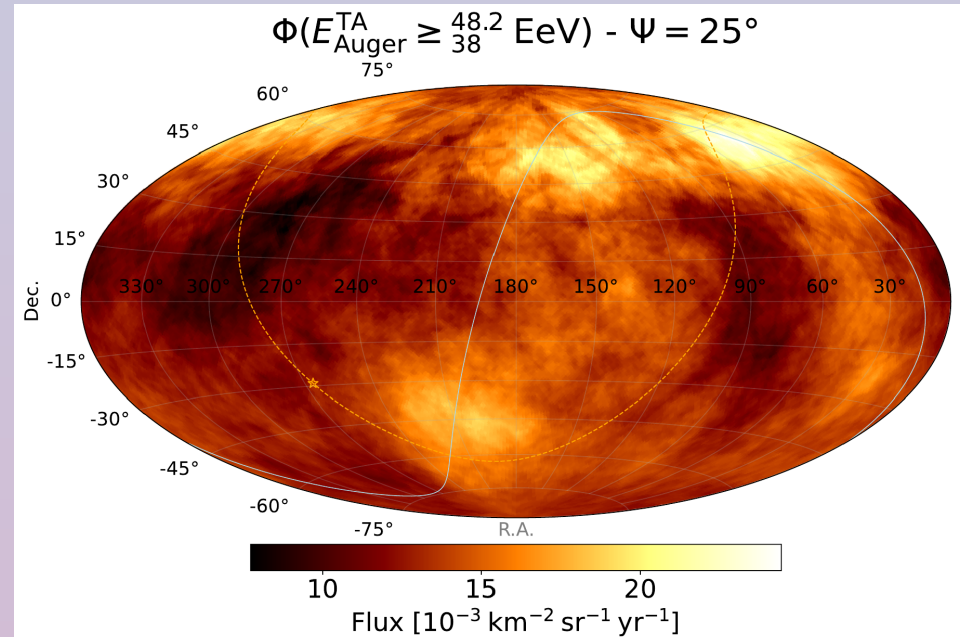
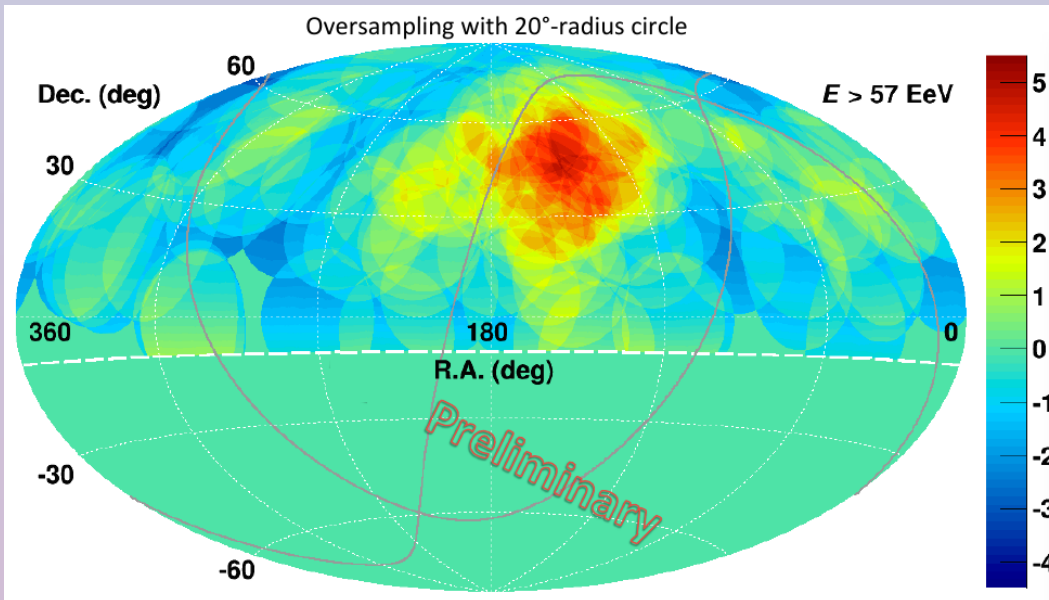


What are UHECR sources?

- Arrival directions are measured with **good precision** ($\sim 1^\circ$)
But
- UHECR deflections from their sources directions are uncertain:
- Uncertain galactic and extragalactic magnetic fields
- Uncertain mass (and charge) composition of UHECR

Achievements

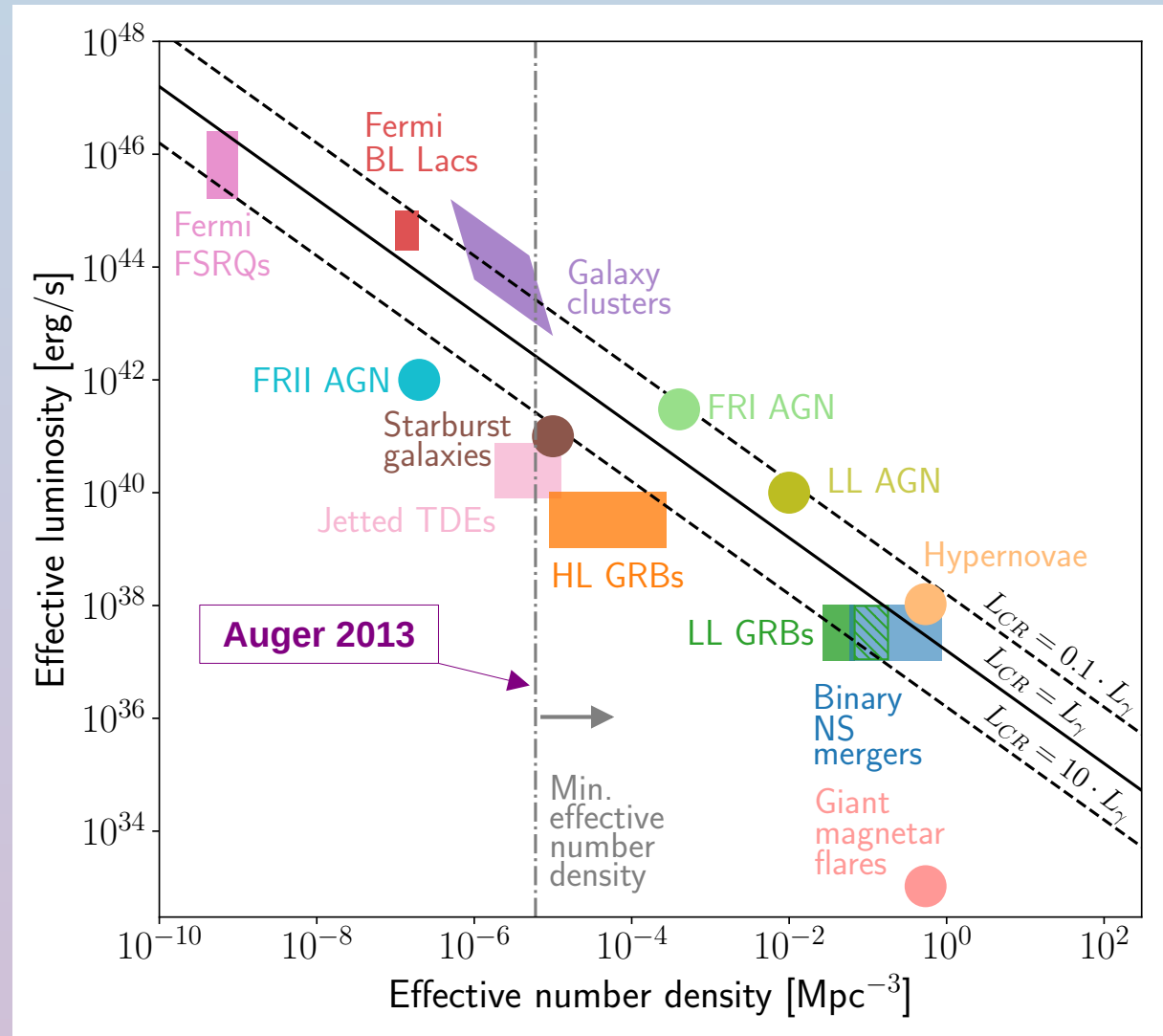
- Overdensities of the UHECR flux observed (TA 2014, Auger 2022) \rightarrow Hard to correlate with a specific source
- Correlations of UHECRs with SBG and AGN source classes (Auger 2018, Auger + TA 2021) \rightarrow Only $\sim 10\%$ of the flux is correlated \rightarrow Hard to interpret unambiguously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



Constraints on UHECR sources: interpretation for source classes

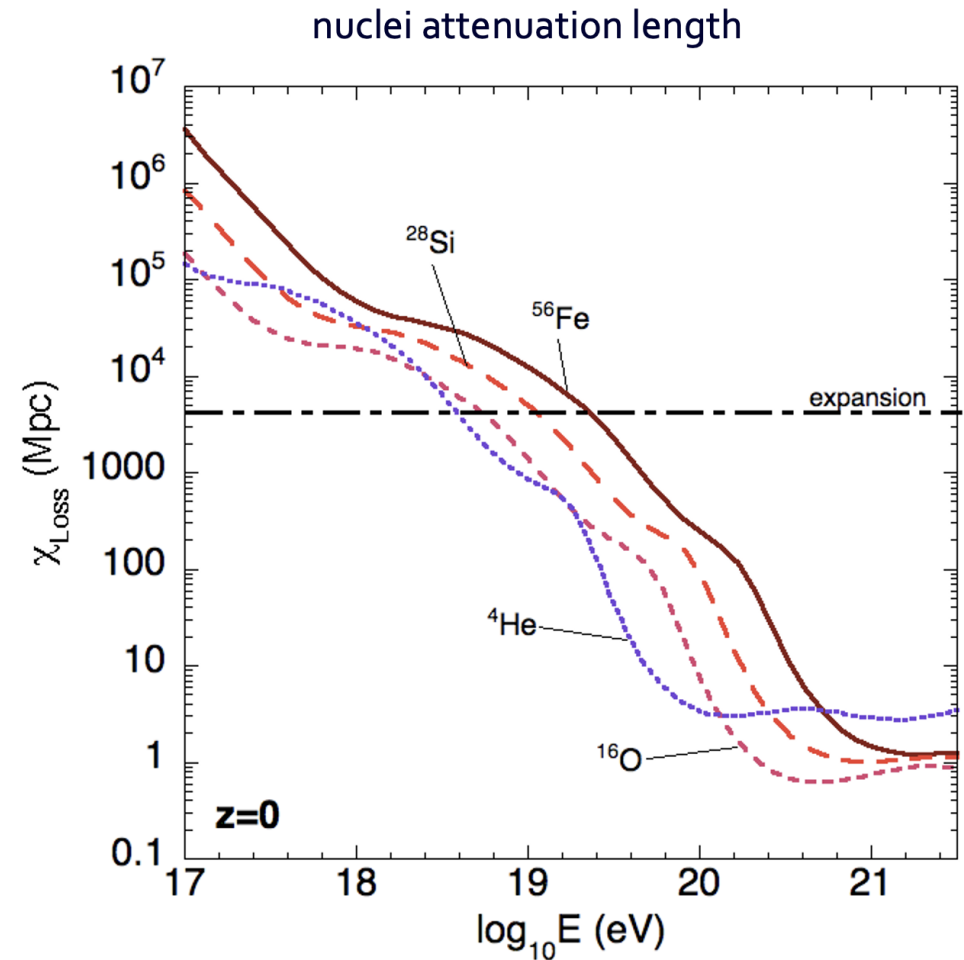
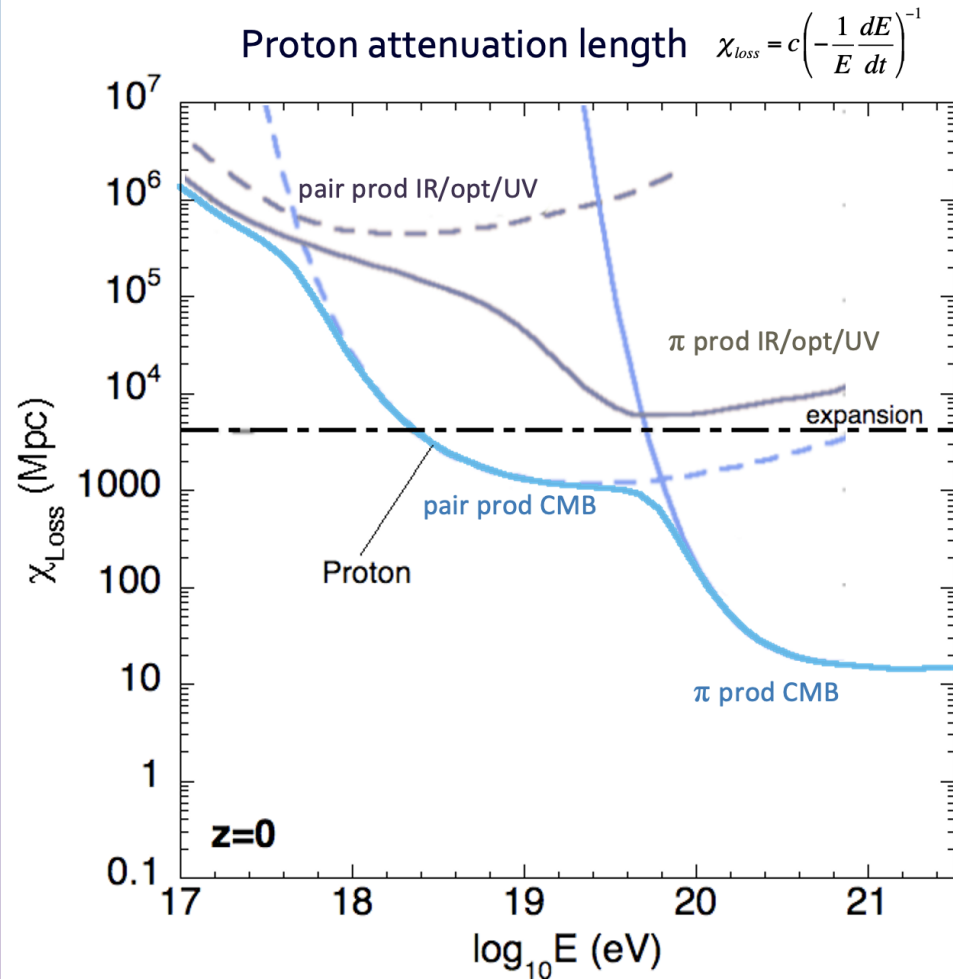
Knowing a source luminosity budget and a number density of sources we can disfavor some source classes:

- 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 (uncertain)



from Alves Batista et al., 2019

Constraints for distance to the closest source from attenuation of highest energy CRs



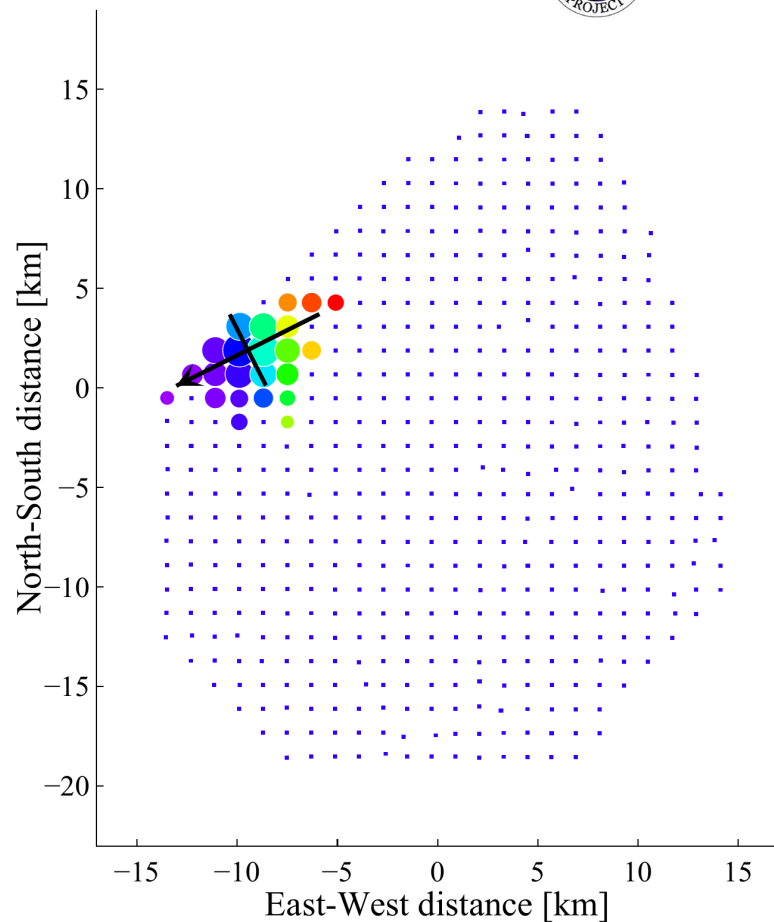
Thanks to Oleg Kalashev for the pictures

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

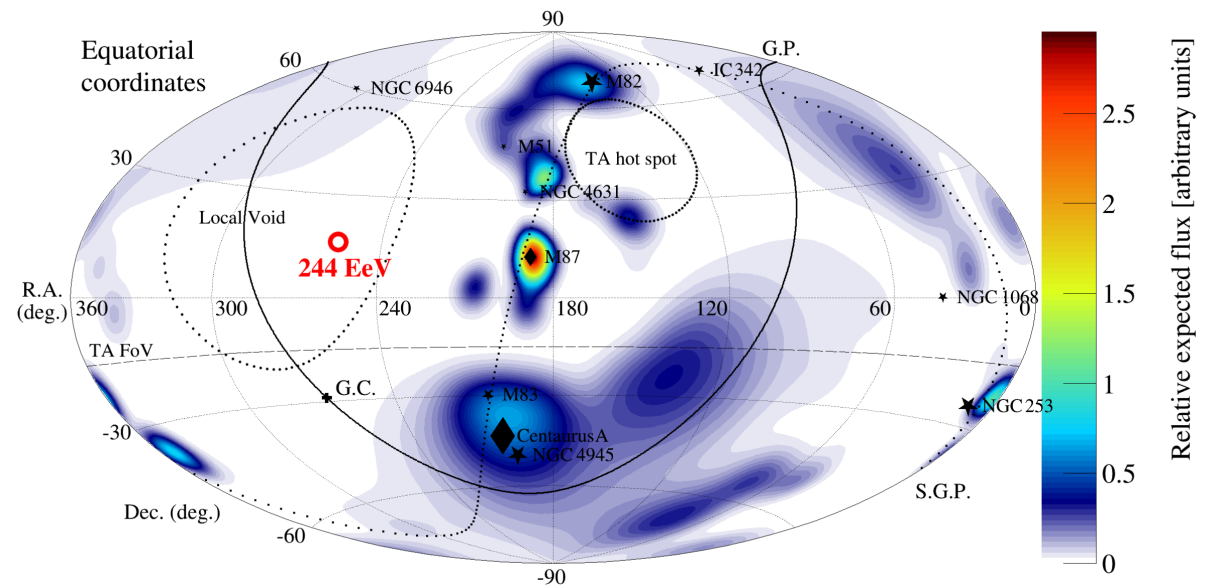
CR event with a second highest energy ever!

Date (UTC)	Energy (EeV)	S_{800} (m^{-2})	Zenith angle	Azimuth angle	Right Ascension	Declination
27 May 2021 10:35:56	244 ± 29 (stat.) $^{+51}_{-76}$ (syst.)	530 ± 57	$38.6 \pm 0.4^\circ$	$206.8 \pm 0.6^\circ$	$255.9 \pm 0.6^\circ$	$16.1 \pm 0.5^\circ$

Surface detector array of TA



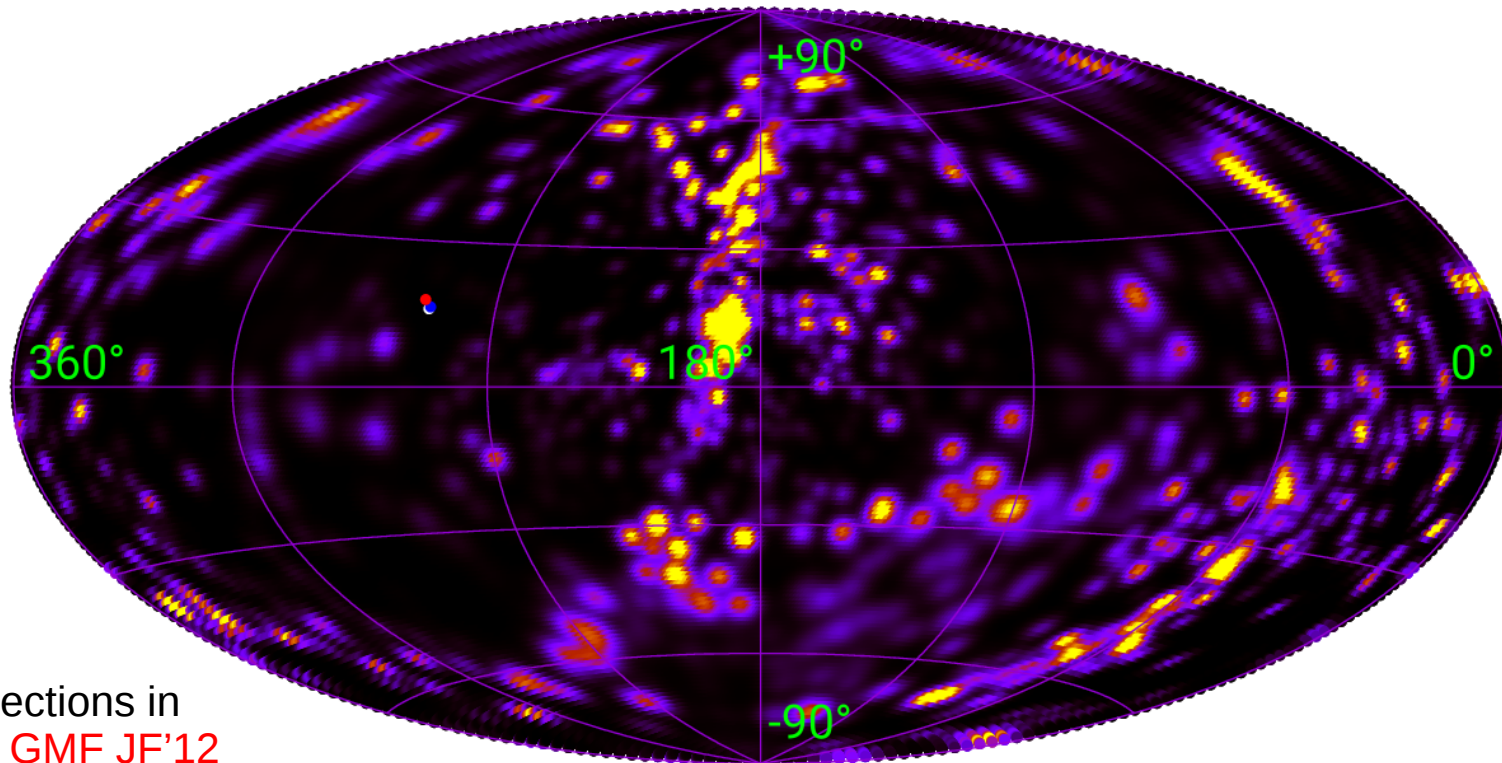
TA collaboration
Science 382 (2023) 903



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: $E = 244 \text{ EeV}$, no deflections in EGMF
- The relative expected flux at the event direction is less than 1% → **proton scenario is disfavored**



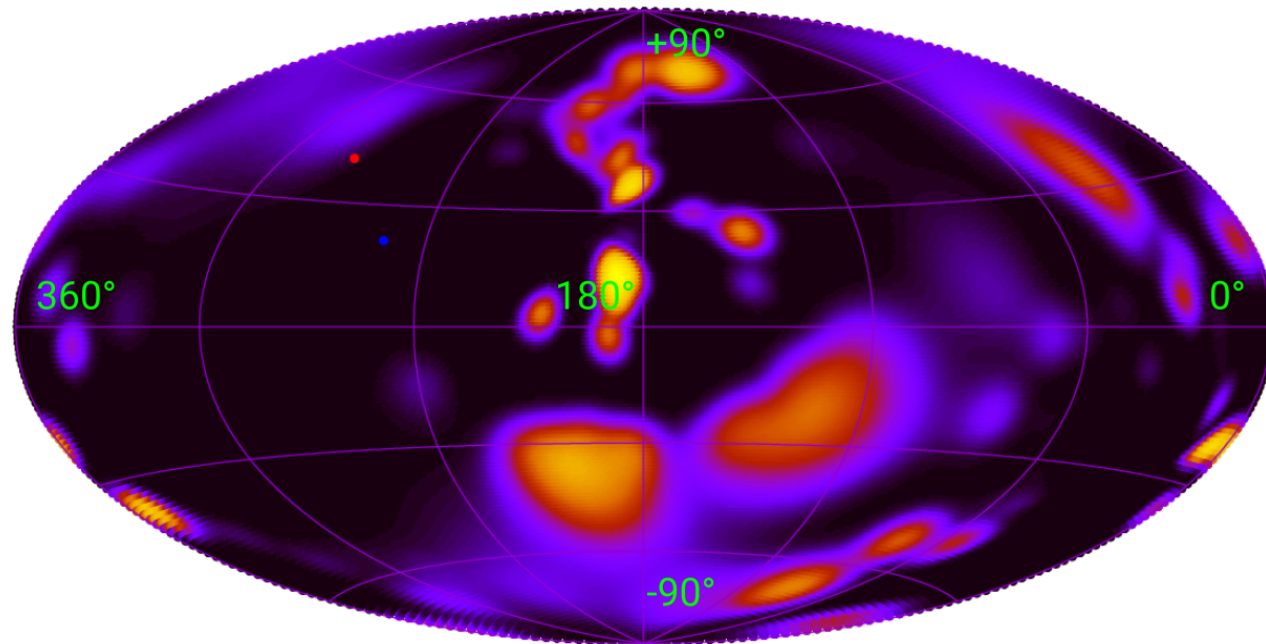
Deflections in
reg. GMF JF'12
reg. GMF PT'11

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.)

$E = 244 \text{ EeV}$, P ($Z = 15$), no EGMF



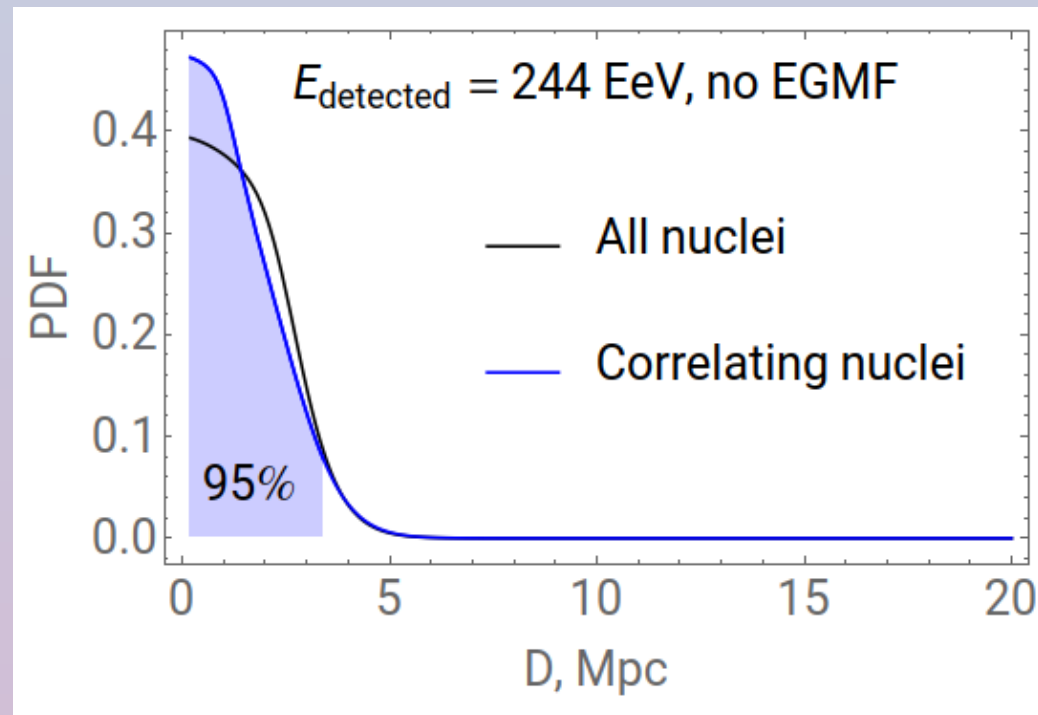
Correlation with sources, nucleus scenario

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: $F_{\text{tot}} = F(D < 100 \text{ Mpc})$
 - Probability to have a source within D_0 : $p(D_0) = F(D < D_0) / F_{\text{tot}}$
 - 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)



Constraints on the sources number density

Now we have the constraints on the distance to the closest source: $D < 5.0_{-0.0}^{+8.0}$ 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

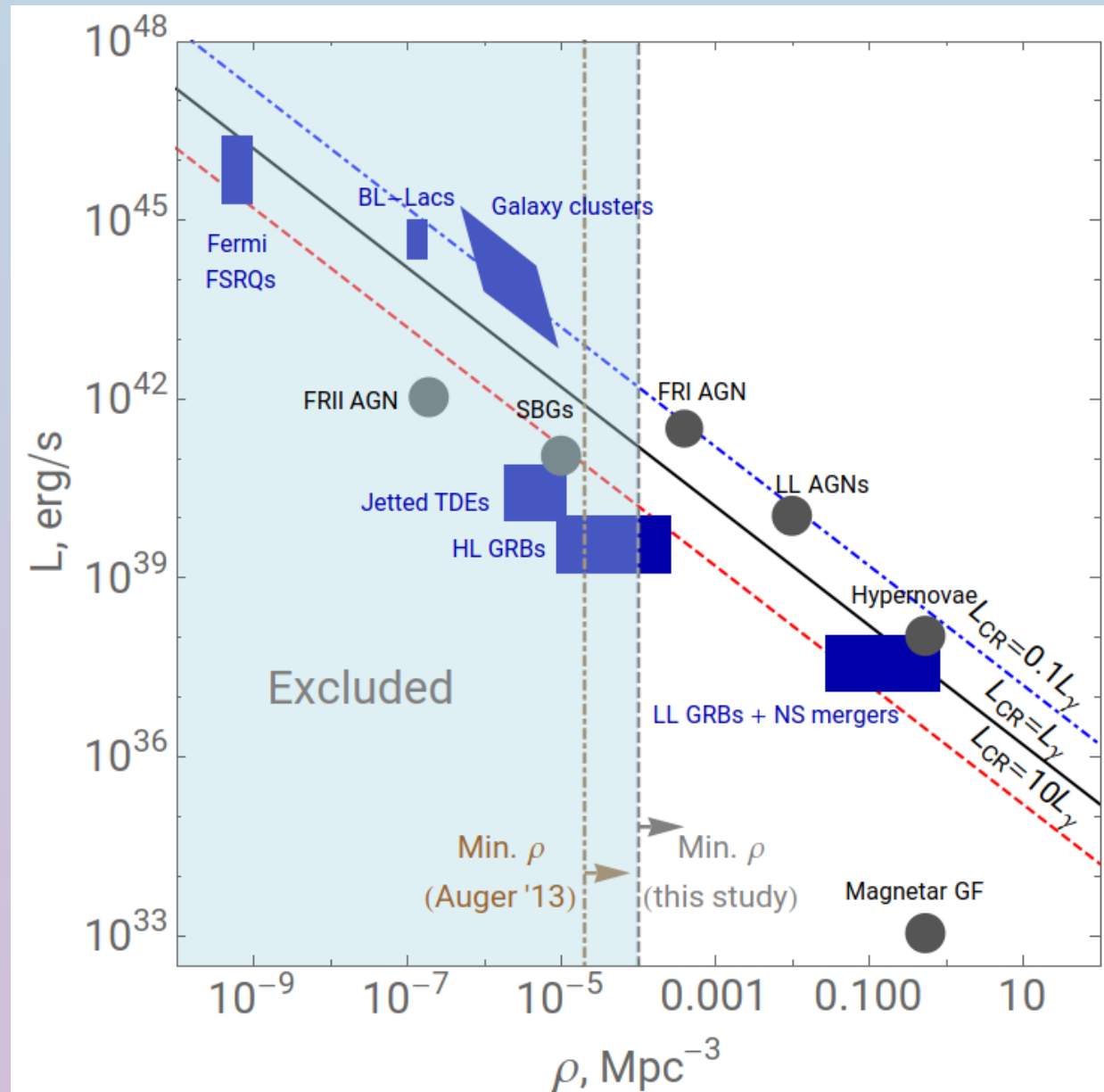
To get 95% C.L. constraints on ρ we simulate the number of source distribution realizations and require to have at least one source in $V = 4/3 \pi D^3$ in at least 5% of realizations

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



Conclusions

- UHECR event of extremely high energy (244 EeV) was detected by the Telescope Array
- The event cannot be a proton because of the lack of correlation with any possible source
- The source of this particle is not farther than **5 Mpc**
- We obtained the strongest up to date conservative constraint on a number density of UHECR sources: $\rho > 1.0 \cdot 10^{-4} \text{ Mpc}^{-3}$
- The constraint for the number density of UHECR sources that emit heavy nuclei is set for the first time
- The constraints also disfavor SBGs, Jetted TDEs and Galaxy Clusters as the main sources of UHECR

Supported by Russian Science Foundation

Thank you!



Backup Slides

Constraints on UHECR source number density

- 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](#))

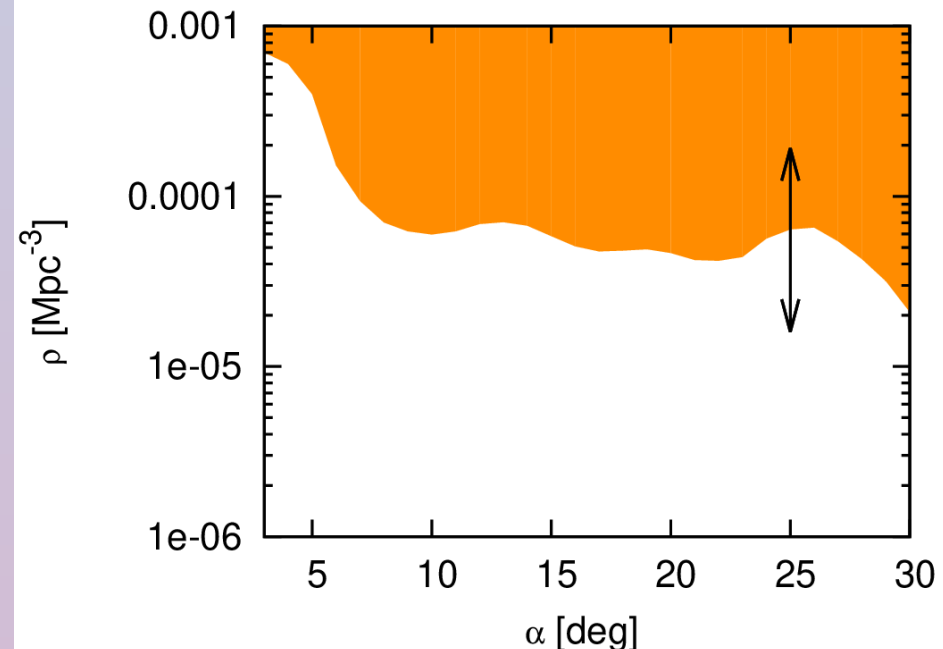
$$n(\alpha) = \sum_{i=2}^N \sum_{j=1}^{i-1} \Theta(\alpha - \alpha_{ij}), \text{ where } \alpha \text{ is a separation angle between two events}$$

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

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

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

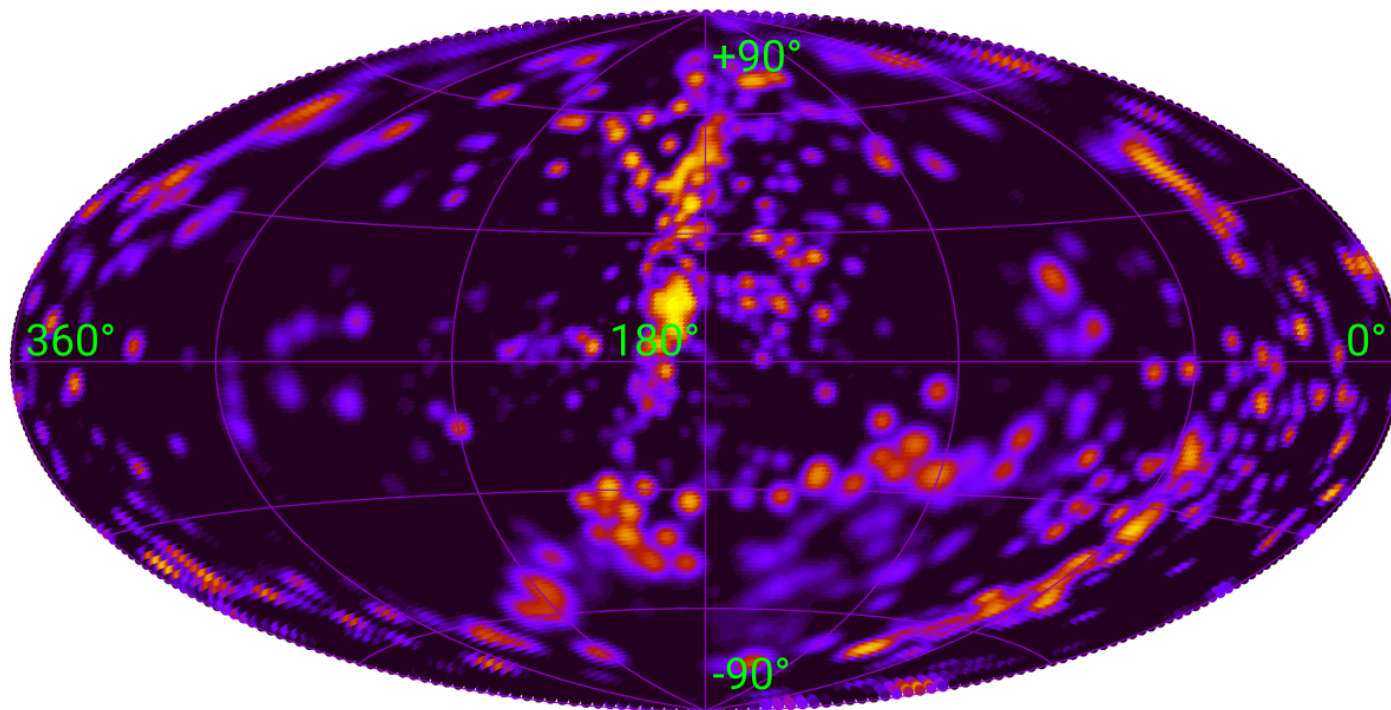
Sources injecting something heavier than Si are not bound by these constraints!



Constraints from attenuation of UHECRs: hints

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

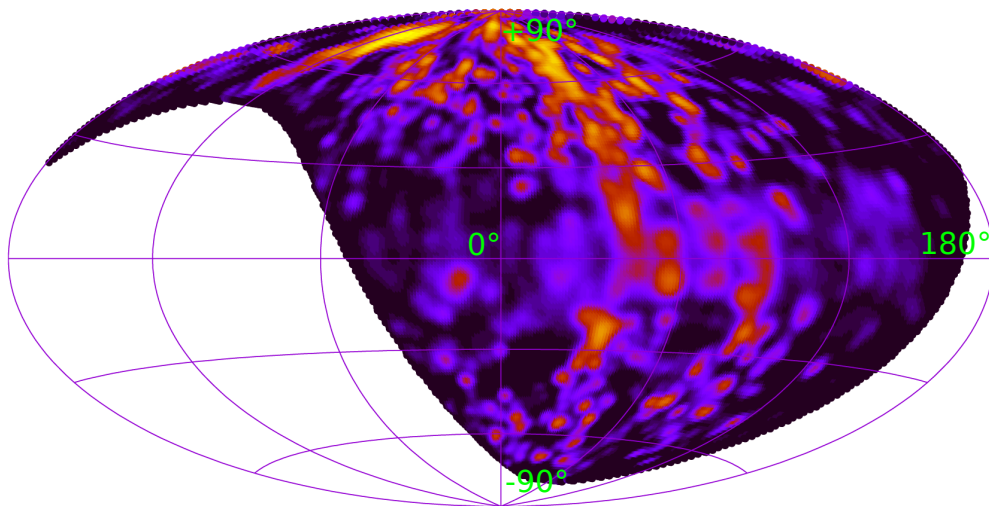
- Value of E_{detected} affects result much
- Detected particle type effect is even larger
- Idea: constrain the particle type by looking for event correlation with all possible sources (LSS)



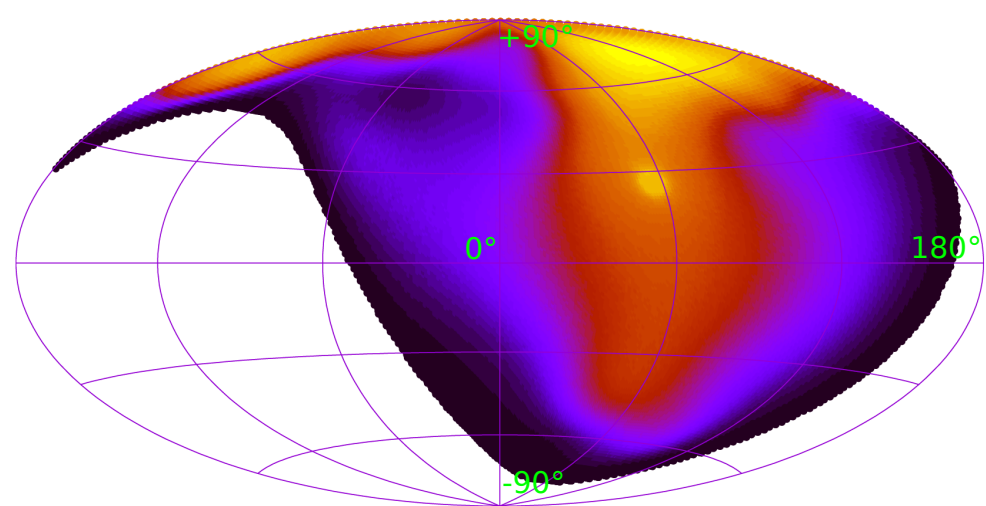
Maps of expected UHECR sources: details

- Sources in LSS: 2MRS catalog from 5 Mpc up to 250 Mpc ($\rho \sim 10^{-2} \text{ Mpc}^{-3}$)
- 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 $E = 100 \text{ EeV}$



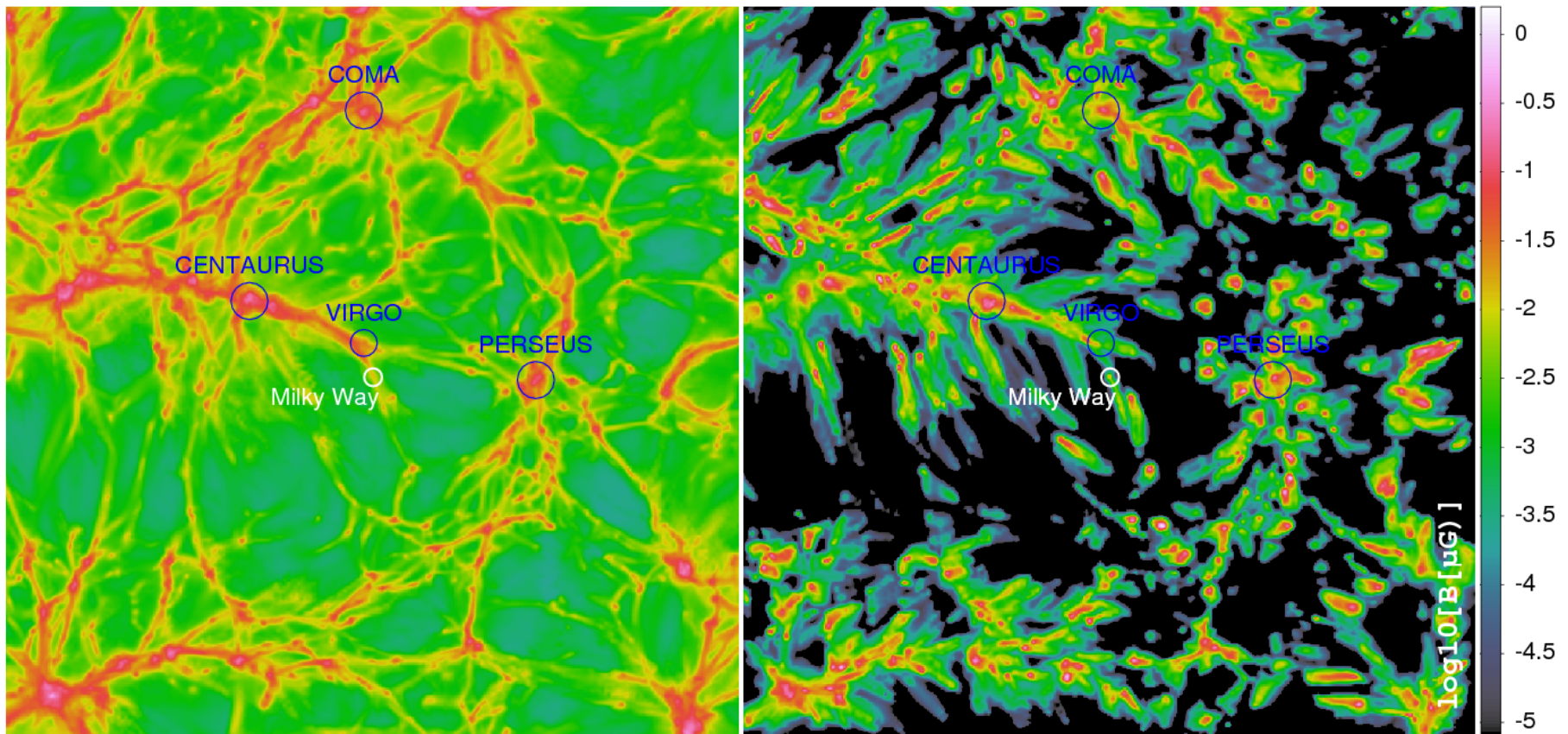
Iron map at $E = 100 \text{ EeV}$



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: $B_{\text{IGMF}} < 1.7 \text{ nG}$ with correlation length $\lambda_{\text{IGMF}} \sim 1 \text{ Mpc}$
- 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

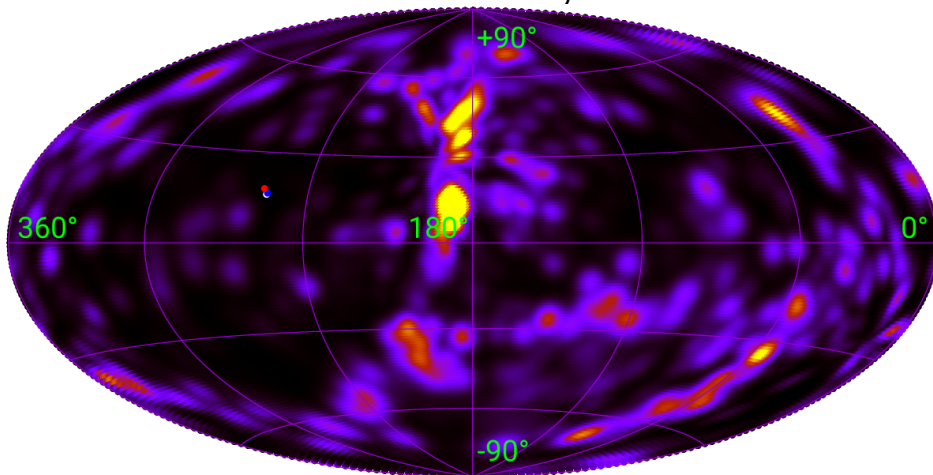
Correlation with sources, proton scenario: uncertainties

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

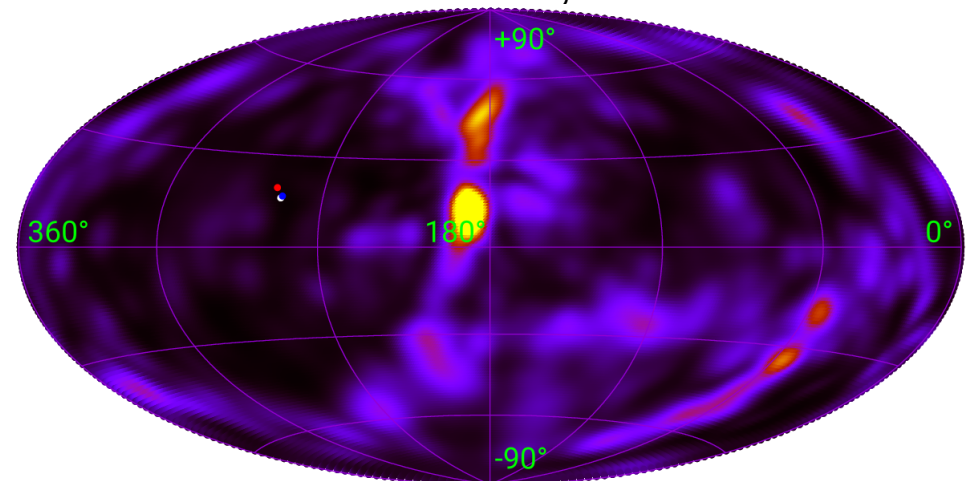
- Scenario Ia: $E = 244 \text{ EeV}$, extreme EGMF
- Scenario Ib: $E = E_{\text{detected}} - 2\sigma (\text{stat.}) - (\text{sys.}) = 135 \text{ EeV}$, extreme EGMF

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!

$E = 244 \text{ EeV}$, EGMF



$E = 135 \text{ EeV}$, EGMF



Correlation with sources, nucleus scenario: uncertainties

Take into account energy uncertainty and possible EGMF

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

Constrain the distance with the same procedure: $D < 13.4 \text{ Mpc}$

Constraint for the source number density: $D < 13.4 \text{ Mpc} \rightarrow \rho > 5.2 \cdot 10^{-6} \text{ Mpc}^{-3}$

$E = 168 \text{ EeV}$, S (Z = 16), extreme EGMF

