# Регистрация космической частицы экстремально высокой энергии

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## **Ultra-high energy cosmic rays**



- Flux < 1 km<sup>-2</sup>yr<sup>-1</sup>sr<sup>-1</sup>
- Steeply falling spectrum
- Origin still unknown (extragalactic)
- Detecting via showers of charged particles in atmosphere



## **TELESCOPE ARRAY**

#### Наземные детекторы (2008)

- 507 детекторов
- 1.2 км промежутки
- 3 м² площадь детектора
- ~700 км<sup>2</sup> площадь установки

#### Флуоресцентные телескопы (2007)

- 3 Станции
- 12-14 телескопов в каждой
- 3°–31° угол обзора над горизонтом

Энергии: 10<sup>18</sup> – 10<sup>20</sup> eV Зенитные углы: 0° – 55° Склонения: -24° – +90°



# Детектирован второй по энергии КЛ за всю историю наблюдений!

2021/05/27 10:35, Только SD наблюдения



# Свойства экстремального КЛ

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



# Свойства экстремального КЛ

#### Тип частицы

- НЕ молния! (проверено по двум системам наблюдений)
- Нет FD наблюдений (X<sub>max</sub>)
- Анализ SD наблюдаемых с помощью машинного обучения
  - · Гамма-квант исключен на 3.8 σ
  - Для различения типа ядра пока не хватает точности метода (единичное событие!)

#### Another idea: constraints from attenuation of highest energy CRs



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

/

### **Constraints from attenuation of UHECRs: hints**

MK, arXiv: 2311.14628

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

- Value of E<sub>detected</sub> 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)



#### **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%  $\rightarrow$  proton scenario is disfavored



#### **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:  $E = E_{detected} 2\sigma$  (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!



#### **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<sub>tot</sub> = F(D<100 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



#### **Constraints on the sources number density**

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

We need to translate this into constraint on the UHECR source number density  $\rho$ 

Assume the sources are distributed in the Universe according to Poisson distribution:  $e^{-\rho V} (\rho V)^N$ 

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

N is a number of sources inside the volume V

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

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

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

#### **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



Source models from Alves Batista et al., 2019

## Conclusions

- An extremely energetic CR event was detected by Telescope Array
- The event is not a gamma-ray
- 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: ρ > 1.0 · 10<sup>-4</sup> Mpc<sup>-3</sup>
- 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



# **Backup slides**

#### 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)

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

- $\rho > 2 \cdot 10^{-5}$  Mpc<sup>-3</sup> for injected nuclei with Z<14 ( $\alpha$  = 30°)
- $\rho > 6 \cdot 10^{\text{-5}}$  Mpc^{\text{-3}} for injected nuclei with Z<6 ( $\alpha$  = 10°)
- $\rho > 7 \cdot 10^{-4}$  Mpc<sup>-3</sup> for injected p ( $\alpha = 3^{\circ}$ )

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



#### Maps of expected UHECR sources: details

- Sources in LSS: 2MRS catalog from 5 Mpc up to 250 Mpc ( $\rho$ ~10<sup>-2</sup> Mpc<sup>-3</sup>)
- 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



### 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:  $B_{IGMF} < 1.7 \text{ nG}$  with correlation length  $\lambda_{IGMF} \sim 1 \text{ Mpc}$
- Deflections in the largest (from simulations) local EGMF is subdominant for our setup
- Model the deflections as an additional uniform smearing of the sources

0 COMA -0.5 -1 -1.5 CENTAURUS CEN -2 VIRGO PERSEUS -2.5 Milky Way -3 -3.5 -4 -4.5

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

**Primordial EGMF** 

Astrophysical EGMF

## 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)

