UHECR anisotropy and search for their sources

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Outline

- Ultra-high energy cosmic rays (UHECR)
- Search for sources: cosmic rays astronomy?
- UHECR anisotropy observations
- UHECR anisotropy interpretations
  - Search for close source
  - Constraints for sources number density
  - Interpretation of correlations with source classes
- Perspectives

Ultra-high energy cosmic rays

- Protons and nuclei, E > 1 EeV (10^{18} eV)
- Enregy range not studied in terrestrial experiments
- Flux is very low ~ 1 $km^{-2}yr^{-1}sr^{-1}$
- Only indirect detection (interaction with the atmosphere)
- Origin is unknown (extragalactic)

From the list of 30 unsolved physical problems for XXI century

27. Проблема темной материи (скрытой массы) и ее детектирования.
28. Происхождение космических лучей со сверхвысокой энергией.
29. Гамма-всплески. Гиперновые.

V.L. Ginzburg, 2001

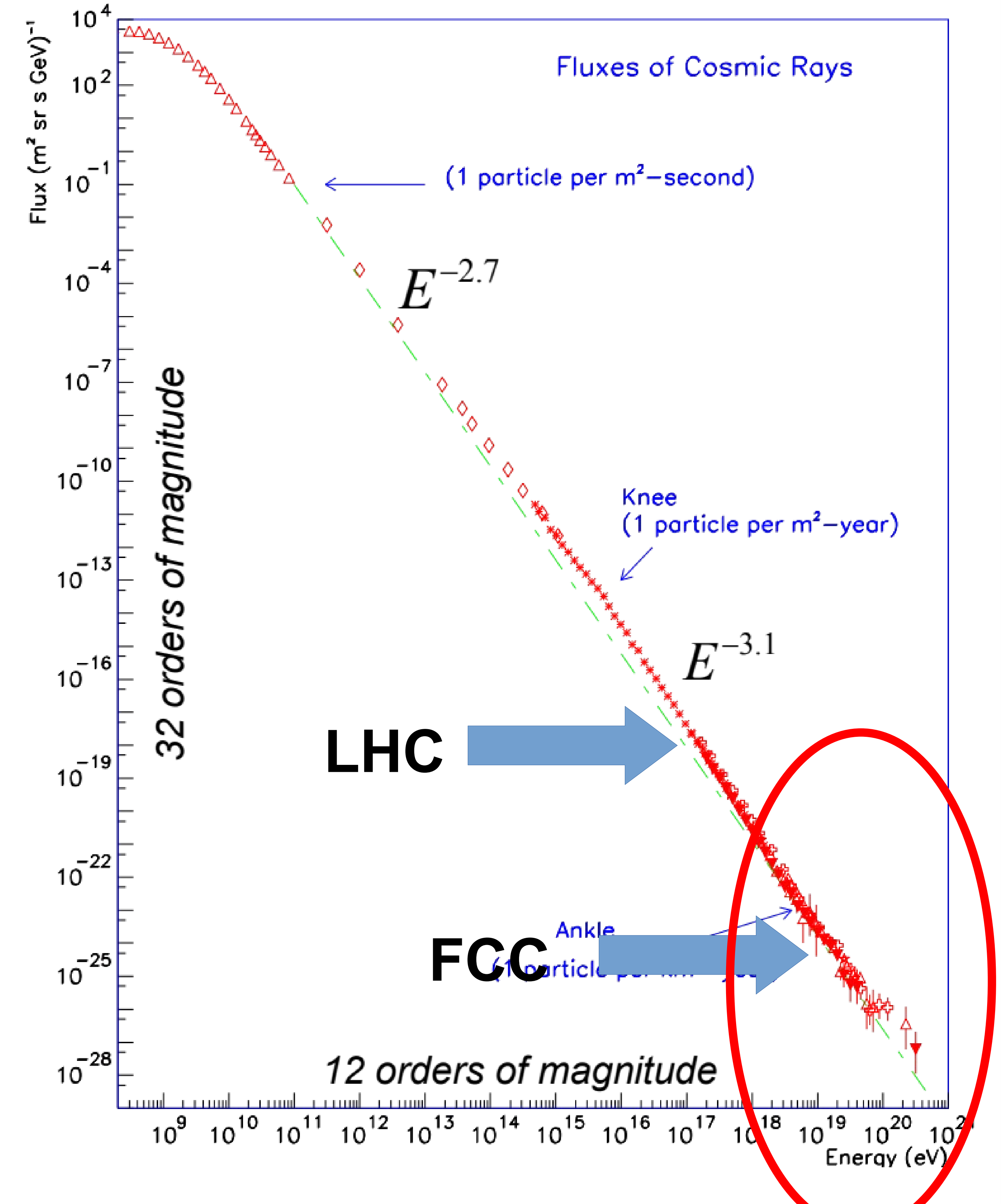
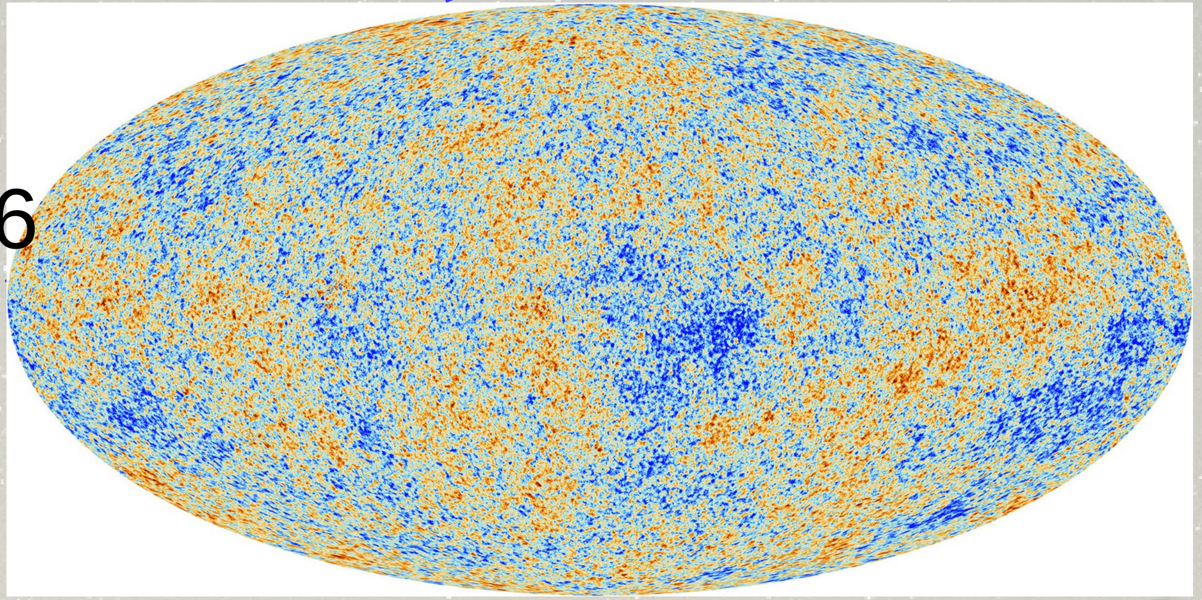


Fig.: Bhattacharjee and Sigl, Phys. Rept. 327 (2000) 109

Indication for UHECR extragalactic origin

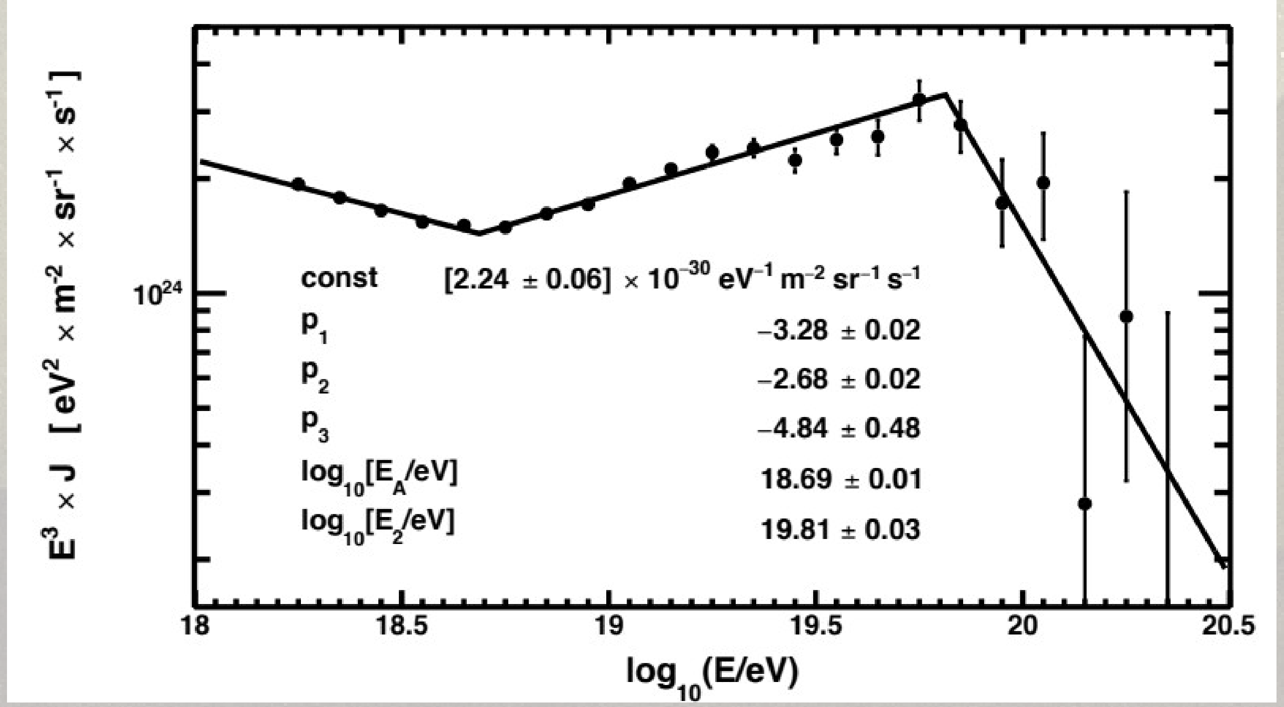
- CMB discovery: 1964
- Greisen, Zatsepin and Kuzmin (GZK–effect) $p\gamma \rightarrow p\pi$: 1966

  Cosmic rays with E ~10^{20} eV cannot reach the Earth from sources at D ~100 Mpc due to energy loss in scatterings at CMB



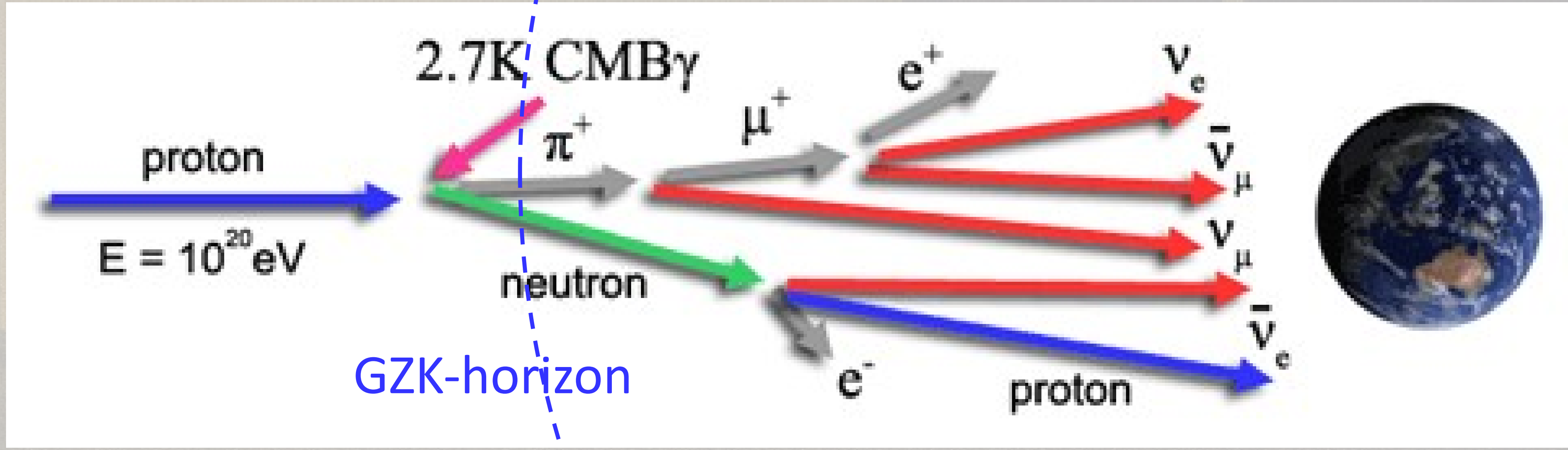
Planck, 2015

Spectrum cutoff appears at energies E ≳ 40 EeV: it is observed experimentally



Telescope Array @ ICRC-2015

Sources should be inside the horizon!



Indication for UHECR extragalactic origin

Dipole in the skymap

E > 8 EeV, l = 233° , b = −13°

Significance > 6σ

Maximum flux is uncorrelated with GC and slightly correlated with Gal.disk

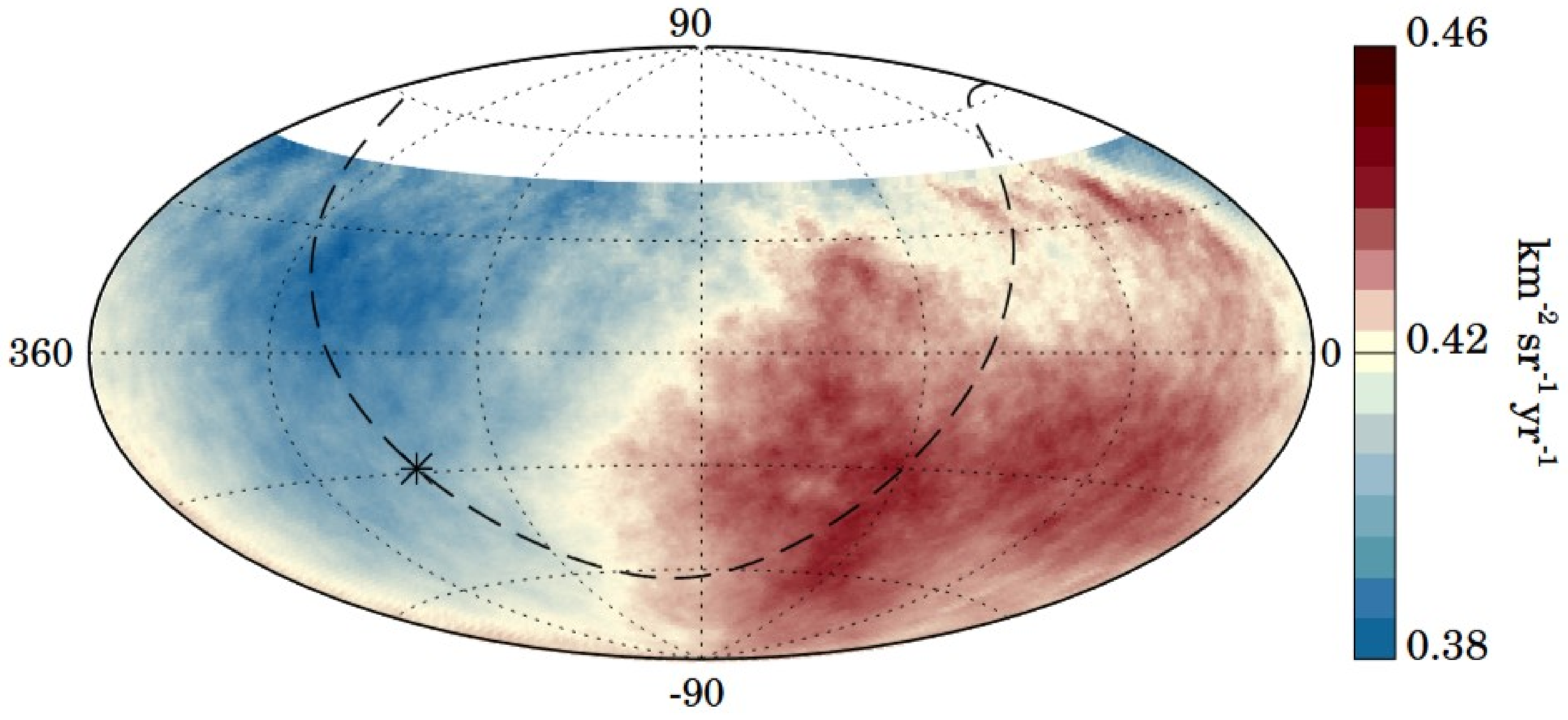


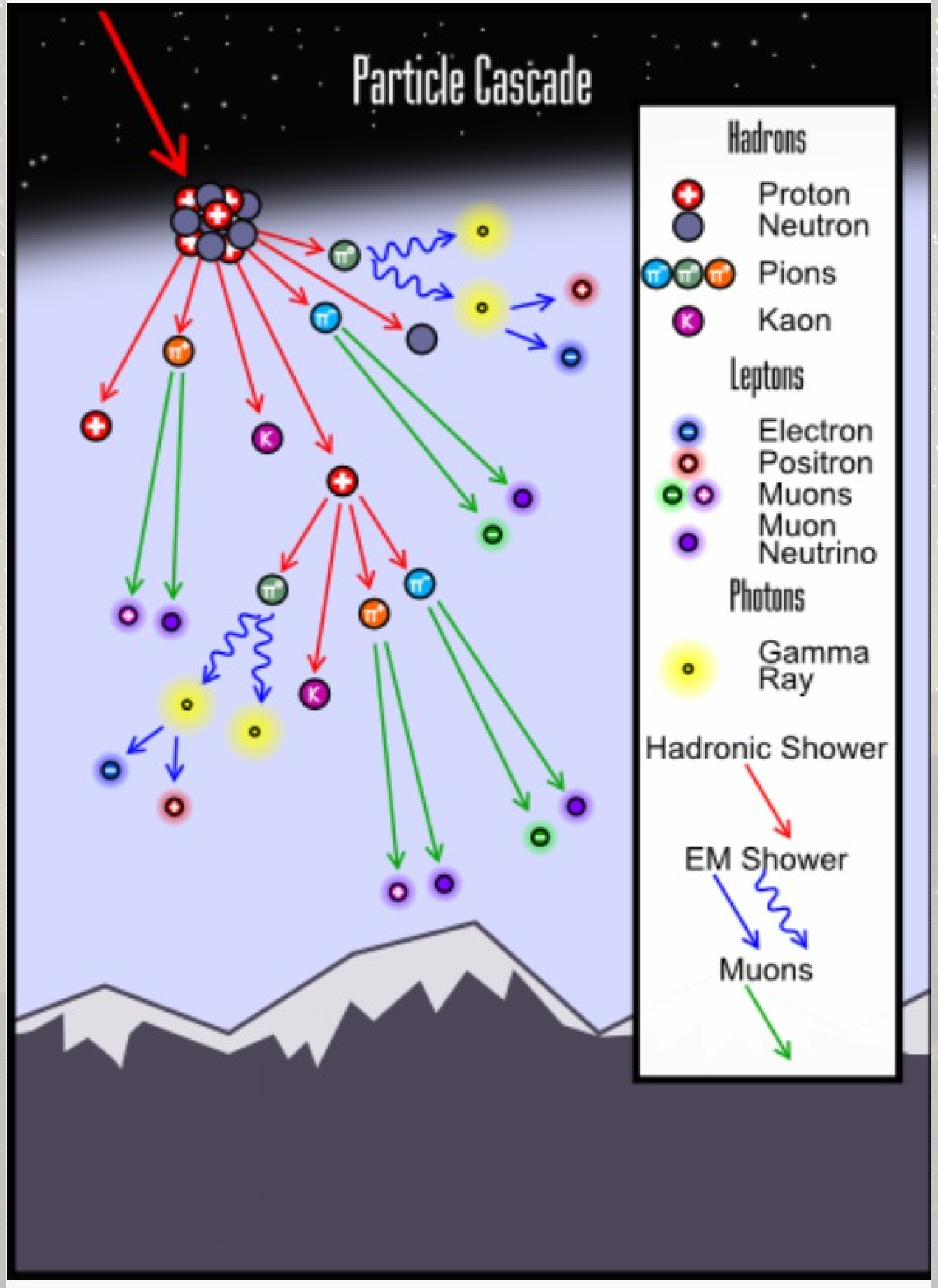
Figure 2: **Map showing the fluxes of particles in equatorial coordinates.** Sky map in equatorial coordinates, using a Hammer projection, showing the cosmic-ray flux above 8 EeV smoothed with a 45° top-hat function. The Galactic center is marked with an asterisk and the Galactic plane is shown by a dashed line.

Auger, Science 357 (2017) 6537, 1266

Cosmic rays observation

6

How to observe UHECR?



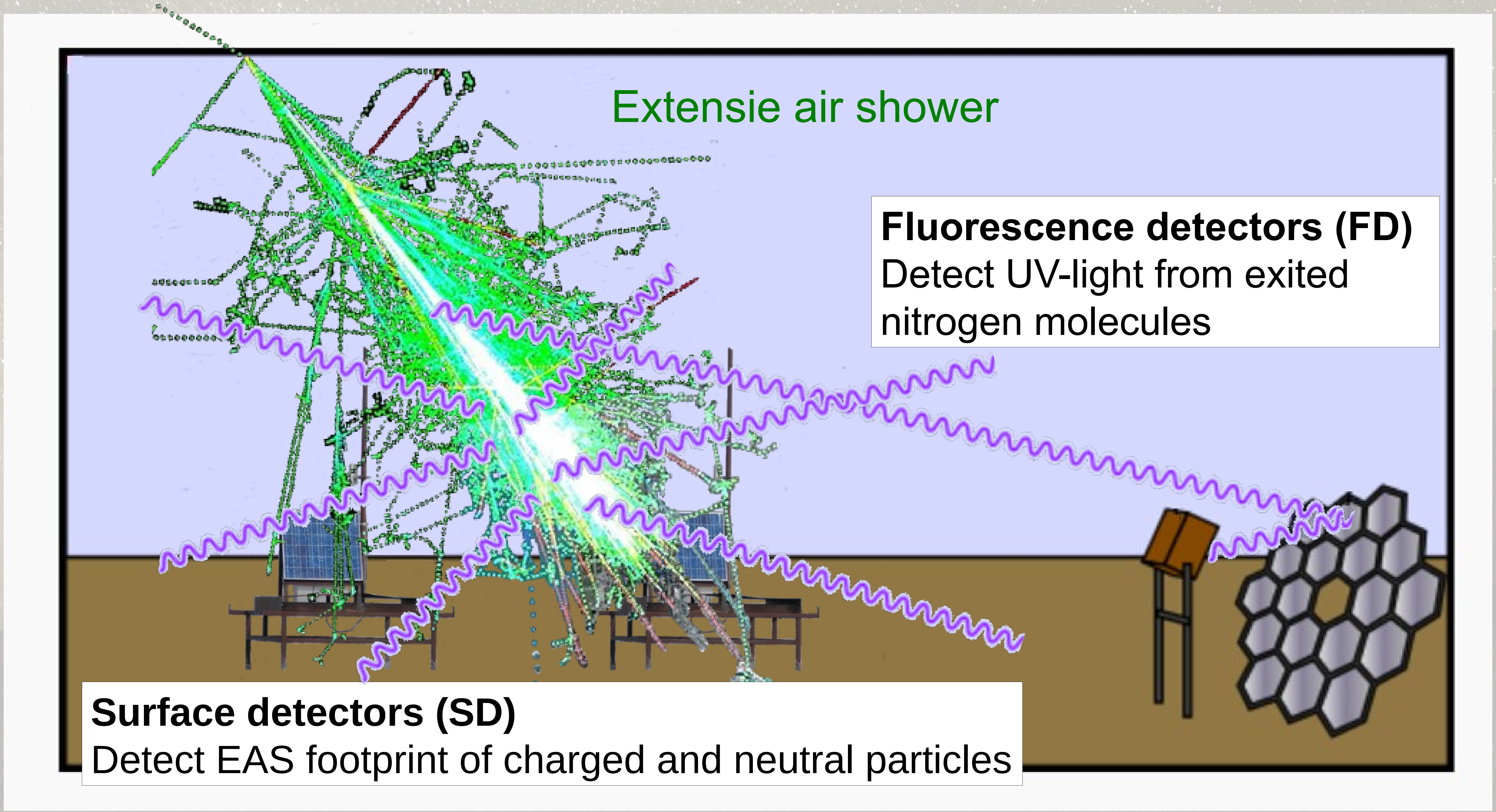
Indirect detection

- Cosmic ray collide with the nuclei in the upper layers of the atmosphere (altitude ~ 10 km)
- Cascade of high energy particles appears
- Cascade develops further, so that billions of particles reach the ground

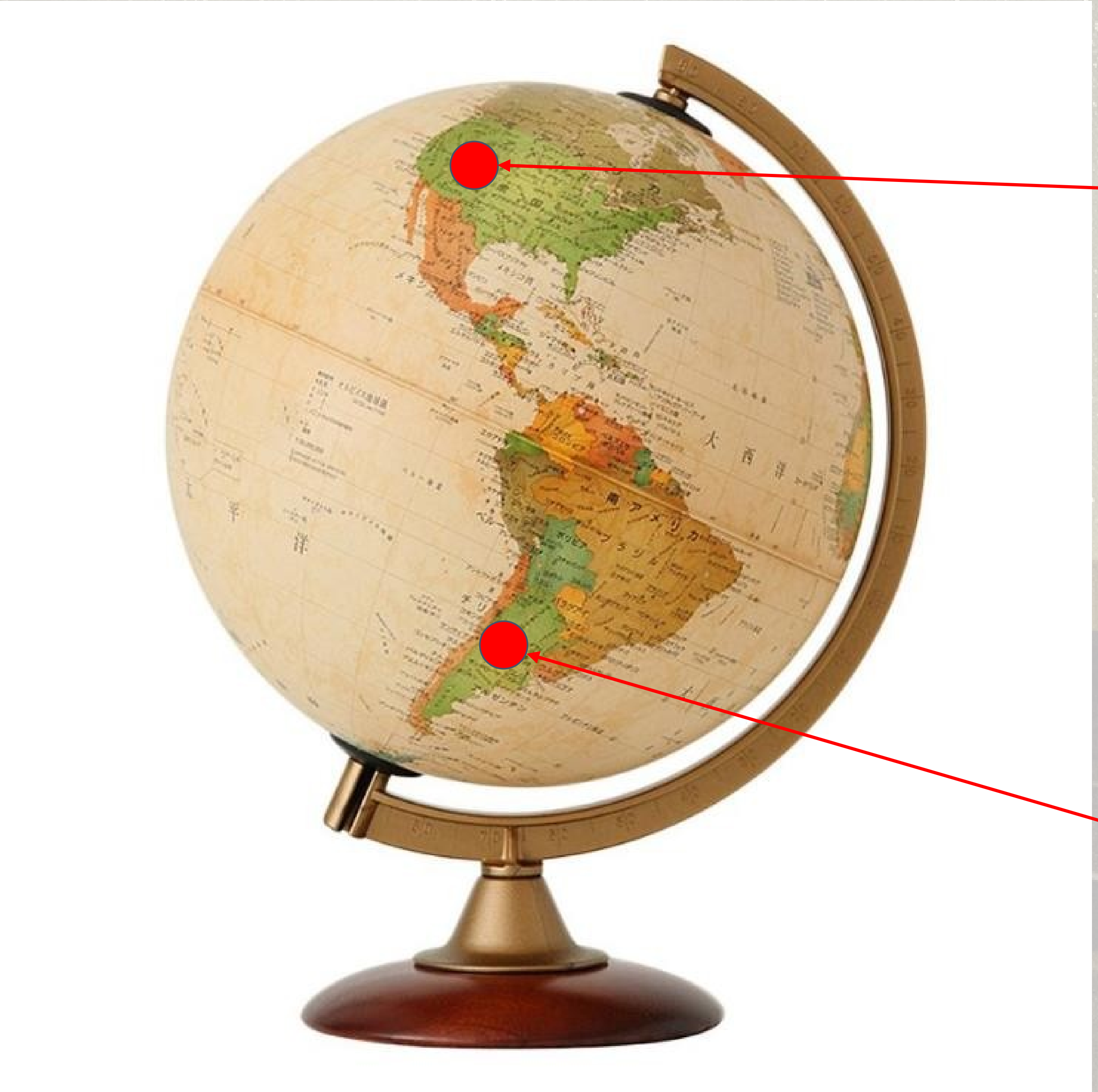
This is an extensive air shower (EAS)

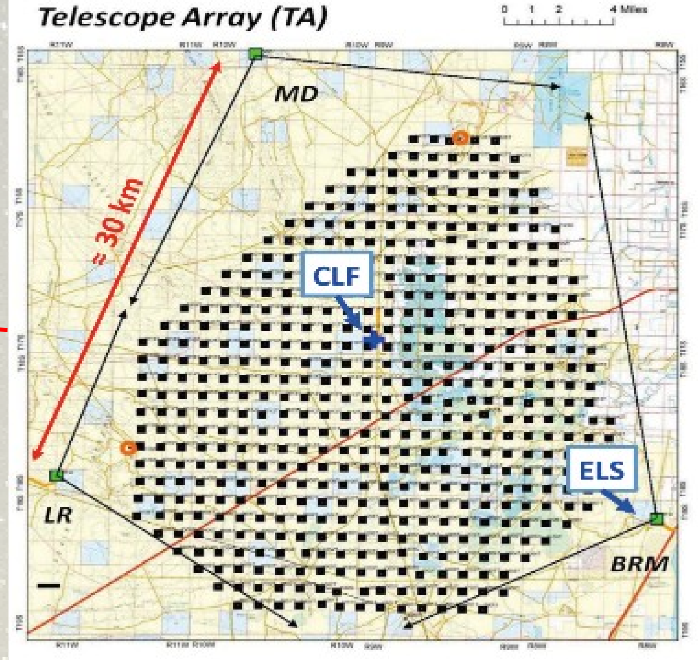
Disovered by Pierre Auger in 1939

How to detect EAS?

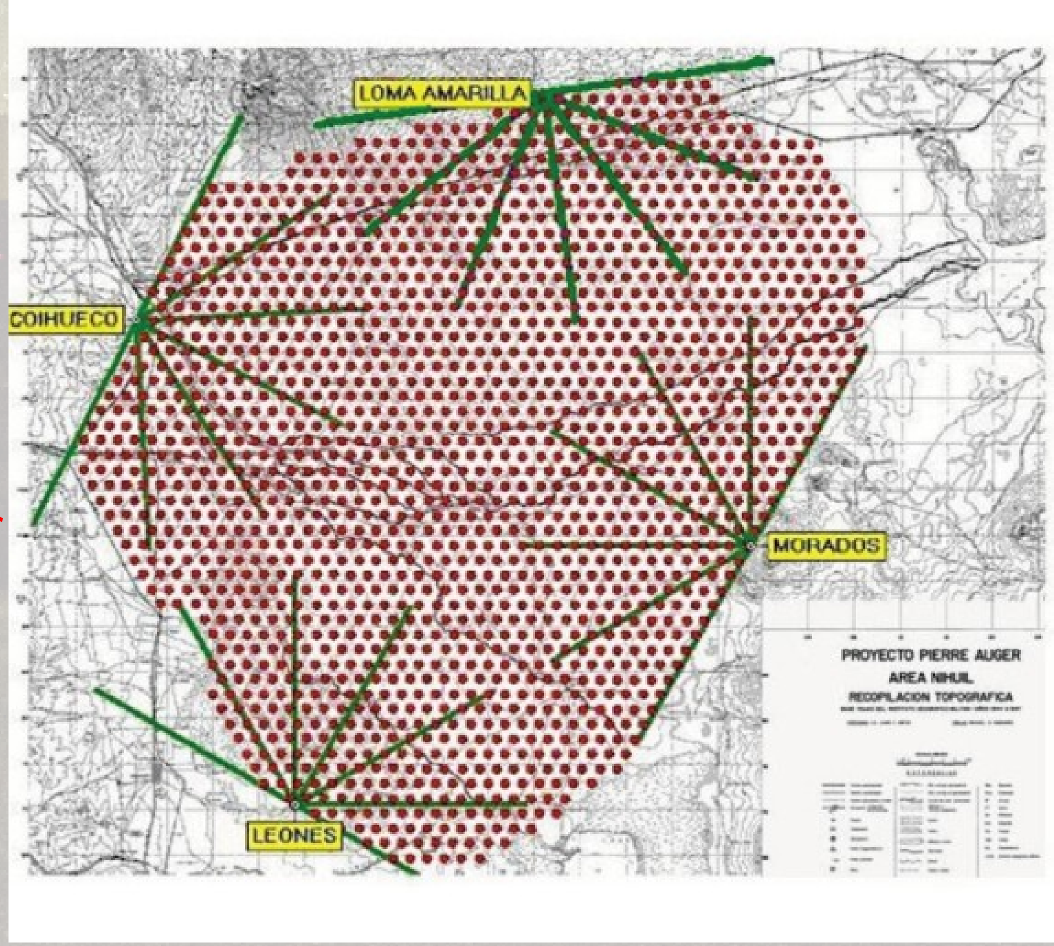


Two largest modern experiments for UHECR observation



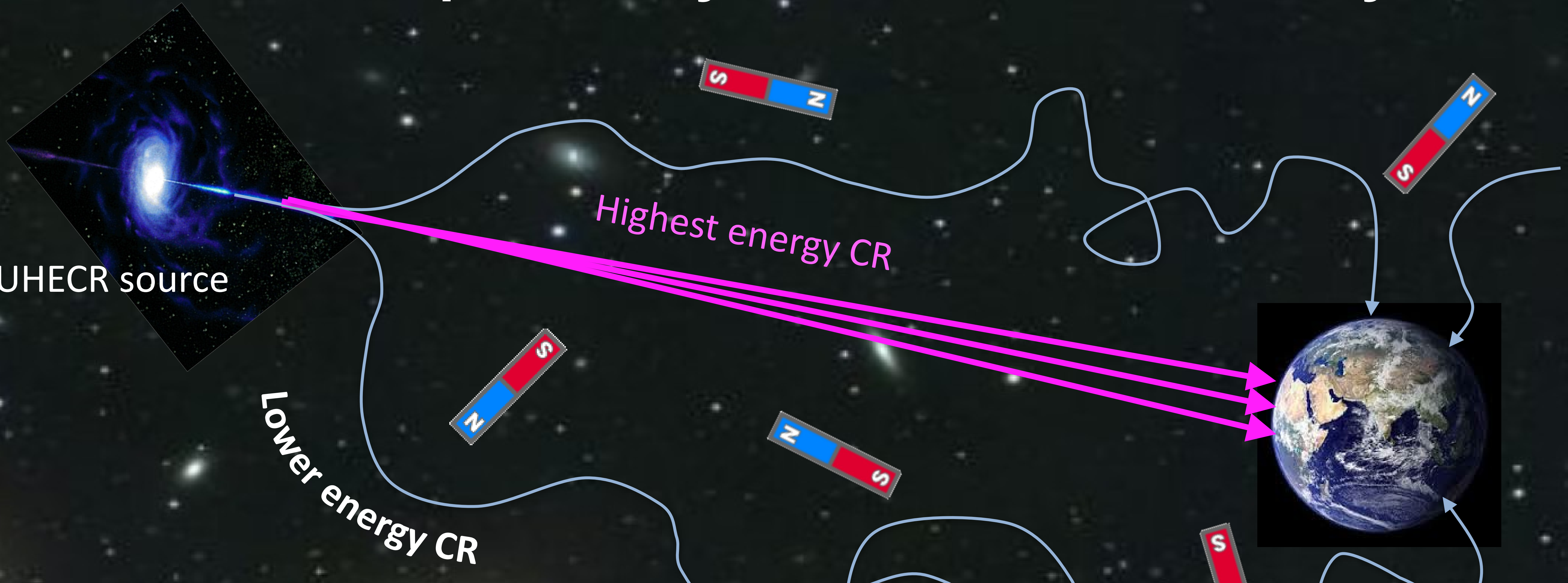


TA: 39°N
700 km²



Auger: 35°S
3000 km²

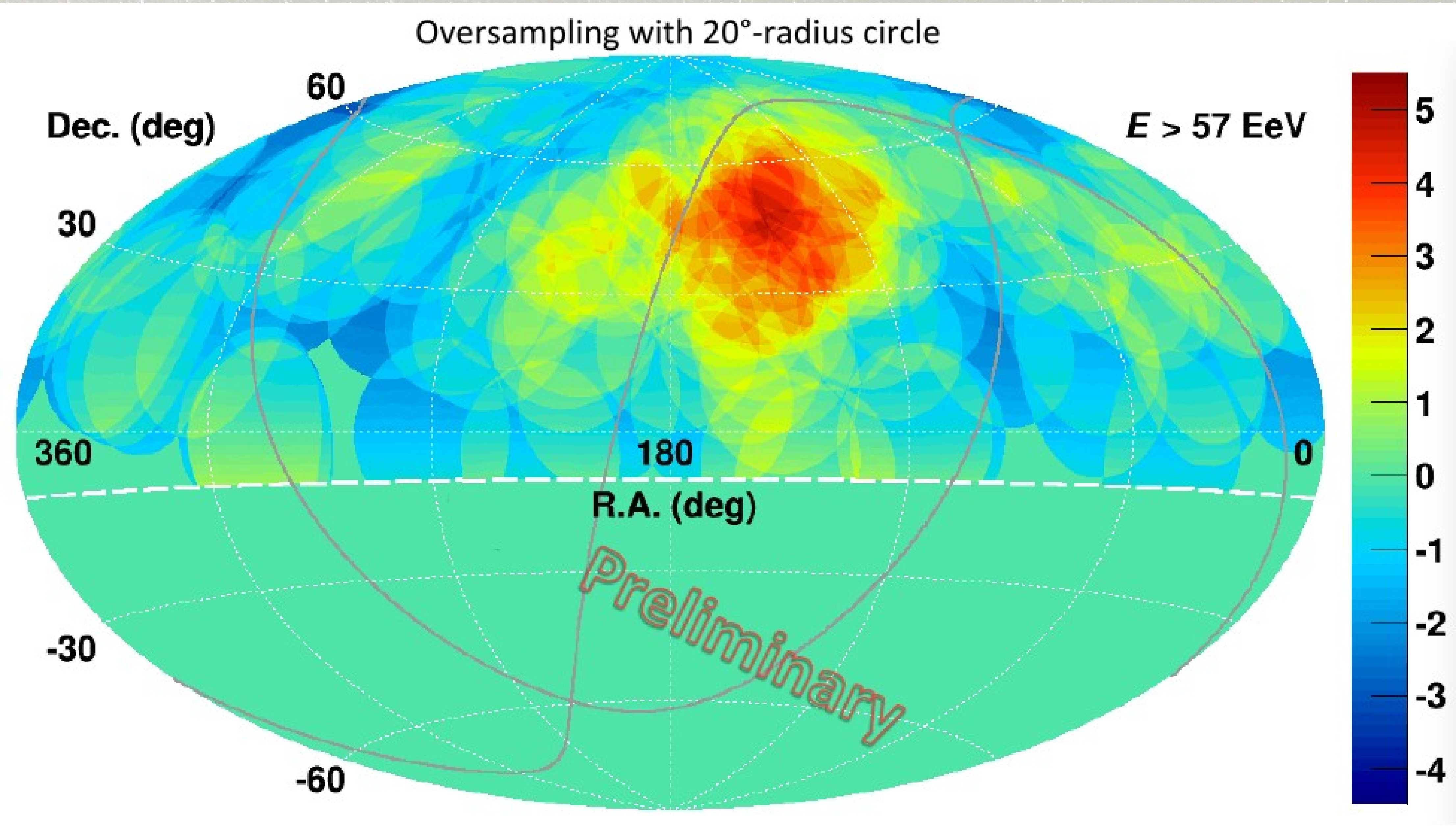
Is there a possibility for UHECR «astronomy»?



- CR of lower energies
- Large deflections in cosmic magnetic fields
- Flux at Earth is almost isotropic

- CR of higher energies
- Small deflections in magnetic fields (?)
- A hope to identify sources

Current observations of UHECR anisotropy

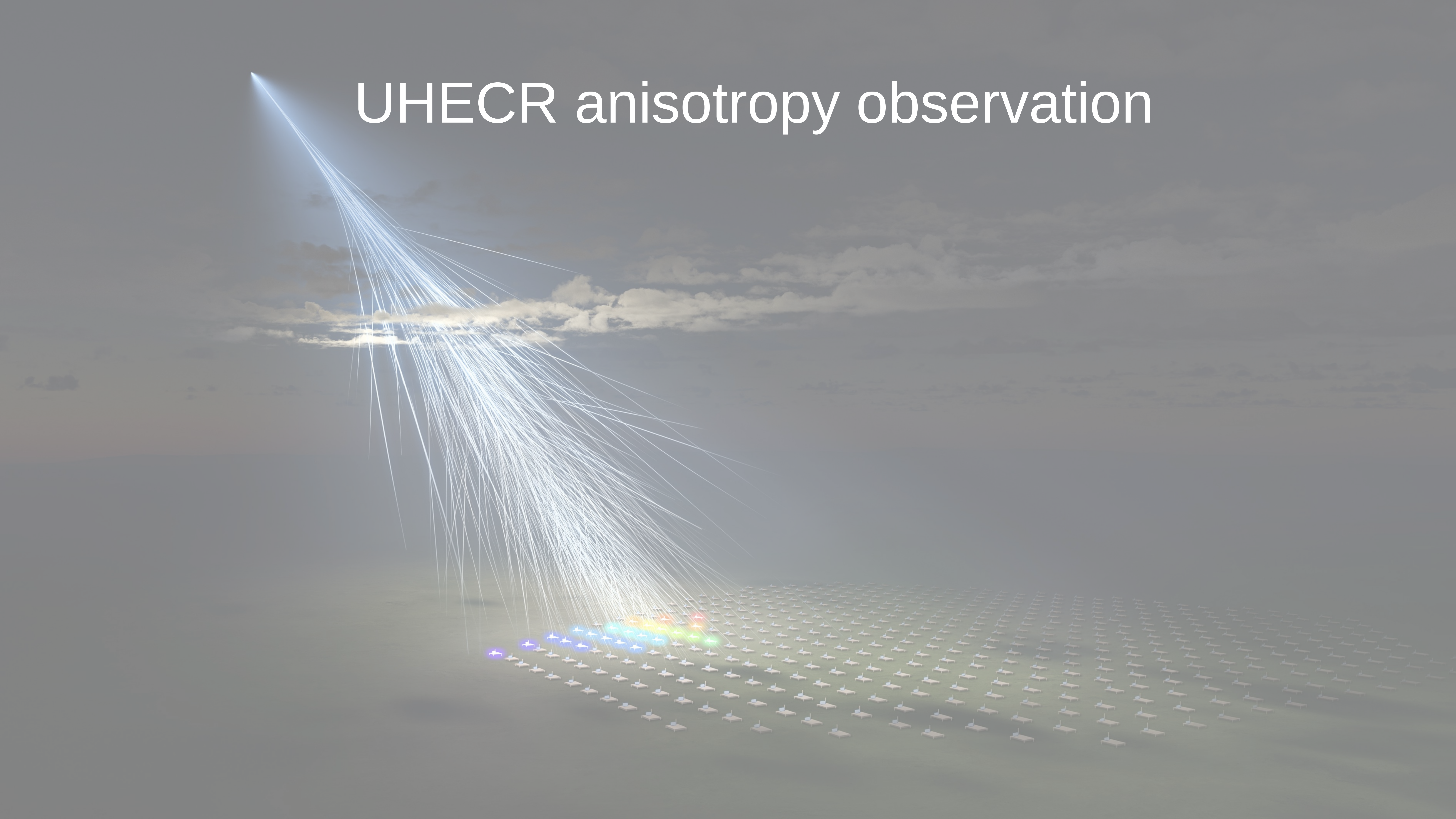


- UHECR arrival directions are measured with relatively good accuracy (~1°)

But

- The theoretical uncertainties for expected deflections are larger:
  - Uncertainties of galactic and extragalactic magnetic fields
  - Uncertain mass (a hence charge) composition of UHECR

UHECR anisotropy observation



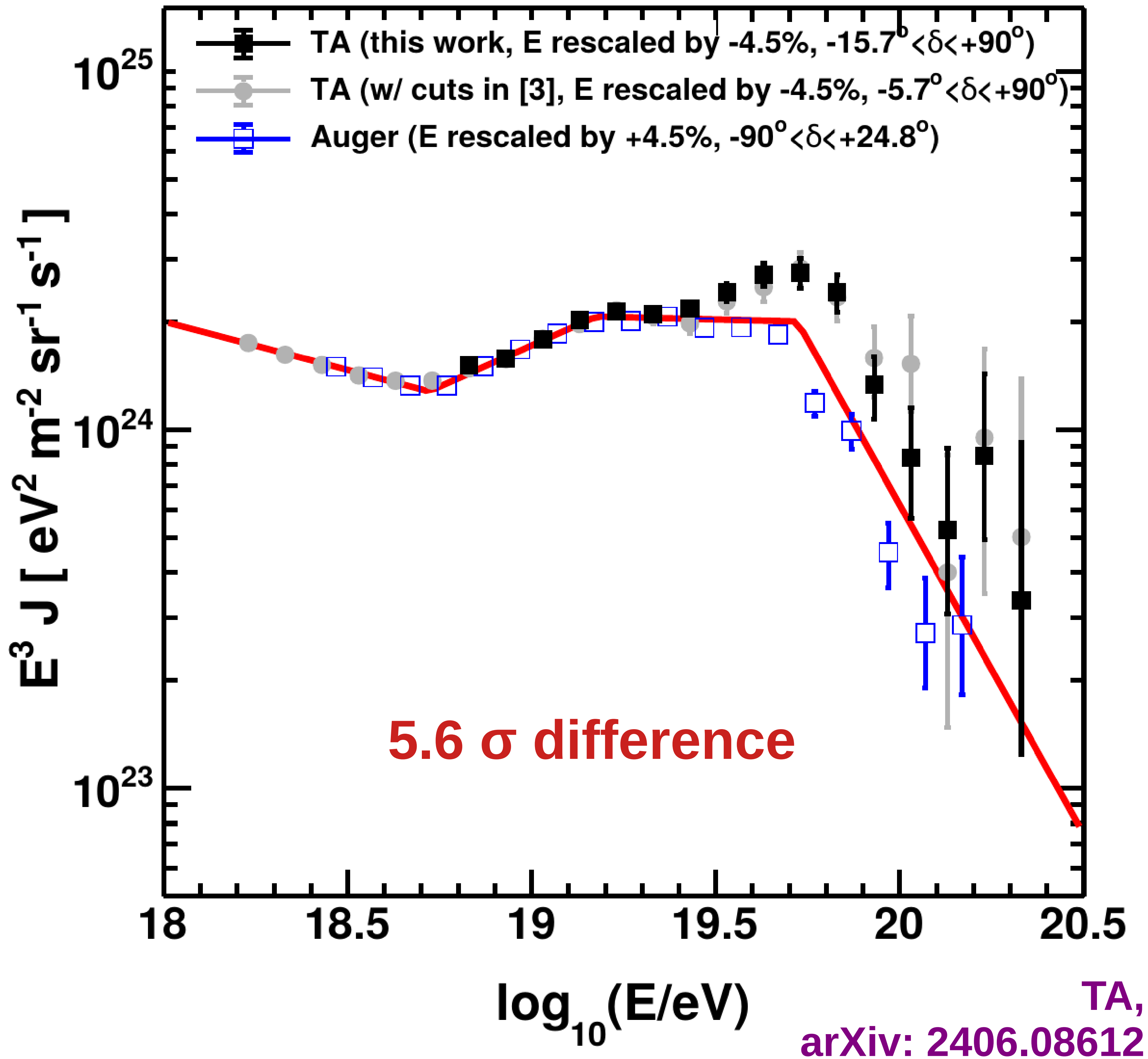
Difference in UHECR spectra between northern and southern sky

UHECR spectra of Auger and TA are significantly different at E ≳30 EeV

To exclude unaccounted experimental effects: look for common band of the sky: -5˚ < δ < -24.8˚

Cut out exposure edges and hotspots areas (that can cause secondary differences). The remaining difference is insignificant: **1.8 σ**

The 5.6 σ difference in full fields of view
TA: -15.7˚ < δ < 90˚
Auger: -90˚ < δ < -24.8˚

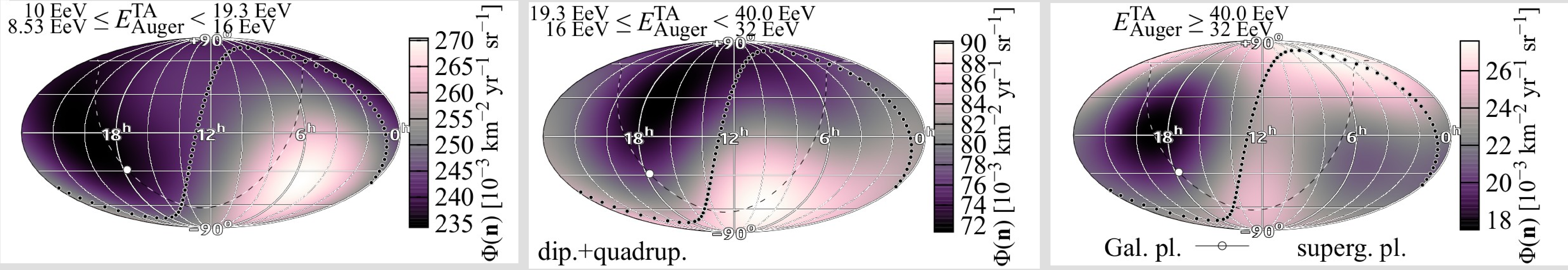


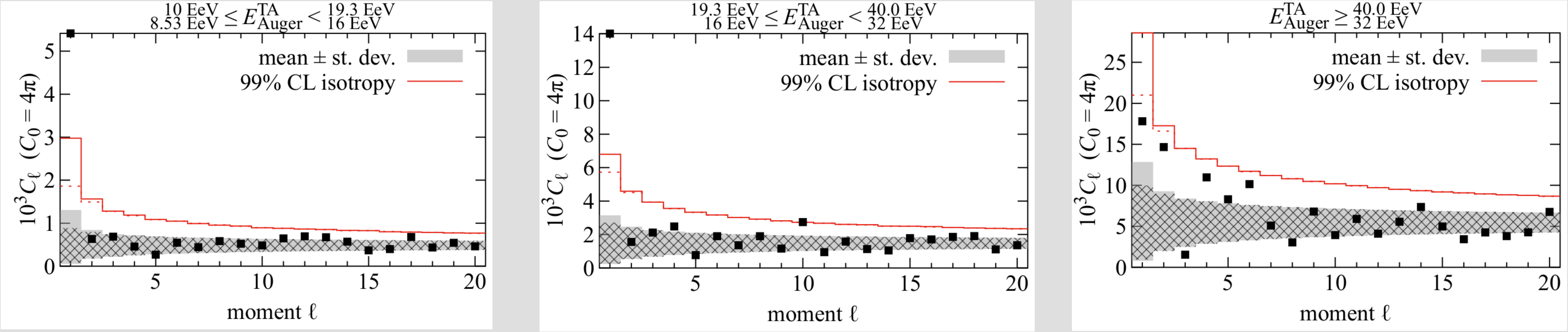
TA,
arXiv: 2406.08612

Large scale anisotropy in full sky: multipole analysis

Joint Auger + TA working group on UHECR anisotropy

Auger and TA @ UHECR-2024

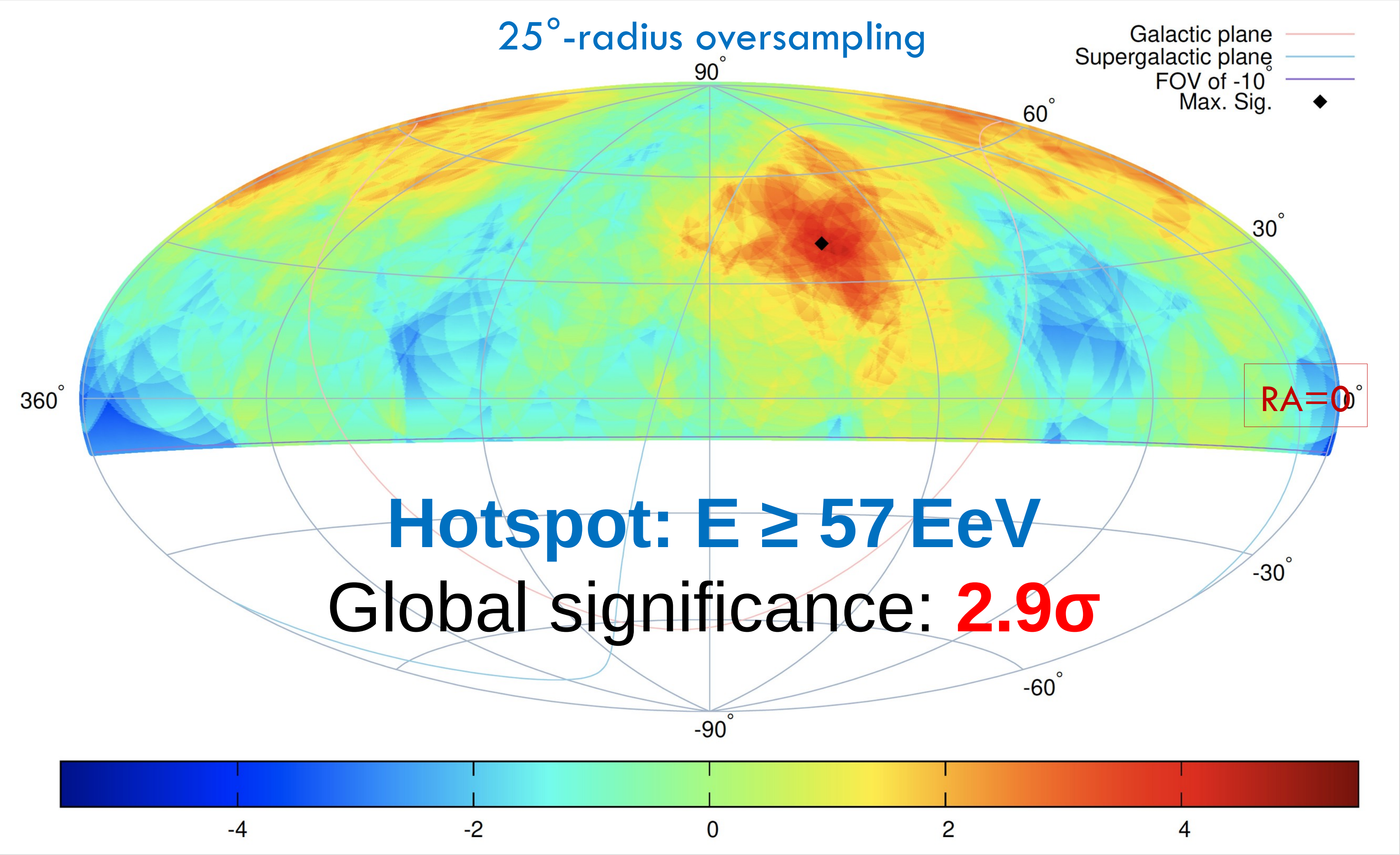




Dipole with ~5% amplitude and 4.6 σ is directed to outer Galaxy

Difference in dipole direction comparing to Auger only analysis (~90° at E > 30 EeV)

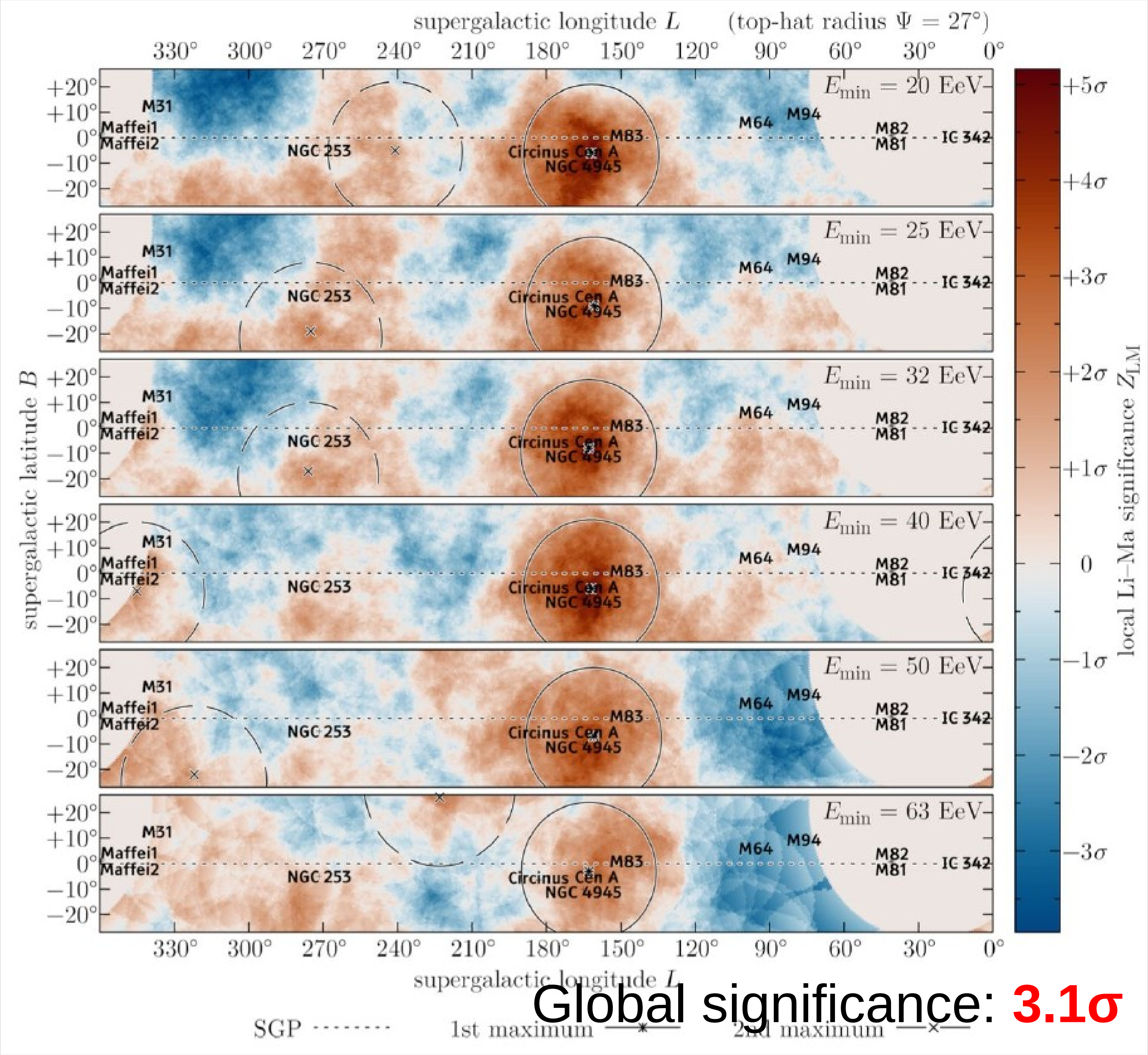
Medium scale anisotropy: search for overdensities



Hotspot: E ≥ 57 EeV

Global significance: **2.9σ**

TA @ ICRC-2025



Global significance: **3.1σ**

Auger, ApJ 984 (2025) 123

Correlation with separate classes of sources: 2-parameter TS

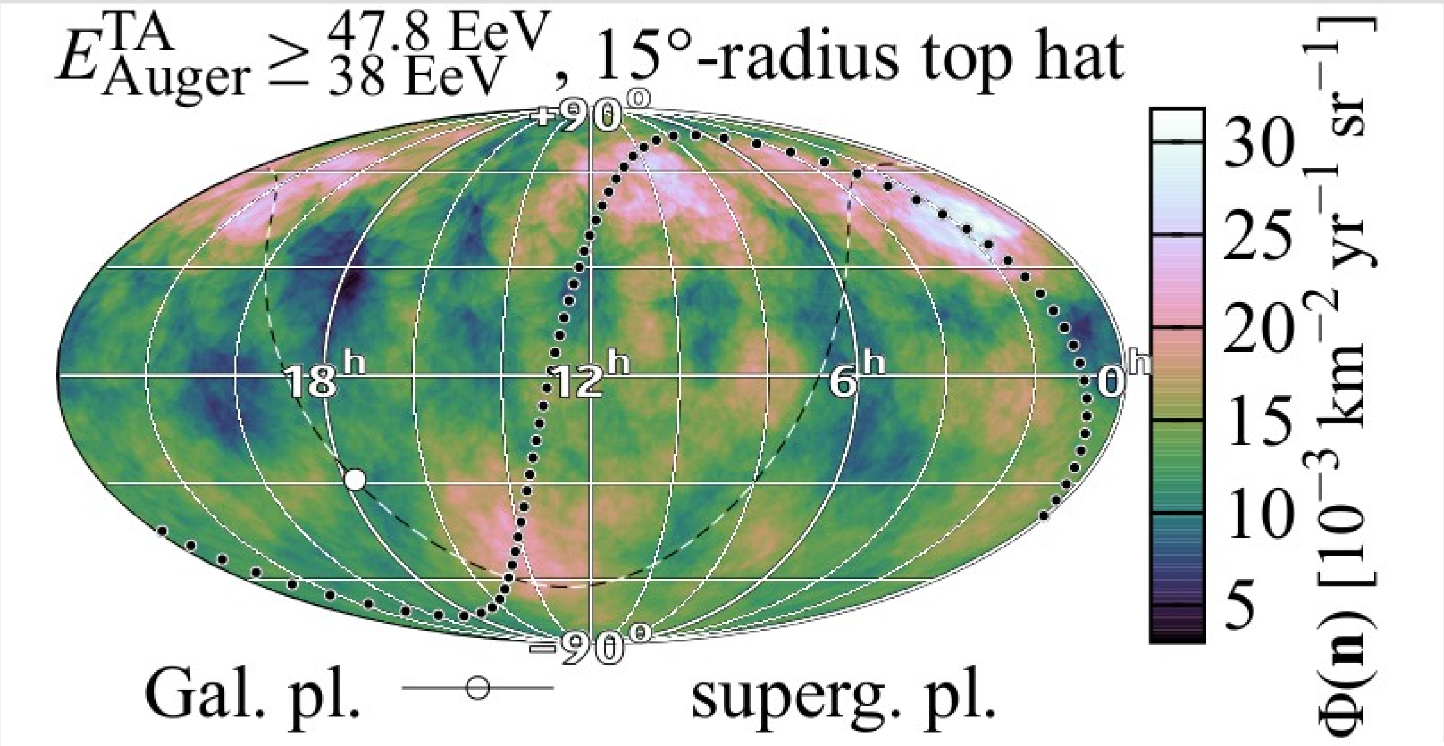
Joint Auger + TA working group on UHECR anisotropy

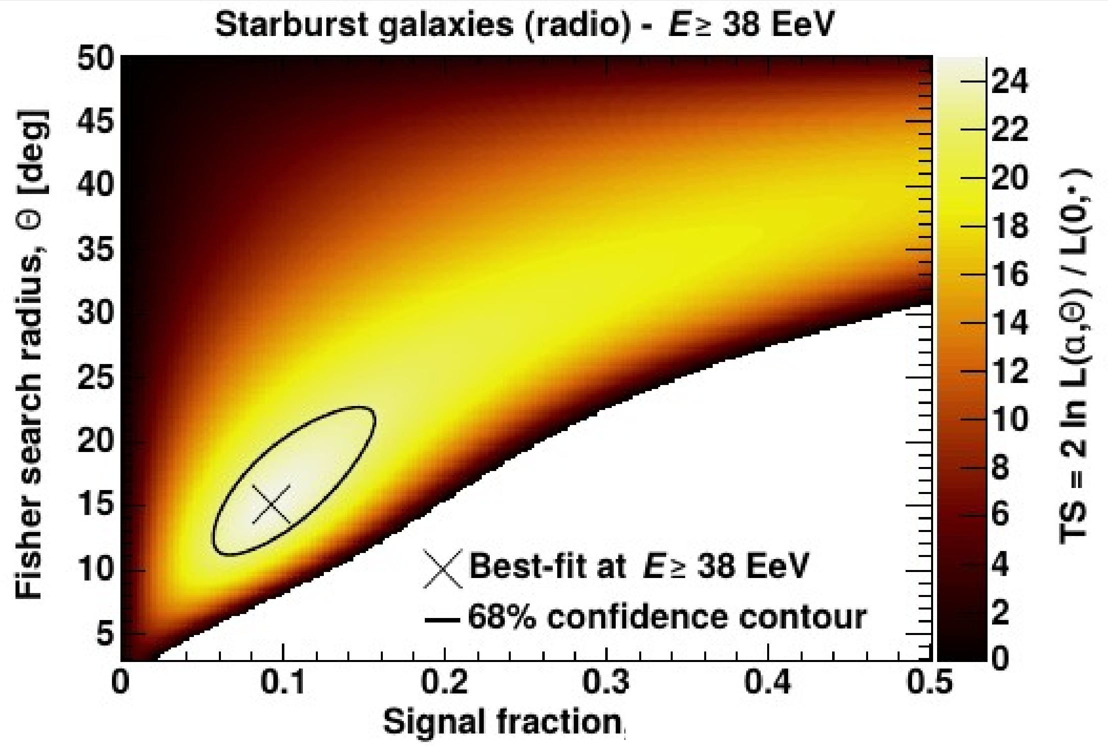
- Bulid catalog of sources: 2MRS, SBG

  (JCAP 10 (2019) 073)
- Compute an expected flux map
- Define test statistics with 2 parameters (smearing of sources and signal fraction) to quantify the correlation
- Compute TS for data set:

$$TS(f,\theta) = \sum_{\text{events}} \ln \frac{\Phi(f,\Theta,\mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)}$$

- Maximize TS over f and Θ





Correlation with all galaxies $1\,\text{Mpc} \leq D < 250\,\text{Mpc}$ (2MRS catalog)

dataset	$E^{\min}_{\text{Auger}}$	$E^{\min}_{\text{TA}}$	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$(19^{+15}_{-7})^\circ$	$(25^{+24}_{-10})\,\%$	14.7	2.8σ
UHECR 2024	37 EeV	46.5 EeV	$(26^{+13}_{-15})^\circ$	$(30^{+26}_{-17})\,\%$	13.5	2.6σ

Auger and TA @ UHECR-2024

Correlation with starburst galaxies $1\,\text{Mpc} \leq D < 130\,\text{Mpc}$ (Lunardini+ '19 catalog)

dataset	$E^{\min}_{\text{Auger}}$	$E^{\min}_{\text{TA}}$	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$(15.4^{+5.2}_{-3.0})^\circ$	$(11.7^{+4.7}_{-2.9})\,\%$	30.5	4.6σ
UHECR 2024	38 EeV	47.8 EeV	$(15.0^{+5.0}_{-2.9})^\circ$	$(11.1^{+4.4}_{-2.8})\,\%$	29.5	4.4σ

Correlation with separate classes of sources: 1-parameter TS

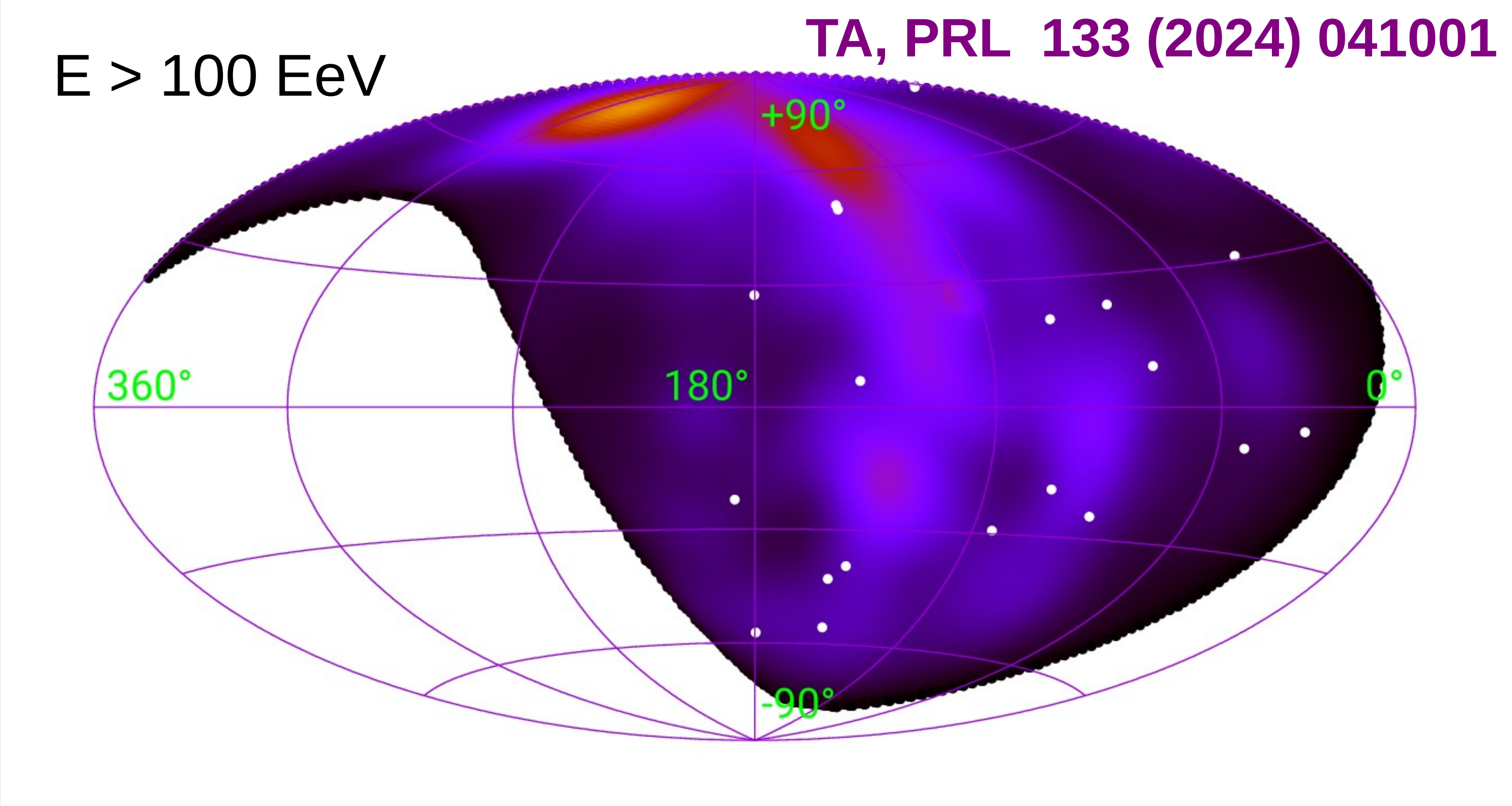
Mostly similar to previous:

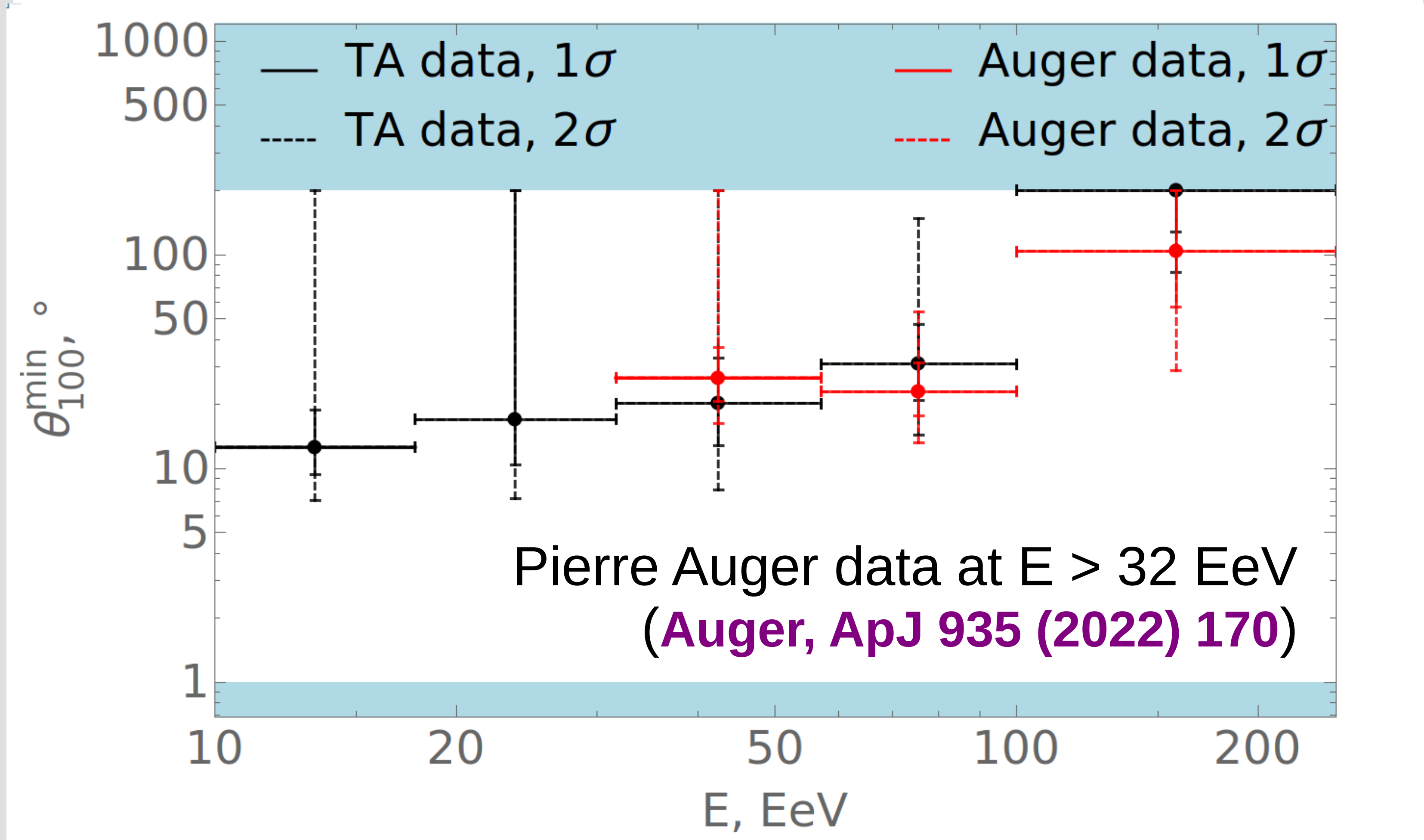
- Use catalog of LSS sources (based on 2MRS)
- Compute an expected flux map
- Define 1-parameter (smearing of sources) test statistics to quantify the correlation
- Compute TS for data set

$$TS(\theta) = -2 \sum_k \left(\sum_i \ln \frac{\Phi_k(\theta, \mathbf{n}_i)}{\Phi_{\mathrm{iso}}(\mathbf{n}_i)} \right)$$

- Maximize TS over θ

Both TA and Auger:
~2σ correlation with LSS at 57 < E < 100 EeV
Complete isotropy at E > 100 EeV

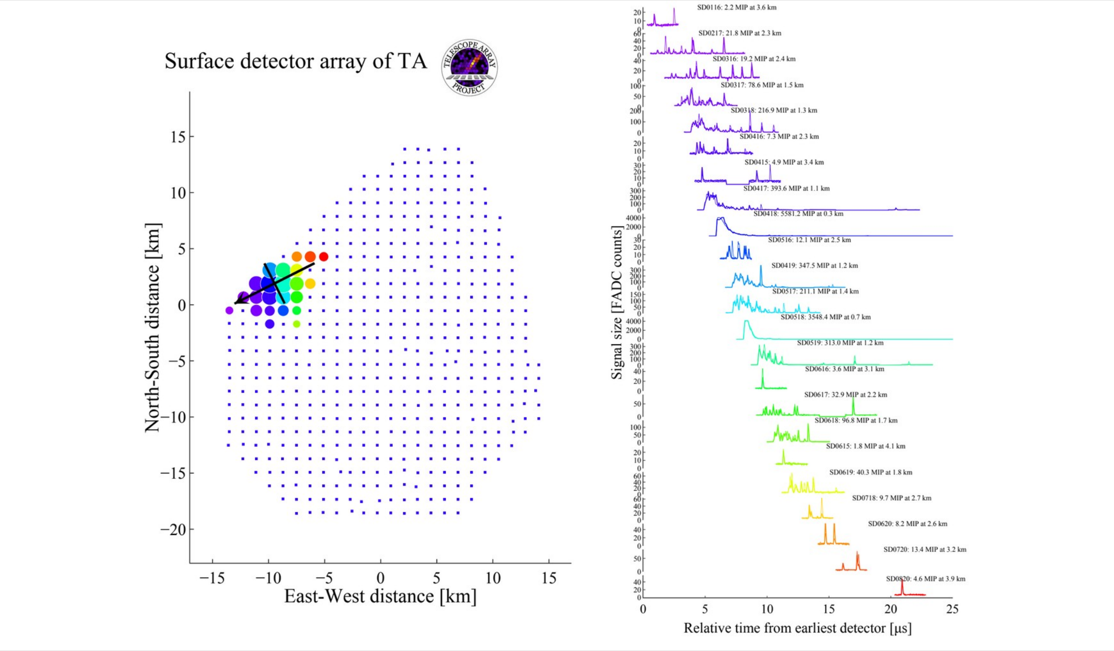


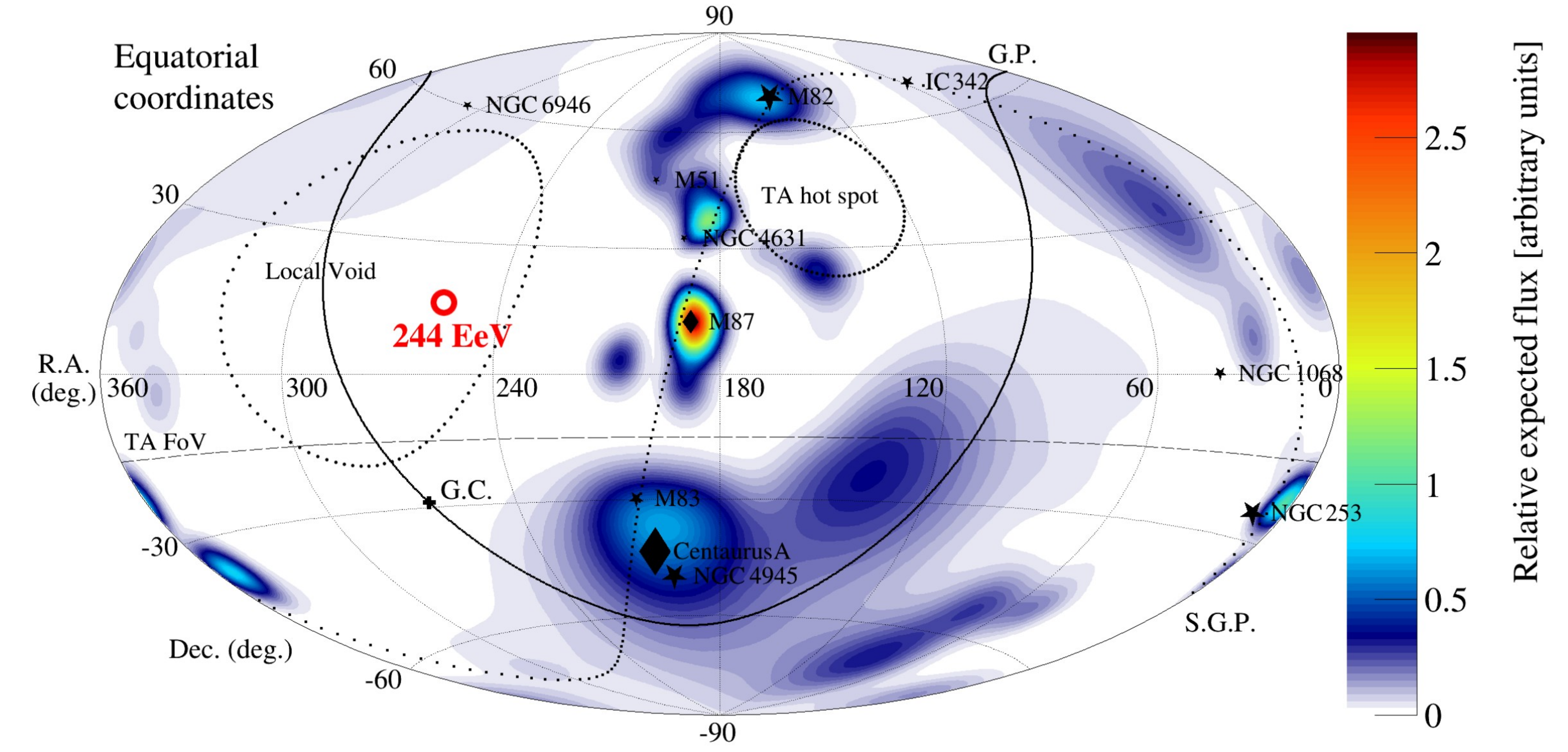


Particle with second highest energy ever (aka Amaterasu)

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±0.4°	206.8±0.6°	255.9±0.6°	16.1±0.5°

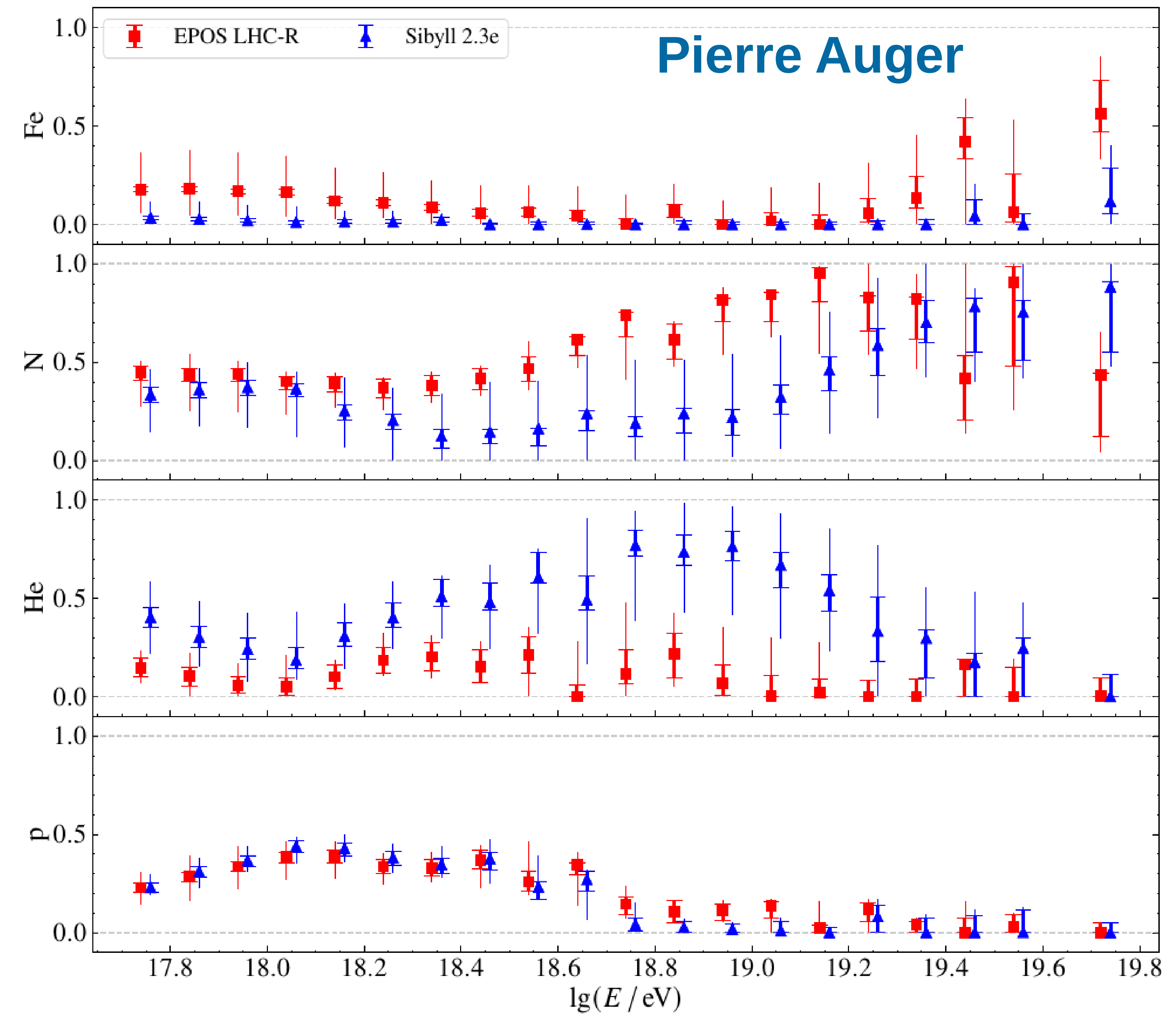
- Uncorrelated with LSS (like other events at E > 100 EeV)
- Not a gamma-ray: 3.8 σ exclusion using neural net





UHECR mass composition

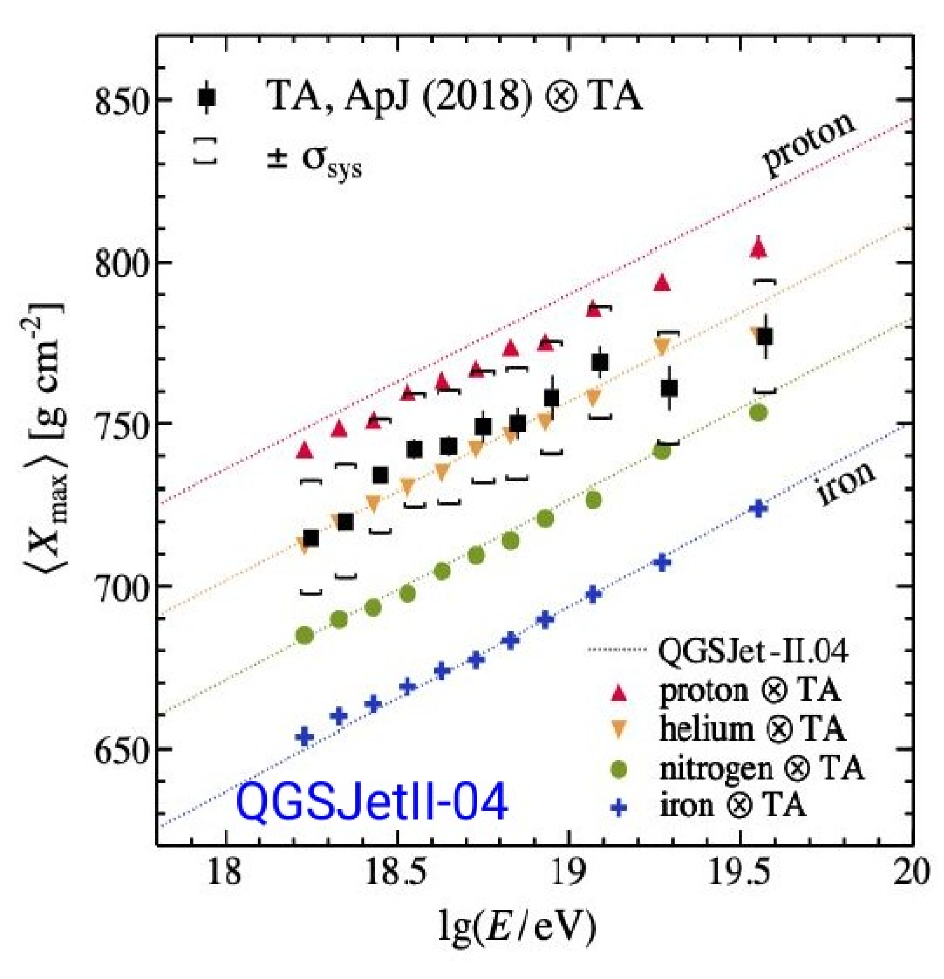
Mass composition is a key parameter for interpretation of anisotropy measurements

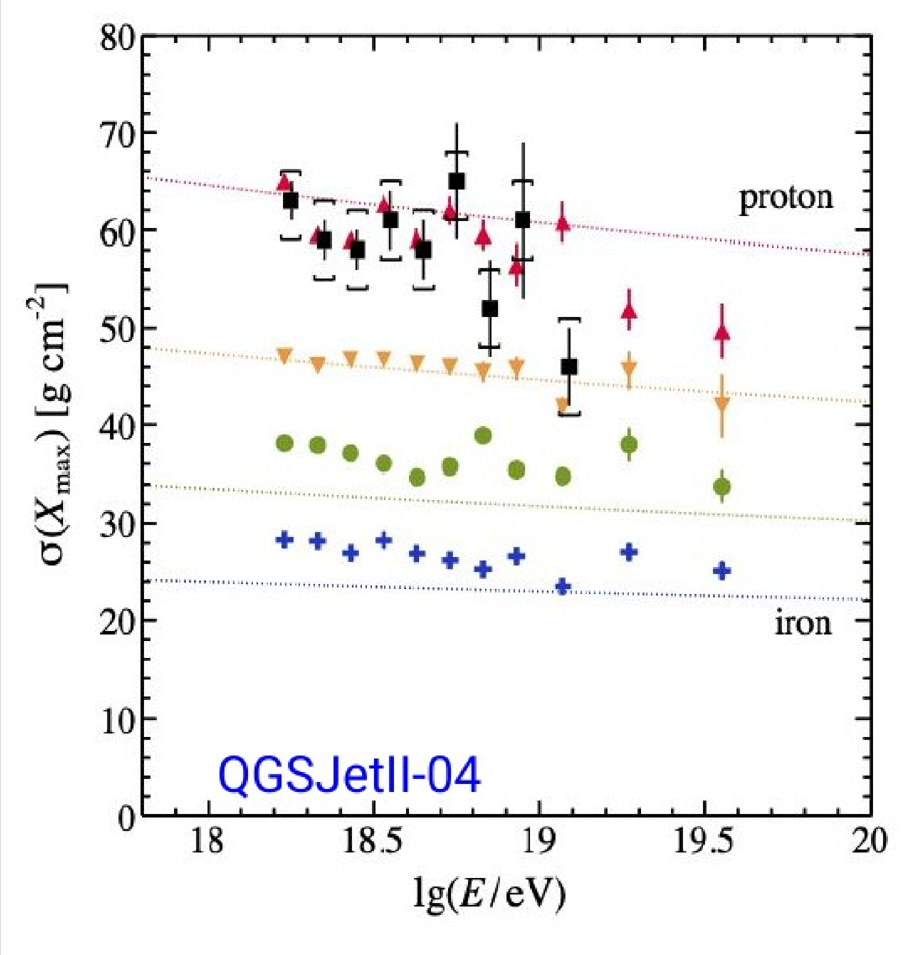


But

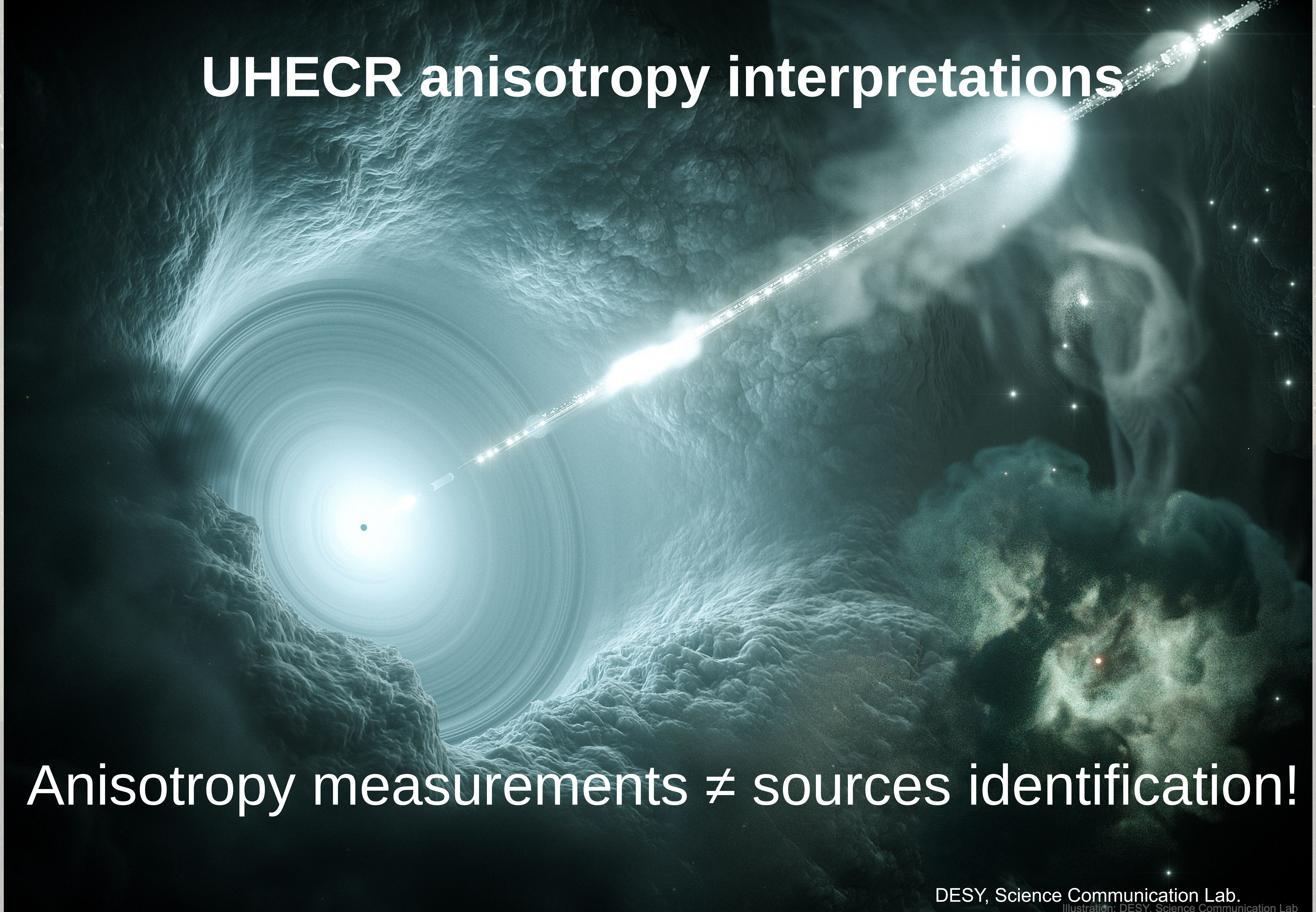
- There is a large systematic due to EAS modeling, especially hadronic interaction models
- Results of TA and Auger are different (studies in the joint working group are not finished)

Telescope Array





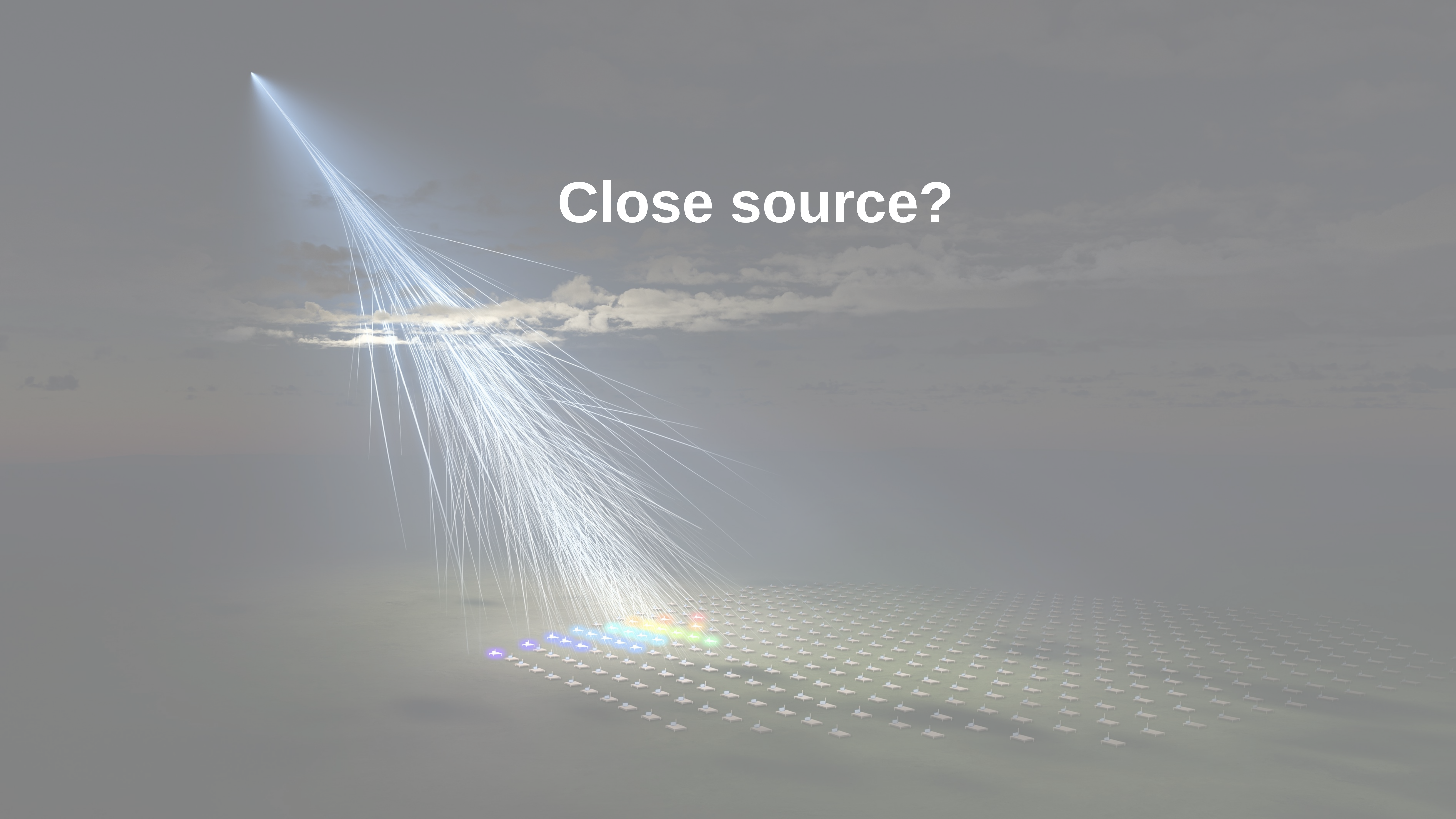
UHECR anisotropy interpretations



Anisotropy measurements ≠ sources identification!

DESY, Science Communication Lab.

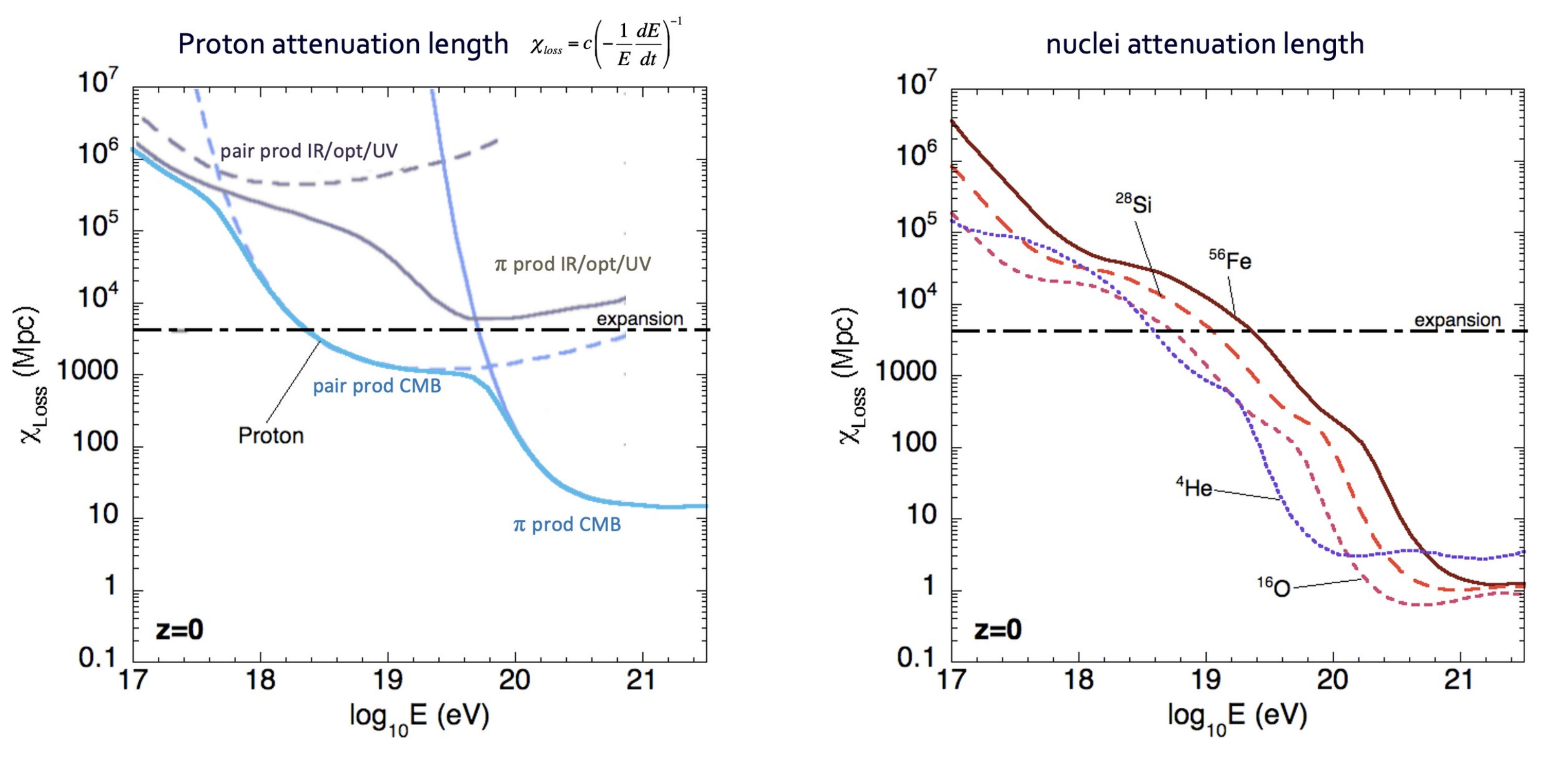
Close source?

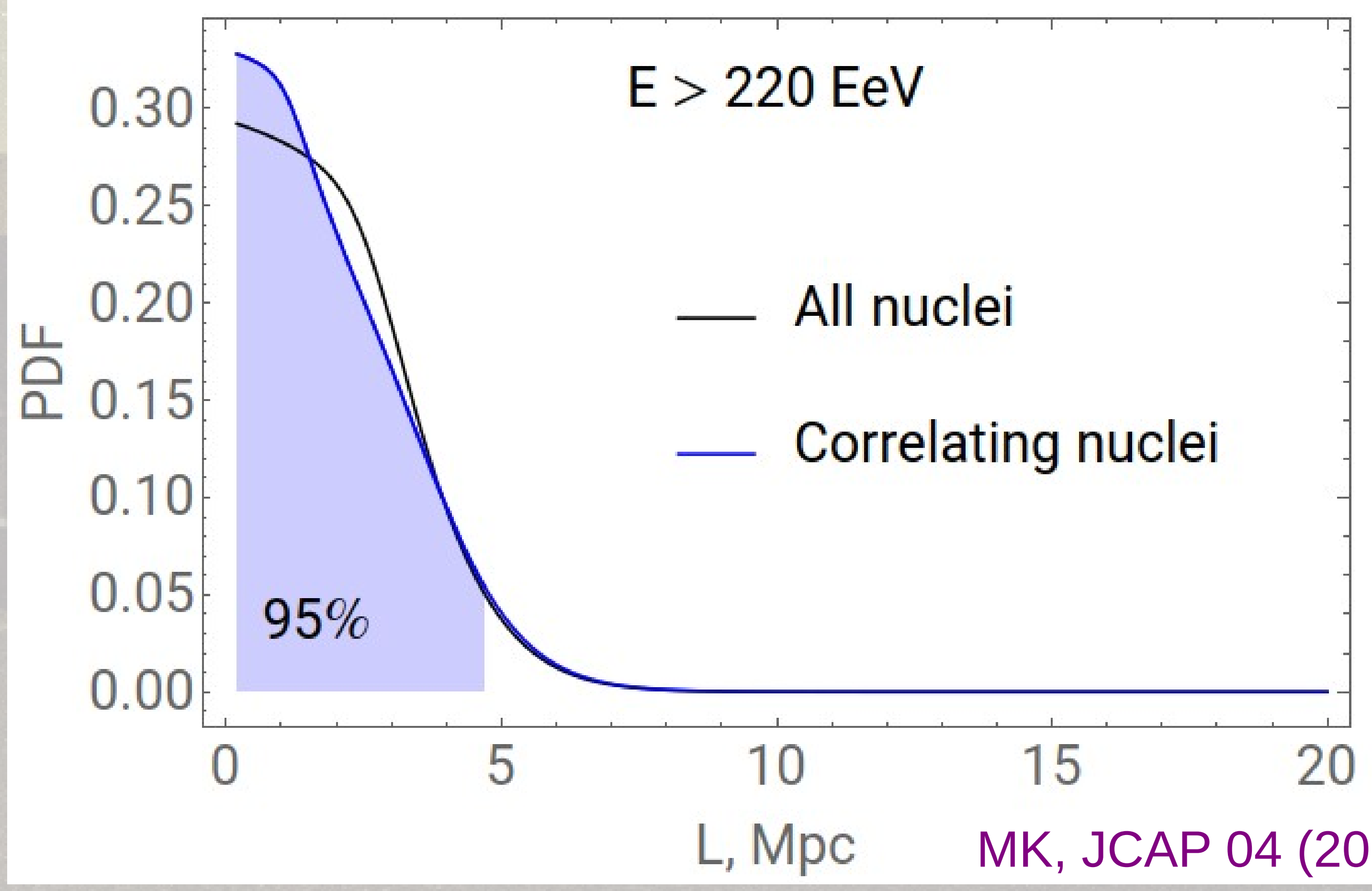


Distance to the source of extreme particle

- The source of the extreme energy particle should be close due to GZK-effect
- Conservatively assume that source emits iron nuclei
- The lightest nucleus that correlates with any galaxy is phosphorus (Z = 15)
- Compute the distance where 95% of the flux originates

- **In conservative scenario (E = 220 EeV, strong EGMF):**
  the source is not farther than 4.7 Mpc at 95% C.L.
  (13.4 Mpc for systematically shifted energy)





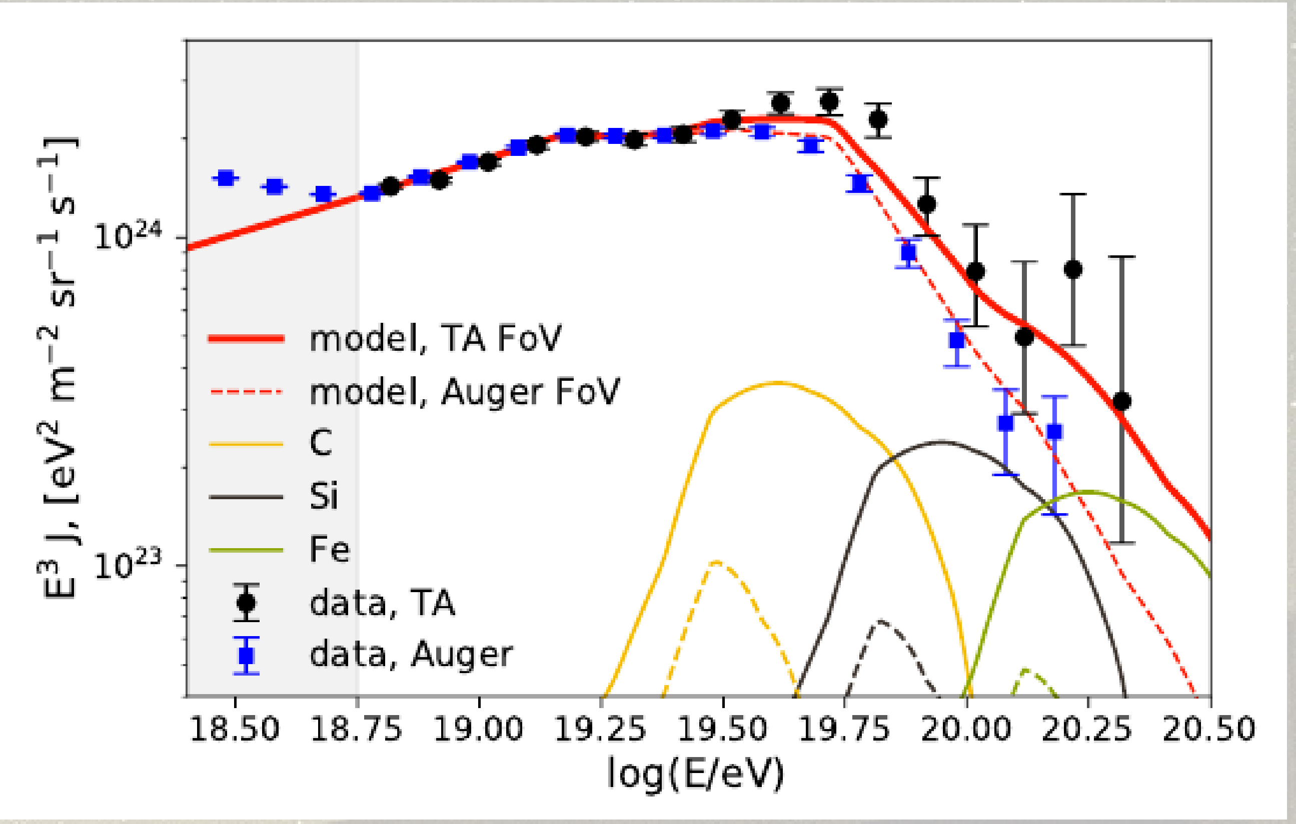
MK, JCAP 04 (2024) 042

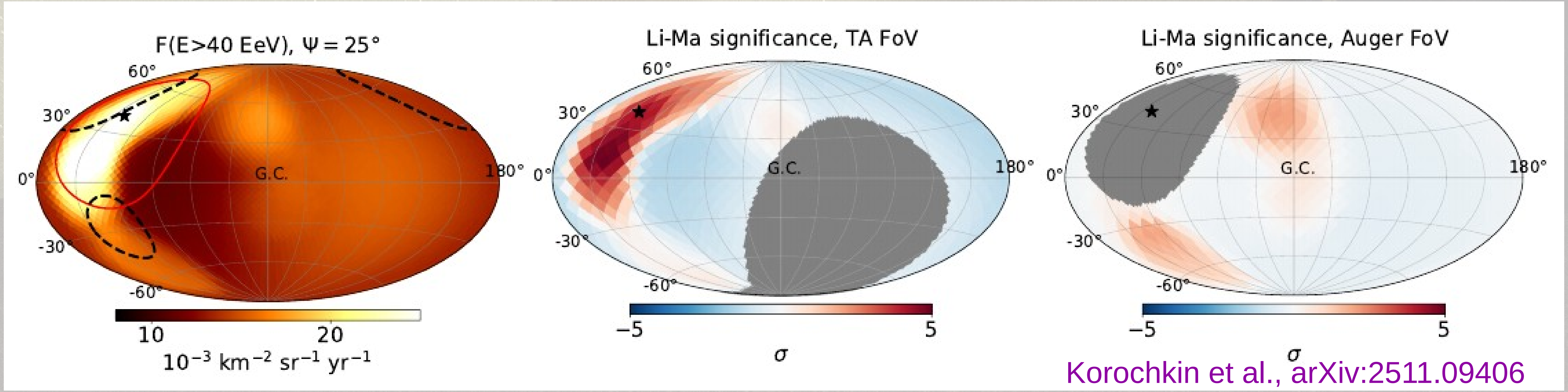
Close source as explanation for TA-Auger discrepancy

Assume close (extragalactic) source on top of dipole flux from distant sources

Varying its position it is possible to:

- reproduce hot-spot visible for TA but not for Auger
- reproduce hard injected spectrum and medium composition visible by Auger
- alleviate the tension between TA and Auger spectrum at highest energies
- reproduce the shift of dipole direction between Auger-alone and TA-Auger



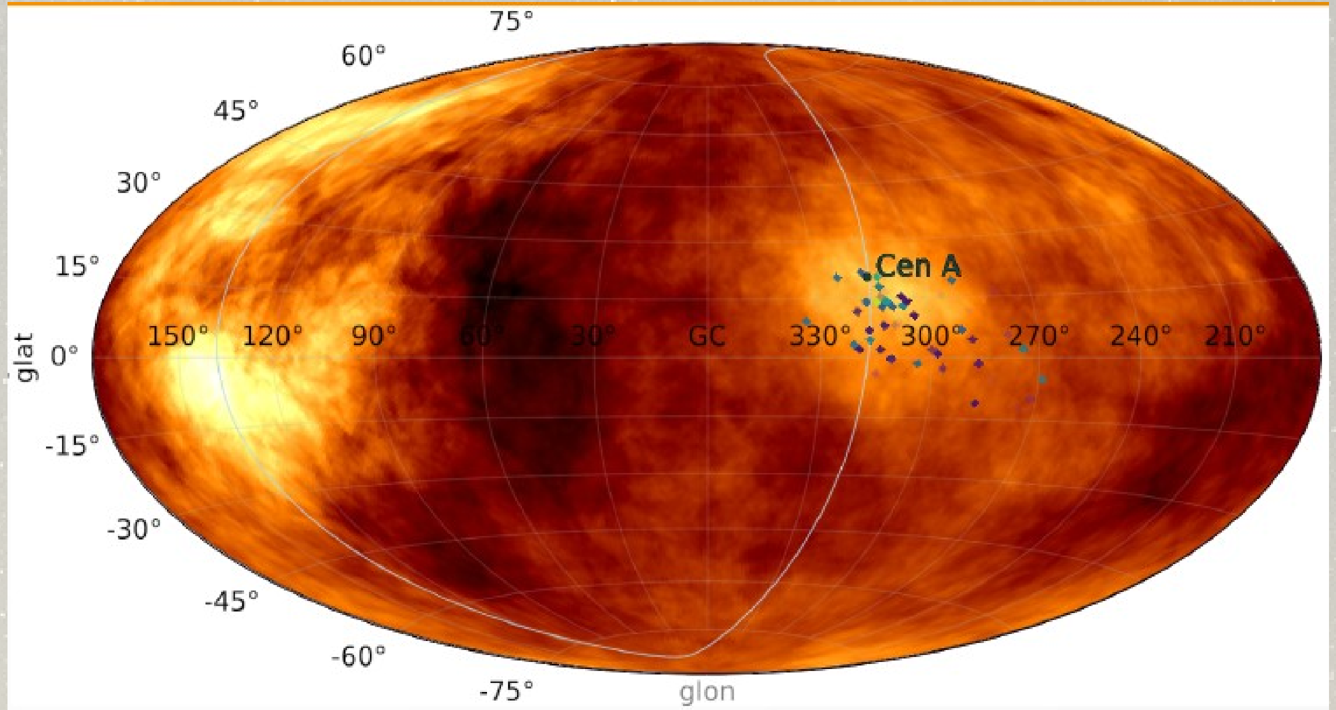


Korochkin et al., arXiv:2511.09406

Location and identification of possible close UHECR source(s)

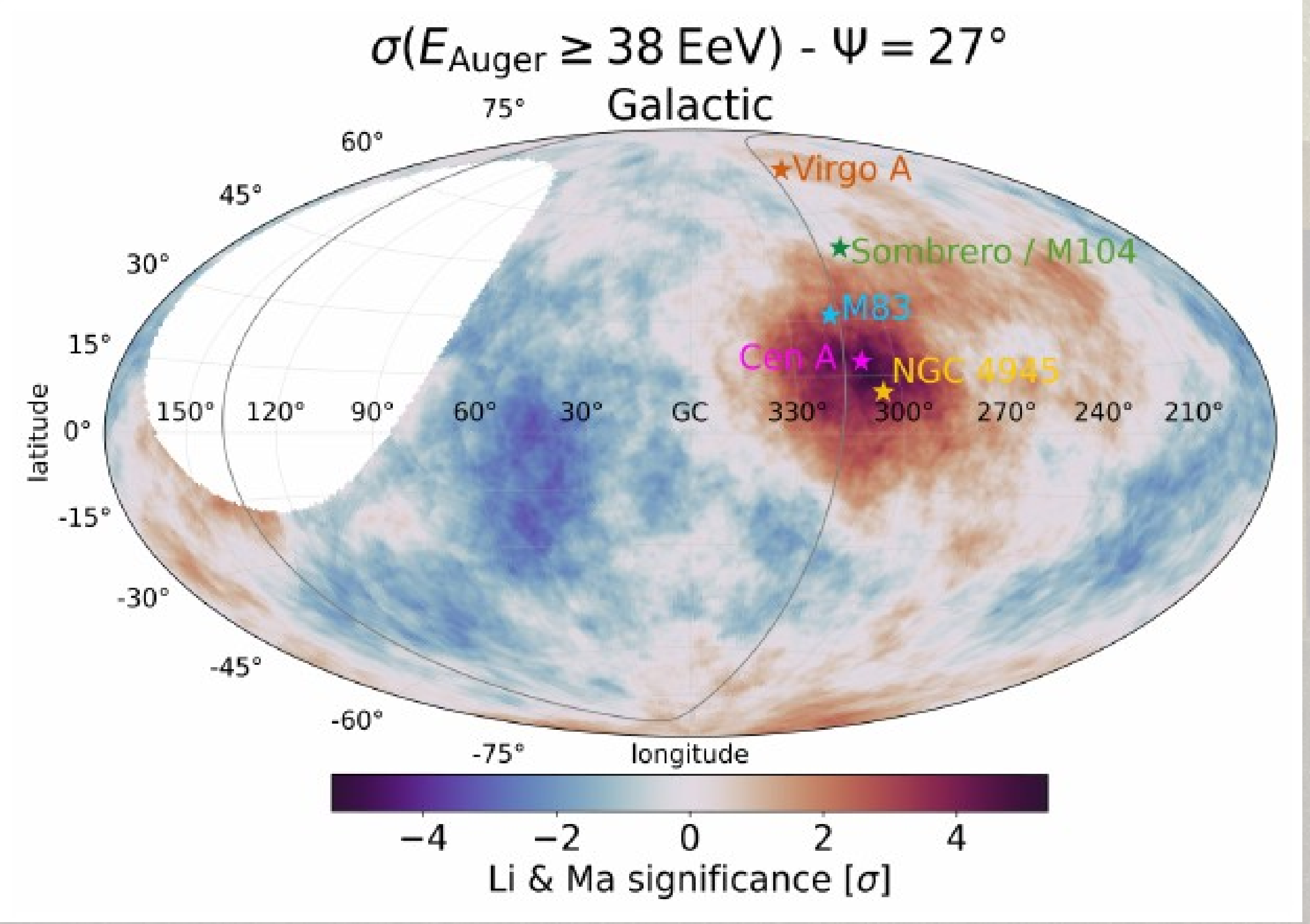
Difficult to decipher the real source from the image:

- Cen A hot-spot is reproducible in scenarios with various sources (Cen A, NGC4945, M83, Sombrero)
- Result depends on UHECR composition and magnetic field models



Carbon nuclei with E = 60 EeV
from Cen A
B=3 nG
Lc=0.3 Mpc
GMF in JF12 model

Dolgikh et. al, IJMPA 40 (2025) 2540012



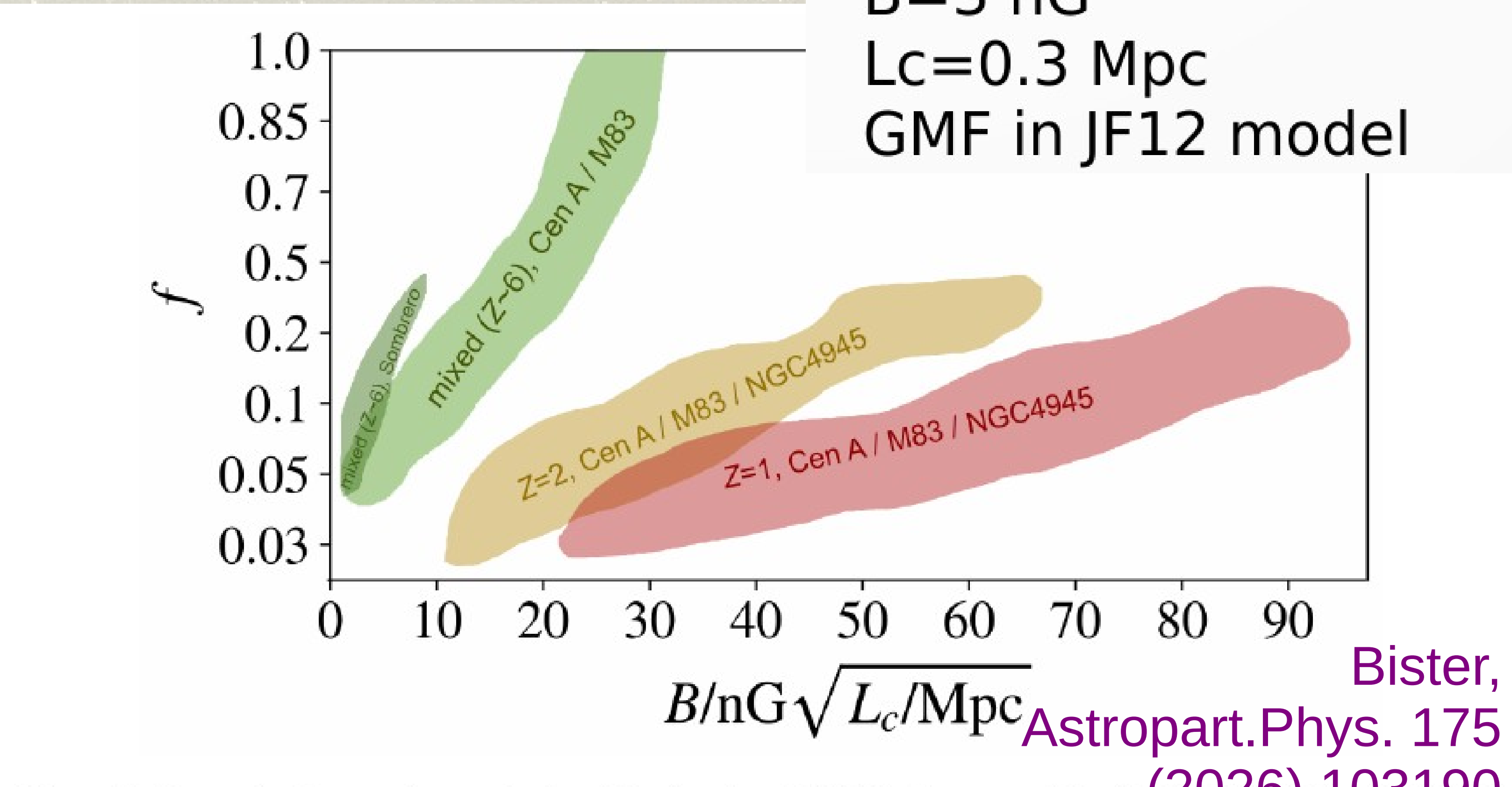
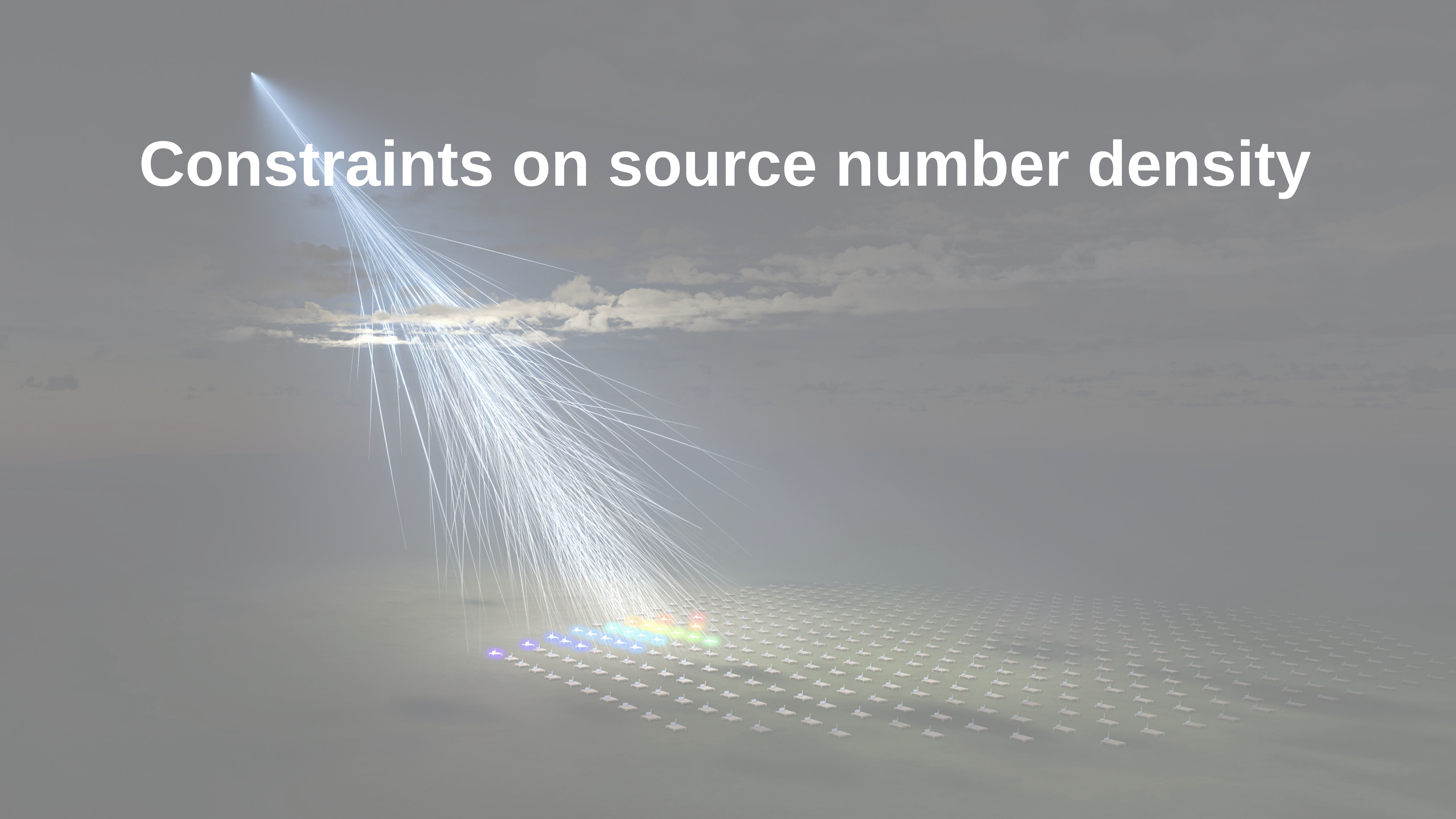


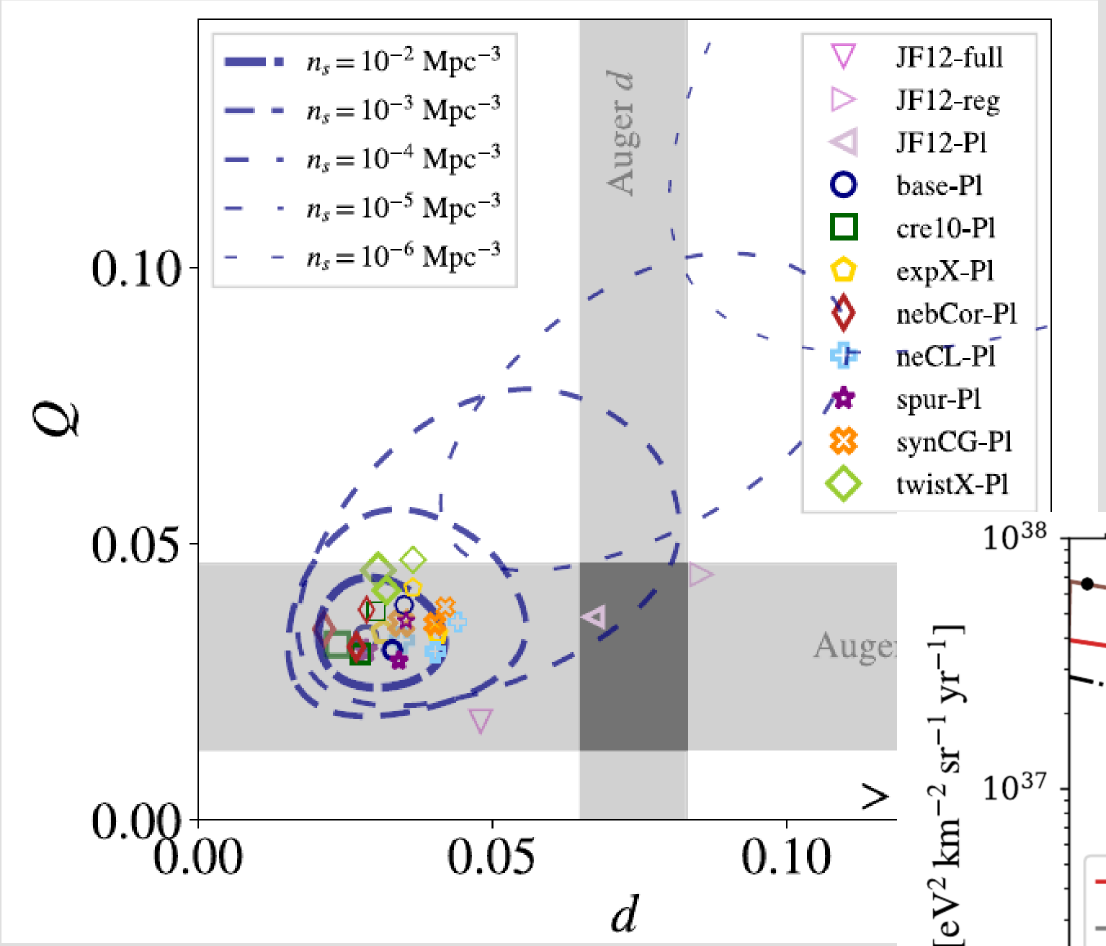
Figure 13: Summarized constraints on the signal fraction f and EGMF to be compatible with the UHECR data $\gtrsim$ 30 EeV.

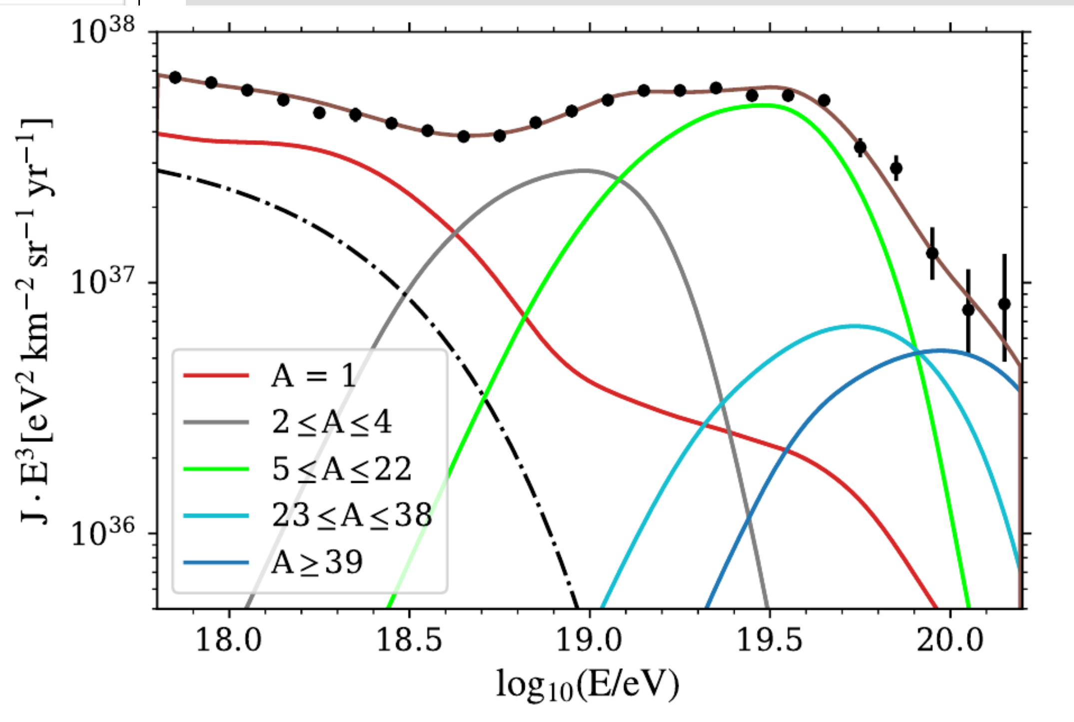
Bister, Astropart.Phys. 175 (2026) 103190

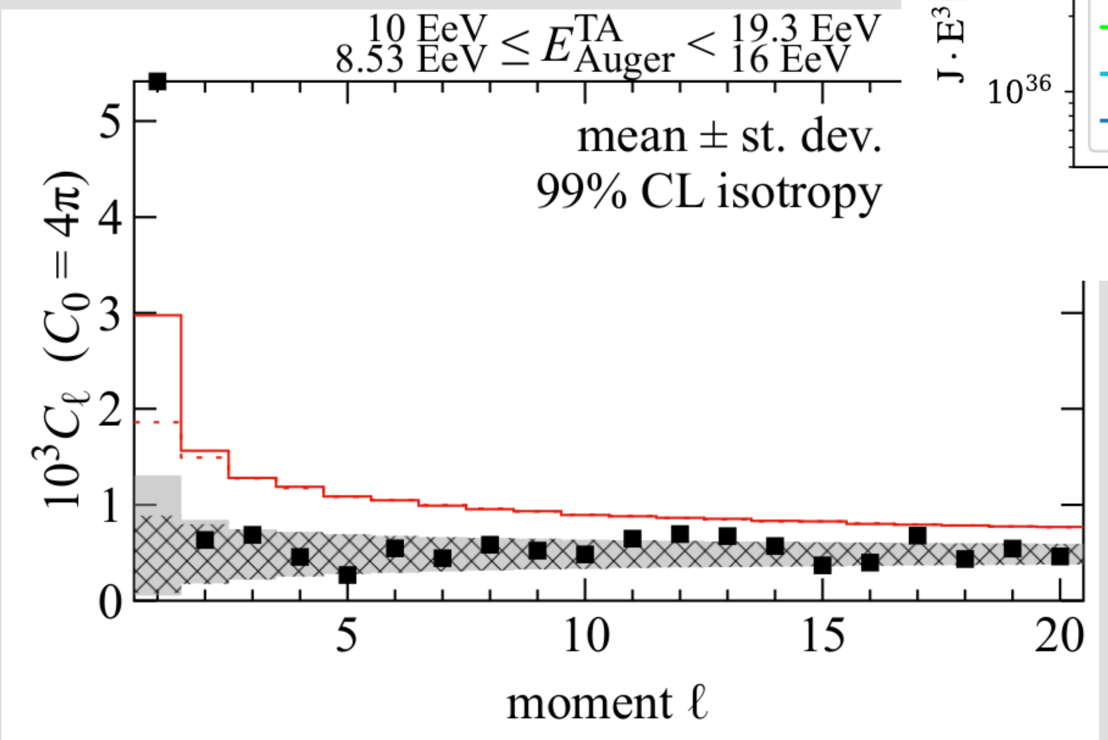
Constraints on source number density



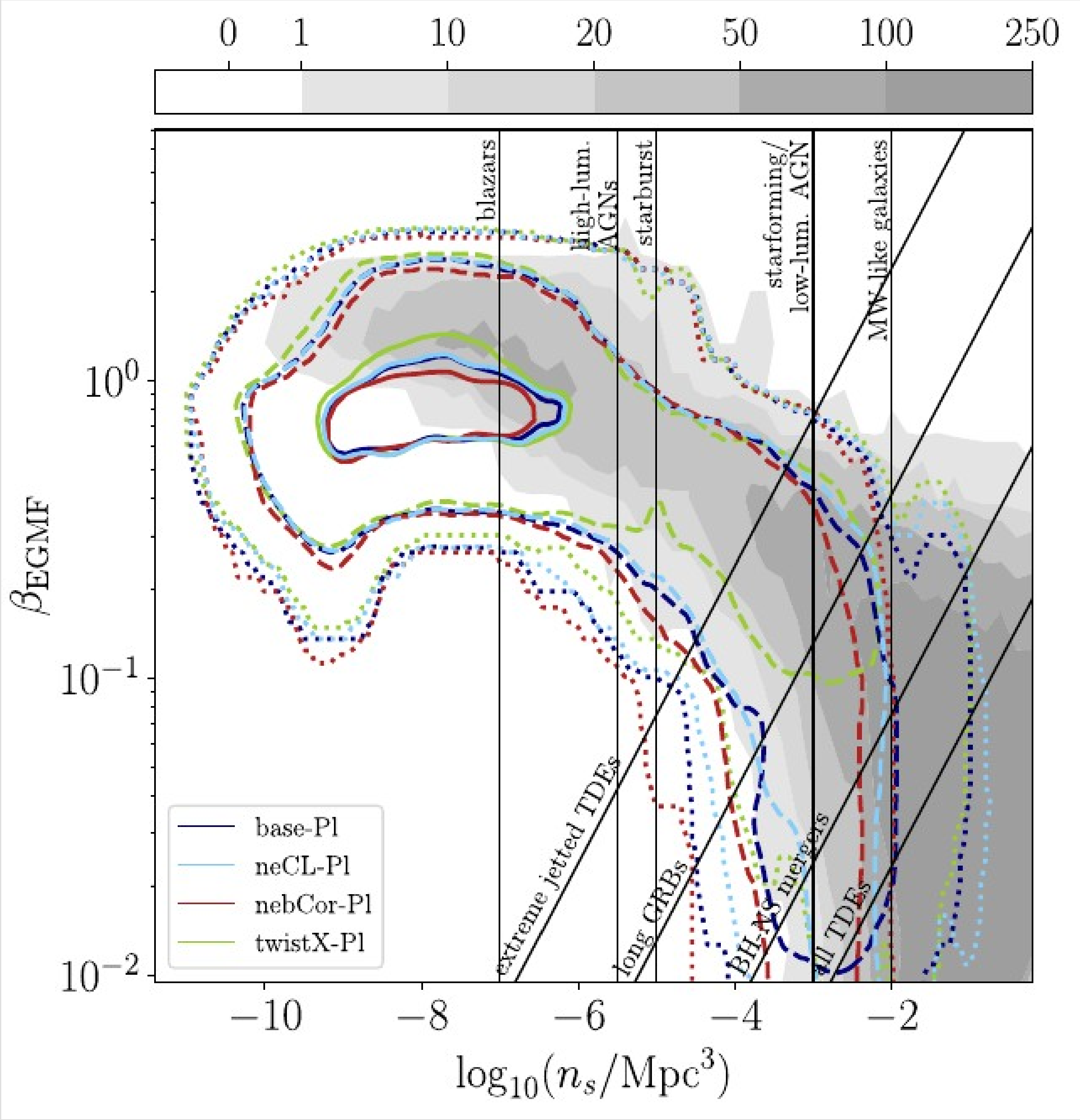
Constraints of source number density from multipole anisotropy







Bister et al., ApJL 975 (2024) 21



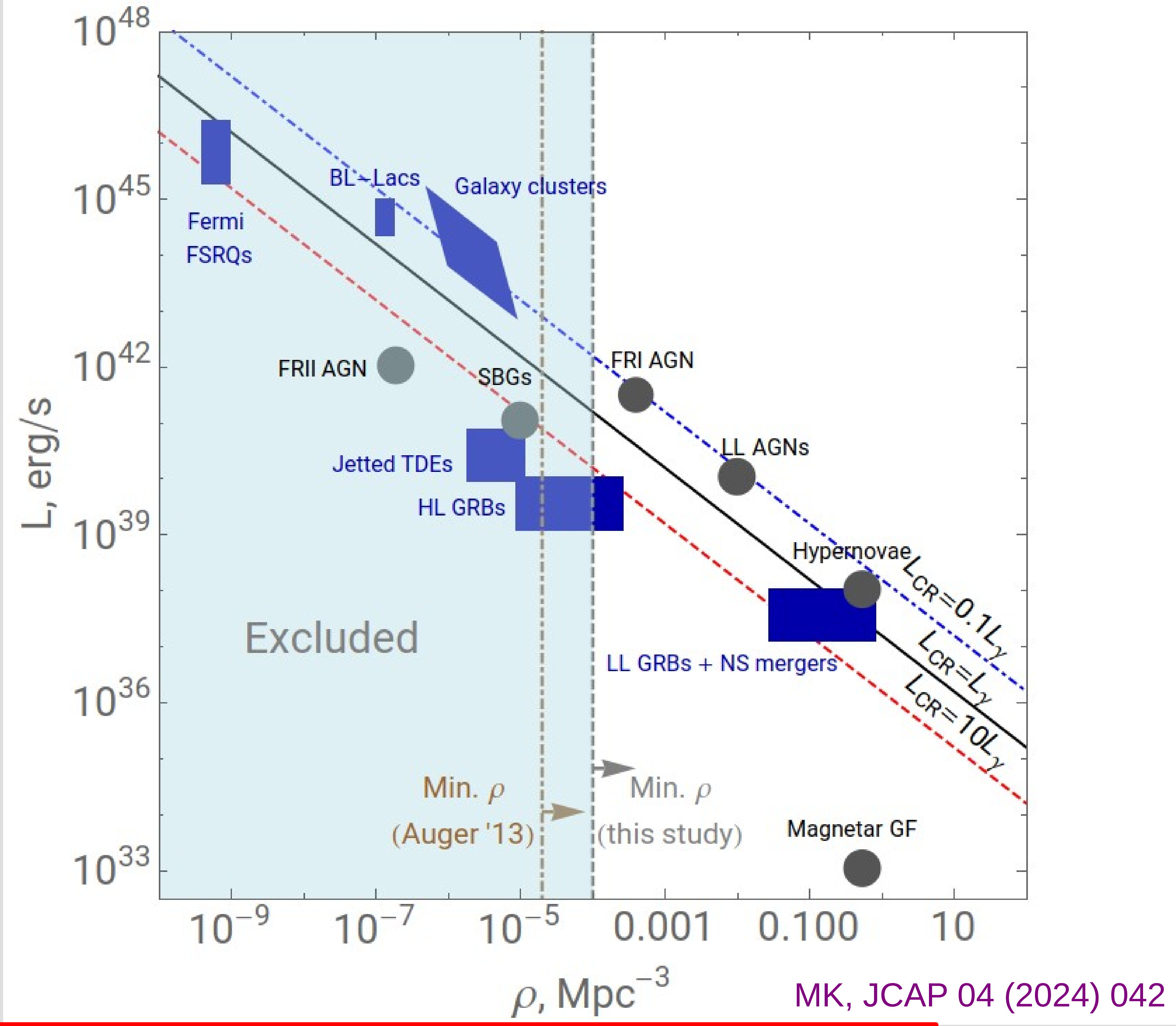
$$\beta_{\mathrm{EGMF}} = B/\mathrm{nG}\sqrt{\lambda_c/\mathrm{Mpc}}$$

Results strongly depends on:

- GMF model
- Composition assumption (Auger X_{max})

Constraints on source number density and source classes from highest energy particle

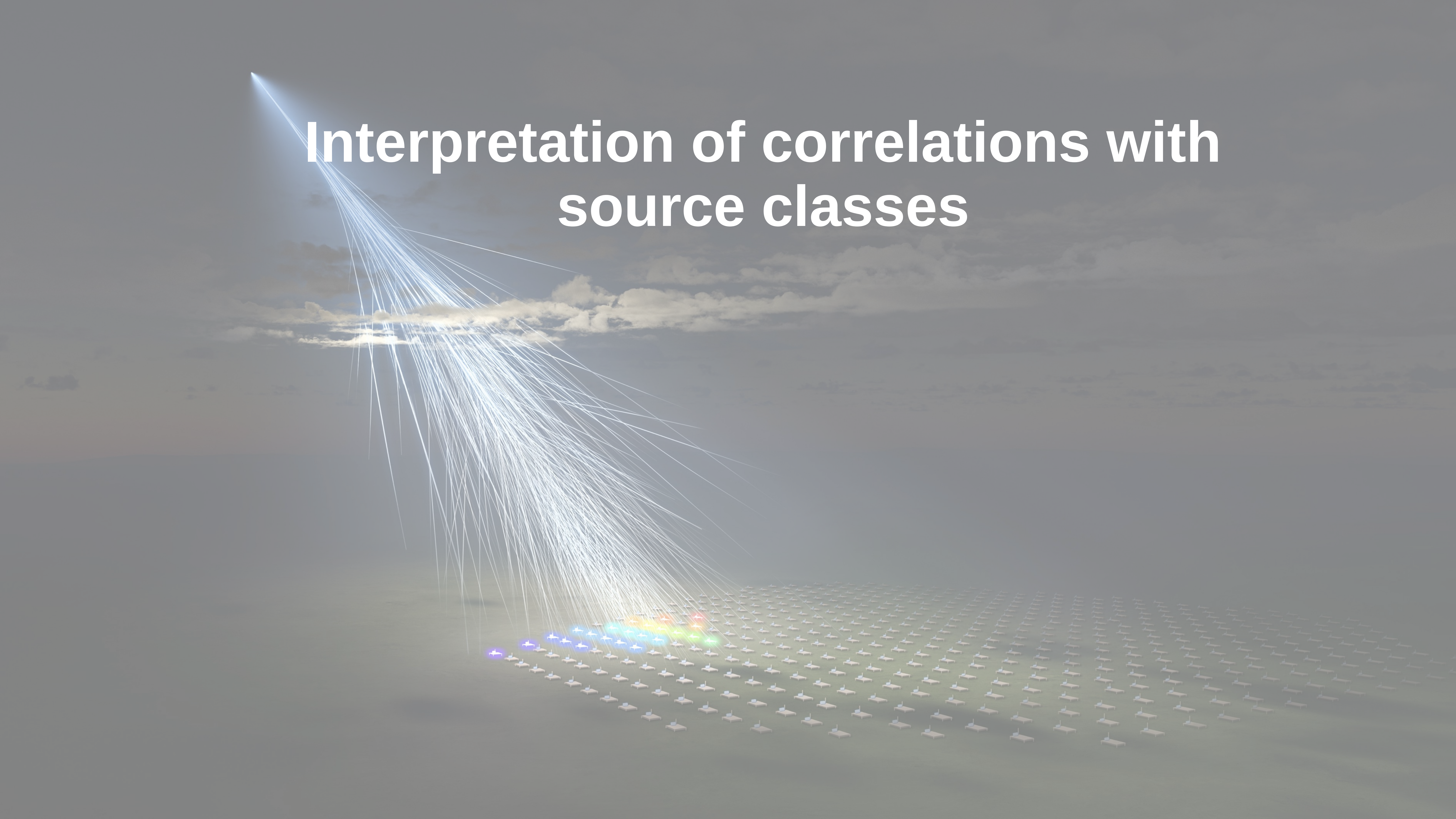
- First conservative constraints on source number density
- Does not depend on assumptions about GMF and EGMF
- Some classes of source are excluded as main sources of UHECR
- Some classes are allowed, including transients



MK, JCAP 04 (2024) 042

D < 5.0 Mpc ⇒ $\rho > 1.0 \cdot 10^{-4}$ Mpc^{-3}

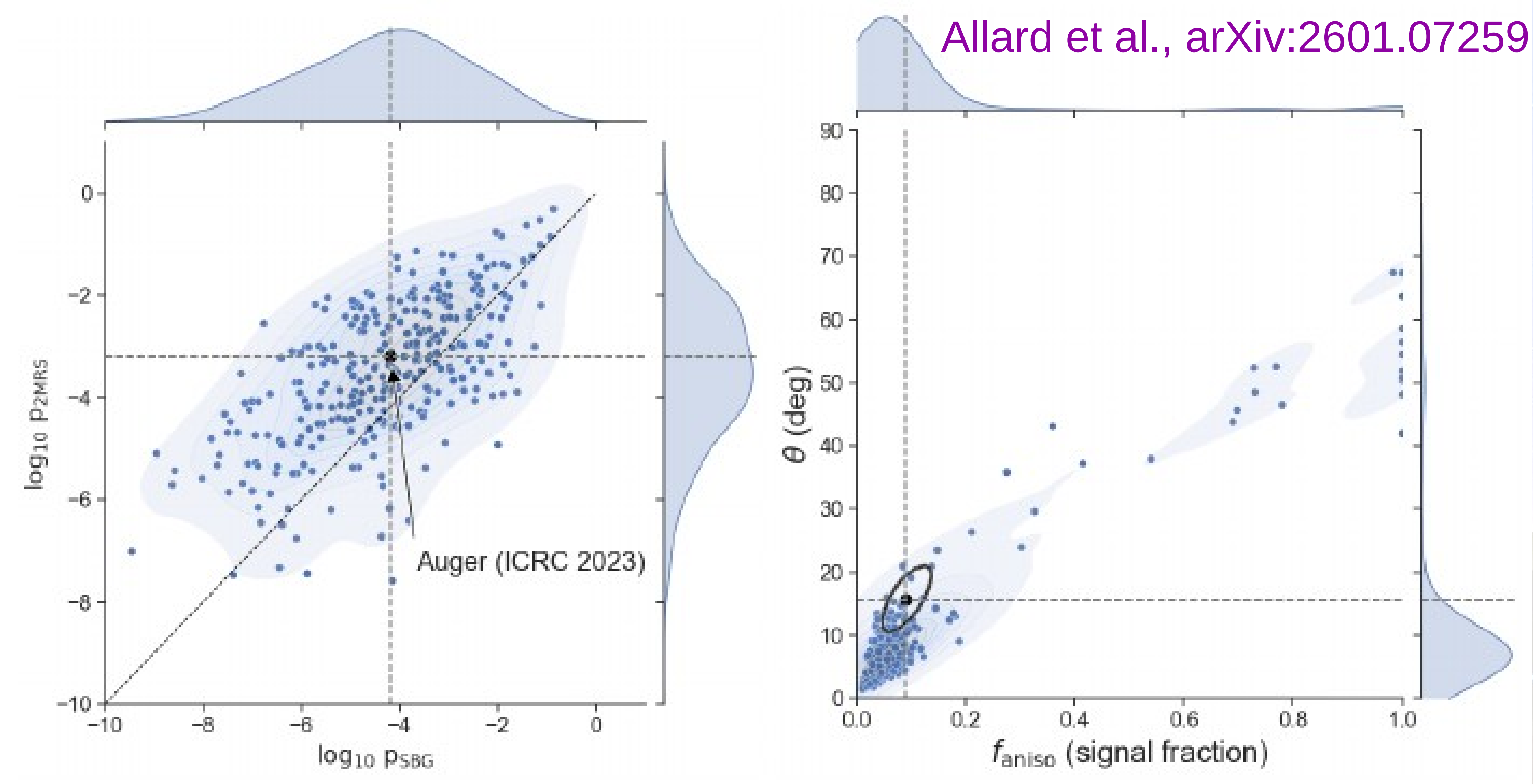
Interpretation of correlations with source classes



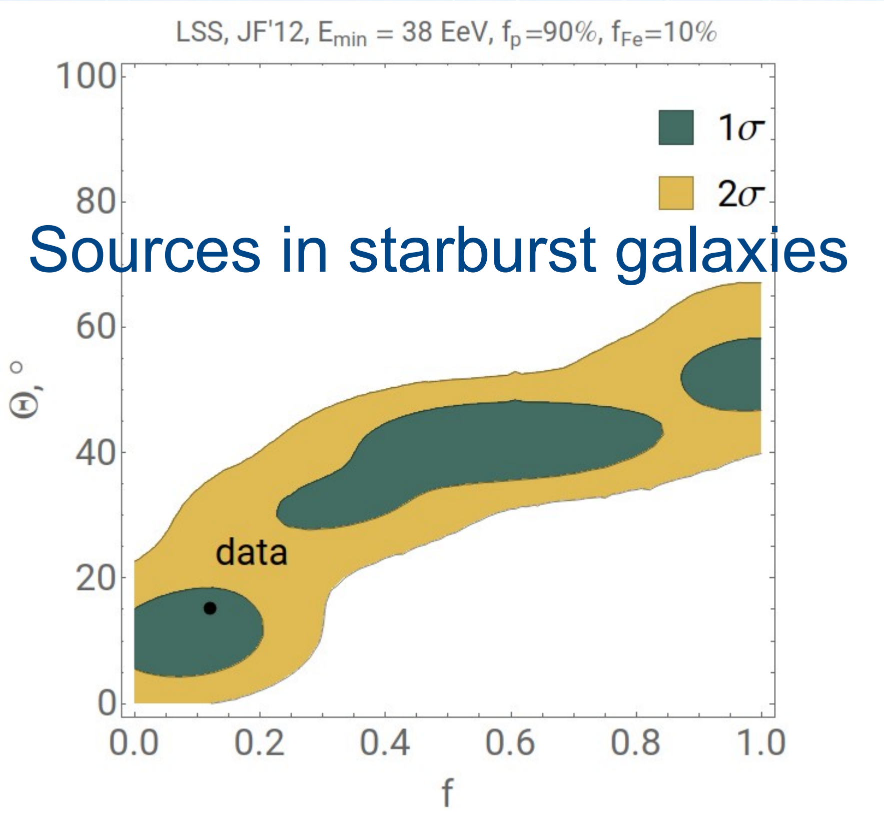
Interpretation of UHECR correlation with source classes

- Assume sources either in LSS or in SBG and various injected composition models
- Generate Monte-Carlo sets
- Apply TS-analysis for SBG correlation

Allard et al., arXiv:2601.07259

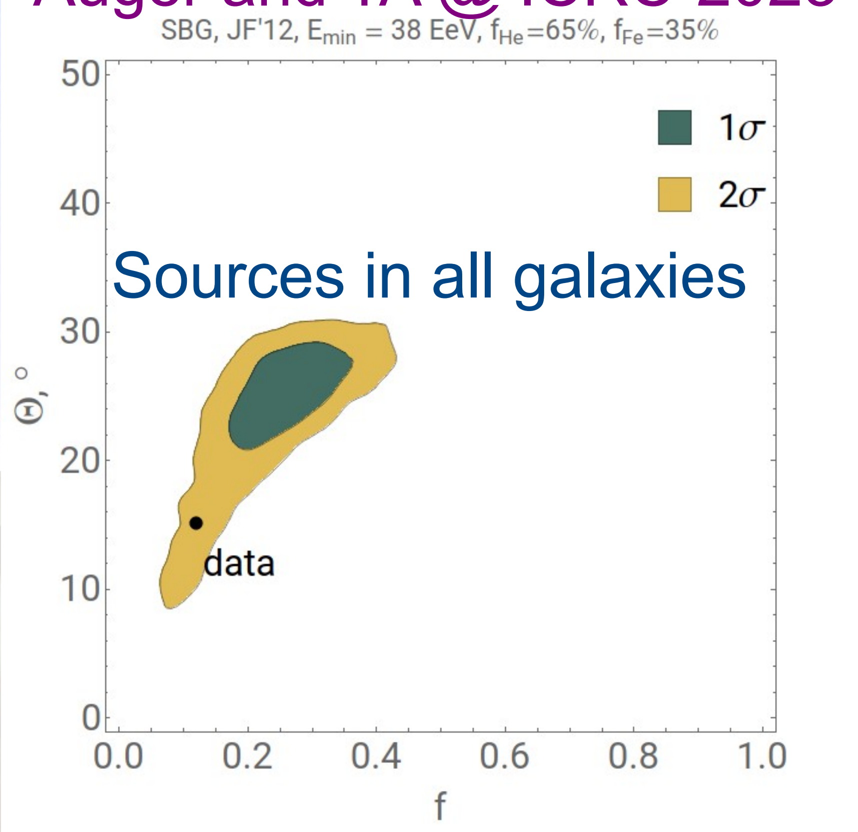


Sources in starburst galaxies



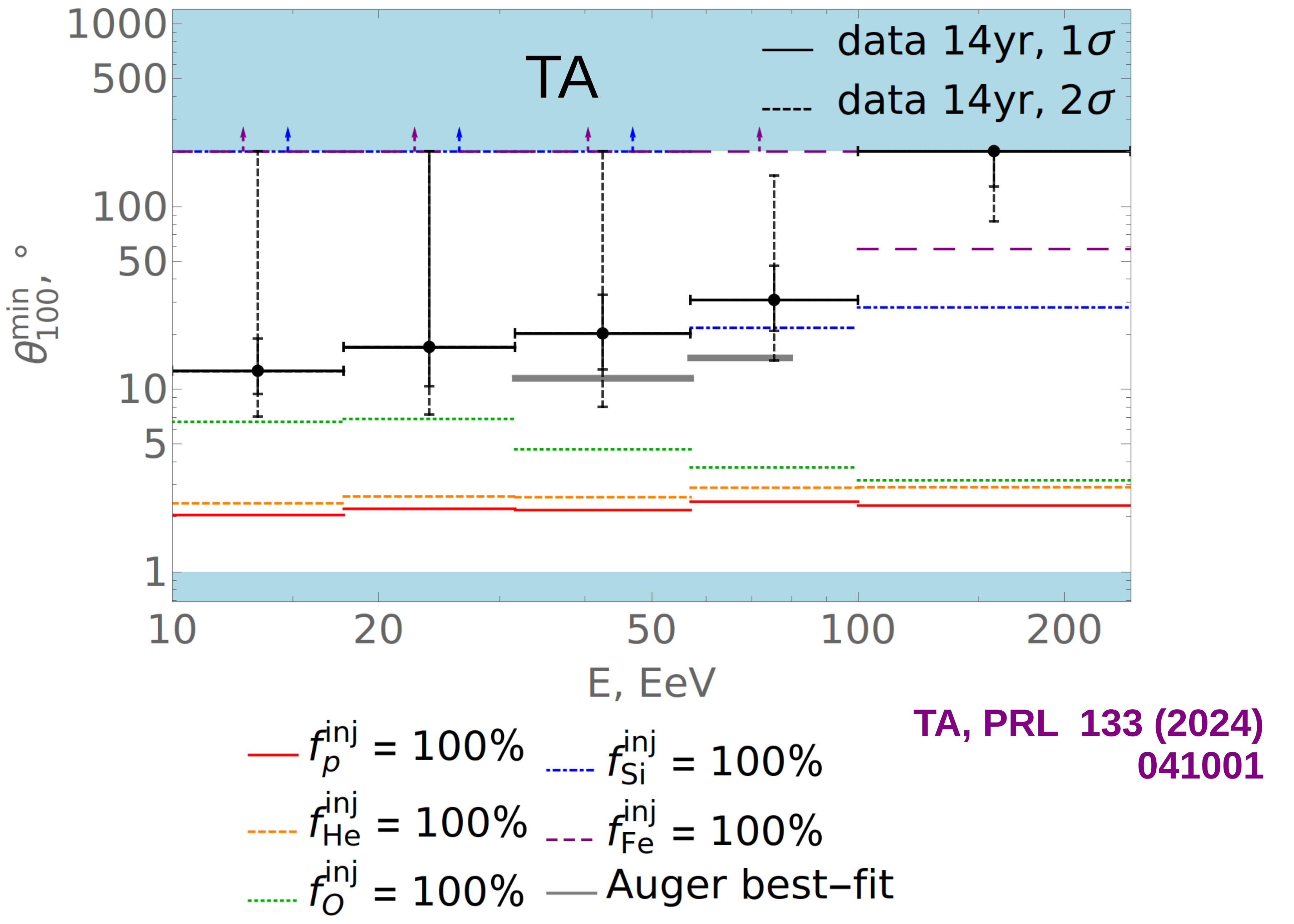
Auger and TA @ ICRC-2023

Sources in all galaxies

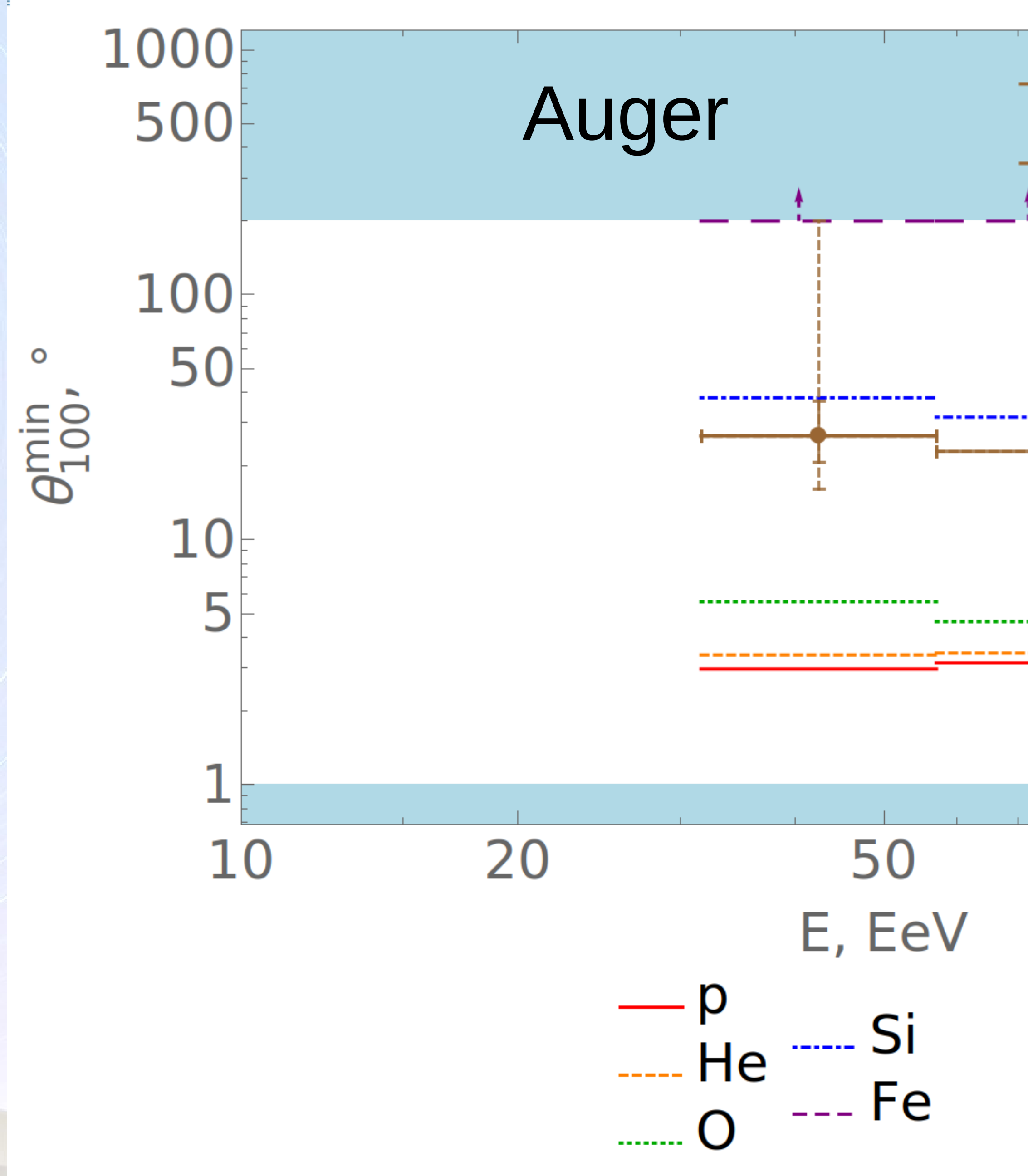


Correlation with a separate source class is not specific to it!

Correlation with LSS vs. composition models



TA, PRL 133 (2024) 041001



Pierre Auger data at E > 32 EeV (**Auger, ApJ 935 (2022) 170**)

Correlation with LSS is present at **57 < E < 100 EeV** but not very significant (~2σ) its interpretation may be ambiguous

Both TA and Auger data favors heavy composition at E > 100 EeV

Correlation with LSS: larger catalog

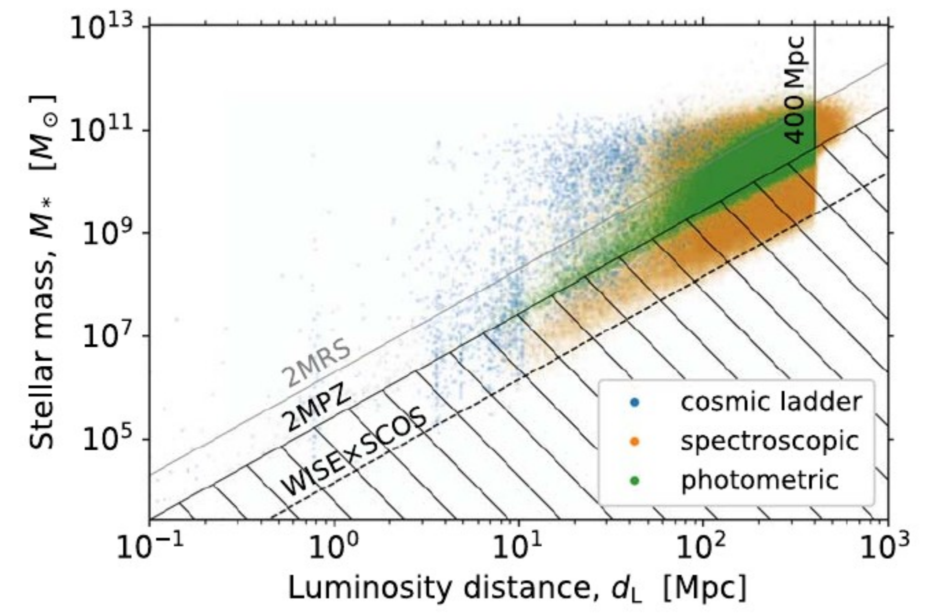
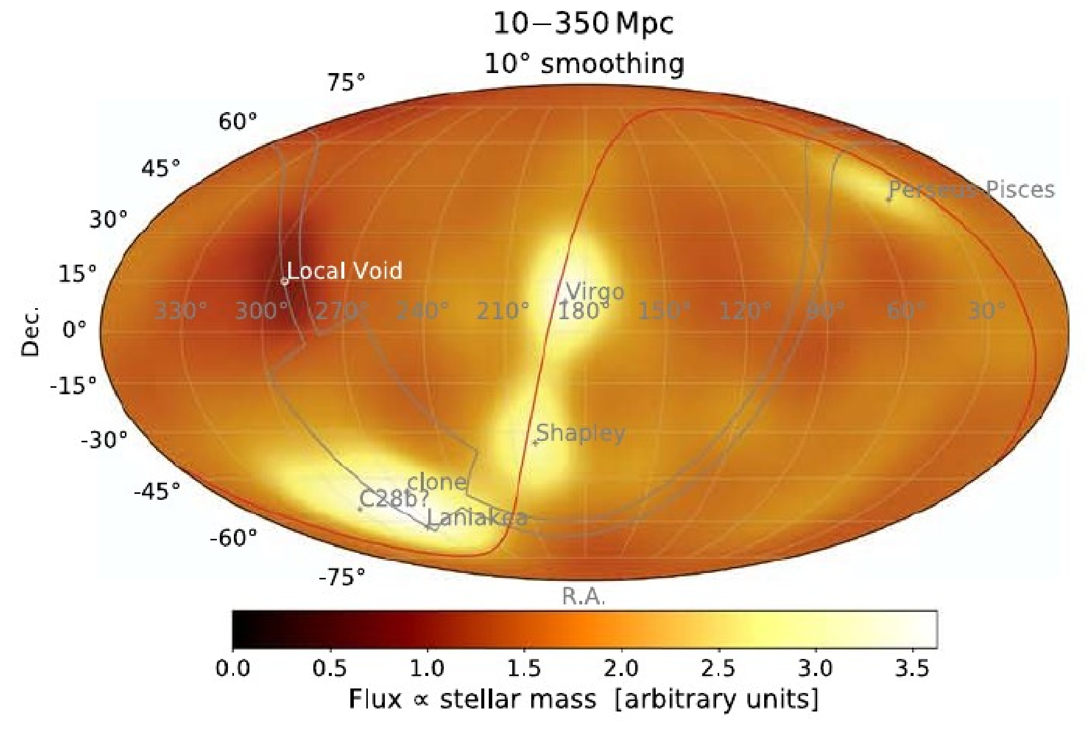
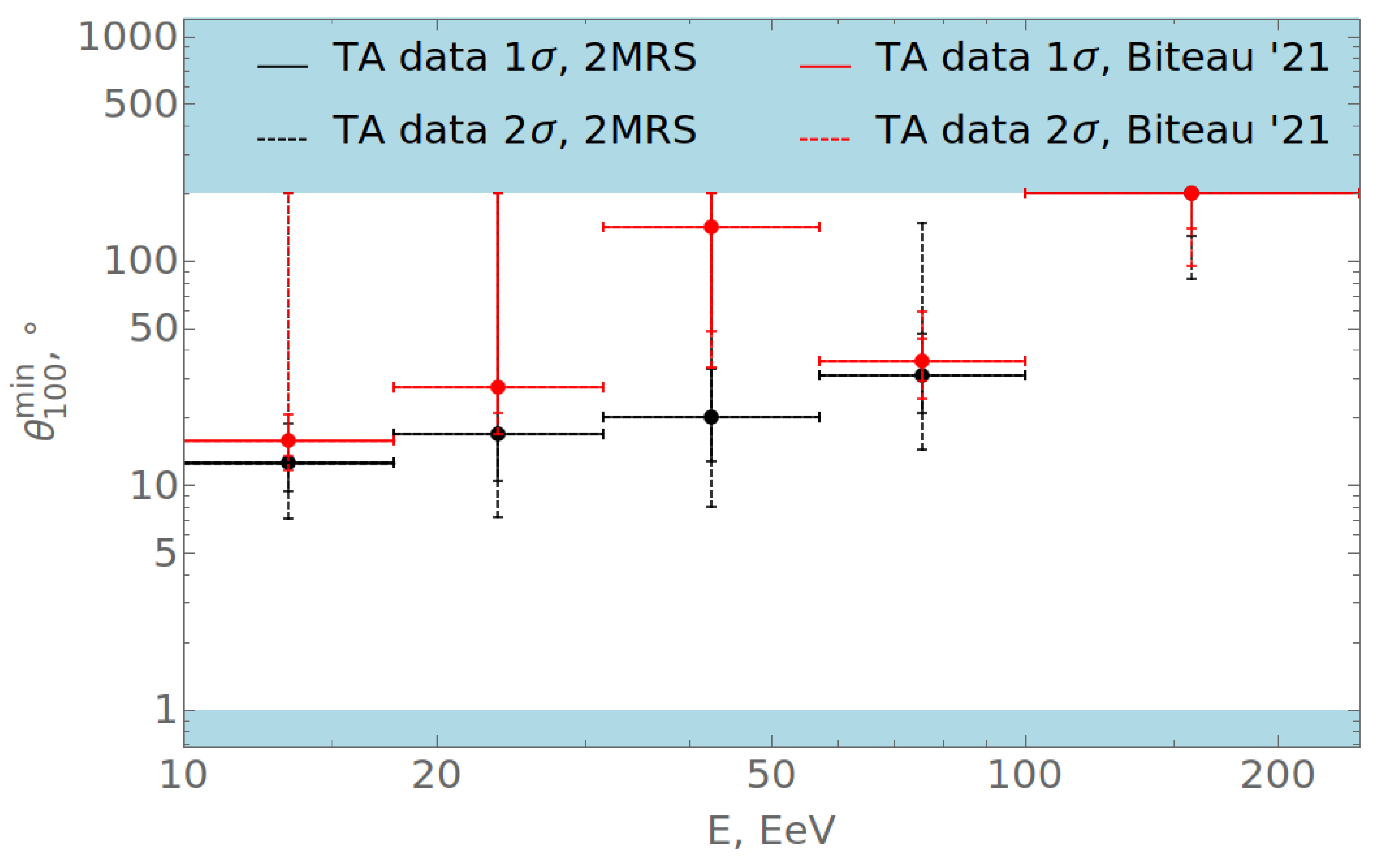


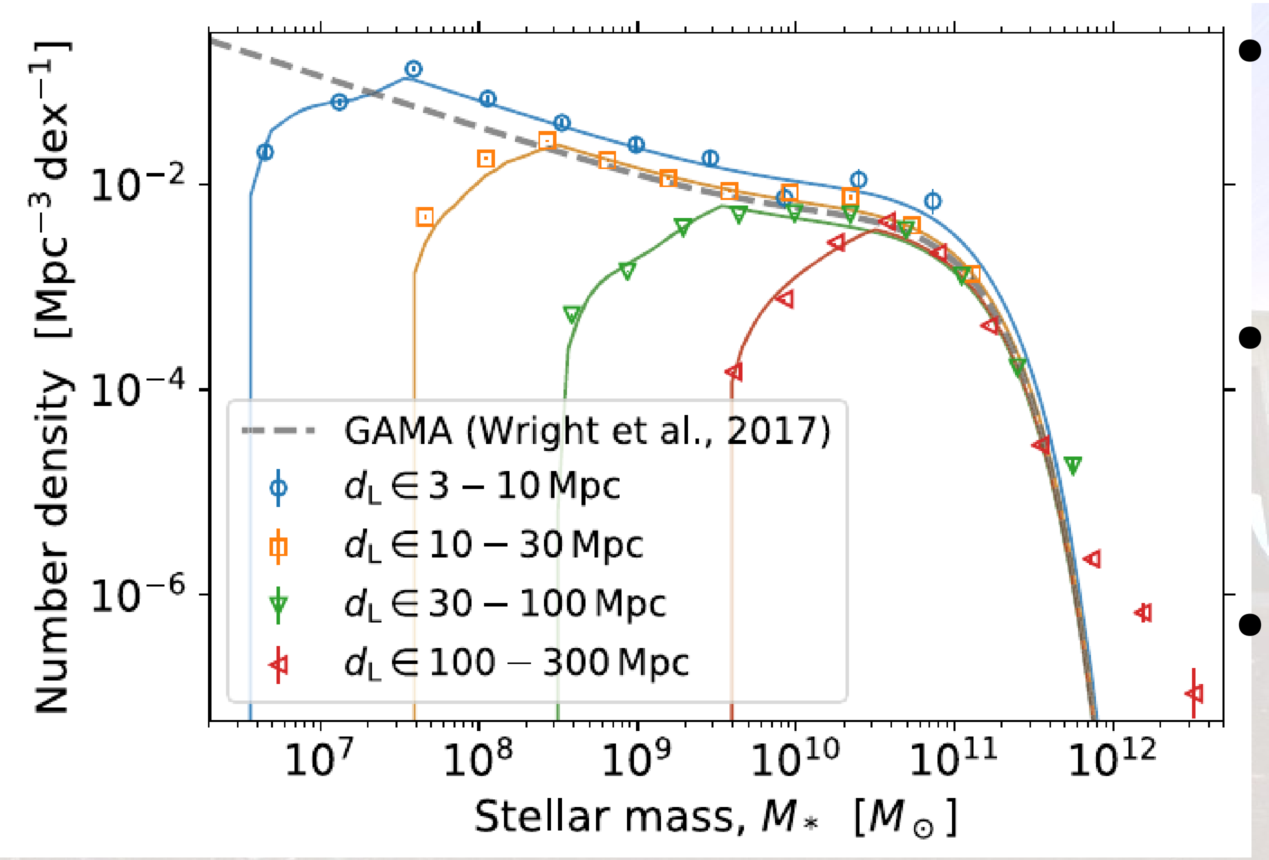
Figure 2. The stellar masses of galaxies vs. revised luminosity distances from cosmic-ladder (blue), spectroscopic (orange), and photometric (green) estimates. The flux limits of 2MRS, 2MPZ, and WISE × SCOS are indicated as solid gray, solid black, and dashed black lines, respectively. For reference, the 400 Mpc cut placed by the MANGROVE authors is indicated as a vertical solid line. The distance of galaxies farther away are derived from spectroscopic measurements, superseding the initial 2MPZ photometric estimate. The hashed region is excluded in the present study.





Biteau, ApJS 256 (2021) 15

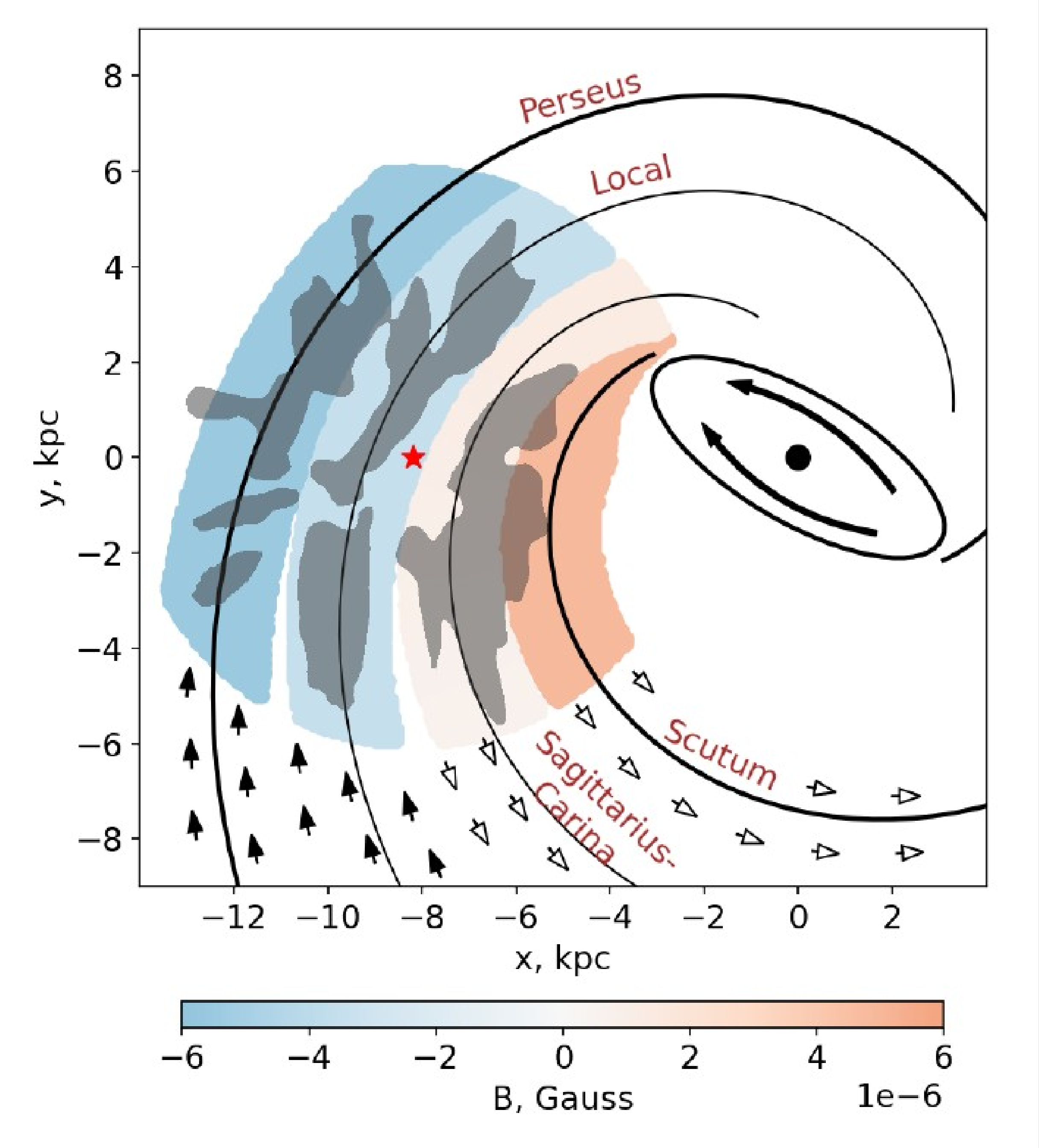
Catalog with x2 objects in 5 < L < 250 Mpc (2MRS → 2MRS + 2MPZ)



- At E < 57 EeV and E > 100 EeV the TA data looks more isotropic with new catalog
- At 57 < E < 100 EeV the correlation with LSS is increased to **3.4 σ** (comparing to **2.0 σ** in 2MRS alone)
- **This indicates that correlation is real and standard galaxies are the sources of UHECR**

Perspectives

Improvement of galactic and extragalactic magnetic field models



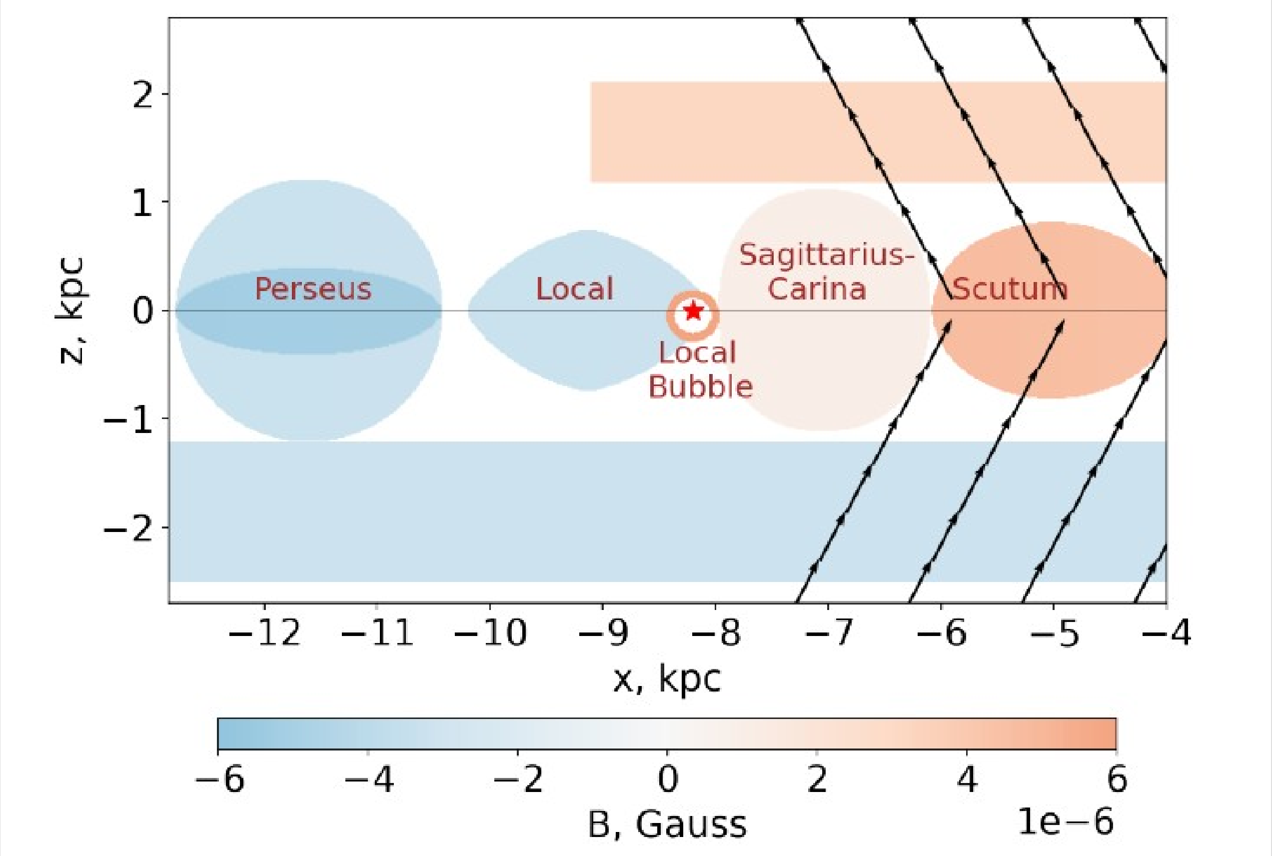
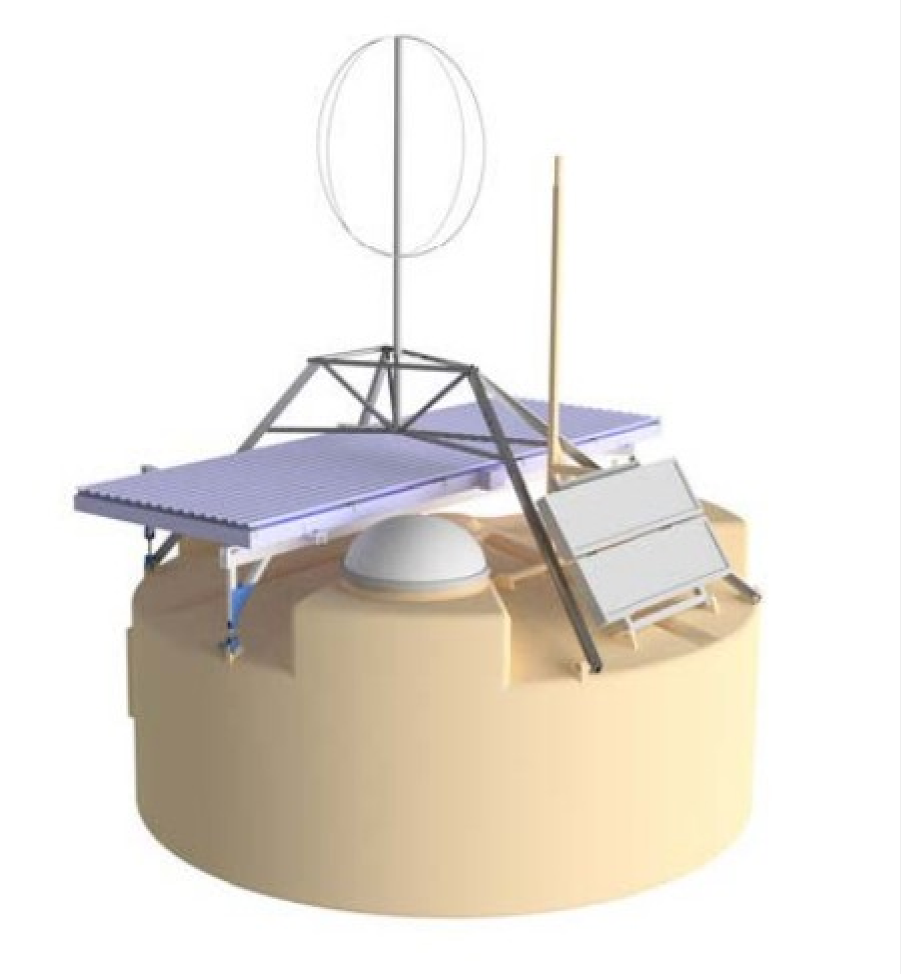


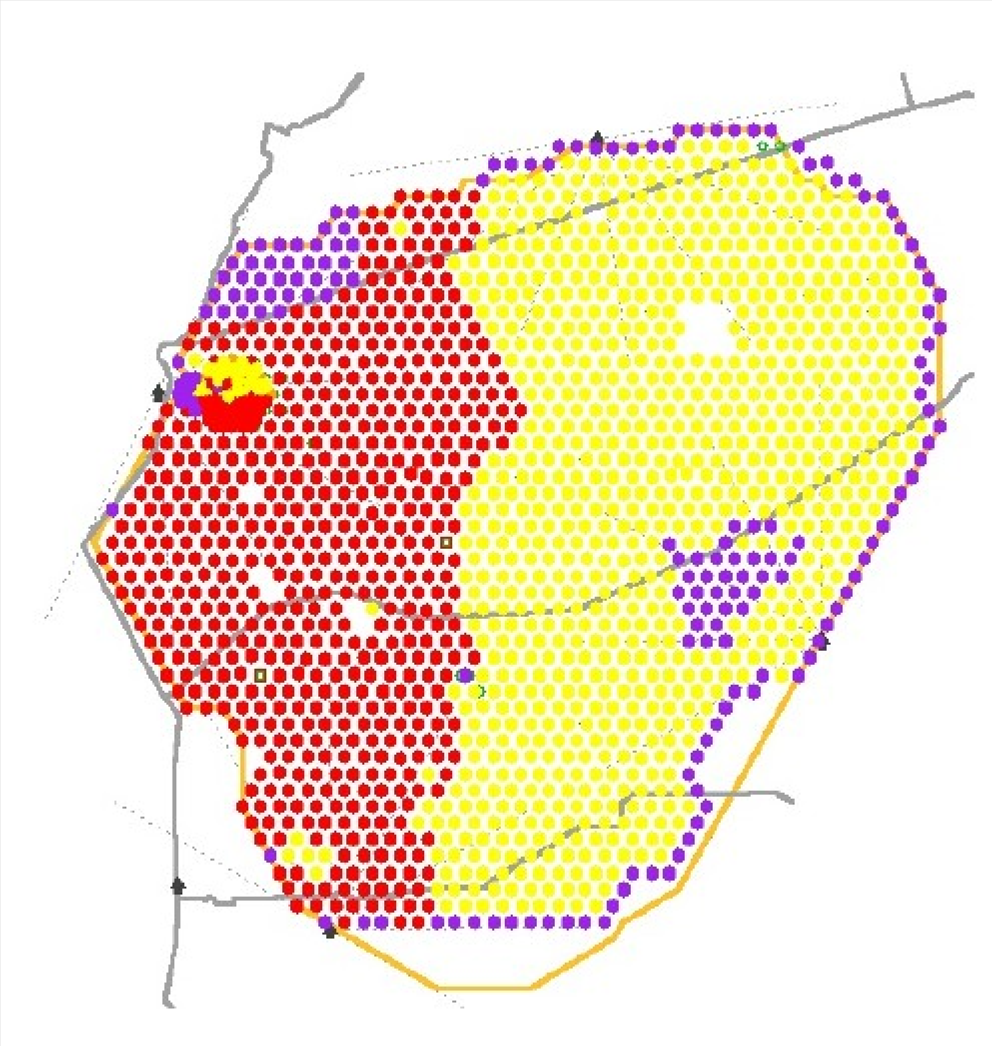
Fig. 4. Section of the best-fit GMF model by the plane $y = 0$, which is perpendicular to Galactic plane and come through Sun (red star) and Galactic center. Blue and orange regions are the magnetic arms, northern and southern toroidal field and the Local Bubble. The color map is the same as in Fig. 3. Black arrows show the direction of the X-shaped field. Red star marks the position of the Sun.

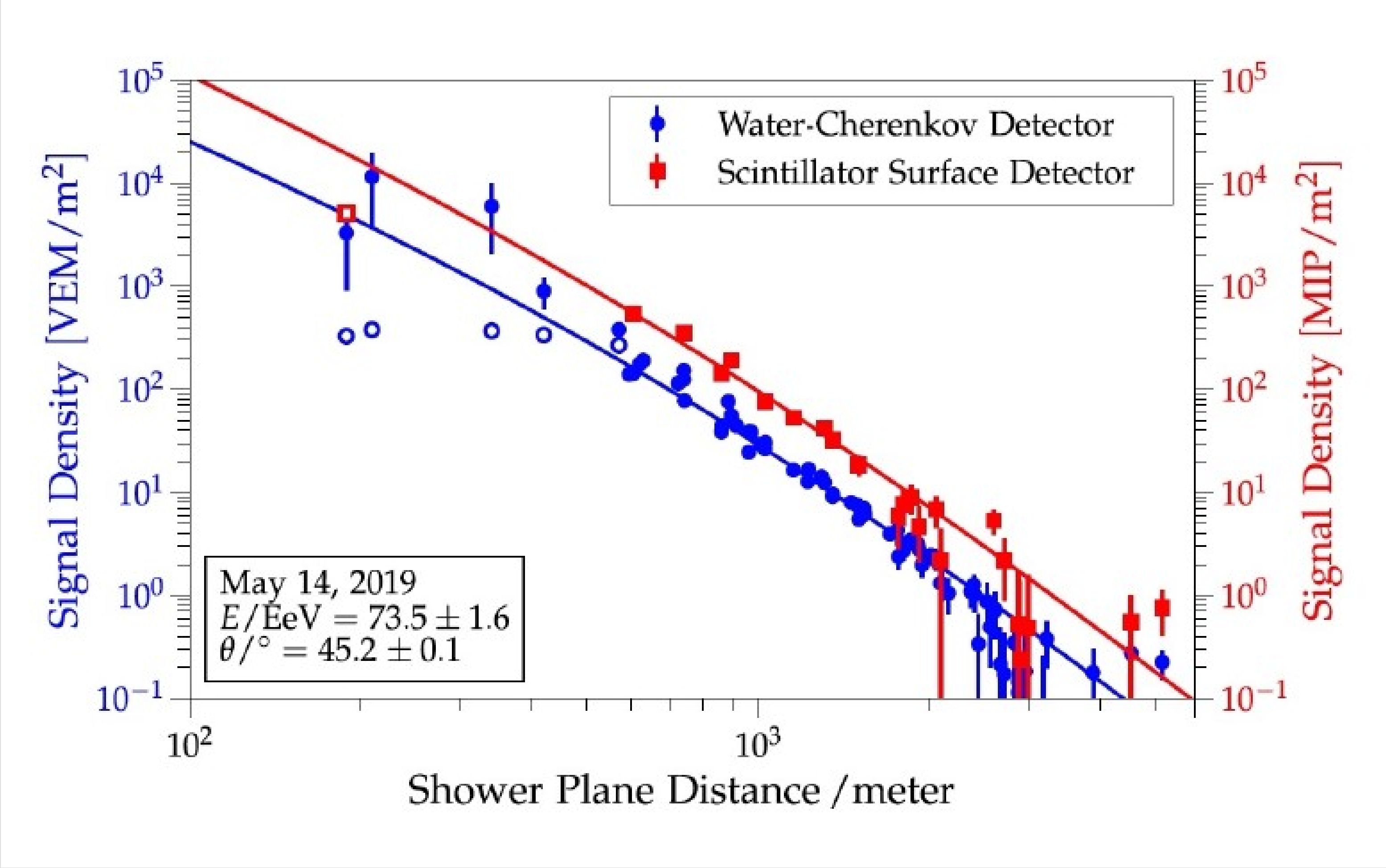
Korochkin, Semikoz, Tinyakov, A&A 693 (2025) A284

- Taking into account an additional structure (magnetic bubble around local stellar group) significantly improved both synchrotron radiation fit and UHECR dipole fit
- Fields of galactic halo and local extragalactic structures (filaments) are still very uncertain
- **Need to improve the models further!**

Astronomy with separated light CR (?): AugerPrime upgrade

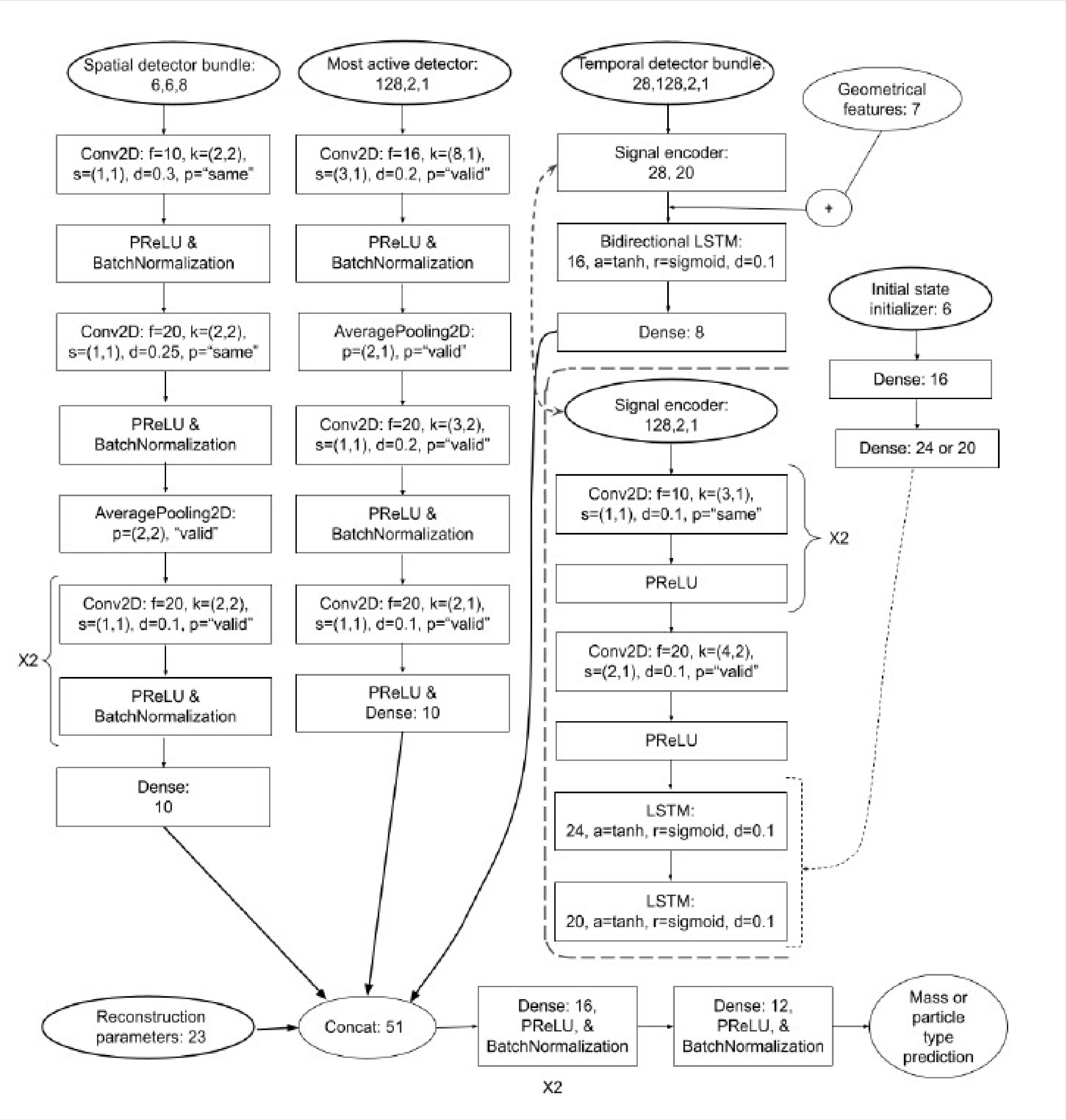


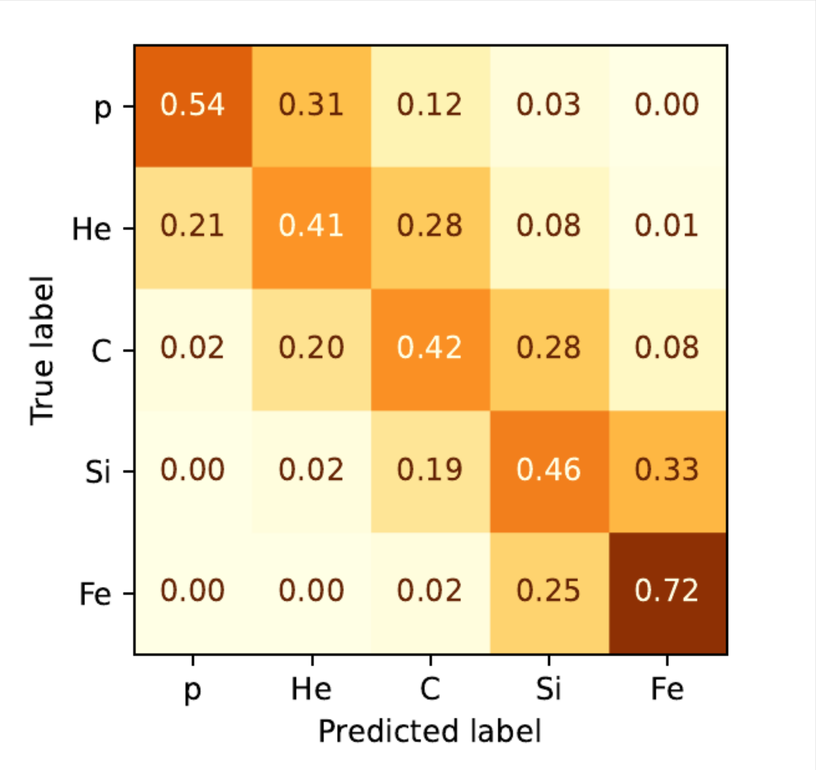


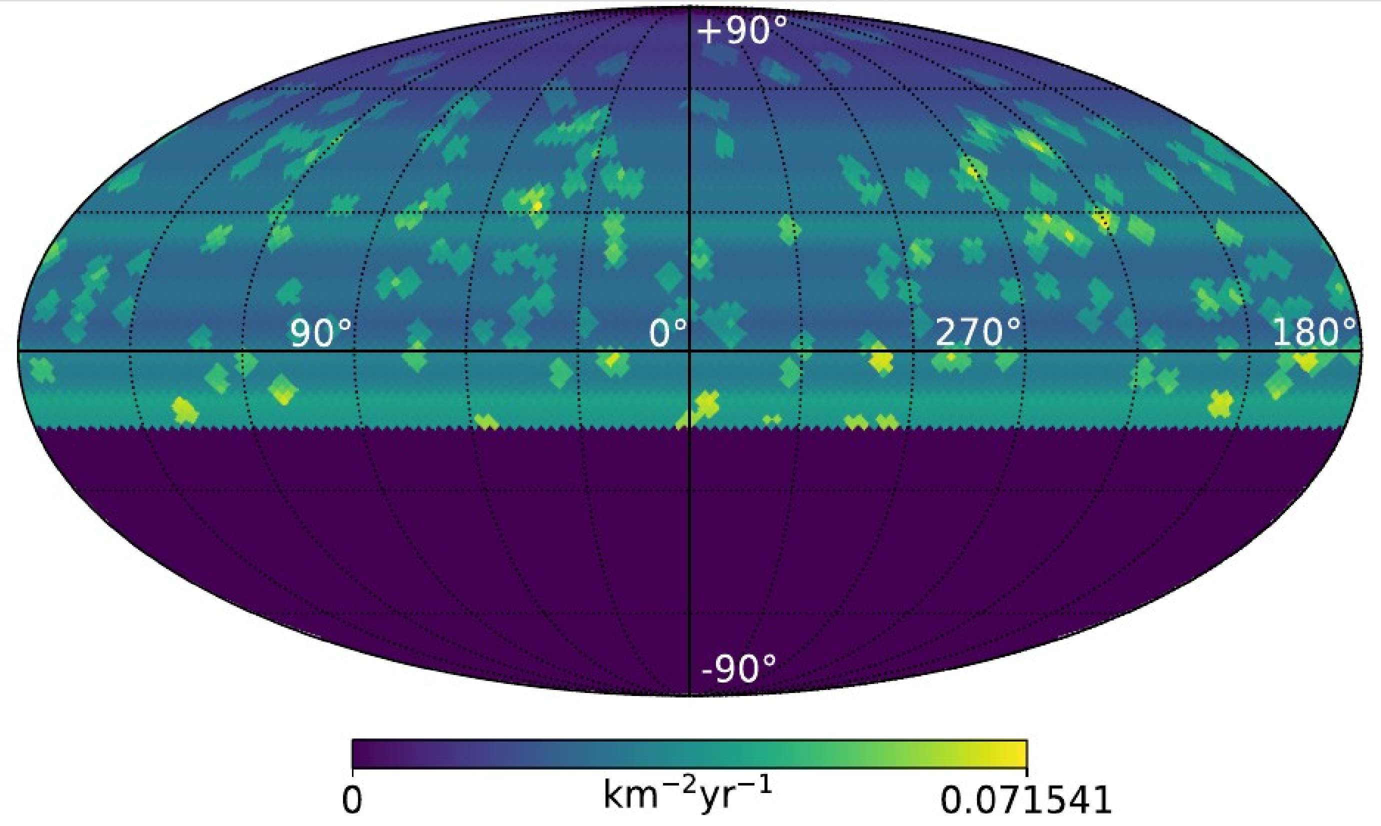


- Better mass components separation (water Cherenkov detector as muon detector)
- Hope for extraction of the light component at highest energies (if any) and for identification of its source

Astronomy with separated light CR (?): machine learning

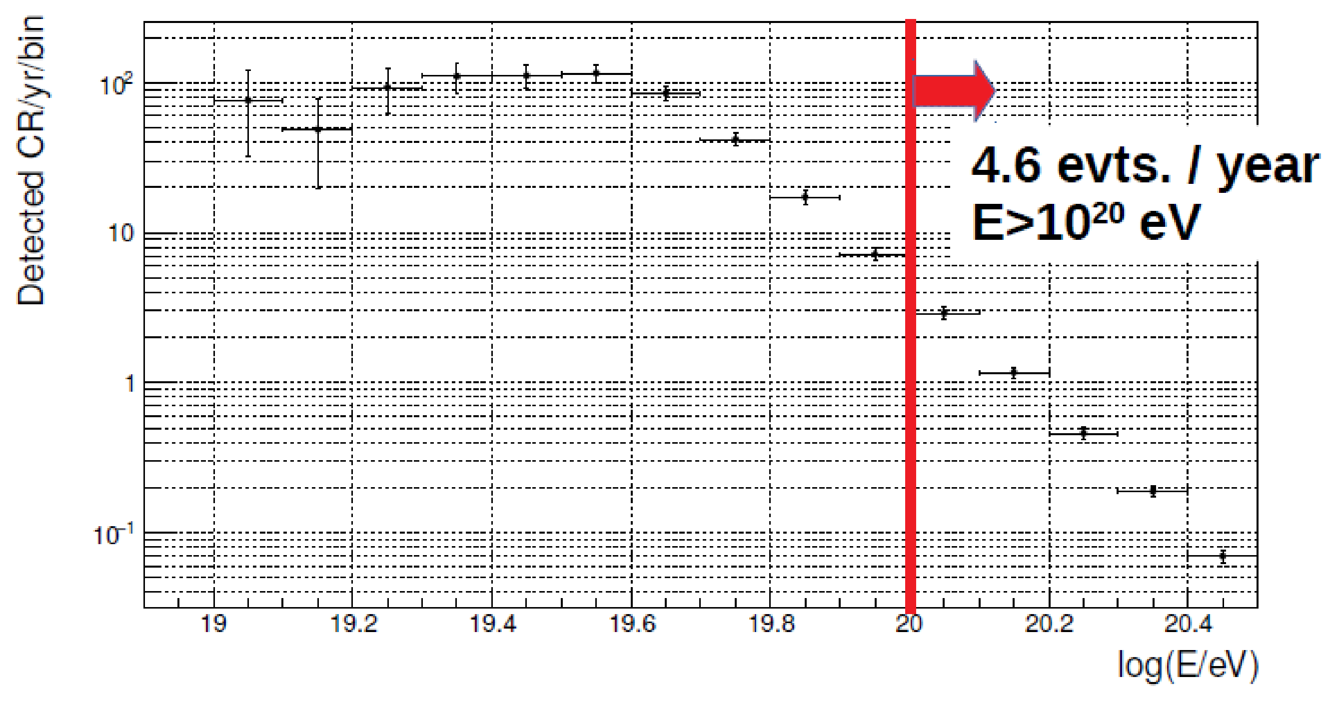




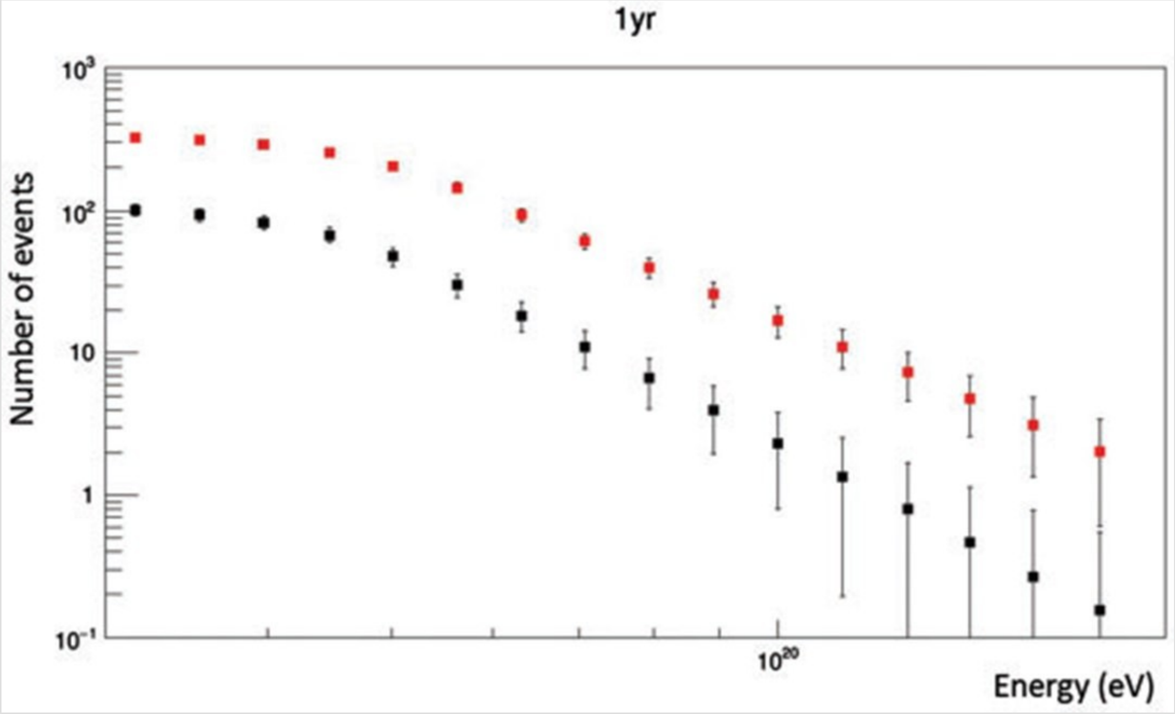


Larger statistics at highest energies

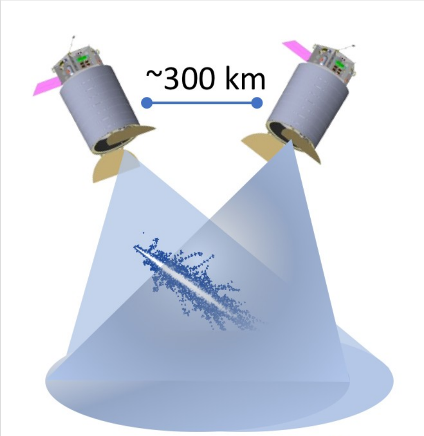
Statistics expected for Auger spectrum

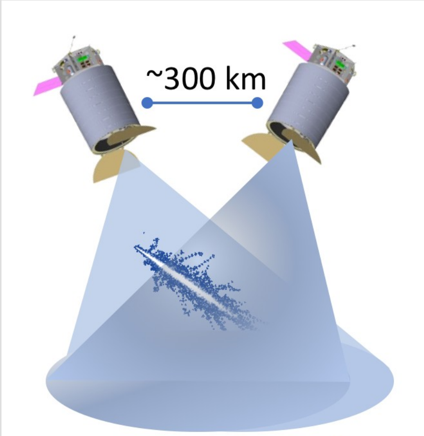


Test TA (north) and Auger (south) spectrum discrepancy in 1 year

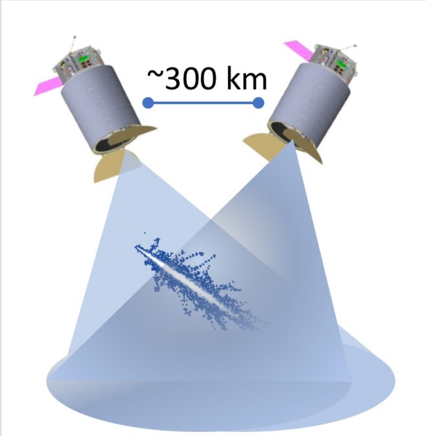


ERA (extreme relativistic astrophysics): group of satellite observatories for UHECR





…



Angular resolution:
1-7°
Energy resolution:
15-25%

- Telescope type: one mirror
- Field of view: ≥ 10°
- Aperture: ~2 m^2
- Pixel size: 1-2 mrad
- Telescope mass: 100 kg
- Energy consumption: 100 W
- Number of telescopes: 10.
- Total exposure: 20000 km^2 sr yr

✓Expected statistics (E>50 EeV) – more than 100 events/yr.
✓Uniform sky coverage
✓Test TA-Auger spectrum discrepancy in 1 year
✓Test for close source
✓Improvement of composition from anisotropy measurement at highest energies

Conclusions

Current status:

- UHECR origin still unknown
- Mass composition at highest energies is not light
- Several anisotropy signatures detected
  - Dipole
  - Medium scale excesses
  - Correlations with LSS
- Interpretation of these observations is not straightforward
- There should be a close source, but its identification is difficult due to not heavy UHECR composition and MF uncertainties
- Source number density is not very low: many potential source classes are ruled out

Perspectives:

- Improvement of models of cosmic magnetic fields is needed
- Hope for CR astronomy with extracted light UHECR component
- Larger statistics at highest energies is needed, better with full sky coverage: ERA project

Thank you for the attention!

Supported by the Ministry of Science and Higher Education of the Russian Federation under the contract 075-15-2024-54

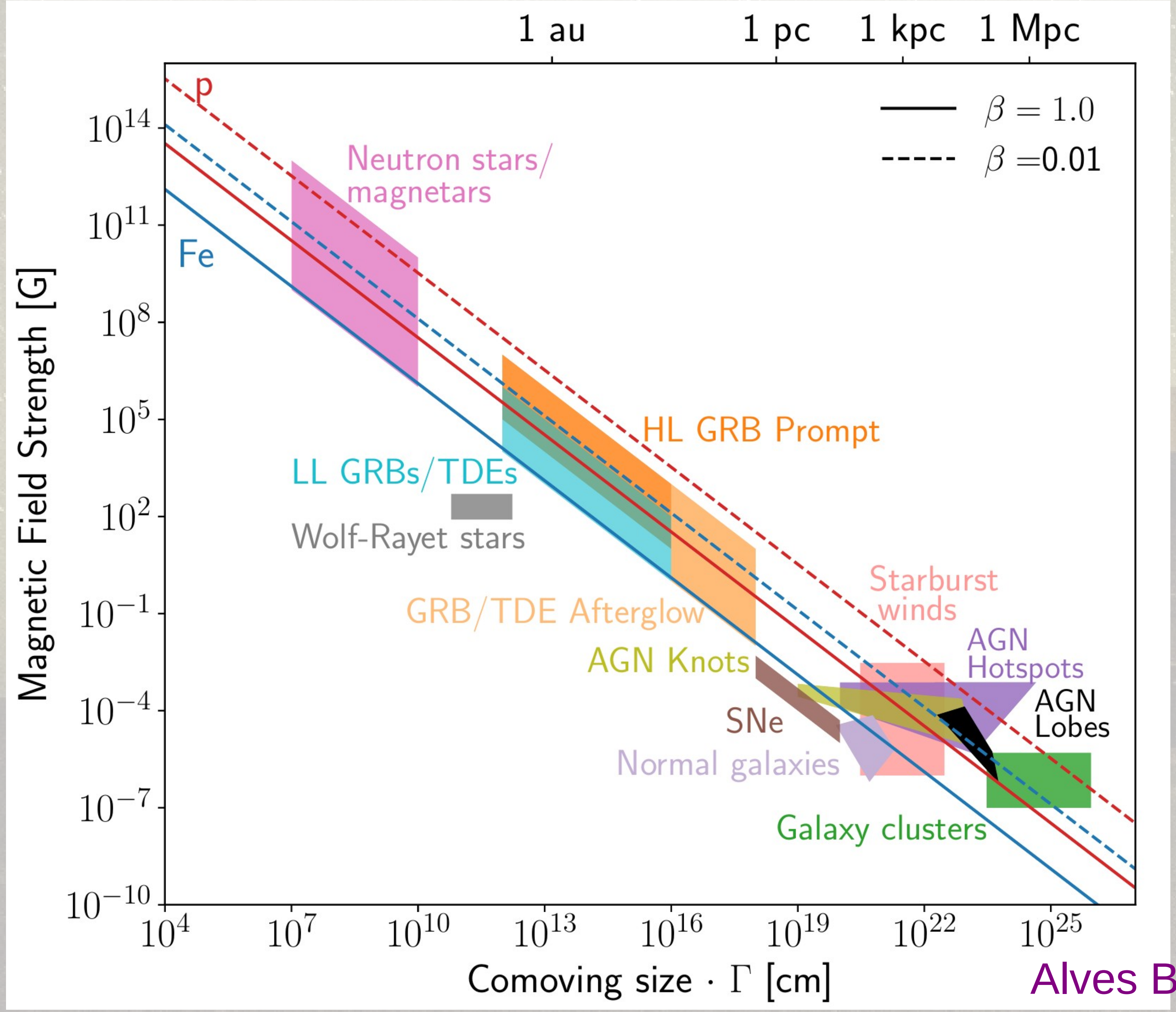
Backup slides

Another approach: constrain possible source classes

Hillas criterion

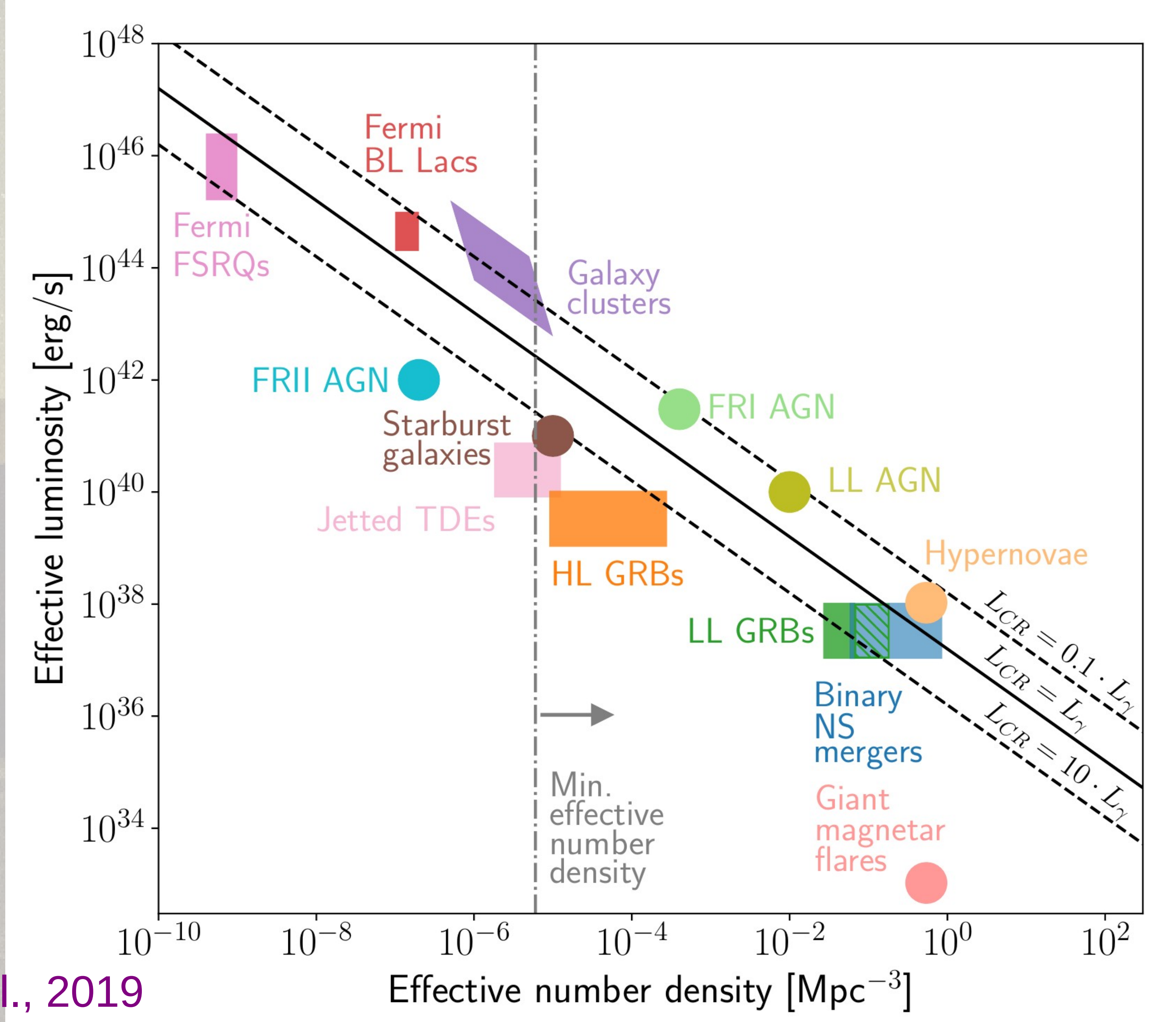
R = E/qB — larmor radius
$\mathbf{E_{max} = \beta_{shock} qBR\Gamma}$ — maximum energy

Sources below the lines are excluded



Criterion of full energetics

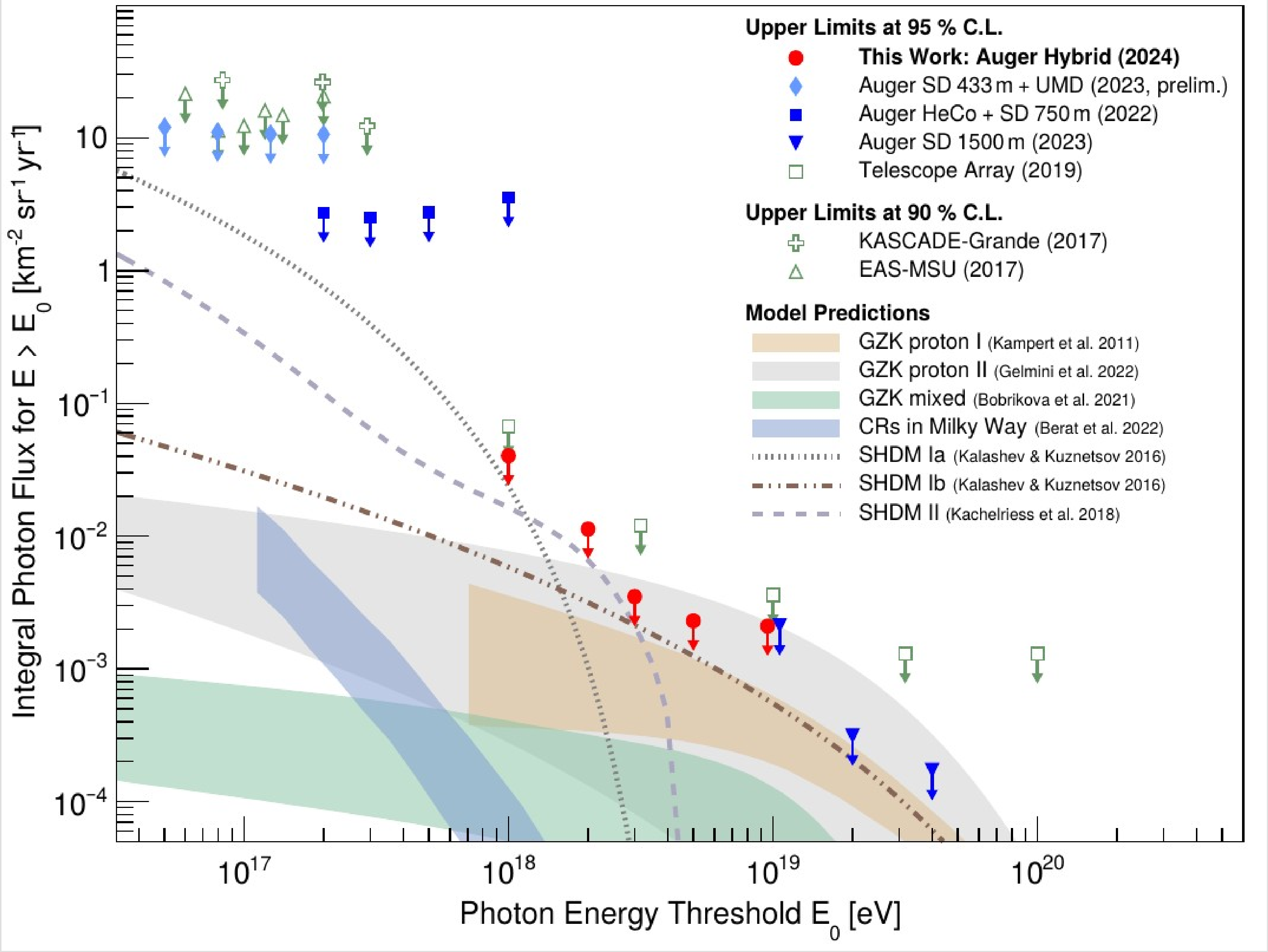
$\mathbf{L = 5\times10^{44}}$ **erg/(Mpc³ yr)** — total luminosity of sources to get observed spectrum (Auger, 2017)
Depends on $\mathbf{E_{min}}$ of galactic-extragalactic transition and $\mathbf{L_\gamma/L_{CR}}$
Sources below the lines are excluded



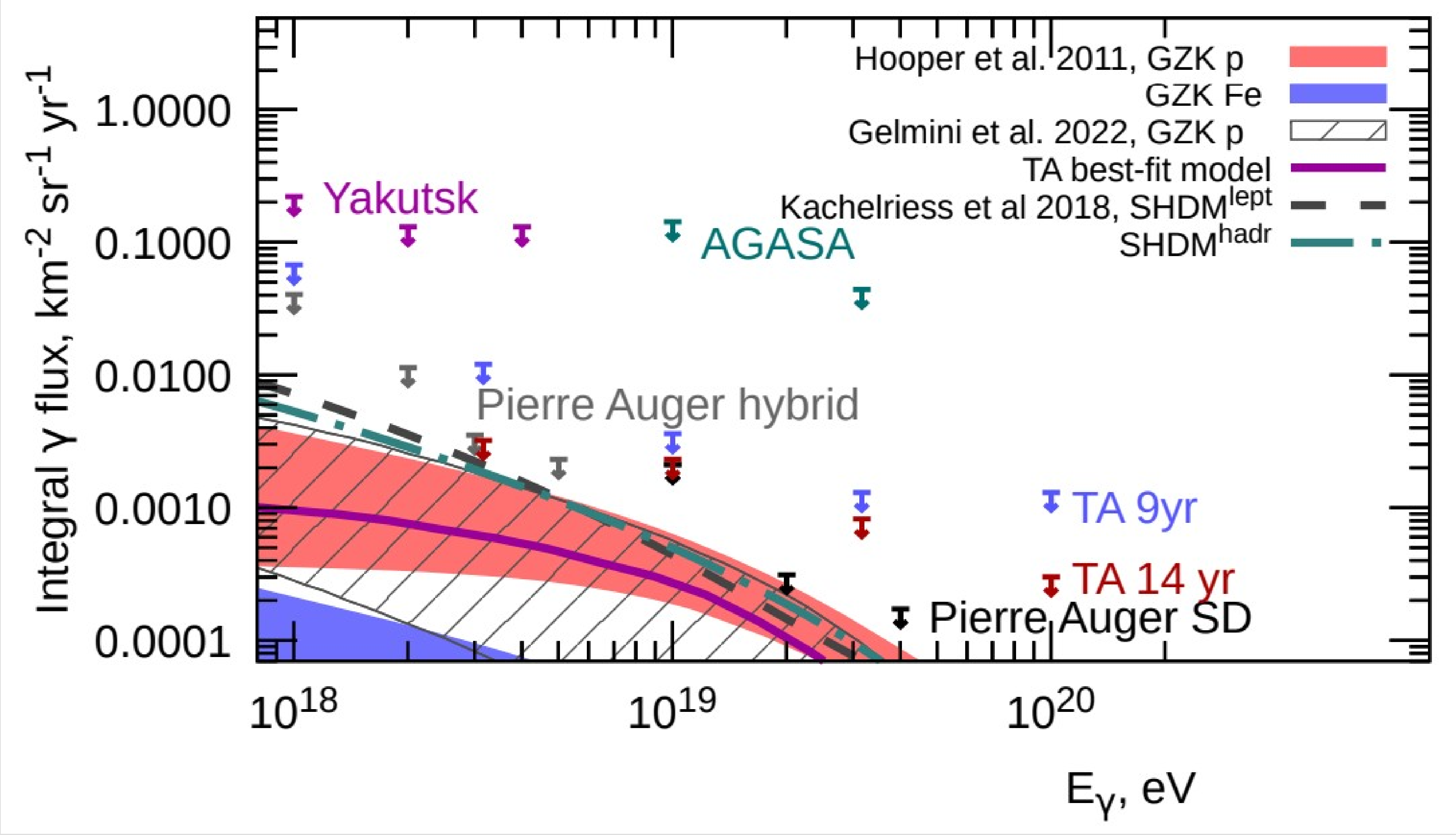
Alves Batista et al., 2019

Search for ultra-high energy gamma rays

Auger, arXiv:2406.07439



Telescope Array, arXiv:2512.01638



- Low chances for detection of cosmogenic gamma-rays (UHECRs are likely not protons)
- No hints for UHE gamma-rays from heavy DM decay
- UHE gamma is not perspective for multimessenger study of possible UHECR sources

Anomalous UHECR correlation with BL Lacs

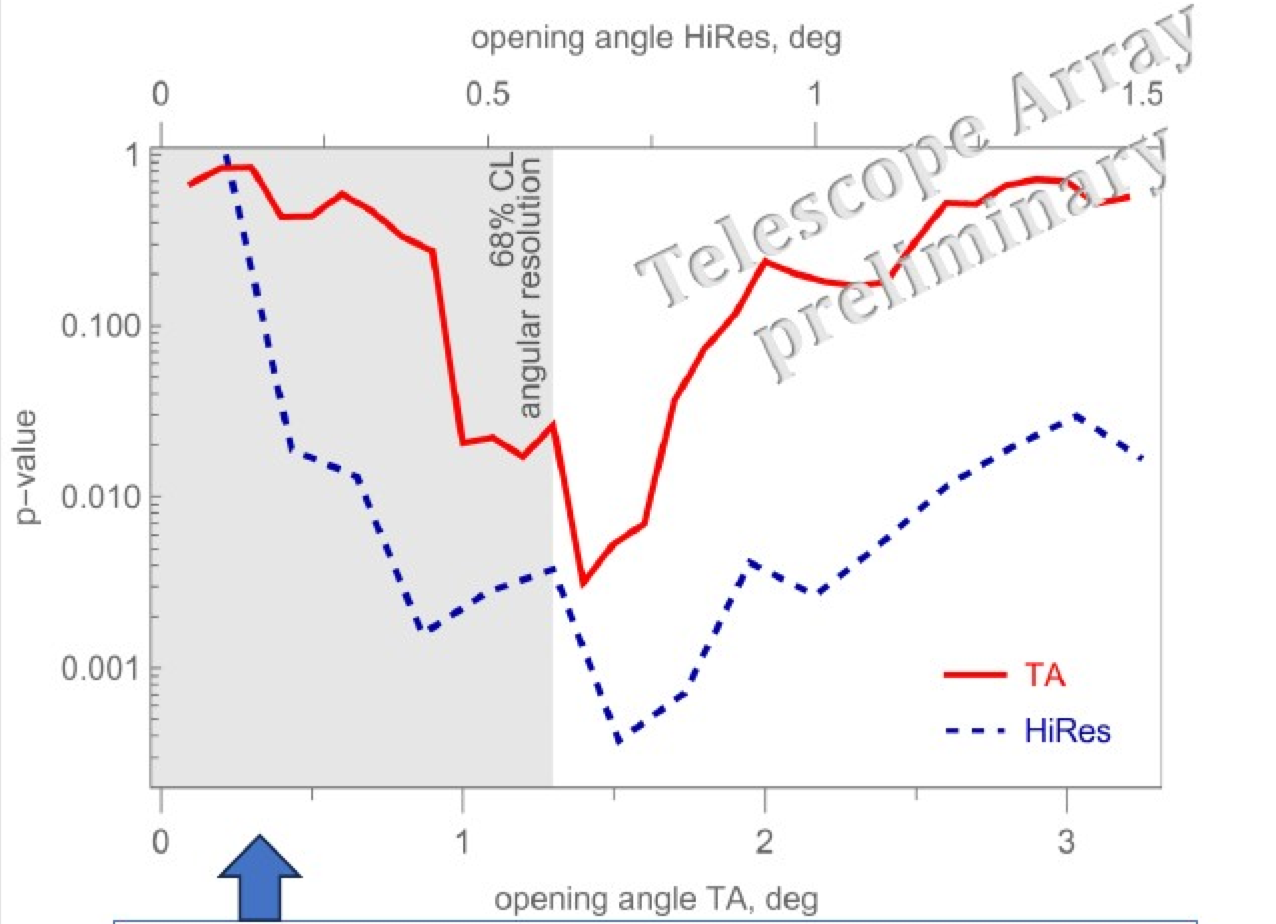
Results of HiRes experiment:

- Correlation of CR at E > 10 EeV with catalog of 156 distant BL Lacs
- Only a small fraction of flux correlates (~3%)
- No explanation in with standard physiscs — sources are too far away (D > 500 Mpc)

D.Gorbunov et al., JETP Lett 80 (2004) 145
HiRes, ApJ 636 (2006) 680

Results with TA data

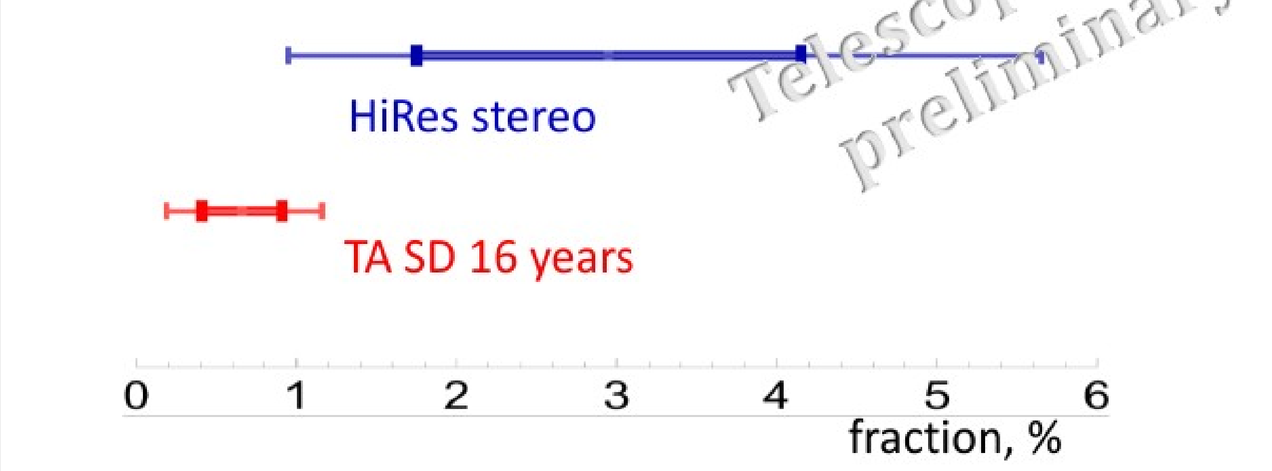
TA @ UHECR-2024



opening angles scaled to 68% CL resolutions

fraction of excess events from BLLs in the data set:

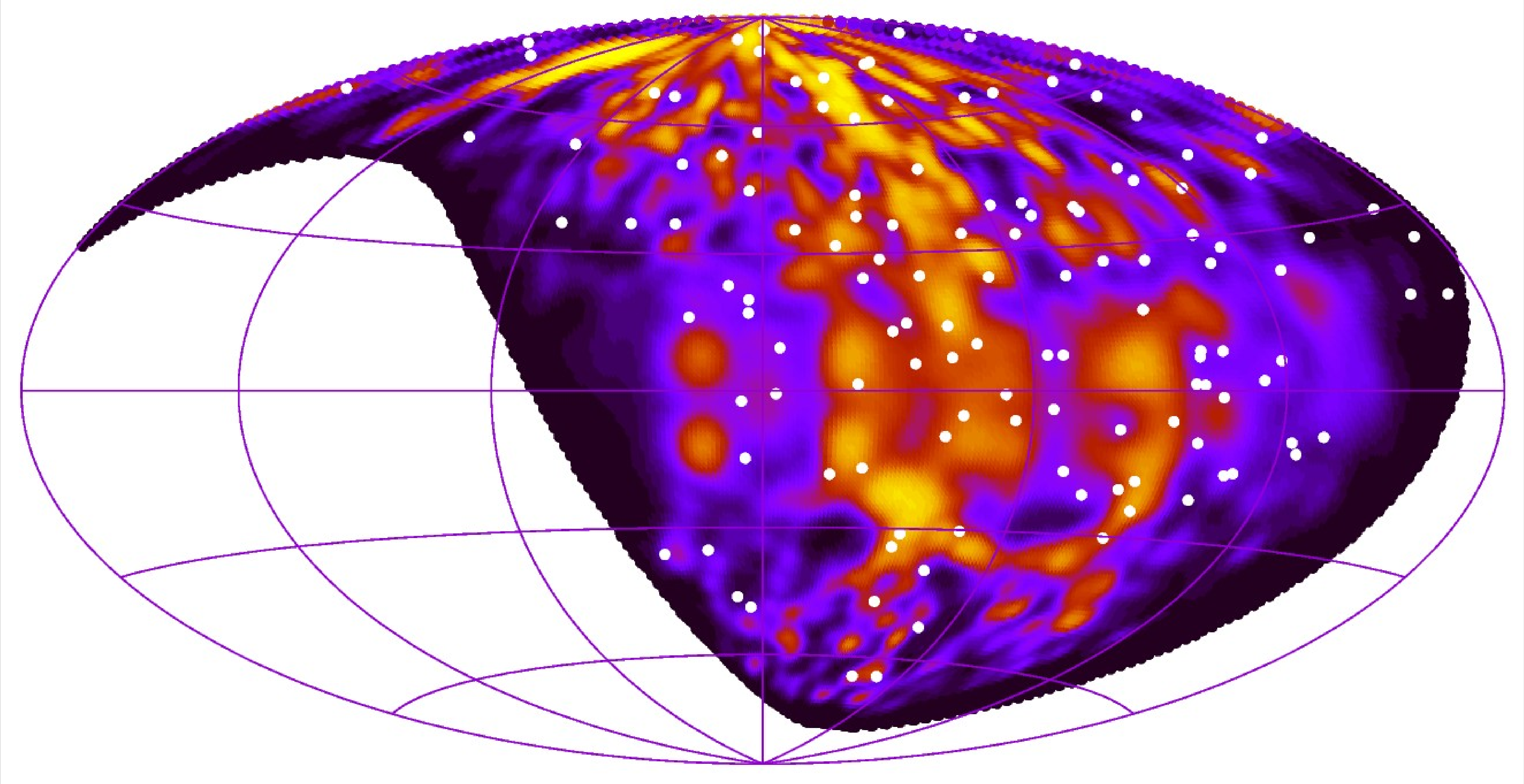
Data set	fraction, %	68% CL	95% CL
HiRes stereo	3.0	± 1.2	$^{+2.7}_{-2.0}$
TA SD	0.66	± 0.25	$^{+0.50}_{-0.47}$



Correlation is visible in TA!
Fraction of correlating events is lower but consistent with HiRes

post-trial p-value = 0.03
(2.2 σ)

Оценка массового состава из отклонений от ожидаемых источников



MK & P.Tinyakov, arXiv:2011.11590

Трехшаговый подход

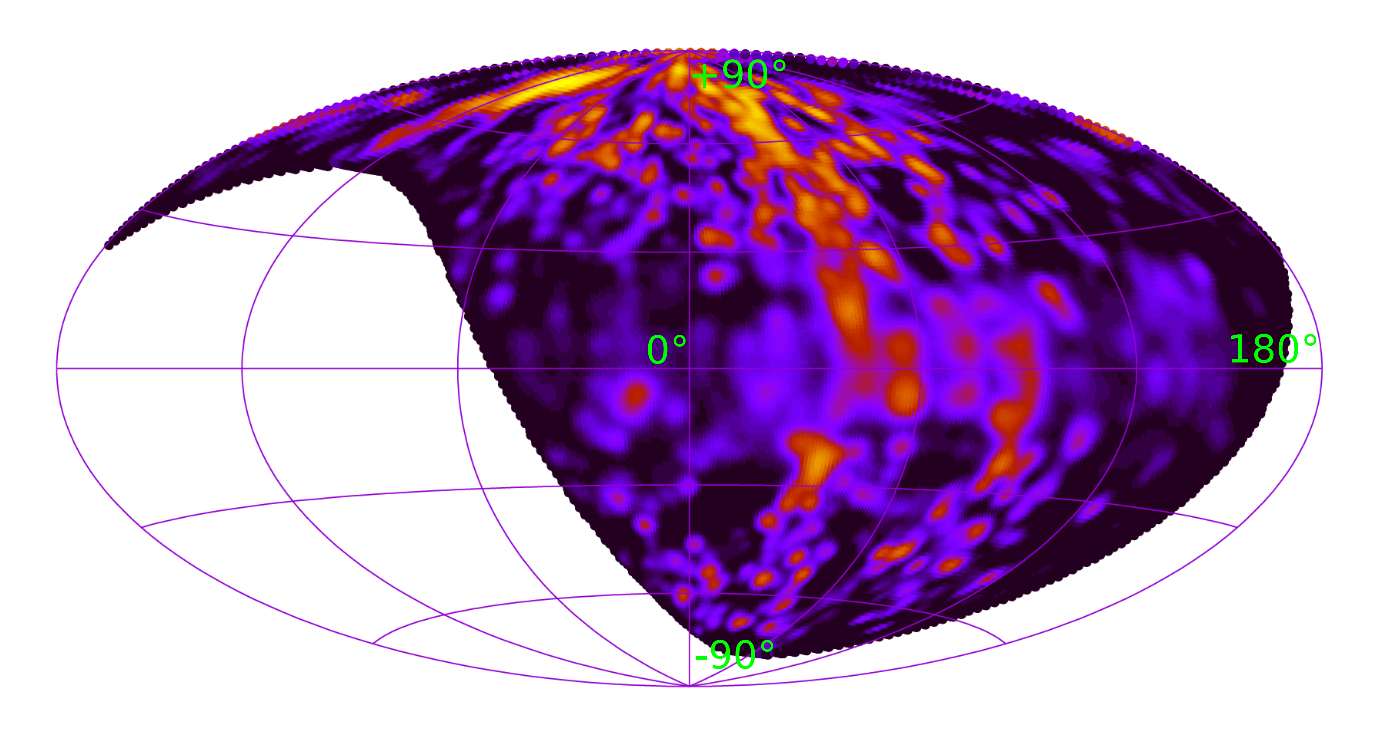
1. **Ввести статистический критерий: устойчивую меру** отклонения набора КЛУВЭ от их ожидаемых источников в LSS
2. **Симулировать реалистичные наборы КЛУВЭ,** испускаемые из источников и различающиеся массовым составом
3. **Применить стат.критерий** одинаково к симулированным наборам и к реальным данным и оценить какие составы совместны с данными

Step two: realistic UHECR mock sets

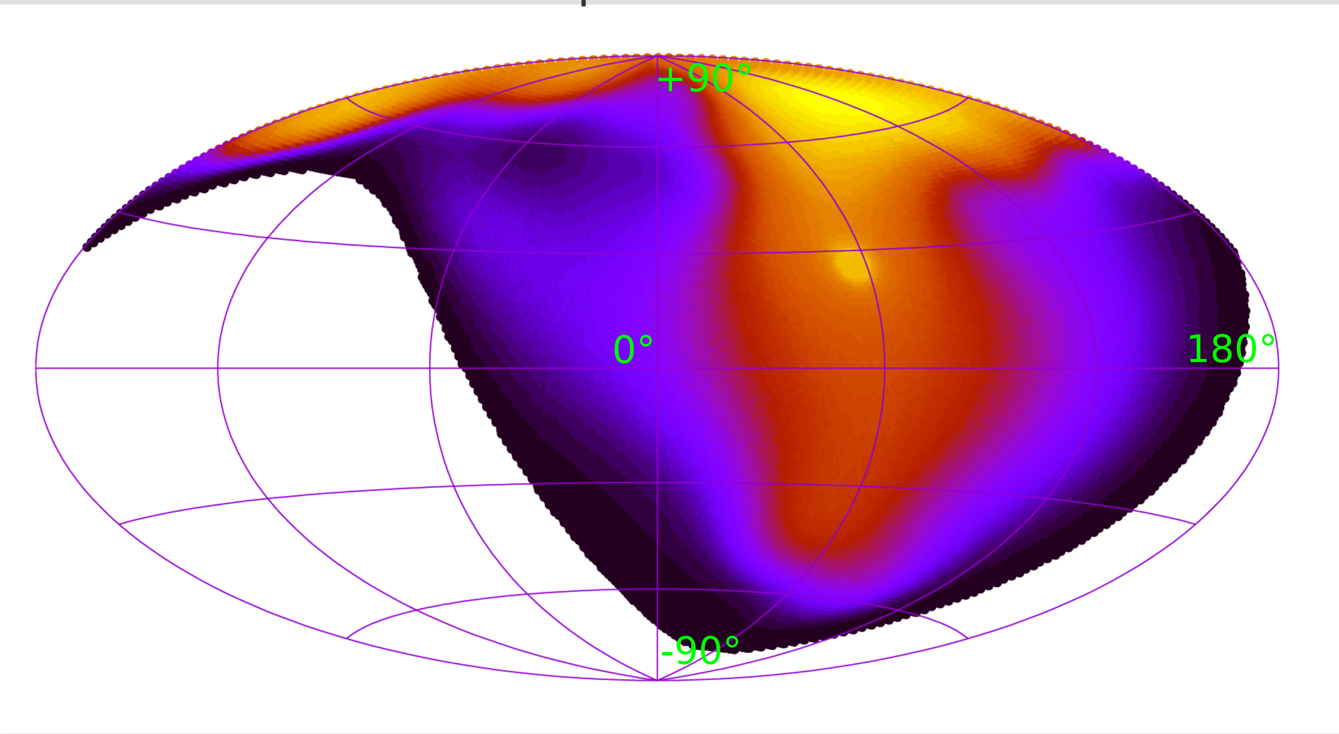
Generate UHECR sets with state-of-art simulated skymaps

- Sources in LSS (corrected 2MRS catalog up to 250 Mpc, isotropy farther)
- Properly attenuated injected primaries (p-He-O-Si-Fe), secondaries for He & O are included (SimProp 2.4)
- Fix best fit injection spectrum separately for each primary (di Matteo & Tinyakov 2018)
- No EGMF deflections
- GMF deflections: backtracking for regular component,
- Non-uniform gaussian smearing for random component (Pshirkov et al. 2013)
- Sets are generated according to these maps with a spectrum adjusted to the observed one (TA@ICRC 2015)
- Effectively infinite statistics (statistical effects are reflected only in the data)
- **Only free parameters of the model are fractions of each primary**
- **All other uncertainties: to study separately (subominant!)**

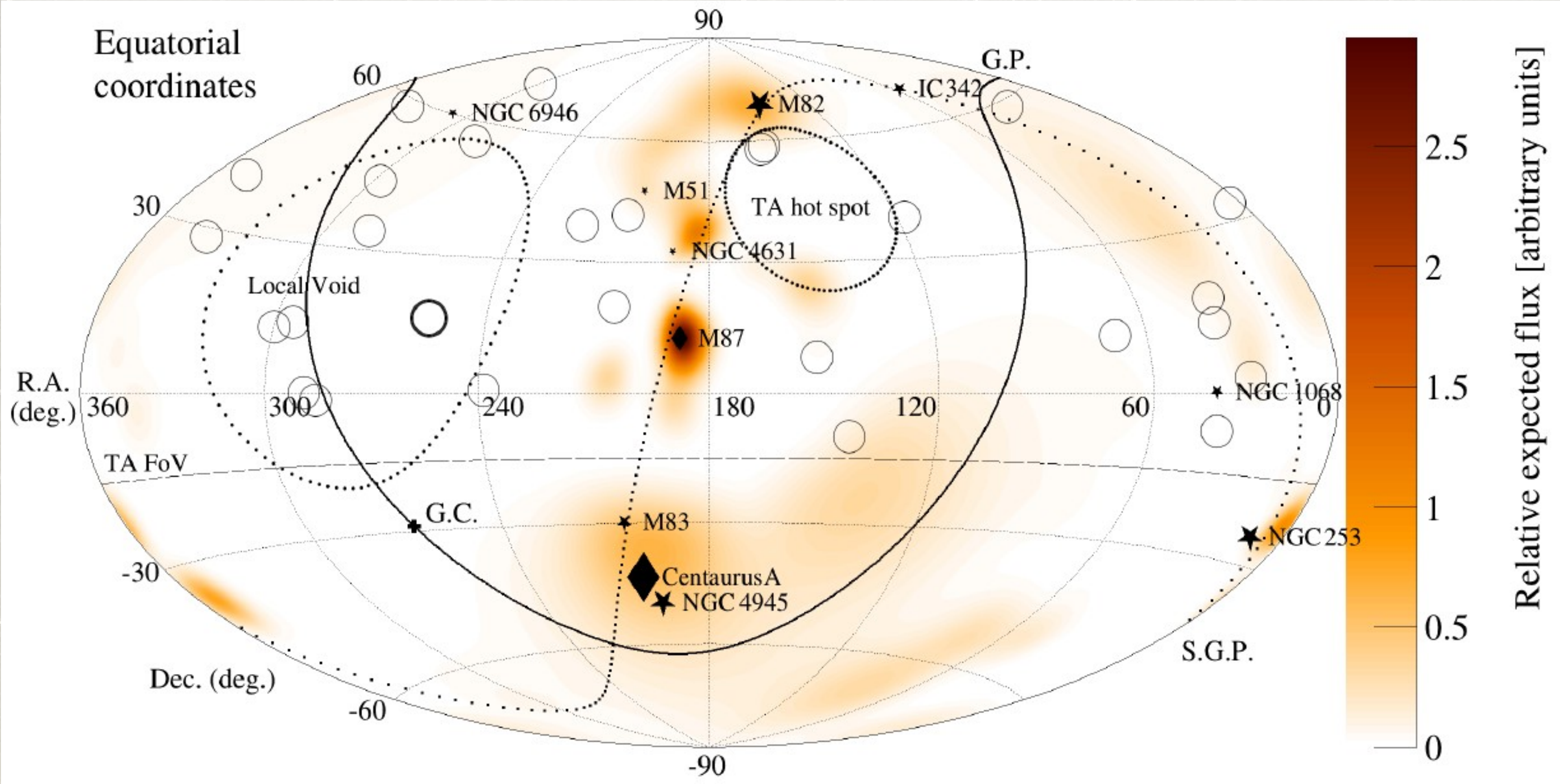
Proton map at E = 100 EeV



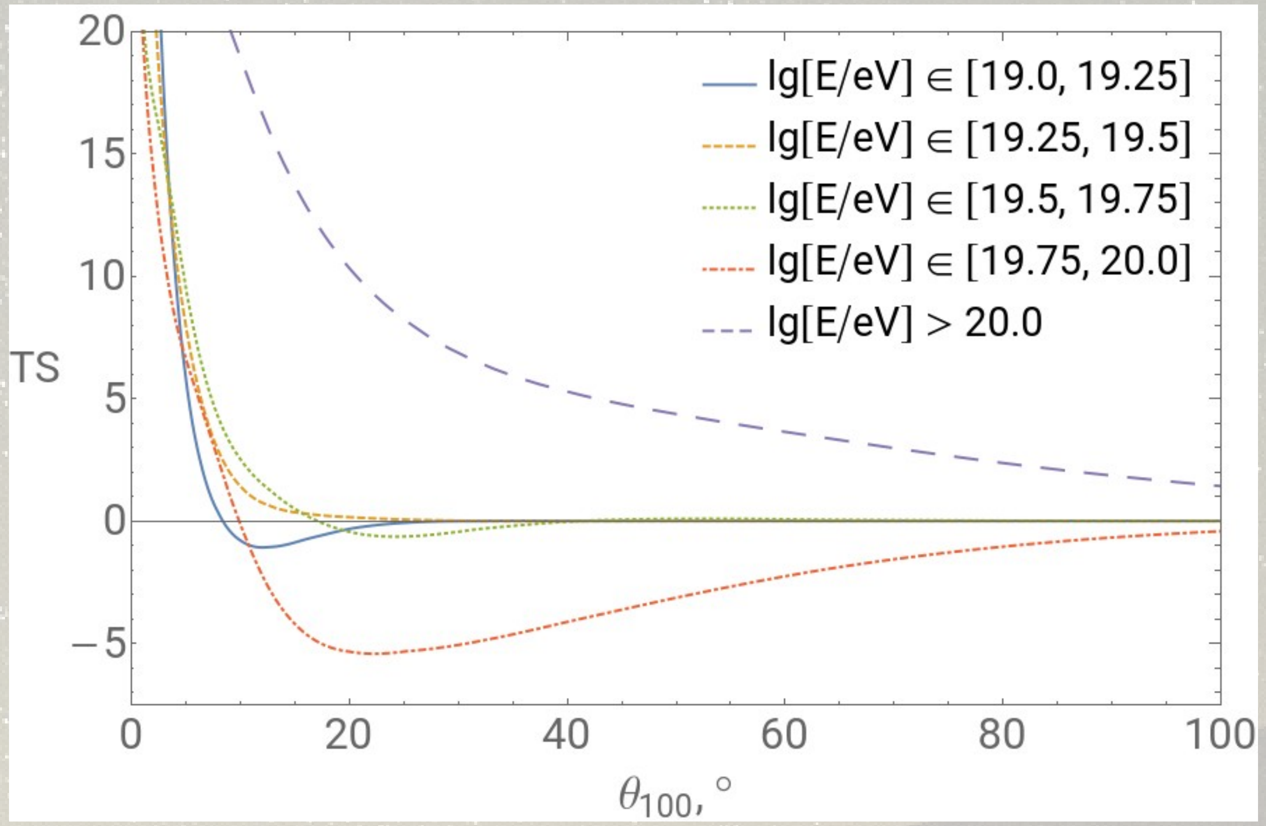
Iron map at E = 100 EeV



Оценка массового состава из отклонений от источников: результаты



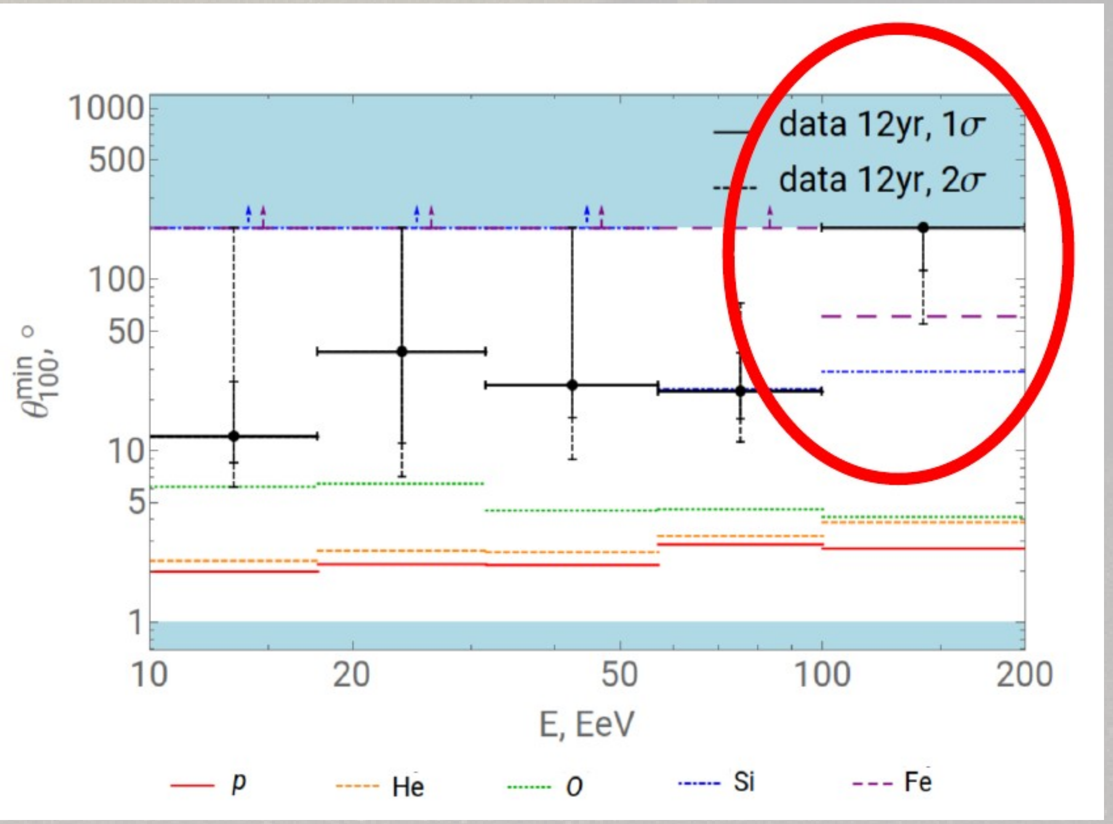
Карта ожидаемого потока КЛ при *E* > 100 ЭэВ



Сравниваем с симуляциями

$$TS(\theta) = -2\sum_{E_k}\left(\sum_i \ln \frac{\Phi_{E_k}(\theta, \mathbf{n}_i)}{\Phi_{\mathrm{iso}}(\mathbf{n}_i)}\right)$$

θ — средний угол отклонения КЛ от ожидаемых источников (галактик)

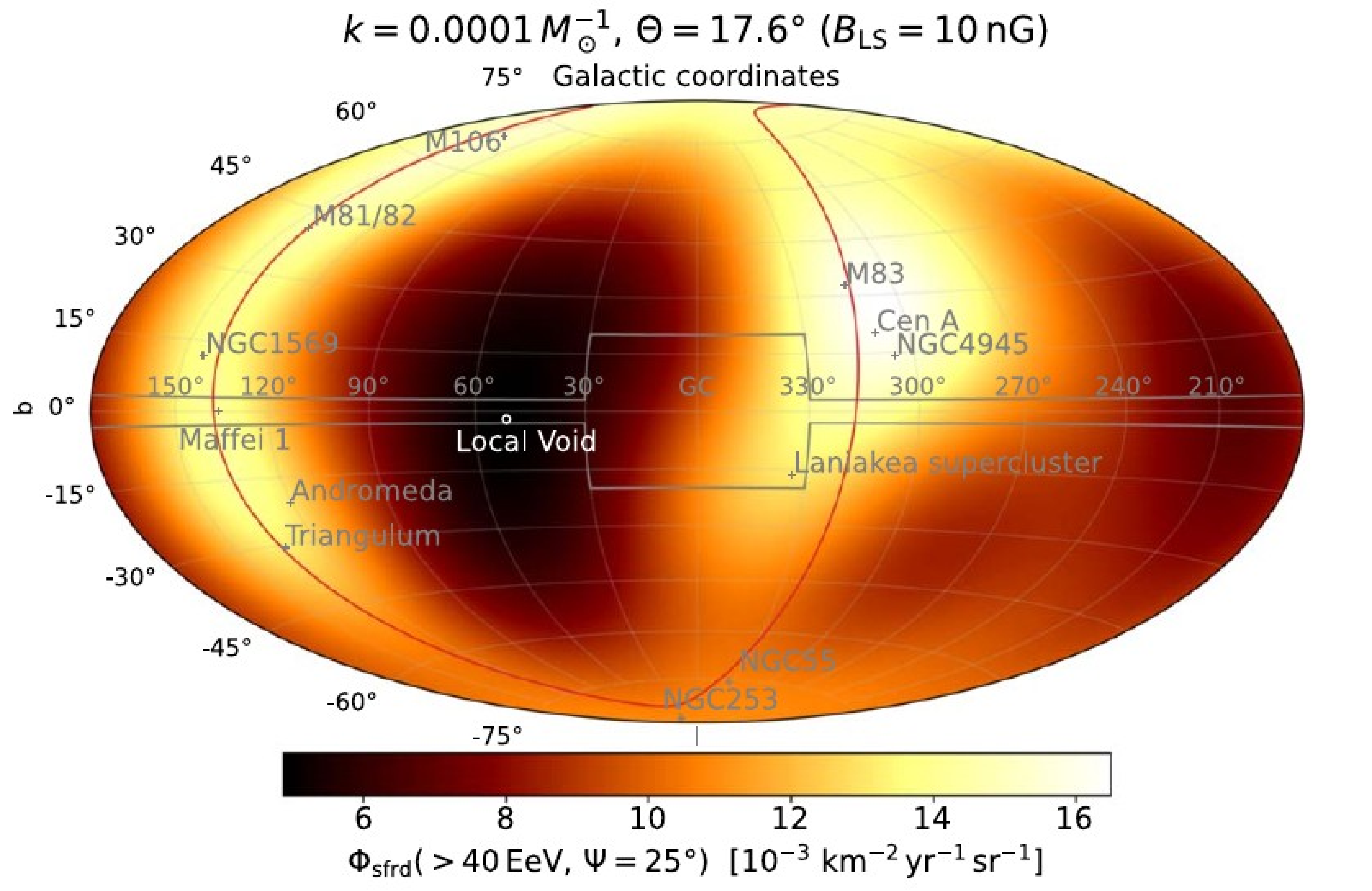


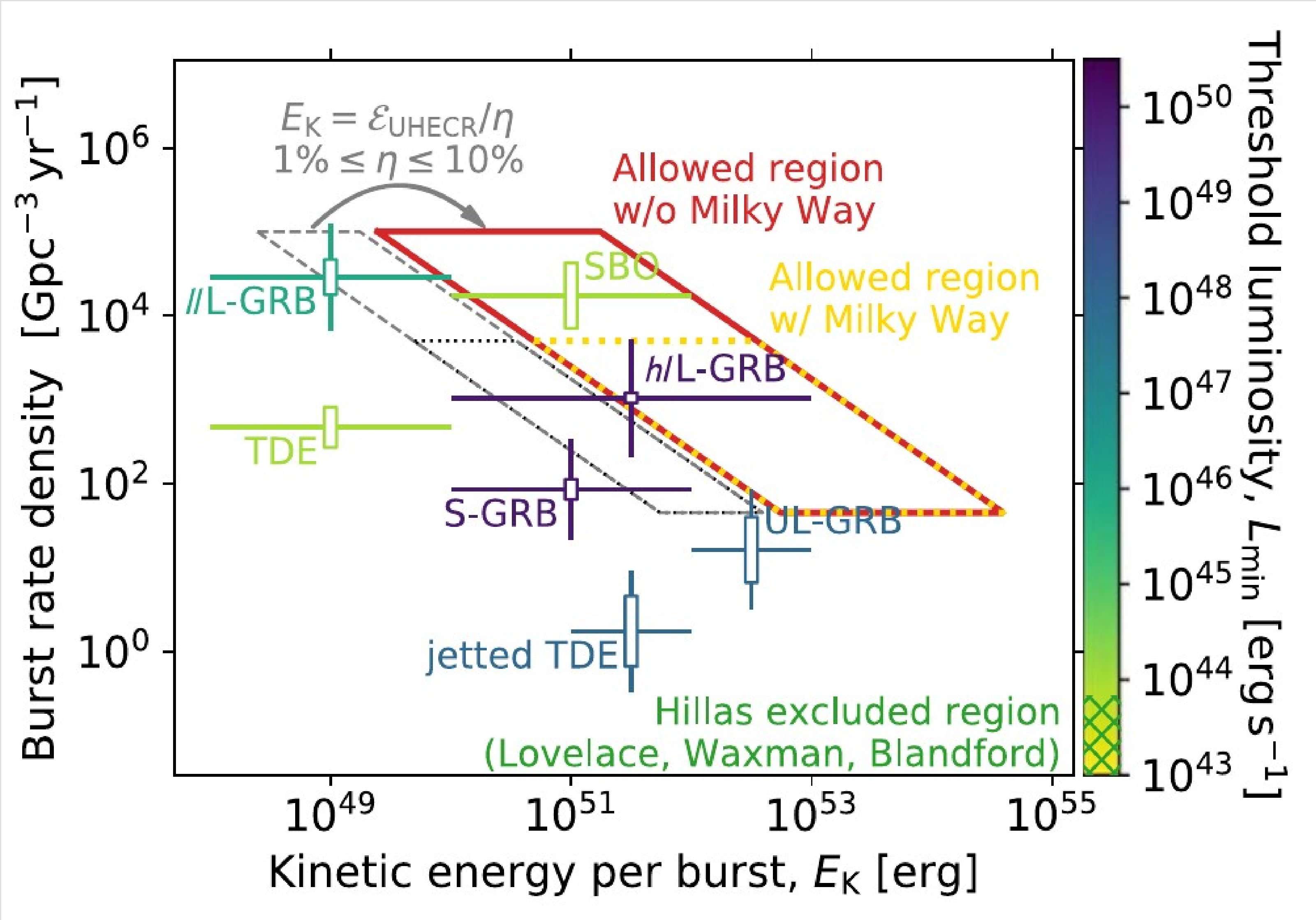
При E > 100 ЭэВ КЛ очень изотропны — **указание на очень тяжелый состав**

TA,
arXiv:2406.19286
arXiv:2406.19287

Ограничения на транзиентные источники из распределения событий и X_{max} Auger

Marafico et al., arXiv:2405.17179



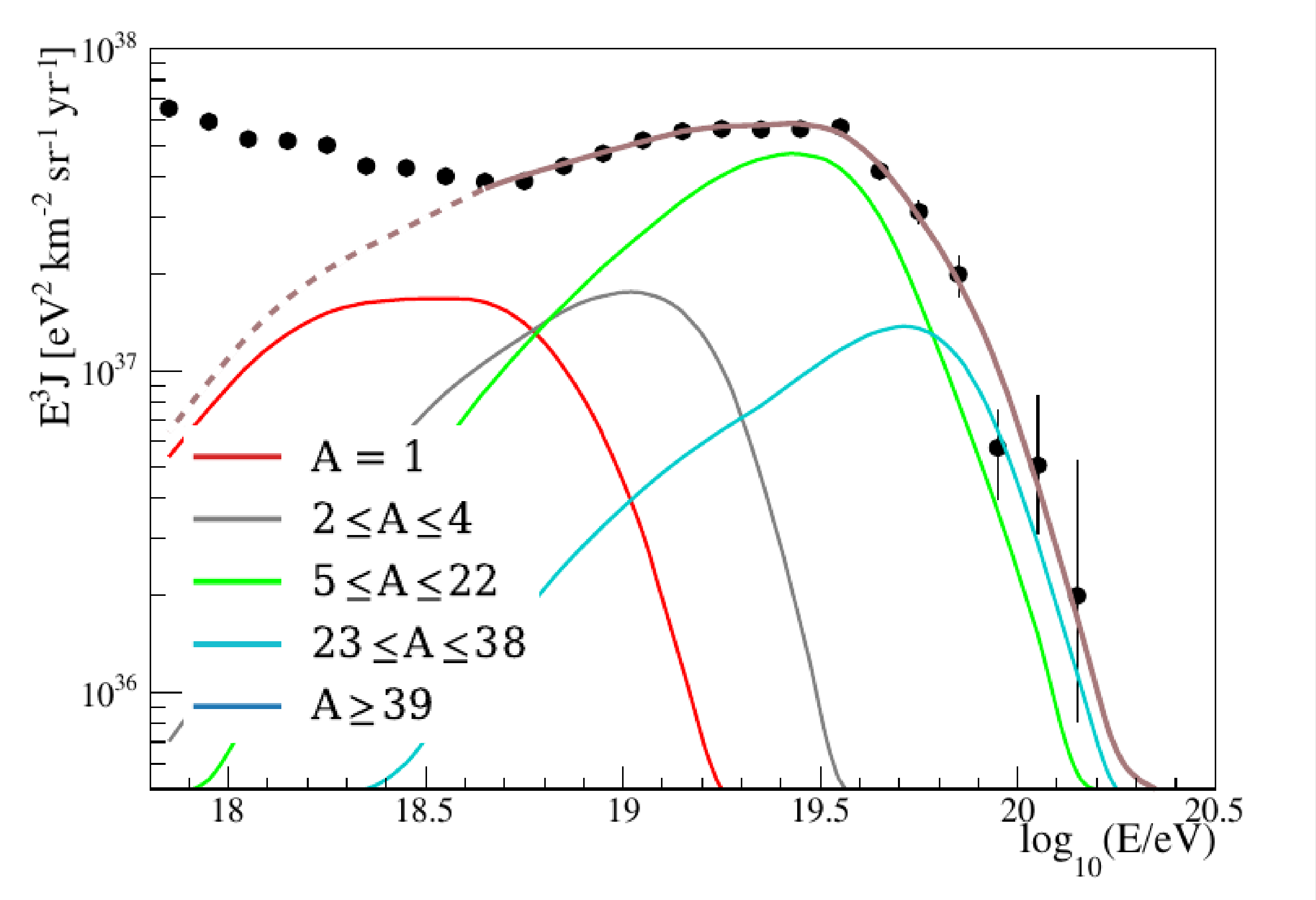


Фит спектра, X_{max} Auger и направлений прихода КЛУВЭ случайными картами транзиентных источников в LSS

- Использование трех наблюдаемых позволяет снять вырождение между темпом вспышек и энергией на одну вспышку (важны задержки сигнала из-за космических магнитных полей)
- Всем условиям удовлетворяют HL long GRB и Supernova Shock Breakouts
- Результаты зависят от предположений о галактических и внегалактических магн.полях

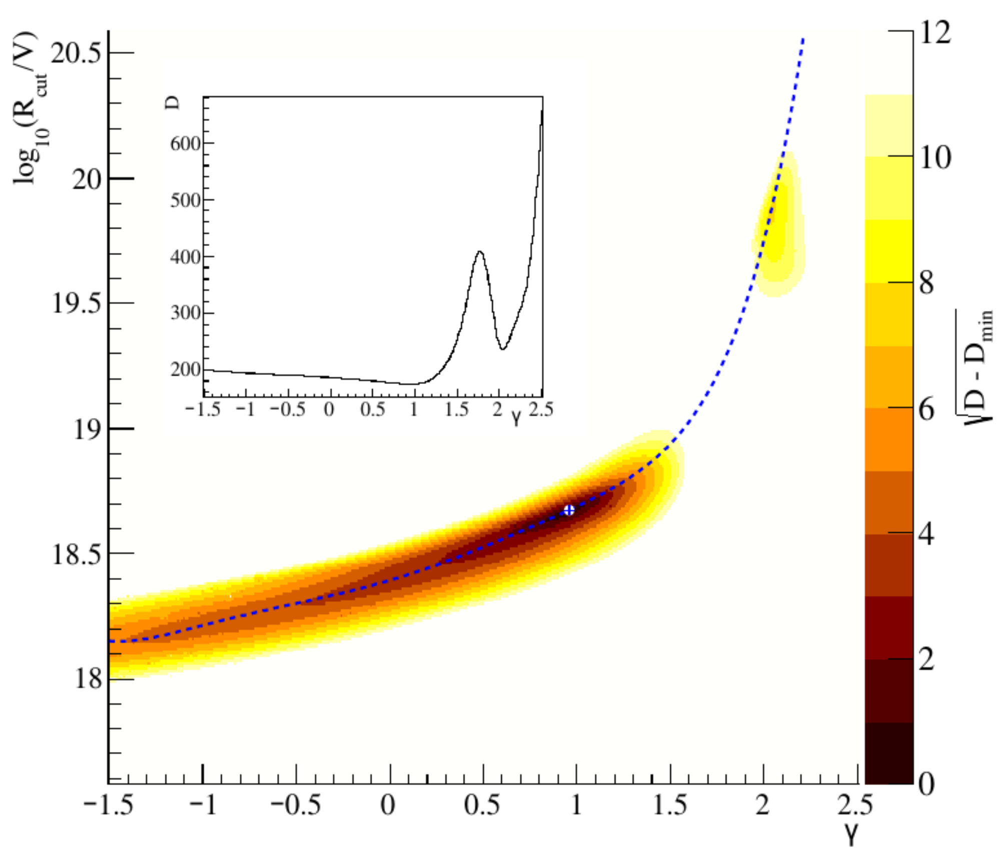
Какой состав КЛУВЭ испускают источники?

Одновременный фит спектра и Xmax определенной моделью инжекции,
с учетом эффектов распространения и детектирования (существенная модельная зависимость)



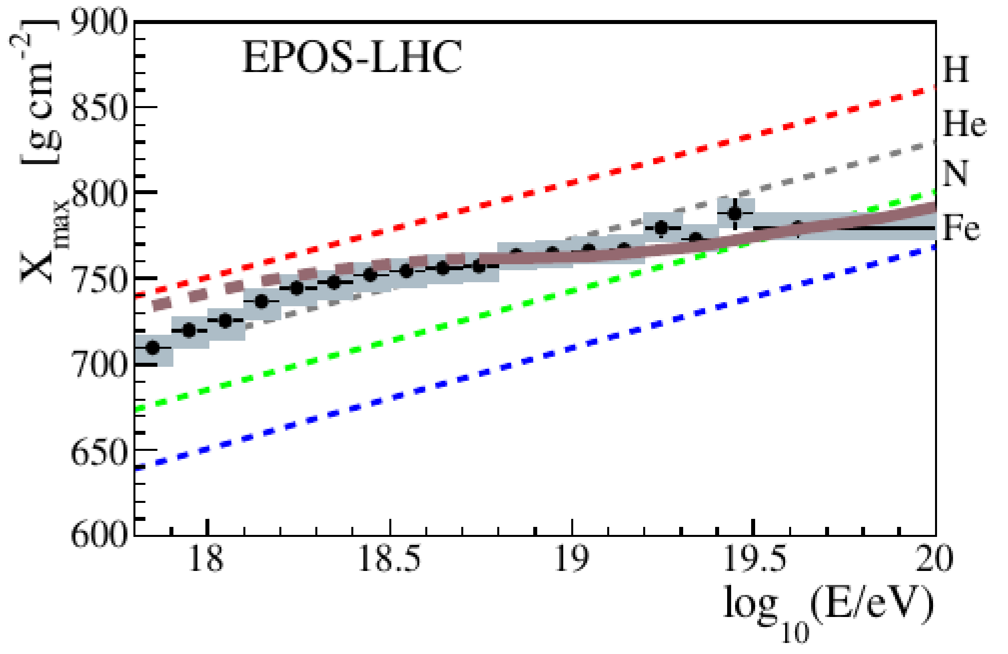
$$\tilde{Q}_A(E) = \tilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \le Z_A\, R_{\rm cut}; \\ \exp\left(1 - \frac{E}{Z_A\, R_{\rm cut}}\right), & E > Z_A\, R_{\rm cut}, \end{cases}$$

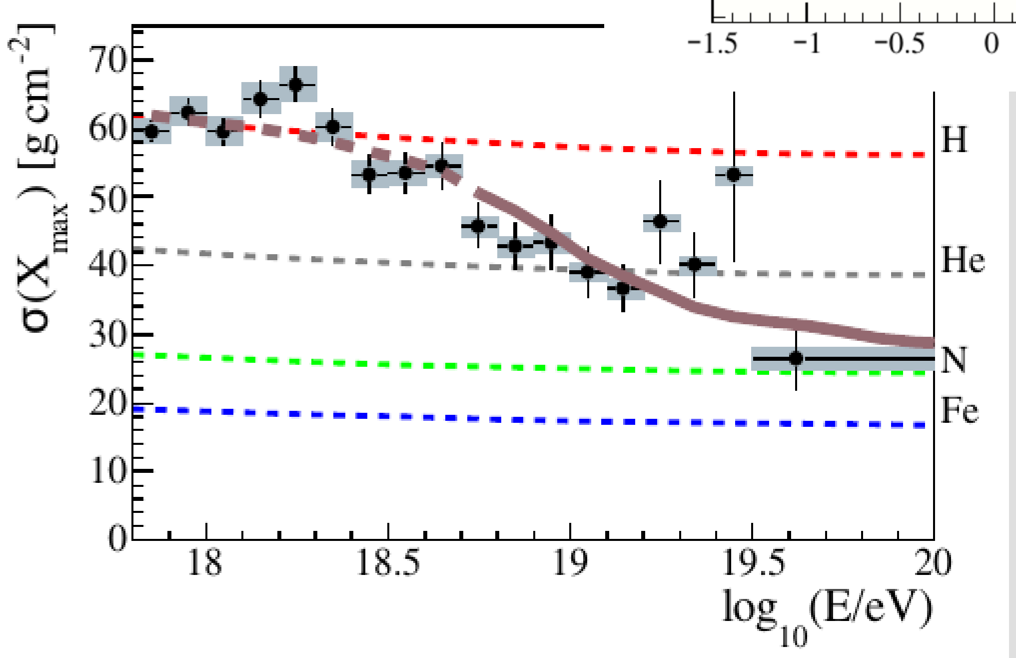
Auger, arXiv:1612.07155



Спектр очень жесткий!

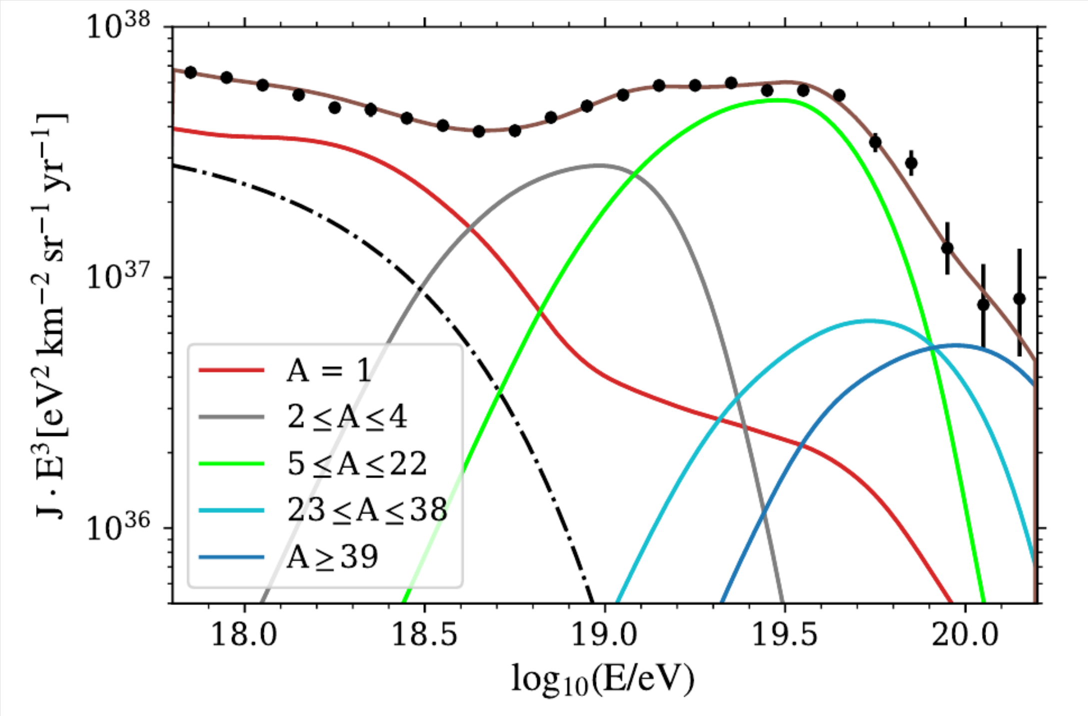
reference model	best fit
γ	1.22
$\log_{10}(R_{\rm cut}/{\rm V})$	18.72
$f_{\rm H}(\%)$	6.4
$f_{\rm He}(\%)$	46.7
$f_{\rm N}(\%)$	37.5
$f_{\rm Si}(\%)$	9.4
$\Delta X_{\rm max}/\sigma_{\rm syst}$	-0.63
$\Delta E/\sigma_{\rm syst}$	$+0.00$
D/n	166.5/117
$D\ (J),\ D\ (X_{\rm max})$	12.9, 153.5





Какой состав КЛУВЭ испускают источники?

Auger, arXiv:2211.02857

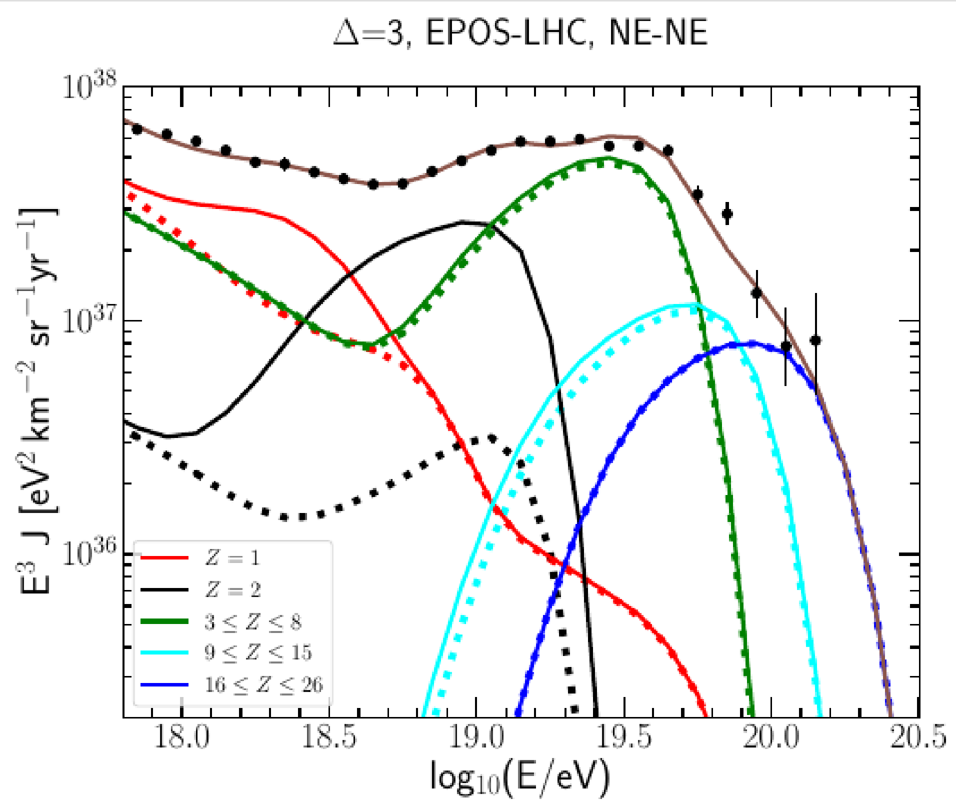


$$\tilde{Q}_A(E) = \tilde{Q}_{0A}\left(\frac{E}{E_0}\right)^{-\gamma}\begin{cases}1, & E \leq Z_A R_{cut};\\ \exp\left(1-\frac{E}{Z_A R_{cut}}\right), & E > Z_A R_{cut},\end{cases}$$

Galactic contribution (at Earth)	pure N	
$J_0^{Gal}/(eV^{-1}\,km^{-2}\,sr^{-1}\,yr^{-1})$	$(1.06 \pm 0.04)\times 10^{-13}$	
$\log_{10}(R_{cut}^{Gal}/V)$	17.48 ± 0.02	
EG components (at the escape)	LE	HE
$\mathcal{L}_0/(10^{44}\,erg\,Mpc^{-3}\,yr^{-1})$ *	6.54 ± 0.36	5.00 ± 0.35
γ	3.34 ± 0.07	-1.47 ± 0.13
$\log_{10}(R_{cut}/V)$	>19.3	18.19 ± 0.02
I_H (%)	100 (fixed)	0.0 ± 0.0
I_{He} (%)	—	24.5 ± 3.0
I_N (%)	—	68.1 ± 5.0
I_{Si} (%)	—	4.9 ± 3.9
I_{Fe} (%)	—	2.5 ± 0.2
D_J (N_J)	48.6 (24)	
$D_{X_{max}}$ ($N_{X_{max}}$)	537.4 (329)	
D (N)	586.0 (353)	

Добавили галактическую компоненту или вторую внегалактическую:
Спектр основной компоненты растущий!

Дополнительно учли возможное наличие внегал. магн.поле
Можно получить спектр в источниках близкий к E^{-2} если есть сильное поле:
$B_{rms} \simeq (50-100)nG\ (20Mpc/D)\ (100kpc/\lambda)^{1/2}$

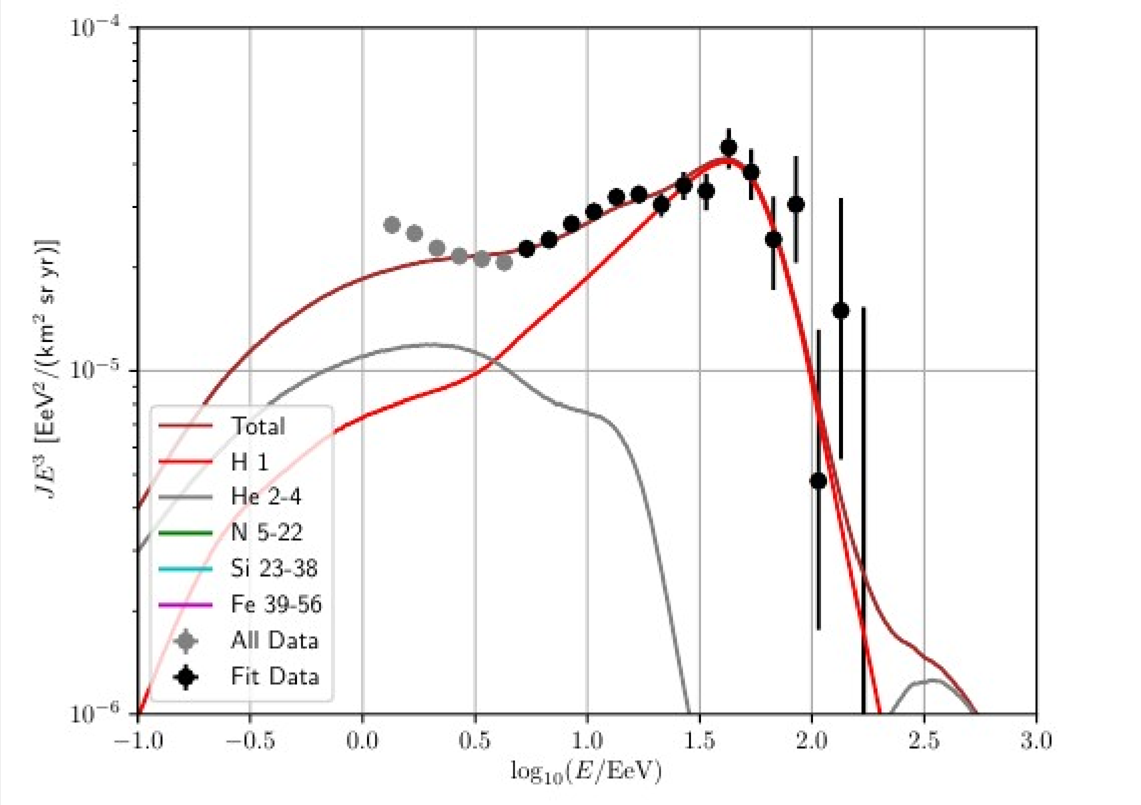


Auger, arXiv:2404.03533

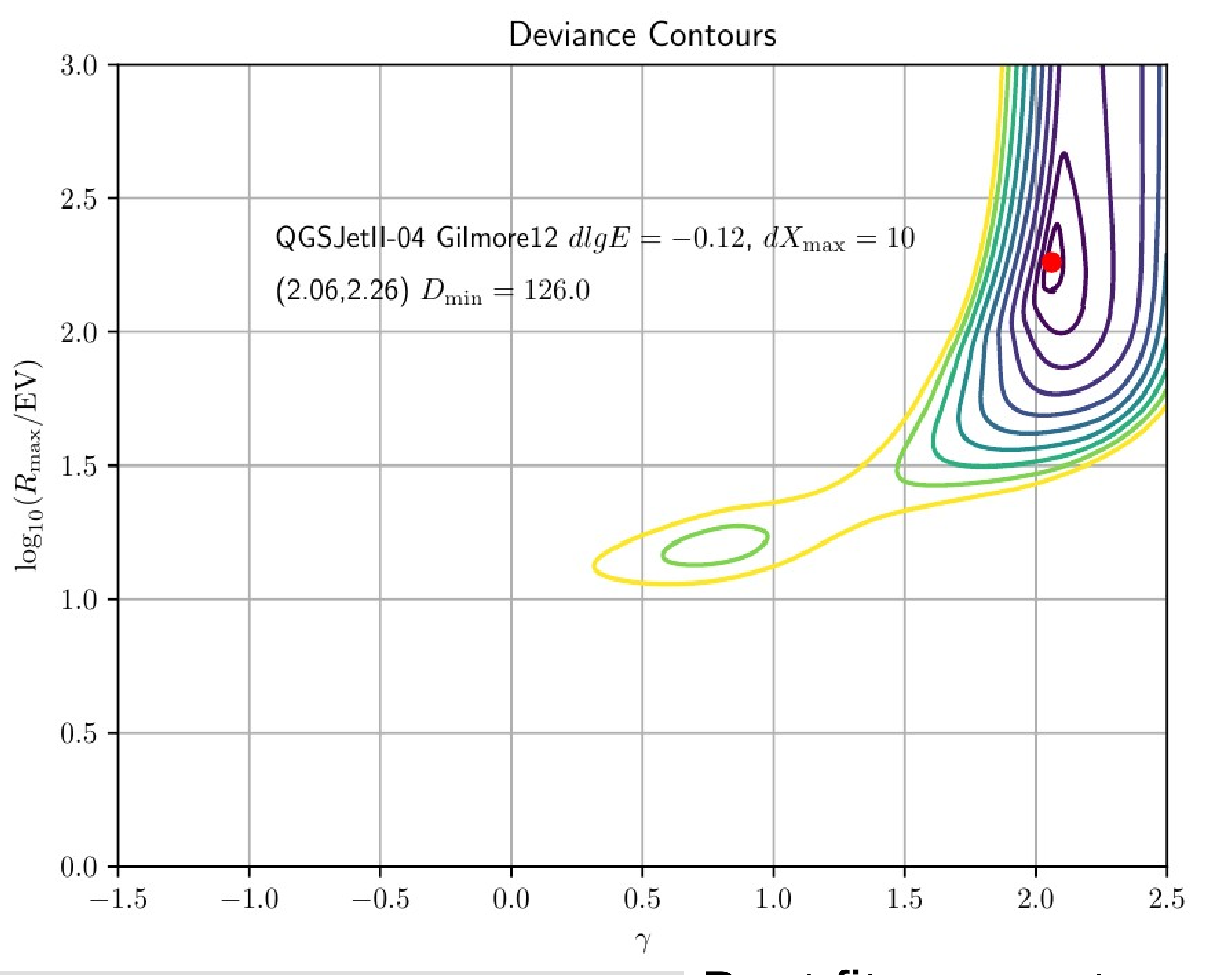
with EGMF, NE-NE

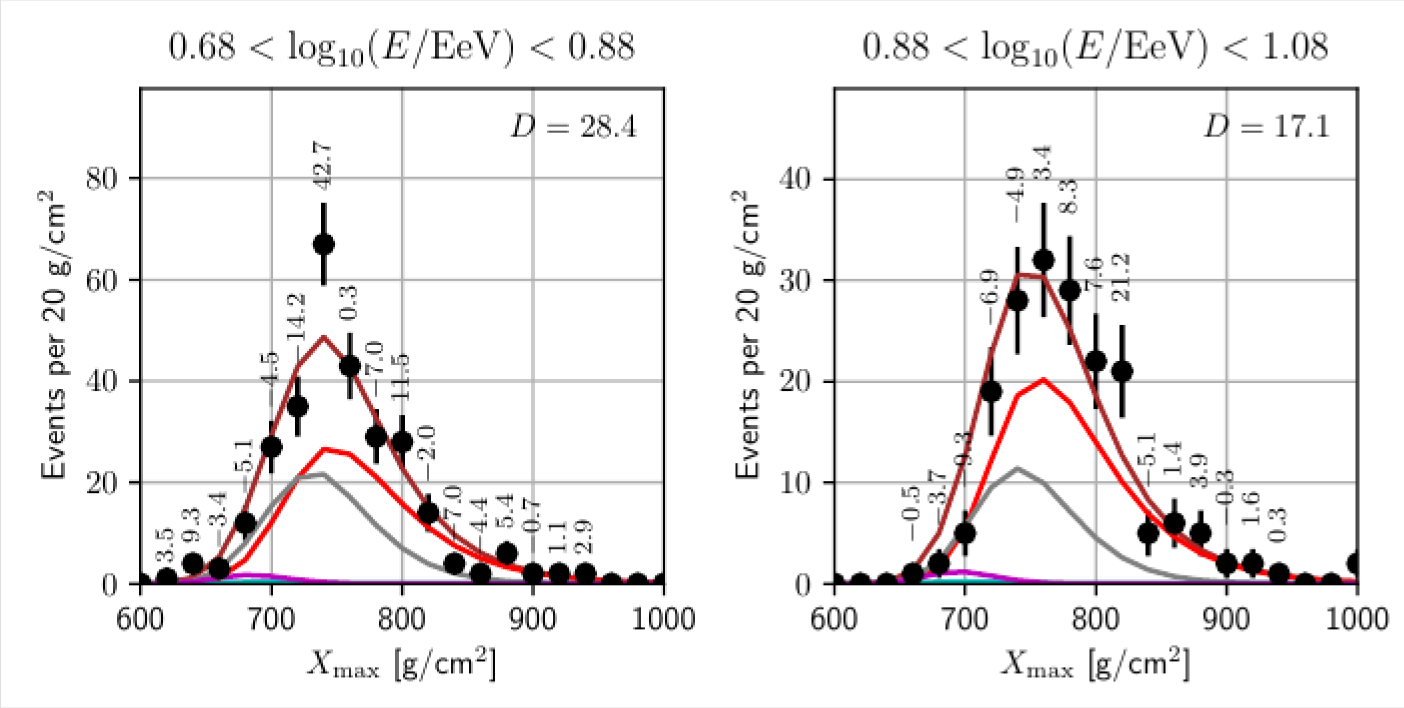
Δ	EPOS-LHC γ_H	R^H_{cut} [EeV]	γ_L	R^L_{cut} [EeV]	X_s	R_{crit} [EeV]	D ($N = 353$)	Sibyll 2.3d γ_H	R^H_{cut} [EeV]	γ_L	R^L_{cut} [EeV]	X_s	R_{crit} [EeV]	D ($N = 353$)
1	−2.19	1.35	3.54	> 60	0	–	572	−1.67	1.42	3.37	2.21	0	–	660
2	1.03	6.02	3.62	> 51	> 3.2	1.97	583	1.35	6.22	3.53	> 25	> 3.1	1.54	635
3	1.43	7.50	3.69	> 61	2.8	2.79	614	2	7.50	3.62	> 31	2.6	3.77	640
SFR-NE														
1	−2.09	1.39	3.24	> 63	0	–	578	−1.64	1.44	3.03	2.89	0	–	665
2	1.12	6.14	3.33	> 61	> 3.5	2.11	586	1.45	6.29	3.21	> 37	> 3.2	1.67	635
3	1.49	7.52	3.41	> 57	2.7	3.15	617	2.07	7.49	3.31	> 33	2.8	3.52	637

Какой состав КЛУВЭ испускают источники?



$$\tilde{Q}_A(E) = \tilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \le Z_A R_{\mathrm{cut}}; \\ \exp\left(1 - \frac{E}{Z_A R_{\mathrm{cut}}}\right), & E > Z_A R_{\mathrm{cut}}, \end{cases}$$



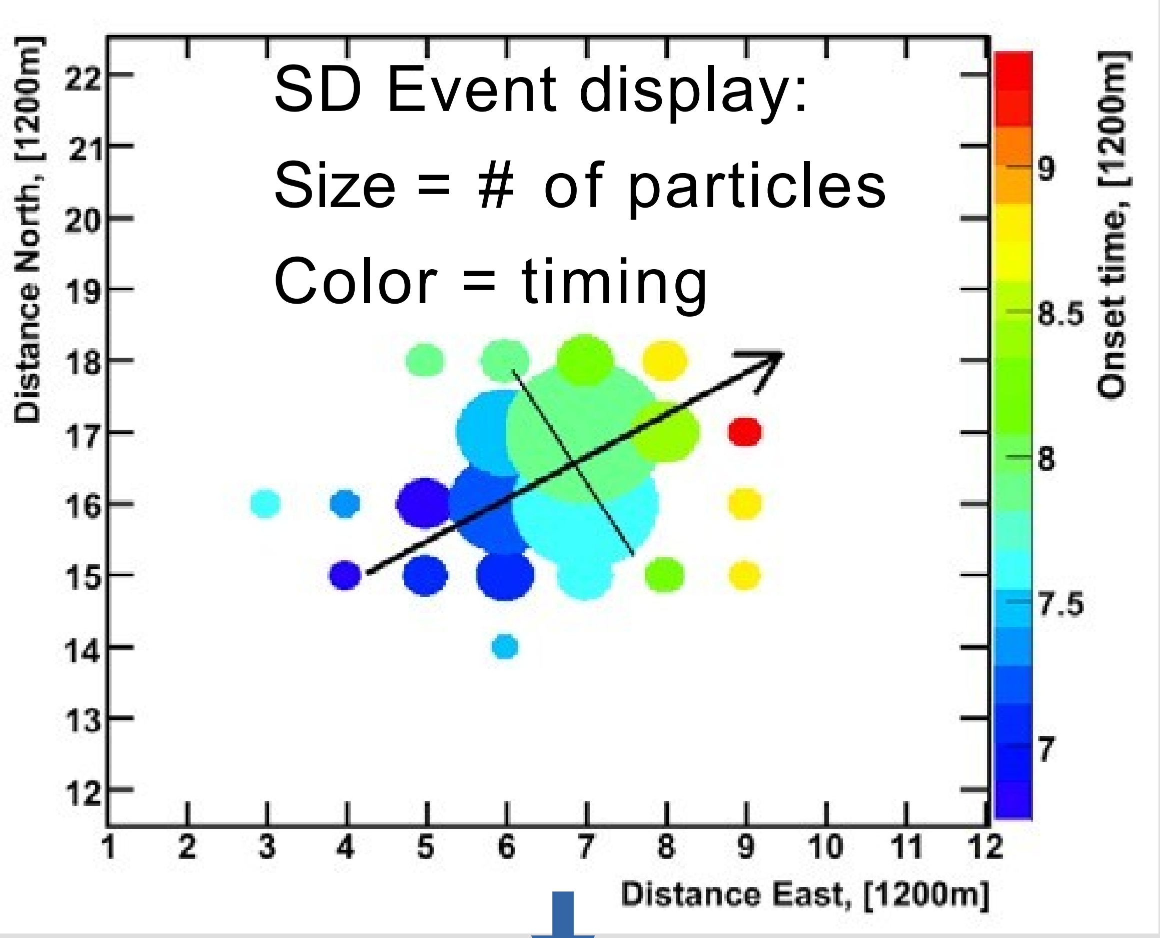


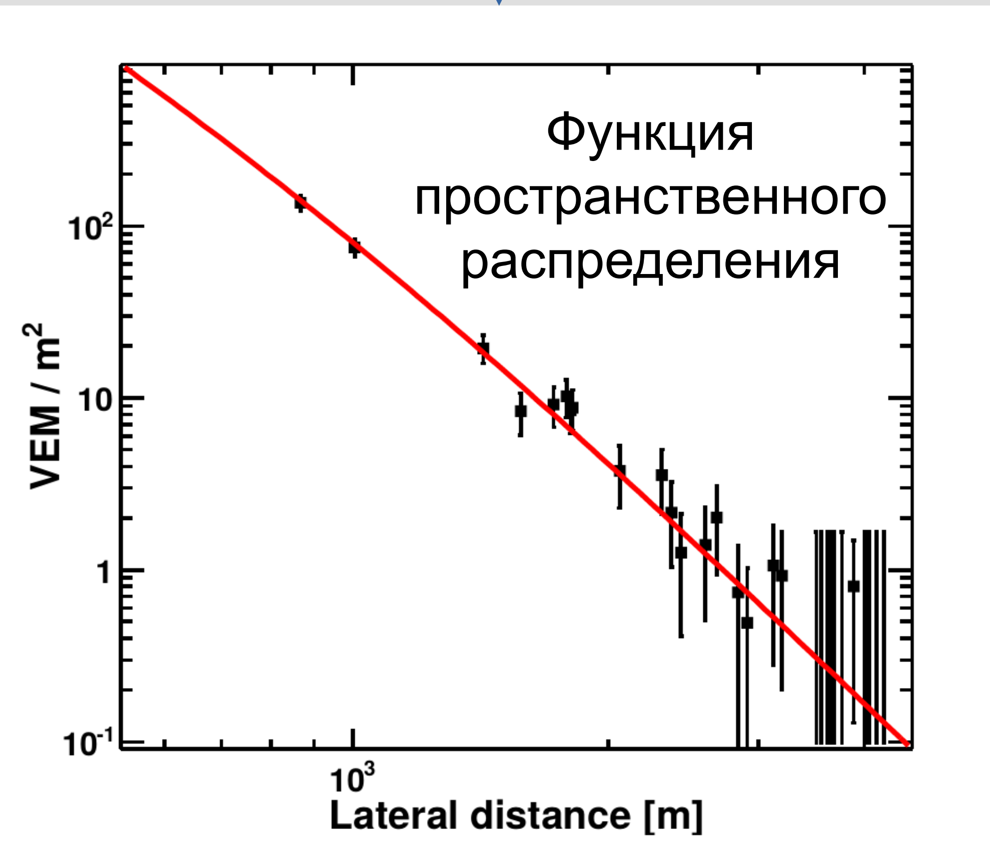
Параметры близки к ожидаемым из классической теории ускорения КЛ

Best fit parameters:
γ = 2.06
R_{cut} = 182 EV
Q_{0p} = 0.0%,
Q_{oHe} = 99.2%,
Q_{0N} = 0.0%,
Q_{0Si} = 0.0%,
Q_{0Fe} = 0.8%

TA @ ICRC-2021

Реконструкция наземного события

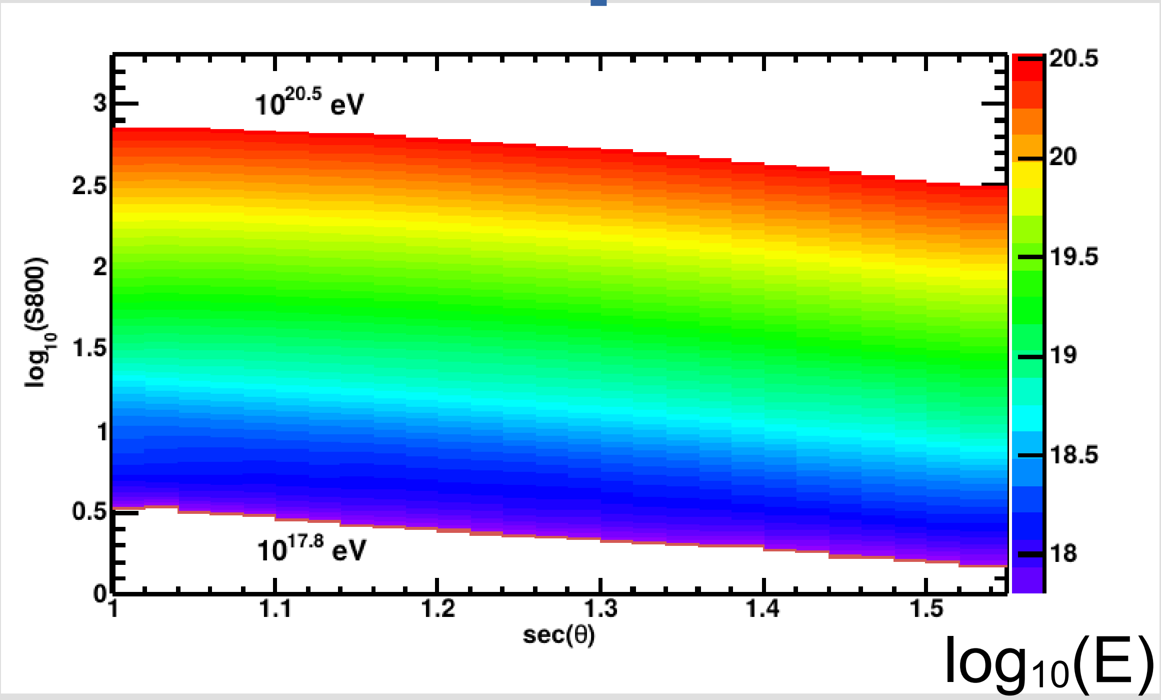




$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

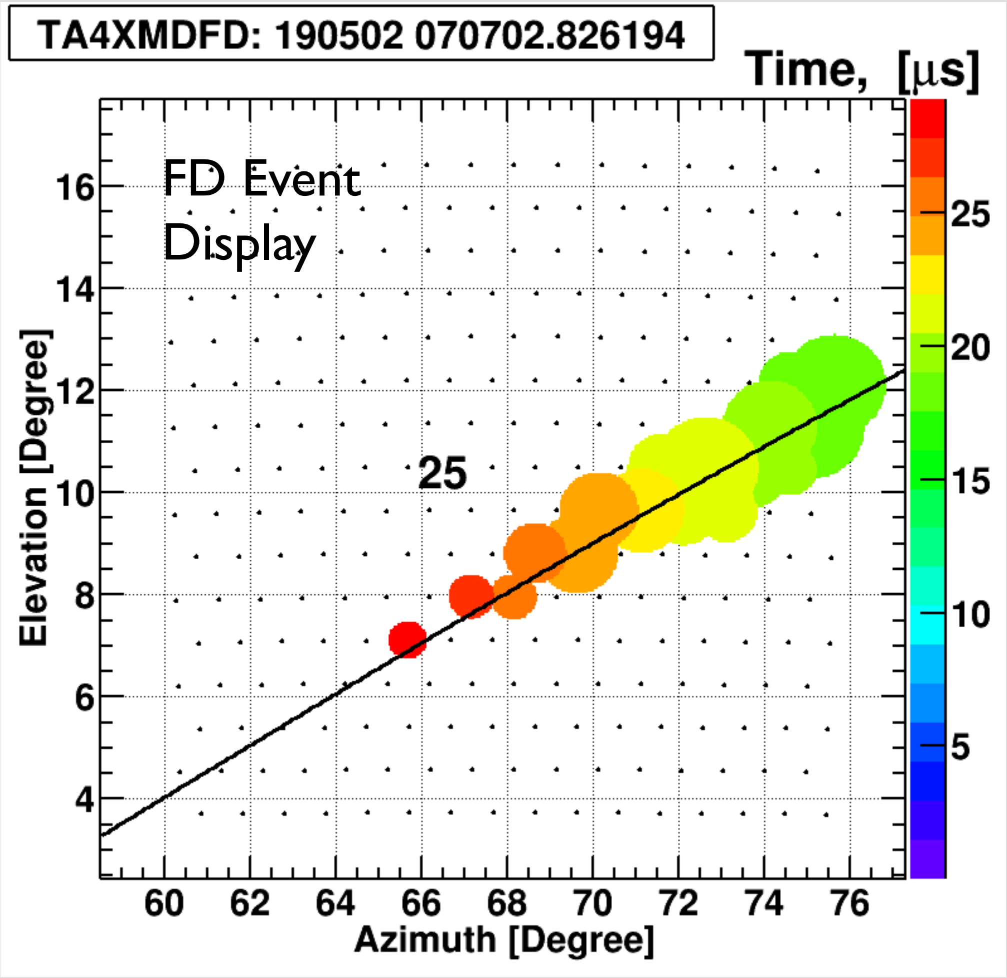
$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta) - 1]$$

s — расстояние до оси ливня
θ — зенитный угол



$E = E(\rho_{800}, \theta)$

Реконструкция флуоресцентного события

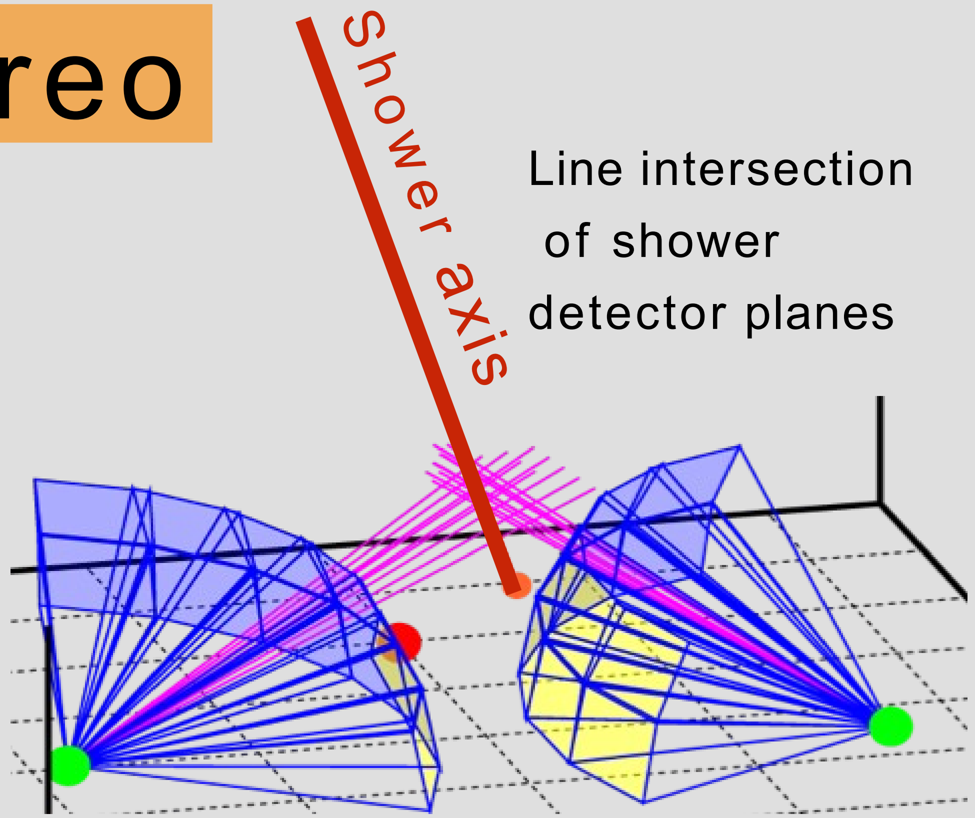


SD энергия перешкалируется к более точному FD масштабу

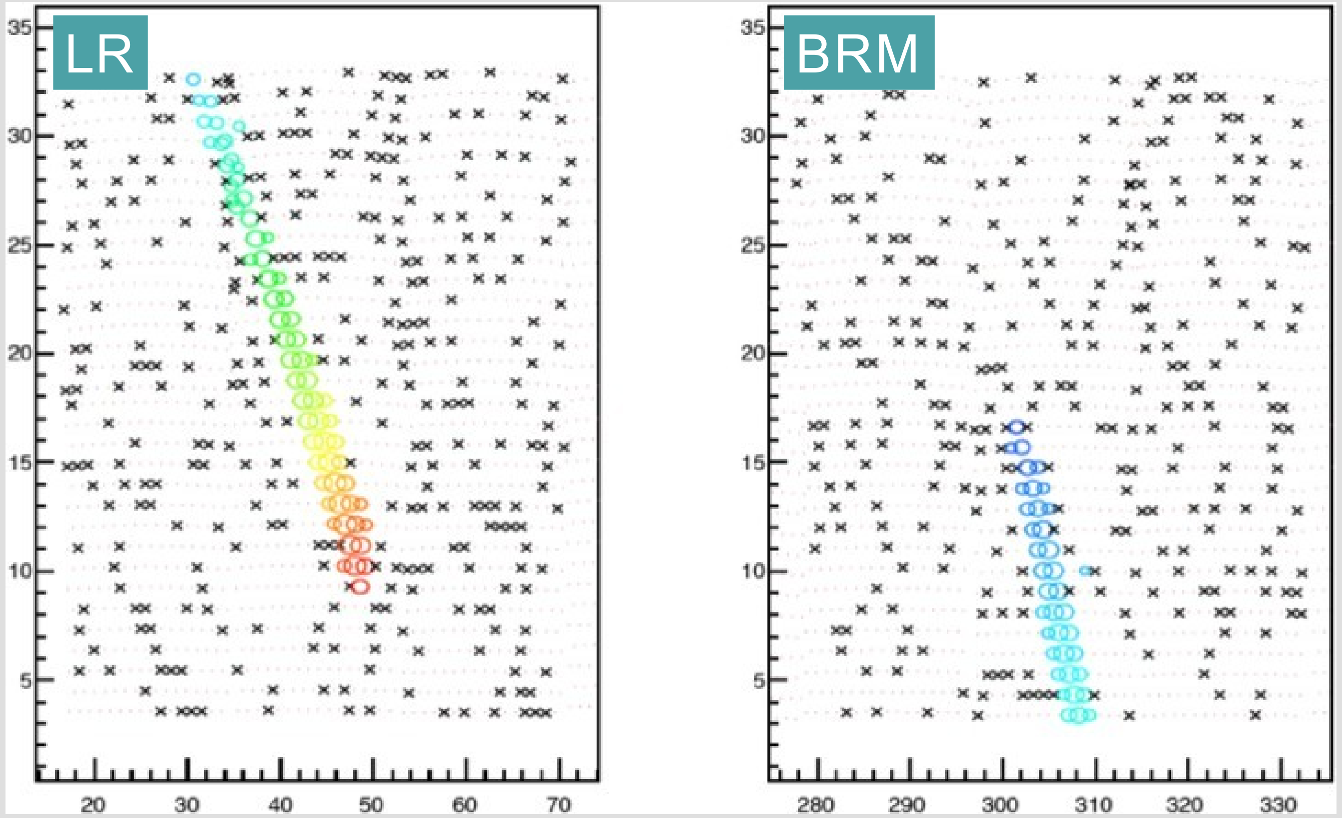
$E_{final} = E_{SD} / 1.27$

FD Event reconstruction

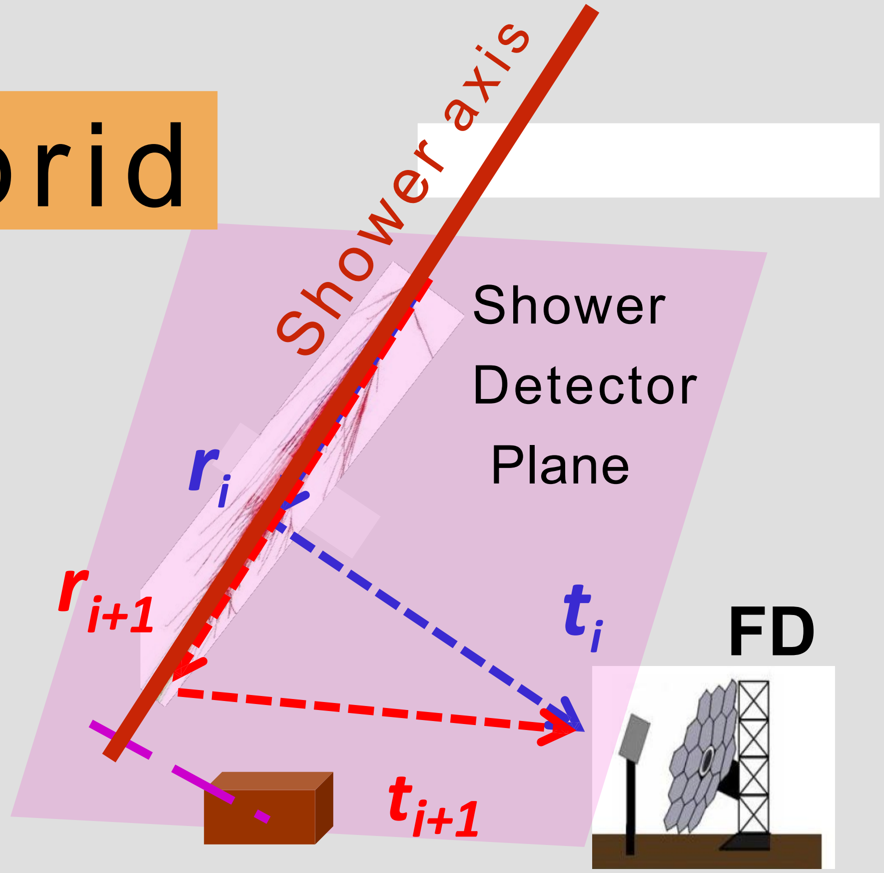
Stereo



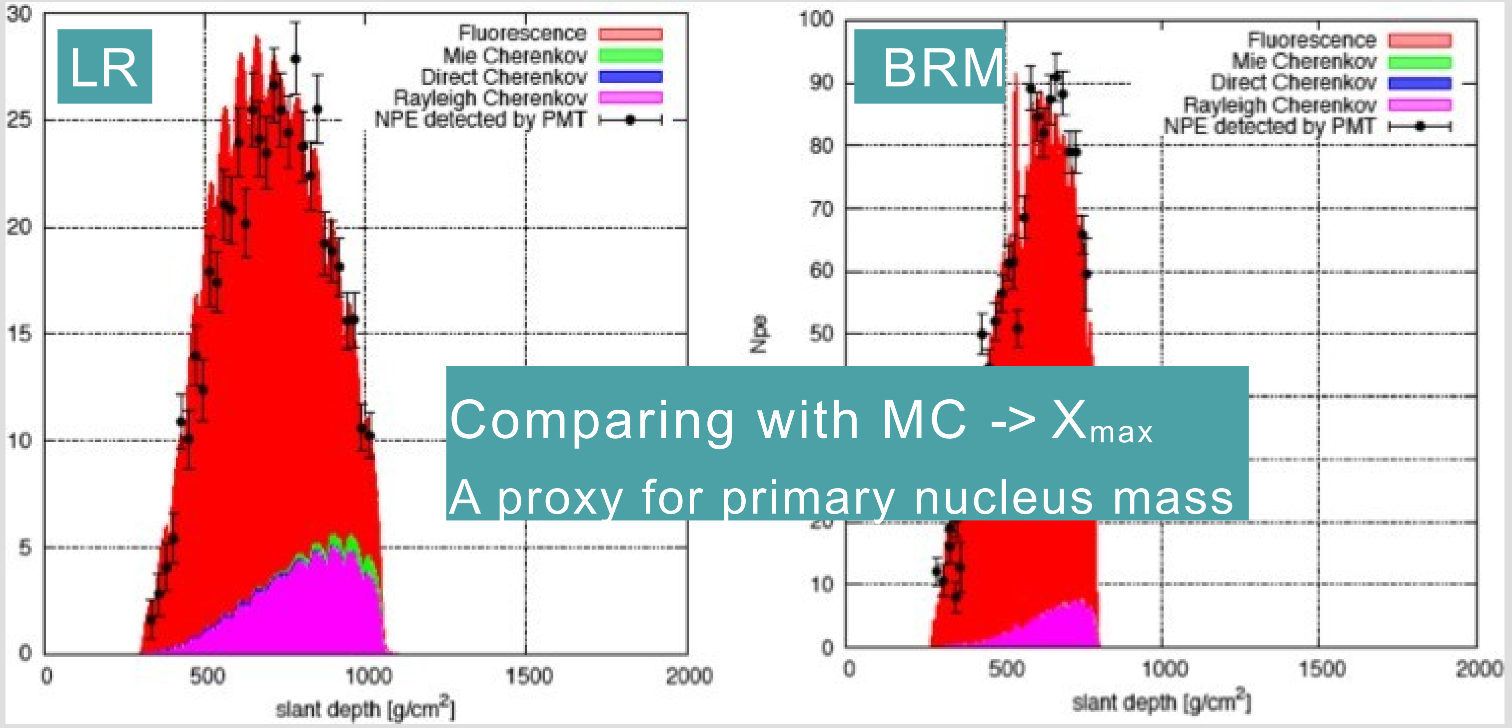
observed images



Hybrid



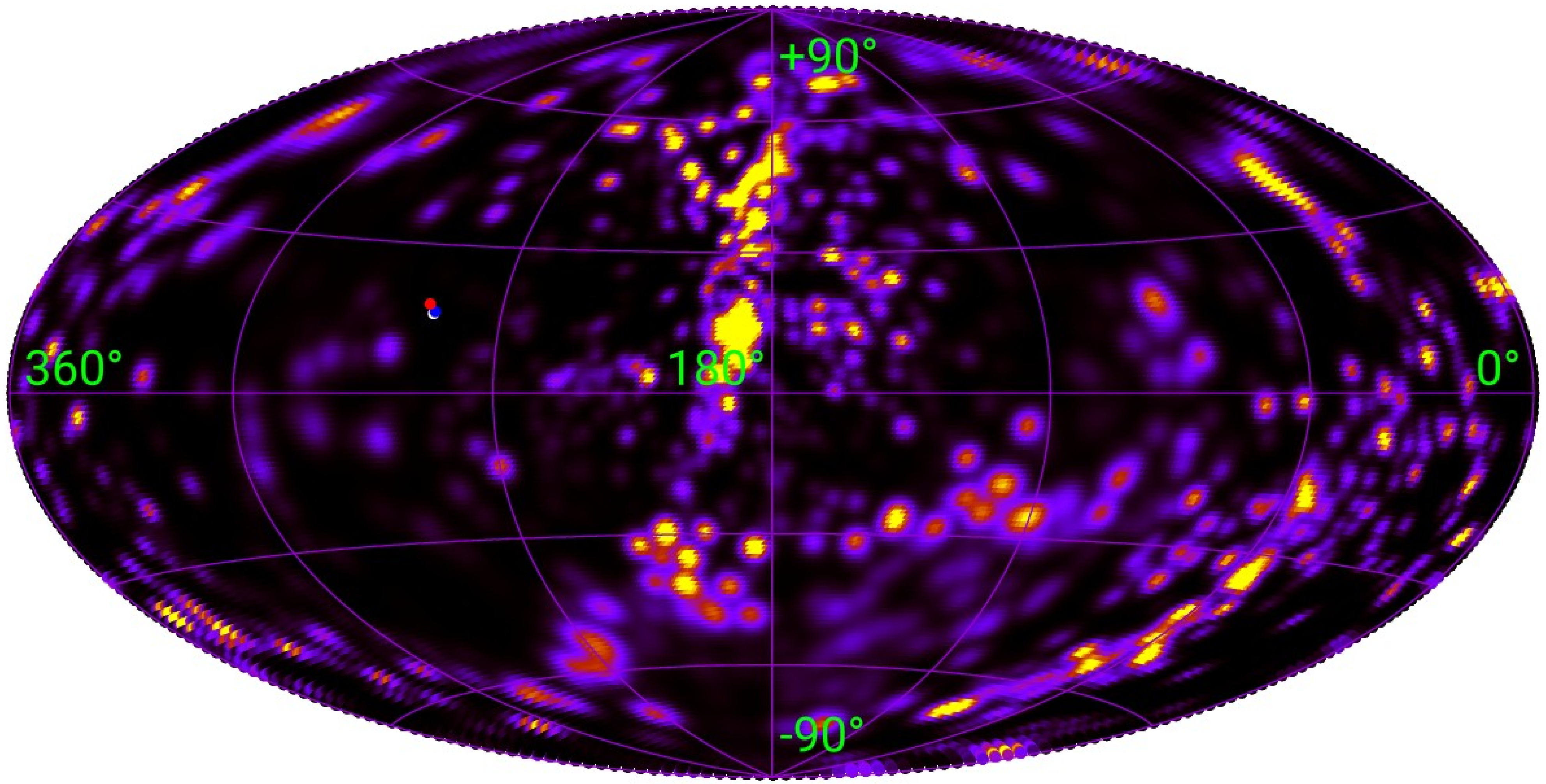
reconstructed shower profiles



Comparing with MC -> X_{max}
A proxy for primary nucleus mass

Корреляция с источниками, протонный сценарий

- Предположим что источник находится в какой-то галактике и он испускает протон
- Базовый сценарий: E = 244 ЭэВ, отклонение в галактическом магн. поле учтено, внегалактическое поле слабое
- Относительный ожидаемый поток с направления прихода частицы менее 1%→ базовый протонный сценарий маловероятен

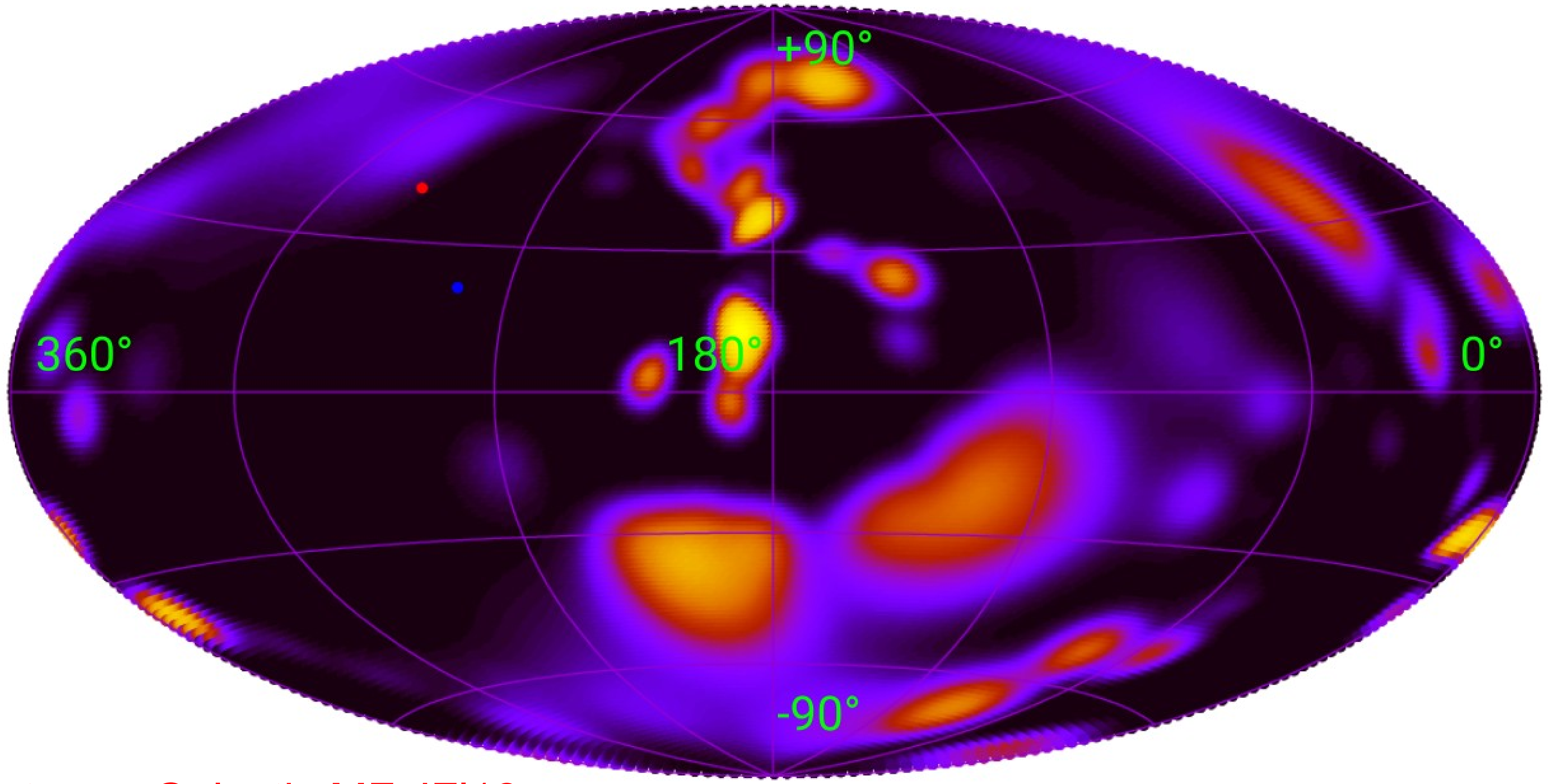


Red dot: reg. Galactic MF JF'12
Blue: reg. Galactic MF PT'11

Корреляция с источниками, ядерный сценарий

- Предположим что источник испускает какое-то ядро
  - Из-за рассеяния на космическом фоновом излучении рождается каскад ядер с меньшим зарядом и протонов
  - Базовый сценарий: E = 244 ЭэВ, отклонение в галактическом магн. поле учтено, внегалактическое поле слабое
- Хотим поставить ограничения на корреляцию с 95% точностью:
  - Каков минимальный заряд излученного ядра чтобы относительный ожидаемый поток с направления прихода составлял хотя бы 5 %?

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



Red dot: reg. Galactic MF JF'12
Blue: reg. Galactic MF PT'11

Ограничения на концентрацию источников КЛ

Мы получили ограничение на расстояние до ближайшего источника: $D < 5.0^{+8.0}_{-0.0}$ Mpc
(нижней неопределенности нет из за ограничения каталога)

Хотим перевести это в универсальное ограничение на концентрацию источников КЛ: ρ

Считаем, что источники распределены во Вселенной вцелом случайно, по Пуассону

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

N — количество источников в объеме V

Чтобы получить ограничения на ρ на уровне 95% мы симулируем множество Пуассоновых реализаций 3D карты источников и требуем чтобы хотя бы один источник попадал в объем $V = 4/3\ \pi\ D^3$ по крайней мере в 5% реализаций

В базовом ядерном сценарии получаем D < 5.0 Mpc → ρ > 1.0 · 10^{-4} Мпк$^{-3}$

Распространенность элементов в Солнечной Системе