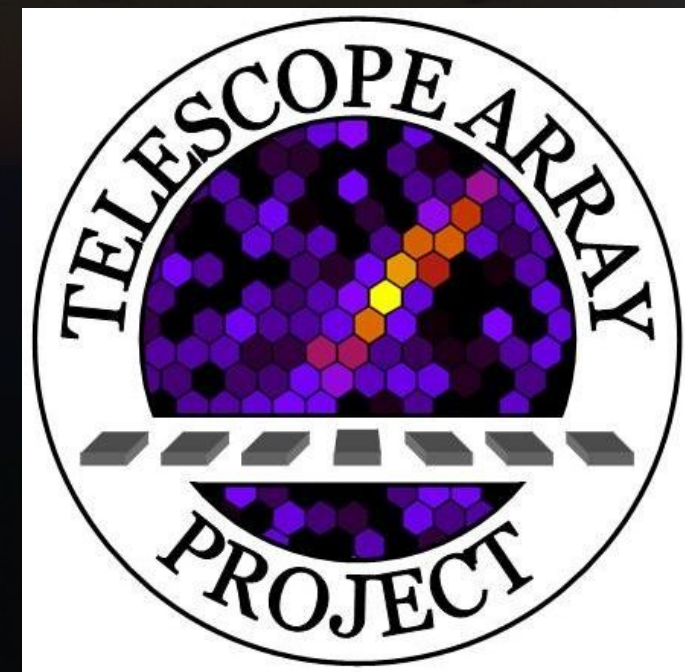


UHECR anisotropy and search for their sources

Mikhail Kuznetsov
INR RAS



Quarks-2026
Petrozavodsk, 23.05.2026

Outline

- Ultra-high energy cosmic rays (UHECR)
- Search for sources: cosmic rays astronomy?
- UHECR anisotropy observations
- UHECR anisotropy interpretations
 - Anisotropy measurements \neq sources identification!
 - Search for close source(s)
 - Constraints for source number density
 - Distinguish source classes
- Perspectives

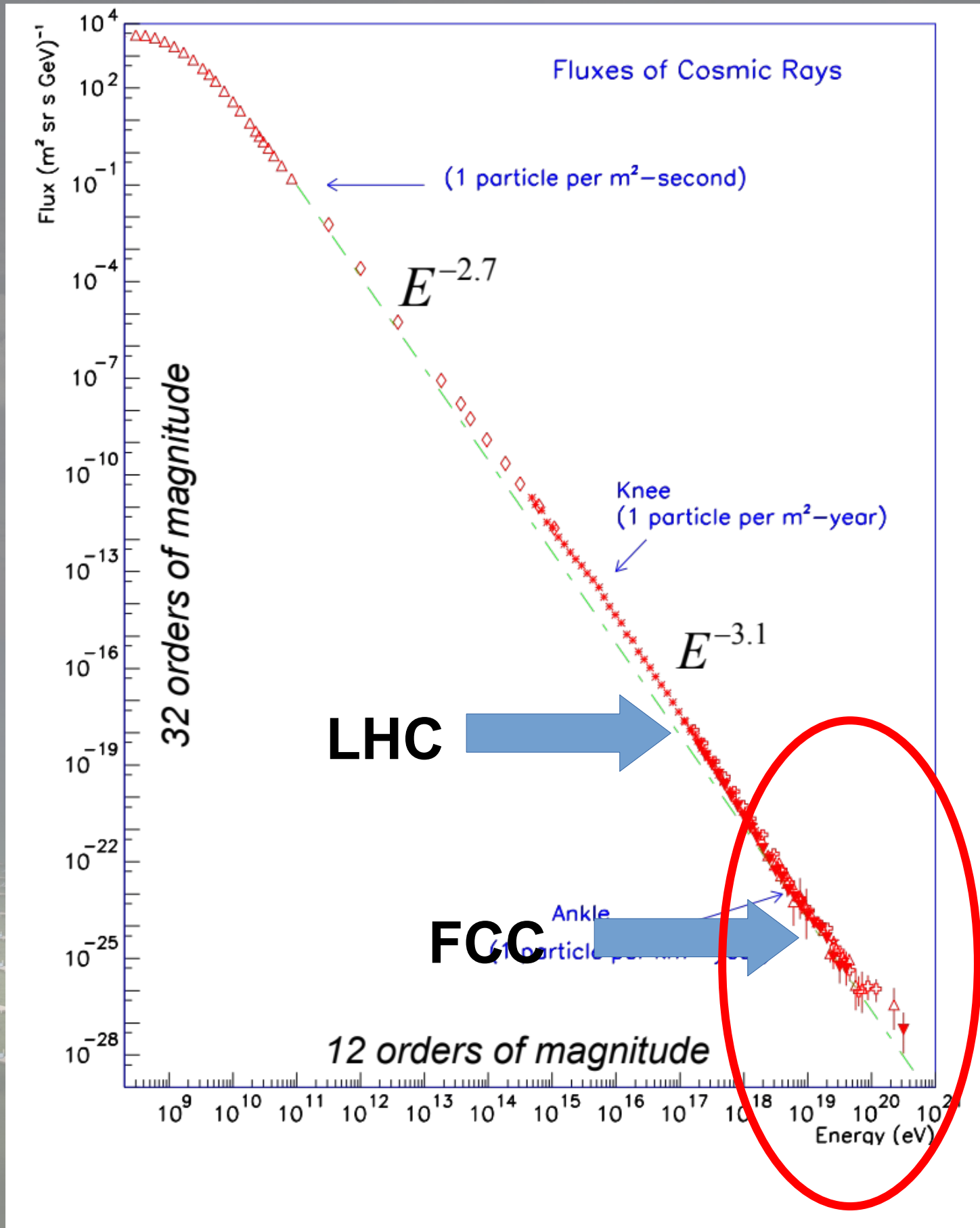
Ultra-high energy cosmic rays

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

From the list of 30 unsolved physical problems for XXI century

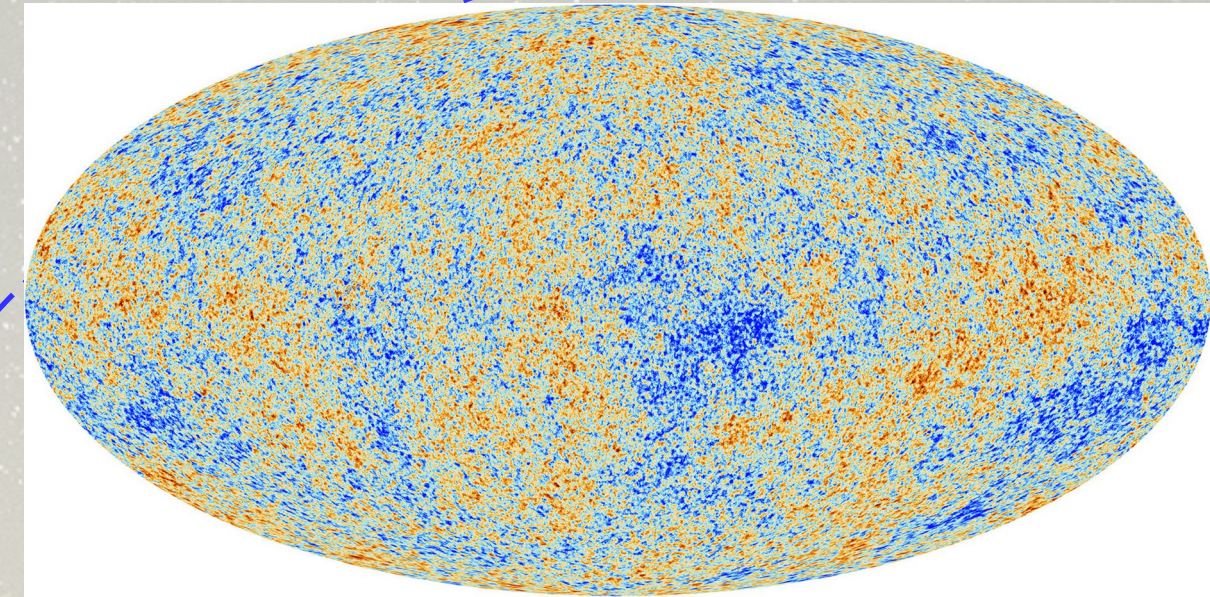
27. Проблема темной материи (скрытой массы) и ее детектирования.
28. Происхождение космических лучей со сверхвысокой энергией.
29. Гамма-всплески. Гиперновые.

V.L. Ginzburg, 2001



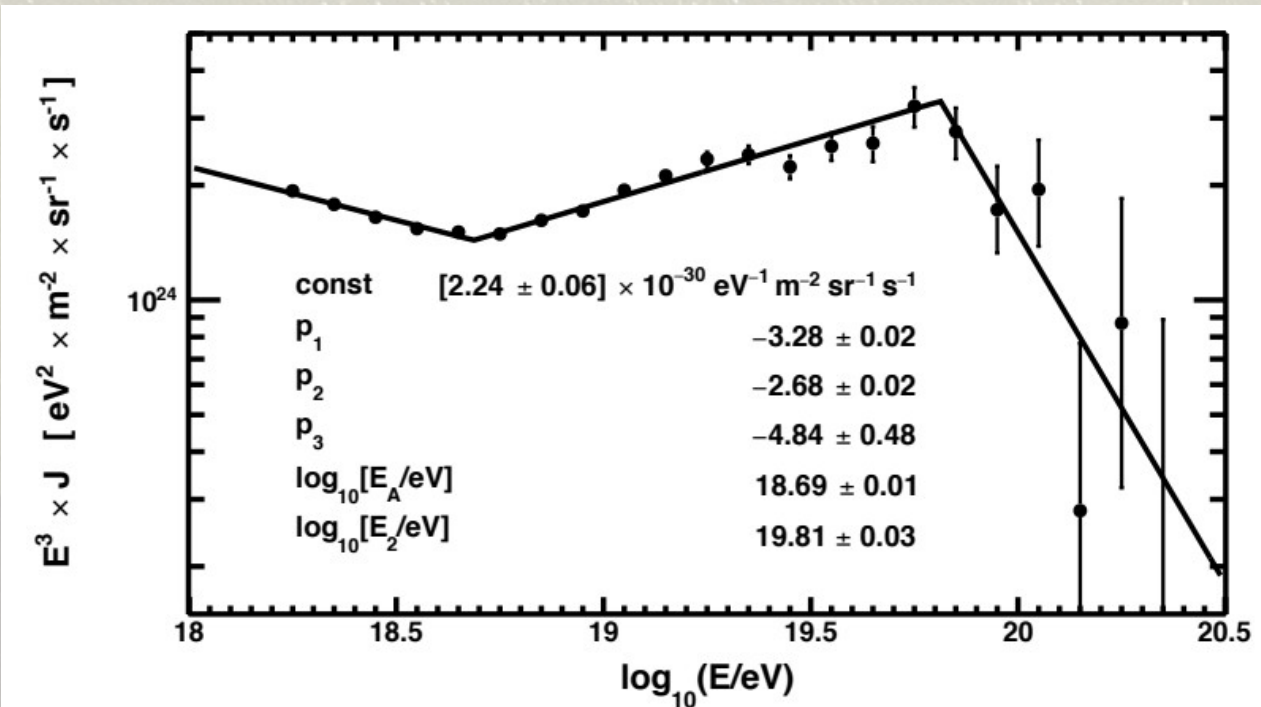
Why UHECR are extragalactic?

- CMB discovery: 1964
- Greisen, Zatsepin and Kuzmin (GZK-effect) $p\gamma \rightarrow p\pi$: 1966
 - Cosmic rays with $E \sim 10^{20}$ eV cannot reach the Earth from sources at $D \sim 100$ Mpc due to energy loss in scatterings at CMB

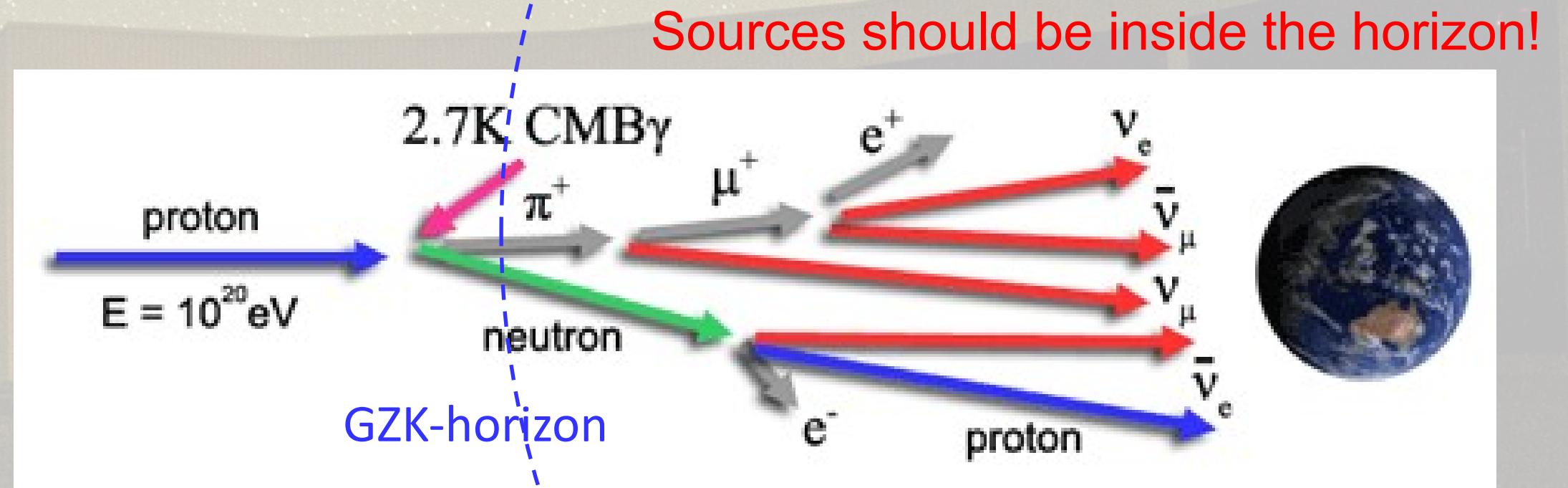


Planck, 2015

Spectrum cutoff appears at energies $E \gtrsim 40$ EeV: it is observed experimentally



Telescope Array @ ICRC-2015



Why UHECR are extragalactic?

Dipole in the skymap
 $E > 8 \text{ EeV}$, $l = 233^\circ$, $b = -13^\circ$
Significance $> 6\sigma$

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

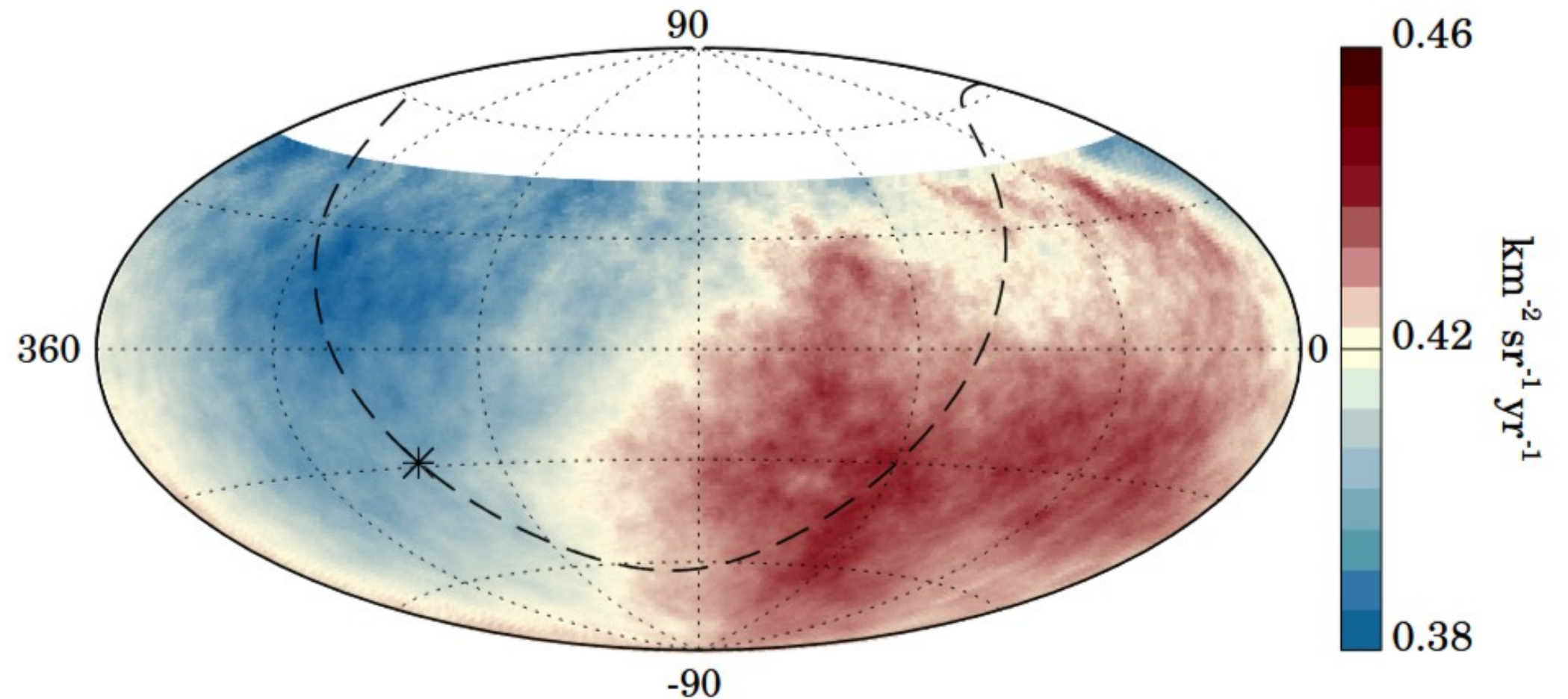


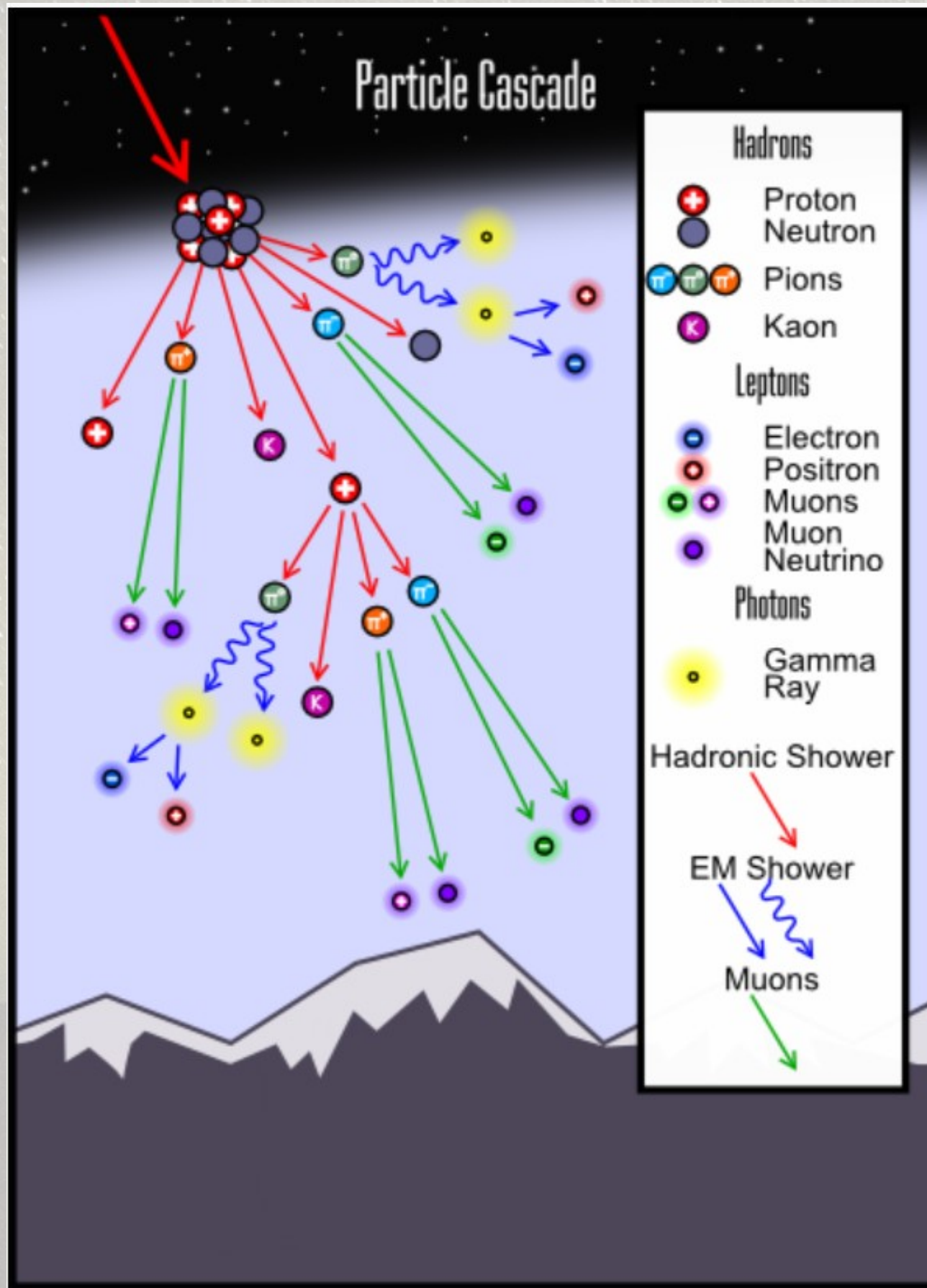
Figure 2: Map showing the fluxes of particles in equatorial coordinates. Sky map in equatorial coordinates, using a Hammer projection, showing the cosmic-ray flux above 8 EeV smoothed with a 45° top-hat function. The Galactic center is marked with an asterisk and the Galactic plane is shown by a dashed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

Auger, Science 357 (2017) 6537, 1266

Cosmic rays observation



How to observe UHECR?



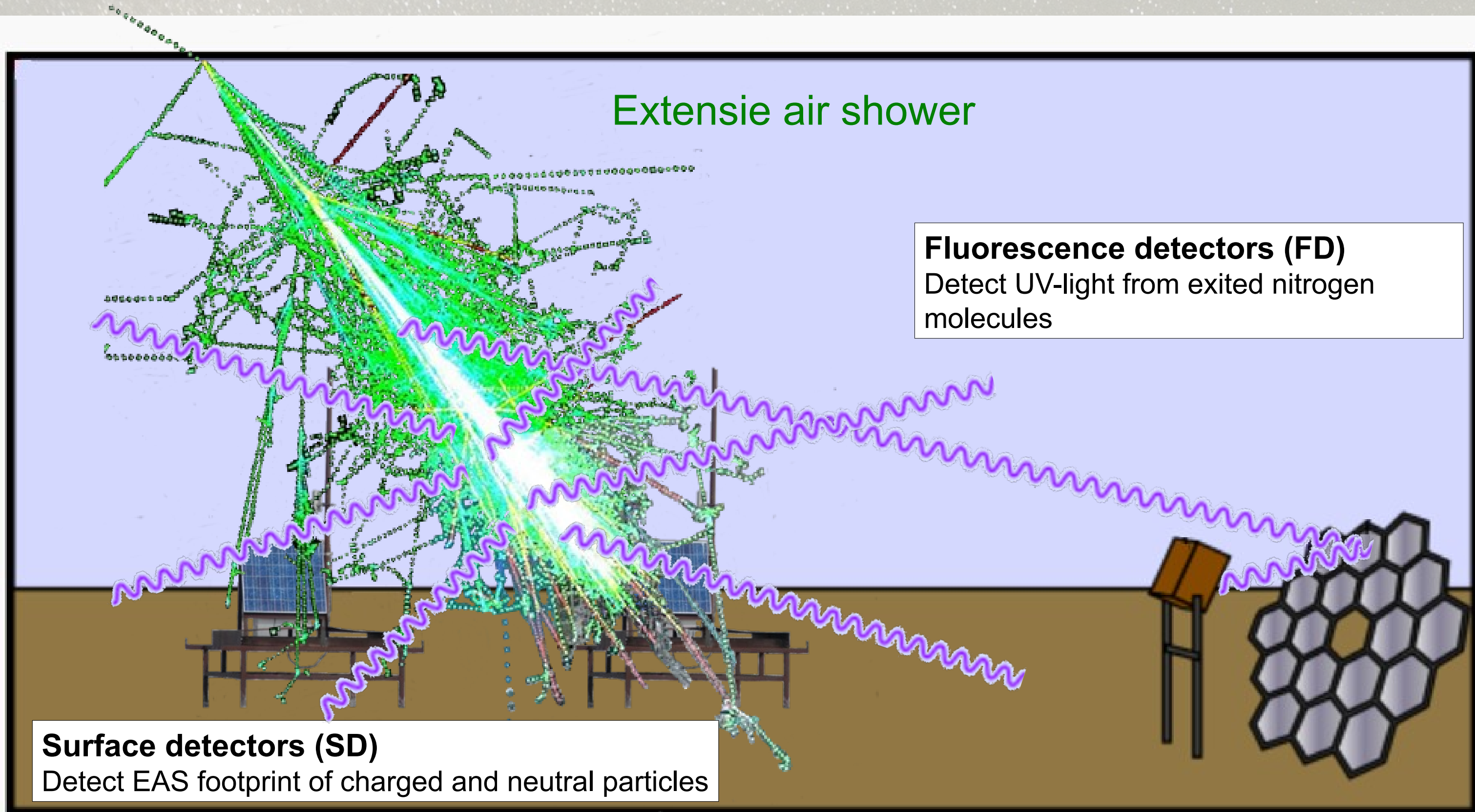
Indirect detection

- 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

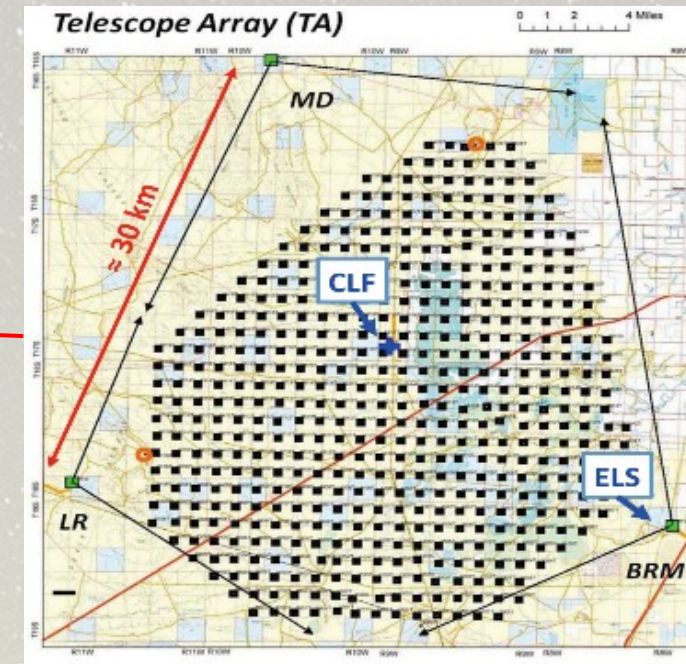
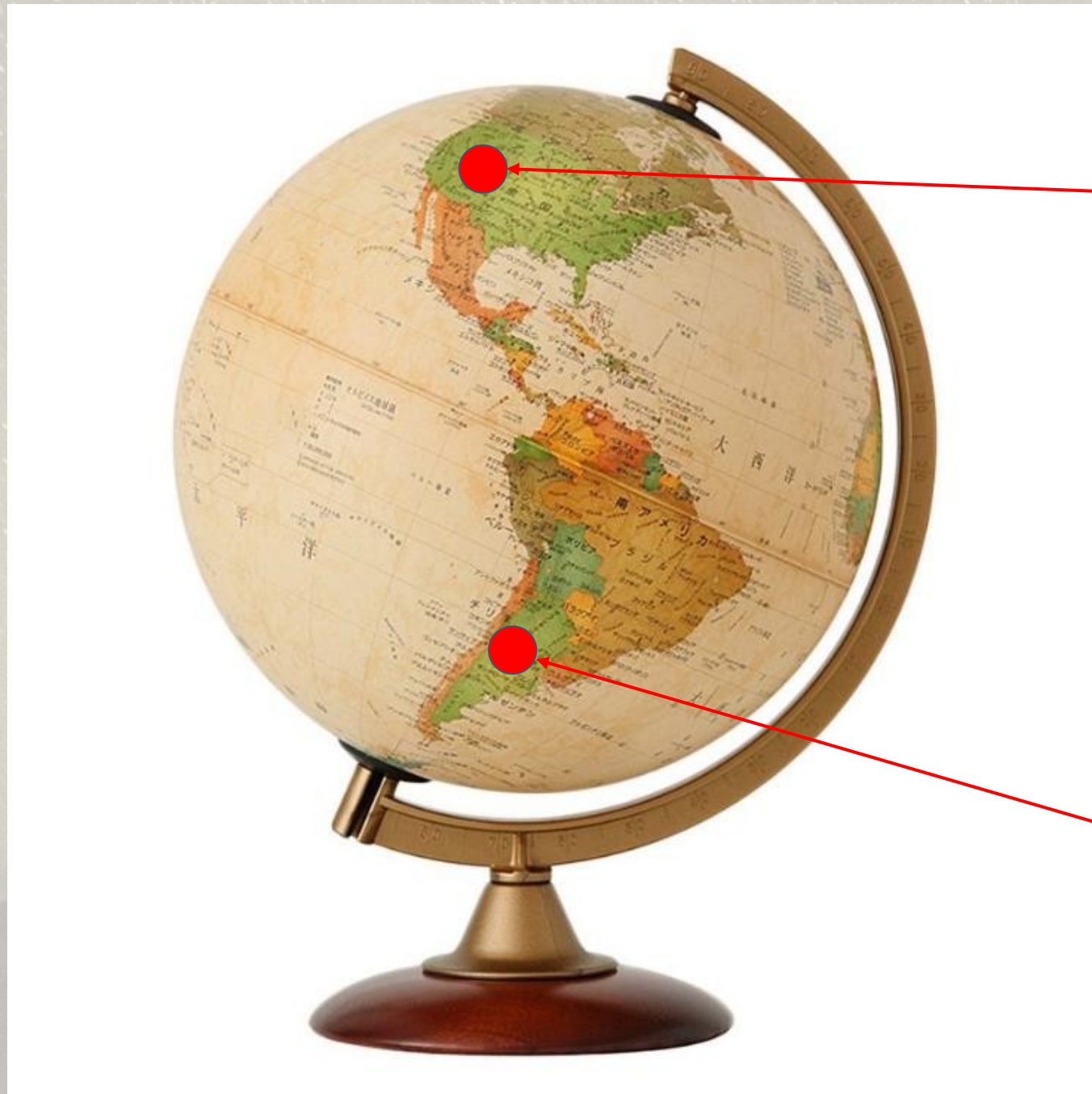
It is extensive air shower (EAS)

Discovered by Pierre Auger in 1939

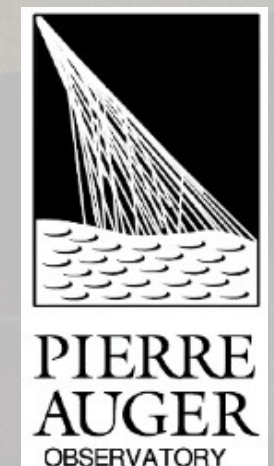
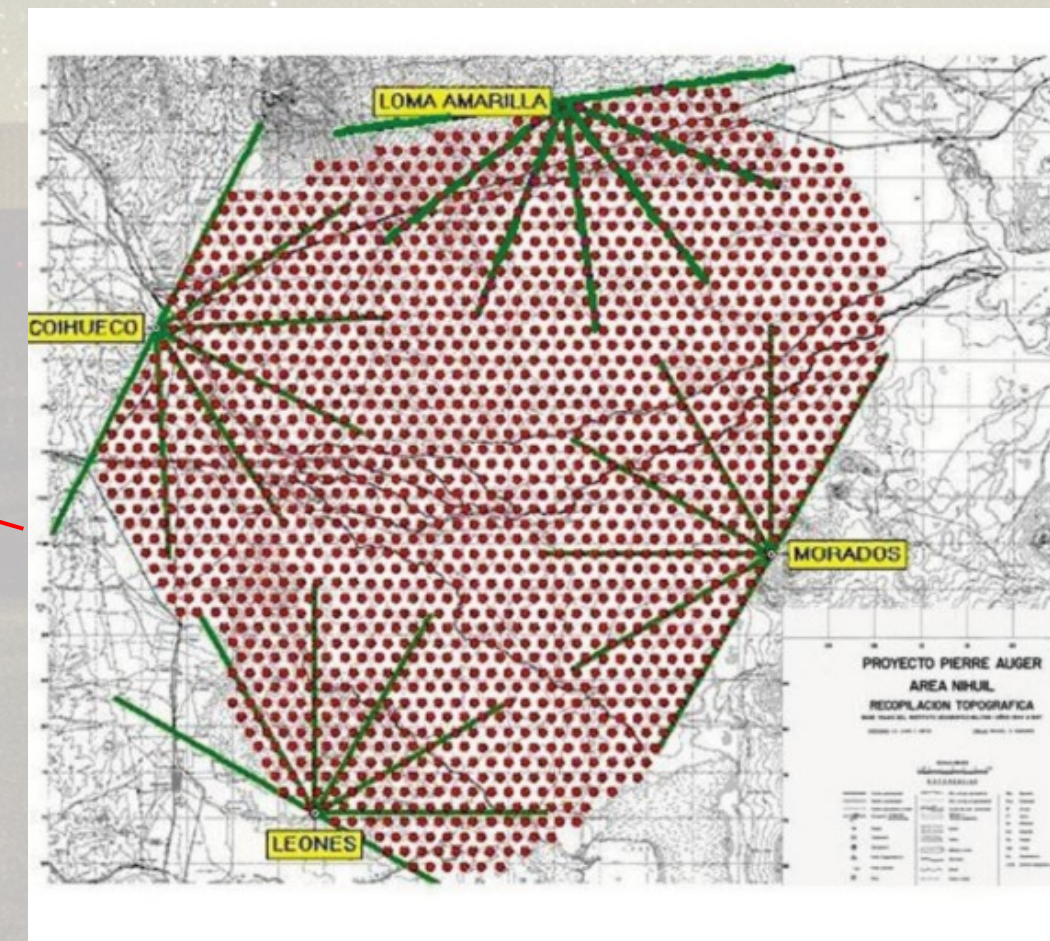
How to detect EAS?



Two largest modern experiments for UHECR measurement

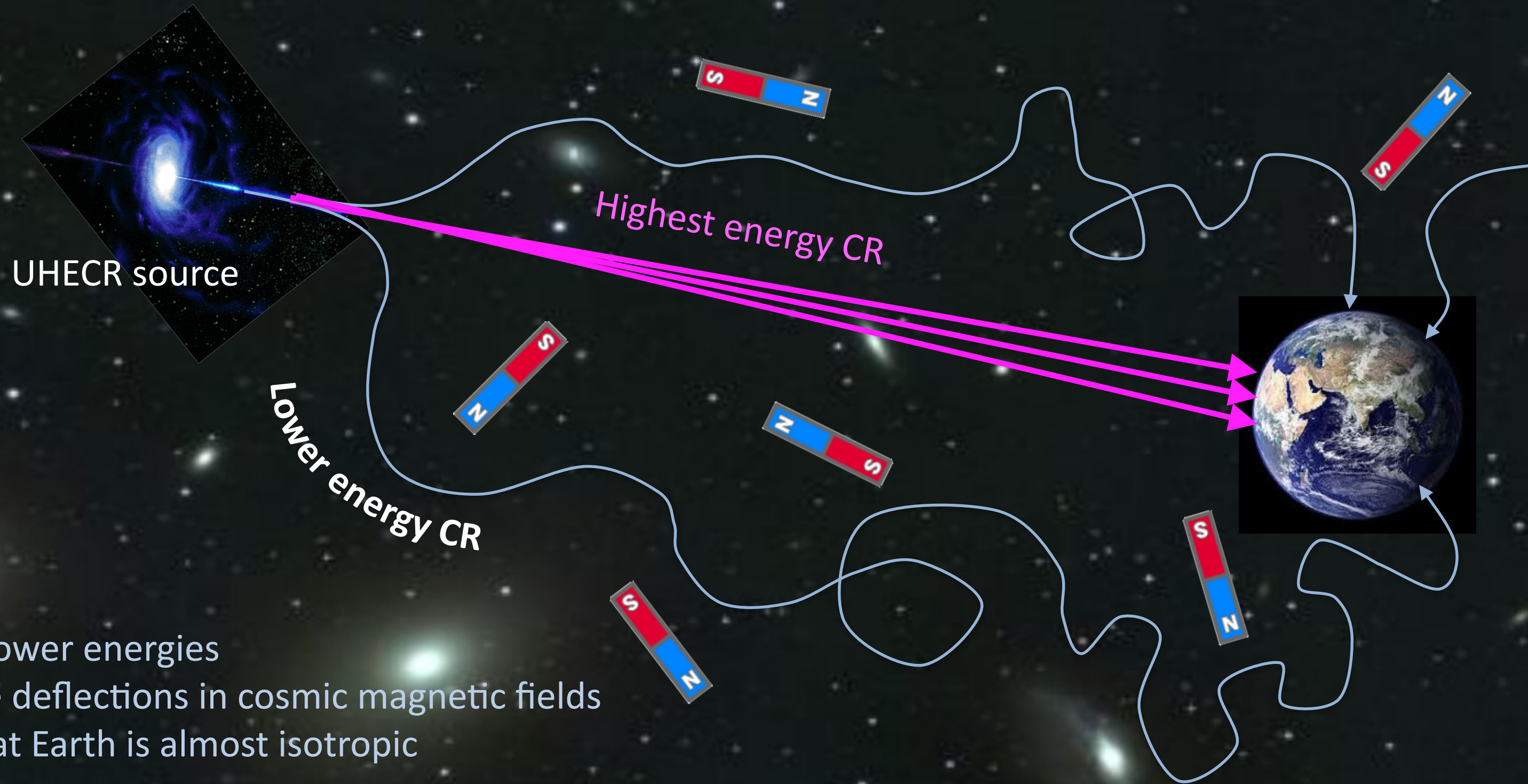


TA
39°N
700km²



Auger
35°S
3000km²

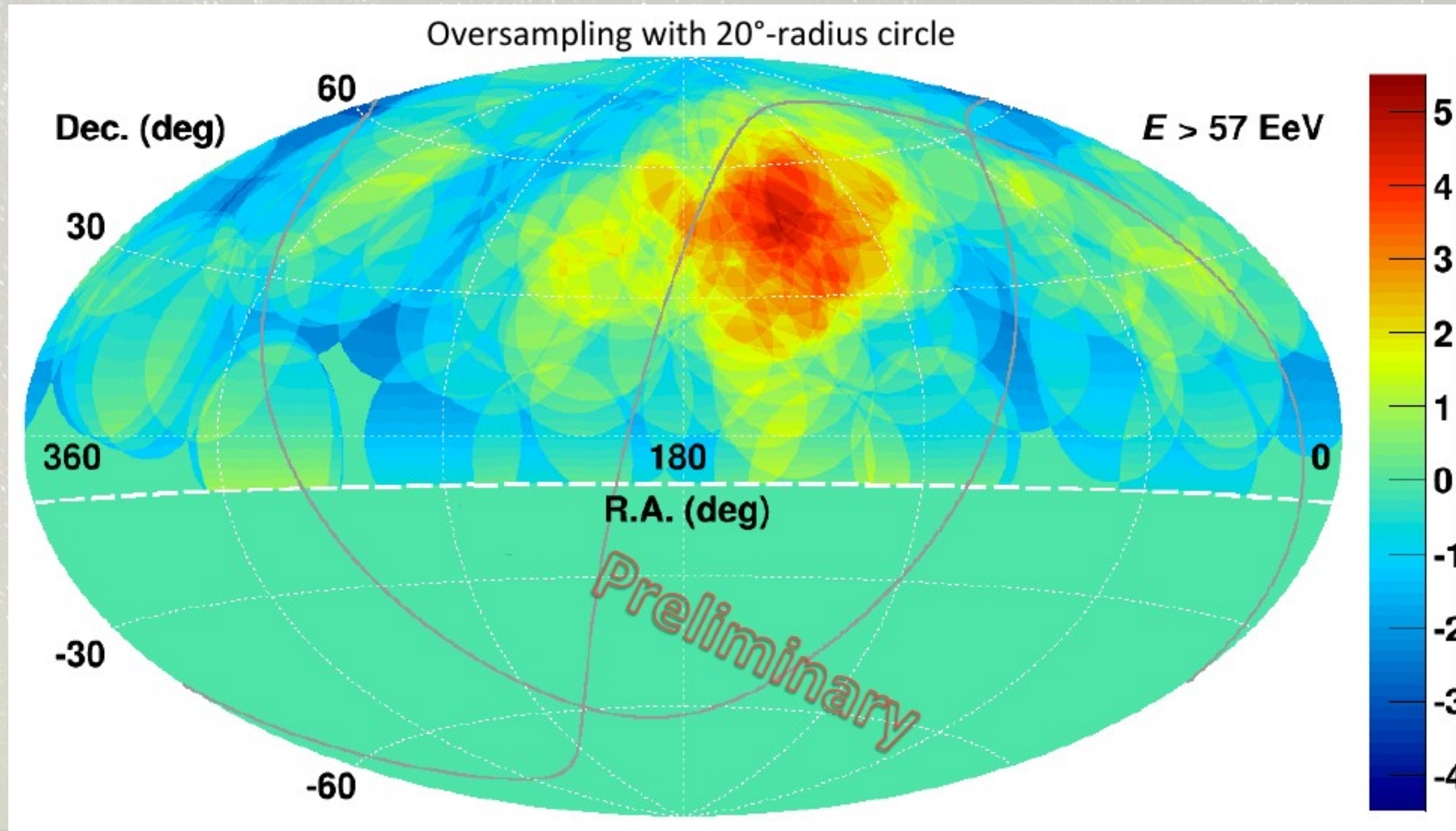
Is there possibility for UHECR «astronomy»?



- ❖ 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 measuring with good accuracy ($\sim 1^\circ$)
- **But**
- The theoretical uncertainties for expected deflections are larger:
 - Uncertainties of galactic and extragalactic magnetic fields
 - Uncertain mass (and hence charge) composition of UHECR

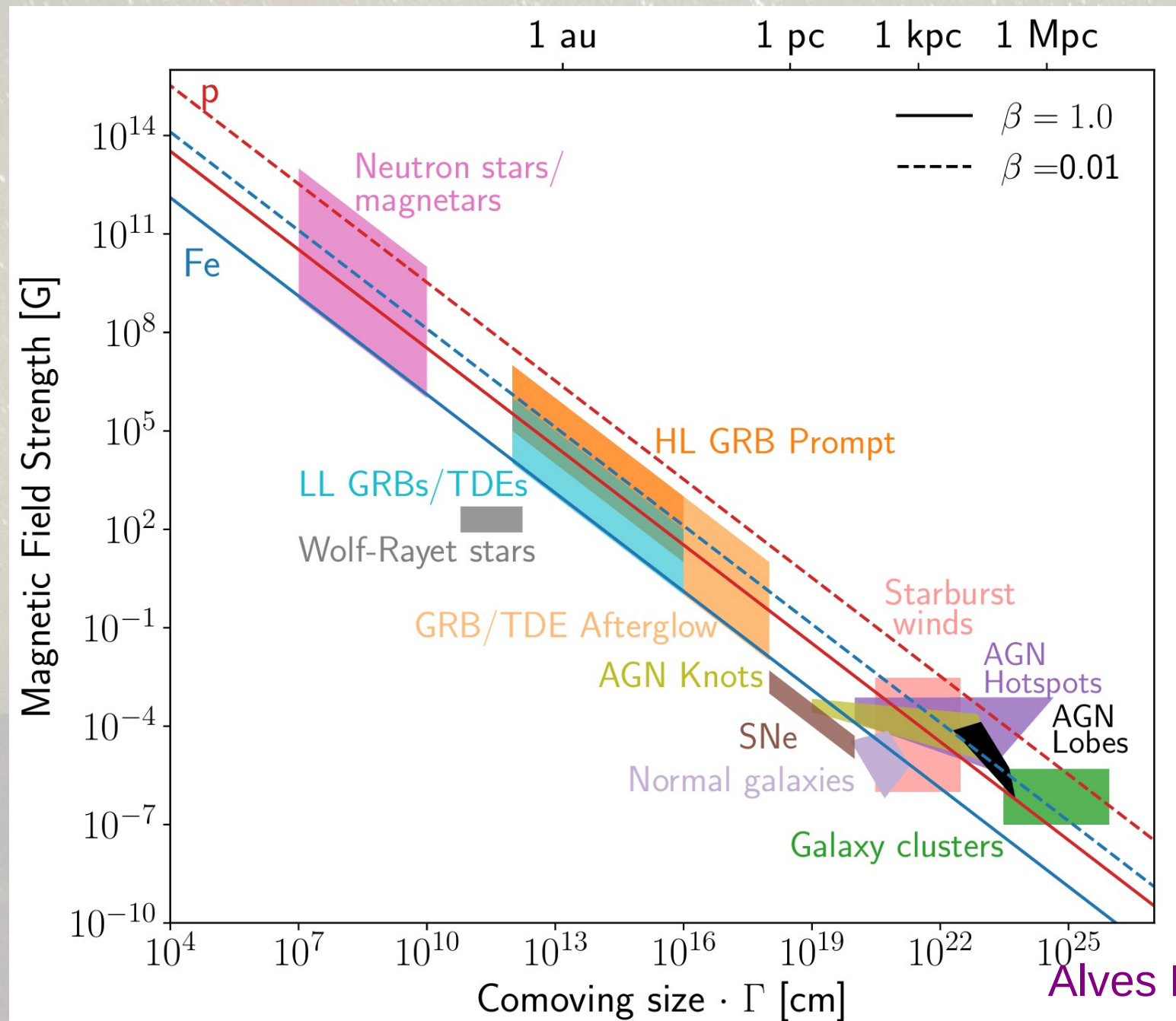
Another approach: constrain possible source classes

Hillas criterion

$R = E/qB$ — larmor radius

$E_{\max} = \beta_{\text{shock}} q B R \Gamma$ — maximum energy

Sources below the lines are excluded

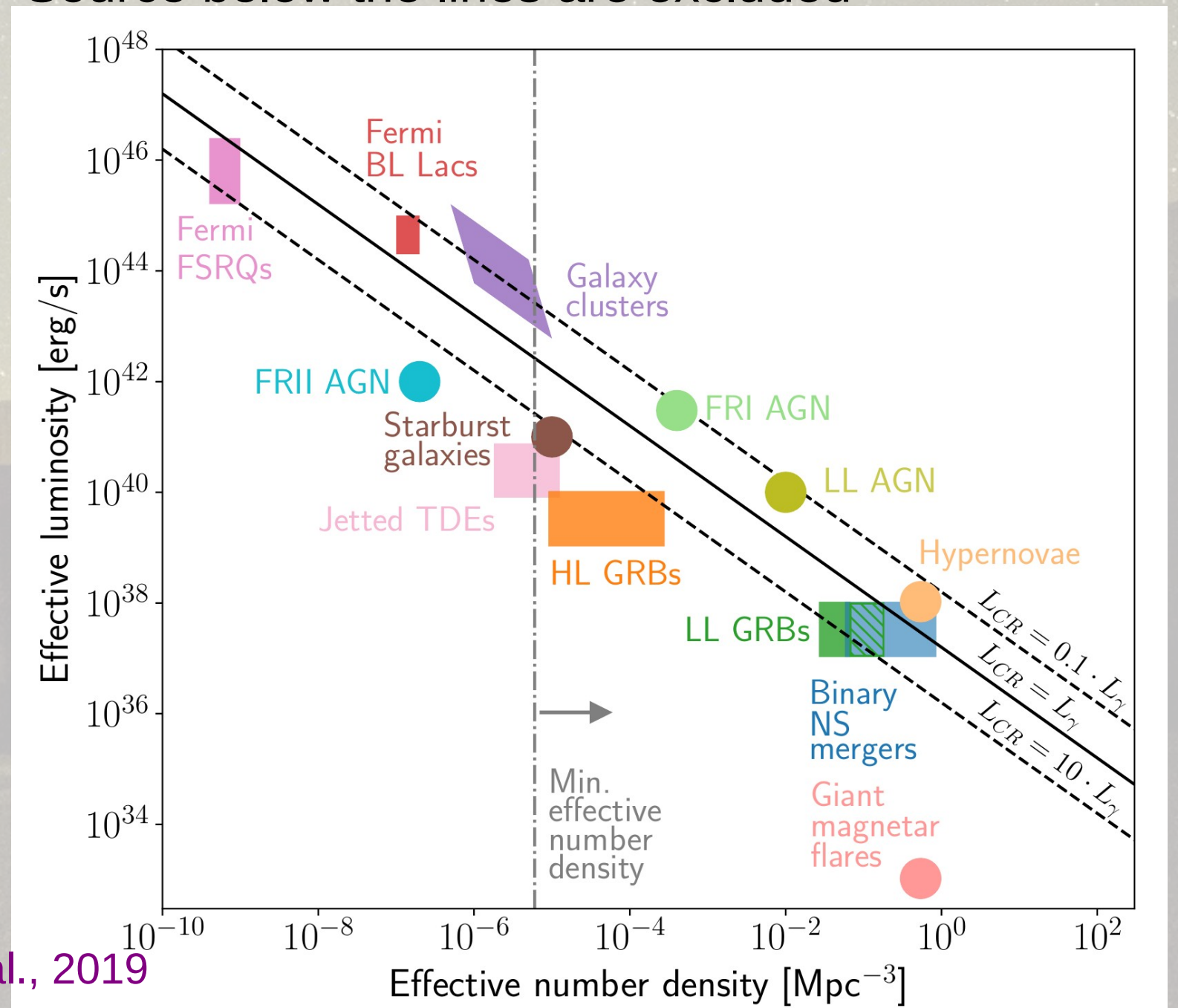


Alves Batista et al., 2019

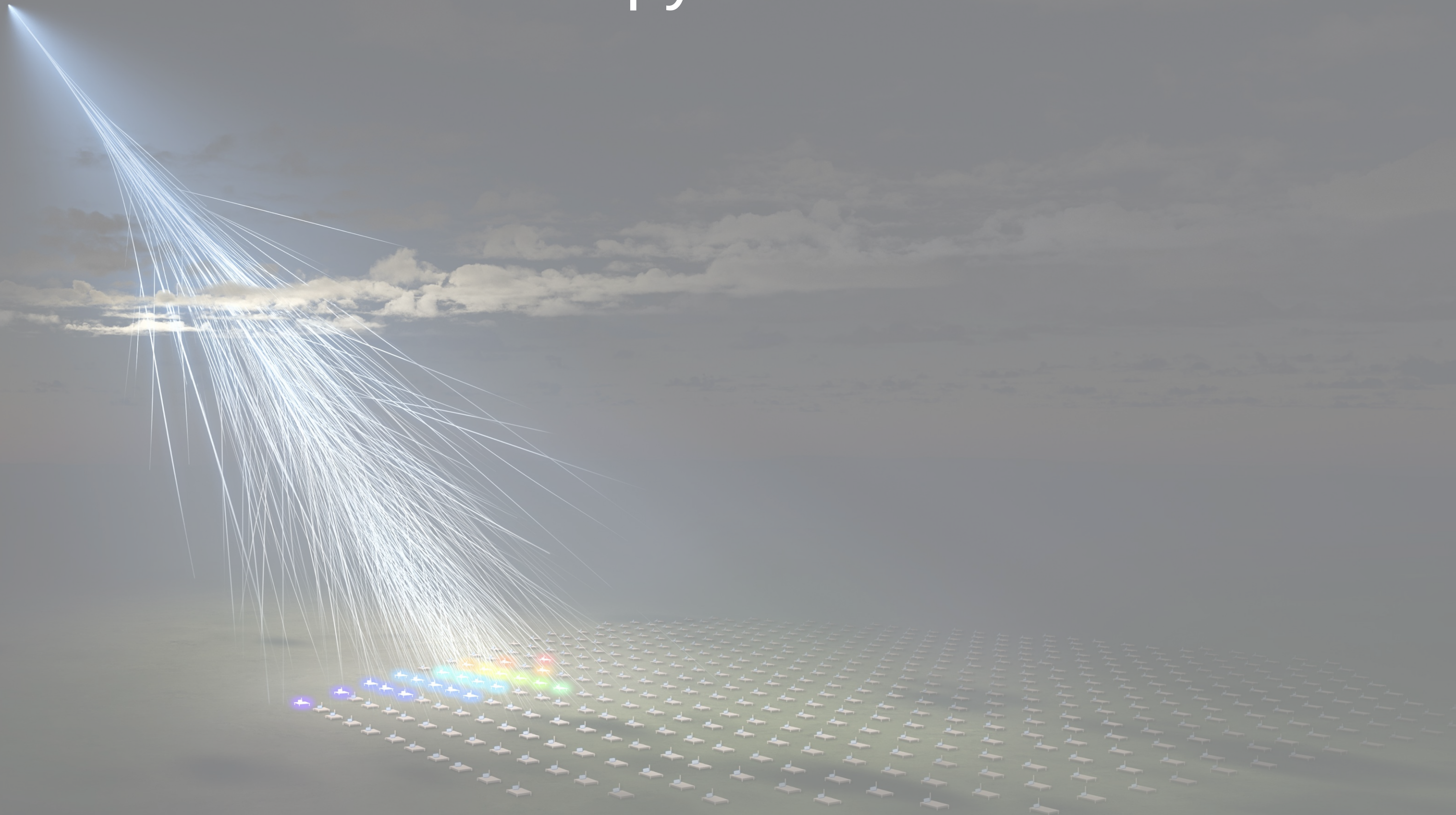
Criterion of full energetics

$L = 5 \times 10^{44}$ erg/(Mpc³ yr) — total luminosity of sources to get observed spectrum (Auger, 2017)
Depends on E_{\min} of galactic-extragalactic transition and L_{γ}/L_{CR}

Source below the lines are excluded



UHECR anisotropy observations



Difference in UHECR spectra between northern and southern sky

UHECR spectra measured by Auger and TA are significantly different at $E \gtrsim 30$ EeV

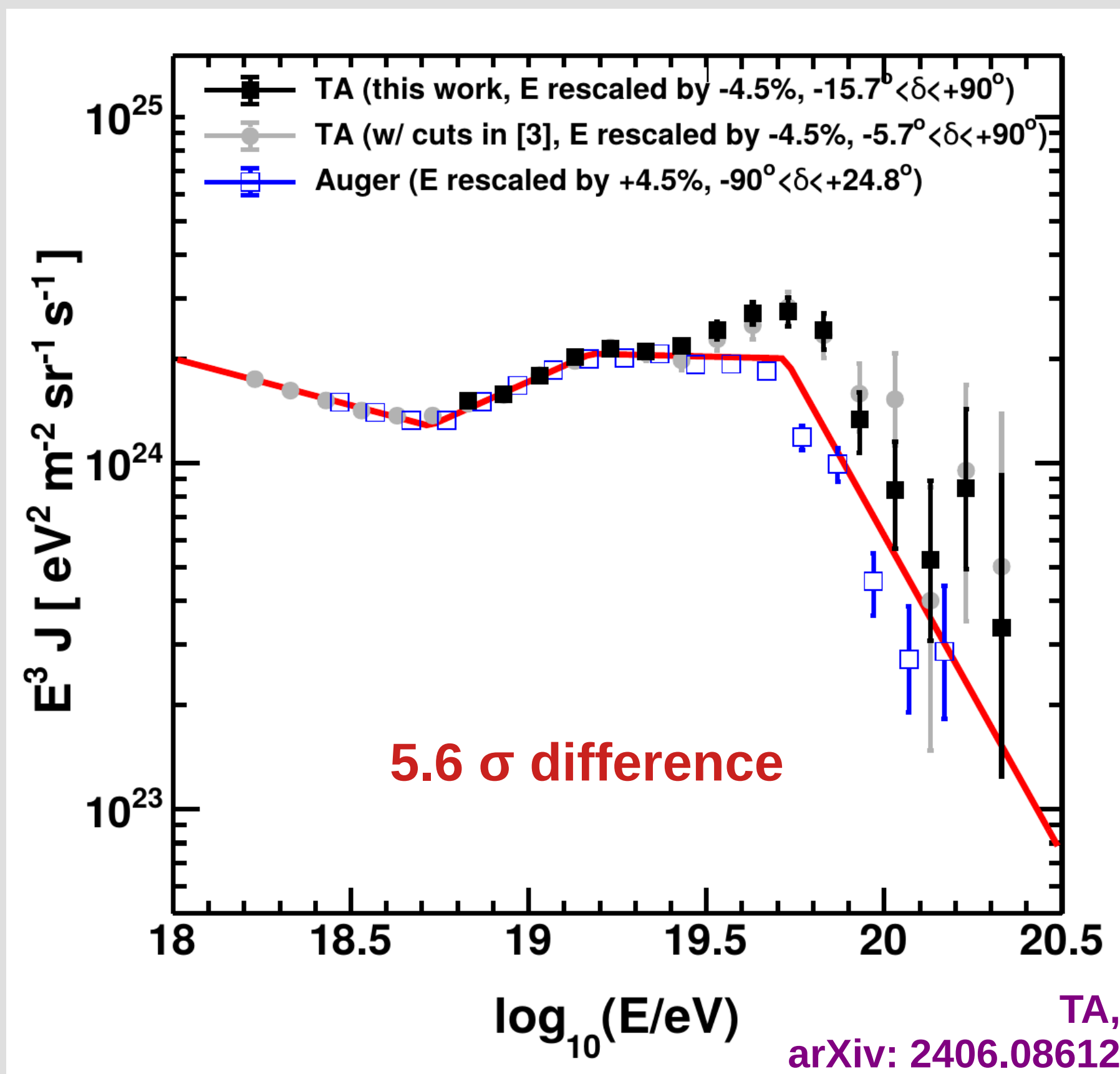
Need to exclude unaccounted experimental effects: look for common band of the sky:
 $-5^\circ < \delta < -24.8^\circ$

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

The 5.6 σ difference in full fields of view

TA: $-15.7^\circ < \delta < 90^\circ$

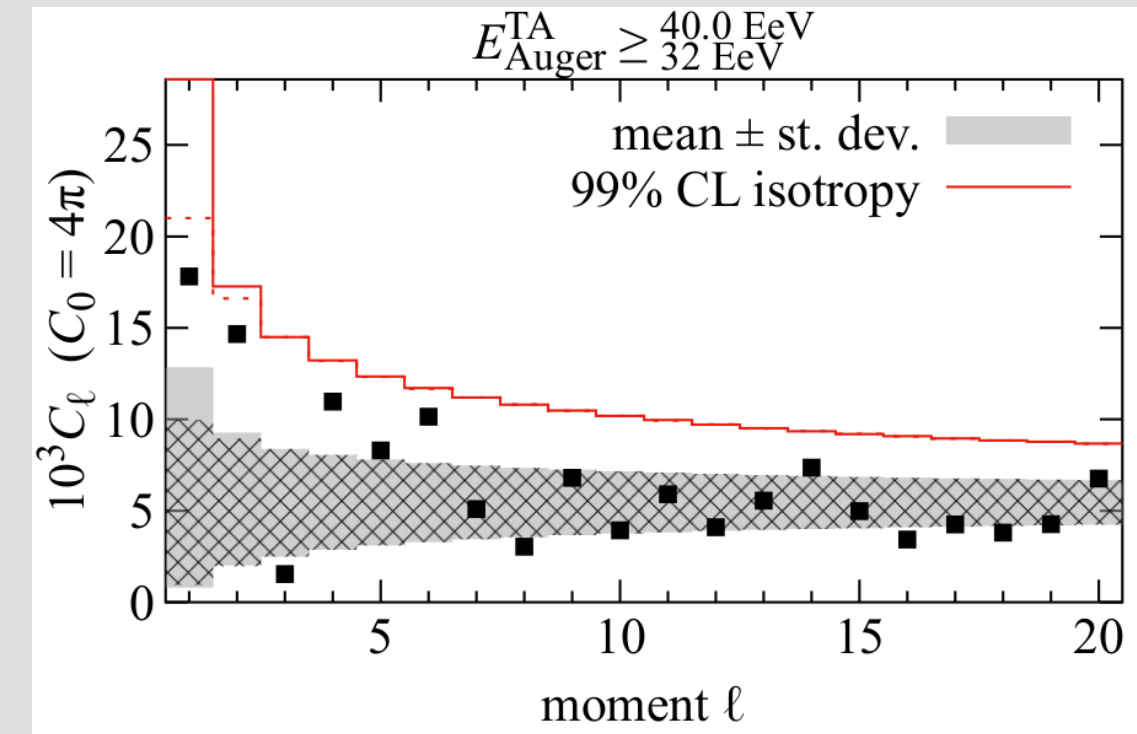
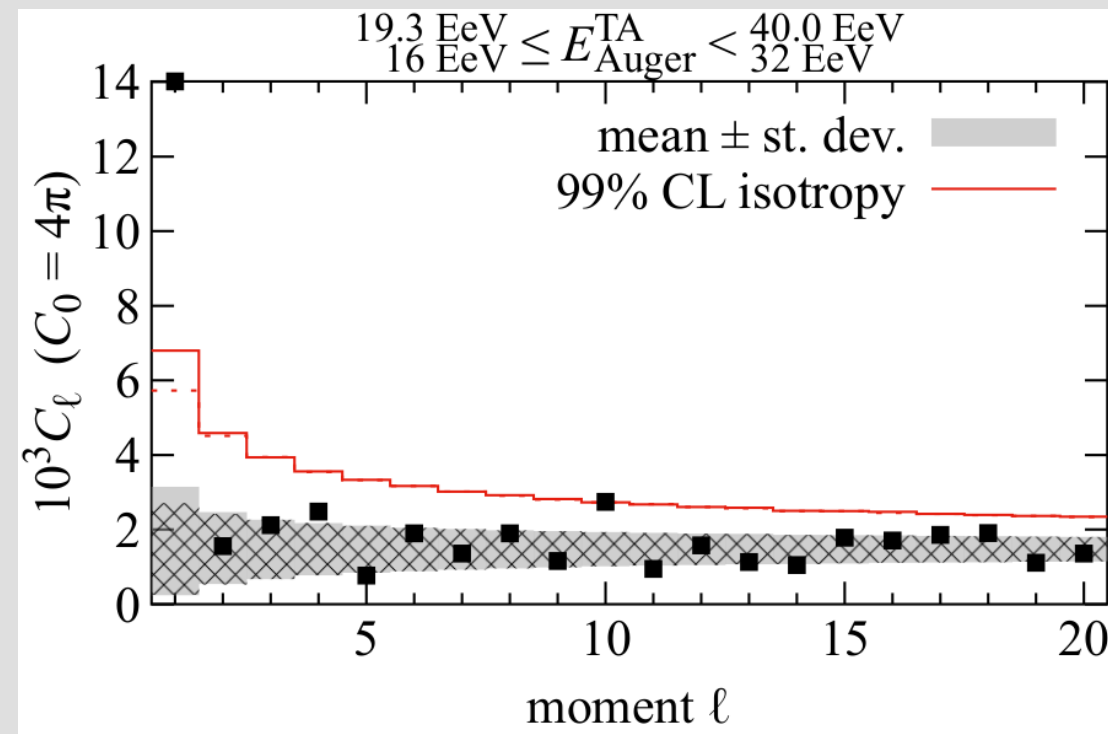
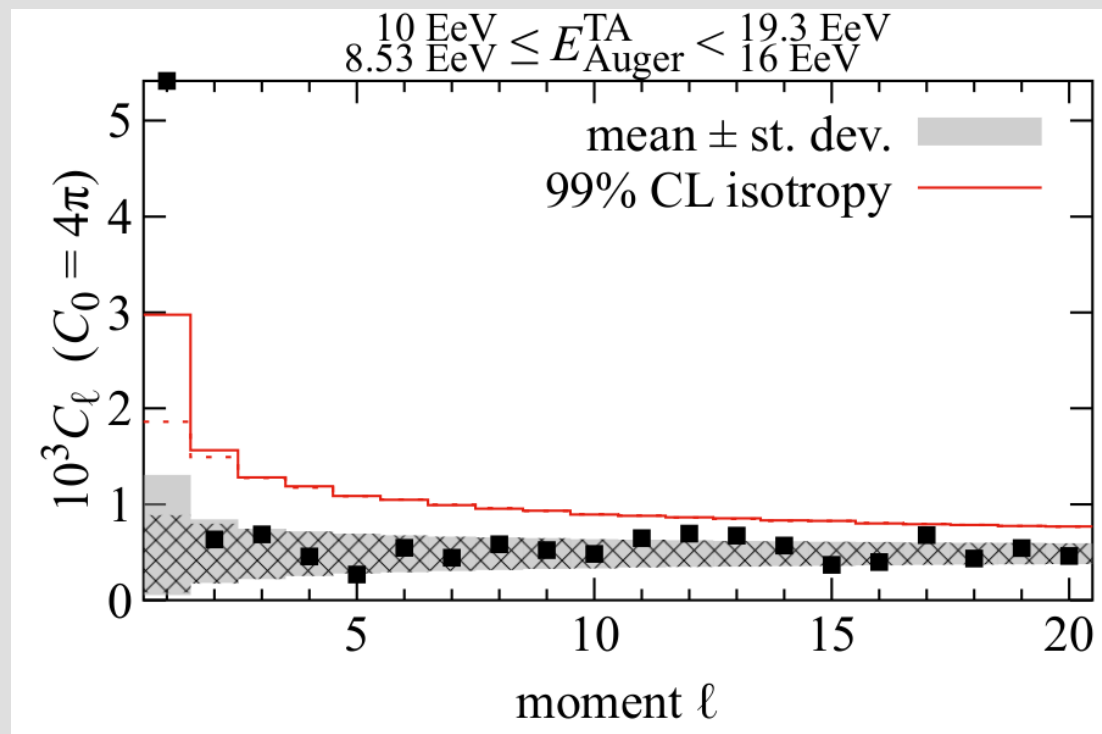
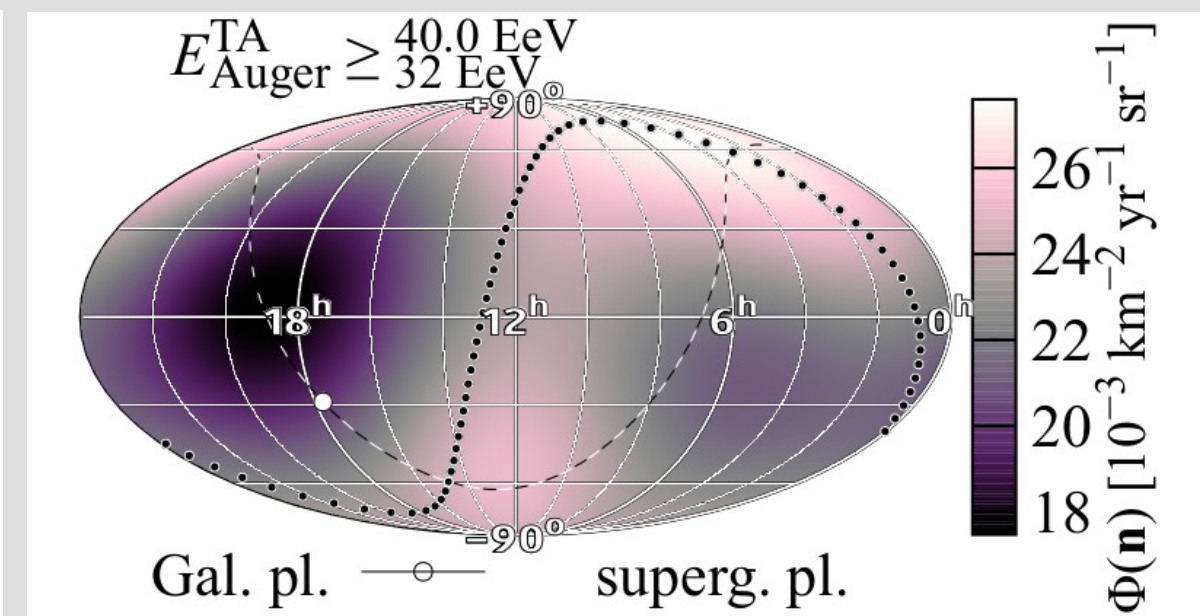
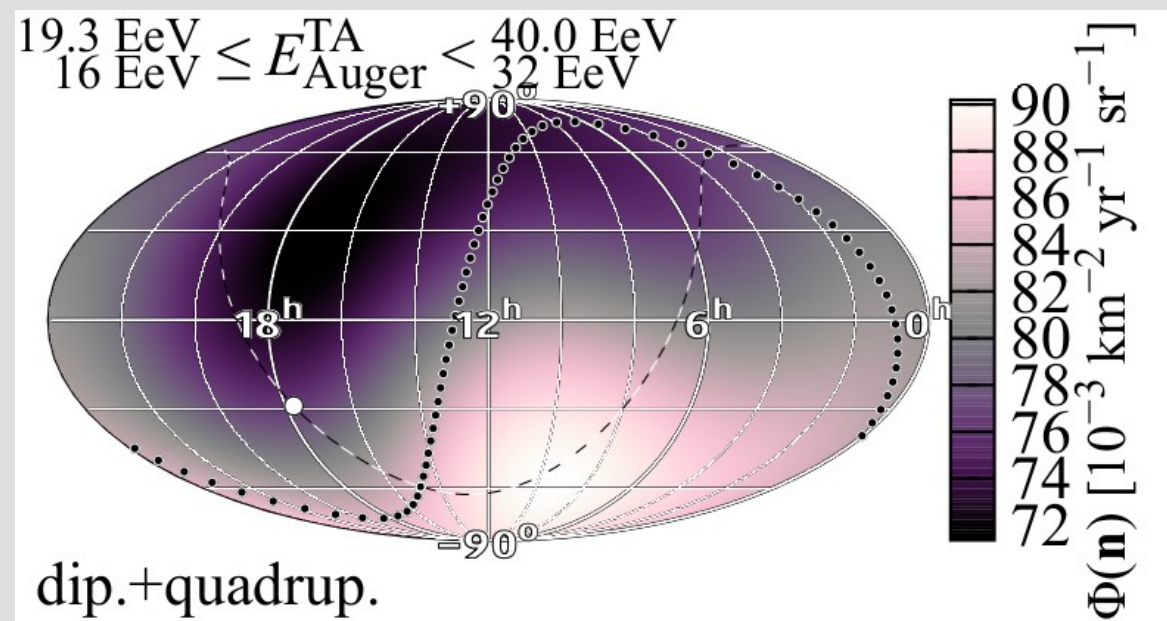
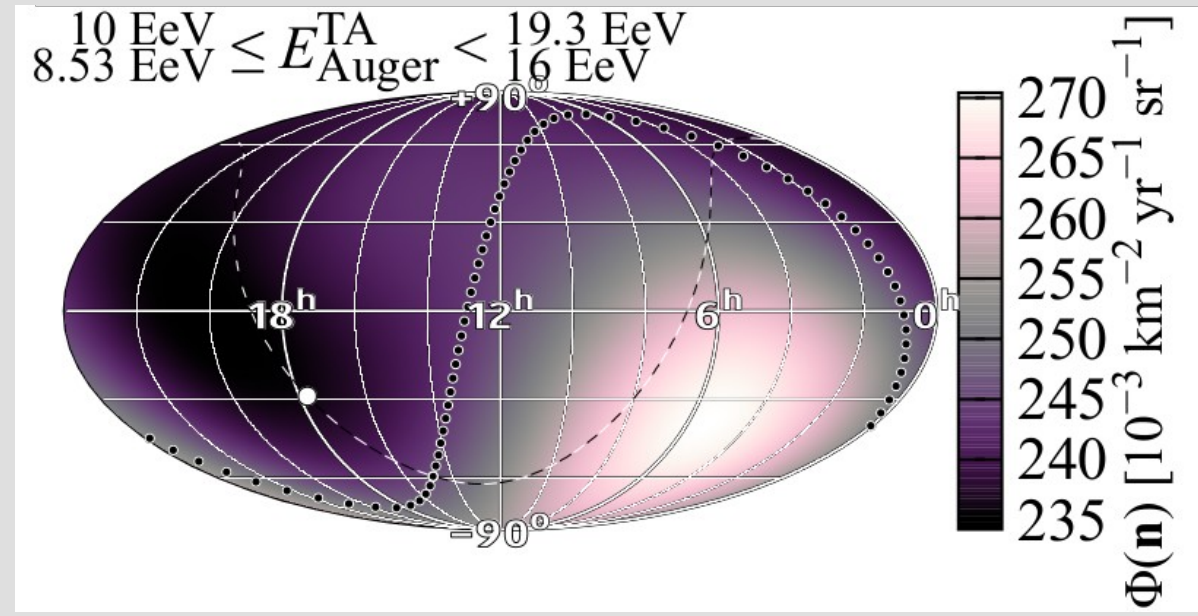
Auger: $-90^\circ < \delta < -24.8^\circ$



Large scale anisotropy in full sky: multipole analysis

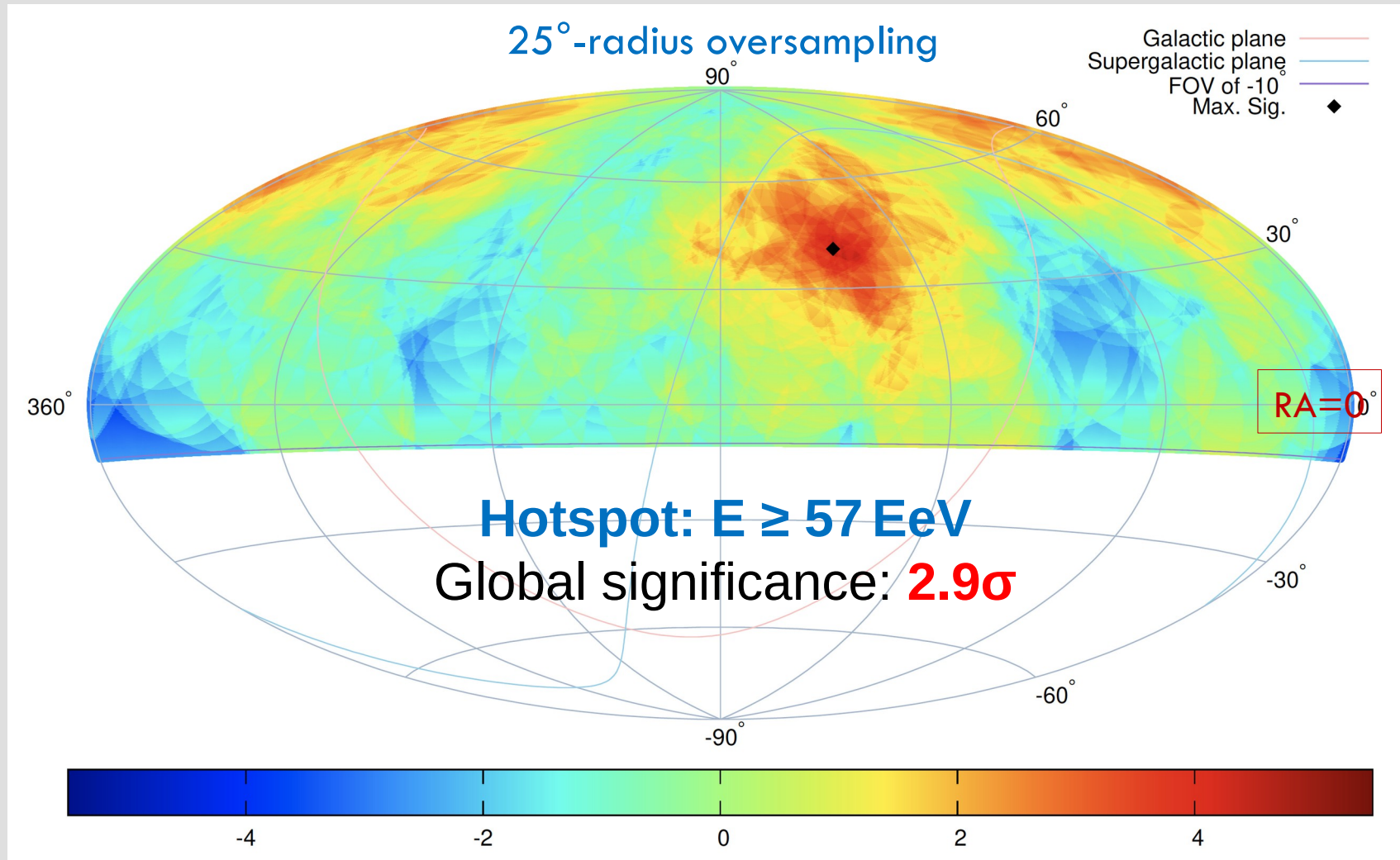
Joint Auger + TA working group on UHECR anisotropy

Auger and TA @ UHECR-2024

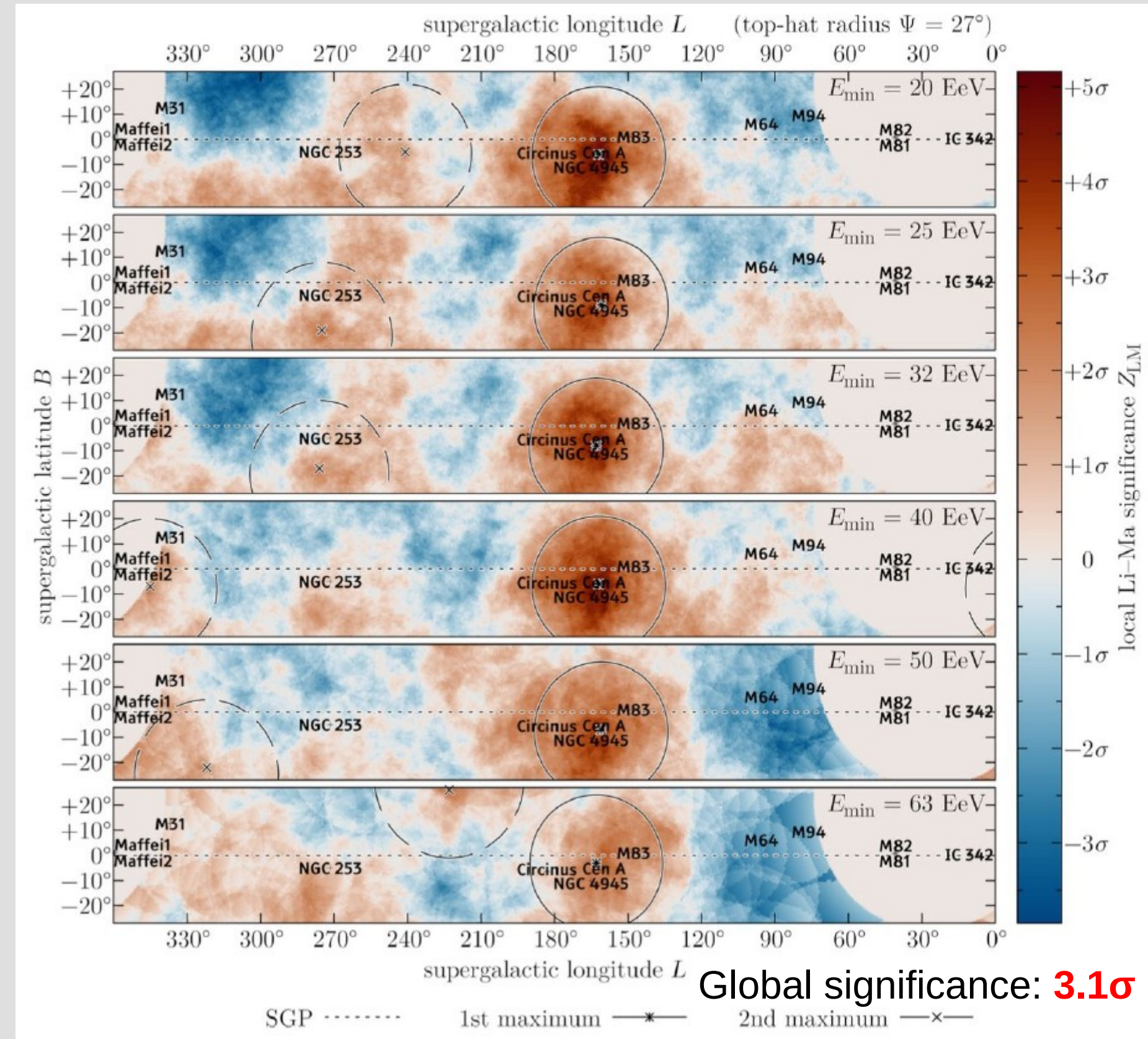


Dipole with ~5% amplitude and 4.6σ is directed to outer Galaxy
 Difference in dipole direction comparing to Auger only analysis ($\sim 90^\circ$ at $E > 30 \text{ EeV}$)

Medium scale anisotropy: search for overdensities



TA @ ICRC-2025



Correlation with separate classes of sources: 2-parameter TS

Joint Auger + TA working group on UHECR anisotropy

Build catalog of sources (LSS, SBG)

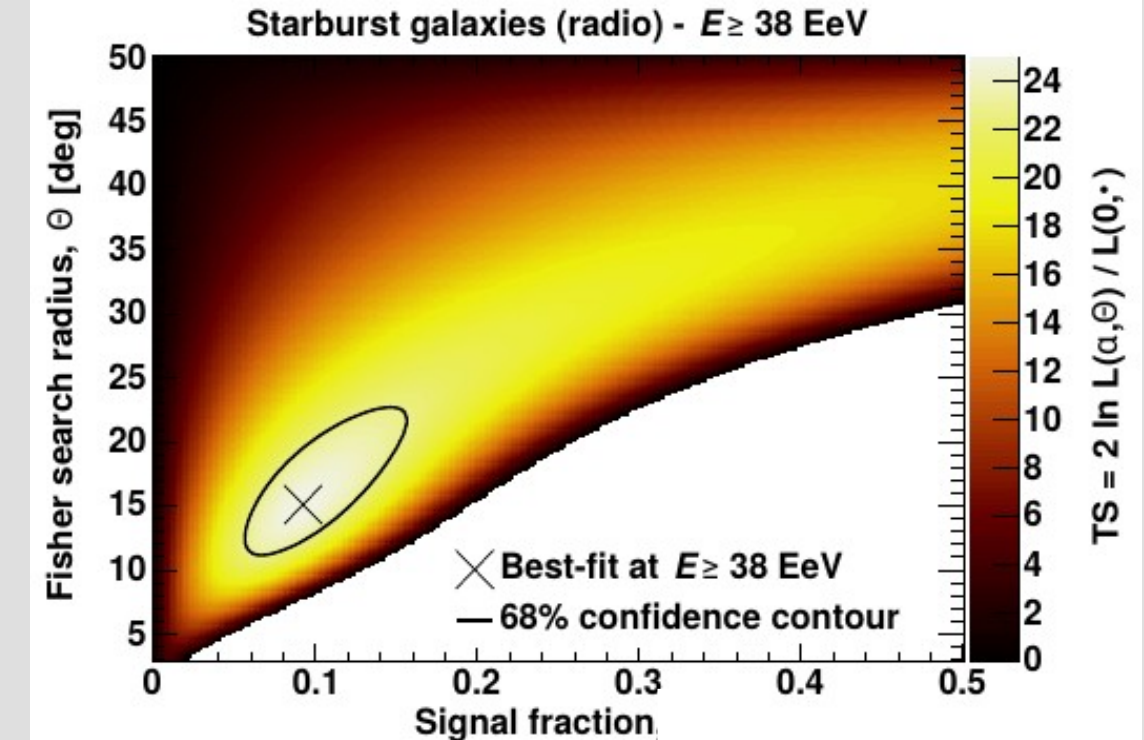
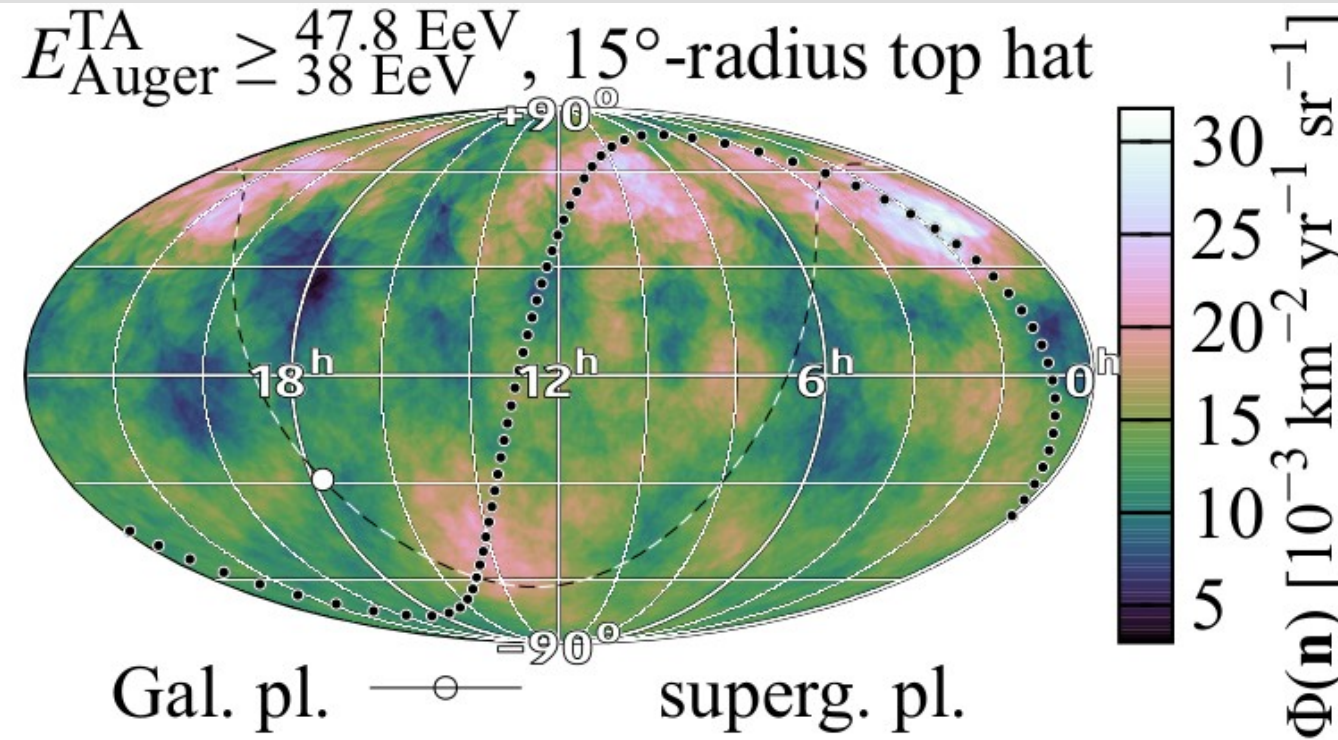
Compute an expected flux map

Define 2-parameter (size of sources and signal fraction) test statistics 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	$E_{\text{Auger}}^{\text{min}}$	$E_{\text{TA}}^{\text{min}}$	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$(19_{-7}^{+15})^\circ$	$(25_{-10}^{+24})\%$	14.7	2.8σ
UHECR 2024	37 EeV	46.5 EeV	$(26_{-15}^{+13})^\circ$	$(30_{-17}^{+26})\%$	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	$E_{\text{Auger}}^{\text{min}}$	$E_{\text{TA}}^{\text{min}}$	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$(15.4_{-3.0}^{+5.2})^\circ$	$(11.7_{-2.9}^{+4.7})\%$	30.5	4.6σ
UHECR 2024	38 EeV	47.8 EeV	$(15.0_{-2.9}^{+5.0})^\circ$	$(11.1_{-2.8}^{+4.4})\%$	29.5	4.4σ

Correlation with separate classes of sources: 1-parameter TS

Mostly similar to previous:

Build catalog of LSS sources

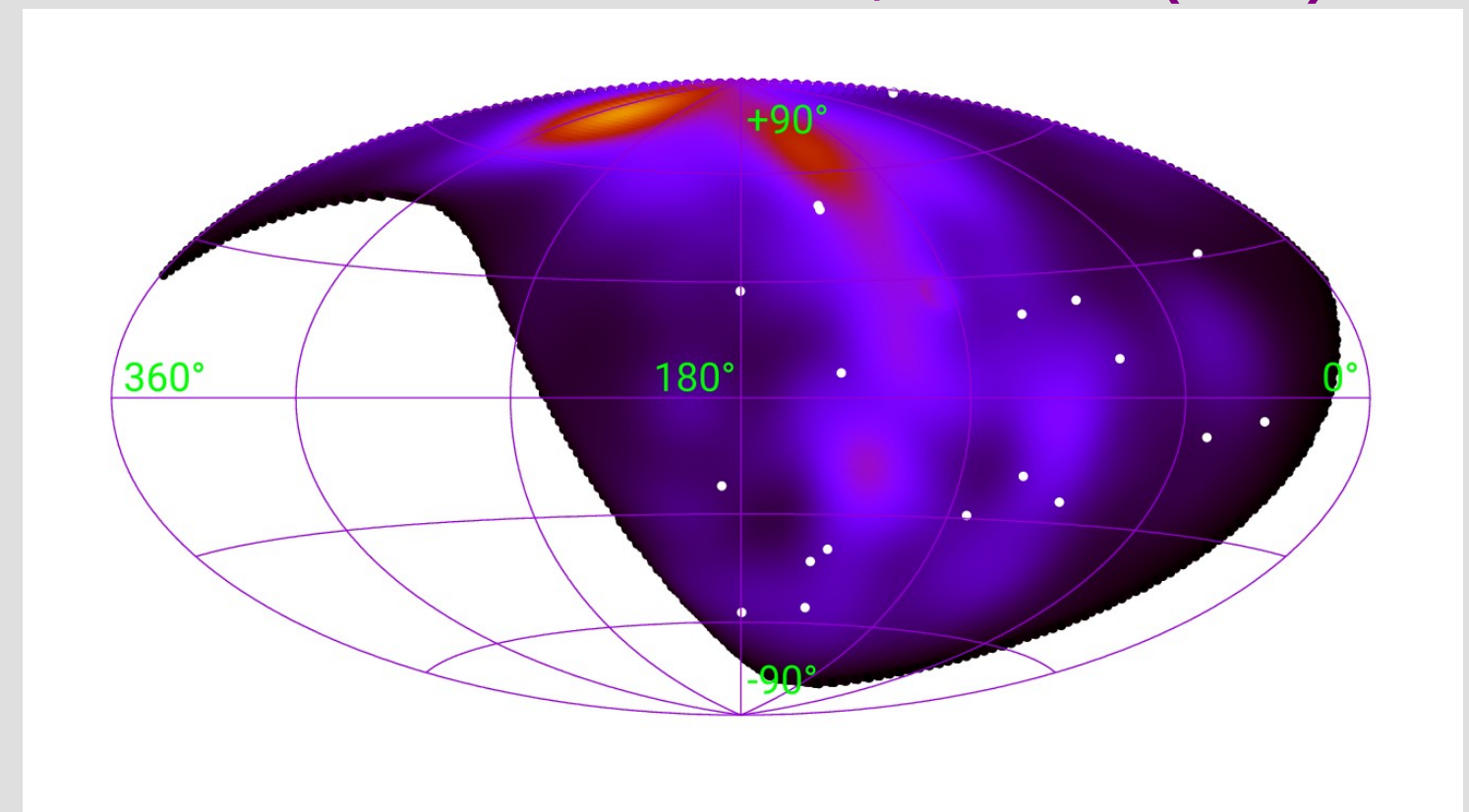
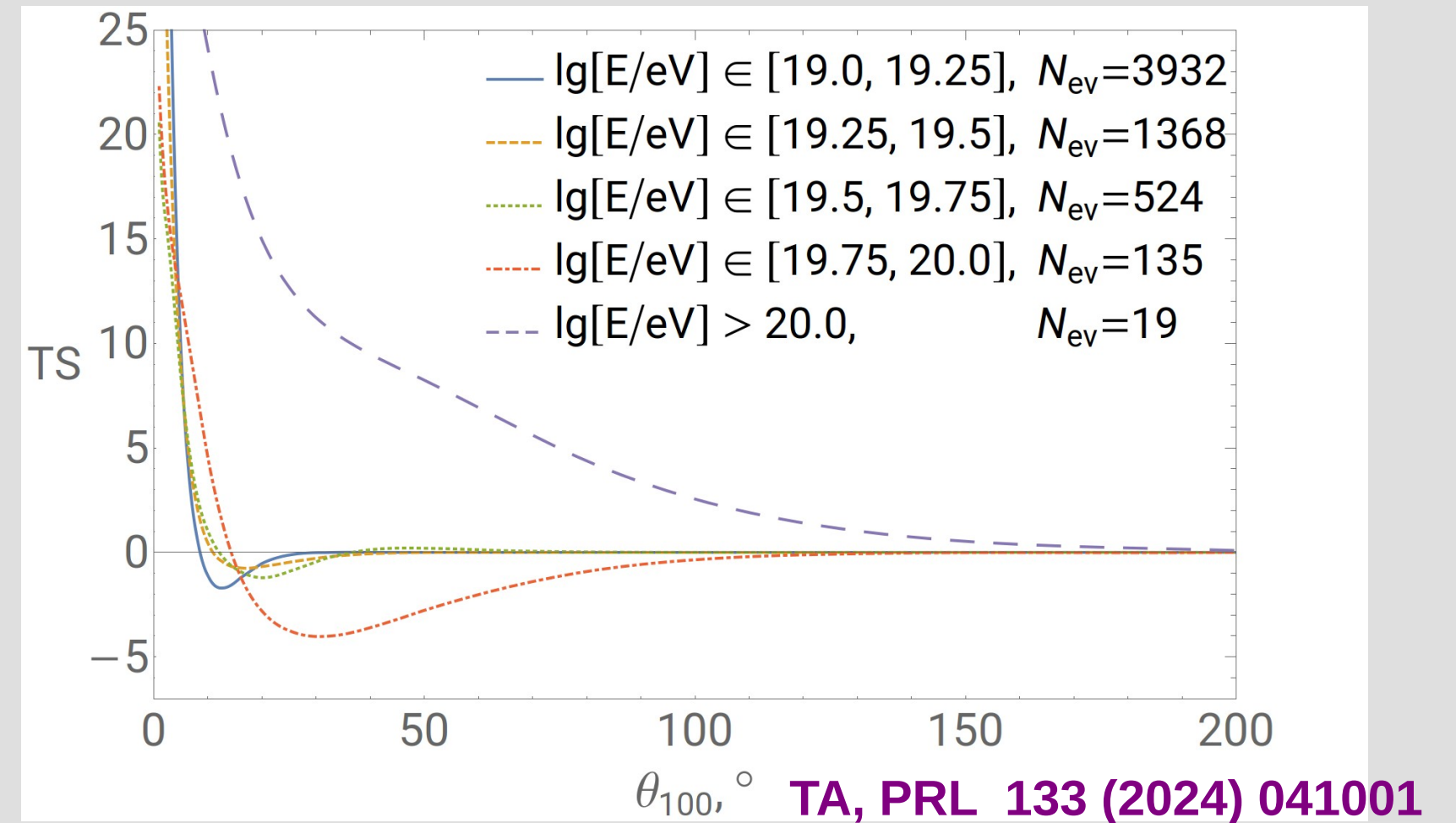
Compute an expected flux map

Define 1-parameter (size of sources) test statistics to quantify the correlation

Compute TS for data set

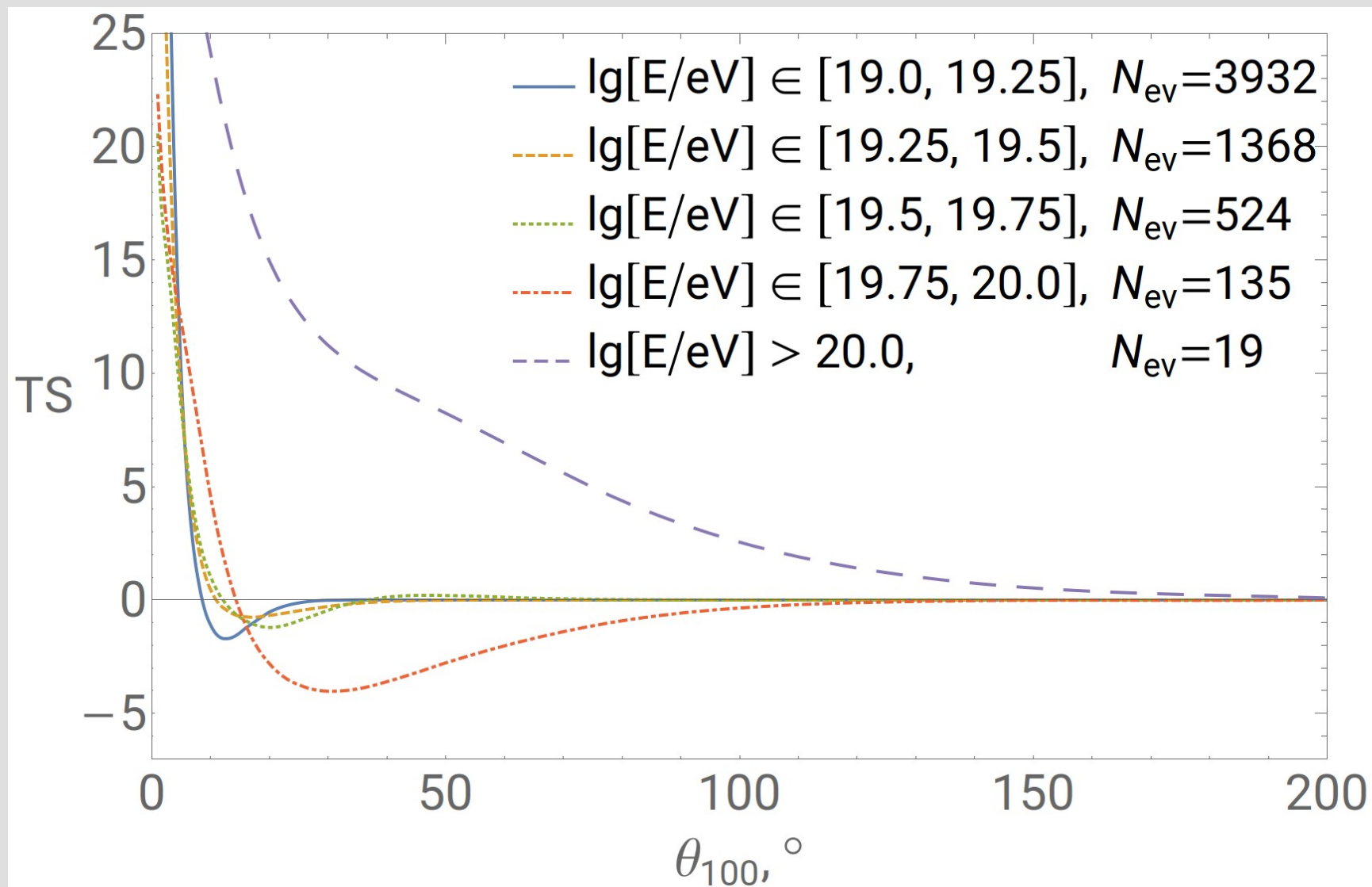
$$TS(\theta) = -2 \sum_k \left(\sum_i \ln \frac{\Phi_k(\theta, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)} \right)$$

Maximize TS over θ



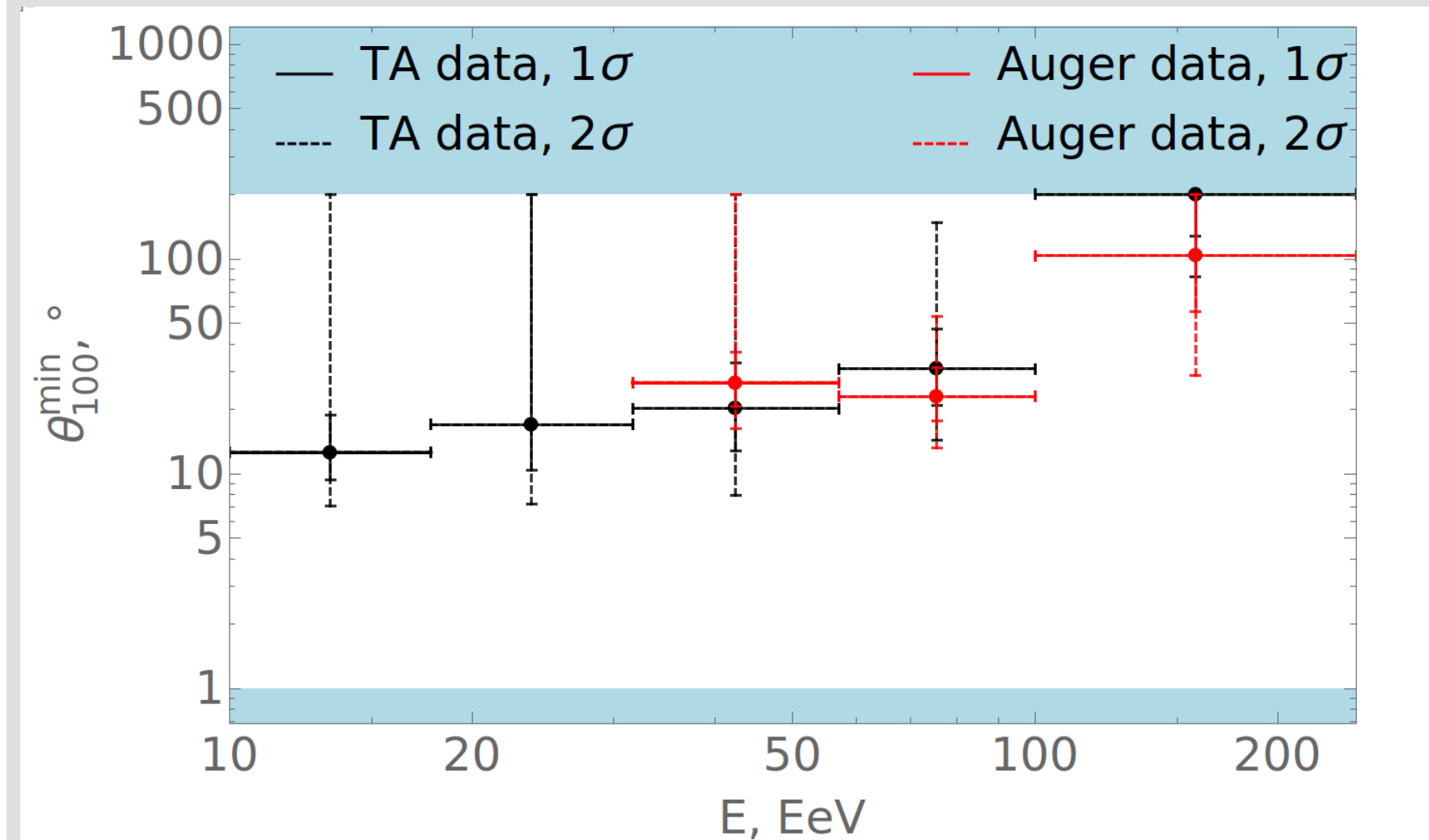
Correlation with separate classes of sources: 1-parameter TS

TS for TA data



TA vs. Auger data

- Auger data on arrival directions and energies of UHECR at $E > 32 \text{ EeV}$ ([Auger, ApJ 935 \(2022\) 170](#))



TA
2.0 σ correlation with LSS at $57 < E < 100 \text{ EeV}$
 Complete isotropy at $E > 100 \text{ EeV}$

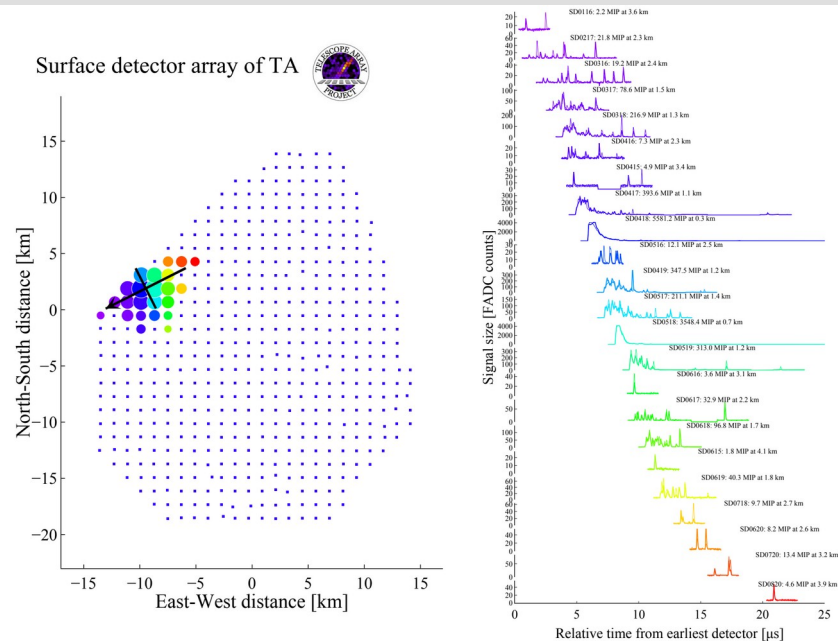
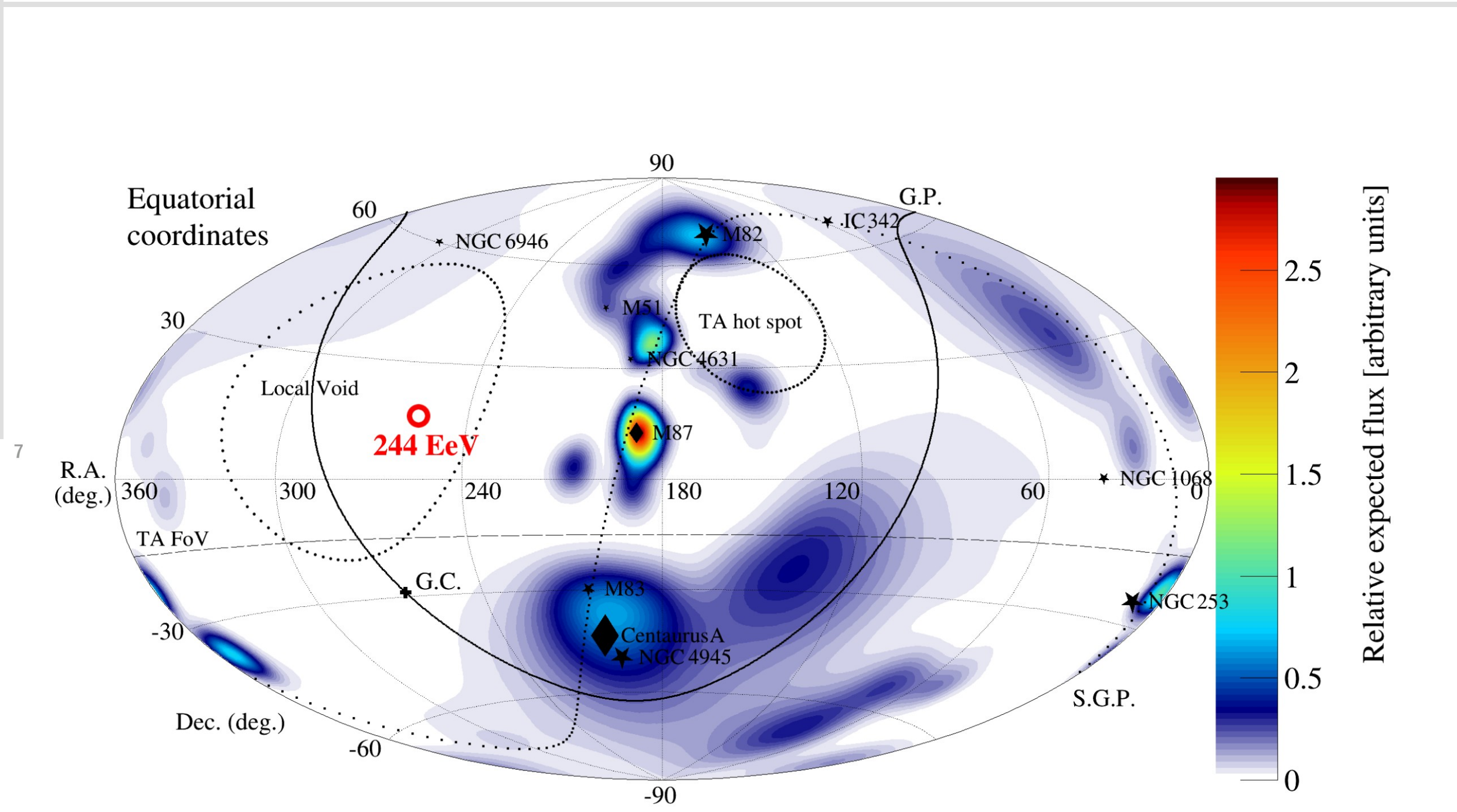
Auger
2.2 σ correlation with LSS at $57 < E < 100 \text{ EeV}$
 Complete isotropy at $E > 100 \text{ EeV}$

The TS looks quite similar between TA and Auger!

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	$38.6 \pm 0.4^\circ$	$206.8 \pm 0.6^\circ$	$255.9 \pm 0.6^\circ$	$16.1 \pm 0.5^\circ$

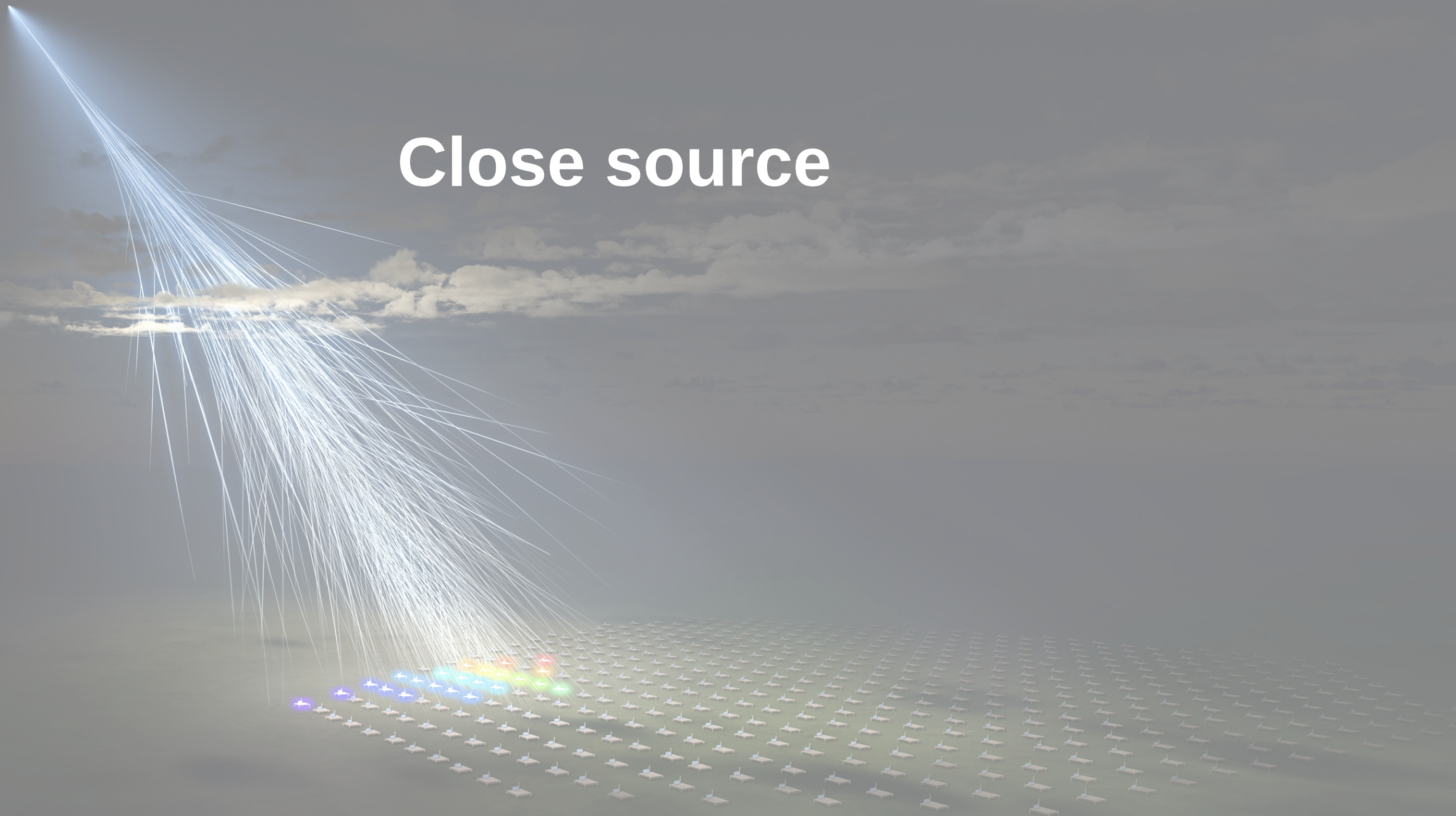
- Uncorrelated with LSS (like other events at $E > 100$ EeV)
- Not a gamma-ray 3.8σ exclusion using Neural Net



UHECR anisotropy interpretations

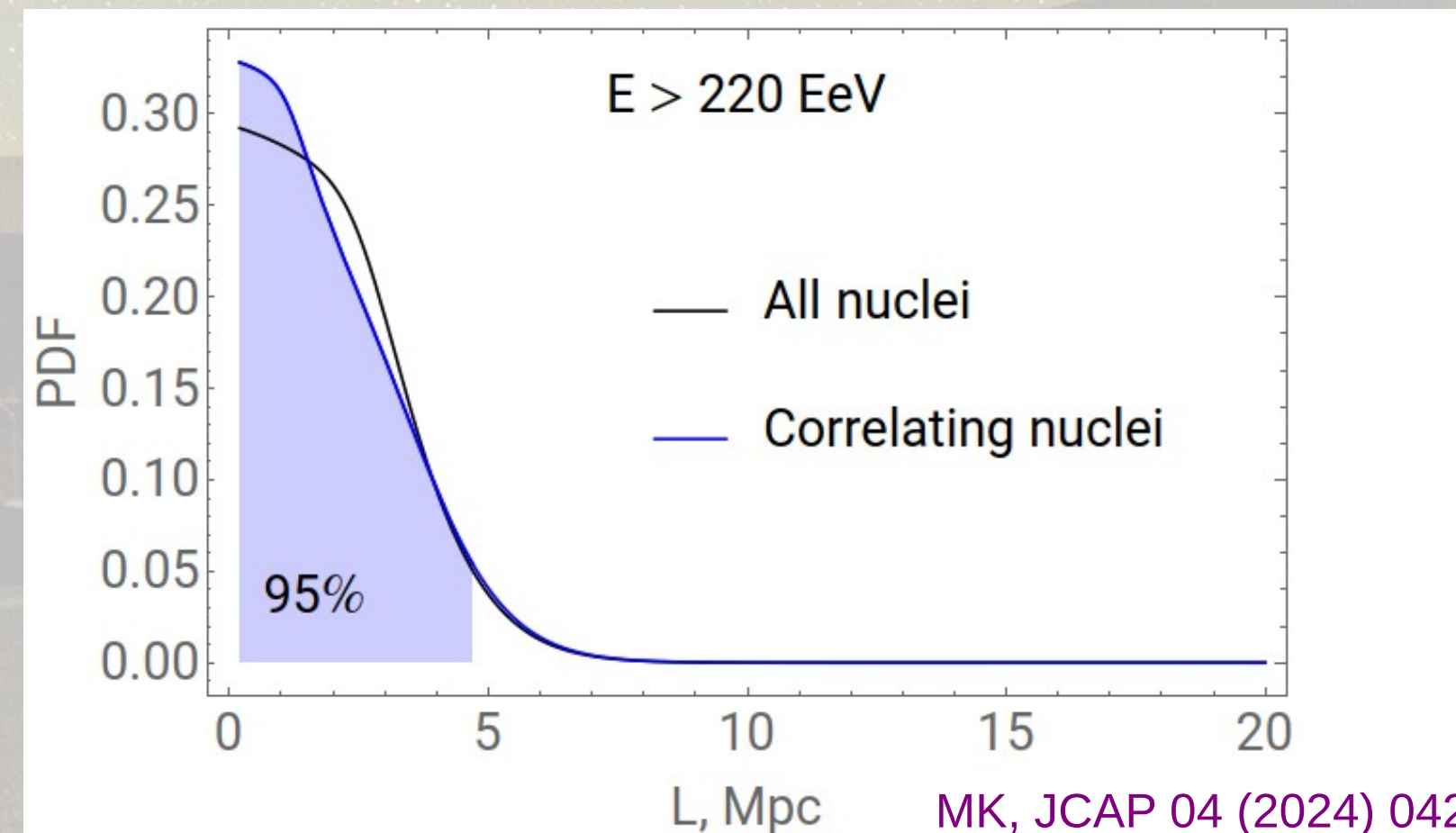
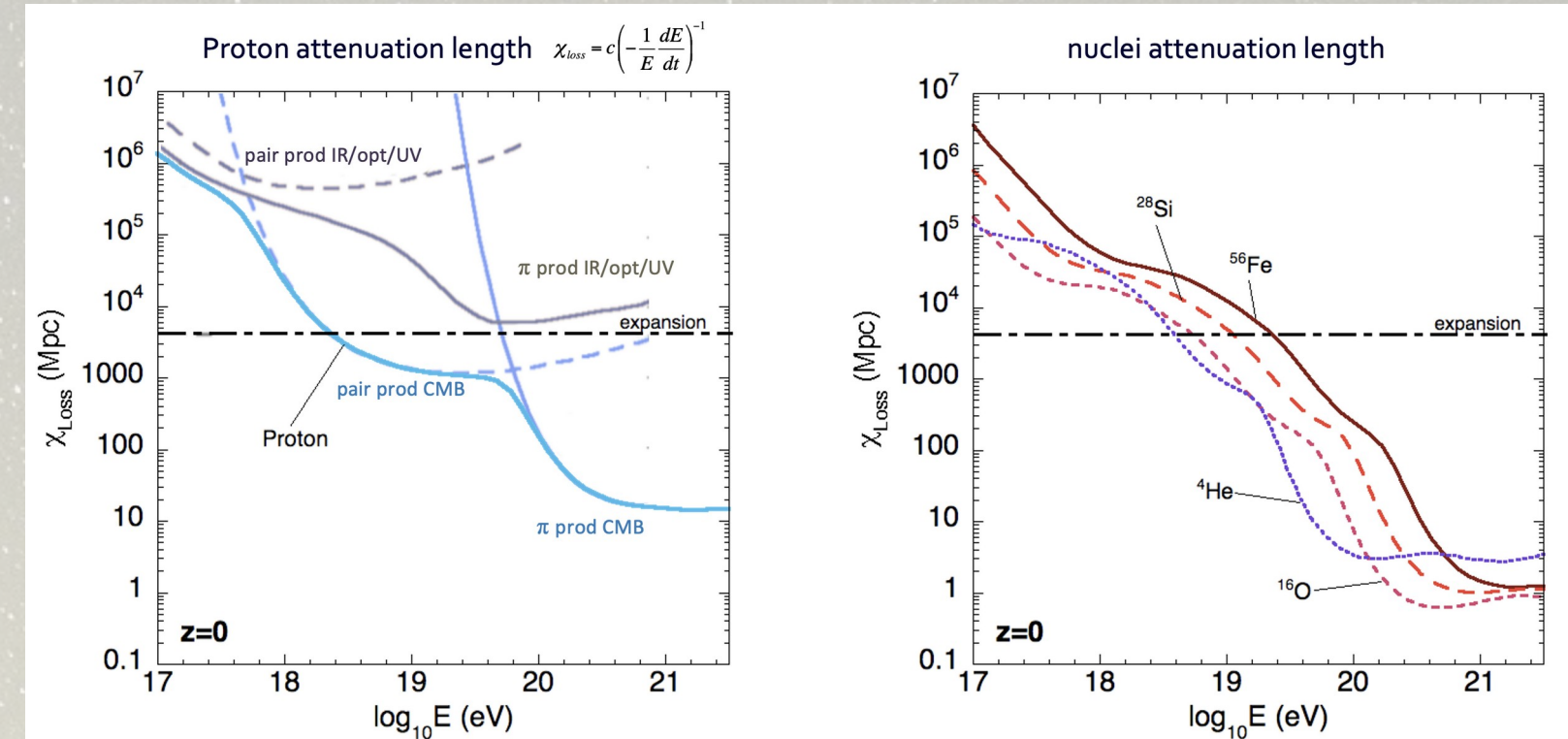
Anisotropy measurements \neq sources identification

Close source

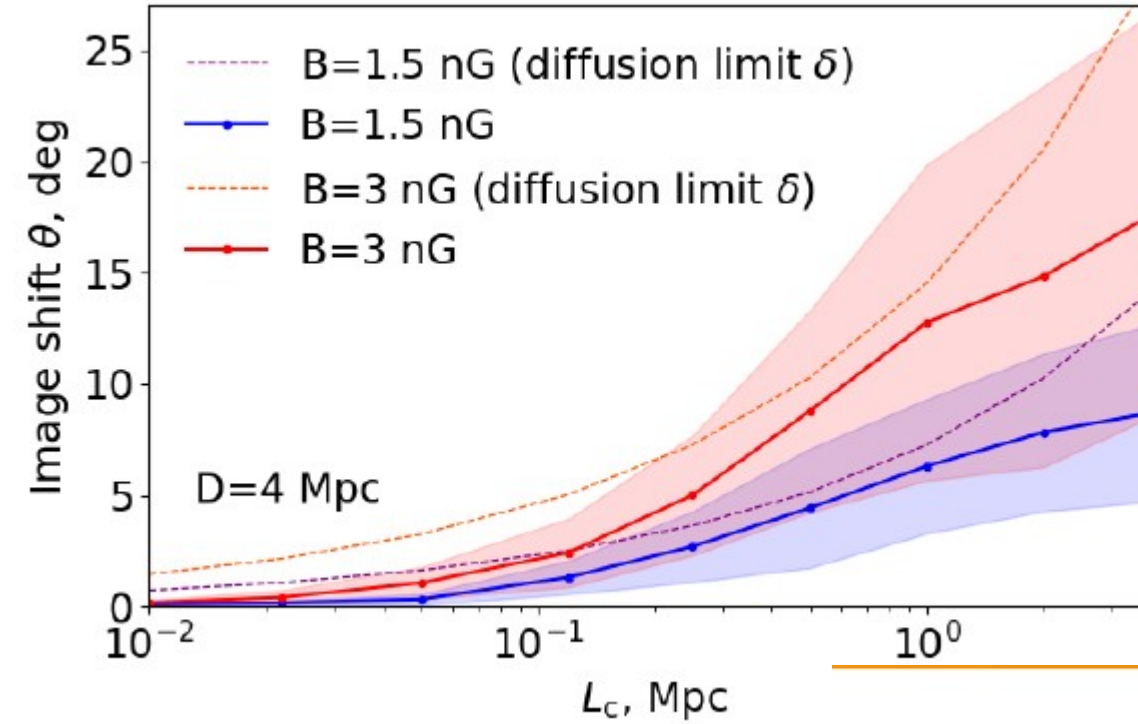
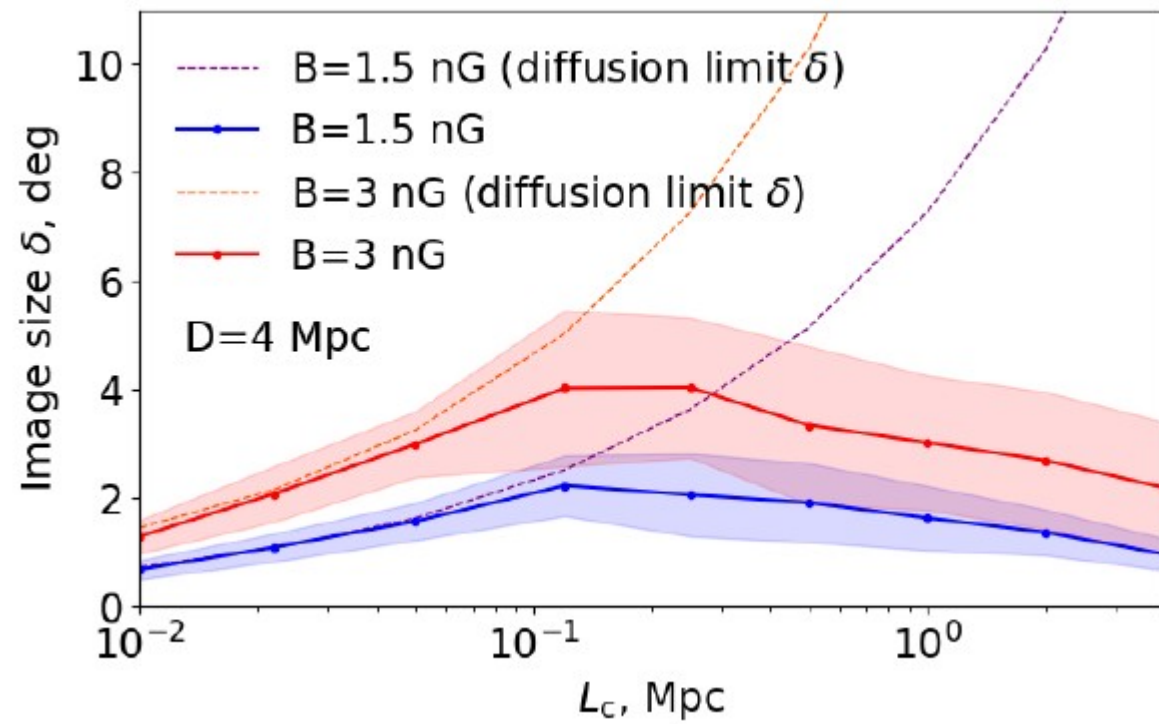


Distance to the source of extreme particle

- The source of such an 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 of origin of 95% of the flux
- **In conservative scenario ($E = 220 \text{ EeV}$, strong EGMF) the source is not farther than 4.7 Mpc at 95% C.L.**



Location and identification of possible close UHECR source(s)



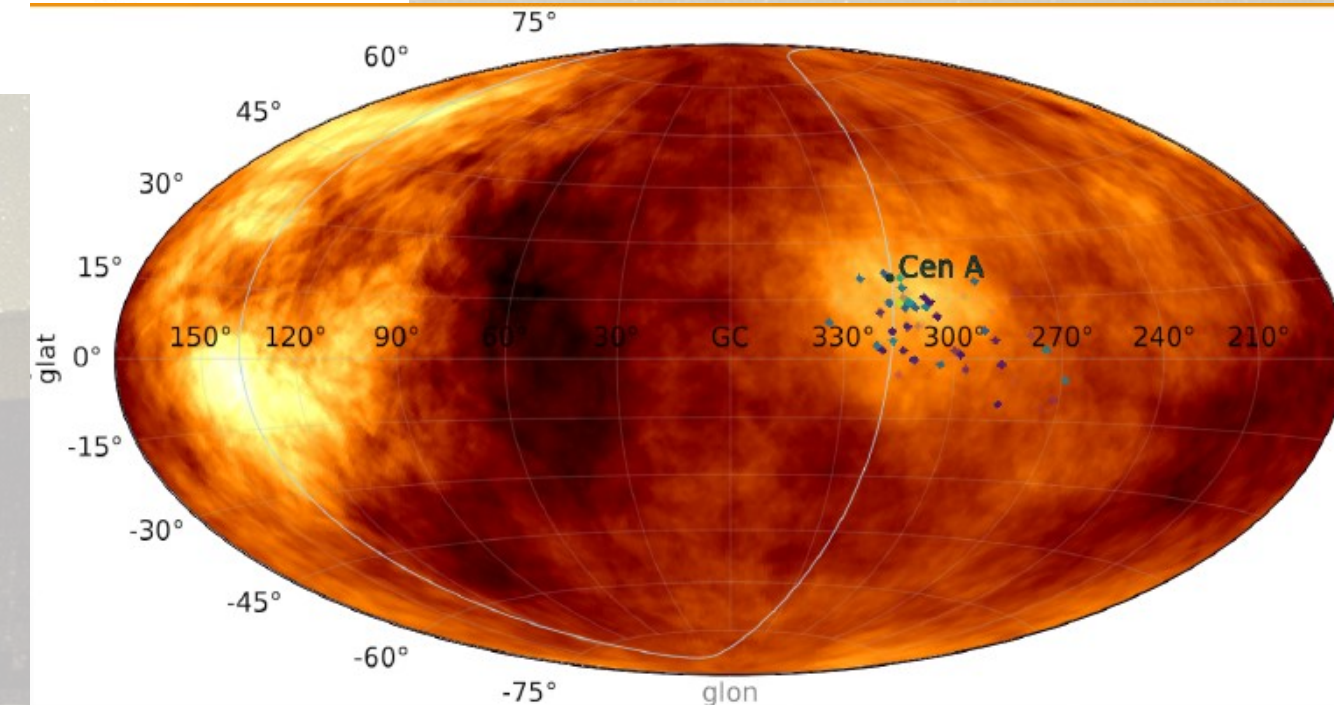
K.Dolgikh et. al, IJMPA 40 (2025)
2540012
+
talk at this conference

Detailed study of turbulent EGMF deflections:

- Image shift
- Smaller image size
- Both effects depend on EGM parameters and realization

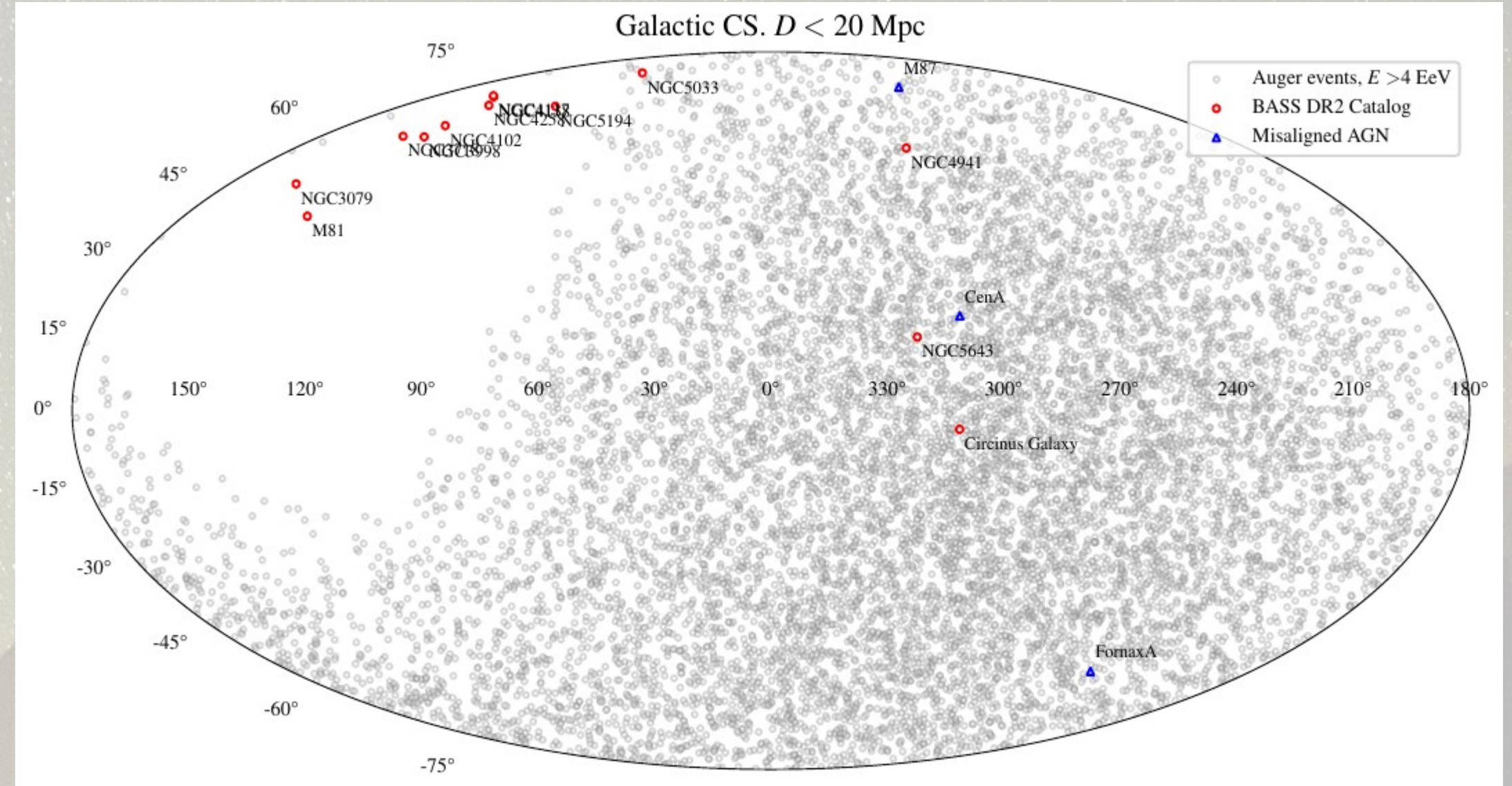
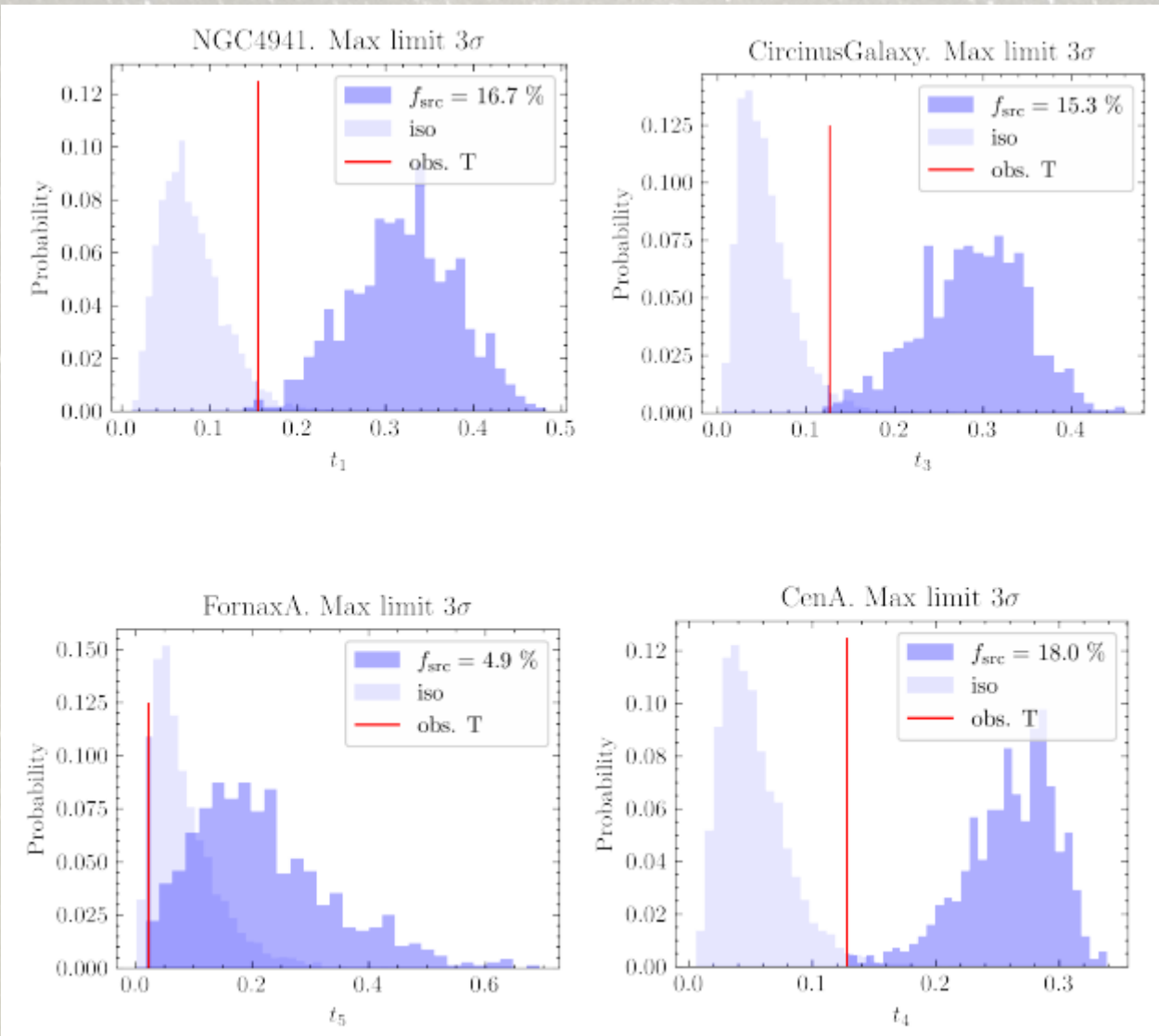
Difficult to decipher the real source from the image:

- For instance, M83 or Cen A can be the sources of «CenA excess»



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

Location and identification of possible close UHECR source(s)



talk by Iu.Moroz at this conference

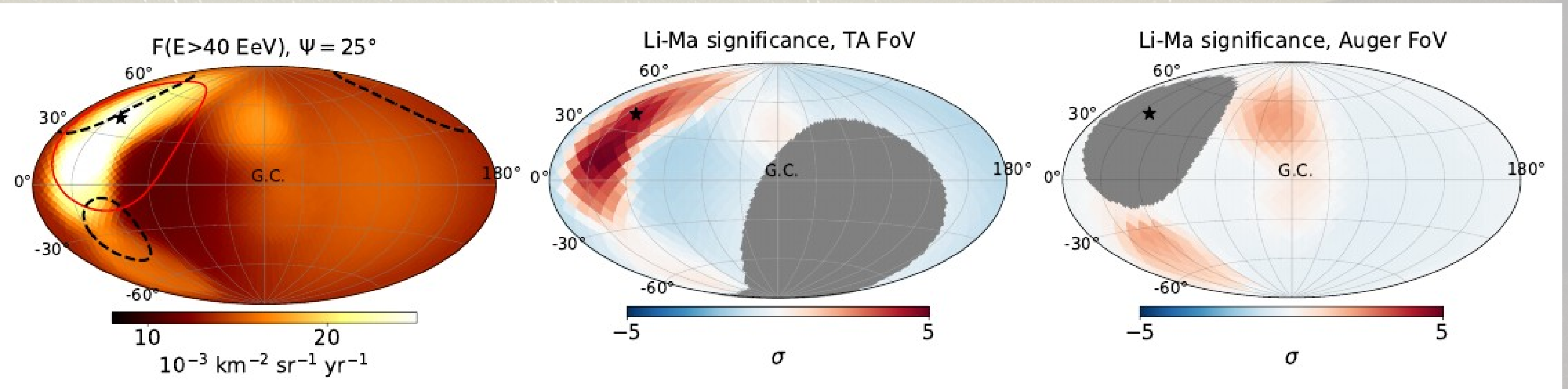
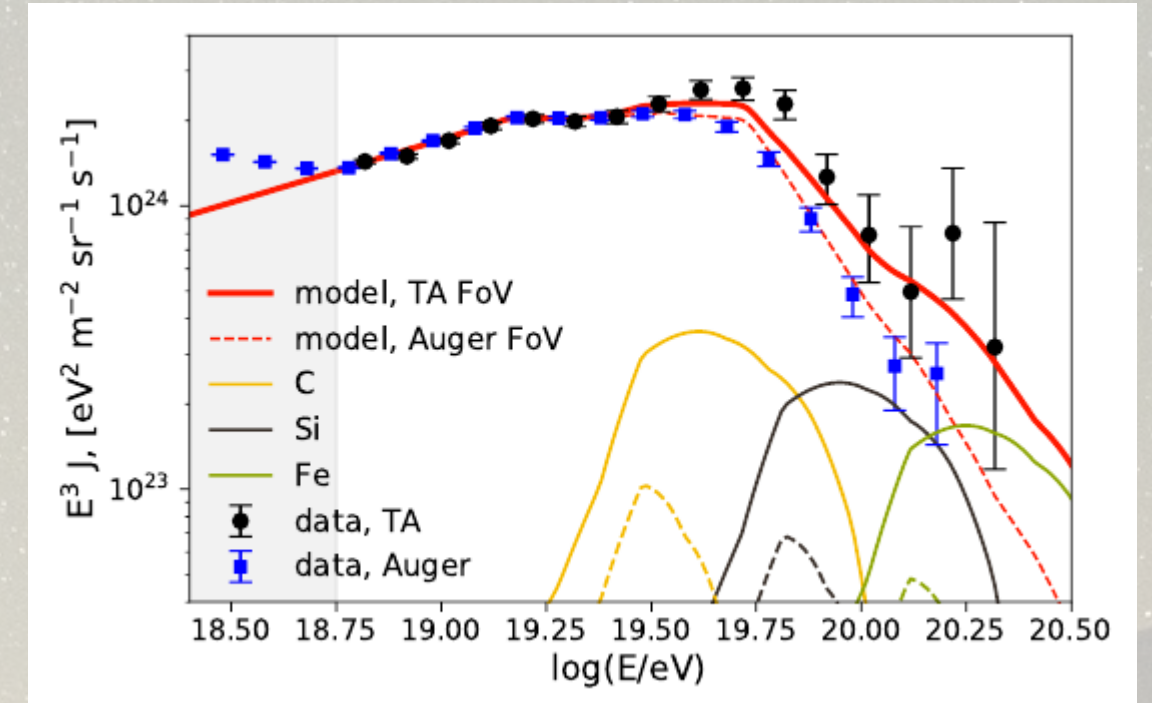
- Neural net to distinguish contribution of a distinct close source in (slightly) anisotropic event set.
- Can eliminate dependence on GMF model
- Result depends on assumed mass composition
- Ambiguity if there are several sources

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 hotspot 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



Identification of possible close source of Cen A excess

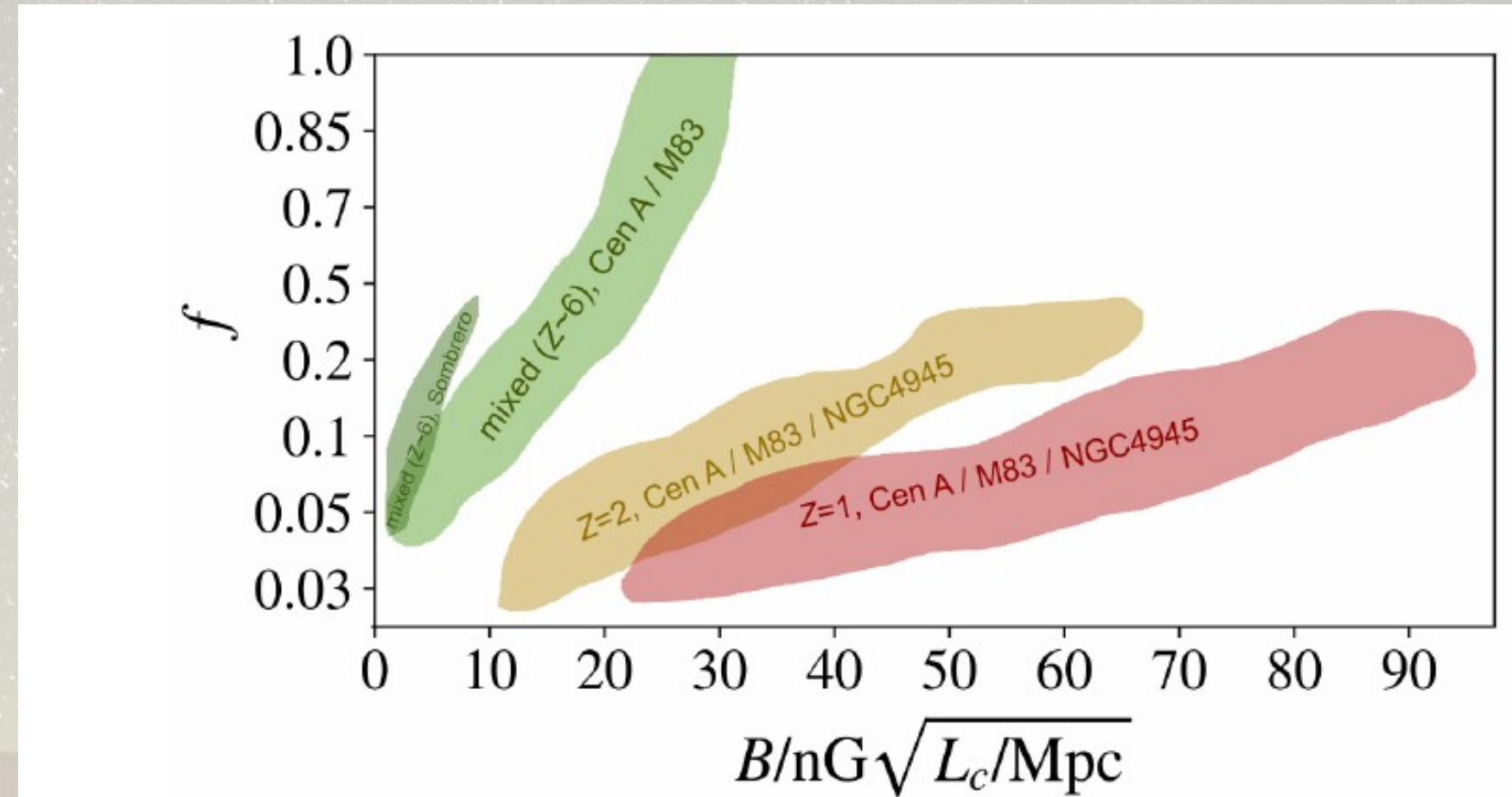
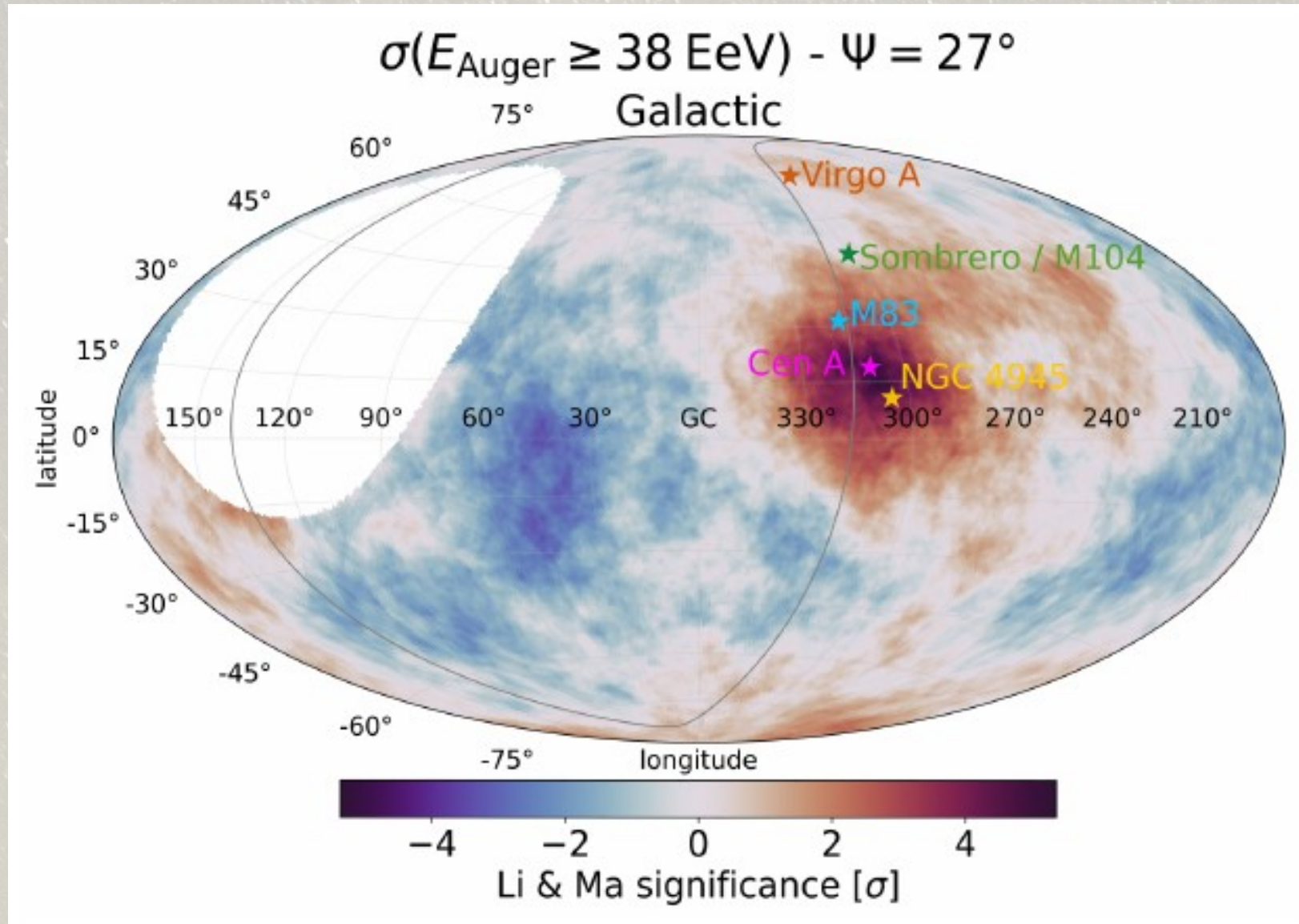
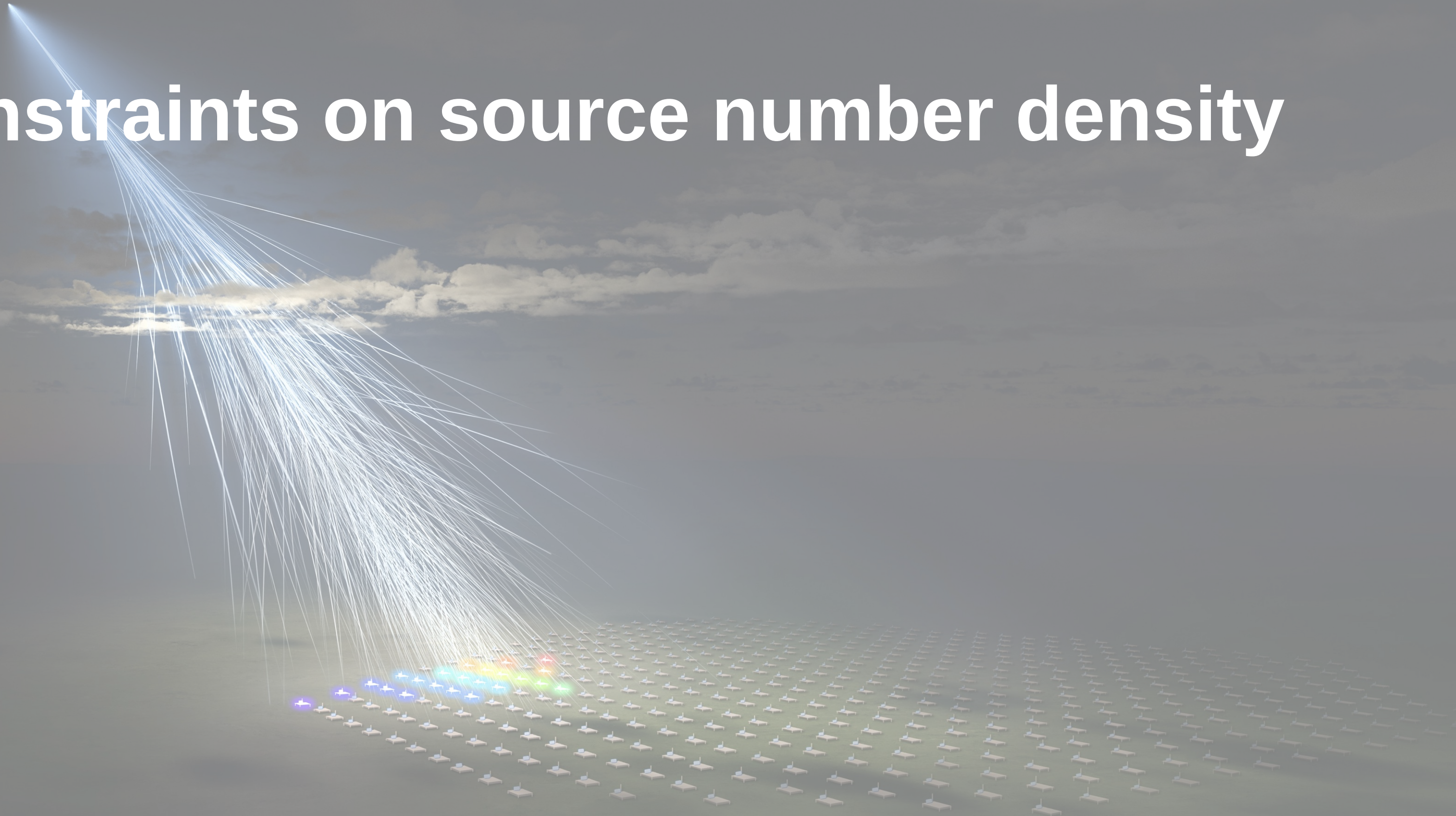


Figure 13: Summarized constraints on the signal fraction f and EGMP to be compatible with the UHECR data $\gtrsim 30 \text{ EeV}$.

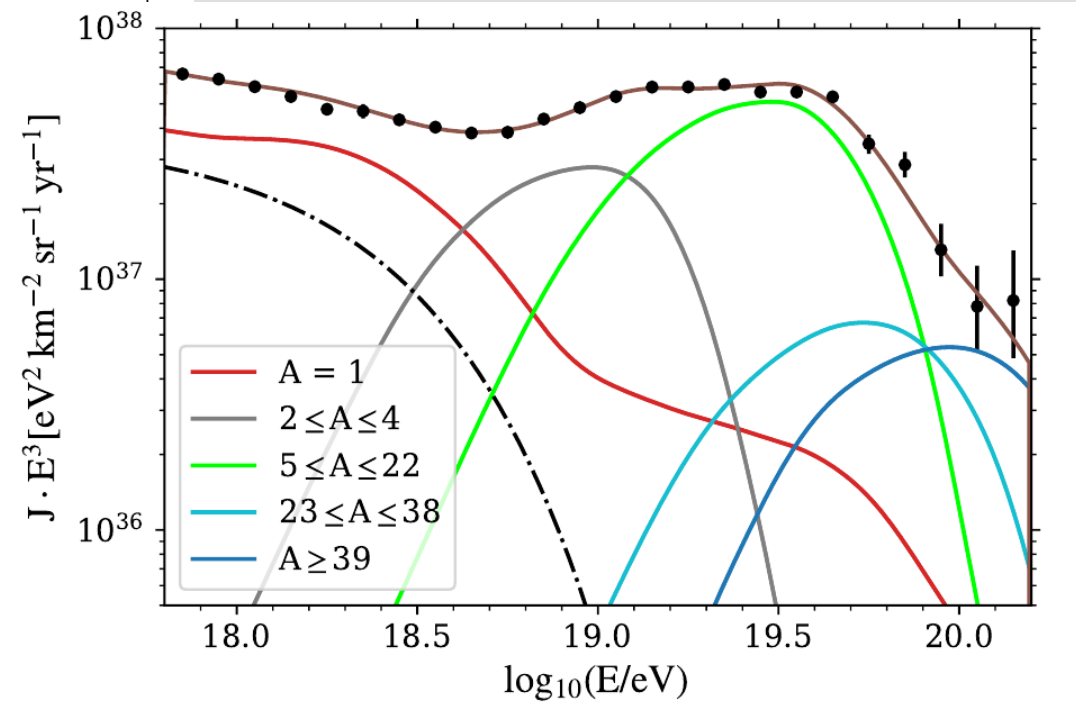
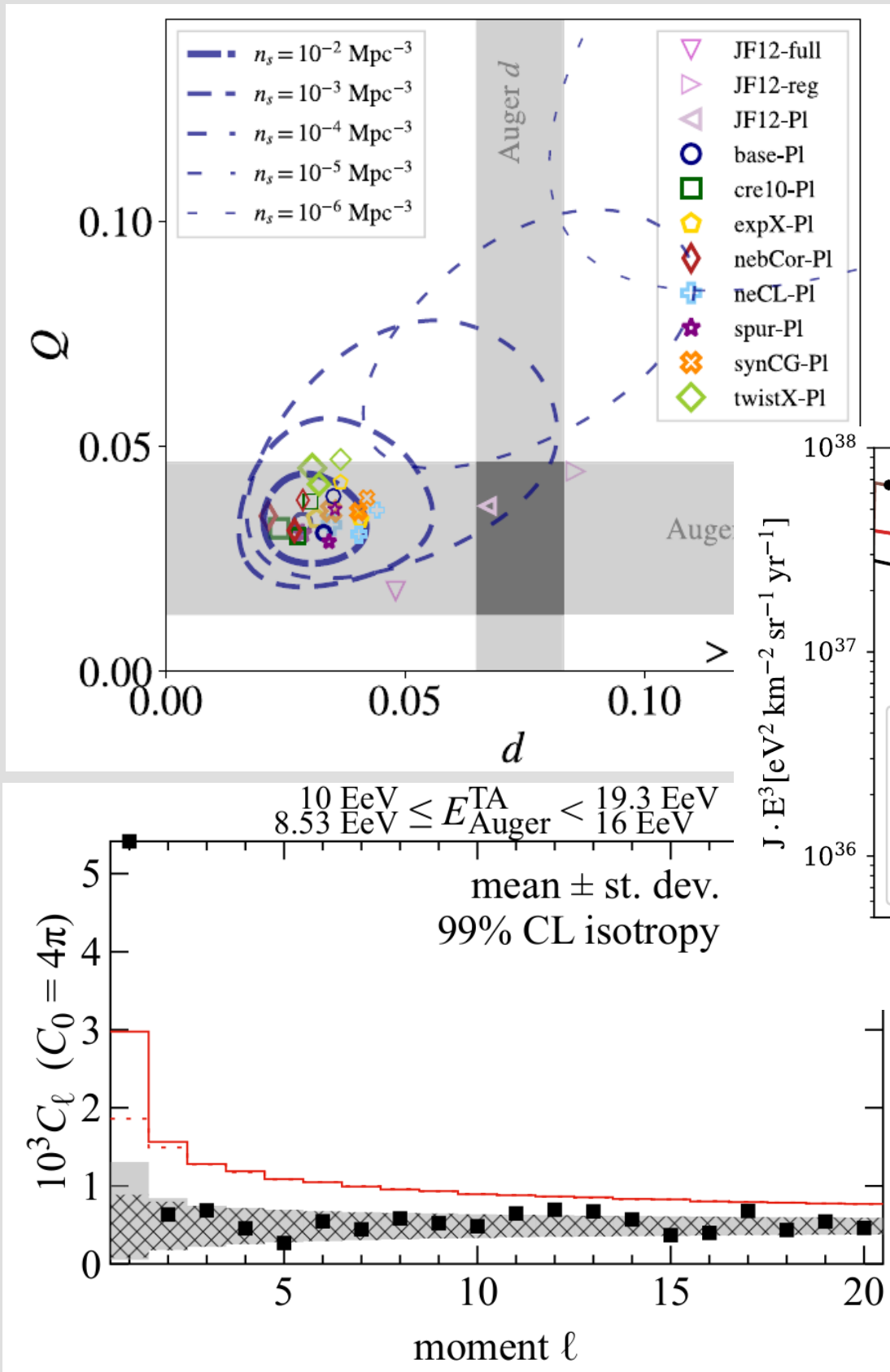
T. Bister, *Astropart.Phys.* 175 (2026) 103190

Cen A hotspot is reproducible in scenarios with various sources (Cen A, NGC4945, M83, Sombrero), depending on composition and magnetic field models

Constraints on source number density



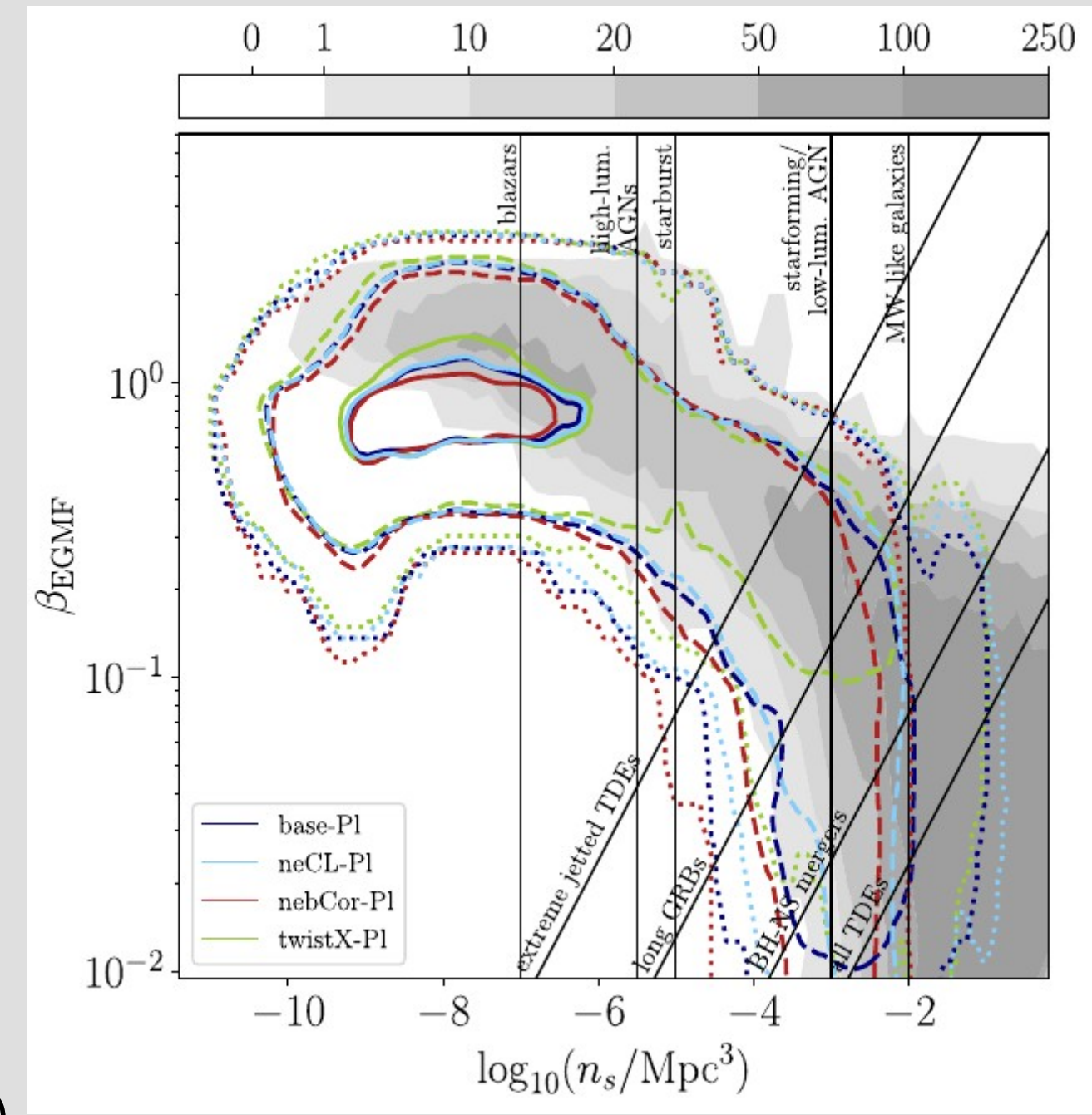
Constraints of source number density from multipole anisotropy



Results strongly depends on:

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

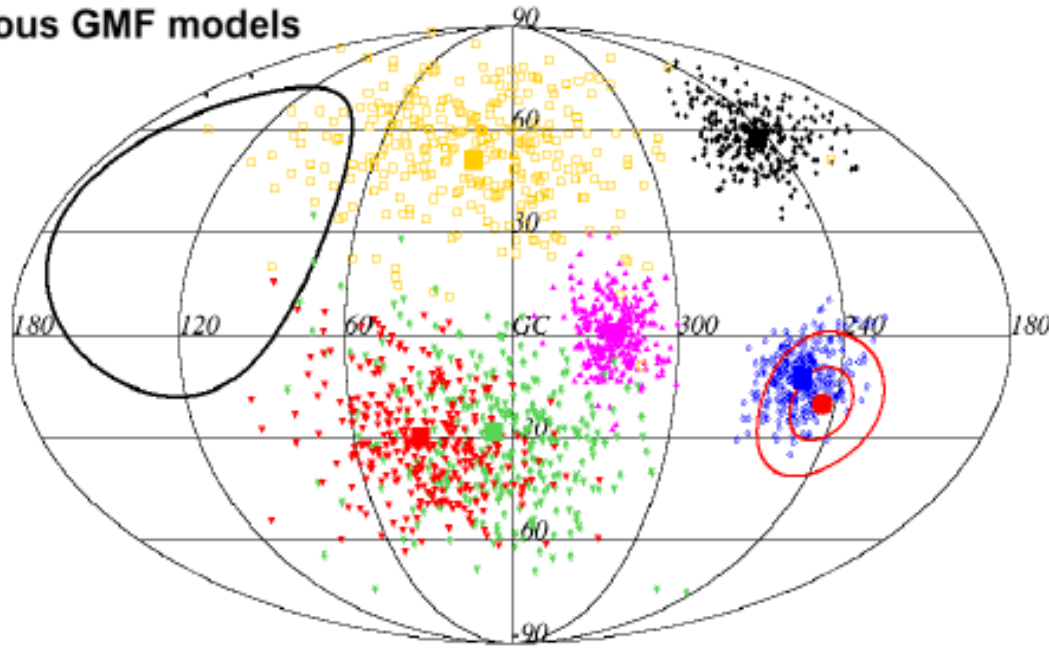
Bister et al., ApJL 975 (2024) 21



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

Reproduce large and medium scale anisotropy by simulations of sources in LSS

Model I
Various GMF models



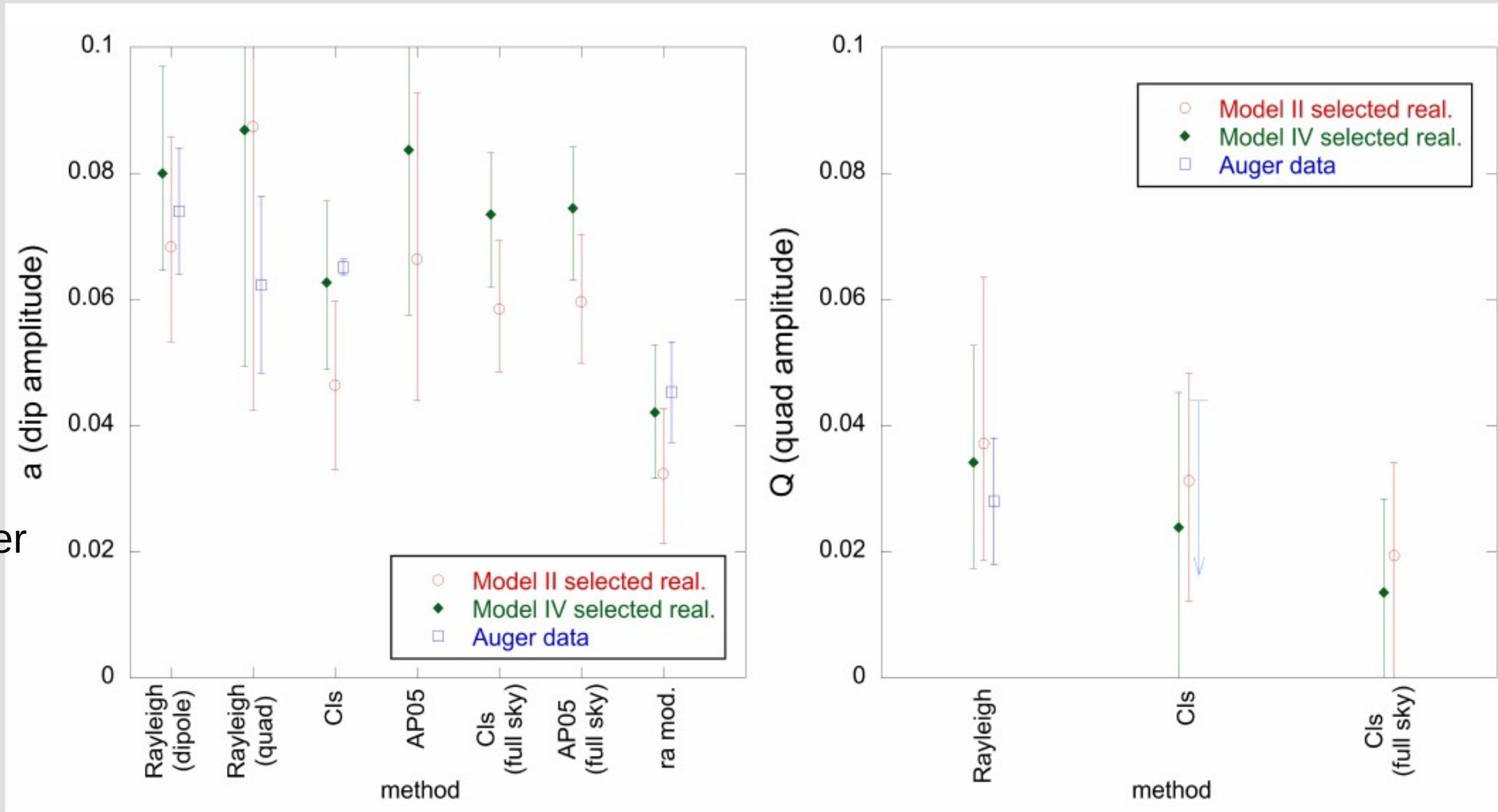
Assume sources in LSS with varying number density.

It is possible to reproduce:

- dipole amplitude and direction
- quadrupole amplitude
- location of Cen A excess

Issues:

- strong dependence on GMF model
- strong dependence on source number density
- composition is fixed to Auger model, otherwise also strong dependence

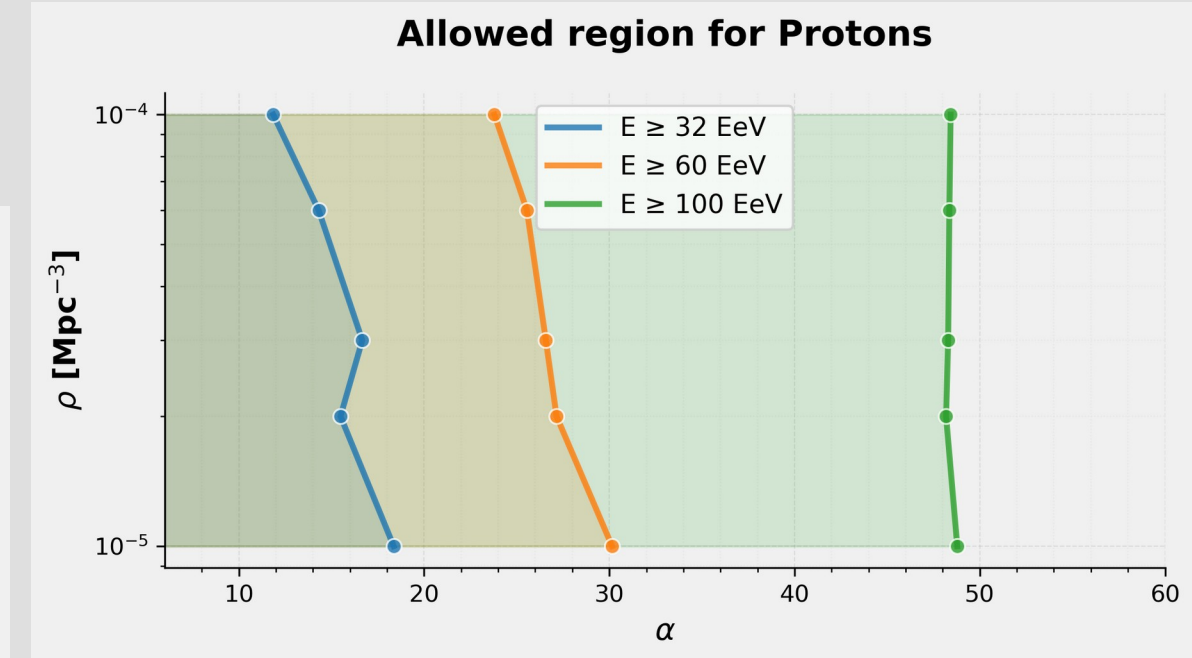
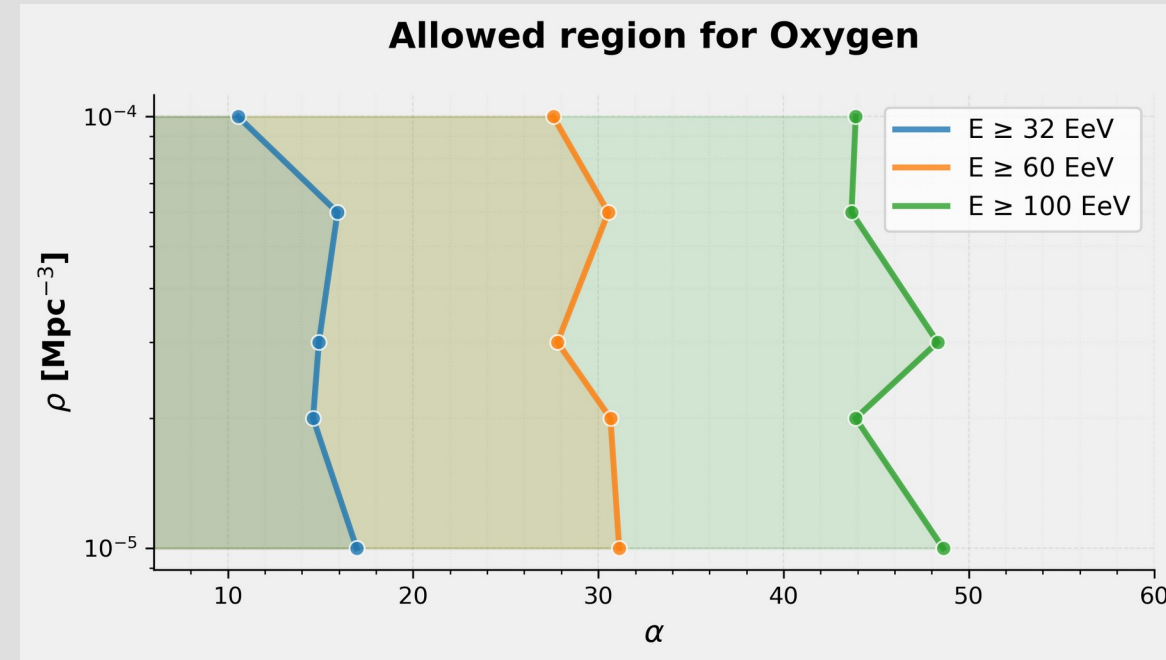
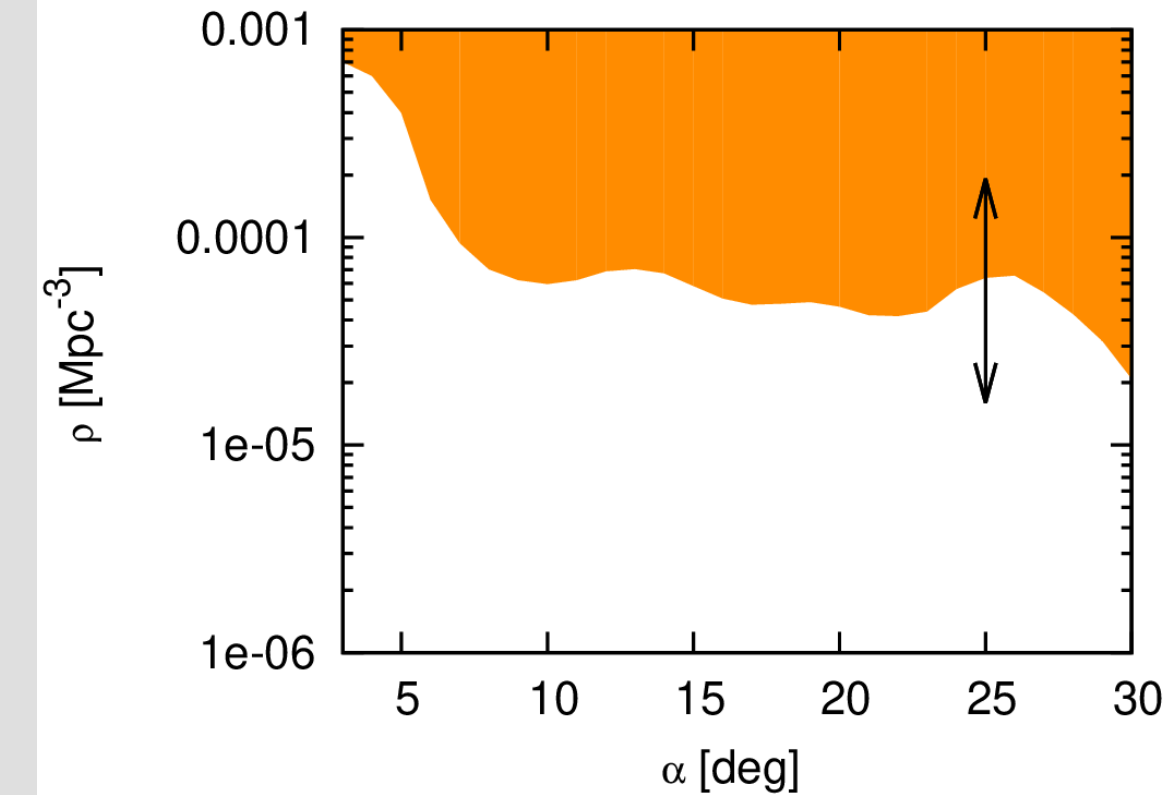


Allard et al., arXiv:2601.07259

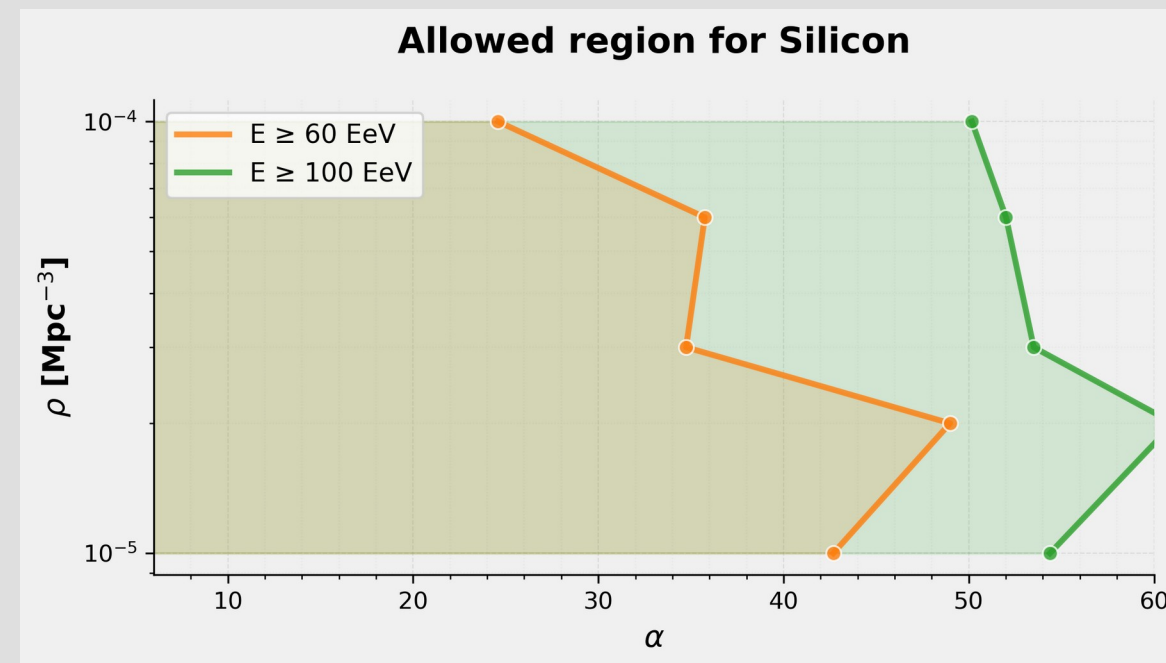
Constraints of source number density from autocorrelation

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

Auger, JCAP 05 (2013) 009



talk by A.Pavliuk at this conference



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

Does not take into account GMF and secondary particles in propagation

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

Take into account secondaries and GMF

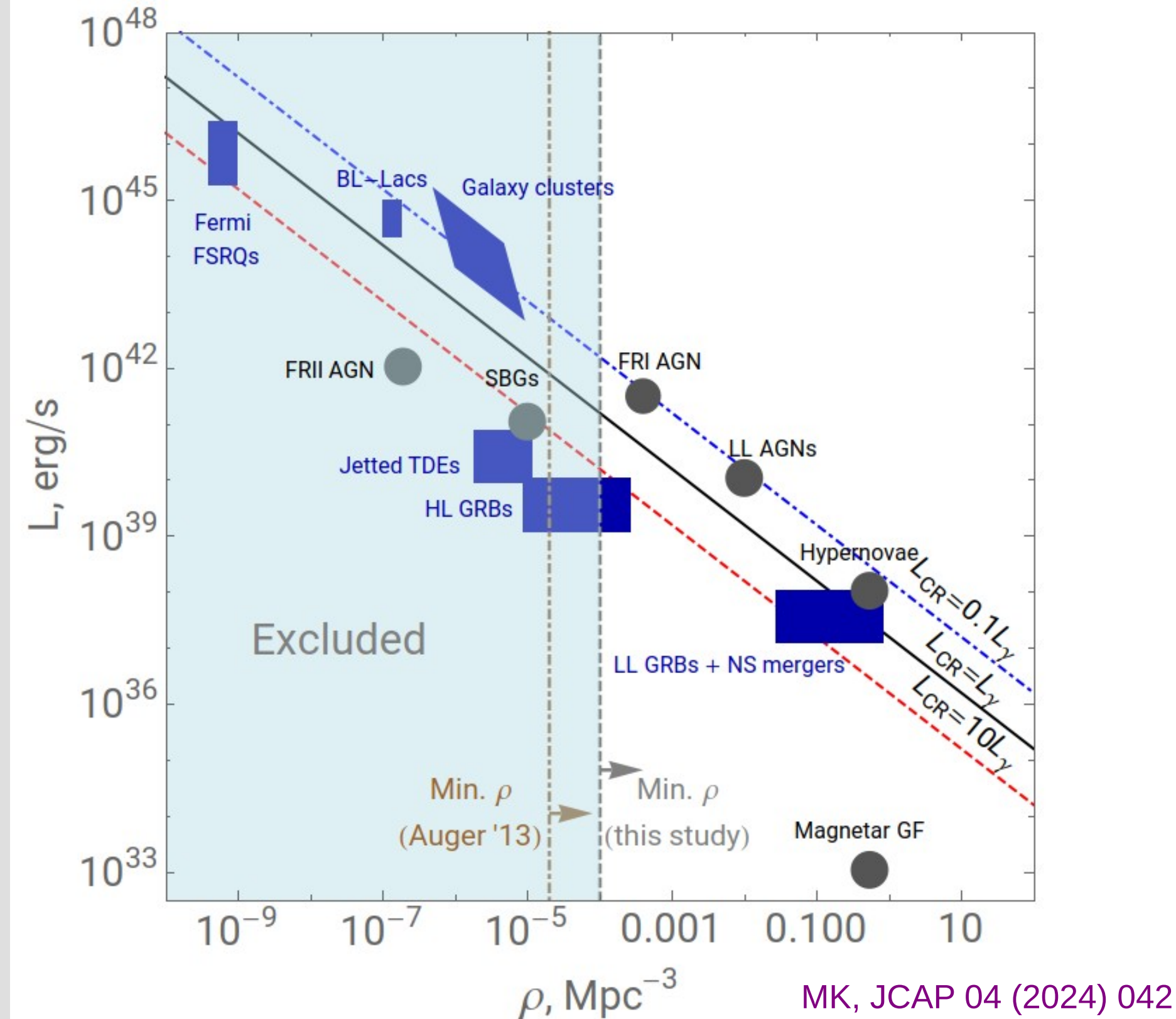
Autocorrelation angle α is only a technical parameter here (we reject the source model if $AC_{\text{model}}(\alpha) > AC_{\text{data}}(\alpha)$ at any α)

All values of ρ excluded for p, He and O, but no value for Si

The measurement constrain the composition but not source number density, yet

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



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

A 3D visualization of a neural network layer. A grid of small, light-colored rectangular nodes is arranged on a flat surface. A bright blue beam of light originates from the top left and fans out, illuminating a specific region of the grid. This region contains several nodes that are highlighted with vibrant colors: purple, blue, cyan, green, yellow, orange, and red. The background is a dark, cloudy sky.

Interpretation of correlations with source classes

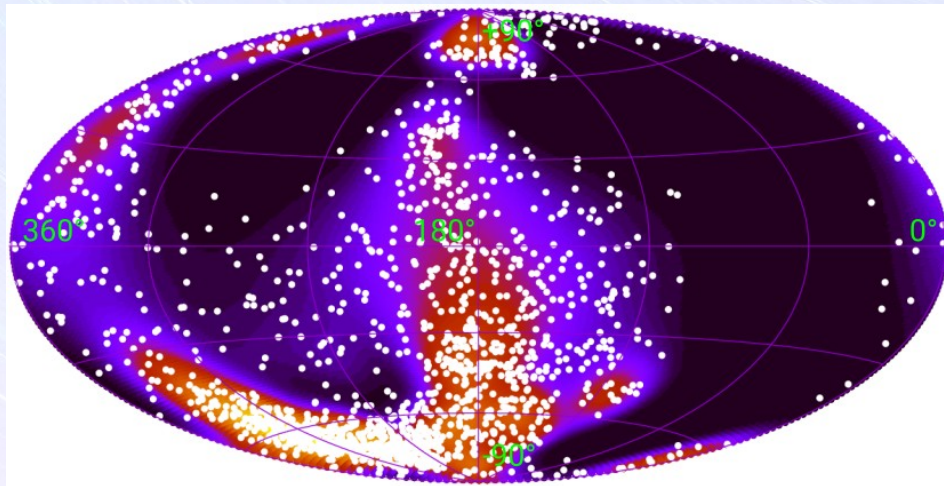
Interpretation of UHECR correlation with source classes

Auger and TA @ ICRC-2023

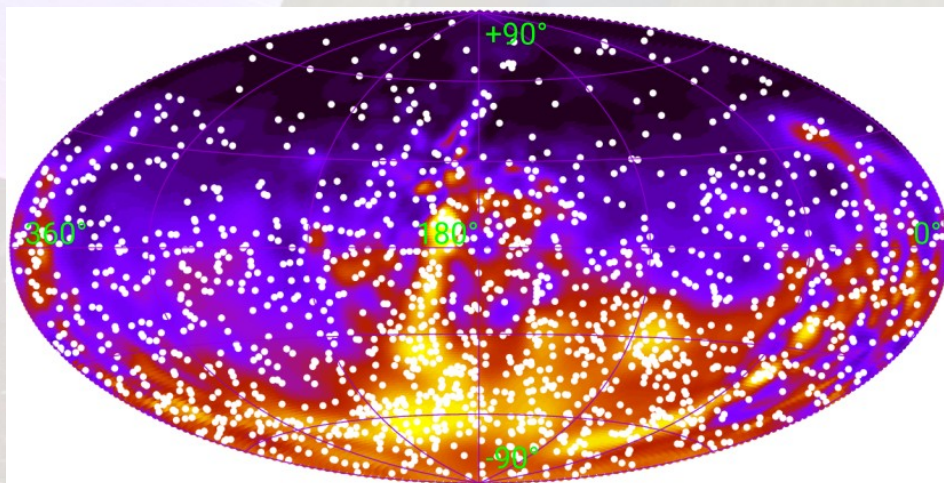
Сделаем реалистичные Монте-Карло симуляции наблюдаемых КЛ

- Инжекция из источников с заданным спектром
- Инжектированный массовый состав - произвольный
- Поглощение при распространении в межгалактической среде
- Отклонение в магнитном поле Млечного Пути
- Оценка корреляции только с каталогом starburst галактик

Источники в starburst галактиках

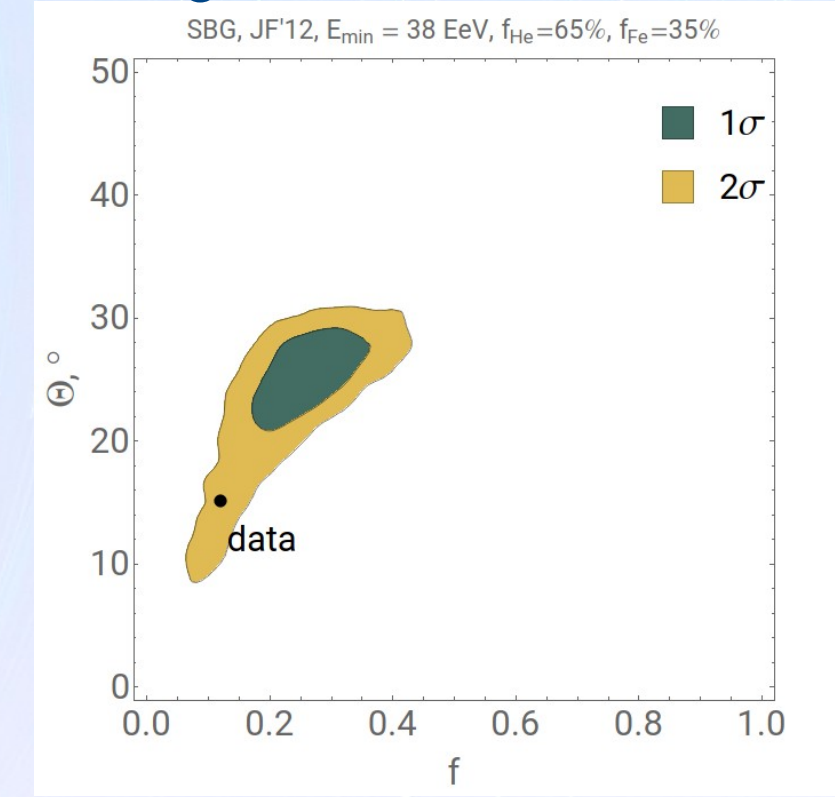
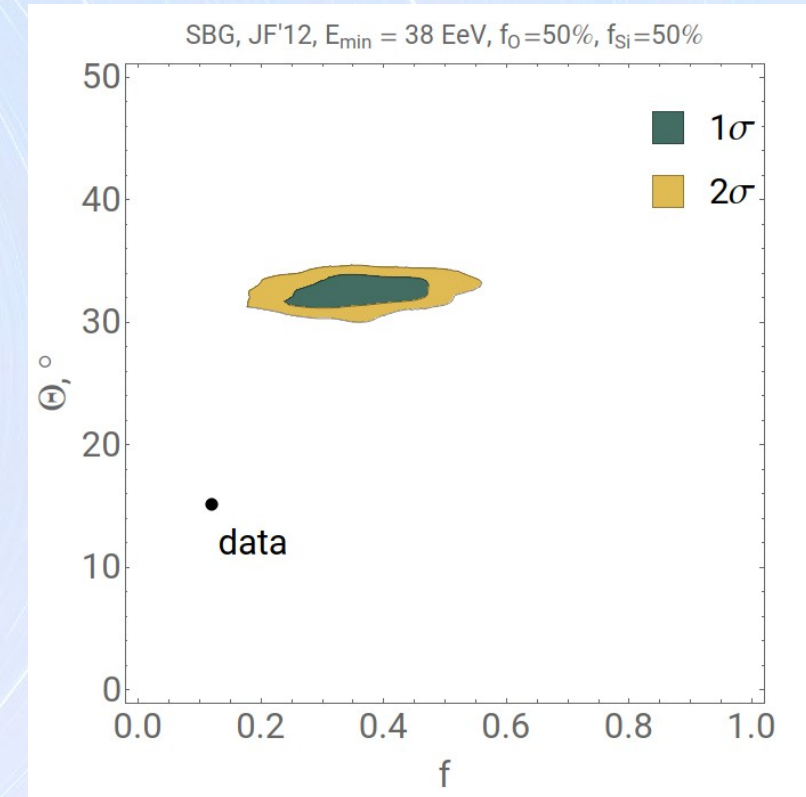


Источники во всех галактиках

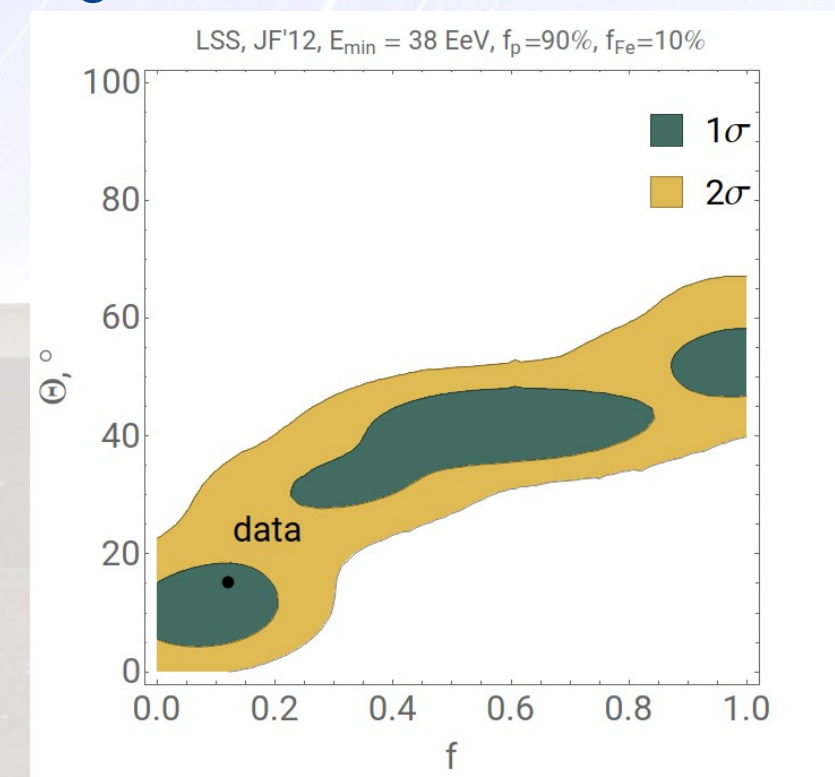
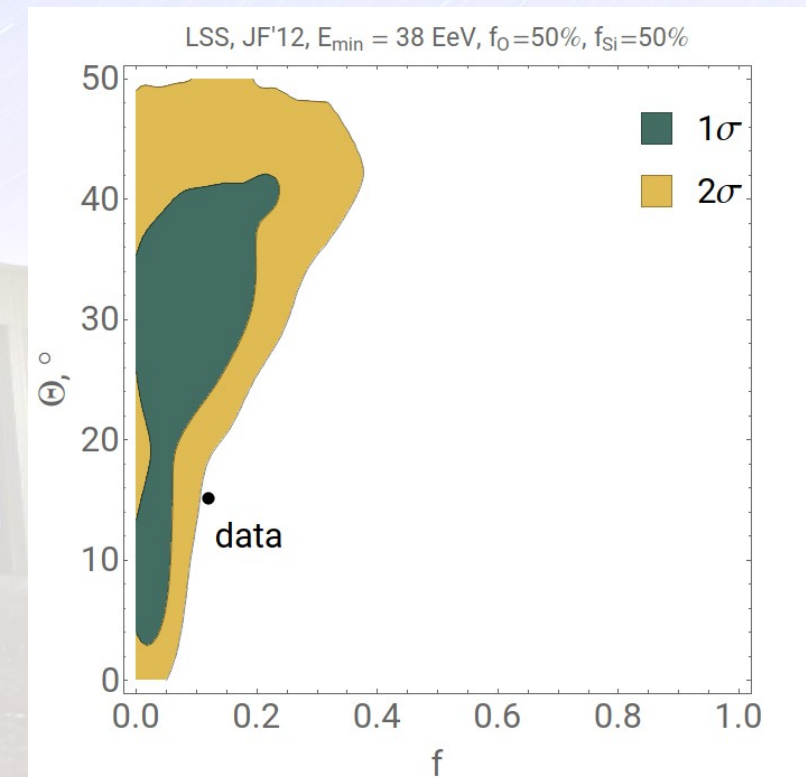


Т.о. **интерпретация** наблюдаемой TA+Auger корреляции с SBG галактиками **неоднозначна**: такой же сигнал могут обеспечить и другие источники

Sources in starburst galaxies



Sources in all galaxies



Interpretation of UHECR correlation with source classes

Assume sources in LSS, $\rho > 10^{-3} \text{ Mpc}^{-3}$ and injected composition fitted to Auger spectrum and X_{max}

$$dN_i/dR = \alpha_i \times KR^{-\beta} \exp(-R/R_{\text{max}})$$

Model	β	$\alpha(H)$	$\alpha(He)$	$\alpha(C)$	$\alpha(O)$	$\alpha(Si)$	$\alpha(Fe)$	R_{max} (EV)	evolution
A	-0.45	20.	49.	10.	16.	2.7	1.3	1.6	yes

Generate Monte-Carlo sets



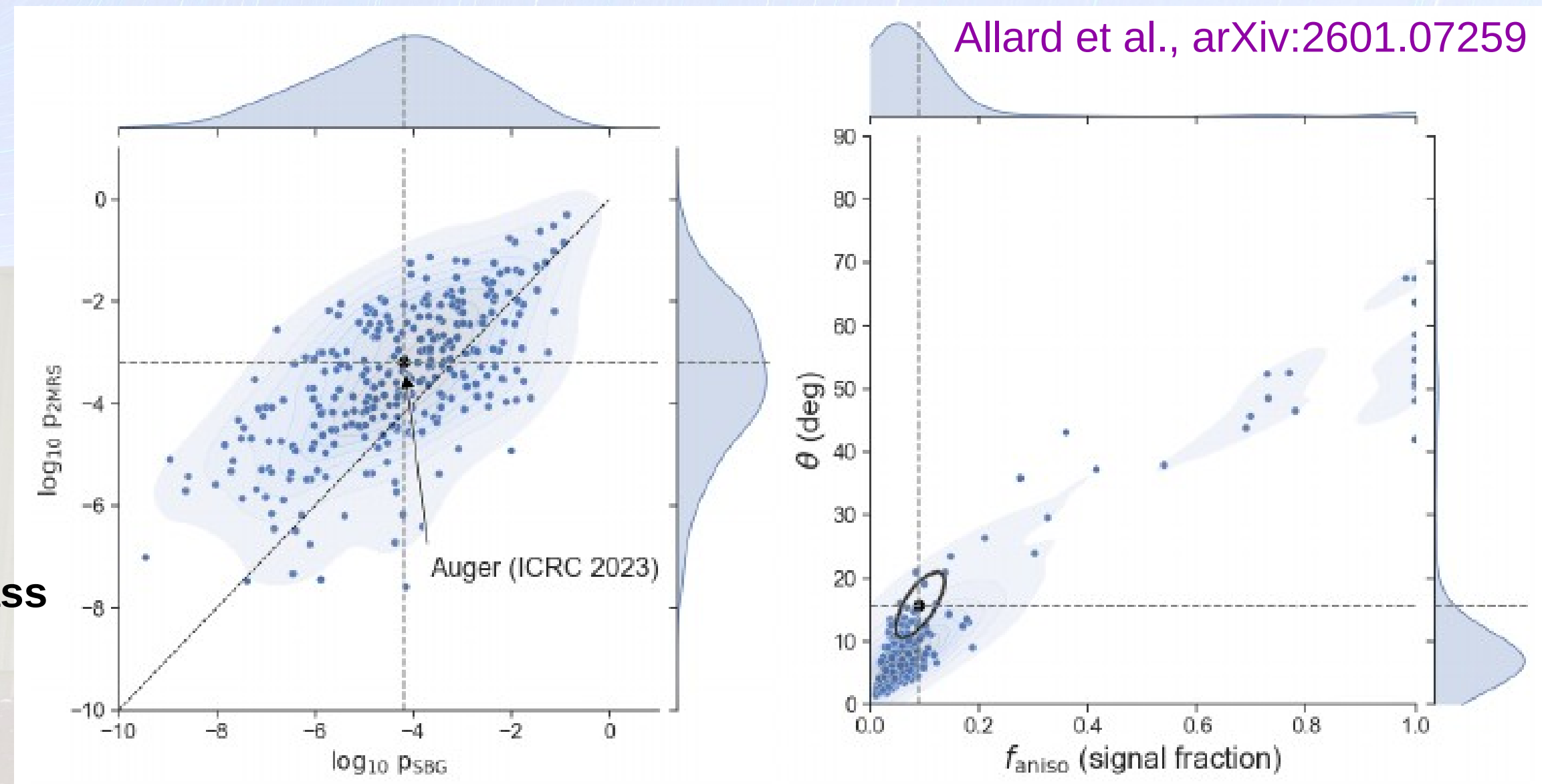
Apply TS-analysis for either SBG or LSS



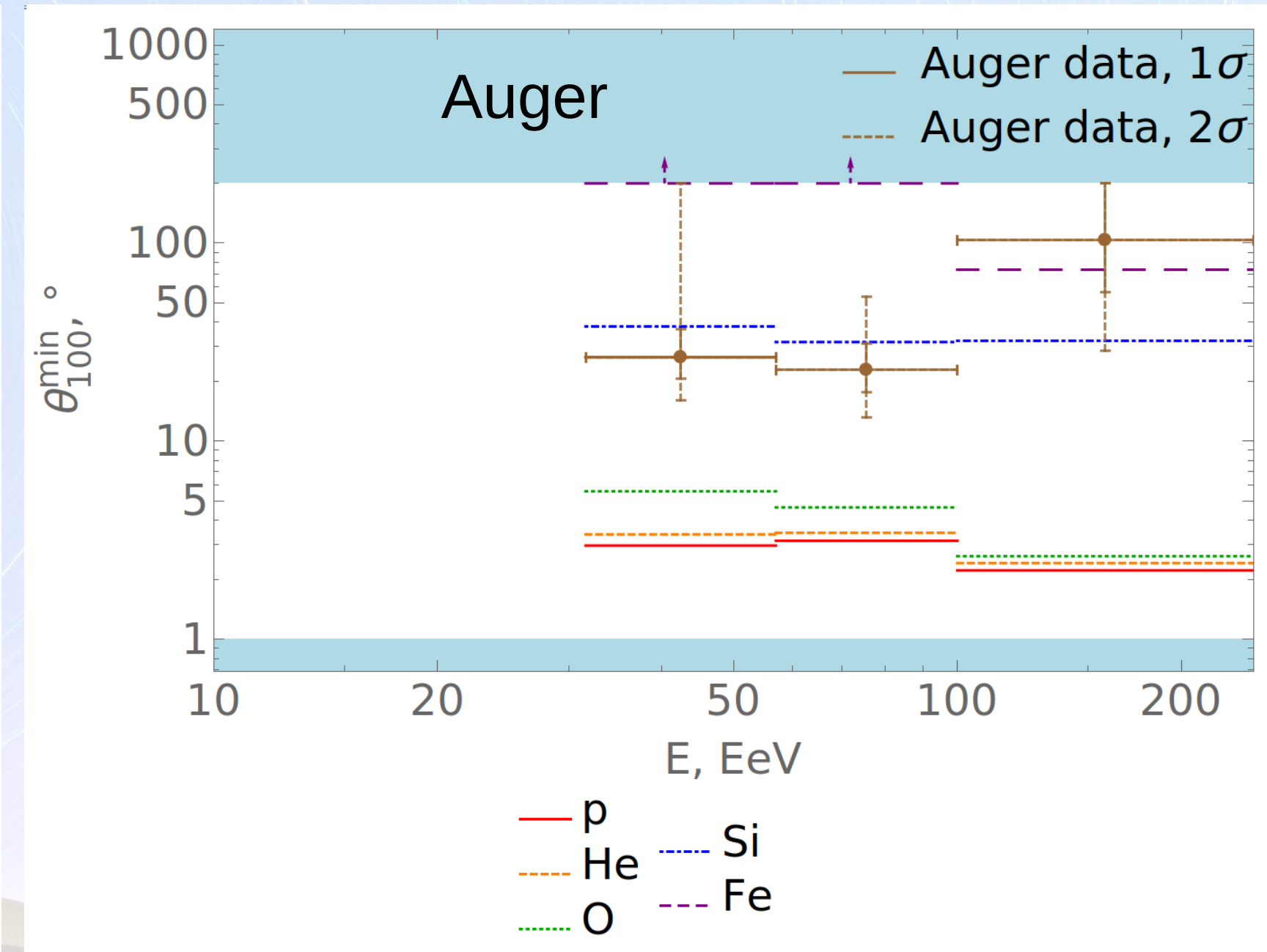
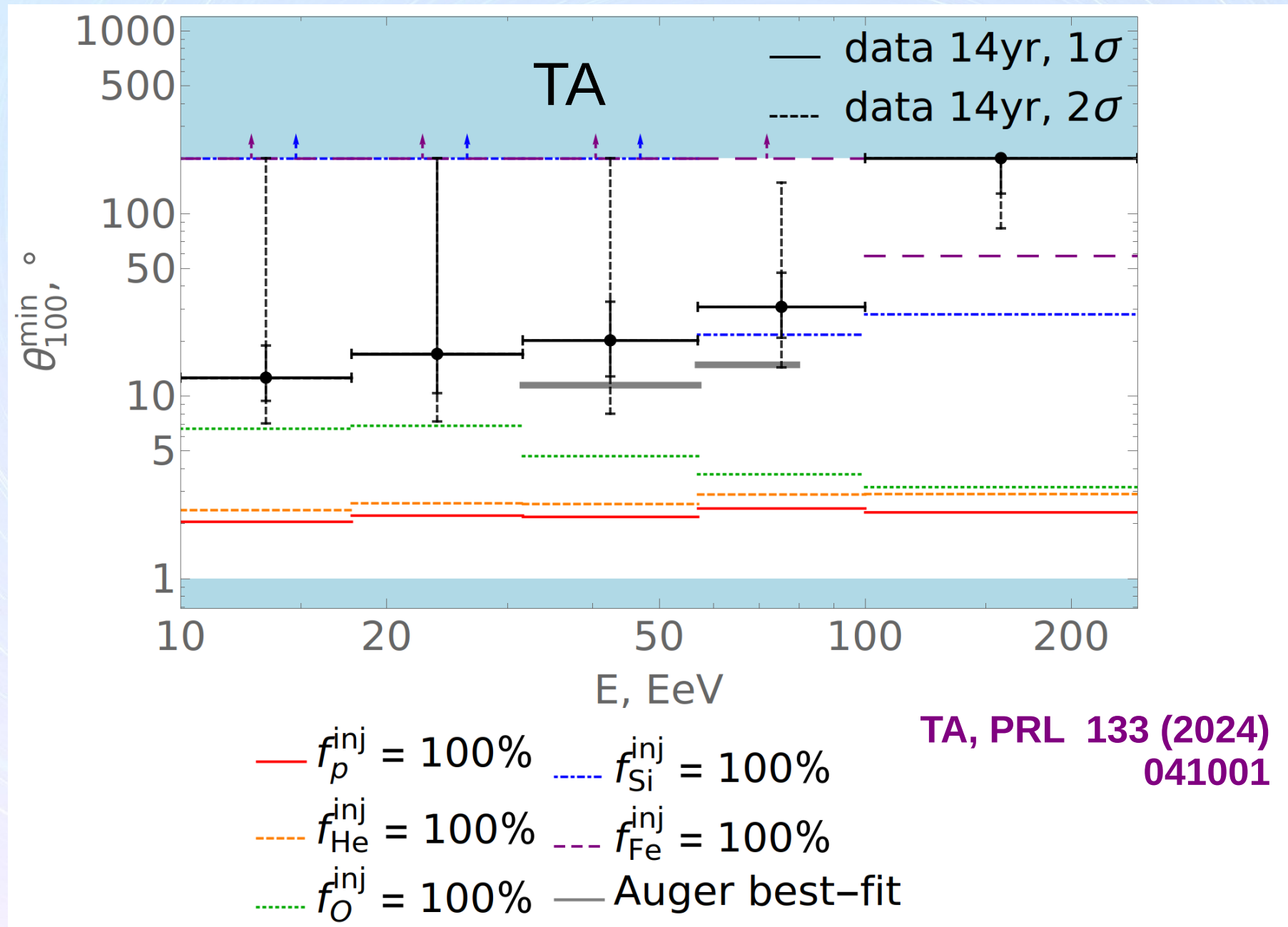
Good agreement with both



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



Correlation with LSS vs. composition models



Correlation with LSS is present but not very significant ($\sim 2\sigma$), and its interpretation may be ambiguous

But both TA and Auger data favors heavy composition at $E > 100$ EeV

Correlation with LSS: smaller galaxies

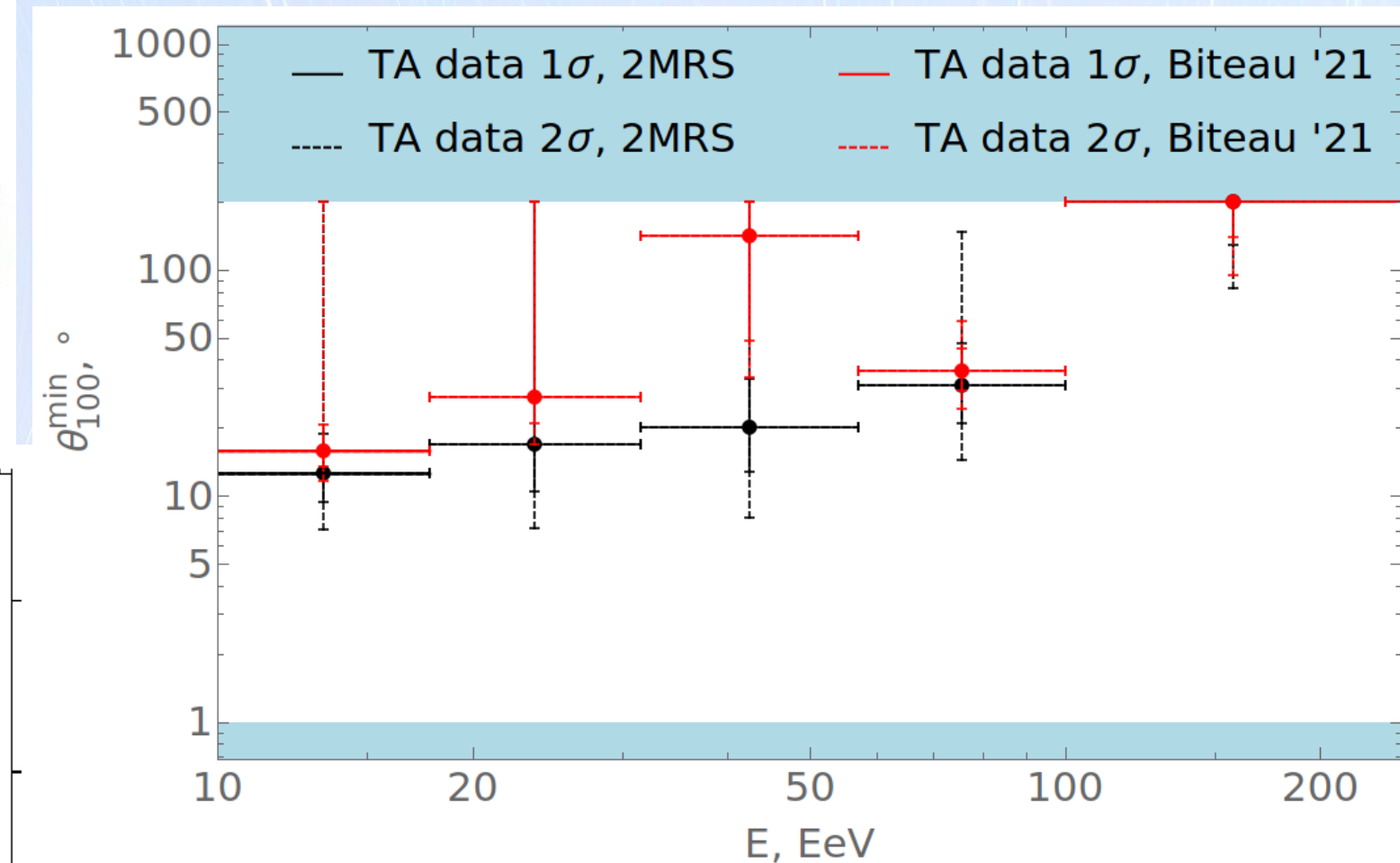
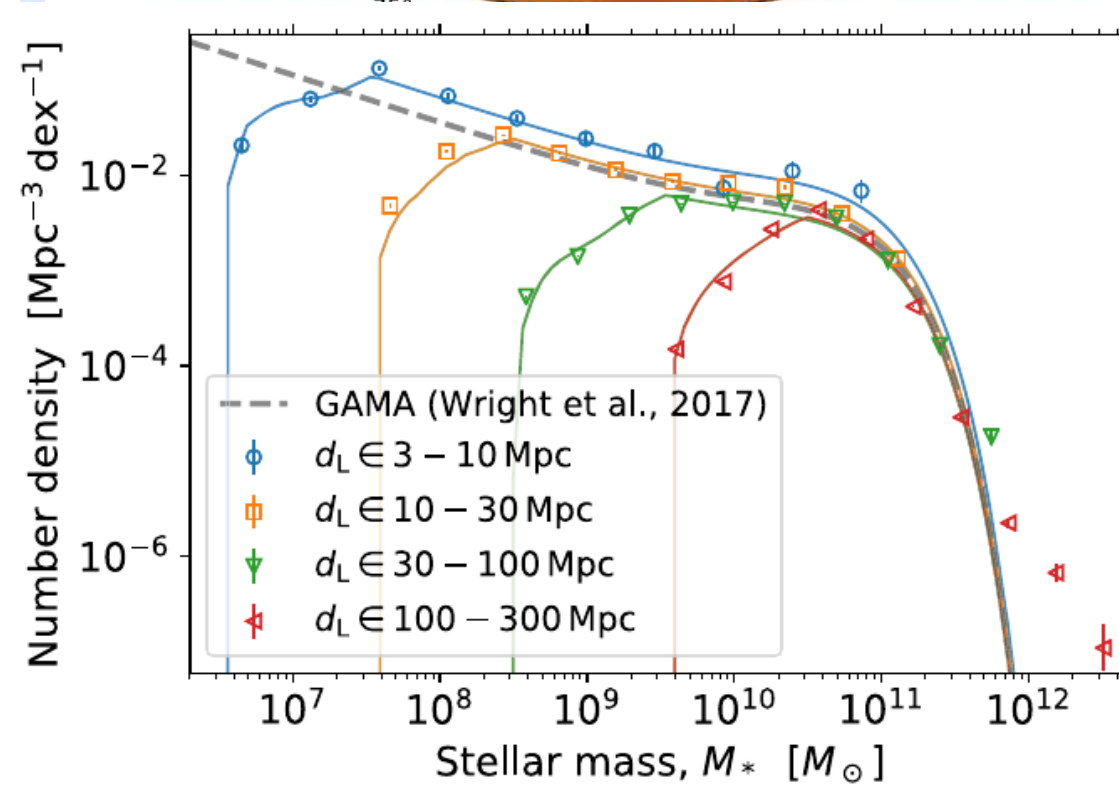
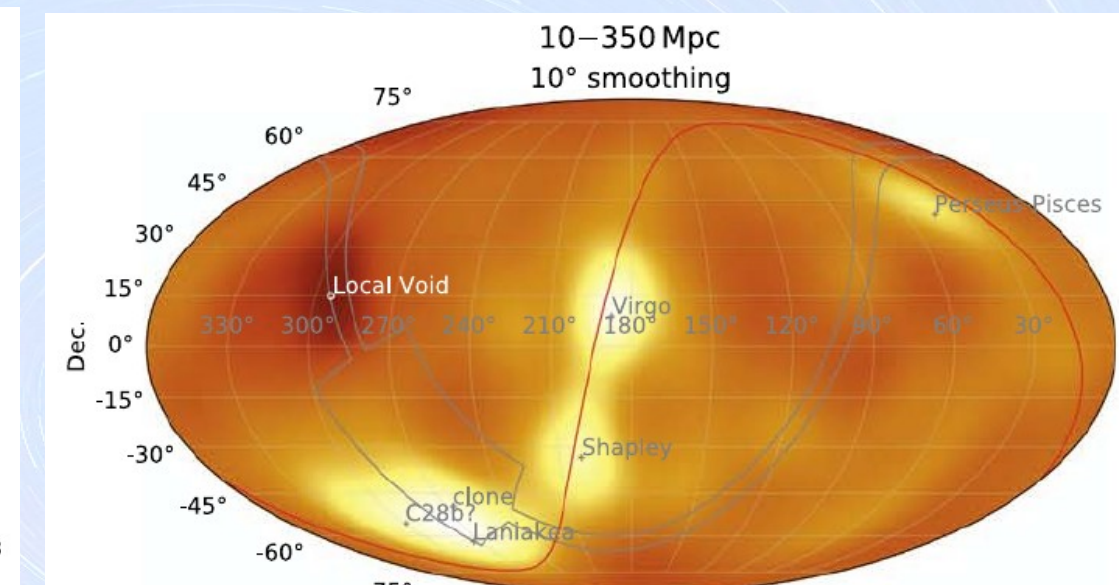
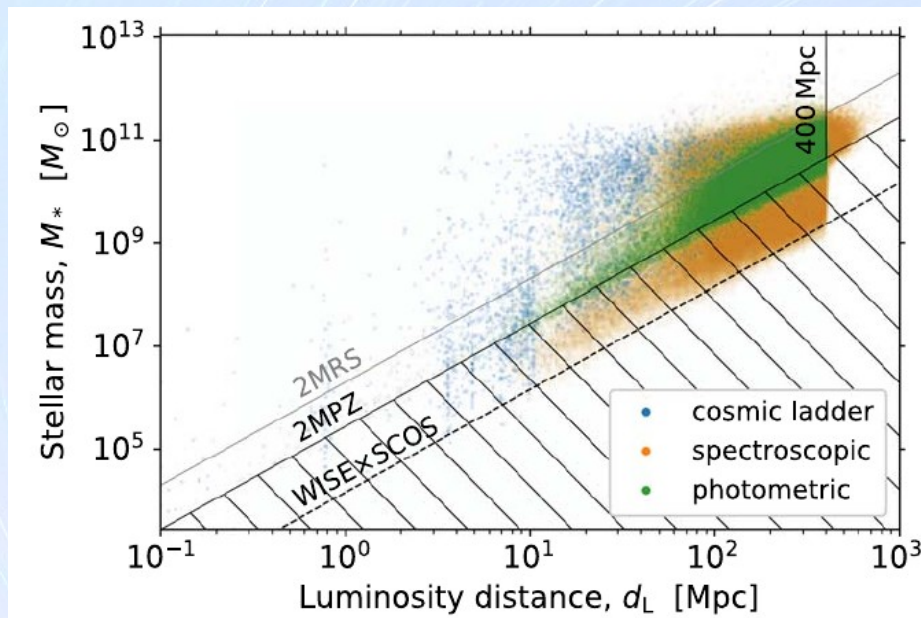


Figure 2. The stellar masses of galaxies vs. revised luminosity distance from cosmic-ladder (blue), spectroscopic (orange), and photometric (green) estimates. The flux limits of 2MRS, 2MPZ, and WISE \times SCOS are indicated as solid gray, solid black, and dashed black lines, respectively. For reference 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 hatched region is excluded in the present study.

Biteau, ApJS 256 (2021) 15

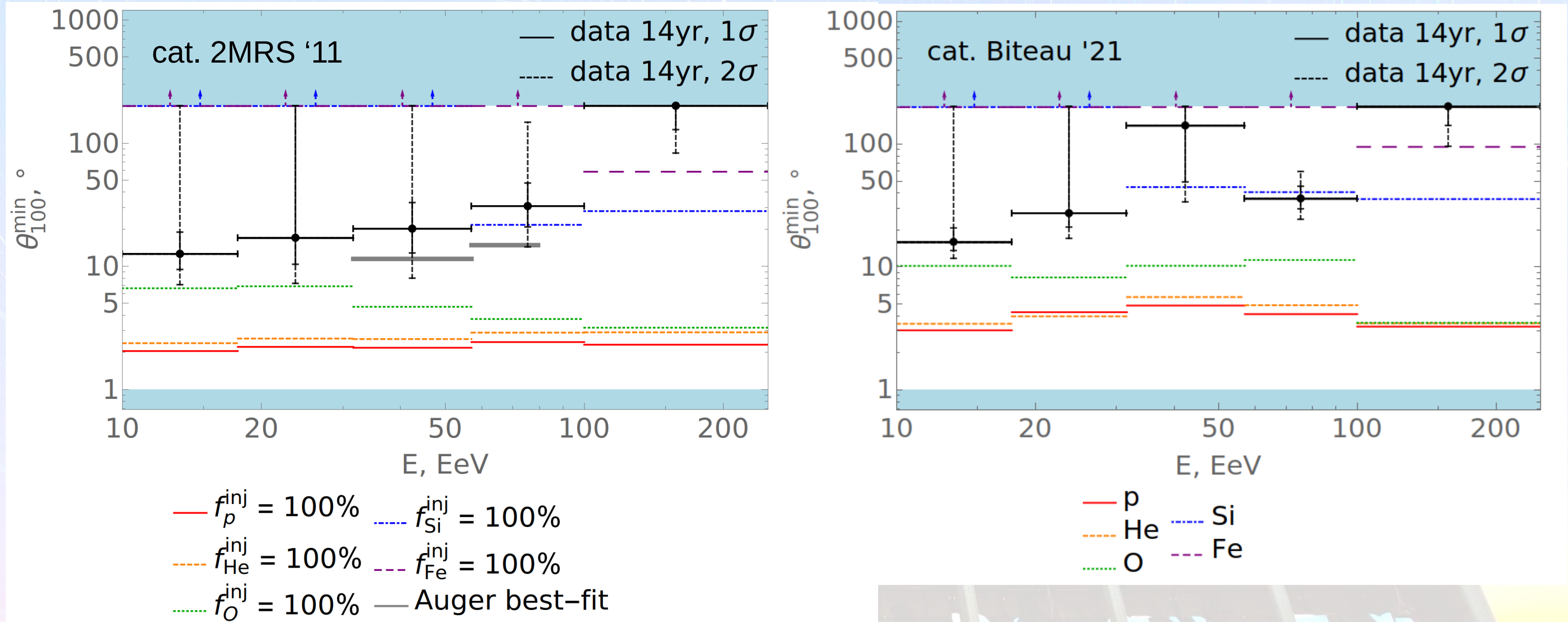
Catalog with lower threshold for galaxy masses:

- $M_* \gtrsim 10^{7.5} M_\odot$
($M_* \gtrsim 10^{8.5} M_\odot$ in basic catalog)
- no sources at $D < 5$ Mpc

- At $E < 57$ EeV and $E > 100$ EeV the 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)!
- **This suggests that lower mass galaxies make a contribution to UHECR flux**

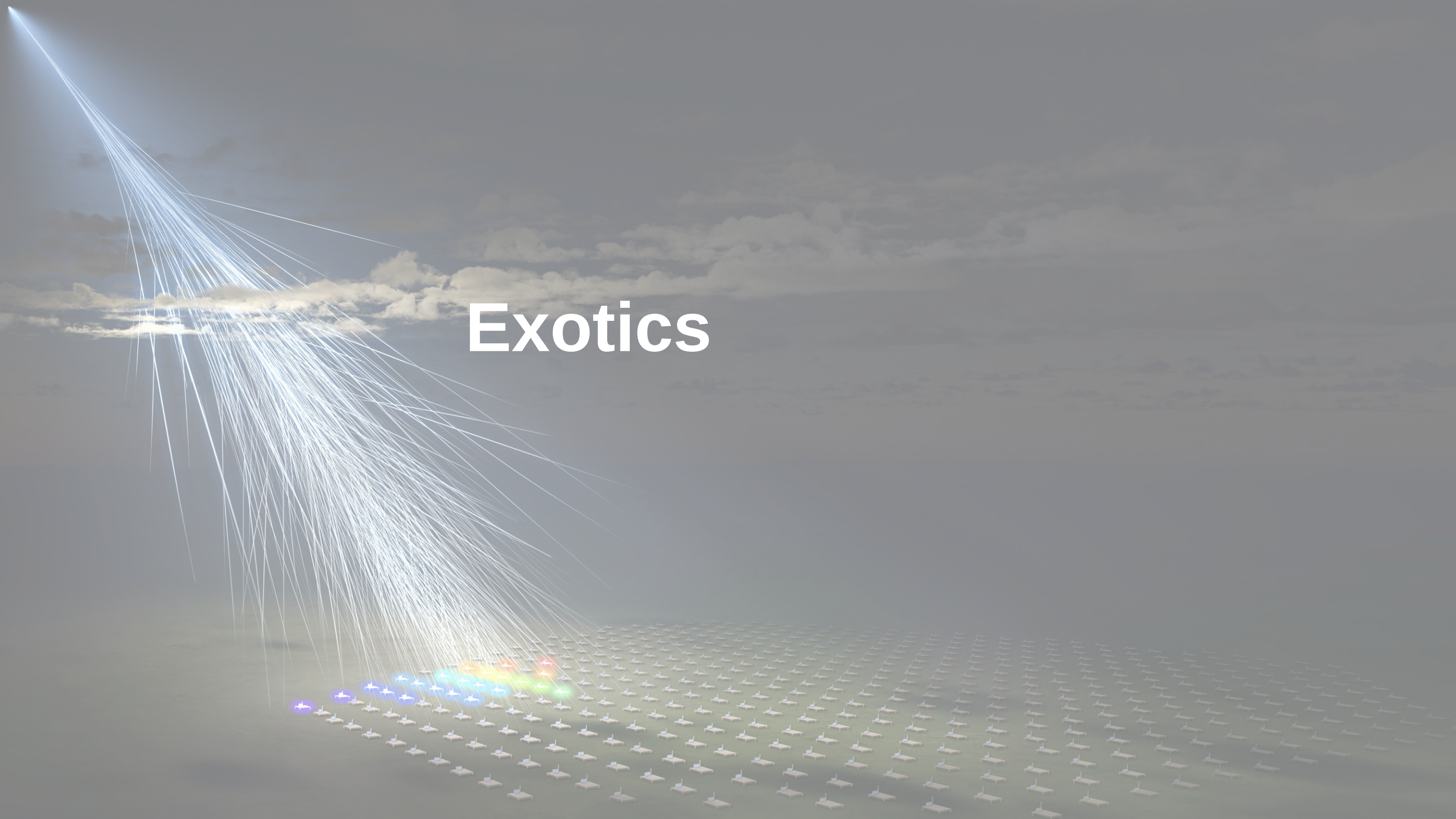
Correlation with LSS vs. composition models

Telescope Array



Results for mass composition for denser catalog (Biteau'21) are similar: heavy injected composition at highest energies

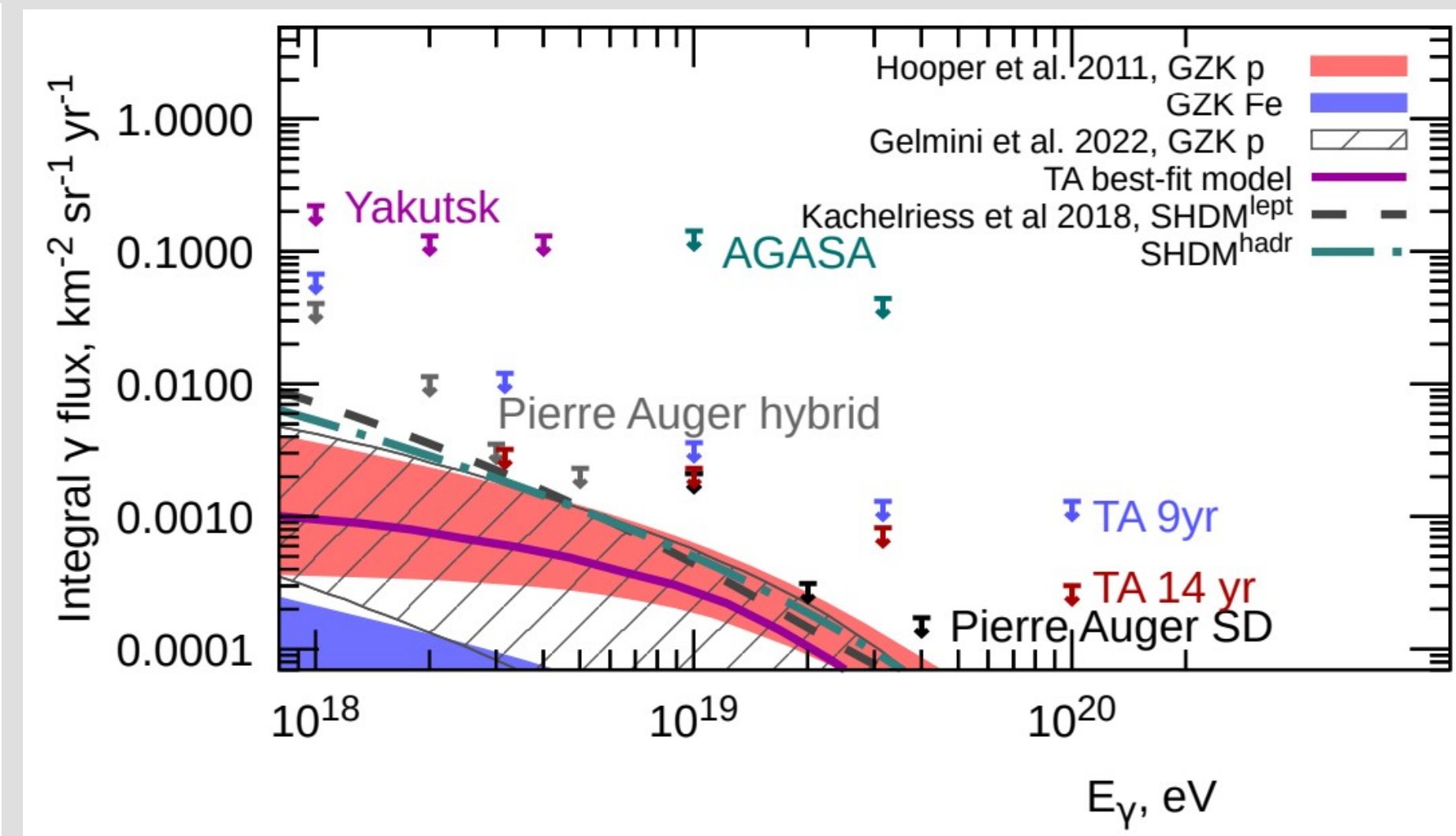
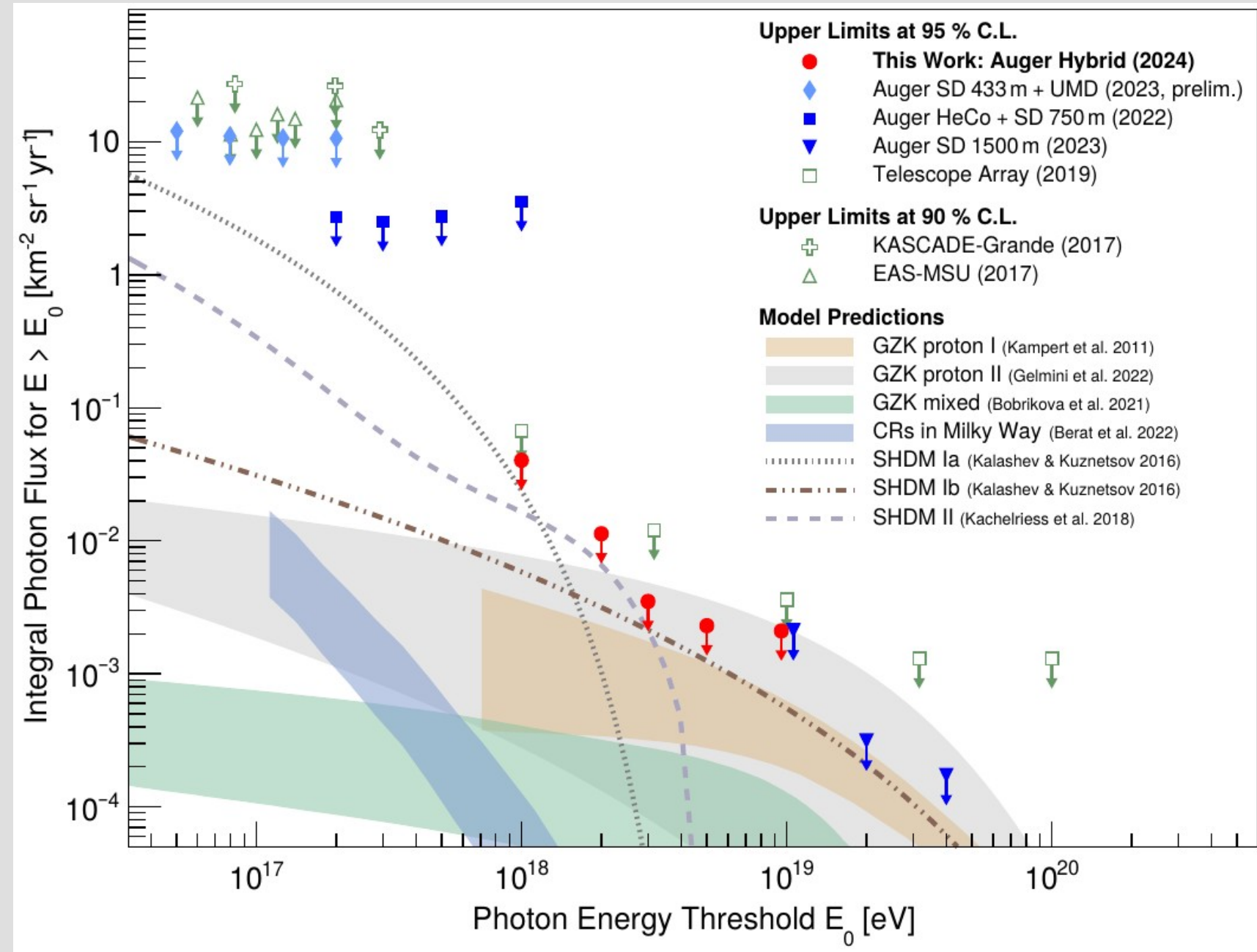
Exotics



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

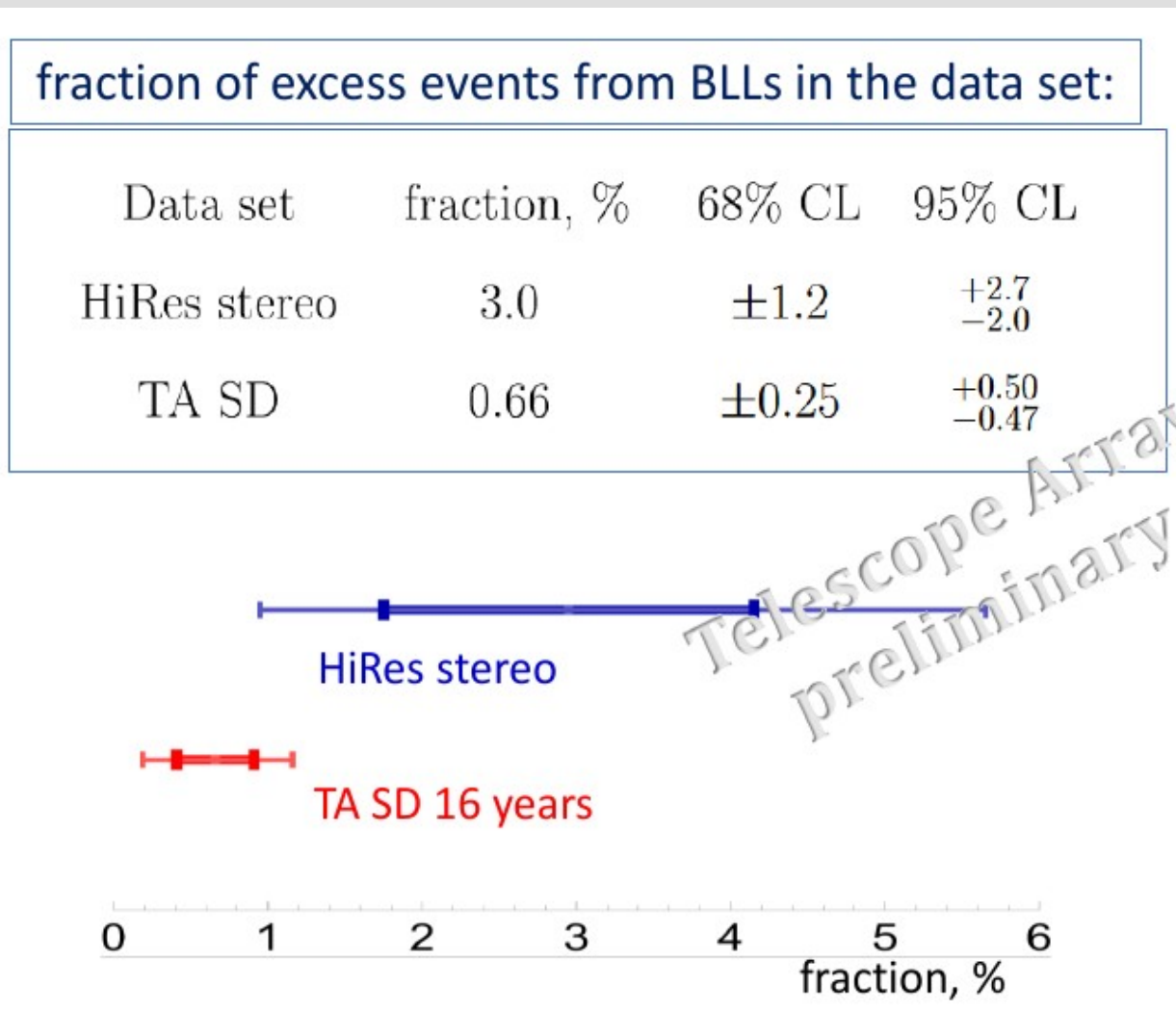
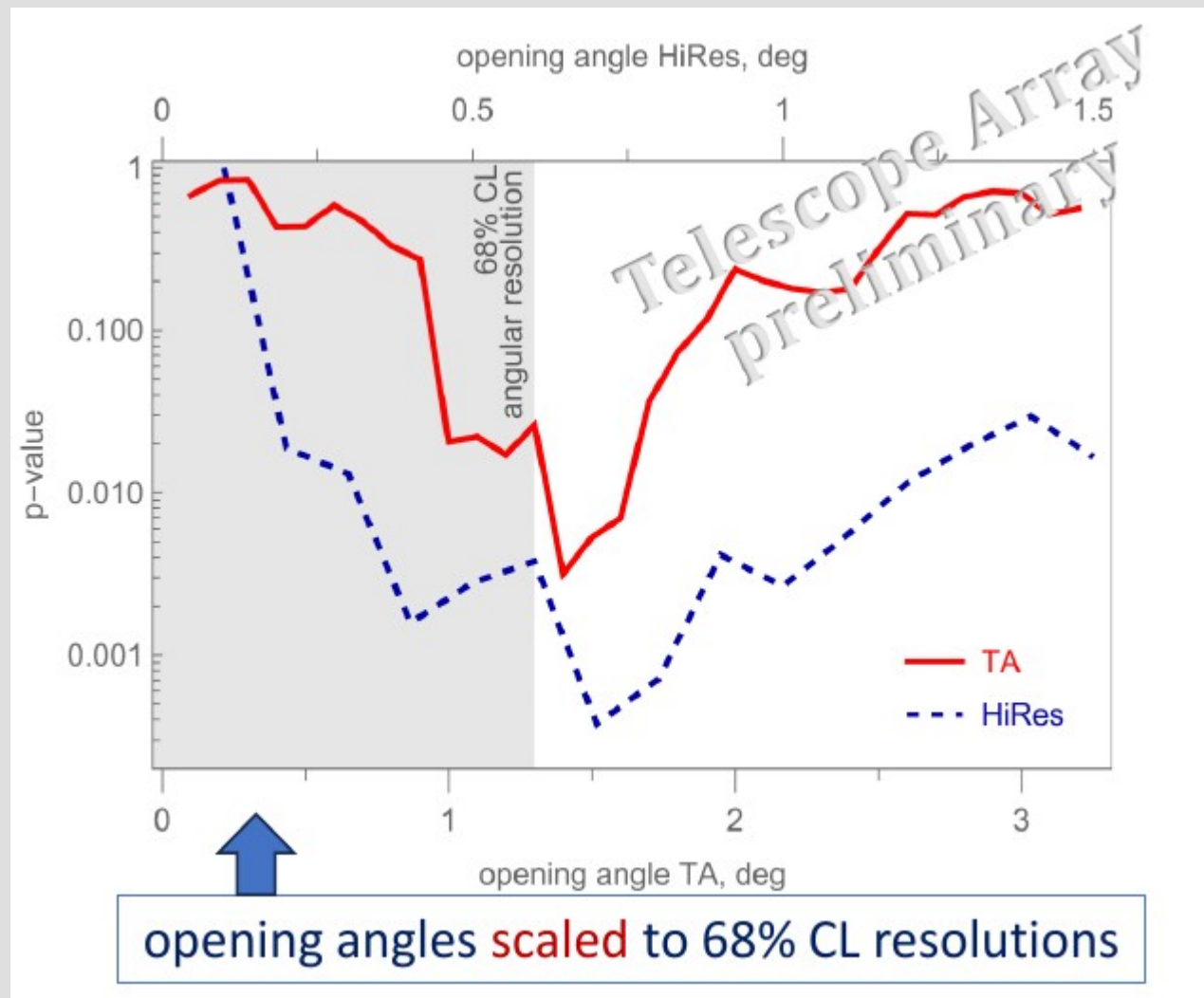
Results of HiRes experiment:

- Correlation of CR at $E > 10$ EeV with catalog of 156 distant BL Lacs
- Only a small fraction of flux correlates ($\sim 3\%$)
- No explanation in with standard physics — 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



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

post-trial p-value = 0.03
(2.2σ)

Perspectives



Improvement of galactic and extragalactic magnetic field models

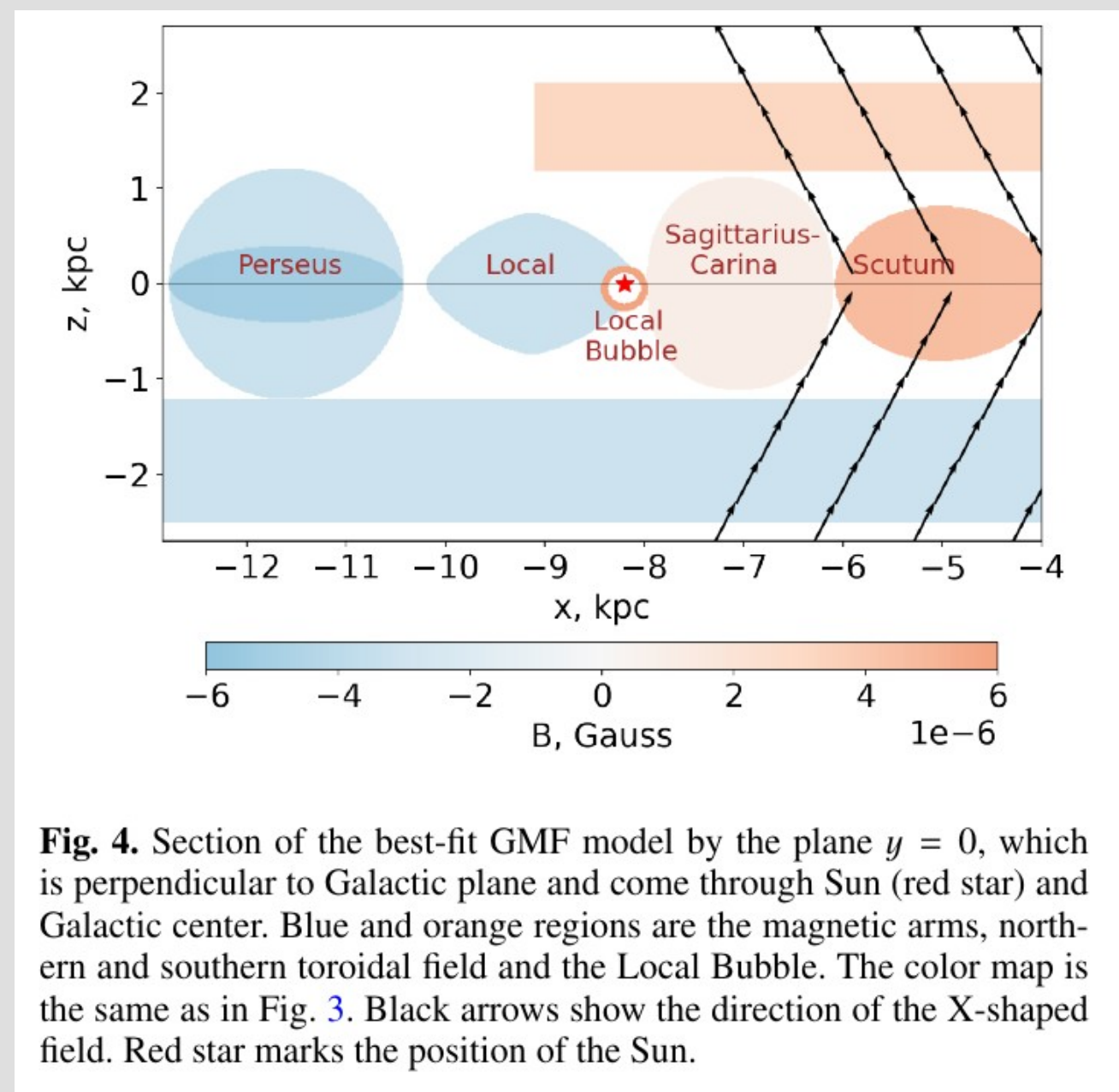
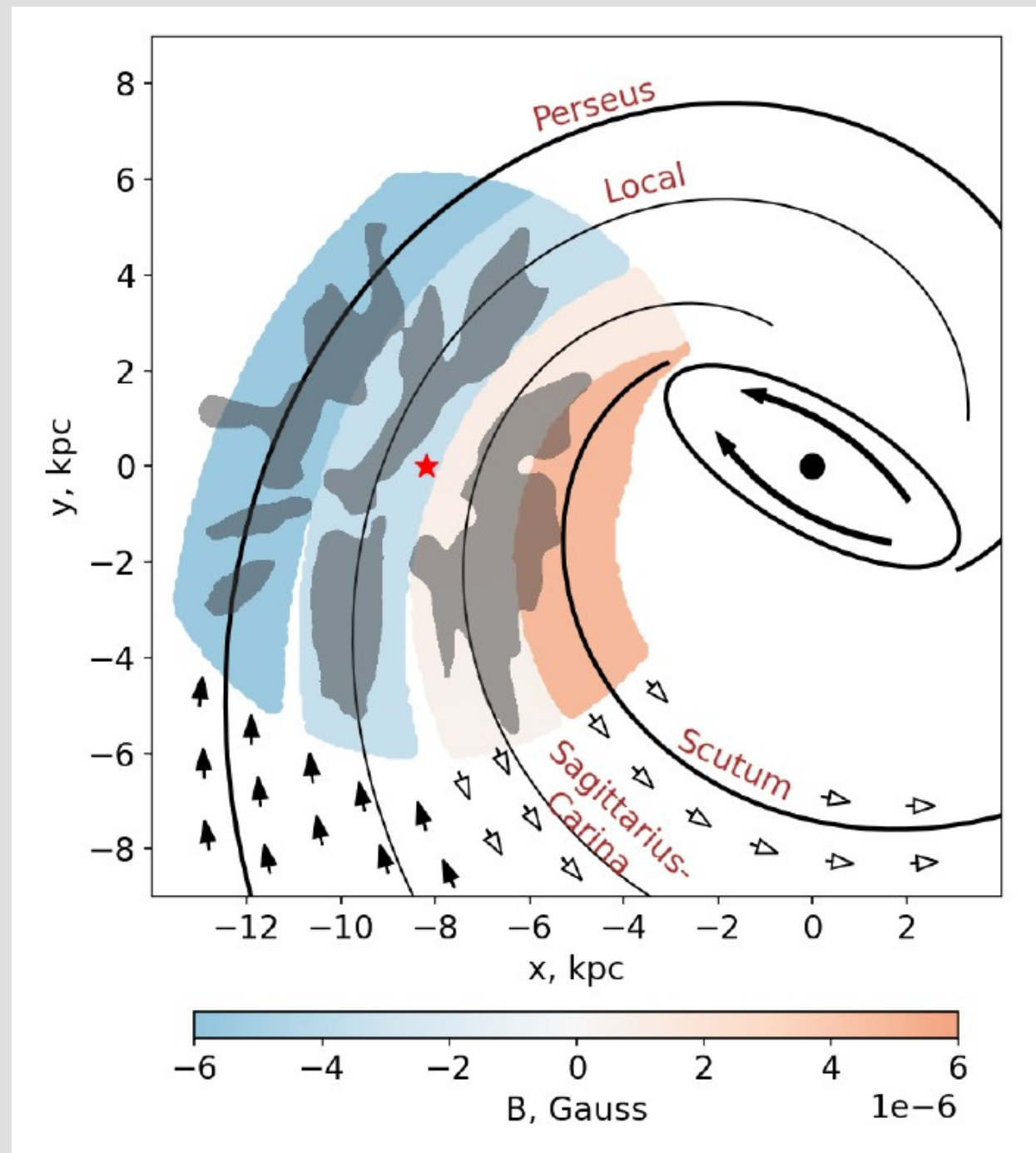
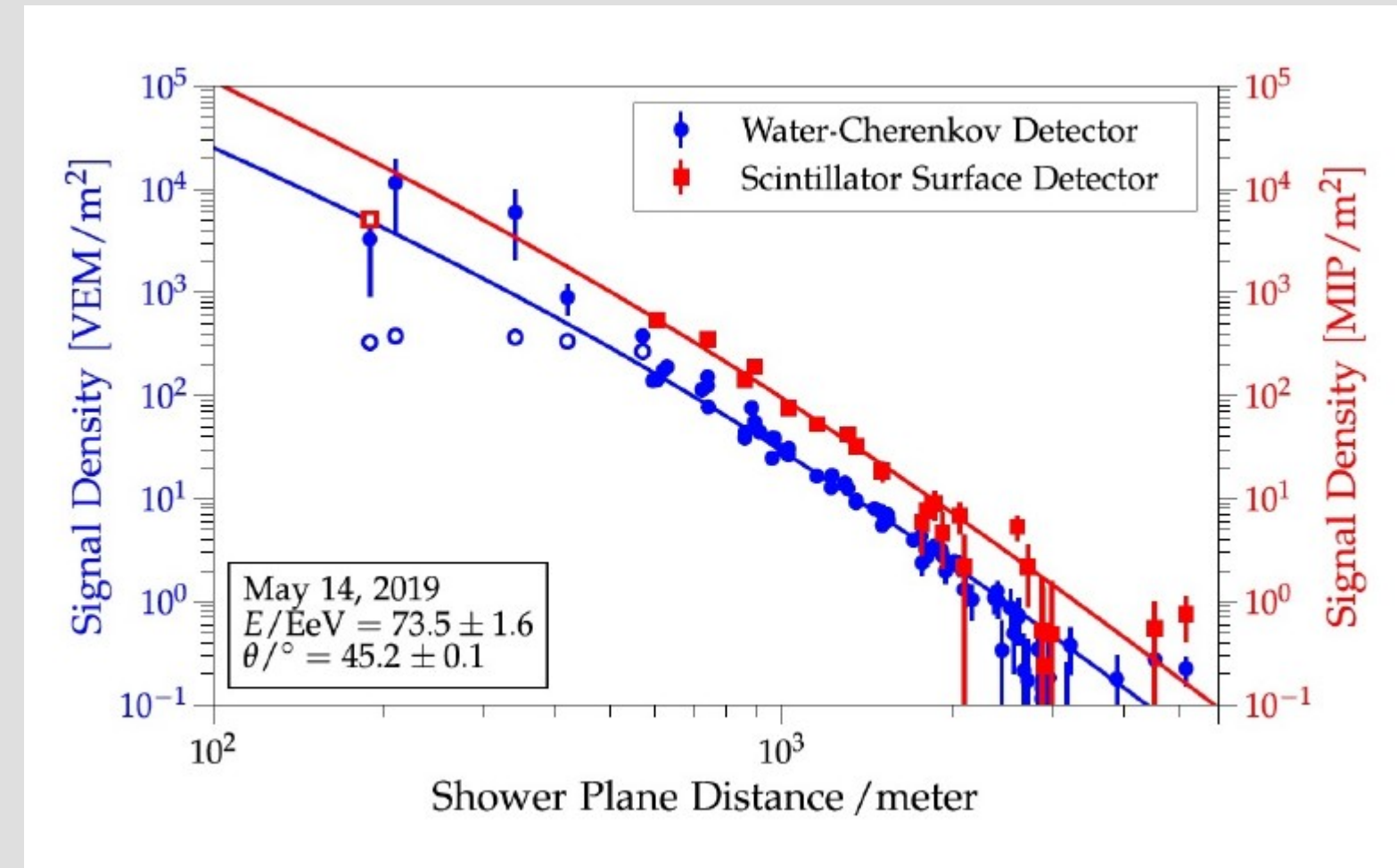
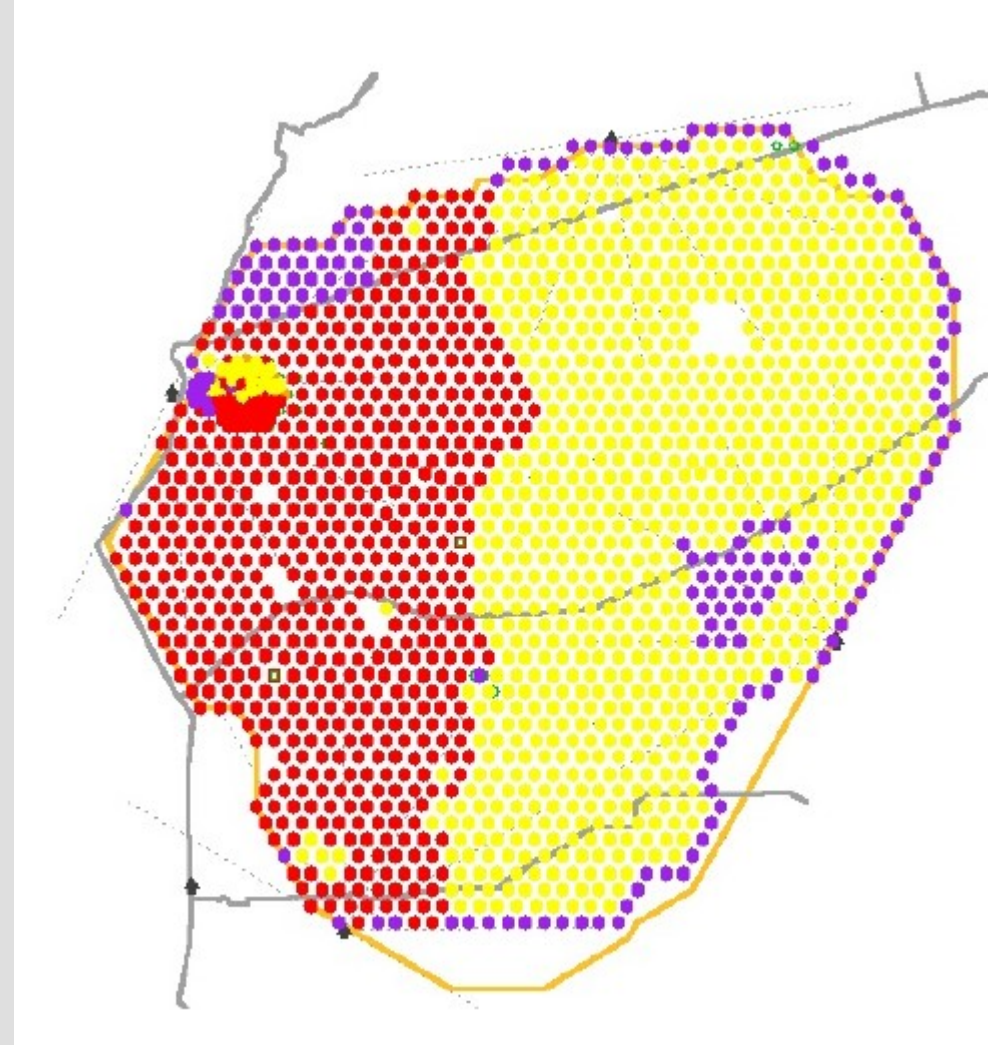
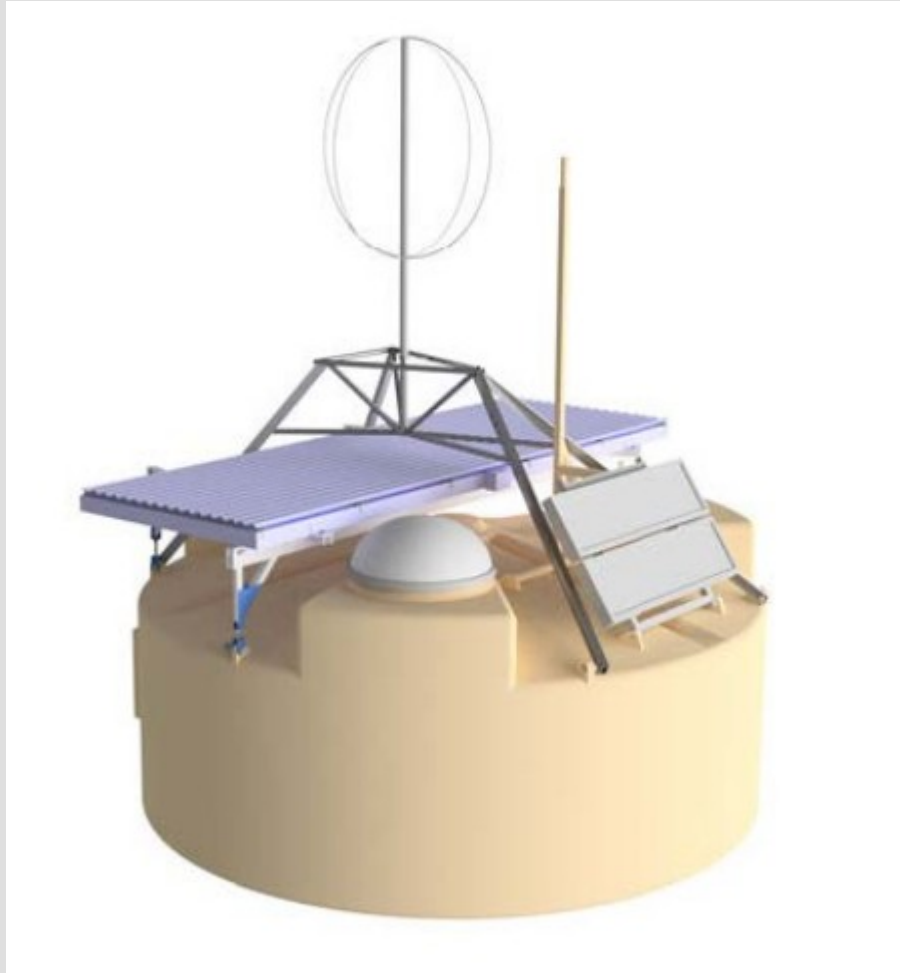


Fig. 4. Section of the best-fit GMF model by the plane $y = 0$, which is perpendicular to Galactic plane and come through Sun (red star) and Galactic center. Blue and orange regions are the magnetic arms, northern and southern toroidal field and the Local Bubble. The color map is the same as in Fig.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

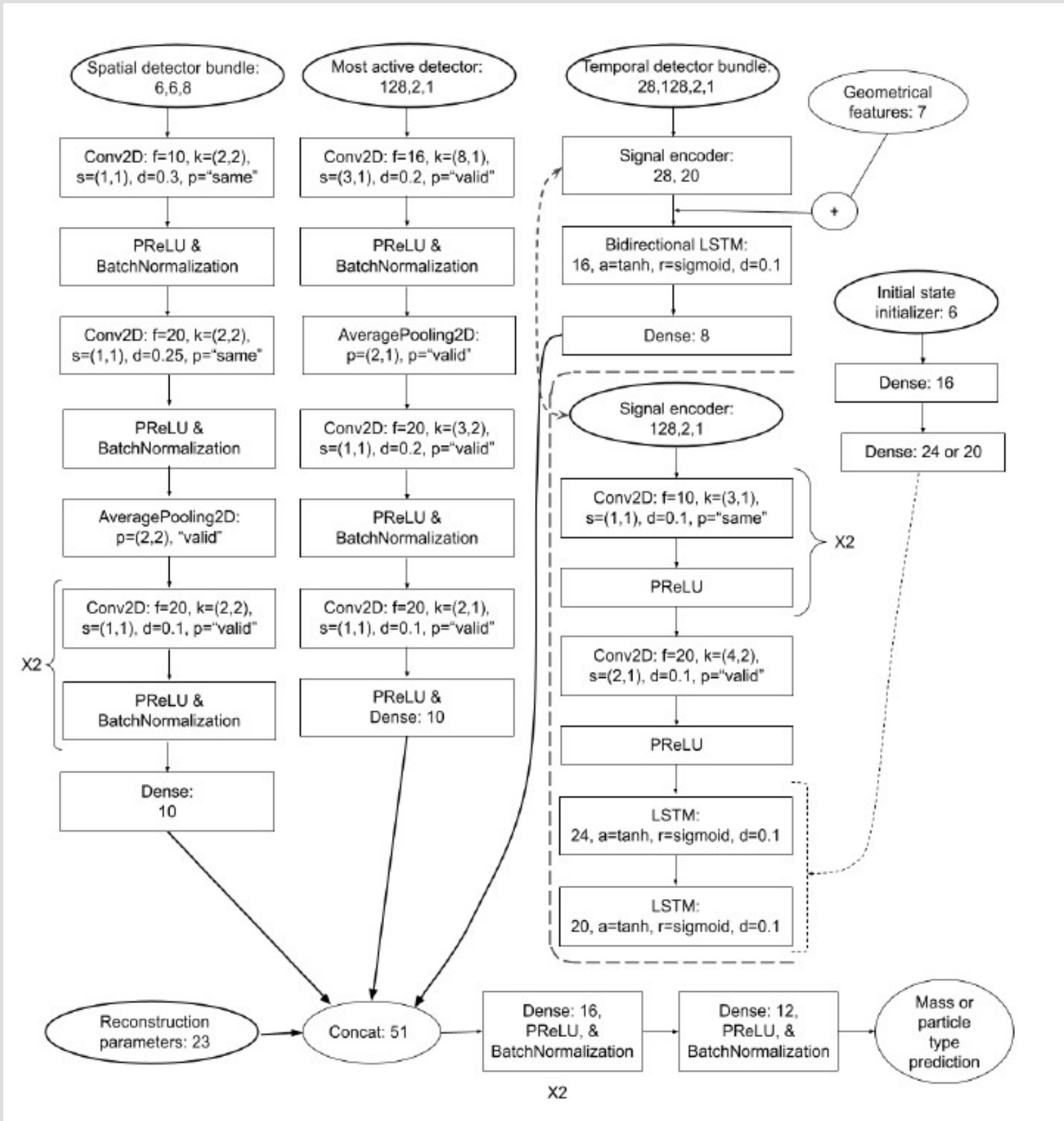
- Taking into account an additional structure (magnetic bubble around local stellar group) improved both synchrotron radiation fit and UHECR dipole fit
- Fields of galactic halo and local extragalactic structures (filaments) are still very uncertain
- Need to improve the models further!

Astronomy with separated light CR (?): AugerPrime upgrade

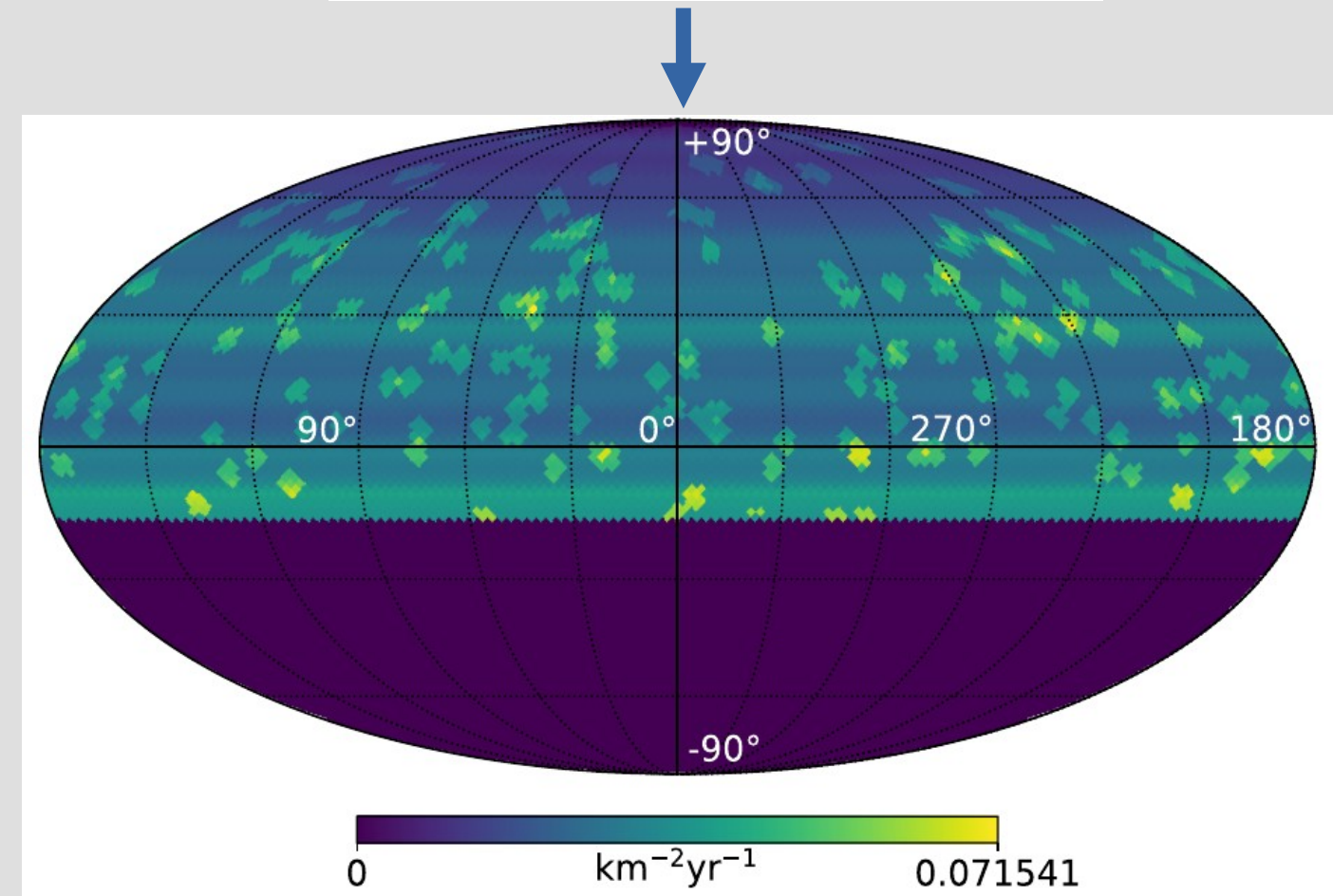


- Better mass components separation (WCD as muon detector)
- Hope for extraction of the light component at highest energies (if any) and for identification of its source

Astronomy with separated light CR (?): machine learning

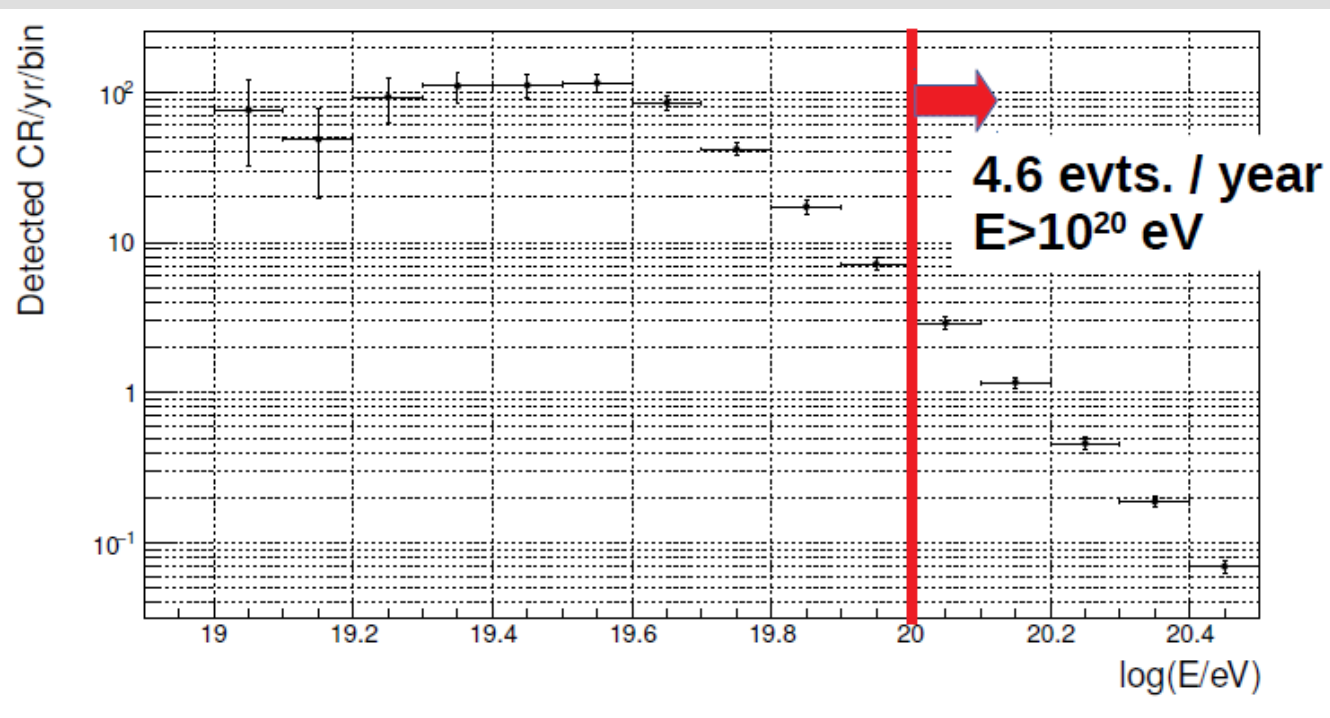


True label \ Predicted label	p	He	C	Si	Fe
p	0.54	0.31	0.12	0.03	0.00
He	0.21	0.41	0.28	0.08	0.01
C	0.02	0.20	0.42	0.28	0.08
Si	0.00	0.02	0.19	0.46	0.33
Fe	0.00	0.00	0.02	0.25	0.72

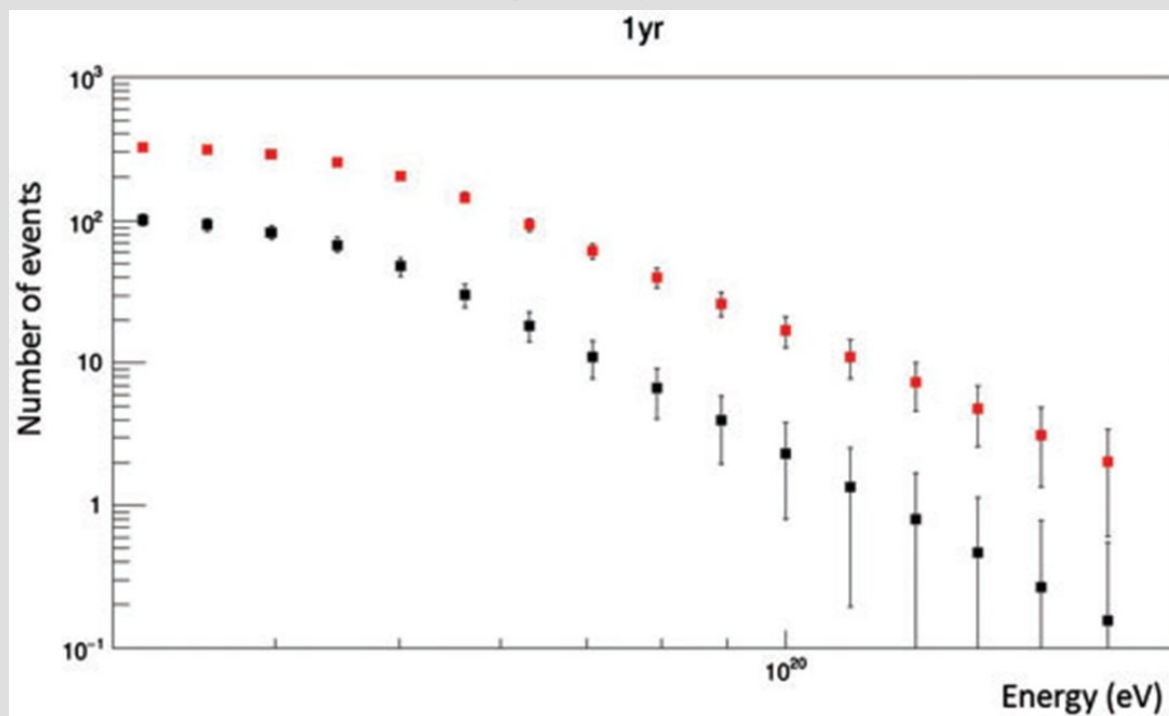


Larger statistics at highest energies

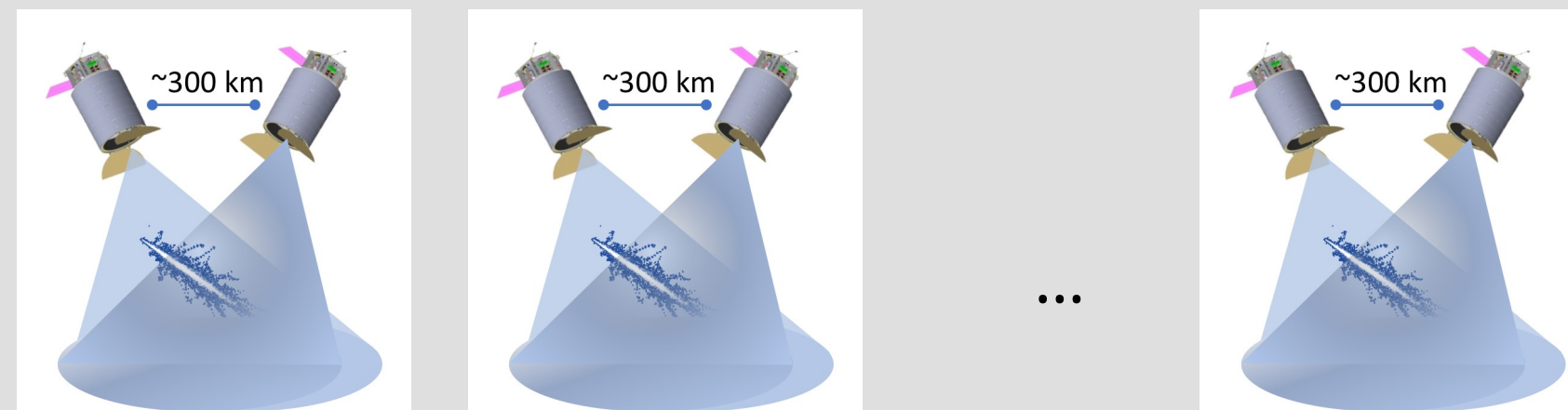
Statistics expected for Auger spectrum



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%**

- Тип телескопа: однозеркальный
- Поле зрения одного телескопа: $\geq 10^\circ$
- Площадь входного окна: $\sim 2 \text{ м}^2$
- Угловой размер пикселя: 1-2 мрад
- Масса телескопа: 100 кг
- Энергопотребление: 100 Вт
- Количество телескопов – 10.
- Экспозиция $20000 \text{ км}^2 \text{ ср год}$

- ✓ Expected statistics ($E > 50 \text{ EeV}$) – 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

talk by P.Klimov at this conference

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 light UHECR composition and MF uncertainties
- Source number density is not very low: many potential source classes are ruled out

Perspectives:

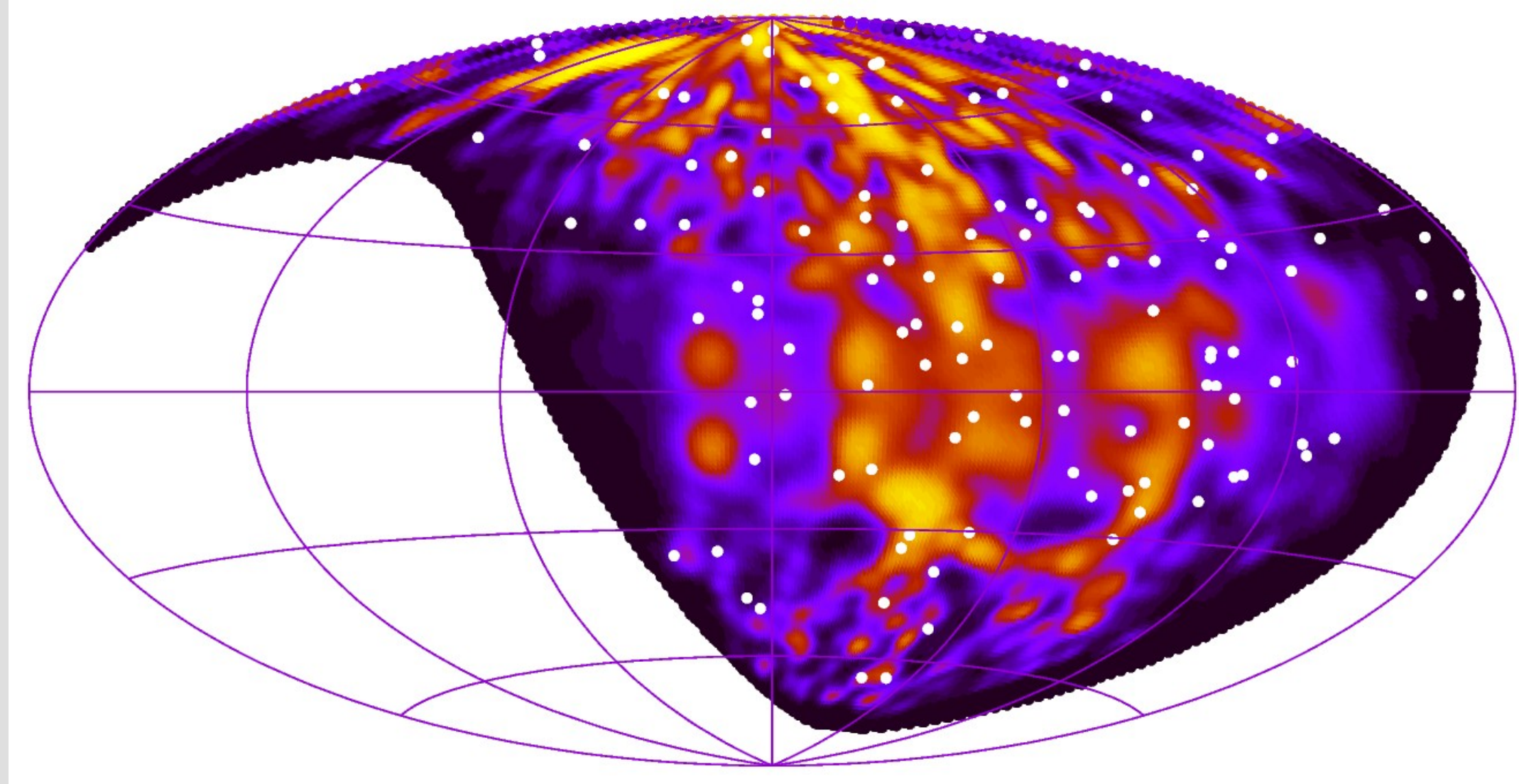
- Improvement of models of cosmic magnetic fields is needed
- Hope for CR astronomy with extracted light UHECR component
- Larger statistics at highest energies is needed, better with full sky coverage: ERA project

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

Оценка массового состава из отклонений от ожидаемых источников

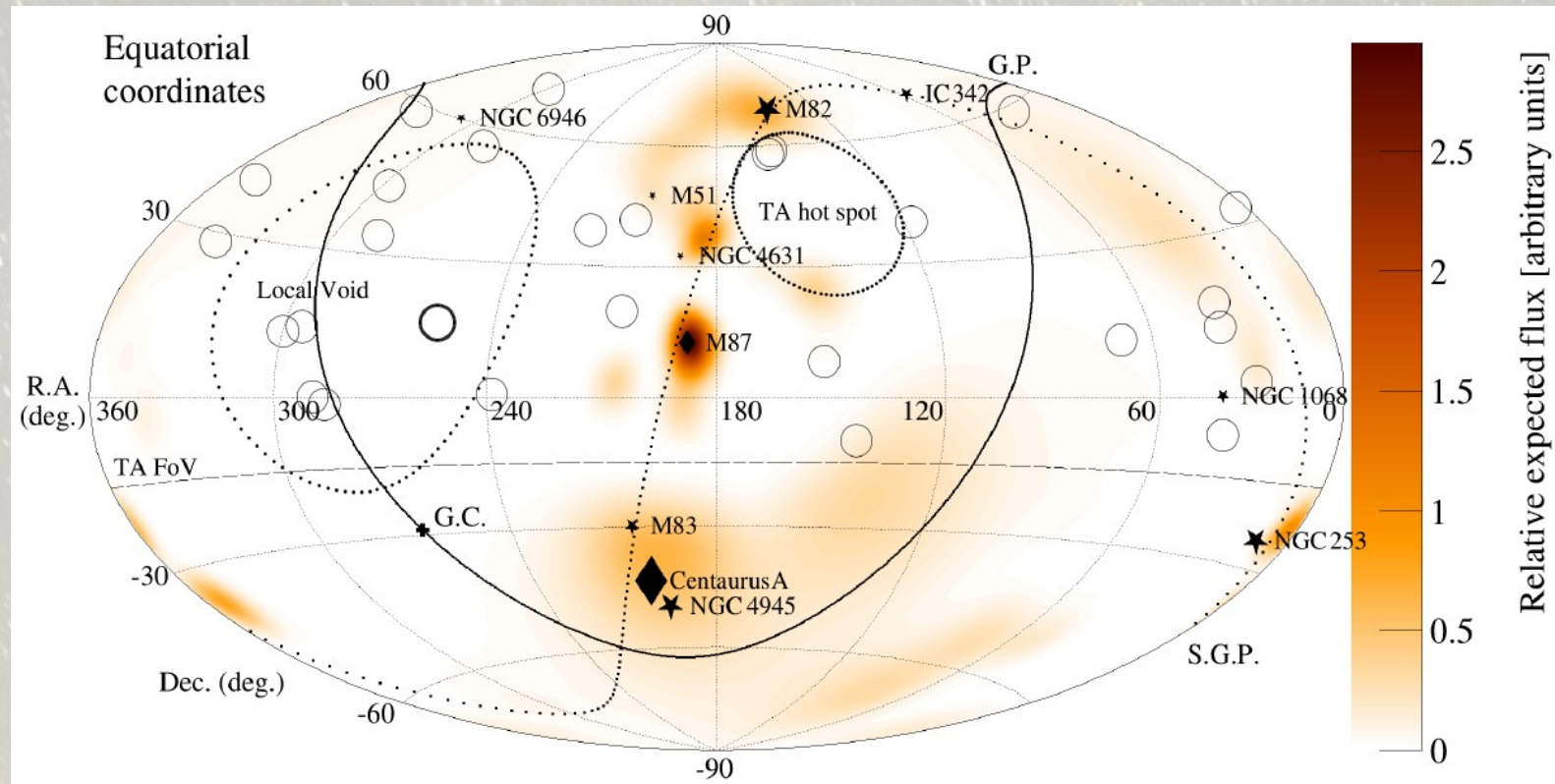


МК & P.Tinyakov,
arXiv:2011.11590

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

Оценка массового состава из отклонений от источников: результаты

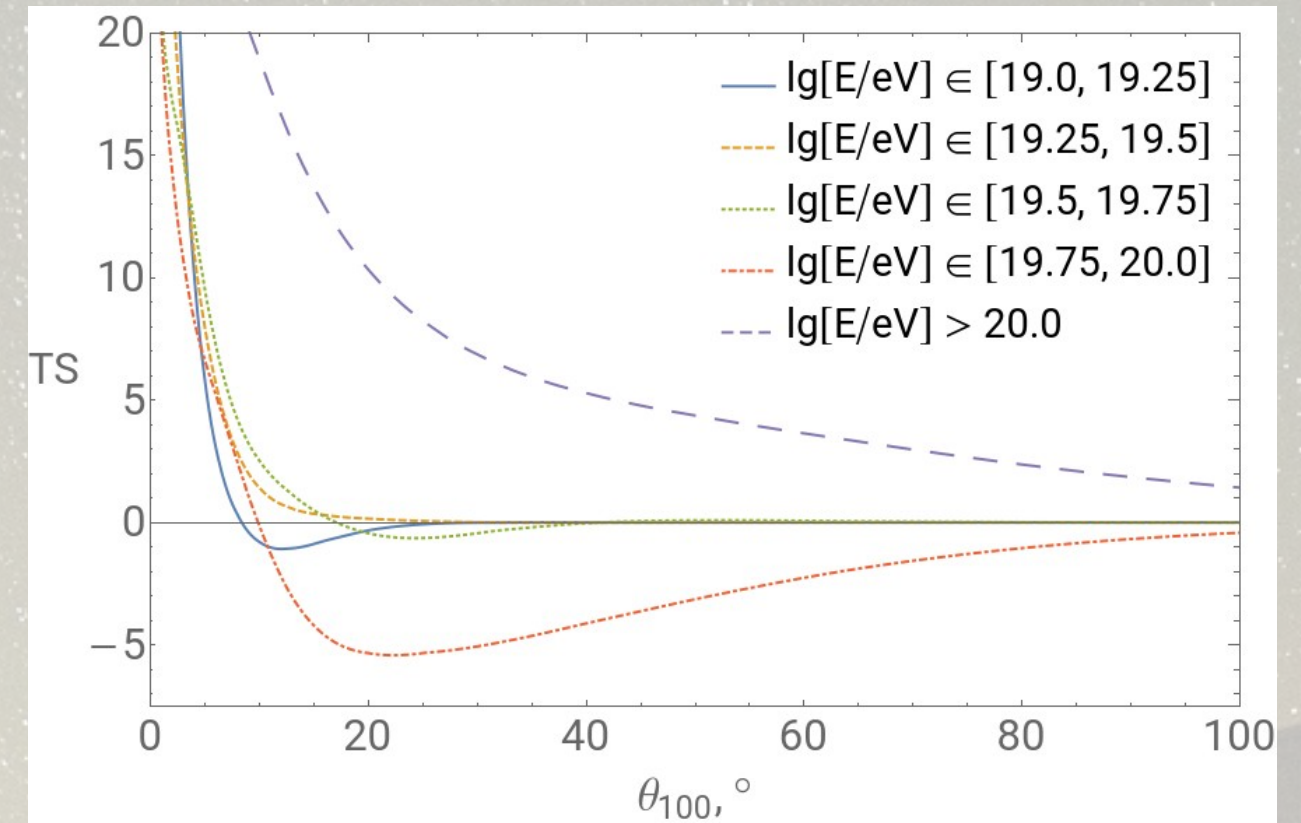


Карта ожидаемого потока КЛ при $E > 100$ ЭэВ

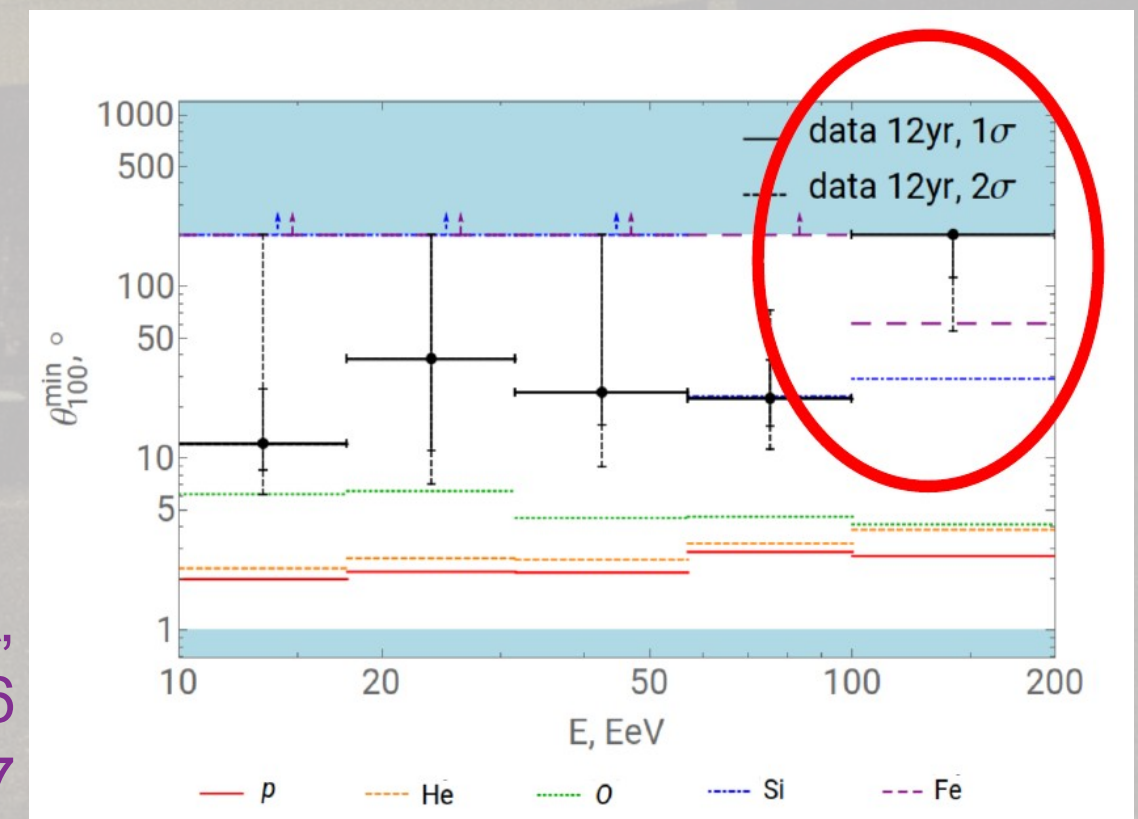
$$TS(\theta) = -2 \sum_{E_k} \left(\sum_i \ln \frac{\Phi_{E_k}(\theta, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)} \right)$$

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

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

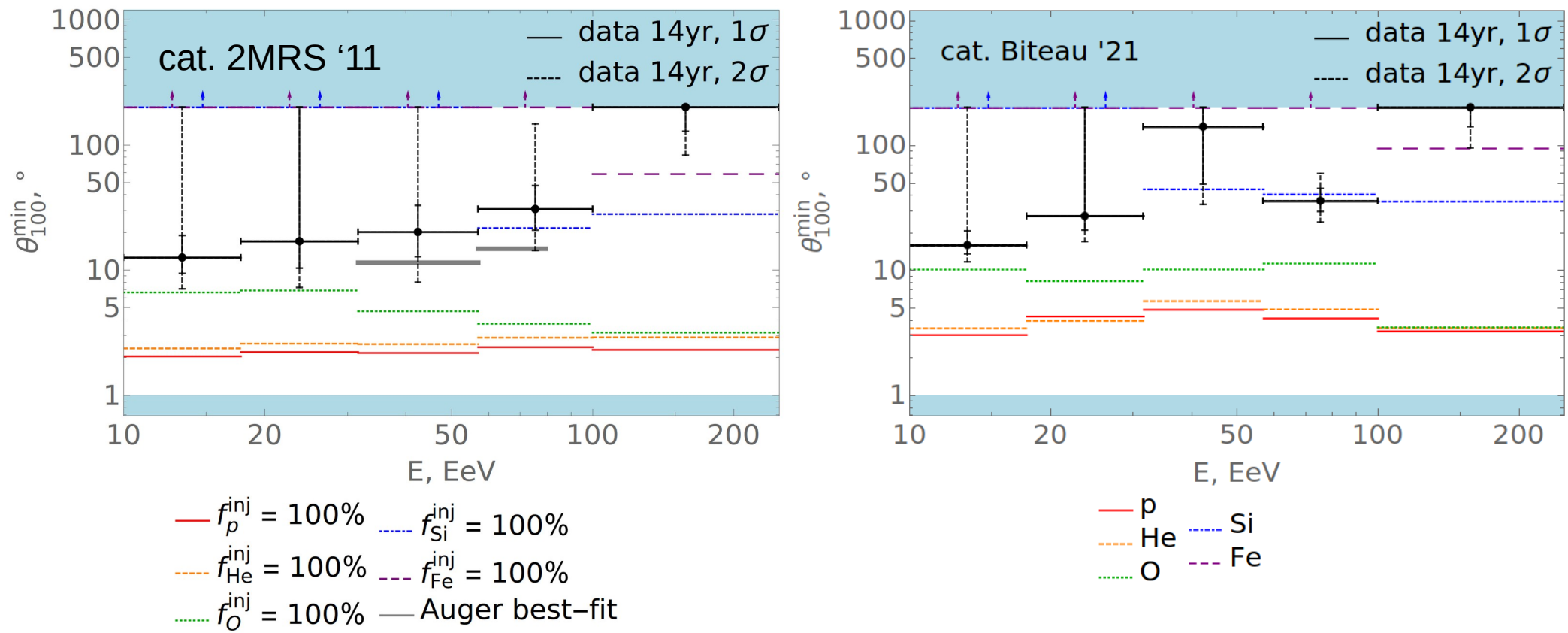


Сравниваем с симуляциями



ТА,
arXiv:2406.19286
arXiv:2406.19287

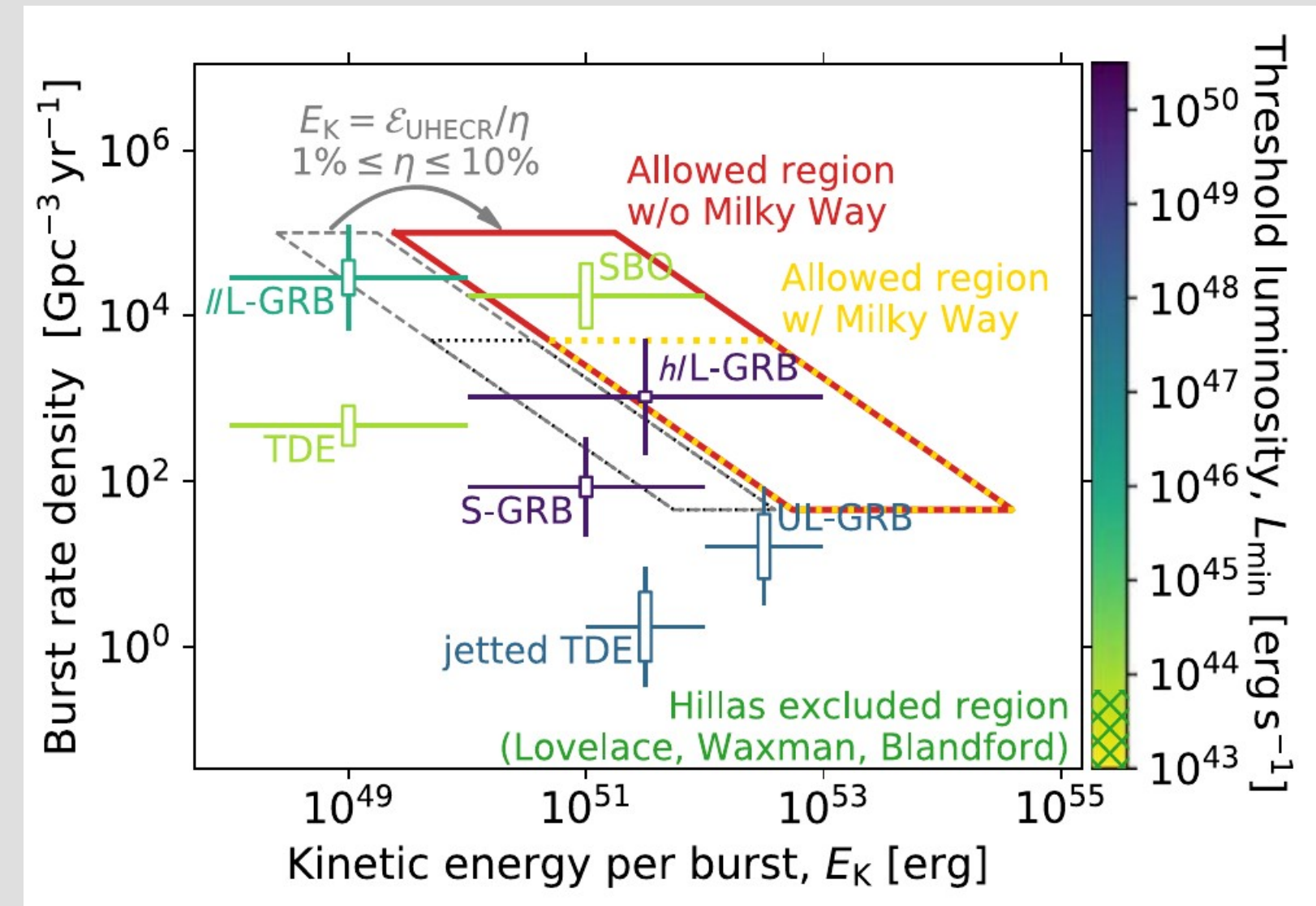
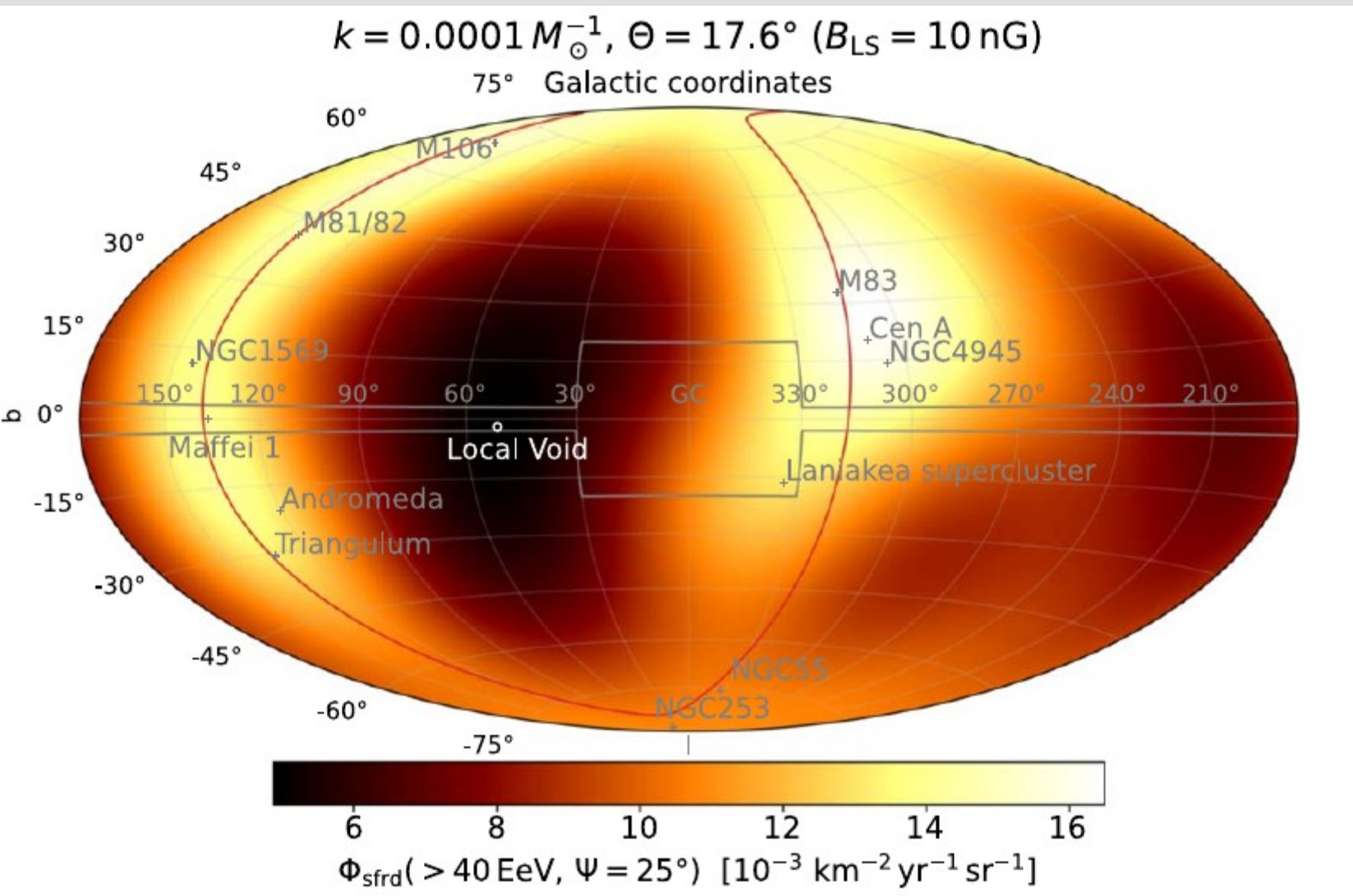
New catalog of sources



New results for composition are supporting our old results

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

Marafico et al., arXiv:2405.17179

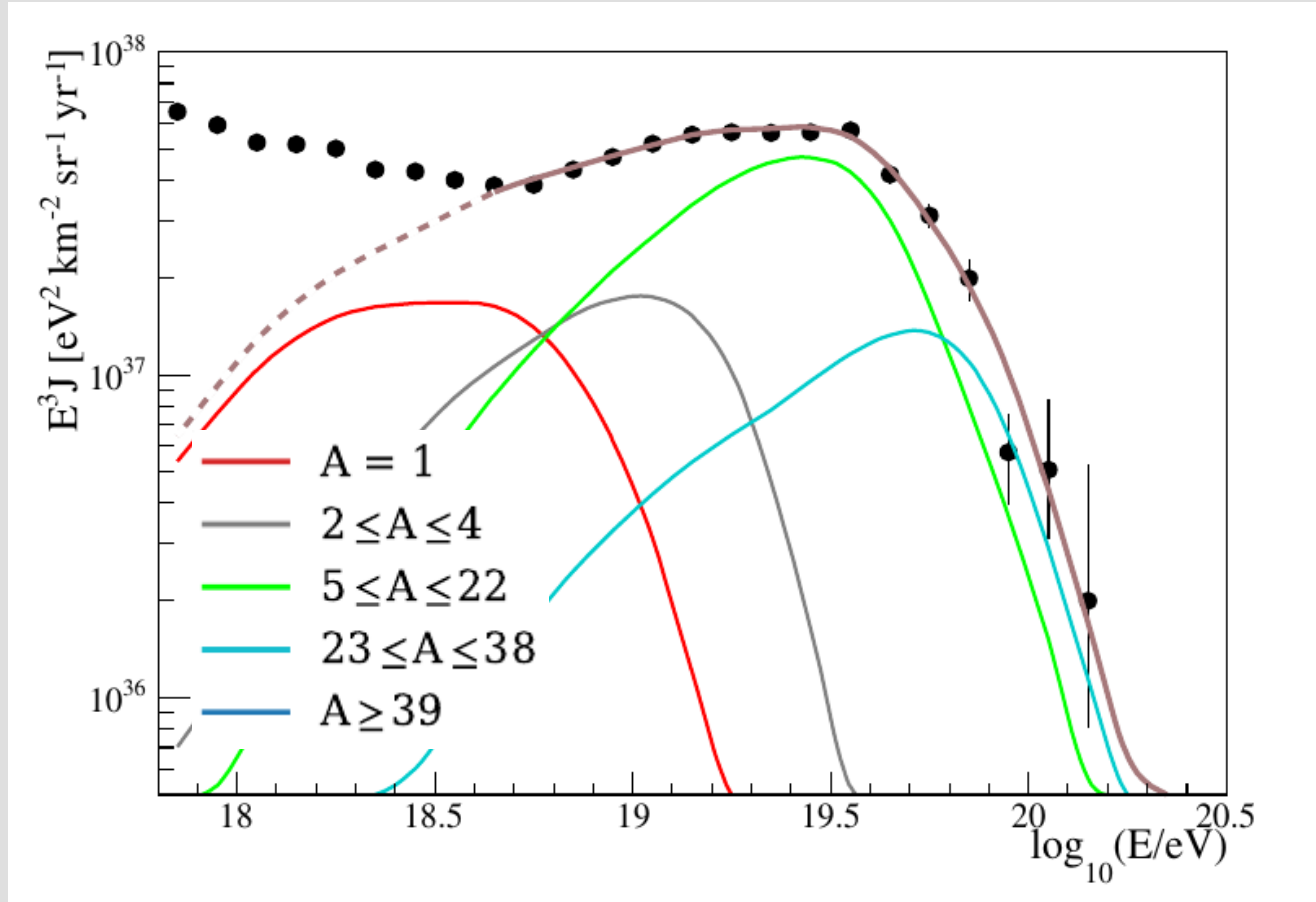


- Фит спектра, X_{\max} Auger и направлений прихода КЛУВЭ случайными картами транзиентных источников в LSS
- Использование трех наблюдаемых позволяет снять вырождение между темпом вспышек и энергией на одну вспышку (важны задержки сигнала из-за космических магнитных полей)
 - Всем условиям удовлетворяют HL long GRB и Supernova Shock Breakouts
 - Результаты зависят от предположений о галактических и внегалактических магн. полях

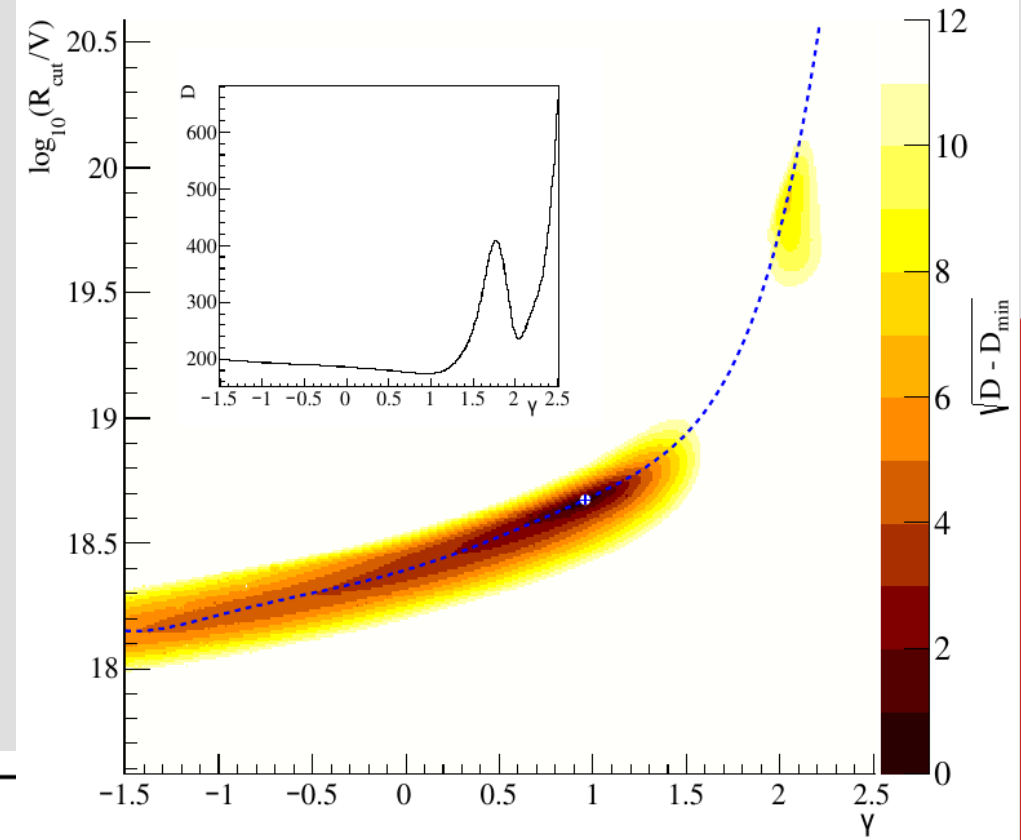
Ойконому вариативность источников \Leftrightarrow транзиенты

Какой состав КЛУВЭ испускают источники?

Одновременный фит спектра и X_{\max} определенной моделью инжекции, с учетом эффектов распространения и детектирования (существенная модельная зависимость)

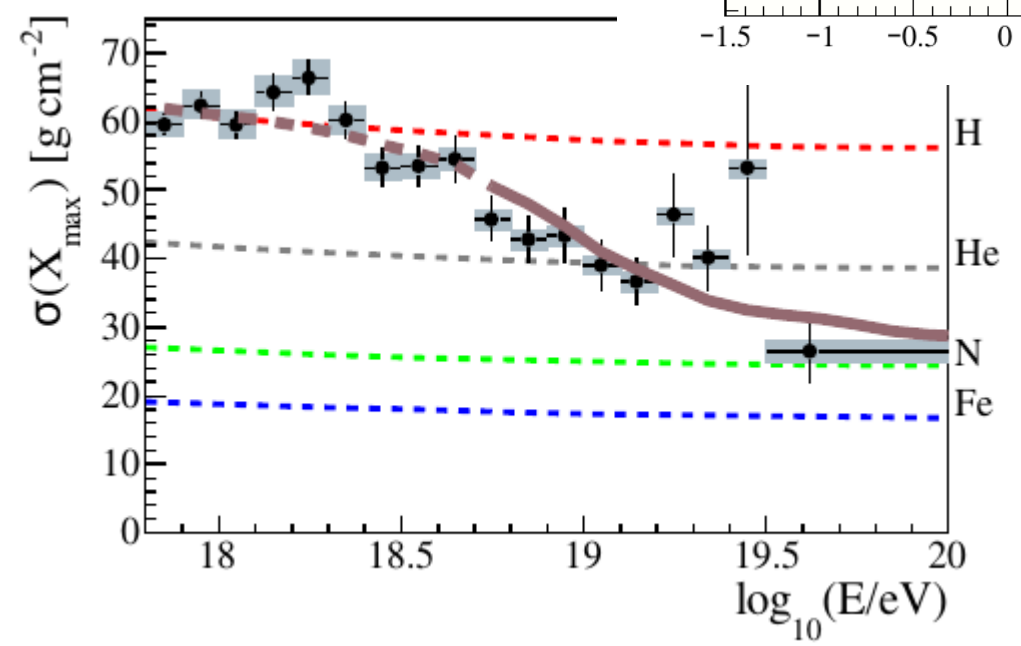
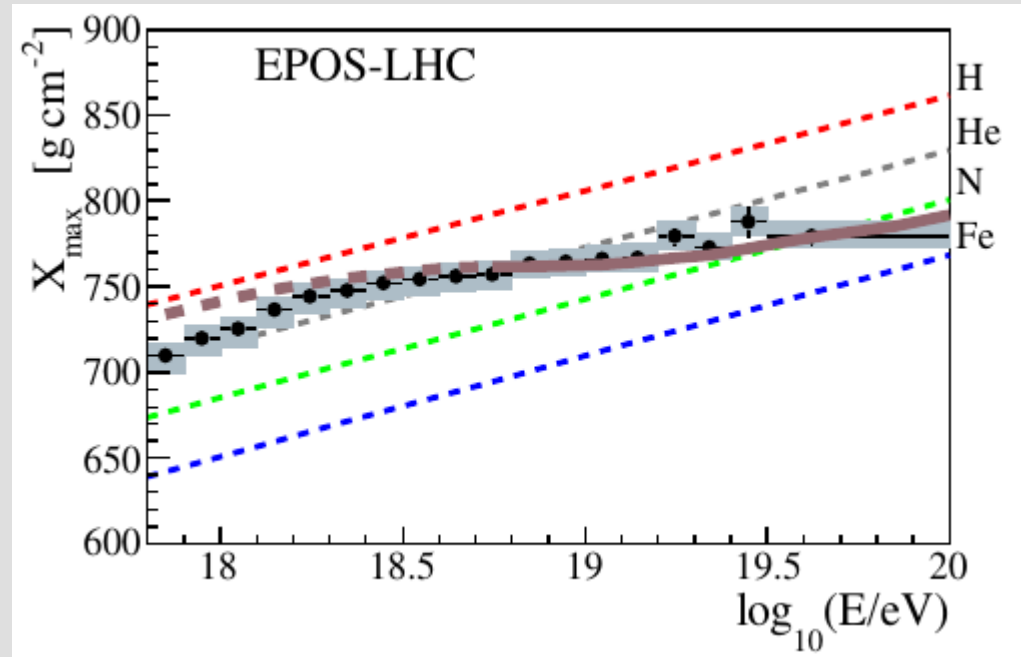


$$\tilde{Q}_A(E) = \tilde{Q}_{0A} \left(\frac{E}{E_0} \right)^{-\gamma} \begin{cases} 1, & E \leq Z_A R_{\text{cut}}; \\ \exp\left(1 - \frac{E}{Z_A R_{\text{cut}}}\right), & E > Z_A R_{\text{cut}}, \end{cases}$$



Auger, arXiv:1612.07155

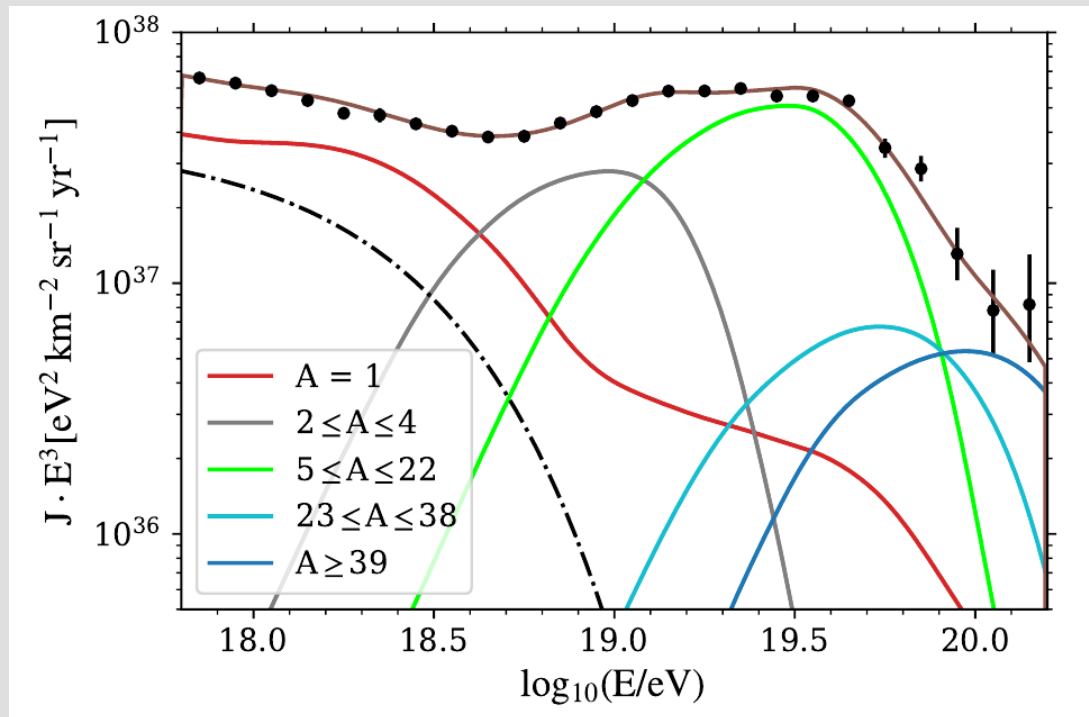
Спектр очень жесткий!



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

Какой состав КЛУВЭ испускают источники?

Auger, arXiv:2211.02857



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

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

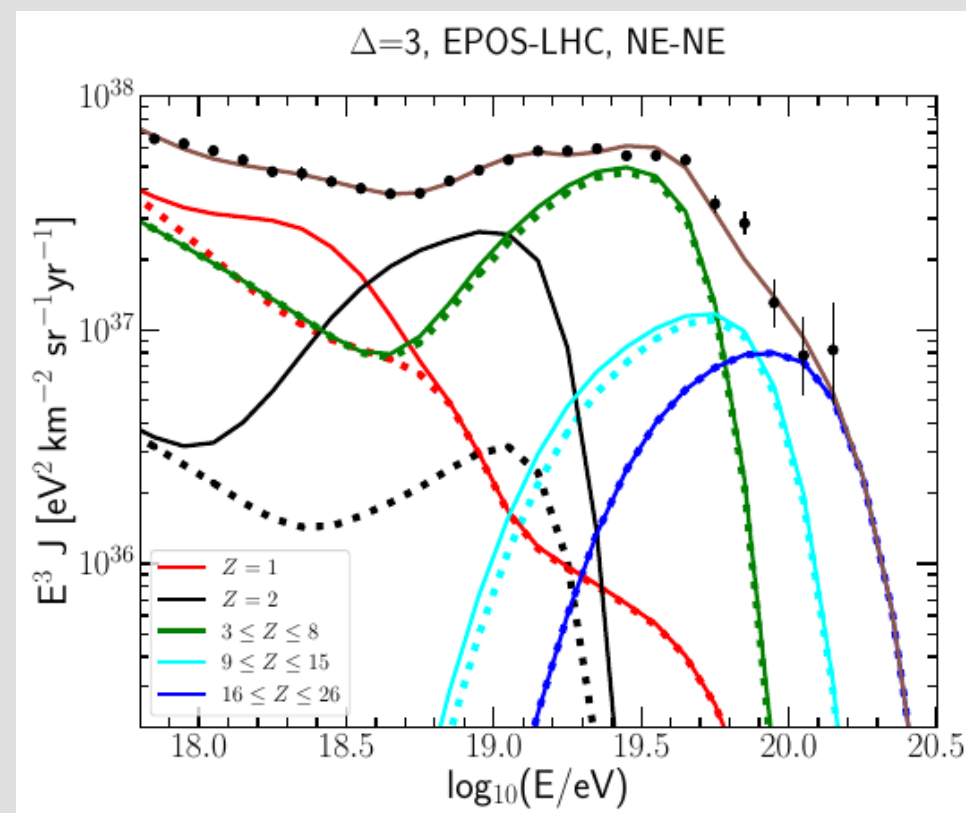
Galactic contribution (at Earth)	pure N	
$J_0^{\text{Gal}} / (\text{eV}^{-1} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1})$	$(1.06 \pm 0.04) \times 10^{-13}$	
$\log_{10}(R_{\text{cut}}^{\text{Gal}}/V)$	17.48 ± 0.02	
EG components (at the escape)	LE	HE
$\mathcal{L}_0 / (10^{44} \text{ erg Mpc}^{-3}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

Дополнительно учли возможное наличие внегал. магн. поле

Можно получить спектр в источниках близкий к E^{-2} если есть сильное поле:

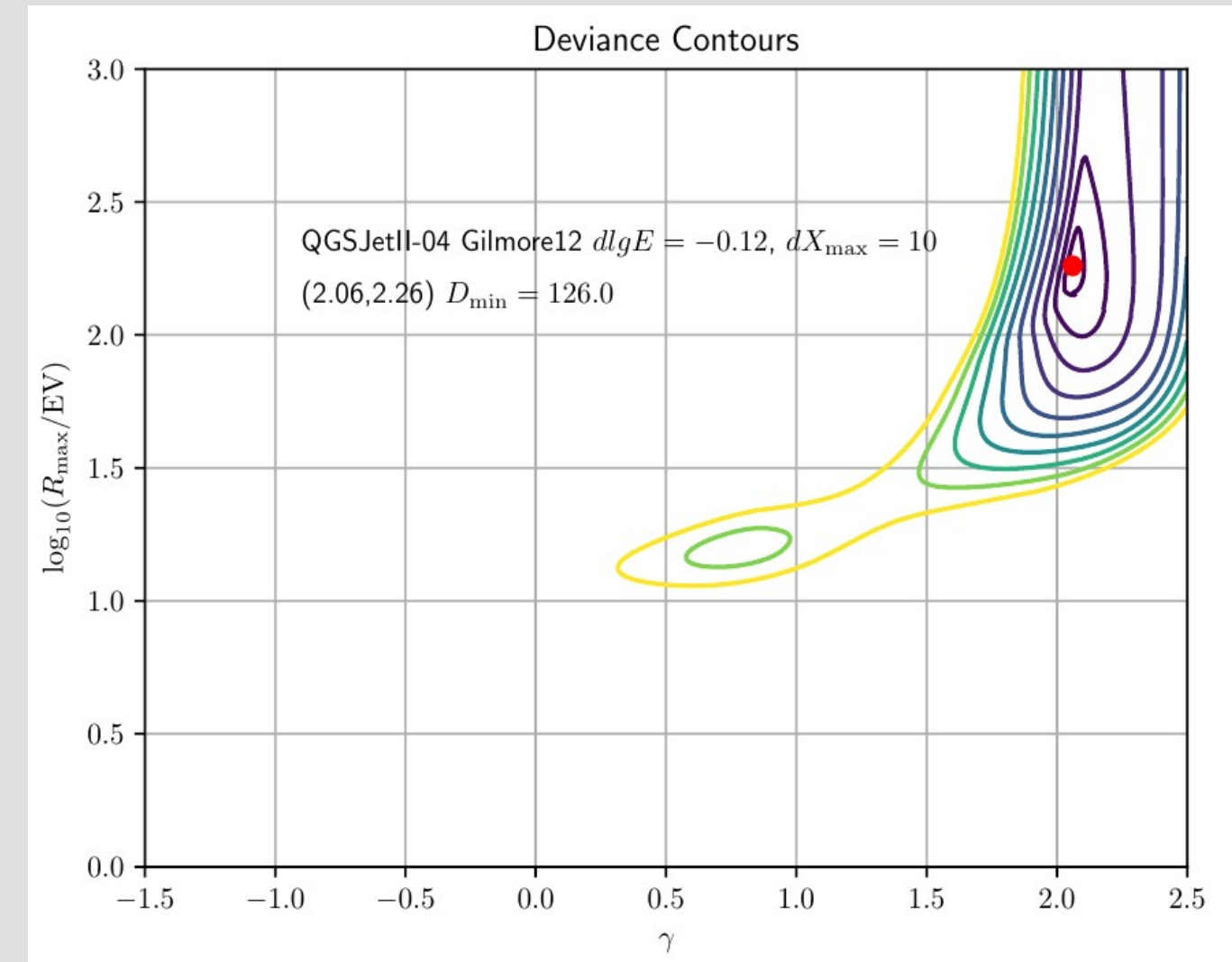
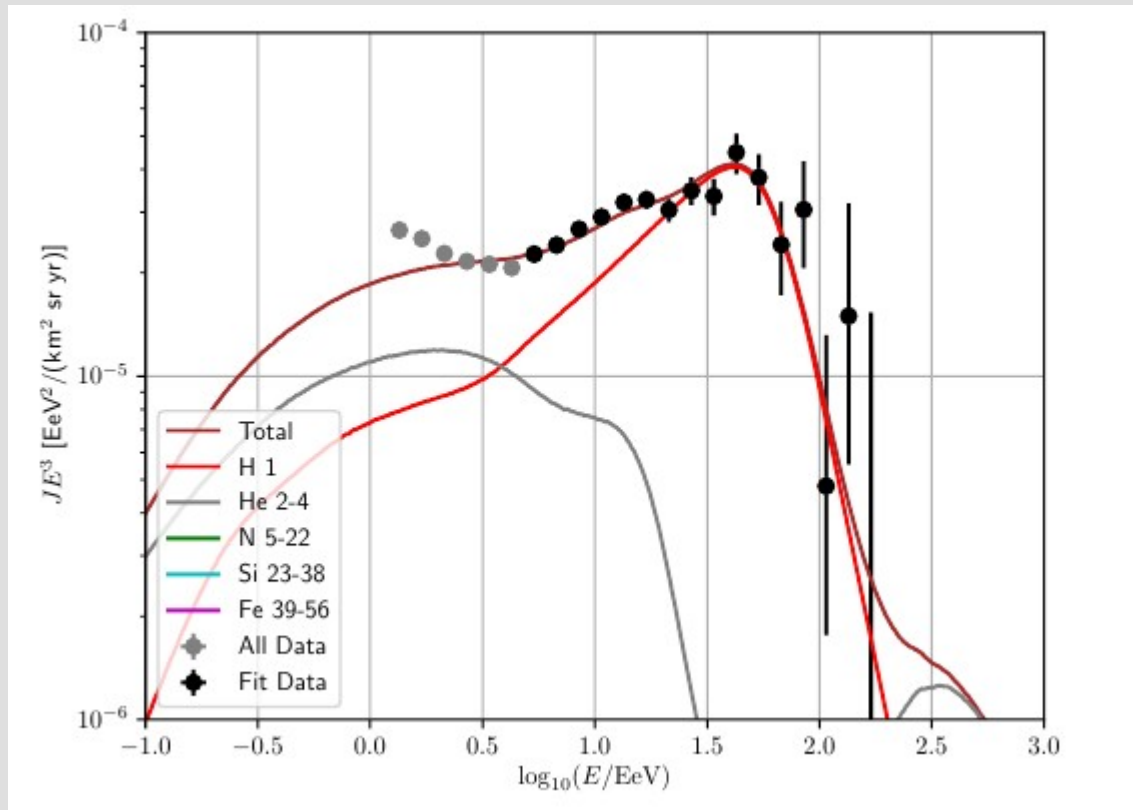
$$B_{\text{rms}} \approx (50-100) \text{ nG } (20 \text{ Mpc}/D) (100 \text{ kpc}/\lambda)^{1/2}$$

Auger, arXiv:2404.03533

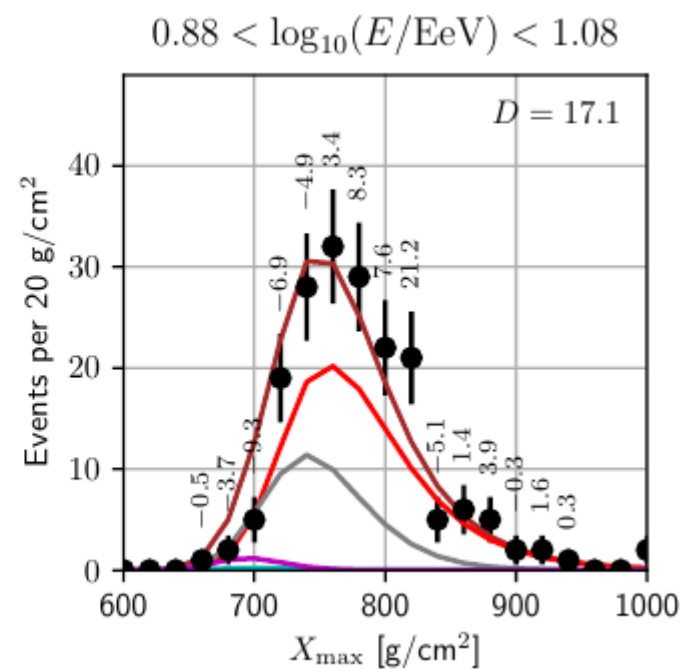
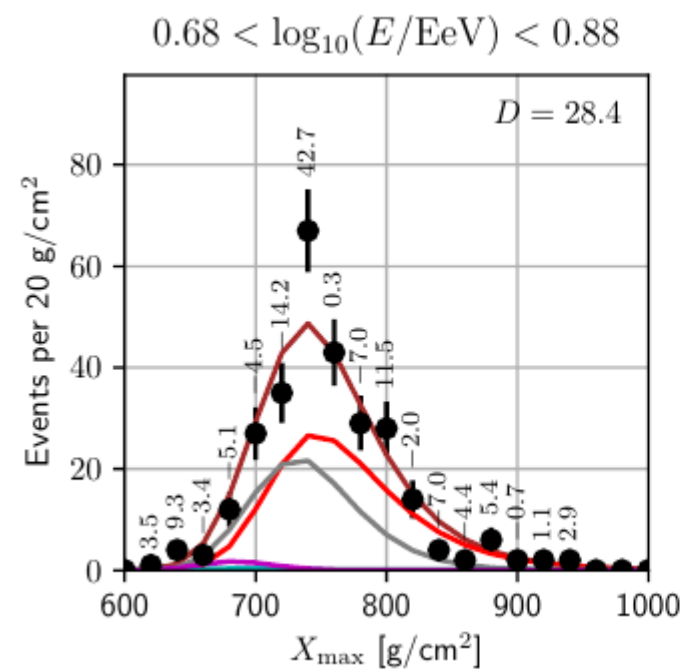


Δ	with EGMF, NE-NE							Sibyll 2.3d							
	EPOS-LHC				Sibyll 2.3d			EPOS-LHC				Sibyll 2.3d			
	γ_{H}	$R_{\text{cut}}^{\text{H}}$ [EeV]	γ_{L}	$R_{\text{cut}}^{\text{L}}$ [EeV]	X_s	R_{crit} [EeV]	D ($N = 353$)	γ_{H}	$R_{\text{cut}}^{\text{H}}$ [EeV]	γ_{L}	$R_{\text{cut}}^{\text{L}}$ [EeV]	X_s	R_{crit} [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?



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

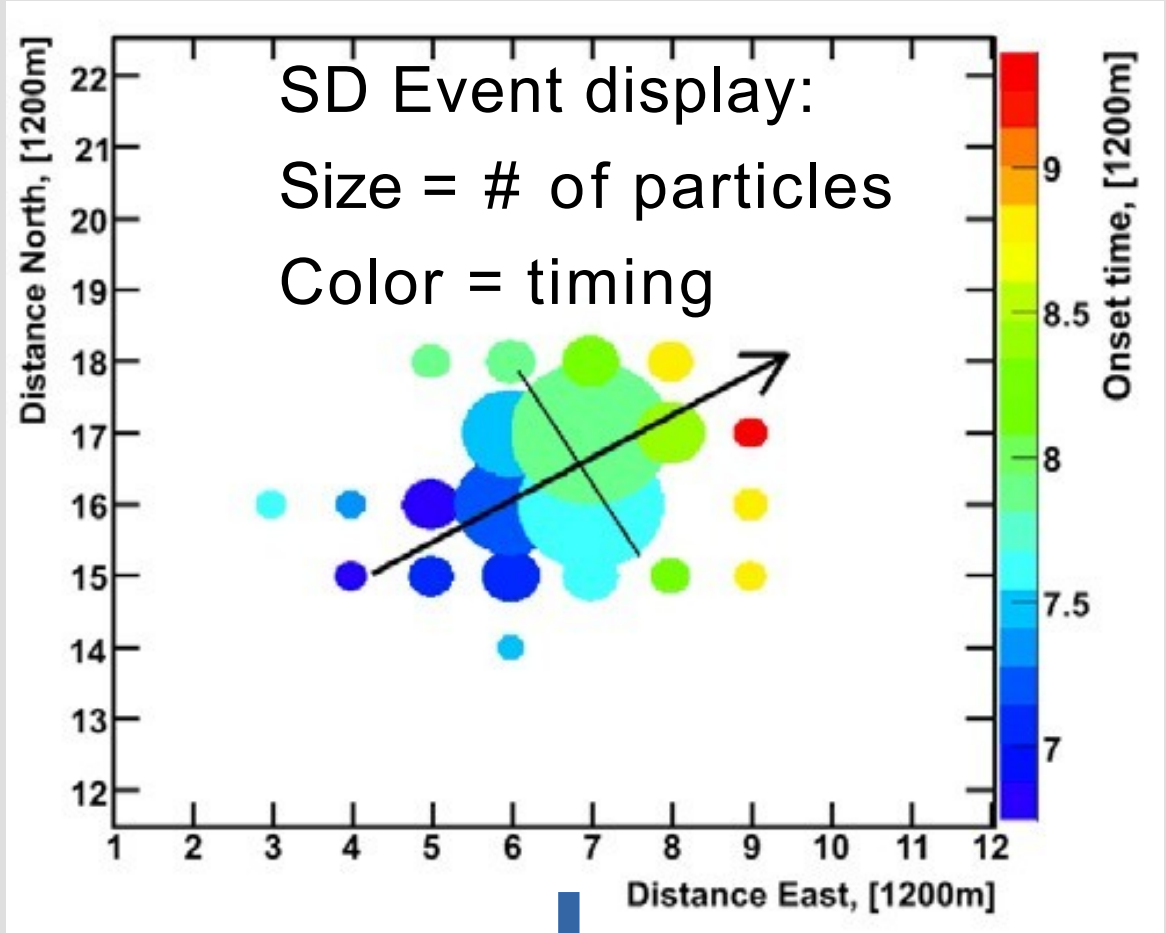


Параметры близки к ожидаемым из классической теории ускорения КЛ

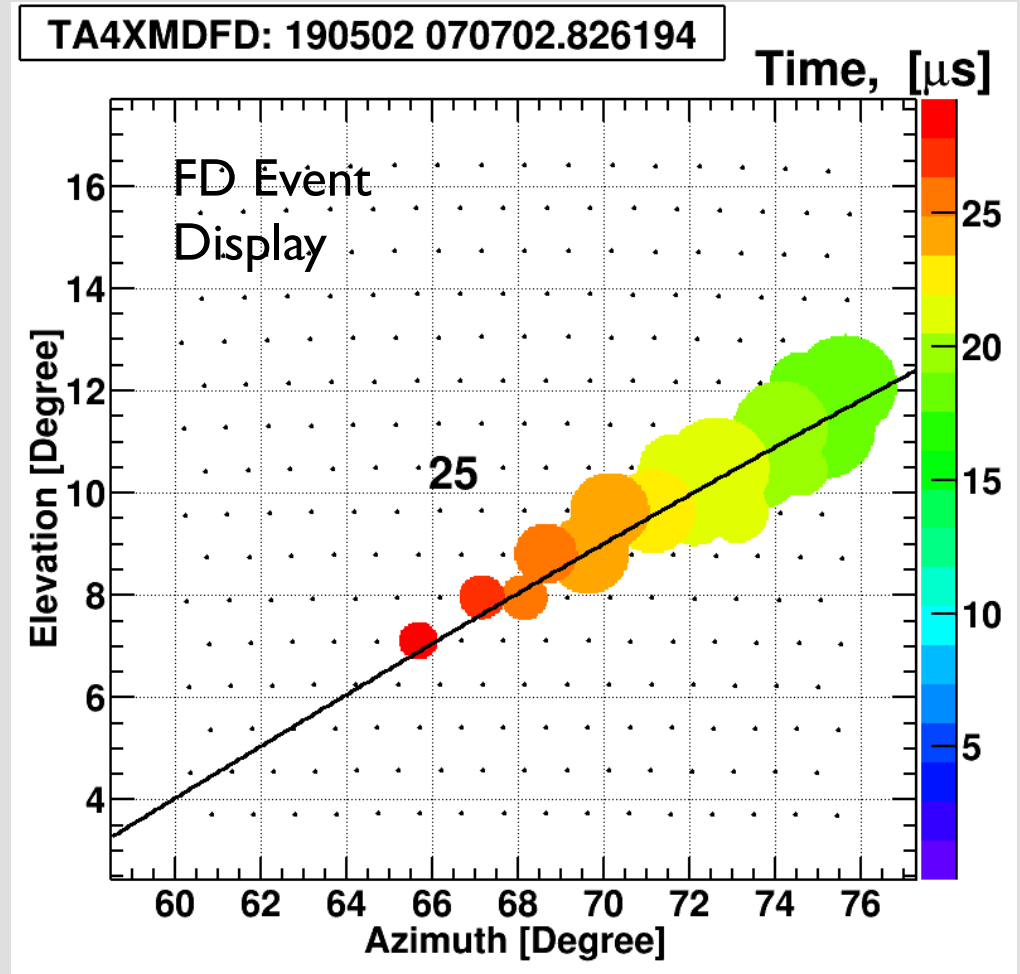
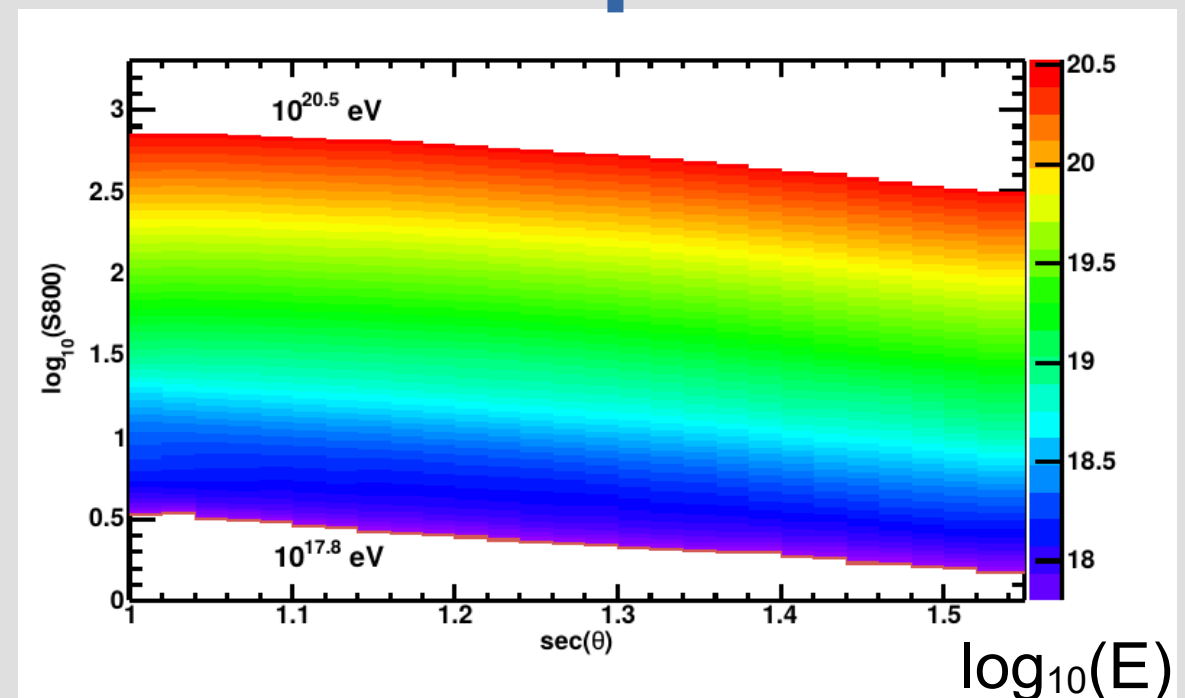
Best fit parameters:
 $\gamma = 2.06$
 $R_{\text{cut}} = 182 \text{ EV}$
 $Q_{0p} = 0.0\%$,
 $Q_{0He} = 99.2\%$,
 $Q_{0N} = 0.0\%$,
 $Q_{0Si} = 0.0\%$,
 $Q_{0Fe} = 0.8\%$

Реконструкция наземного события

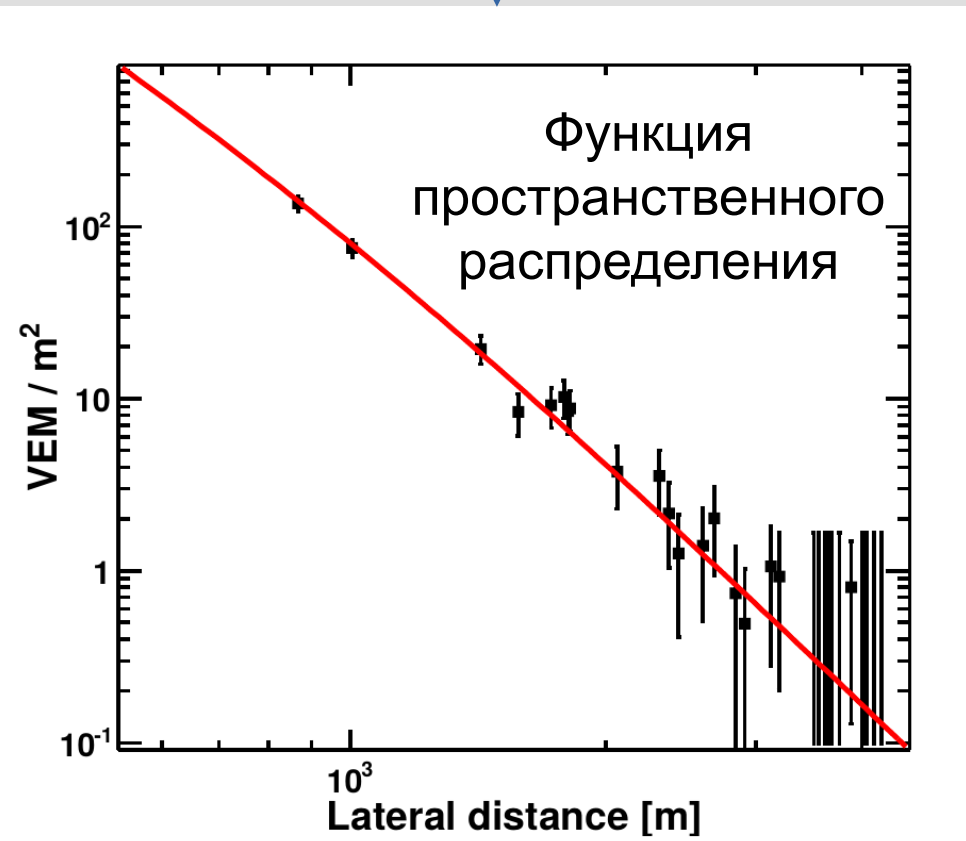
Реконструкция флуоресцентного события



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



SD энергия перешкалируется к более точному FD масштабу

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


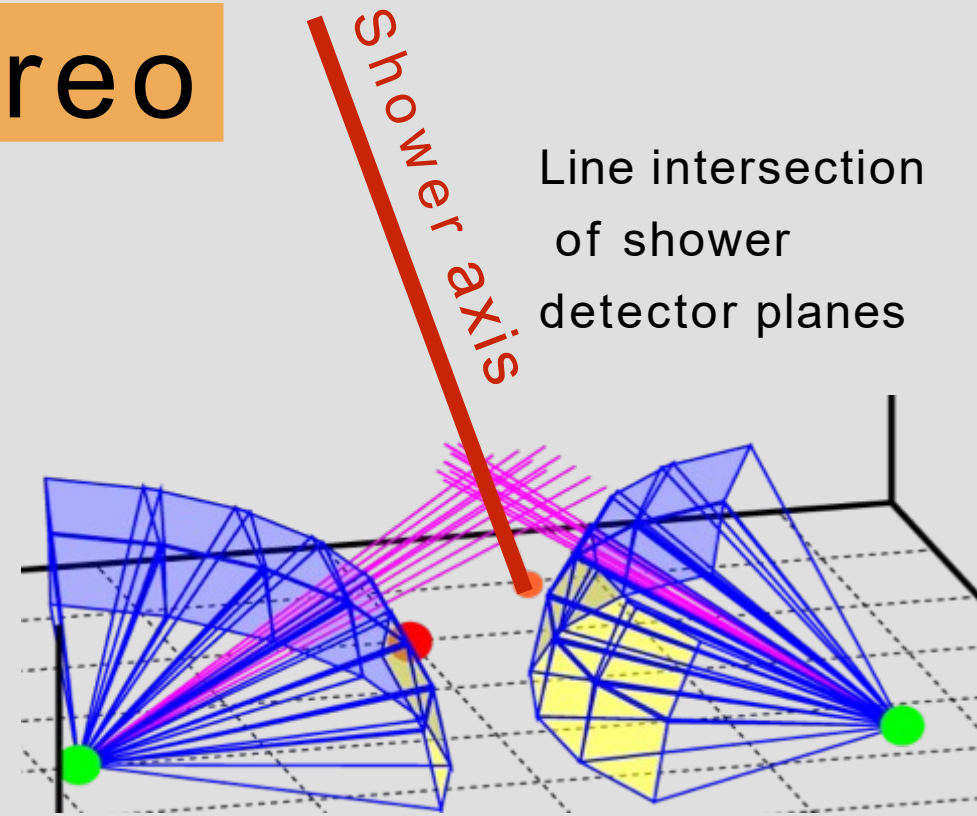
$$\rho = A \left(\frac{s}{91.6\text{m}} \right)^{-1.2} \left(1 + \frac{s}{91.6\text{m}} \right)^{-(\eta(\theta)-1.2)} \left(1 + \left[\frac{s}{1000\text{m}} \right]^2 \right)^{-0.6}$$

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

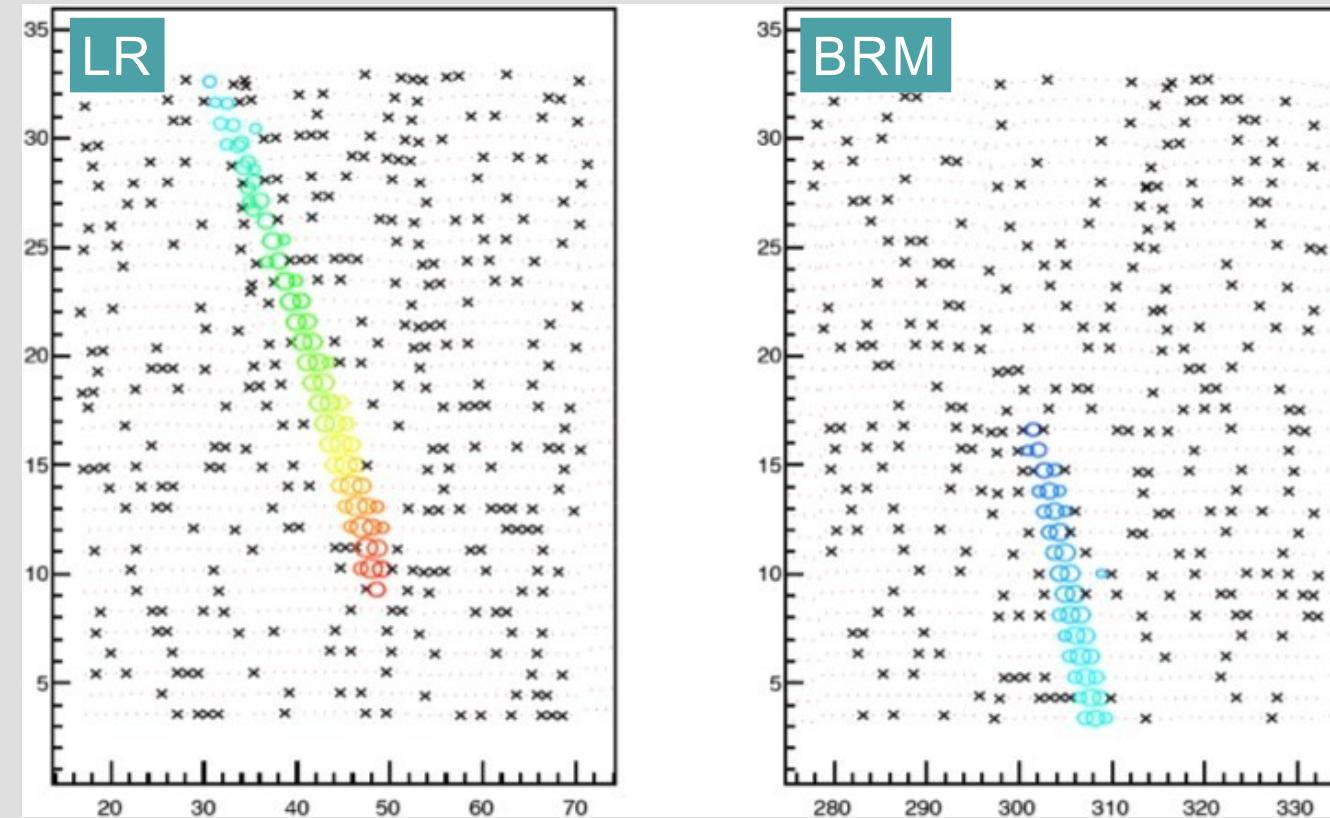
s — расстояние до оси ливня
 θ — зенитный угол

FD Event reconstruction

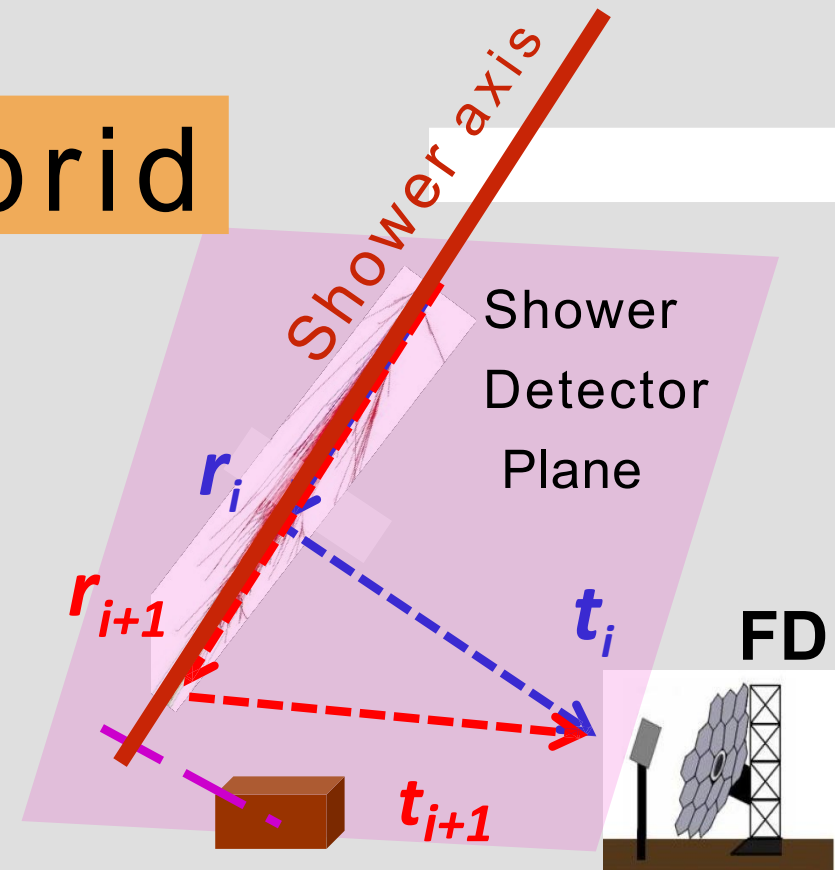
Stereo



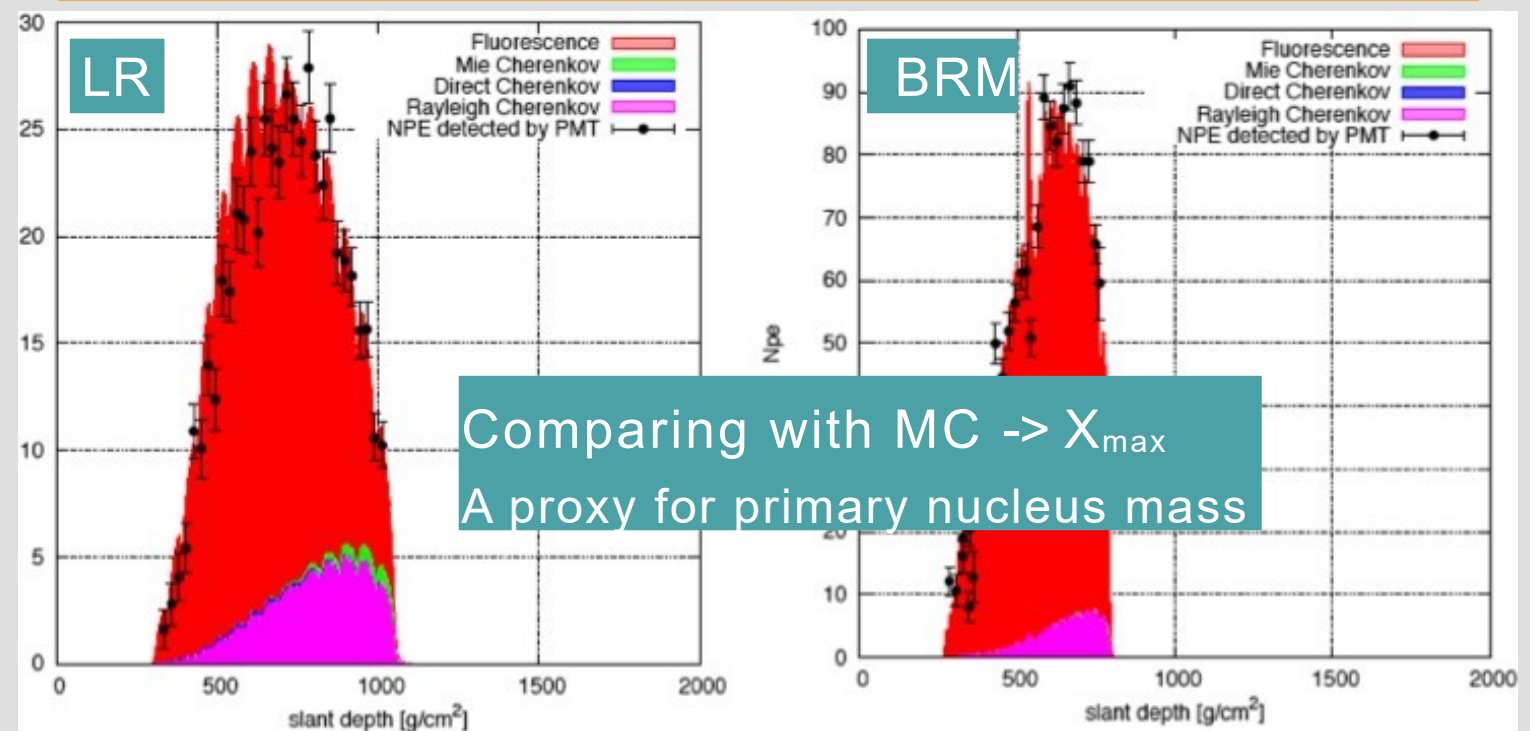
observed images



Hybrid



reconstructed shower profiles



Comparing with MC $\rightarrow X_{\text{max}}$
A proxy for primary nucleus mass

Ускорение КЛ в их возможных источниках

Критерий Хилласа

$R = E/qB$ — ларморовский радиус

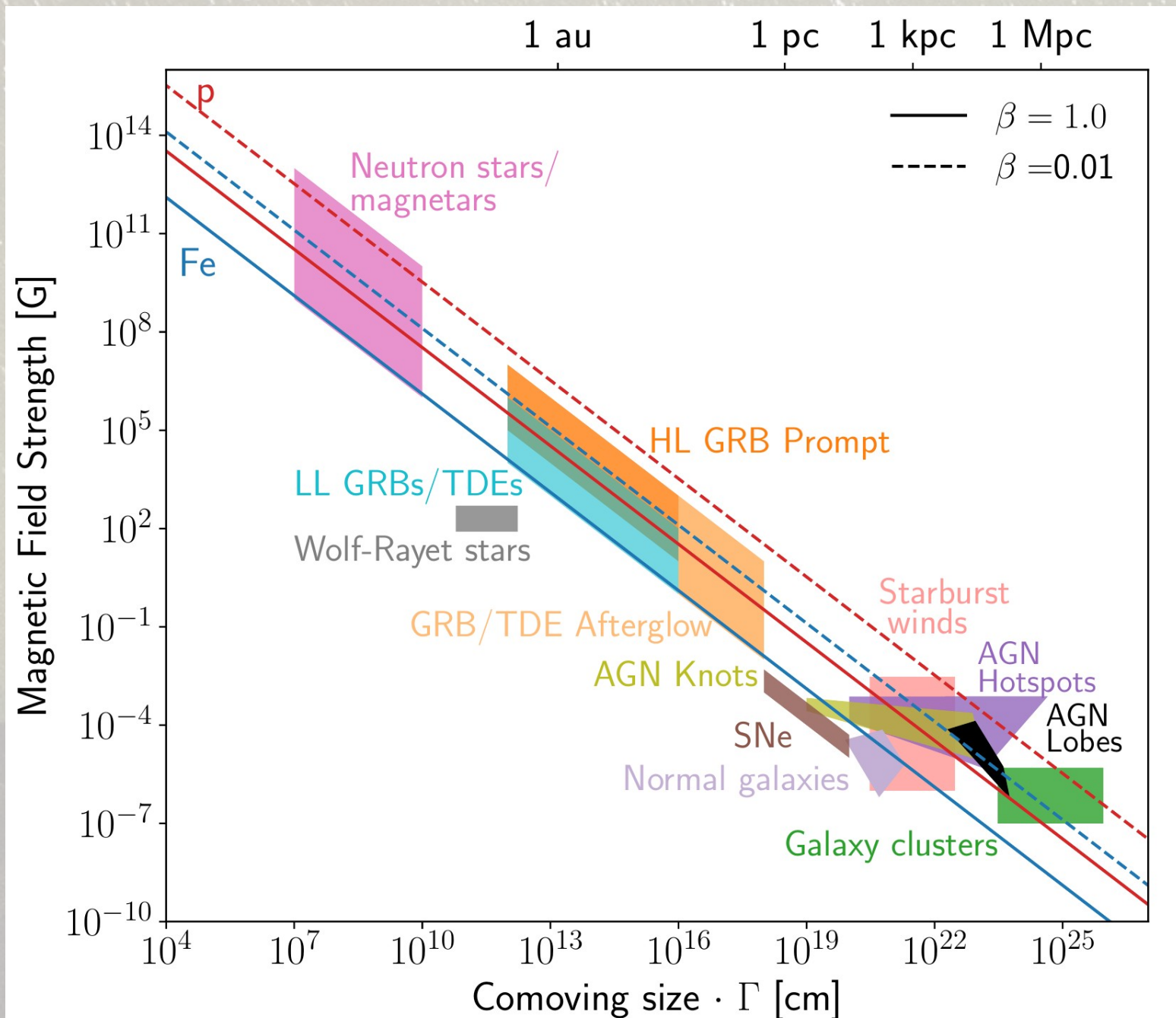
$E_{\max} = \beta_{\text{shock}} qBR\Gamma$ — максимальная достижимая энергия

Классы источников под прямыми — исключены

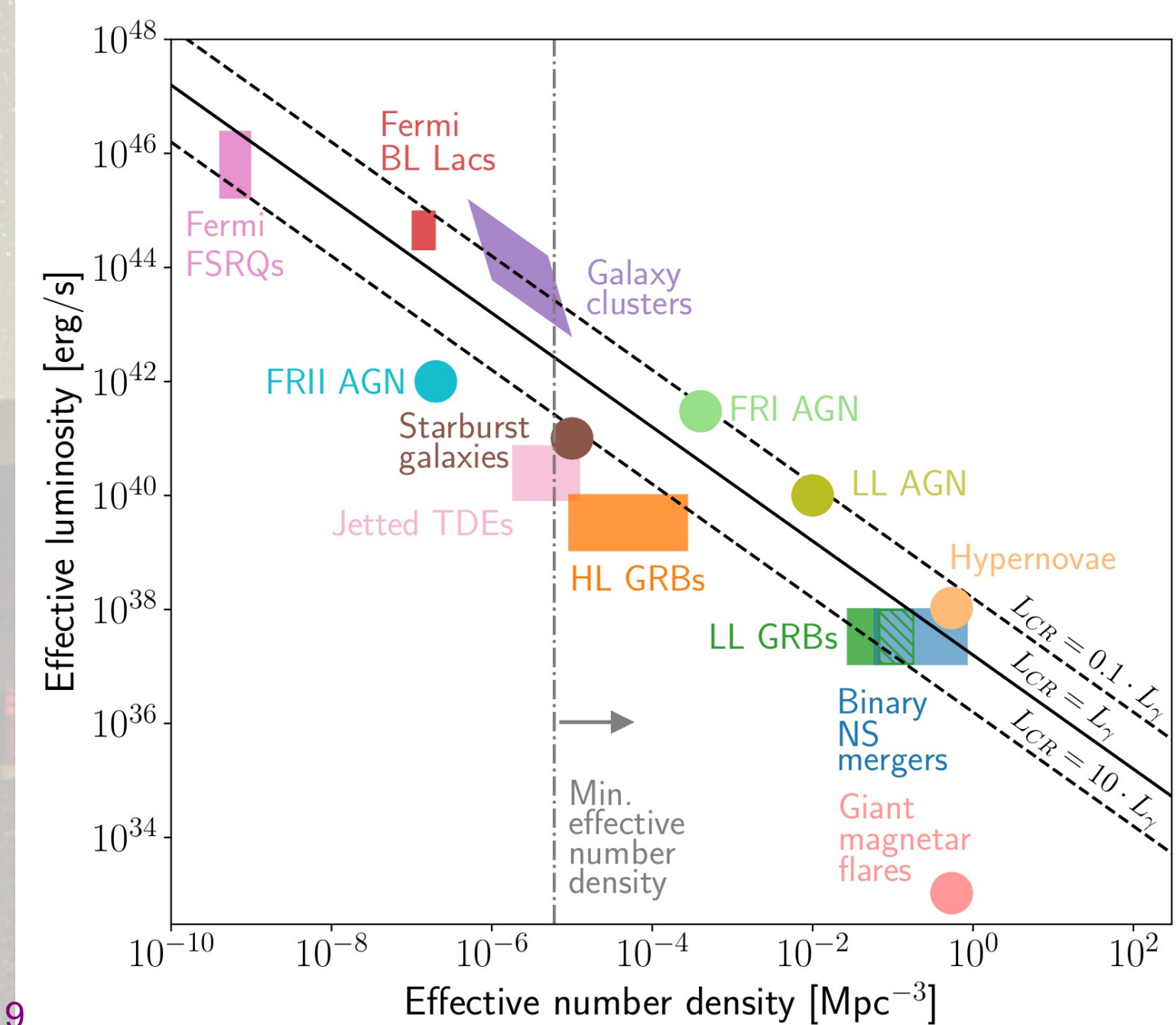
Критерий общей энергетики

$L = 5 \times 10^{44} \text{ erg}/(\text{Mpc}^3 \text{ yr})$ — совокупная светимость источников, необходимая чтобы получить наблюдаемый спектр КЛ (Auger, 2017)

Зависит от E_{\min} внегалактических КЛ и соотношения L_{γ}/L_{CR}
Классы источников под прямыми — исключены



Alves Batista et al., 2019

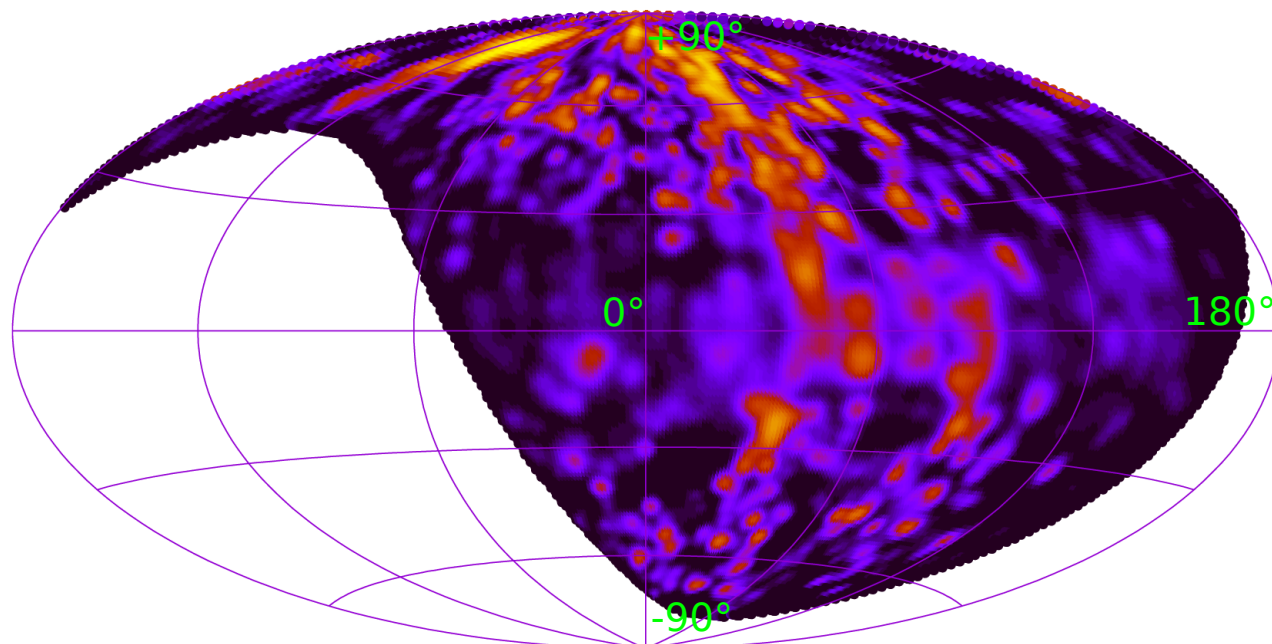


Step two: realistic UHECR mock sets

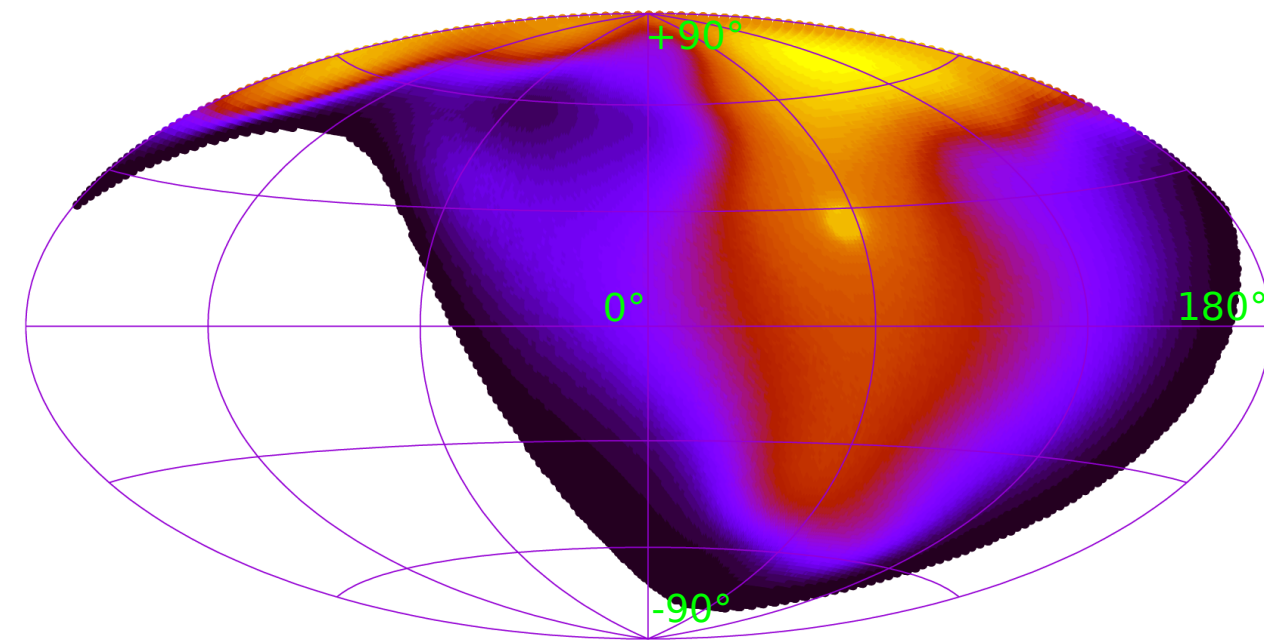
Generate UHECR sets with state-of-art simulated skymaps

- 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

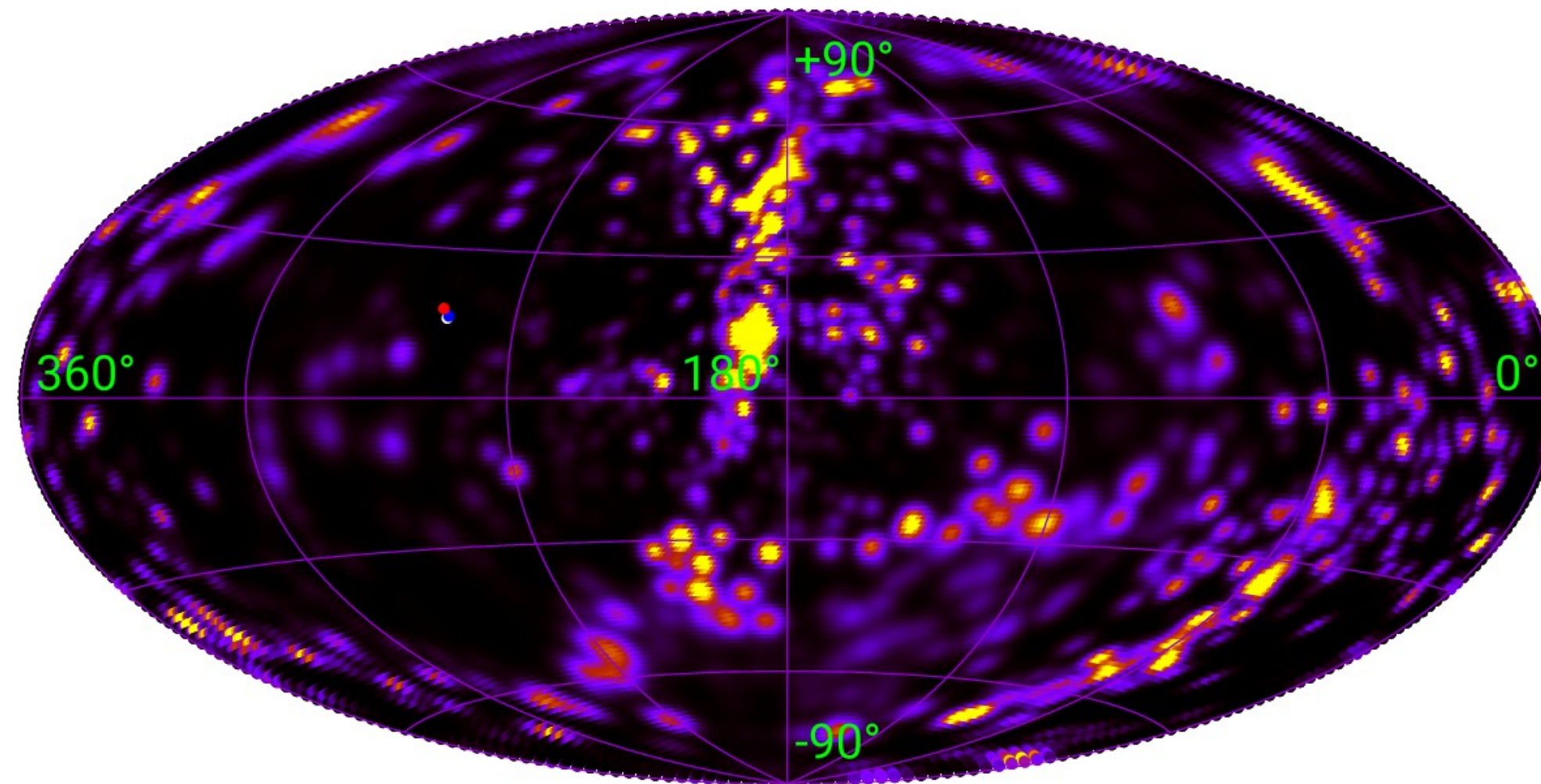


Iron map at E = 100 EeV



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**



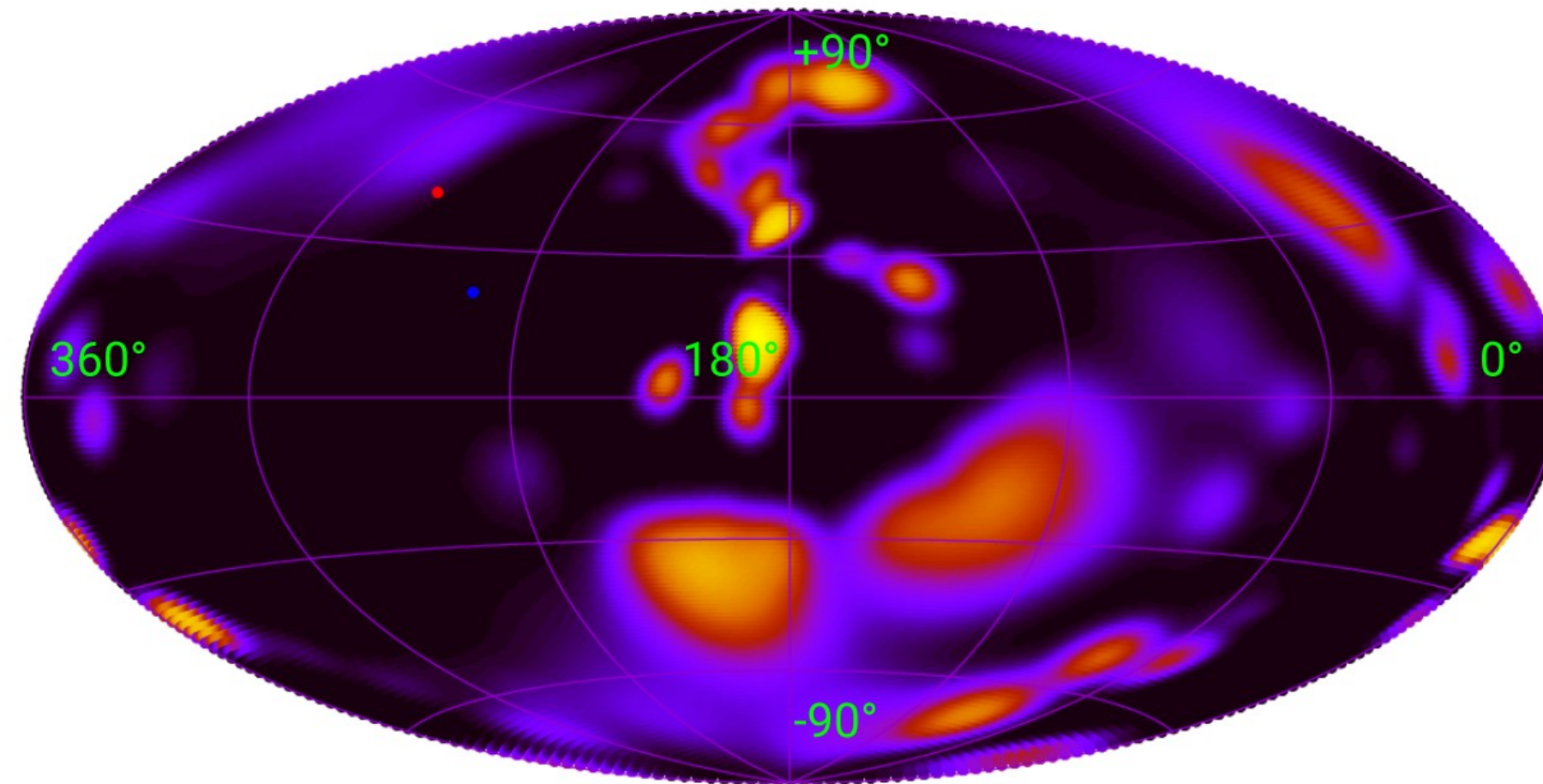
Red dot: reg. Galactic MF JF'12

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

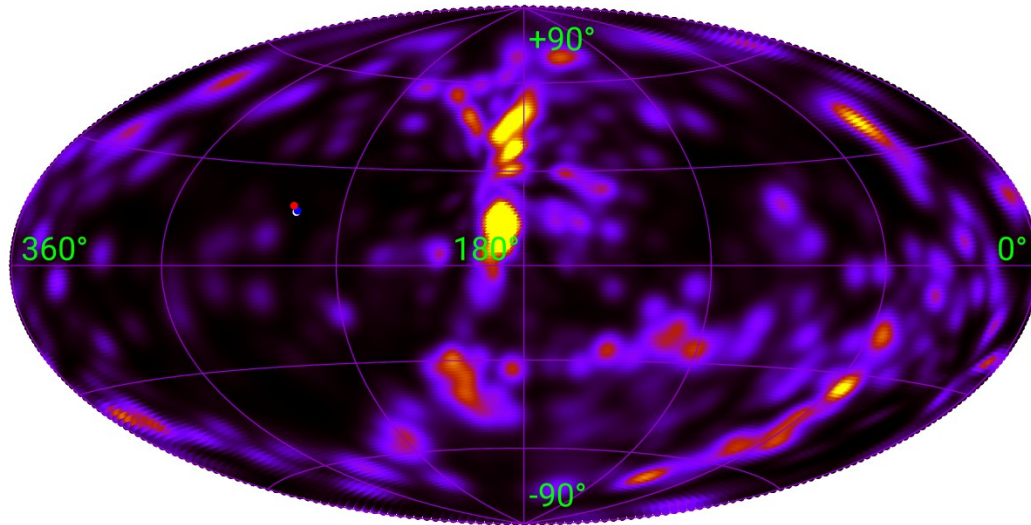
Blue: reg. Galactic MF PT'11

Correlation with sources, proton scenario: uncertainties

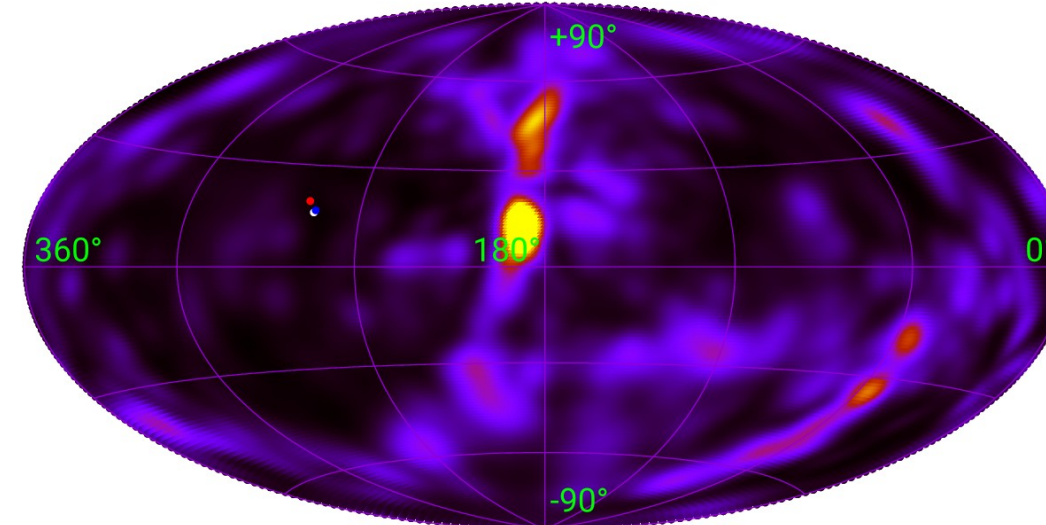
We can constrain the distance to the source by analyzing the CR propagation

- 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



Ограничения на концентрацию источников КЛ

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

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

Считаем, что источники распределены во Вселенной в целом 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 $D < 5.0$ Мpc $\rightarrow \rho > 1.0 \cdot 10^{-4}$ Мпк⁻³

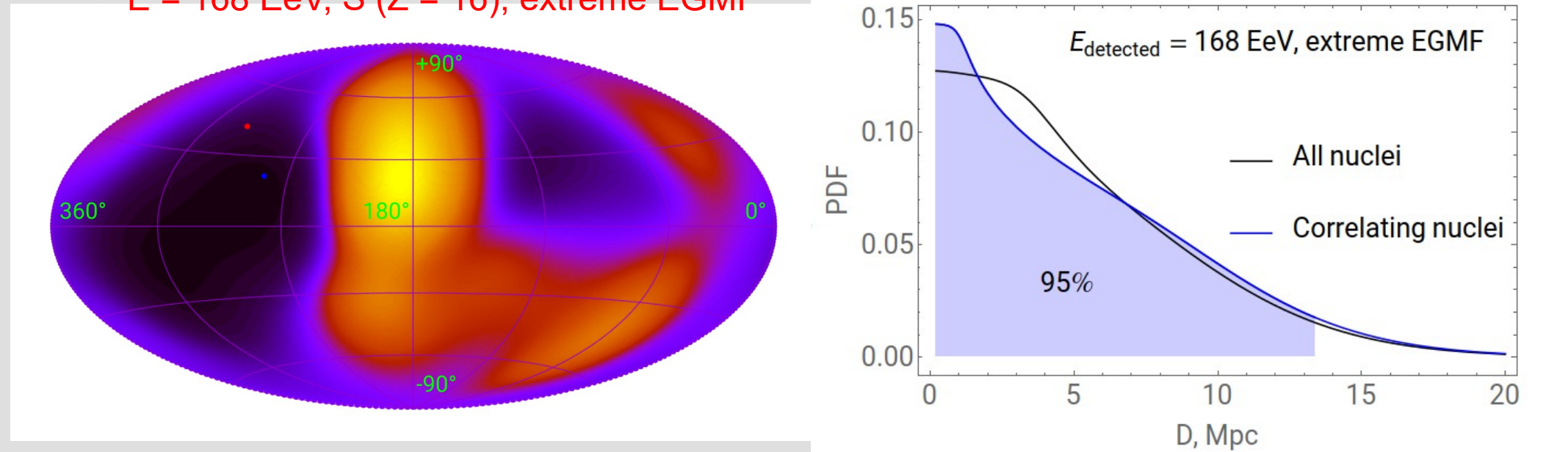
Correlation with sources, nucleus scenario: uncertainties

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: $D < 13.4 \text{ Mpc}$

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



Распространенность элементов в Солнечной Системе

