

From Composition to Deflections: UHECRs in the Galactic Magnetic Field



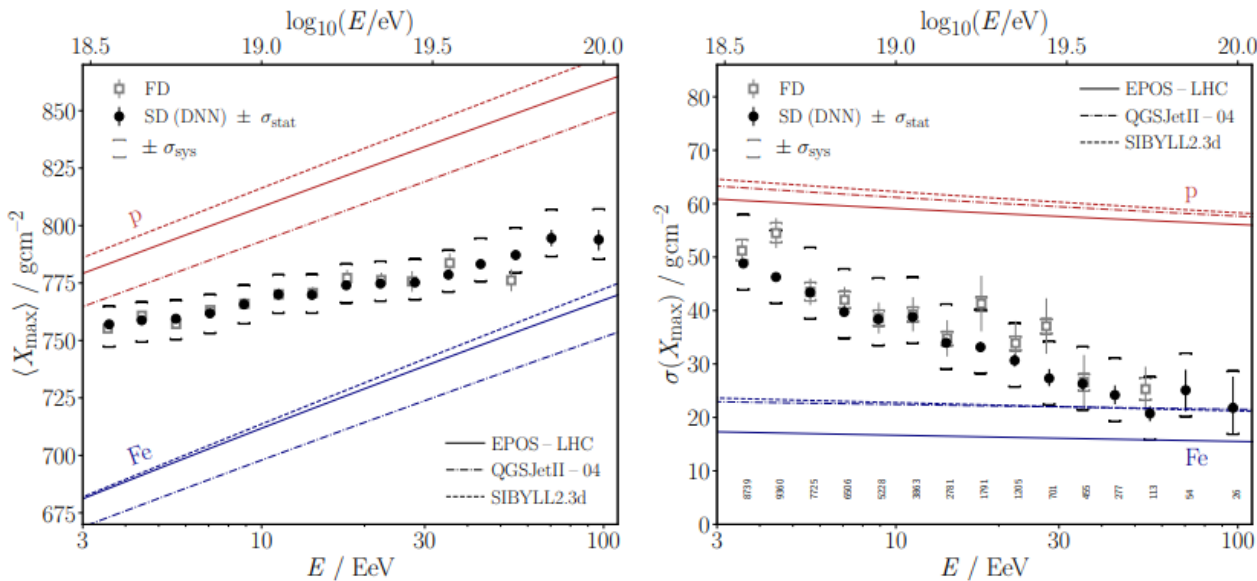
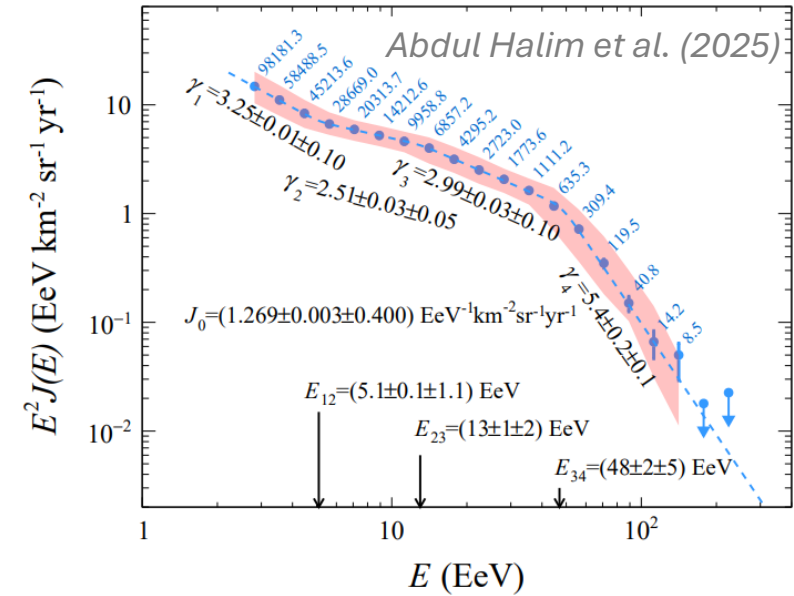
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6.5.2026

Alena Bakalová

Ultra-high-energy cosmic rays

- Ultra-high-energy cosmic rays (UHECRs $E \geq 10^{18}$ eV)
- Steeply falling **energy spectrum**
- Multiple features where spectral index changes
 - Ankle $\sim 5 \cdot 10^{18}$ eV
 - Instep $\sim 13 \cdot 10^{18}$ eV
 - Suppression $\sim 5 \cdot 10^{19}$ eV

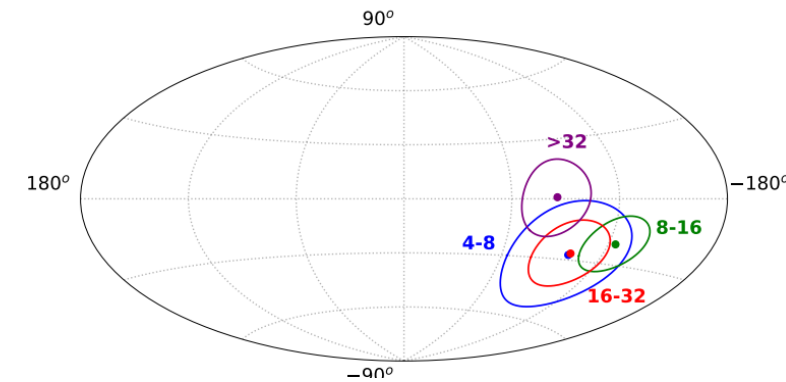
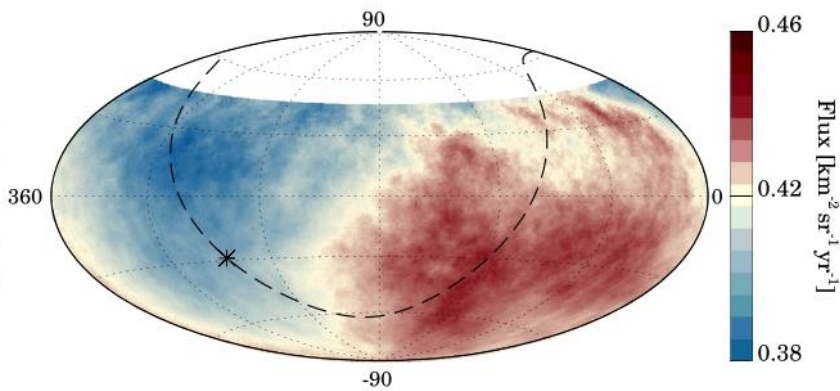
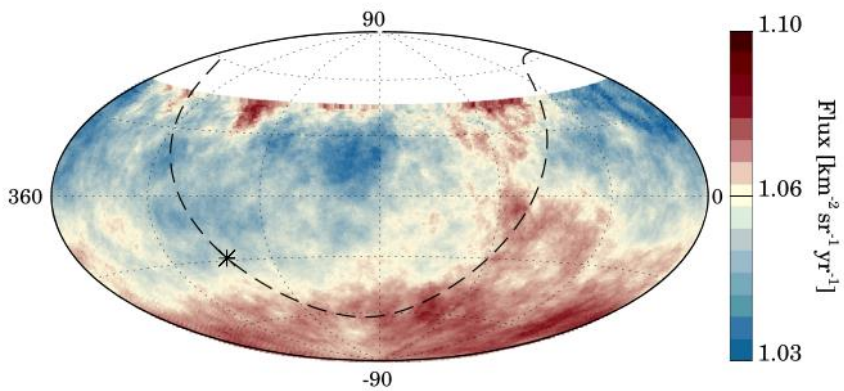
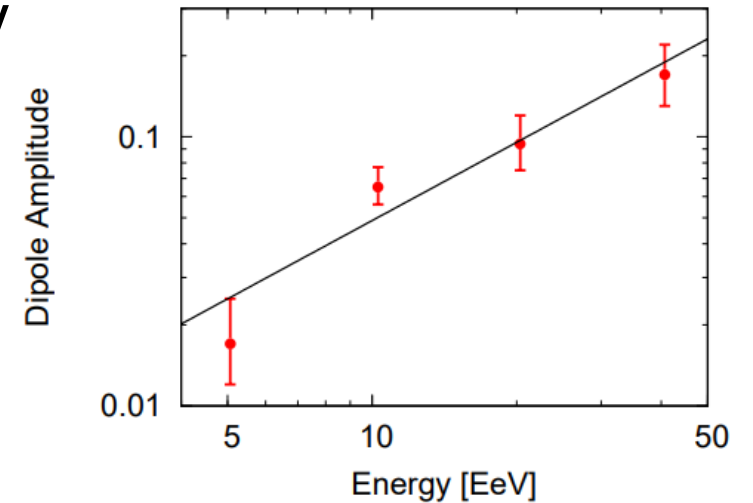


Abdul Halim et al. (2025)

- **Mass composition** evolving with energy
- Heavier composition with energy above $\sim 10^{18.1}$ eV
- Inference of mass depends on hadronic interaction model (HIM)
 - Abdul Halim et al. (2024) – data prefer deeper X_{\max} and larger hadronic signals than HIM predictions
 - New HIMs in 2026 (deeper X_{\max} predictions)

Anisotropies in arrival directions

- Dipole in the arrival directions of cosmic rays above 8 EeV
- Points $\sim 125^\circ$ from the Galactic center - suggests an **extragalactic origin**
- Amplitude $7.4^{+1.0}_{-0.8}$ %, direction $(l, b) = (233^\circ, -13^\circ)$ and significance 6.8σ
- Amplitude evolves with energy



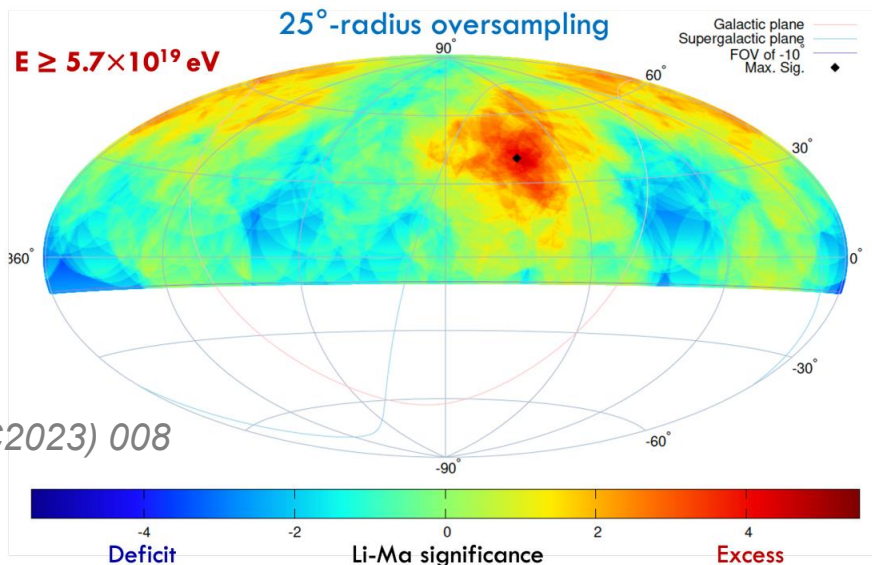
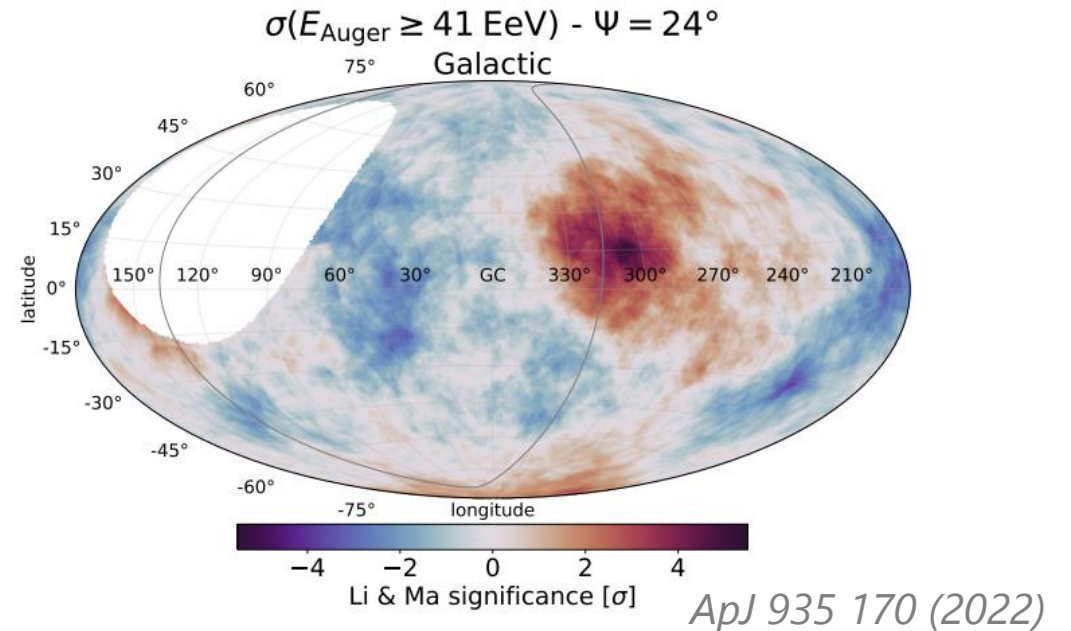
Abdul Halim et al. (2024)

Aab et al. (2018)

Anisotropies in arrival directions

Blind search for excess at the Pierre Auger Observatory

- $E > 41$ EeV with top-hat smoothing 24° in coordinates $(l, b) = (305.4^\circ, 16.2^\circ)$
- 153 observed events 97.7 expected from isotropy
- Hotspot located 2.9° from NGC 4945 and 5.1° from Centaurus A

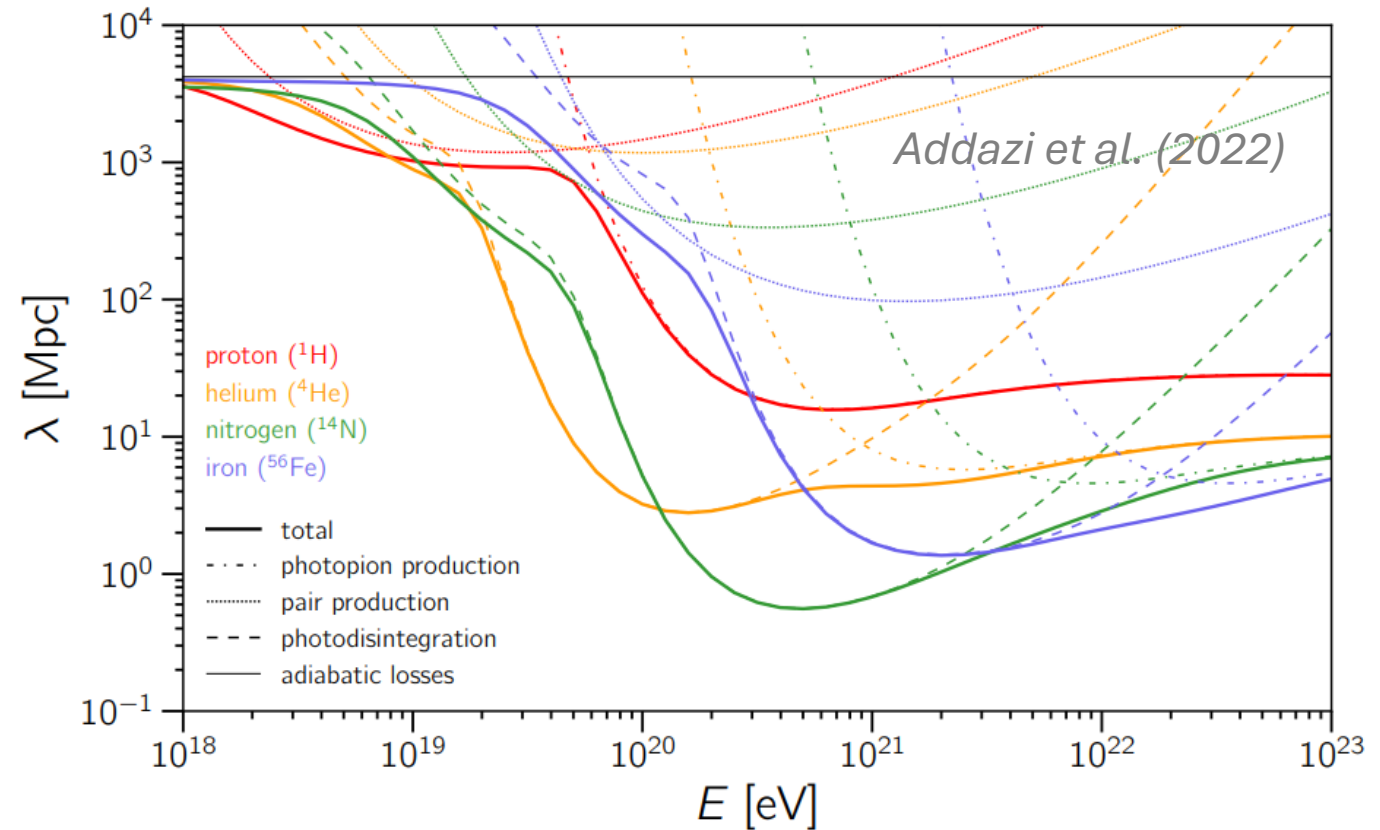


Blind search for excess at Telescope Array

- Hotspot
 - For $E > 57$ EeV at $(\alpha, \delta) = (144^\circ, 40.5^\circ)$
 - 44 observed events vs. 18 expected from isotropy
- Perseus-Pisces supercluster excess
 - For $E > 25$ EeV at $(\alpha, \delta) = (17.9^\circ, 35.2^\circ)$

Propagation of UHECRs in the Universe

- Cosmic rays interact with ambient photon fields and matter in the Universe
- Interactions with CMB and EBL
 - **Photo-pion production**
 - **Electron pair production**
 - **Photodisintegration of nuclei**

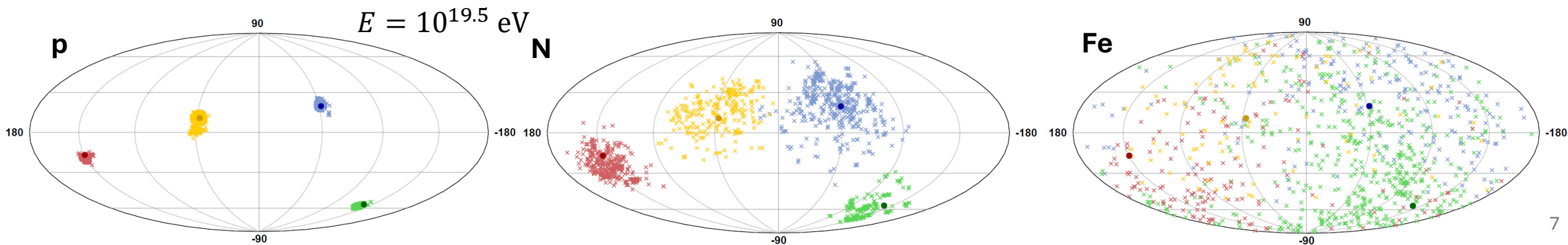


→ limited horizon from which UHECR can come from at the highest energies

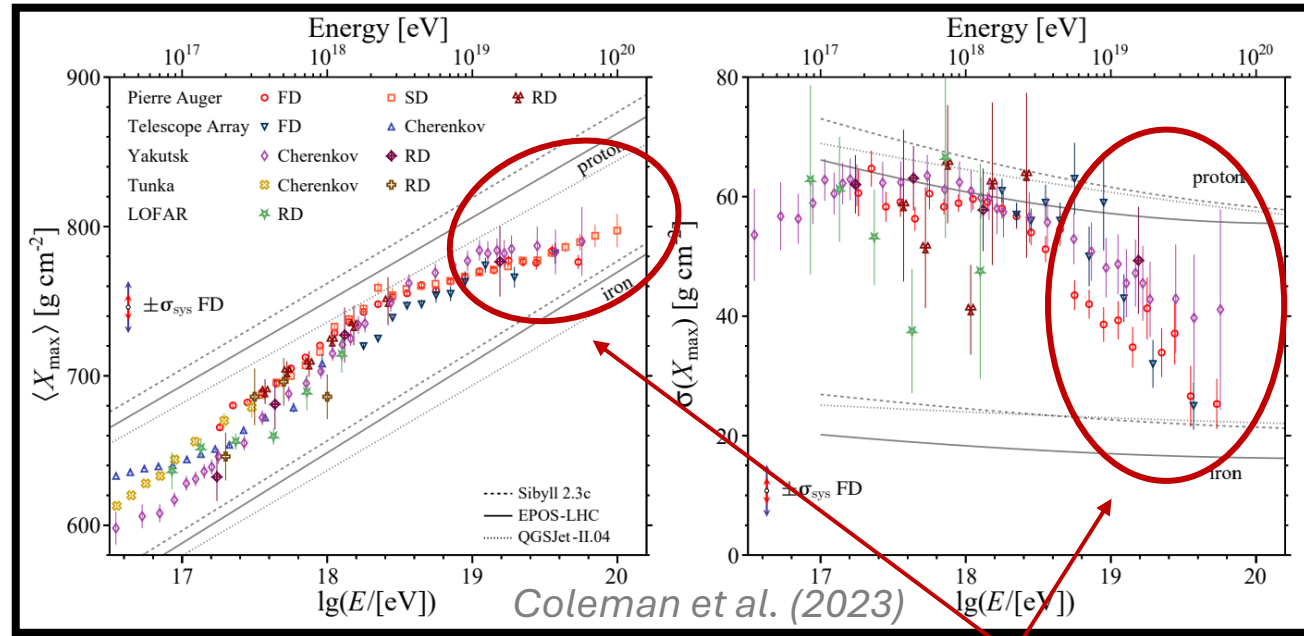
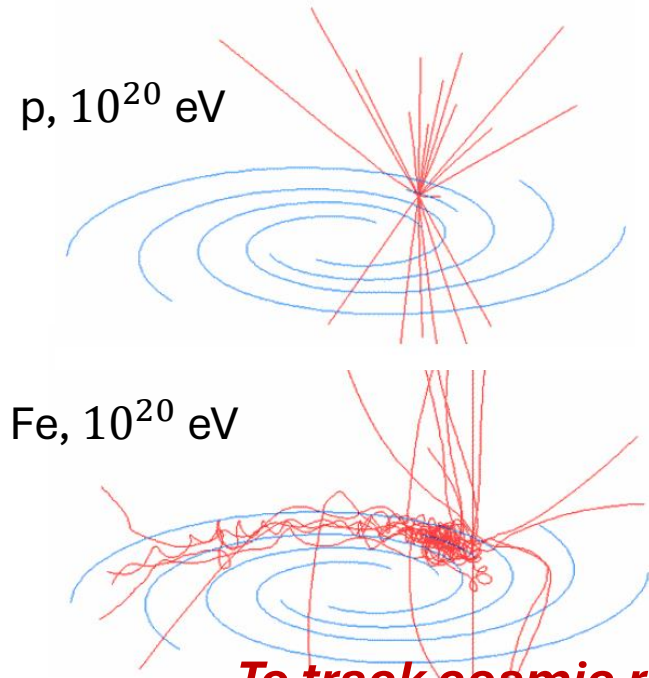
Propagation in the Universe: Deflections in magnetic fields

- Cosmic rays are charged – trajectories influenced by magnetic fields in the universe:
 - **Extragalactic magnetic fields (EGMF)**
 - **Galactic magnetic field (GMF)**
- Deflections depend on the particle's rigidity $R = E/Z$

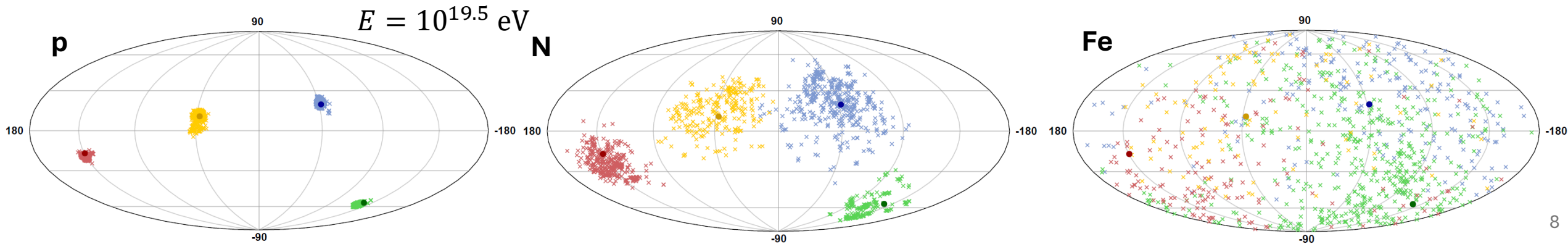
To track cosmic rays back to their sources we need high energy light particles!



Propagation in the Universe: Deflections in magnetic fields



To track cosmic rays back to their sources we need high energy light particles!



Models of the Galactic magnetic field

Inferred from measurements of

1. **Faraday rotation measures**

$$\propto \int_0^L n_e(s) B_{\parallel}(s) ds$$

COMPLEMENTARY
MEASUREMENTS

2. **Polarized synchrotron intensity**

$$\propto \int_0^L n_{cr,e}(s) B_{\perp}(s) ds$$

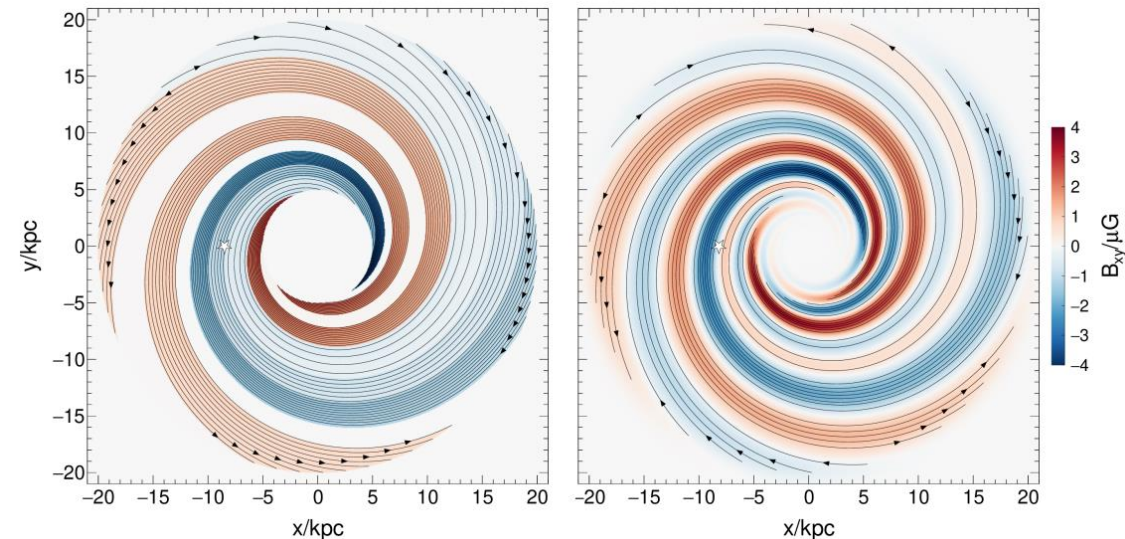
Coherent component

- Superposition of large-scale **halo field** (toroidal and poloidal) and **disk field** (logarithmic spiral field)

Turbulent component

- Random turbulent field on small scales

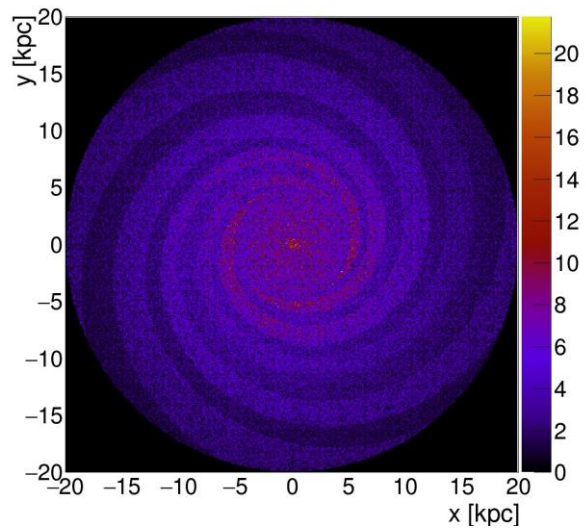
- Jansson-Farrar 2012 (**JF12**)
- Terral-Ferrière 2017 (**TF17**)
- Unger-Farrar 2023 (**UF23**)
- Korochkin-Semikoz-Tinyakov (**KST24**)



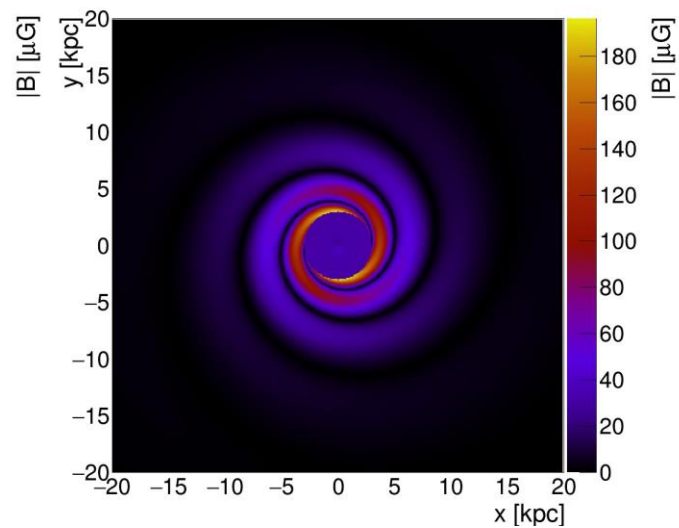
Unger & Farrar, APJ, 970 (2024) 1, 95

Models of GMF

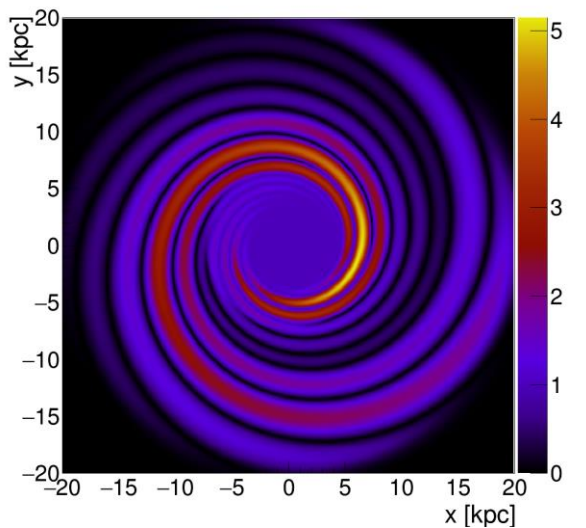
JF12Planck



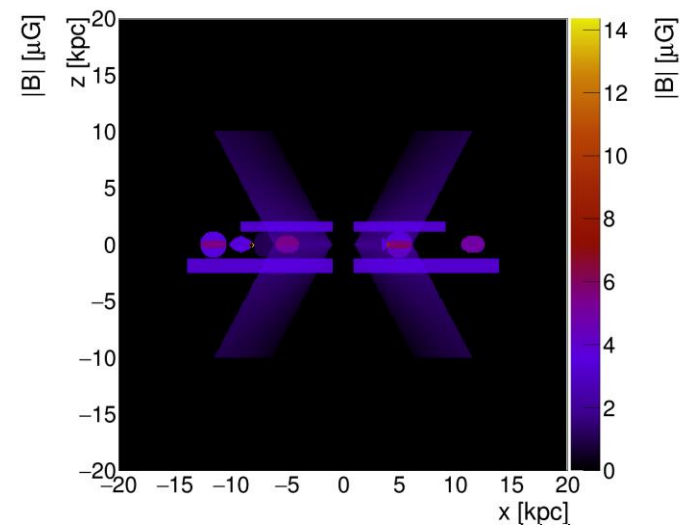
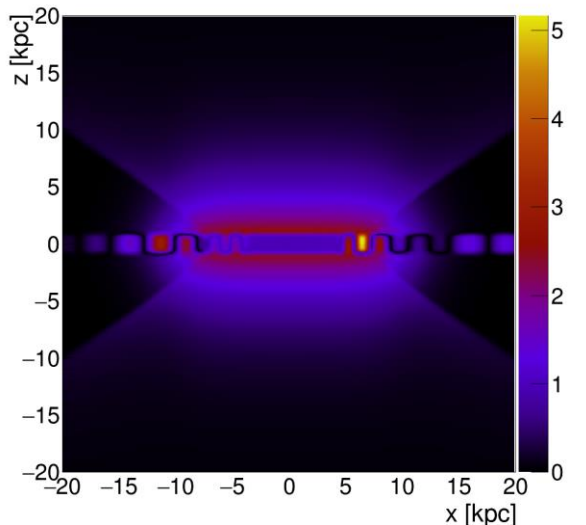
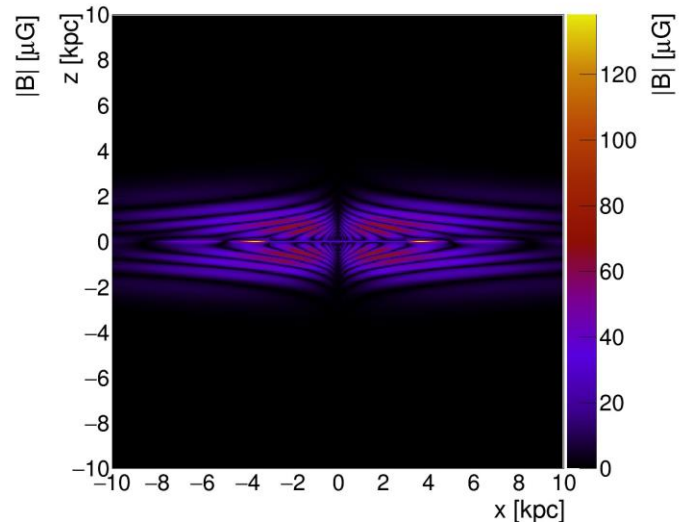
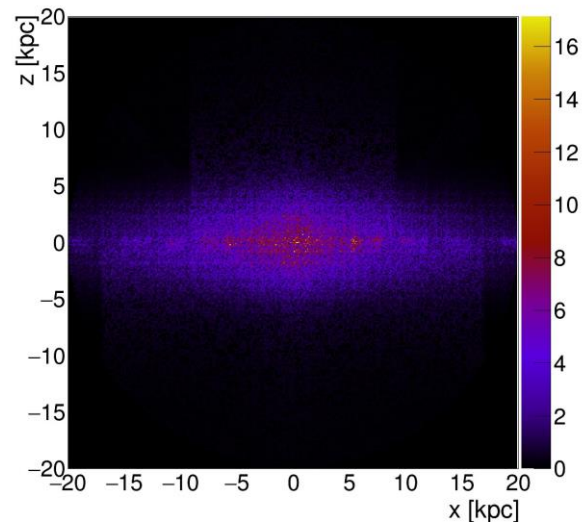
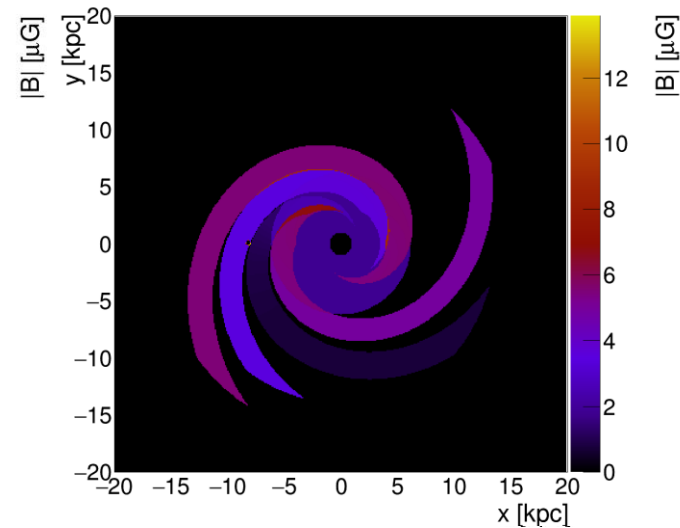
TF17: Ad1C1



UF23 base

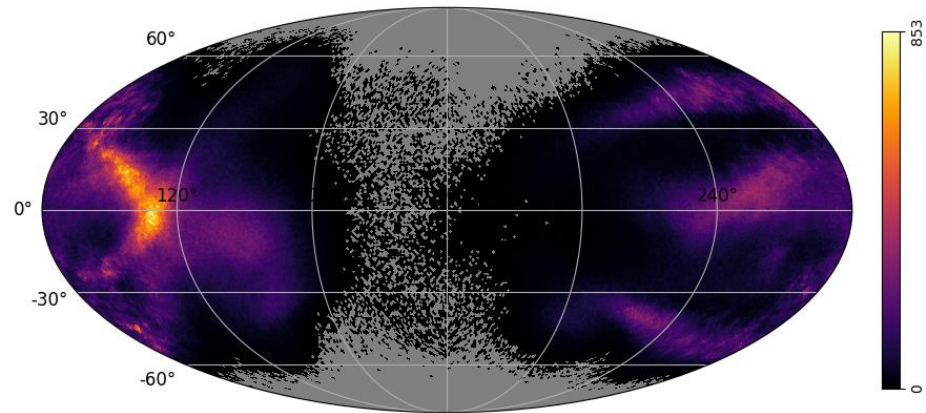


KST24

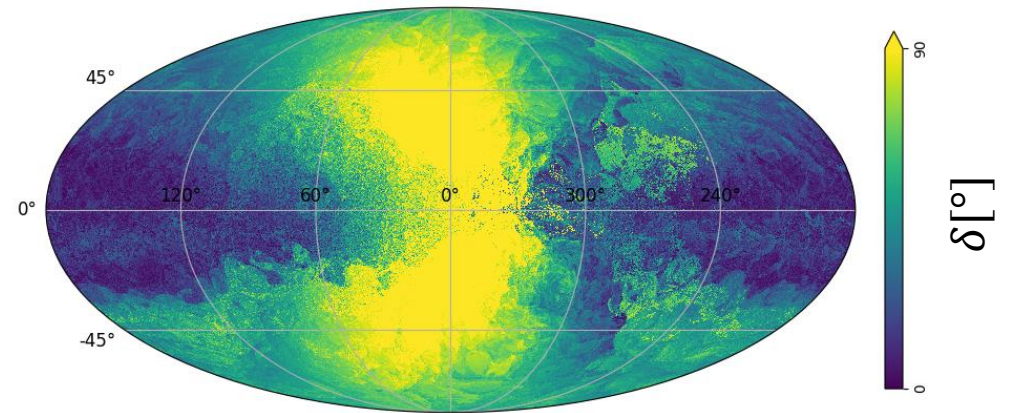


Galactic magnetic field deflections

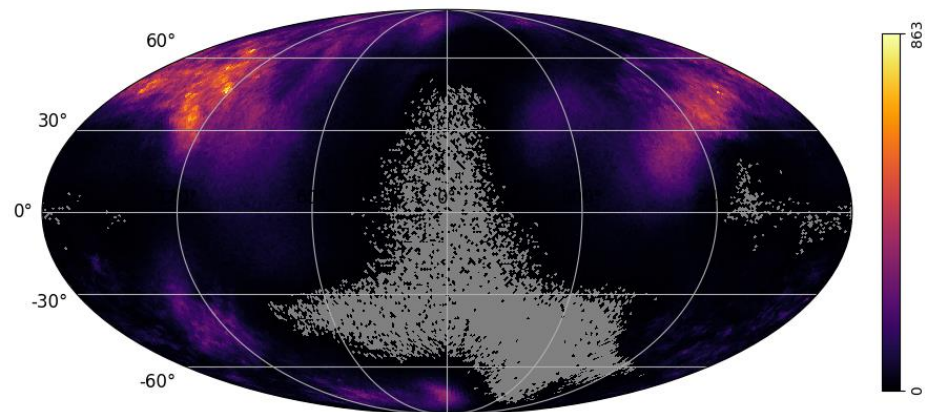
R = 6 EV



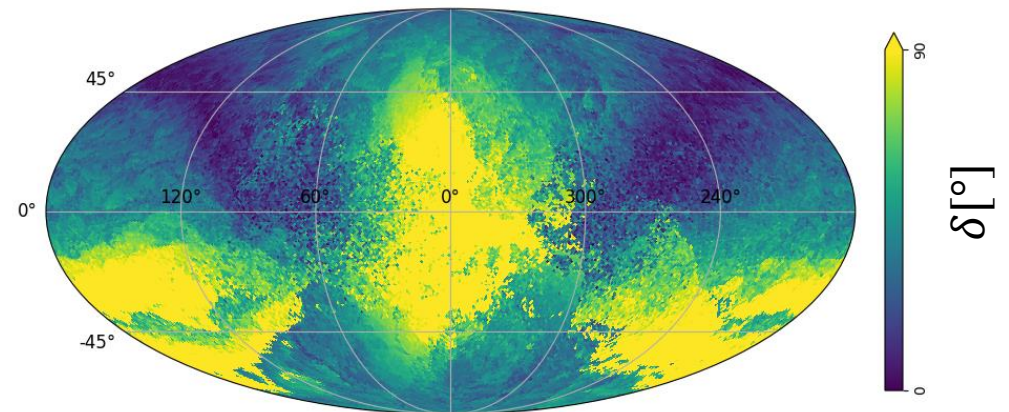
UF23base+Pl turb



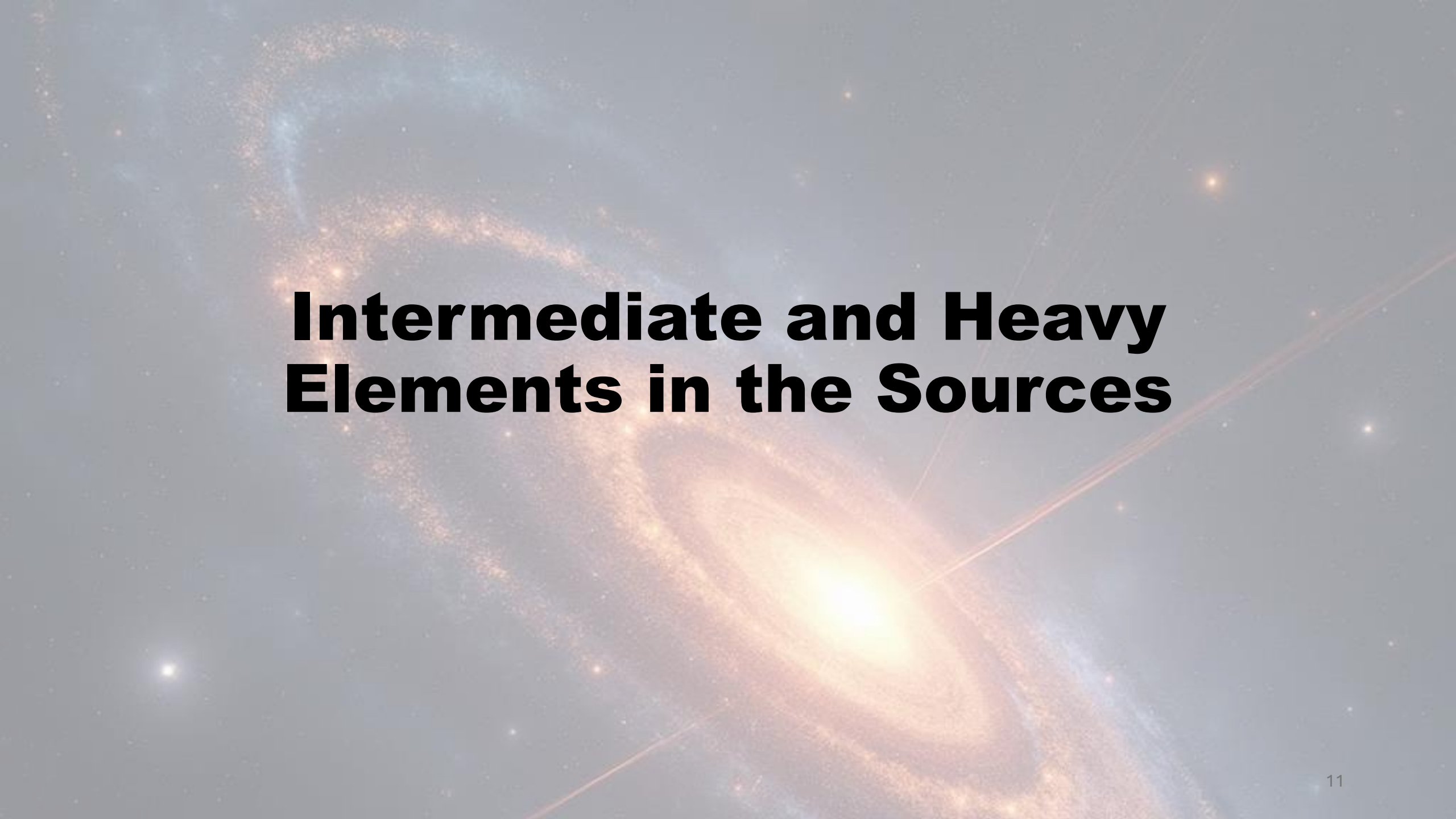
UF23base+Pl turb



KST24+Pl turb



KST24+Pl turb



Intermediate and Heavy Elements in the Sources

Intermediate and heavy elements in the sources

- To accelerate and preserve intermediate (CNO) and heavy (Si–Fe) nuclei, UHECR sources require:

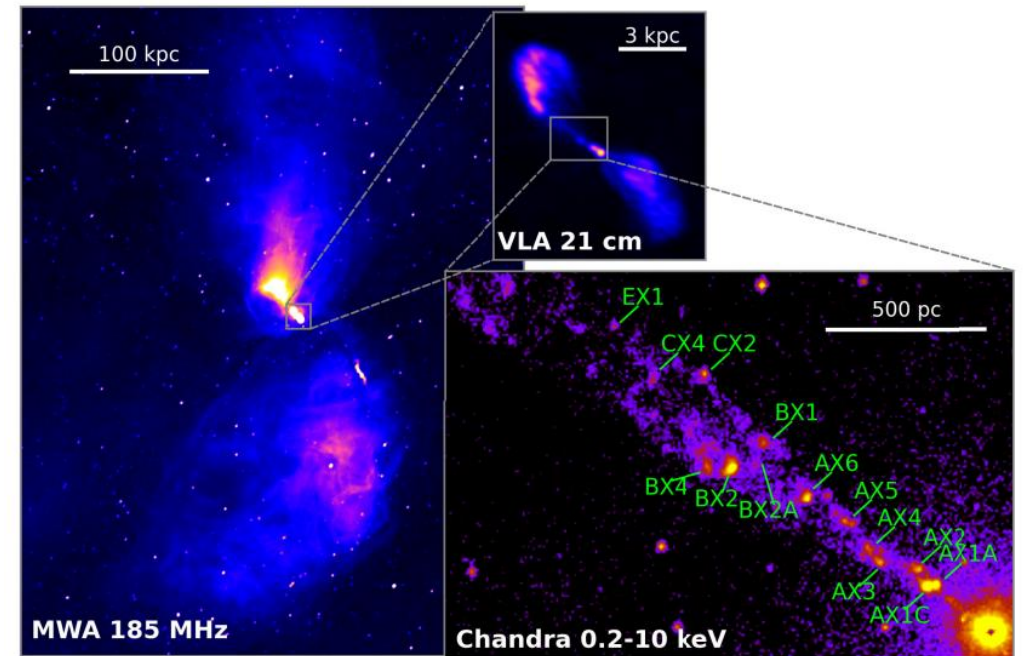
1. Metal-rich environment

starburst galaxies, **baryon-loaded AGN jets**,
supernova ejecta, neutron-star merger ejecta

2. Sufficiently low photodisintegration opacity

environments with moderate UV/X-ray photon densities, **acceleration far from the central engine**, extended jets and large-scale shocks

3. Fast acceleration $\tau_{acc} < \tau_{dis}$



de Oliveira et al. (2025)

AGN jet-star interactions

- Jet-star interactions mass loading of the jets (Komissarov 1994)
- Jet-star interactions suggested from X-ray observations. Knots in Cen A jet (Wykes et al. 2015, Snios et al. 2019)
- Winds of massive stars composition similar to CR mass composition (Thoudam et al. 2016, Wykes et al. 2015, Wykes et al. 2018)

Particle type	C/He = 0.1 $f(\times 10^{49} \text{ erg})$	C/He = 0.4 $f(\times 10^{49} \text{ erg})$
Proton	8.11	8.11
Helium	0.67	0.78
Carbon	2.11×10^{-2}	0.73×10^{-2}
Oxygen	2.94×10^{-2}	2.94×10^{-2}
Neon	4.41×10^{-3}	4.41×10^{-3}
Magnesium	6.03×10^{-3}	6.03×10^{-3}
Silicon	5.84×10^{-3}	5.84×10^{-3}
Iron	5.77×10^{-3}	5.77×10^{-3}

Wolf-Rayet (WR) stars

- Massive stars with weak hydrogen spectral lines
- Strong stellar winds – high loss rate of material
- Rich in helium, CNO and silicon



AGNs jets enriched by Wolf-Rayet stars

A. L. Müller, A. Araudo, A. Bakalová PoS(ICRC2025)343

- WR star embedded in an AGN jet
 - Stellar wind-jet interaction forms a **bow shock**
 - Kelvin-Helmholtz instabilities cause wind jet **material mixing**
 - Particles are **accelerated up to UHE**

Centaurus A case study

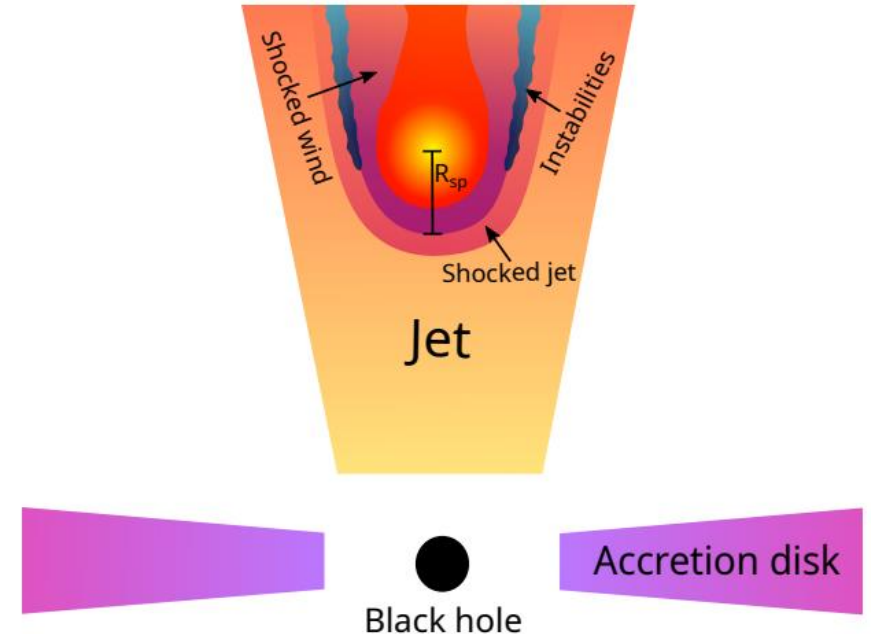
- Mass composition He, C, O, Ne, Mg, Si, Fe with fractions λ_A

$$\dot{M}_{WR} = 10^{-4} M_{\odot} \text{yr}^{-1} \quad L_{jet} = 10^{43} \text{erg s}^{-1}$$

$$\frac{d\dot{N}_A}{dE} = \kappa_A E^{-\gamma} \exp(-E/E_A^{max}) \quad E_A^{max} = Z_A E_p^{max}$$

$$\epsilon L_{jet} = \sum_A \int_{m_A c^2}^{E_A^{max}} E \frac{d\dot{N}_A}{dE} dE$$

ϵ ... fraction of jet power used for particle acceleration



AGNs jets enriched by Wolf-Rayet stars

- Comparing the predicted flux with Auger flux measurement

$$J_{\text{Auger}}(> 10^{19.3} \text{ eV}) = 8.4 \times 10^{37} \text{ erg Mpc}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Centaurus A case study

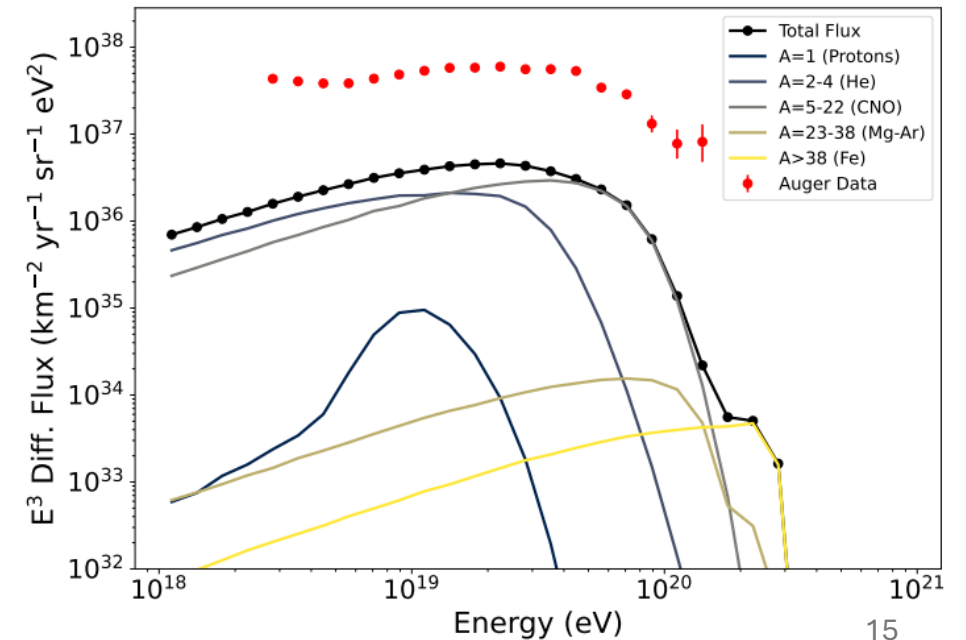
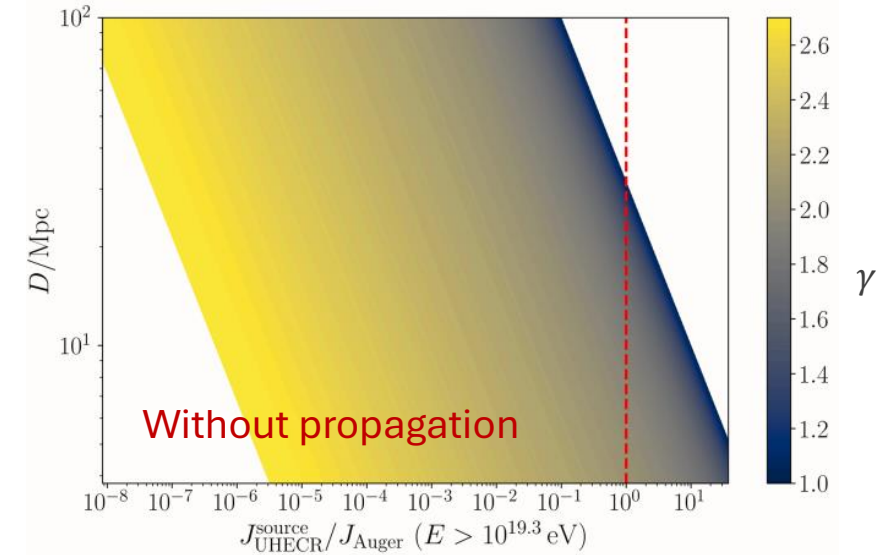
- $\gamma = 2.0$ (Fermi acceleration), $E_p^{max} = 6.15 \text{ EeV}$, $\epsilon = 0.3$

→ **Predicted flux on Earth between $\sim (6 - 60) \text{ EeV}$ lower by a factor of ~ 10 than measured one**

- Higher luminosity of Cen A in the past
- Additional sources contributing

→ **Underpredicts the flux at the highest energies**

- Additional source/higher rigidity cutoff/larger iron fraction



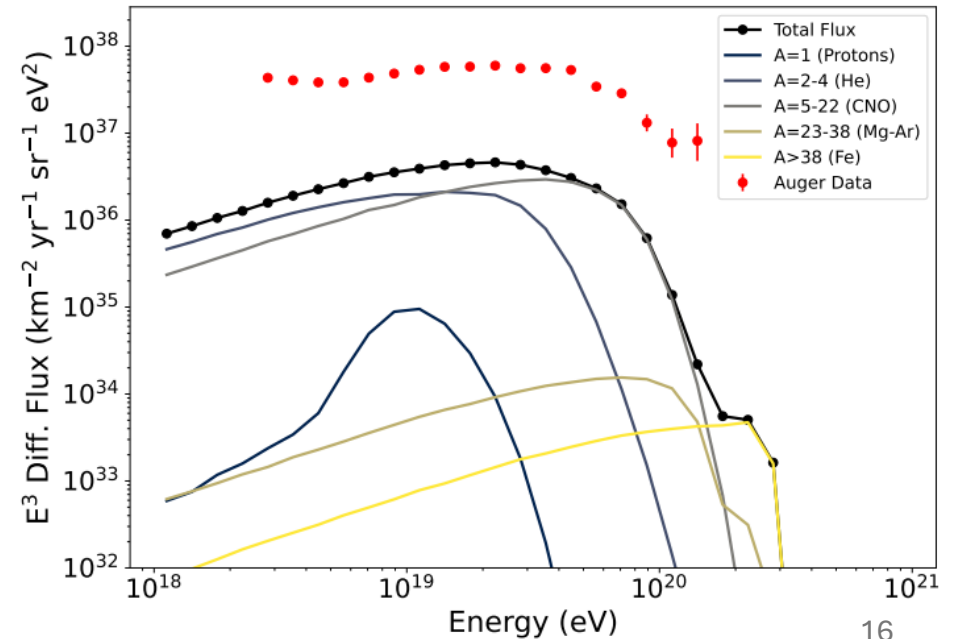
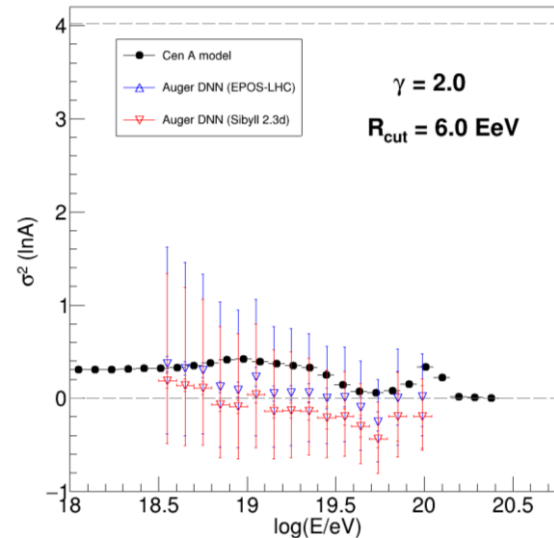
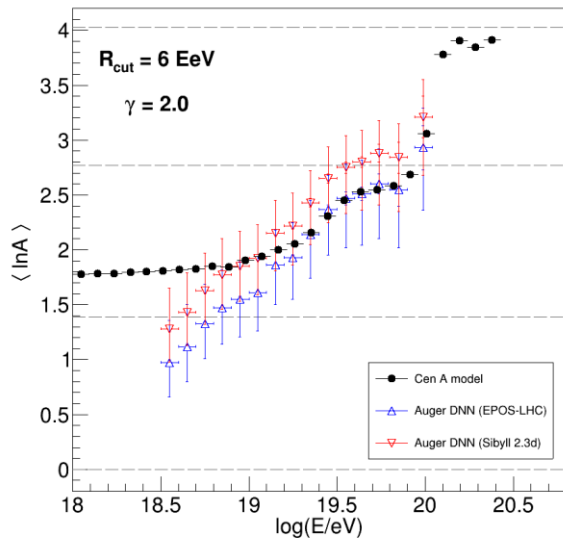
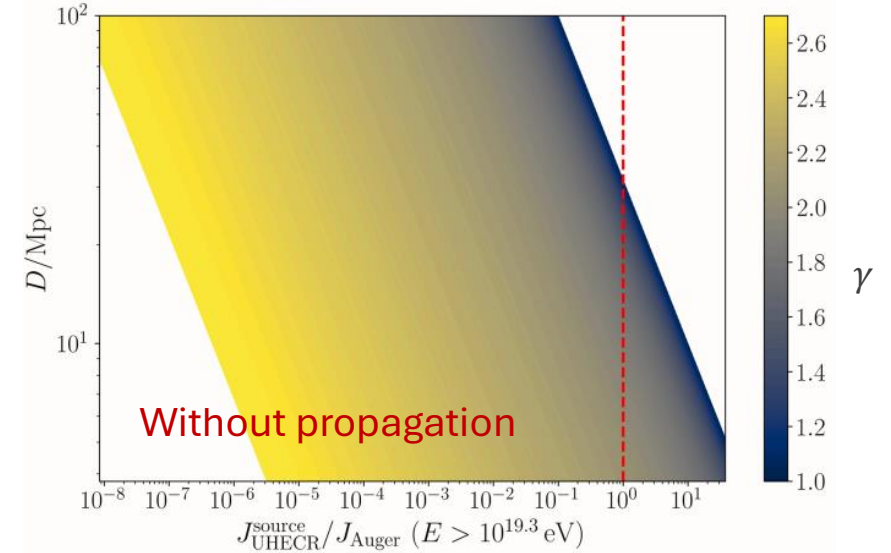
AGNs jets enriched by Wolf-Rayet stars

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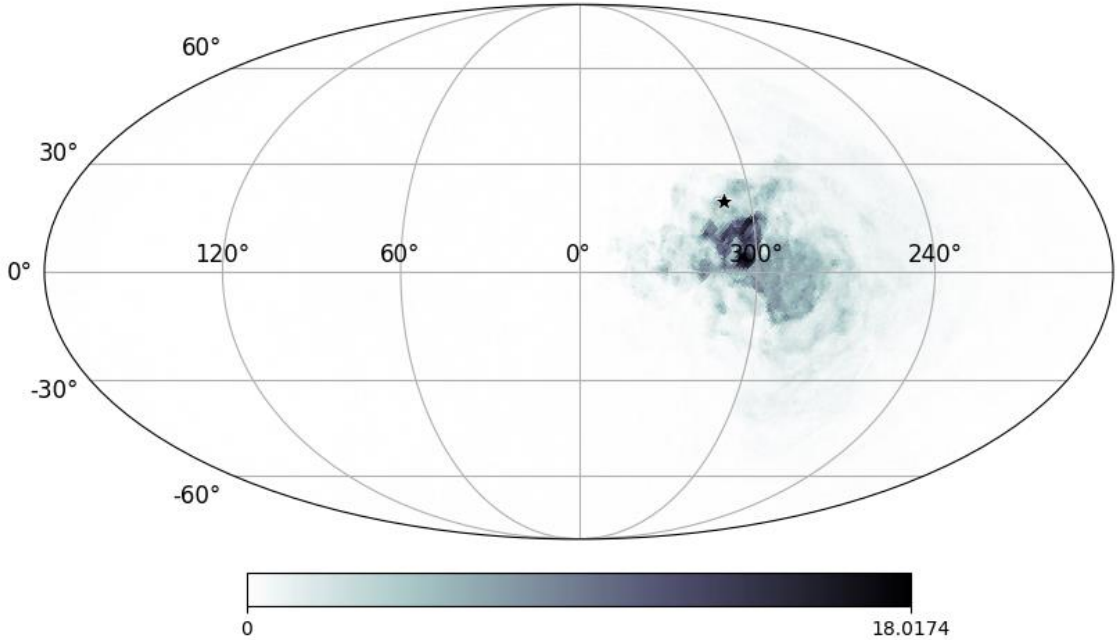
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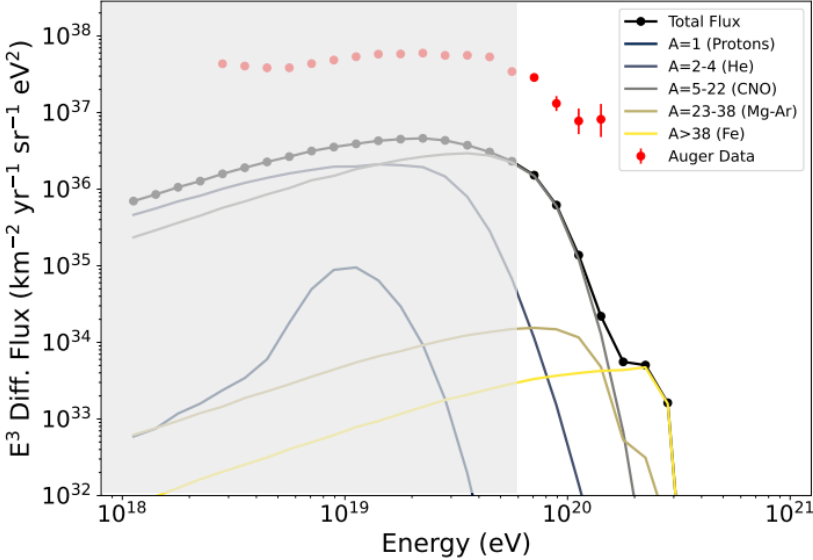
AGNs jets enriched by Wolf-Rayet stars

UF23base +Pl turb

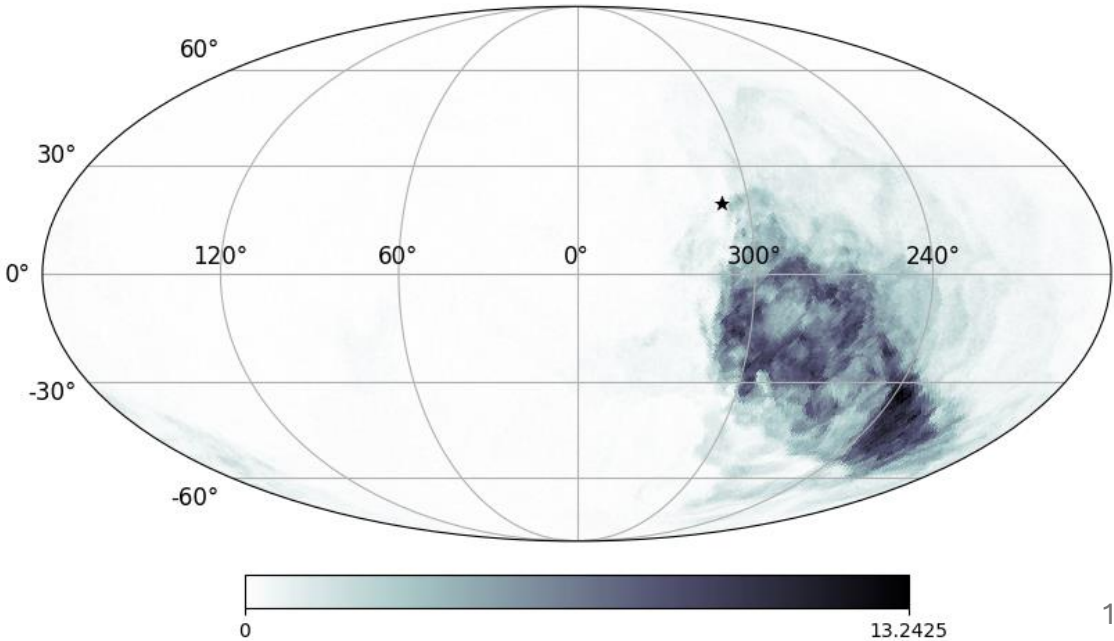


Predicted arrival directions above 40 EeV on Earth

$$\text{EGMF smearing } \delta_{\text{EGMF}} = \frac{10^\circ}{R/10 \text{ EV}}$$



KST24+Pl turb





Extreme Mass Composition Scenario and its Implications

A heavy metal scenario of UHECRs:

an extreme mass composition scenario

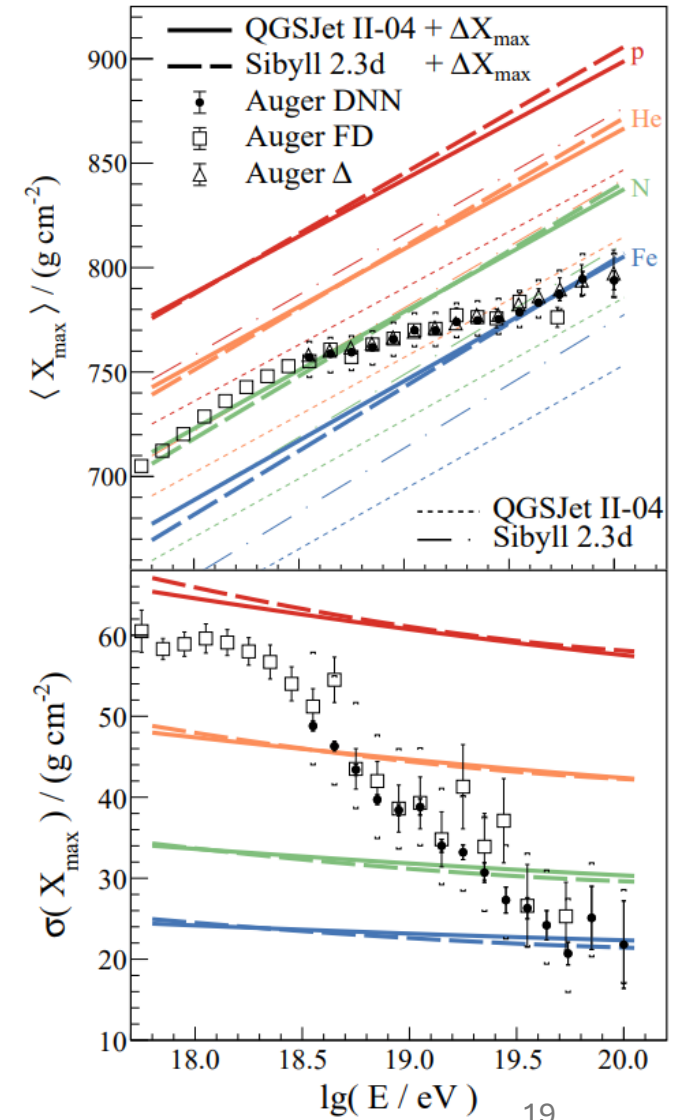
[Jakub Vicha et al 2025 ApJL 986 L34 \[arXiv:2504.11985\]](#)

- **Motivation:** Indications of X_{\max} scale being out of the range of HIM predictions *Auger PRD 109 (2024) 102001*
- **Assumptions:**
 1. Only freedom in model predictions is X_{\max} scale:
 $X_{\max} \rightarrow X_{\max} + \Delta X_{\max}$
 2. Pure Fe nuclei above $10^{19.6}$ eV

$$\begin{aligned} \text{Sibyll 2.3d: } \Delta X_{\max} &= 29 \pm 1_{-7}^{+12} \text{ g/cm}^2 \\ \text{QGSJet II-04: } \Delta X_{\max} &= 52 \pm 1_{-8}^{+11} \text{ g/cm}^2 \end{aligned}$$

Consequences

- ❖ Primary fraction fits from X_{\max} distributions
- ❖ Energy spectrum of individual primaries
- ❖ Hadronic interactions (muon puzzle reduced by half)
- ❖ Extragalactic dipole direction, UHECR deflections from sources

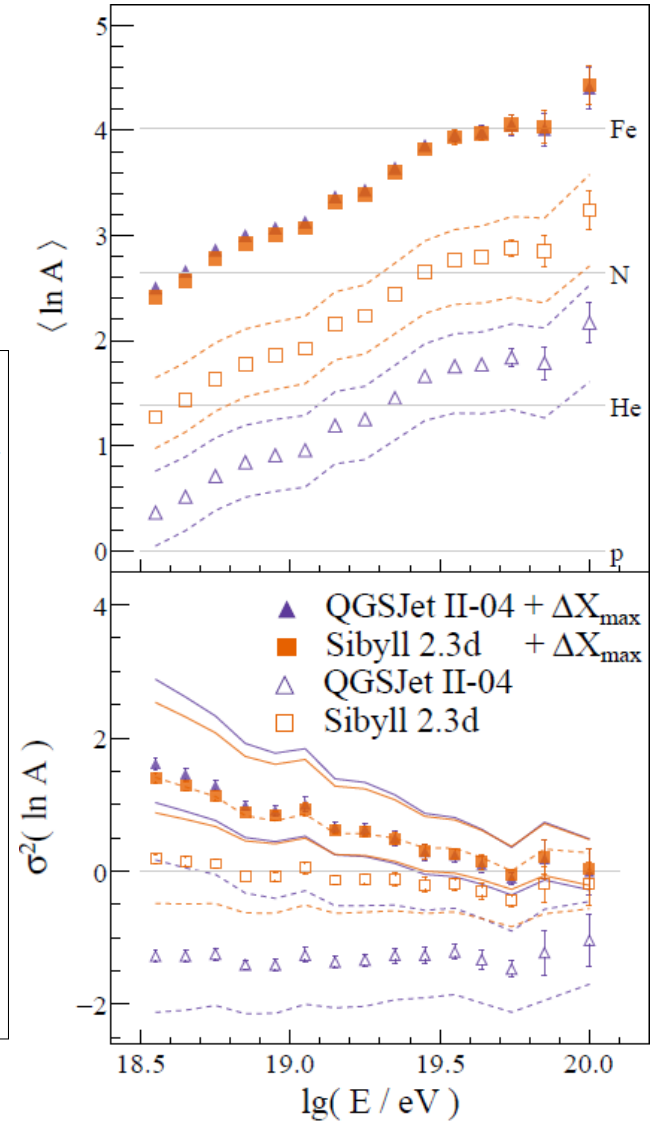
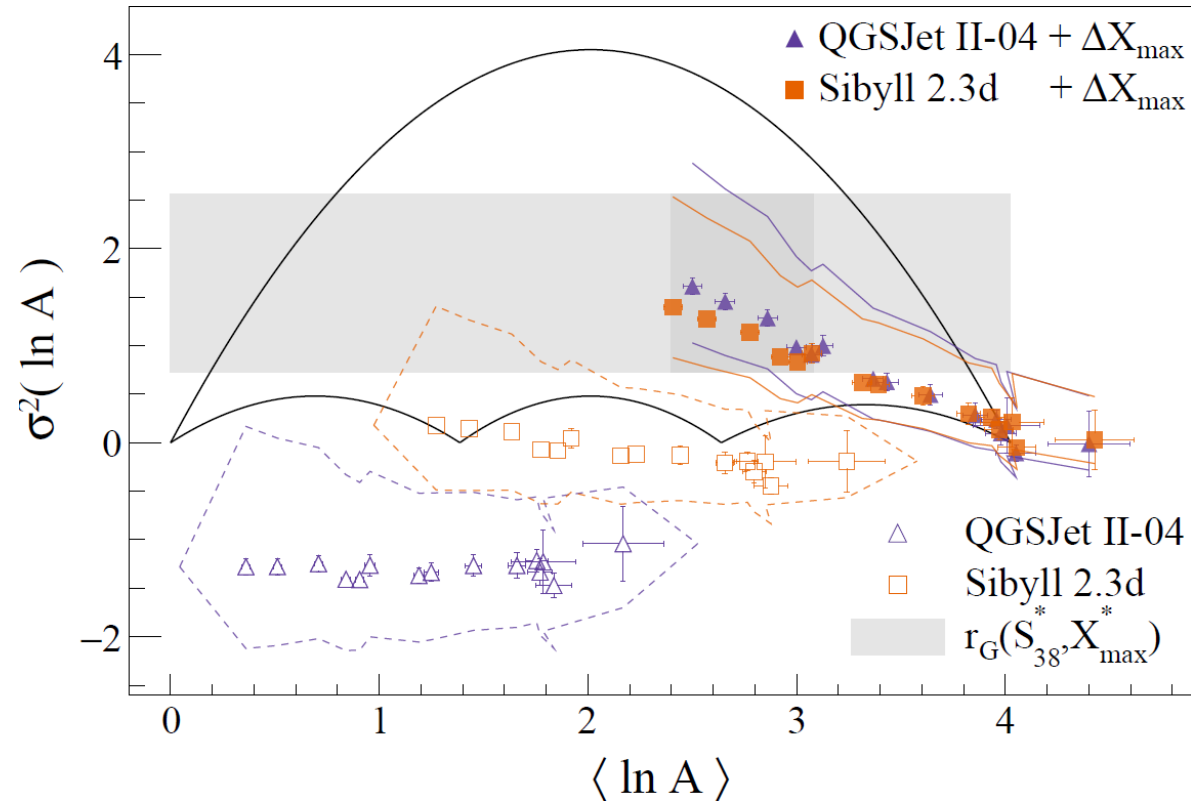
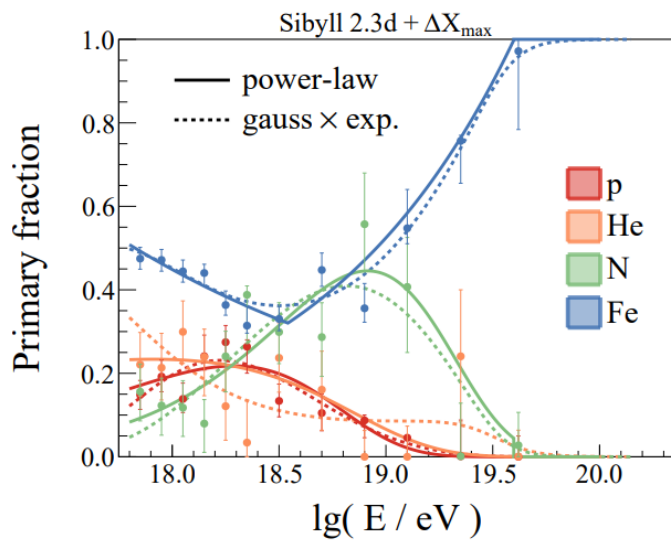


Interpretation of the mass composition with shifted X_{\max} scale

- Shifted X_{\max} scale

→ Gradual increase of $\langle \ln A \rangle$ with gradual decrease/flattening of $\sigma^2(\ln A)$

→ $\ln A$ moments within the allowed region of the *umbrella* plot



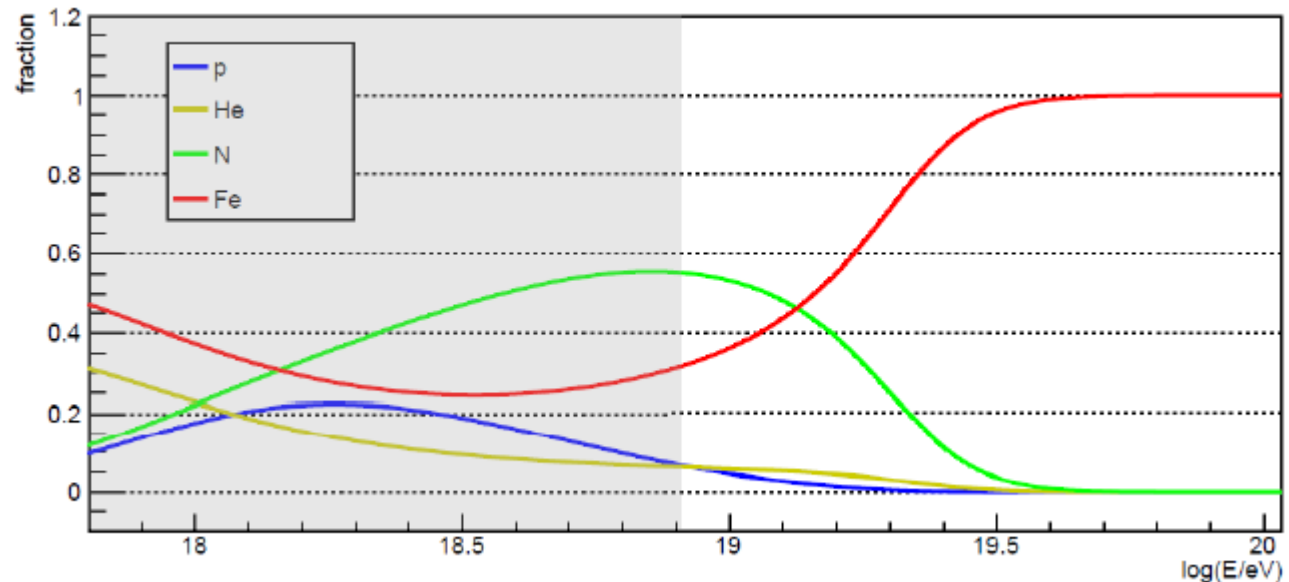
Dipole anisotropy within the HM scenario

Is it possible to obtain a dipole above 8 EeV consistent with Auger measurements with the mass composition of HM scenario?

Heavier mass composition \rightarrow isotropisation of CRs in the GMF, “larger” dipole amplitude of the CR flux needed before entering the Galaxy

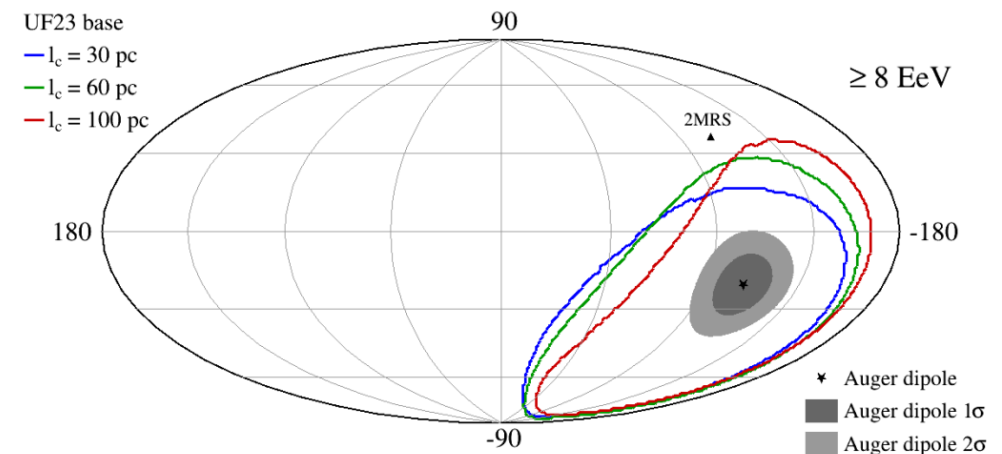
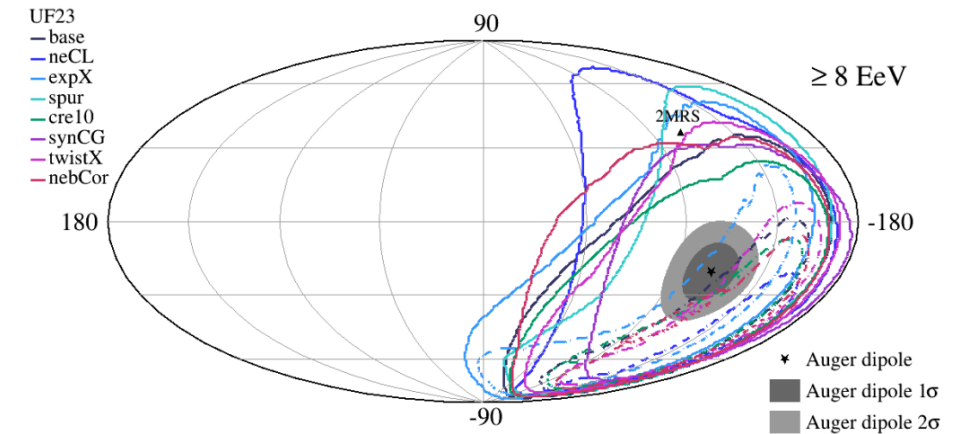
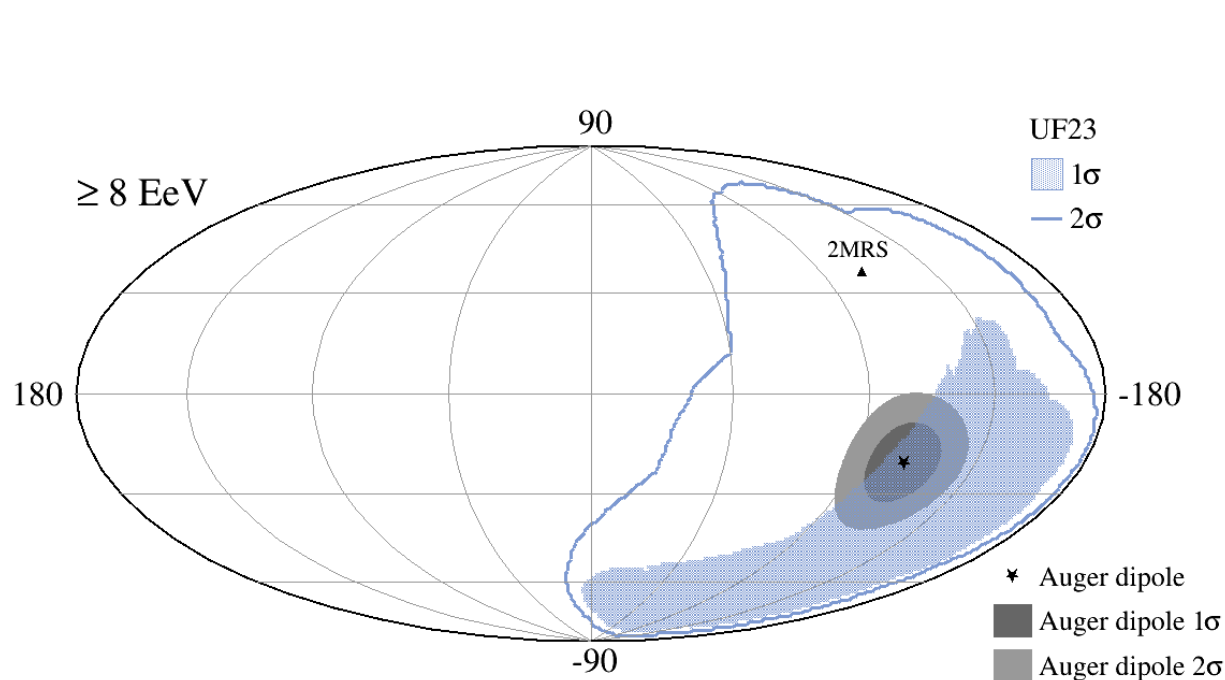
Model

- Ideal dipole distribution of extragalactic flux of cosmic rays above 8 EeV
- Sibyll 2.3d + ΔX_{\max}
- GMF: UF23 models + JF12Planck turbulent



Dipole anisotropy within the HM scenario

*Is it possible to obtain a dipole above 8 EeV consistent with Auger measurements with the mass composition of HM scenario? **YES***



Testing correlation of UHECR arrival directions with AGNs and SBGs under the HM scenario

A. Bakalová, A.L. Müller, J. Vicha PoS(UHECR2024)069, PoS(ICRC2025)179

- Modelling the flux maps from candidate AGNs and SBGs **with GMF**
- Assuming pure iron nuclei **on the sources** (not Earth) above 40 EeV
- Catalogue sources
 1. **Starburst galaxies** - selection from *Lunardini et al. 2019*, 43 SBGs within ~ 100 Mpc
 2. **Active galactic nuclei** - 55 AGNs within 250 Mpc from *Fermi-LAT 4LAC* catalogue

Extragalactic propagation:

1D CRPropa simulations
from candidate sources



Galactic propagation:

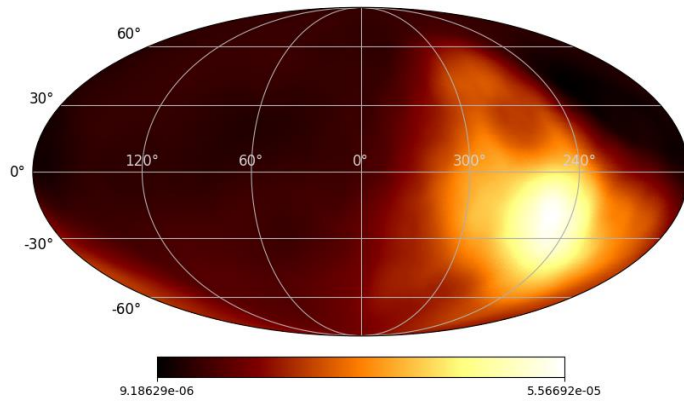
Extragalactic directions
smeared with $\delta_{EGMF}(R)$
→ GMF lenses



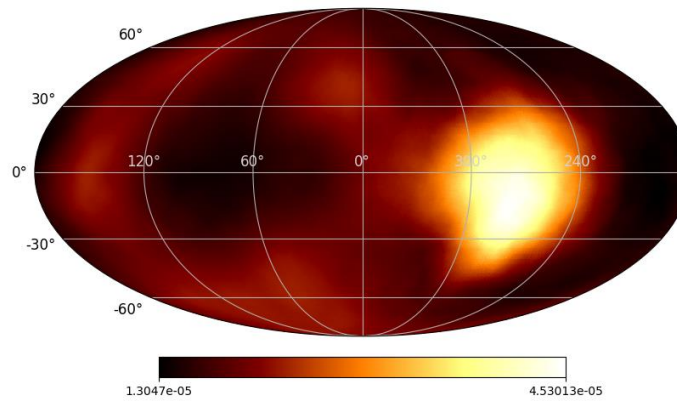
Model flux maps:

Particles reweighted
by source flux and
energy spectrum

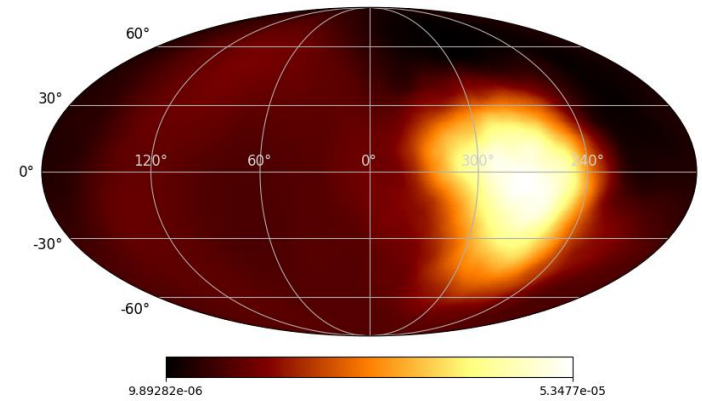
Flux maps from catalogue sources



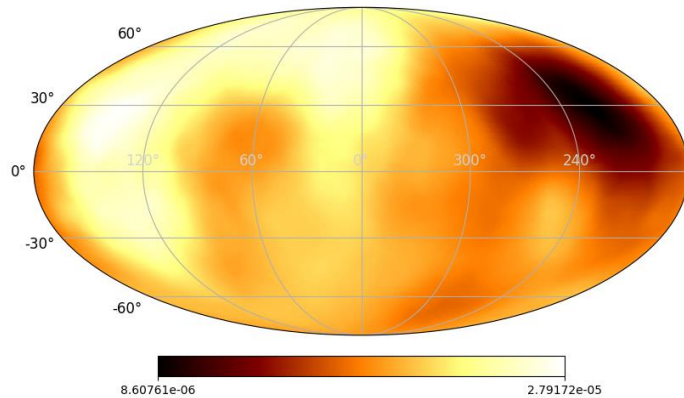
KST24+Pl turb, AGNs



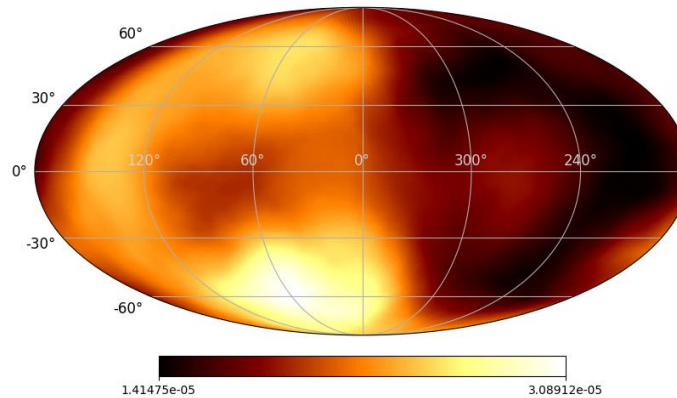
UF23base+Pl turb, AGNs



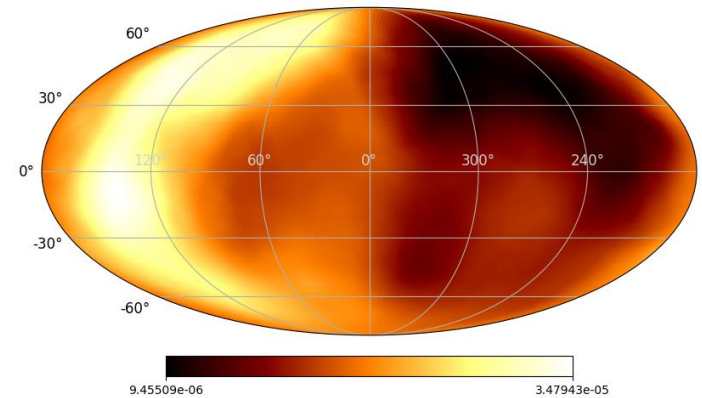
JF12Planck, AGNs



KST24+Pl turb, SBGs



UF23base+Pl turb, SBGs



JF12Planck, SBGs

Correlation of arrival directions above 40 EeV

- Compare the model scenarios with the arrival directions of cosmic rays above 40 EeV (*Auger ApJ 2022*)
- Models consist of an isotropic background and a contribution from the catalogue with a fraction f_{cat} and a blurring angle δ_{EGMF}
- Likelihood ratio test with isotropy as null hypothesis: $TS = -2(\ln\mathcal{L}_{\text{iso}} - \ln\mathcal{L}_{\text{model}})$

AGNs	GMF	TS_{max}	$\delta_0[^\circ]$	$f_{\text{cat}}[\%]$
	KST24	4.32	0.4	10
	UF23base	7.35	0.6	25
	JF12Planck	7.62	1.0	15

→ **AGN model**: modest preference over isotropy with $TS_{\text{MAX}} = 7.62$

→ **SBG model**: the TS values are consistently negative

Current work with M. Benedová: same analysis with Auger combined fit mass composition, stay tuned!

Summary

- GMF largely influences the trajectories of UHECRs
 - Needs to be accounted for when searching for their sources
 - UHECR source interpretation strongly depends on GMF uncertainties
- **WR stars in AGN jets**
 - Possible scenario of intermediate-heavy elements in UHECRs
 - Predicted flux on Earth between $\sim (6-60)$ EeV lower by a factor of ~ 10 than measured one (Higher activity in the past? Additional sources?)
- **Heavy metal scenario of UHECRs**
 - Extreme mass composition scenario
 - Consistent interpretation of Auger data, reduces the muon puzzle by half
 - GMF isotropises the flux, no strong correlation found with nearby AGNs or SBGs

THANK YOU FOR YOUR ATTENTION!