The Imprint of Large Scale Structure on the Ultra-High-Energy Cosmic Ray Sky

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Groundbreaking discovery by Pierre Auger Observatory

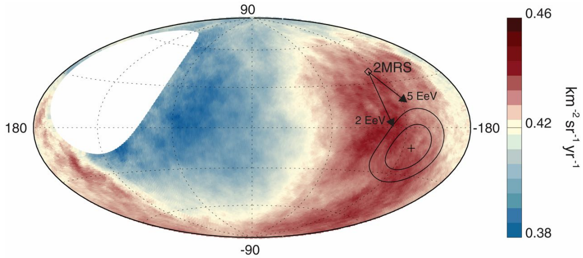


Figure: Dipole anisotropy >8 EeV (Science 2017)

- $6.6^{+1.2}_{-0.8}$ percent dipole amplitude
- 6σ significance in $d_{\perp}$ (ApJ 2020)

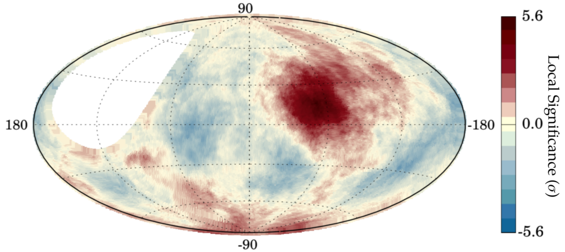
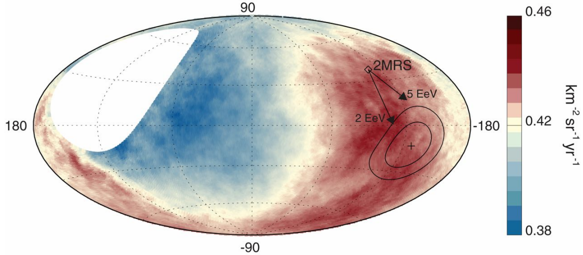


Figure: Hot spot >38 EeV (Auger PoS(ICRC2019)206)

- 5.6σ local Li-Ma significance
- 3.9σ post-trial significance

Motivation of this research



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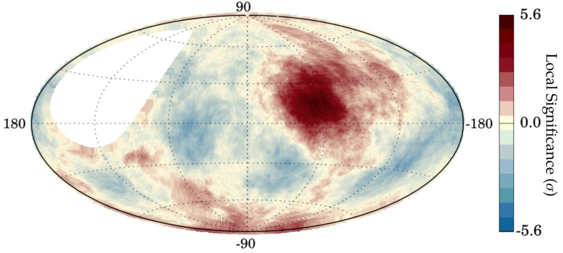

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Motivation:

Can we extract information from the observed anisotropies?

Origin, composition, hadronic interaction models, etc

Large-Scale Structure (LSS)

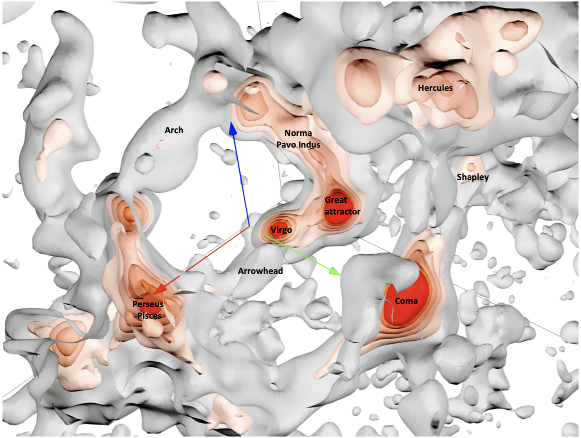


Figure: 3D visualization of the density field of the local universe. Credit: Daniel Pomarède

- We assume UHECR sources (many) follow the large-scale structure
  (Globus, Piran, Hoffman, Carlesi, & Pomarède 2019)
- LSS density field reconstructed from the *CosmicFlows-2* catalog of peculiar velocities
  (Tully et al 2014, Hoffman et al 2018)

Energy loss mechanisms

- GZK effect (Greisen 1966, Zatsepin and Kuzmin 1966)
  $\gamma_{\rm CMB} + p \to \Delta^+ \to p + \pi^0$
  $\gamma_{\rm CMB} + p \to \Delta^+ \to n + \pi^+$
- photodisintegration, pair production etc.

- CRPropa propagation simulation:
  The next paper is a key upgrade to the DGF model.

- "d90 treatment":
  Contribution of flux from distance z: $\exp\left[-\ln(10)\, z/d_{90}(A, E)\right]$
  when diffusion is negligible

Diffusion in the EGMF

- Diffusion of cosmic rays in Extragalactic Magnetic Field (EGMF) **may** limit the size of the cosmic-ray observable Universe

- " Sharp Horizon treatment": (Globus, Piran 2017)

  Defined horizon H (Mpc):
  $H(E, Z, B_{\rm EG}, \lambda_{\rm EG}) = \min(\sqrt{d_{\rm diff}\chi_{\rm loss}}, \chi_{\rm loss})$

  Contribution of flux from distance z:
  1 with $z < H$, 0 with $z \geq H$

- $B_{\rm EG} = 0.1$–10 nG, $\lambda_{\rm EG} = 0.08$–0.5 Mpc
  $D_{\rm EG}(B_{\rm EG}, \lambda_{\rm EG}, E/Z)$

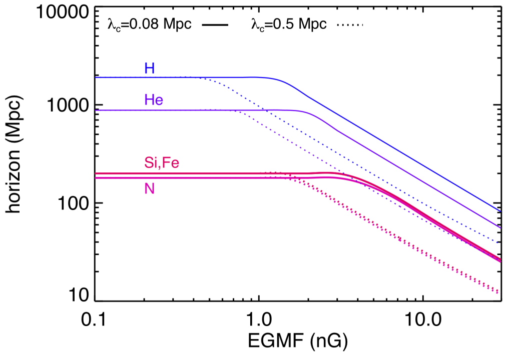
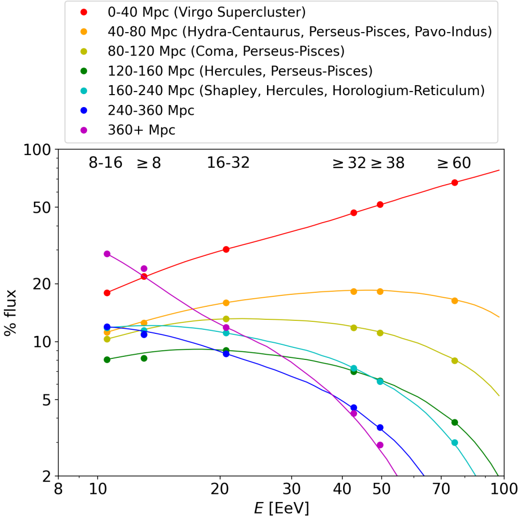
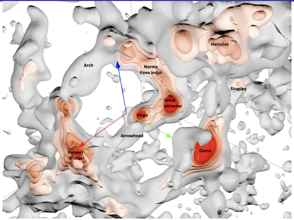


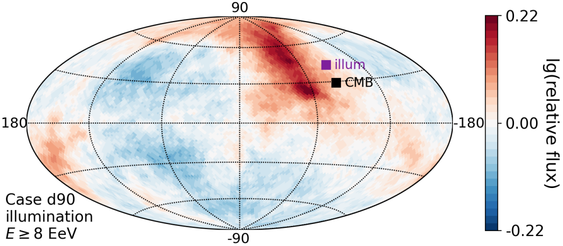
Figure: UHECR horizon of different atomic nuclei of 5 EV rigidity ($R \equiv E/Z$)

Shell contribution

d90 treatment

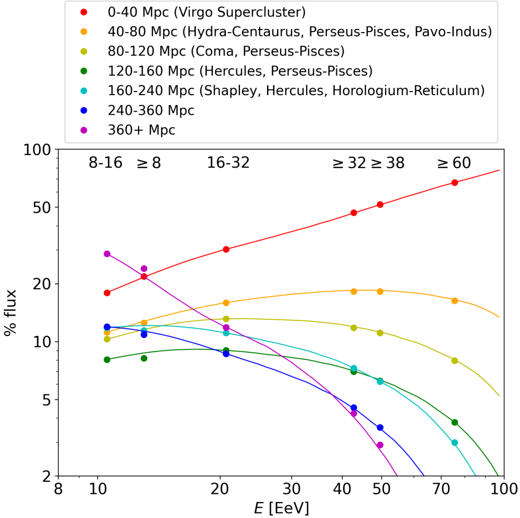




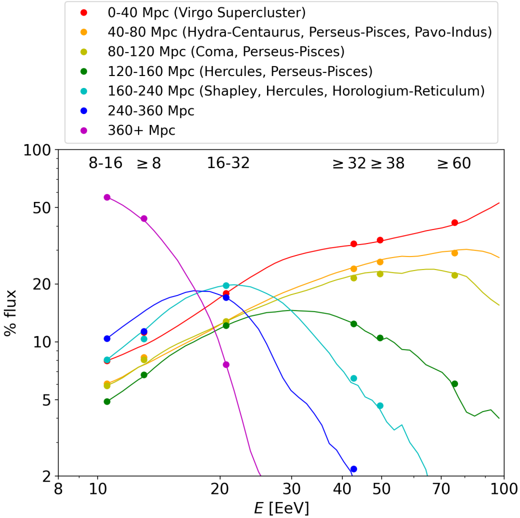


illumination map: the cosmic ray flux at the surface of our Galaxy

d90 treatment



sharp horizon treatment



Galactic Magnetic Field

- Cosmic rays are deflected by the Galactic Magnetic Field (GMF)
- GMF model adopted: JF12
  (Jansson and Farrar 2012)
  1.8 billion simulated trajectories
  (Farrar and Sutherland 2017)
- GMF coherence length $\lambda_{\rm G} = 30$–100 pc

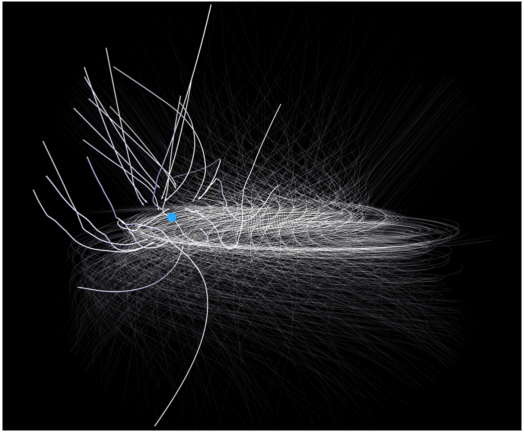
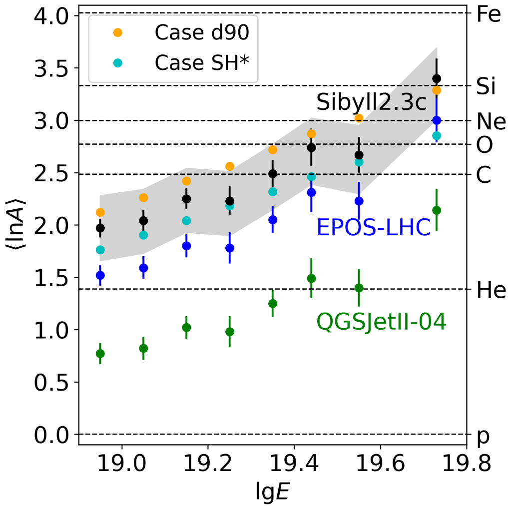
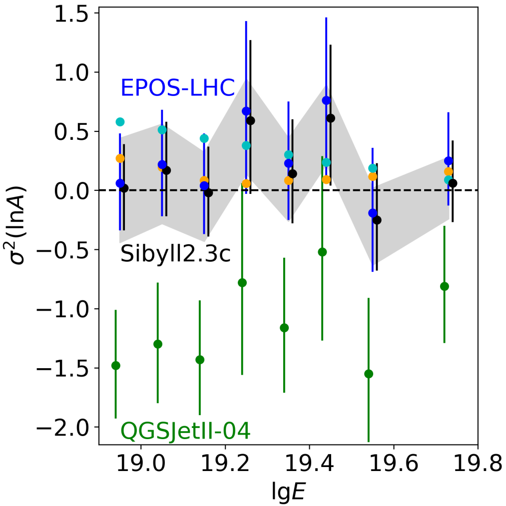


Figure: Trajectories of isotropically arriving CRs in GMF. $R = 3$EV. $\lambda_{\rm G} = 100$ pc. (Farrar et al. 2015)

Uncertainty in composition





Fitting the observations

We fit to the following observations:

i) 9 **dipole components** d_x, d_y, d_z in the three energy bins: 8-16, 16-32 and ≥ 32 EeV (Auger ApJ 2020), denoted "dipole" below;

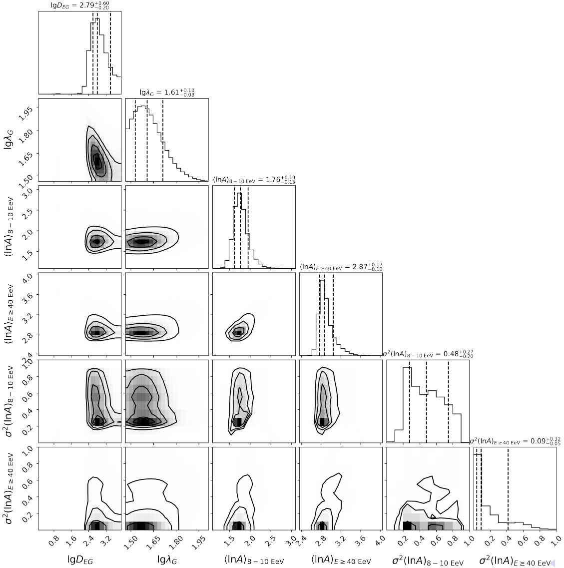
ii) The **arrival directions of 1288 events above 38 EeV** observed by Auger, reconstructed from the Li-Ma sky map (ICRC2019-206), denoted "events" below;

iii) The $\langle \ln A \rangle$ and $\sigma^2(\ln A)$ inferred by Auger from **Xmax measurements** in the 8 energy levels ≥ 8 EeV (ICRC2019-408), for each hadronic interaction model (HIM).

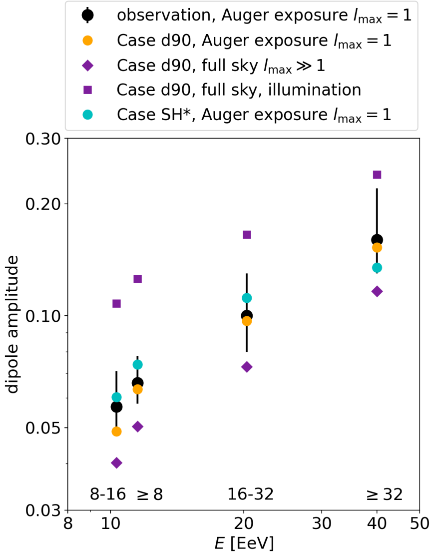
We have a set of 6 model parameters Θ: extragalactic diffusion $D_{\mathrm{EG,5EV}}$, coherence of the ramdom field of the GMF λ_{G}, and 4 parameters of the arrival composition Ω.

$$\begin{aligned} \ln L \equiv & \ln L(\mathrm{dipole} \mid \Theta; \mathrm{source}) + \ln L(\mathrm{events} \mid \Theta; \mathrm{source}) \\ & + \ln L(\langle \ln A \rangle \mid \Omega; \mathrm{HIM}) + \ln L(\sigma^2(\ln A) \mid \Omega; \mathrm{HIM}) \end{aligned} \tag{1}$$

Parameters are generally well-constrained

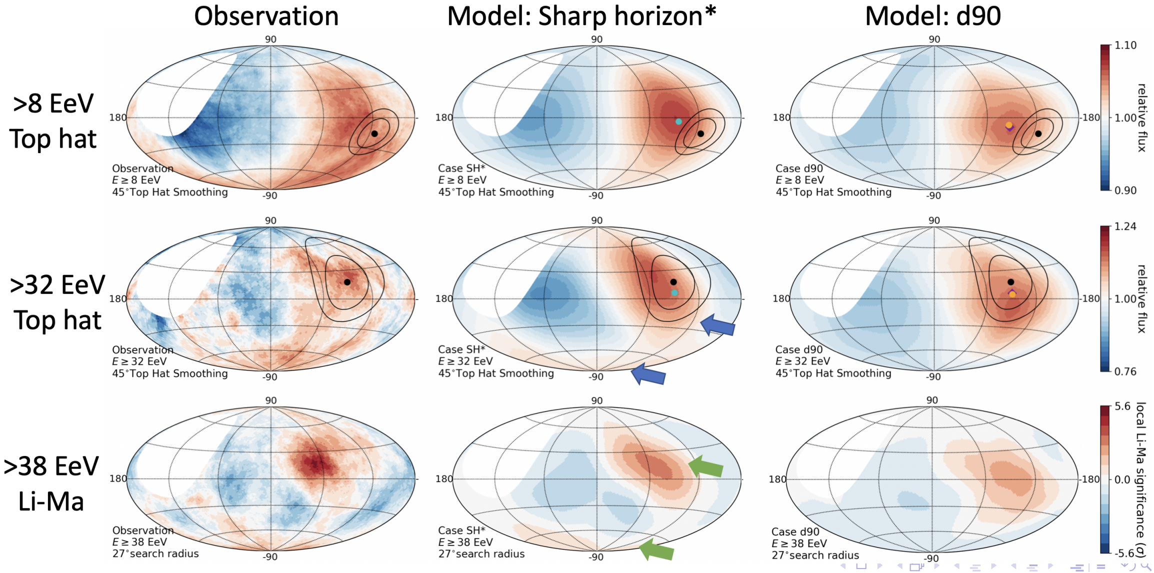


Dipole amplitude

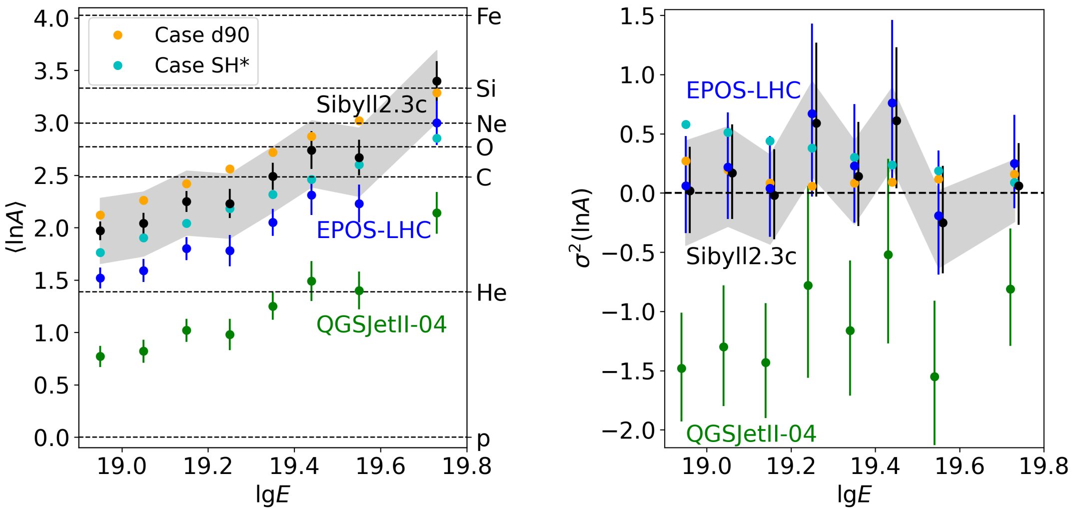


Excellent agreement on dipole amplitude between model (orange and cyan dots) and data (black)

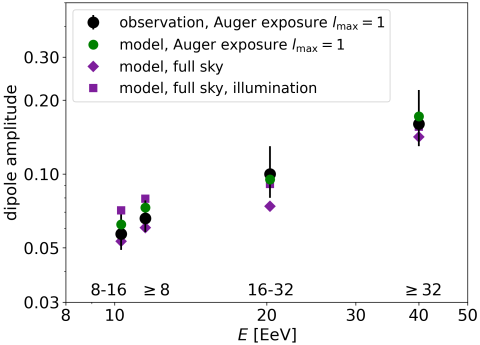
Anisotropies with best-fit parameters

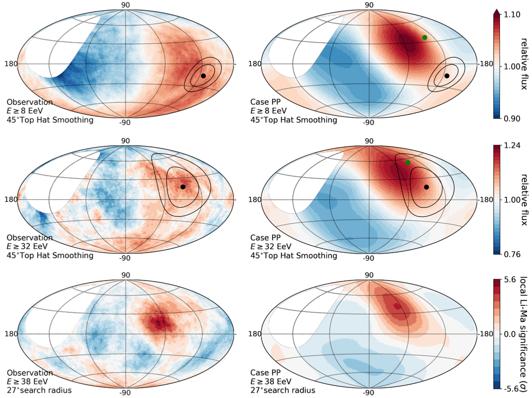


Best-fit compositions

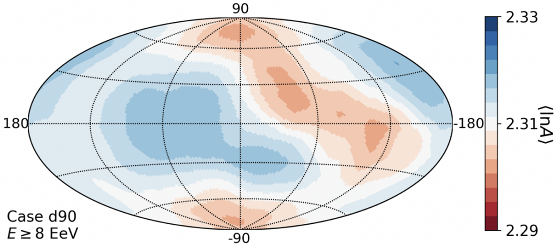


Pure proton rejected





New (not included in the ApJL paper)



Sky map of cosmic ray composition of the d90 model for E ≥ 8 EeV, smoothed by 30 degree (same as right plot)

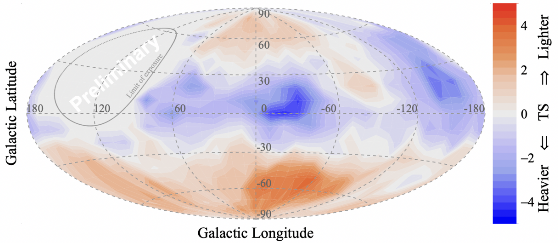
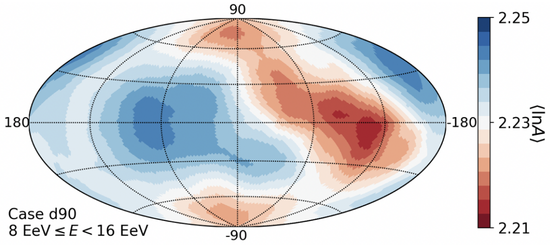
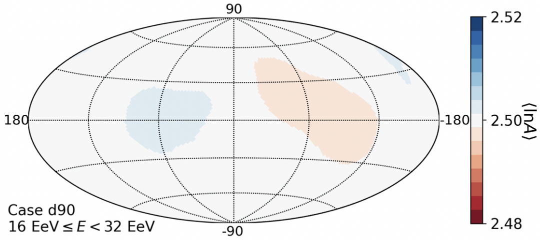


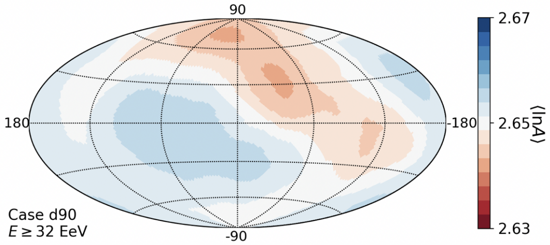
Figure 8: Sky map of comic ray composition for $E \geq 10^{18.7}$ eV

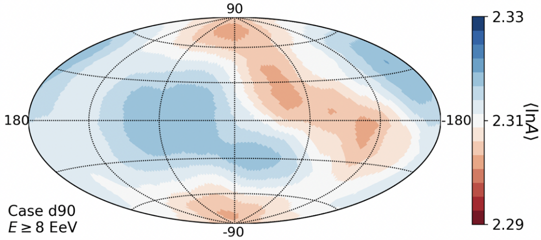
Auger ICRC2021_321

Composition anisotropy









Summary

- Assumption that UHECR injection follows the large scale matter distribution gives a **good accounting of Auger dipole anisotropy measurements** above 8 EeV.
  – *Rather than few prominent sources, there may be many weak ones.*

- Auger hotspot and the excess near Galactic south pole may not require individual source, whereas TA hotspot is more likely the result of a nearby source.

- If sources follow LSS, pure proton composition can be ruled out — on anisotropy grounds alone.

Future work (new paper)

- Have more accurate treatment of attenuation with CRPropa simulation

  Directly fit source spectrum and composition

  Investigate source density.

  Update compositional anisotropy, directly compare to Auger data

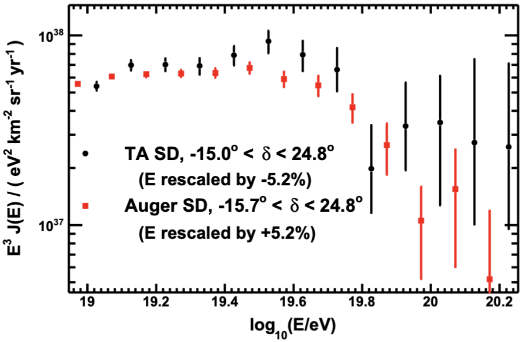
- Maybe possible to subtract inhomogeneous "continuum" background to better reveal individual sources.

  Can Auger hotspot arise from large scale structure or need individual source? What is the cause of TA hotspot?

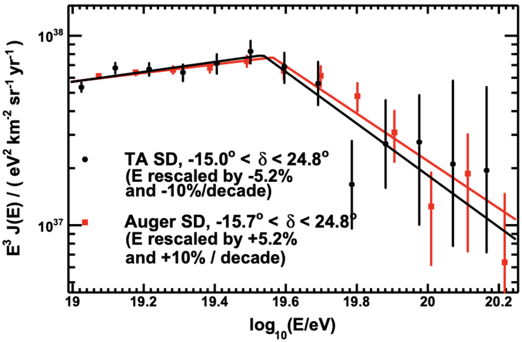
- Potential new data release: Fit to the arrival directions of events (binned by energy) instead of fitting to the dipole. CosmicFlows3 has the south pole wall.

Back-up slides

TA hotspot

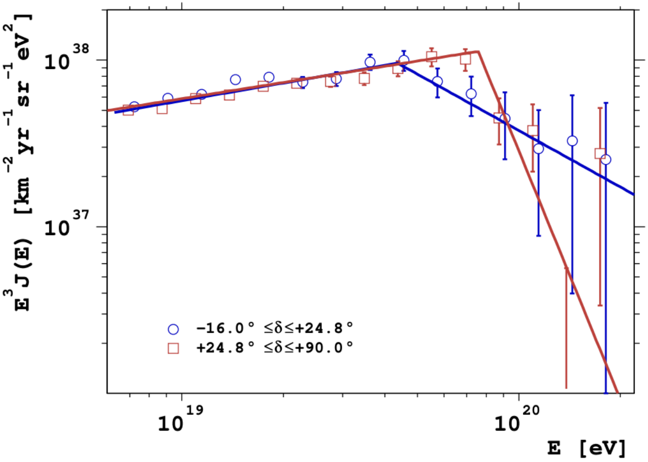


TA SD, -15.0° < δ < 24.8°
(E rescaled by -5.2%)
Auger SD, -15.7° < δ < 24.8°
(E rescaled by +5.2%)
E³ J(E) / (eV² km⁻² sr⁻¹ yr⁻¹)
log10(E/eV)



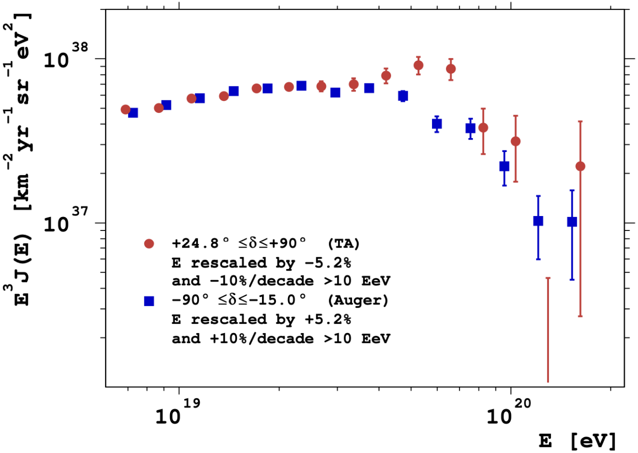
TA SD, -15.0° < δ < 24.8°
(E rescaled by -5.2%
and -10%/decade)
Auger SD, -15.7° < δ < 24.8°
(E rescaled by +5.2%
and +10% / decade)
E³ J(E) / (eV² km⁻² sr⁻¹ yr⁻¹)
log10(E/eV)

TA hotspot



$E^3 J(E)$ [km^{-2} yr^{-1} sr^{-1} eV^2]
10^{38}
10^{37}
10^{19}
10^{20}
E [eV]
$-16.0° \leq \delta \leq +24.8°$
$+24.8° \leq \delta \leq +90.0°$

TA hotspot



10^{38}
10^{37}
$E^3 J(E)$ [km^{-2} yr^{-1} sr^{-1} eV^2]
+24.8° ≤δ≤+90° (TA)
E rescaled by -5.2%
and -10%/decade >10 EeV
-90° ≤δ≤-15.0° (Auger)
E rescaled by +5.2%
and +10%/decade >10 EeV
10^{19}
10^{20}
E [eV]

Discussions: Degeneracy of EGMF parameters

◇ Notes:

- Diffusion coefficient is what matters in propagation in EGMF.

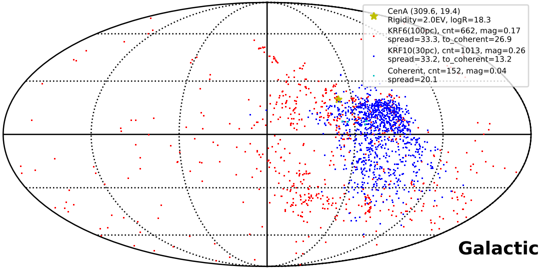
$$D \approx 0.03 \left(\frac{\lambda_{\mathrm{Mpc}}^2 E_{\mathrm{EeV}}}{Z B_{\mathrm{nG}}} \right)^{\frac{1}{3}} + 0.5 \left(\frac{E_{\mathrm{EeV}}}{Z B_{\mathrm{nG}} \lambda_{\mathrm{Mpc}}^{0.5}} \right)^2 \mathrm{Mpc}^2 \mathrm{Myr}^{-1}$$

(Globus, Allard & Parizot 2008)

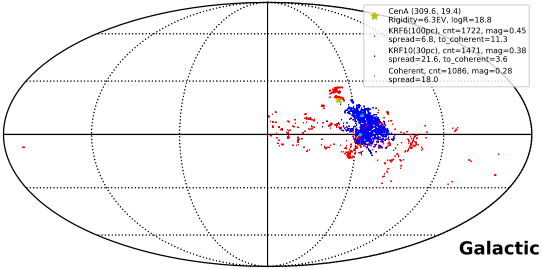
The second term dominates. $D \propto B_{\mathrm{nG}}^{-2} \lambda_{\mathrm{Mpc}}^{-1}$. Assume $\lambda_{\mathrm{Mpc}} = 0.2$ for the rest of the talk.

CR rigidity and GMF coherence length

Blue: $\lambda_G = 30$ pc. Red: $\lambda_G = 100$ pc. Parameter range considered: $L = 30$–100 pc



(a) $R \equiv E/Z = 2$ EV

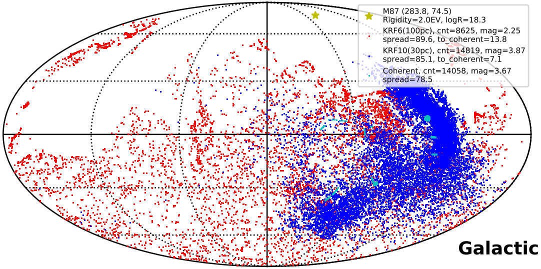


(b) $R \equiv E/Z = 6.3$ EV

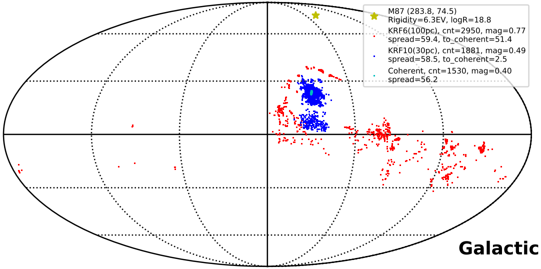
Figure: Trajectories starting from Cen A direction. (Farrar and Sutherland 2017)

CR rigidity and GMF coherence length

Blue: $\lambda_{\mathrm{G}} = 30$ pc. Red: $\lambda_{\mathrm{G}} = 100$ pc. Parameter range considered: $L = 30$–100 pc



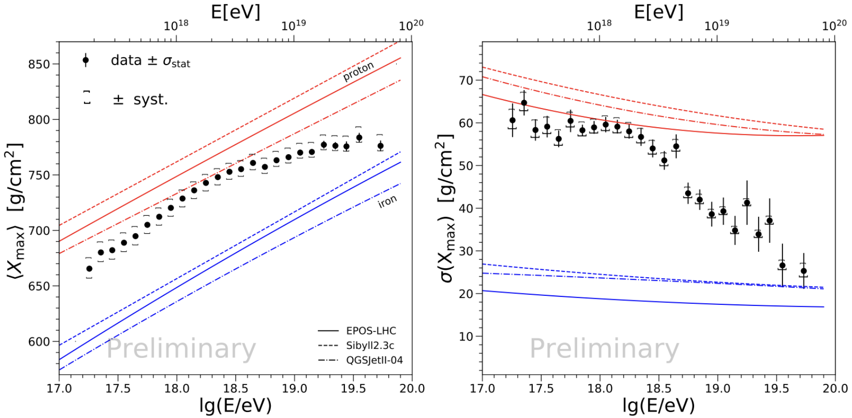
(a) $R \equiv E/Z = 2$ EV



(b) $R \equiv E/Z = 6.3$ EV

Figure: Trajectories starting from M87 direction. (Farrar and Sutherland 2017)

We aren't sure about the composition of UHECRs



- In the Heitler model of extensive air showers, the depth of shower maximum $\langle X_{max} \rangle$ is a linear function of the logarithm of the shower energy per nucleon: $\langle X_{max} \rangle = X_0 + D \log_{10} \left(\frac{E}{E_0 A} \right)$

Composition of UHECRs

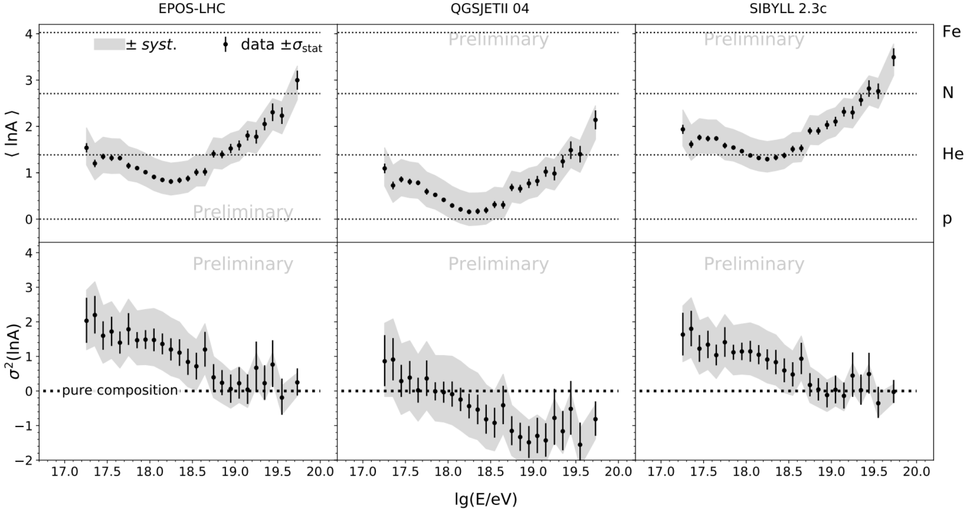


Figure: Auger ICRC2019