

On the Origin of the Ultra-High Energy Cosmic Ray Anisotropy

Chen Ding^{1*} Noémie Globus^{1,2†} Glennys R. Farrar¹

¹New York University

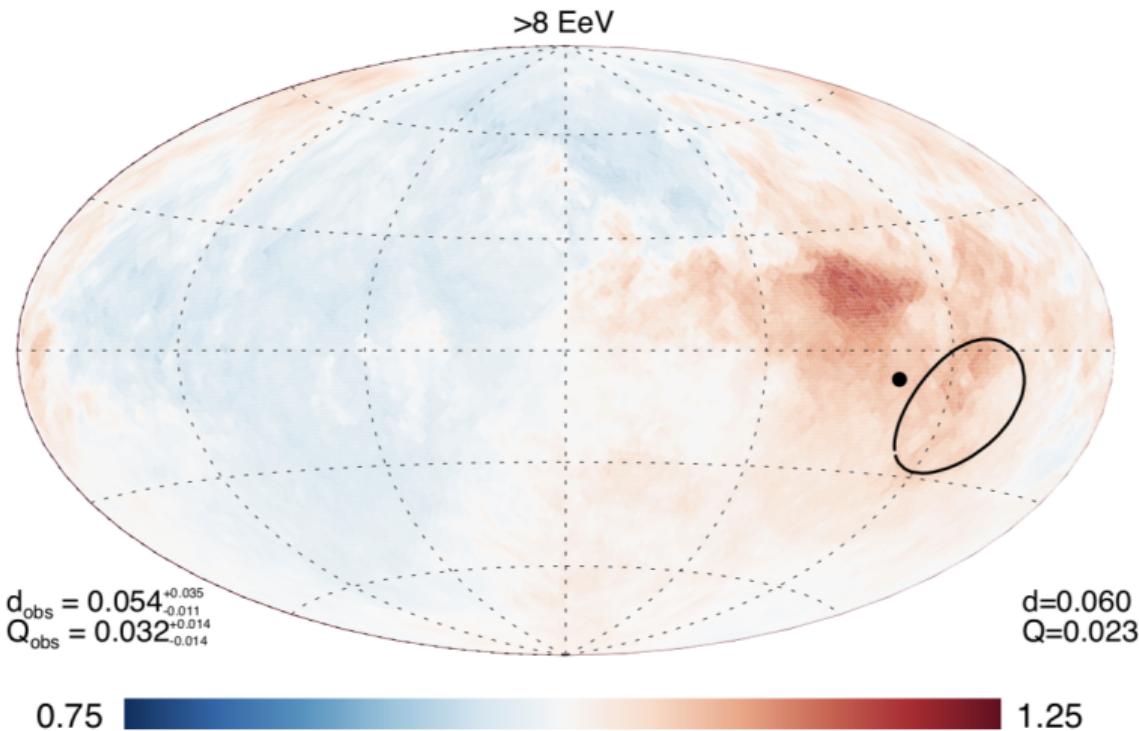
²Flatiron Institute

*: Speaker

†: Lead author of PoS(ICRC2019)243

ICRC2019, July 30, 2019

Bottom line: a successful model of UHECR anisotropy



- dipole only
 $d_{\text{obs}} = 6.5^{+1.3\%}_{-0.9\%}$
 $d_{\text{model}} = 6.6\%$
- dipole and quadrupole
 $d_{\text{obs}} = 5.4^{+3.5\%}_{-1.1\%}$
 $d_{\text{model}} = 6.0\%$
 $Q_{\text{obs}} = 0.032 \pm 0.014$
 $Q_{\text{model}} = 0.023$

Ingredients: UHECR horizons

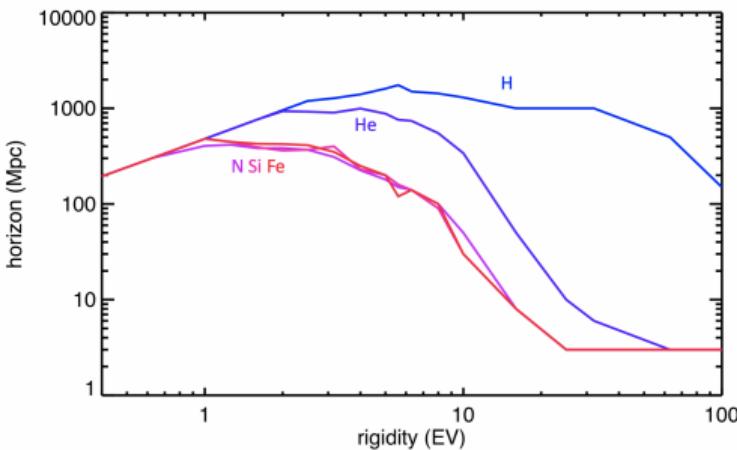
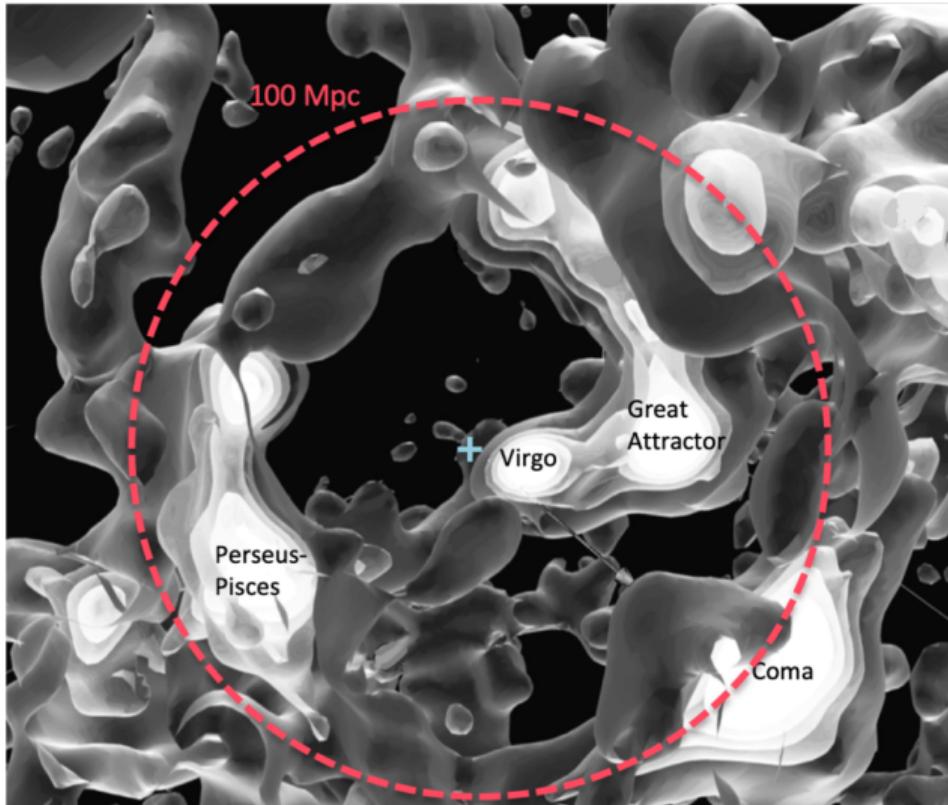


Figure: UHECR horizon in extragalactic magnetic field of 0.6 nG with 0.2 Mpc coherence length.

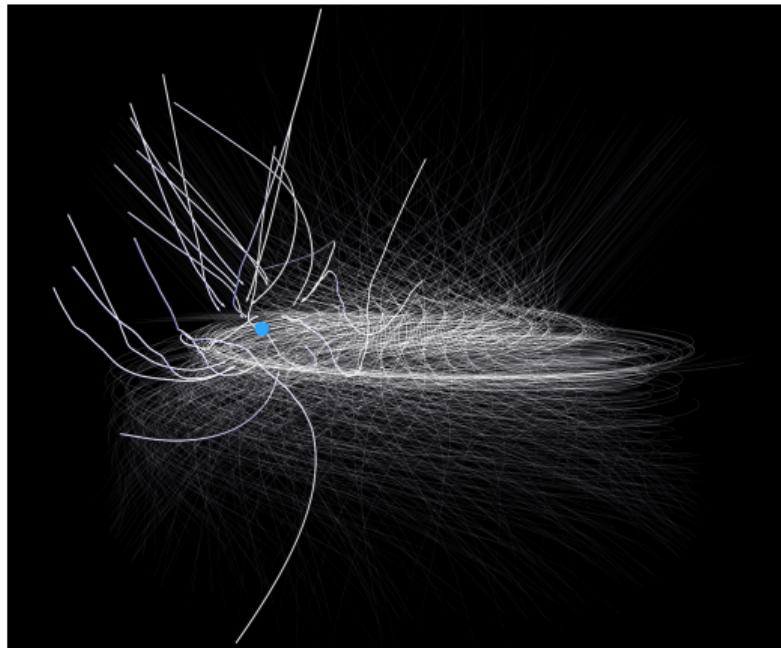
- UHECR horizons H : maximum linear distance (not propagation distance) between source and the Earth.
$$H(E, Z, B_{\text{nG}}, \lambda_{\text{Mpc}}) = \min(\sqrt{d_{\text{diff}} d_{\text{loss}}}, d_{\text{loss}})$$
(Globus, Piran 2017)
- Rigidity $R = E/Z$
Low R : H is limited by Hubble time
High R : H is limited by energy loss distance
- EGMF parameter range considered:
 $B = 0.1\text{--}30 \text{ nG}$
 $\lambda = 0.08\text{--}0.5 \text{ Mpc}$

Ingredients: Large-Scale Structure (LSS)



- 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)

Ingredients: Galactic Magnetic Field (GMF)



- Jansson and Farrar 2012 (JF12)
- 1.8 billion backtracking trajectories (Farrar and Sutherland 2017)
- Simulated additional trajectories in lower rigidity down to $\log_{10}[R(V)] = 17.4$ in 0.1 binning

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

Ingredients: GMF coherence length and rigidity

Blue: $L = 30$ pc. Red: $L = 100$ pc. Parameter range considered: $L = 30\text{--}100$ pc

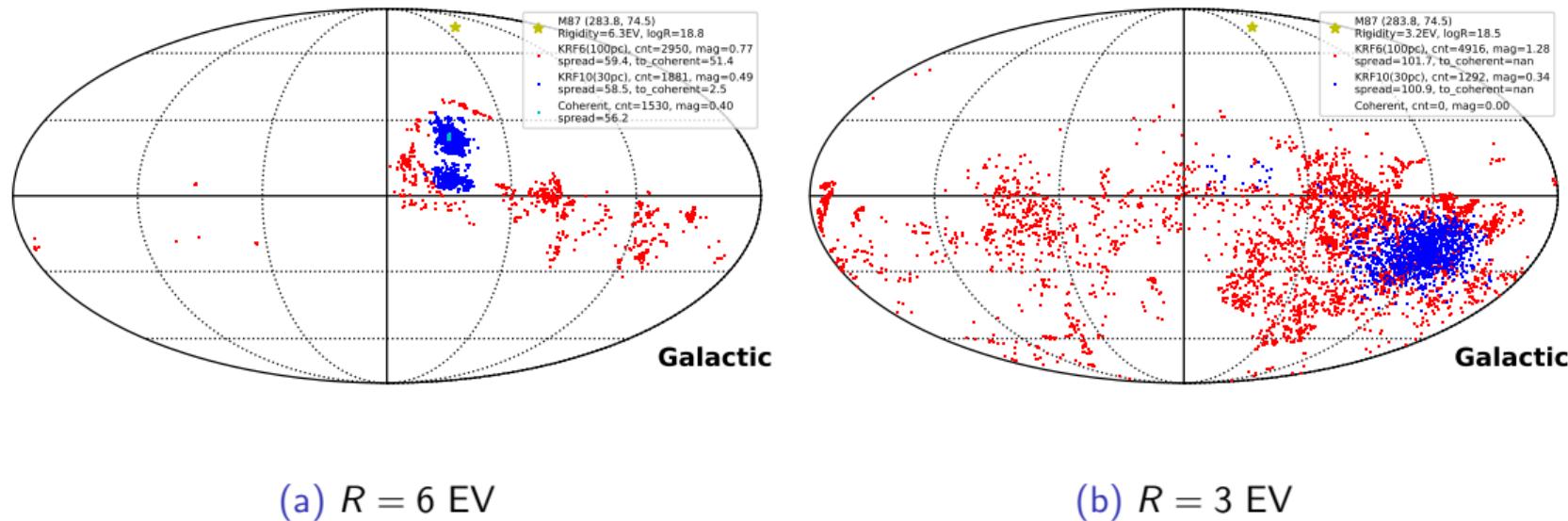
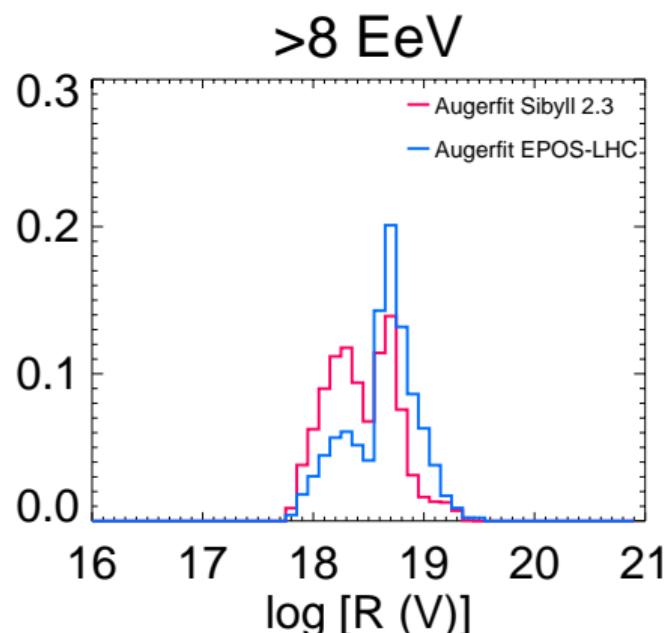


Figure: Trajectories starting from M87 direction. (Farrar and Sutherland 2017)

Ingredients: Rigidity spectrum

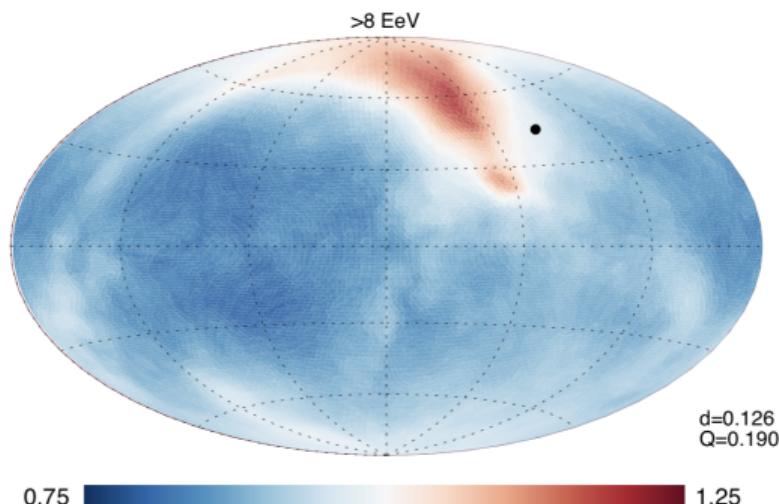


- Rigidity distribution of all cosmic rays >8 EeV, calculated from energy spectrum and composition
- We test composition models Sibyll 2.3/EPOS-LHC, mixed/pure proton, Auger fit/MUF.

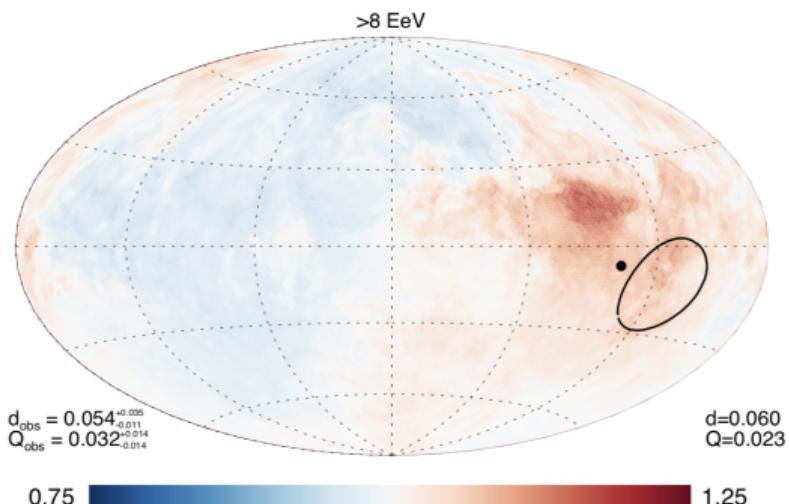
MUF (Muzio, Unger, Farrar 2019) updates UFA (Unger, Farrar, Anchordoqui 2015), a physically motivated model of energy spectrum and composition.

Output: Sky maps

(a) Illumination map >8 EeV



(b) Arrival map >8 EeV



IMPACT OF GMF IS CRUCIAL.

Summary of parameters explored

- ◊ Parameters:
 - EGMF coherence length $\lambda = 0.08\text{--}0.5 \text{ Mpc}$
 - EGMF magnitude $B = 0.1\text{--}30 \text{ nG}$
 - GMF coherence length $L = 30\text{--}100 \text{ pc}$
 - composition models: Sibyll 2.3/EPOS-LHC, mixed/pure proton, Auger fit/MUF)
- ◊ Notes:
 - Diffusion coefficient is what matters in propagation in EGMF.

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

(Globus, Allard & Parizot 2008)

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

Results: Both EGMF and GMF play a role

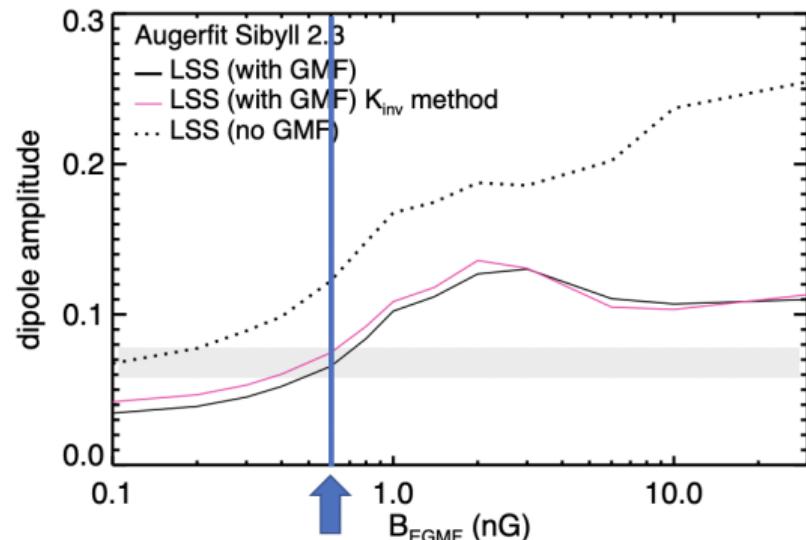
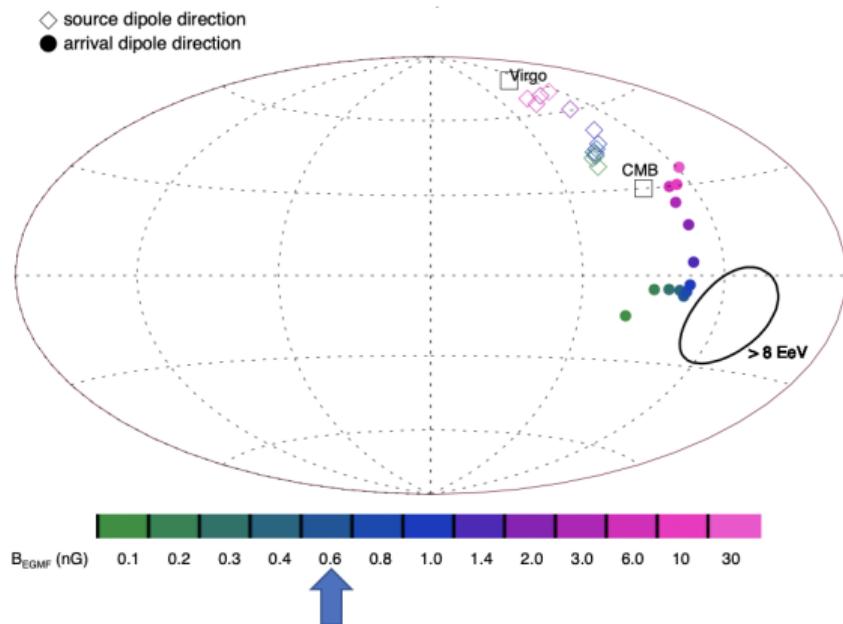
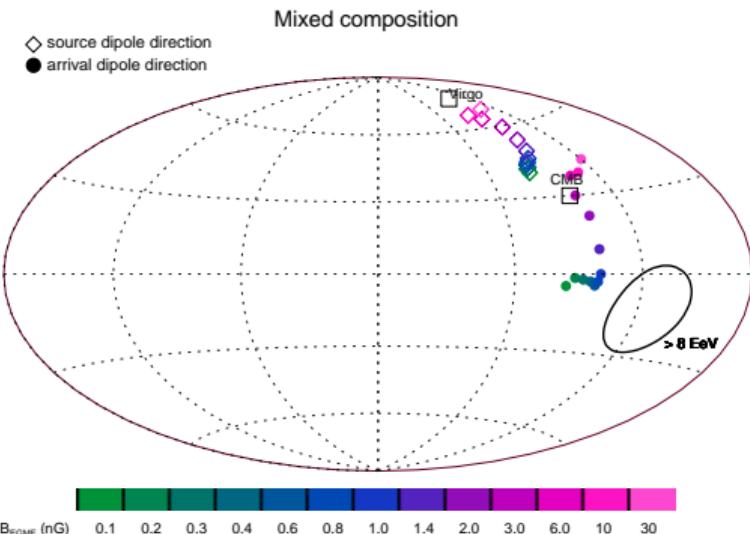


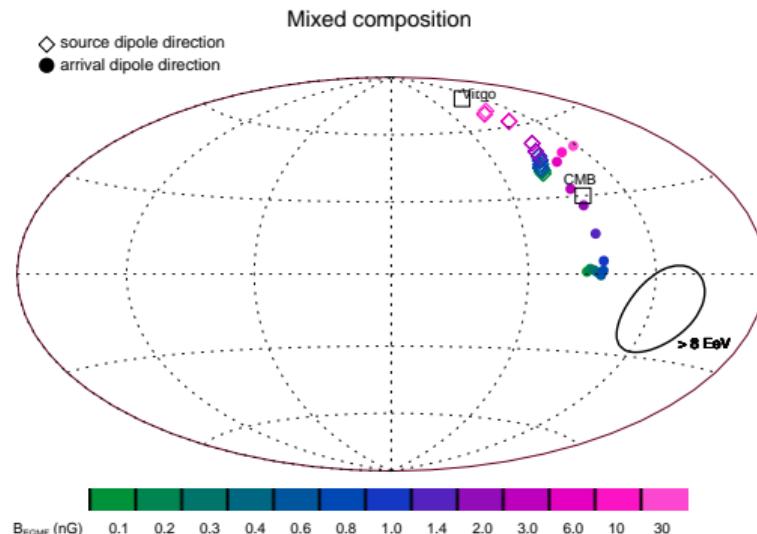
Figure: Sibyll, mixed composition.

Left panel: Hollow diamonds are dipole directions of illumination maps.
Solid dots are dipole directions of arrival maps.

Results: Both Sibyll and EPOS compositions give similarly good fits

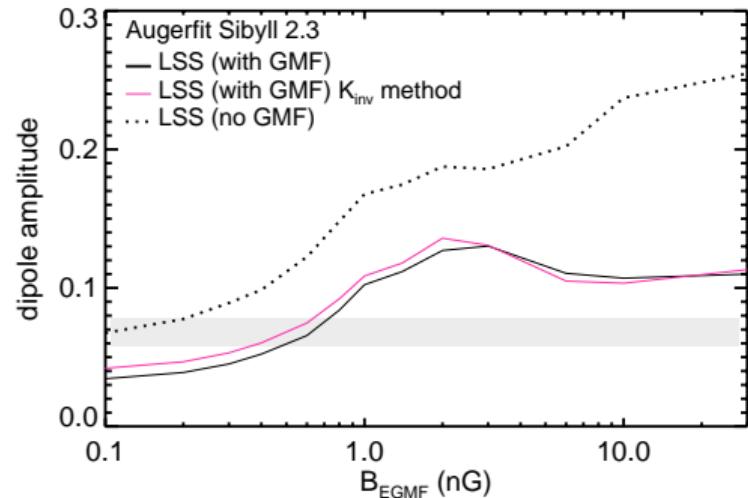


(a) Sibyll 2.3, mixed composition

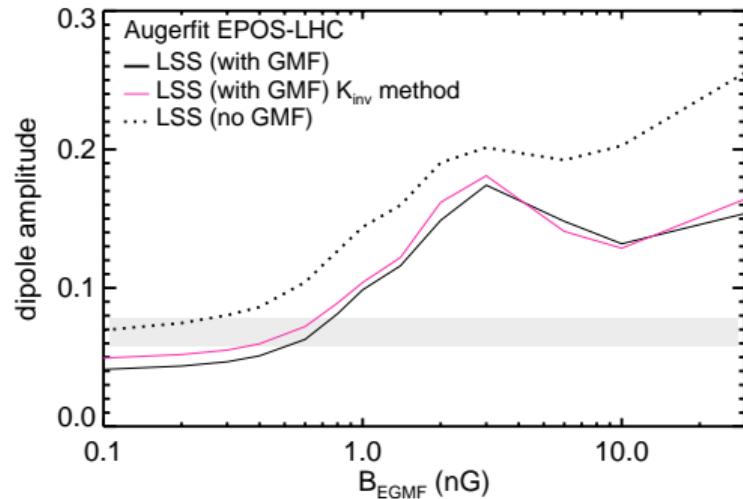


(b) EPOS-LHC, mixed composition

Results: Both Sibyll and EPOS compositions give similarly good fits

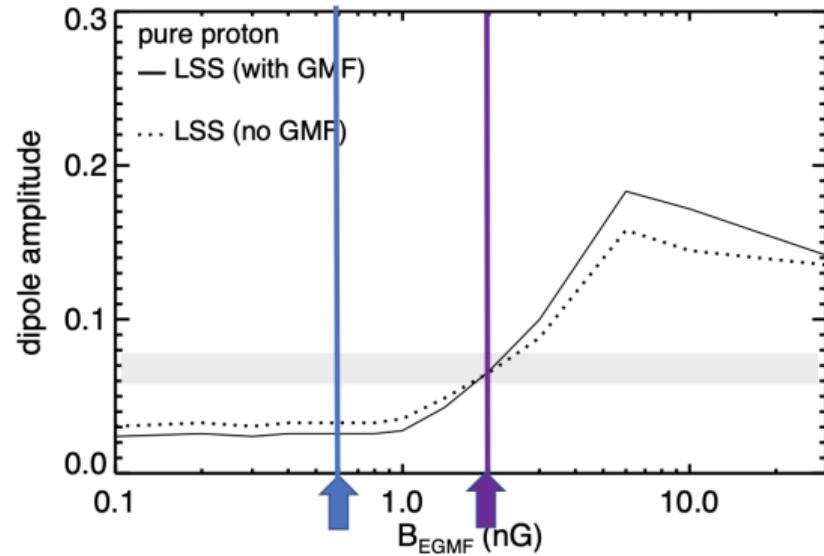
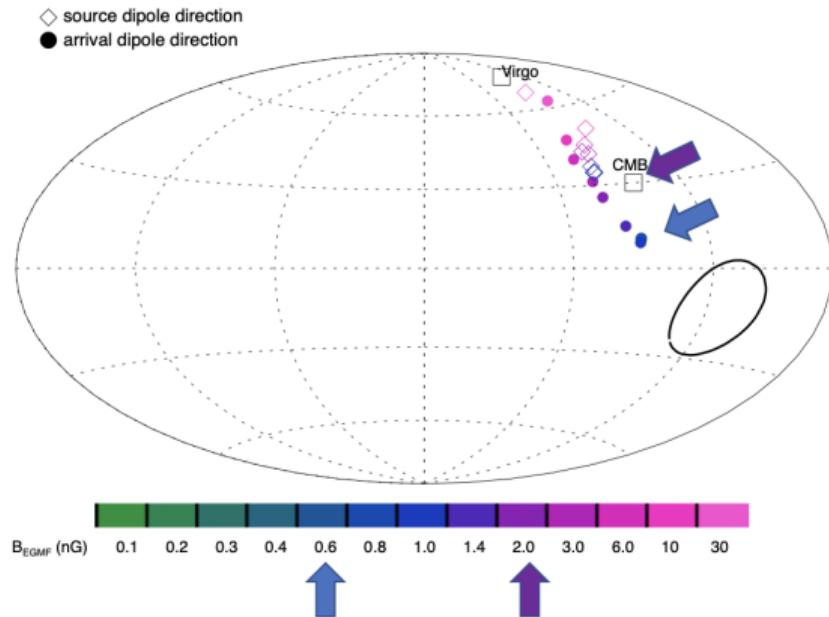


(a) Sibyll 2.3, mixed composition.



(b) EPOS-LHC, mixed composition

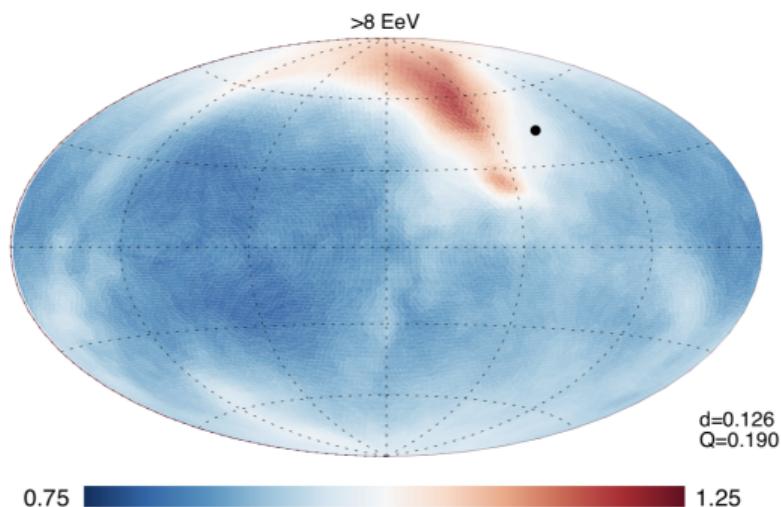
Results: Pure proton does not work for our model



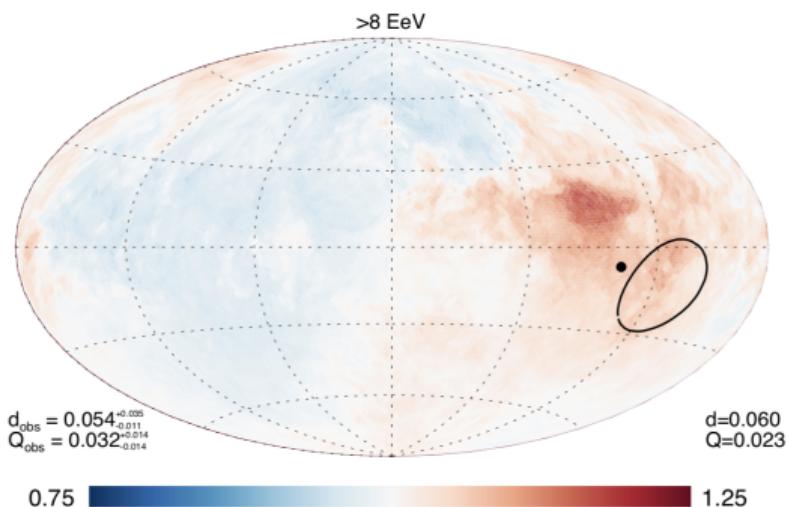
CAN'T SIMULTANEOUSLY EXPLAIN MAGNITUDE AND DIRECTION

Results: >8 EeV

(a) Illumination map >8 EeV



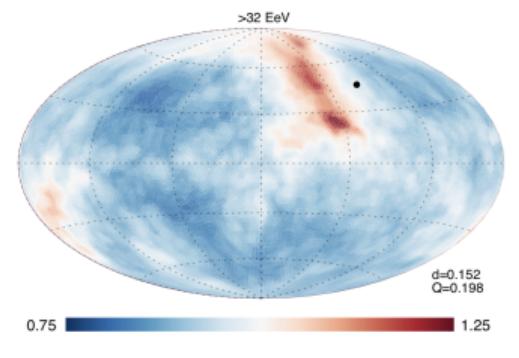
(b) Arrival map >8 EeV



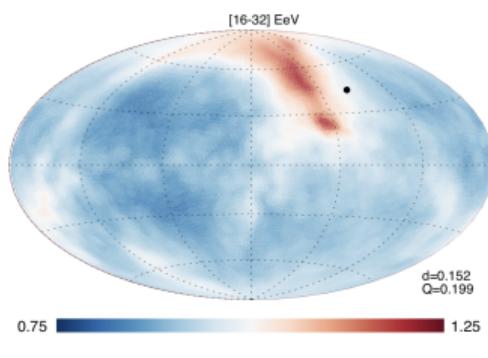
BOTH EGMF AND GMF PLAY ESSENTIAL ROLE.

Results: Illumination maps for different energies

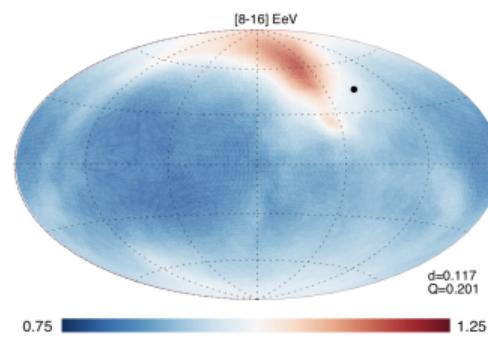
(a) >32 EeV



(b) 16-32 EeV



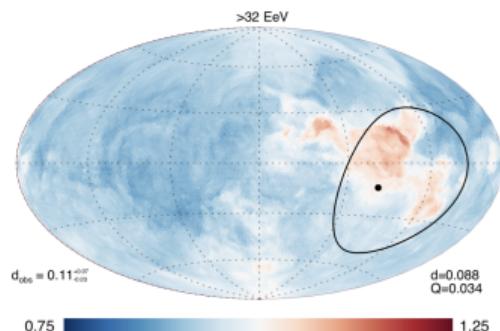
(c) 8-16 EeV



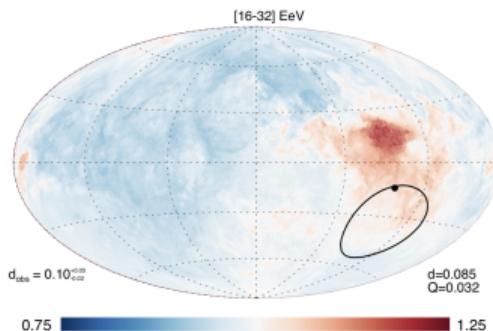
ILLUMINATION DIPOLE weakly dependent on E

Results: Arrival maps for different energies

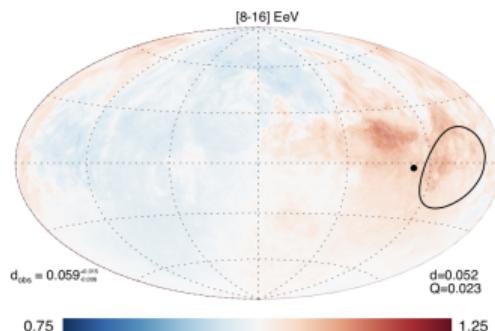
(a) >32 EeV



(b) 16-32 EeV



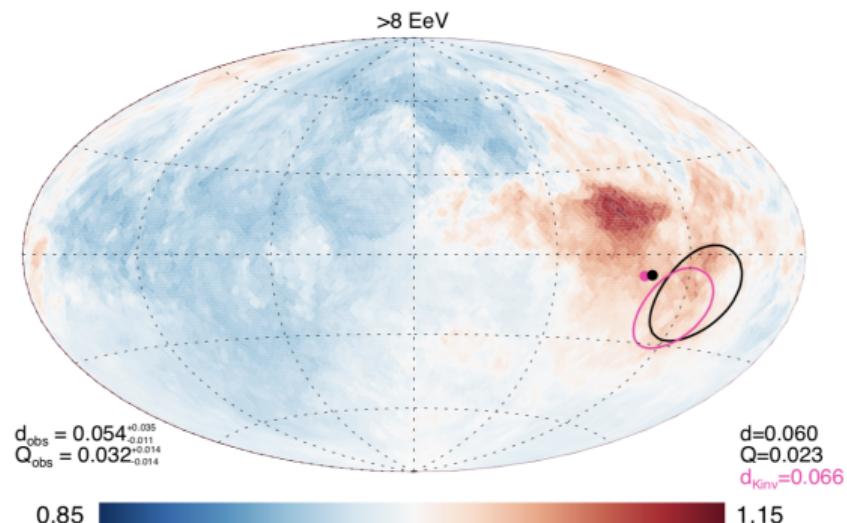
(c) 8-16 EeV



ARRIVAL DIPOLE weakly dependent on E

Subtleties: impact of exposure on the observed dipole

- According to our model, the dipole reconstructed with Auger exposure (pink dot) is very close to true one (black dot).
- Pink vs black circles show sensitivity of Auger reconstruction to method used.



Summary

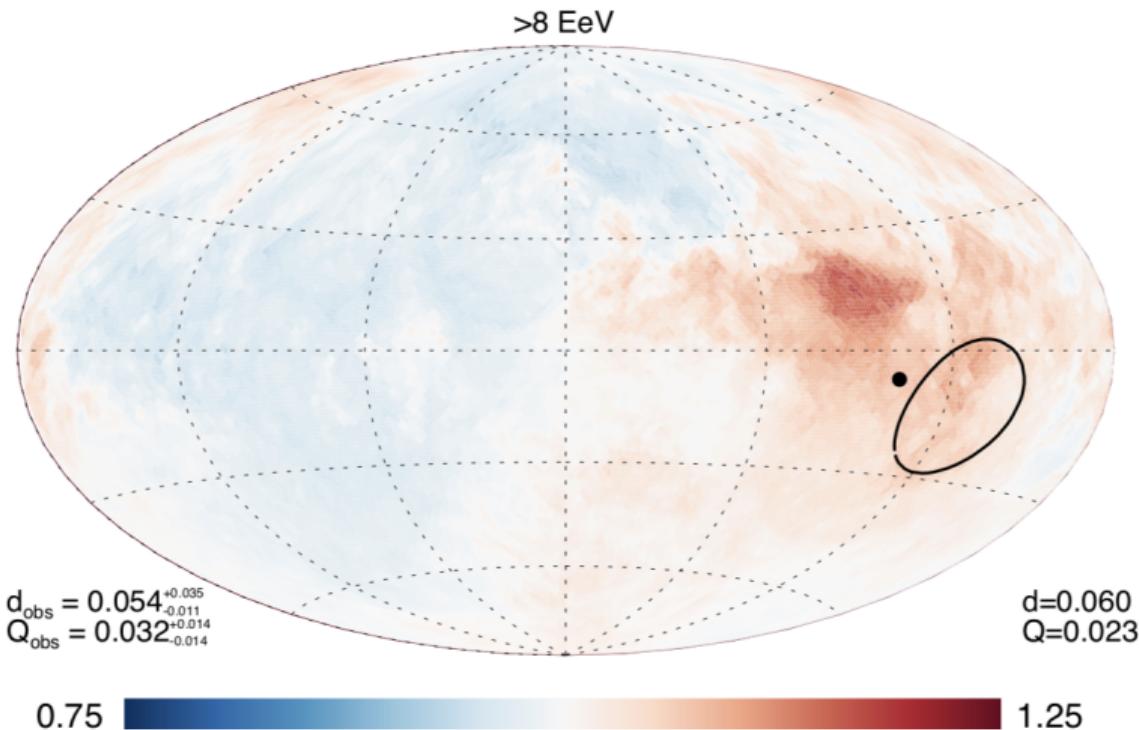
We've built a physically motivated, LSS-based model for the UHECR anisotropy >8 EeV.

- Consistent with Auger dipole & quadrupole observations >8 EeV
- Dipole direction only weakly dependent on energy from 8 to 32 EeV
- Both EGMF and GMF play crucial role.
Best-fit parameters: EGMF $B \approx 0.6$ nG, $\lambda \approx 0.2$ Mpc; GMF $L_{\text{coh}} \approx 75$ pc
- Insensitive to hadronic interaction models (Sibyll 2.3/EPOS-LHC)
- Pure proton cannot fit both dipole amplitude and direction.

Future work: TA/Auger hotspots, Individual sources, GMF variations, interpretation of energy dependence (if established)

Thank you.

Bottom line: a successful model of UHECR anisotropy



- dipole only
 $d_{\text{obs}} = 6.5^{+1.3\%}_{-0.9\%}$
 $d_{\text{model}} = 6.6\%$
- dipole and quadrupole
 $d_{\text{obs}} = 5.4^{+3.5\%}_{-1.1\%}$
 $d_{\text{model}} = 6.0\%$
 $Q_{\text{obs}} = 0.032 \pm 0.014$
 $Q_{\text{model}} = 0.023$

Back-up slides

Groundbreaking discovery by Pierre Auger Observatory

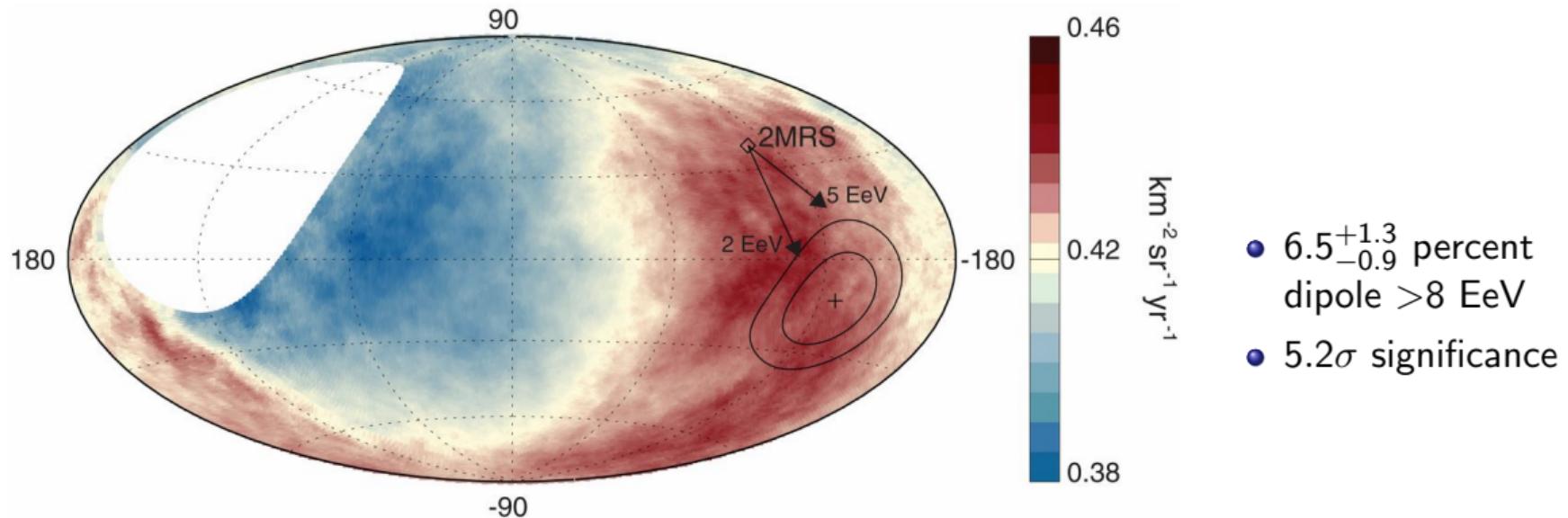
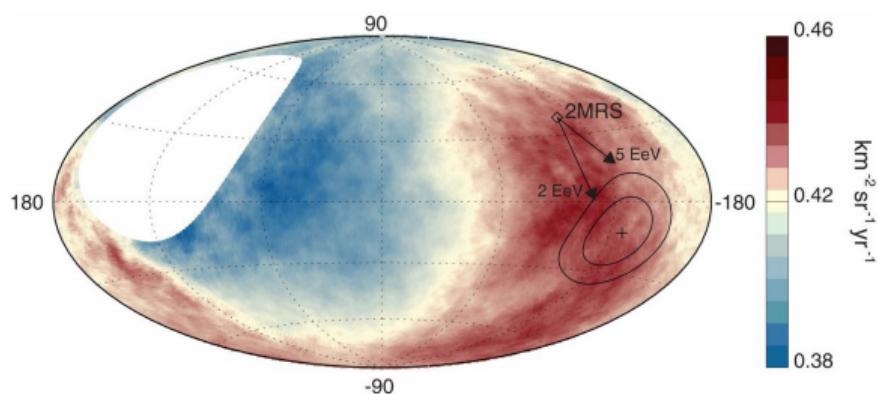
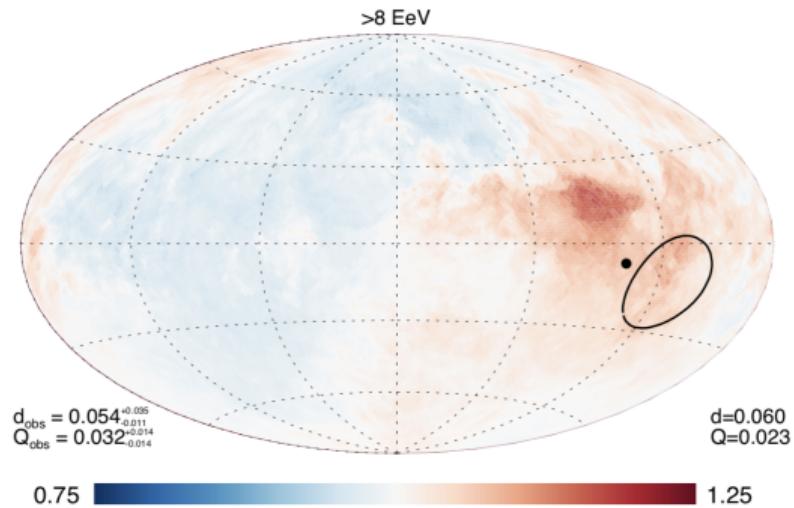


Figure: Science 2017, The Pierre Auger Collaboration

Observation and Our Model



(a) Science 2017, The Pierre Auger Collaboration



(b) Prediction of our model

Composition

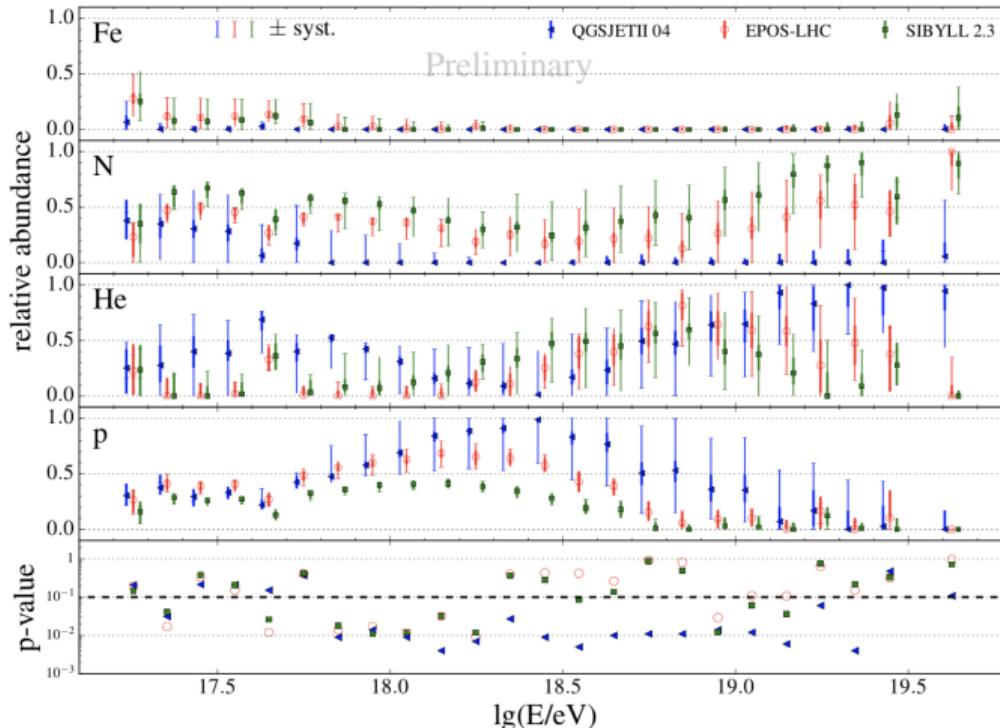


Figure: PoS(ICRC2017)506

Composition

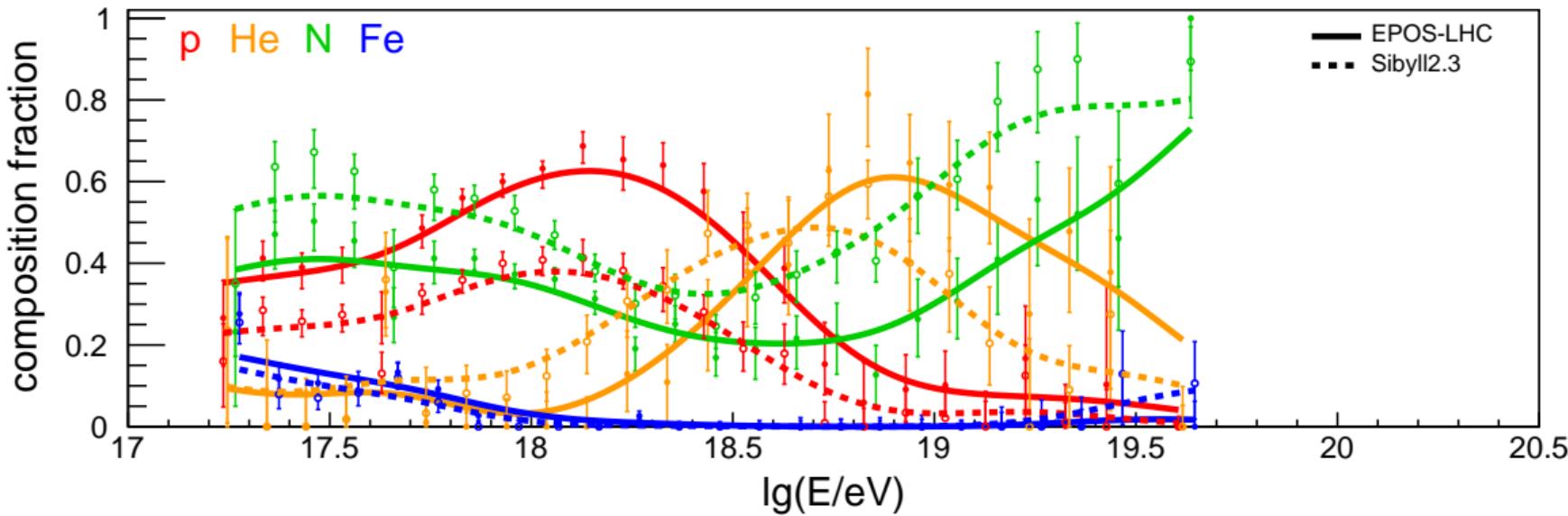
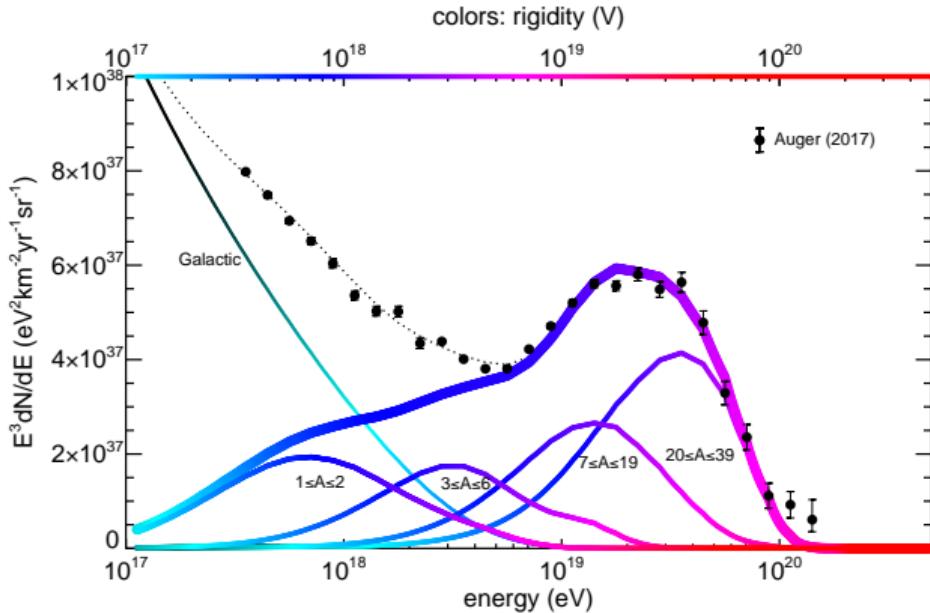


Figure: from arXiv:1903.06714. The composition fraction of N and Fe indicates the existence of galactic cosmic rays < 3 EeV

Energy spectrum and composition



- In UFA/MUF model, >8 EeV cosmic rays are $\approx 100\%$ extragalactic.
- Rigidity increases slowly over a large energy range, reflecting the Peters Cycle.
UFA (2015) is a physically motivated model which gives good fit to energy spectrum and Xmax data. MUF (2019, Muzio, Unger, Farrar) succeeds UFA.