UHECR anisotropy and extragalactic magnetic fields with the Telescope Array

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MOTIVATION

- UHECR are remarkably isotropic $\Longrightarrow$ limited information is contained in their arrival directions
- Many uncertainties:
  - composition?
  - Galactic magnetic field (GMF)?
  - extragalactic fields (EGMF)?
- Despite all these issues, can we still extract useful conclusions from the observed distribution of arrival directions?

METHOD

General flow:

(1) Choose an observable
- sensitive to deflections
- as simple as possible
- max. insensitive to the details of GMF

(2) Calculate its value & distribution for the data
- use LLH approach

(3) In a given model (sources, injected spectrum and composition) calculate the predicted sky distribution of UHECR. Calculate our observable; compare to the data.
- to predict sky distributions use all the available knowledge: energy attenuation, energy-dependent effects of magnetic fields etc.
- use as large statistics as needed to make stat errors small

METHOD: observable

OBSERVABLE: mean deflection w/r to LSS at $E = 100$ EeV *Kuznetsov & PT, JCAP 04 (2021) 065*

- Generate flux maps $\Phi_E(n)$ from LSS assuming protons with the arrival energy E
- Smear it with the angle $100\text{EeV}/E \cdot \theta_{100}$
- Calculate LLH for a given UHECR event set

$$\mathcal{L}(\theta) = -2 \sum_{\text{E bins, } k} \left(\sum_{\text{events } i} \ln \frac{\Phi_k(\theta_{100}, n_i)}{\Phi_{iso}(n_i)} \right)$$

- Determine the minimum $\Longrightarrow \theta_{100}$

One event set gives 1 function $\mathcal{L}(\theta)$ and 1 value of θ_{100} (the positon of the minimum) together with its confidence intervals (distributed as χ^2 with 1 dof)

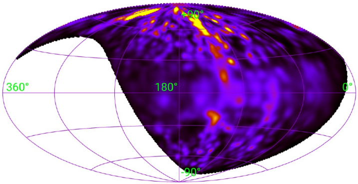
METHOD: mock sets for testing models

Generate as realistically as possible, with as large statistics as needed:

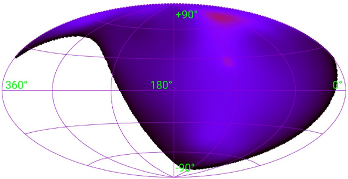
- first generate probability skymaps, then mock sets from these maps
- assume sources in LSS (corrected 2MRS catalog up to 250 Mpc, isotropy farther)
- attenuate for p-He-O-Si-Fe (SimProp), include secondaries for O and He
- best fit injection spectrum separately for each primary (adjusted to the observed one, cf.TA@ICRC2015)
- EGMF deflections: uniform smearing, if present
- GMF deflections: PT11 or JF12 regular field (backtracking); b-dependent Gaussian smearing for random component (all rigidity-dependent)

Free parameters: injected fractions of each primary

Proton map at E = 100 EeV



Iron map at E = 100 EeV



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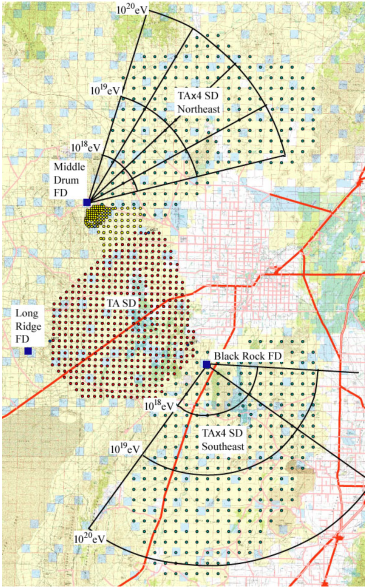
TELESCOPE ARRAY LAYOUT



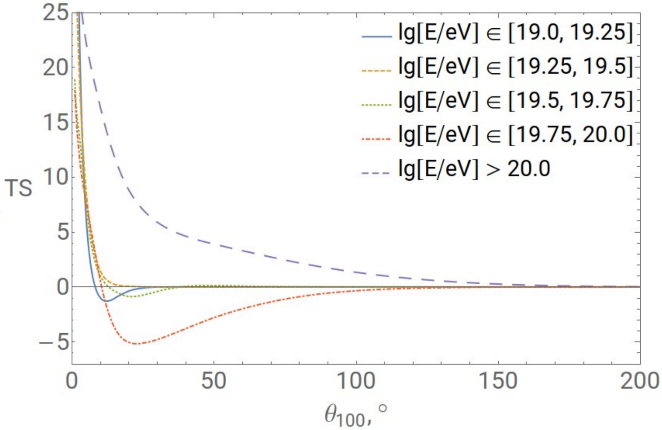
- $\sim$ 140 collaborators from 5 countries
- Main SD detector: 507 scintillators with 1.2 km spacing covering 680 km^2; fully operational since May 2008
- 3 fluorescence sites, 38 telescopes
- Extension by $\times$4 under construction

DATA

- In this talk: data from the TA Surface detector taken from May 2008 to May 2020 (12 years)
- zenith angle up to 55°, loose border cut
- geometrical acceptance
- 5146 above 10 EeV
- 353 above 40 EeV
- 137 above 57 EeV
- angular resolution: better than 1.5°
- energy resolution: $\sim 20\%$

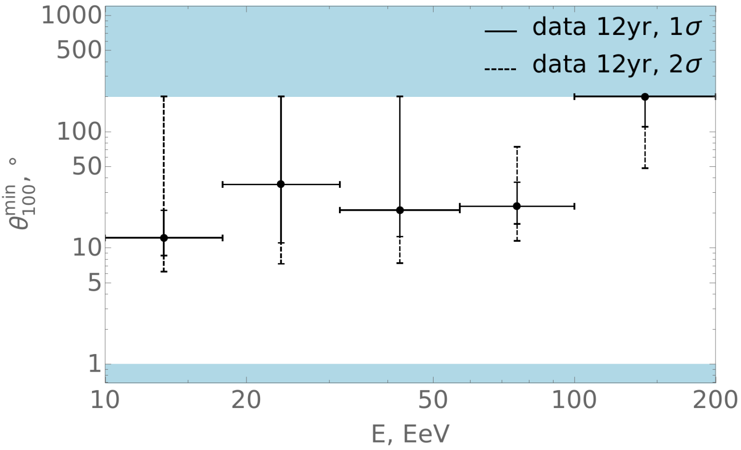
LIKELIHOOD FOR THE DATA

- $\mathcal{L}(\theta_{100})$ curves in energy bins:



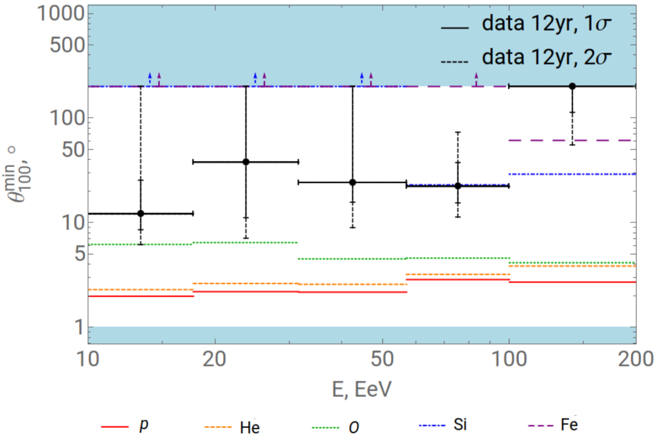
LIKELIHOOD FOR THE DATA

- Measurements of θ_{100} in bins (positions of minima and confidence intervals):



COMPARISON TO MODELS: HIGH E

- Pure composition models, EGMF=0, GMF=PT11



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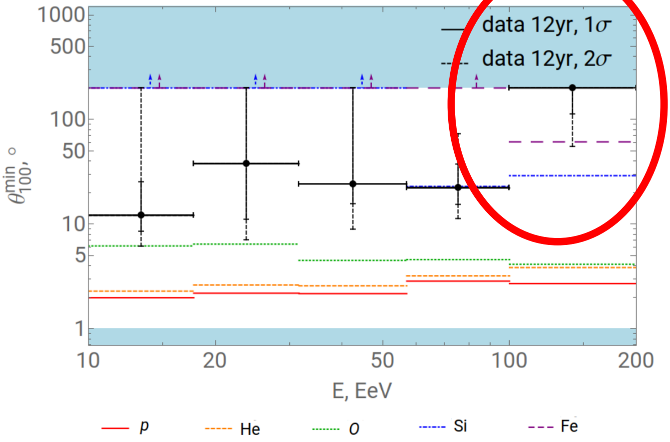
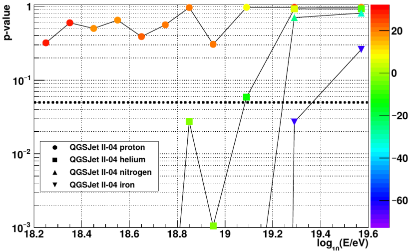


$\Longrightarrow$ Even iron is in tension with the data

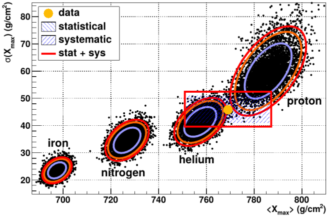
COMPARISON TO MODELS: LOW E

TA FD composition measurement:

- In the lowest energy bin $[10, 10^{1.25}]$ EeV the TA FD data indicate a light composition, p or He:



TA FD (BR+LR) ApJ 858 (2018) 76

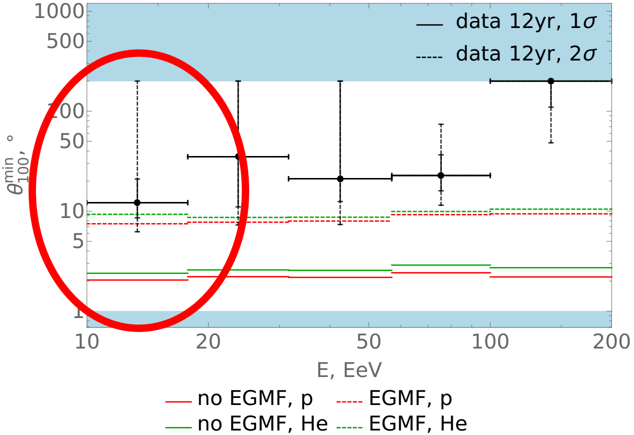


- In tension with measured deflections? Not necessarily.

EGMF

- Relax the assumption EGMF $= 0$
- Assume EGMF$\neq 0$ in voids (gives largest deflections)
- Take largest realistic EGMF magnitude still compatible with experimental bounds: $B = 1.7$ nG, correlation length $\lambda = 1$ Mpc
- $\Longrightarrow$ Additional direction-independent deflections: 7° for protons at 100 EeV and $d = 250$ Mpc

COMPARISON TO MODELS: LOW E



- $\Longrightarrow$ Extreme EGMF makes observed isotropy compatible with measured light composition at low E. Indication of large EGMF?

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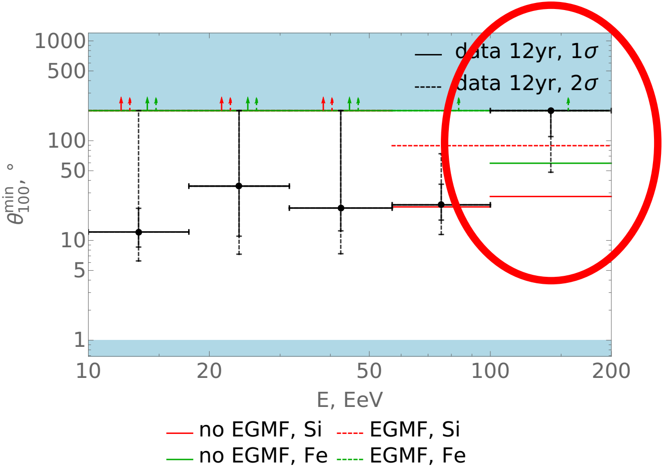
EGMF AT HIGH E

- What EGMF$\neq$ 0 gives at high energies?
- $\Longrightarrow$ Fe fits; Si still in some tension



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CONCLUSIONS

Under the assumption that sources follow LSS:

- At high energies: an indication of a heavy composition (EGMF does not change the picture qualitatively)
- At low energies: protons or helium without EGMF do not work; large EGMF at the limit of current experimental bounds makes light composition (p or He) compatible with the data

BACKUP

RARE SOURCES