UHECR mass composition from their arrival directions with the Telescope Array

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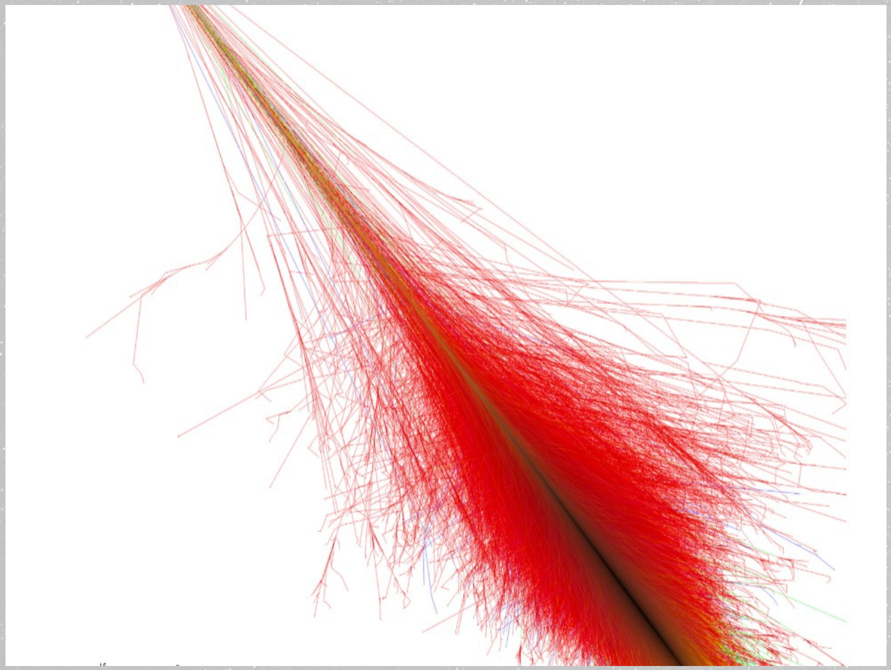
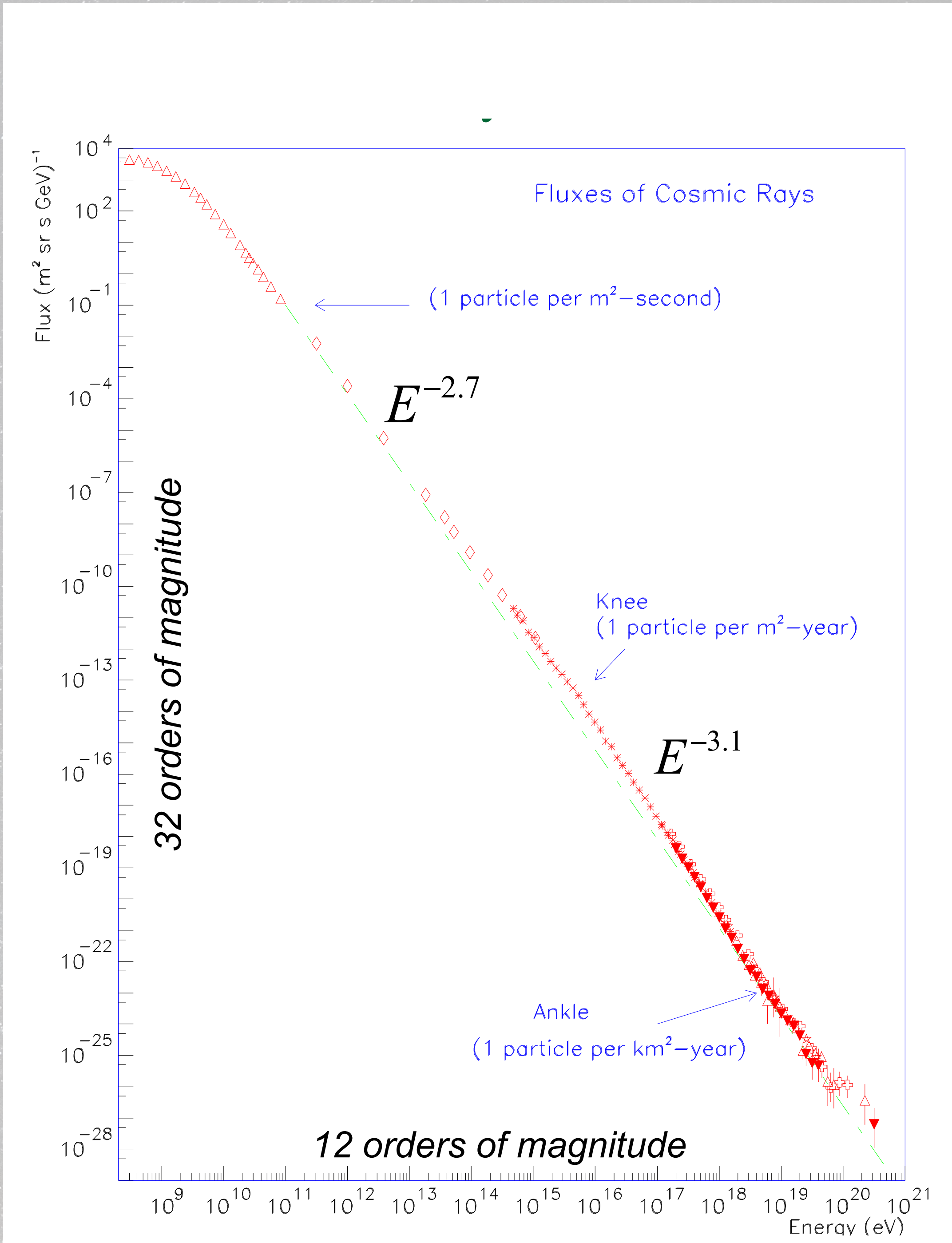
for the Telescope Array collaboration

QUARKS-2024
Pereslavl-Zalessky, 21.05.24

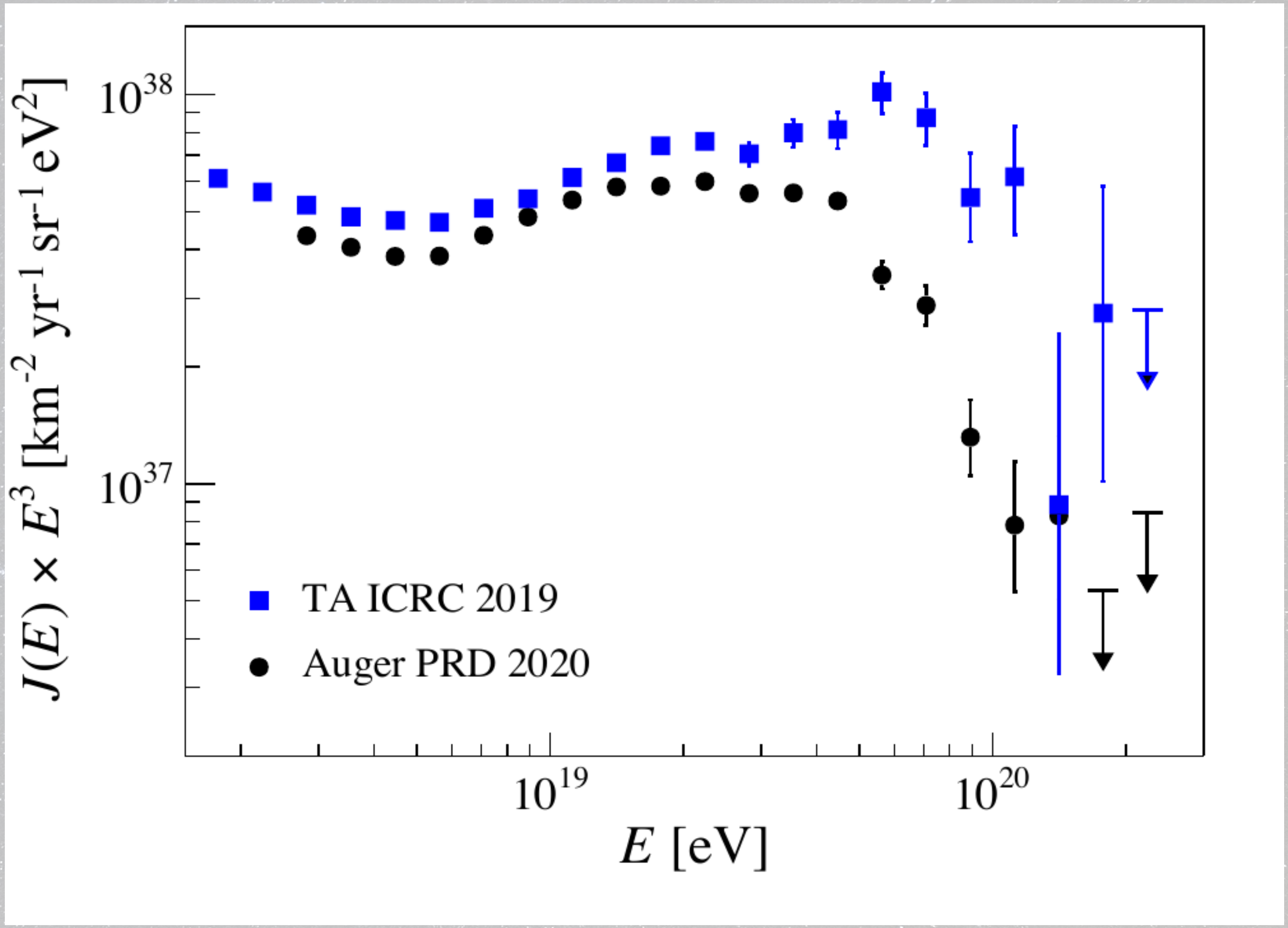
Ultra-high energy cosmic rays

- Charged particles with E > 1 EeV
- Flux ~ 1 $km^{-2}yr^{-1}sr^{-1}$
- Steeply falling spectrum
- Origin still unknown (extragalactic)
- Detecting via showers of charged particles in the atmosphere





UHECR observables: energy spectrum



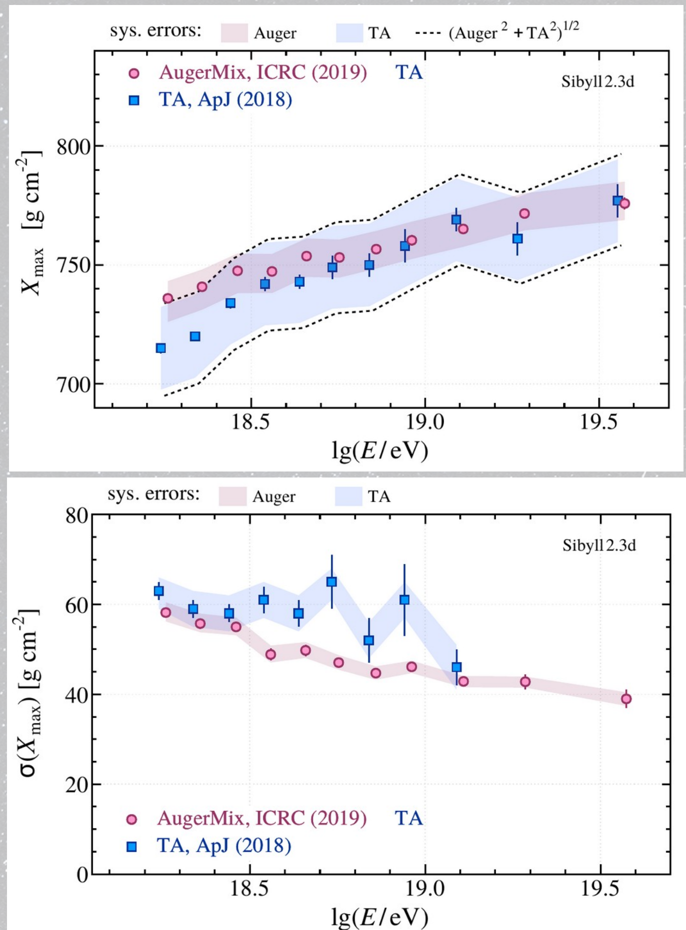
- Spectrum **shape is similar in both TA and Auger** experiments: a cutoff at high energies is observed

But

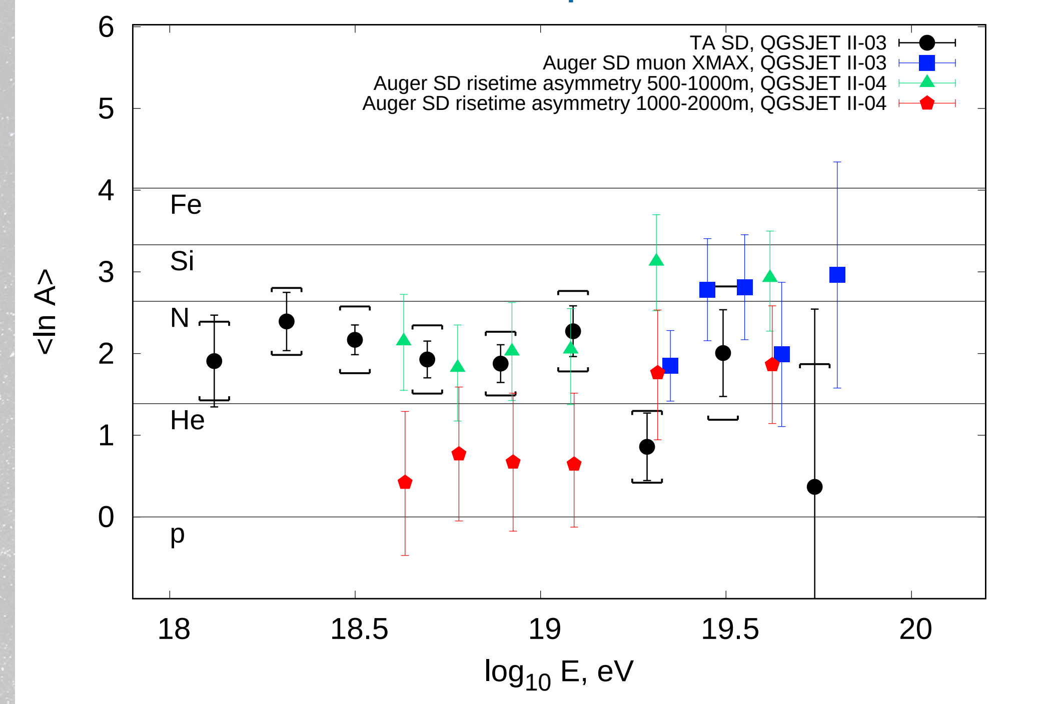
- Spectrum measurements alone have **limited potential** to determine the UHECR origin
- Cut-off is due to GZK effect (protons) or due to the end of injection spectrum (nuclei)?

UHECR observables: mass composition

FD composition



SD composition



- Composition measurements have **good potential** to determine the UHECR origin

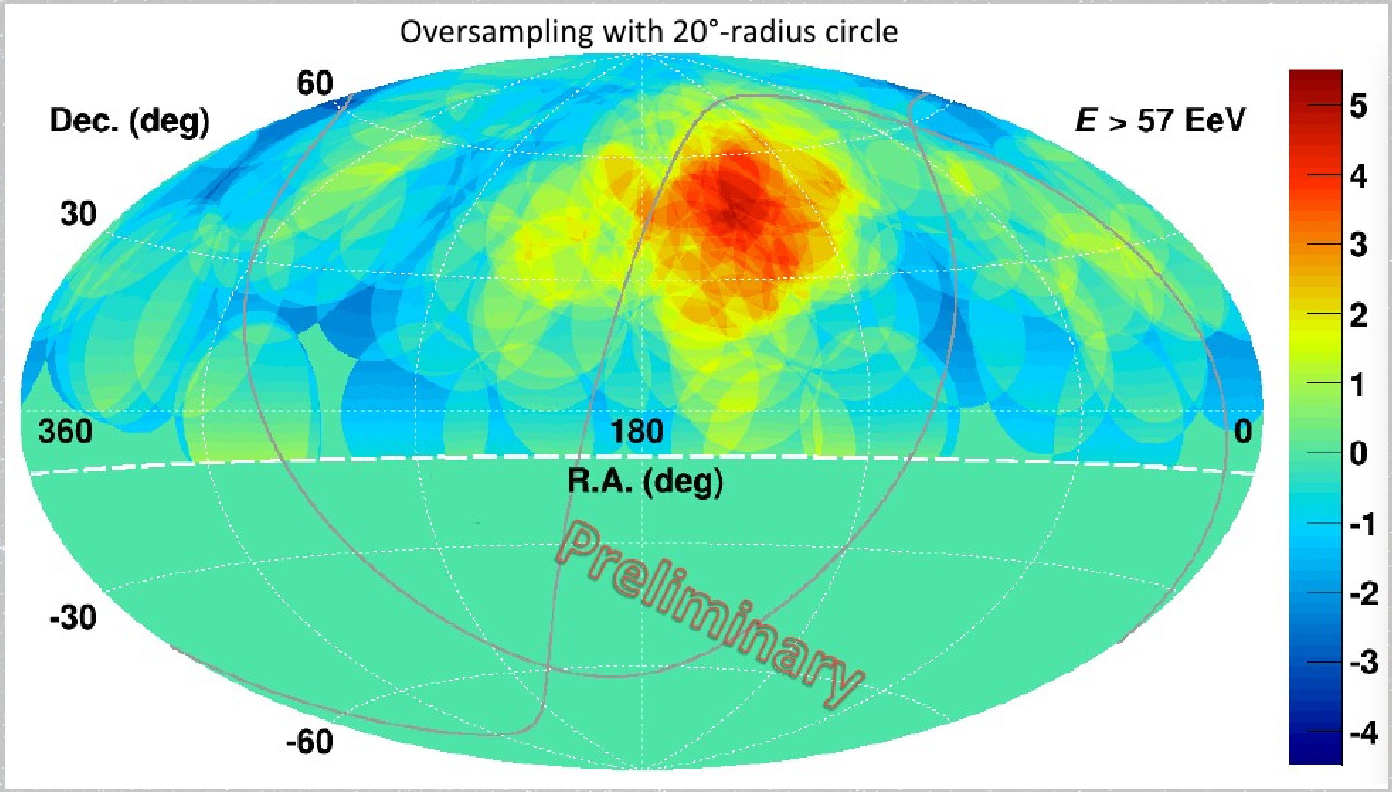
But

- There is still a **discrepancy** between the modern experiments
  - Systematics are **hardly controllable** for surface observations
  - Statistics is **very limited** for fluorescence observations

Also

- At E > 100 EeV the statistics is ~20 events: not enough for both methods

UHECR observables: anisotropy

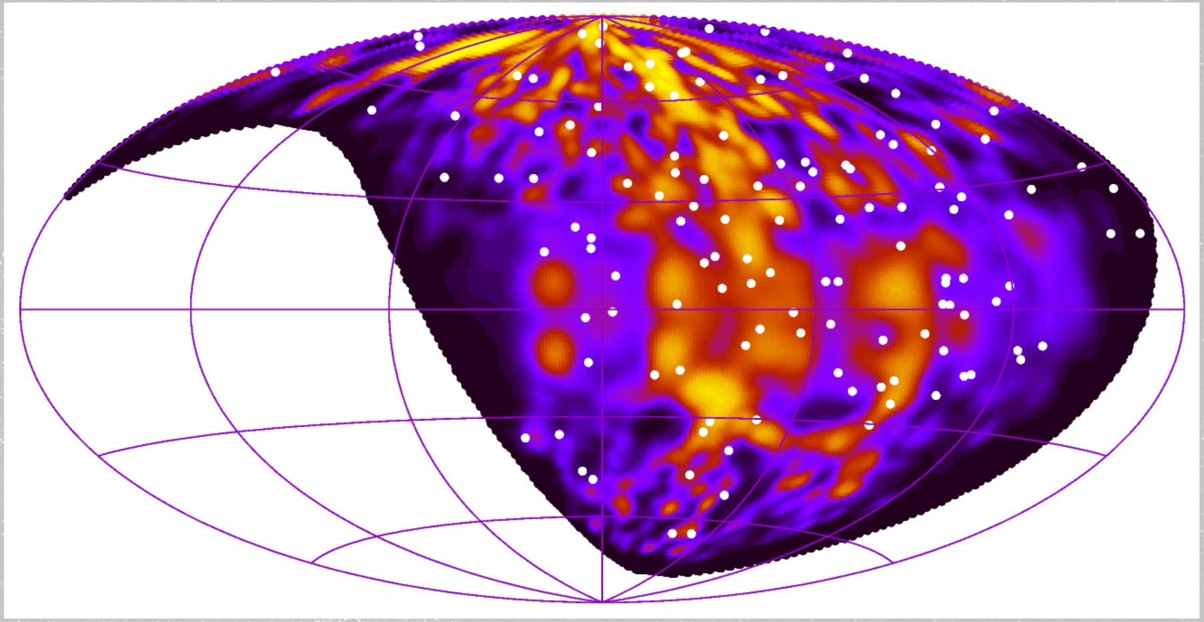


- Arrival directions are measured with **good precision** (~1°)

But

- Have **limited potential** to determine the UHECR origin due to their deflections:
  - Uncertain galactic and extragalactic magnetic fields
  - Uncertain mass (and charge) composition of UHECR

What can we learn from a distribution of UHECR in the sky?



- Sources: no clear evidence for particular sources

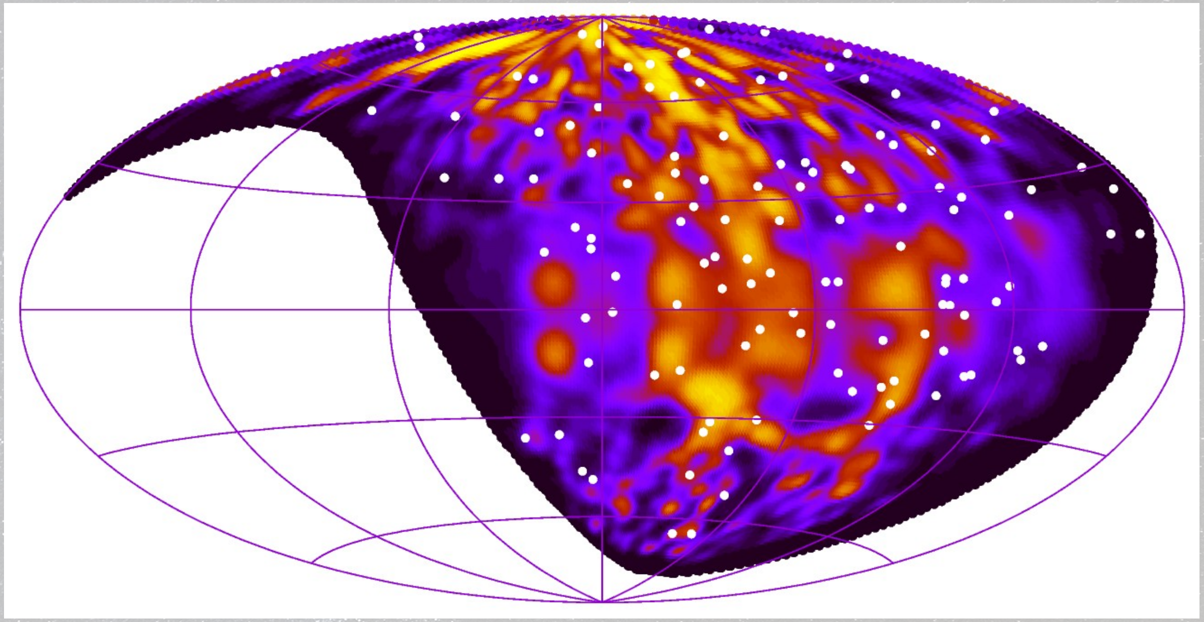
- Magnetic fields
  - EGMF: observations B < 1 nG
  - EGMF: simulations B < 0.01 nG

  } likely negligible
  - GMF: B ~ μG, factor 2 uncertainty between models in terms of deflections

- Mass composition: up to factor 26 uncertainty (p and Fe) in terms of deflections

UHECR flux model

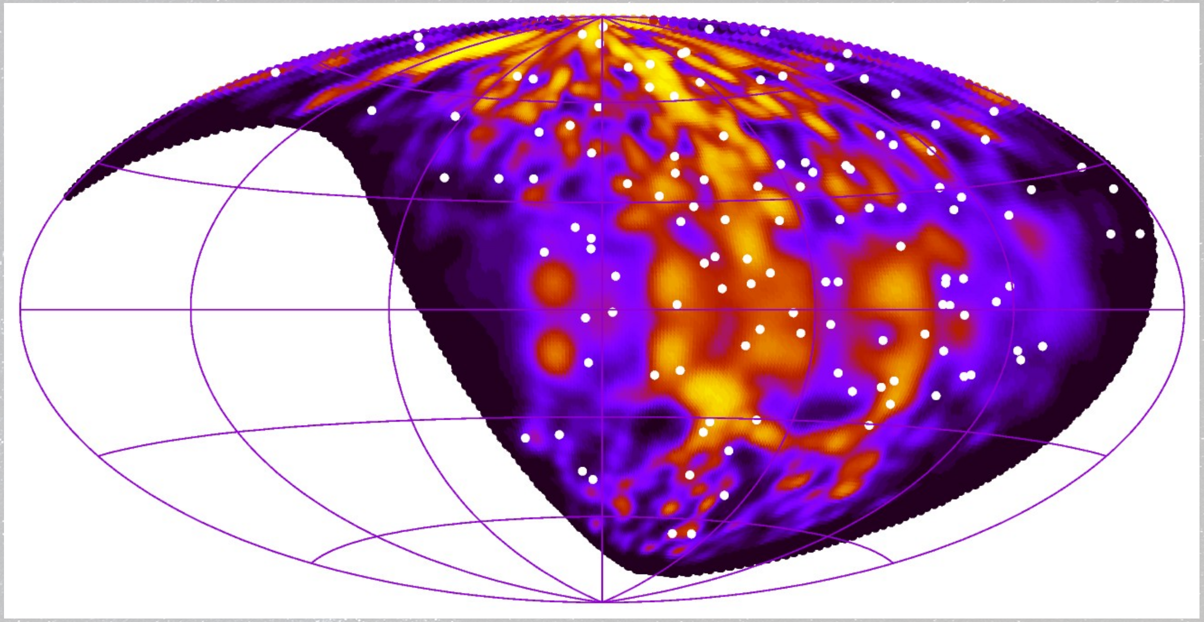
How to disentangle all the uncertainties?



- Sources: the most conservative model – 2MRS + isotropy for far sources – covers all the scenarios without large anisotropy
- Magnetic field
  - EGMF deflections: neglect altogether (B ≤ 0.1 nG)
  - GMF deflections: fix one of the models (regular + random)

  } Study the impact of MF variation later
- Mass composition: can be studied as a largest uncertainty of the flux model

Approach to mass composition inference



Three-step approach

MK & P.Tinyakov, 2021

1. **Introduce test statistics: a robust measure** of UHECR set deflection from LSS
2. **Simulate realistic UHECR mock sets** originating from LSS with various injected mass compositions
3. **Apply the test statistics** to both mock sets and data set and infer the mass composition from data

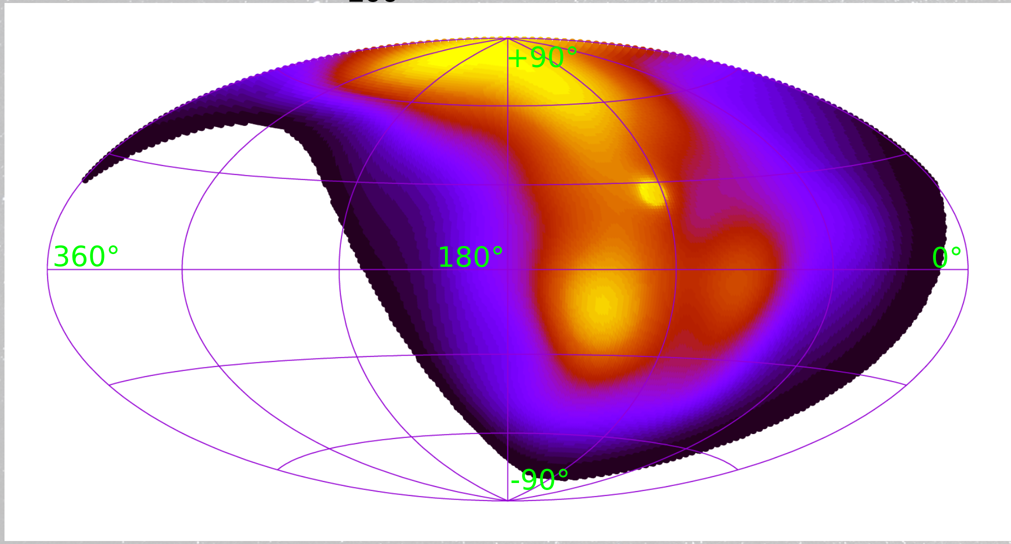
Step one: TS construction

Compute event-set likelihood as a function of events positions at
skymap Φ with smeared LSS-sources

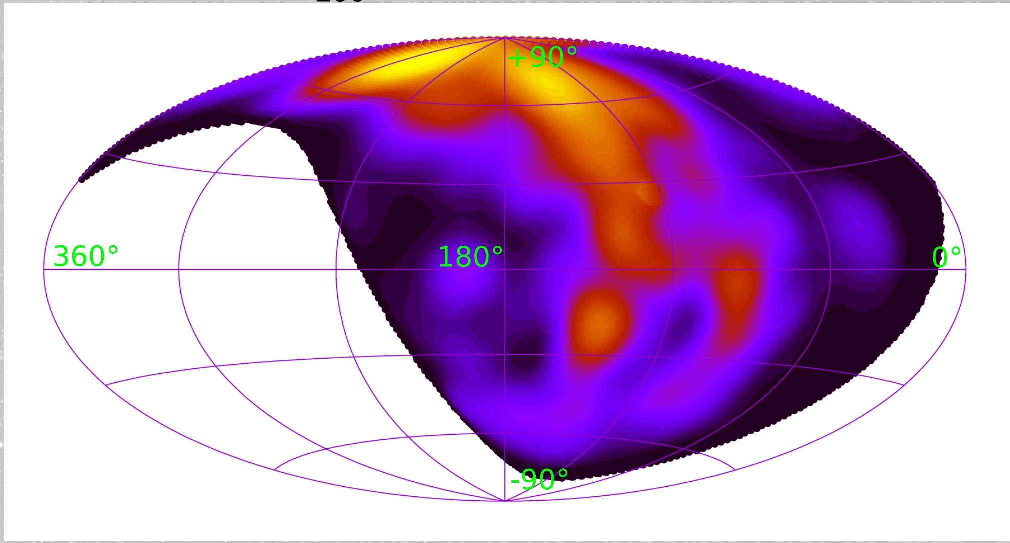
$$TS(\theta_{100}) = -2 \sum_{E_k} \left(\sum_{i}^{\text{events}} \ln \frac{\Phi_{E_k}(\theta_{100}, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)} \right)$$

- The likelihood is sensitive for *average* magnitude of deflections in a given event-set
- For each event set we get one number, a position of TS minimum – an average deflection angle recalculated to 100 EeV: $\theta_{100,\,min}$

Map θ_{100} = 10°, E = 57 EeV



Map θ_{100} = 10°, E = 100 EeV



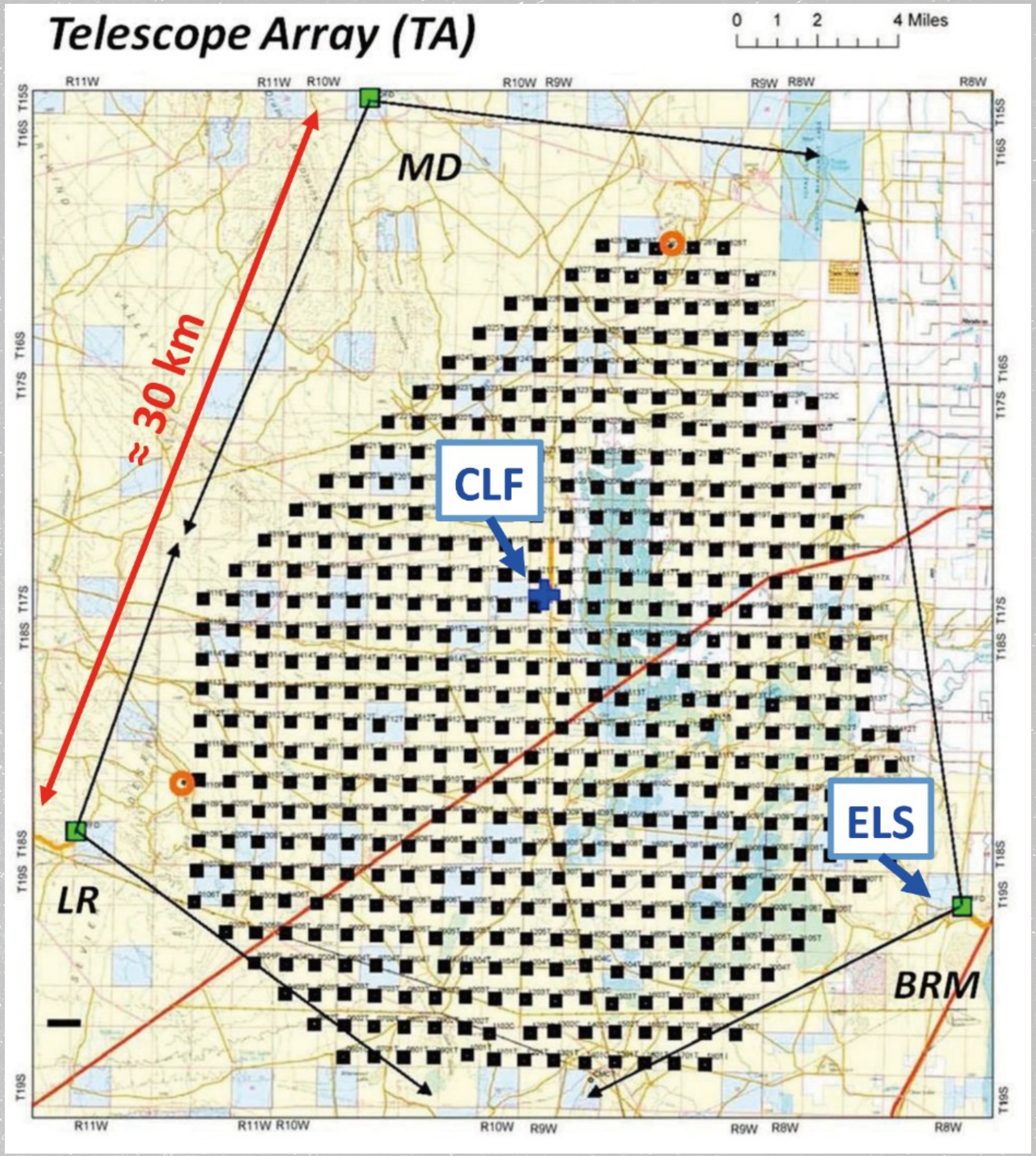
Telescope Array Surface Detector

The Experiment

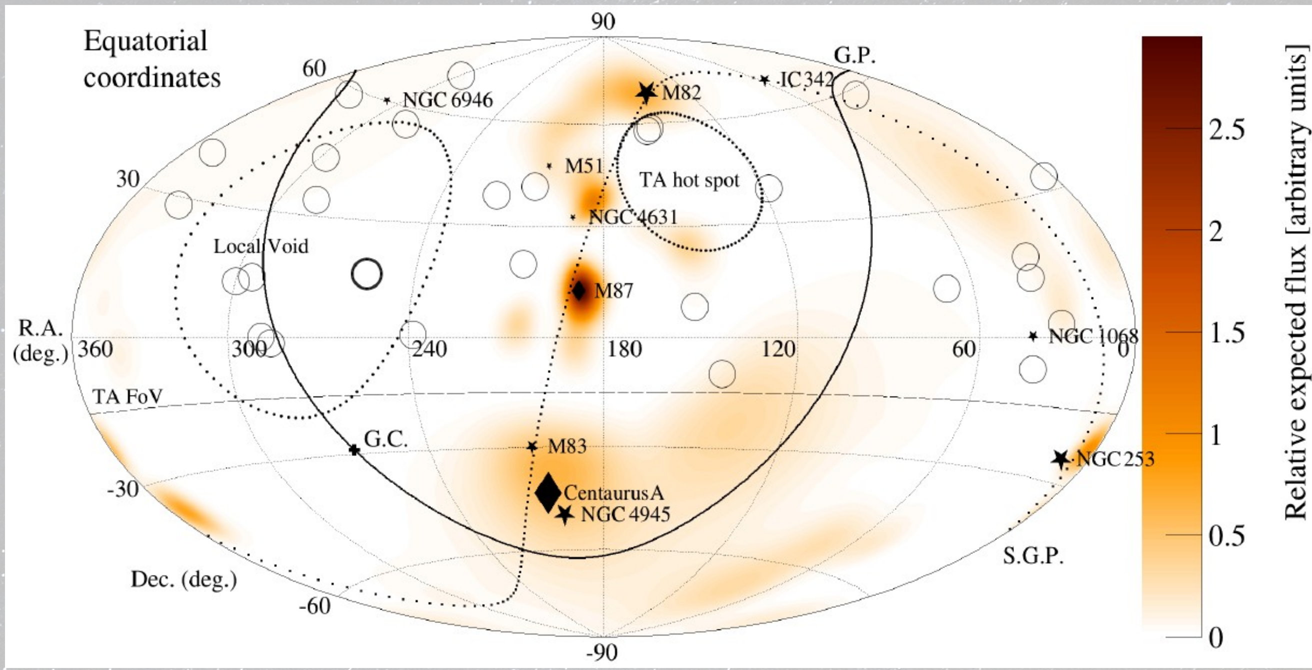
- Largest UHECR experiment in the Northern Hemisphere
- 507 SD stations
- ~700 km² area, 16 years of continuous data collection

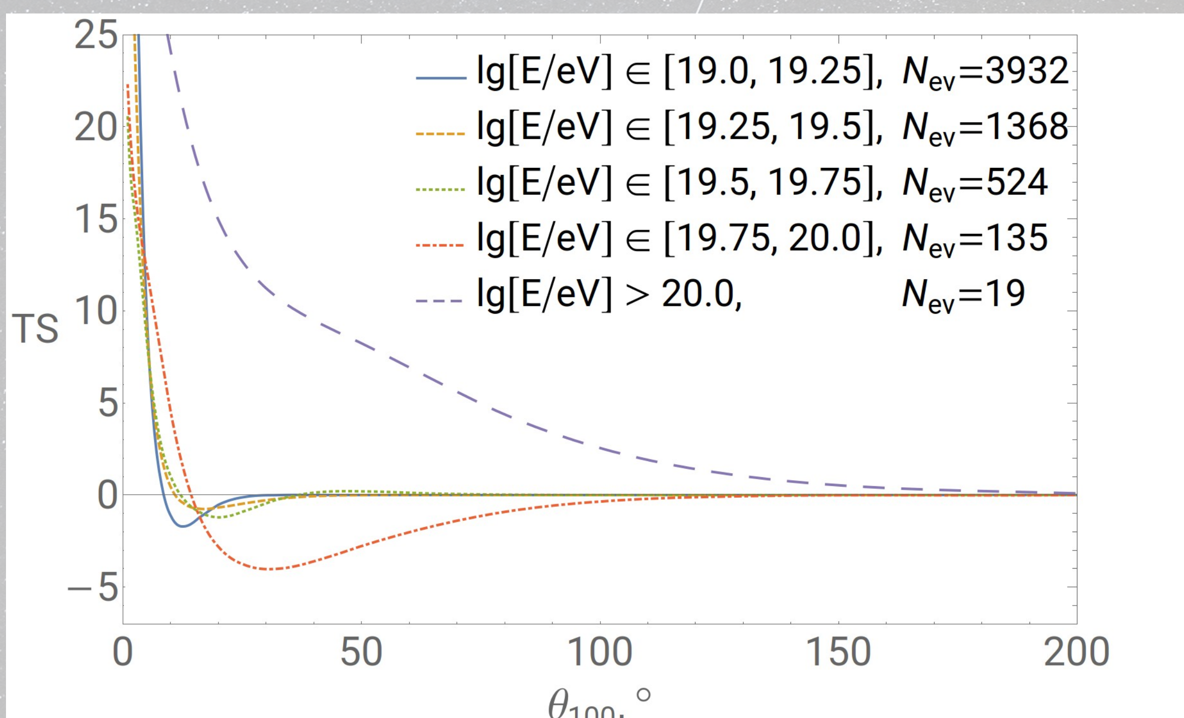
The Data Set

- 14 years of SD data
- “Anisotropy cuts” (zen. ang. < 55°)
- Cut to remove possible lightnings: ±10 min around each NLDN event
- ~6000 events with E > 10 EeV



TS for TA SD data





TA collab. Science 382 (2023) 903

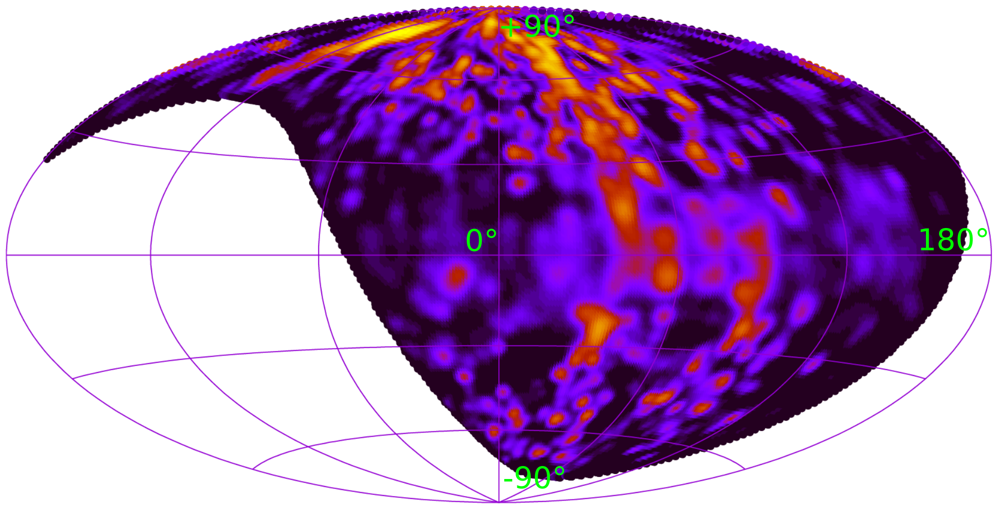
- Extremeley energetic event detected: 244 EeV
- It is uncorrelated with the LSS
- The whole data set with E > 100 EeV is also uncorrelated with the LSS

Step two: realistic UHECR mock sets

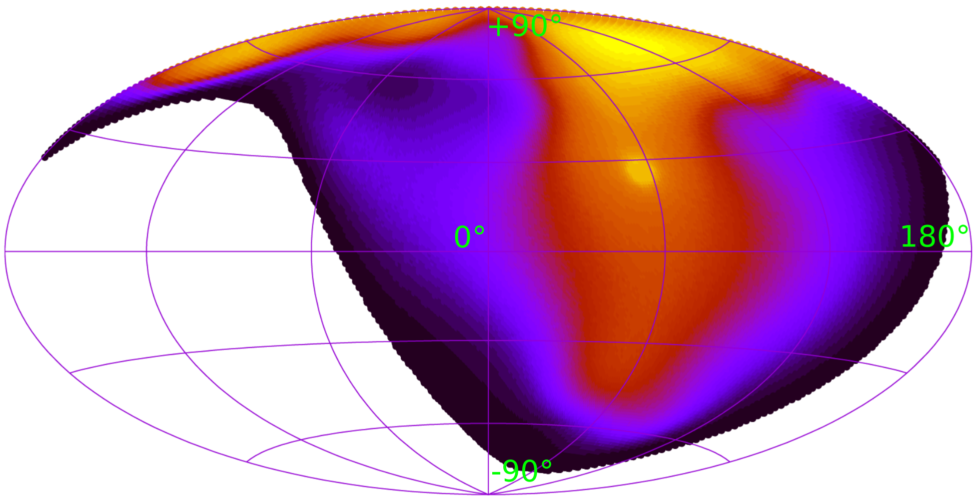
Generate UHECR sets with state-of-art simulated skymaps

- 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



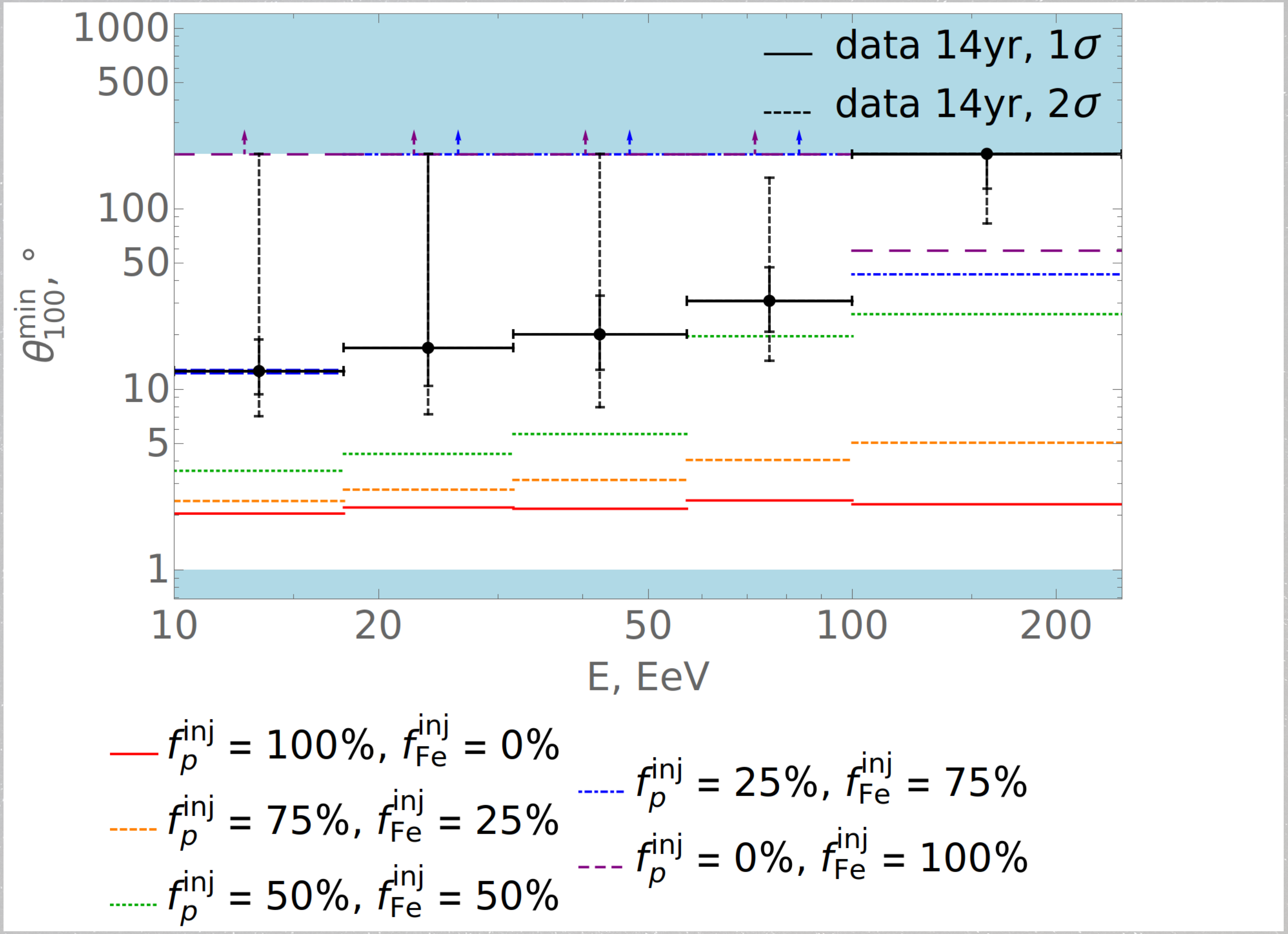
Iron map at E = 100 EeV



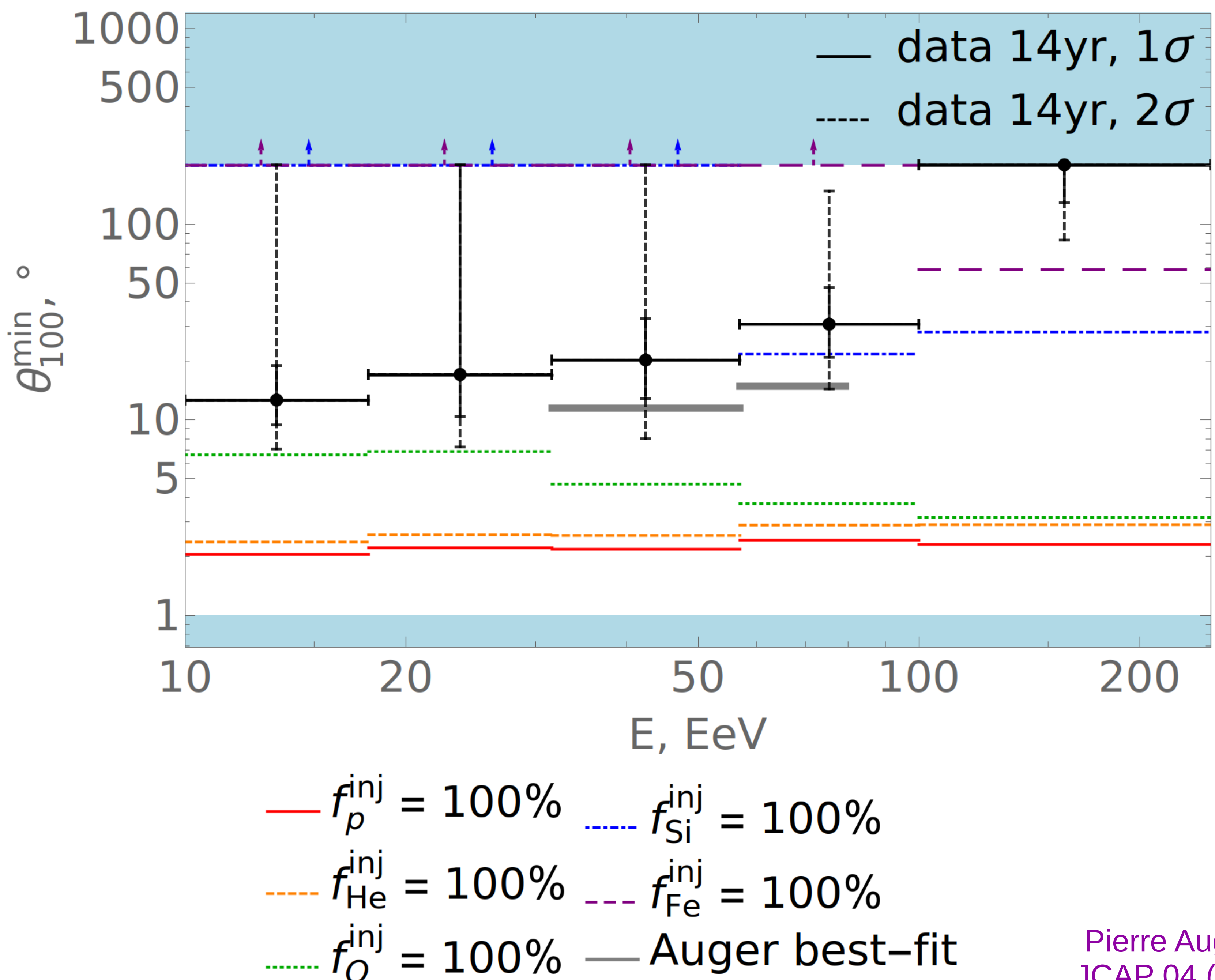
Step three: apply TS to both data and mock sets

Each injected composition model gives a line at some value of $\theta_{100, min}$:

to be confronted with the data



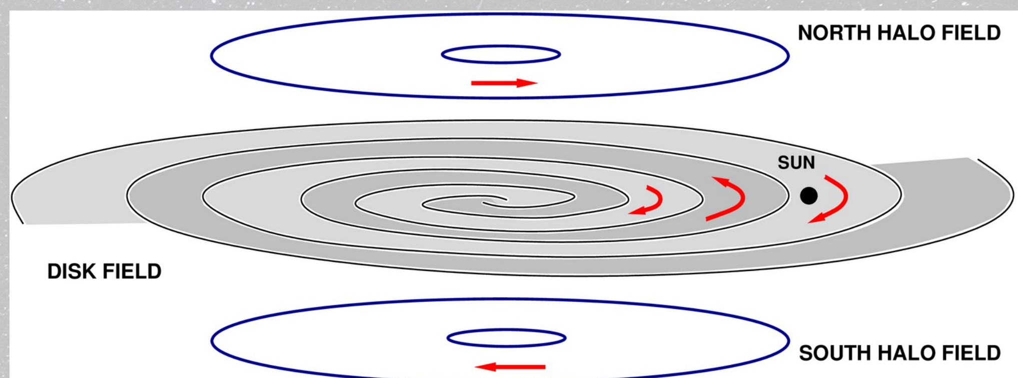
TS: injected pure elements vs the data



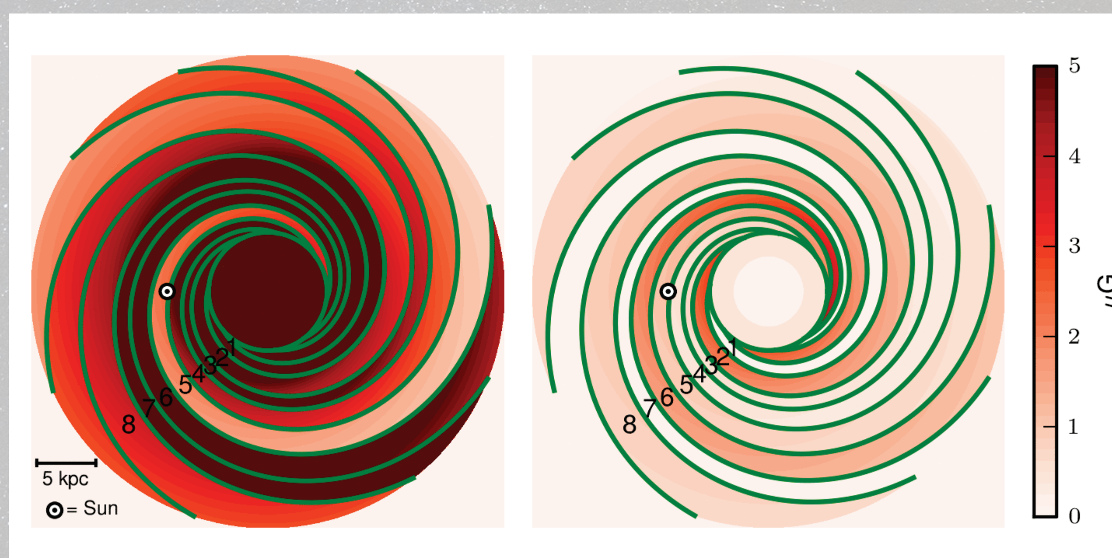
Pierre Auger collab.
JCAP 04 (2017) 038

Galactic magnetic fields

- Regular and random component, average magnitude is ~1 μG <=> 3° deflection for proton at 100 EeV
- Two reference models of regular field: Pshirkov-Tinyakov ‘11 & Jansson-Farrar ‘12
- Extragalactic UHECR sources get coherent shift in regular field and non-uniform gaussian smearing in random field

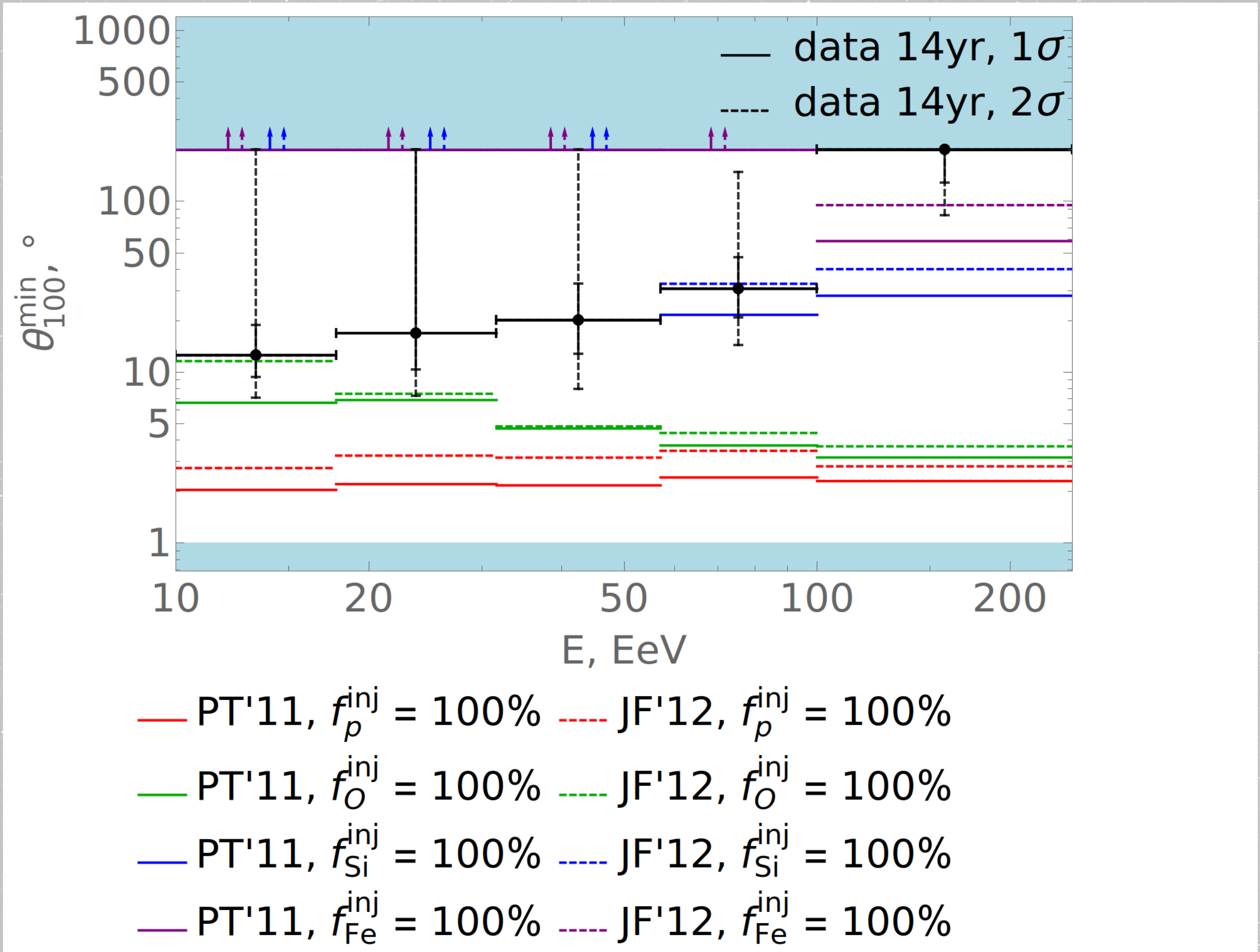


PT’11



JF’12

Results and GMF uncertainty

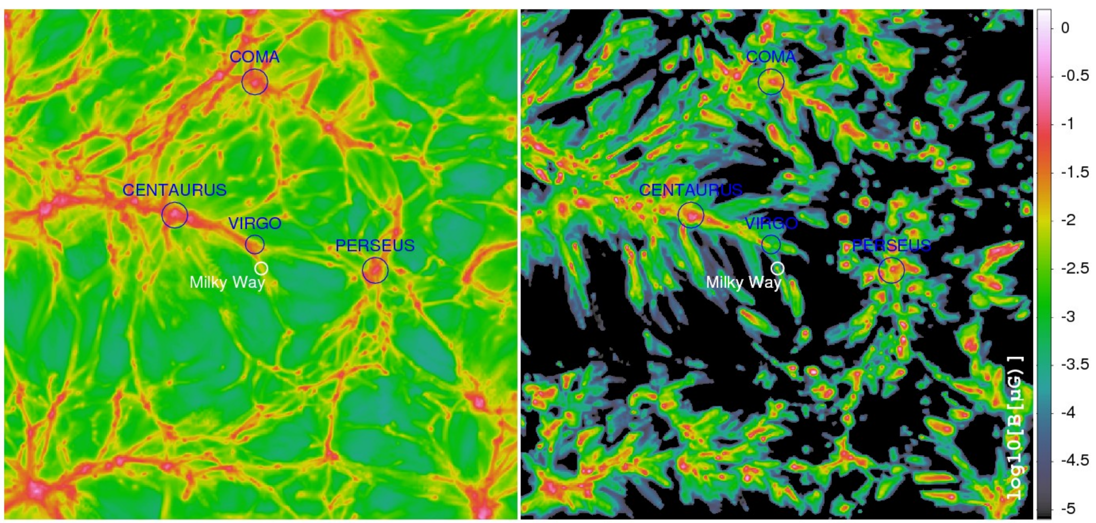


Results at all energies are stable

Extragalactic magnetic fields

- Global field in LSS voids (IGMF) and local extragalactic structures field
- Two possible origins: primordial or astrophysical
- Highly uncertain: B_{IGMF} < 1.7 nG with correlation length λ_{IGMF} ~ 1 Mpc or B < 0.05 nG with cosmological scale λ_{IGMF}
- Given the UHECR attenuation length, this yields up to 7° proton deflection at 100 EeV
- Simulated as uniform gaussian smearing for all sources

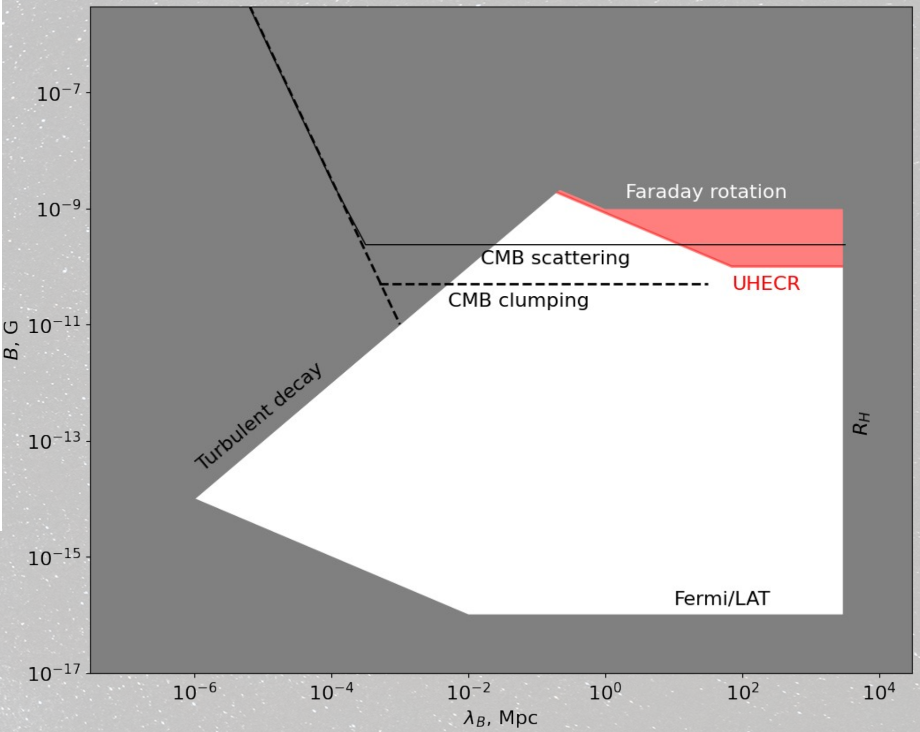
Local EGMF: simulations [Hackstein et al. 2018]



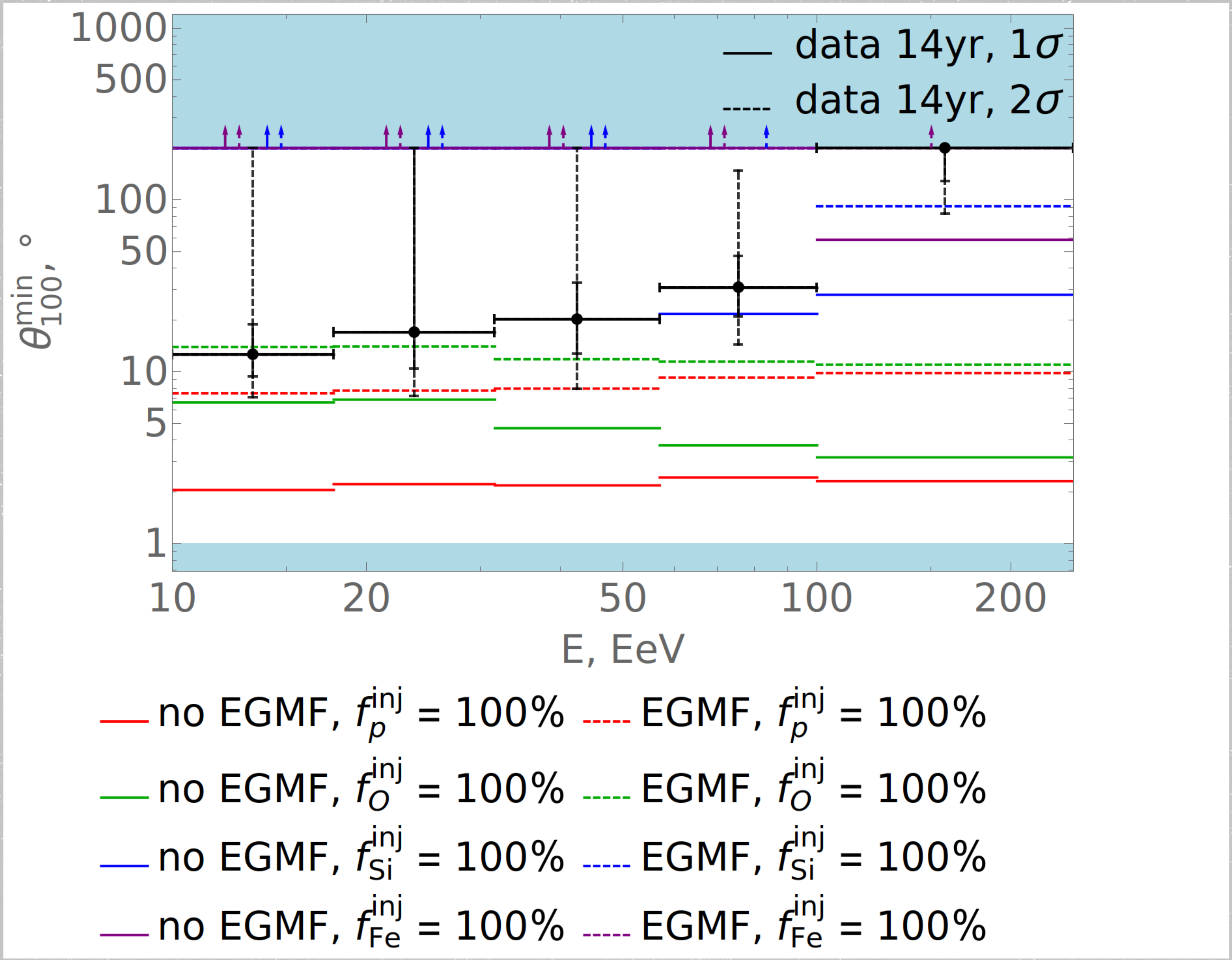
Primordial EGMF

Astrophysical EGMF

Global EGMF:
observations [Neronov et al. 2022]



Results and EGMF uncertainty



Results at E > 100 EeV are stable

Uncertainty of source number density

In our basic simulated sets all galaxies are UHECR sources:

$\rho \sim 10^{-2}$ Мпк$^{-3}$

The lower limit for sources emitting light-to-intermediate composition:

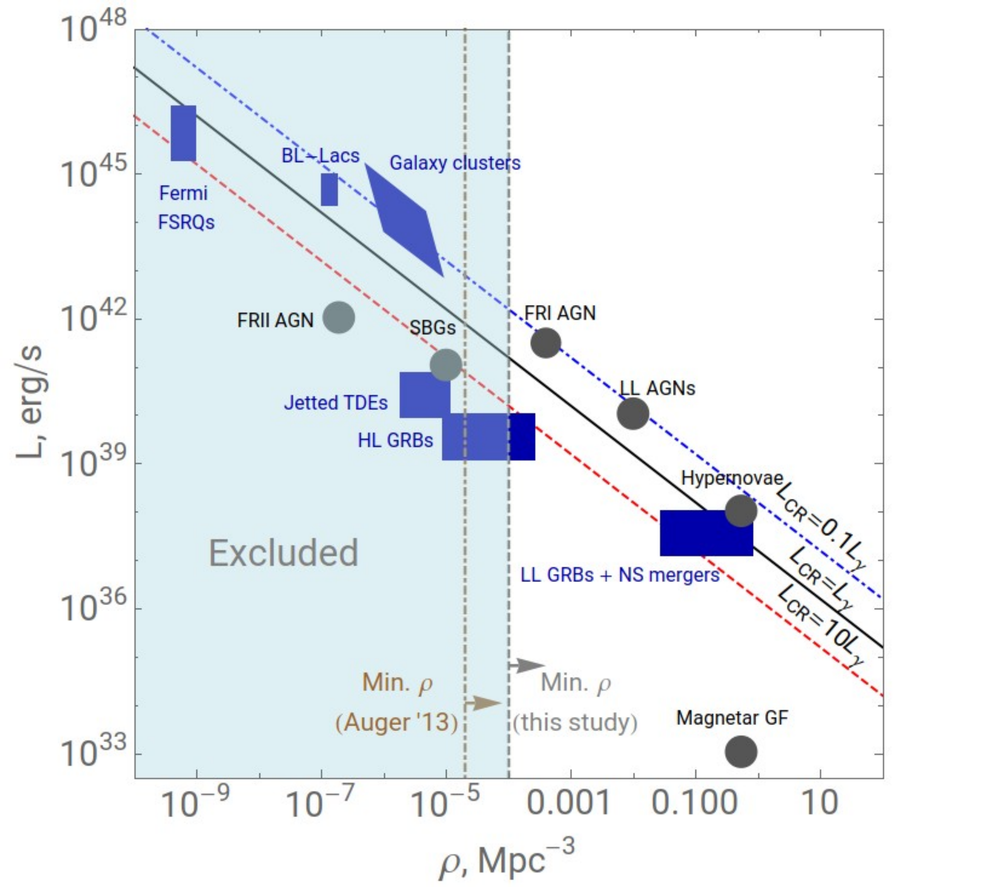
$\rho > 2 \cdot 10^{-5}$ Мпк$^{-3}$

Pierre Auger collab. 2013

For sources emitting heavy composition:

$\rho > 10^{-4}$ Мпк$^{-3}$

MK 2024

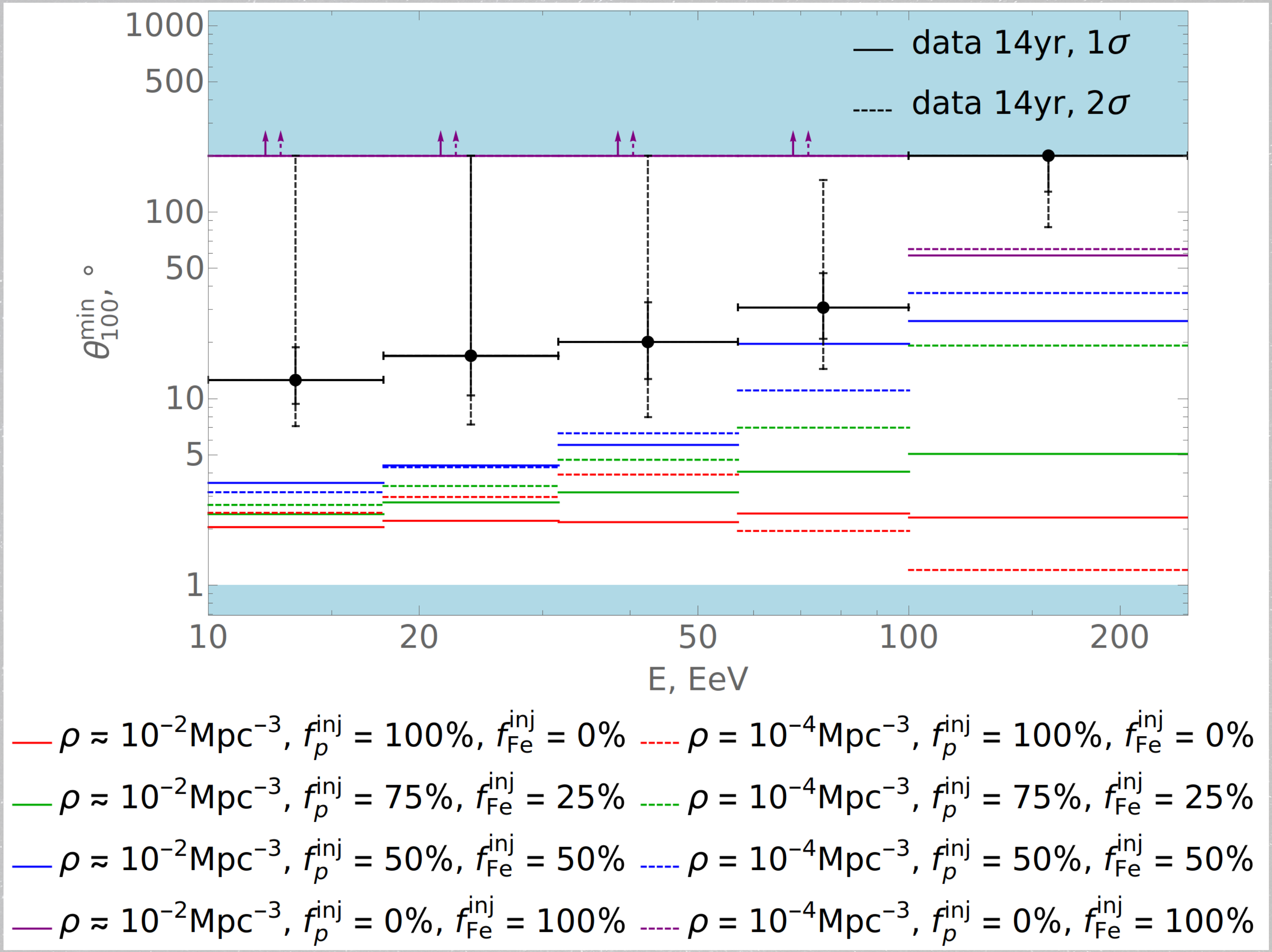


Test the robustness of our results for sournce number density uncertainty

- Test two scenarios: $\rho_0 = 10^{-4}$ Мпк$^{-3}$ и $\rho_0 = 2 \cdot 10^{-5}$ Мпк$^{-3}$
- Make random thinning of 2MRS catalog to get $\rho = \rho_0$
- Make 20 thinned catalogs (to get the ~5% accuracy)
- Simulate mock event sets with various compositions for each of these catalogs
- Apply the same TS (based on the full 2MRS) to each mock set
- Pick the catalog where the results are the most discrepant from the basic ones

Results and source number density uncertainty I

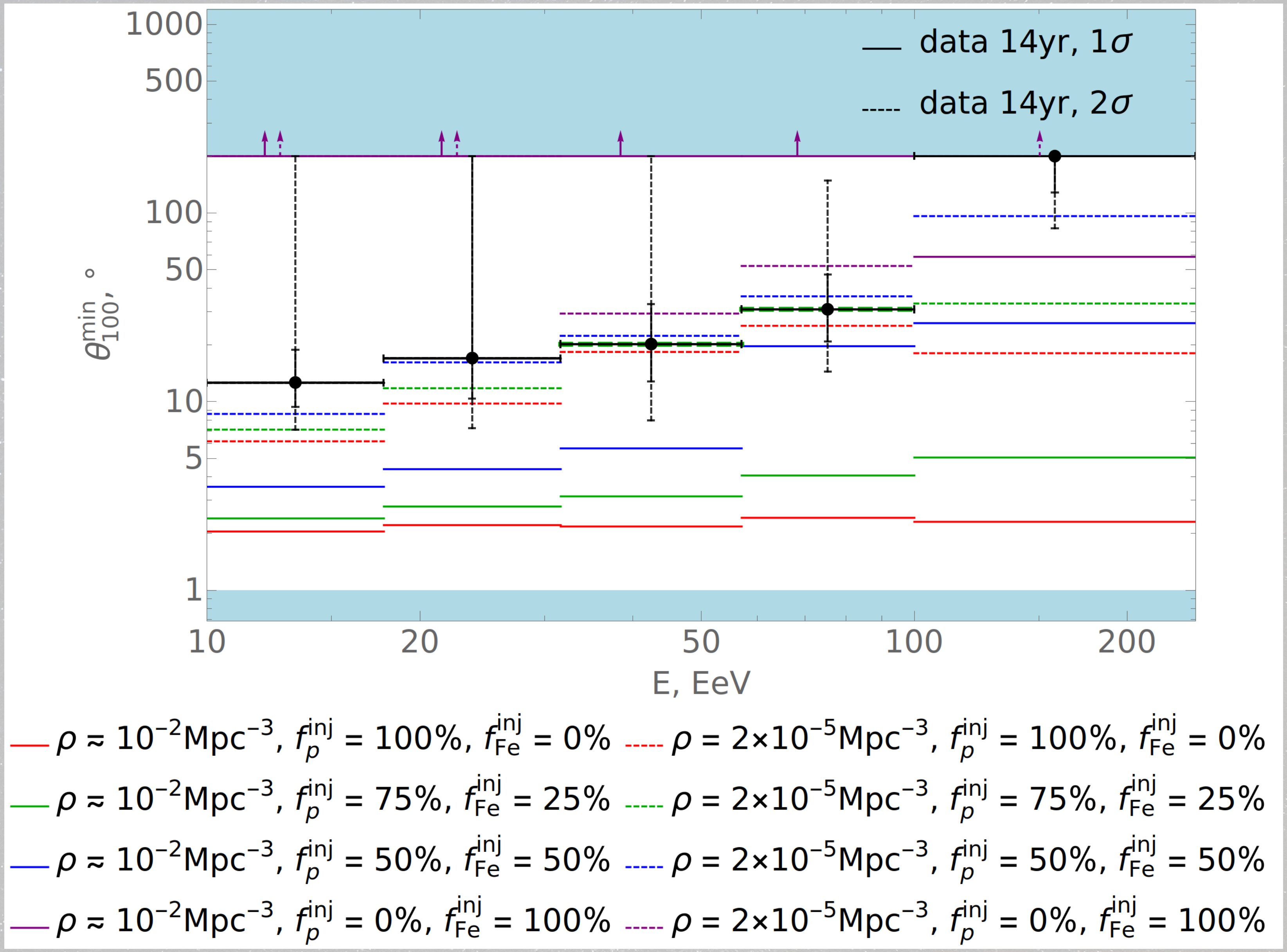
$\rho = 10^{-4}$ Mpc^{-3}



Results at all energies are stable

Results and source number density uncertainty II

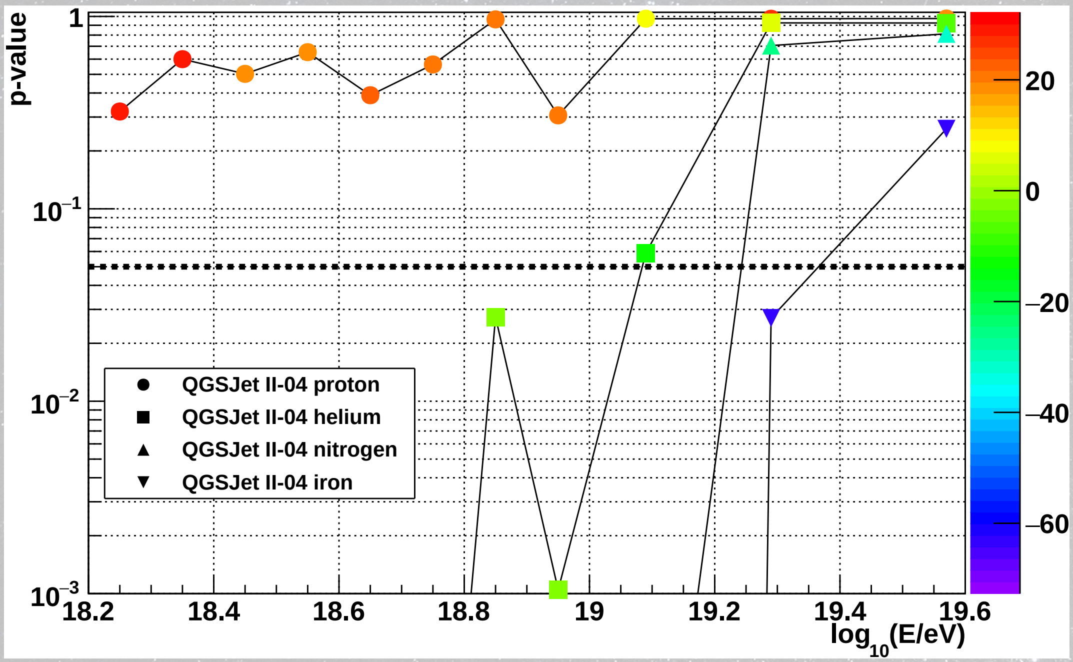
$\rho = 2\cdot10^{-5}$ Mpc^{-3}

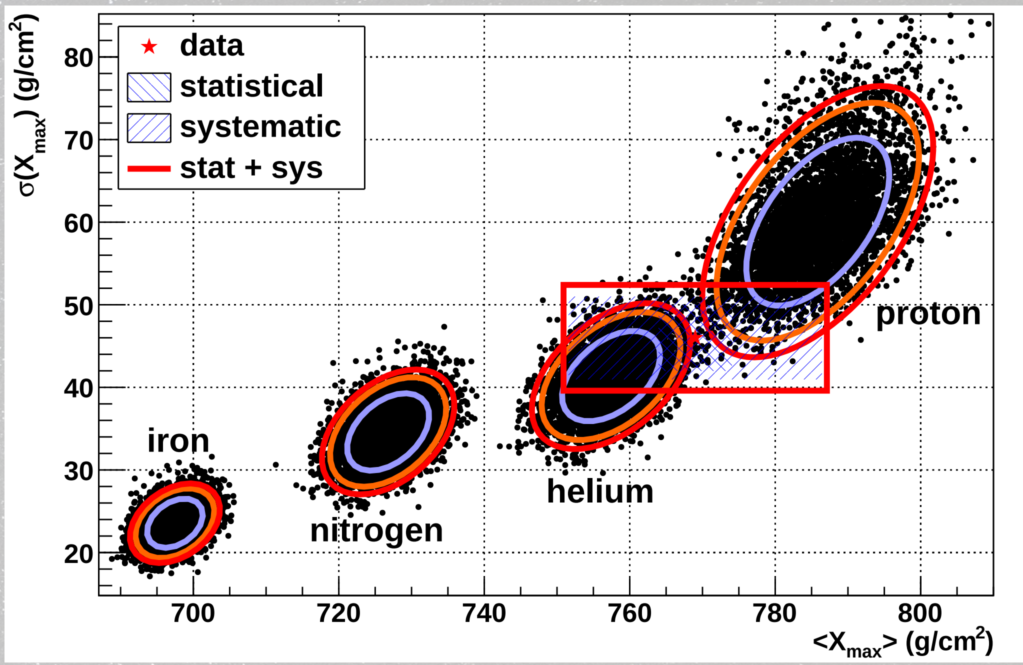


Results at E > 100 EeV are stable

Bonus: compare with FD composition measurements

Standard method (FD) Telescope Array measurements are consistent with
p and He composition at 10 < E < 20 EeV

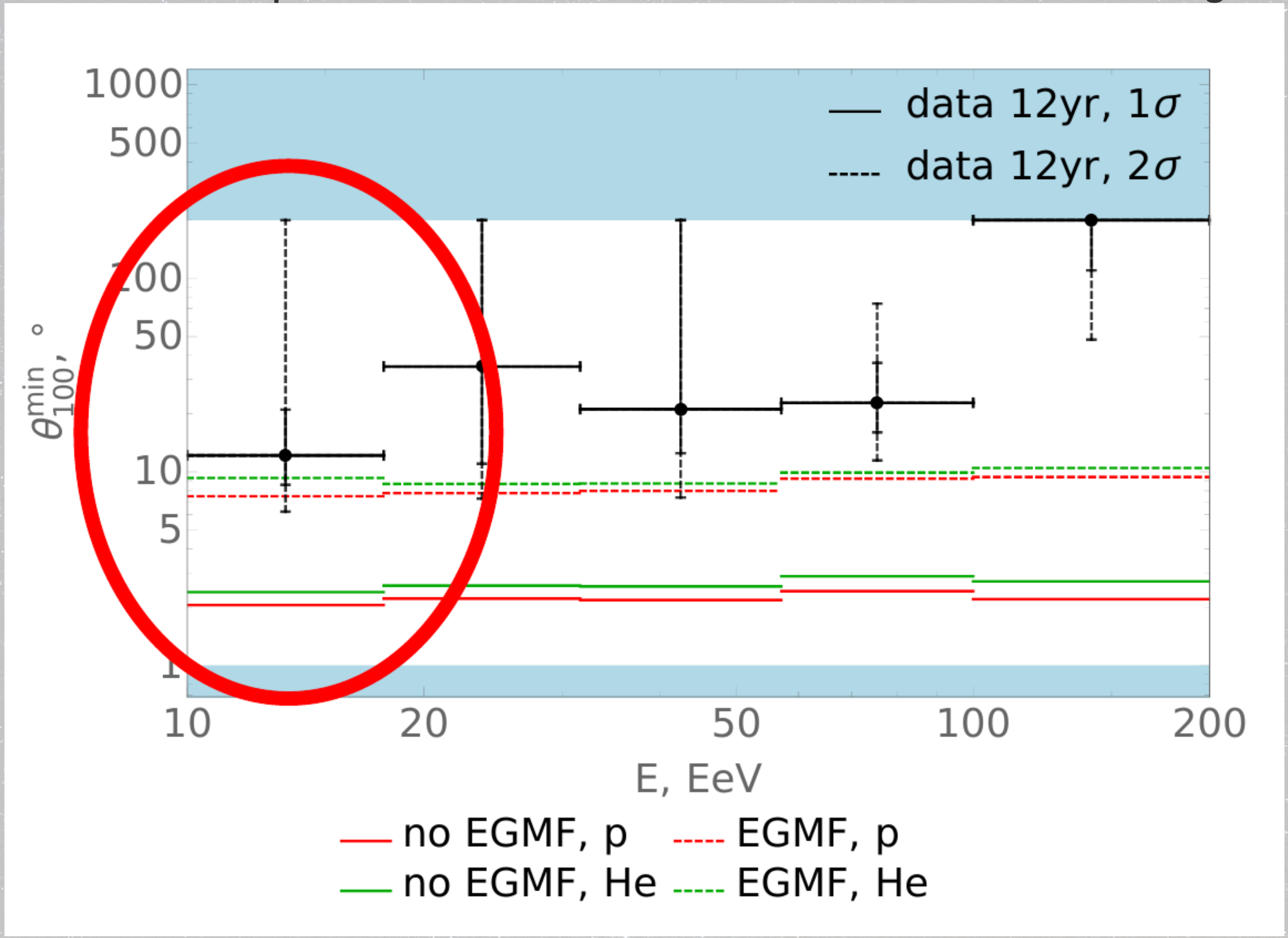




TA collab., ApJ 858 (2018) 76

Bonus: compare with FD composition measurements

How to reconcile our results about large deflections at 10 < E < 20 EeV with p and He composition measured with the FD at these energies?



Indication for strong EGMF?!

Conclusions

- **A new method** to estimate UHECR injected mass composition from their arrival directions is developed and applied to the Telescope Array data
- The most interesting (and unique) **results are at E > 100 EeV** – events are **uncorrelated with LSS**
- This implies a **very heavy composition** – indication for **spectrum cutoff in sources** rather than GZK cutoff
- This **result is robust to all known uncertainties**, including those of galactic and extragalactic magnentic fields and UHECR source number density

Thank you!

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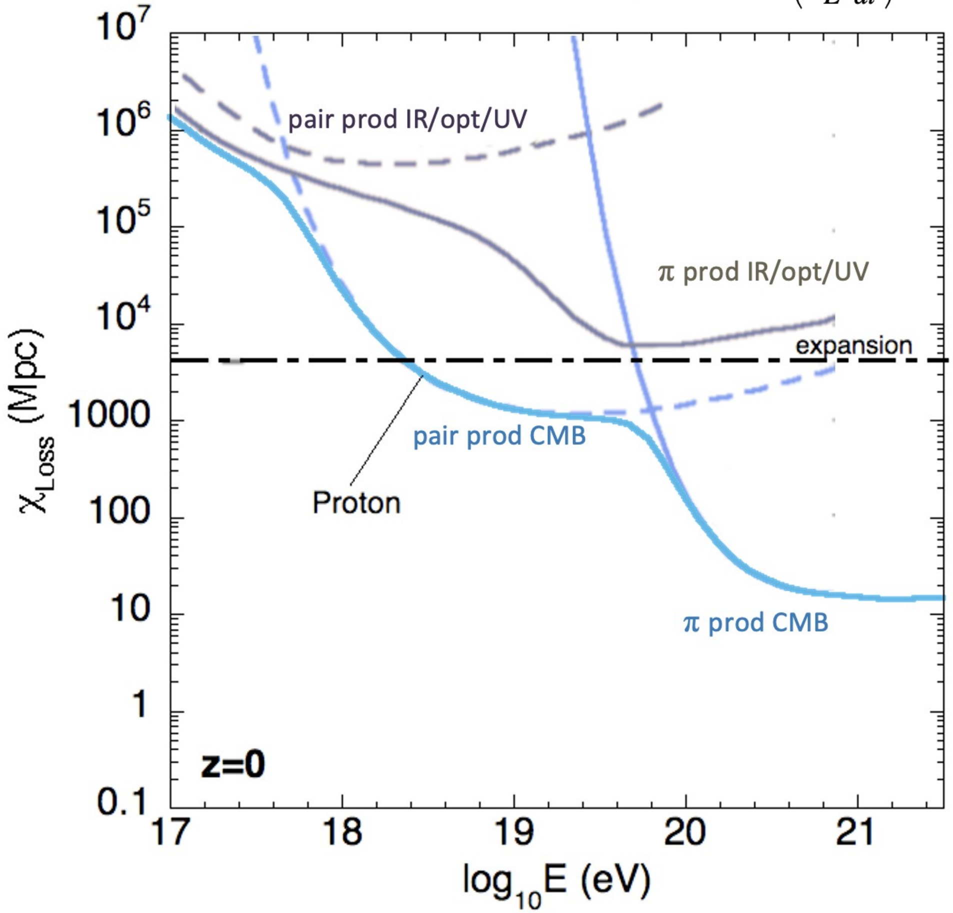
Backup slides

UHECR attenuation

- UHECR are attenuated on soft photon cosmic background (EBL, CMB, Radio bckg.)
- The attenuation length is L~1 Gpc at 10 EeV and L~100 Mpc at 100 EeV
- We can see only sources in local Universe

Proton attenuation length $\chi_{loss} = c\left(-\frac{1}{E}\frac{dE}{dt}\right)^{-1}$



nuclei attenuation length