UHECR mass composition from anisotropy with the Telescope Array

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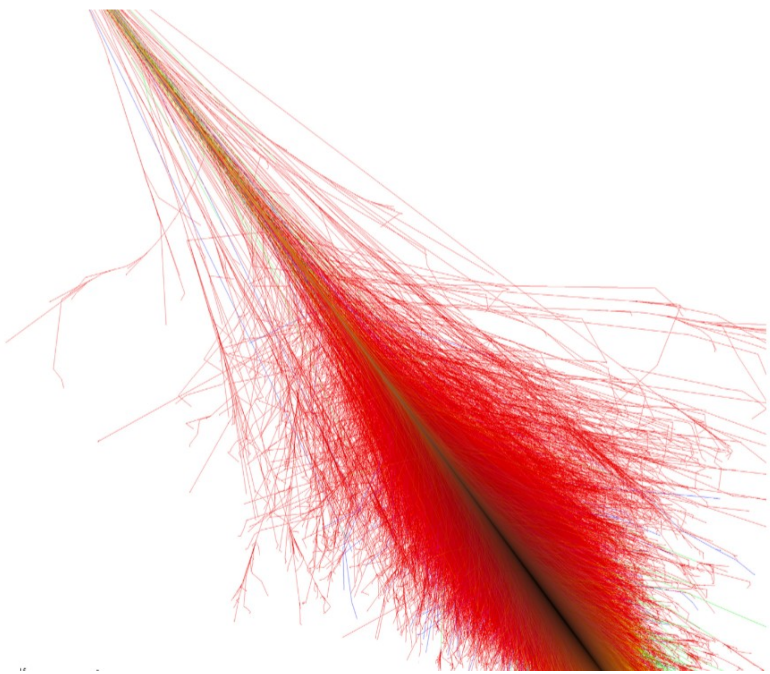
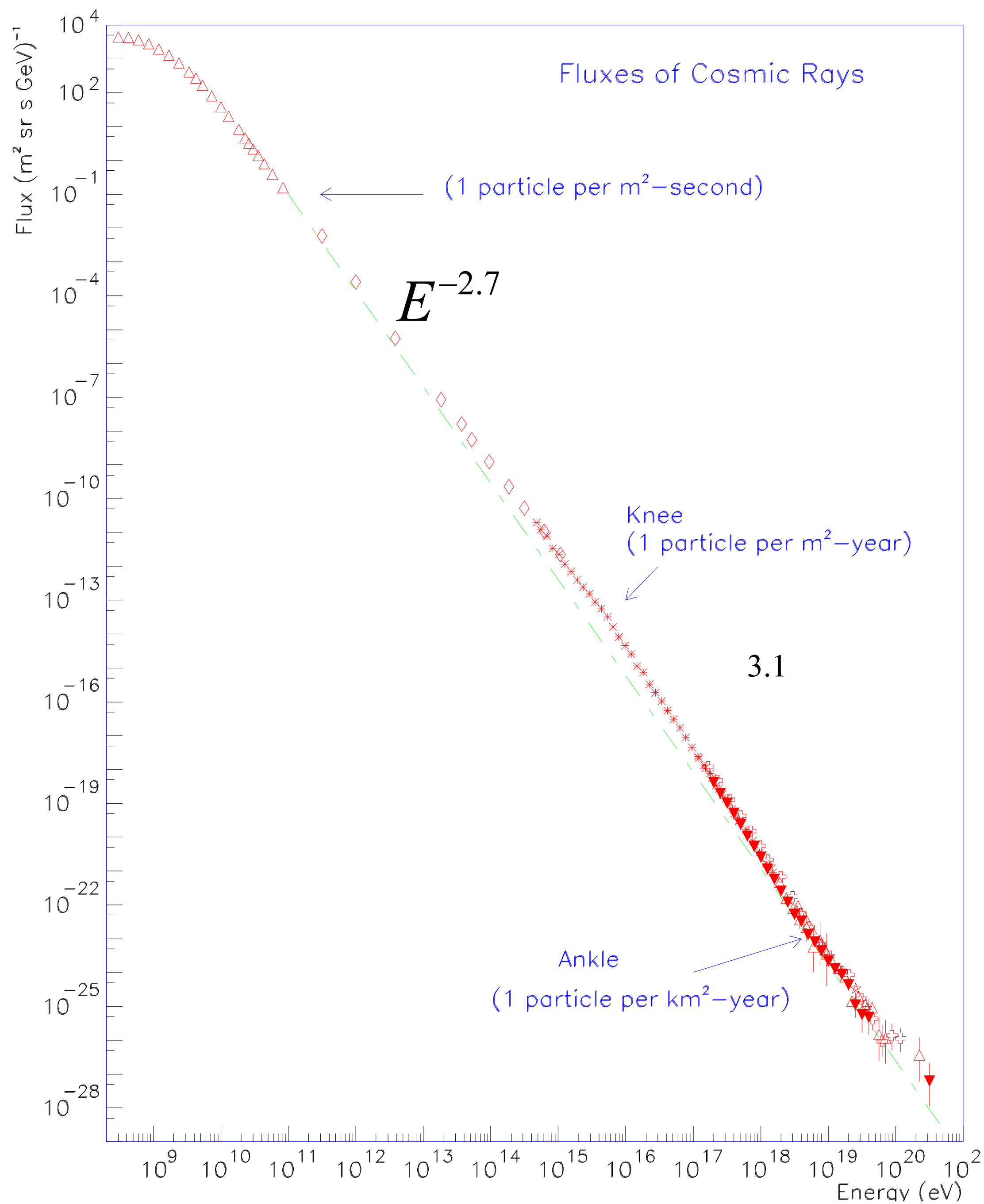
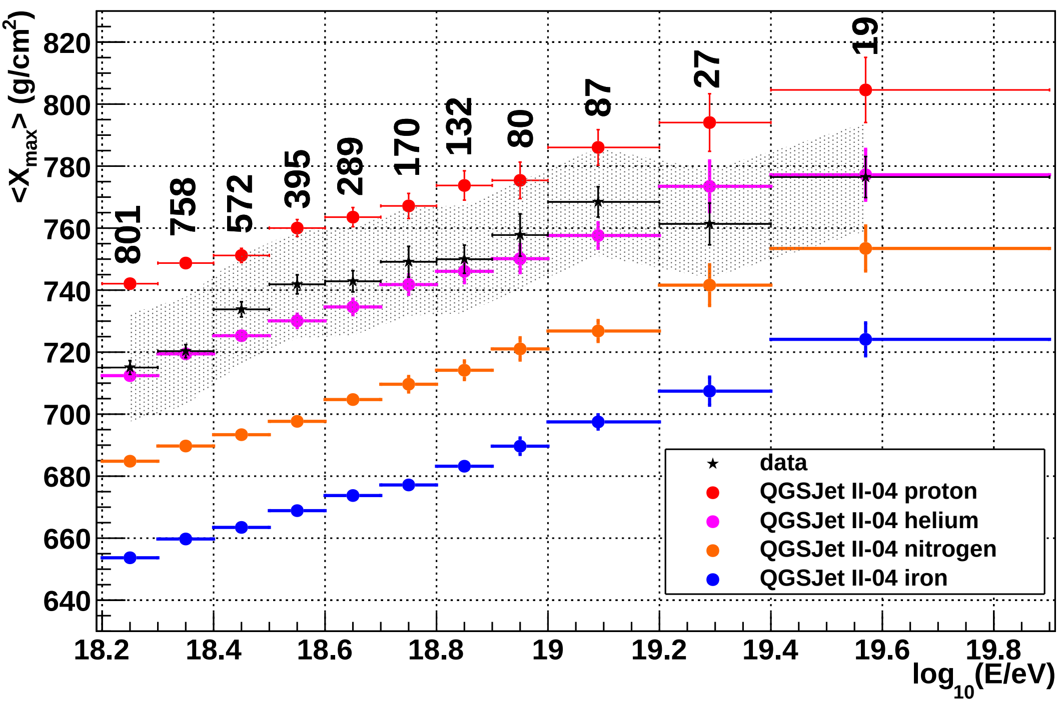
Ultra-high energy cosmic rays

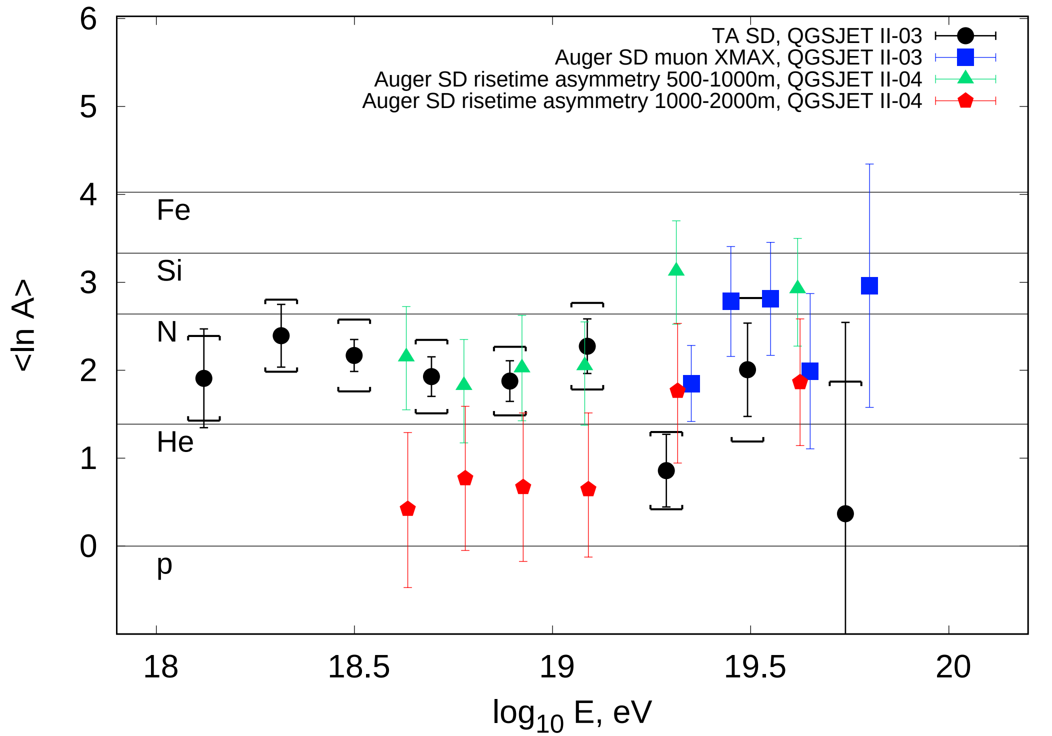
- Charged particles with E > 1 EeV
- Flux ~ 1 $km^{-2}yr^{-1}sr^{-1}$
- Steeply falling spectrum
- Origin still unknown (extragalactic)
- Detecting via showers of charged particles in atmosphere





UHECR observables: composition





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

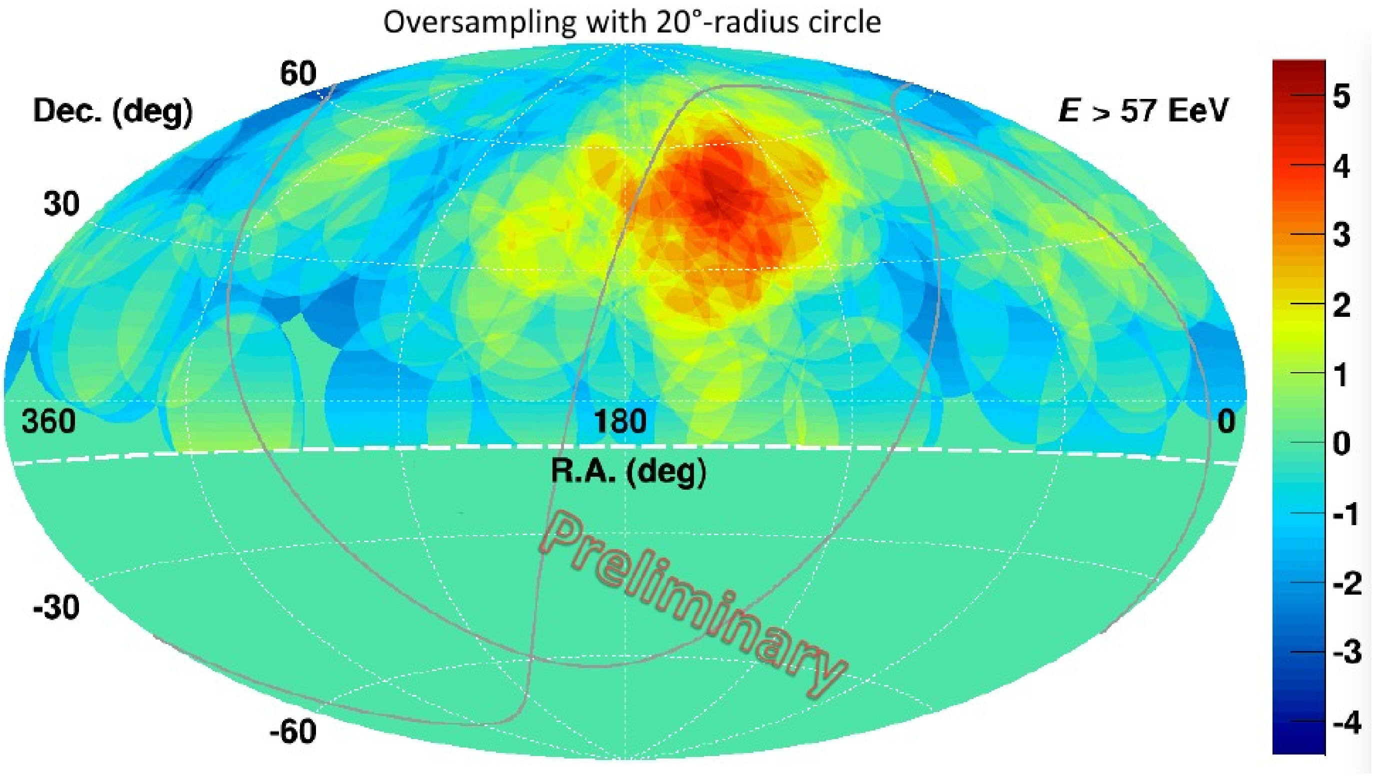
But

- There is 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 ~15 events: not enough for both methods

UHECR observables: anisotropy

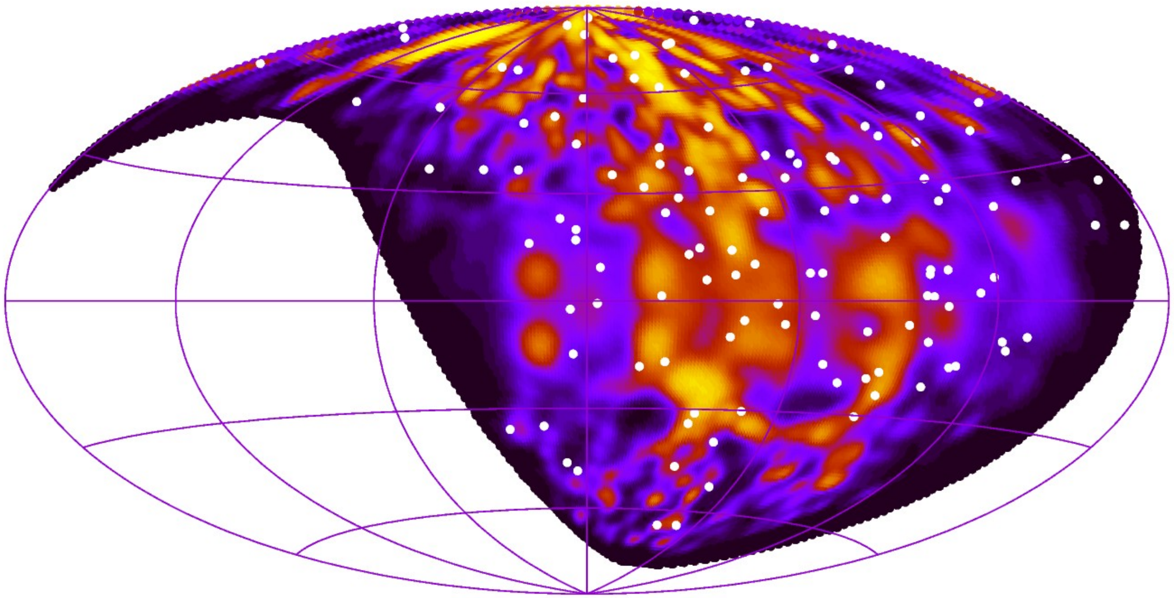


- Arrival directions are measured with **good precision** (~1°)

But

- Have **limited potential** to determine the UHECR origin due to their deflections:
- 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

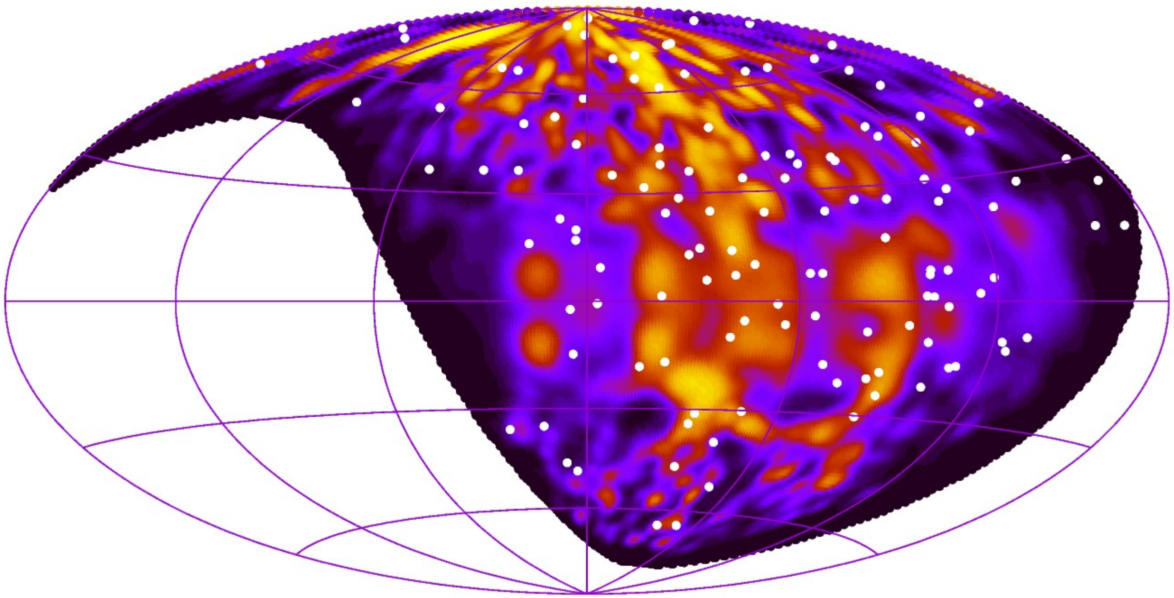
- Magnetic fields
  - EGMF: observations B < 1 nG
  - EGMF: simulations B ~ 0.01 nG

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

- Mass composition: up to factor 26 uncertainty in terms of deflections

UHECR flux model

How to disentangle all the uncertainties?

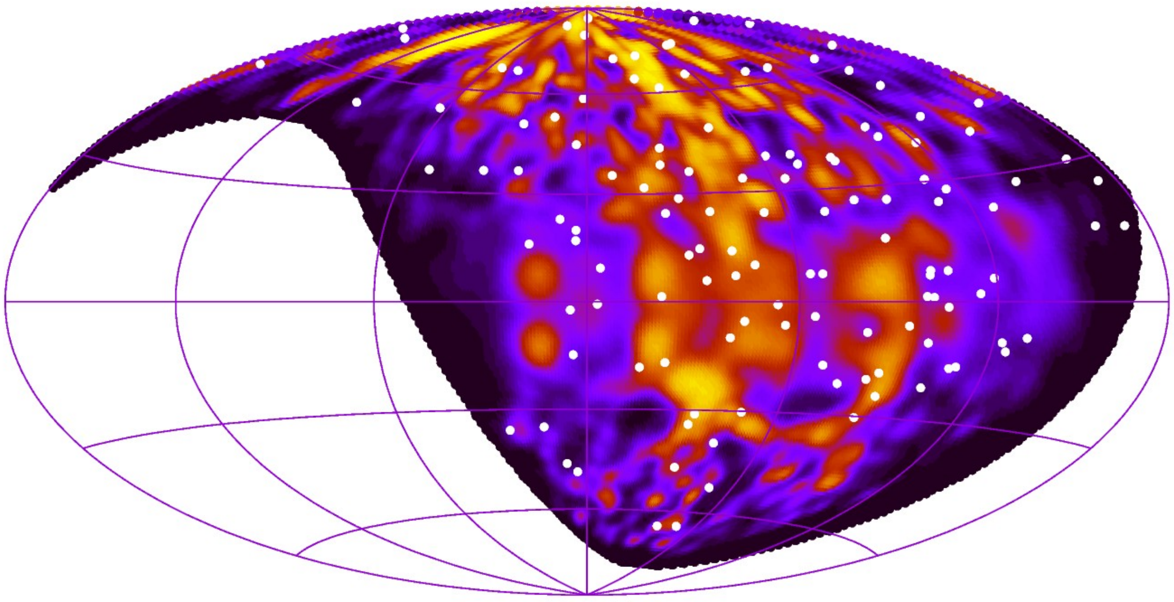


- Sources: the most conservative model – 2MRS + isotropy for far sources – covers all scenarios without large anisotropy
- Magnetic field
  - EGMF deflections: neglect altogether ($B \leq 0.1$ nG)
  - GMF deflections: fix one of the models (regular + random)

  } 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, JCAP 04 (2021) 065

- **Simulate realistic UHECR mock sets** originating from LSS with varying mass composition
- Introduce a **robust measure** of UHECR set characteristic deflection from LSS
- **Apply the measure** to both mock sets and data set and infer the mass composition from data

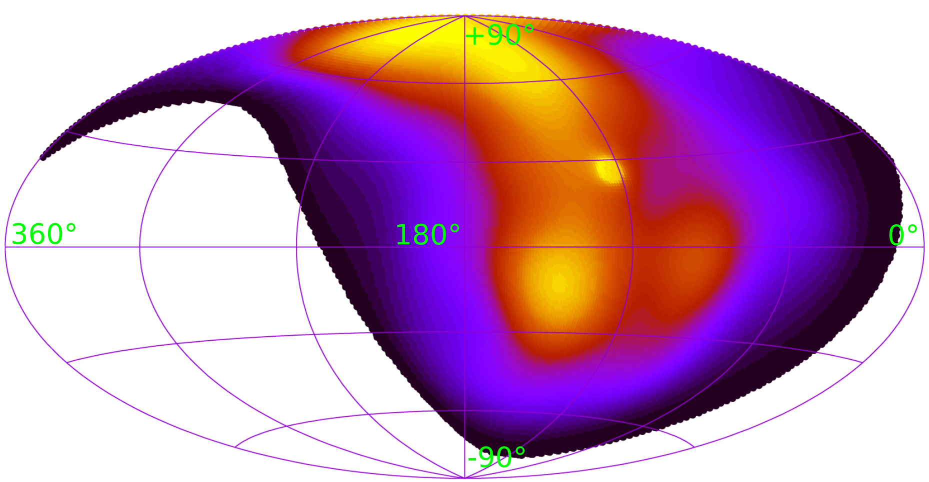
TS construction

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

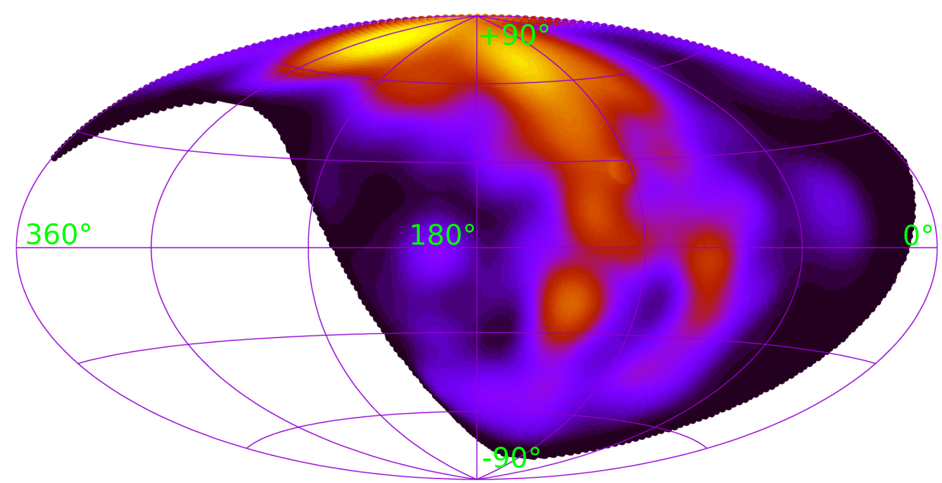
$$TS(\theta_{100}) = -2 \sum_{E_k} \left(\sum_{i}^{\text{events}} \ln \frac{\Phi_{E_k}(\theta_{100}, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)} \right)$$

- 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



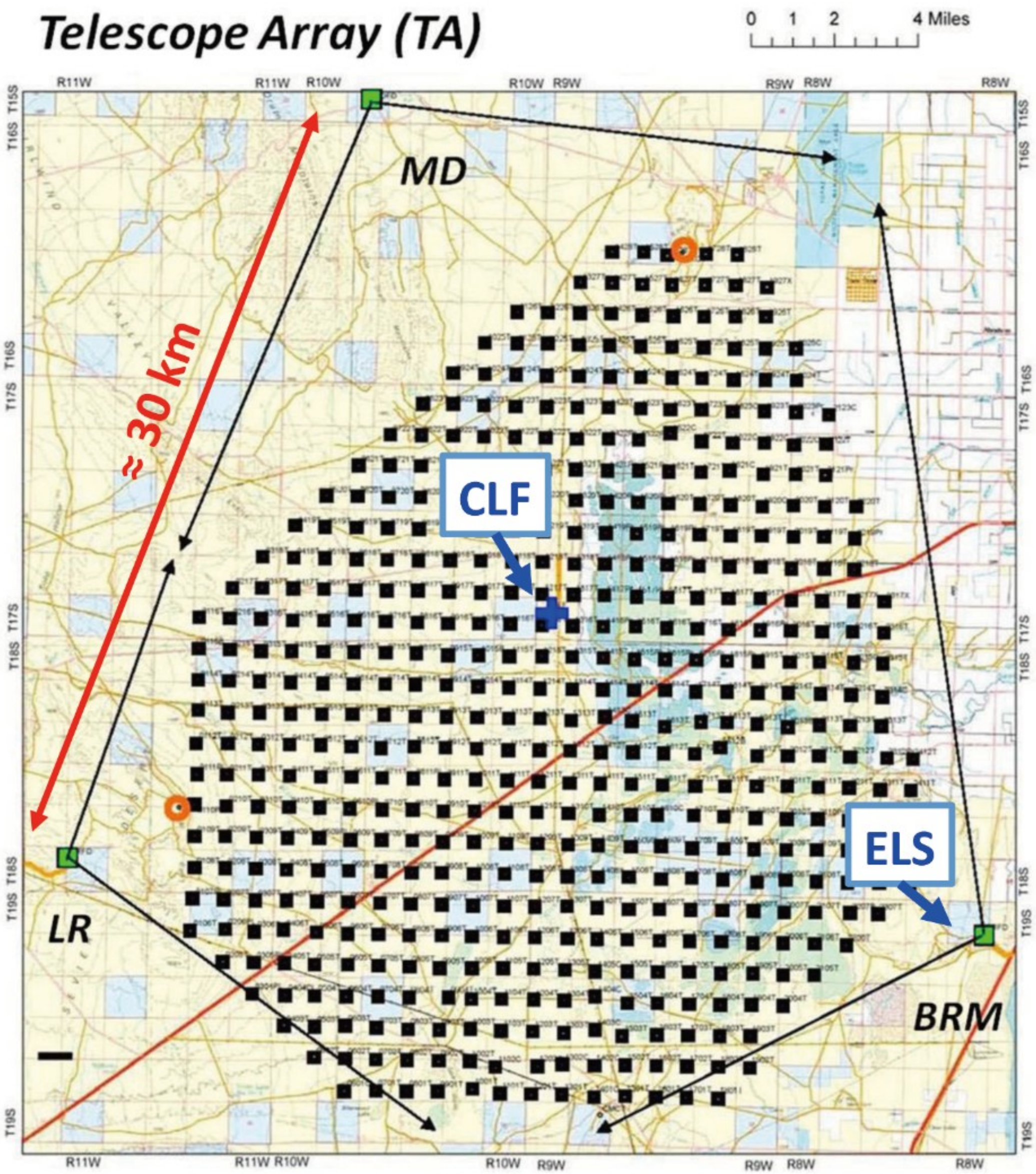
Telescope Array Surface Detector

The Experiment

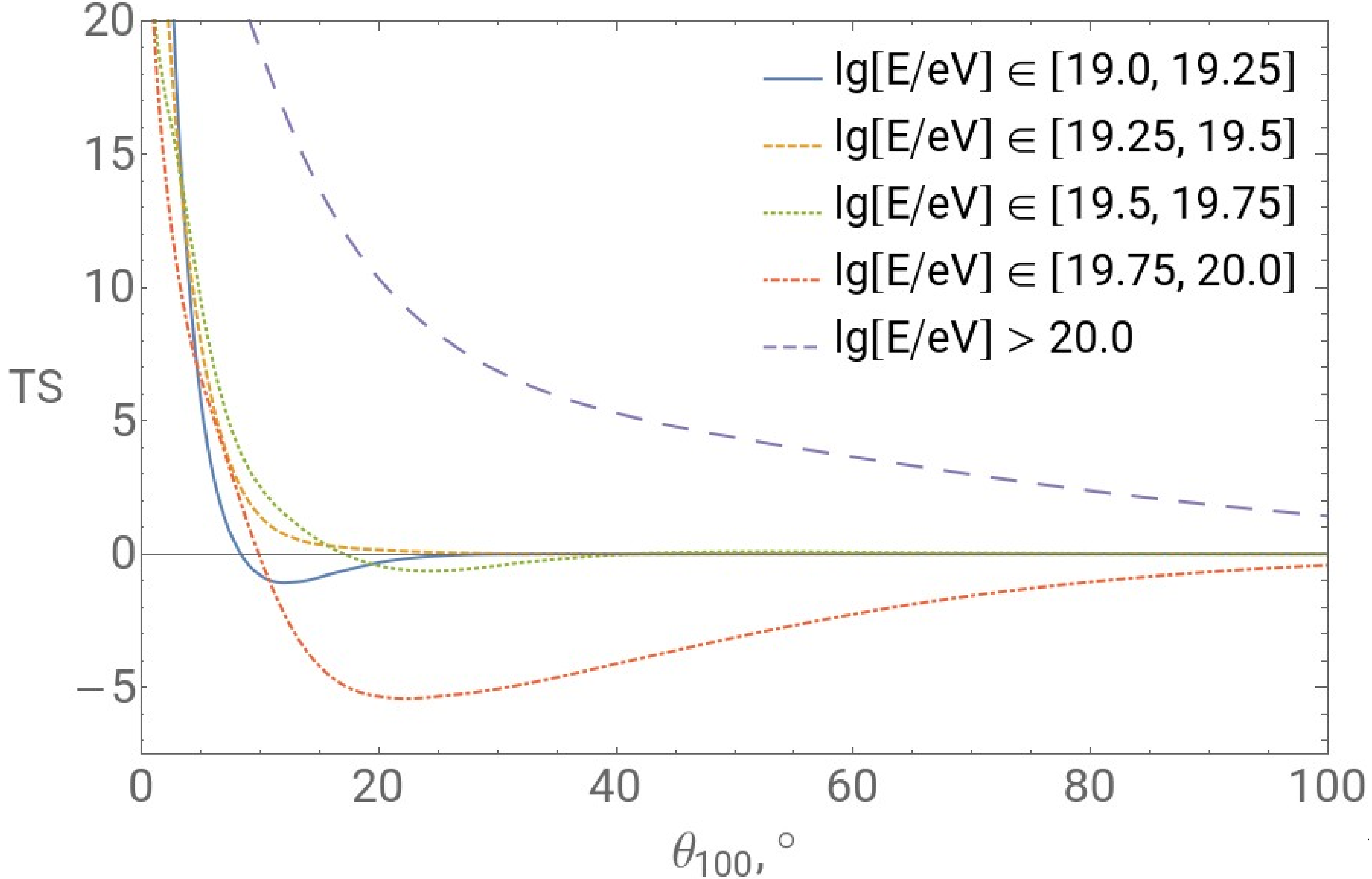
- Largest UHECR experiment in the Northern Hemisphere
- 507 SD stations
- ~700 km² area, 14 years of continuous data collection

The Data Set

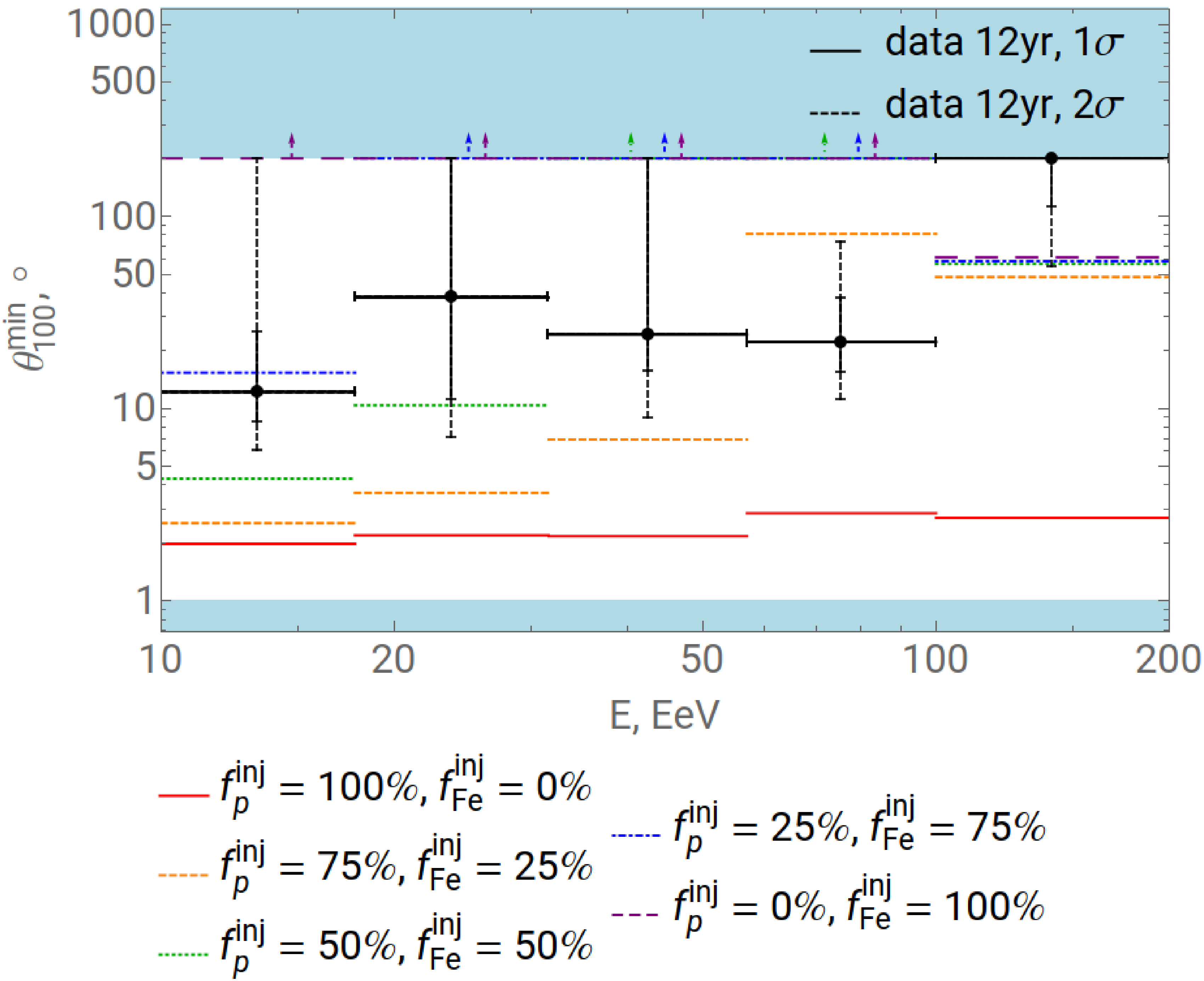
- 12 years of SD data
- “Anisotropy cuts” (Z.A. < 55°)
- Cut to remove possible lightnings: ±10 min around each NLDN event
- ~5000 events with E > 10 EeV



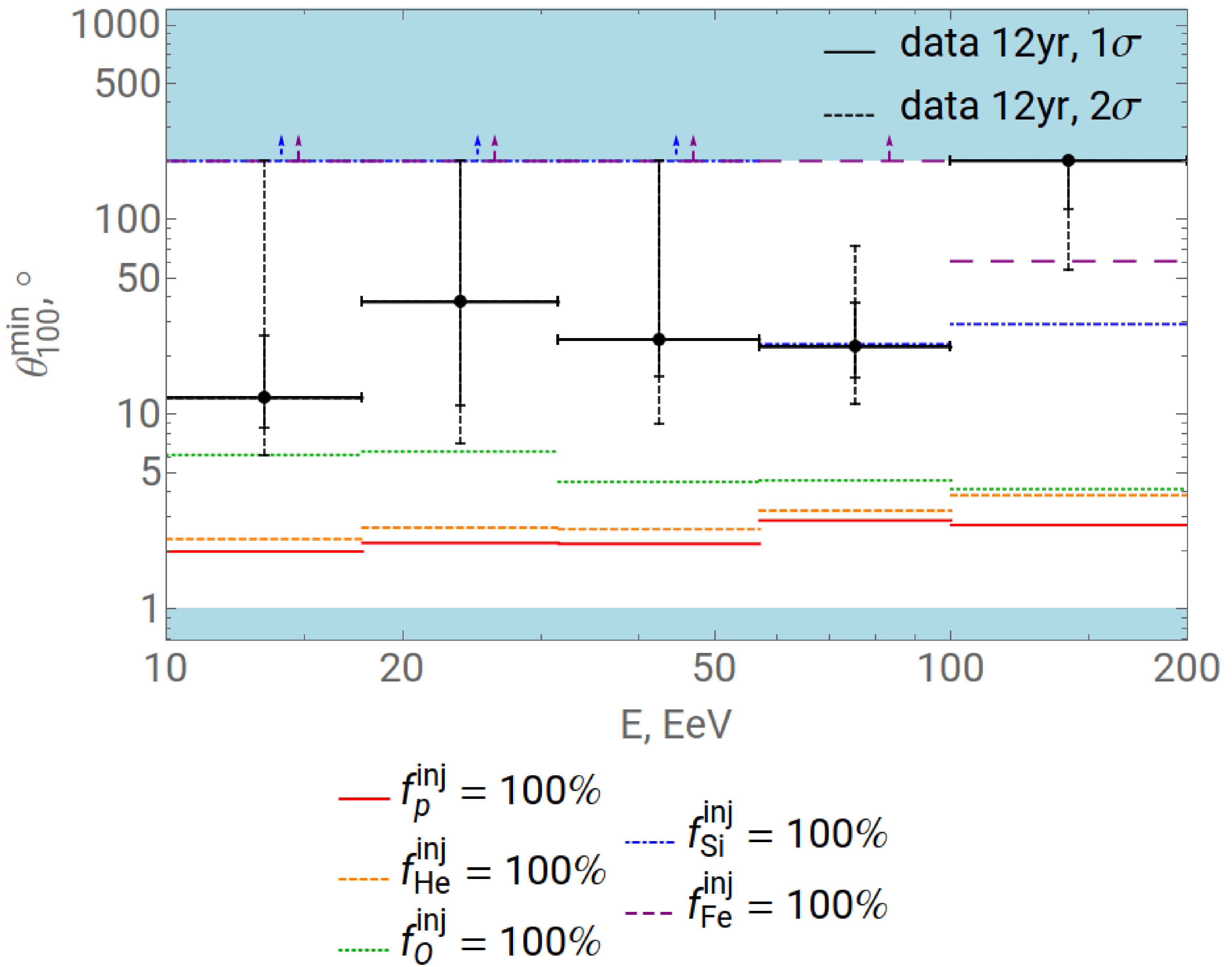
TS for TA SD data



Injected p-Fe mixes vs data

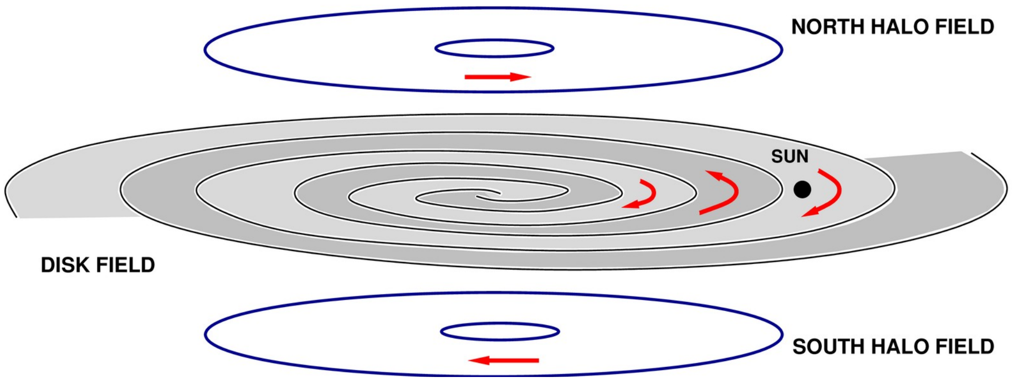


Injected pure elements vs data

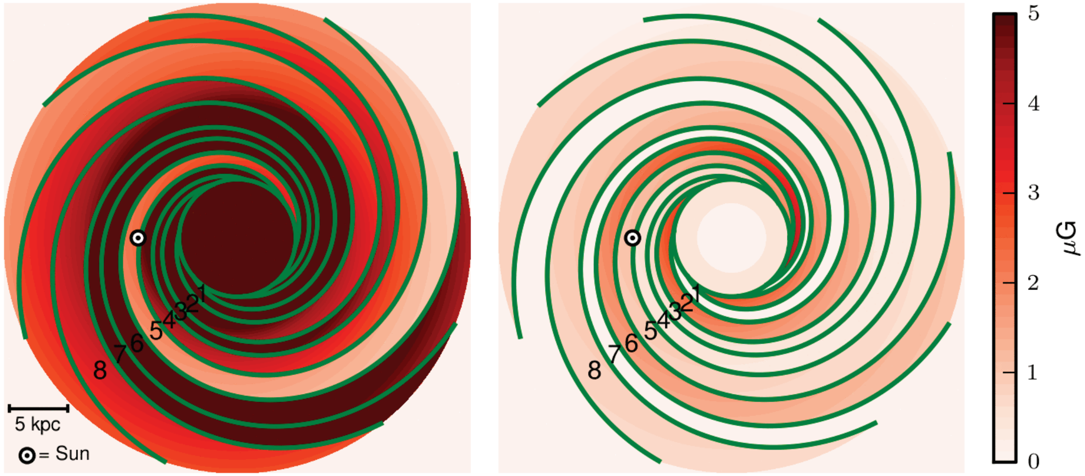


Galactic magnetic fields

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

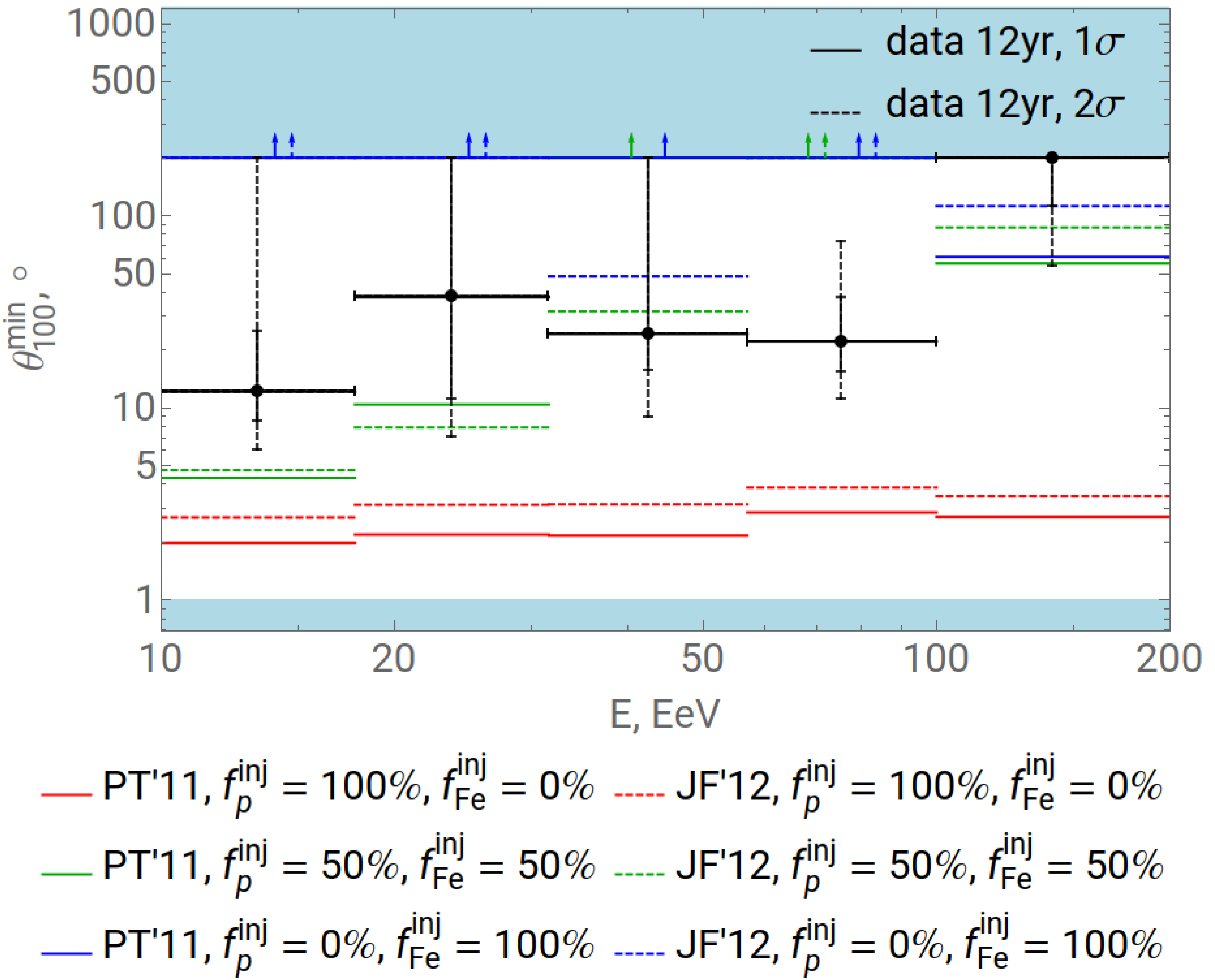


PT'11



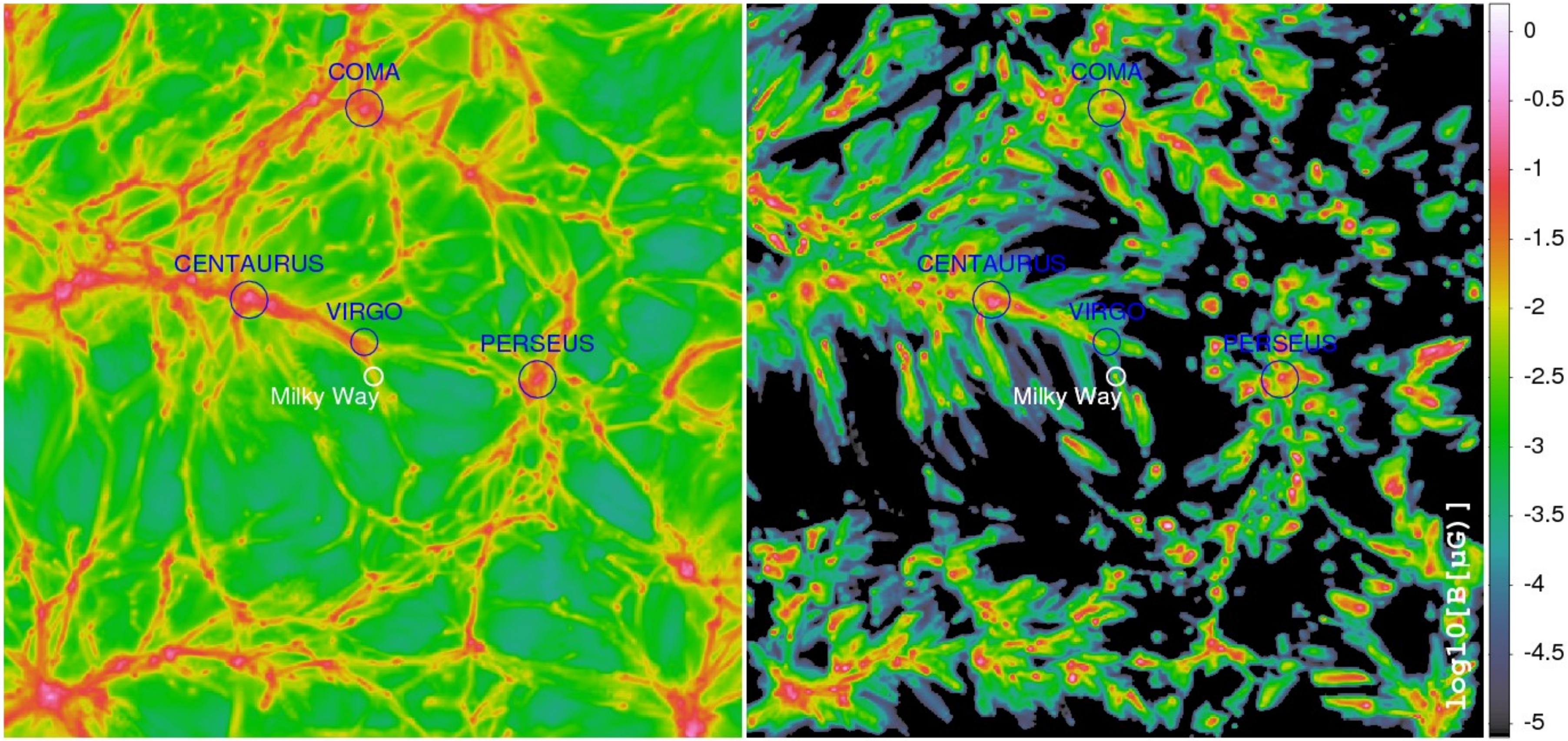
JF'12

GMF uncertainty impact on results



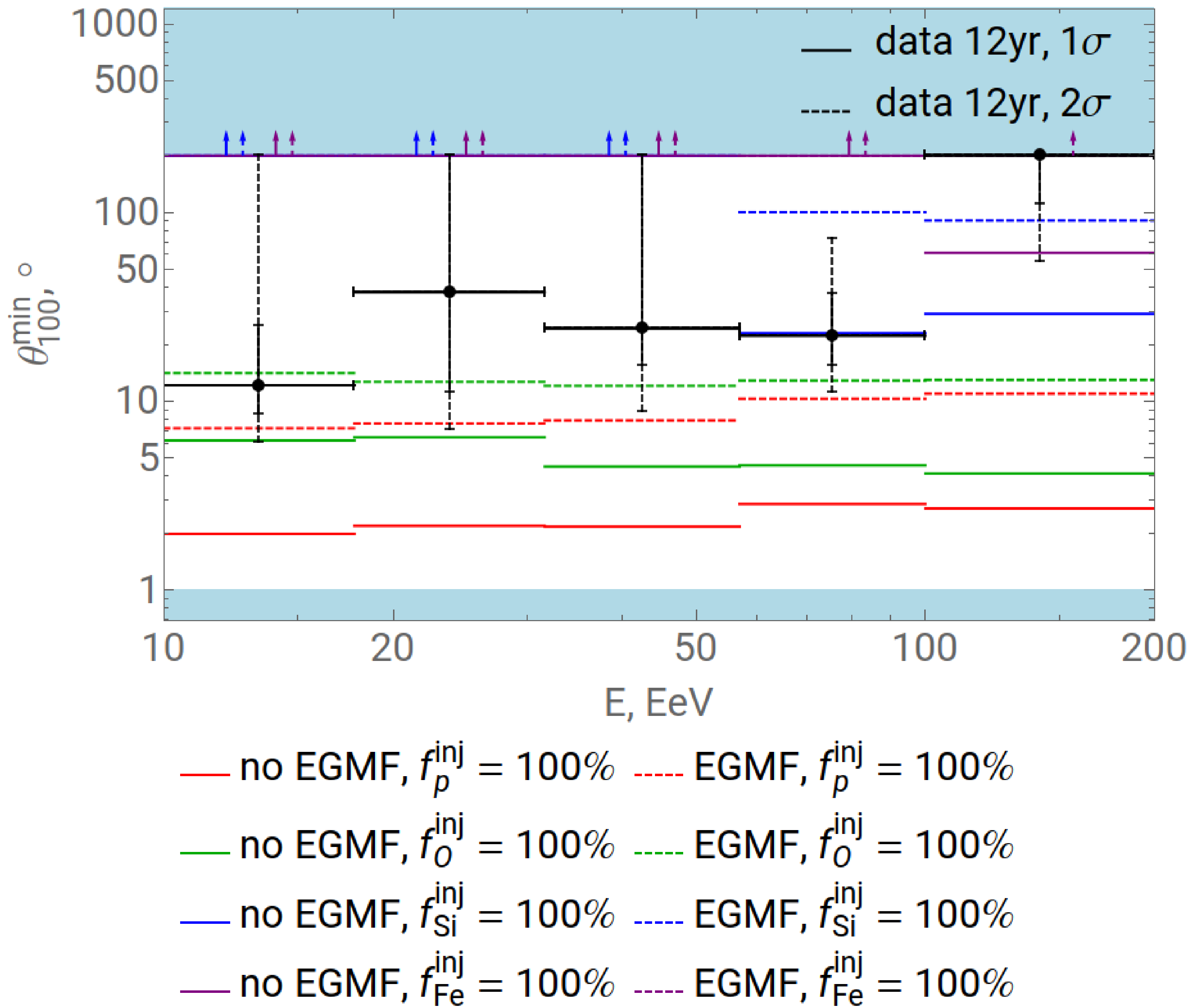
Extragalactic magnetic fields

- 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 $\lambda_{IGMF} \sim 1$ 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



Primordial EGMF Astrophysical EGMF

EGMF uncertainty impact on results



Conclusions

- A new and independent method to infer UHECR injected mass composition
- The most interesting (and unique) results are at **E > 100 EeV** – very heavy composition
- This result is almost independent of magnentic fields properties (even for extreme EGMF)

Thank you!

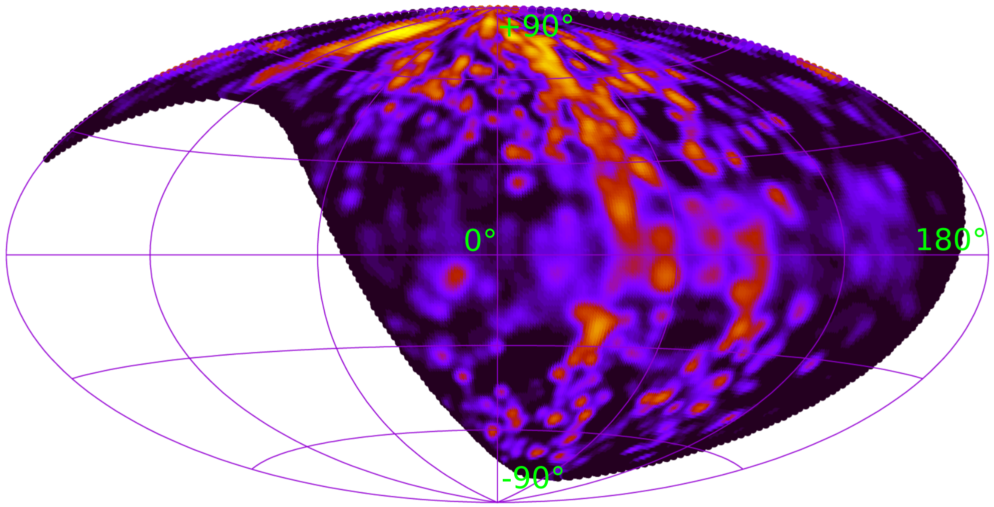
Backup slides

Realistic UHECR mock sets

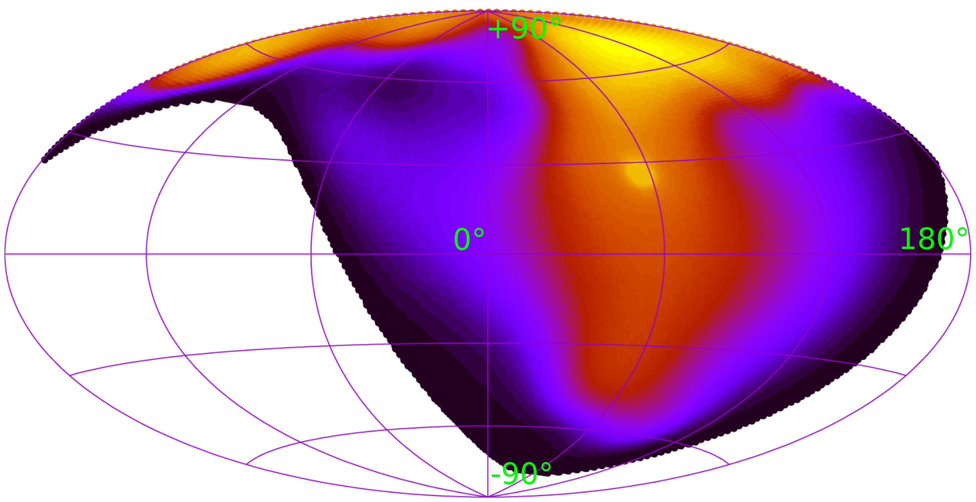
Generate mock UHECR sets with state-of-art simulated skymaps

- Sources in LSS (corrected 2MRS catalog up to 250 Mpc, isotropy farther)
- Properly attenuated primaries (p-He-O-Si-Fe), secondaries for He & O included
- Fix best fit injection spectrum separately for each primary (MNRAS 476 (2018) 715)
- No EGMF deflections
- GMF deflections: PT'11 or JF'12 regular component,
- b-dependent gaussian smearing for random component (all rigidity dependent)
- Angular resolution: additional 1° uniform smearing
- Sets are generated according to these maps with a spectrum adjusted to the observed one (TA@ICRC 2015)
- Only free parameters of the model flux are fractions of each primary (also systematics from MF parameters)

Proton map at E = 100 EeV



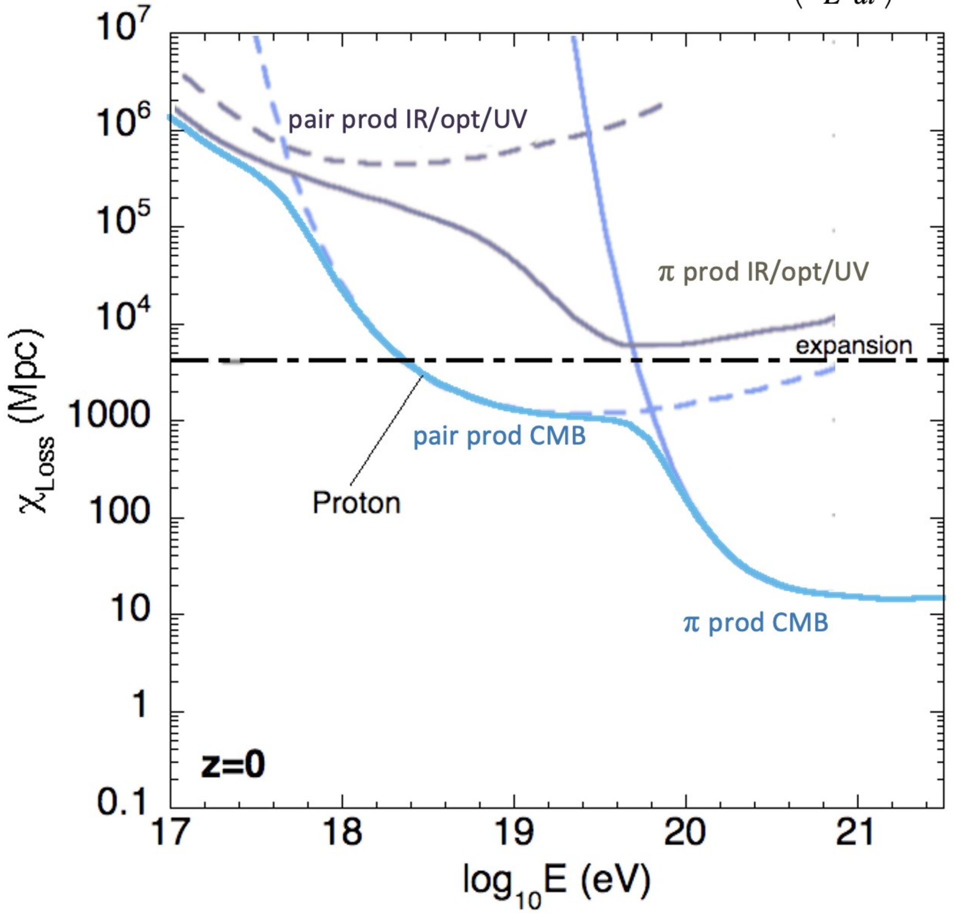
Iron map at E = 100 EeV



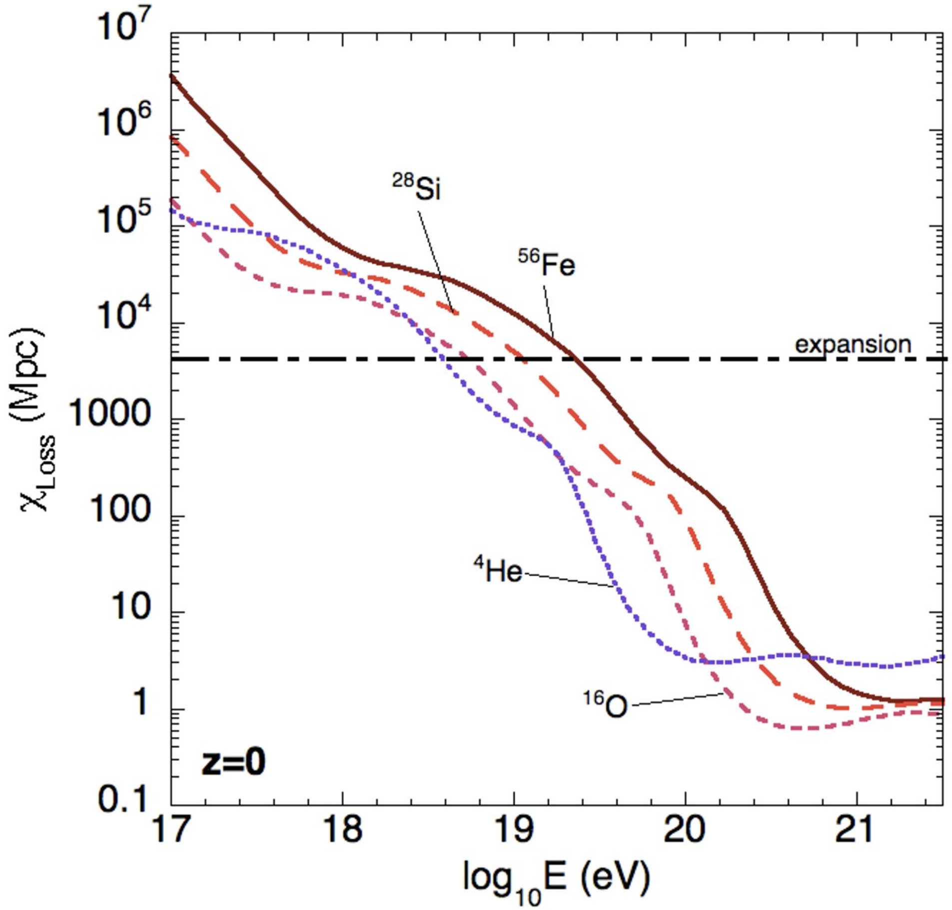
UHECR attenuation

- 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



Composition constraints from the TS

- For a given composition model simulate a mock event set **with very large statistics**
- Find the TS minimum position $\theta_{100,\ min}$ **:** for the given composition model it is just a number (very sharp TS distribution due to large statistics of mock set)
- Compare $\theta_{100,\ min}$ with the **full TS shape of data set**
- Find all the composition models compatible with data at some confidence level
- Due to small expected deflections method is reliable at E > 100 EeV even with small statistics