UHECR mass composition from arrival directions with the Telescope Array SD

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ICRC-2021 07.21, Online

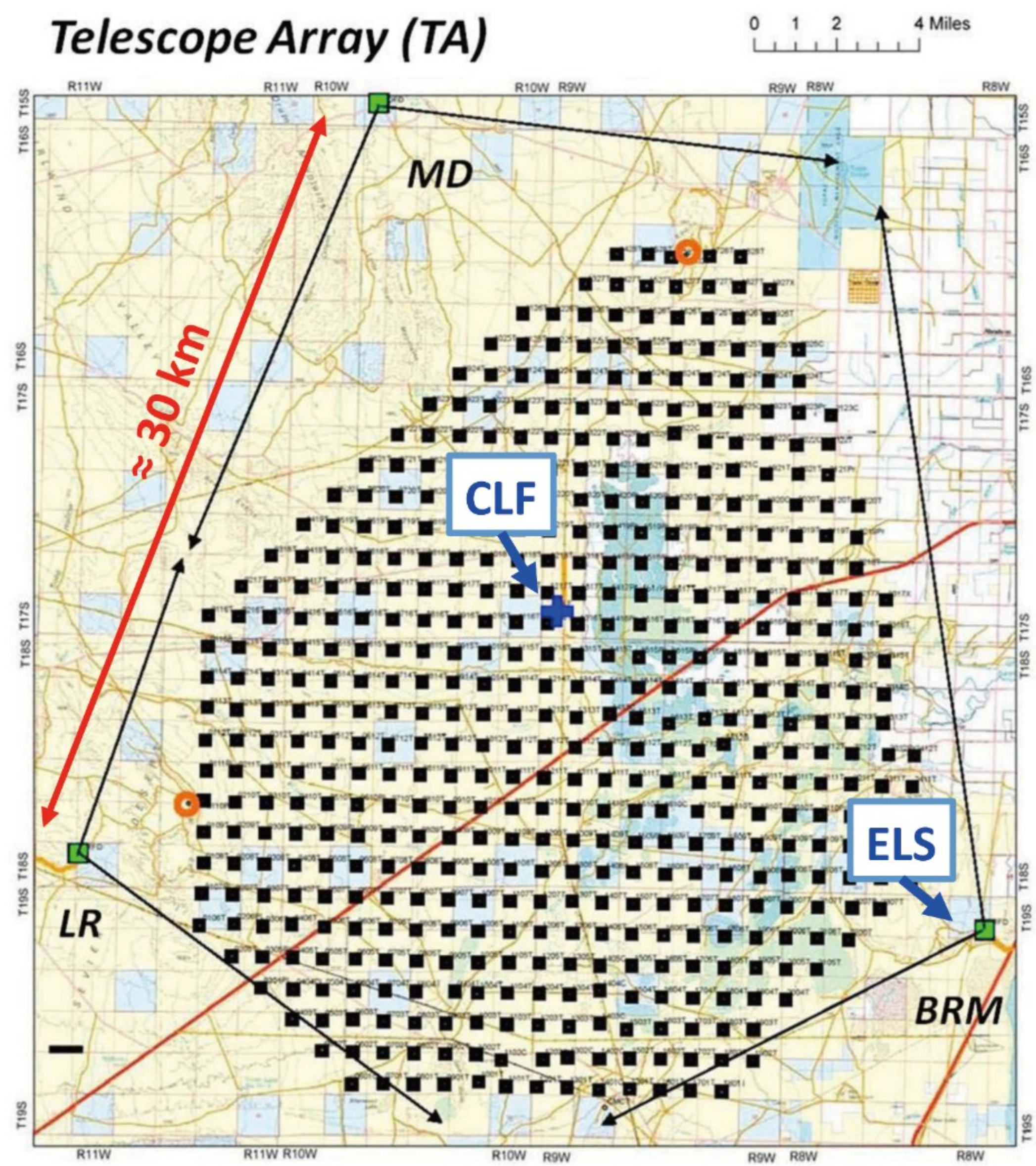
Telescope Array Surface Detector

The Experiment

- Largest UHECR experiment in the Northern Hemisphere
- 507 SD stations
- ~700 km^2 area, 13 years of continuous data collection

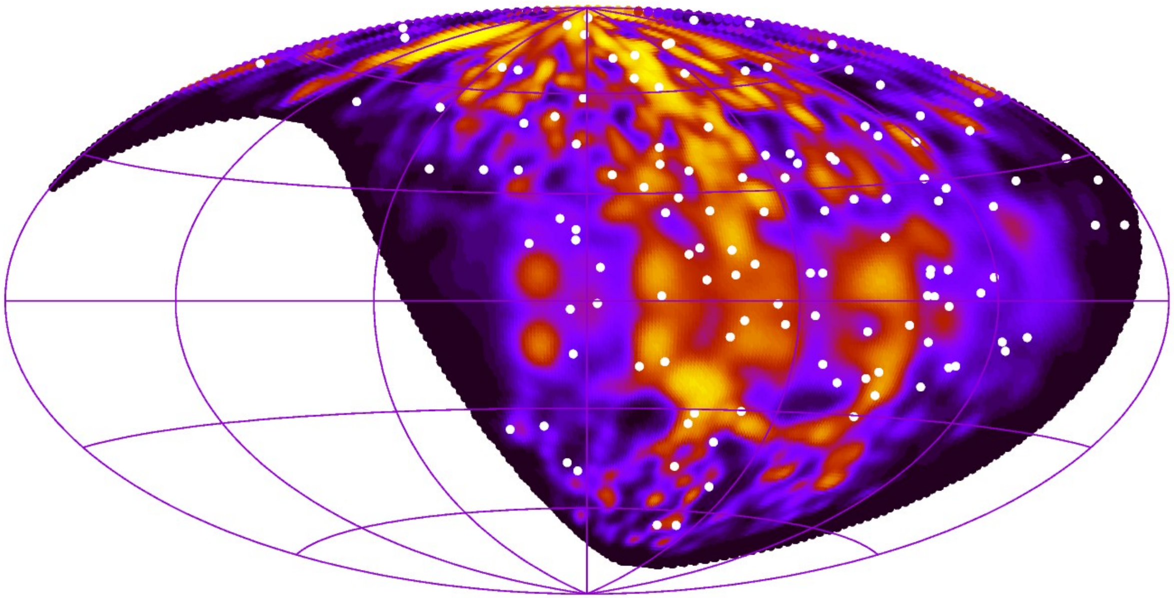
The Data Set

- 11 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



* See backup for details

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



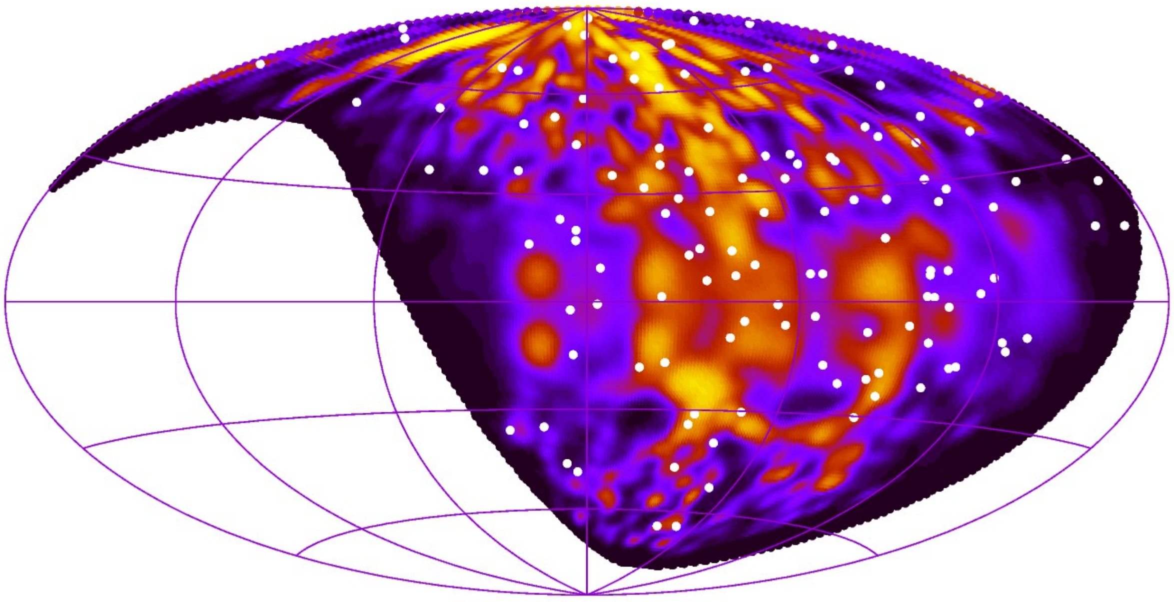
- Sources: no clear evidence for particular sources

- Magnetic fields
  - EGMF: observations B < 1 nG } likely negligible
  - 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?



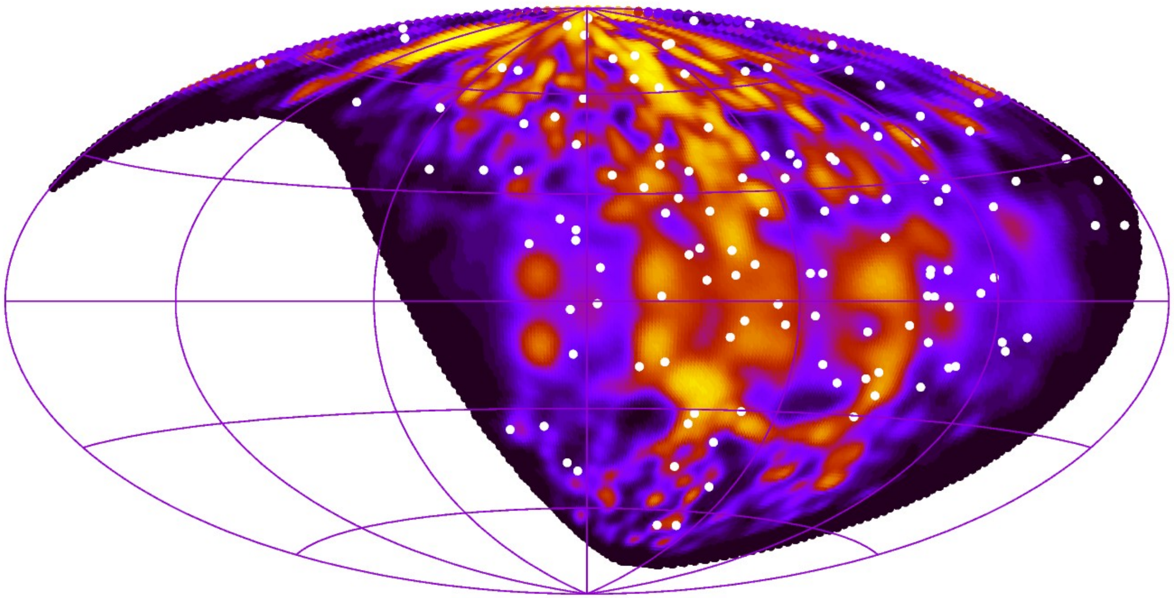
- Sources: fix the most conservative model – 2MRS + isotropy for far sources – covers all scenarios without large anisotropy

- 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

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

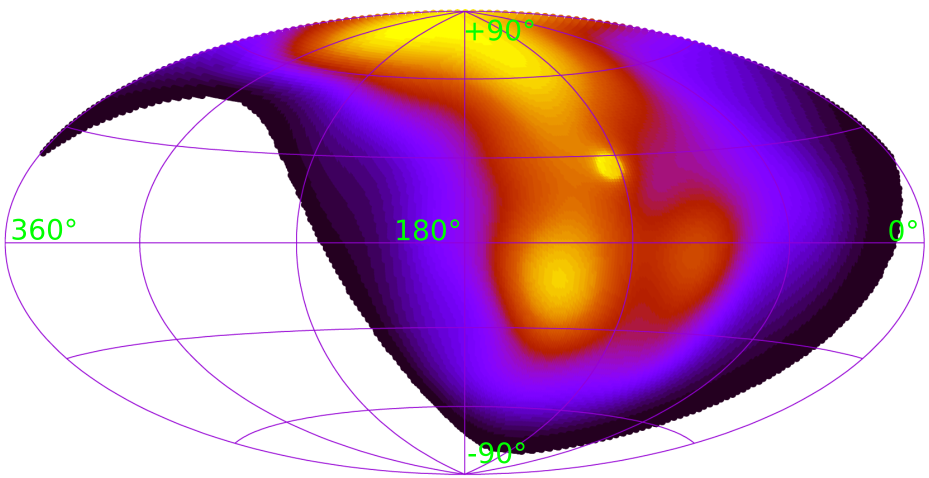
Likelihood construction I

Compute event set likelihood as a function of events positions at
skymap Φ(E) that accounts for uniform gaussian smearing of LSS only

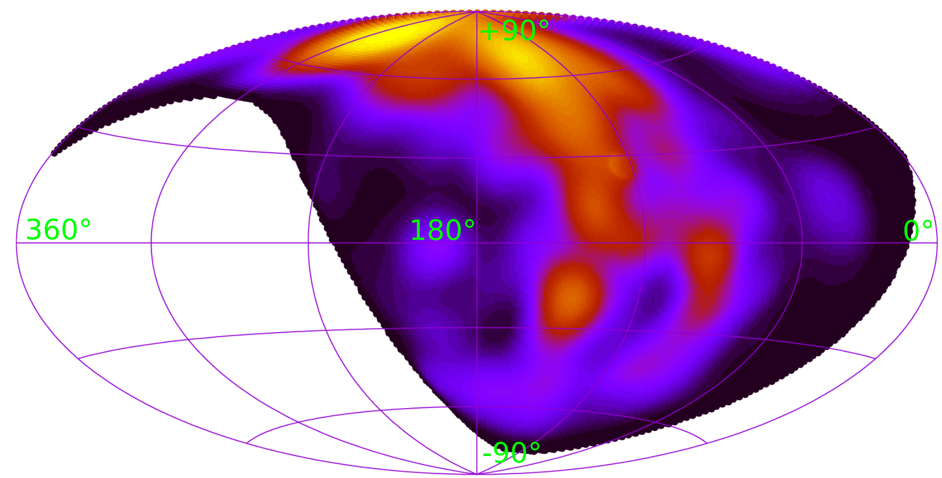
- Sources in LSS: flux limited & corrected for incompleteness 2MRS catalog from 5 to 250 Mpc, isotropy farther
- Attenuated as protons with $E^{-2.5}$ injection spectrum
- All MF: uniform gaussian smearing θ (energy dependent, varying form one map set to another)

The likelihood is sensitive for average magnitude of deflections in a given event set

Map θ_{100} = 10°, E = 57 EeV



Map θ_{100} = 10°, E = 100 EeV



Likelihood construction II

- Define LLH as a function of events on a skymap Φ:

$$\mathcal{L}(\theta) = \sum_{\text{events}} \ln \frac{\Phi(\theta, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)}$$

-

- Define Test Statistics as sum of likelihoods over all energy bins k:

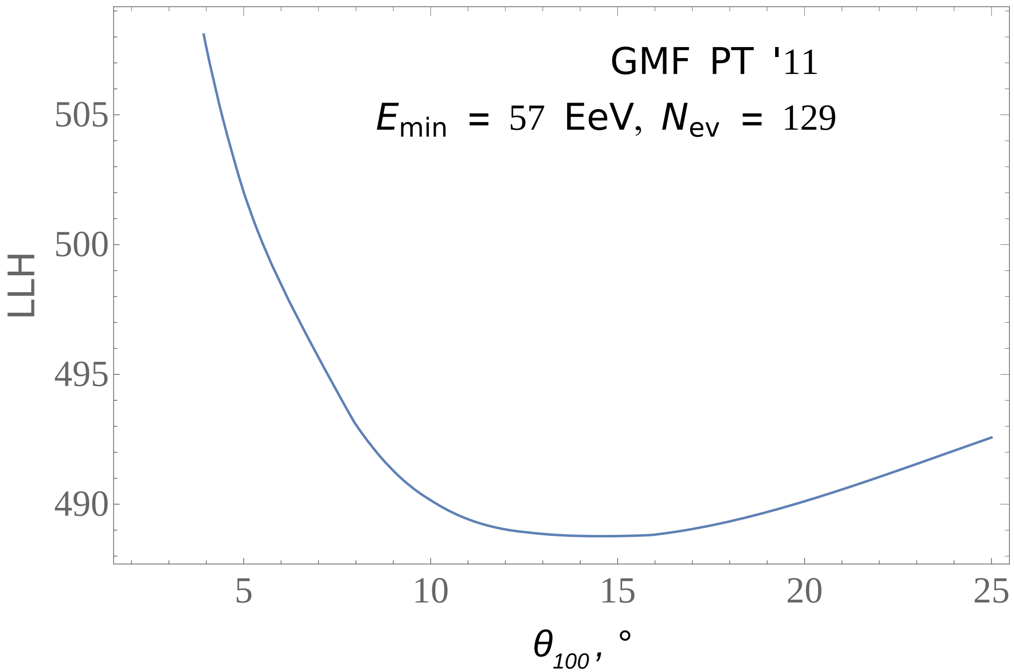
$$TS(\theta) = -2 \sum_k \left(\sum_i \ln \frac{\Phi_k(\theta, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)} \right)$$

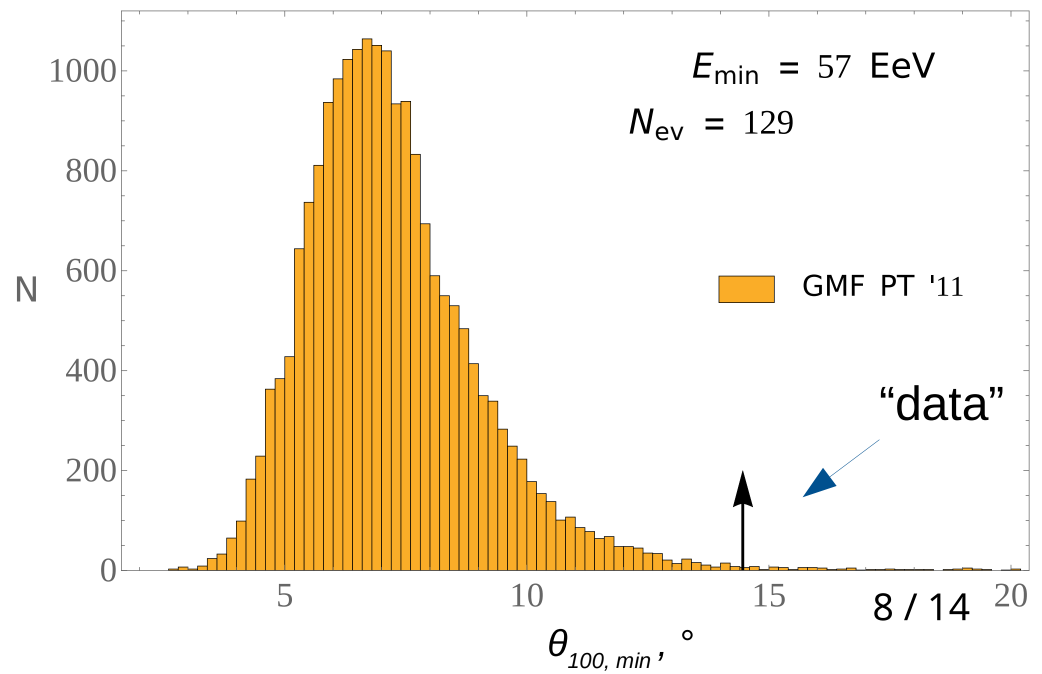
- TS is distributed as χ^2 with one d.o.f.
- For each event set we get one number, position of TS minimum – a typical deflection angle at 100 EeV – $\theta_{100,\,\text{min}}$

Composition constraint from the likelihood

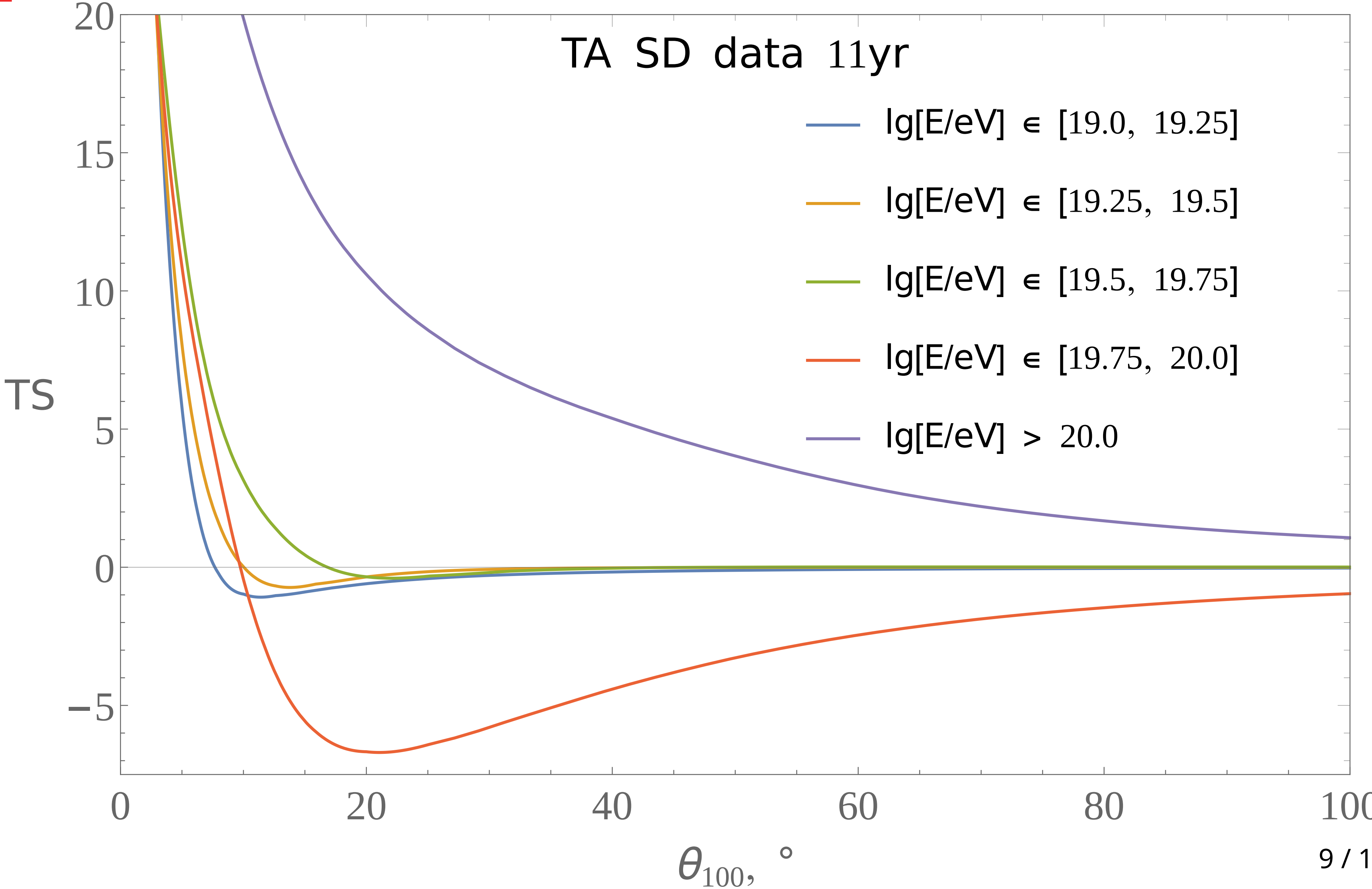
- Simulate a large number of mock event sets with realistic GMF, propagation and TA SD spectrum at detection for a given composition model
- Find the TS minimum position $\theta_{100,\ min}$ for each set and build the distribution for the composition model
- Compare the $\theta_{100,\ min}$ distribution with the measured TS minimum of data set $\theta_{100,\ data}$
- Constrain the given composition model from data at some confidence level

Example: The given model is 2.75 σ away from the given "data" set





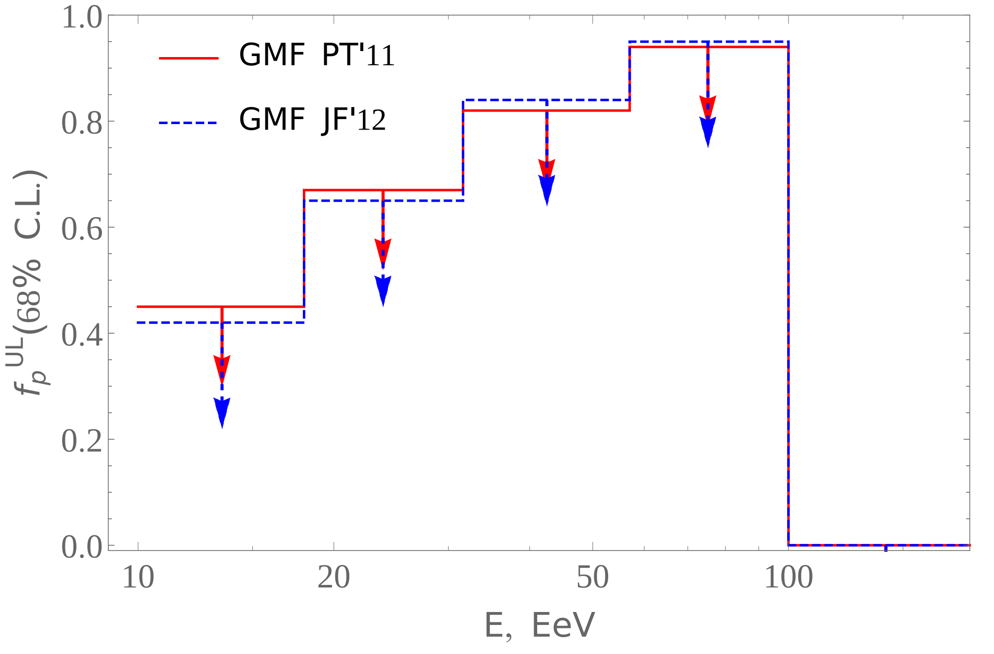
TS for TA SD data

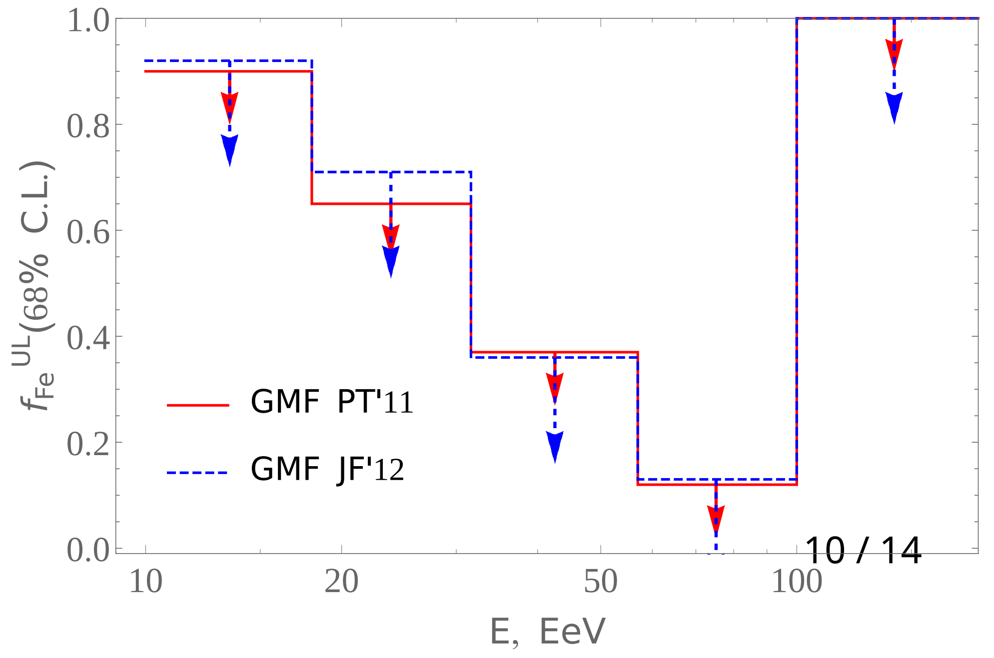


Composition constraints from TA SD data

Assume p-Fe mix with constant proton fraction f_p and iron fraction $f_{Fe} = 1 - f_p$

- A clear trend of decreasing protons and increasing iron with energy*
- An abrupt leap to pure iron (or even heavier particles) at E > 100 EeV
- Results are conservative to possible intermediate nuclei admixture
- Results are almost independent of the assumed GMF model





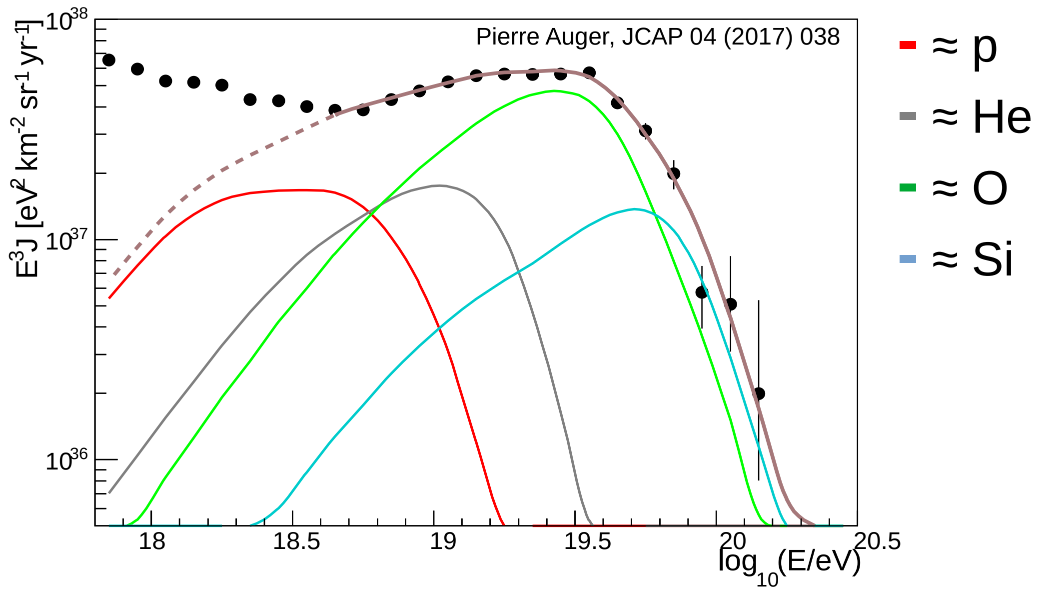
* Should not be interpreted as constraints on mean lgA

Constraint for Auger composition model

Auger best-fit composition
Pierre Auger, JCAP 04 (2017) 038

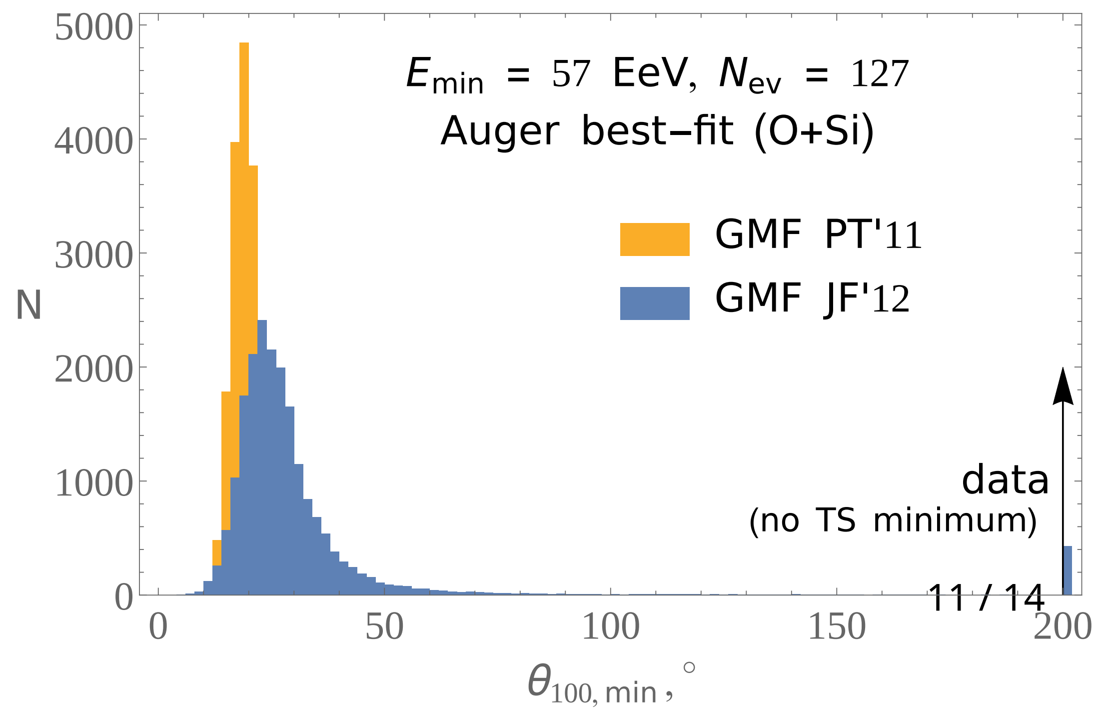
O + Si, E > 57 EeV*

GMF PT' 11: p-value = 0.0024
GMF JF' 12: p-value = 0.019



Auger best-fit composition model is in tension with TA SD data at highest energies

The result is dominated by TA E > 100 EeV "ultra-heavy" events



* No energy rescaling is assumed between TA and Auger

Conclusions

- New method of composition study that works even at highest energies
- Sources in LSS are numerous – covers all scenarios without large anisotropy
- Results almost independent of magn.fields properties (if EGMF is not extreme)
- TA SD data favors proton fraction increasing and iron fraction decreasing with energy from 10 EeV up to E = 100 EeV
- At E > 100 EeV data favors pure iron (or even more deflected particles – exotics?)
- Method would benefit from statistics increase and full sky coverage

Thank you!

Backup slides

The TA SD event quality cuts for this study

- $E > 10$ EeV,
- Zenith angle < 55°,
- Event includes at least 5 SD counters,
- χ^2 / n.d.o.f. < 4 (both LDF & geom. fits),
- $\Delta S_{800}/S_{800} < 0.25$,
- Δ arrival direction < 5°,
- Largest signal counter is surrounded by 4 working counters that are not necessarily its nearest neighbors
- Cut to remove possible lightnings: ±10 min around each NLDN event (~0.7% of all TA SD events that pass all other quality cuts)