Highlights from the Telescope Array Experiment

6th ICPPA, Moscow 1 December 2022

Mikhail Kuznetsov, INR RAS, Moscow
for the TA Collaboration

photo by Oleg Kalashev

Supported by Russian Science Foundation

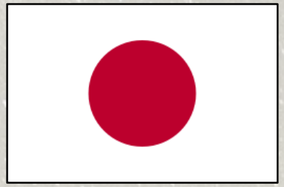
Outline

- Telescope Array observatory and TAx4 upgrade
- UHECR energy spectrum results
- Composition results
- Anisotropy results
- Summary

Telescope Array: the largest cosmic ray observatory in the Northern Hemisphere

140 members , 32 institutes, 7 countries


USA

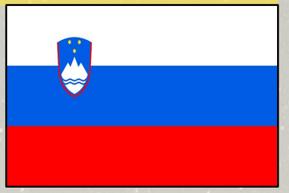

Japan

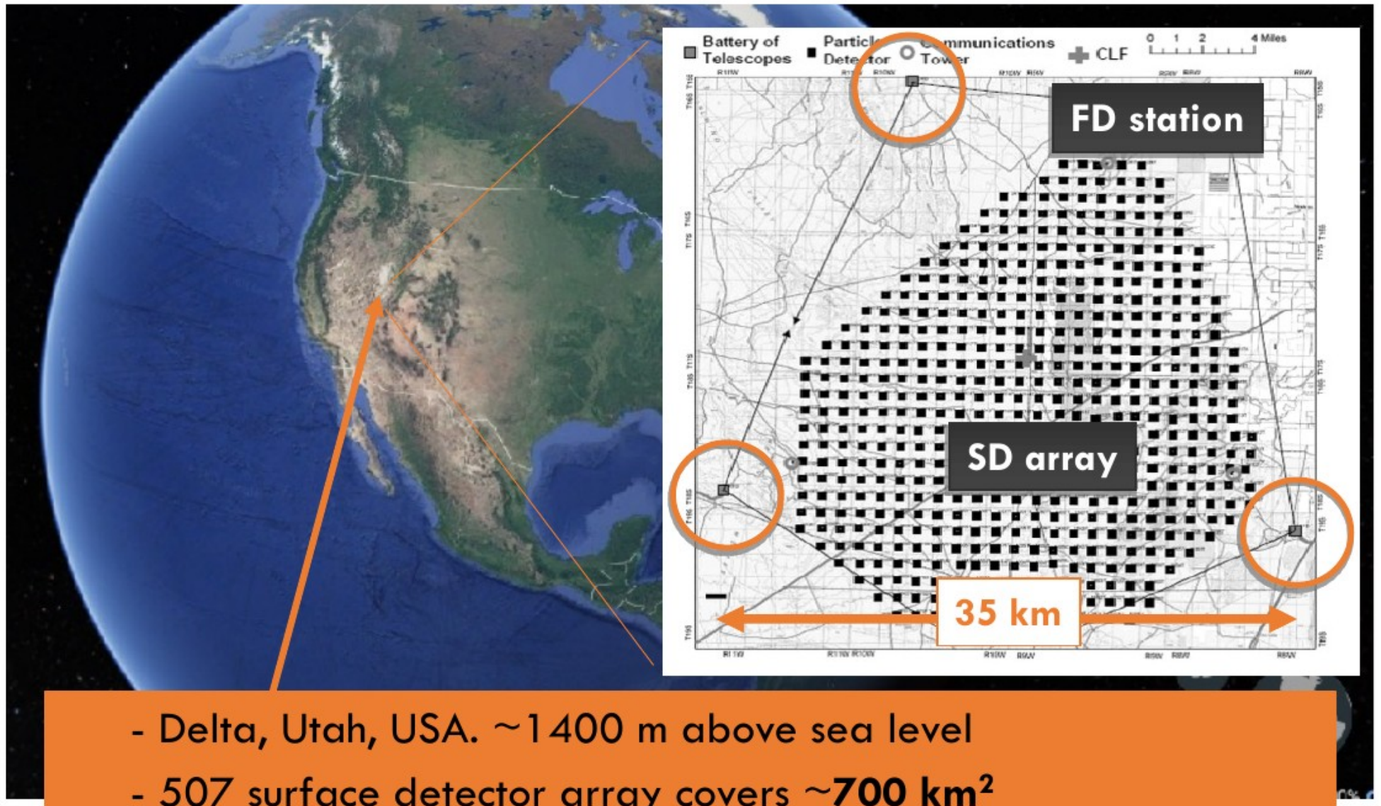

Korea


Russia


Belgium

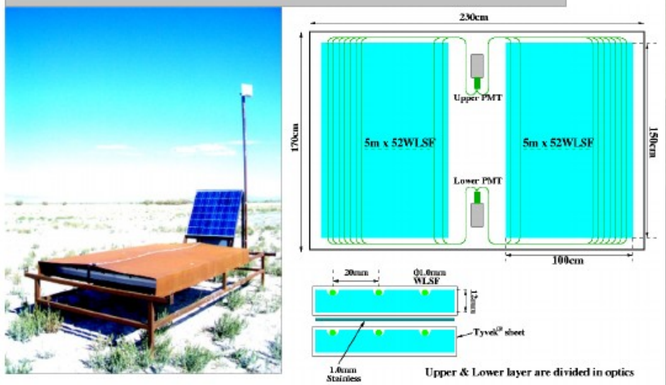

Czech Republic


Slovenia



- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers ~**700 km²**
- 38 telescopes at 3 stations to observe the sky above the array

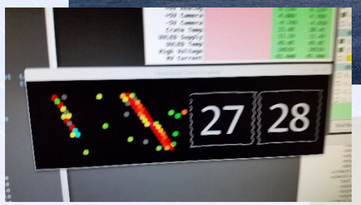
Surface Detector: Plastic Scintillator



Fluorescence Detector: PMT camera

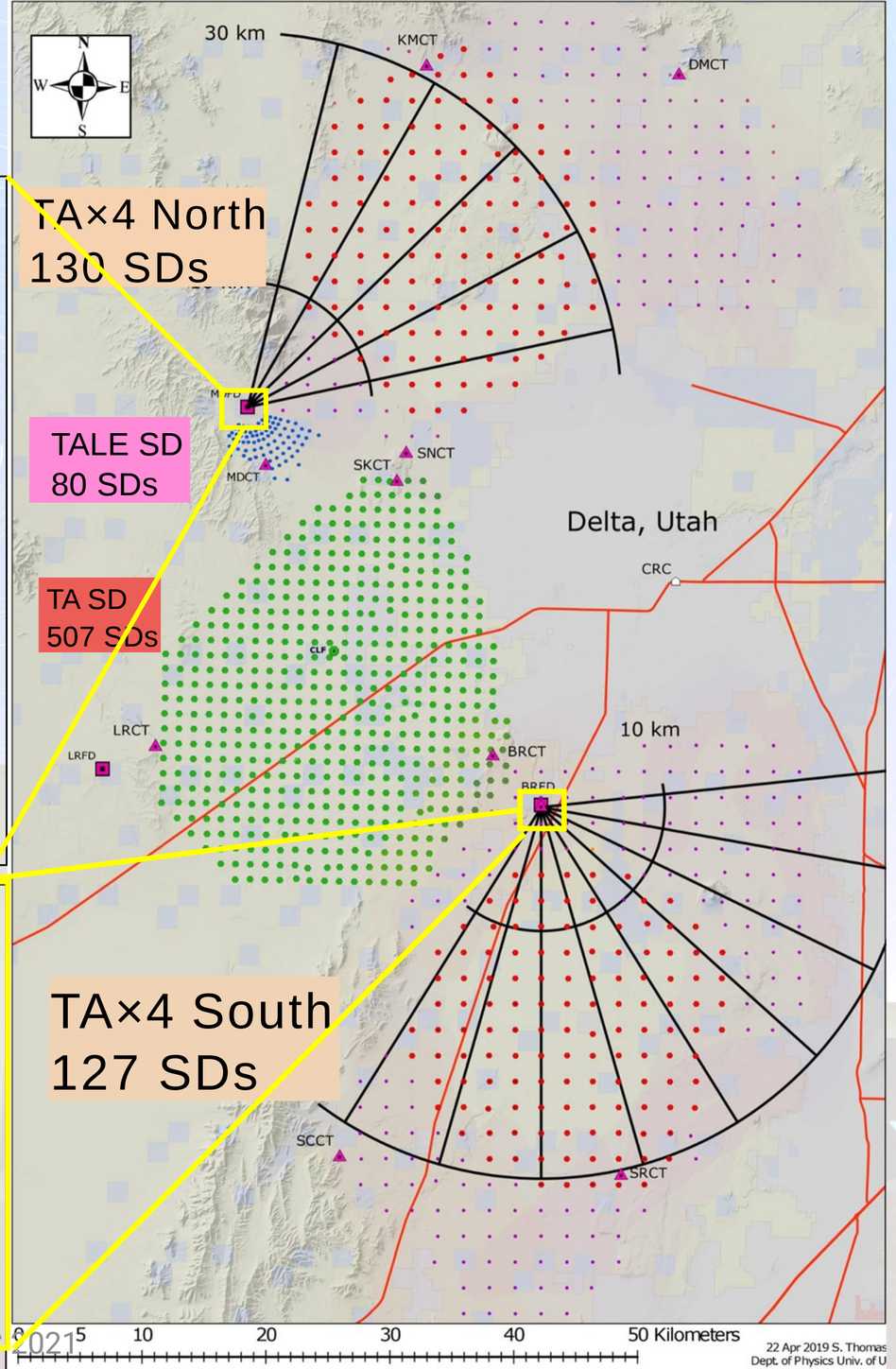
TA×4

TA×4 northern FD station



routine observation
since Jun. 2019

TA×4 southern FD station

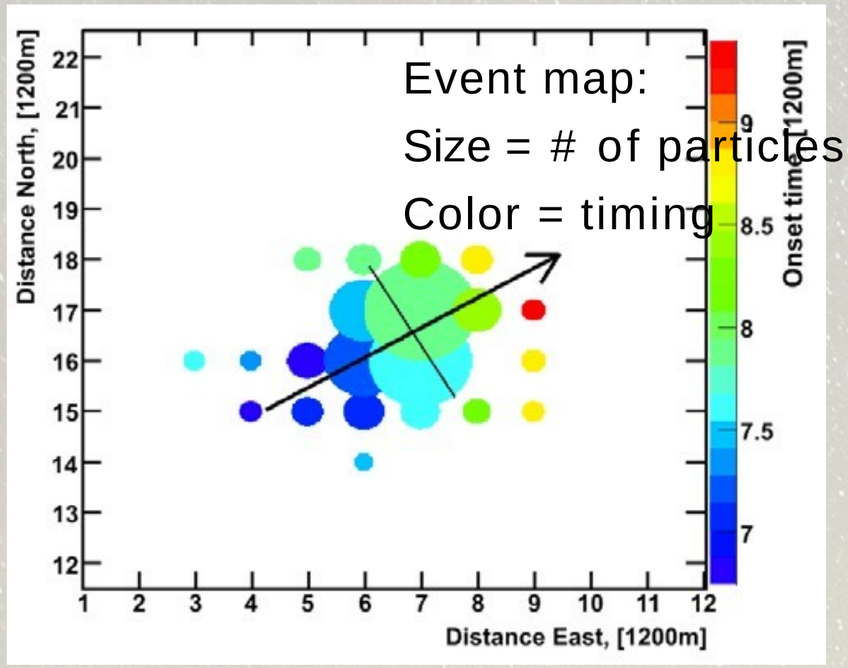


- Fourfold increase in size of TA SD array (up to 3000 km^2).
- Triple statistics for E>20 EeV in 5 years.

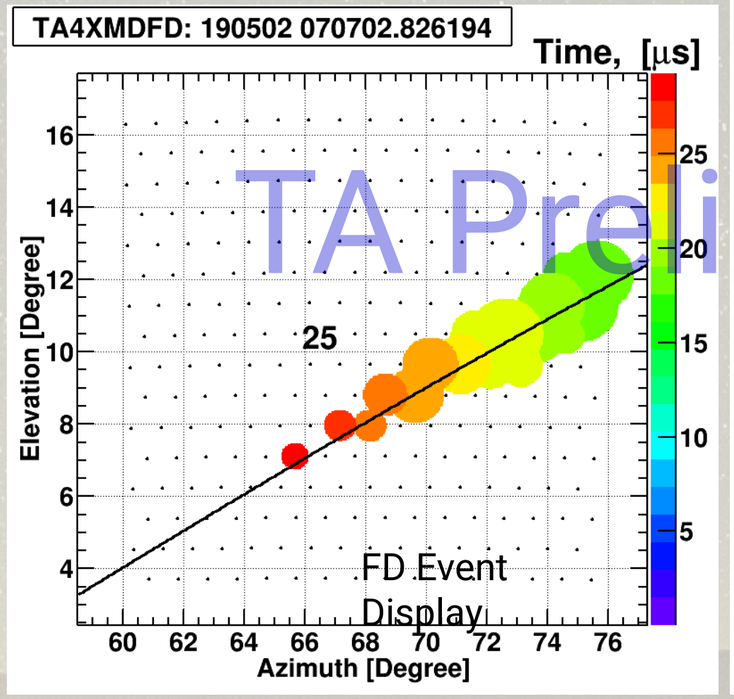
- Hybrid experiment:
- 2 new FD stations, 12 telescopes

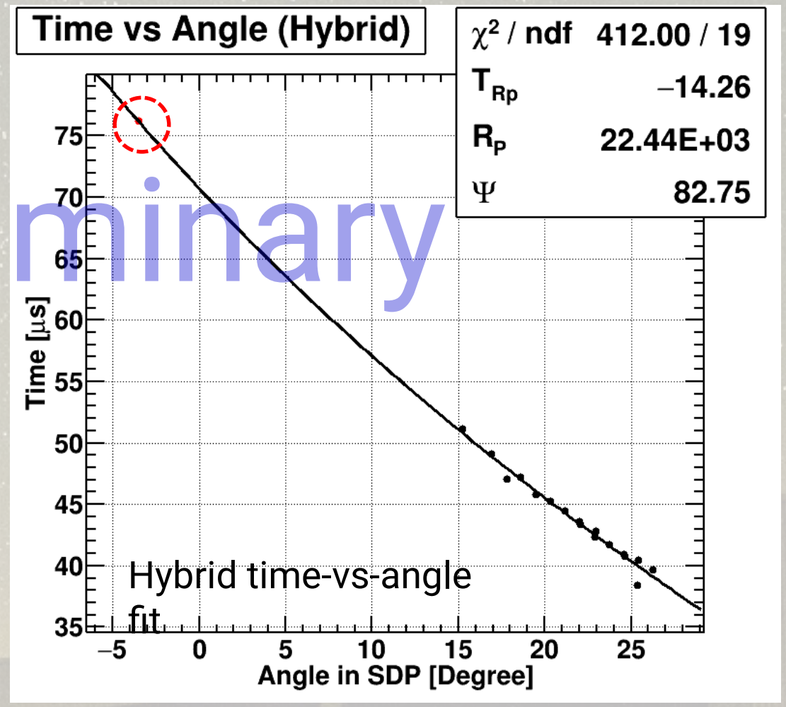
- 257 SD scintillators out of 500 are installed and operational since Nov. 2019

SD event reconstruction

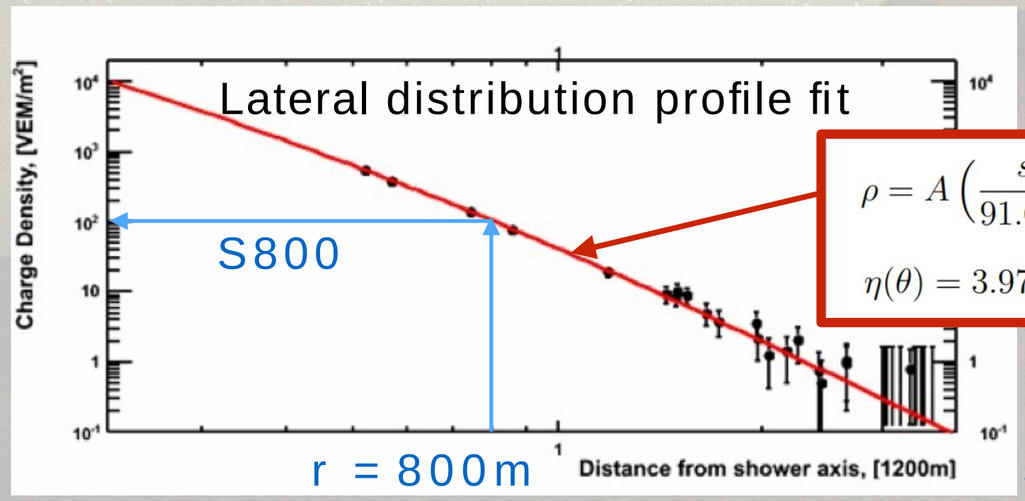


Hybrid (FD+SD) event reconstruction





TA Preliminary



SD energy is rescaled to calorimetric FD energy scale

$$\rho = A\left(\frac{s}{91.6\text{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\text{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\text{m}}\right]^{2}\right)^{-0.6}$$

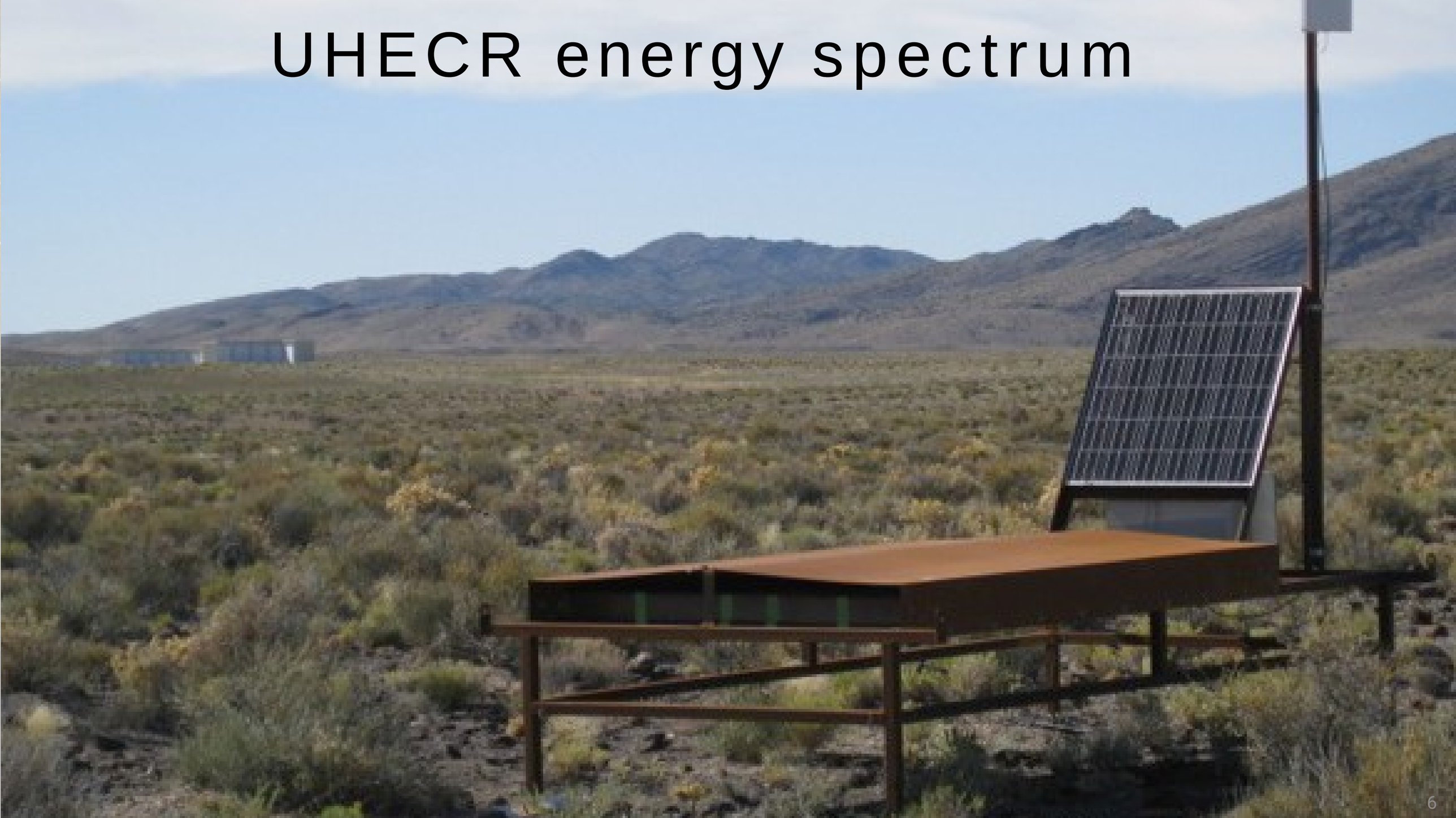
$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta)-1]$$

Empirical formula used by AGASA

$E_{final} = E_{SD} / 1.27$

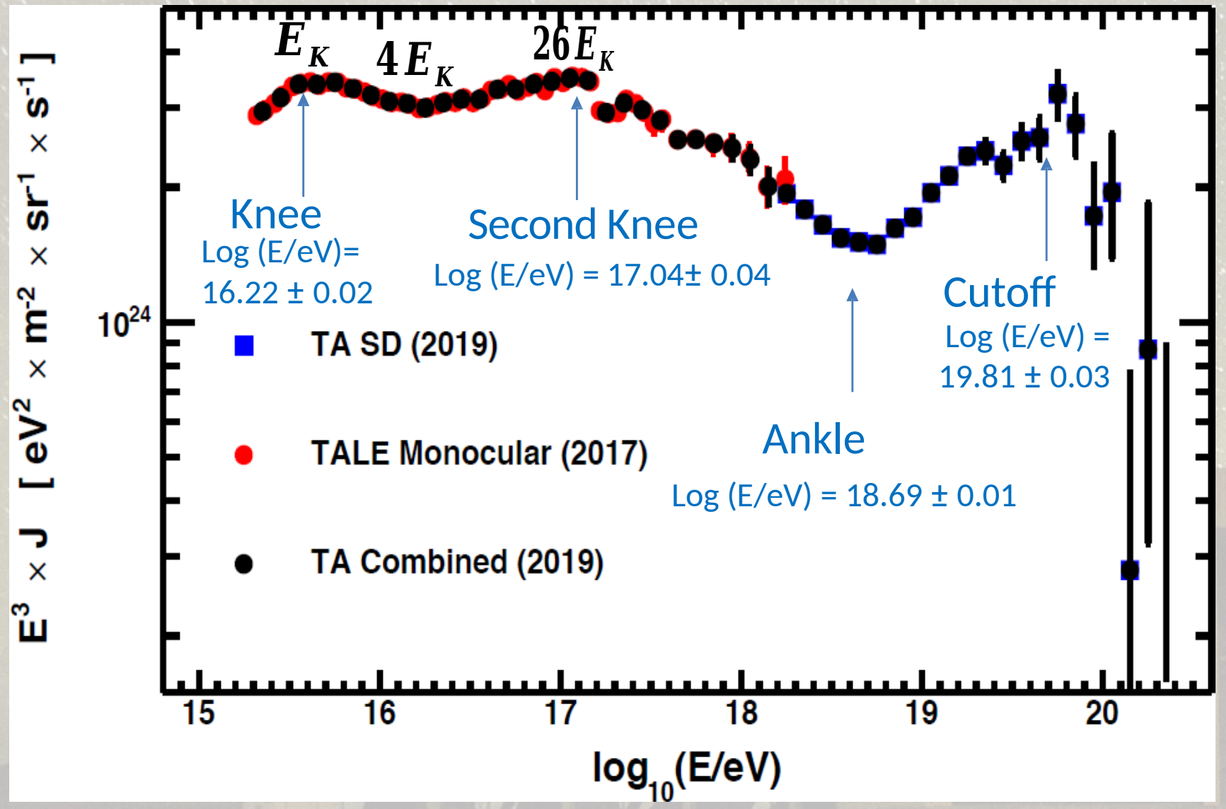
S800 --> primary energy

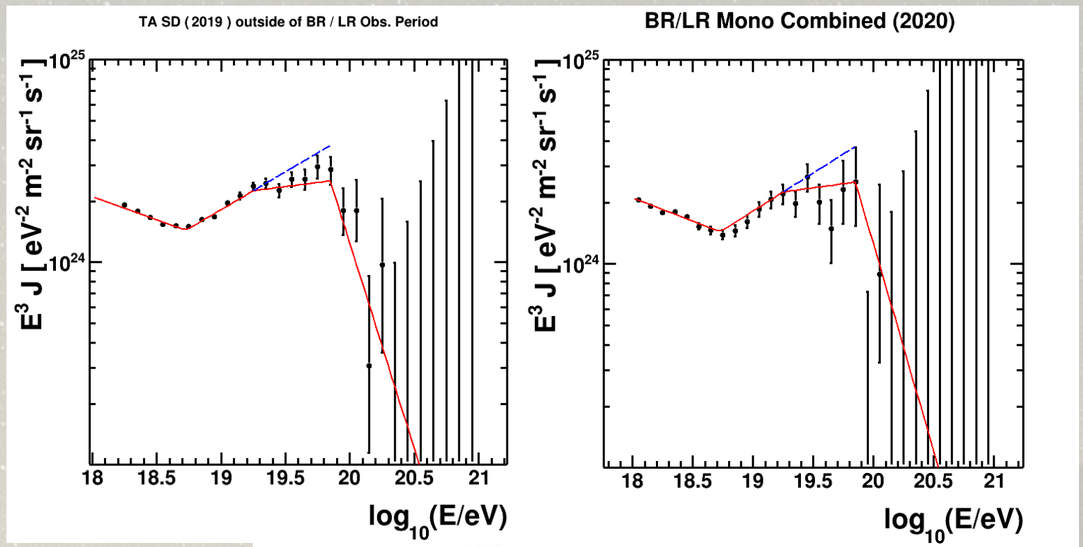
UHECR energy spectrum

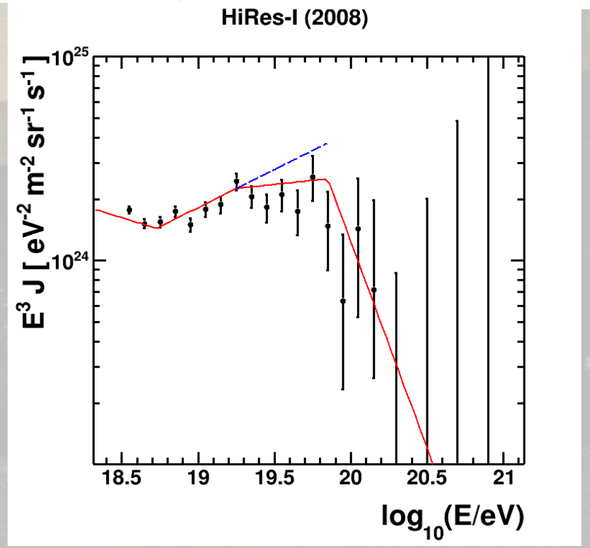


The "*Instep*" feature

Combined TA spectrum:
22 months TALE FD + 11 years TA SD data

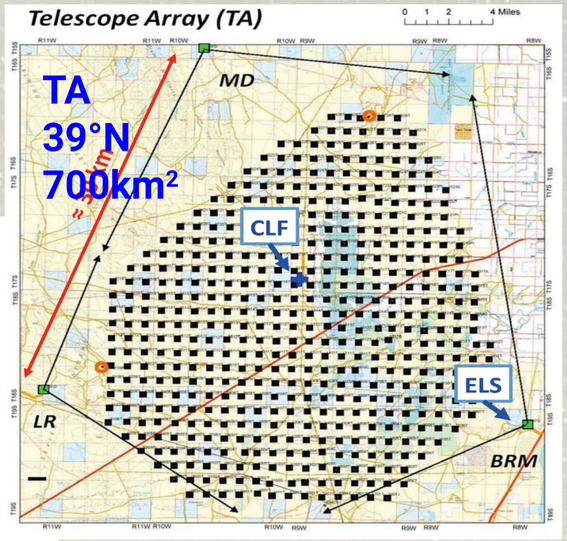


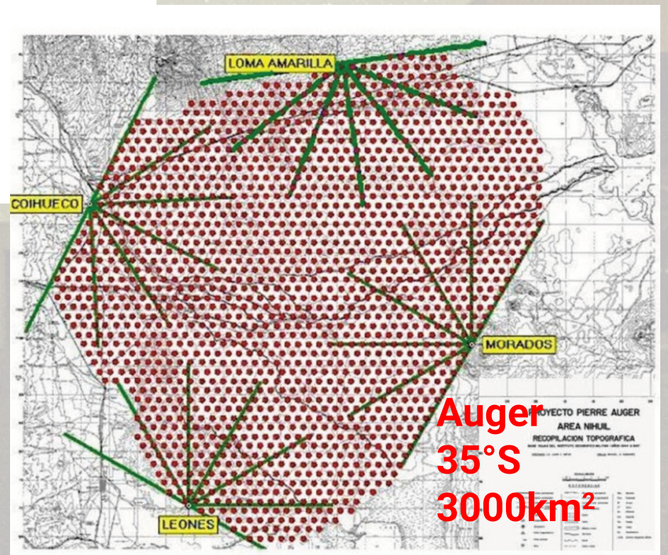




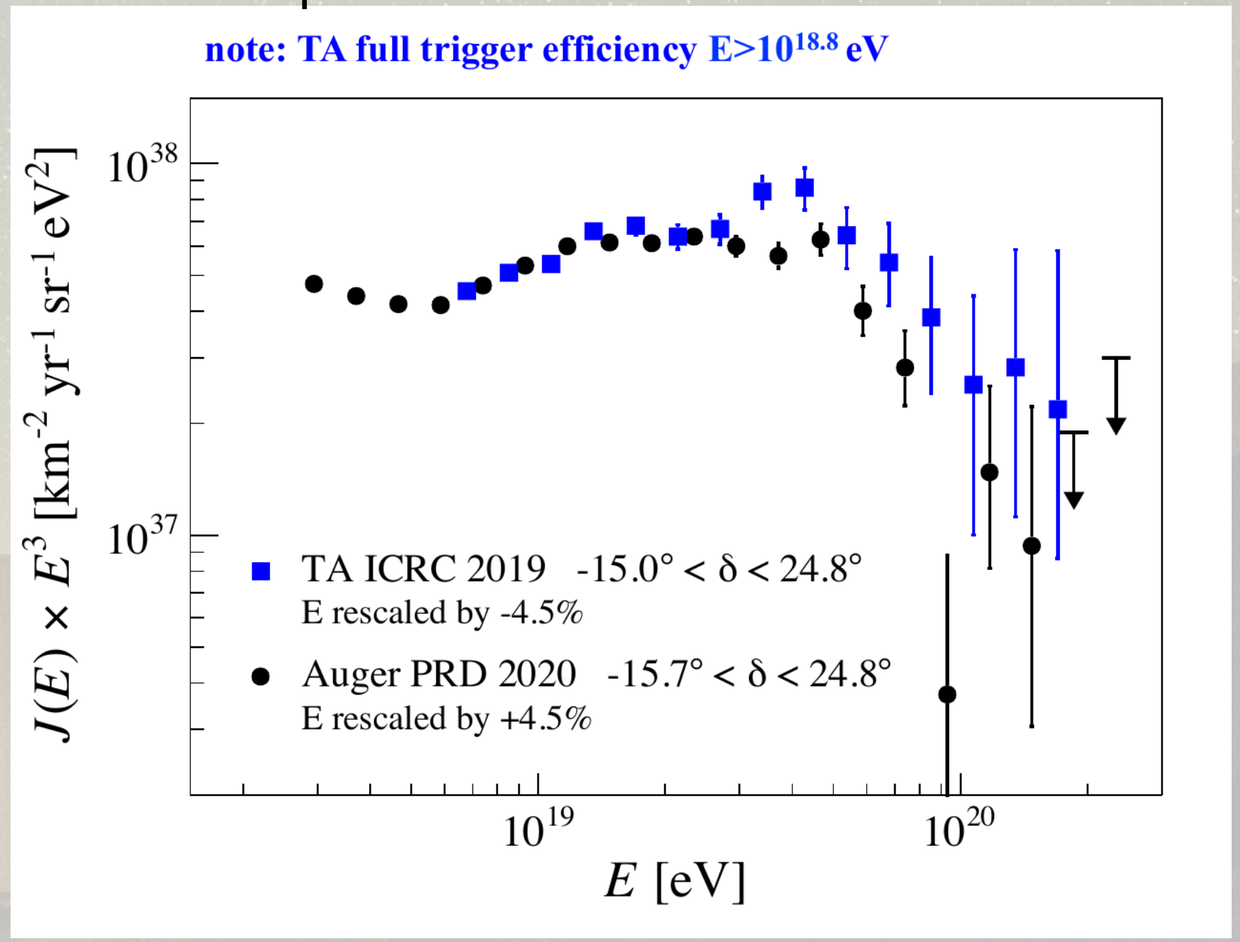
TA SD + TA FD + HiRes data: we observe the *Instep* feature in the Northern Hemisphere at **$10^{19.22\pm0.08}$ eV** with a **4.0 σ** significance

Joint Auger + TA spectrum Working Group result





In TA – Auger common declination band: spectrum should be the same

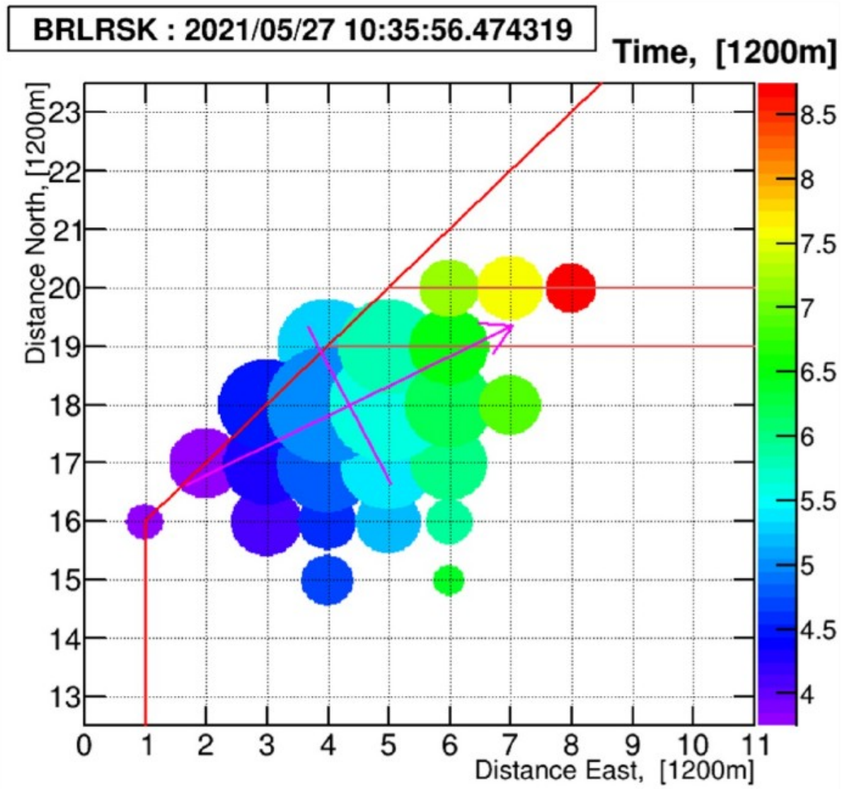


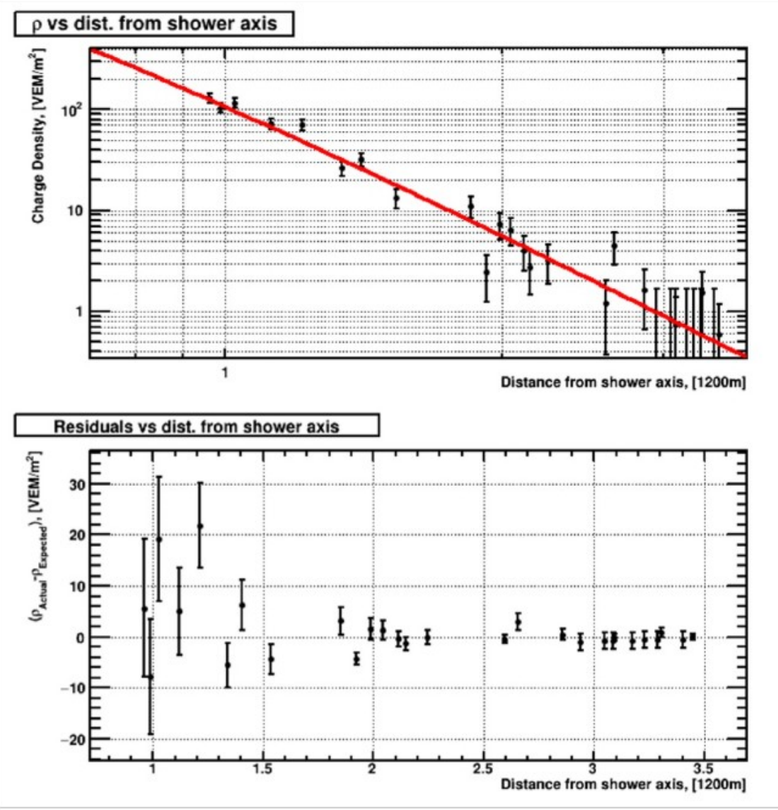
Absolute energy scale difference 9%, on top of this **3.0 σ** difference persists at higher energies – work in progress

Highest energy event observed at 27 of May 2021

$E \approx 10^{20.4}$ eV

Figure 5.8: **Left:** SD display of the highest energy event seen by TA, at $10^{20.4}$ eV. The circle size represents the SD integrated signal, while the color represents the relative time. The shower core and direction are shown by the cross. **Right:** The longitudinal profile of the event. The two counters closest to the core of the shower were saturated and are not included. The value of $S(800)$ is 530 VEM/m^2.





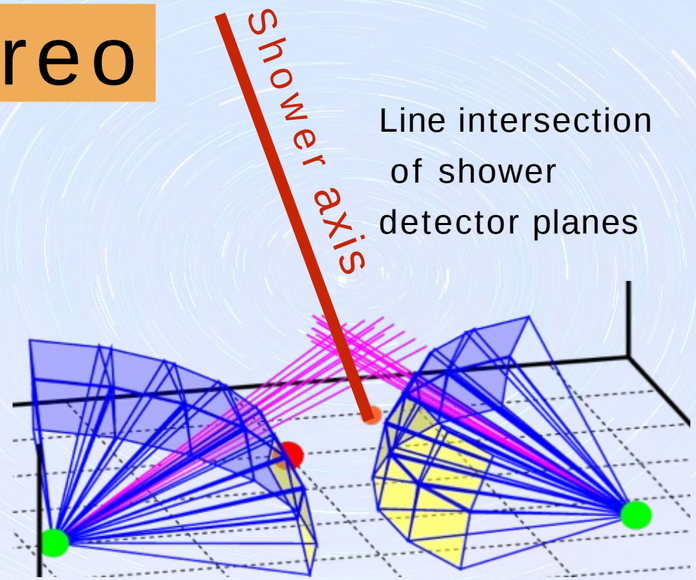
Snowmass 2021 whitepaper, arXiv:2205.05845

UHECR mass composition

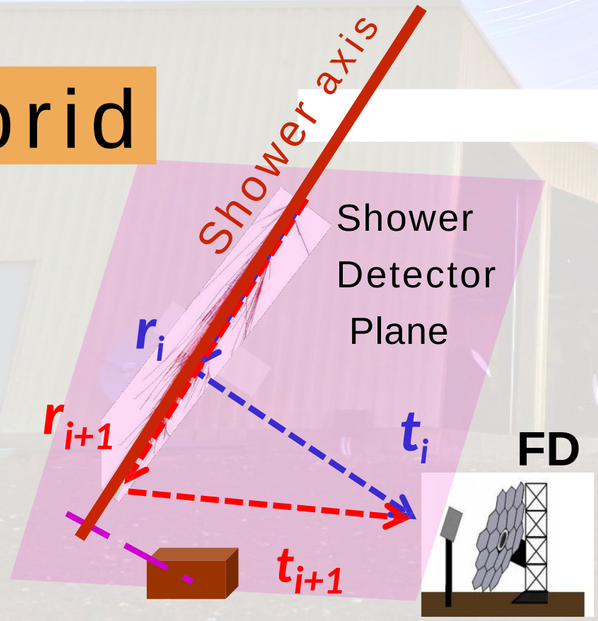
10

FD Event reconstruction

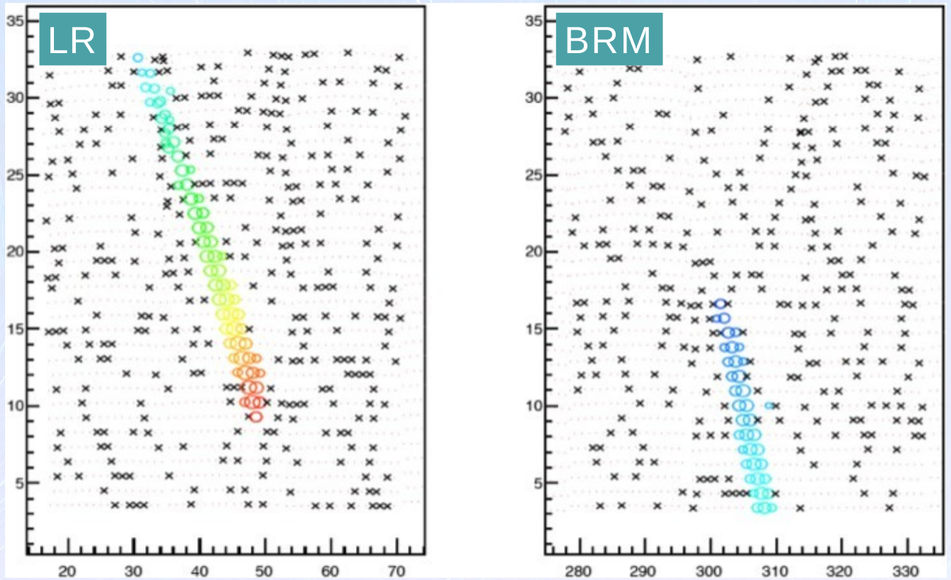
Stereo



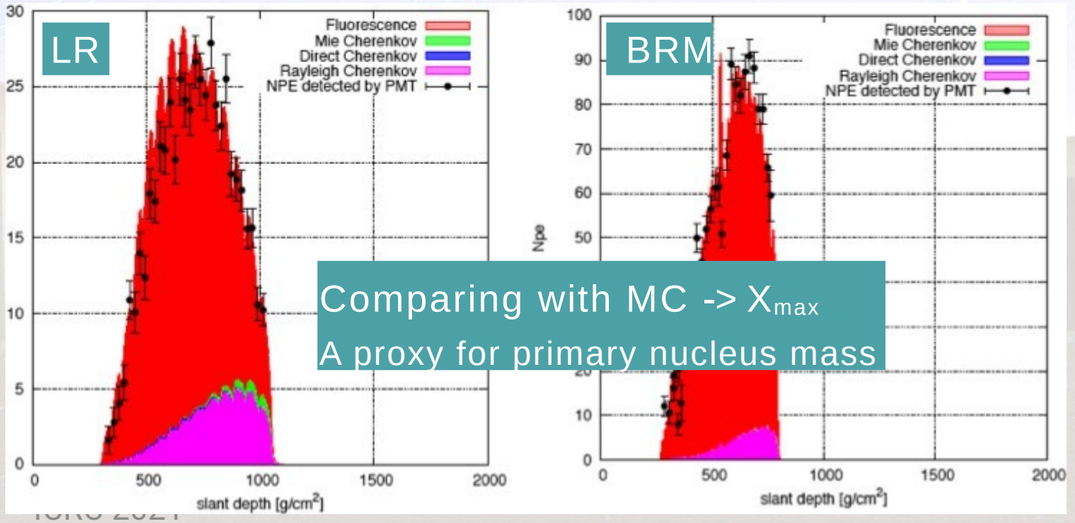
Hybrid



observed images



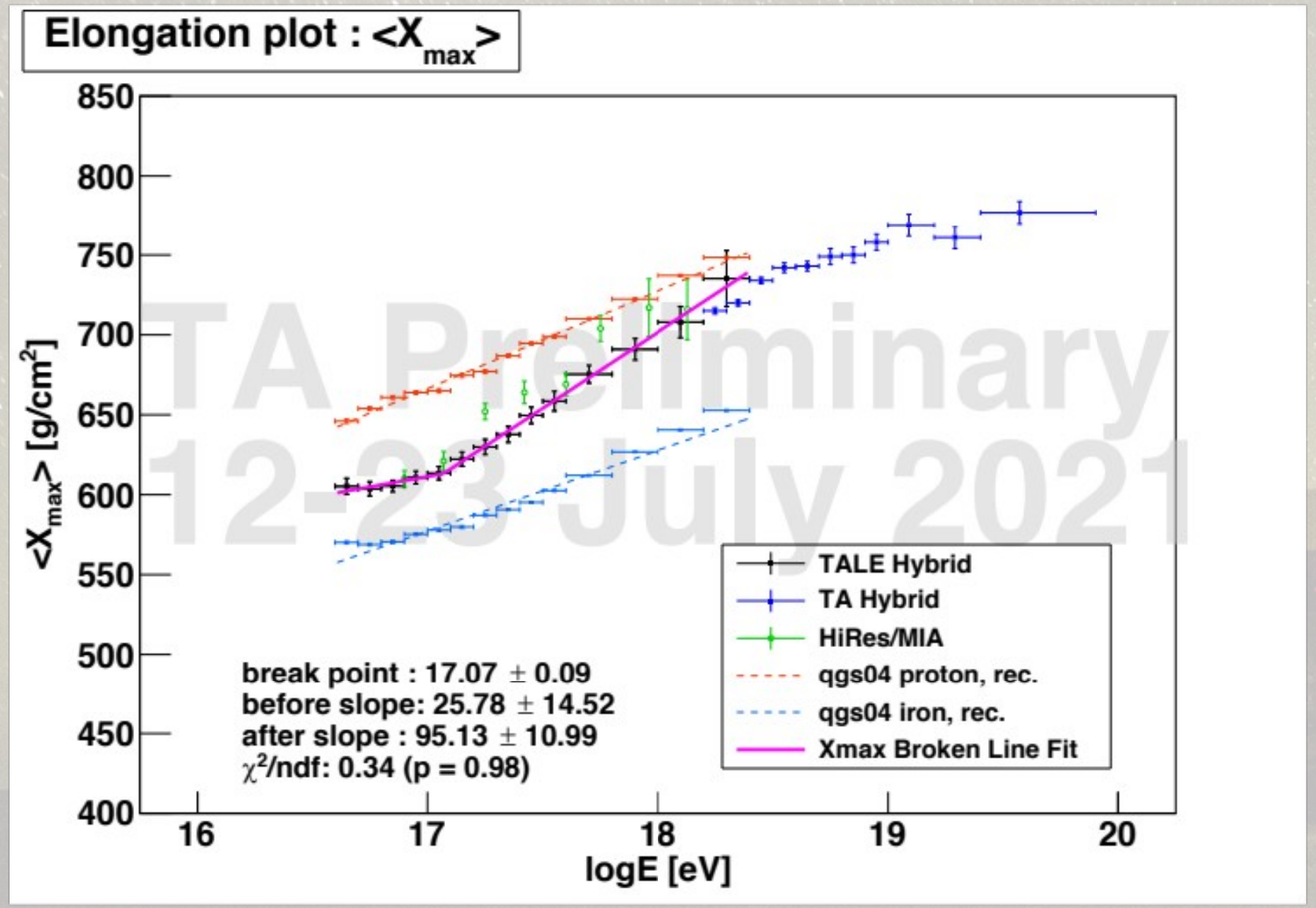
reconstructed shower profiles



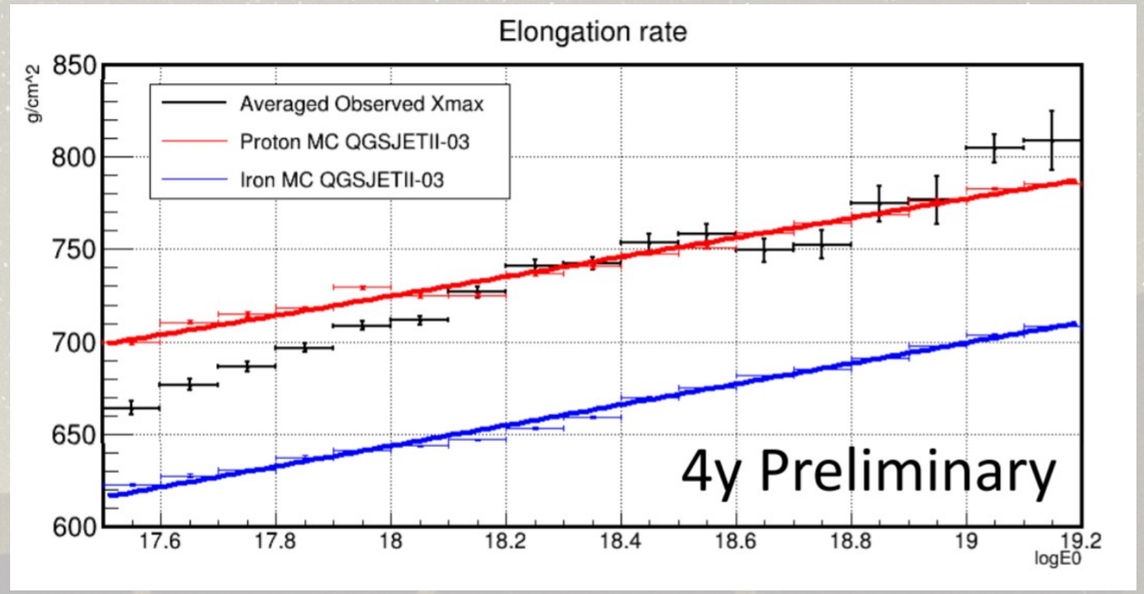
Comparing with MC -> X_{max}
A proxy for primary nucleus mass

TA and TALE hybrid X_{MAX}

TALE hybrid



TA hybrid

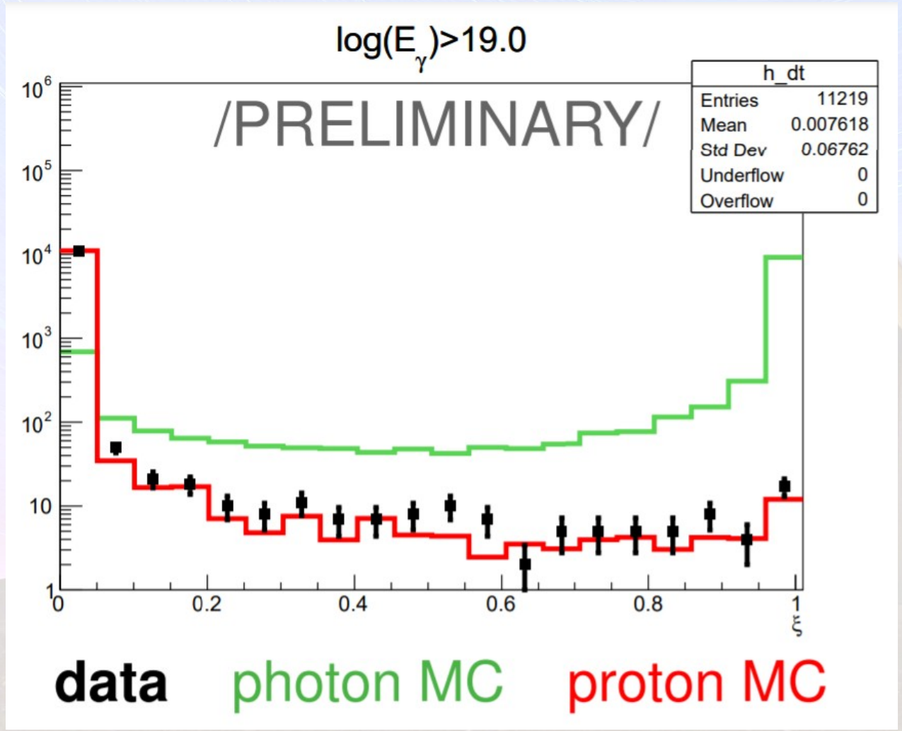


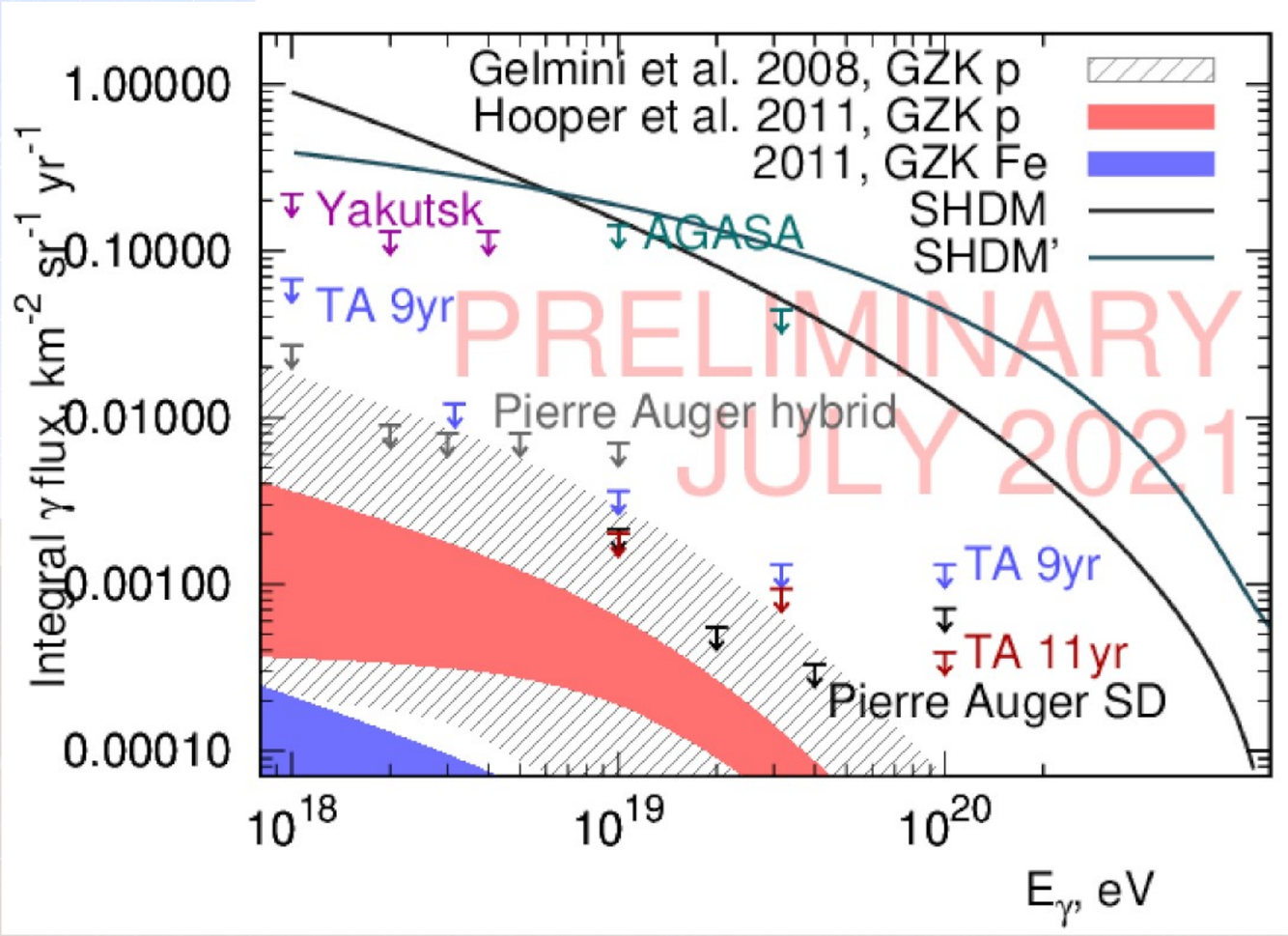
TA SD UHE photon limits

p-γ classifier based on Neural Network

Uses full time-resolved signals from all triggered SD stations along with 16 composition-sensitive observables

E_0, eV	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	2	1	0
$\bar{n}$ <	6.72	5.14	3.09
A_{eff}	3428	5546	7875
F_γ <	2.0×10^{-3}	9.3×10^{-4}	3.9×10^{-4}



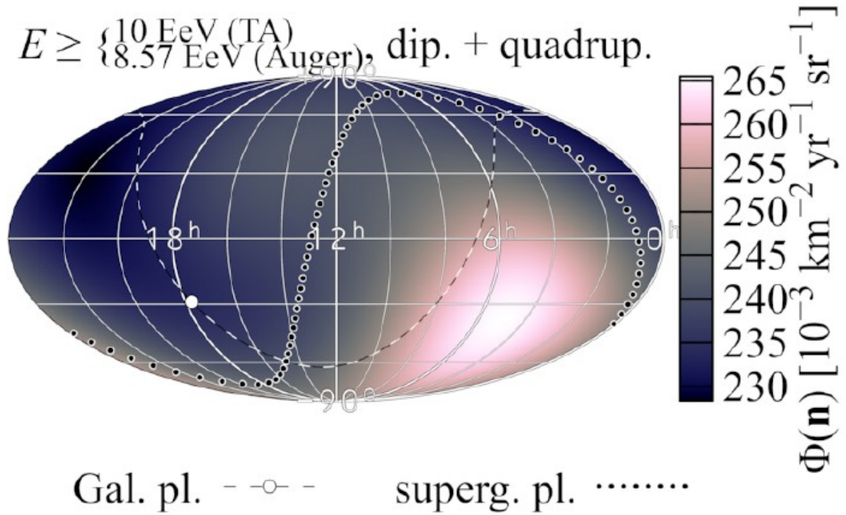


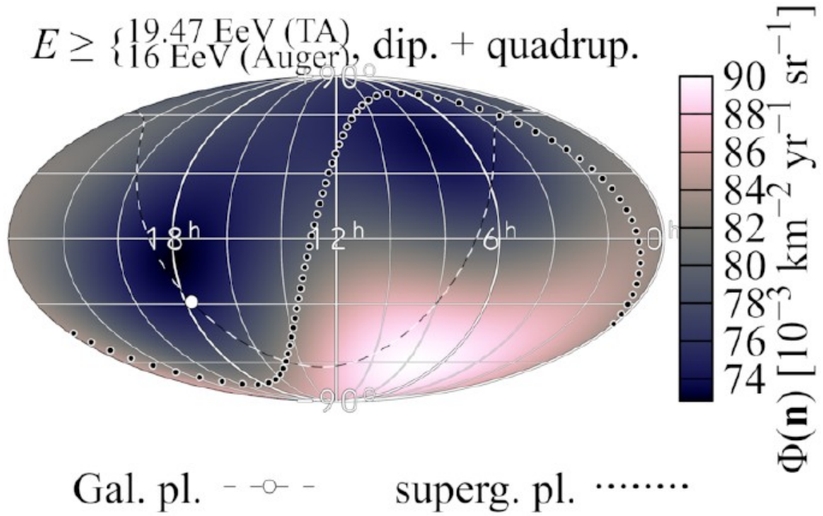
UHECR Anisotropy

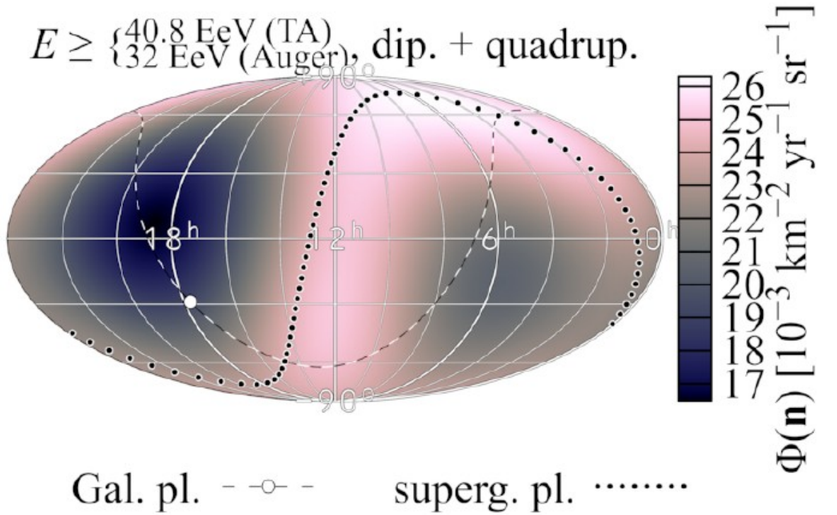
Large scale anisotropies (multipole analysis)

Joint Auger + TA anisotropy Working Group result

Dipole + quadrupole reconstruction







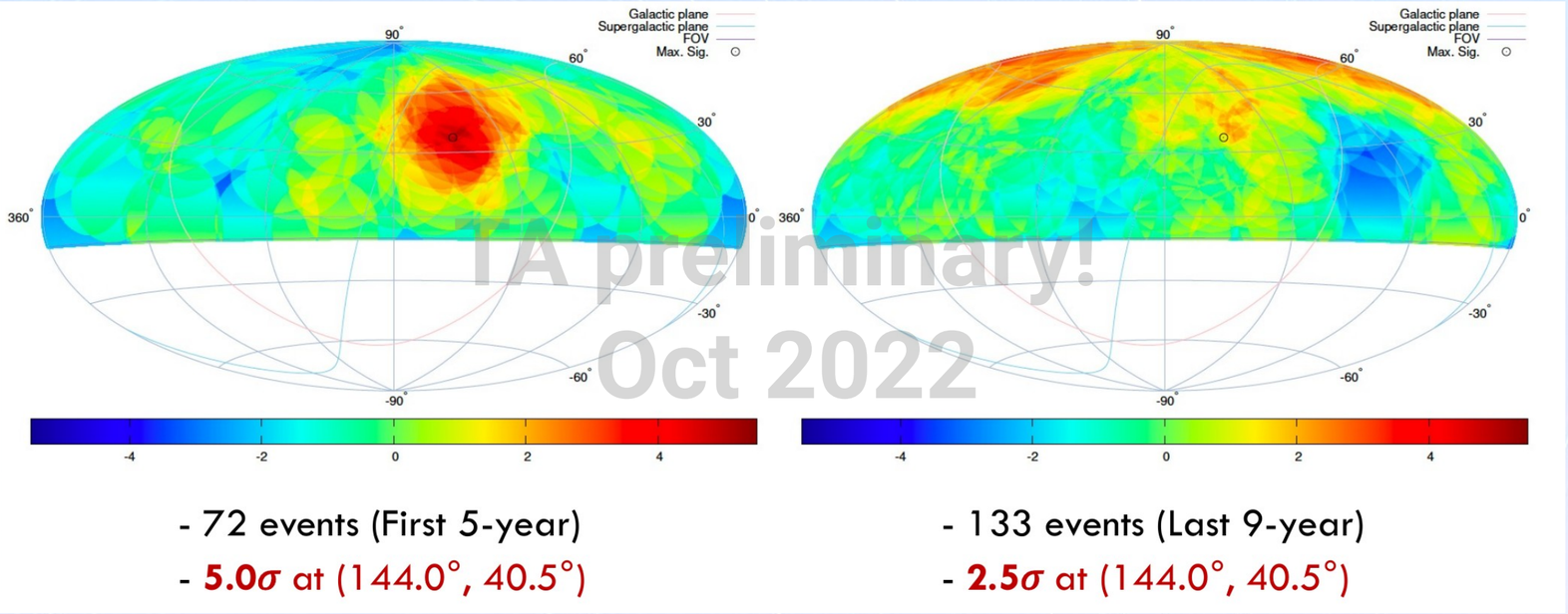
$$\Phi(\mathbf{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\mathbf{n}) = \Phi_0 \left(1 + \mathbf{d}\cdot\mathbf{n} + \tfrac{1}{2}\mathbf{n}\cdot\mathbf{Q}\mathbf{n} + \ldots\right)$$

Energy between TA and Auger is rescaled using common declination band:

$E_{Auger} = E_0\, e^{-0.154}\, (E_{TA} / E_0)^{0.937}$; $E_0 = 10^{19}$ eV

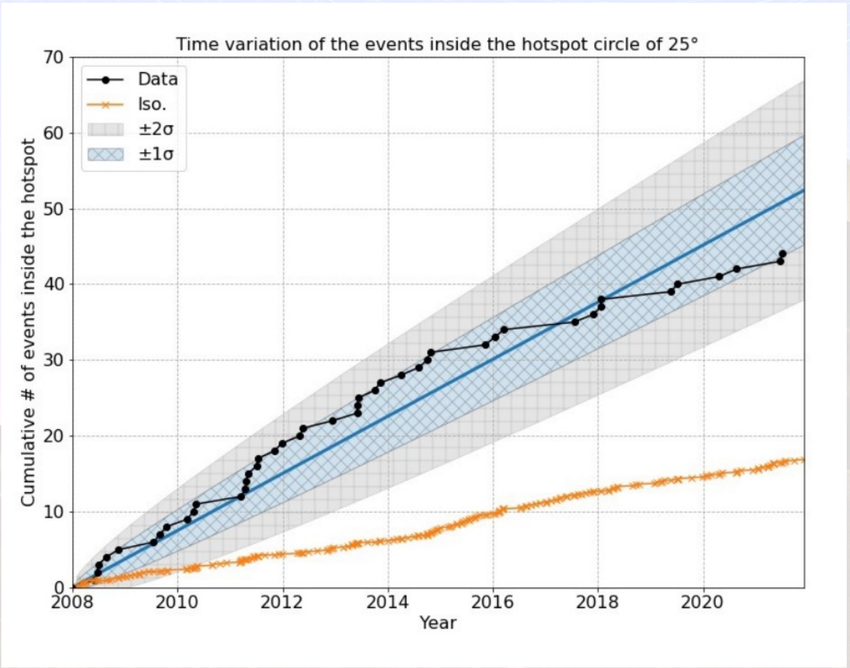
E_{Auger} [EeV] E_{TA} [EeV]	$[8.57, 16)$ $[10, 19.47)$	$[16, 32)$ $[19.47, 40.8)$	$[32, +\infty)$ $[40.8, +\infty)$
d_x [%]	$-0.7 \pm 1.1 \pm 0.0$	$+1.6 \pm 2.0 \pm 0.0$	$-5.3 \pm 3.9 \pm 0.1$
d_y [%]	$+4.8 \pm 1.1 \pm 0.0$	$+3.9 \pm 1.9 \pm 0.1$	$+9.7 \pm 3.7 \pm 0.0$
d_z [%]	$-3.3 \pm 1.4 \pm 1.3$	$-6.0 \pm 2.4 \pm 1.3$	$+3.4 \pm 4.7 \pm 3.6$
$Q_{xx} - Q_{yy}$ [%]	$-5.1 \pm 4.8 \pm 0.0$	$+13.6 \pm 8.3 \pm 0.0$	$+43 \pm 16 \pm 0$
Q_{xz} [%]	$-3.9 \pm 2.9 \pm 0.1$	$+5.4 \pm 5.1 \pm 0.0$	$+5 \pm 11 \pm 0$
Q_{yz} [%]	$-4.9 \pm 2.9 \pm 0.0$	$-9.6 \pm 5.0 \pm 0.1$	$+11.9 \pm 9.8 \pm 0.2$
Q_{zz} [%]	$+0.5 \pm 3.3 \pm 1.7$	$+5.2 \pm 5.8 \pm 1.7$	$+20 \pm 11 \pm 5$
Q_{xy} [%]	$+2.2 \pm 2.4 \pm 0.0$	$+0.2 \pm 4.2 \pm 0.1$	$+4.5 \pm 8.1 \pm 0.1$

CR clustering: Hotspot update (14 yr data)



- 72 events (First 5-year)
- **5.0σ** at (144.0°, 40.5°)

- 133 events (Last 9-year)
- **2.5σ** at (144.0°, 40.5°)

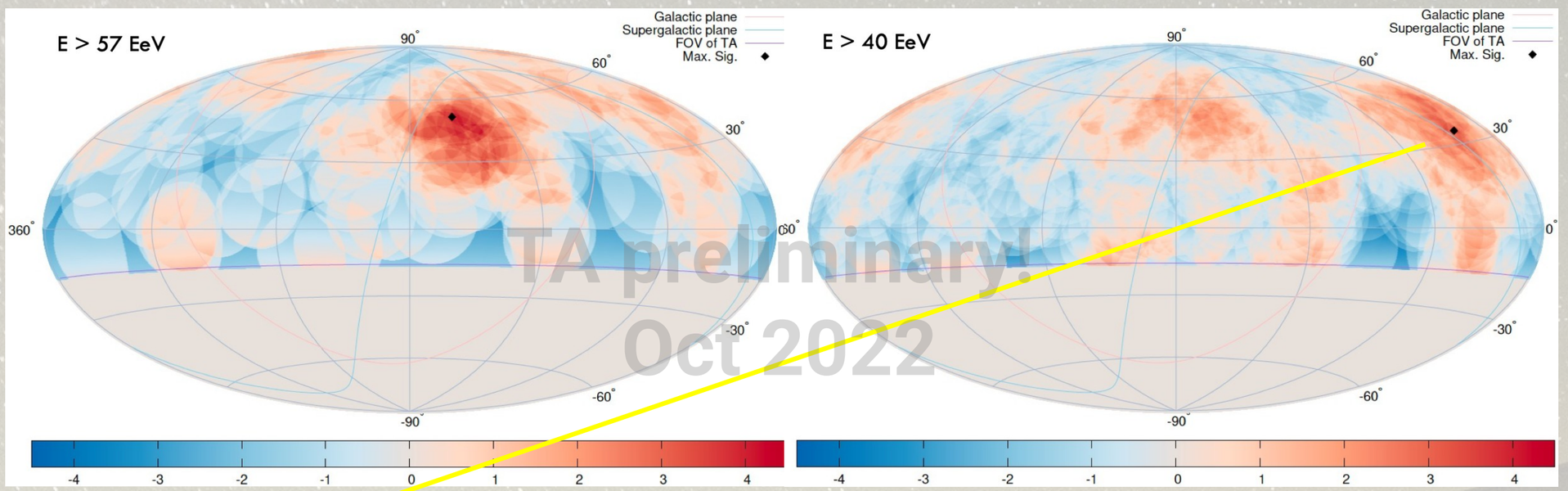


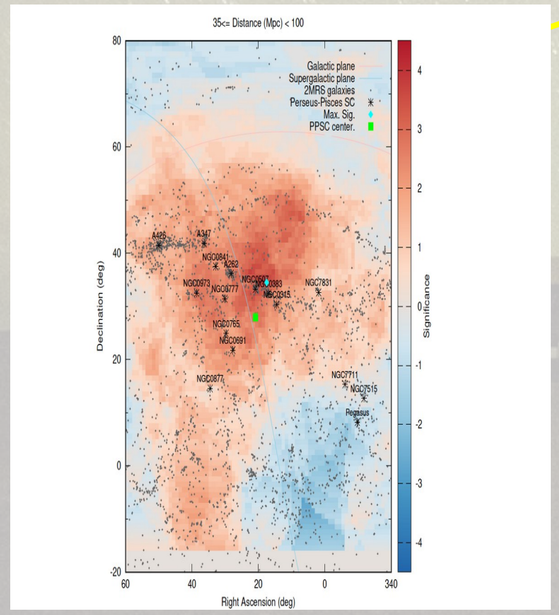
Energy E > 57 EeV

Overall post-trial significance has dropped from 3.4σ to 3.2σ

The growth rate of events inside the hotspot is consistent with the linear one within ~ 1σ

CR clustering: lower energies



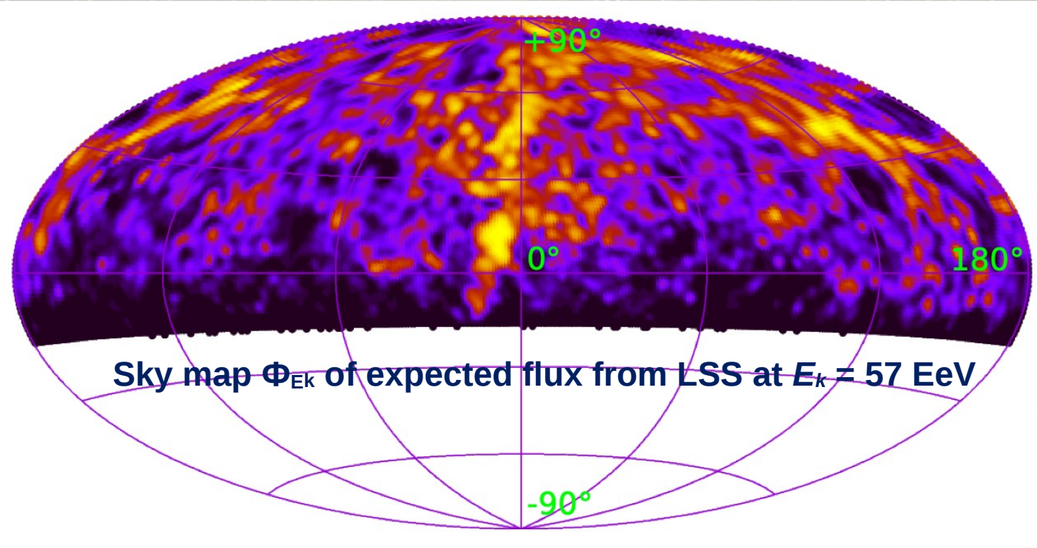


Hint of excess in the direction of Perseus-Pisces supercluster: 3.5 σ local significance

Chance probability to have the excess from Perseus-Pisces superculser: 3.2 σ

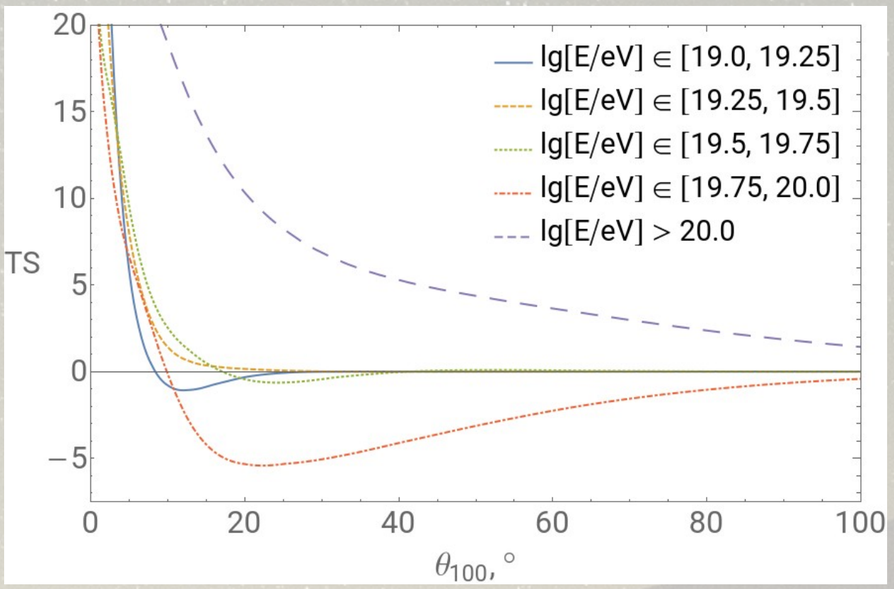
Chance probability to have the excess from other major superclusters: 2.6 σ

Correlation with LSS: measure for UHECR injected mass composition



Sky map Φ_{Ek} of expected flux from LSS at E_k = 57 EeV

Compute TS for SD data

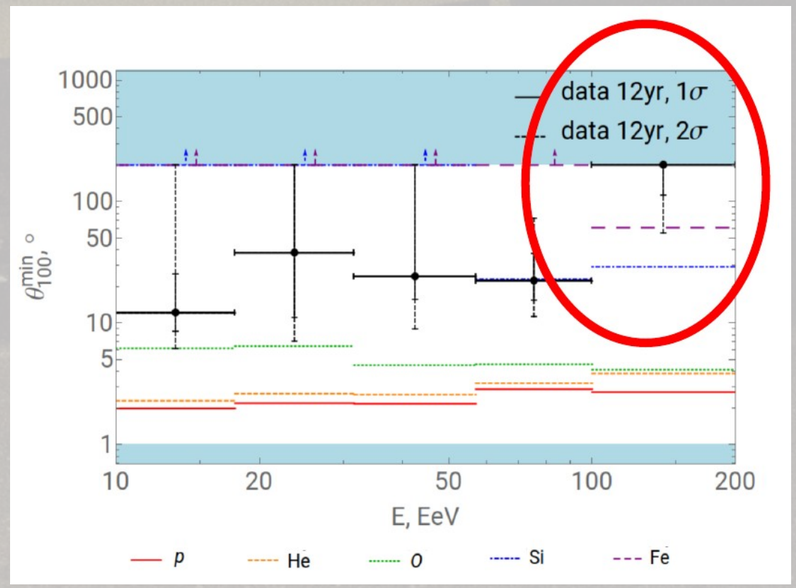


$$TS(\theta) = -2\sum_{E_k}\left(\sum_i \ln\frac{\Phi_{E_k}(\theta,\mathbf{n}_i)}{\Phi_{\rm iso}(\mathbf{n}_i)}\right)$$

θ is an average deflection of event set from expected sources in LSS

Compare with various primaries simulations

MK & P. Tinyakov, JCAP 04 (2021) 065

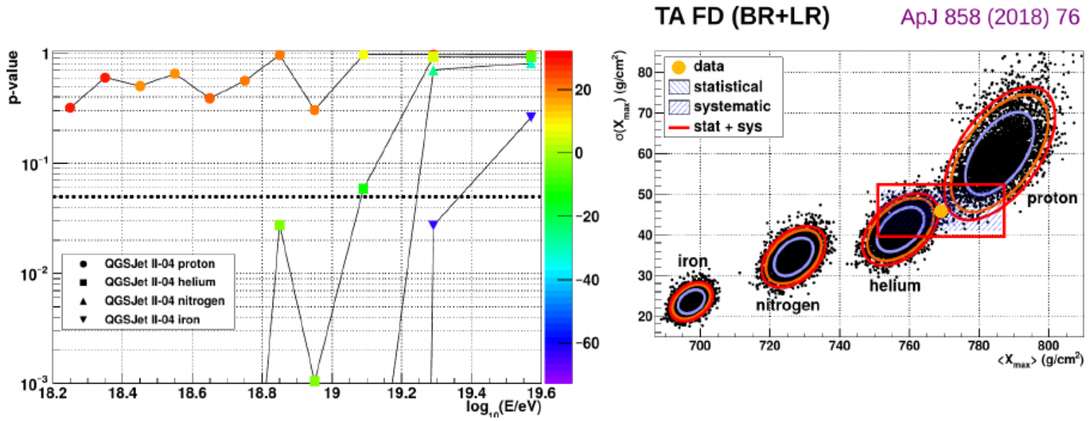


- Small deflections and light composition are disfavored at all $E > 10^{19}$ eV (EGMF = 0)
- At $E > 10^{20}$ eV data is very isotropic so that **even injected iron is in tension with data**

Correlation with LSS vs. X_{max} composition

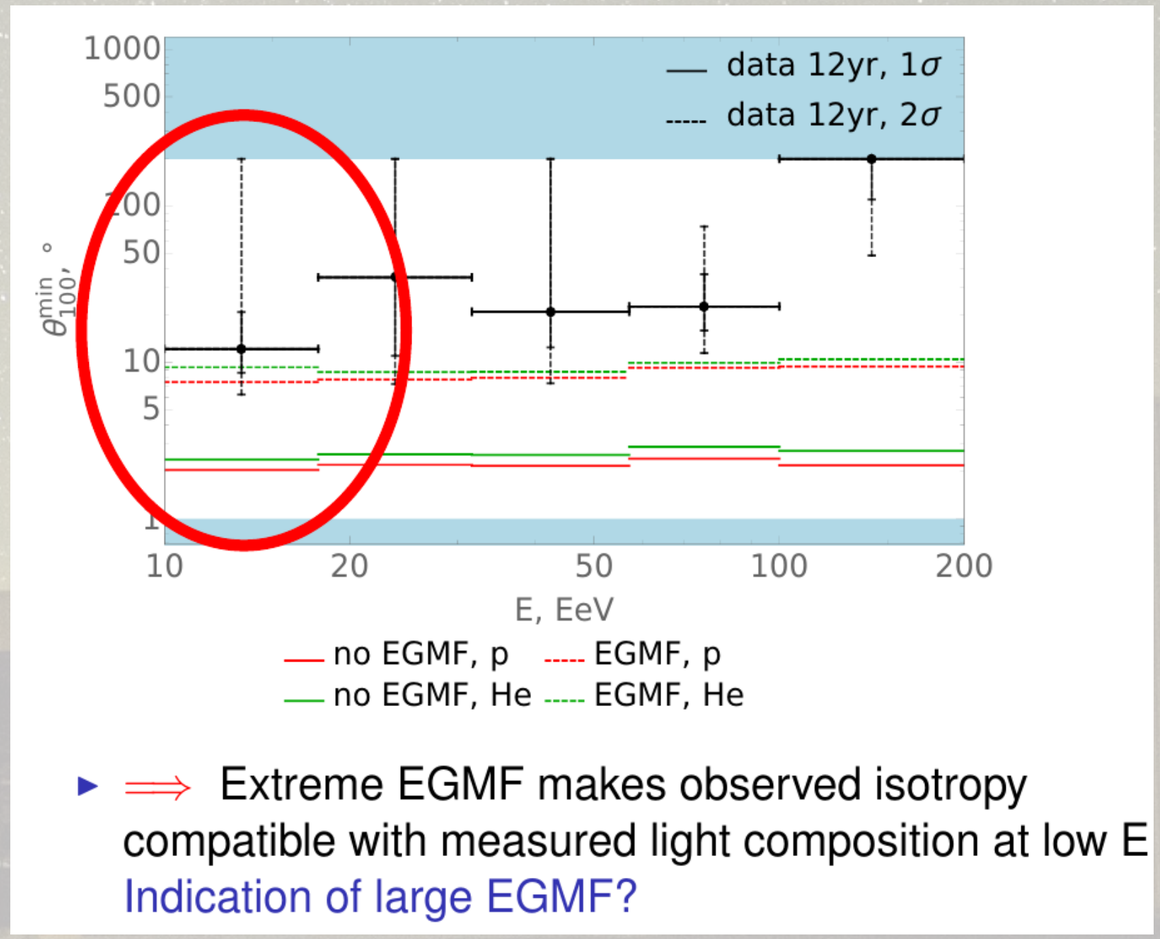
TA FD composition measurement:

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



- In tension with measured deflections? Not necessarily.

Add the largest allowed EGMF to simulations



- ⟹ Extreme EGMF makes observed isotropy compatible with measured light composition at low E

  Indication of large EGMF?

Summary

- Telescope Array is the largest UHECR Observatory in the Northern Hemisphere
- Energy spectrum is measured from $10^{15.5}$ to $10^{20.5}$ eV (5 decades)
  - New feature (hardening) in the energy spectrum at ~$10^{19.3}$eV
  - TA Low Energy Extension (TALE) energy spectrum indicated that second knee may result from Peters cycle ($10^{15.6}$eV-$10^{17.1}$eV)
- Between $10^{18.0}$ eV and $10^{19.1}$eV TA hybrid data is compatible with predominantly light elements such as protons and helium
- Indications of anisotropy at 40 < E < 100 EeV
  - Hint of excess in the direction of Perseus Pisces E > $10^{19.3}$eV
  - Hotspot in the direction of Ursa Major (3.2σ post trial)
- Very isotropic data at E > 100 EeV → Indication of heavy composition?
- Large deflections at 10 < E < 40 EeV + light composition from X_{max} → Indication of strong EGMF?
- We need much more data at high energy end → TAx4 in operation!