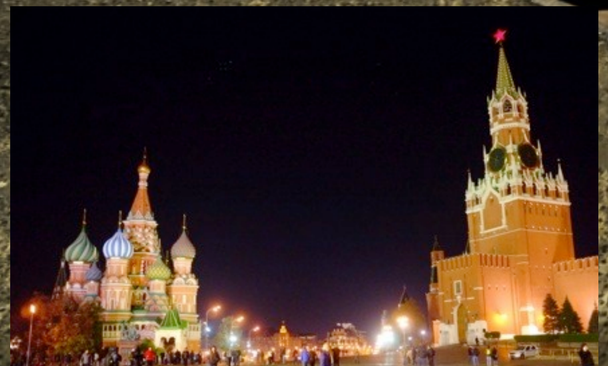
Recent results of ultrahigh-energy cosmic rays observed with the Telescope Array Experiment



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ICPPA- 2018, October 26th, 2018

Telescope Array collaboration

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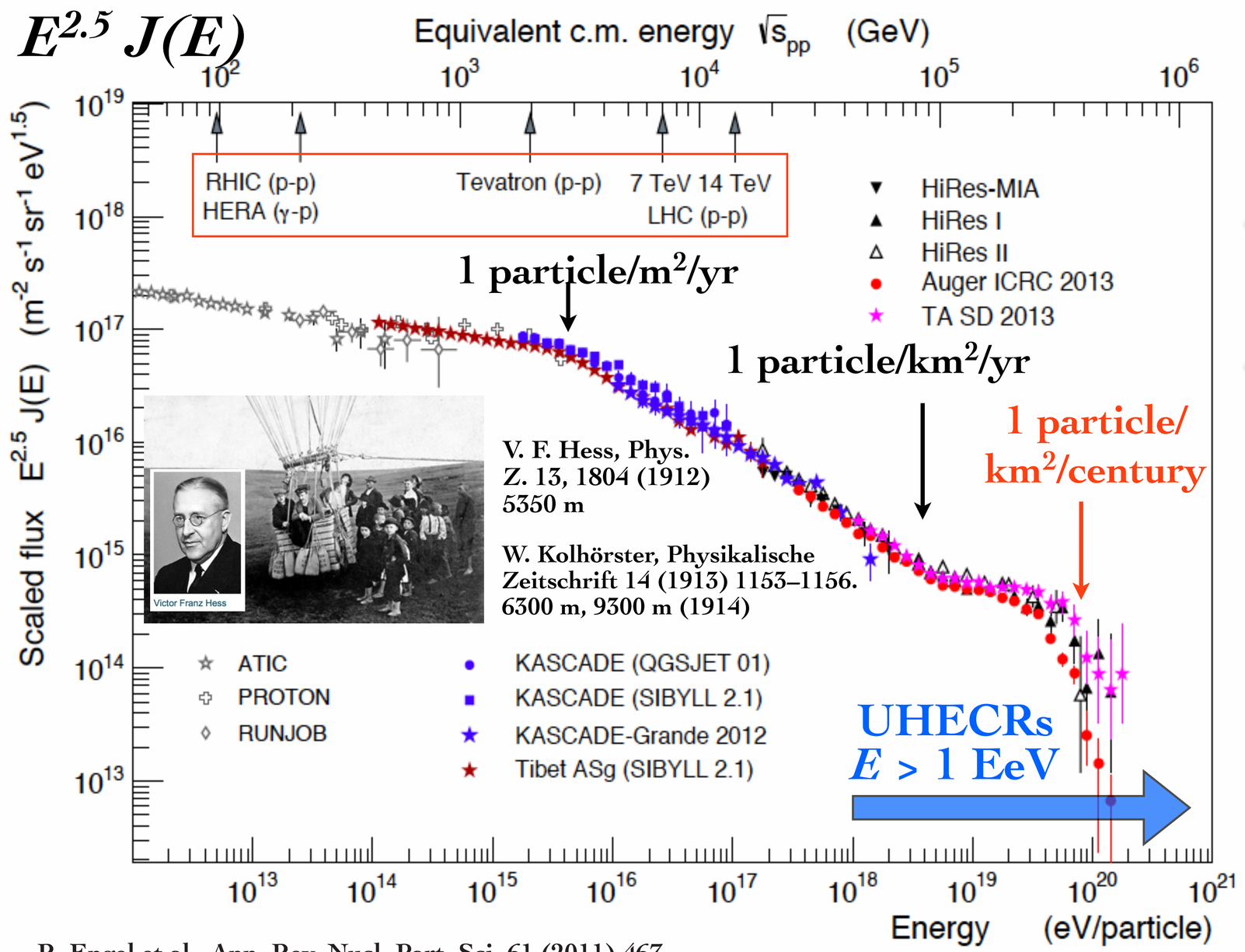
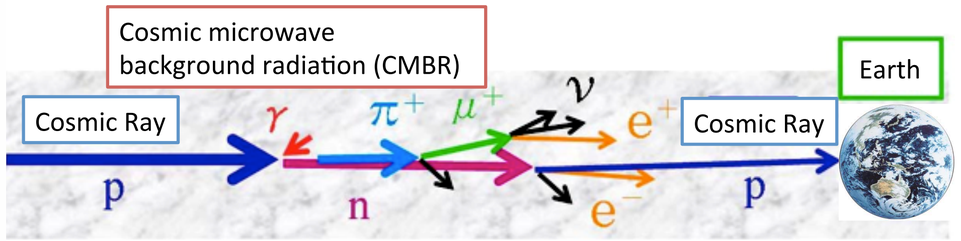
Japan, USA, Russia, South Korea, Belgium, Czech republic

* Deceased

Ultrahigh-energy cosmic rays (UHECRs)



R. Engel et al., Ann. Rev. Nucl. Part. Sci. 61 (2011) 467



- The most energetic particles in the Universe.
  - $\sqrt{s_{pp}}$ > 100 TeV
- Greisen-Zatsepin-Kuzmin (GZK) suppression is expected at the highest energies
  - limited sources in nearby universe (50 - 100 Mpc)
- less deflection in galactic/extragalactic magnetic fields
  - Correlation with nearby objects (UHECR astronomy)
- **Telescope Array Experiment (700 km²)**
- **Pierre Auger Observatory (3000 km²)**

Telescope Array Experiment (TA)

- **Largest cosmic ray detector in the Northern hemisphere**
  ~ 700 km^2 at Utah, USA
- Fluorescence detector + Surface detector array

Surface detector array

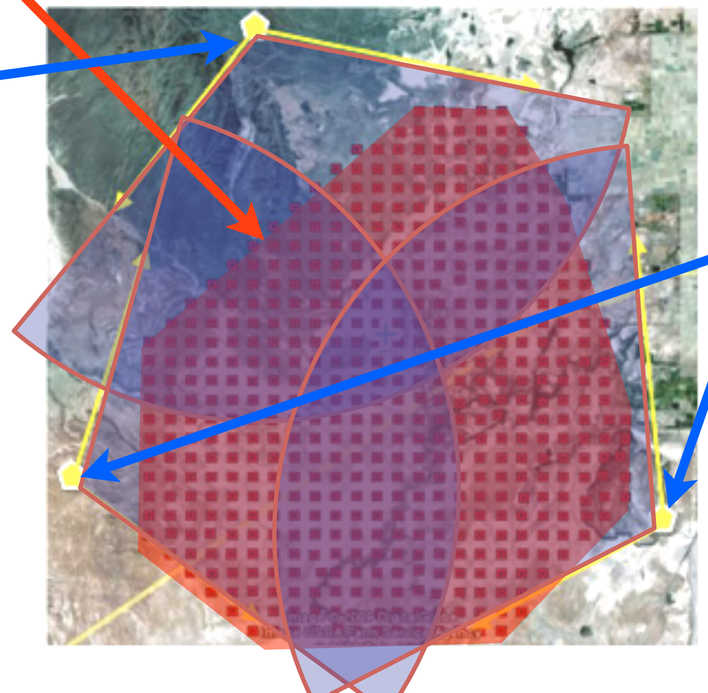
507 Scintillator, 1.2 km spacing

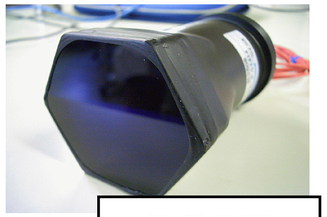
Fluorescence detector at two southern stations

Spherical segment mirror (6.8 m^2) + 256 Photomultiplier tube(PMTs)/camera, 12 newly designed telescopes

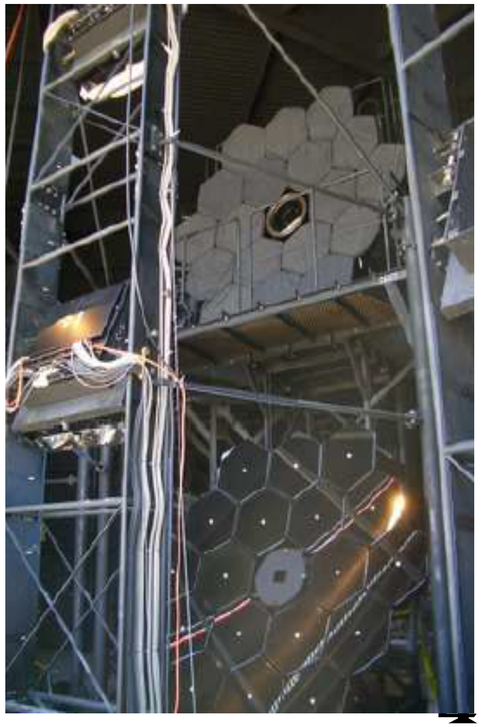
Fluorescence detector at a northern station

Refurbished
from HiRes experiment,
Spherical mirror 5.2 m^2,
256 PMTs/camera,
14 telescopes

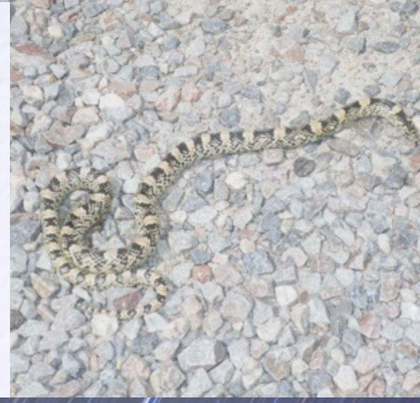




PMT

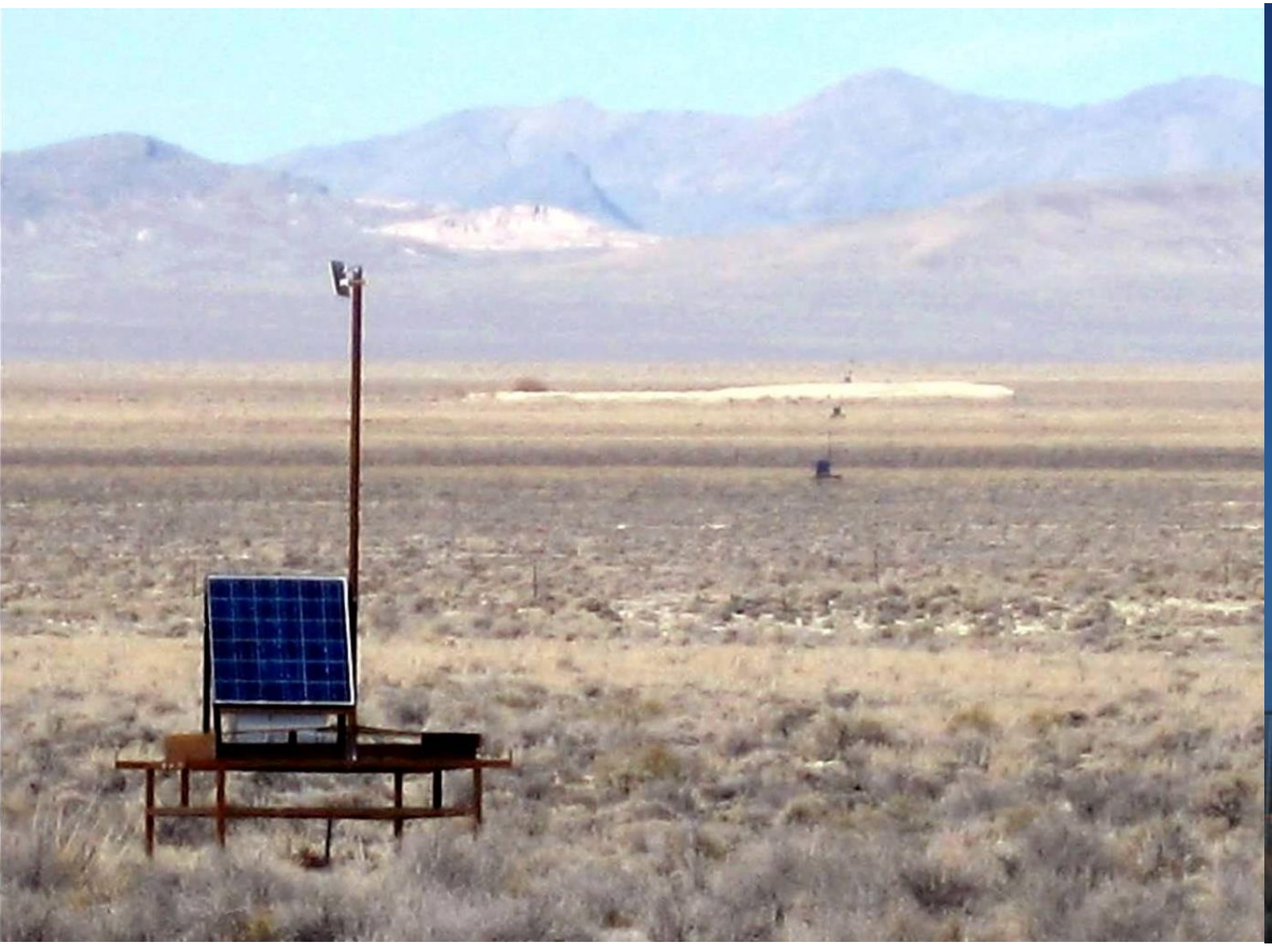


Experimental site



Telescope Array Experiment (TA)

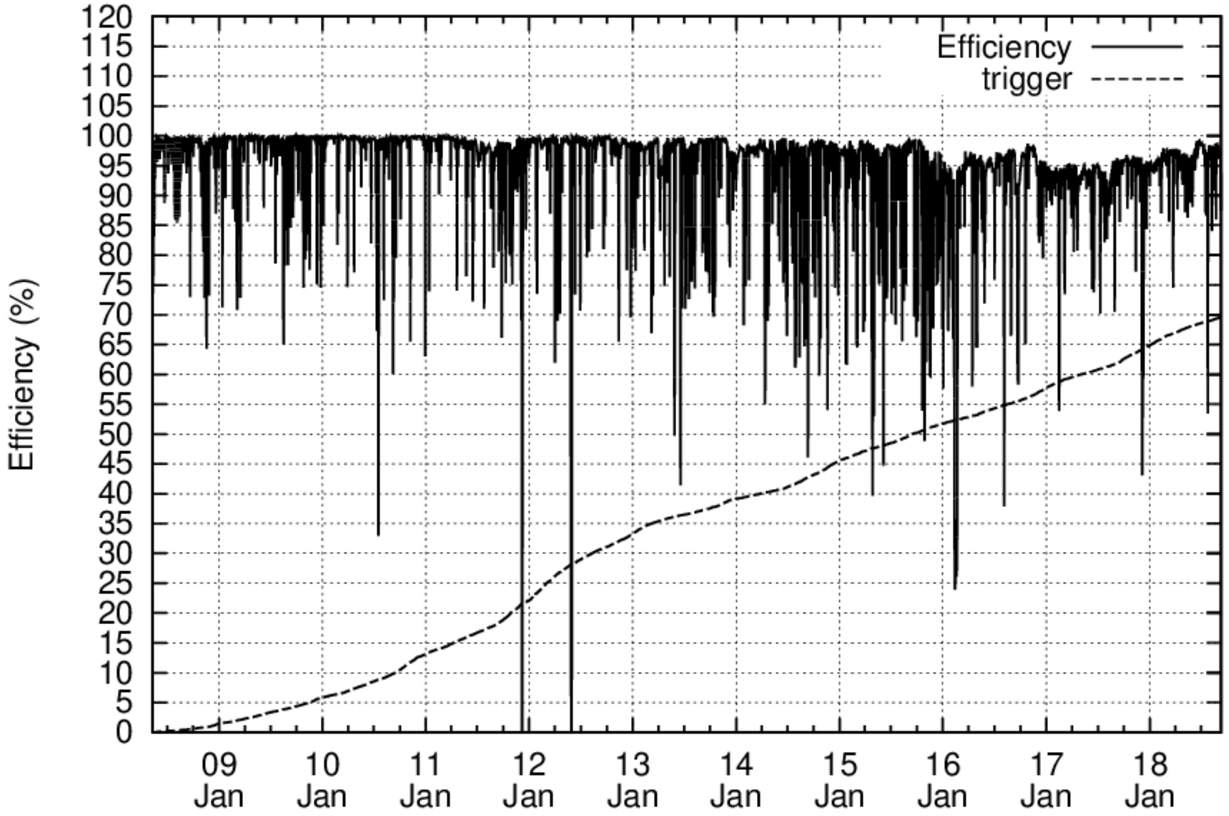
Surface detector array (SD) Fluorescence detector (FD)



10-years steadily operation

Surface detector array (SD)

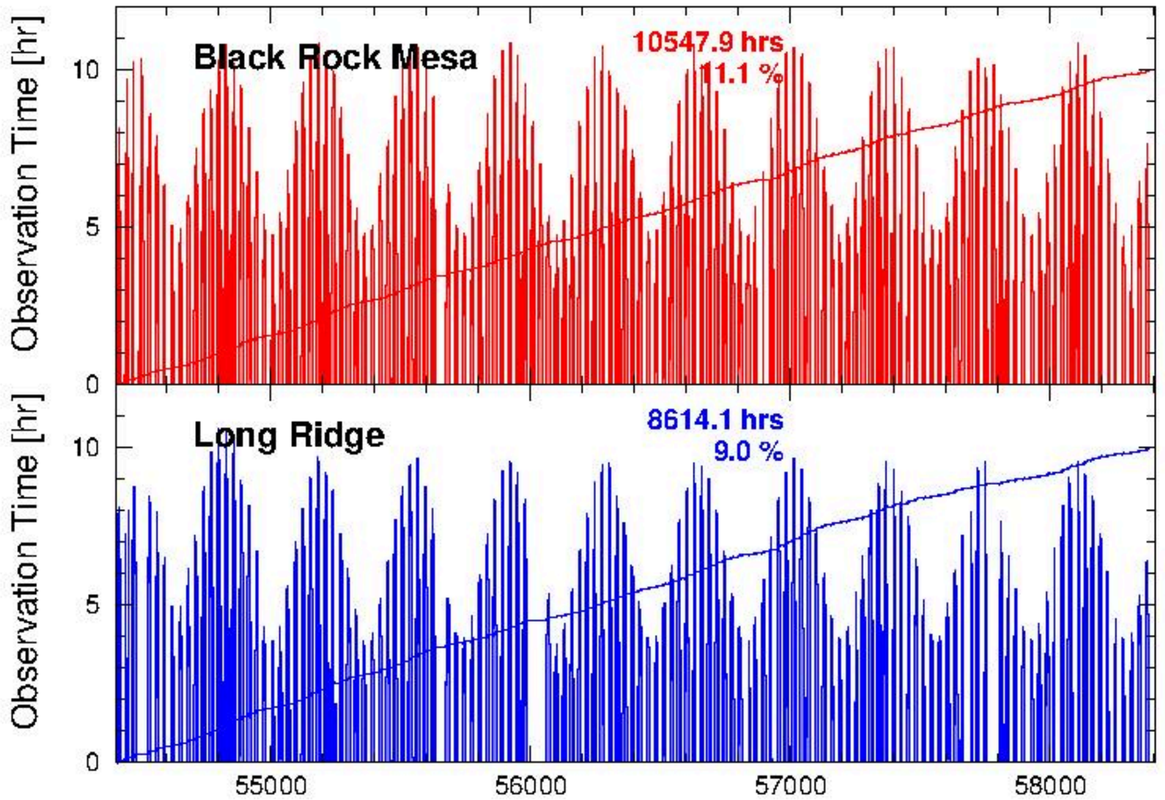
~95% duty operation



2008 2018

Fluorescence detector (FD)

Clear moonless night
~10% duty operation

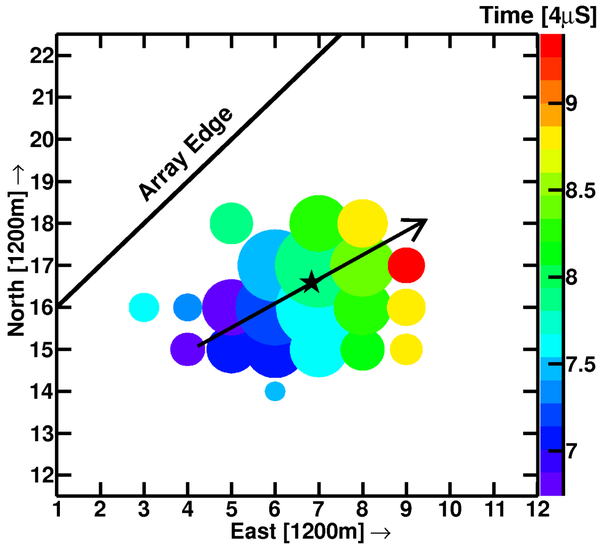


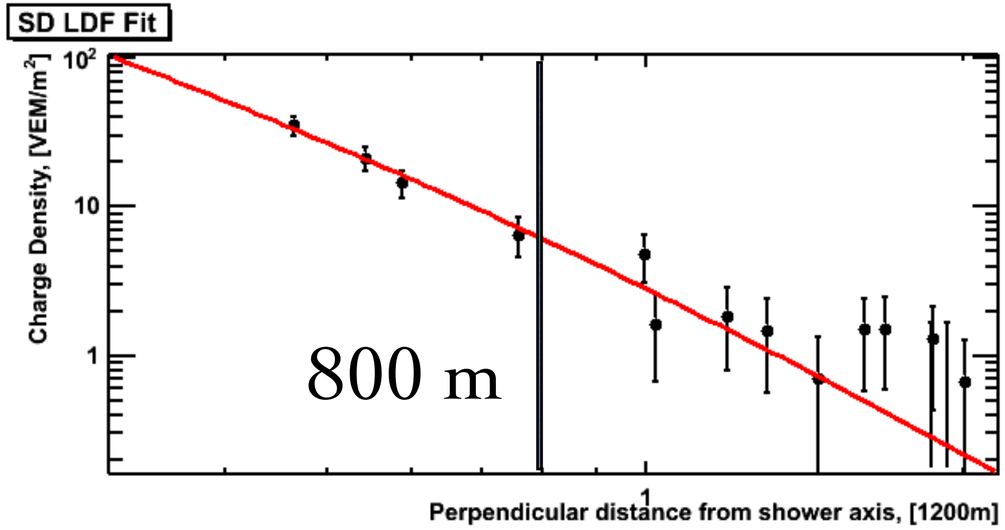
2008 2018

UHECR event

Surface detector array (SD)

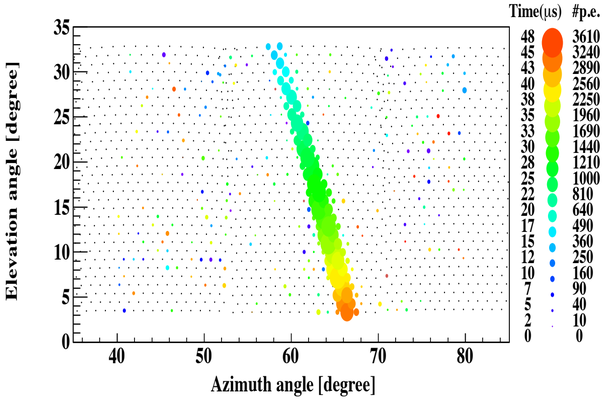
- Observe lateral density distribution
- Charge density at 800 m, S_{800} as energy indicator

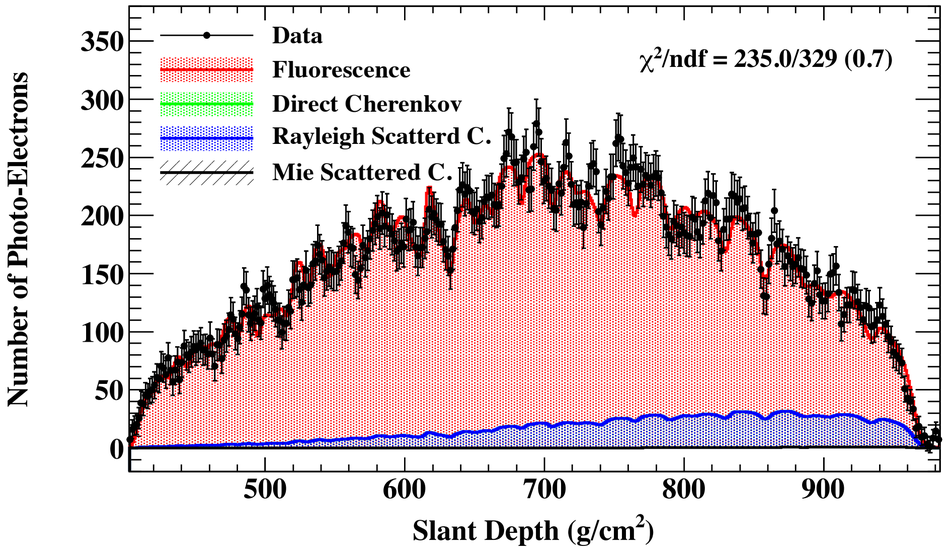




Fluorescence detector (FD)

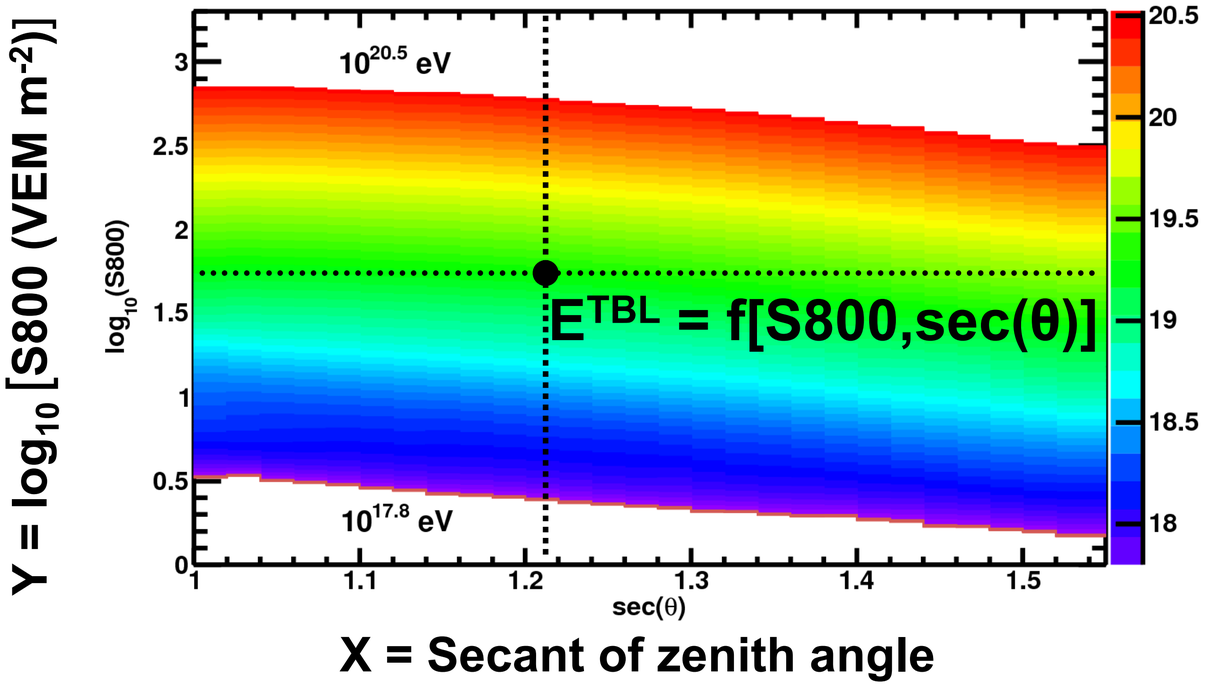
- Observe longitudinal development
- Reconstruct **calorimetric energy**
- **Mass composition sensitive**
- $\Delta X_{max} = 25$ g/cm^2



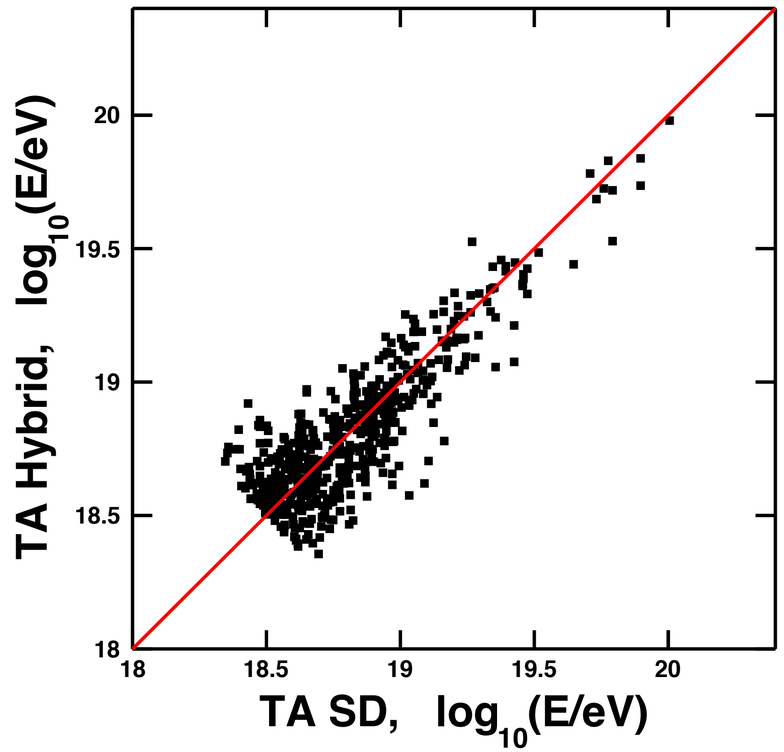


Energy estimation by TA SD

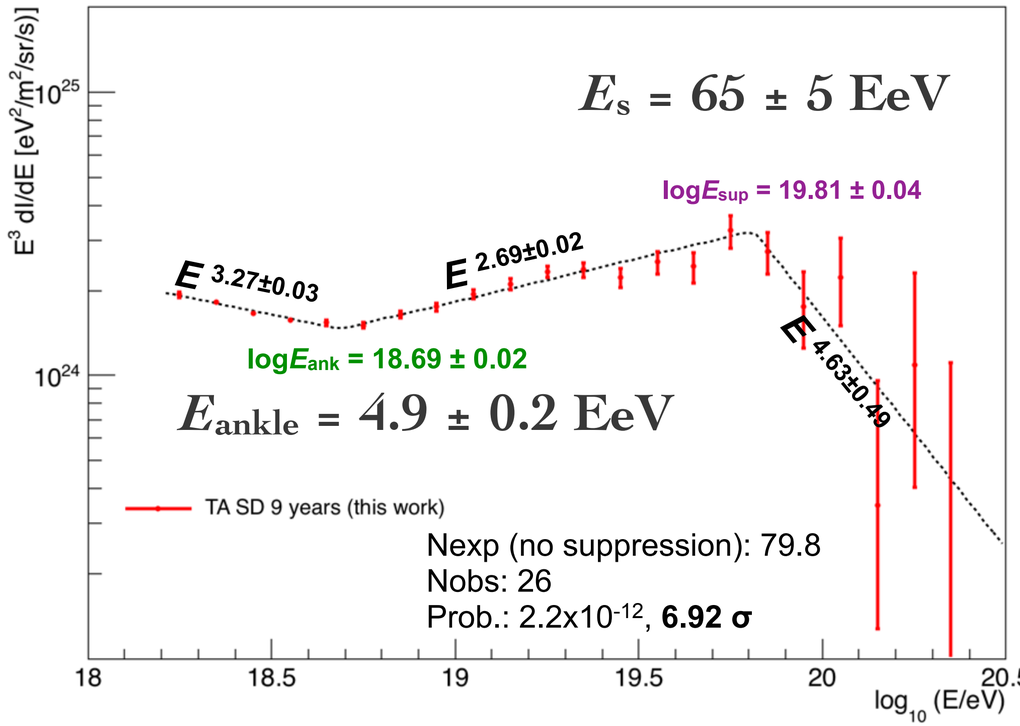
- A look up table made from Monte Carlo simulation
- Event energy E_{TBL} = function of S_{800} and zenith angle, sec(θ)

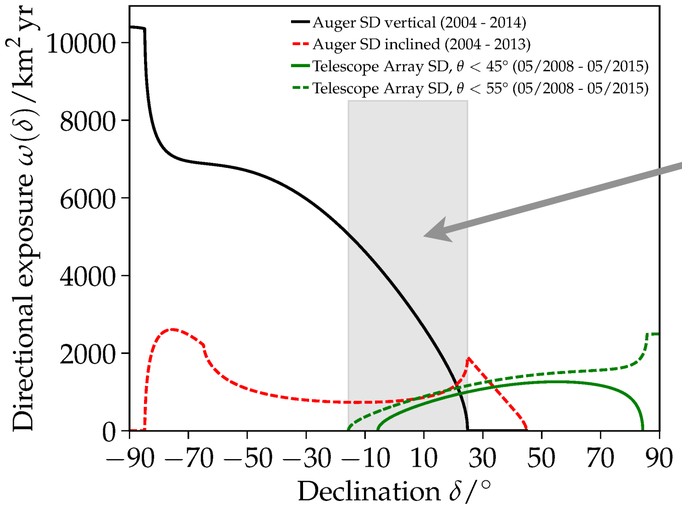


- E_{TBL} is rescaled by the FD reconstructed energy to estimate final energy of SD, $E_{SD,final}$
- $E_{SD,final} = E_{TBL}/1.27$,
- **~1.5 degree in direction, ~20% in energy resolution**



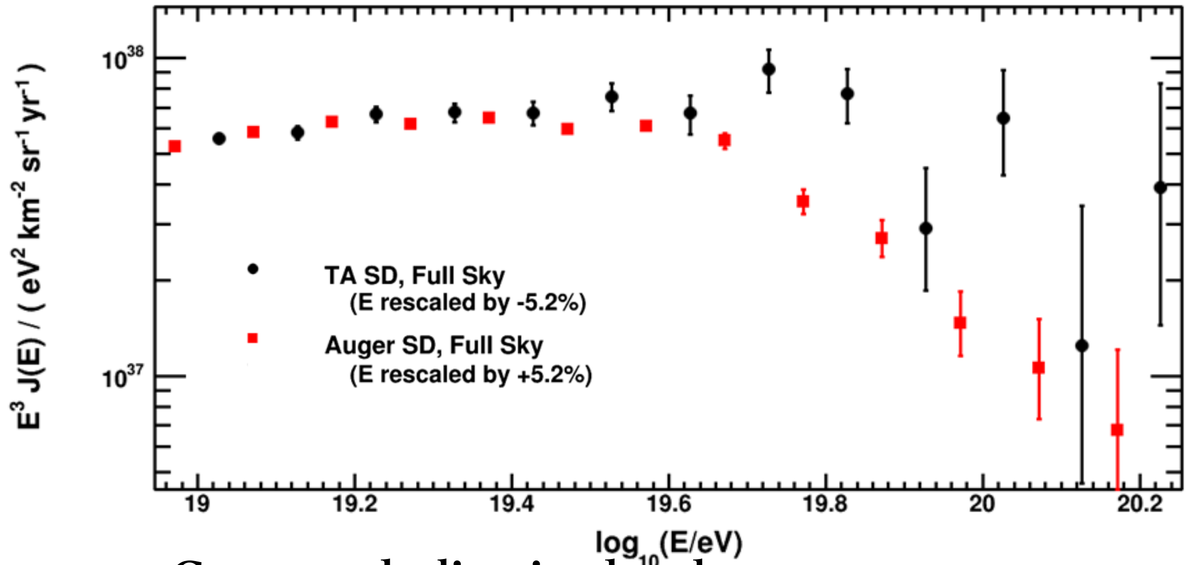
Energy spectrum



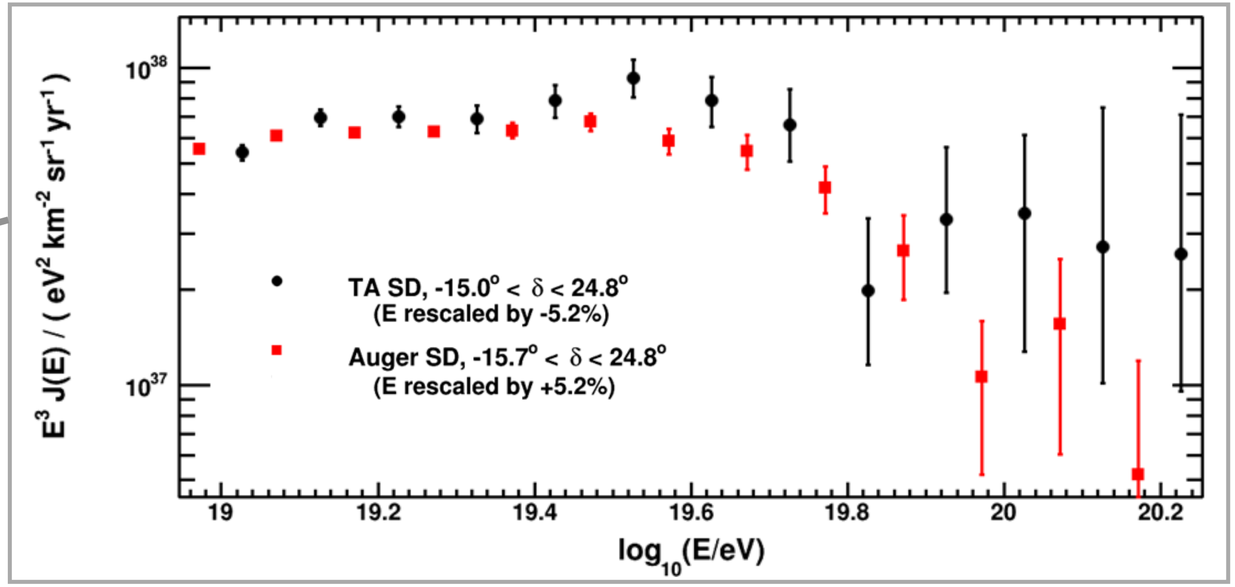


Y. Tsunesada, D. Ivanov
in ICRC 2017

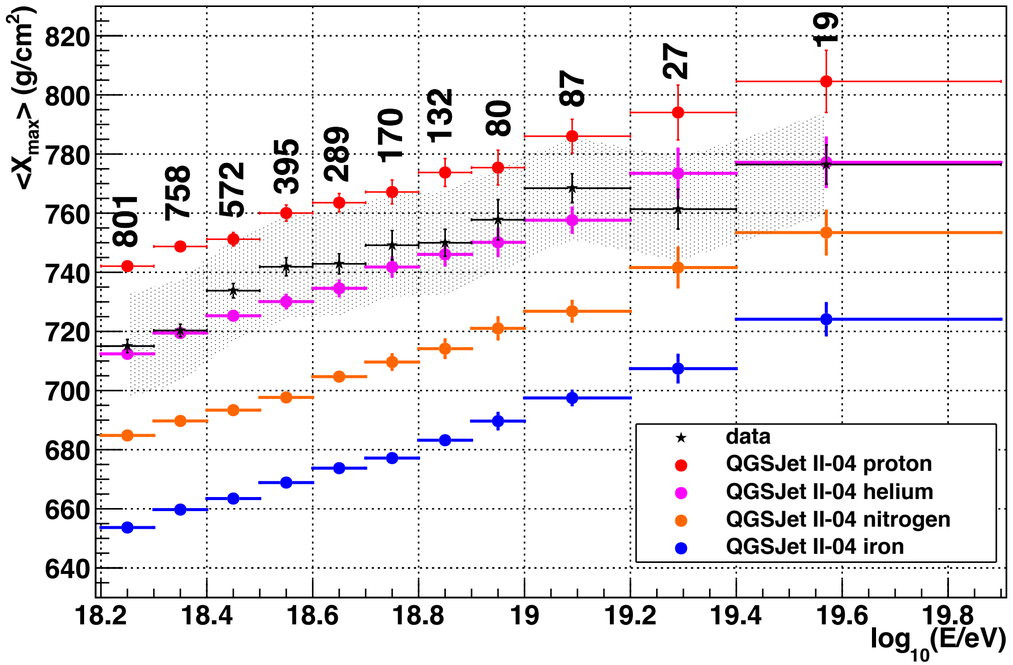
Entire sky of TA and Auger

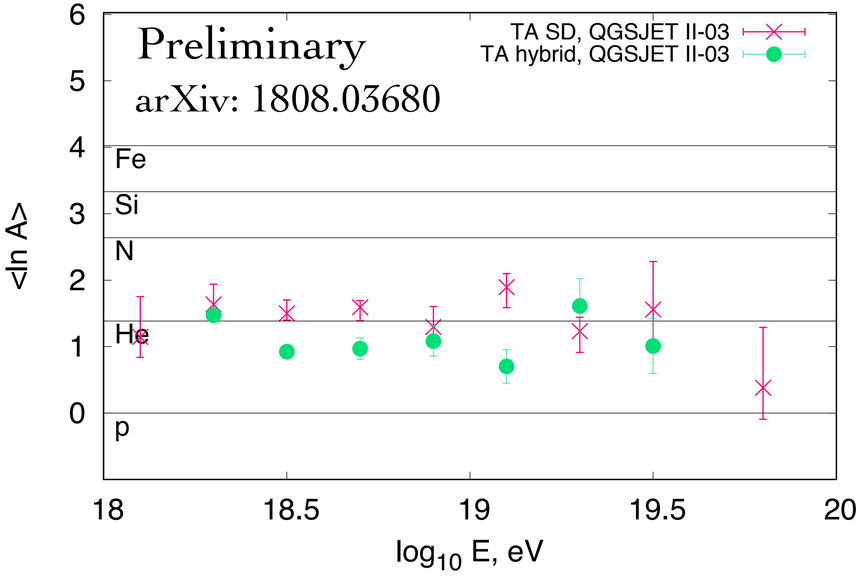


Common declination band



Mass composition using X_{max}



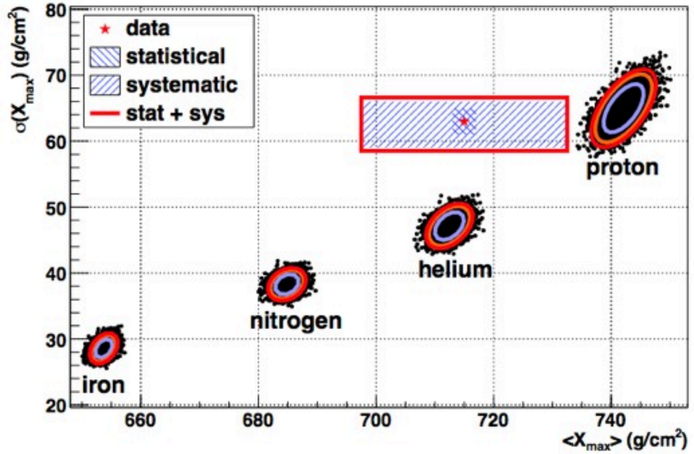


Take away message

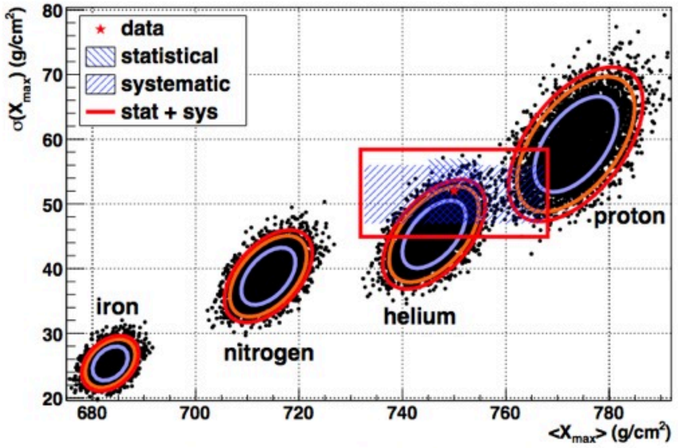
TA and Auger composition measurements (Xmax) **agree within the systematics**

$18.2 < \log_{10}(E/eV) < 19.0$

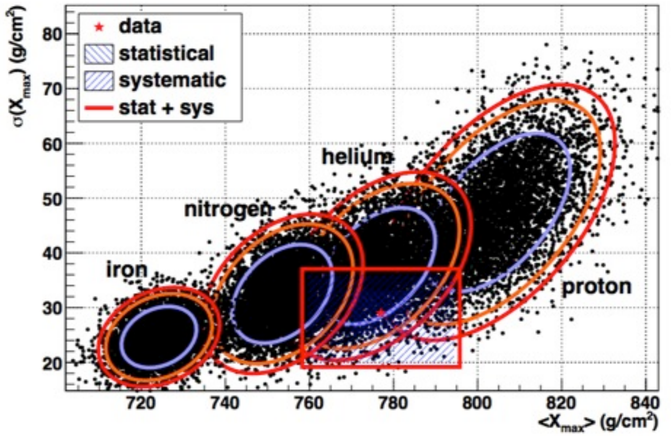
V. de Souza et al (Mass Composition WG), Proc. of ICRC 2017



(a) $18.2 \leq \log_{10}(E/eV) < 18.3$



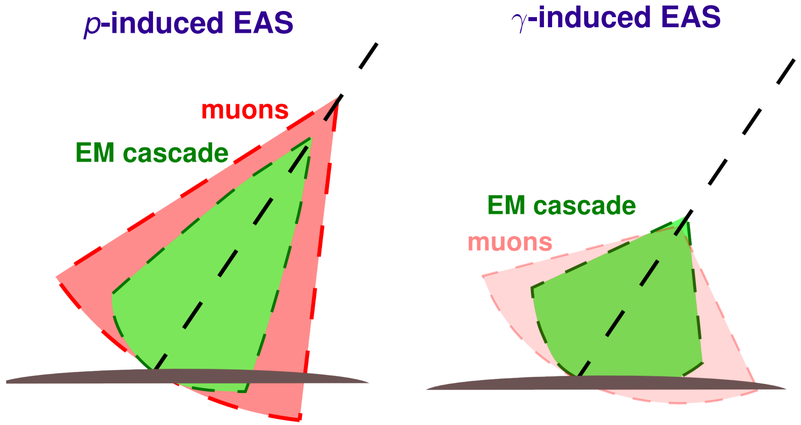
(a) $18.8 \leq \log_{10}(E/eV) < 18.9$

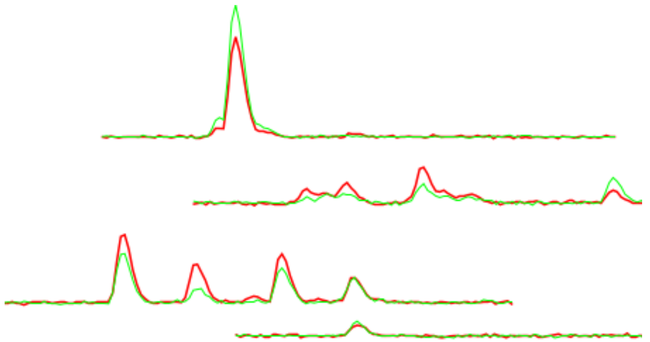


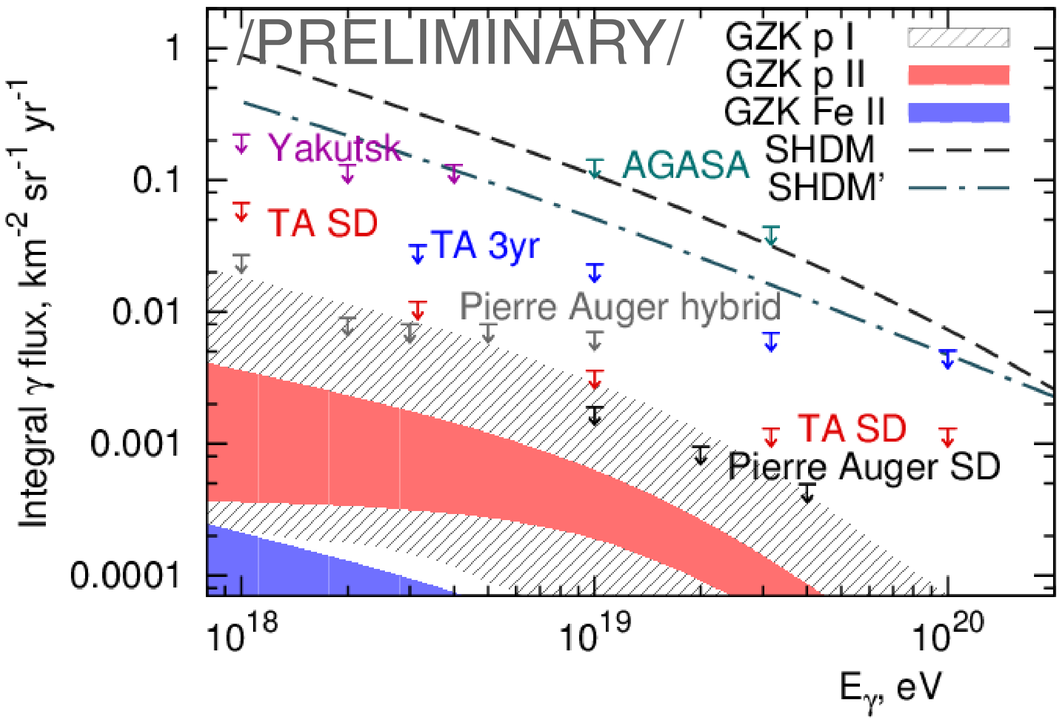
(e) $19.4 \leq \log_{10}(E/eV) < 19.9$

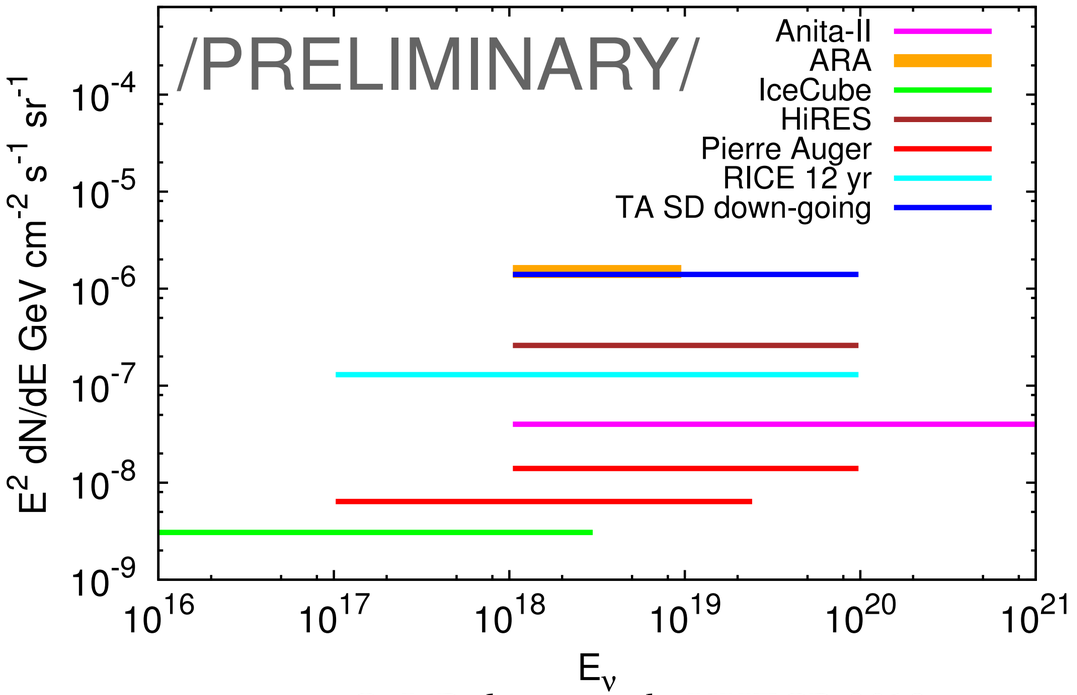
ApJ, 858, 76(2018)

No GZK γ-ray and neutrino at the highest energies







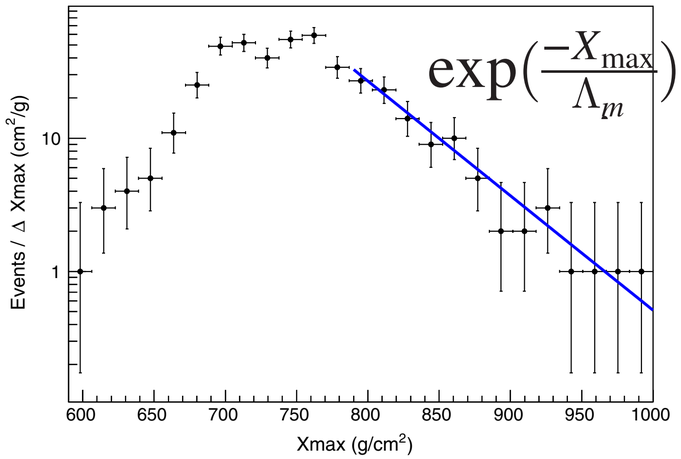


G. I. Rubtsov et al., UHECR 2018

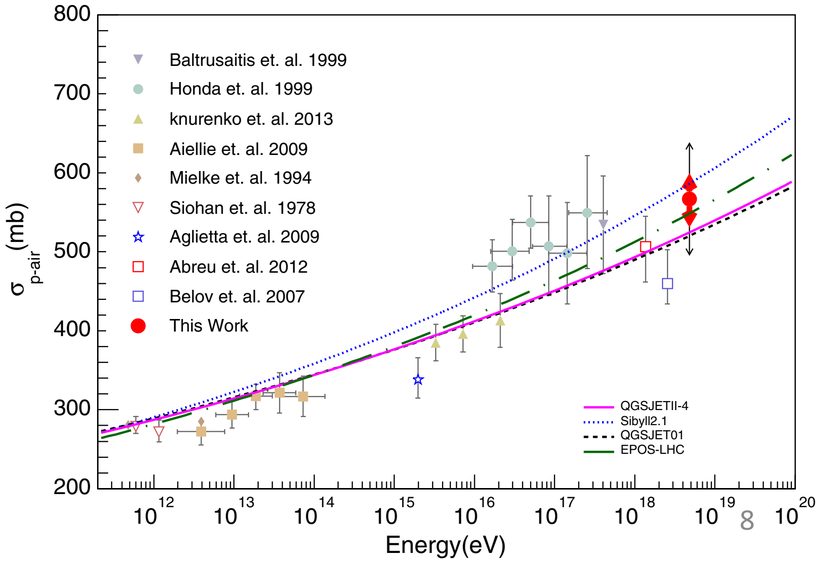
Interaction physics (√s~100 TeV)

Cross section

$10^{18.3}$ eV < E < $10^{19.3}$ eV



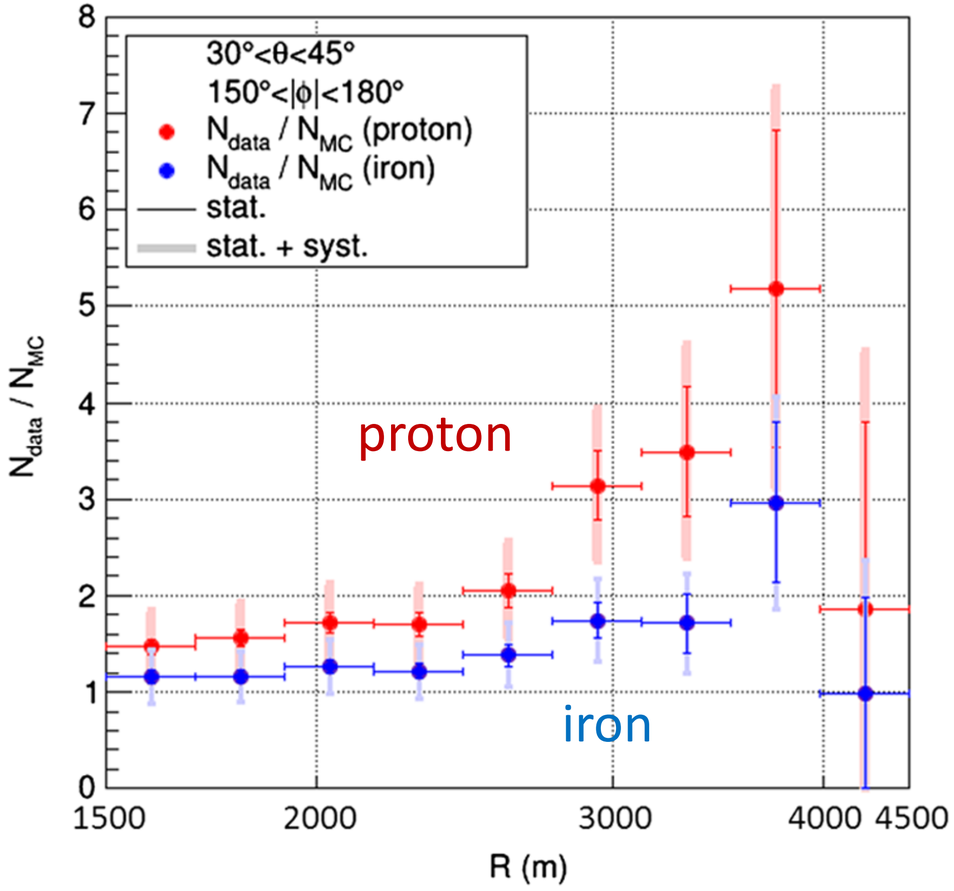
$$\sigma_{p-air}^{inel} = \left(567.0 \pm 70.5[stat]^{+29}_{-25}[sys]\right)mb$$



Phys. Rev. D92, 032007 (2015)

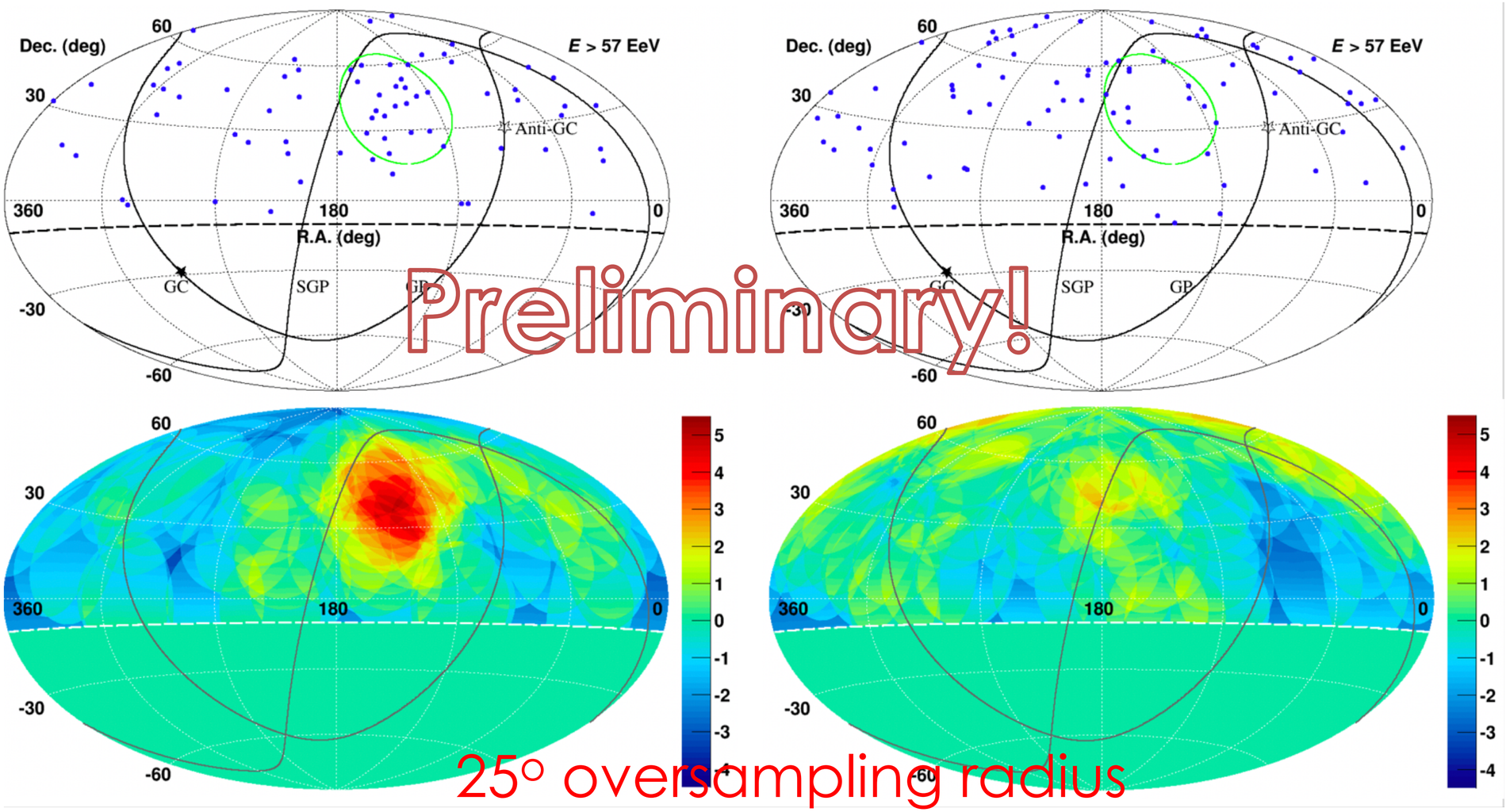
Muon deficits in simulation

$10^{18.8}$ eV < E < $10^{19.2}$ eV



Phys. Rev. D 98, 022002 (2018)

TA hotspot updates (E>57 EeV)



25° oversampling radius

1st-half 5 years : 72 events

Hotspot position = 5.0σ

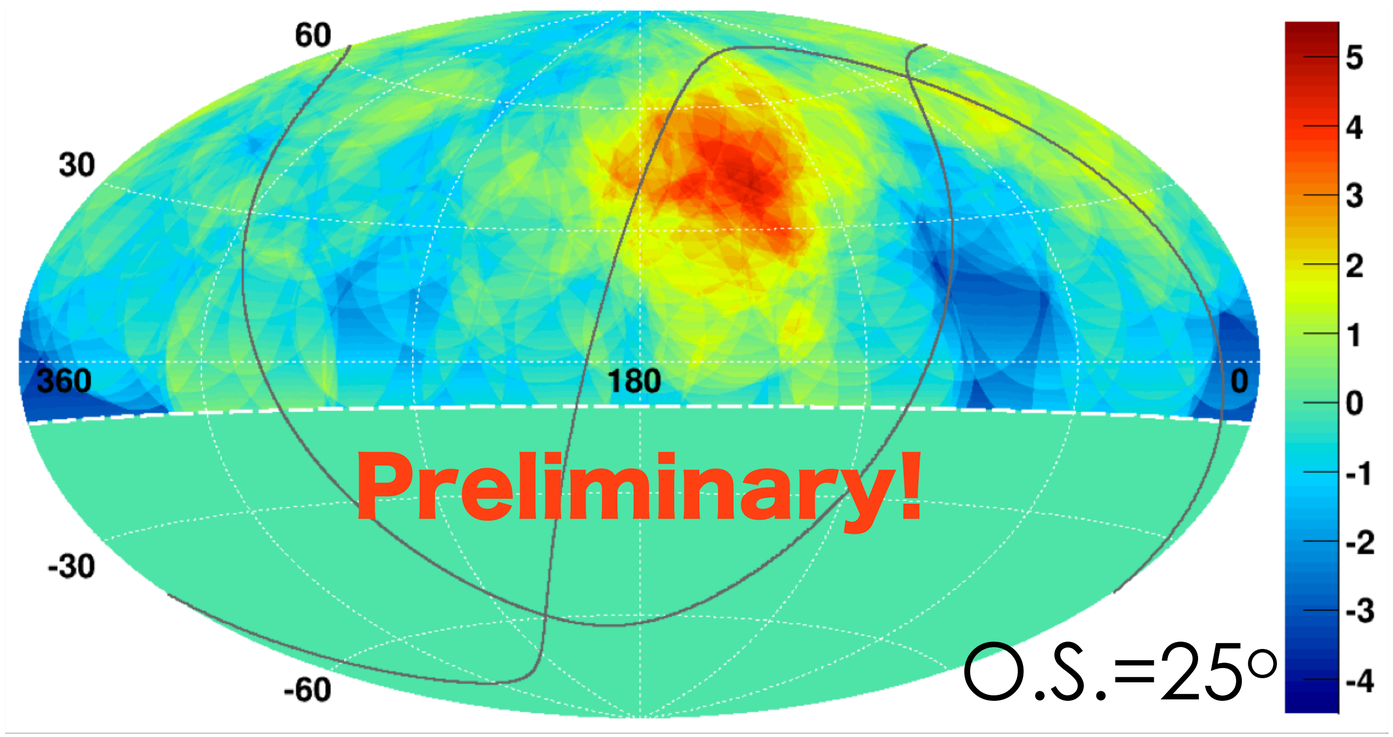
2nd-half 5 years : 85 events

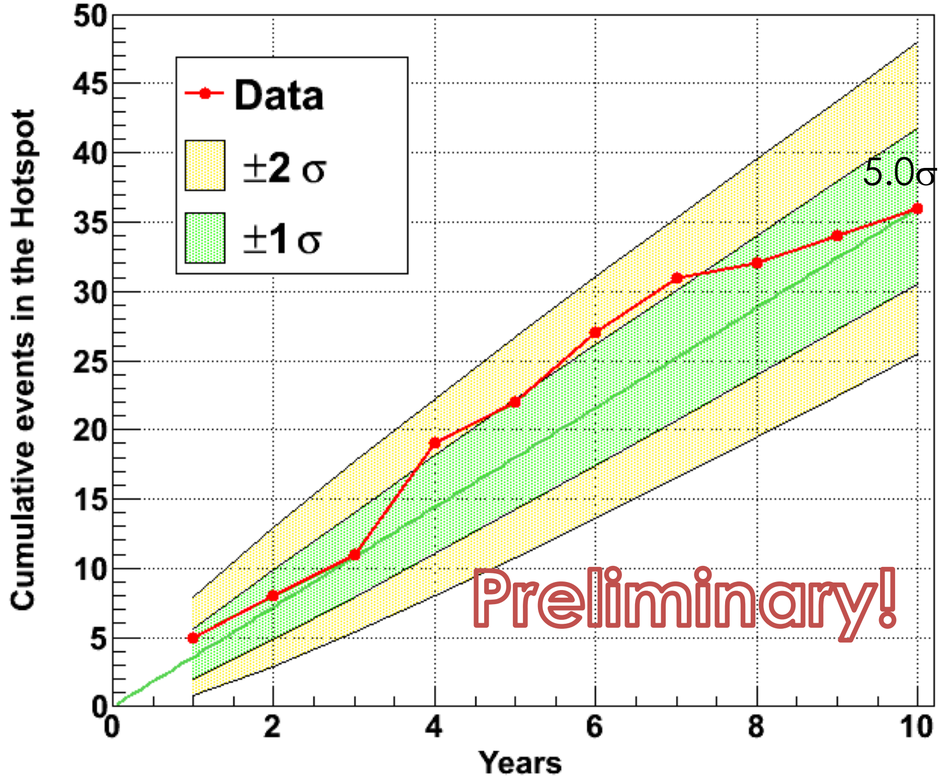
Hotspot position = 2.0σ

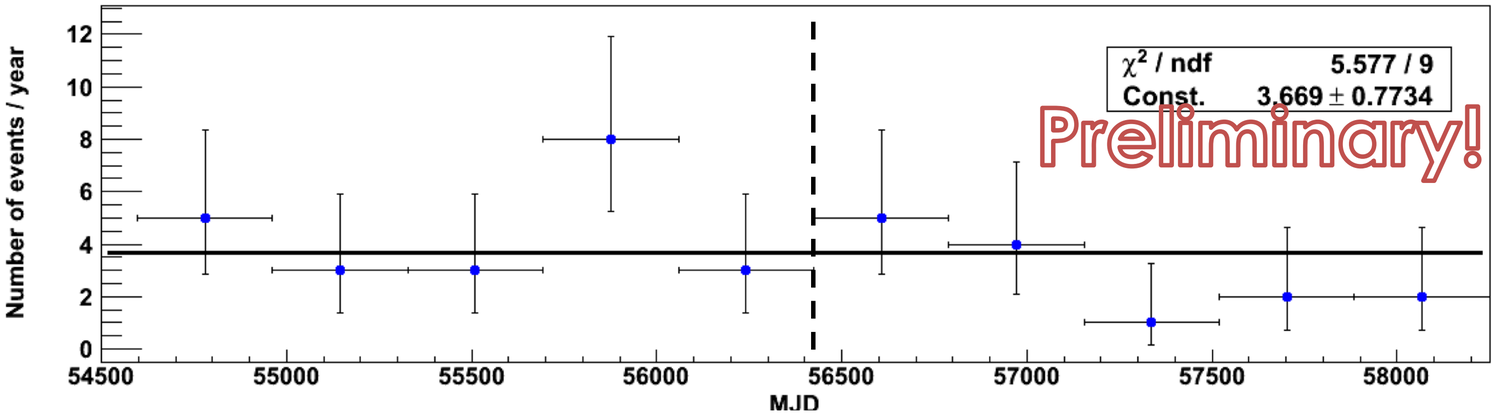
From JPS2018 meeting S. Ogio & K. Kawata

K. Kawata et al., UHECR 2018

10-years TA hotspot (E>57 EeV)





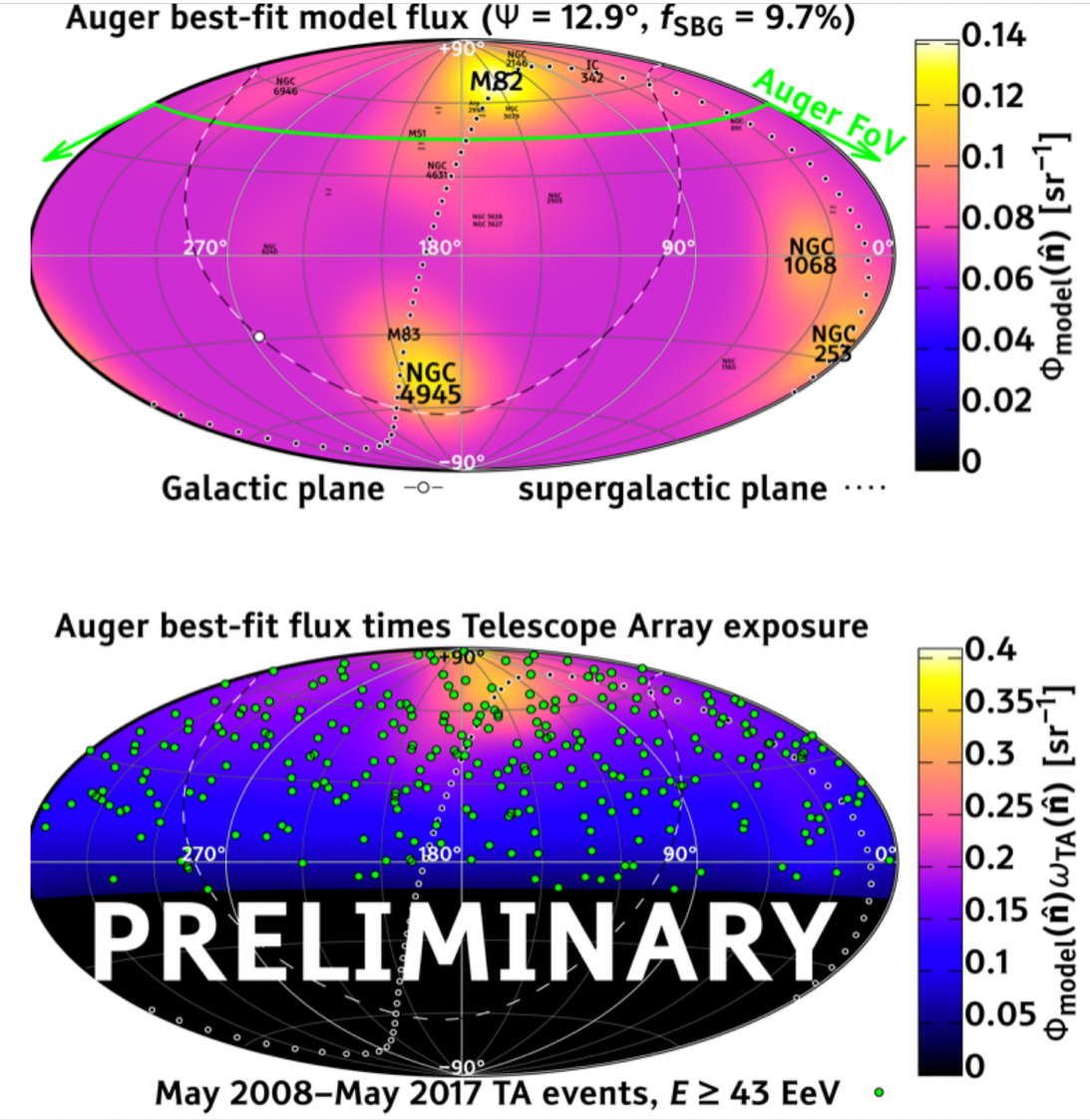


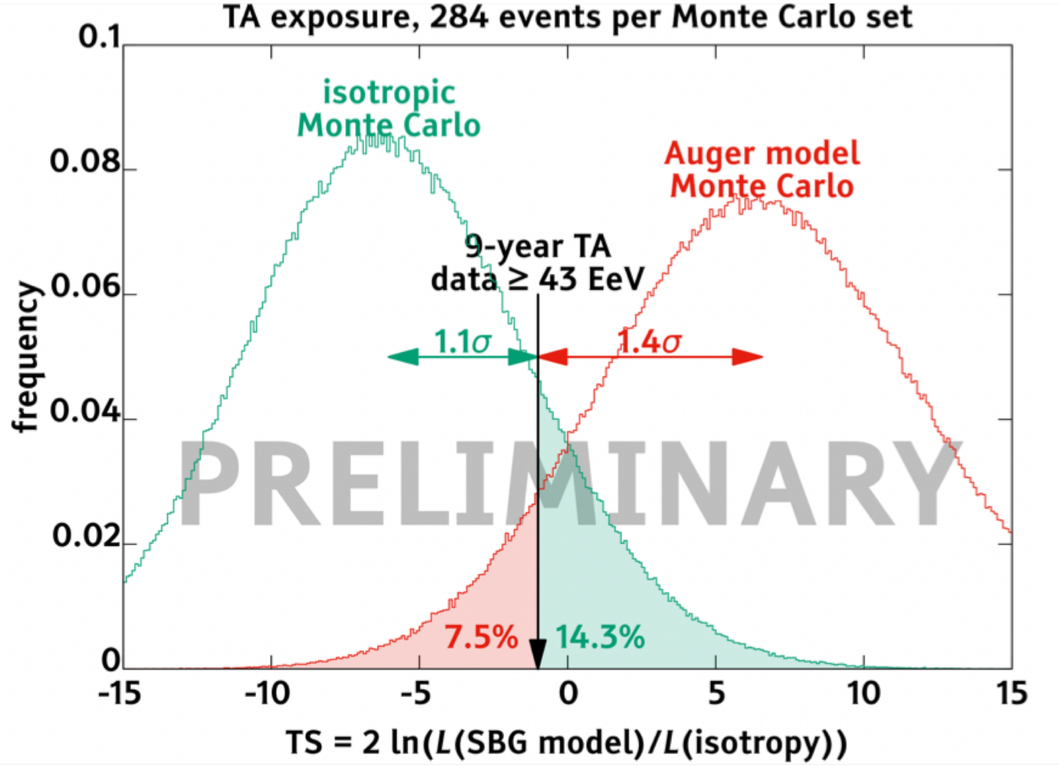
Hotspot position	Search radius	ON	α*OFF (OFF)	ON/OFF ratio (α)	σ
RA:144.3° Dec: 40.3°	25°	36	12.6 (121)	0.10435	5.0

K. Kawata et al., UHECR 2018

Flux pattern analysis using starburst galaxies catalog

Follow-up analysis of the Auger result of ApJL 853:L29 (2018)





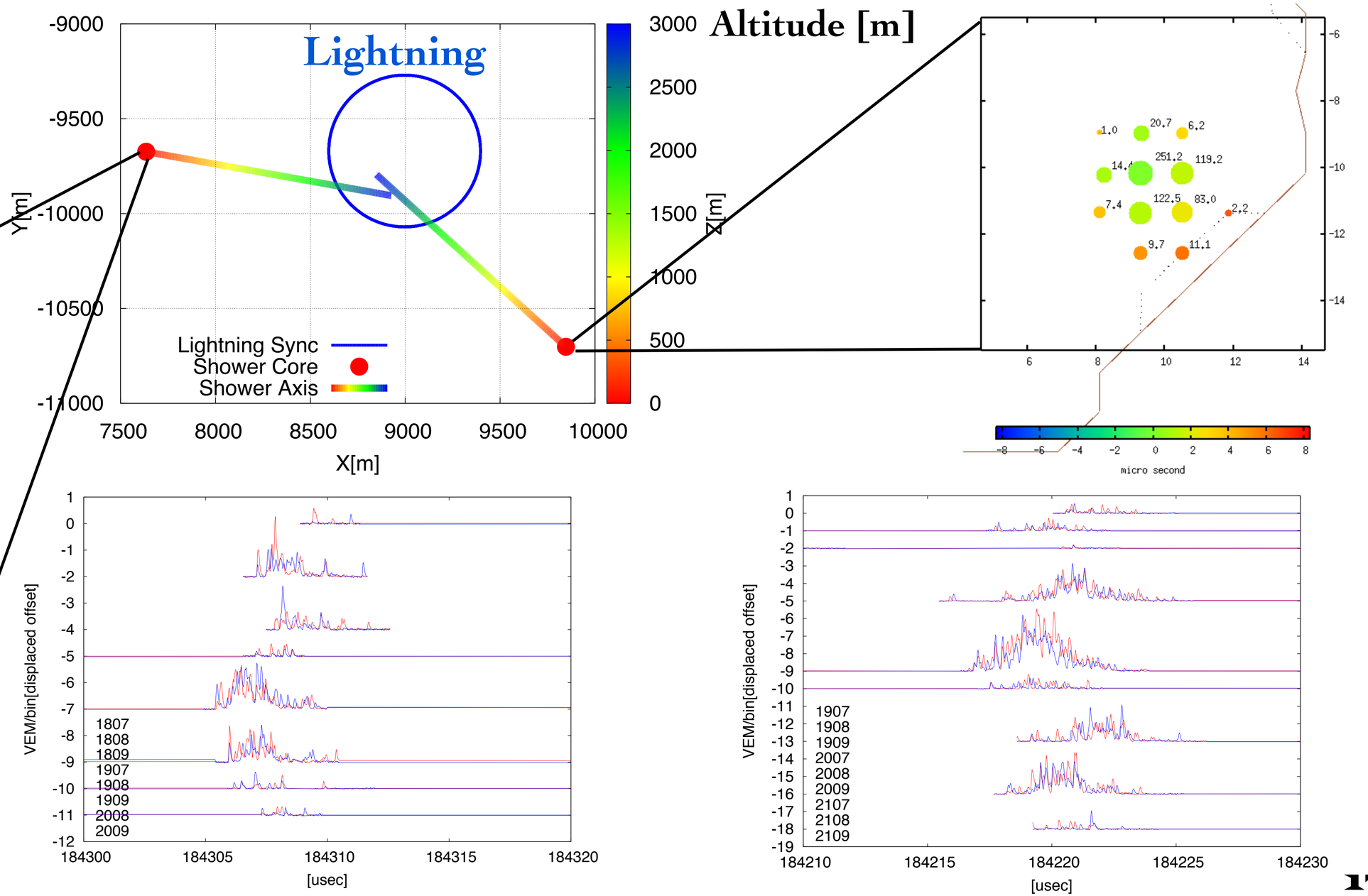
~1.1σ compatible with 100% isotropic

~1.4σ compatible with starbursts

A. di Matteo, T. Fujii, K. Kawata (UHECR2018 Poster)
Abbasi+2018, arXiv:1809.01573

Short-time bursts showers correlating with lightnings

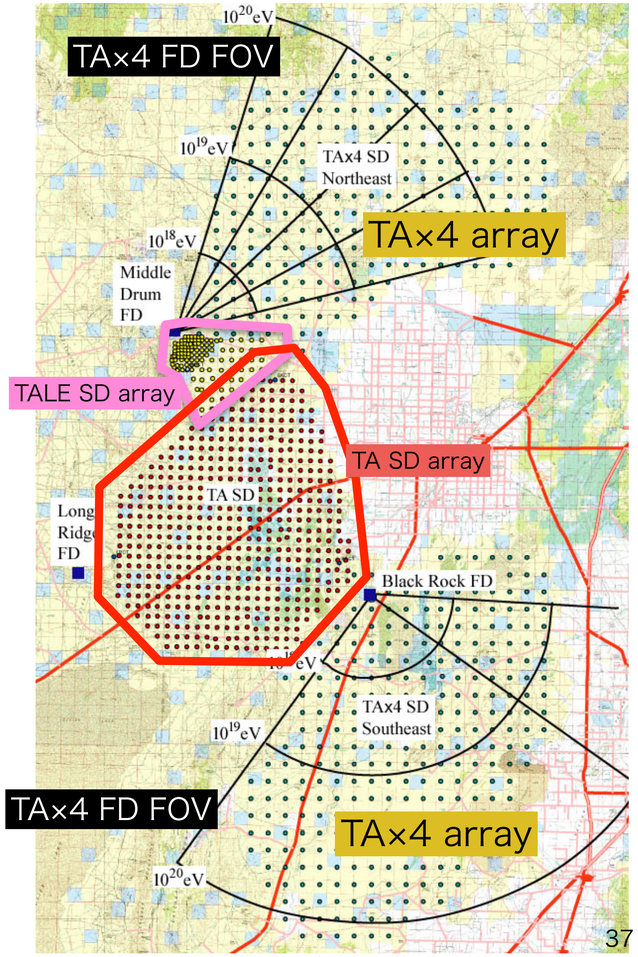
Physics Letters A 381
(2017) pp. 2565-2572

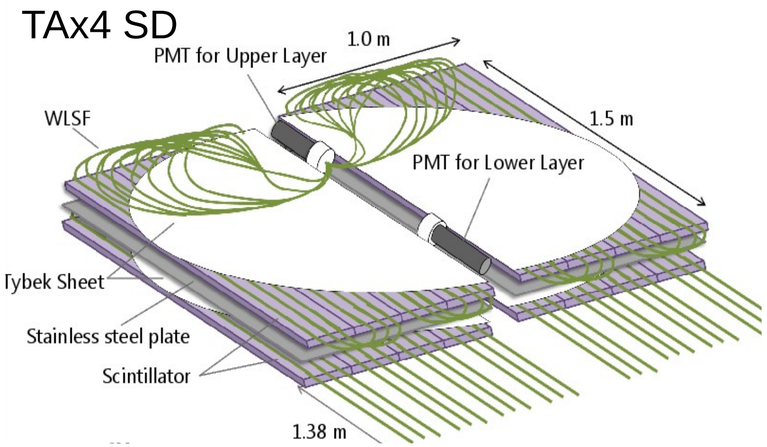


Ongoing upgrade: TA×4

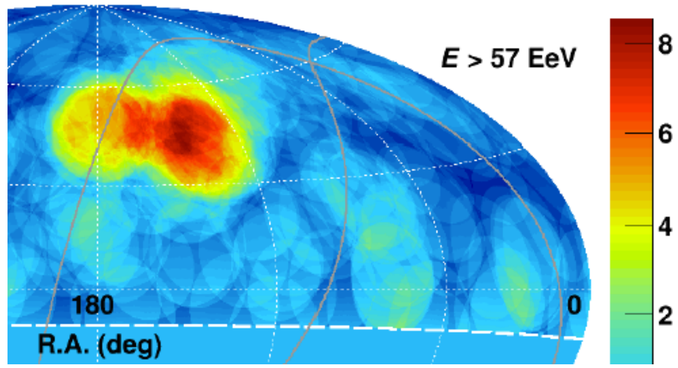
Achieving a detailed measurement on the hotspot

TA×4 will enlarge the fourfold coverage, **3000 km²**



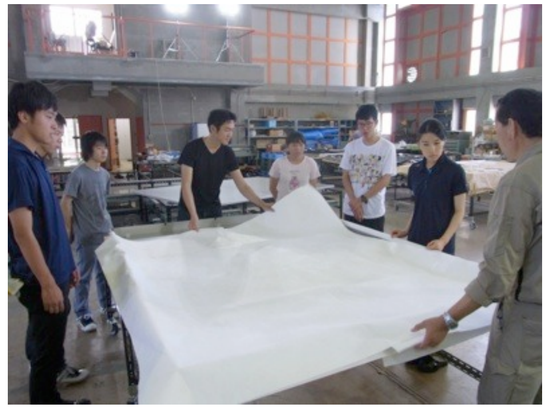


Expected in 2020 (Simulation)



E. Kido et al., UHECR 2018

SD assembling @ Akeno



TA×4 FD constructed (2018 Feb)

Summary and future perspectives

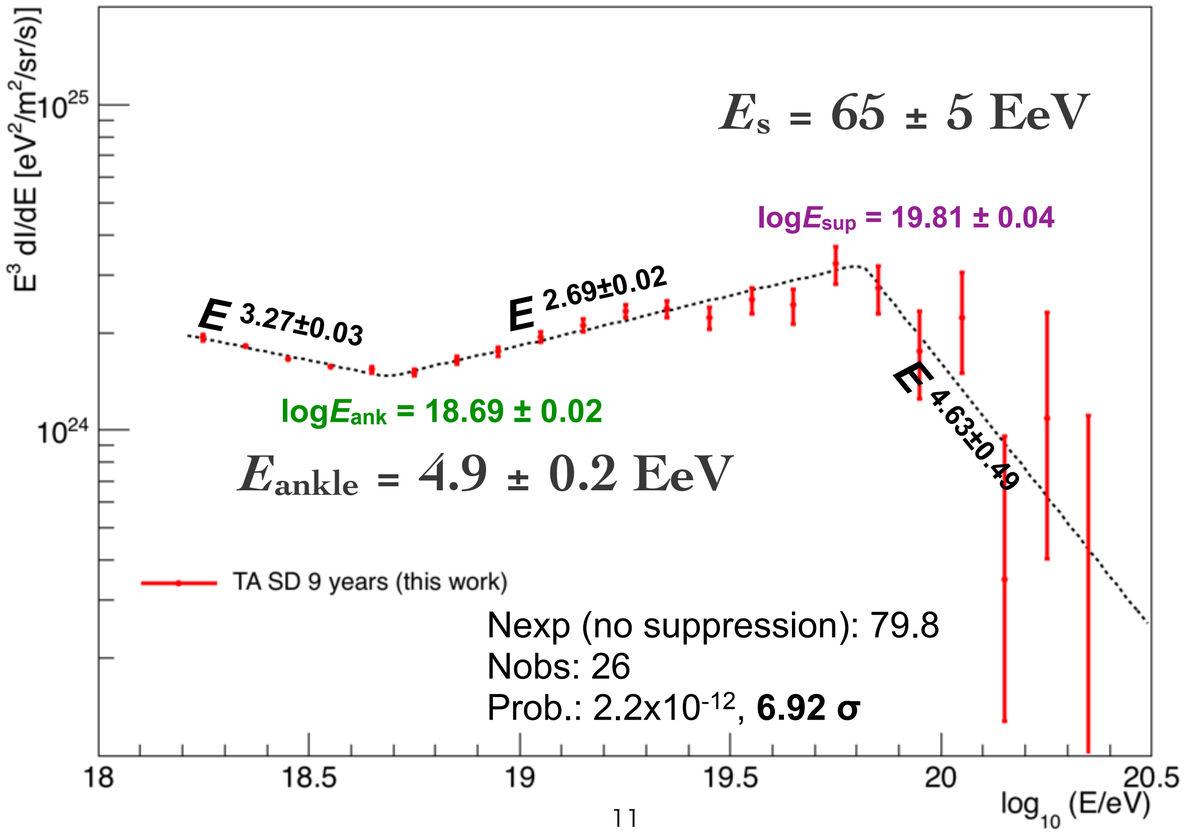
- Achieve 10-years observation with Telescope Array Experiment.
- Precise measurements on energy spectrum, mass composition and anisotropy at the northern hemisphere.
- Pioneering studies on the interaction physics beyond the LHC energies.
- Short-time burst showers correlating with lightings.

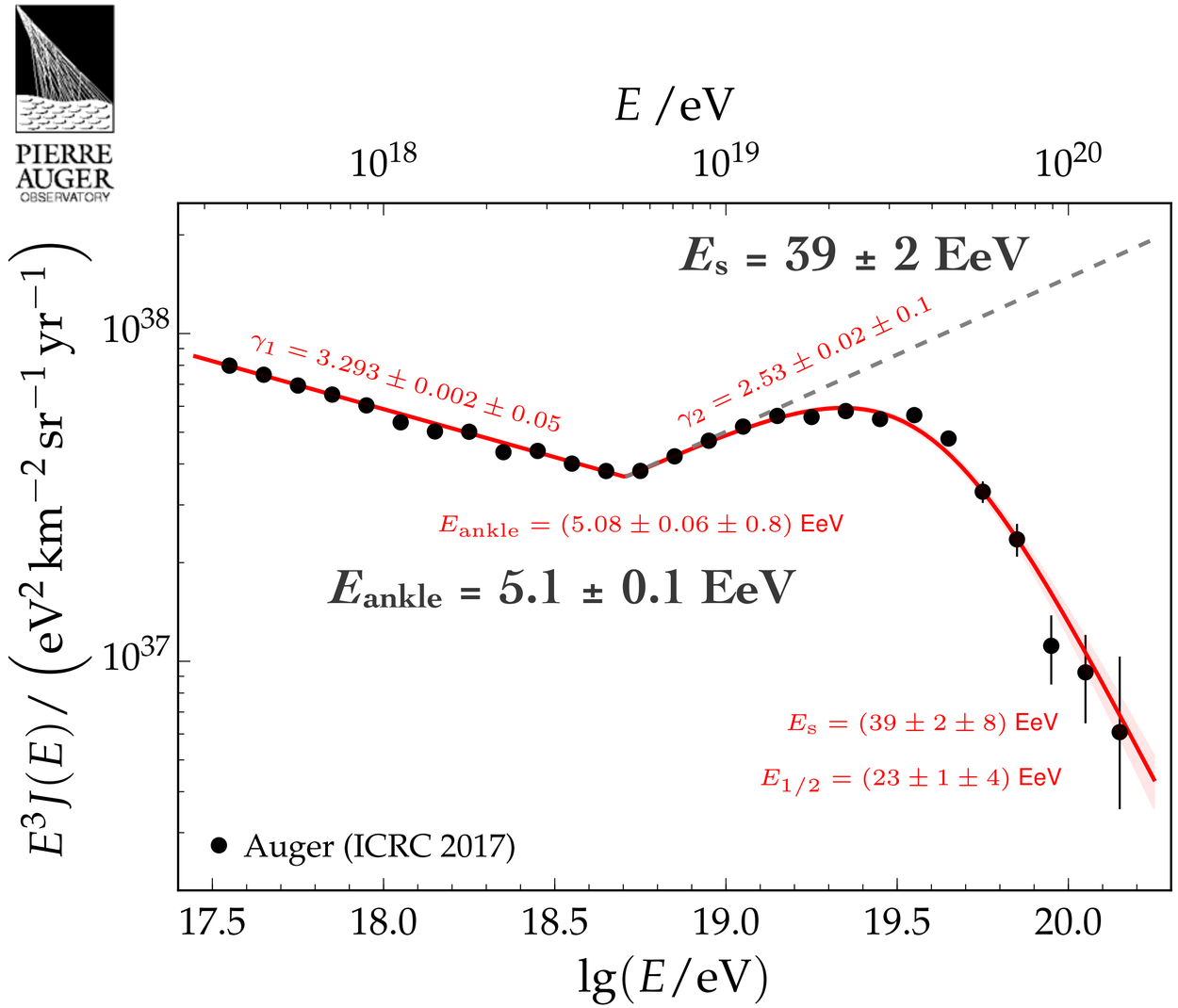
- TA×4 will provide us a four-times statistics of UHECRs.

СПАСИБО !

Backup

Energy spectrum



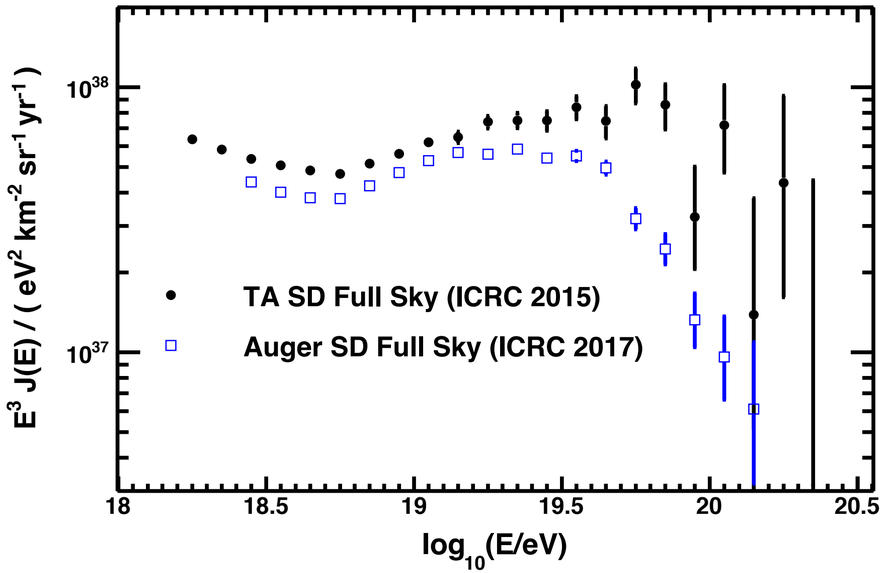


Y. Tsunesada in ICRC 2017

F. Fenu, M. Unger in ICRC 2017

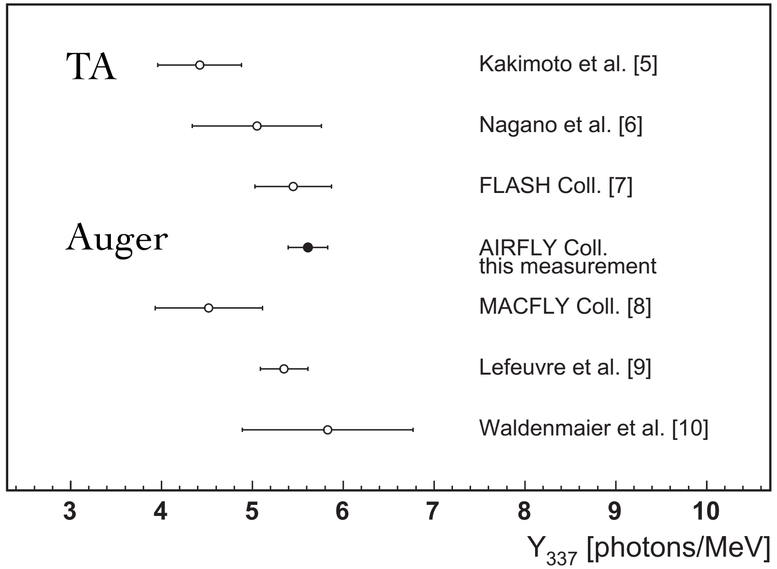
Energy spectrum comparison

10% energy scale difference in TA/Auger
Systematic uncertainties: **14%** in Auger, **21%** in TA

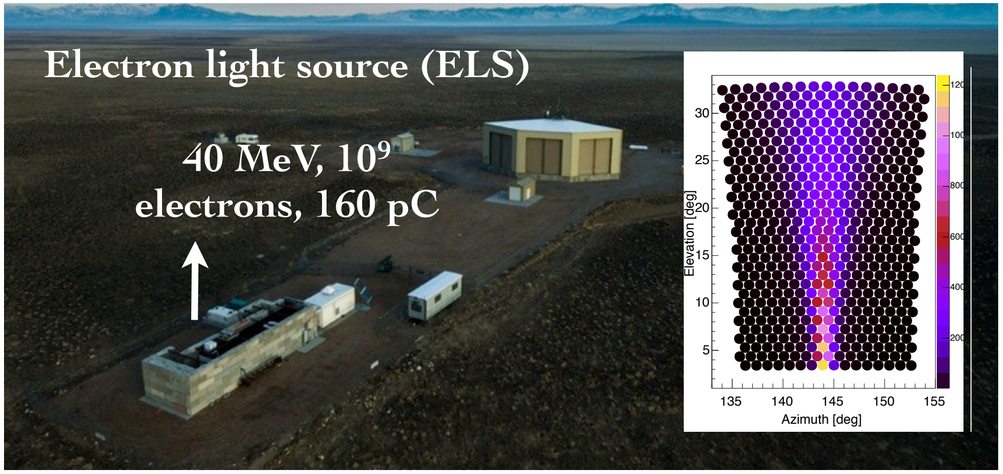


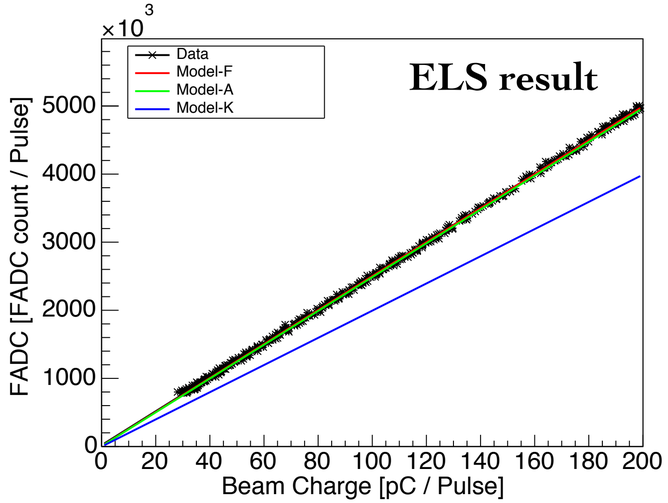
D. Ivanov et al. (Spectrum working group), ICRC 2017

Fluorescence yield (FY)

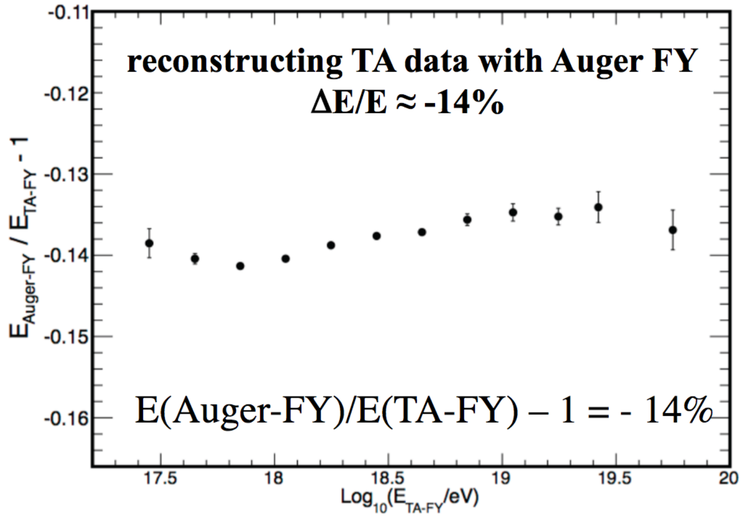


M. Ave et al. Astropart.Phys. 42 (2013) 90–102



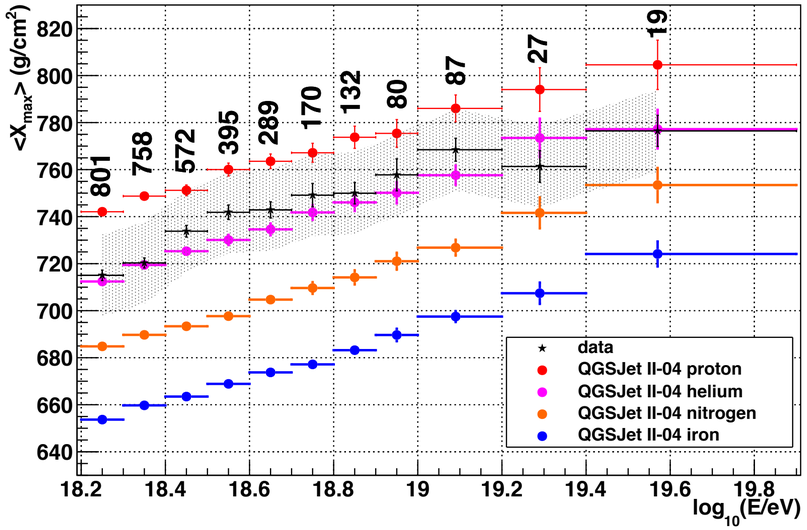


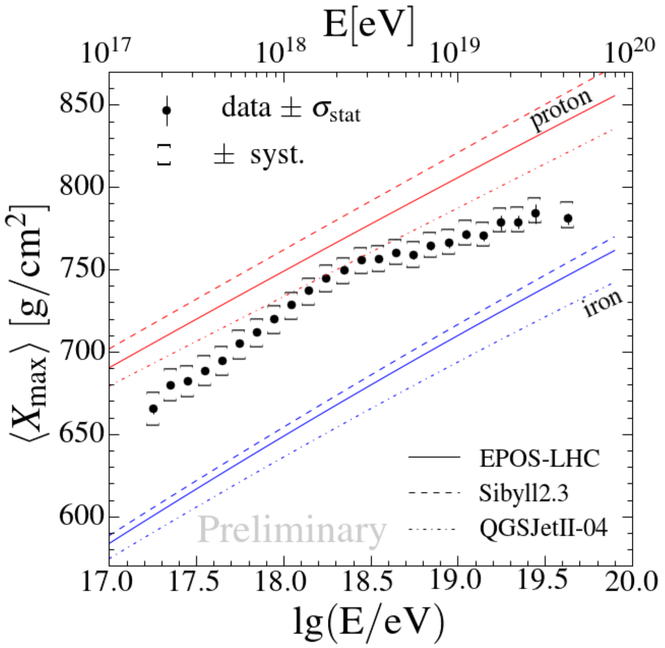
BK Shin et al., PoS (ICRC2015) 640



V. Verzi et al., PTEP. 12A103 (2017),
T. Fujii et al., Proc of ICRC 2017

Mass composition analysis using X_{max}





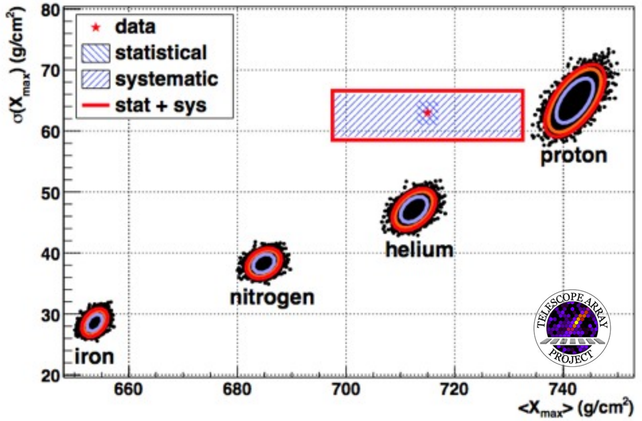
PIERRE AUGER OBSERVATORY

Take away message

TA and Auger
composition measurements (Xmax)
agree within the systematics
$18.2 < \log_{10}(E/\mathrm{eV}) < 19.0$

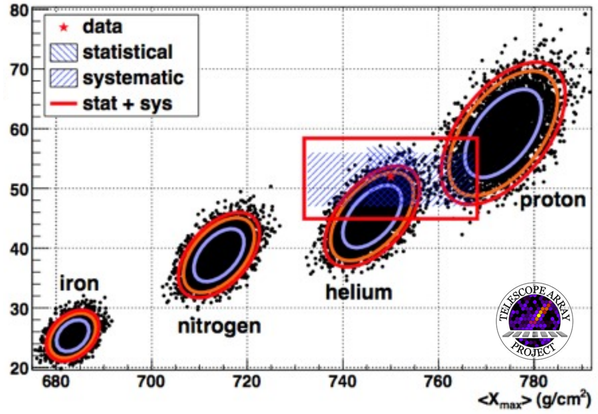
V. de Souza et al (Mass Composition WG), Proc. of ICRC 2017

18.2 ≦ log(E) < 18.3, N = 801



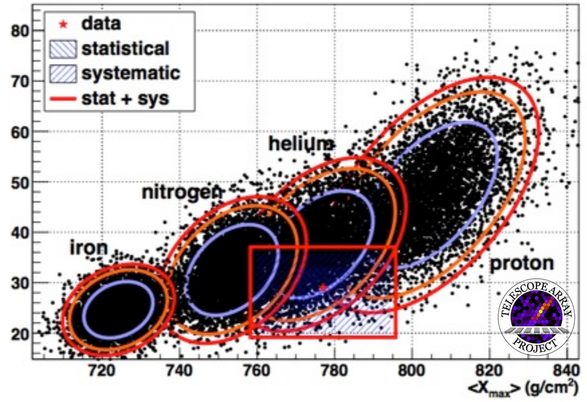
(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

18.8 ≦ log(E) < 18.9, N = 132



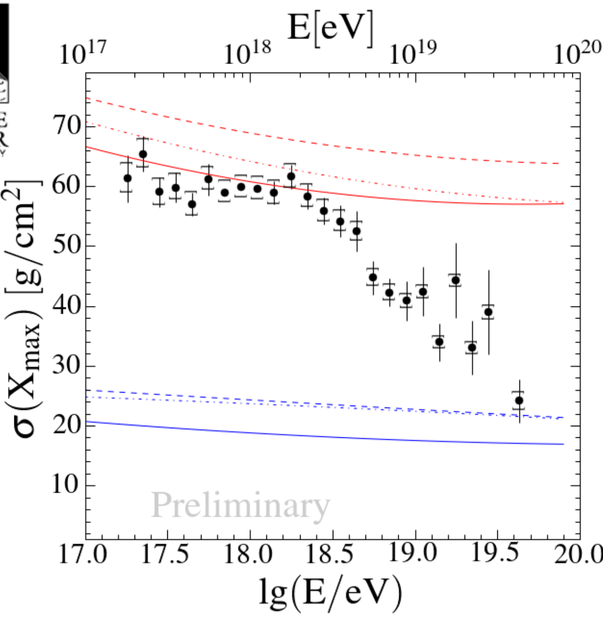
(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$

19.4 ≦ log(E) < 19.9, N = 19



(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

PIERRE AUGER OBSERVATORY



W. Hanlon ISVHECRI 2018,
TA collab. ApJ, 858, 76(2018)

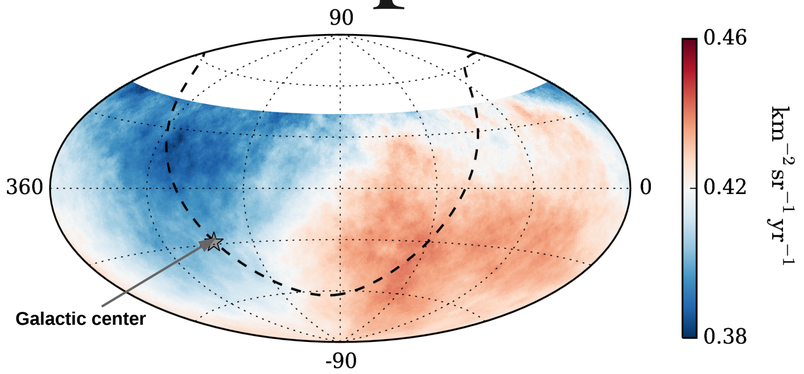
M. Unger et al., ICRC 2017, J. Bellido et al., ICRC 2017

Large/intermediate scale anisotropies

Auger dipole: $E > 8$ EeV, 6.5% dipole structure with 5.2σ

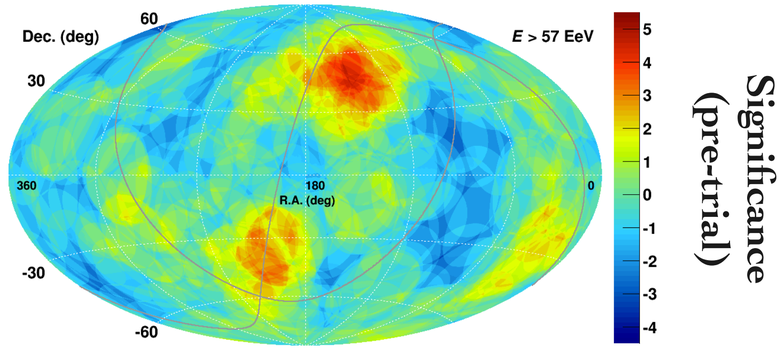
Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005\ ^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047\ ^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

Energy (EeV)	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d (°)	Dipole right ascension α_d (°)
4 to 8	−0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
≥8	−0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10



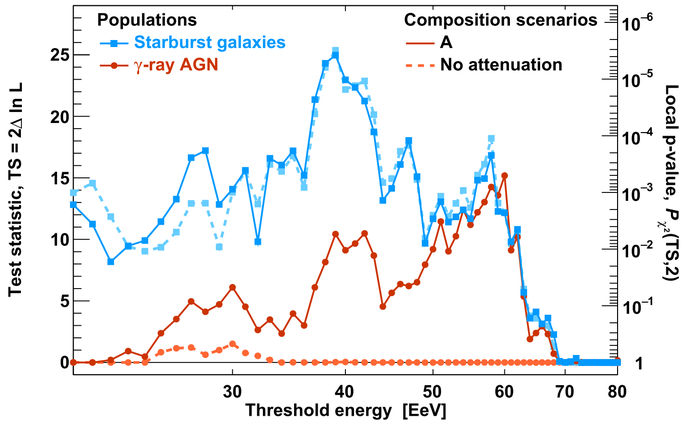
Pierre Auger collab. Science 357, 1266 (2017)

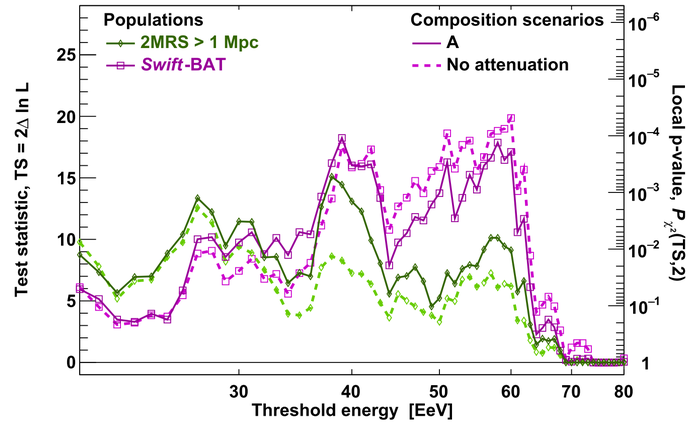
- **TA Hotspot**: $E > 57$ EeV, 3.4σ (5.1σ local) anisotropy [TA collab. ApJL, 790:L21 (2014)]
- TA (7 years, 109 events above 57 EeV)+ Auger(10 years, 157 events above 57 EeV), 20° circle oversampling
  - $E > 57$ EeV, no excess from the Virgo cluster



K. Kawata et al., Proc. of ICRC 2015

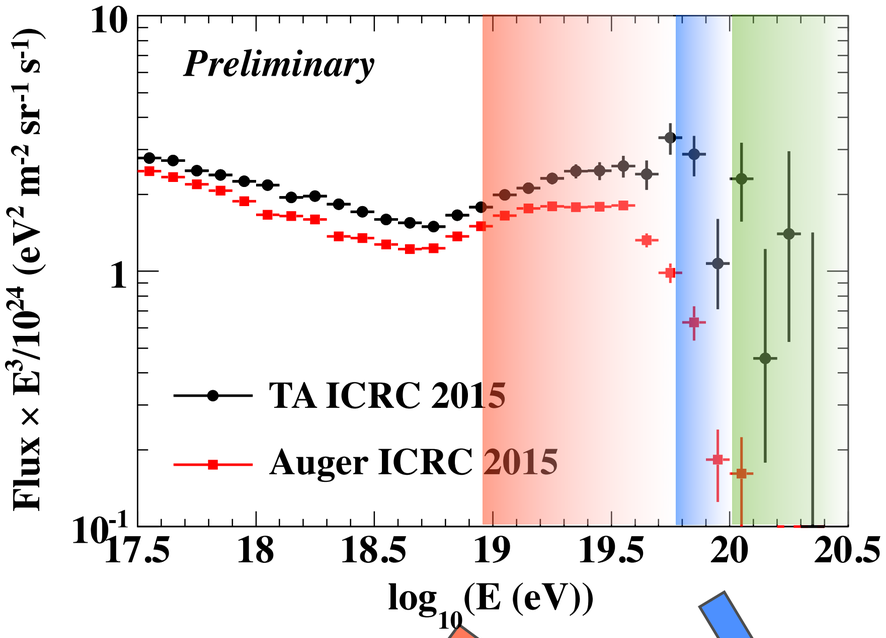
- Flux pattern correlation [Pierre Auger collab. ApJL, 853:L29 (2018)]
  - With a flux pattern of starburst galaxies, isotropy of UHECR is disfavored with **4.0σ** confidence above **39 EeV**
    - **9.7% anisotropic fraction and 12.9° angular scale**
  - The other three flux patterns: 2.7σ–3.2σ

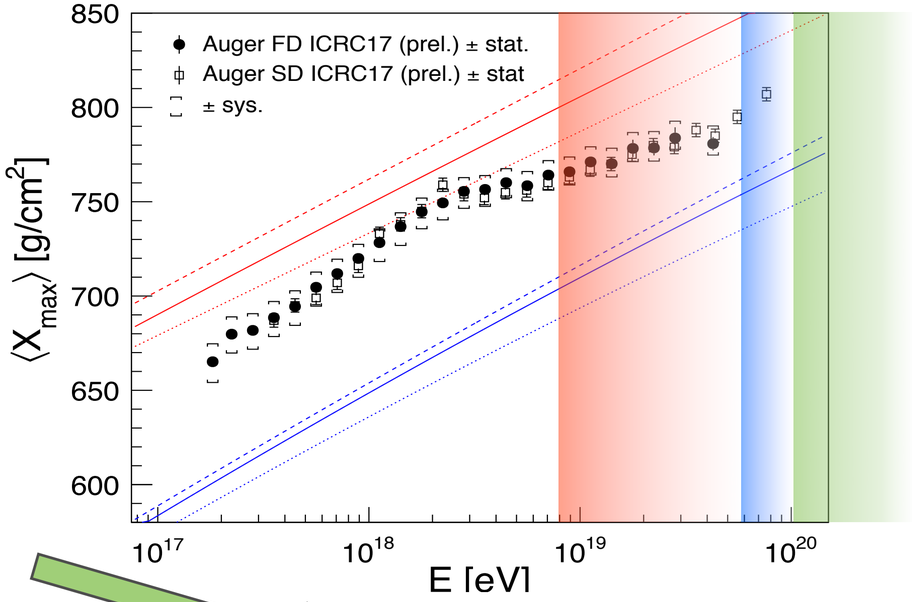




An overview of energy spectrum, mass composition and anisotropy

Data points from I. Valino et al., Proc. of ICRC 2015, D. Ivanov at al., Proc. of ICRC 2015

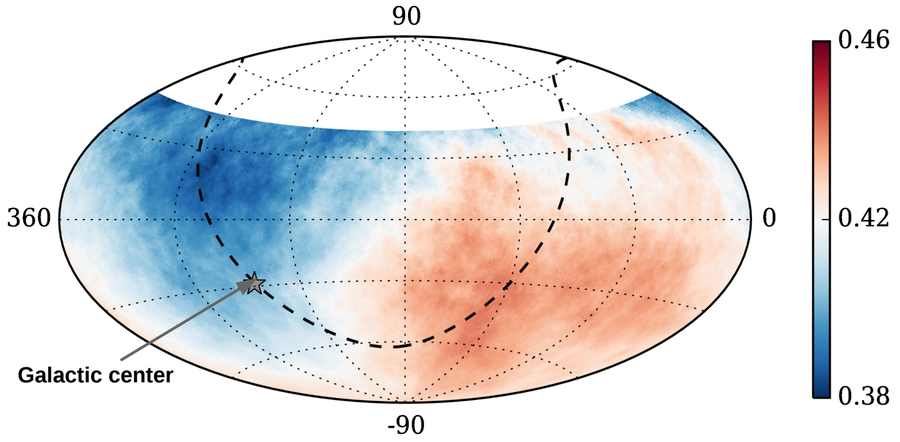




P. Sanchez-Lucas et al., Proc of ICRC 2017 Pierre Auger collab., Phys.Rev.D 96,122003 (2017)

E > 8 EeV

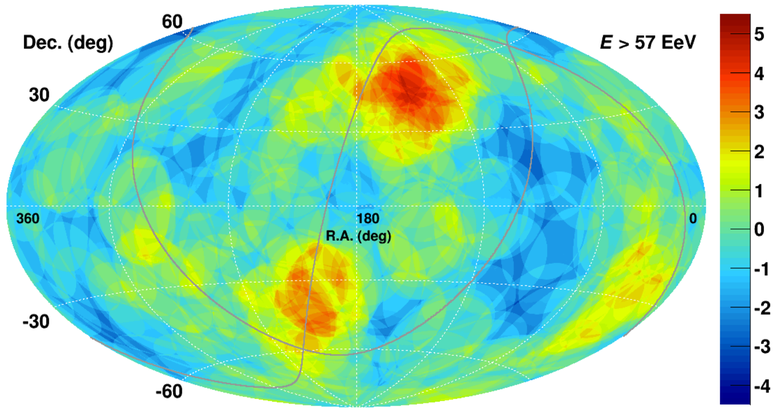
Pierre Auger Collab. Science 357, 1266 (2017)



Increase dipole amplitude above 4 EeV
arXiv:1808.03579

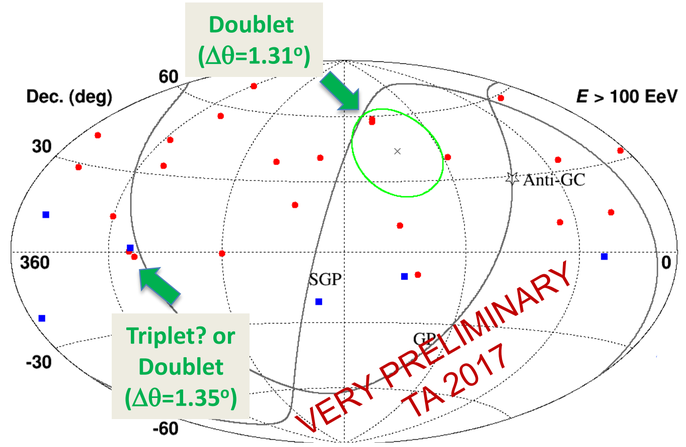
E > 57 EeV

K. Kawata et al., Proc. of ICRC 2015



E > 100 EeV

S. Troitsky et al., Proc. of ICRC 2017



⇒ Need more statistic of ultrahigh energy cosmic rays (UHECRs)

Physics goal and future perspectives

Origin and nature of ultrahigh-energy cosmic rays (UHECRs) and particle interactions at the highest energies

5 - 10 years

Exposure and full sky coverage

TA×4 + Auger

K-EUSO : pioneer detection from space with an uniform exposure in northern/southern hemispheres

Detector R&D

Radio, SiPM,

Low-cost fluorescence detector

"Precision" measurements

AugerPrime

Low energy enhancement (Auger infill+HEAT+AMIGA, TALE+TA-muon+NICHE)

LHCf/RHICf for tuning models

10 - 15 years

Next generation observatories

In space (100×exposure): POEMMA

Ground (10×exposure with high quality events): FAST

FAST
Fluorescence detector Array of Single-pixel Telescopes