Ultra-high energy cosmic rays: current status

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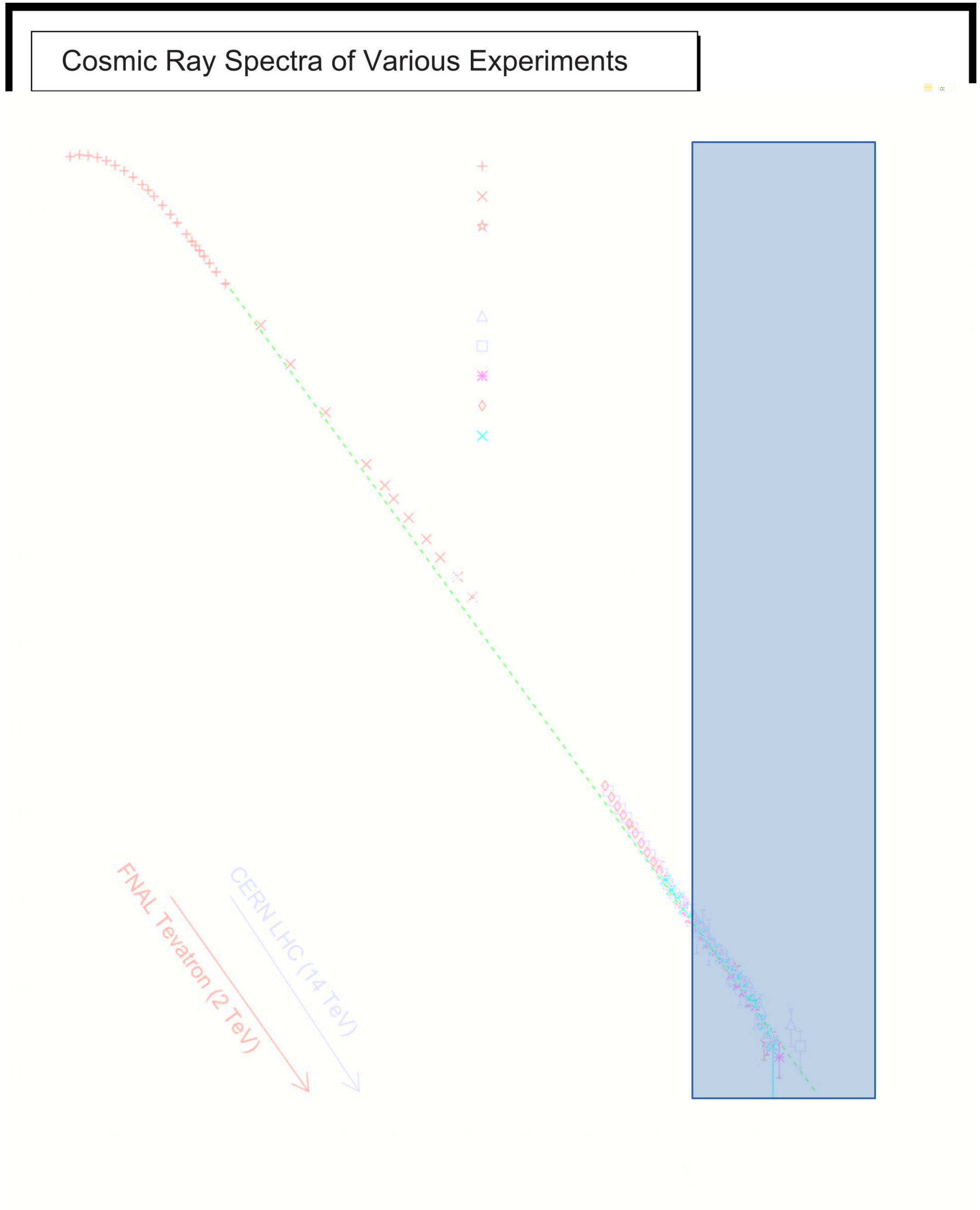
VLVnT - 2018 Very Large Volume Neutrino Telescopes, Dubna, 03 Oct 2018

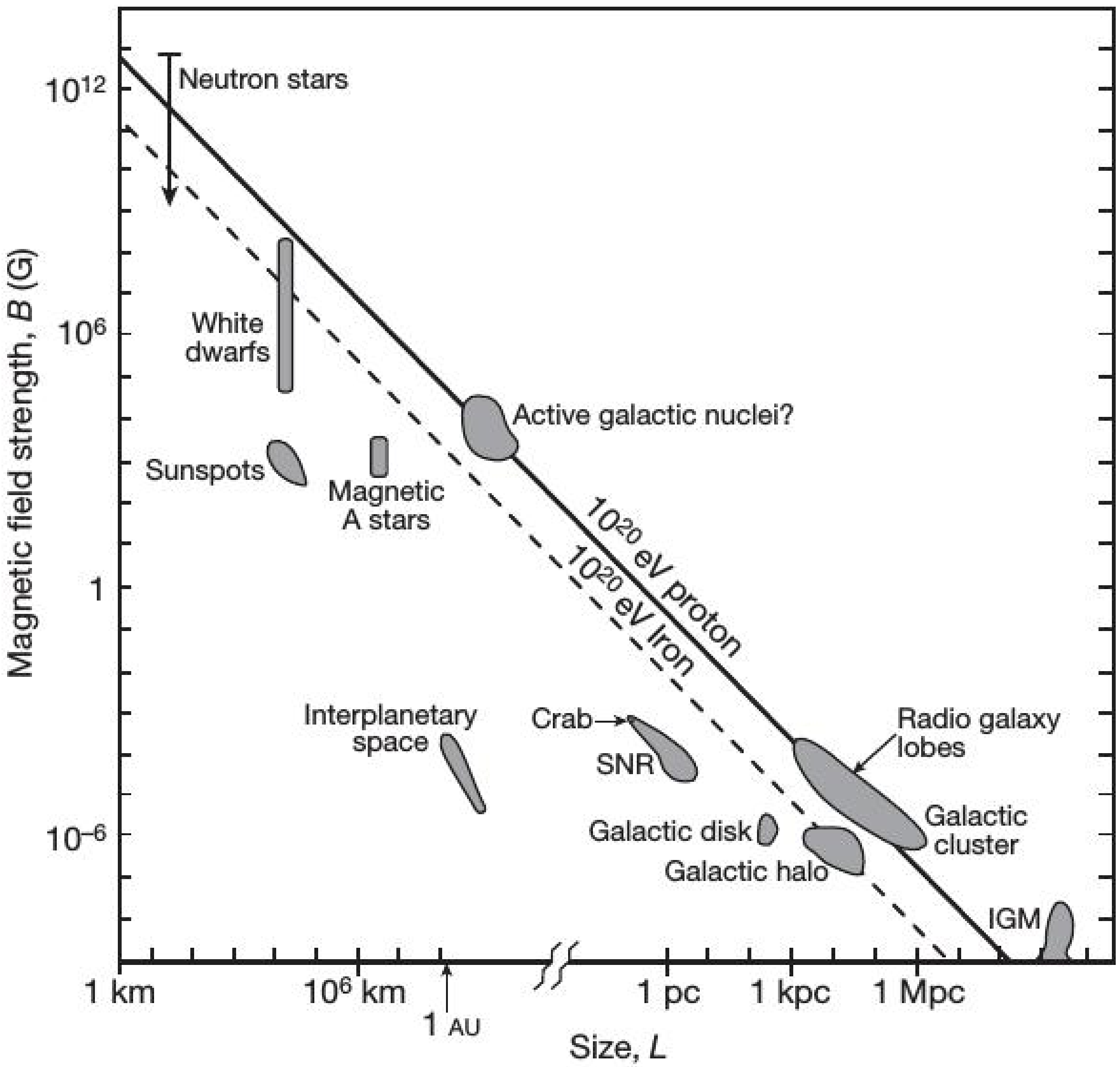
Overview

- Experiments
- Spectrum
- Composition
- Anisotropy
- Future

UHECRs


Cosmic Ray Spectra of Various Experiments
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)

UHECRs sources

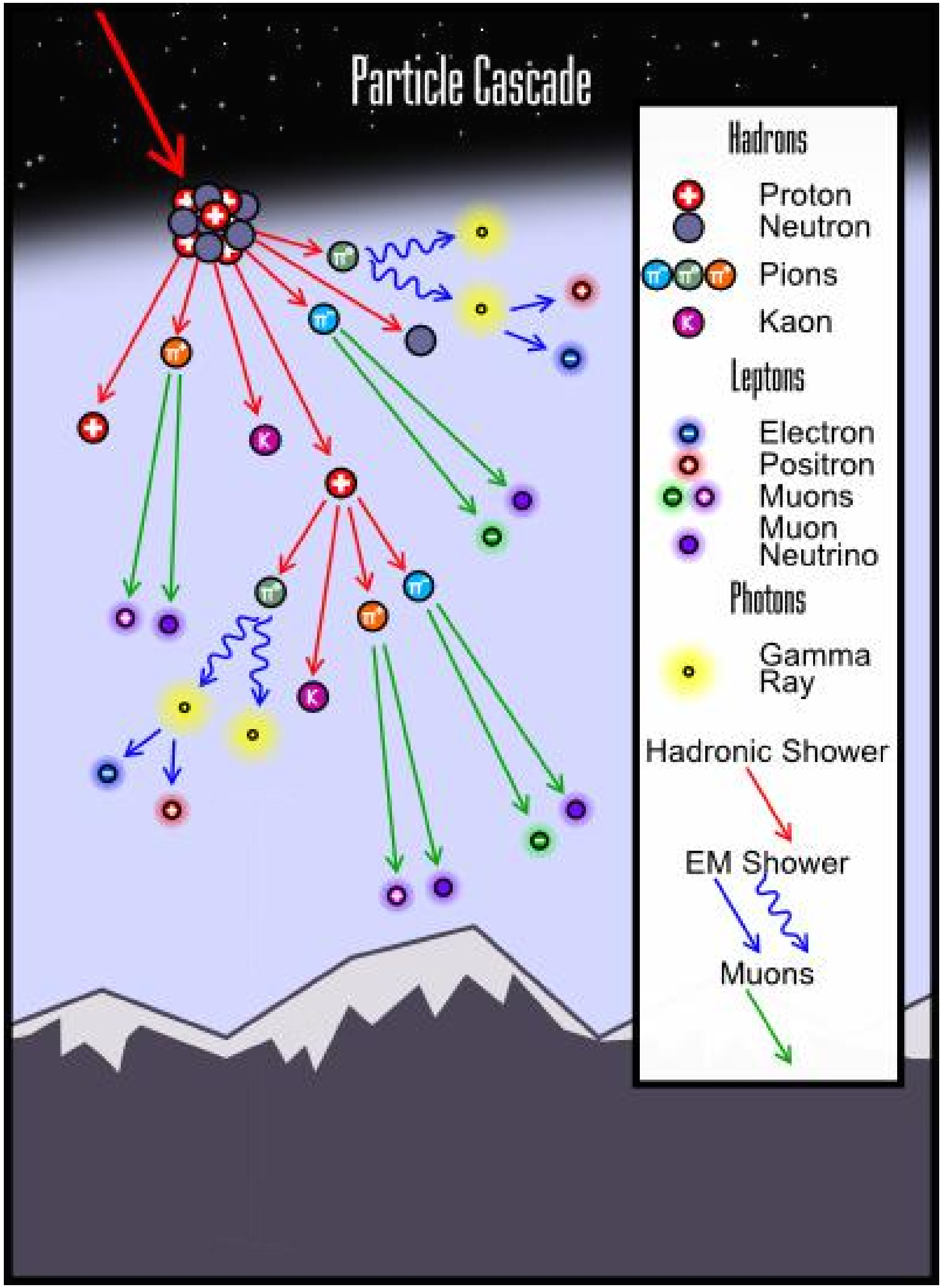


Confinement:

$E_{max} \sim ZBL$

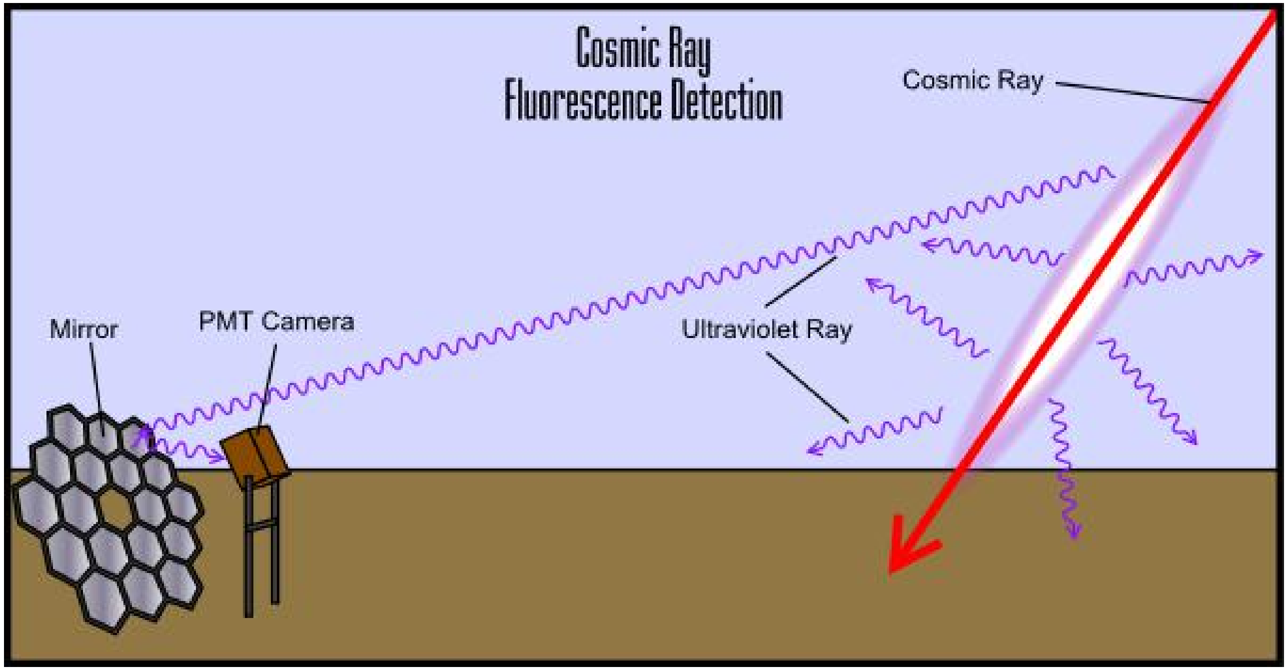
From Bauleo&Martino,2009

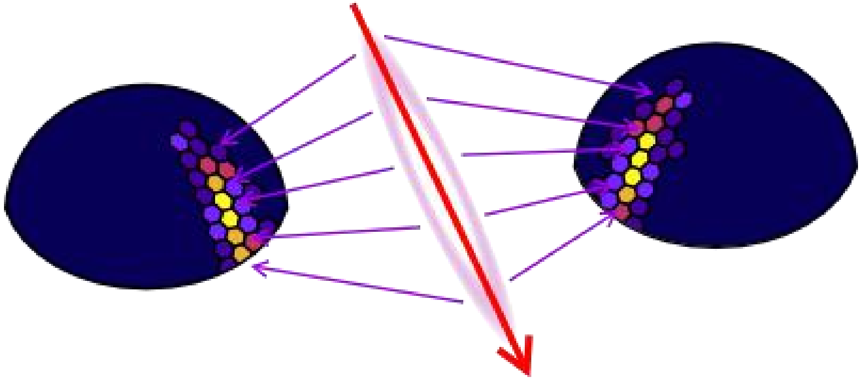
UHECR: EAS



www.telescoparray.org

UHECR detection: fluorescence





www.telescoparray.org

UV-radiation from N nuclei excited by EAS

+ Allows to observe full development of the shower

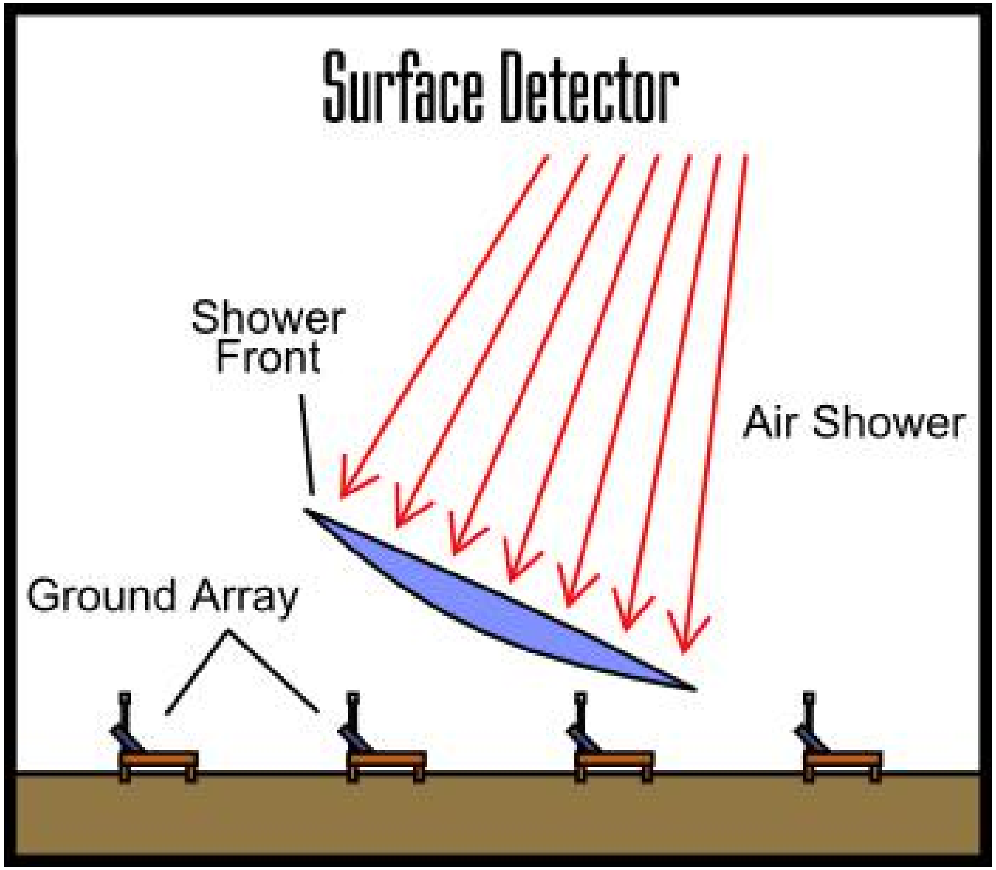
+ We can retrieve energy of the primary CR from the UV-yield

+ Position of the shower maximum X_{max} can be used to infer mass composition

+Stereo observations give reasonable angular accuracy

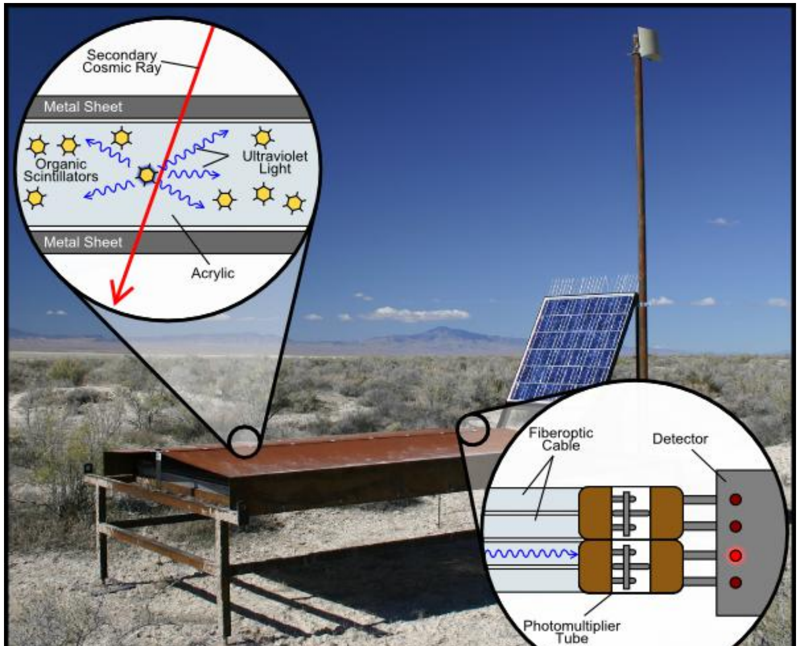
- Low duty cycle (~10%): lower statistics

UHECR detection: surface detectors



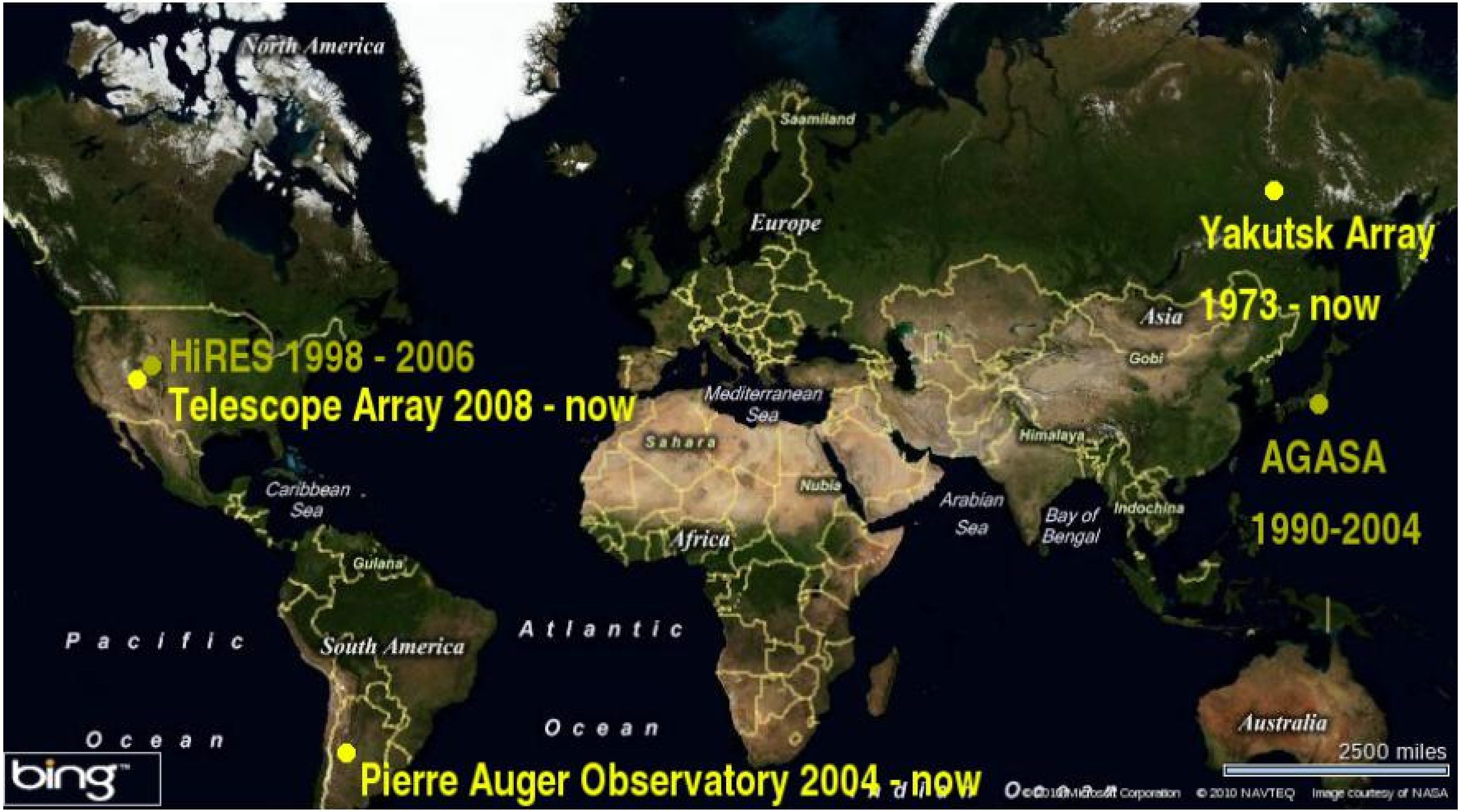
Charged particles reaching Earth's surface:

+High duty cycle (~100%)
+Well-defined exposure
- Large systematic uncertainties, stronger dependence on hadronic models
- It is problematic to get energy from SD observation alone

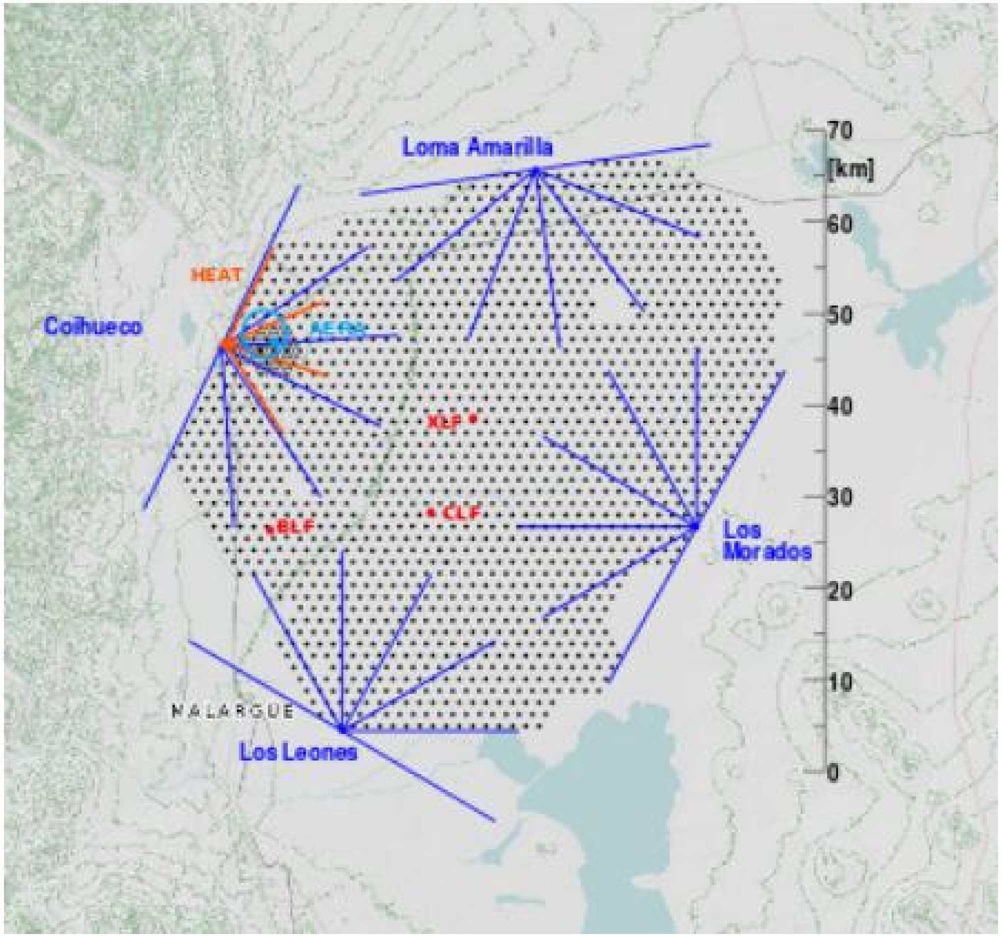


www.telescoparray.org

UHECR experiments



UHECR experiments: Pierre Auger Observatory (PAO)

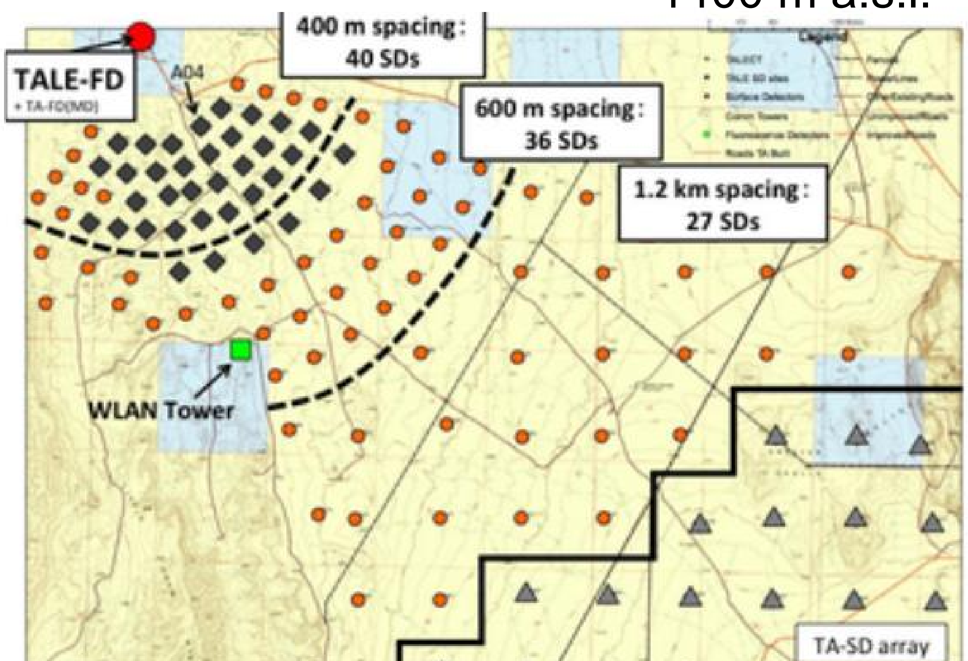


~1400 m a.s.l.

- Malargüe, Mendoza, Argentina
- 35°12′24″S, 69°18′57″W
- Since 2004
- Hybrid detector
- Surface detectors (SD)
  - SD-1500:
    - 1660 detectors @1.5 km,
    - ~3000 km²
  - SD-750 (lower threshold):
    - 49 @ 750 m, 24 km²
- Fluorescence detectors(FD)
  - 5 FD stations
  - 27 telescopes total

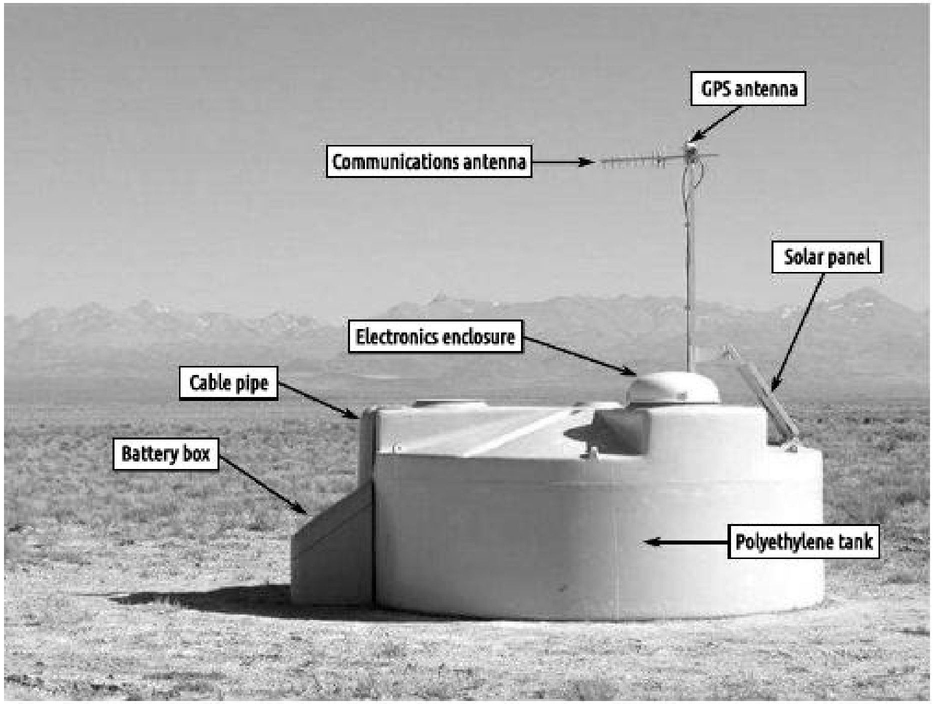
UHECR experiments: Telescope Array (TA)

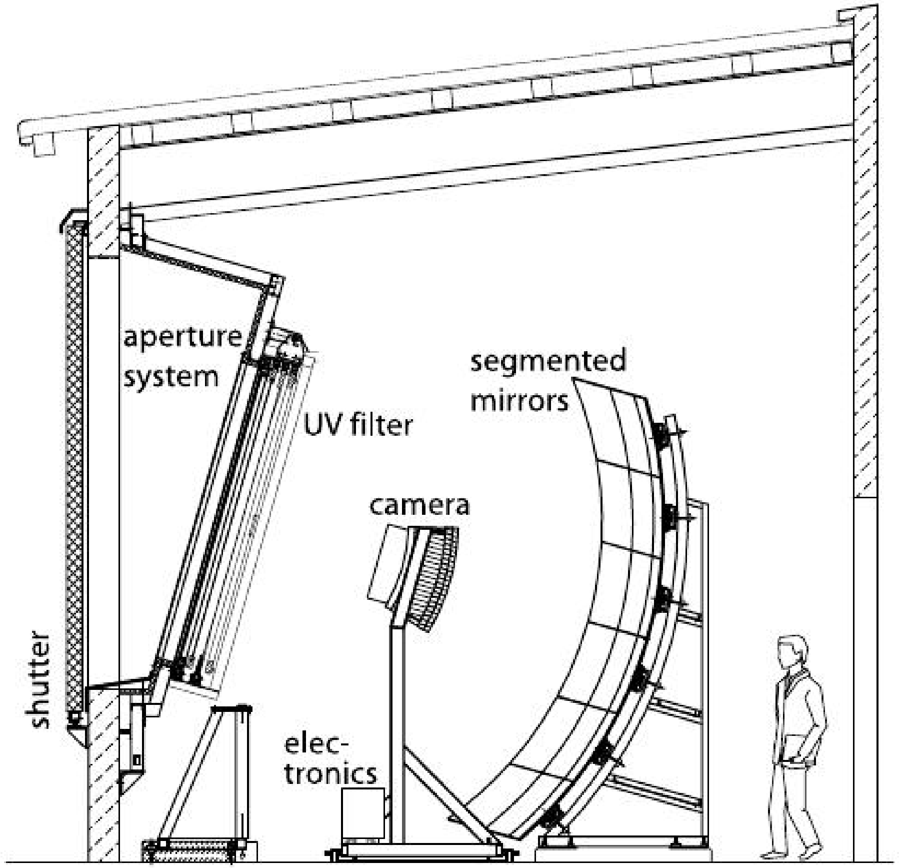
~1400 m a.s.l.



- Delta, Utah, USA
- 39°17′49″N 112°54′31″W
- Since 2008
- Surface detectors (SD):
  - 507 detectors @ 1.2 km,
    - ~700 km^2
- Fluorescence detectors(FD):
  - 3 FD stations
  - 38 telescopes total
- TALE:
  - SD:400->600->1200 m separation
  - 103 SD, 70 km^2
  - 10 extra FD telescopes

PAO detectors

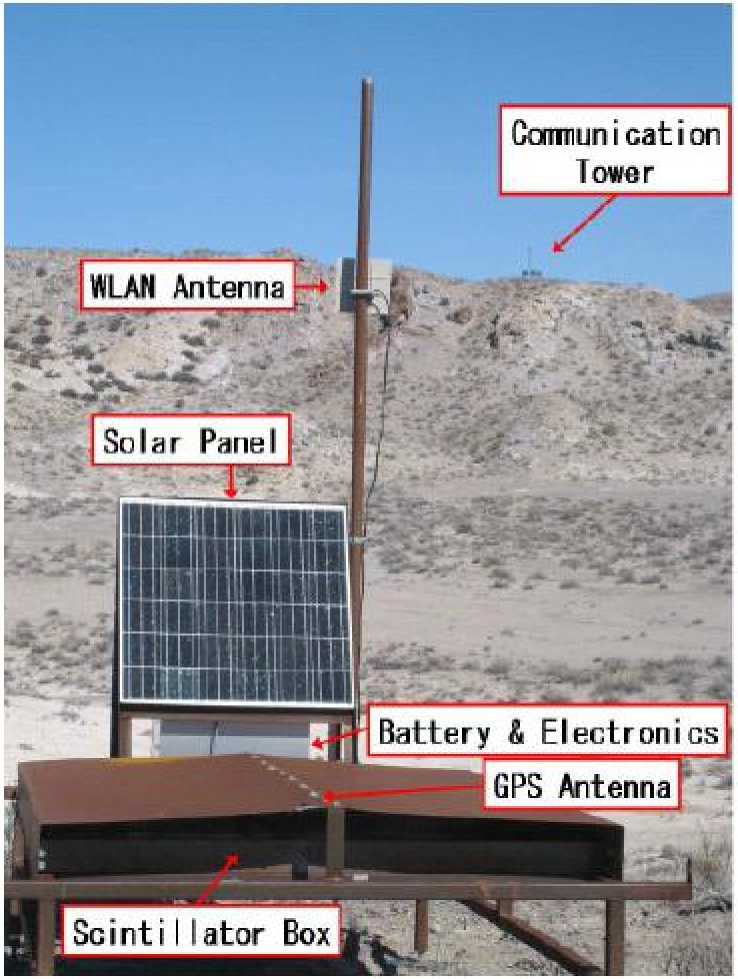


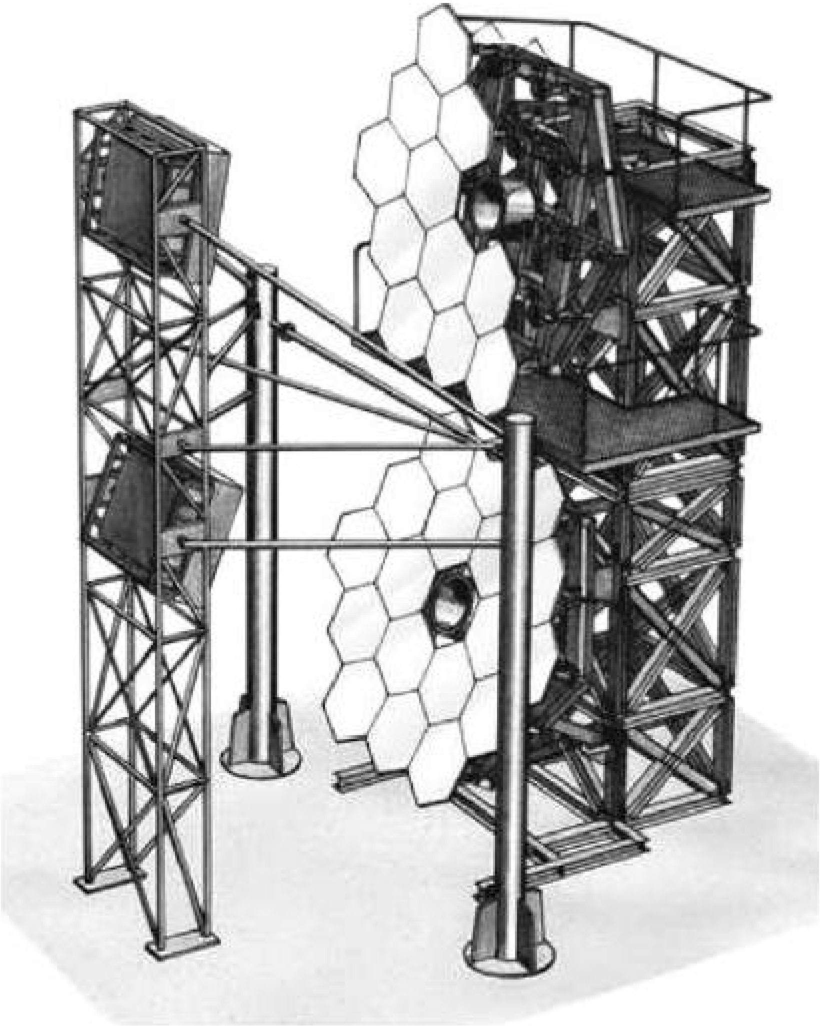


- 12 m^3 pure water

from Verzi et al, 2017

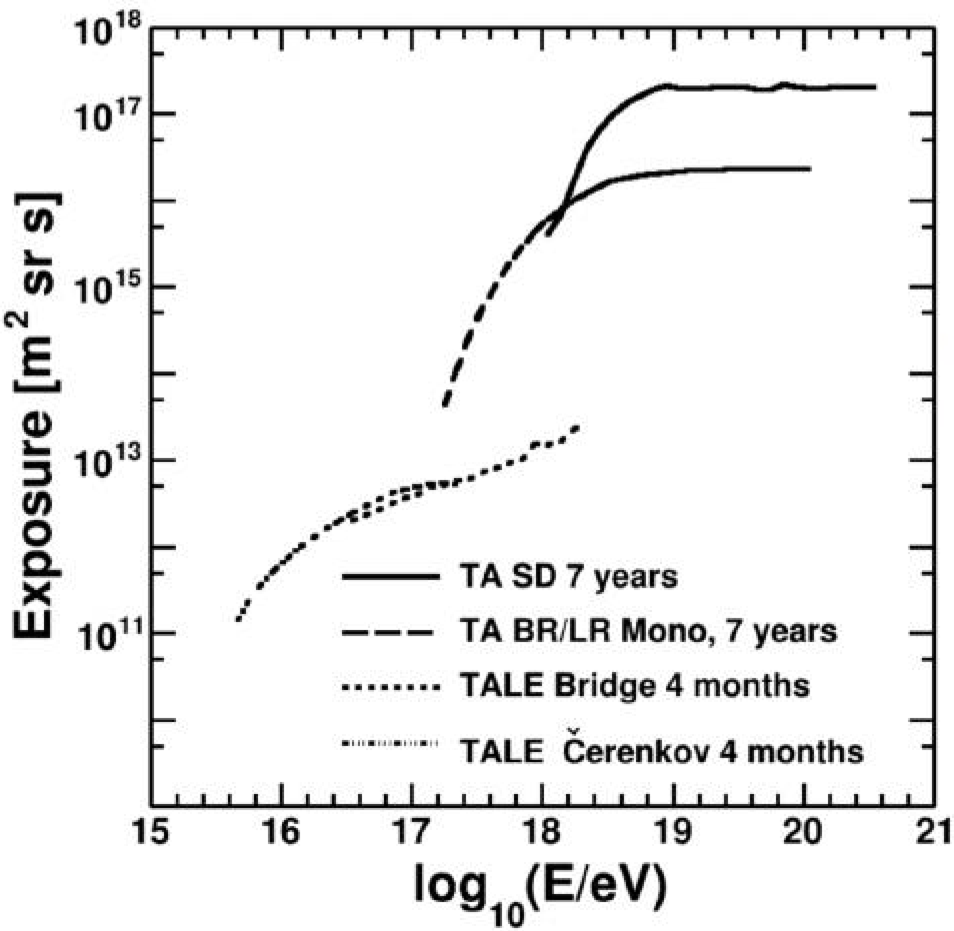
TA detectors



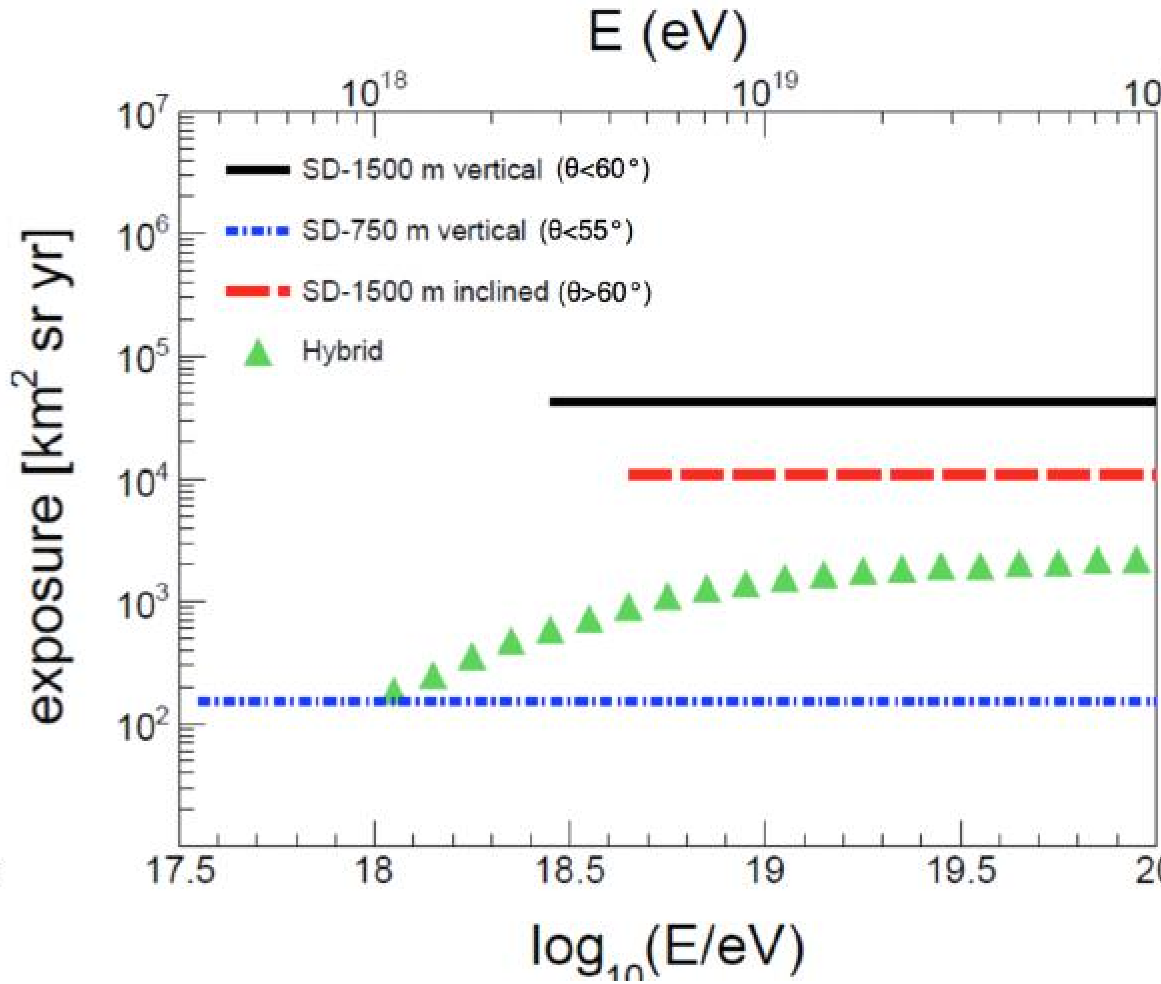


- 3 m^2 scintillators x 2 layers

Exposures (1/2)

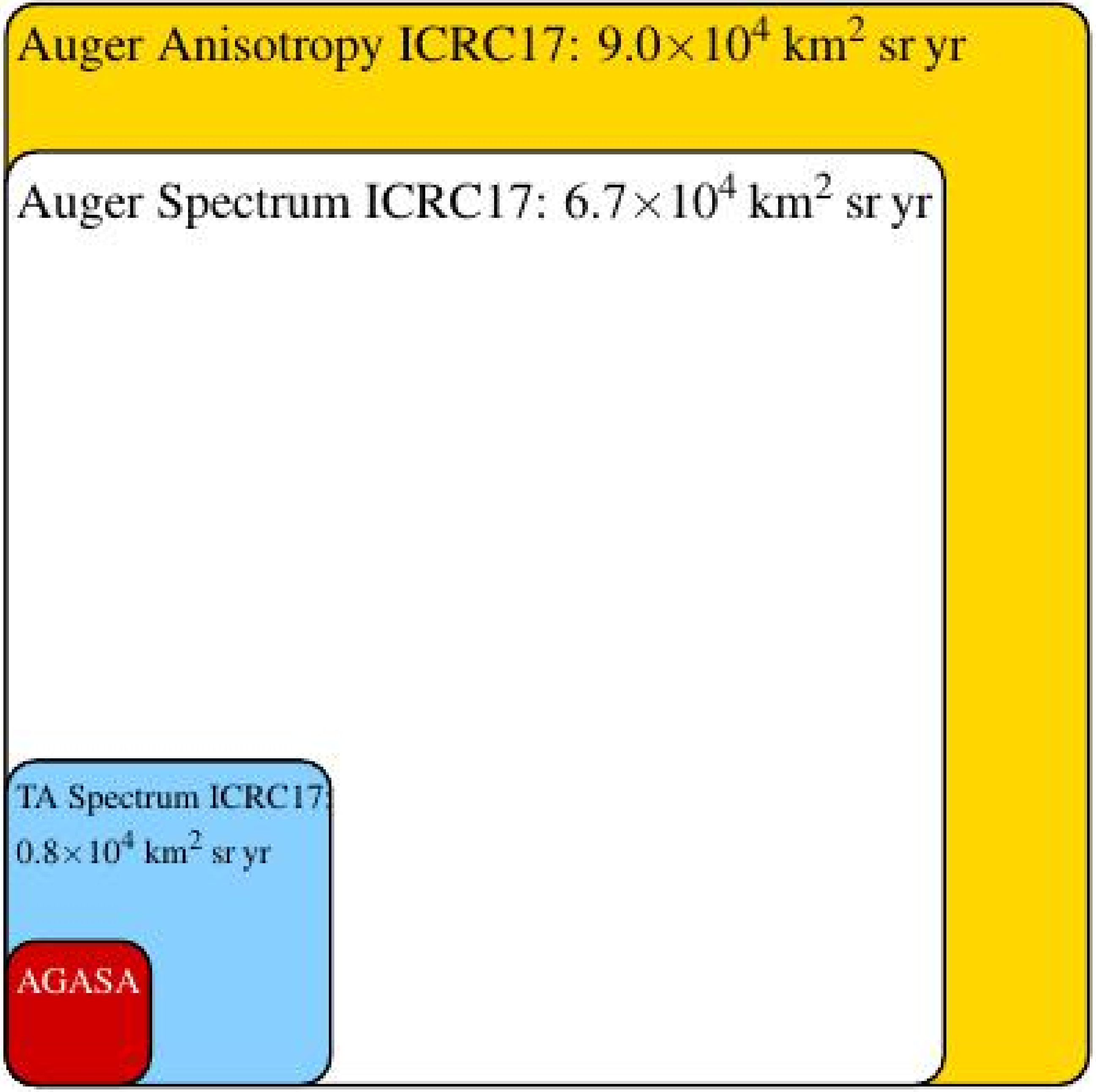


D. Ivanov for TA, ICRC 2015



I. Valino for PAO, ICRC 2015

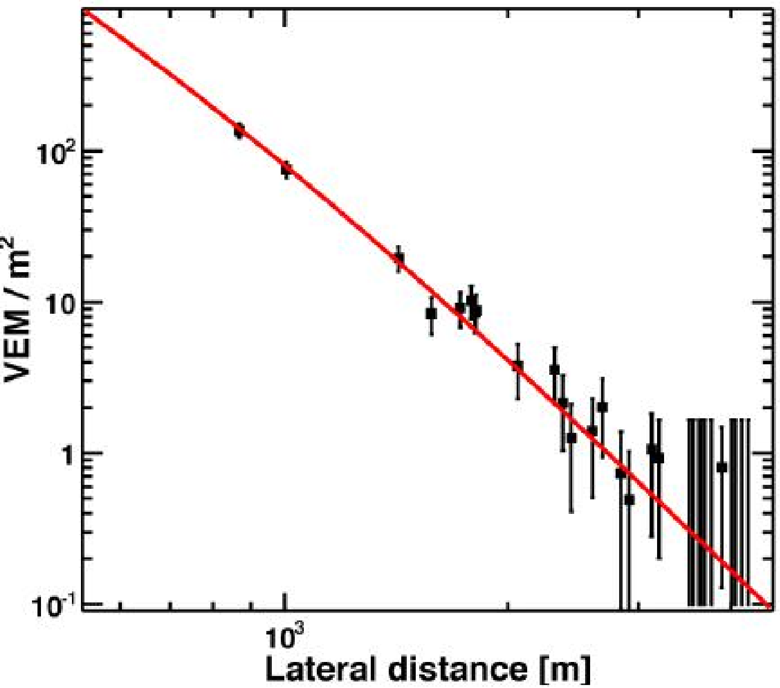
Exposures (2/2)

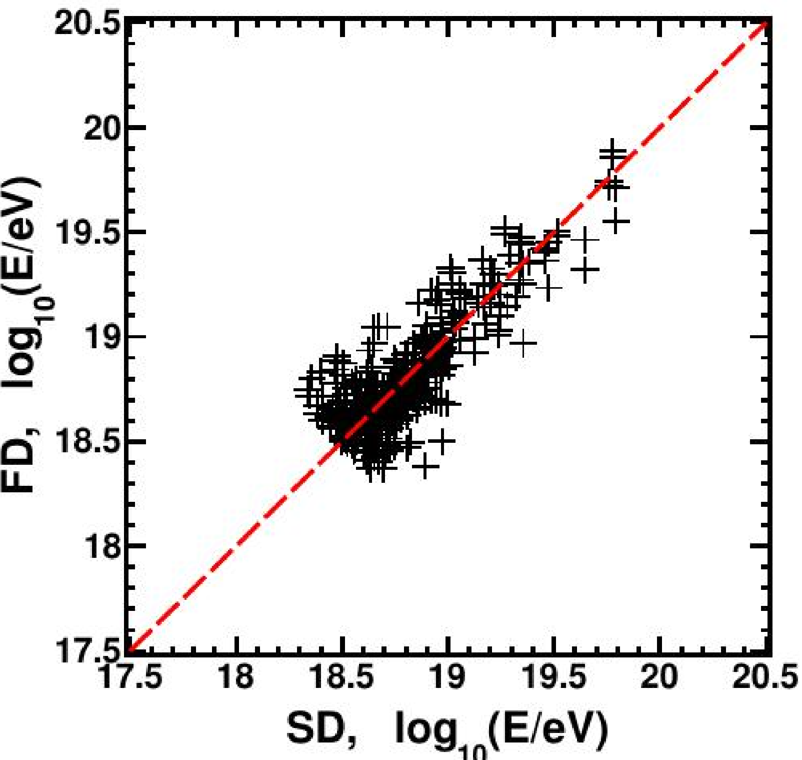


M. Unger for PAO, ICRC 2017

SPECTRUM

Energy reconstruction





- TA as an example
- **FD:** calculate shower energy from the observed signal and known UV yield.
- **SD:** flux at r_{opt} (800 m) as an energy estimator
- Correction for attenuation (depending on zenith angle)
- Calibrated with a set of hybrid events with known E_{FD}

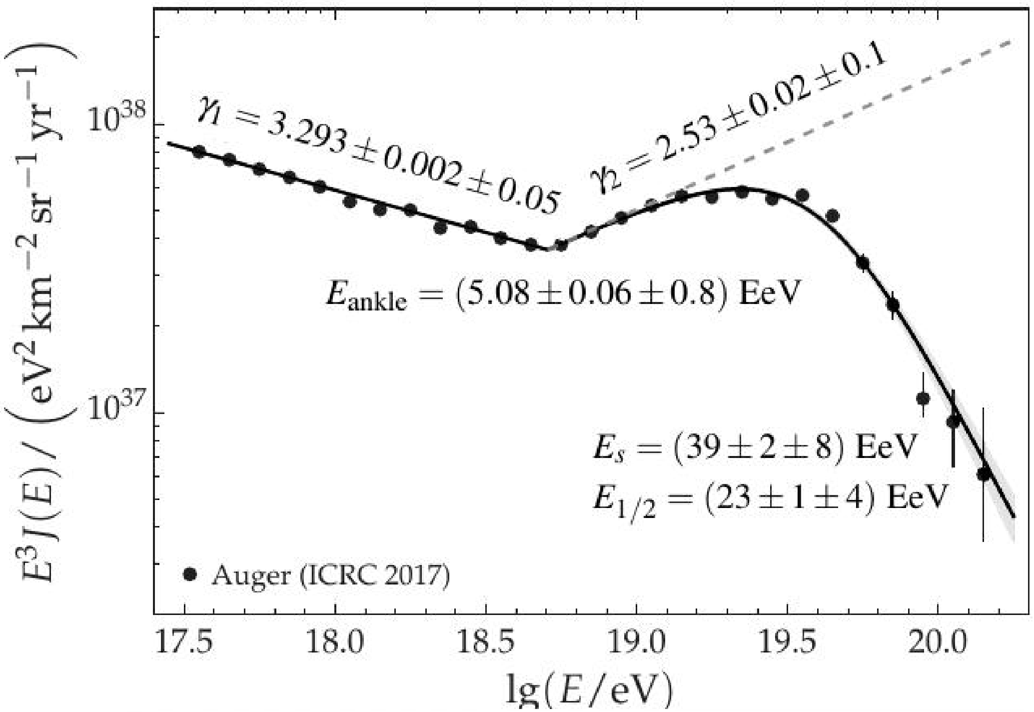
Energy reconstruction: uncertainties

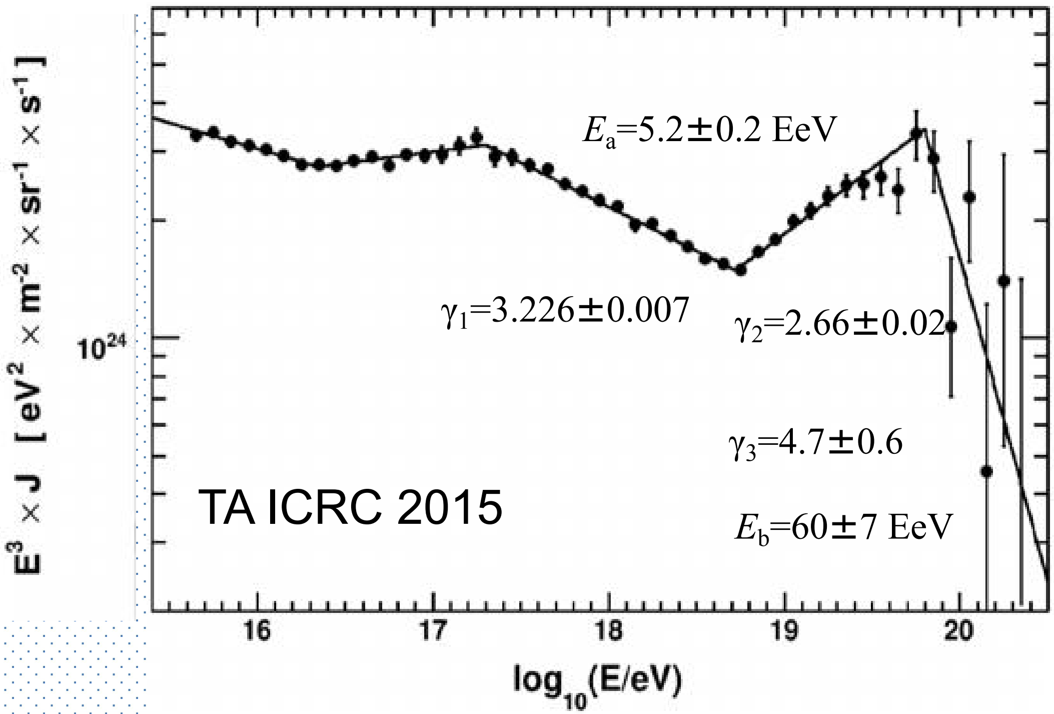
Parameters of TA SD calibration	
Number of Hybrid events	551
E_{SDMC}/E_{FD}	1.27
Energy resolution	18.0<log(*E*)<18.5, 36% 18.5<log(*E*)<19.0, 29% 19.0<log(*E*), 19%

Systematic uncertainties on the Energy scale		
	TA	**PAO**
Fluorescence yield	11%	3.6%
Atmosphere	11%	3.4-6.2%
FD calibration	10%	9.9%
FD reconstruction	9%	6.5-5.6%
Invisible energy	5%	3-1.5%
Other contributions		5%
Total	21%	14%

from Verzi et al, 2017

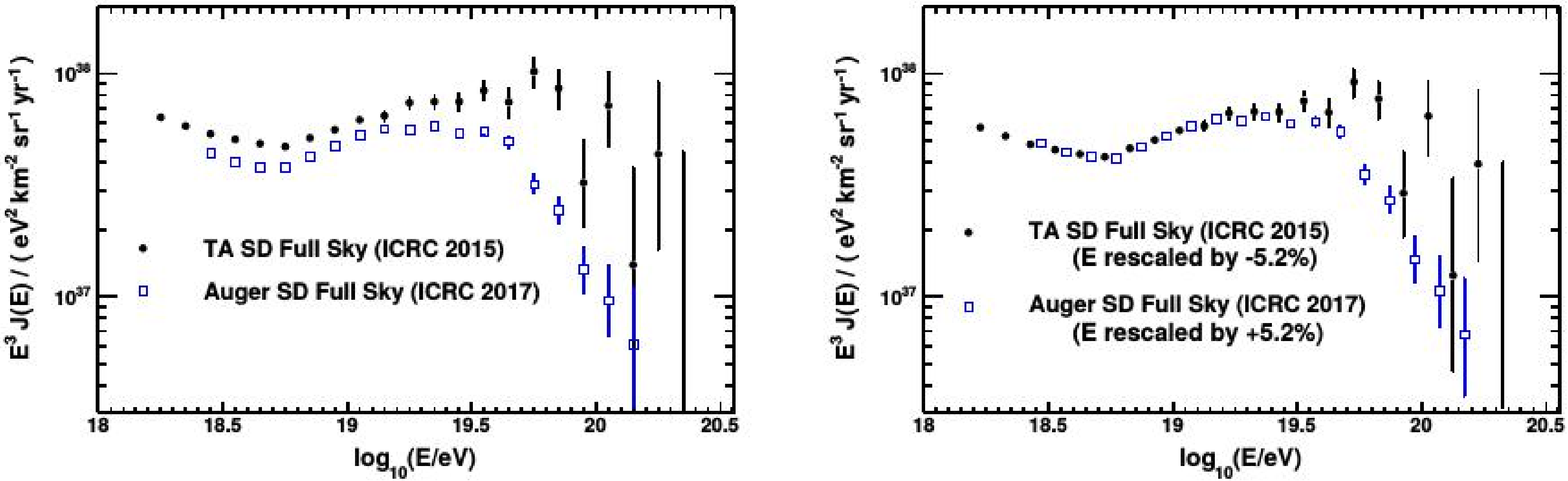
Energy spectrum





- Ankle (hardening) at several EeV
- Cut-off at several tens EeV

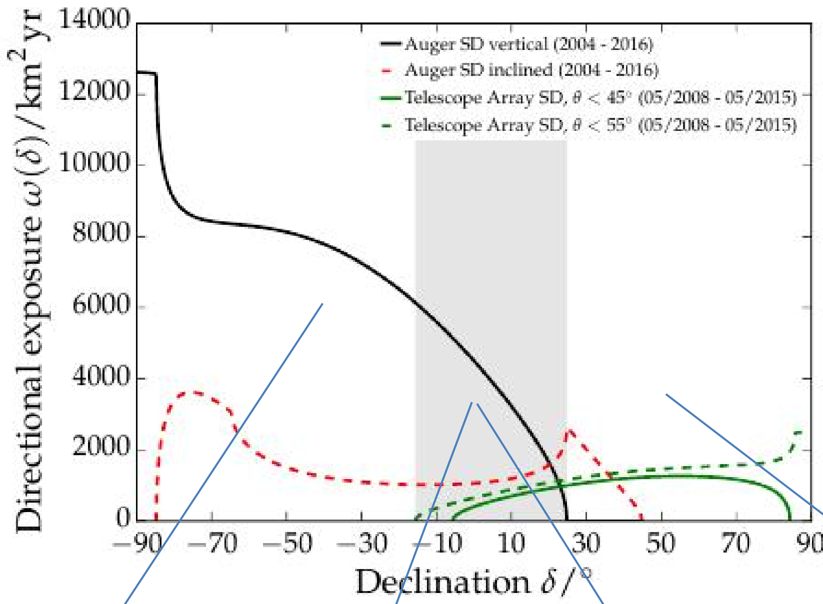
Energy spectrum: comparison (1/2)



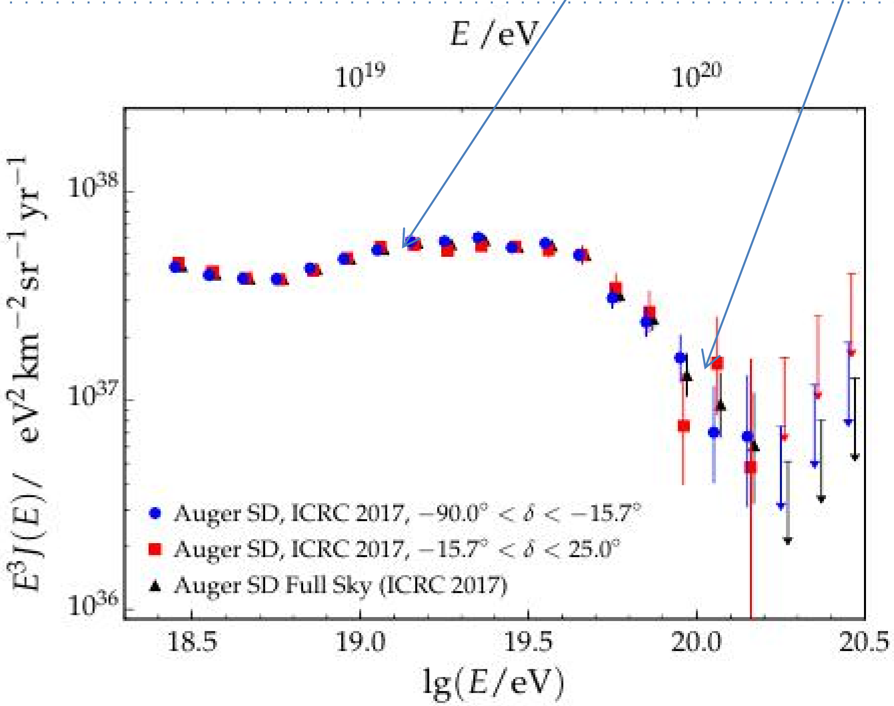
TA/PAO WG 1801.01018

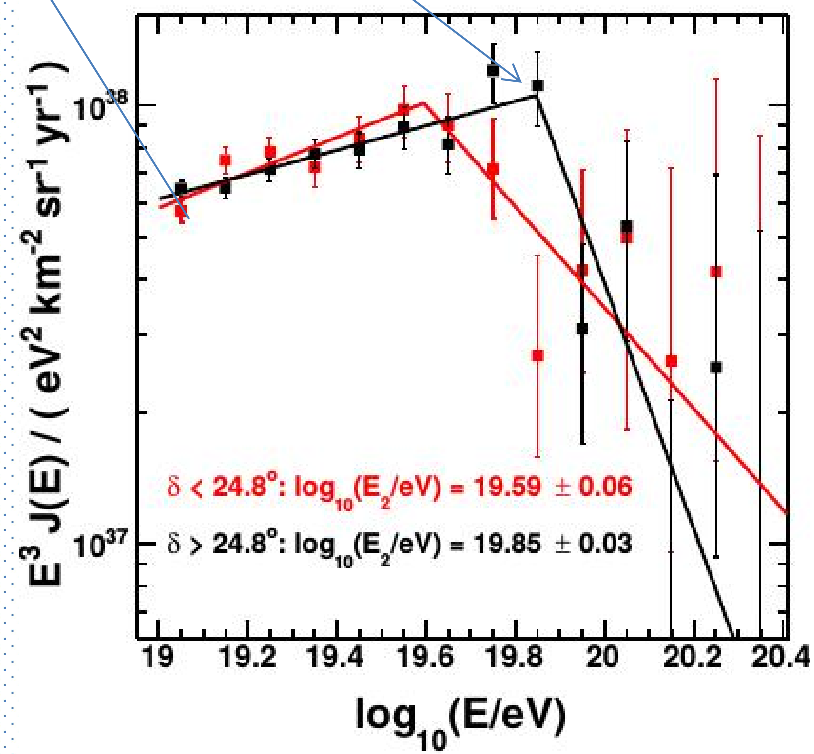
- Perfect agreement up to the cut-off well within experimental uncertainties
- Some discrepancy above the cut-off

Energy spectrum: comparison (2/2)

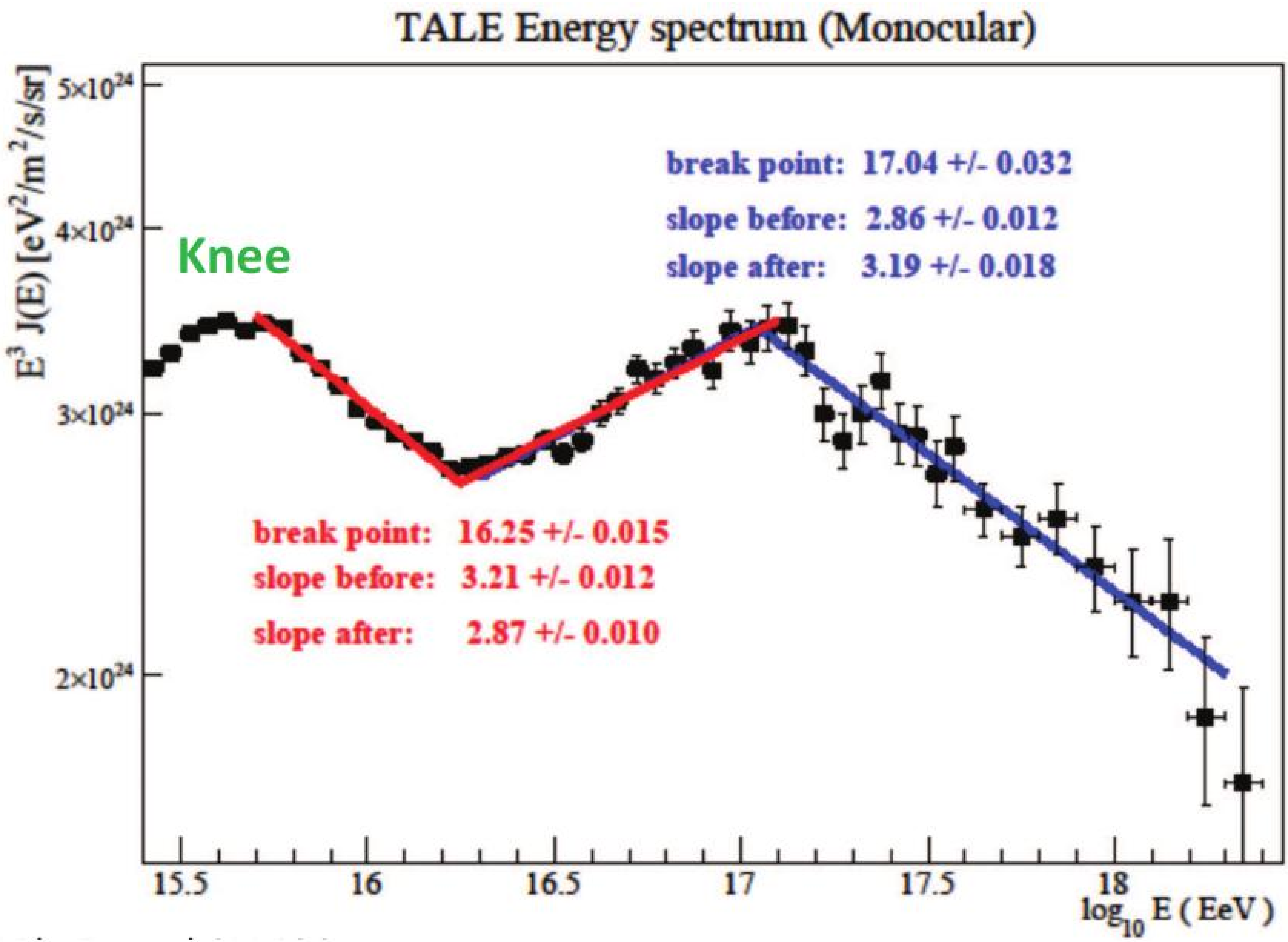


- PAO spectrum is declination independent
- Hints on the declination dependency in the TA spectrum



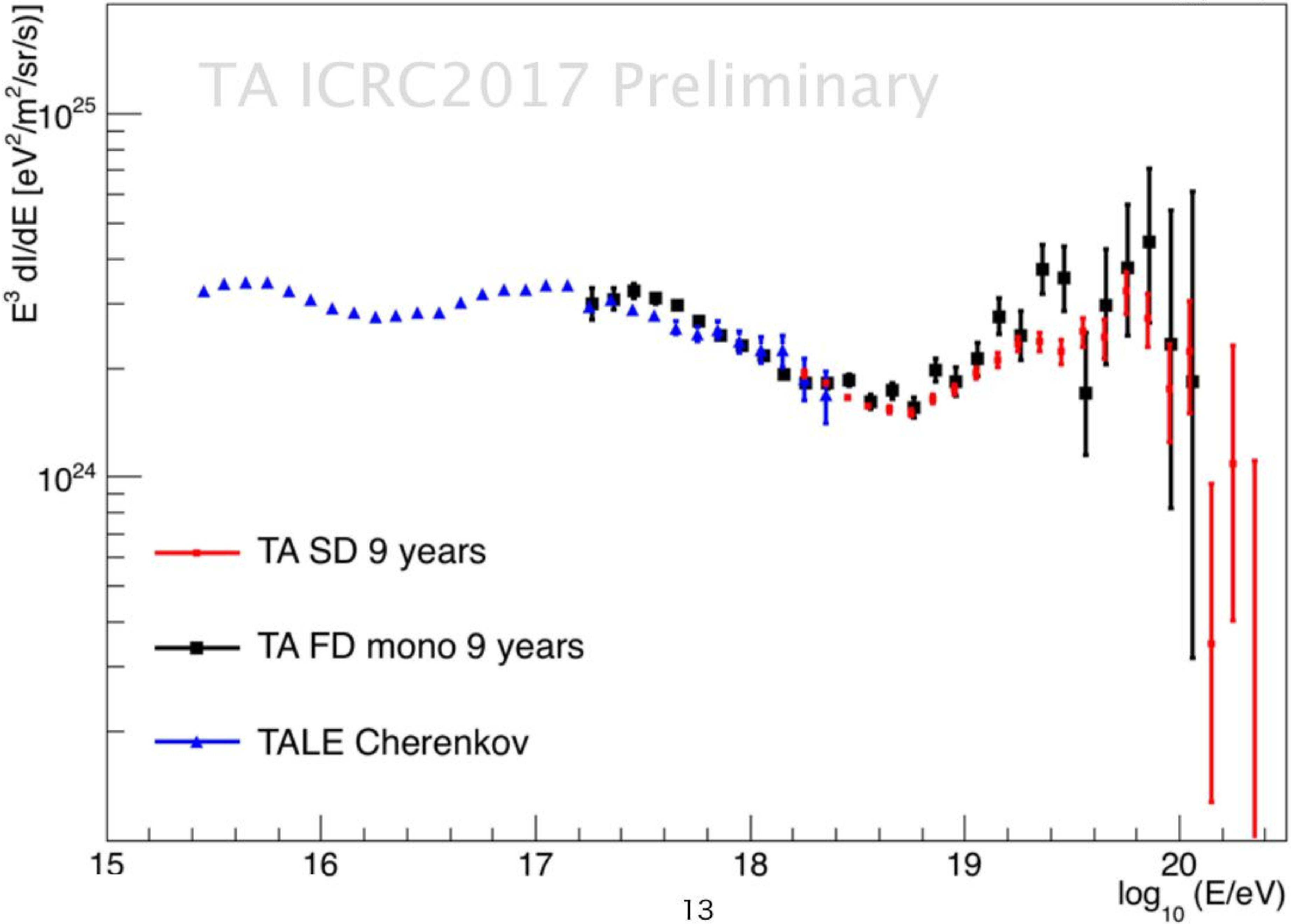


TALE mono spectrum (3.5 years of data)



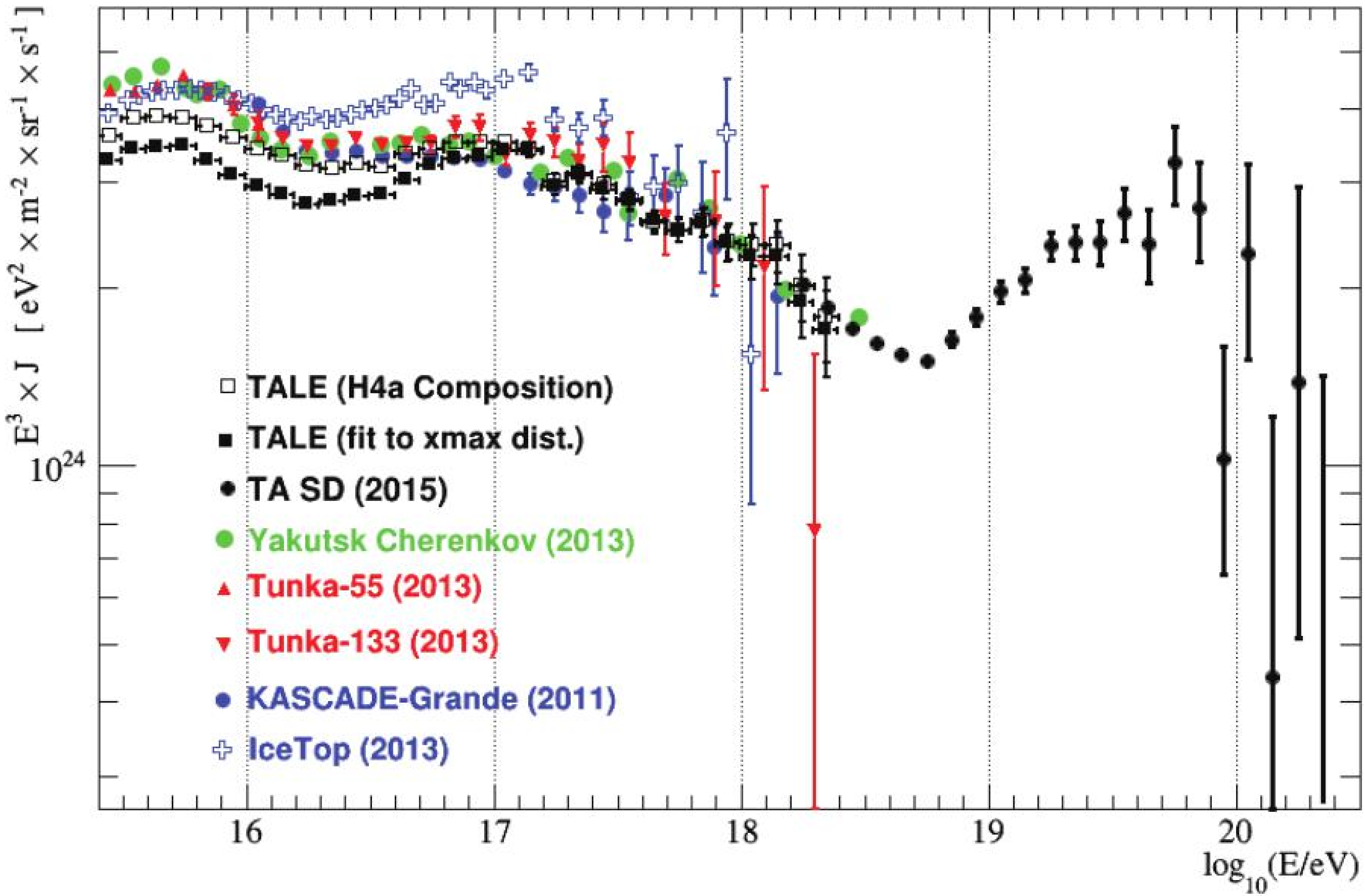
ICRC2017

TA +TALE combined spectrum (1/2)



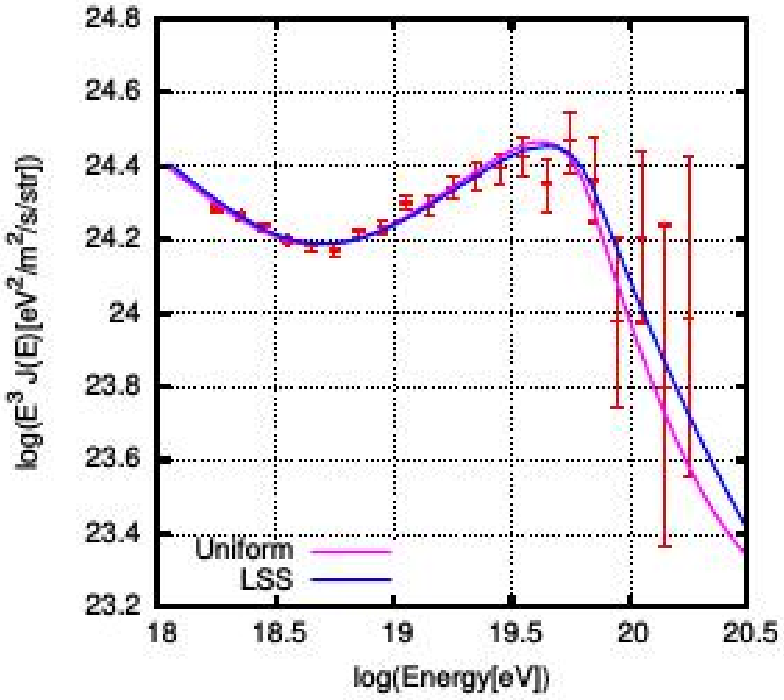
ICRC2017

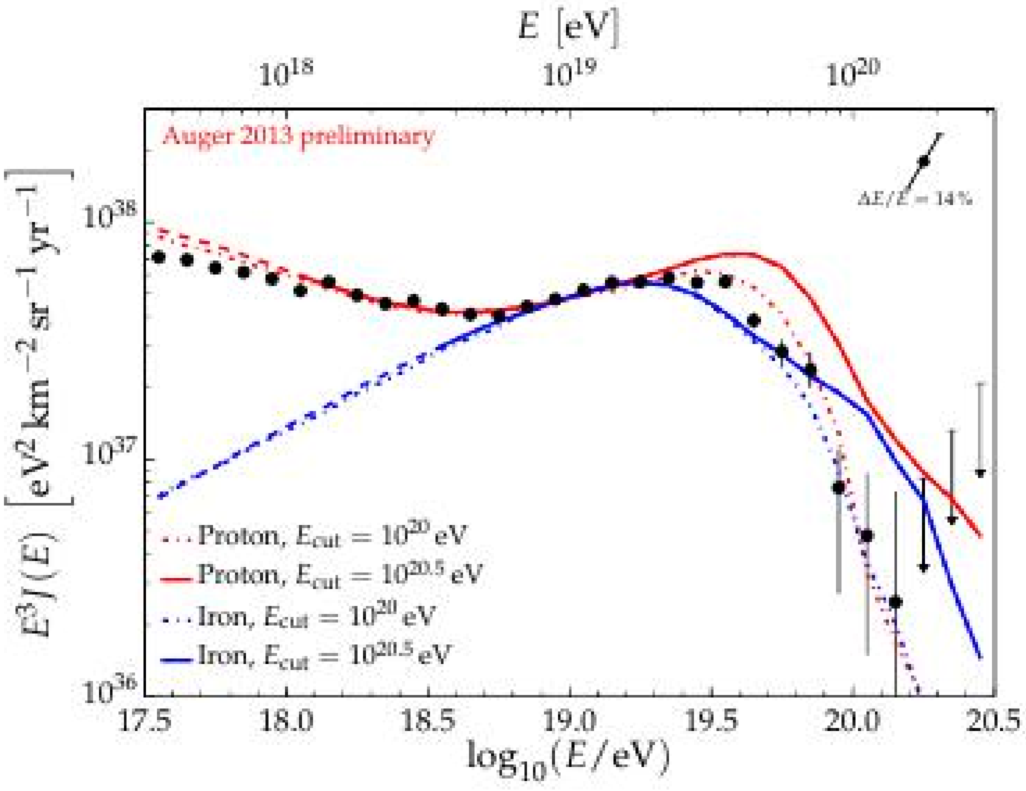
TA +TALE combined spectrum (2/2)



ICRC2017

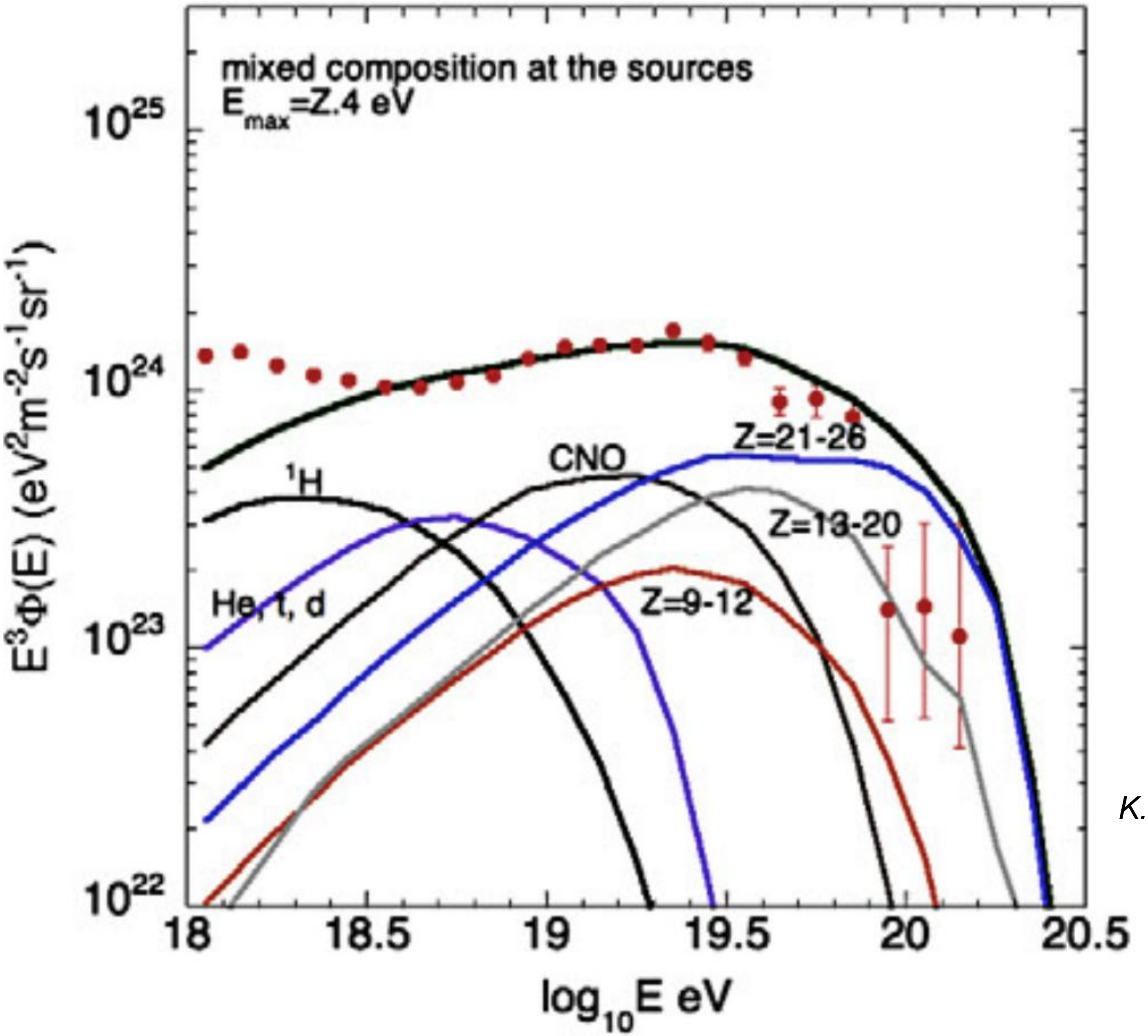
Origin of the cut-off: propagation?





K. Kampert 1404.6515

Origin of the cut-off: maximal energy at the sources?



K. Kampert 1404.6515

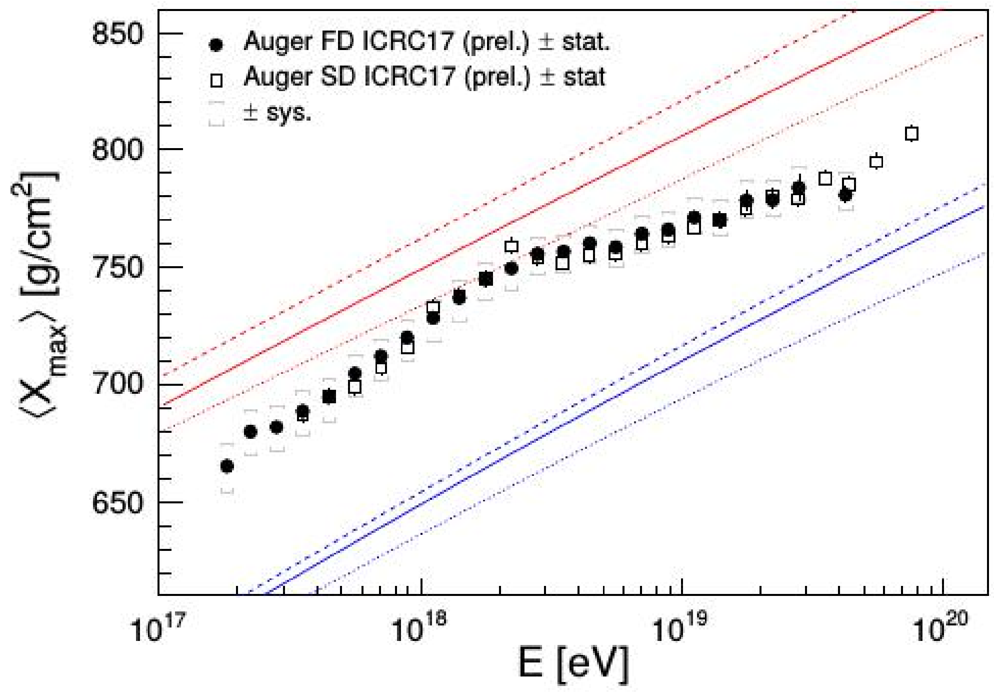
- Knowledge of the mass composition will help to disentangle!

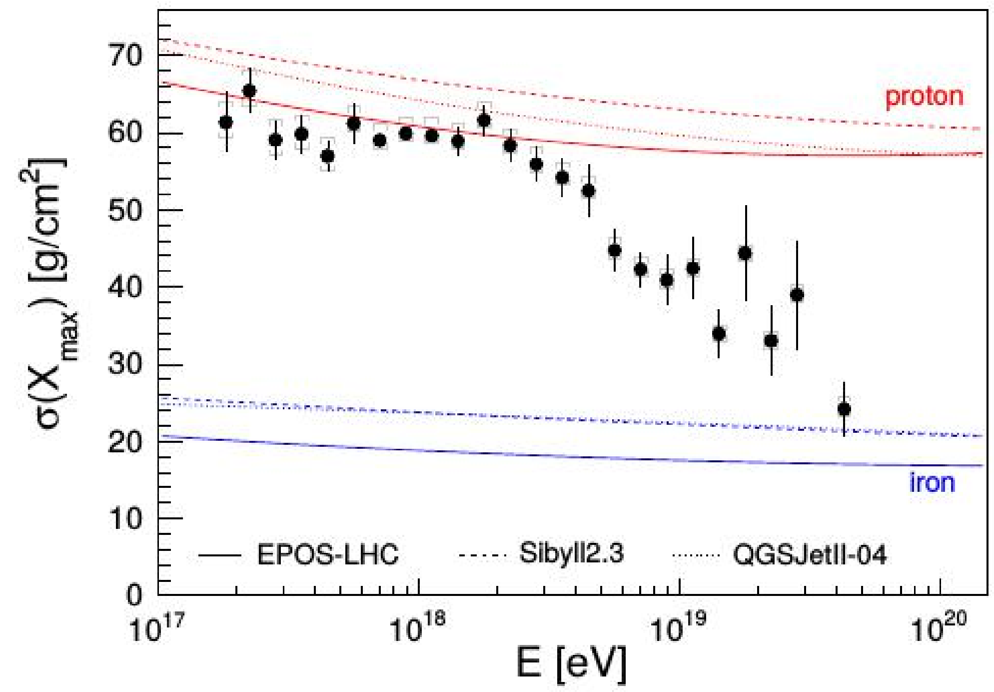
MASS COMPOSITION

Mass composition estimation

- Mostly from fluorescent detectors: X_{max}.
- $<X_{max}>$ increases with E -- CR 'penetrates' deeper.
- Shower for nuclei with mass number A is a superposition of A proton showers with initial energy E/A, i.e. showers are *shallower* for heavier nuclei.
- Also Xmax tends to fluctuate less from shower to shower in this case, $\sigma(X_{max})$ decreases.
- Advanced analyses now use full Xmax distribution, not only first momenta.

Mass composition: Auger



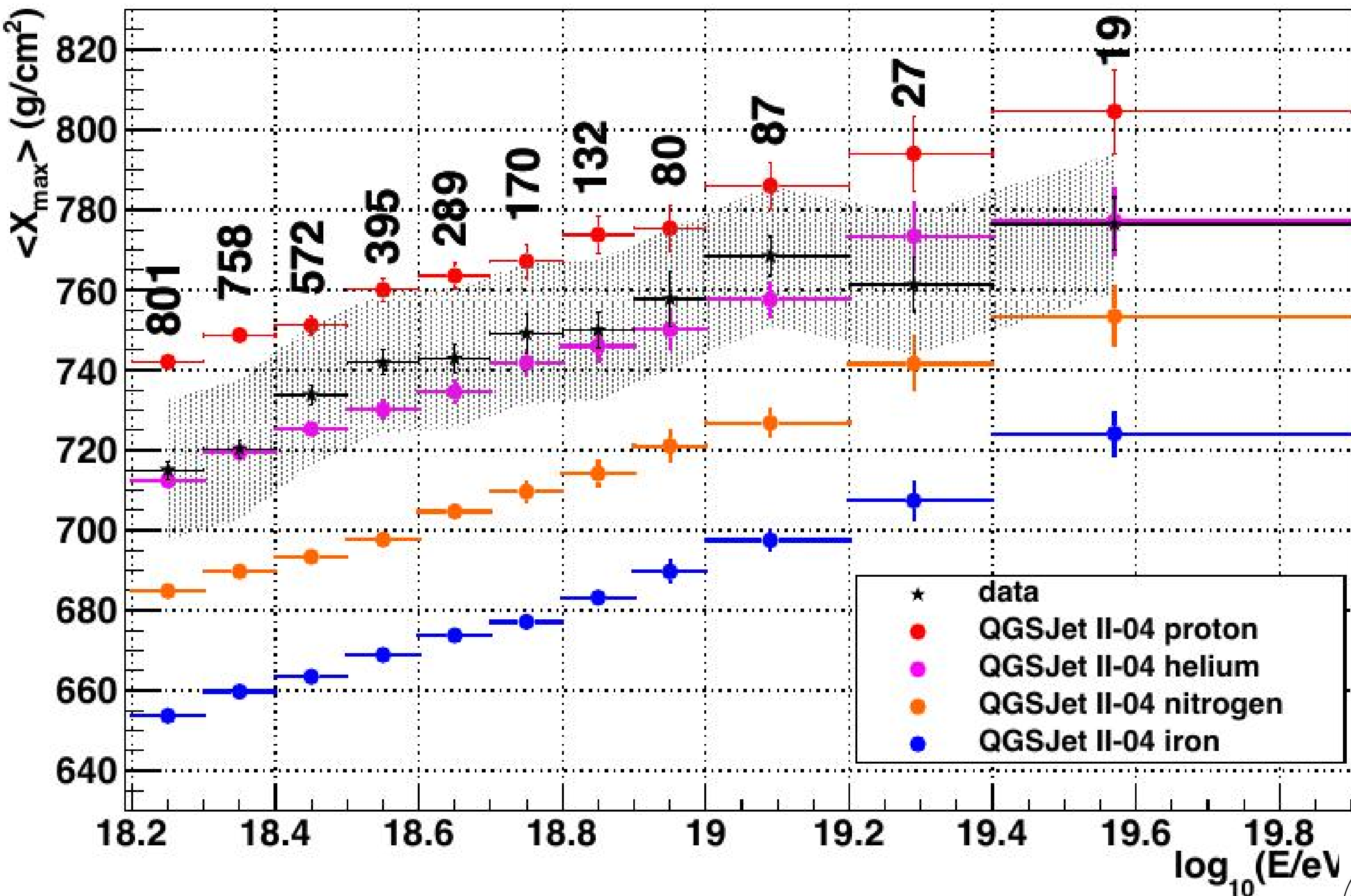


- UHECR mass reaches the minimum around several EeV.
- Afterwards composition is becoming heavier
- Slight discrepancy between $X_{\max}$ and $\sigma(X_{\max})$ results.
- Two highest bins (from the SD risetime method) are different -- do the composition becomes lighter again?

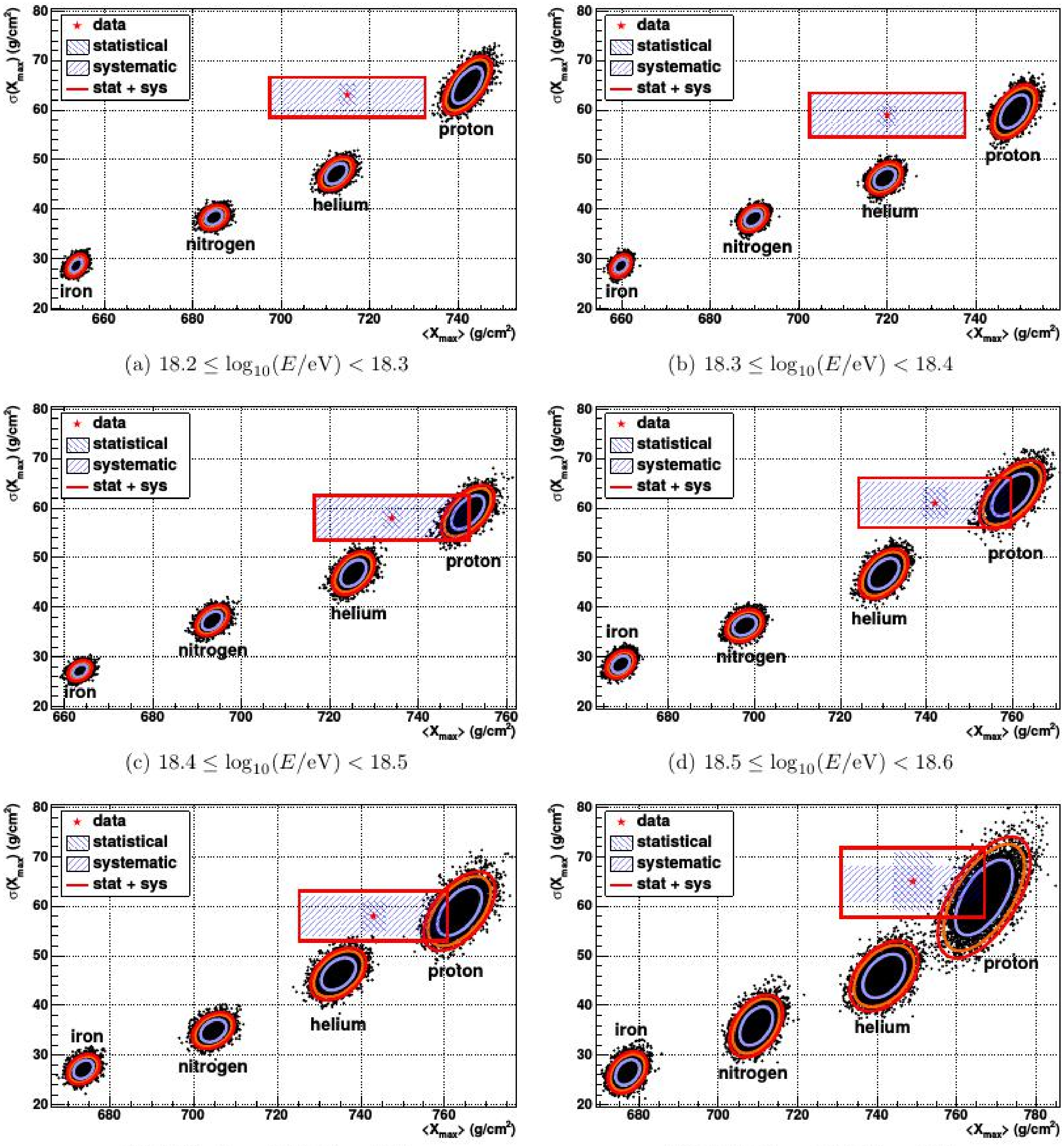
Mass composition: TA (1/3)

Data: 27 May 2008 - 29 Nov. 2016

Ap. J., 858, 76(2018)
arXiv: 1801.09784



Mass composition: TA (2/3)



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

(b) $18.3 \le \log_{10}(E/\mathrm{eV}) < 18.4$

(c) $18.4 \le \log_{10}(E/\mathrm{eV}) < 18.5$

(d) $18.5 \le \log_{10}(E/\mathrm{eV}) < 18.6$

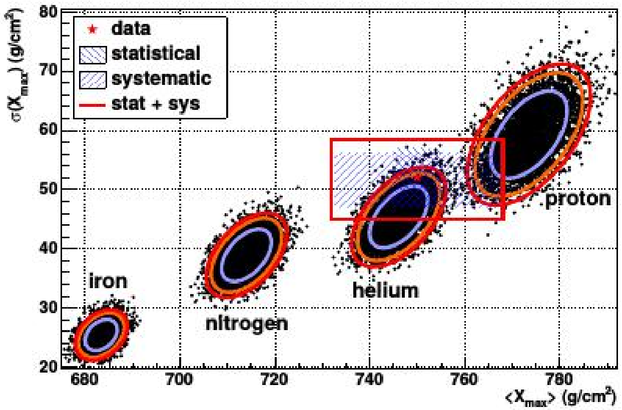
(e) $18.6 \le \log_{10}(E/\mathrm{eV}) < 18.7$

(f) $18.7 \le \log_{10}(E/\mathrm{eV}) < 18.8$

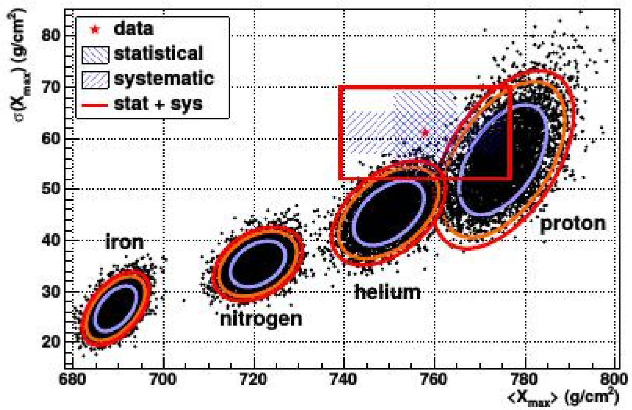
Ap. J. 858, 76 (2018)
arXiv:1801.09784

- Data vs MC
- Compare both X_{max} and σ_{Xmax}
- Data – rectangles, MC – contours
- Single primary, 5000 MCs
- At low energies data with a 10-20 g/cm^2 shifts looks like protons

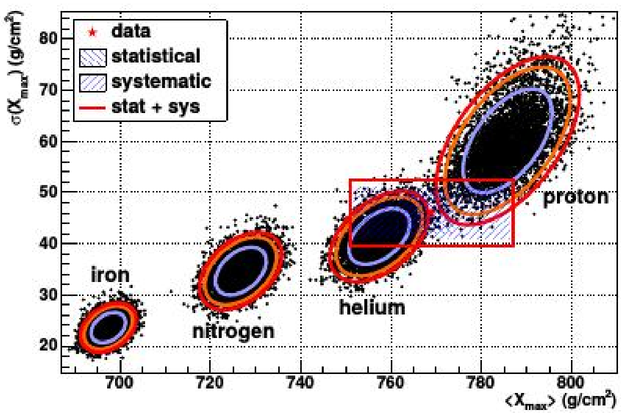
Mass composition: TA (3/3)



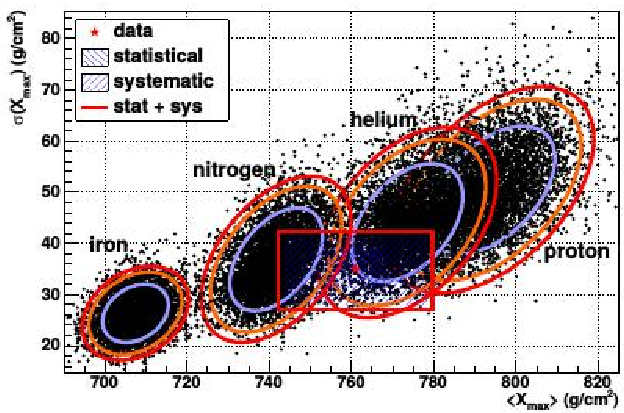
(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$



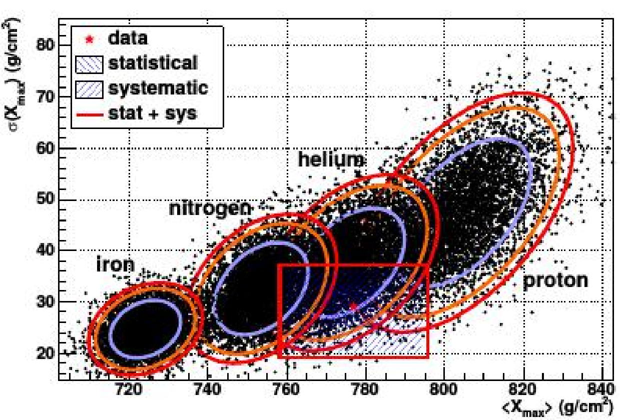
(b) $18.9 \leq \log_{10}(E/\mathrm{eV}) < 19.0$



(c) $19.0 \leq \log_{10}(E/\mathrm{eV}) < 19.2$



(d) $19.2 \leq \log_{10}(E/\mathrm{eV}) < 19.4$

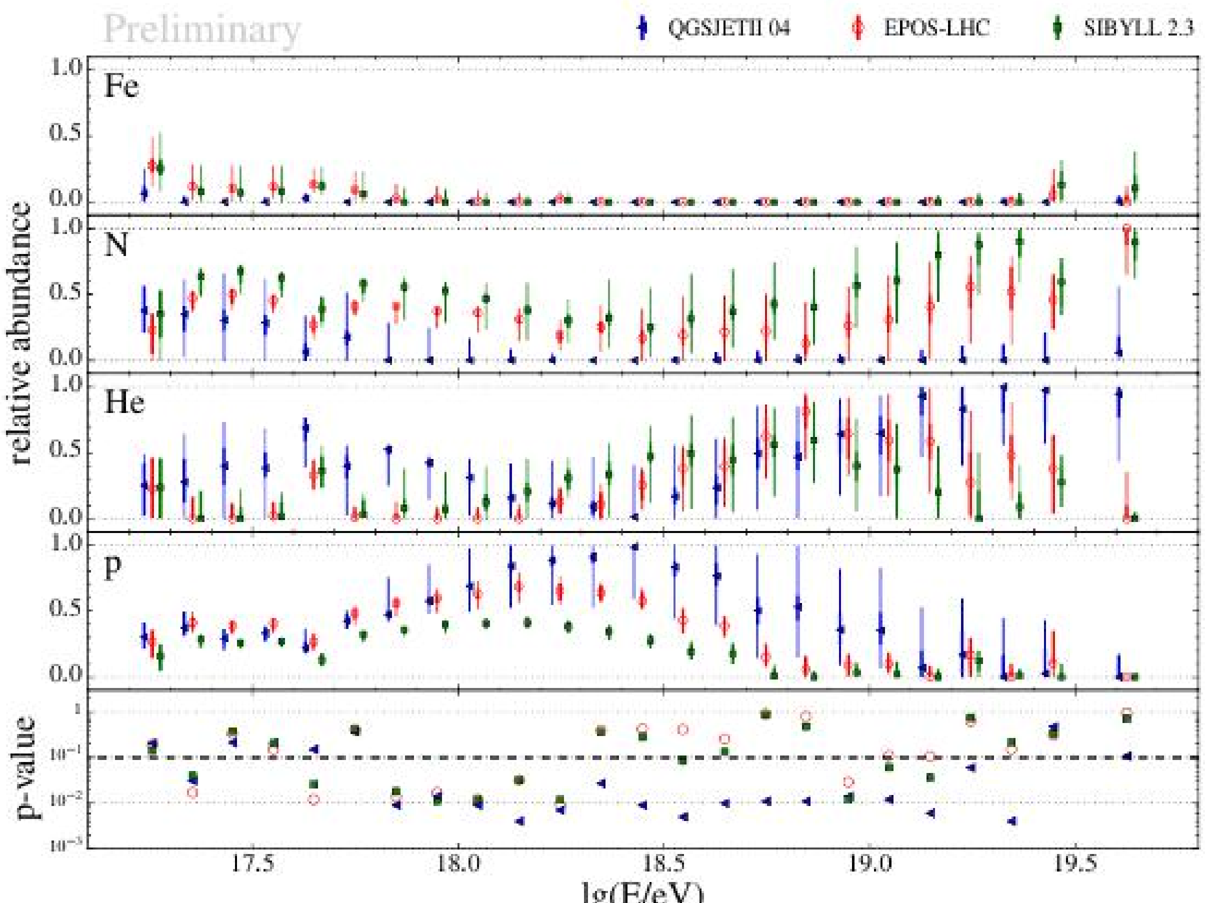


(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

Ap. J. 858, 76 (2018)
arXiv:1801.09784

- At higher energies primaries seem to be heavier than protons
- Small statistics

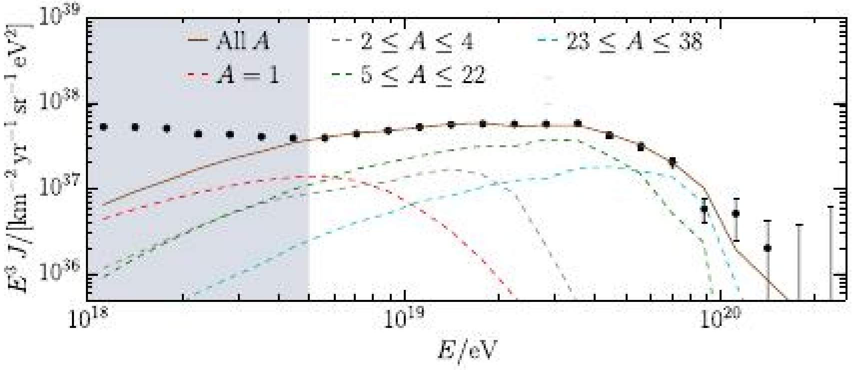
Mass composition: fitting the X_{max} disribution

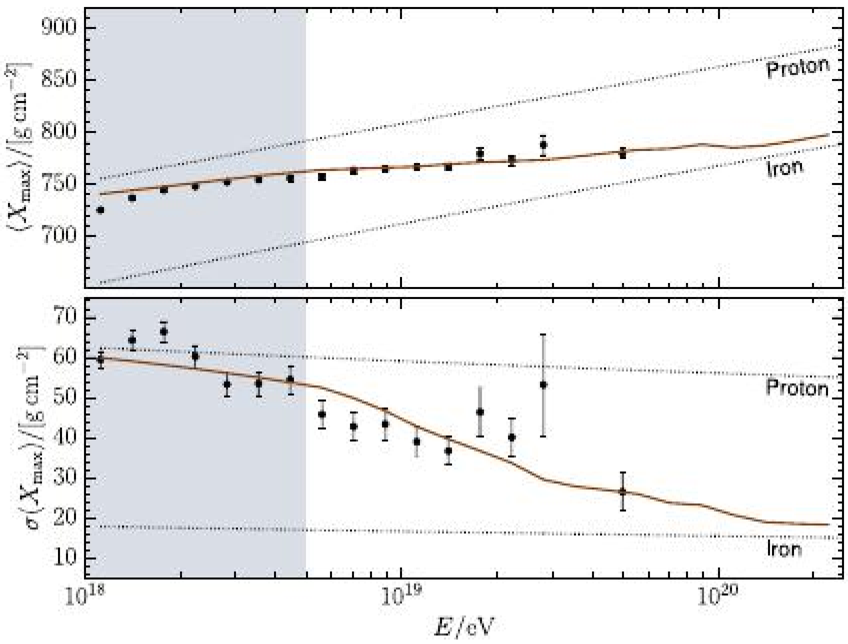


PAO ICRC 2017

- The distribution is fitted by the mix of 4 elementary groups: p, Ne, N, Fe.
- Increase in <A> comes from the change of dominating group.
- No Fe at the highest energies (yet)

The mix and the spectrum

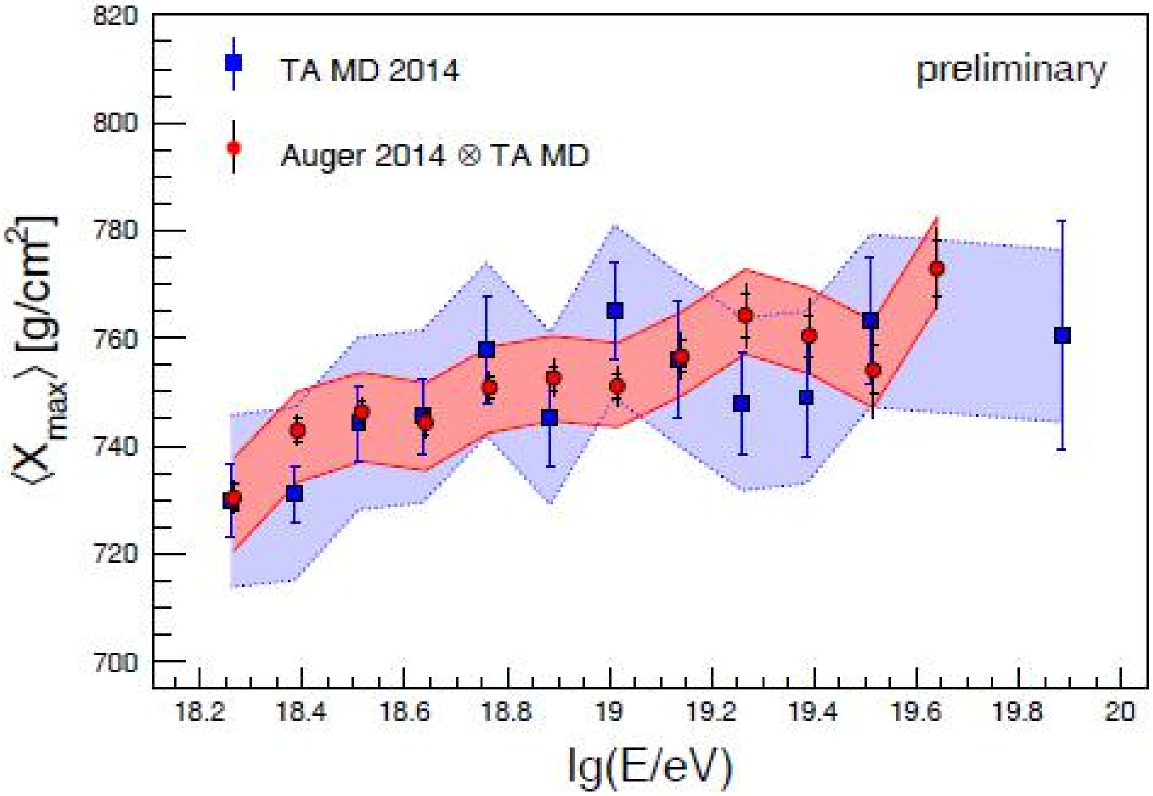




arXiv:1708.06592

- The best mix represents the spectrum pretty closely
- CRs below ~4-5 EeV must be galactic
- What about last points?

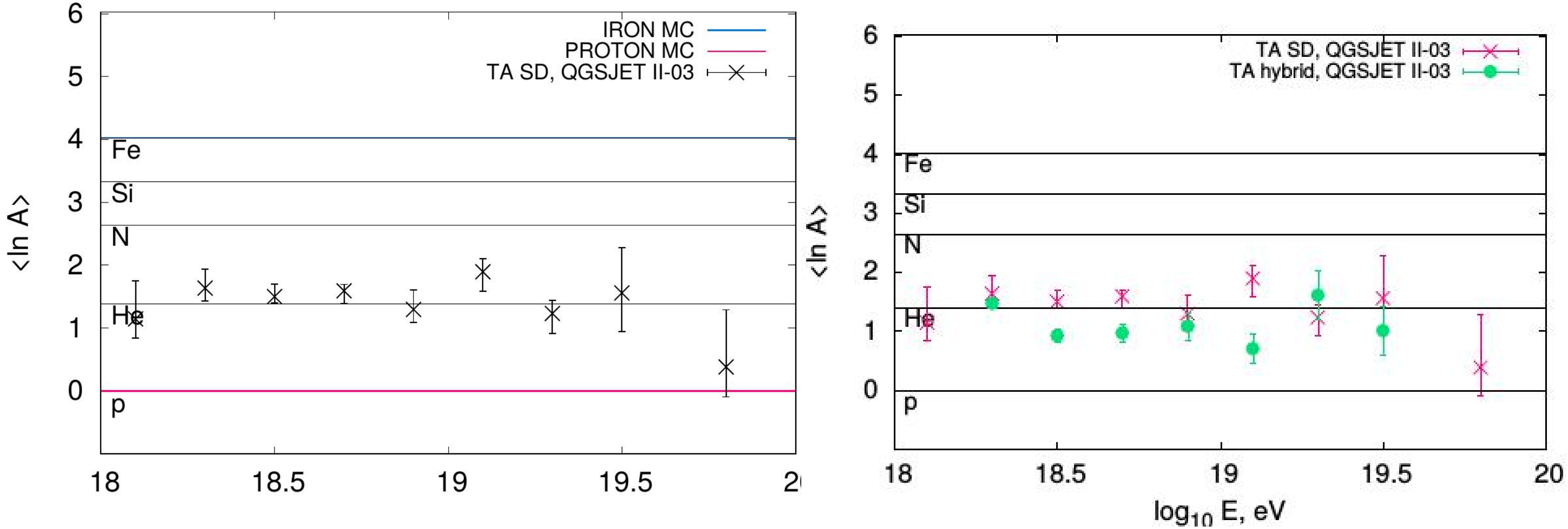
Mass composition: TA/PAO comparison



average difference: $\langle\Delta\rangle = (2.9 \pm 2.7\ (\text{stat.}) \pm 18\ (\text{syst.}))\ \text{g/cm}^2$

- Analysis methods are different and that makes impossible a simple $<X_{max}>$ comparison
- Solution: take 'Auger mix', run it through the TA pipeline
- Result: TA observations are not incompatible with PA mix.
- The same results with full distributions as well.

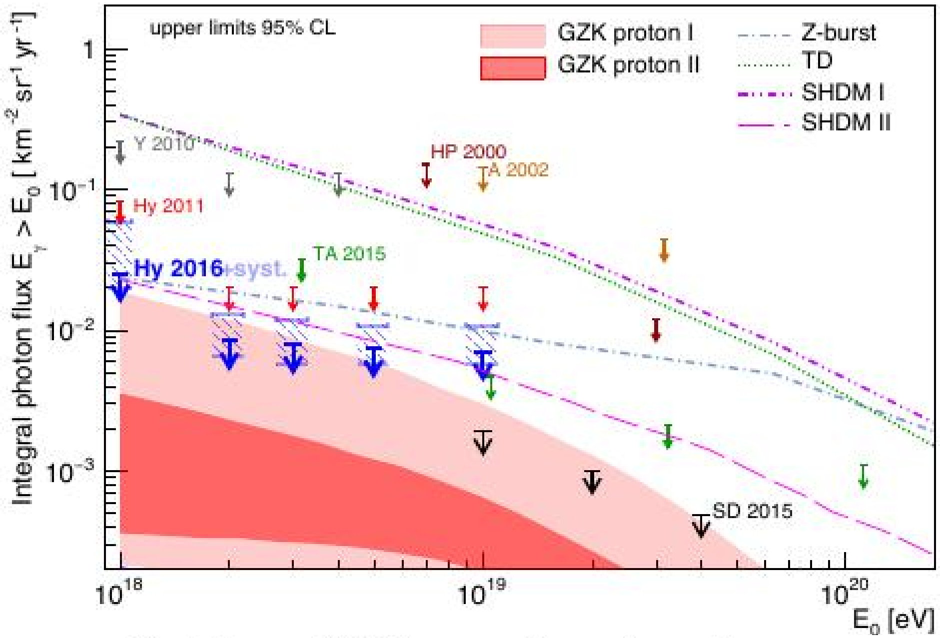
Mass composition future: SD analysis

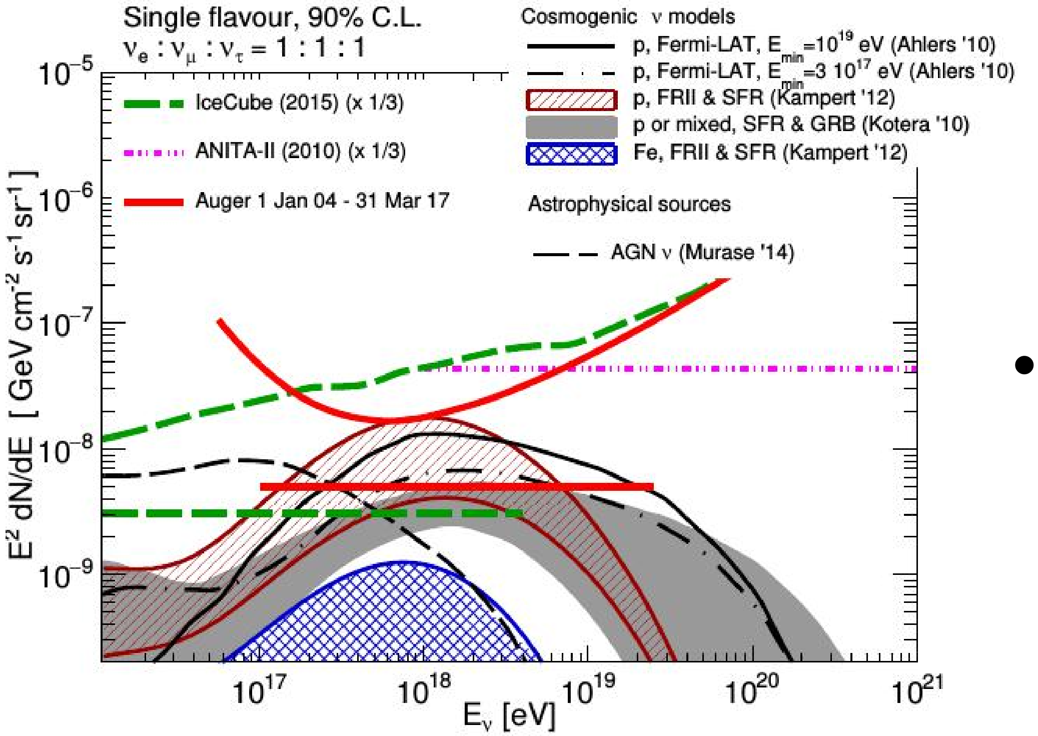


TA. 1808.03680

- Low FD statistics makes studies at $E>10^{19.6}$ eV virtually impossible
- We need to use SD data
- ML. Multivariate analysis (BDT) with 14 observables allowed to move further up to 10^{20} eV.
- Composition is light at the highest energy, 'He'-like.

UHECR ν's and γ's

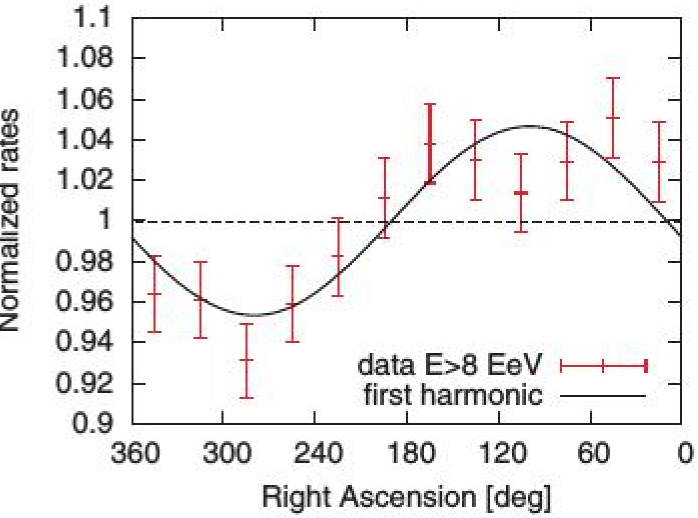




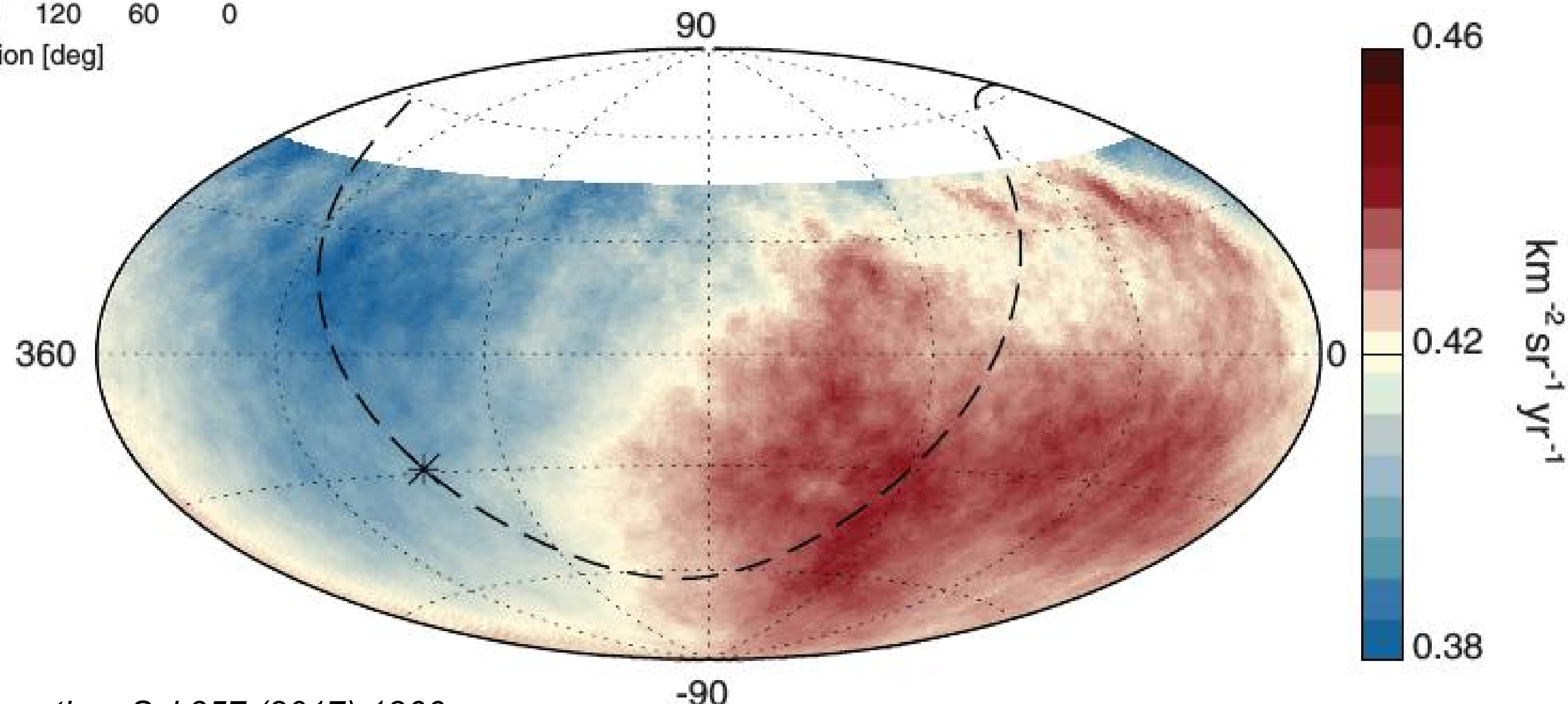
- UHECR detectors are VLVNTs indeed
- No neutrino (or photon) candidates were observed in PA or TA data
- Absence of this cosmogenic particles has already put limits on strong evolution models/proton model -- complimentarity
- SHDM is strongly disfavoured

ANISOTROPY

Anisotropy: large scale (1/3)



- There is a clear dipole excess in 4-8 EeV energy bin
- It's far from the GC pointing at the extragalactic origin of UHECRs



Auger collaboration, Sci 357 (2017) 1266

Anisotropy: large scale (2/3)

Table 1. First harmonic in right ascension. Data are from the Rayleigh analysis of the first harmonic in right ascension for the two energy bins.

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}

Table 2. Three-dimensional dipole reconstruction. Directions of dipole components are shown in equatorial coordinates.

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

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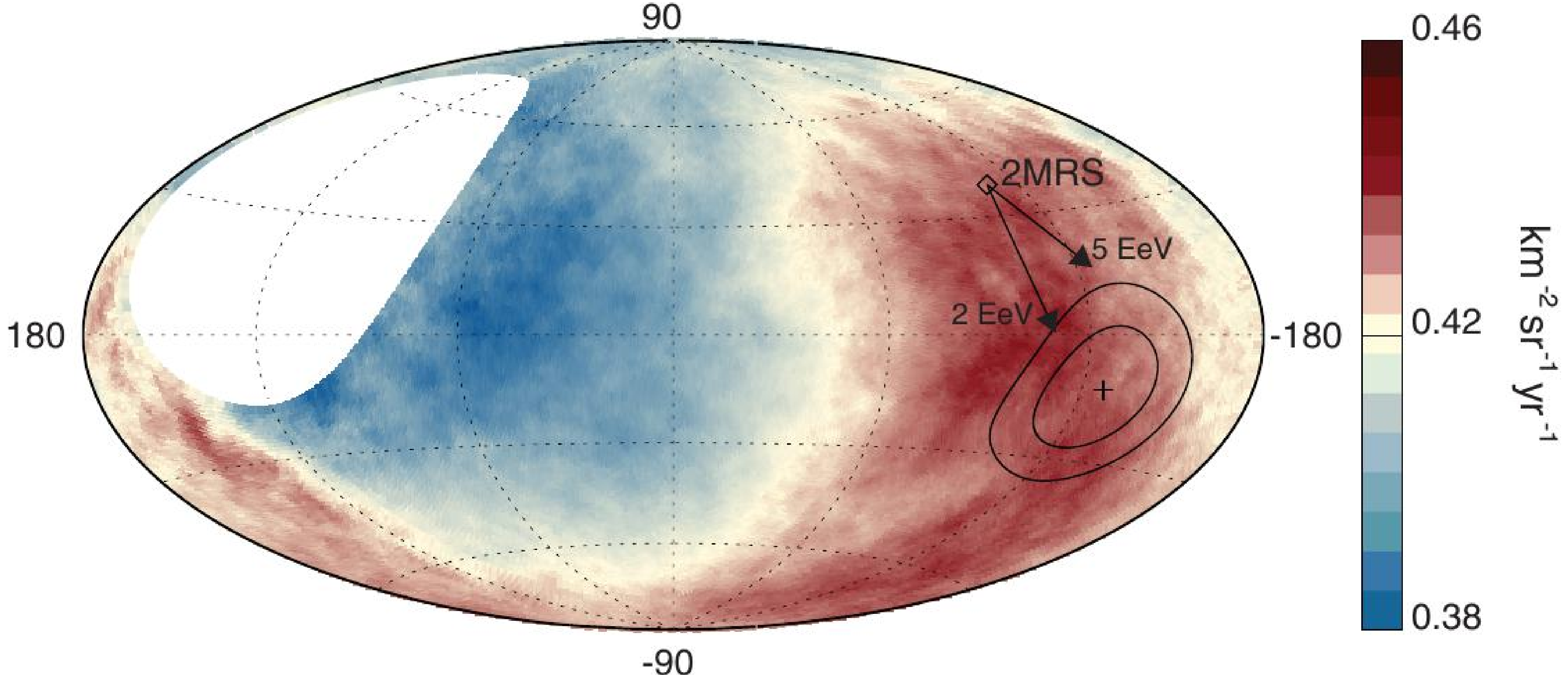
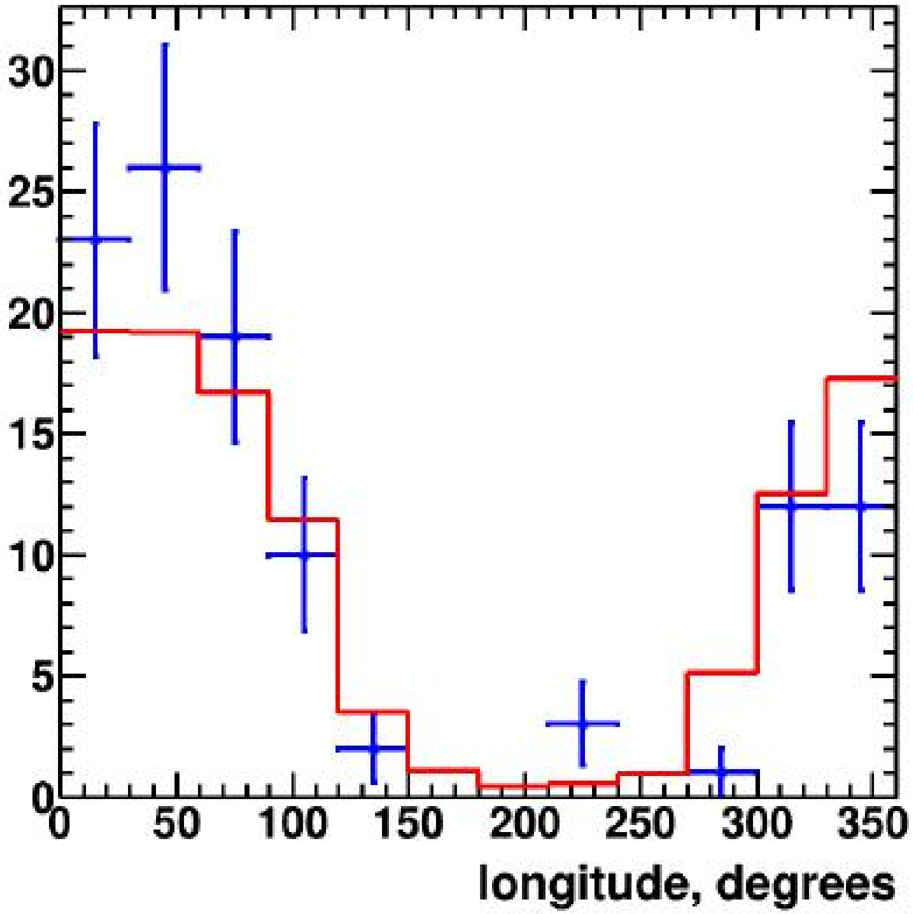
Anisotropy: large scale (3/3)

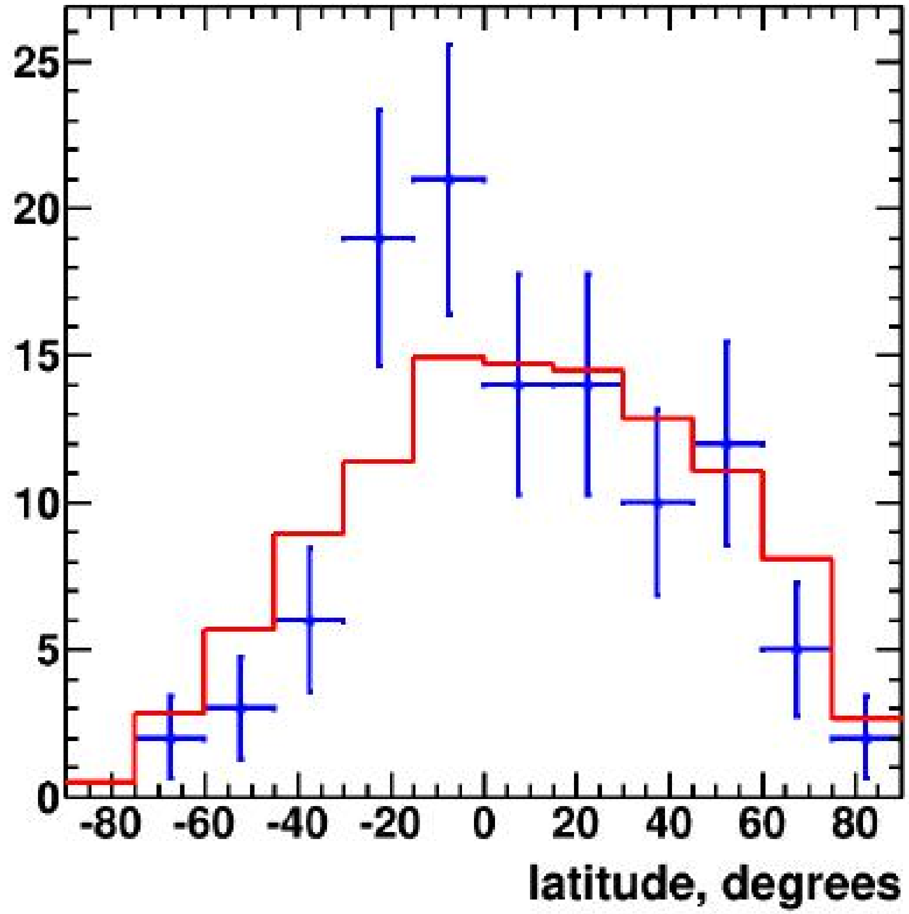


Auger collaboration, Sci 357 (2017) 1266

- Local anisotropy is caused by the LSS
- Good agreement with the 2MRS data + deflections from the GMF

1 Anisotropy: TA medium scale (1/5)

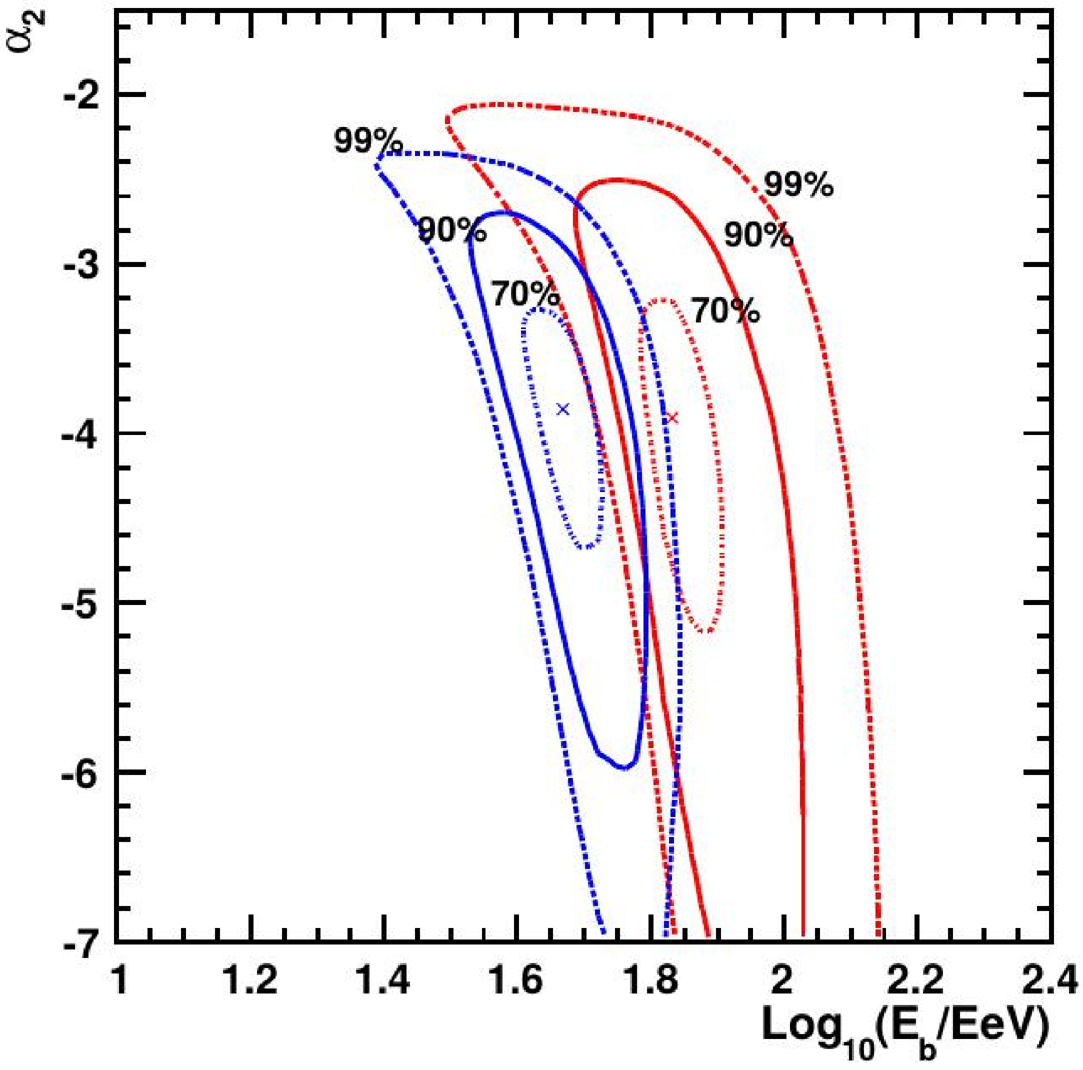




- KS p-value 0.01 data/iso for E>57 EeV in SG lat
- All other distros (*E,* longitude) are compatible

1 Anisotropy: TA medium scale (2/5)

arXiv:1707.04967

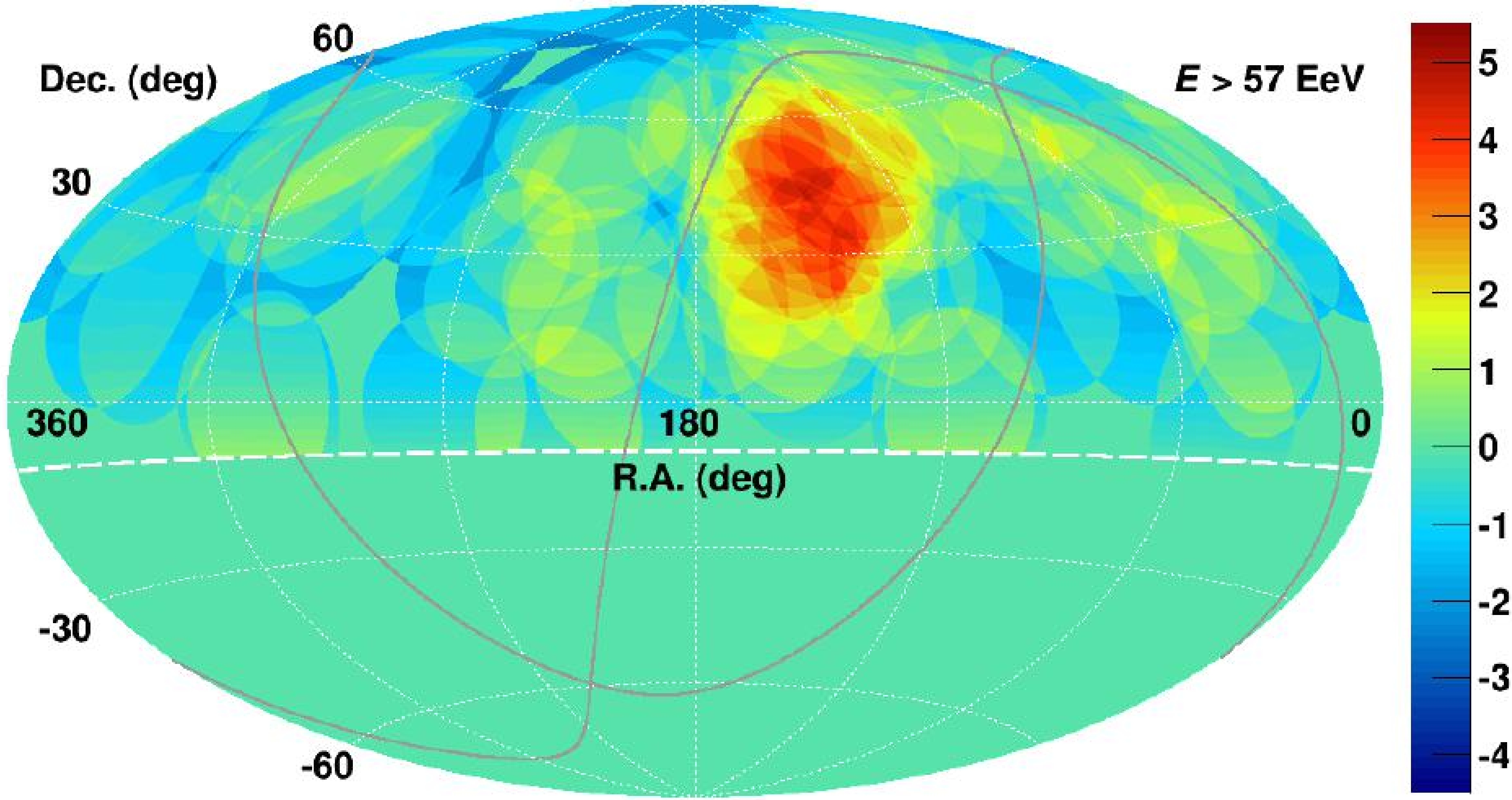


Region	C_o	α_1	$\log_{10}(E_b/EeV)$	α_2
All	$2.14^{+0.34}_{-0.30} \times 10^{+4}$	$-1.775^{+0.053}_{-0.053}$	$1.778^{+0.040}_{-0.068}$	$-3.91^{+0.64}_{-0.66}$
On source	$(1.1128 \times 10^{+4})$	(-1.775)	$1.832^{+0.069}_{-0.041}$	$-3.91^{+0.70}_{-1.30}$
Off source	$(1.0286 \times 10^{+4})$	(-1.775)	$1.668^{+0.052}_{-0.053}$	$-3.86^{+0.58}_{-0.82}$

TABLE I. Parameters of the best fit broken power law in the SGP case.

- In the SGP region break is higher @ 3.2σ

1 Anisotropy: TA medium scale (3/5)

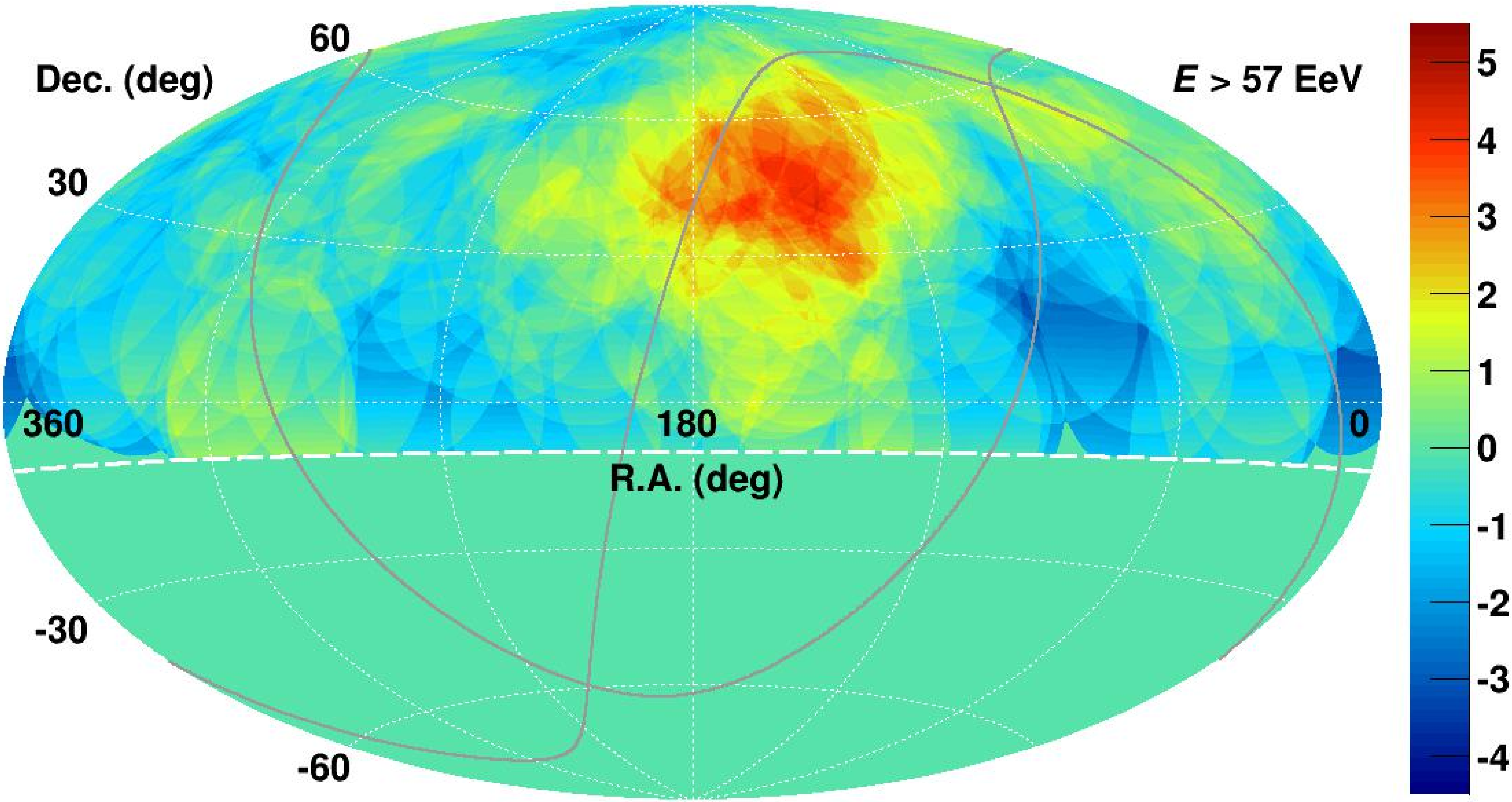


Total events: 72
Observed: 19
Expected : 4.5

Best circle center: RA=146.7°, Dec=+43.2°
Best circle radius: 20°
Local significance : 5 σ
Global significance : 3 σ

5 years

1 Anisotropy: TA medium scale (4/5)

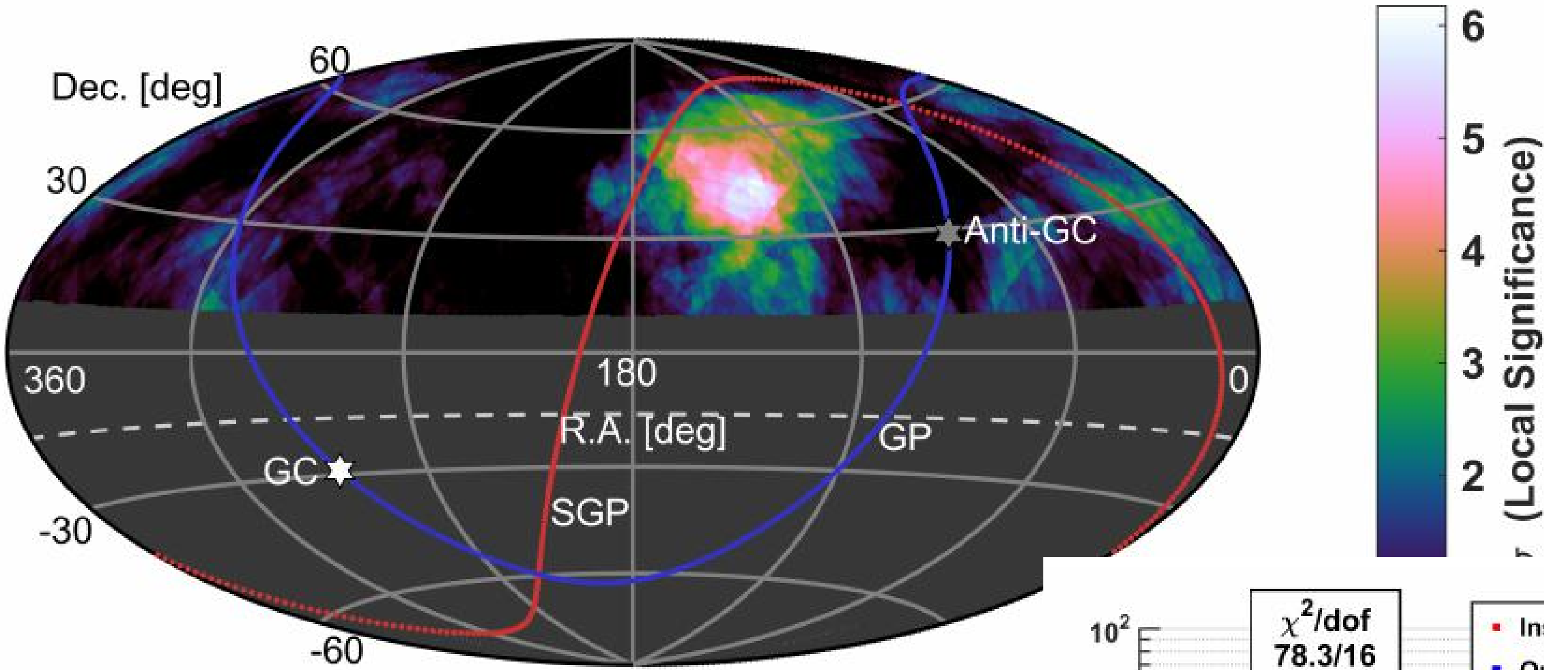


Total events: 143
Observed: 34
Expected : 13.5

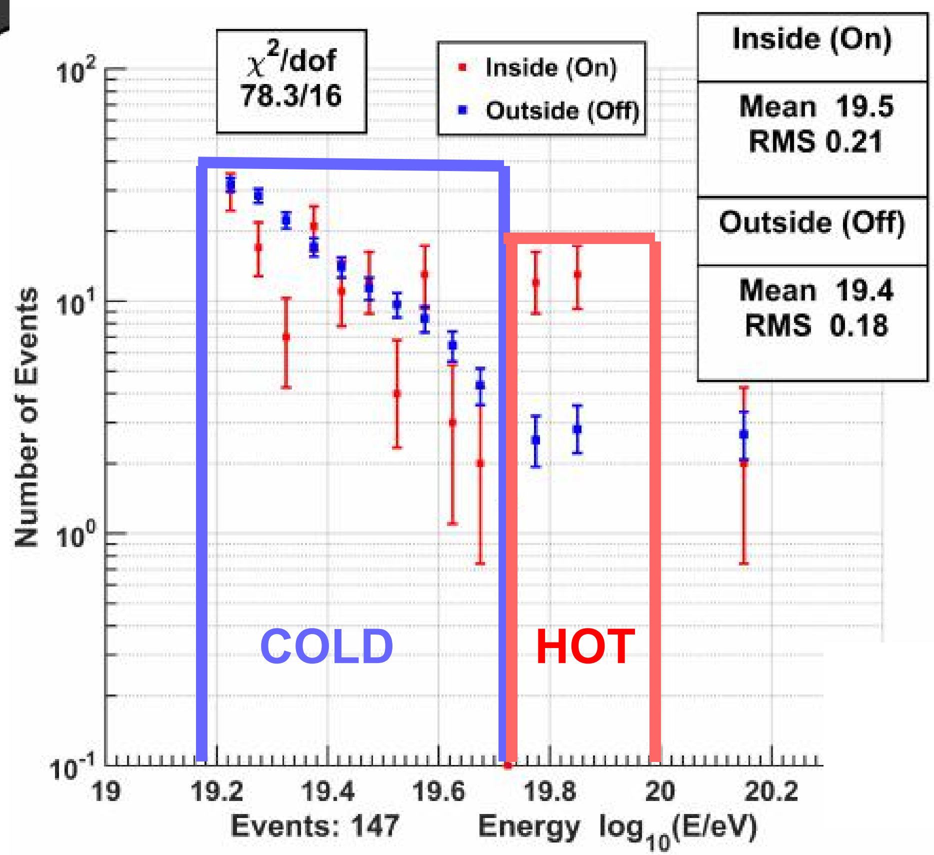
Best circle center: RA=144.3°, Dec=+40.3° Best circle radius: 25°
Local significance : 5 σ
Global significance : 3 σ

9 years

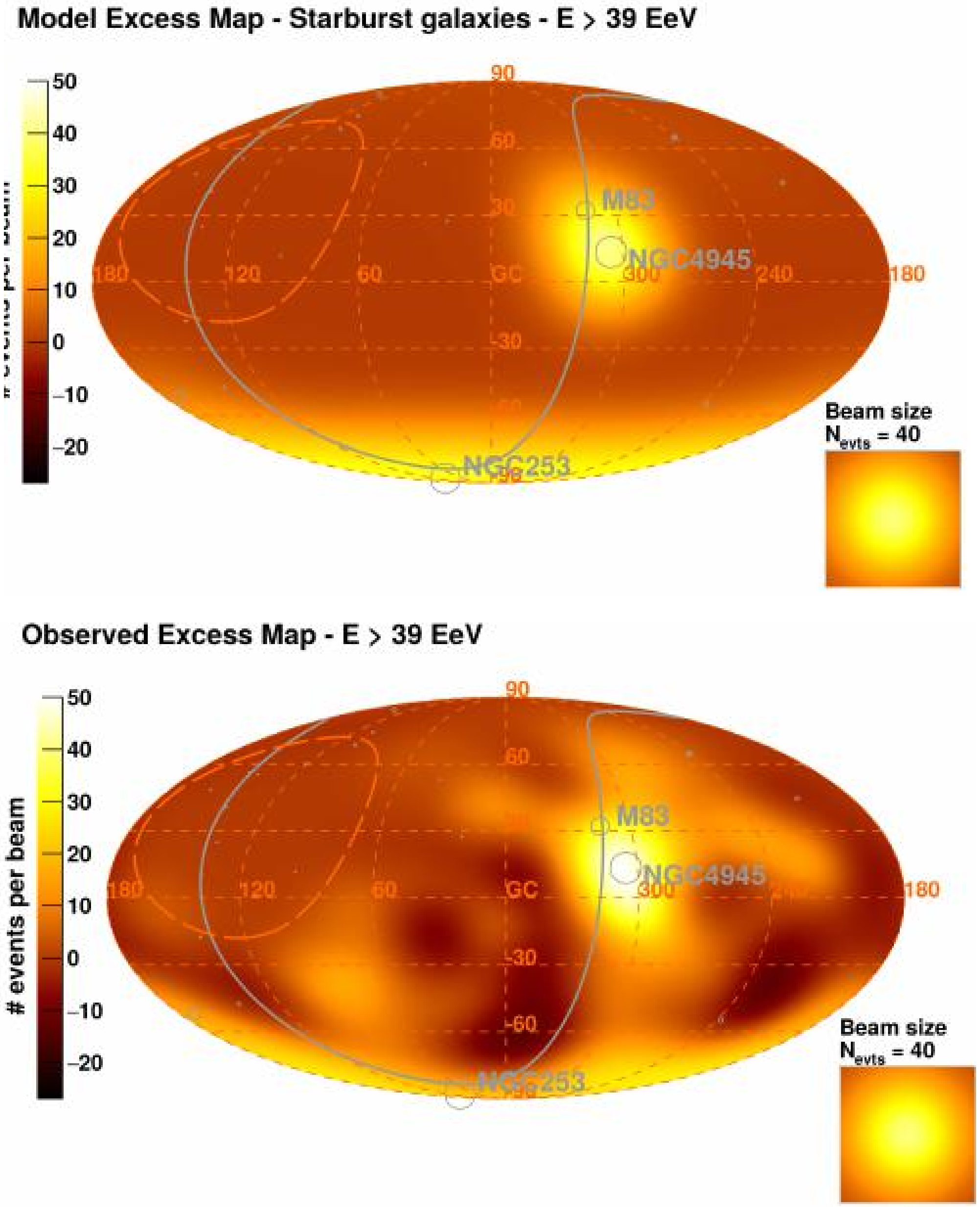
Anisotropy: TA medium scale (5/5)



- 'Coldspot' at $10^{19.2}$-$10^{19.7}$ eV
- Very close to hotspot
- 3.7σ global significance



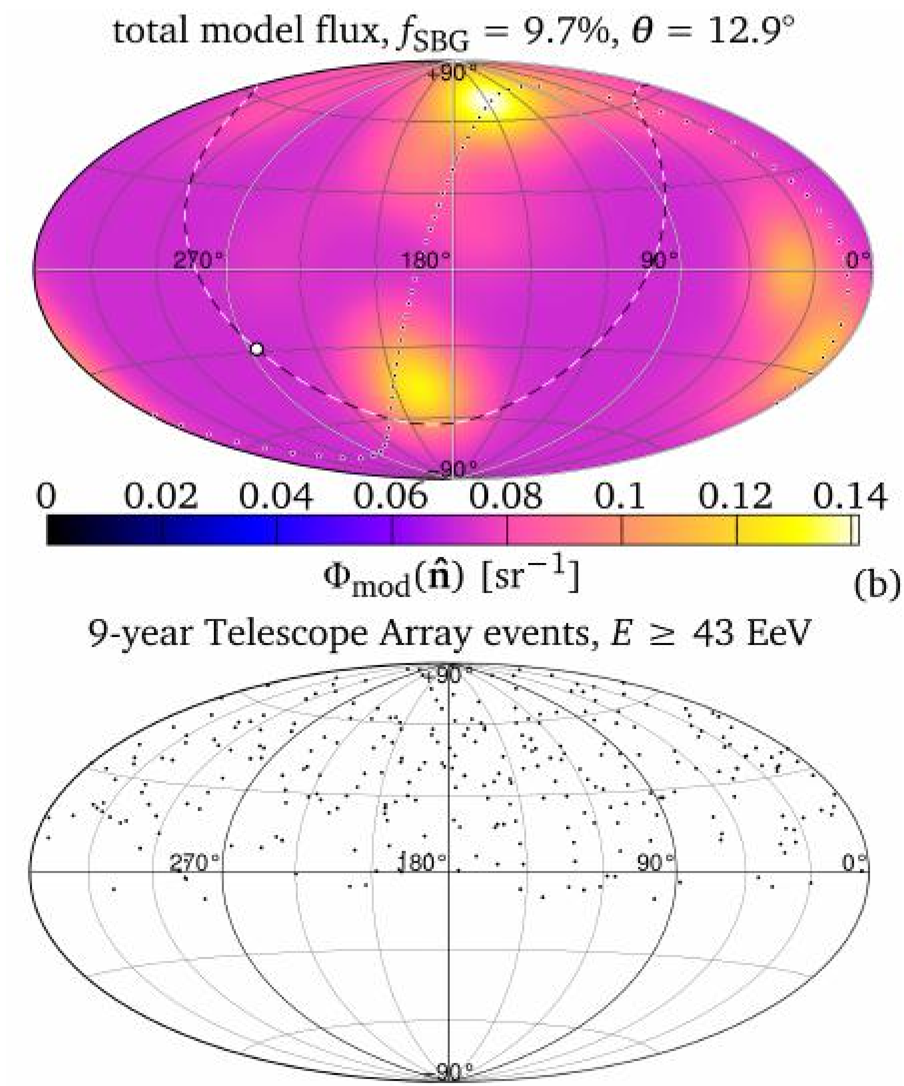
Anisotropy: PA SBG correlation



Auger collaboration, ApJL 853:L29 (2018)

- Model: flux proportional to $L_{1.4\text{GHz}}$
- Add uniform component (arbitrary fraction)
- Smear with Gaussian (arbitrary radius)
- Maximum Likelihood -- obtain TS from the observed data
- !No deflections in GMF
- 4 σ for SBG model with source fraction 9.7% and smearing radius 12.9°

Anisotropy: TA SBG correlation



- Model: the same as the Auger model with the fixed source fraction 9.7% and smearing radius 12.9°
- "The result of this test was inconclusive, being compatible both with isotropy to within 1.2σ and with the Auger result to within 1.3σ."

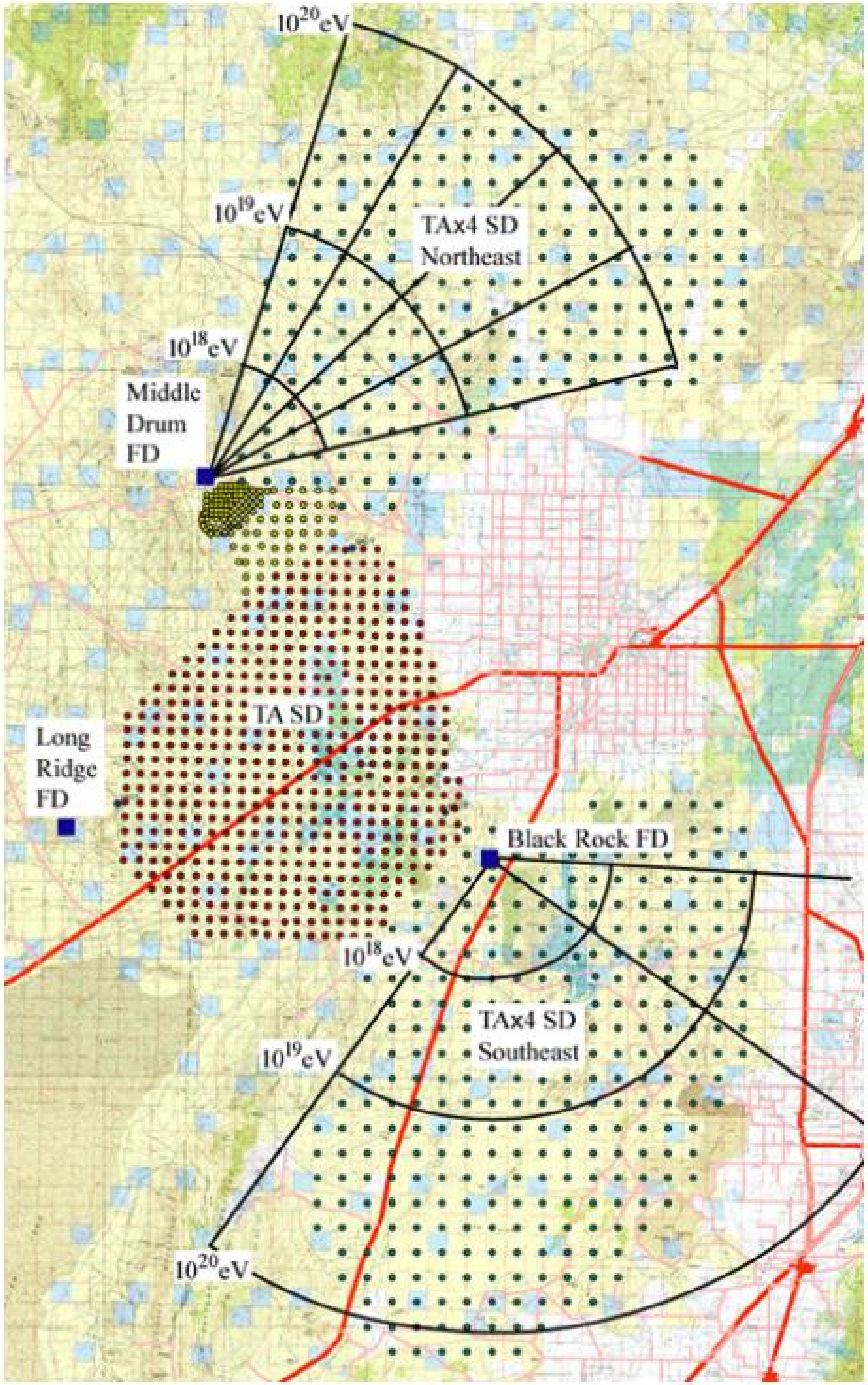
1809.01573

FUTURE

Future: Auger Prime

- Major upgrades
- Add scintillator on top of each WCD -- different sensititivity allows to disentangle muon and electrons/positrons/gamma
- Bury large scintillators under detectors in the infill array (SD-750) . AMIGA will study muon component.
- Variable HV -- observe under 'full moon' -- increase FD statistics.
- Aim: Mass composition studies on event-by event basis

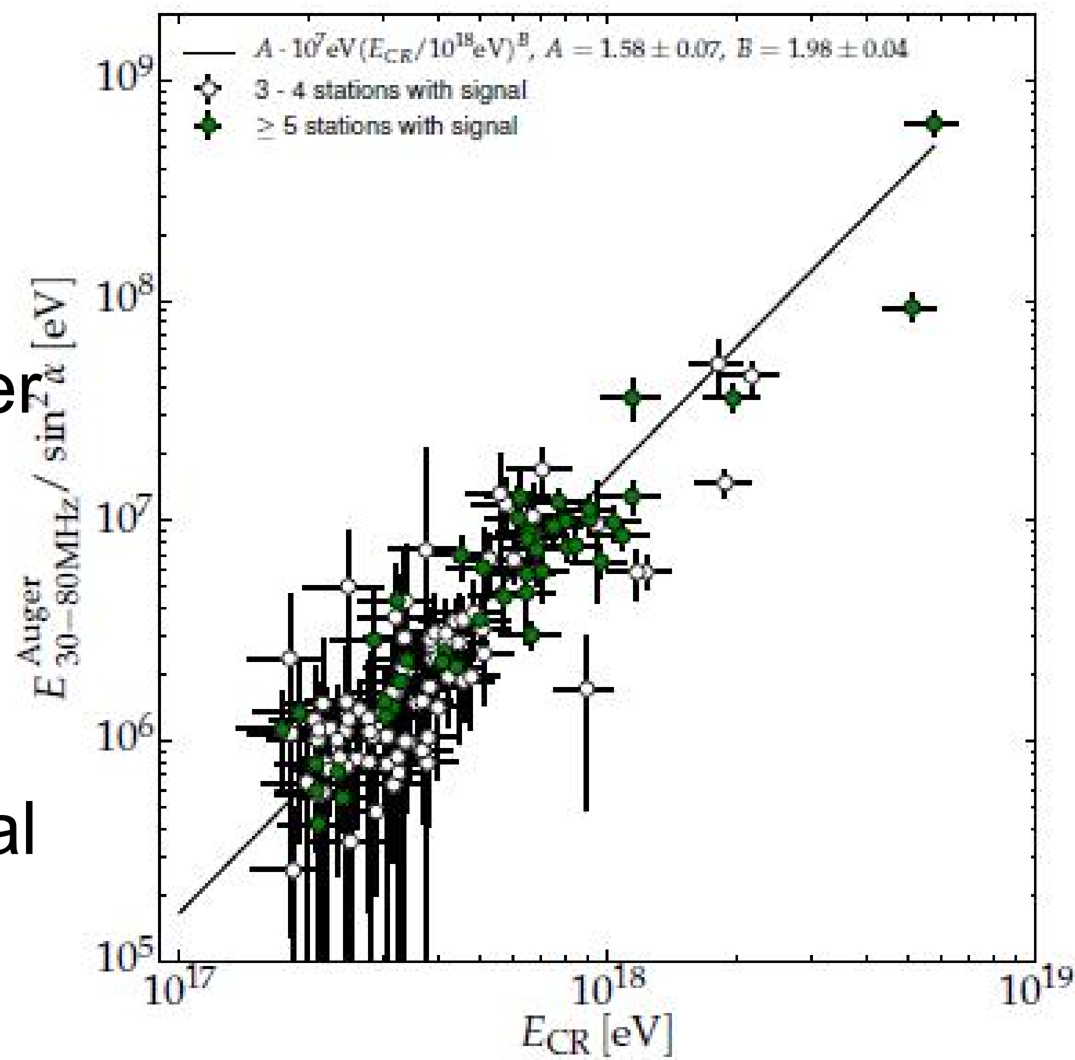
Future:TAx4



- TAx4 now under construction: 500 new detectors with 2.08 km spacing, 2 new FD stations
- Will double TA data sample by mid-2021

Future: UHECR @ radio. AERA

- Auger Engineering Radio Array
- 153 stations covering 17 km^2
- Self-trigger, triggers from other detectors
- 100% duty cycle
- Especially useful for horizontal (neutrino) showers
- Energy calibration



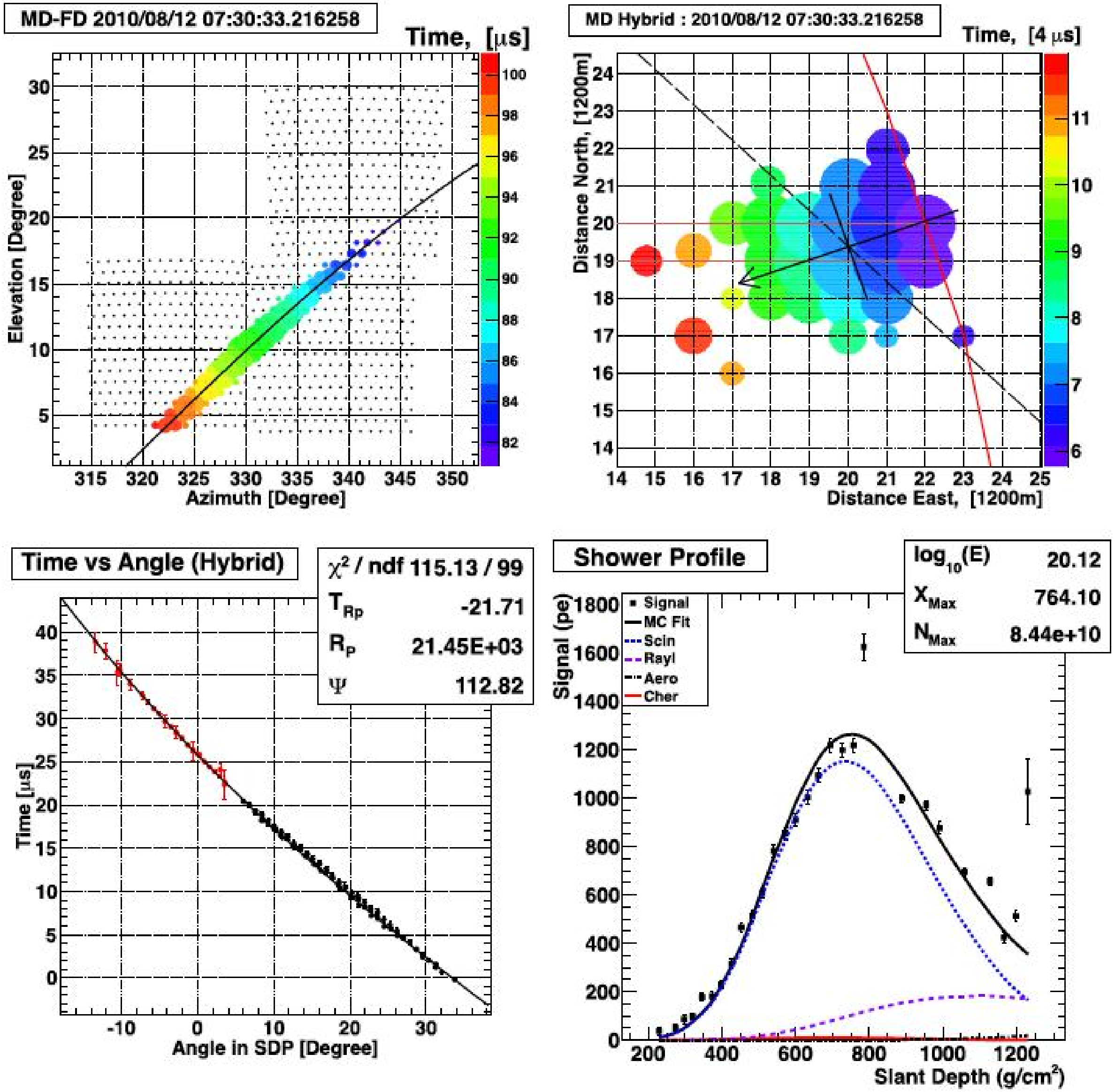
Aab et al., PRL2016

THANK YOU!

Backup

Backup

TA: hybrid event



- E=1.3x10^{20} eV
- Θ=55.7○

l TA SD spectrum (9 years of data)