A personal decadal survey in ultrahigh-energy cosmic-ray observatories

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The Hakubi Center for Advanced Research, Kyoto University
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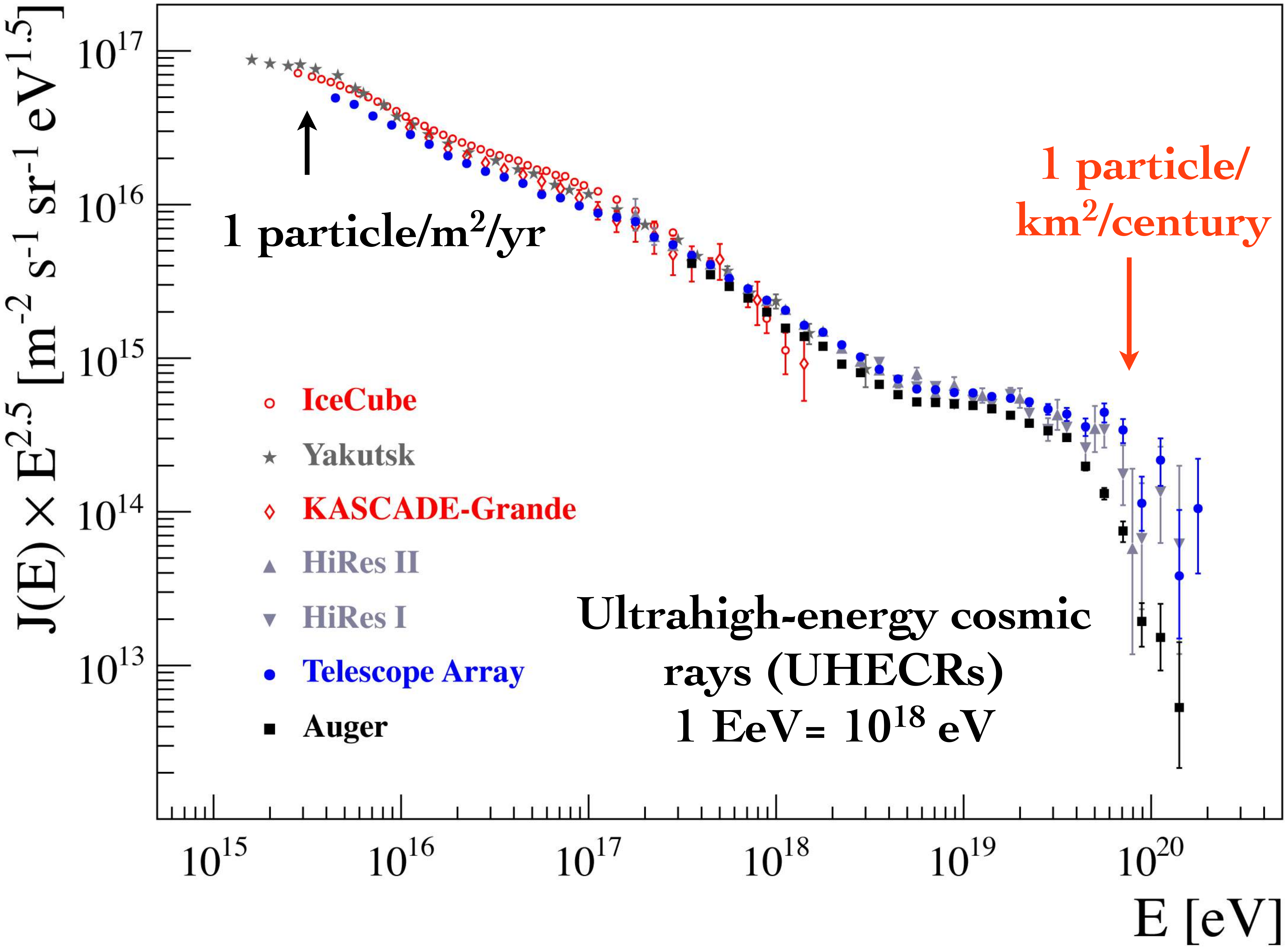
Due to a significantly improved statistics of ultrahigh-energy cosmic rays (UHECRs) by the Telescope Array Experiment and Pierre Auger Observatory, we firmly confirmed a suppression of the energy spectrum at the highest energies and observed intriguing large-scale anisotropies in arrival directions of UHECRs. We also encountered a gradually transition to a heavier composition, a deficit of the number of muons in simulations and a lack of desired small-scale anisotropies.

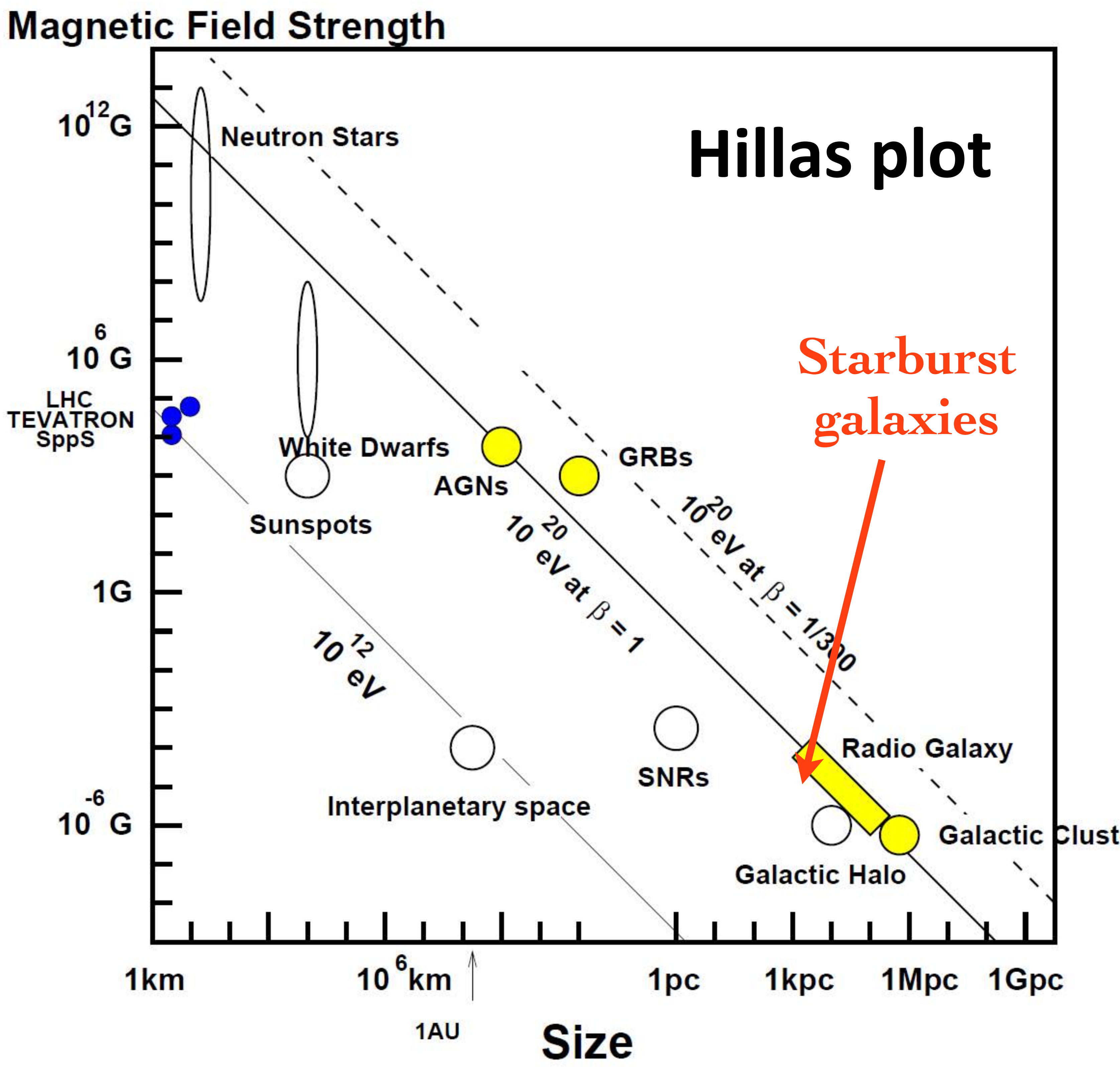
In this talk, I highlight recent results of the two observatories including on-going updates and then address scientific goals and requirements for future UHECR observatories in next decade. I introduce three ideas as a personal decadal survey: ① **a fine-pixel fluorescence telescope for low-energy extension**, ② **a layered Water-Cherenkov detector array** for sub-EeV anisotropy and ultrahigh-energy photon search, and ③ **a low-cost fluorescence telescope array** suitable for measuring the properties of UHECRs with an unprecedented aperture.

Energy spectrum of cosmic rays

$E^{2.5}\, J(E)$



V. Verzi et al., PTEP, 2A103 (2017)



$$E_{\max} \leq \gamma e Z B R$$

γ : Lorentz factor of shock

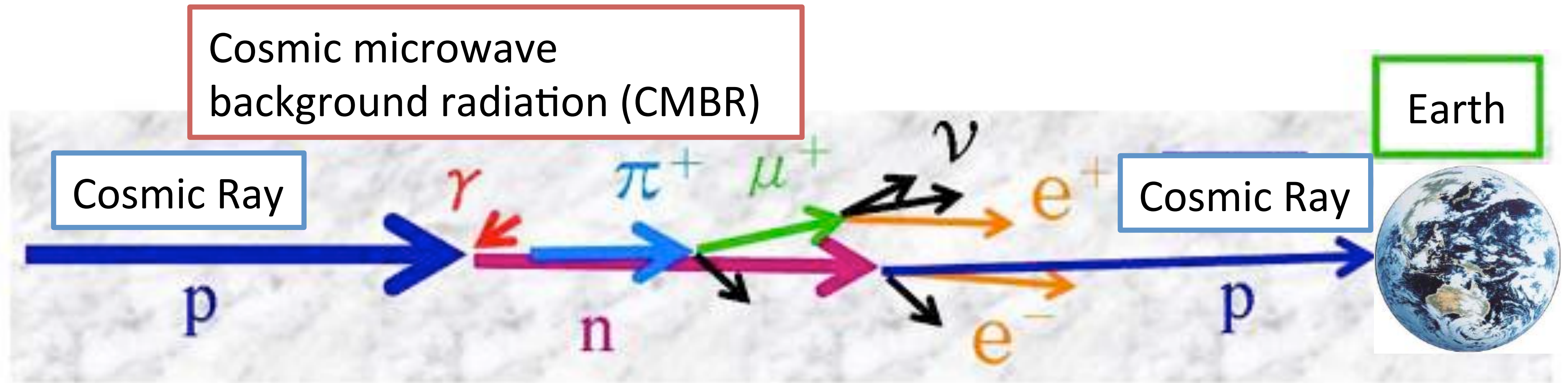
Z : atomic number

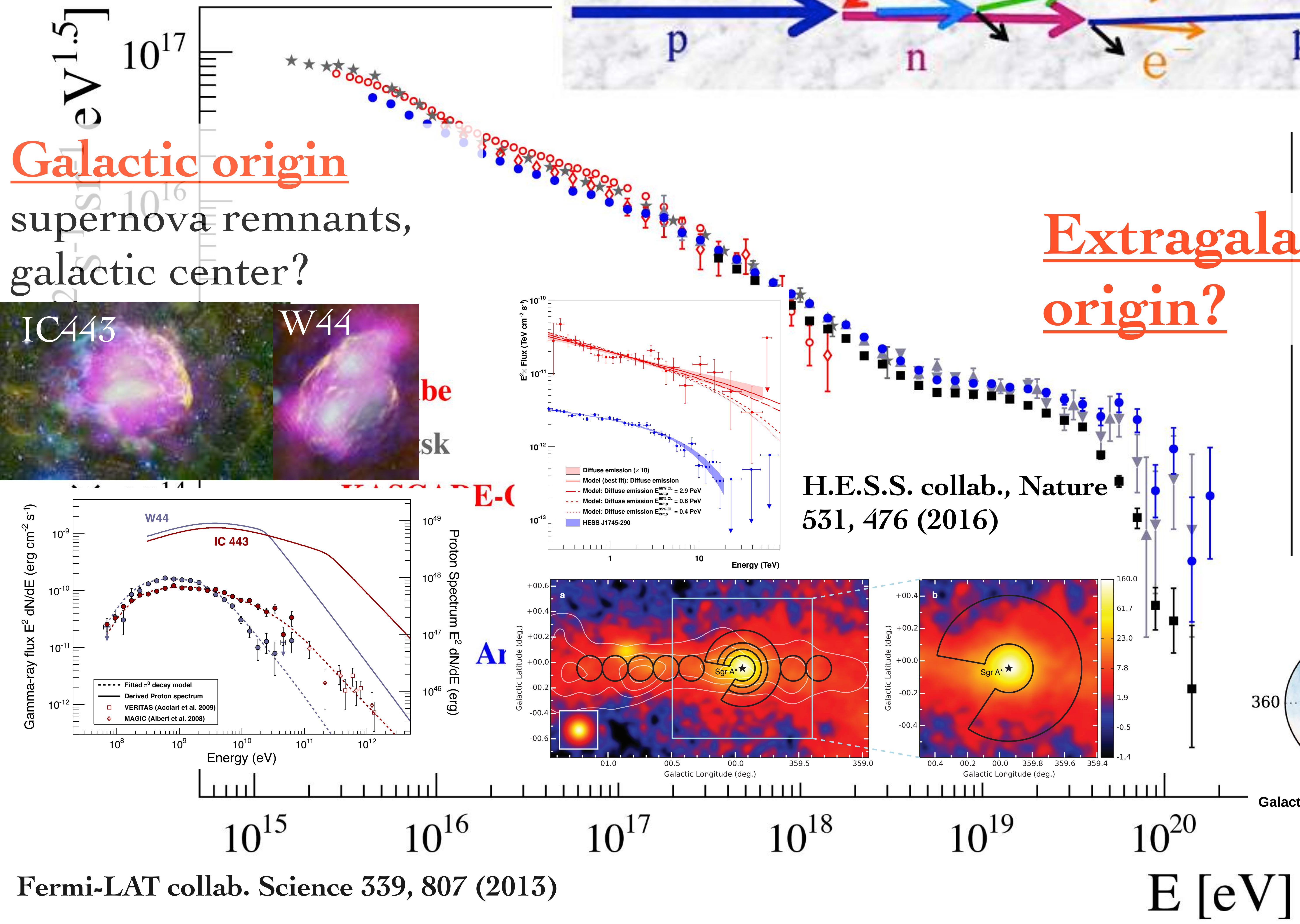
B : magnetic field strength

R : size

A. M. Hillas, Astron. Astrophys., 22, 425 (1984)

Energy spectrum of cosmic rays





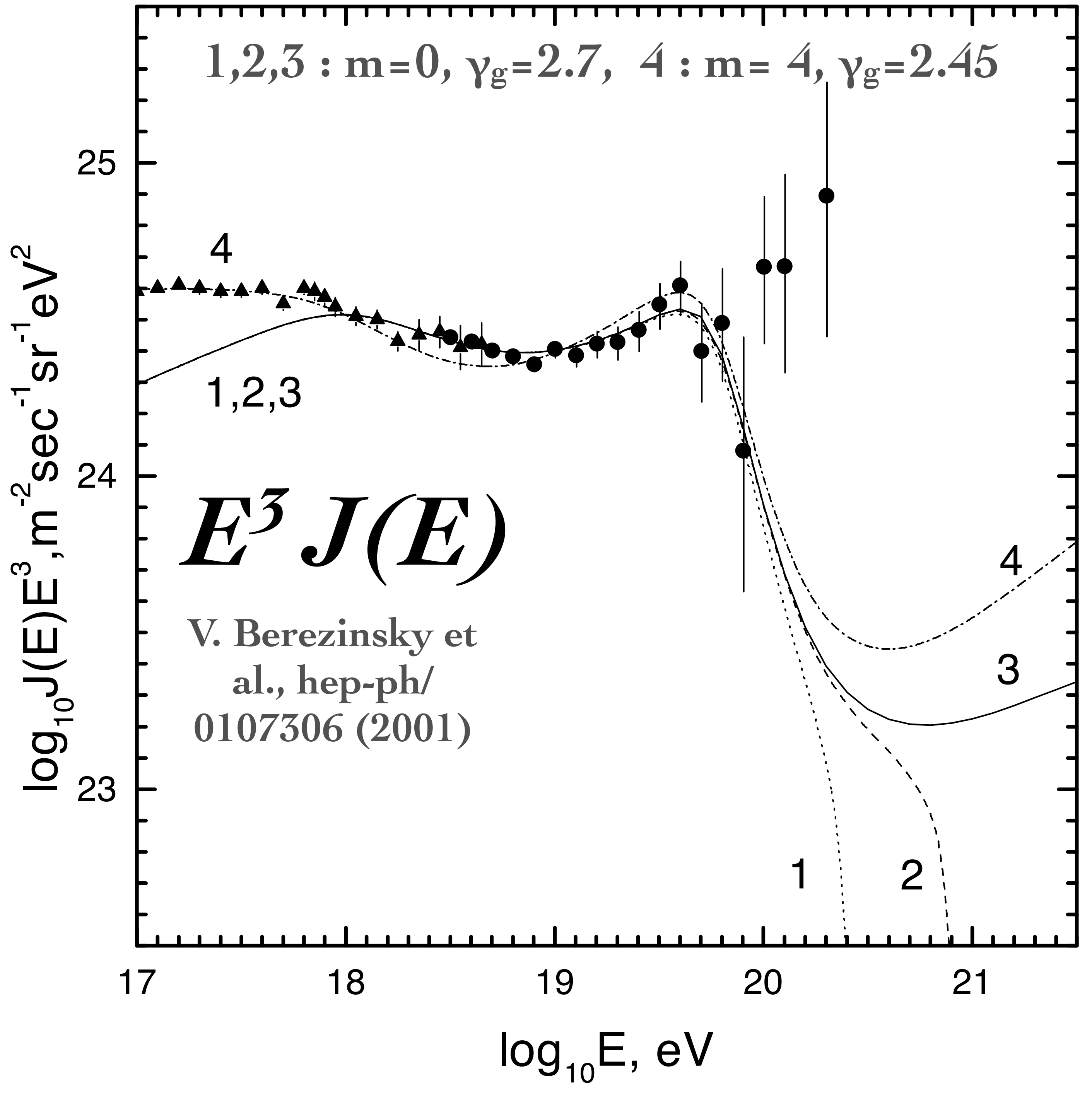
Galactic origin

supernova remnants, galactic center?

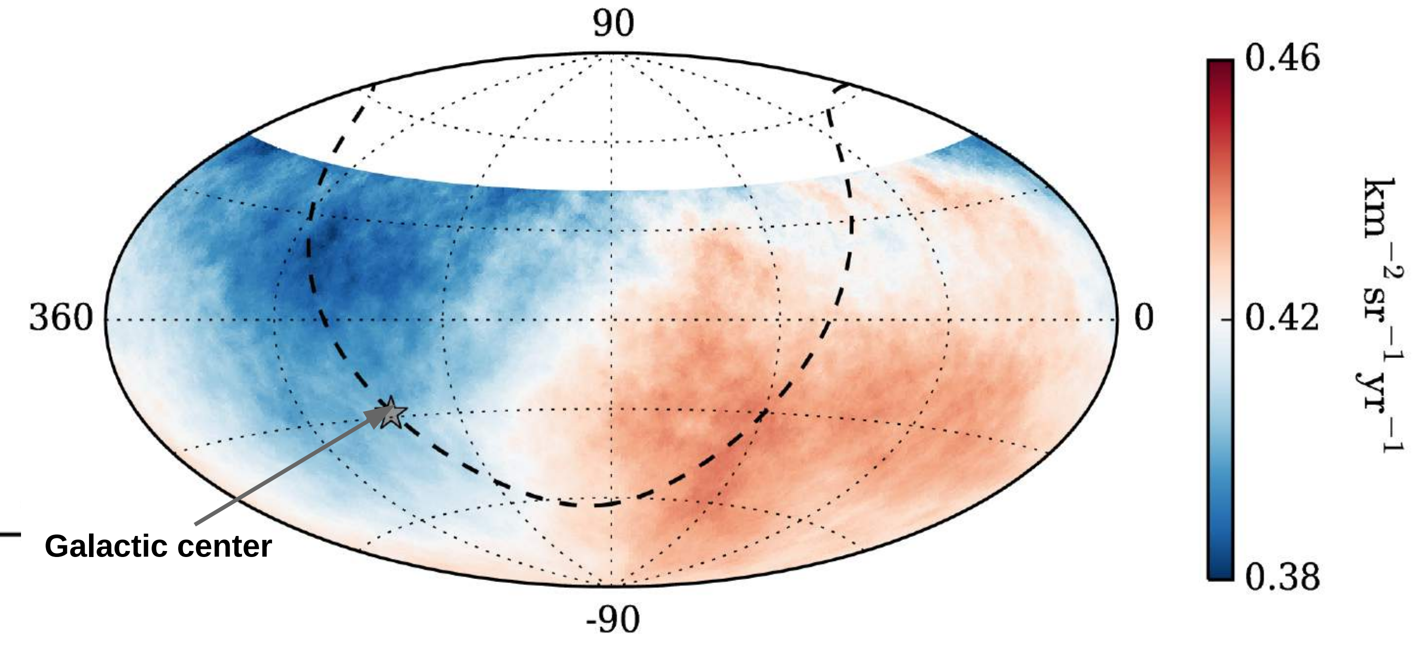
Fermi-LAT collab. Science 339, 807 (2013)

H.E.S.S. collab., Nature 531, 476 (2016)

Extragalactic origin?



E > 8 EeV



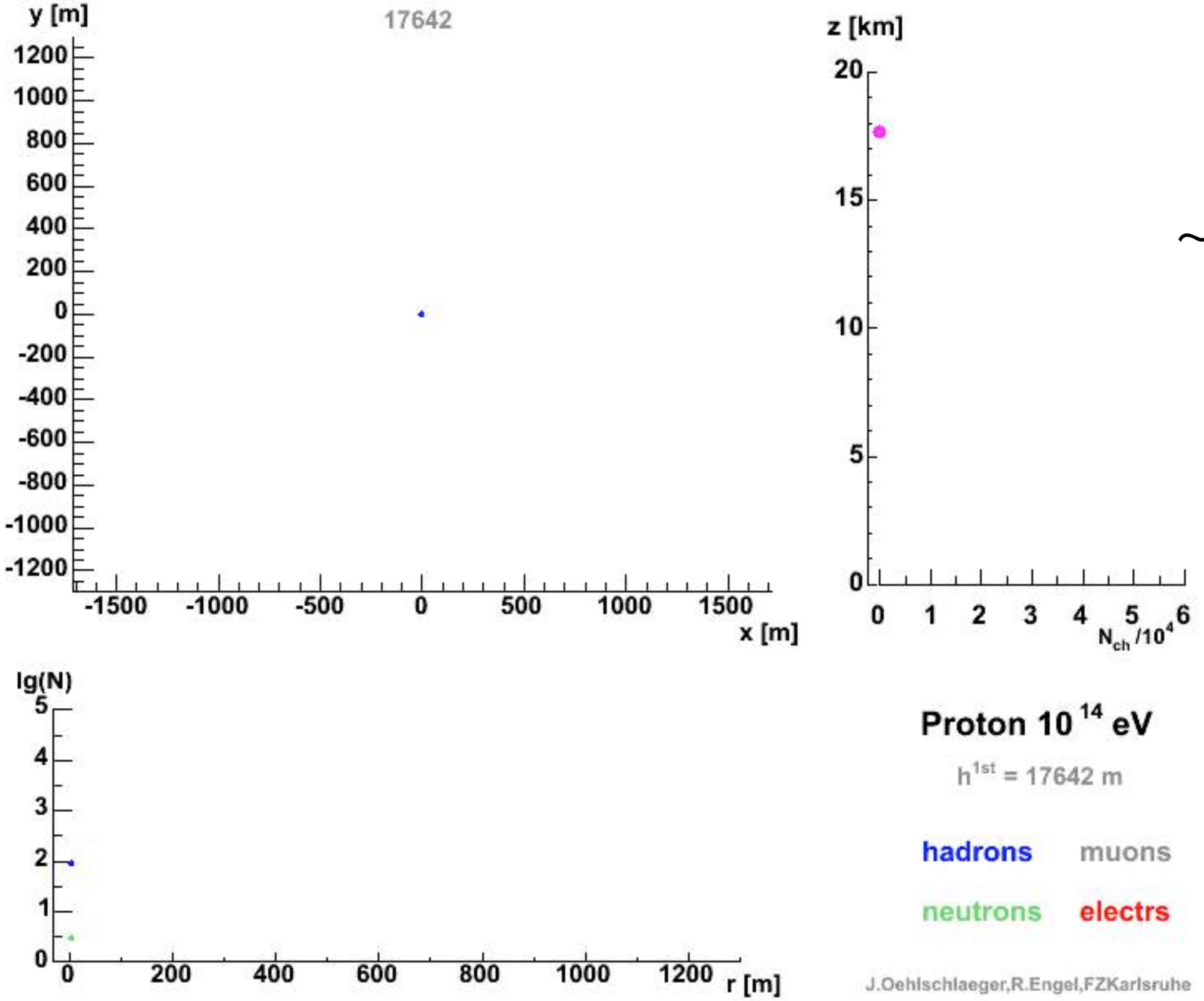
Where is the maximum energy of cosmic ray, *E*max?

Pierre Auger Collab. Science 357, 1266 (2017)

V. Verzi et al., PTEP, 2A103 (2017)

UHECR detections

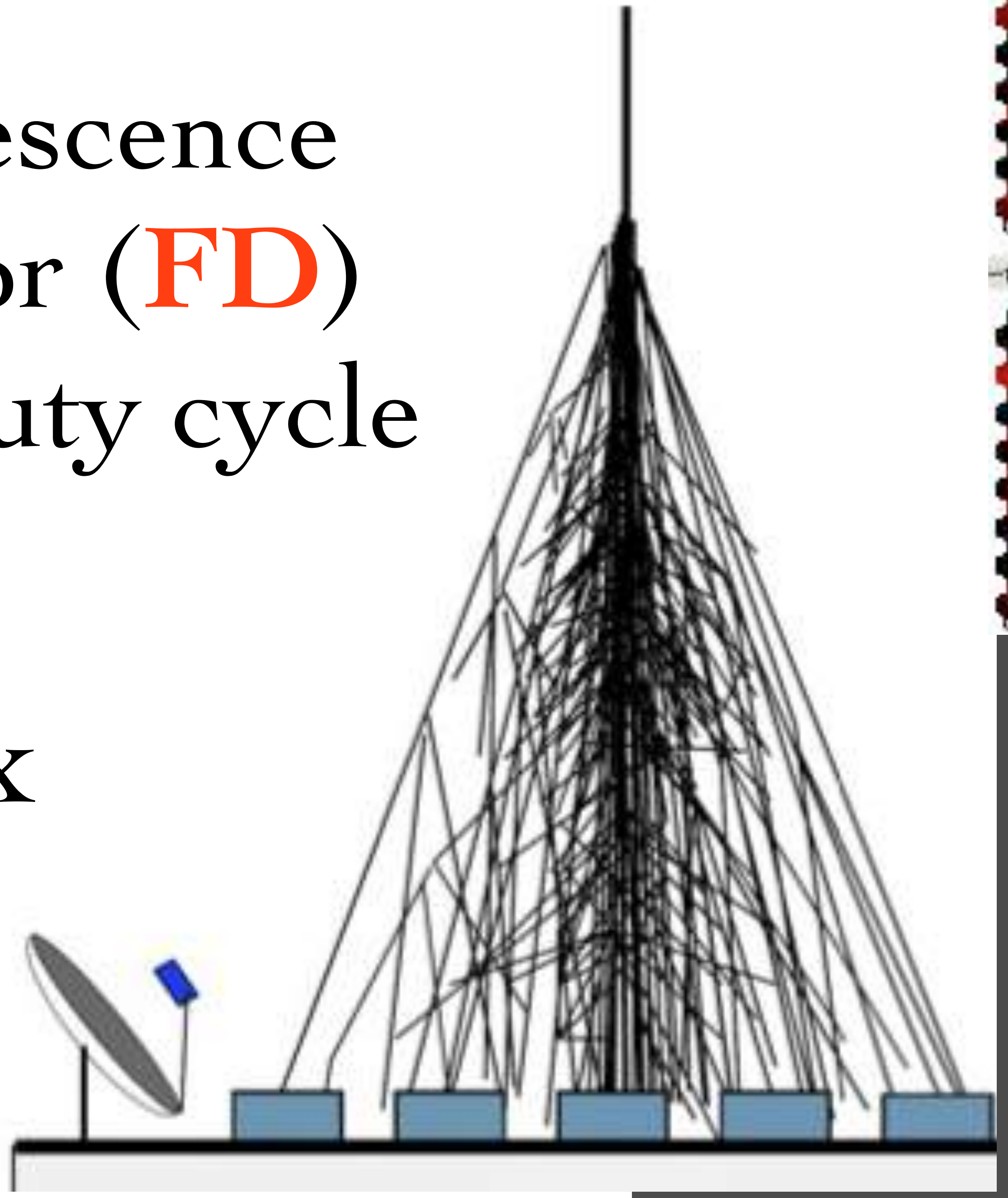
Longitudinal Development

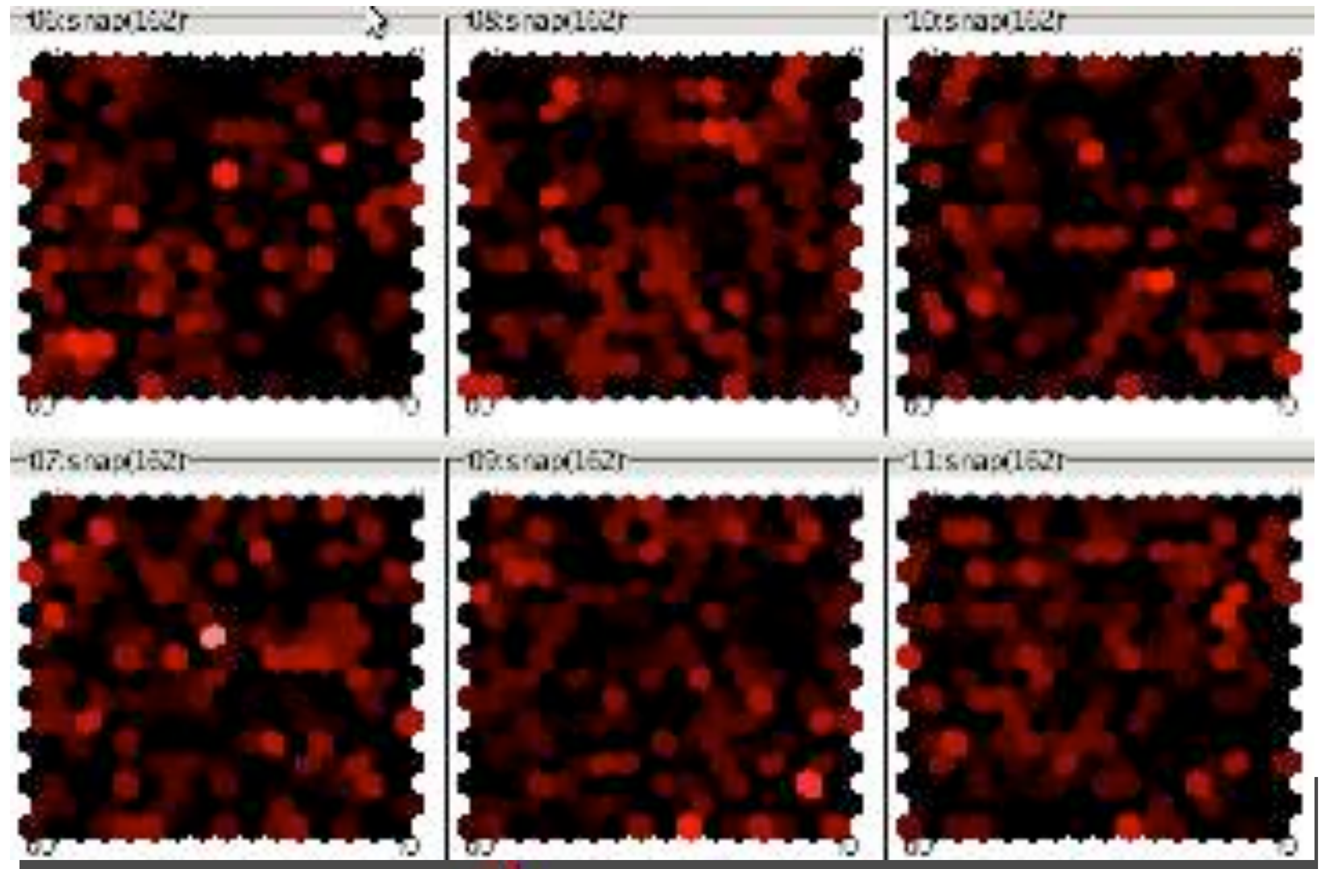


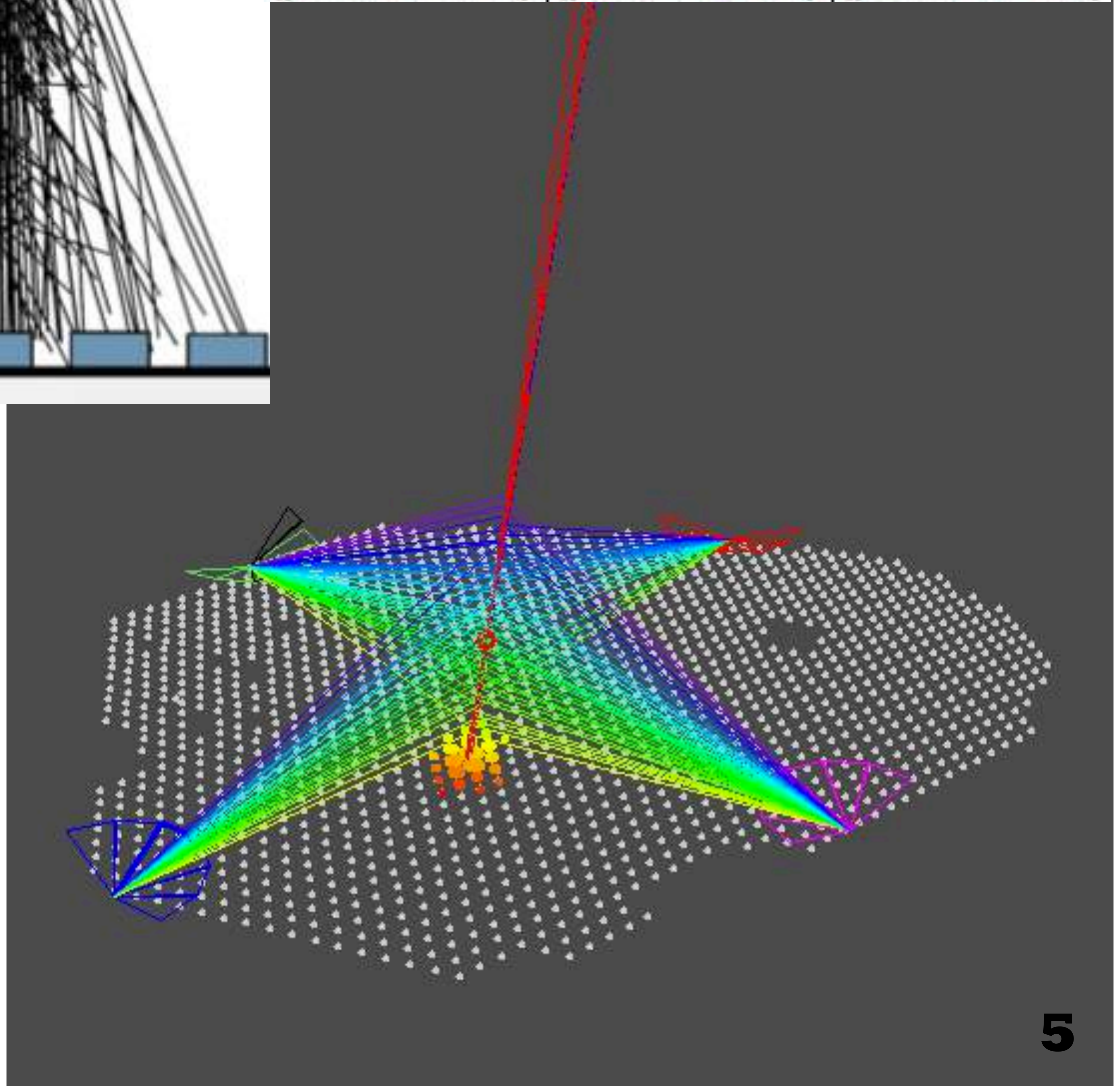
Lateral Density Distribution

Fluorescence detector (**FD**)
~10% duty cycle

Xmax







Surface detector array (**SD**)
~100% duty cycle

CORSIKA software https://web.ikp.kit.edu/corsika/movies

UHECR observatories

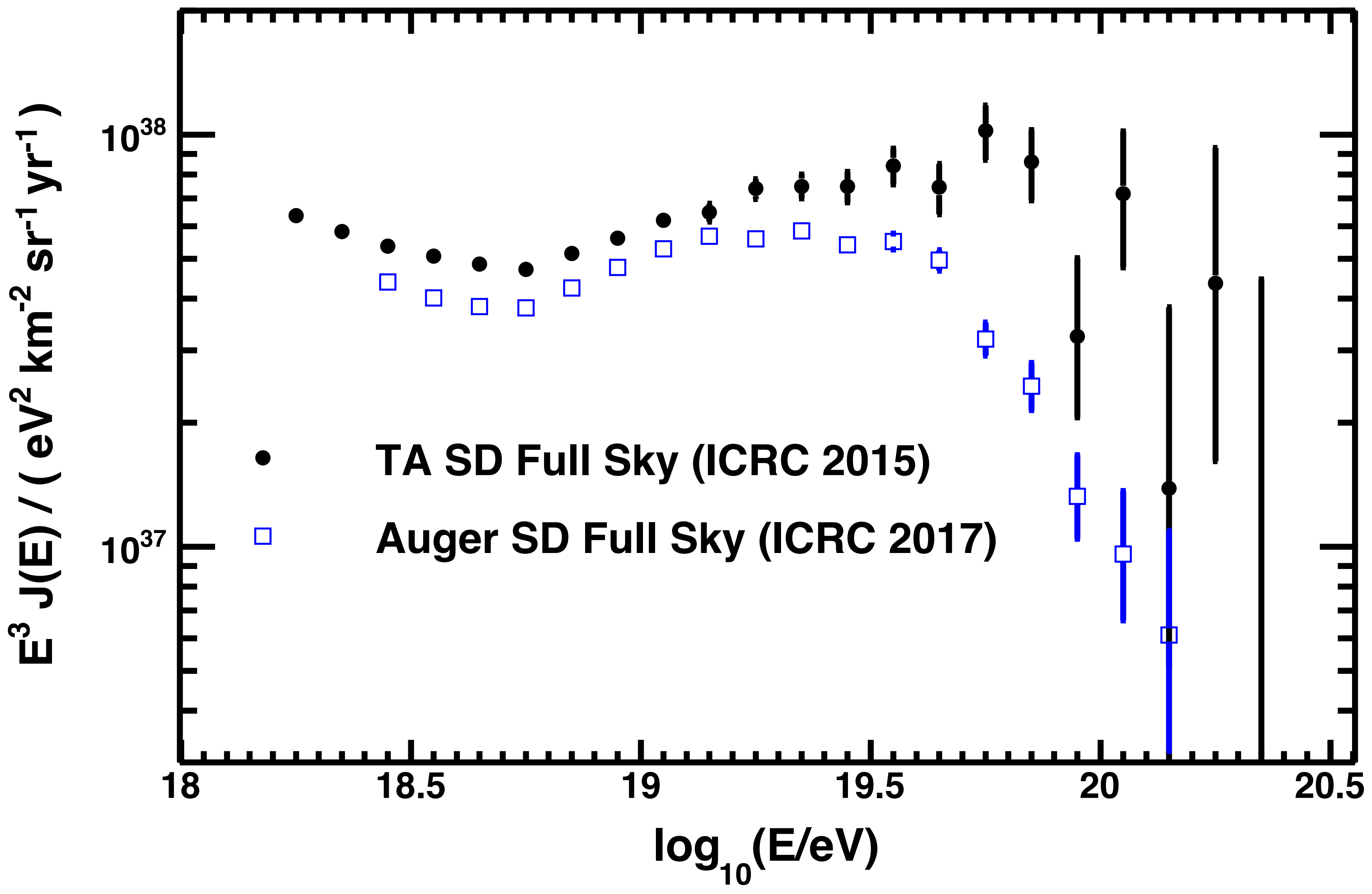
Google Earth

- Telescope Array Experiment (TA)
  - Utah, USA
  - 700 km^2
    - TA×4 → 3,000 km^2

- Pierre Auger Observatory (Auger)
  - Malargue, Argentina
  - 3,000 km^2
    - AugerPrime: additional scintillator

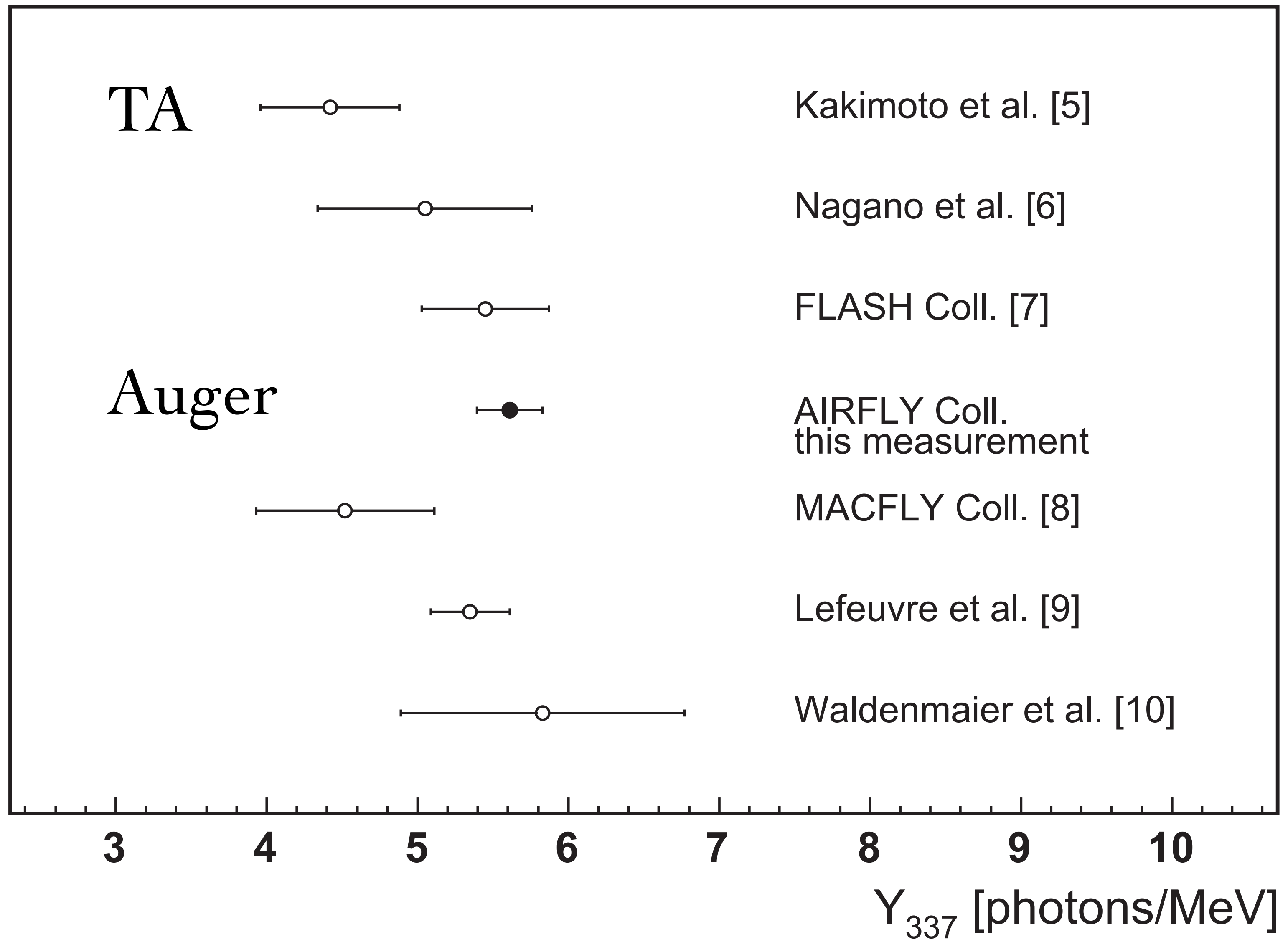
Energy spectrum at the highest energies

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



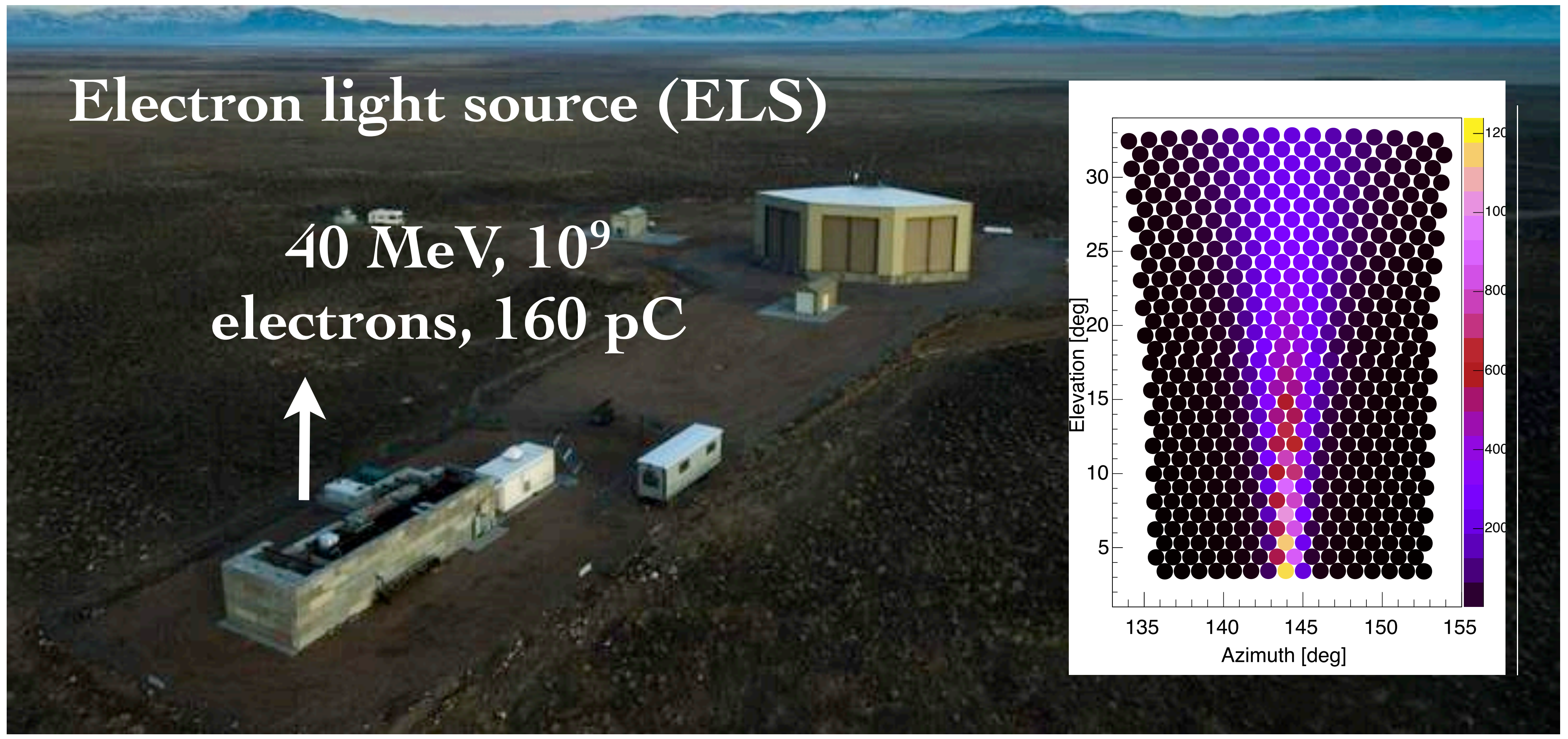
D. Ivanov et al. (Spectrum working group), ICRC 2017

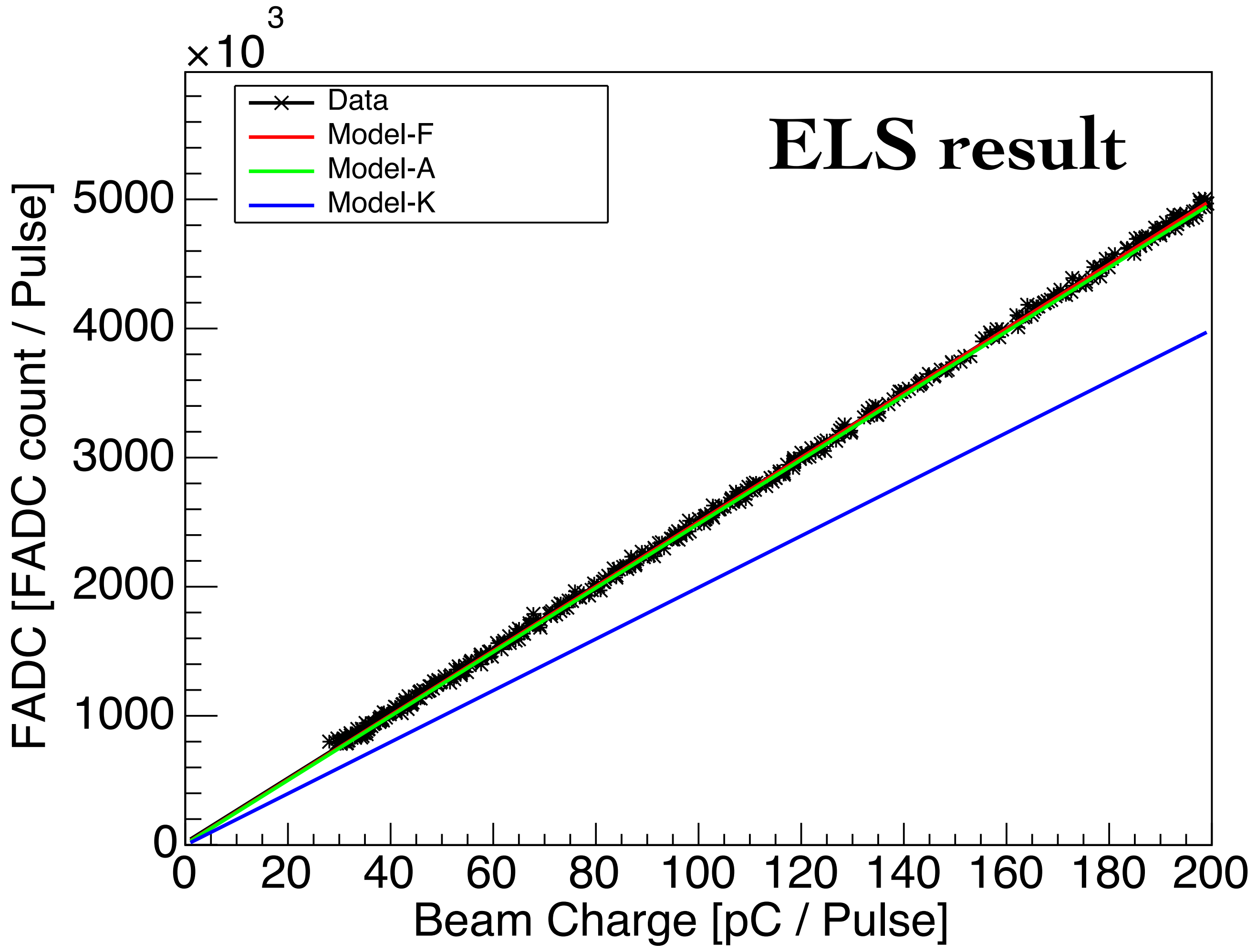
Fluorescence yield (FY)



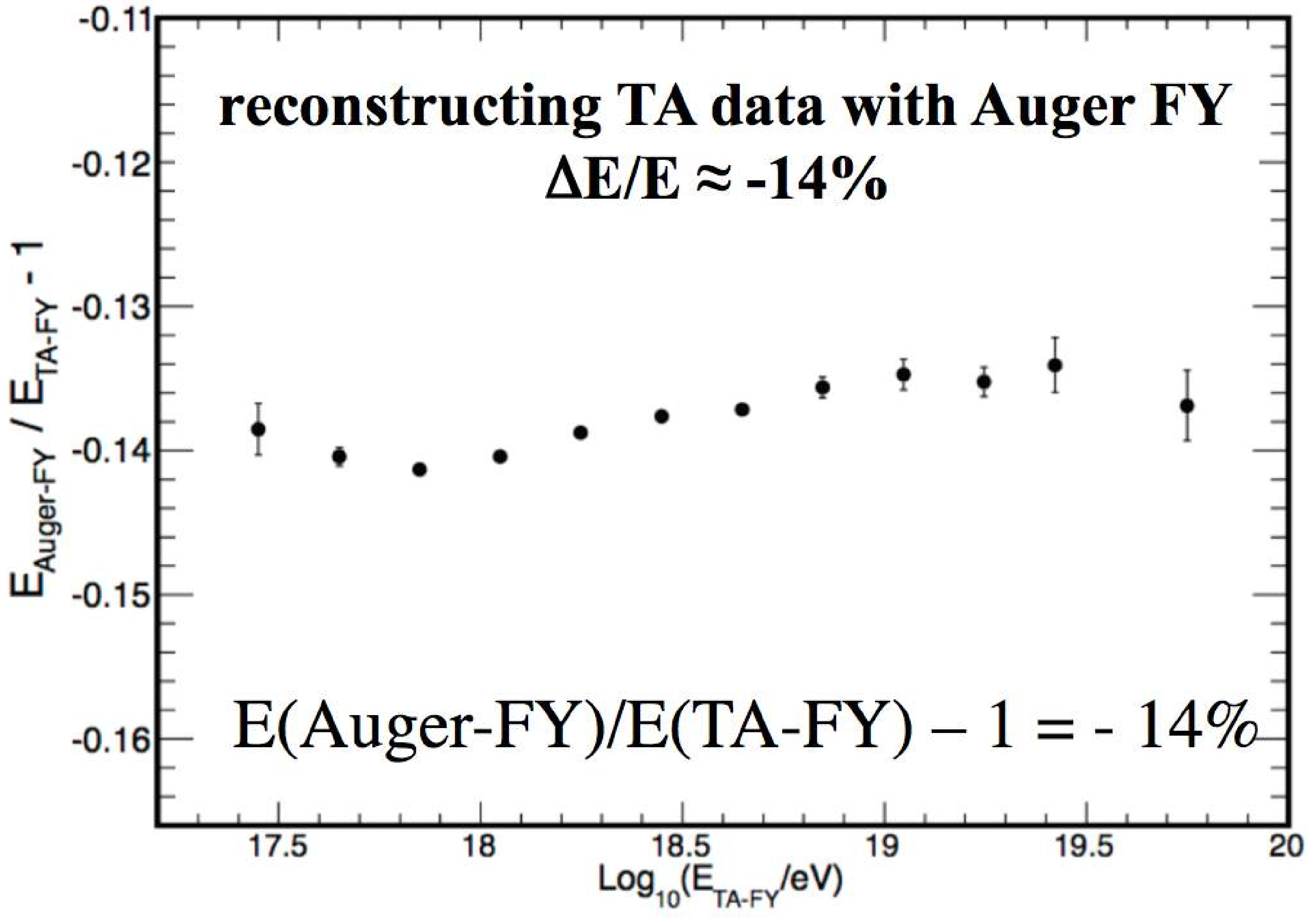
M. Ave et al. Astropart.Phys. 42 (2013) 90–102

Precision measurement of fluorescence technique



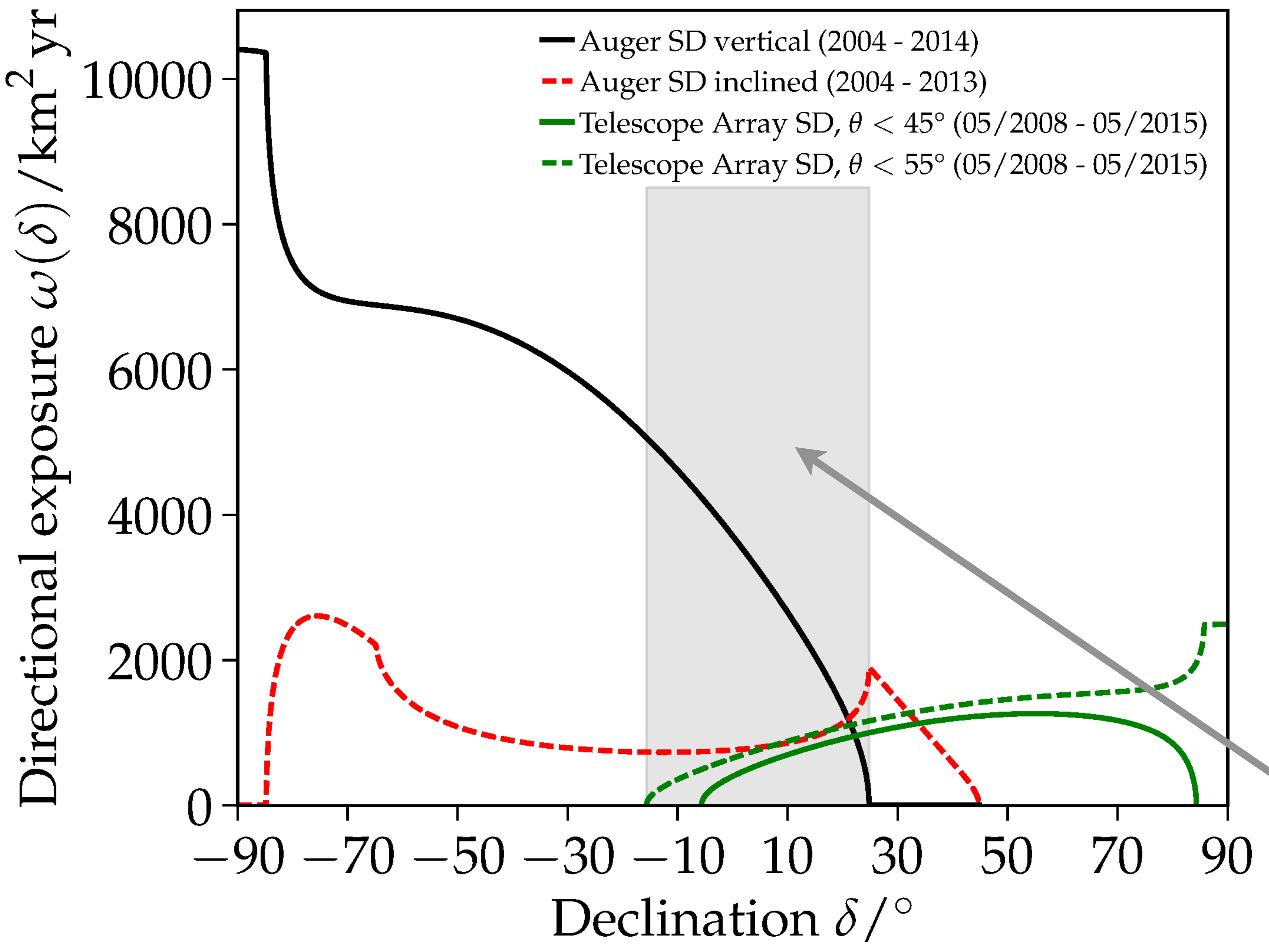


BK Shin et al., PoS (ICRC2015) 640

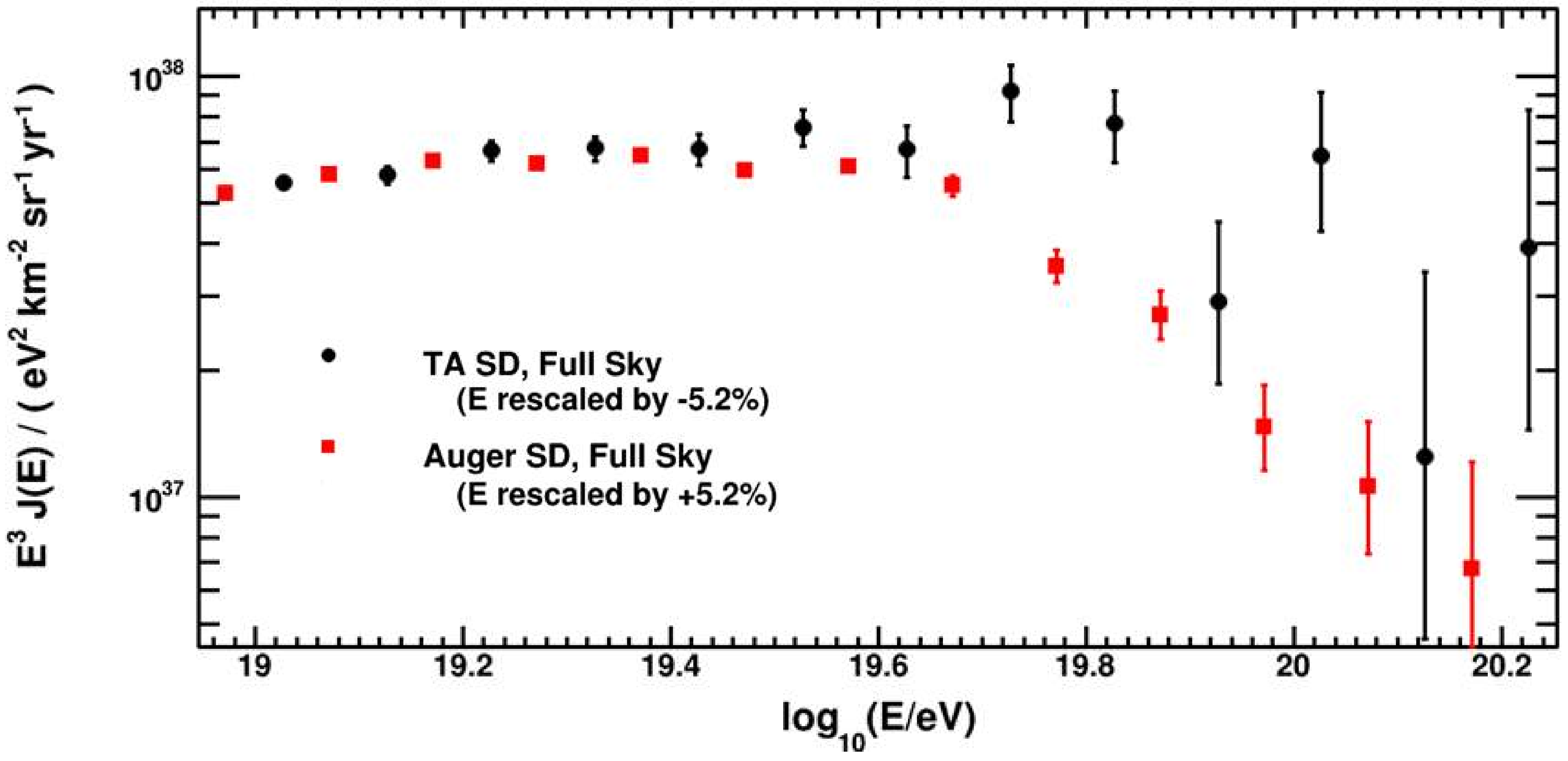


V. Verzi et al., PTEP. 12A103 (2017),
T. Fujii et al., Proc of ICRC 2017

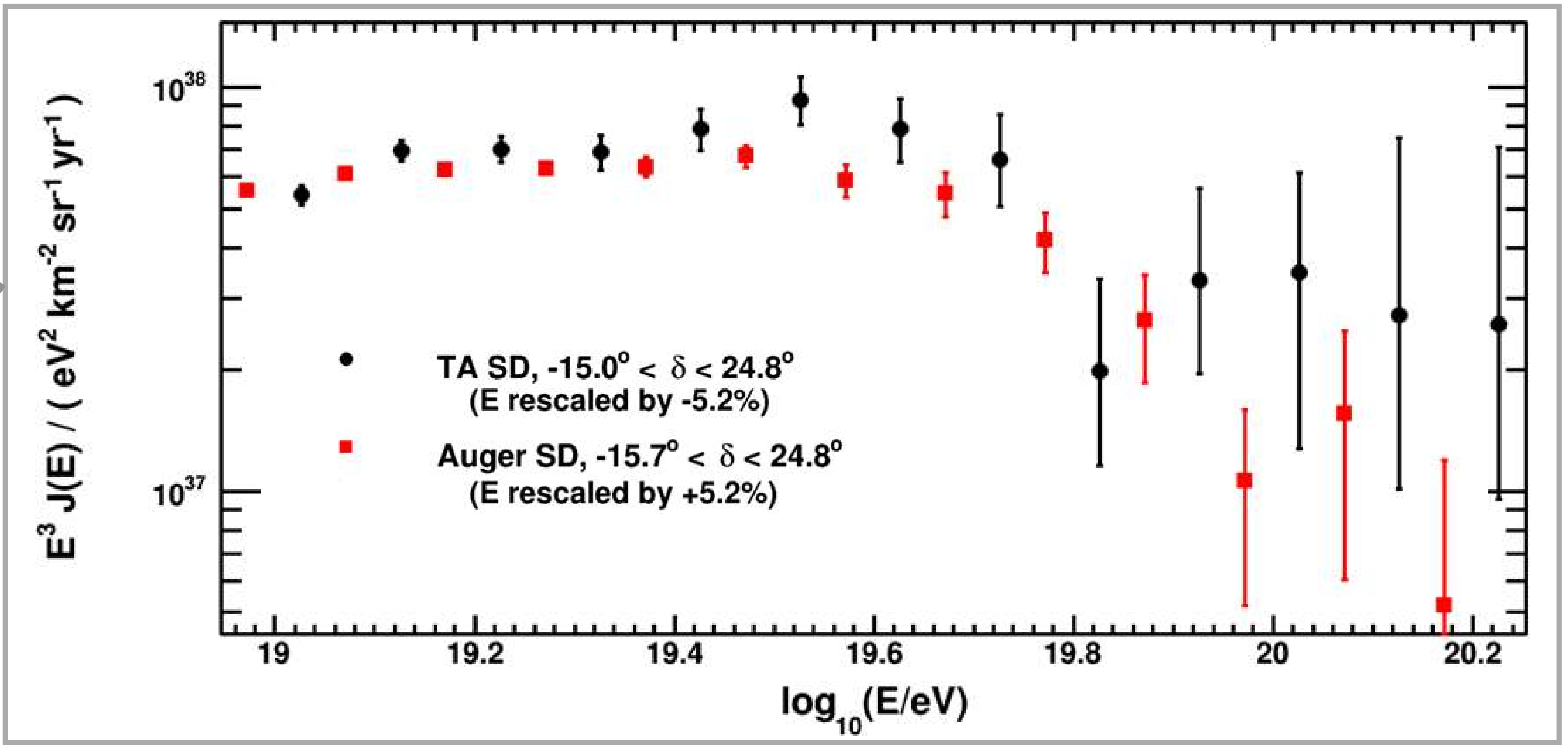
Declination dependence of energy spectra



Entire sky of TA and Auger

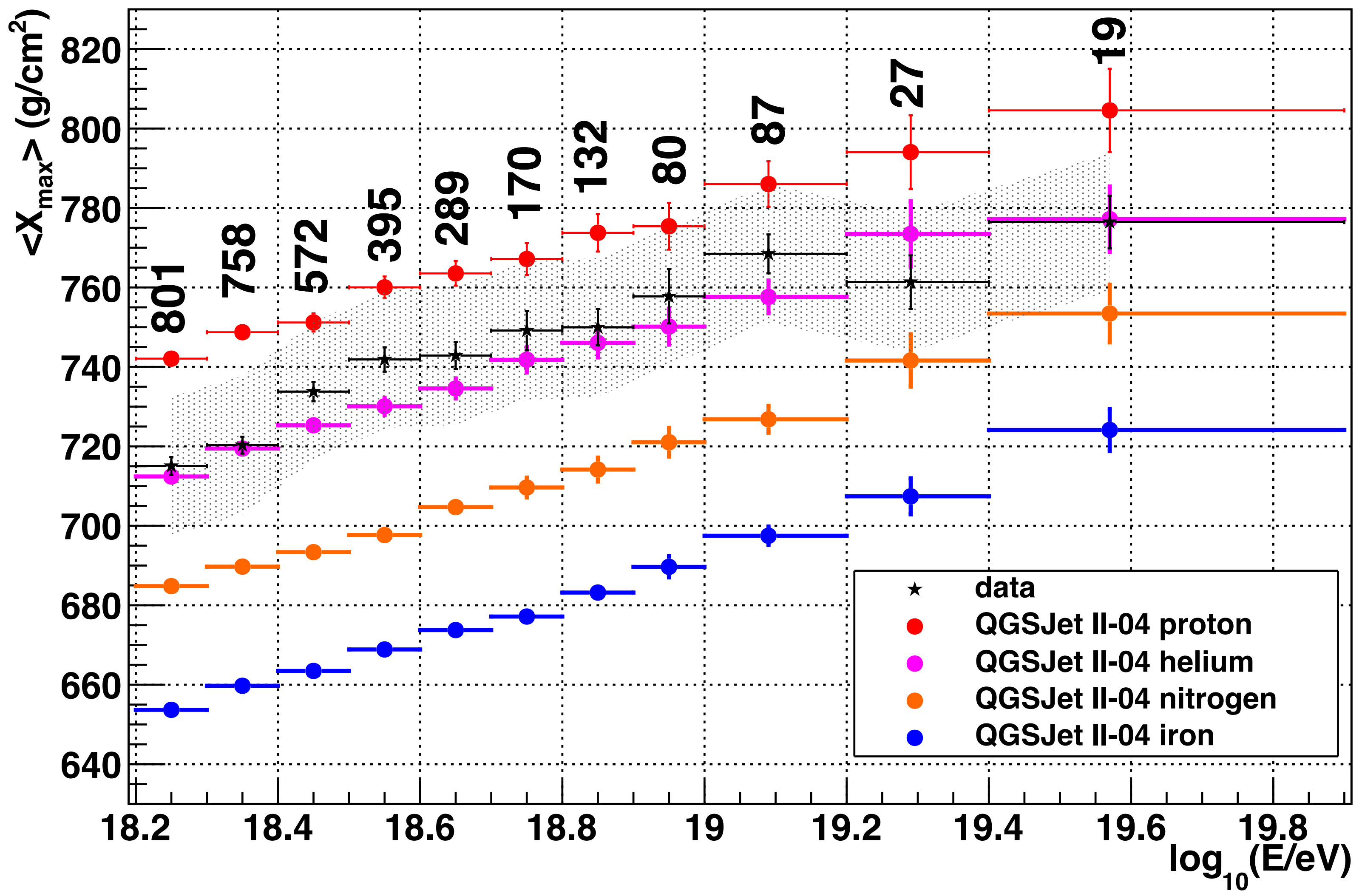


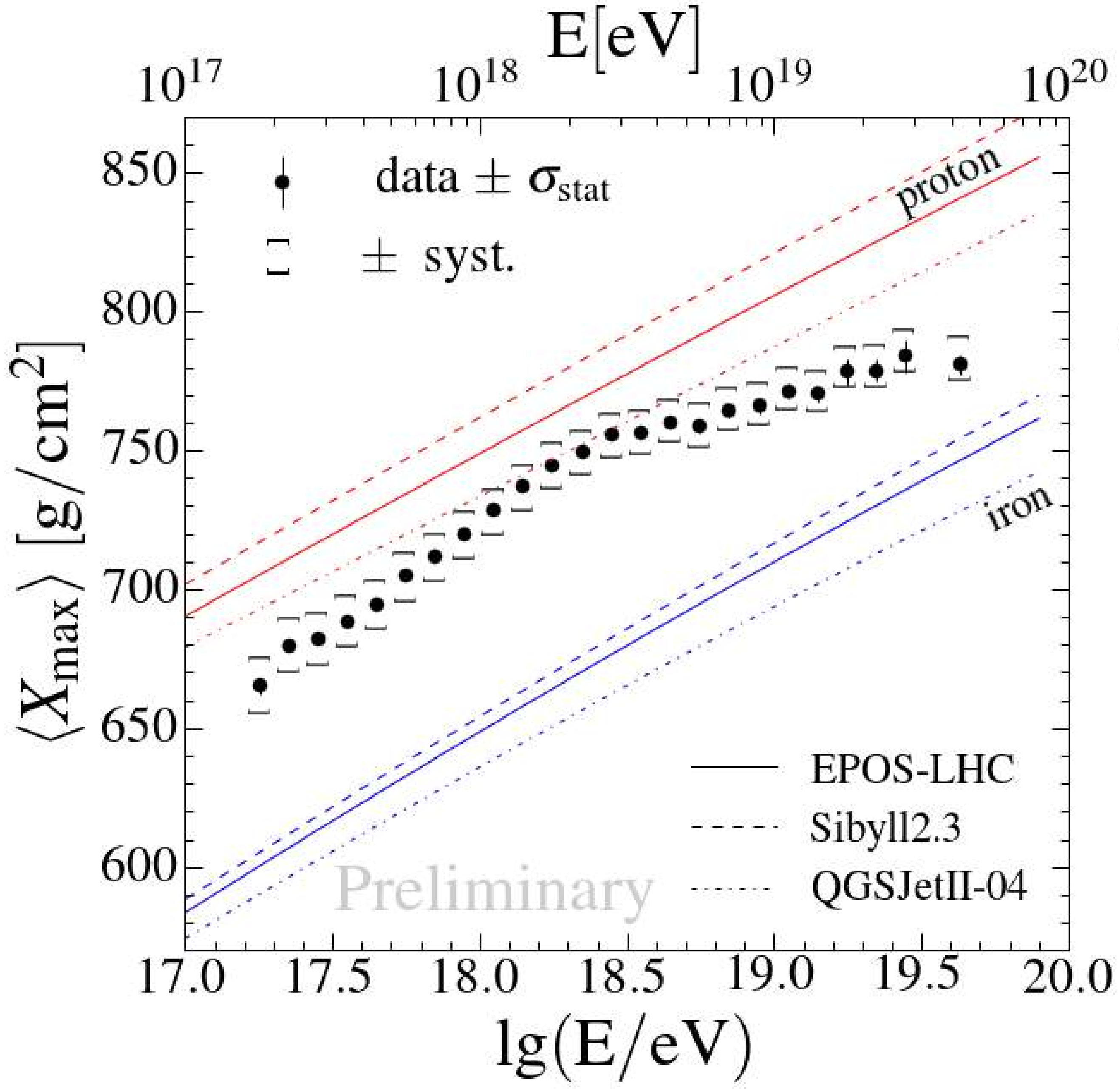
Common declination band



Y. Tsunesada, D. Ivanov in ICRC 2017

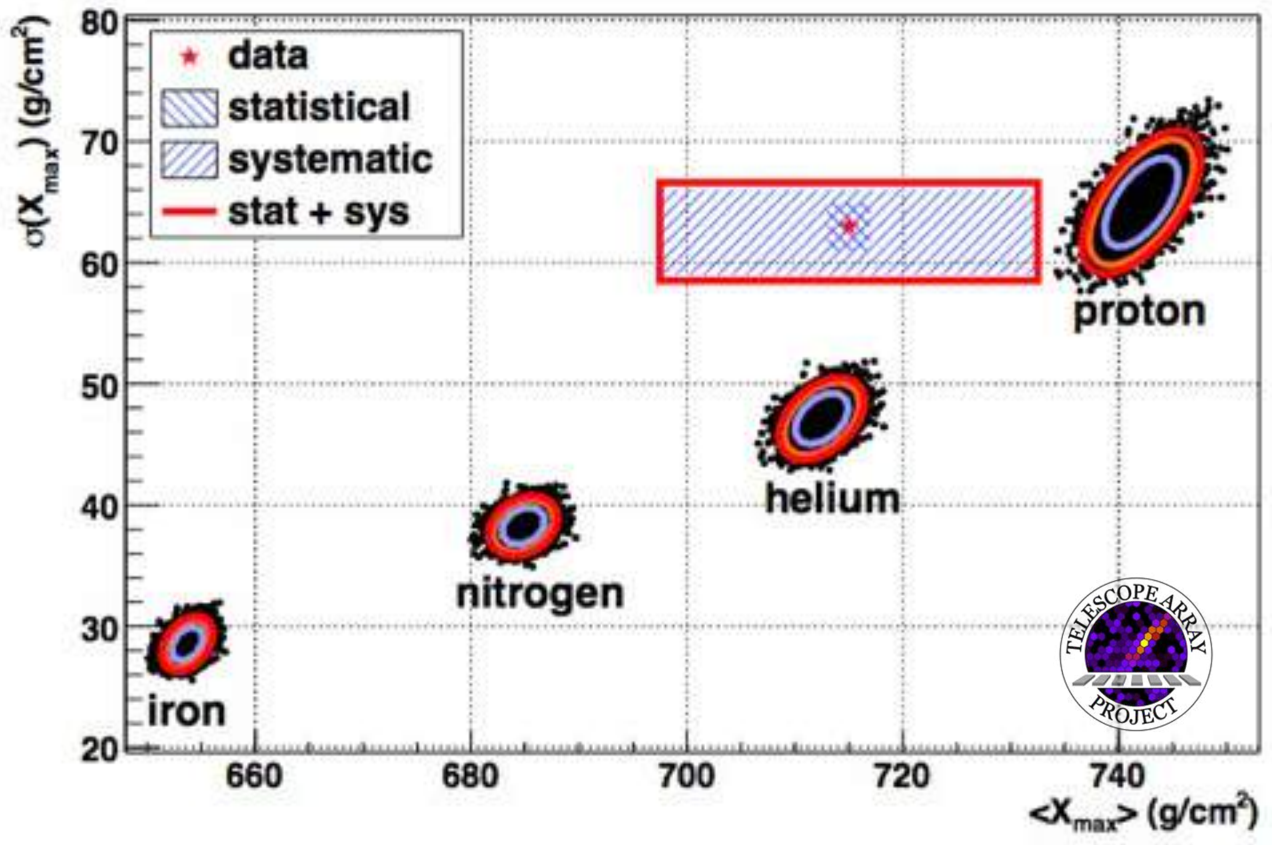
Mass composition using X_{max}





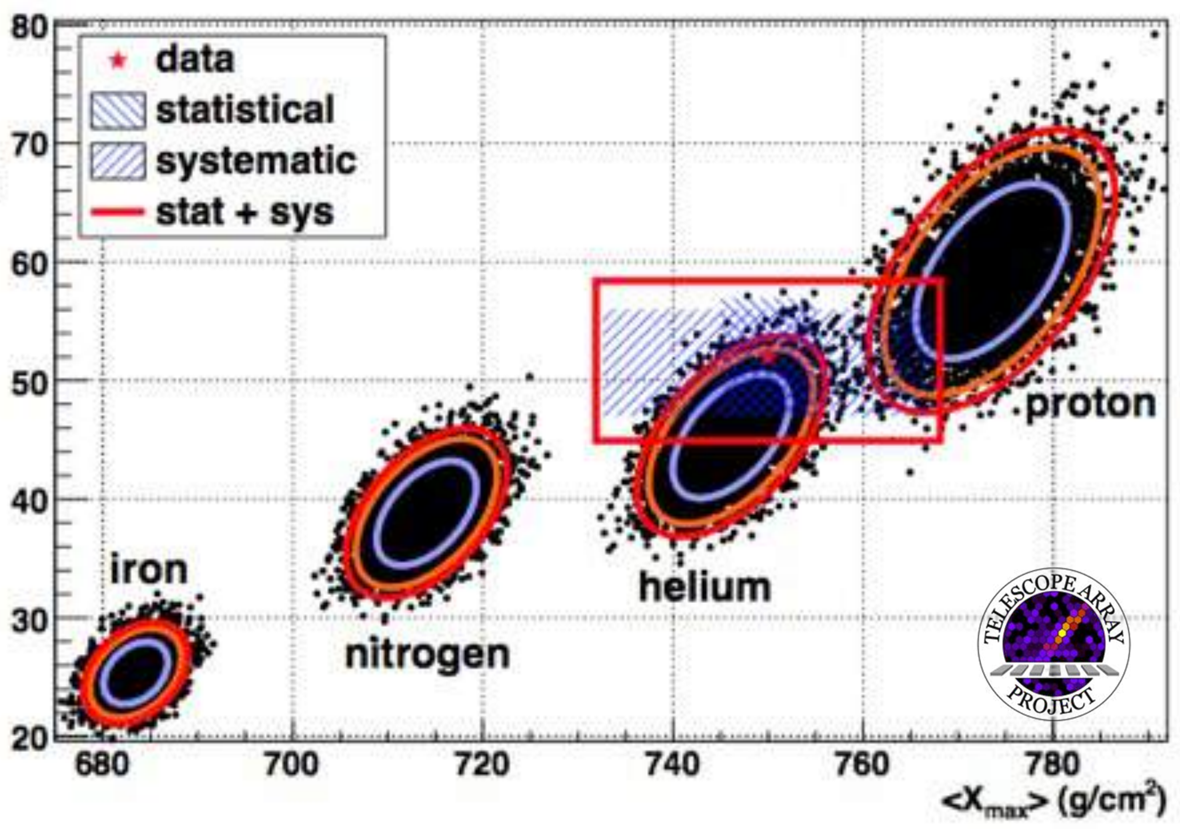
Proton dominated at $10^{18.4}$ eV,
Narrowing σ(Xmax)

18.2 ≦ log(E) < 18.3, N = 801



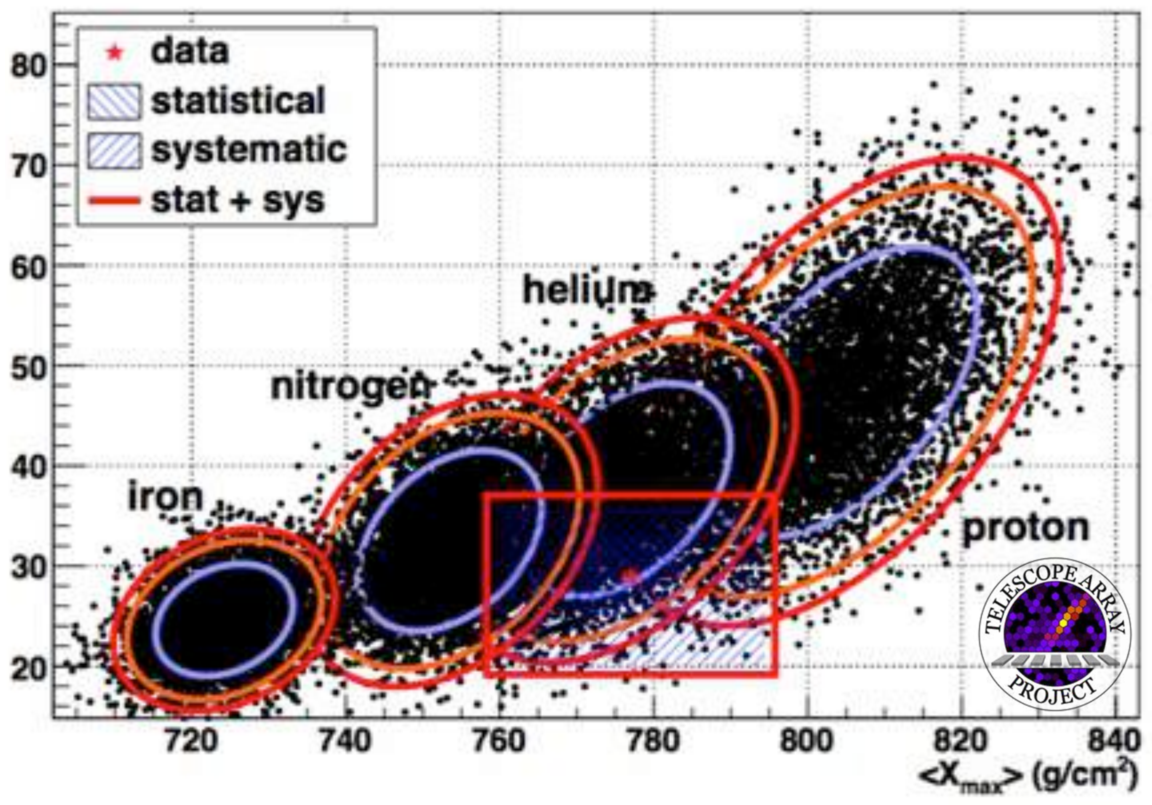
(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

18.8 ≦ log(E) < 18.9, N = 132

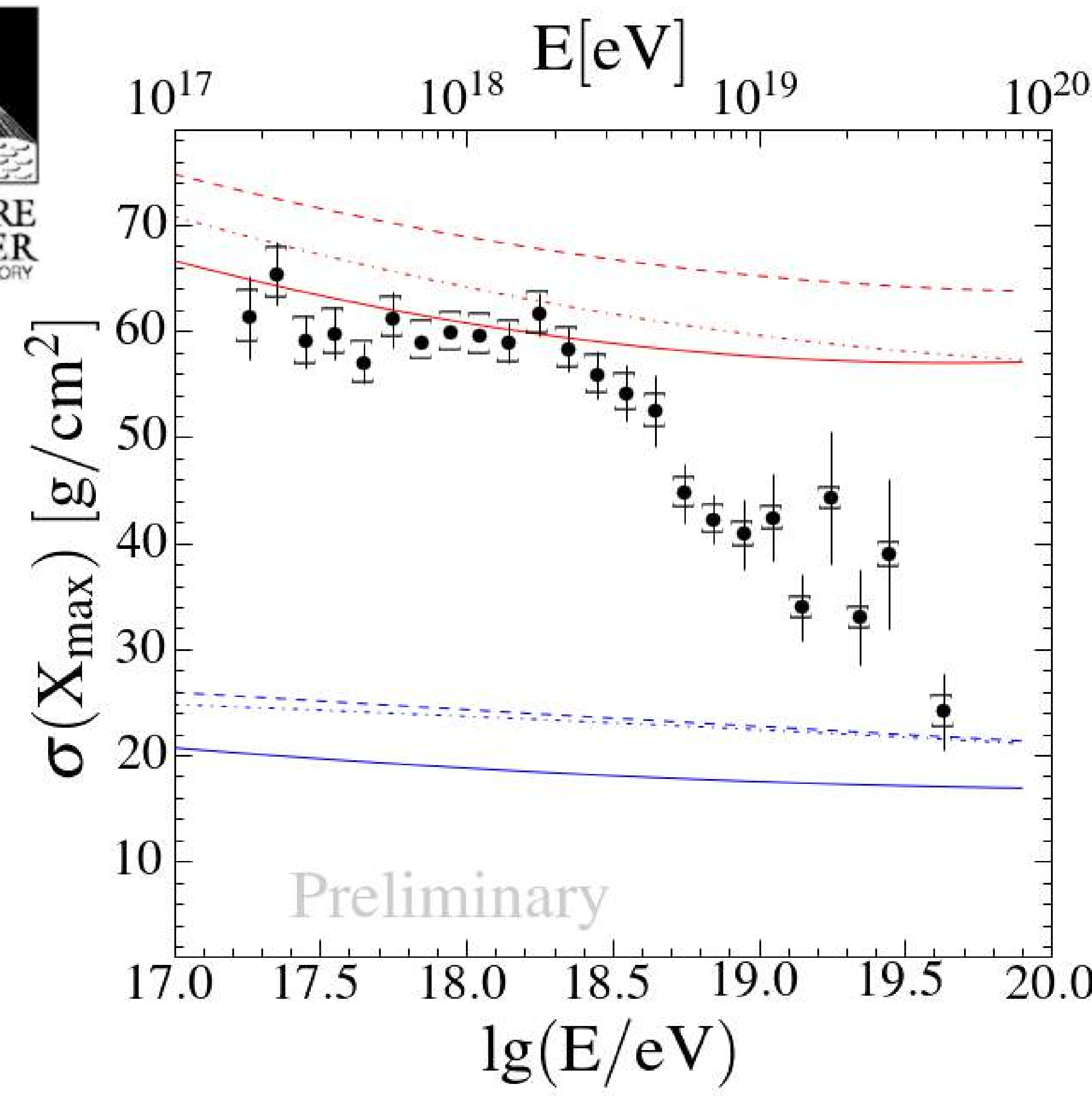


(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$

19.4 ≦ log(E) < 19.9, N = 19



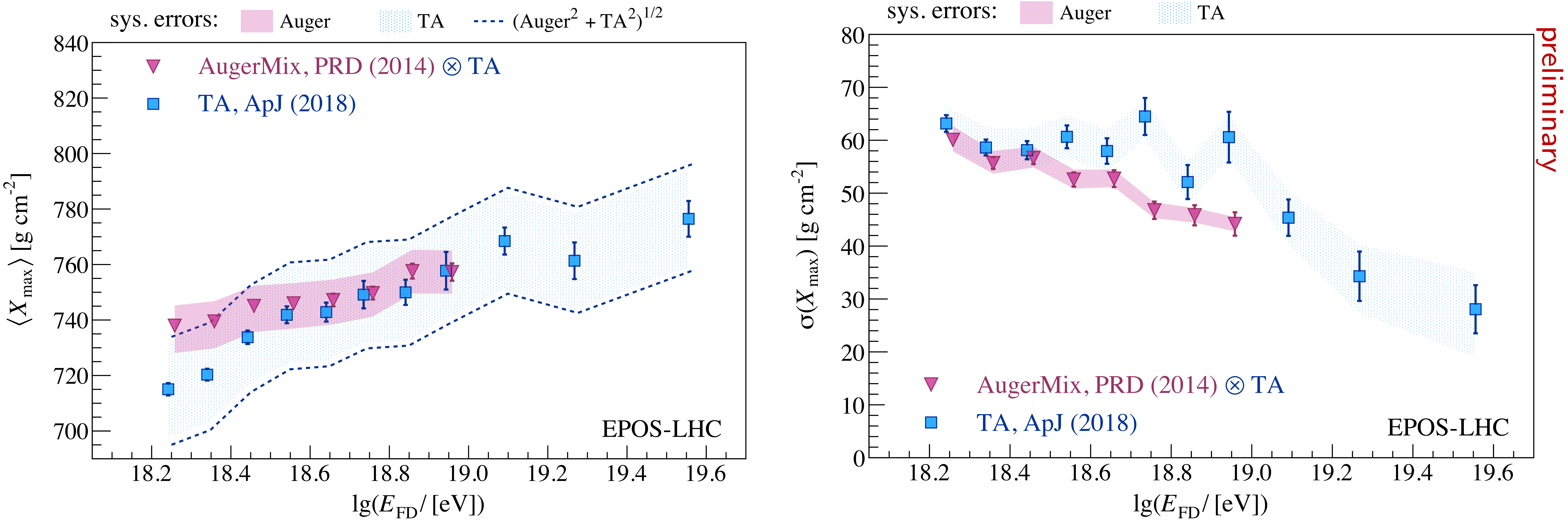
(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$



TA collab. ApJ, 858, *76*(2018)

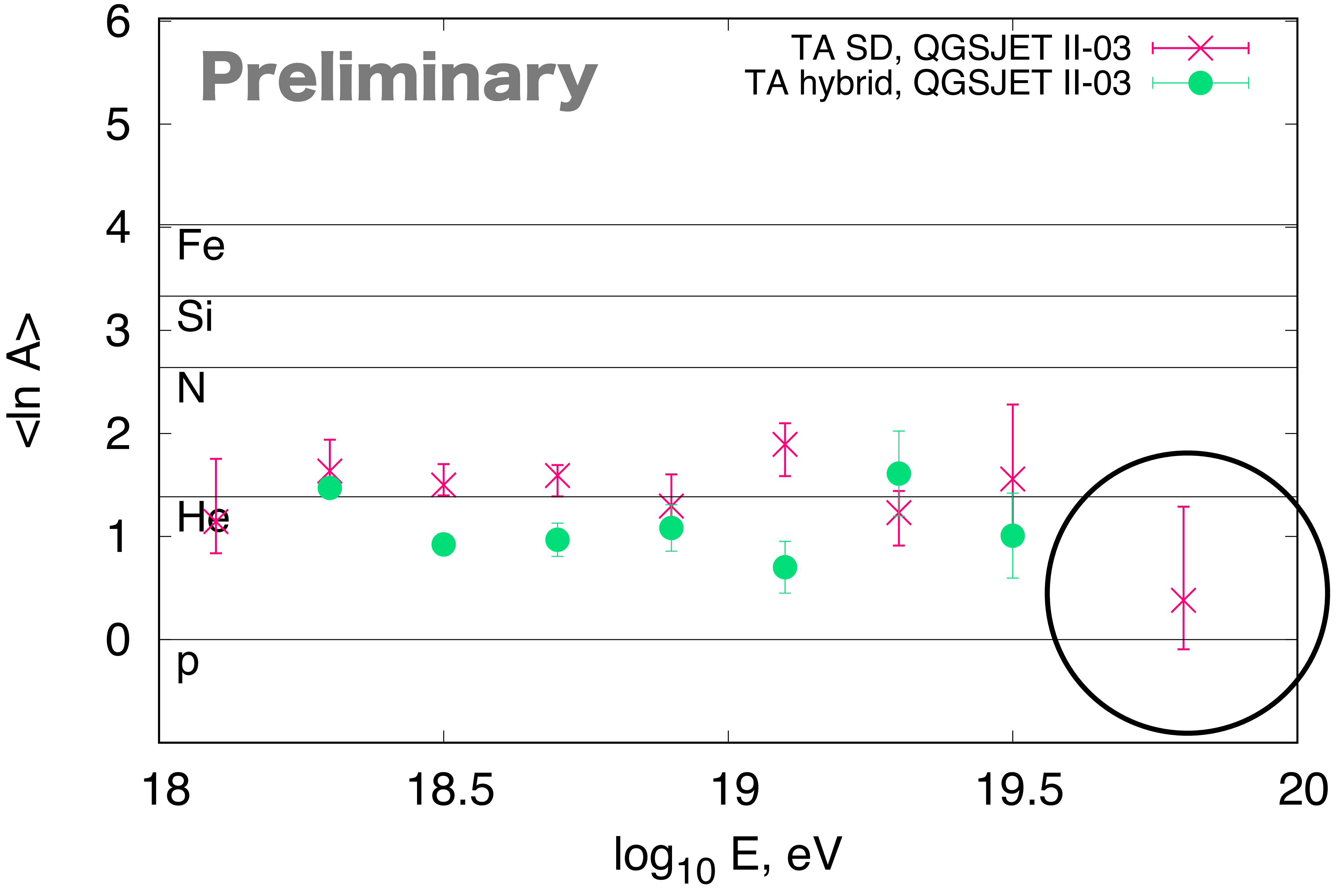
M. Unger et al., ICRC 2017, J. Bellido et al., ICRC 2017

TA's X_{max} analysis assuming Auger's mixed composition

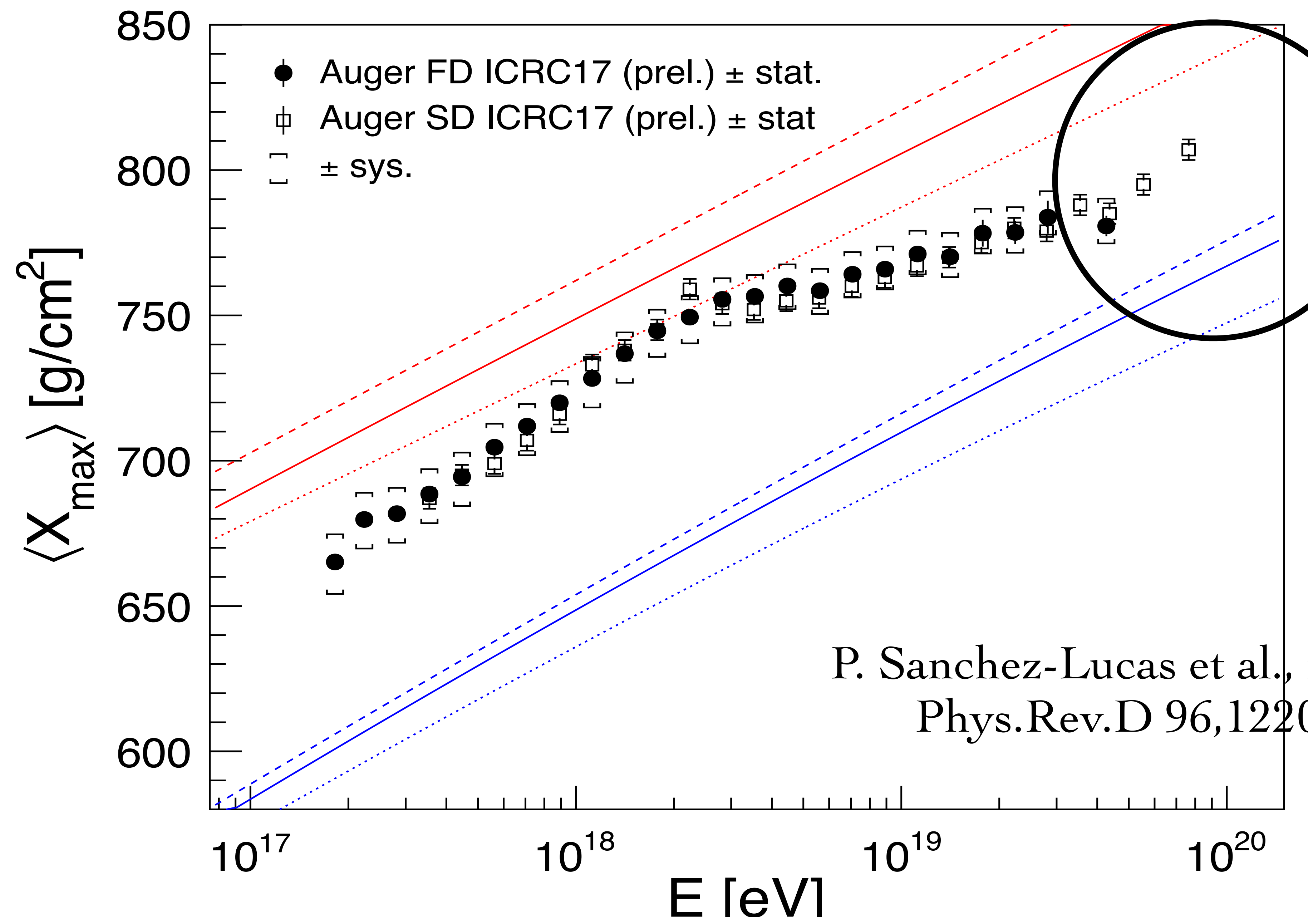


A. Yushkov et al., (Mass Composition WG), UHECR 2018

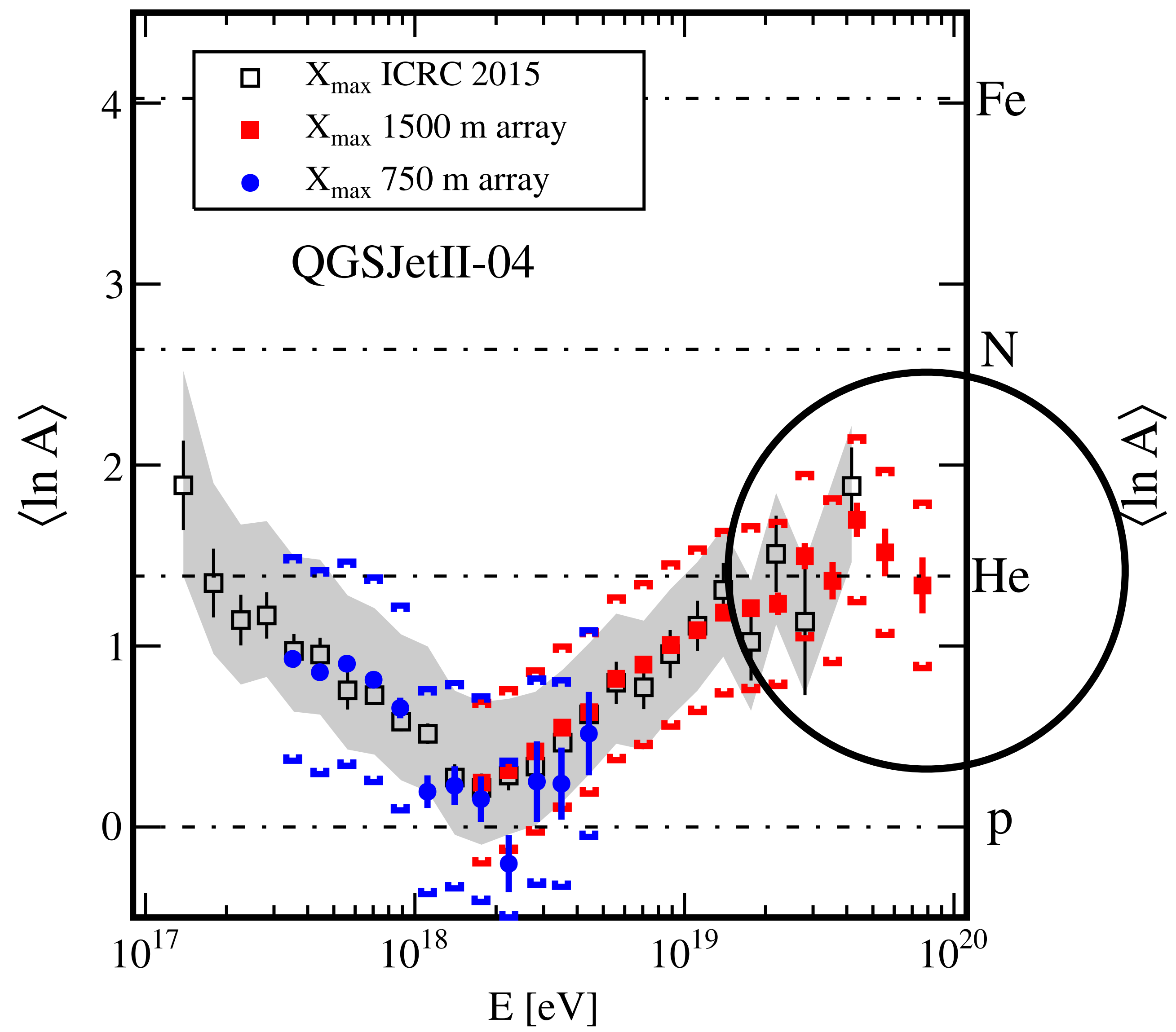
Mass composition analysis using surface detector array

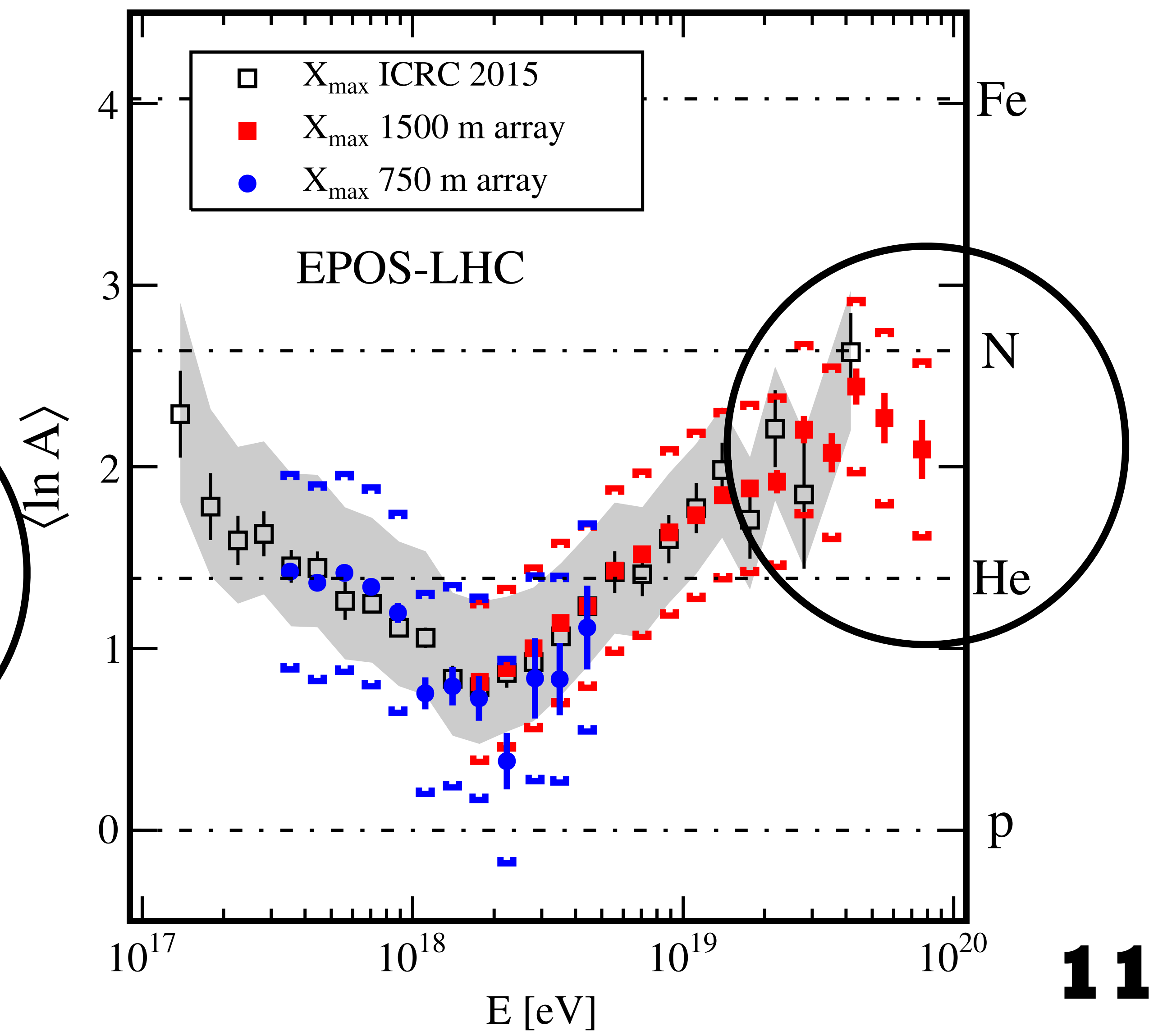


Y. Zhezher et al. in ICRC 2017, arXiv: 1808.03680



P. Sanchez-Lucas et al., in ICRC 2017,
Phys.Rev.D 96,122003 (2017)

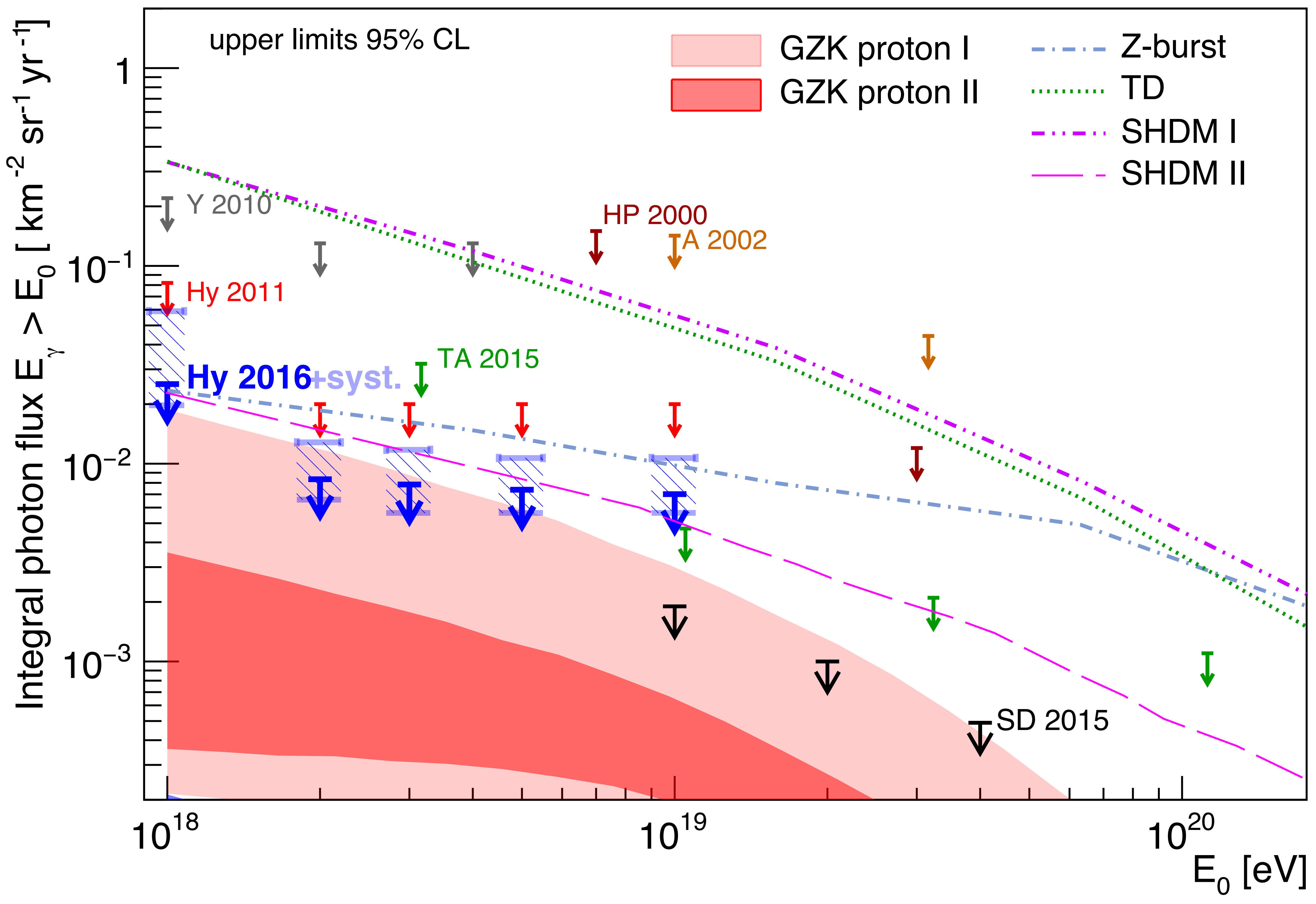




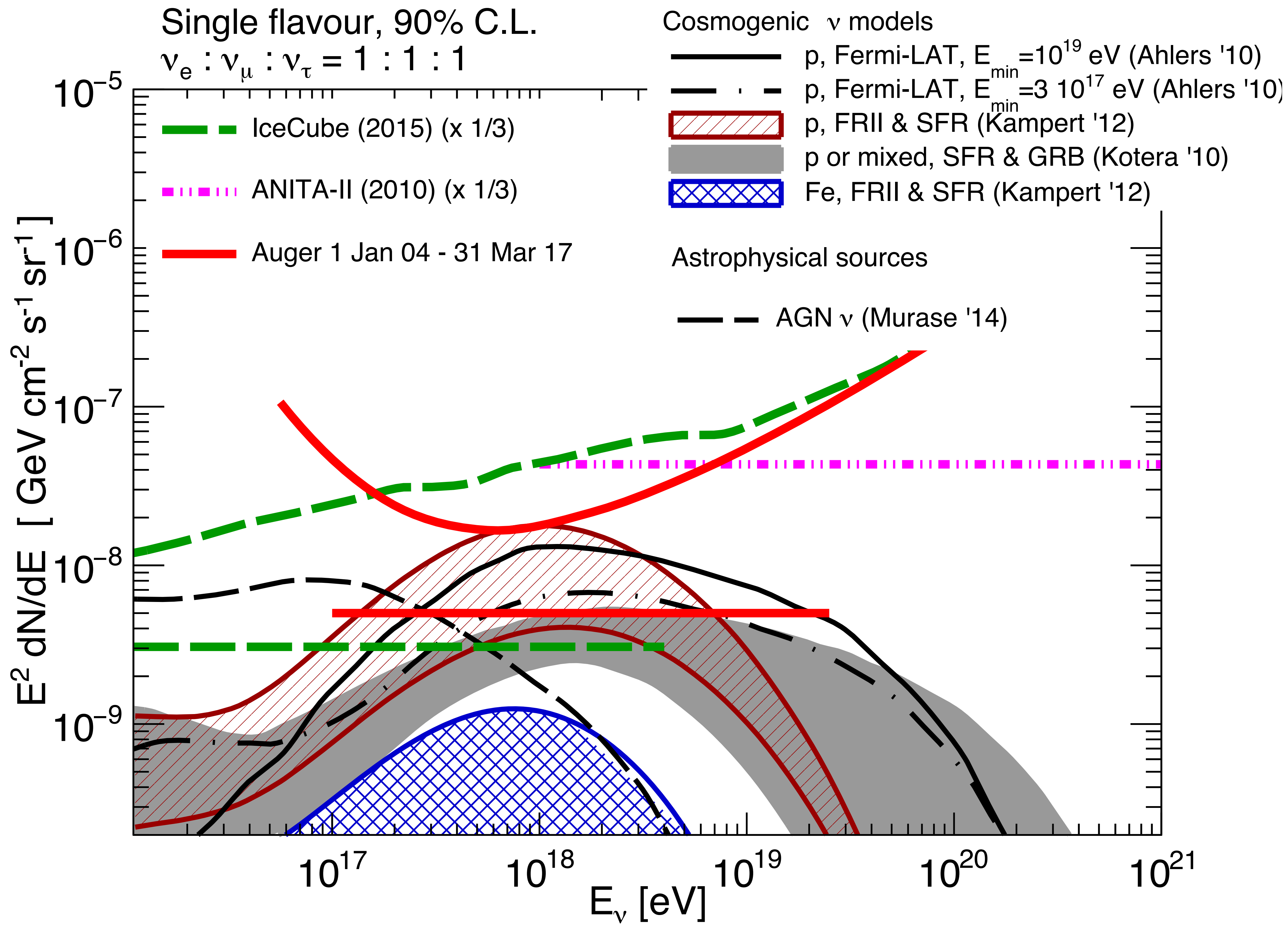
Are cosmic rays accelerated to 10^{21} eV (= 1 ZeV)?

ZeVatron in the Universe?

No GZK γ and ν at the highest energies



Pierre Auger collab., JCAP04 (2017) 009



E. Zas, Proc. of ICRC 2017

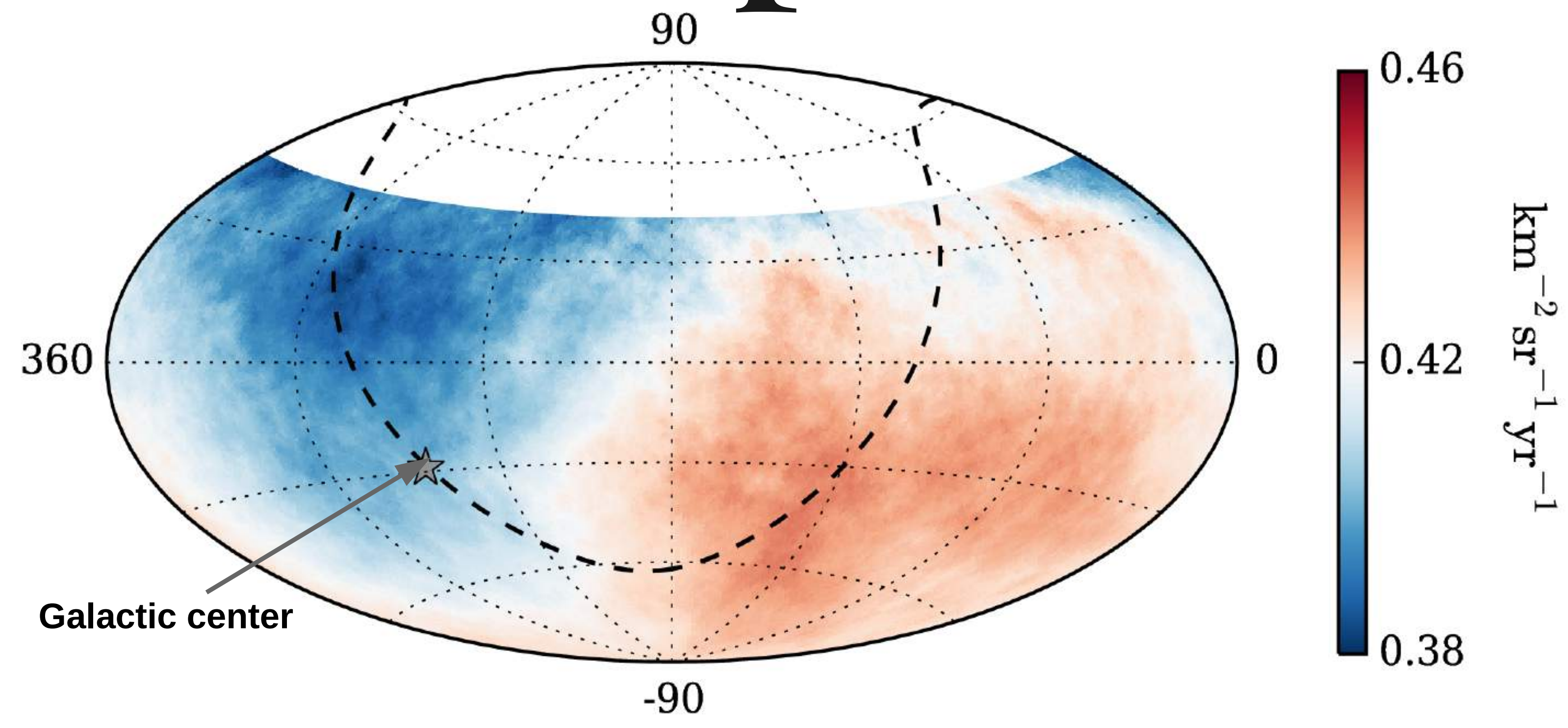
- Top-down models are ruled out.
- Auger limits become sensitive to GZK-ν and γ

Large/intermediate scale anisotropies

Auger dipole: E > 8 EeV, 4.7% dipole with 5.2σ

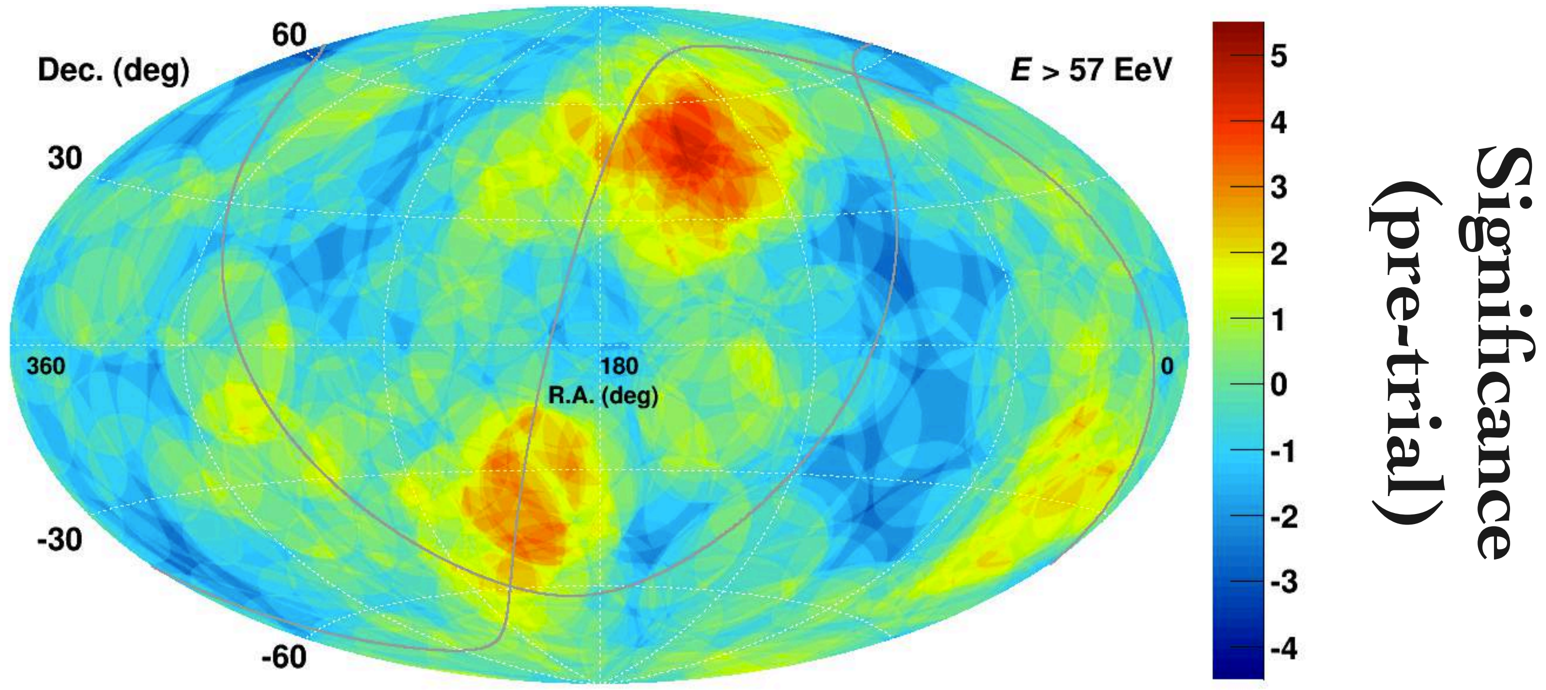
Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

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



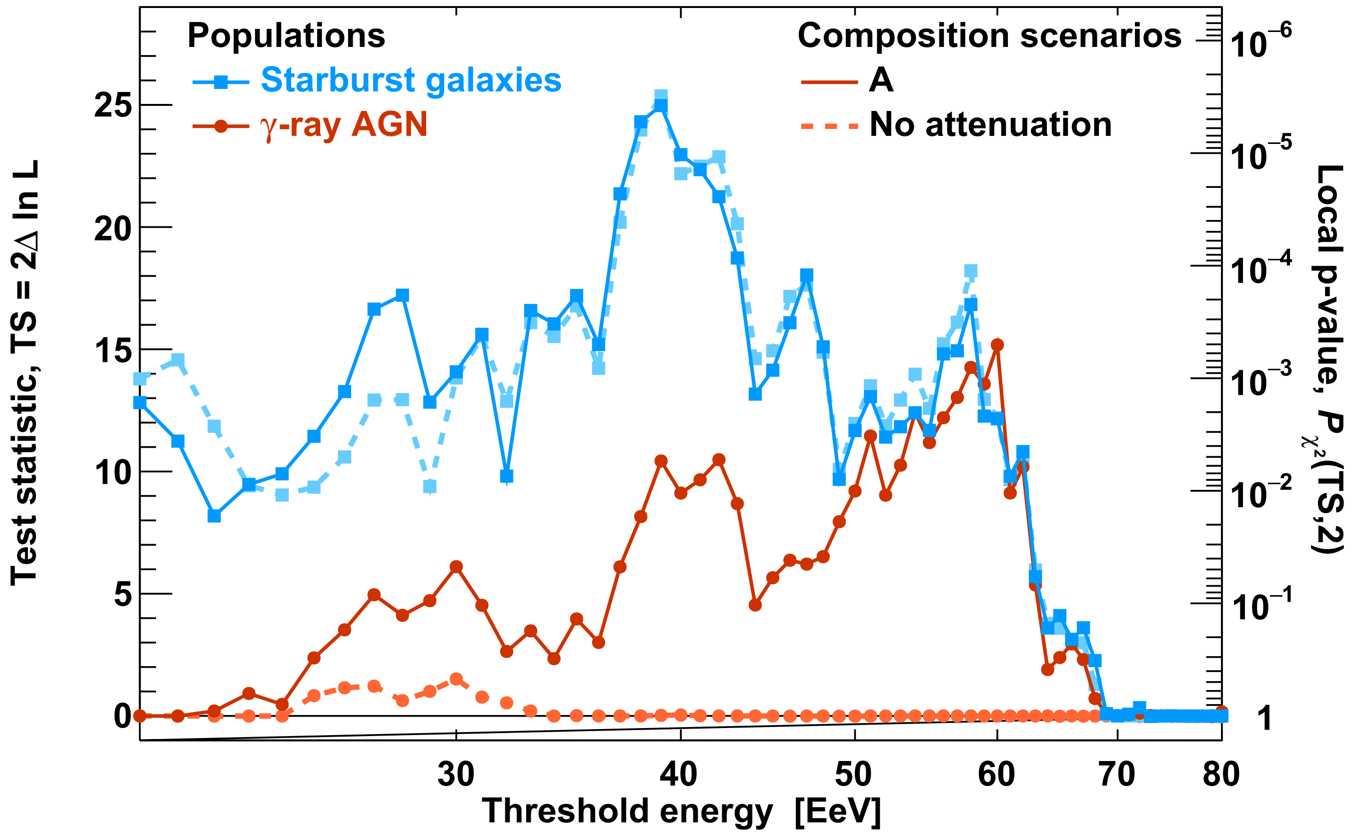
Pierre Auger collab. Science 357, 1266 (2017)

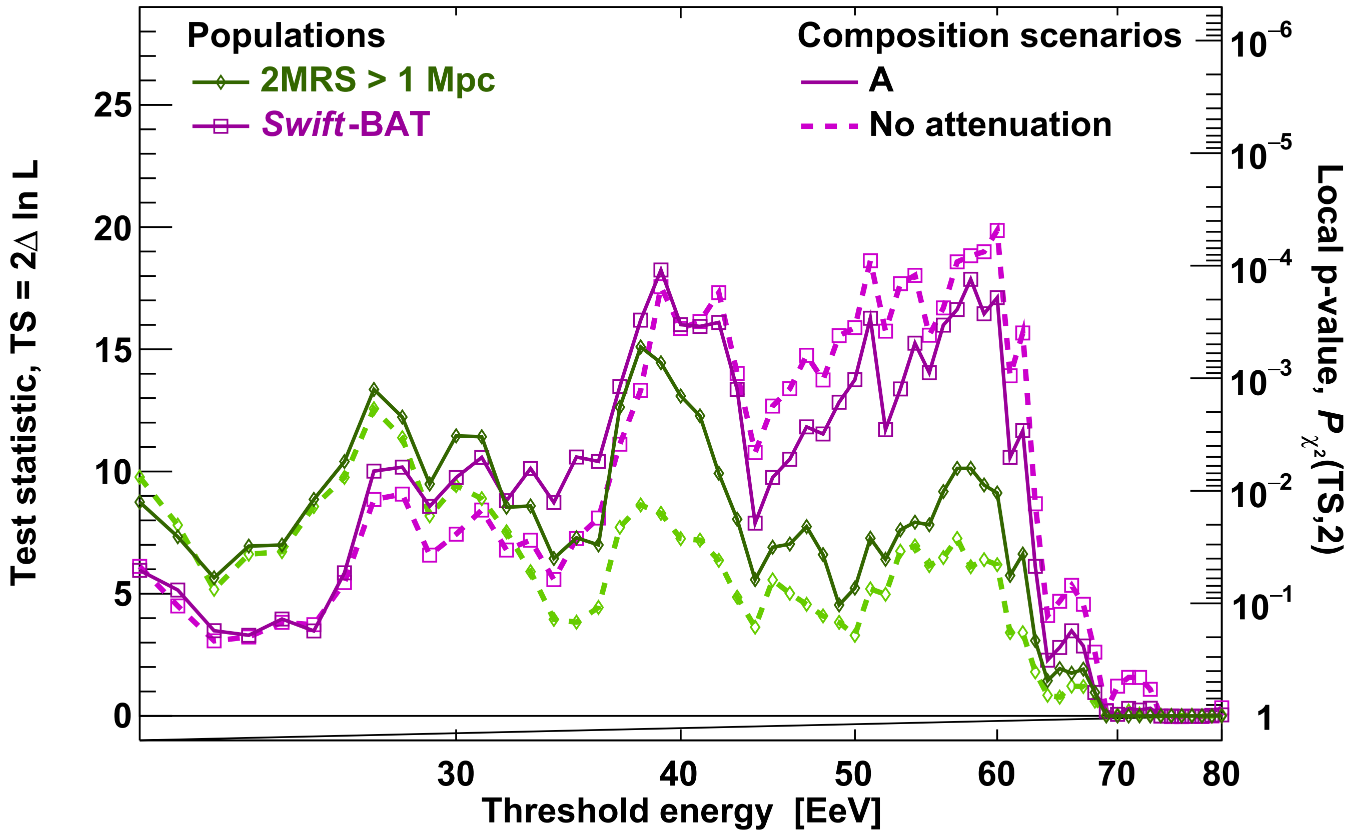
- TA Hotspot: E > 57 EeV, **3.4σ** anisotropy [TA collab. ApJL, 790:L21 (2014)]
- TA (7 years, 109 events above 57 EeV)+ Auger(10 years, 157 events above 57 EeV), 20° circle oversampling
  - E > 57 EeV, no excess from the Virgo cluster



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

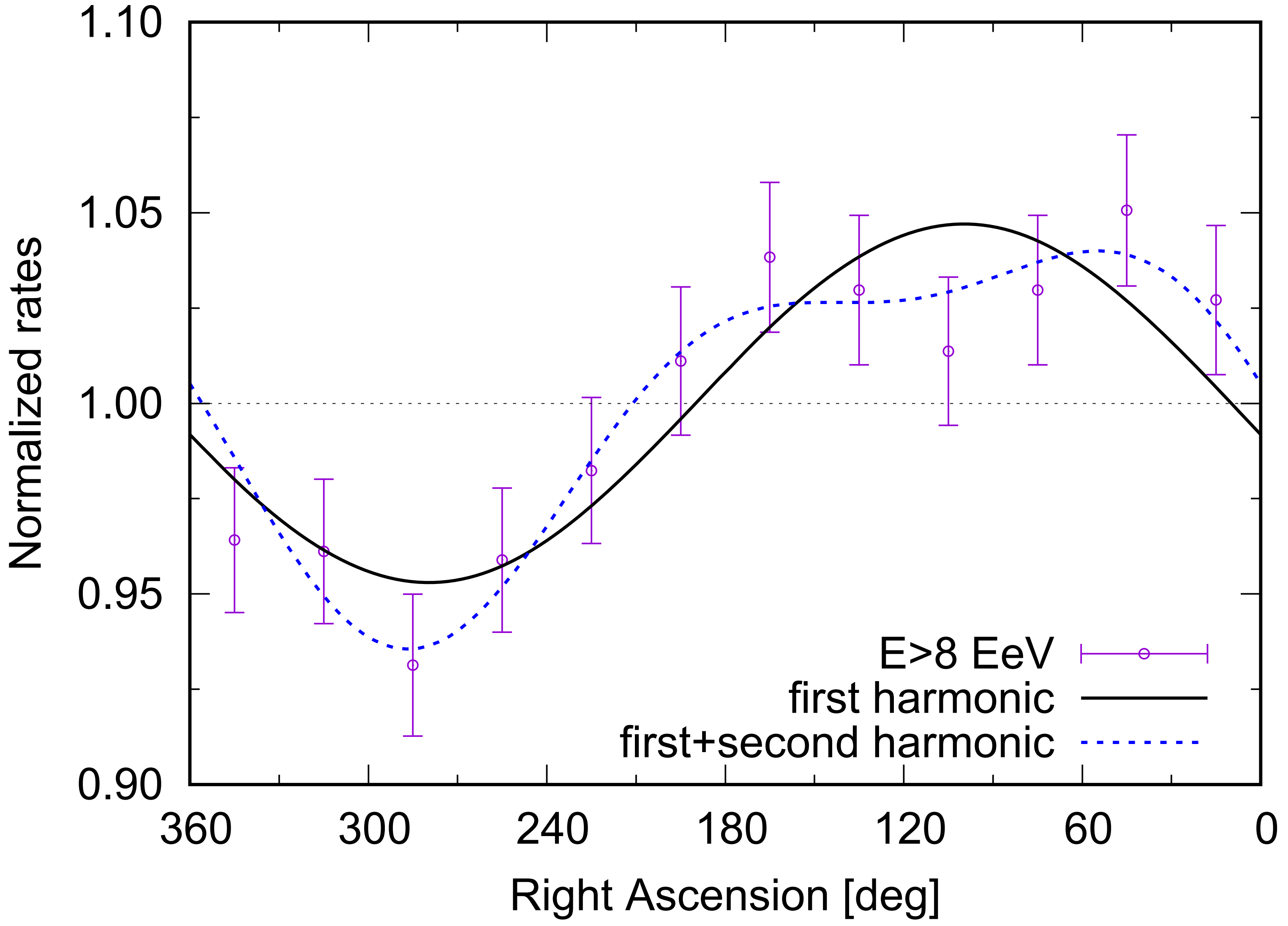
- Flux pattern correlation [Pierre Auger collab. ApJL, 853:L29 (2018)]
  - With a flux pattern of starburst galaxies, isotropy of UHECR is disfavored with **4.0σ** confidence above 39 **EeV**
    - **9.7% anisotropic fraction and 12.9° angular scale**
  - The other three flux patterns: 2.7σ–3.2σ





PIERRE AUGER OBSERVATORY

Large scale anisotropy above 4 EeV



Energy (EeV)	Events	k	r_k^α	$\varphi_k^\alpha(°)$	$P(\geqslant r_k^\alpha)$
4–8	81,701	1	0.005	80 ± 60	0.60
		2	0.002	70 ± 80	0.94
⩾8	32,187	1	0.047	100 ± 10	2.6×10^{-8}
		2	0.018	21 ± 12	0.065

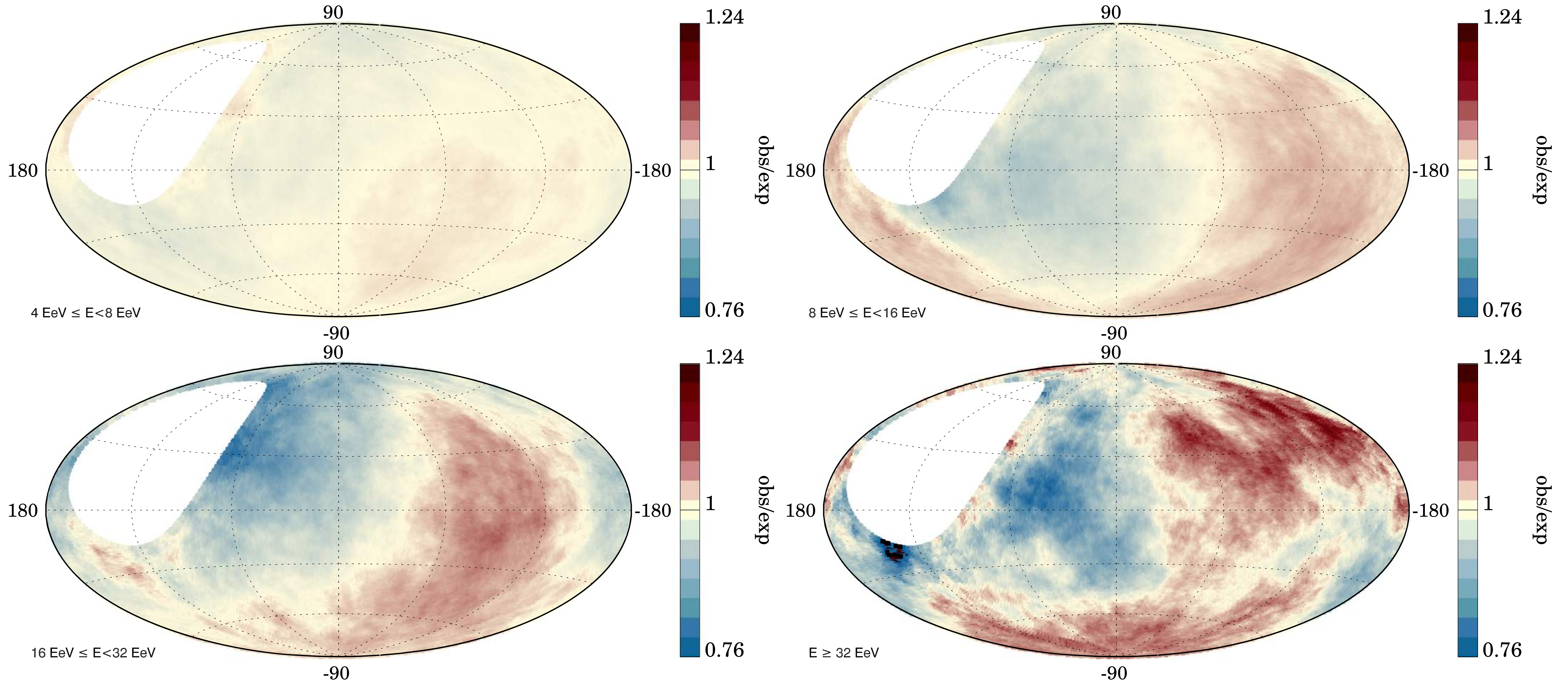


Figure 4. Maps in Galactic coordinates of the ratio between the number of observed events in windows of 45° and those expected for an isotropic distribution of arrival directions, for the four energy bins above 4 EeV.

Table 5

Three-dimensional Dipole Reconstruction for Energies above 4 EeV

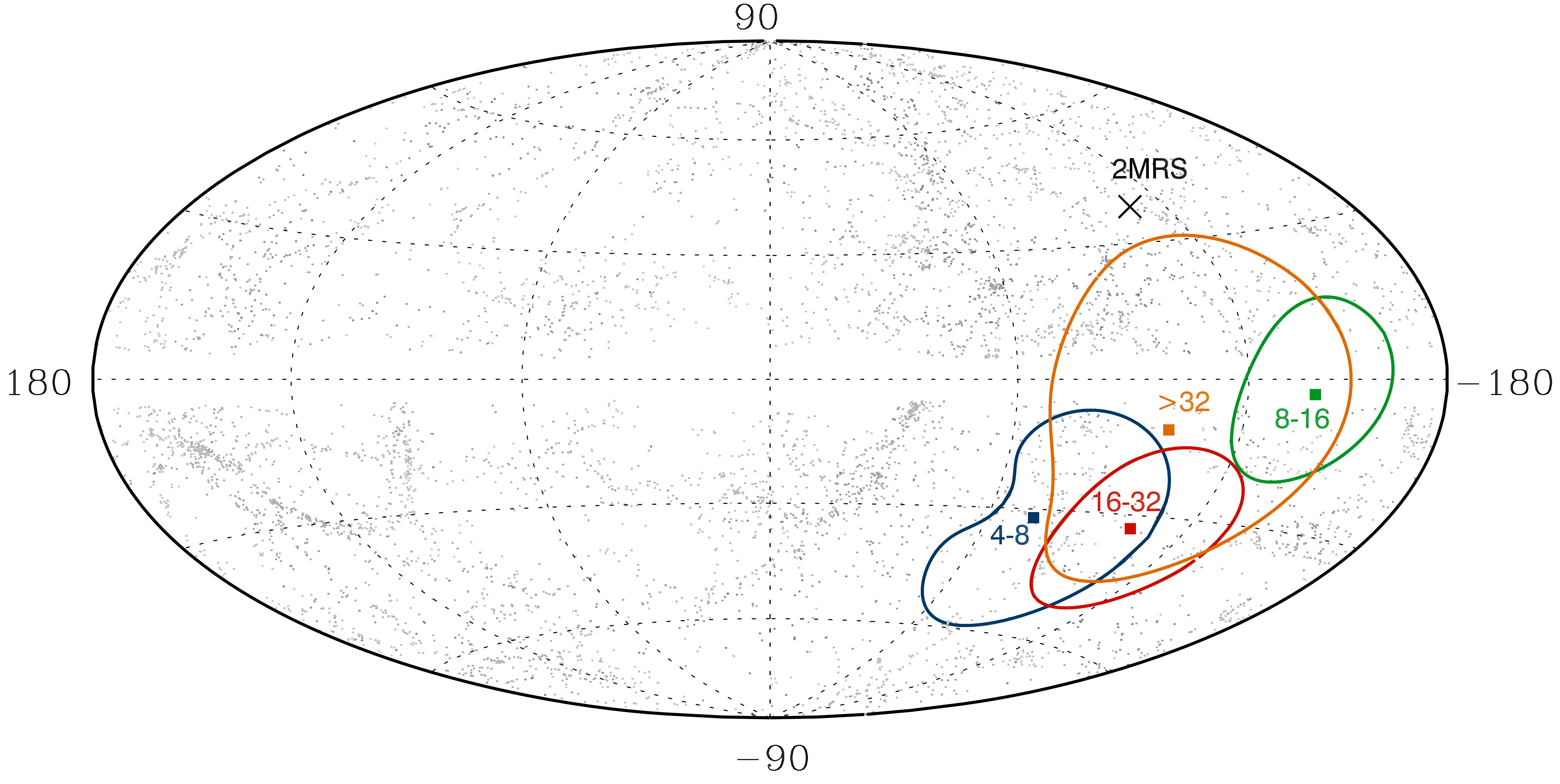
Energy (EeV)		$d_\perp$	d_z	d	α_d (deg)	δ_d (deg)
Interval	Median					
4–8	5.0	$0.006^{+0.007}_{-0.003}$	-0.024 ± 0.009	$0.025^{+0.010}_{-0.007}$	80 ± 60	-75^{+17}_{-8}
⩾8	11.5	$0.060^{+0.011}_{-0.010}$	-0.026 ± 0.015	$0.065^{+0.013}_{-0.009}$	100 ± 10	-24^{+12}_{-13}
8–16	10.3	$0.058^{+0.013}_{-0.011}$	-0.008 ± 0.017	$0.059^{+0.015}_{-0.008}$	104 ± 11	-8^{+16}_{-16}
16–32	20.2	$0.065^{+0.025}_{-0.018}$	-0.08 ± 0.03	$0.10^{+0.03}_{-0.02}$	82 ± 20	-50^{+15}_{-14}
⩾32	39.5	$0.08^{+0.05}_{-0.03}$	-0.08 ± 0.07	$0.11^{+0.07}_{-0.03}$	115 ± 35	-46^{+28}_{-26}

ApJ, 868:4 (2018)

PIERRE AUGER OBSERVATORY

Large scale anisotropy above 4 EeV

Power law index: 0.79±0.19
Constant amplitude disfavored with 3.7σ



Auger collab., ApJ, 868:4 (2018)

Prediction of dipole amplitude using Auger mixed composition

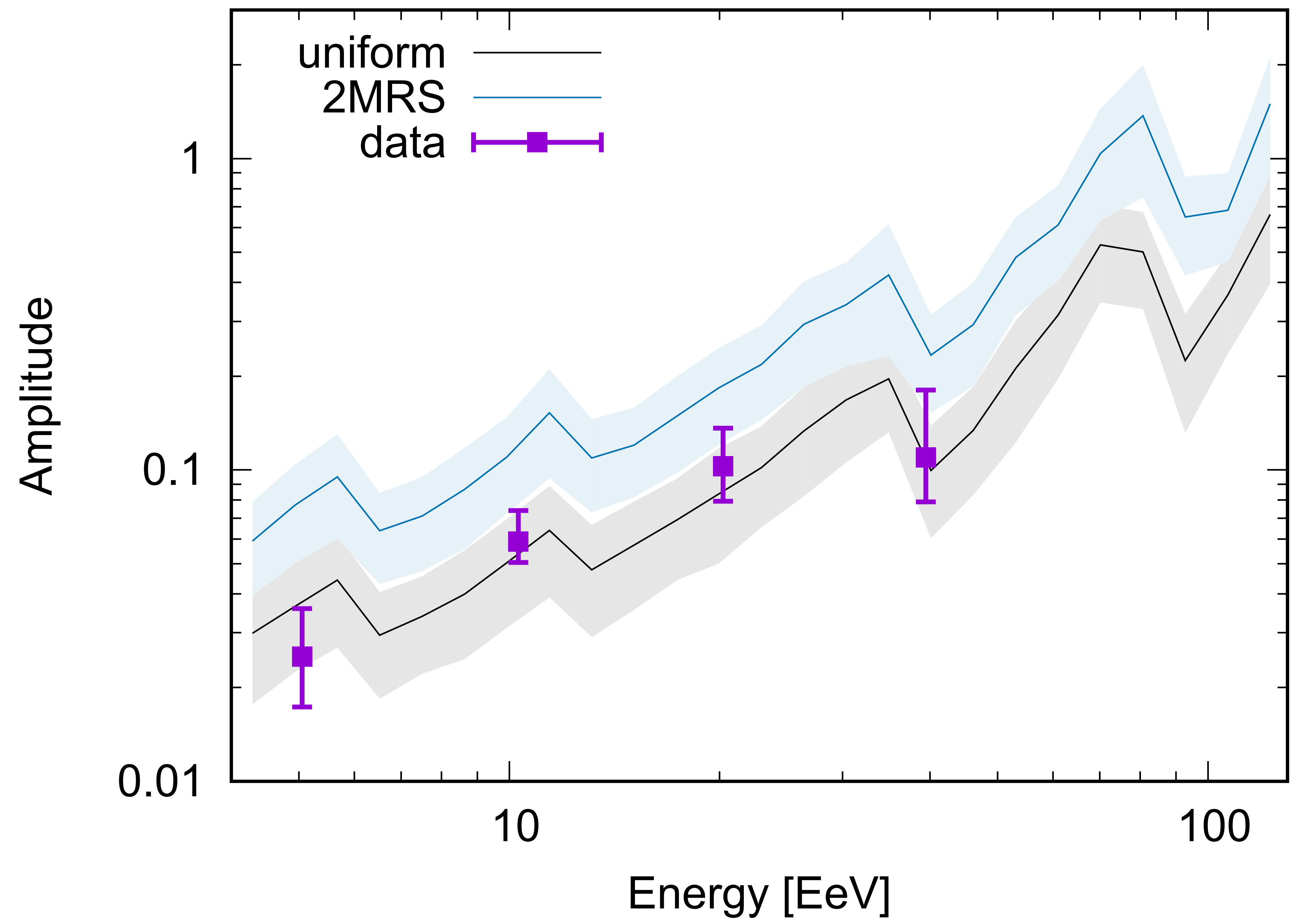
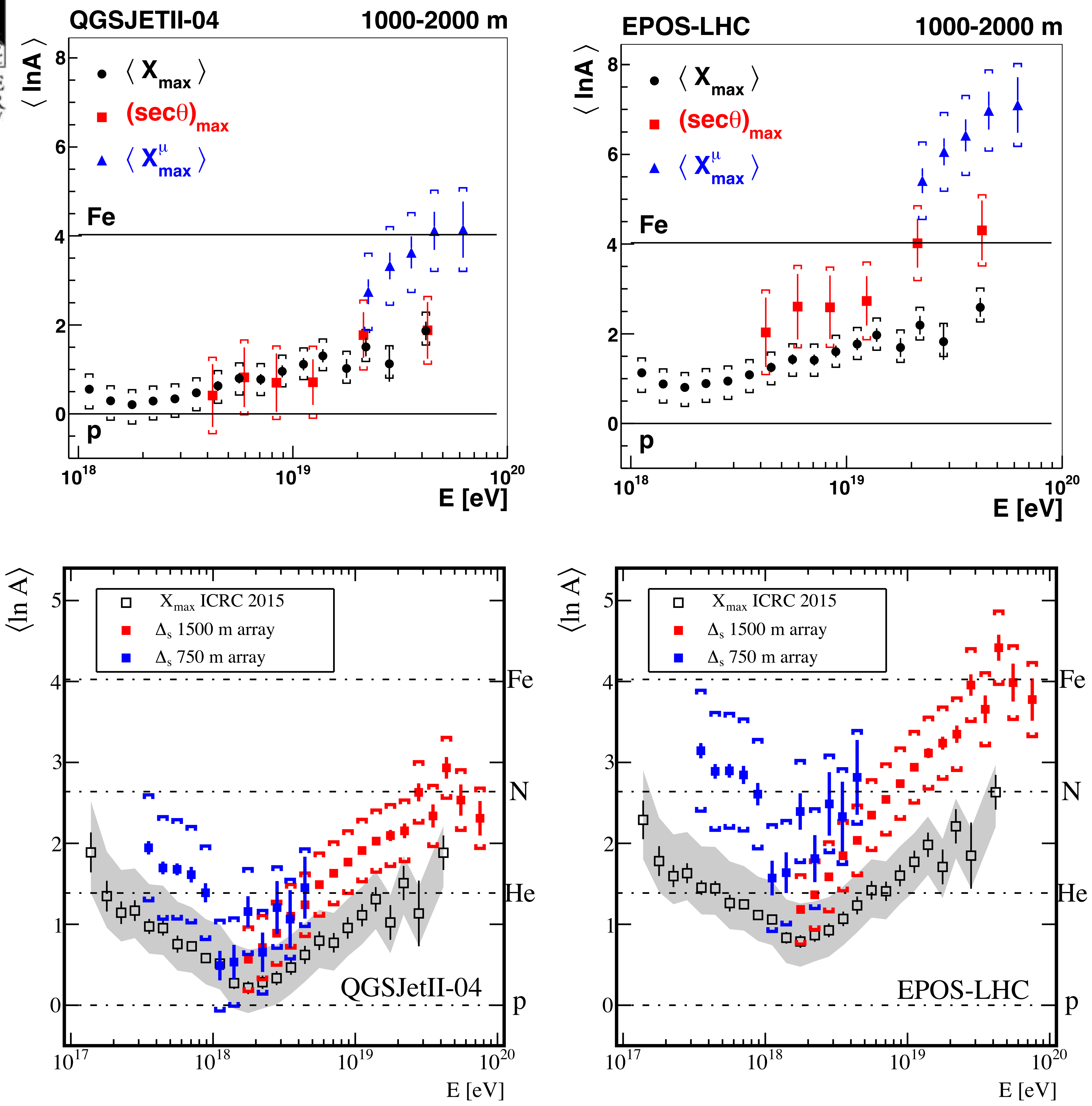
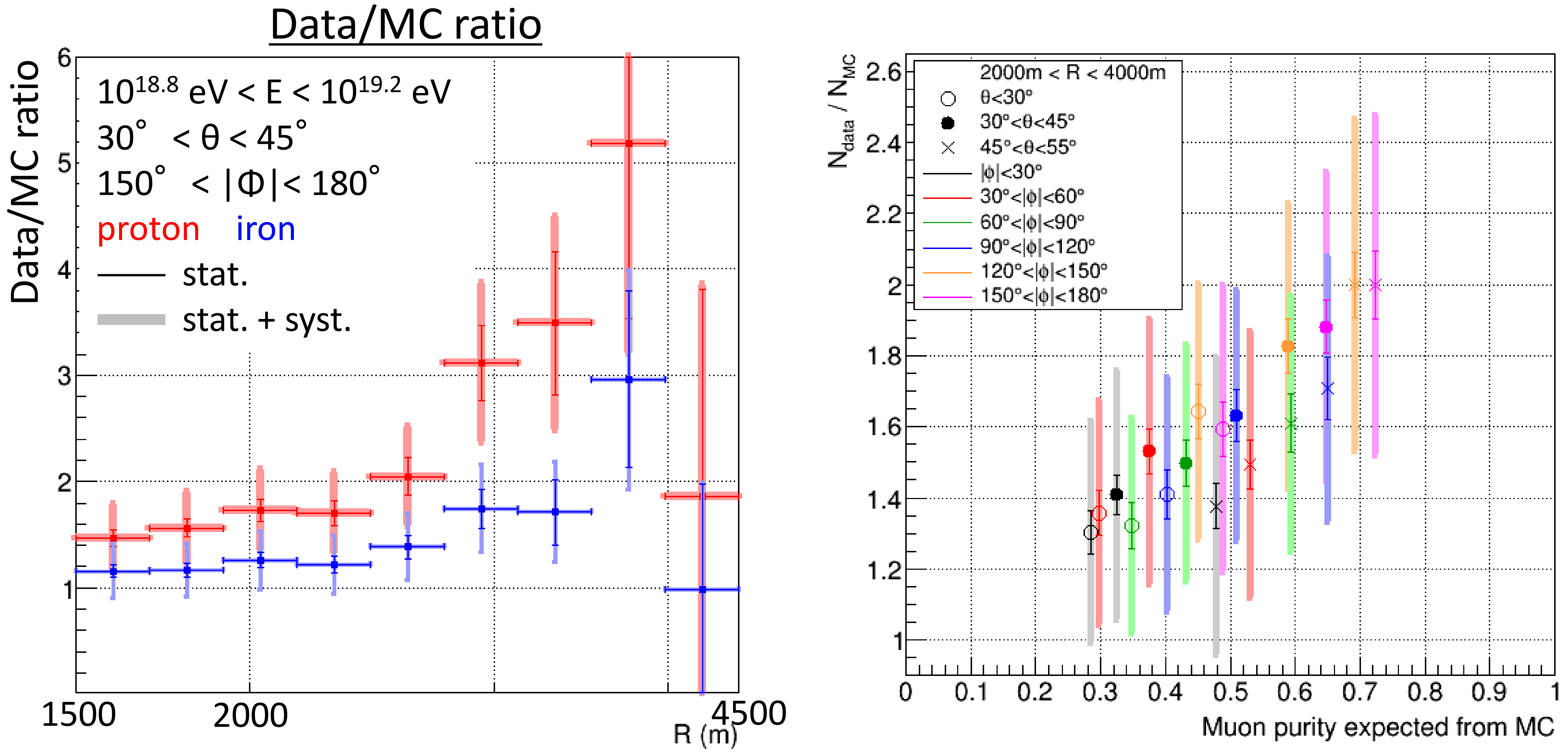


Figure 6. Comparison of the dipole amplitude as a function of energy with predictions from models (Harari et al. 2015) with mixed composition and a source density $\rho = 10^{-4}$ Mpc^{-3}. CRs are propagated in an isotropic turbulent extragalactic magnetic field with rms amplitude of 1 nG and a Kolmogorov spectrum with coherence length equal to 1 Mpc (with the results having only mild dependence on the magnetic field strength adopted). The gray line indicates the mean value for simulations with uniformly distributed sources, while the blue one shows the mean value for realizations with sources distributed as the galaxies in the 2MRS catalog. The bands represent the dispersion for different realizations of the source distribution. The steps observed reflect the rigidity cutoff of the different mass components.

Muon deficits in hadron interaction models





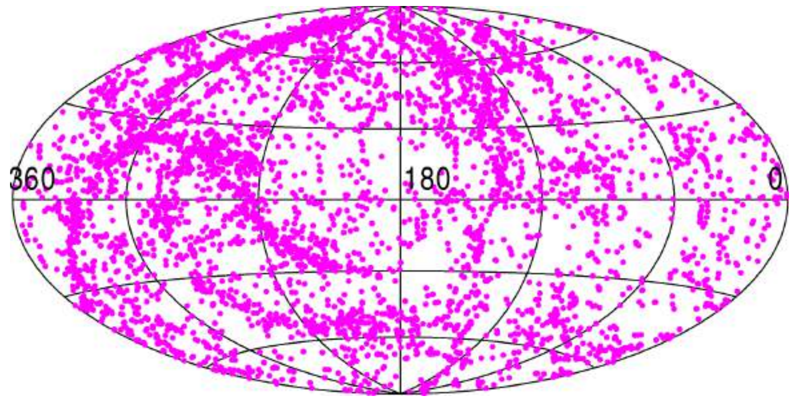
R. Takeishi, ISHVECRI 2018, Ph.D. thesis (2017)

- In higher muon purity, larger deficits in models
- Need more muon production in the simulation.

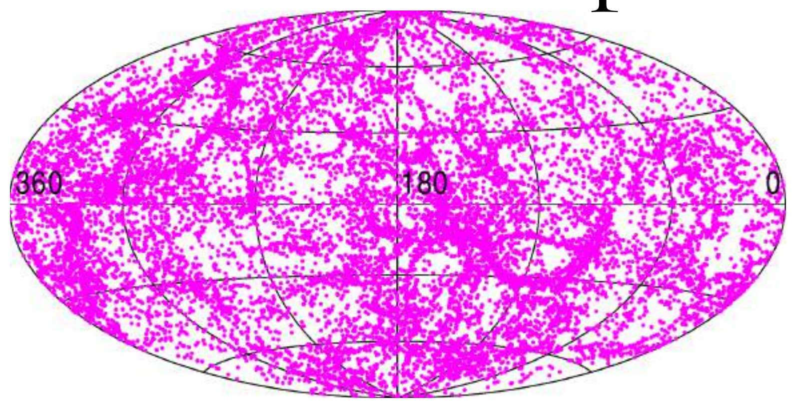
P. Sanchez-Lucas, ICRC 2017, Pierre Auger collab., Phys.Rev.D 93,072006 (2016), Pierre Auger collab., Phys.Rev.D 96,122003 (2017)

Hadron-interaction-model independent measurements

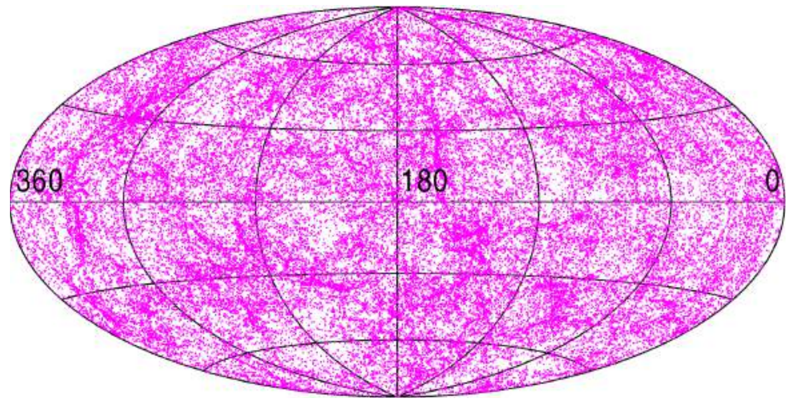
0 - 50 Mpc



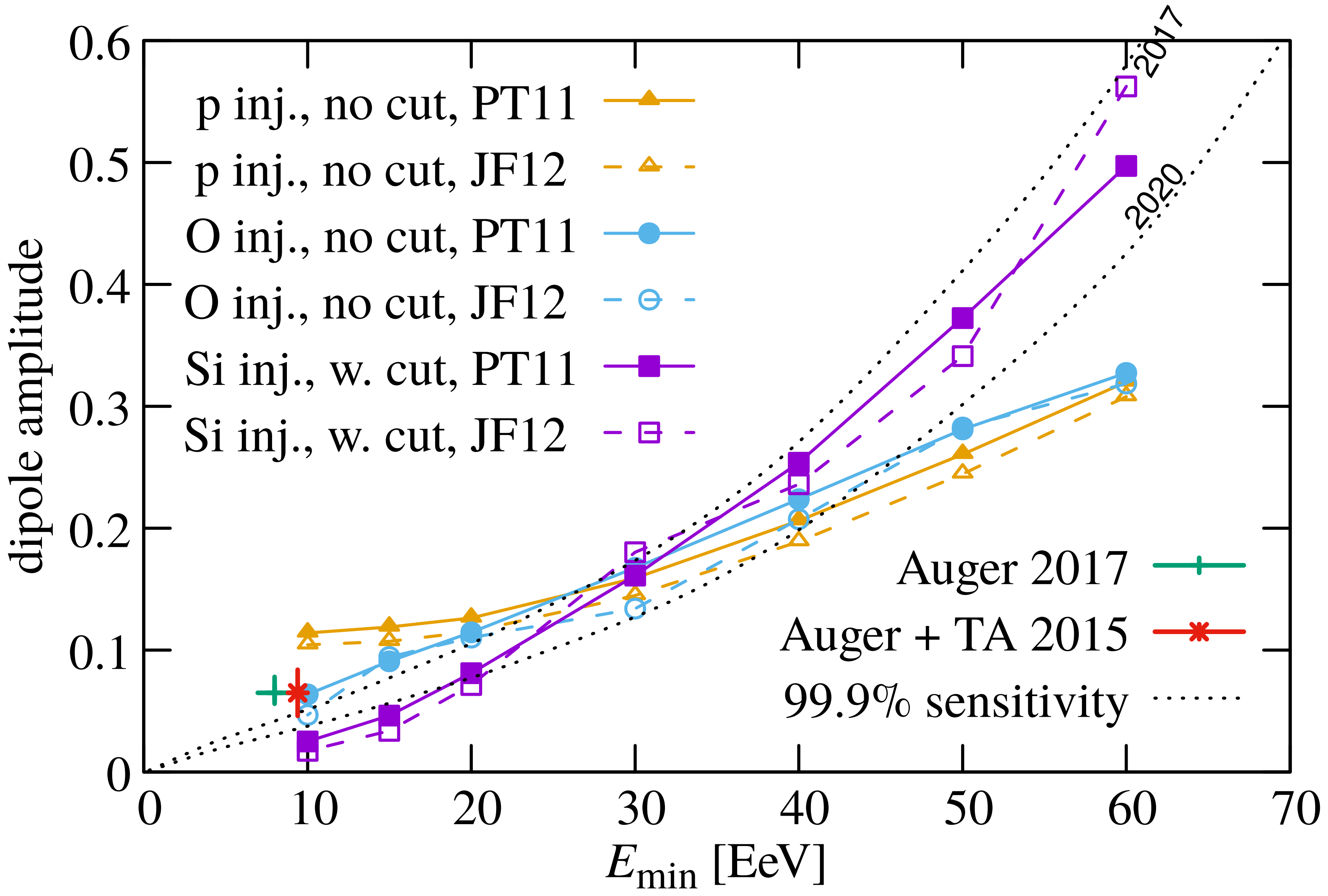
50 - 100 Mpc



100 - 250 Mpc



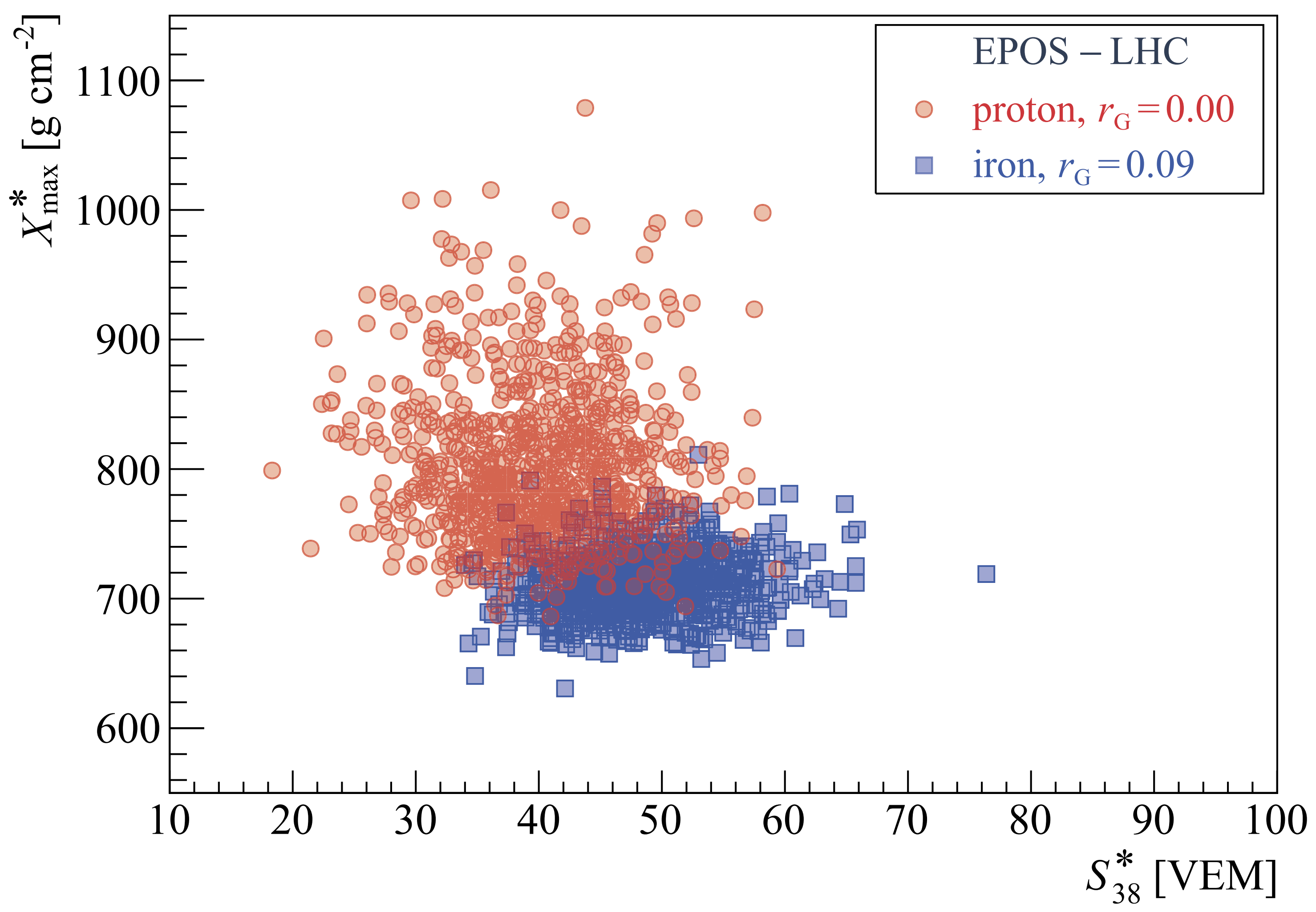
Predicted dipole amplitude

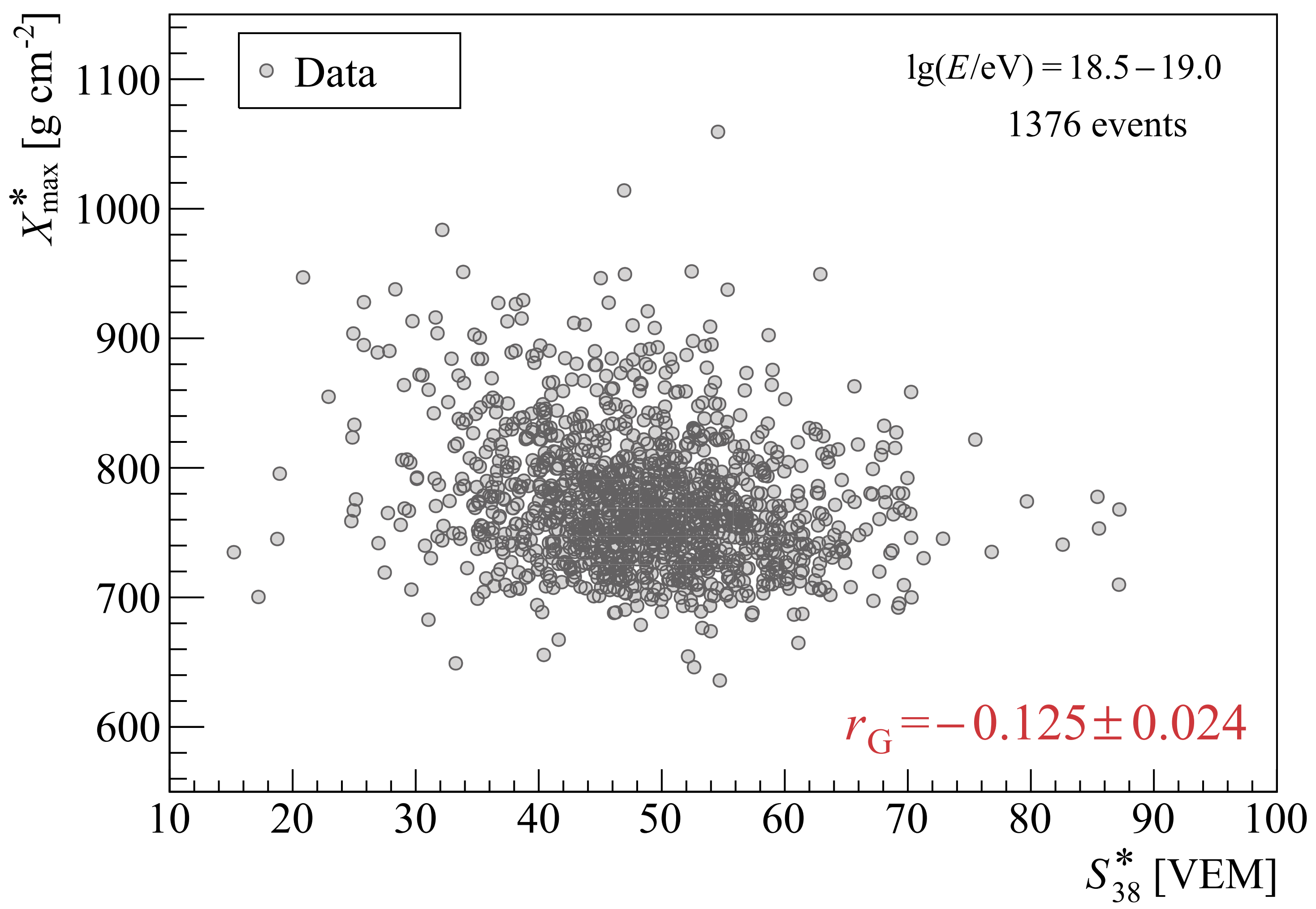


A. di Matteo and P. Tinyakov, https://doi.org/10.1093/mnras/sty277

(2MASS Redshift survey galaxies)

Correlation measurement

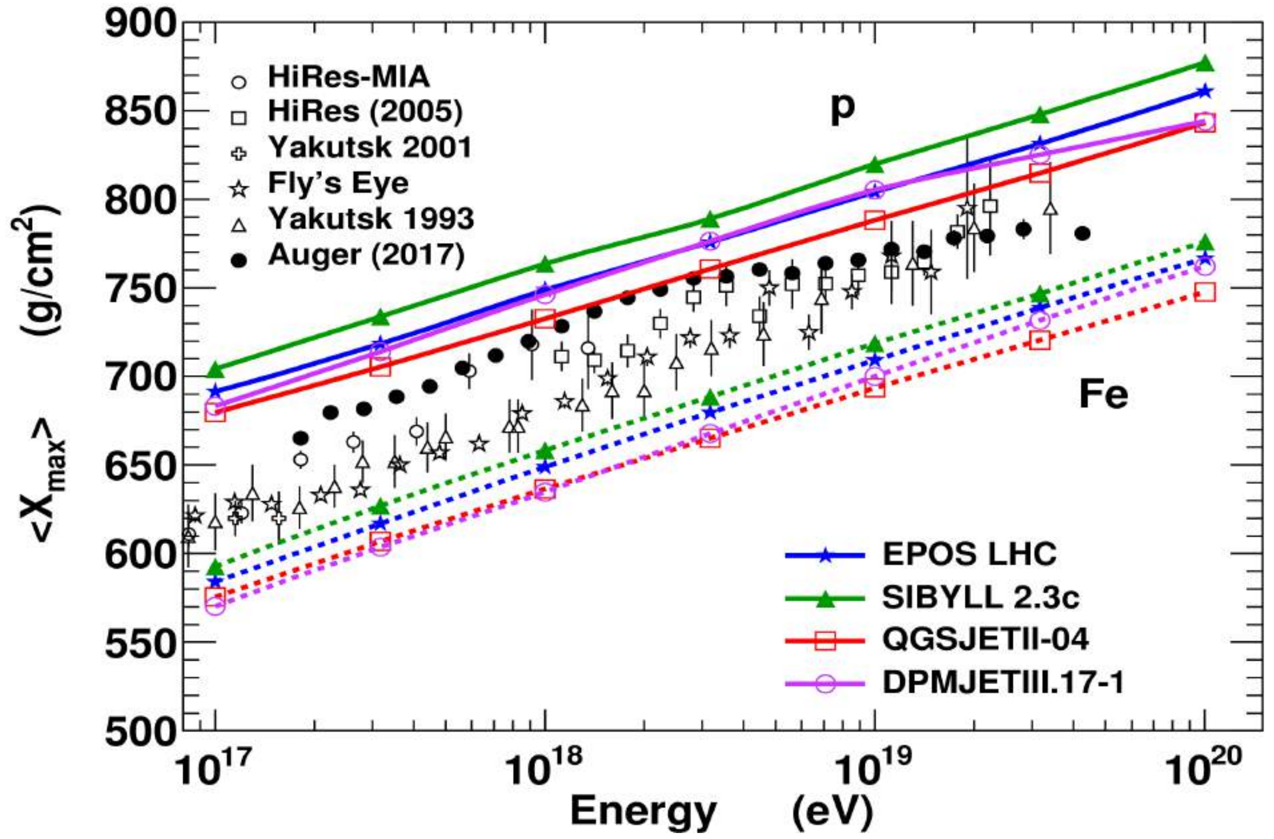




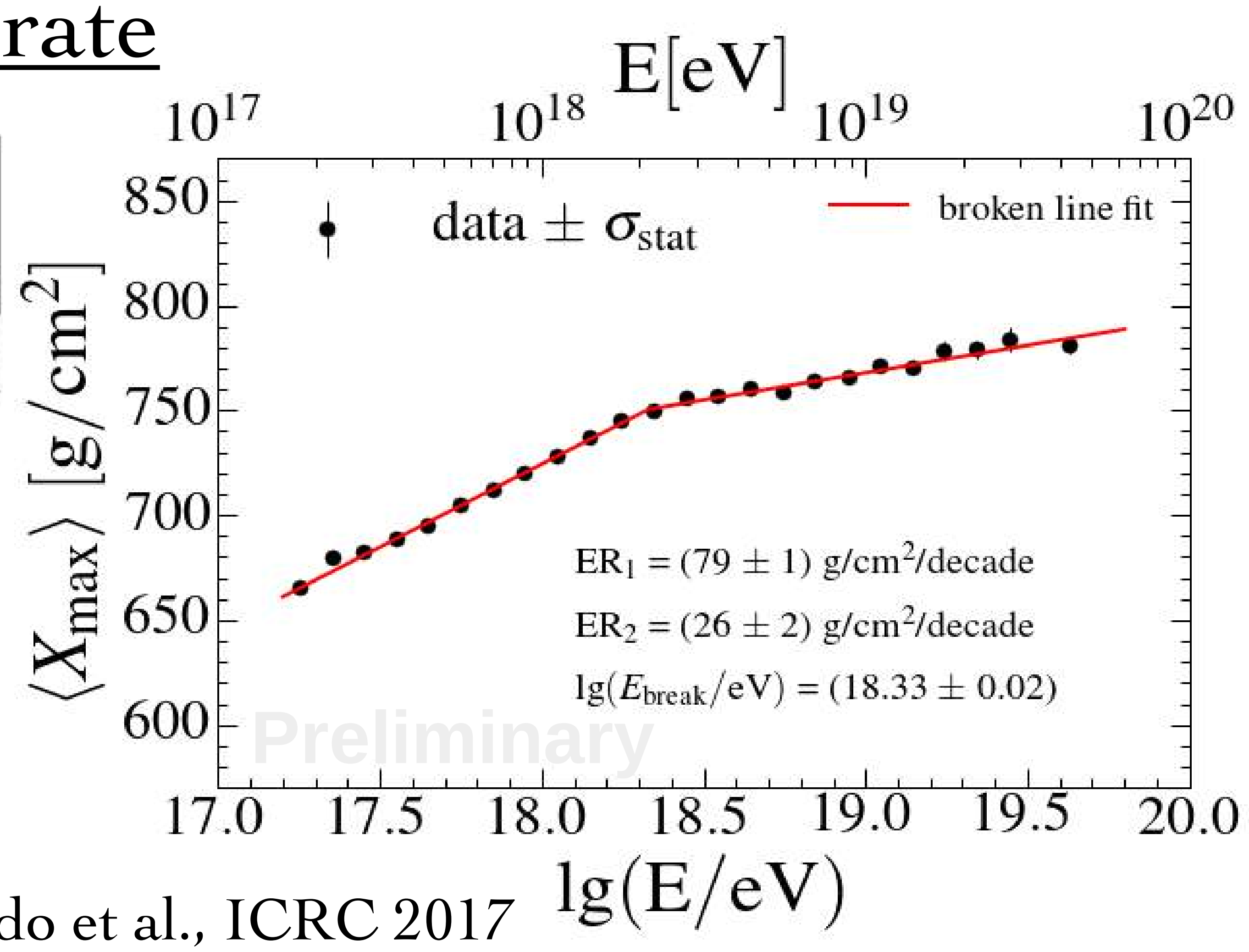
Mixed composition at the ankle

Pierre Auger collab., Phys.Lett. B 762, 288 (2016)

Elongation rate

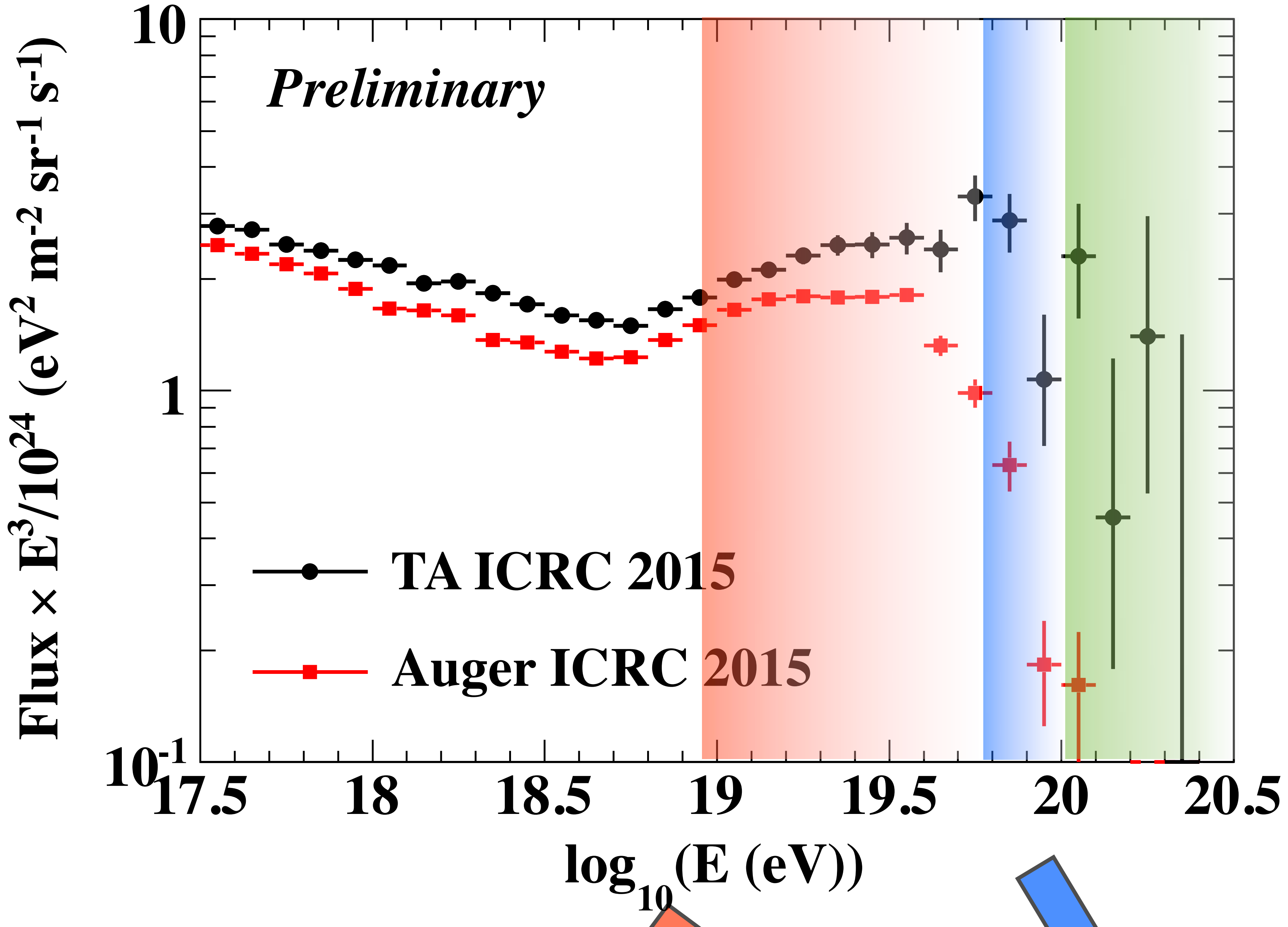


T. Pierog, ISVHECRI 2018

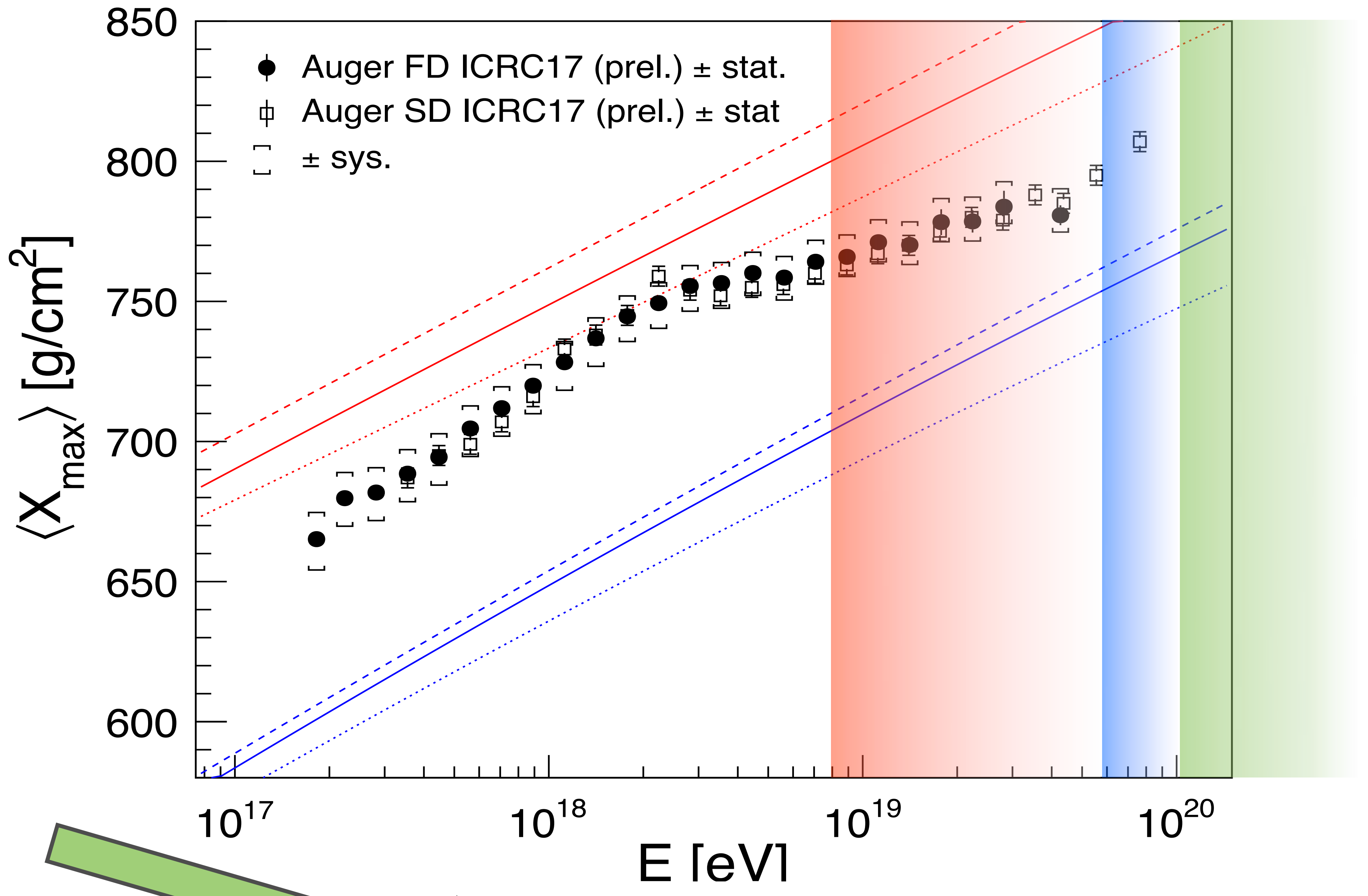


J. Bellido et al., ICRC 2017

An overview of energy spectrum, mass composition and anisotropy



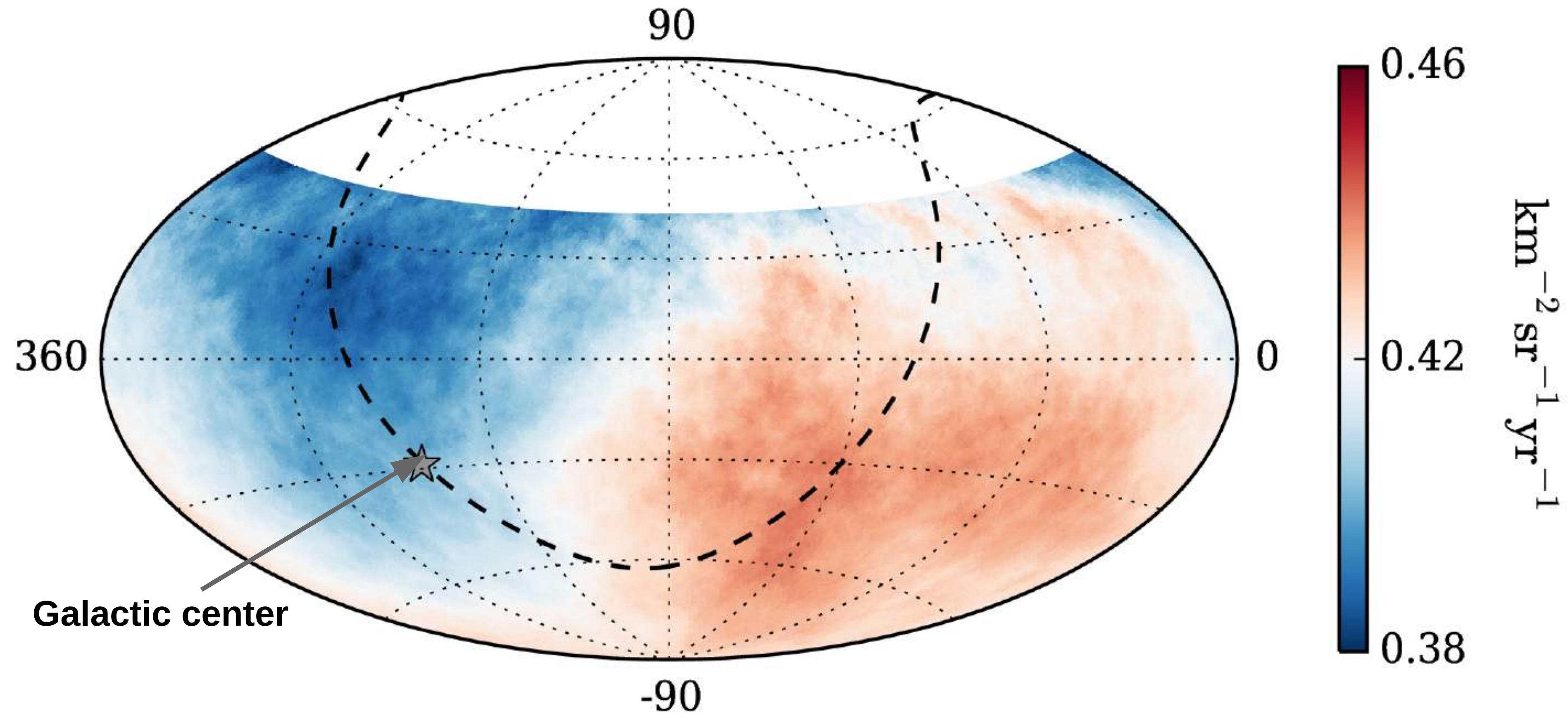
Data points from I. Valino et al., Proc. of ICRC 2015, D. Ivanov at al., Proc. of ICRC 2015



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

E > 8 EeV

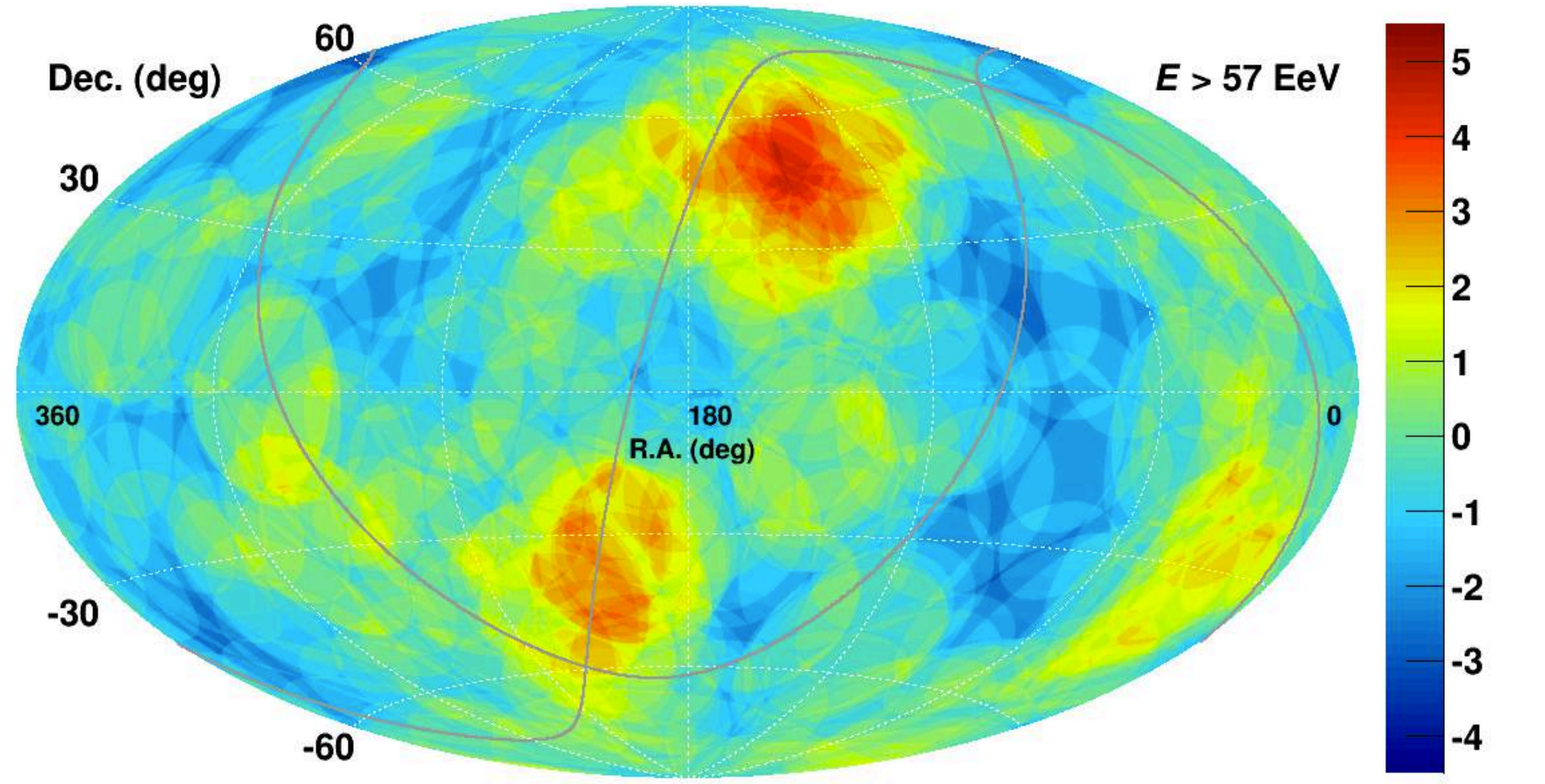
Pierre Auger Collab. Science 357, 1266 (2017)



Increase dipole amplitude above 4 EeV

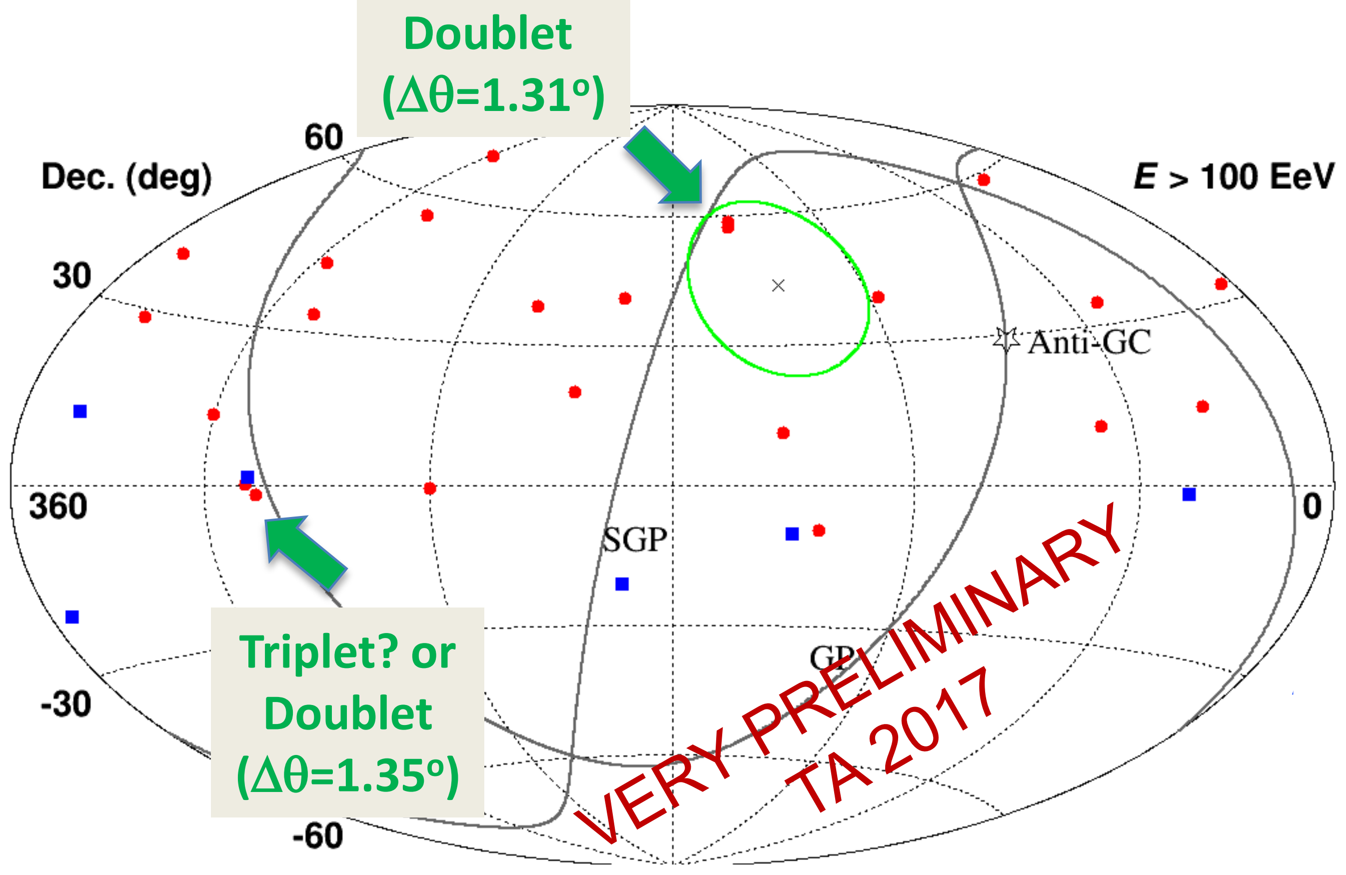
E > 57 EeV

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



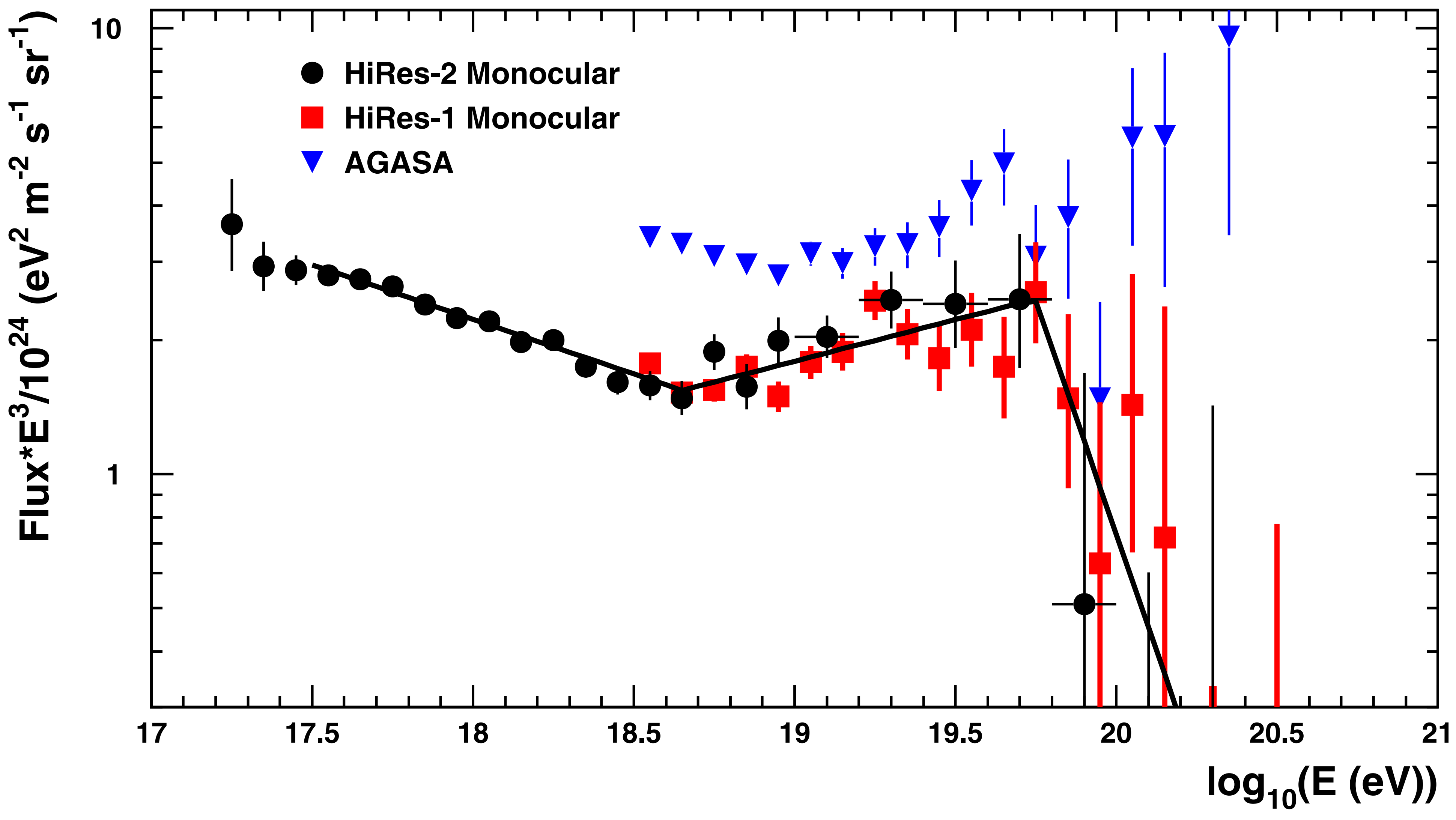
E > 100 EeV

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



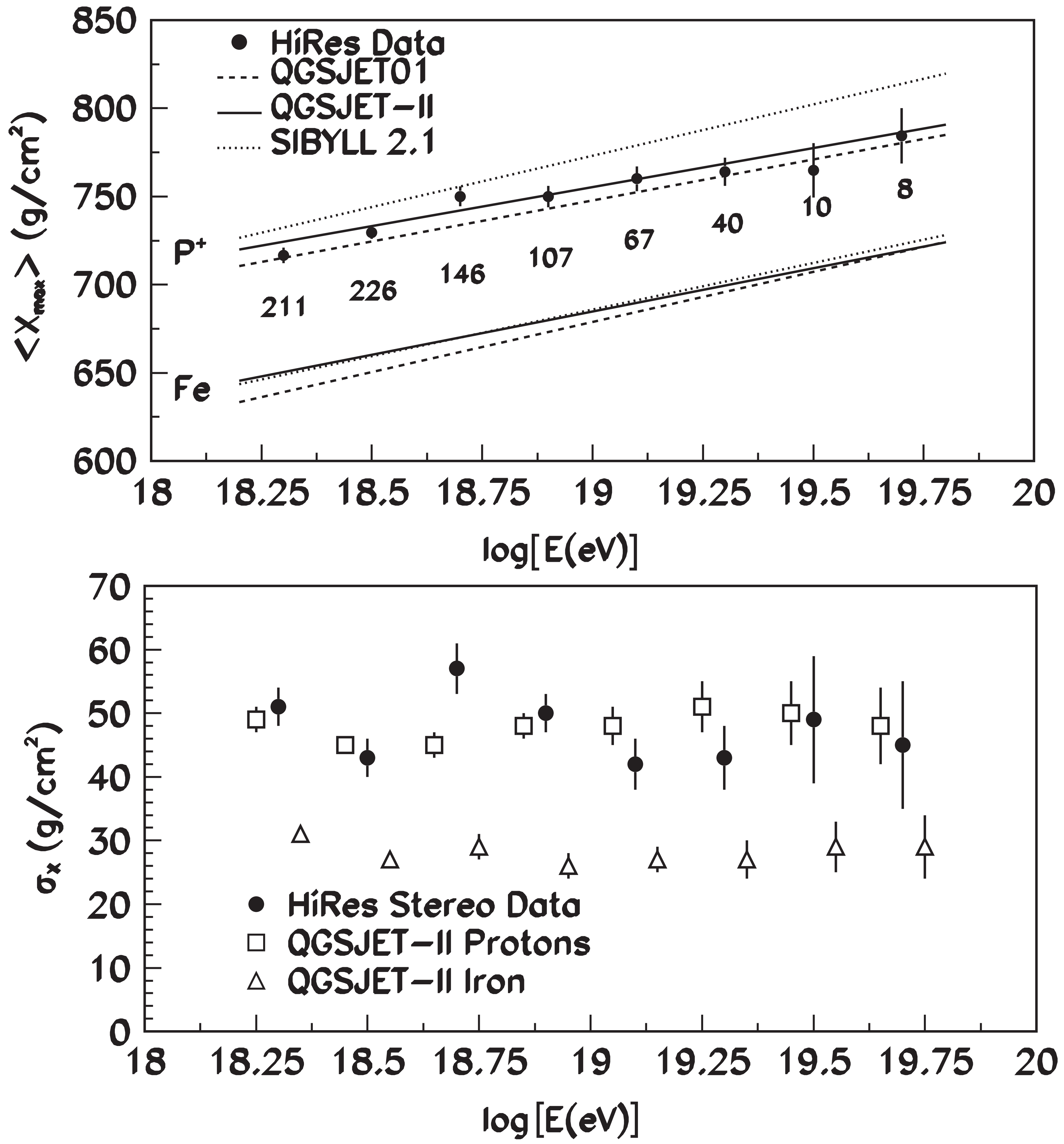
⇒ Need more statistic of ultrahigh energy cosmic rays (UHECRs)

AGASA/HiRes results (2003)



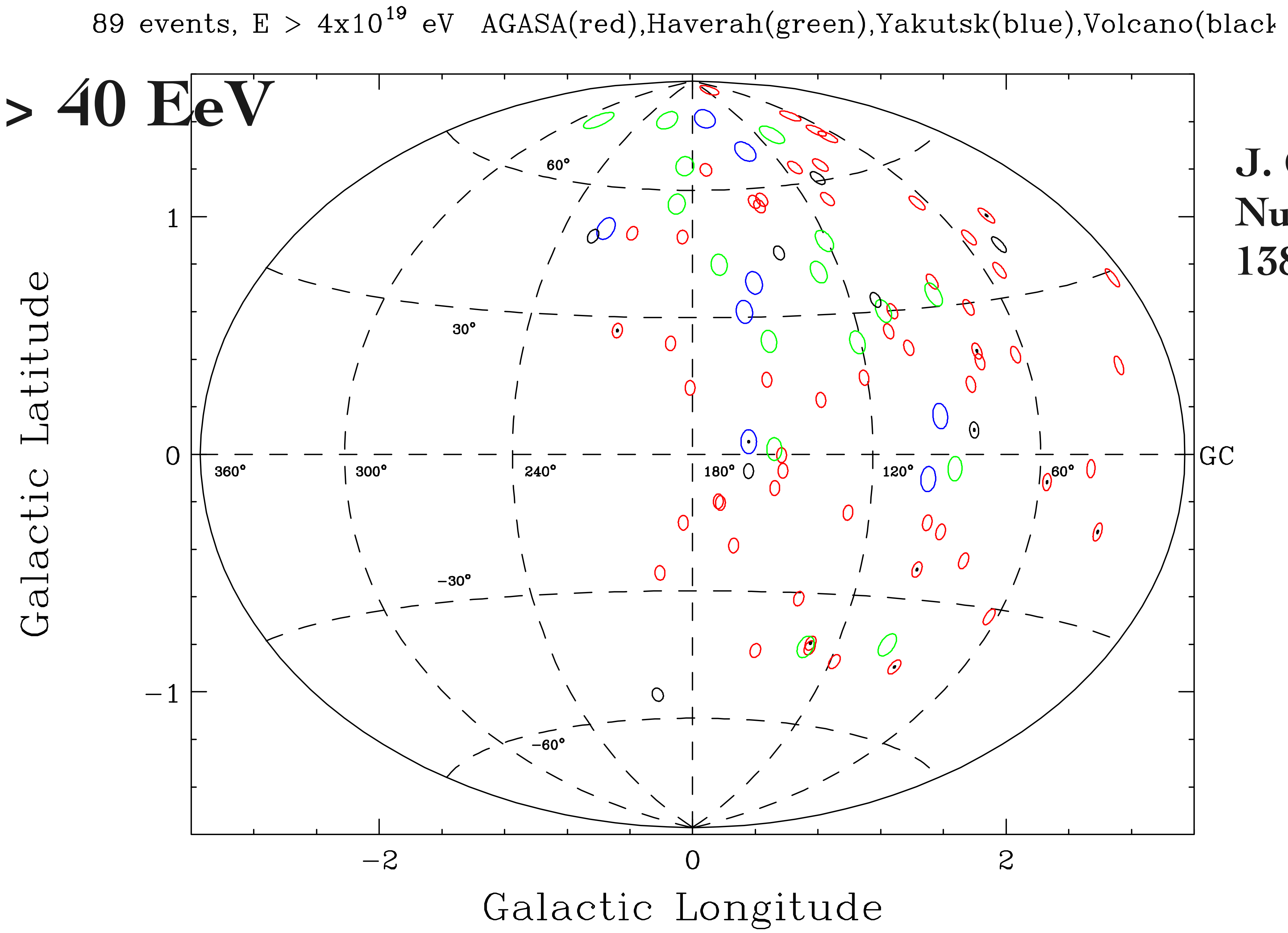
M. Takeda et al., PRL 81, 1163 (1998)

R. Abbasi et al., PRL 100, 101101 (2008)



R. Abbasi et al., PRL 104, 161101 (2010)

$E > 40$ EeV



J. Cronin, Nucl.Phys.Proc.Suppl. 138:465 (2005)

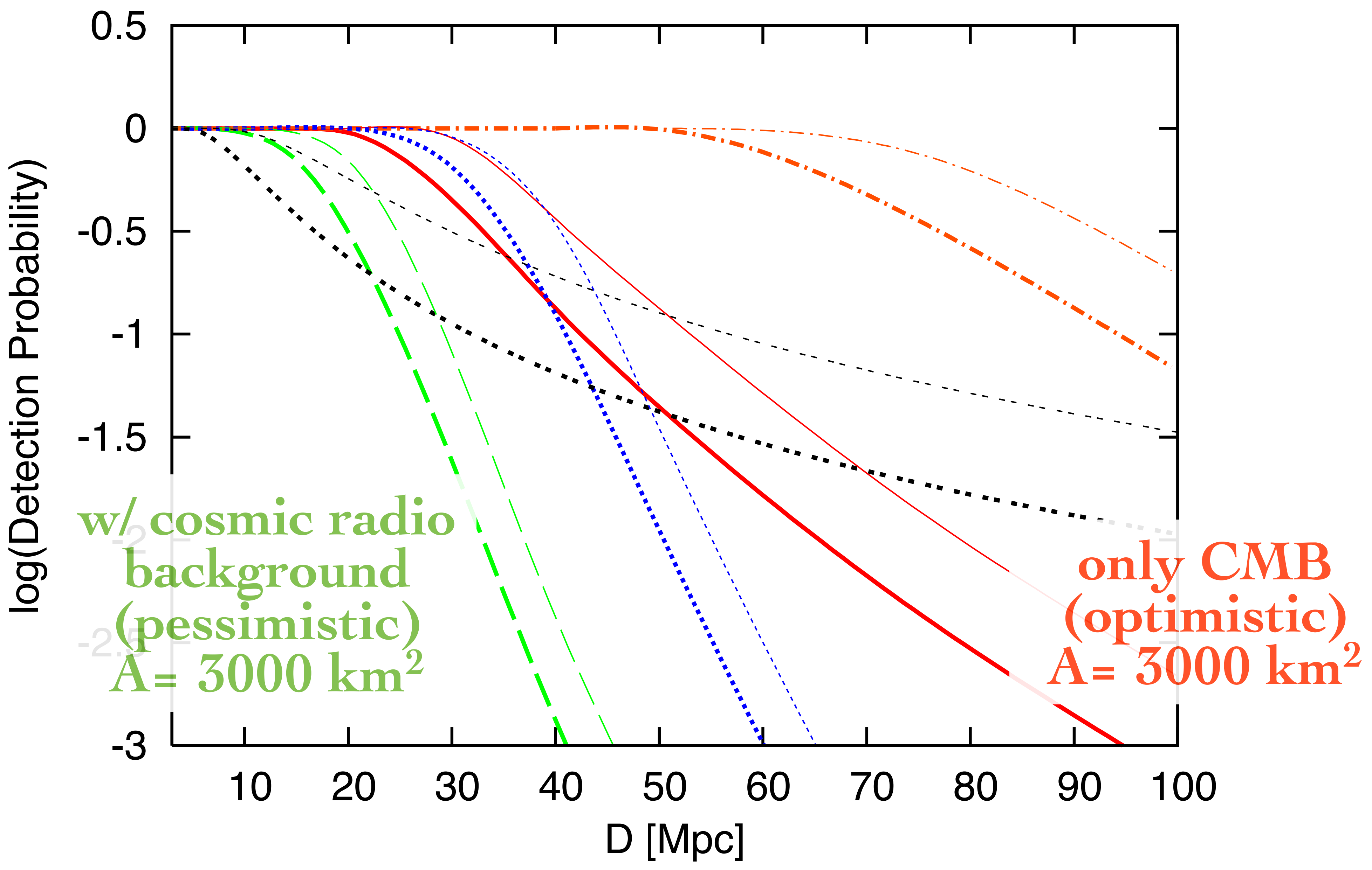
- Super-GZK cosmic rays?
- Proton dominated?
- Small-scale anisotropy?

Due to a significantly improved statistics of ultrahigh-energy cosmic rays (UHECRs) by the Telescope Array Experiment and Pierre Auger Observatory, we firmly confirmed a suppression of the energy spectrum at the highest energies and observed intriguing large-scale anisotropies in arrival directions of UHECRs. We also encountered a gradually transition to a heavier composition, a deficit of the number of muons in simulations and a lack of desired small-scale anisotropies.

In this talk, I highlight recent results of the two observatories including on-going updates and then address scientific goals and requirements for future UHECR observatories in next decade. I introduce three ideas as a personal decadal survey: ① **a fine-pixel fluorescence telescope for low-energy extension**, ② **a layered Water-Cherenkov detector array** for sub-EeV anisotropy and ultrahigh-energy photon search, and ③ **a low-cost fluorescence telescope array** suitable for measuring the properties of UHECRs with an unprecedented aperture.

Expected results from ongoing upgrades and smoking gun

- Expected (optimistic) results in next 5 years
  - TA×4: confirmation of the TA hotspot with >5σ
  - AugerPrime: indication of small scale anisotropies selecting a light composition, proton fraction at 10^{20} eV.
  - Interaction model: < 20 g/cm^2 uncertainty on X_{max} at 10^{20} eV



- **Smoking gun of cosmic ray origin** ⇒ γ-rays detection spacial coincidence with UHECR hotspot
  - **γ-ray: limited sources in nearby universe**
    - bursts of γ-rays above 10 EeV, 1-100 events
      - **3000 km^2 : 25 - 40 Mpc (TA×4, Auger)**
      - **30000 km^2: 40 - 80 Mpc**
      - **300 km^2 : 5 - 10 Mpc**

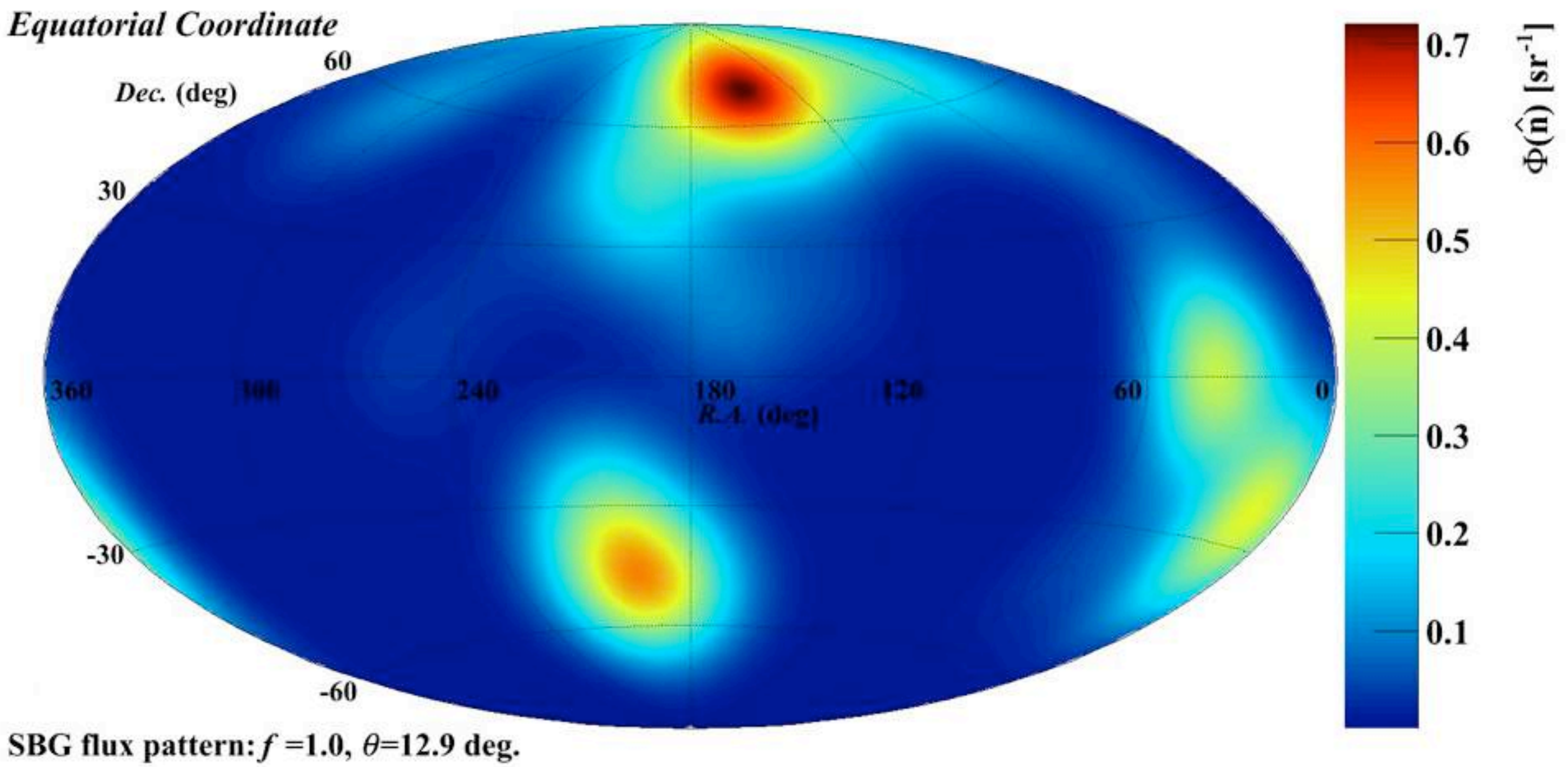
FIG. 3: The comparison of Poisson probabilities to detect UHE (> 10 EeV) photons and high-energy (> 10 PeV) neutrinos from a LL GRB-like UHECR burst. For UHE photons, $A = 3000$ km^2 without the CRB (solid lines), $A = 3000$ km^2 with the CRB (dashed lines), $A = 3 \times 10^5$ km^2 without the CRB (dotted-dashed lines), and $A = 3 \times 10^5$ km^2 with the CRB (dotted lines). For neutrinos, $A = 1$ km^2 (double-dashed lines), assuming IceCube-like detectors. Thick and thin lines are for $\tilde{\mathcal{E}}^{\rm iso}_{\rm HECR} = 10^{50.5}$ erg and $\tilde{\mathcal{E}}^{\rm iso}_{\rm HECR} = 10^{51}$ erg, respectively.

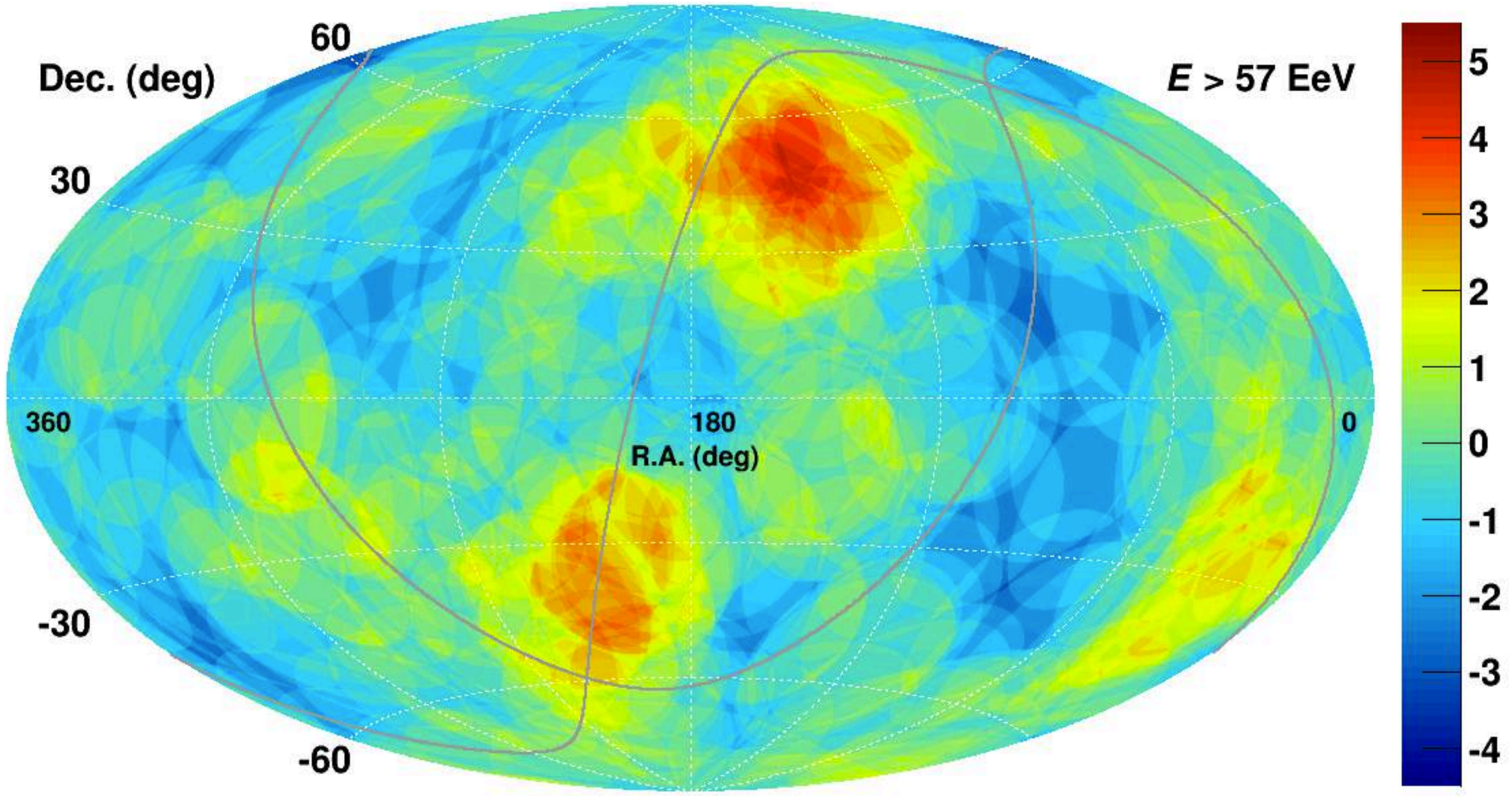
K. Murase, Phys.Rev.Lett. 103 (2009) 081102

Addressing the intermediate anisotropies

SBG flux map, Φ=12.9°

TA+Auger at E>57 EeV





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

4σ at 39 EeV, only 9.7% anisotropic fraction

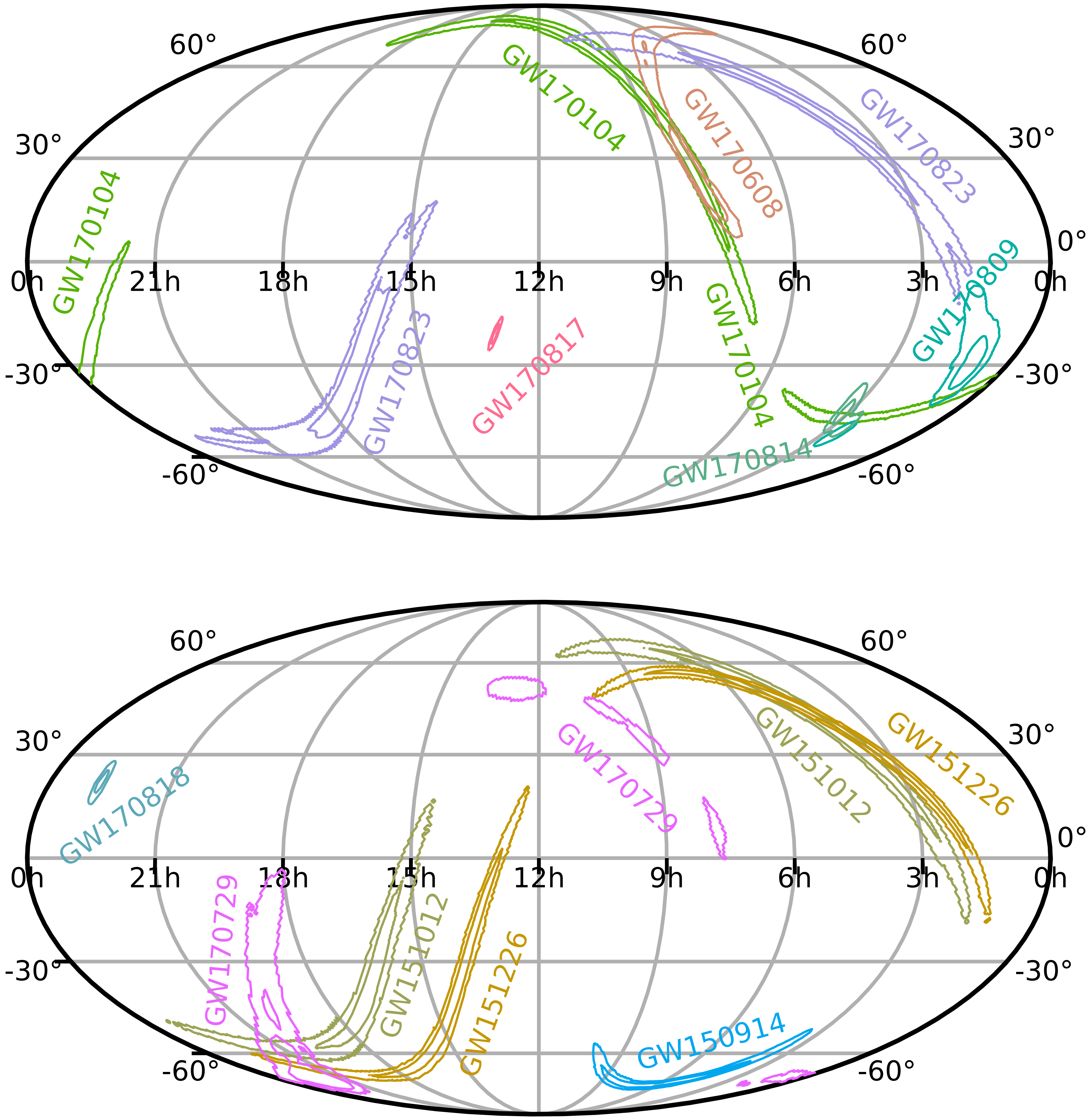
Starburst galaxies detected by Fermi

Pierre Auger Collaboration, ApJL 853:L29 (2018)

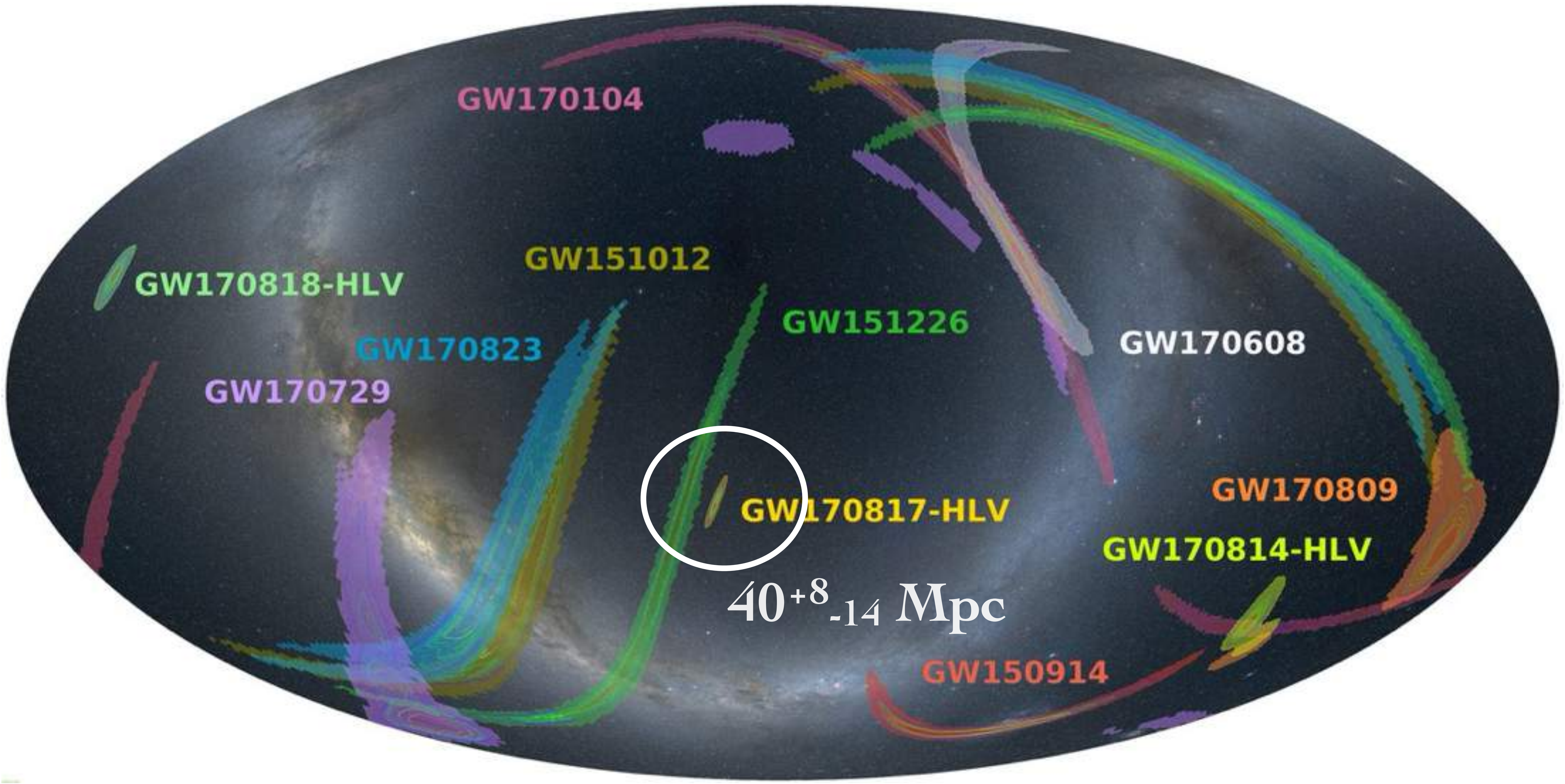
SBGs	l (°)	b (°)	Distance[a] (Mpc)	Flux Weight (%)	Attenuated Weight: A/B/C (%)	% Contribution[b]: A/B/C (%)
NGC 253	97.4	−88	2.7	13.6	20.7/18.0/16.6	35.9/32.2/30.2
M82	141.4	40.6	3.6	18.6	24.0/22.3/21.4	0.2/0.1/0.1
NGC 4945	305.3	13.3	4	16	19.2/18.3/17.9	39.0/38.4/38.3
NGC 1068	172.1	−51.9	17.9	12.1	5.6/7.9/9.0	6.4/9.4/10.9

10 EeV γ-ray with 300 km^2 : 5 - 10 Mpc

GWTC-1: Gravitational Wave Transient Catalog



arXiv: 1811.12907



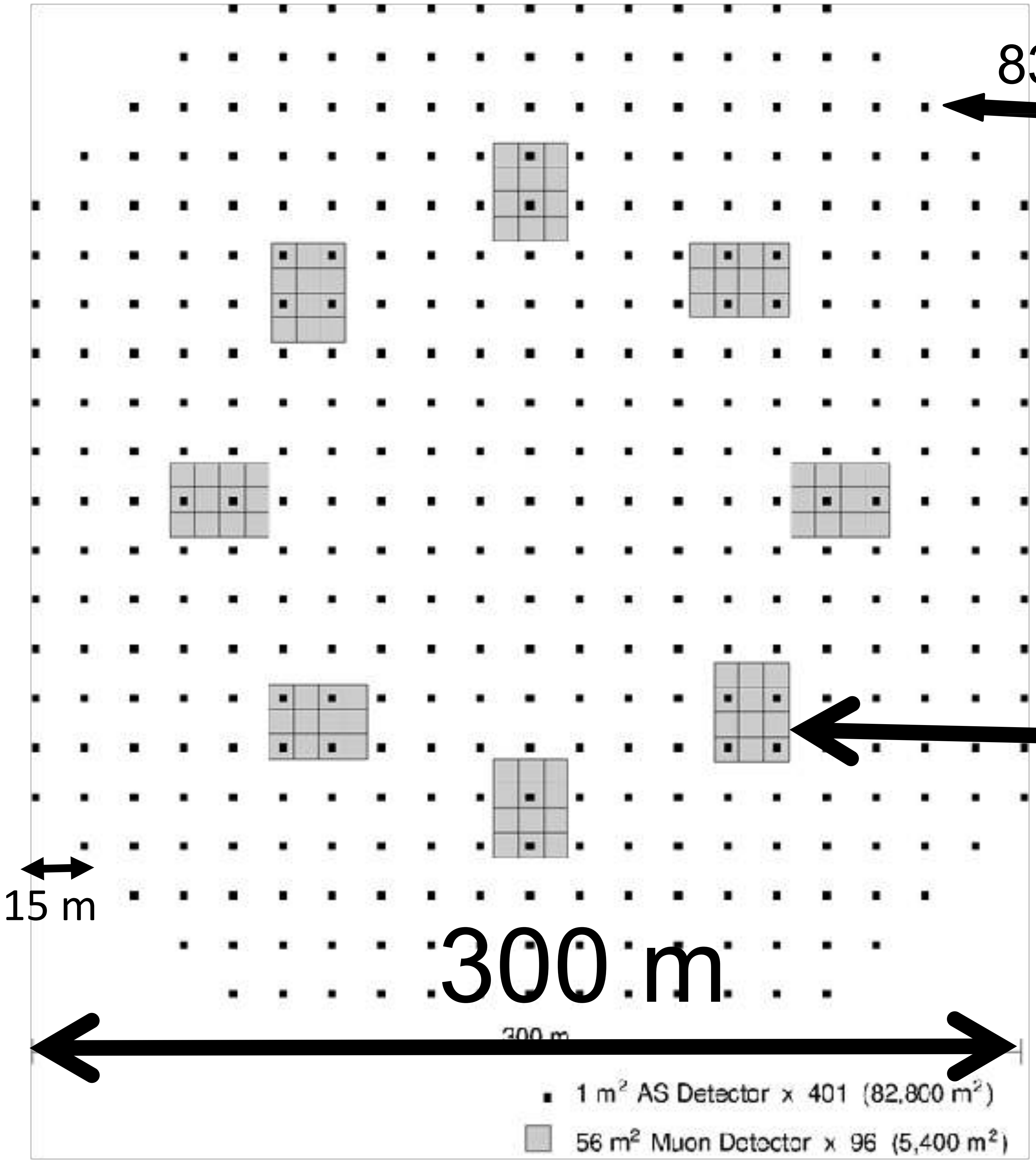
credit: Guiseppe Greco, Axel Mellinger

γ-ray 10 EeV with 30,000 km^2: 40 - 80 Mpc

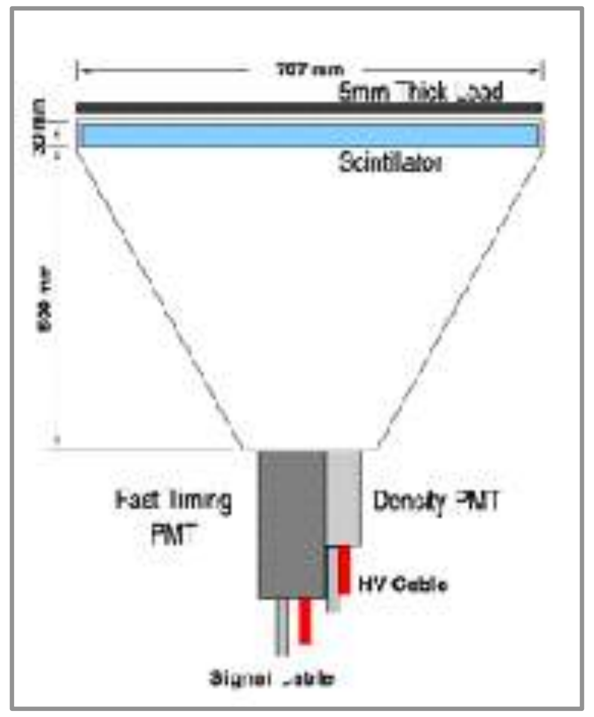
UHE γ-ray burst driven multi-messenger

Established method for γ-ray detections

Schematic view of ALPACA

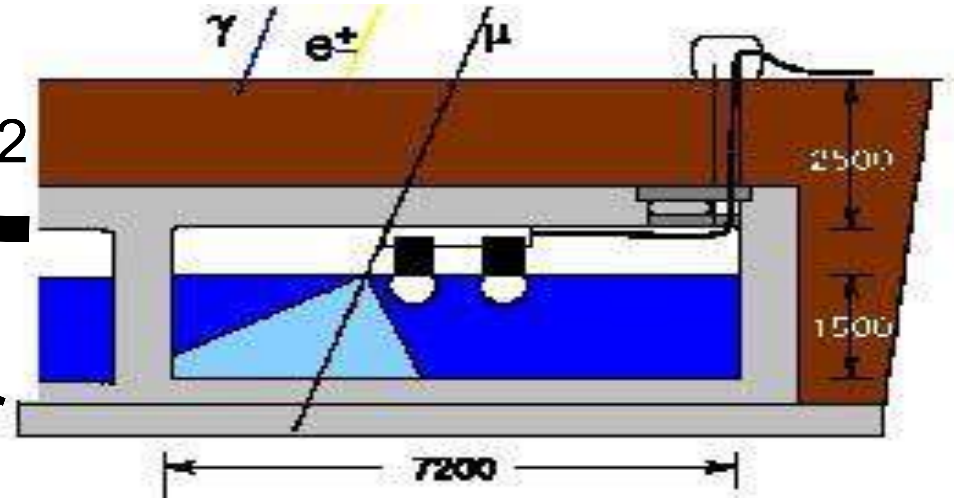


83,000 m²
Air Shower Array



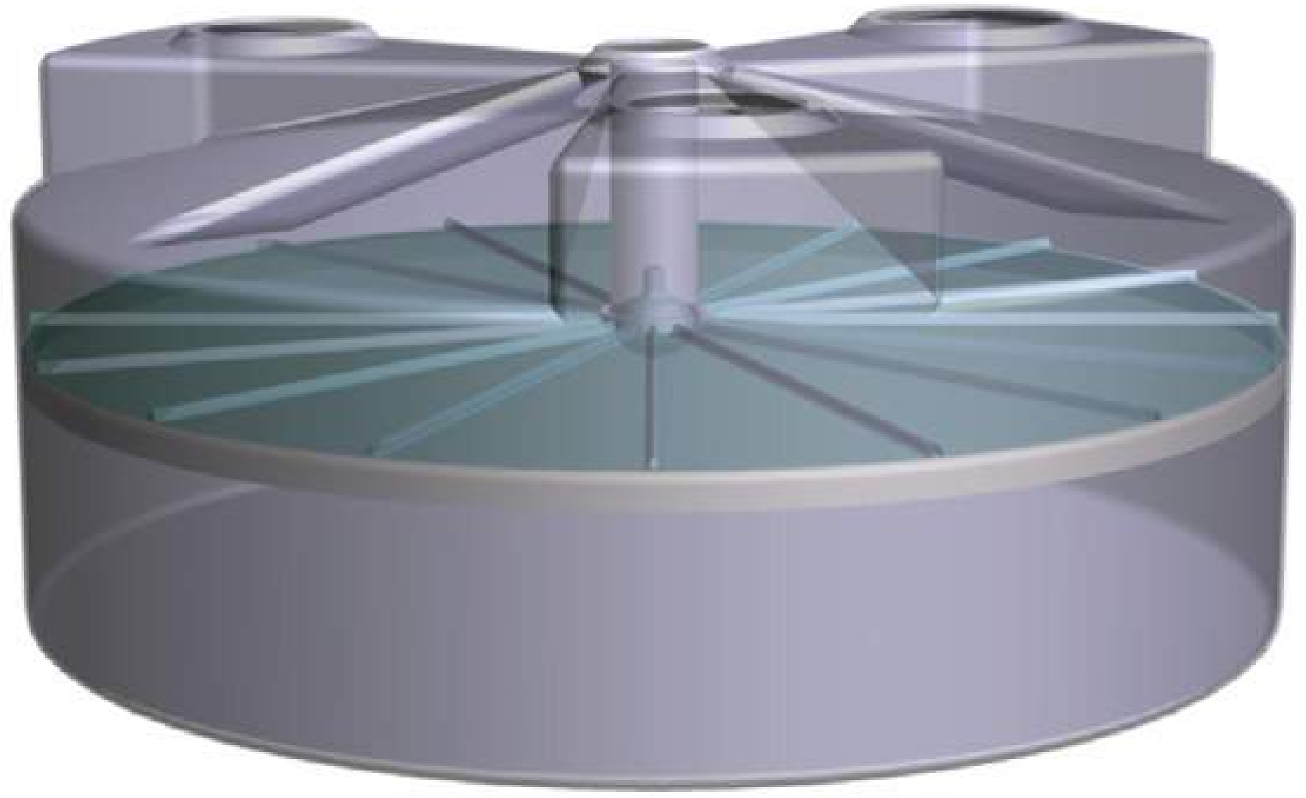
1m² plastic scintillation detector

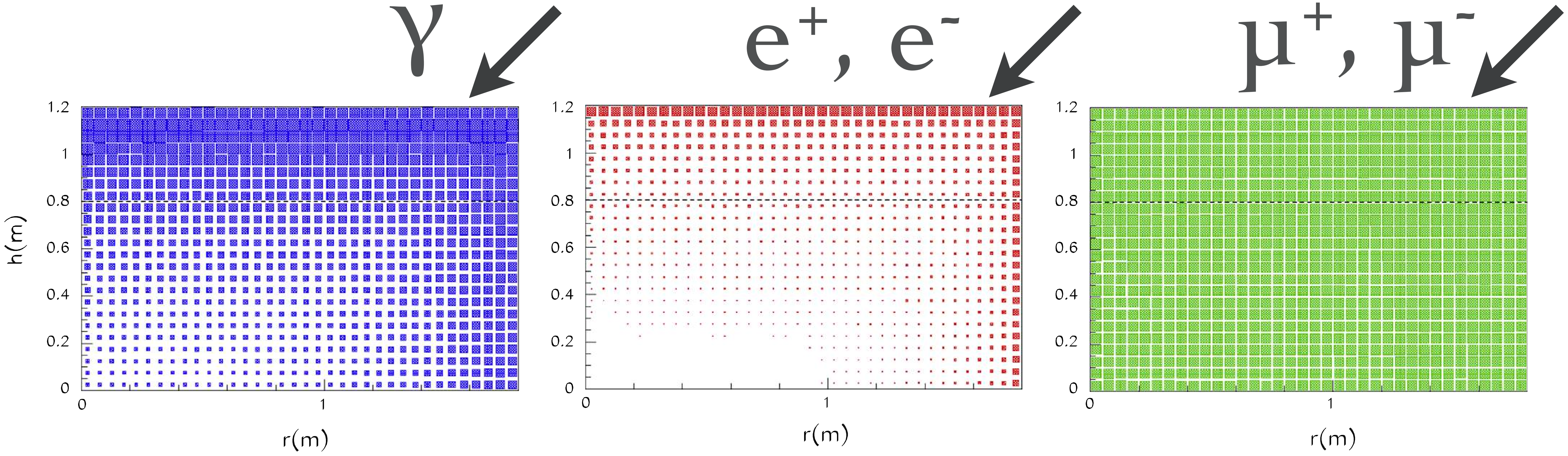
5,400 m²
Muon Detector Array

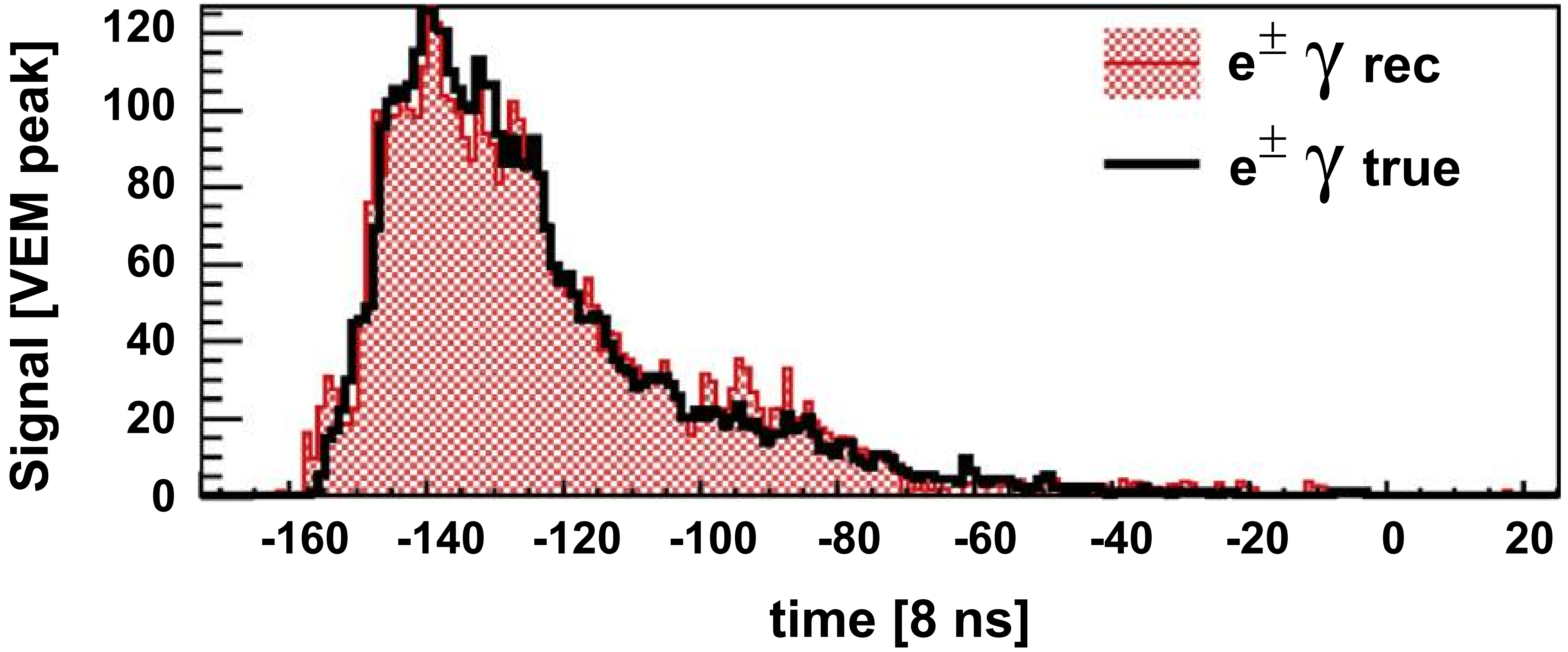


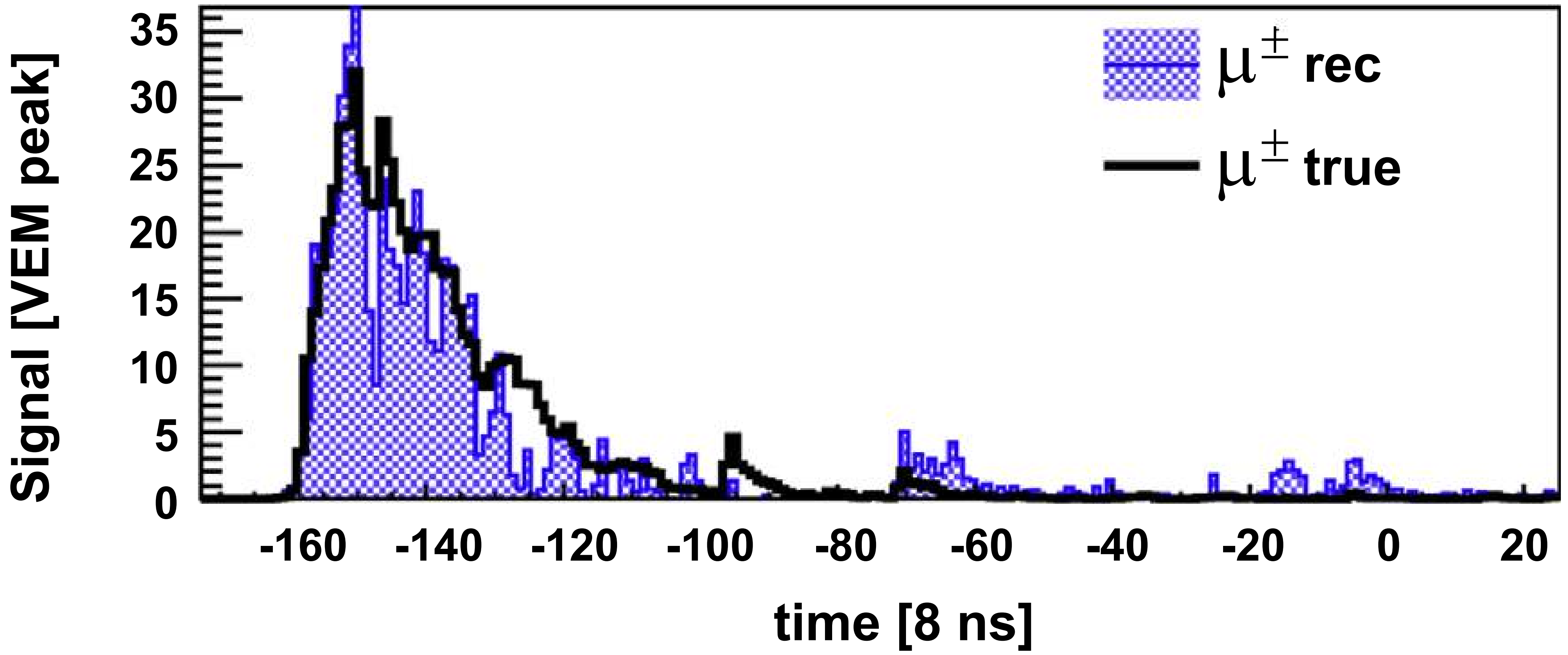
Underground water Cherenkov muon detector (56 m² / unit)

Surface detector array of Layered Observational Water-cherenkov counters





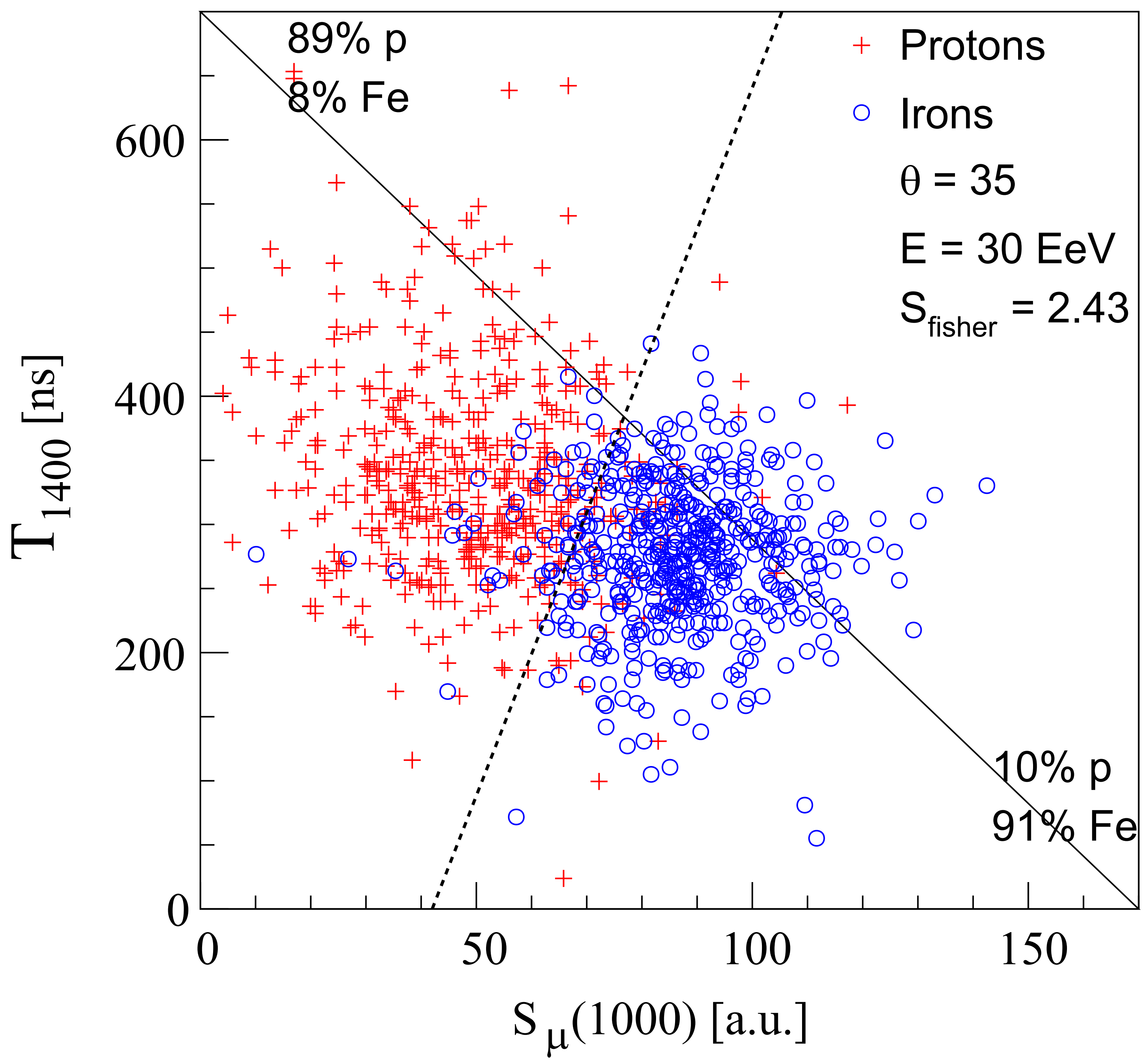


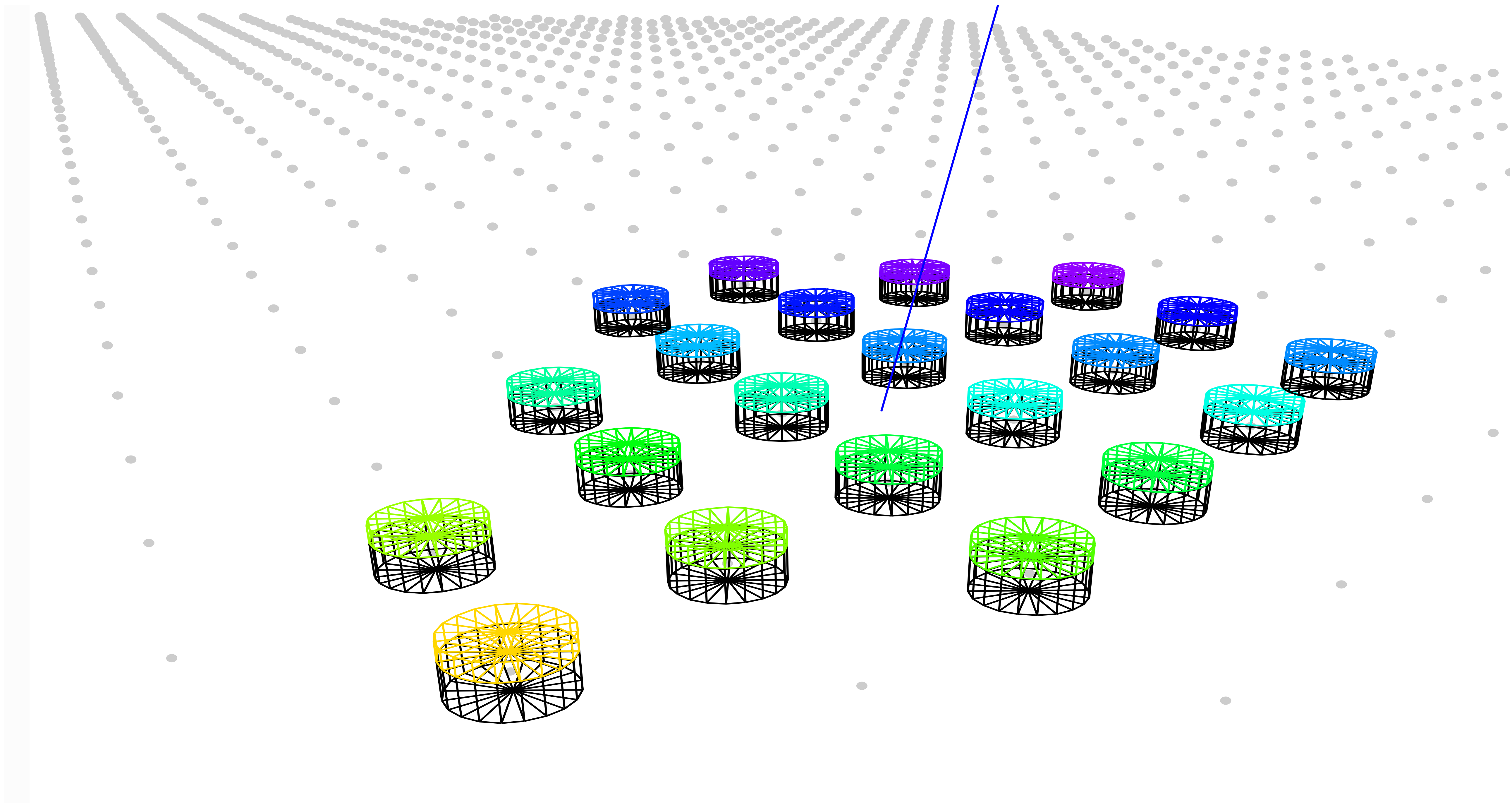


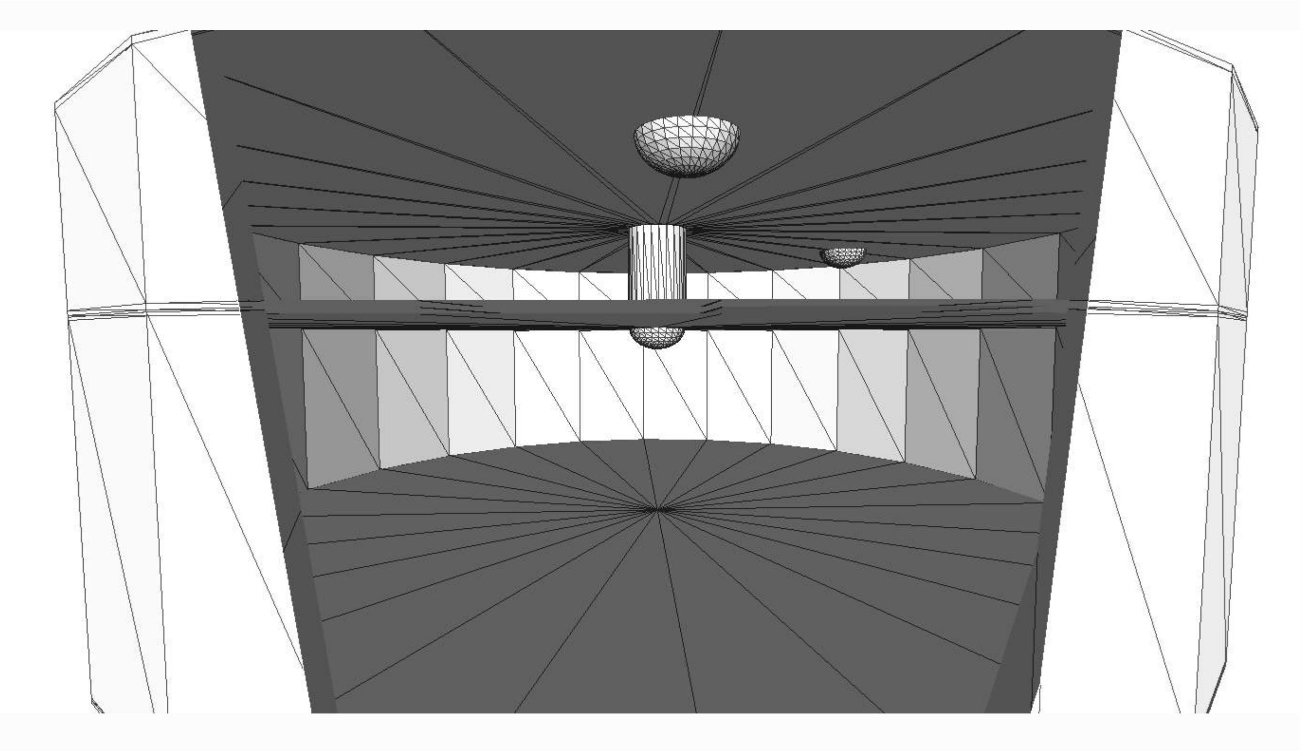
Nuclear Instruments and Methods in Physics Research A 767 (2014) 41–49

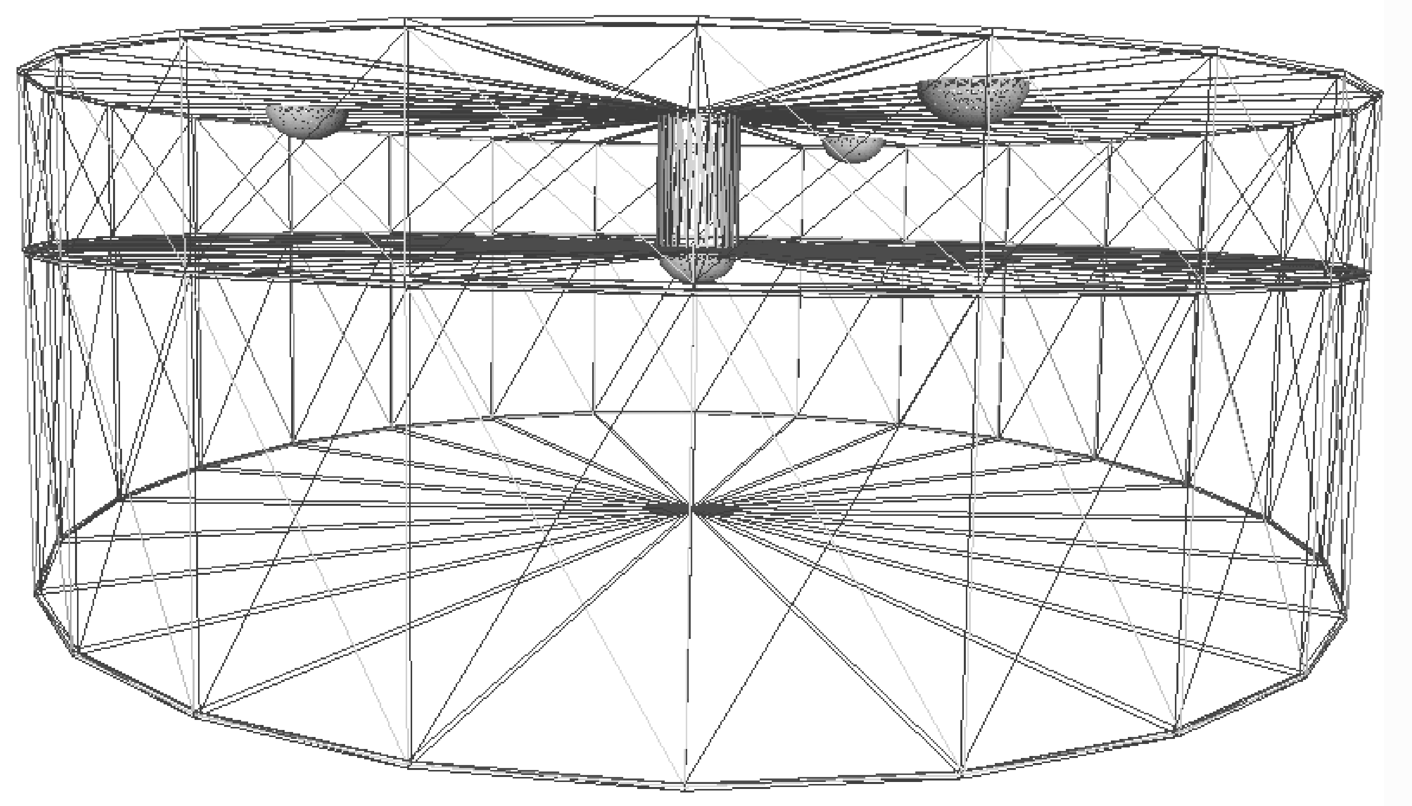
Antoine Letessier-Selvon [a,*], Pierre Billoir [a], Miguel Blanco [a], Ioana C. Mariş [a,b], Mariangela Settimo [a]

Surface detector array of Layered Observational Water-cherenkov counters



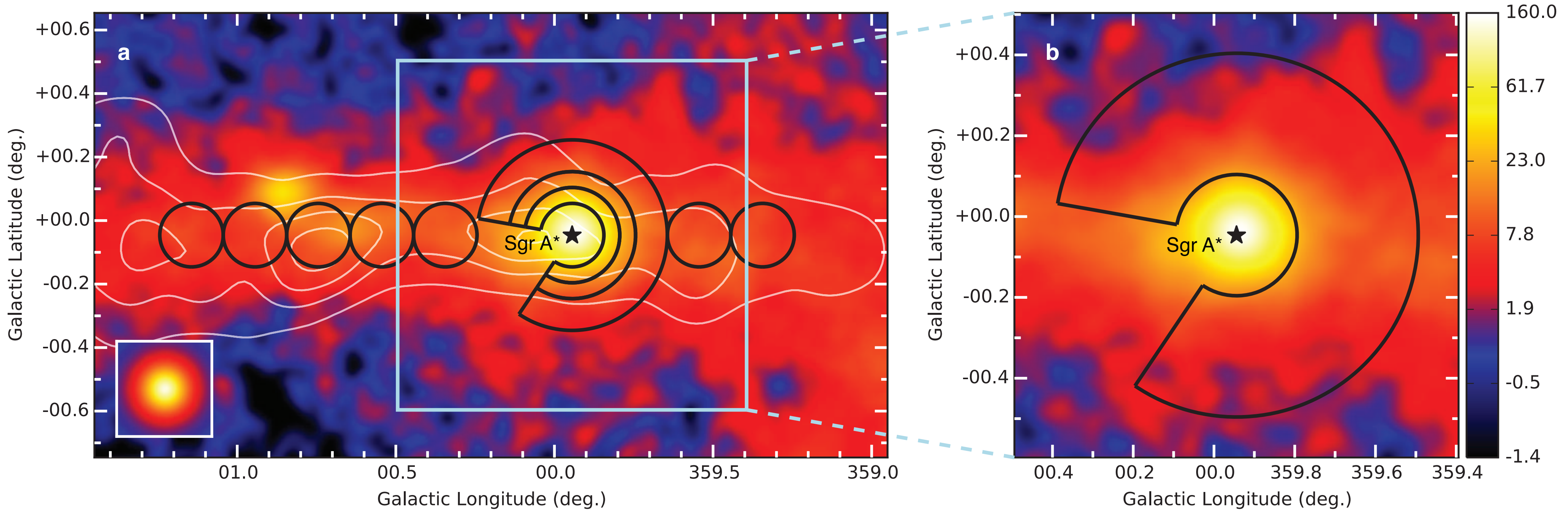






- 750 m spacing in triangular arrangement
- 10 m^2, 800 stations → ~200 km^2 ,
  - 16 million USD for detectors
- 100% efficiency above $10^{17.5}$ eV
  - p/Fe separation: 10^{-1}, γ/Hadron separation: 10^{-3}

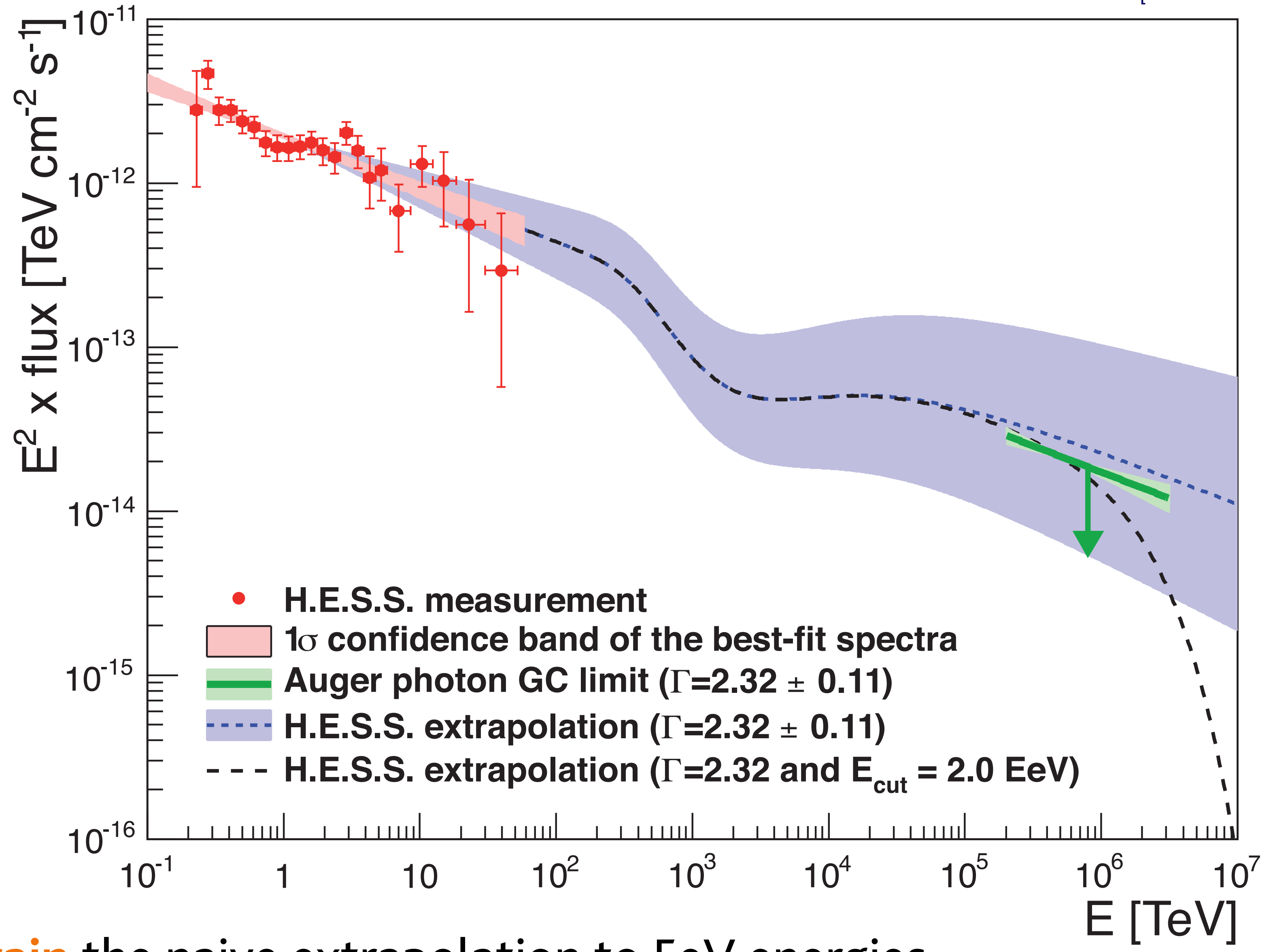
Sub-EeV γ-ray search and anisotropy



Targeted photon search: galactic center

- Interpretation of H.E.S.S. PeVatron results for the galactic center region

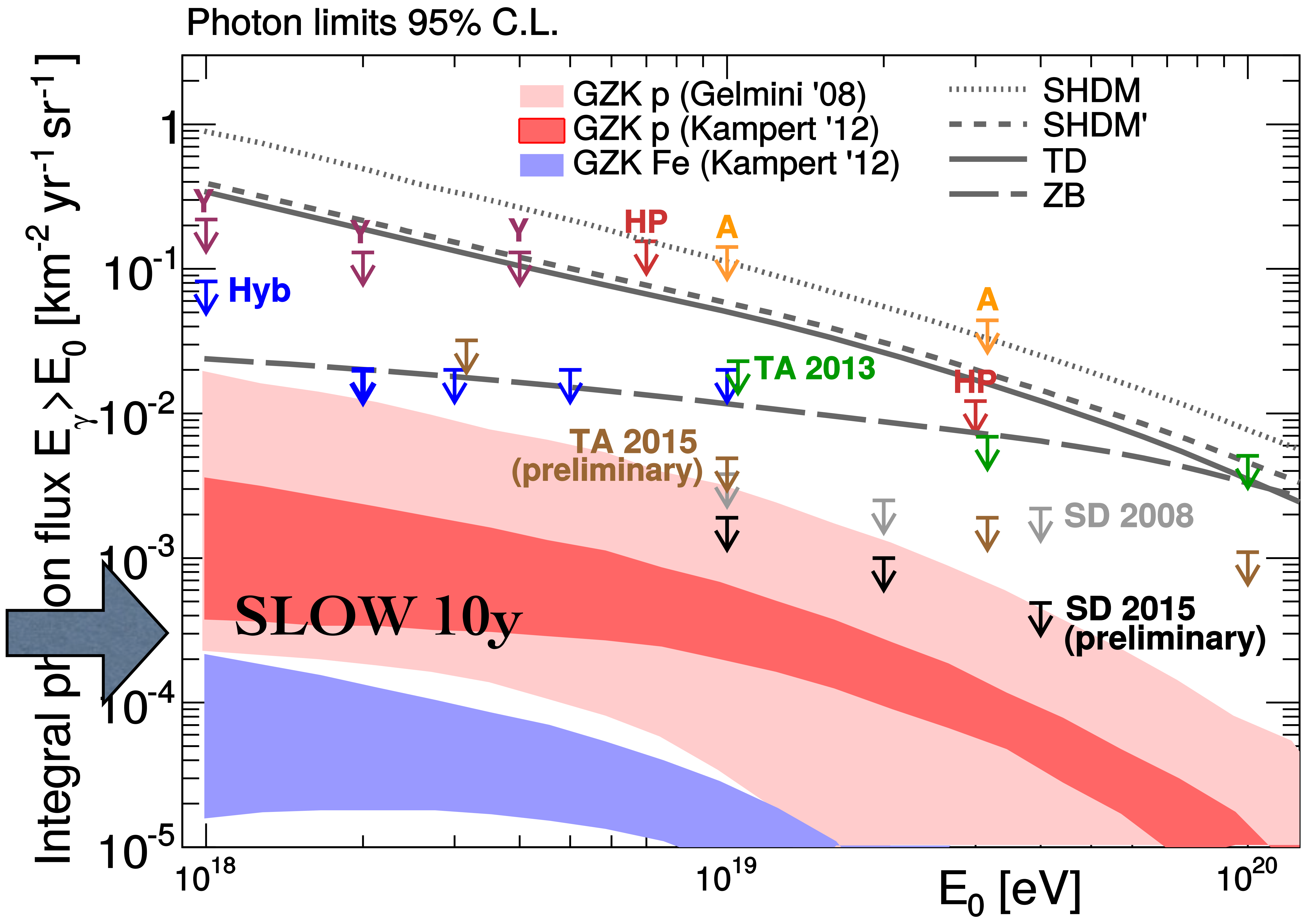
[The H.E.S.S. Collaboration, Nature 531 (2016) 476]



- Constrain the naive extrapolation to EeV energies
- Upper limit on the cutoff energy of 2 EeV

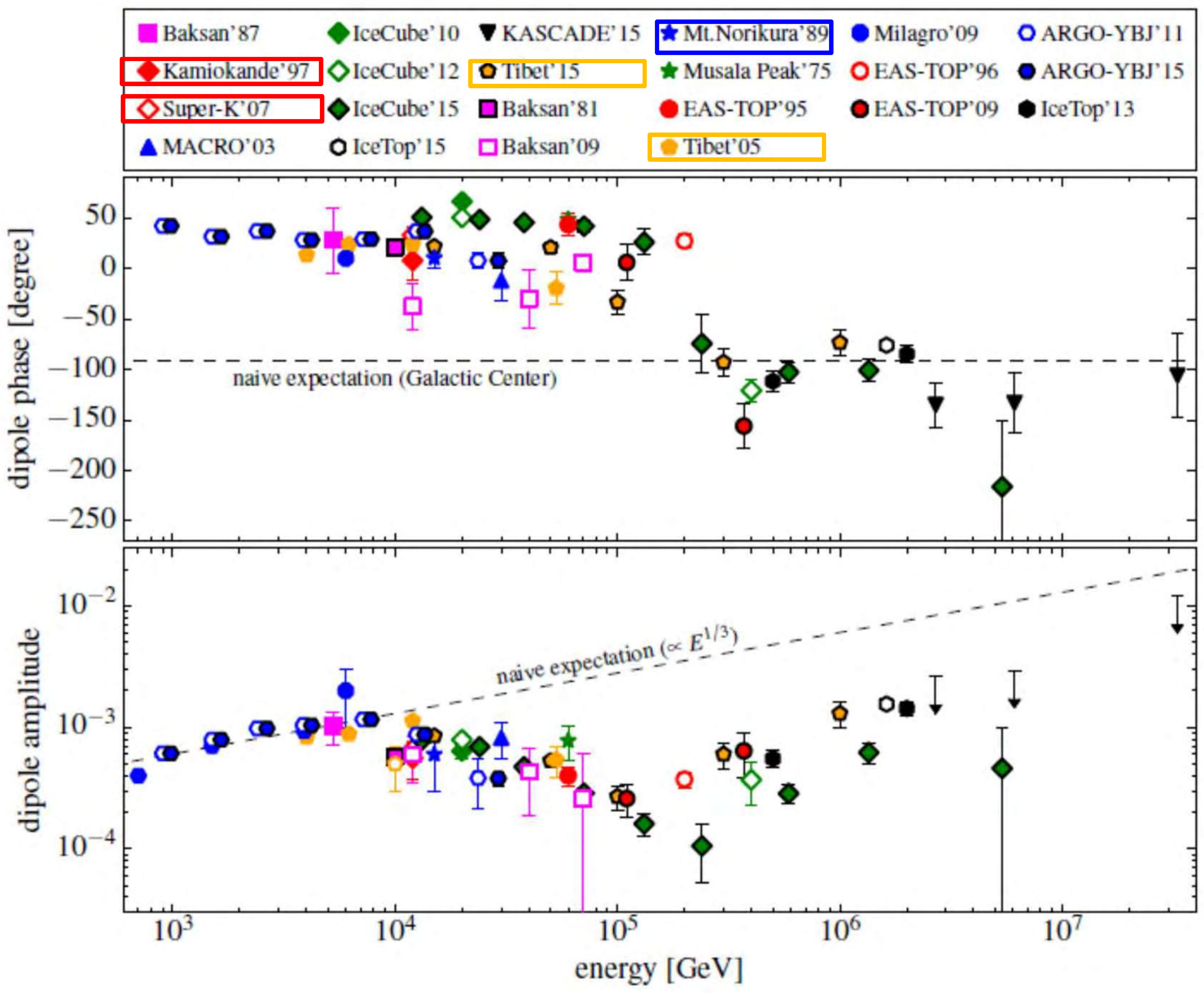
[The Pierre Auger Collaboration, ApJ 837 (2017) L25]

18.07.2017 Marcus Niechciol (Pierre Auger Collaboration) | ICRC 2017 (Busan) | CRI183 11 / 12

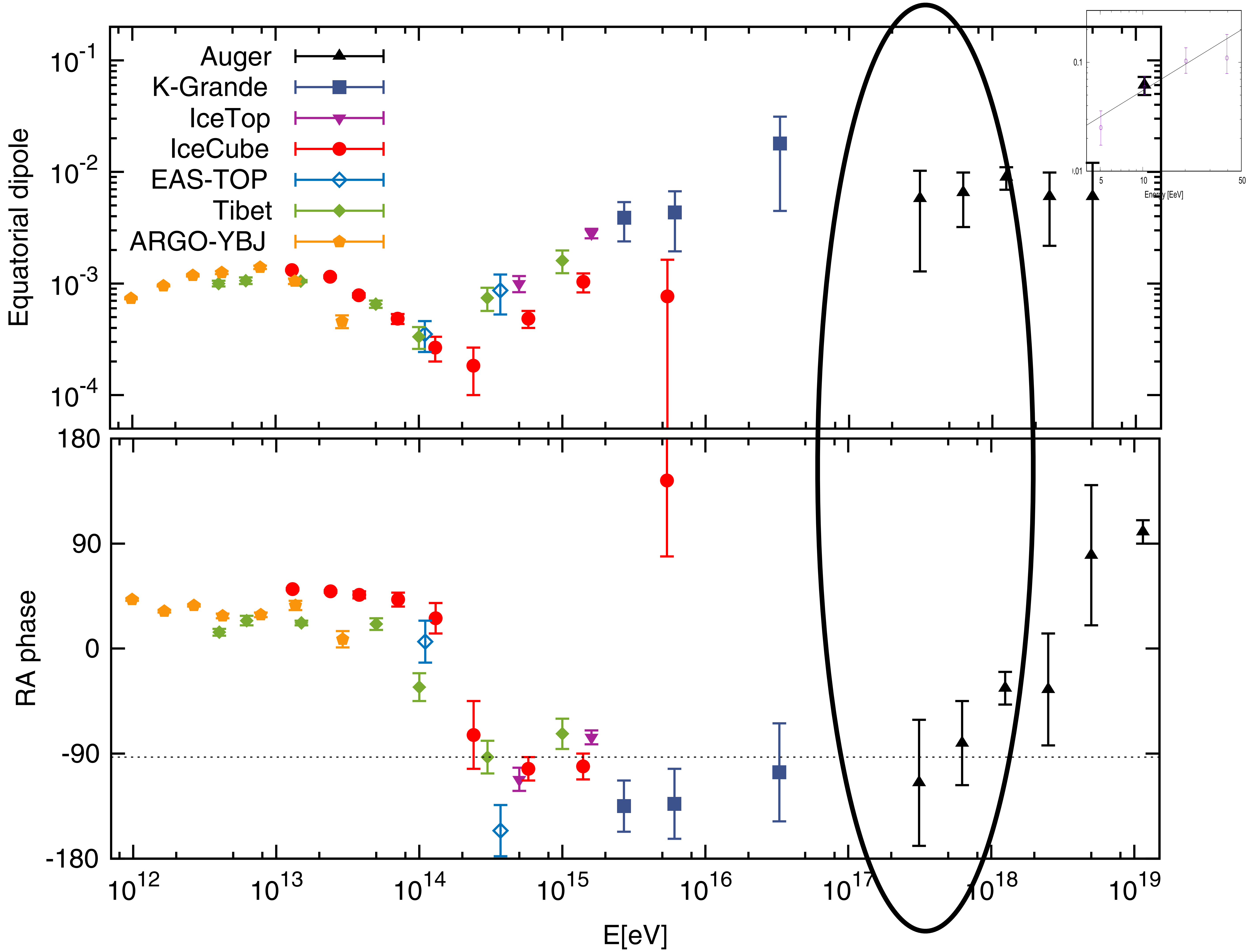


- ✦ First GZK γ and γ-ray burst detections.
- ✦ Large scale anisotropy using different compositions.
- ✦ Tuning the hadron interaction model at LHC energies

Why sub-EeV?: transition of the equatorial dipole

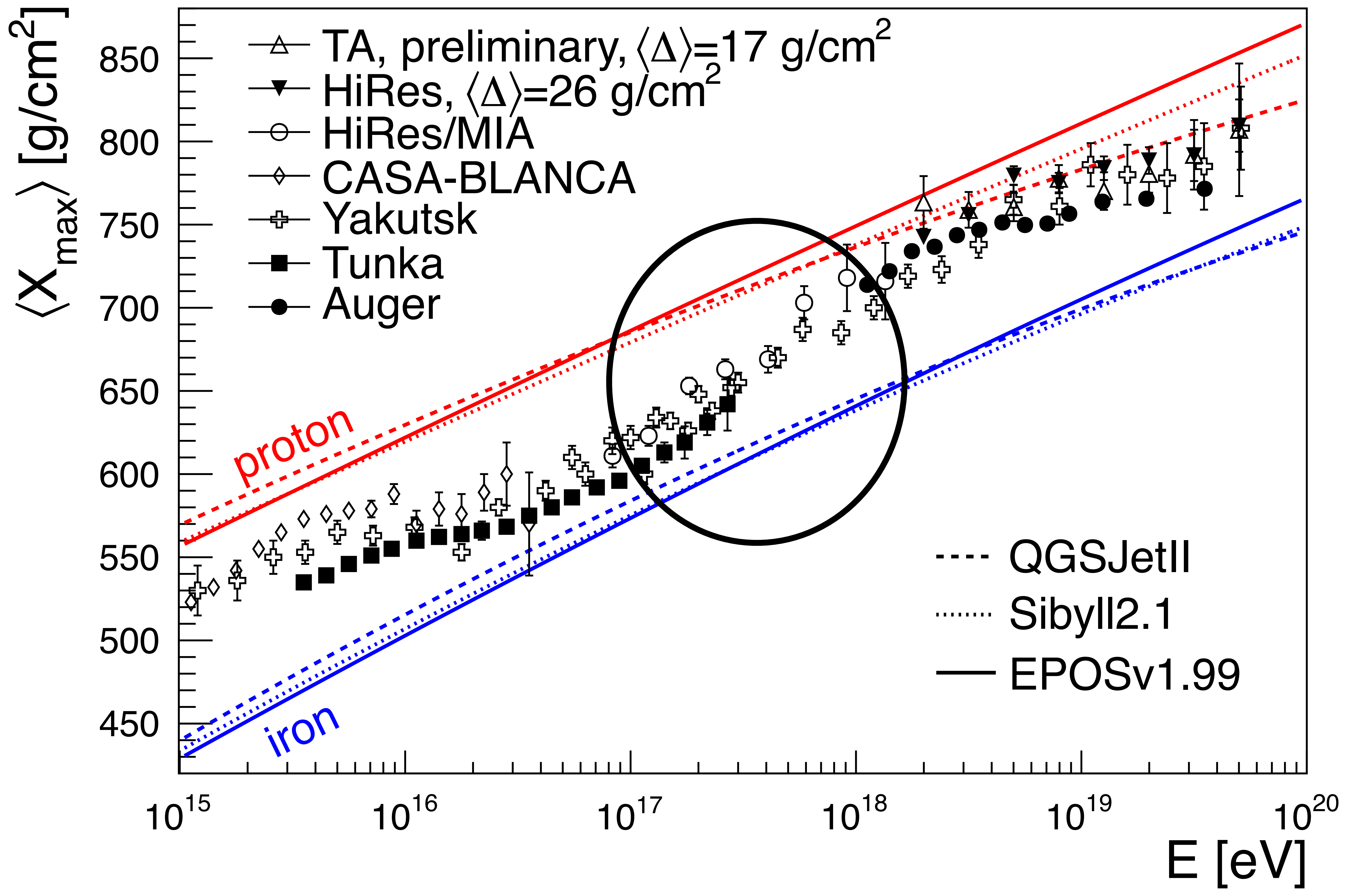


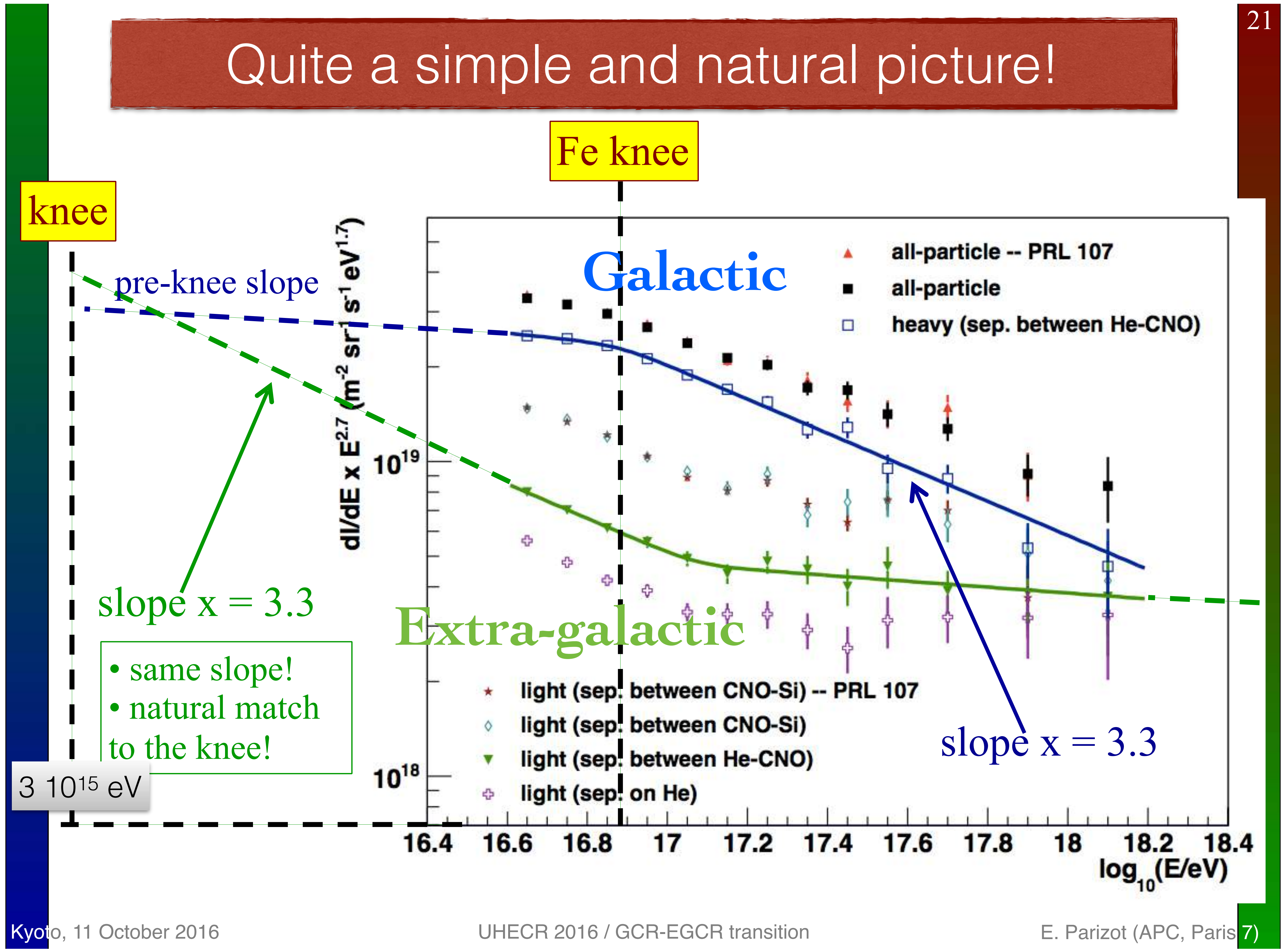
S. Mollerach, E. Roulet / Progress in Particle and Nuclear Physics 98 (2018) 85–118



宗像@ICRR共同利用成果発表 2018/12/18

Why sub-EeV?: transition of mass composition, galactic/extra-galactic



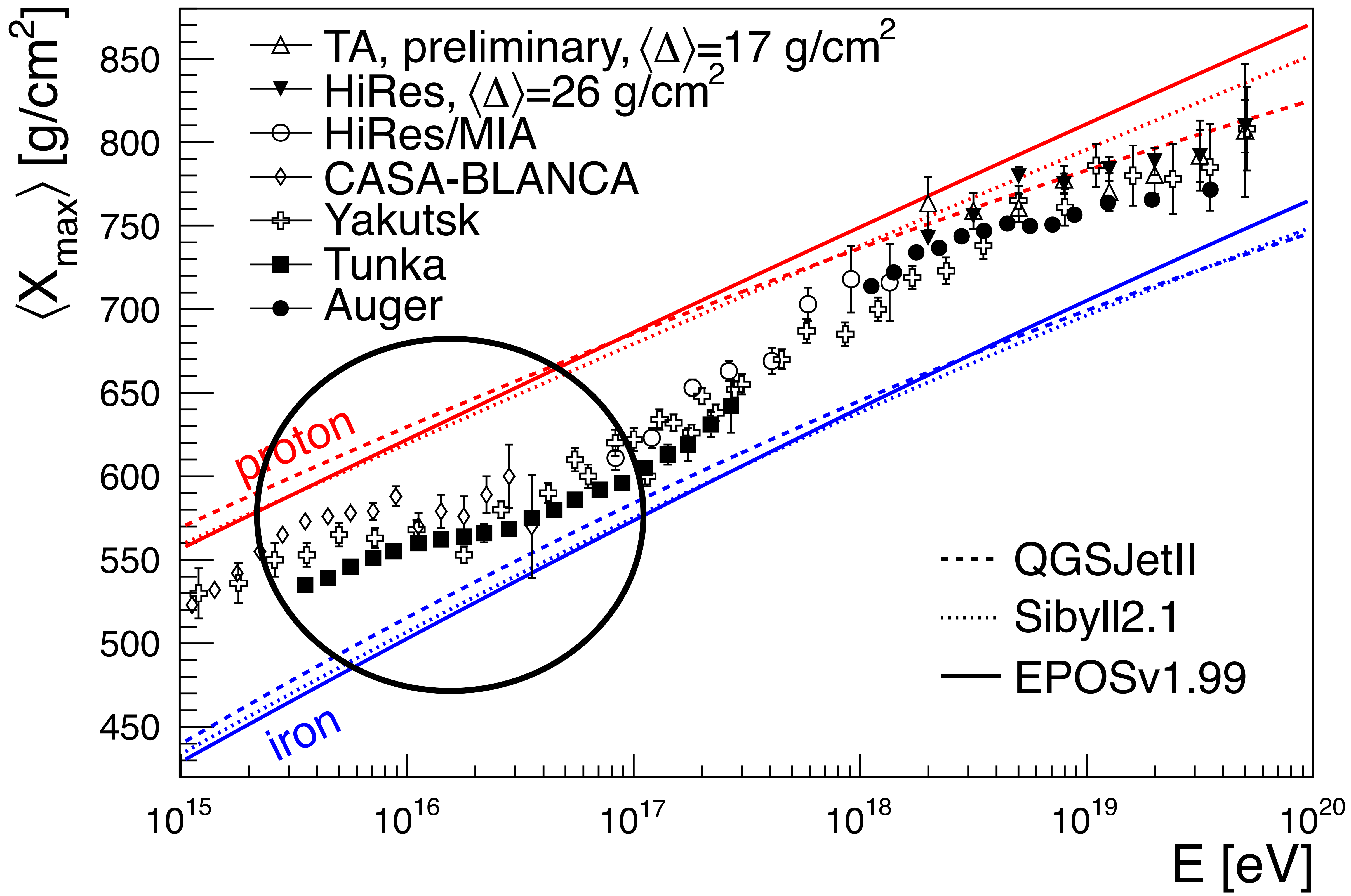


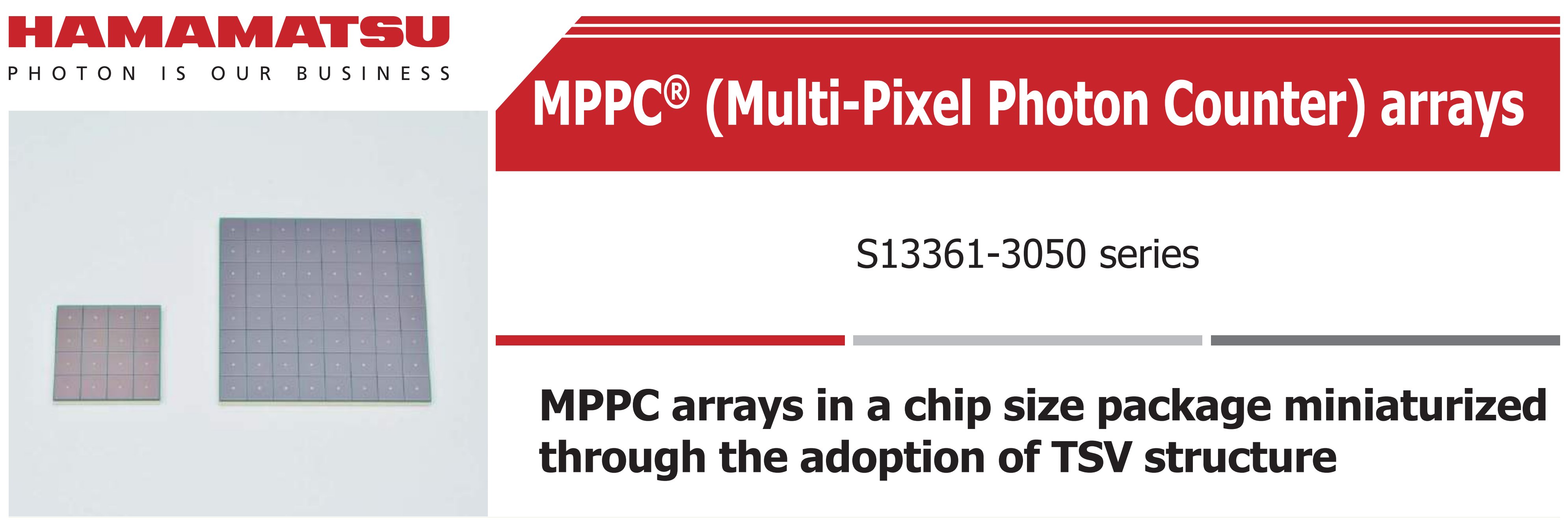
fluorescence detection above 10^{17} eV

E. Parizot in UHECR 2016

M. Unger, K. Kampert, Astropart.Phys. 35 (2012) 660-678

A fine-pixel fluorescence telescope





- 1 pixel: 3 mm × 3 mm, 8 × 8 pixels per module
- 100 modules ⇒ 25 cm × 25 cm (40 kUSD)
- 80 × 80 pixels covering in 25° × 25 °
    - 0.3° × 0.3° per pixel FoV with 1 m^2 aperture
- Xmax detection using fluorescence technique above $10^{15.5}$ eV at high altitude of 4000 m (like ALPACA)

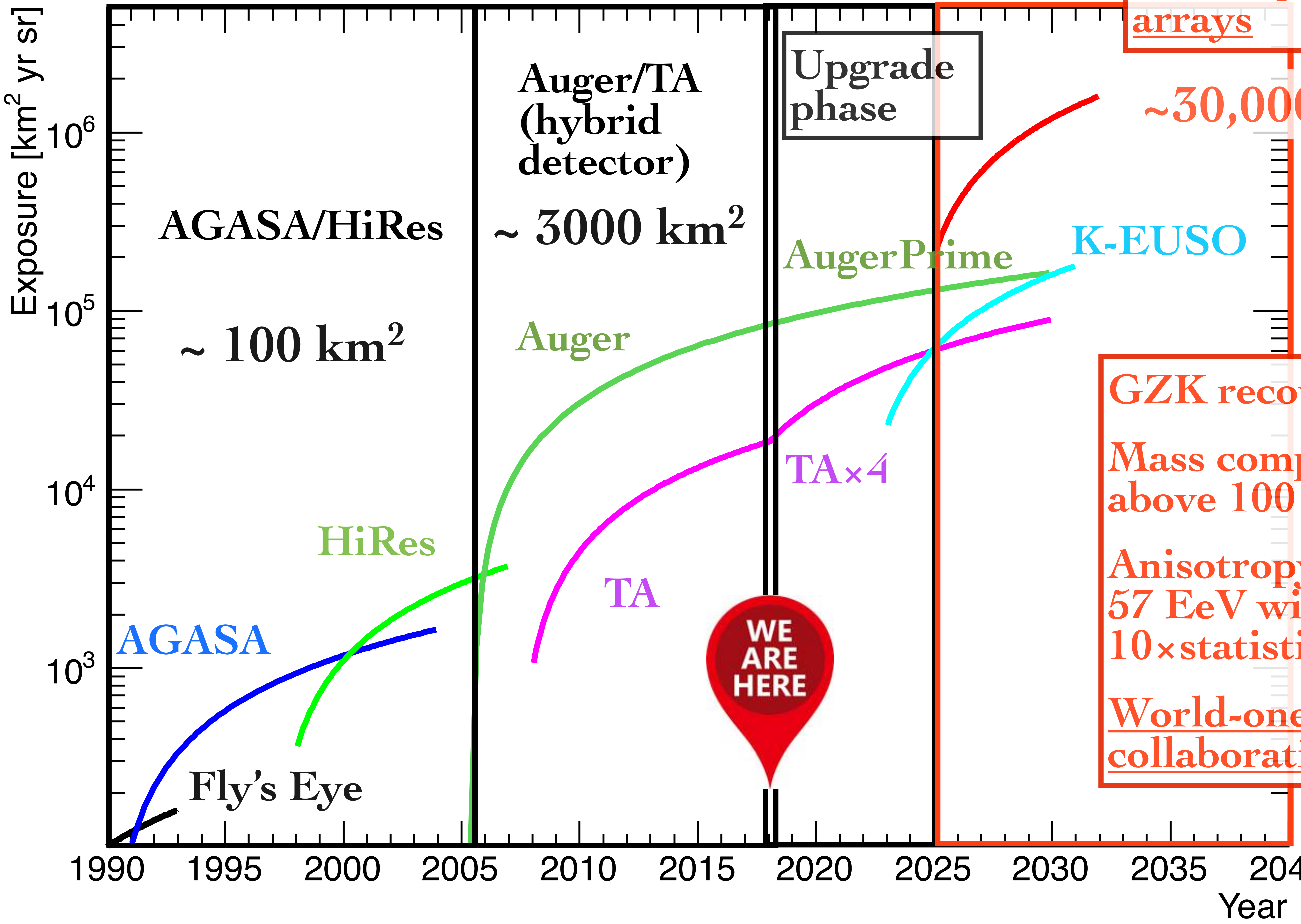
Future ground array for UHECR detections

AGASA

HiRes

Telescope Array Experiment

Pierre Auger Observatory



Future ground arrays

GZK recovery

Mass composition above 100 EeV

Anisotropy above 57 EeV with 10×statistics

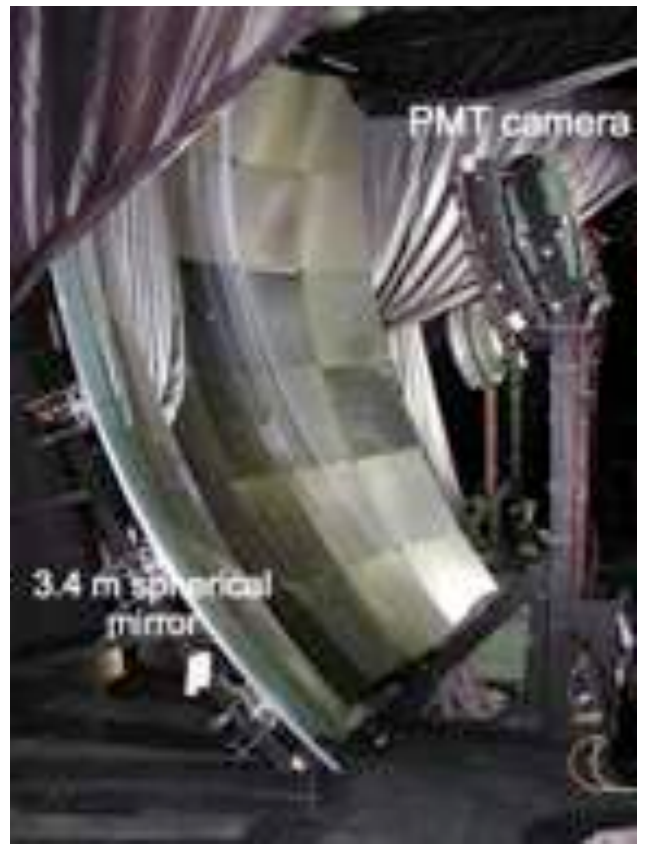
World-one collaboration

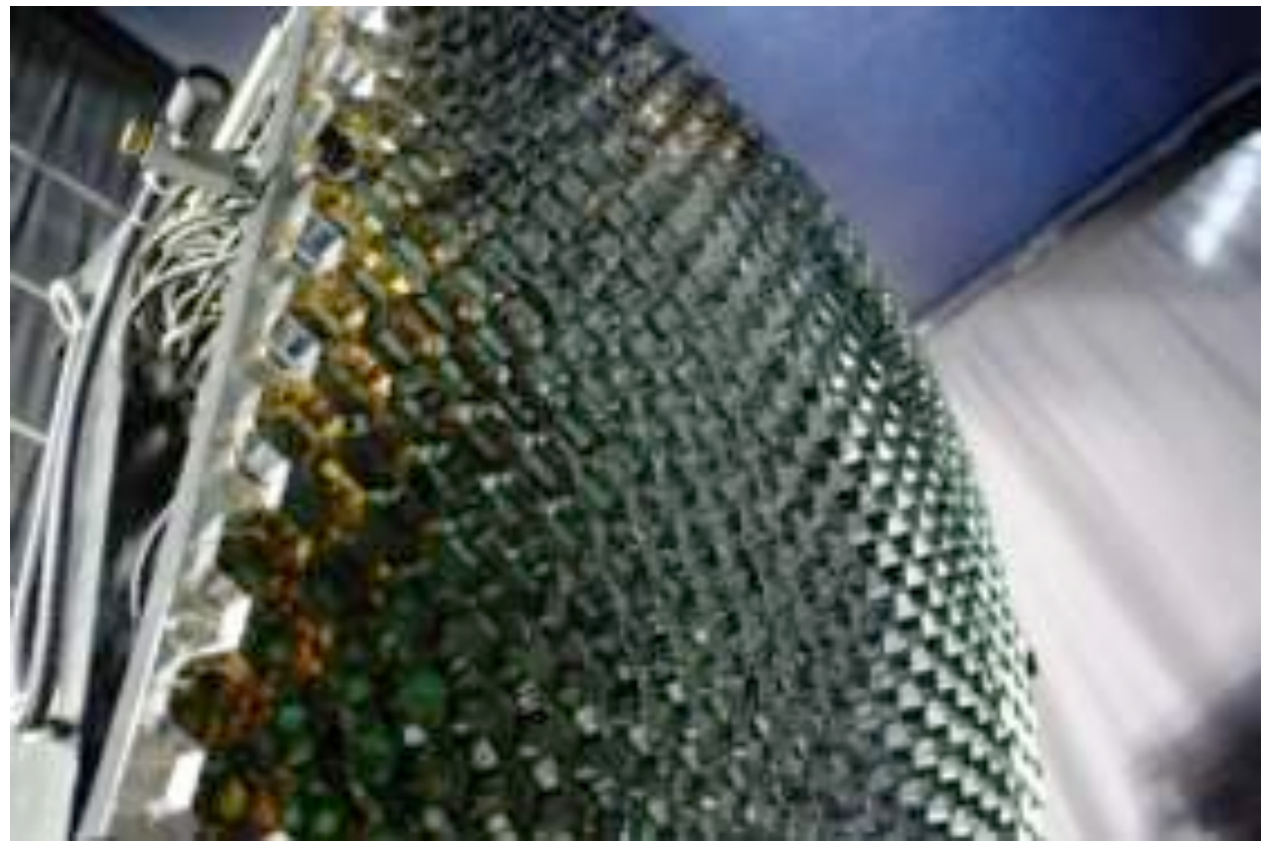
FAST
Fluorescence detector Array of Single-pixel Telescopes

Fluorescence detector Array of Single-pixel Telescopes

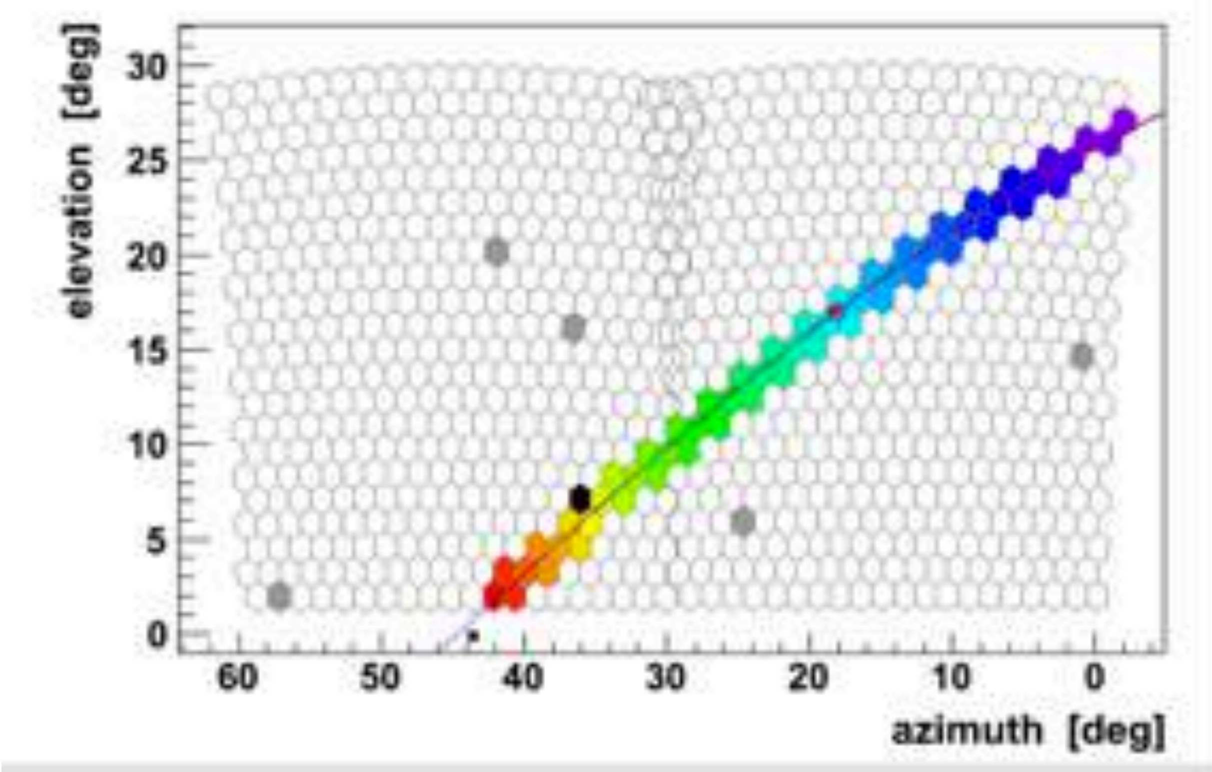
- Target : > $10^{19.5}$ eV, ultra-high energy cosmic rays (UHECR) and neutral particles
  - Huge target volume ⇒ Fluorescence detector array

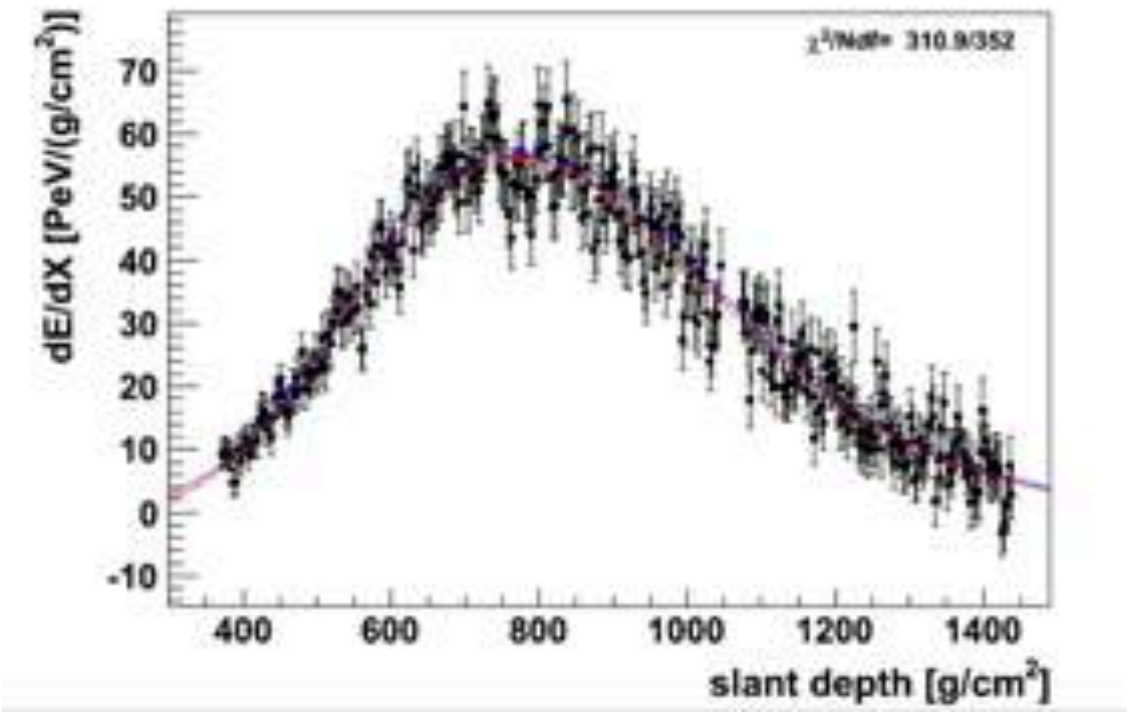
Fine pixelated camera



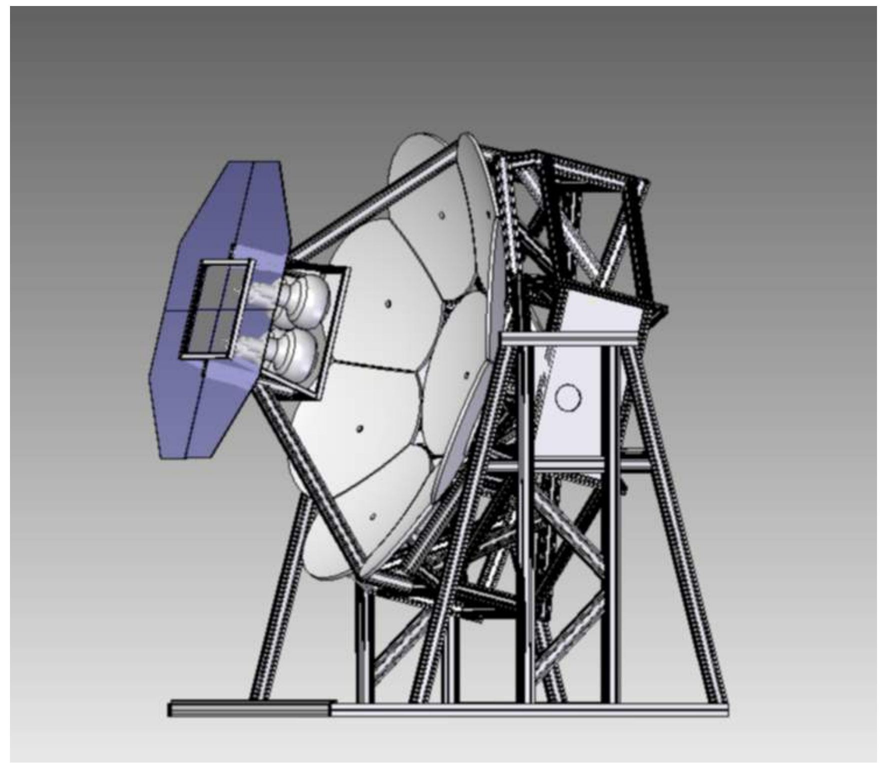


Too expensive to cover a huge area

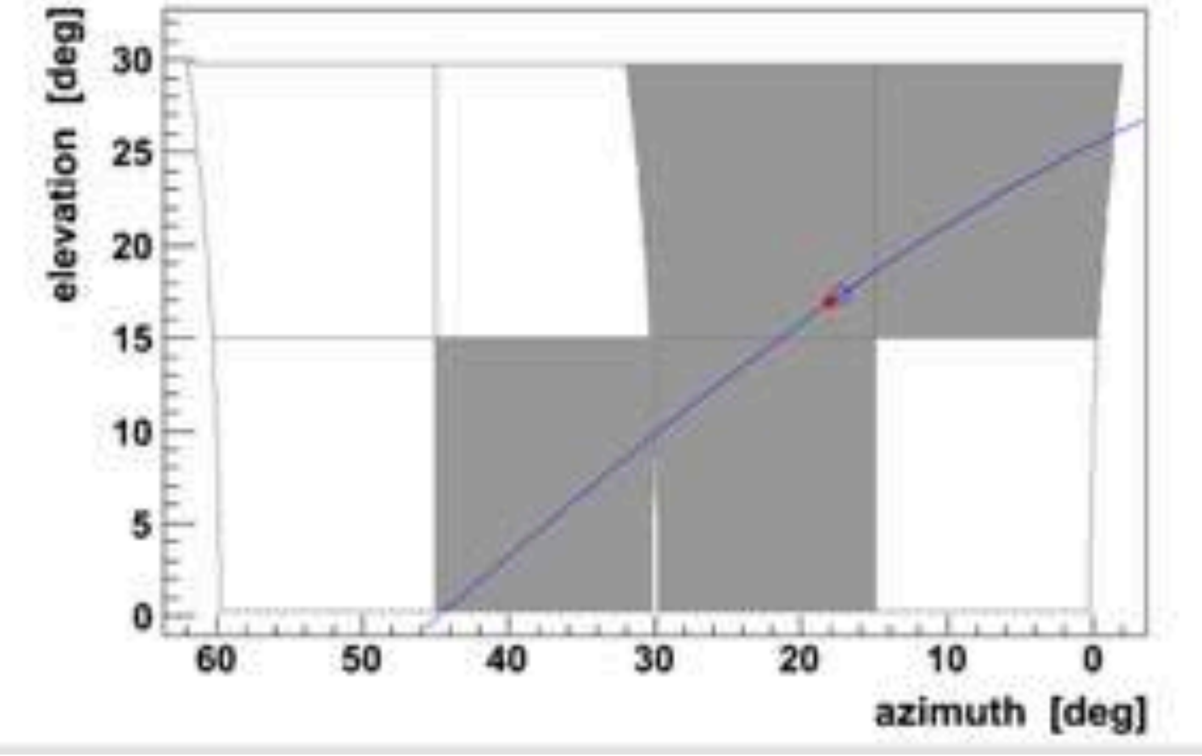


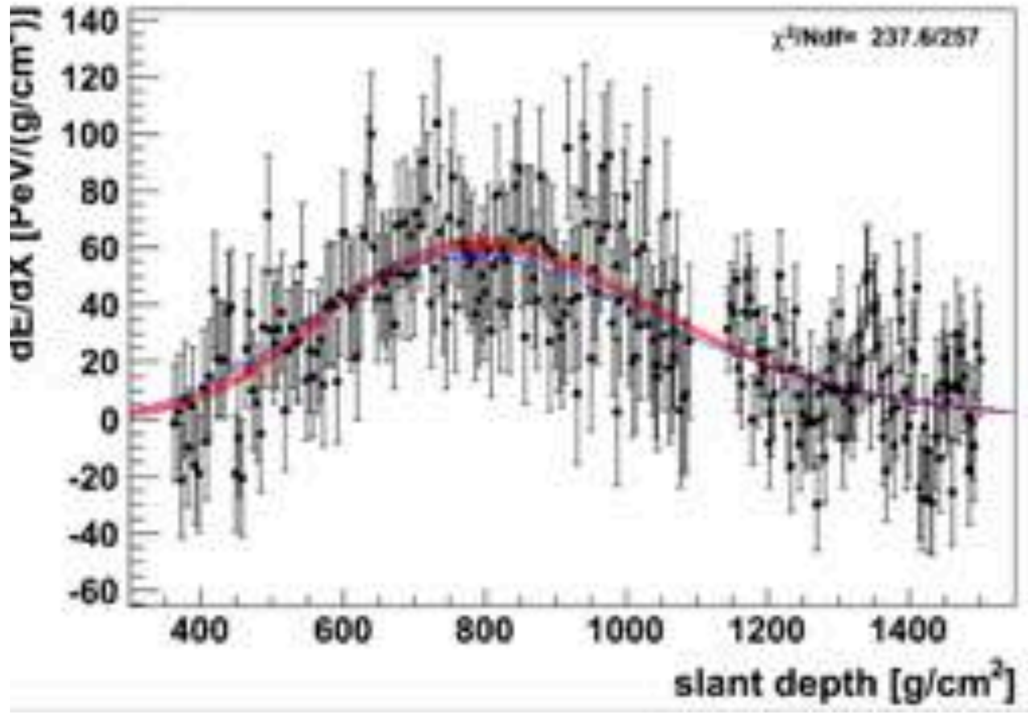


Single or few pixels and smaller optics



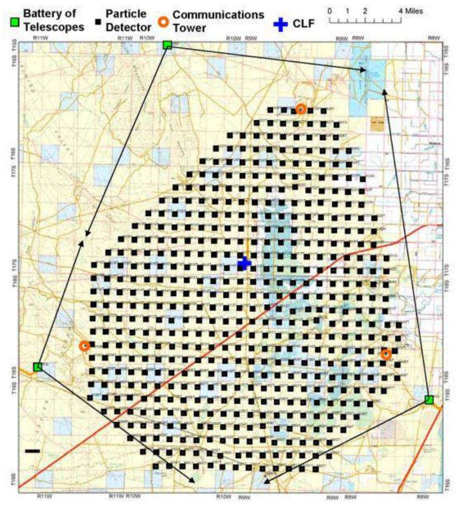
Low-cost and simplified telescope





FAST Fluorescence detector Array of Single-pixel Telescopes

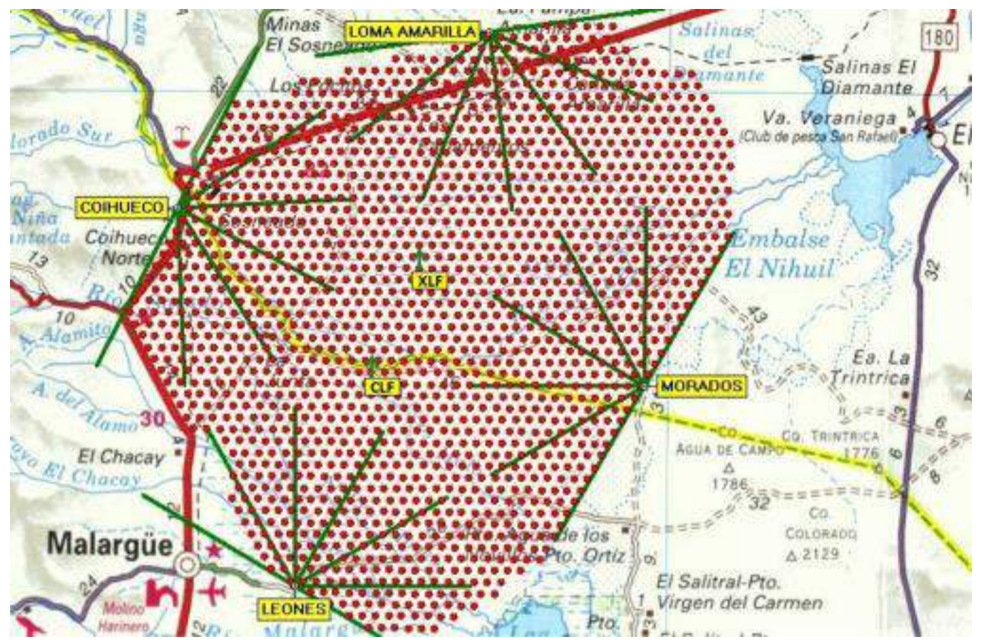
Fluorescence detector Array of Single-pixel Telescopes

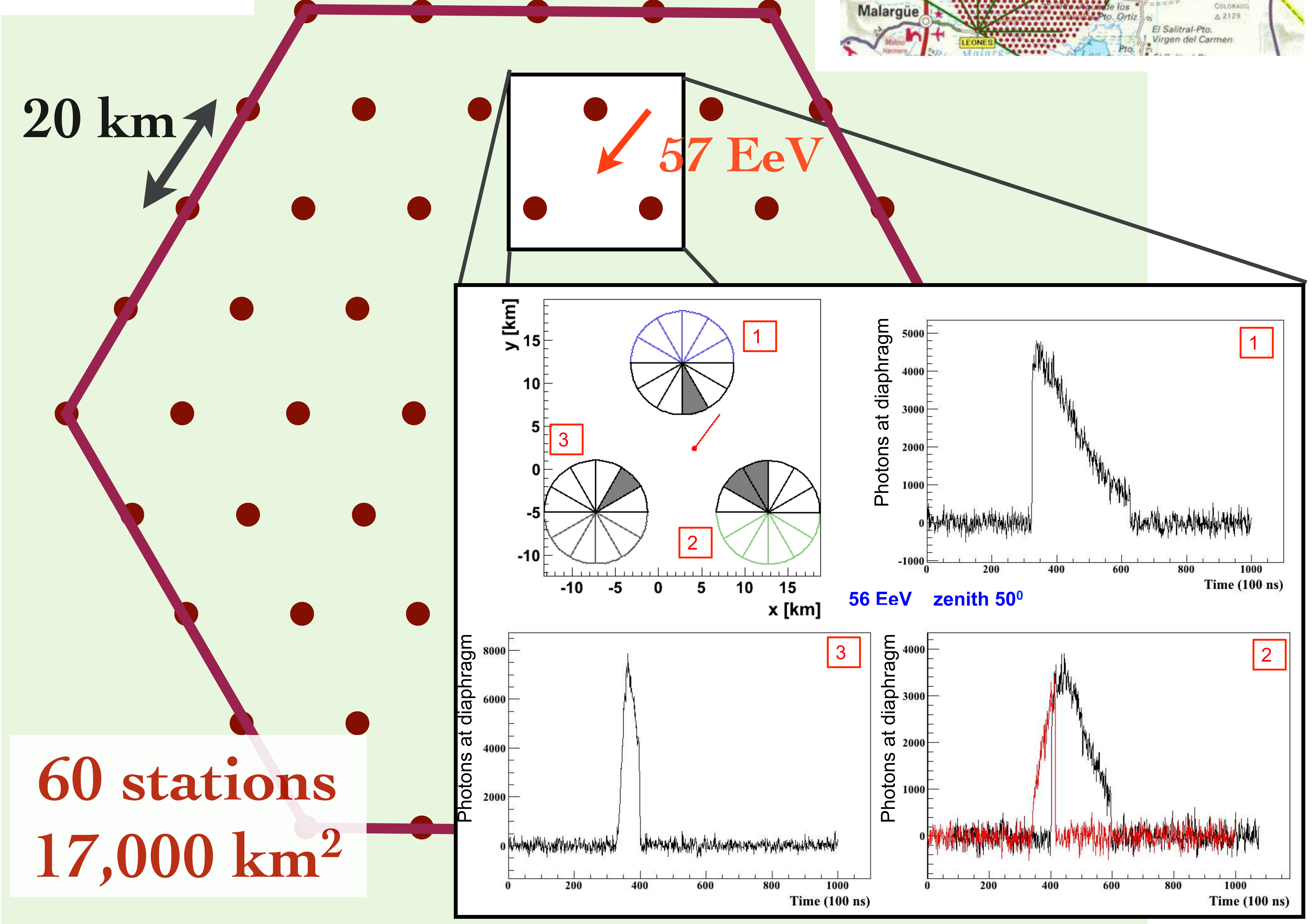


TA
700 km^2

(same scale)

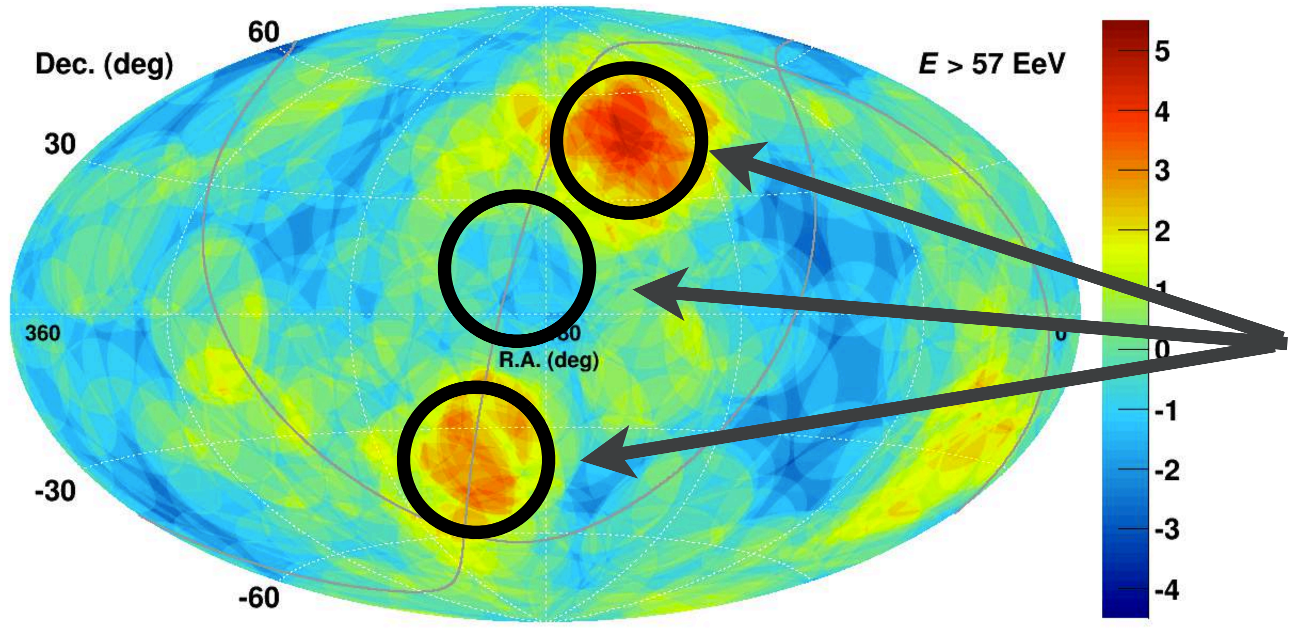
Auger
3000 km^2





- Each telescope: 4 PMTs, 30°×30° field of view (FoV)
  - **Reference design: 1 m^2 aperture, 15°×15° FoV per PMT**
  - Each station: 12 telescopes, 48 PMTs, 30°×360° FoV.
- Deploy on a triangle grid with **20 km** spacing, like **"Surface Detector Array".**
- With **500 stations**, a ground coverage is **150,000 km^2.**
  - ~100 million USD for detectors

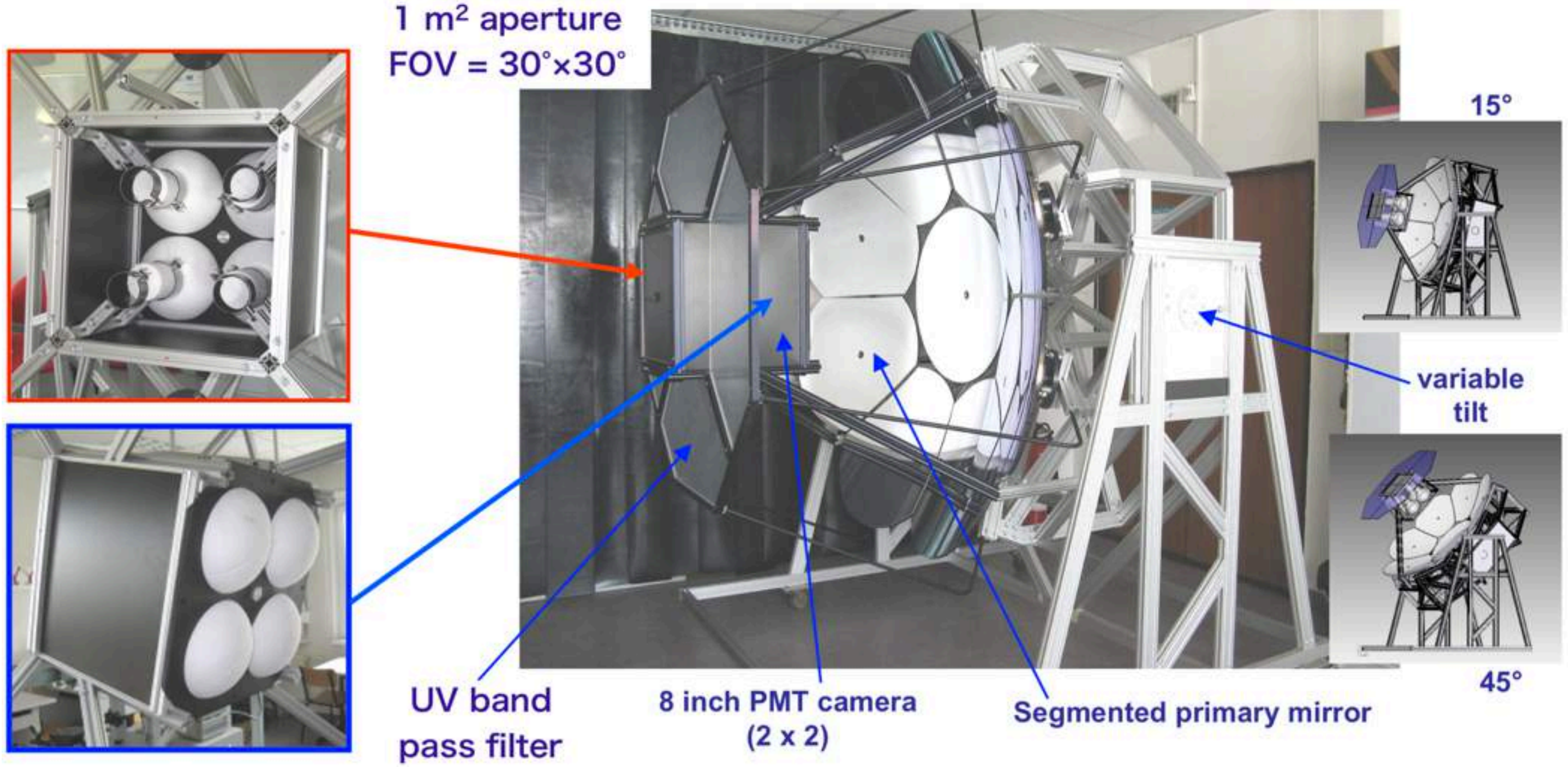
5 years: 5100 events (E > 57 EeV),
650 events (E > 100 EeV)



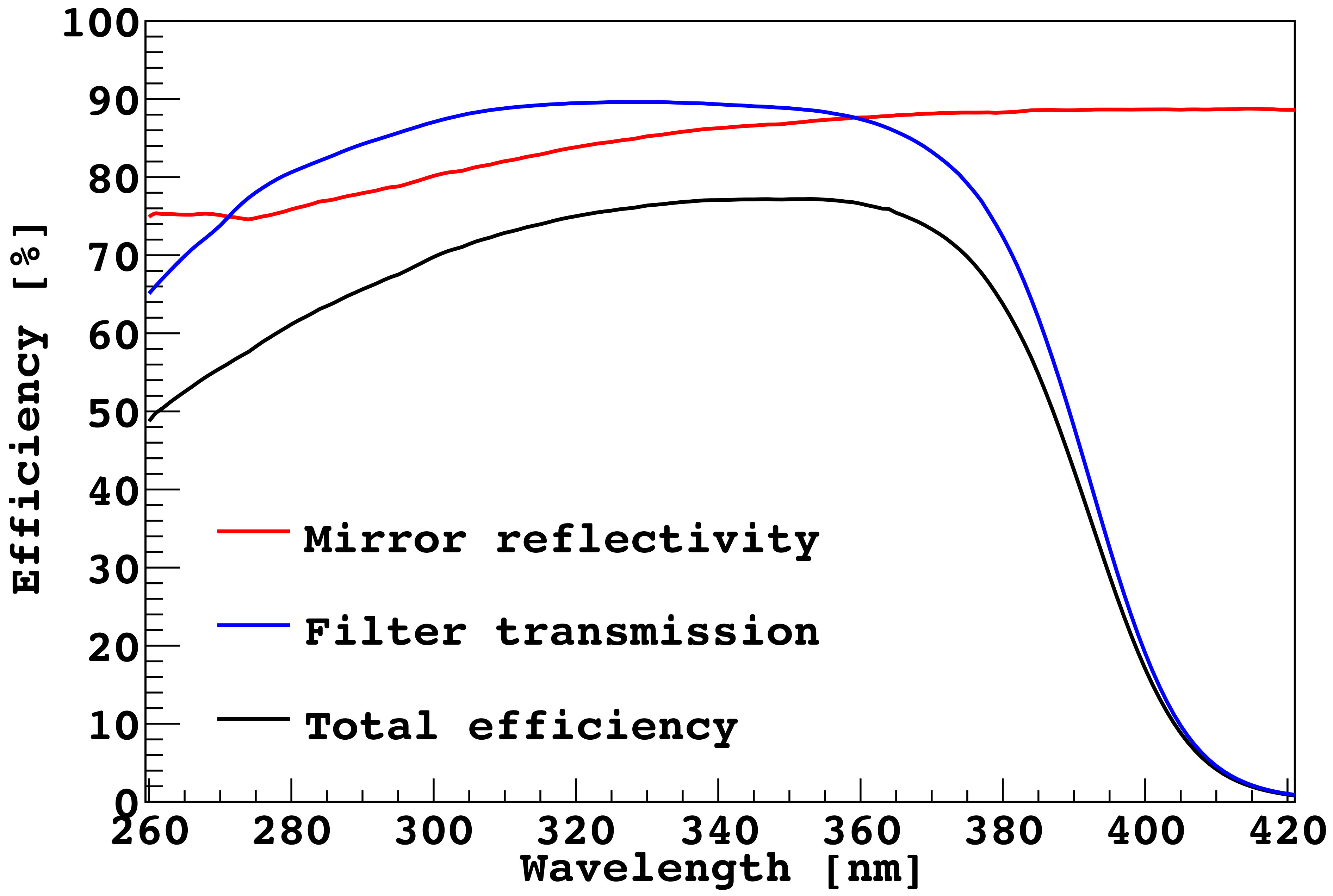
Directional studies on both energy spectrum and X_{max}.

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

FAST fluorescence telescope



Reference: D. Mandat et al., JINST 12, T07001 (2017)

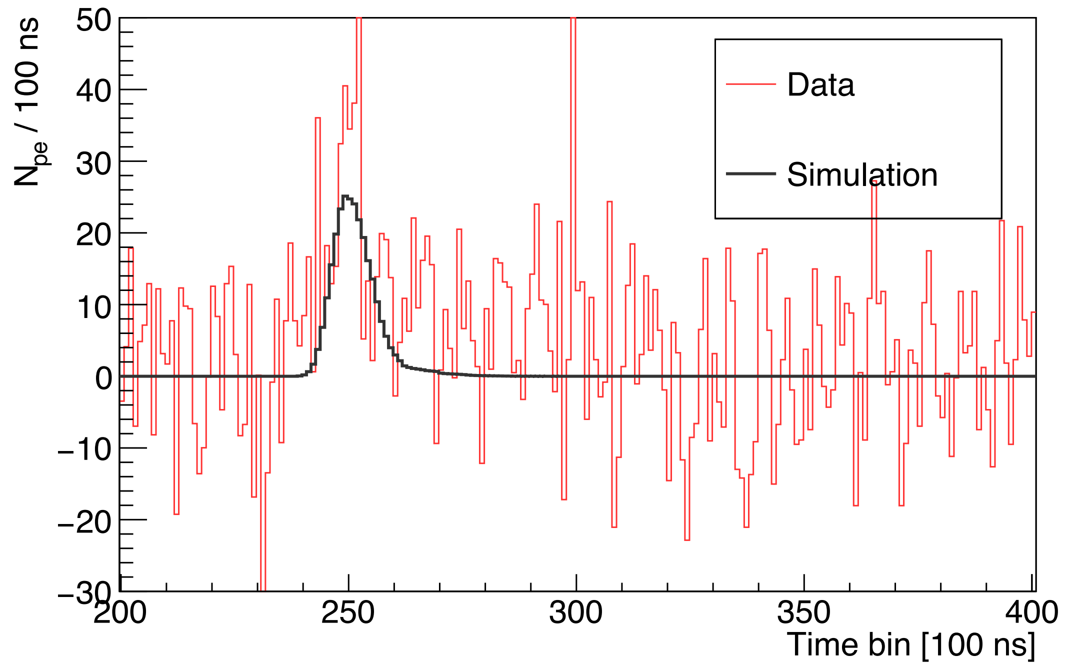


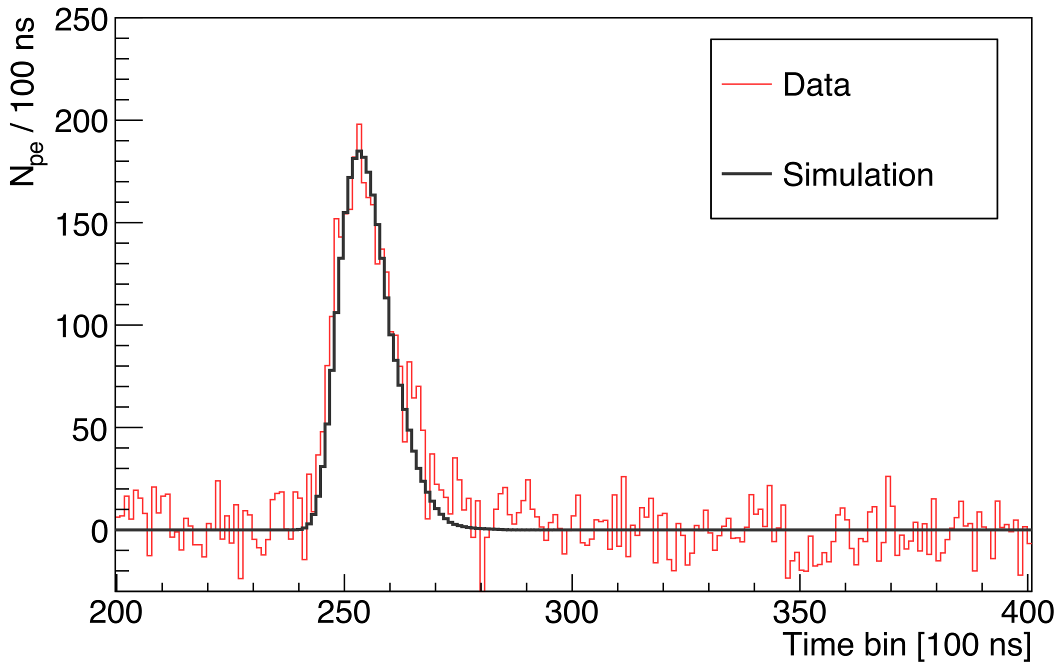
- 4 PMTs (20 cm, 8 dynodes R5912-03MOD, base E7694-01)
  - 1 m^2 aperture of the UV band-pass filter (ZWB3), segmented mirror of 1.6 m diameter
- 3 telescopes has been installed at Utah
  - remote operation and automatic shutdown
- 425 hours observation by October 2018

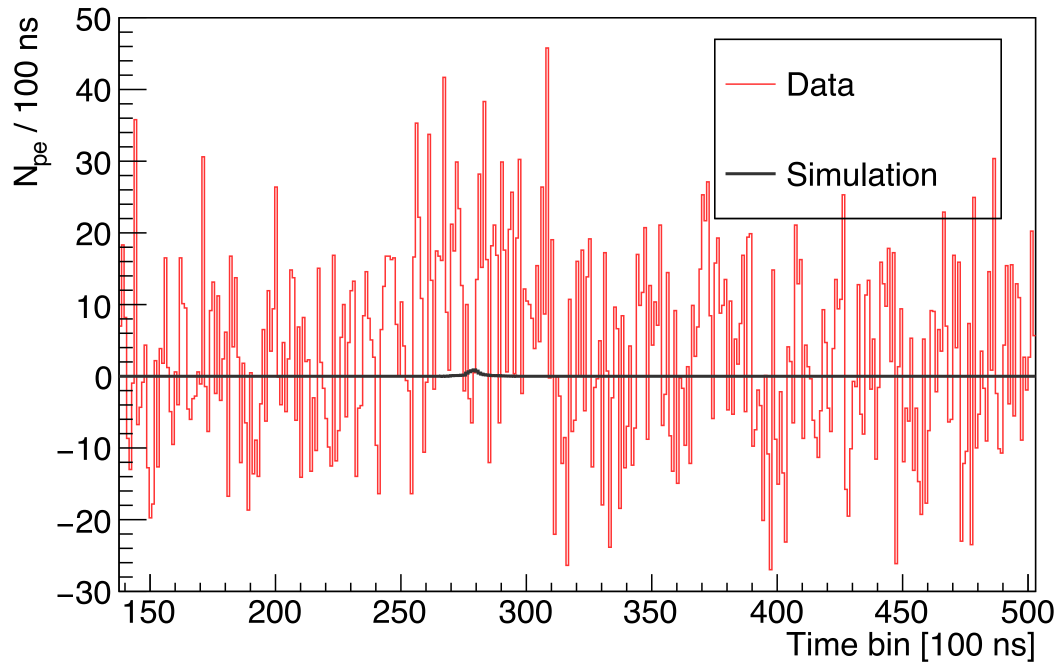
FAST
Fluorescence detector Array of Single-pixel Telescopes

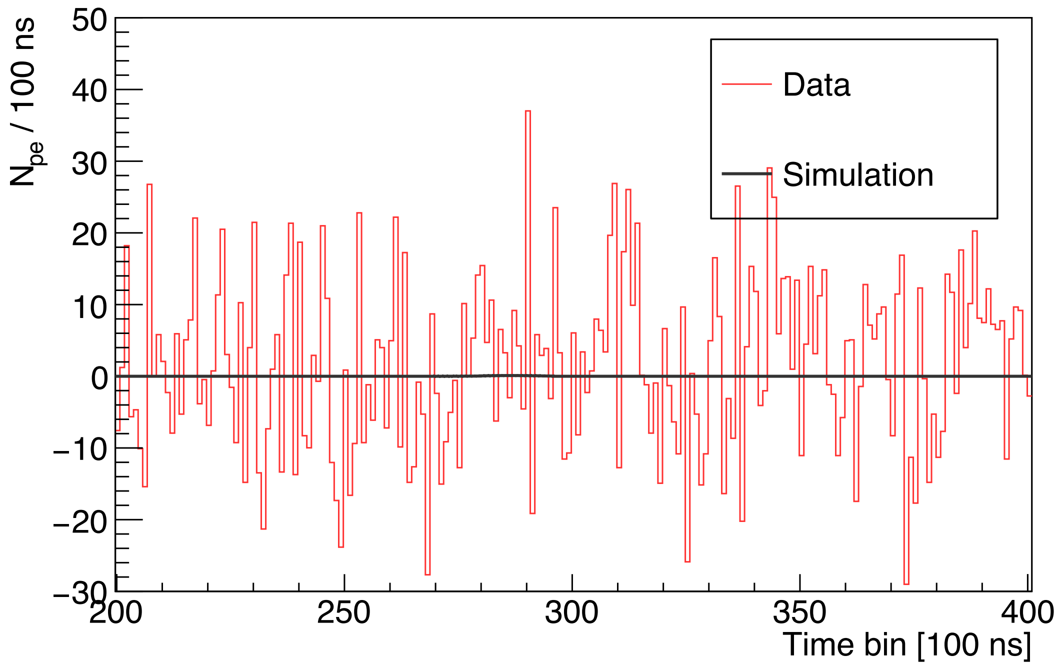
Reconstruction result of the highest event

Work: Justin Albury, Jose Bellido

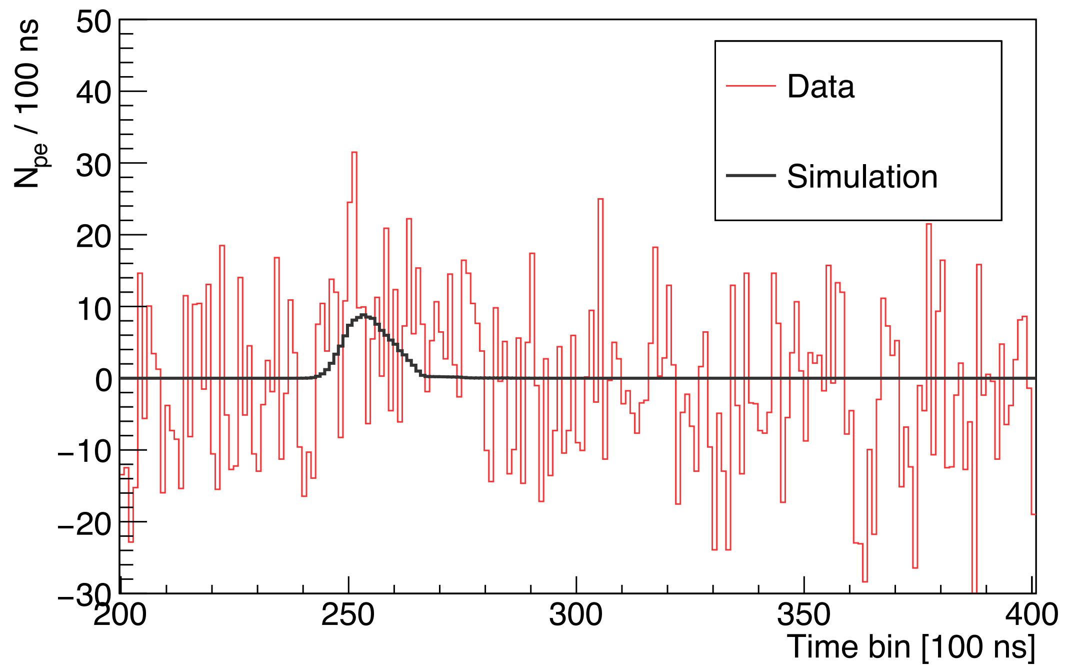


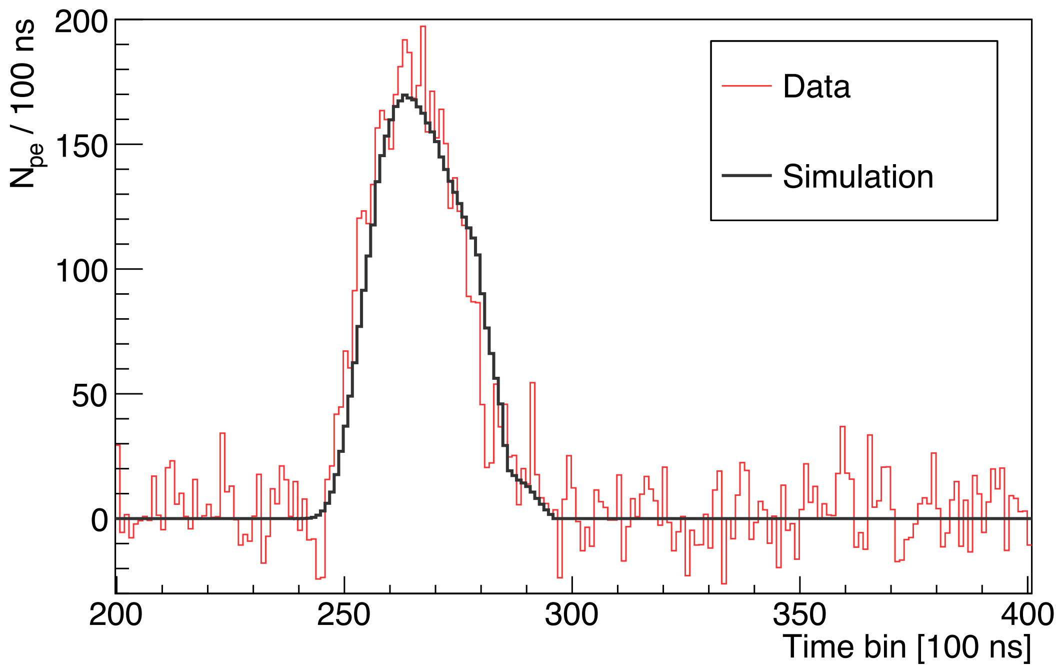


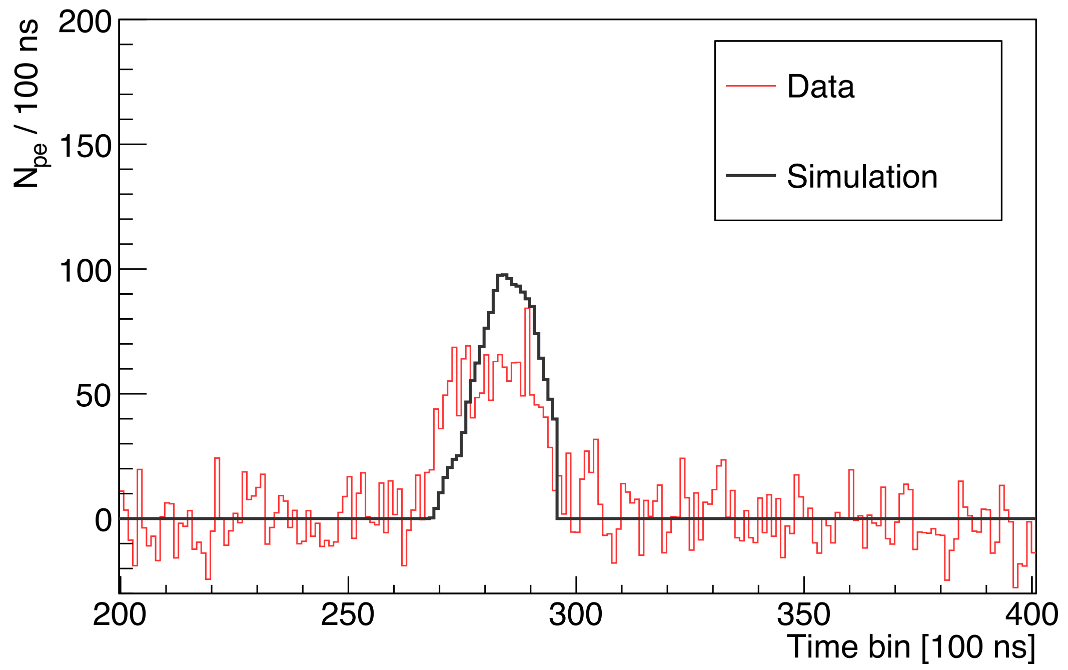


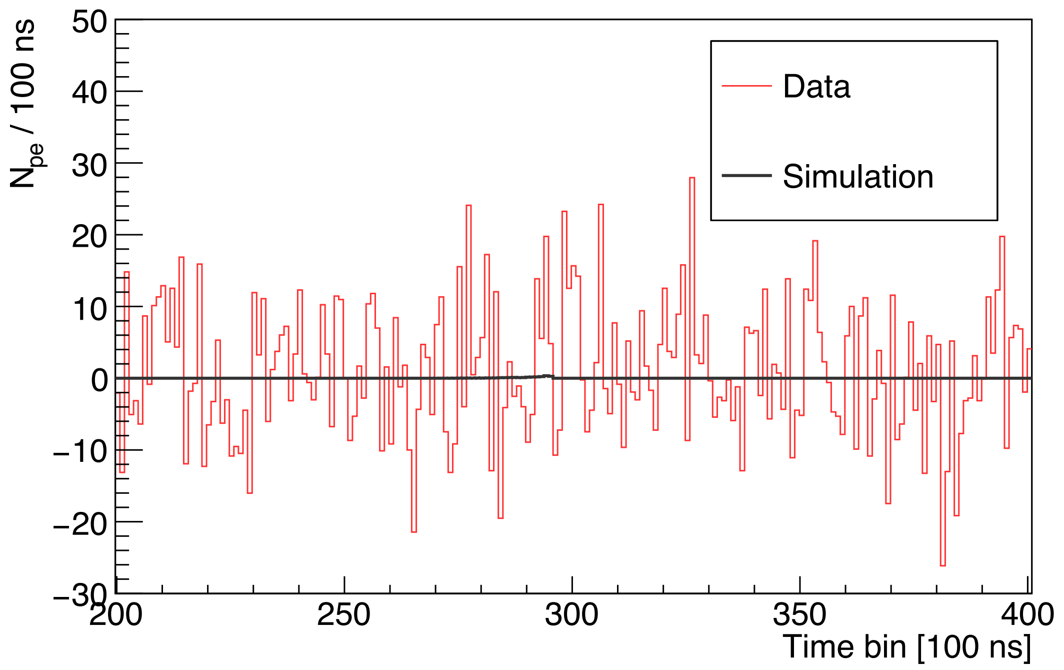


Preliminary



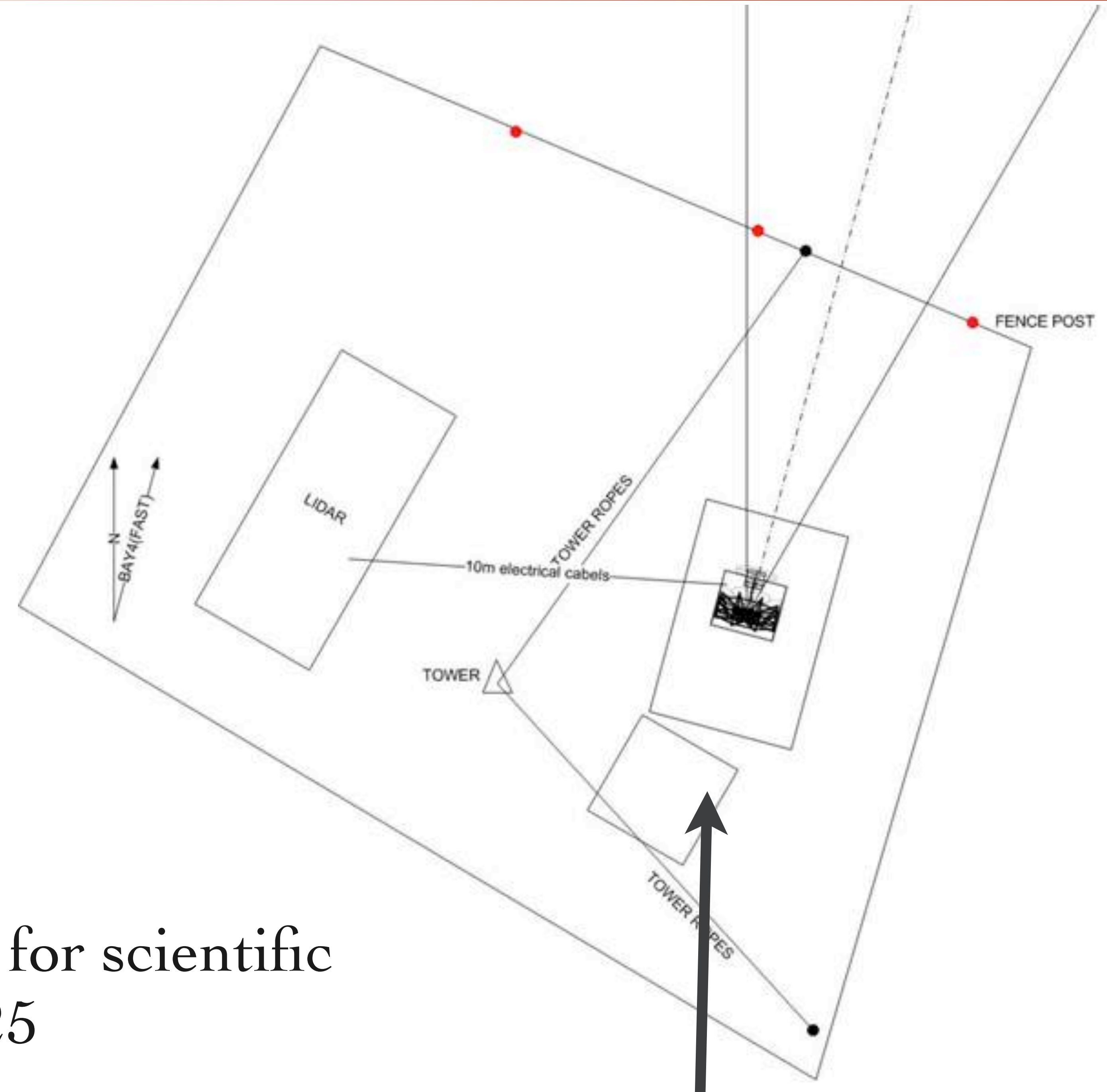






Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
59.8 deg	-173.3 deg	7.9 km	-9.0 km	842 g/cm^2	17.3 EeV
+0.4	+0.5	+0.2	+0.2	+10	+0.3
-0.7	-1.5	-0.2	-0.2	-10	-0.7

Future plan: FAST telescope to be installed in Auger



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Summary and future perspectives

- Future scientific goals for on-going upgrades:
  - TA×4: confirmation of the TA hotspot with >5σ
  - AugerPrime: indication of small scale anisotropies selecting a light composition, proton fraction at 10^{20} eV
  - Interaction model: < 20 g/cm^2 uncertainty on Xmax at 10^{20} eV
- **Smoking gun of cosmic ray origins: γ-rays detection spacial coincidence with UHECR hotspot**
  - As a personal decadal survey,
    - A fine-pixel fluorescence telescope for low-energy extension
    - SLOW: A layered Water-Cherenkov detector array for sub-EeV anisotropy and ultrahigh-energy photon search
    - FAST: A low-cost fluorescence telescope array suitable for measuring the properties of UHECRs with an unprecedented aperture

A homework from Jim

"I hope you can bring the single pixel fluorescence detector to practical application. While most of my colleagues are pleased with the results of Auger, I am disappointed we failed to find sources. Instrumentation like yours may make that possible some day"
James Cronin (The 1980 Nobel Prize in Physics)