Observation of the universe's highest energetic particles and a next-generation observatory

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ICEHAP seminar
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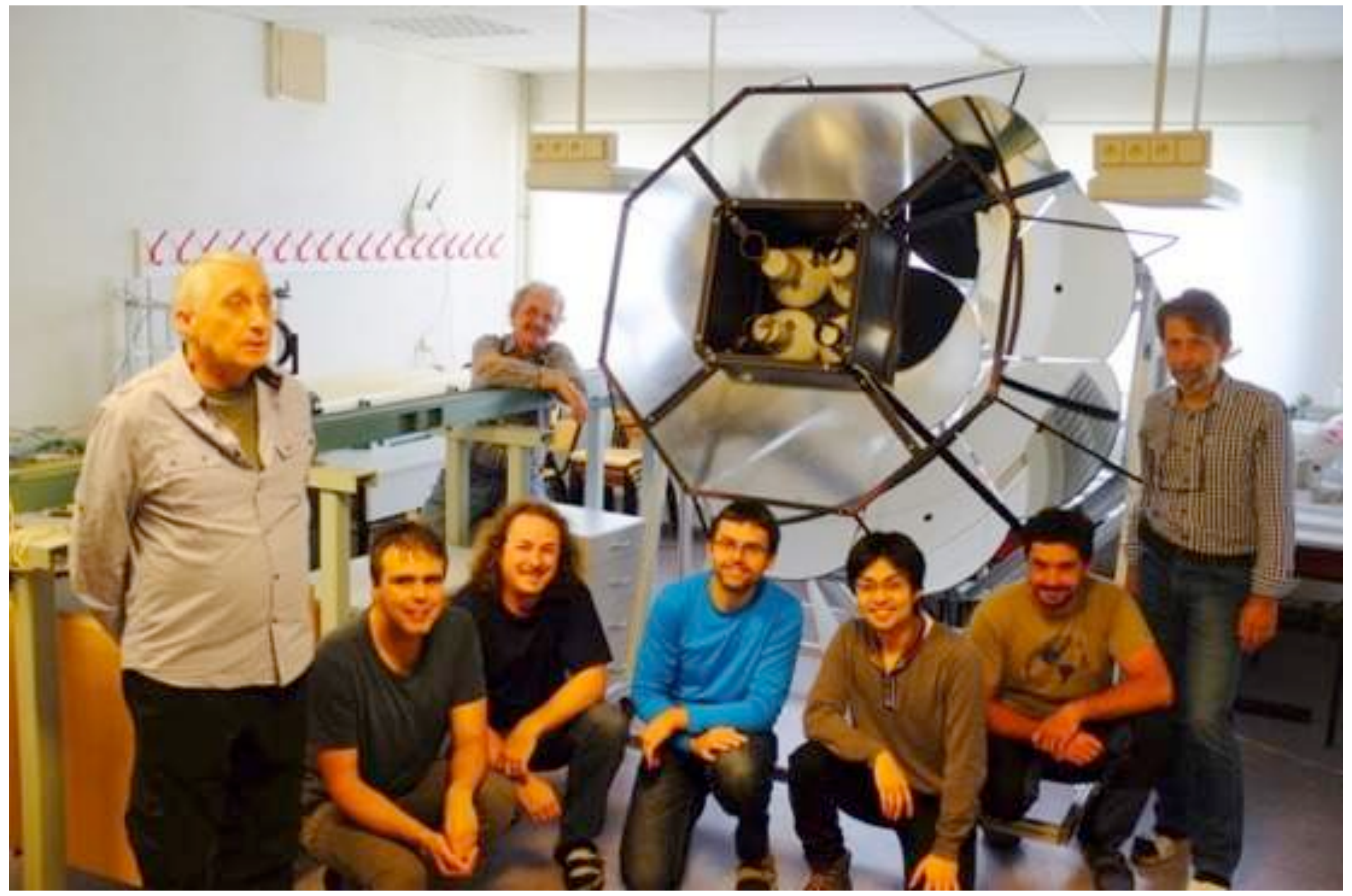
Image from Quanta magazine

TELESCOPE ARRAY PROJECT

PIERRE AUGER OBSERVATORY

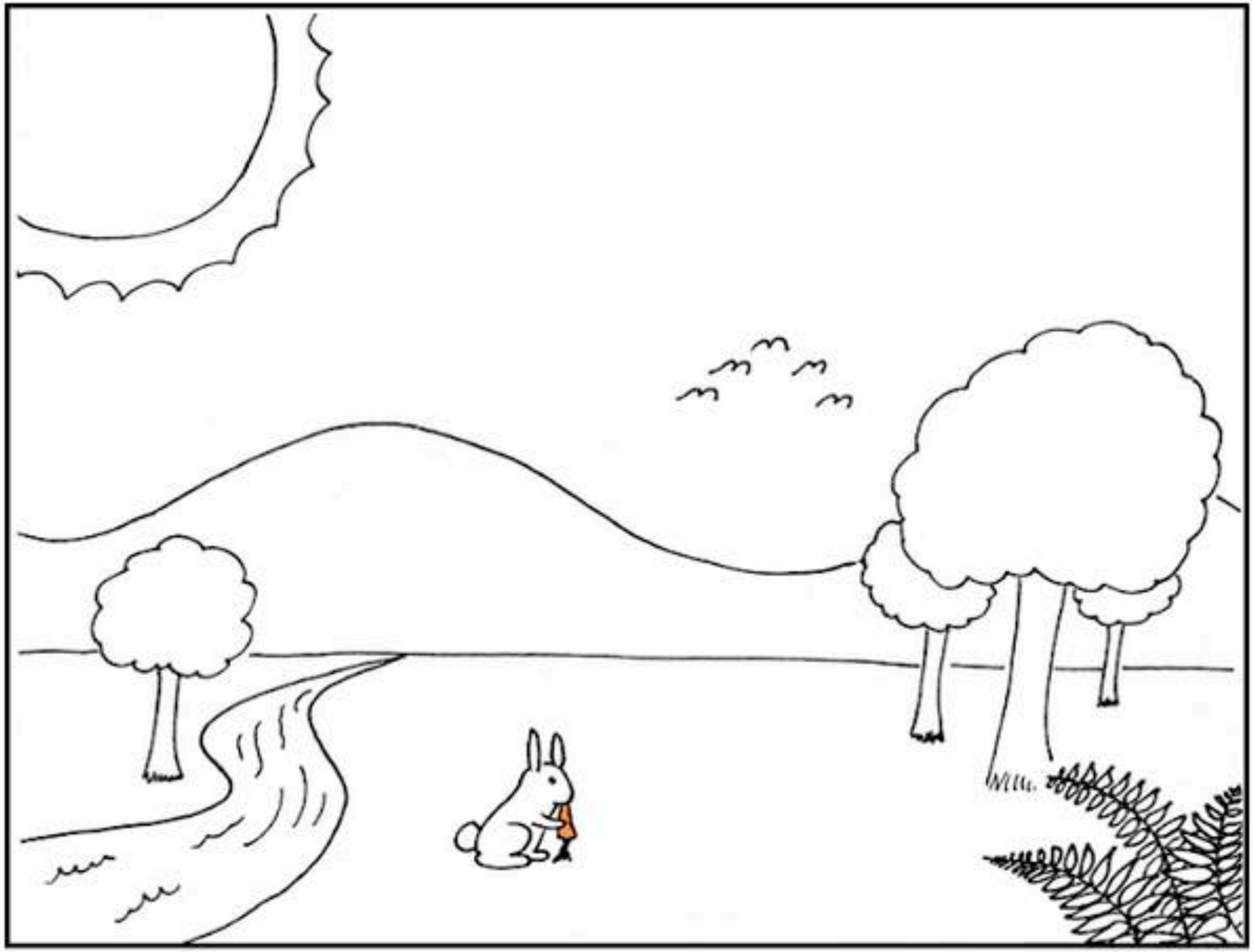
FAST
Fluorescence detector Array of Single-pixel Telescopes

F A S T
Fluorescence detector Array of Single-pixel Telescopes



This is how scientists see the world.

credit: http://abstrusegoose.com



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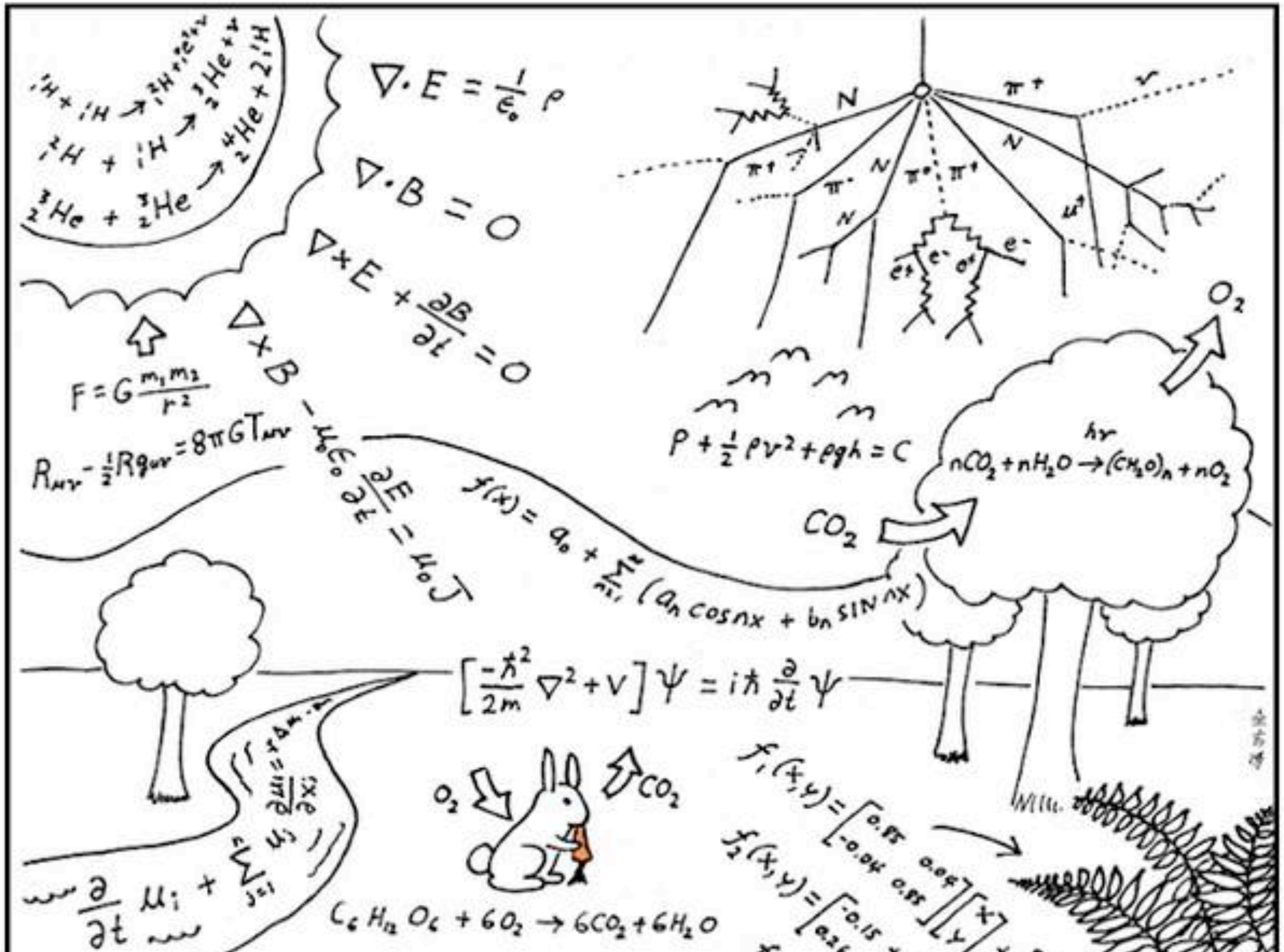

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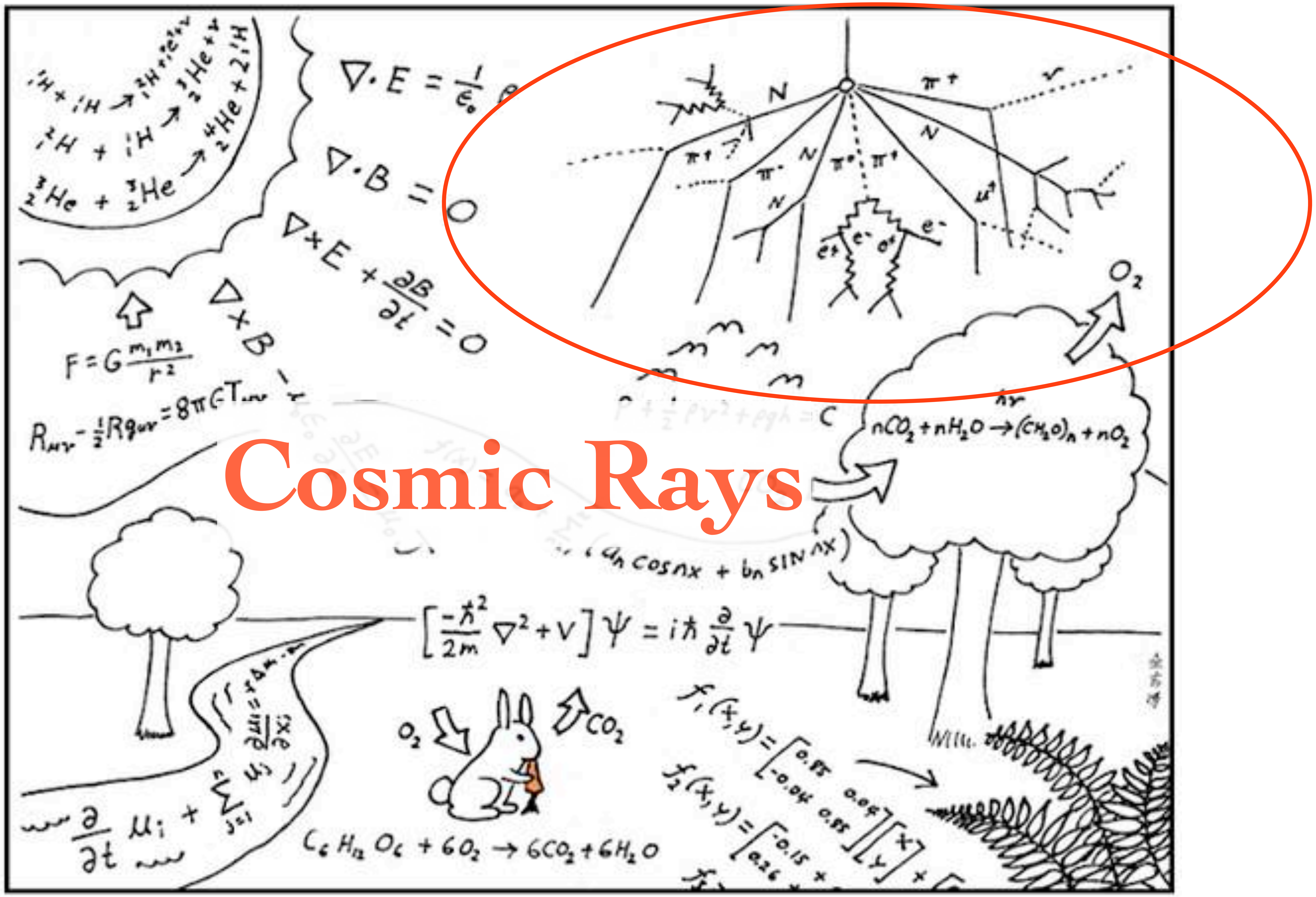
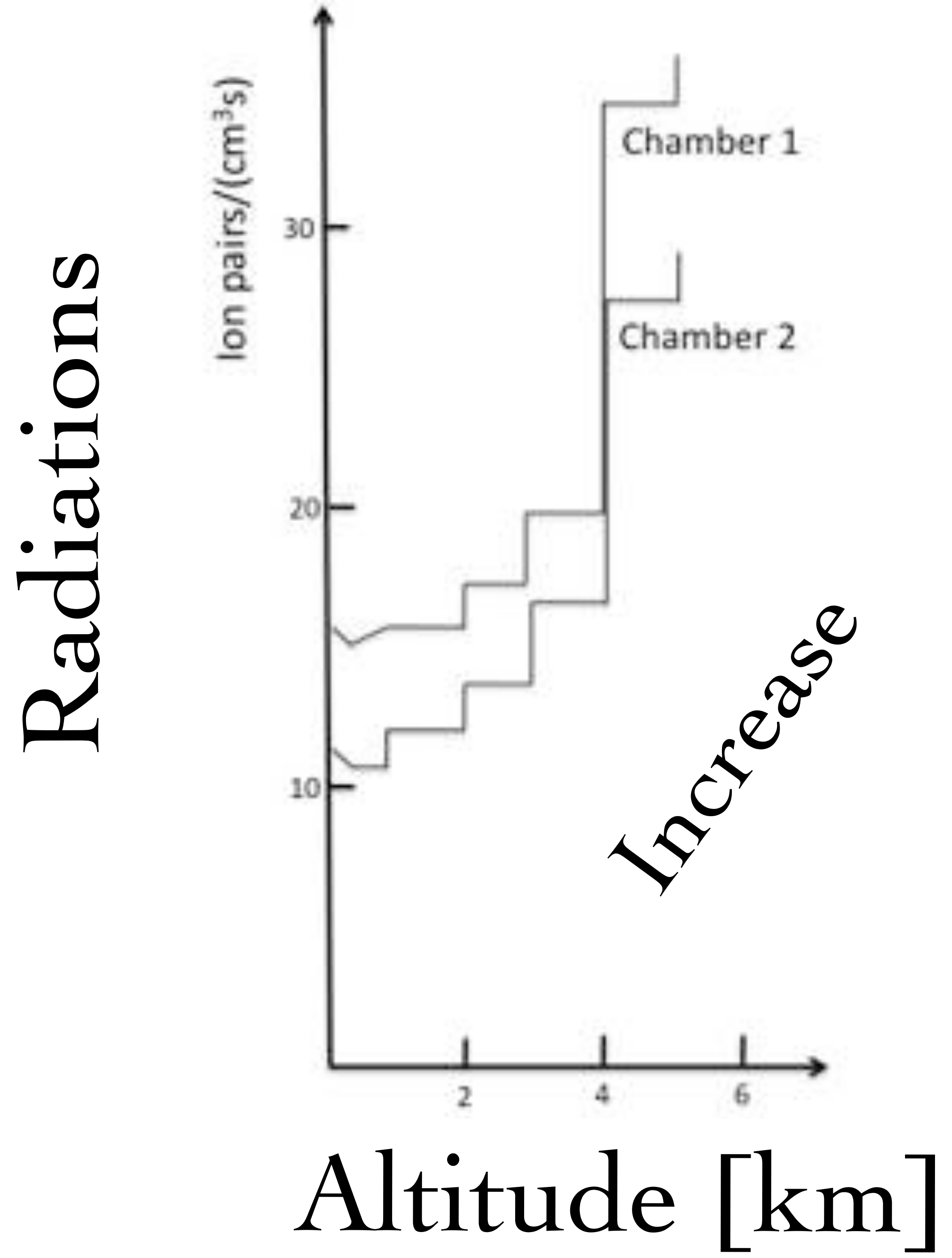


What are Cosmic Rays?

- Energetic particles injected from the universe.
- Discovered by V. F. Hess (1912)
  - **Proton(90%), Helium(8%) and heavier nuclei**
  - **E > 10^{19} eV, ultrahigh-energy cosmic rays (UHECR)**



Grandson of Hess

Memorial Stone

Cosmic Ray Anniversary on Aug. 7th 2012





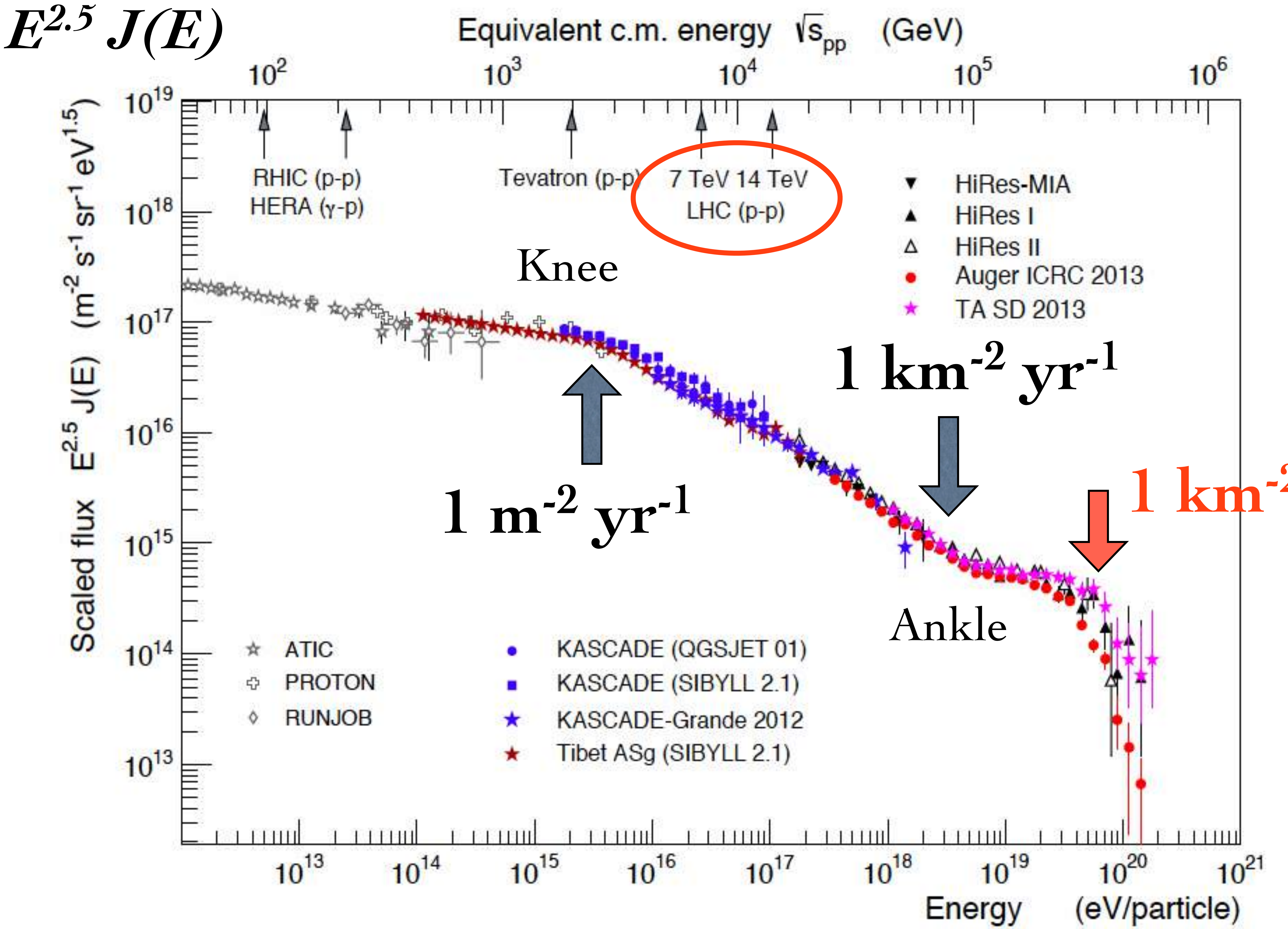

Anatoli

Physics goal of UHECR Astrophysics

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

- How frequent?
- What kind of particle?
- Where come from?

How frequent?: Energy spectrum

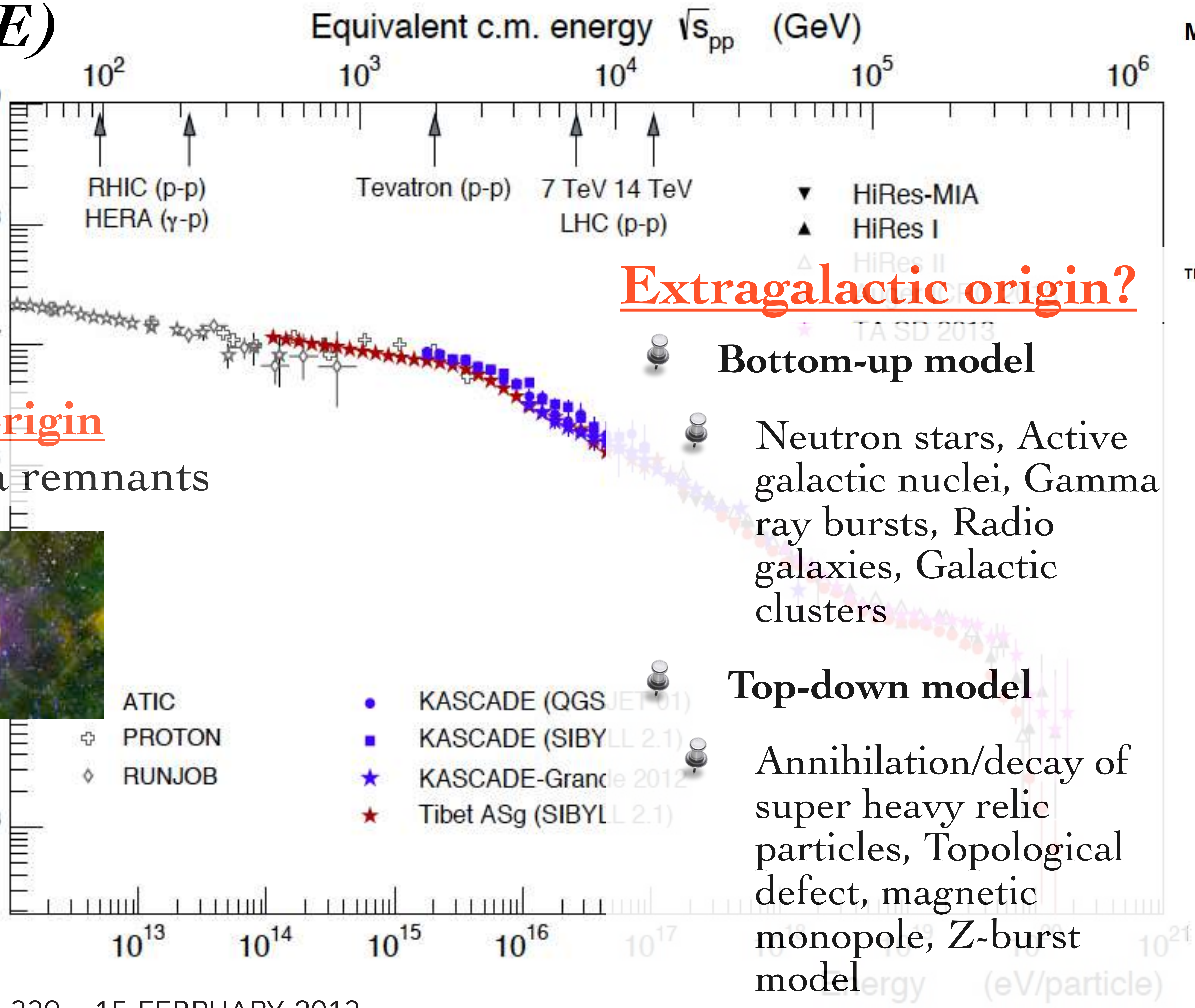


Larger energy than the largest accelerator (LHC)

Very infrequent, a large sensitive area needed

Acceleration Scenario toward 10^{20} eV

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

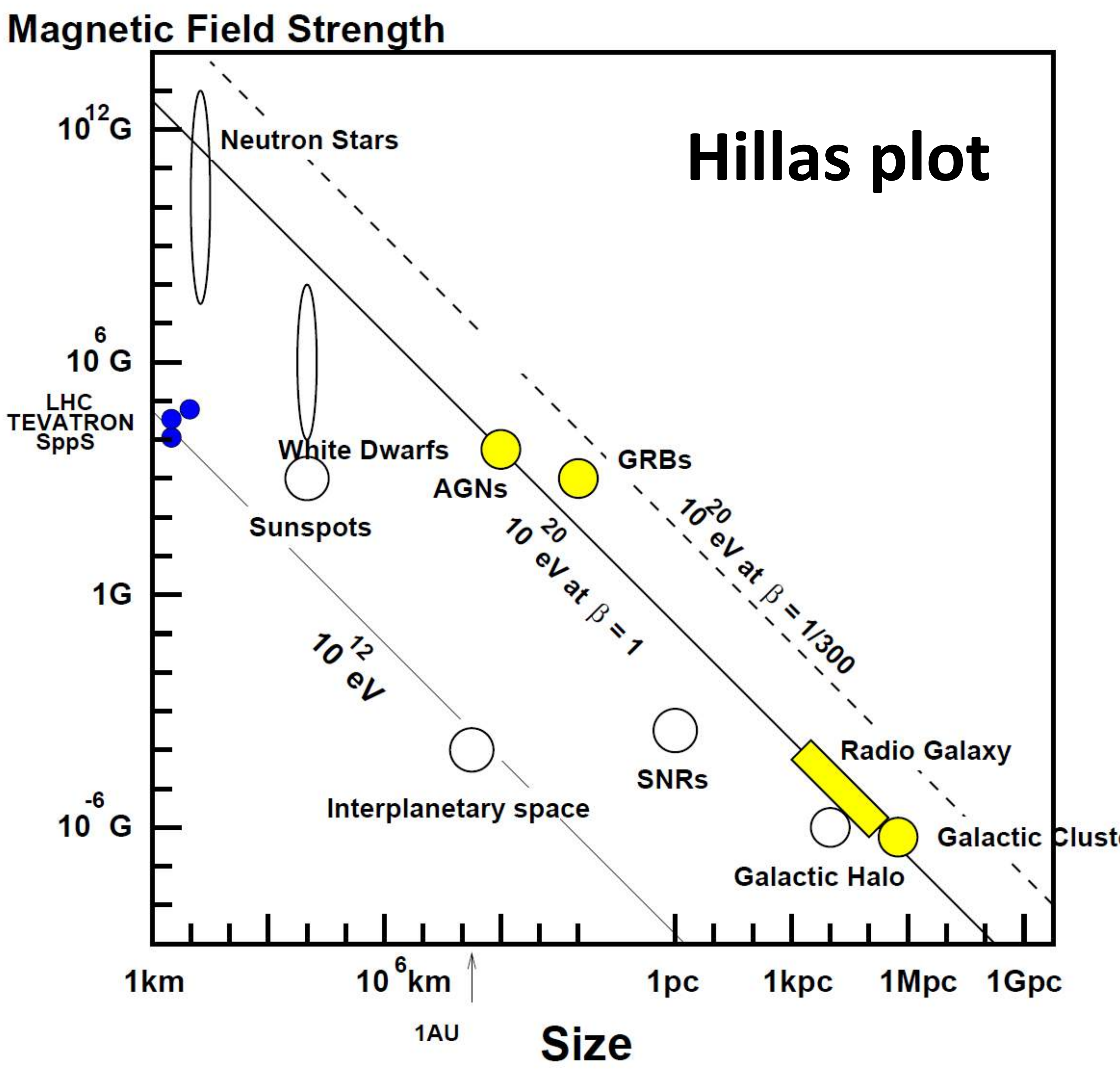


Galactic origin

Supernova remnants

Extragalactic origin?

- **Bottom-up model**
  - Neutron stars, Active galactic nuclei, Gamma ray bursts, Radio galaxies, Galactic clusters
- **Top-down model**
  - Annihilation/decay of super heavy relic particles, Topological defect, magnetic monopole, Z-burst model

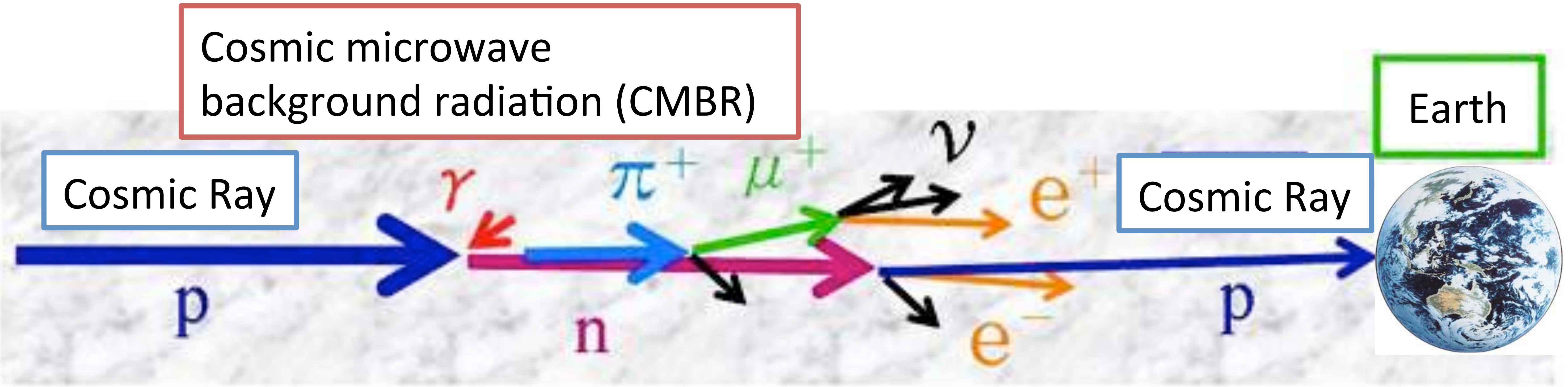


$$E_{\max} \leq \gamma e Z B R$$

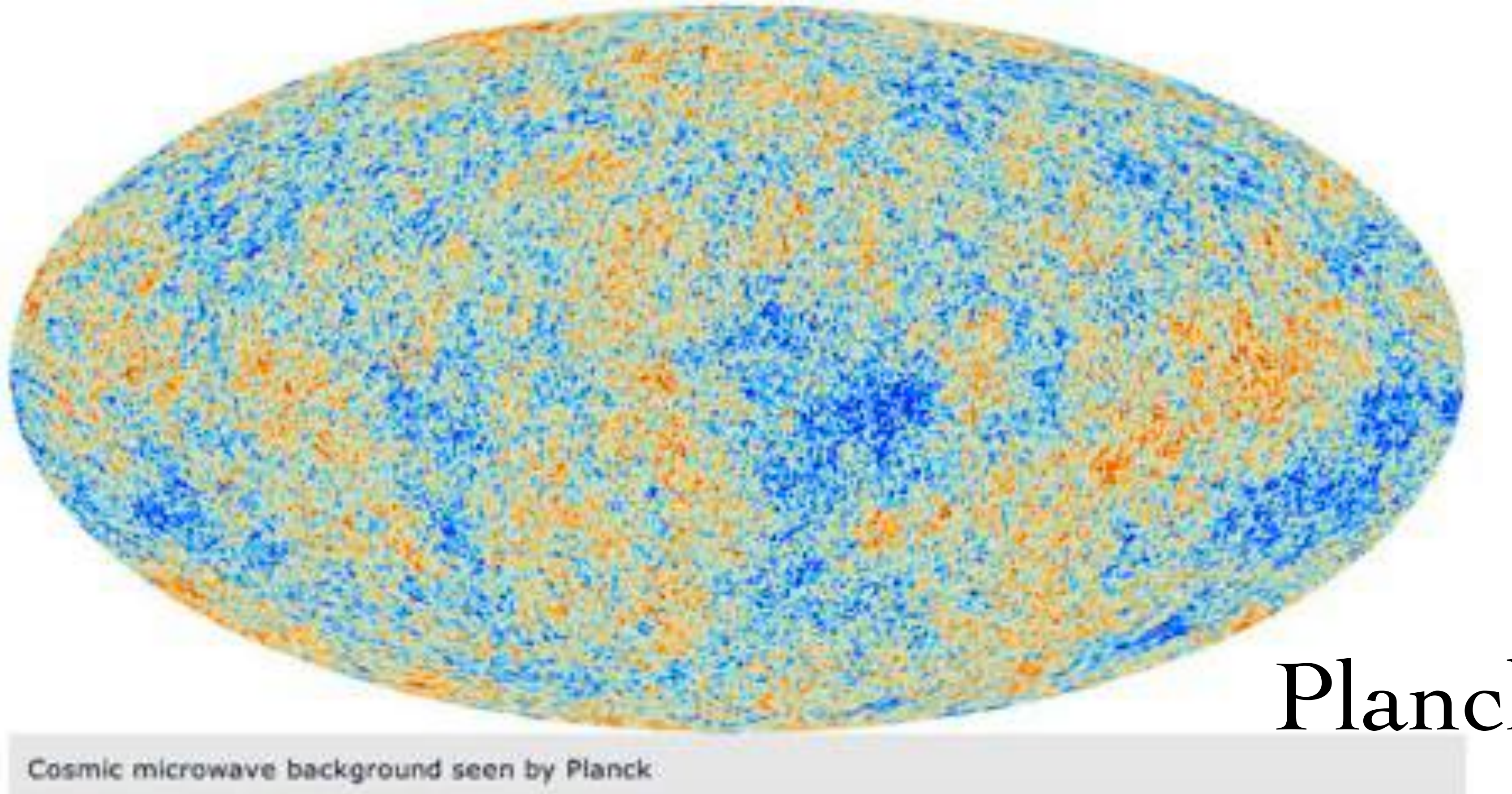
γ : Lorentz factor of shock
Z : atomic number
B : magnetic field strength
R : size

SCIENCE VOL 339 15 FEBRUARY 2013

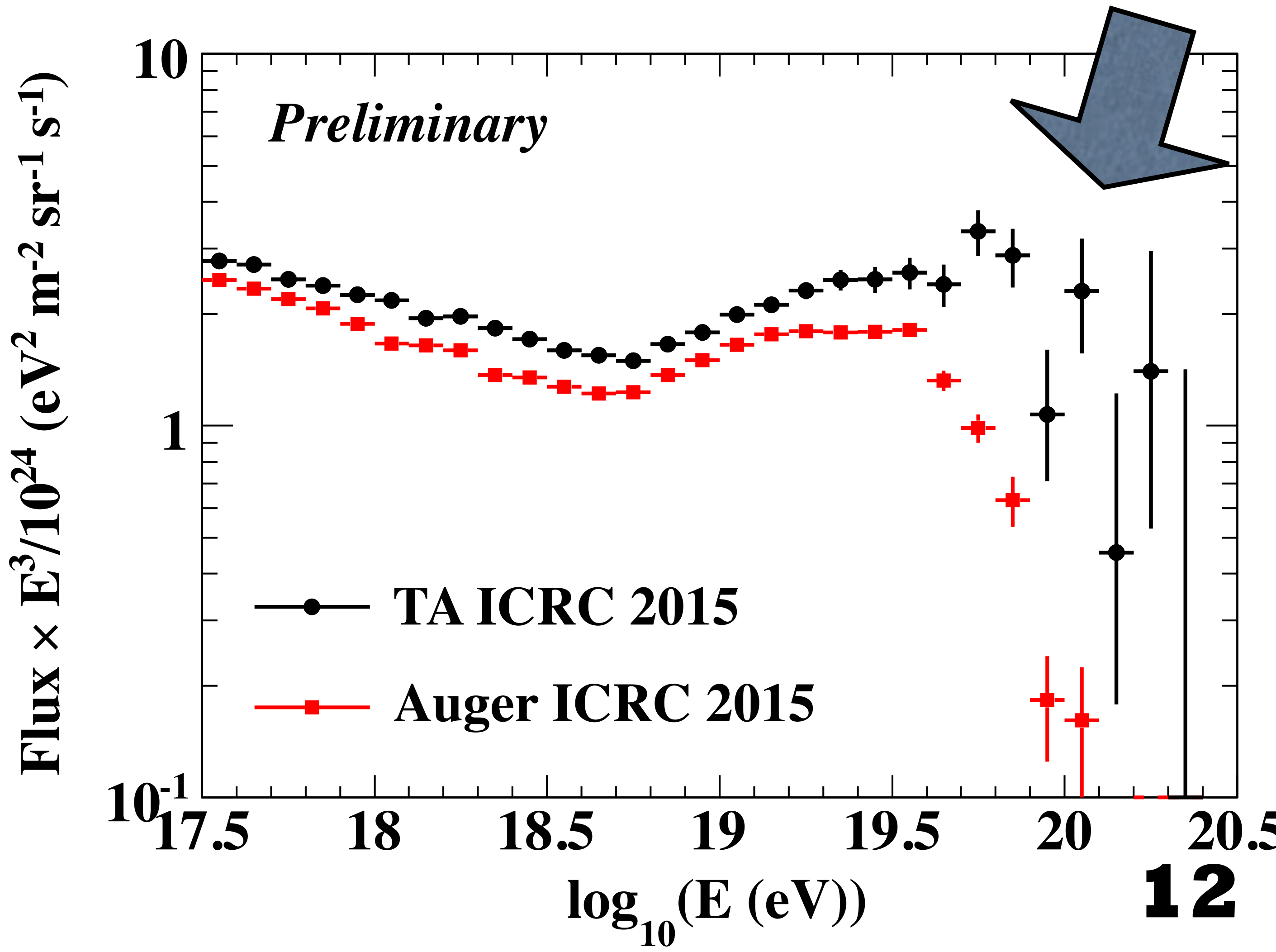
Greisen-Zatsepin-Kuzmin (GZK) Cutoff



- Interaction between UHE **protons** with energies above **$10^{19.75}$ eV** and CMBR via a pion production. **Heaver nuclei** also interact with CMBR via photo-disintegration.
  - Mean free path : 50-100 Mpc (Nearby sources compared to the universe size)
- Expect suppression of flux above $10^{19.7}$ eV.



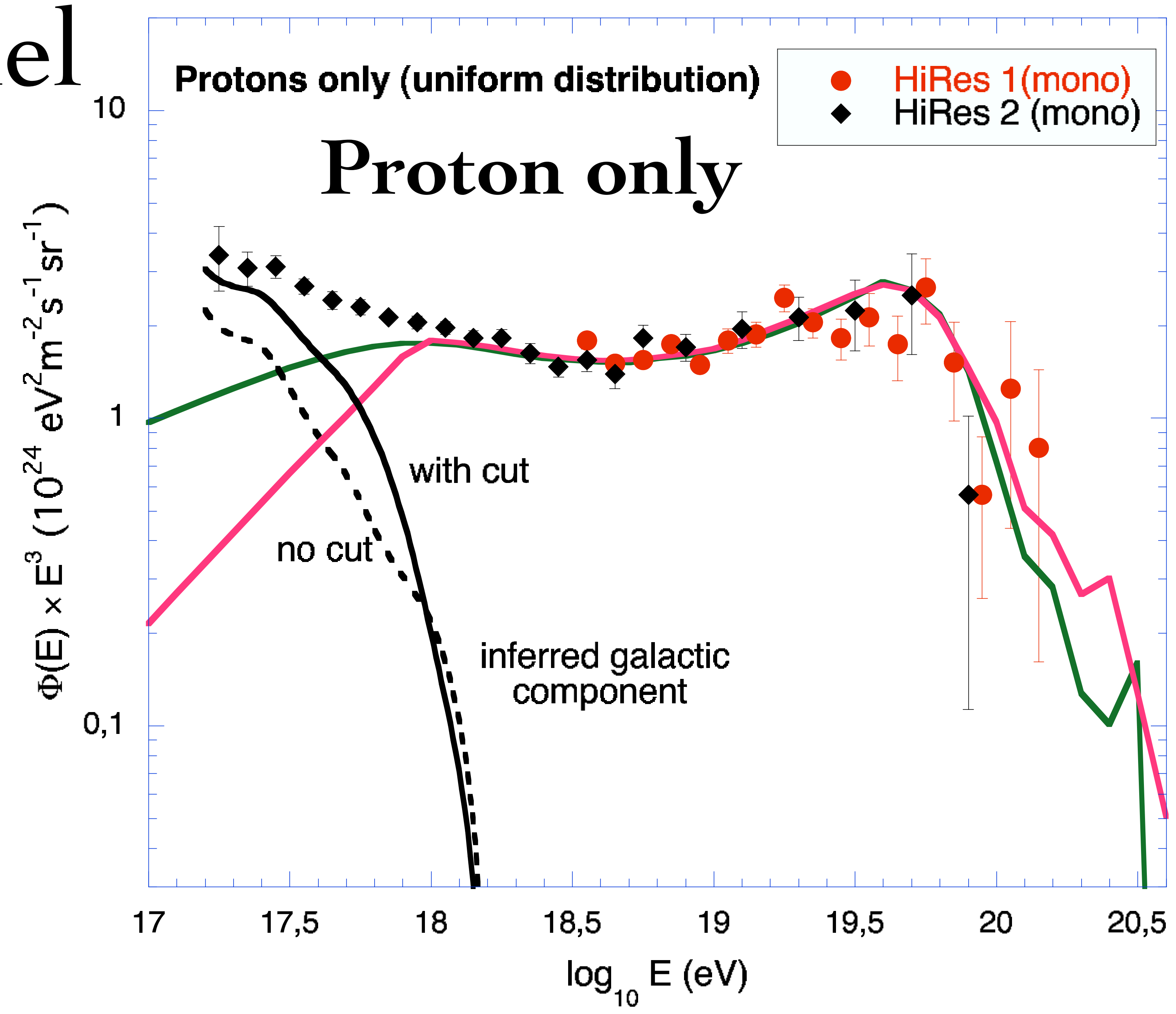
Planck 2013



1 pc = 3.26 l.y. ~ 3×10^{16} m

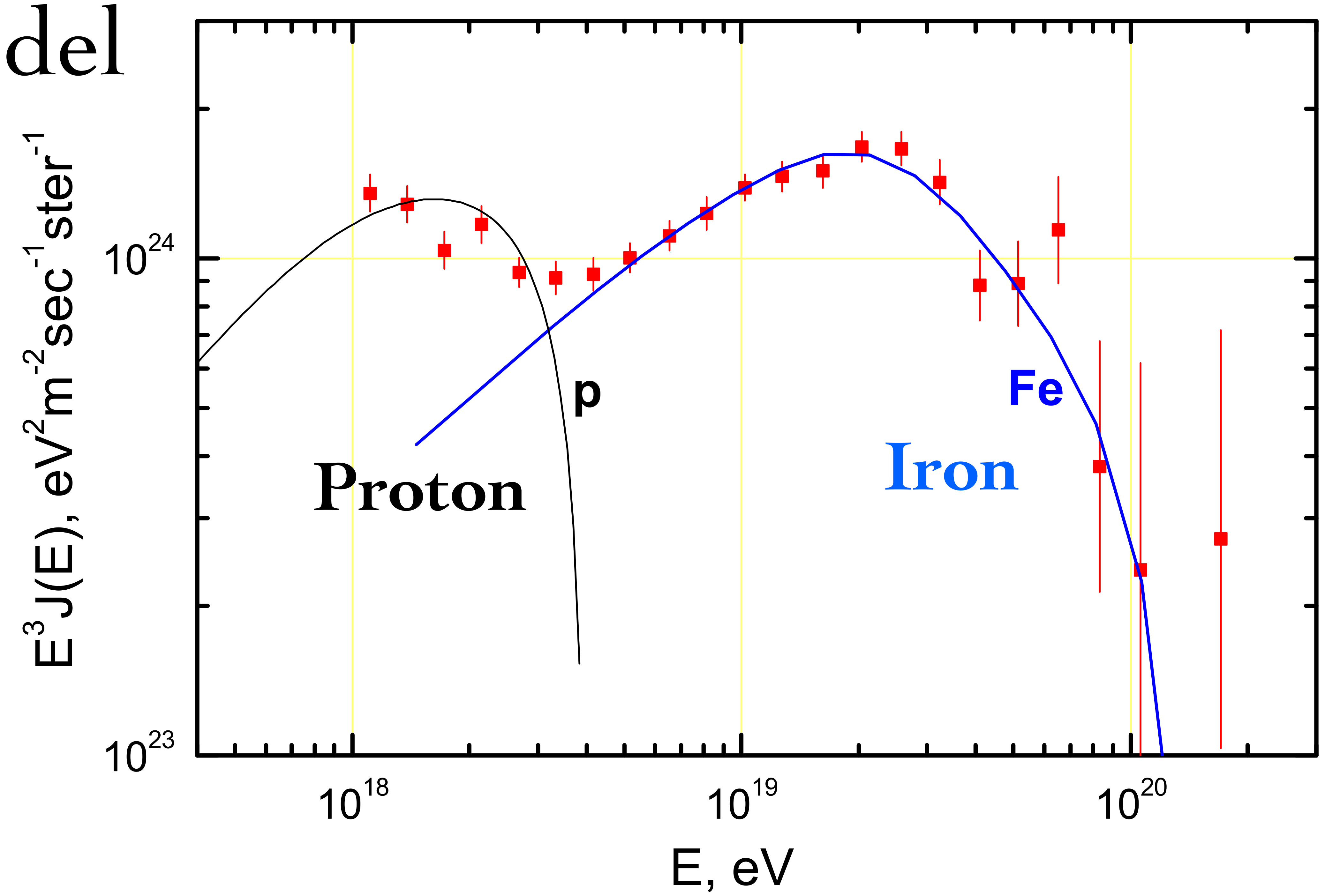
Theoretic models of ankle structure

Dip model



- Suppression = GZK cutoff
- Observed “ankle” = pair creation “dip”
- Transition takes place well before the “ankle”.

Ankle model



- Suppression = acceleration limit
- Ankle structure = transition of origins
- Not “dip”

Mass composition measurement needed.

D. Allard et al., Astropart.Phys. 27 (2007) 61-75,

R. Aloisio et al. Astropart. Phys. 34 (2011) 620–626

UHECR Astronomy

- Flux suppression → Nearby Universe → Large scale structure
- UHECR → Small deflection in galactic/extragalactic magnetic field

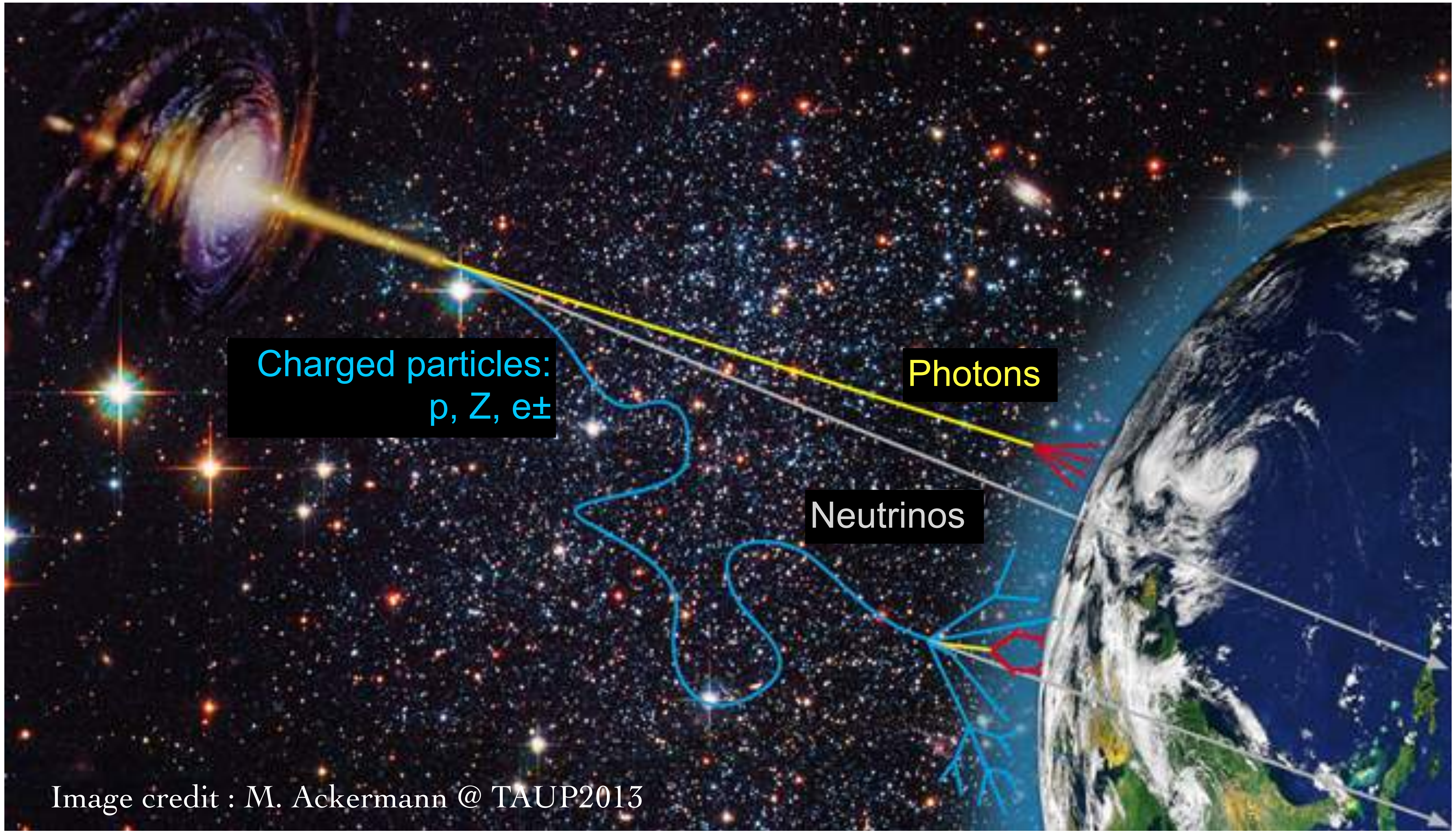


Image credit : M. Ackermann @ TAUP2013

$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times10^{19} eV}{E/Z}$$

Correlation with Nearby sources

↓

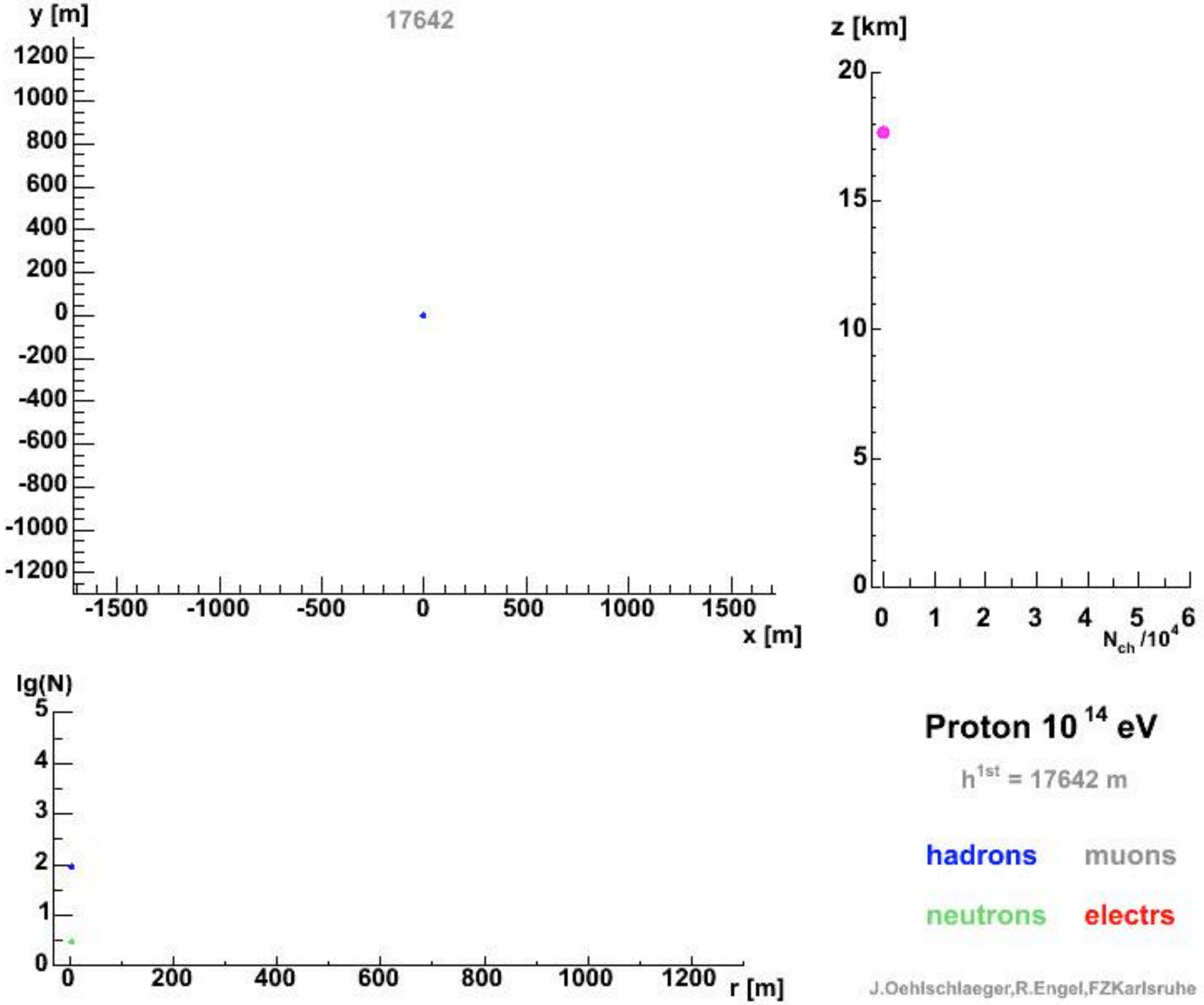
UHECR Astronomy

How to detect very infrequent UHECRs?
= Extensive air shower (EAS)

Image credit: ASPERA/Novapix/L.Bret

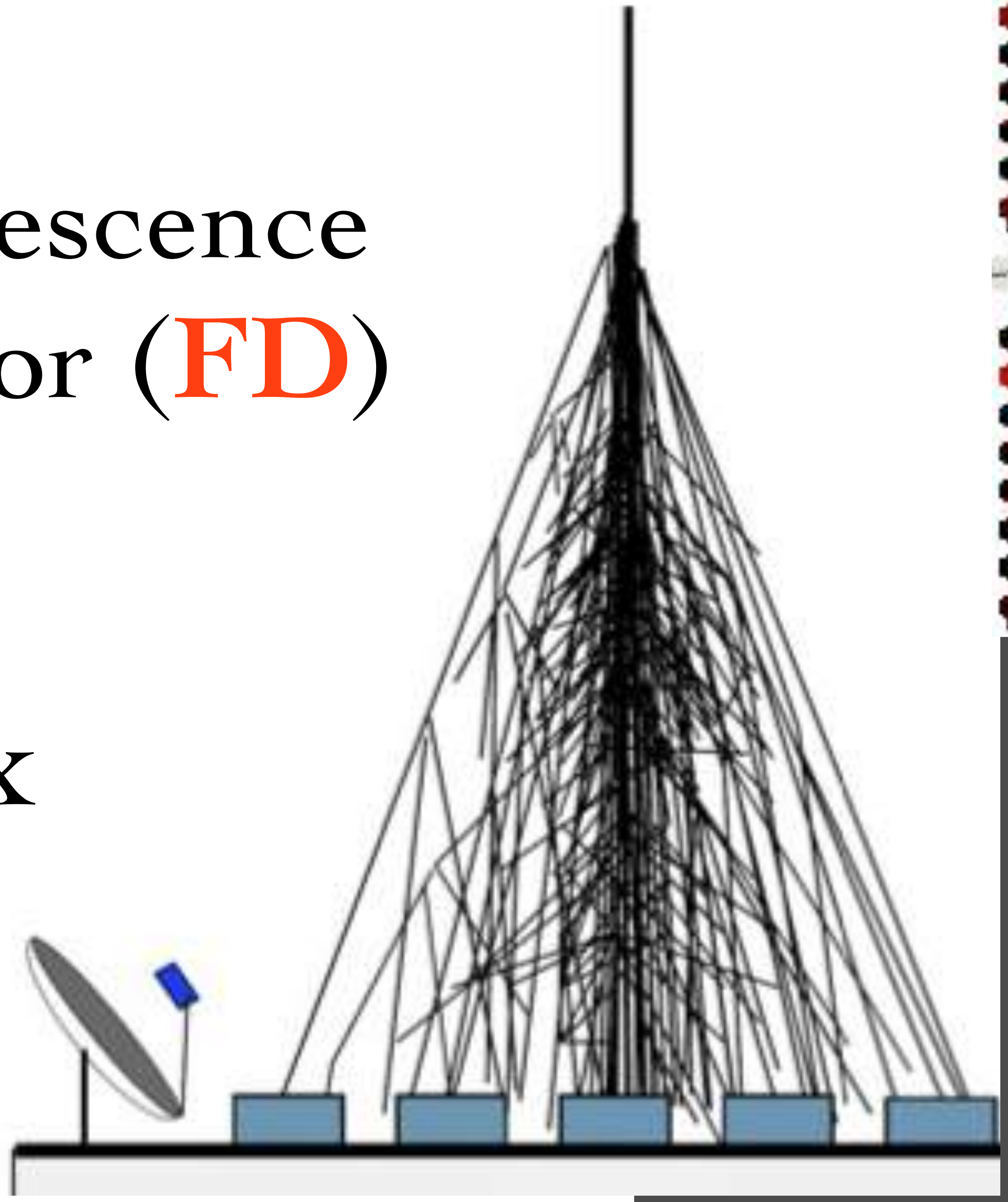
How to observe extensive air shower (EAS)

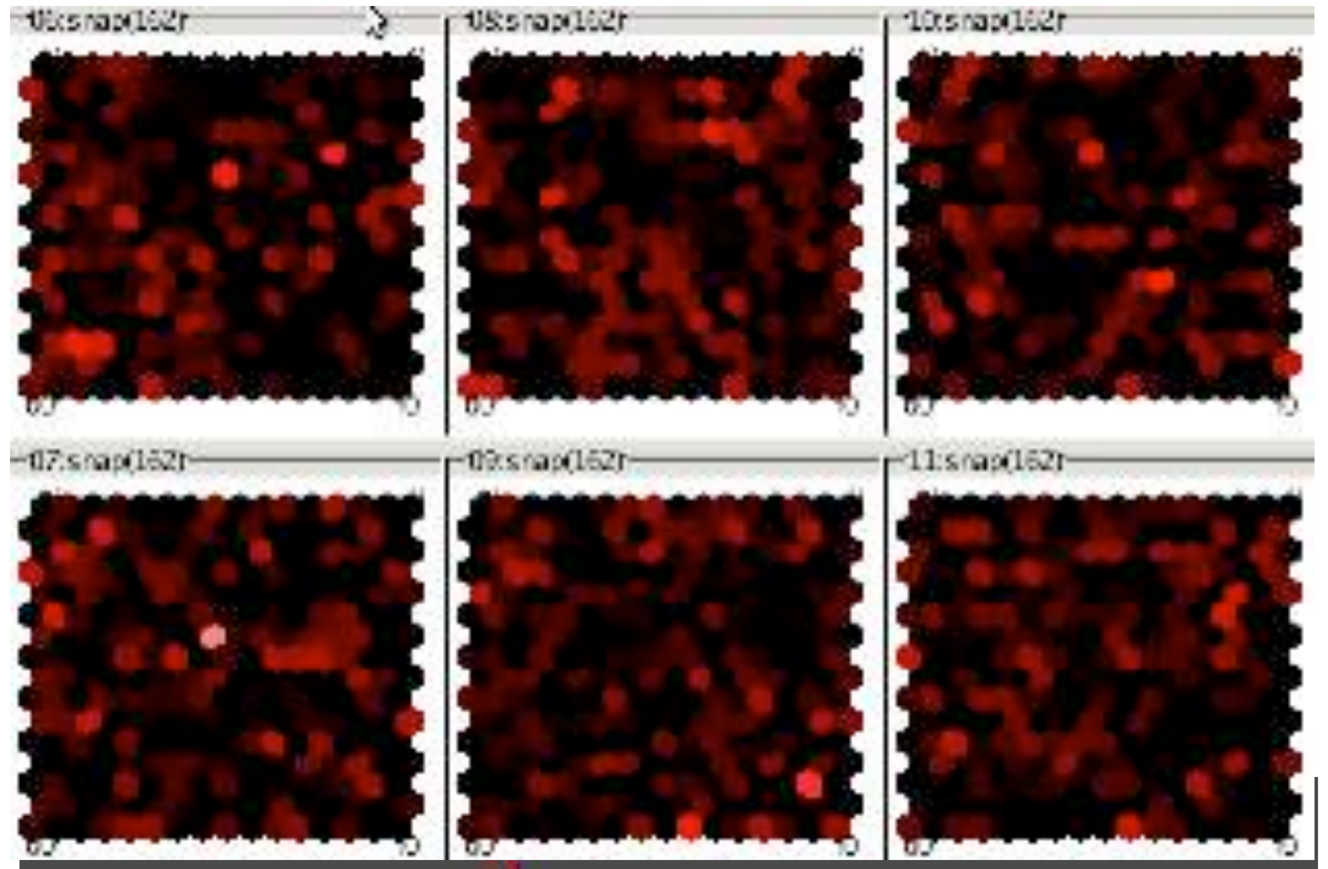
Longitudinal Development

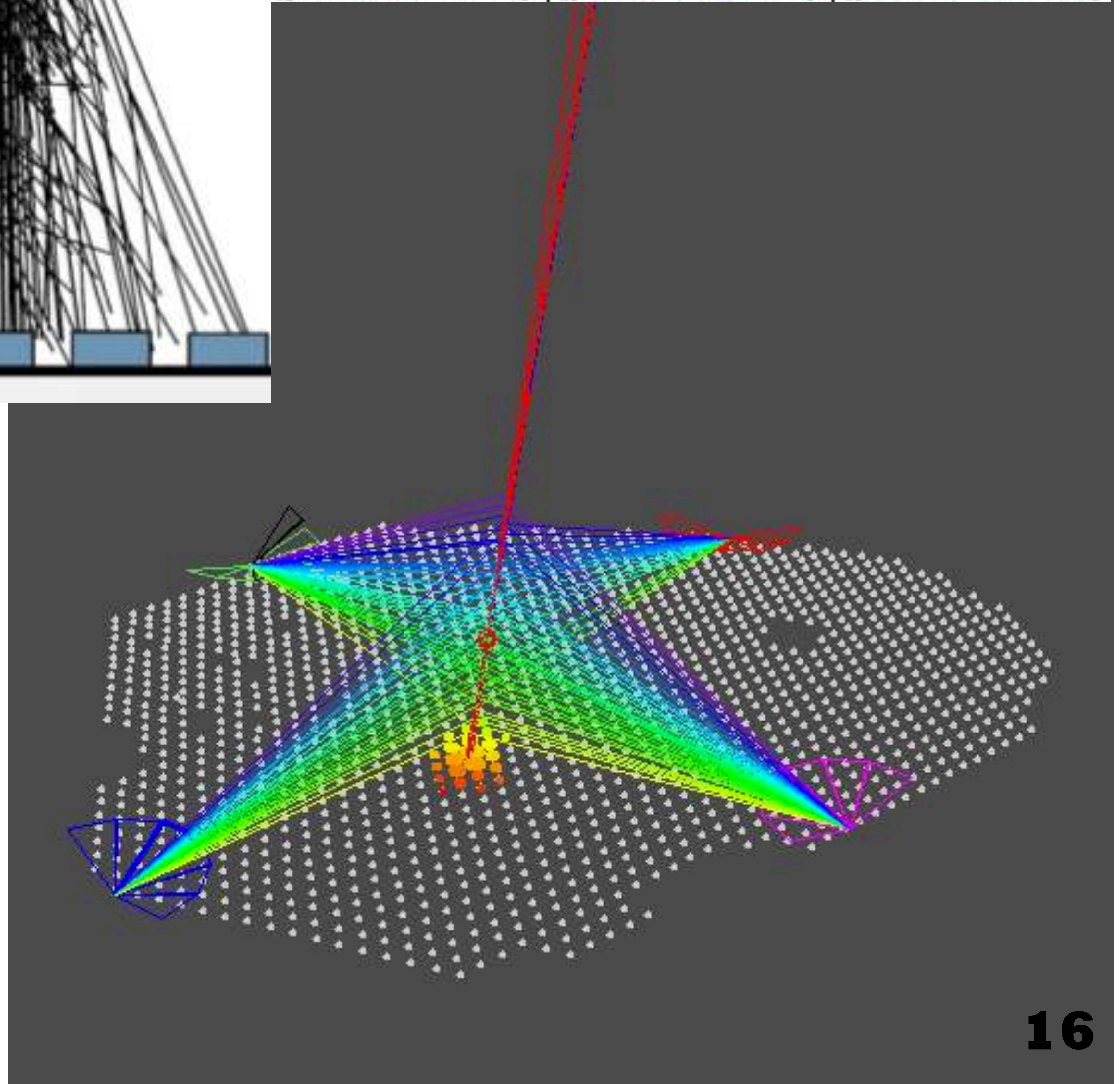


Fluorescence detector (**FD**)

Xmax







Surface detector array (**SD**)

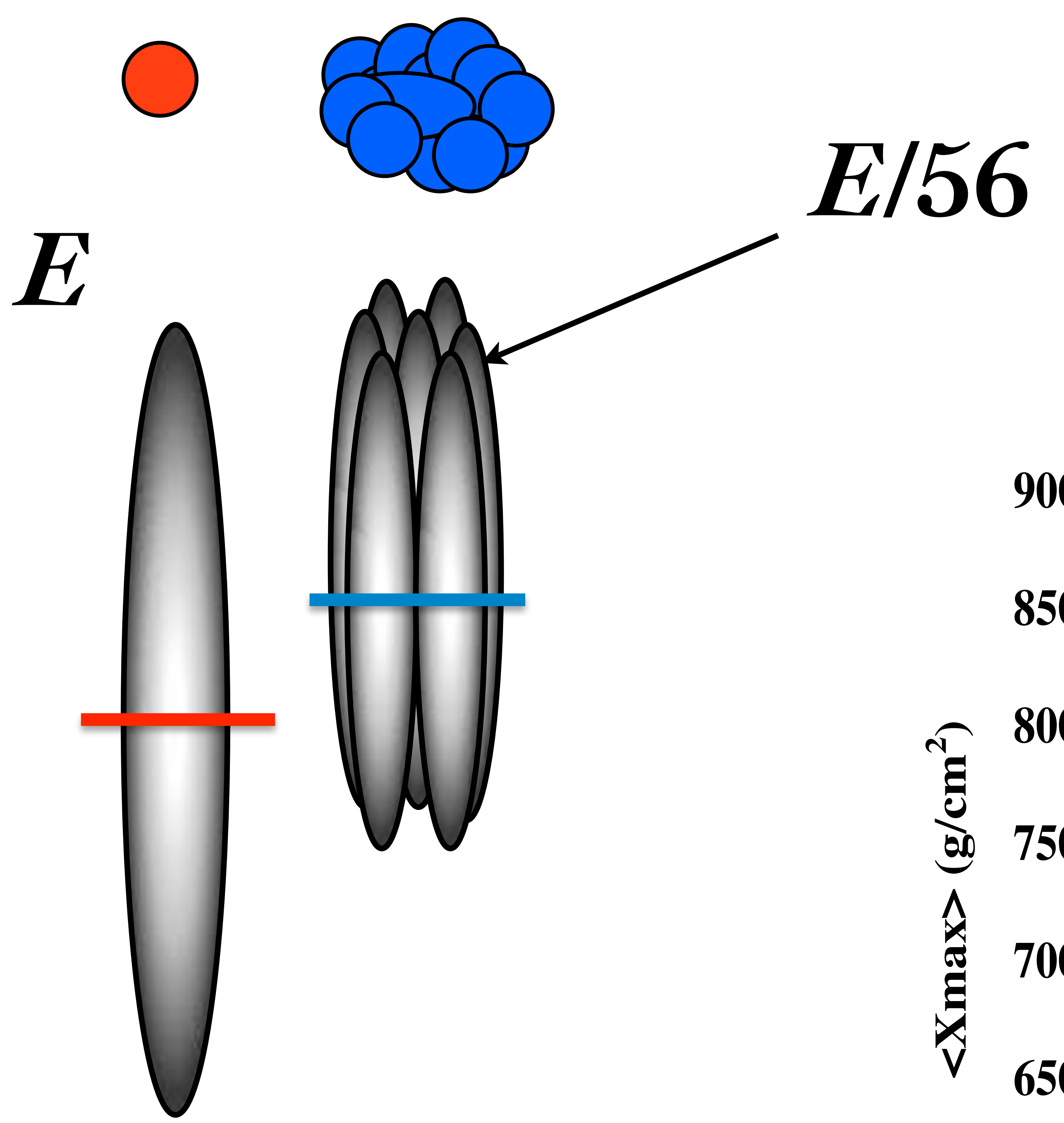
Lateral Density Distribution

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

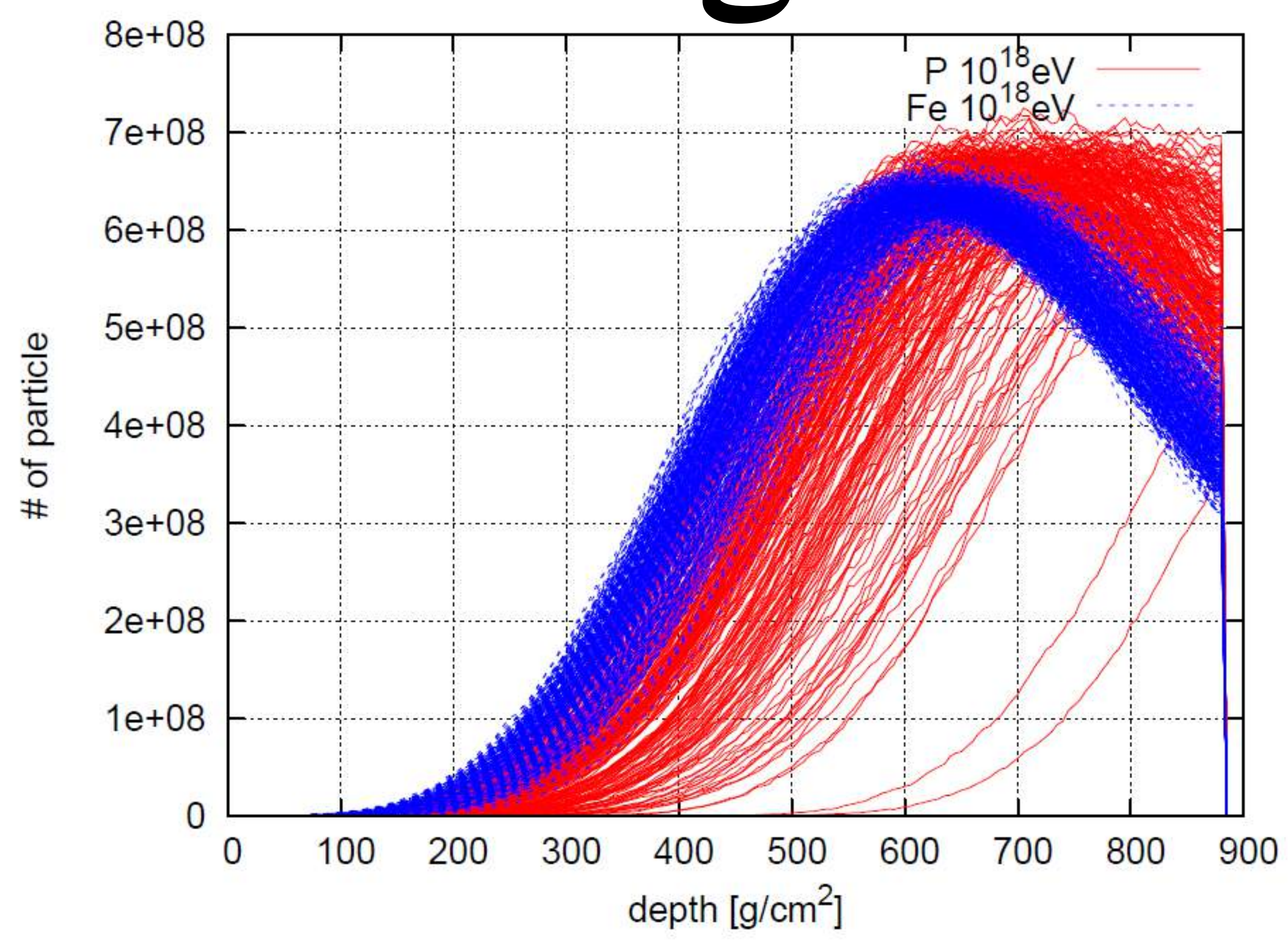
Mass composition measurement using *X*max

With the same energy, ***E***

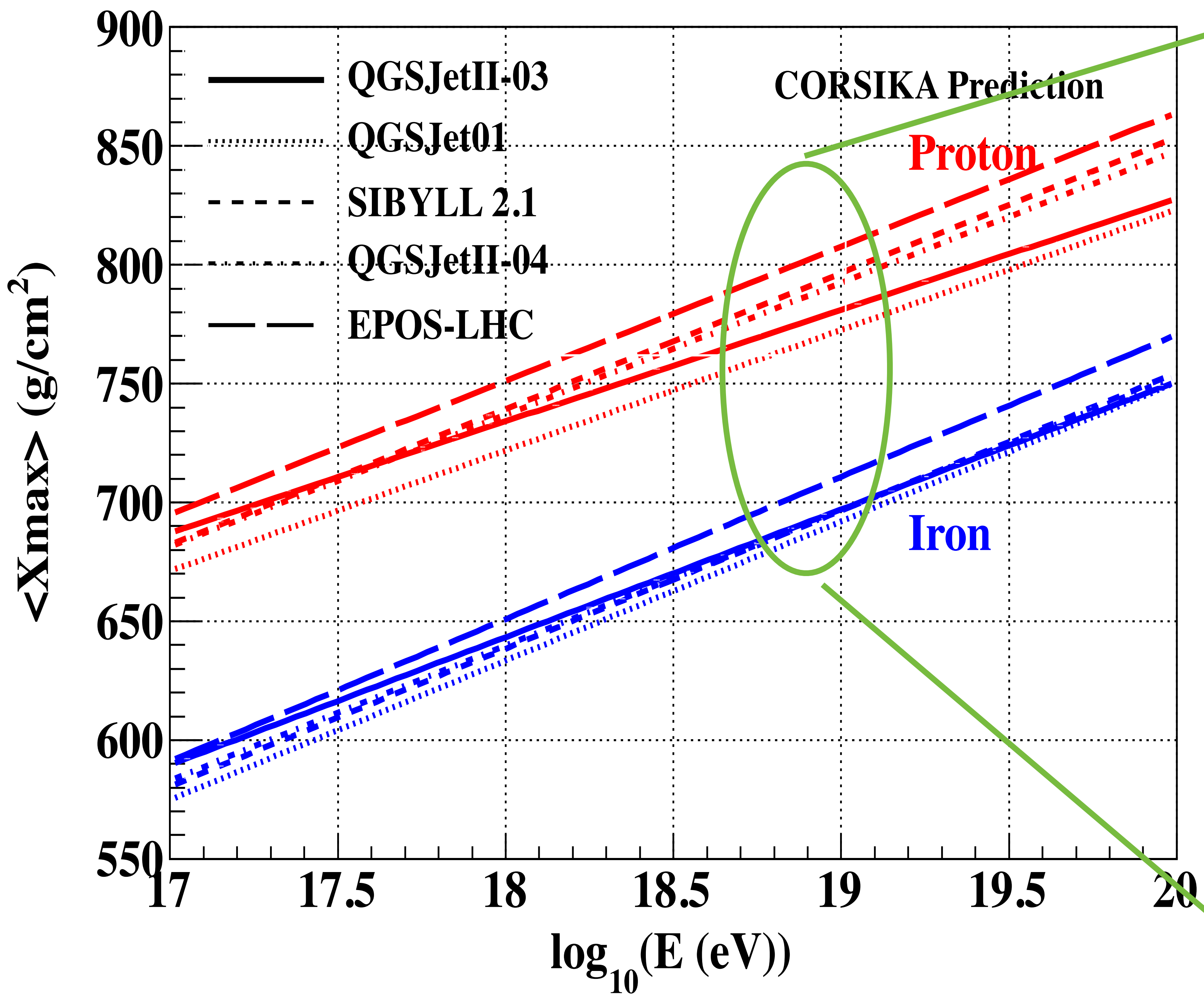
Proton(1) Iron(56)

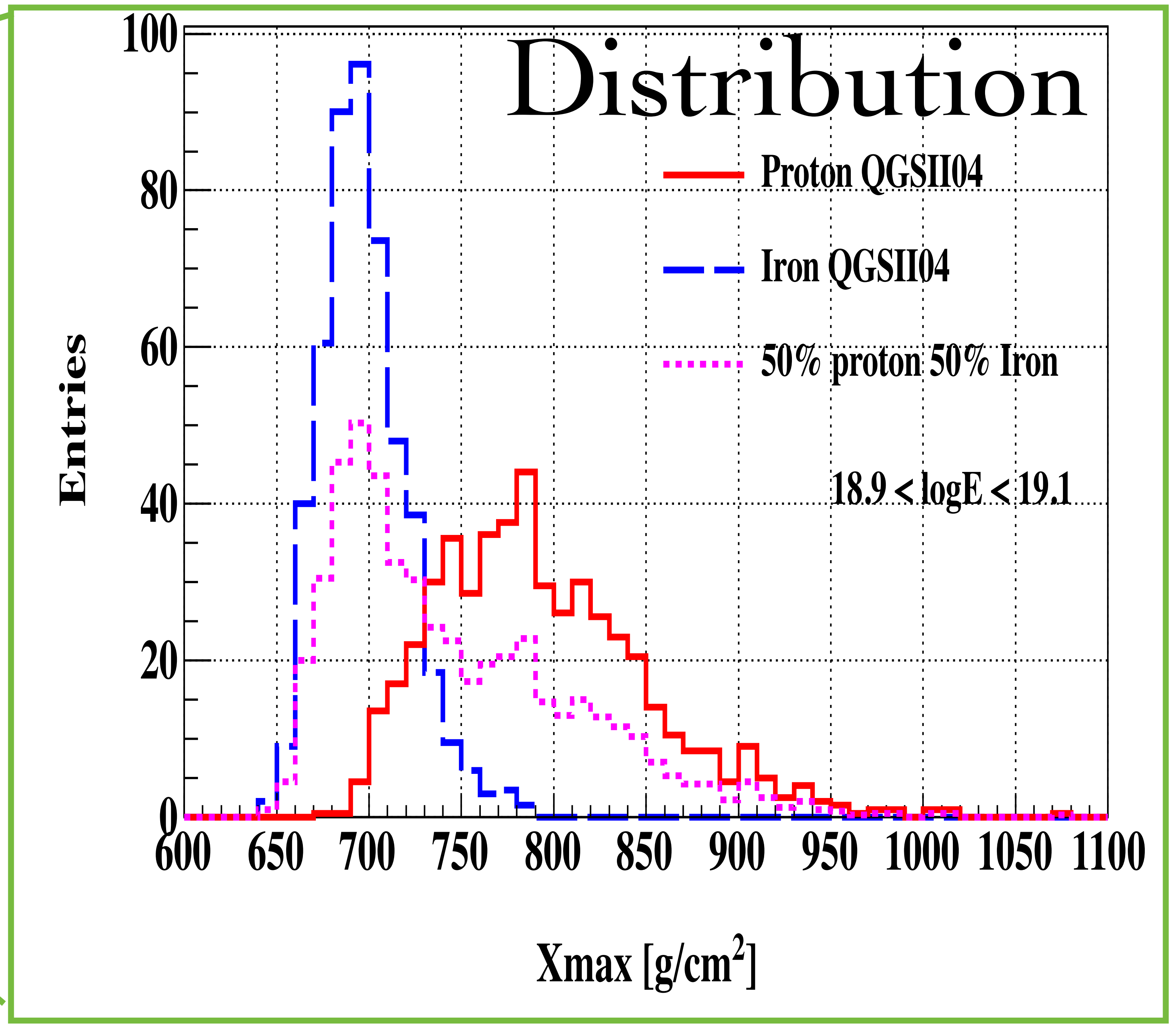


longitudinal developments for Proton and Iron primaries.



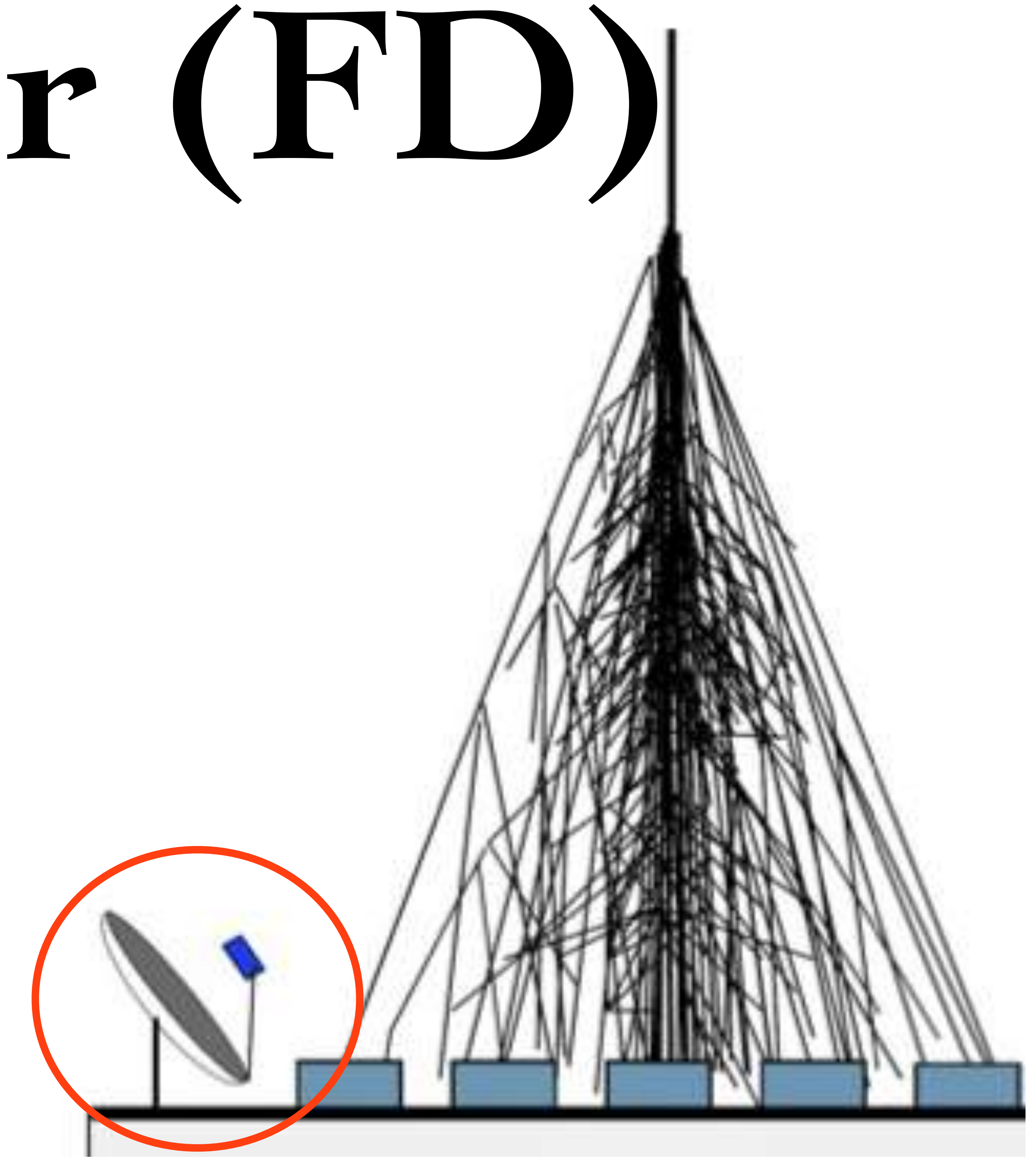
Average

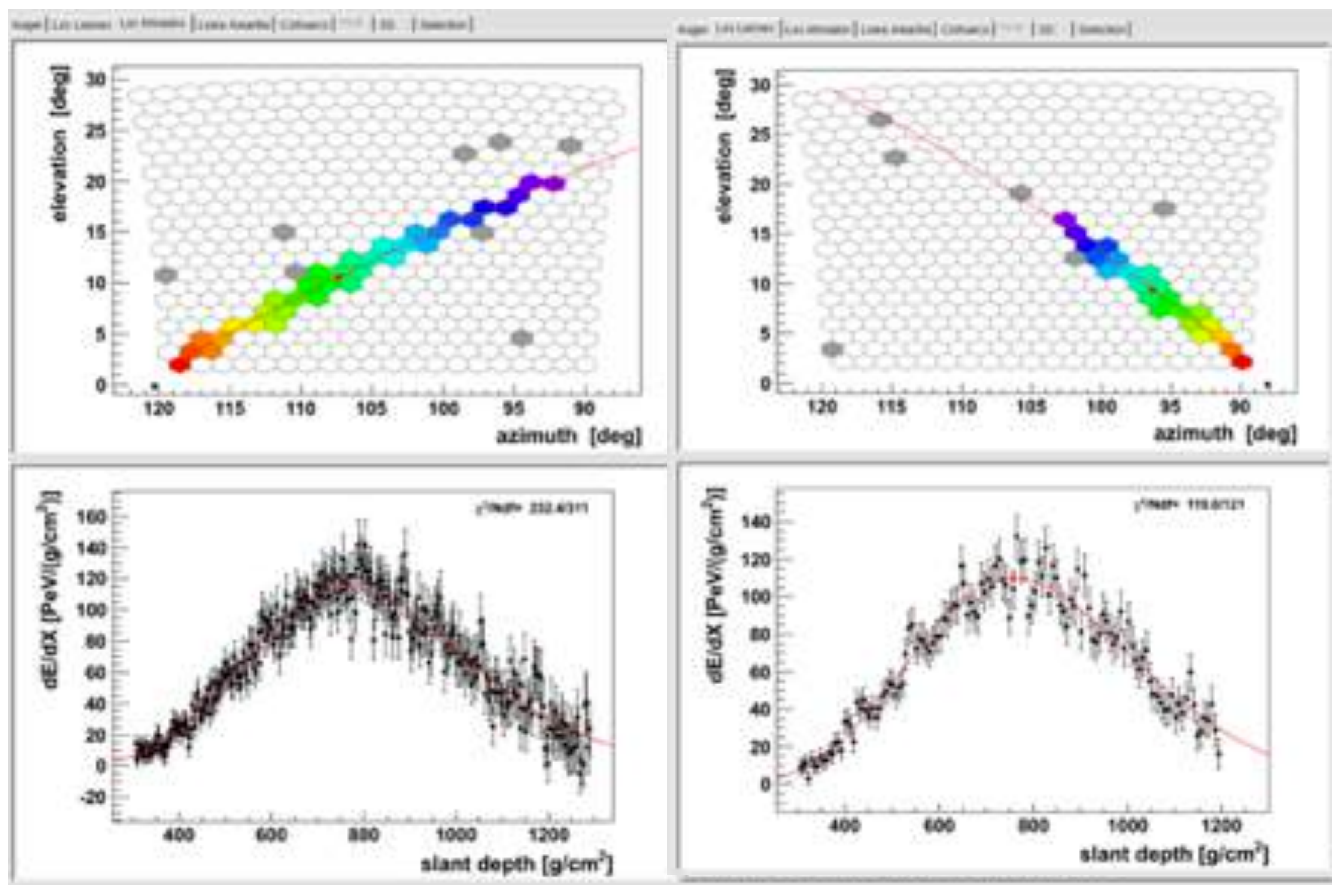




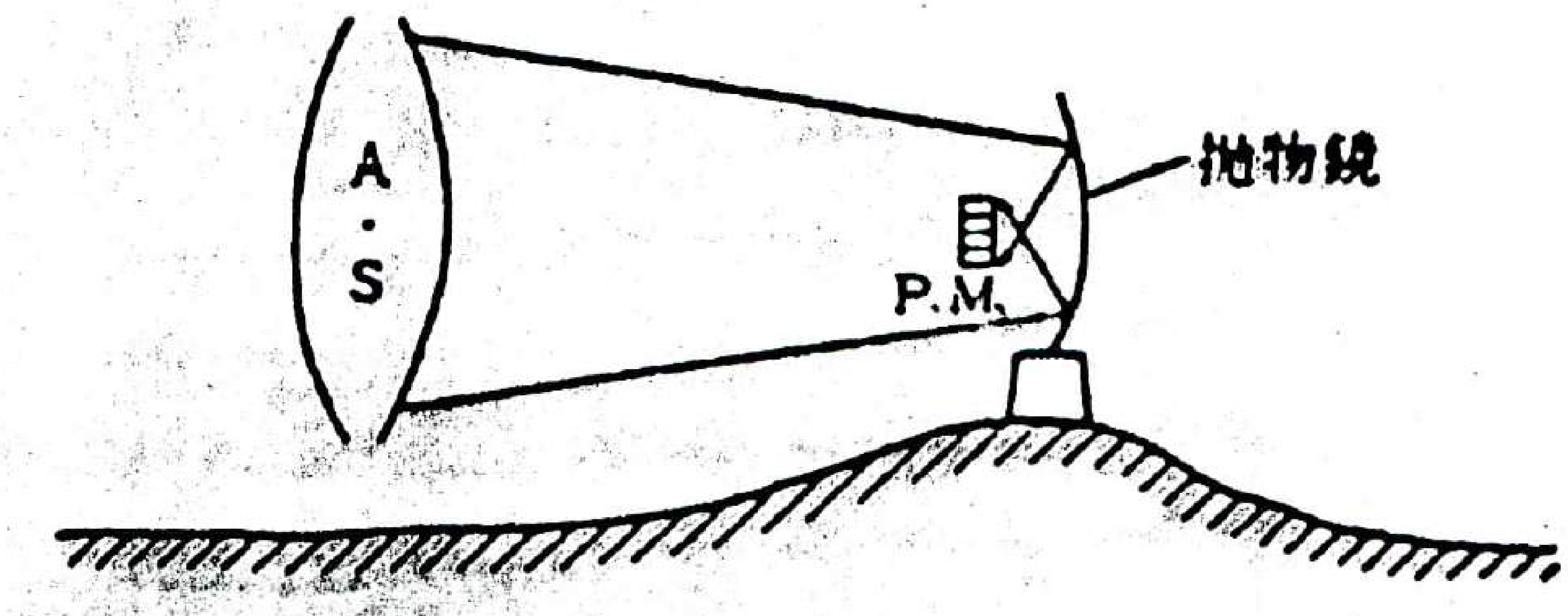
Fluorescence detector (FD)

- Detecting fluorescence photons emitted from atmospheric molecule excited by EAS.
- Measuring longitudinal development of EAS including ***X*max** = sensitive to mass composition
  - Only moonless clear night, duty cycle, **10~15%**
- less dependence on hadronic interaction model.
- Many calibration factors: atmosphere, mirror reflectance, filter transparency, PMT gain.



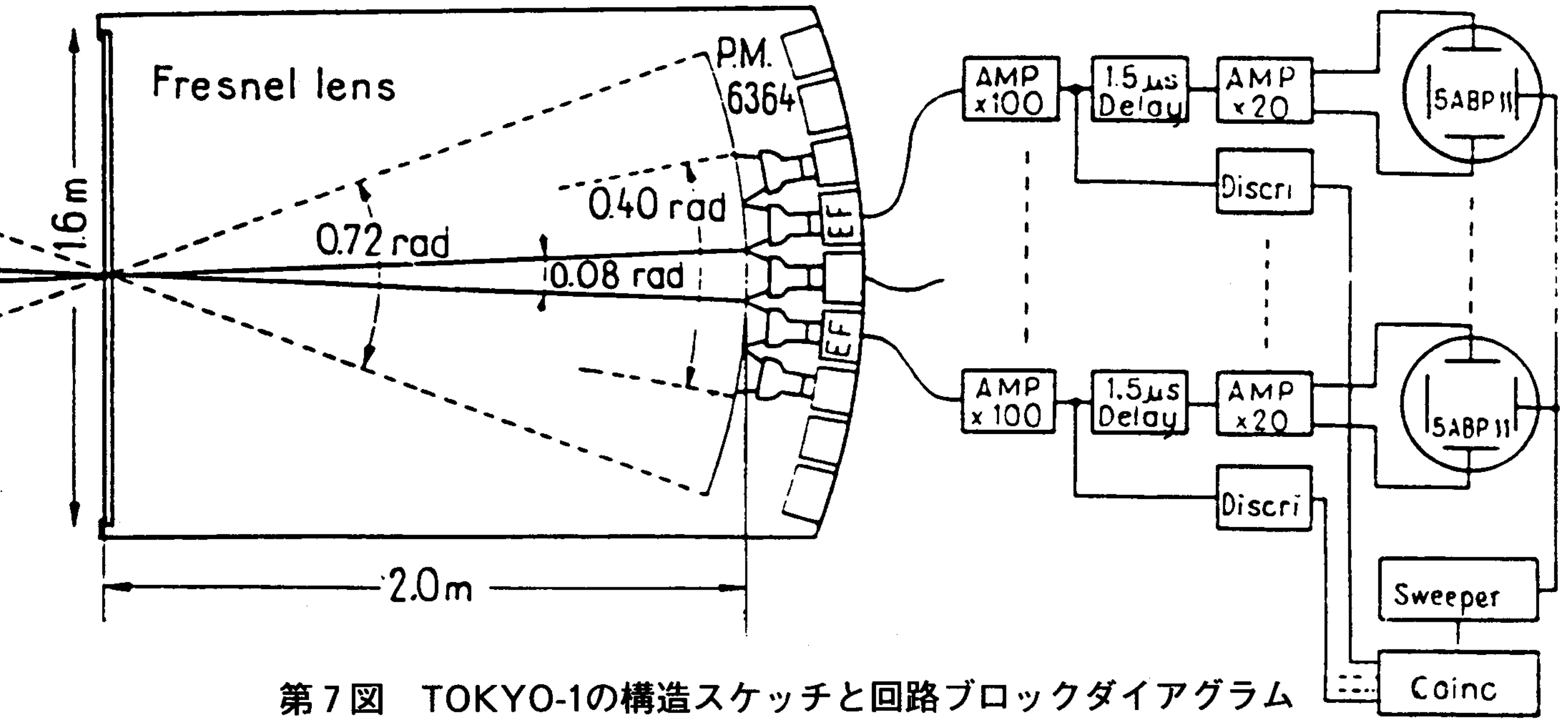


History of fluorescence technique

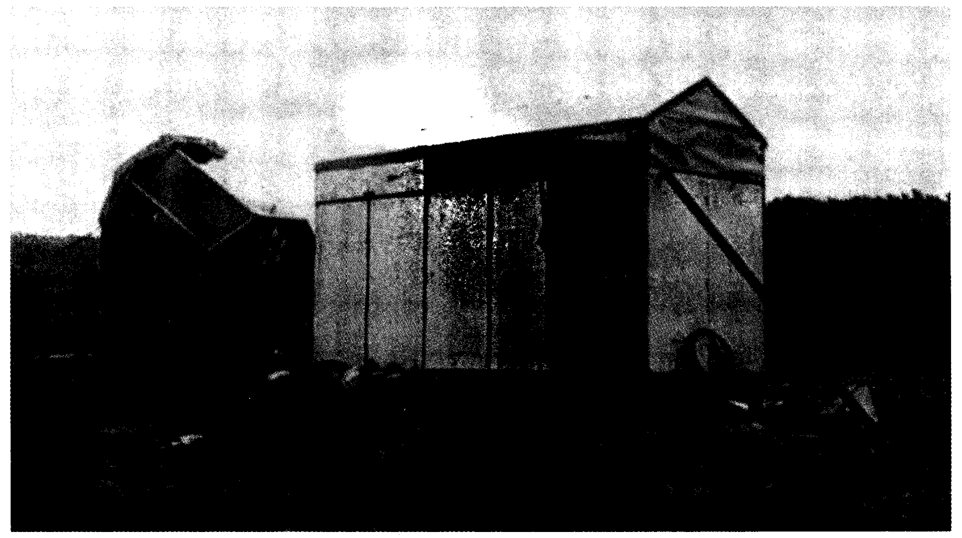


第3図　1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

Fresnel lens + PMTs



第７図　TOKYO-1の構造スケッチと回路ブロックダイアグラム



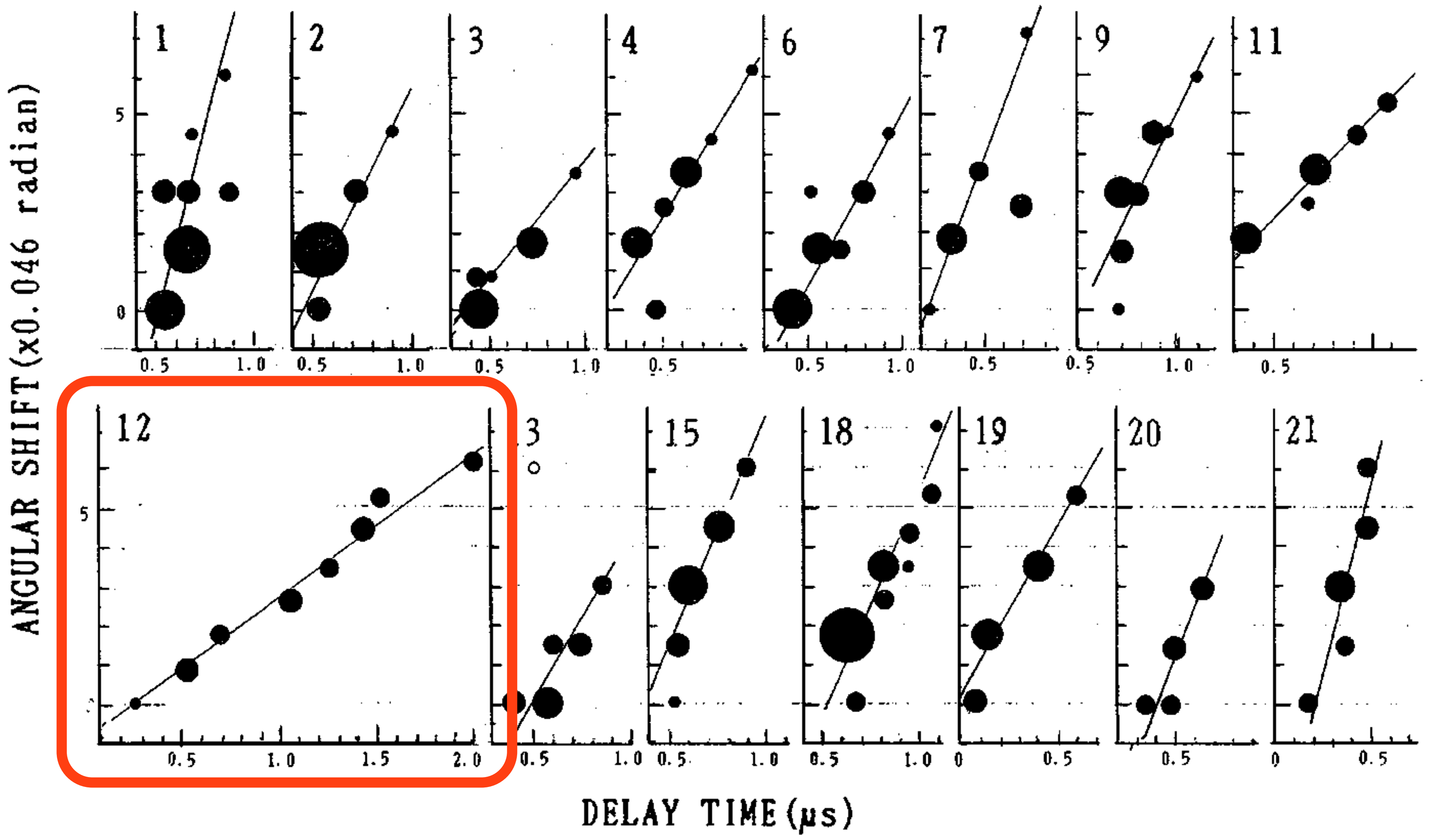
第８図　ＴＯＫＹＯ－１の設置写真

- In 1958, proposal of fluorescence technique (Suga, Oda＠Norikura symposium)
  - Many photomultiplier tubes on the focal plane of Fresnel lens/mirror to observe fluorescence light.
  - Observe longitudinal profile including Xmax to be sensitive to the mass composition of cosmic ray.
    - In 1969, first detection of fluorescence light by TOKYO-1 (Tanahashi et al. @Doudaira Observatory, Japan)

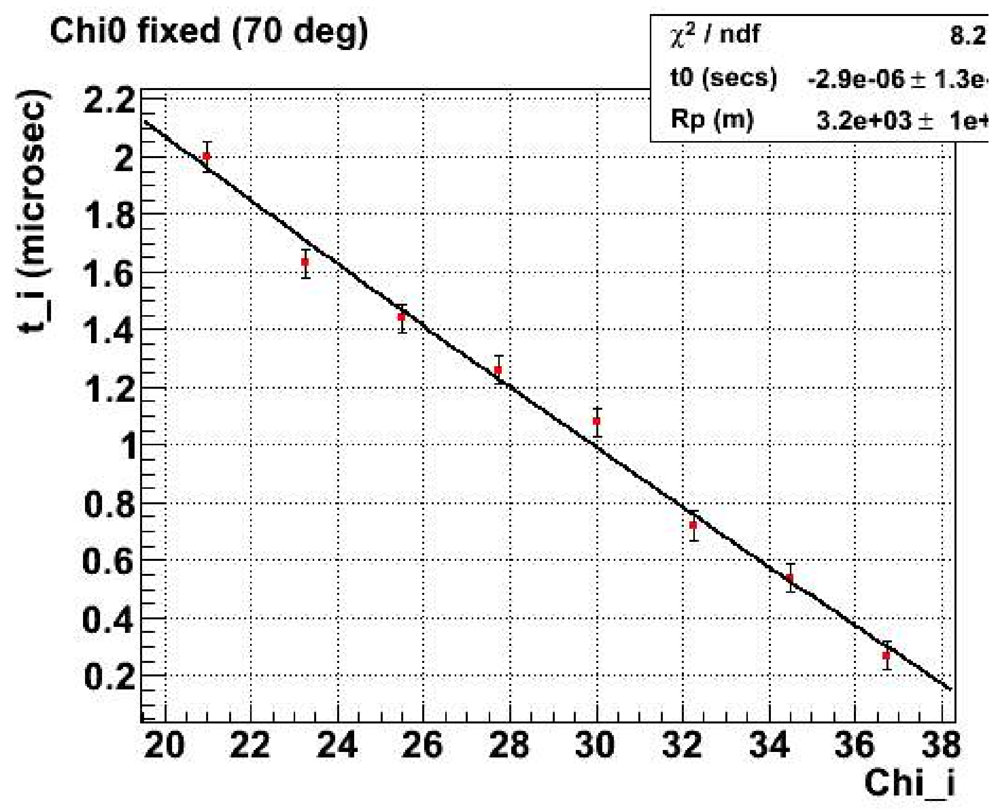
Reference: 空気シャワー観測による宇宙線研究の歴史 永野元彦, 大気の蛍光観測による宇宙線実験の始まり 棚橋五郎

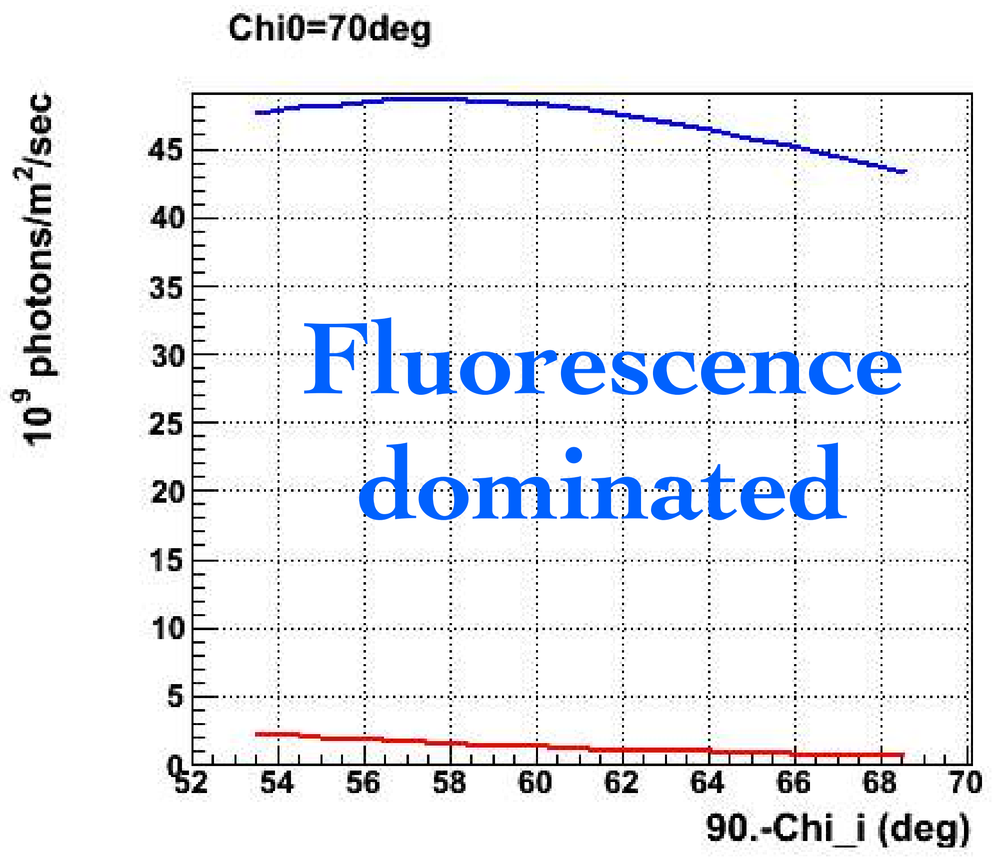
First detection of EAS using fluorescence technique

Candidates observed by TOKYO-1 (1969)

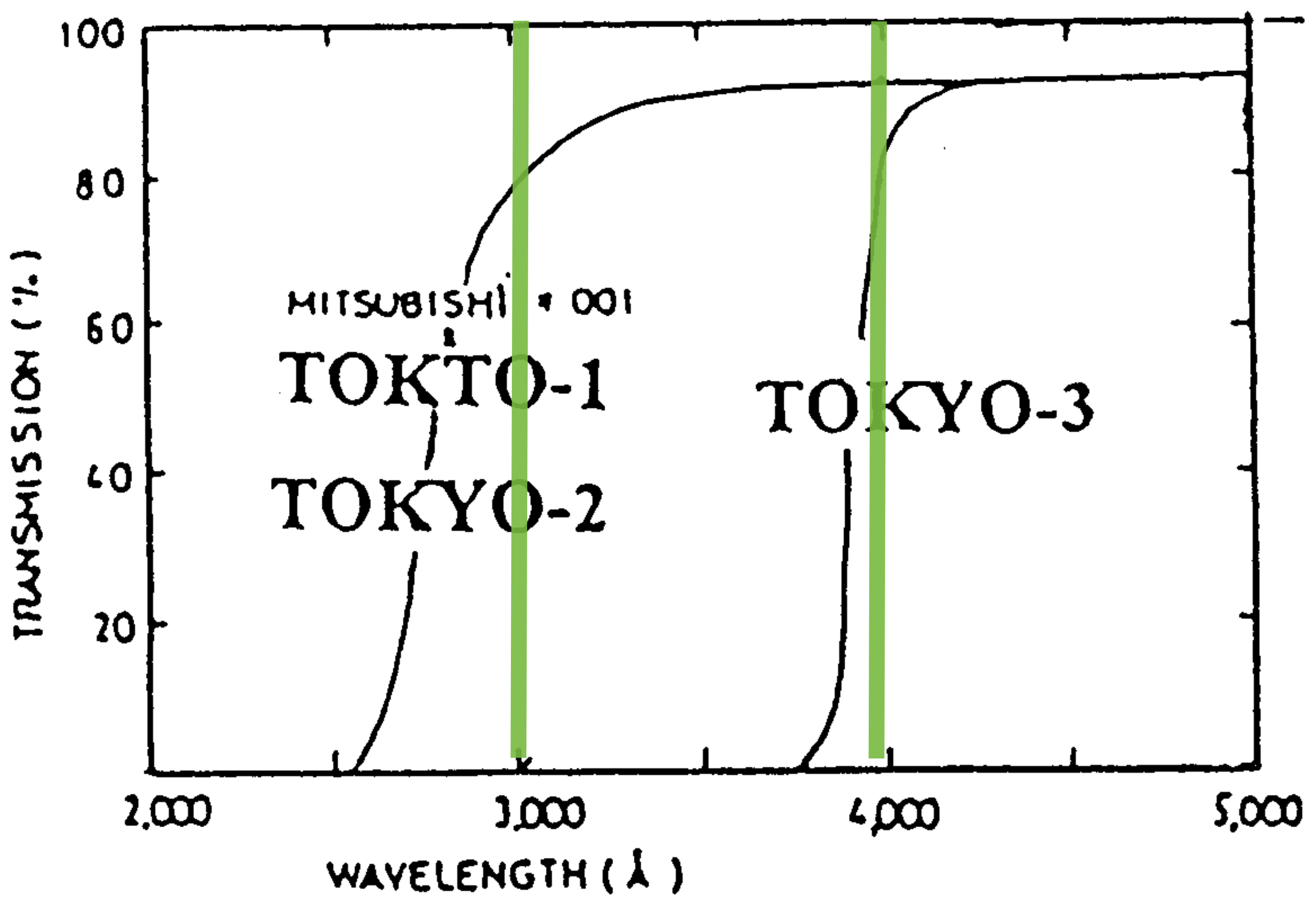


Re-analysis by B. Dawson *et al*. (2011)





- Long signal duration for event 12.
- The event is consistent with the fluorescence-dominated shower with **5×10^{18} eV, 680 g/cm^2** (B. Dawson, arXiv: 1112.5686).
- In the upgrade detector of TOKYO-3, the 4 m^2 lens was unfortunately UV **protected** one.
- Fly's Eye experiment, Telescope Array experiment and Pierre Auger Observatory established the fluorescence technique and reported physics results.



第６図　プラスチックレンズの光透過性能
（TOKYO-1,TOKYO-2,TOKYO-3）

M. Ave et al. / Astroparticle Physics 28 (2007) 41–57

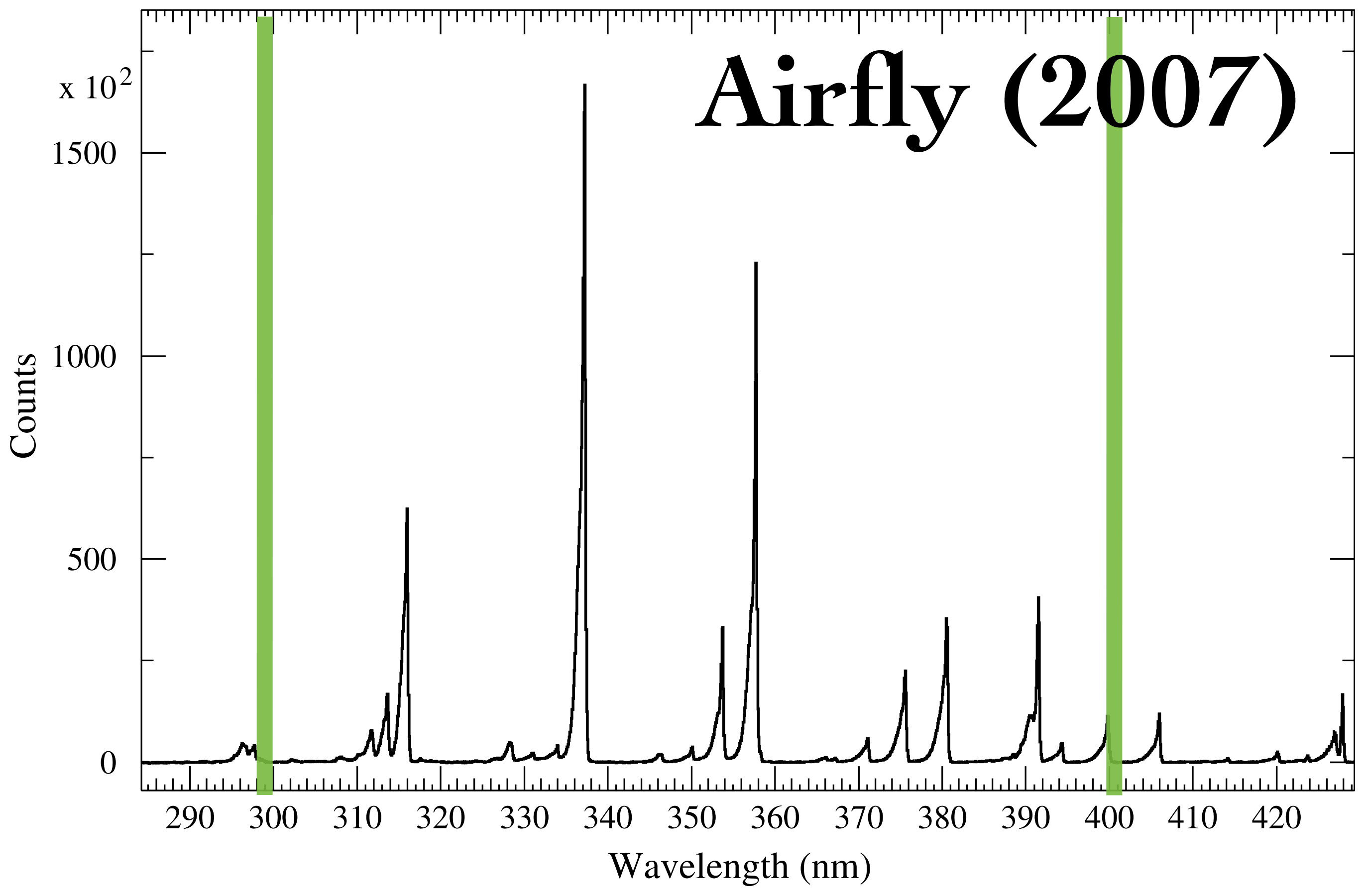
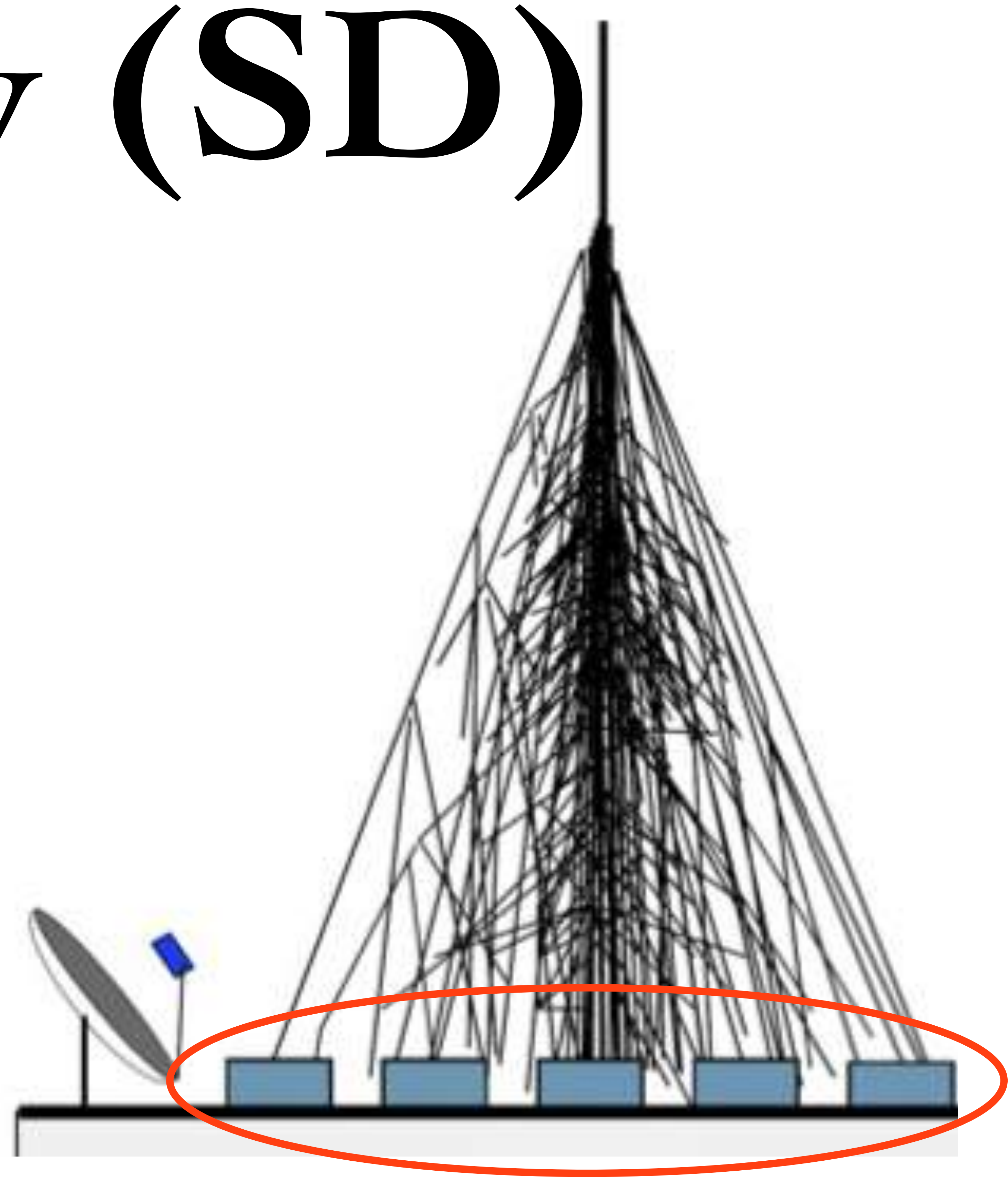
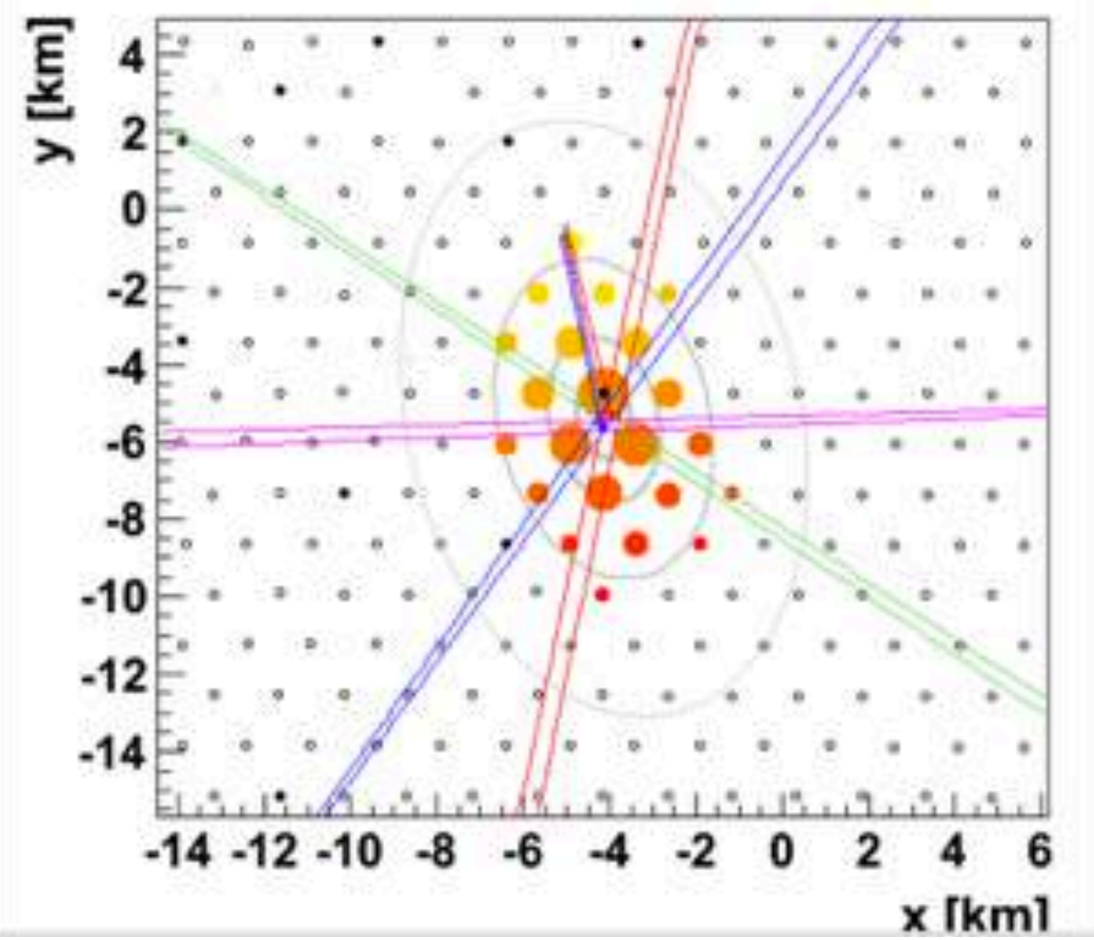


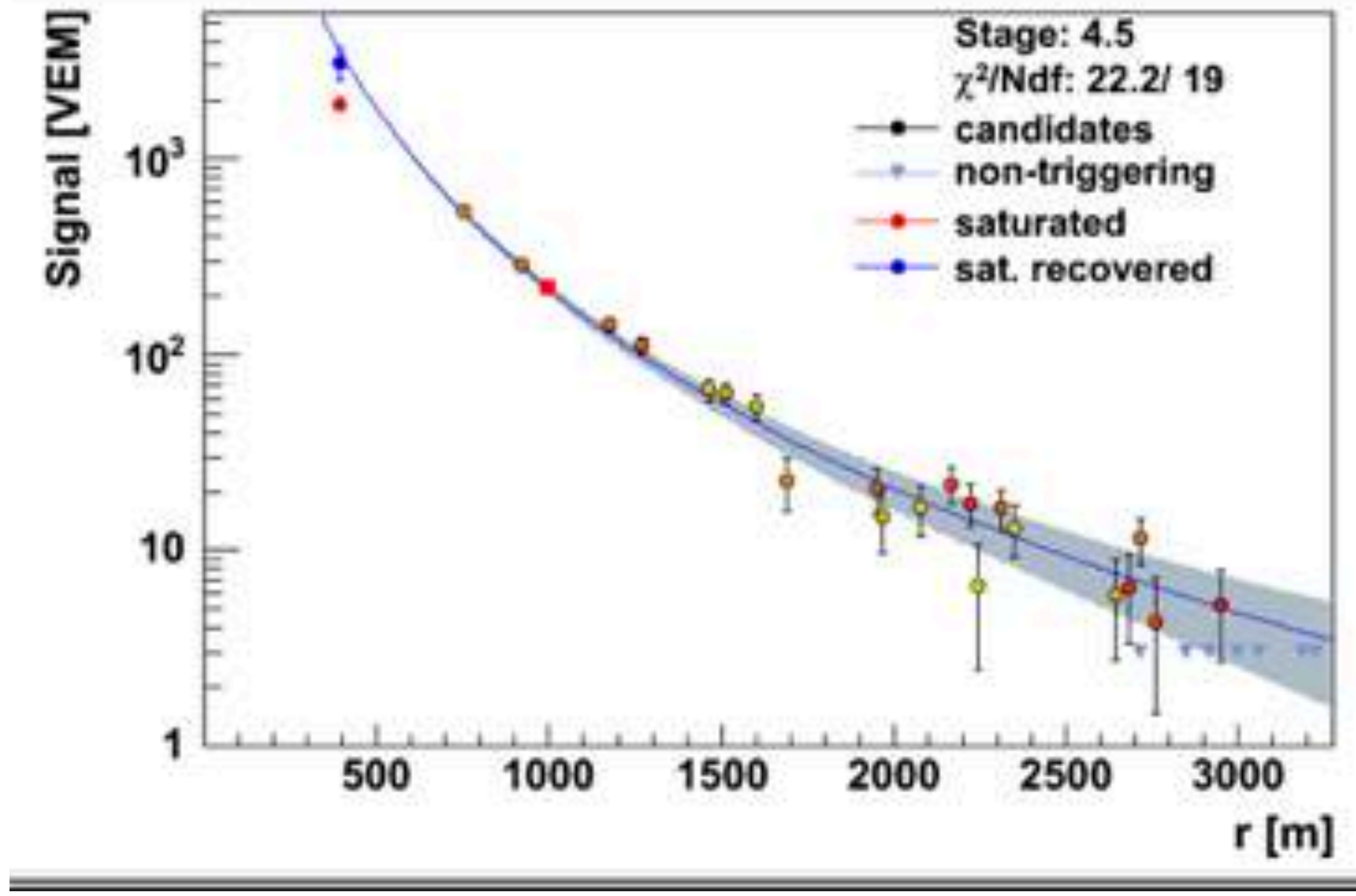
Fig. 4. Measured fluorescence spectrum in dry air at 800 hPa and 293 K.

Surface detector array (SD)

- Observing EAS particles on the ground by SD array
  - Measuring lateral density distributions
    - 24 hour, 365 days operation, **Duty cycle ~100%**
- A large systematic uncertainty due to hadron interaction models.



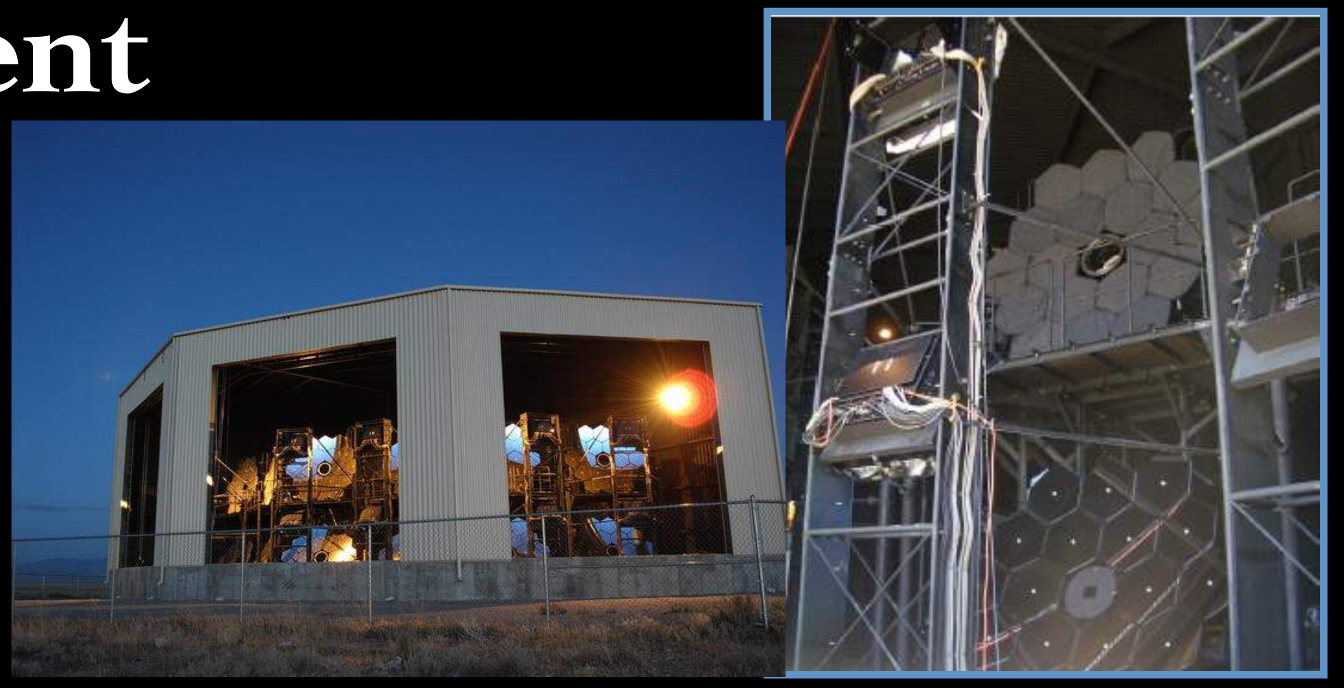




UHECR observatories

Google Earth

- Telescope Array Experiment (TA)
  - Utah, USA
  - 700 km^2 ($\rightarrow$ 3,000 km^2)
  - ~7 events/year ($\rightarrow$ 30)



- Pierre Auger Observatory (Auger)
  - Malargue, Argentina
  - 3,000 km^2
  - ~30 events/year

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

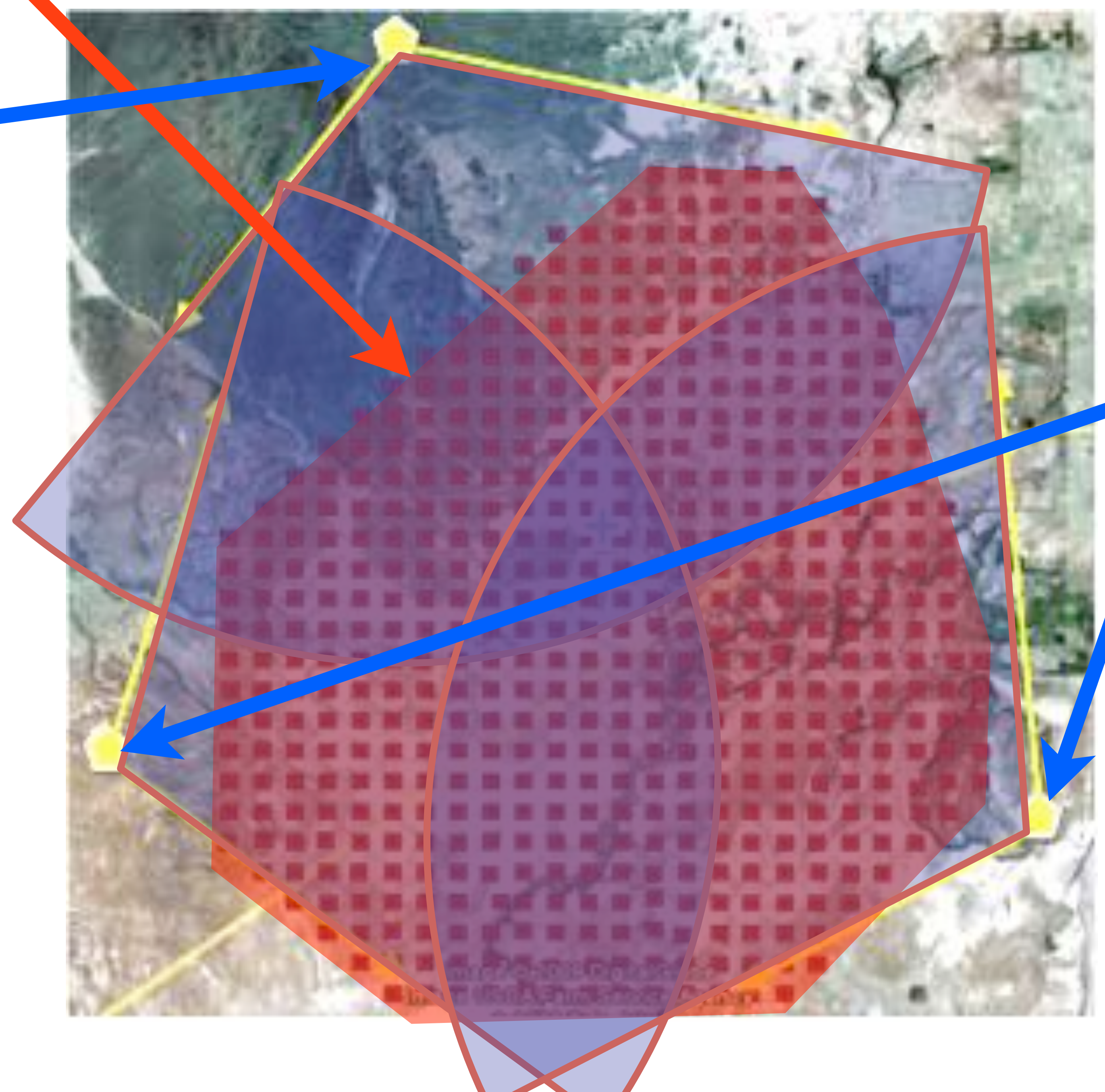
507 Scintillator, 1.2 km spacing

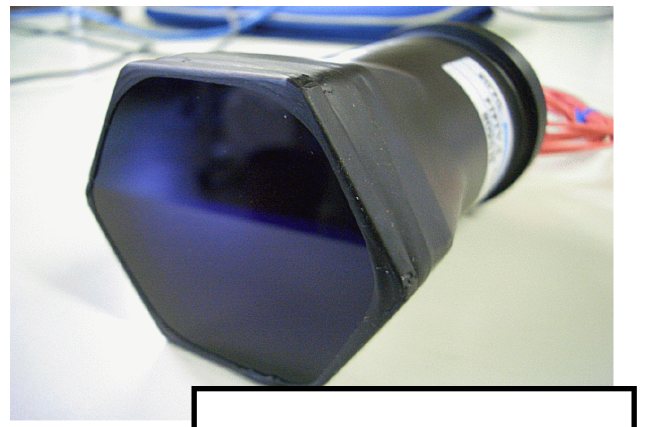
Fluorescence Detector at BRM and LR stations

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

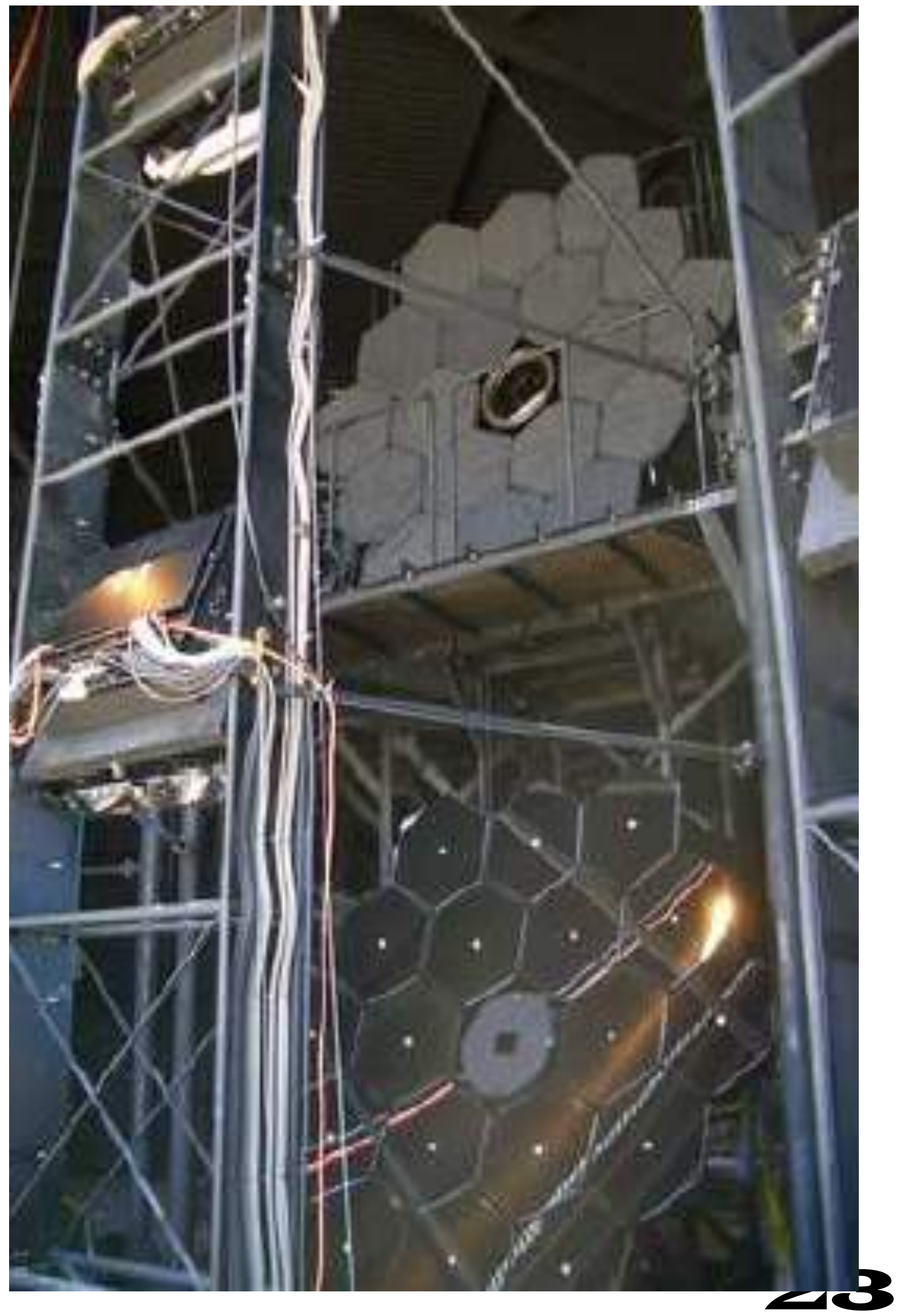
Fluorescence detector at MD station

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





PMT

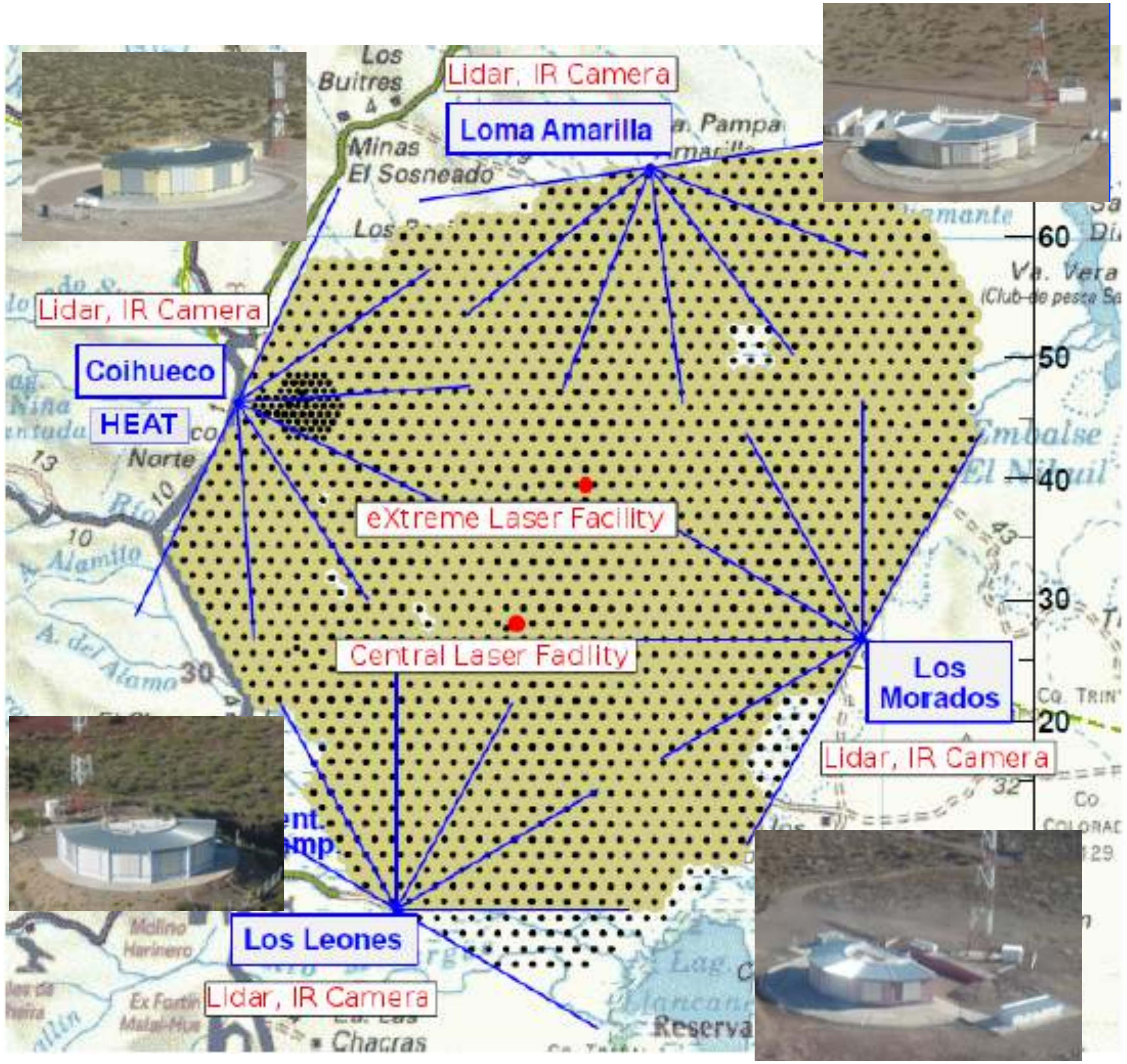


Delta, Utah, USA

Pierre Auger Observatory (Auger)

The world's largest UHECR observatory 3000 km^2

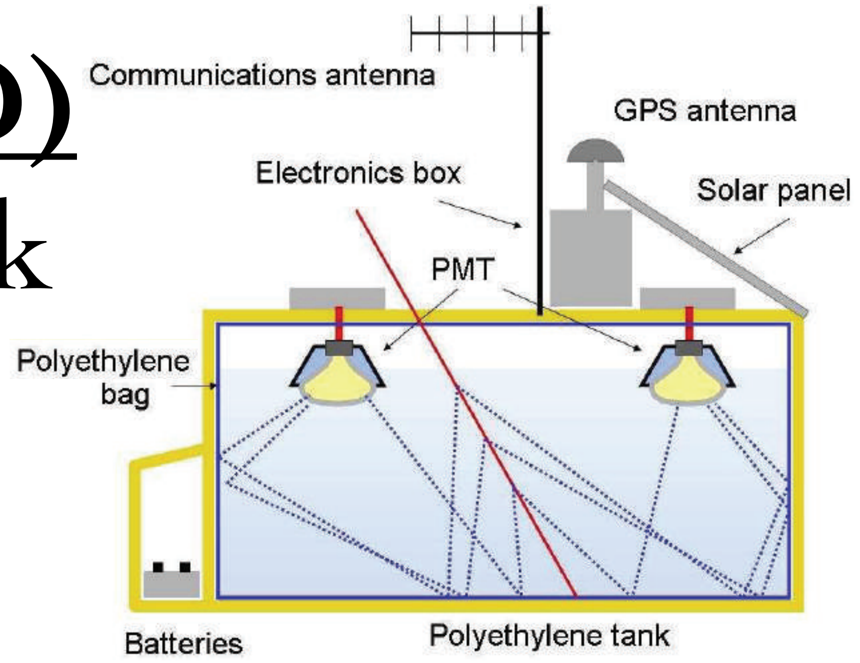
(2004 -) completed in 2008

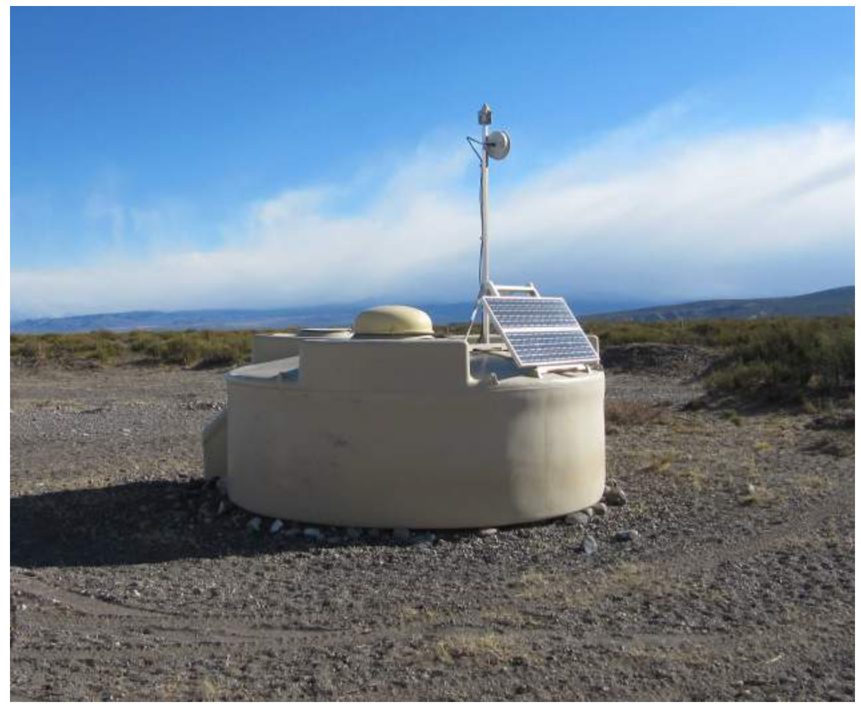


Surface Detector (SD)

Water Cherenkov Tank

1.5 km spacing, 1600 stations

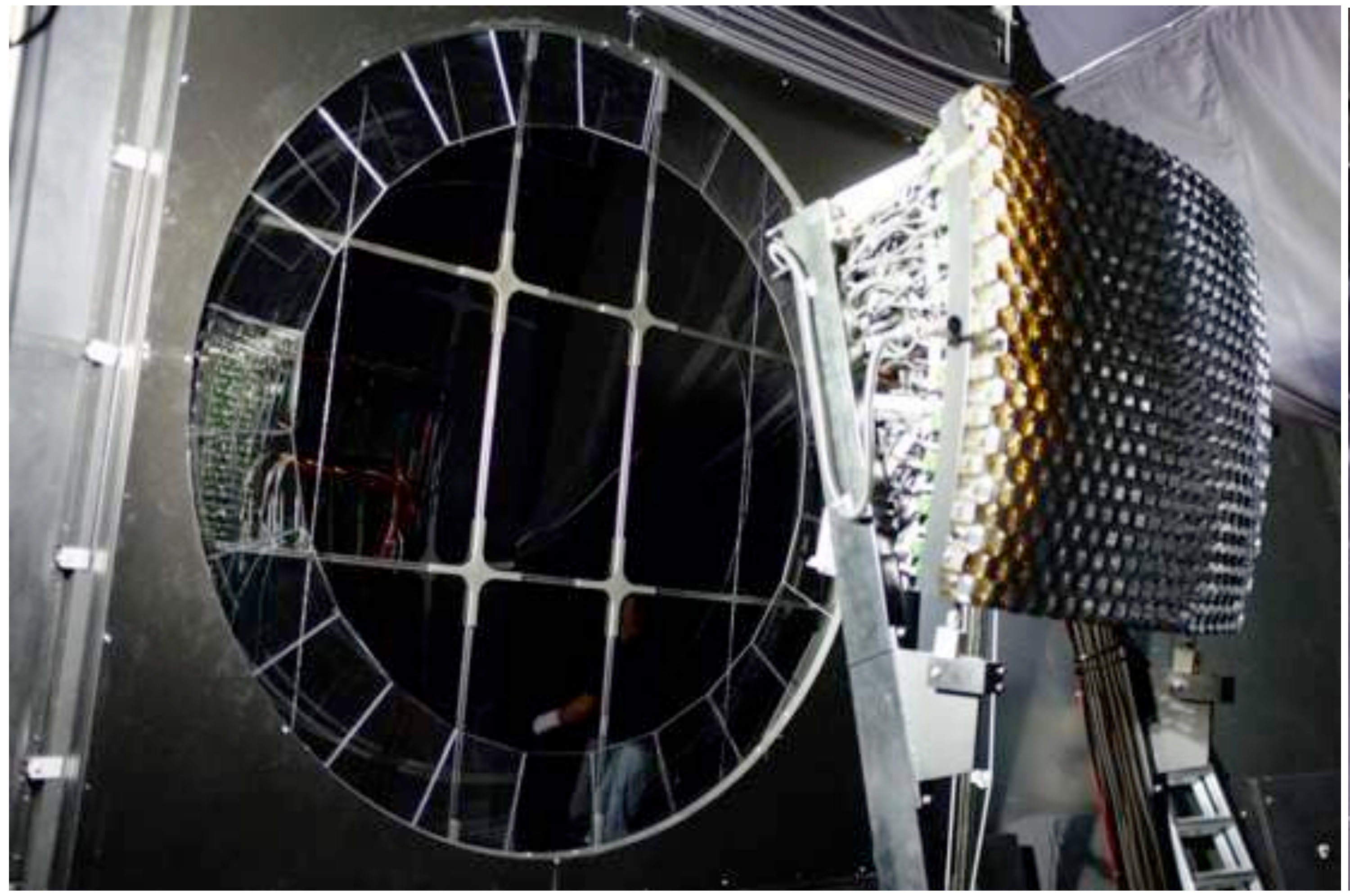




Fluorescence Detector (FD)

3.4 m spherical mirror, 440 PMT, 30° × 30° FOV

light guide + collector ring, 4 × 6 telescope



PIERRE AUGER OBSERVATORY

Malargüe, Mendoza, Argentina

Annual parade and AugerPrime 2015 ceremony

Scale of UHECR Observatory

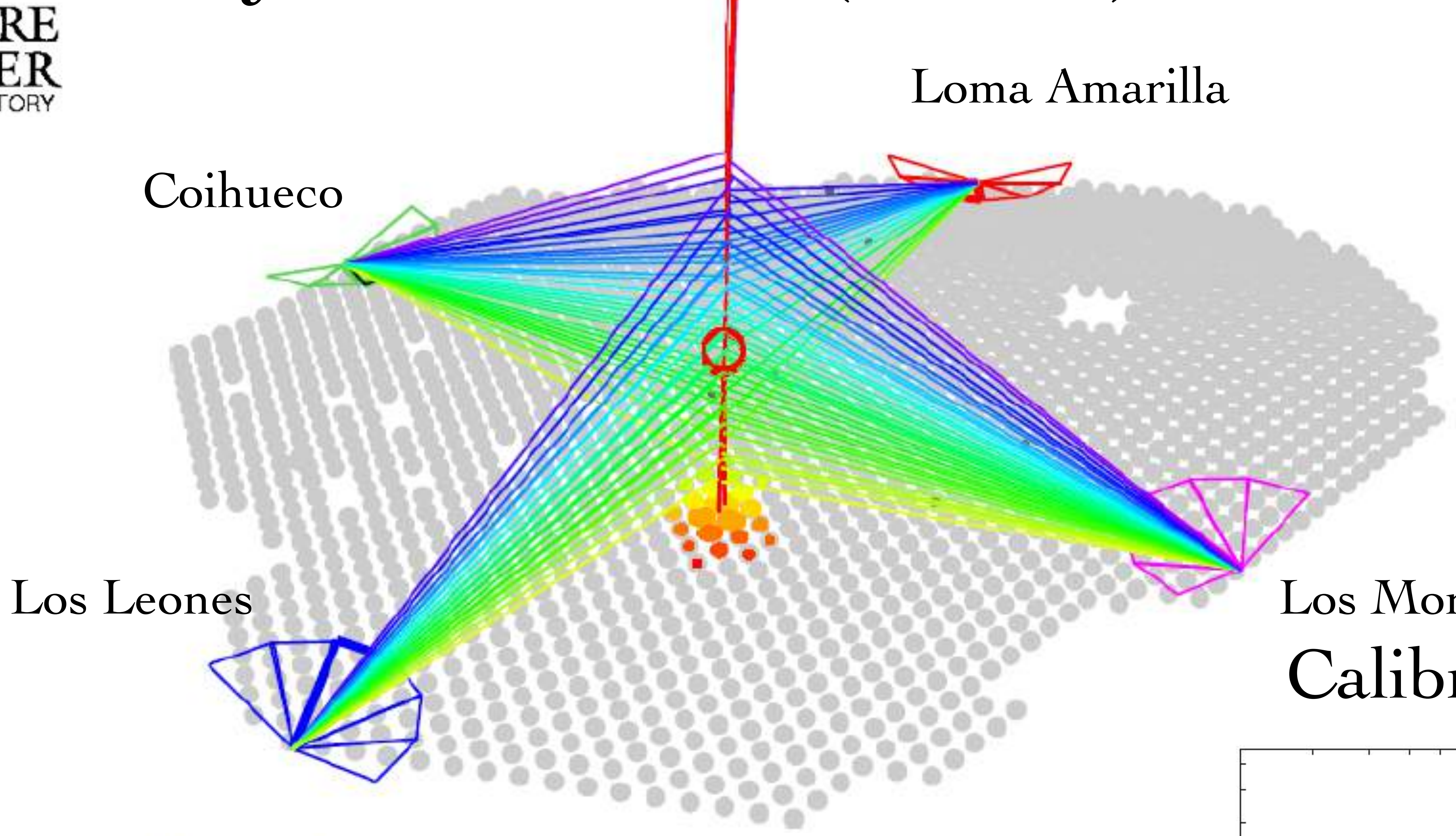
Scale of UHECR Observatory

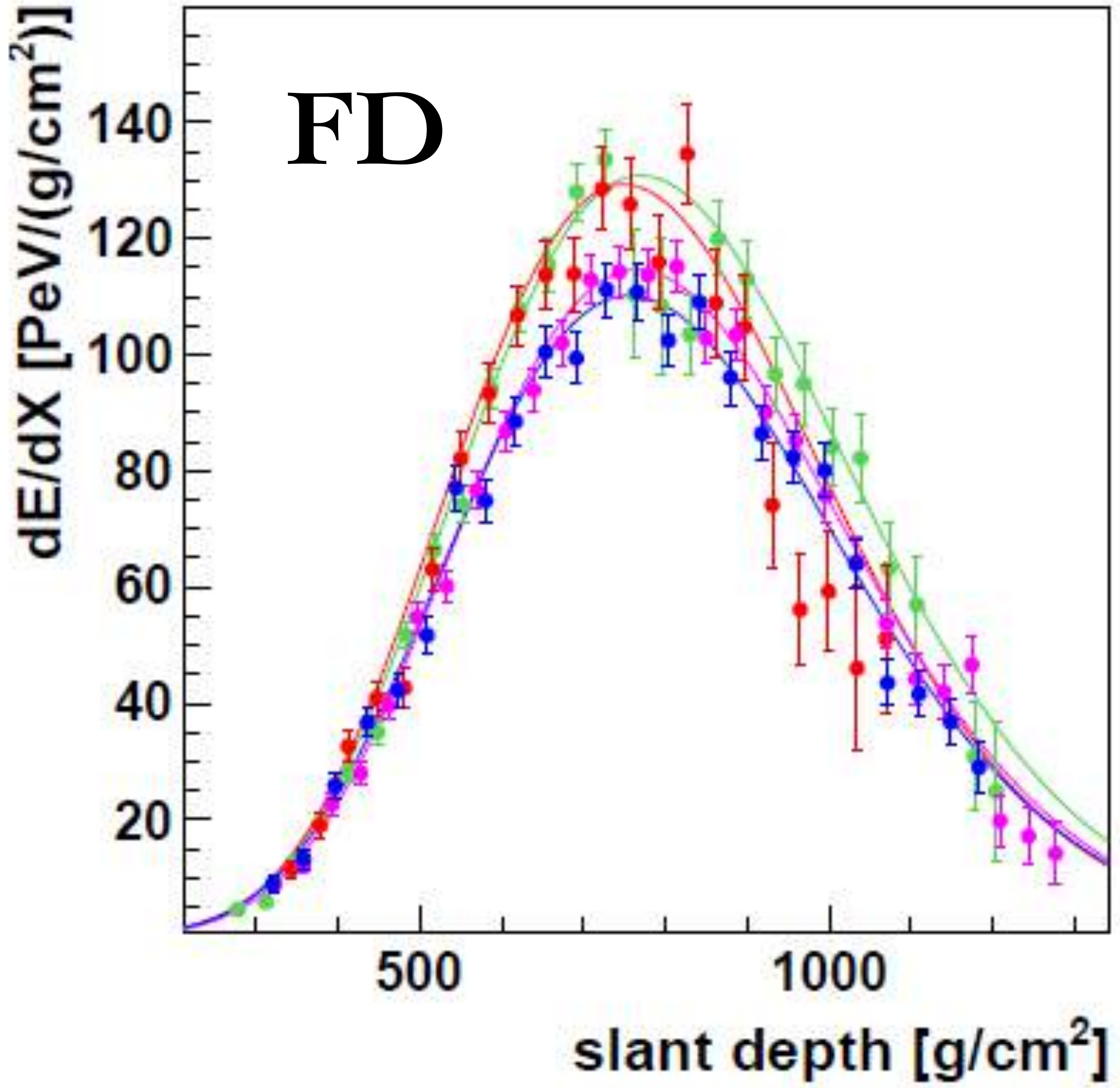
Scale of UHECR Observatory

An observed event

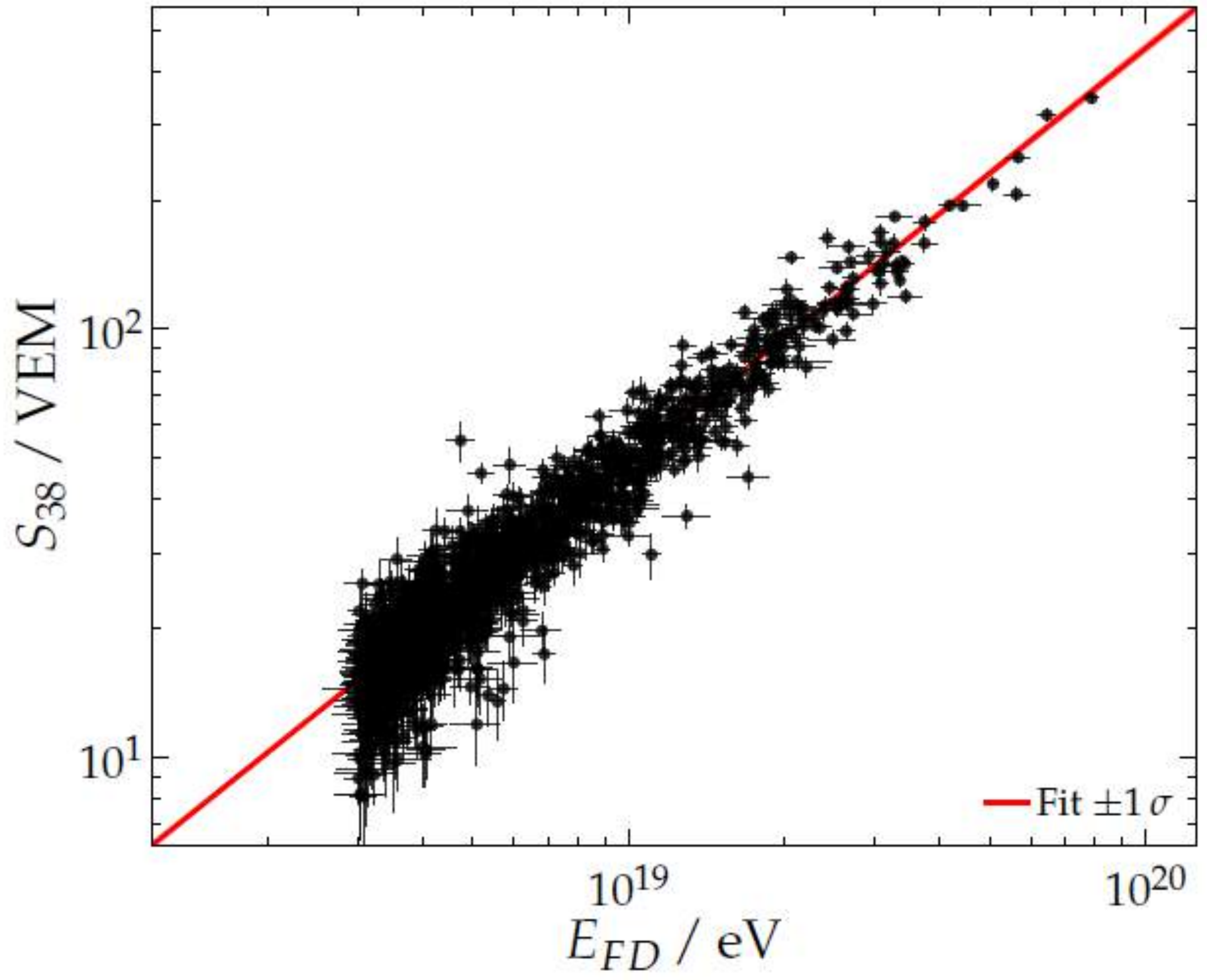
PIERRE AUGER OBSERVATORY

Hybrid observation (FD+SD)

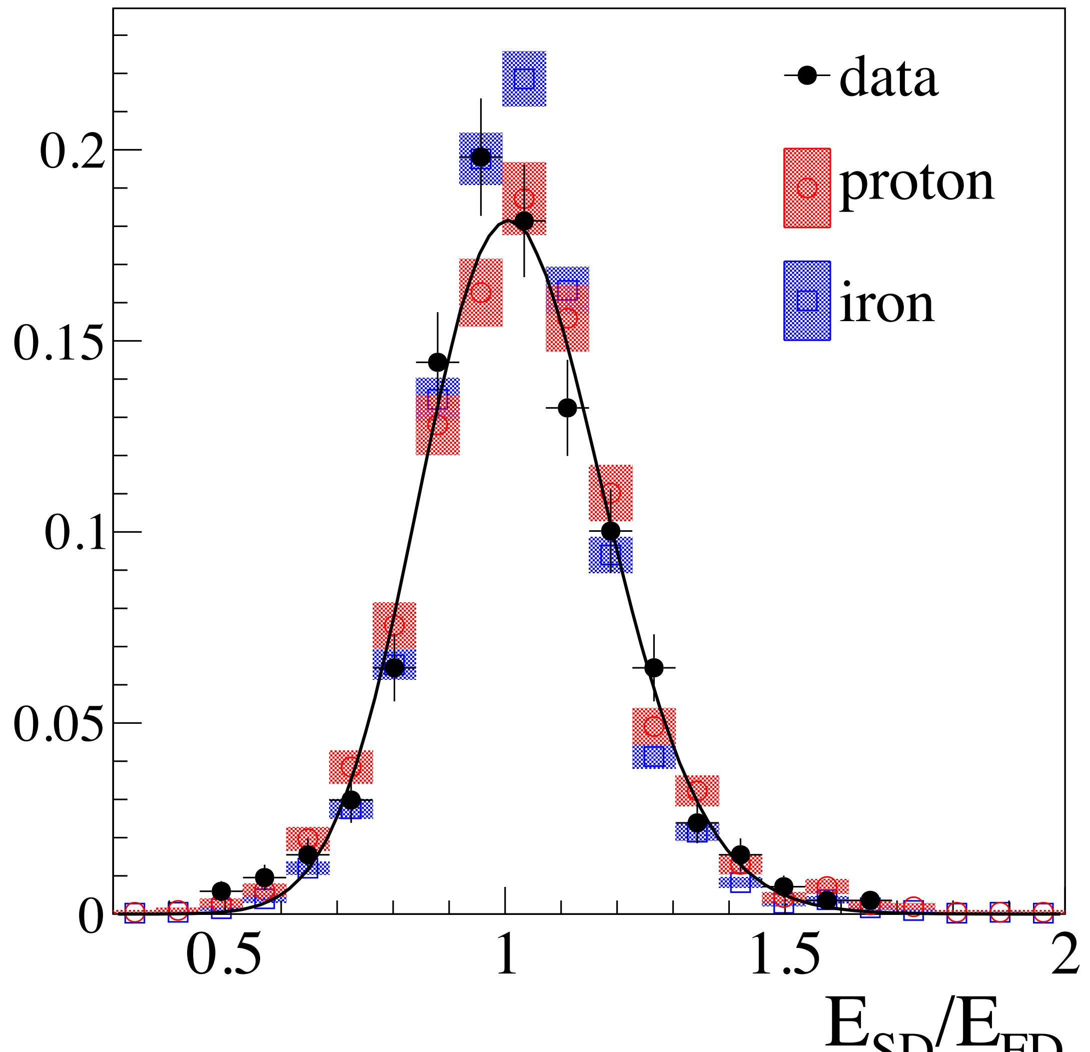




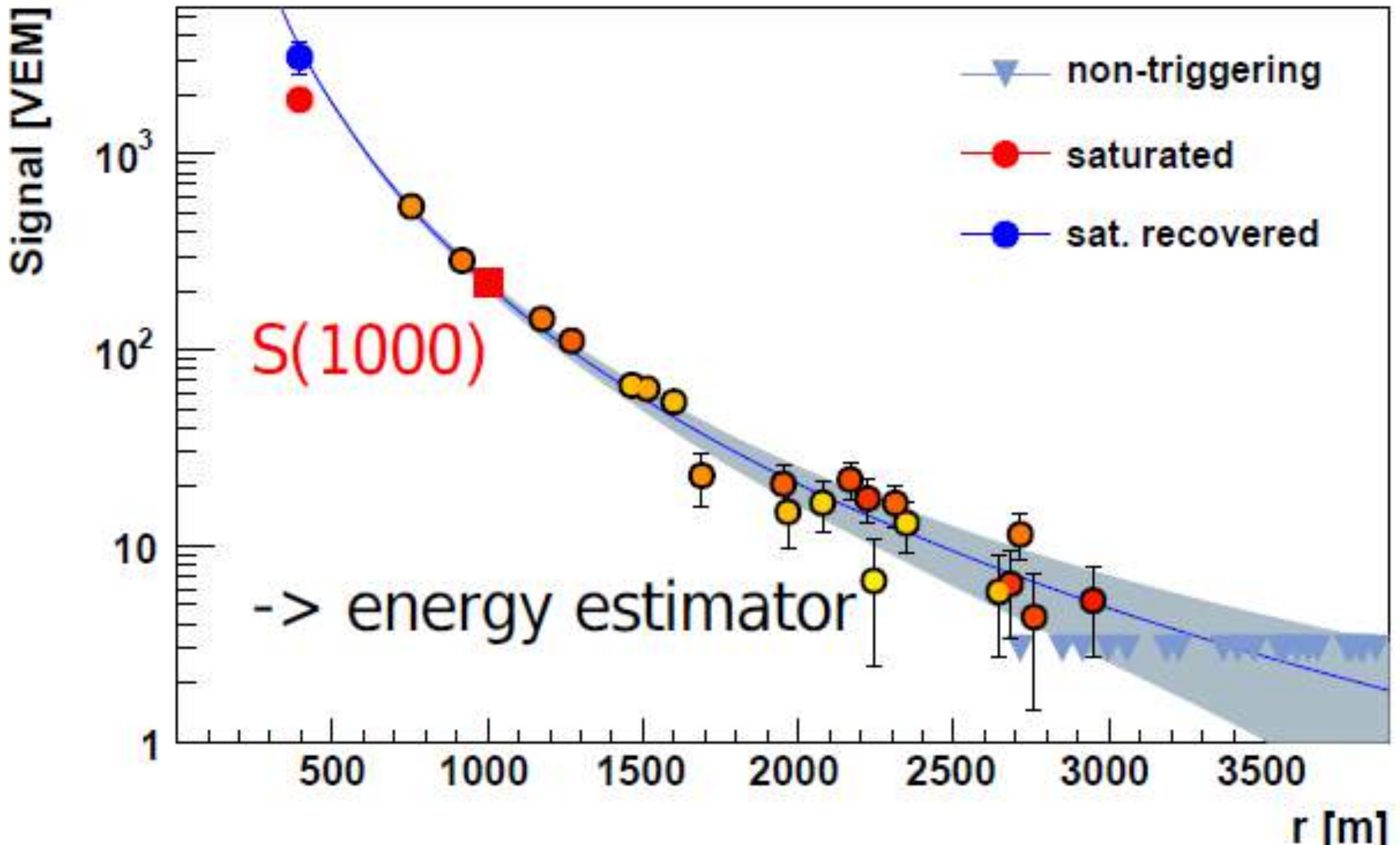
Calibrated by E_{FD}



$E_{\mathrm{SD}}/E_{\mathrm{FD}}$



SD



Intermediate summary

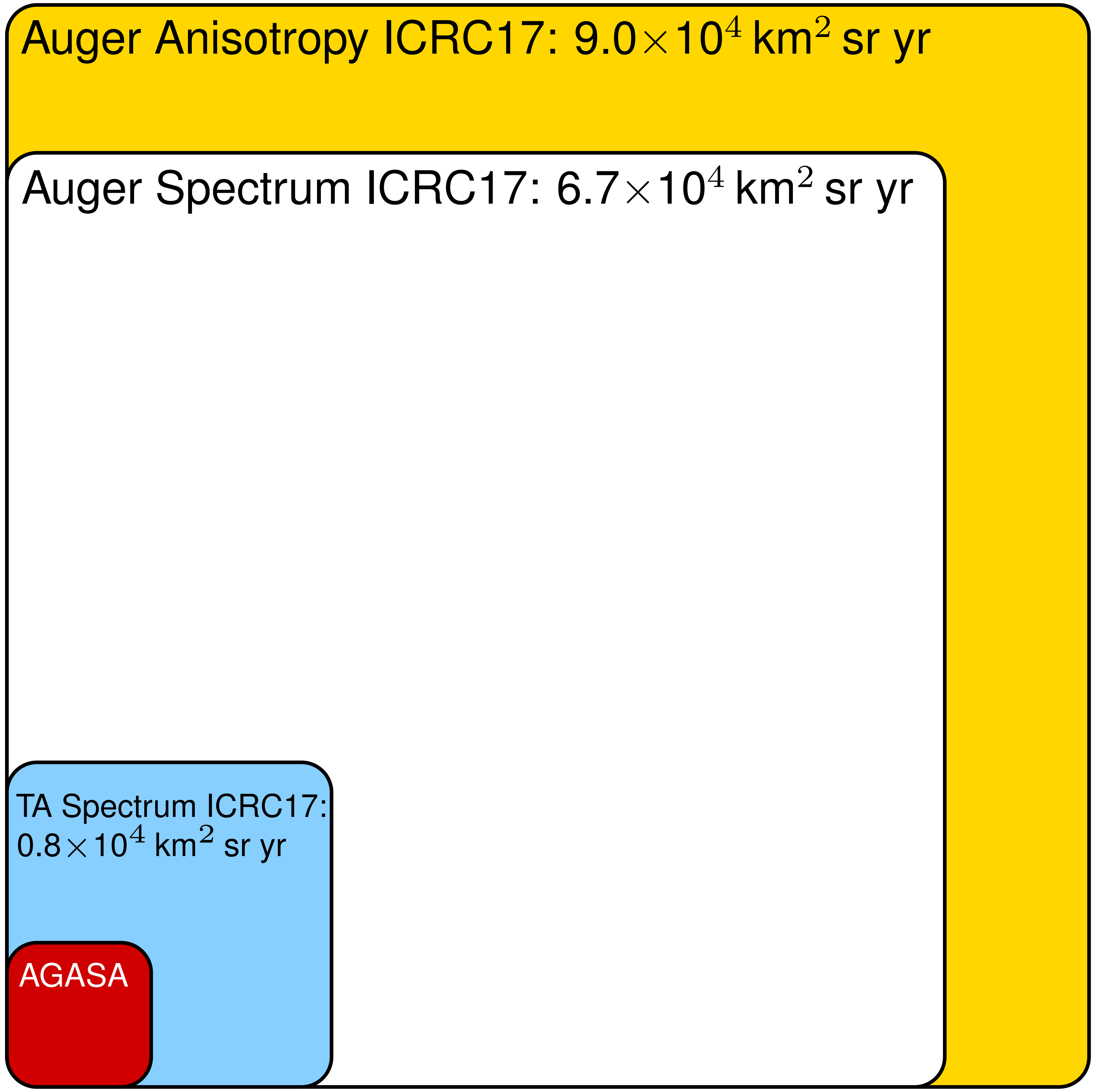
- Ultrahigh-energy cosmic rays (UHECRs) are **most energetic particles in the universe**.
- This energy is much larger than human-made accelerator in ground. But **very infrequent** as 1 particle km^{-2} century^{-1}. **Very large coverage** required to detect UHECRs.
- **GZK cutoff** is expected above cosmic rays with energy of $10^{19.7}$ eV.
- **Small deflection** of UHECR will provide us a next-generation astronomy.
- Three important measurements: **energy spectrum, mass composition, arrival direction**
- Measurements of **extensive air shower** induced by UHECR with the hybrid detector (SD and FD).
- The largest cosmic-ray observatories in operation: **Telescope Array experiment** (700 km^2, USA) **Pierre Auger Observatory** (3000 km^2, Argentina)

Quick question?

Photography : Steven Saffi, Production assistant : Max Malacari http://vimeo.com/88029390

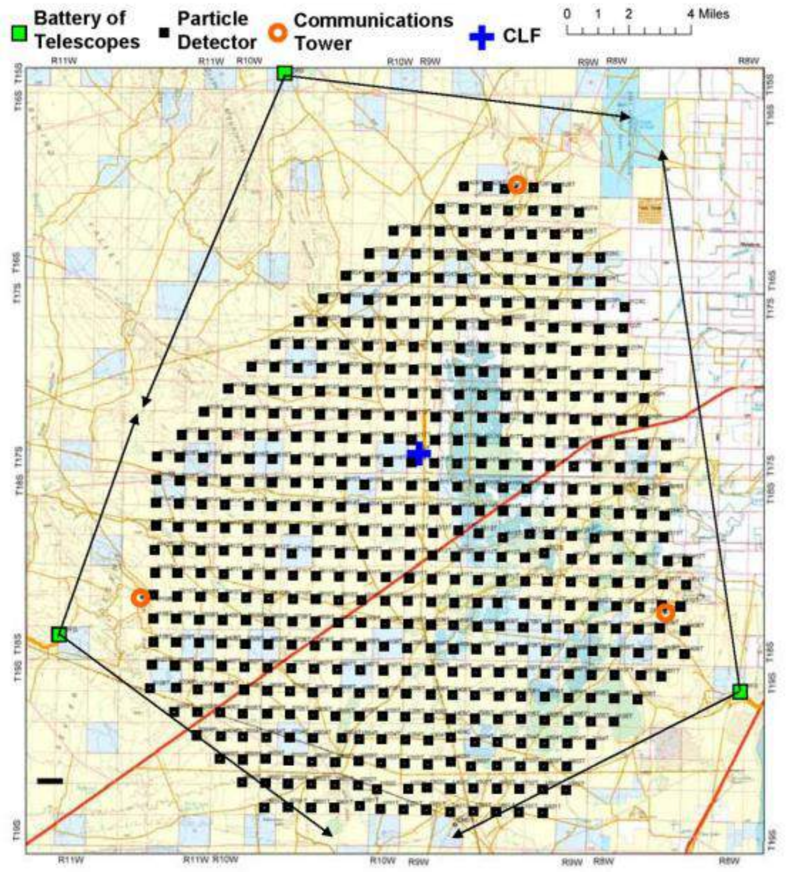
Recent Results in ICRC2017

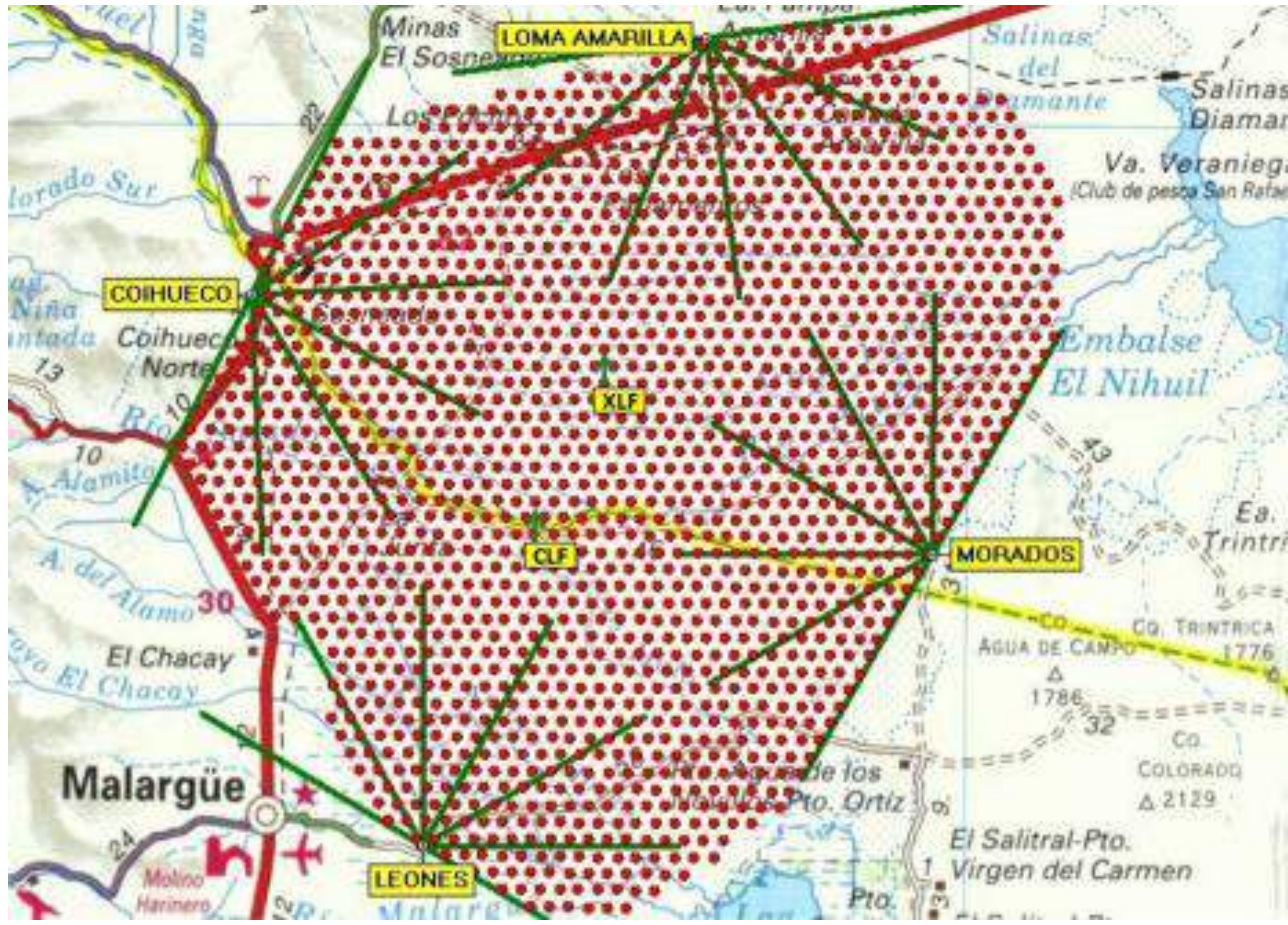
TA/Auger exposure comparison



TELESCOPE ARRAY PROJECT

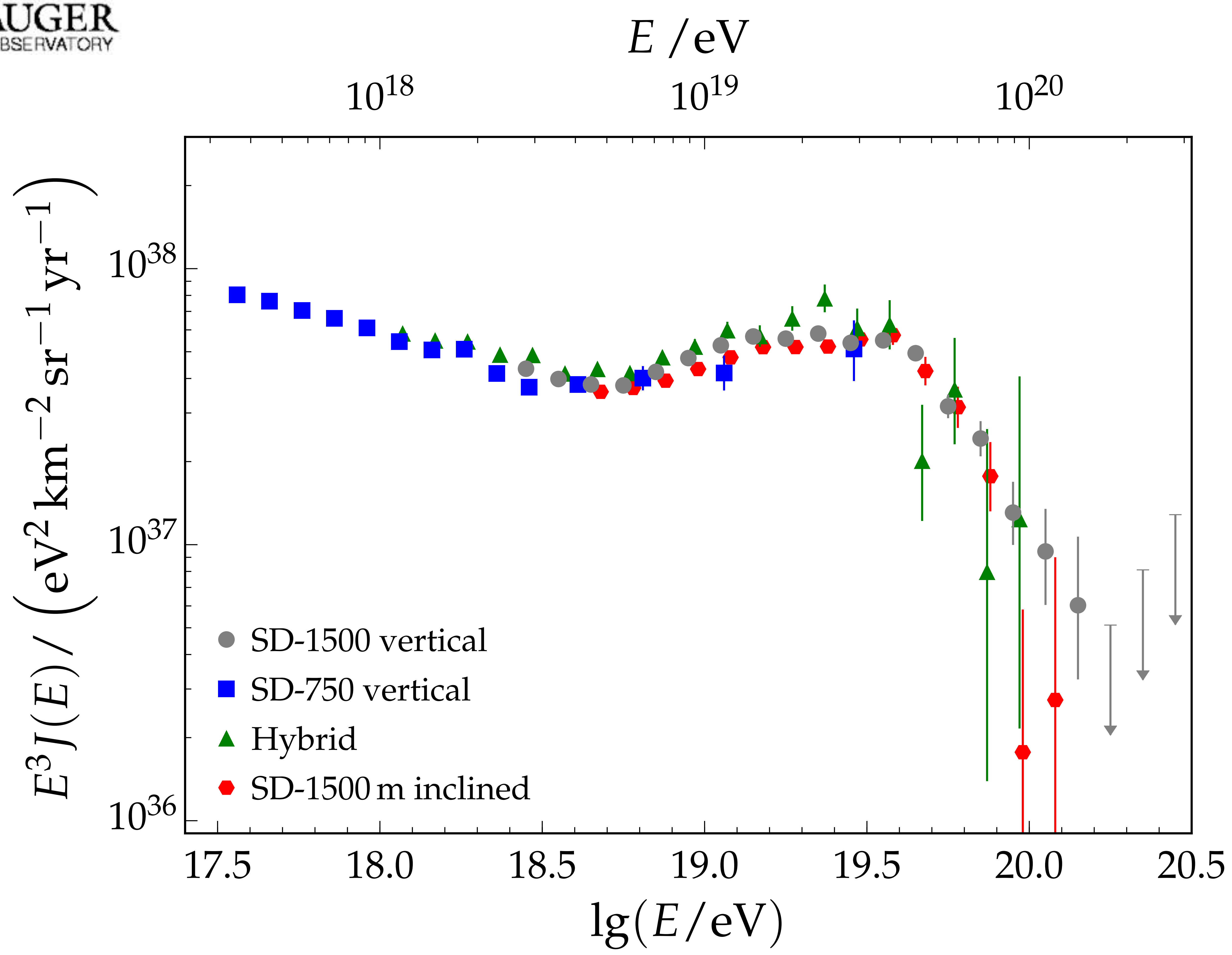
PIERRE AUGER OBSERVATORY

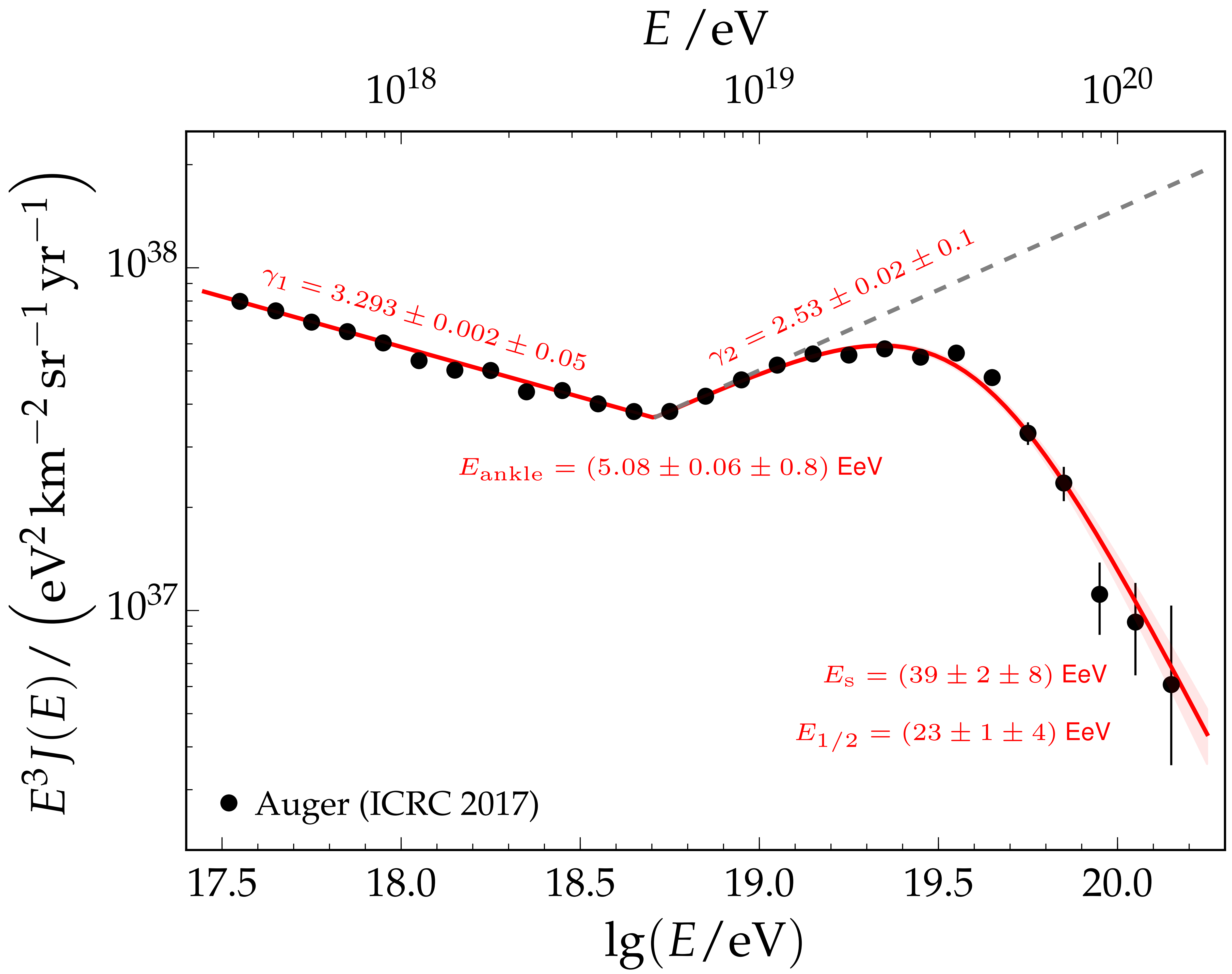




M. Unger in ICRC 2017

Auger energy spectrum

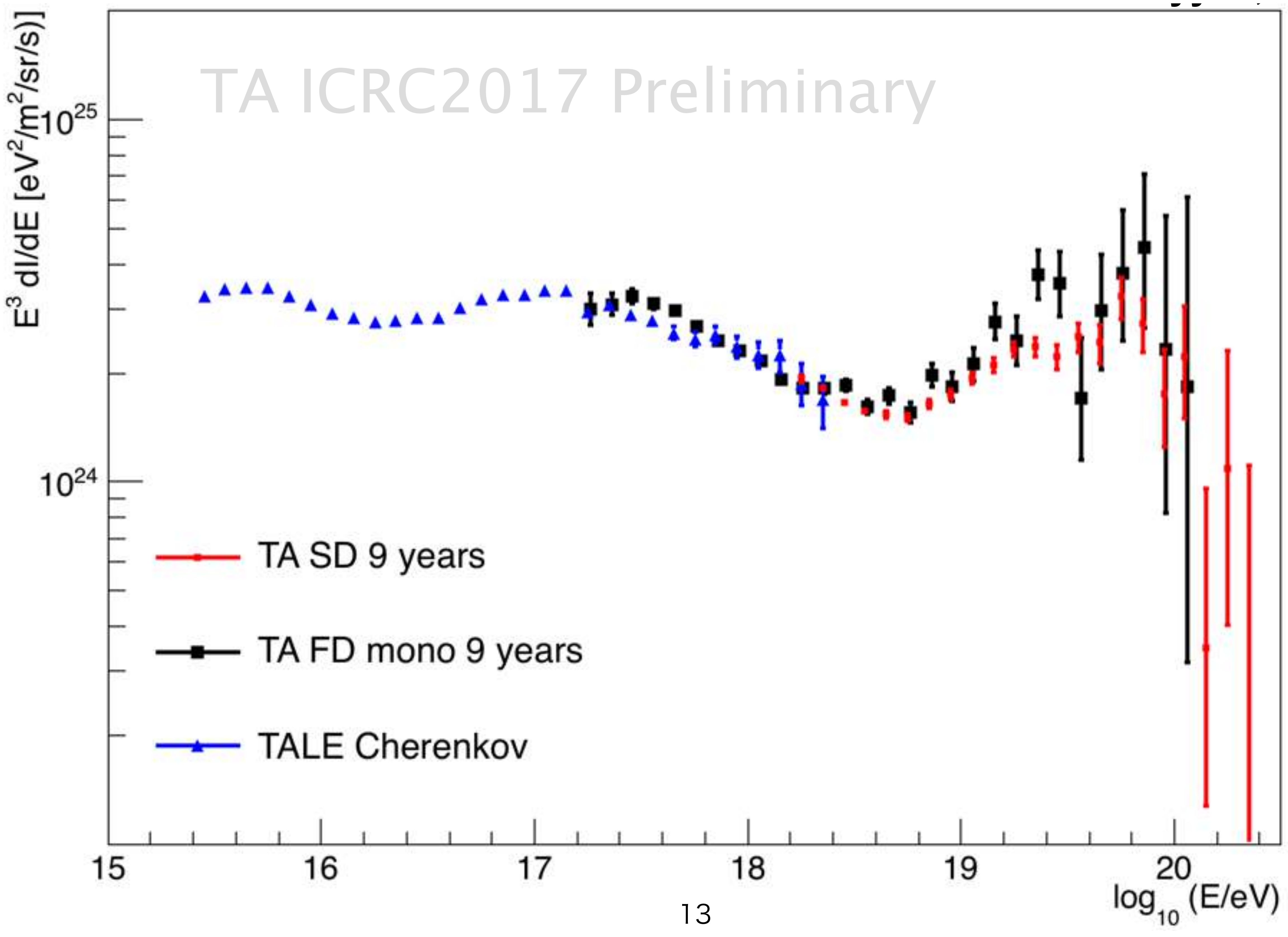


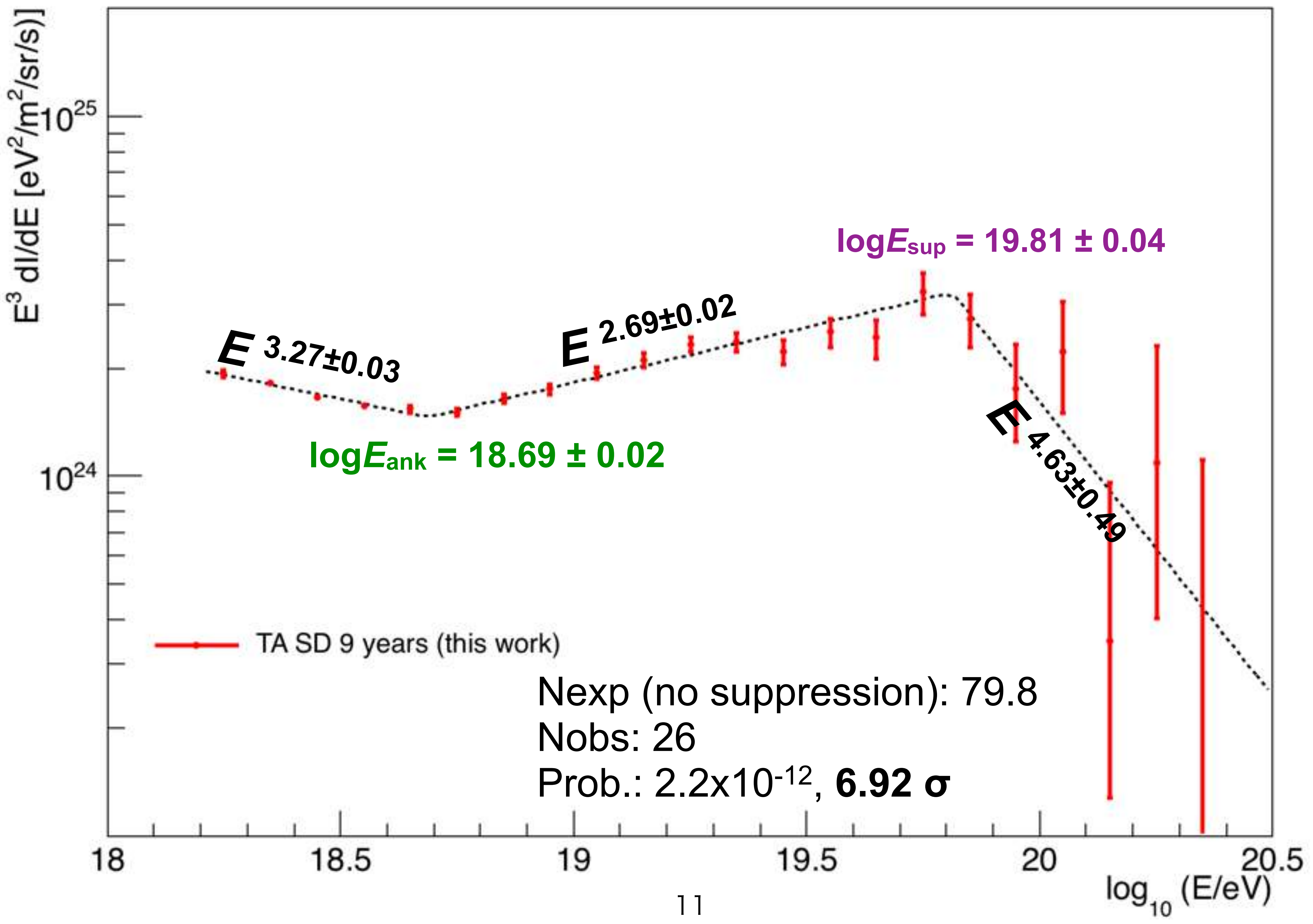


Update atmospheric analysis and geometry, +1% ~ +4%

F. Fenu, M. Unger in ICRC 2017

TA energy spectrum

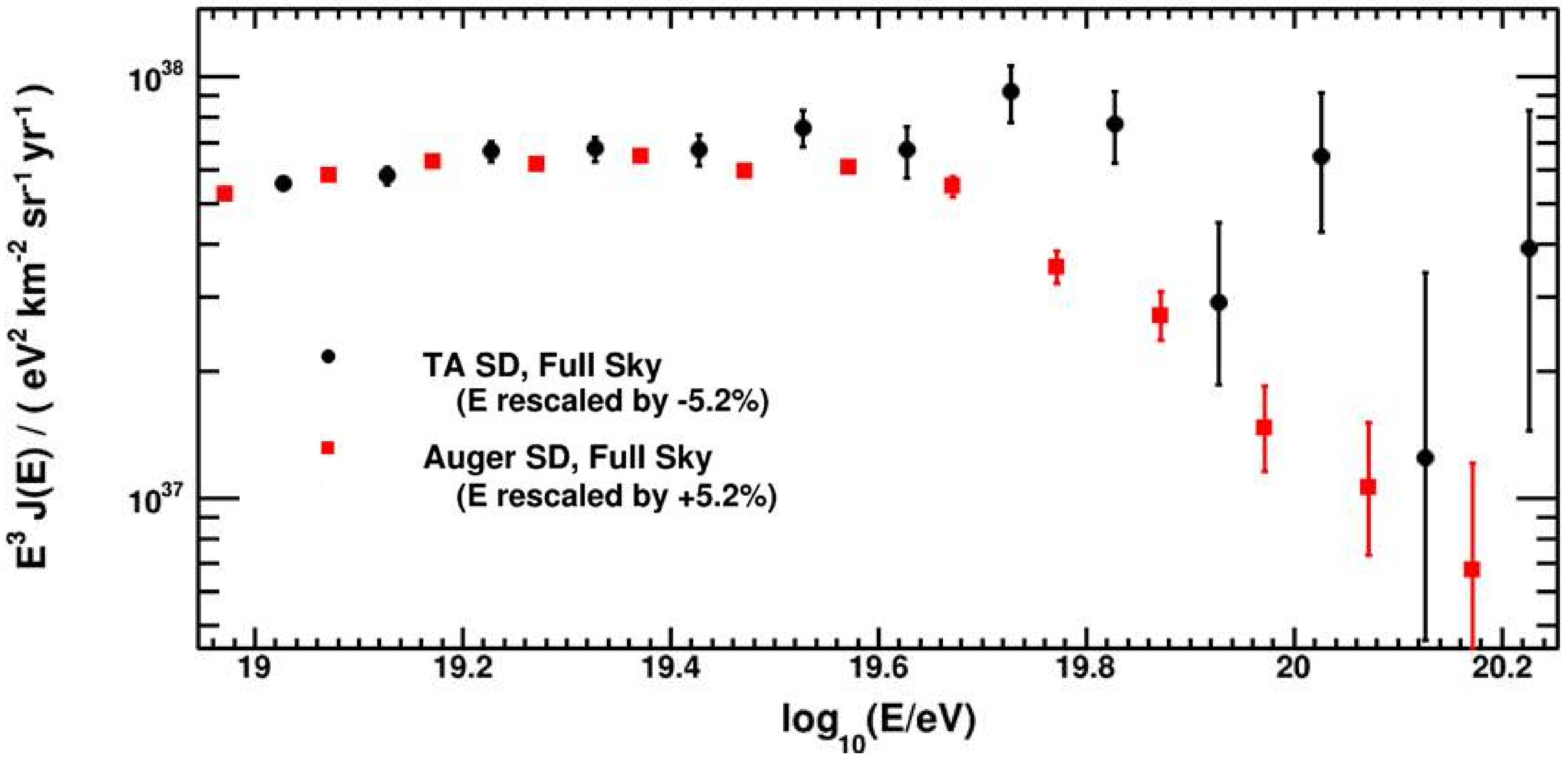




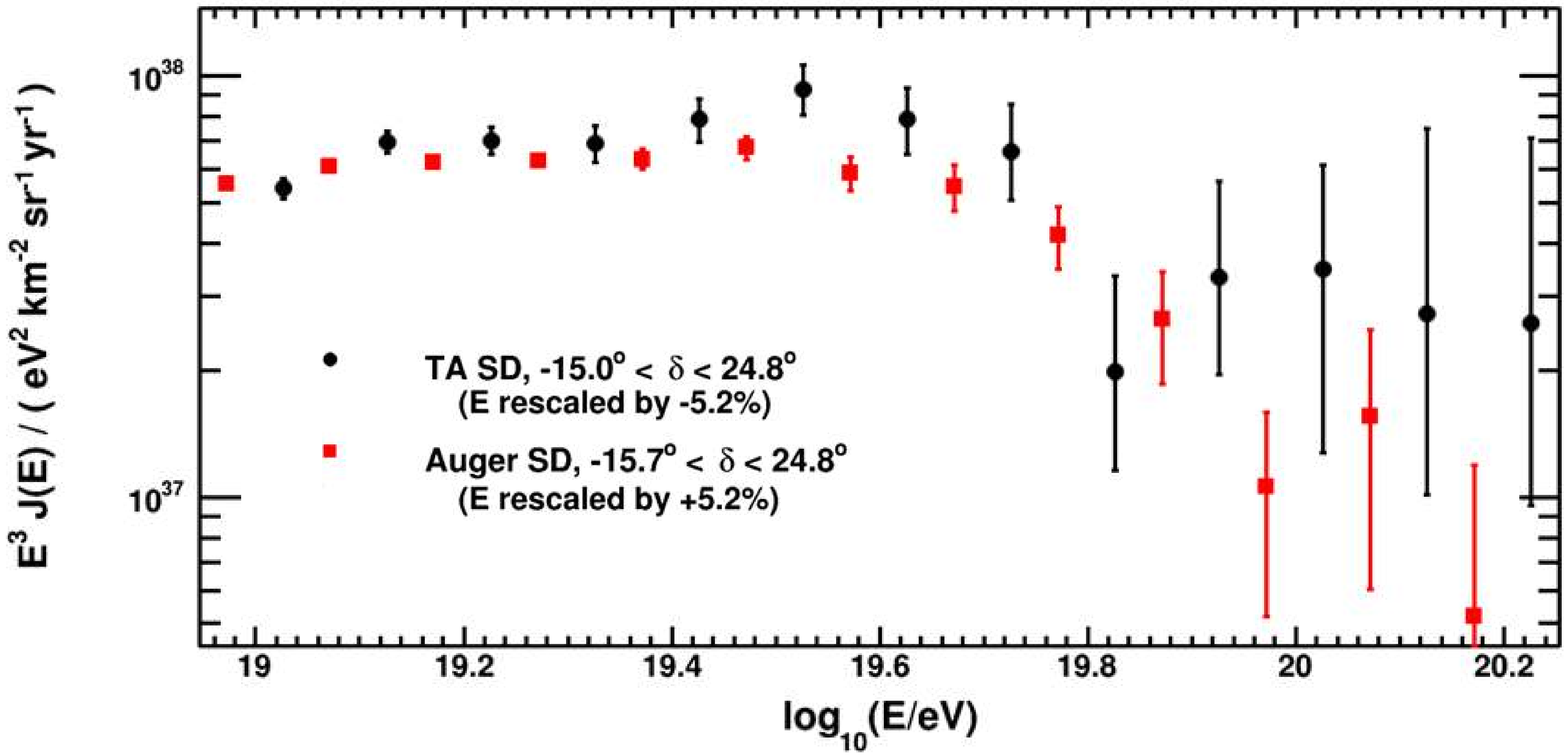
T. AbuZayyad, Y. Tsunesada in ICRC 2017

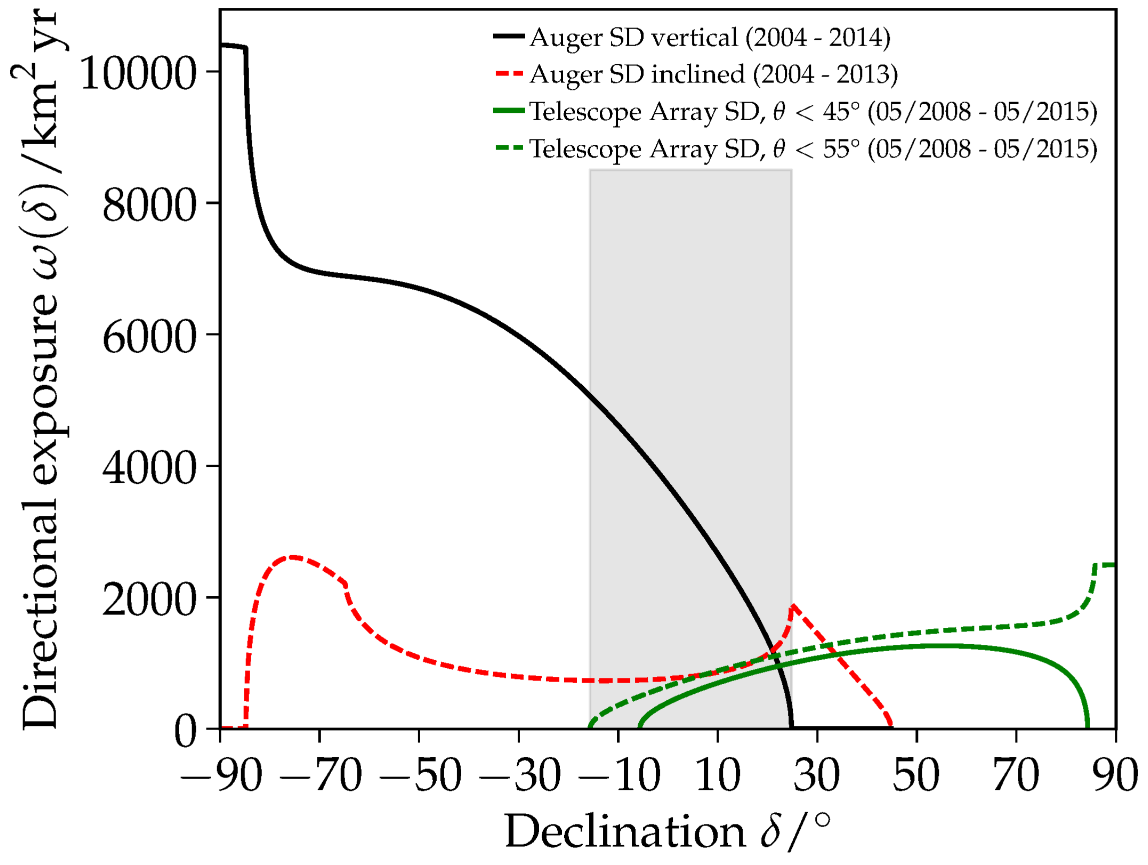
Spectrum discrepancy at highest energies

Entire skies of Auger and TA



Common declination band

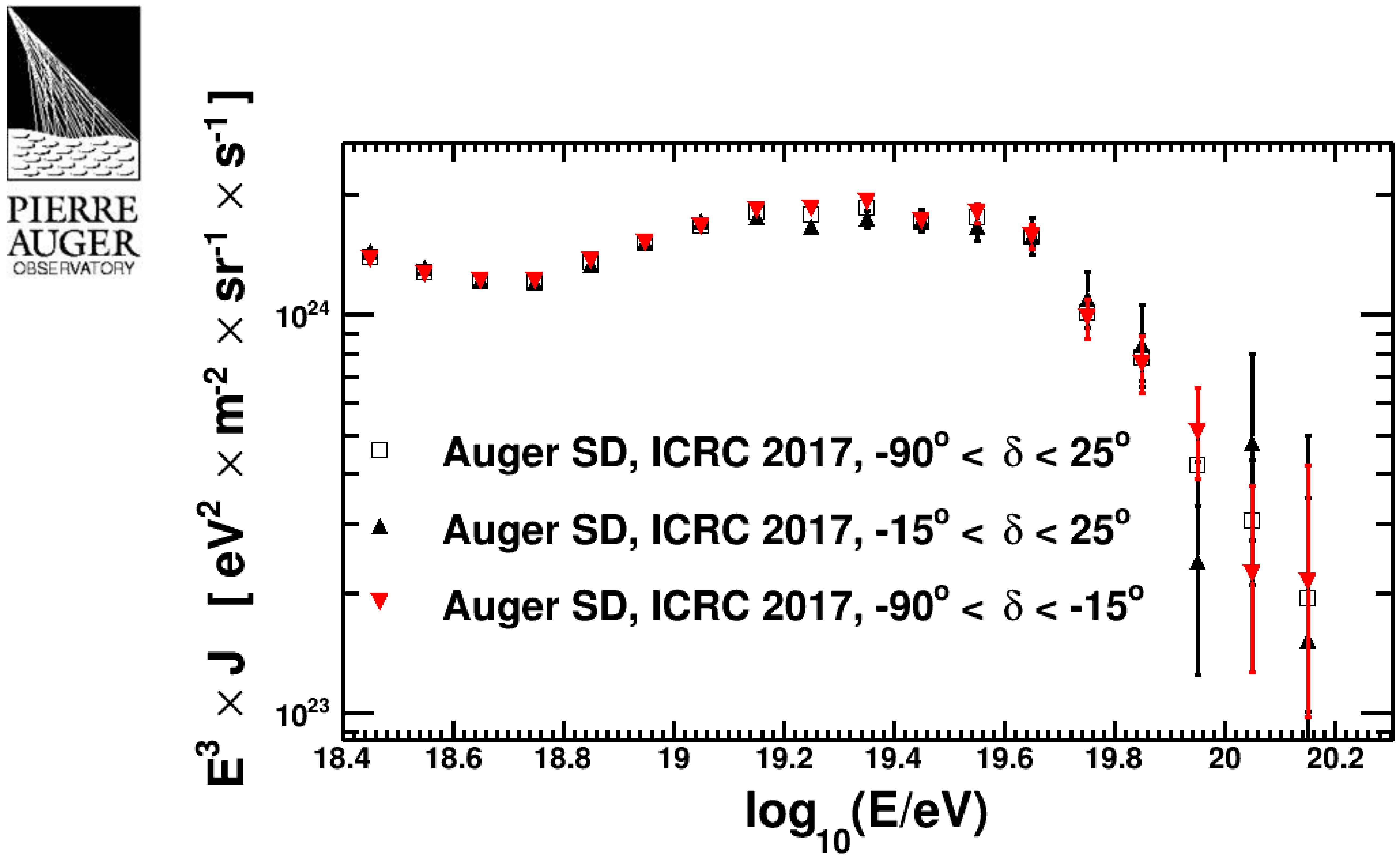


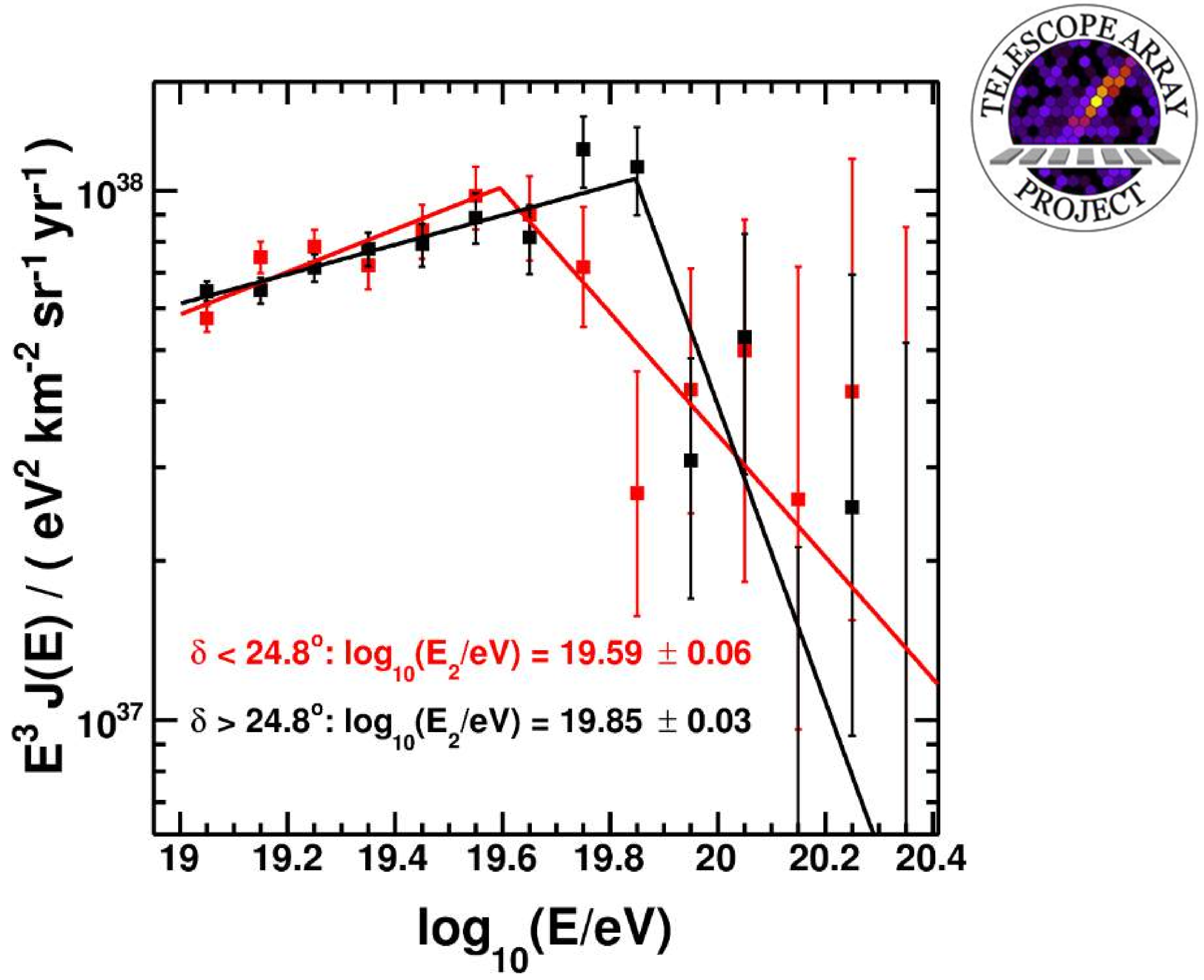


- Rescaled to fit the ankle spectrum.
- Spectrum discrepancy at the highest energies.
  - Good agreement if we select events in the common declination band,
- Northern/southern hemisphere difference or detector systematics.

D. Ivanov in ICRC 2017

Declination dependence?



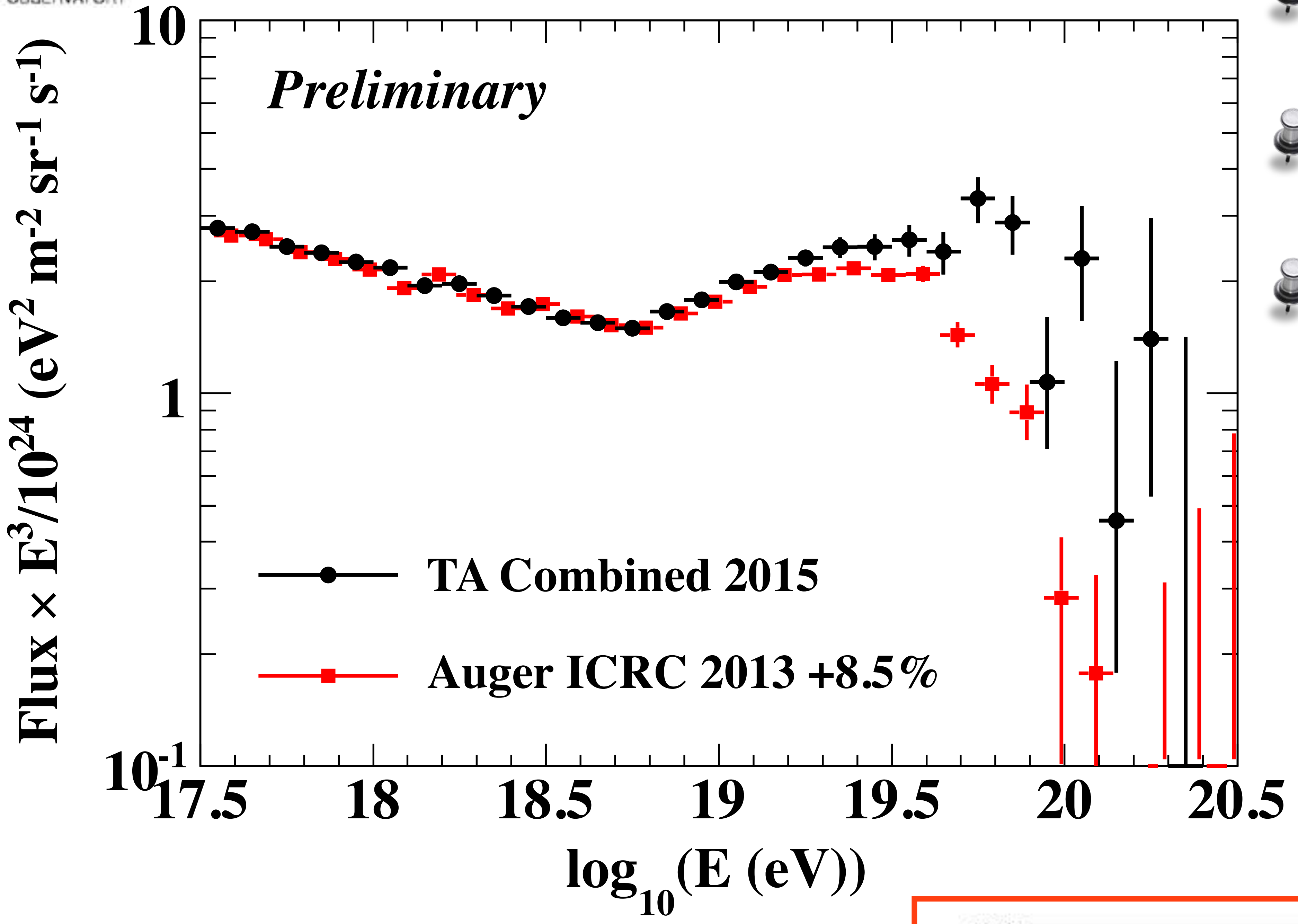


- No declination dependence in Auger.
- 3.9σ difference of the fitted broken energies in TA.

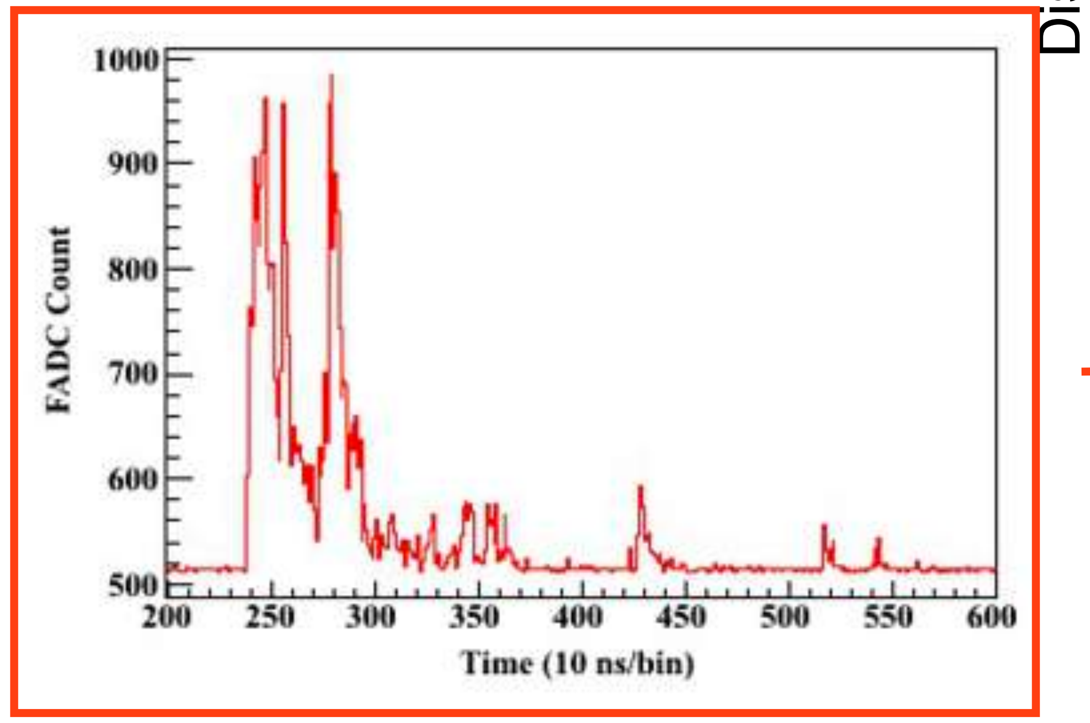
D. Ivanov in ICRC 2017

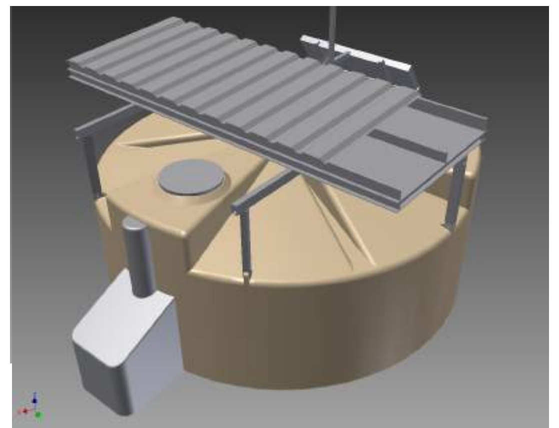
Detector exchange to understand the discrepancy

- Pioneering measurements by TASD and Auger water tank
- 2014/Nov/28 15:43:01.453549
- Energy: 3.04 EeV, zenith: 46.8 deg (Preliminary)

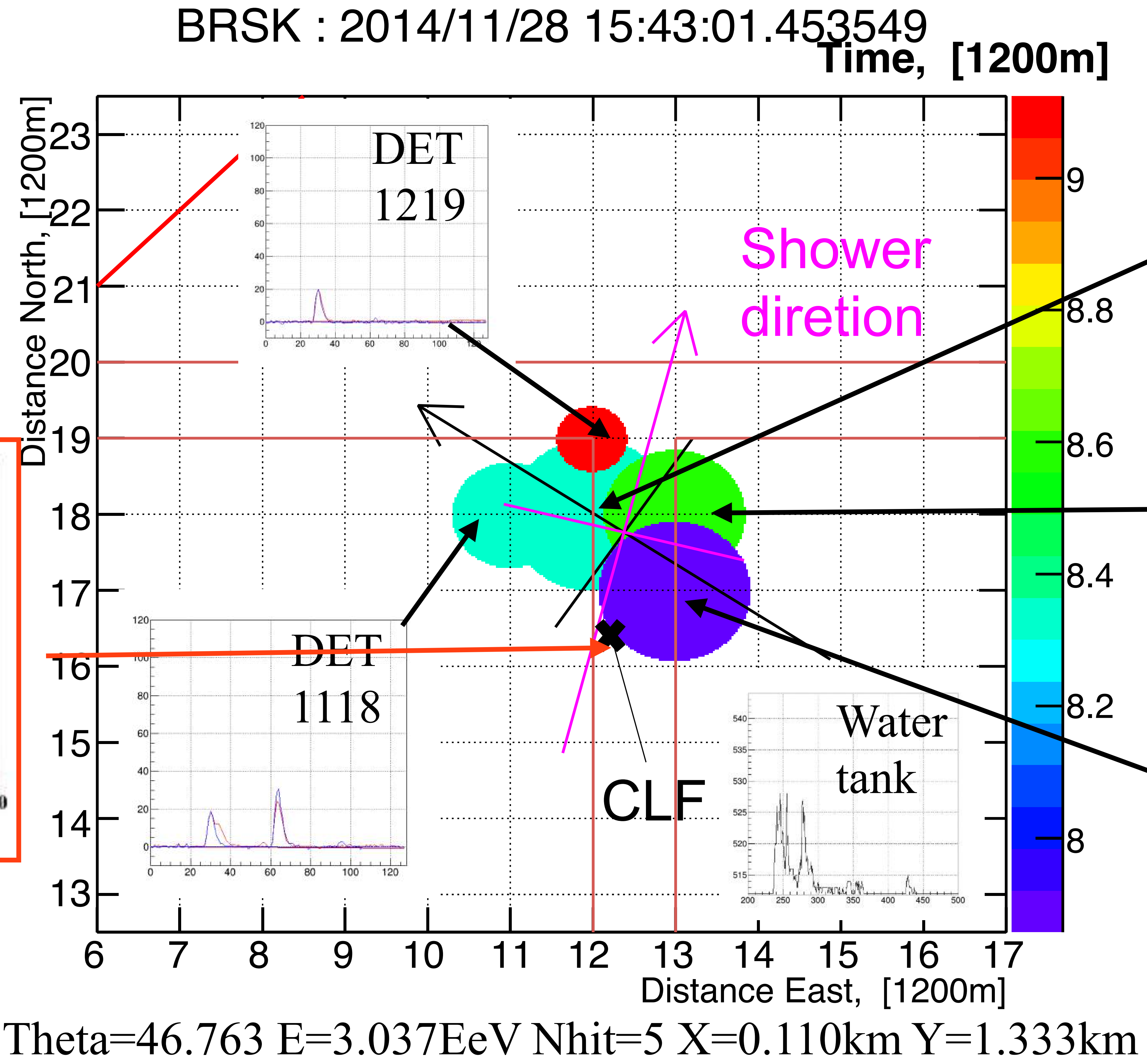


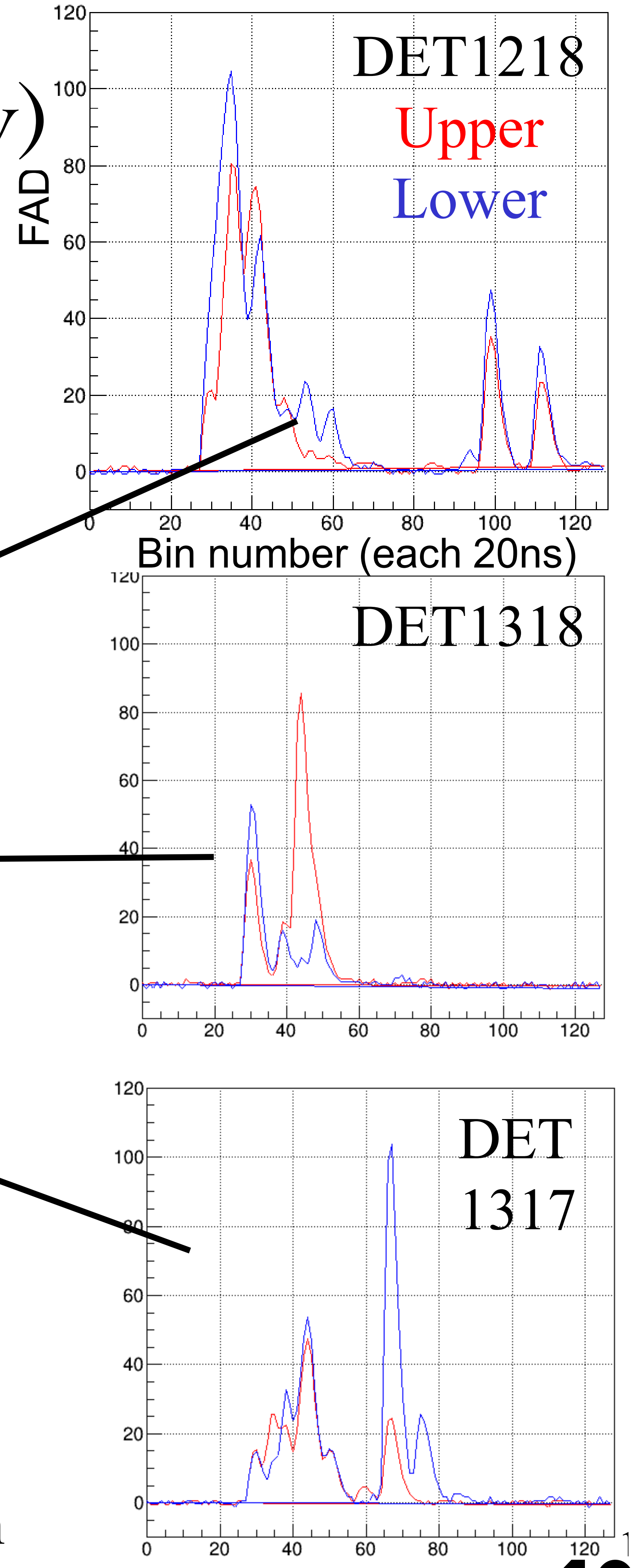
R. Takeishi et al., ICRC2015,



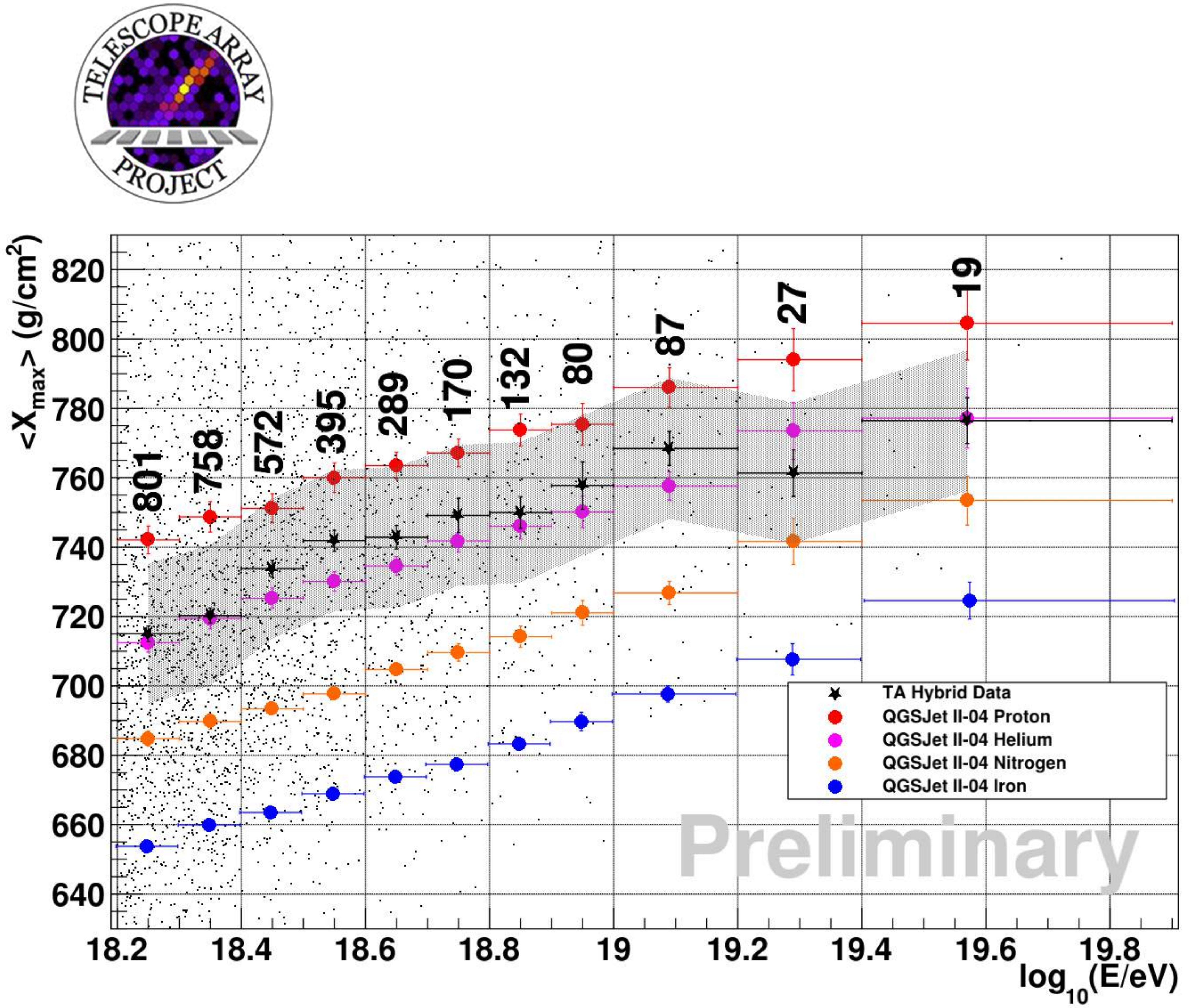


AugerPrime

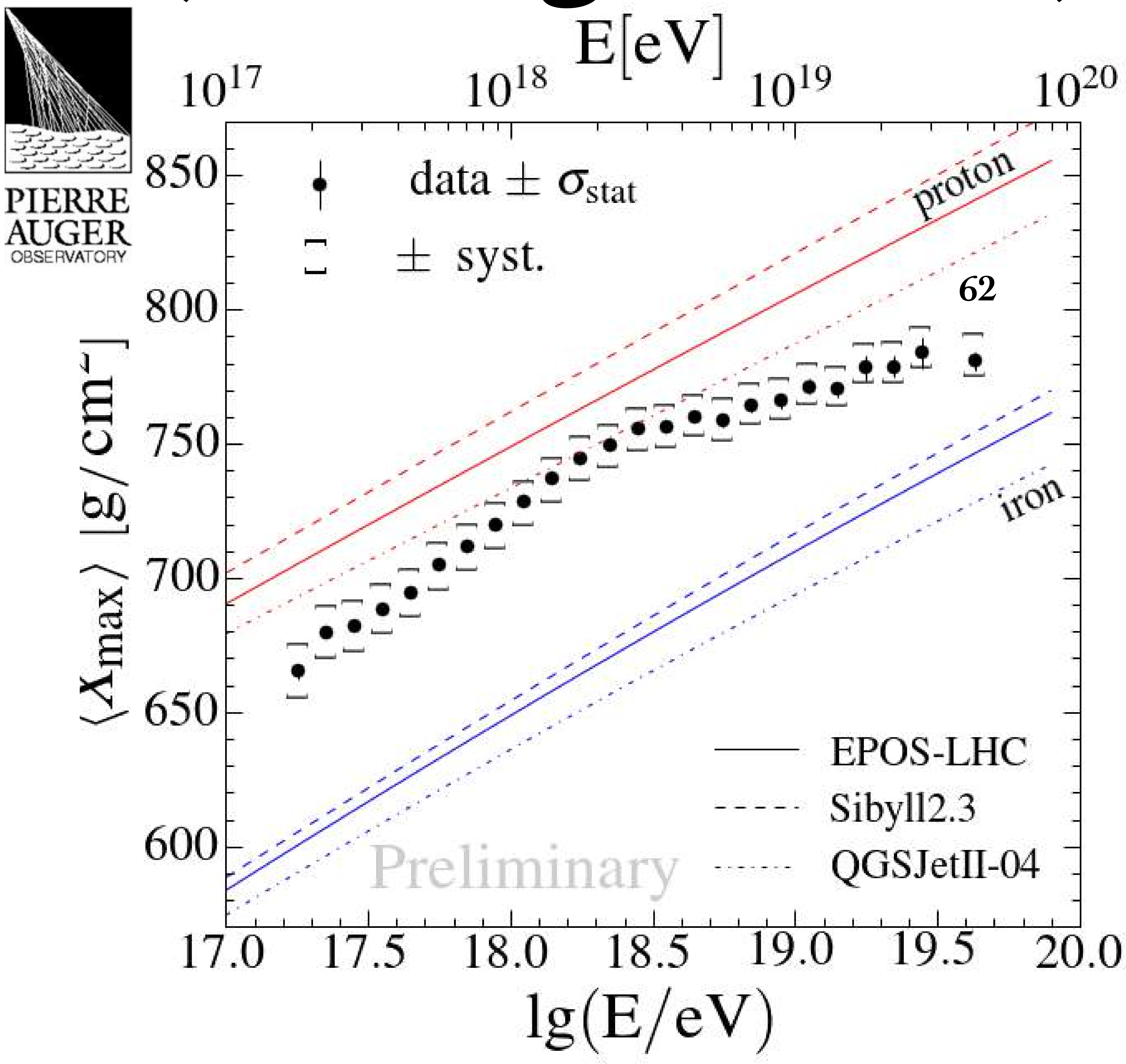




Mass composition (Average *X*max)



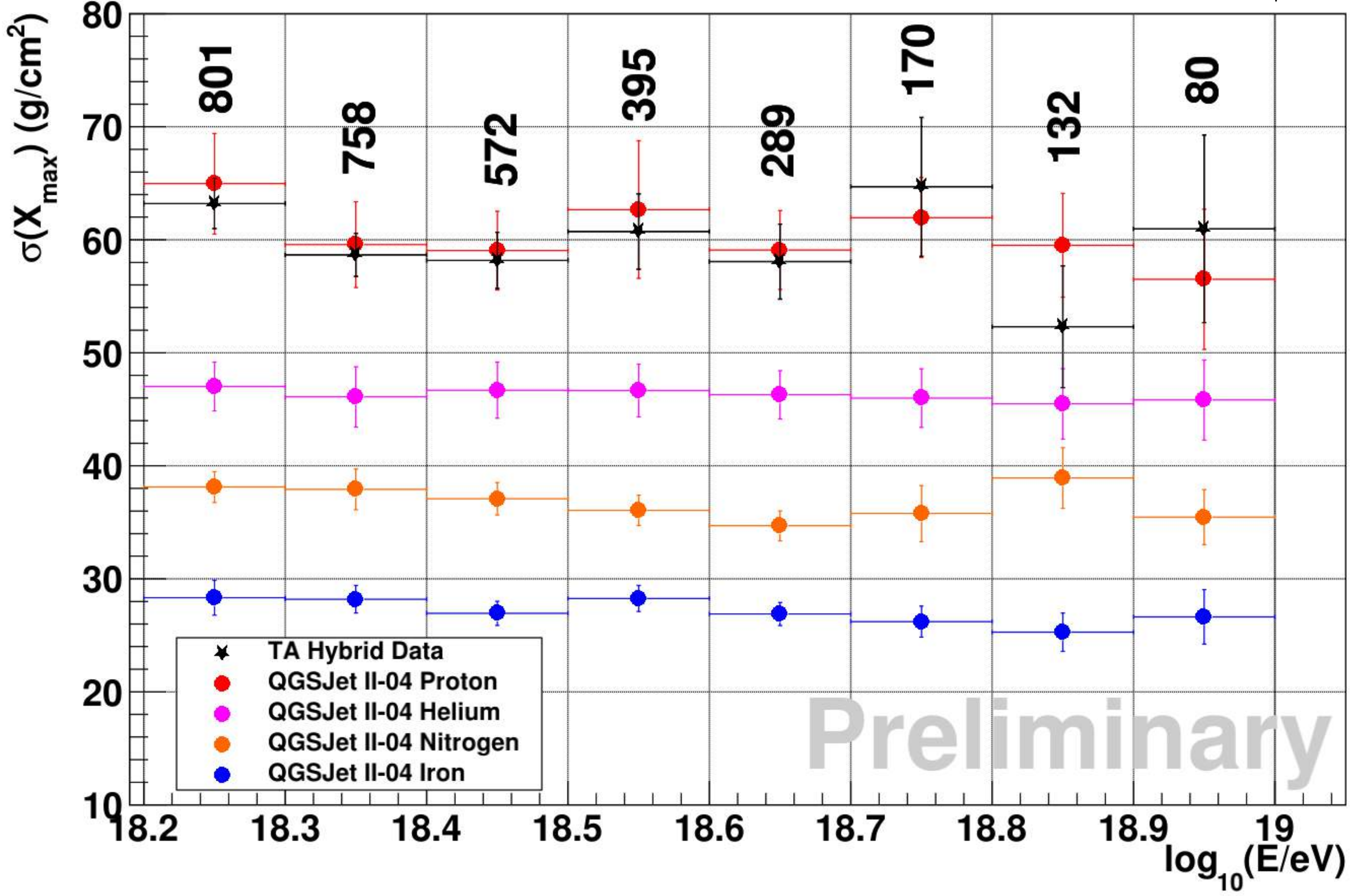
W. Hanlon in ICRC 2017

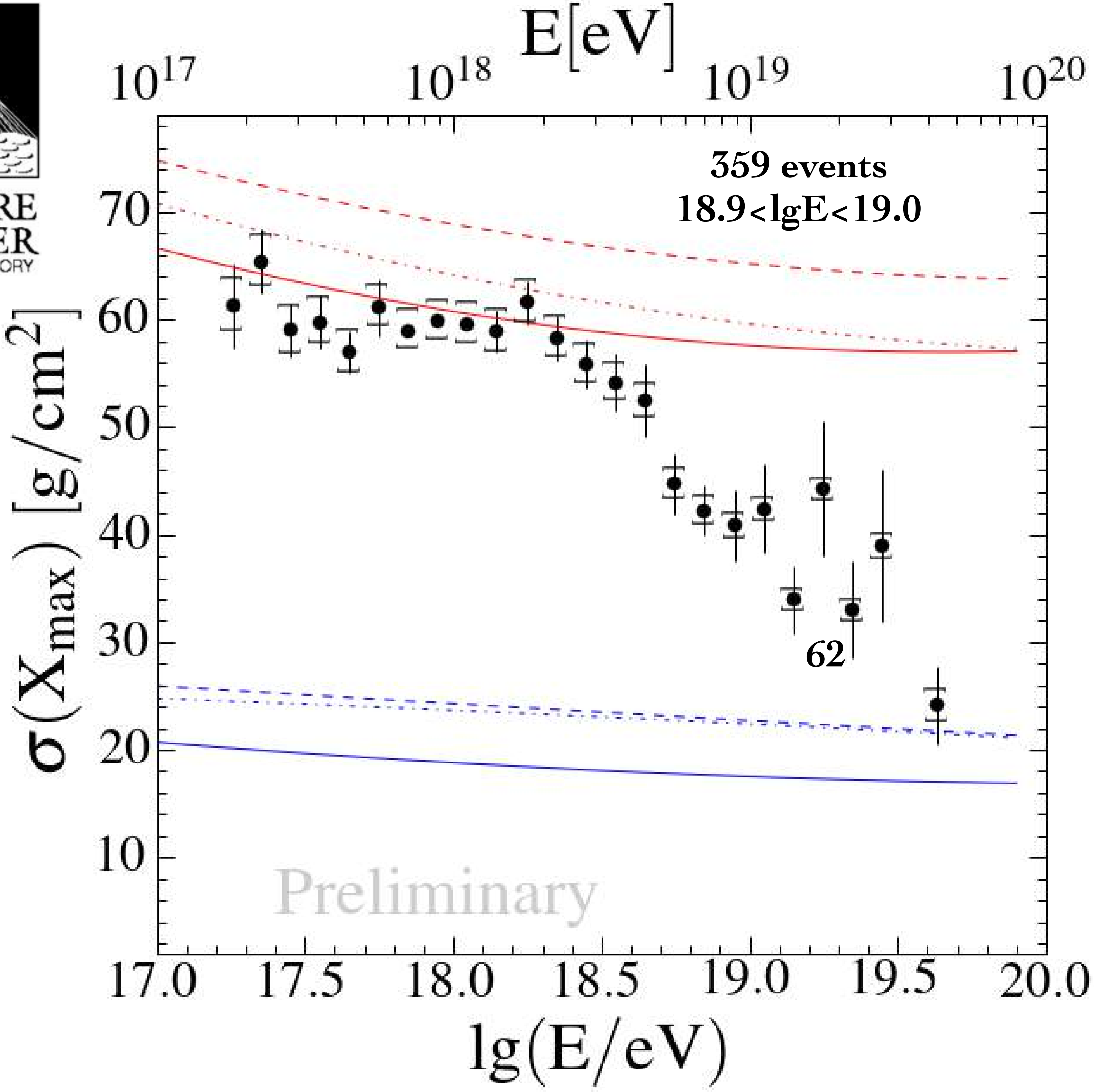


J. Bellido in ICRC 2017

Mass composition (Xmax distribution)

log$E$=19.0

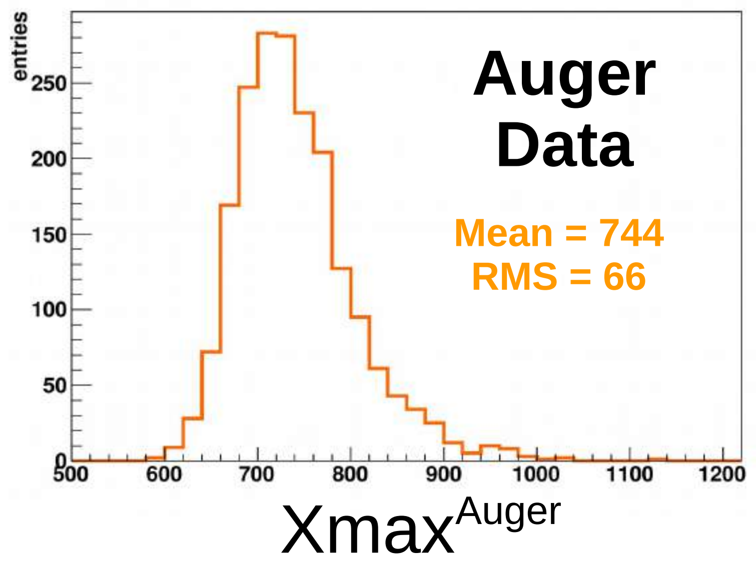


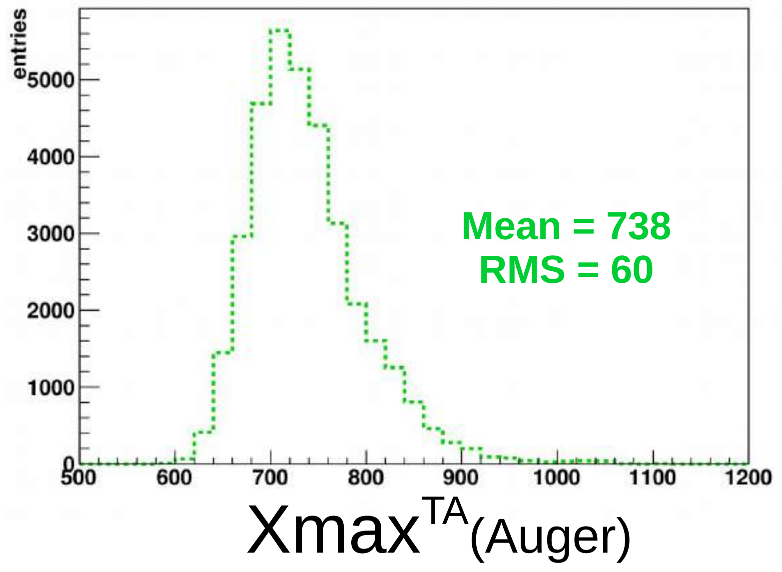


W. Hanlon in ICRC 2017

J. Bellido in ICRC 2017

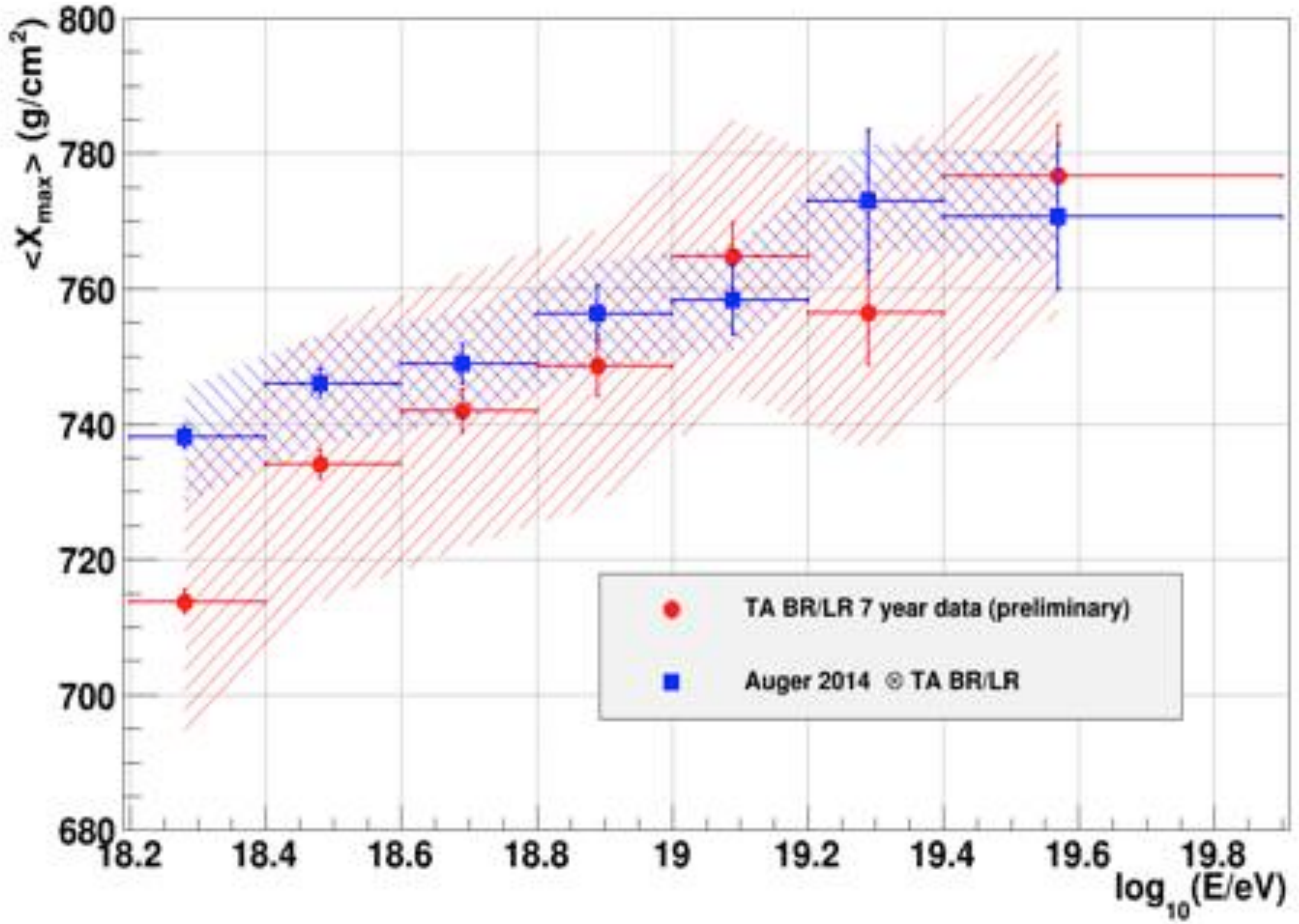
Summary from Xmax working group



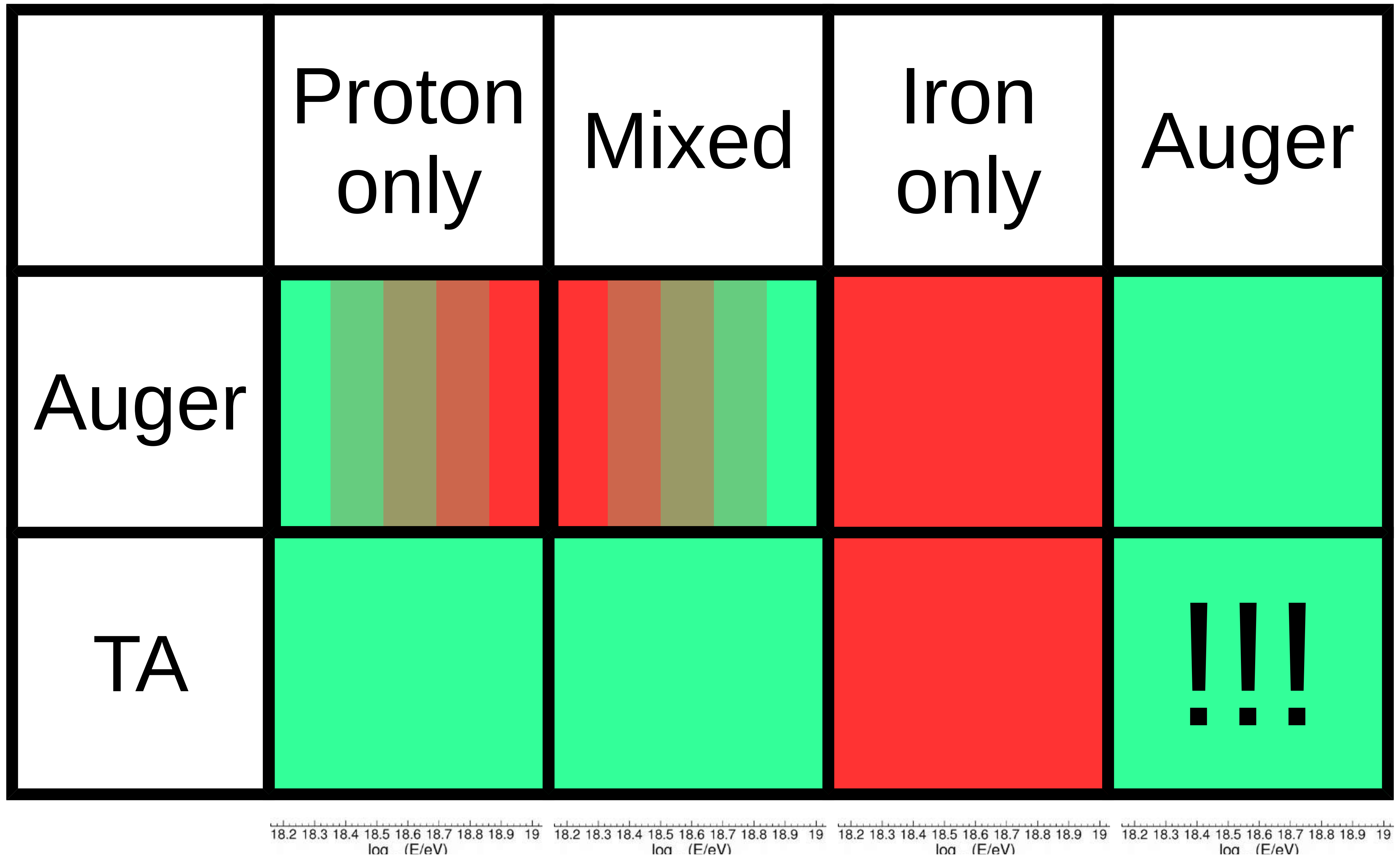


TA Detector Simulation

TA Analysis



Compatible Incompatible



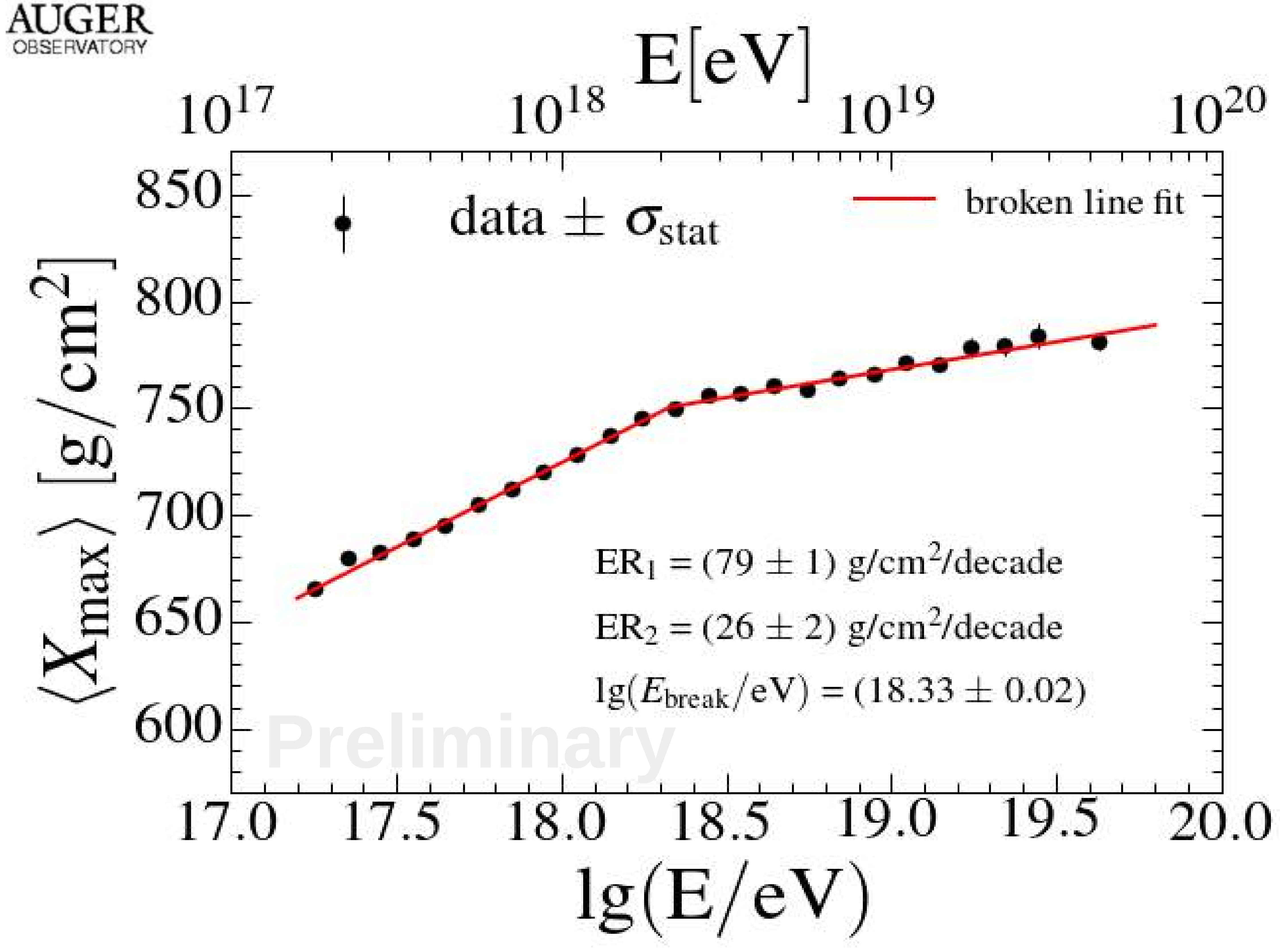
Take away message

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

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

V. de Souza in ICRC 2017

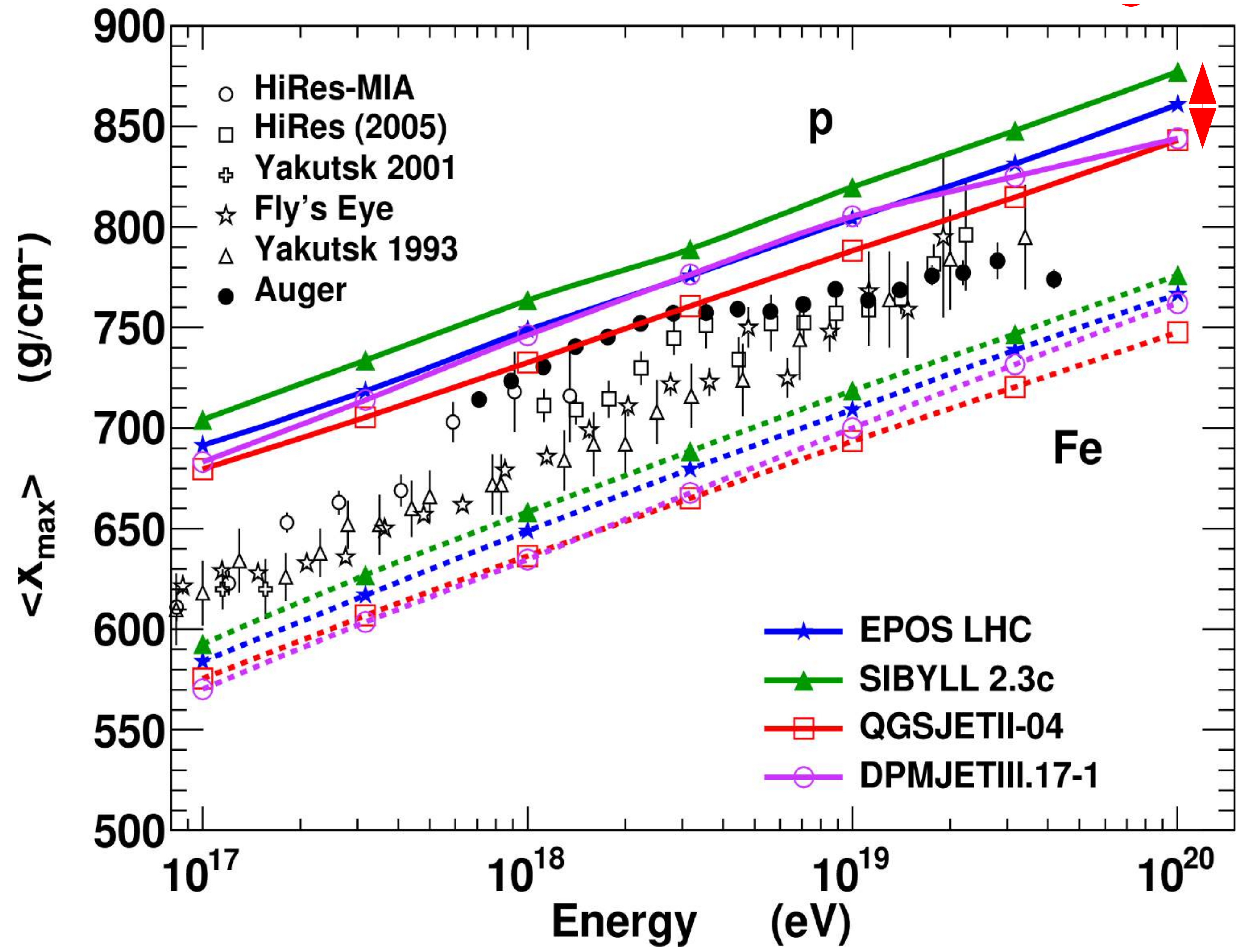
Elongation rate



- Elongation rates indicate a transition of the mass composition.

J. Bellido in ICRC 2017

- **Very similar elongation rate (slope)** for all post-LHC models, ~ 50 g/cm^2/decade
  - minimum given by QGSJetII-04
  - maximum given by Sibyll 2.3c

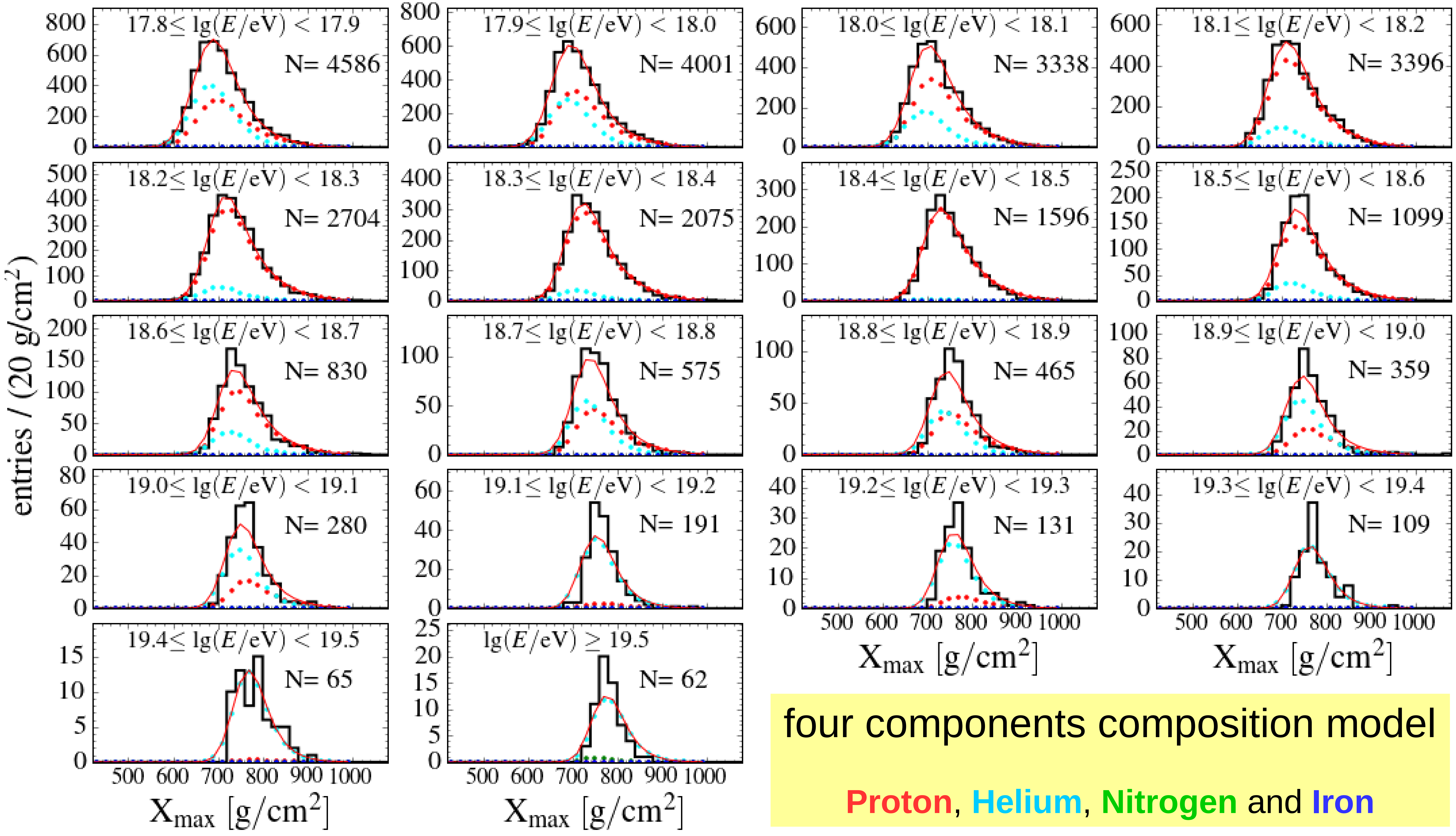


T. Pierog in ICRC 2017

PIERRE AUGER OBSERVATORY

X_{max} distributions (FD)

Interpreting X_{max} distributions with **QGSJETII-04**



four components composition model

Proton, **Helium**, **Nitrogen** and **Iron**

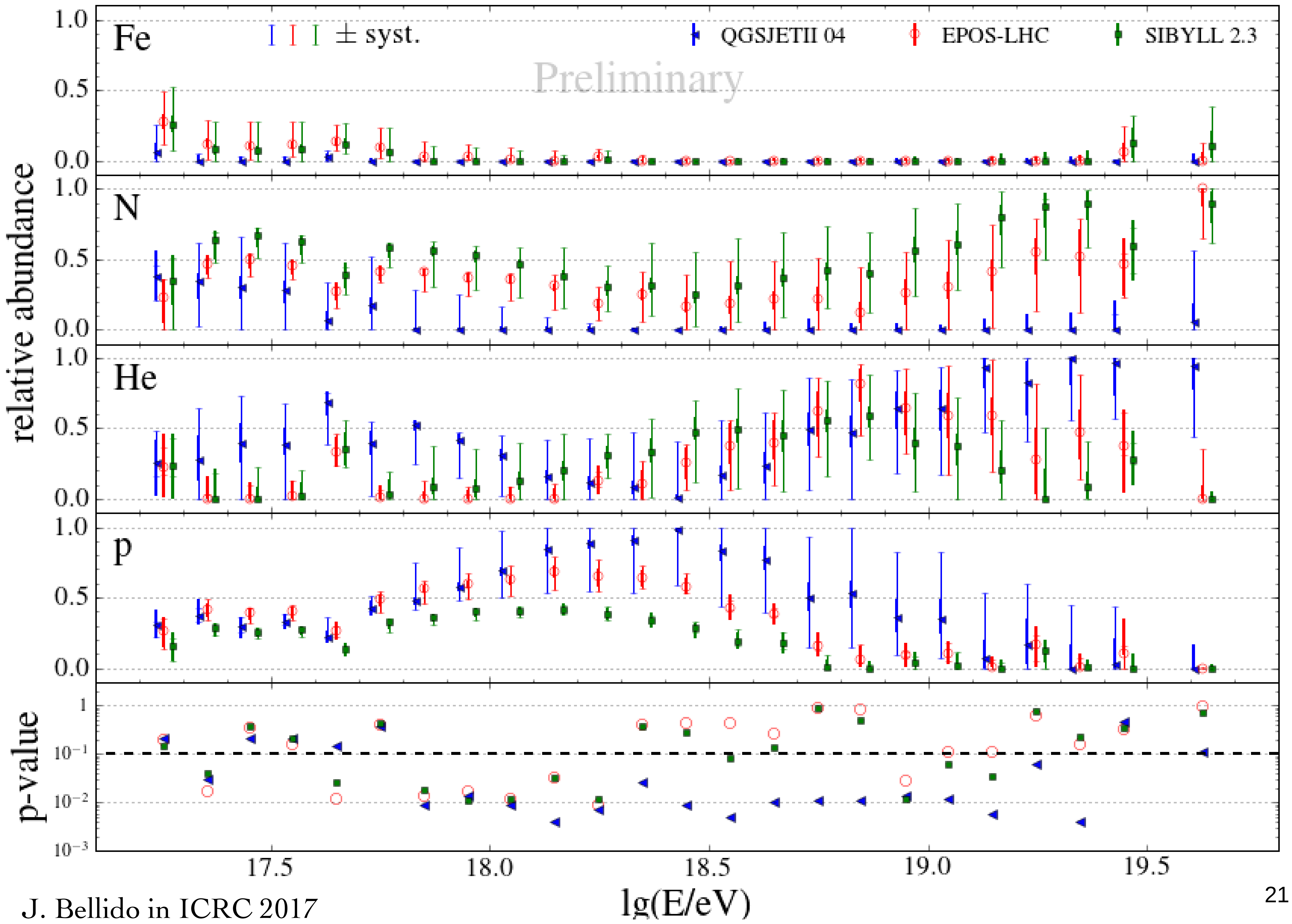
Sum of four components

20

J. Bellido in ICRC 2017

Composition fractions

(obtained from fits to the X_{max} distributions)

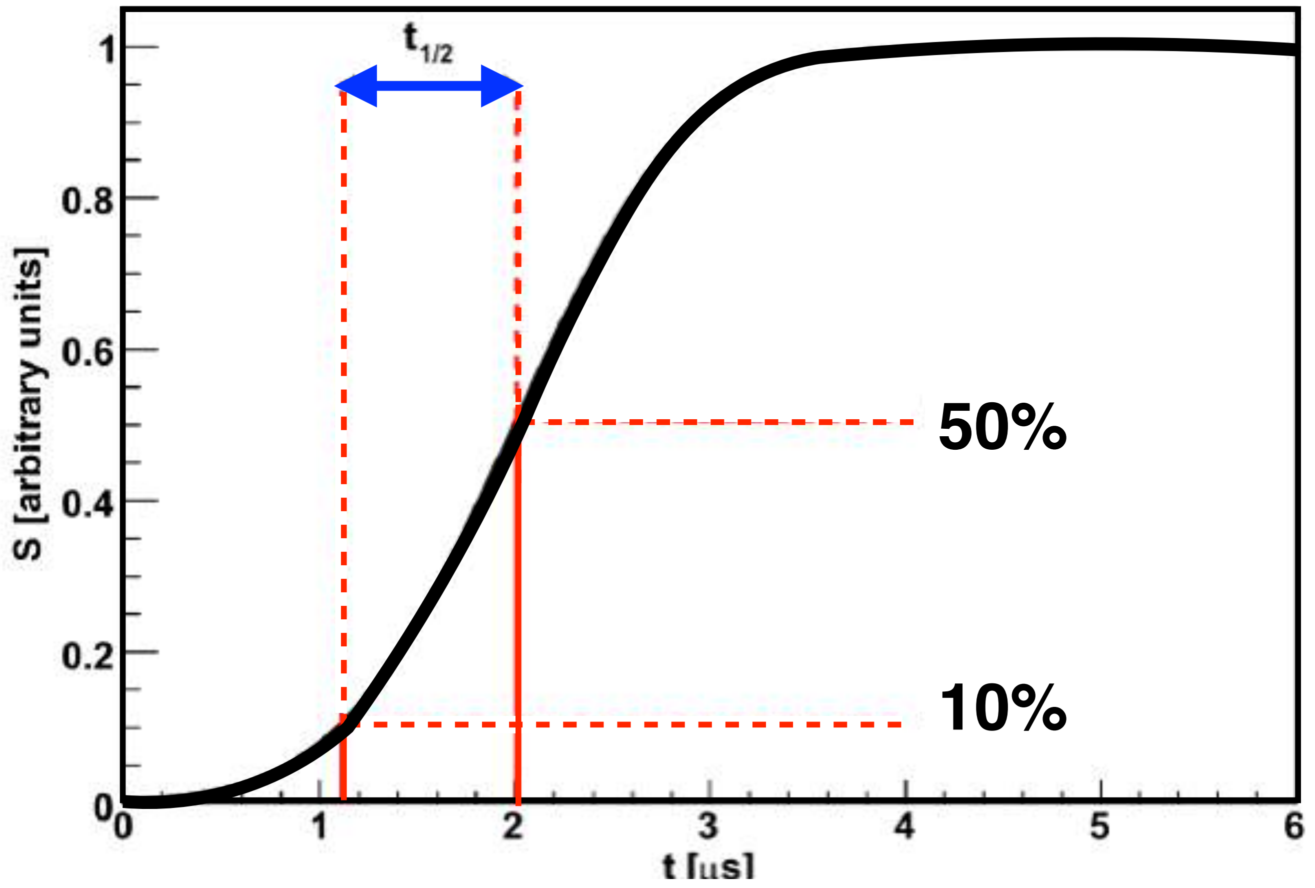


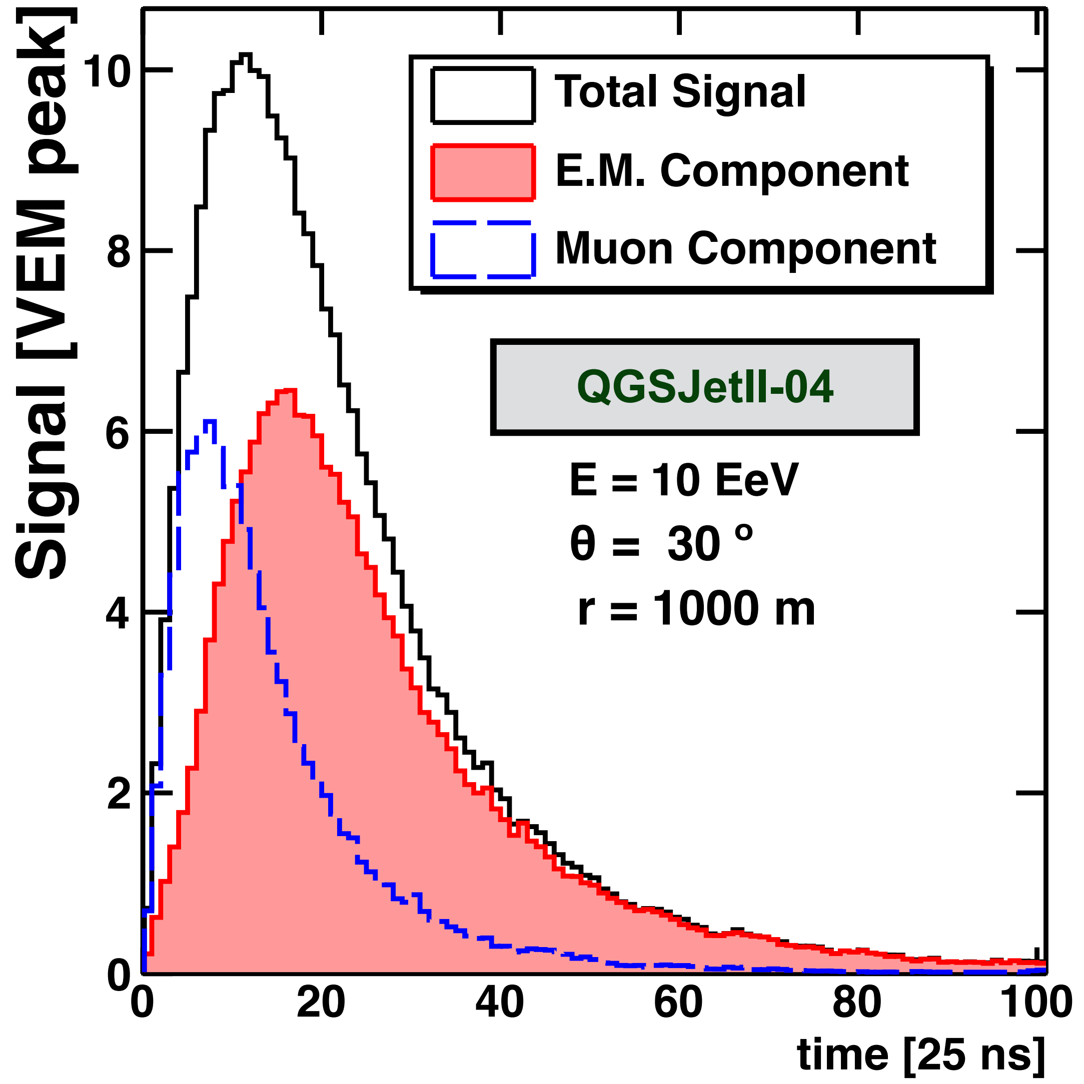
J. Bellido in ICRC 2017

Mass composition using Auger SD

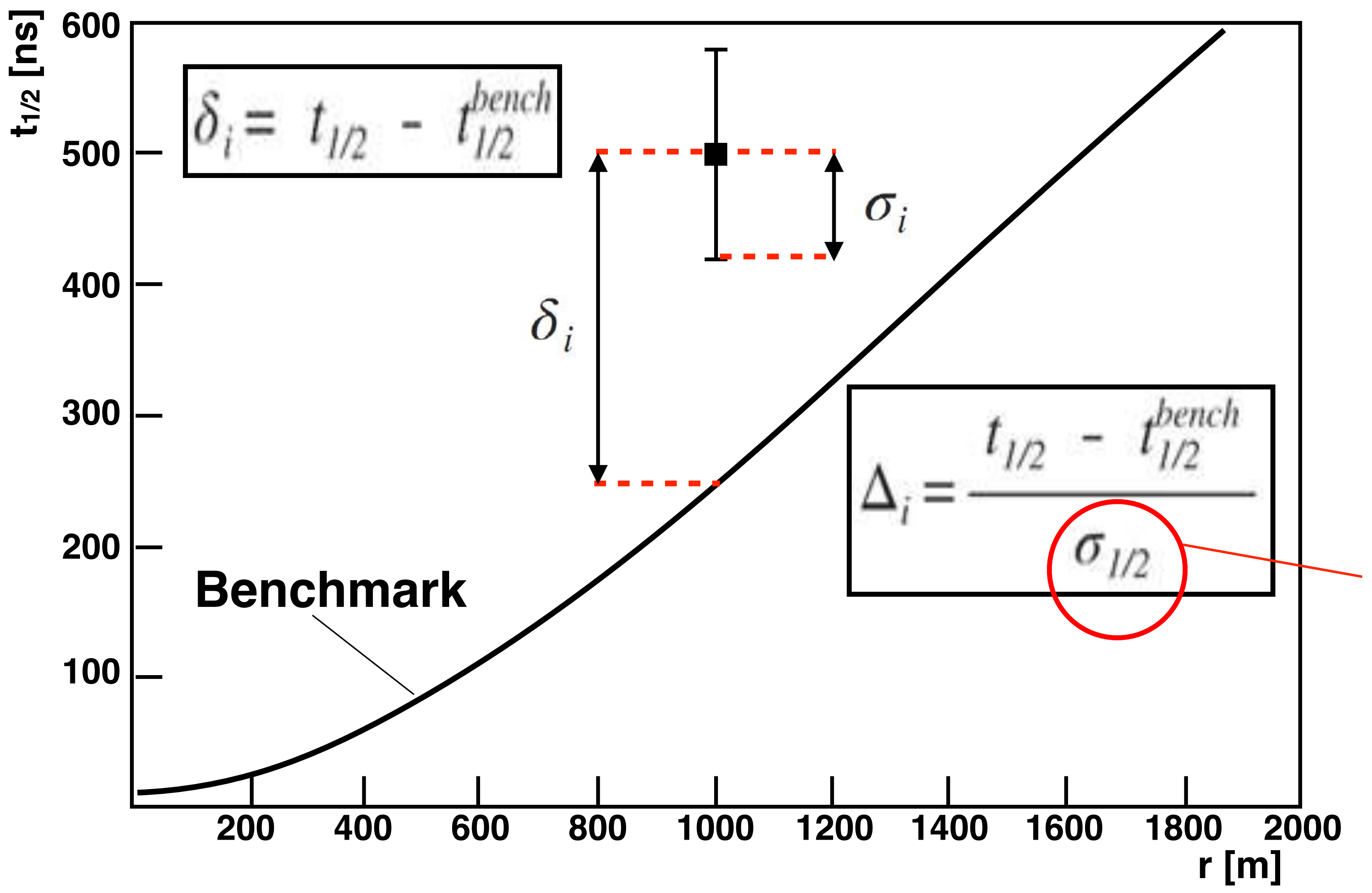
PIERRE AUGER OBSERVATORY

The risetime is the time taken by the integrated signal of the surface detectors to rise from 10% to 50% of its total value





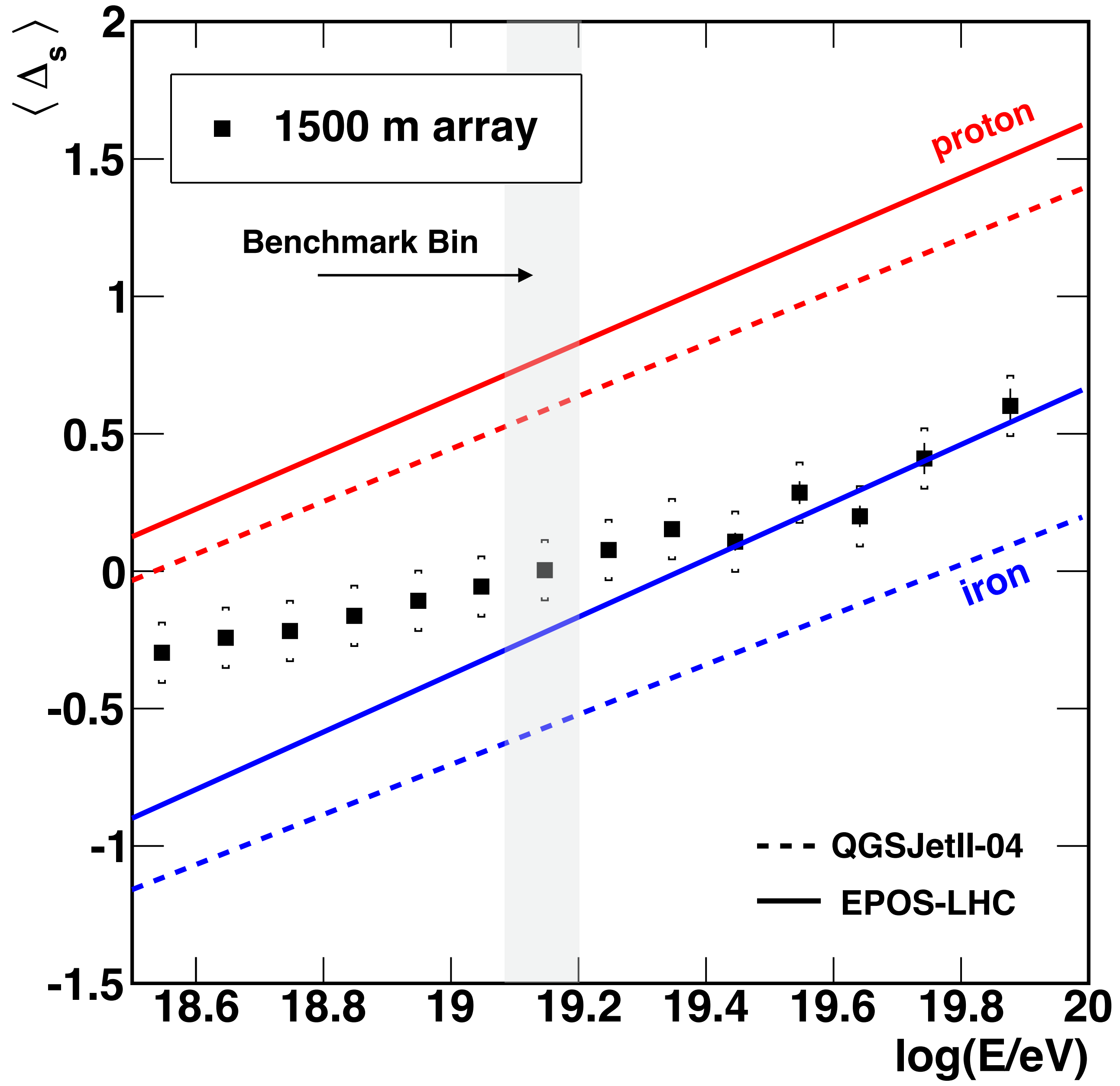
P. Sanchez-Lucas in ICRC 2017

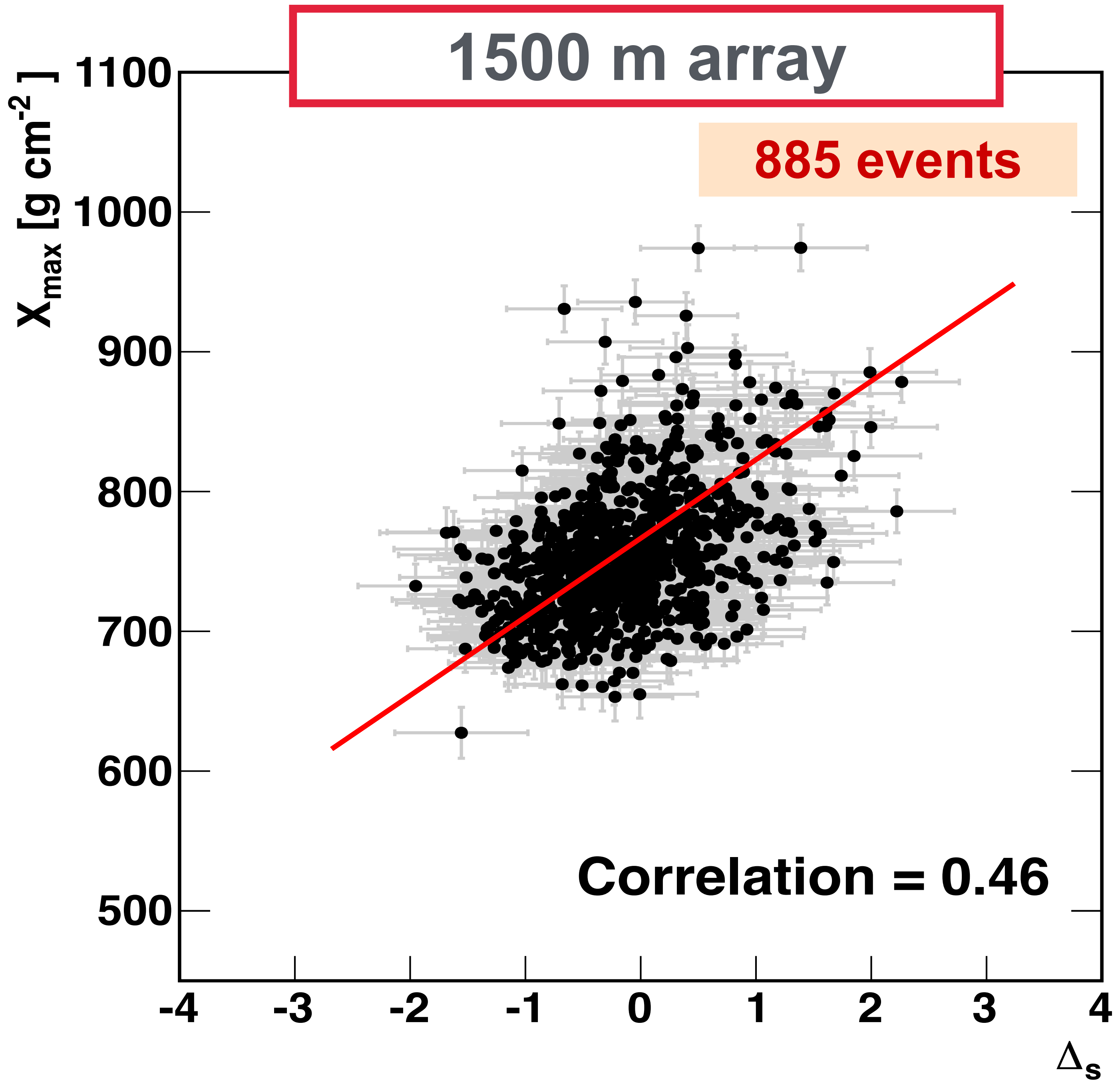


N: number of detectors in an event

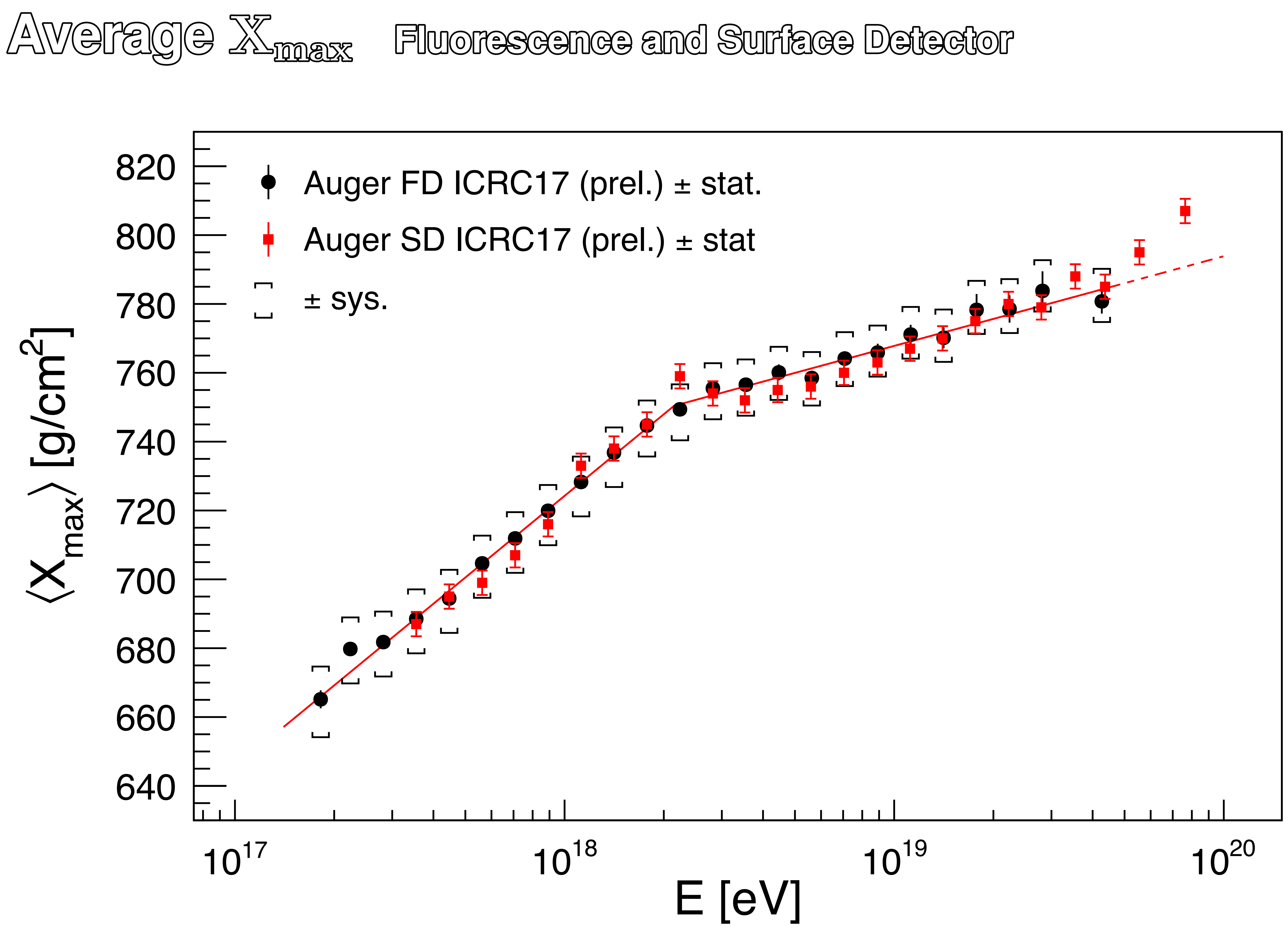
$$\Delta_s = \frac{1}{N} \sum_{i=1}^{N} \Delta_i$$

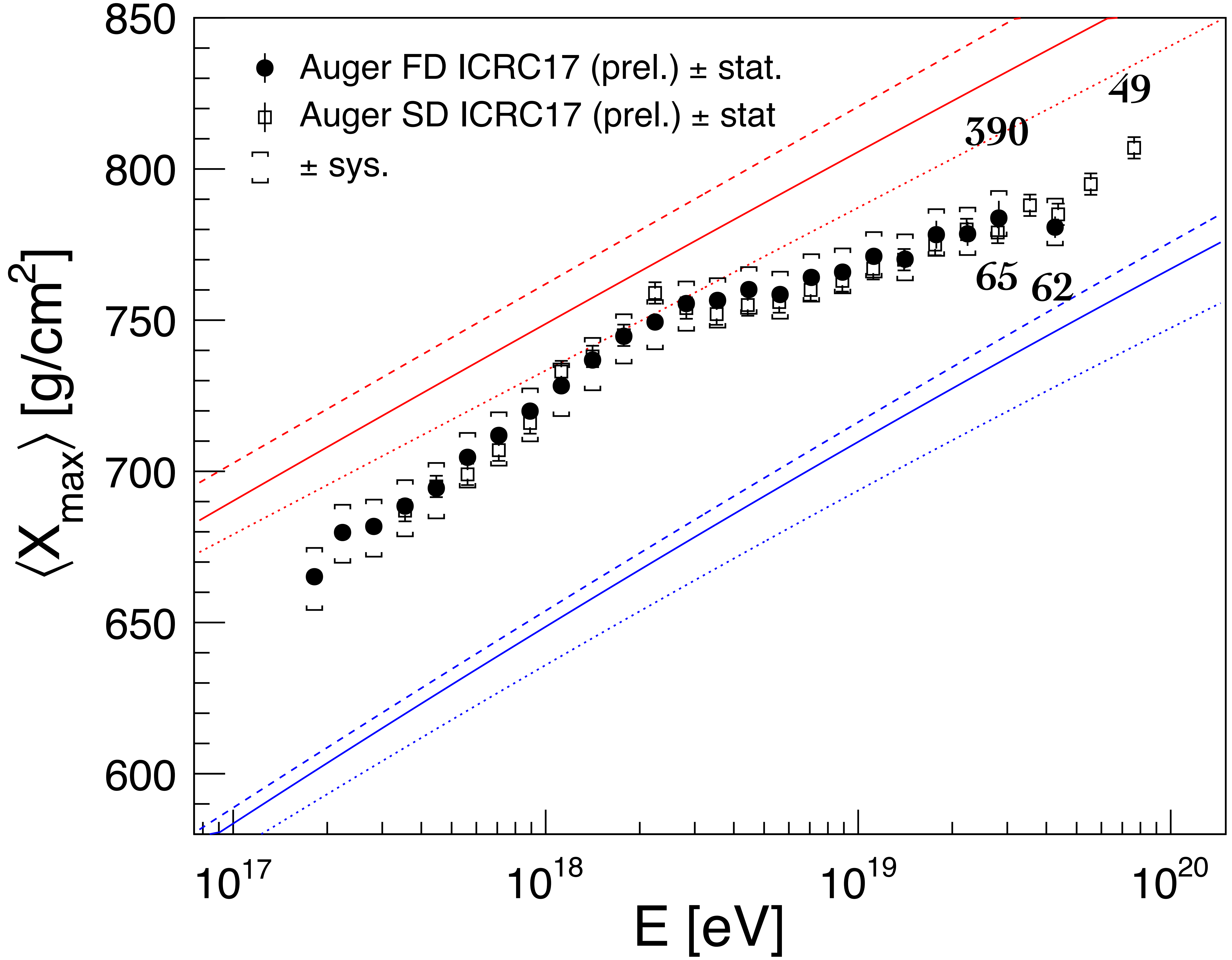
1500 m array





Average Xmax

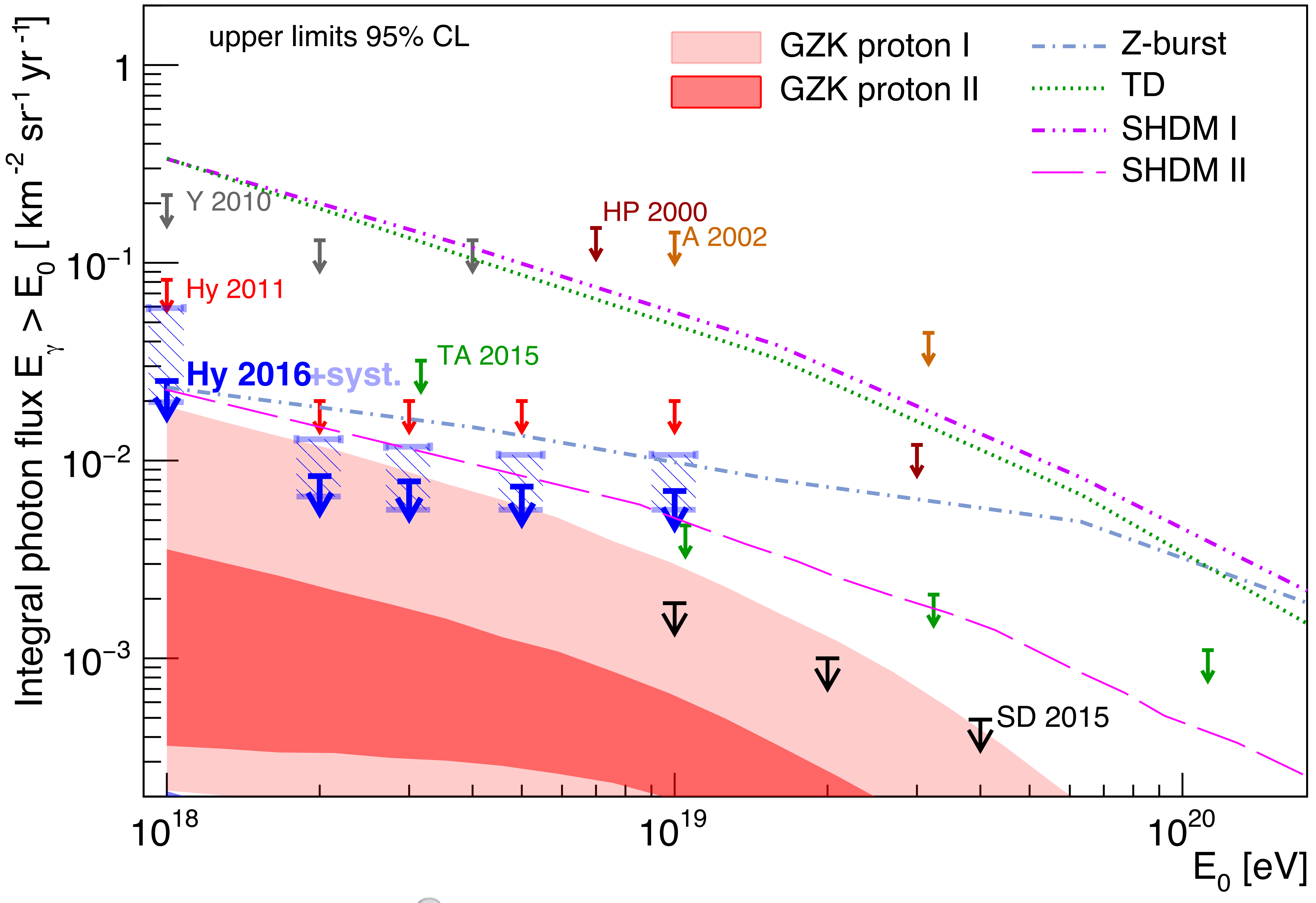


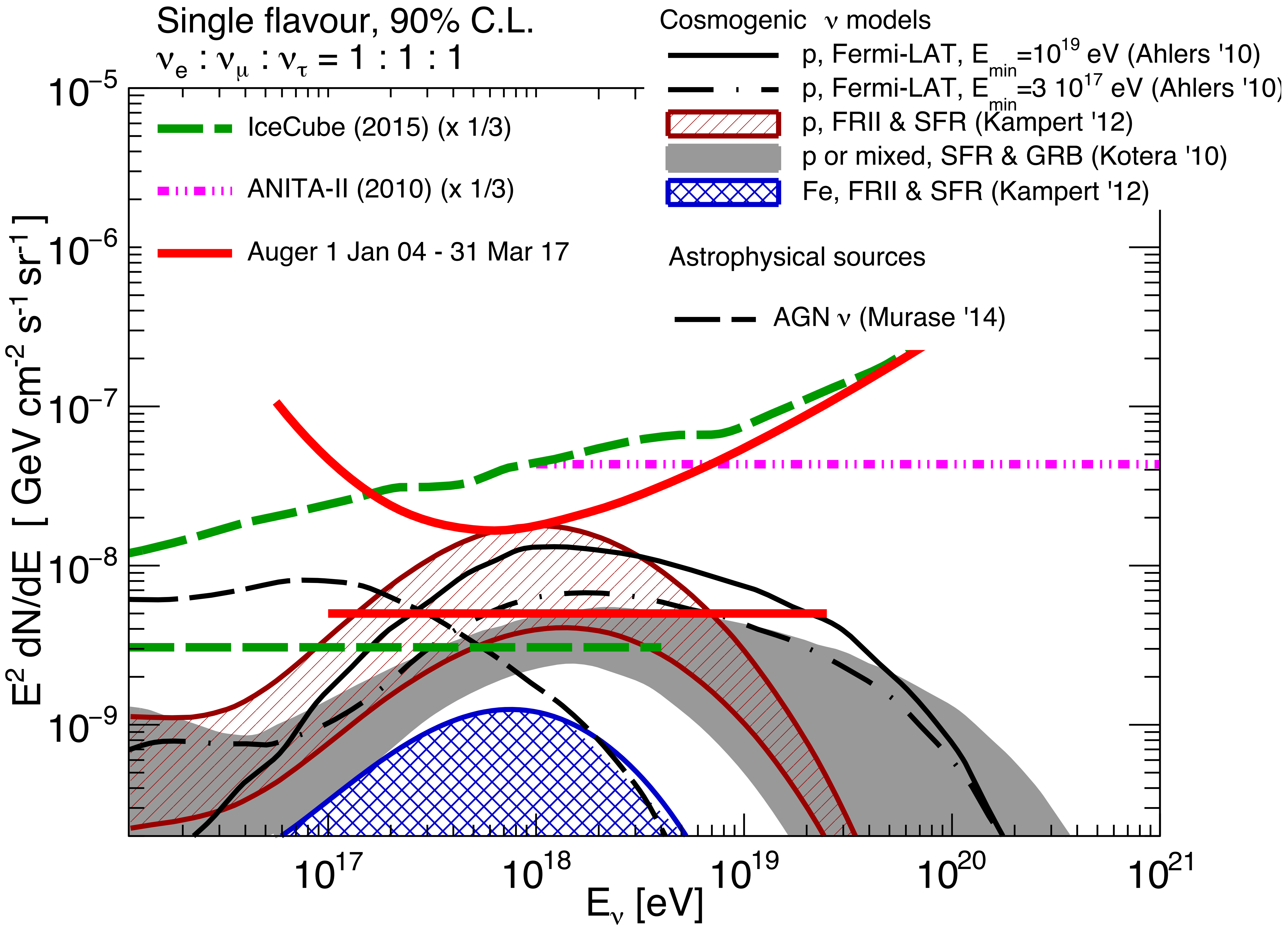


- Lighter composition above $10^{19.7}$ eV?

P. Sanchez-Lucas, M. Unger in ICRC 2017

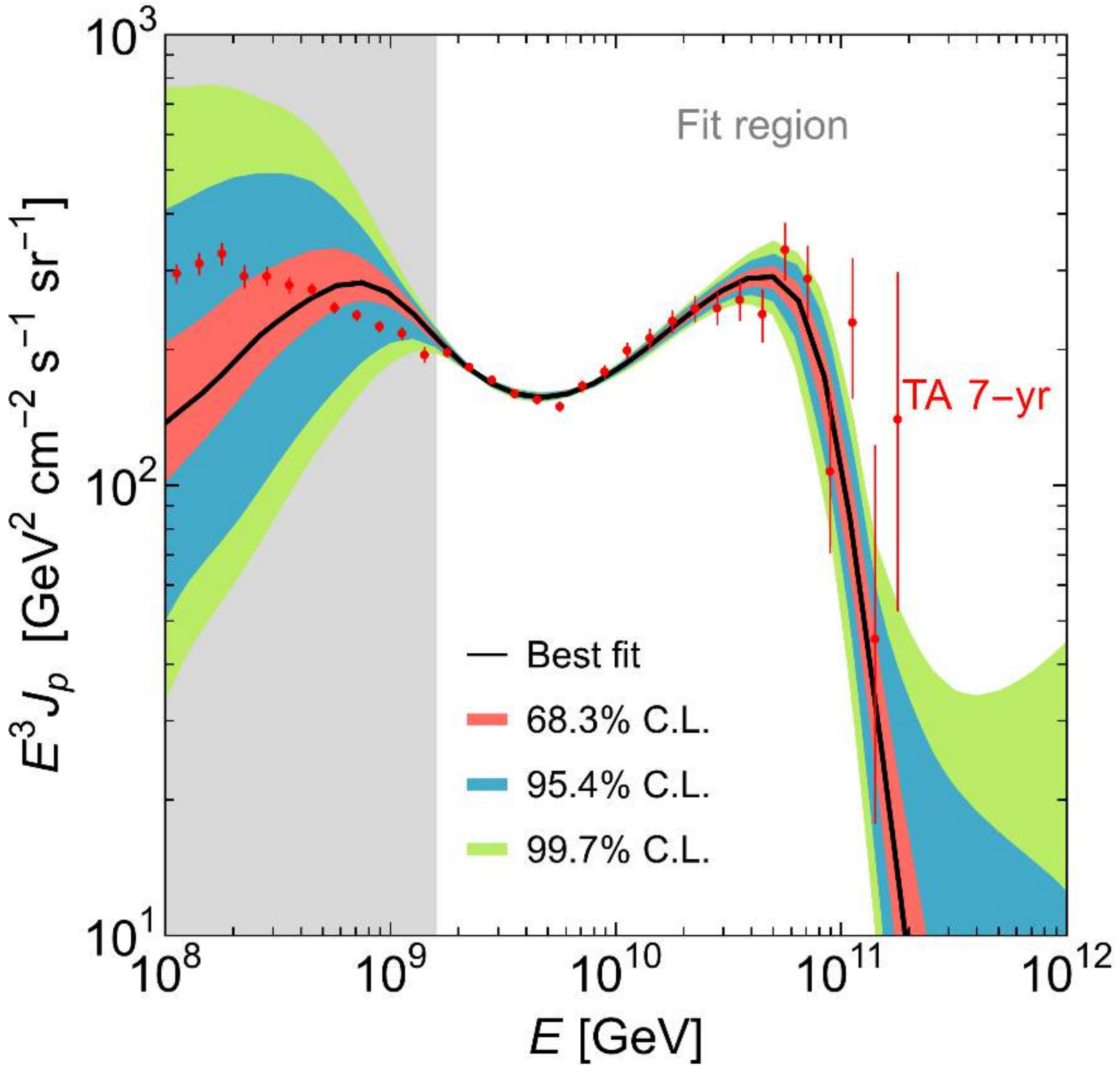
No GZK γ and ν at highest energies

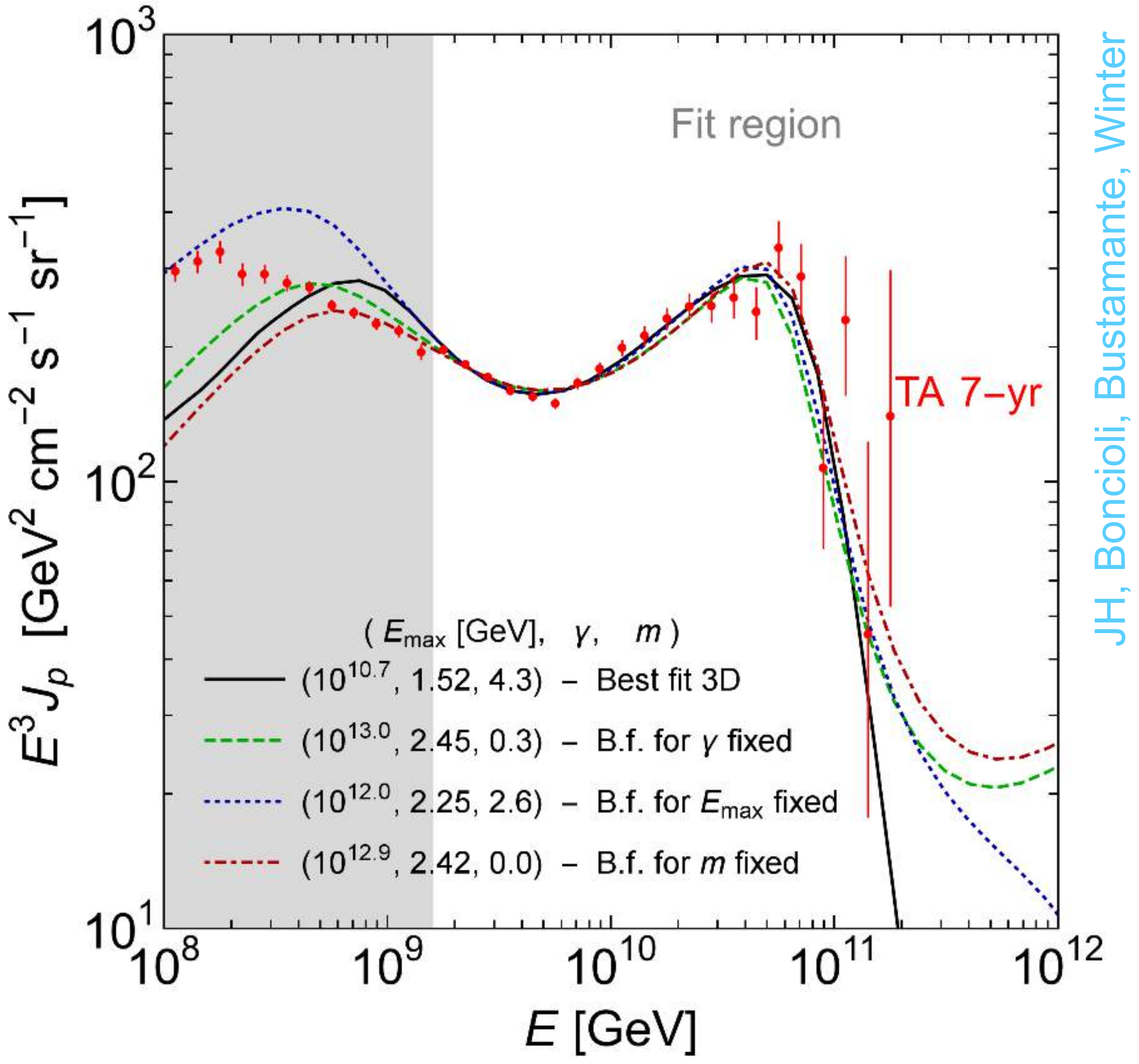




- Top-down models are ruled out.
- Auger limits become sensitive to GZK-ν and γ

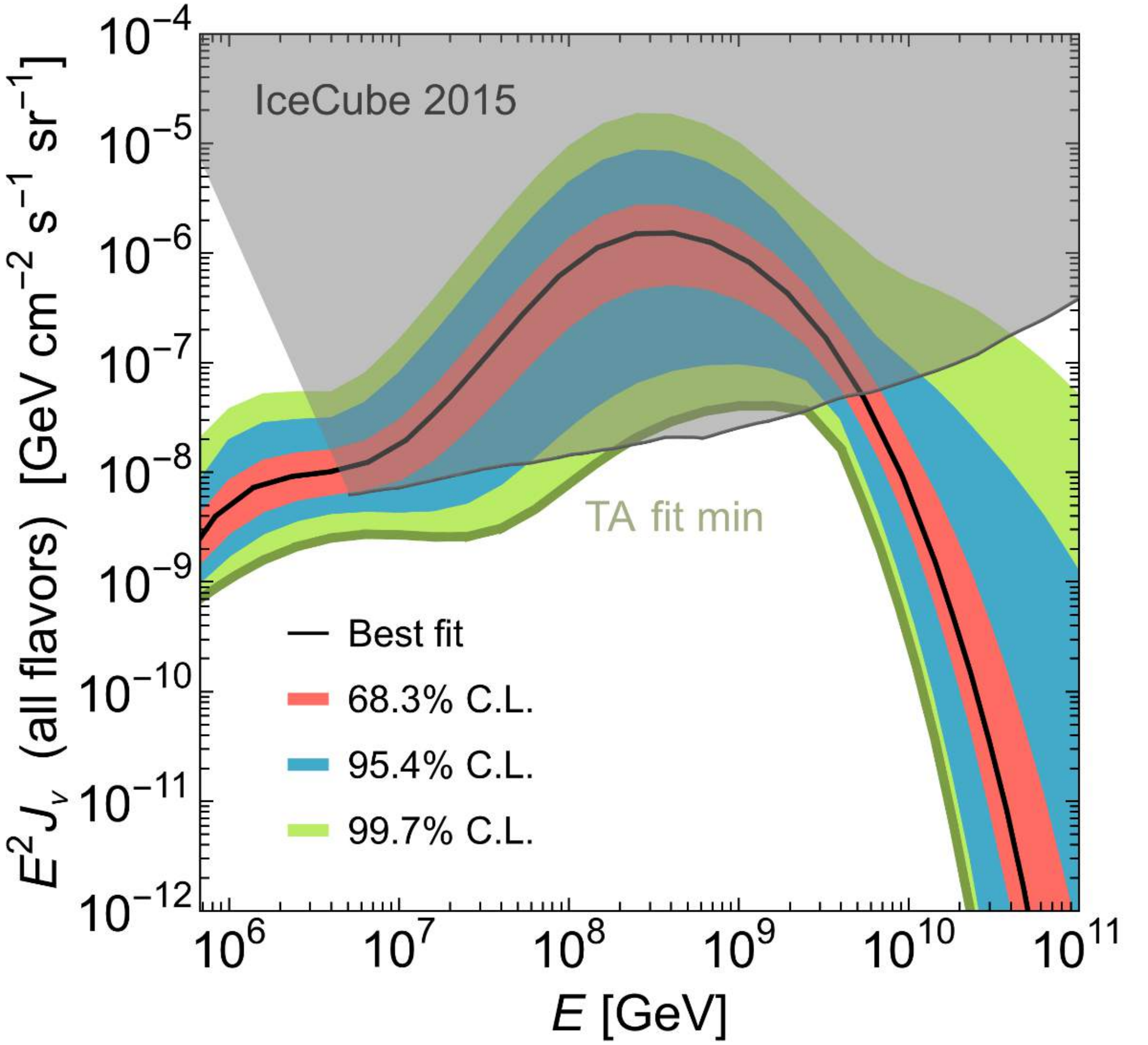
In tension of the dip model by IceCube limit





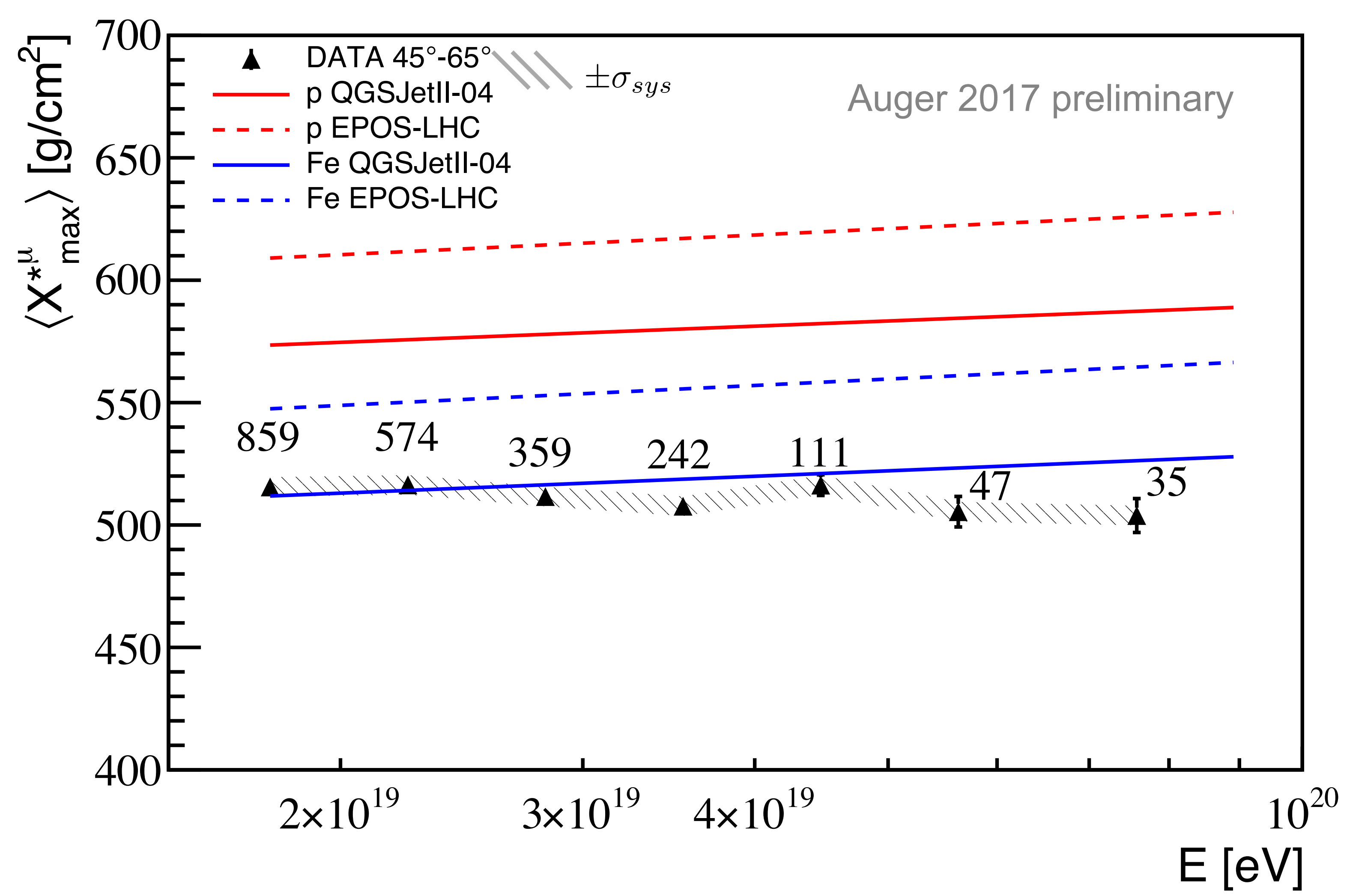
JH, Boncioli, Bustamante, Winter ApJ 825:122 (2016)

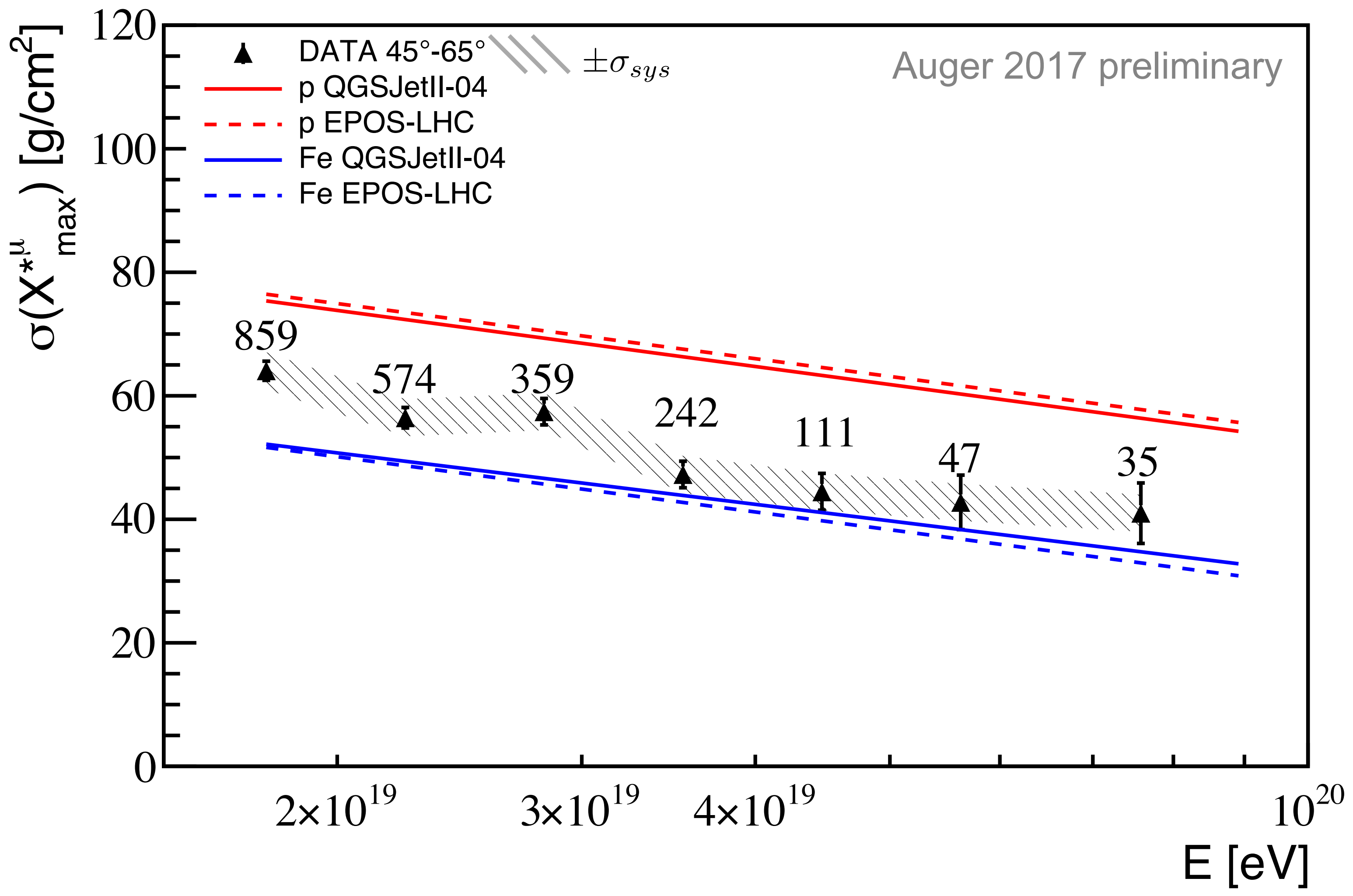
JH, Boncioli, Bustamante, Winter
ApJ 825:122 (2016)

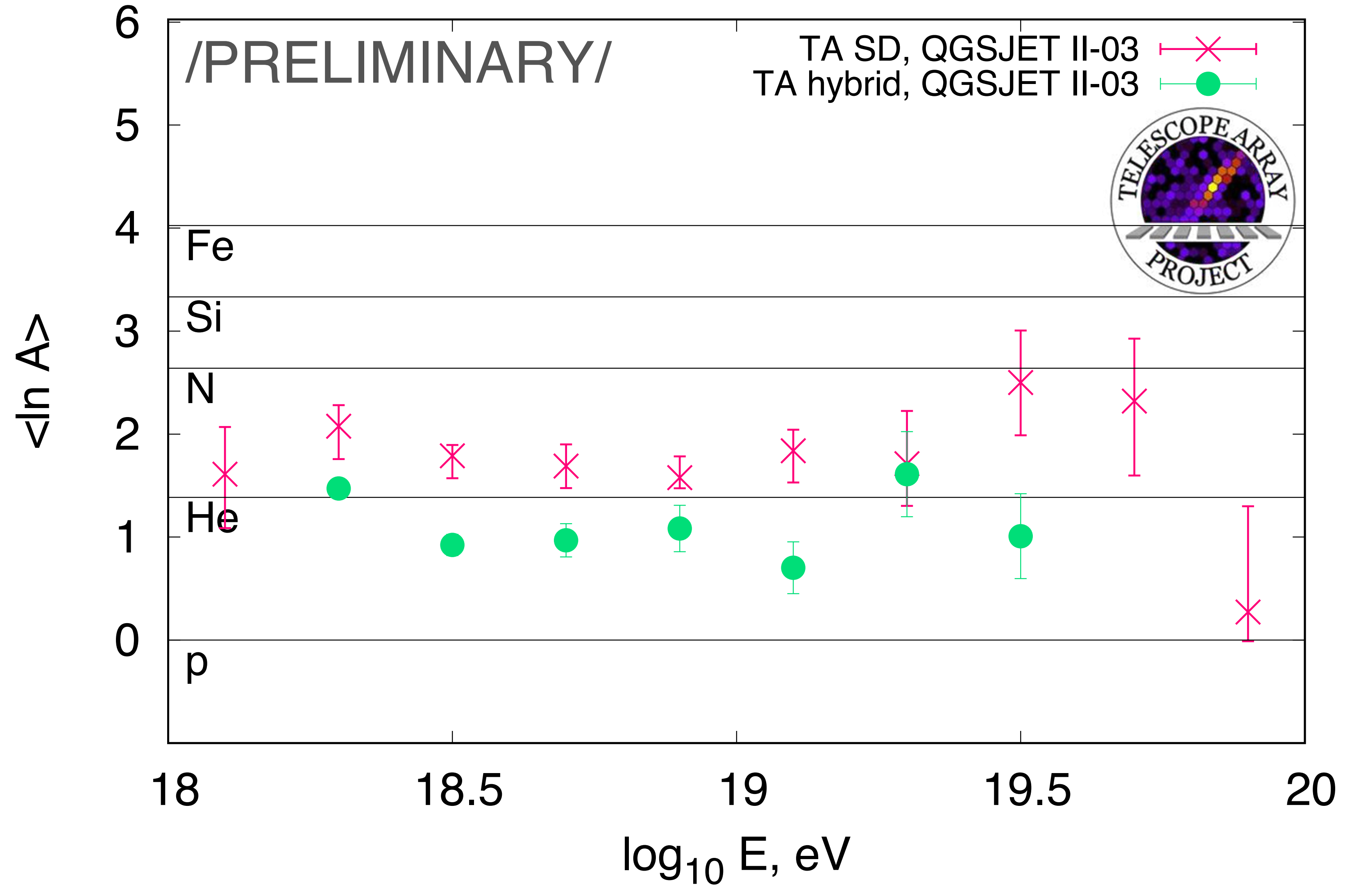


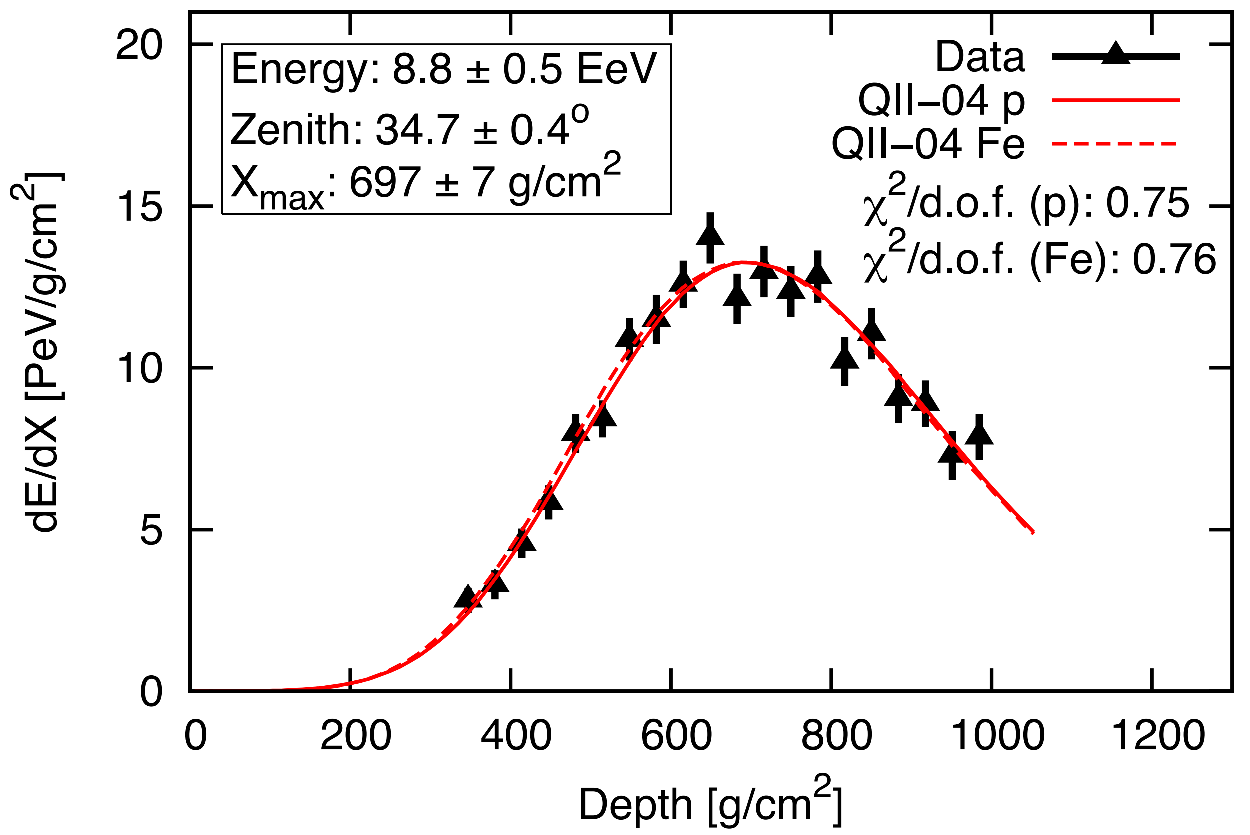
- Low statistics cannot distinguish source- or GZK effect
- Fit driven by ankle region
  - Favours hard spectra....
  - …and strong source evolution
- Overshoot: below fit range
  - Minimal escape energy?
  - Magnetic field diffusion?
  - Or further constraint on Dip model?

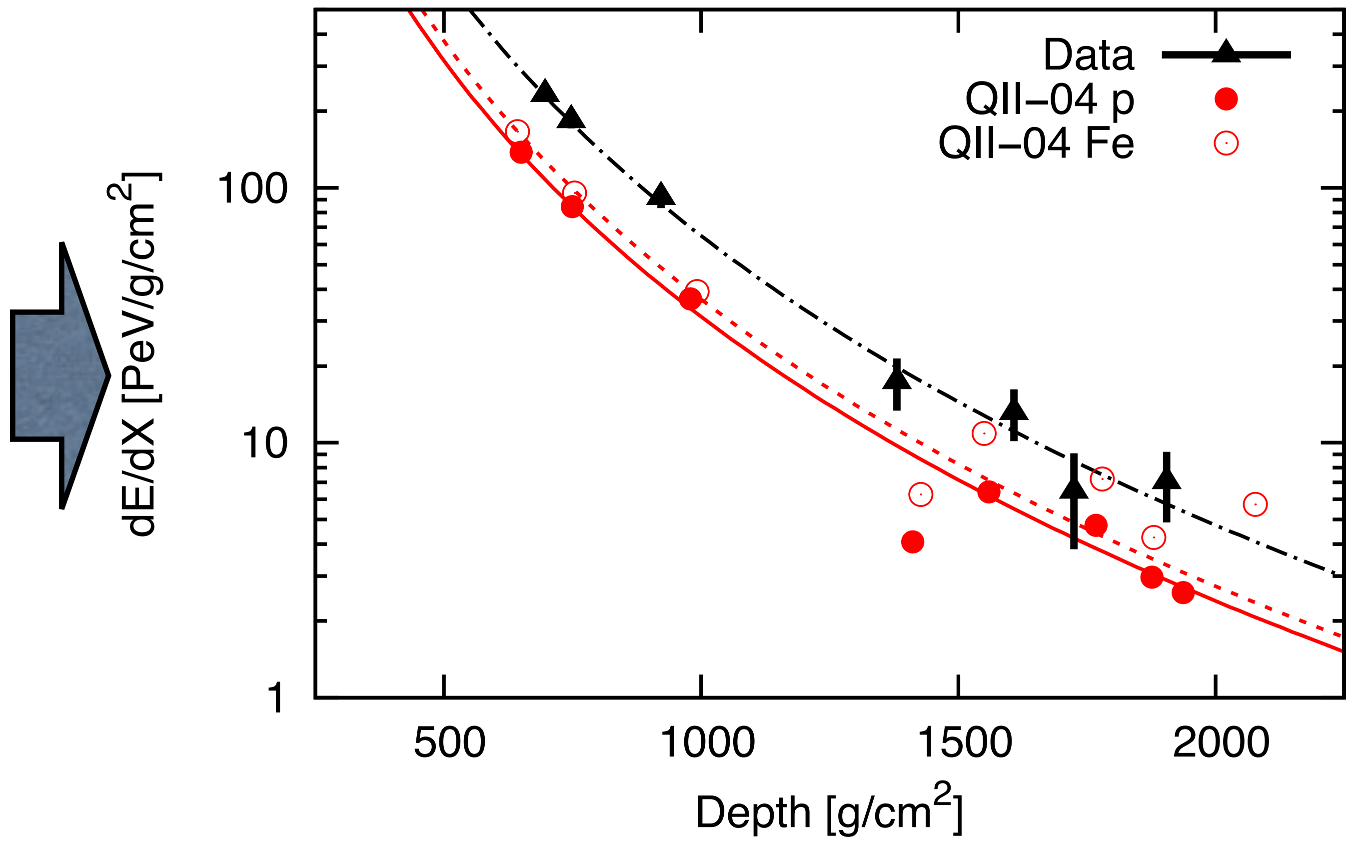
Testing hadron interaction model

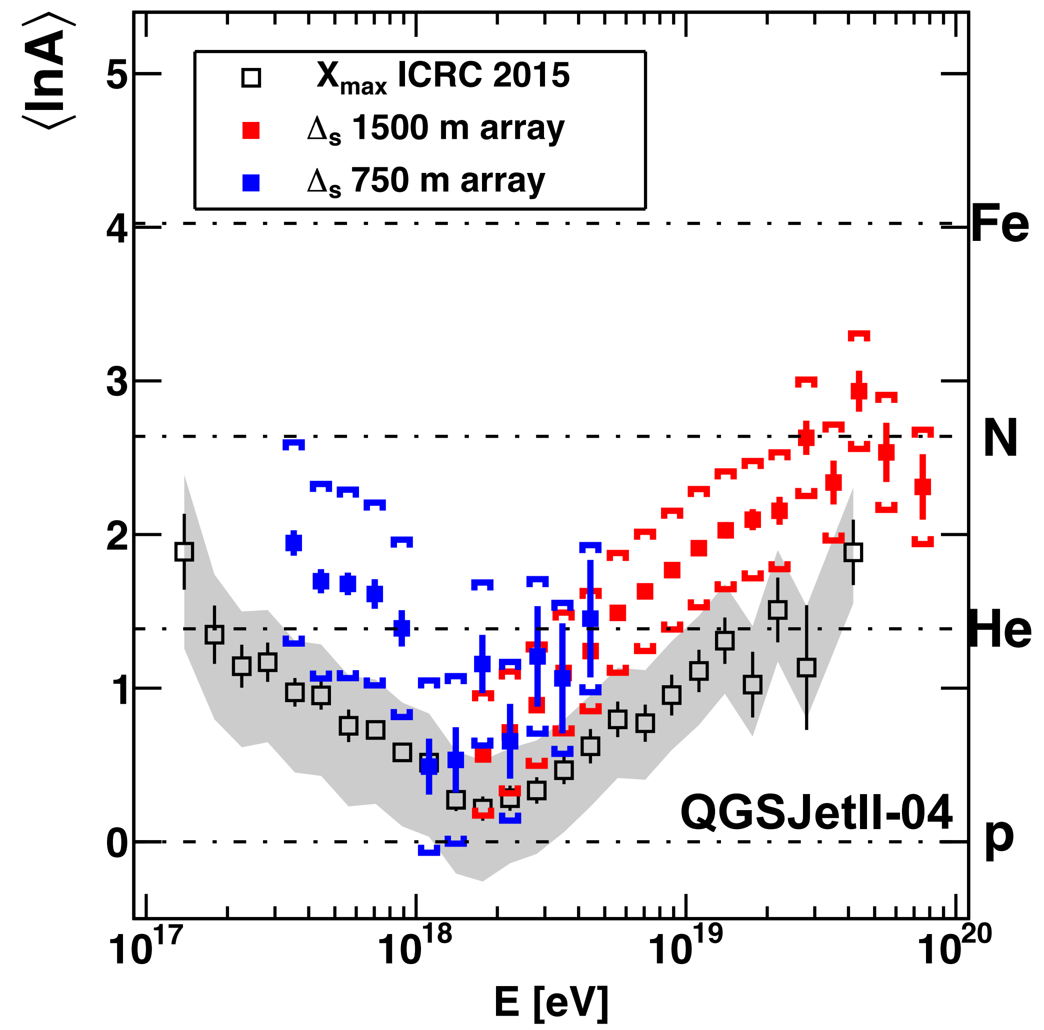


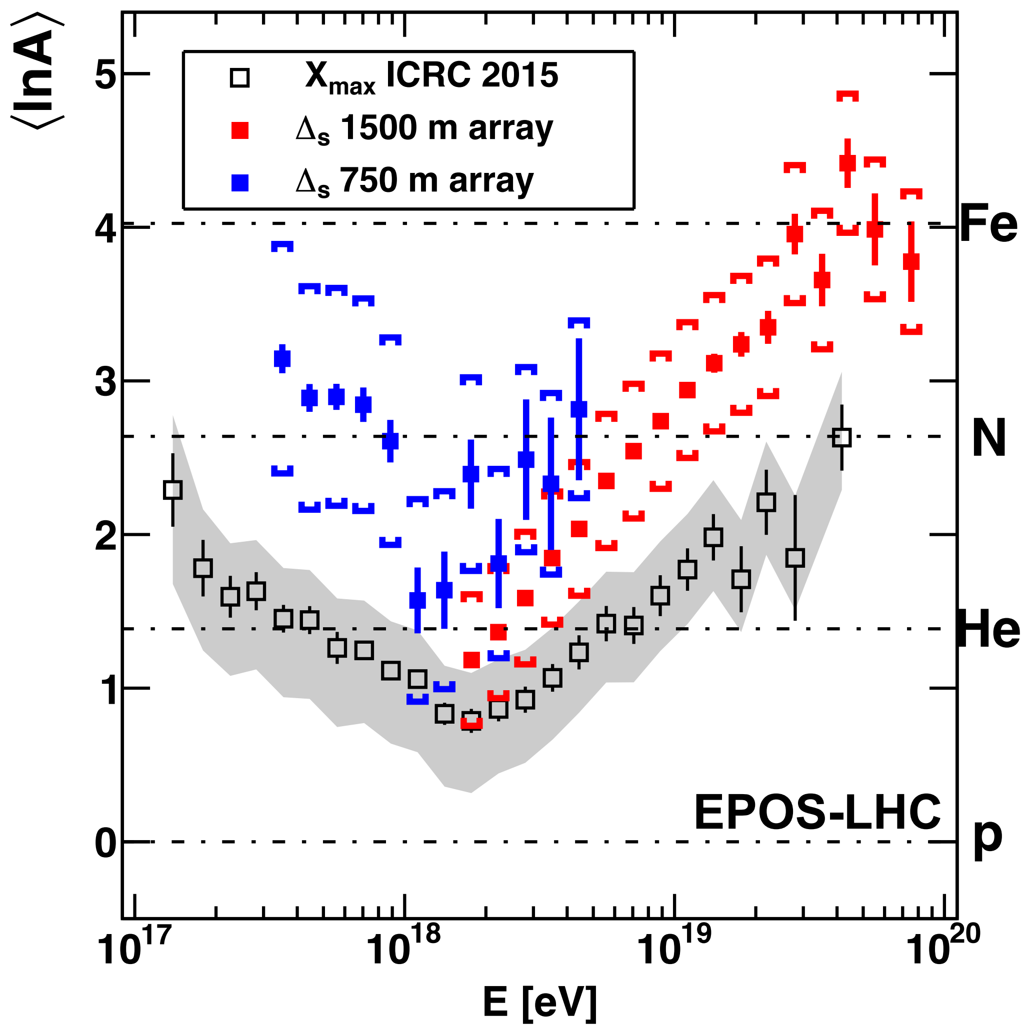












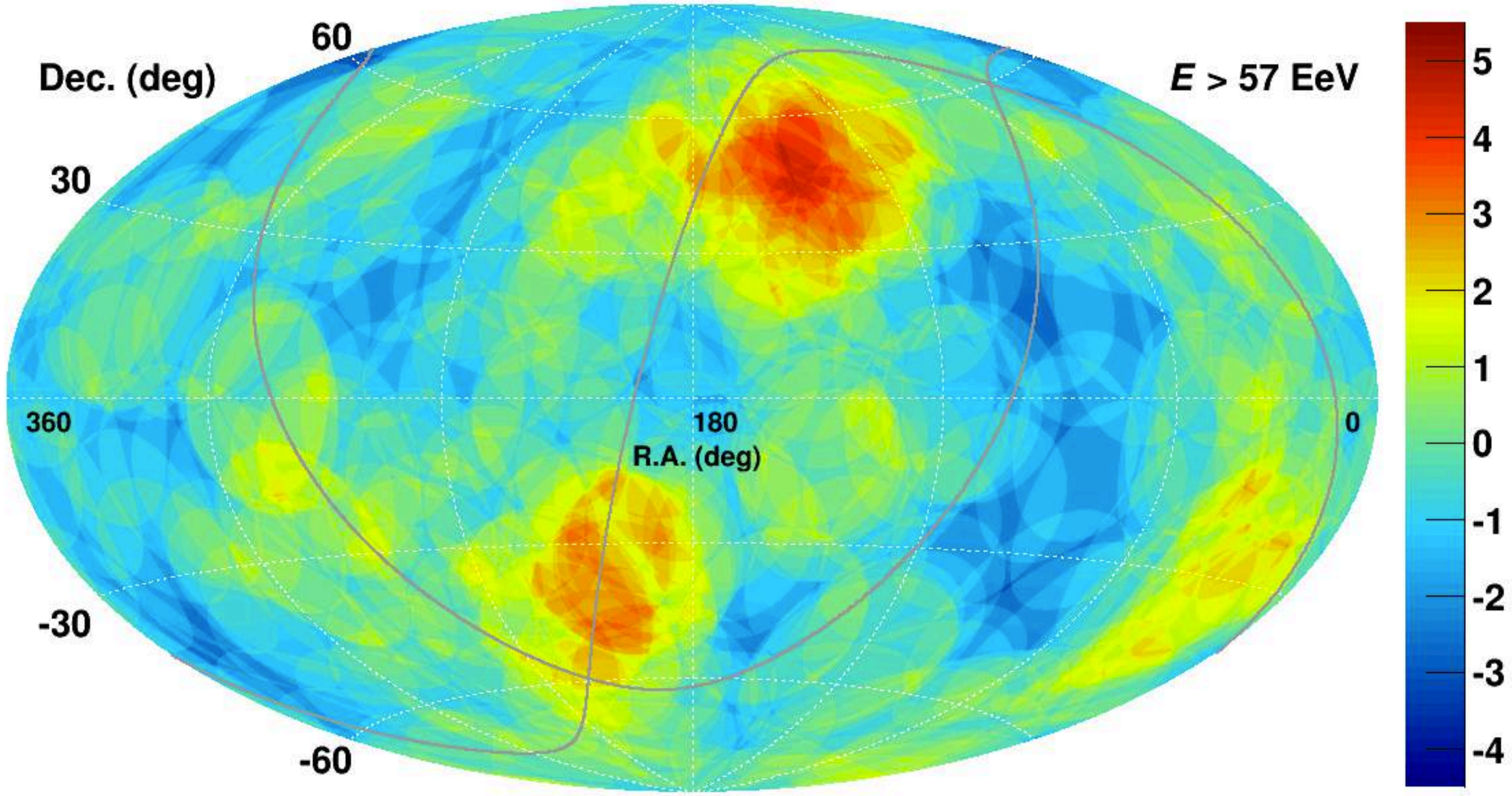
M. Mallamaci, P. Sanchez-Lucas, M. Unger, Y. Zhezher in ICRC 2017

No perfect models at the highest energies…

Anisotropy: hot/warm spots

All Sky Survey with TA&PAO

Oversampling with 20°-radius circle

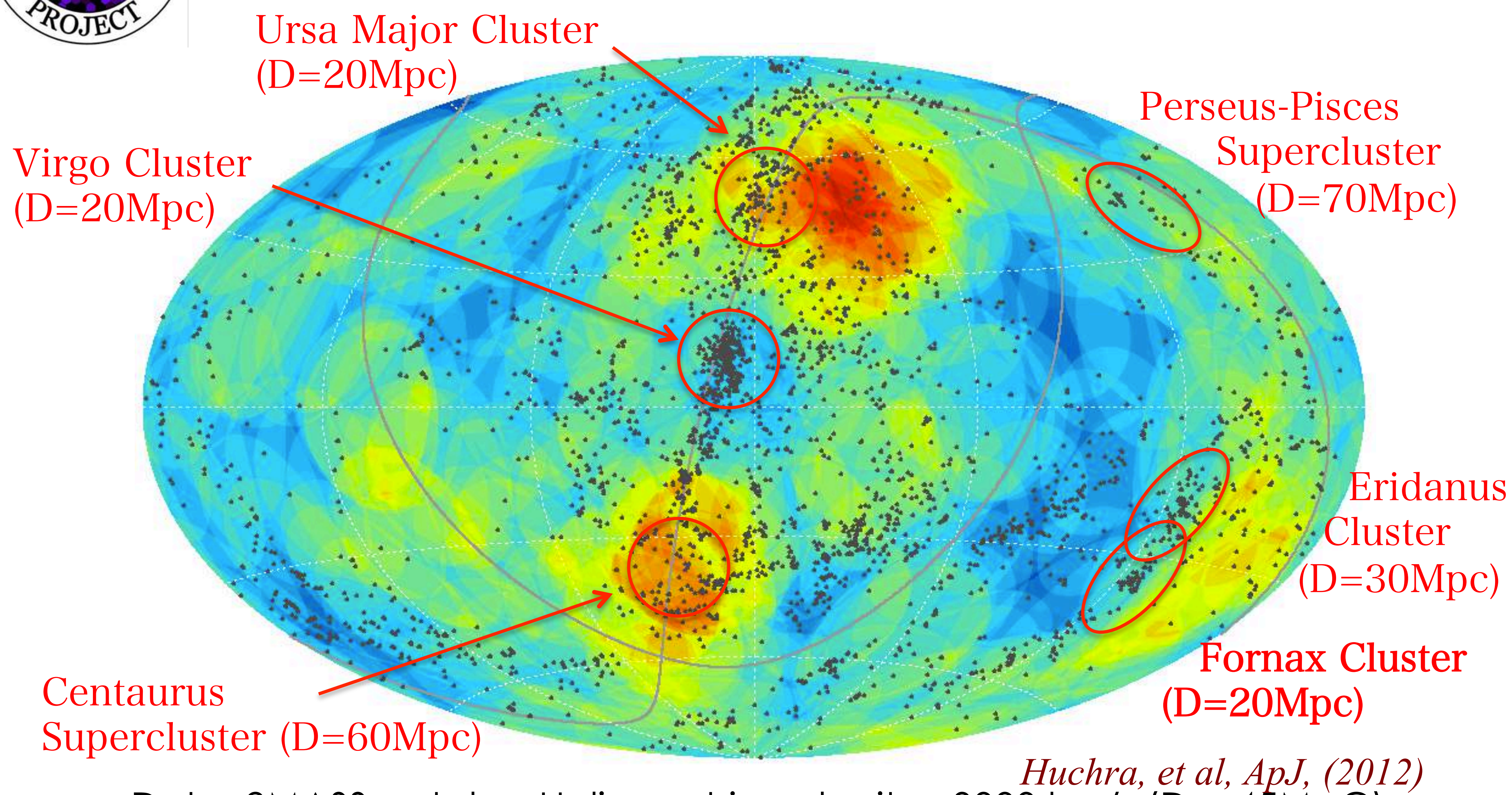


No correction for E scale difference b/w TA and PAO !!

Northern TA : 7 years 109 events (>57EeV)
Southern Auger : 10 years 157 events (>57EeV)

Southern hotspot is seen at Cen A(Pre-trial ~3.6σ)

Nearby Galaxy Clusters



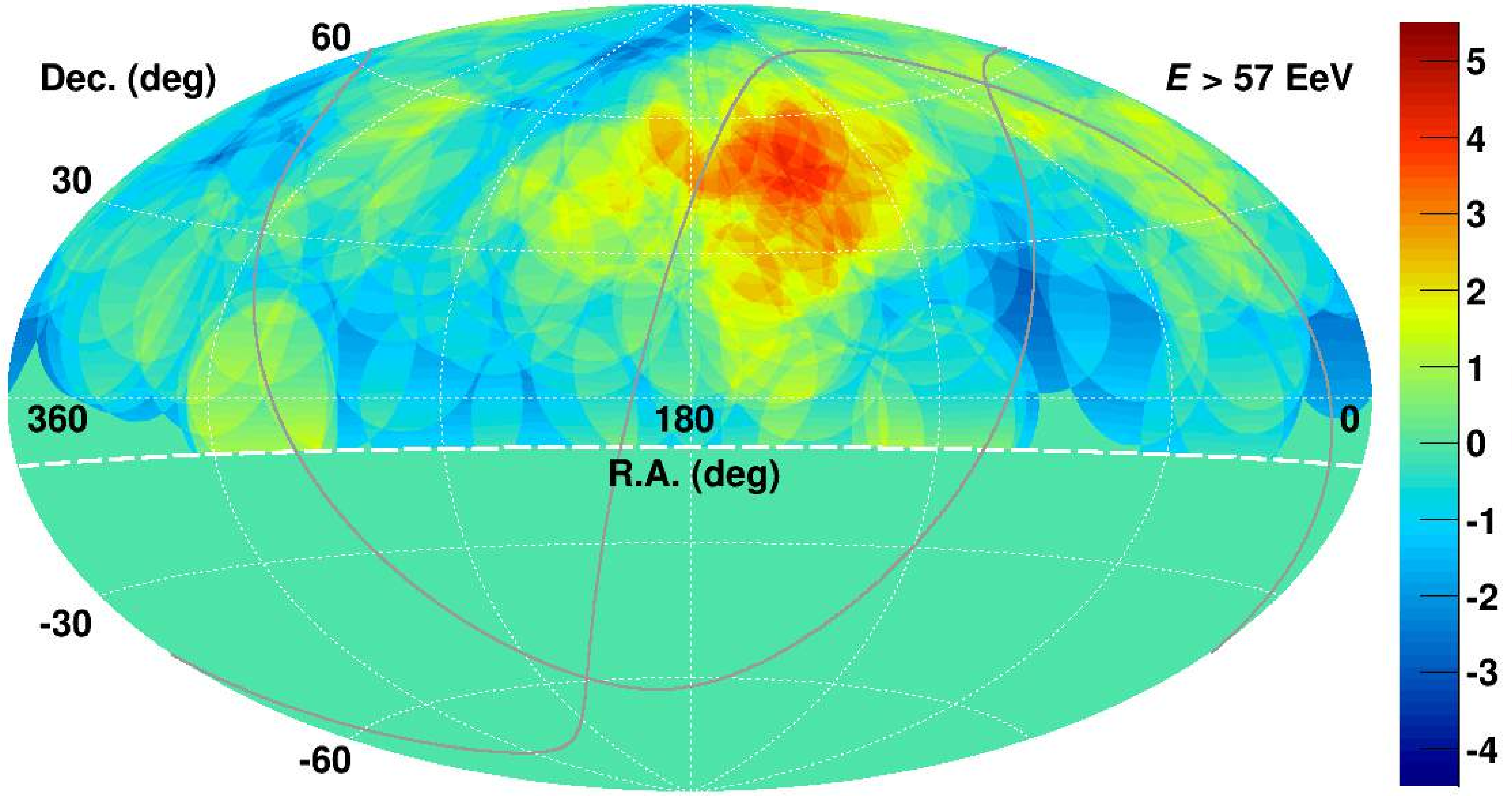
Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

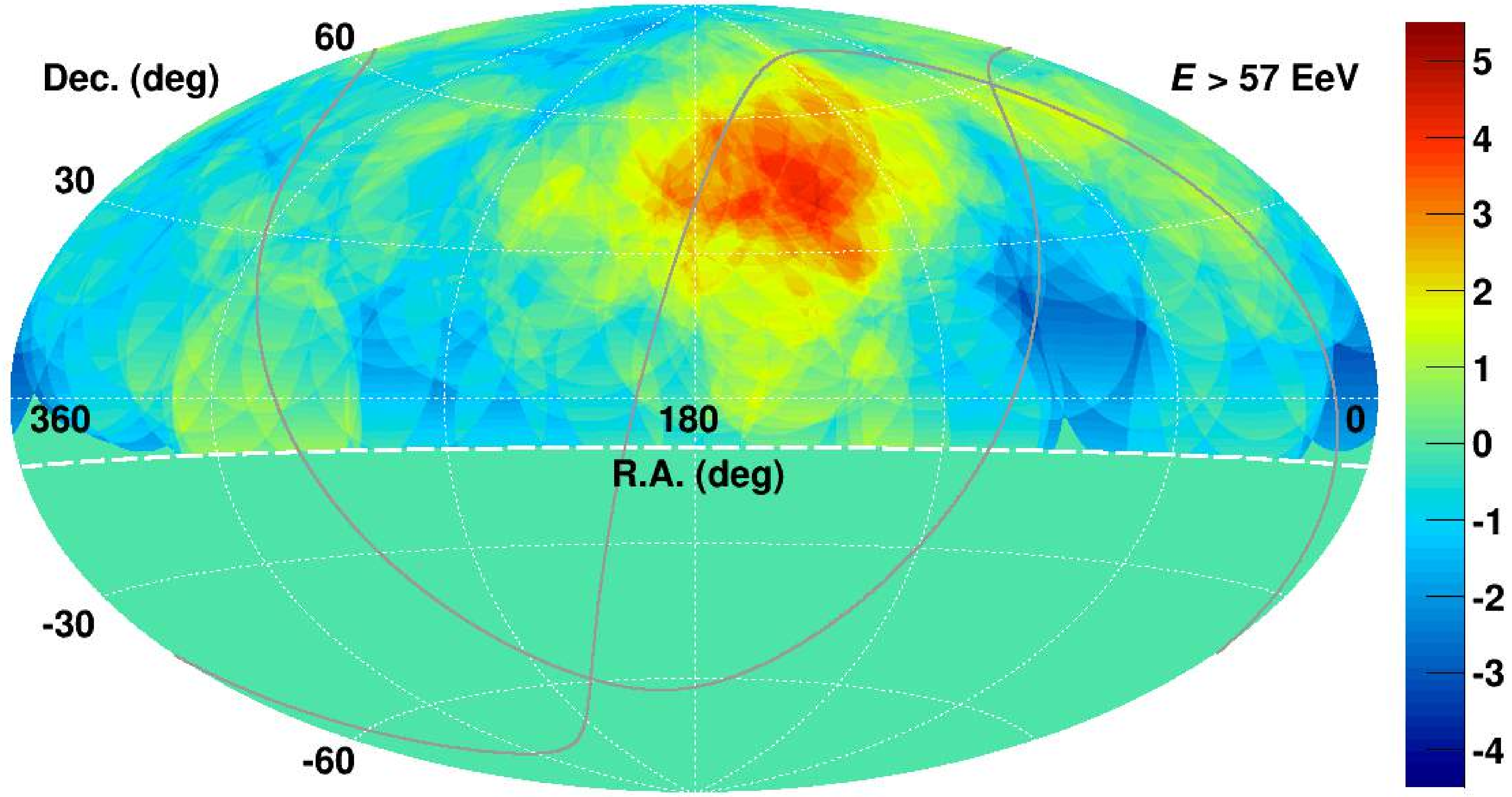
TA hotspot is found near the Ursa Major Cluster

K. Kawata in ICRC 2015

Lack of UHECRs from Virgo cluster.

TA hotspot update





With original 20° oversampling, spot looks larger…. Thus, scan over 15°, 20°, 25°, 30°, & 35°

With 25° oversampling, significance maximum 3σ

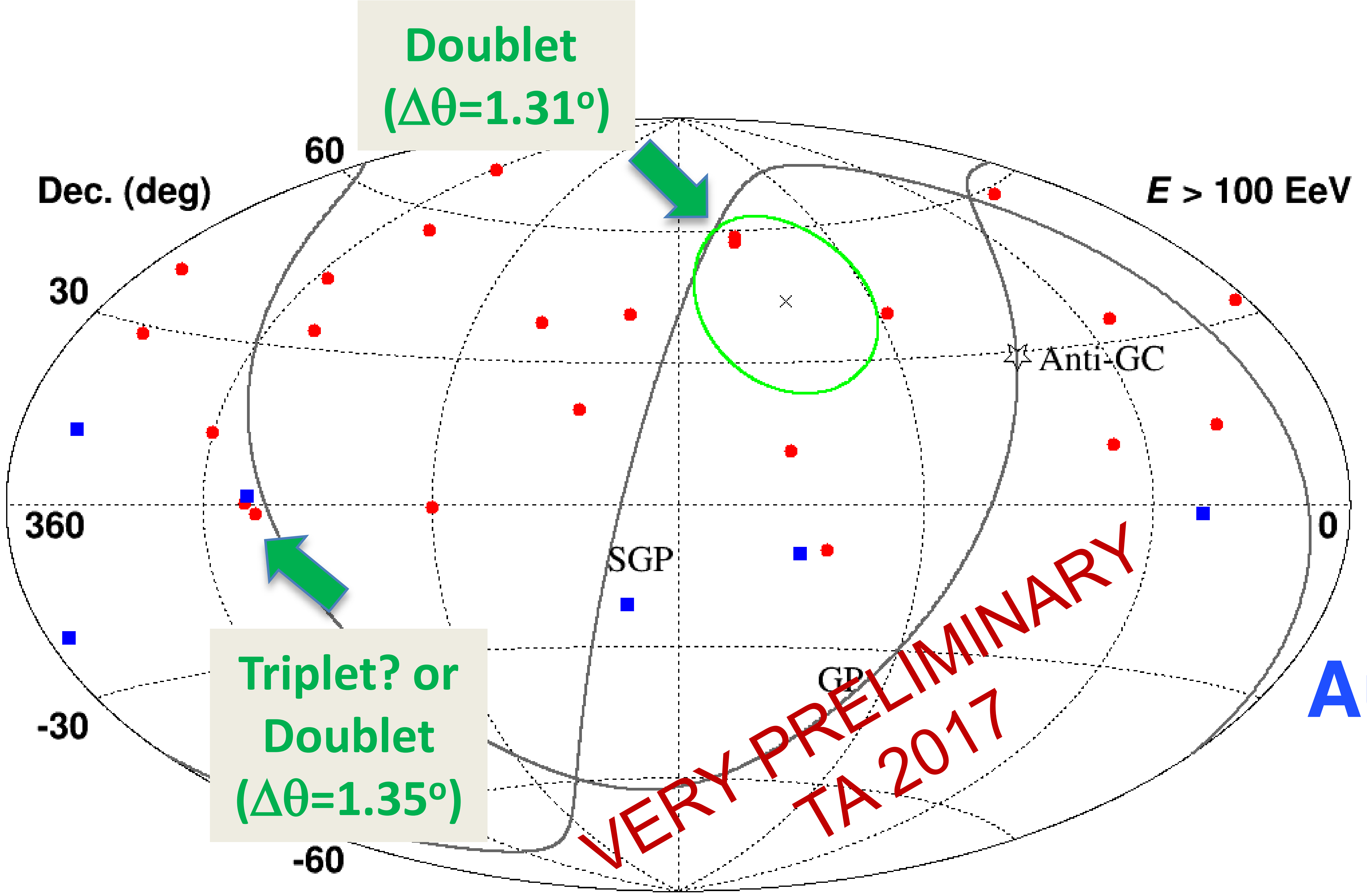
Binsize	15		20		25		30		35	
	Local	Global	Local	Global	Local	Global	Local	Global	Local	Global
Year 5	5.12	3.14	5.43	3.55	5.16	3.19	4.82	2.73	4.33	2.05
Year 7	4.92	2.84	5.37	3.44	5.65	3.80	5.37	3.44	5.03	2.99
Year 9	4.42	2.06	4.72	2.50	5.06	2.96	5.01	2.91	4.66	2.41

J. Matthews in ICRC 2017

2 doublets above 100 EeV

Small-scale anisotropy

Autocorrelations



TA 9 years (23 events)

Auger 6 years (6 events)

2 doublets above 100 EeV.

→ the probability to have ≥2 doublets at $\leq\sqrt{2}$ deg is

P = 0.30% (2.8σ)

S. Troitsky in ICRC 2017

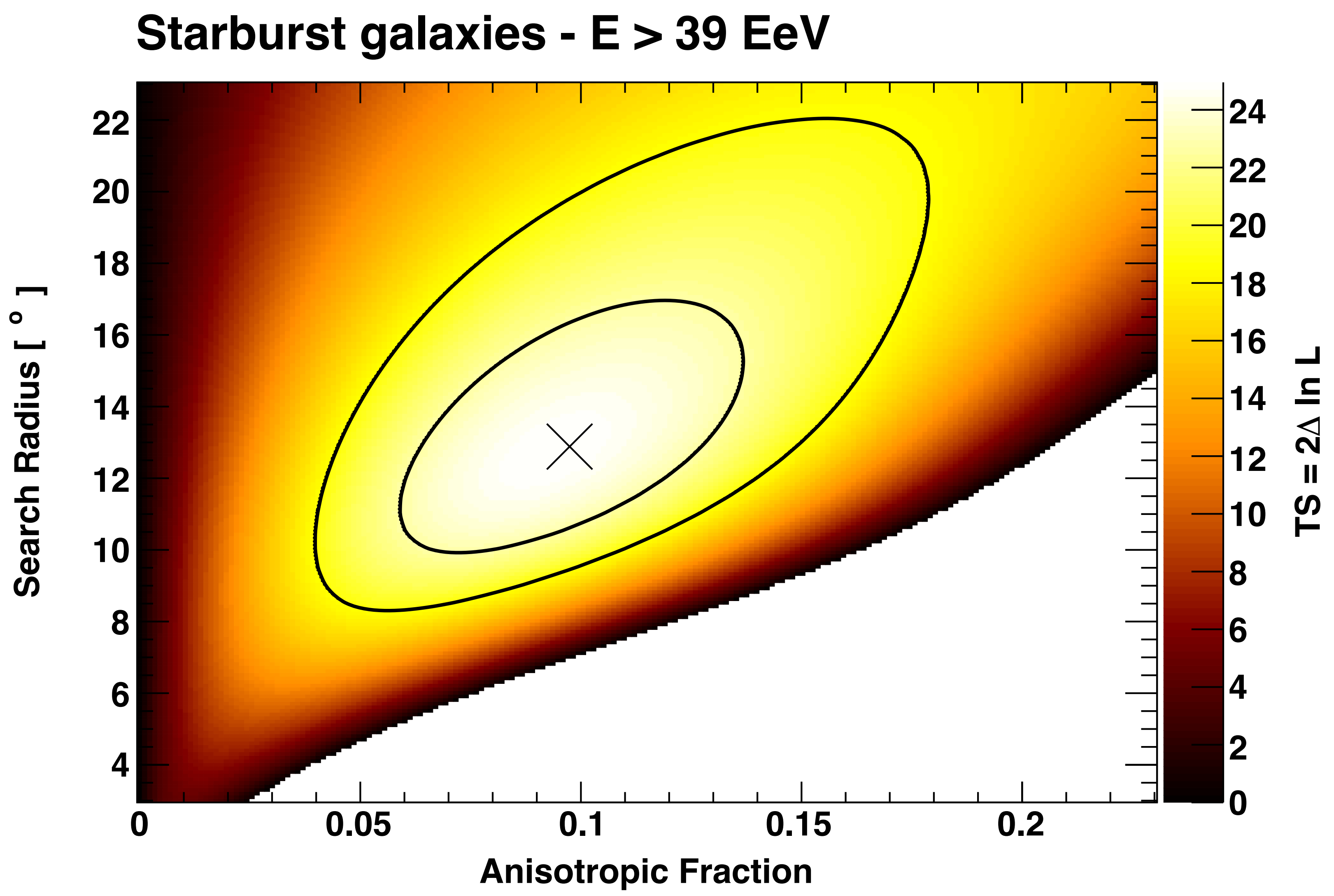
Search for Intermediate-scale UHECR Anisotropies

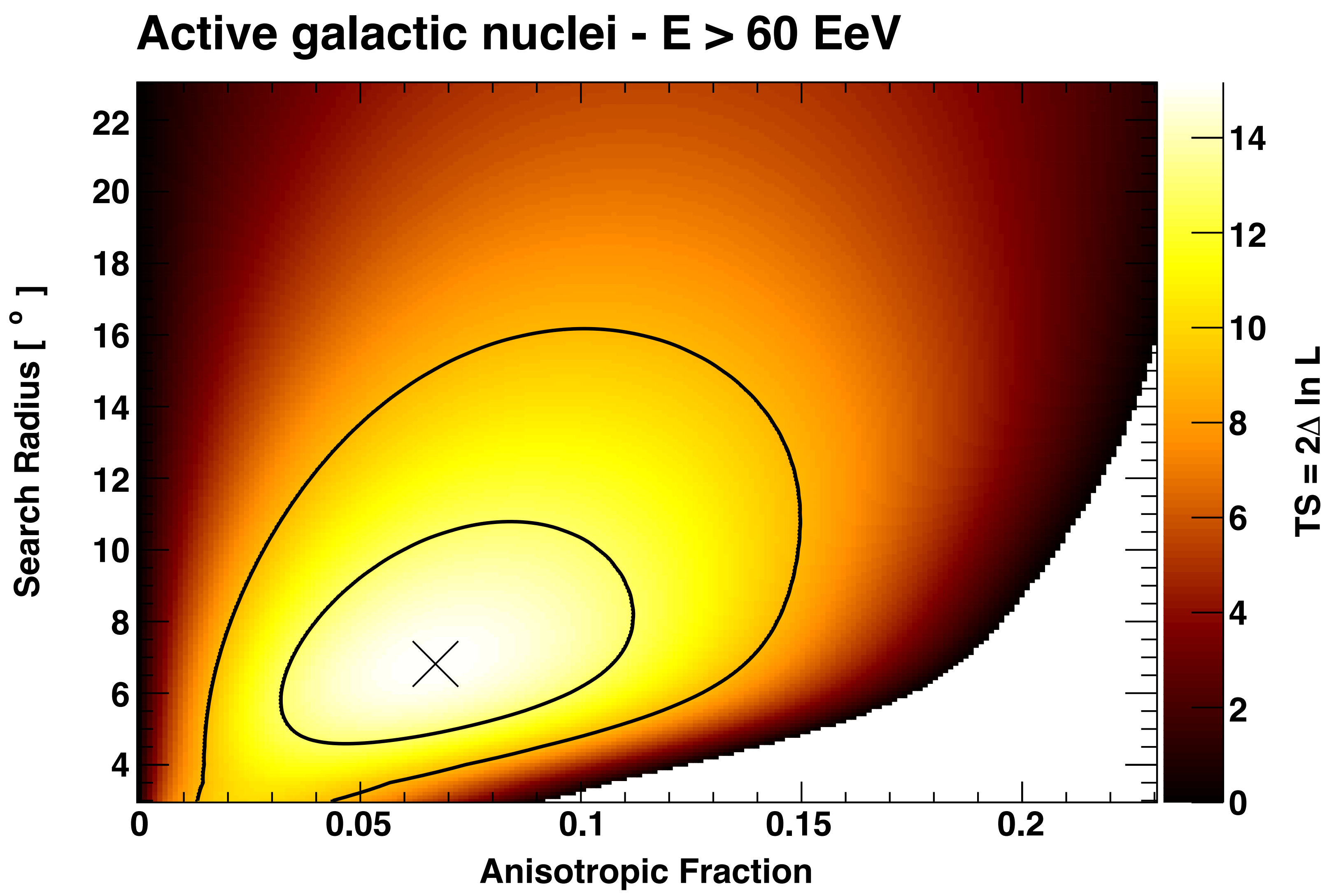
Active Galactic Nuclei

- 2FHL AGNs
- flux proxy: $\Phi(>50\,\mathrm{GeV})$
- 17 objects within 250 Mpc

Star-forming of Starburst Galaxies

- Fermi-LAT search list (Ackermann+~~2016~~) 2012
- $\Phi(>\cancel{1.54},\mathrm{GHz})>0.3$ Jy 1.4 GHz
- flux proxy: $\Phi(>\cancel{1.54},\mathrm{GHz})$
- 23 objects within 250 Mpc



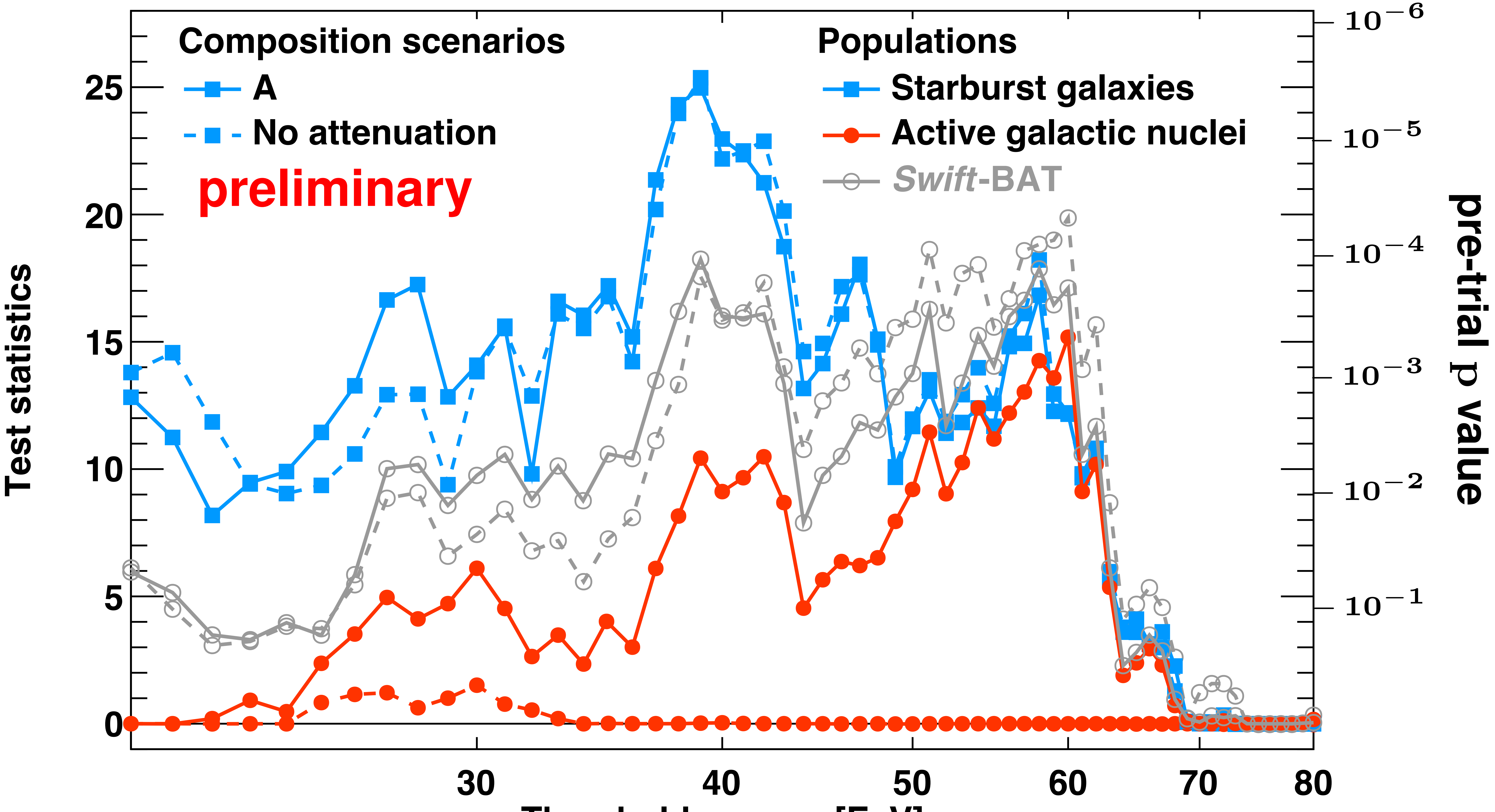


Likelihood ratio analysis

- smearing angle ψ
- H_0: isotropy
- H_1: $(1-f)\times$ isotropy + $f\times$ fluxMap(ψ)
- $\mathrm{TS}=2\log(H_1/H_0)$

M. Unger in ICRC 2017

Search for Intermediate-scale UHECR Anisotropies



5514 events above 20 EeV
820 events above 40 EeV

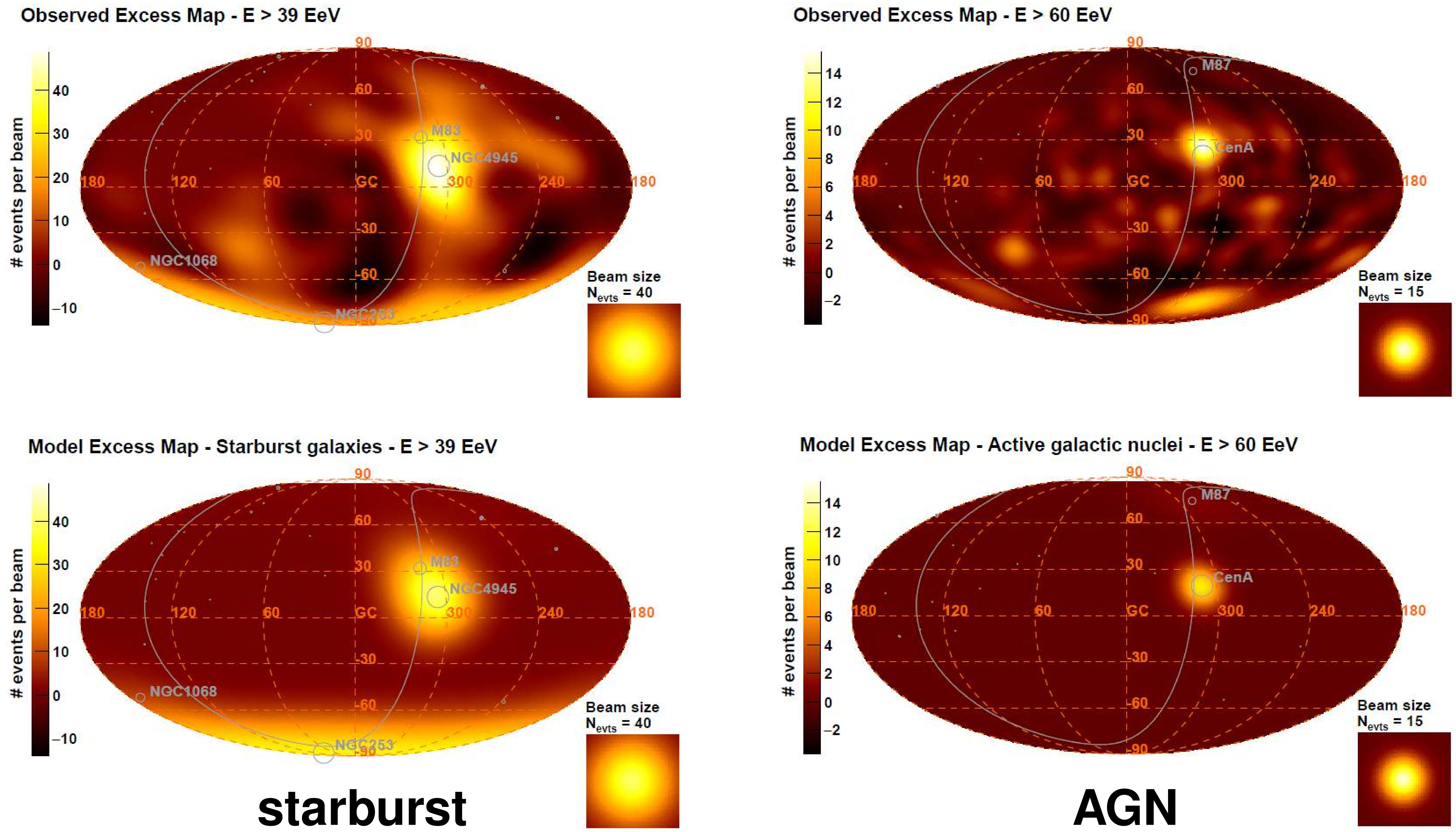
starburst	**AGN**
$f = 10\%,\ \psi = 13^\circ$	$f = 7\%,\ \psi = 7^\circ$
pre-trial* p-value: 4×10^{-6}	pre-trial* p-value: 5×10^{-4}
post-trial** p-value: 4×10^{-5}	post-trial** p-value: 3×10^{-3}
post-trial** significance: $3.9\,\sigma$	post-trial** significance: $2.7\,\sigma$

*incl. f and ψ fit **penalization for energy scan only. $N_{\mathrm{cat}} = 3$, previous searches and hidden trials not accounted for. [21 of 30]

Search for Intermediate-scale UHECR Anisotropies

Galactic coordinate

preliminary

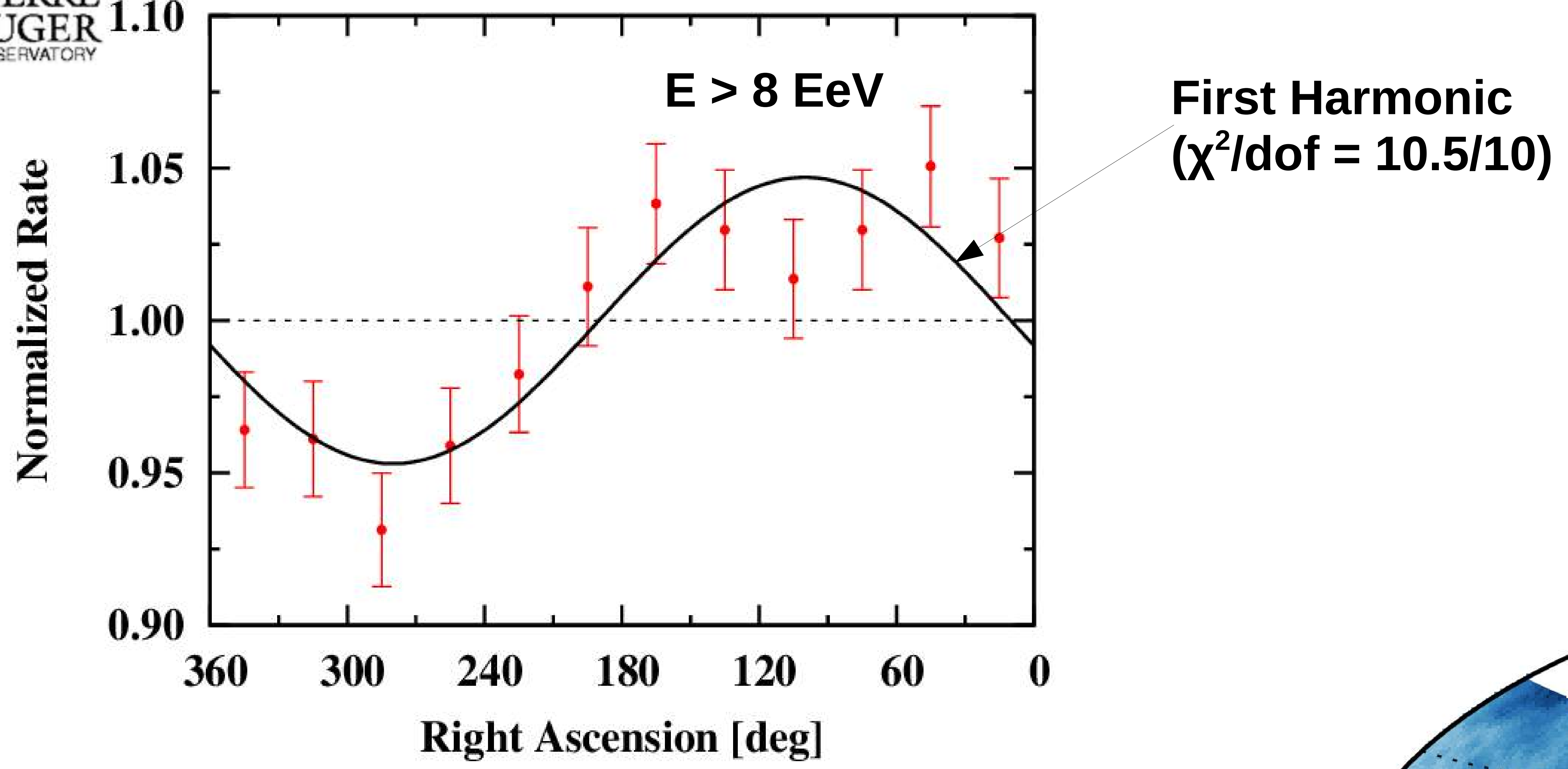


$f = 10\%,\ \psi = 13°$
pre-trial* p-value: 4×10^{-6}
post-trial** p-value: 4×10^{-5}
post-trial** significance: $3.9\,\sigma$

$f = 7\%,\ \psi = 7°$
pre-trial* p-value: 5×10^{-4}
post-trial** p-value: 3×10^{-3}
post-trial** significance: $2.7\,\sigma$

* incl. f and ψ fit ** penalization for energy scan only. $N_{\rm cat} = 3$, previous searches and hidden trials not accounted for.

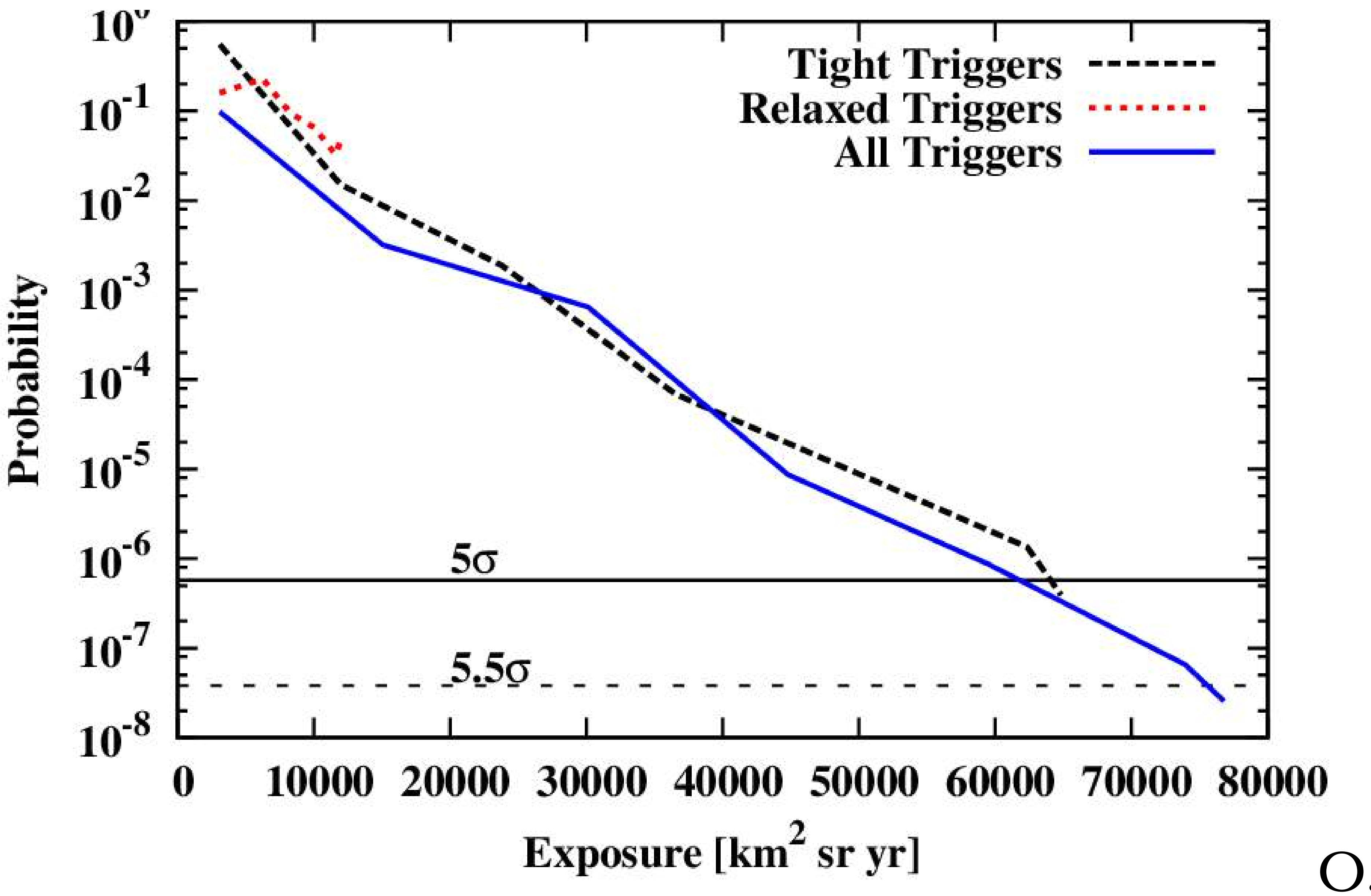
Observation of dipole above 8 EeV

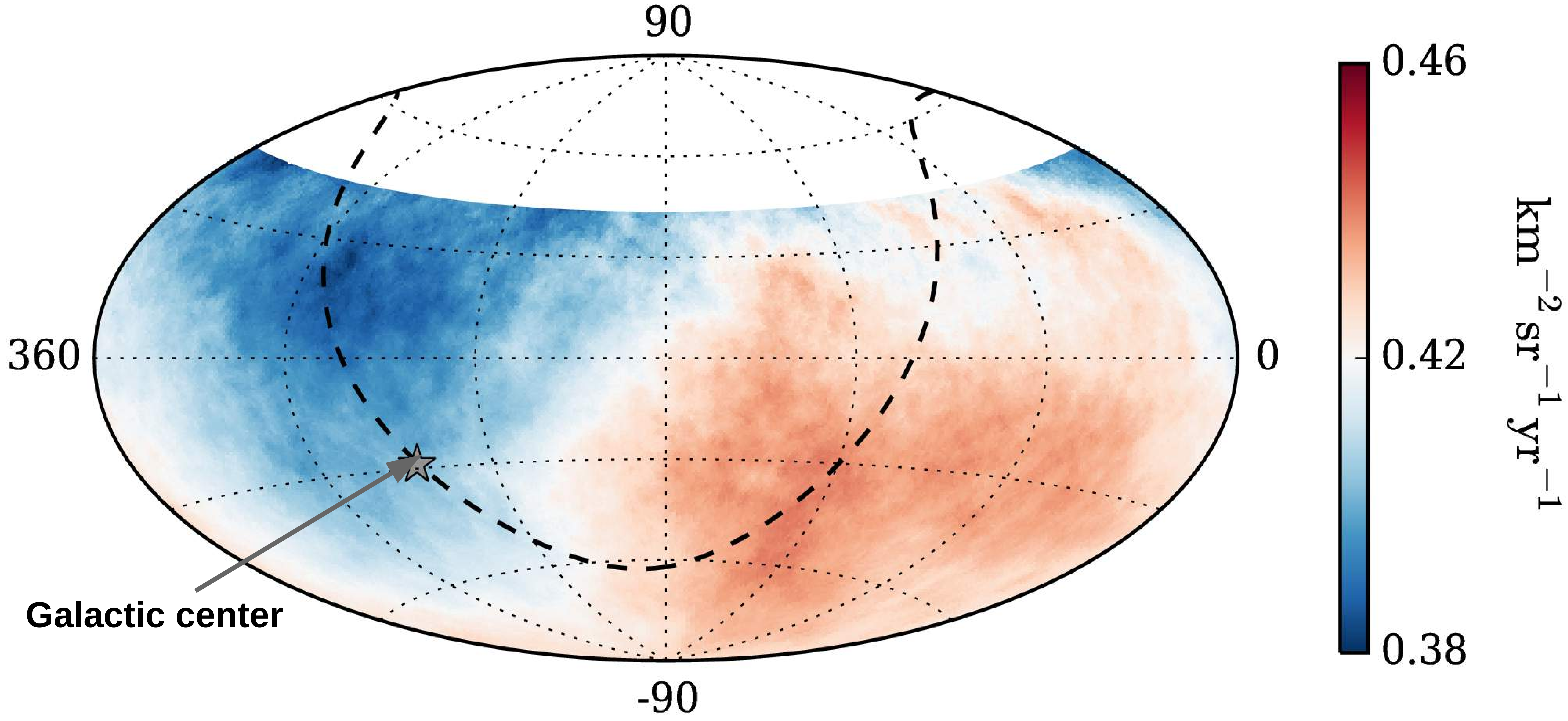


Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)



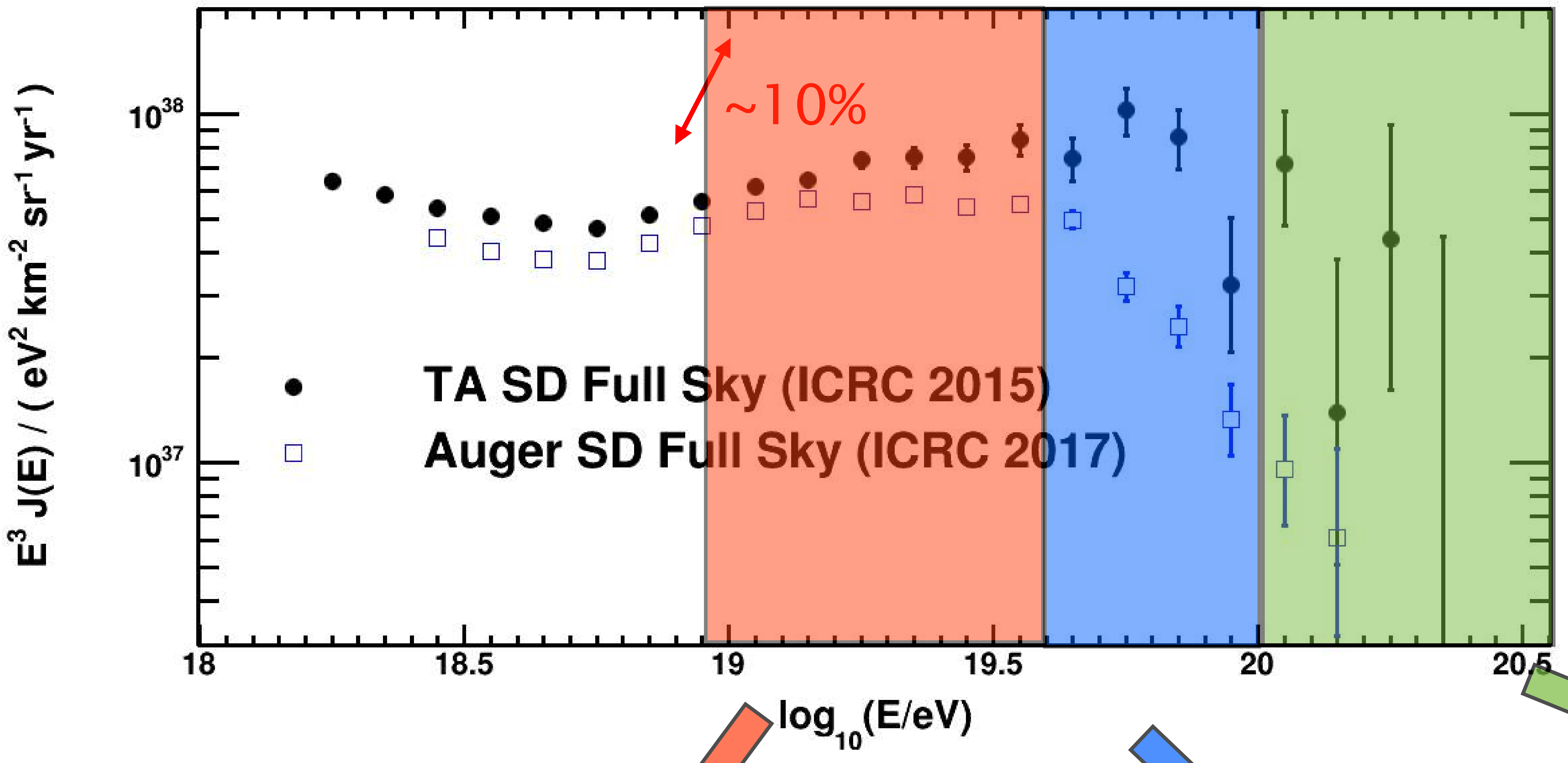


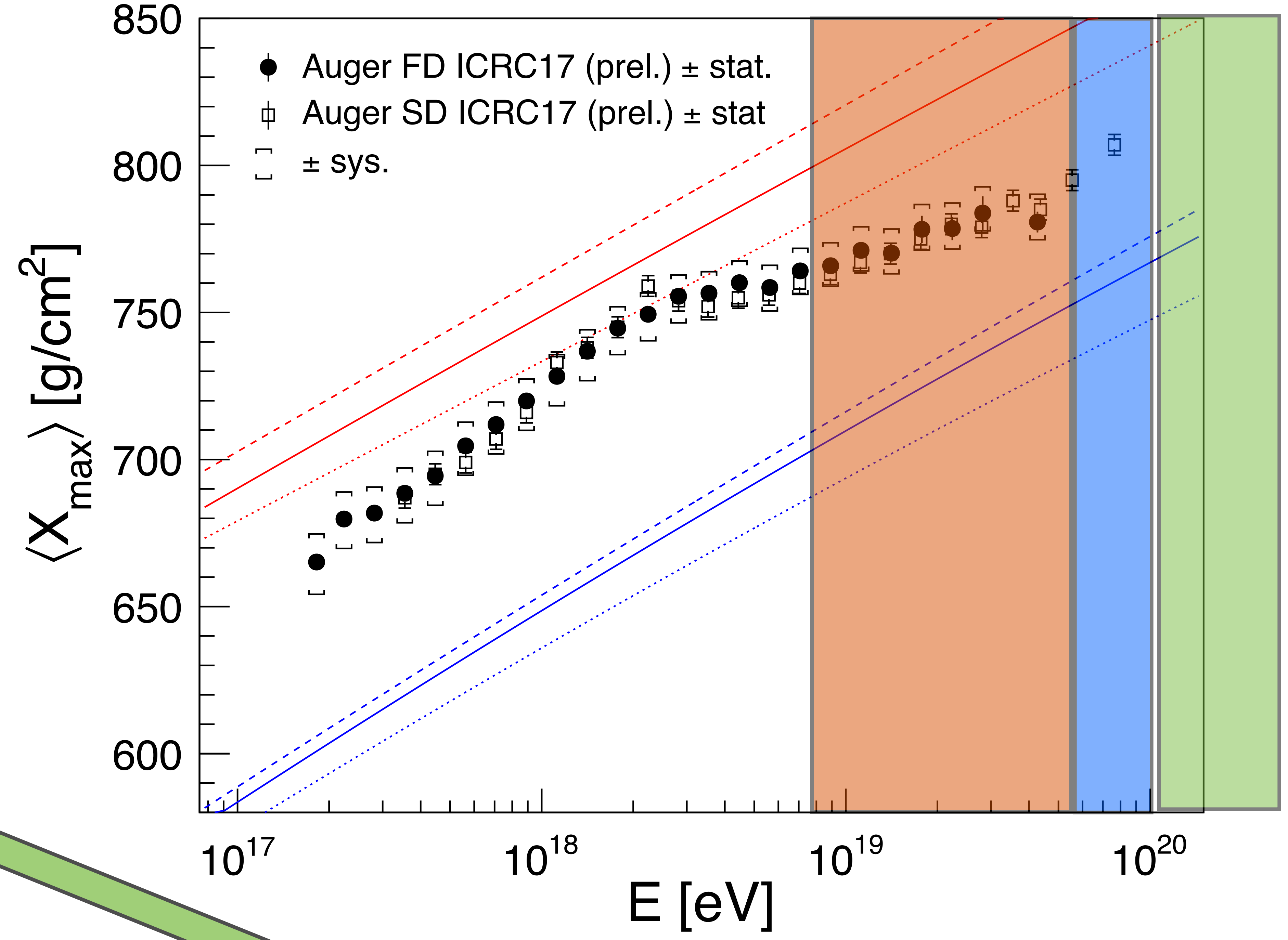
Indicative of an extragalactic origin.

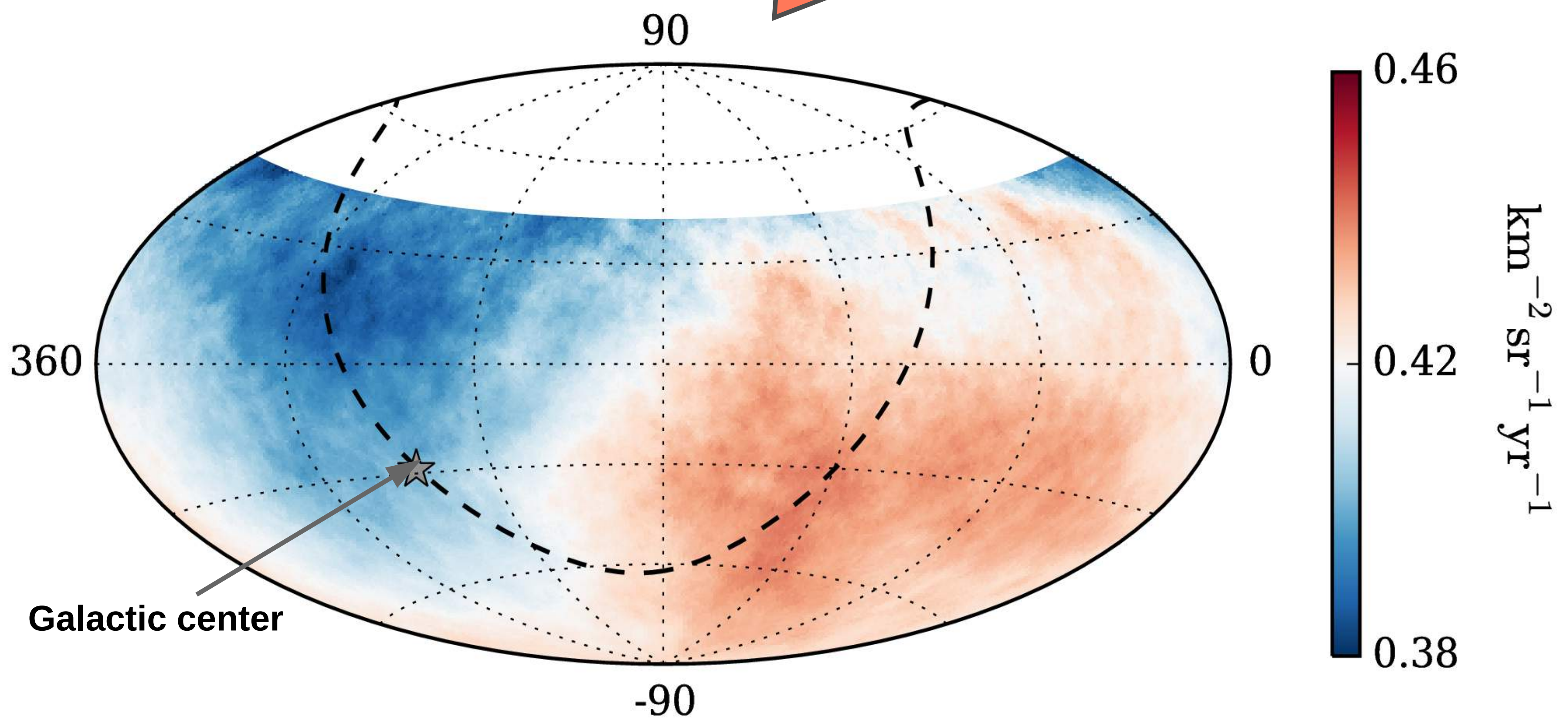
O. Taborda, M. Unger in ICRC 2017

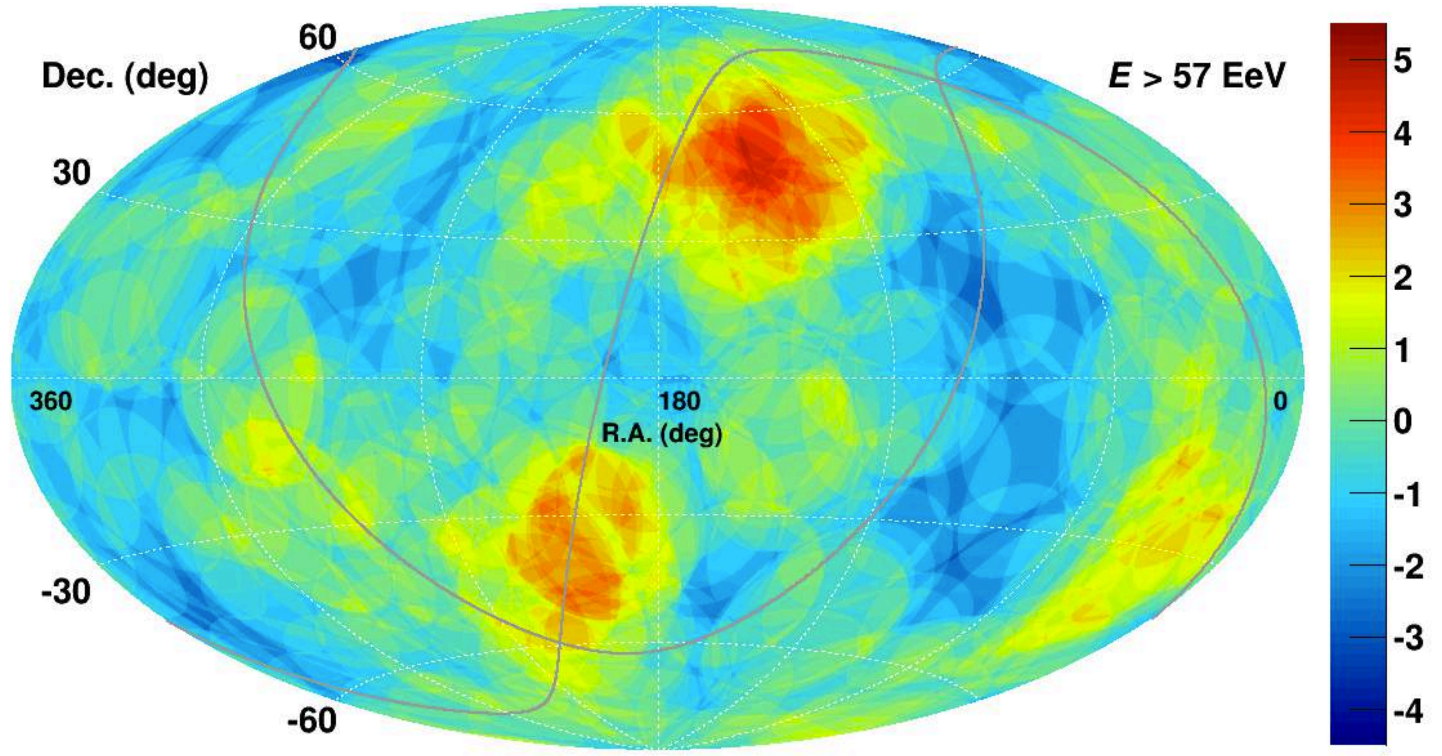
UHECR Astronomy?

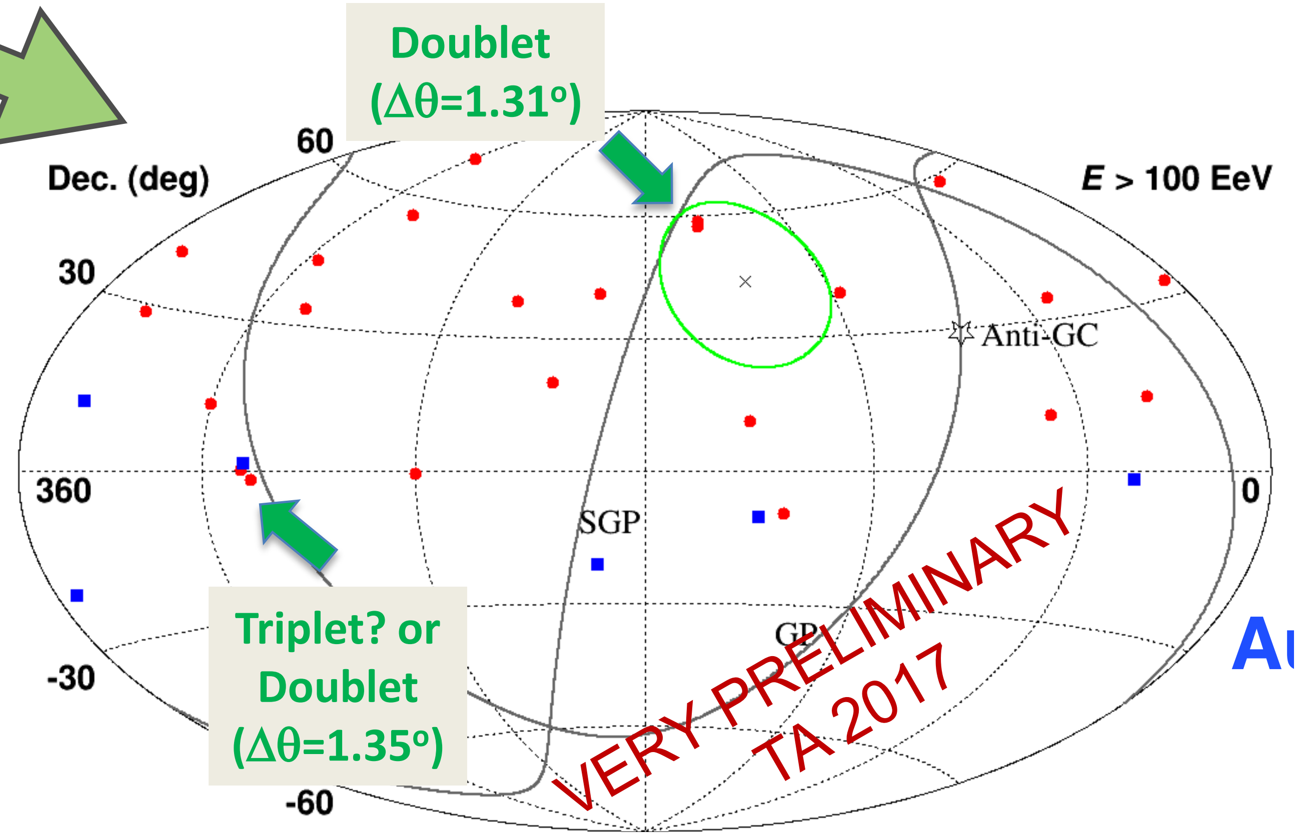
Isotropic (E < 8 EeV)





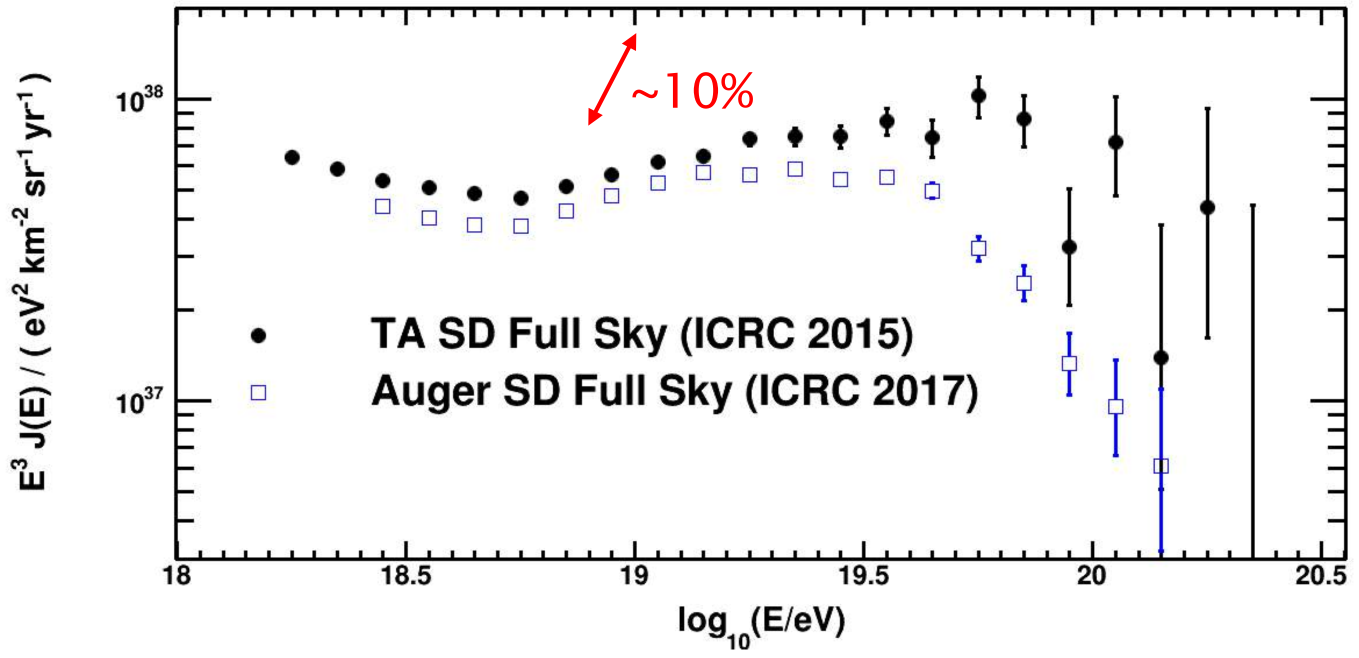


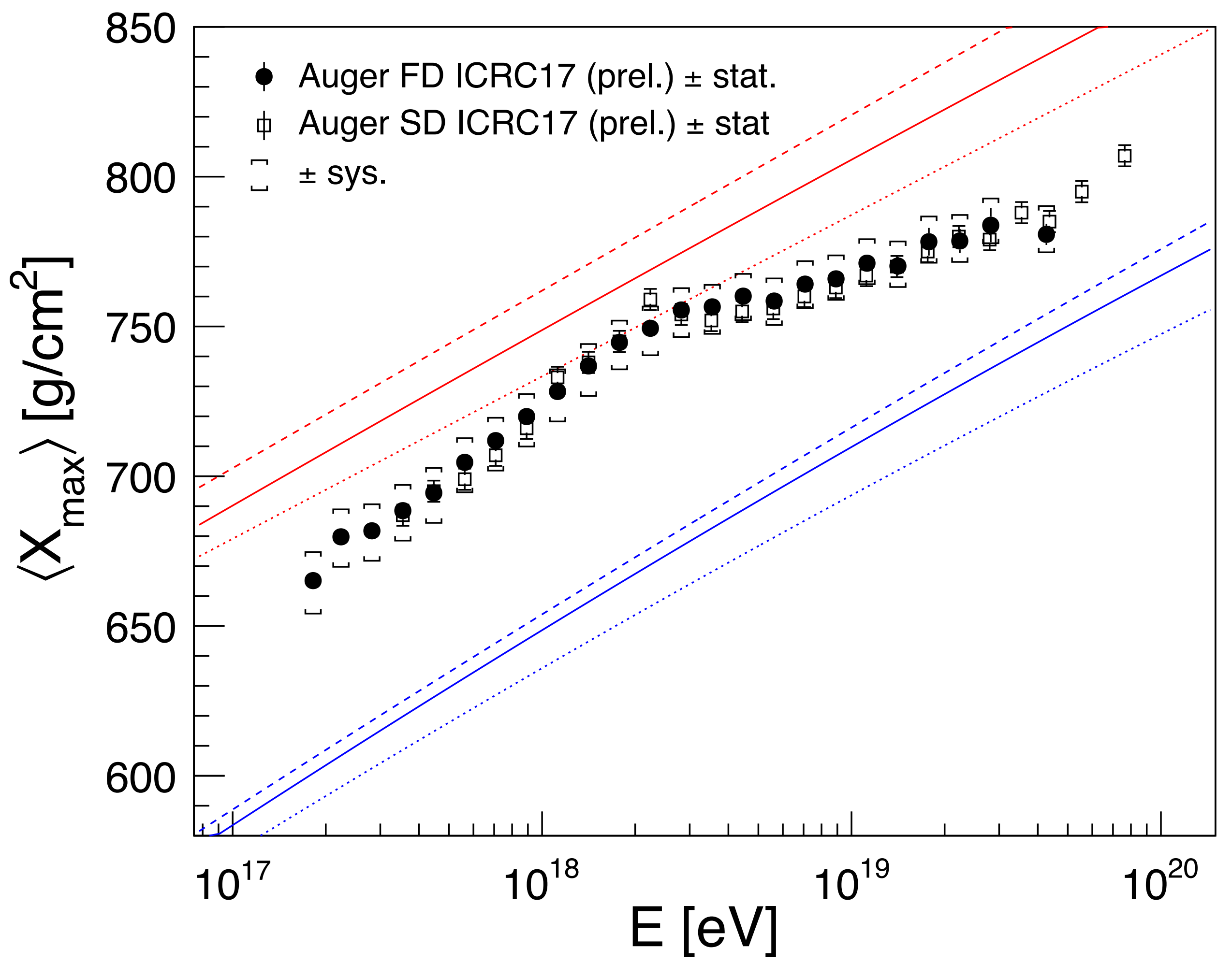




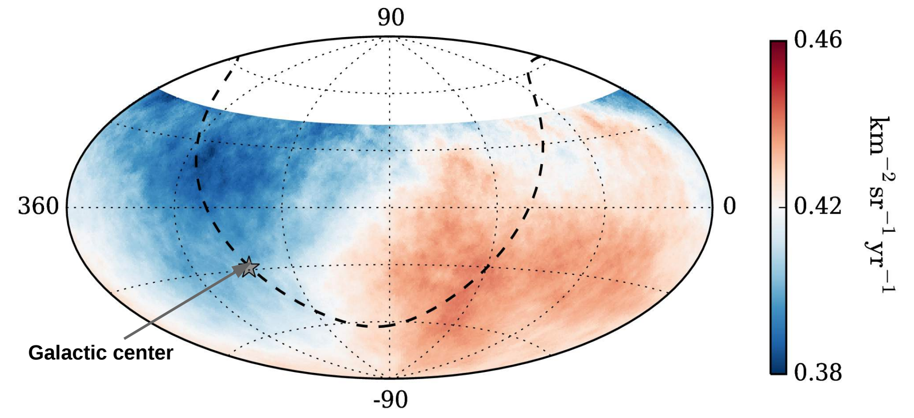
Physics Goal of UHECR Astrophysics

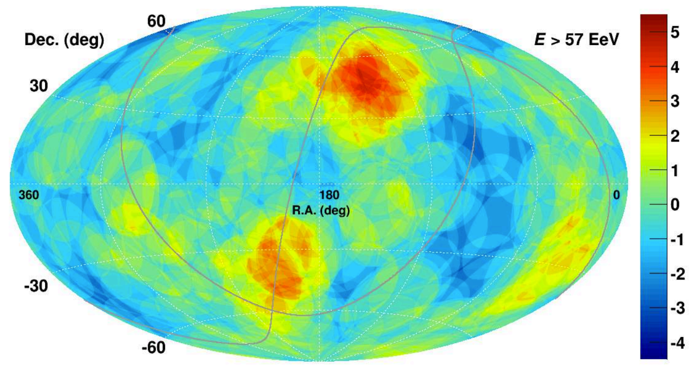
- **Origin and Nature of Ultra-High Energy Cosmic Rays (UHECRs) and Particle Interactions at the Highest Energies**





- How frequent?: Energy spectrum
- What kind of particle?: Mass composition
- Where come from?: Arrival direction





Recent Results and New Puzzle

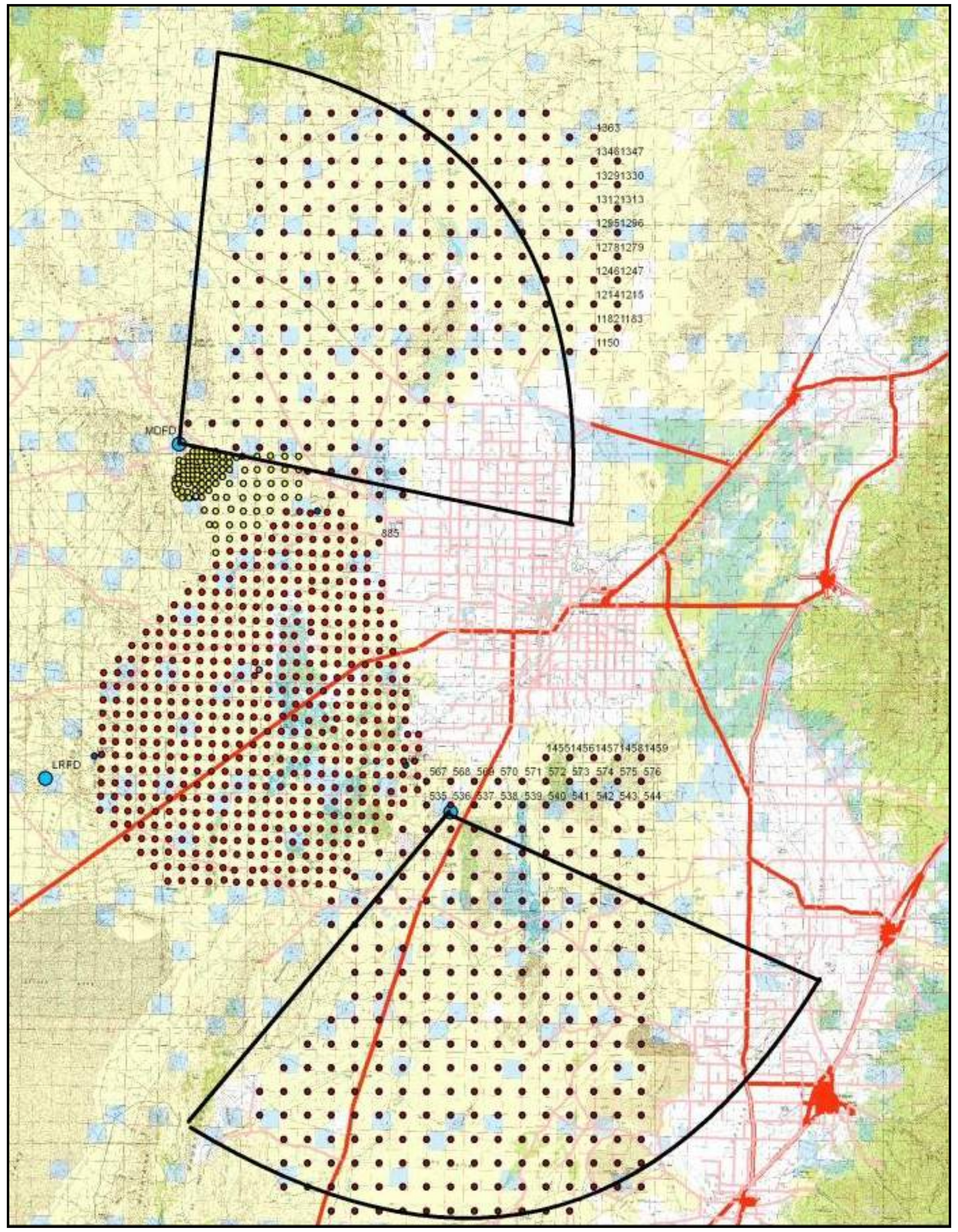
- Precise observation of the flux suppression above $10^{19.5}$ eV, discrepancy on suppression energy in TA/Auger.
- Gradually increase heavier composition above the ankle.
  - lighter composition above $10^{19.7}$ eV?
- Hot/warmspots, correlation with nearby star burst galaxy.

- **Flux suppression due to GZK process or maximum energy of accelerator?**
- **Heavier composition or problem of hadron interaction model? proton fraction, mass composition above $10^{19.7}$ eV?**
- **Anisotropy as indication of additional light component?**
- **Particle physics extrapolation at the highest energies?**

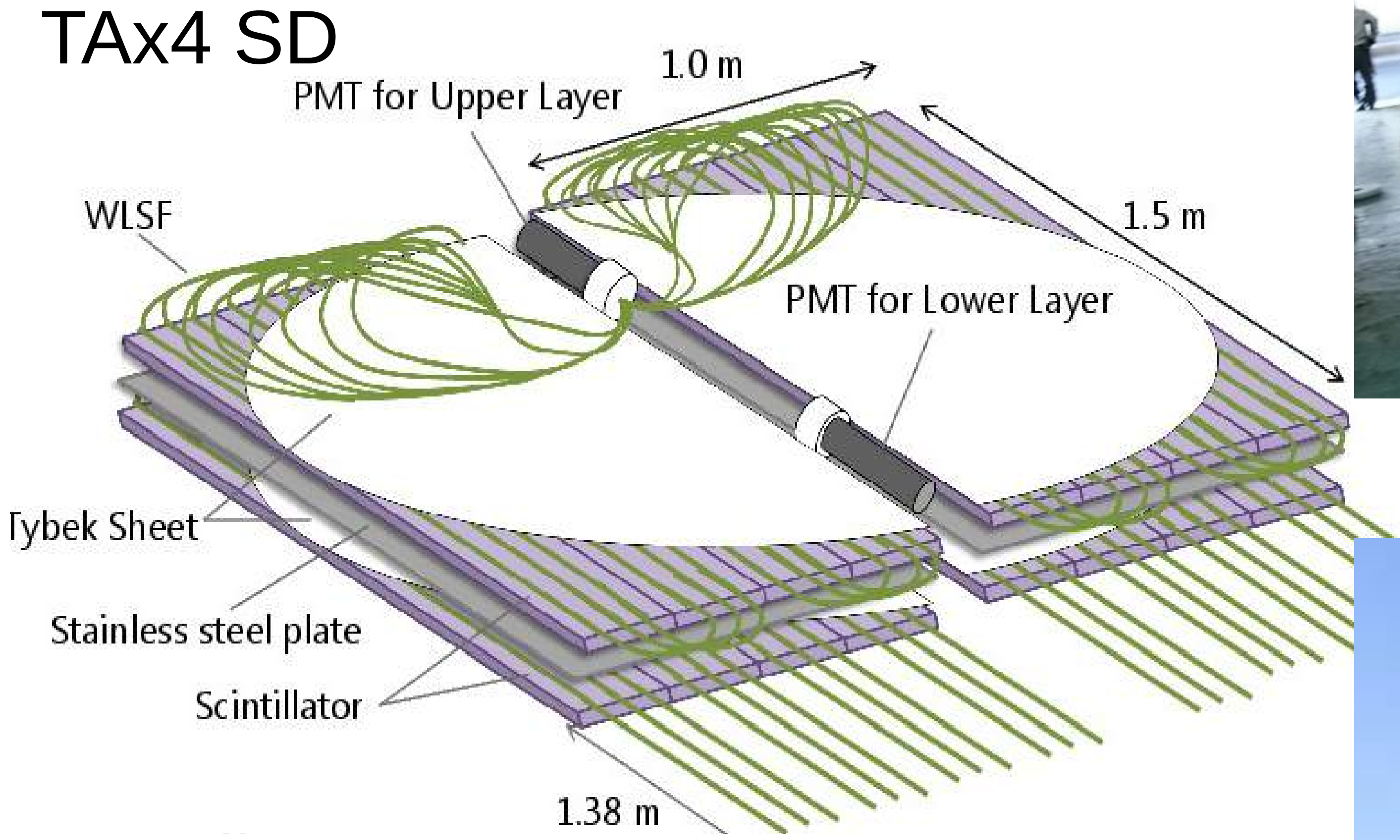
On-going upgrade: TA×4

Detailed measurement on Hotspot

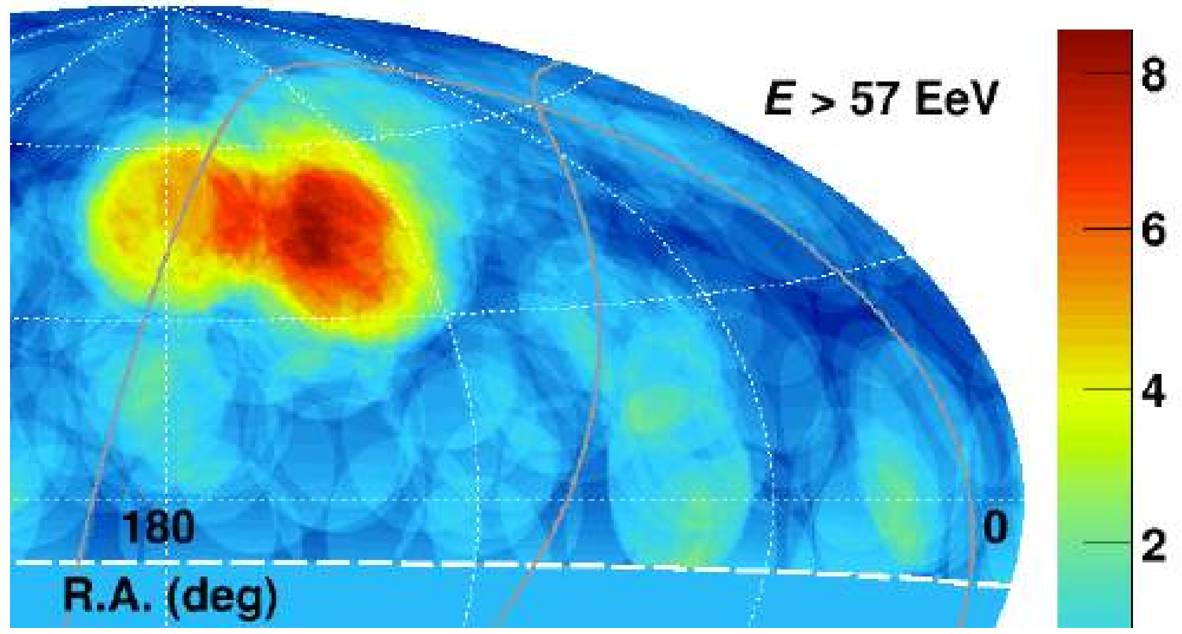
Enlarge the fourfold coverage to TA×4 = Auger, **3000 km²**



E. Kido in ICRC 2017

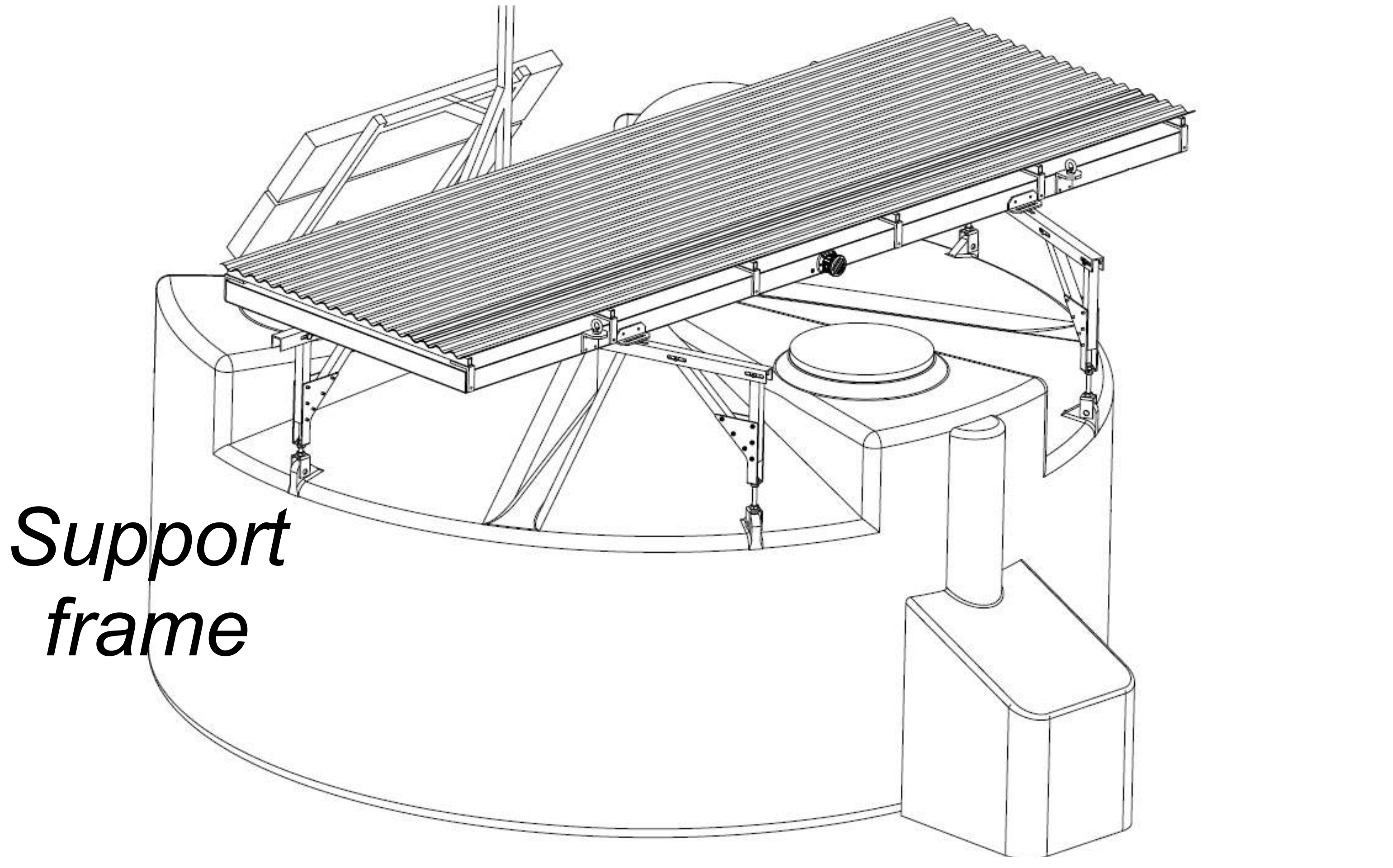


Expected in 2020 (Simulation)

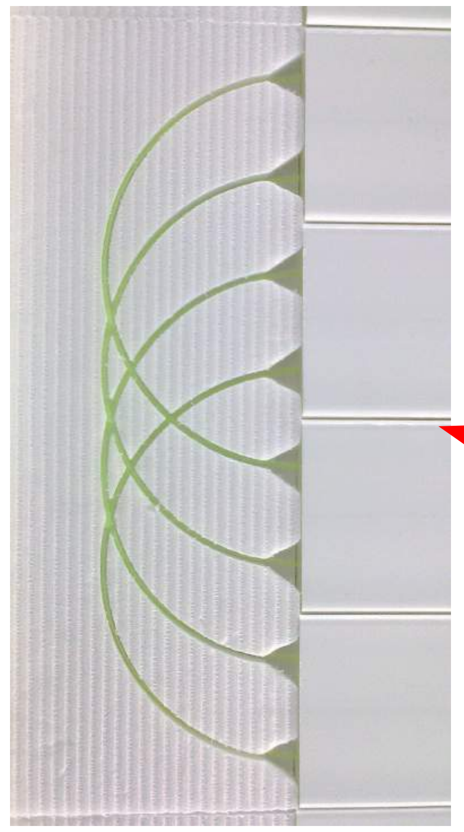


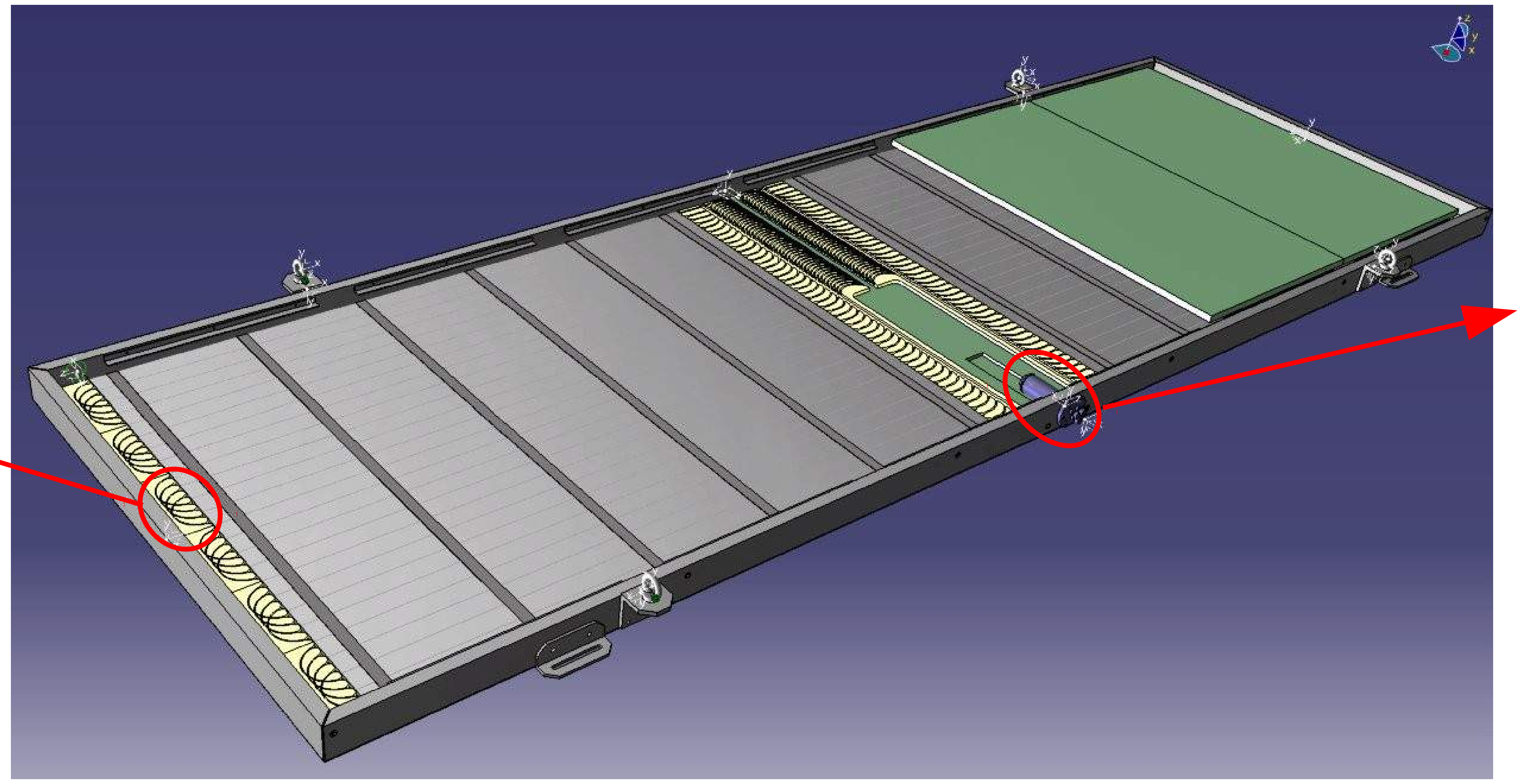
On-going upgrade: AugerPrime

Install 4 m^2 Scintillator to measure the mass composition by SD.

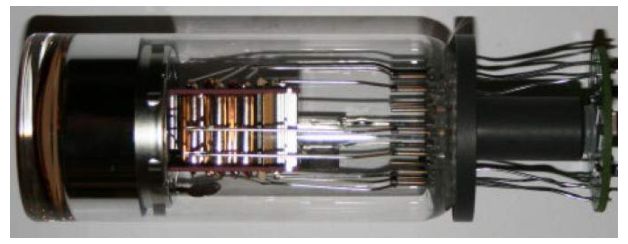


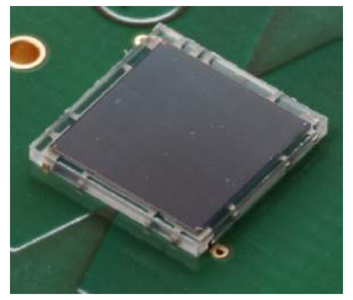
Fibers routing

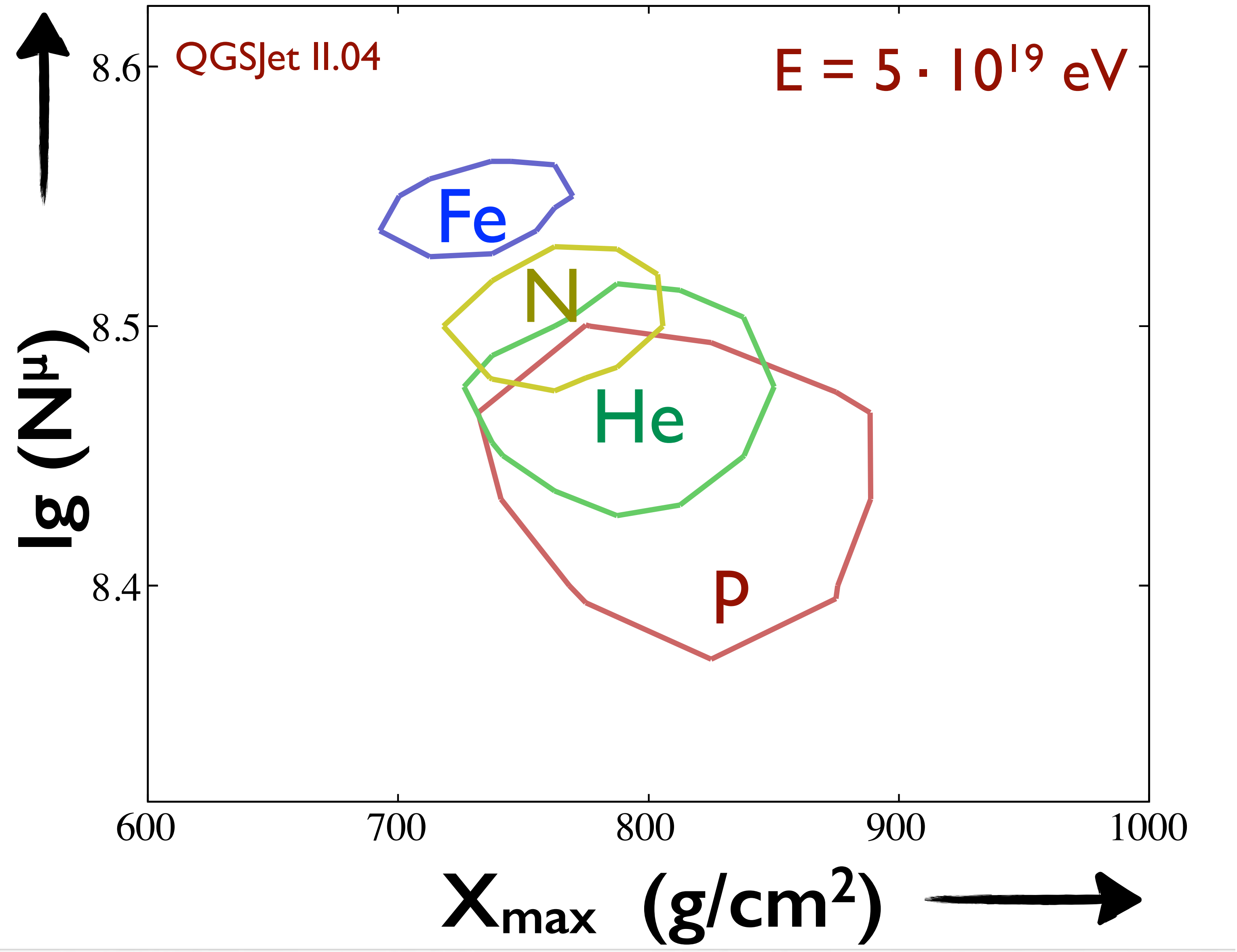




PMT/SiPM







M. Unger R. Smida in ICRC2017

- Improve electromagnetic/muon separation of **SD** to measure the **mass composition above $10^{19.7}$ eV.**
  - Boost in statistics by a factor of ~ 10 compared to FD *X*max analysis.
- Small PMT in the water tank, FD operation during moon night.
- **Origin of flux suppression, proton contribution above $10^{19.7}$ eV, new particle physics beyond the human-made accelerator.**

The EUSO program

1. **EUSO-TA:** ***Ground detector installed in 2013 at Telescope Array site: currently operational***

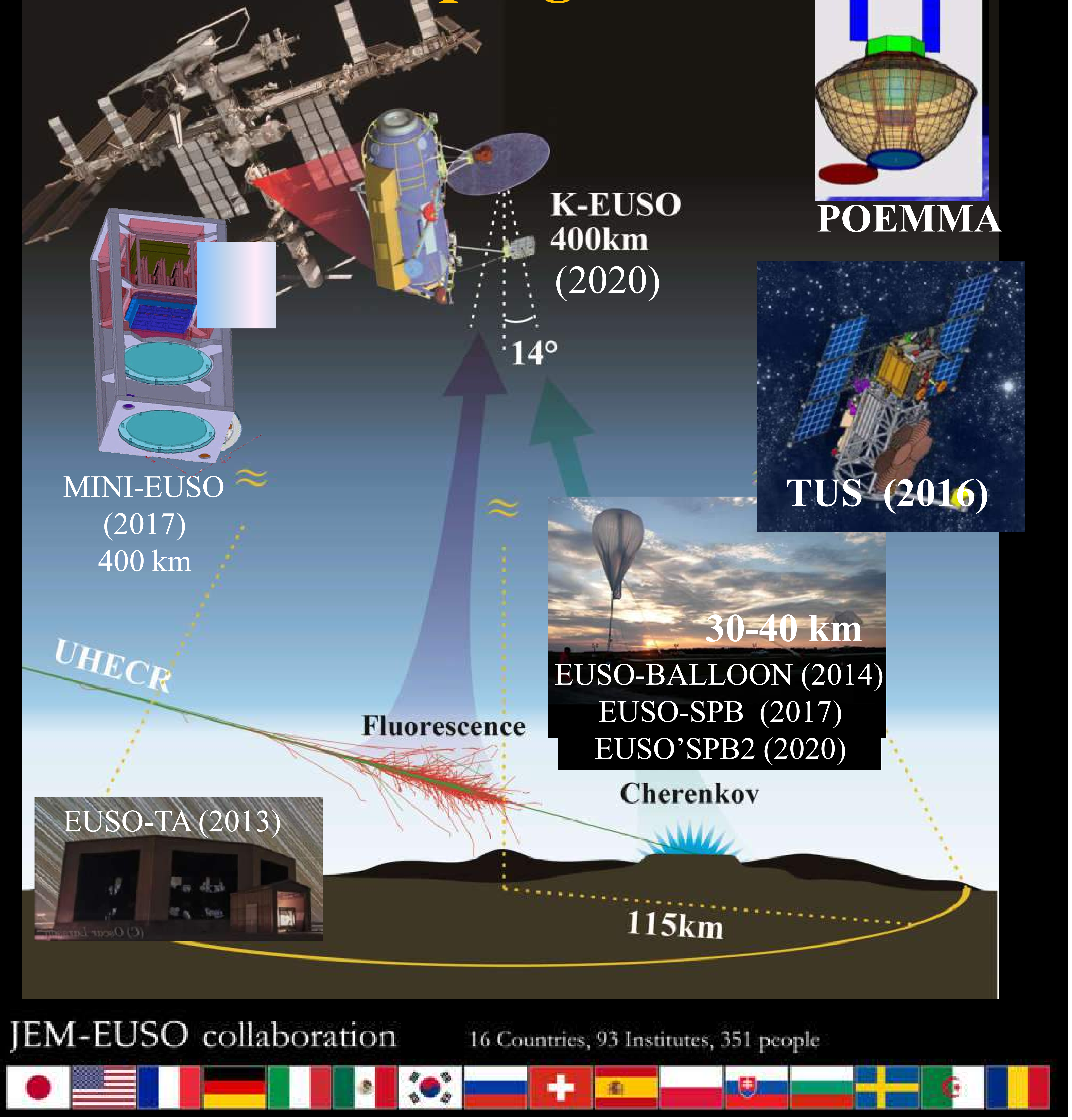
2. **EUSO-BALLOONS:** ***1st balloon flight from Timmins, CA (French Space Agency) Aug 2014; NASA Ultra long duration flight: SPB 2017; NASA SPB-2 2020***

3. **TUS (2016):** free-flyer [307][CRI128]

4. **MINI-EUSO (2017):** ***Detector from International Space Station (ISS: 30kg 2017). Approved by Italian and Russian Space agencies***

5. **K-EUSO (2022):** ***ISS Approved by Russian Space Agency***

6. **POEMMA (2025+):** ***NASA twin free-Flyer***



Physics goal and future perspectives

Origin and Nature of Ultra-high 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 and sizable increase of exposure

Detector R&D
Radio, SiPM,
Low-cost Fluorescence Detector (FD)

“Precision” measurements
AugerPrime
Low energy enhancement
(Auger infill+HEAT+AMIGA, TALE+TA-muon+NICHE)

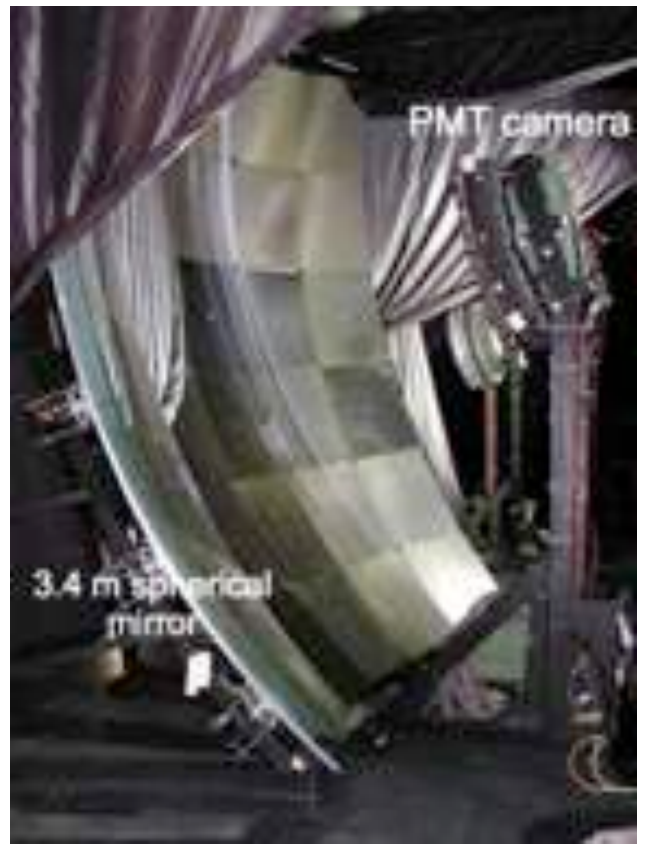
10 - 20 years

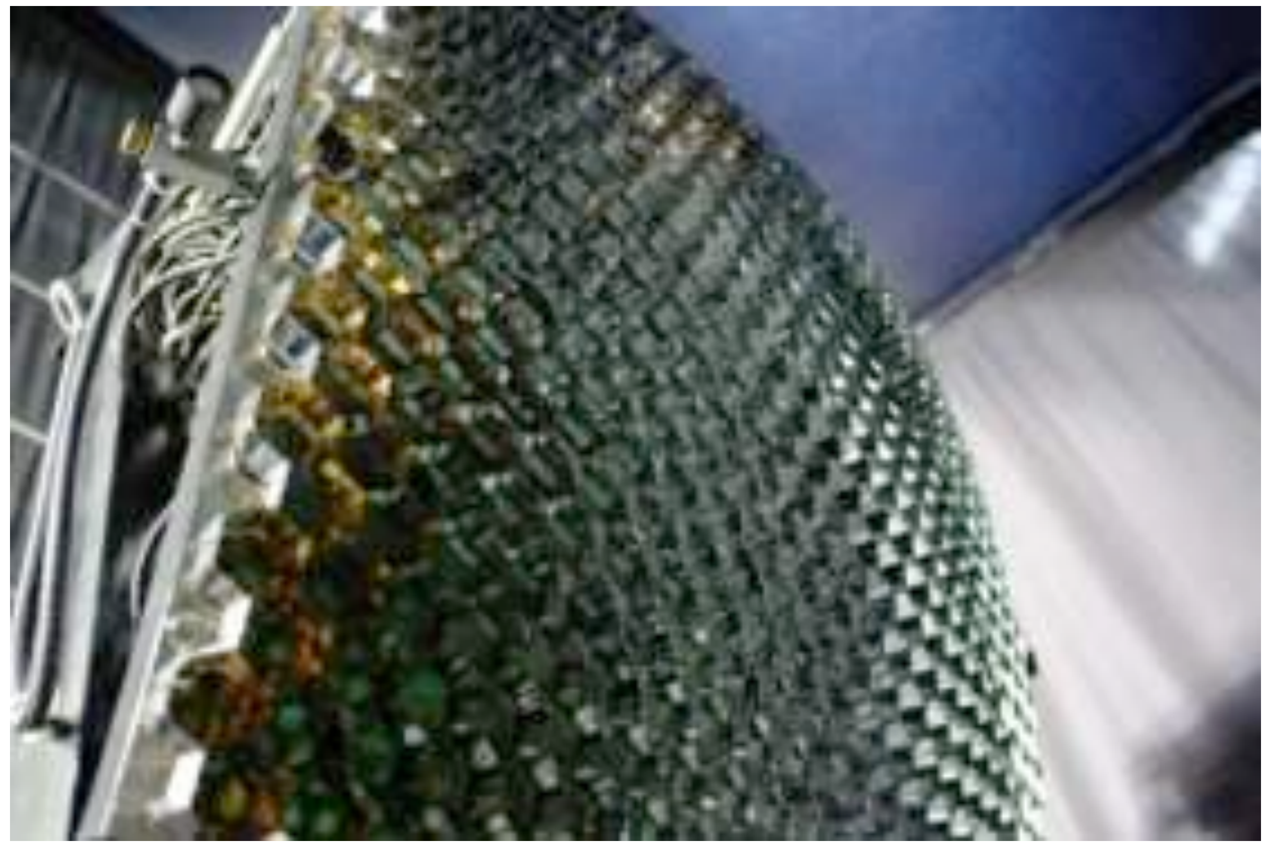
Next-generation observatories
In space (100×exposure): POEMMA, Super-EUSO
Ground (10×exposure with high quality events): FAST
Fluorescence detector Array of Single-pixel Telescopes

Fluorescence detector Array of Single-pixel Telescopes

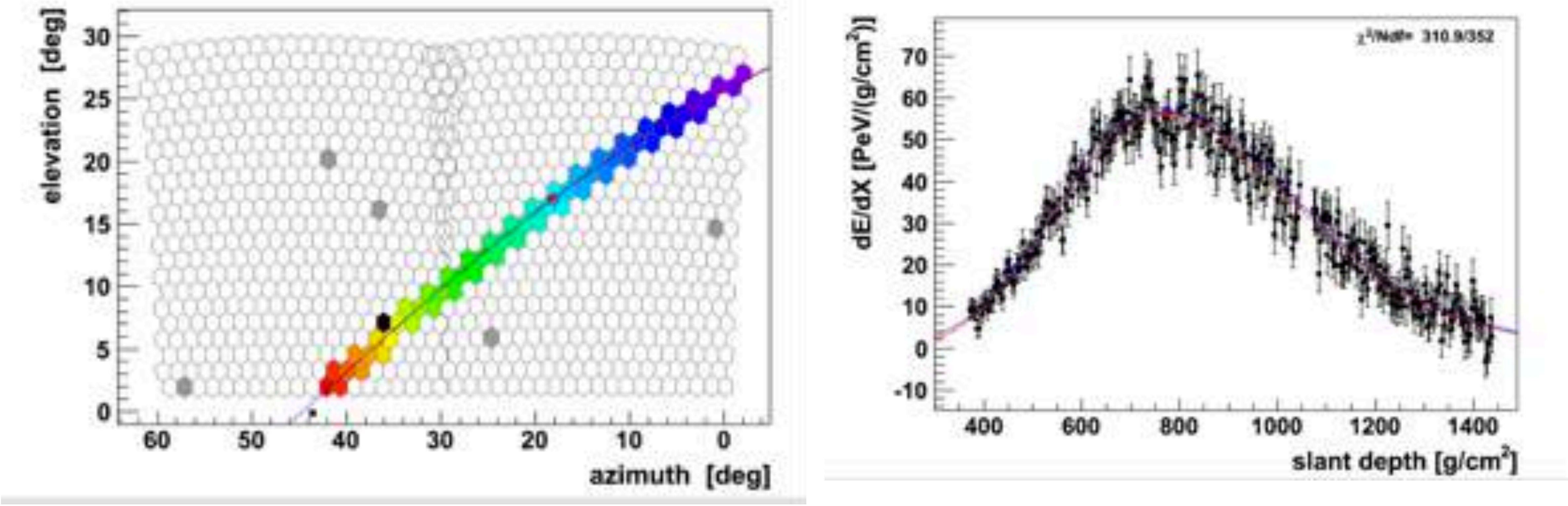
- Target : > $10^{19.5}$ eV, ultra-high energy cosmic rays (UHECR) and neutral particles
- Huge target volume ⇒ Fluorescence detector array

Fine pixelated camera

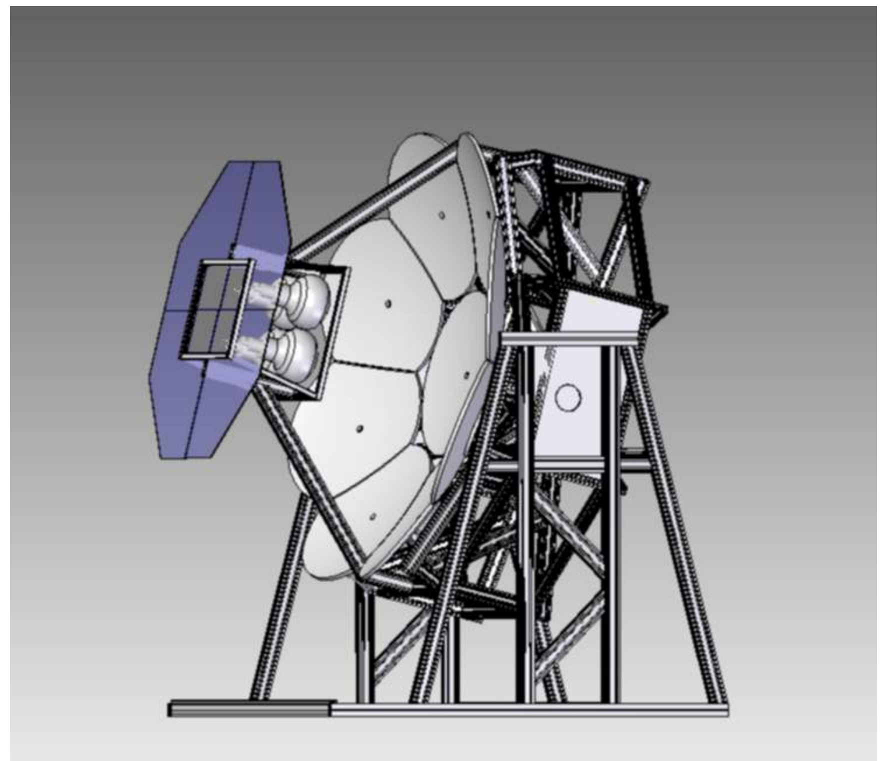




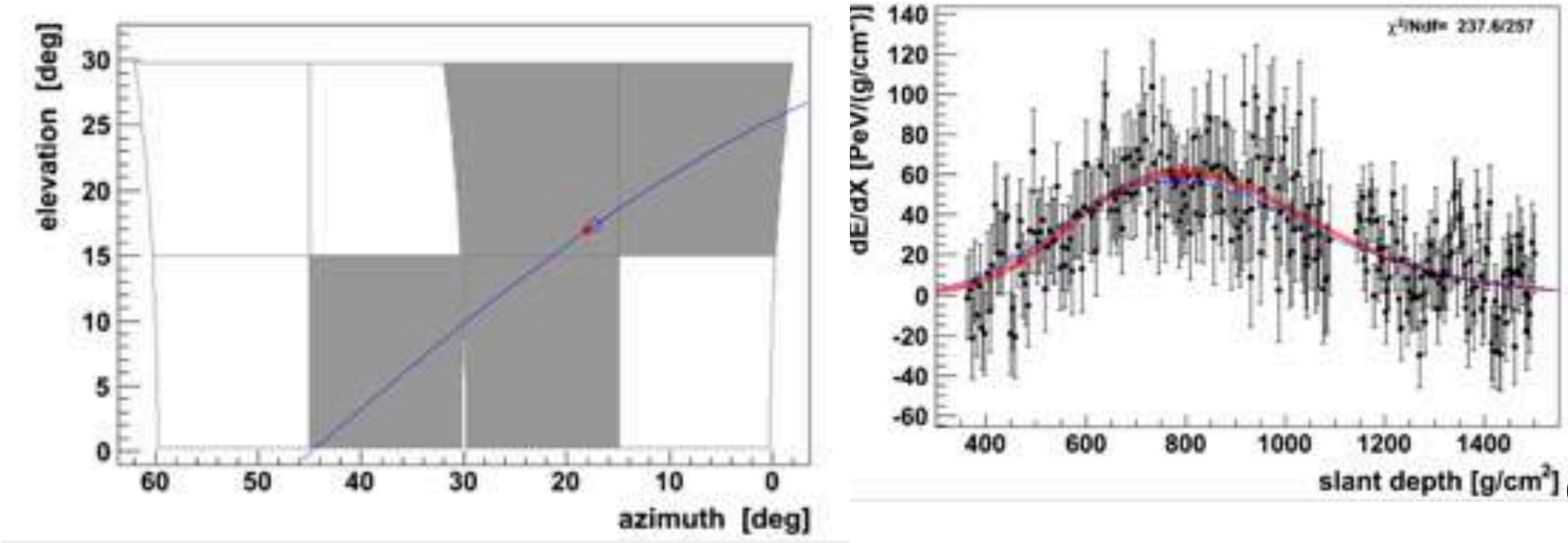
Too expensive to cover a huge area



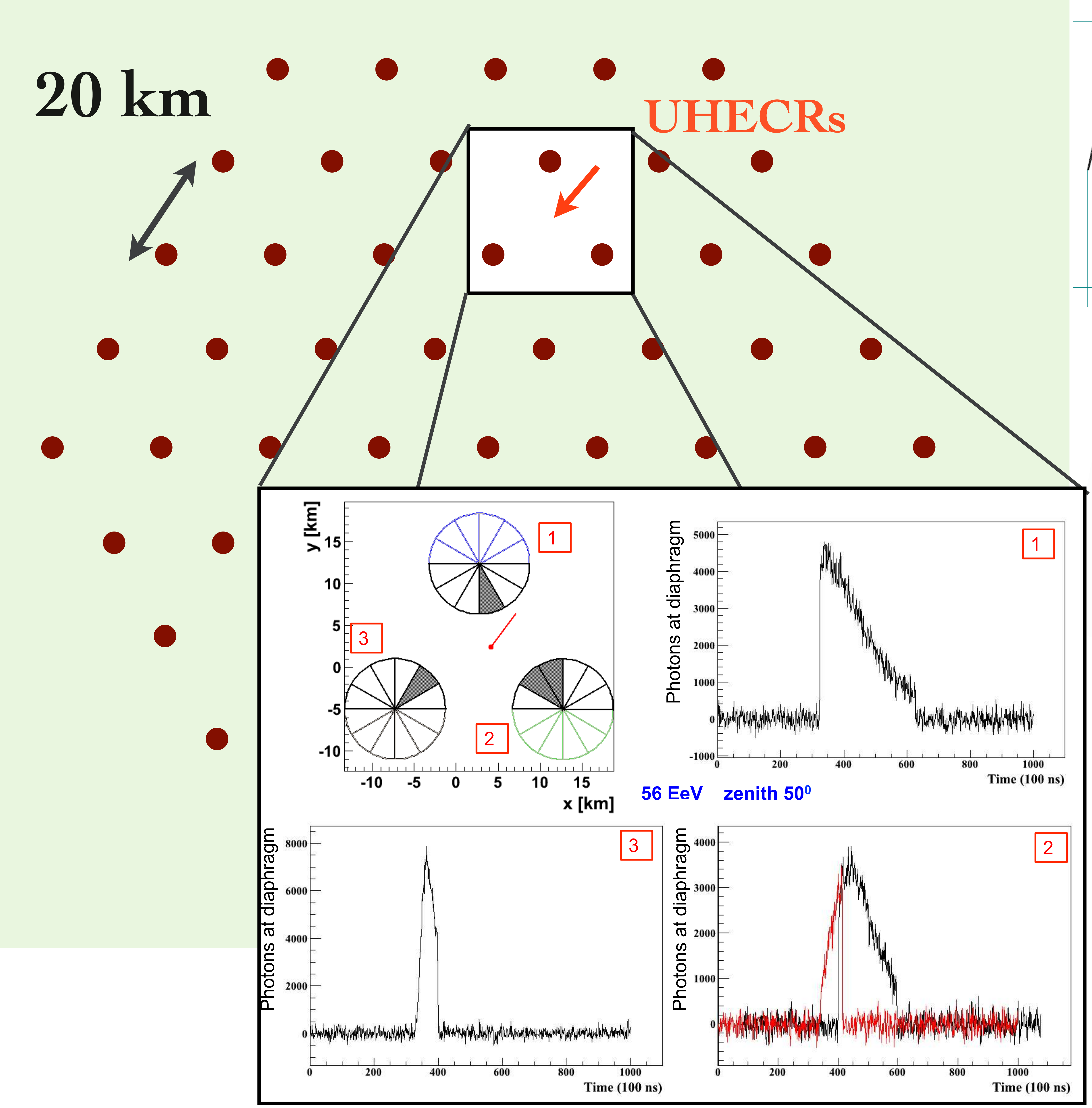
Single or few pixels and smaller optics

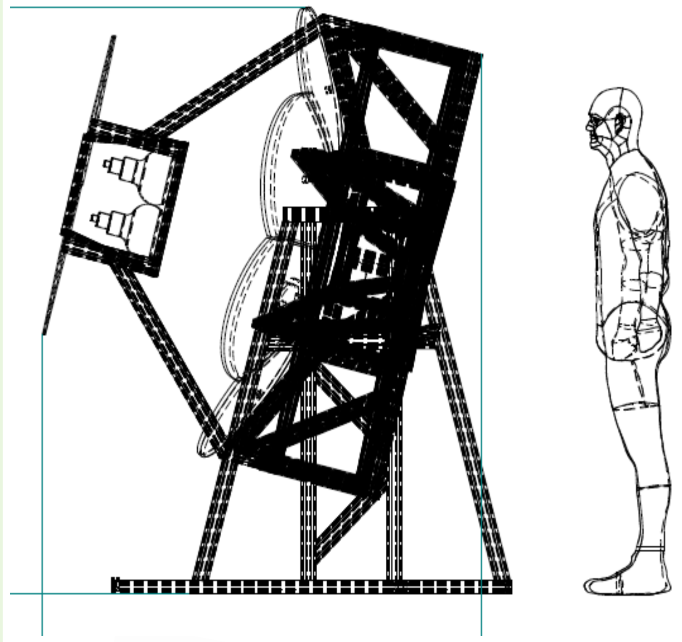


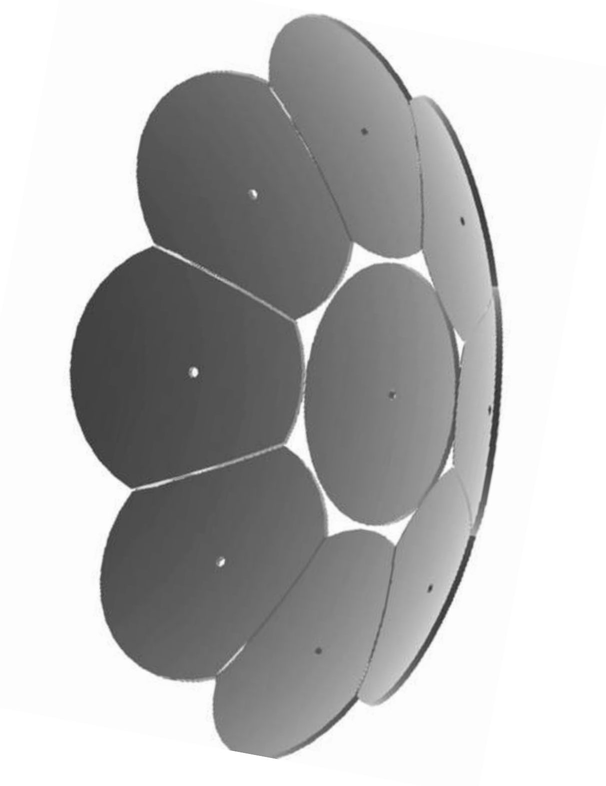
Low-cost and simplified/optimized FD

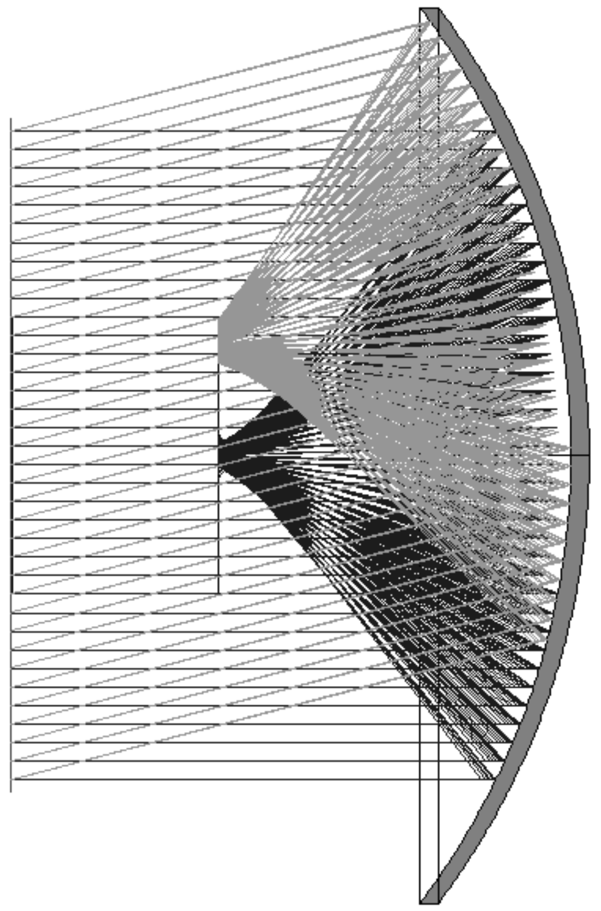


Fluorescence detector Array of Single-pixel Telescopes





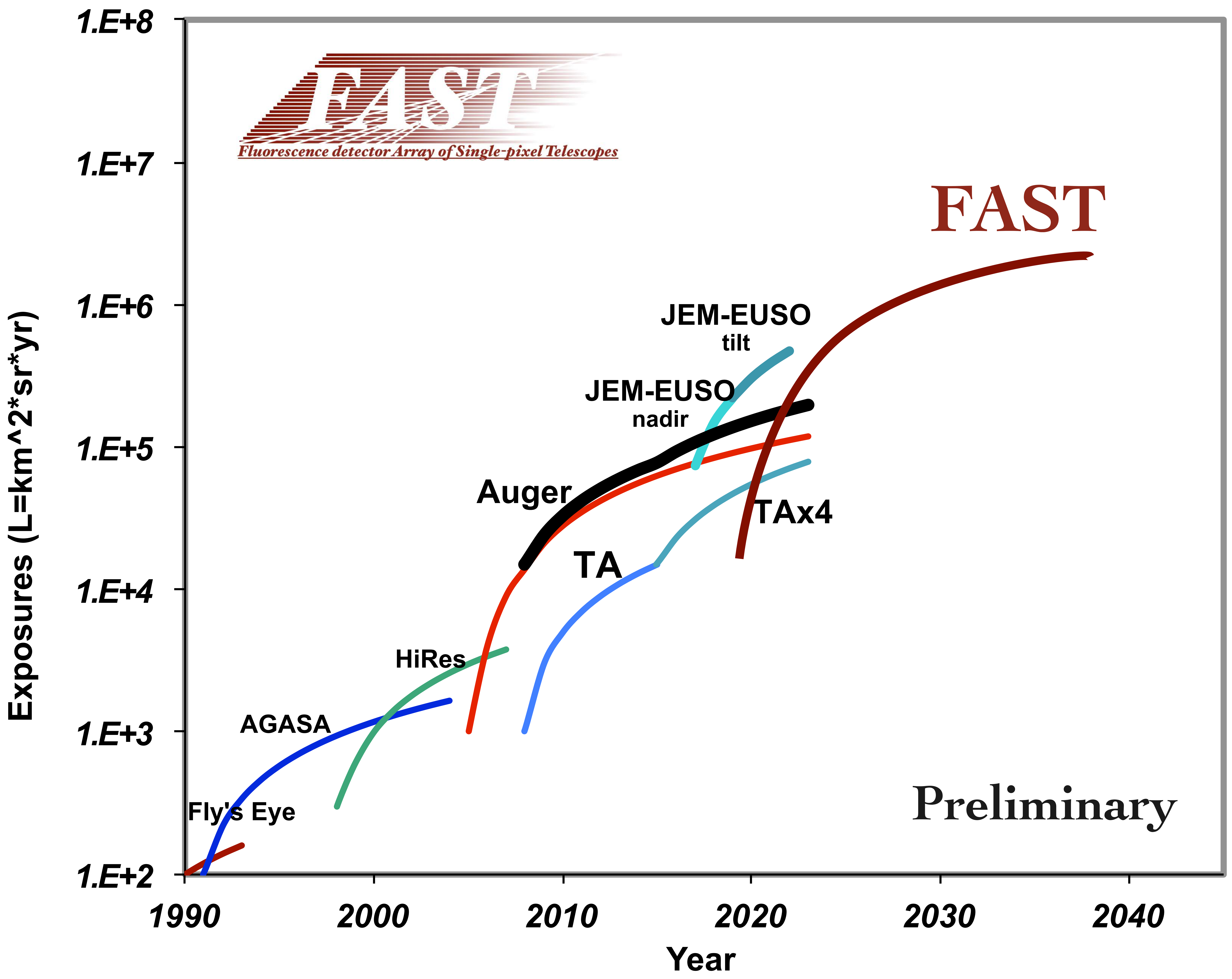




- Each telescope: 4 PMTs, 30°×30° field of view (FoV).
  - **Reference design: 1 m^2 aperture, 15°×15° FoV per PMT**
- Each station: 12 telescopes, 48 PMTs, 30°×360° FoV.
- Deploy on a triangle grid with **20 km** spacing, like **"Surface Detector Array"**.
- If 500 stations are installed, a ground coverage is ~ 150,000 km^2.
- Geometry: Radio, SD, coincidence of three stations being investigated.

FAST
Fluorescence detector Array of Single-pixel Telescopes

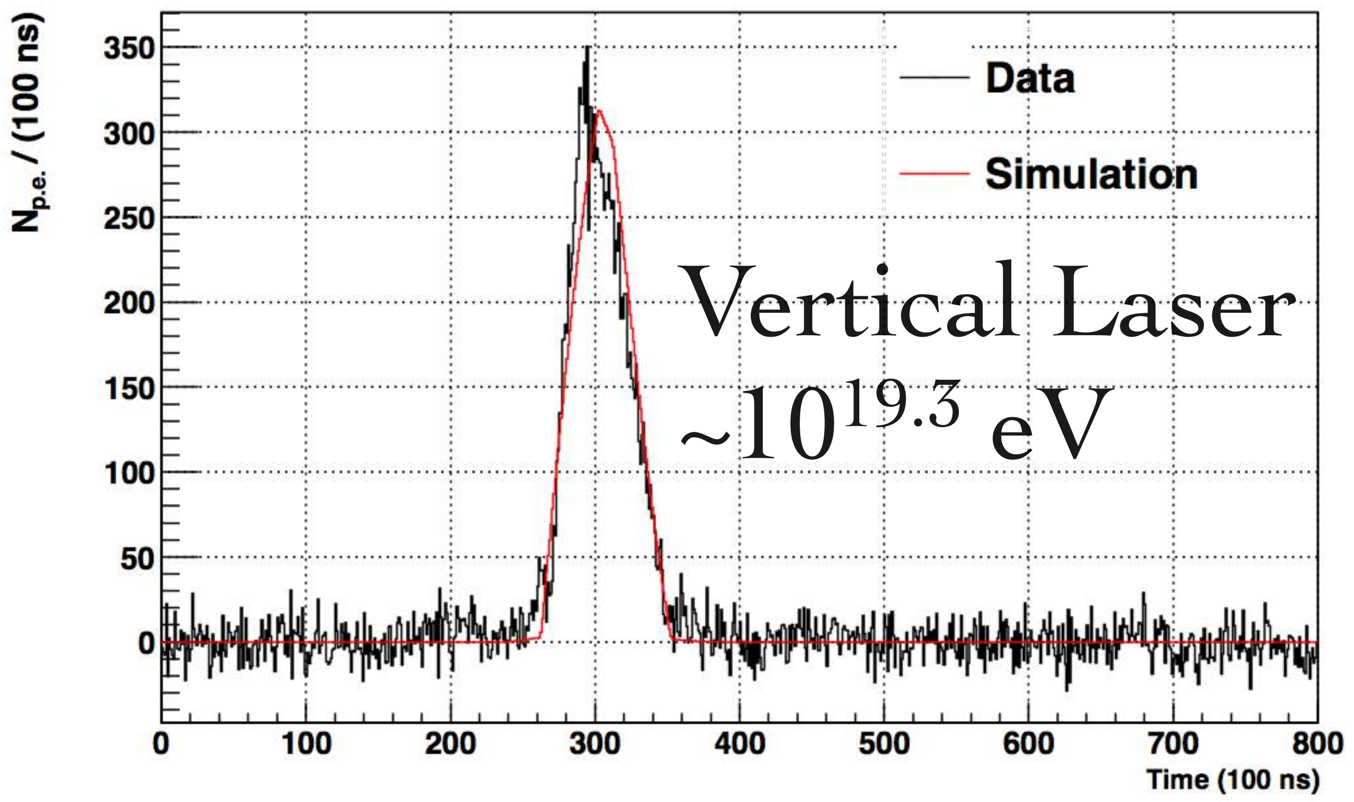
FAST Expected Exposure

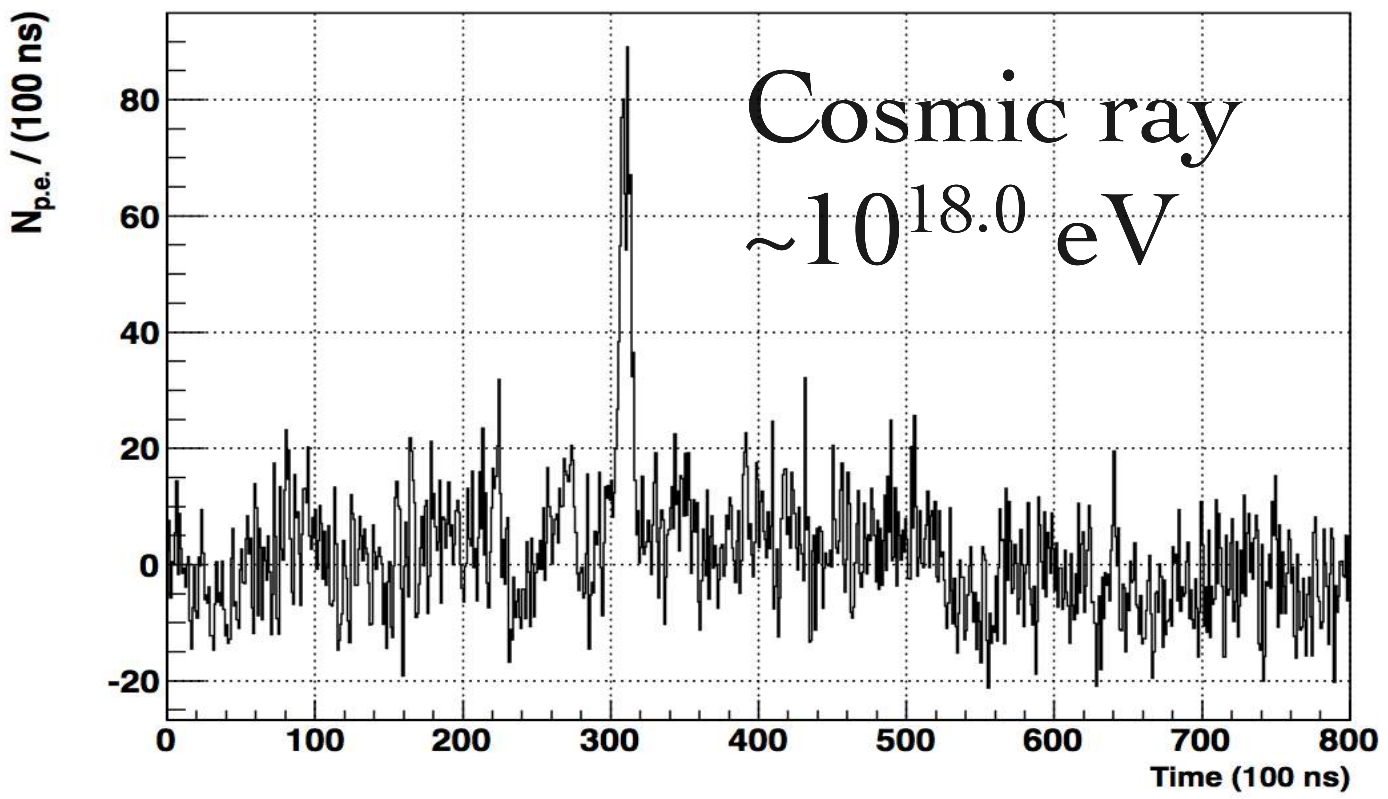


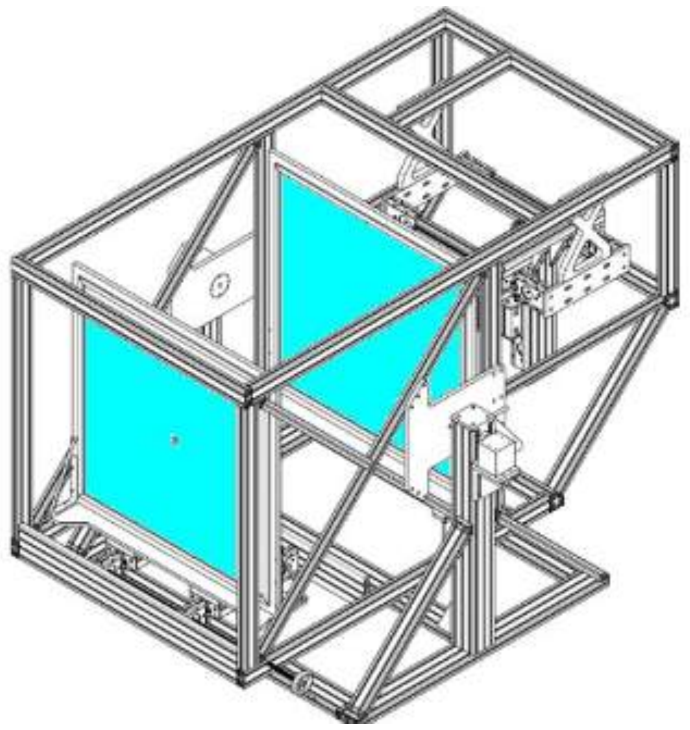
- Conventional operation of FD under 10~15% duty cycle
  - Target: $>10^{19.5}$ eV
- Observation in **moon night** to achieve **30%** duty cycle,
  - Target: **$>10^{19.8}$ eV = Super GZK events**
    - Test operation by Auger FD
- Ground area of 150,000 km^2 with 30% duty cycle = 45,000 km^2 (15×Auger, cost ~100 Million USD)
- **450 events/year**

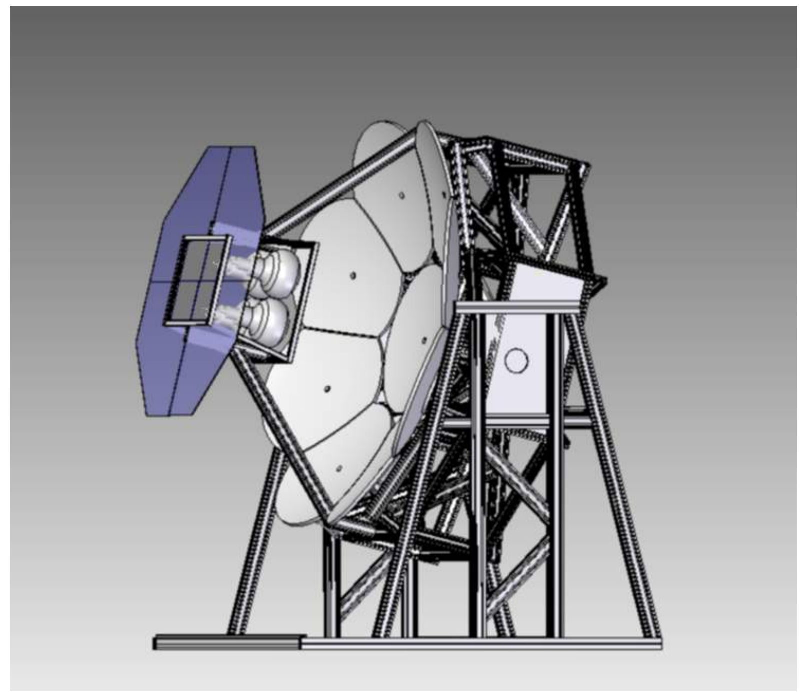
Full-scale FAST Prototype

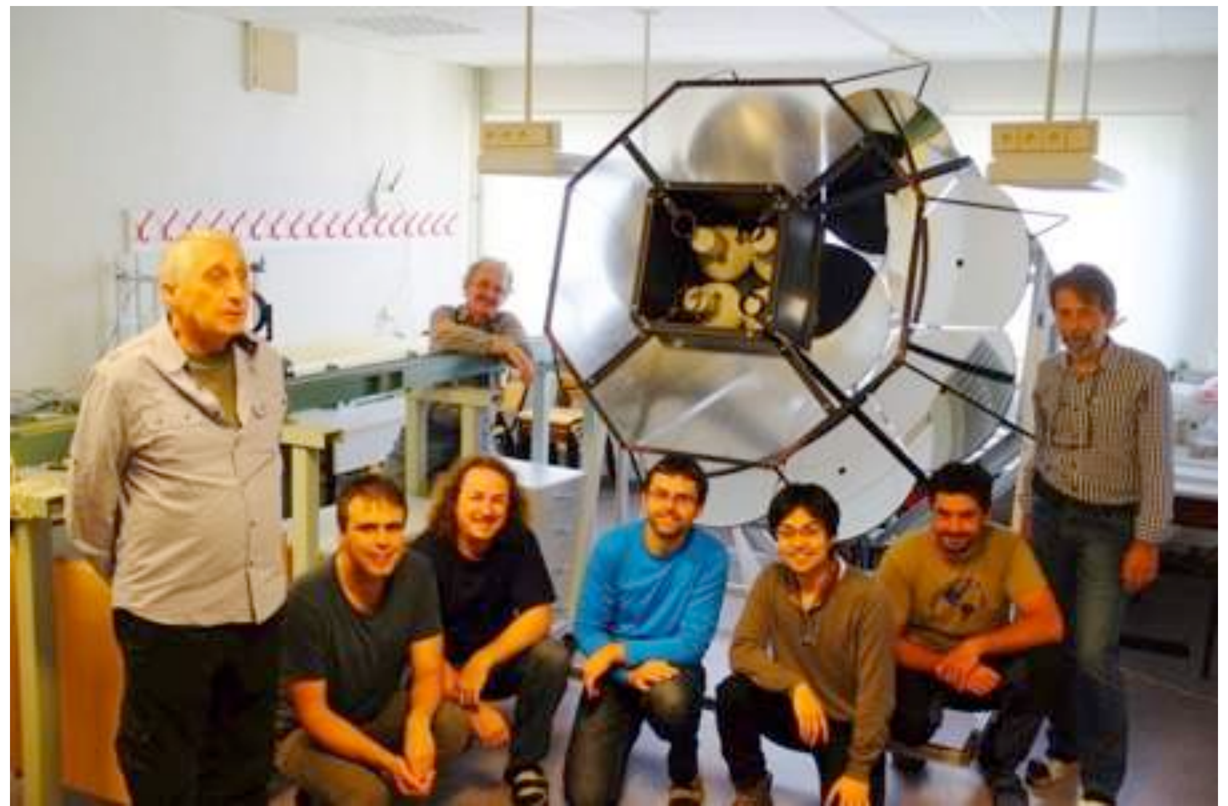
- **Confirmed milestones by EUSO-TA Telescope**
  - Stable operation under high night sky backgrounds.
  - UHECR detection.
    - T. Fujii et al., Astropart.Phys. *74* (2016) 64-72, arXiv: 1504.00692
- **Next milestones by new full-scale FAST prototype**
  - Establish the FAST sensitivity.
  - Detect a shower profile including ***Xmax*** with FAST







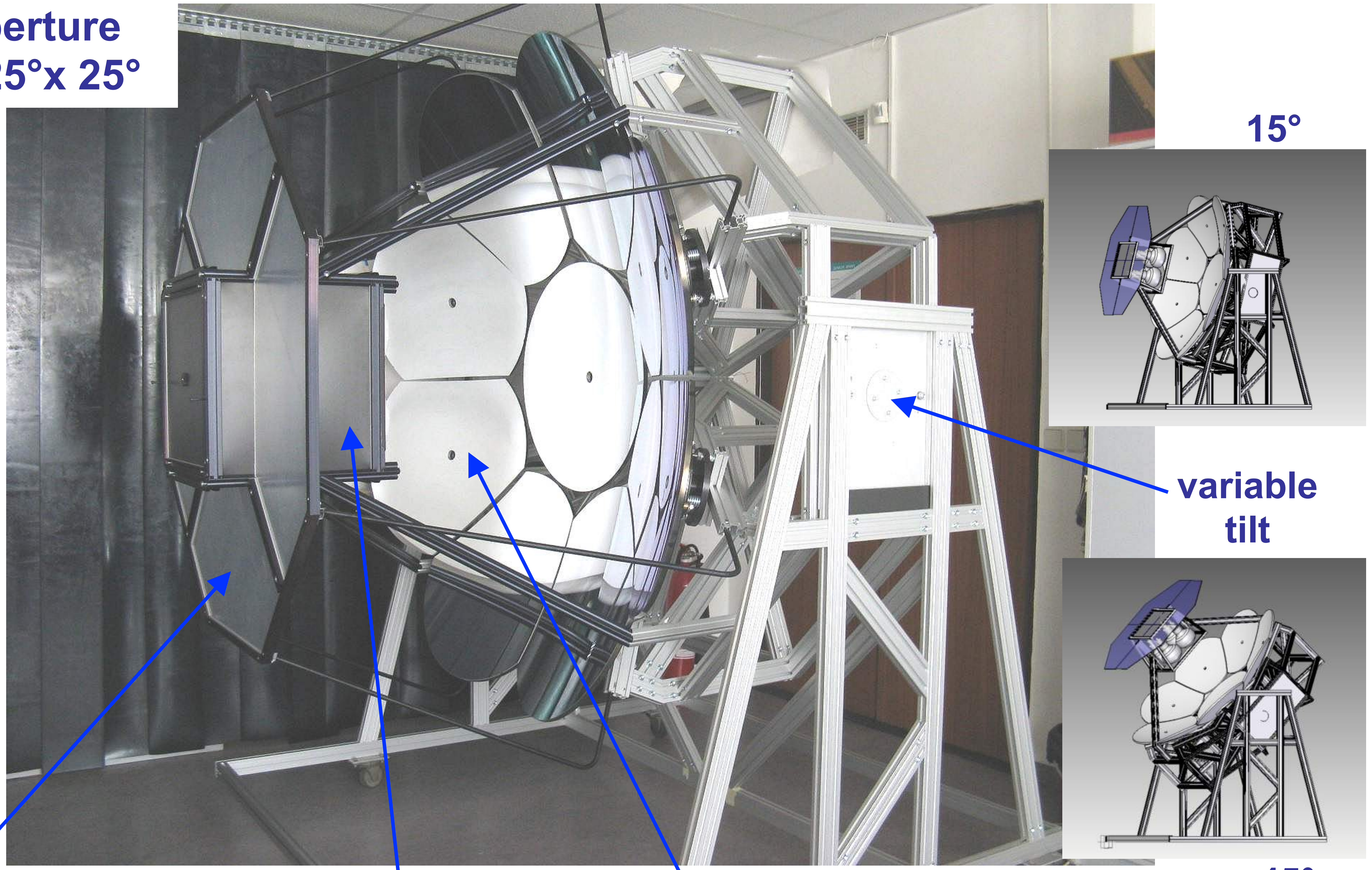





FAST
Fluorescence detector Array of Single-pixel Telescopes

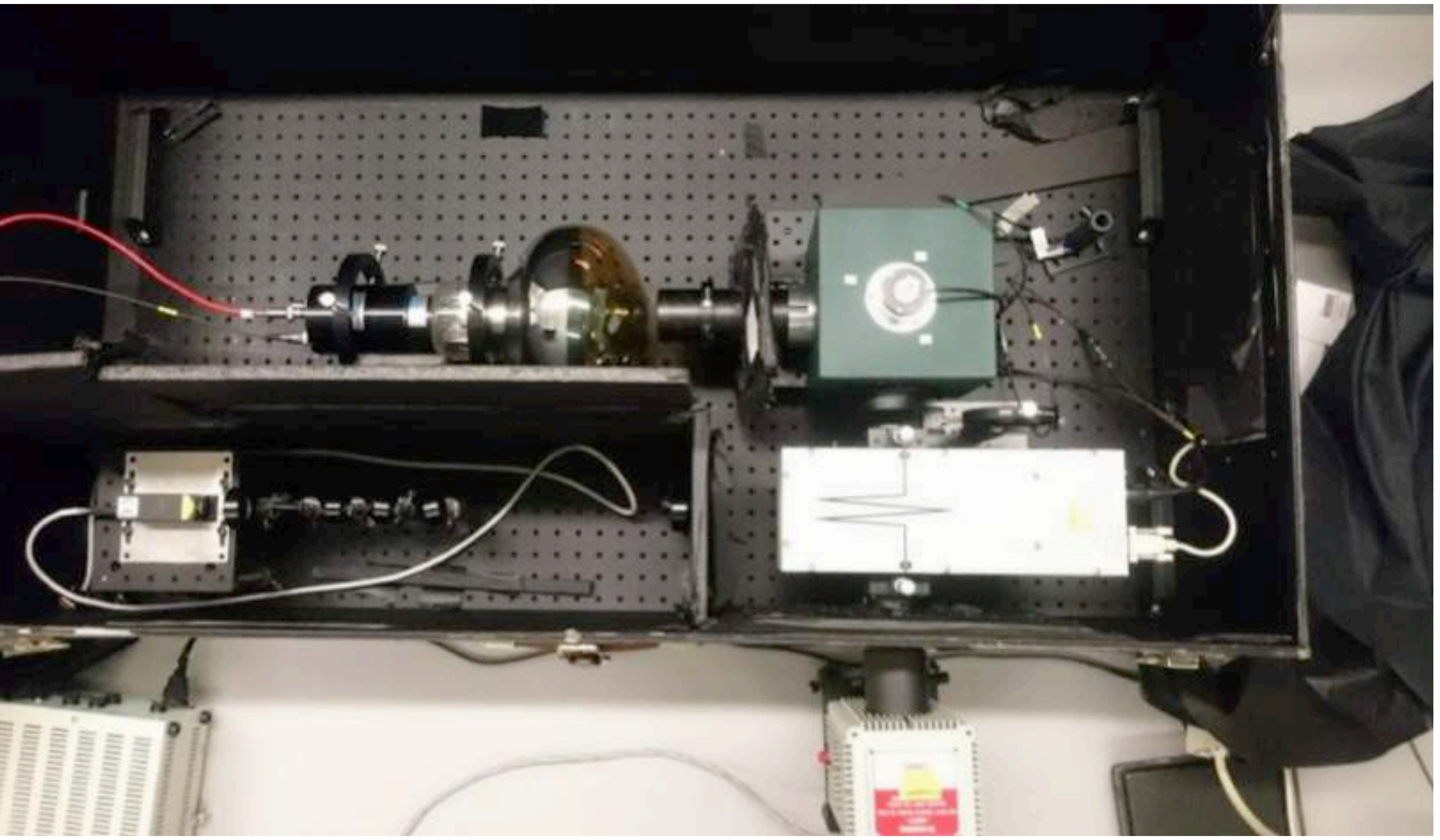
Full scale FAST prototype

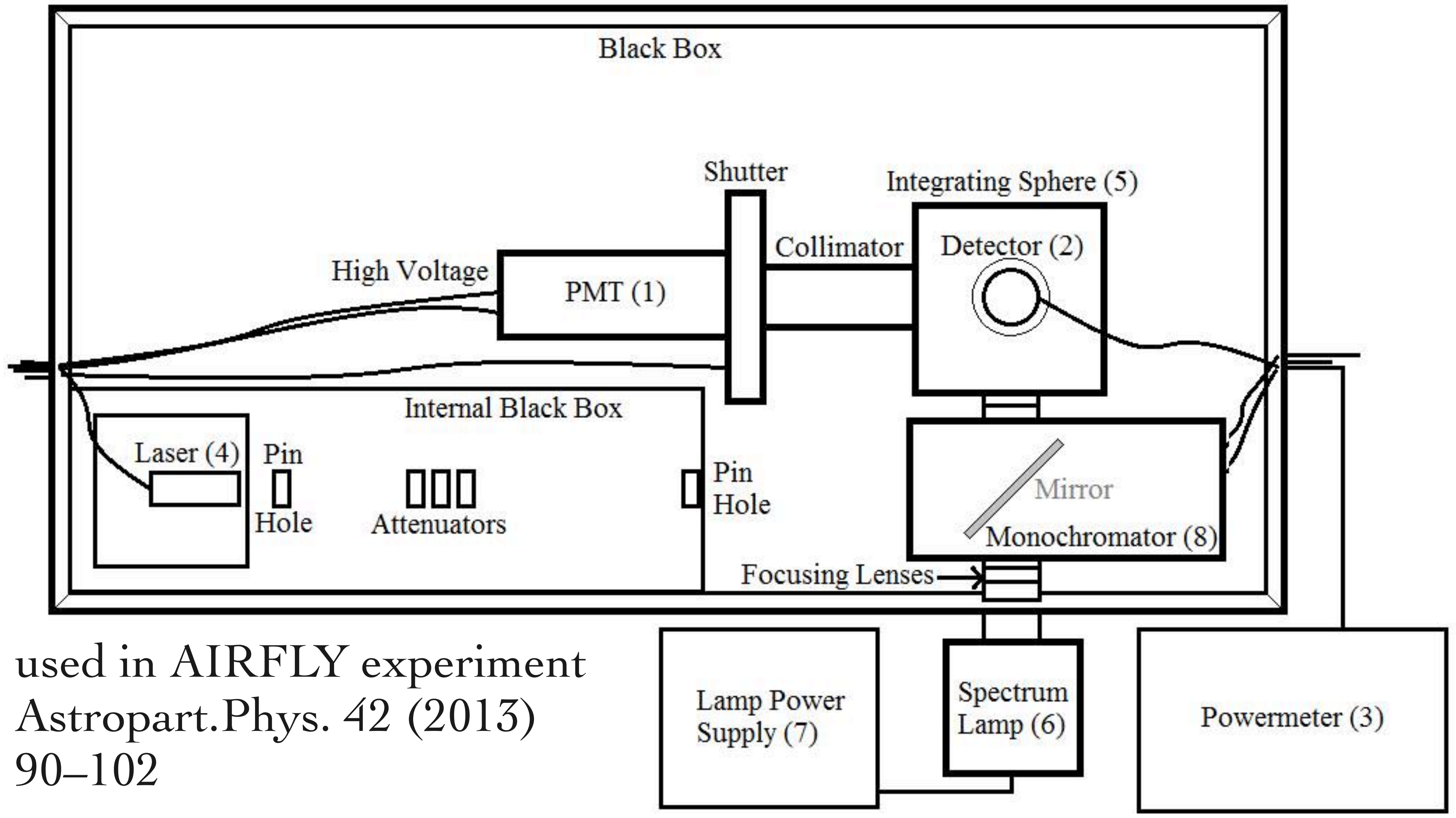
Fluorescence detector Array of Single-pixel Telescopes



PMT Calibration

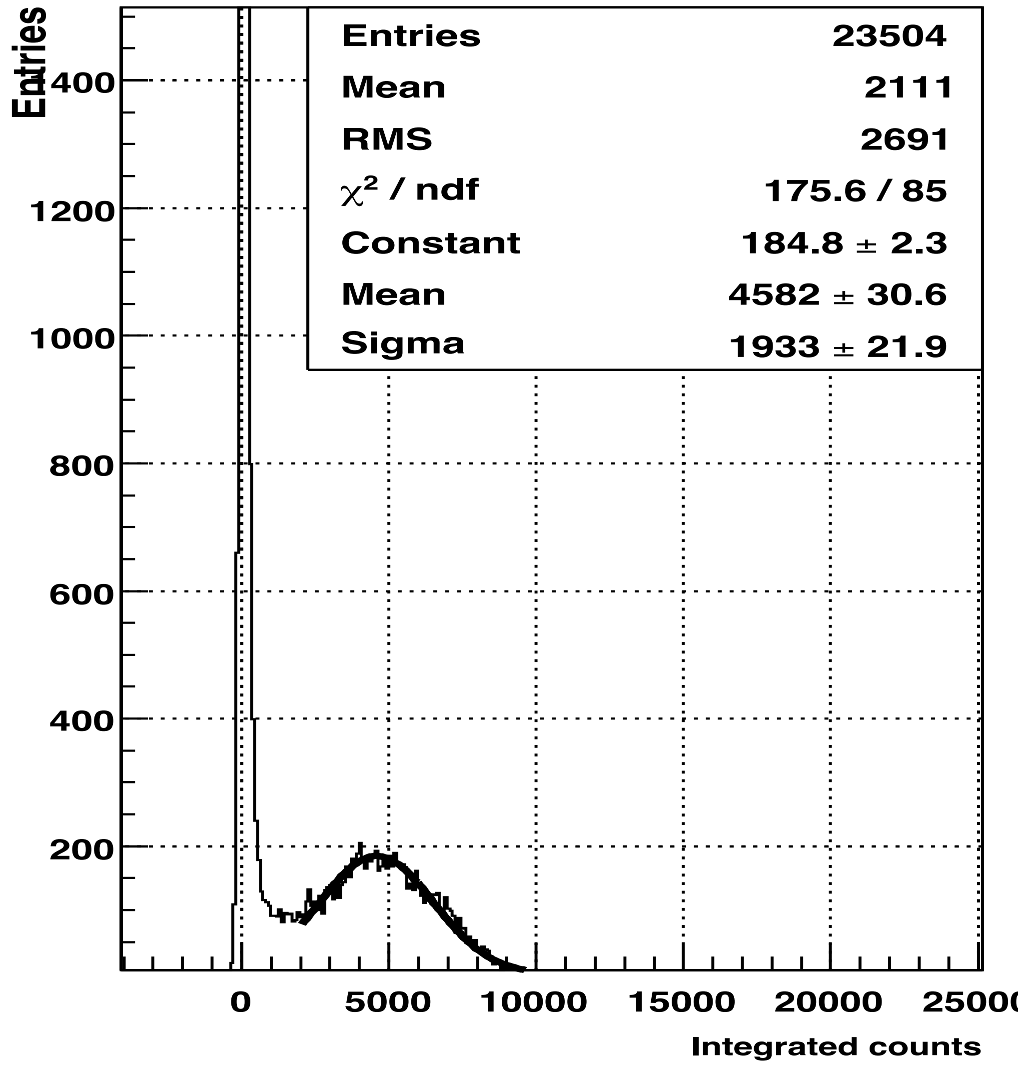
Fluorescence detector Array of Single-pixel Telescopes



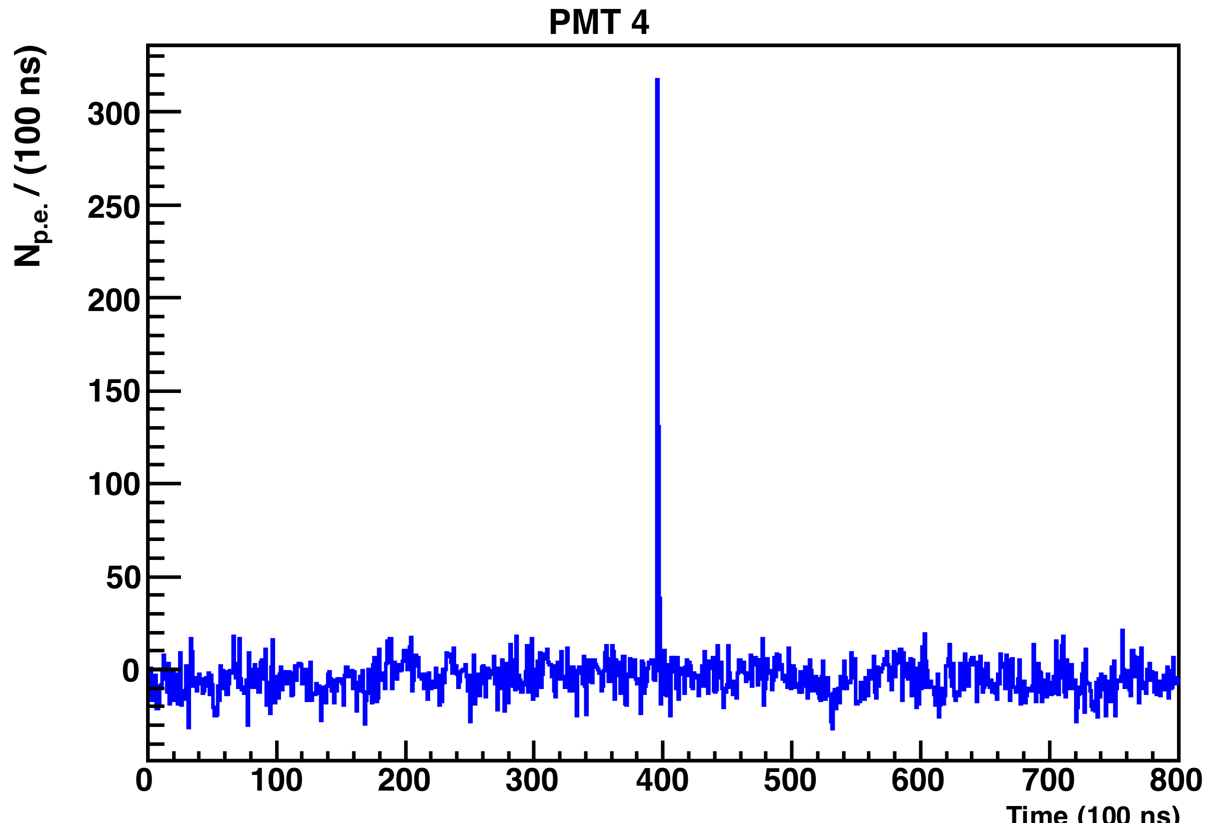


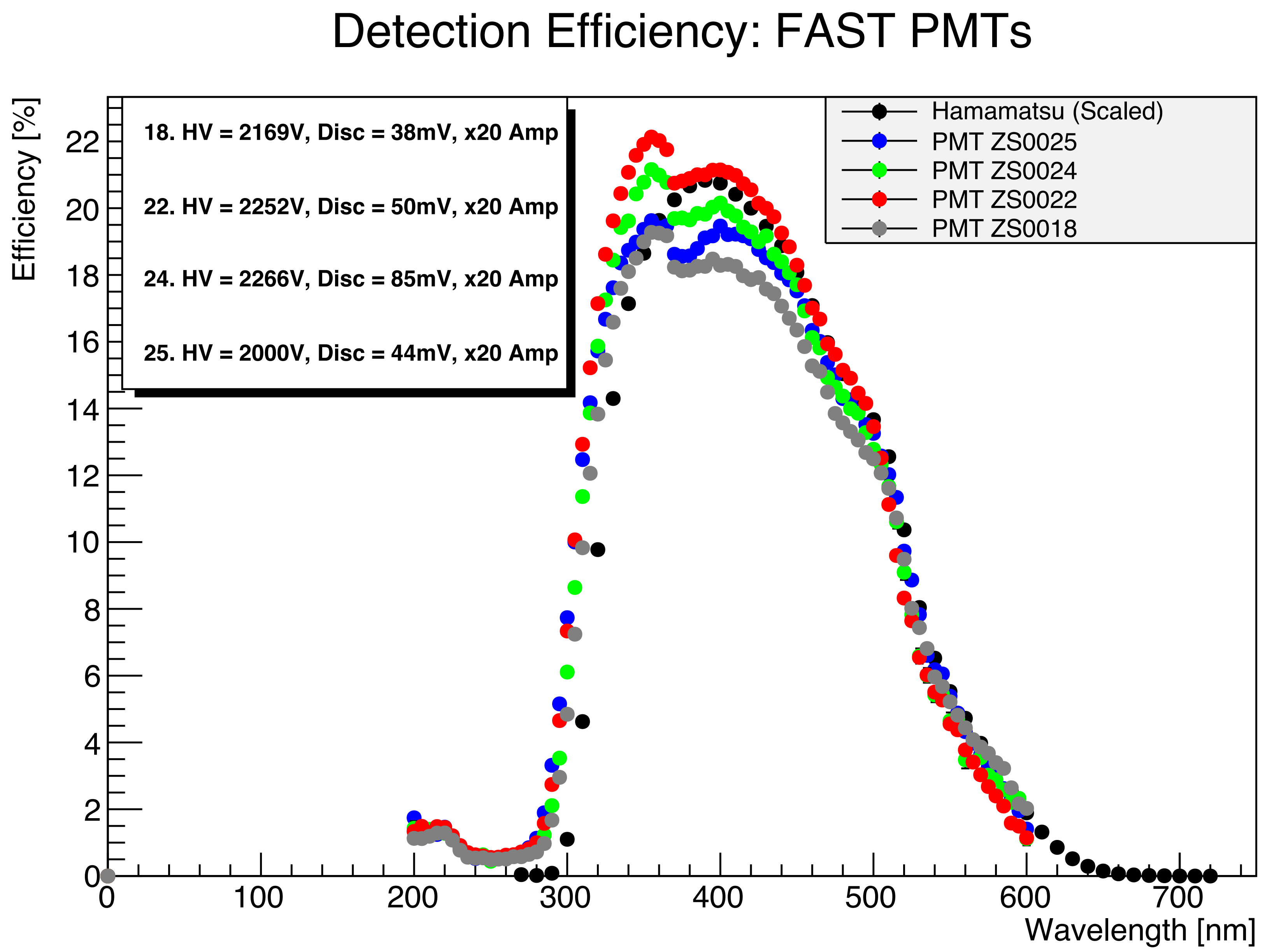
used in AIRFLY experiment Astropart.Phys. 42 (2013) 90–102

Single photo electron

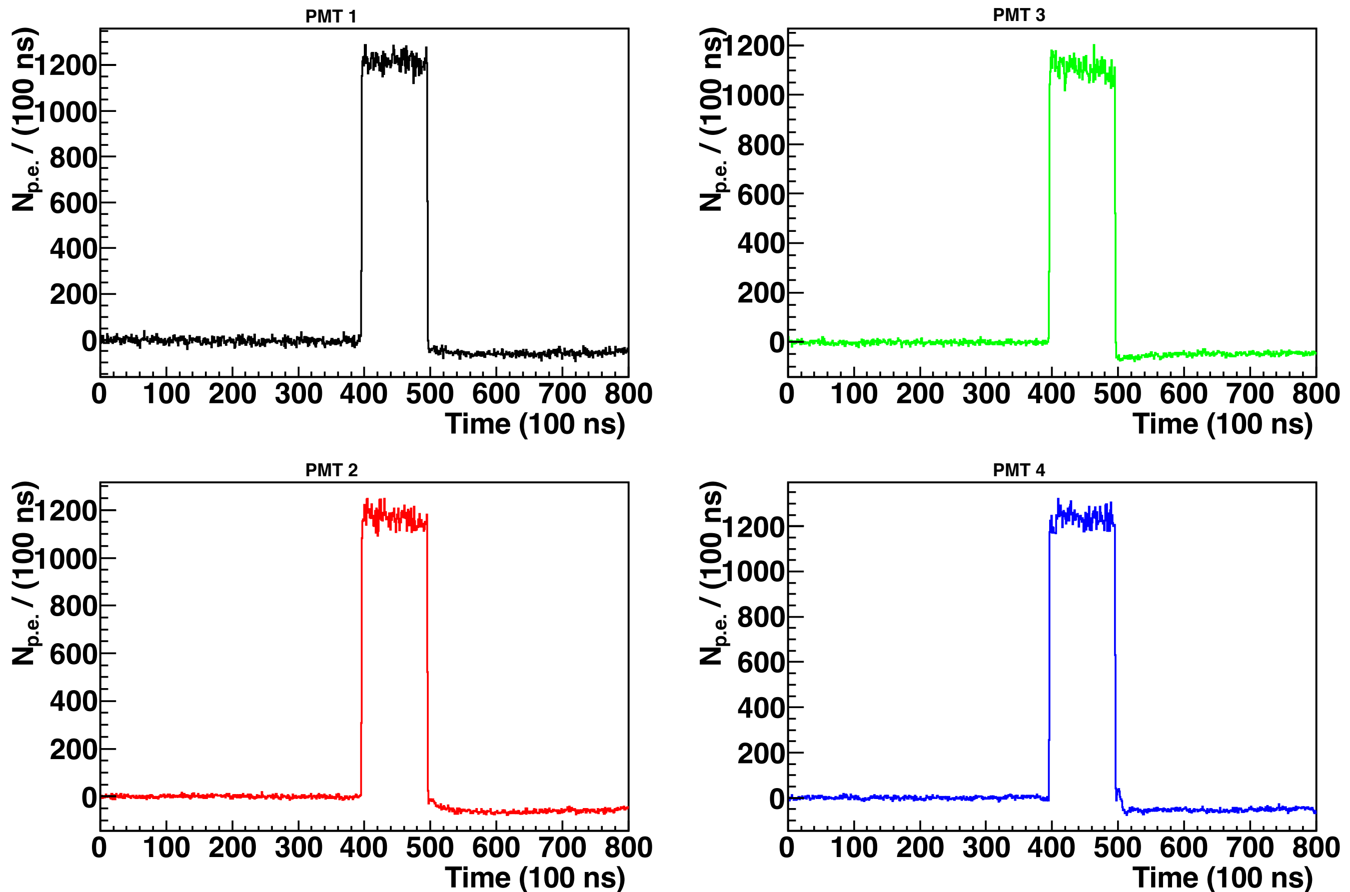


YAP pulser (YAlO3:Ce scintillator + 241Am source) attached on each PMT surface



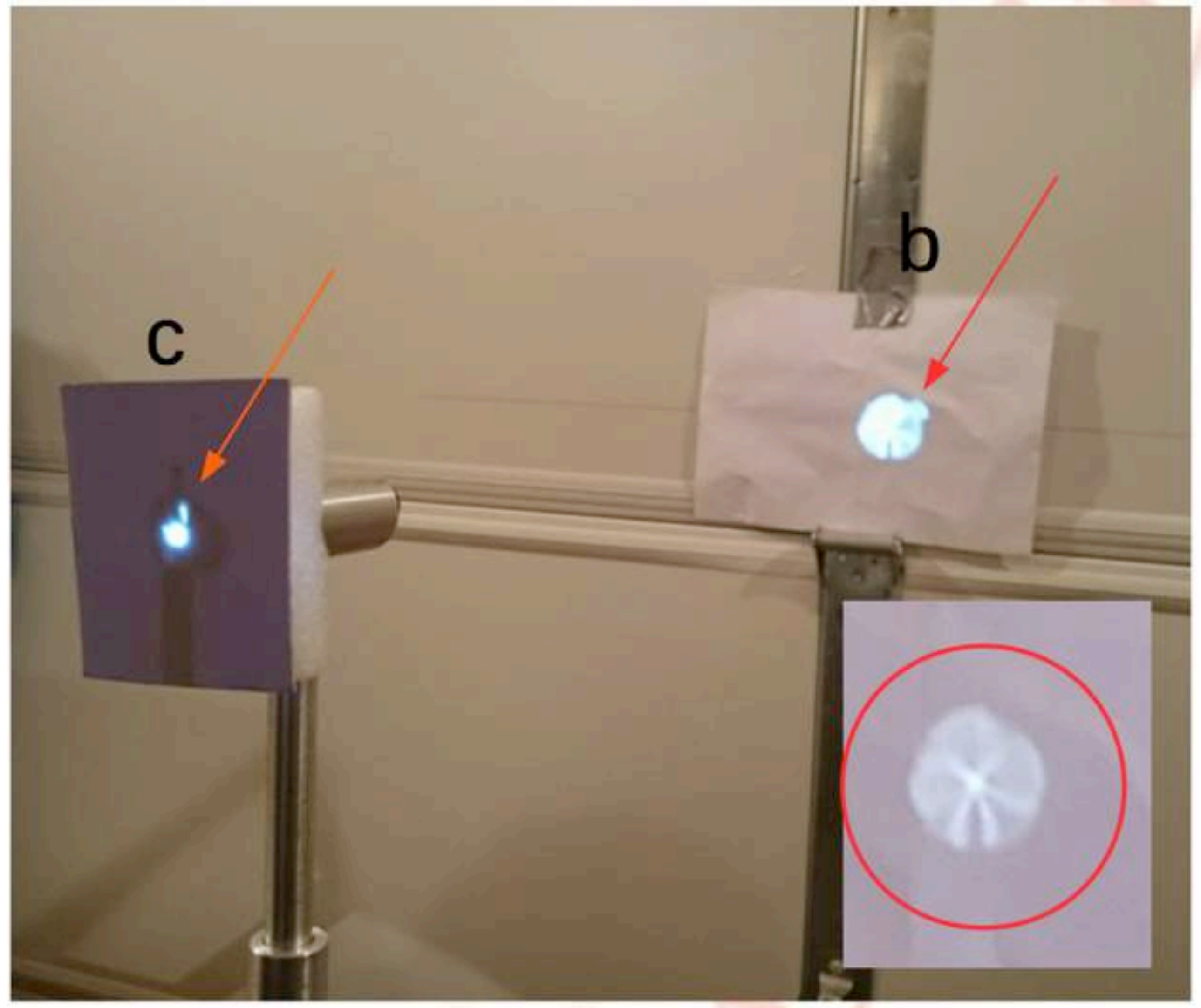


UV LED illuminating the front of the camera

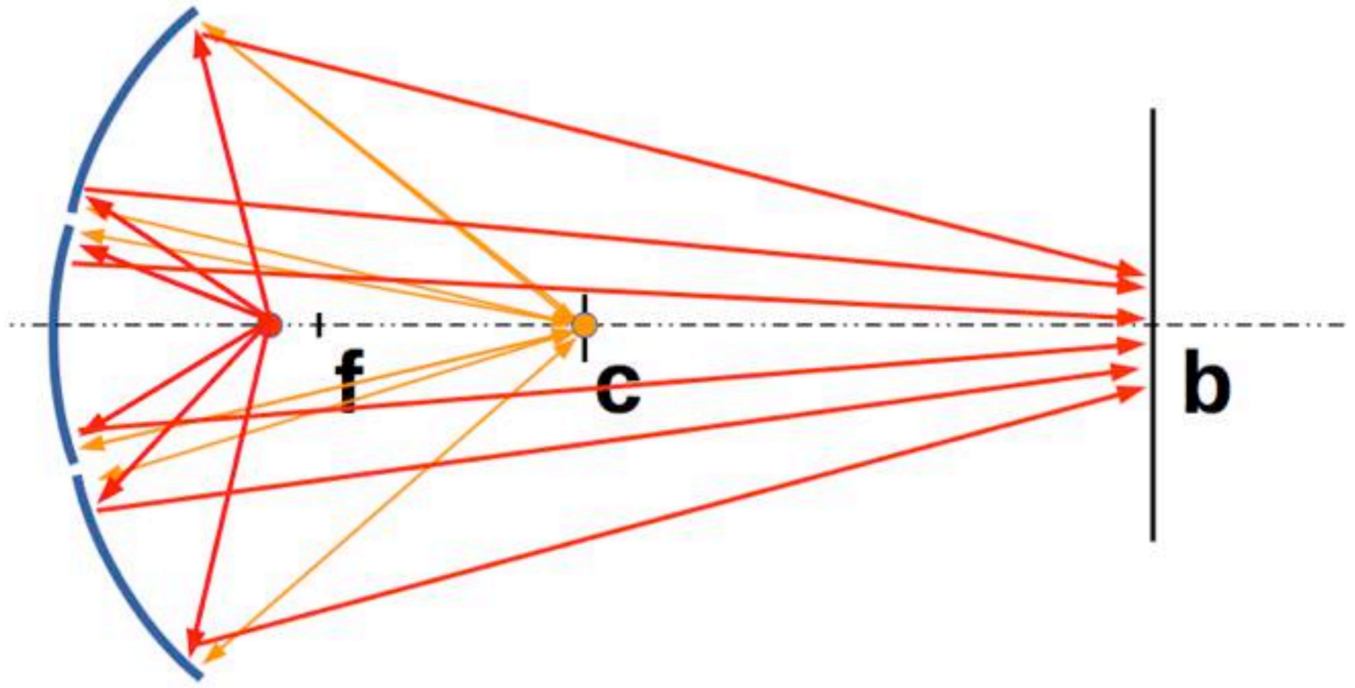


Telescope alignment and raytracing simulation

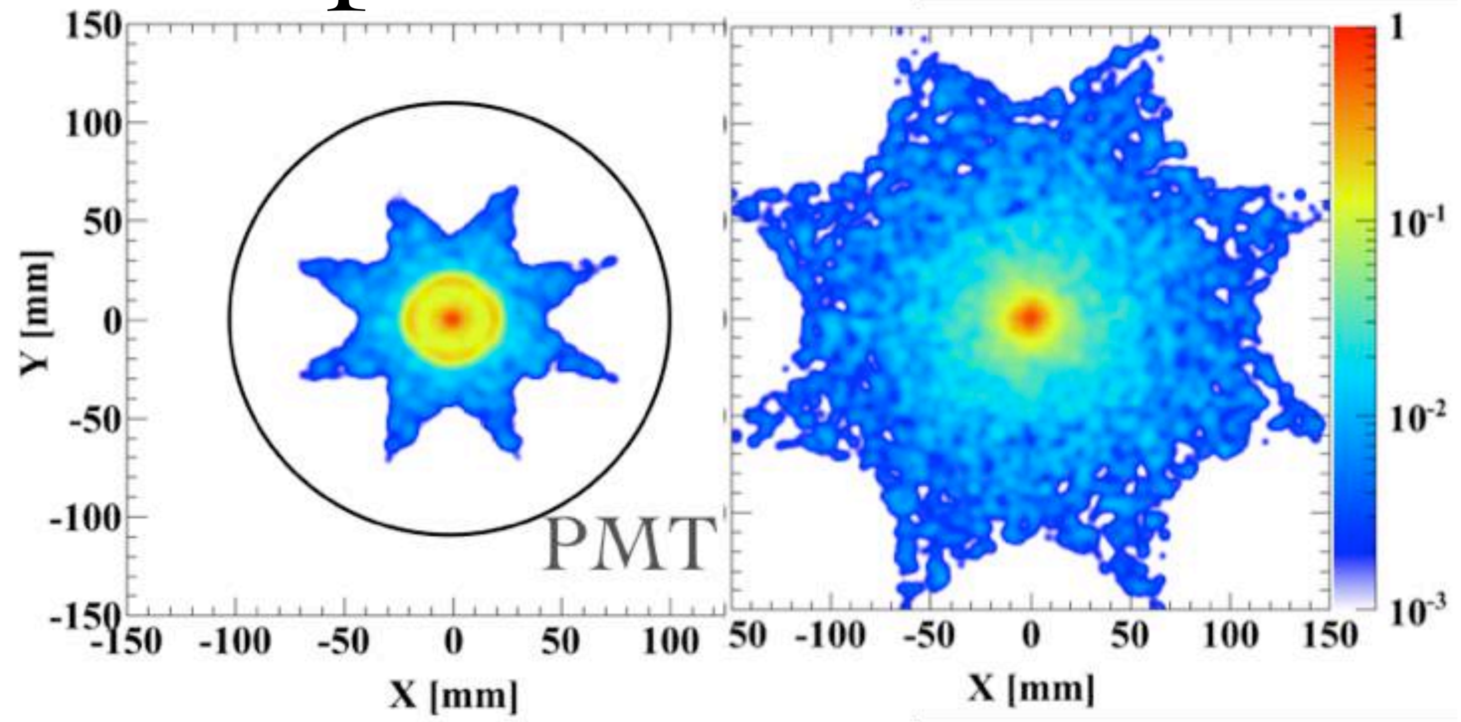
Telescope alignment with stars



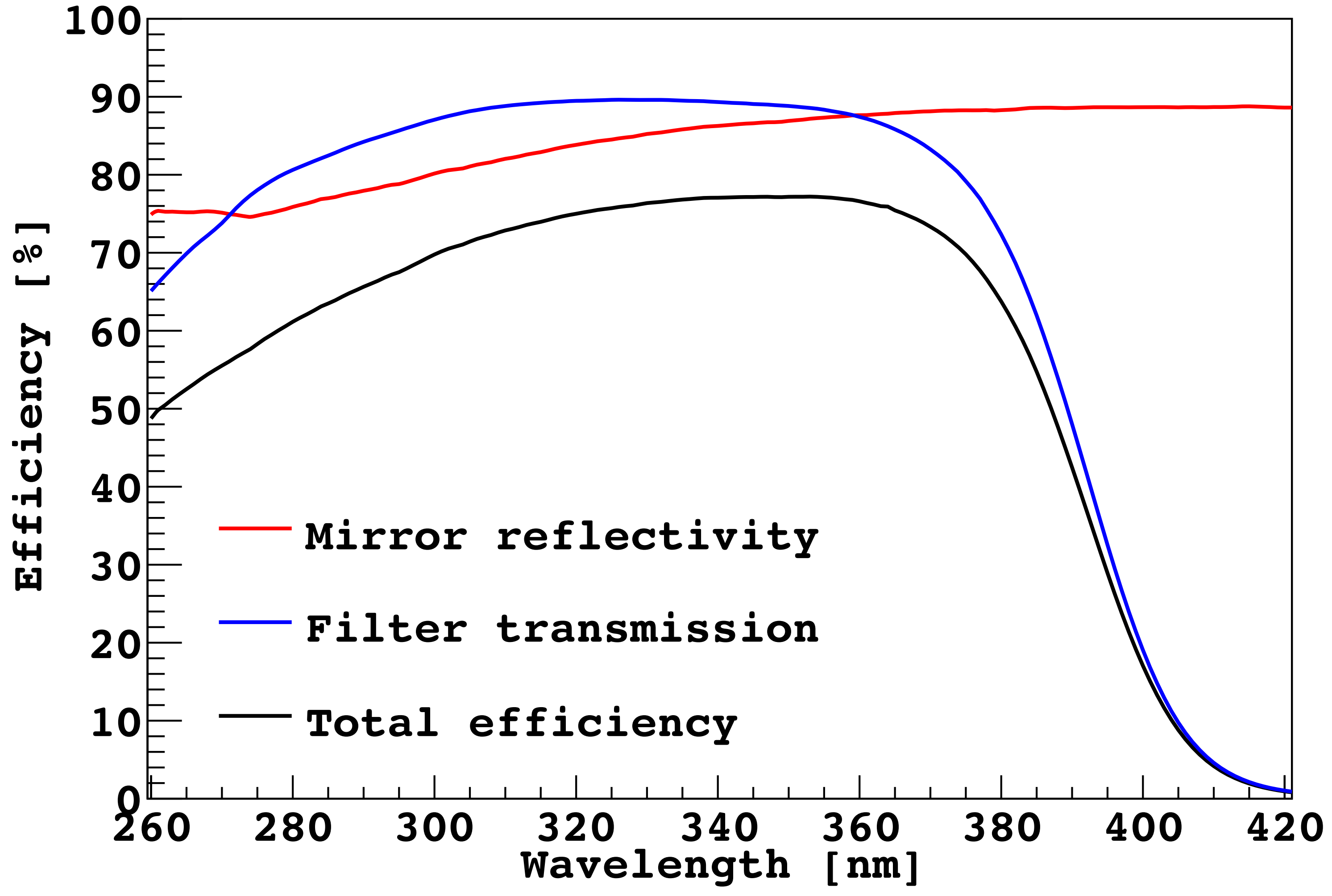
Mirror alignment by 2 LED



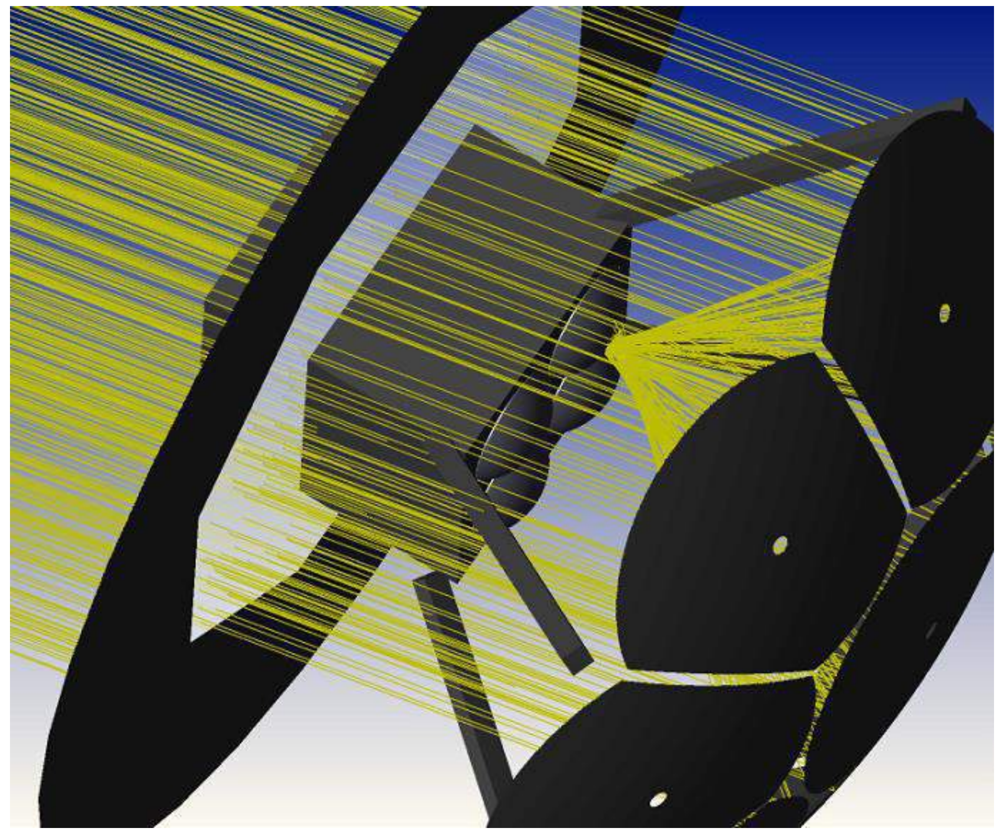
focal plane 50 mm offset

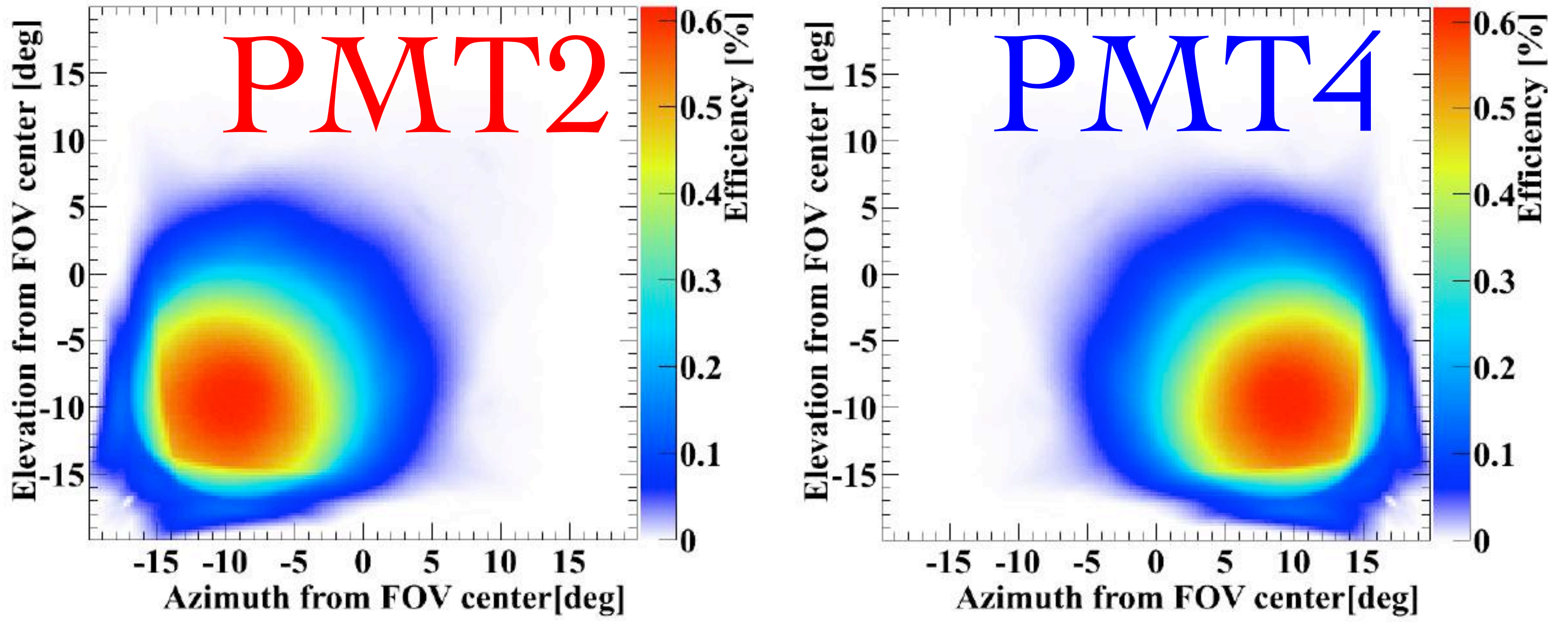


Mirror reflectance and filter transmittance



Raytracing simulation for spot sizes and angular responses



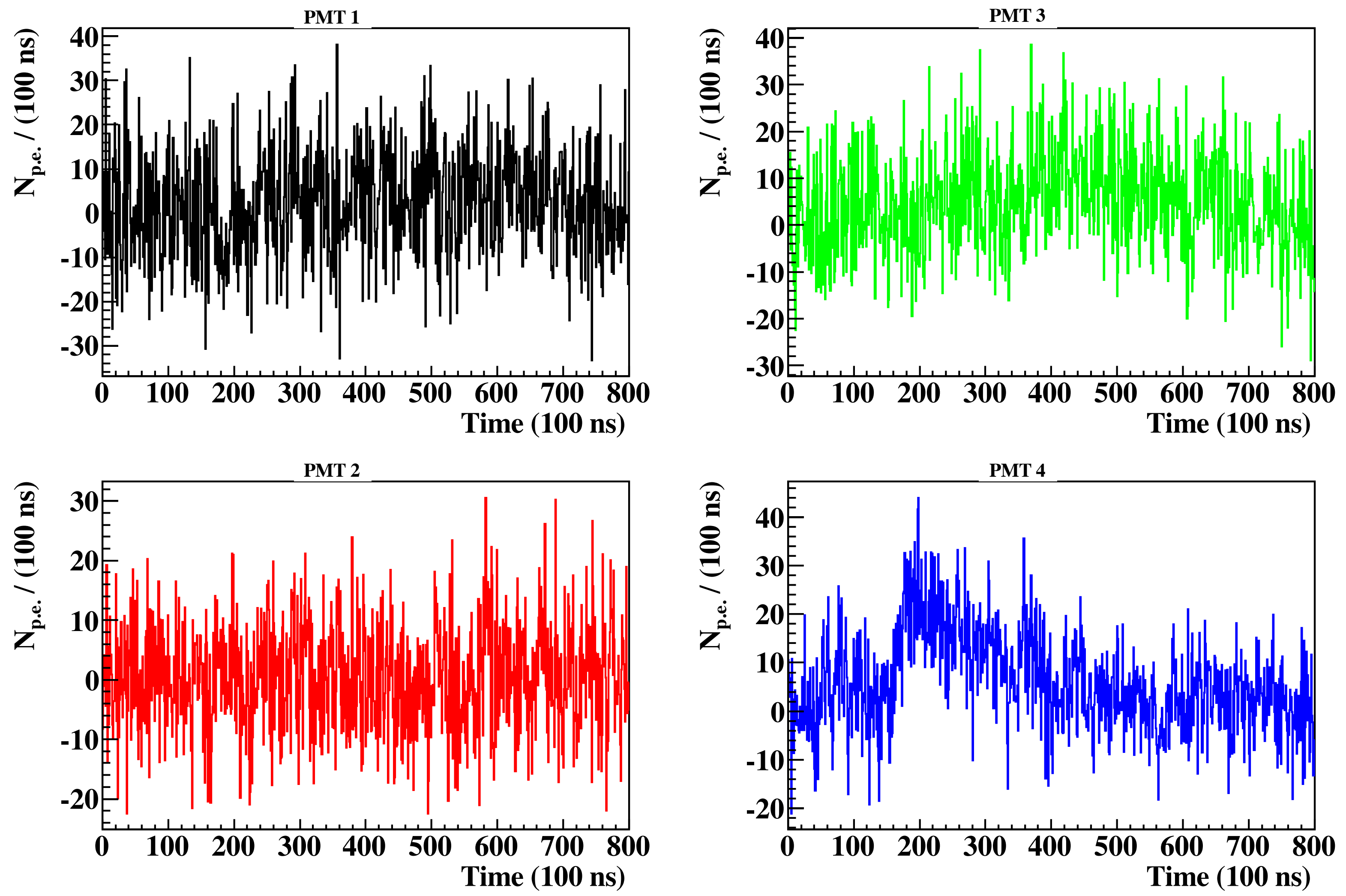


Further information in recently published paper, D. Mandat *et al.*, JINST 12, T07001 (2017)

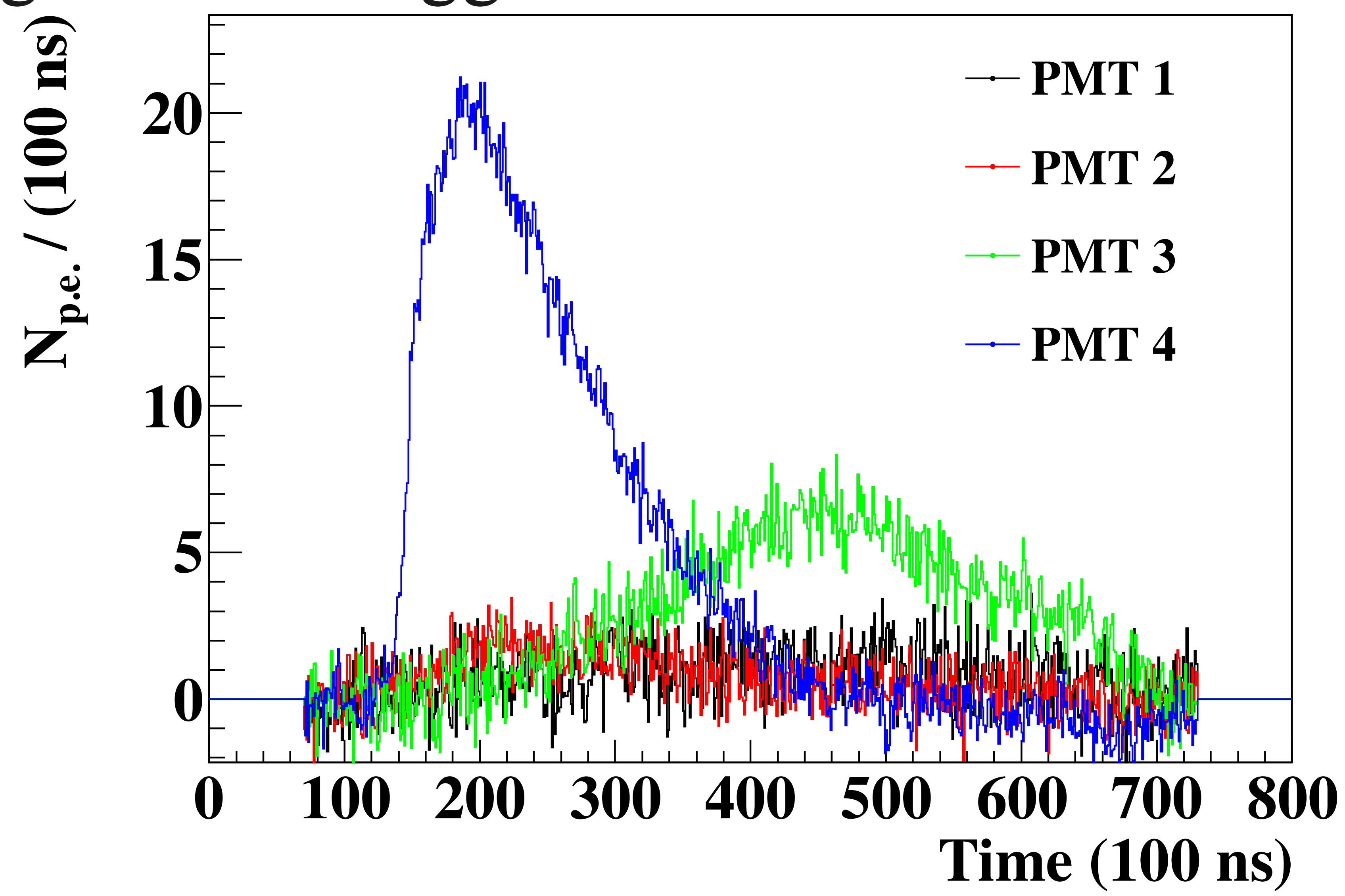
Distant vertical laser comparison in Data/MC

Fluorescence detector Array of Single-pixel Telescopes

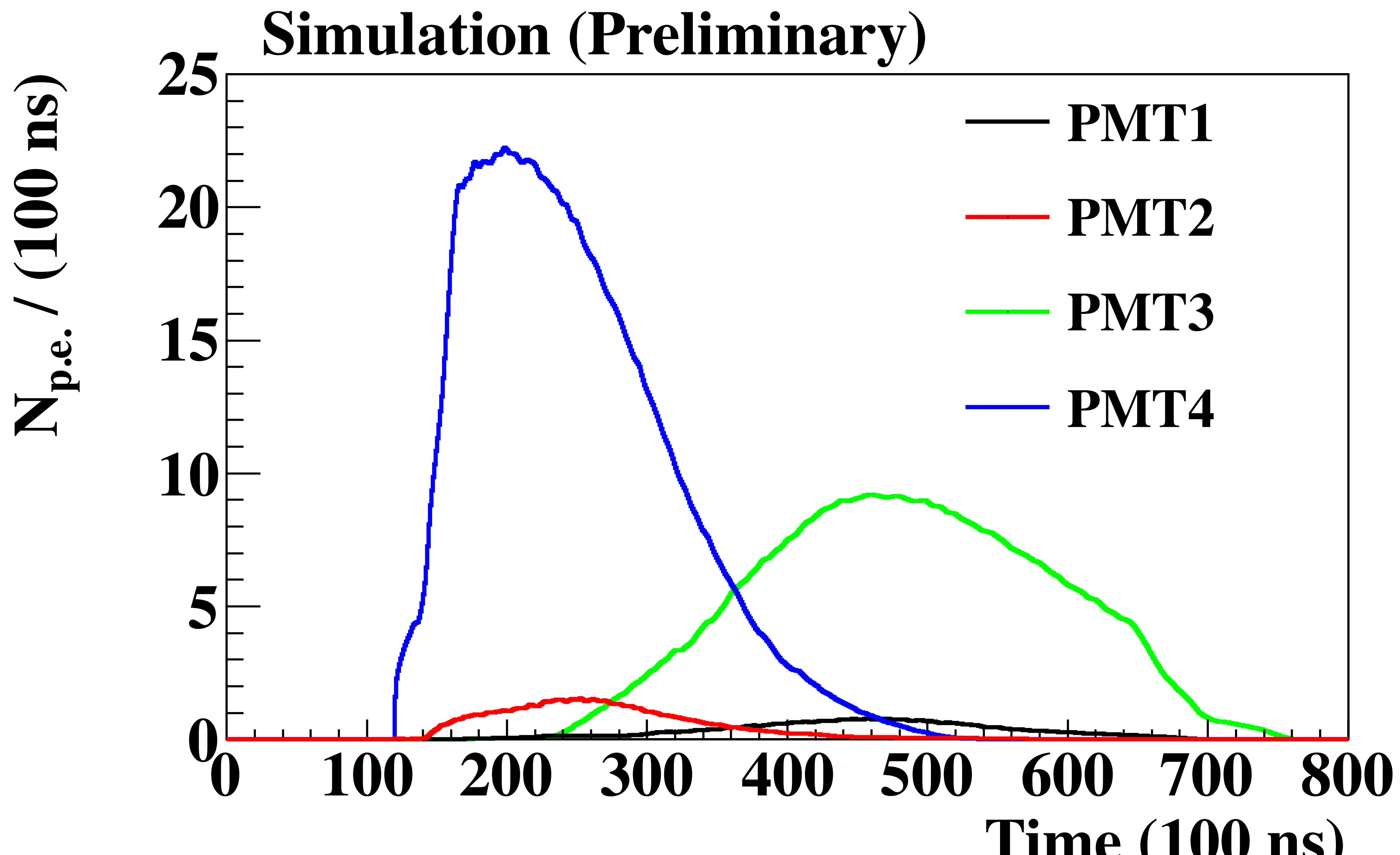
Single event



Average of 284 triggers



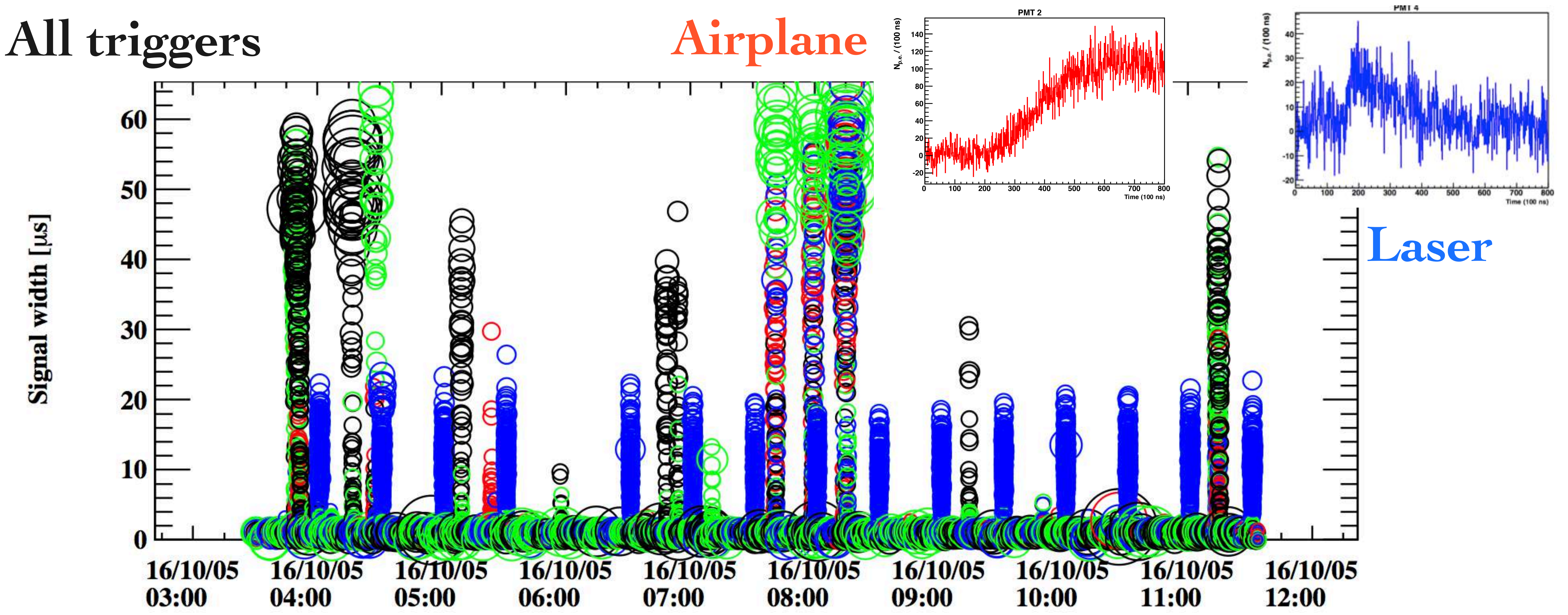
- Ultraviolet vertical laser at a distance of 20.85 km, E = 4.4 mJ, λ = 355 nm,
- Every 30 minutes during a clear night, equivalent to a UHECR with ~$10^{19.5}$ eV
- Calculate expected signal by simulation and good agreement with observed data.
- Monitoring the transparency of the atmosphere.



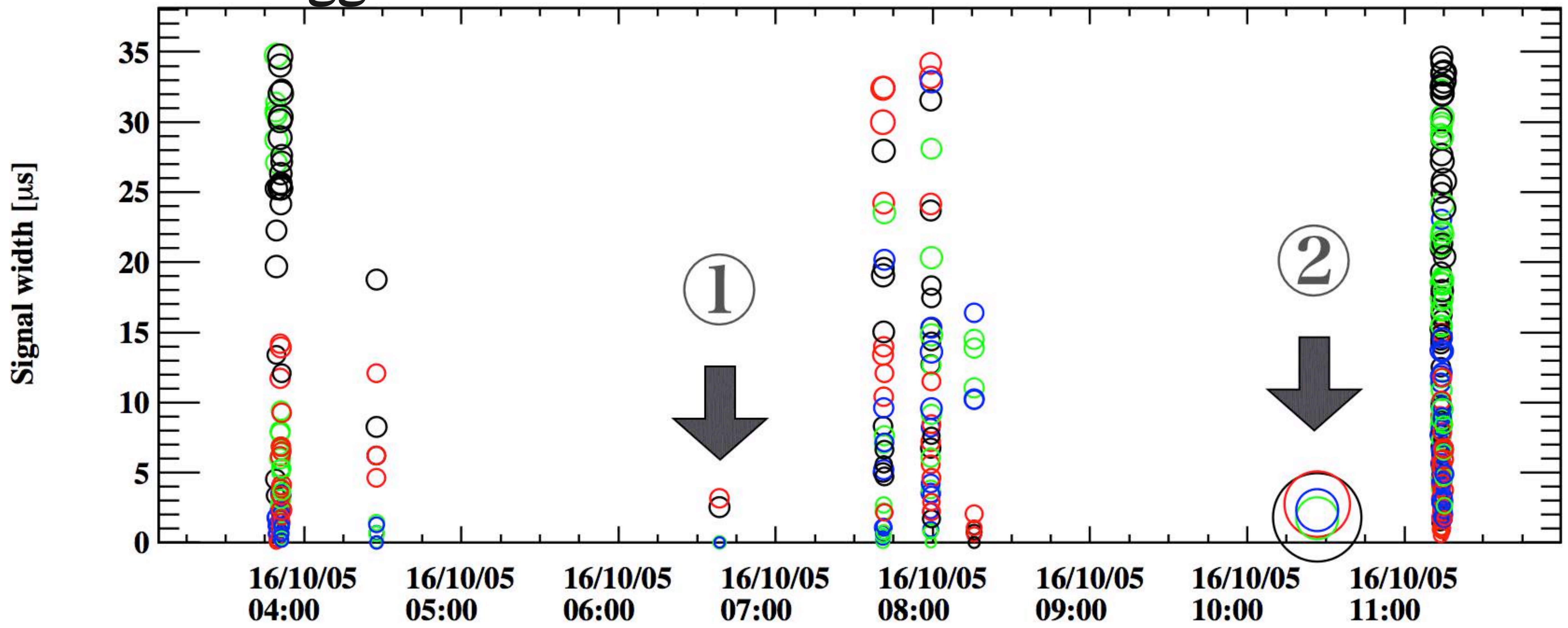
Event search

- Data on Oct.5th 2016
  - 62194 triggers
  - PMT1,2,3,4
- Circle size = significance
- Remove airplane (>35 μs) and laser events (time information).
- Two significant signal in PMTs
  - 90 events survived
  - 2 events found as candidates.
- Check TAFD reconstruction result.

All triggers



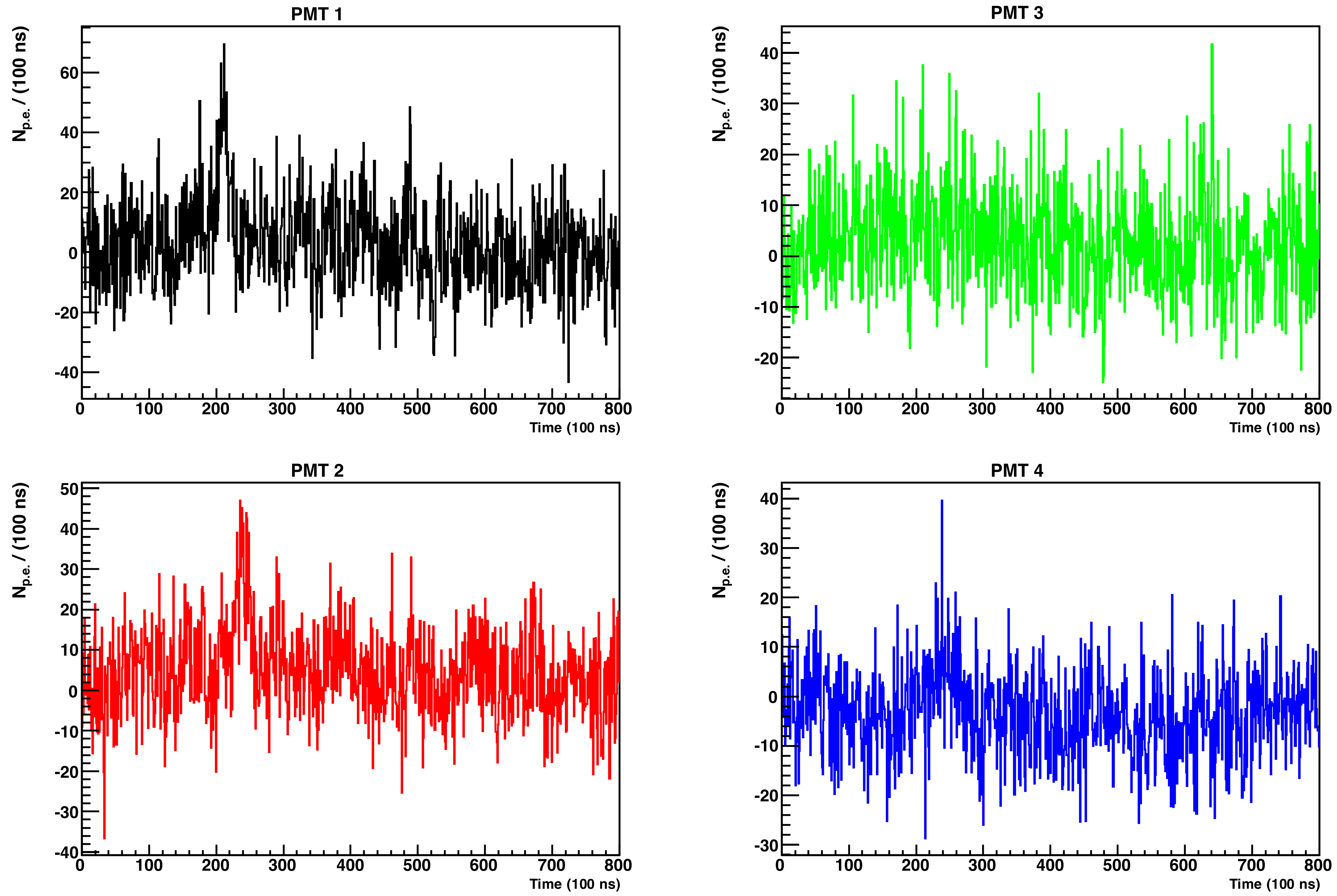
Selected triggers

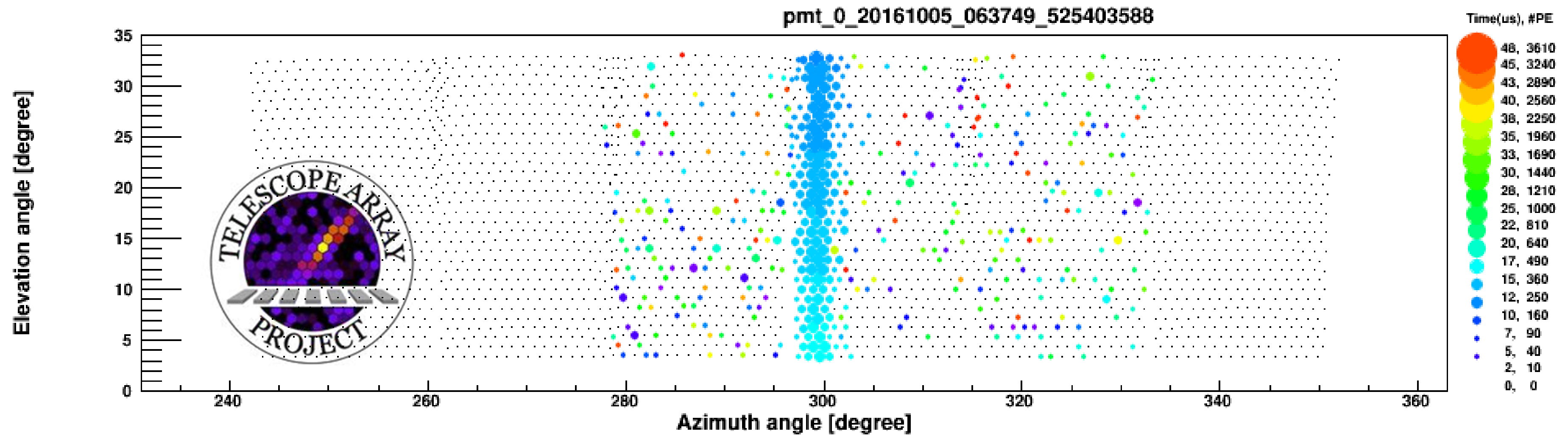


FAST
Fluorescence detector Array of Single-pixel Telescopes

First lights from UHECR

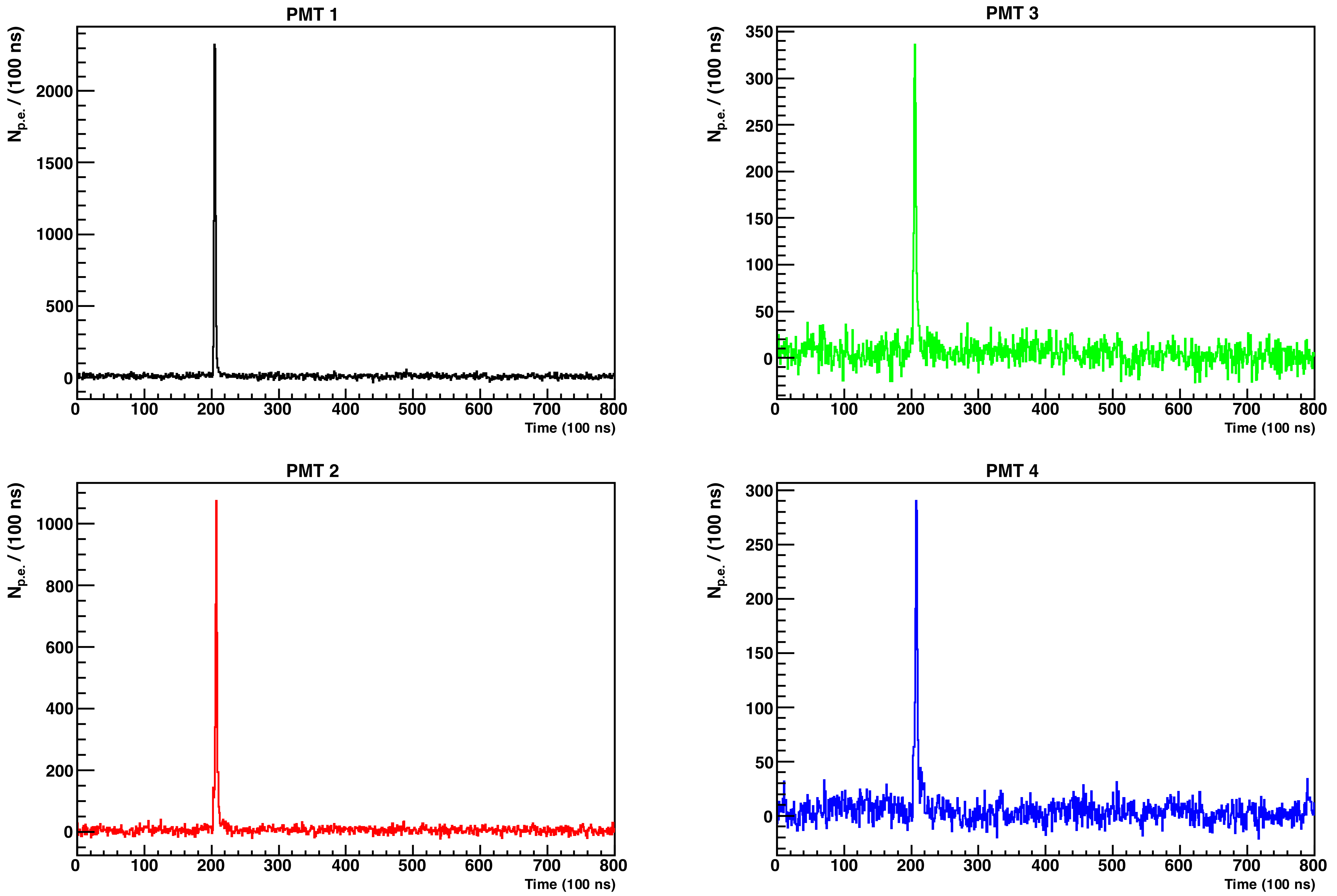
① 2016/10/05 06:37:49.525424540

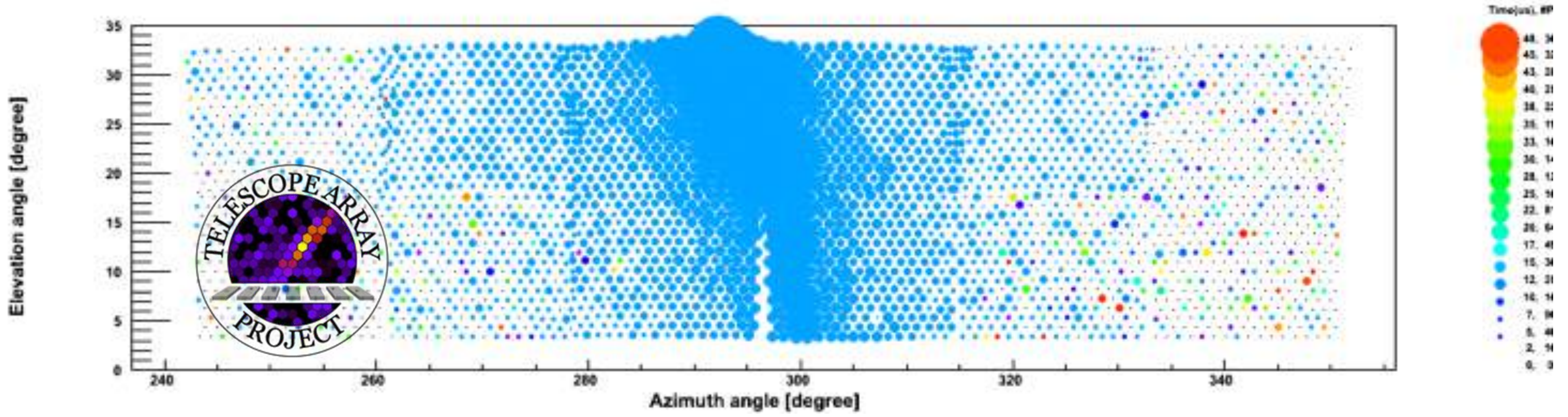




TAFD
$\log E$ = 18.08
R_{p} = 2.40 km

② 2016/10/05 10:25:50.781802380

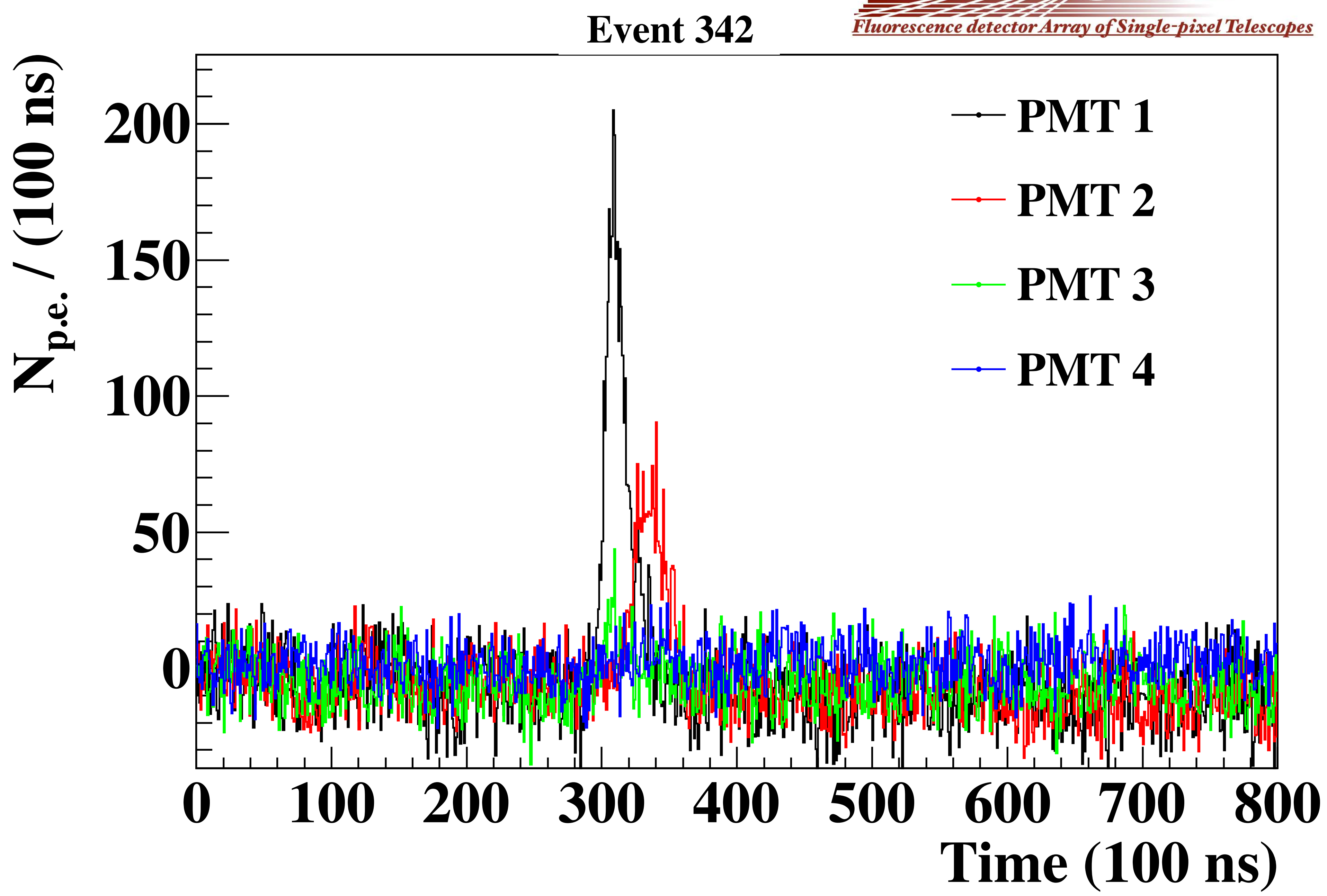


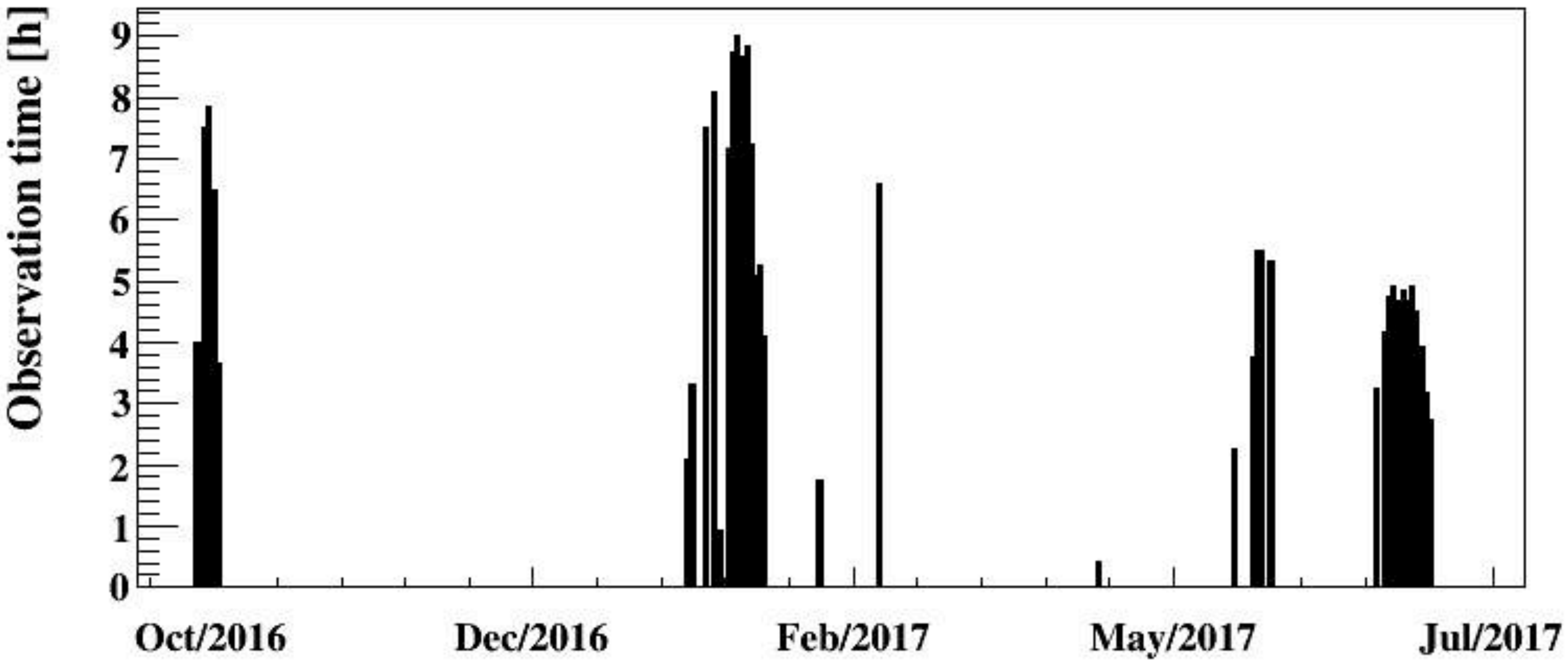


Too close

Highest UHECR, $\log E = 18.55$

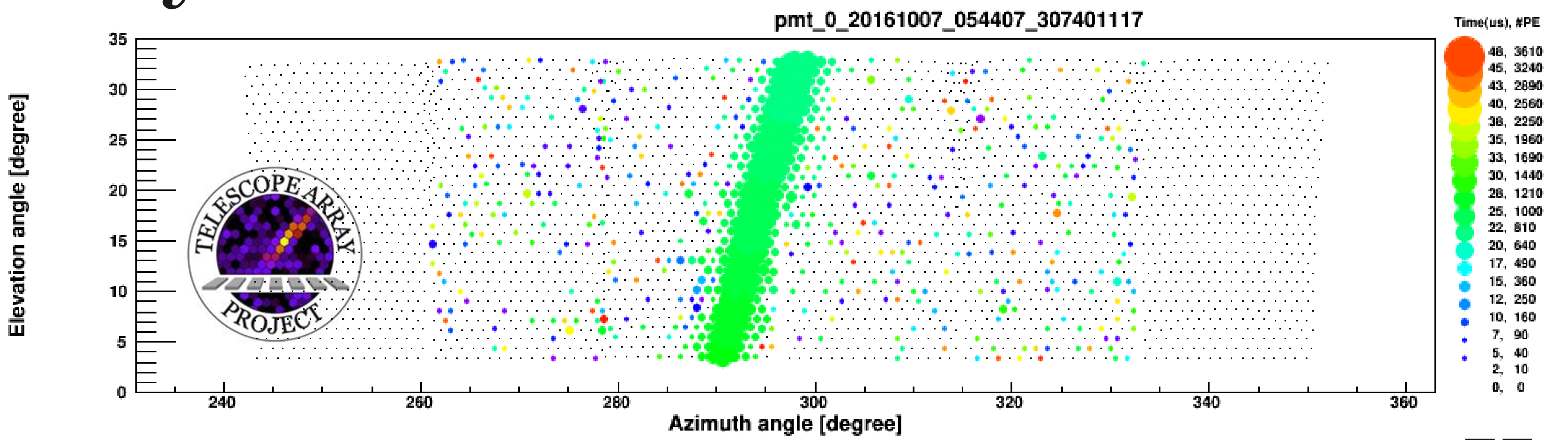
- Fully remote operation
  - Automated shutdown procedure
  - Monitor a shutter by an infrared camera
    - IP camera (PIC1008WN), relay module (ETH002)
- Total operation time reaches 201 hours by July.





18 events found by January (120 hours)

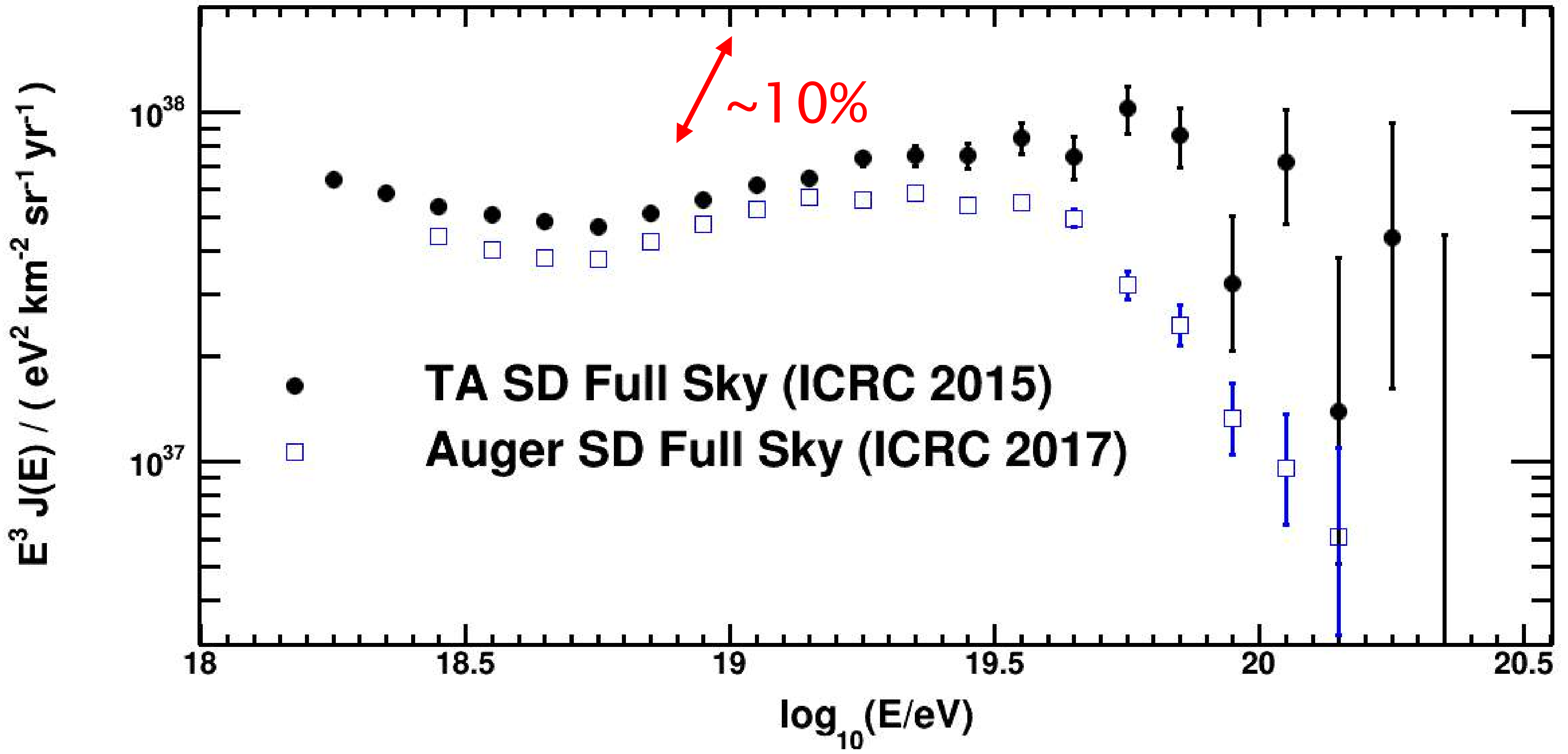
Highest event, $E=10^{18.55}$ eV, $R_p=3.0$ km by TA FD

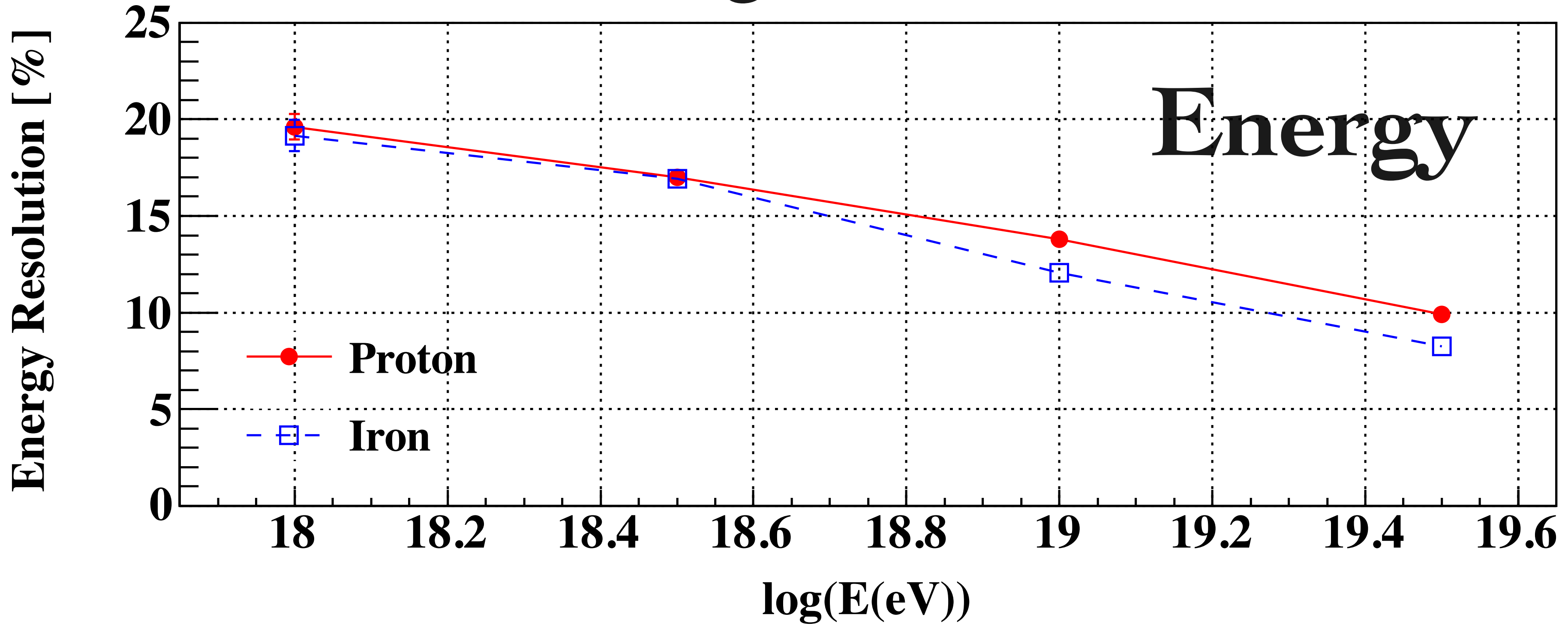


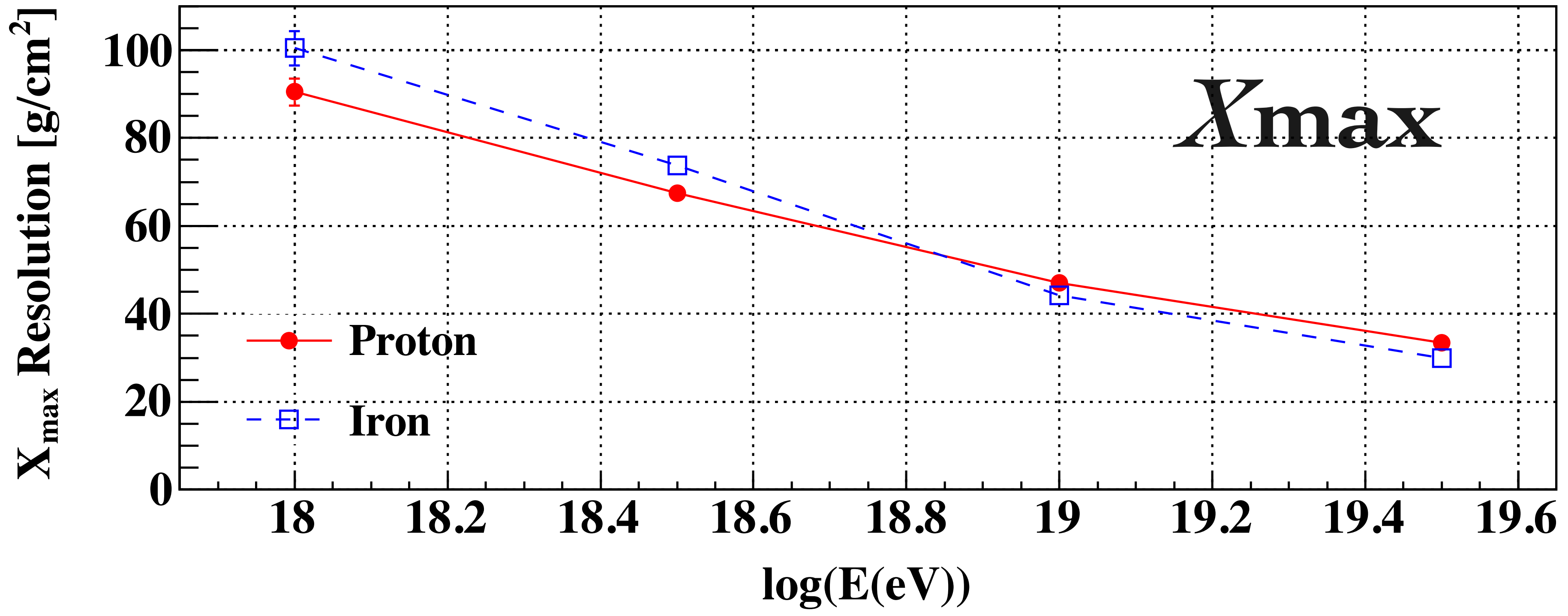
Fluorescence detector Array of Single-pixel Telescopes

Possible Application of FAST Prototype

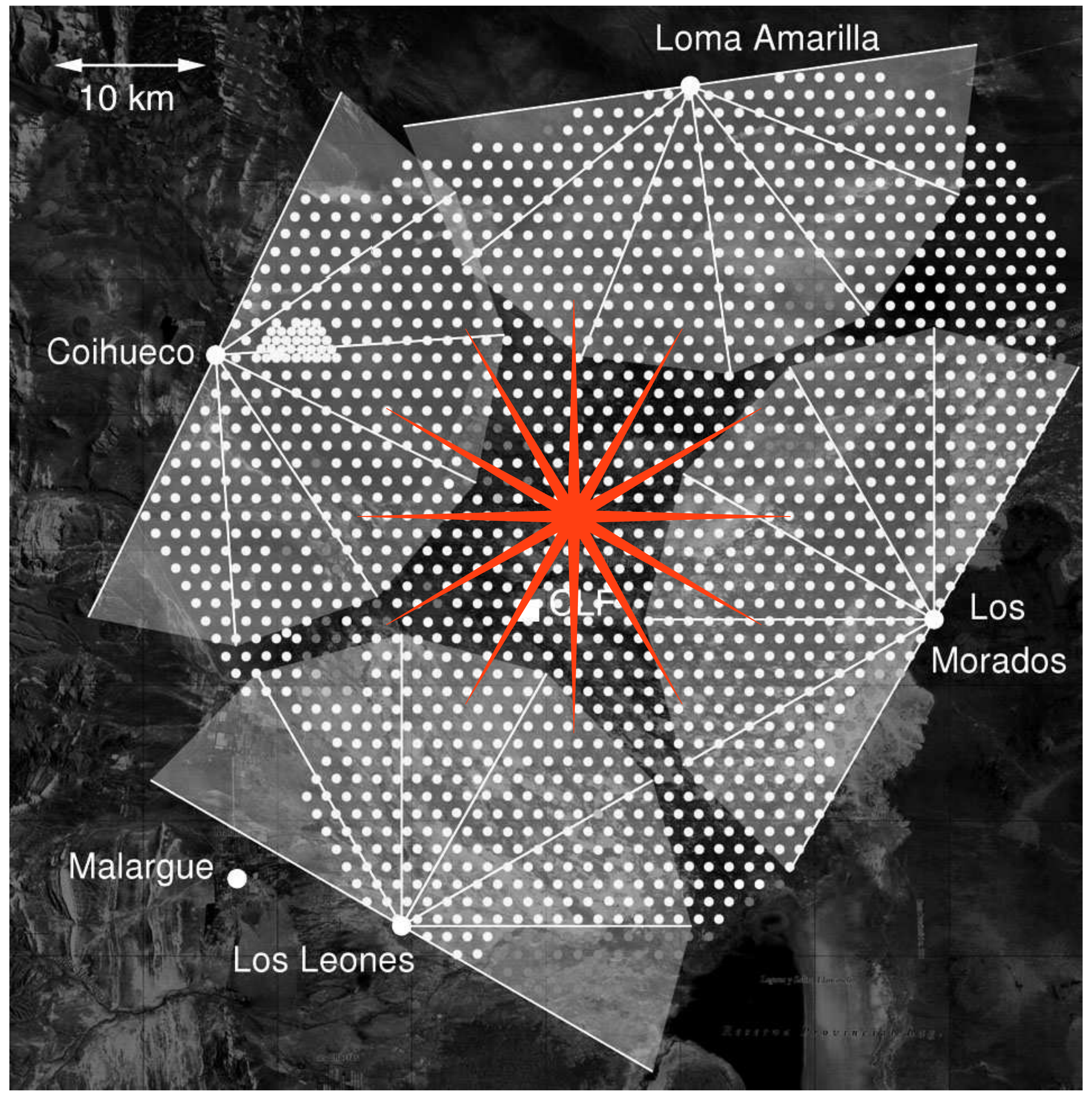
- Install FAST at Auger and TA for a cross calibration.
- Profile reconstruction with geometry given by SD (smearing gaussian width of 1° in direction, 100 m in core location).
  - Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
  - Independent cross-check of **Energy and Xmax** scale between Auger and TA





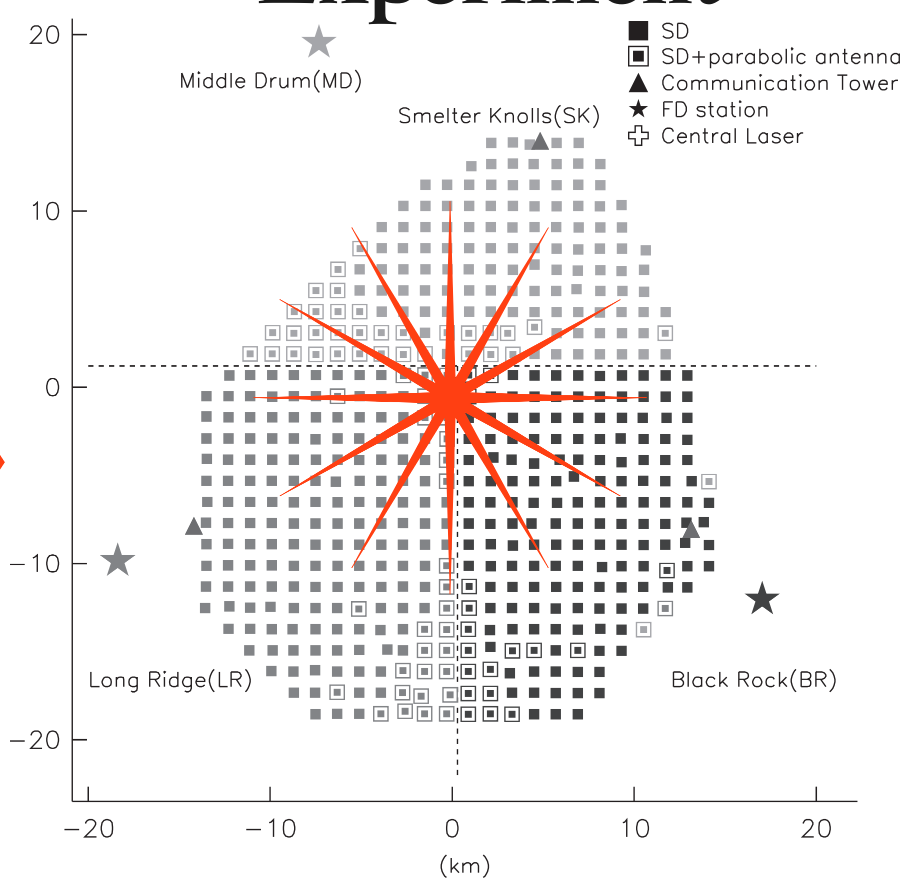


Pierre Auger Observatory



Identical simplified FD

Telescope Array Experiment

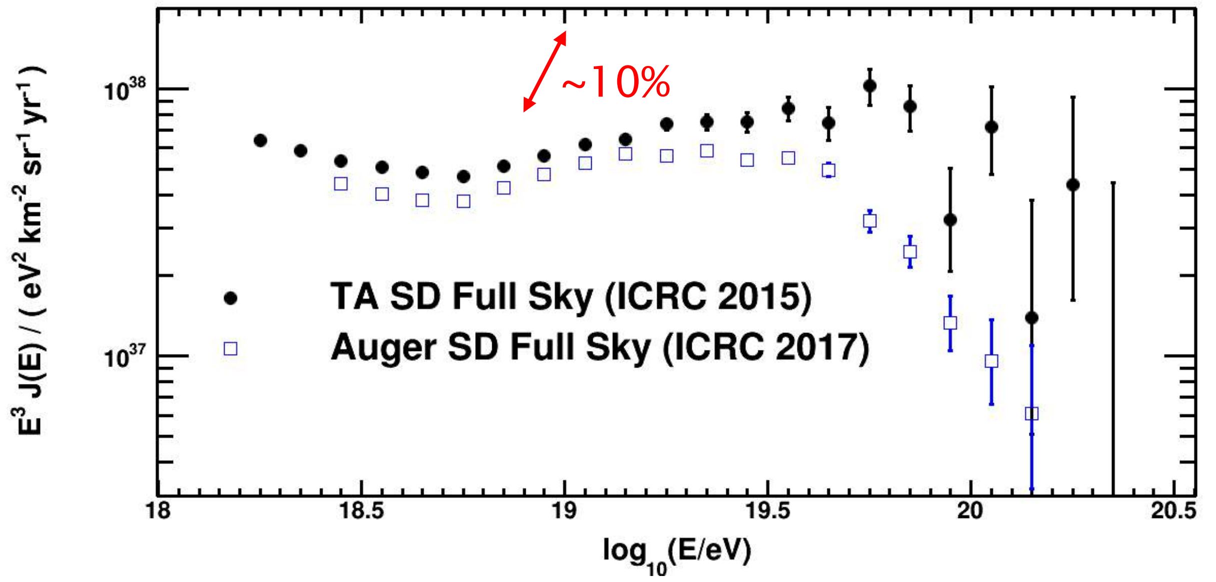


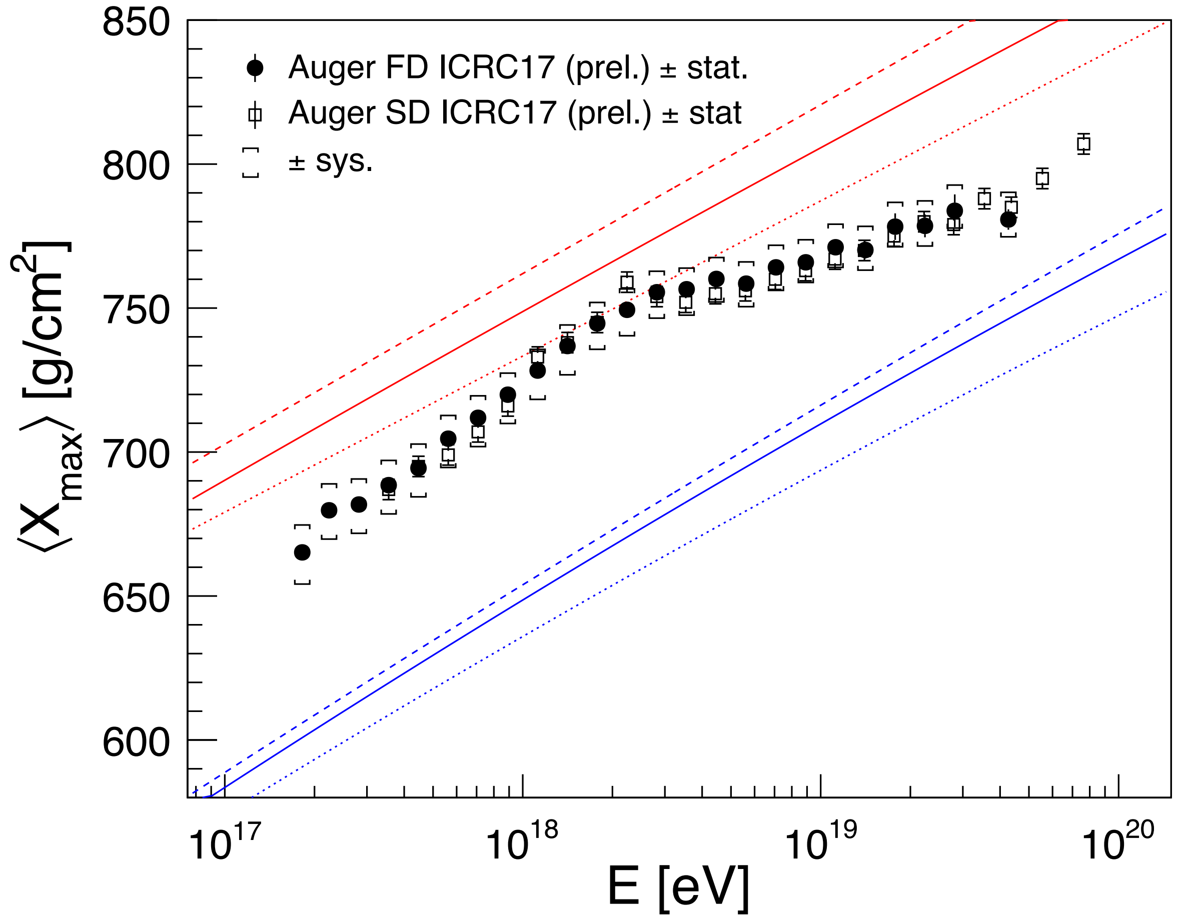
Pierre Auger Collaboration, NIM-A (2010)

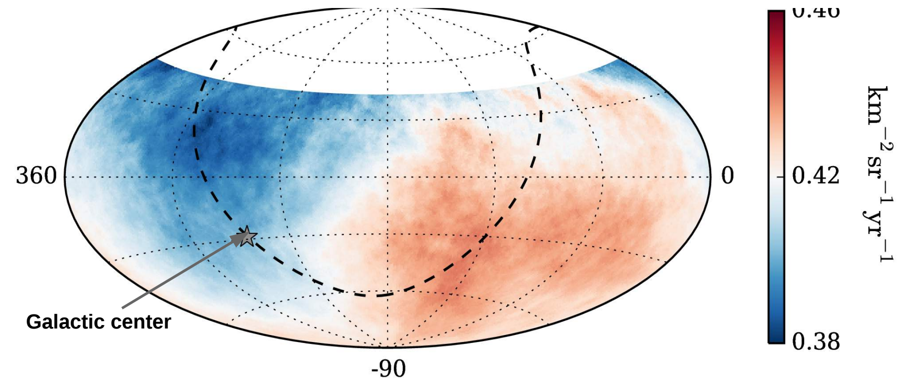
Telescope Array Collaboration NIM-A (2012)

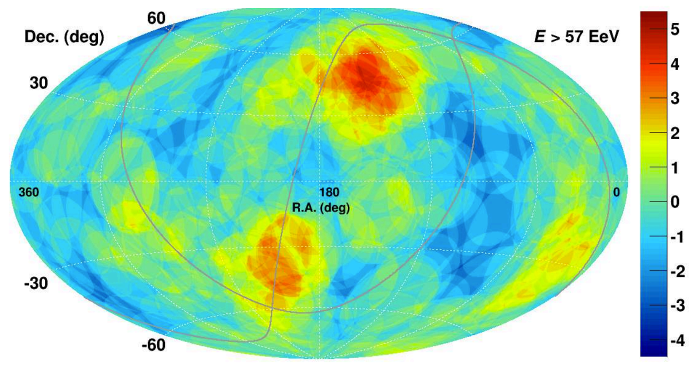
Summary

- Precise observation of the flux suppression above $10^{19.5}$ eV, discrepancy on suppression energy in TA/Auger.
- Gradually increase heavier composition above the ankle.
    - lighter composition above $10^{19.7}$ eV?
- Hot/warm spots, correlation with nearby star burst galaxy.
- **A next-generation observatory is essential to clarify origins of UHECRs.**
    - FAST: fluorescence detector array of Single-pixel Telescopes
        - Installed full-scale FAST prototype at TA site, and detects laser and UHECRs.
        - We will install two more telescopes in September 2017.
        - New collaborators are welcome.









FAST
Fluorescence detector Array of Single-pixel Telescopes

Future observatories: TA×4, AugerPrime, K-EUSO and FAST