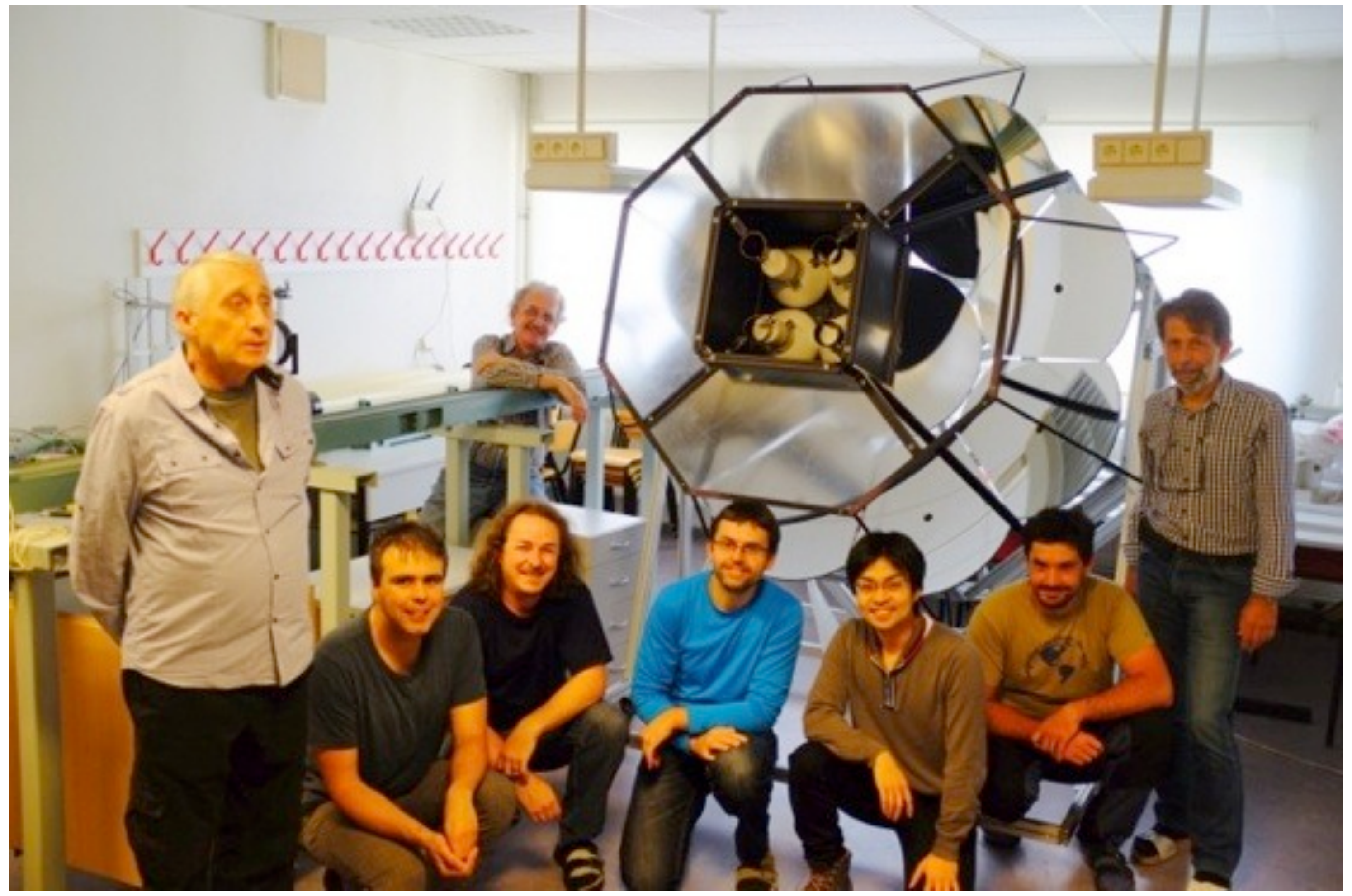
Future Perspectives on the UHECR Observatories and the FAST Project

TELESCOPE ARRAY PROJECT

FAST
Fluorescence detector Array of Single-pixel Telescopes

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



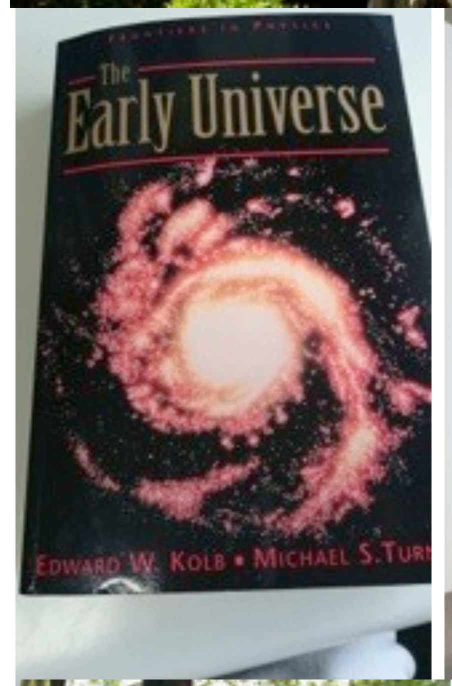
PIERRE AUGER OBSERVATORY

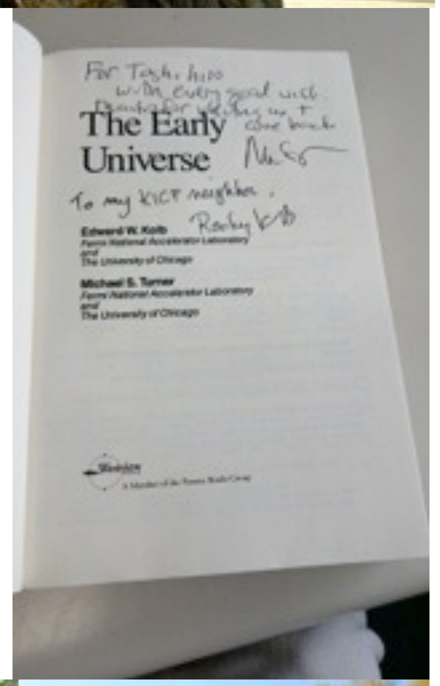
Toshihiro Fujii, ICRR Seminar, 2016/May/24

Toshihiro Fujii

fujii@icrr.u-tokyo.ac.jp

Office: 303, Hometown: Nara, Ikaruga-cho, Horyuji (法隆寺)





Professional Experience

- 2016 - present: JSPS Postdoctoral Fellow (PD), Institute for Cosmic Ray Research, University of Tokyo
- 2015 - 2016: Postdoctoral Scholar, Kavli Institute for Cosmological Physics, University of Chicago
- 2013 - 2016: Collaborative Researcher, Institute for Cosmic Ray Research, University of Tokyo
- 2013 - 2015: Japan Society for the Promotion of Science (JSPS) Postdoctoral Fellow Kavli Institute for Cosmological Physics, University of Chicago
- 2012 - 2013: JSPS Postdoctoral Fellow (PD), Institute for Cosmic Ray Research, University of Tokyo

Education

- 2012: Ph.D. in Science, Osaka City University
  Thesis: "Measurements of the Energy Spectrum and the Mass Composition of Ultra-High Energy Cosmic Rays with Telescope Array Fluorescence Detectors in Monocular Mode"
  Supervisor: Prof. Shoichi Ogio

Research Grants and Fellowships

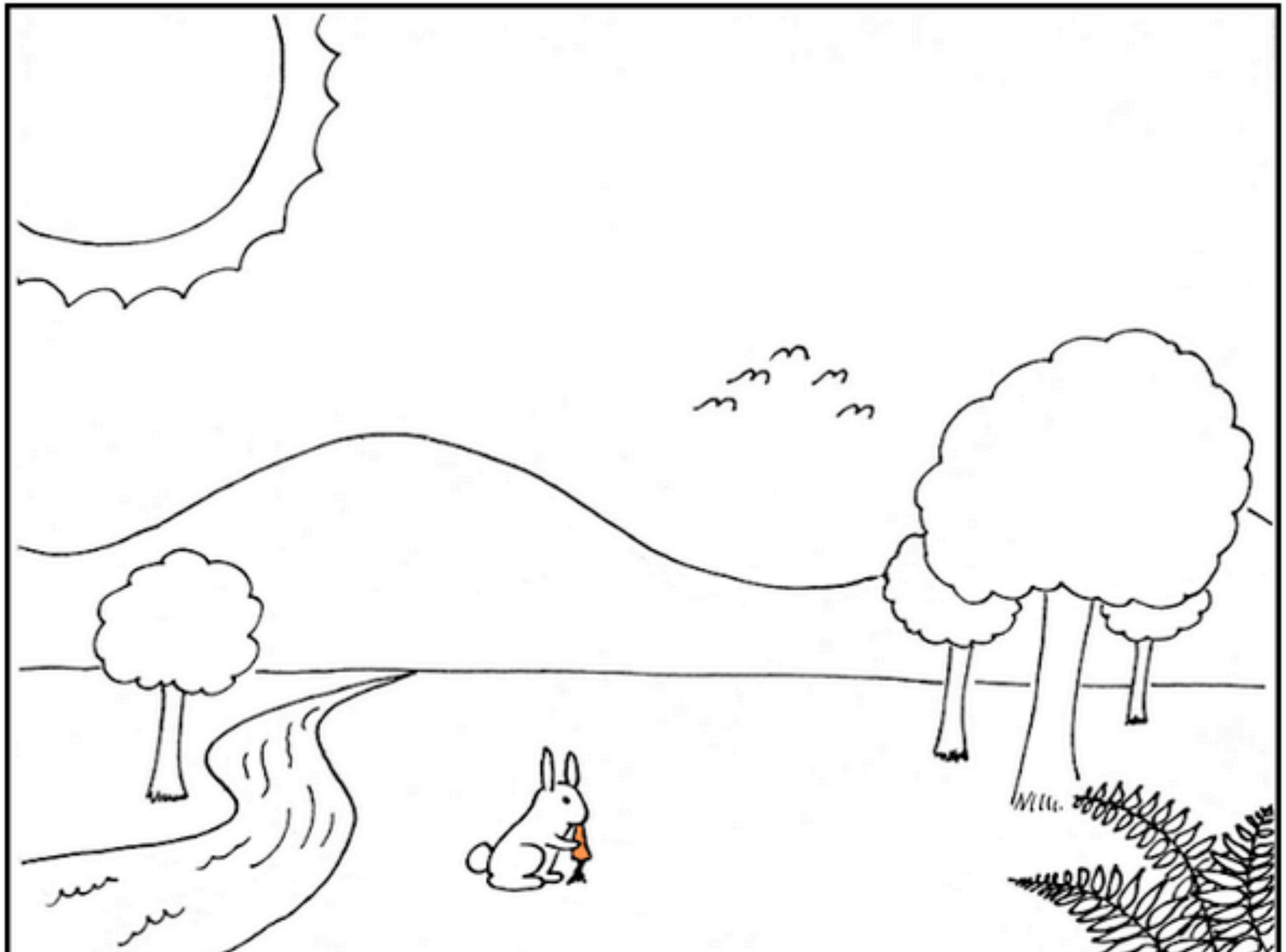
- 2016 - present: JSPS Grant-in-Aid for JSPS Fellows, Grant Number 16J04564, **Principal Investigator**, Title: "Observation of Ultra-High Energy Cosmic Rays and Measurement of Their Mass Composition with the New-Type Fluorescence Detector", University of Tokyo, 3,400,000 JPY (Total expected direct expense)
- 2015 - present: JSPS Grant-in-Aid for Young Scientist (A), Grant Number 15H05443, **Principal Investigator**, Title: "Establishment of New Technique to Observe Ultra-High Energy Cosmic Rays by the New-Type Fluorescence Detector", University of Tokyo, 18,600,000 JPY (Total expected direct expense)

Research Interests

Cosmic Ray Physics, Ultra-High Energy Cosmic Rays (UHECR), Fluorescence Detector, Energy Spectrum, Mass Composition, Ultra-High Energy Neutrino and γ-ray, Particle Astronomy

This is how scientists see the world.

credit: http://abstrusegoose.com



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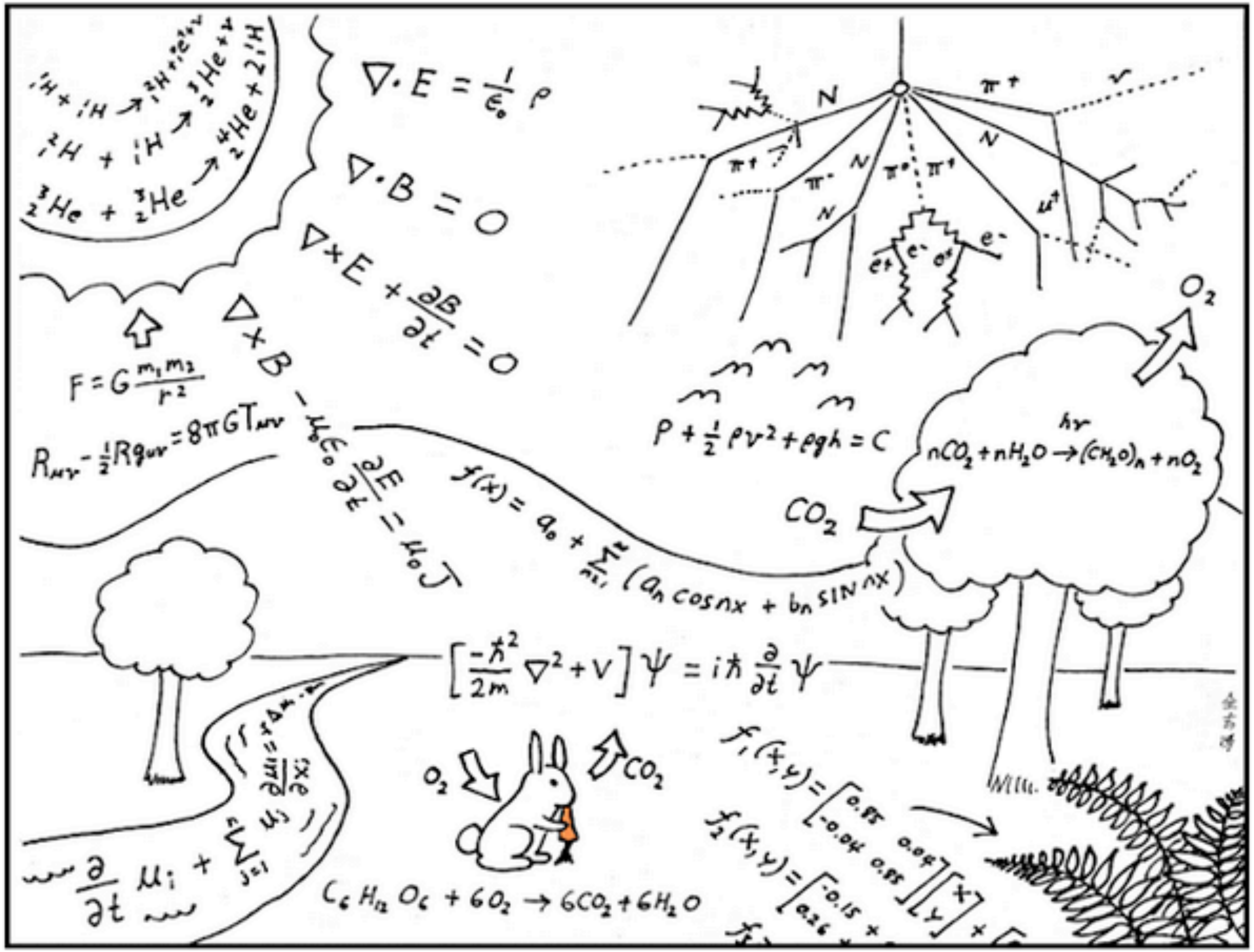

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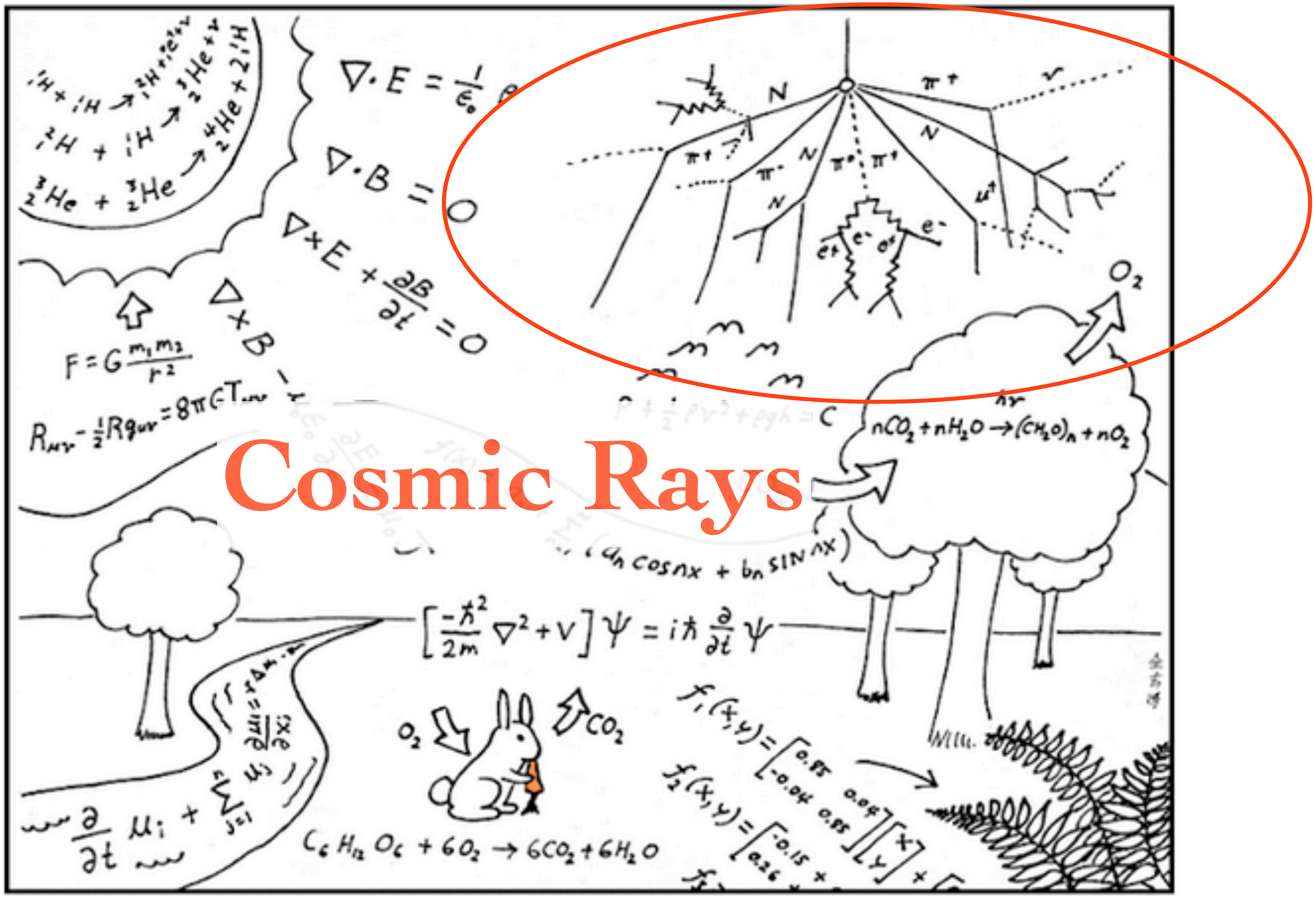
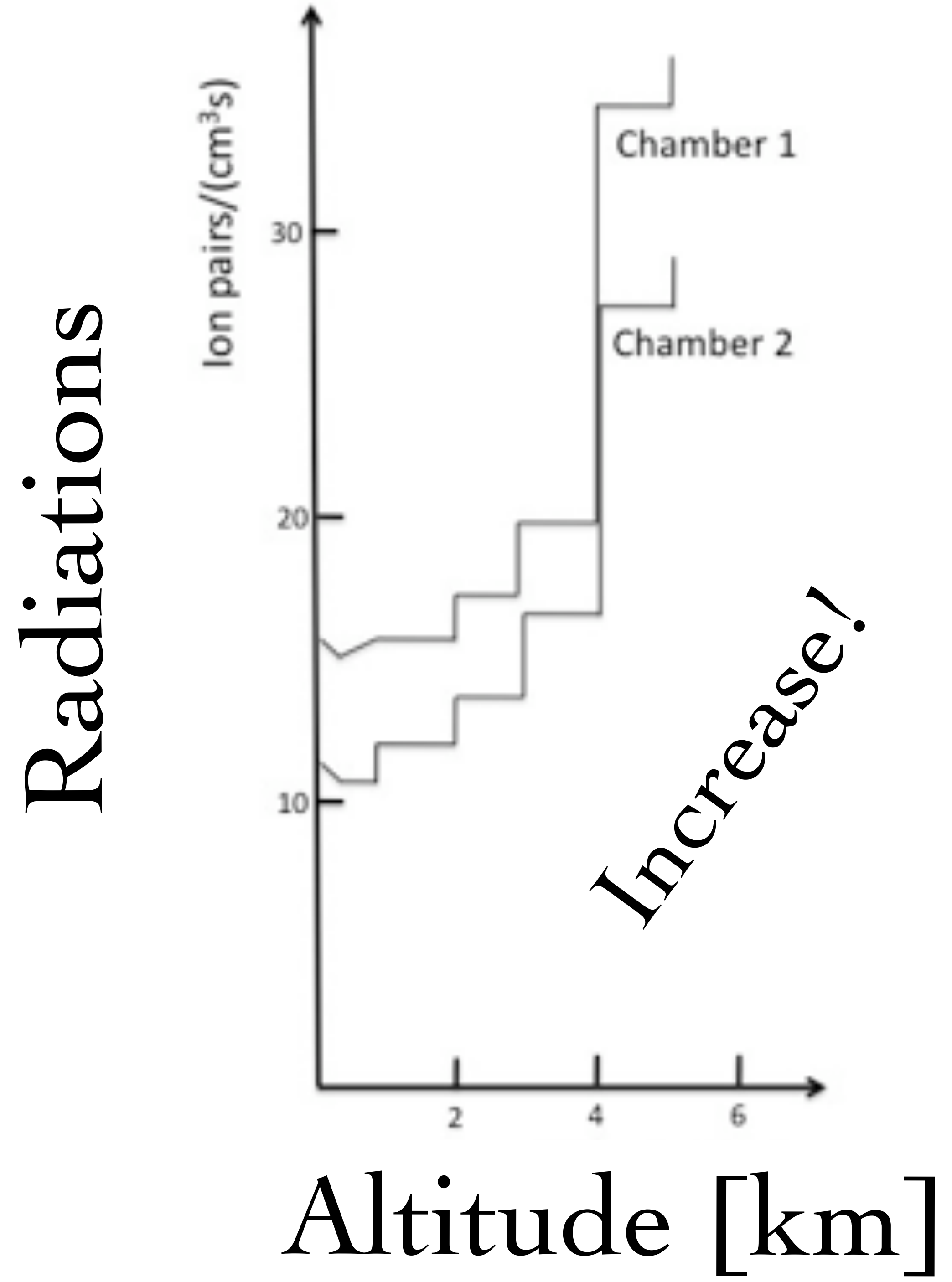


What are Cosmic Rays?

- Energetic particles injected from the universe.
- Discovered by V. F. Hess (1912)
  - **Proton(90%), Helium(8%) or heavier nuclei (1%)**
  - **E > 10^{19} eV, ultra-high energy cosmic rays (UHECR)**




Grandson of Hess

Memorial Stone

Cosmic Ray Anniversary on Aug. 7th 2012

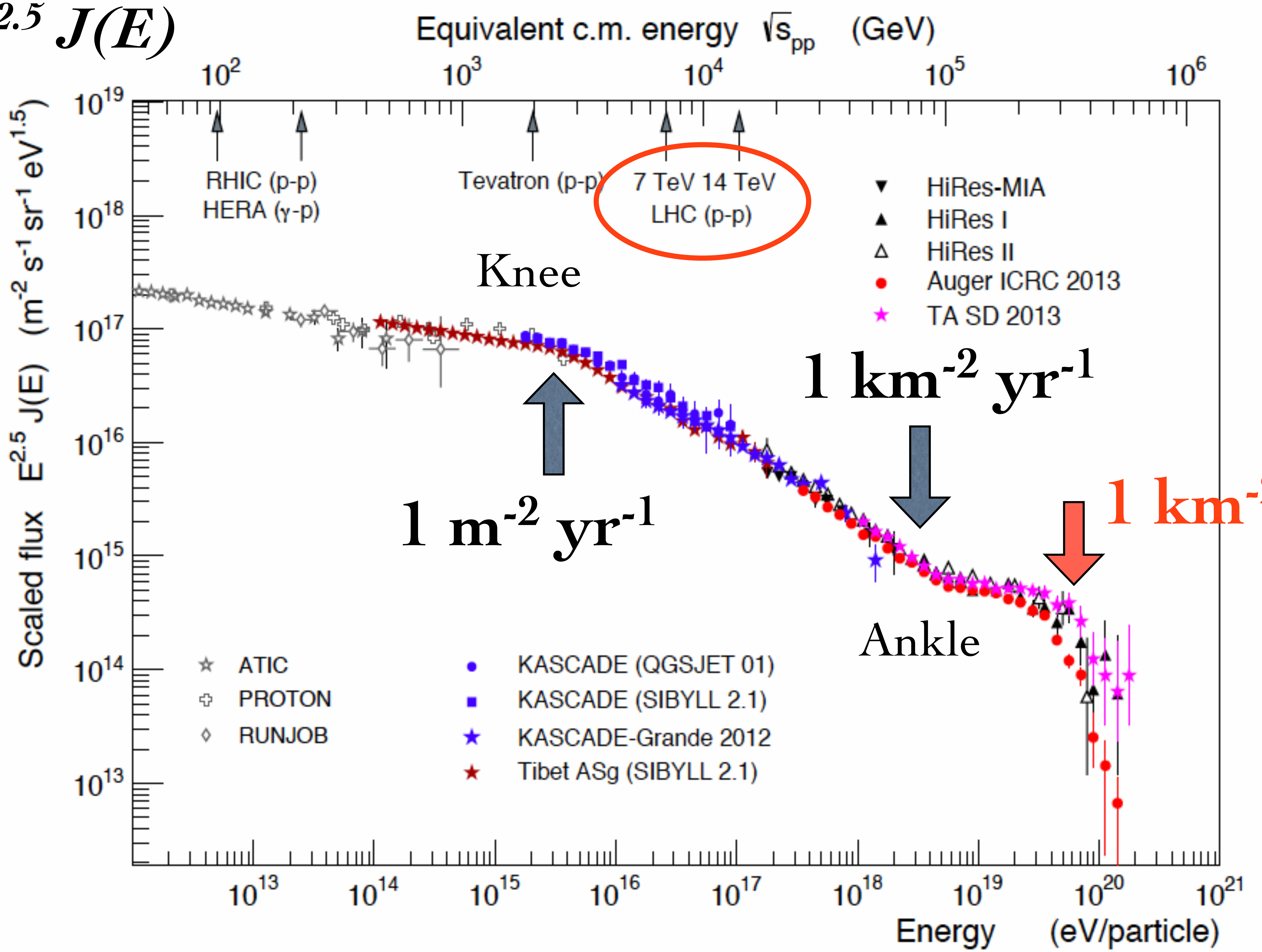
Physics Goal of UHECR Astrophysics

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

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

How frequent?: Energy spectrum

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

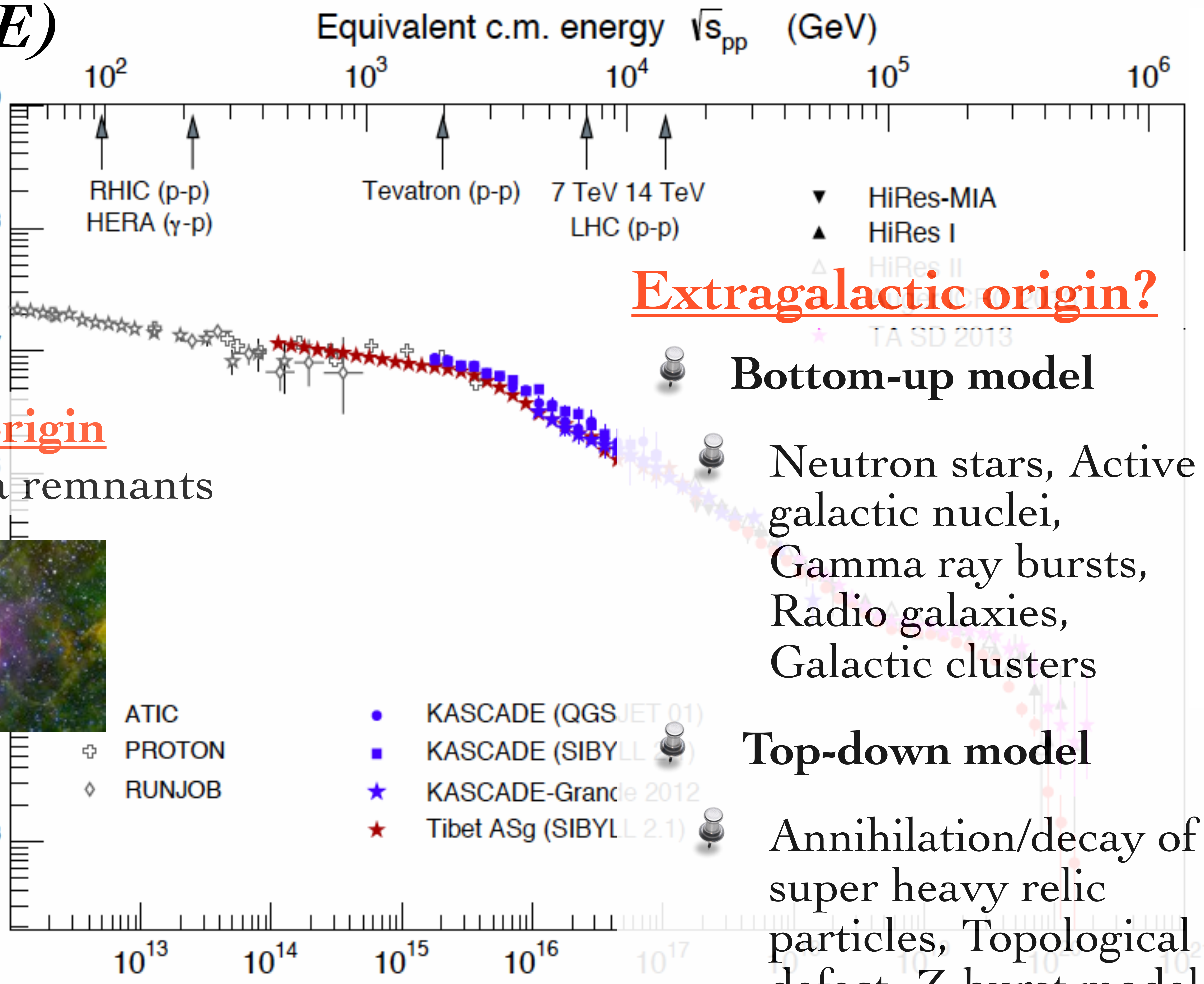


Larger energy than the largest accelerator (LHC)

Very infrequent, a large sensitive area needed

Acceleration Scenario toward 10^{20} eV

$E^{2.5} J(E)$

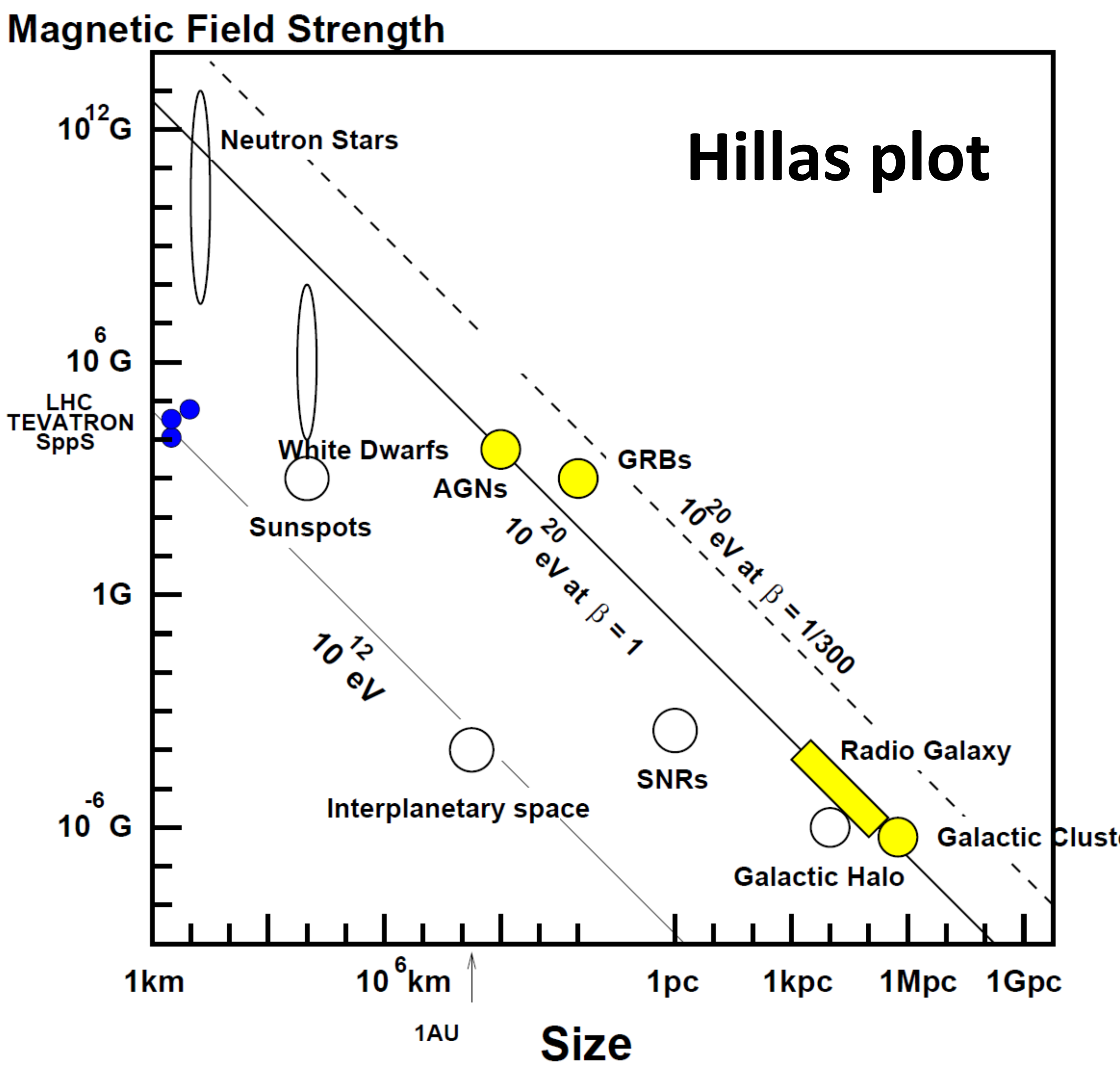


Galactic origin

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, Z-burst model

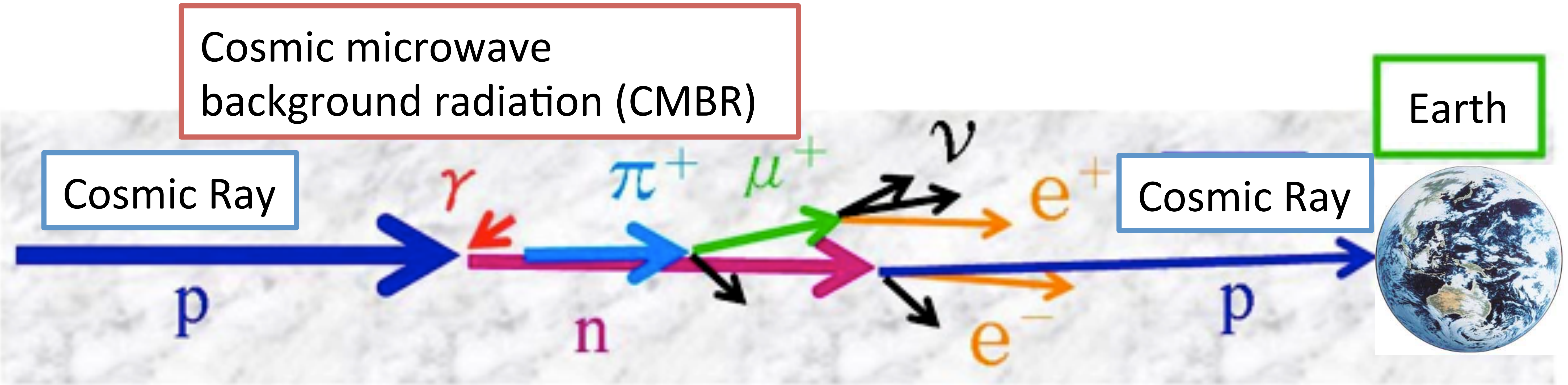


$$E_{\max} \leq \gamma e Z B R$$

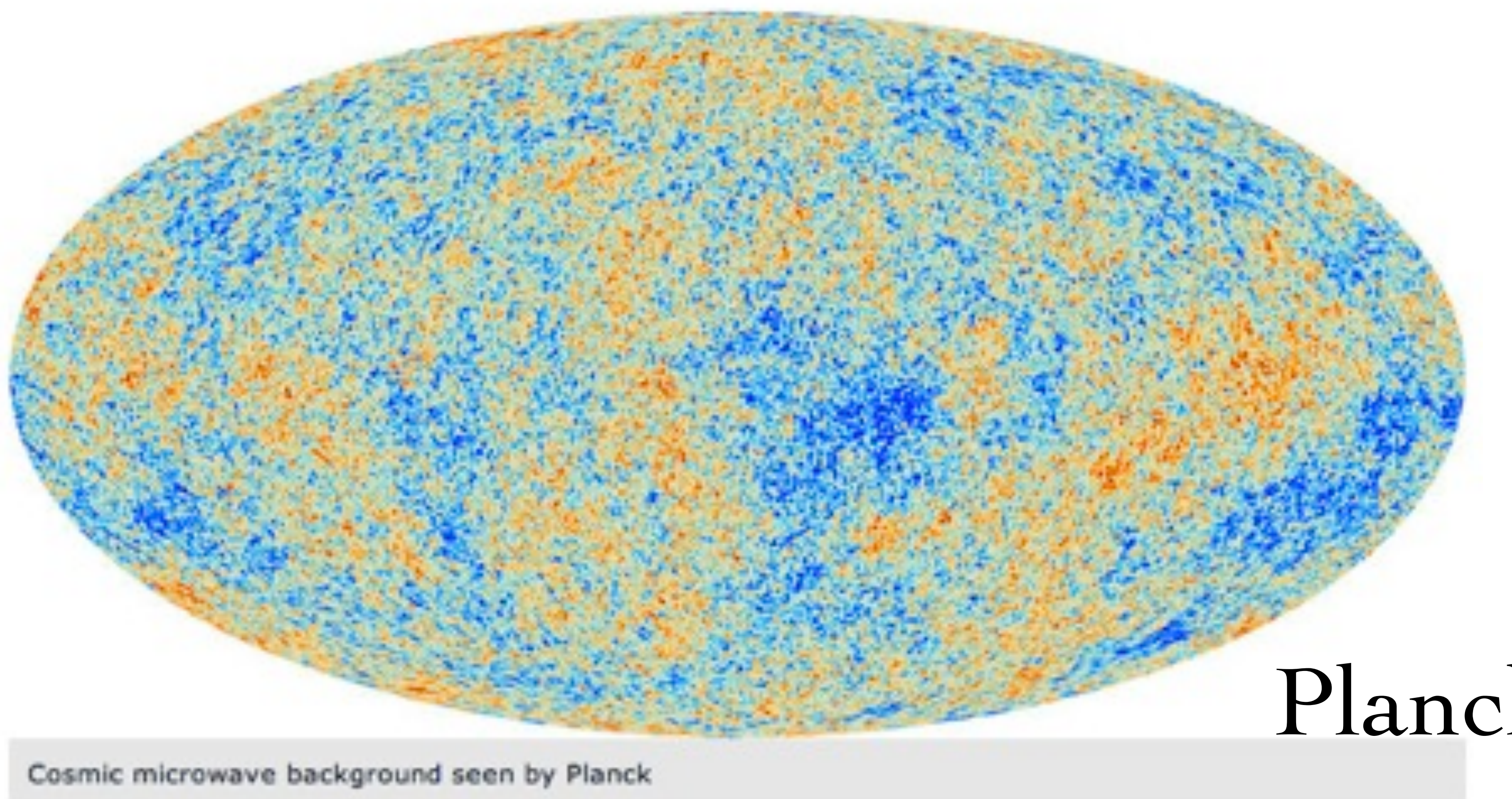
γ : Lorentz factor of shock
Z : atomic number
B : magnetic field strength
R : size

SCIENCE VOL 339 15 FEBRUARY 2013

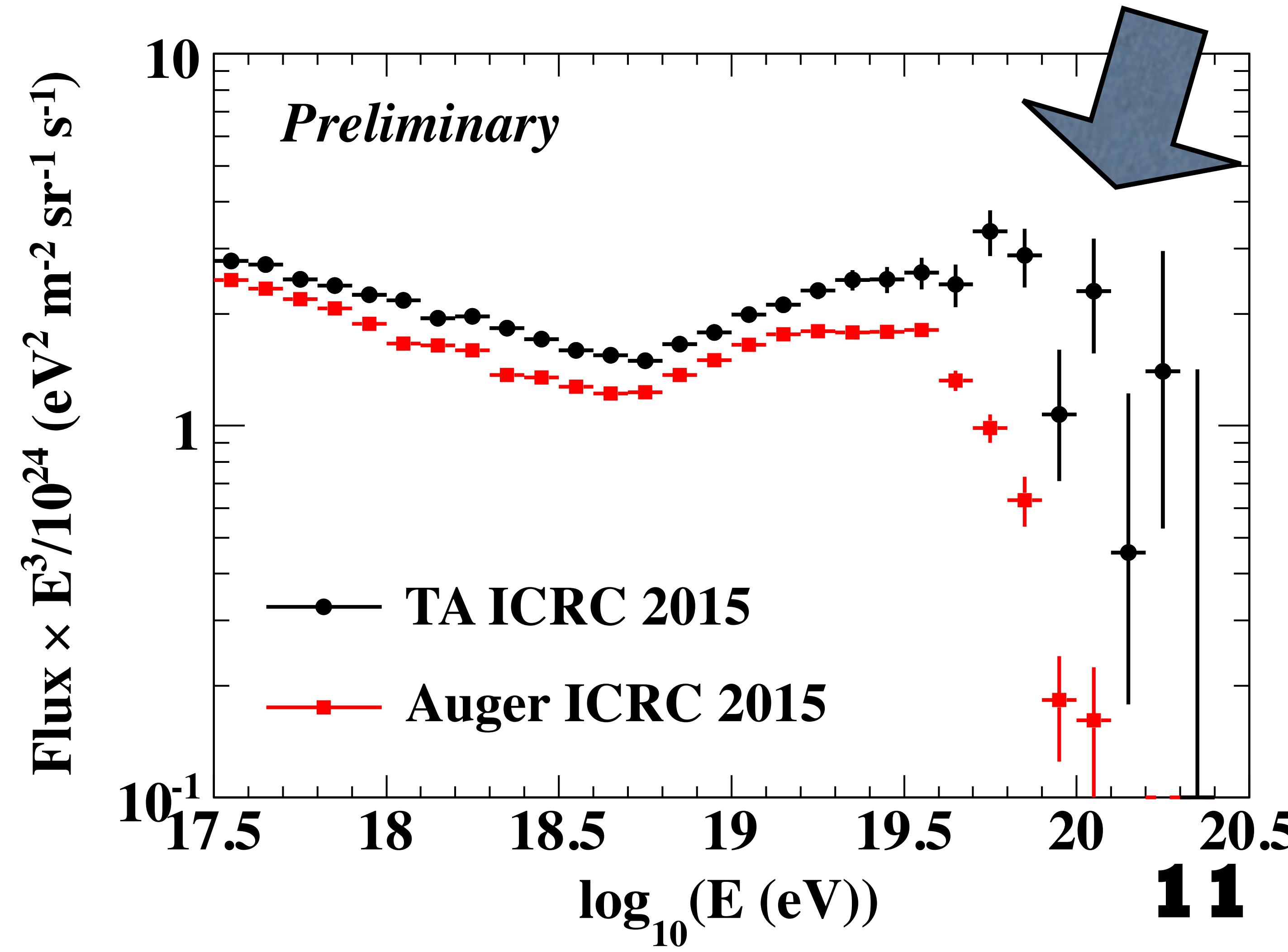
Greisen-Zatsepin-Kuzmin (GZK) Cutoff



- Interaction between UHE **protons** with energies above $\mathbf{10^{19.75}}$ **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



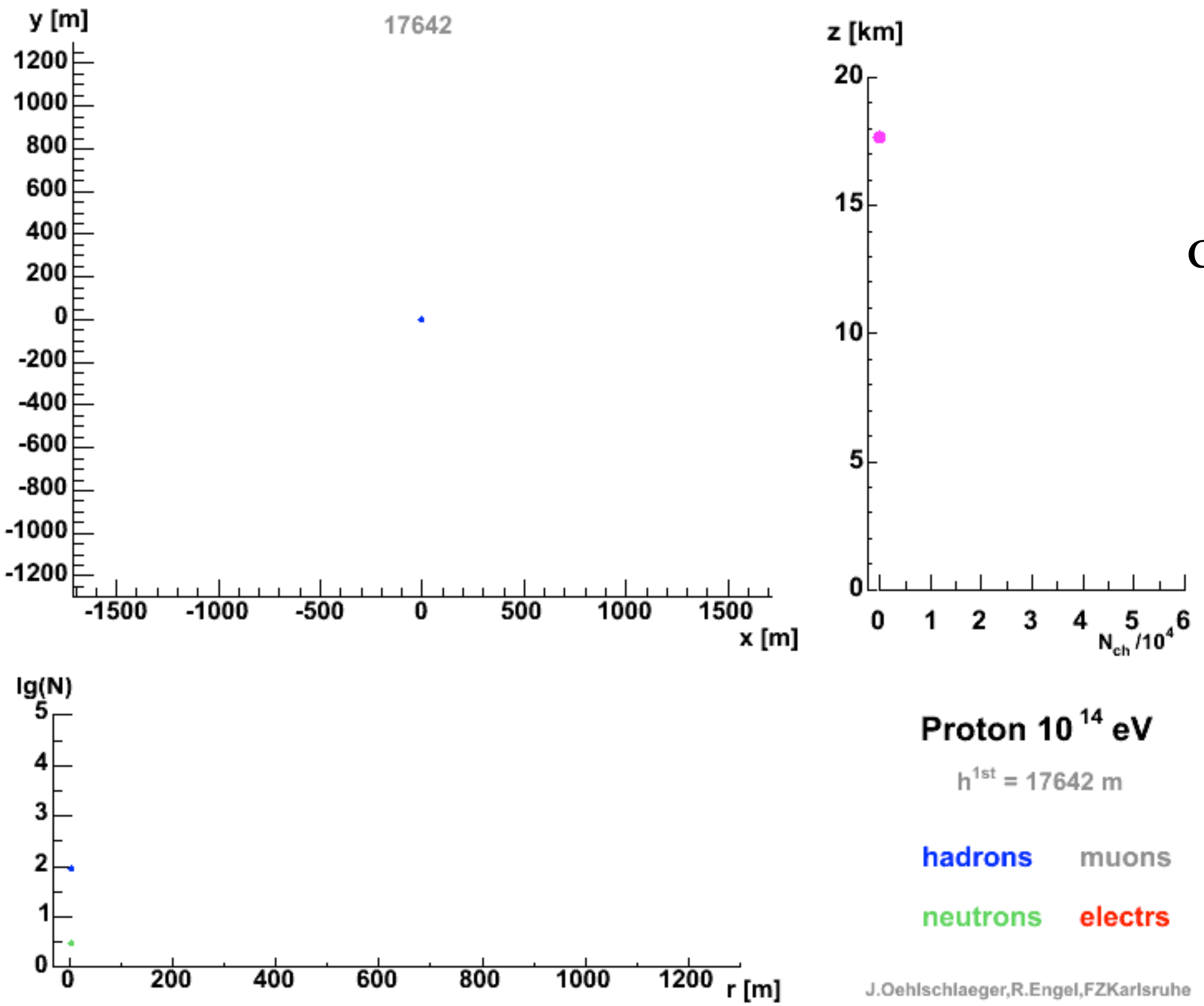
1 pc = 3.26 l.y. ~ 3×10^{16} m

How to detect very infrequent UHECRs?
= Extensive Air Shower (EAS)

Image credit: ASPERA/Novapix/L.Bret

How to observe Extensive Air Shower (EAS)

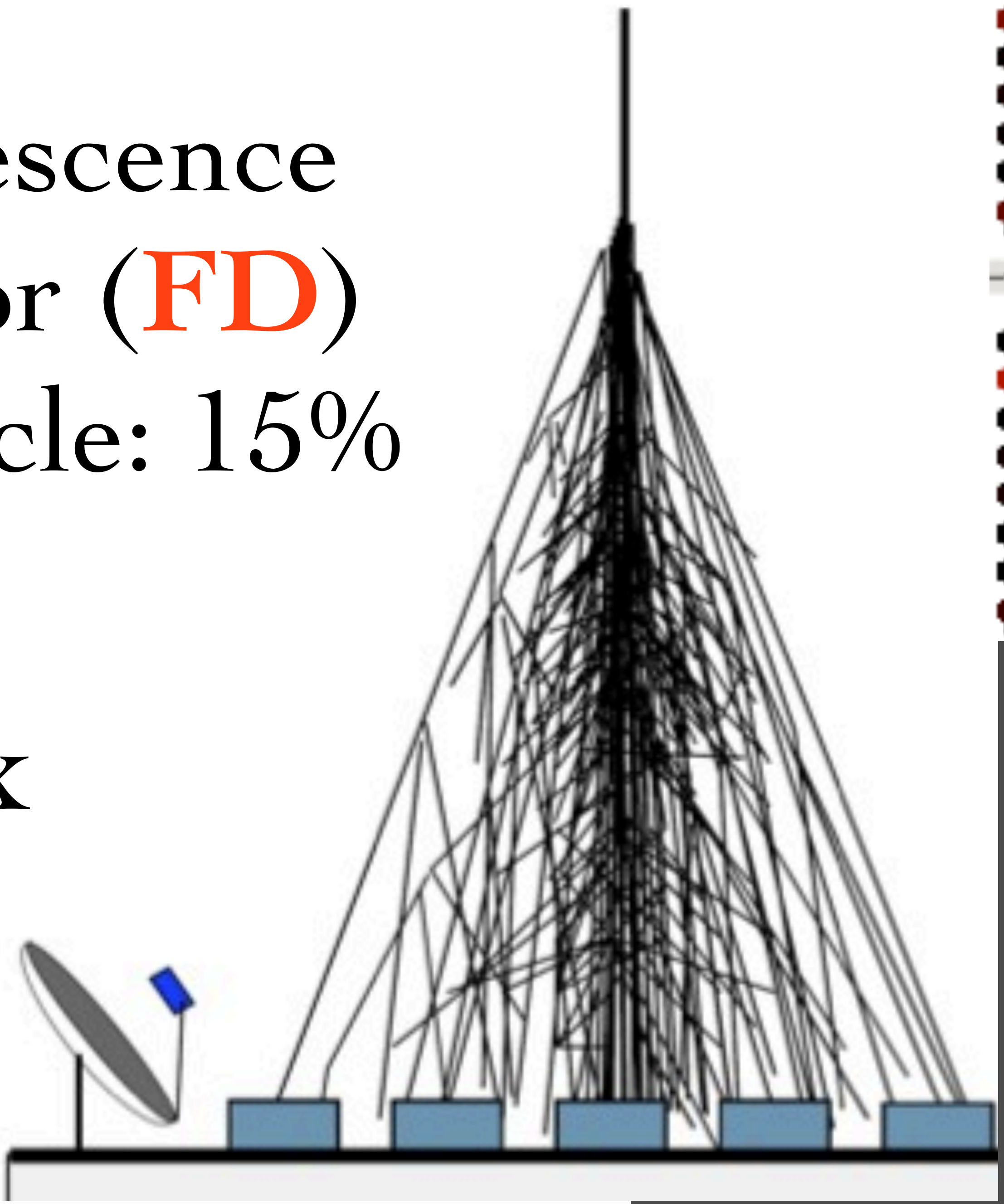
Longitudinal Development

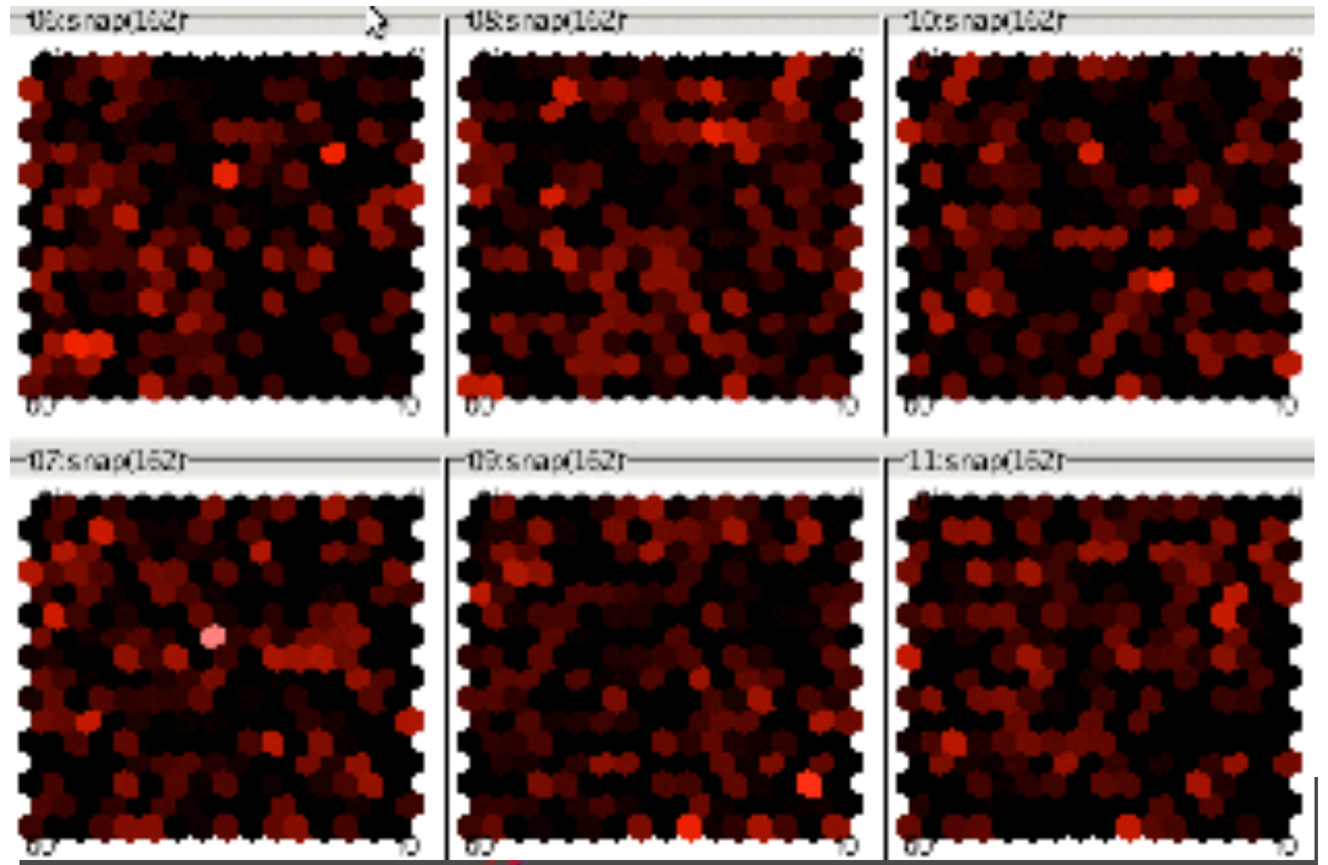


Lateral Density Distribution

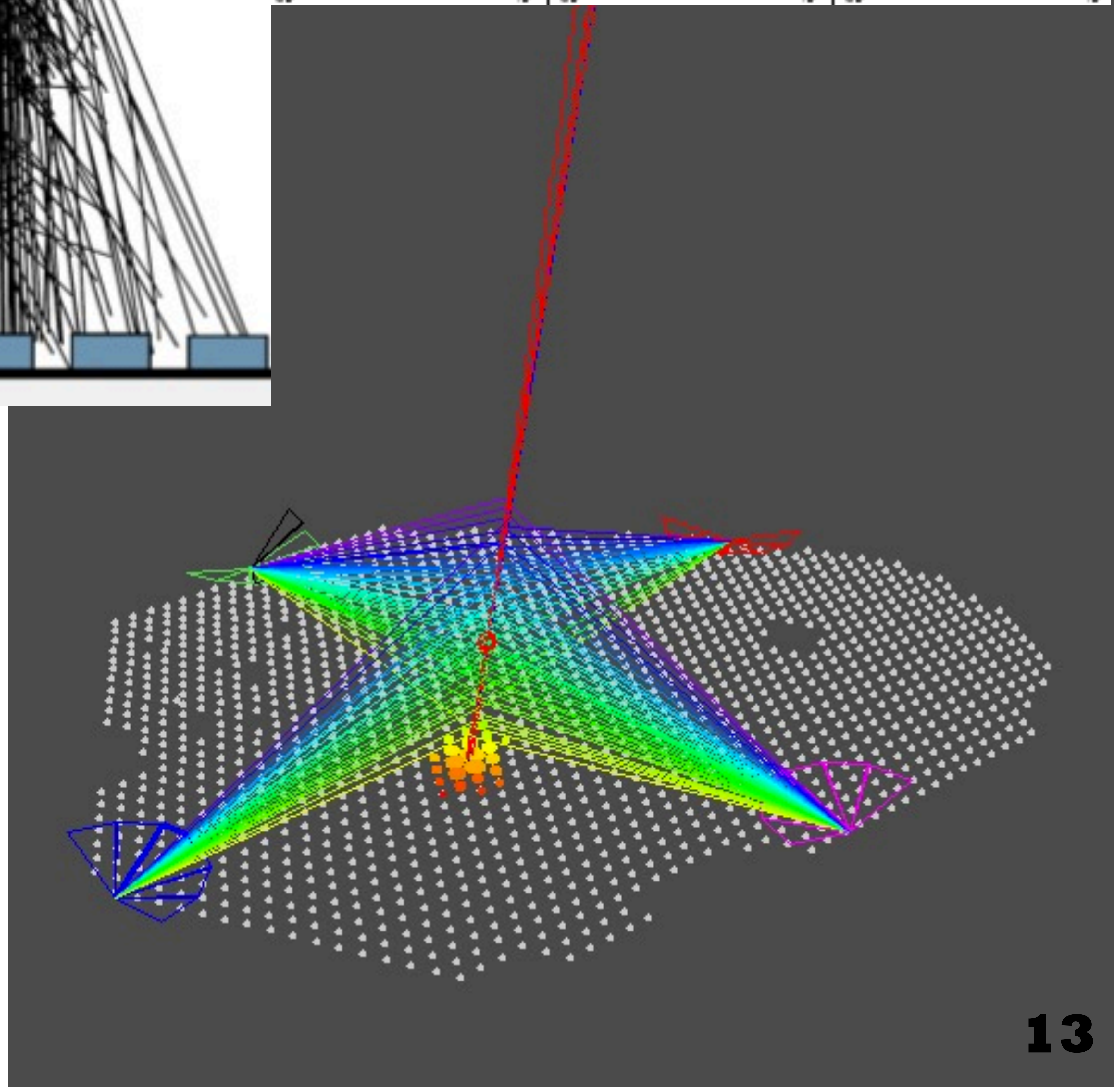
Fluorescence detector (**FD**)
duty cycle: 15%

Xmax





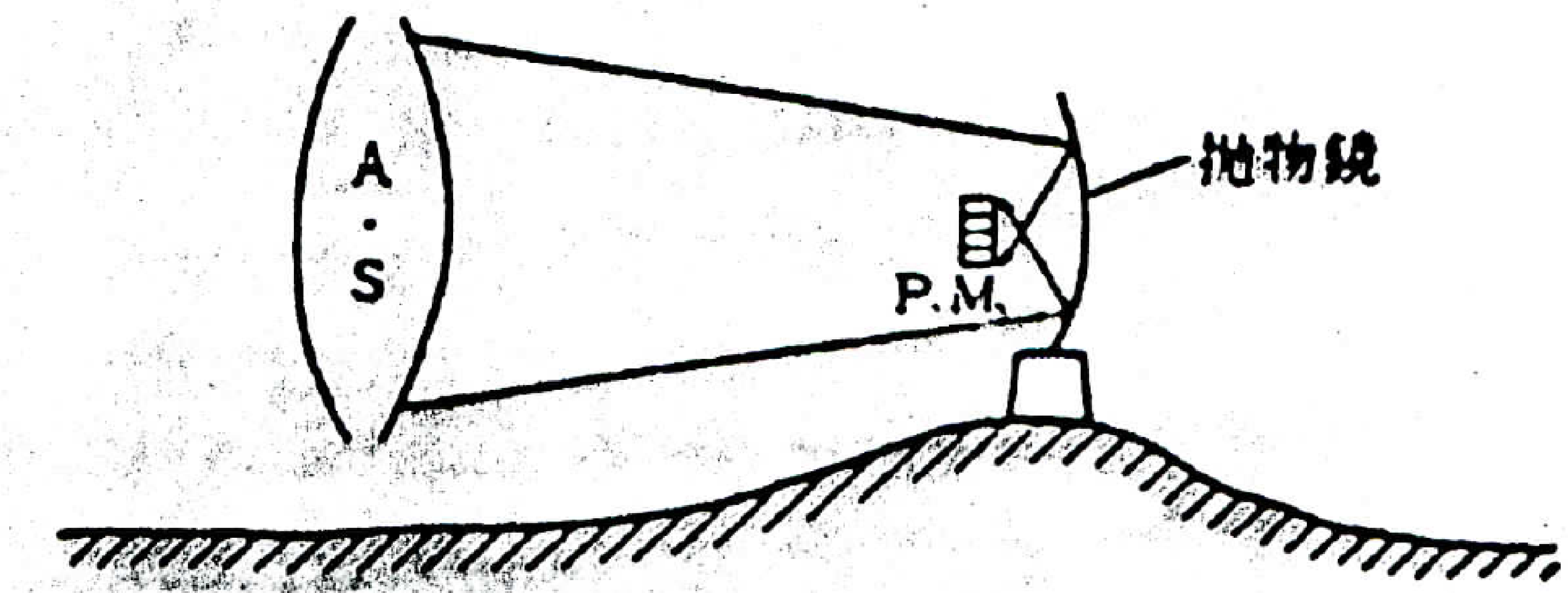
Surface detector array (**SD**)
duty cycle: 100%



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

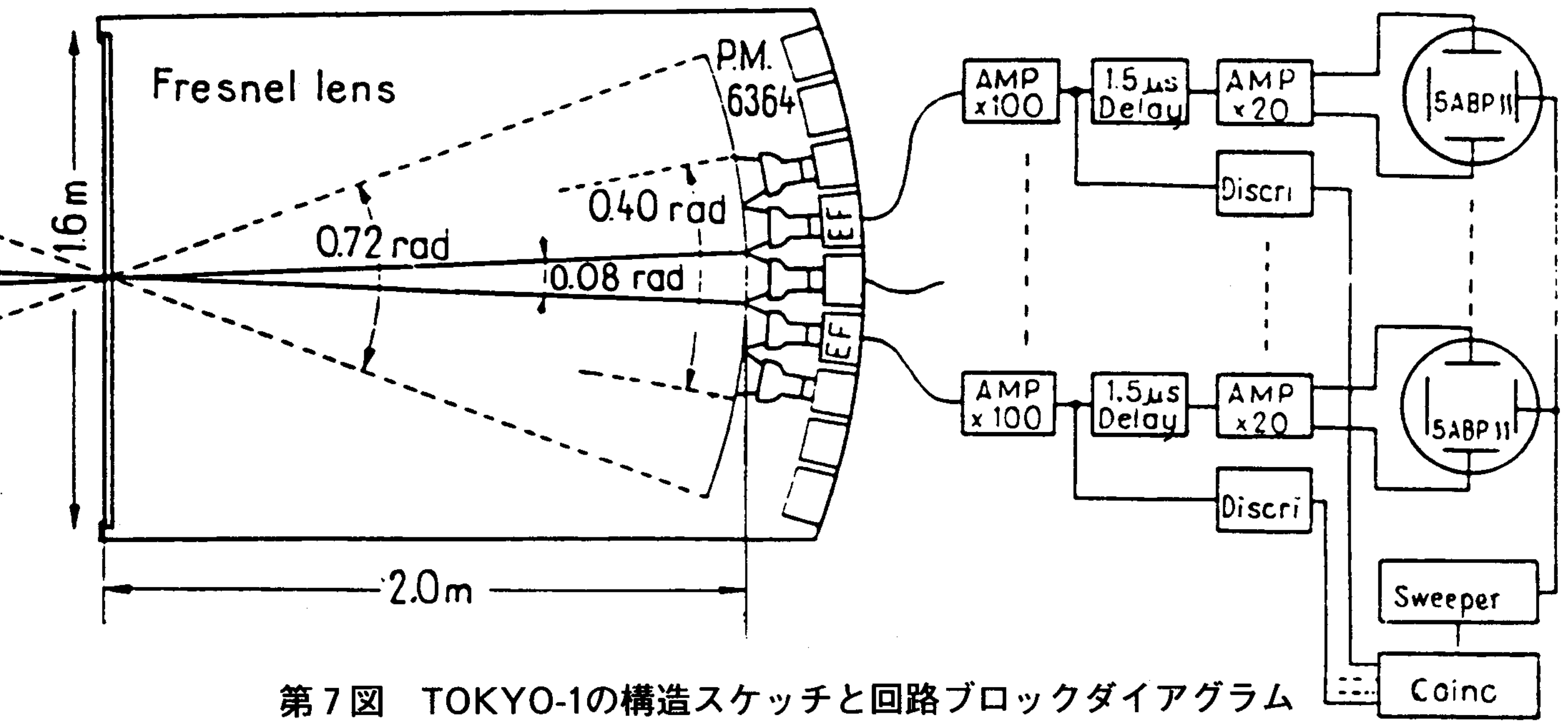
FAST
Fluorescence detector Array of Single-pixel Telescopes

History of Fluorescence Technique

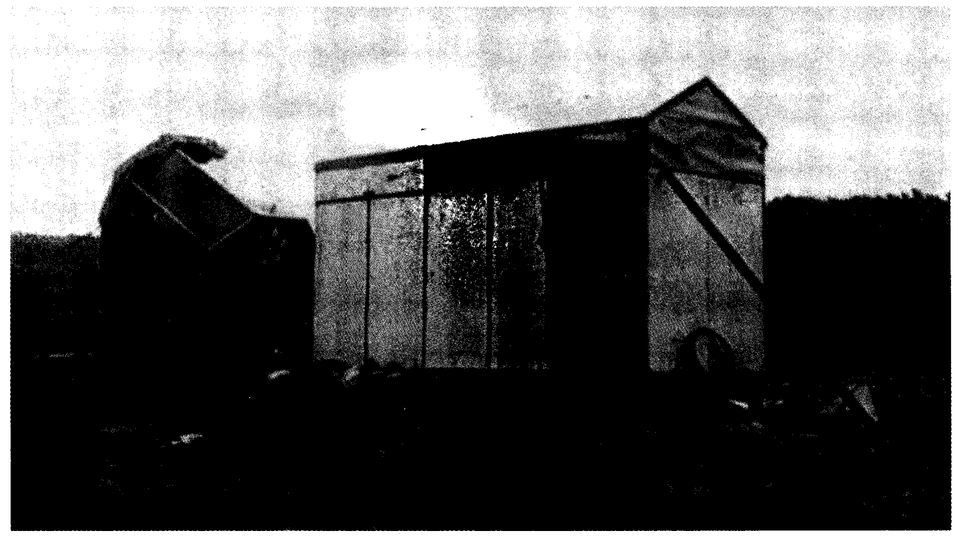


第3図 1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

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

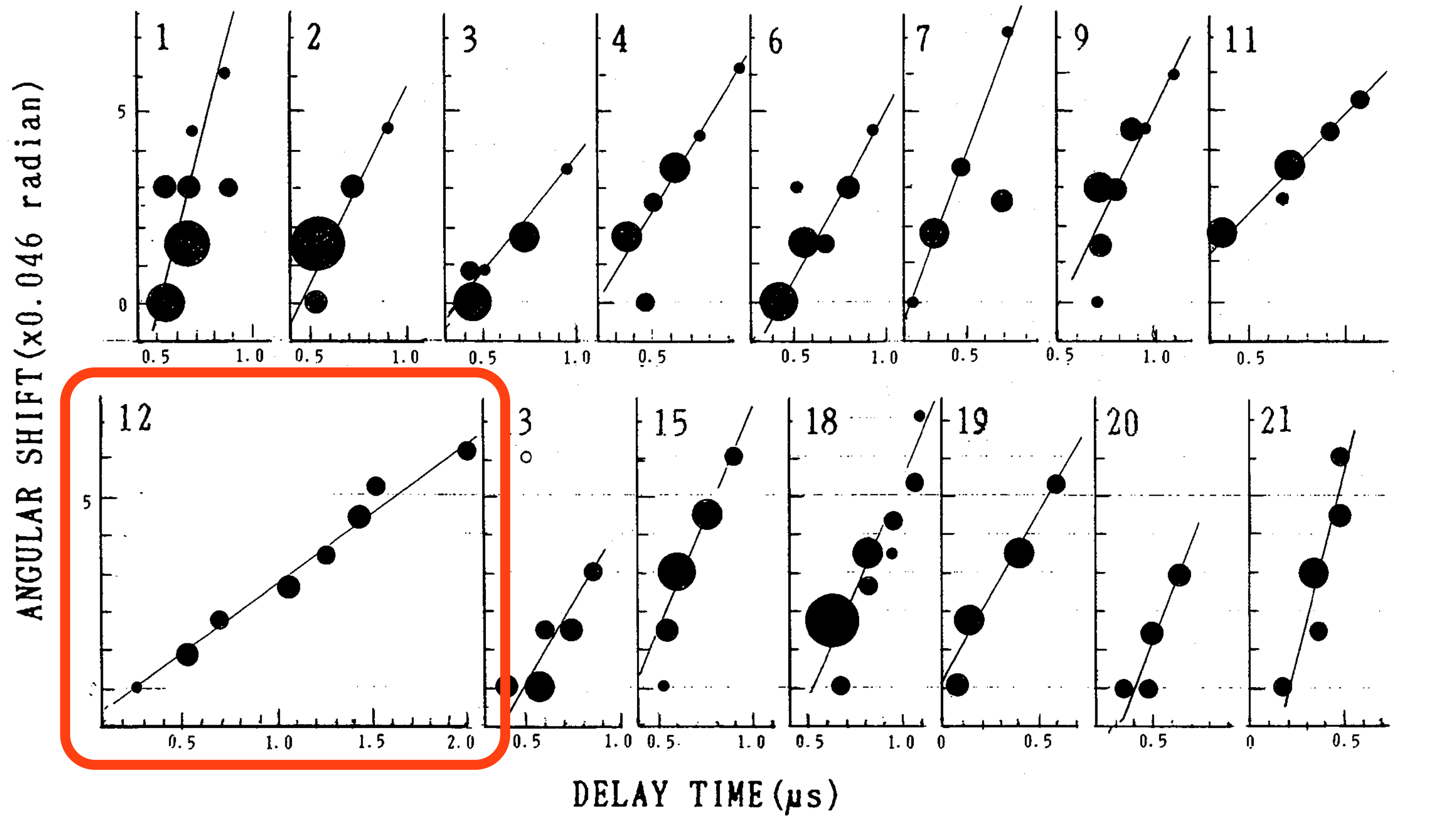

第８図 TOKYO−１の設置写真

- 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)

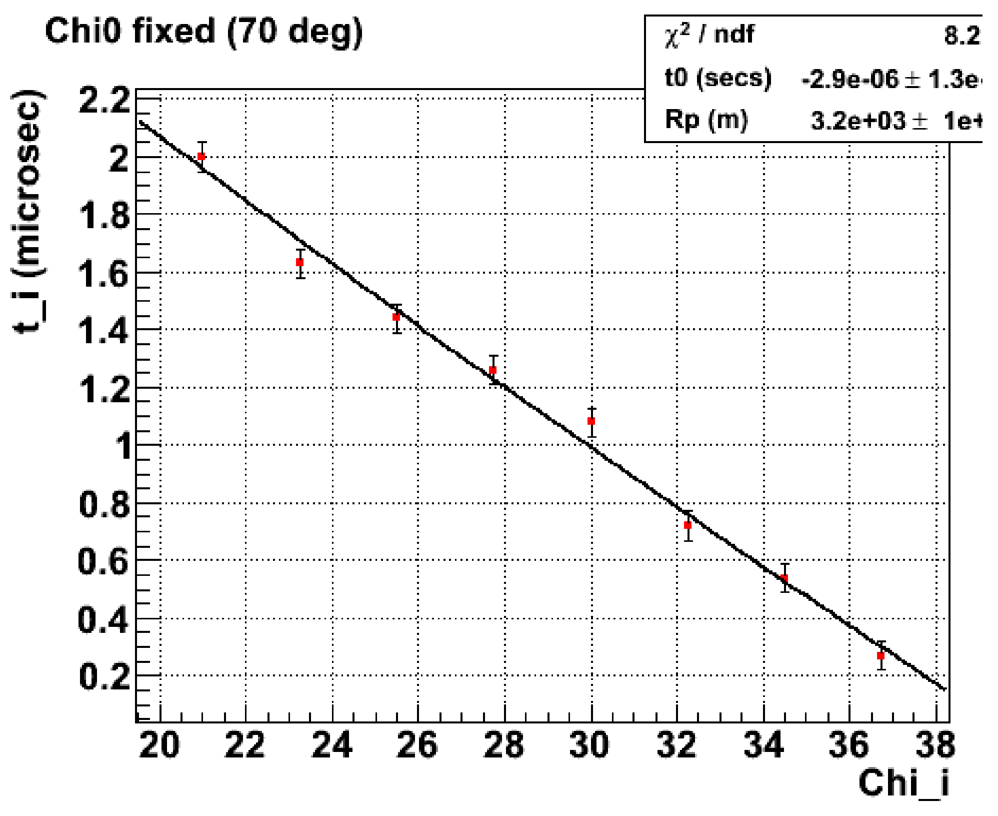
Reference: 空気シャワー観測による宇宙線研究の歴史 永野元彦, 大気の蛍光観測による宇宙線実験の始まり 棚橋五郎

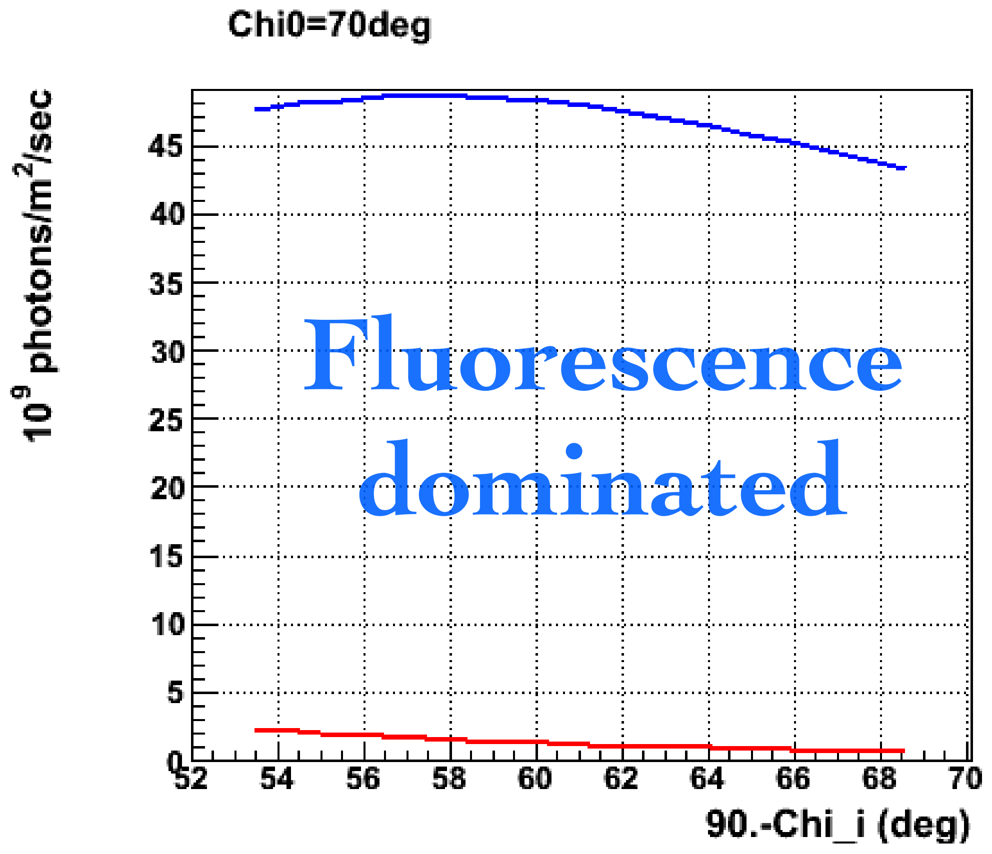
First Detection of Shower by Fluorescence Technique

Candidates observed by TOKYO-1 (1969)

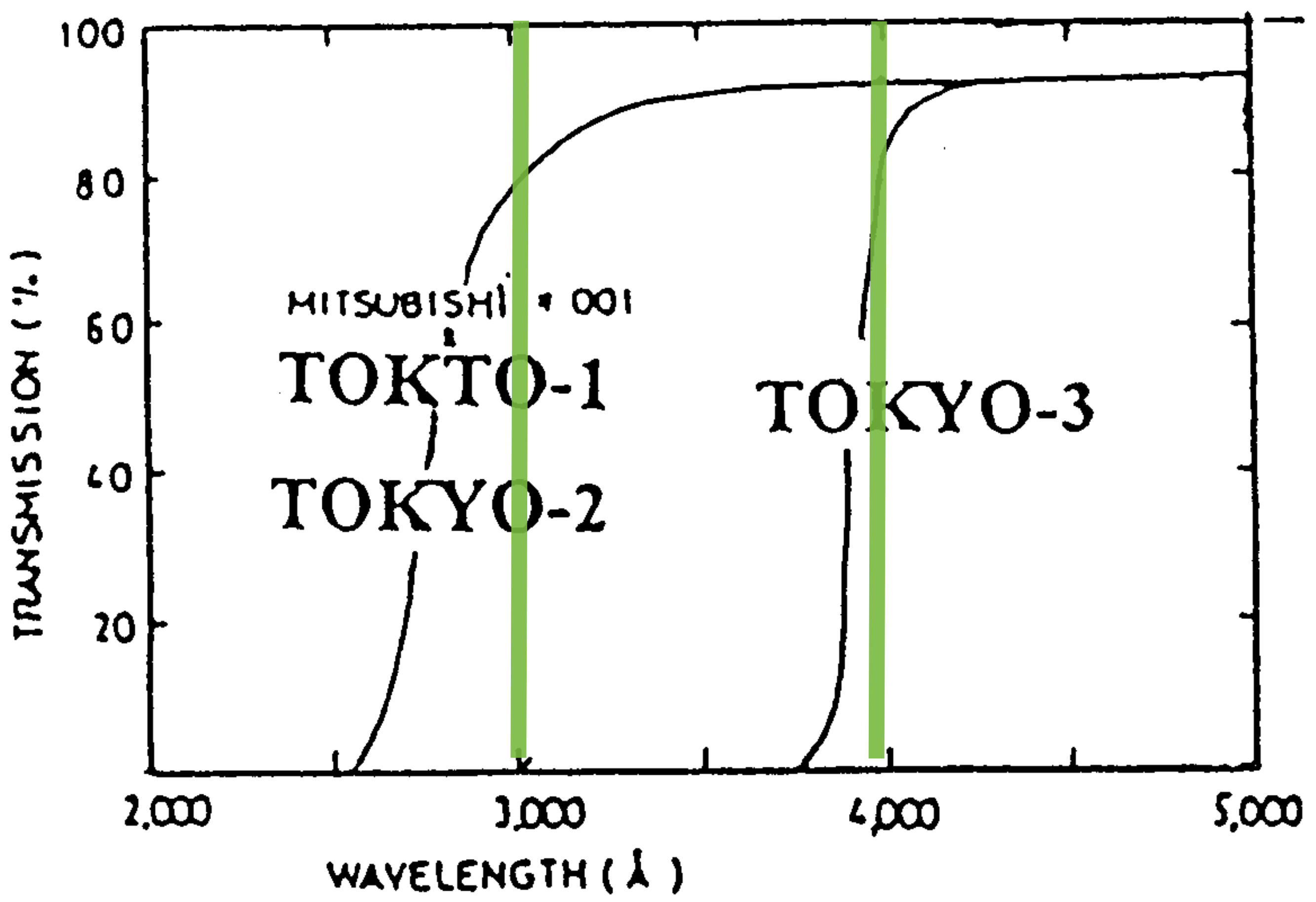


Re-analysis by B. Dawson et al. (2011)





- Long signal duration and the similar amount of light (No. 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, Pierre Auger Observatory established 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

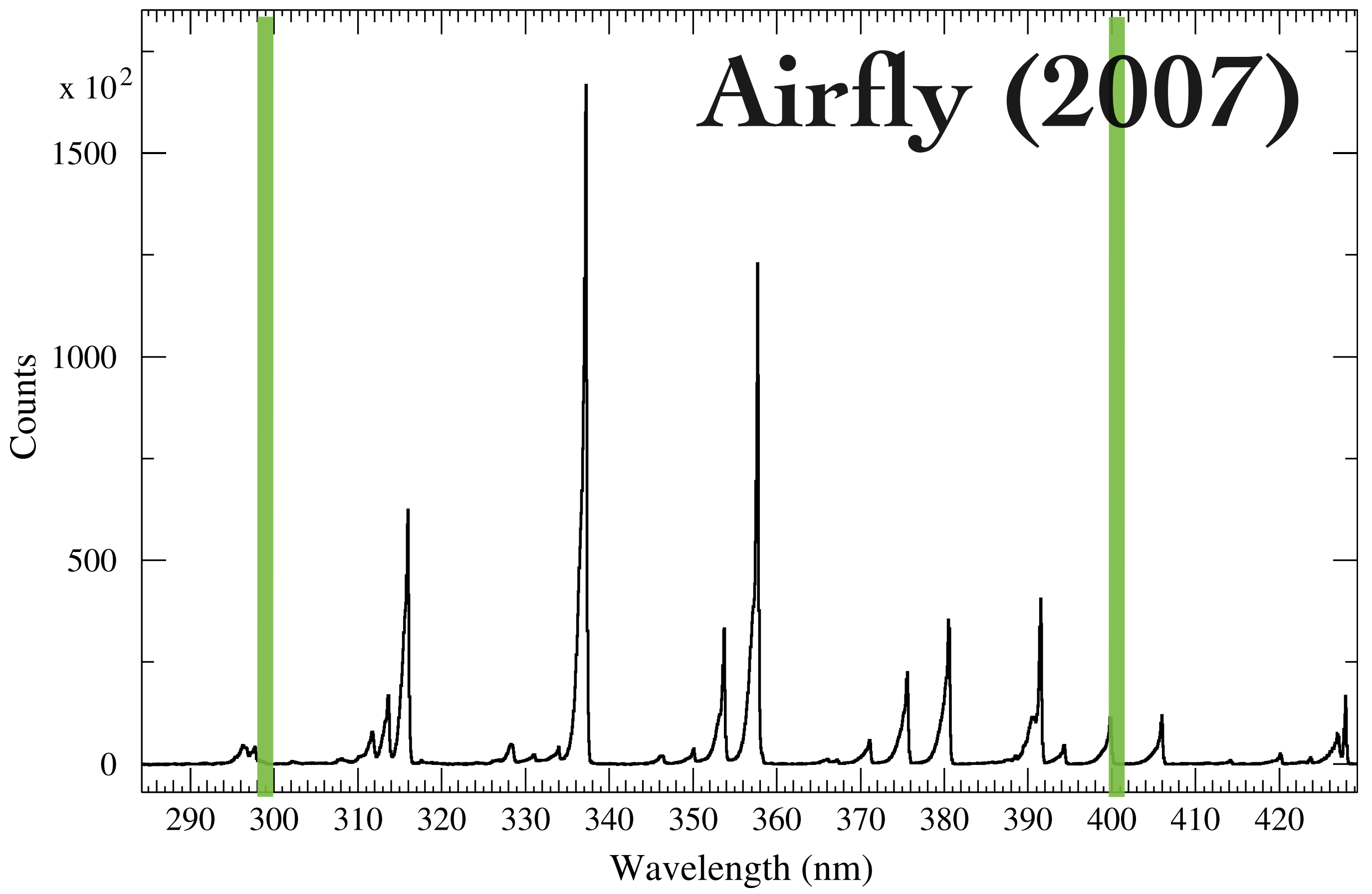
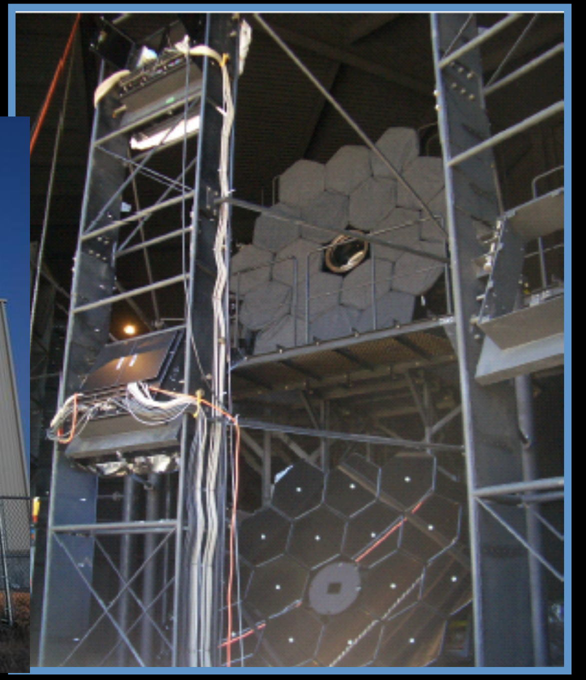


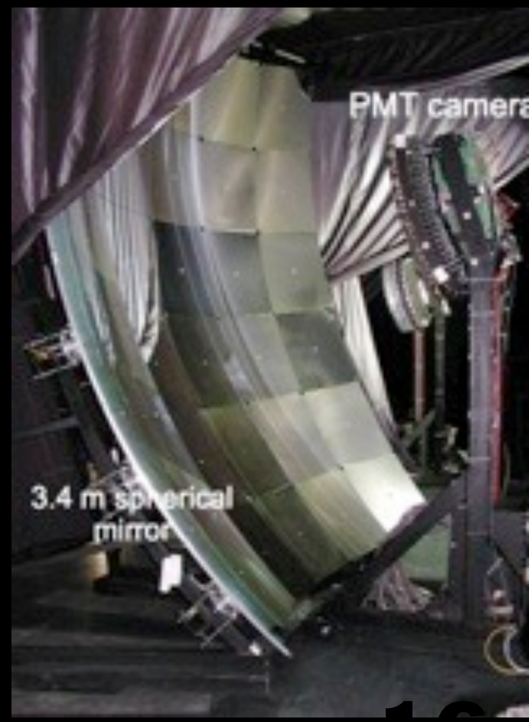
Fig. 4. Measured fluorescence spectrum in dry air at 800 hPa and 293 K.

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

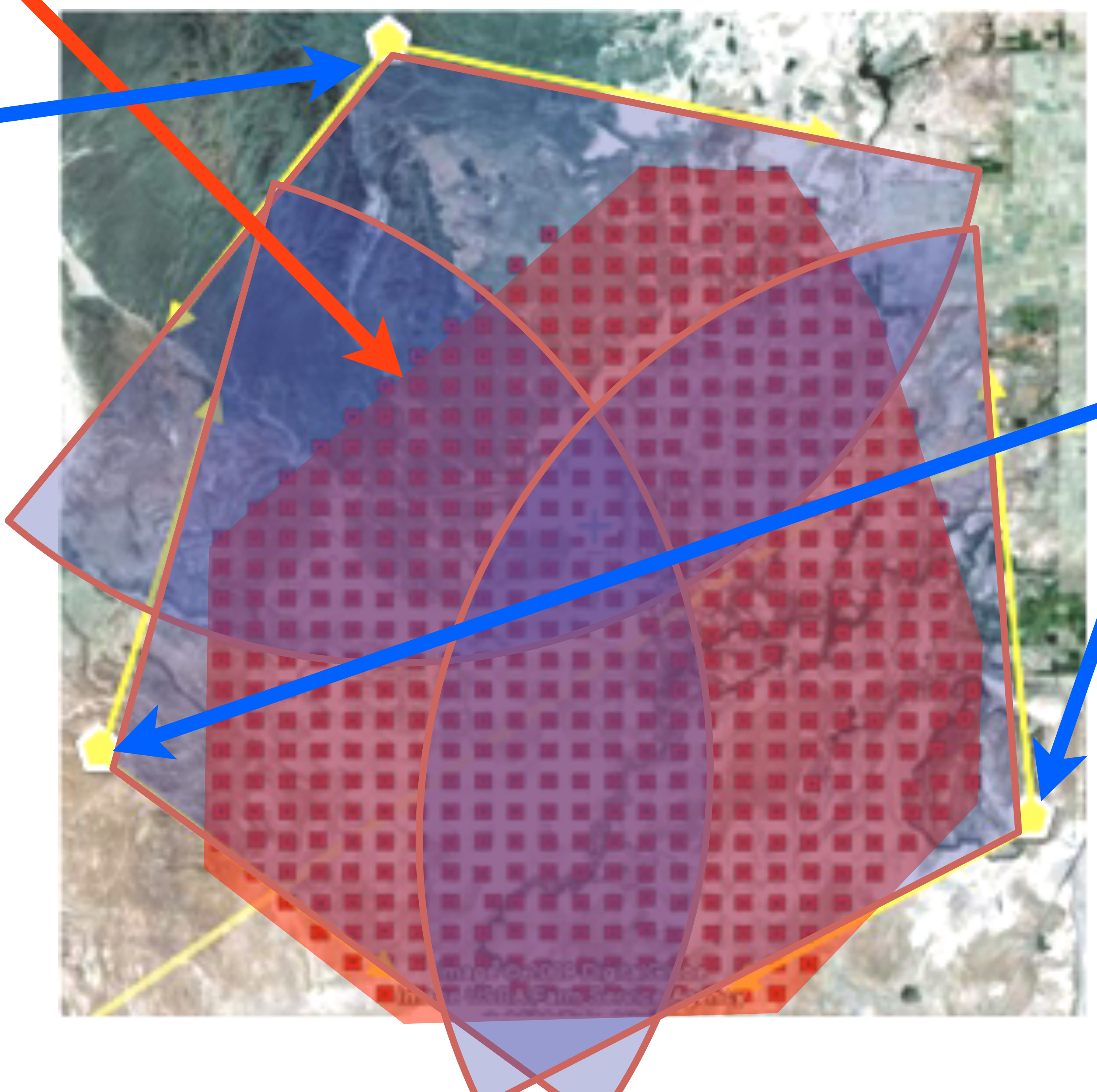
507 Scintillator, 1.2 km spacing

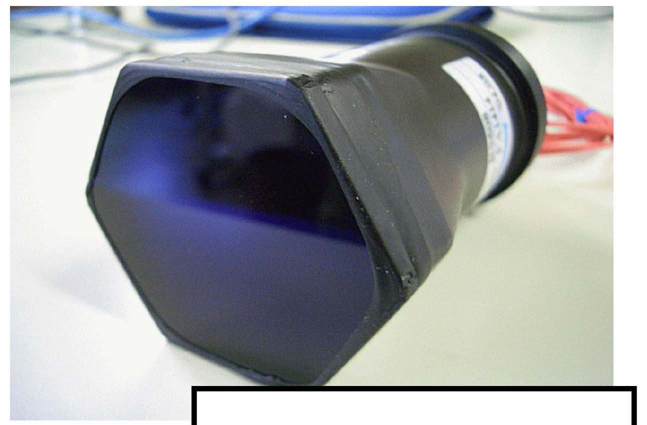
Fluorescence Detector at BRM and LR stations

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

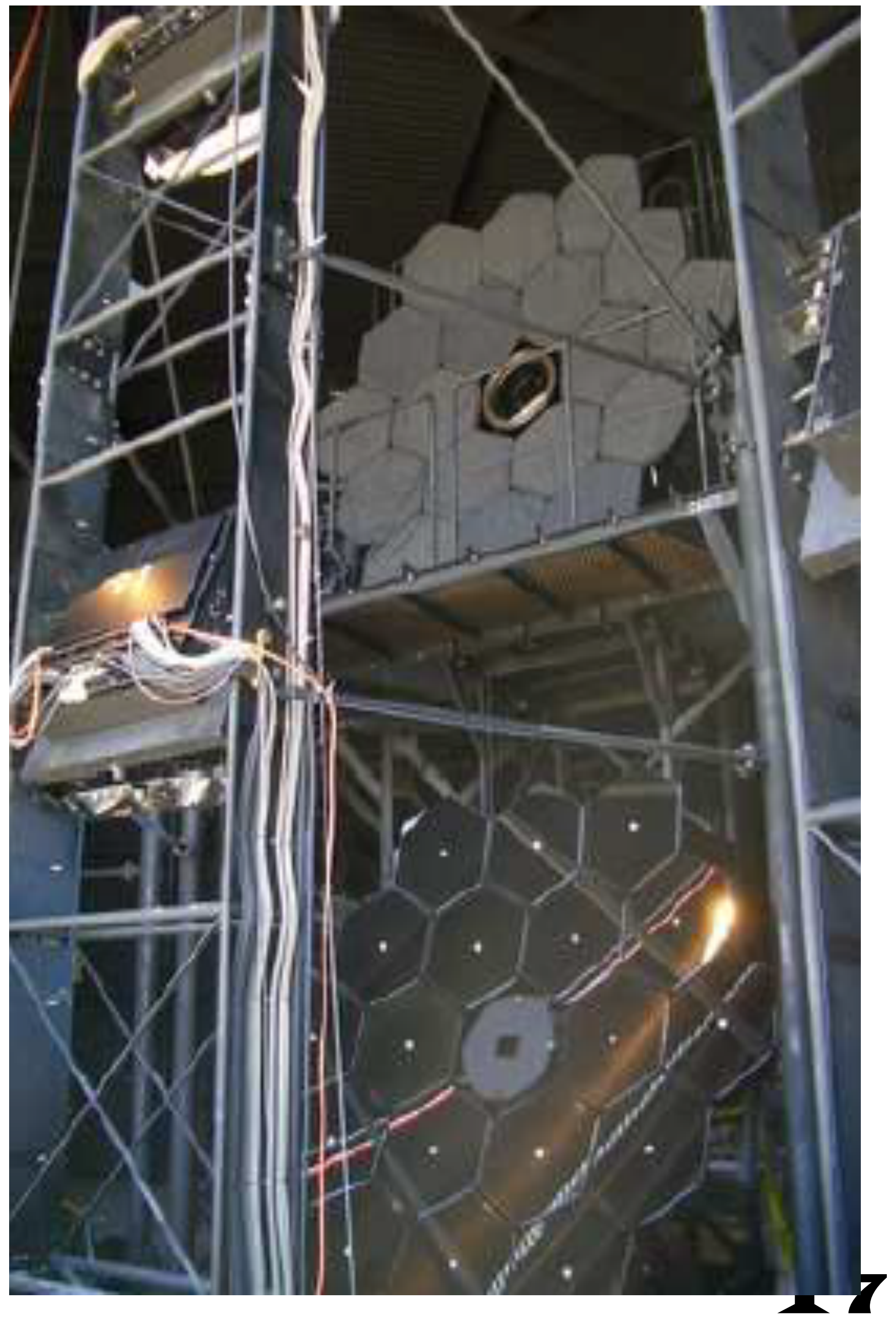
Fluorescence detector at MD station

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





PMT



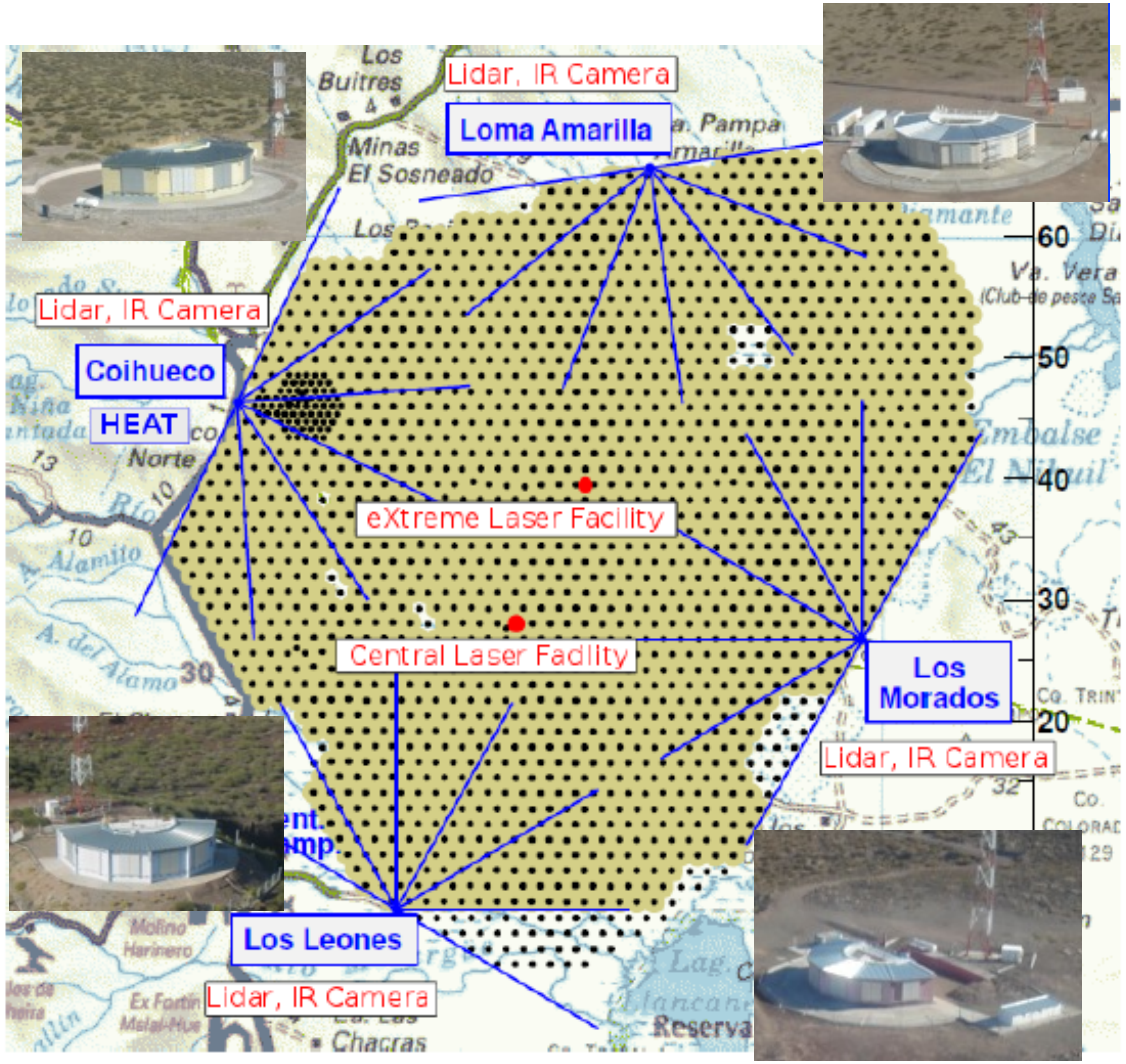
Delta, Utah, USA

PIERRE AUGER OBSERVATORY

Pierre Auger Observatory (Auger)

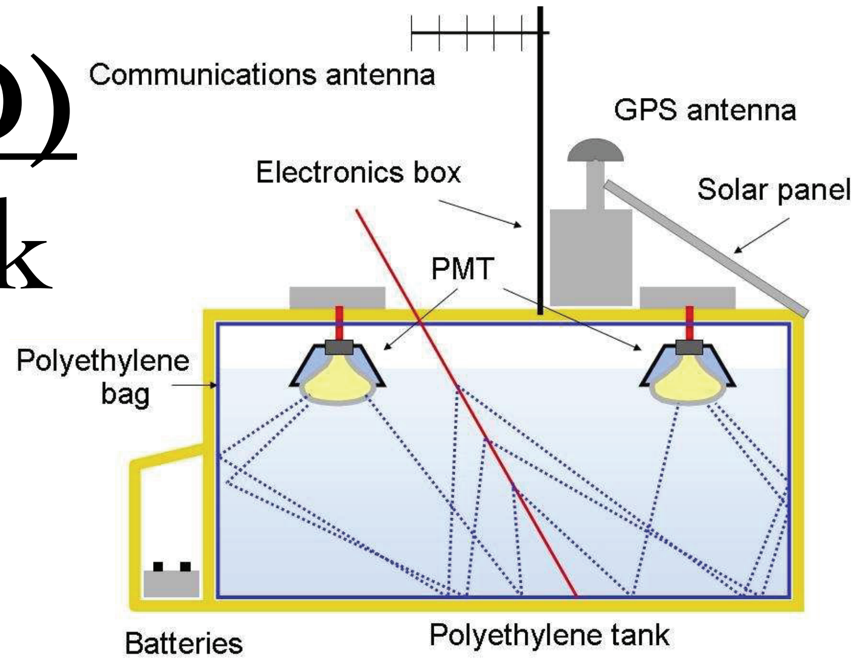
The world's largest UHECR observatory 3000 km^2

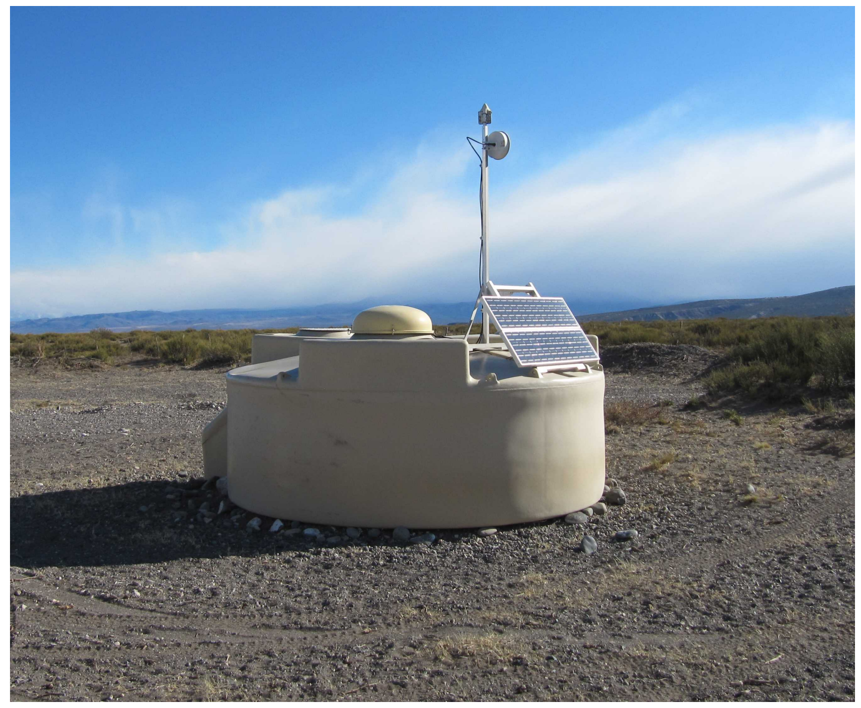
(2004 -) completed in 2008



Surface Detector (SD)

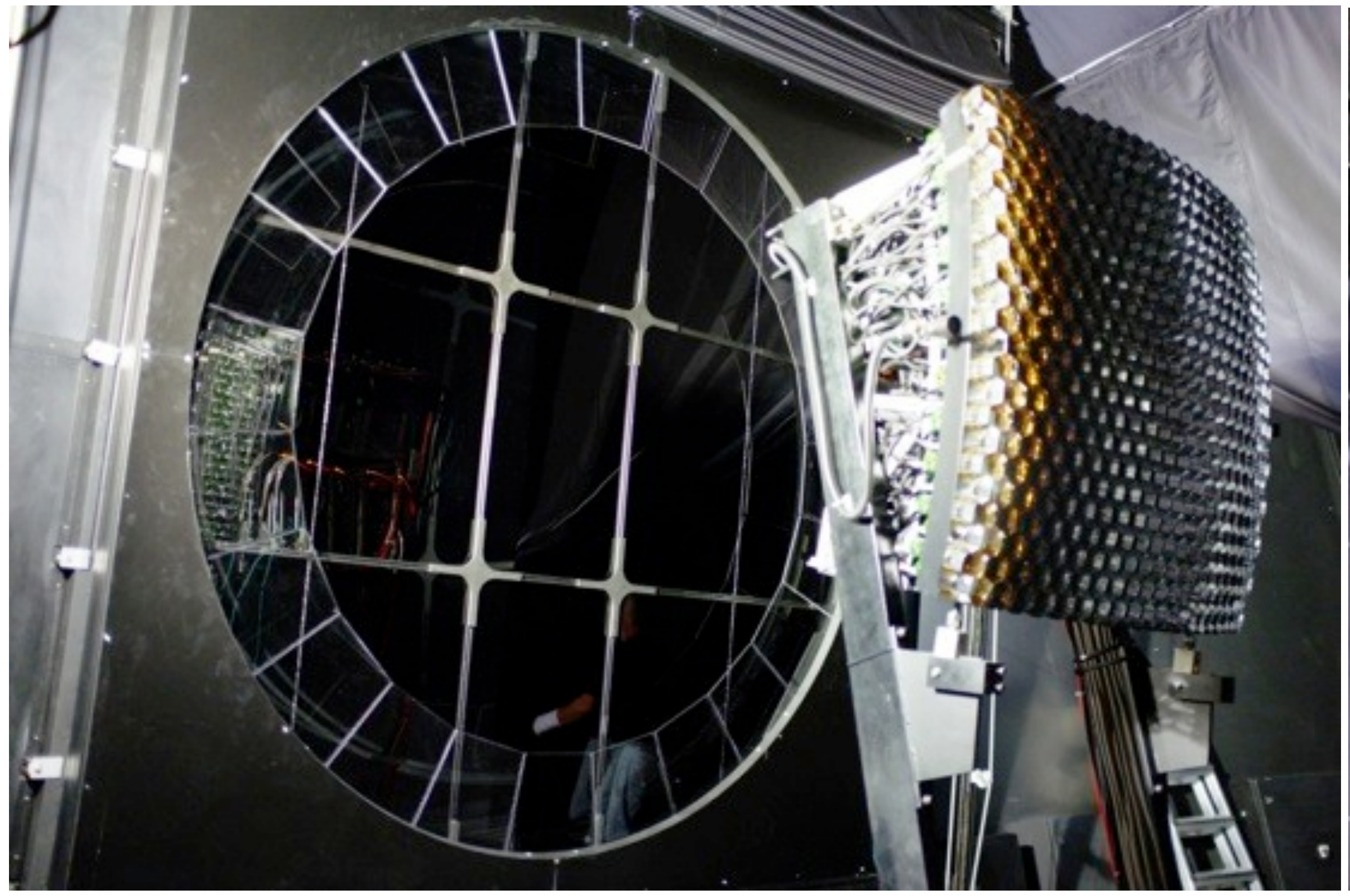
Water Cherenkov Tank
1.5 km spacing, 1600 stations





Fluorescence Detector (FD)

3.4 m spherical mirror, 440 PMT, 30° × 30° FOV
light guide + collector ring, 4 × 6 telescope



Malargüe, Mendoza, Argentina

“Scale” of UHECR Observatory

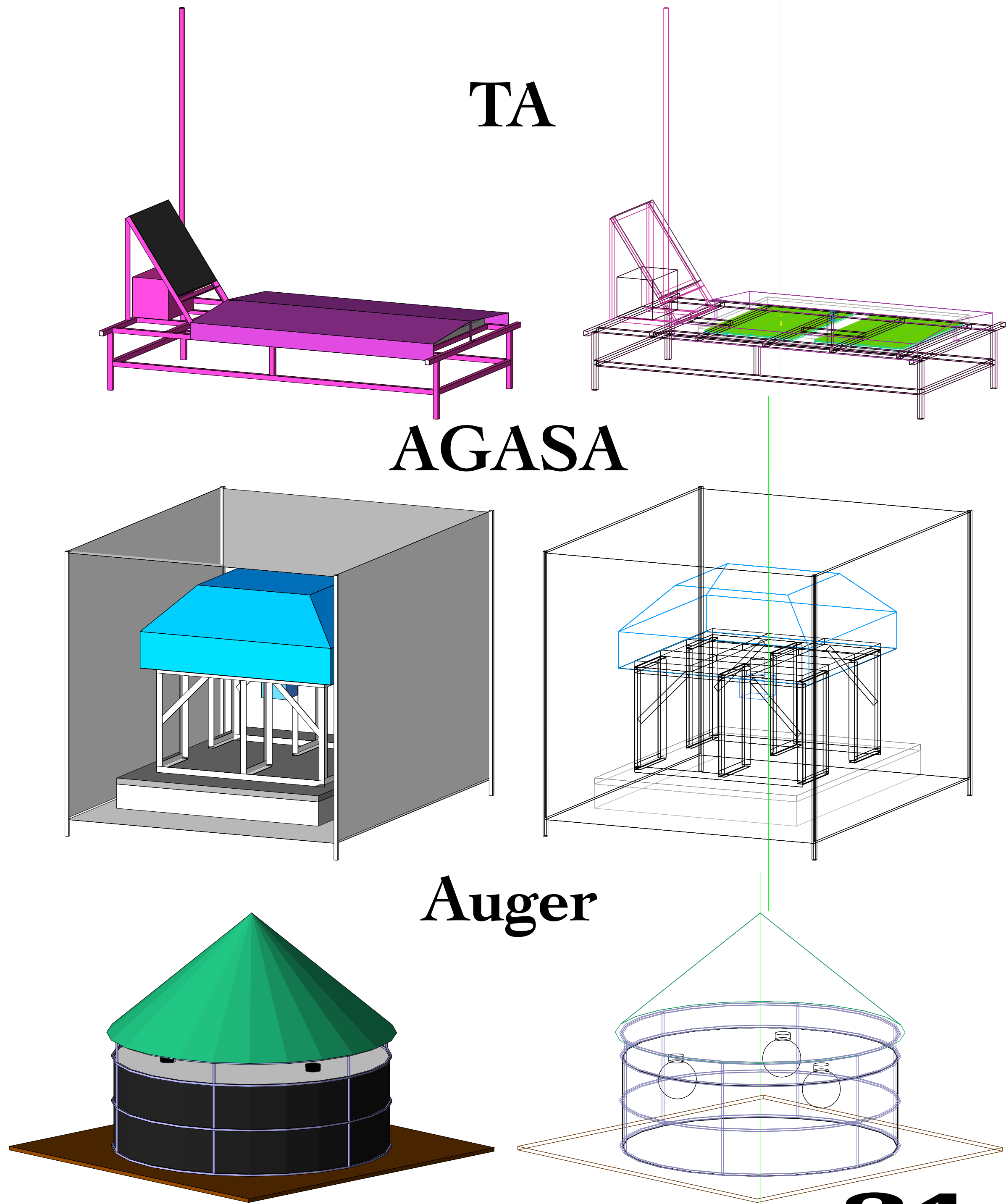
“Scale” of UHECR Observatory

"Scale" of UHECR Observatory

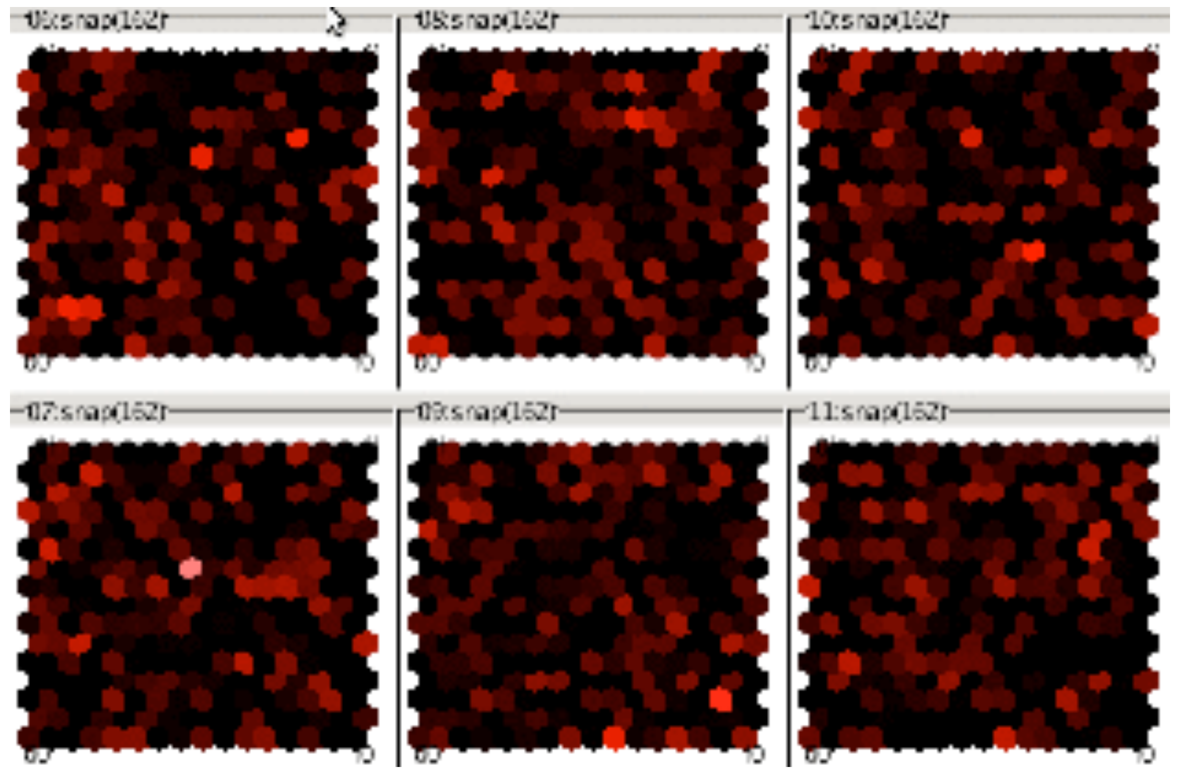
My Contributions to TA

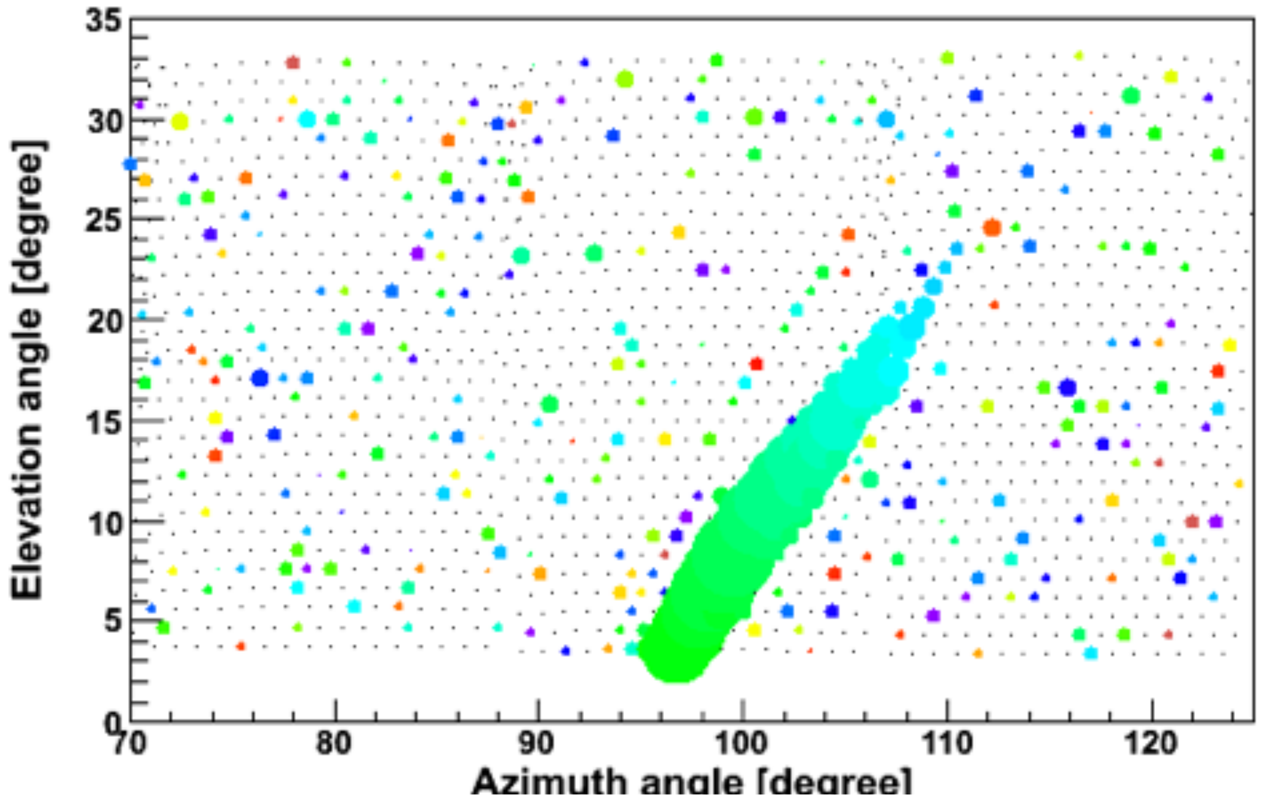
- FD Camera Assembling @Akeno
- Absolute calibration of FD PMT @ICRR
- Detector response simulation with GEANT4
- Operation and maintenance of TA FD @Utah
- TA FD Analysis software development

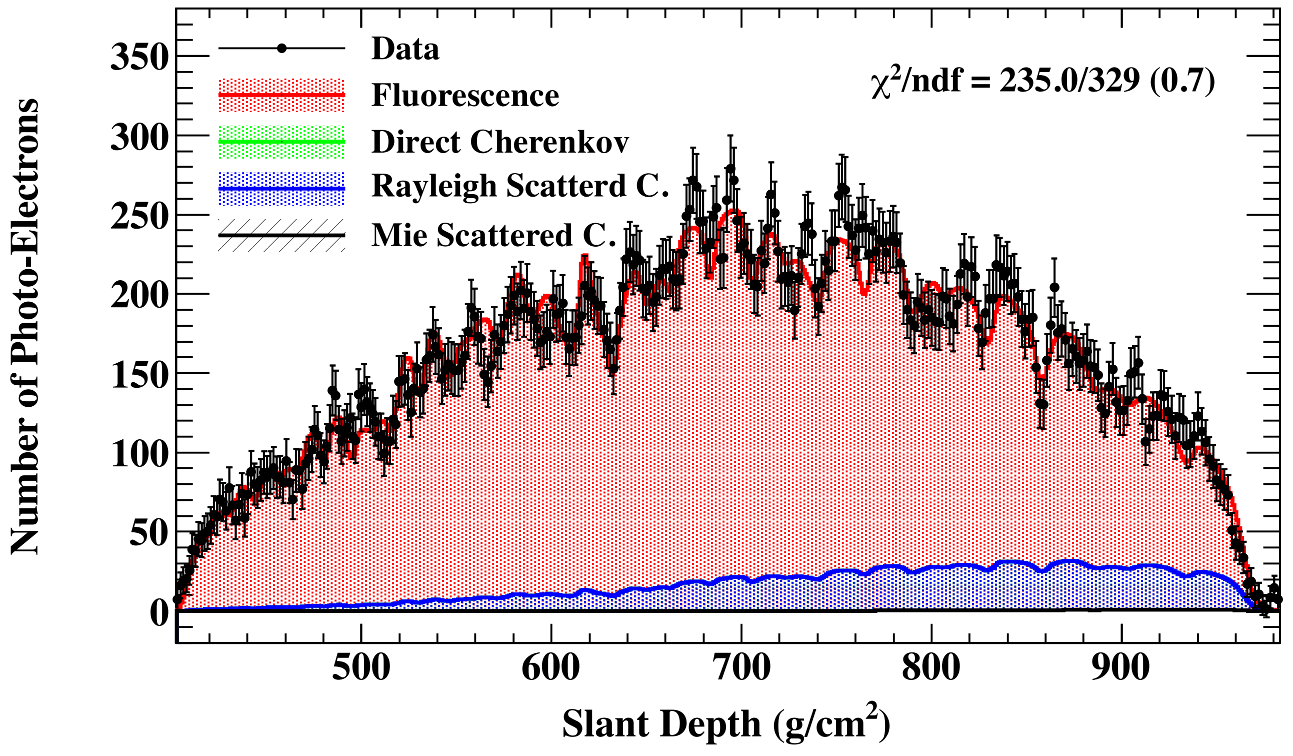


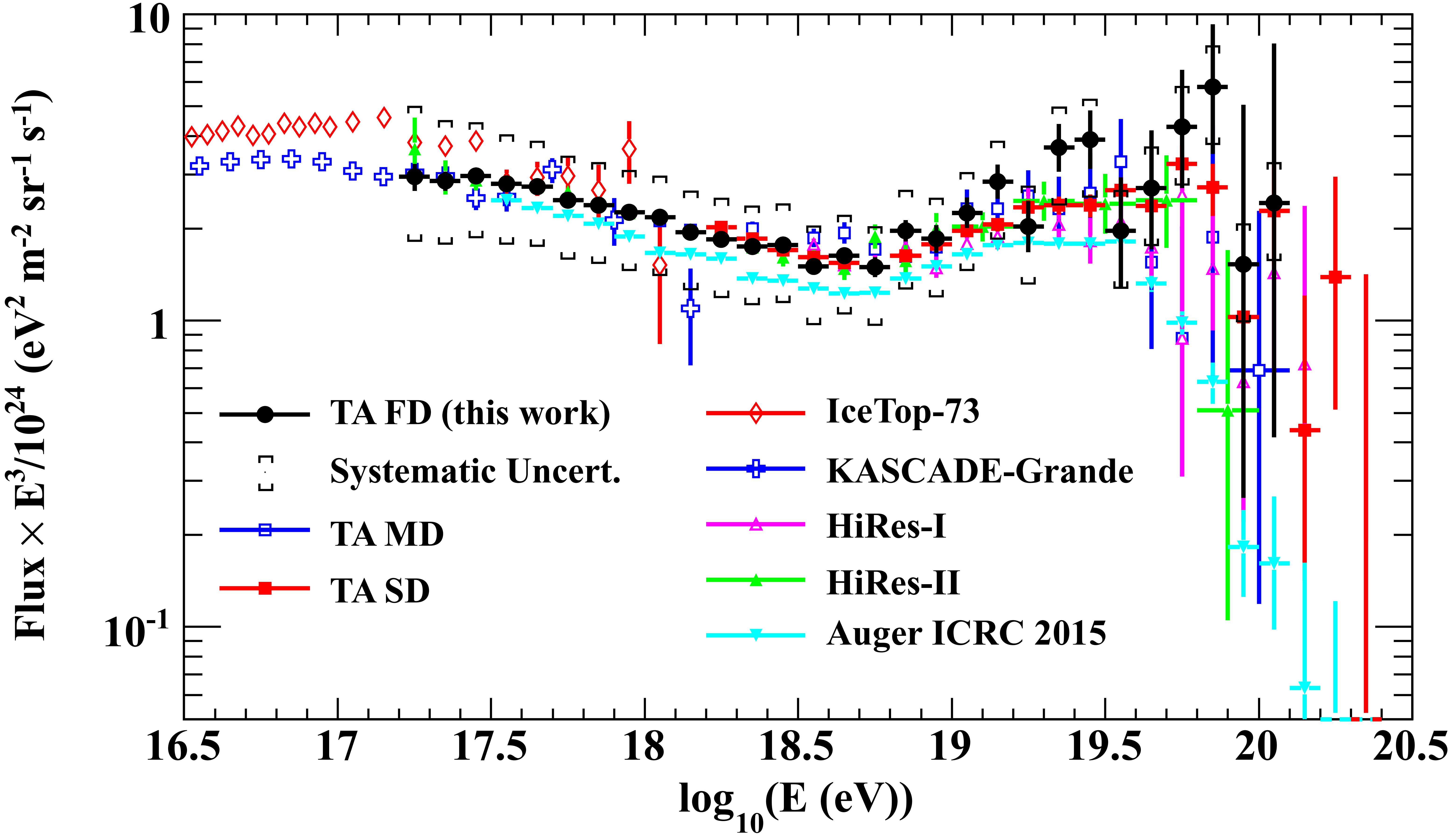

Energy Spectrum by TA FD





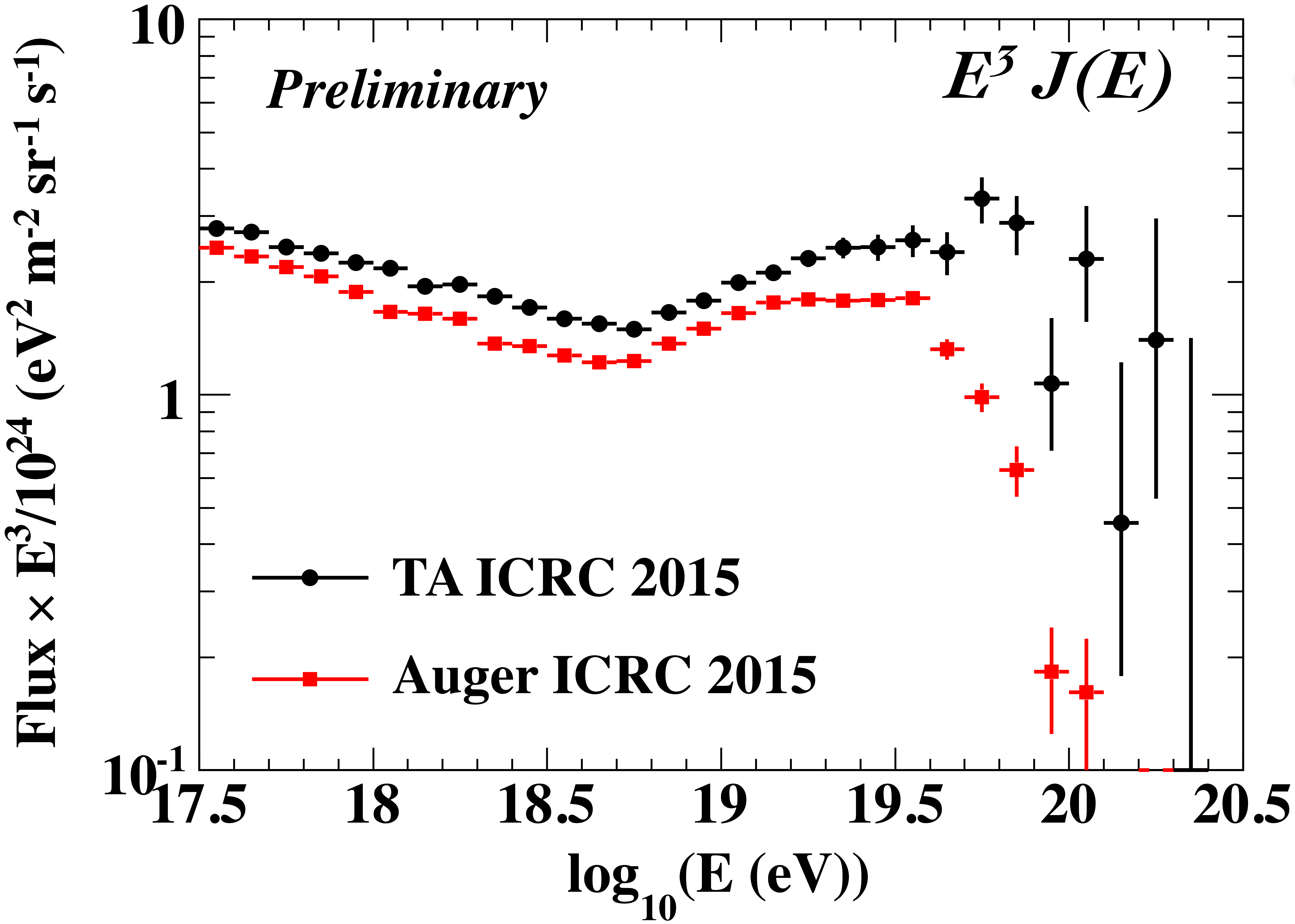


- Reconstruction by one FD station to be sensitive to lower energies.
- Energy spectrum covering three orders of magnitude above $10^{17.2}$ eV



T. Fujii et al., ICRC2015, R. Abbasi, T. Fujii (Corresponding author) et al., Astroparticle Physics 80 (2016) 131-140

How frequent?: Energy Spectrum

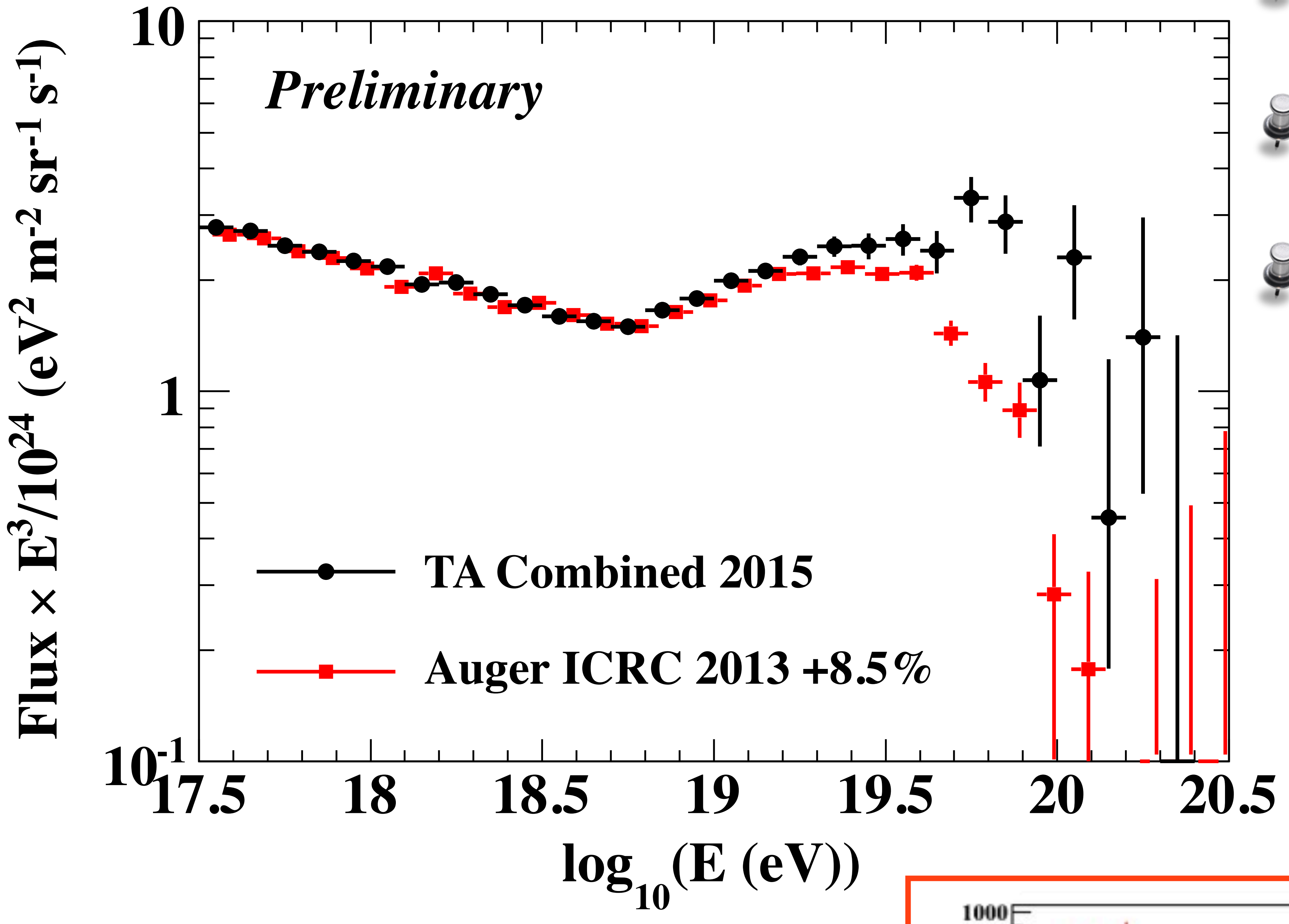


- 8.5% difference on energy scale between Auger and TA.

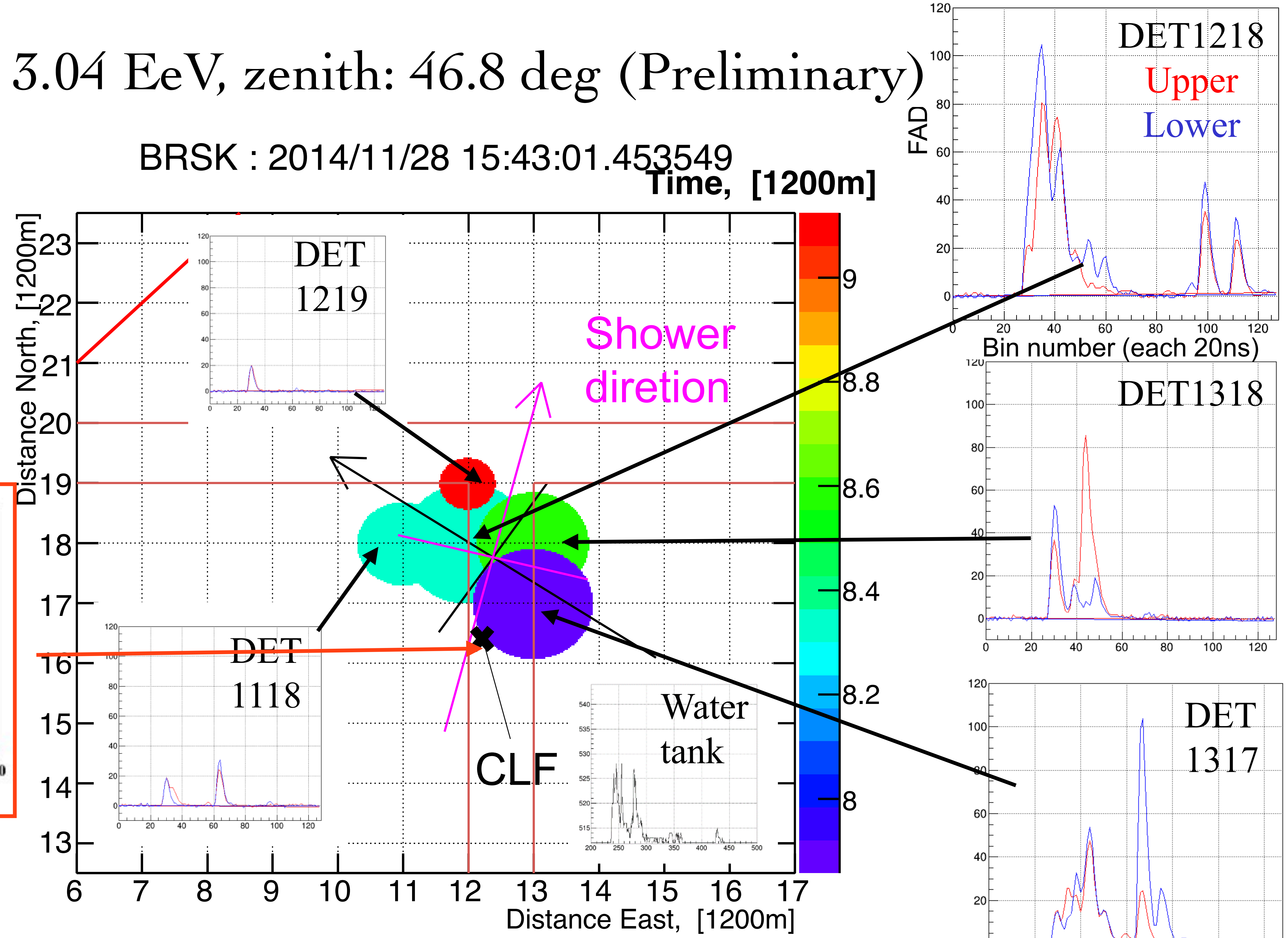
	Auger	TA
E_{ankle} (EeV)	4.8	5.2
E_s (EeV)	42.1	63.0

The energy spectrum around ankle are in good agreement, but an energy of suppression is different.

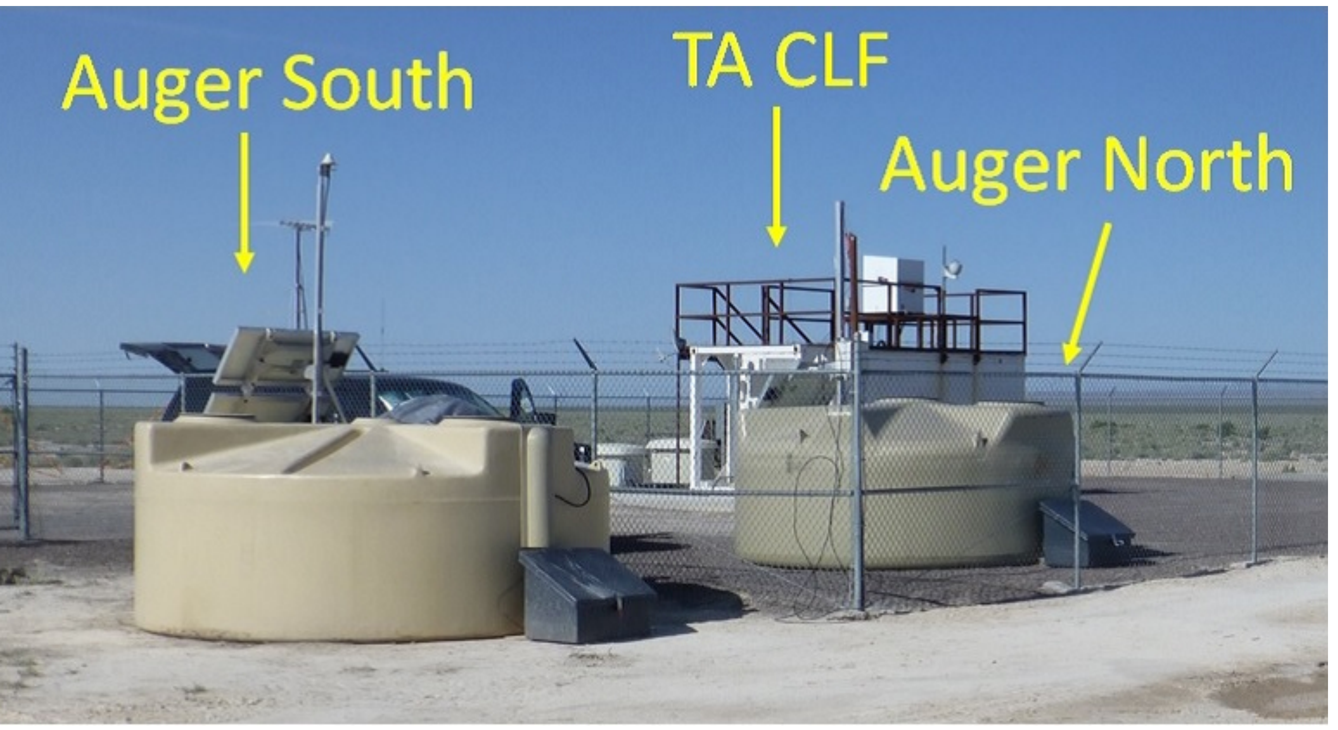
Detector Exchange to Understand the Discrepancy

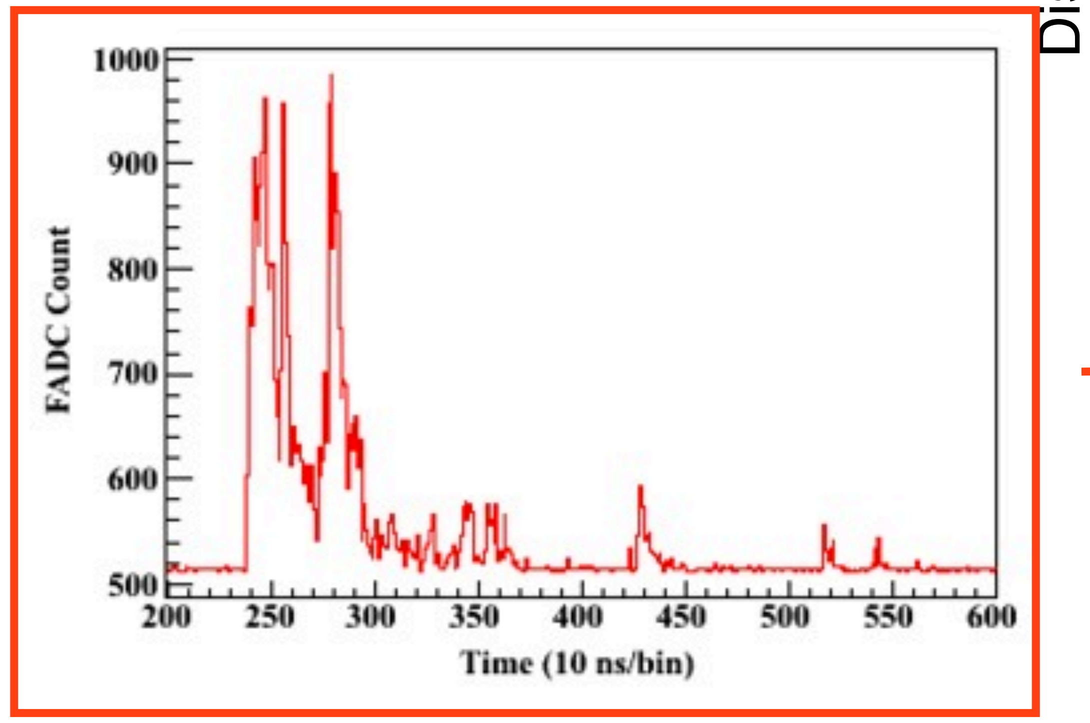


- Pioneering measurements by TASD and Auger water tank
- 2014/Nov/28 15:43:01.453549
- Energy: 3.04 EeV, zenith: 46.8 deg (Preliminary)

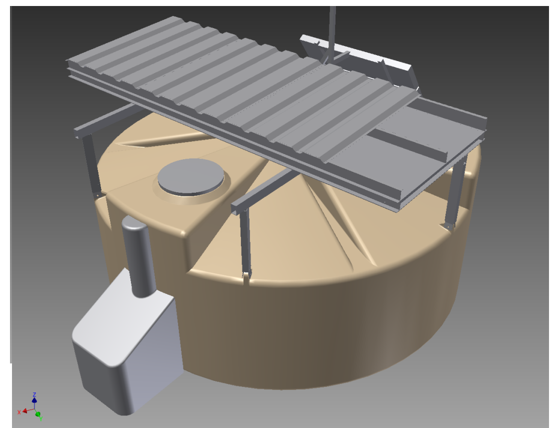


Theta=46.763 E=3.037EeV Nhit=5 X=0.110km Y=1.333km





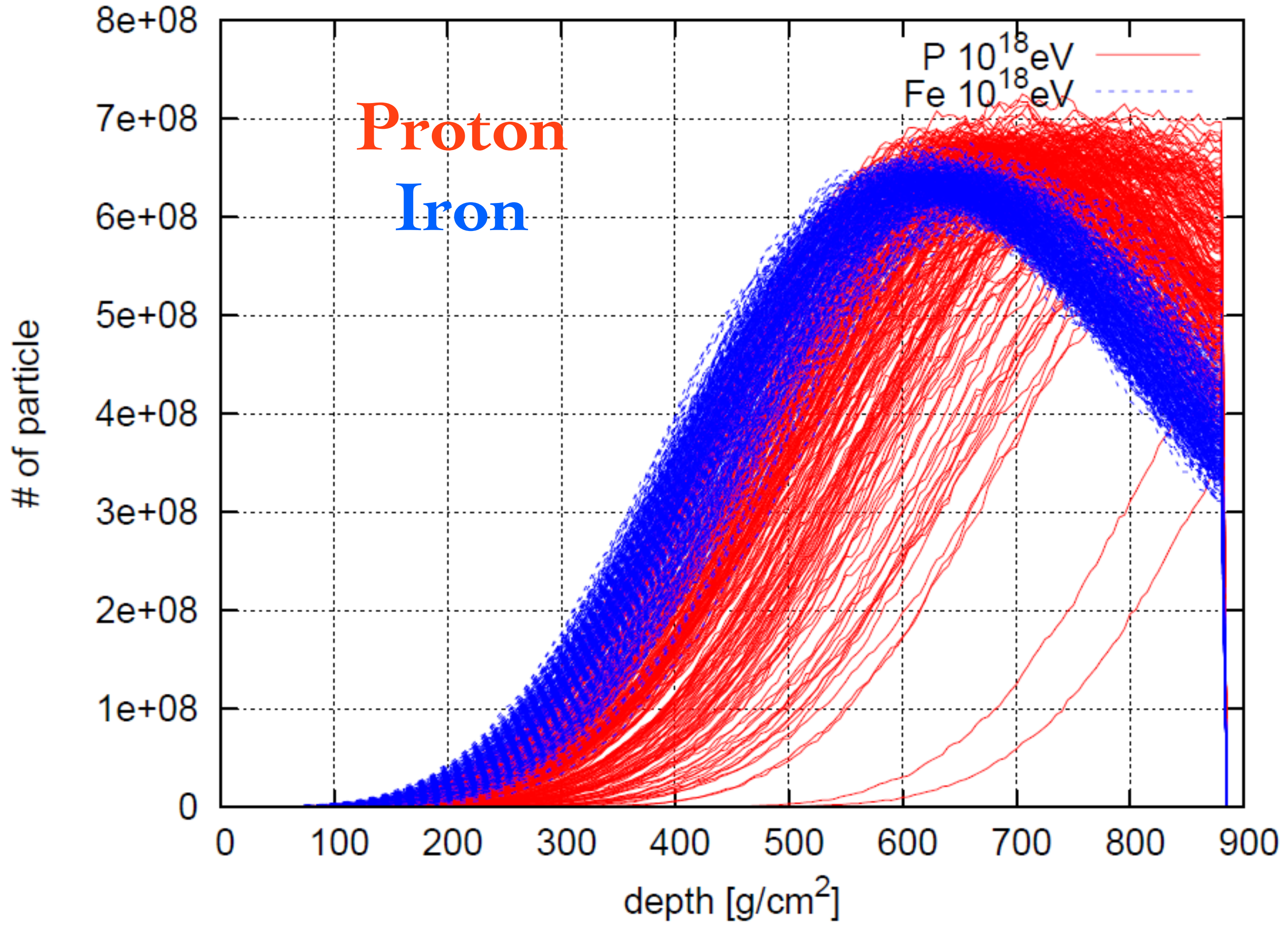
R. Takeishi et al., ICRC2015,

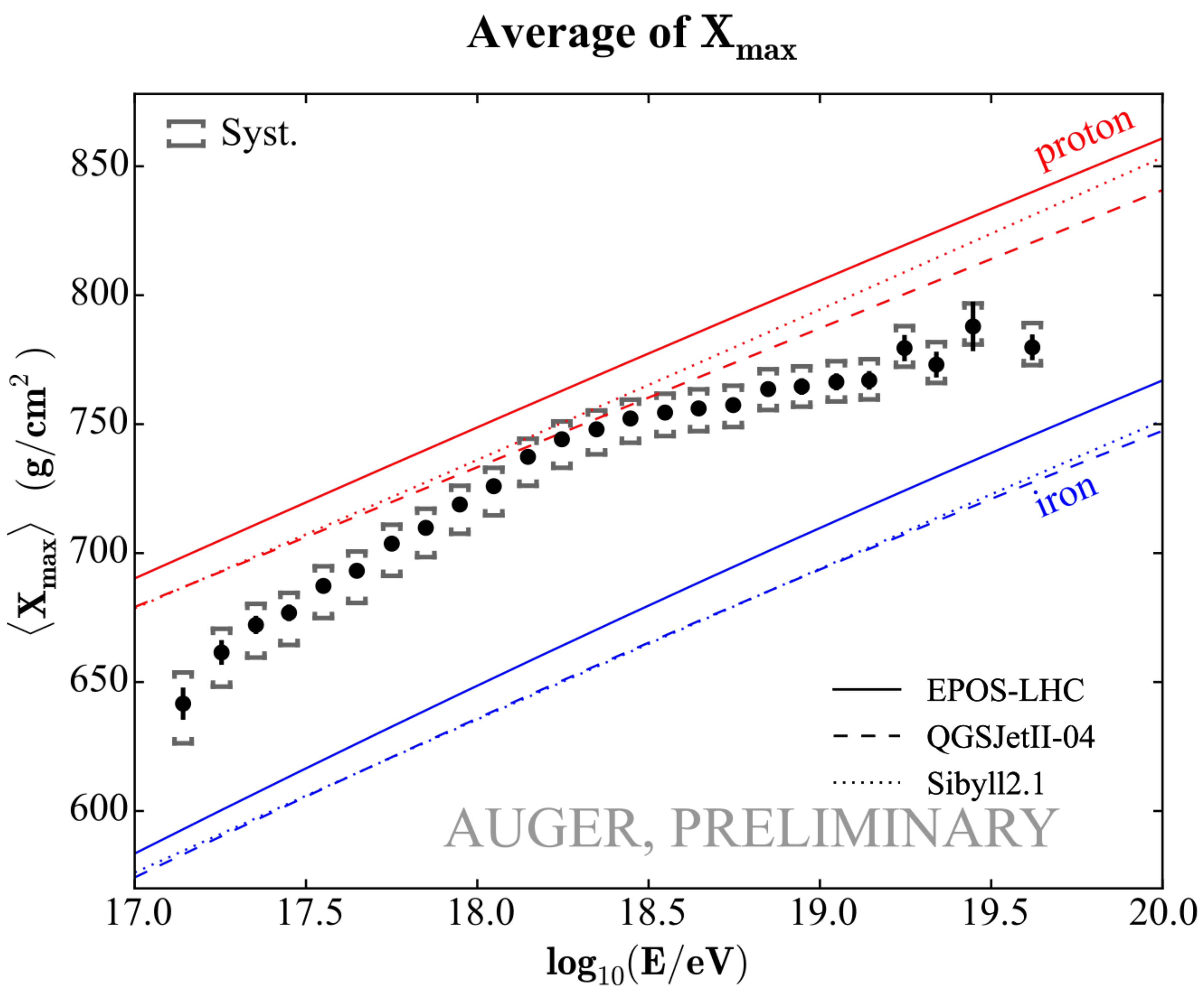


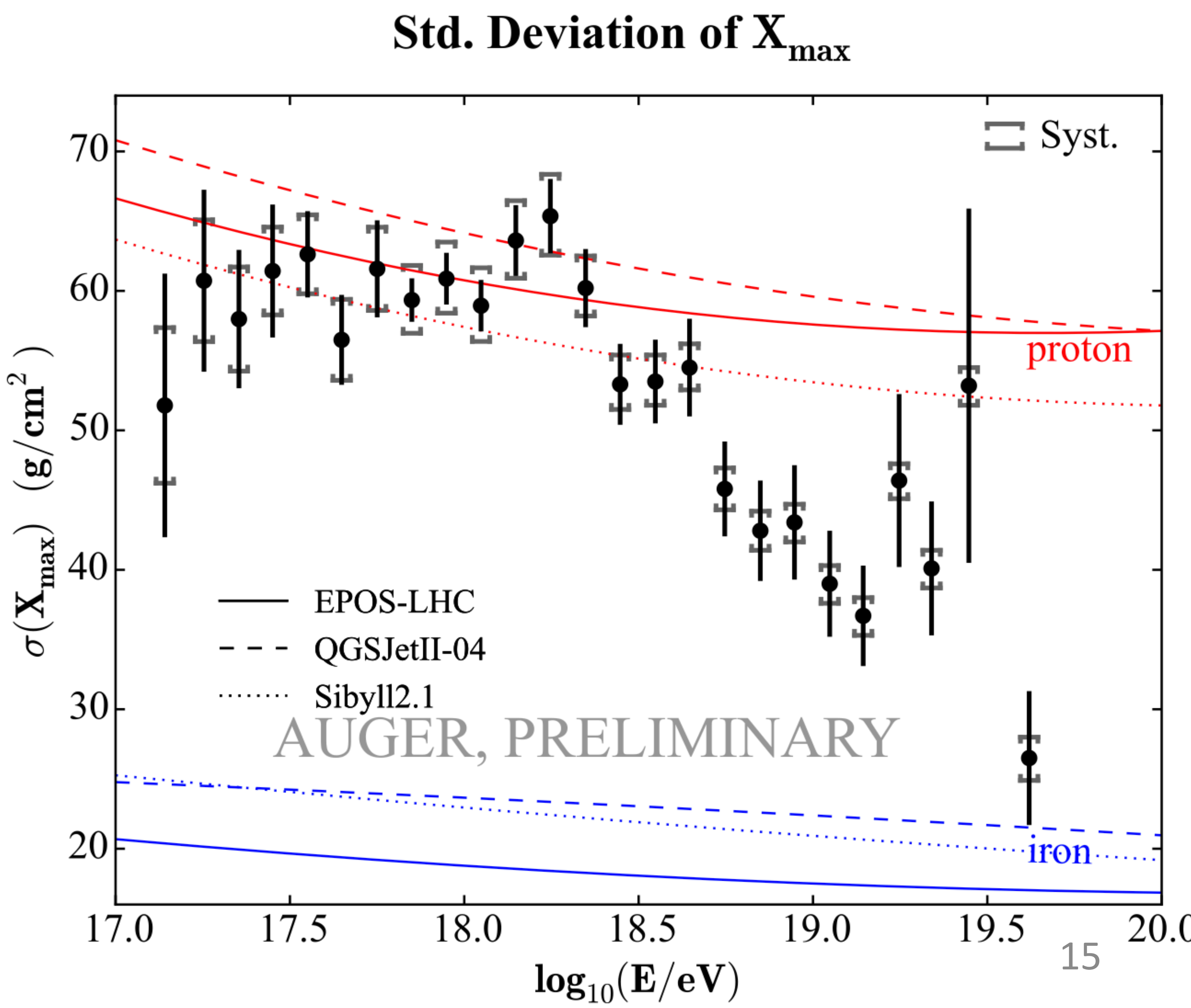
AugerPrime

What kind of particle?: Mass Composition

Is the suppression GZK process or acceleration limit?





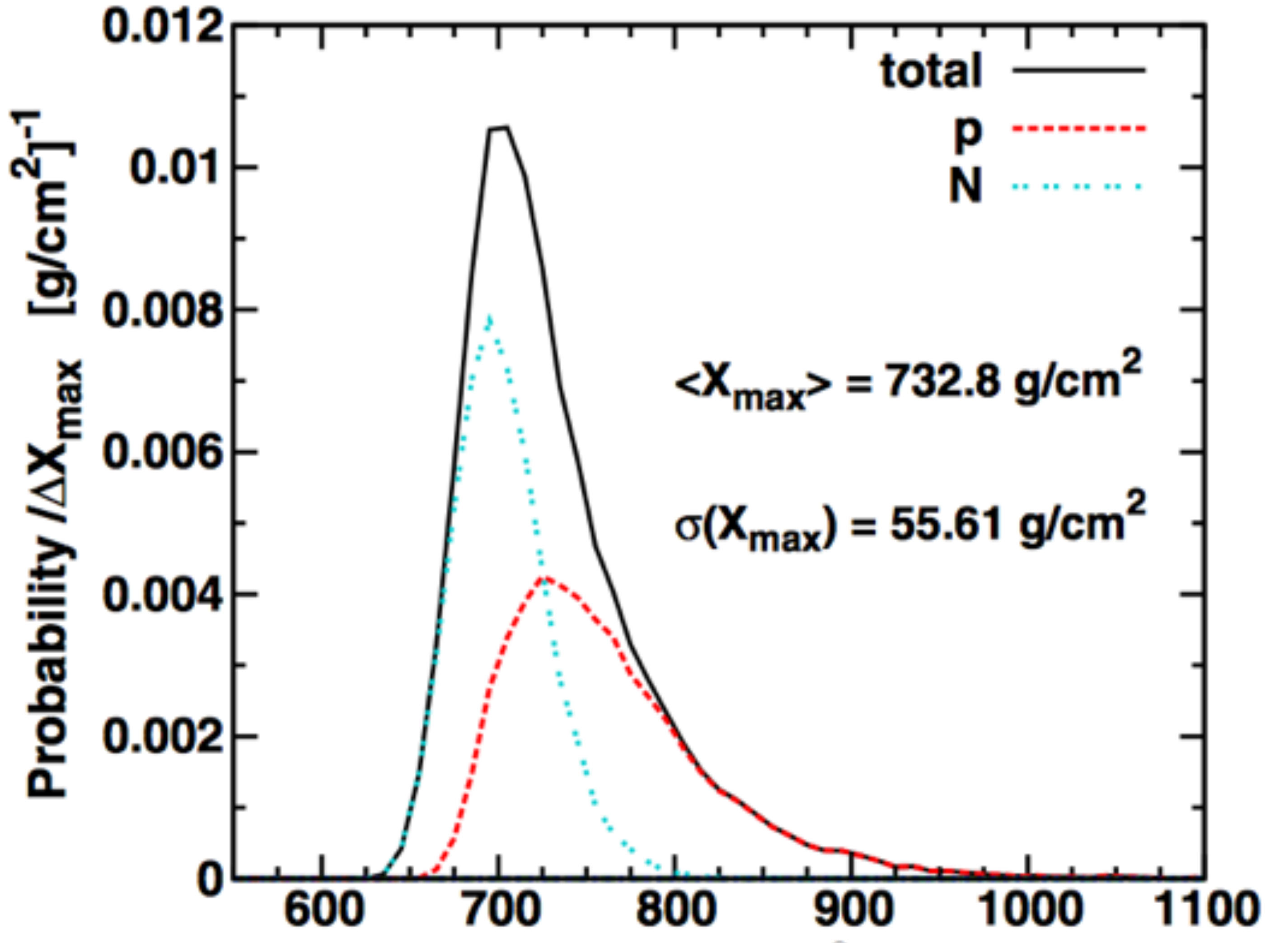


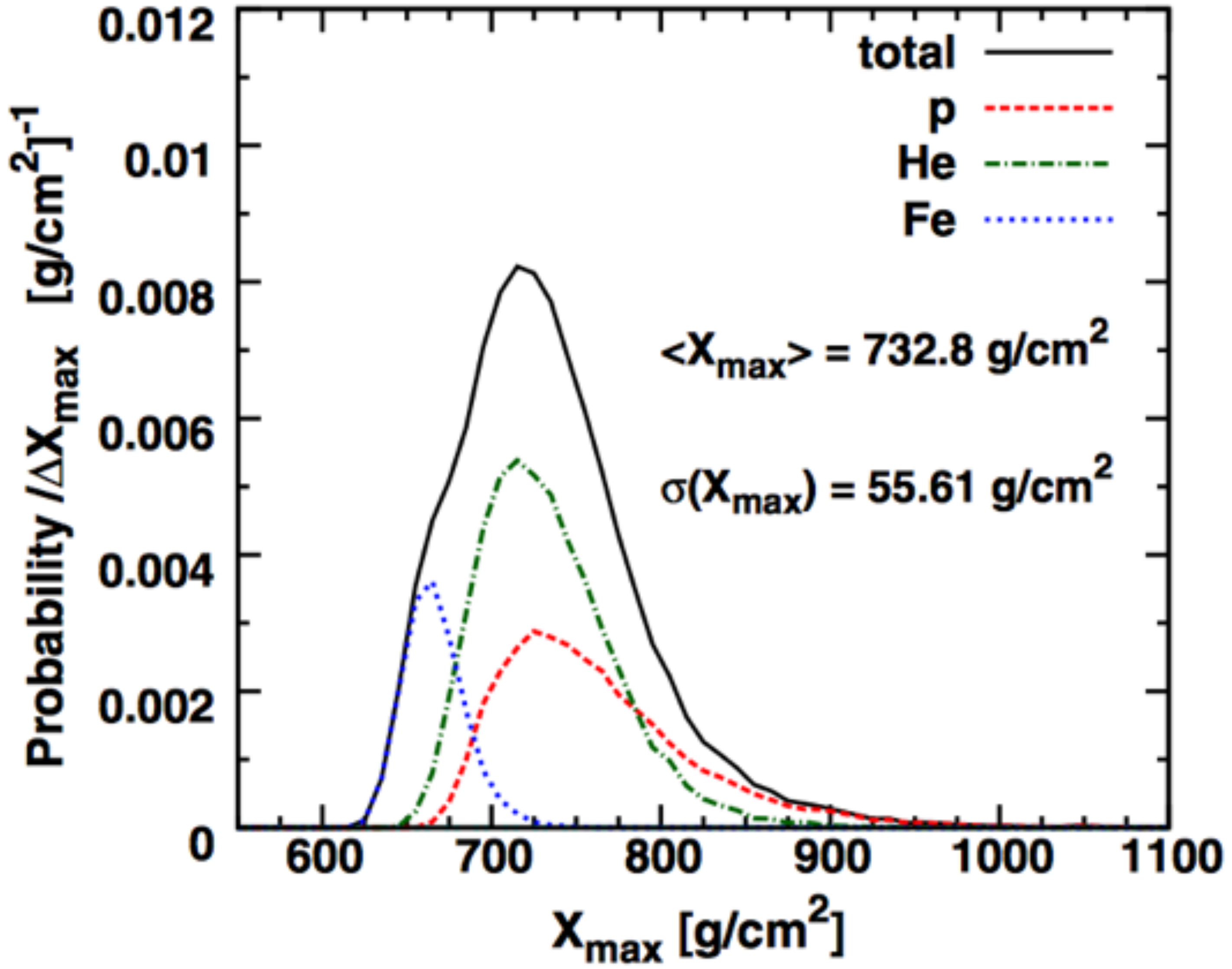
- proton dominated at $10^{18.3}$ eV.
- σ(Xmax) is smaller than proton simulation above 10^{19} eV.
- Suggest a change of composition above ~$10^{18.5}$ eV with increasing mass number and small mixing.

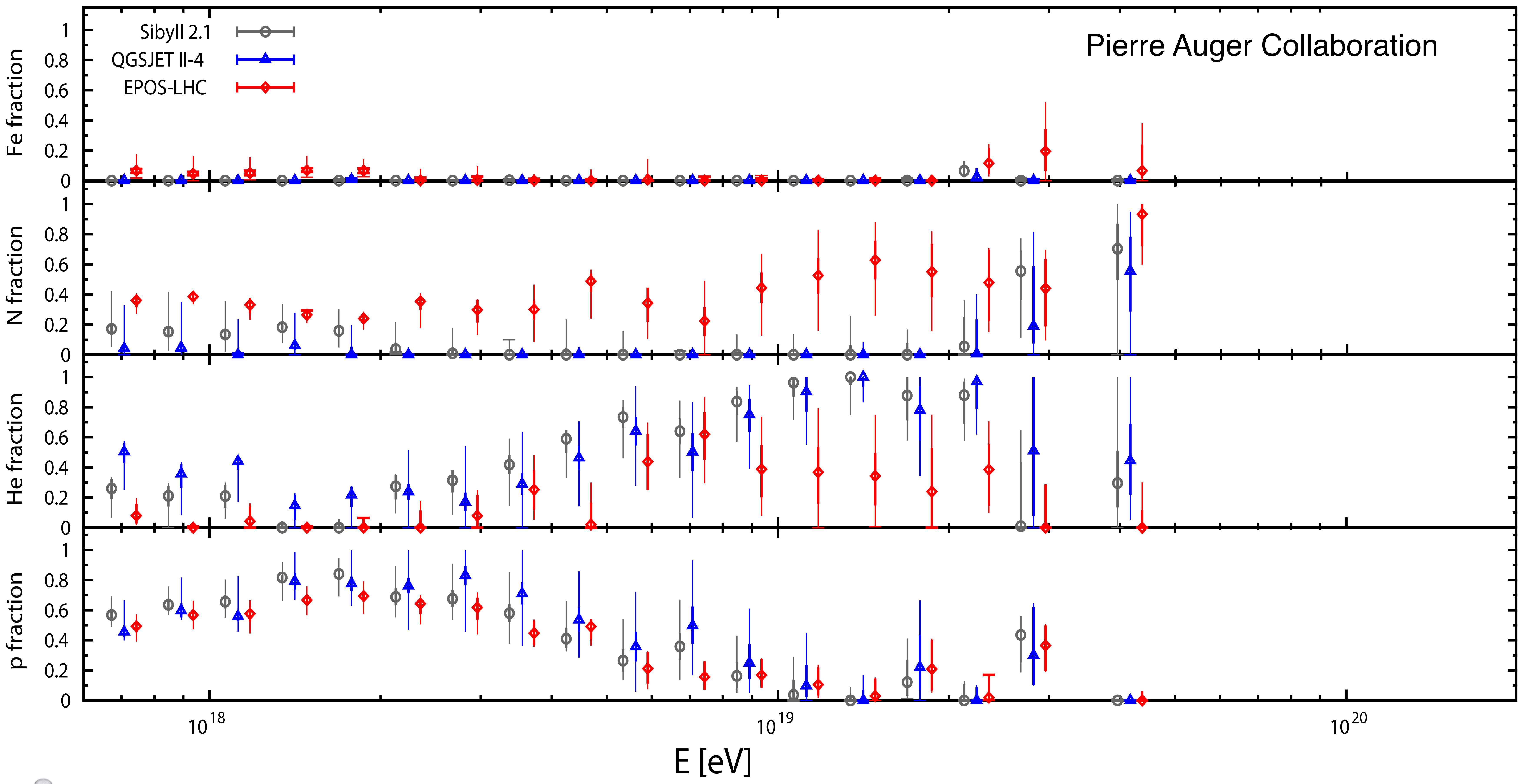
Pierre Auger Collaboration PRD 90 122005 (2014), A. Porcelli in ICRC 2015

Interpretation of Xmax distribution

The same <Xmax> and σ(Xmax) but different mixture.

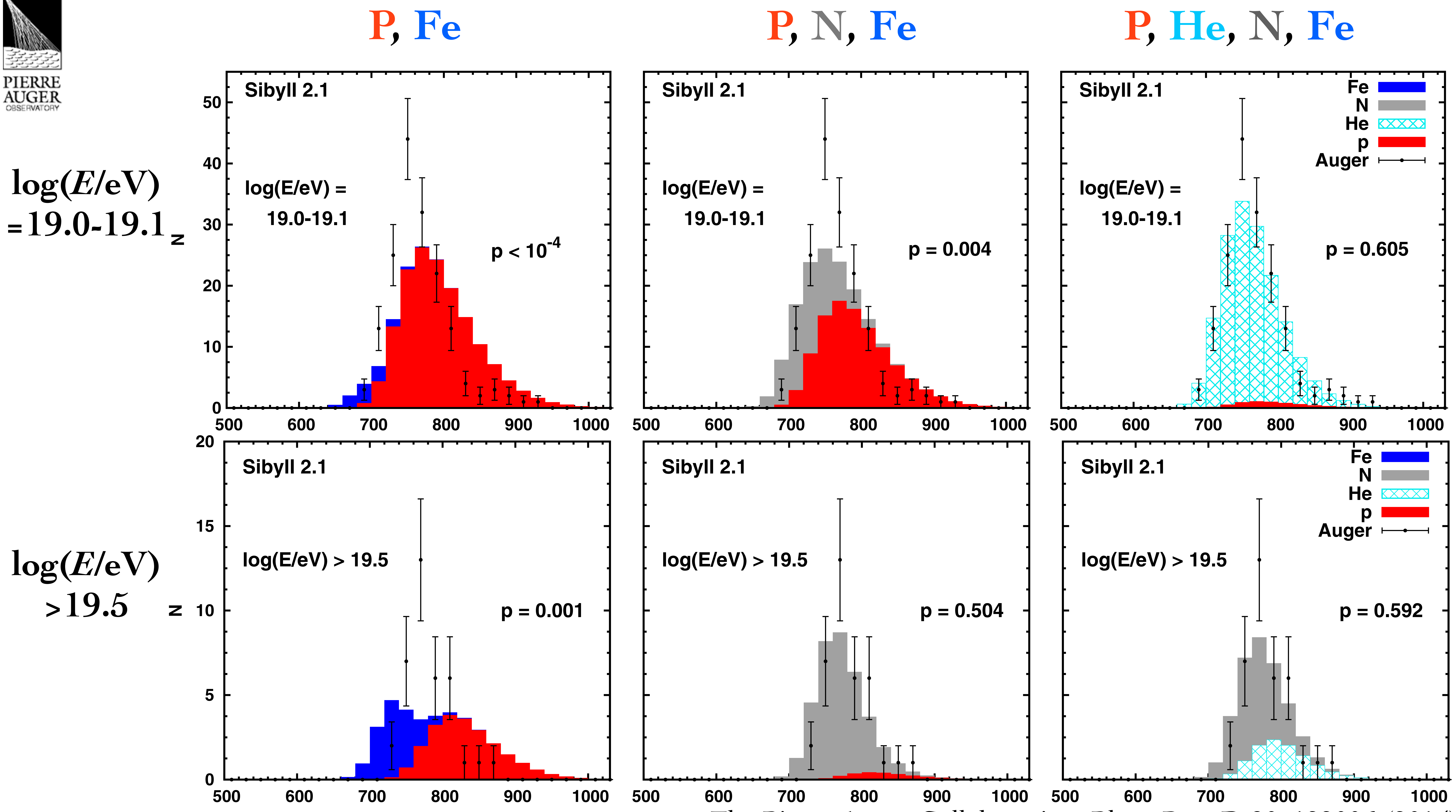






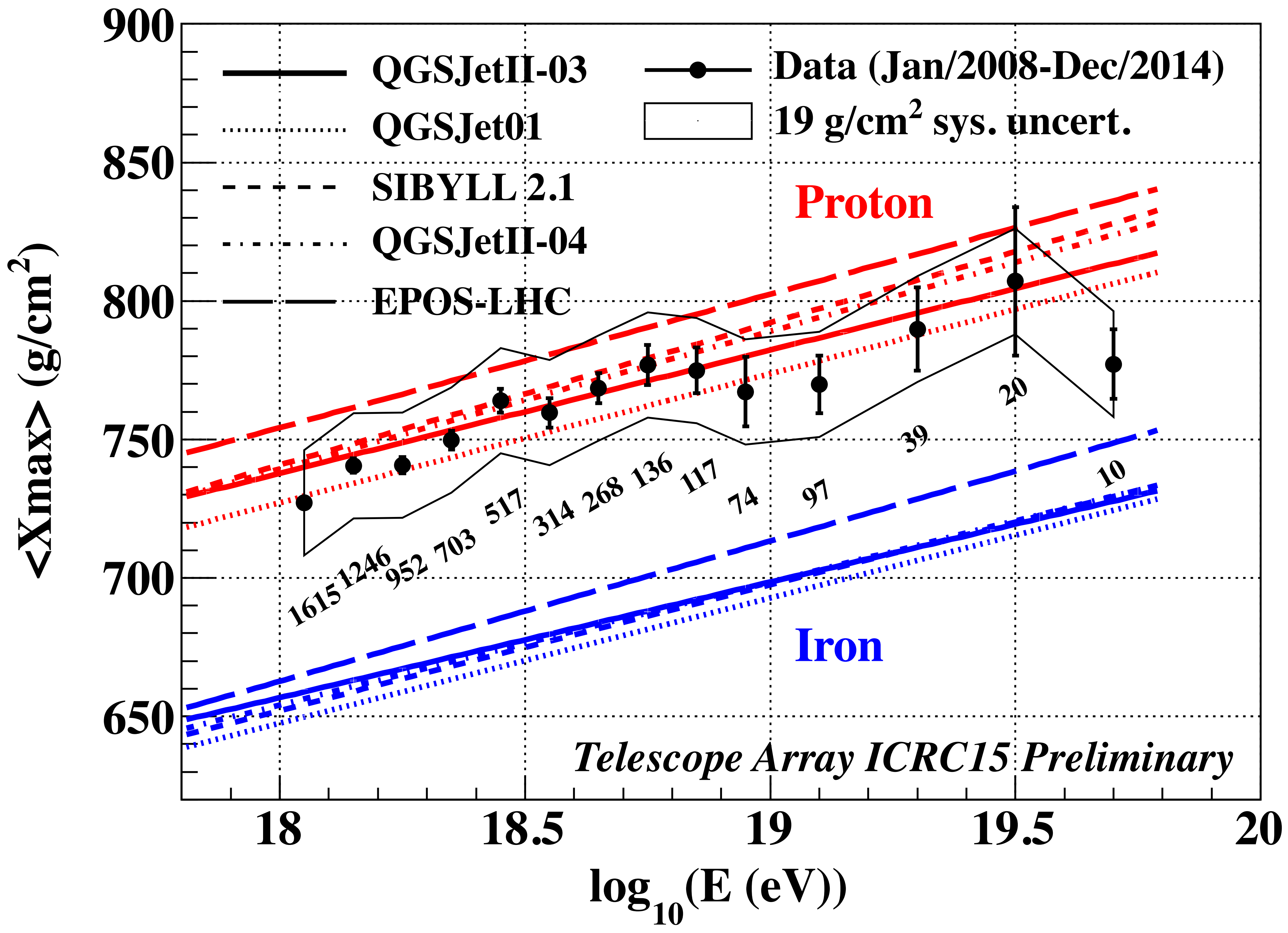
- Intermediate composition, such as helium or nitrogen
- Iron disfavored in all energy range
- No mass composition information above $10^{19.7}$ eV
- or problem in hadronic interaction models

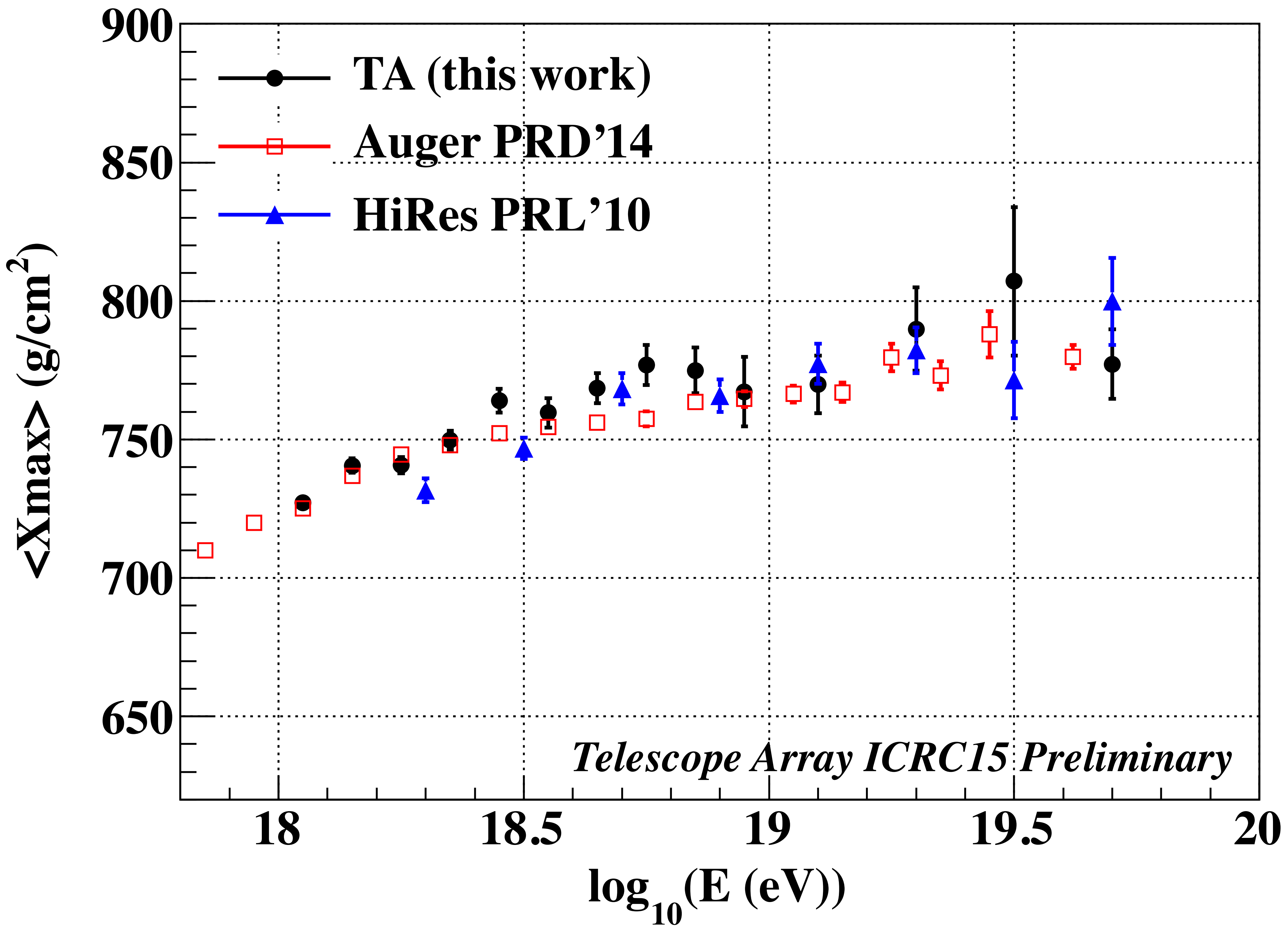
The Pierre Auger Collaboration, Phys. Rev. D 90, 122006 (2014)



The Pierre Auger Collaboration, Phys. Rev. D 90, 122006 (2014)

Mass composition analysis in TA



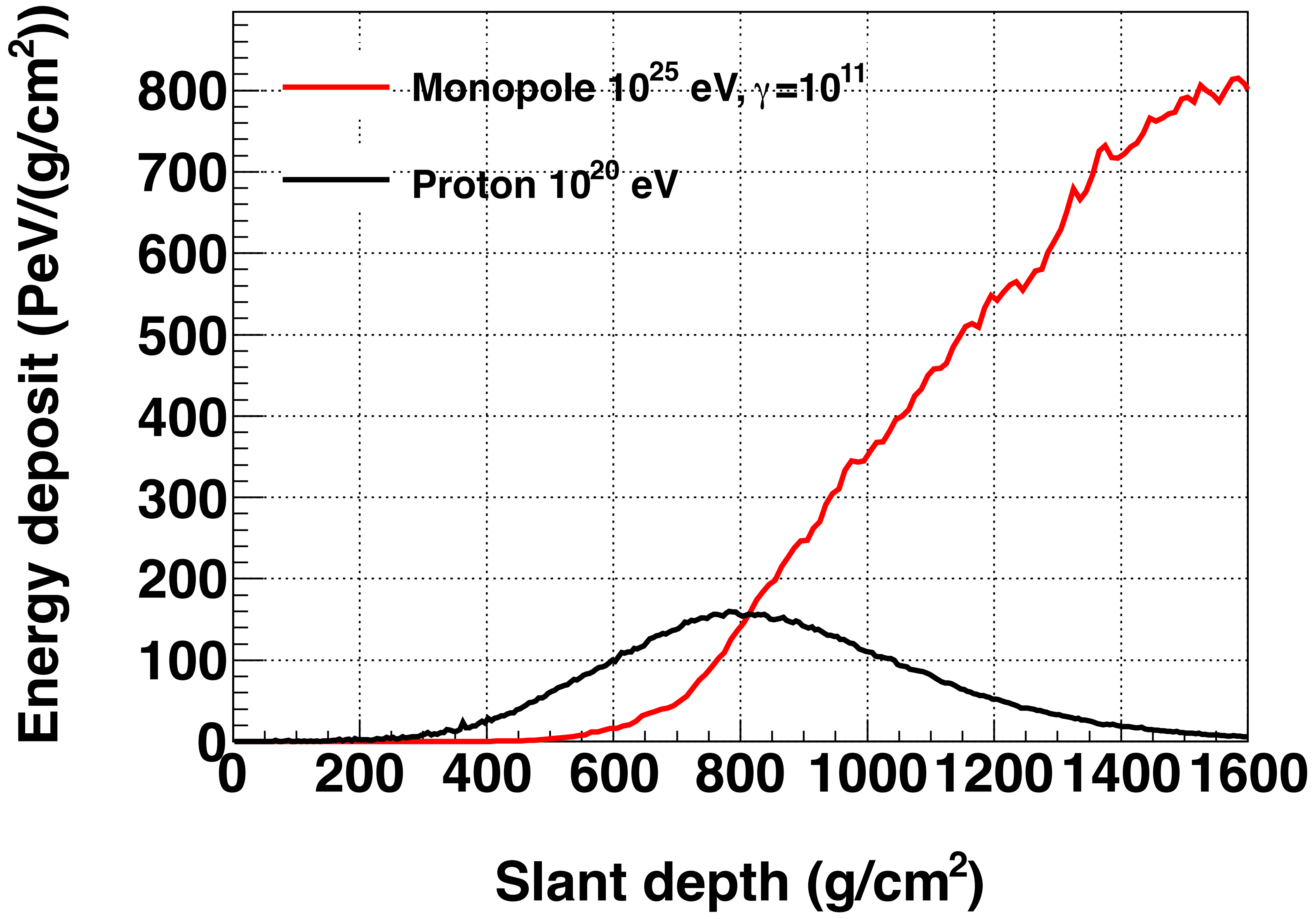


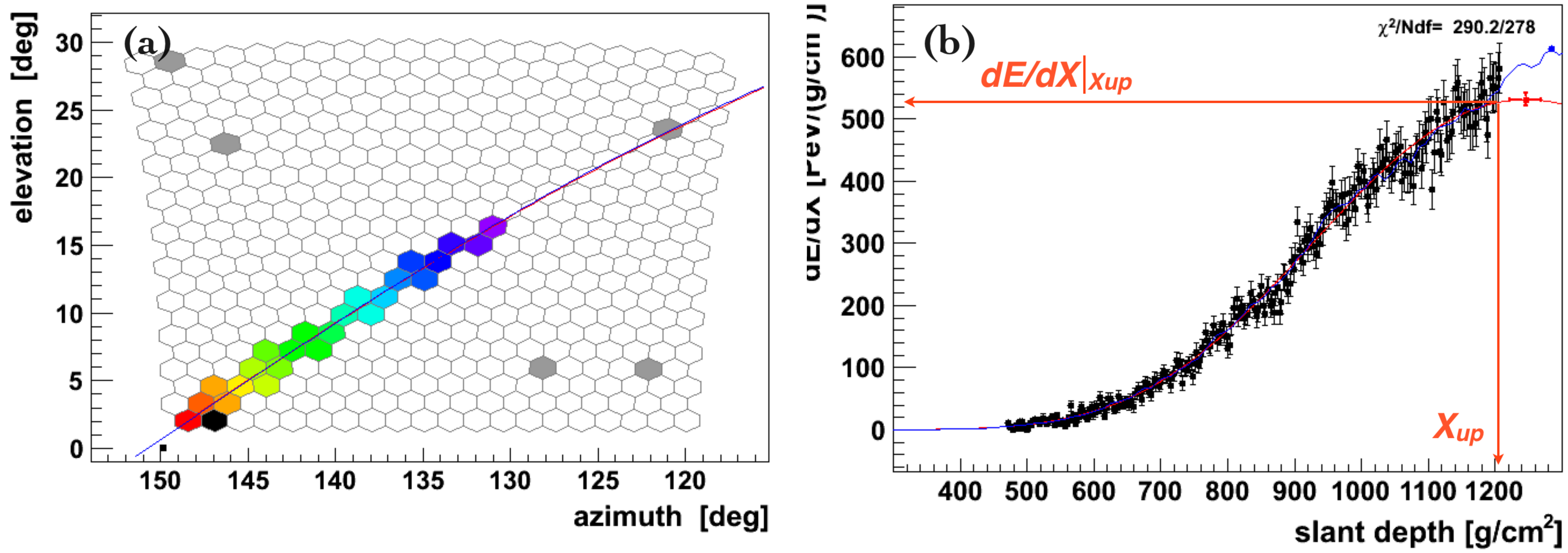
- Apply the Xmax detection bias-free cut like Auger improved method.
- Use the monocular analysis to maximize the statistics.
- Consistent with the proton prediction above 10^{18} eV.
- TA, Auger, HiRes results show a good agreement within the systematic uncertainty.

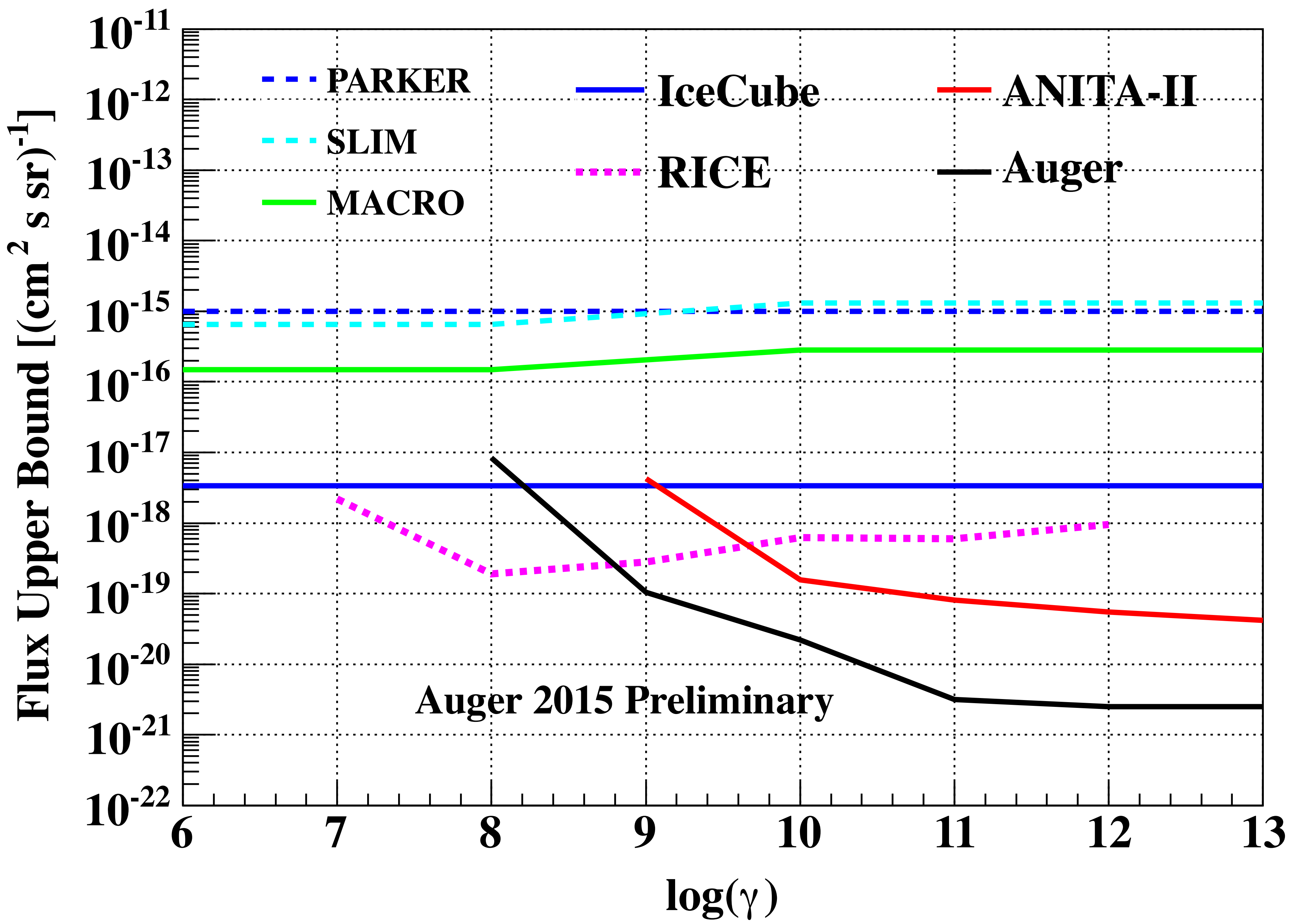
T. Fujii et al., ICRC 2015

Search for Ultra-relativistic Magnetic Monopole

- Supermassive magnetic monopoles ($M \approx 10^{26}$ eV/c^2) could be produced in the early Universe.
- Intermediate mass monopoles (IMMs, M~10^{11}-10^{20} eV/c^2) can reach kinetic energies of ~10^{25} eV by acceleration in the galactic and intergalactic magnetic fields.
- Search for the signal produced by ultra-relativistic magnetic monopole with 10-years Auger FD data.



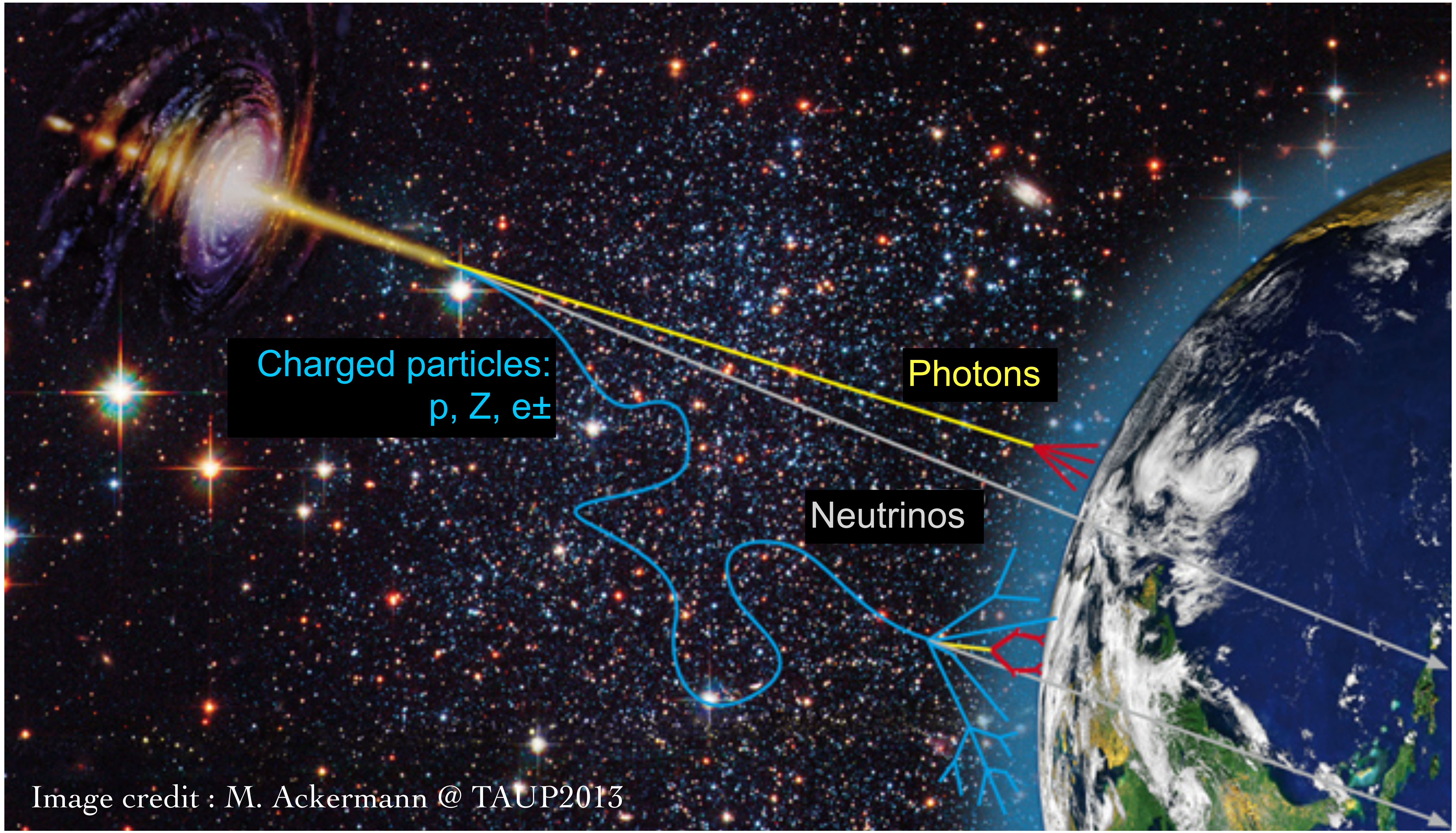




T. Fujii for the Pierre Auger Collaboration, ICRC2015

Where come from?: Arrival direction

- GZK Cutoff → Nearby Universe → Large scale structure
- UHECR → Smaller deflection in galactic/extragalactic magnetic field



$$\delta \simeq 3^o \frac{B}{3\,\mu G} \frac{L}{kpc} \frac{6\times 10^{19}\,eV}{E/Z}$$

Anisotropy of UHECR expected

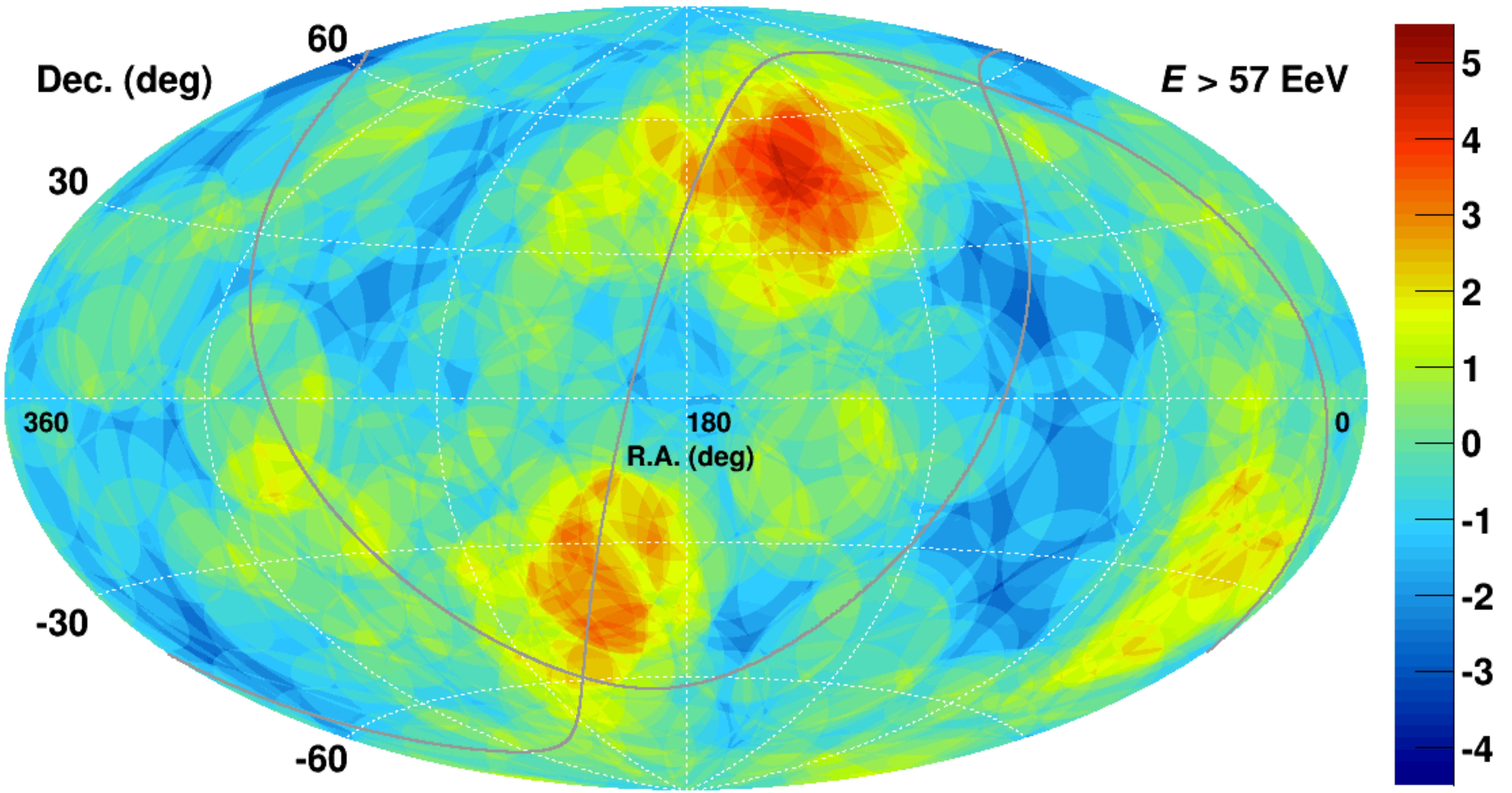
↓

UHECR Astronomy

Where come from?: Arrival direction

Oversampling with 20°-radius circle

TA Hotspot: 5.1σ (pre-trial)
3.4σ (post-trial)

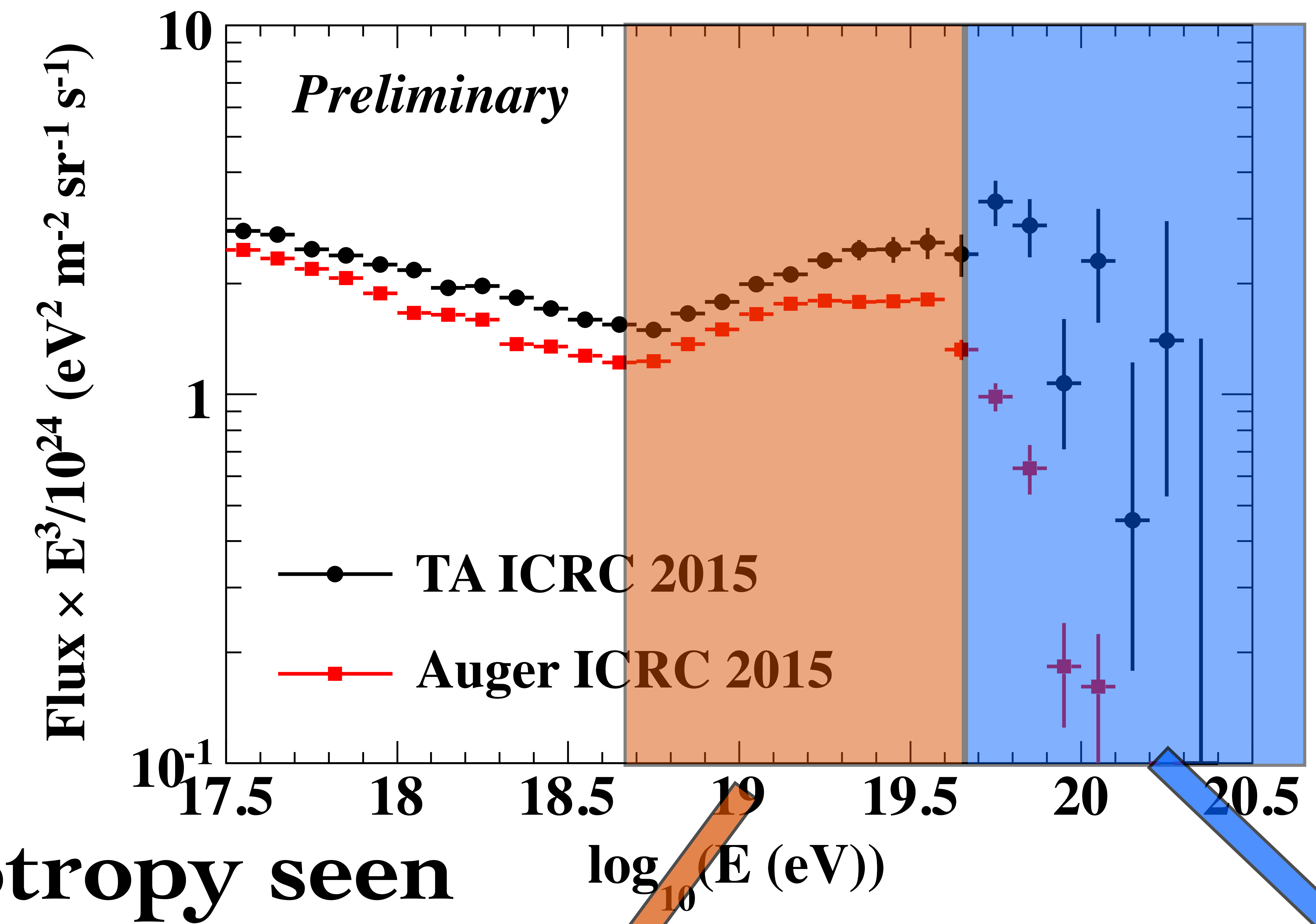


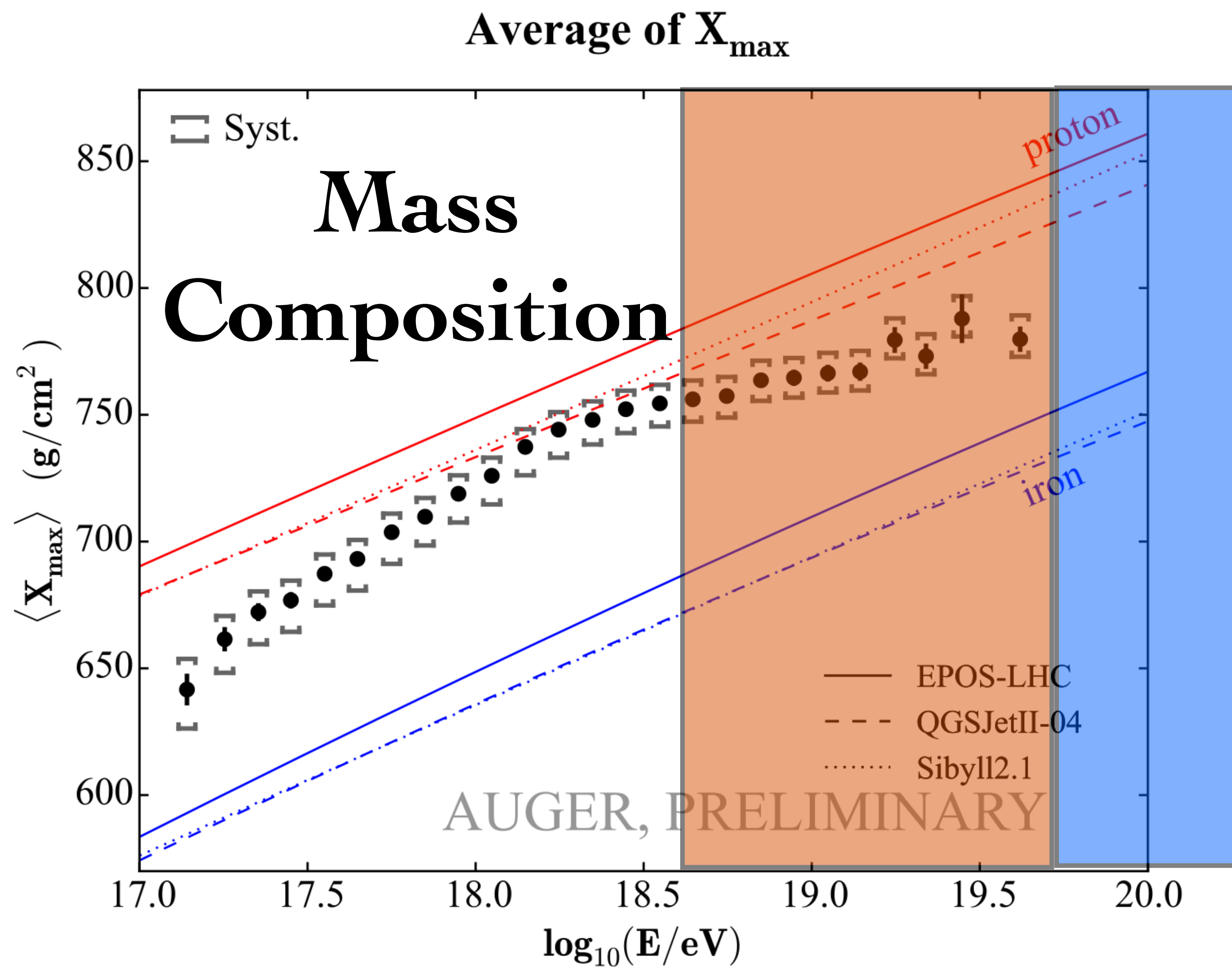
Auger Warmspot: 3.4σ (pre-trial)

Northern TA: 7 years 109 events (>$10^{19.75}$ eV)
Southern Auger: 10 years 157 events (>$10^{19.75}$ eV)

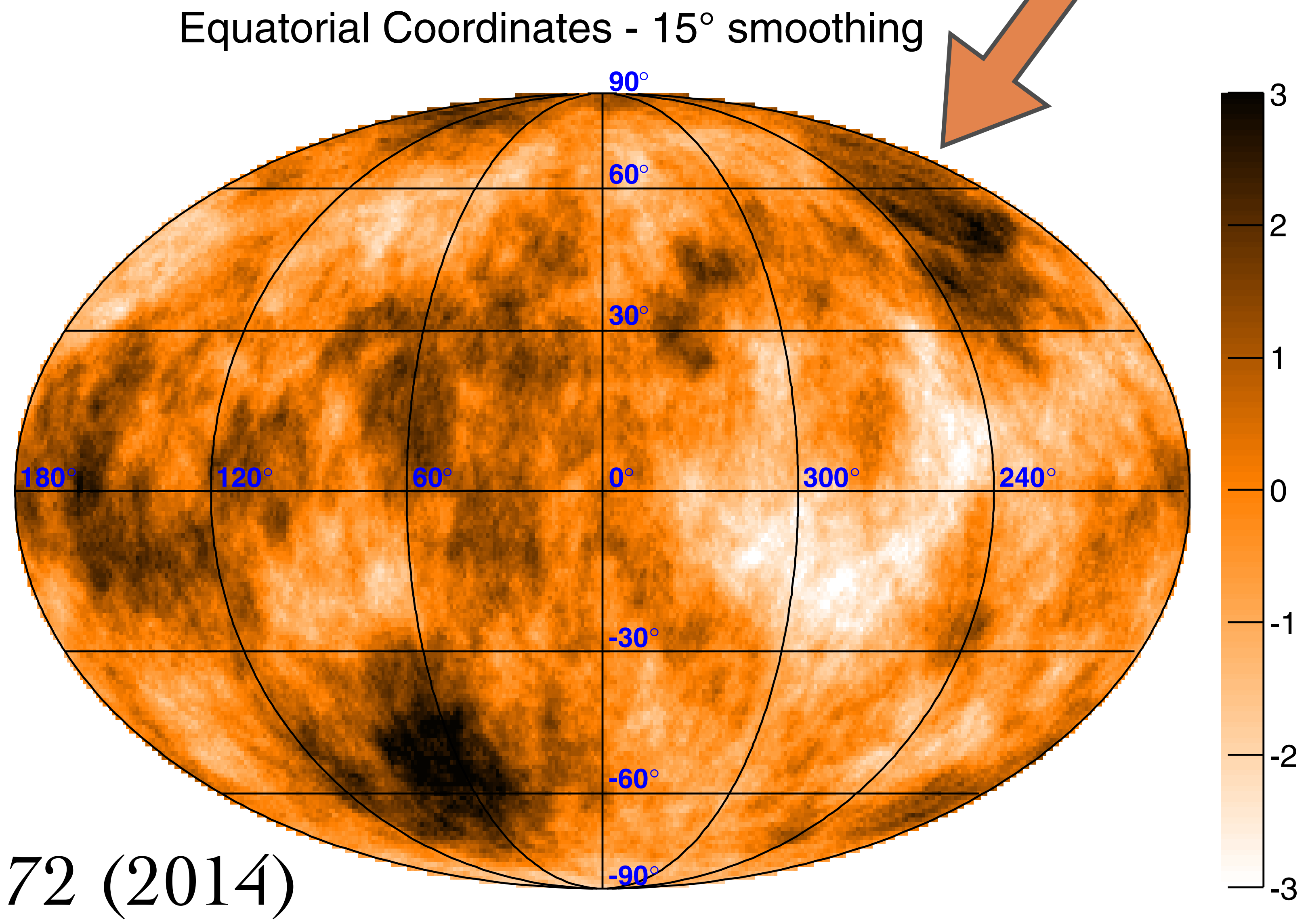
K. Kawata et al., ICRC 2015

UHECR Astronomy?



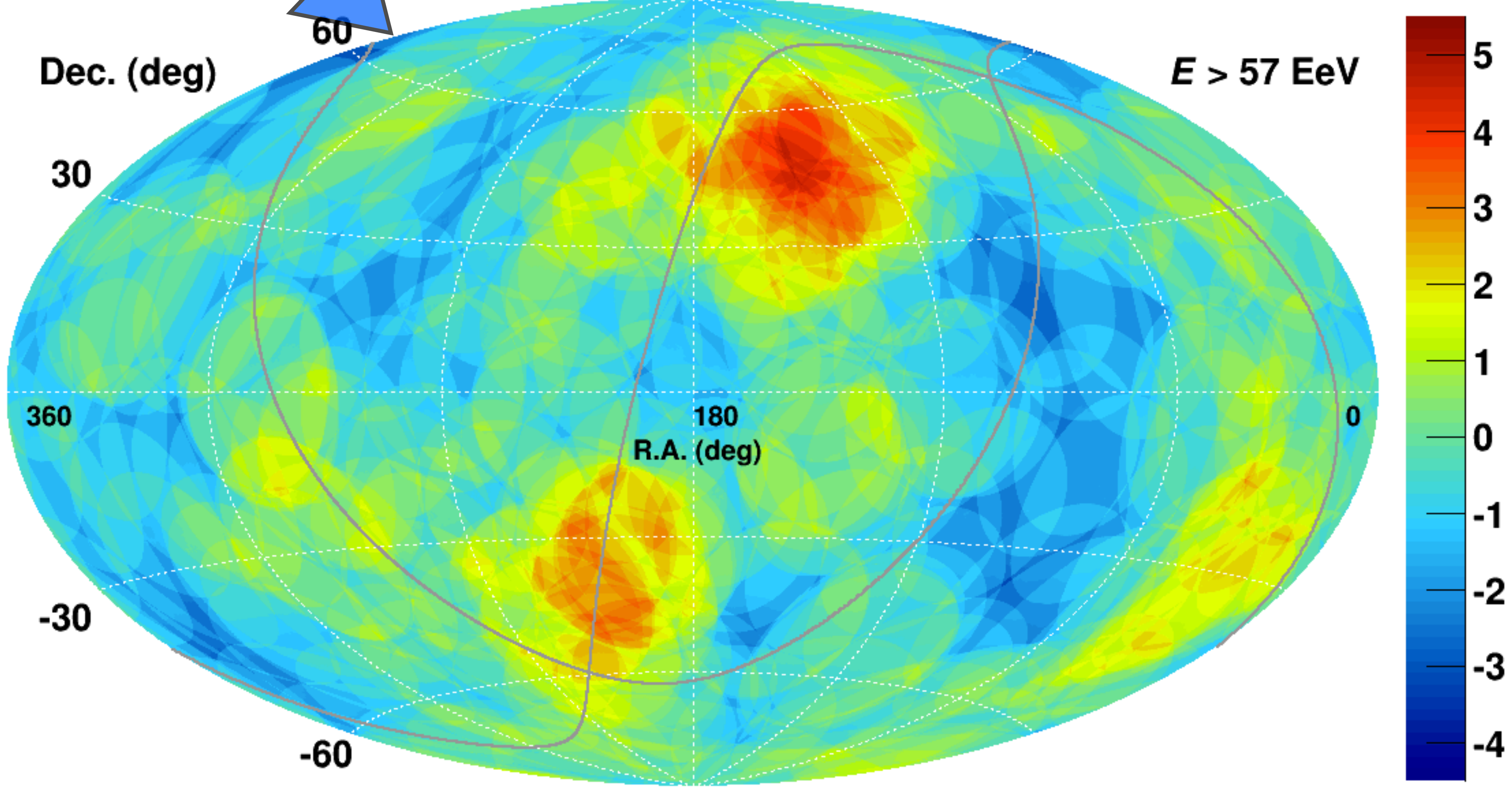


No anisotropy seen



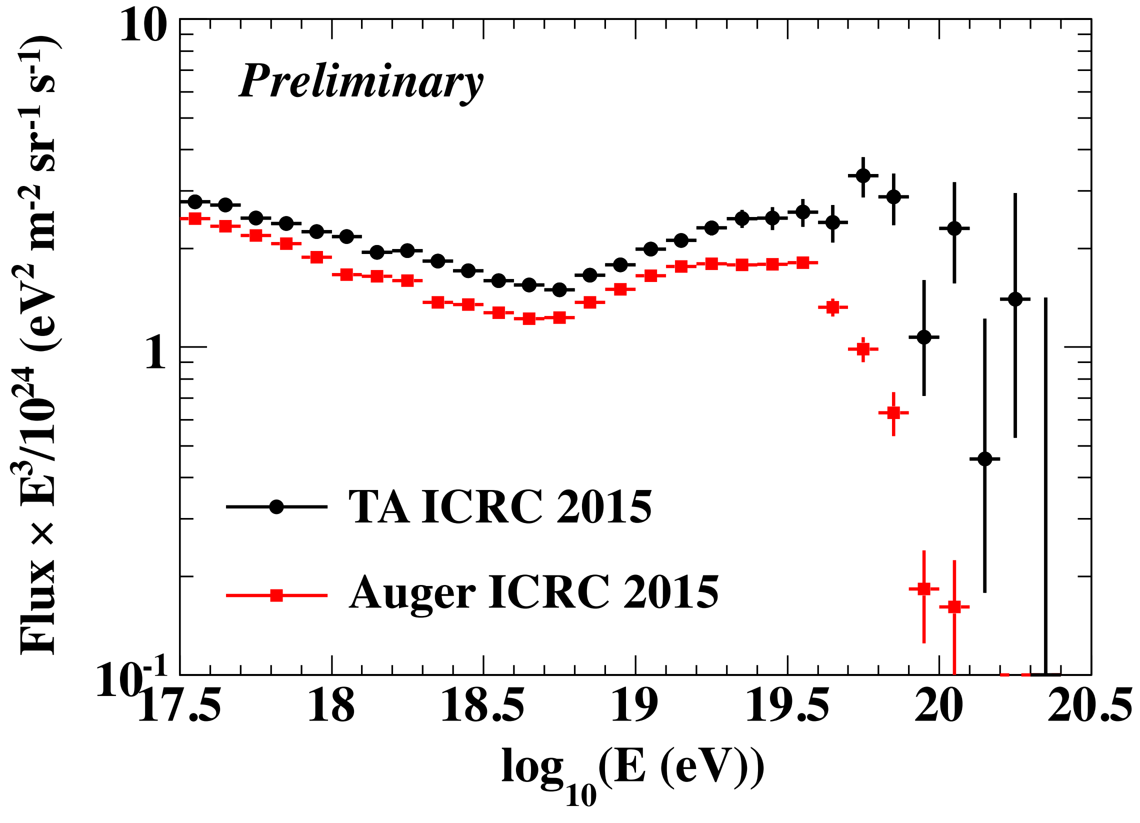
ApJ 794 172 (2014)

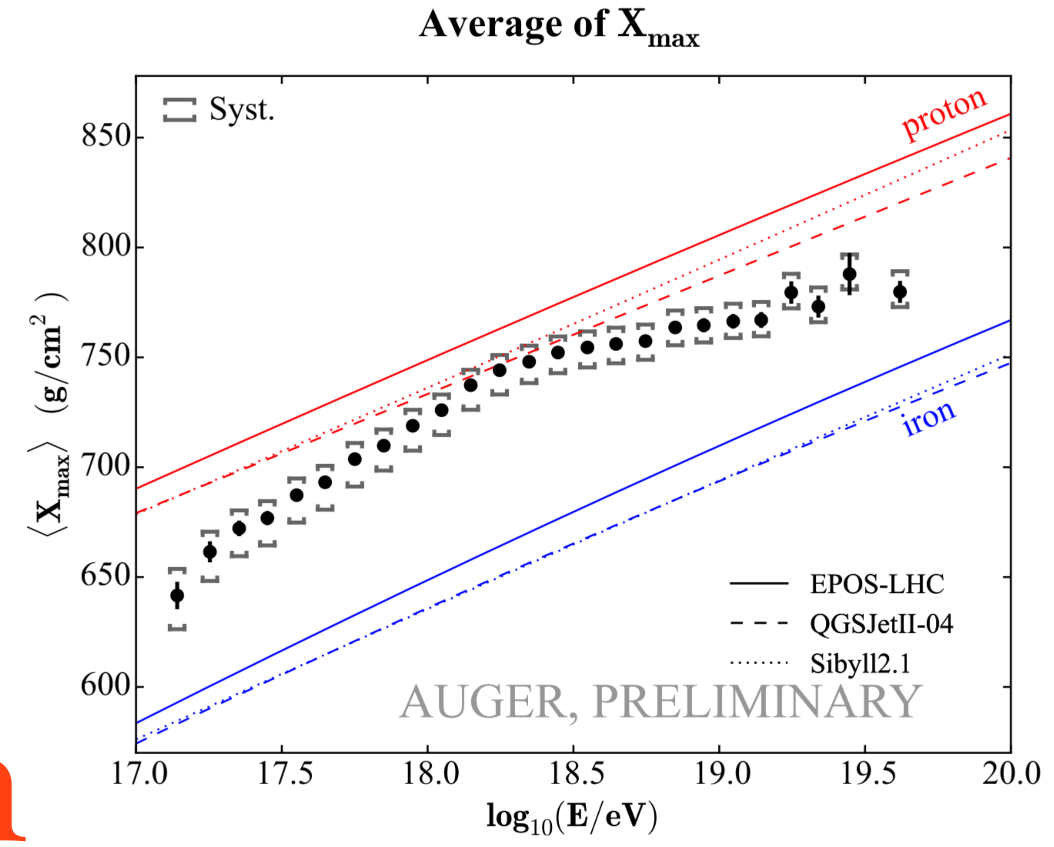
Hotspot/Warmspot



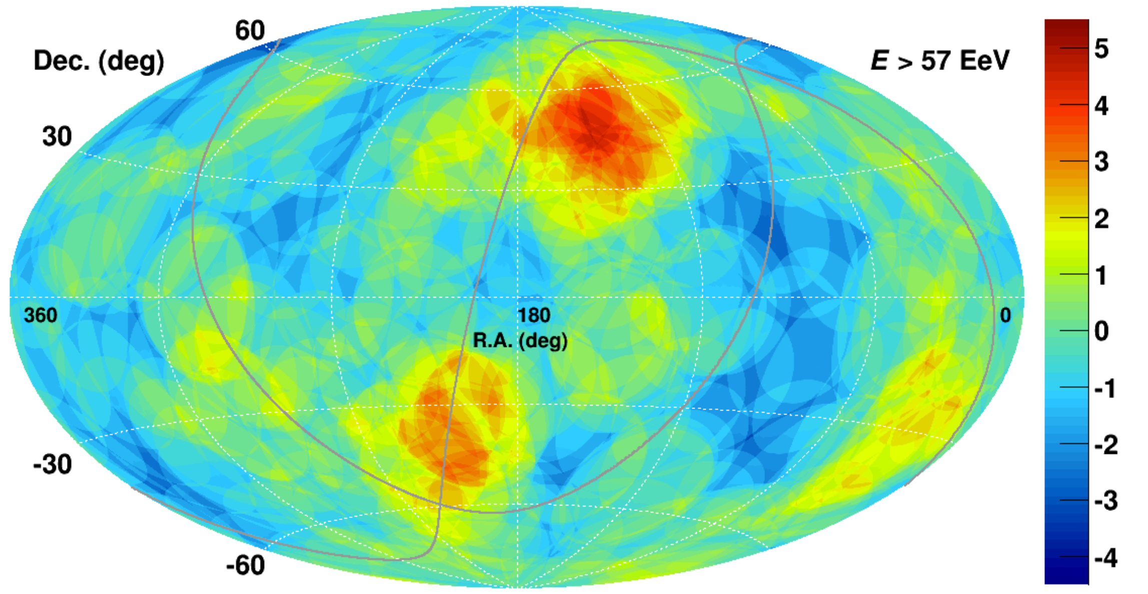
Physics Goal of UHECR Astrophysics

- 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

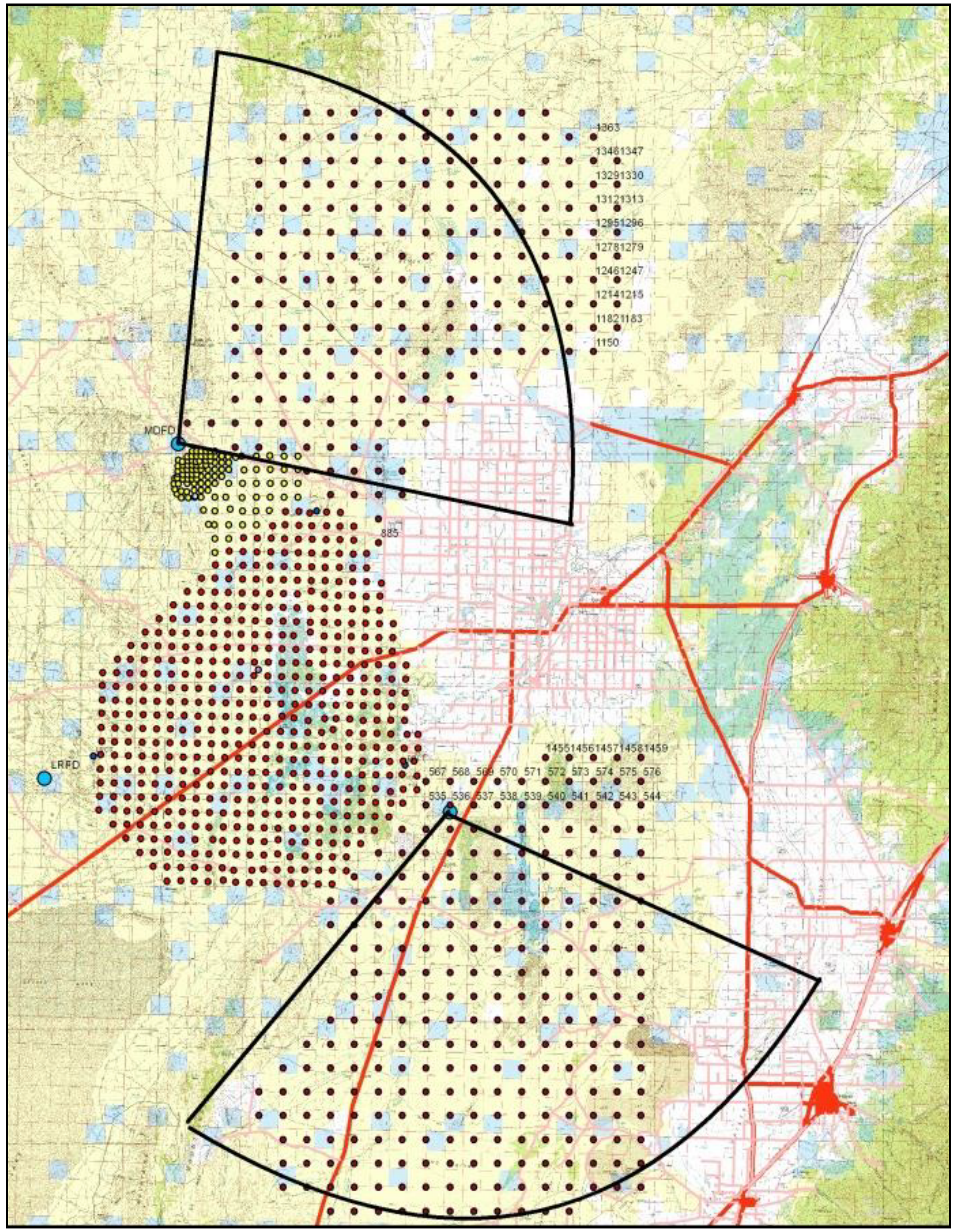
- Precise observation of the flux suppression above $10^{19.5}$ eV.
- Gradually increase heavier composition above ankle.
- Hotspot/Warmspot of UHECRs

- **Flux suppression due to GZK process or maximum energy of accelerator?**
- **Heavier composition or 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?**

TA×4

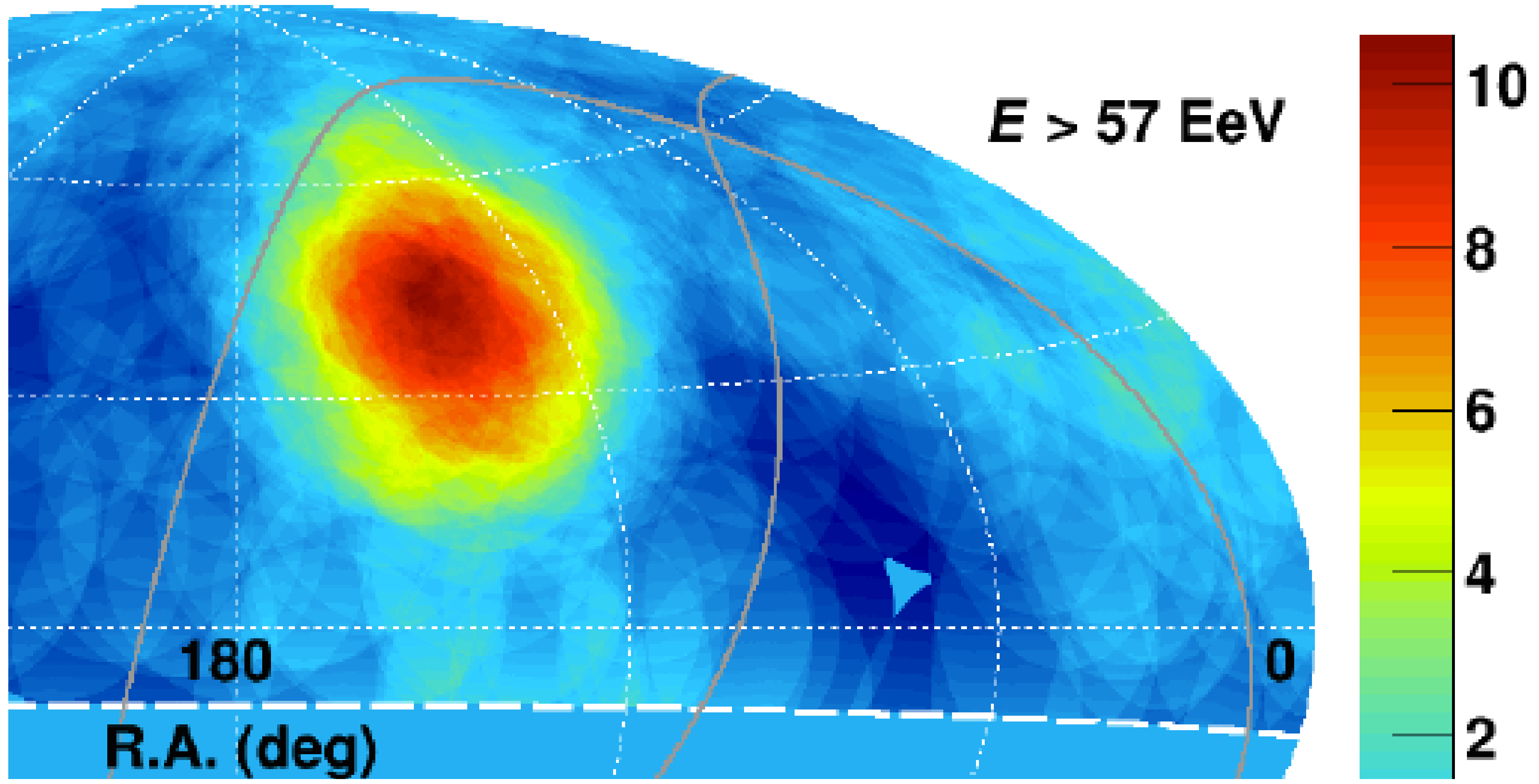
Detailed measurement of the hotspot

Enlarge the fourfold coverage to TA×4 = Auger.

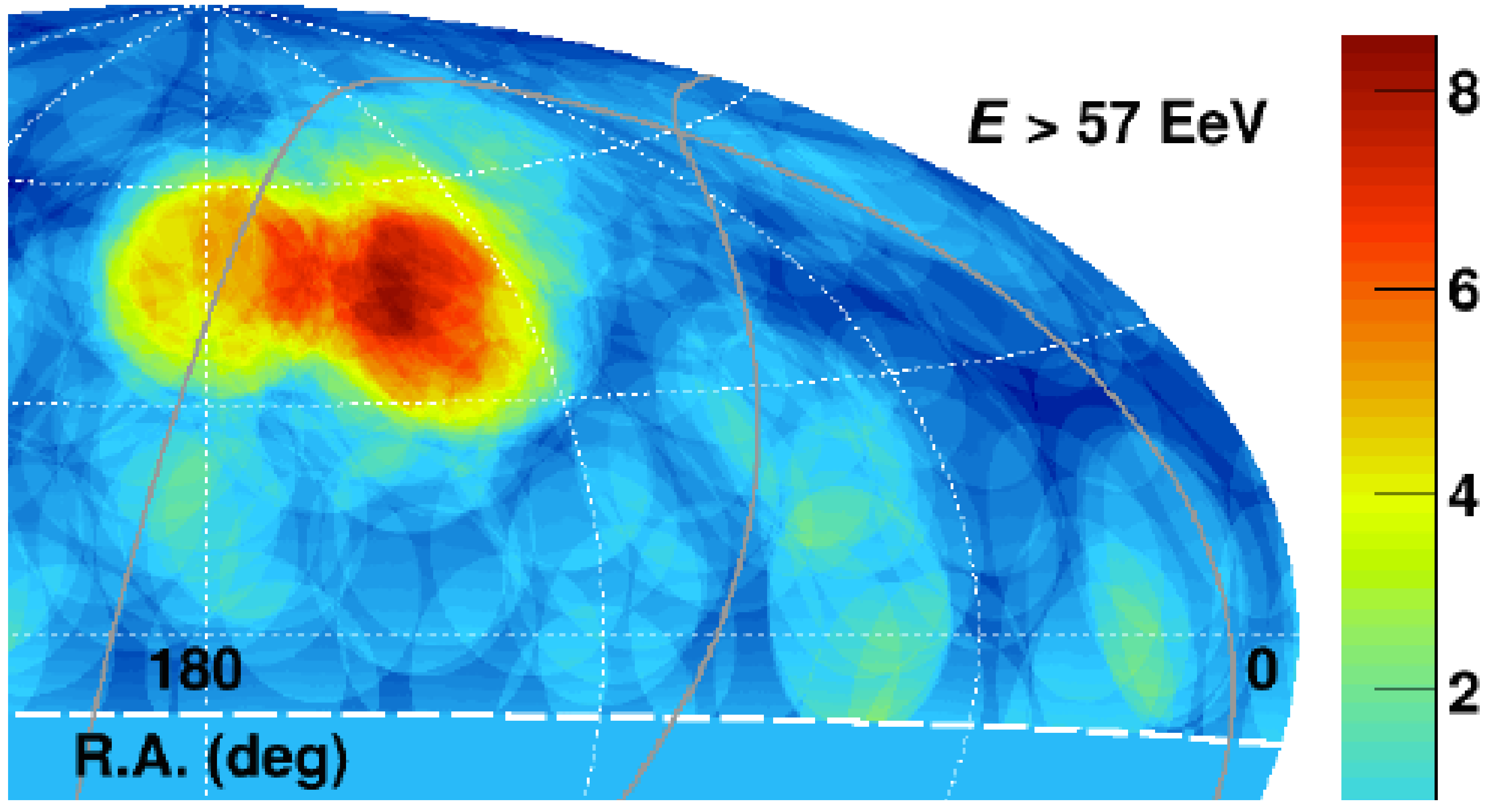


SD part was funded in Japan, 2015.

Expected Result in 2020

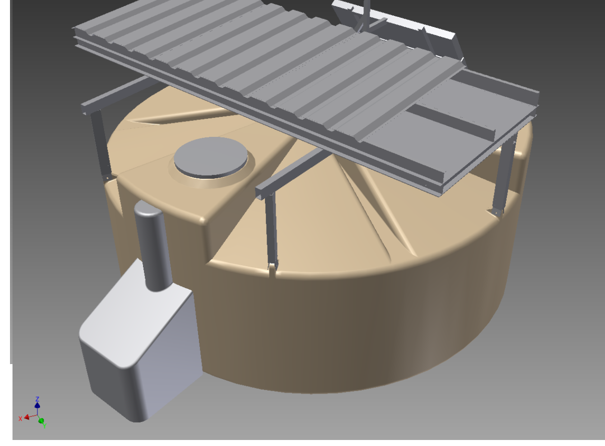


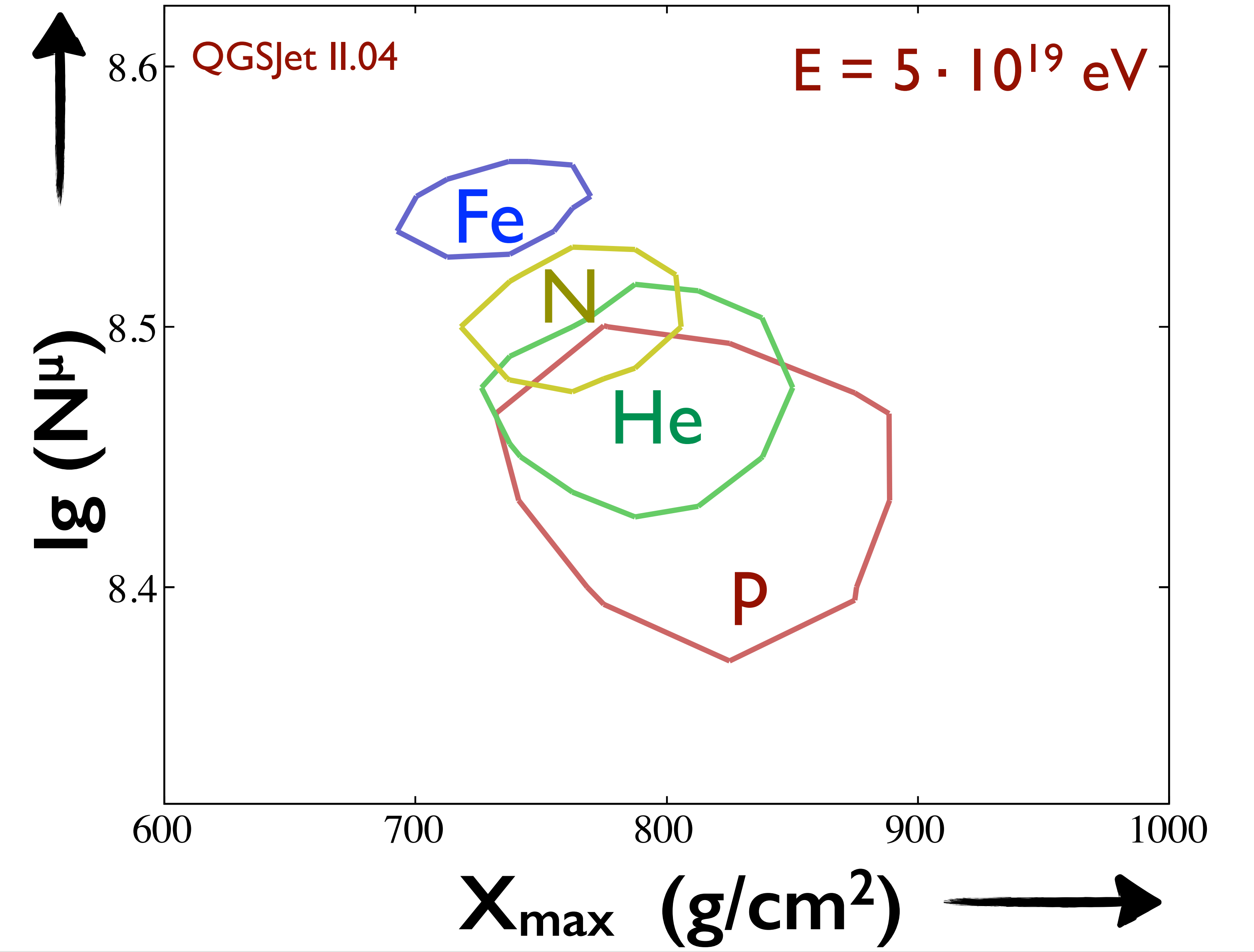
1 cluster (MC)



2 cluster (MC)

AugerPrime

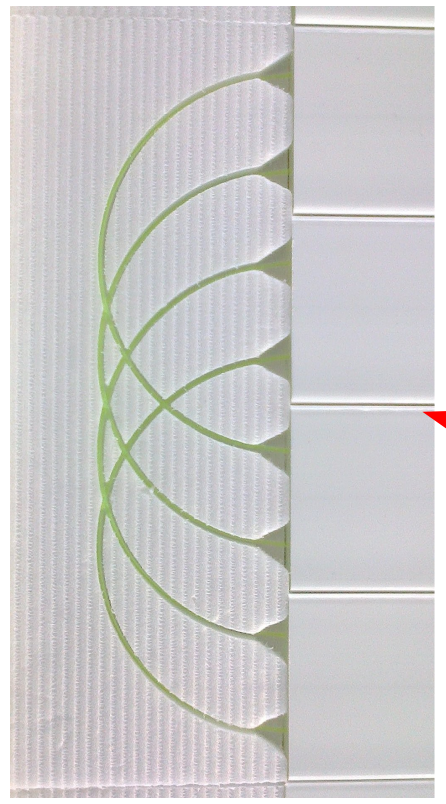


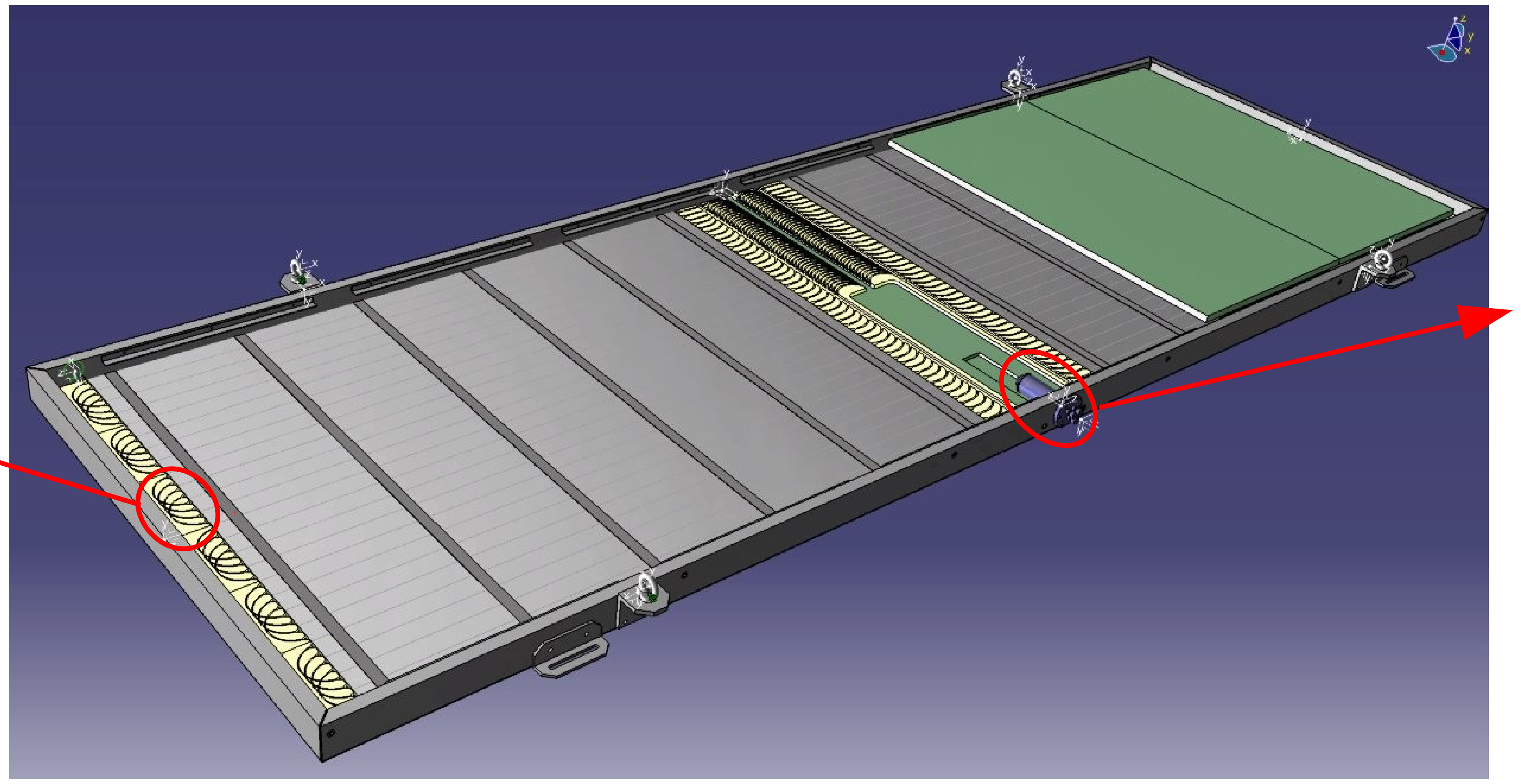


- Primary comic ray identification for next 10 years.
- The key is enhancement electromagnetic/muon separation of **SD** to measure the mass composition.
- Boost in statistics by a factor of ~ 10.
- Sensitive to a proton contribution as low as 10%.

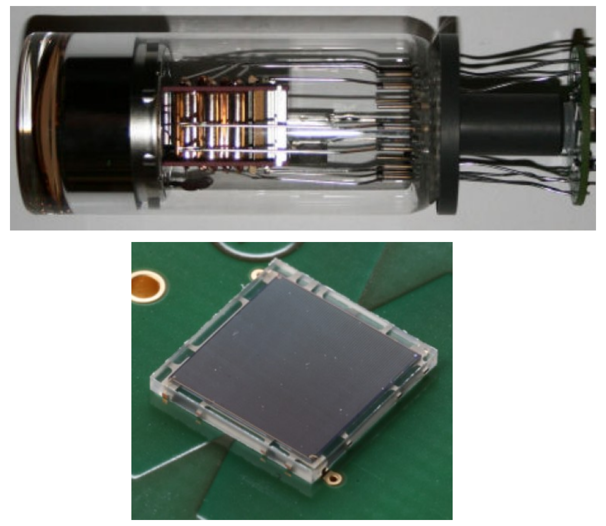
Install 4 m^2 Scintillator to measure the mass composition by SD.

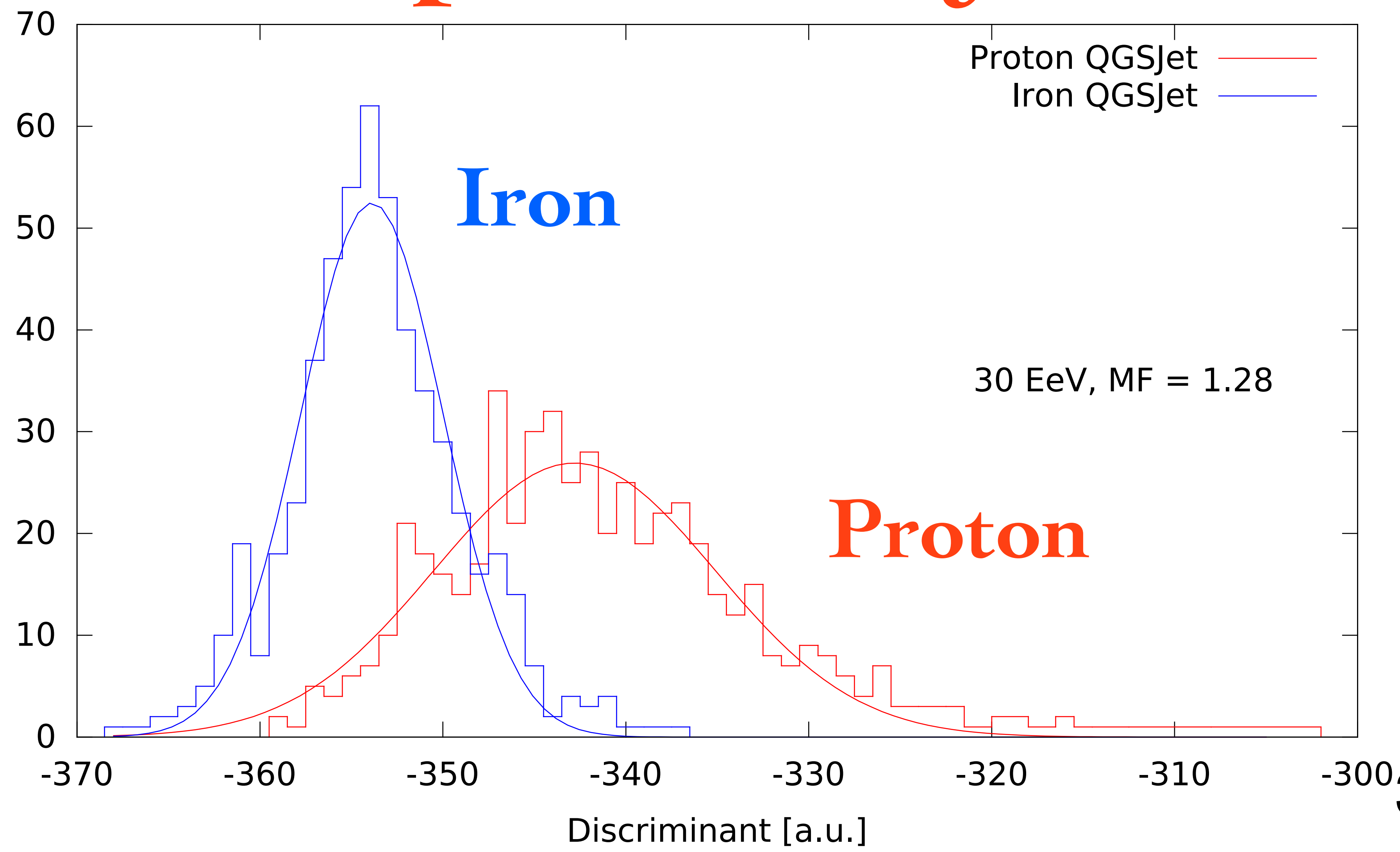
Fibers routing





PMT/SiPM





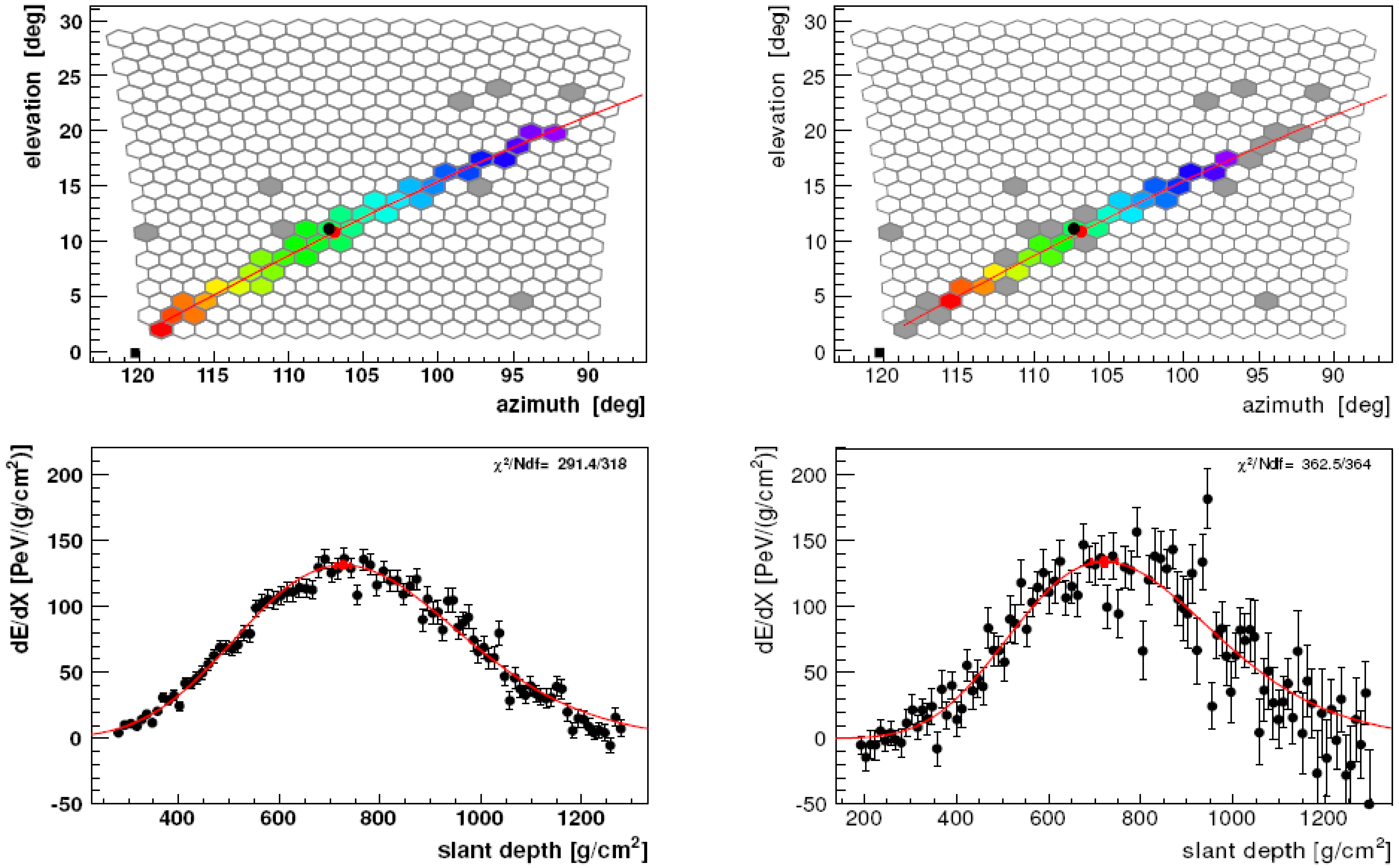
Extended FD Operation

15% duty cycle

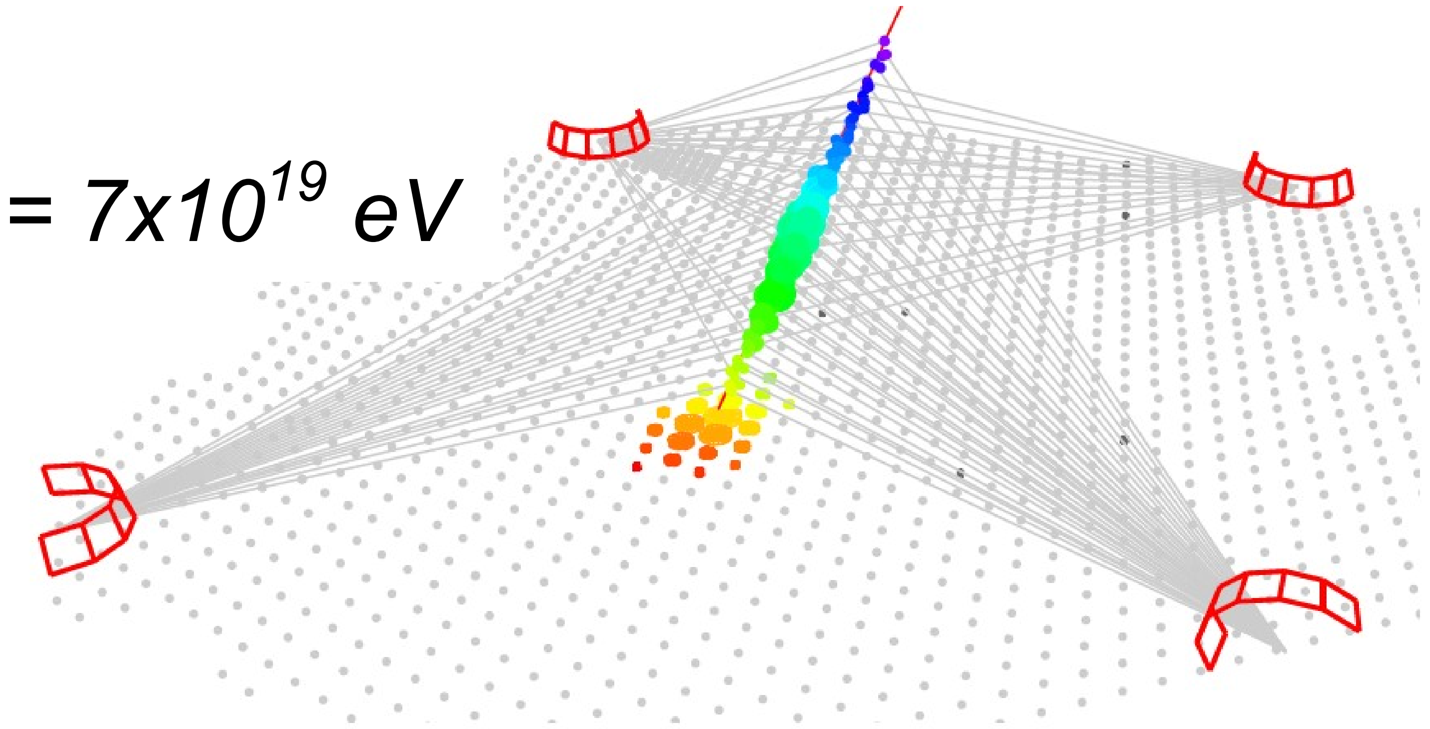
Increase by 50% by measurement during high night sky background

The moon and Jupiter above Los Leones in the morning on 4 Mar, 2015.

Clear sky, no moonlight *40 times higher NSB (90% moon)*



E = 7x10^{19} eV



10x reduced PMT gain by reducing supplied HV.

Successful test has been done last year.

$E = 72 \pm 3$ EeV


PIERRE AUGER
Signature Ceremony of International Agreement
for the Pierre Auger Observatory
Malargüe, 16 November 2015
PIERRE AUGER
www.auger.org

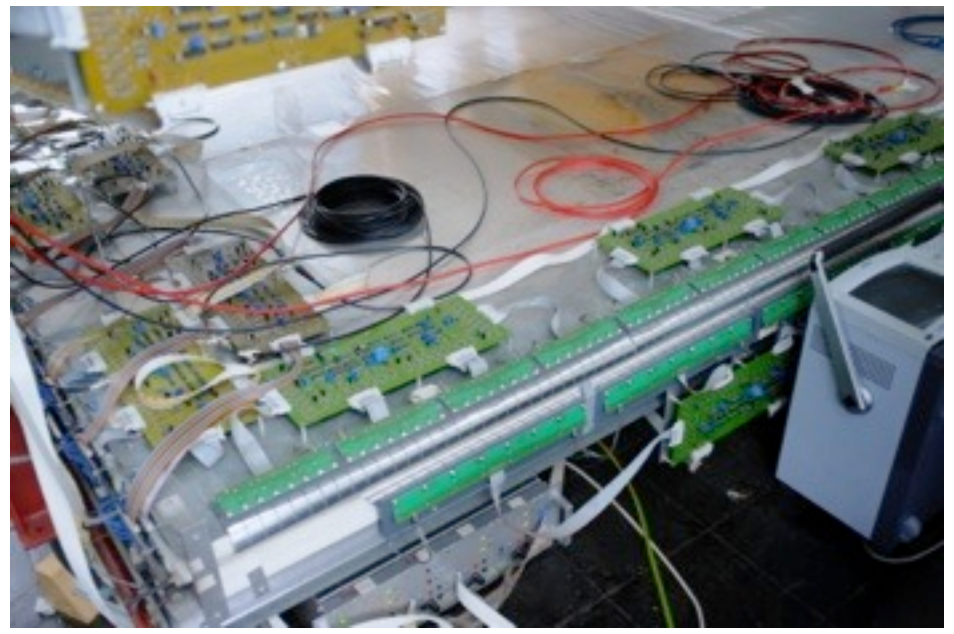

Julio Cobos
Rolando Baldasso


OBSERVATORIO
PIERRE AUGER
Un Experimento Internacional para el Estudio de los Rayos Cósmicos de las Energías más Elevadas

Reuse CDF PMTs for AugerPrime

- 1900 CDF PMTs are available for AugerPrime.
- Check the performance of 20 years-old PMT.

Muon Tomography at KIT



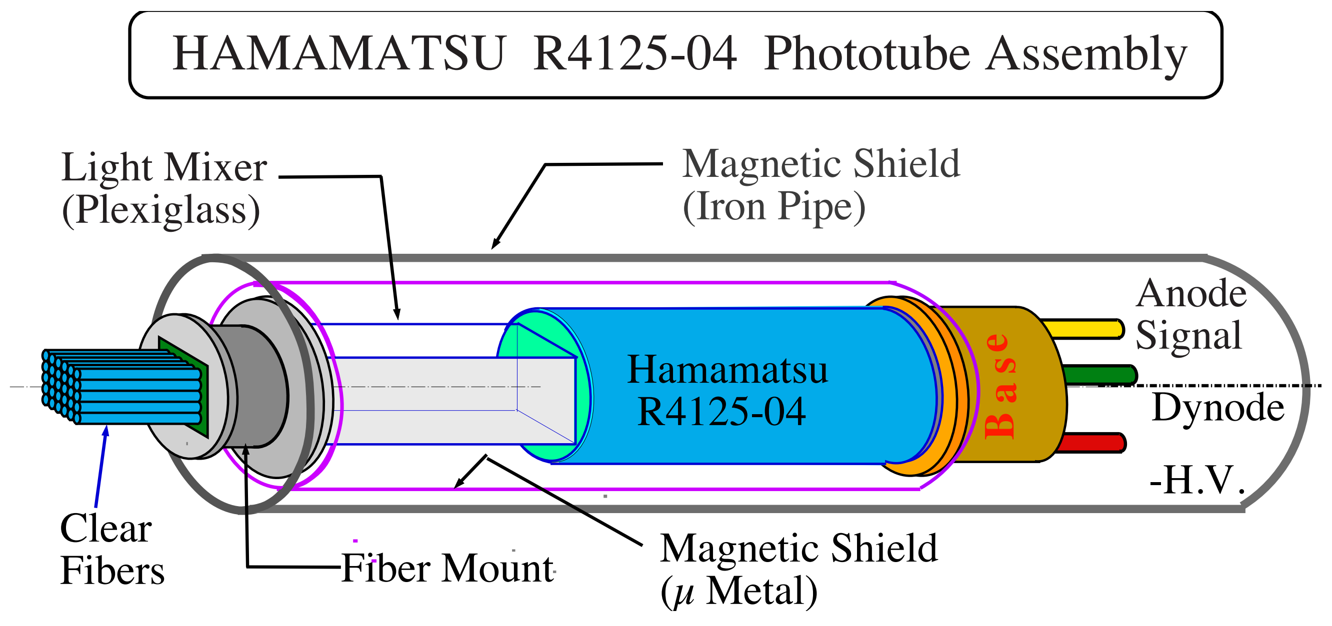
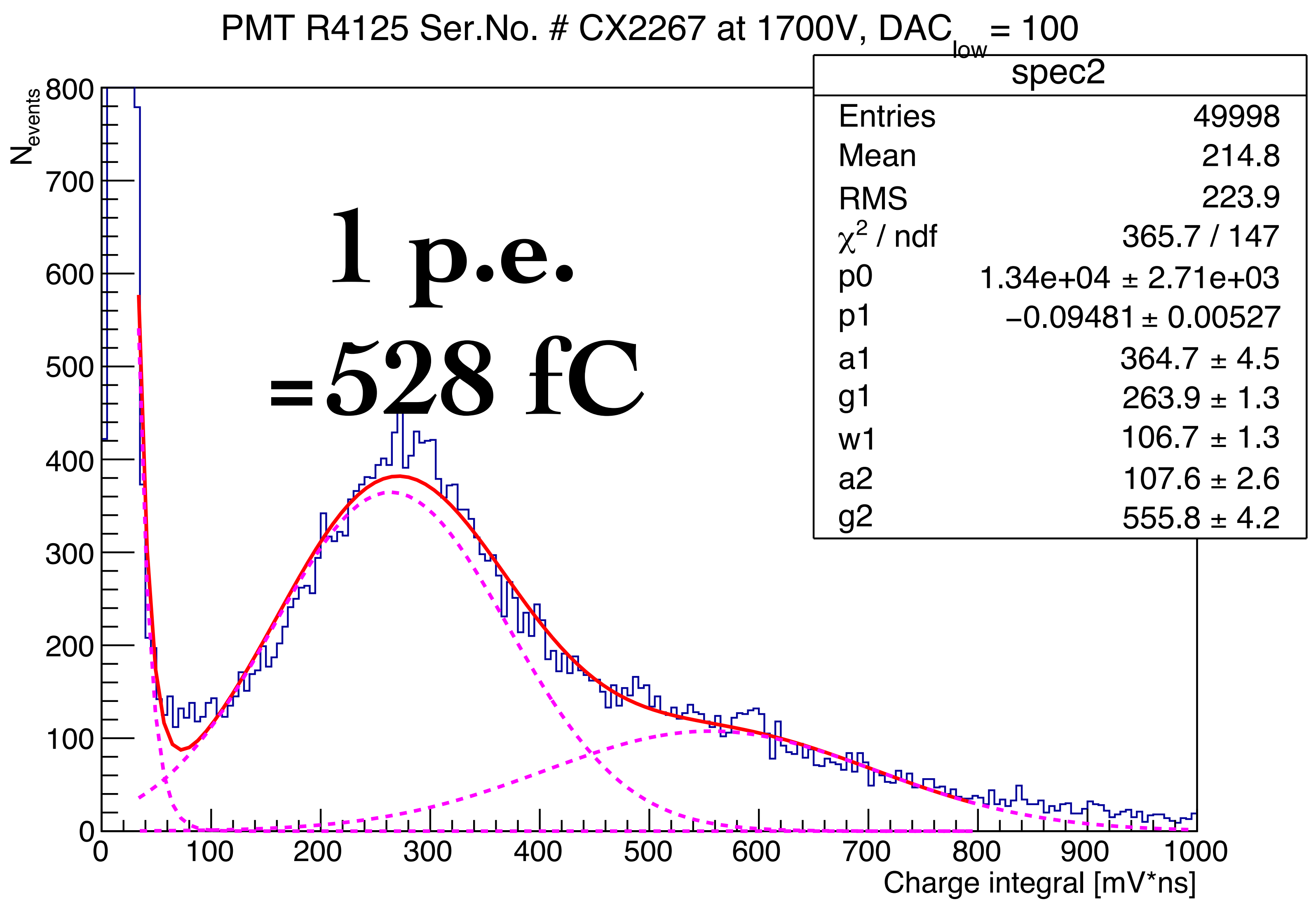
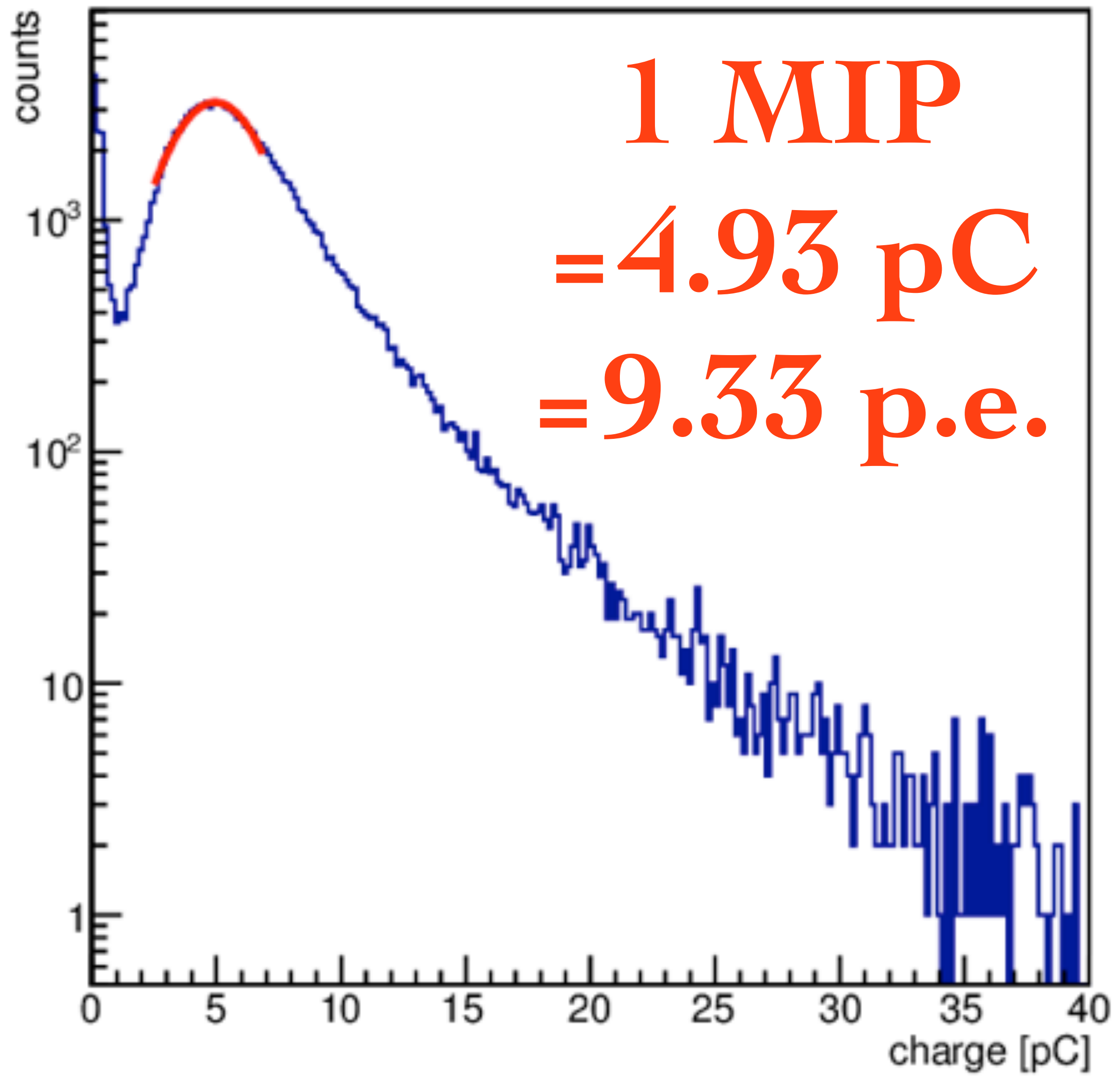
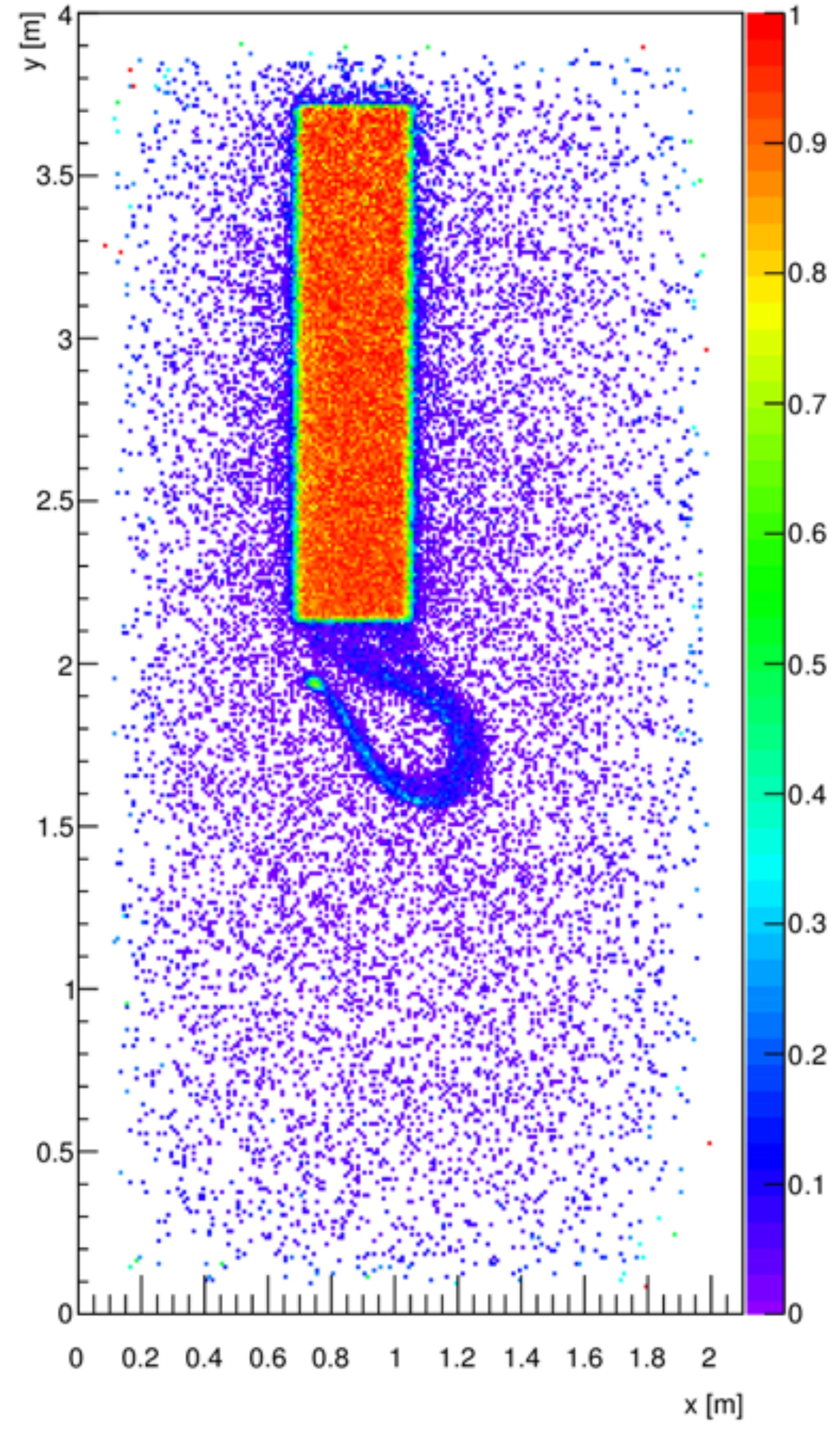


Fig. 3. Sketch of the phototube assembly (not to scale).



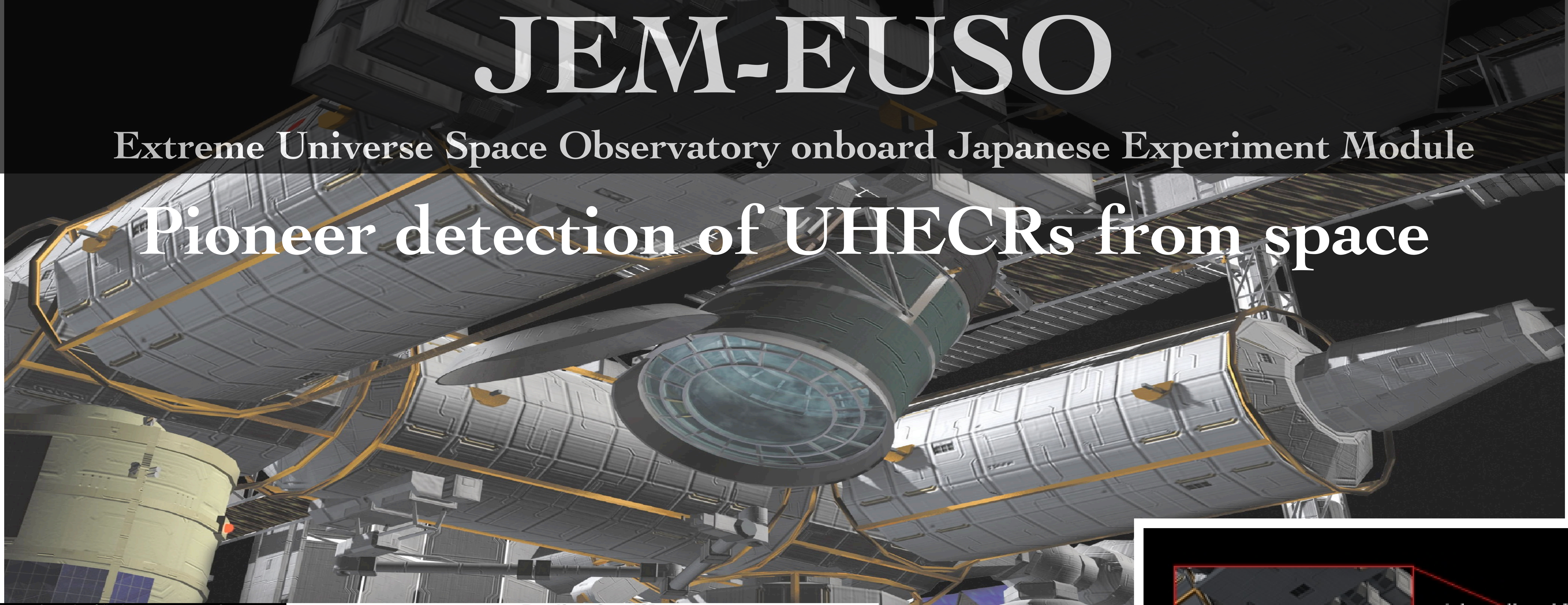


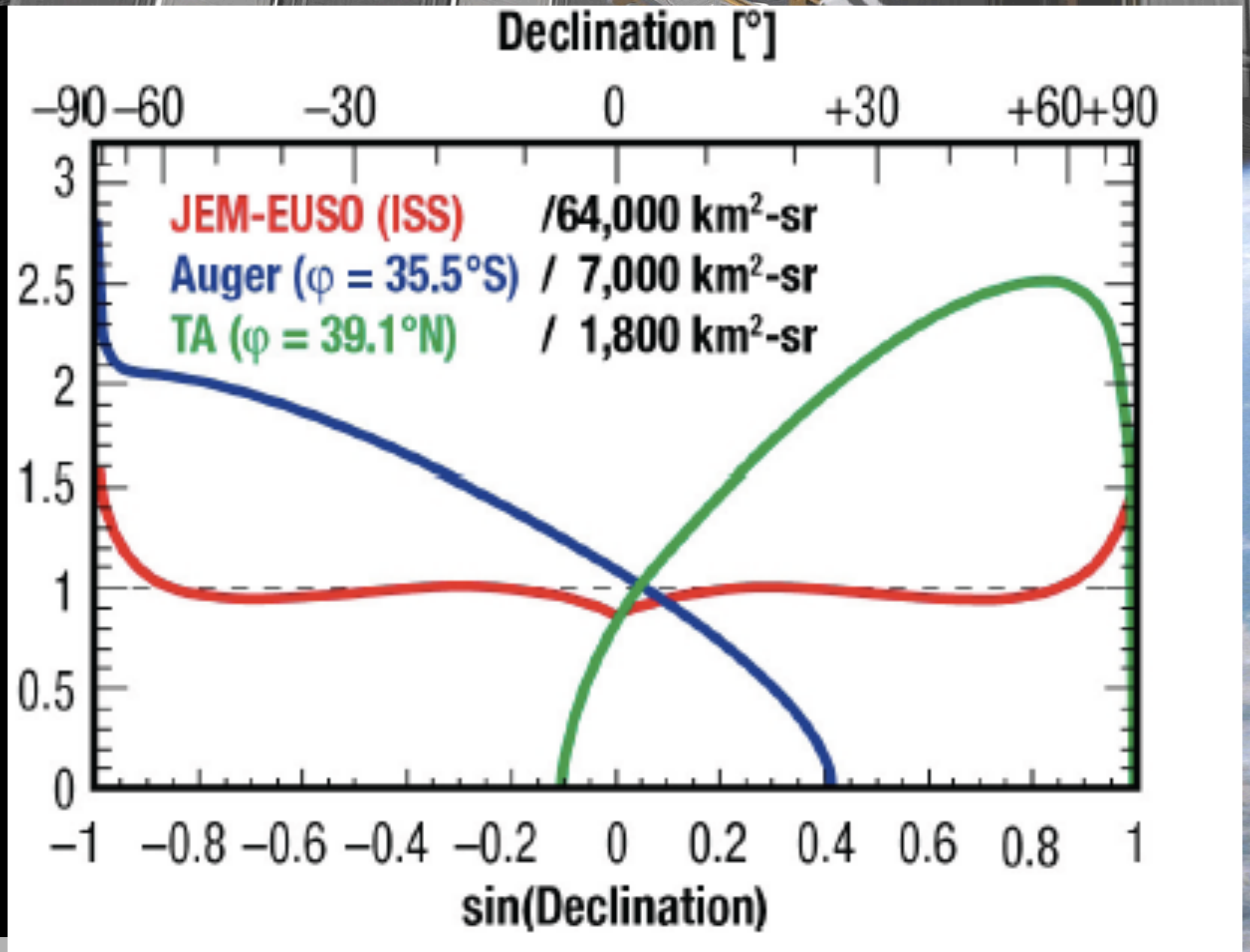


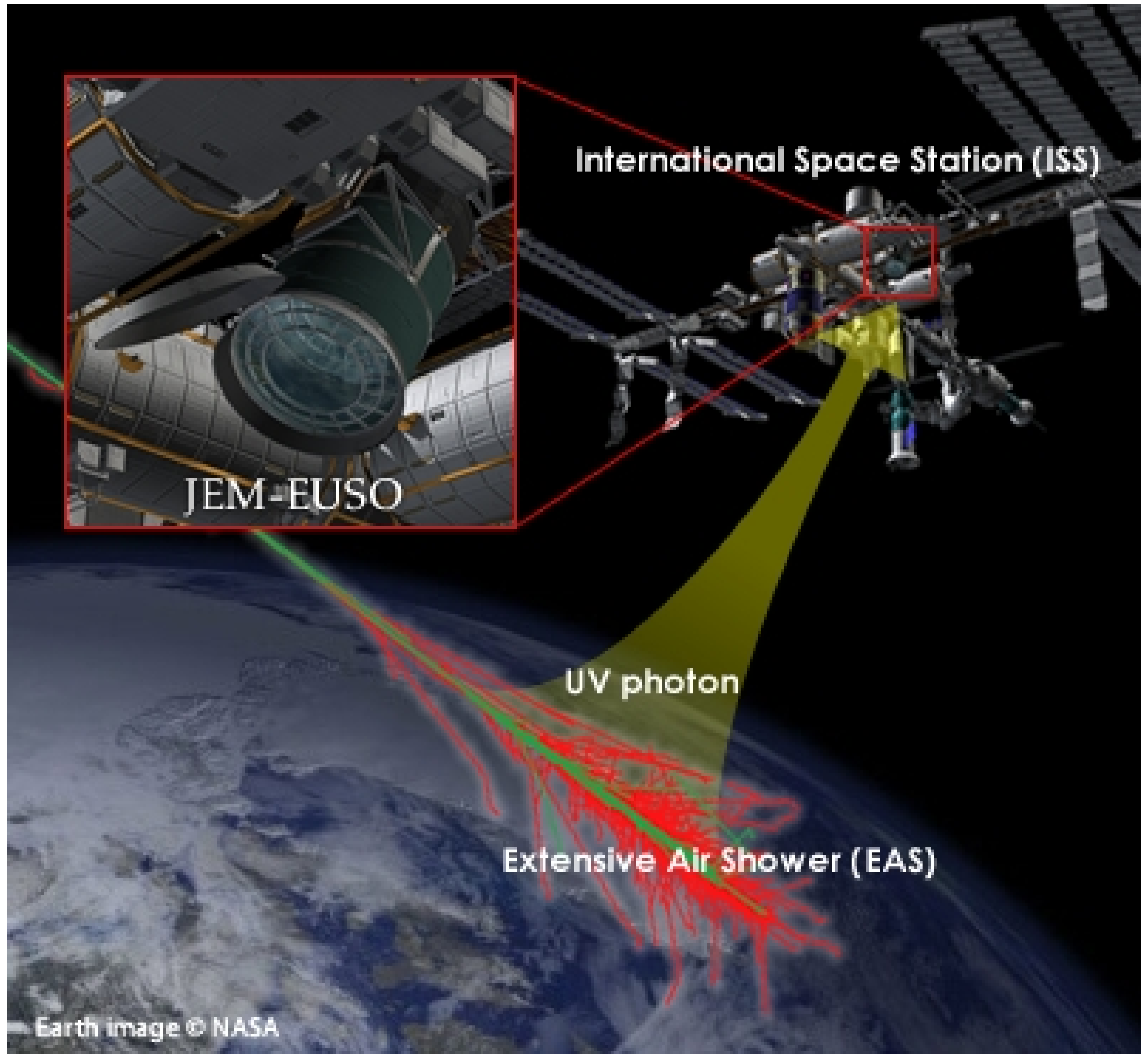
JEM-EUSO

Extreme Universe Space Observatory onboard Japanese Experiment Module

Pioneer detection of UHECRs from space







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
JEM-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): Super-EUSO
Ground (10×exposure with high quality events): FAST

Fluorescence detector Array of Single-pixel Telescopes

Fluorescence detector Array of Single-pixel Telescopes

http://www.fast-project.org

Fluorescence detector Array of Single-pixel Telescopes

FAST

FAST

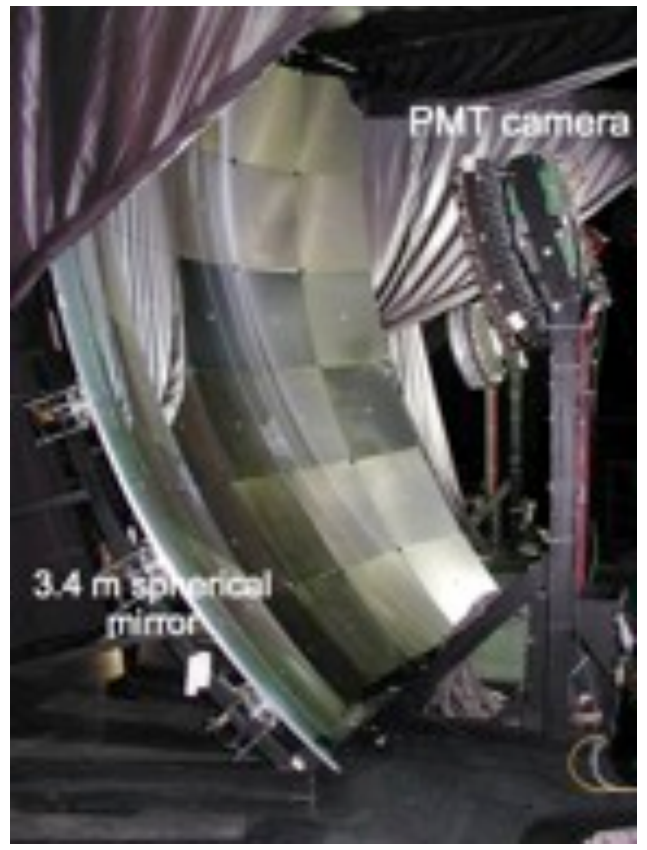
FAST
Fluorescence detector Array of Single-pixel Telescopes

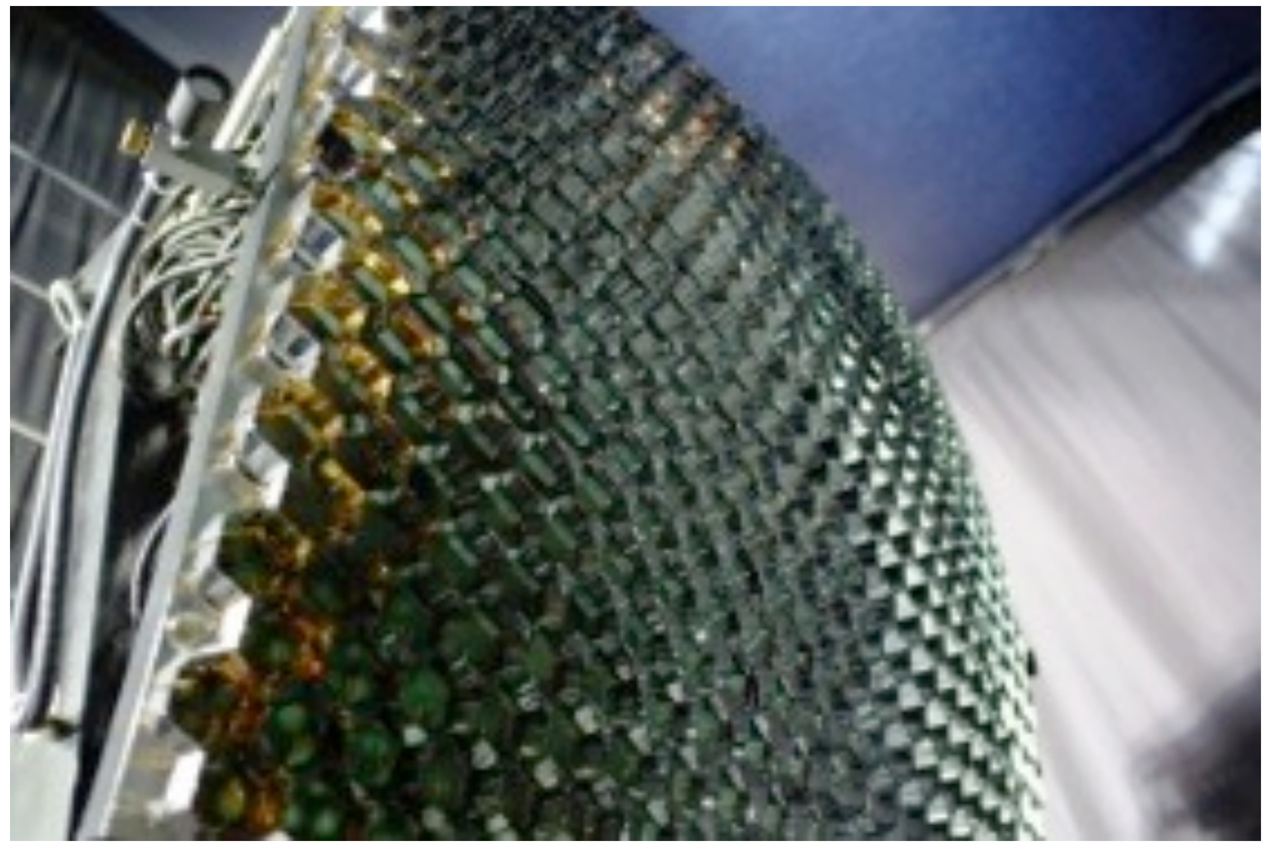
Fluorescence detector Array of Single-pixel Telescopes

Fluorescence detector Array of Single-pixel Telescopes

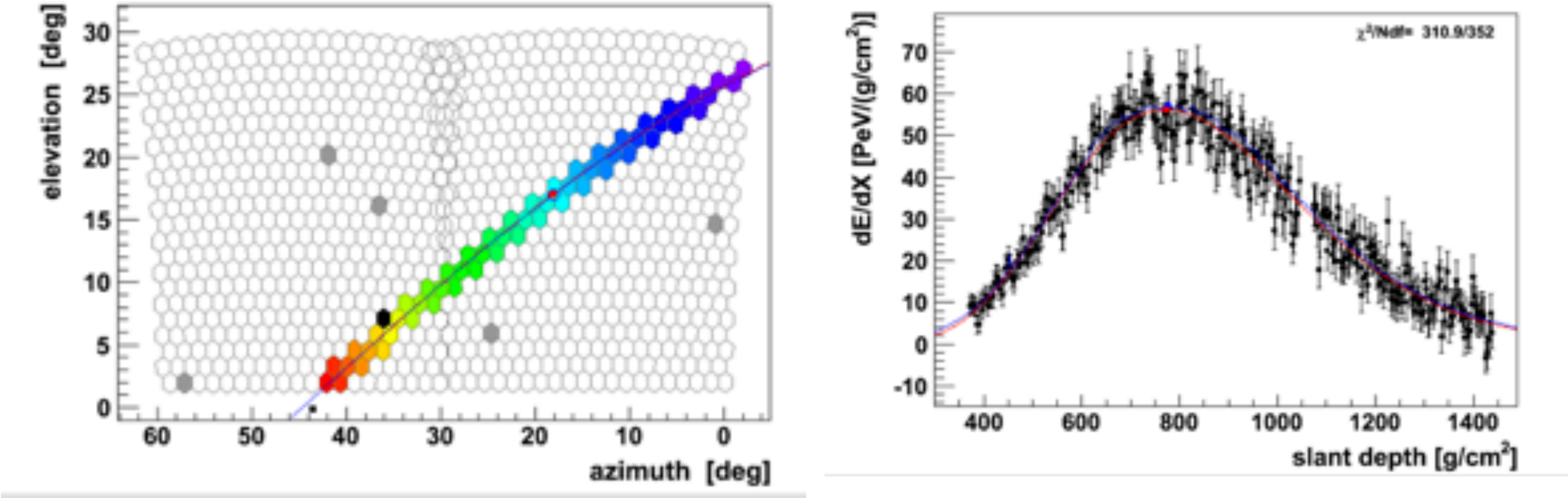
- Target : > $10^{19.5}$ eV, ultra-high energy cosmic rays (UHECR) and neutral particles
- Huge target volume ⇒ Fluorescence detector array

Fine pixelated camera

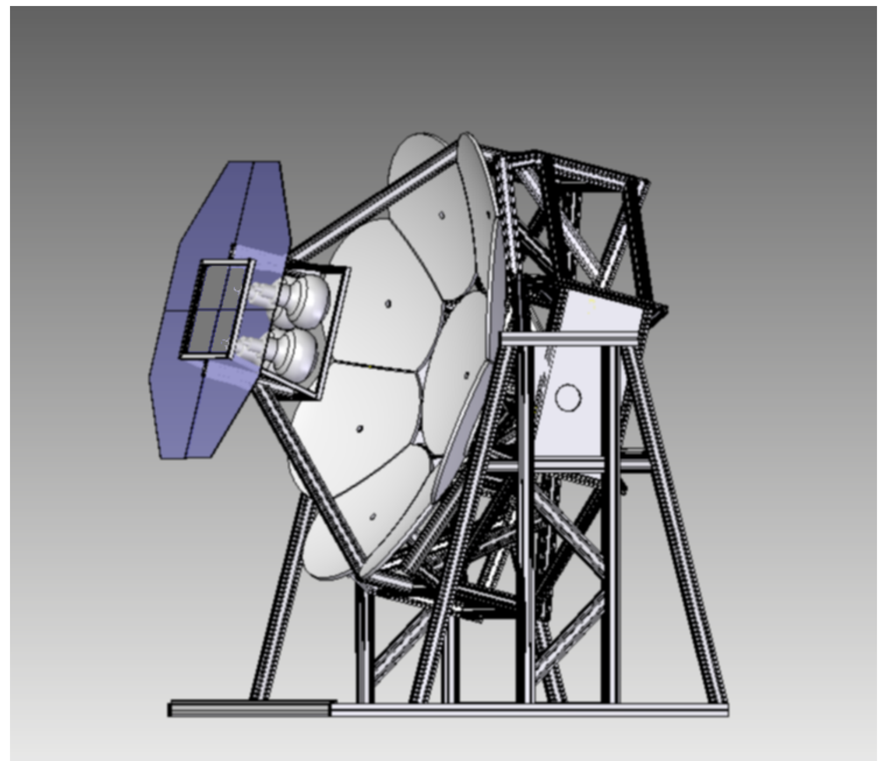




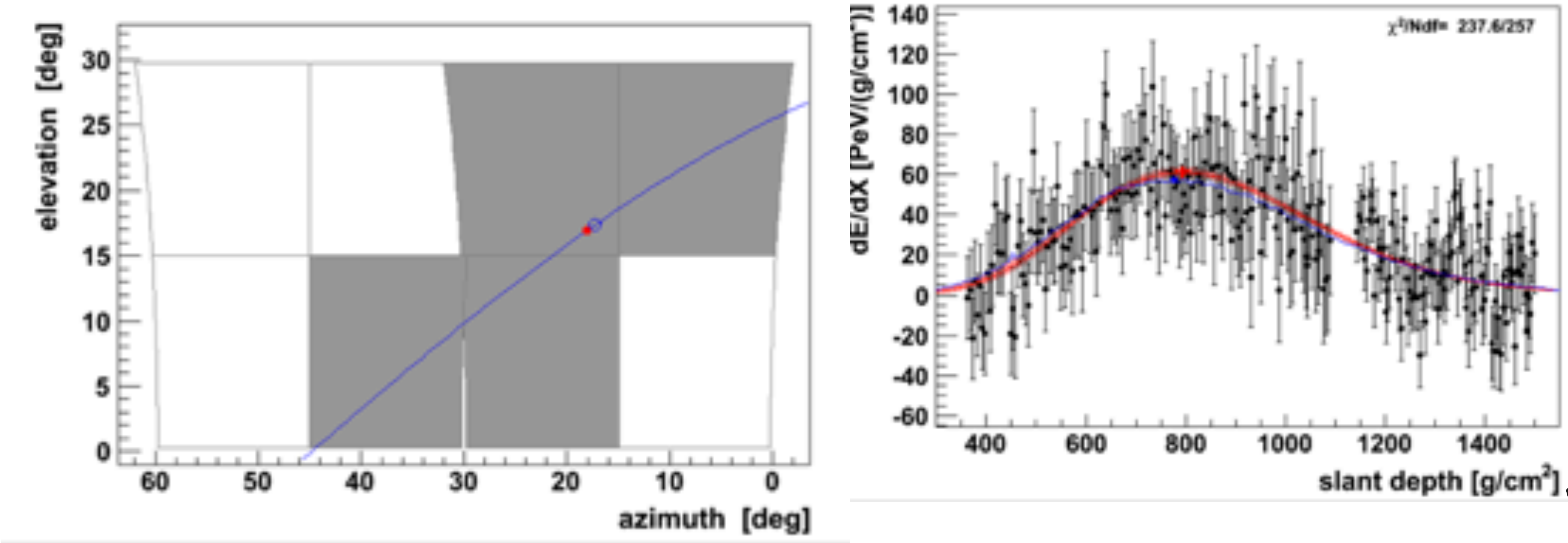
Too expensive to cover a huge area



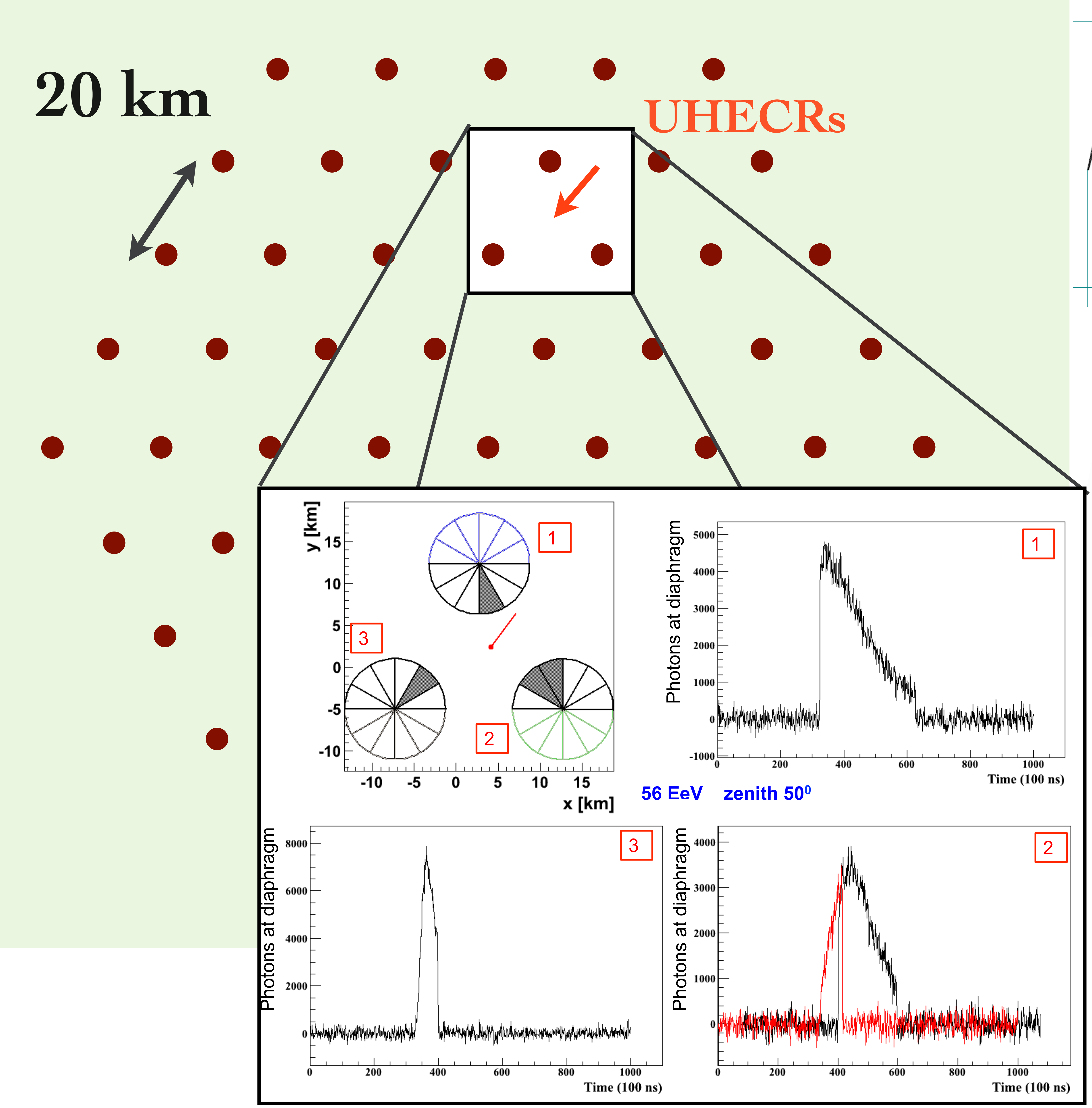
Single or few pixels and smaller optics

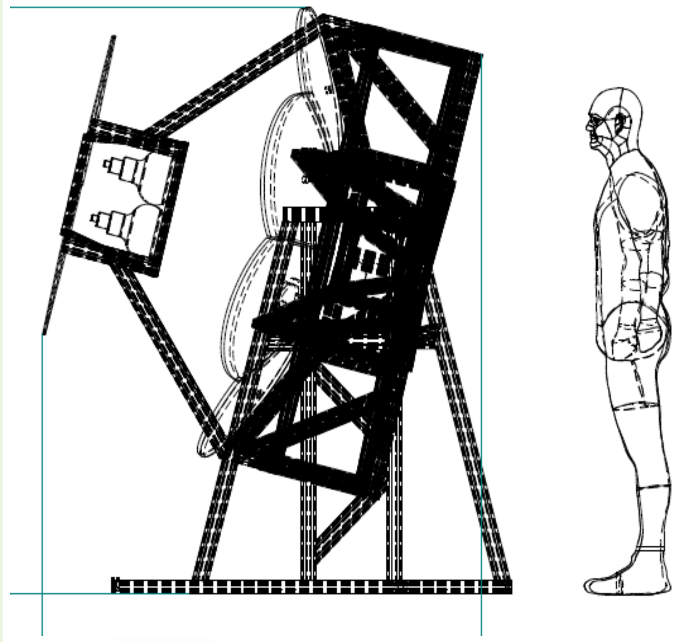


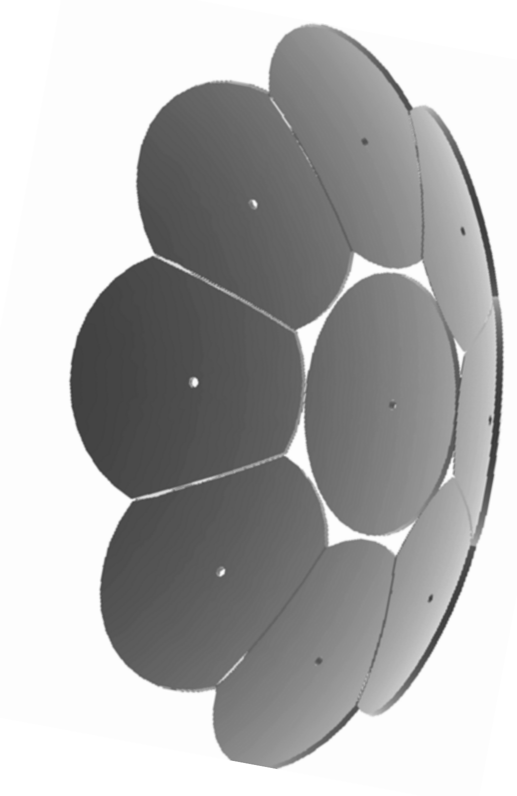
Low-cost and simplified/optimized FD

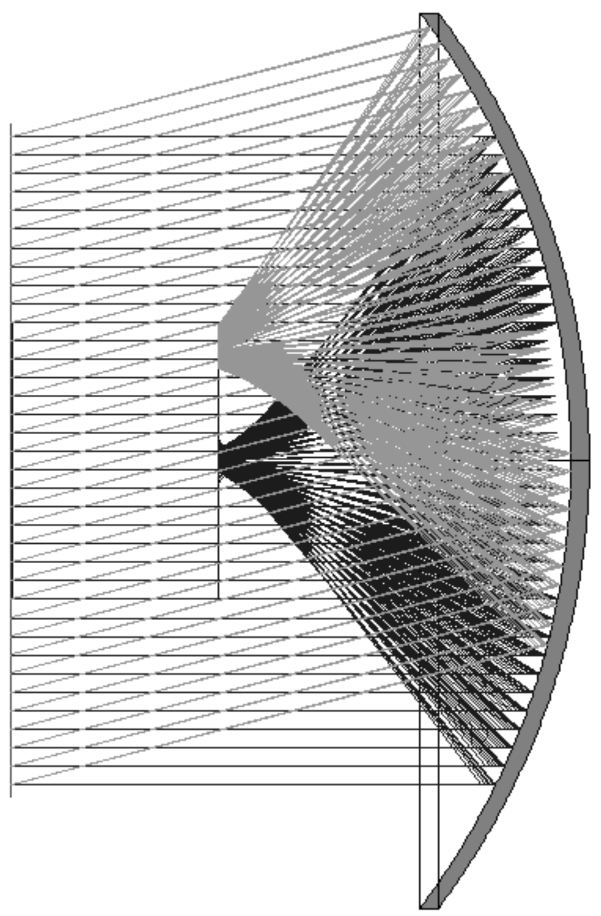


FAST Fluorescence detector Array of Single-pixel Telescopes



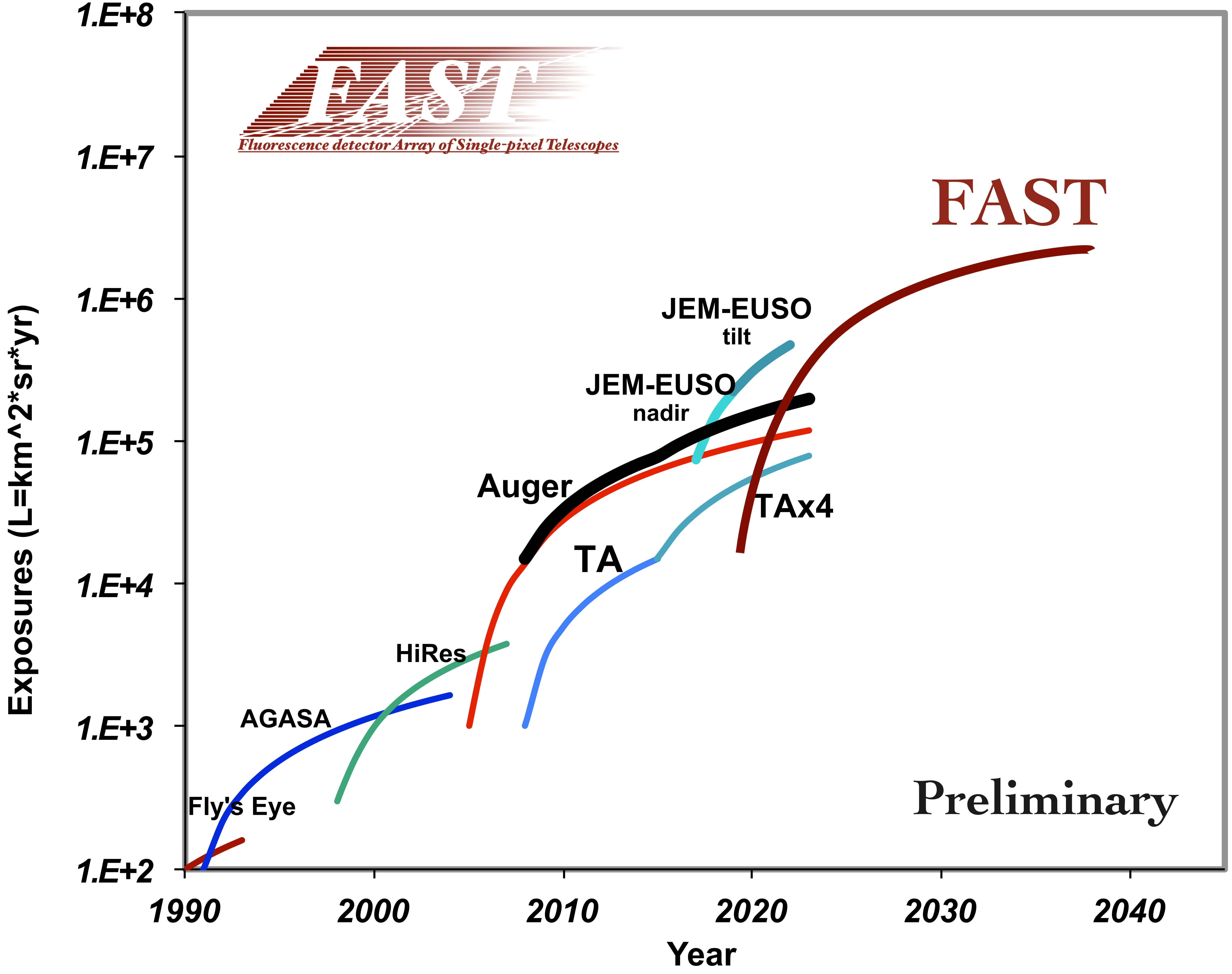






- Each telescope: 4 PMTs, 30°×30° field of view (FoV).
  - Reference design: 1 m^2 aperture, 15°×15° FoV per PMT
- Each station: 12 telescopes, 48 PMTs, 30°×360° FoV.
- Deploy on a triangle grid with **20 km** spacing, like **"Surface Detector Array"**.
- If 500 stations are installed, a ground coverage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

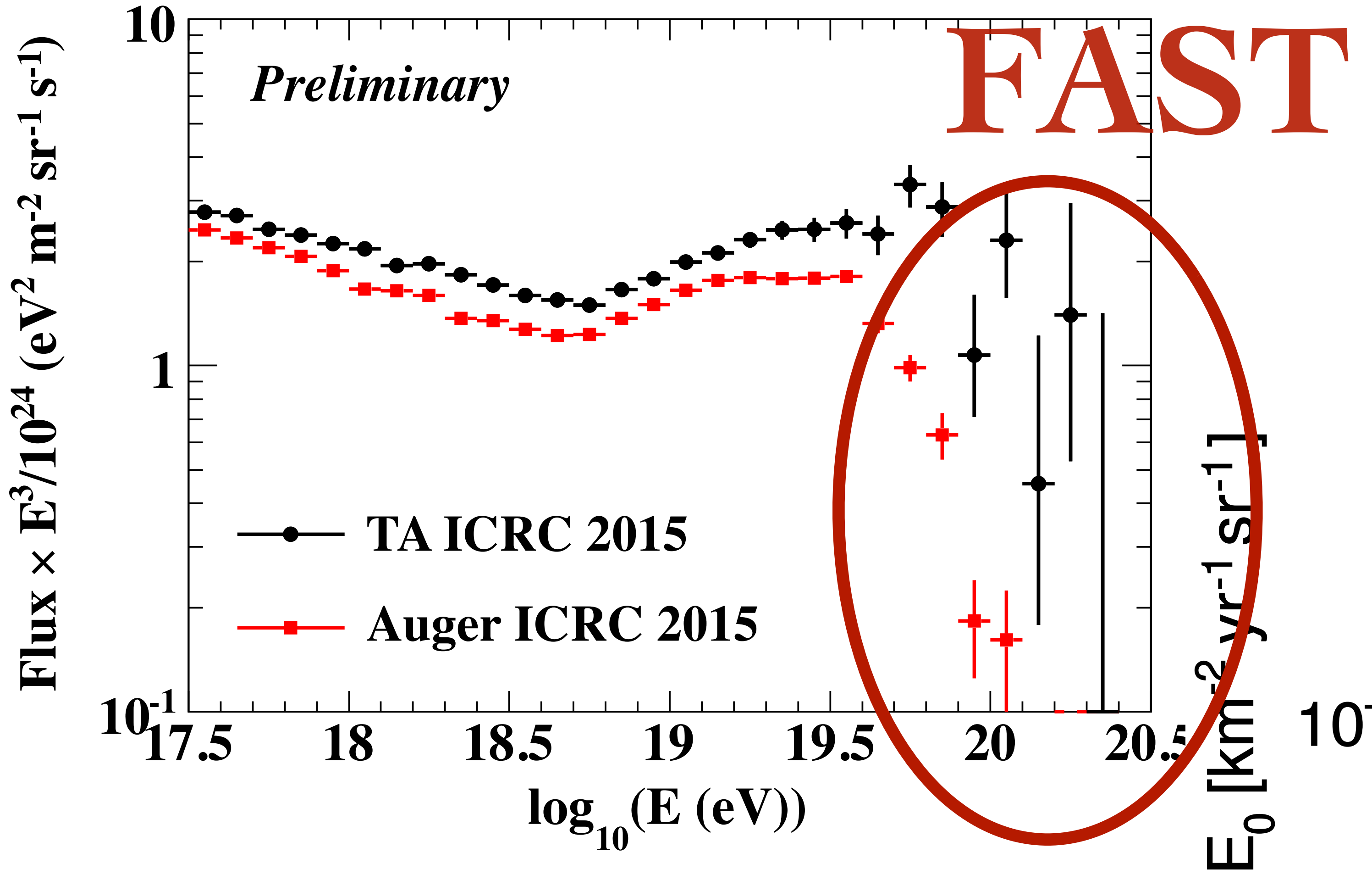
FAST Expected Exposure

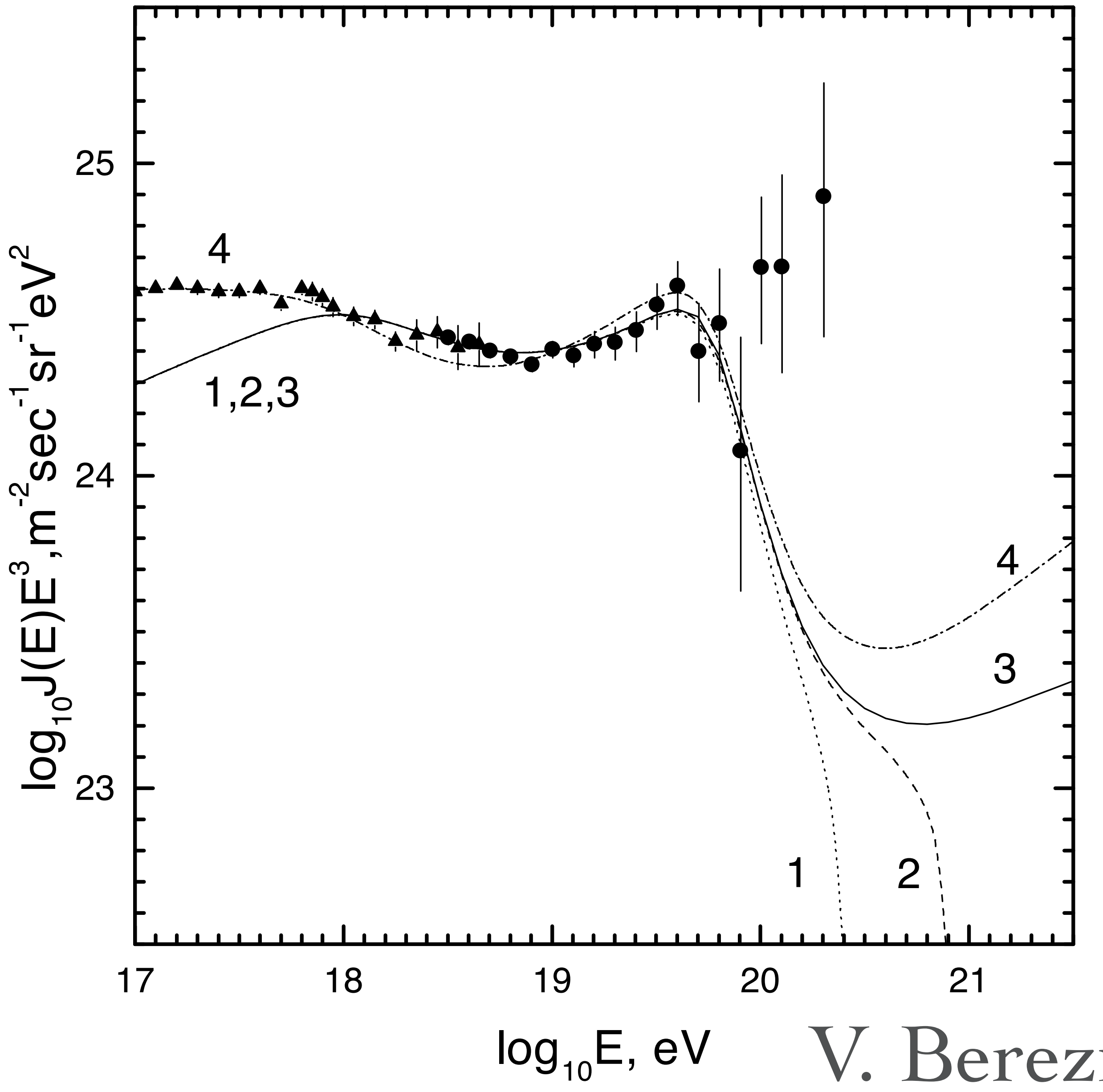


- Conventional operation of FD under 10~15% duty cycle
  - Target: $>10^{19.5}$ eV
- Observation in **moon night** to achieve **30%** duty cycle,
  - Target: **$>10^{19.8}$ eV = Super GZK events**
    - Test operation by Auger FD
- Ground area of 150,000 km^2 with 30% duty cycle = 45,000 km^2 (15×Auger, cost ~75 Million USD)
- **450 events/year**

Physics Target

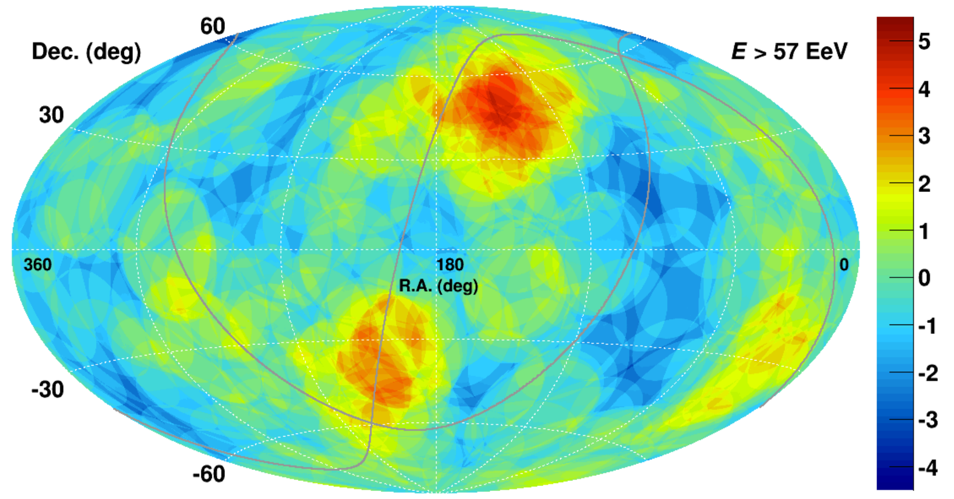
GZK Recovery



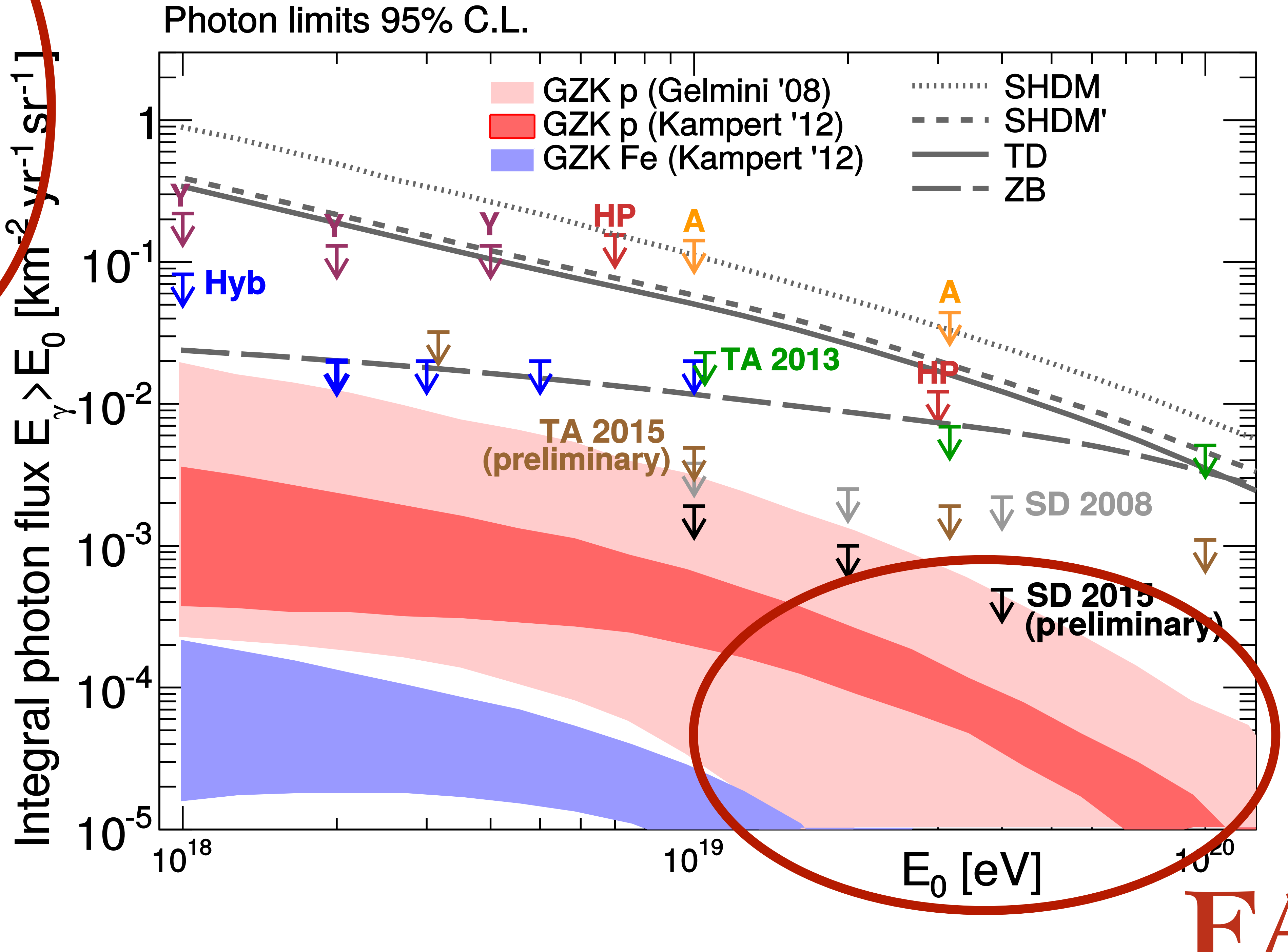


V. Berezinsky et al., (2001)

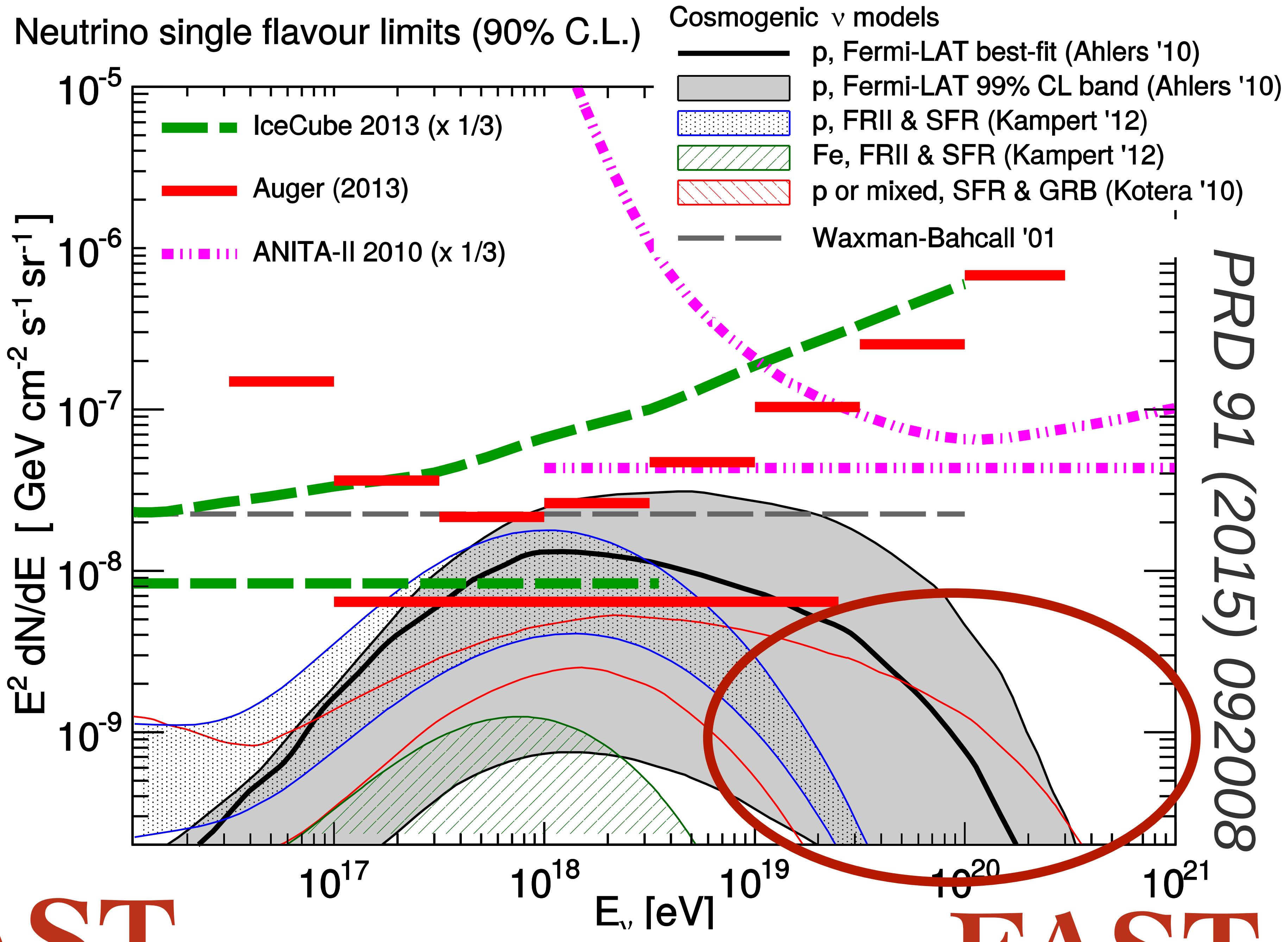
UHECR Anisotropy with ~10x statistics



First detection of UHE photons and neutrinos



FAST



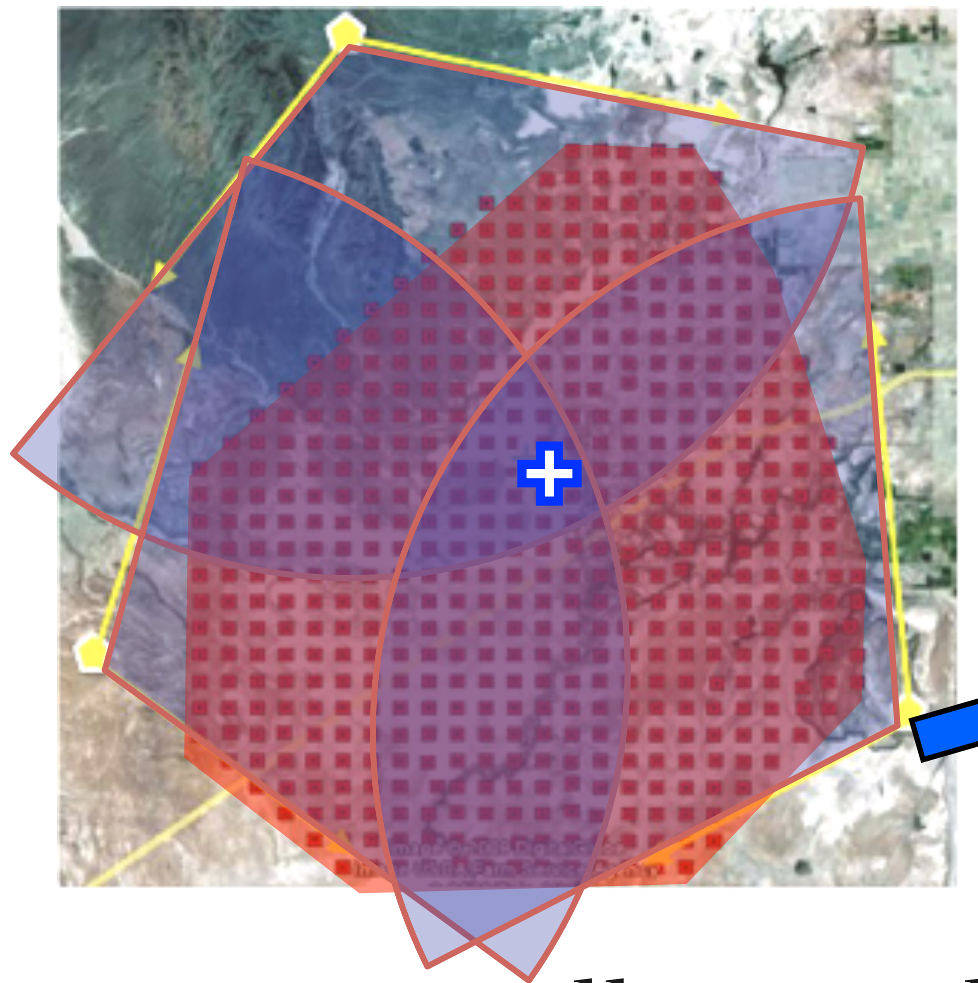
FAST

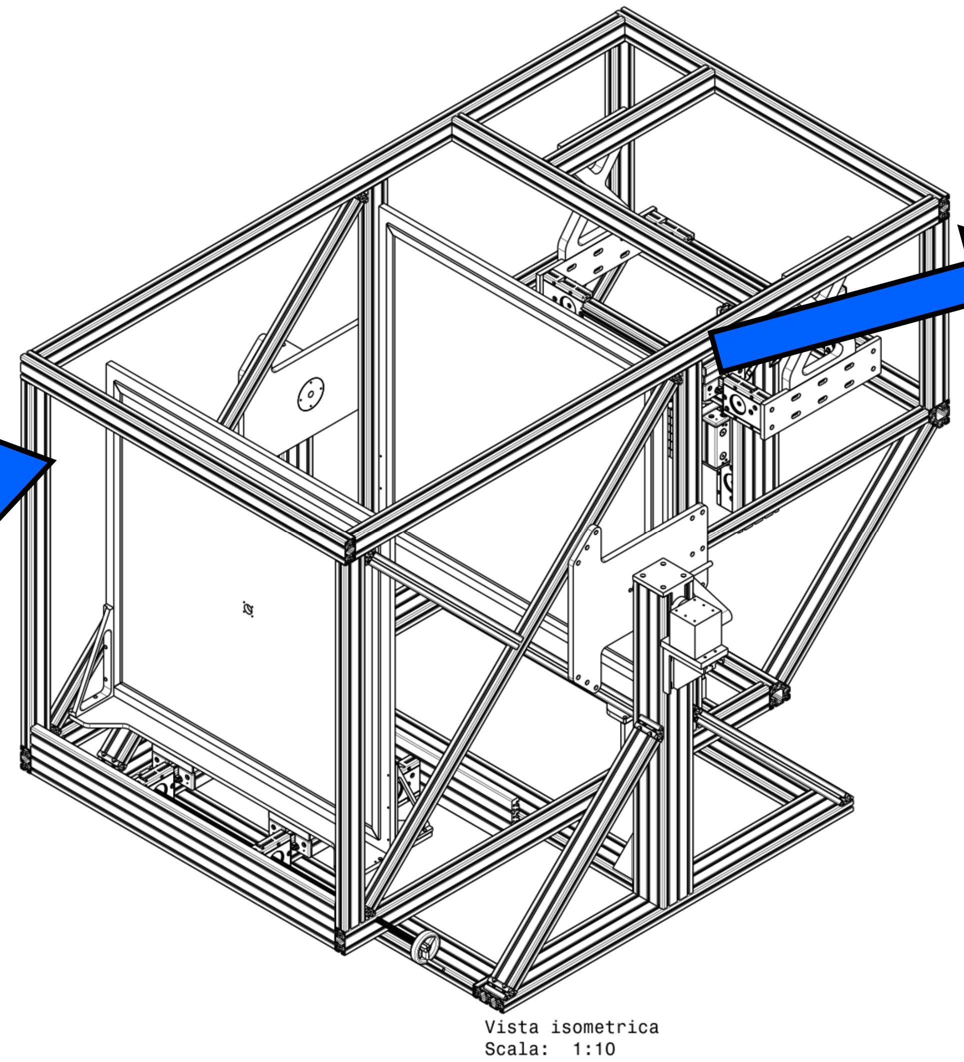
Coincidence of UHECR hotspot and neutral particles

Fluorescence detector Array of Single-pixel Telescopes

R&D for the FAST Project

Telescope Array site | **Black Rock Mesa station** | **EUSO-TA telescope** | **FAST camera**





- ✦ 8 inch PMT (R5912-03, Hamamtsu)
- ✦ PMT base (E7694-01, Hamamatsu, AC coupling)
- ✦ Ultra-violet band pass filter (MUG6, Schott)

- ✦ Temporally use the EUSO-TA optics at the TA site.
  - ✦ Two Fresnel lenses (+ 1 UV acrylic plate in front for protection)
  - ✦ **1 m^2 aperture, 14°×14° FoV ≒ FAST reference design.**
- ✦ Install FAST camera and DAQ system at EUSO-TA telescope.
- ✦ Milestones: Stable observation under large night sky backgrounds, UHECR detection with external trigger from TAFD.

1

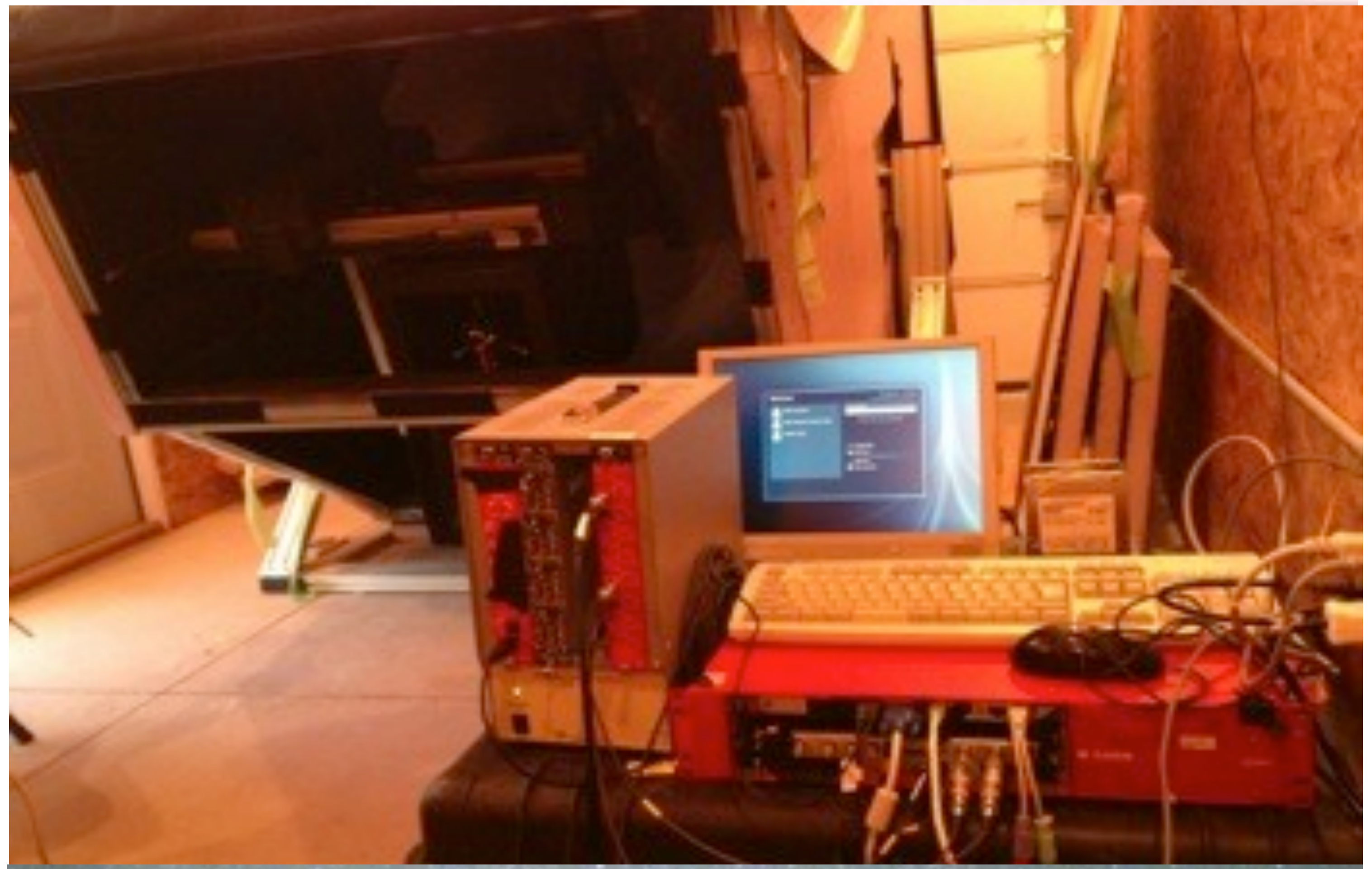
2

3

4

5

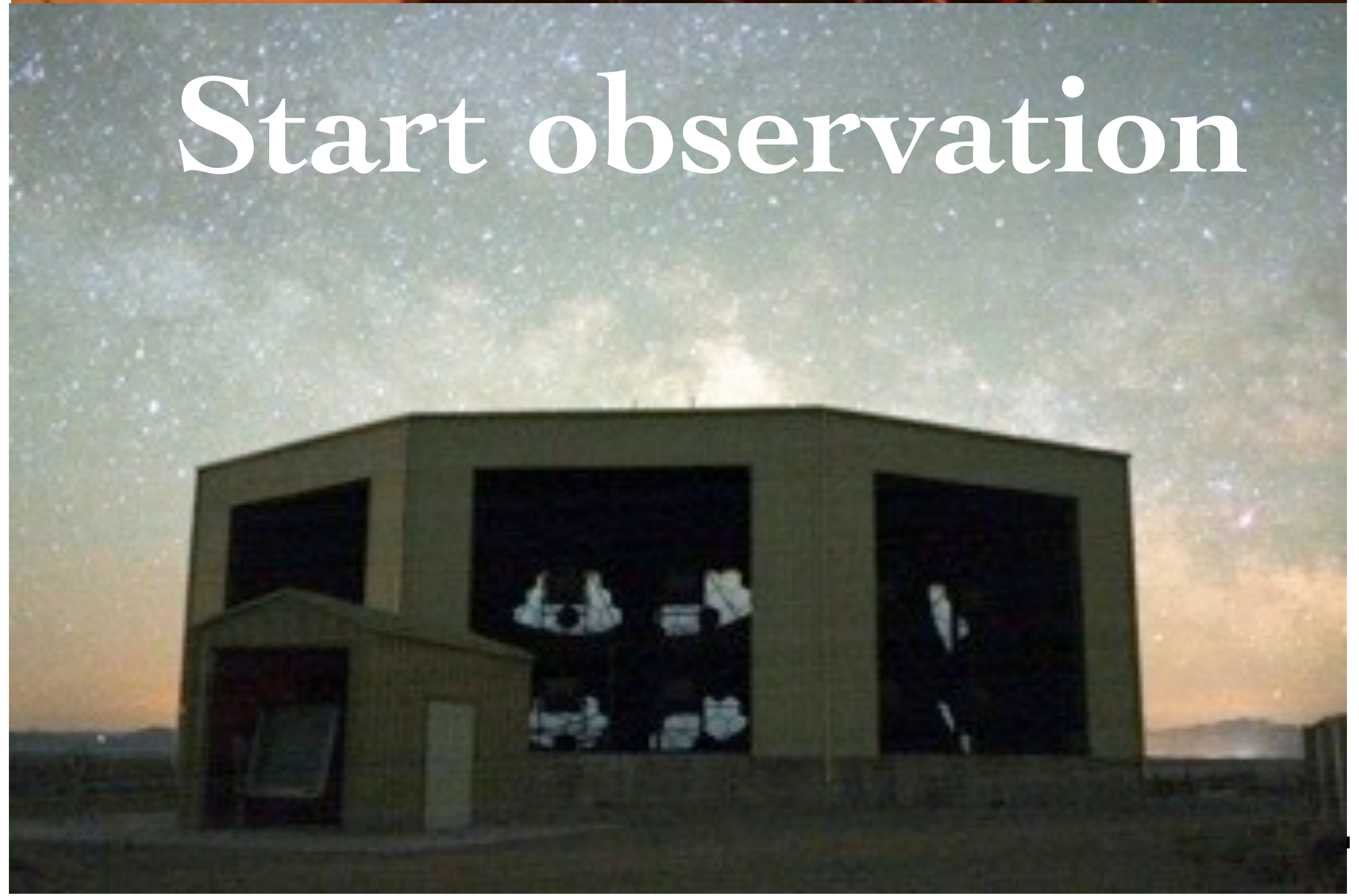
6



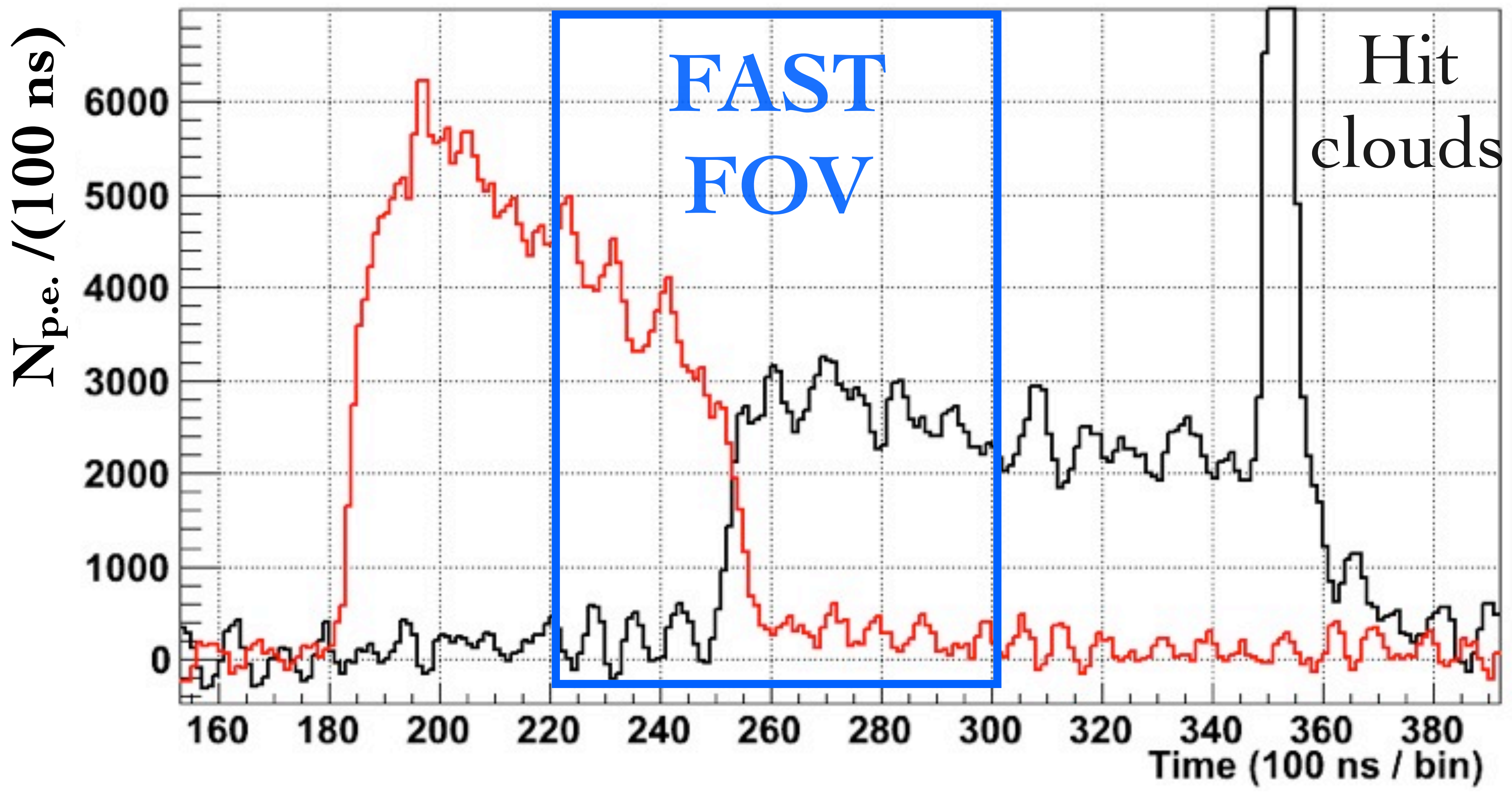
7

8

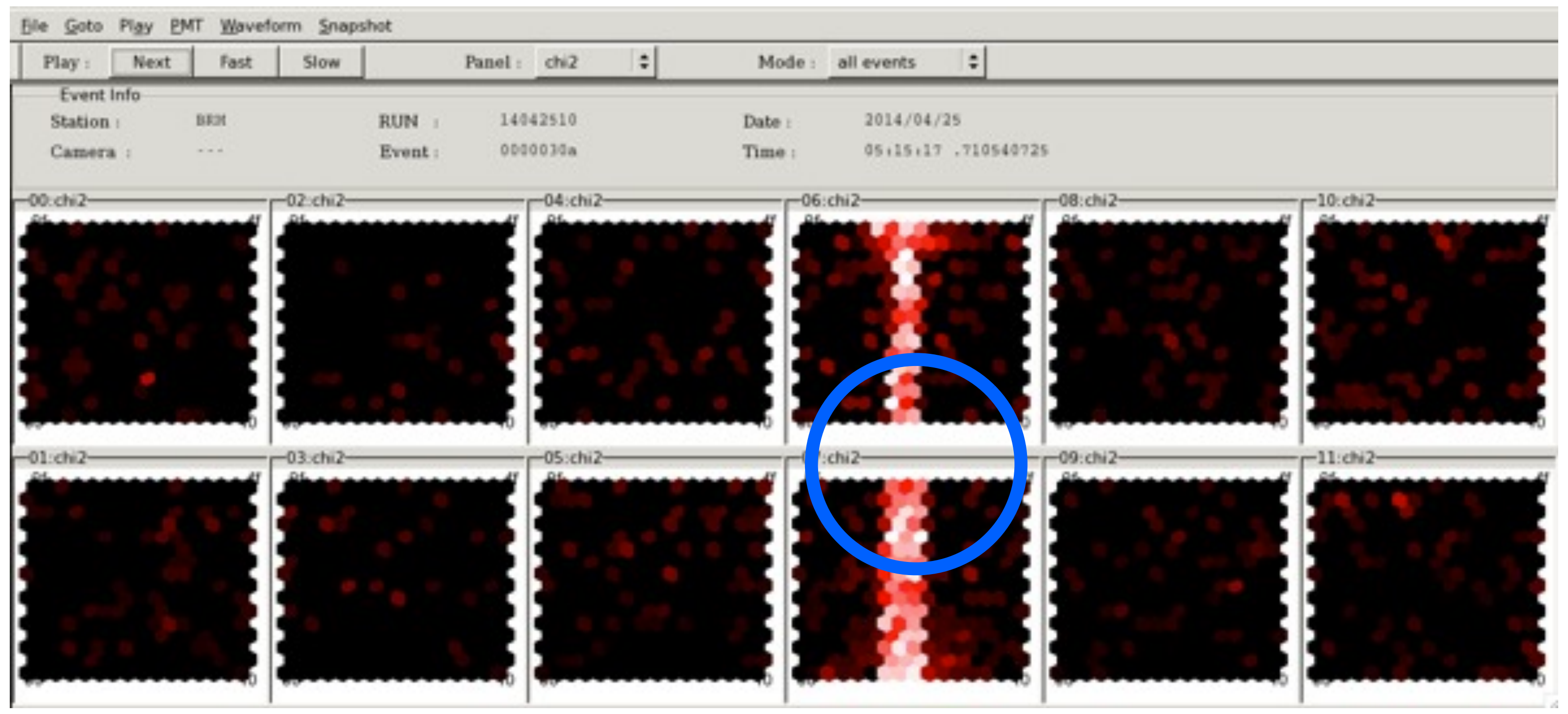
9



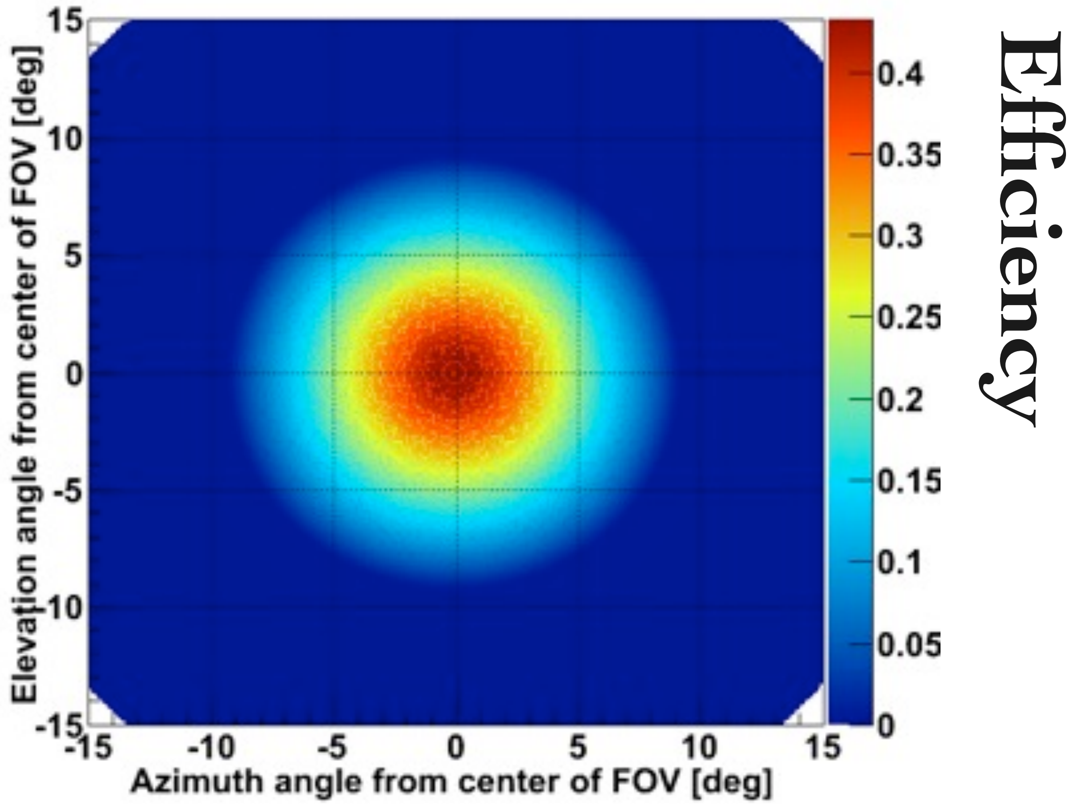
Laser Signal to Check Performance

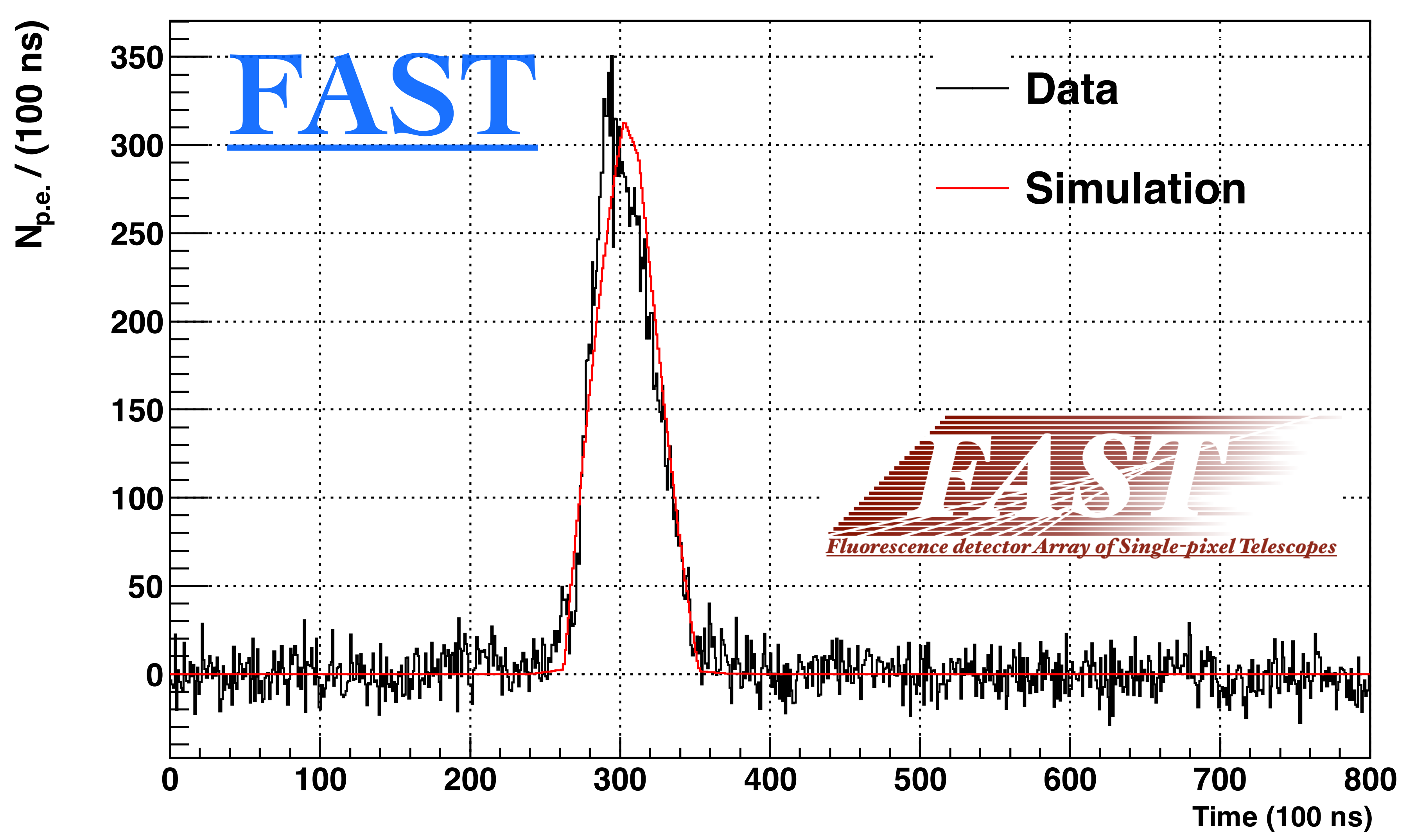


TAFD



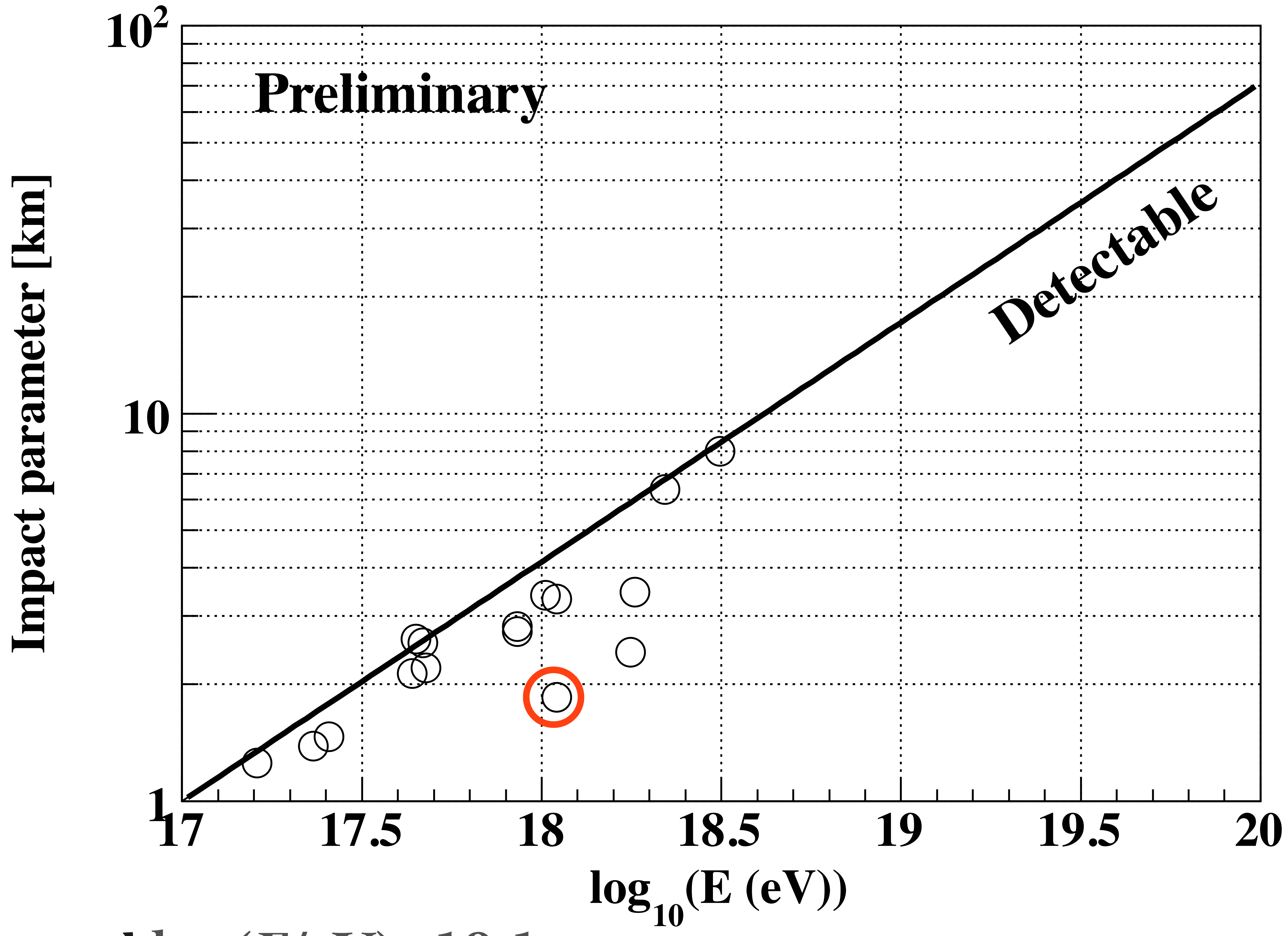
Directional sensitivity by RayTrace of EUSO-TA telescope

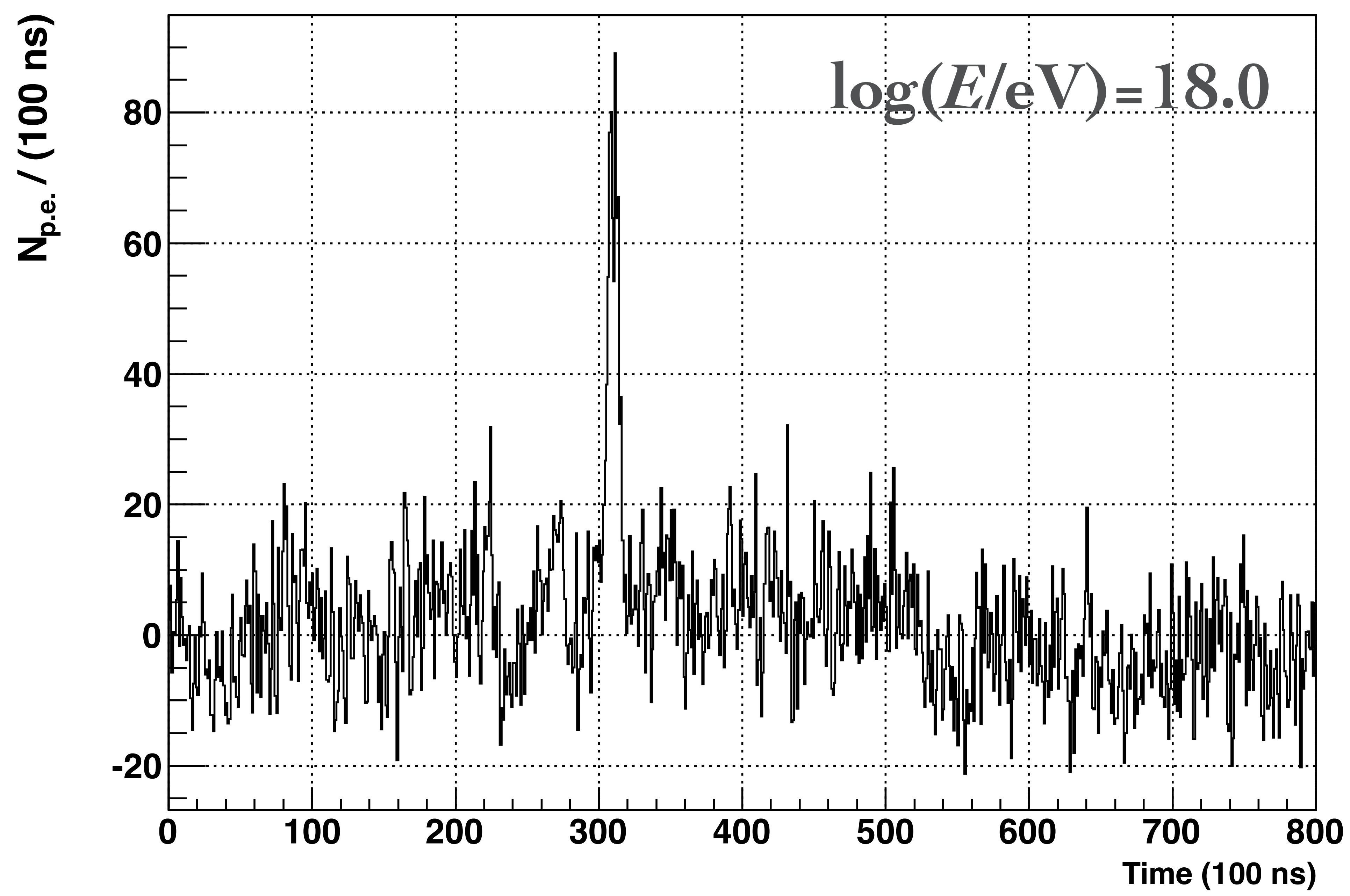




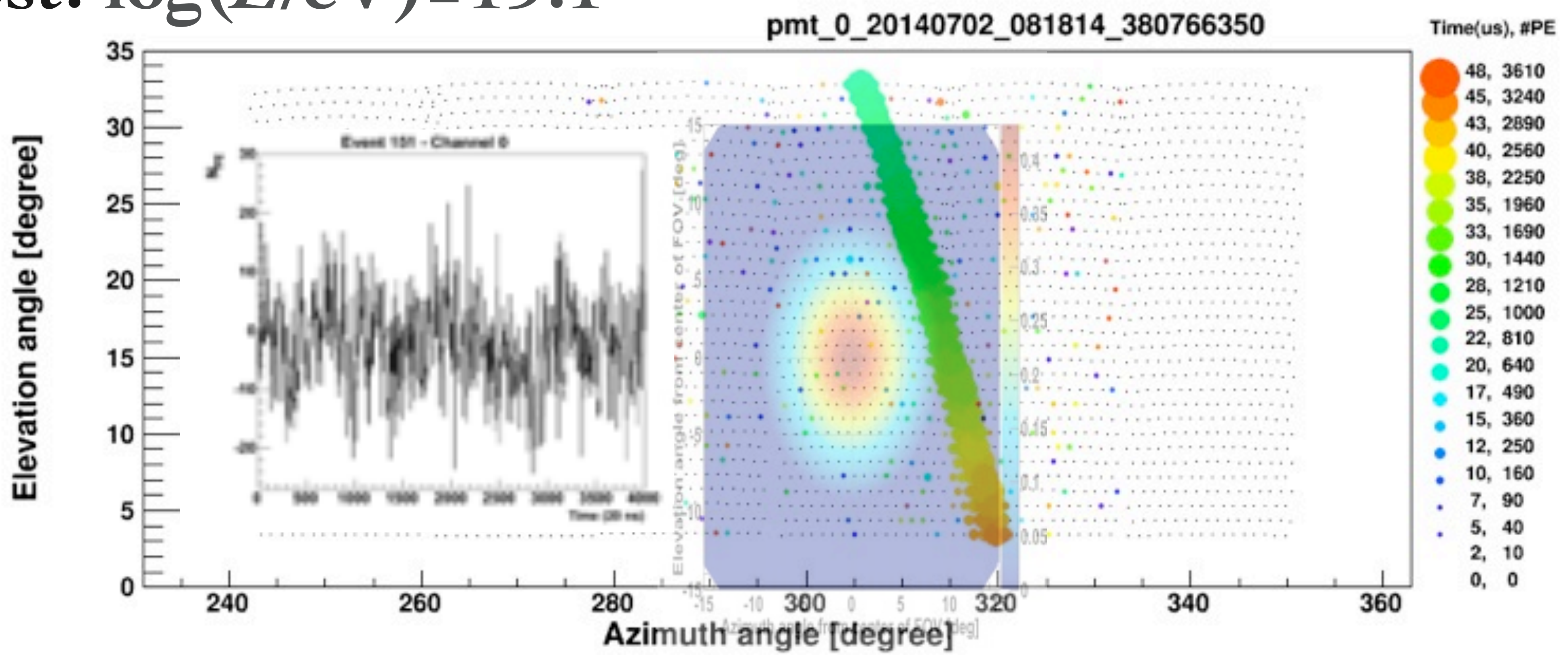
- Vertical Ultra-Violet laser at 6 km from FAST ≒ ~$10^{19.2}$ eV
- Expected signal TAFD/FAST: (7 m^2 aperture × 0.7 shadow × 0.9 mirror) / (1 m^2 aperture × 0.43 optics efficiency) ~10
  - TAFD Peak signal : ~3000 p.e. / 100 ns
  - FAST Peak signal : ~300 p.e. / 100 ns. All shots are detected significantly.
- Agreement of signal shape with simulation.

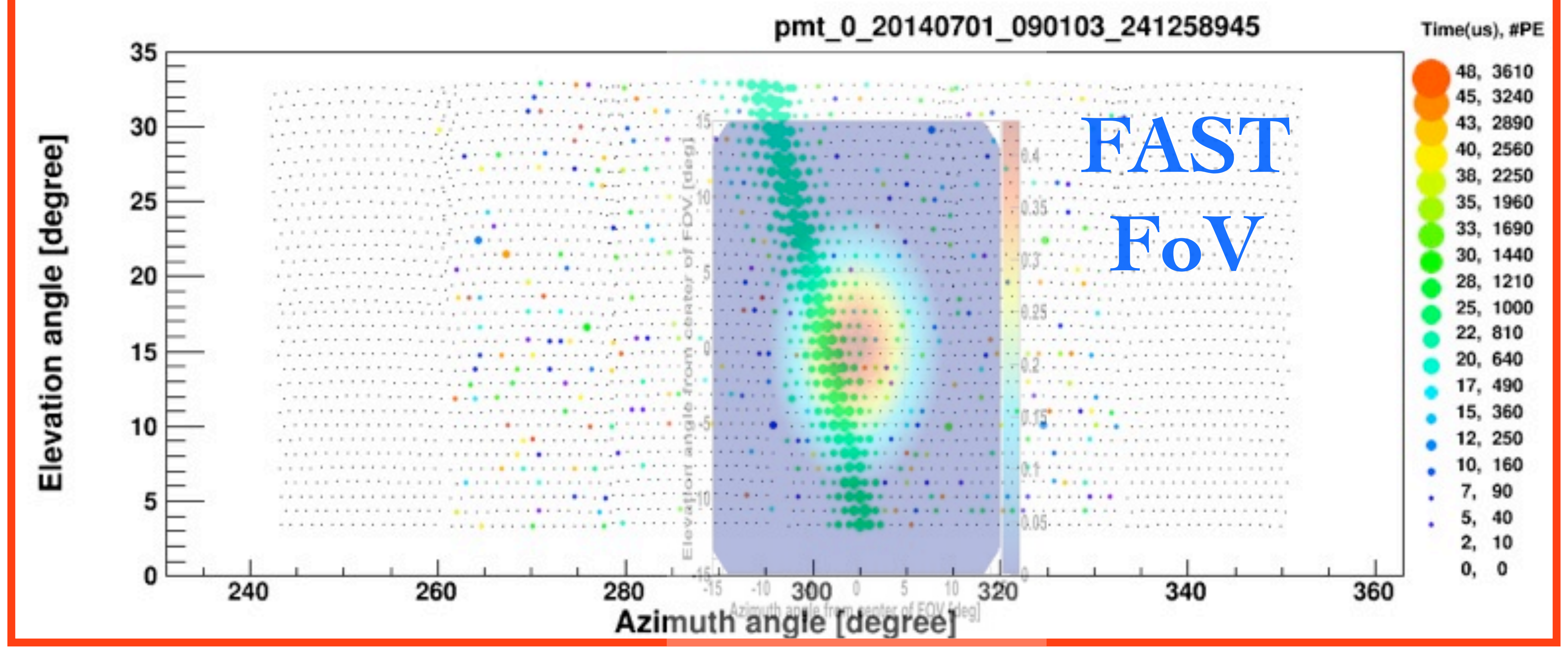
Distance vs Energy (from TAFD) for Candidates





Almost! log(*E*/eV)=19.1

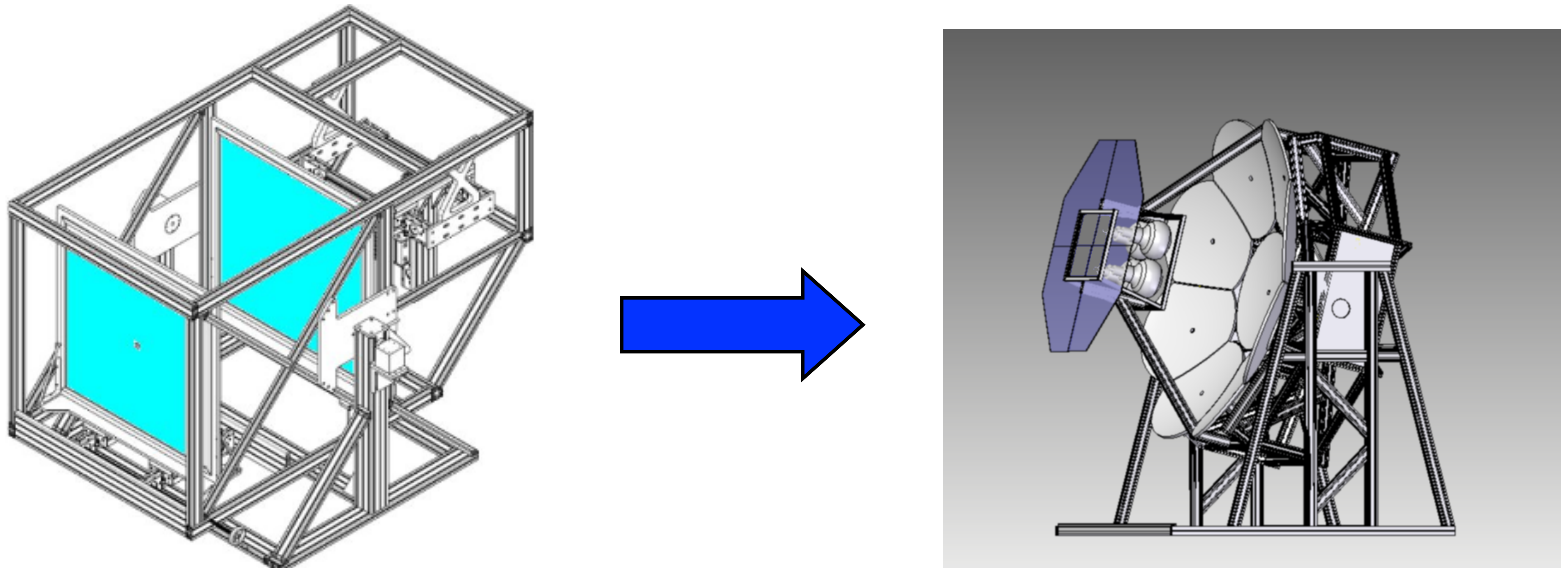




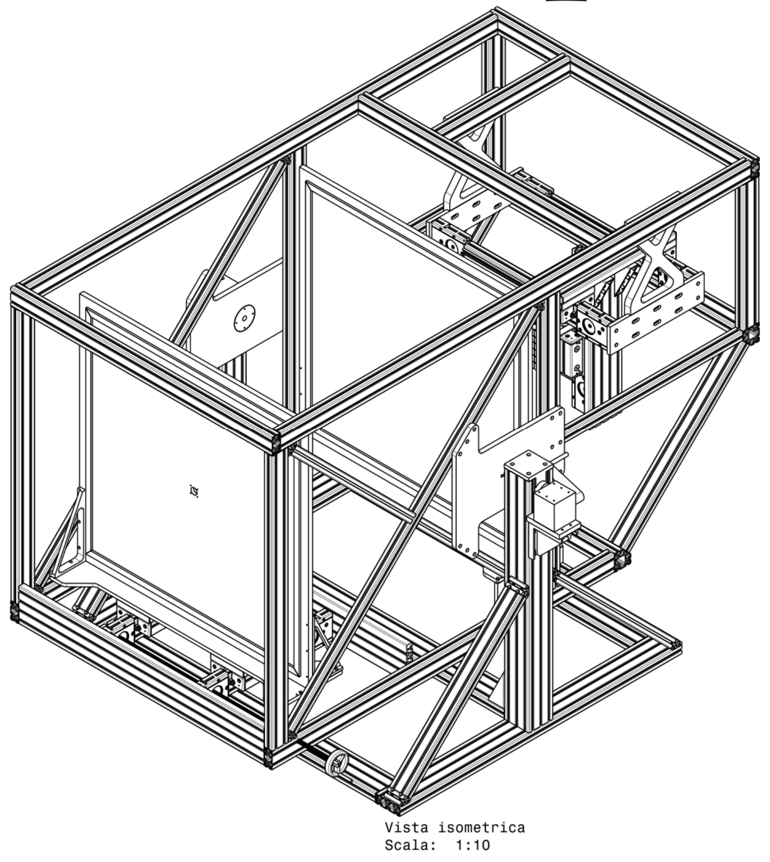
FAST
Fluorescence detector Array of Single-pixel Telescopes

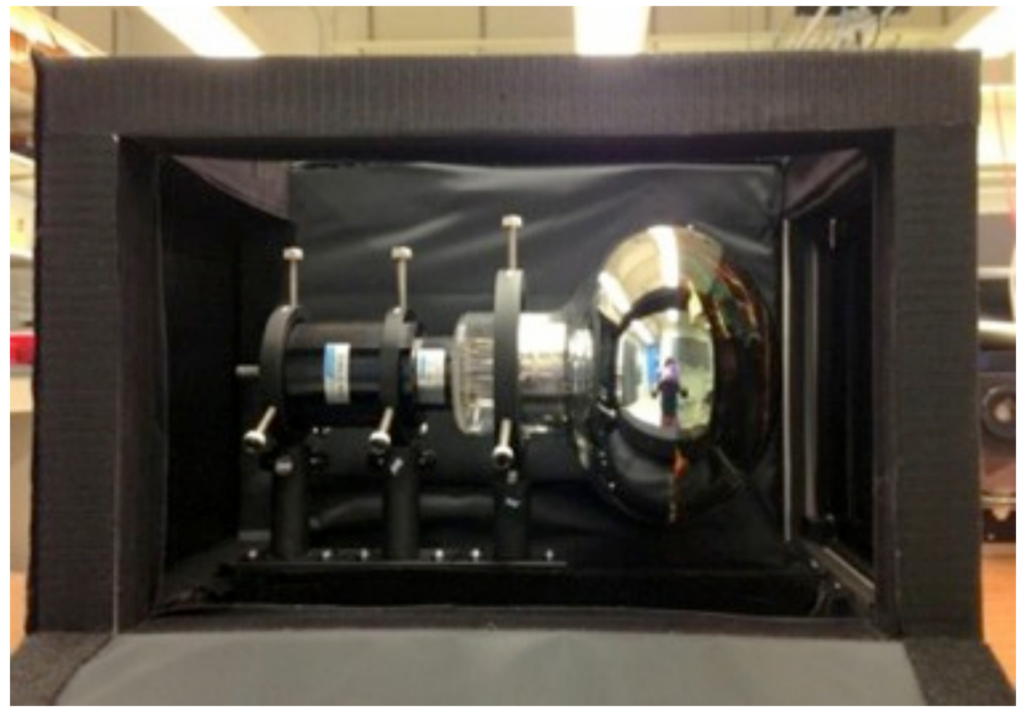
R&D for the FAST Project

- **FAST prototype measurements at Utah**
  - Stable operation under high night sky backgrounds.
  - UHECR detection.
    - Published in Astroparticle Physics *74* (2016) 64-72
- **Next milestones by new full-scale FAST prototype**
  - Establish the FAST sensitivity.
  - Detect a shower profile including ***Xmax*** with FAST

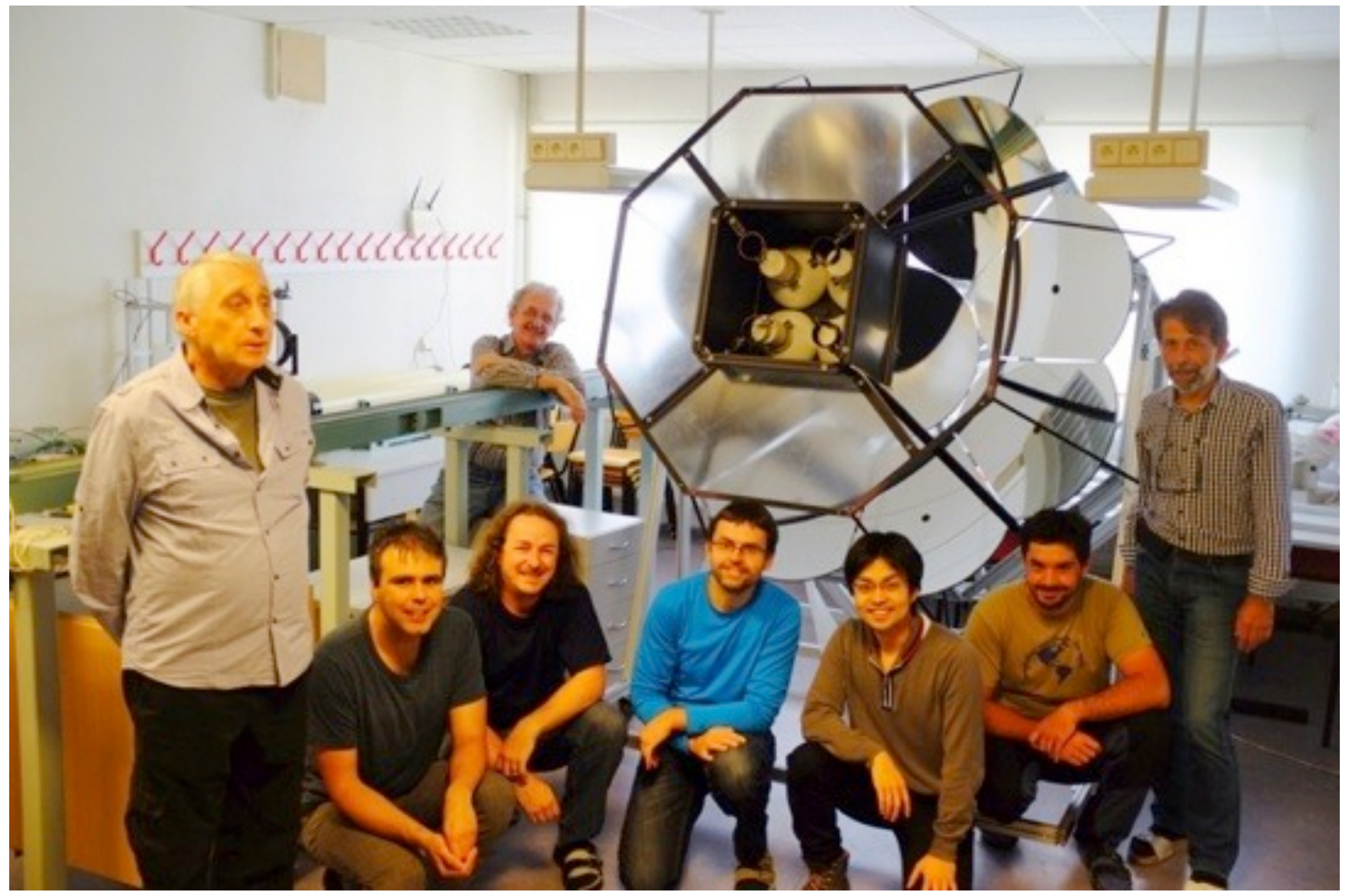


EUSO-TA telescope + **FAST camera**



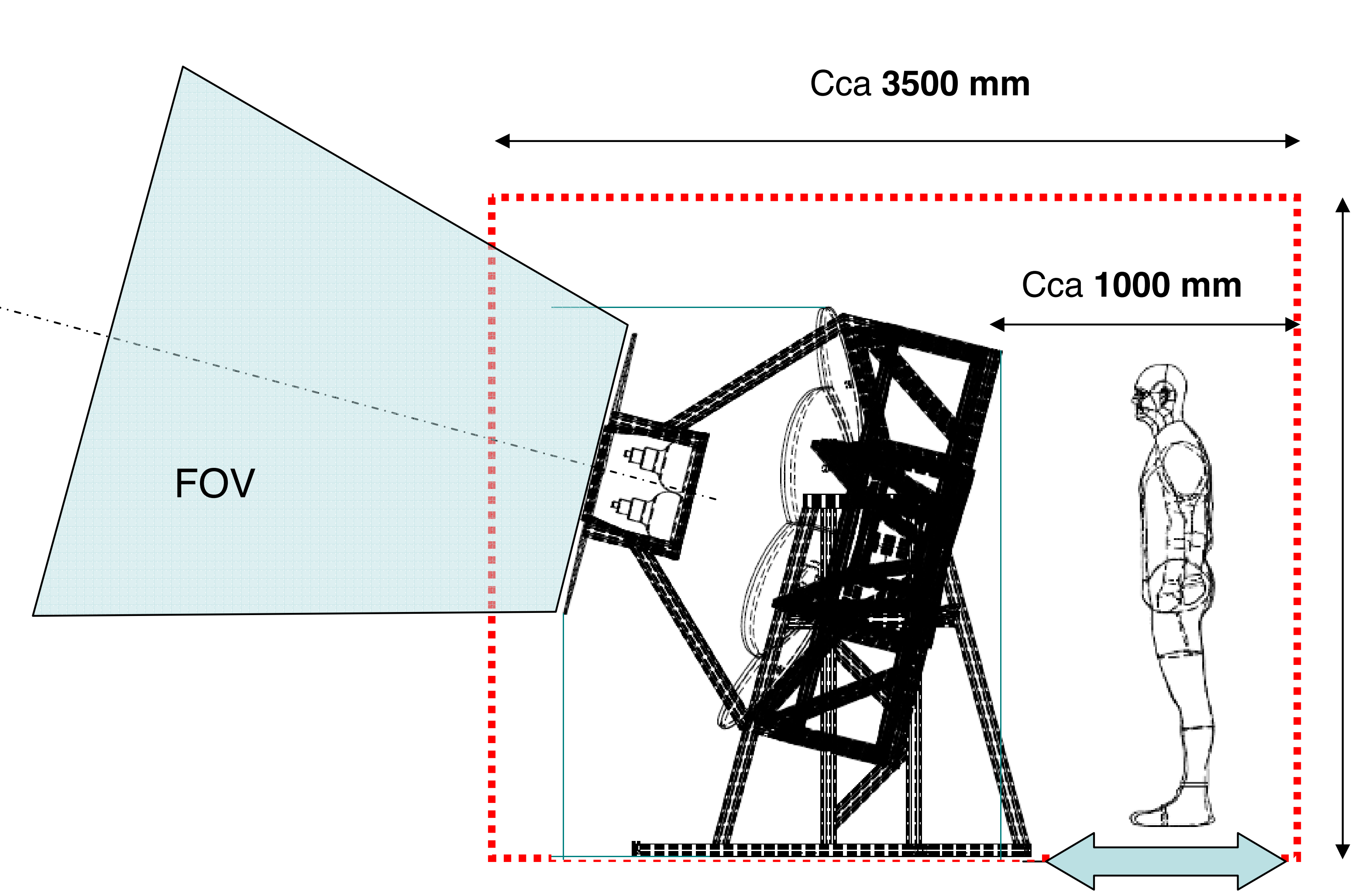


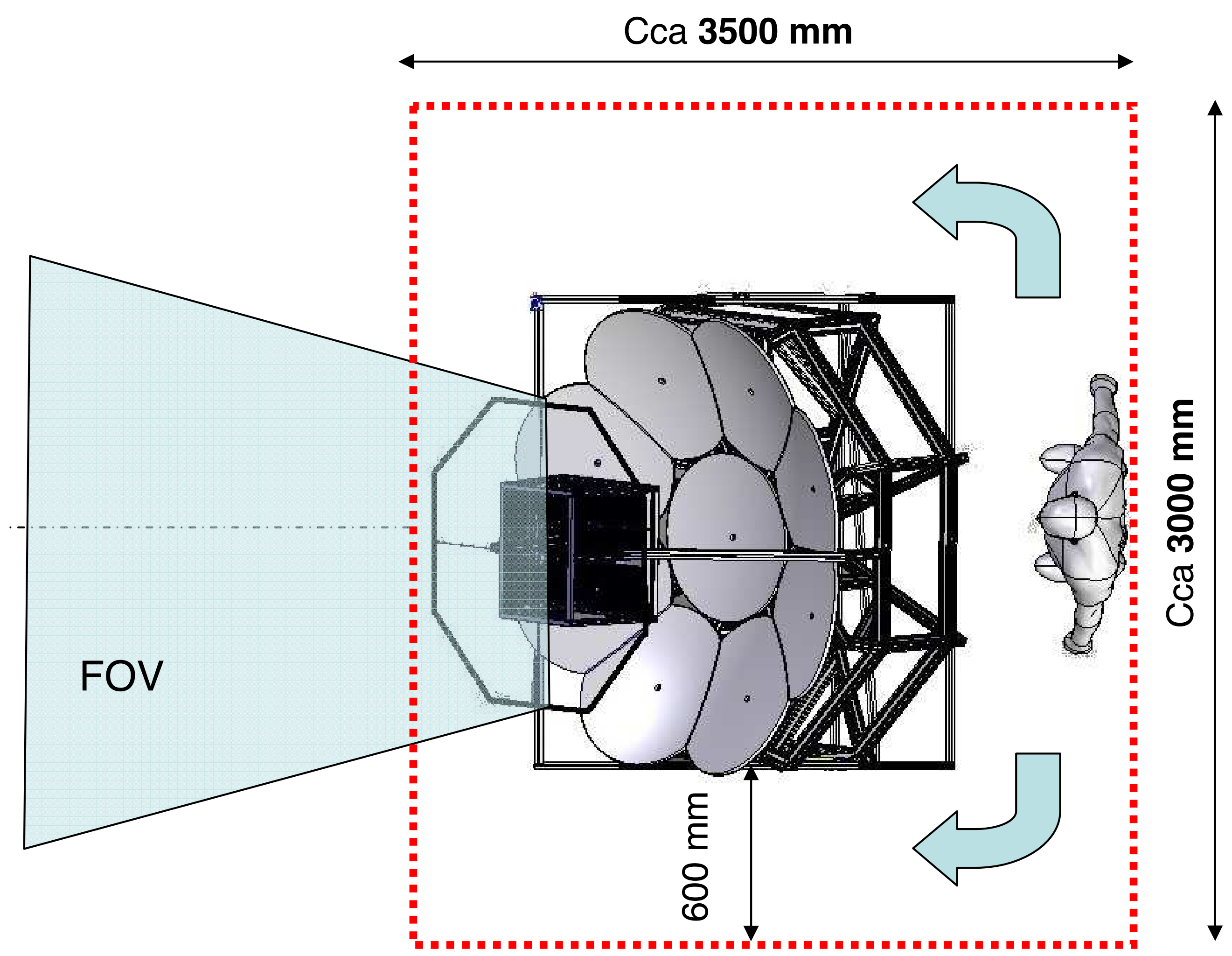
FAST meeting in December 2015
(Olomouc, Czech Republic)



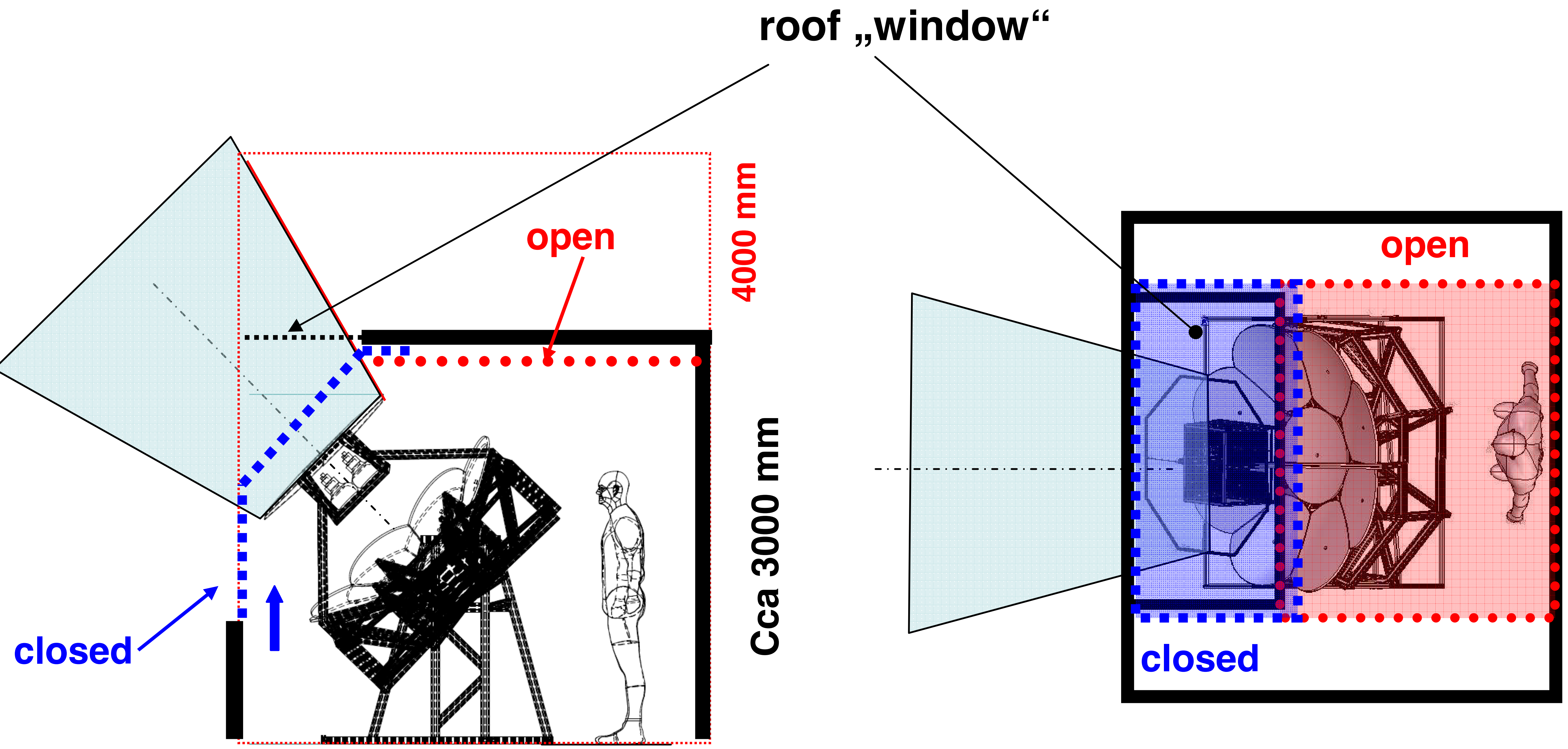
FAST
Fluorescence detector Array of Single-pixel Telescopes

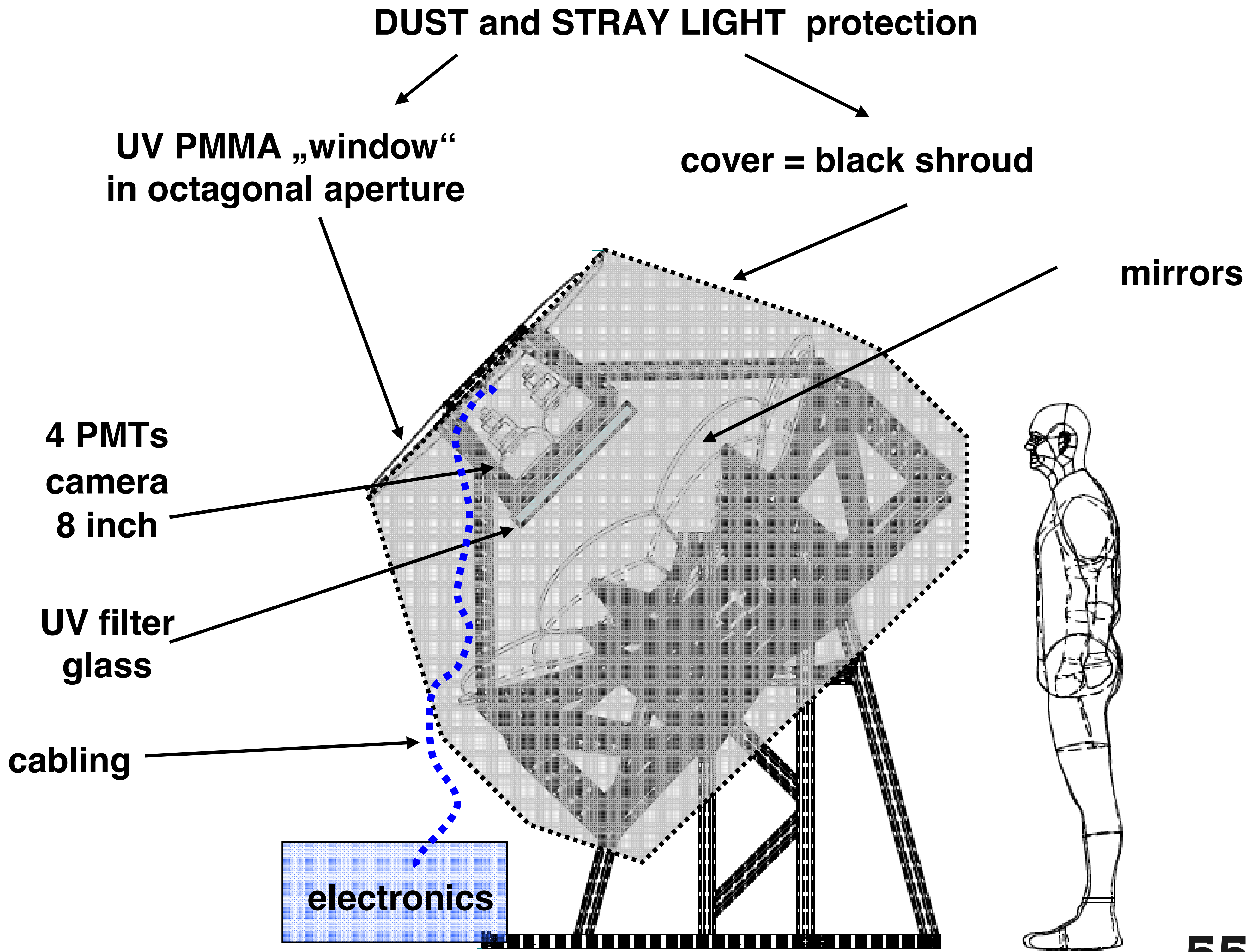
Design of Full-scale FAST Prototype





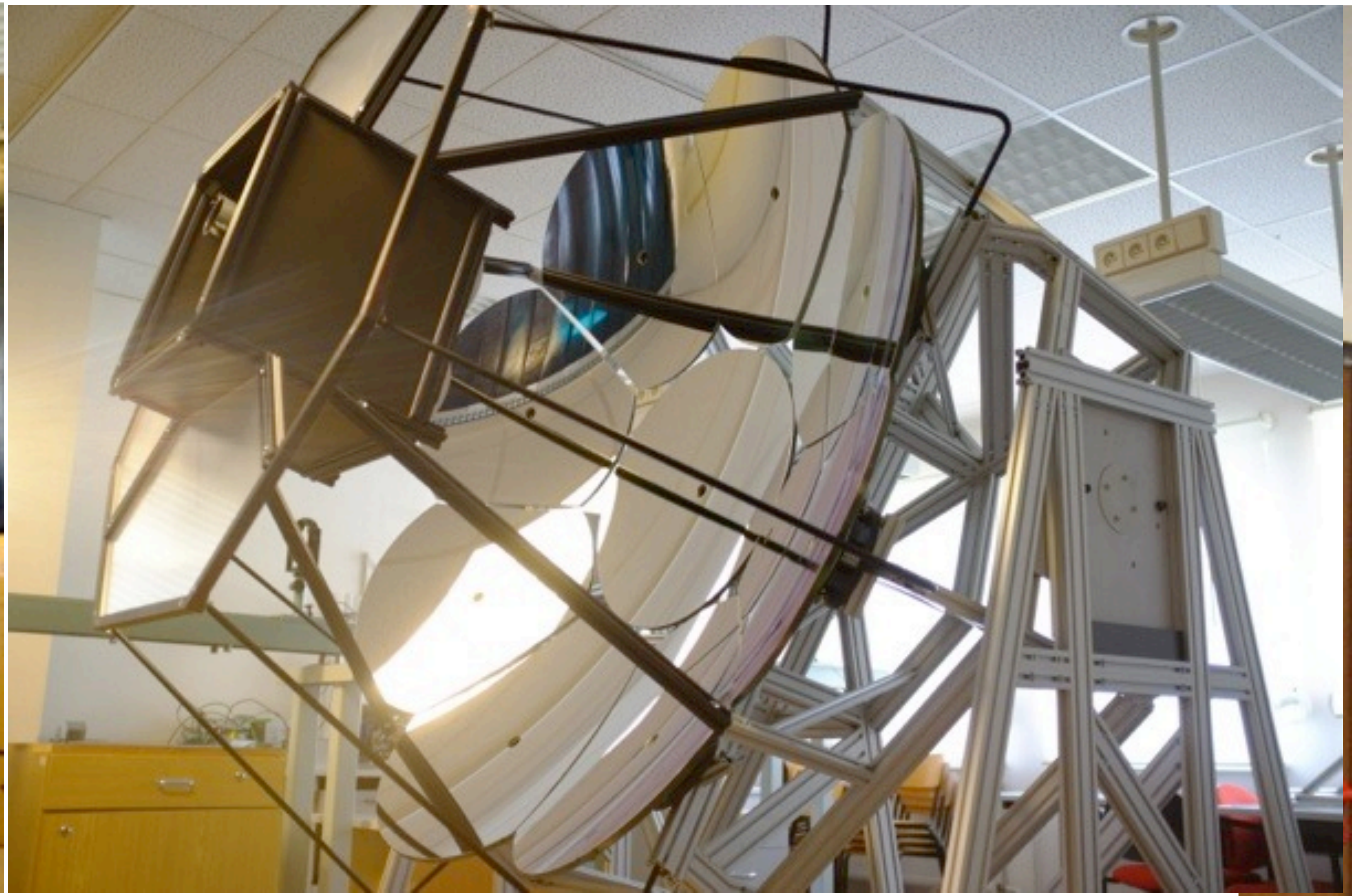
- ✦ Adjustable elevation 15° or 45° to enlarge the FoV of the TA FD.
- ✦ Robust design for maintenance free and stand-alone observation.

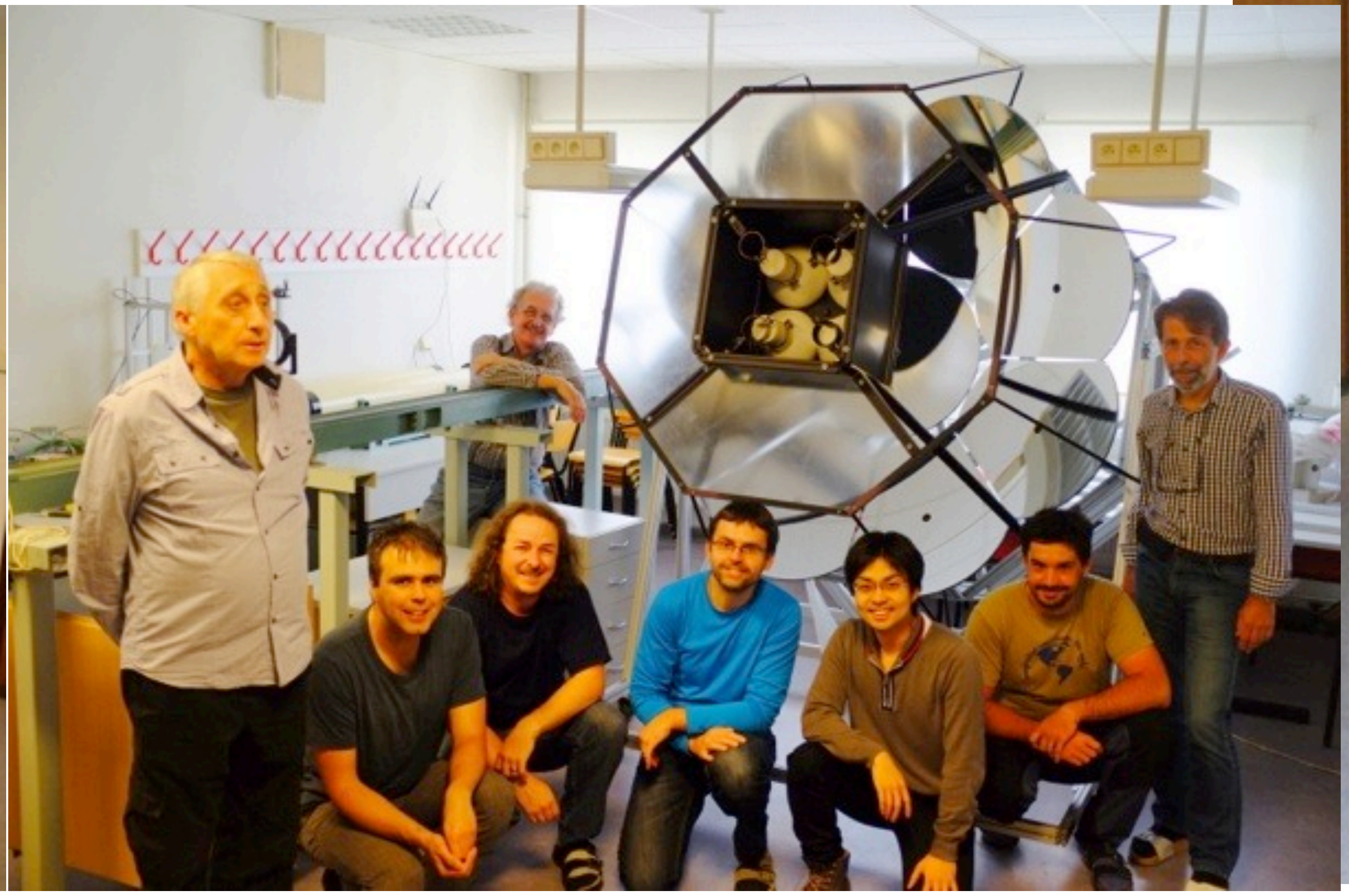


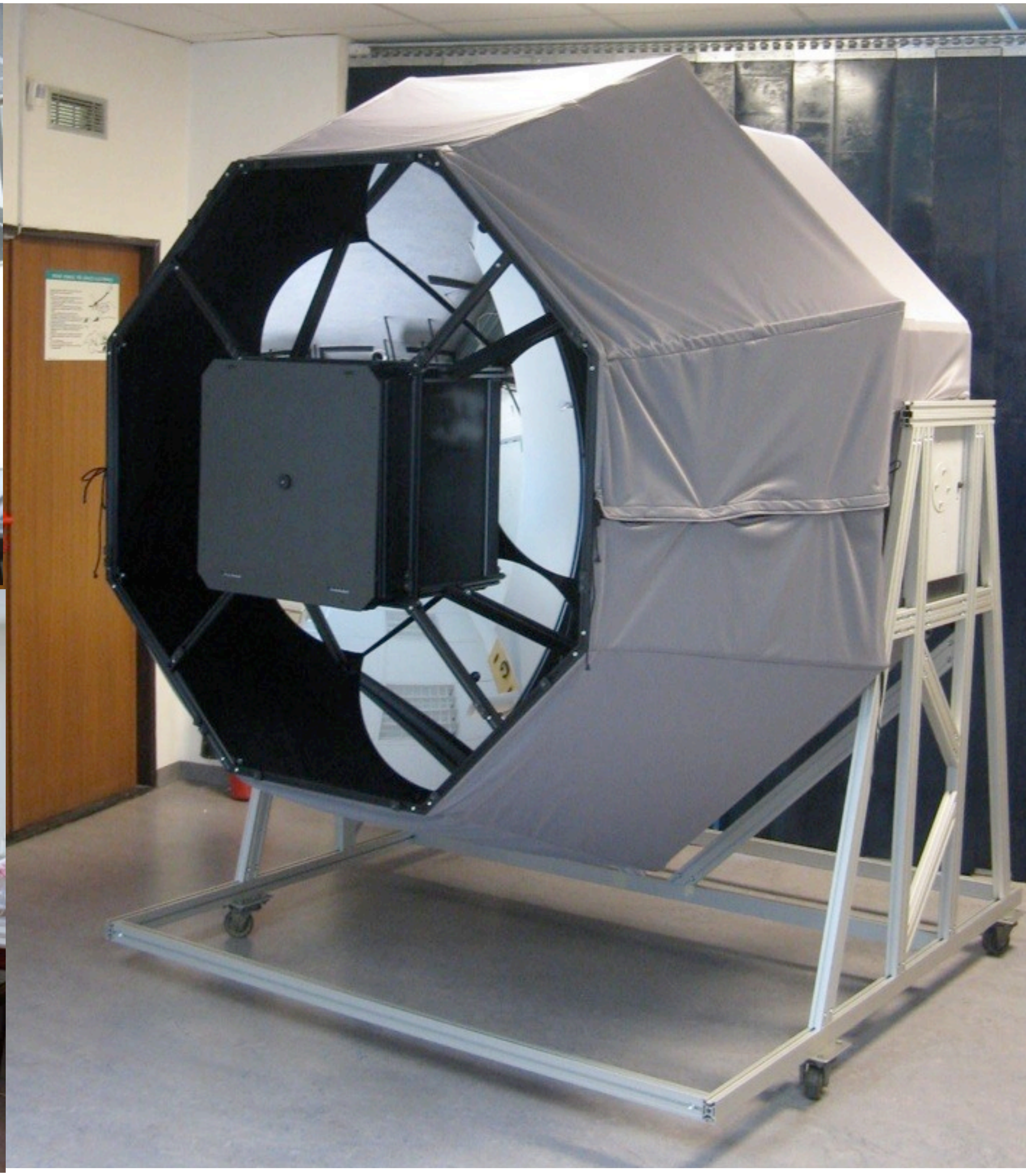


FAST
Fluorescence detector Array of Single-pixel Telescopes

Full-scale FAST Prototype



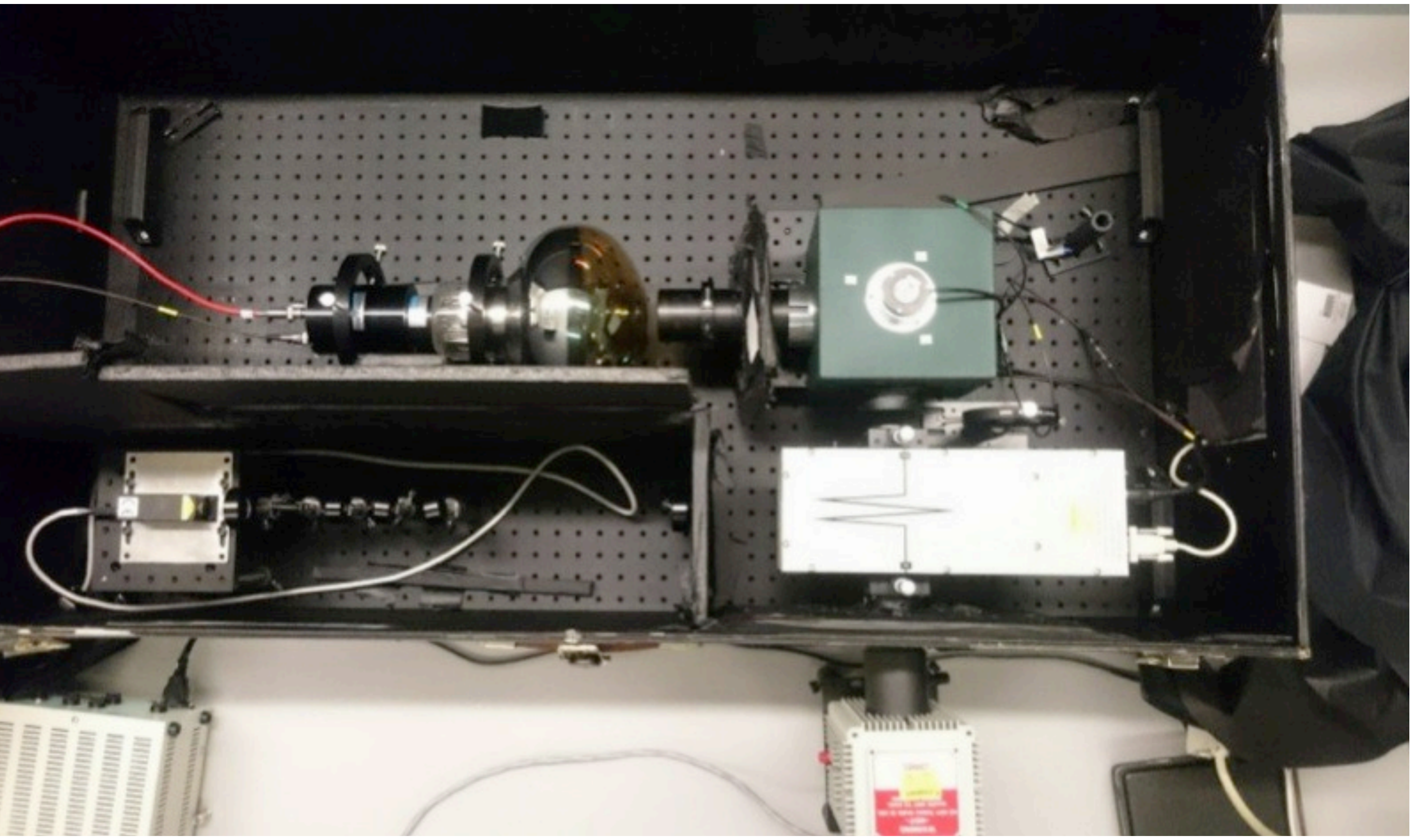


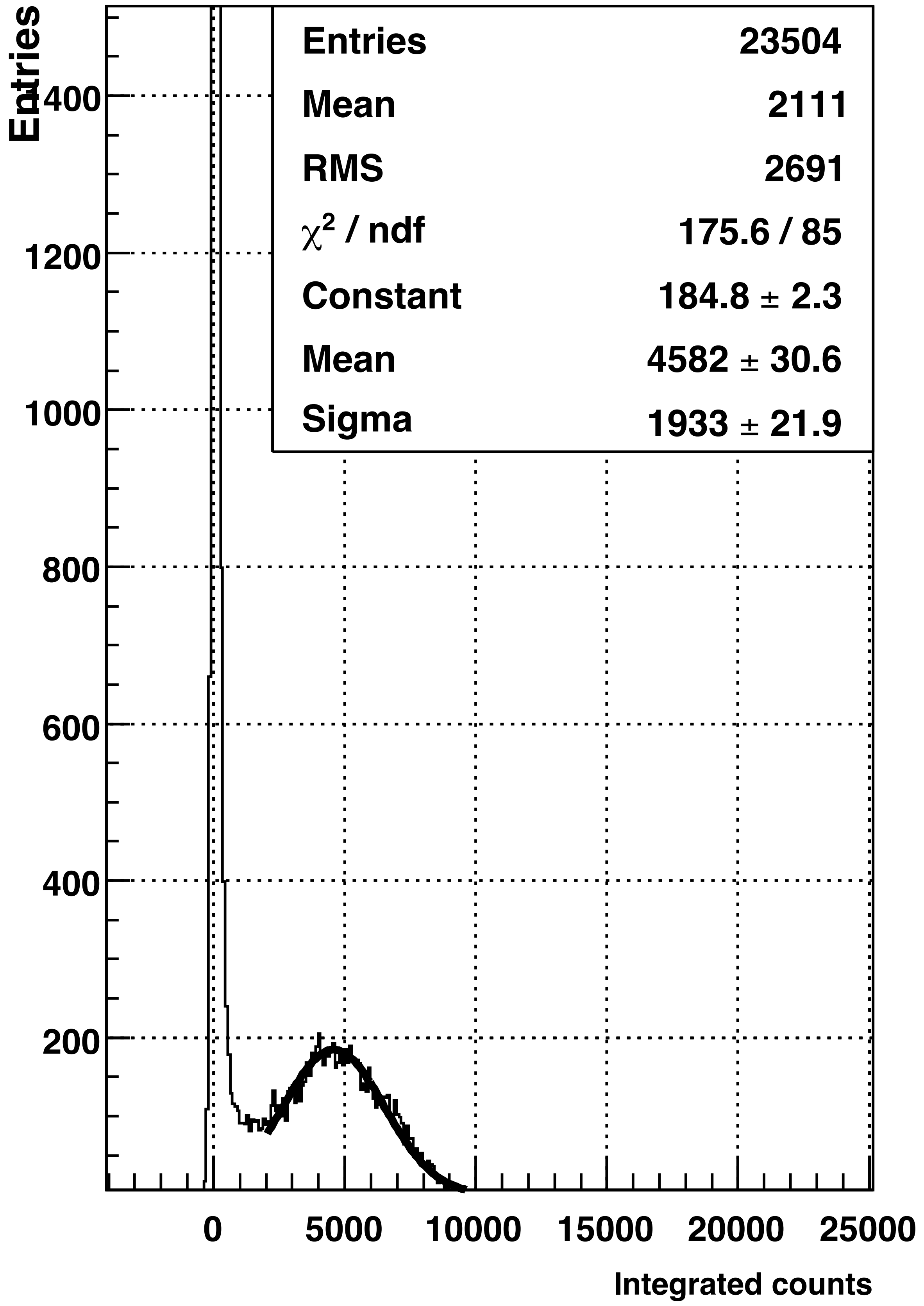


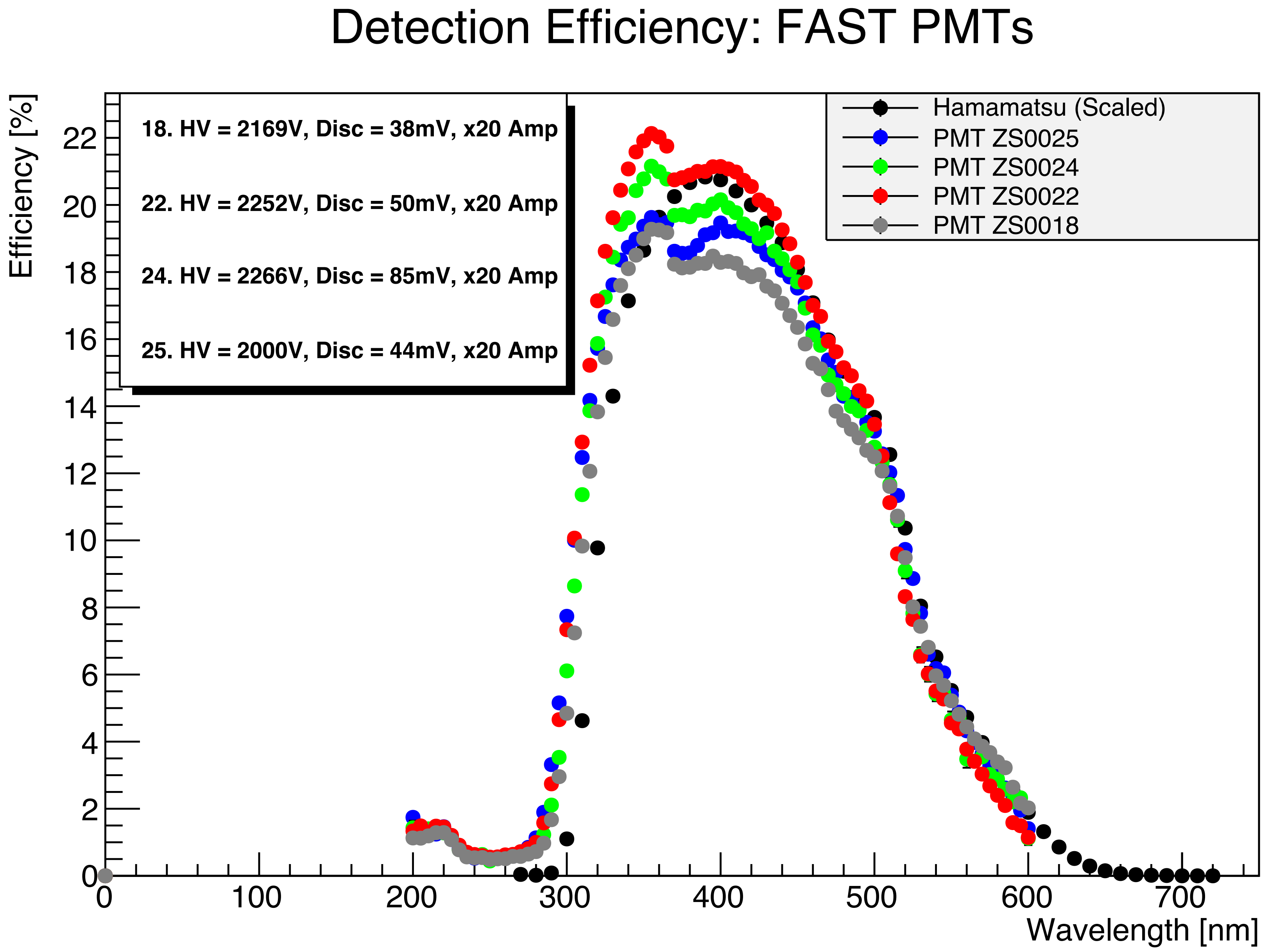
We will install the full-scale FAST prototype at Utah in June/July 2016

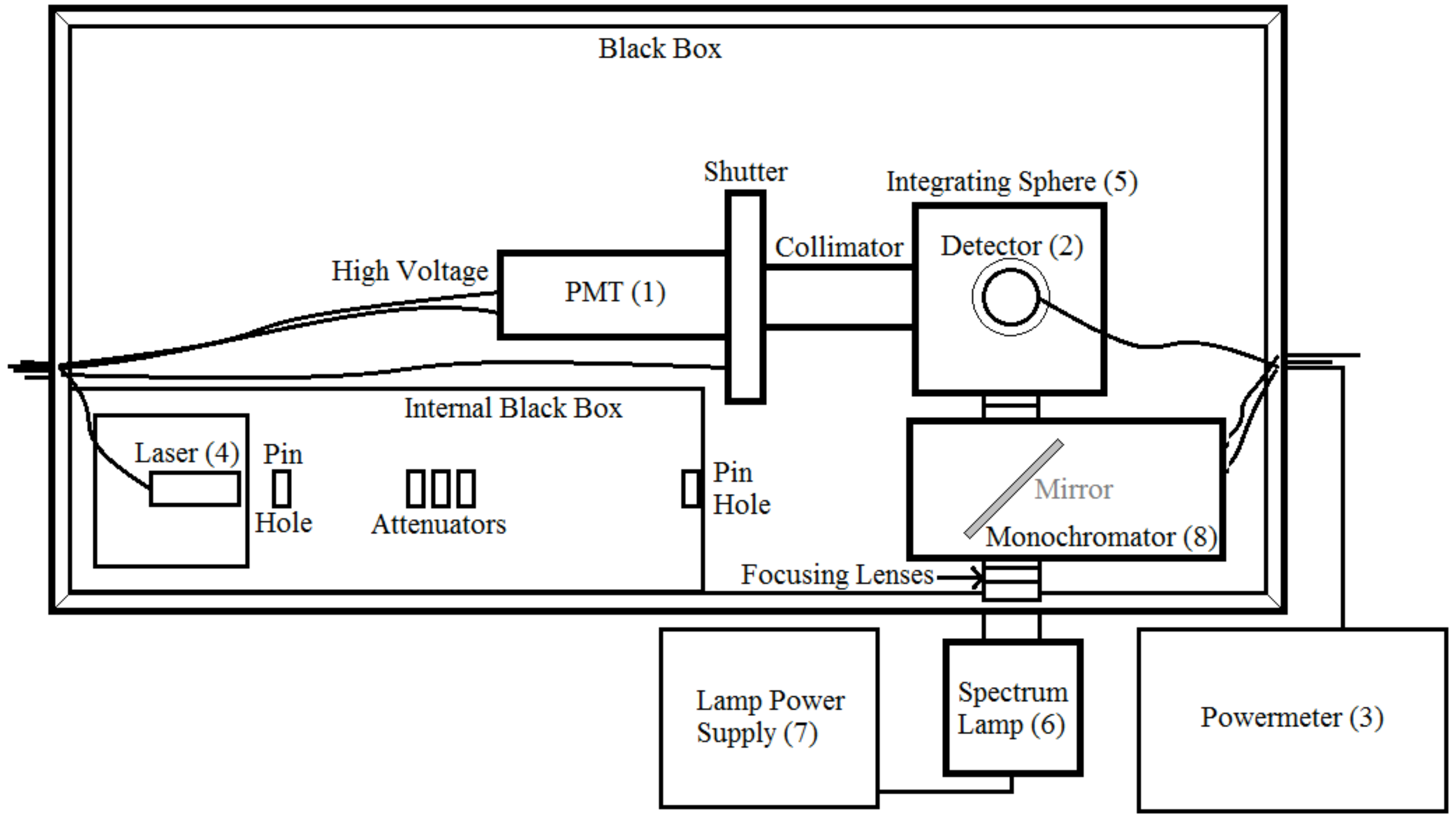
Fluorescence detector Array of Single-pixel Telescopes

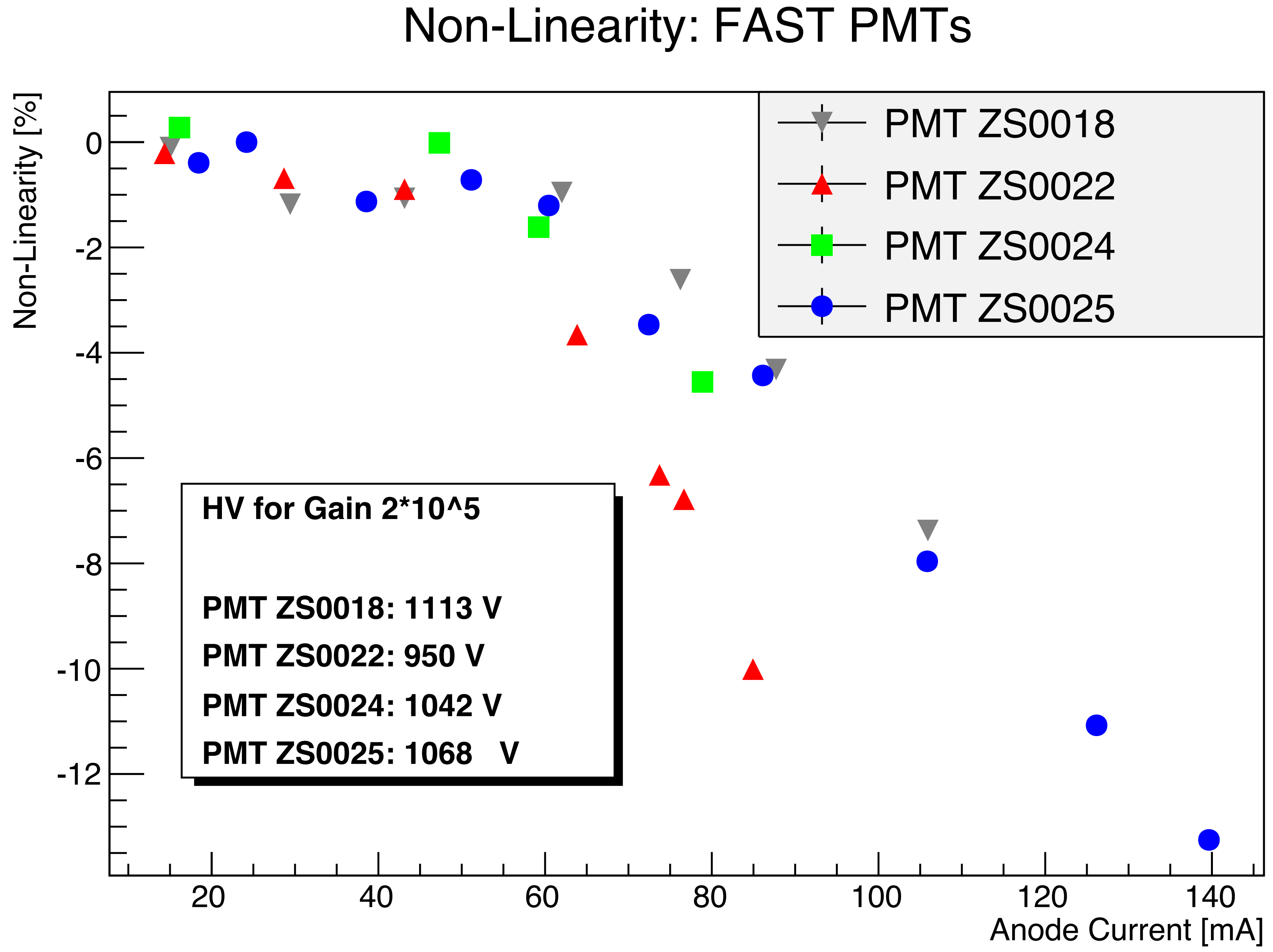
PMT Calibration System









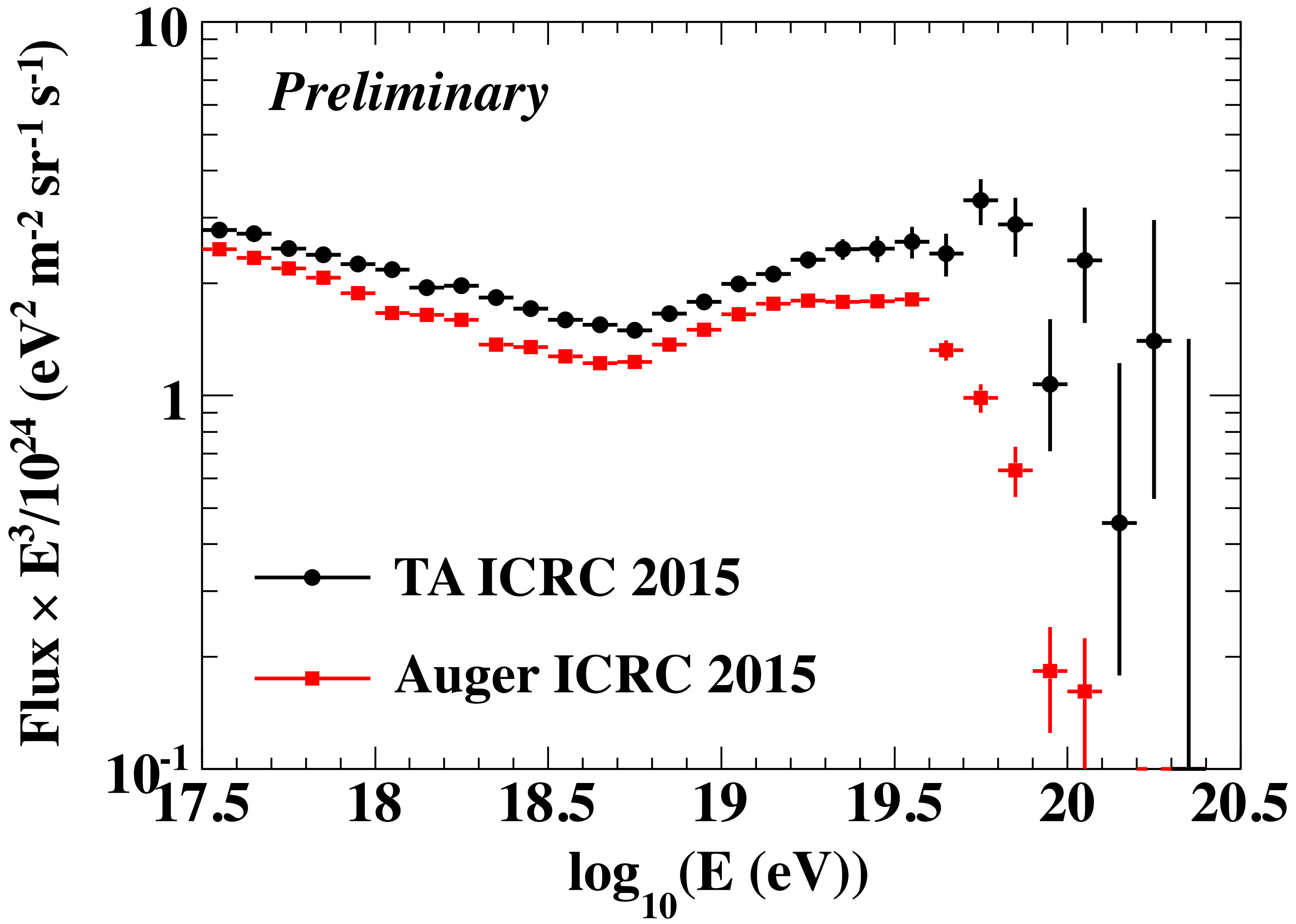


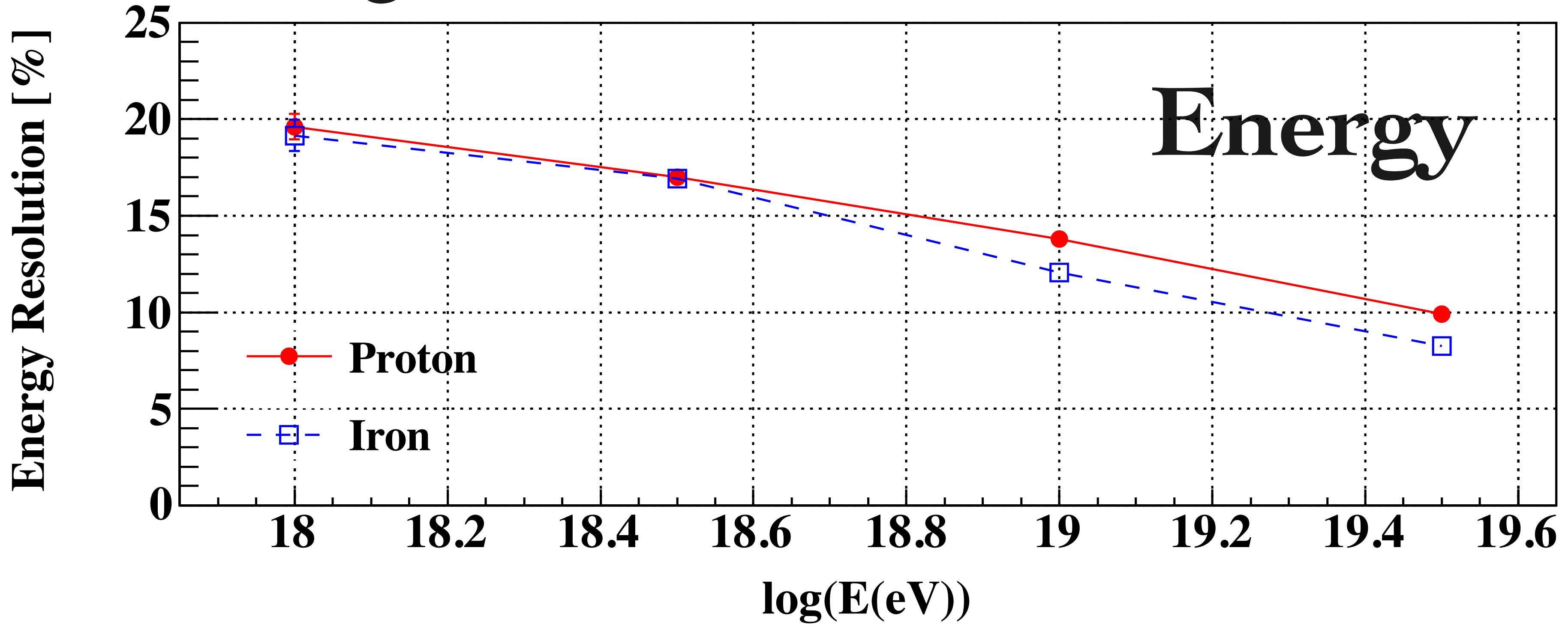
Preparing for full-automatic PMT calibration system

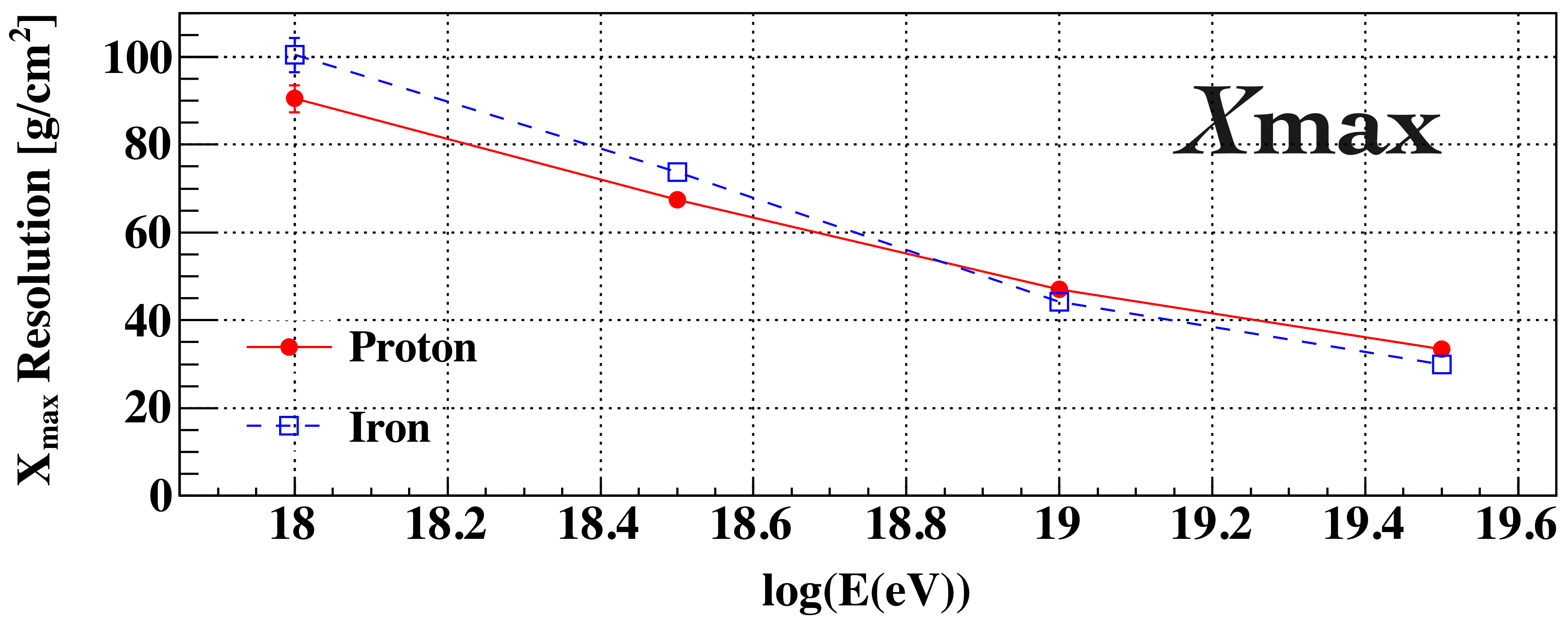
Possible Application of FAST Prototype

Fluorescence detector Array of Single-pixel Telescopes

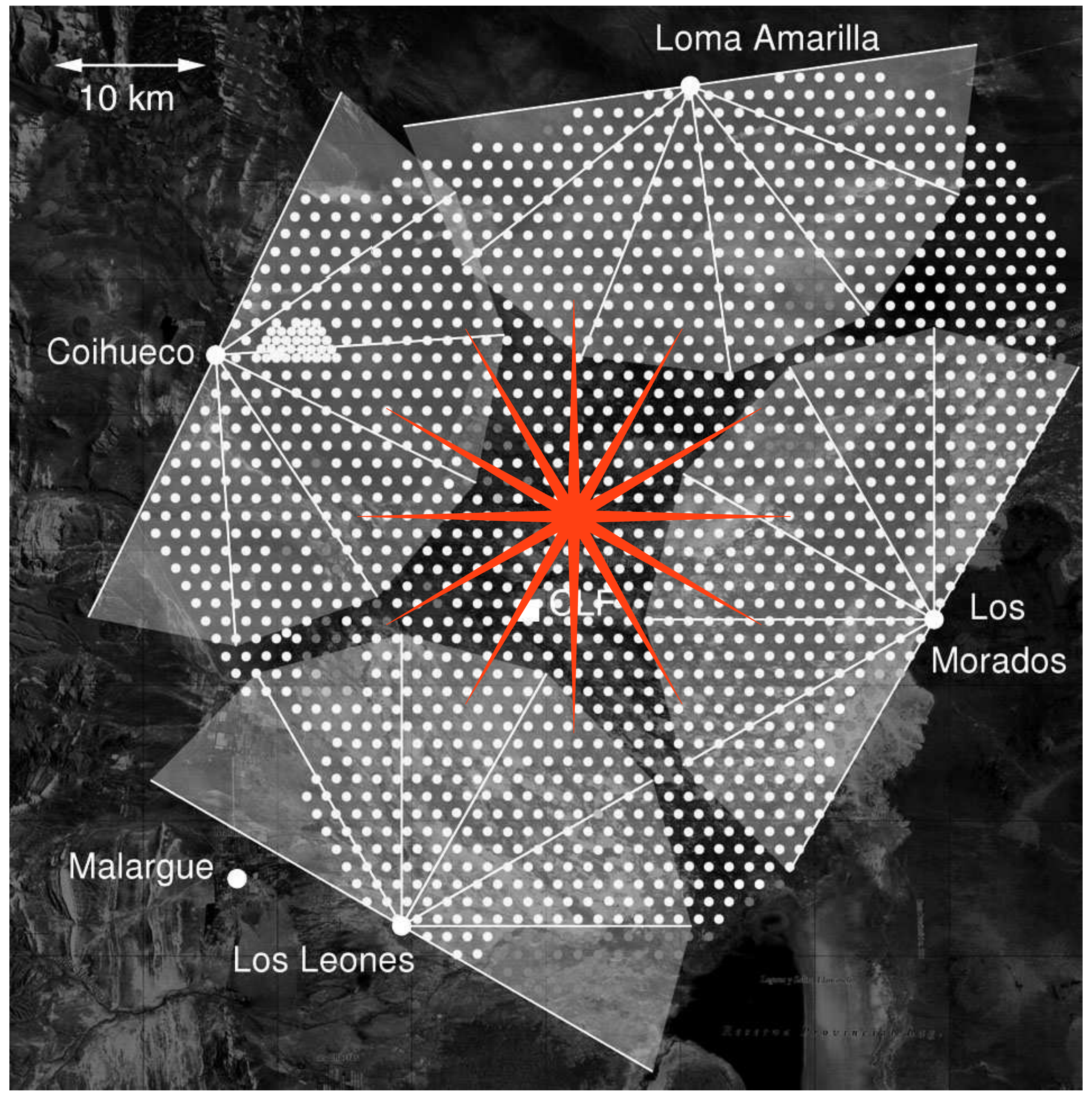
- Install FAST at Auger and TA for a cross calibration.
- Profile reconstruction with geometry given by SD (smearing gaussian width of 1° in direction, 100 m in core location).
  - Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
  - Independent cross-check of **Energy and Xmax** scale between Auger and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





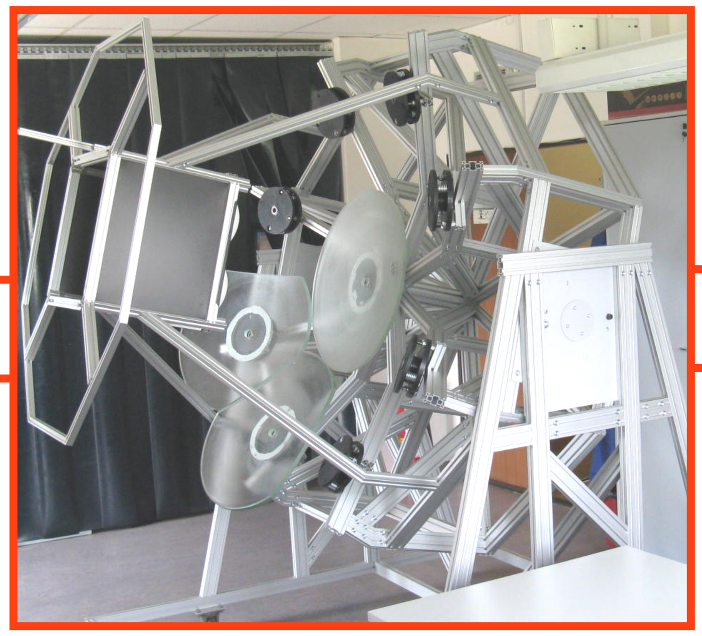


Pierre Auger Observatory

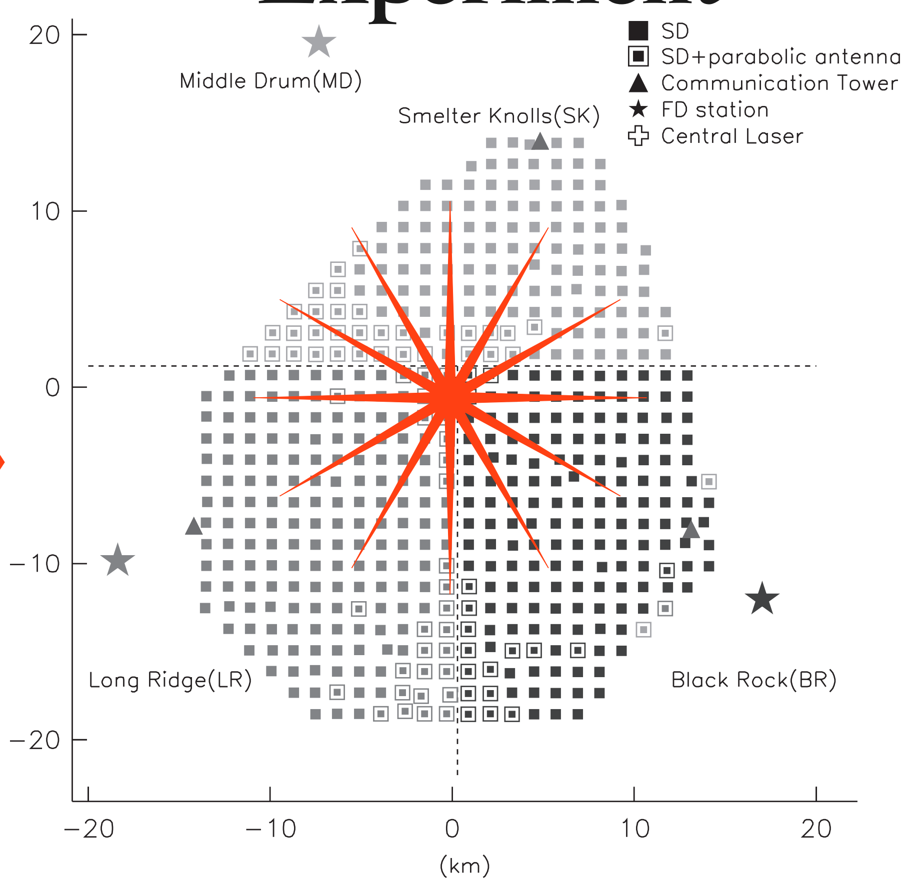


Pierre Auger Collaboration, NIM-A (2010)

Identical simplified FD



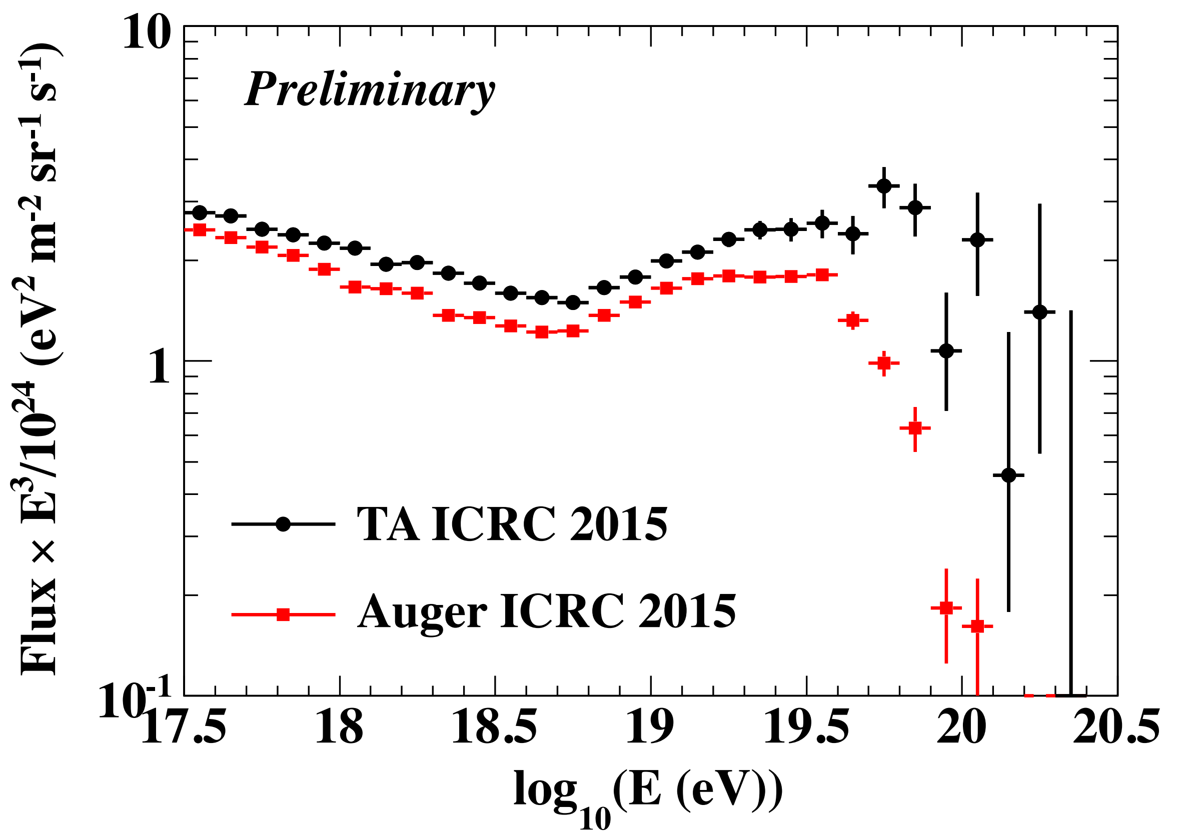
Telescope Array Experiment



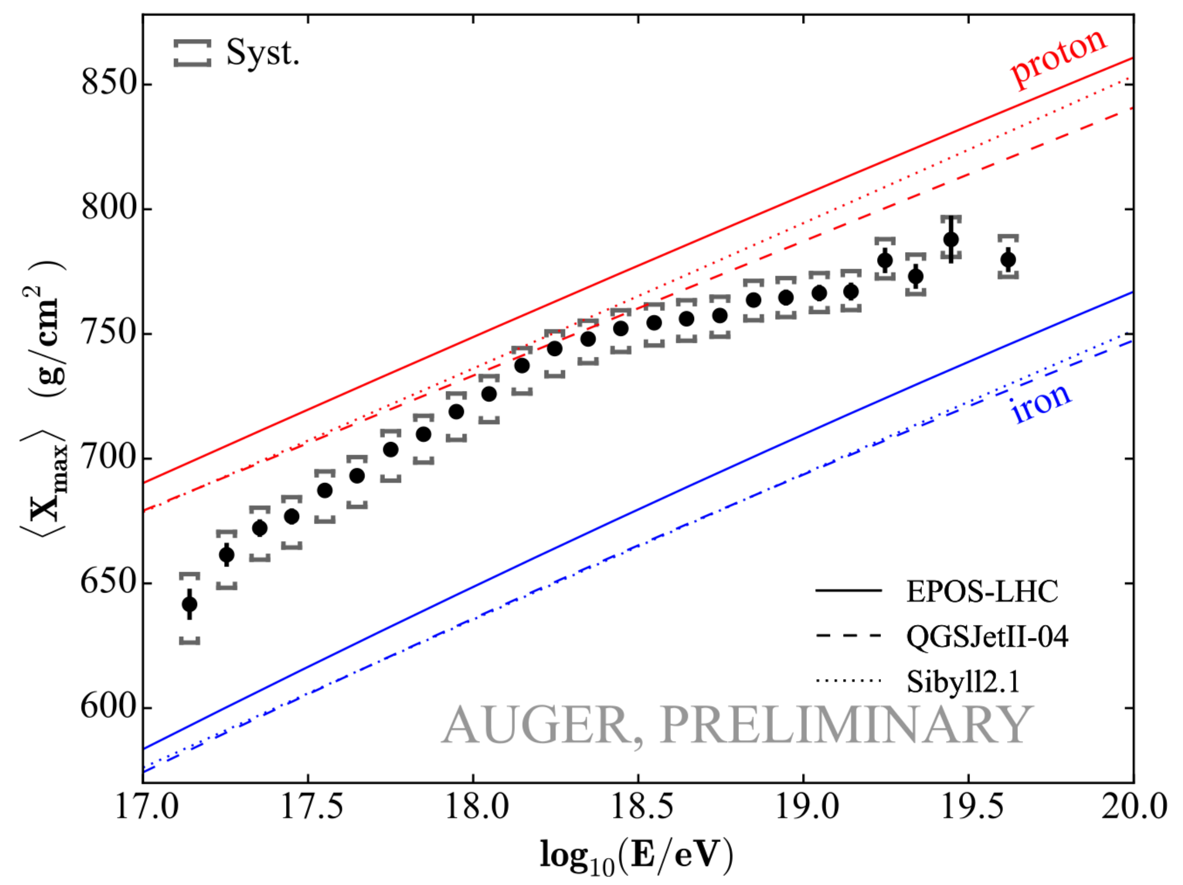
Telescope Array Collaboration NIM-A (2012)

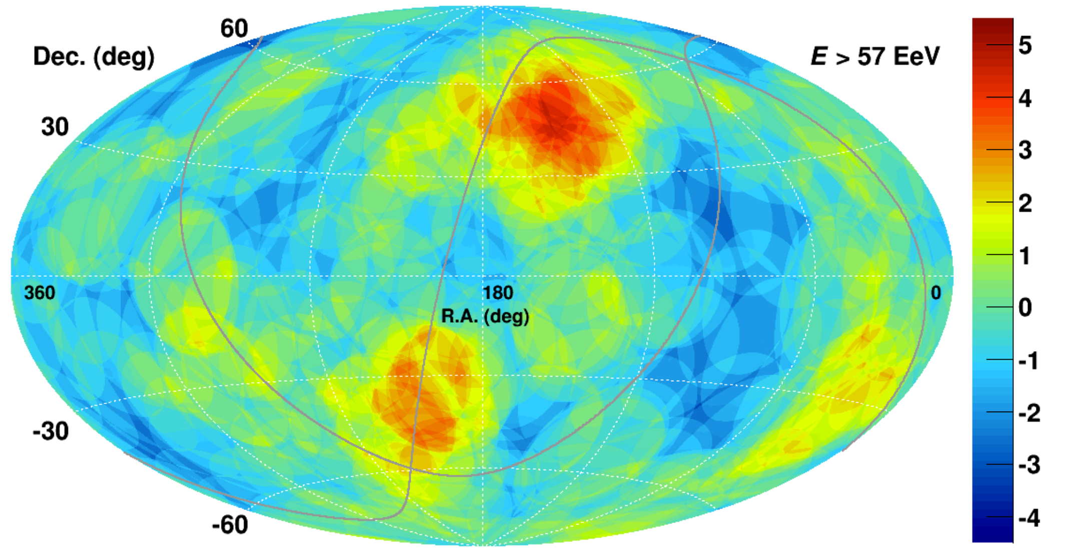
Summary

- Energy spectrum: Precise observation of the flux suppression above $10^{19.5}$ eV.
- Mass composition: Gradually increase heavier composition above ankle.
- Arrival direction: Hotspot/Warmspot of UHECRs
- **Flux suppression due to GZK process or maximum energy of accelerator?**
- **Heavier composition or 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?**



Average of X_{max}





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