October 6th, 2018

A next-generation ground array for the detection of ultrahigh-energy cosmic rays: the Fluorescence detector Array of Single-pixel Telescopes (FAST)

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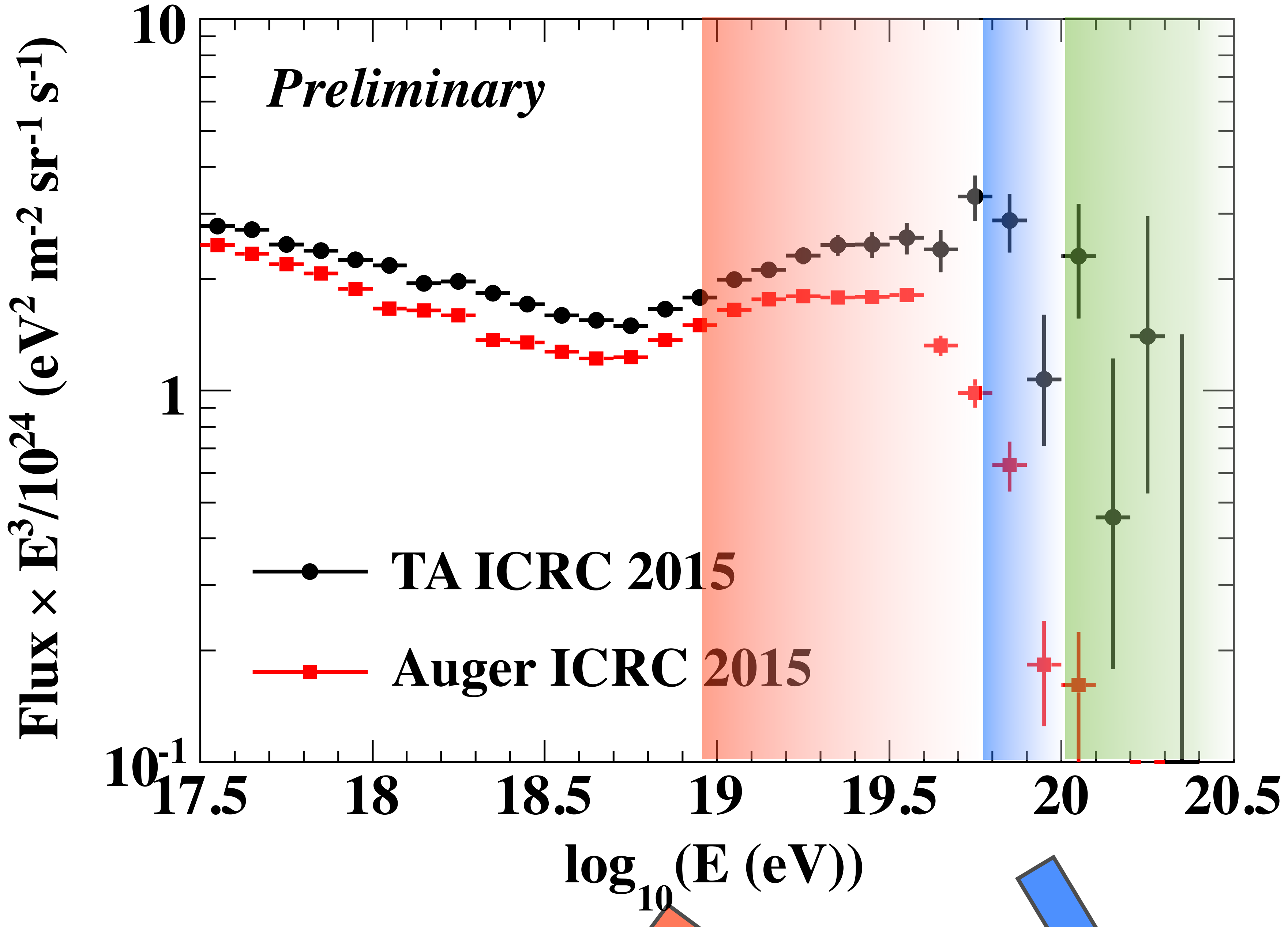
Max Malacari, Justin Albury, Jose Bellido, Ladislav Chytka,
John Farmer, Petr Hamal, Pavel Horvath, Miroslav Hrabovsky,
Dusan Mandat, John Matthews, Xiaochen Ni, Libor Nozka,
Miroslav Palatka, Miroslav Pech, Paolo Privitera, Petr Schovanek,
Stan Thomas, Petr Travnicek (The FAST Collaboration)
UHECR 2018, Paris, France, 12th October 2018

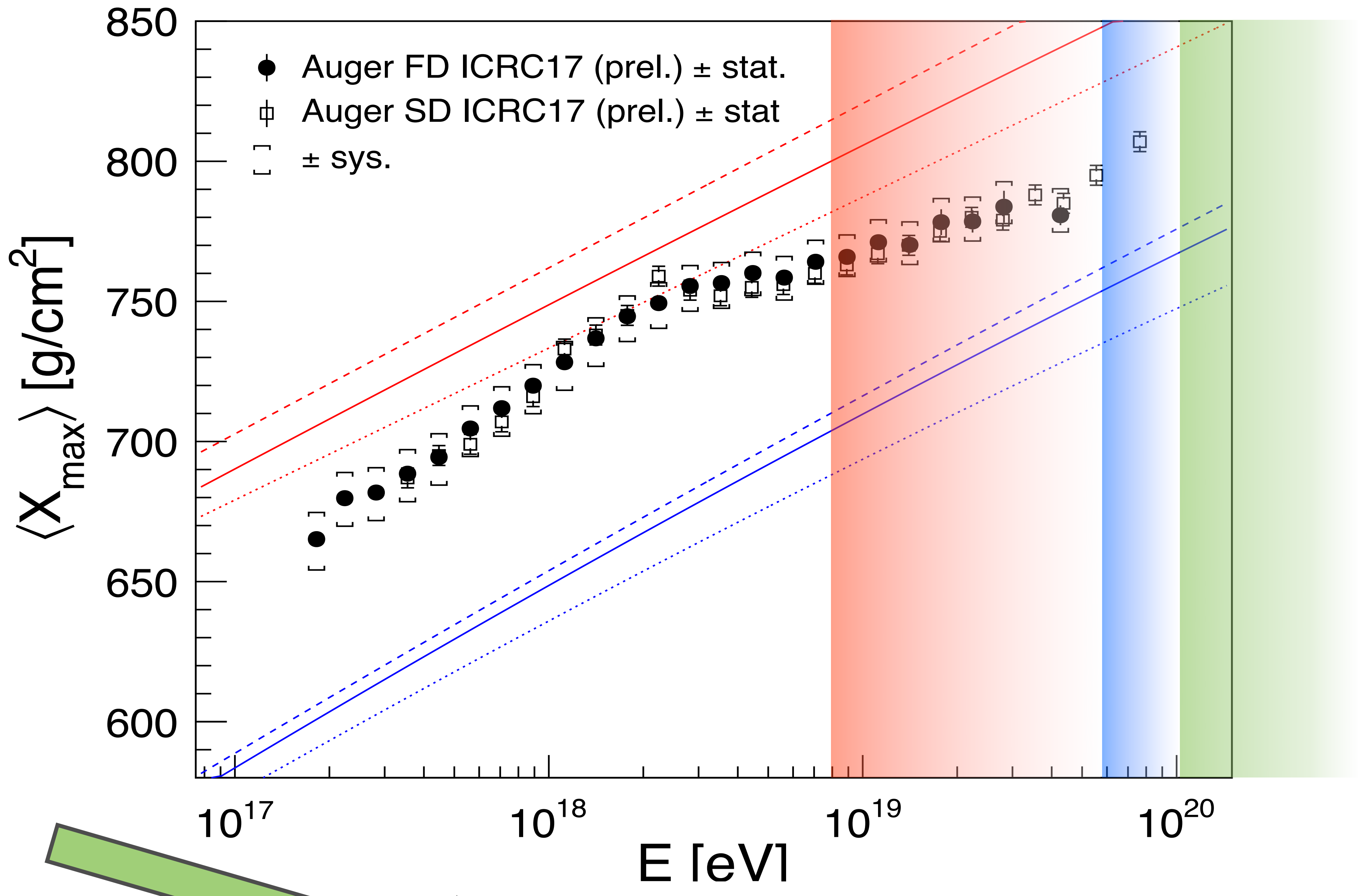
FAST
Fluorescence detector Array of Single-pixel Telescopes

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

Results of energy spectrum, mass composition and anisotropy



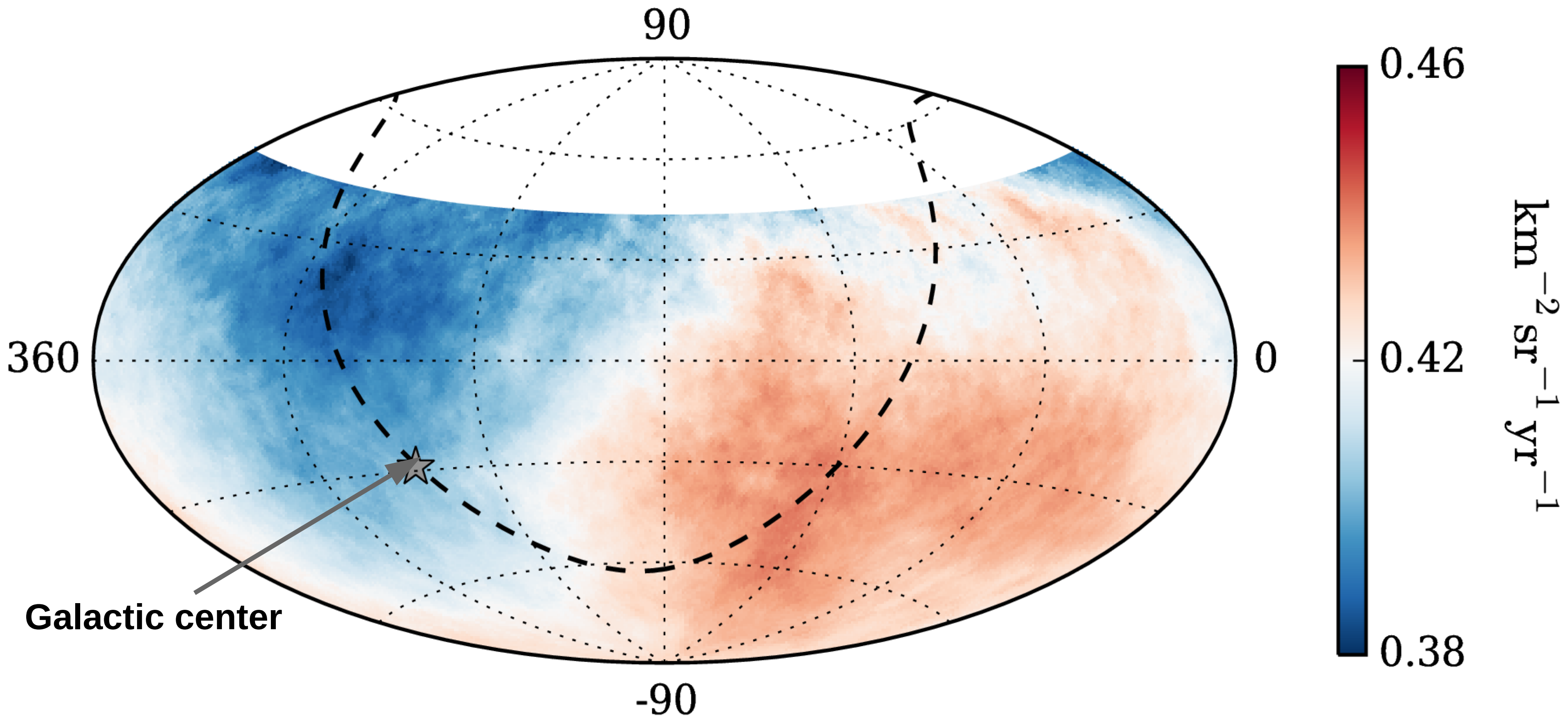
Data points from I. Valino et al., Proc. of ICRC 2015, D. Ivanov at al., Proc. of ICRC 2015



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

E > 8 EeV

Pierre Auger Collab. Science 357, 1266 (2017)

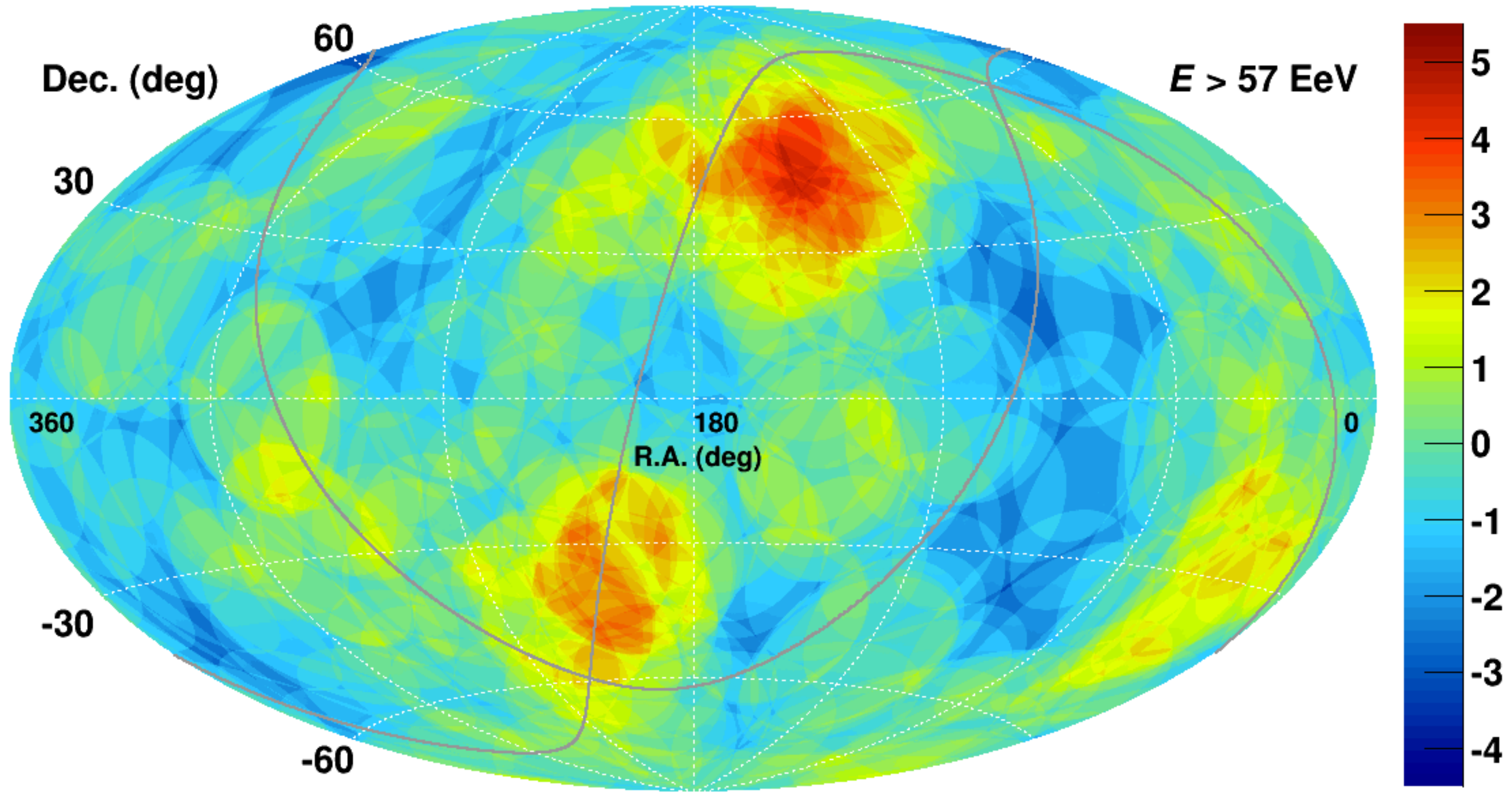


Increase dipole amplitude above 4 EeV

arXiv:1808.03579

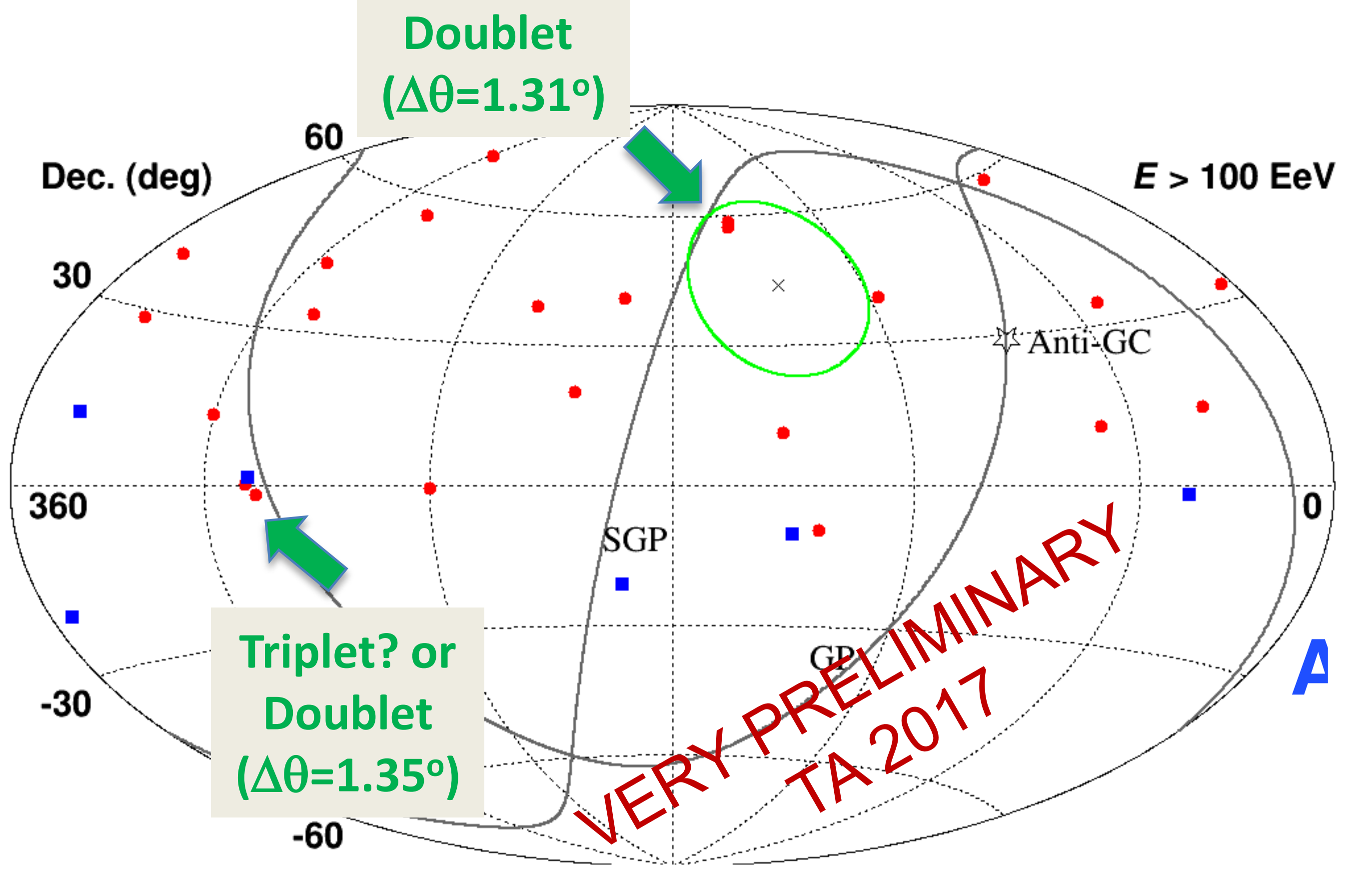
E > 57 EeV

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



E > 100 EeV

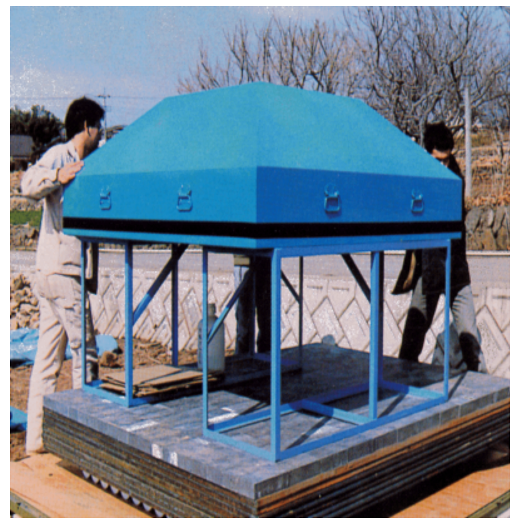
S. Troitsky et al., Proc. of ICRC 2017



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

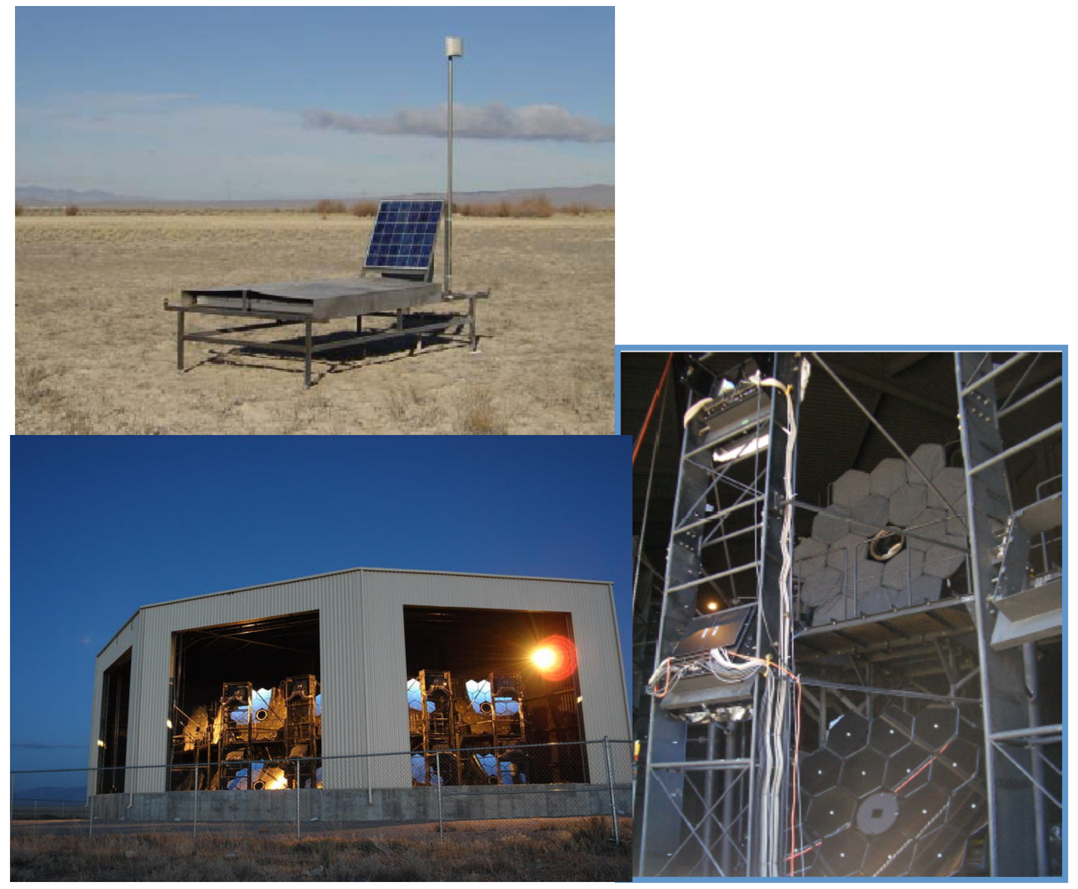
Requirements for a next-generation ground array

AGASA

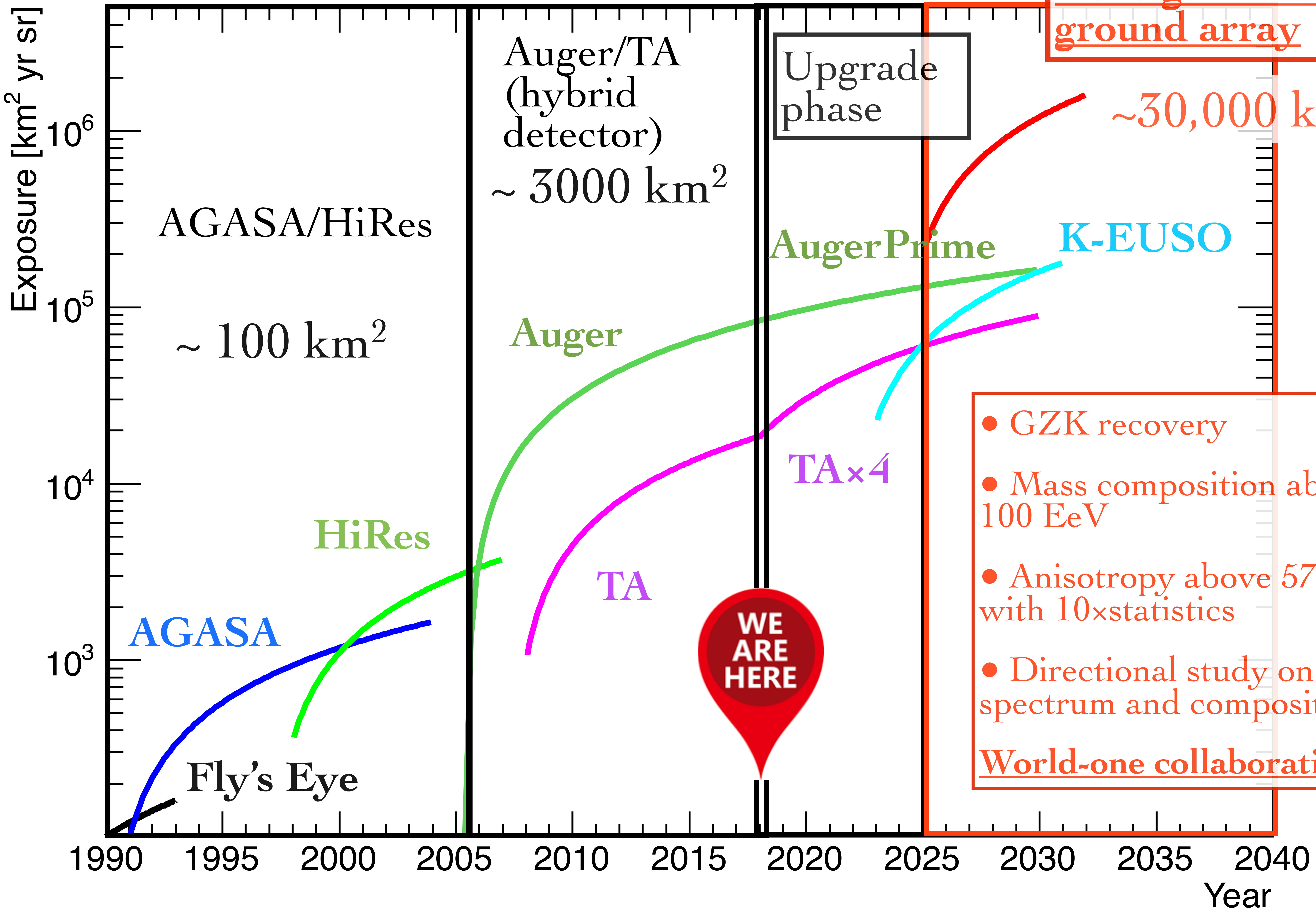


HiRes

Telescope Array Experiment



Pierre Auger Observatory



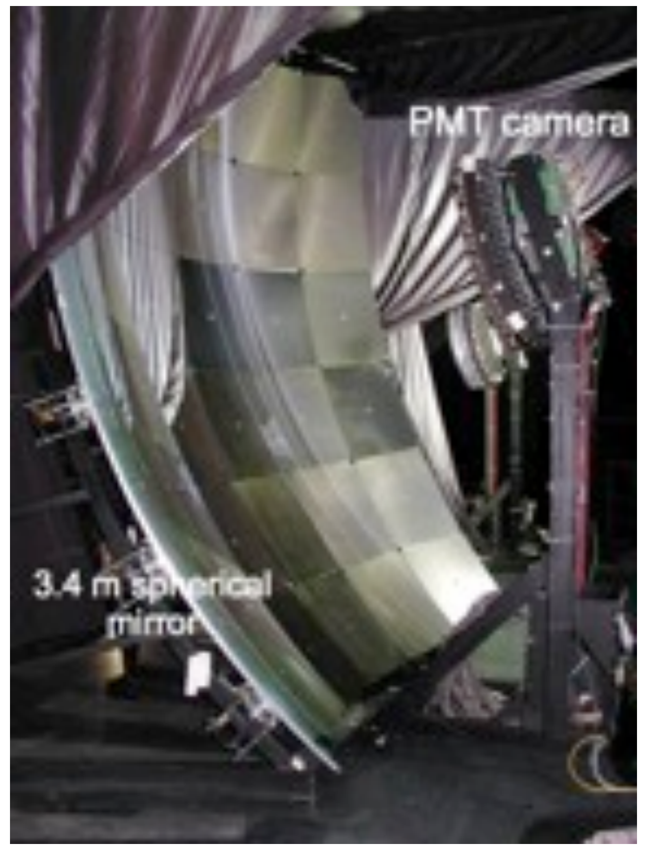
- GZK recovery
- Mass composition above 100 EeV
- Anisotropy above 57 EeV with 10×statistics
- Directional study on spectrum and composition

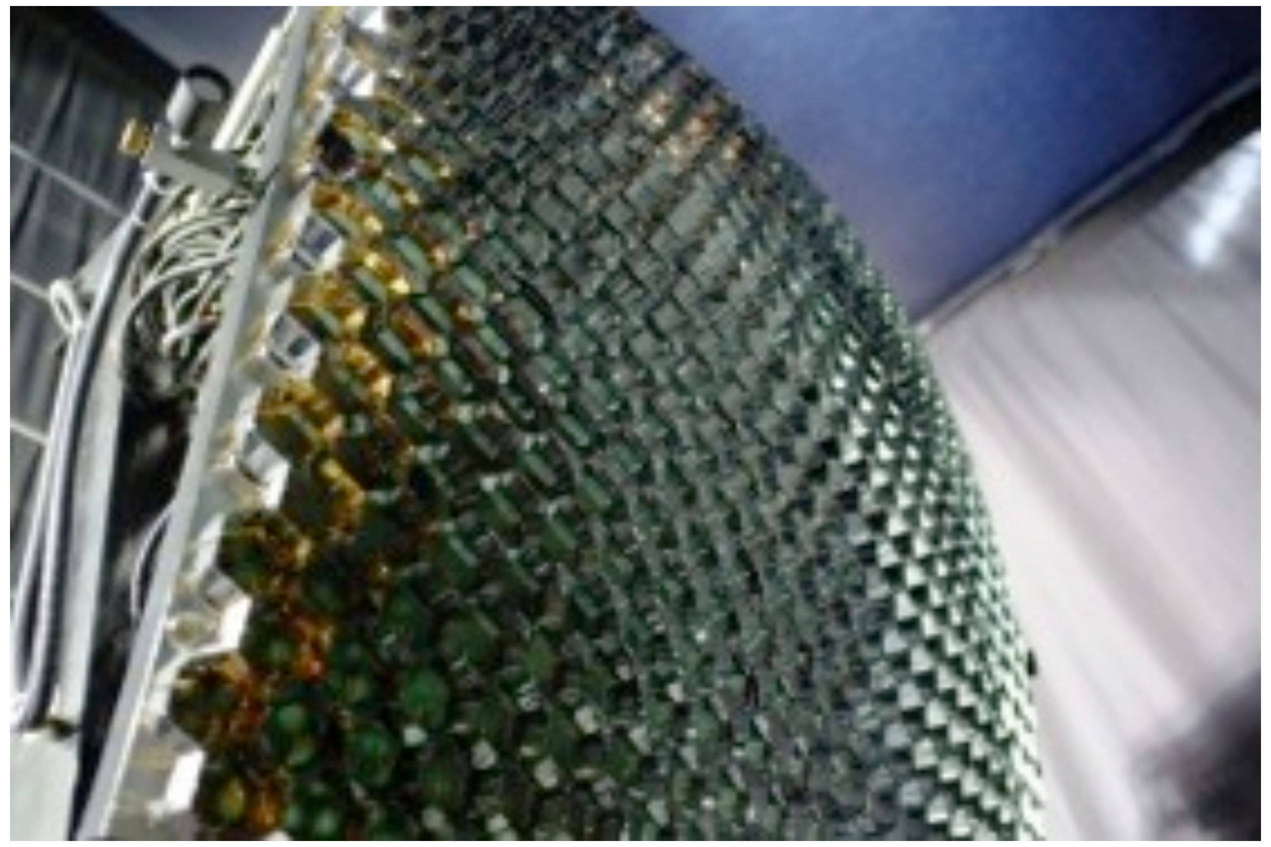
World-one collaboration

Fluorescence detector Array of Single-pixel Telescopes

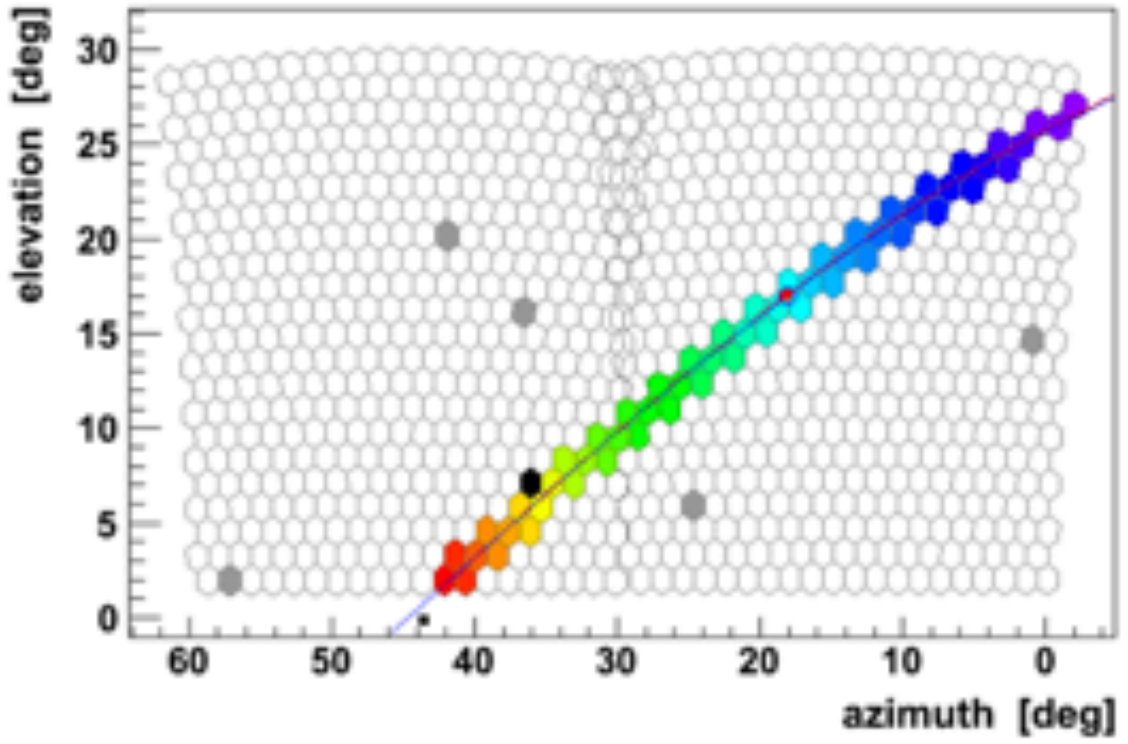
- Target : > $10^{19.5}$ eV, ultra-high energy cosmic rays (UHECR) and neutral particles
  - Huge target volume ⇒ Fluorescence detector array

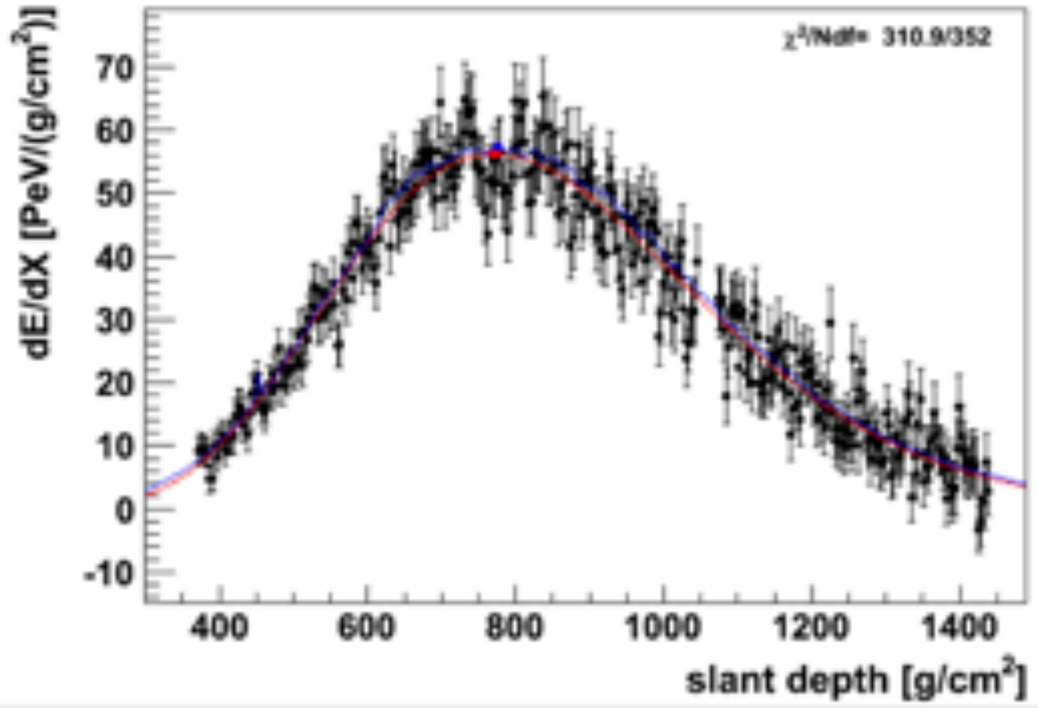
Fine pixelated camera



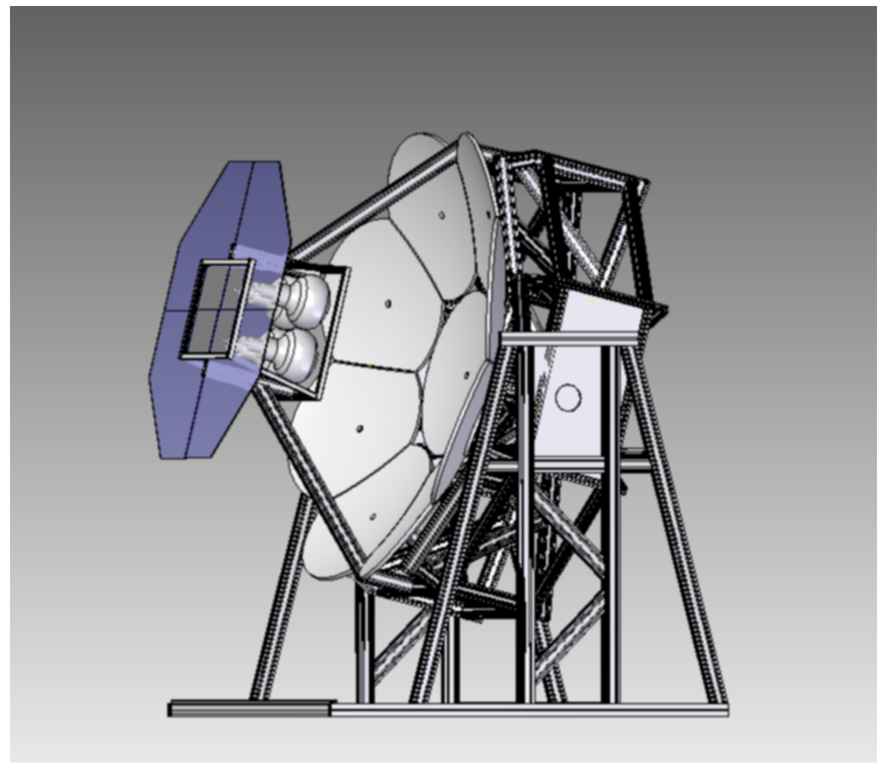


Too expensive to cover a huge area

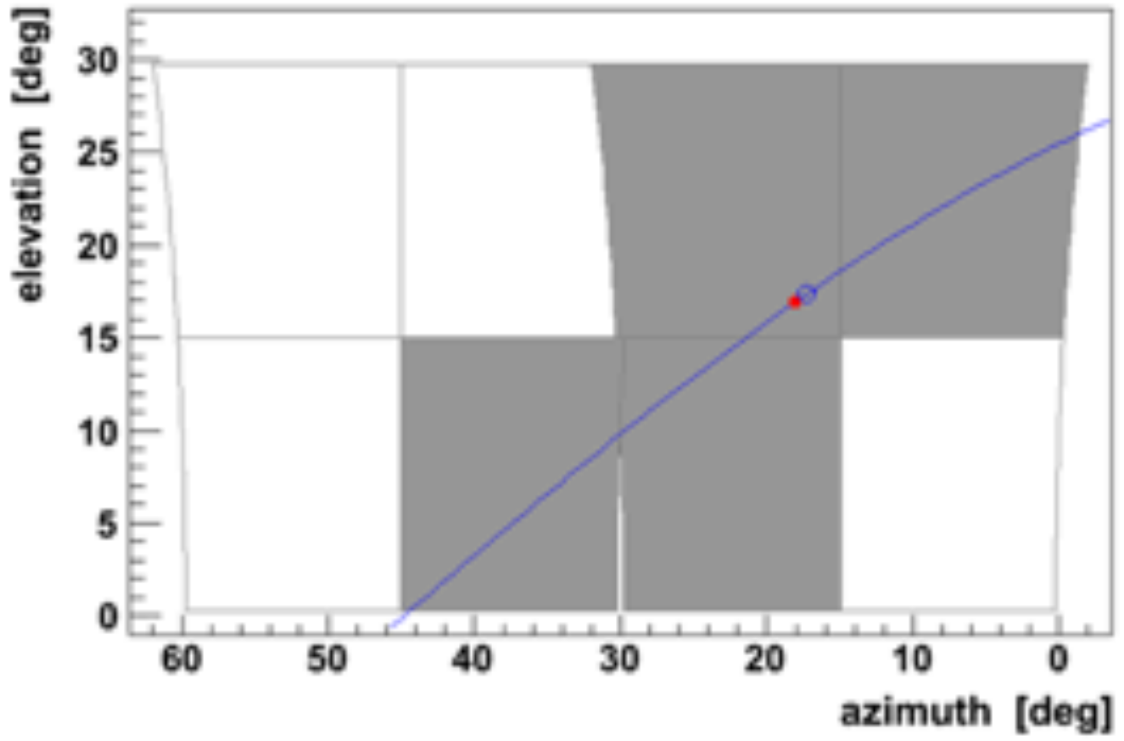


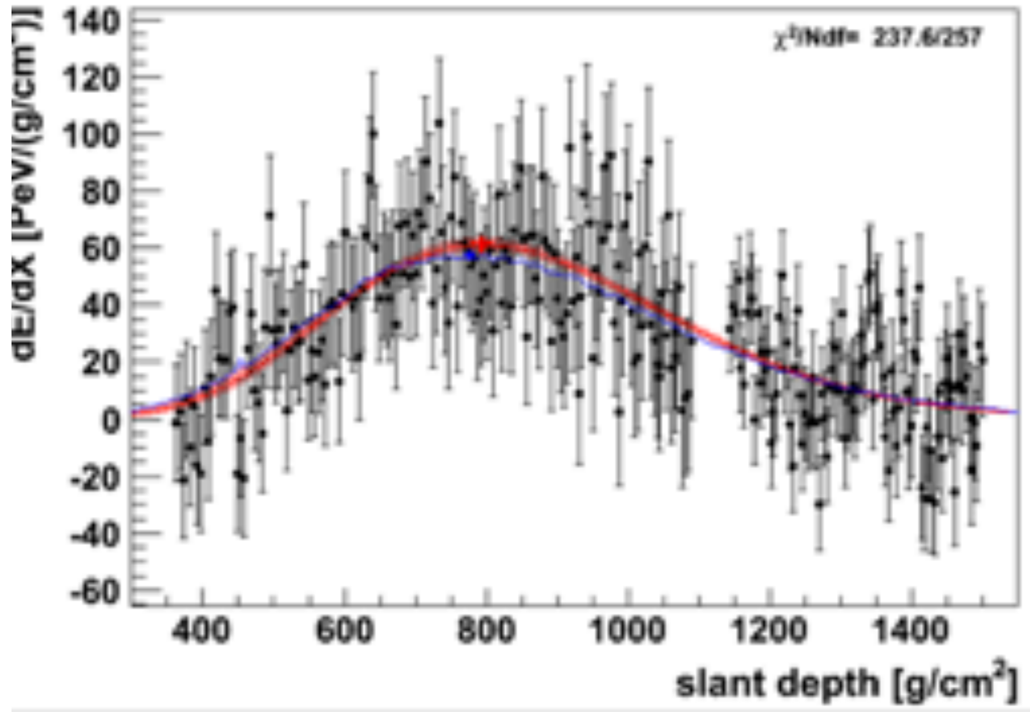


Smaller optics and single or few pixels



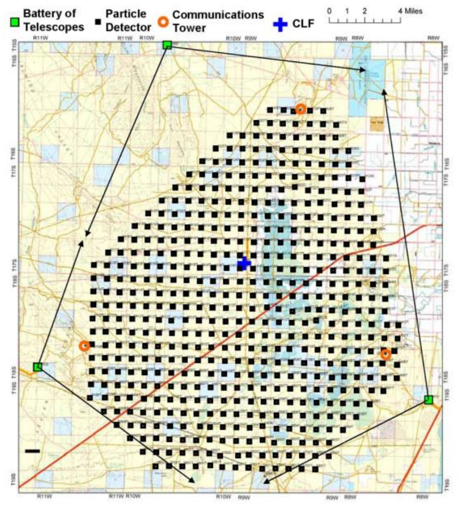
Low-cost and simplified telescope





FAST: Fluorescence detector Array of Single-pixel Telescopes

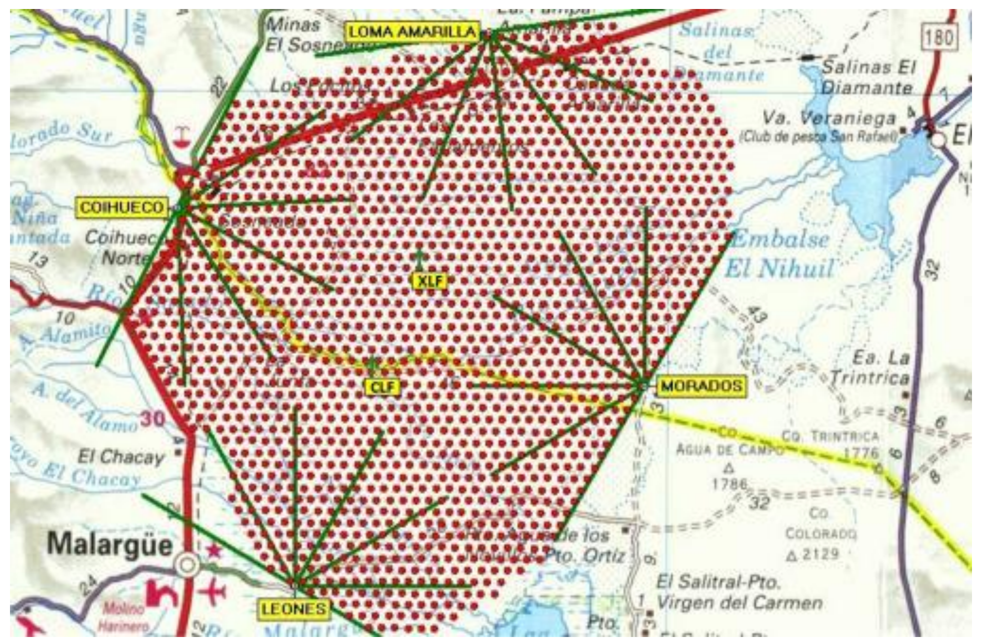
Fluorescence detector Array of Single-pixel Telescopes

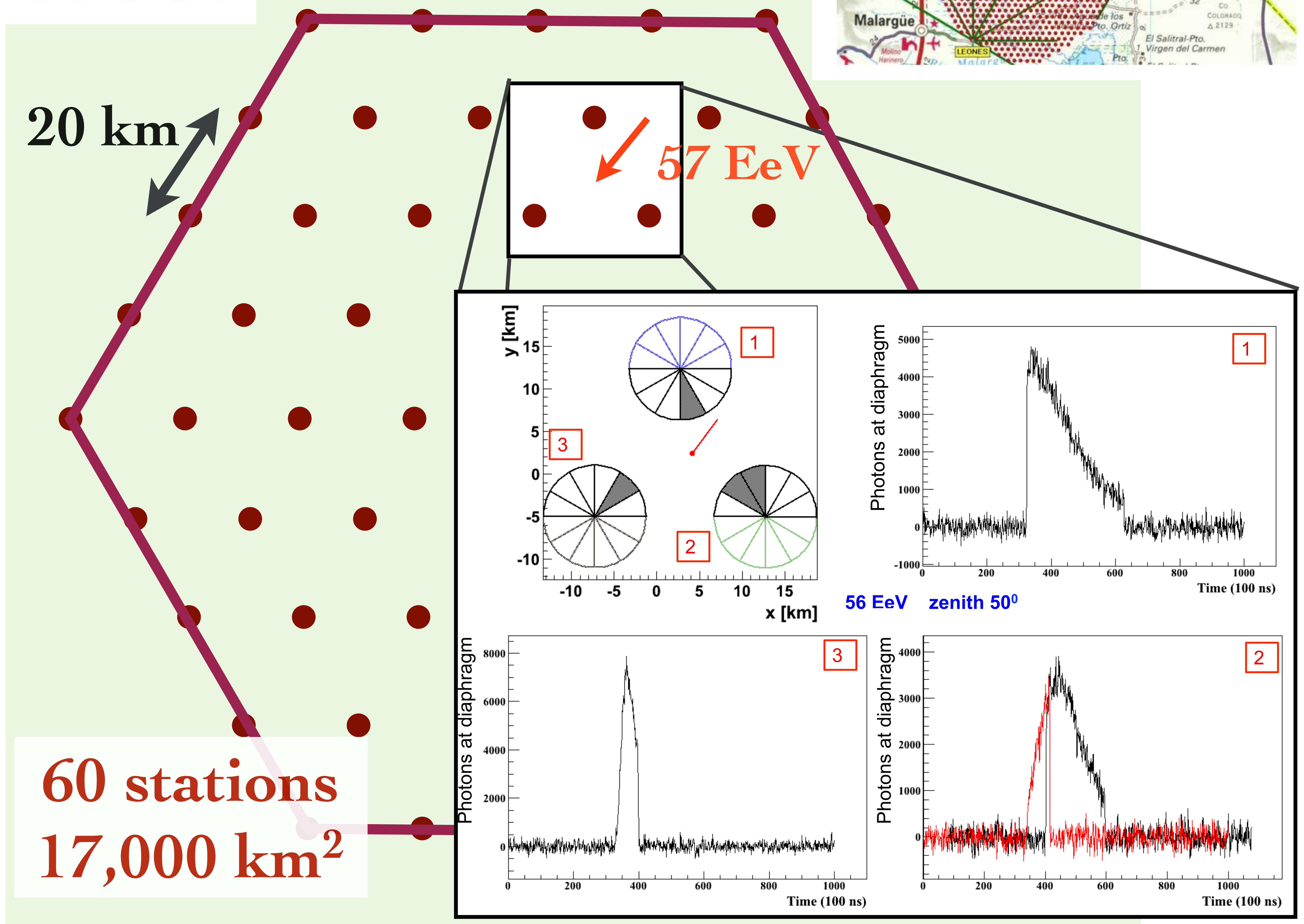


TA
700 km^2

(same scale)

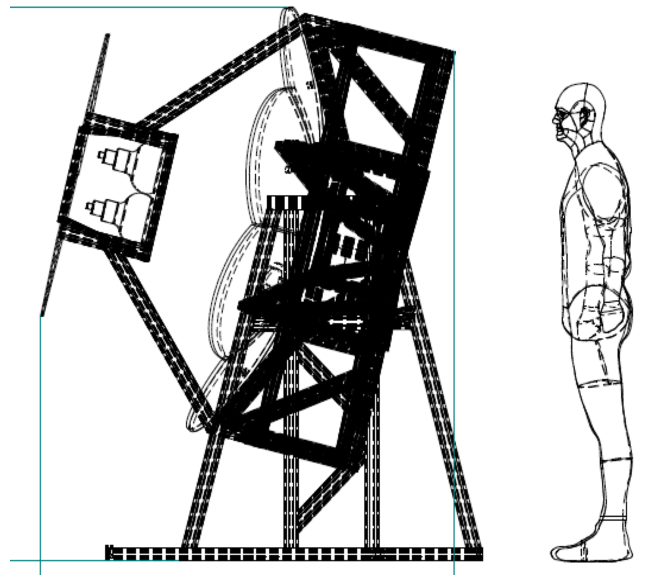
Auger
3000 km^2

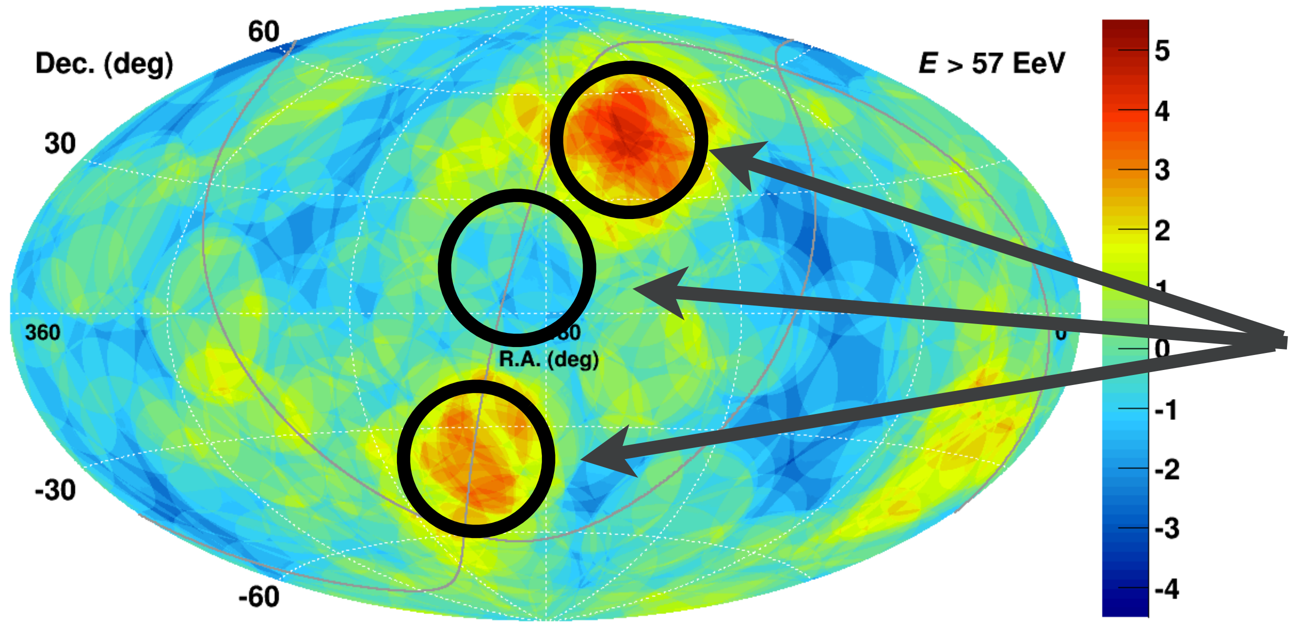




- Each telescope: 4 PMTs, 30°×30° field of view (FoV)
  - **Reference design: 1 m^2 aperture, 15°×15° FoV per PMT**
  - Each station: 12 telescopes, 48 PMTs, 30°×360° FoV.
- Deploy on a triangle grid with **20 km** spacing, like **"Surface Detector Array"**.
- With **500 stations**, a ground coverage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

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





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

Directional study on spectrum and composition from hot/warm spots and Virgo cluster, respectively.

FAST
Fluorescence detector Array of Single-pixel Telescopes

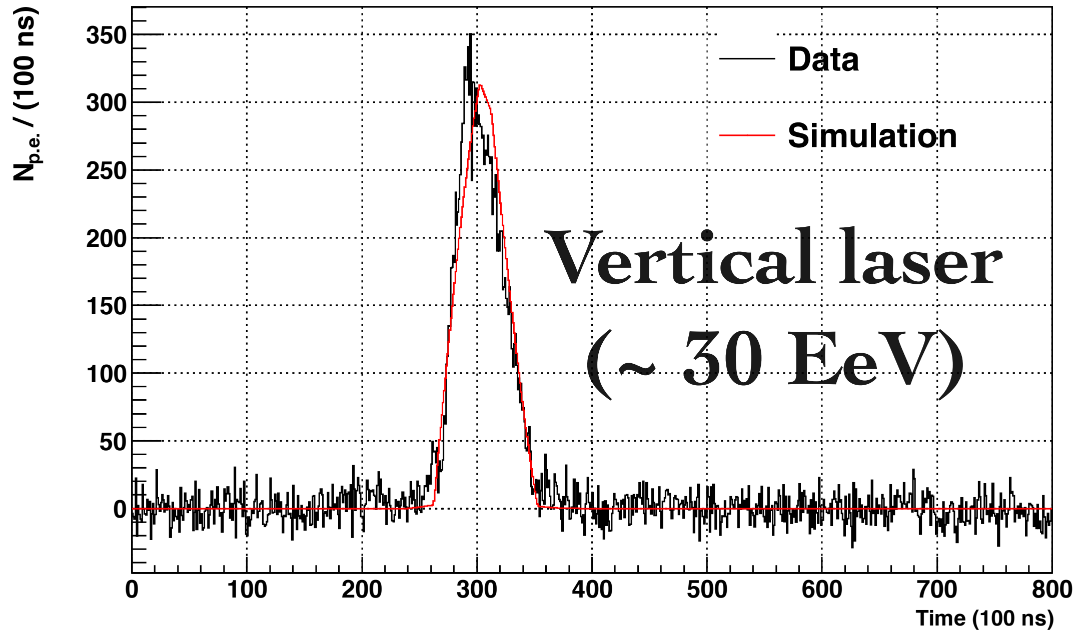
Progress from UHECR 2012

Feb. 2012

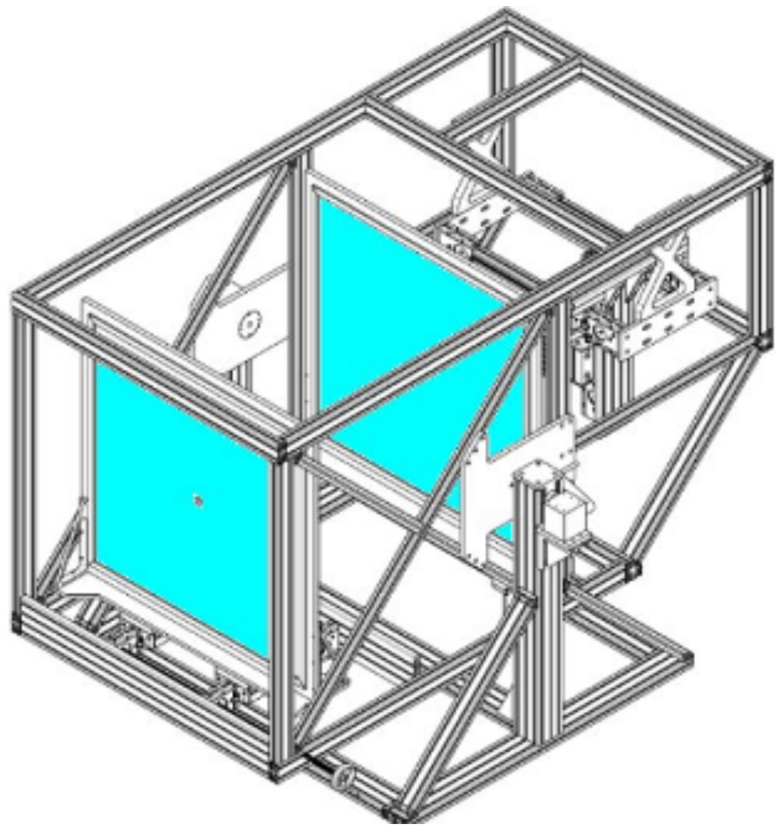
A conceptual design for a large ground array of Fluorescence Detectors

UHECR 2012

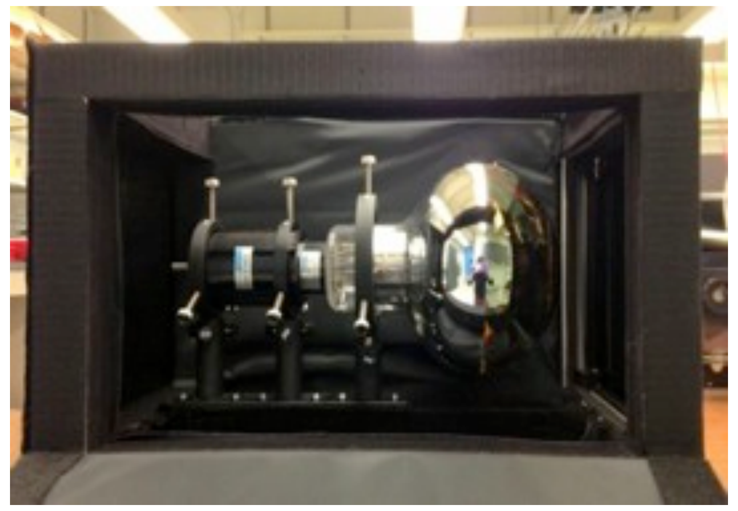
P. Privitera in UHECR 2012

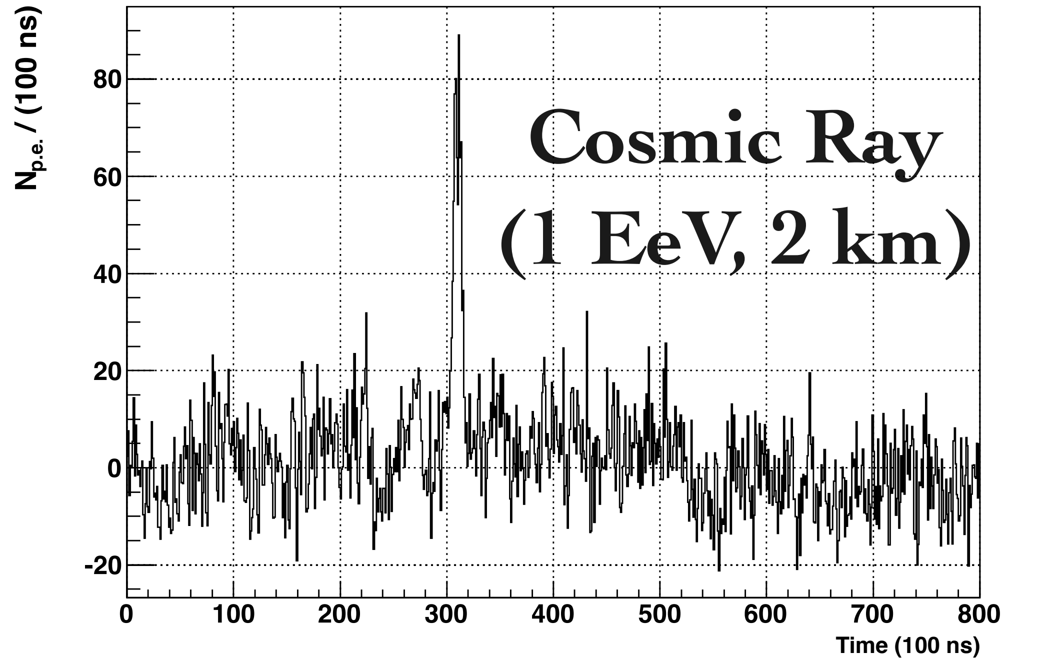


Apr. 2014



EUSO-TA optics
+
Single-pixel camera



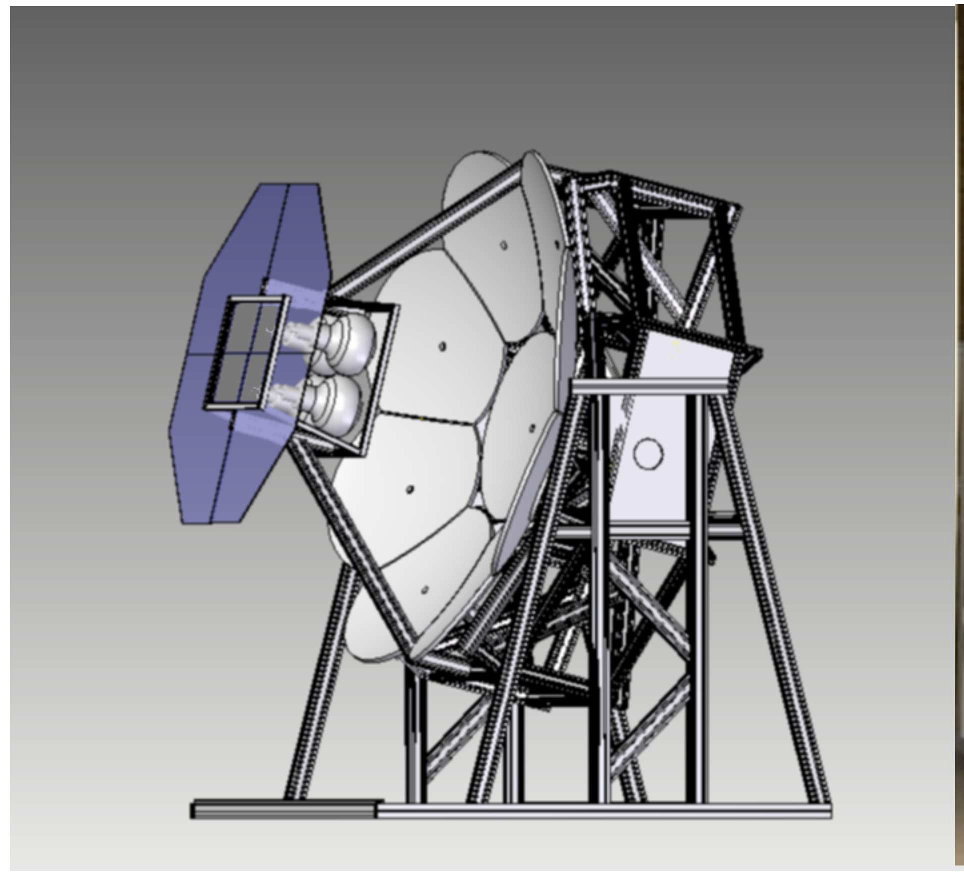


Astroparticle Physics *74* (2016) 64-72

Oct. 2016

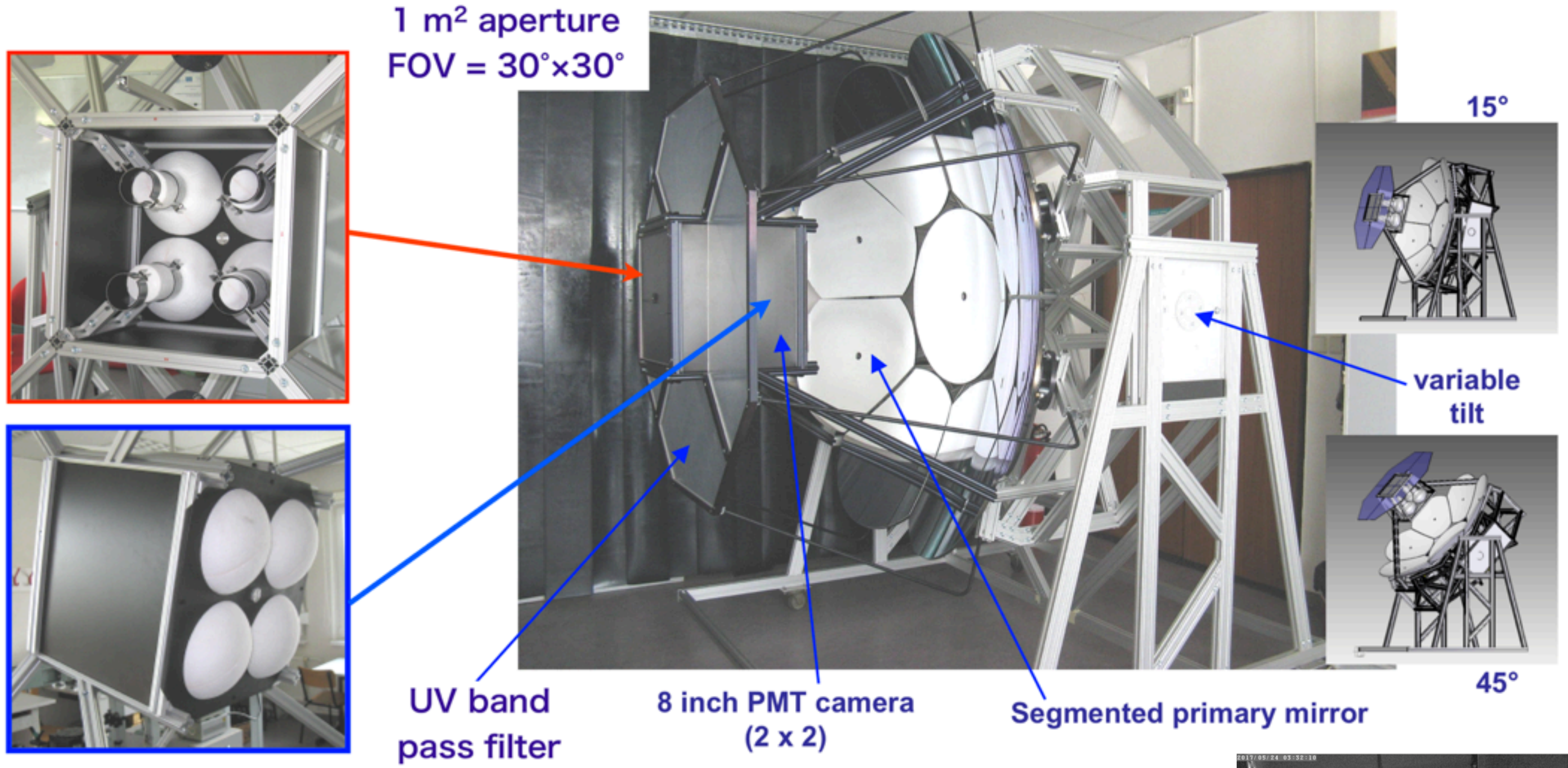
Sep. 2017

Oct. 2018

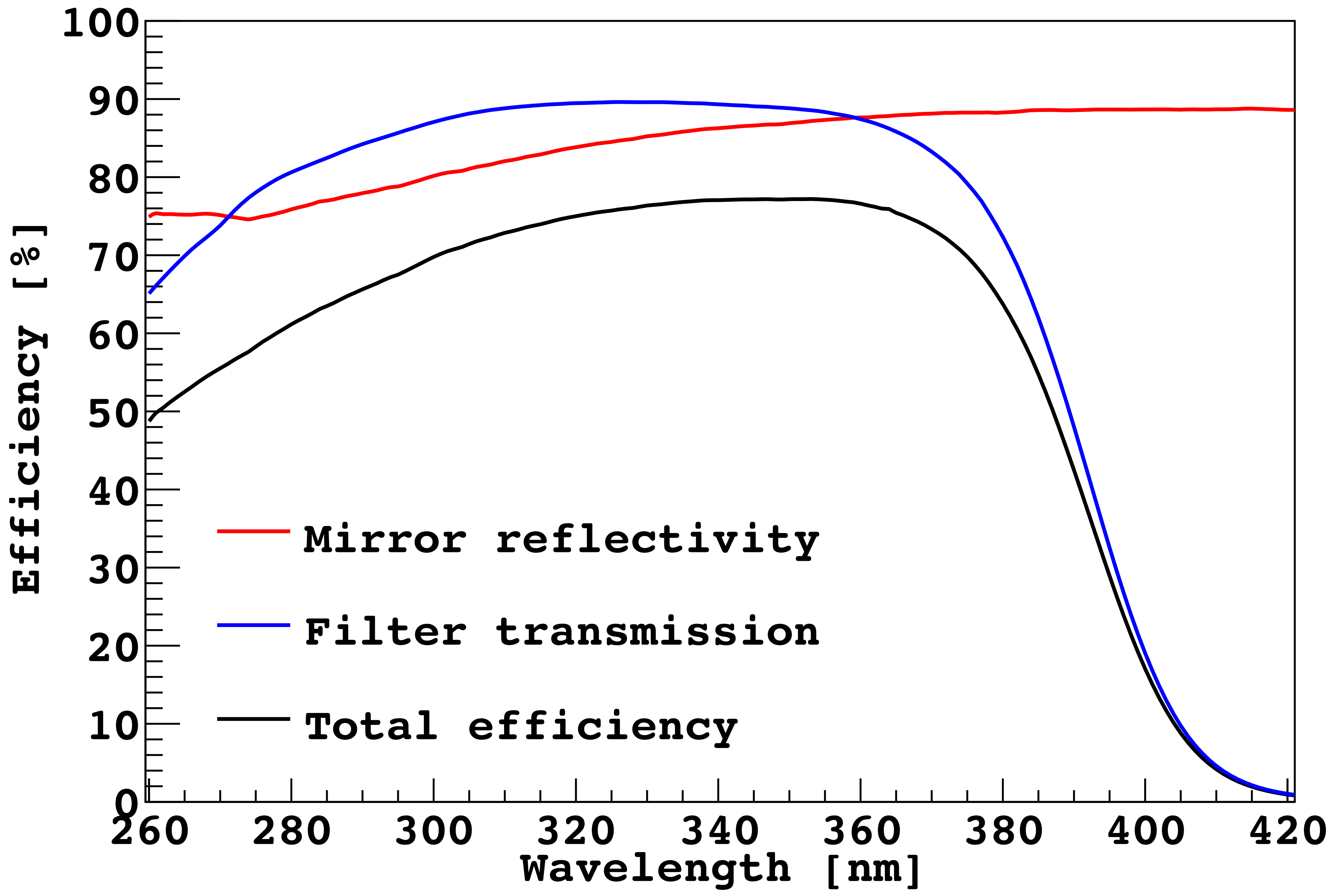


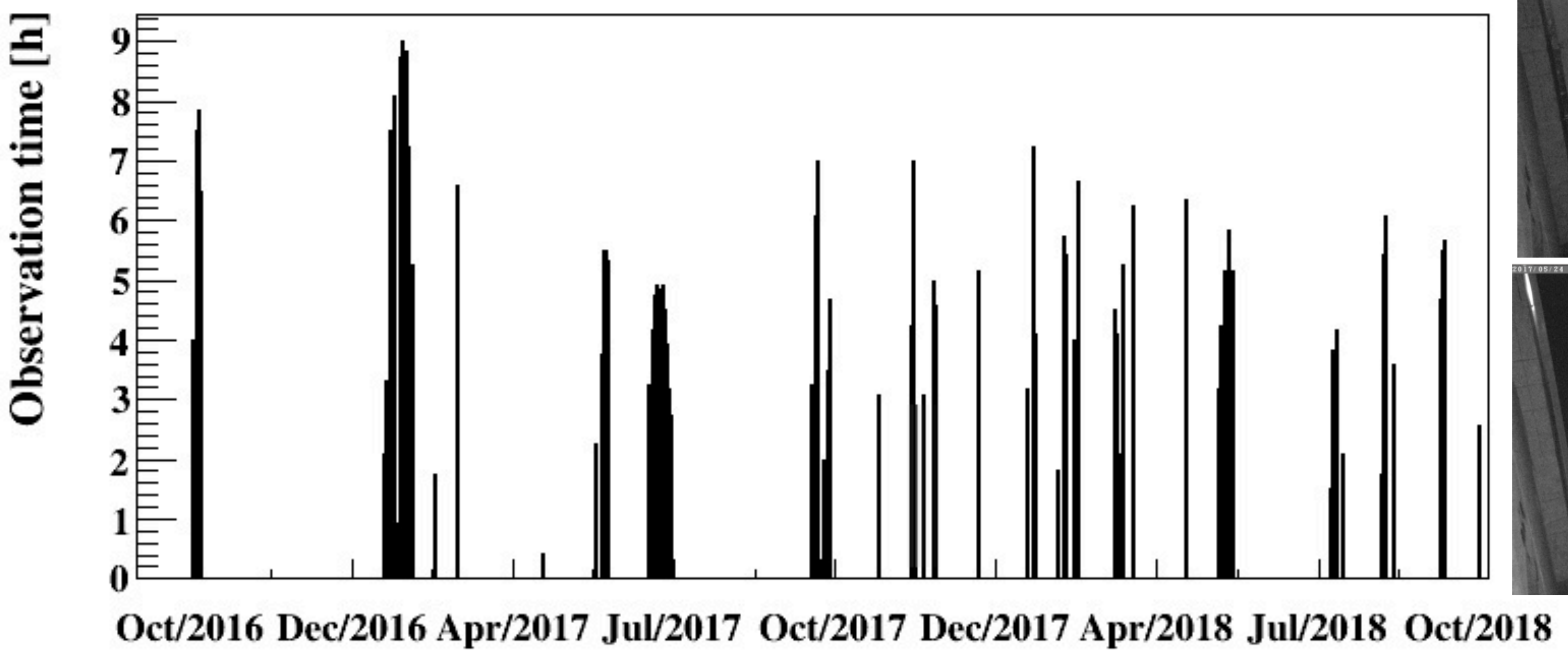
FAST
Fluorescence detector Array of Single-pixel Telescopes

The full-scale FAST telescope



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



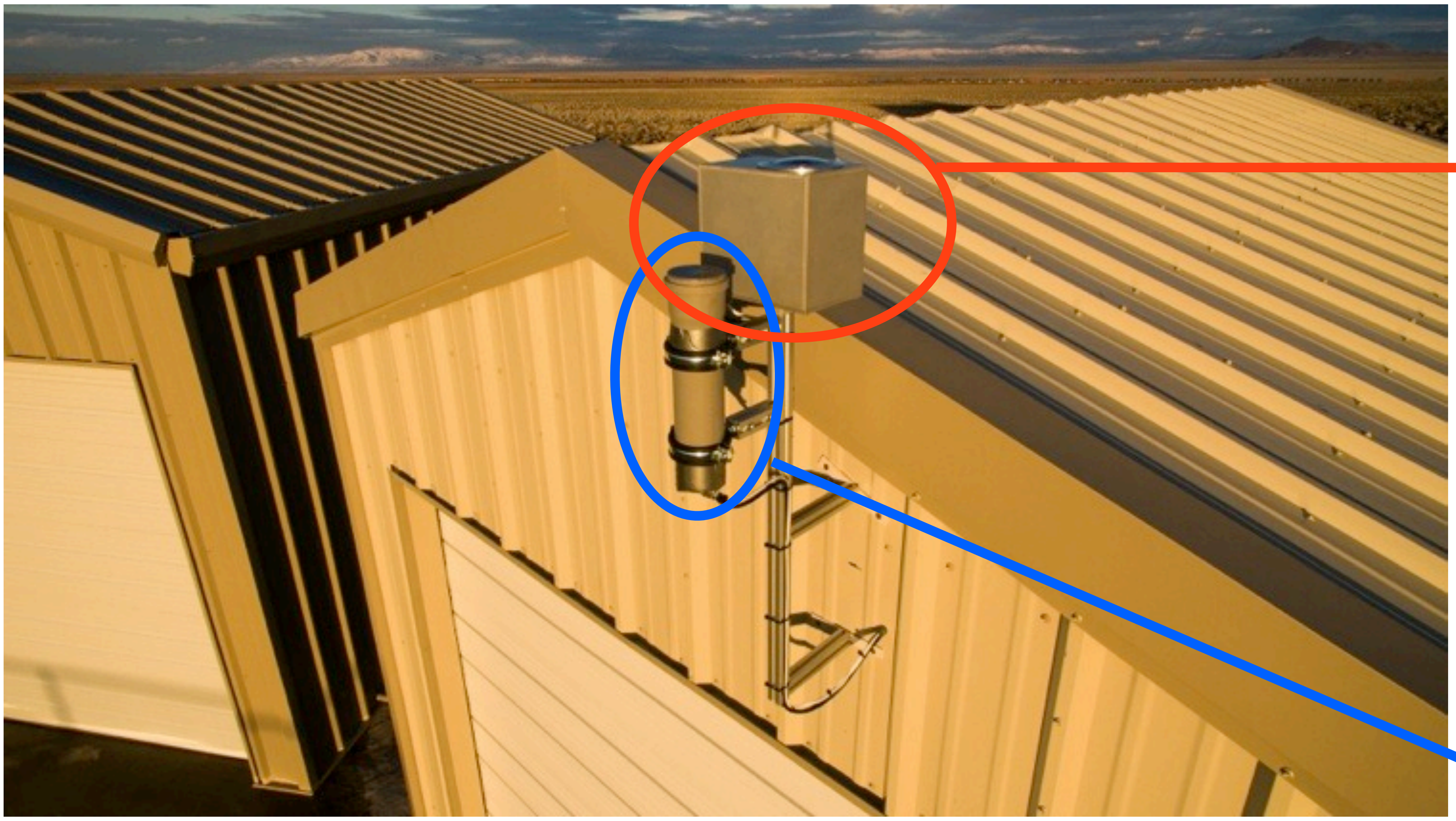


- 4 PMTs (20 cm, 8 dynodes R5912-03MOD, base E7694-01)
- 1 m² aperture of the UV band-pass filter (ZWB3), segmented mirror of 1.6 m diameter
- 3 telescopes has been installed to cover 30°× 90° FoV
  - remote operation and automatic shutdown
- **425 hours observation by October 2018**

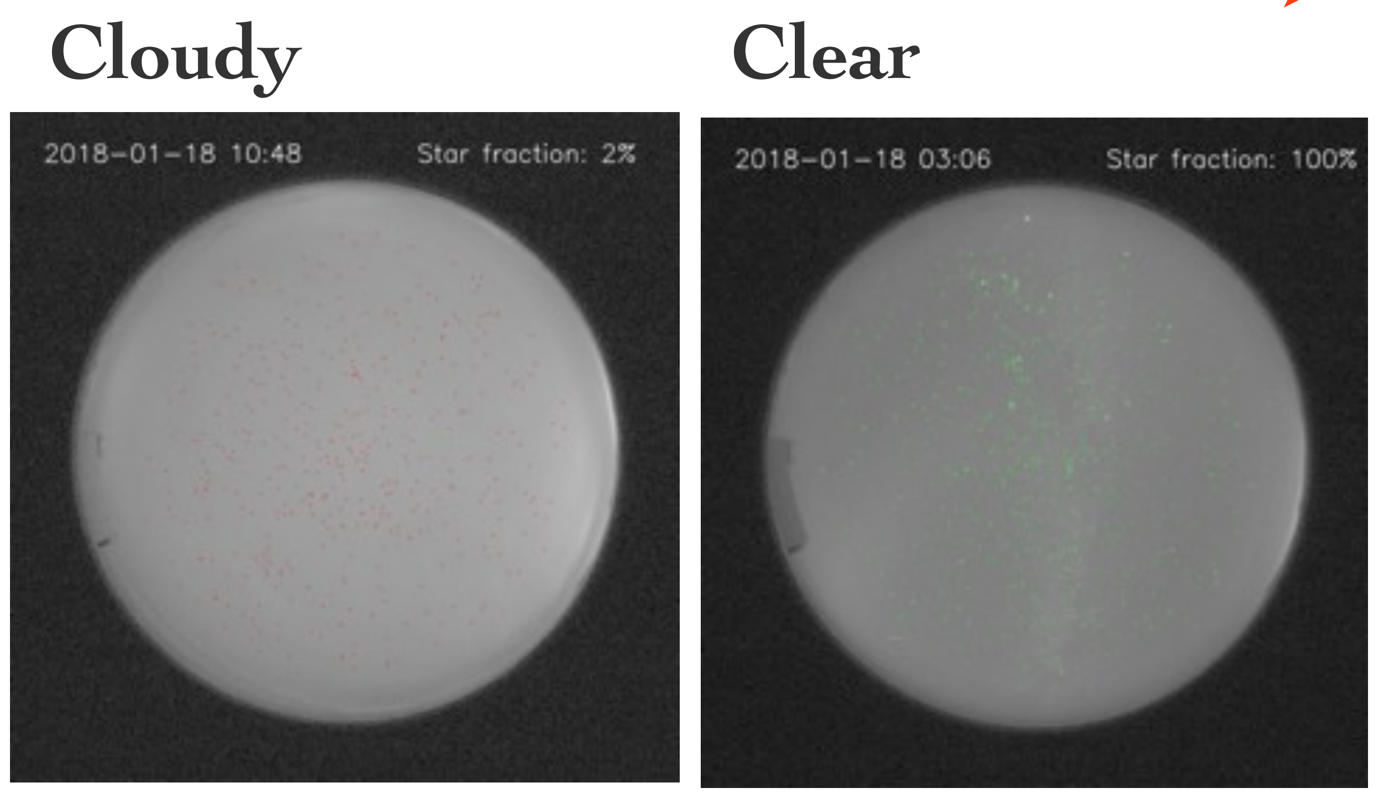
Real-time night sky monitoring

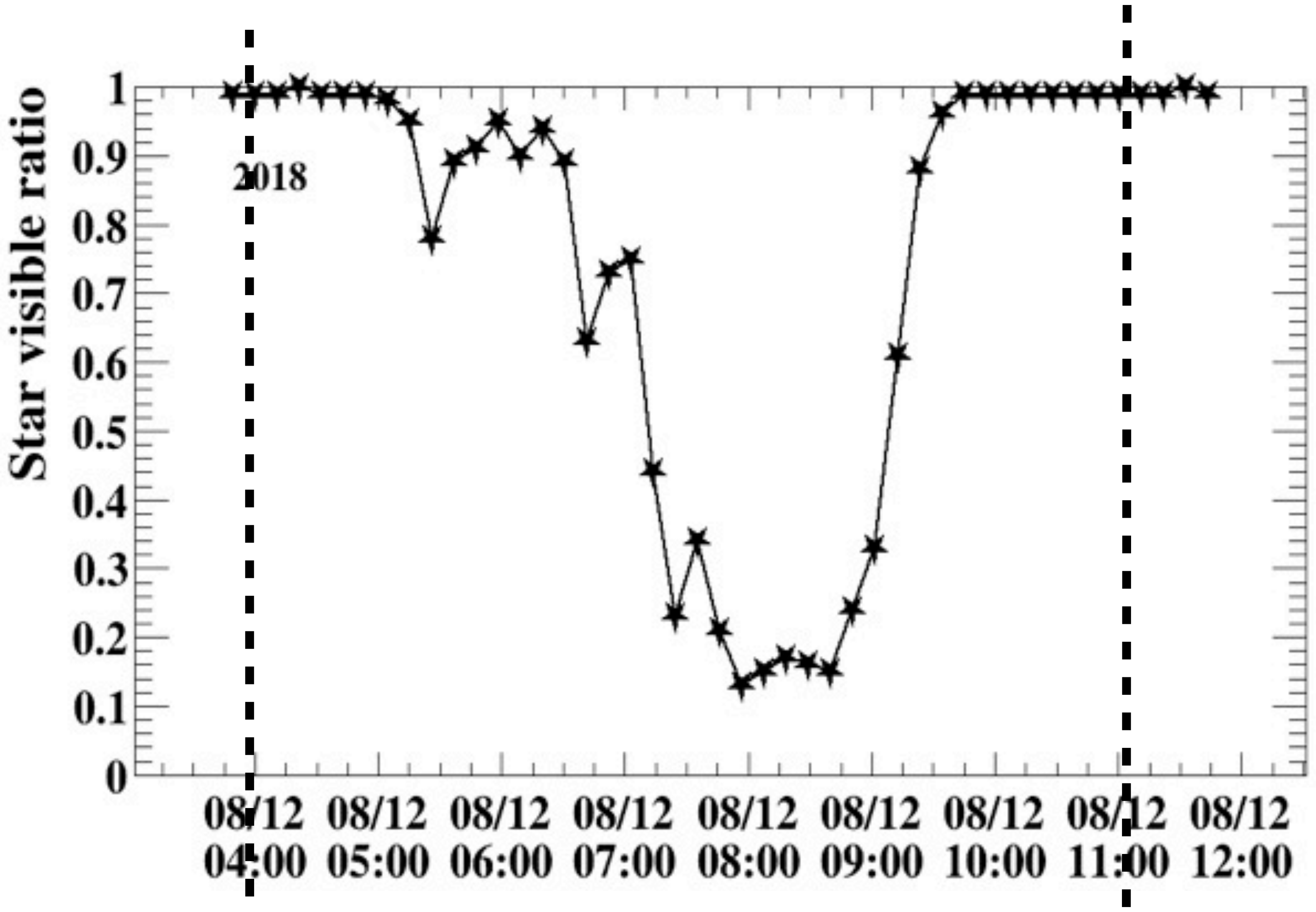
Fluorescence detector Array of Single-pixel Telescopes

Work: Dusan Mandat, Ladislav Chytka

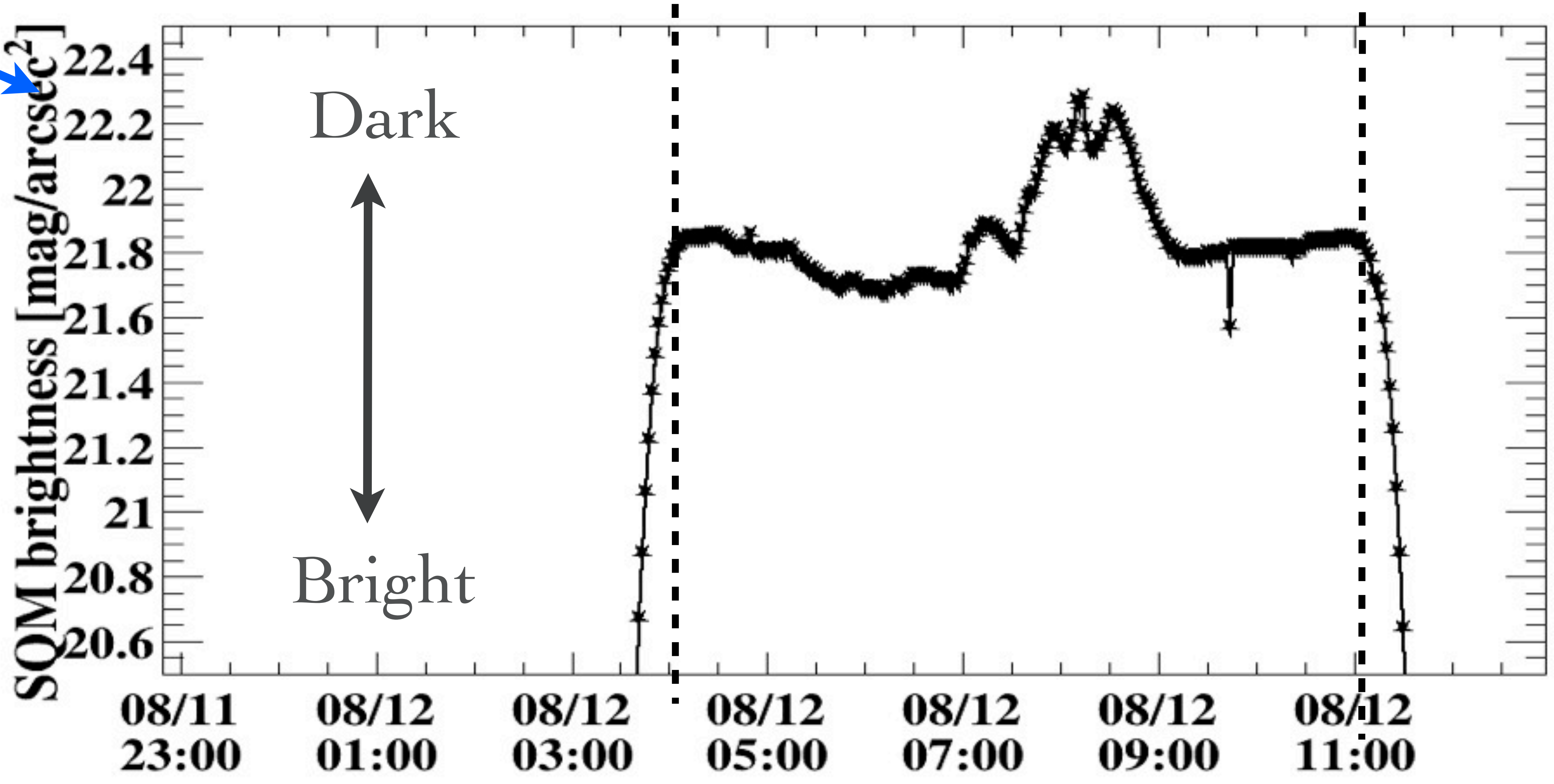


All sky camera

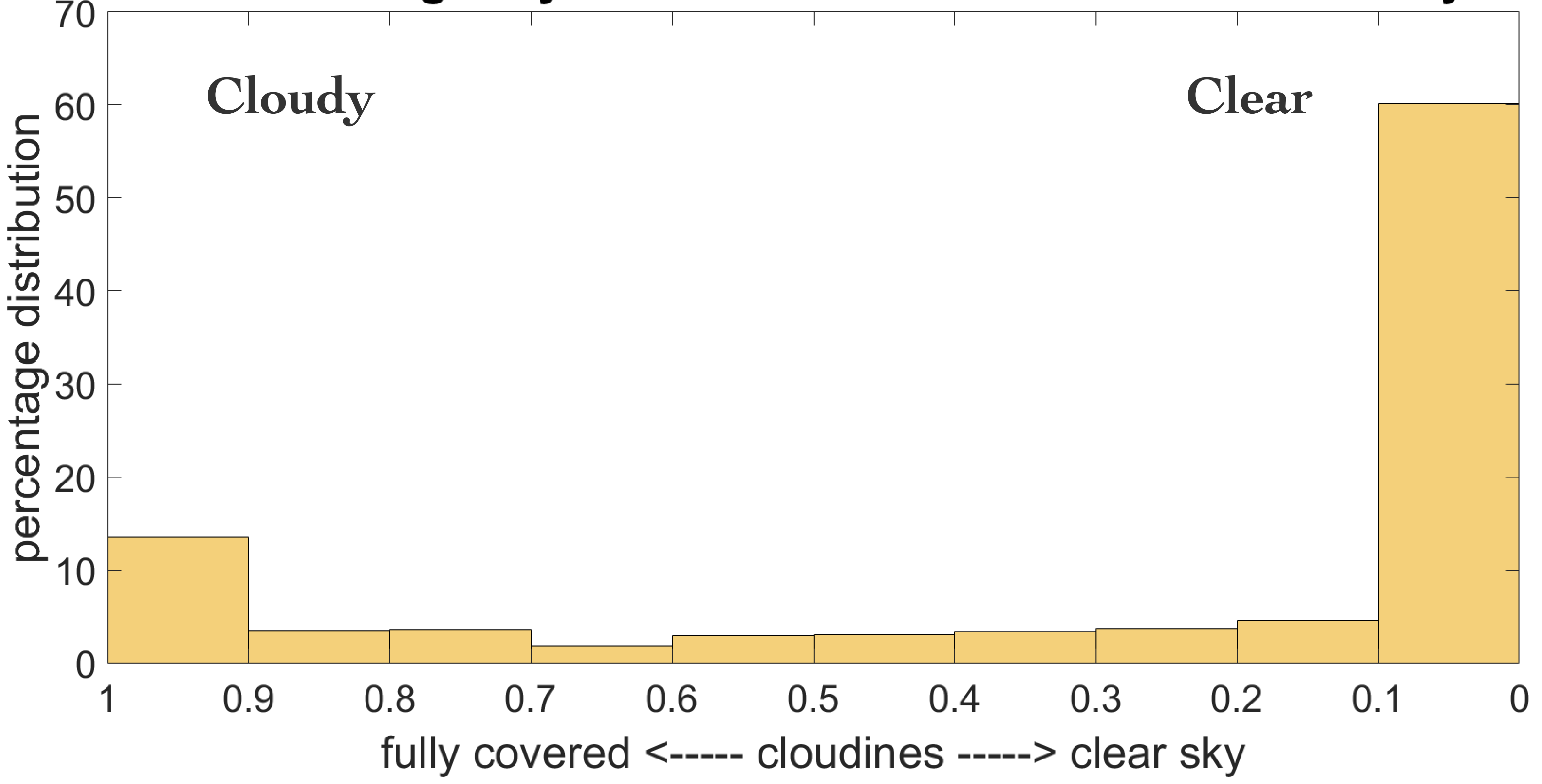




Sky quality monitor



Moonless nightsky cloudiness distribution : 65 % of clear sky

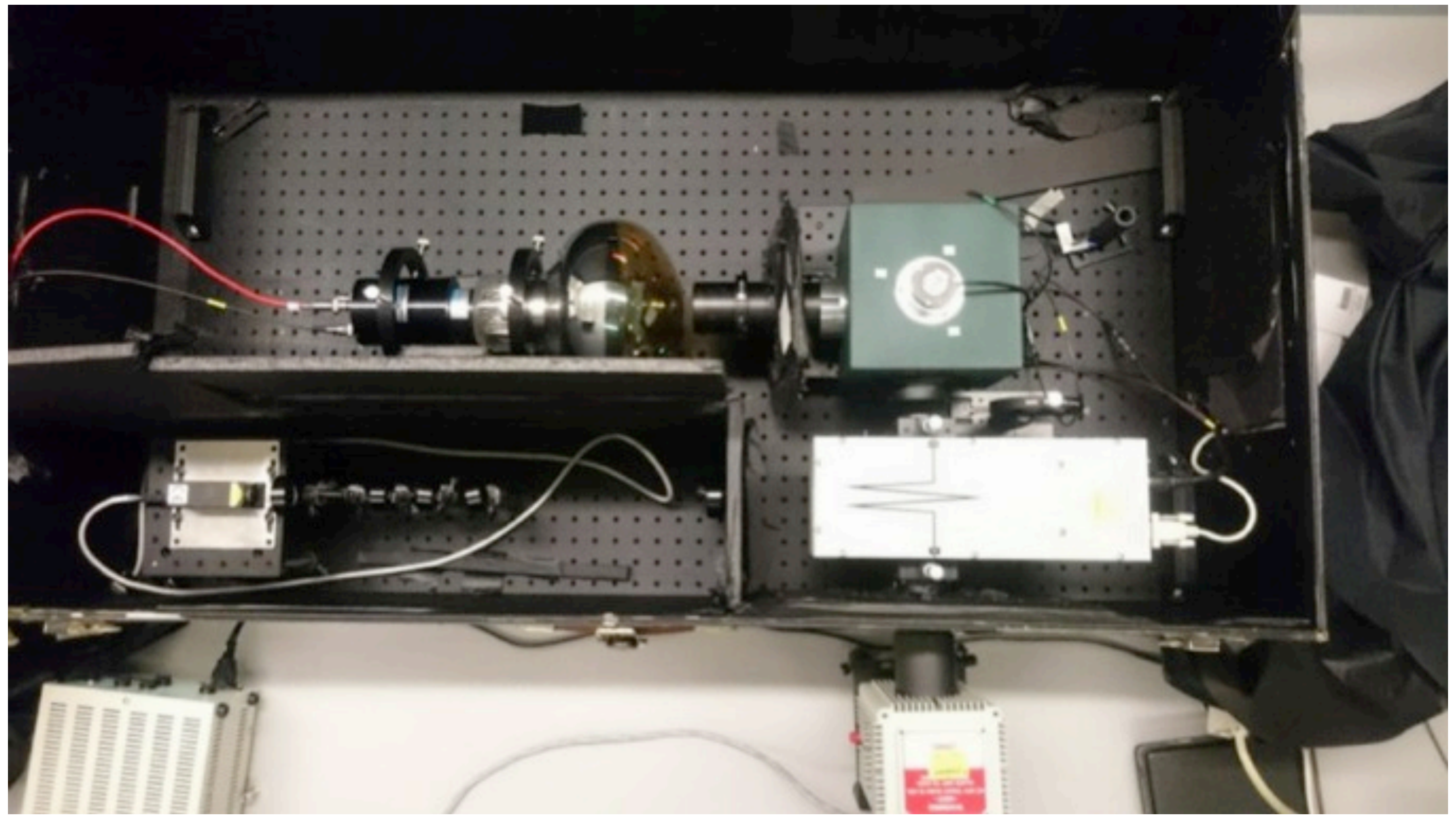


FAST
Fluorescence detector Array of Single-pixel Telescopes

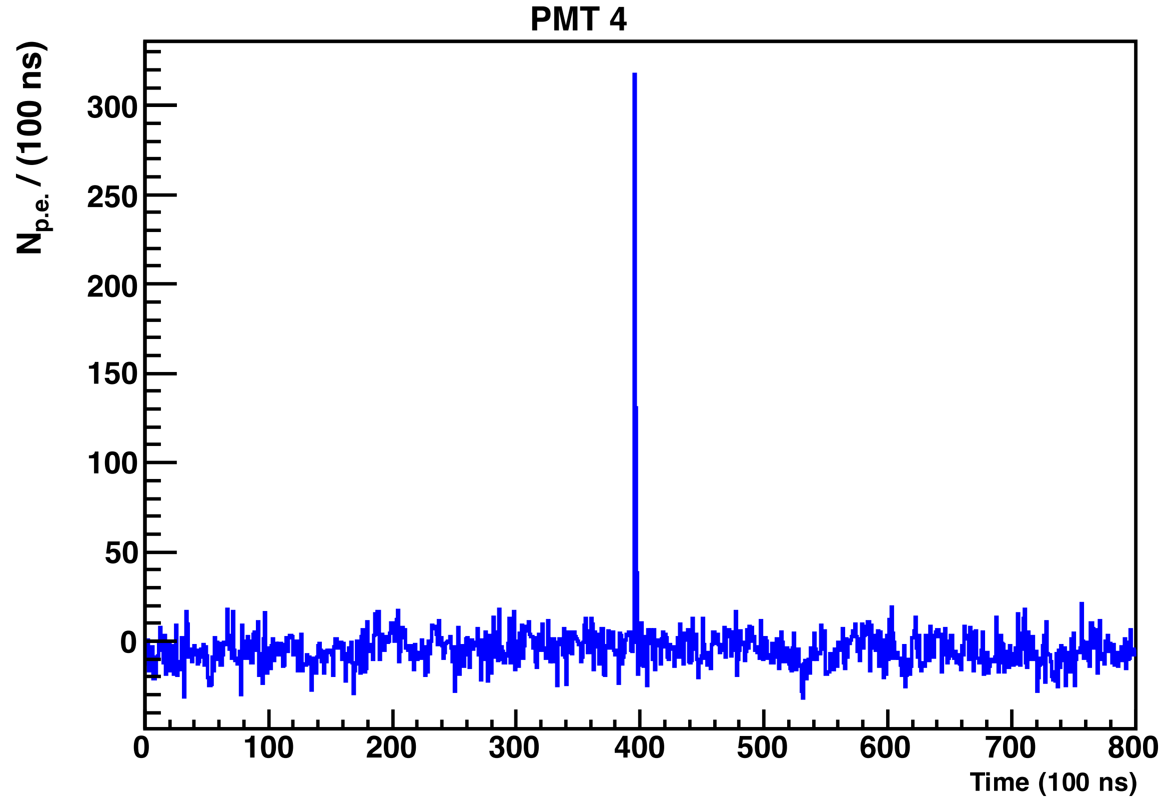
Calibrations for FAST

Absolute calibration in laboratory

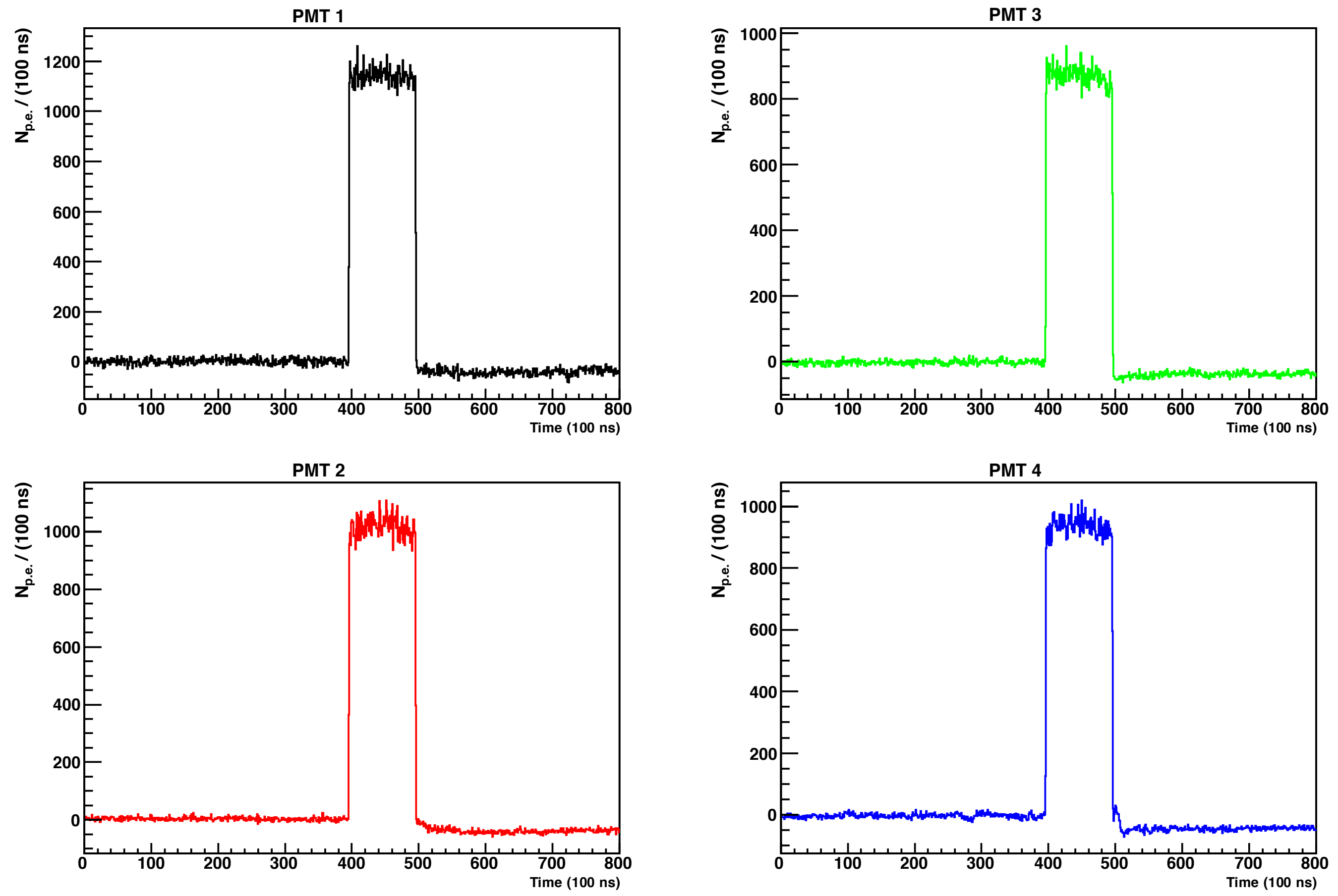
Work: Max Malacari, John Farmer, Dusan Mandat, Petr Hamal



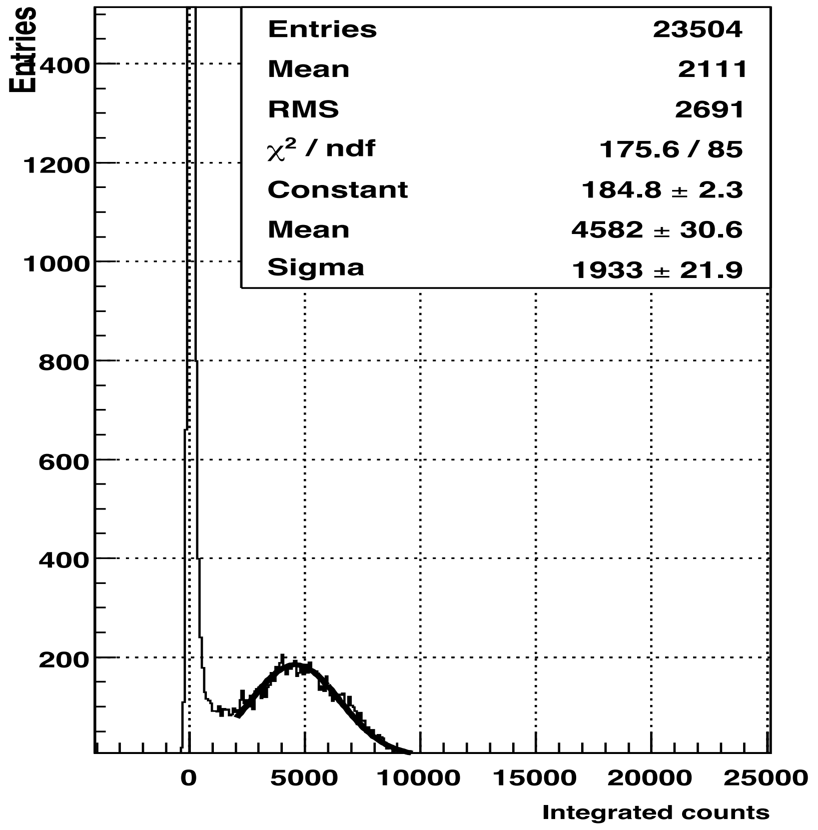
YAP pulser ($YAlO_3$:Ce scintillator + ^{241}Am source) attached on each PMT surface



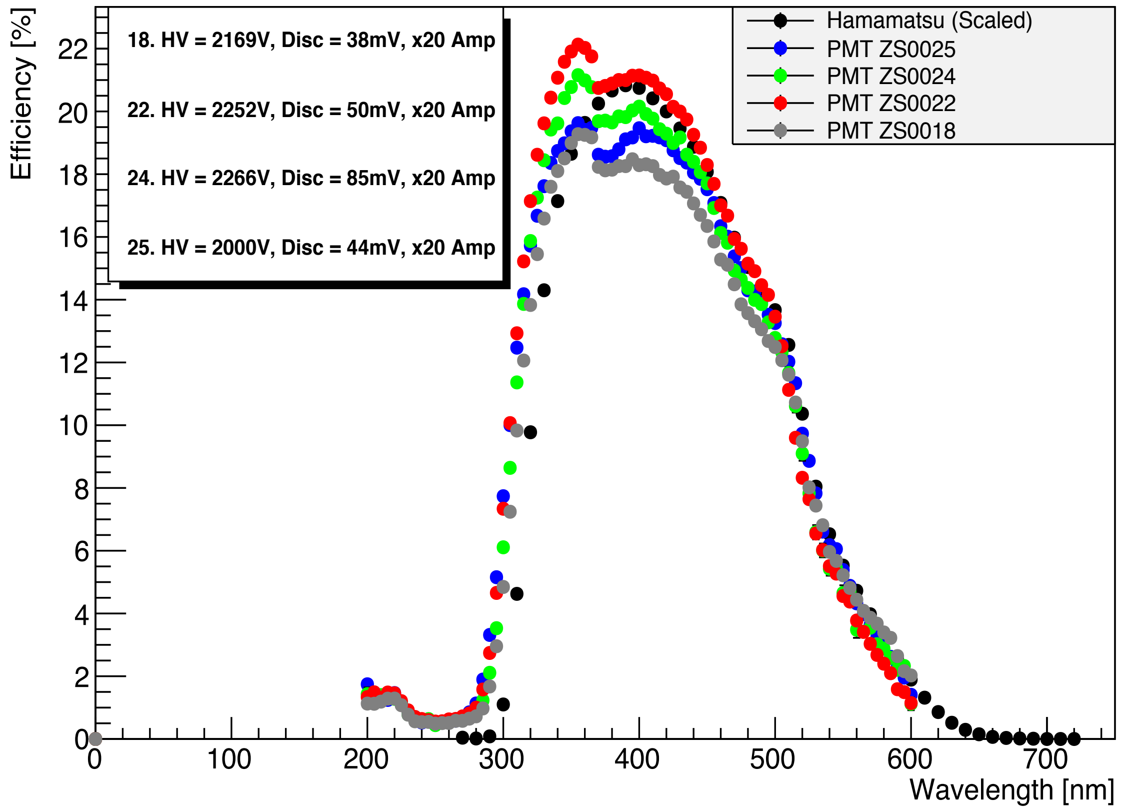
Ultraviolet LED illuminating the front of the camera

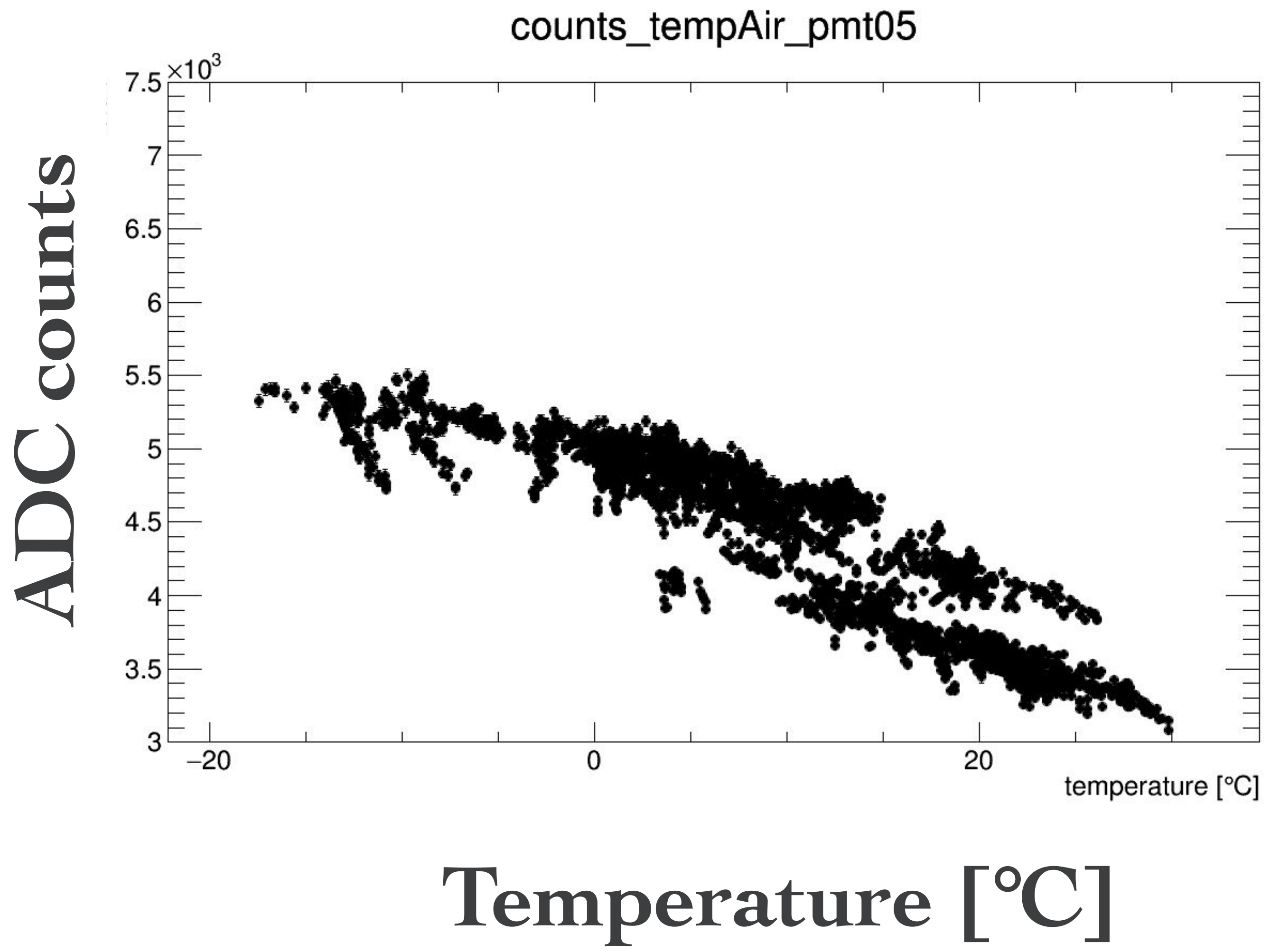


Single photo electron

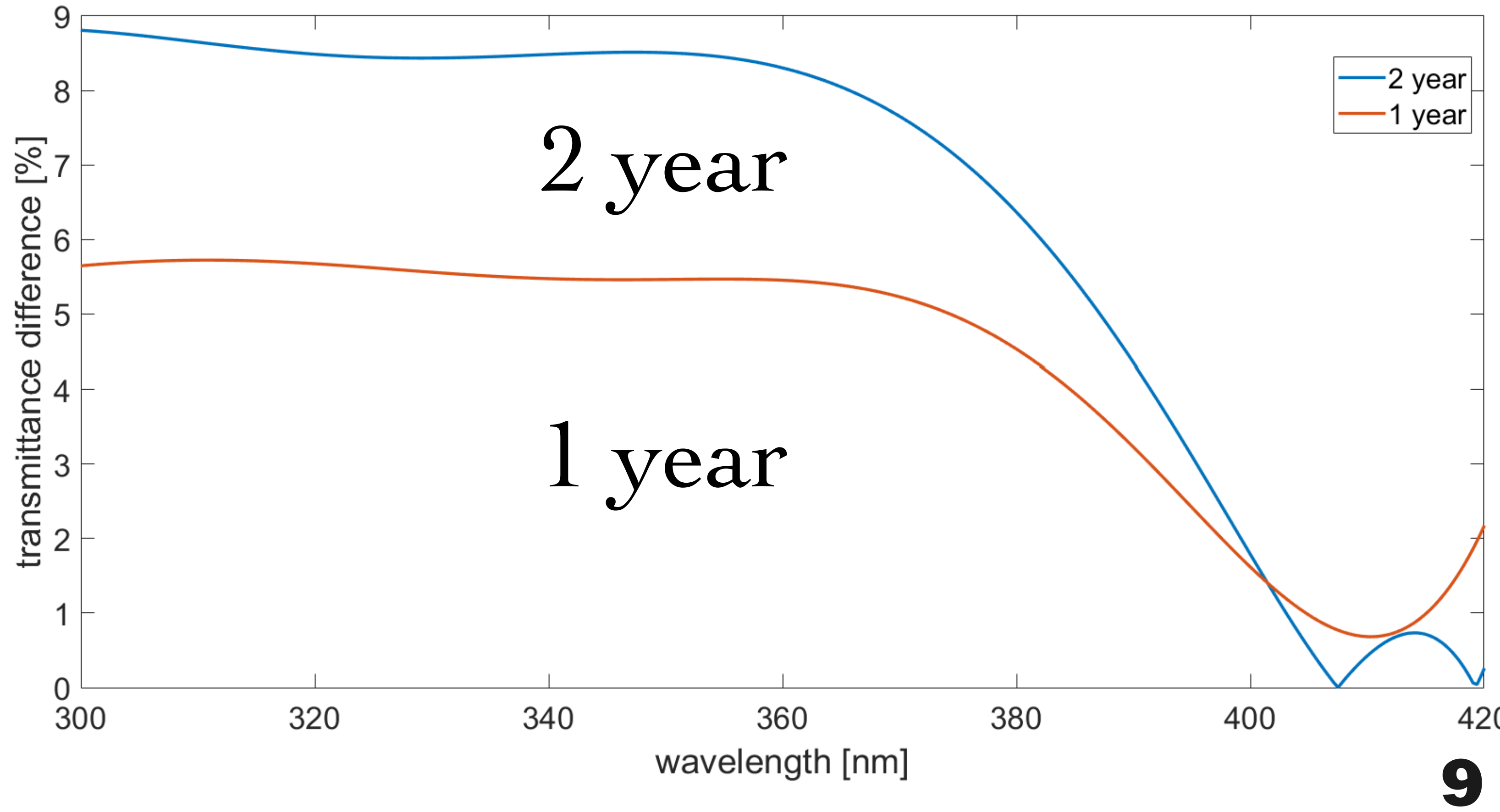


Detection efficiency



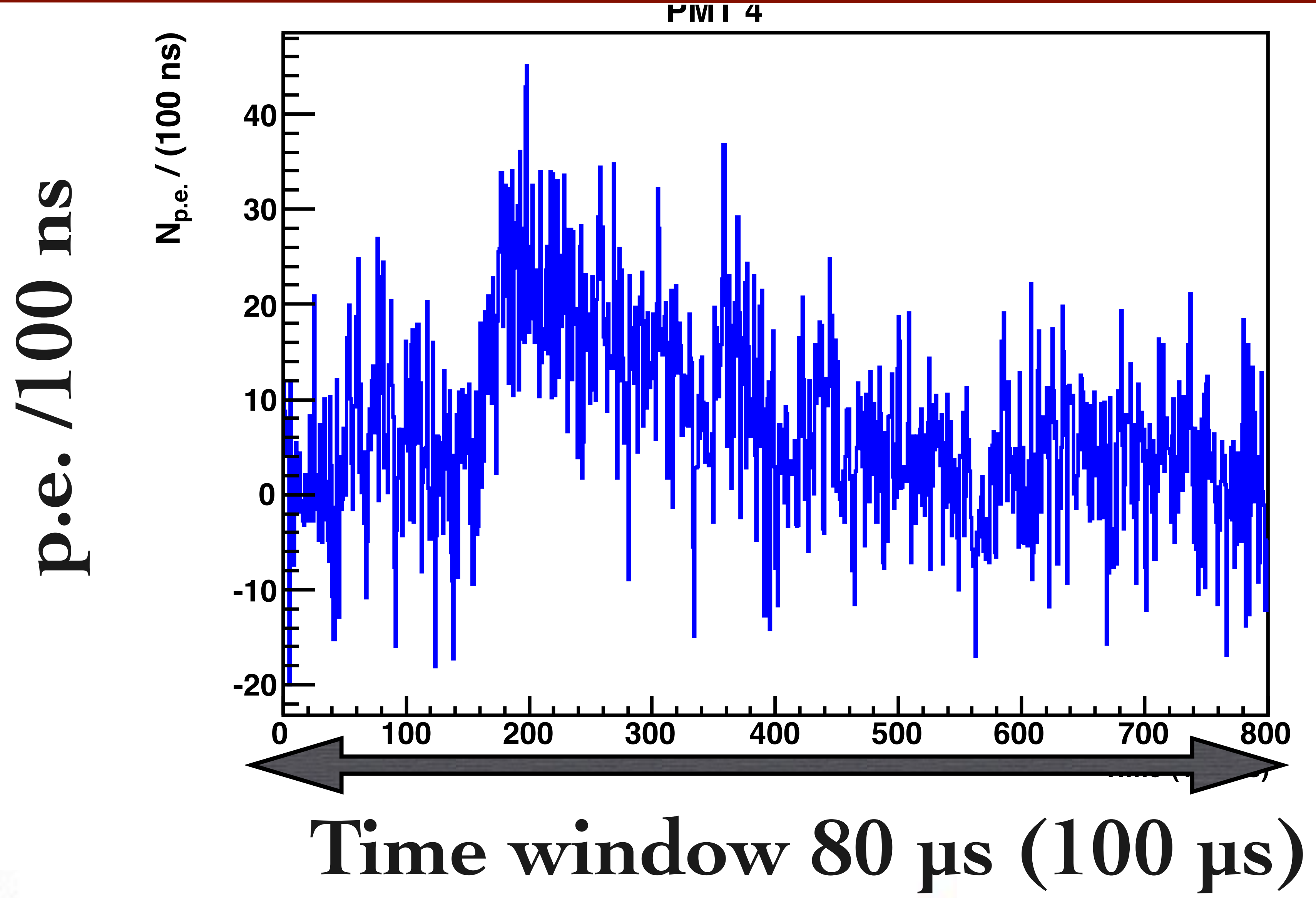


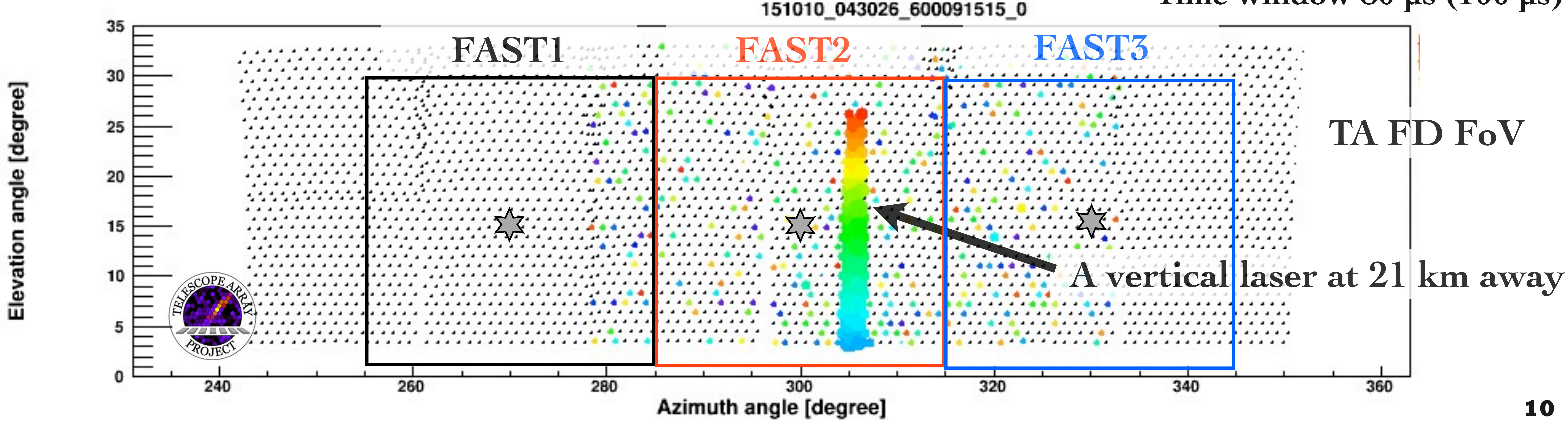
Filter transmittance difference



DAQ setup for the FAST telescopes

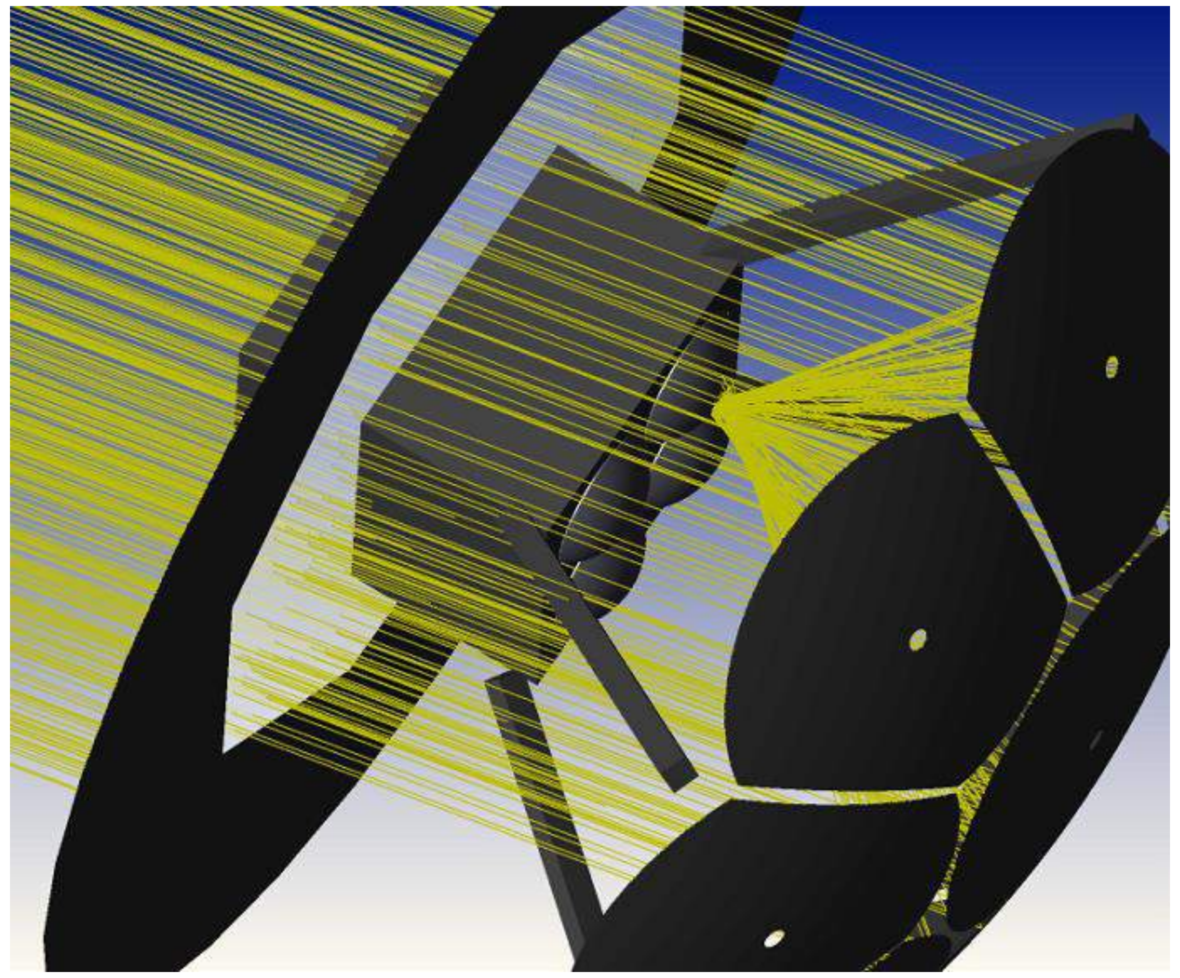
- Receiving the external triggers from TA FD
  - 50 MHz sampling and 14 bits, sum up 5 bins to be 100 ns
- Common field-of-view (FoV) with FAST and TA FD
  - Observe ultraviolet vertical laser at the distance of 21 km.
    - Implemented **internal trigger** (2 adjacent PMTs), successful to detect a vertical laser in a test operation



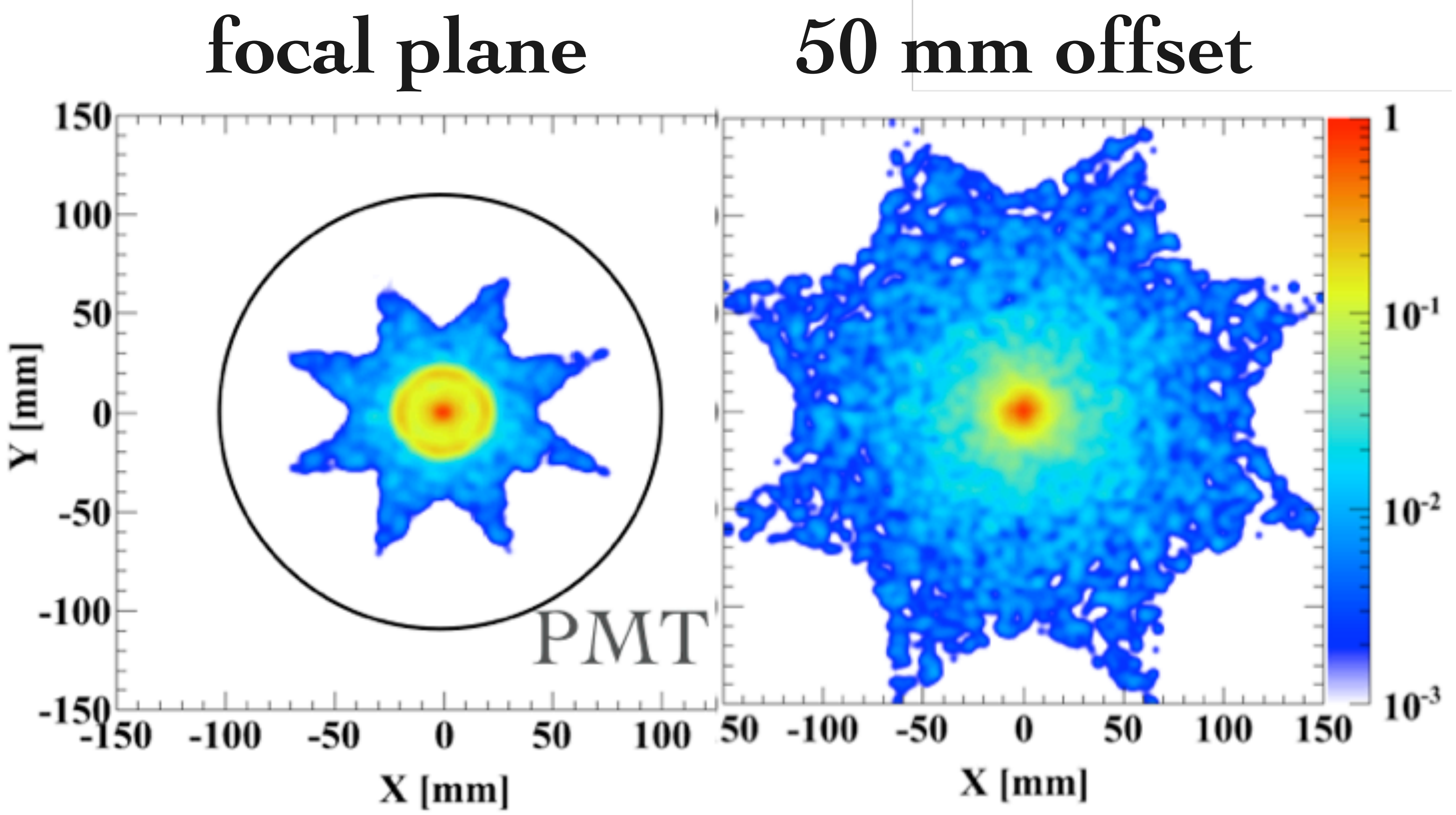


Data/MC comparison with vertical UV laser

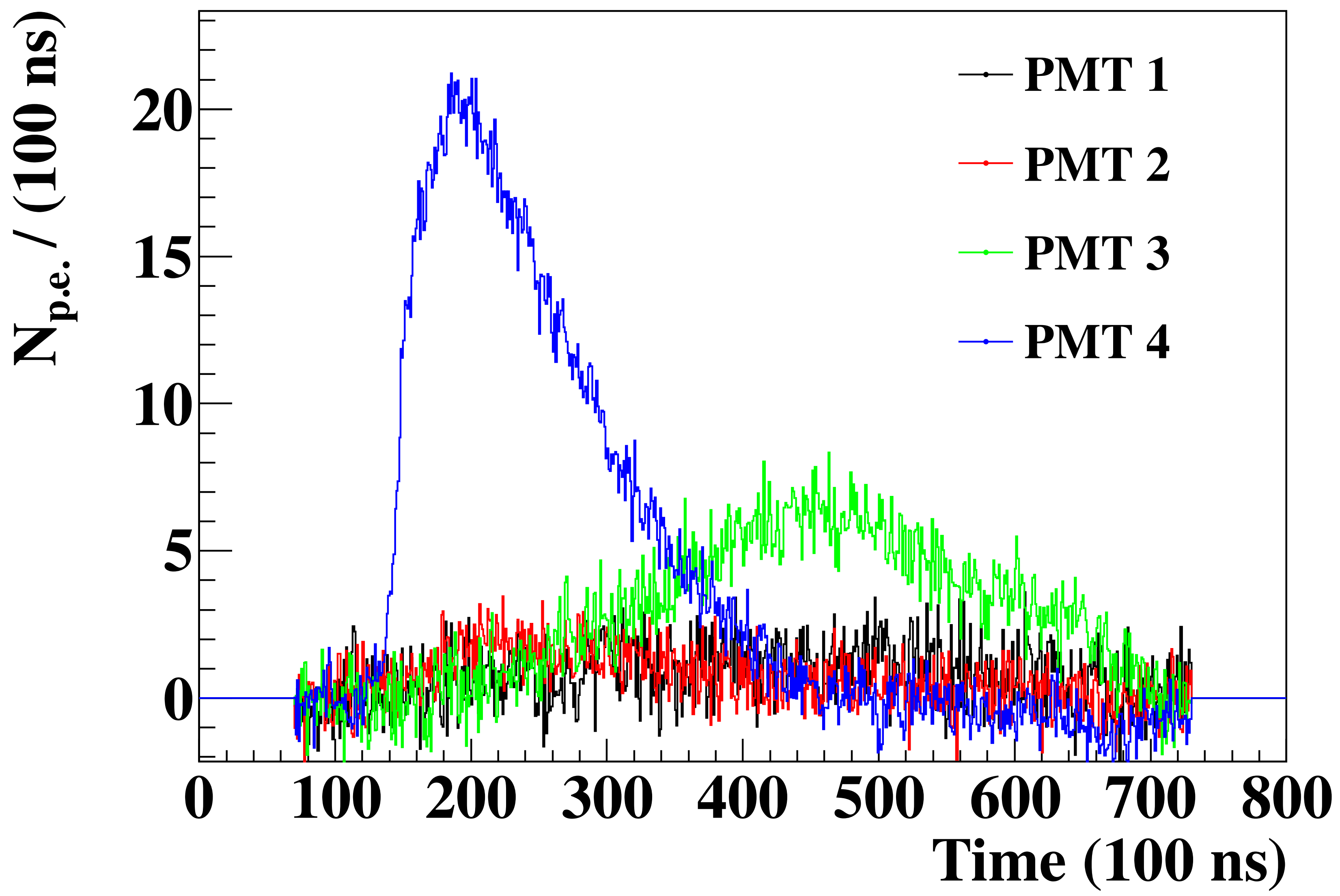
Work: Miroslav Pech, Max Malacari



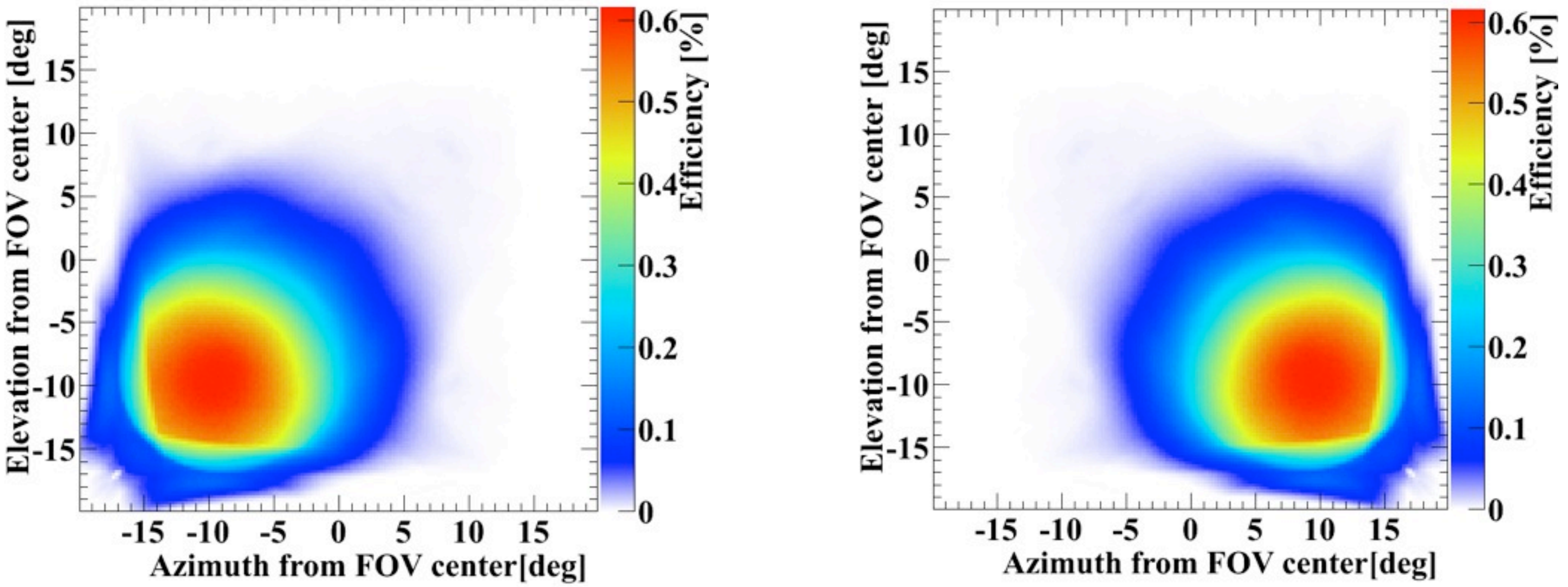
Spot-size

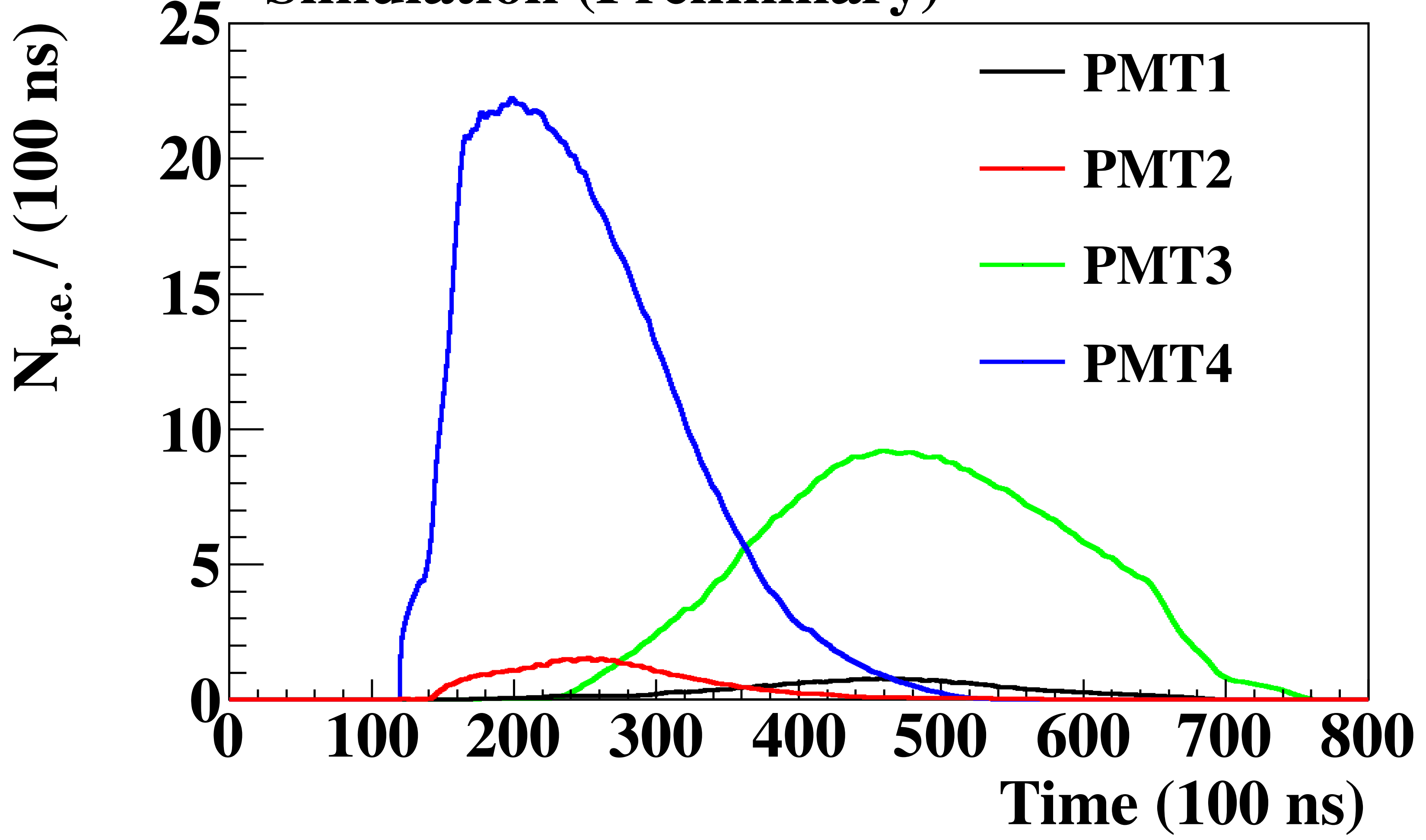


A UV vertical laser at 21 km away



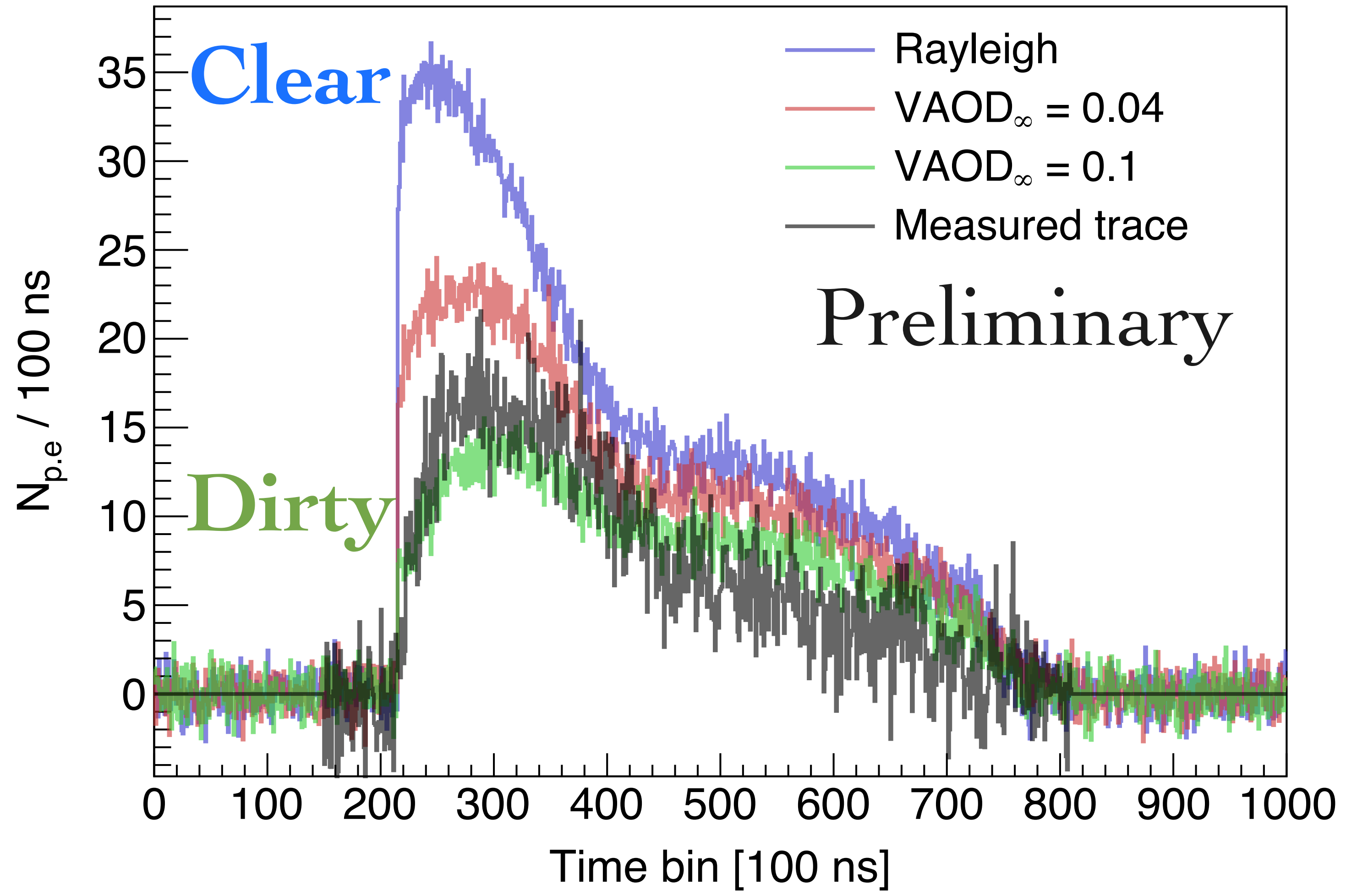
Directional characteristic (PMT2) (PMT 4)

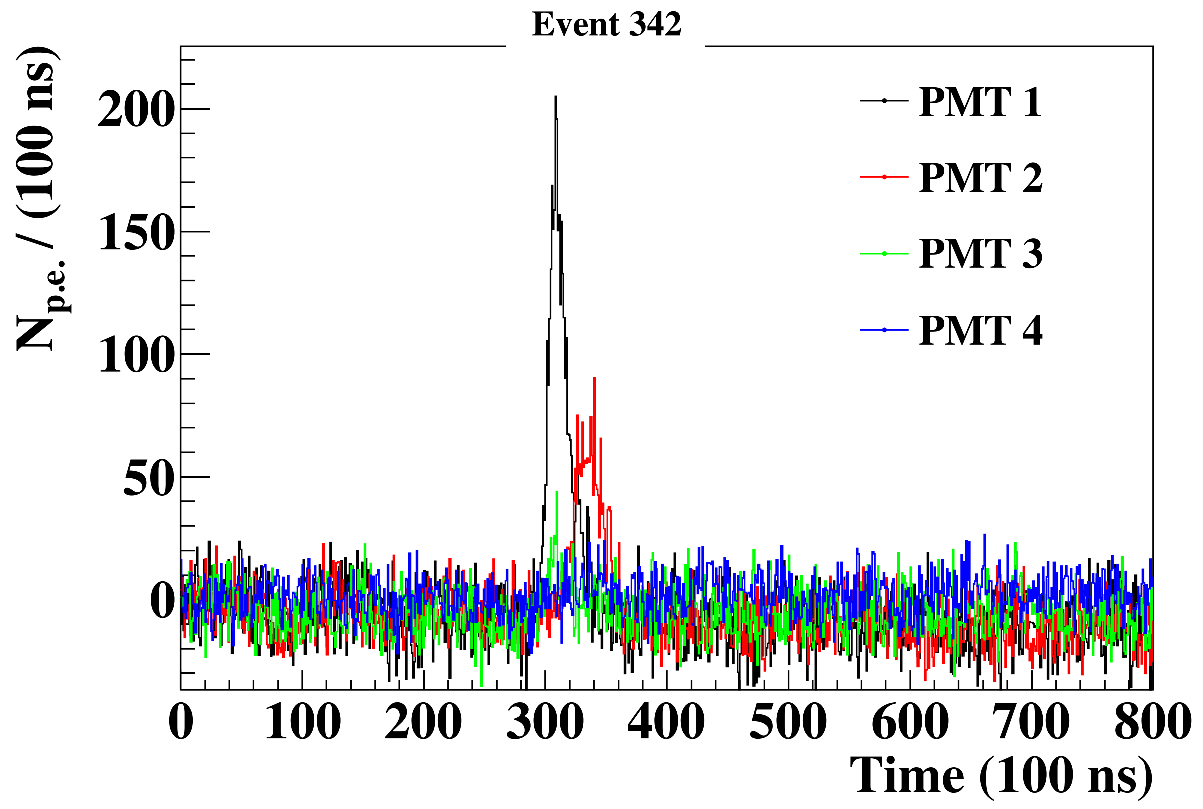




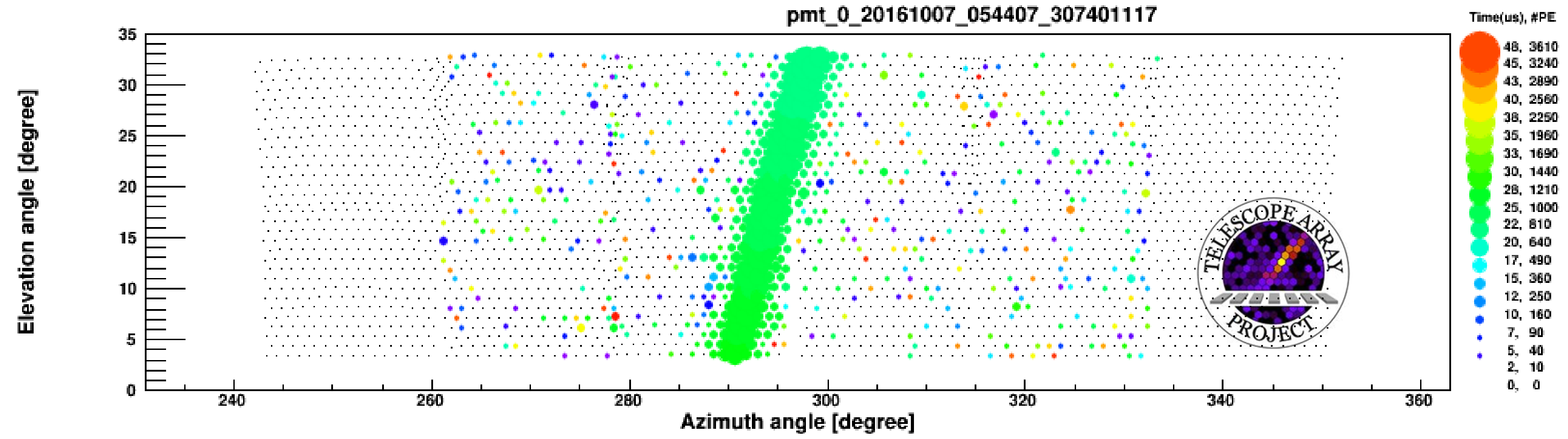
Atmospheric monitoring, UHECR detections

Atmospheric monitor





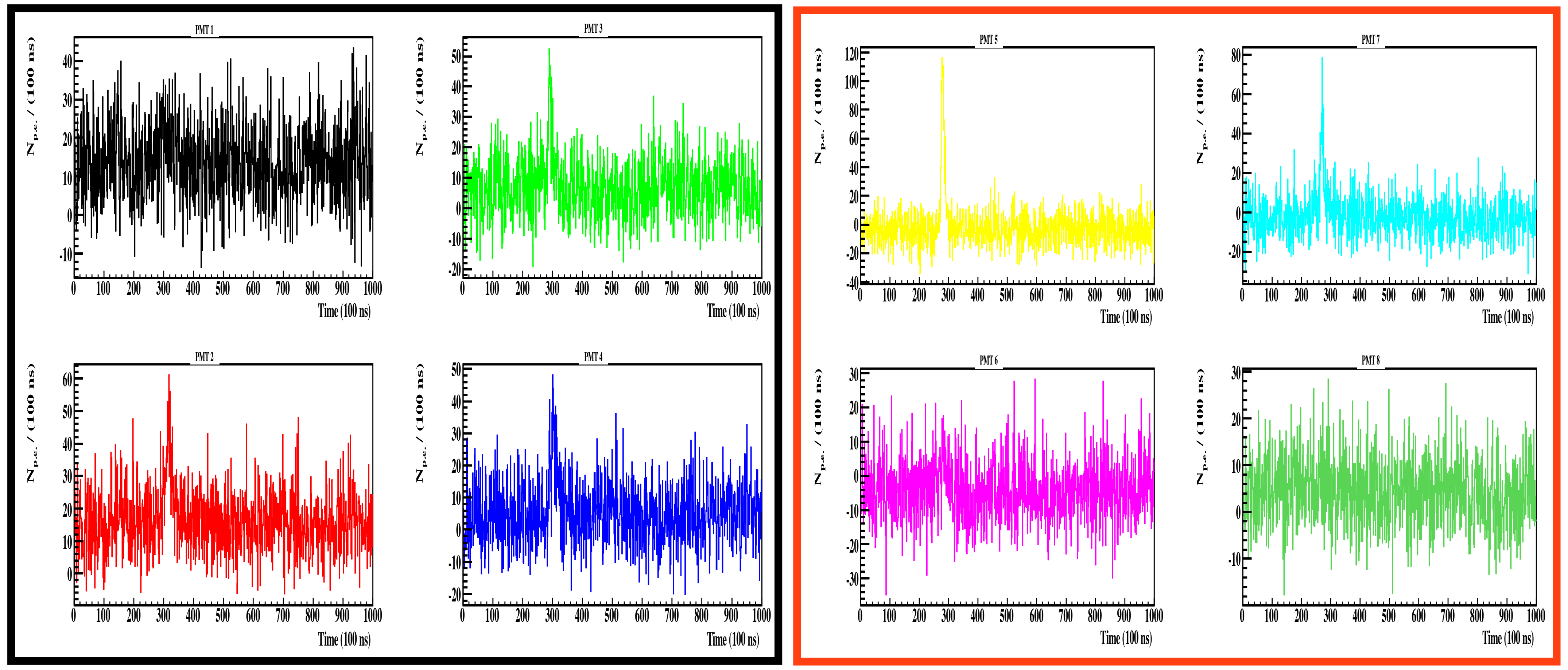
E: 4 EeV, R_p: 3.0 km
(Preliminary)

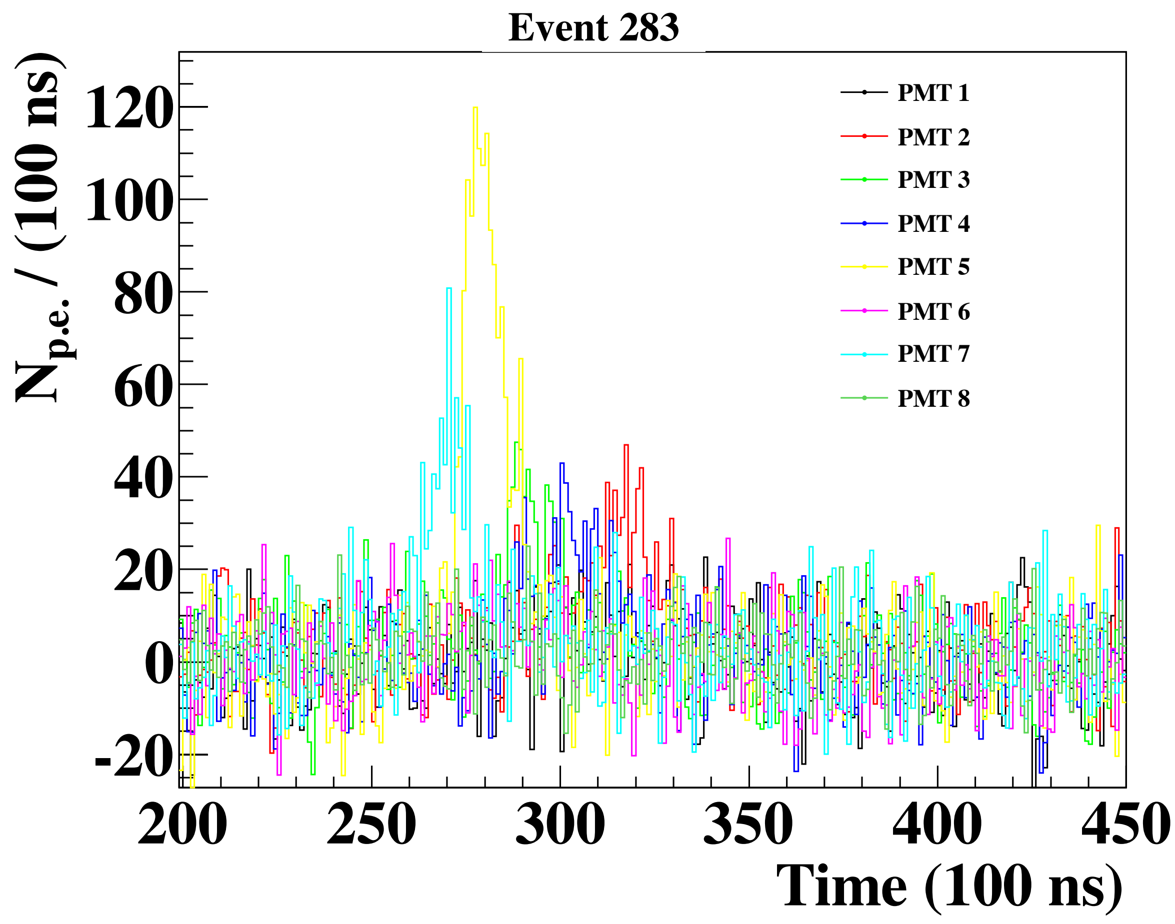


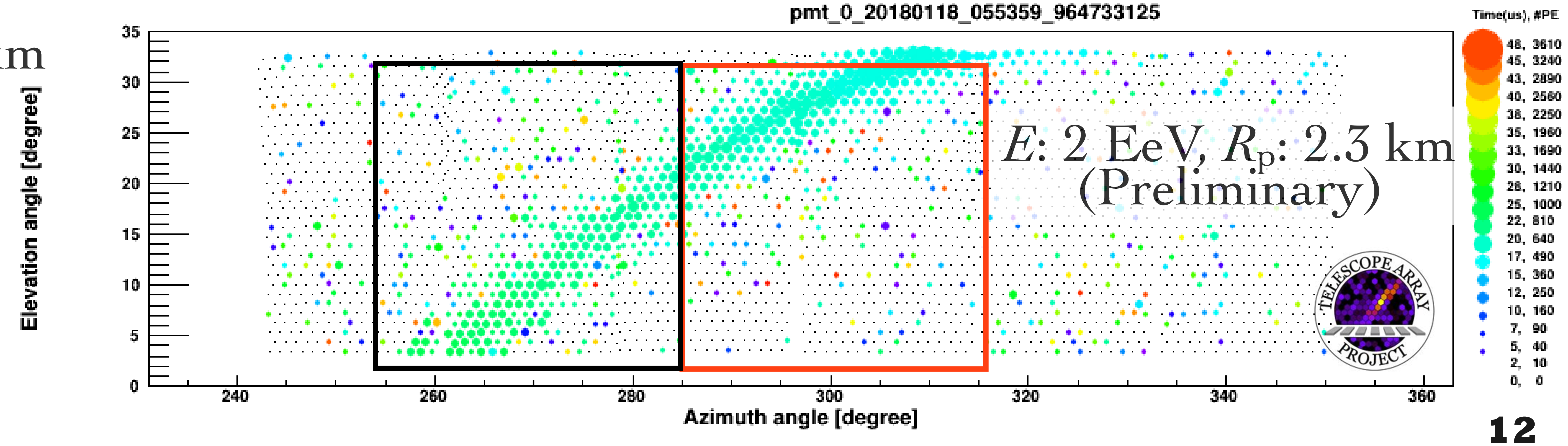
UHECR event search

Work: Max Malacari, John Farmer

25 events (201 hours), in time coincidence with TA FD and significant signals of > 2PMTs with FAST



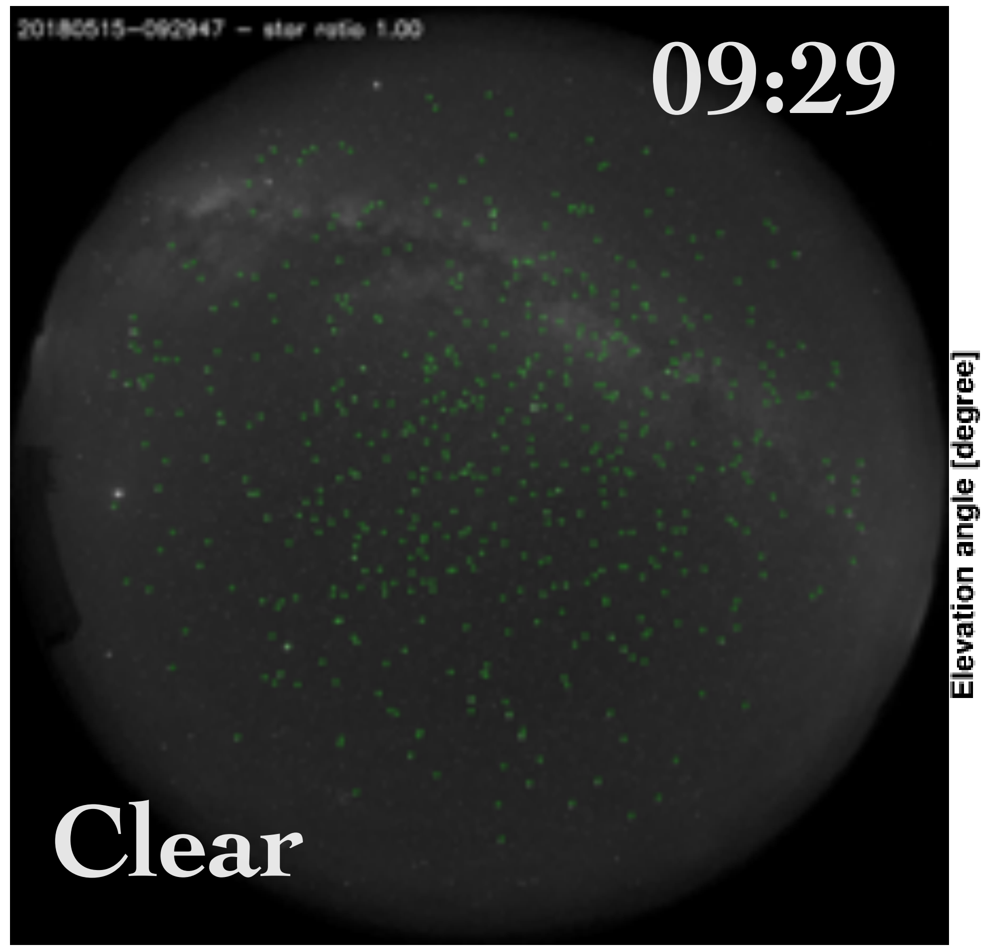




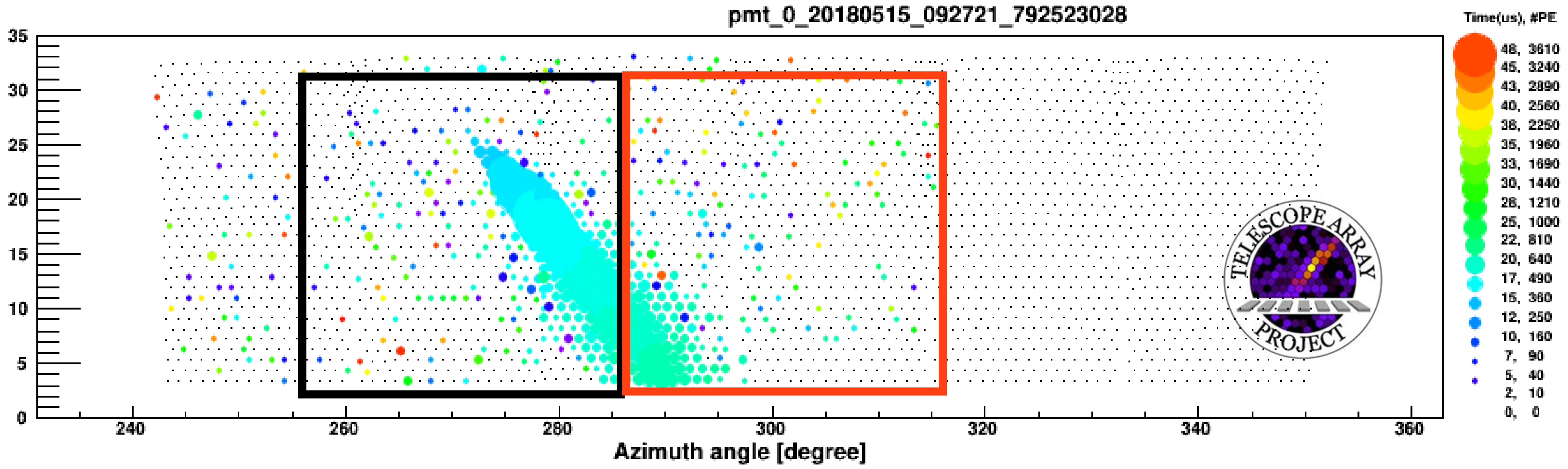
E: 2 EeV, R_p: 2.3 km
(Preliminary)

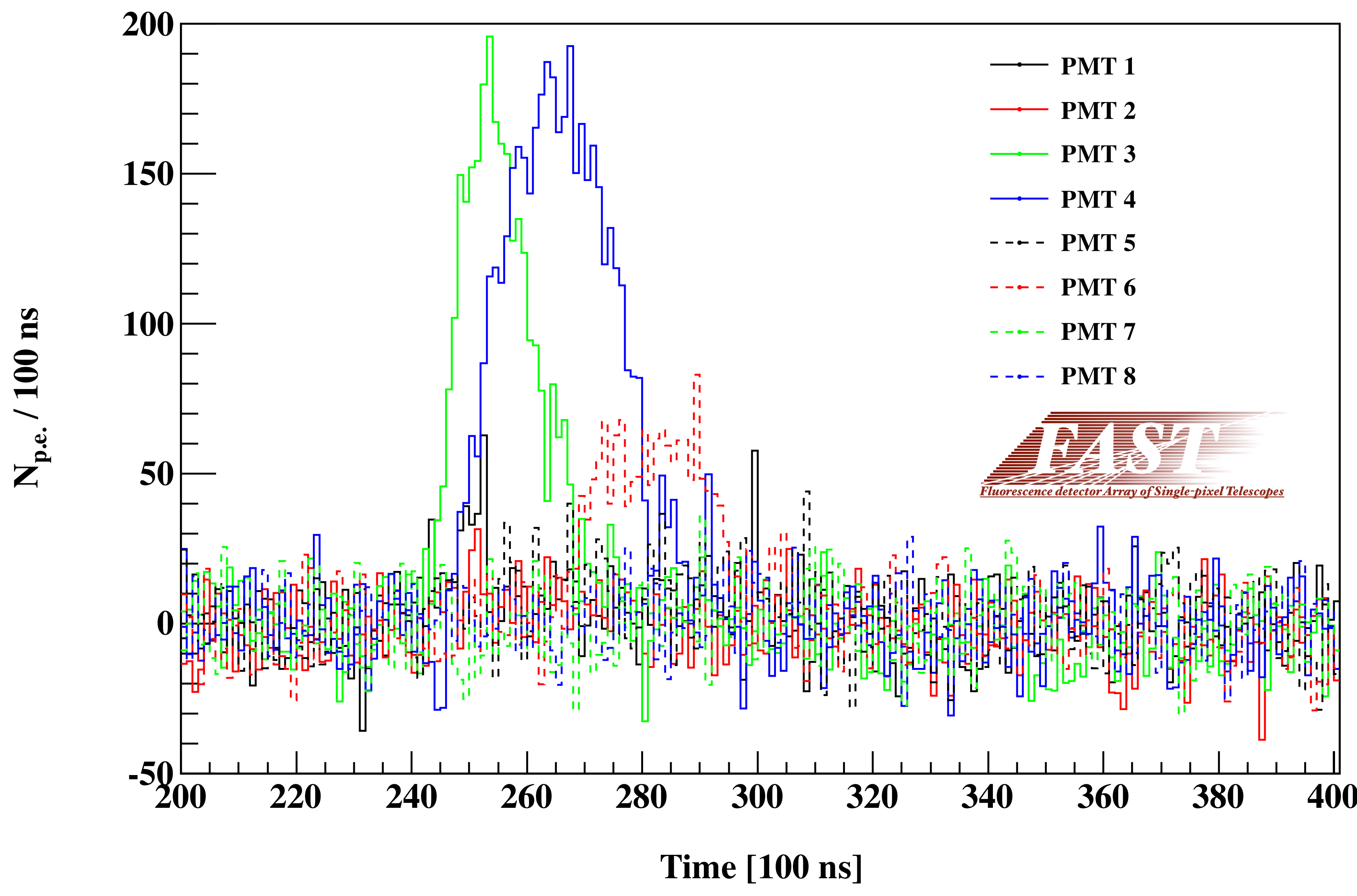
The highest event

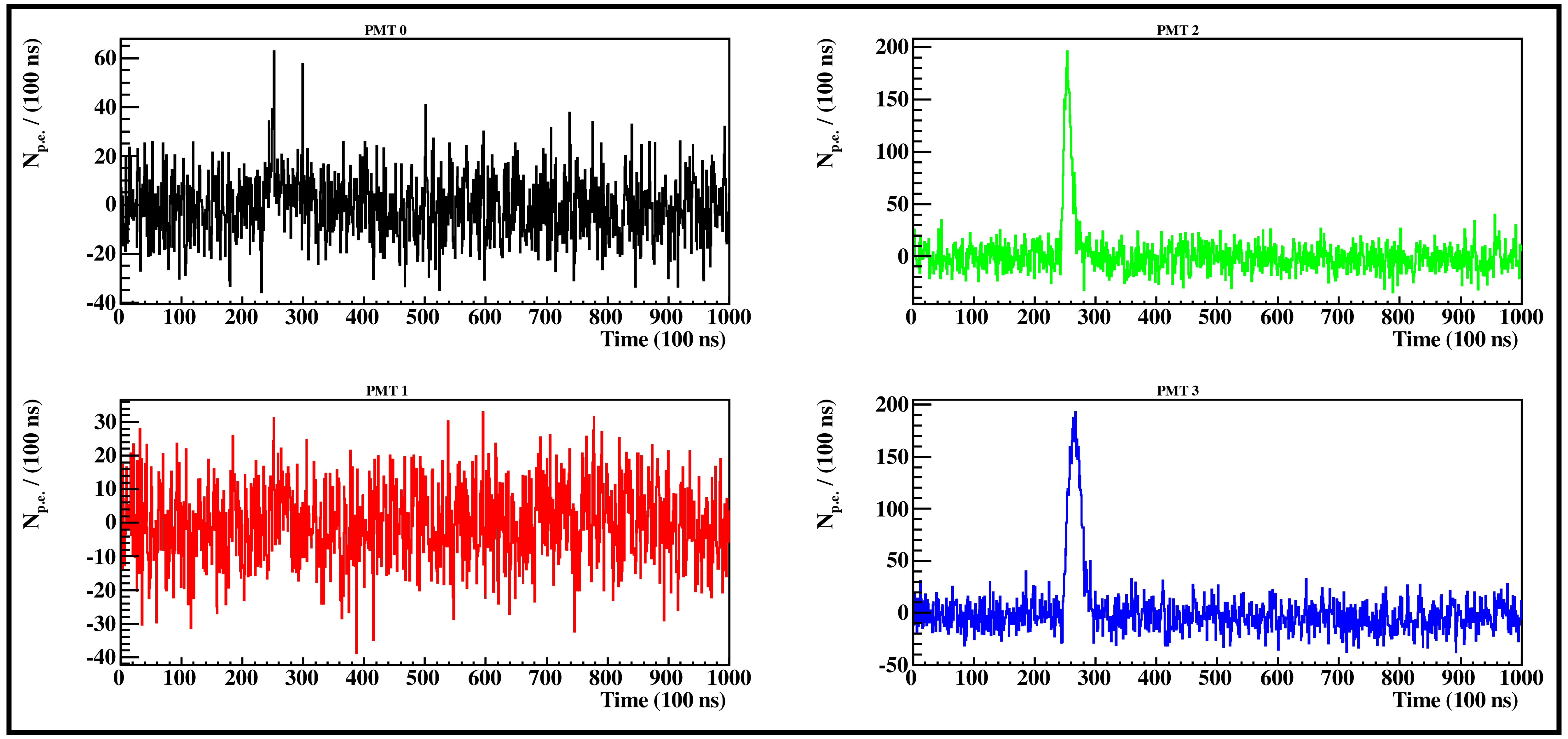
2018/May/15 09:27:21

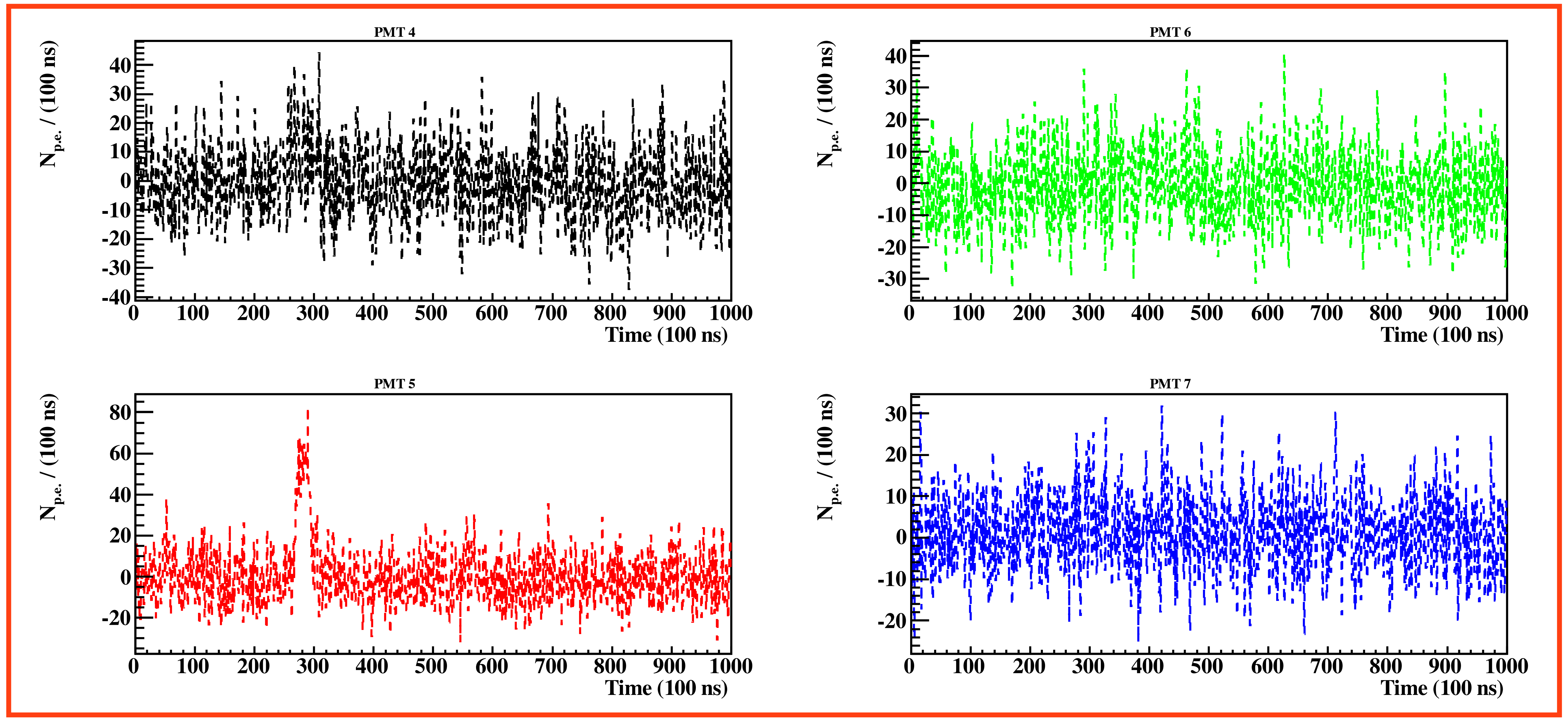


TA FD: 19 EeV, R_p: 6.1 km (Preliminary)









Reconstructing the highest event

Work: Justin Albury, Jose Bellido

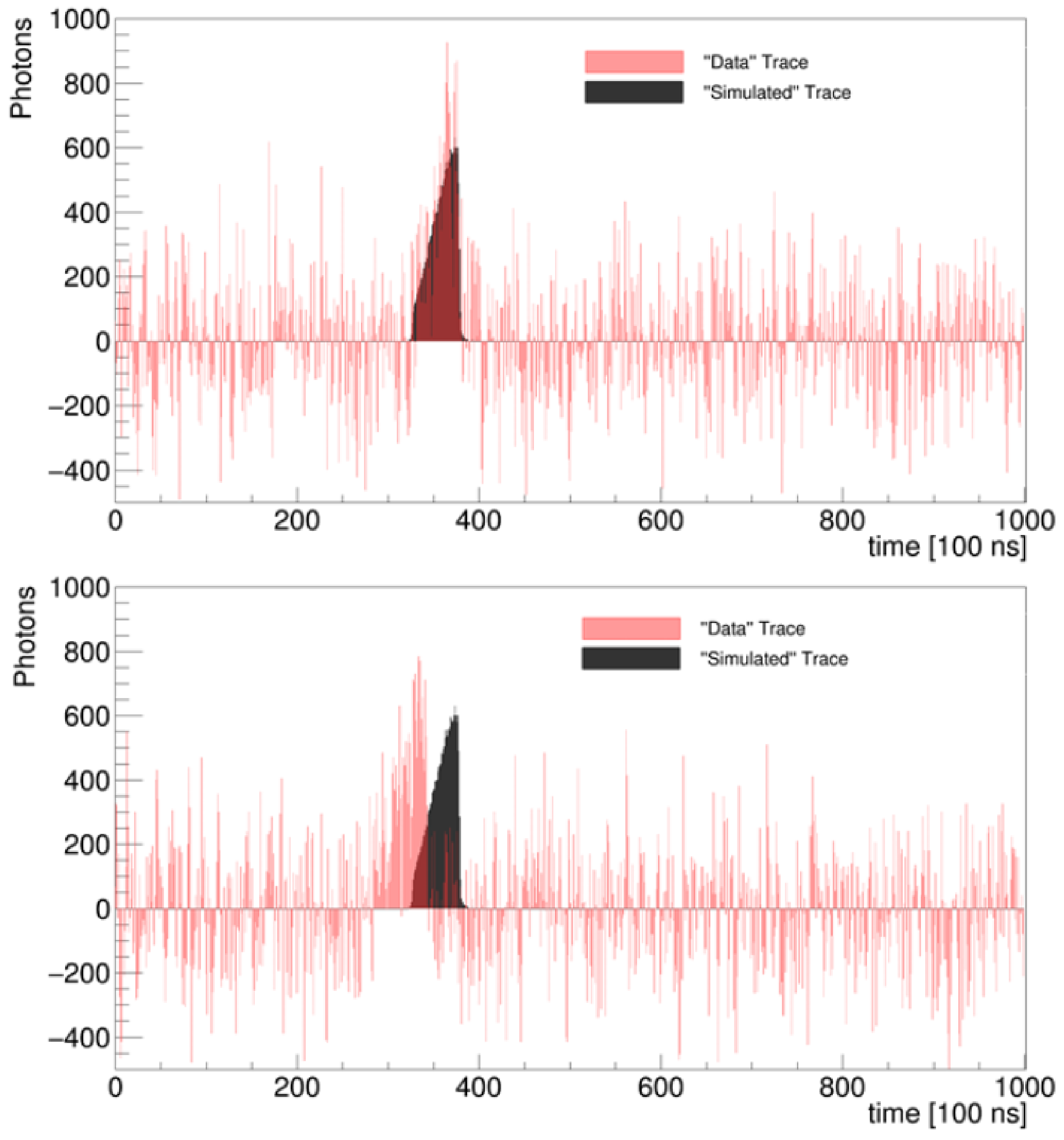
Top-Down Reconstruction

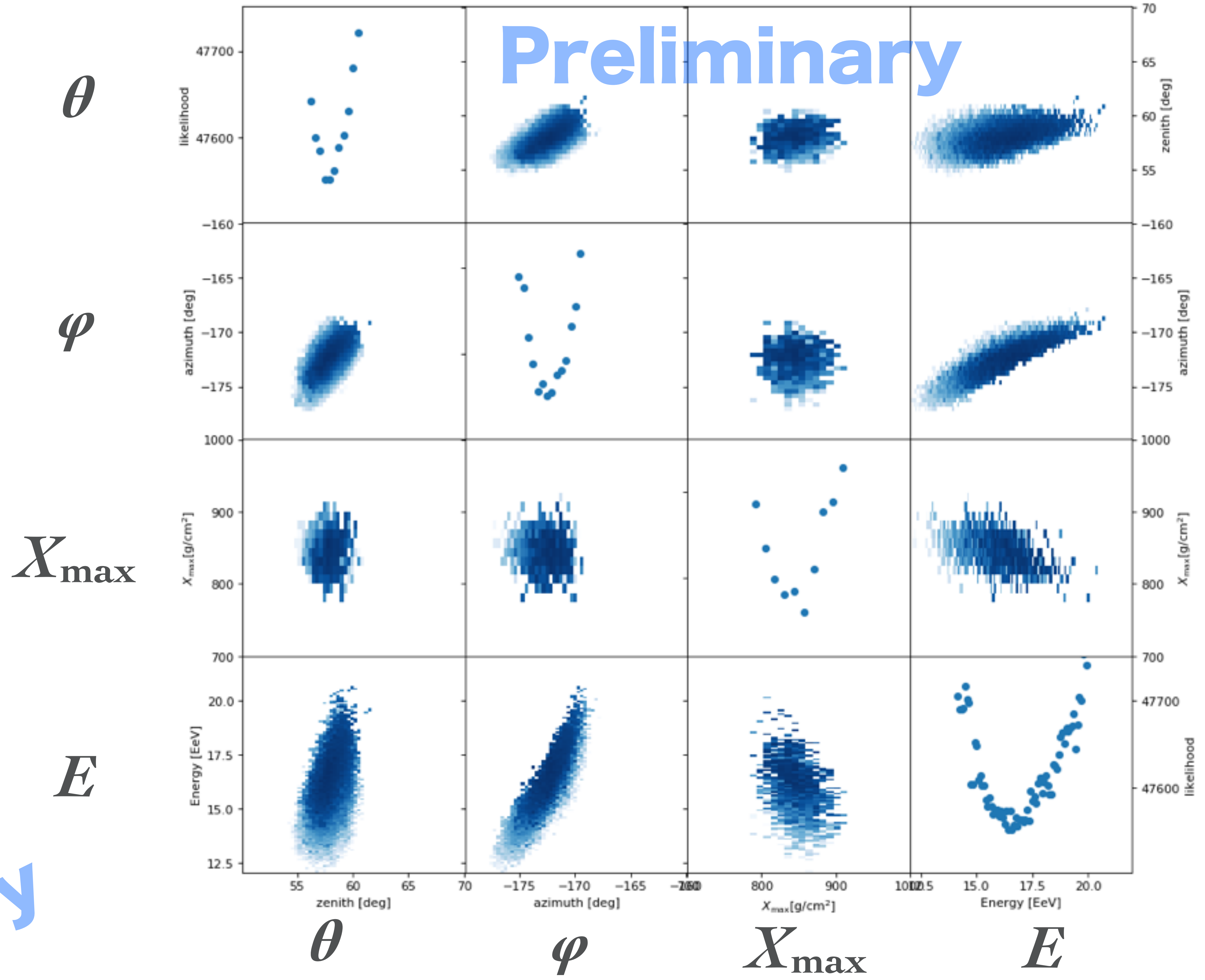
-Using a χ^2 test to compare pulses bin-by-bin

Data Expected($\theta,\varphi,x,y,E,X_{\max}$)

$$\chi^2 = \sum_{\text{pixel } i} \sum_{\text{time } t} \frac{(x(i,t) - A\mu(i,t))^2}{\sigma^2_{\text{NSB}}(i) + A\sigma^2_{\text{signal}}(i,t)}$$

- A is a scale factor for shower energy



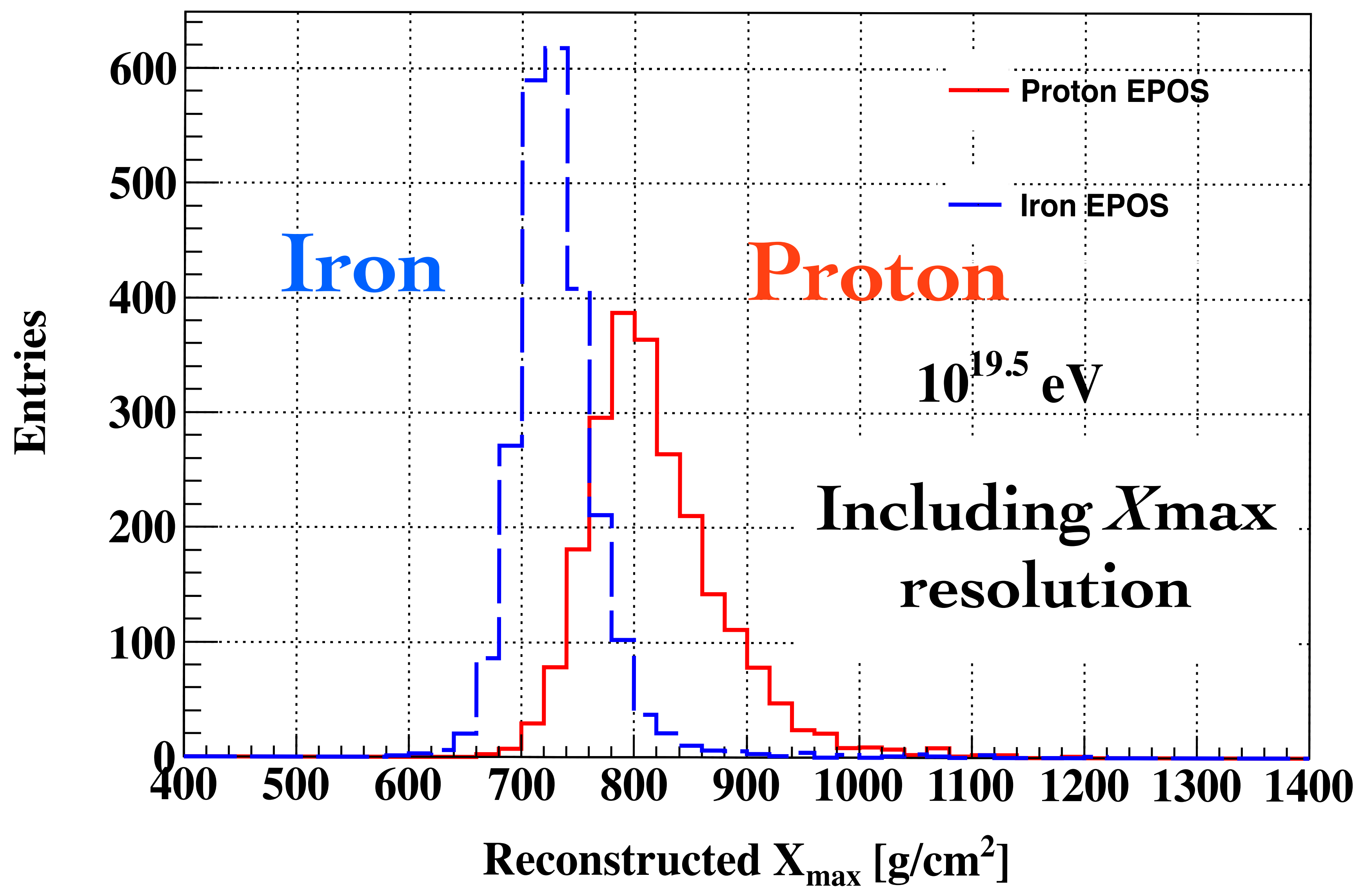


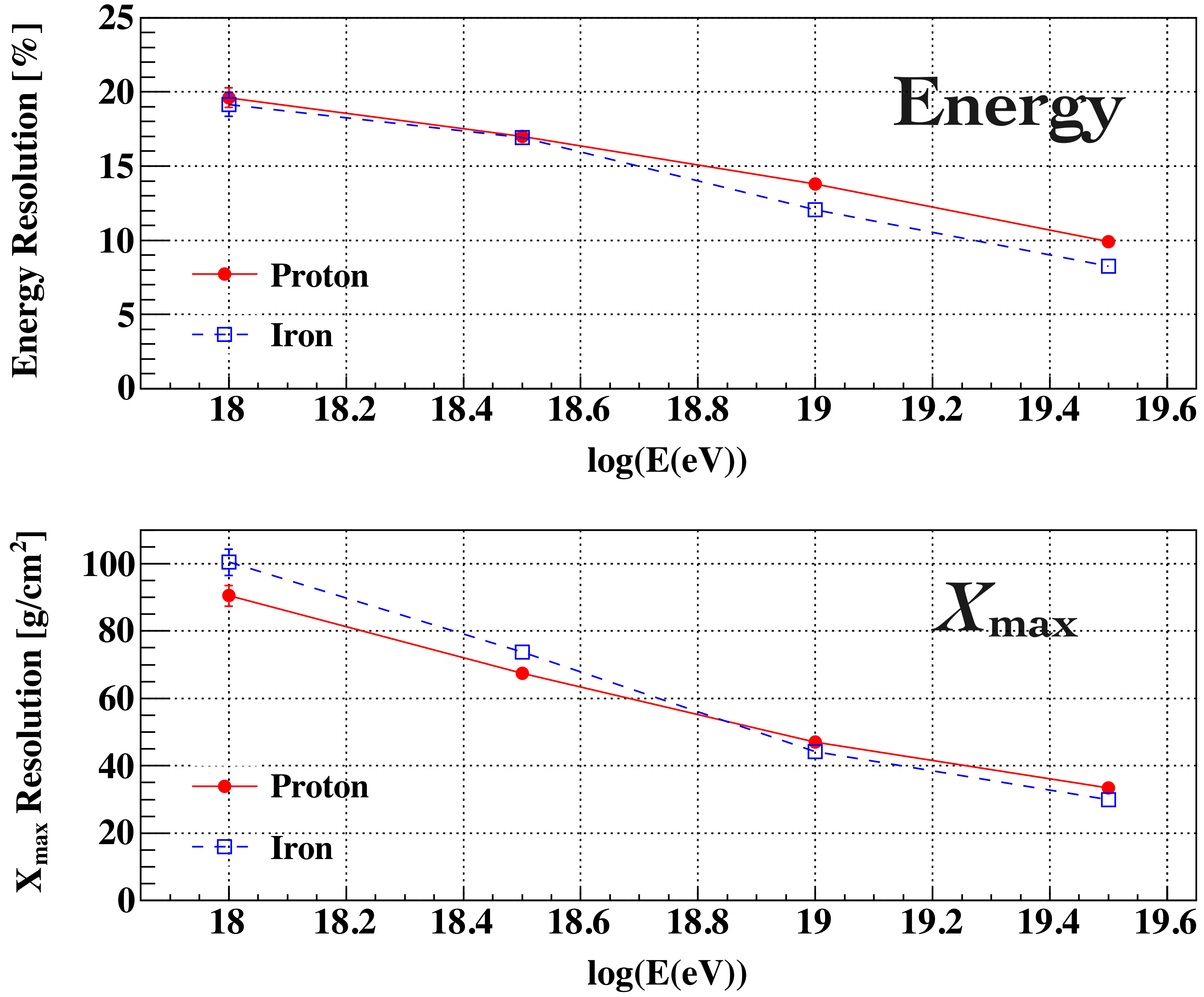
Preliminary

Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
57.7 deg	-172.6 deg	8.1 km	-9.0 km	850 g/cm^2	16.8 EeV
+0.4	+0.5	+0.2	+0.2	+10	+0.3
-0.7	-1.5	-0.2	-0.2	-10	-0.7

Possible application of the FAST prototypes

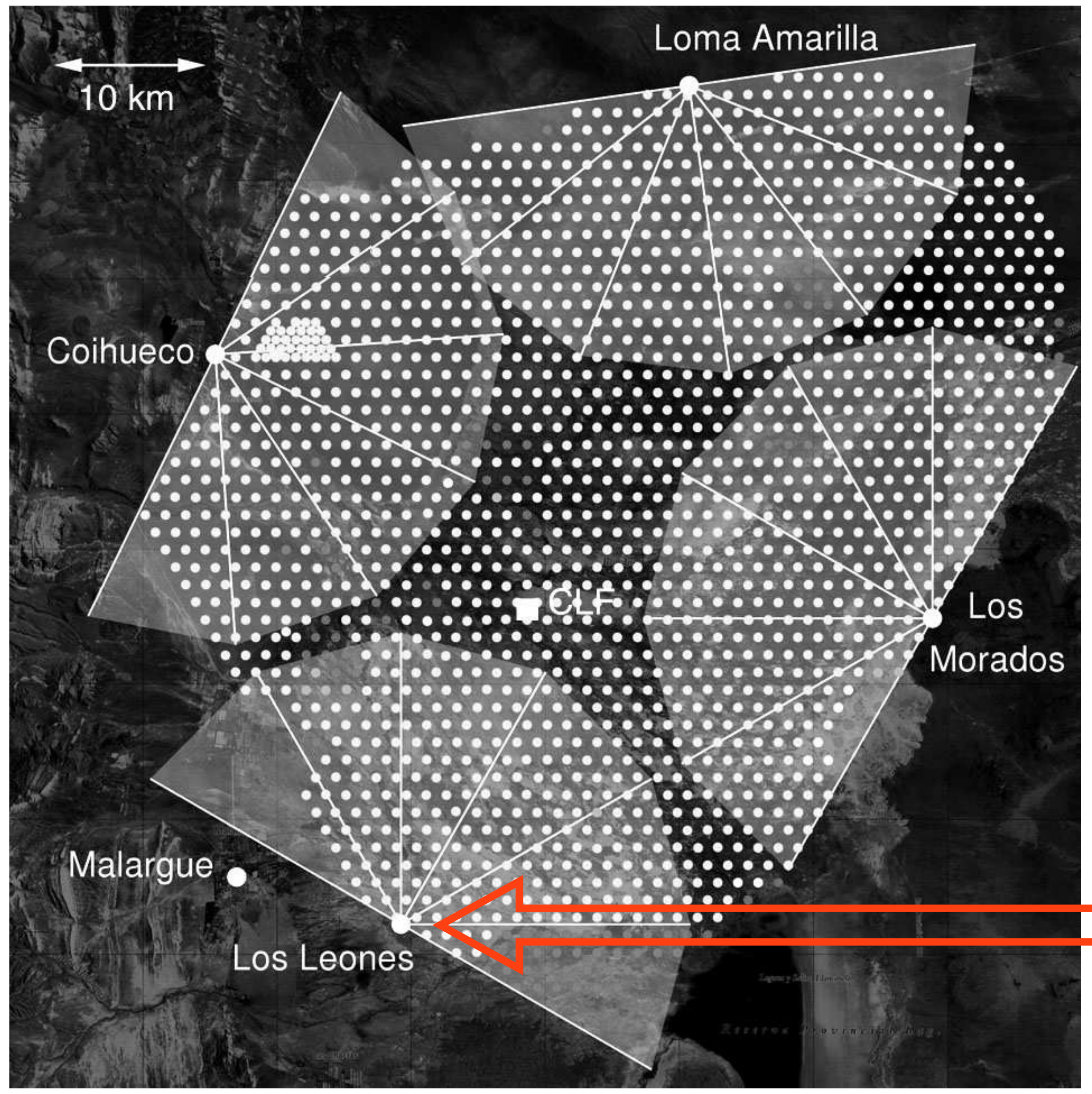
- Install the FAST prototypes at Auger and TA for a study of systematic uncertainties and a cross calibration.
- Profile reconstruction with geometry given by surface detector array (1° in direction, 100 m in core location).
  - Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
  - Independent check of **Energy and X_{max}** scale between Auger and TA





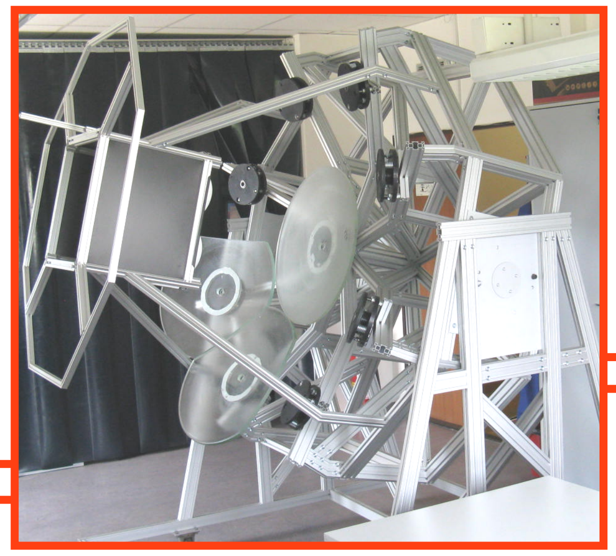
T. Fujii et al., Astropart.Phys., *74*, pp64-72 (2016)

Pierre Auger Observatory

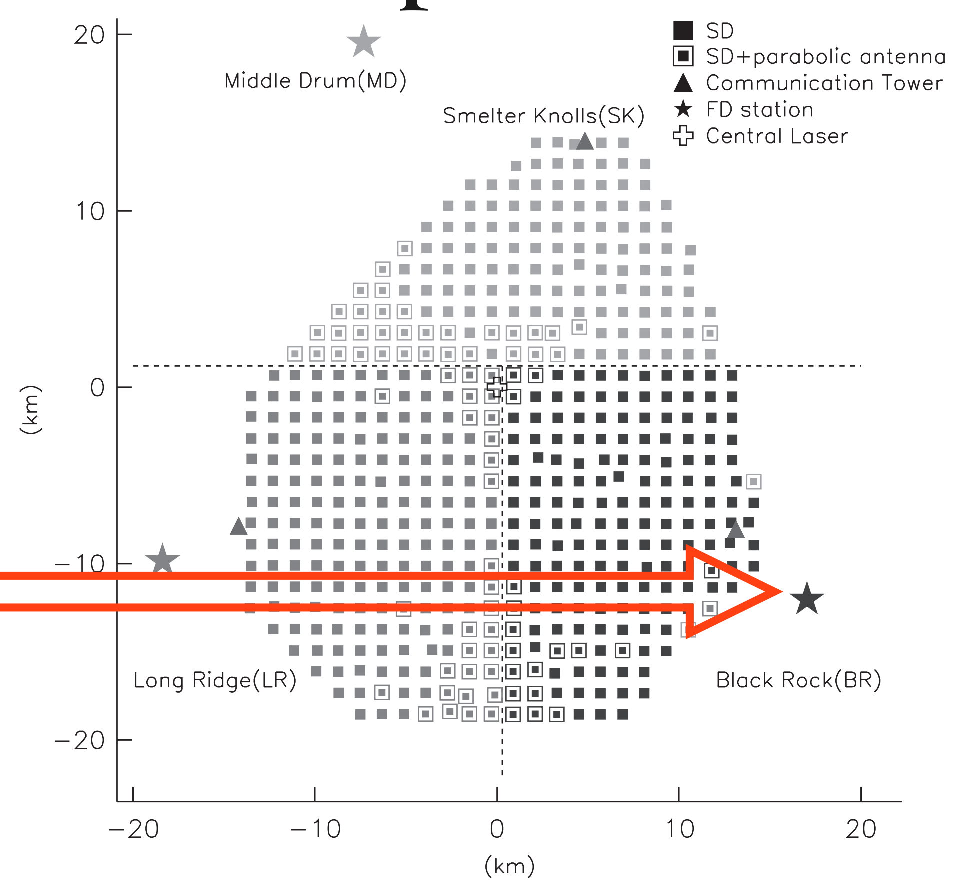


Auger collab., NIM-A (2010)

Identical simplified FD



Telescope Array Experiment

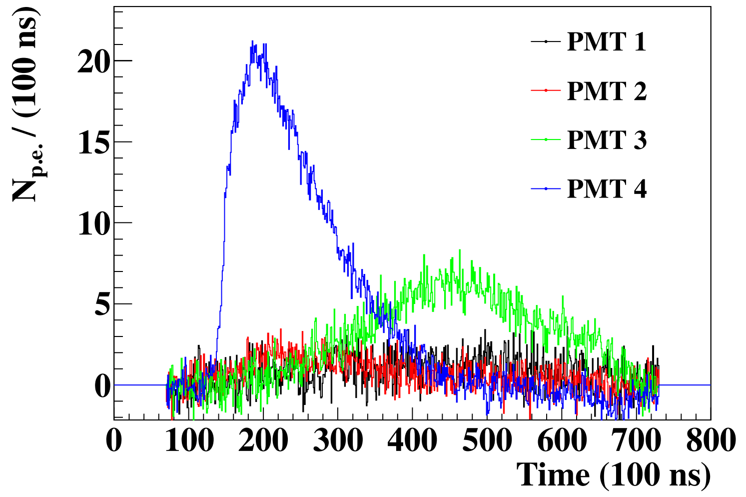


TA collab., NIM-A (2012)

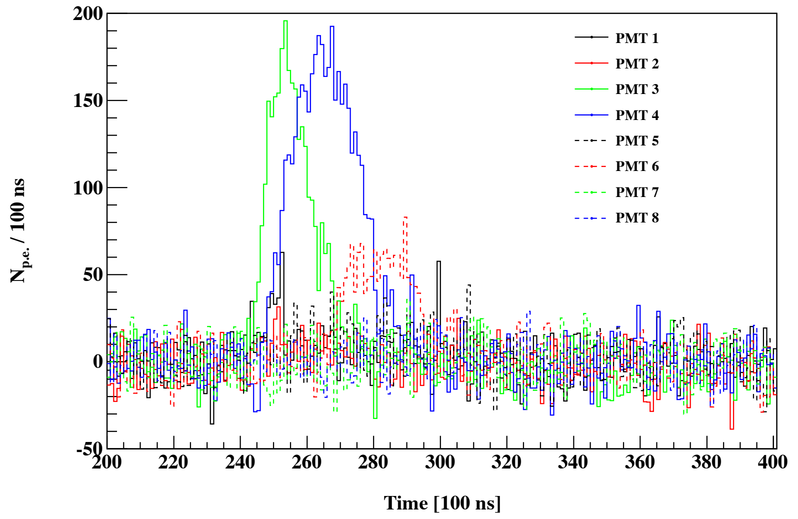
Summary and future plans

- **Fluorescence detector Array of Single-pixel Telescopes (FAST)**
  - Optimization to detect UHECR with economical fluorescence detector array.
    - **10×statistics** compared to Auger and TA×4 **with X_{max}**
  - **UHECR astronomy for nearby universe, directional anisotropy on energy spectrum and mass composition**
- Installed the 3 full-scale FAST telescopes at Telescope Array site
  - Detect a distant vertical laser and UHECRs
  - Stable observation with remote controlling.
- We will continue to operate the telescopes and search for UHECR in coincidence with the TA detectors.
- Plan to install 1st telescope in the Pierre Auger Observatory in 2019
  - Developing new electronics and preparing for stand-alone operation

Laser



UHECR



http://www.fast-project.org

New collaborators are welcome!

Backup

Physics goal and future perspectives

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

5 - 10 years

Exposure and full sky coverage
TA×4 + Auger
K-EUSO : pioneer detection from space with an uniform exposure in northern/southern hemispheres

Detector R&D
Radio, SiPM,
Low-cost fluorescence detector

"Precision" measurements
AugerPrime
Low energy enhancement (Auger infill+HEAT+AMIGA, TALE+TA-muon+NICHE)
LHCf/RHICf for tuning models

10 - 15 years

Next generation observatories
In space (100×exposure): POEMMA
Ground (10×exposure with high quality events): FAST

FAST
Fluorescence detector Array of Single-pixel Telescopes

FAST

Fluorescence detector Array of Single-pixel Telescopes

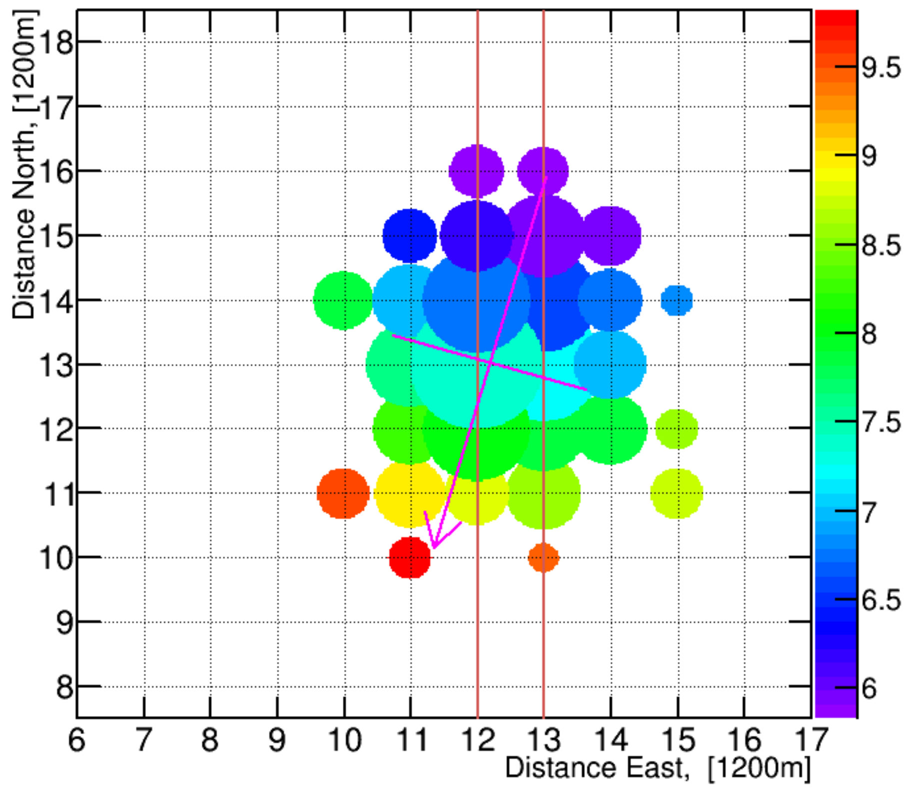
Installation of FAST prototypes (Oct. 2016 and Sep. 2017)

Data analysis and simulation study

Fluorescence detector Array of Single-pixel Telescopes

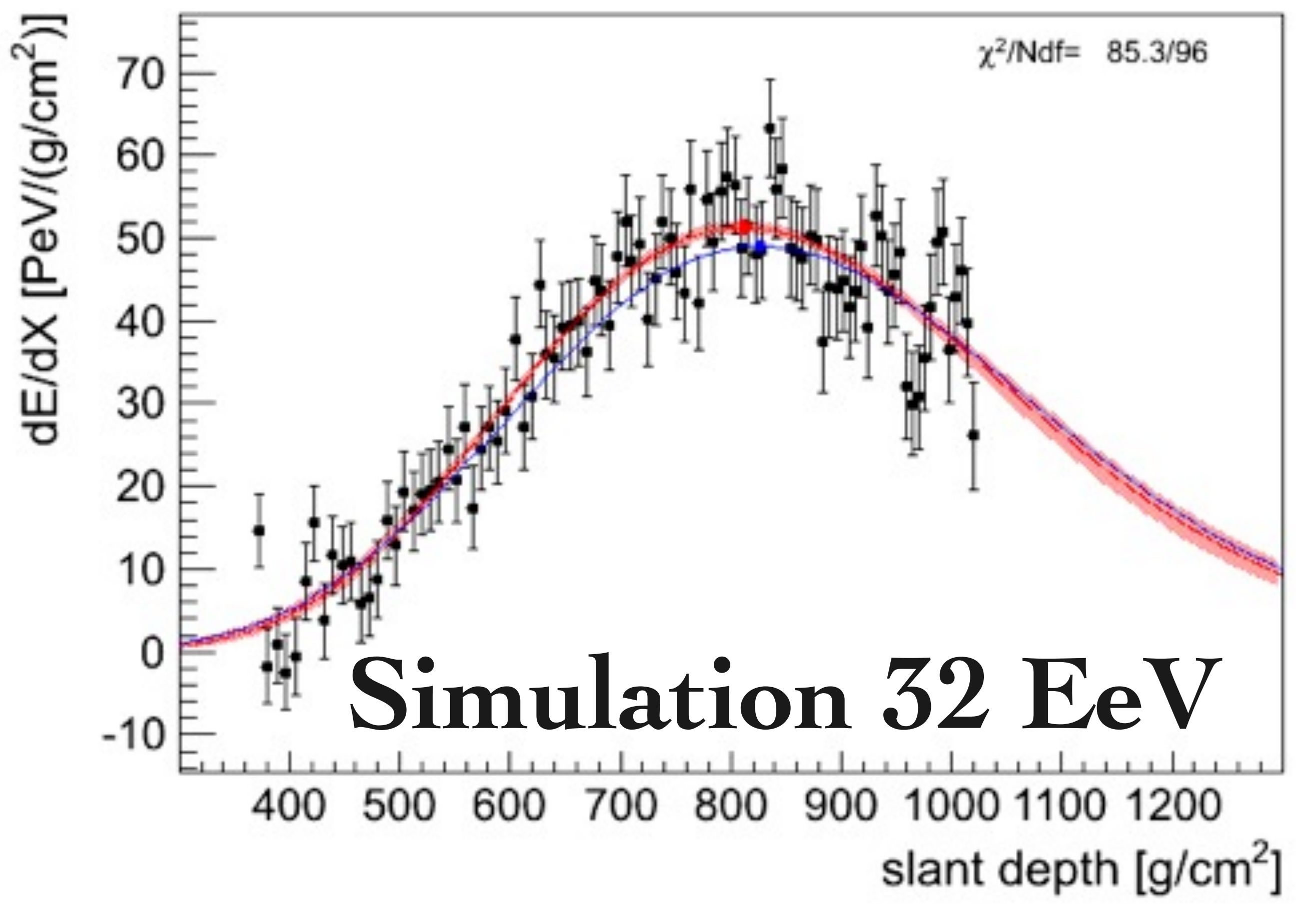
FAST hybrid reconstruction

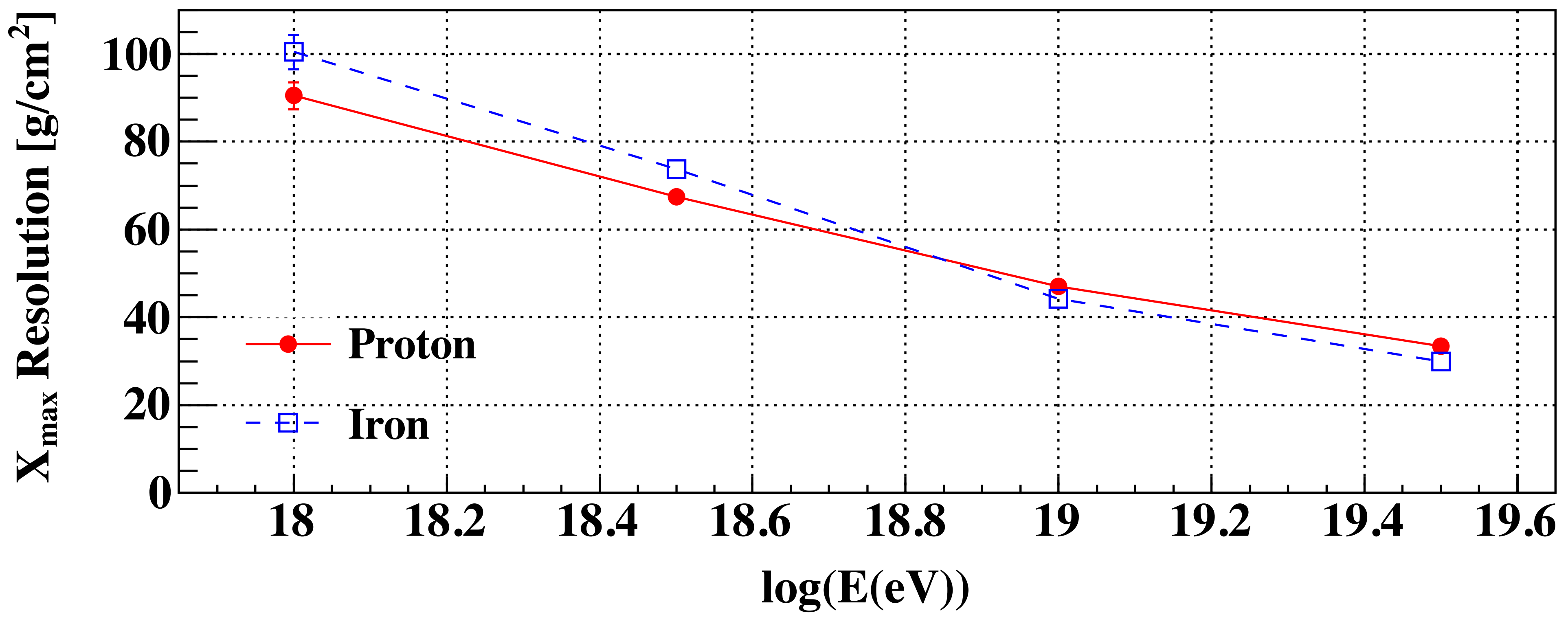
Geometry (given by TASD or FD)



+

Shower Profile (FAST)

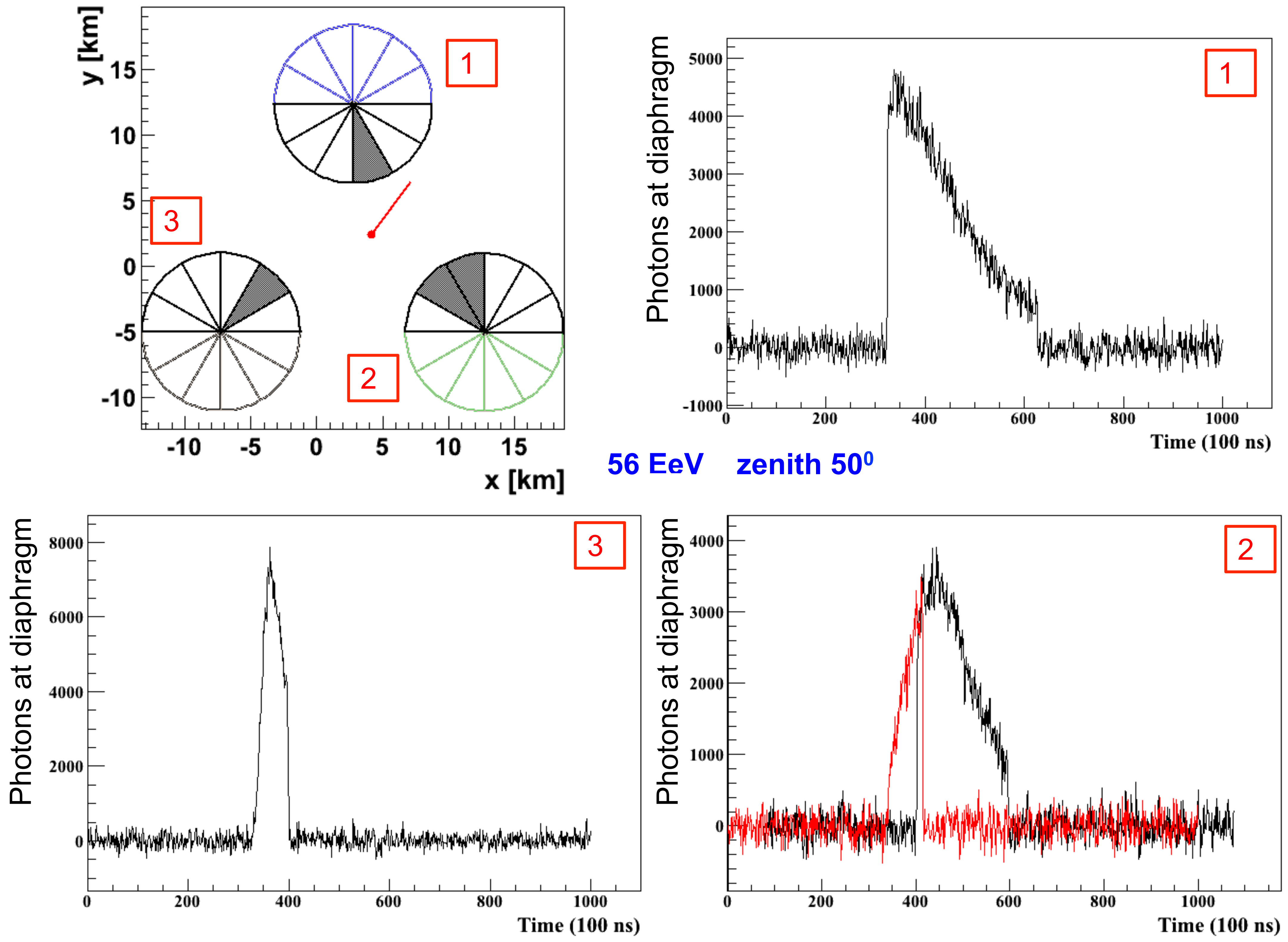




- Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
- Independent cross-check of energy and Xmax scale with simplified FD.

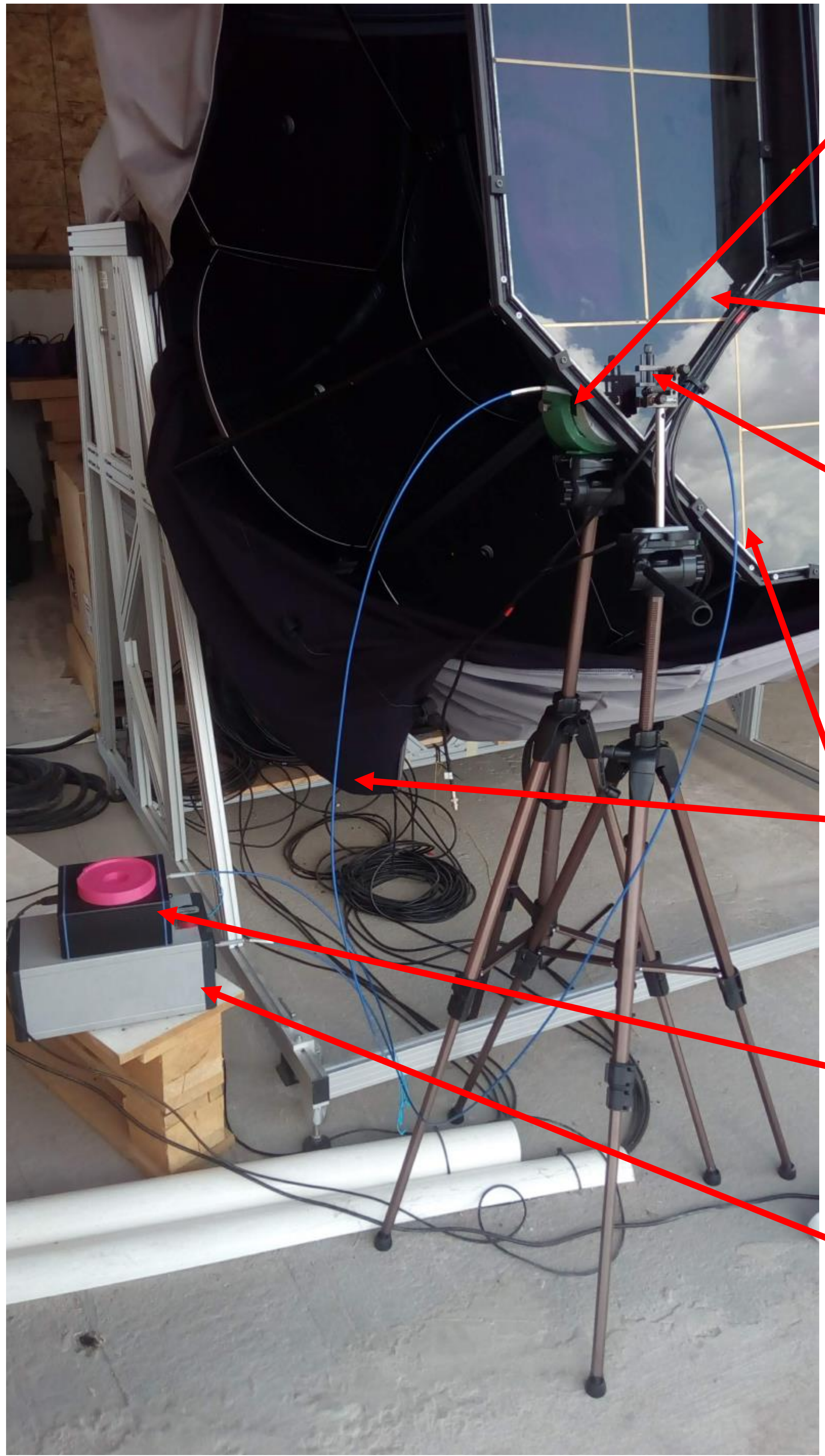
FAST reconstruction

57 EeV Simulation



- Fluorescence detector array with a 20 km spacing.
- Reconstruct geometry and profile

Filter transmittance measurement at site



Intergrating sphere :
AvaSphere-80-Refl

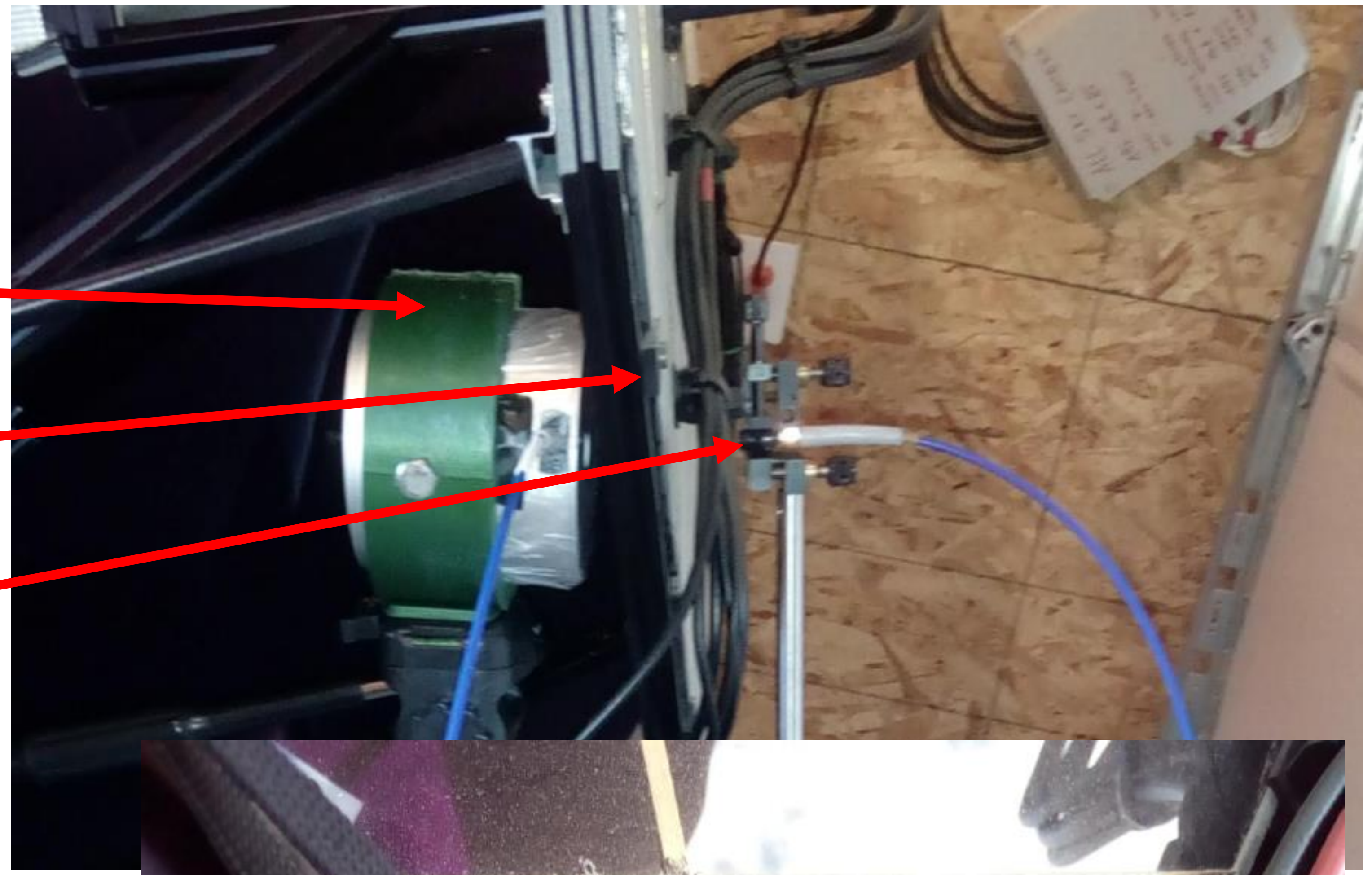
UV filter

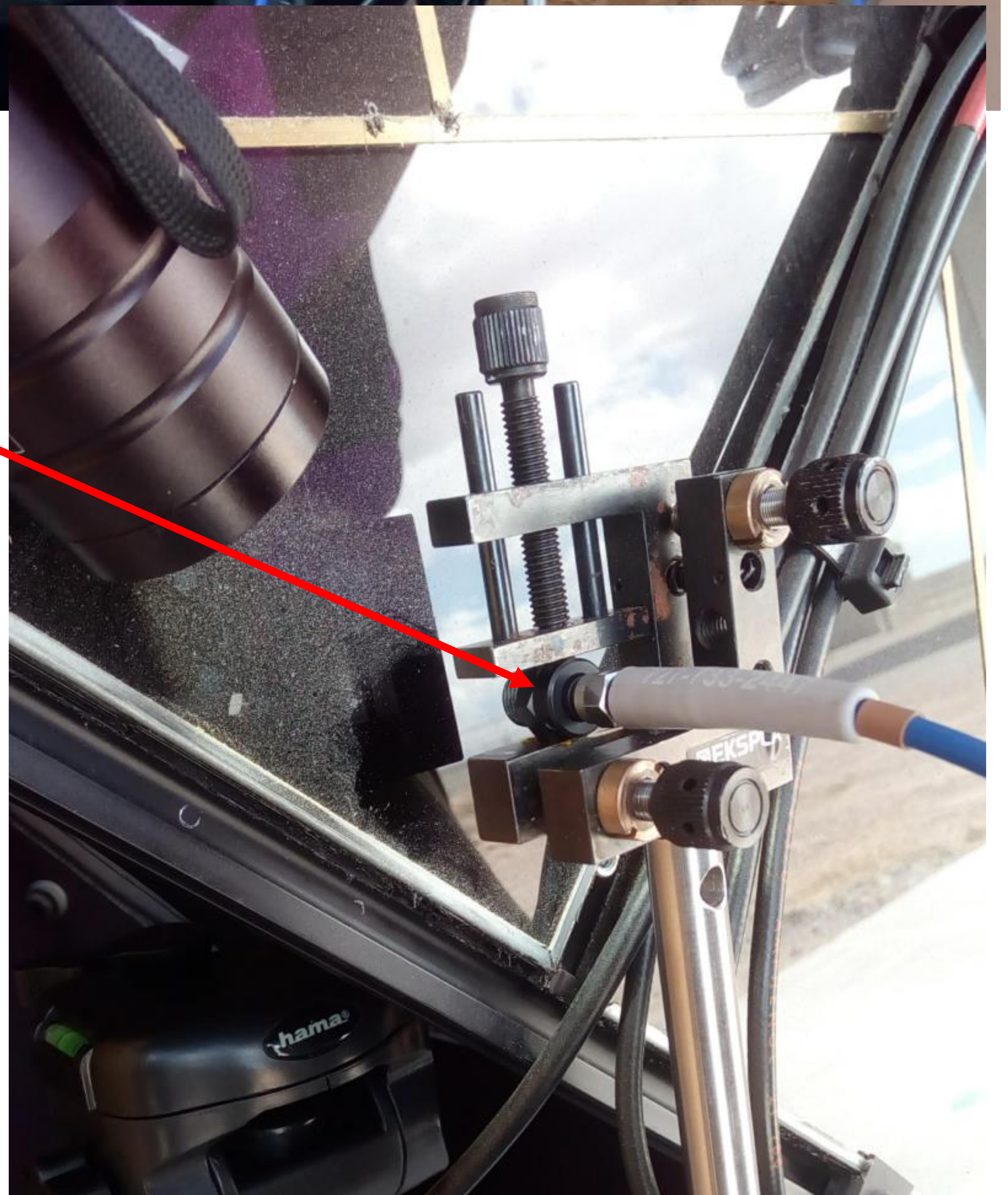
Colimator

Optical Fiber :
FC-XX800-2

Spectrophotometr :
AvaSpec-ULS2048L-USB2-UA-RS

Deuterium/halogen lamp 78W
deuterium, 5W halogen





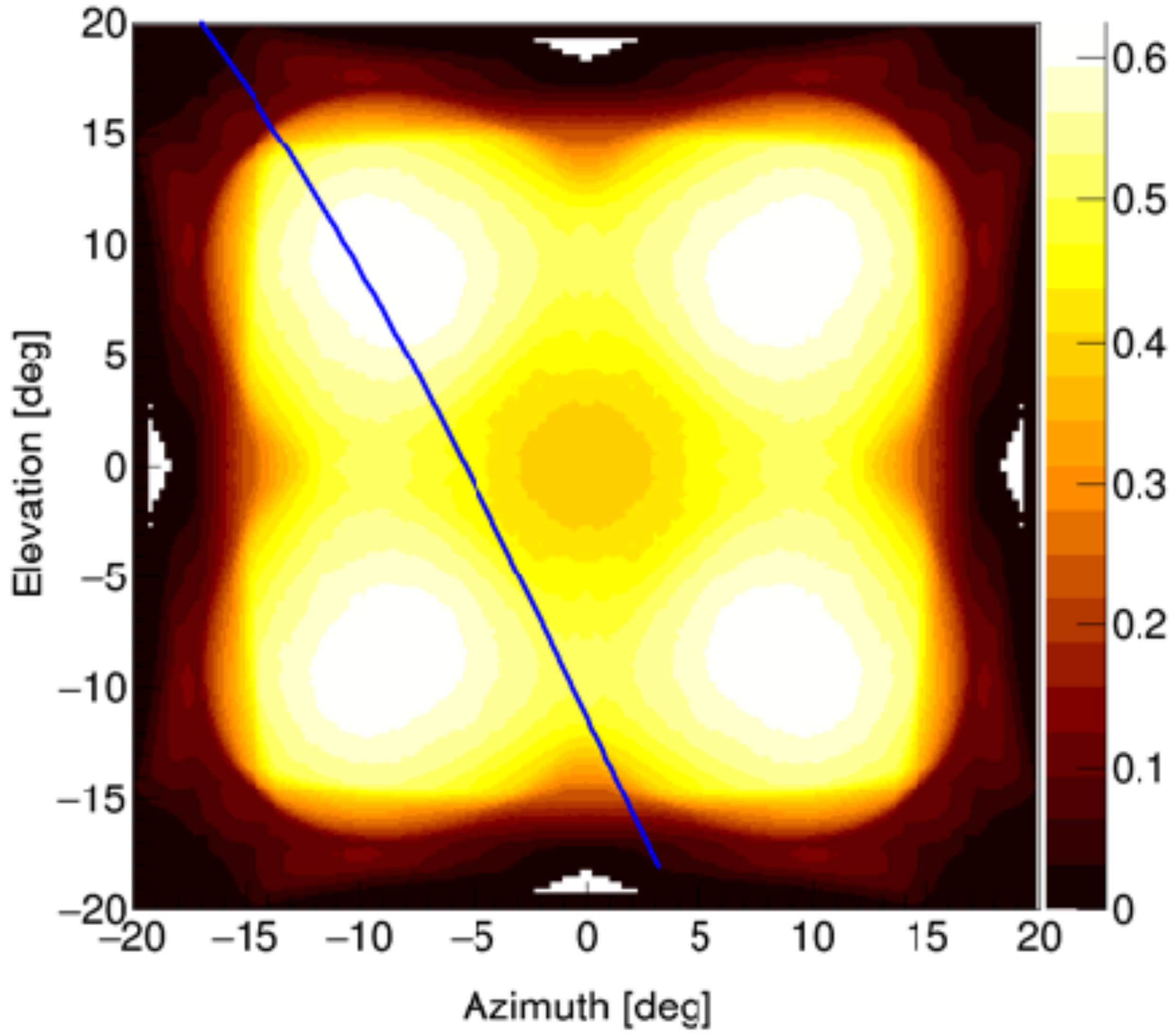
Simulation study

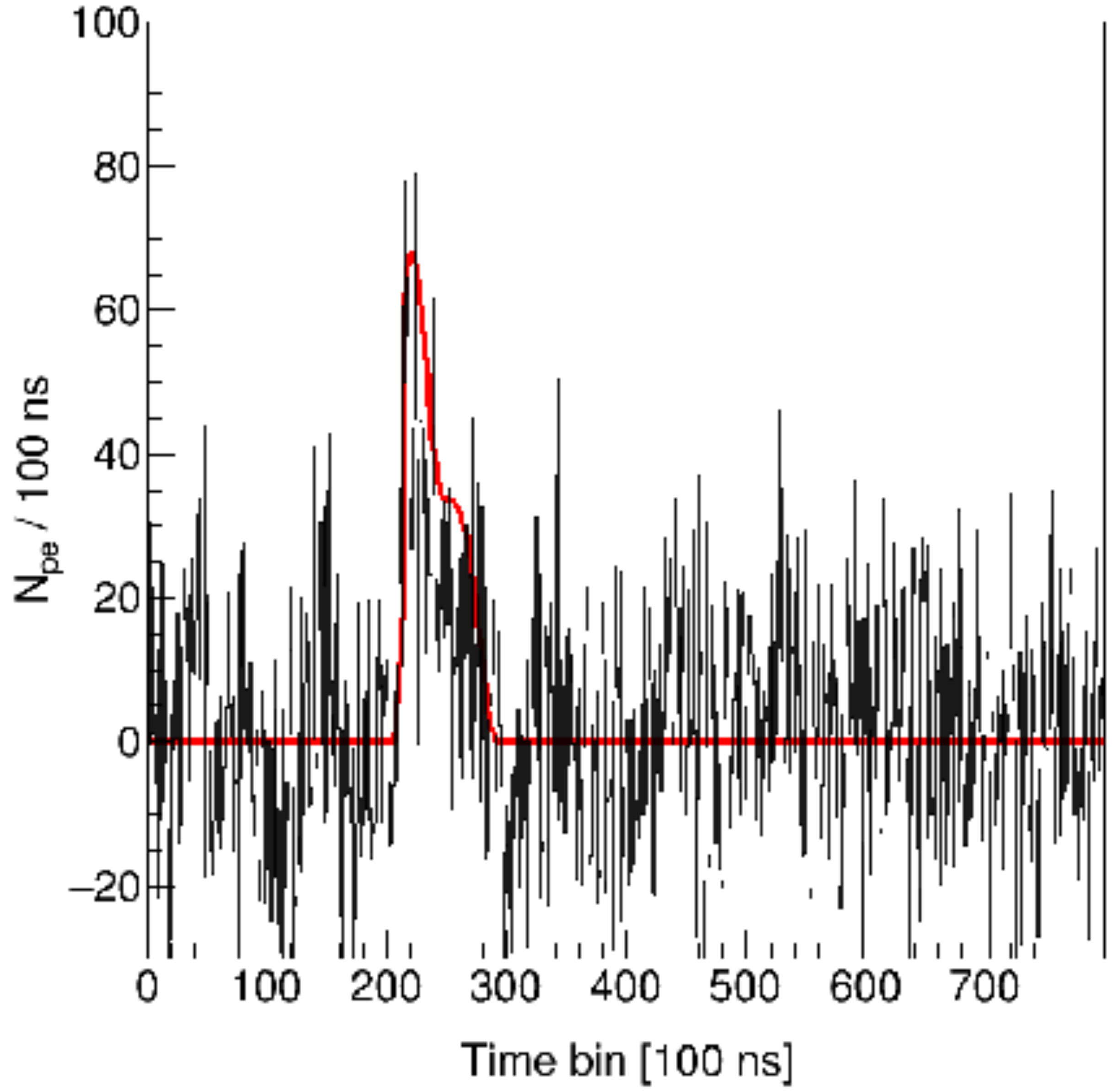
by John and Max

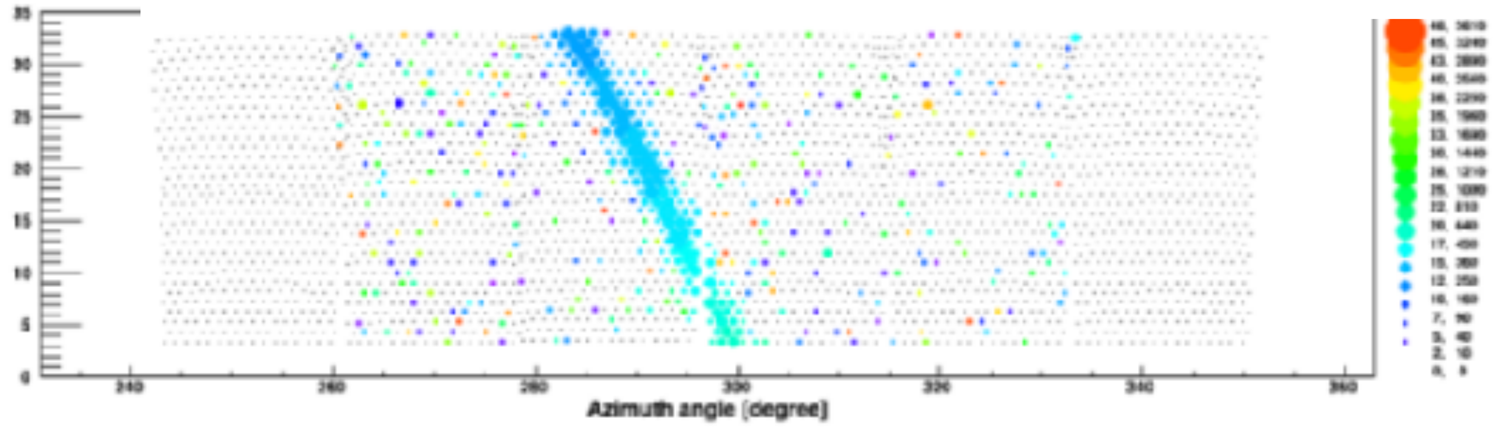
FASTSimulator

Example usage: TA FD Event 31, 19/01/2017

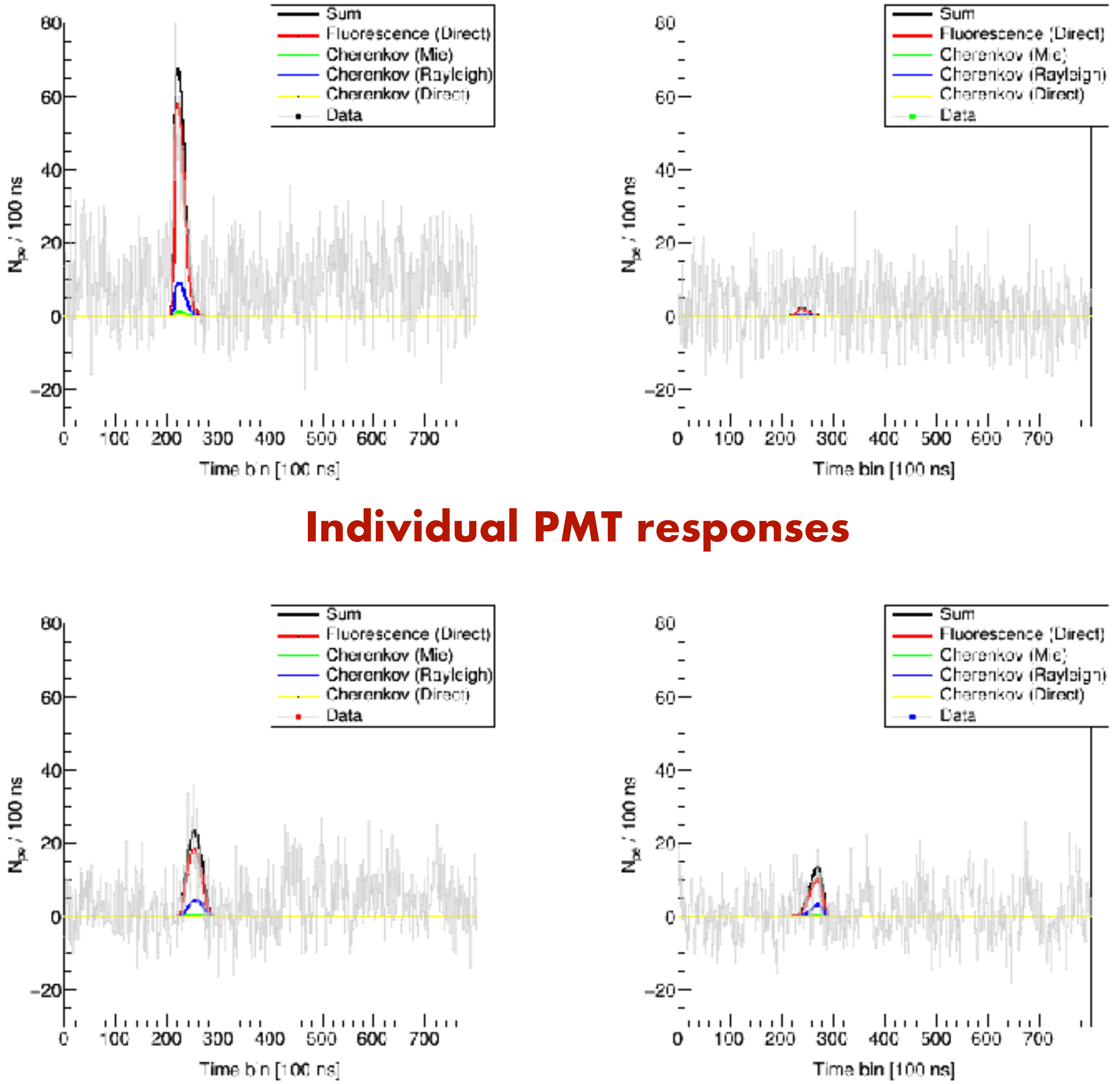
R_p of approx. 3 km, log E = 18.







Event 31: $\log_{10}(E(\mathrm{eV}))$: 17.98, Zen: 34.0°, Azi: 225.8°, Core(0.08, 3.14), Rp: 2.86, Psi: 66.3°, Xmax: 815 g/cm^2 FoV(854 - 1045), Date: 20170119, Time: 04:02:59.140857145



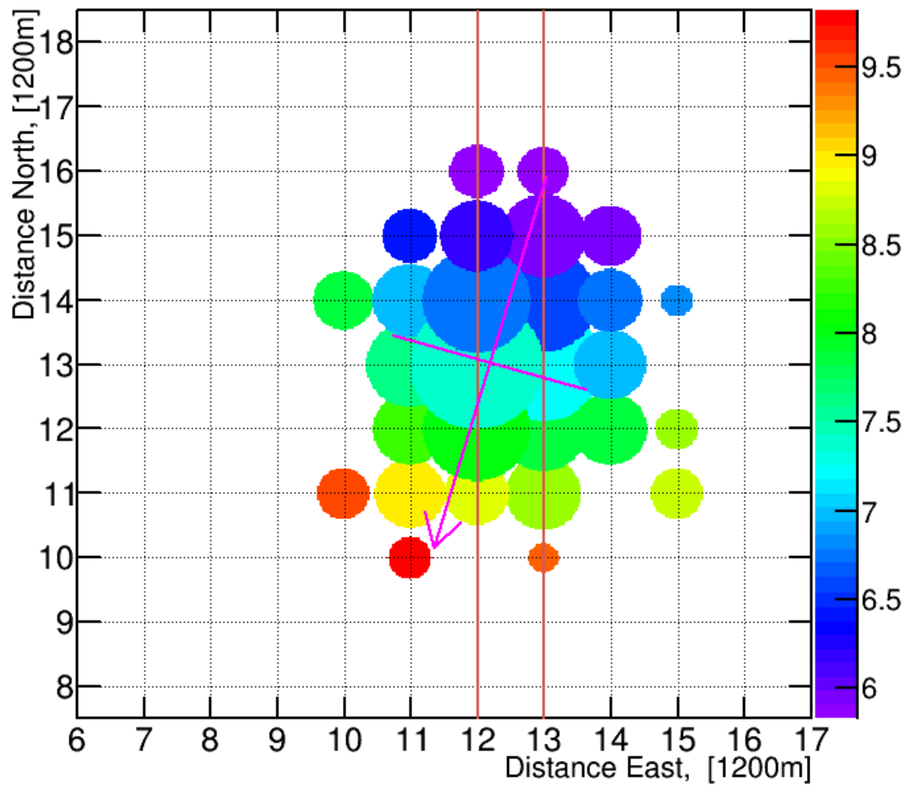
Individual PMT responses

Fluorescence detector Array of Single-pixel Telescopes

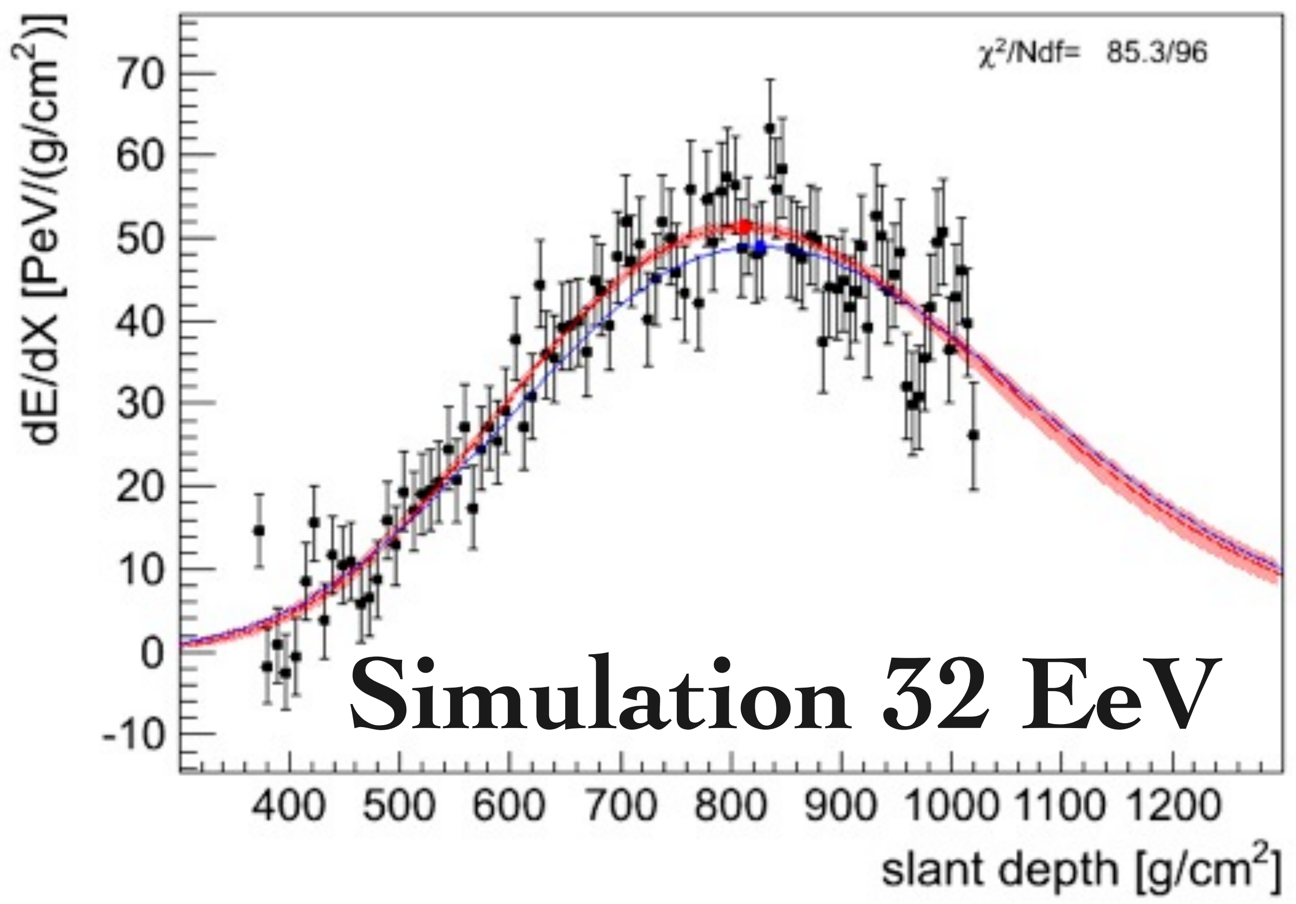
Data analysis and simulation study

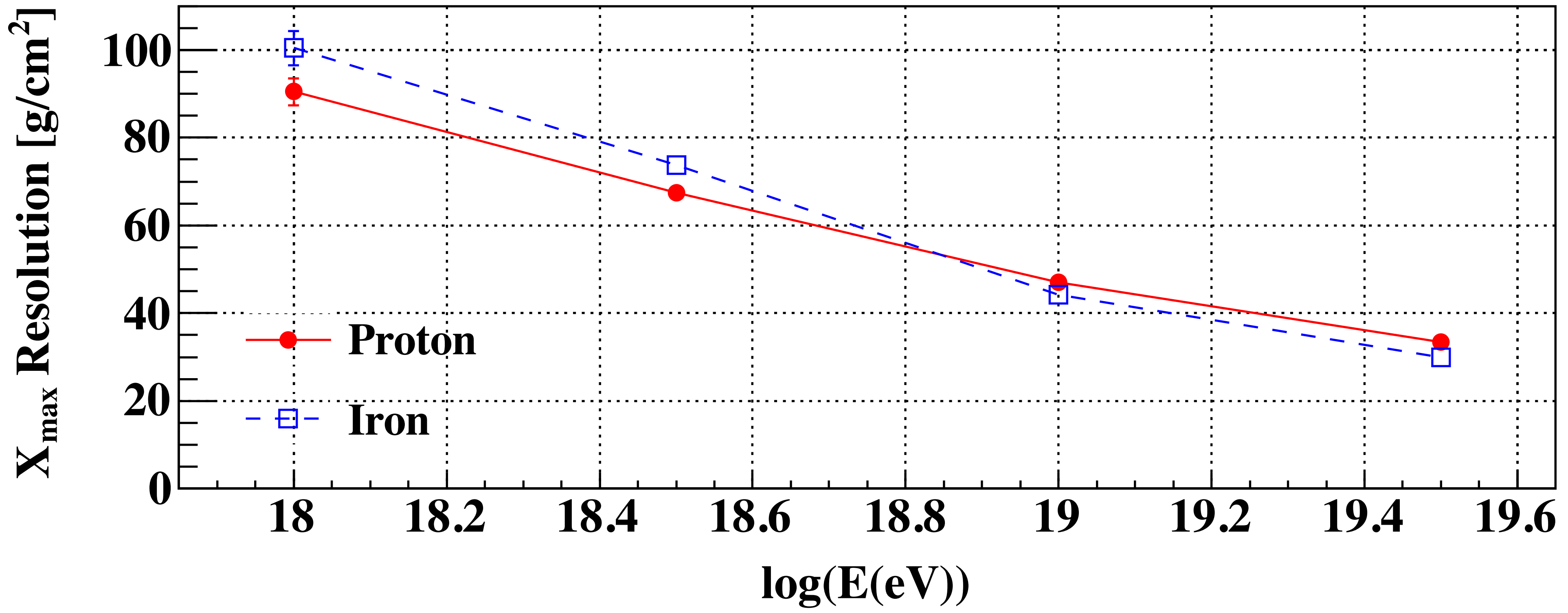
FAST hybrid reconstruction

Geometry (given by TASD)



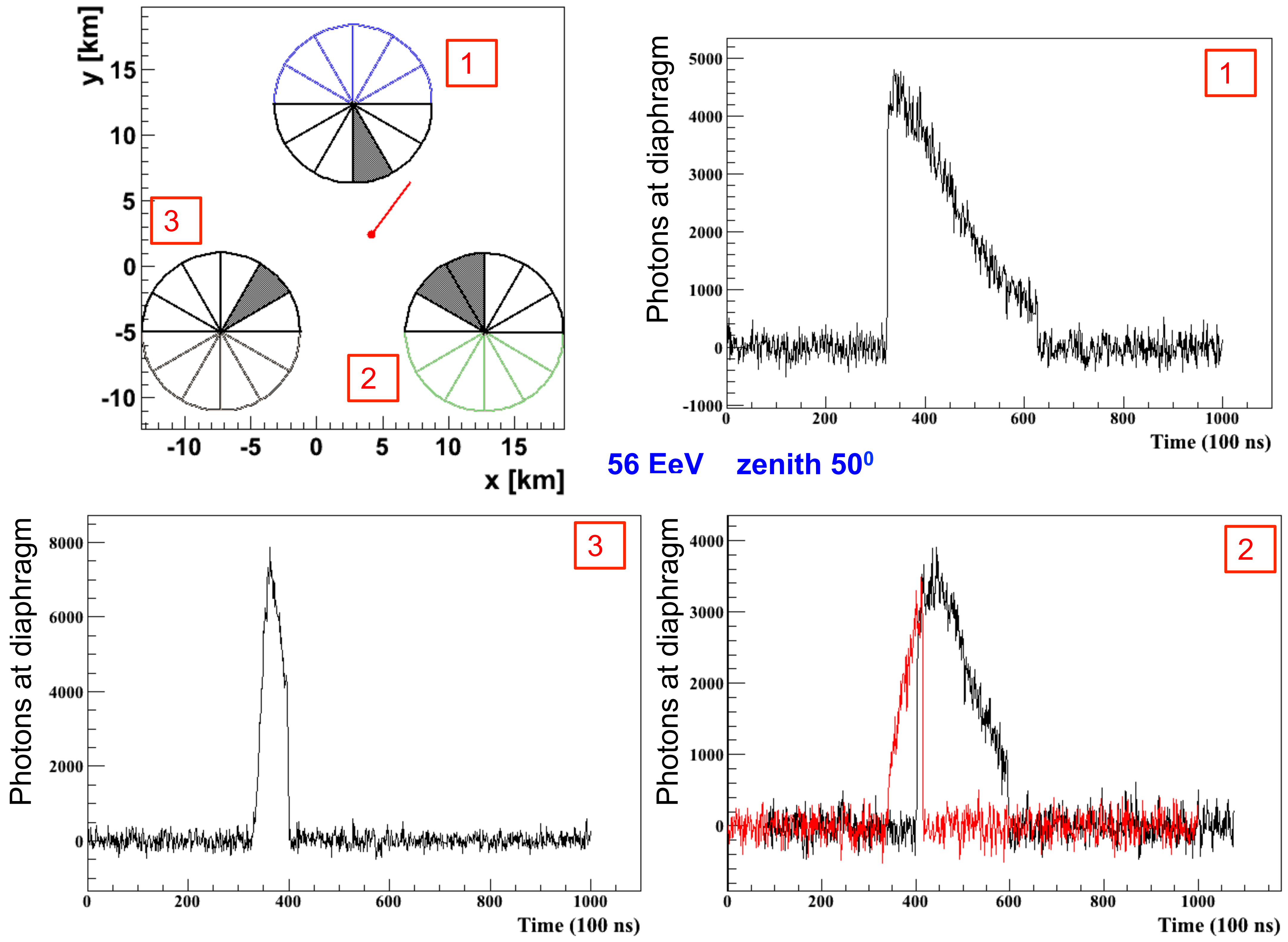
Shower Profile (FAST)





- Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
- Independent cross-check of energy and X_{max} scale with simplified FD.

FAST reconstruction



- Fluorescence detector array with a 20 km spacing.
- Reconstruct geometry and profile

Top-Down reconstruction with FAST

by Justin and Jose

Top-Down Reconstruction

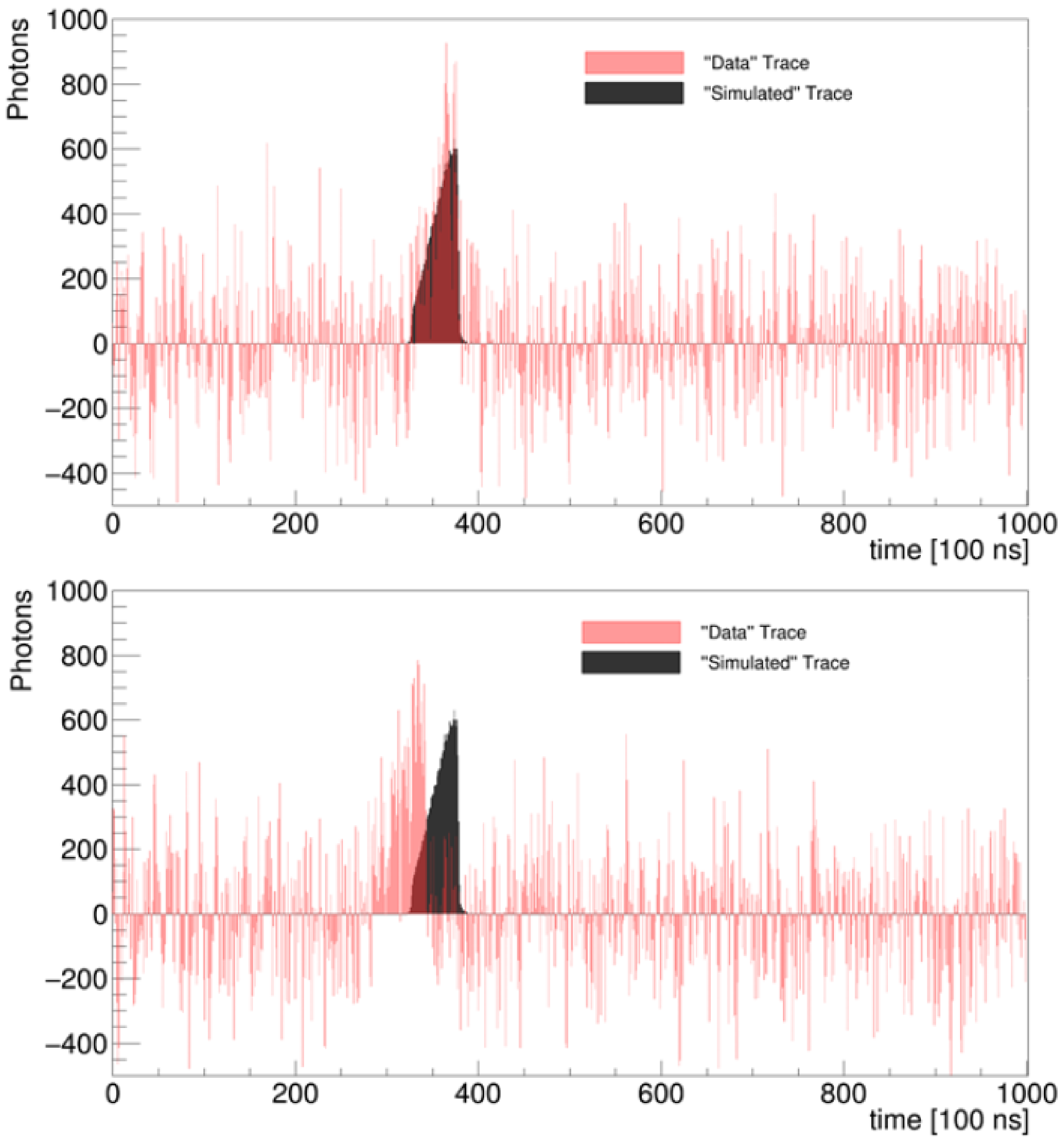
-Using a χ^2 test to compare pulses bin-by-bin

$$\chi^2 = \sum_{\text{pixel } i} \sum_{\text{time } t} \frac{(x(i,t) - A\mu(i,t))^2}{\sigma^2_{\mathrm{NSB}}(i) + A\sigma^2_{\mathrm{signal}}(i,t)}$$

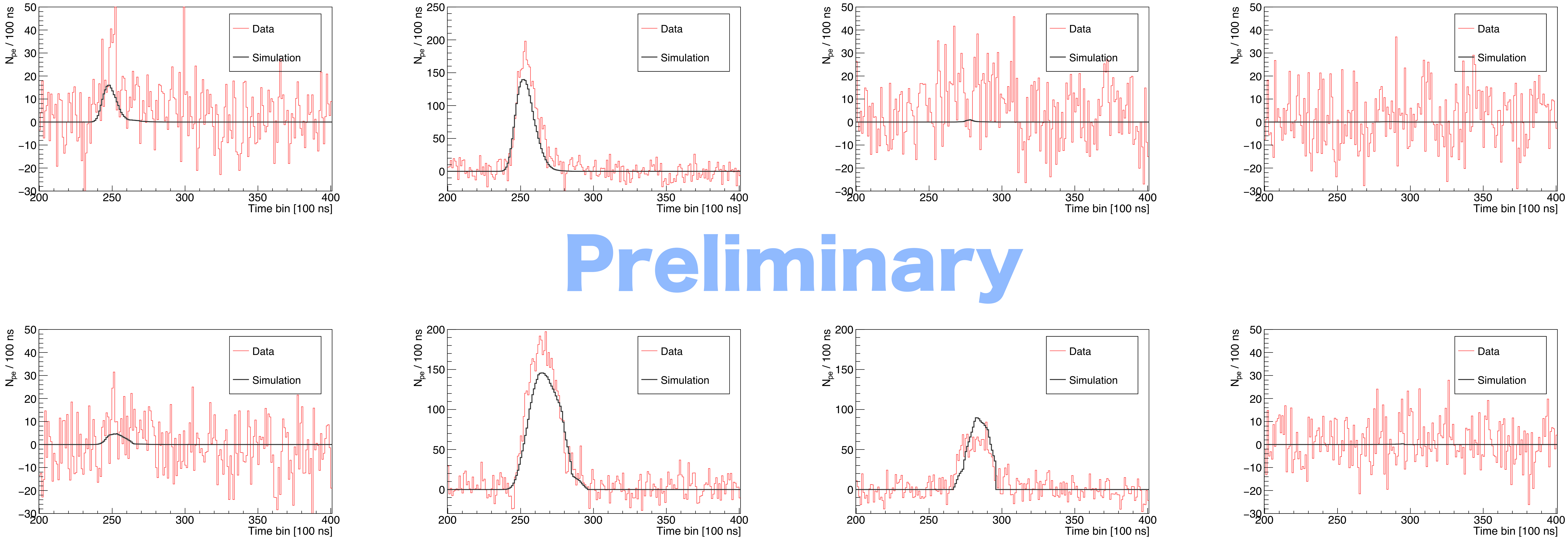
- A is a scale factor for shower energy
- Trace timing fitted as a free parameter in 100 ns steps (accounts for trigger timing fluctuations)
- Signal uncertainty depends on μ:

$$\sigma^2_{\mathrm{signal}} = \sigma^2_{\mathrm{ph}} = \frac{\mu}{k}(1 + V_g)$$

Photon to Photo-electron



Comparison betwen data and the best-fit result from top-down reconstruction



Simulation condition

Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
57.7 deg	-172.6 deg	8.1 km	-9.0 km	850 g/cm^2	16.8 EeV

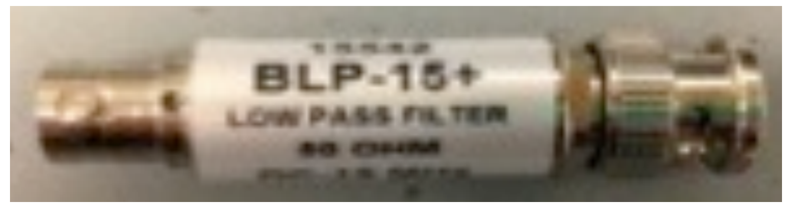
FAST DAQ System

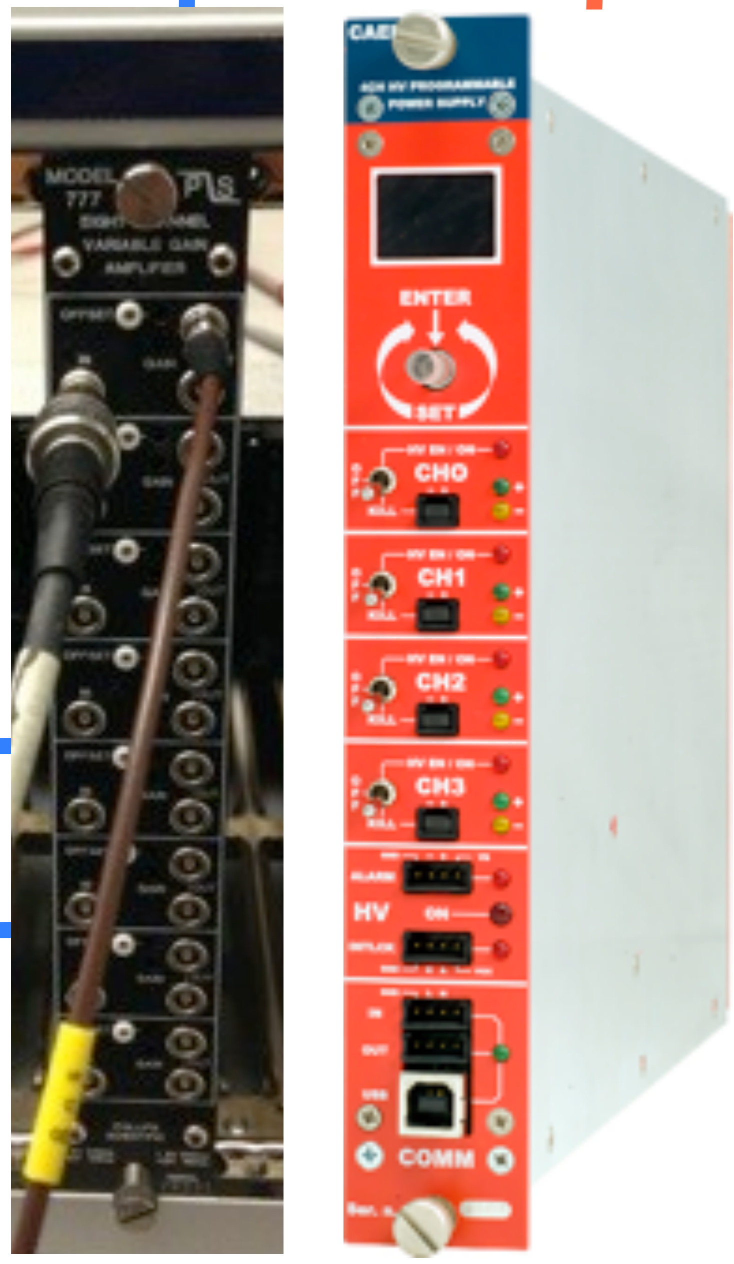
TAFD external trigger, 3~5 Hz

Anode & dynode
Signal

Camera of FAST×4

15 MHz
low pass filter





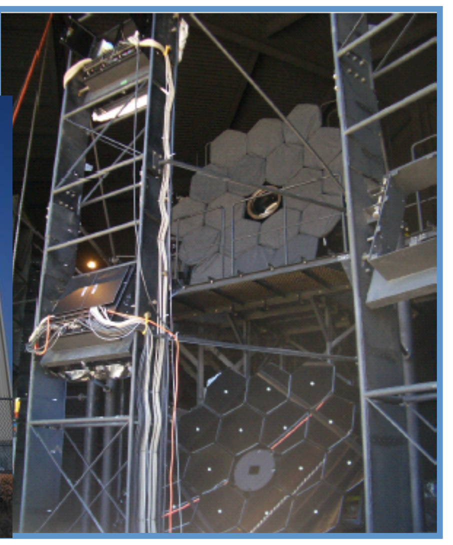
High Voltage power supply,
N1470 CAEN

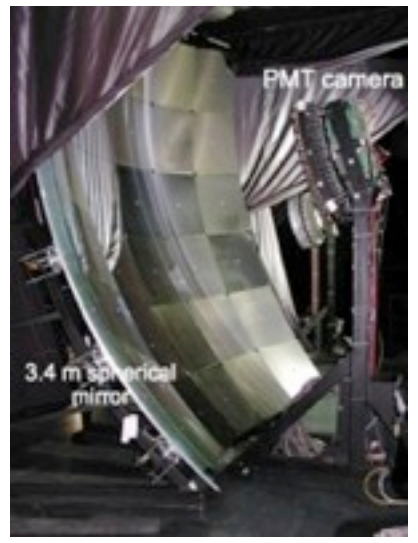
All modules are remotely controlled through wireless network.

Portable VME Electronics
- Struck FADC 50 MHz sampling, SIS3350 for 4 channels
- Updated to SIS3316 for 16 channels
- GPS board, HYTEC GPS2092

777,Phillips scientific
Signal×50

Fluorescence detector Array of Single-pixel Telescopes



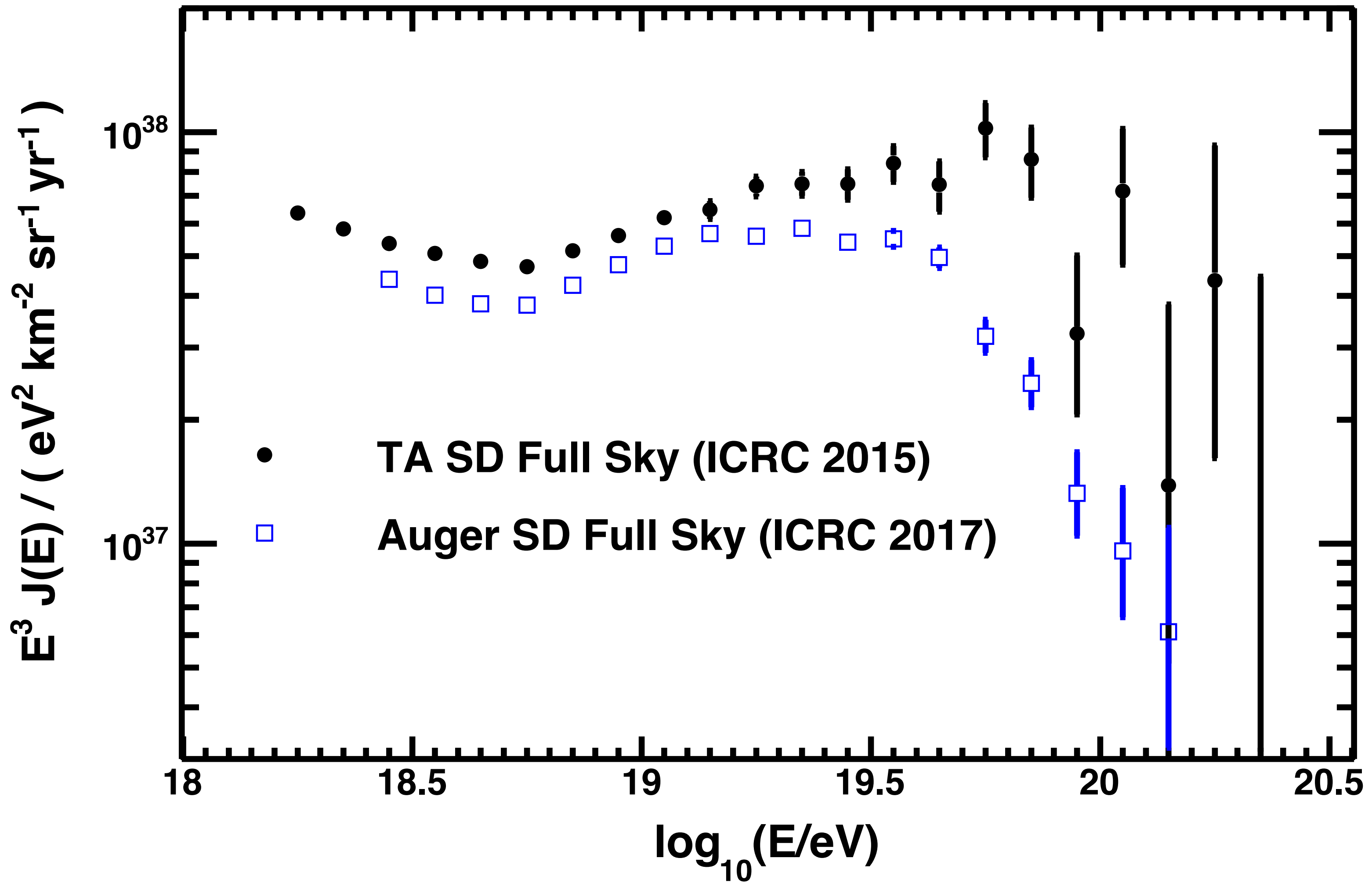


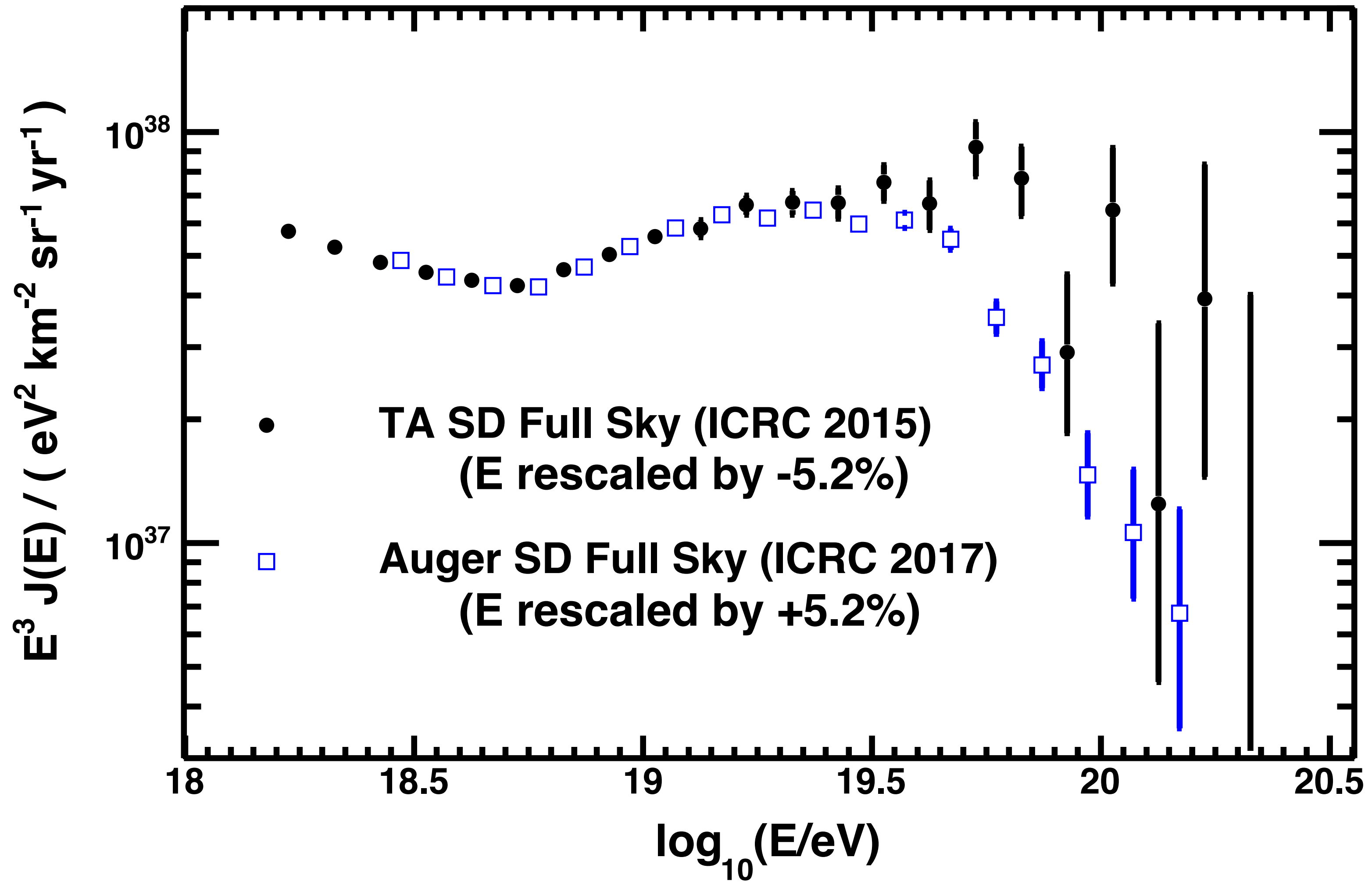
Energy spectrum

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

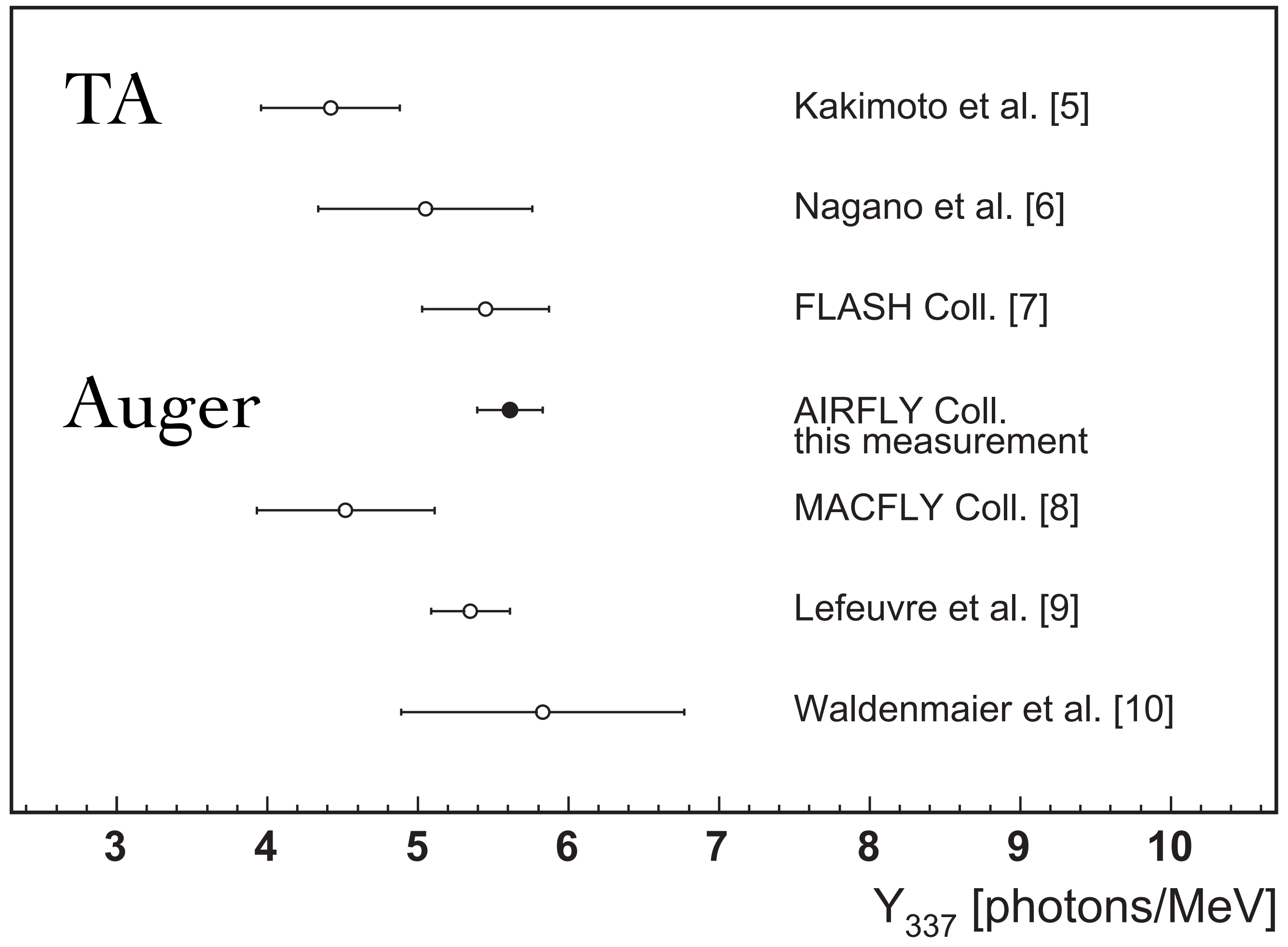
Energy scale determined by fluorescence detector (FD)

Fluorescence yield (FY)

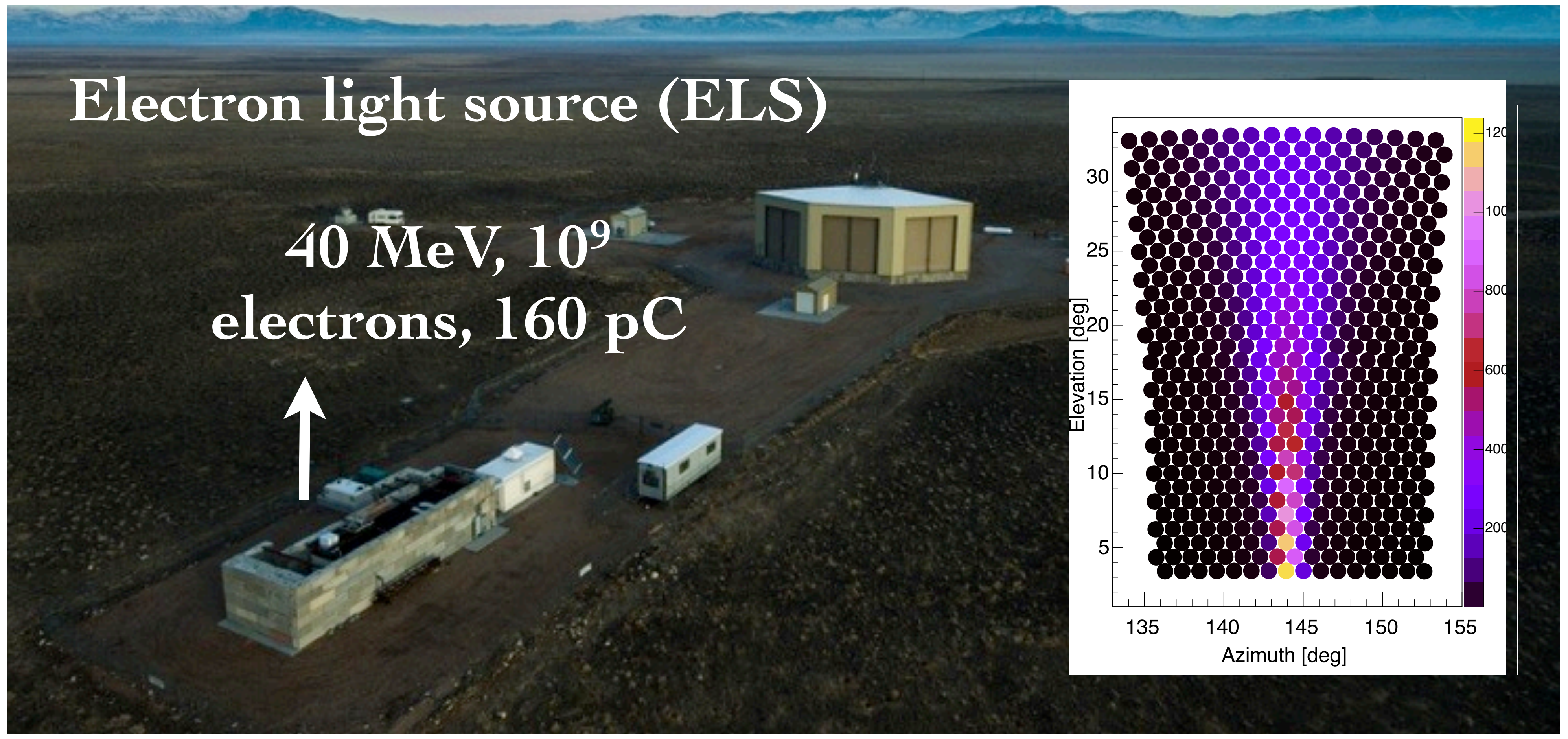


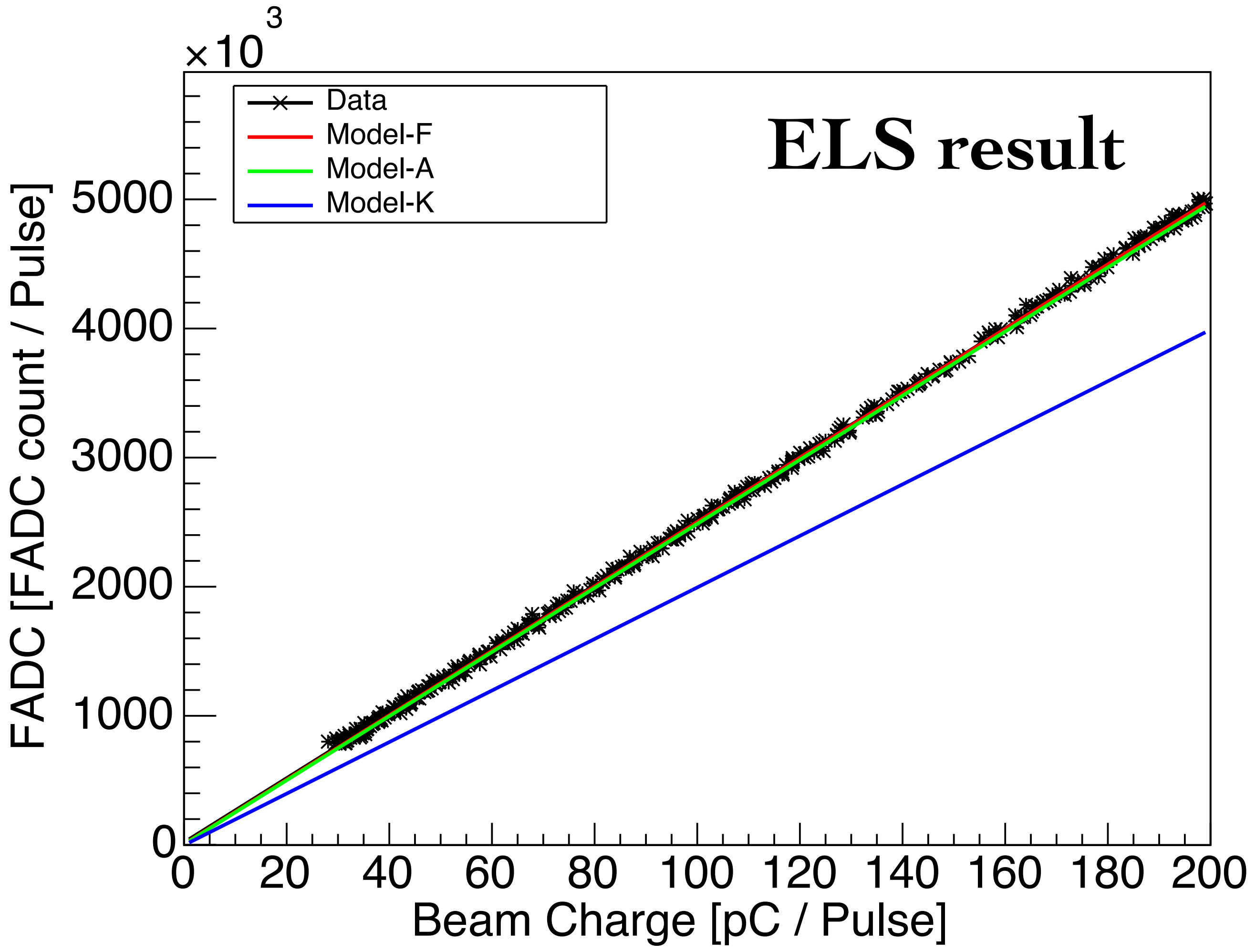


D. Ivanov et al. (Spectrum working group), ICRC 2017

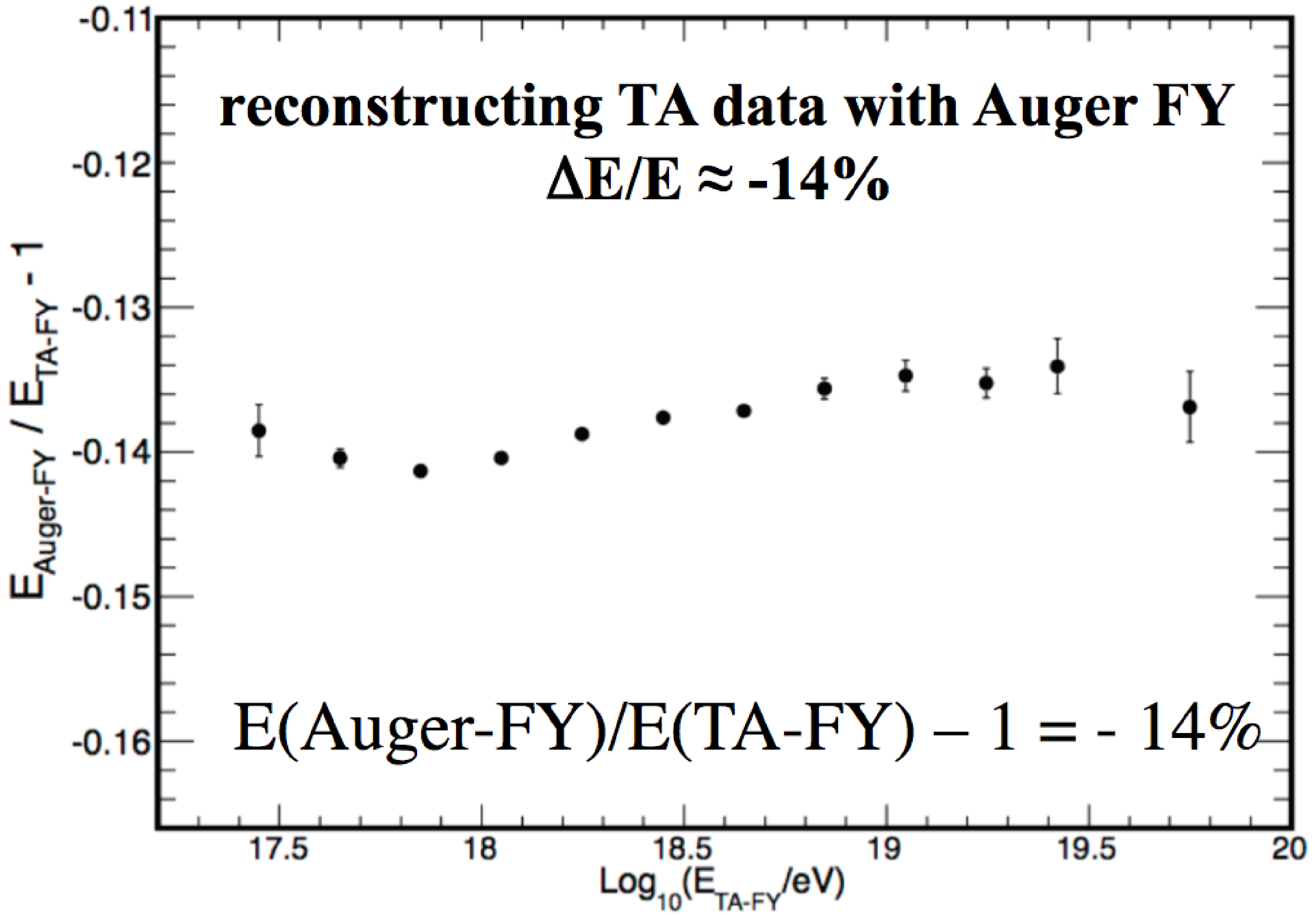


M. Ave et al. Astropart.Phys. 42 (2013) 90–102



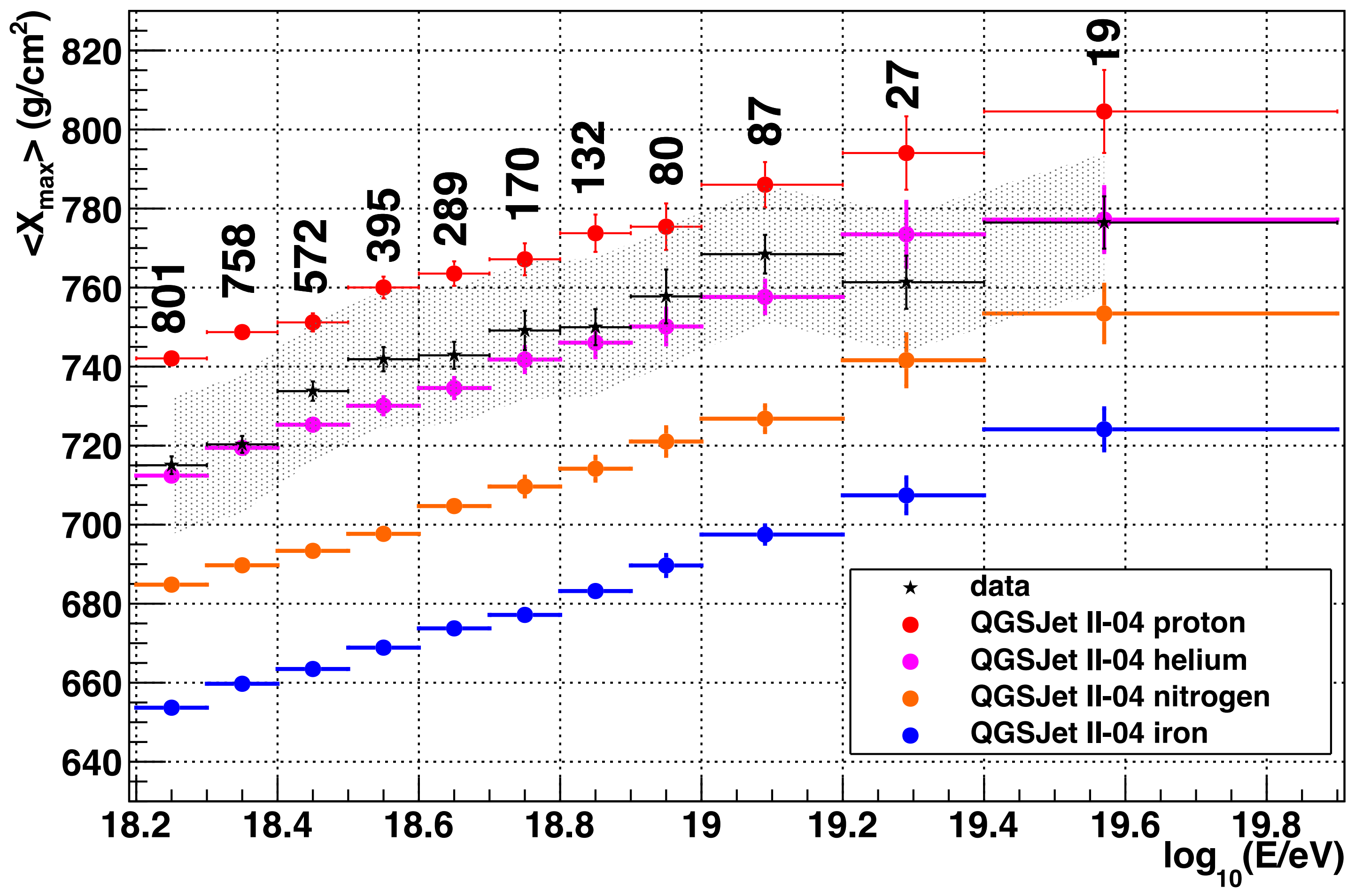


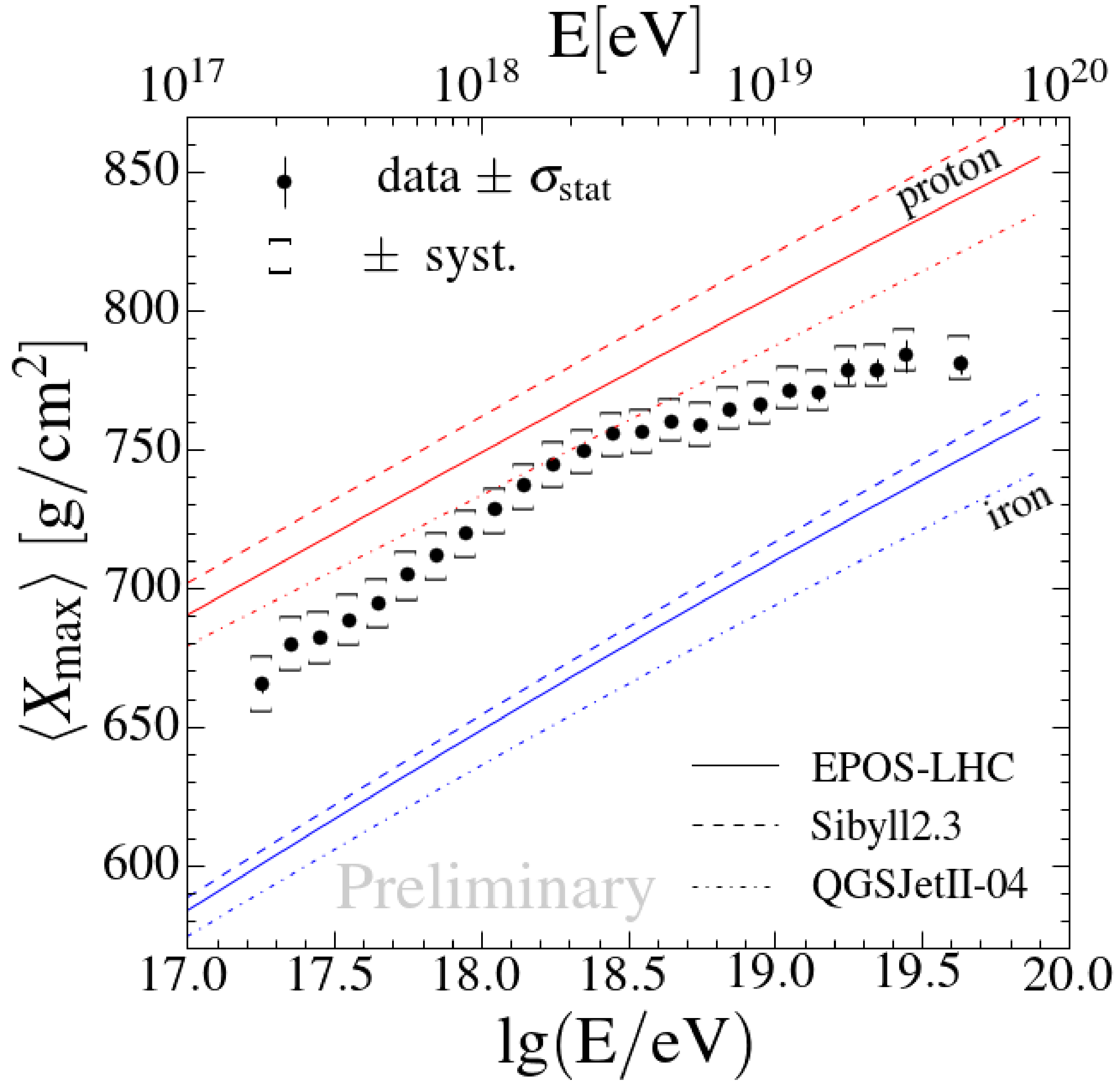
BK Shin et al., PoS (ICRC2015) 640



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

Mass composition



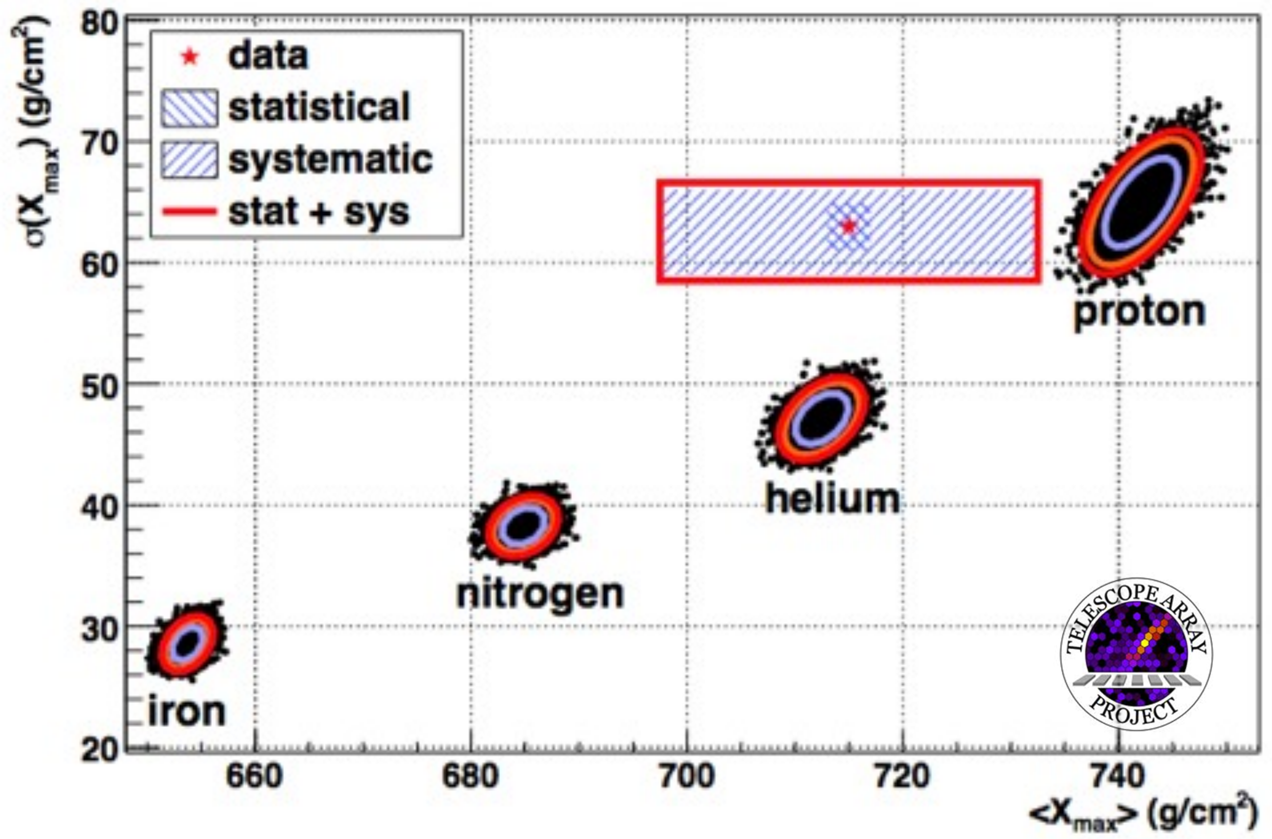


Take away message

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

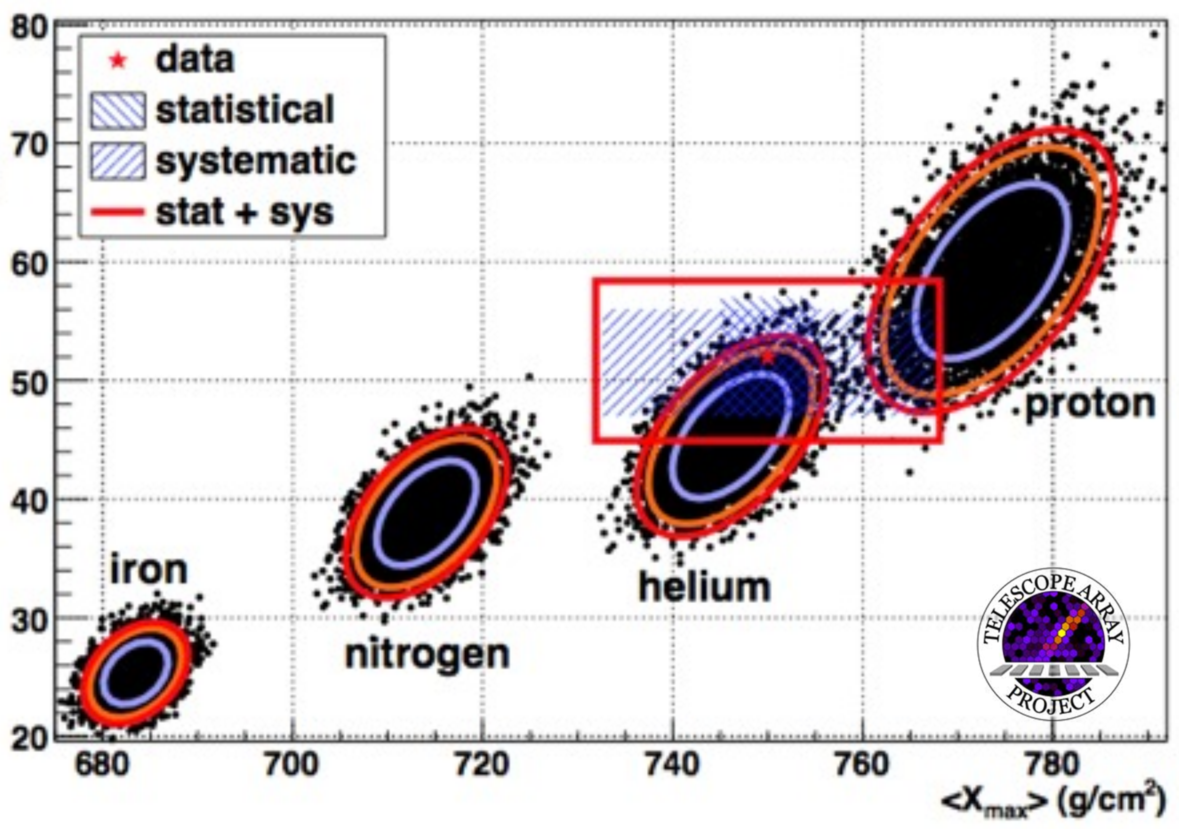
V. de Souza et al (Mass Composition WG), Proc. of ICRC 2017

$18.2 \leq \log(E) < 18.3$, $N = 801$



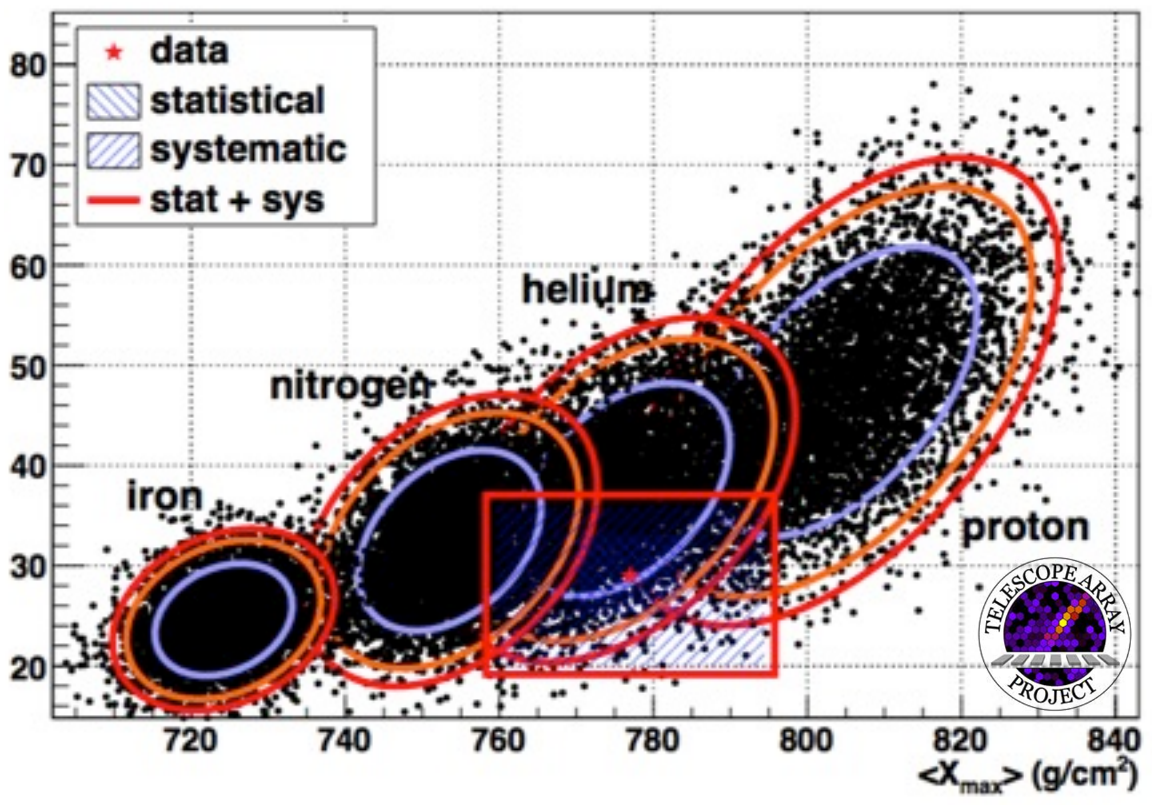
(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

$18.8 \leq \log(E) < 18.9$, $N = 132$

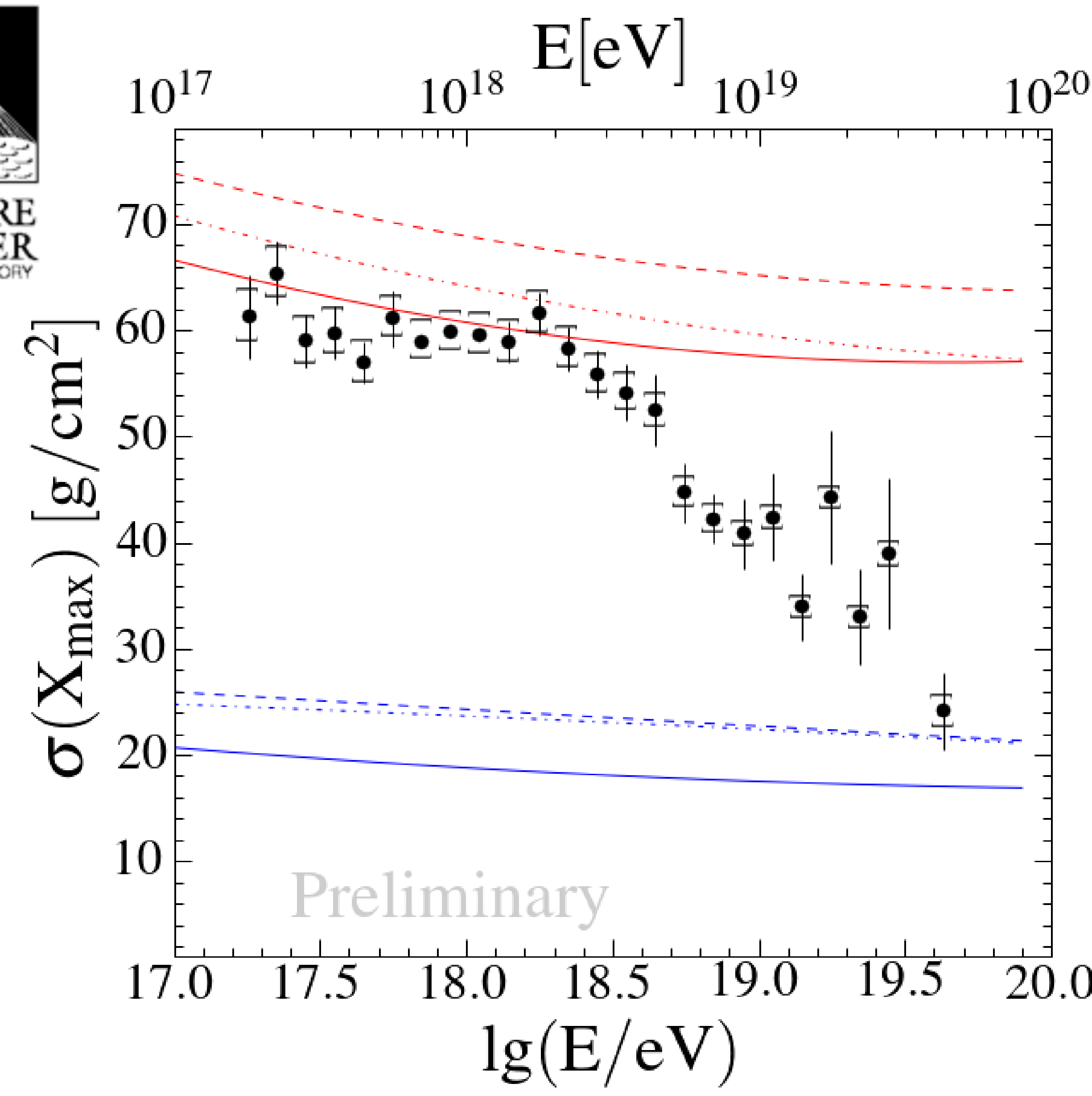


(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$

$19.4 \leq \log(E) < 19.9$, $N = 19$



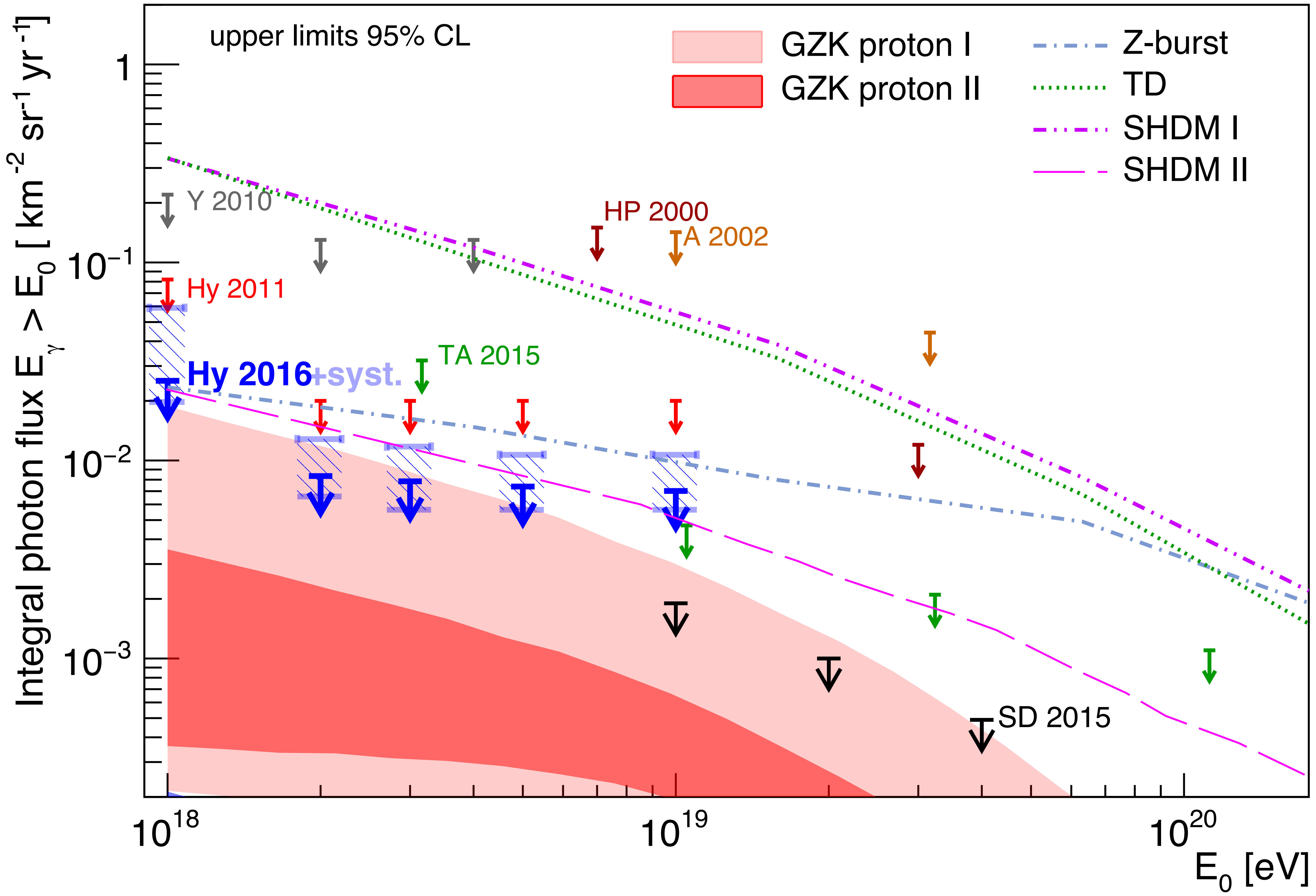
(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$



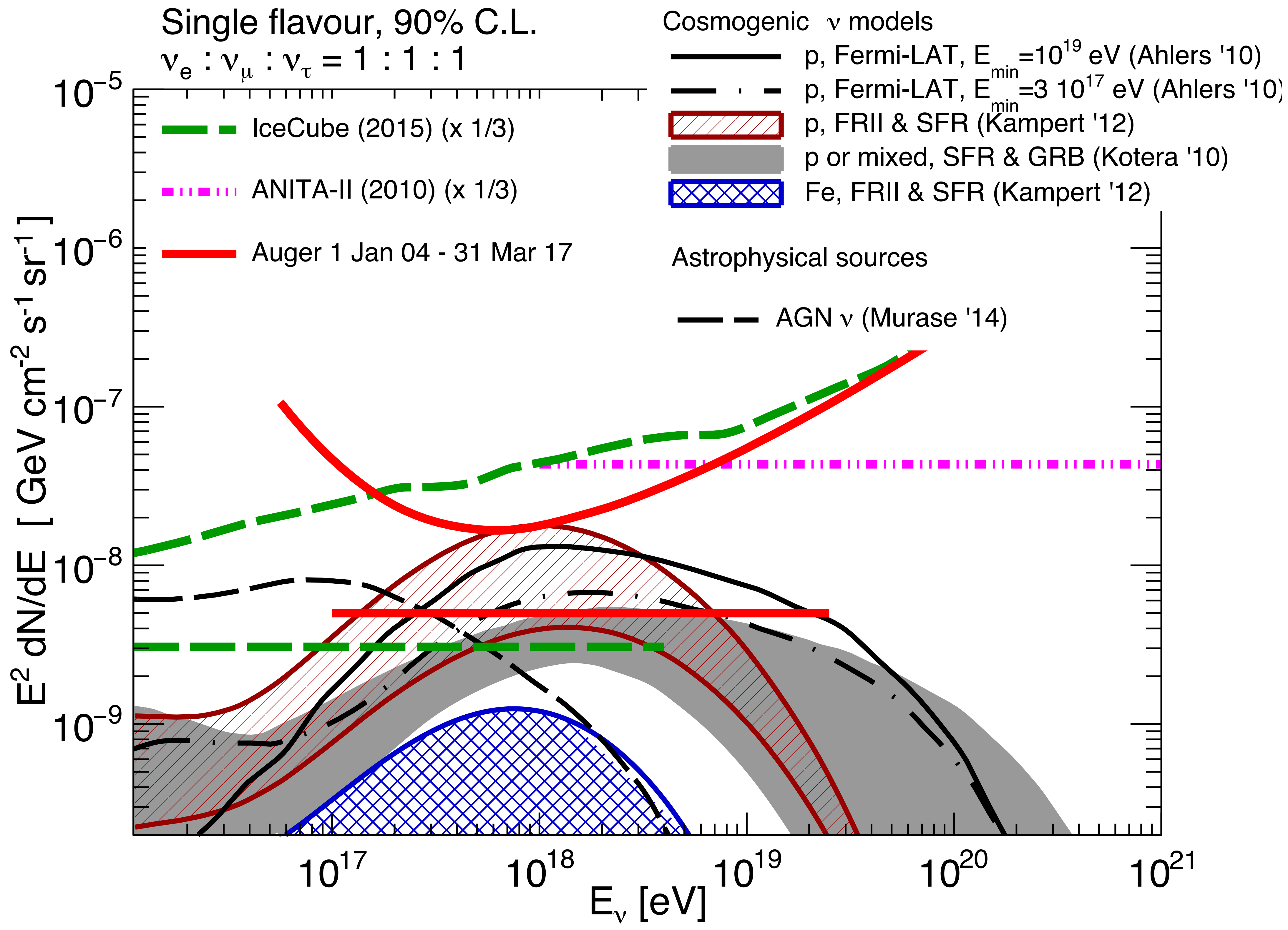
S. Ogio, ISVHECRI 2018, W. Hanlon ISVHECRI 2018, TA collab. ApJ, 858, 76(2018)

S. Petrera, ISVHECRI 2018, M. Unger et al., ICRC 2017, J. Bellido et al., ICRC 2017

No GZK γ and ν at the highest energies



Pierre Auger collab., JCAP04 (2017) 009



E. Zas, Proc. of ICRC 2017

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

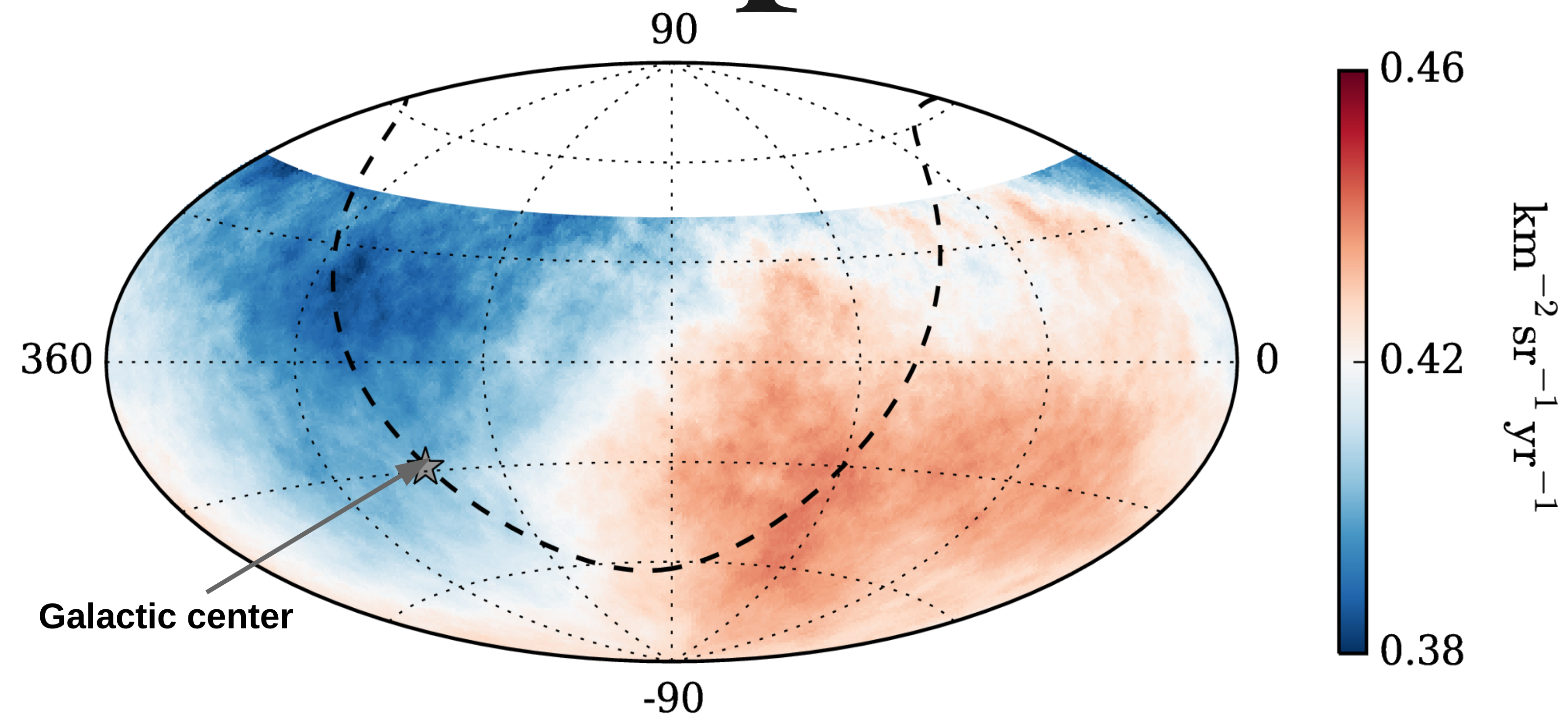
M. Unger, Proc of ICRC 2017

Large/intermediate scale anisotropies

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

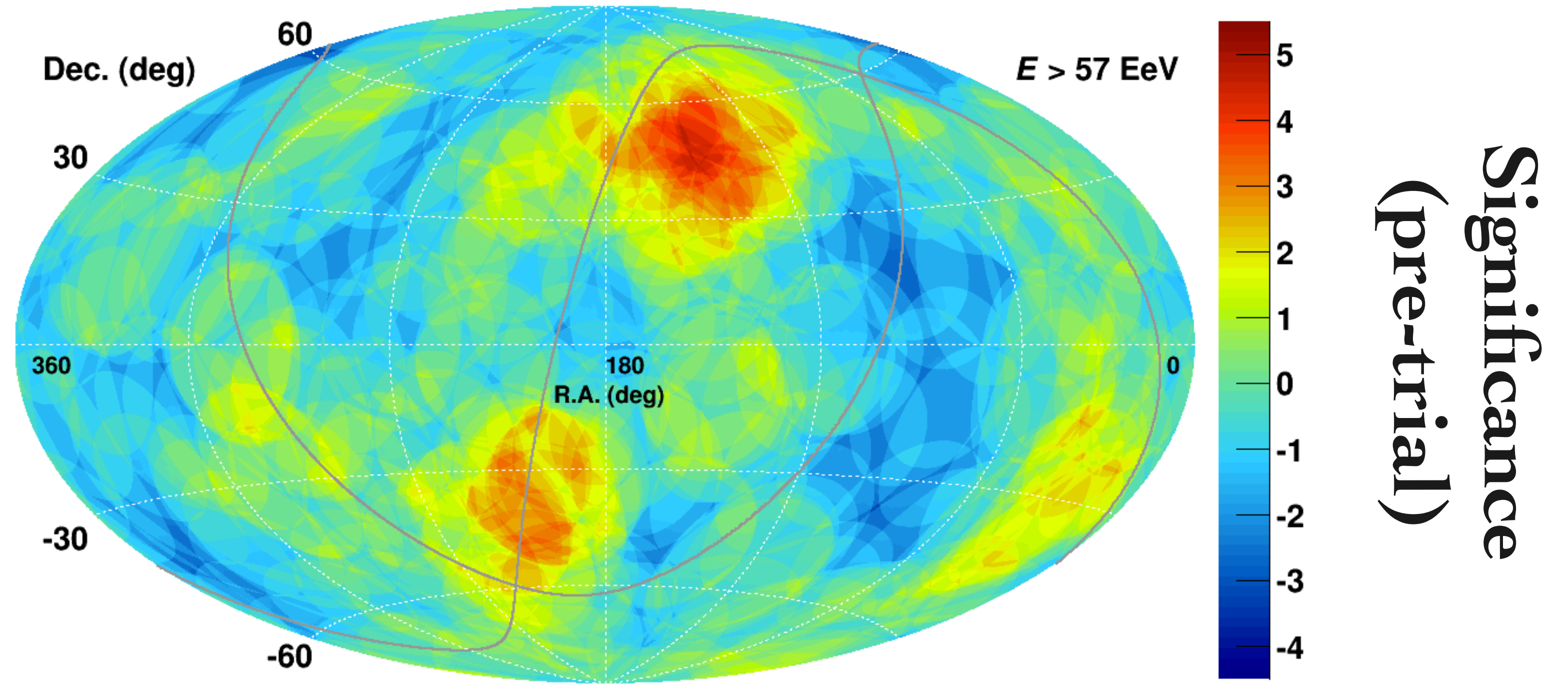
Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

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



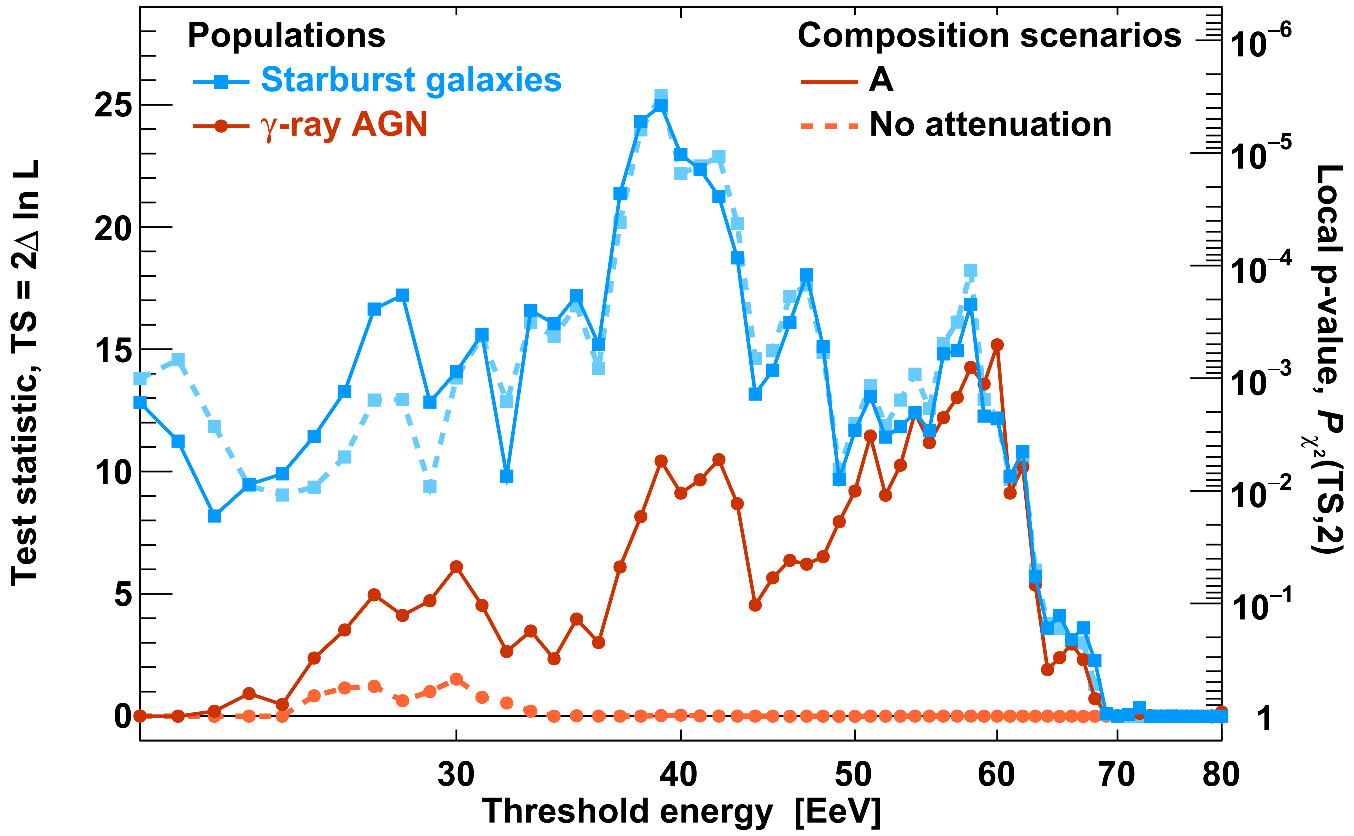
Pierre Auger collab. Science 357, 1266 (2017)

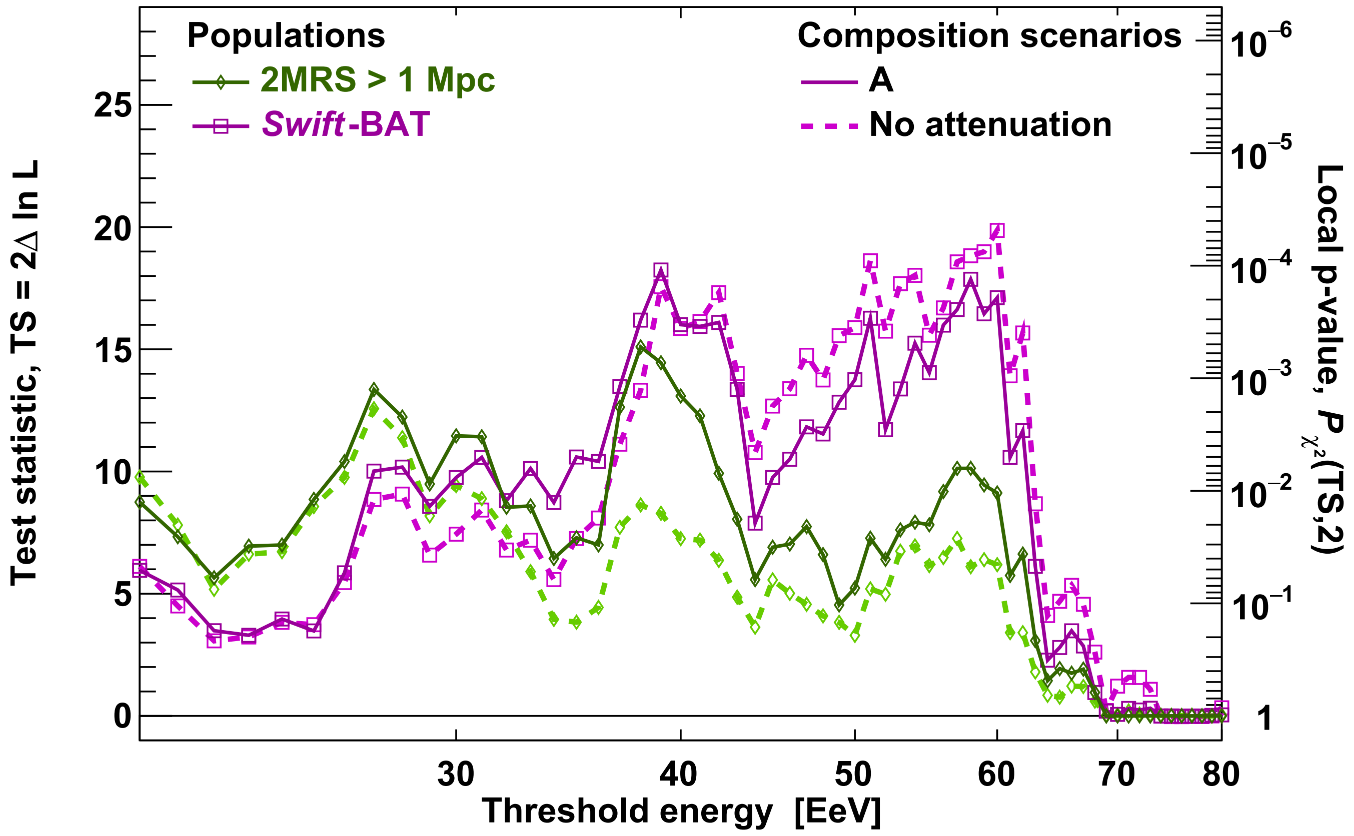
- **TA Hotspot**: E > 57 EeV, **3.4σ** anisotropy [TA collab. ApJL, 790:L21 (2014)]
- TA (7 years, 109 events above 57 EeV)+ Auger(10 years, 157 events above 57 EeV), 20° circle oversampling
  - E > 57 EeV, no excess from the Virgo cluster



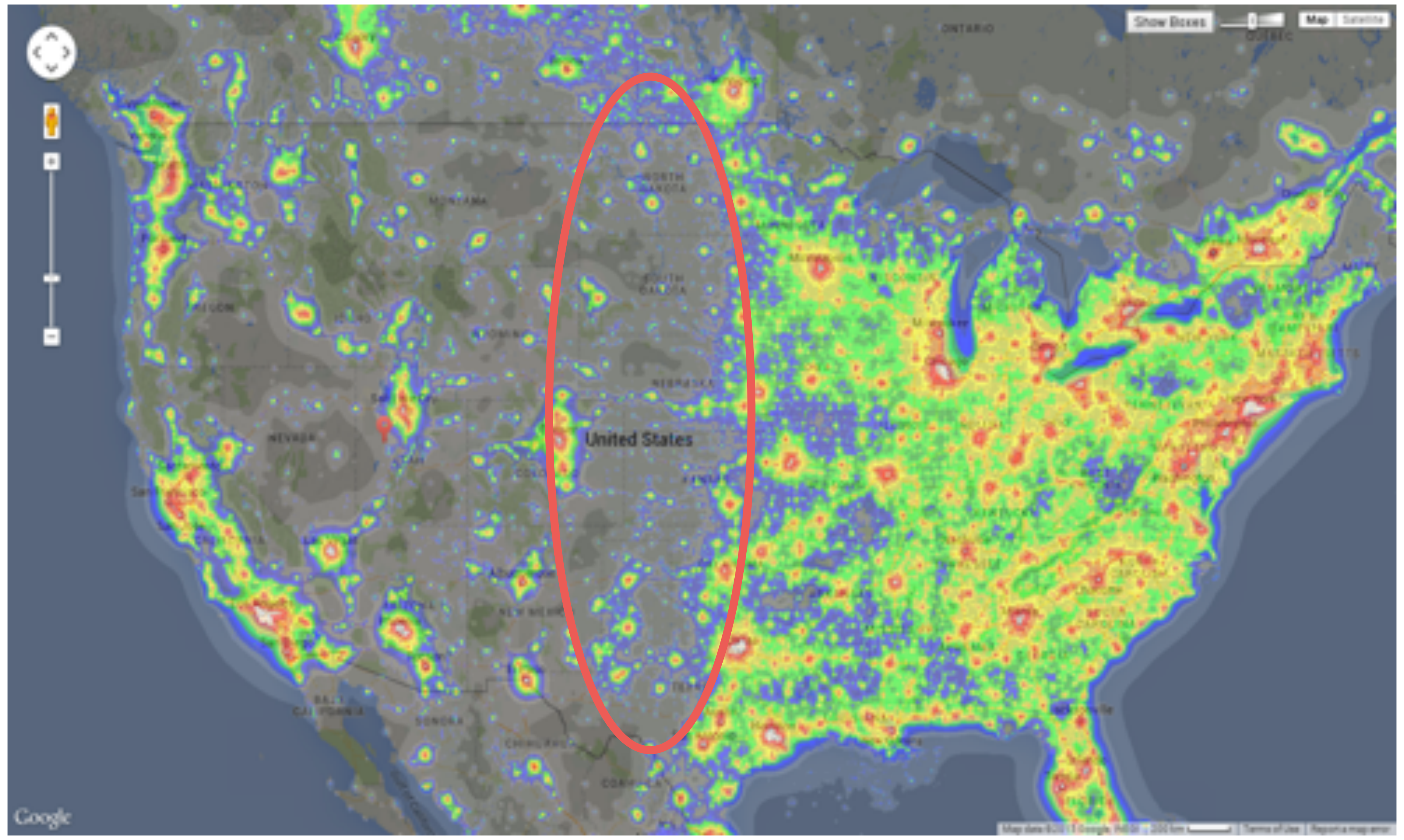
K. Kawata et al., Proc. of ICRC 2015

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

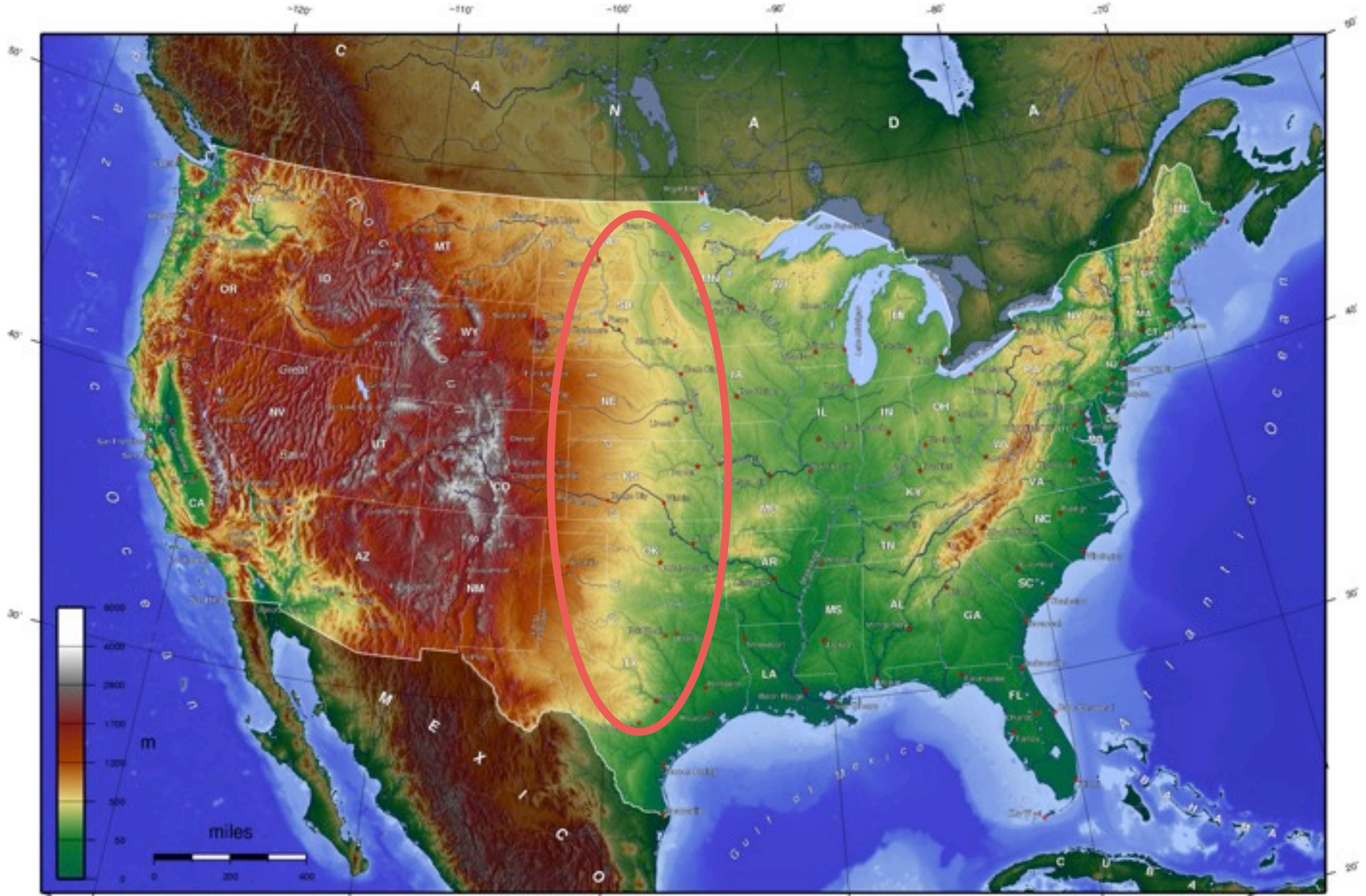




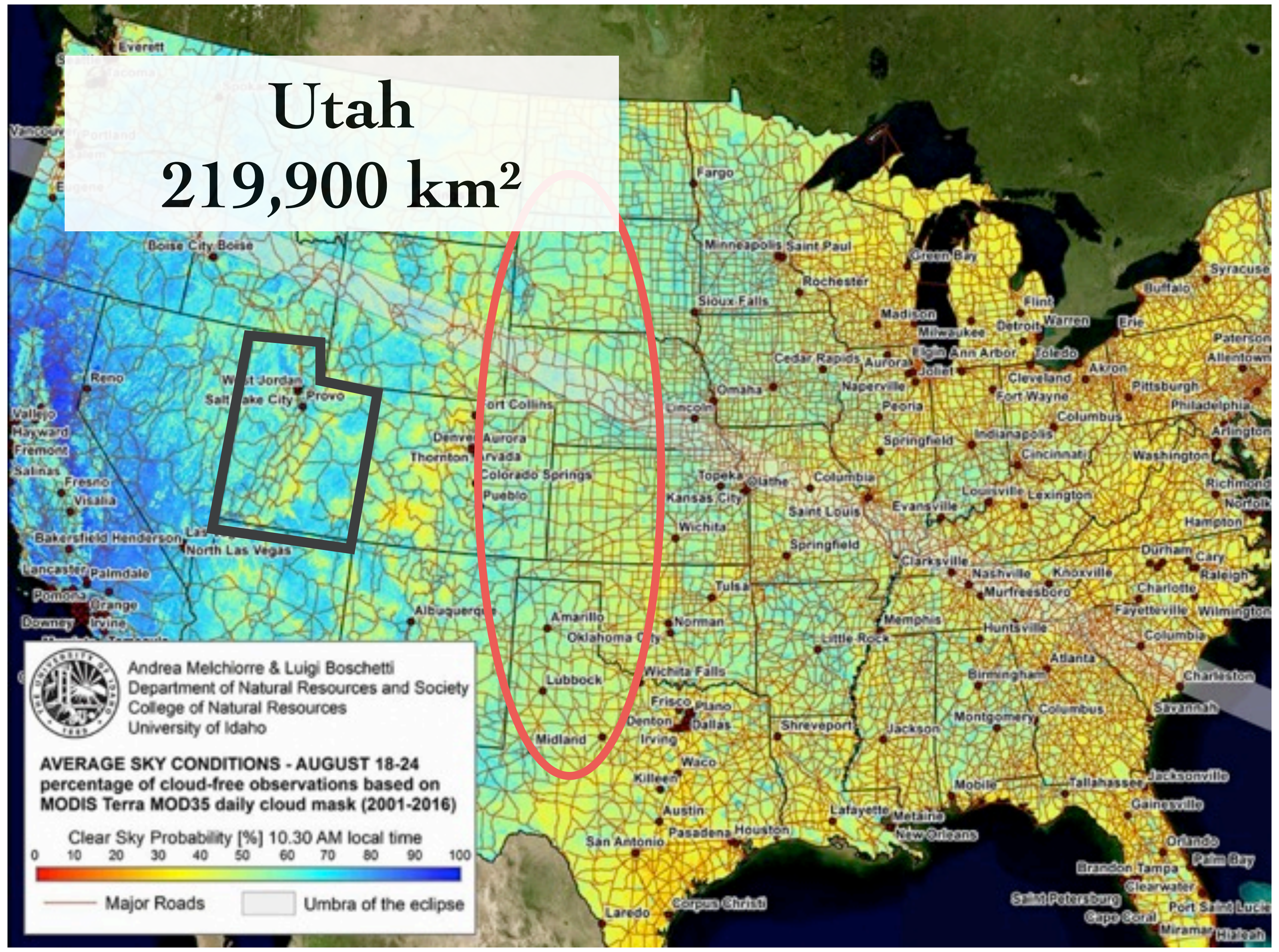
Possible sites



U.S. Light Pollution Map



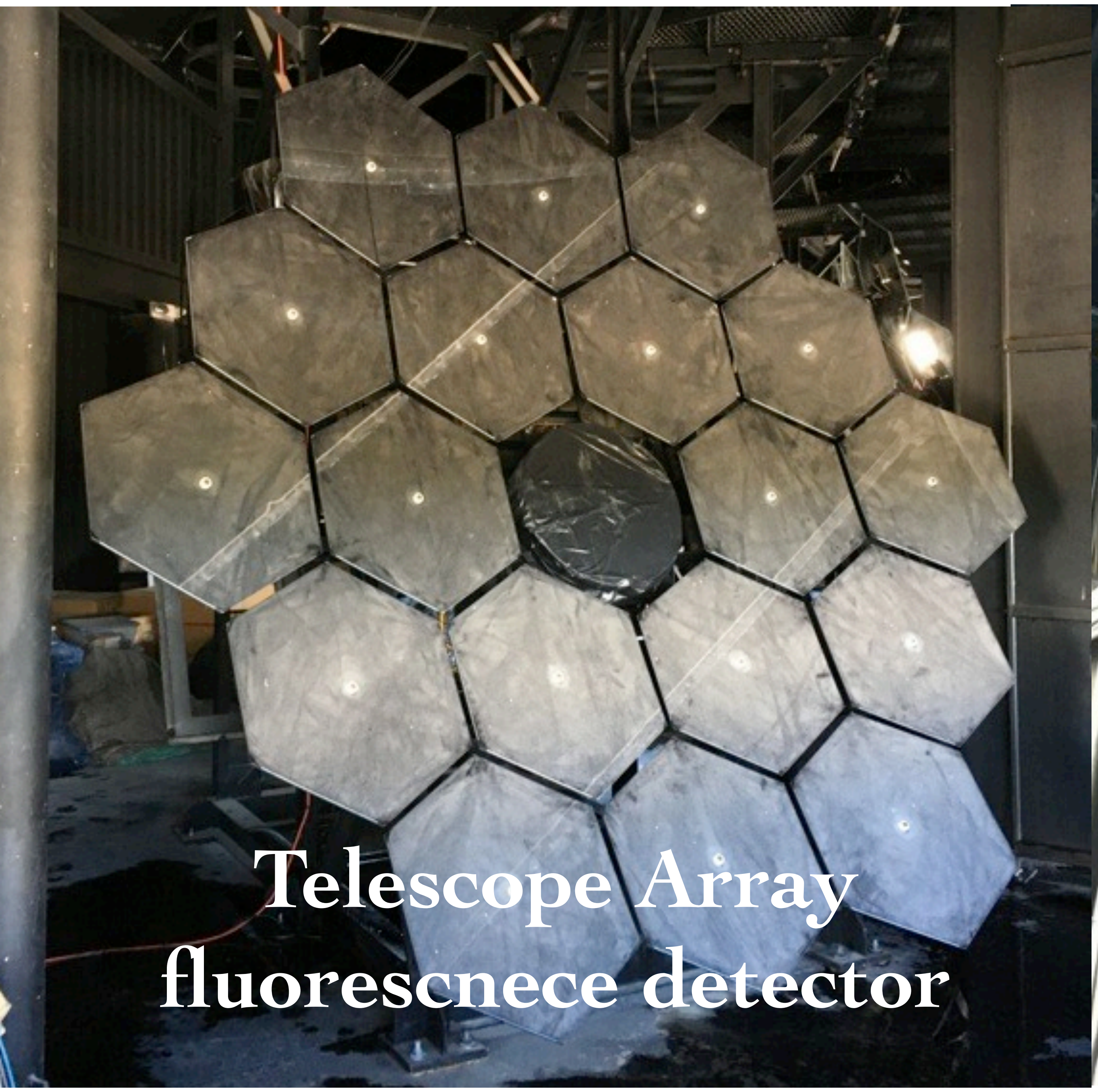
FAST area

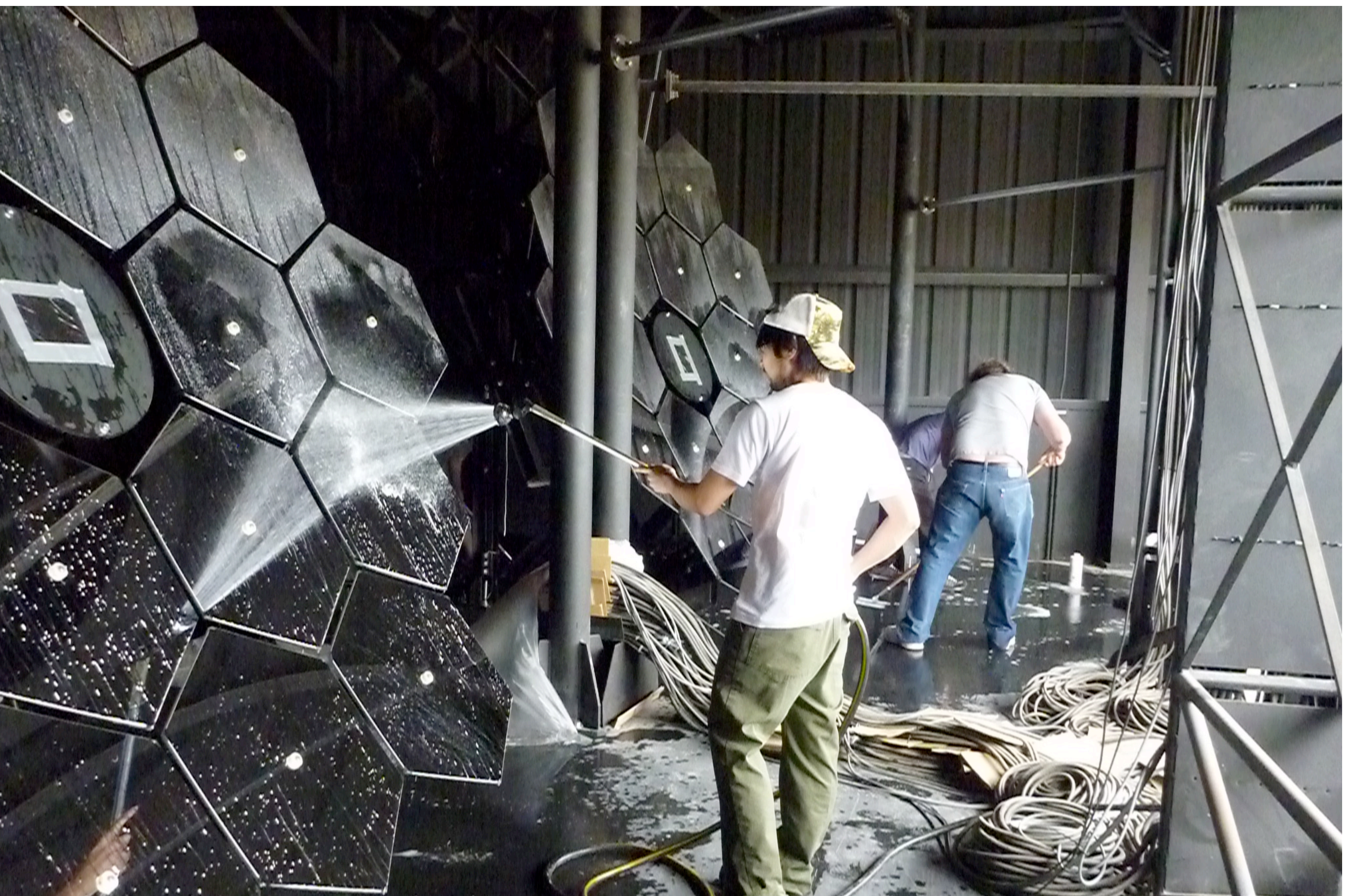


- Possible sites
  - Northern: USA
  - Southern: Argentina

FAST
Fluorescence detector Array of Single-pixel Telescopes

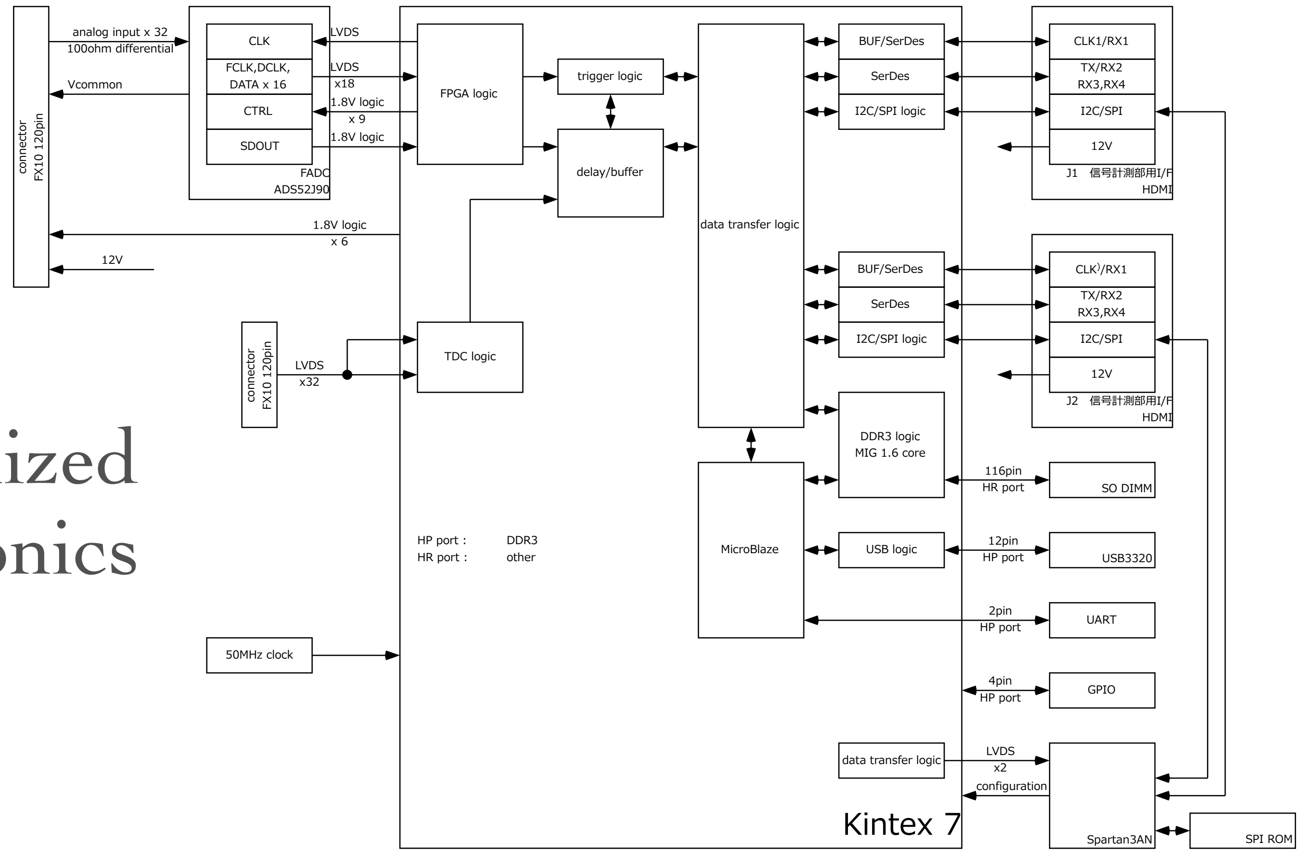
Challenges for fluorescence detectors





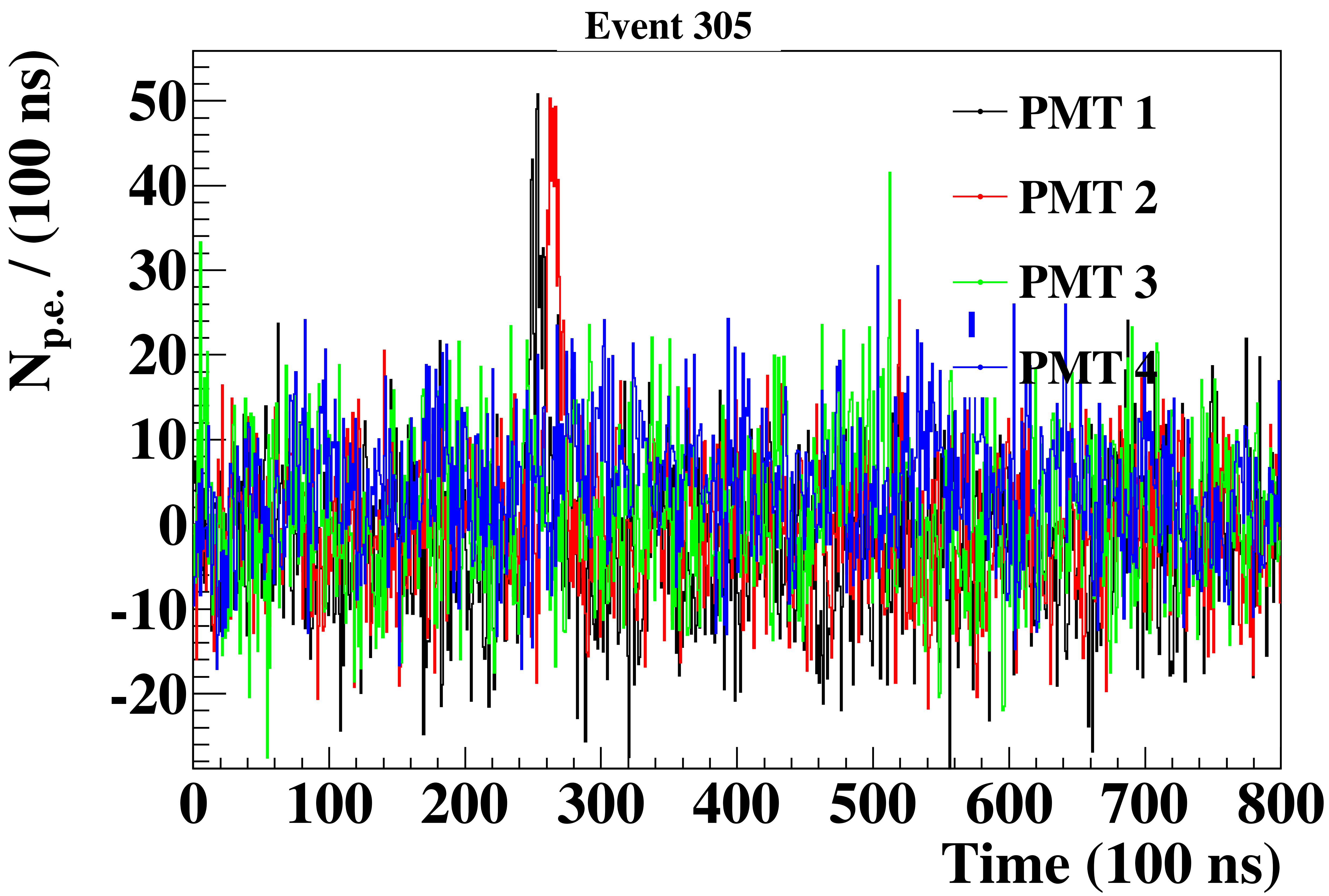
- ✦ Maintenance-free detector
- ✦ Automated operation in the night, fail safe to protect detector
- ✦ Powered by solar panel and batteries and DAQ via wireless-LAN

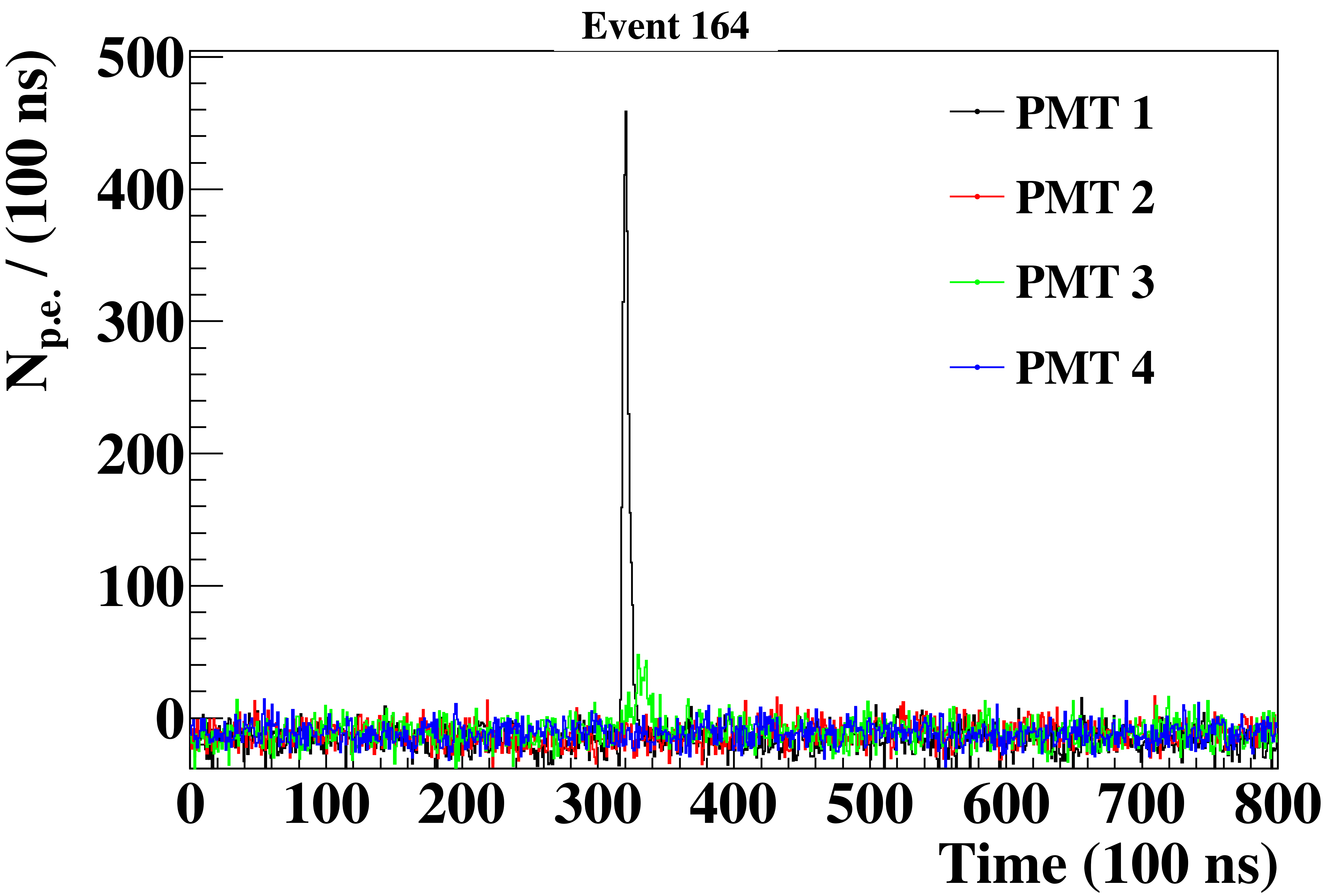
Optimized electronics

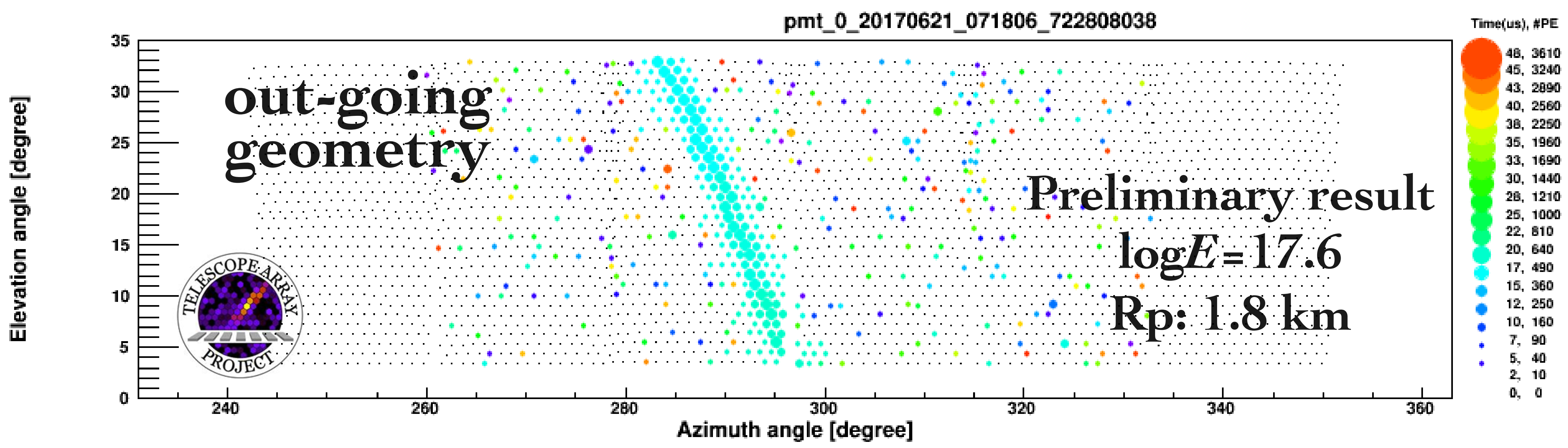


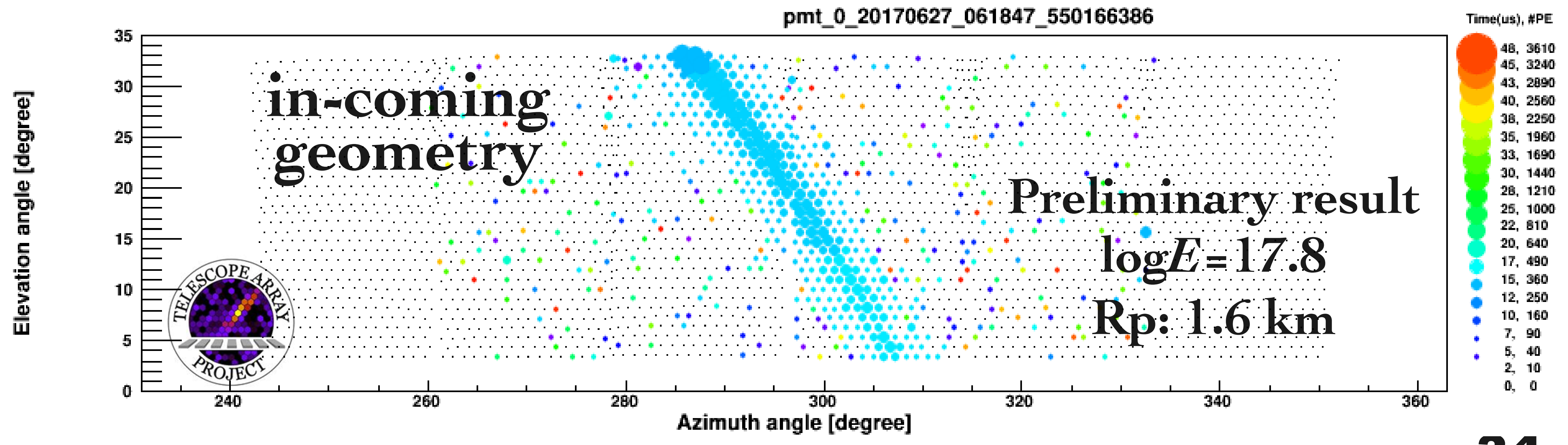
UHECR events

Comparison with TA FD result





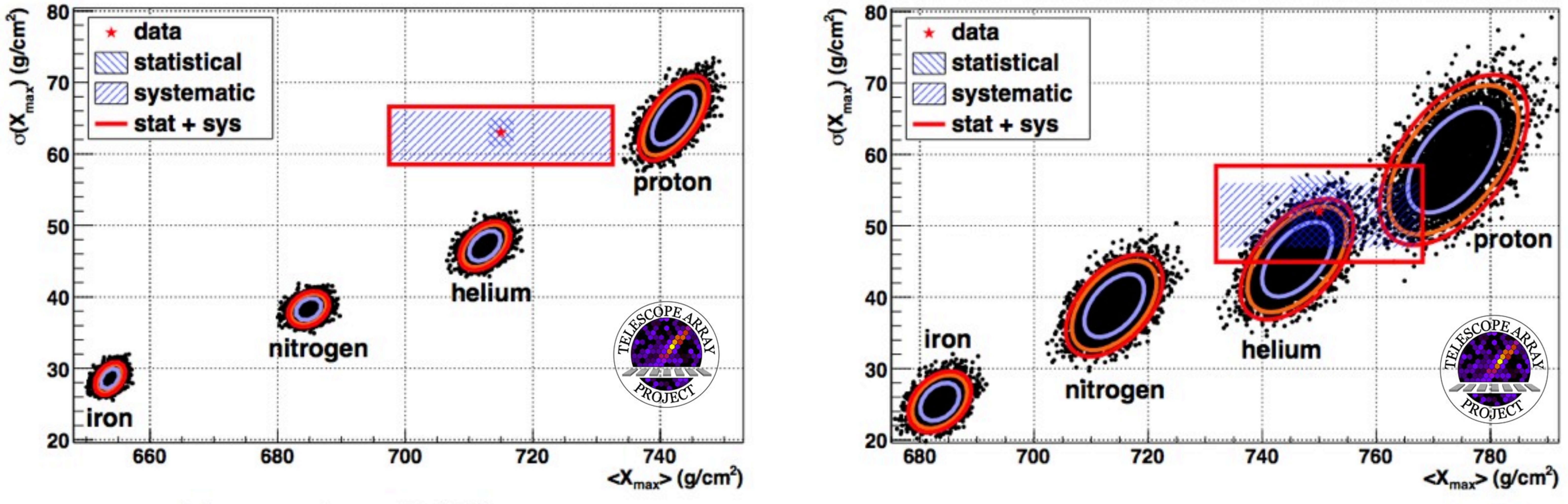




Mass composition (width of *X*max distribution)

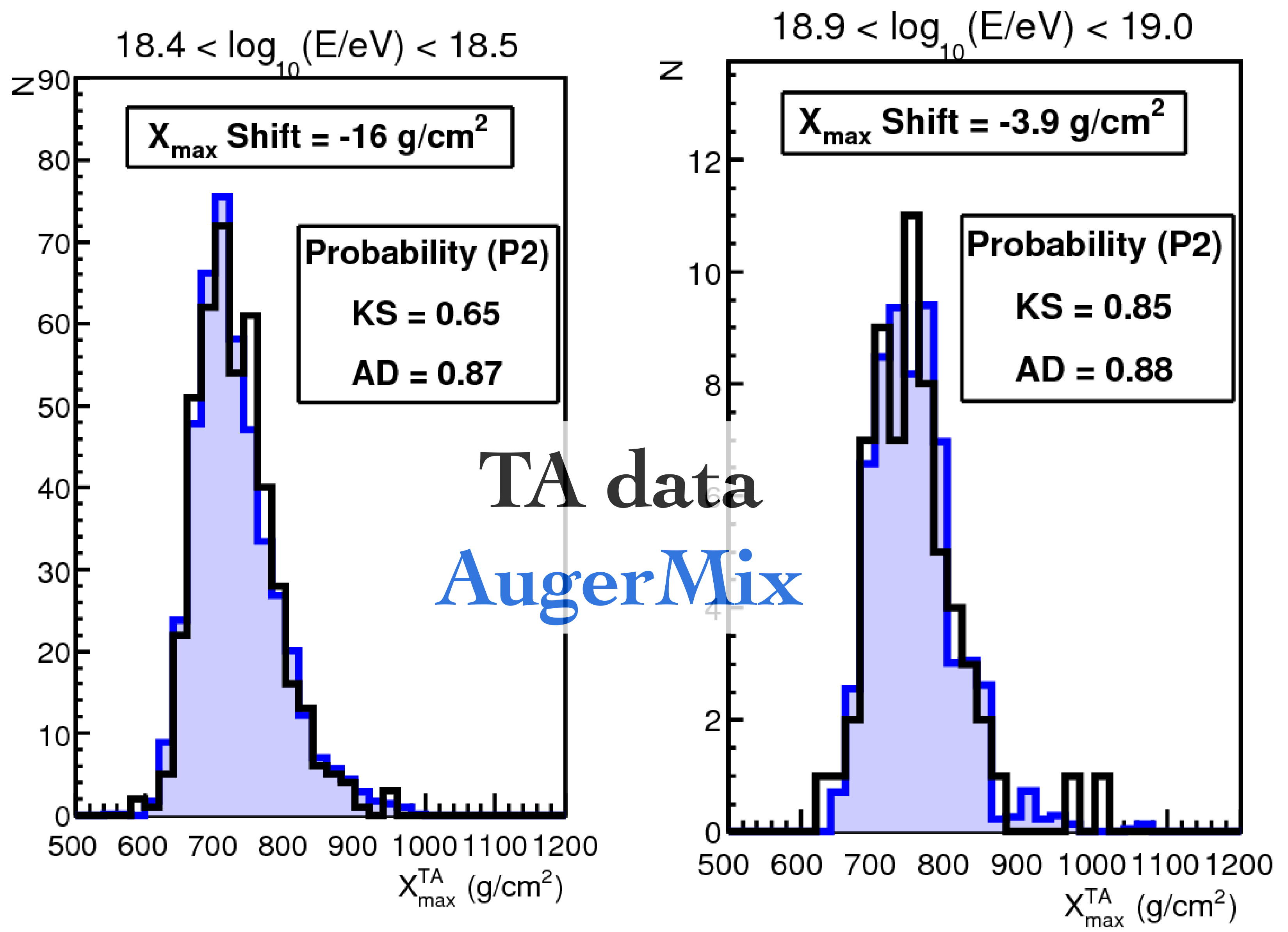
N = 801 events

N = 132 events



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

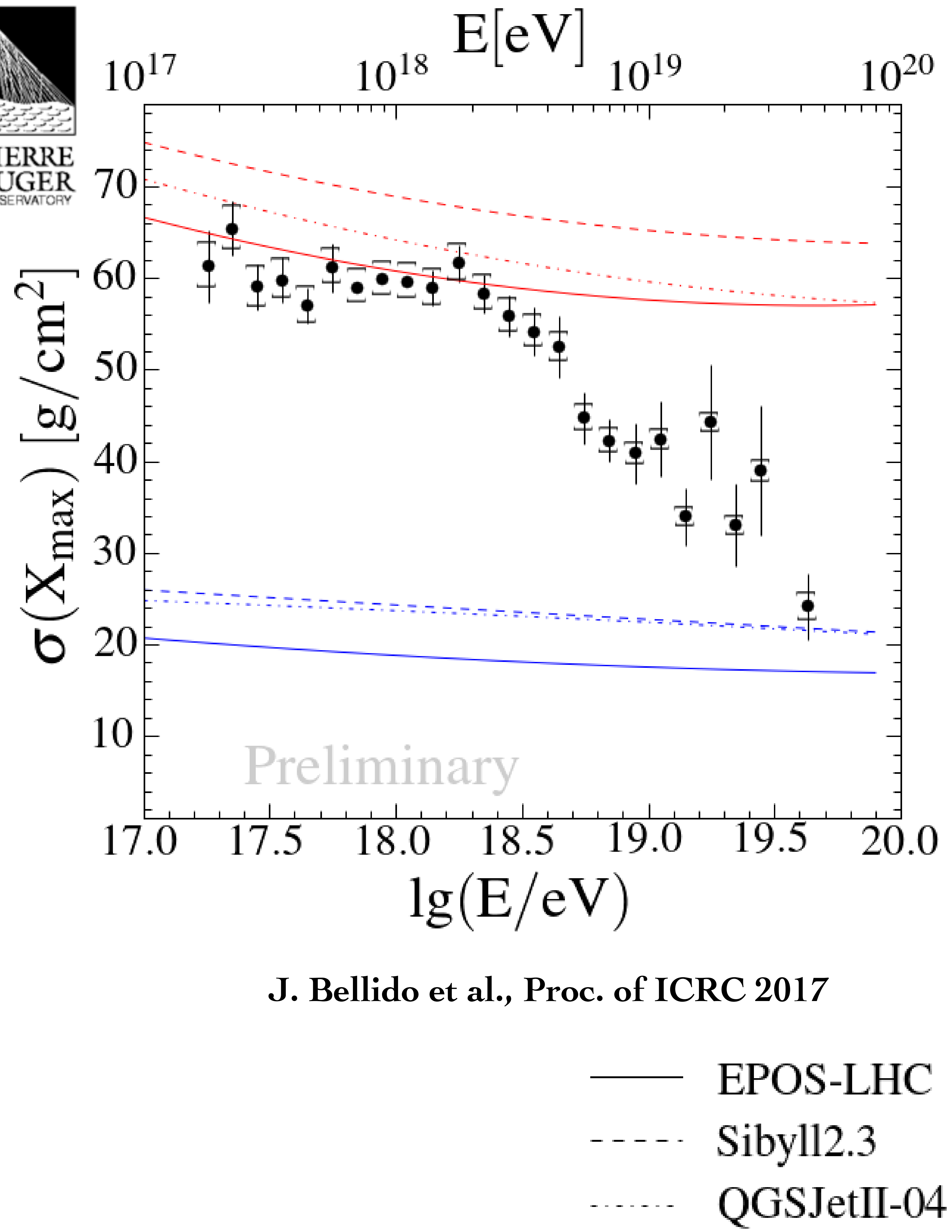
(a) $18.8 \le \log_{10}(E/\mathrm{eV}) < 18.9$



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

Take away message

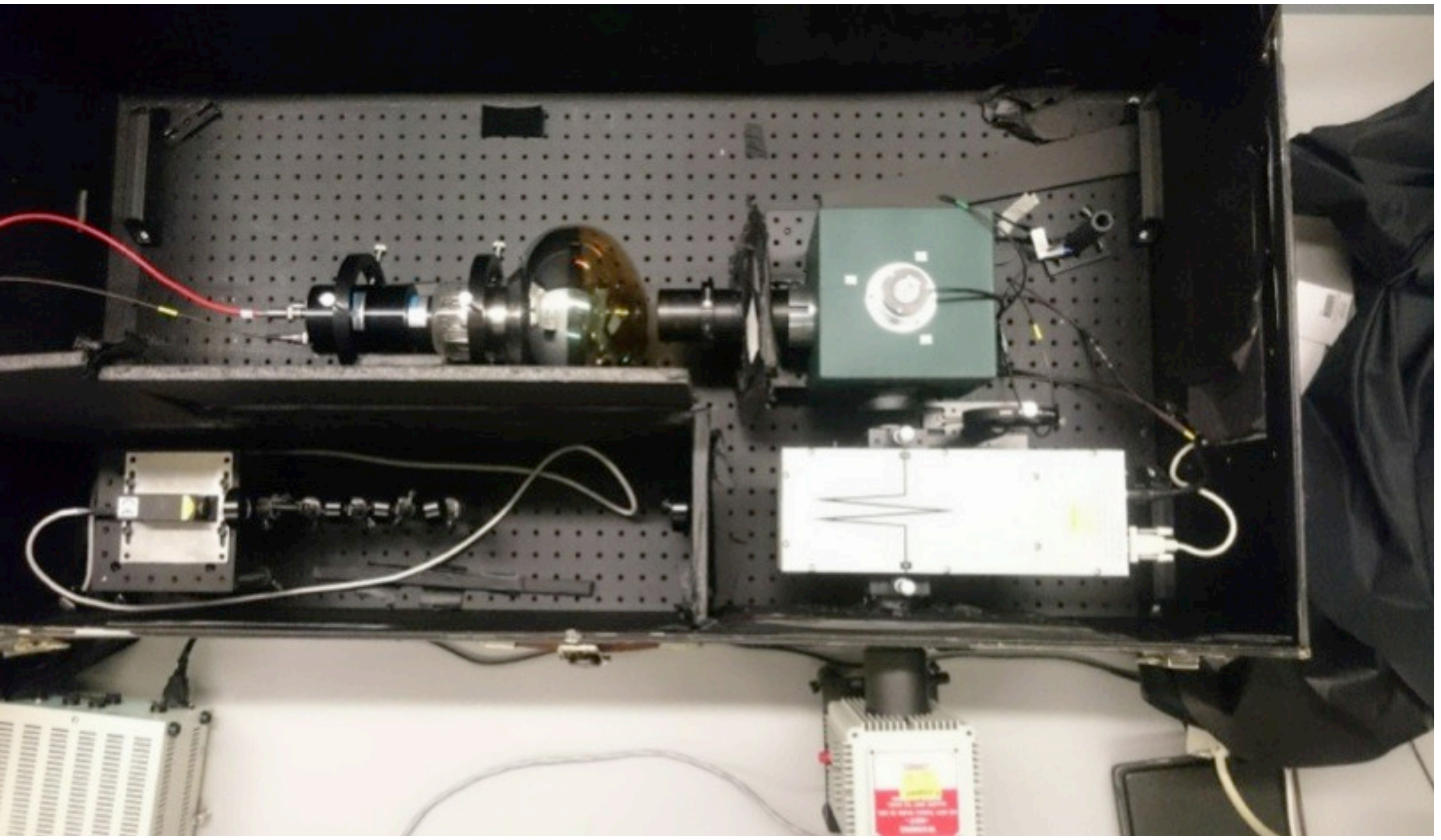
TA and Auger
composition measurements (Xmax)
agree within the systematics
$18.2 < \log_{10}(E/\mathrm{eV}) < 19.0$



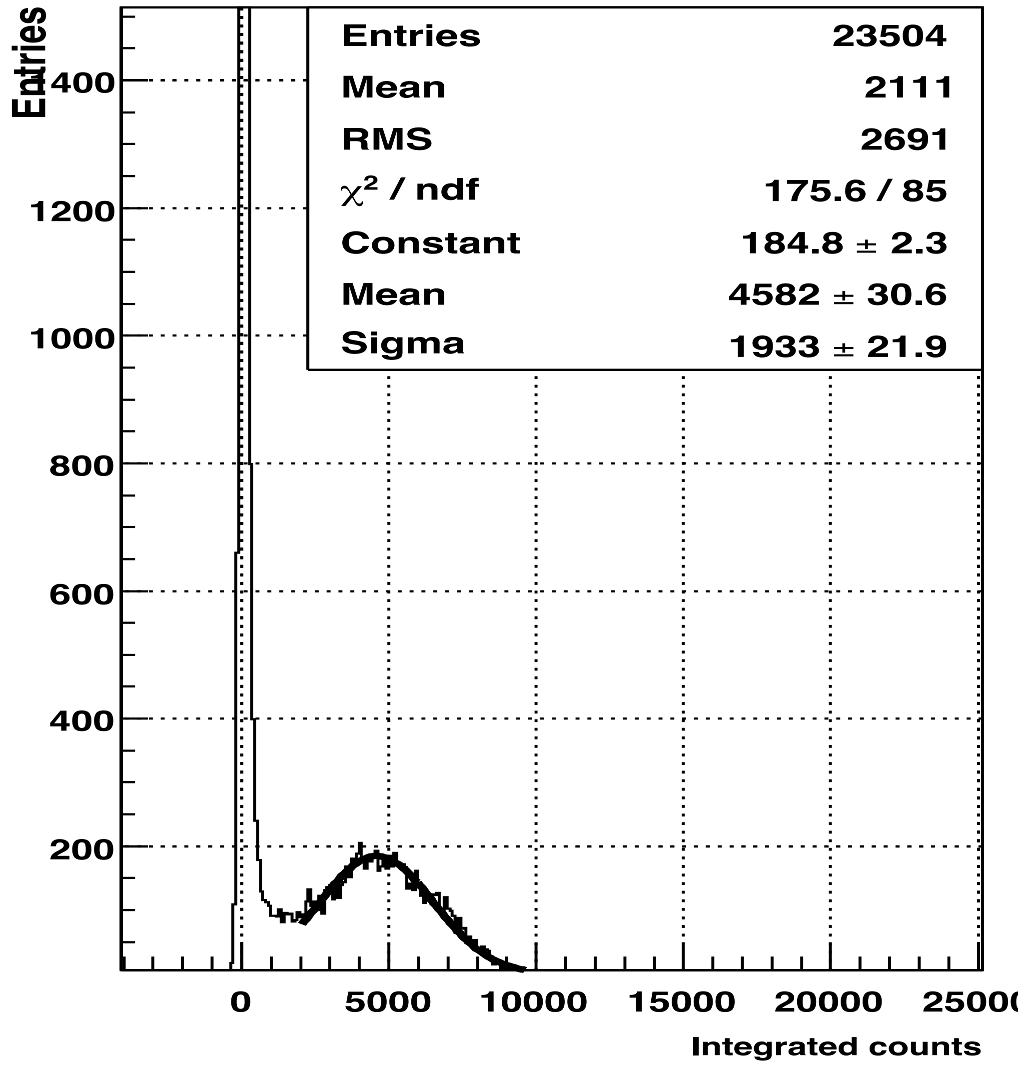
J. Bellido et al., Proc. of ICRC 2017

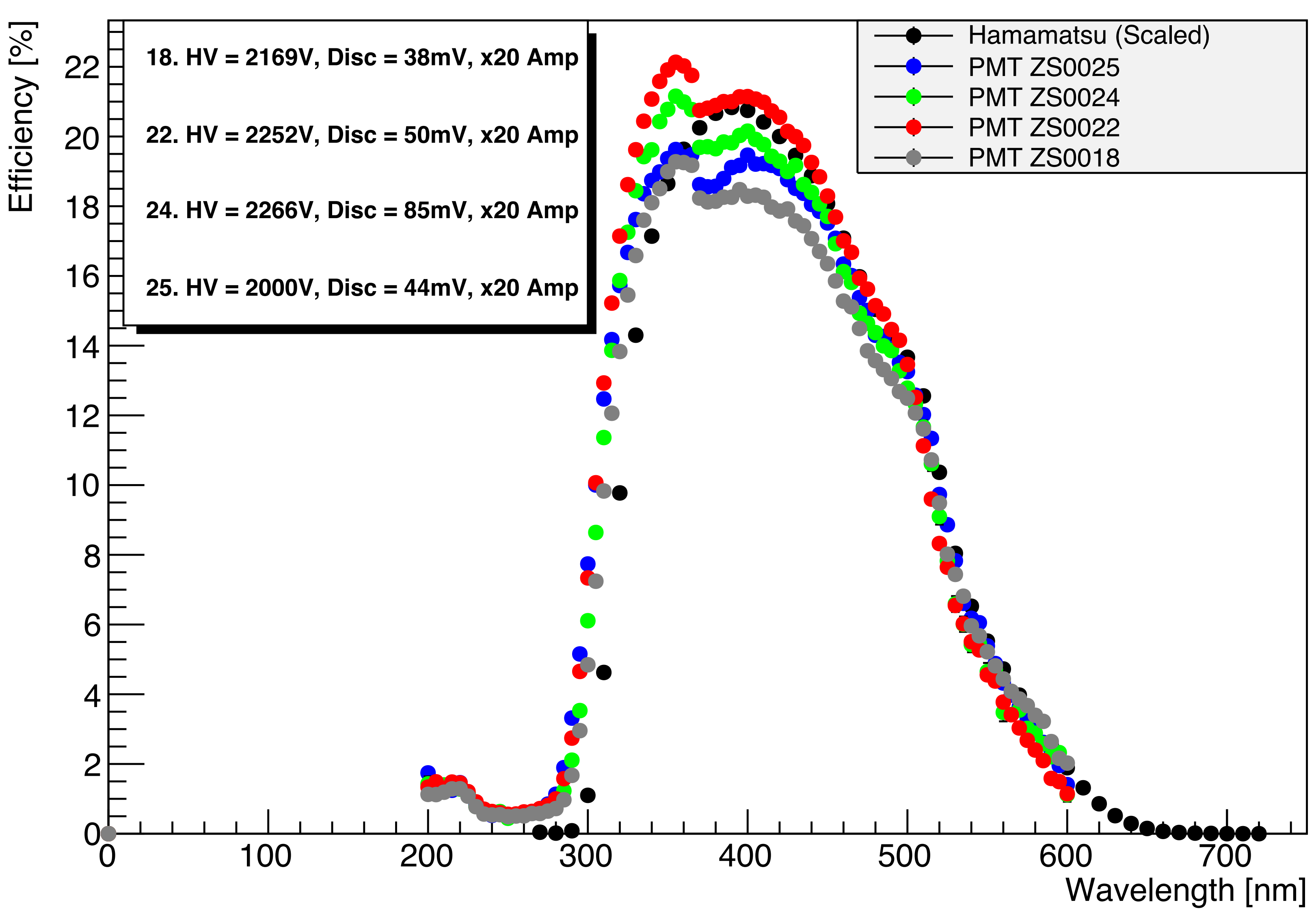
Fluorescence detector Array of Single-pixel Telescopes

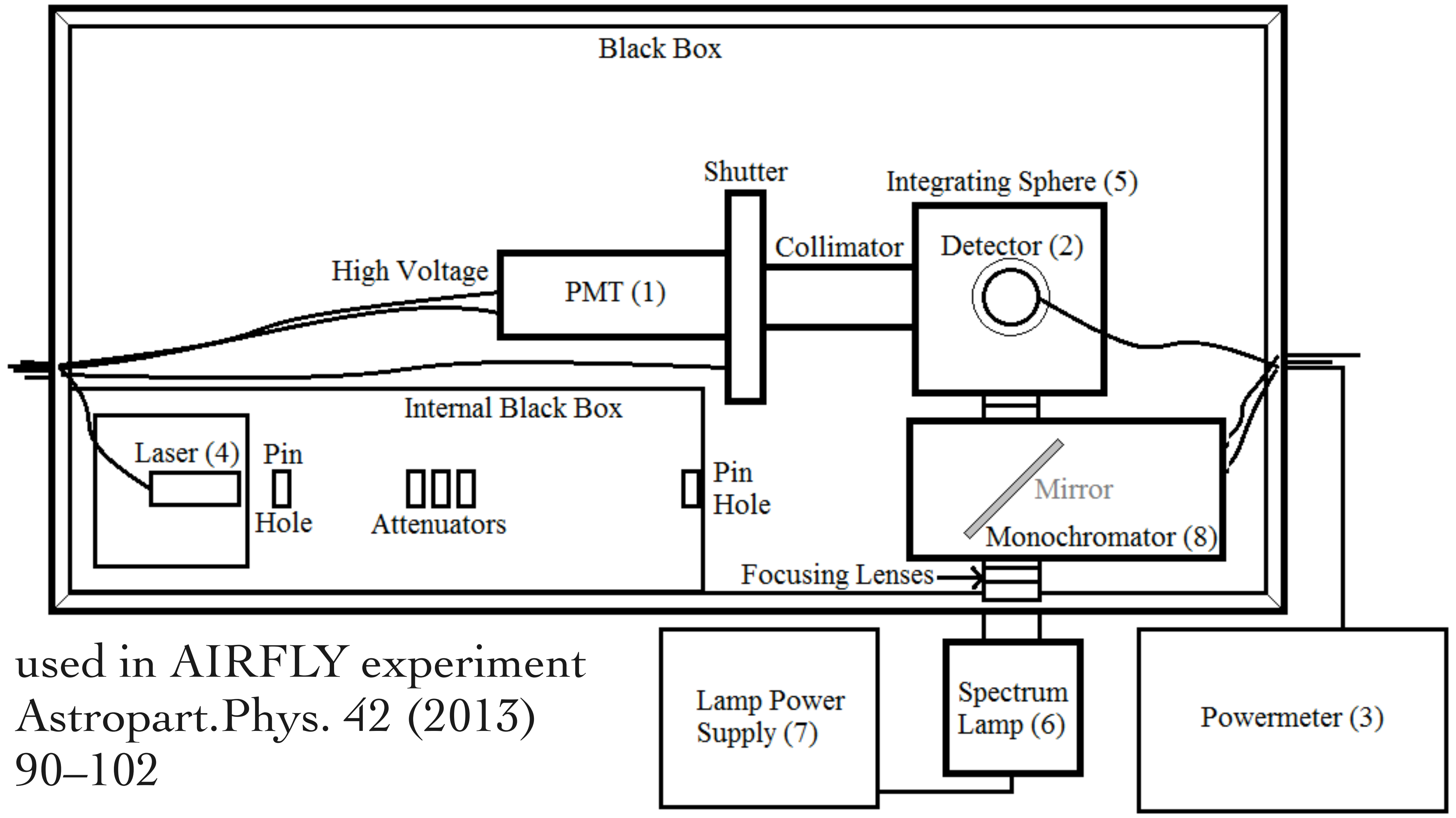
PMT Calibration of FAST



Single photo electron

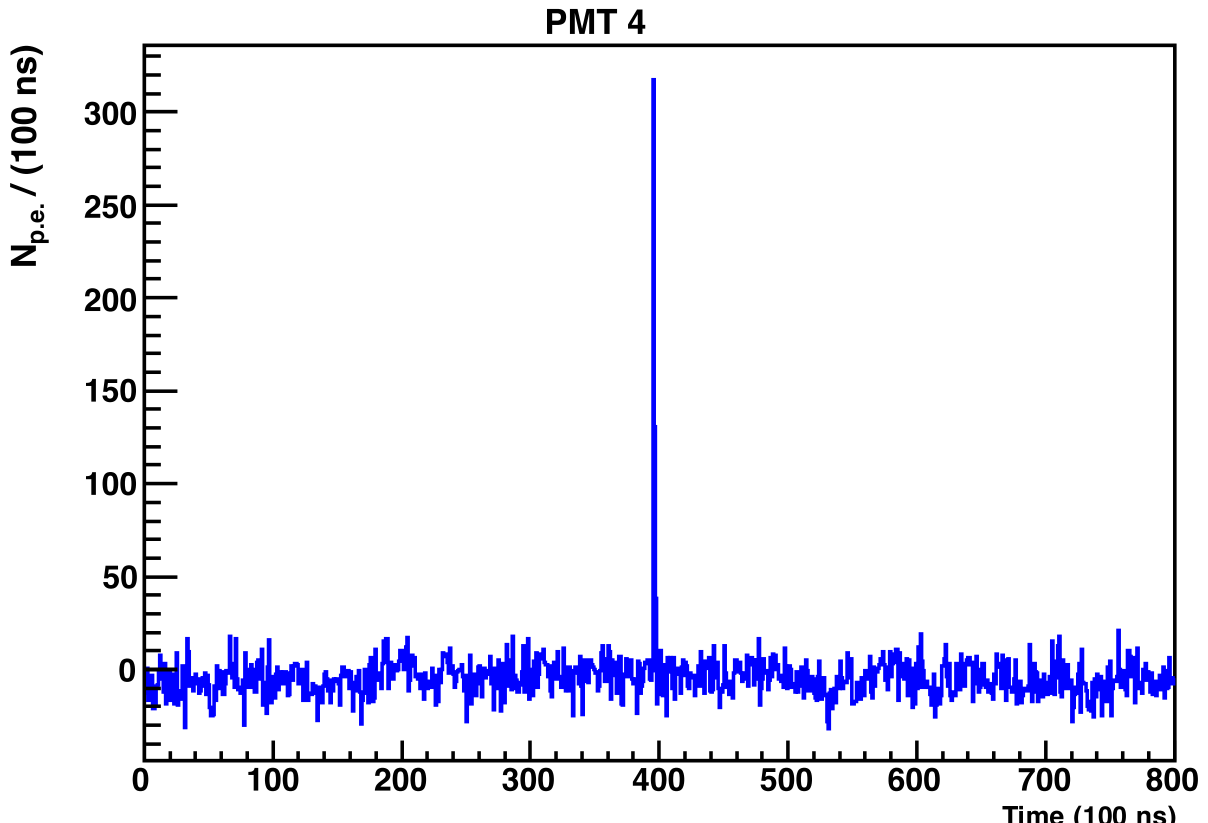




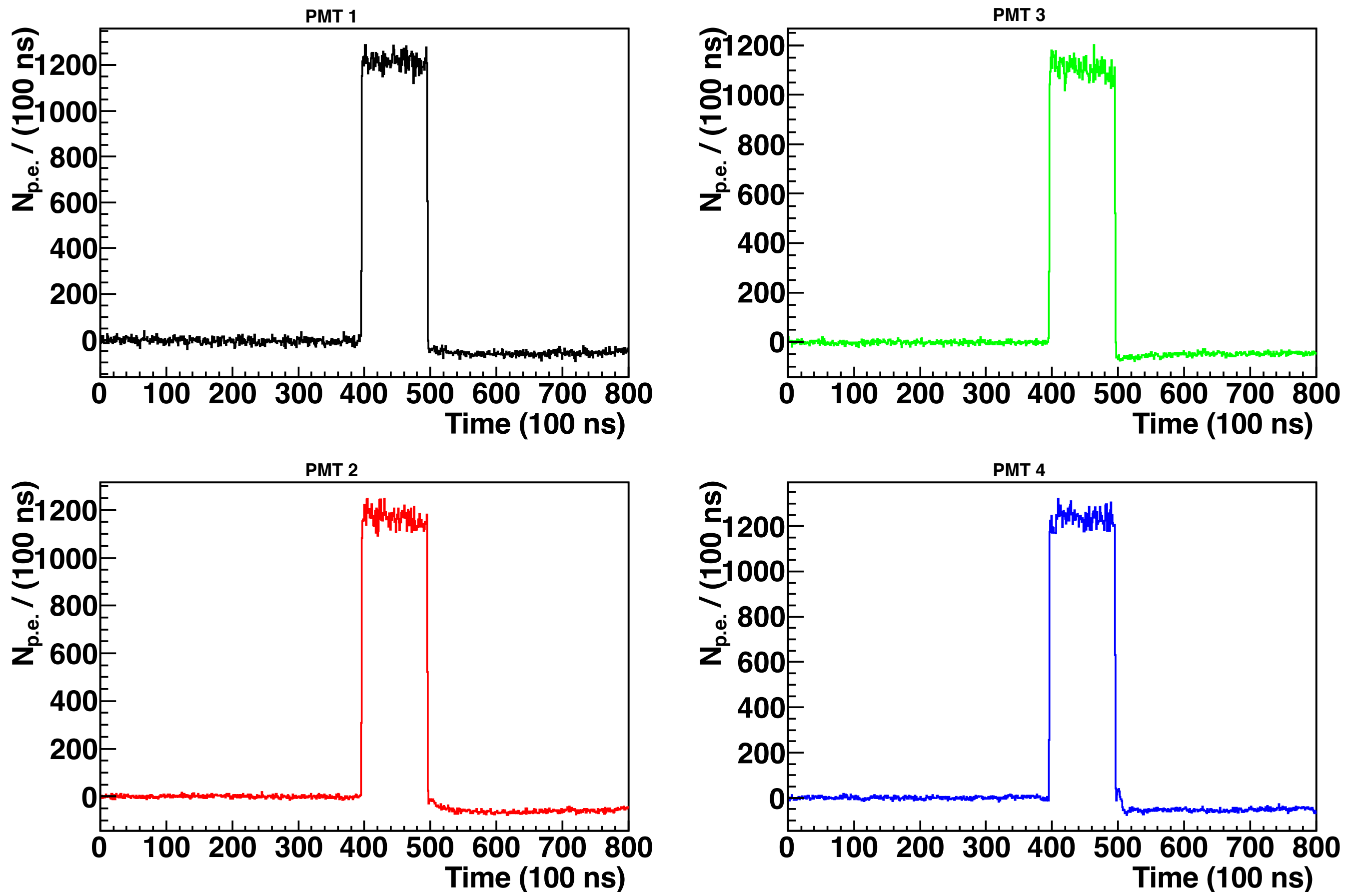


used in AIRFLY experiment
Astropart.Phys. 42 (2013)
90–102

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

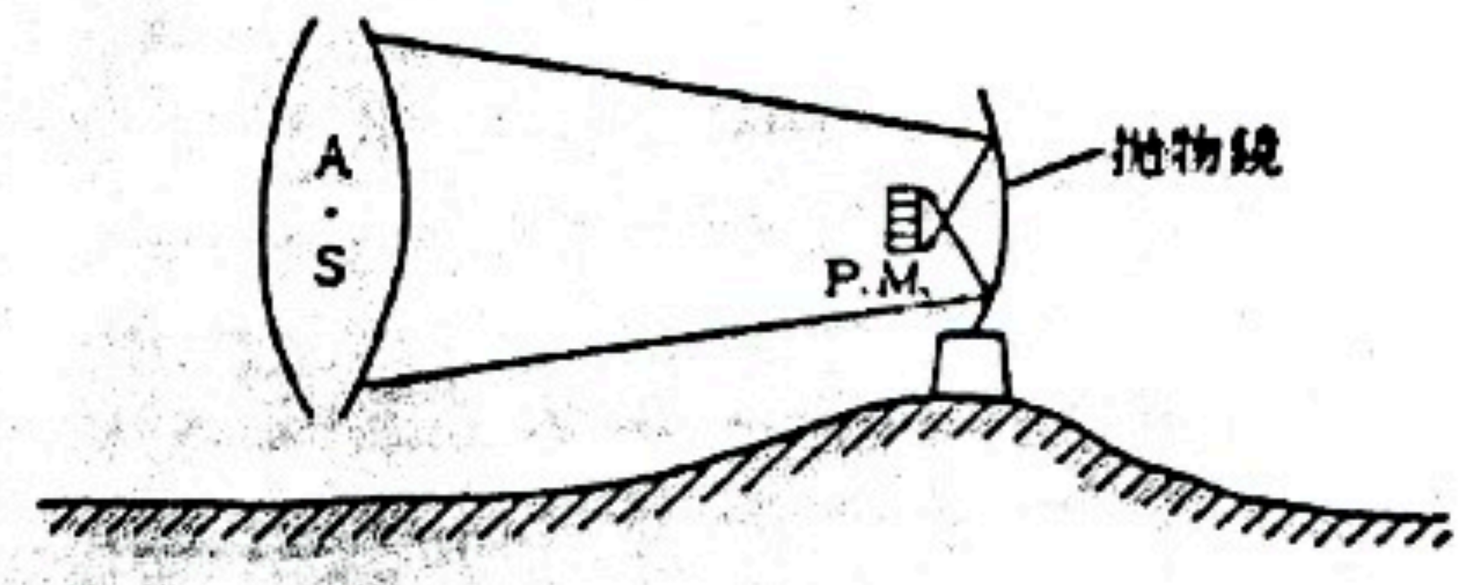


UV LED illuminating the front of the camera



First detection of UHECR using fluorescence technique

- In 1958, Suga and Oda suggested Fluorescence technique at Norikura Symposium.



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

第8図 TOKYO−1の設置写真

- In 1969, first observation by TOKYO-1 (Tanahashi)
  - Fresnel lens + 55 PMTs