Recent results from prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST) in both hemispheres

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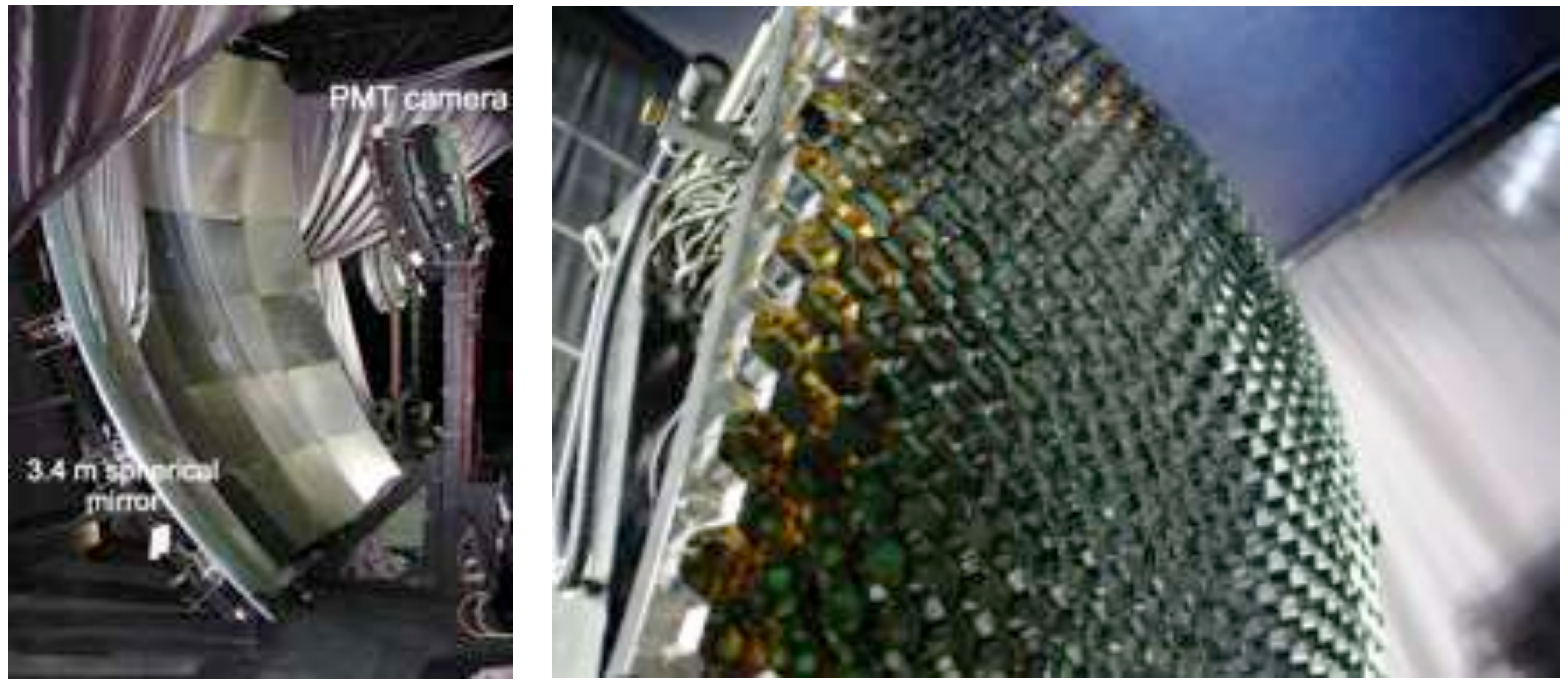
(FAST Collaboration)

UHECR 2022, L'AQUILA, October 7th, 2022

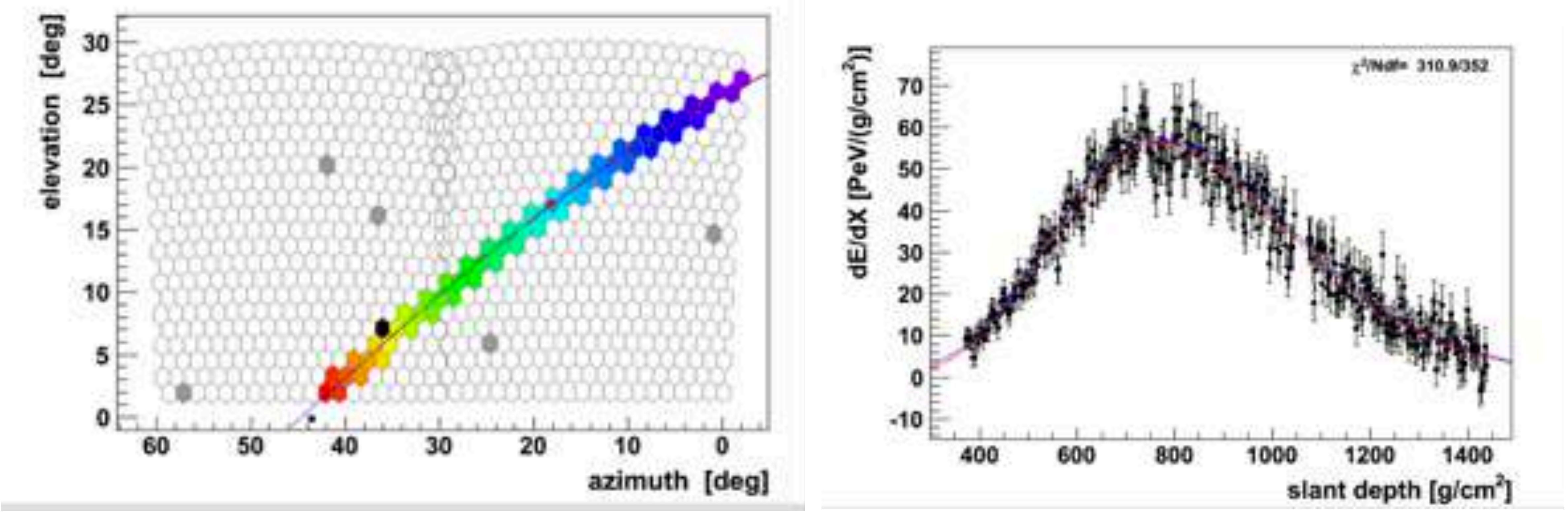
Fluorescence detector Array of Single-pixel Telescopes

- Target : > $10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrino and gamma rays
  - Huge target volume ⇒ Fluorescence detector array

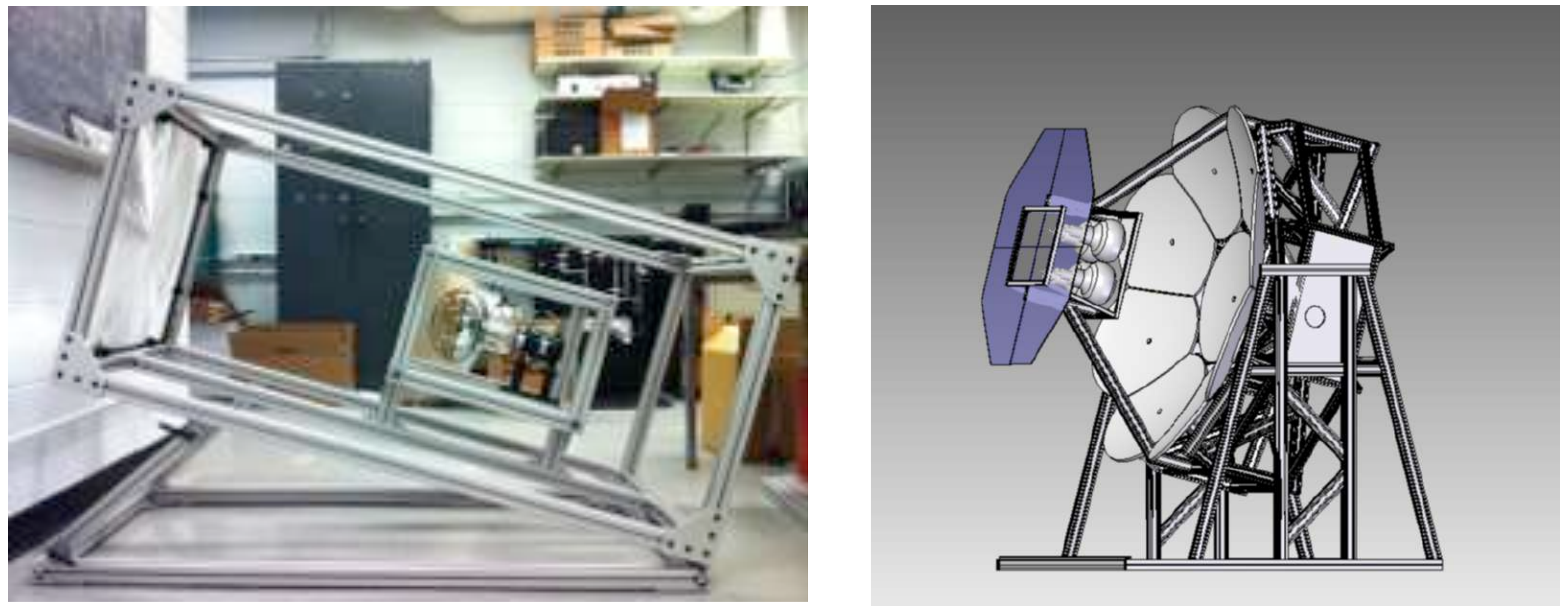
Fine pixelated camera



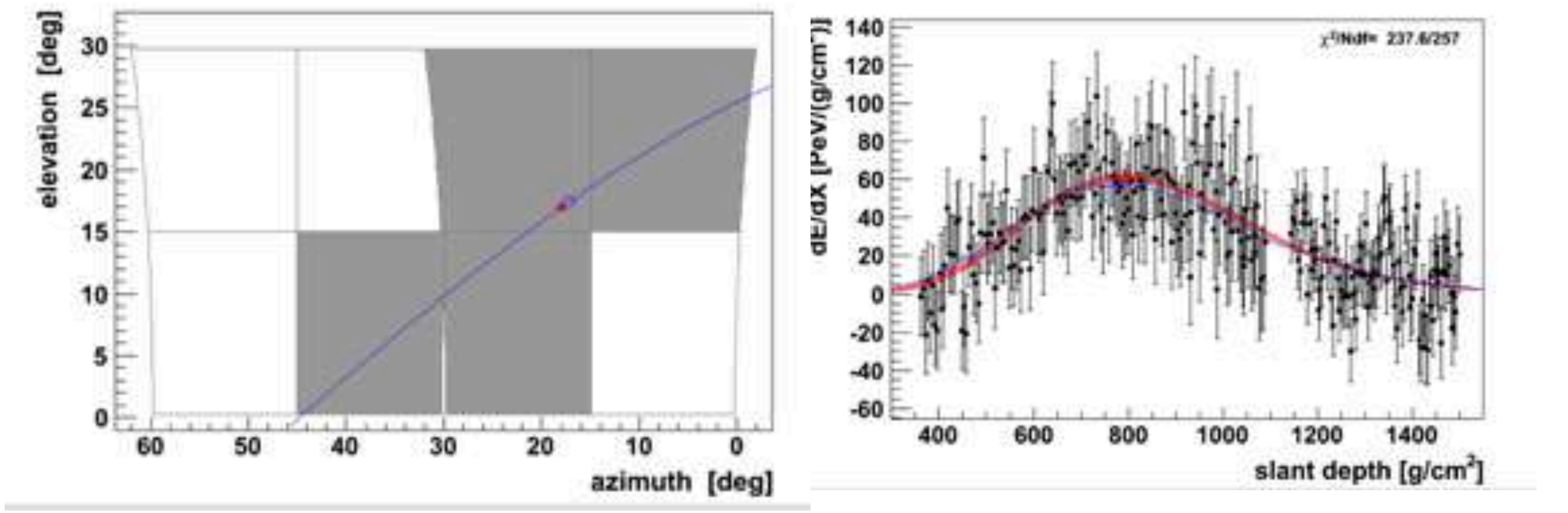
Too expensive to cover a huge area



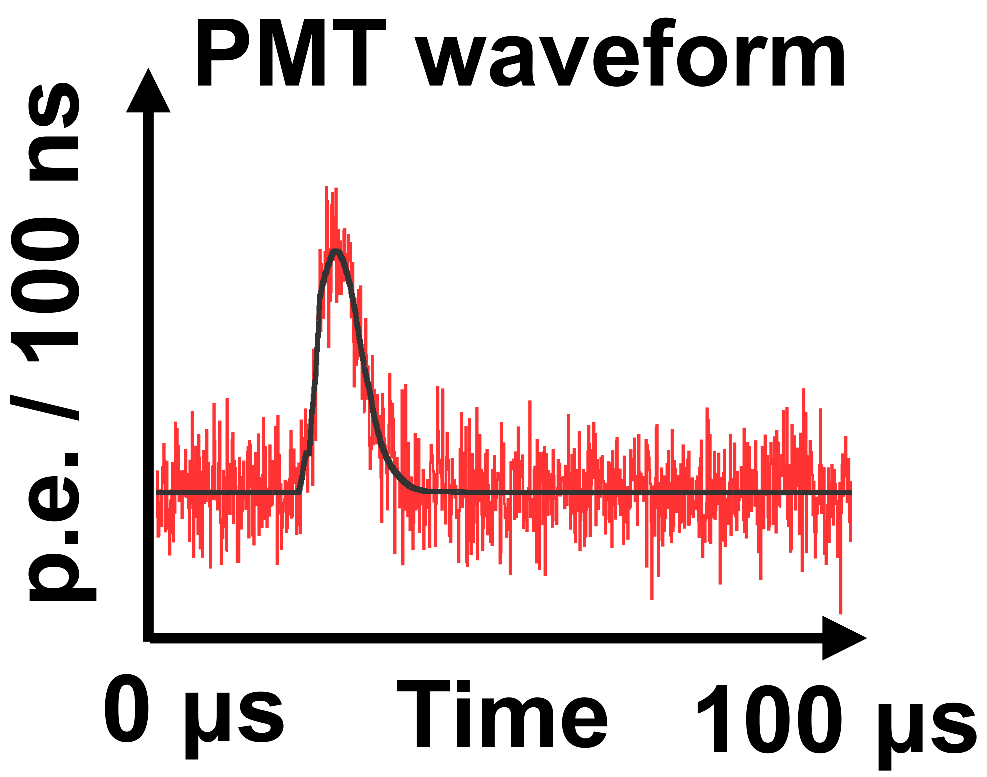
Smaller optics and single or few pixels

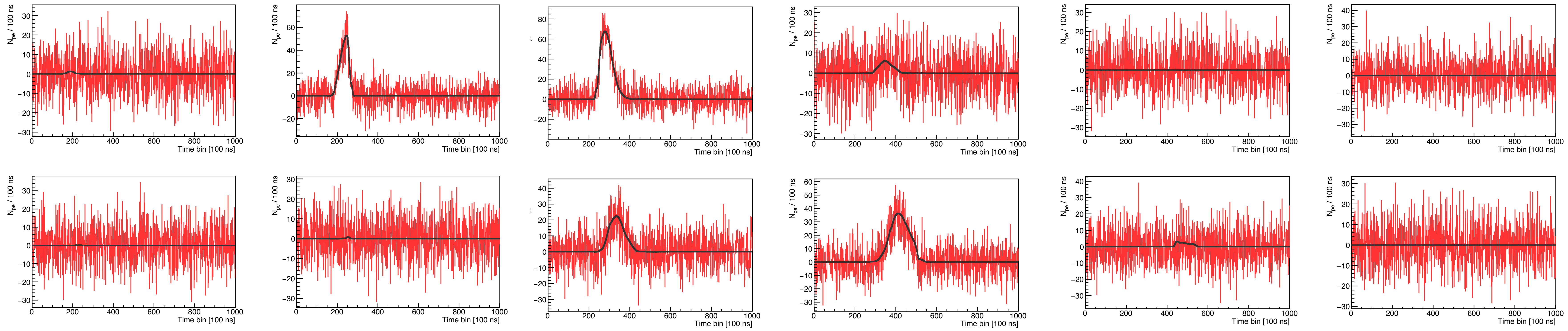


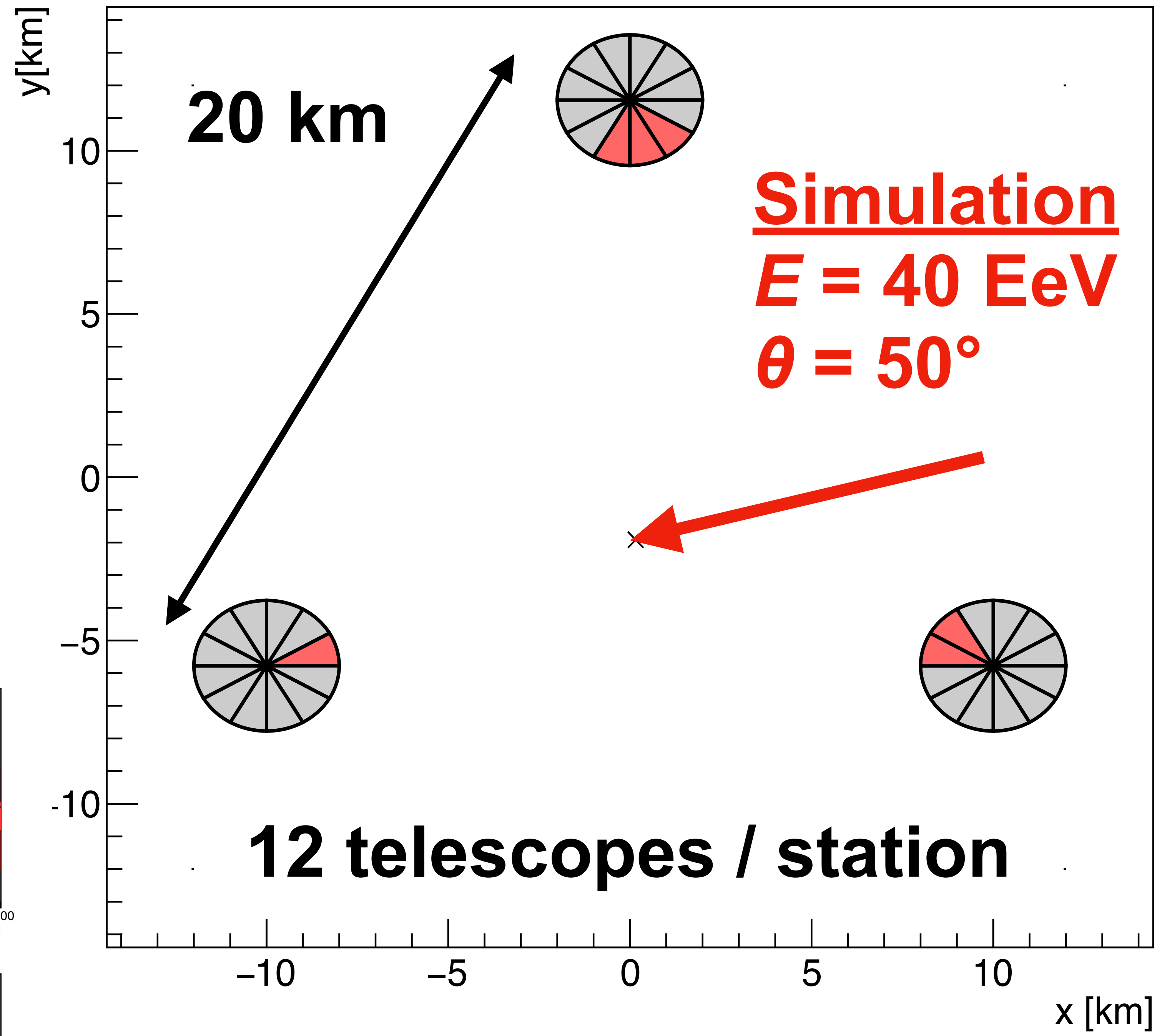
Low-cost and simplified telescope



Fluorescence detector Array of Single-pixel Telescopes

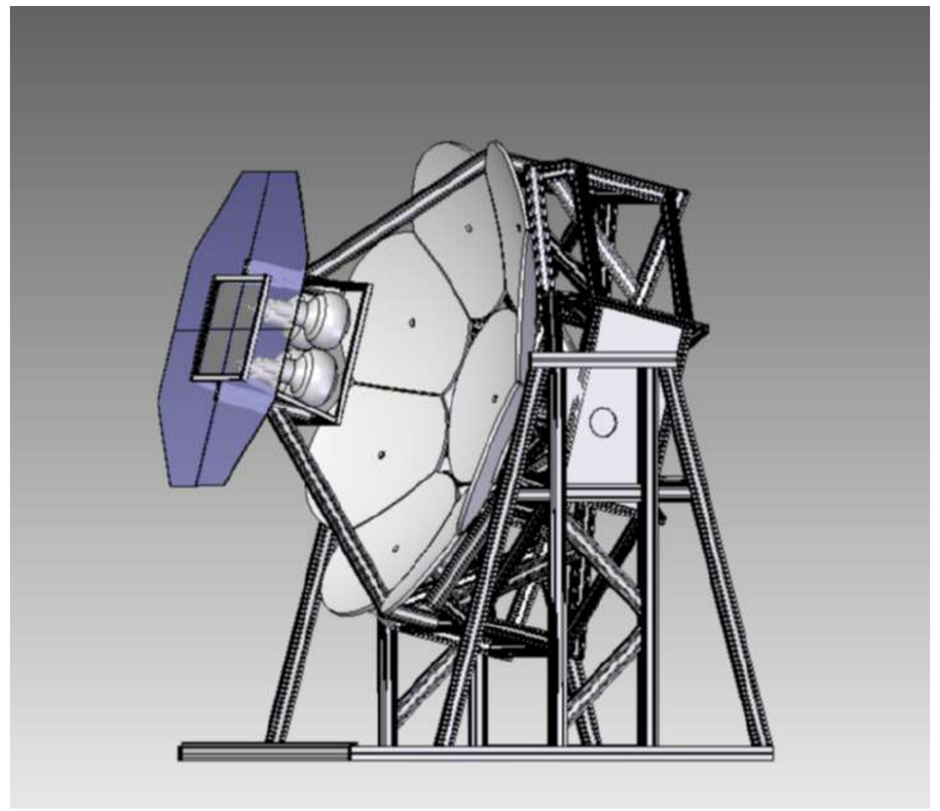






500 stations

→ **150,000 km²**



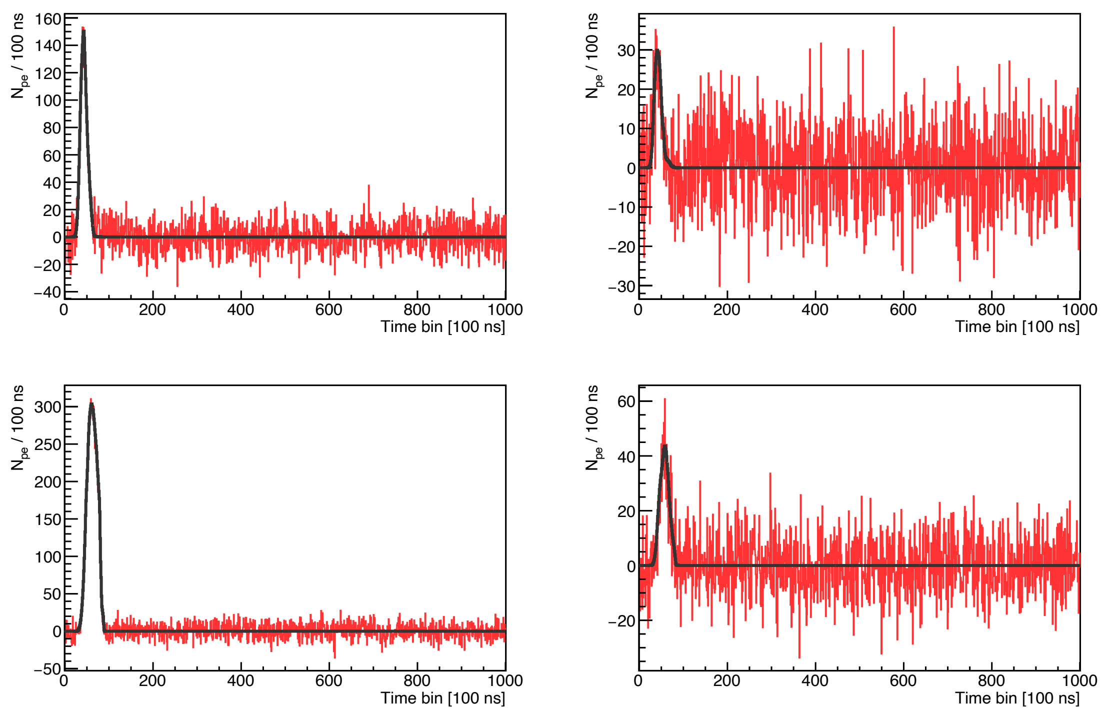
FAST telescope

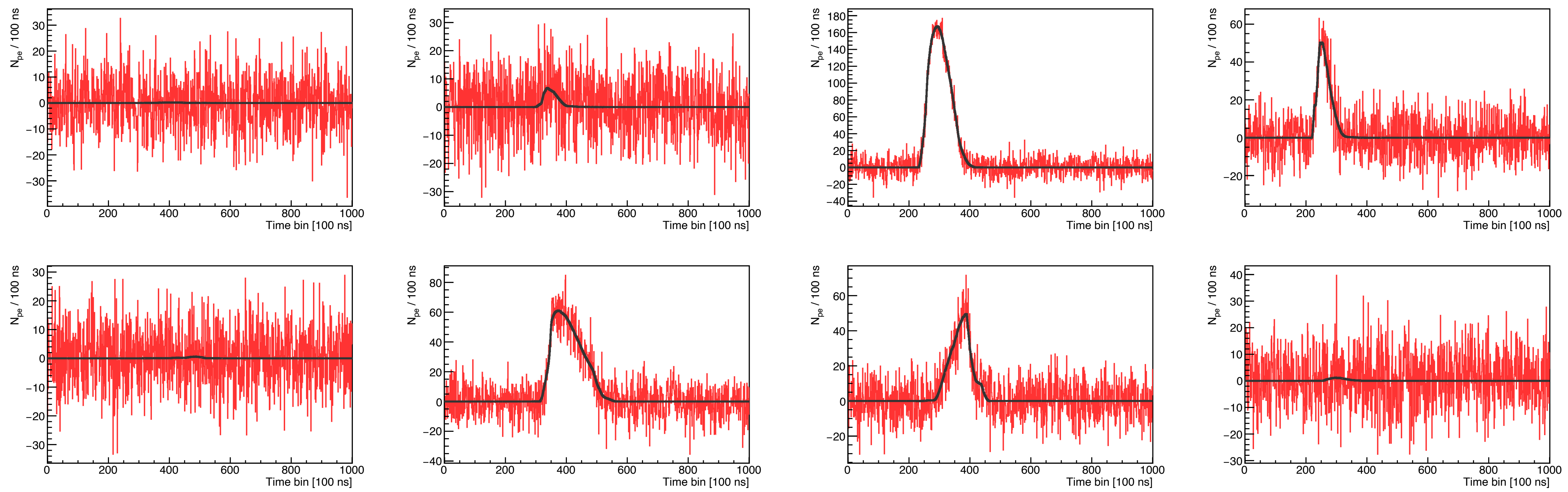
4 PMTs (20 cm diameter)

1 m² aperture (UV filter)

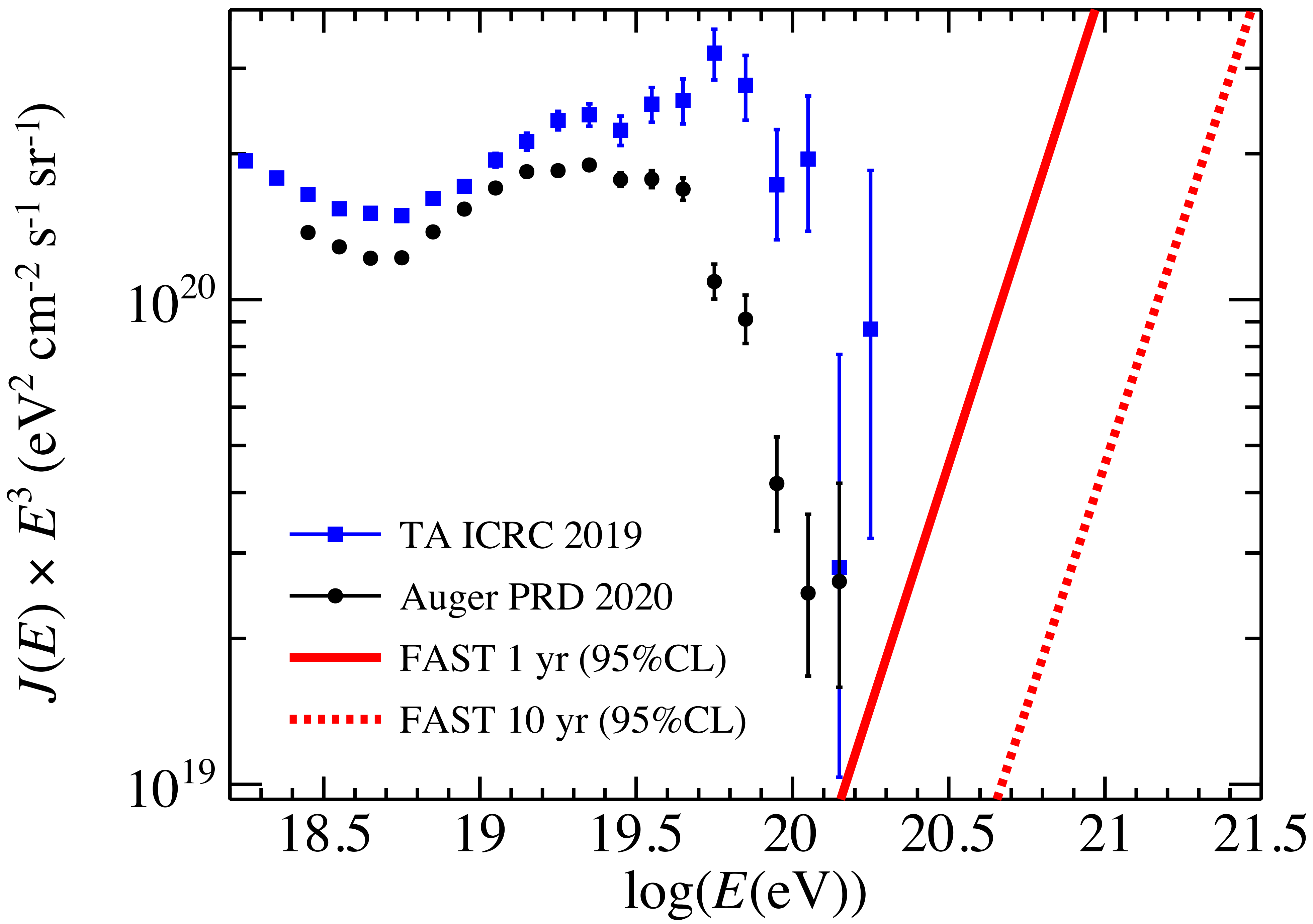
Segmented mirror

in 1.6 m diameter

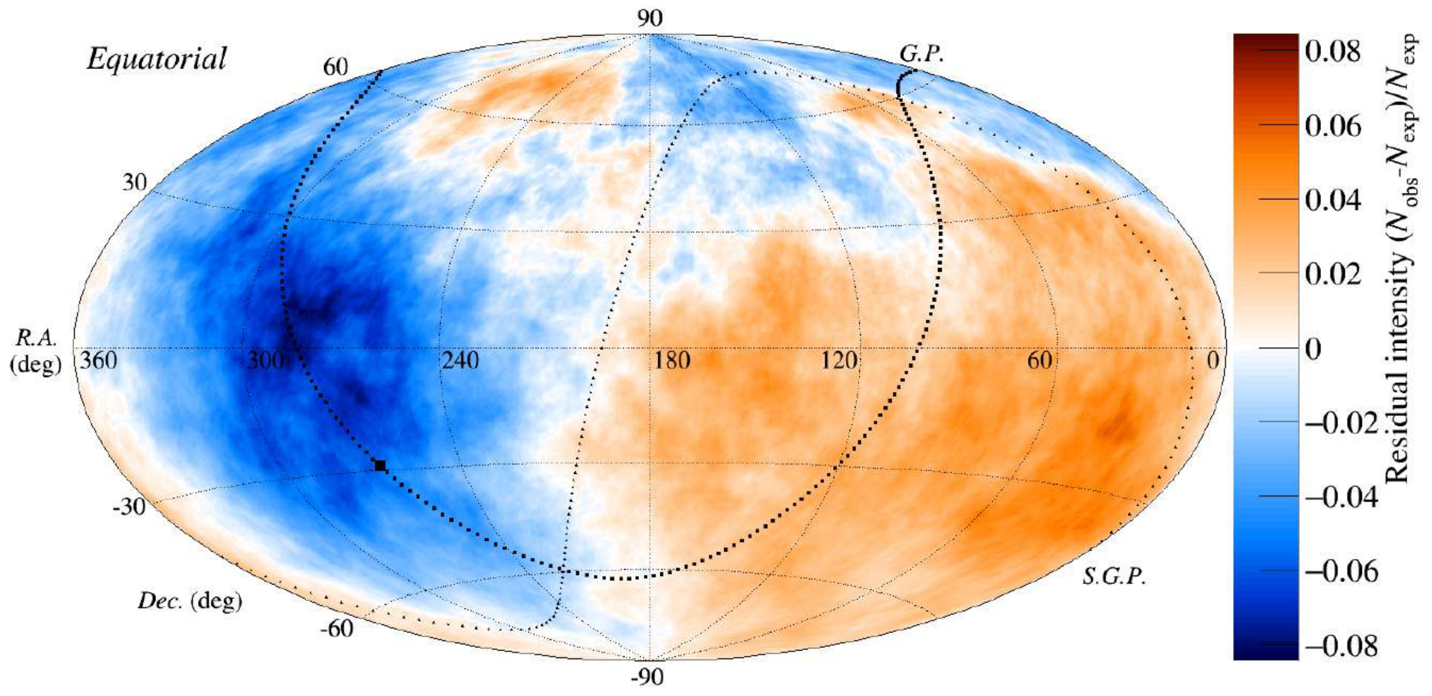




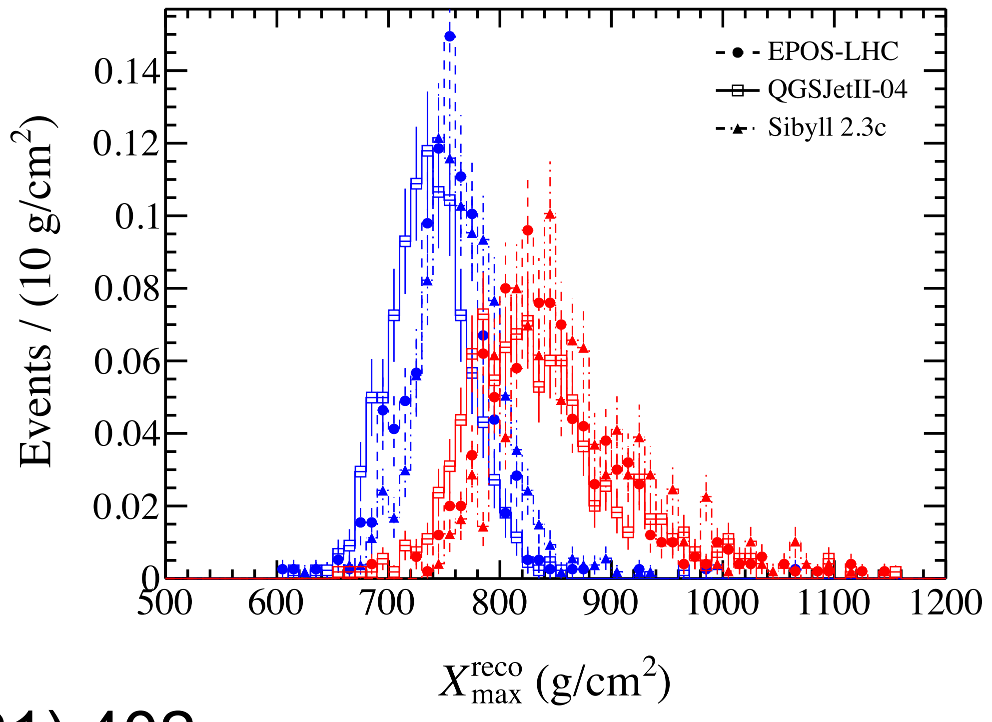
Scientific goals and characteristics with FAST



Dipole as "**standard candle**"



X_{max} at highest



T. Fujii et al., PoS (ICRC2021) 402

- **To clarify origins and natures of UHECRs**
- **Directional anisotropy on spectrum and composition** with 10× (Auger or TAx4) exposure
  - **Pros**
    - Calorimetric energy determination
    - Mass-composition sensitivity using X_{max}
    - Less dependent on hadronic interaction models
  - **Cons**
    - Low duty cycle, 10 - 20%
    - Many calibration components(PMT gains, Optics, atmospheric parameters, telescope direction)
    - Understanding directional exposure
      - Calibration source: large-scale dipole anisotropy
    - **Stand-alone operation required**

FAST
Fluorescence detector Array of Single-pixel Telescopes

Validations of the FAST concept

Feb. 2012

Apr. 2014

Oct. 2016

Sep. 2017

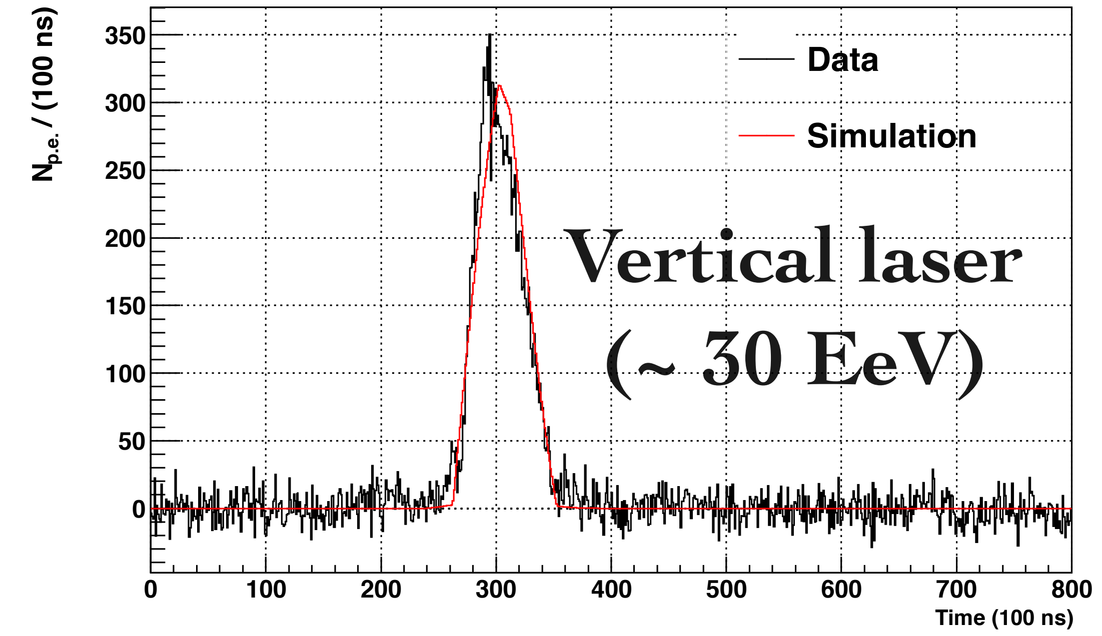
Oct. 2018 @TA

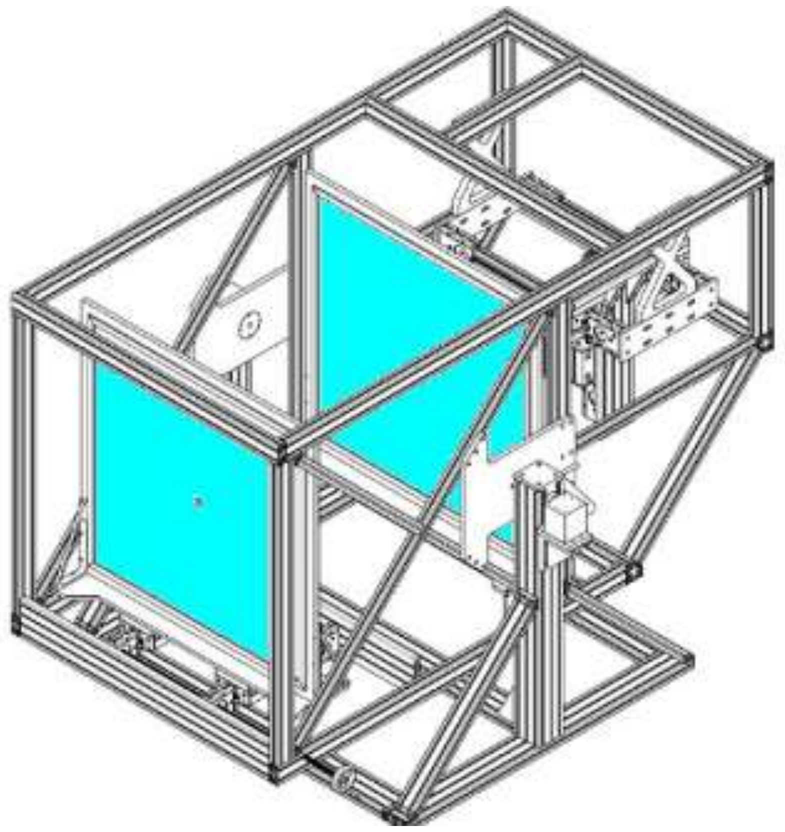
Apr. 2019

Jun. 2022 @Auger

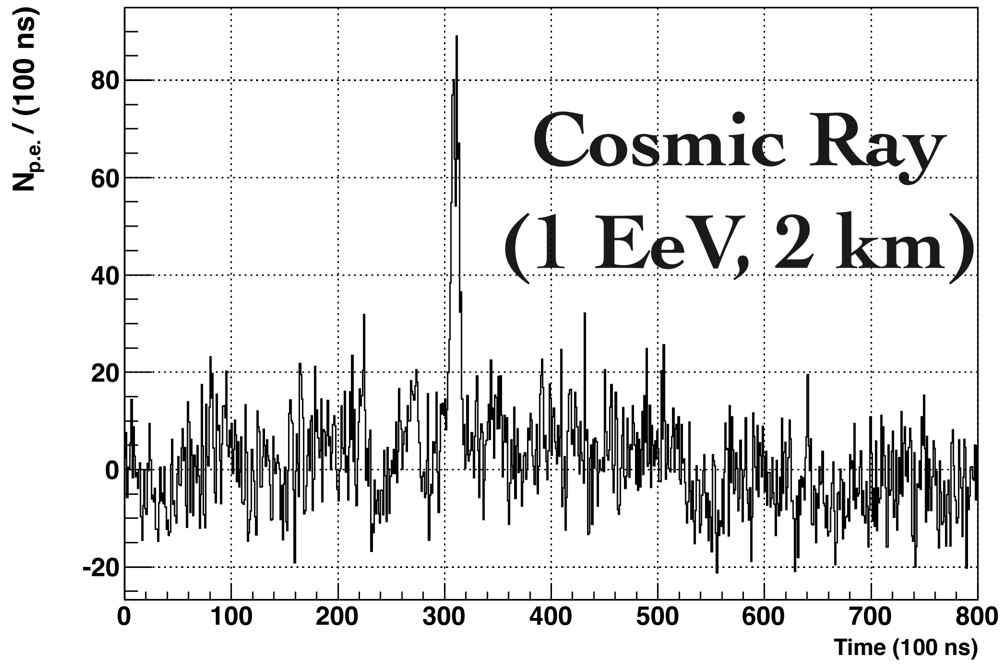
A conceptual design for a large ground array of Fluorescence Detectors

P. Privitera in **UHECR 2012**

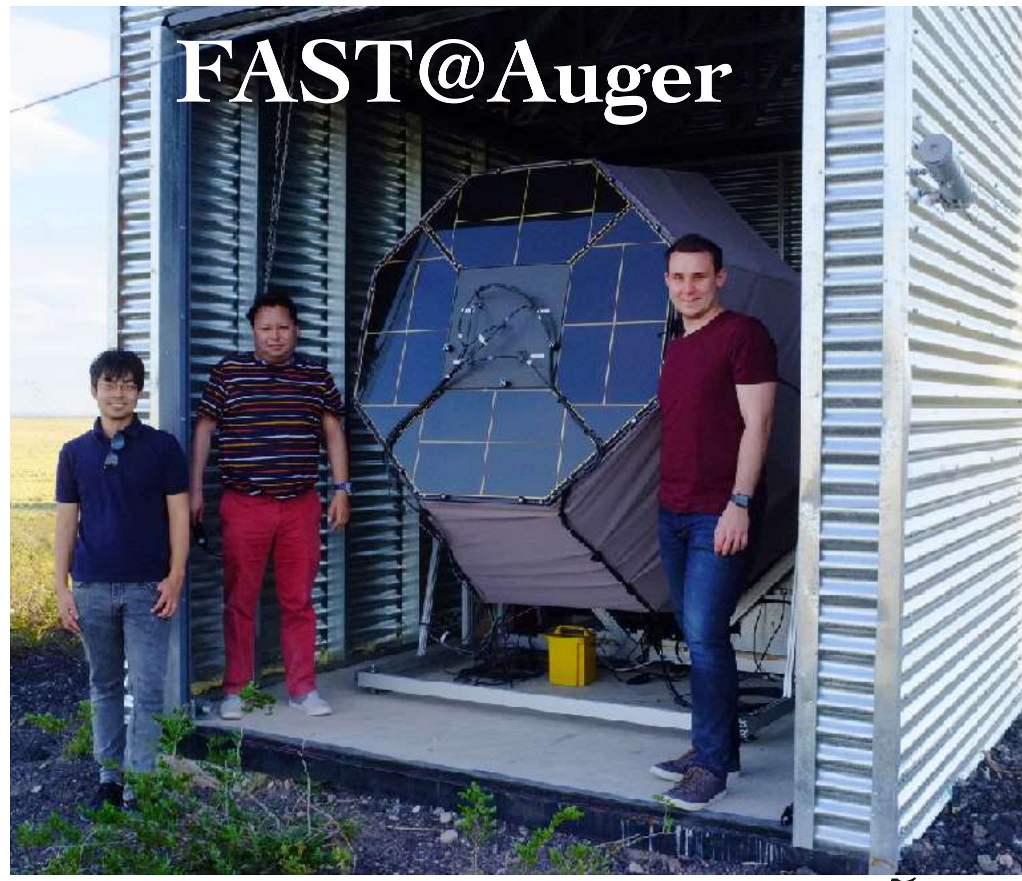




EUSO-TA optics
+
Single-pixel camera



T. Fujii et al., Astroparticle Physics *74* (2016) 64-72



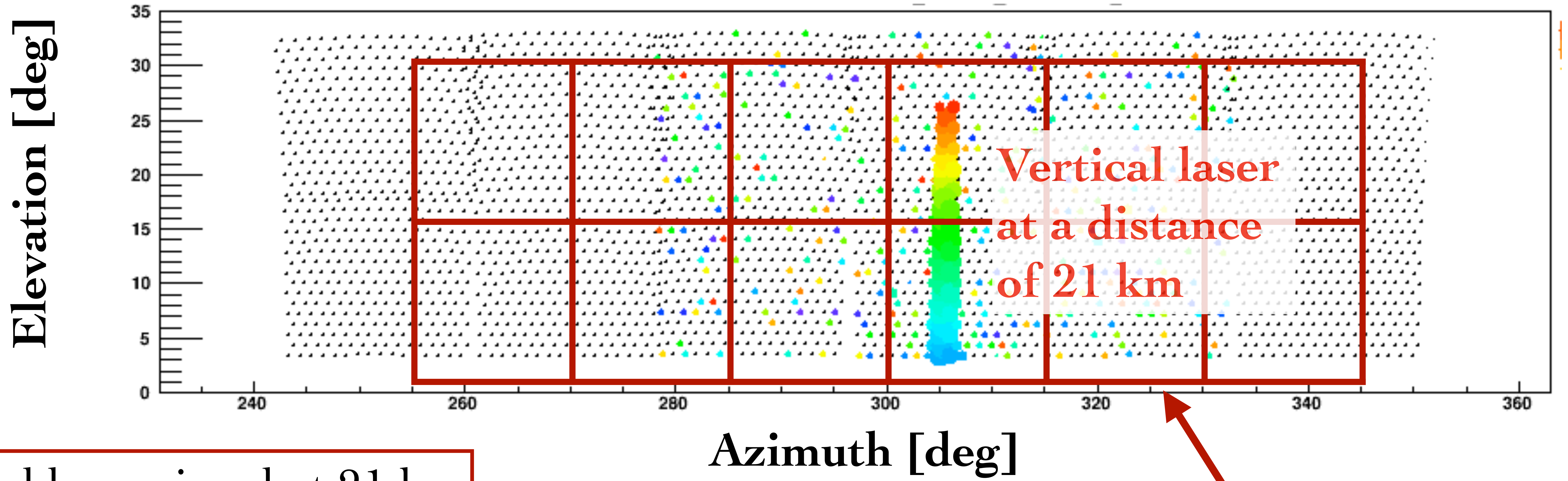
D. Mandat et al., JINST 12, T07001 (2017)

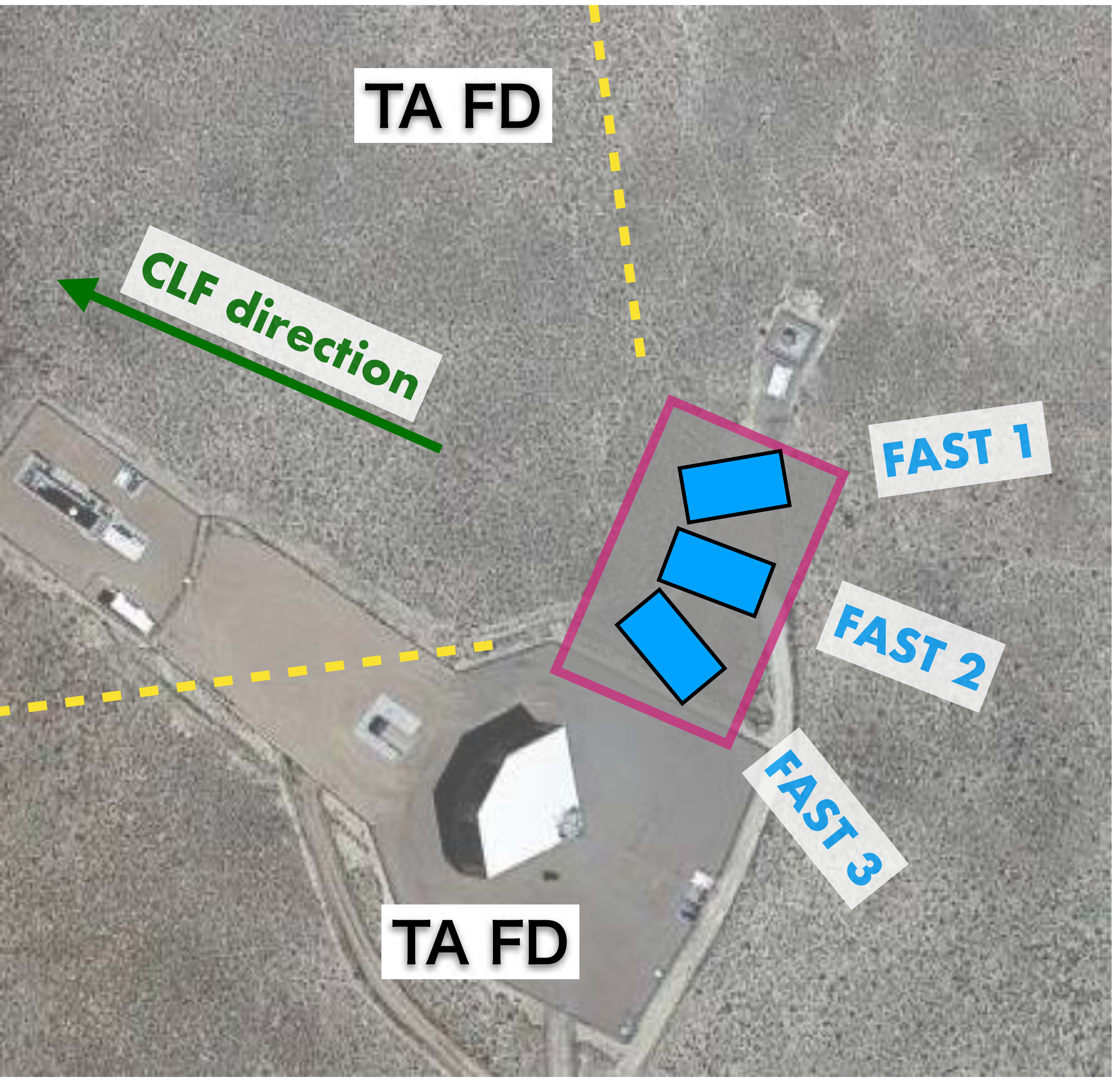
M. Malacari et al., Astroparticle Physics 119 (2020) 102430

FAST@TA observations

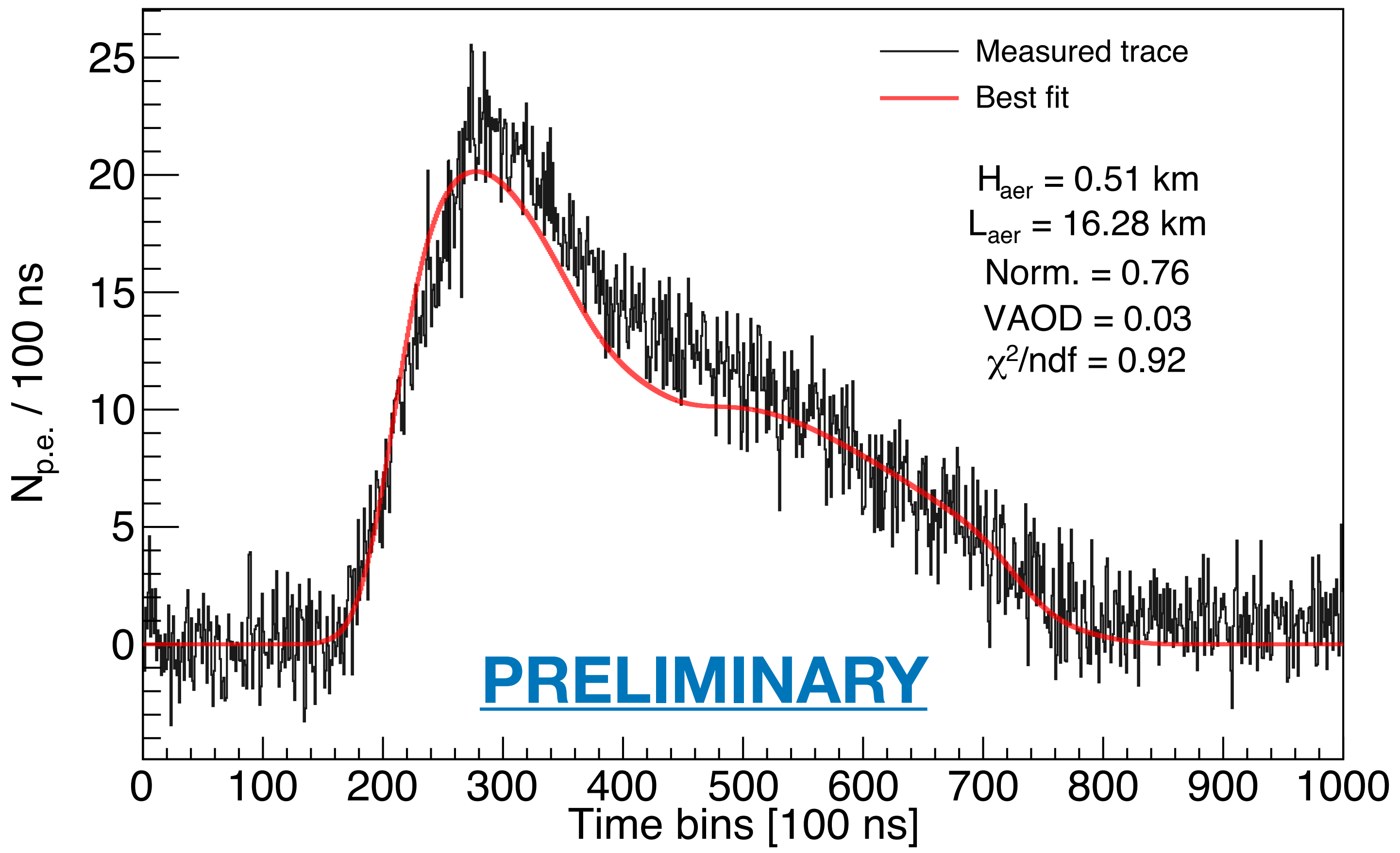
- Remote controlling observation
- Synchronized operation with external triggers from Telescope Array fluorescence detector (TA FD)
- 80% FoV of TA FD

TA FD FoV (12 telescopes, 33°×108°)

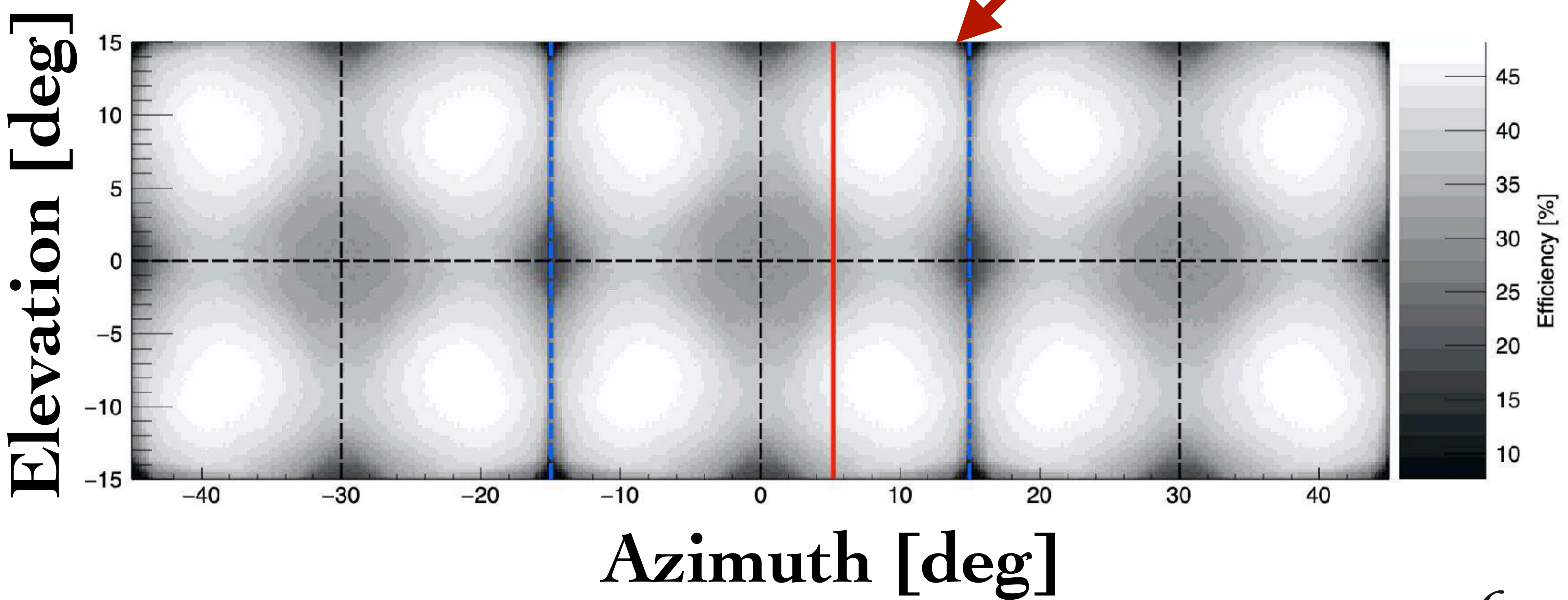




Vertical laser signal at 21 km
(280 shot average)

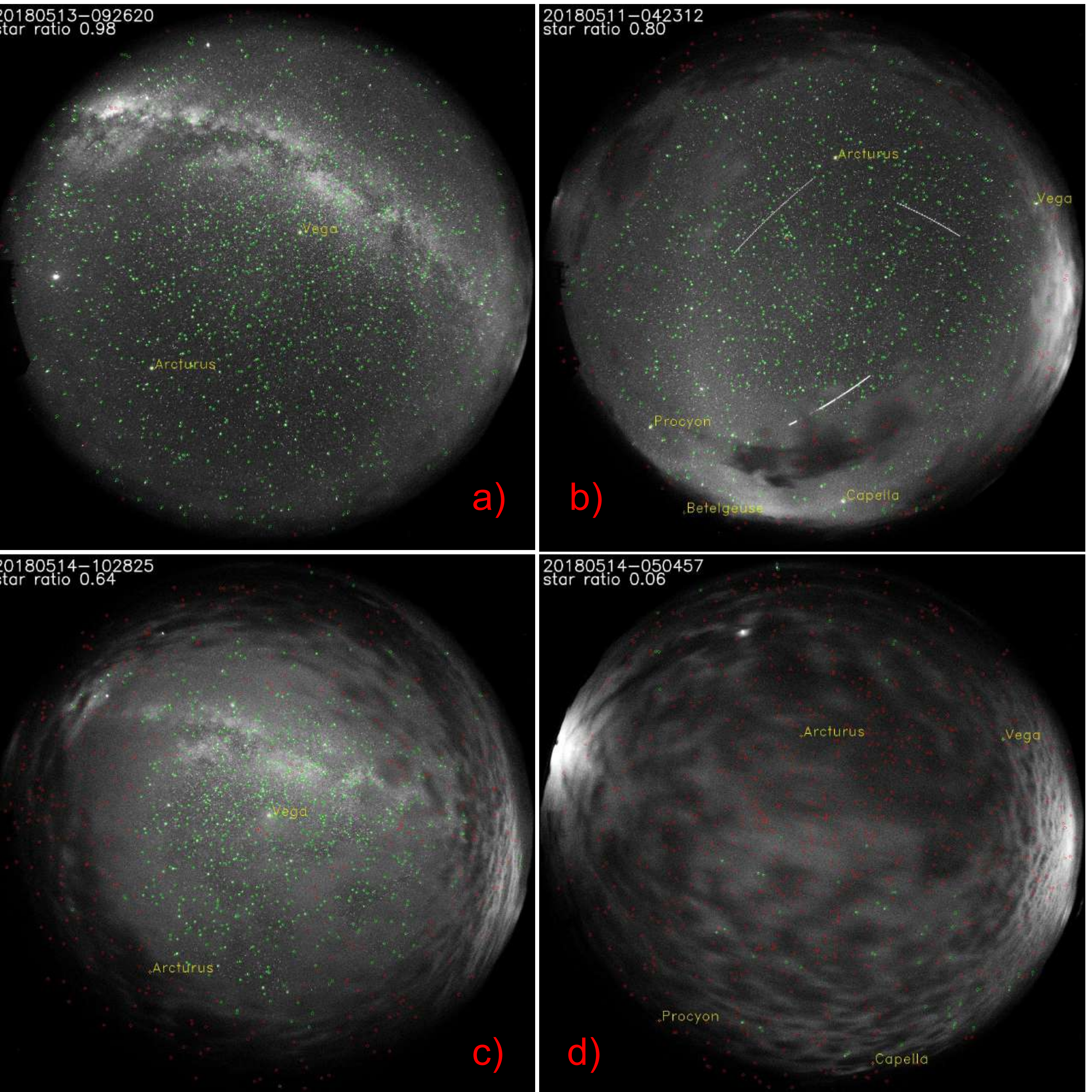


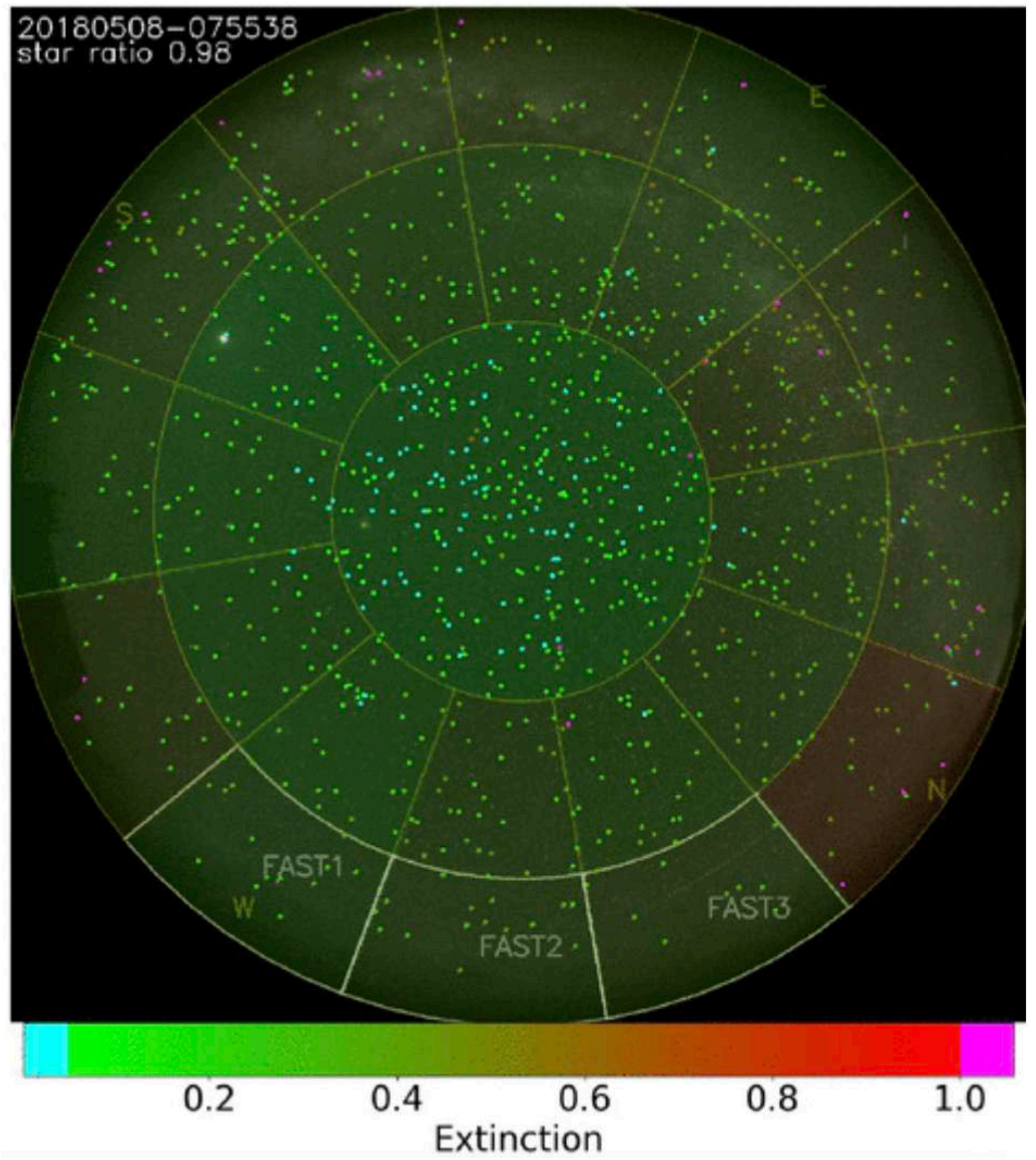
FAST FoV (3 telescopes, 30°×90°)

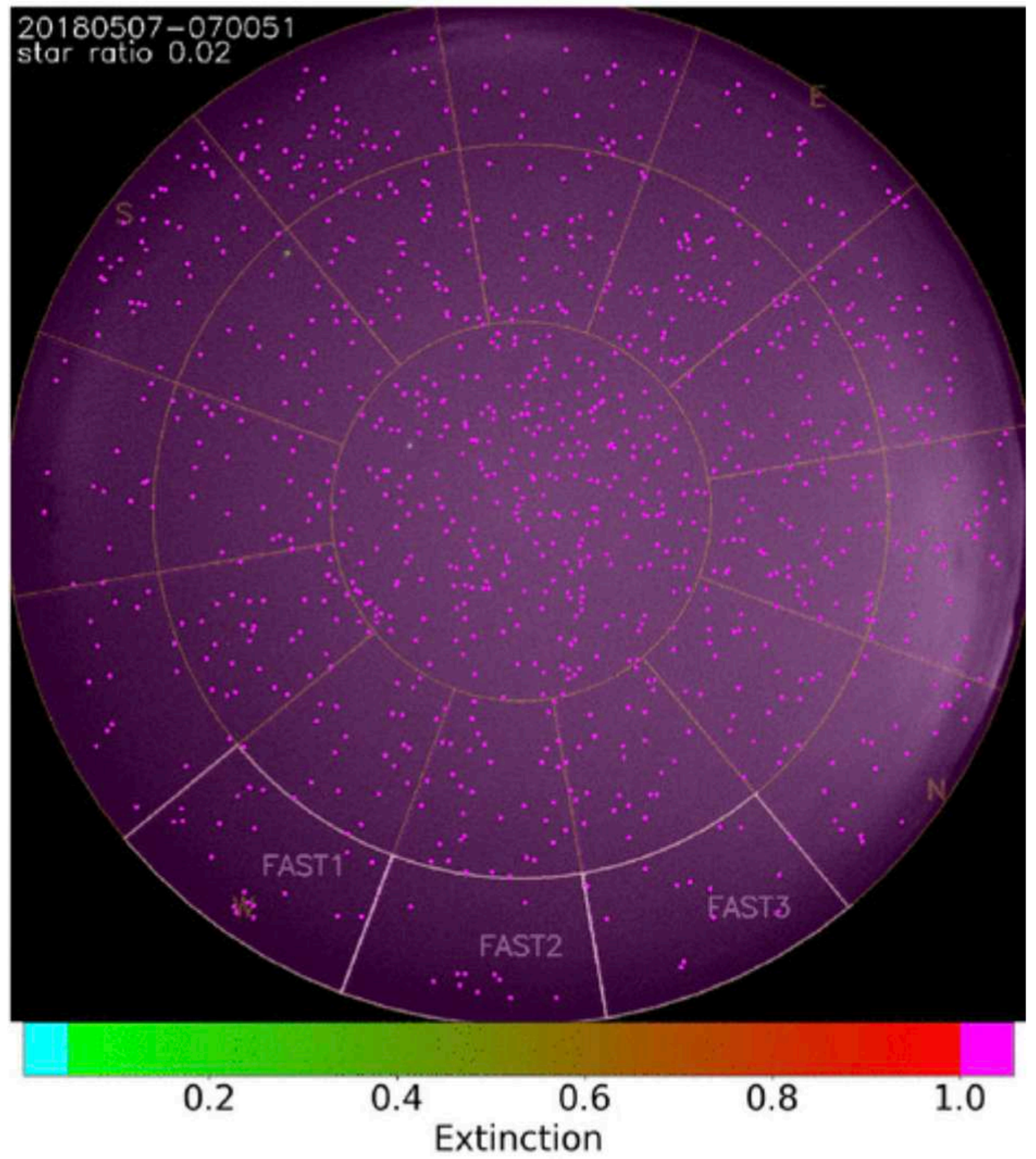


Atmospheric monitoring systems with FAST

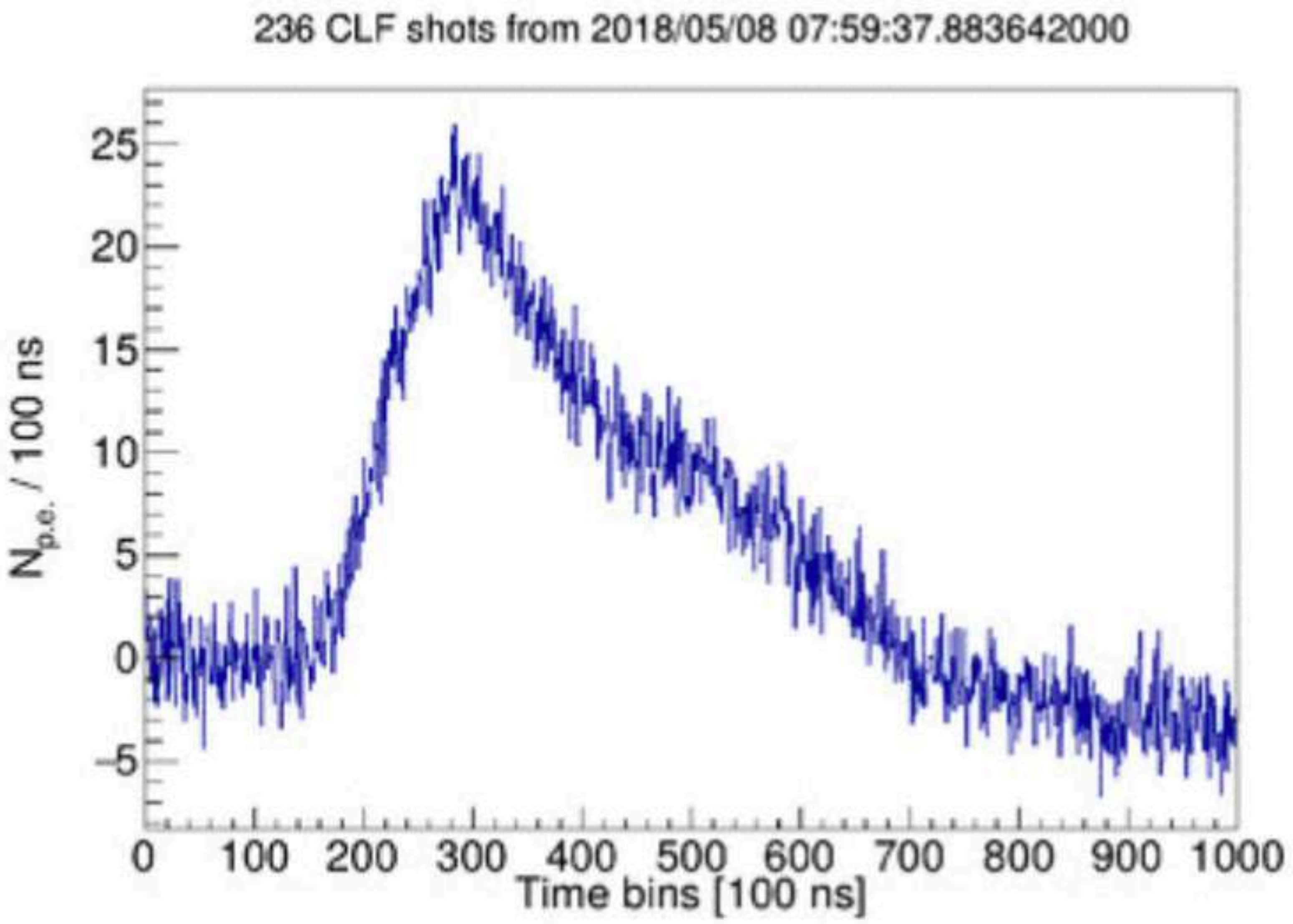
Automated all-sky camera



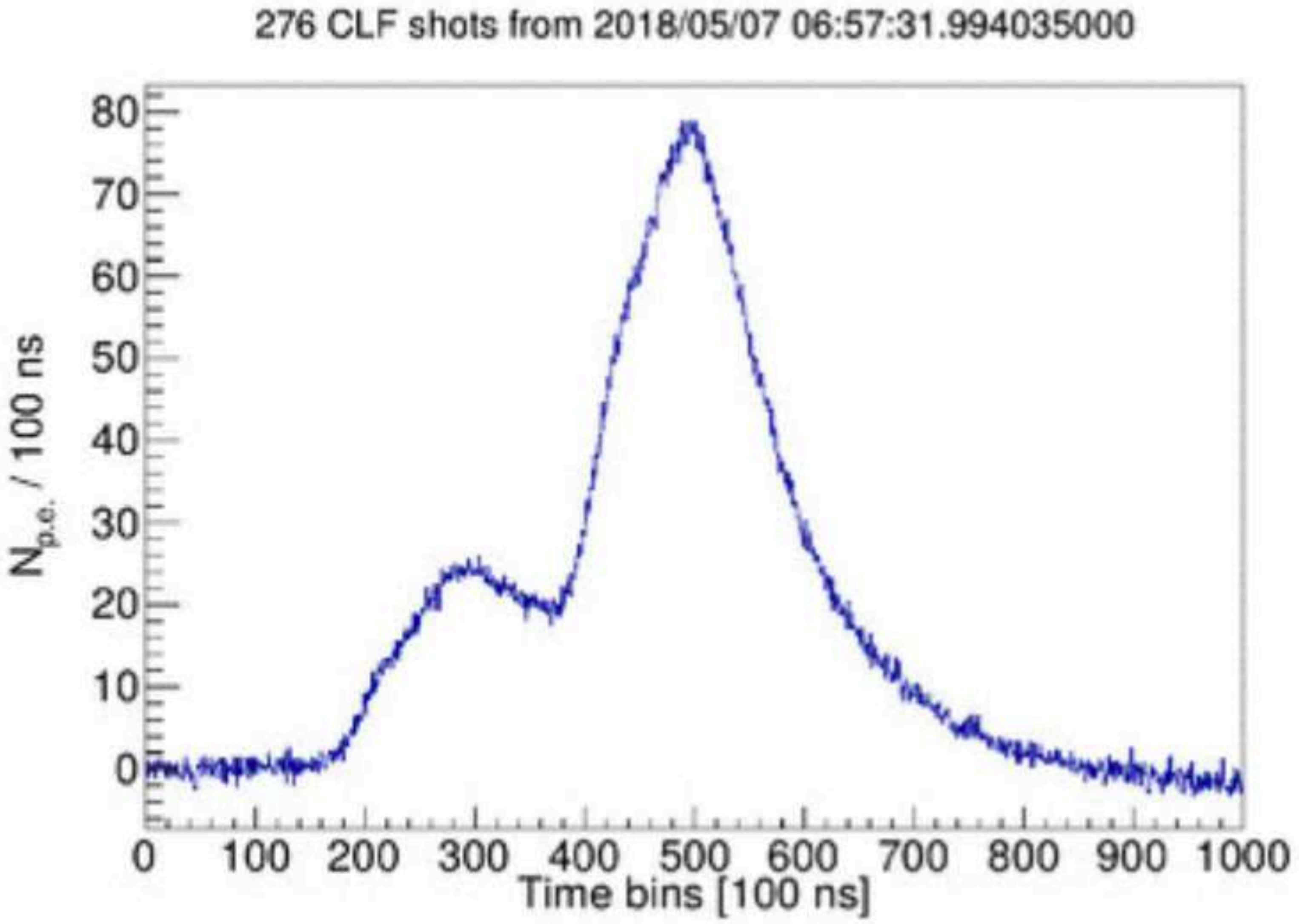




Clear

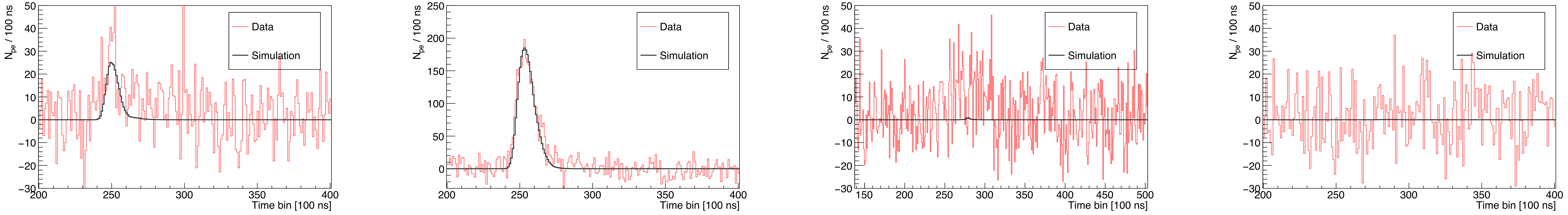


Cloudy

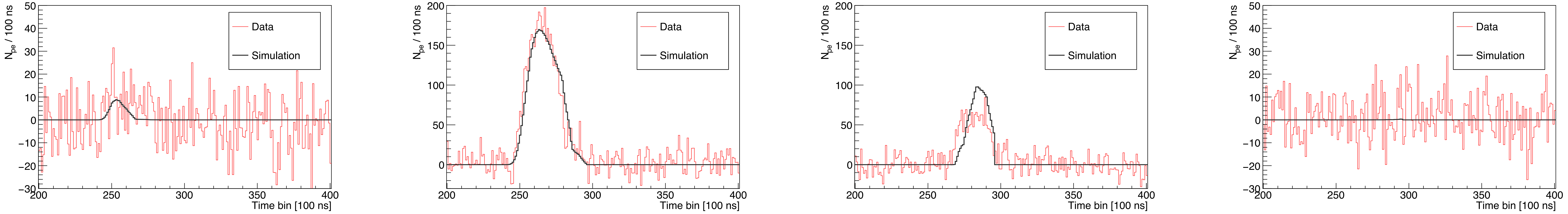


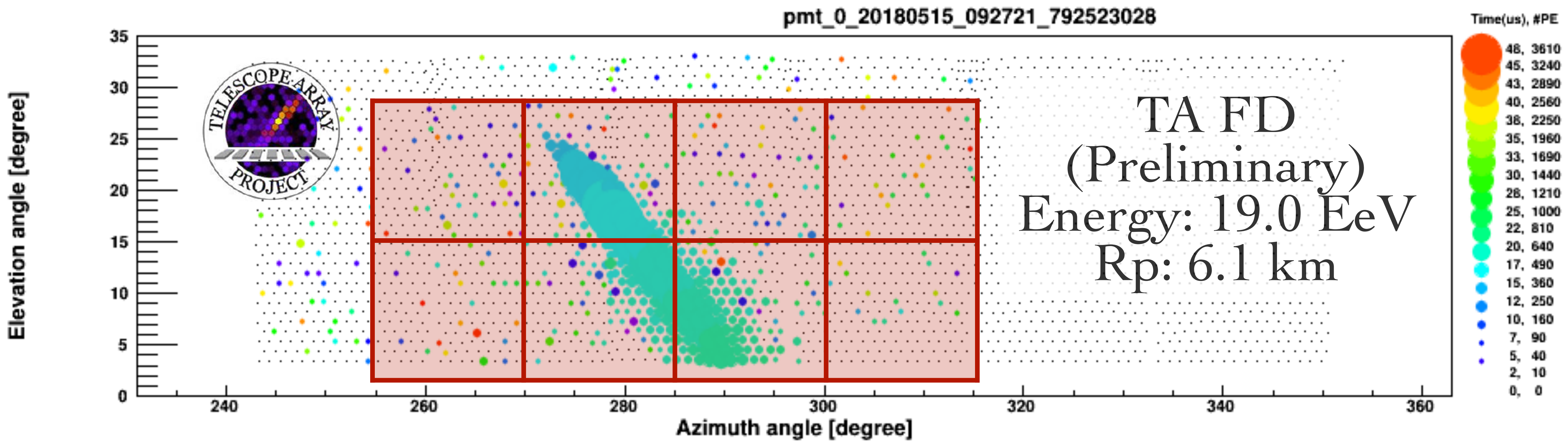
L. Chytka et al. (FAST Collaboration), JINST 15 T10009 (2020)

Cherenkov dominated event



FAST waveforms + Expected signals from top-down reconstruction
(Data, Simulation by the best-fit parameters)



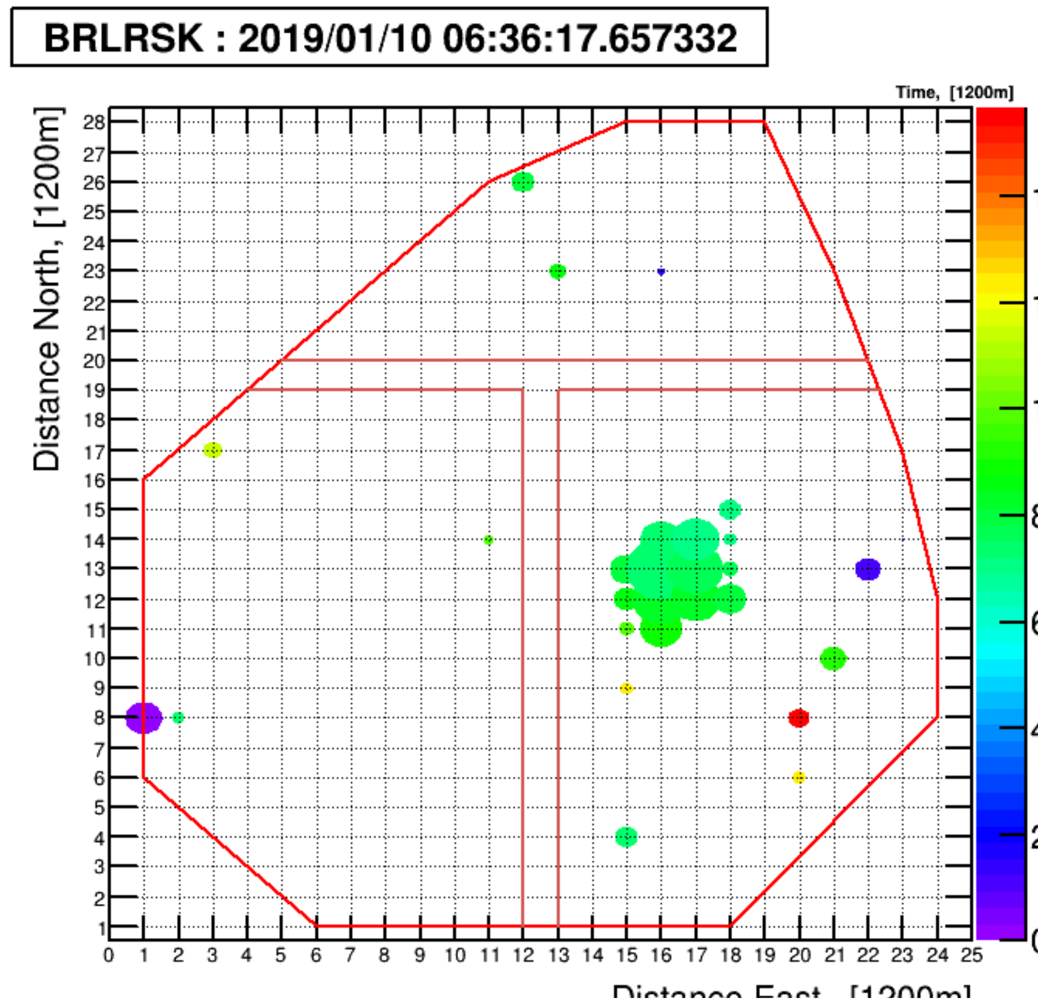


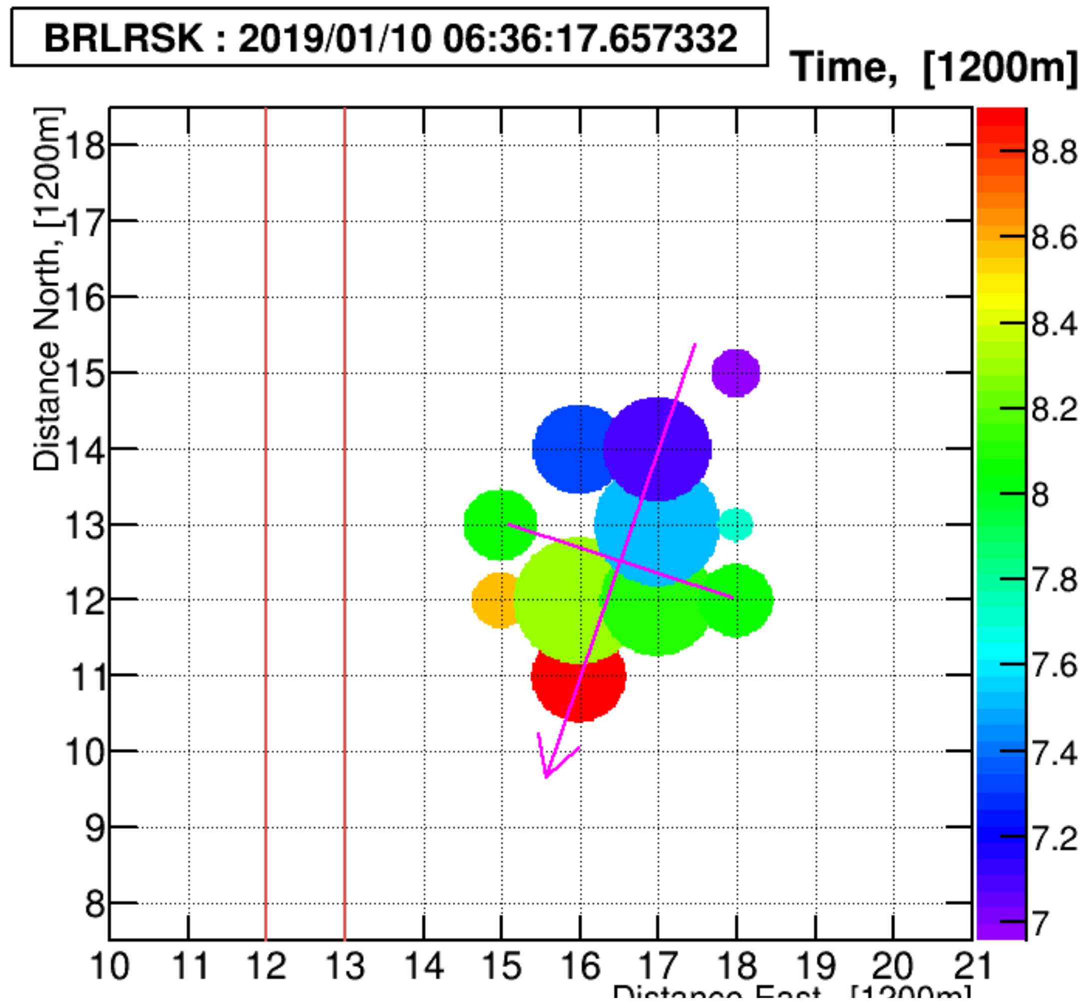
FAST top-down reconstruction (Preliminary)

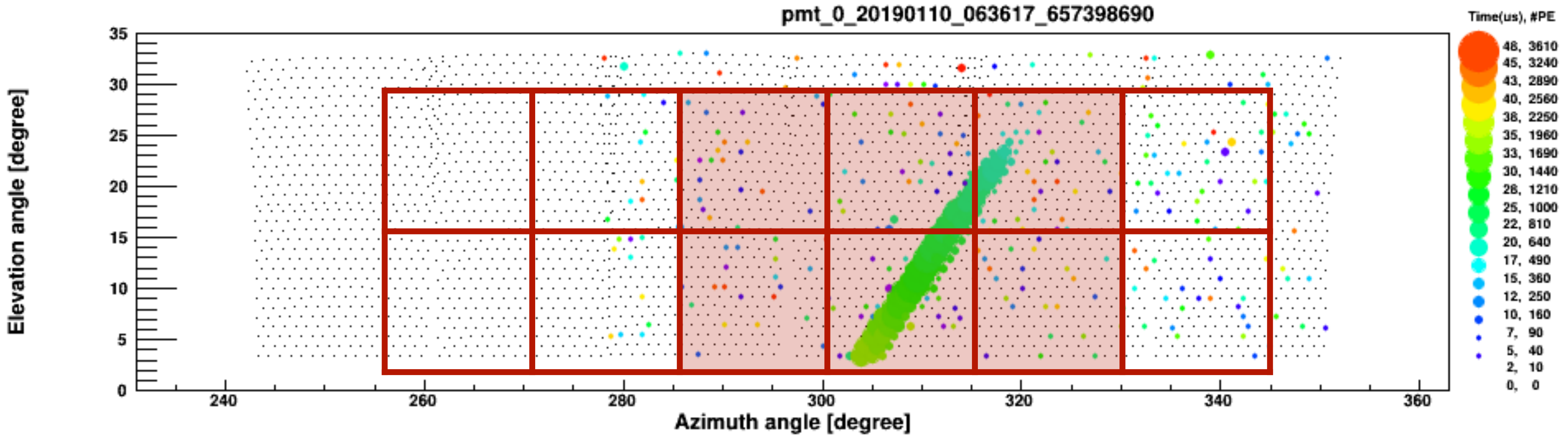
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
59.8 deg	-96.7 deg	7.9 km	-9.0 km	842 g/cm^2	17.3 EeV

Fluorescence dominated event

TA result







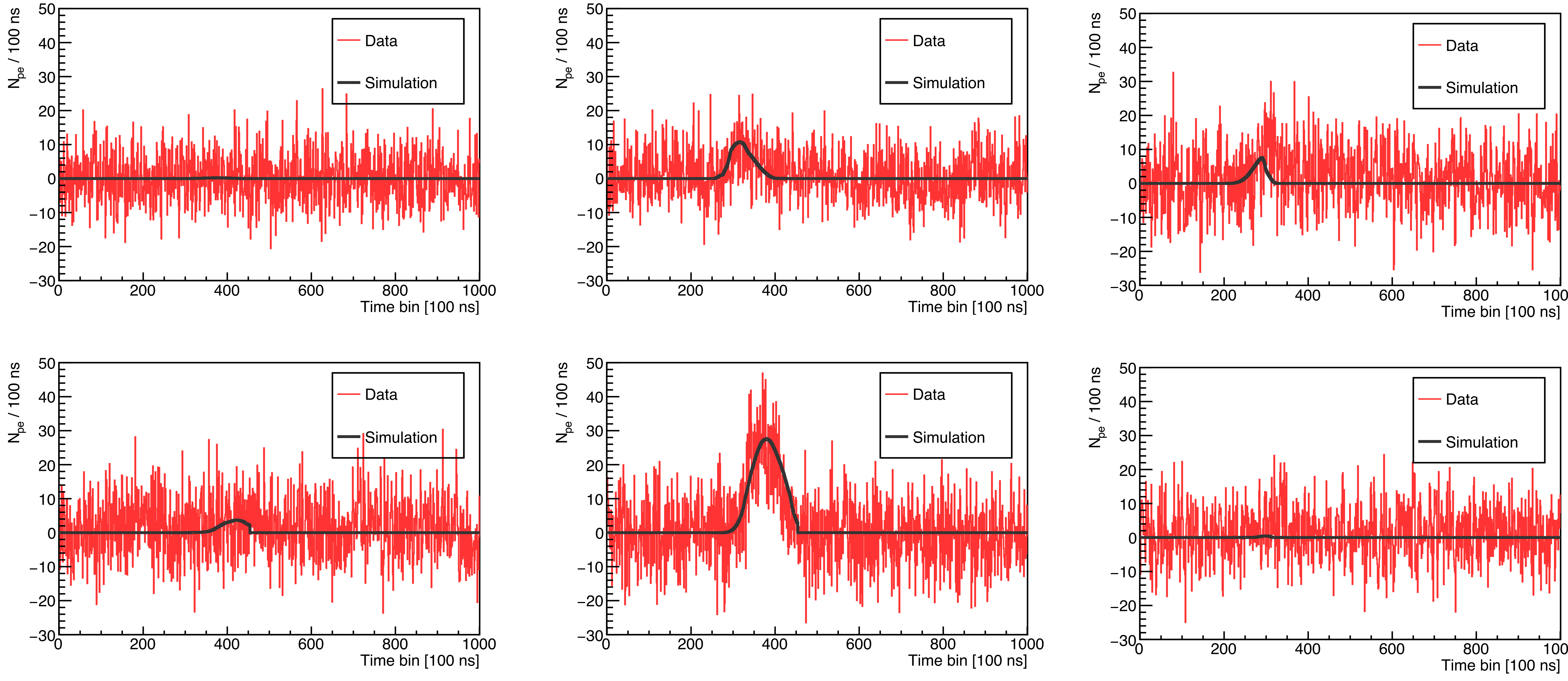
TA SD (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Energy
36.2 deg	18.0 deg	5.0 km	-4.5 km	15.8 EeV

TA FD (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Energy
33.2 deg	35.8 deg	6.1 km	-5.3 km	20.0 EeV

FAST result



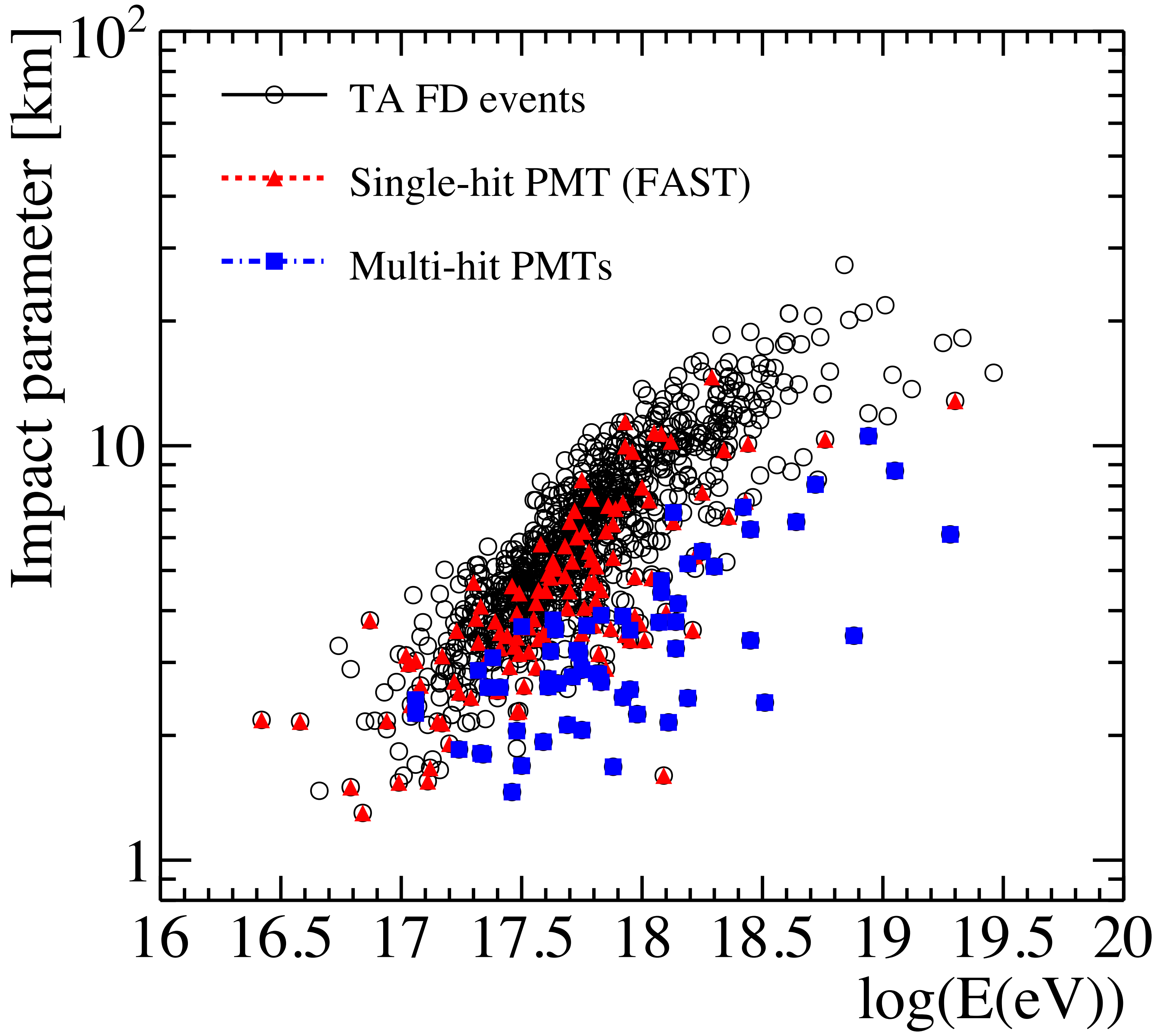
FAST top-down reconstruction (Preliminary)

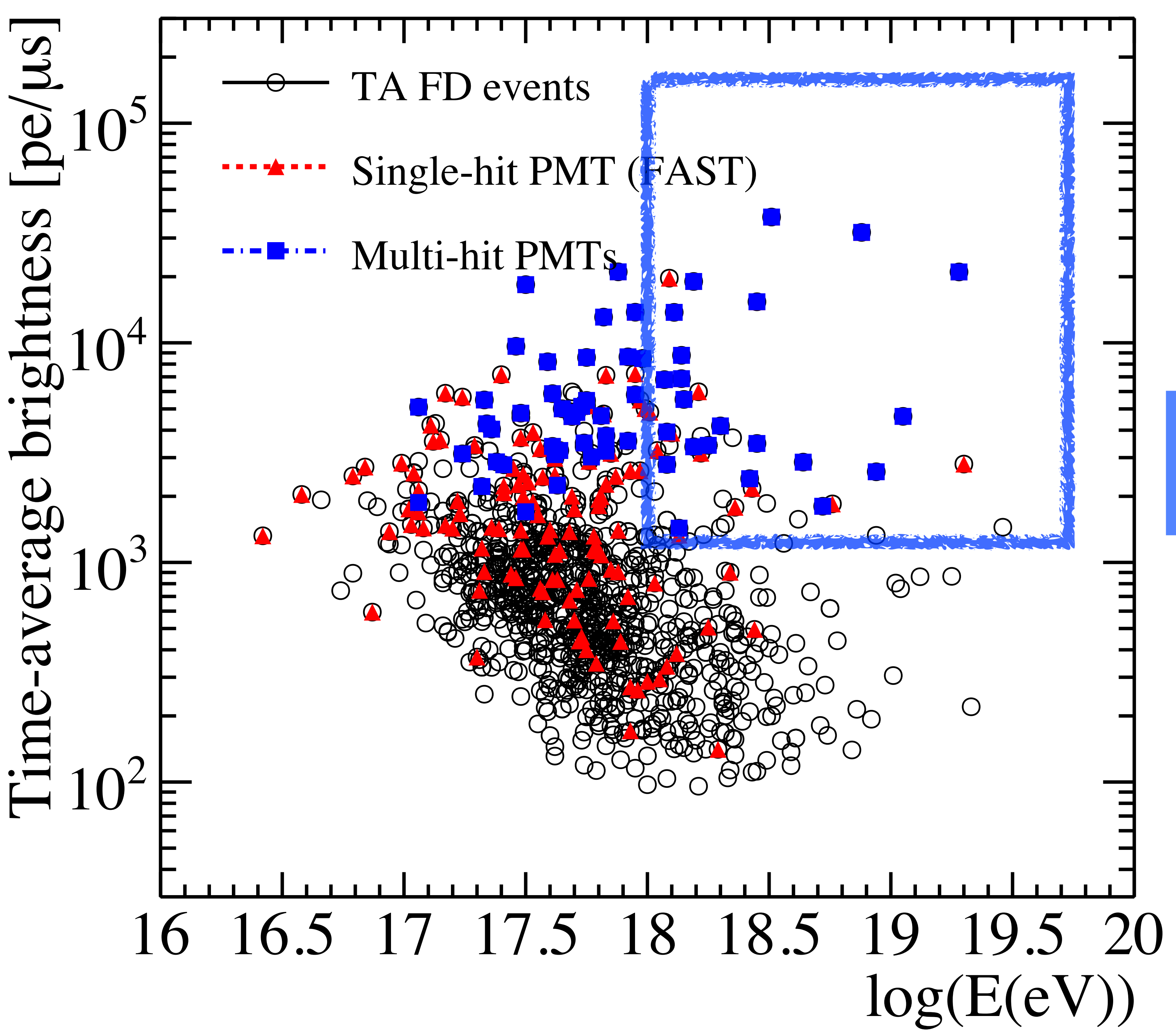
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
33.9 deg	19.3 deg	4.6 km	-4.7 km	808 g/cm^2	18.8 EeV

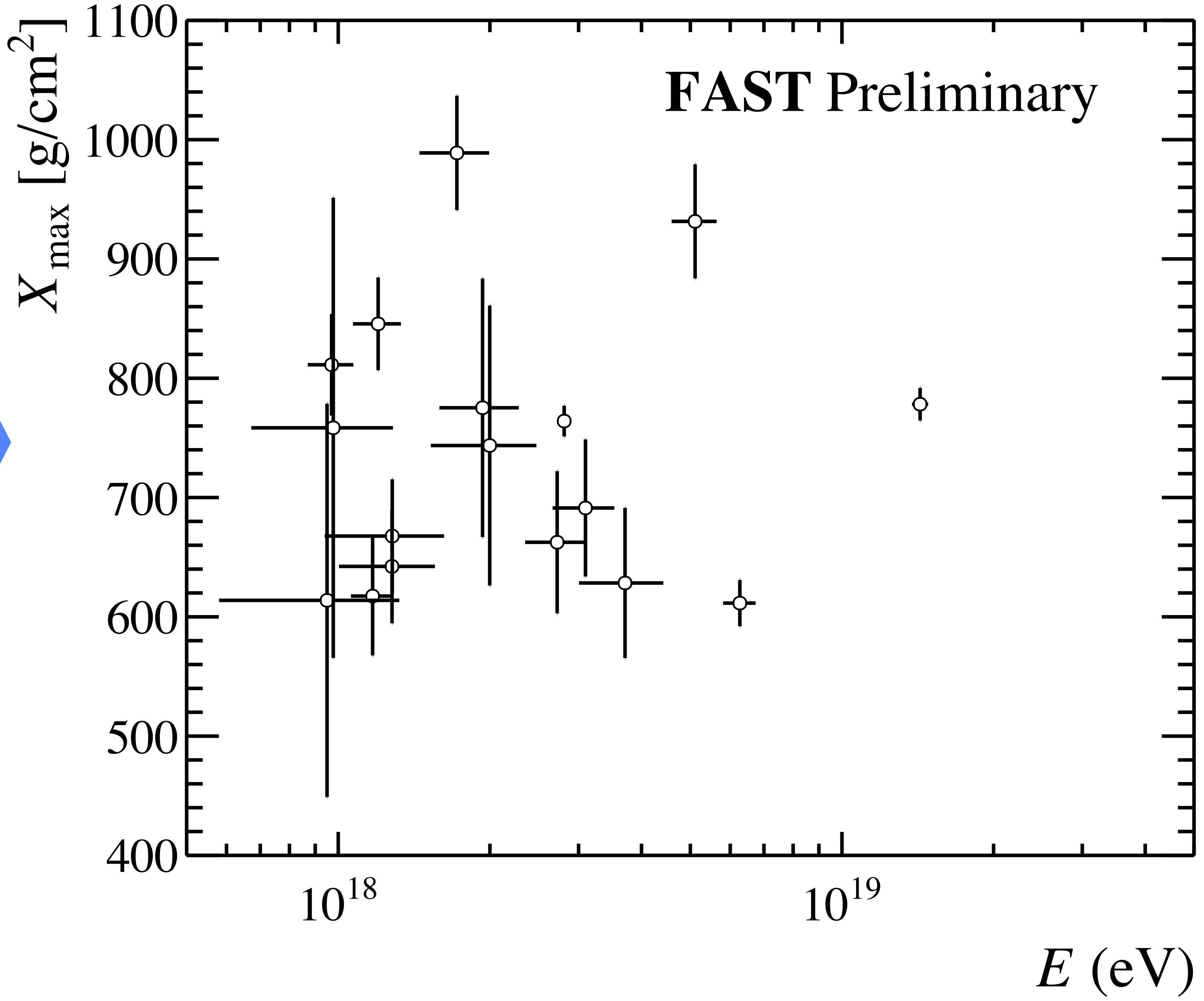
FAST
Fluorescence detector Array of Single-pixel Telescopes

Reconstructing UHECRs with FAST@TA

- Data period: 2018/Mar/19 - 2019/Oct/14, 225 hours
- Event number: **964** (TA FD) -> **179** (Single-hit with FAST, S/N > 6σ, Δt > 500 ns) -> **59** (Multi-hit)
  - The shower parameters are reconstructed by TA FD monocular result





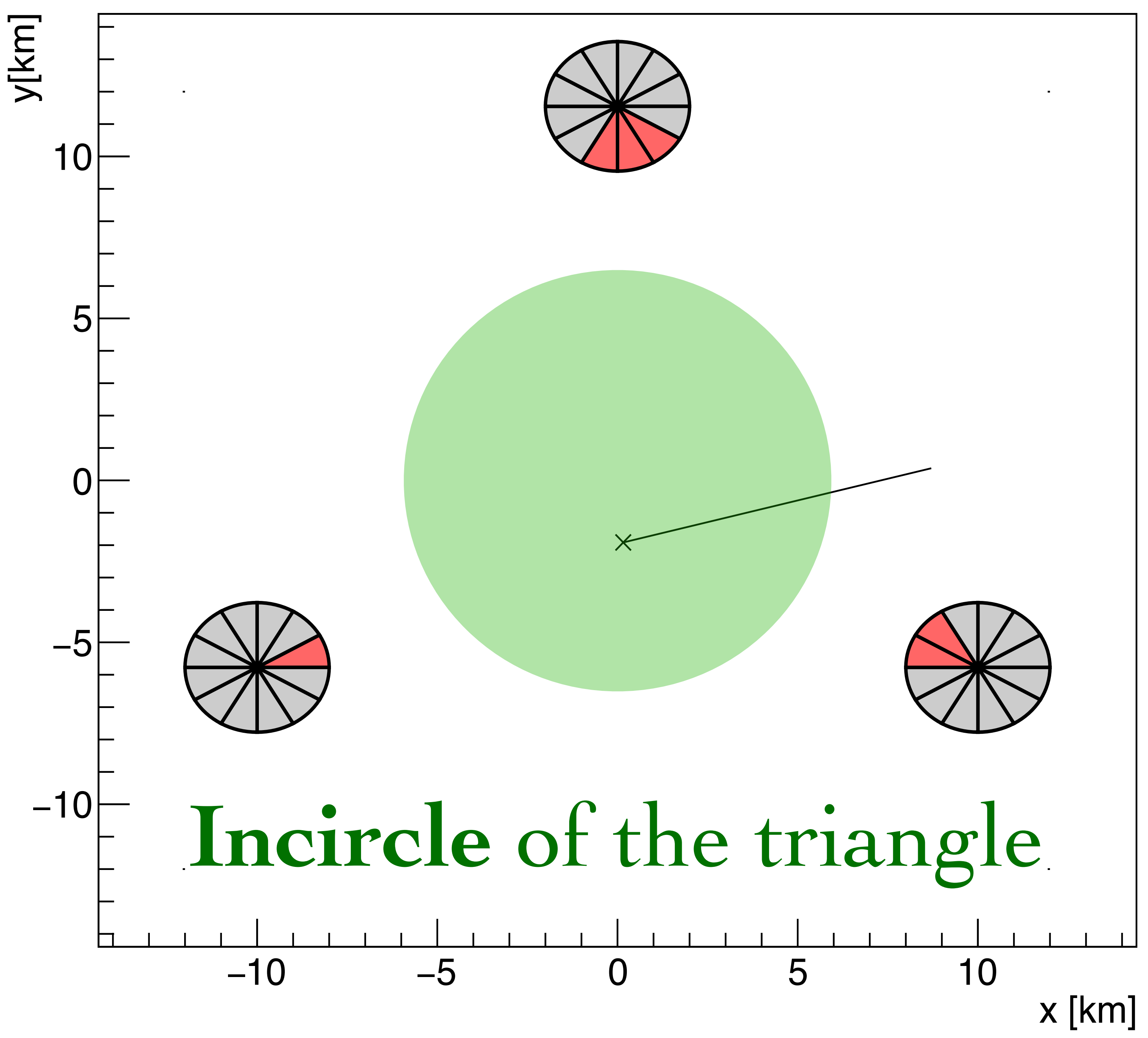


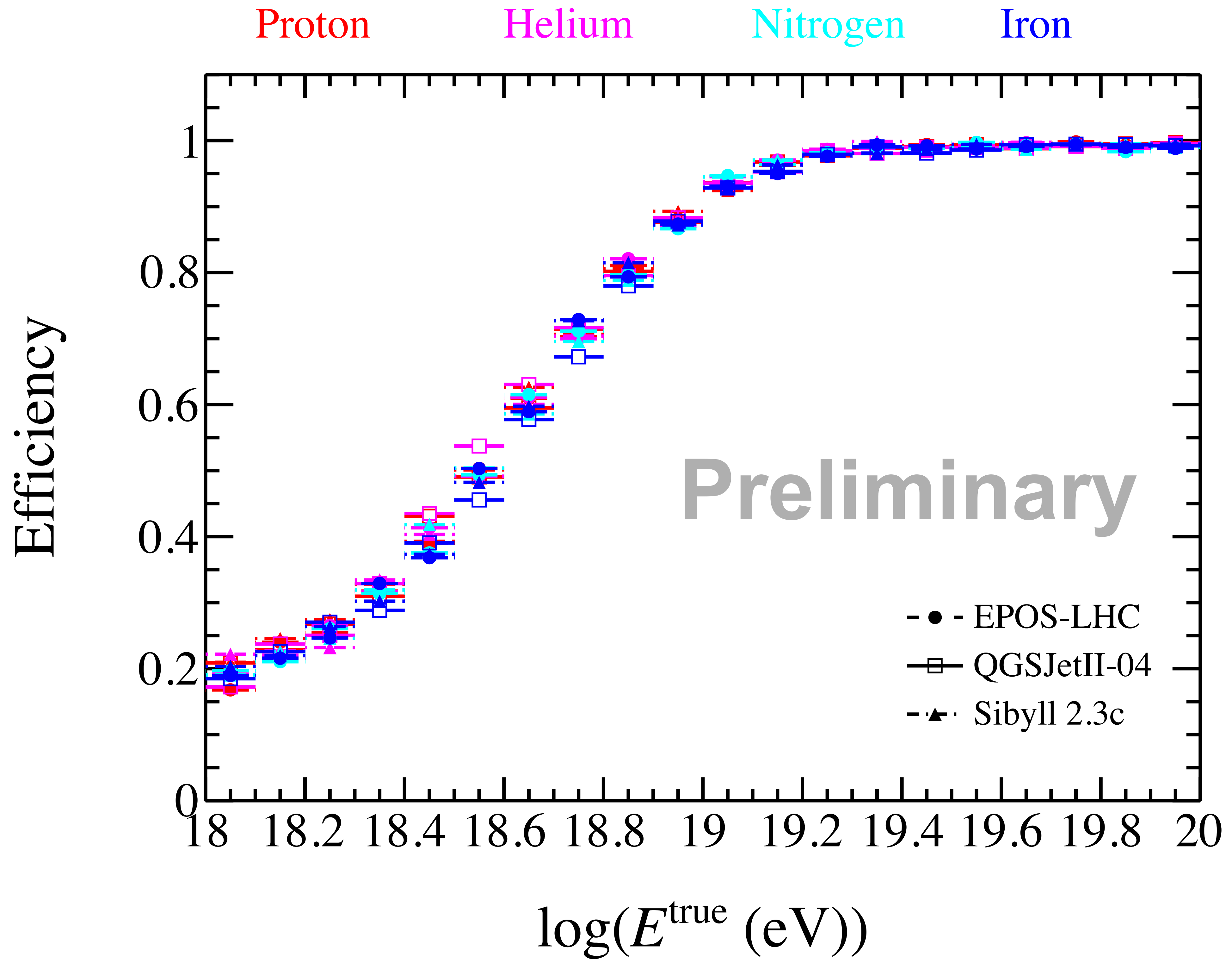
- Use **top-down reconstruction** for **events with multi-hit PMTs above 1 EeV**
  - First-guess geometry given from the TA FD

First guess reconstruction with a FAST array

Work: Justin Albury

- **Training data**: Energy of 1 - 100 EeV, X_{max} of 500 - 1200 g/cm^2, **uniform**
  - Night sky background: σ=10 p.e./100 ns, based on **field measurements at TA and Auger sites**
- **Test data:** X_{max} distributions based on CORSIKA-Conex simulations
  - 4 species (P, He, N, Fe) with 3 interaction models (EPOS-LHC, QGSJetII-04, Sibyll 2.3c)





$$\epsilon = \frac{N_i(E^{\text{true}}_{\text{trigger}})}{N_i(E^{\text{true}}_{\text{thrown}})}$$

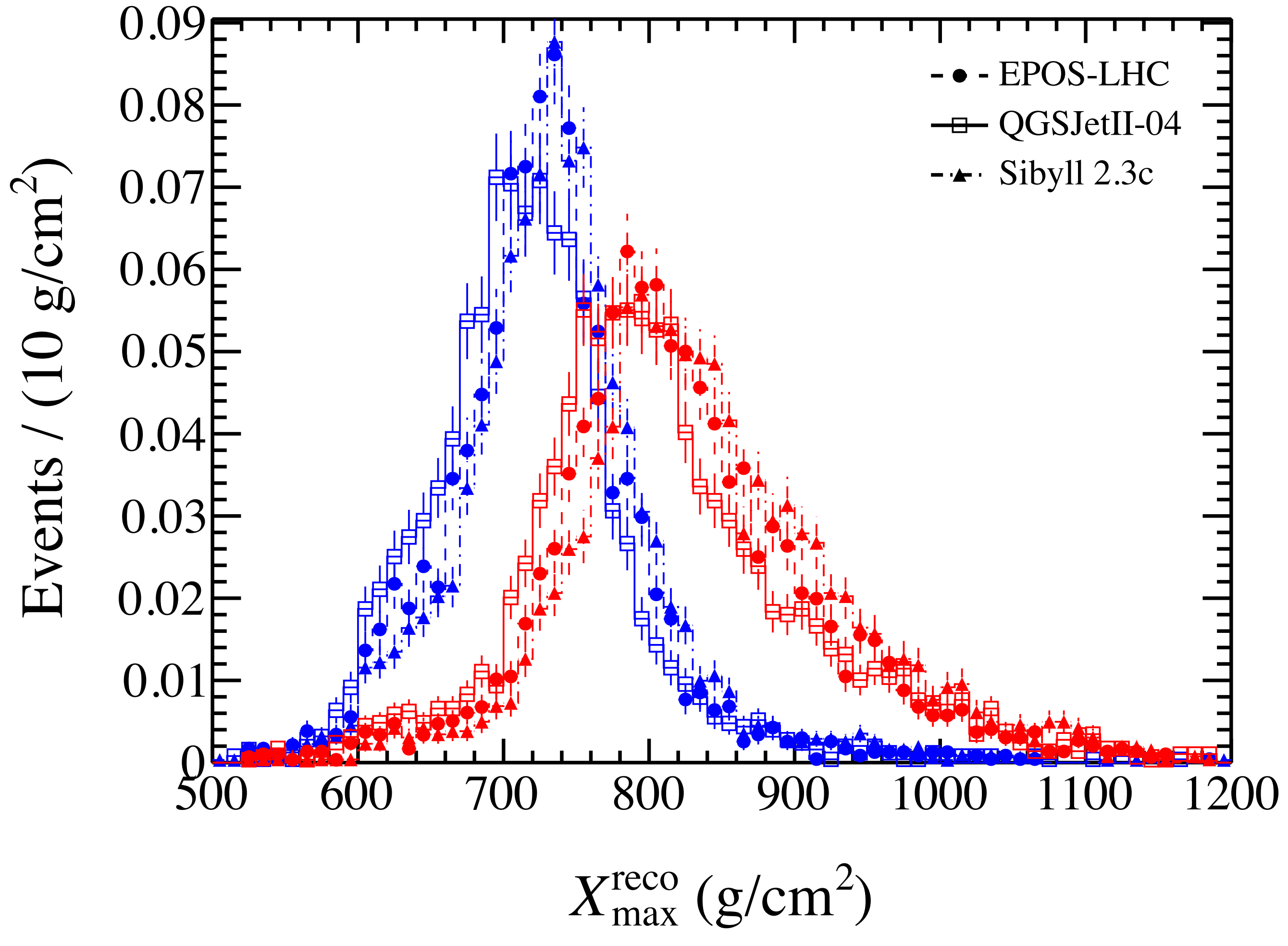
3-fold trigger efficiency

100% above 20 EeV

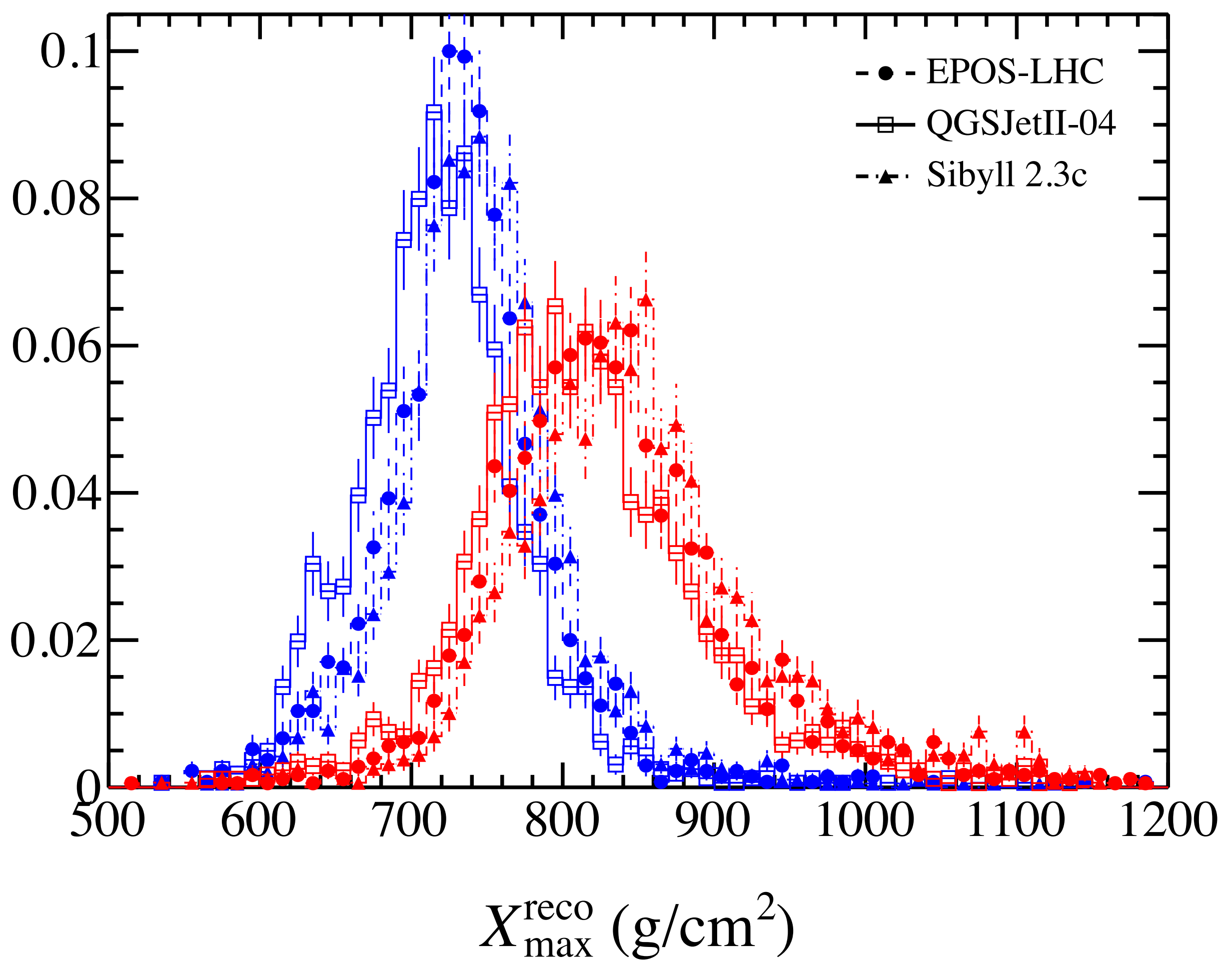
FAST
Fluorescence detector Array of Single-pixel Telescopes

Reconstructed X_{max} distributions

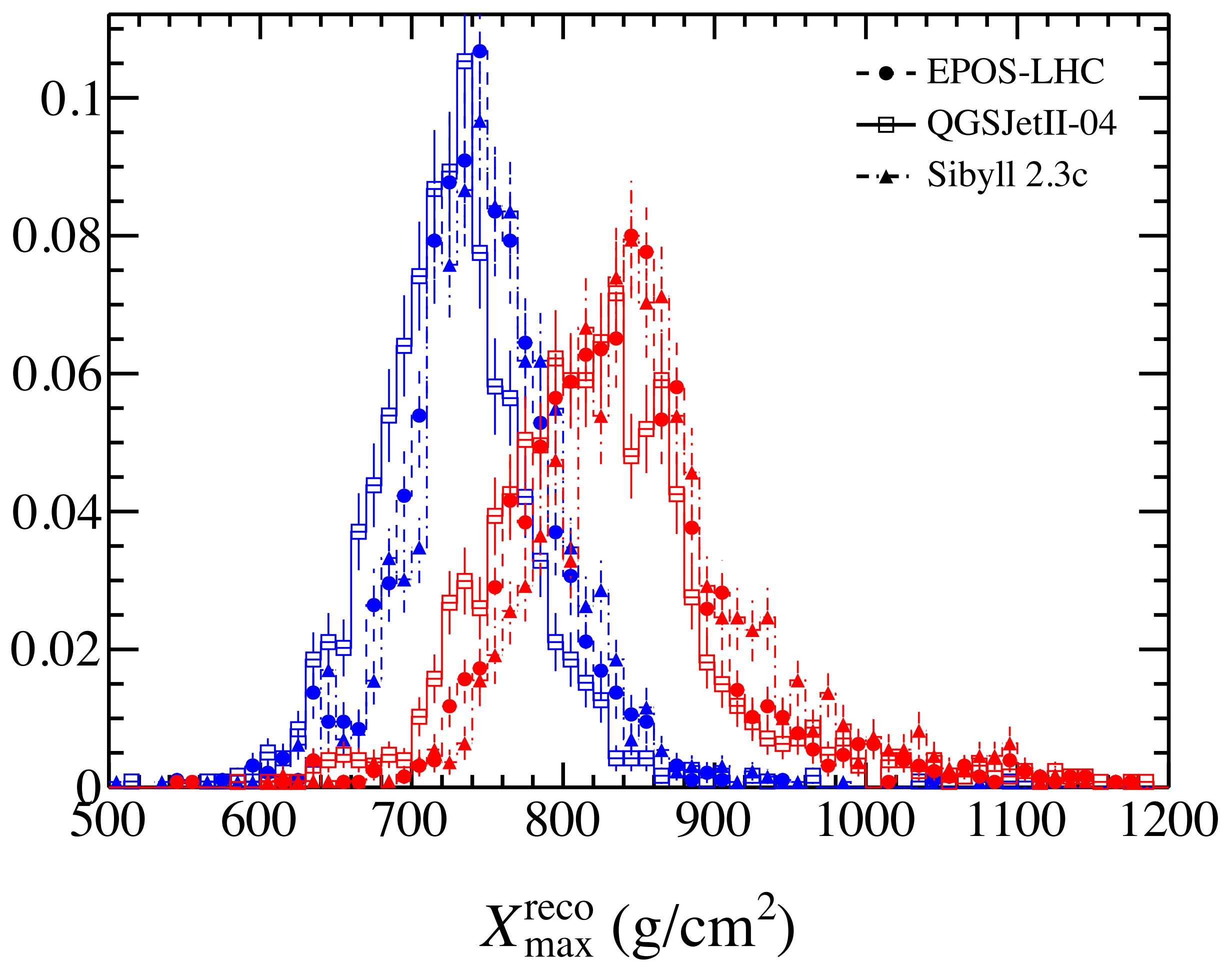
10 - 20 EeV



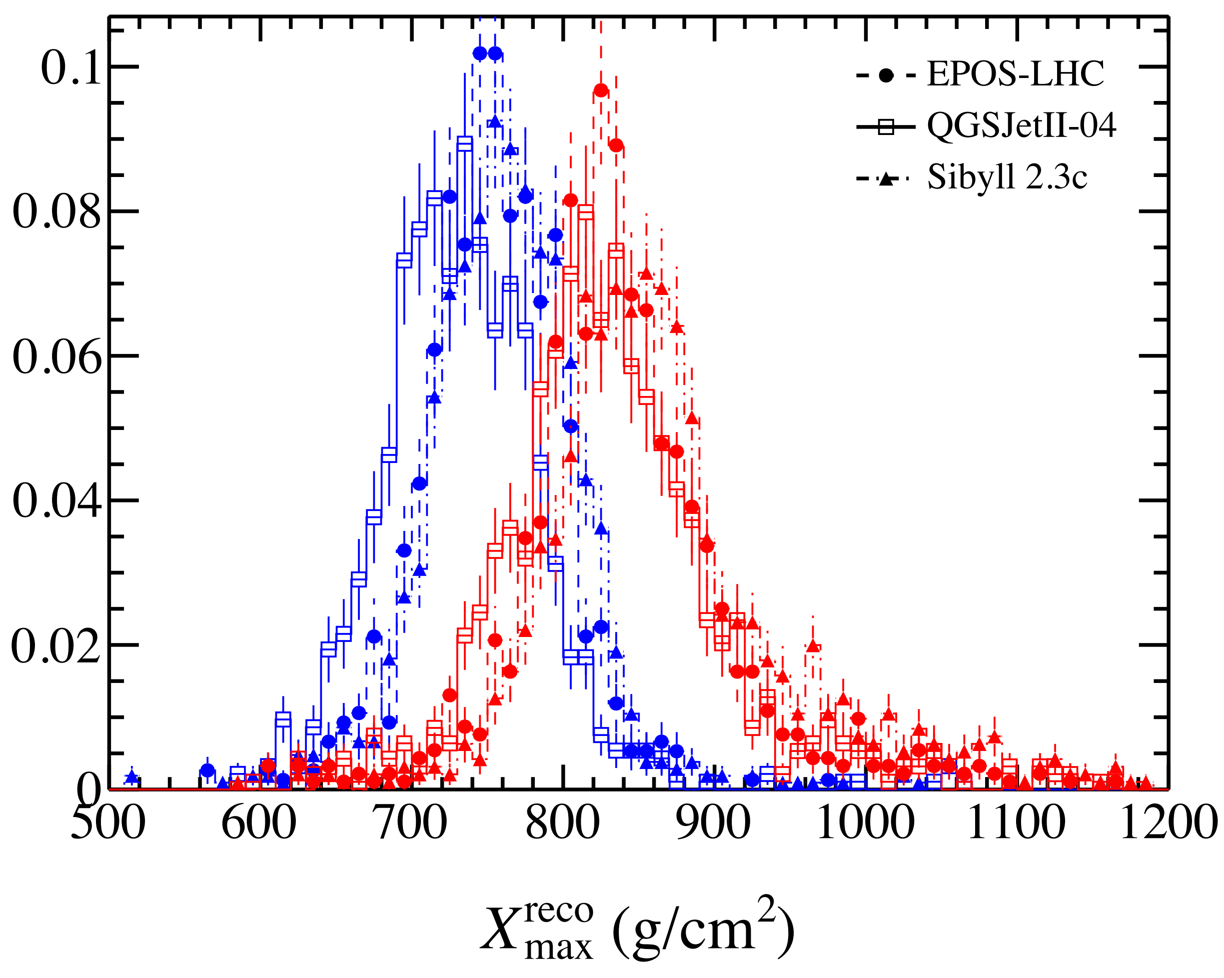
20 - 30 EeV



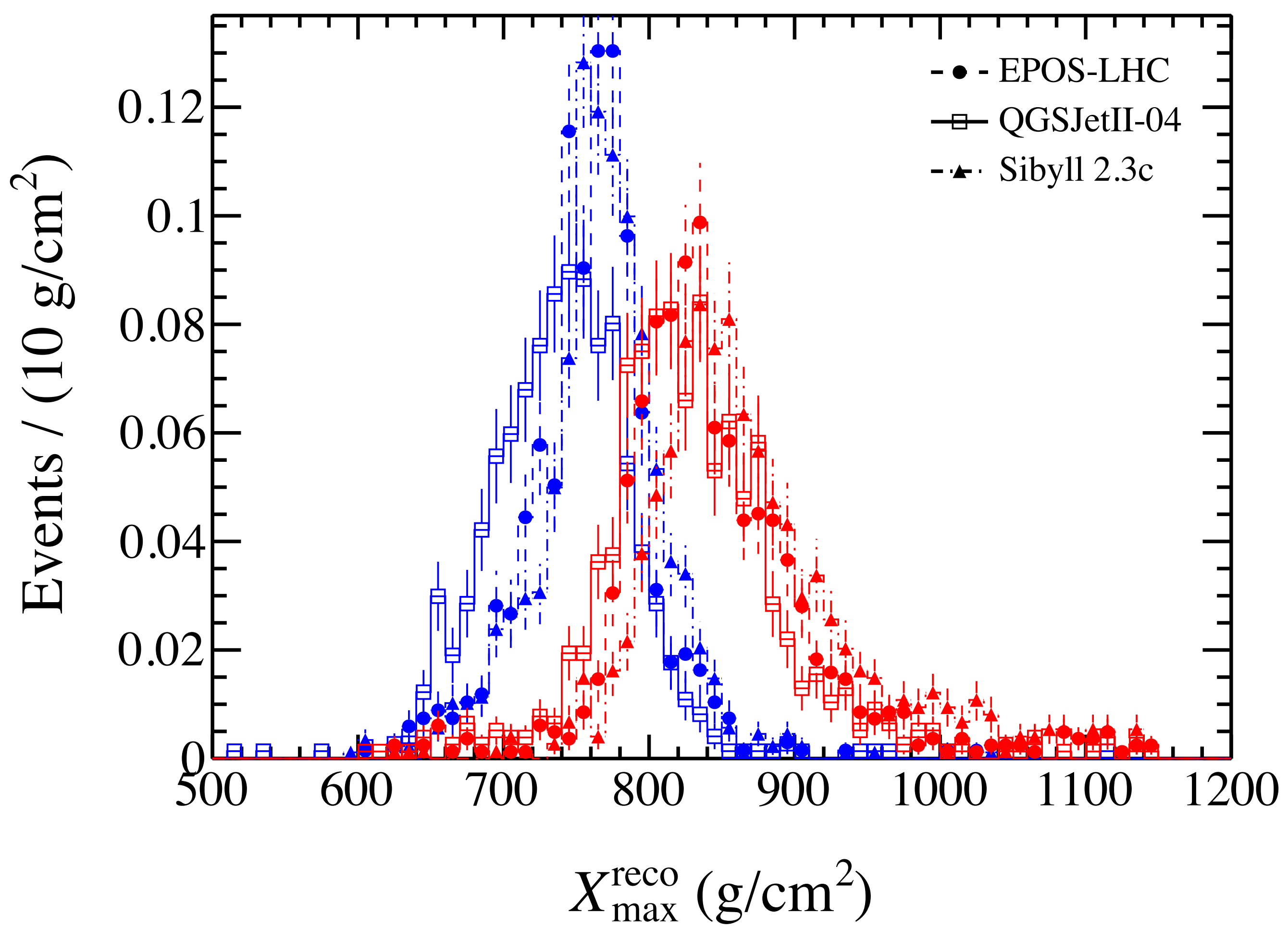
30 - 40 EeV



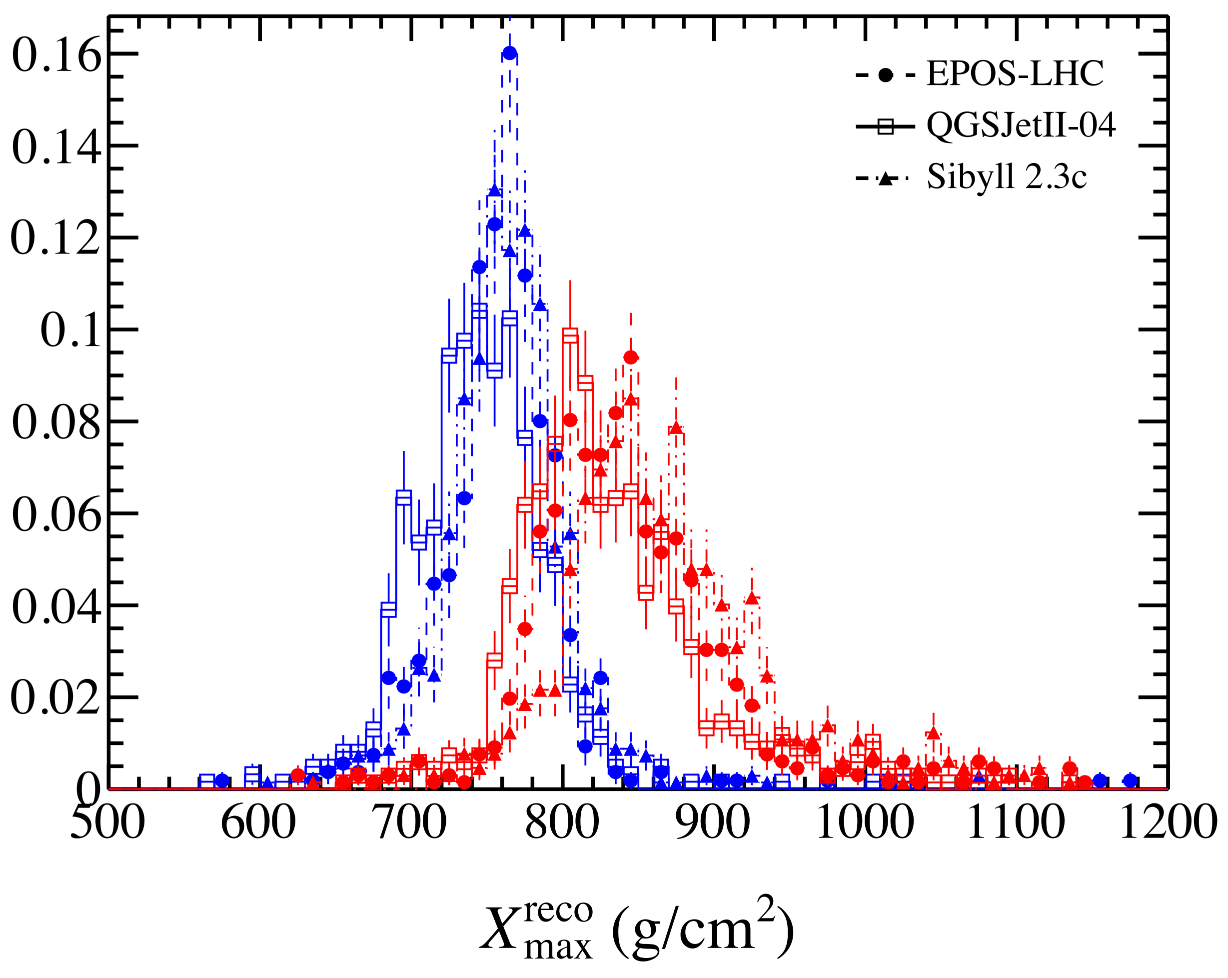
40 - 50 EeV



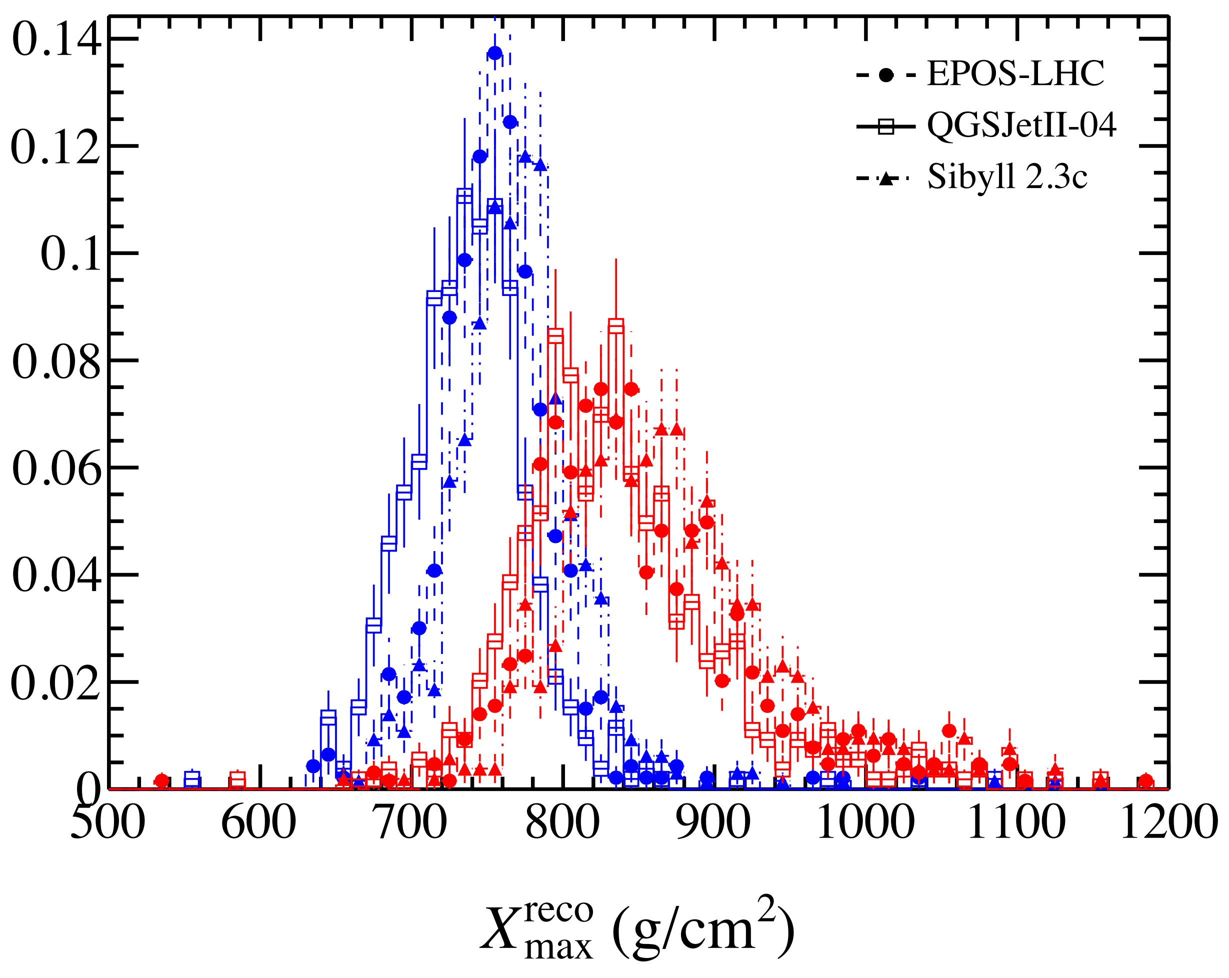
50 - 60 EeV



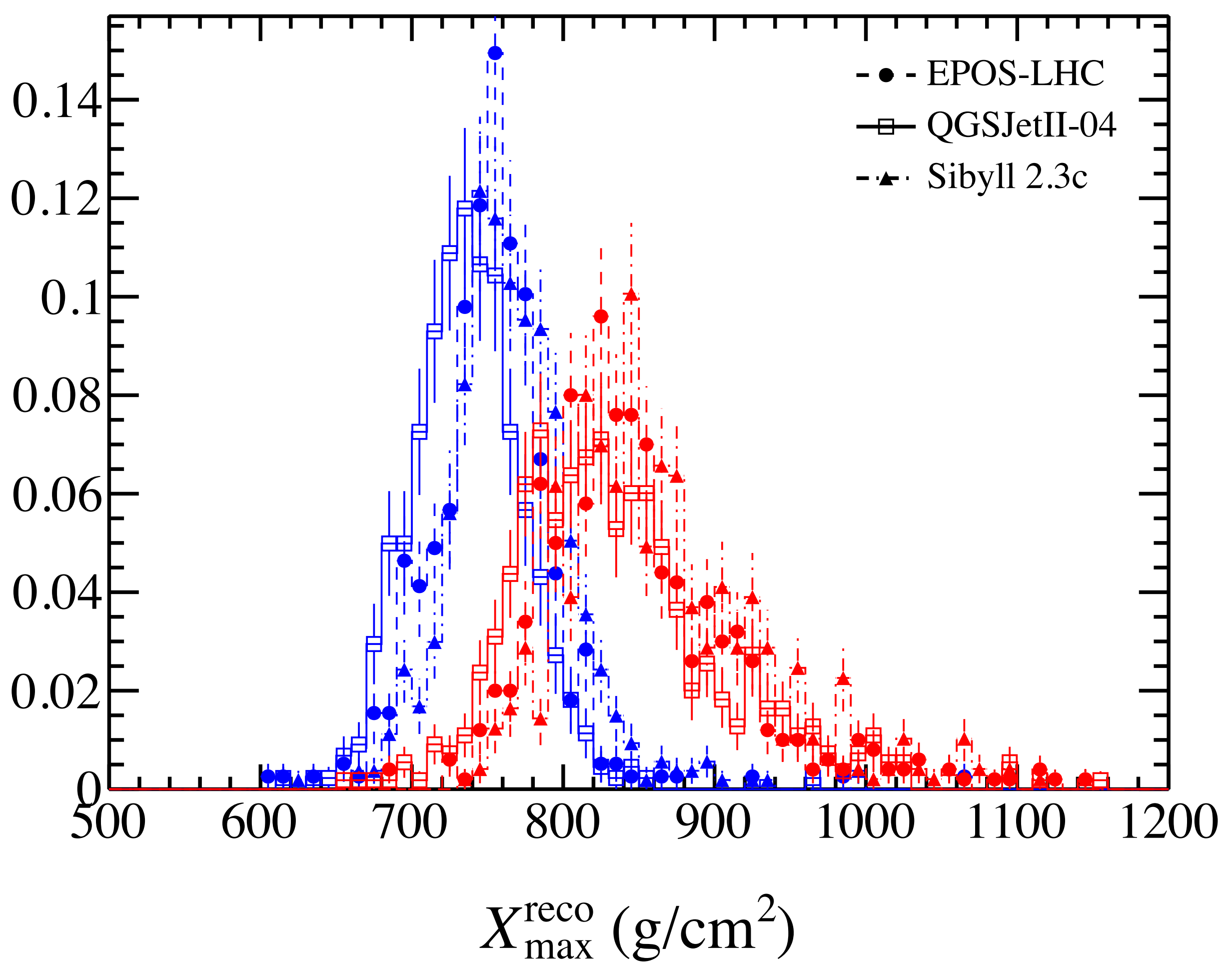
60 - 70 EeV



70 - 80 EeV



80 - 90 EeV



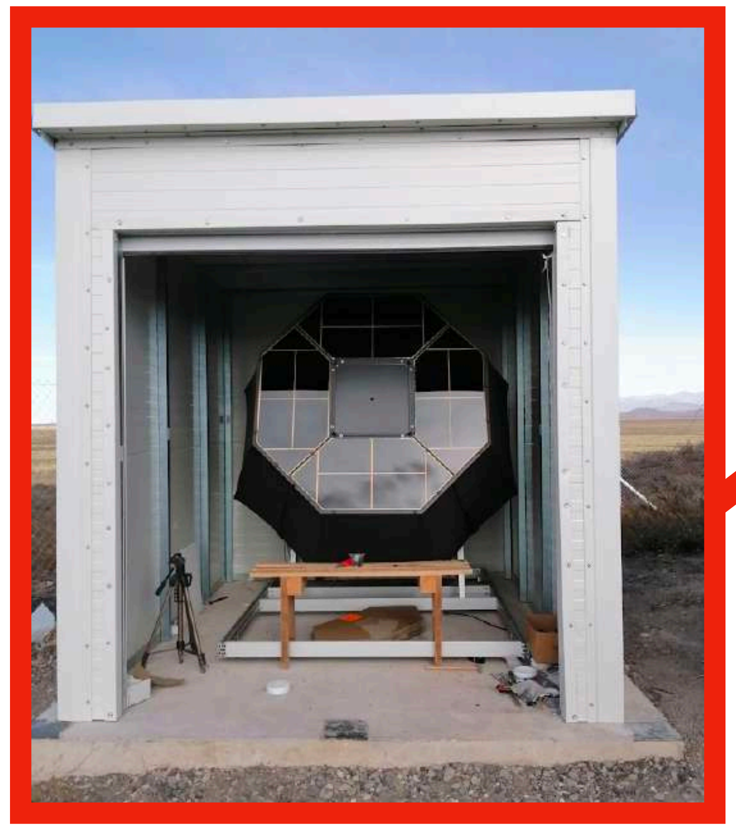
- Resolution@~40 EeV, Arrival direction: 4.2 degrees, Core: 465 m, Energy: 8% Xmax: 30 g/cm^2

FAST@Auger observations

Work: Petr Hamal, Jose Bellido, Justin Albury

Fluorescence detector Array of Single-pixel Telescopes

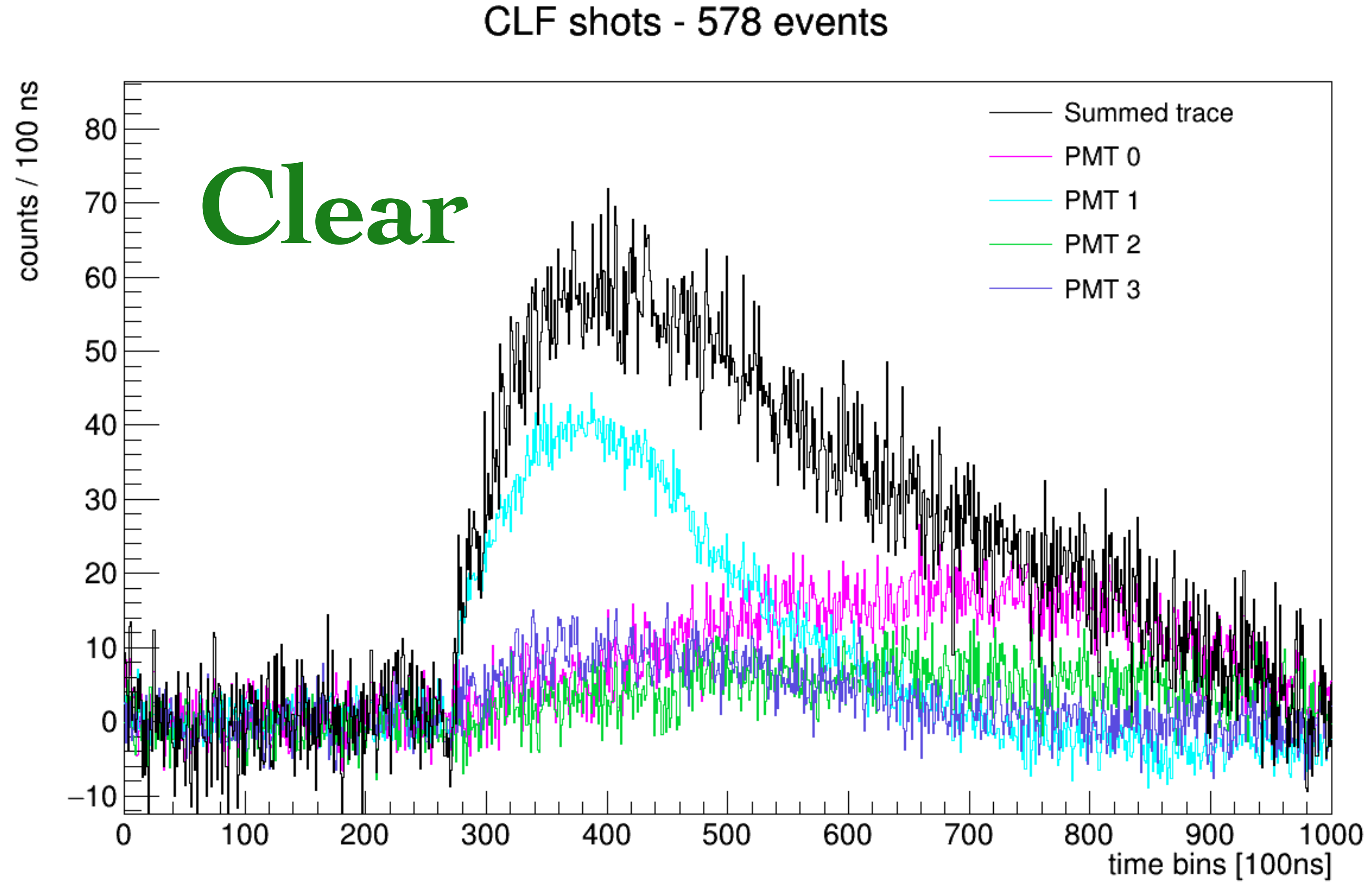
FAST-2 in 2022

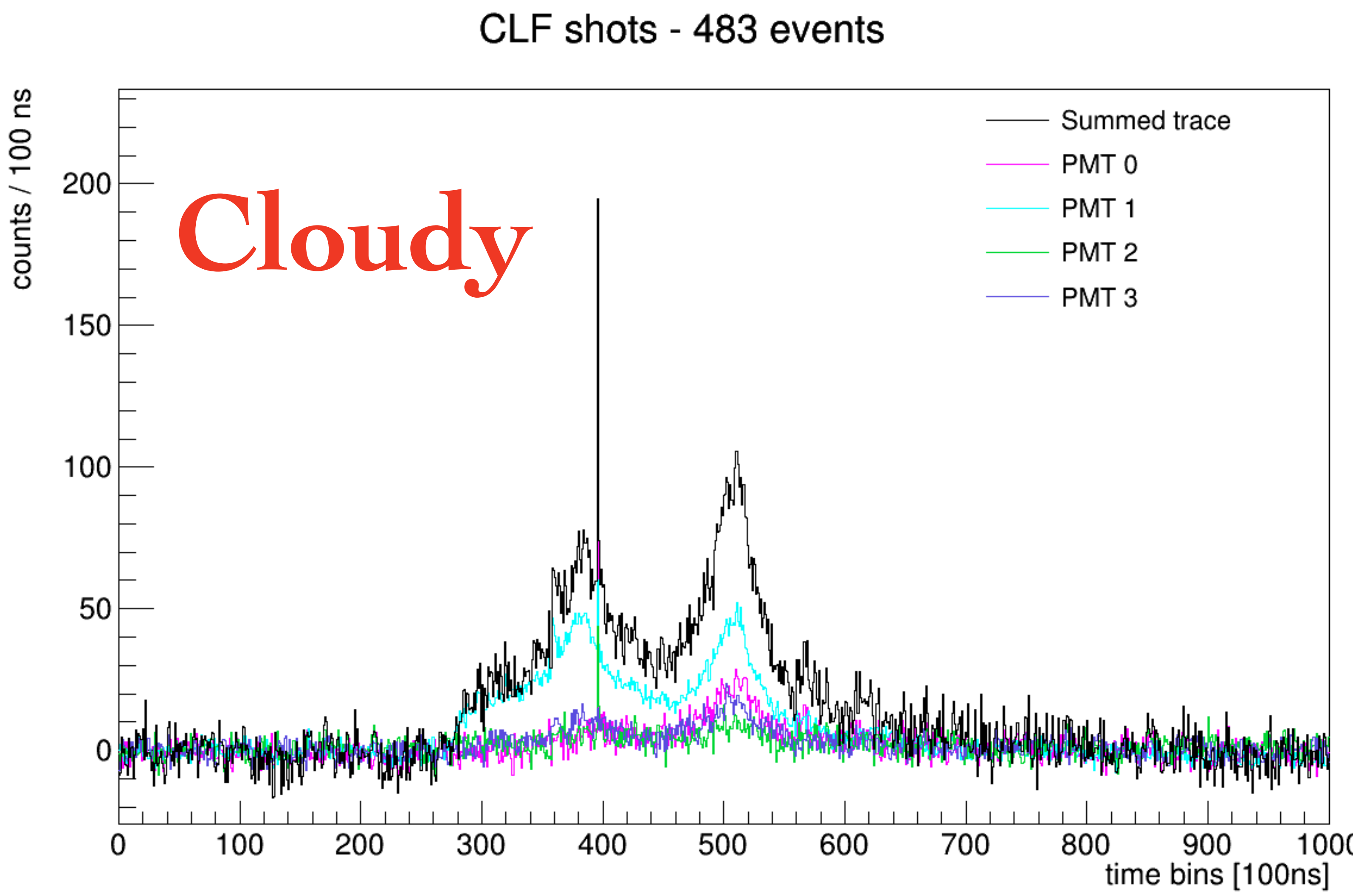


FAST-1 in 2019

✦ https://youtu.be/ceN-IsaWcXg

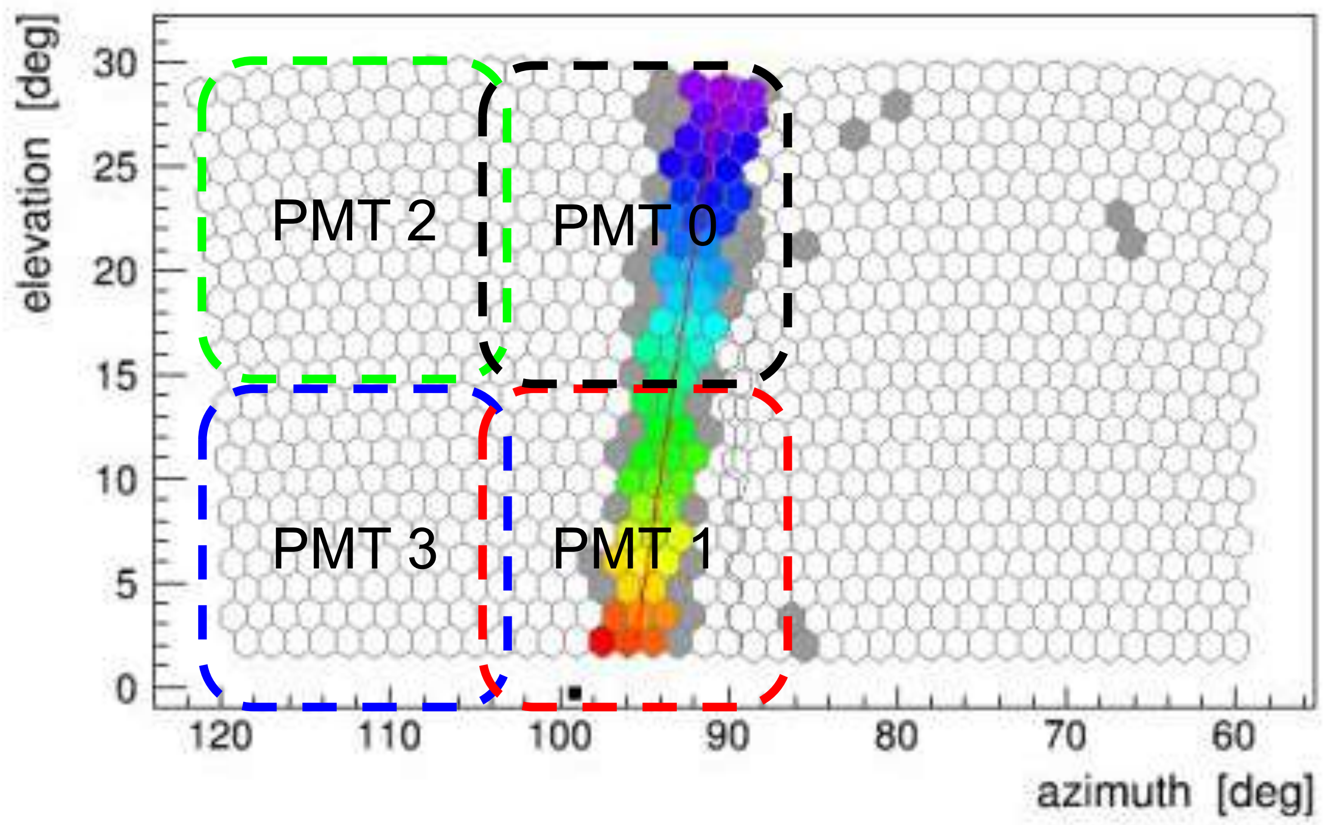
Distant laser at 26 km

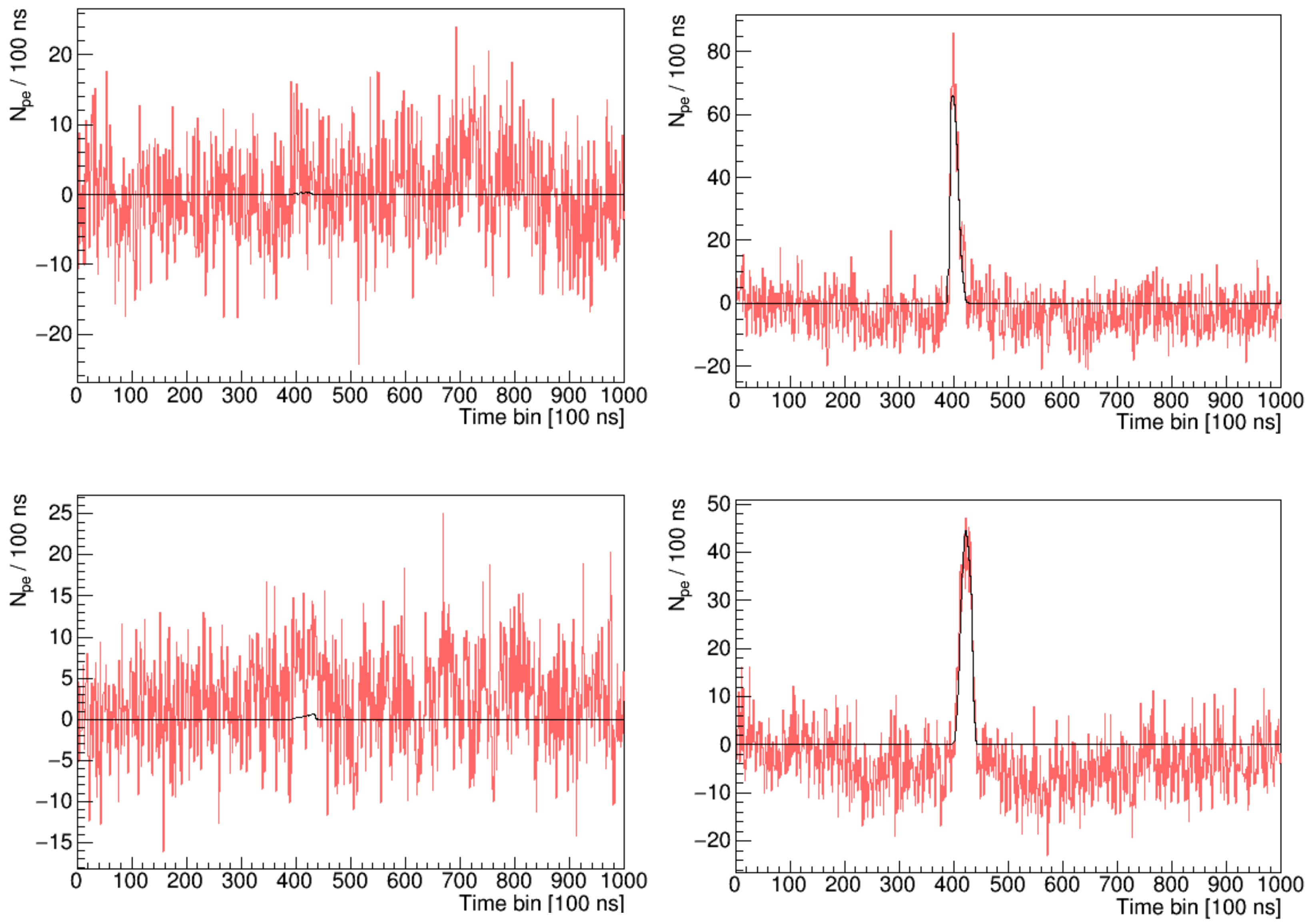




Coincidence event with Auger hybrid

PIERRE AUGER OBSERVATORY

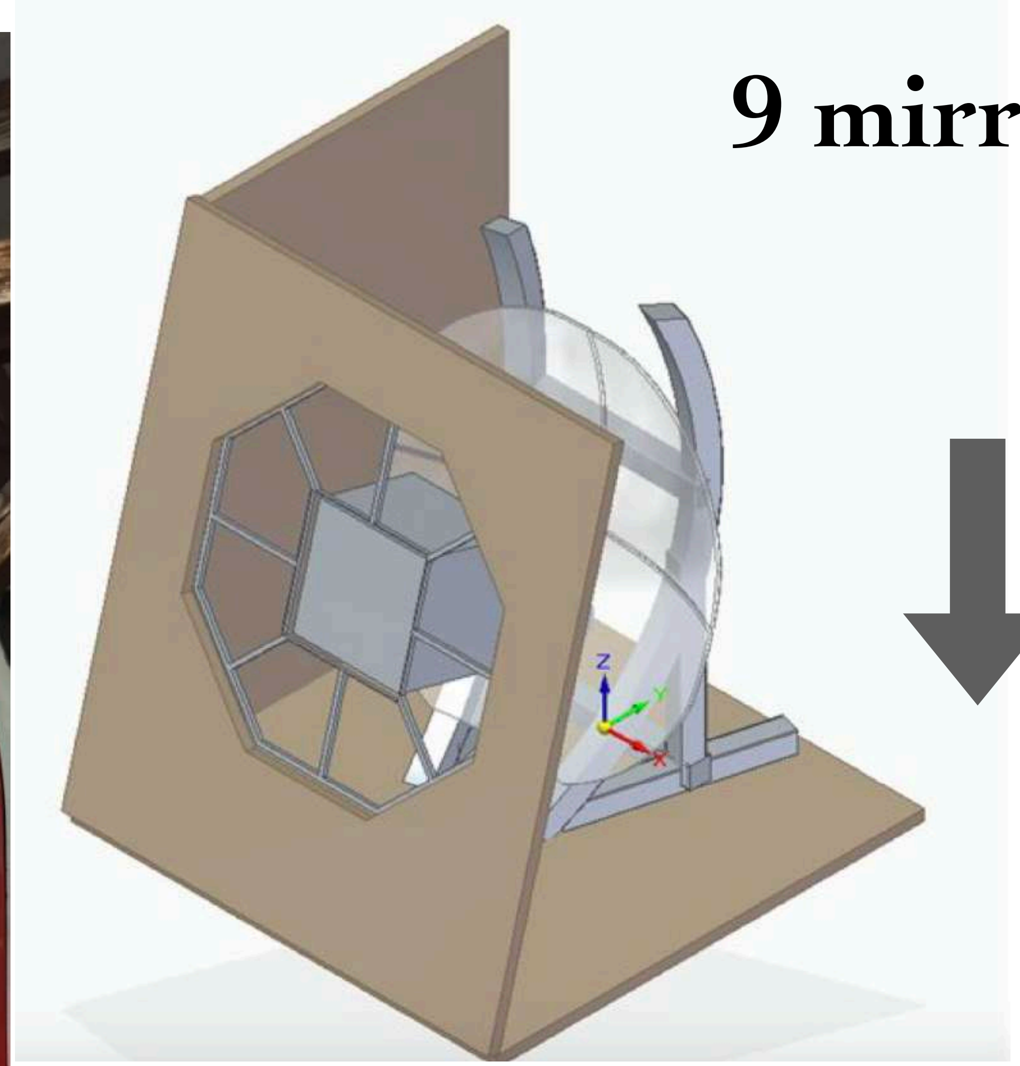




Next: stand-alone operation of FAST array

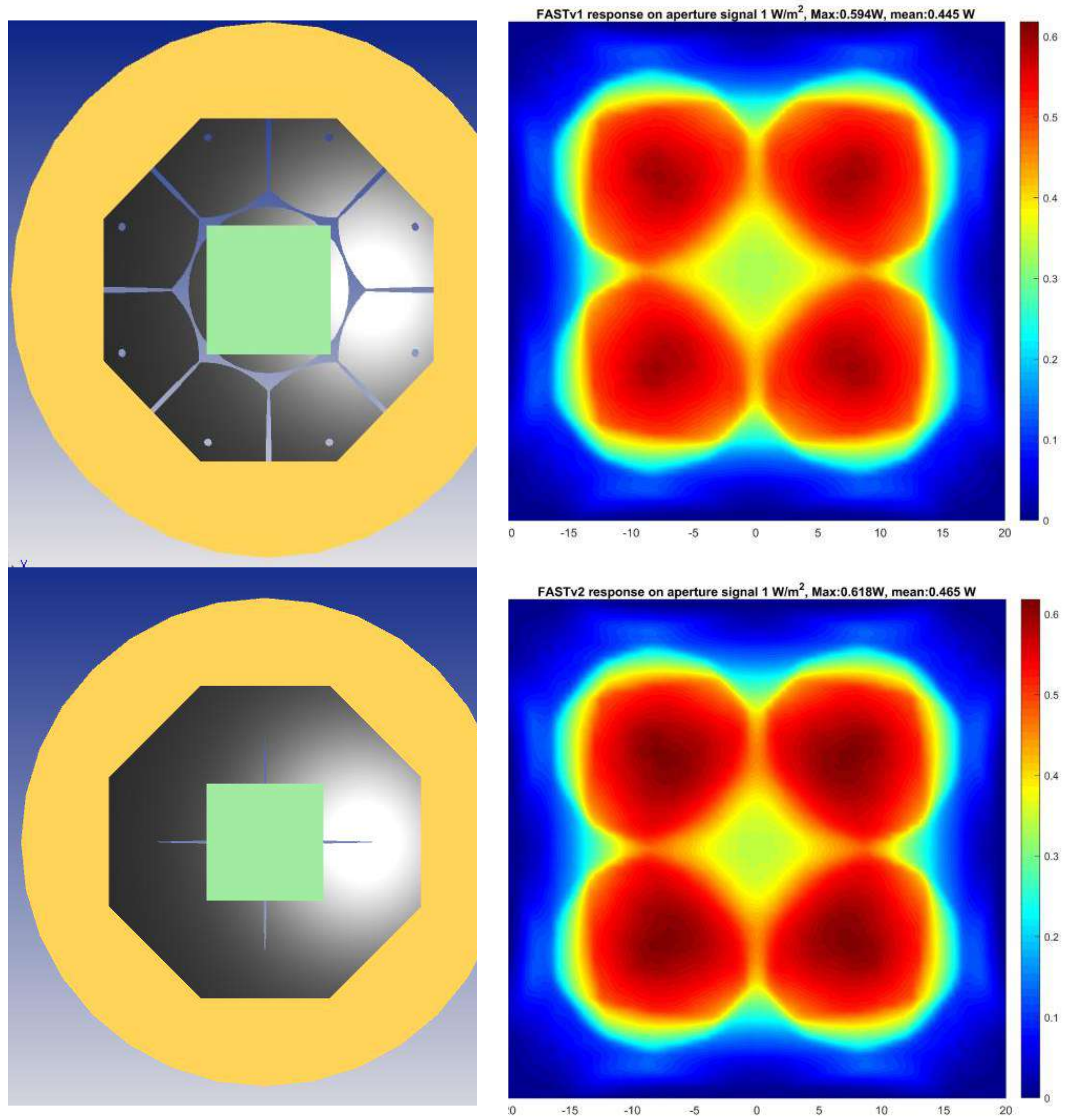
Robust enclosure

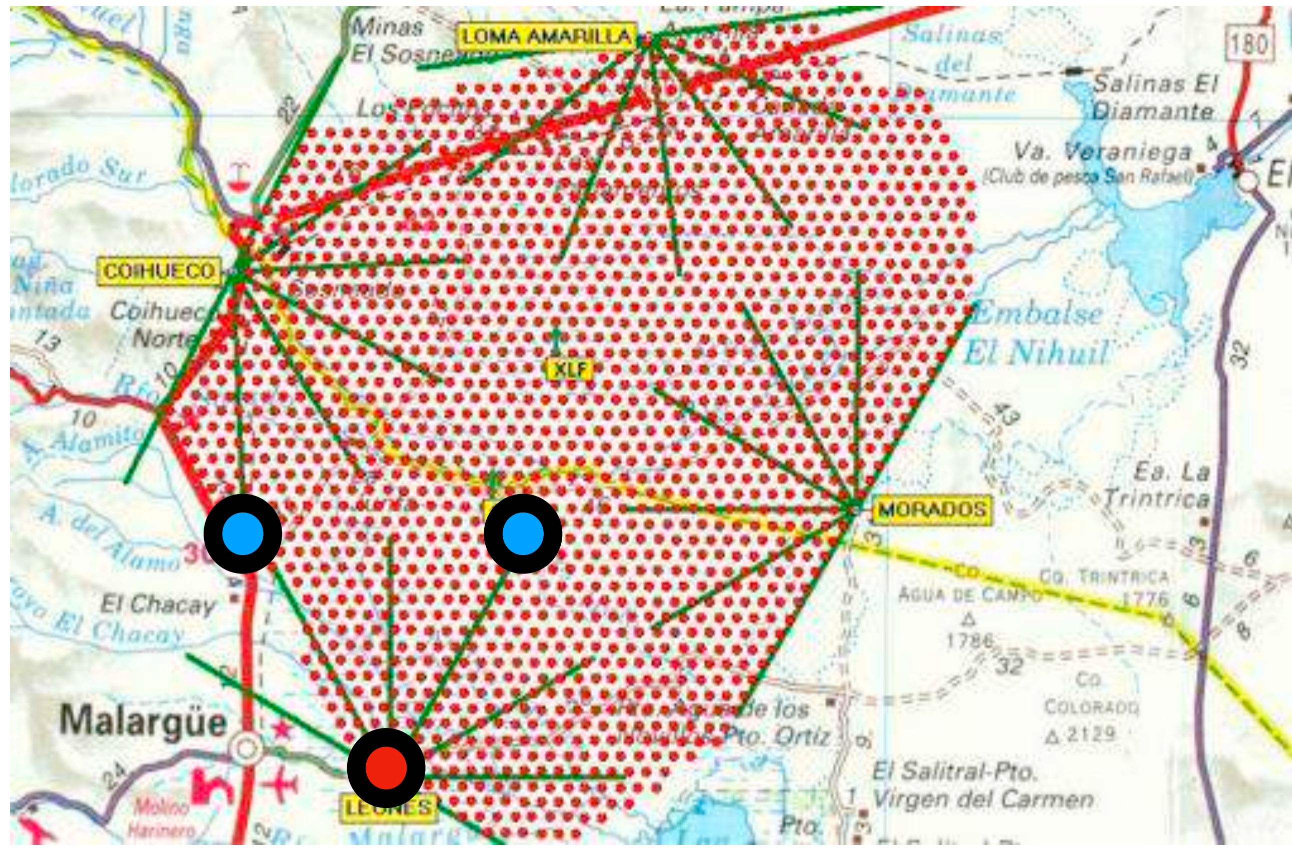
Optimization of optics using 4 mirrors

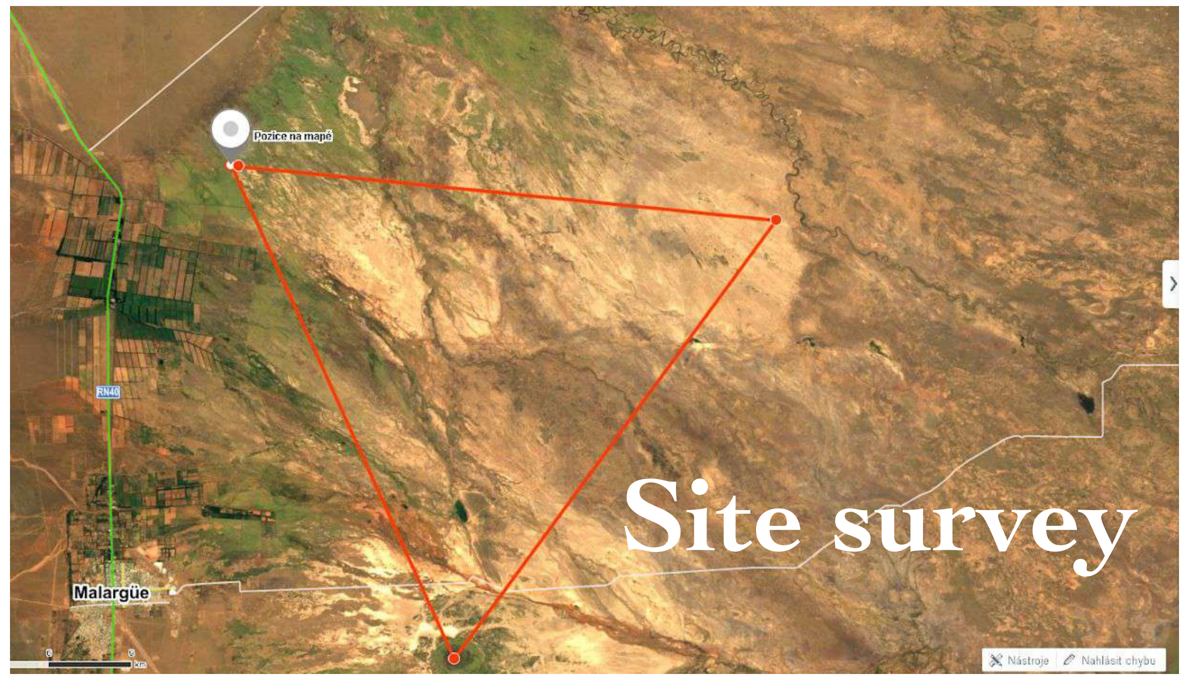


9 mirrors

4 mirrors







New electronics development

MIO | SoC | FADC | AMP

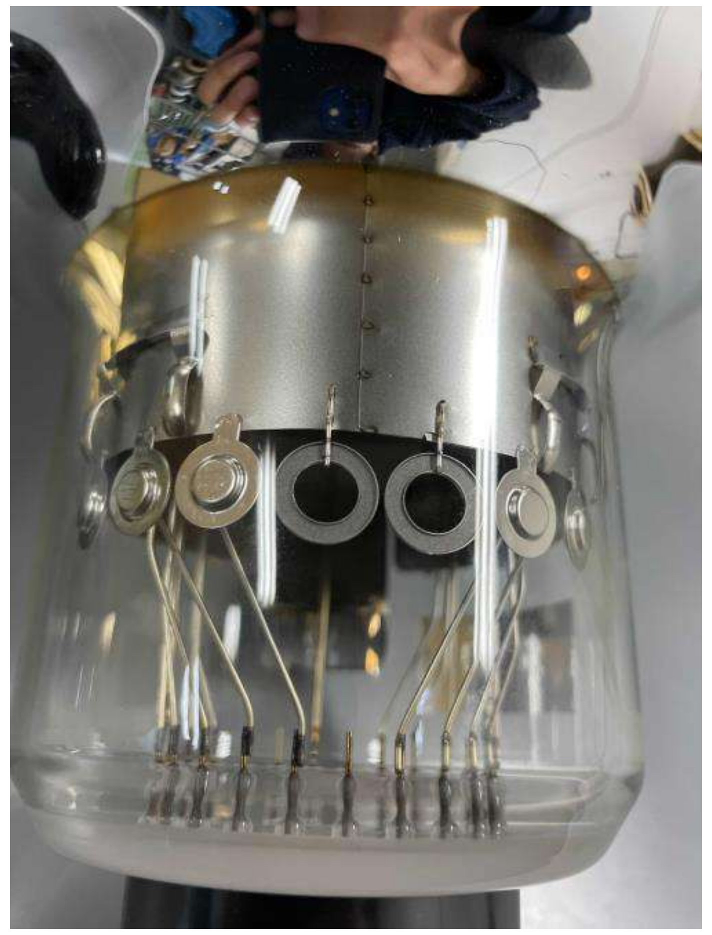
Dual 32ch FADC (ADS52J90), 64ch FADC, 14bit, 32.5 MSPS, 32ch

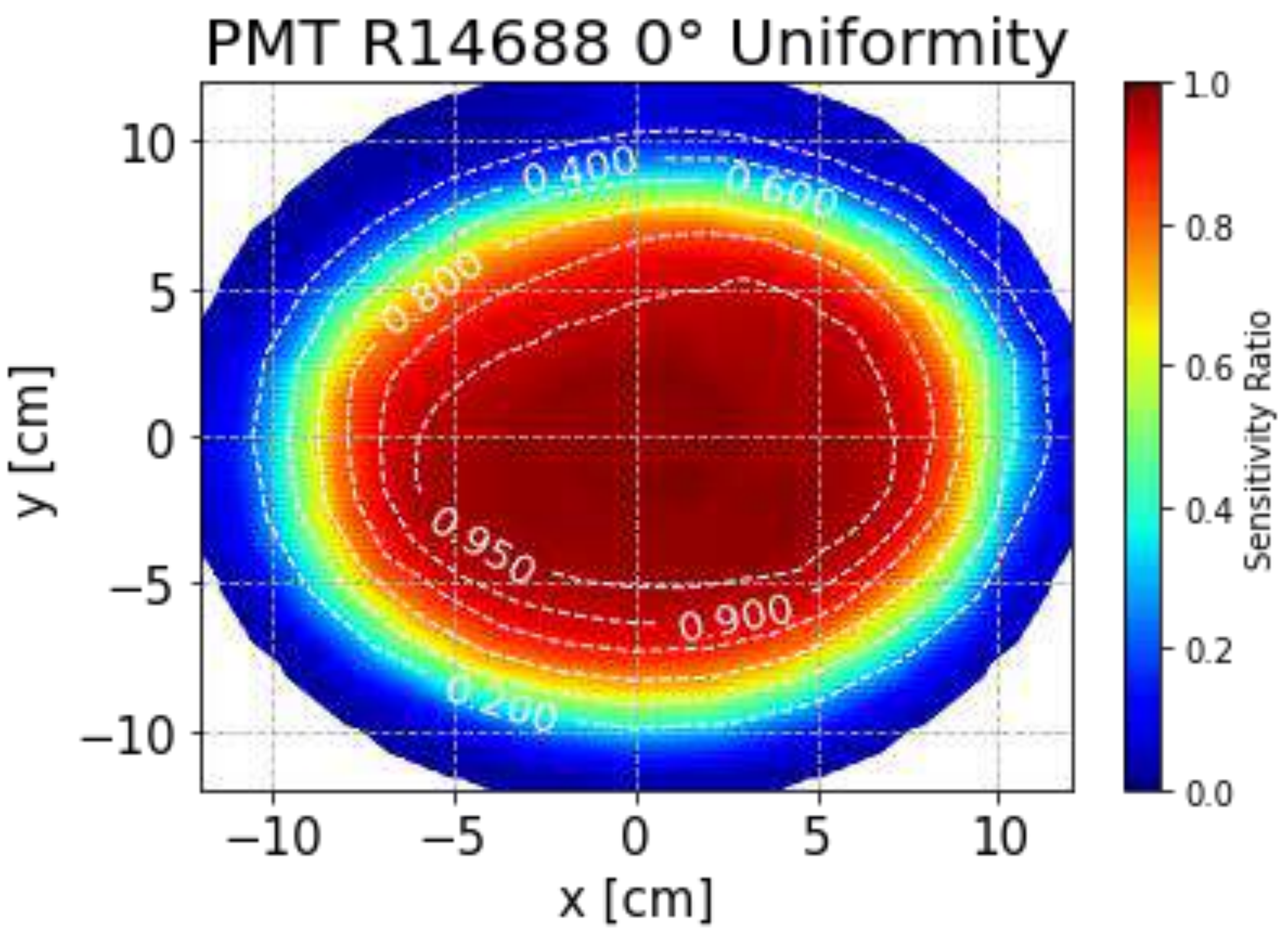
Fluorescence detector Array of Single-pixel Telescopes

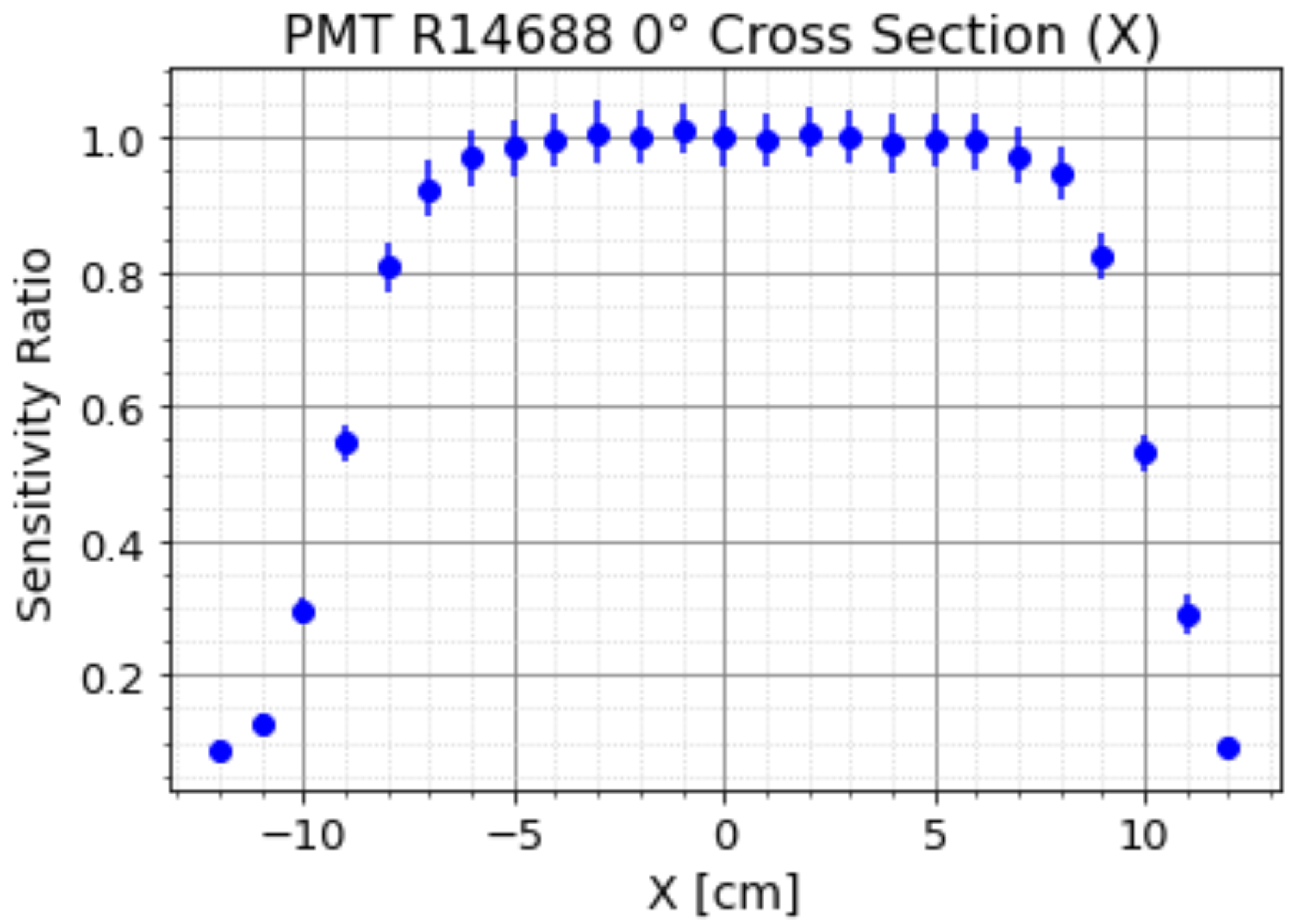
New PMT being developed to reduce non-uniformity

Work: Hiromu Nagasawa

PMT R14688

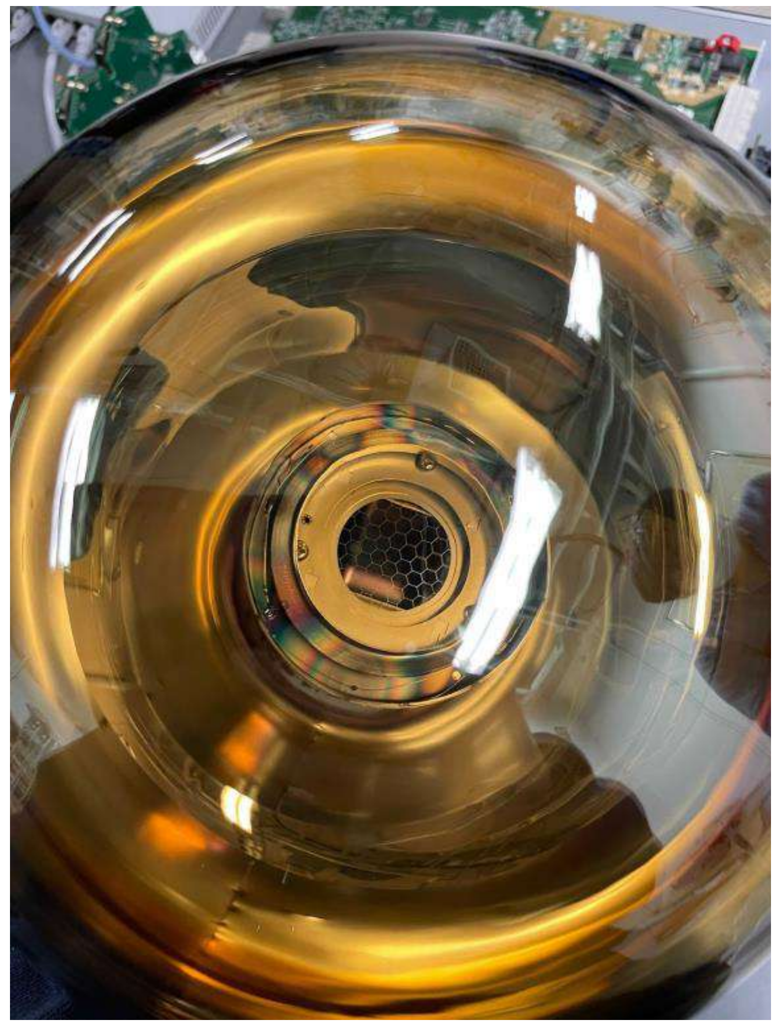


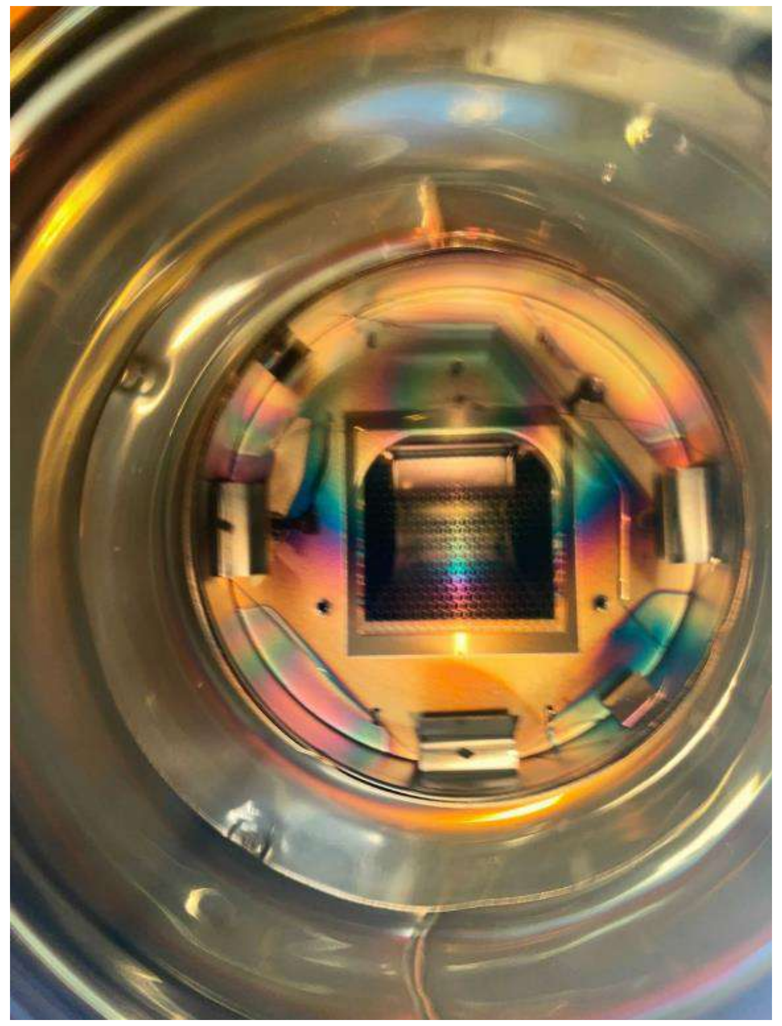




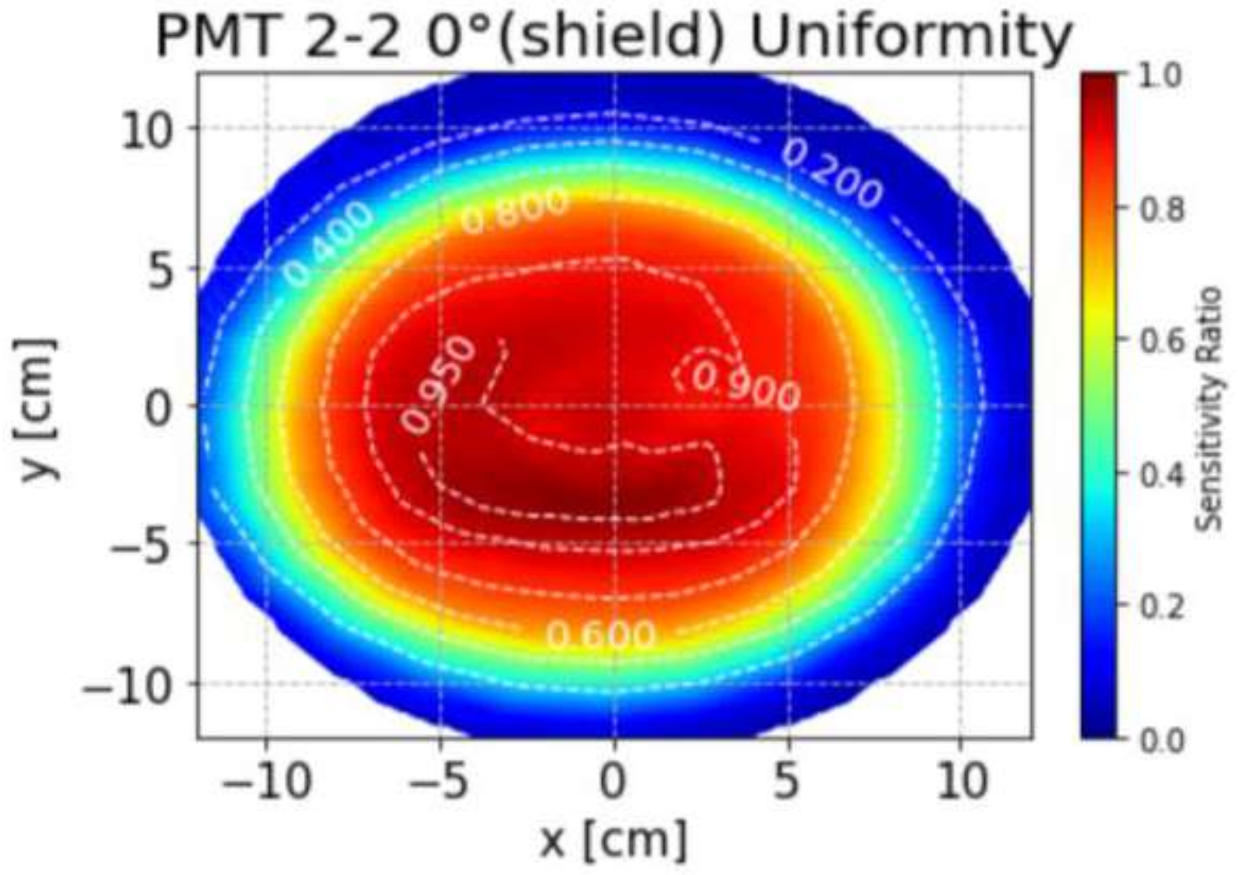
↓ R14688

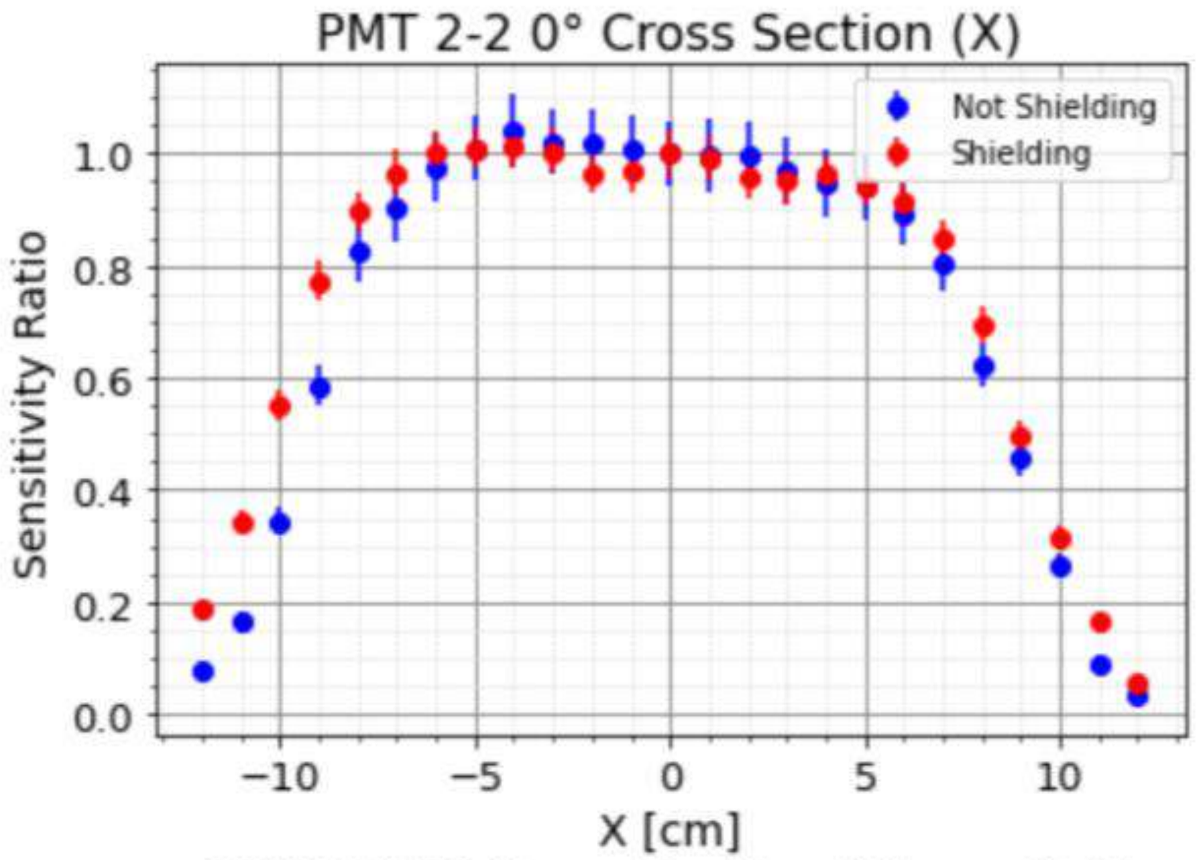
↓ R5912-03





R5912-03, with magnetic shied (FINEMET)



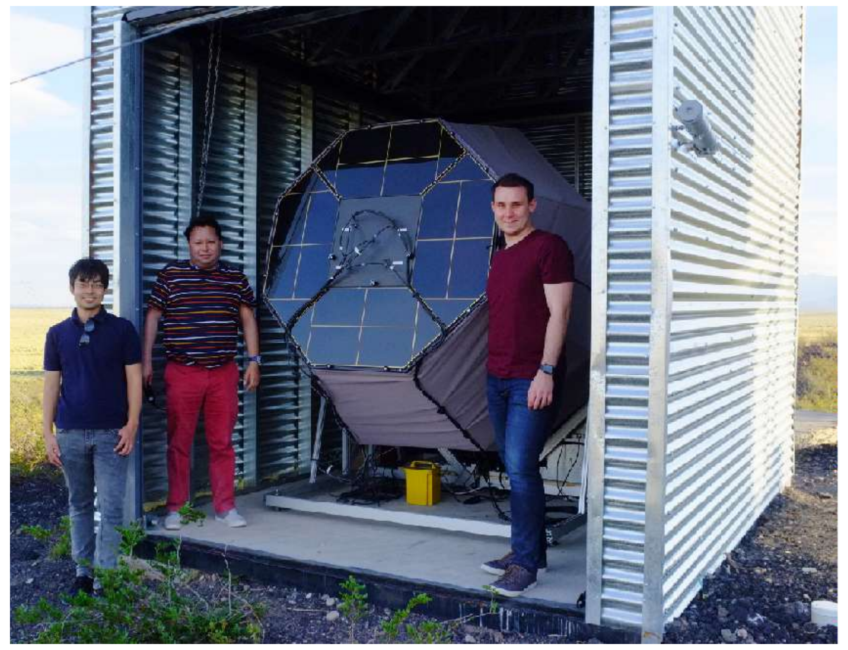


Summary and future plan

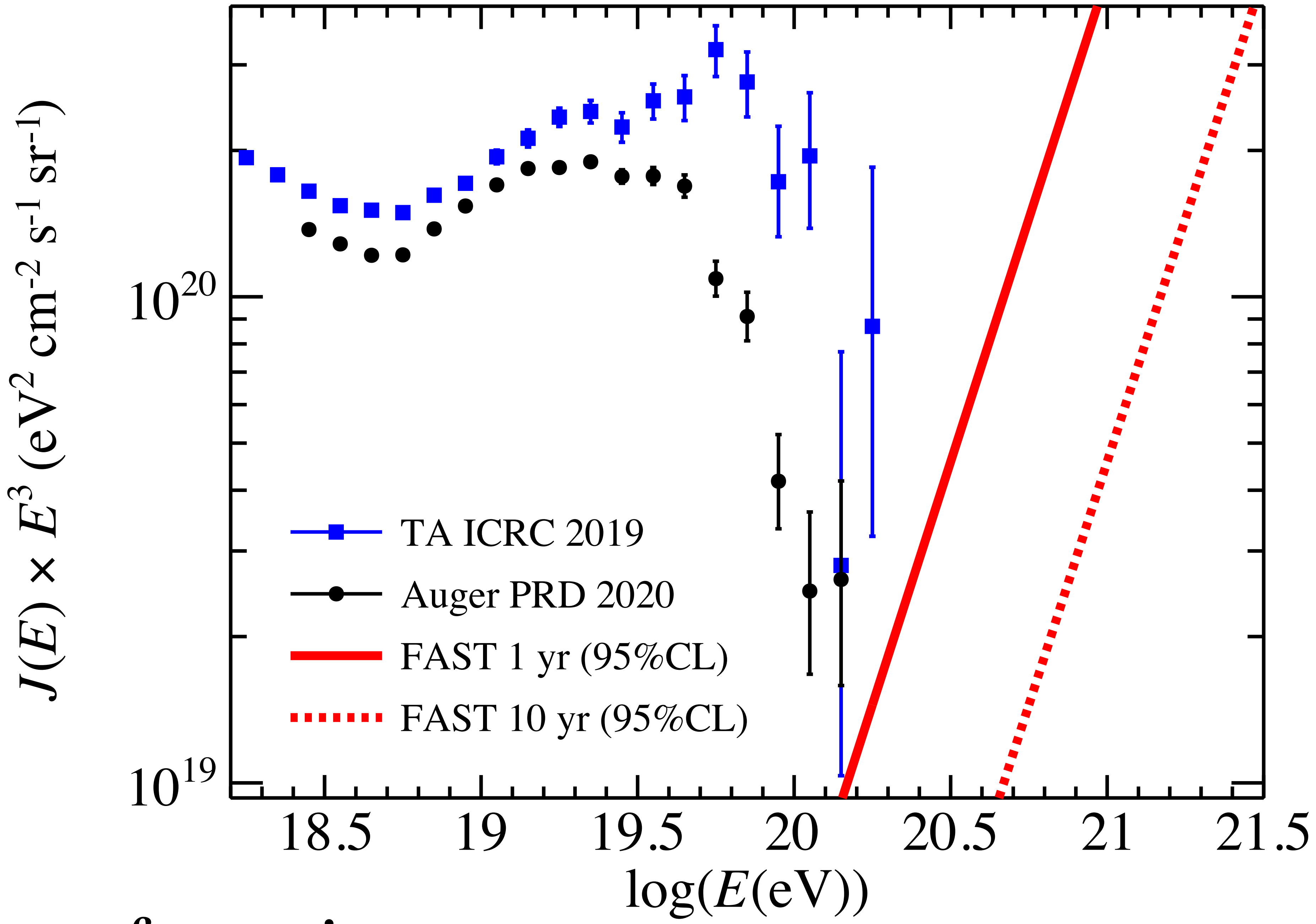
- **Fluorescence detector Array of Single-pixel Telescopes (FAST)**
  - Low-cost fluorescence telescope array
  - Promising concept as next-generation cosmic ray observatory to fulfill requirements
  - Anisotropy with mass composition sensitivity
- **Performance estimation**
  - Arrival direction: 4.2 deg, Core: 465 m
  - Energy: 8%, Xmax: 30 g/cm^2 (Δ ln$A$ ~ 1)
- **Latest results at both northern and southern hemisphere**
  - Identical telescopes installed at Auger and TA for cross calibration
- **Next step and challenges**
  - Stand-alone operation of FAST array in field

FAST@TA

FAST@Auger



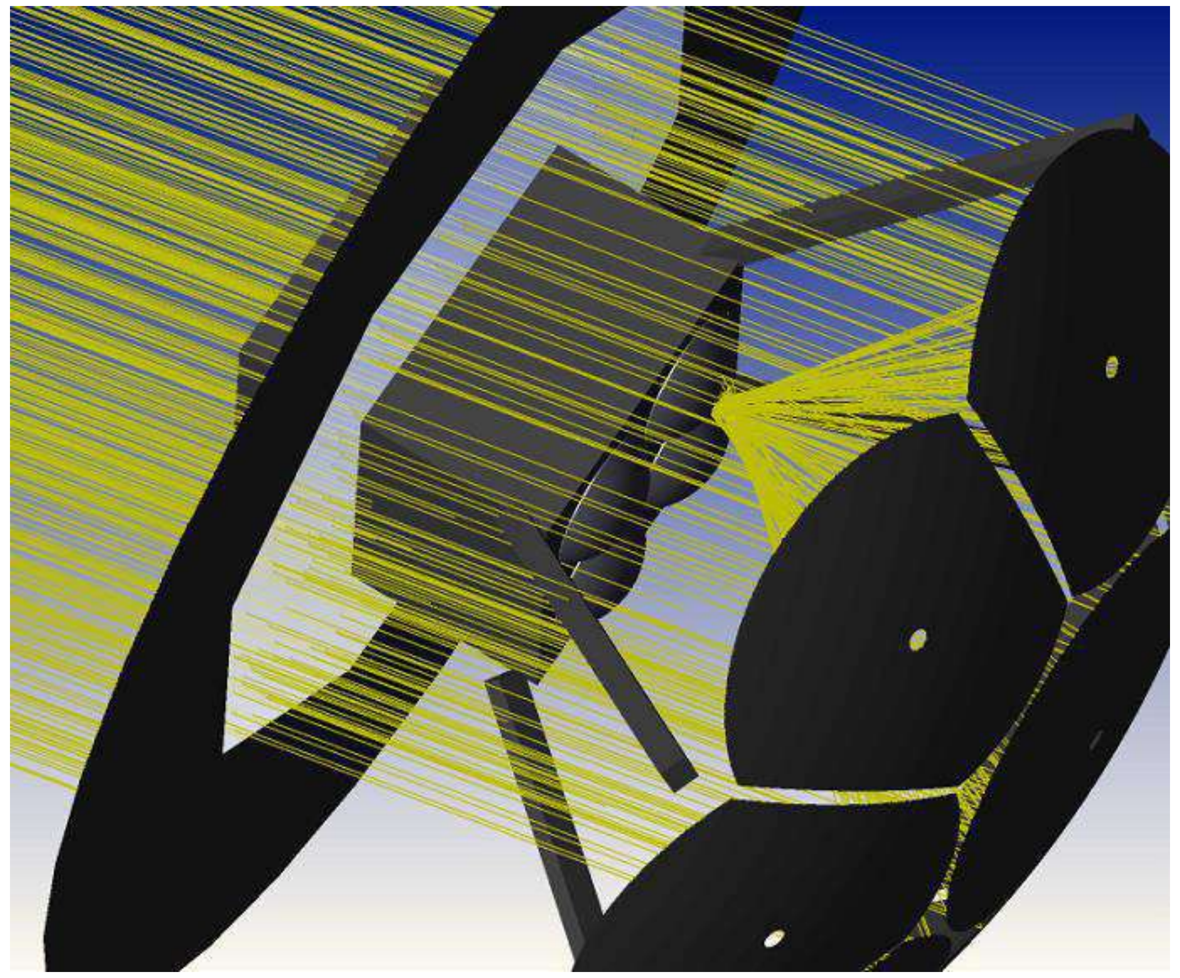
Expected sensitivity with a full-size FAST array



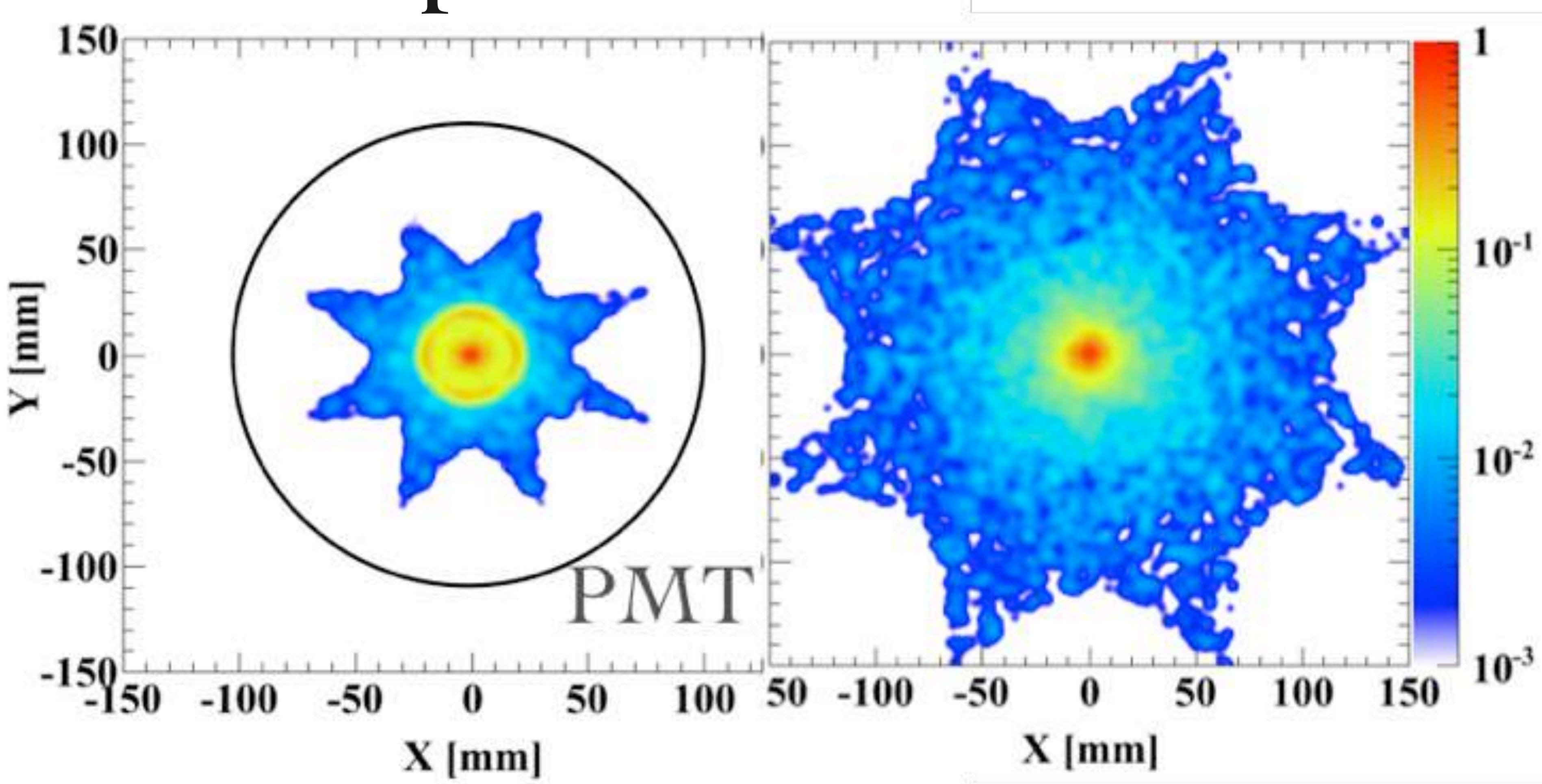
https://www.fast-project.org

Backup

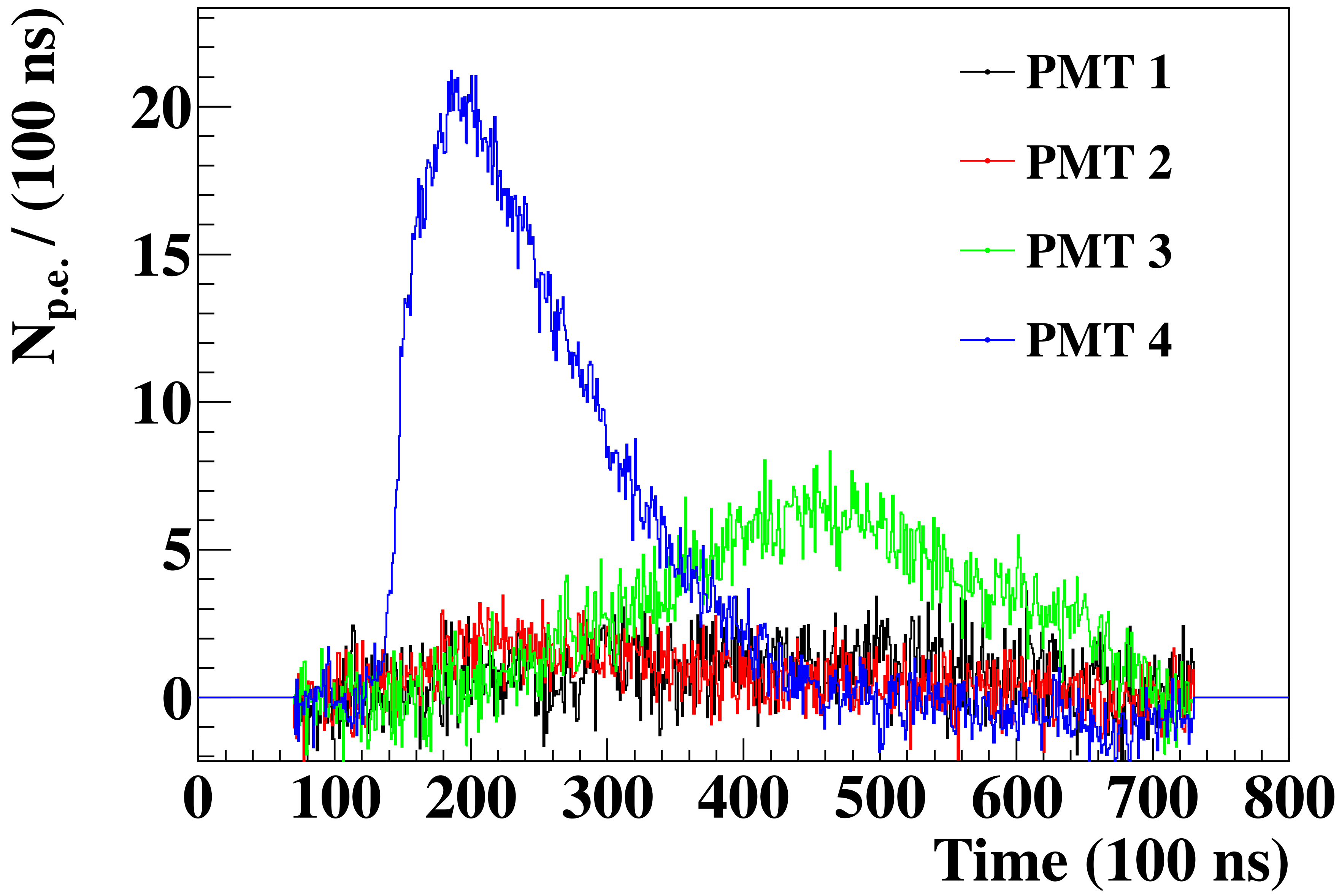
Data/simulation comparison using a distant vertical laser



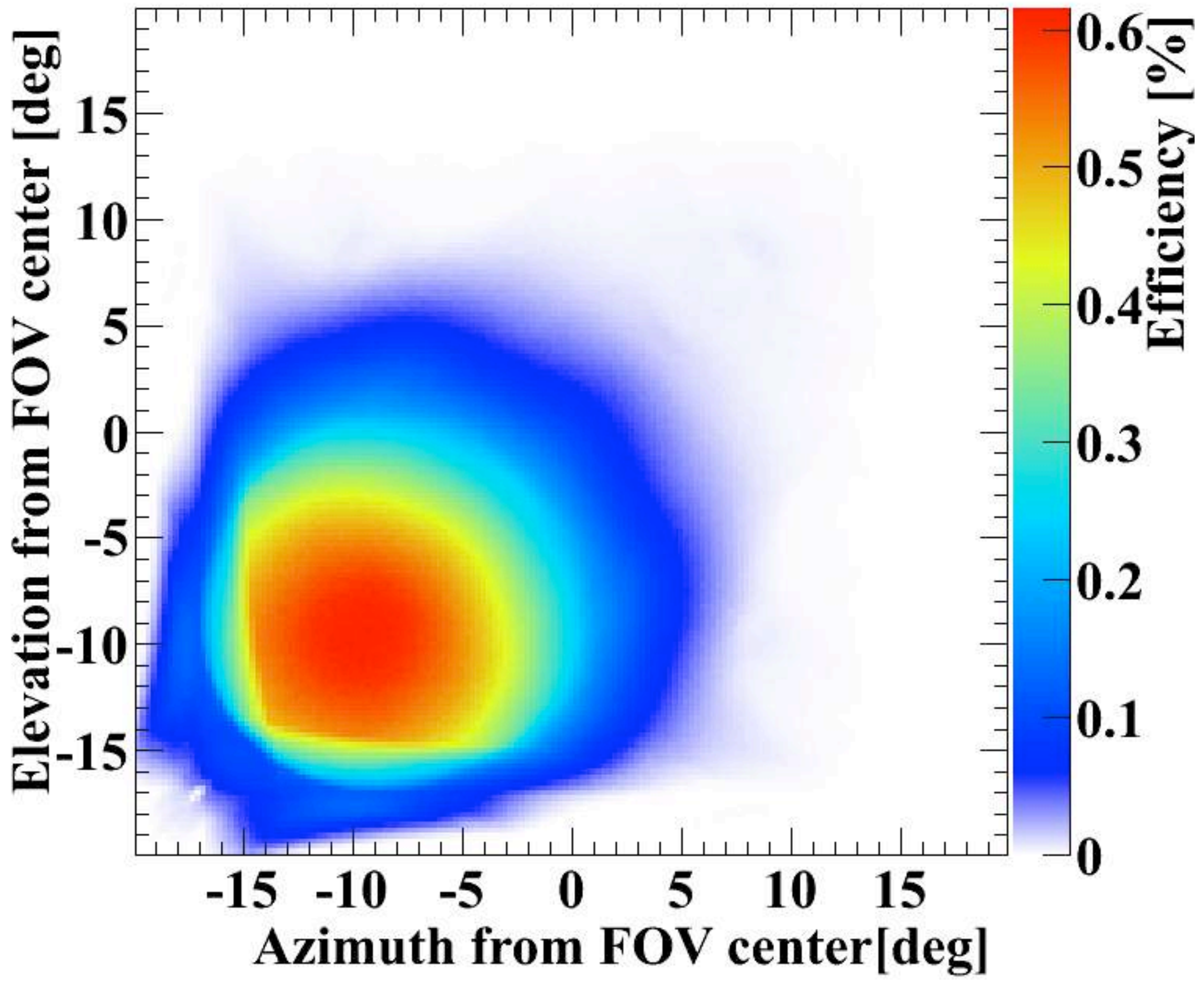
Spot-size



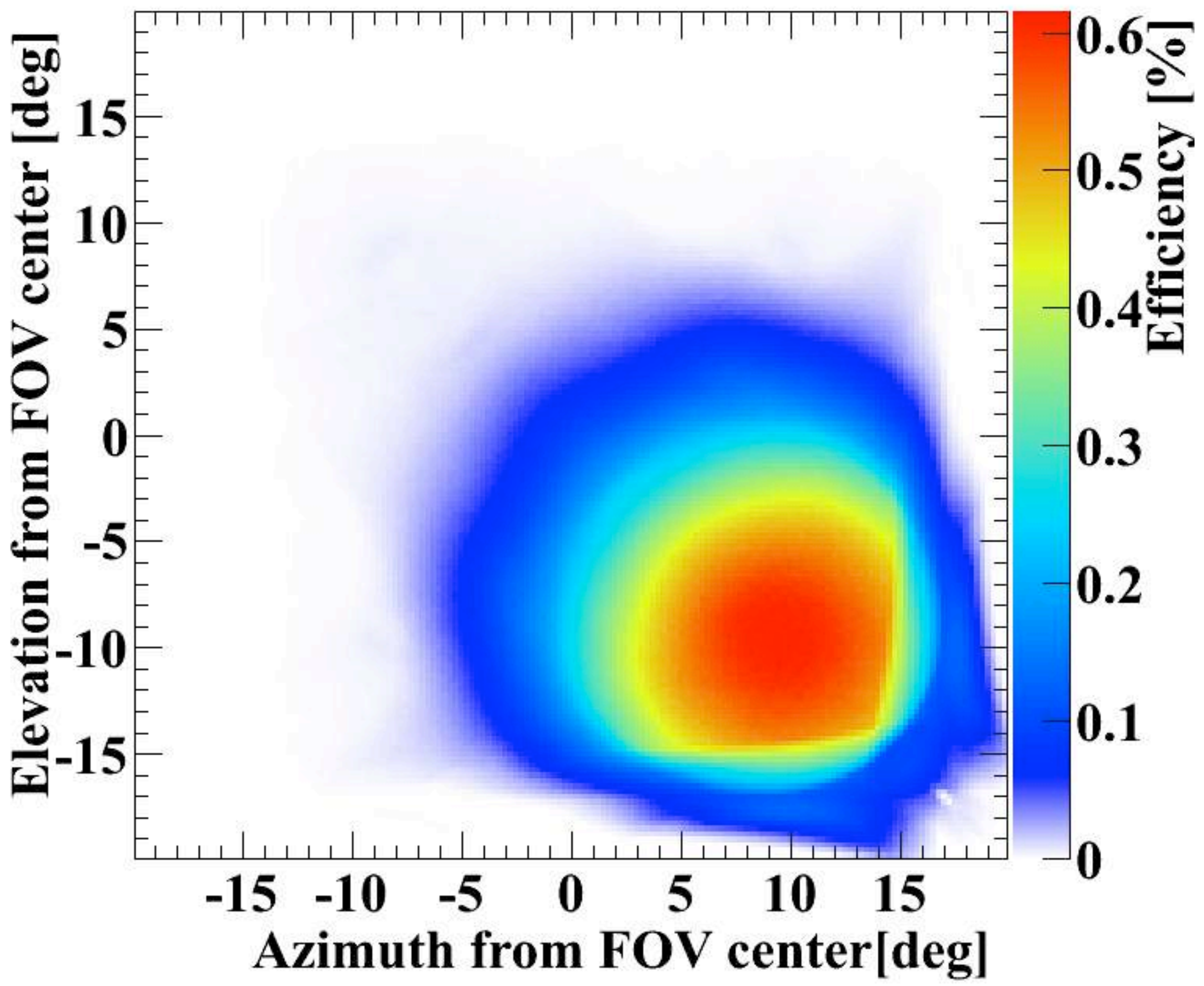
A UV vertical laser at 21 km away



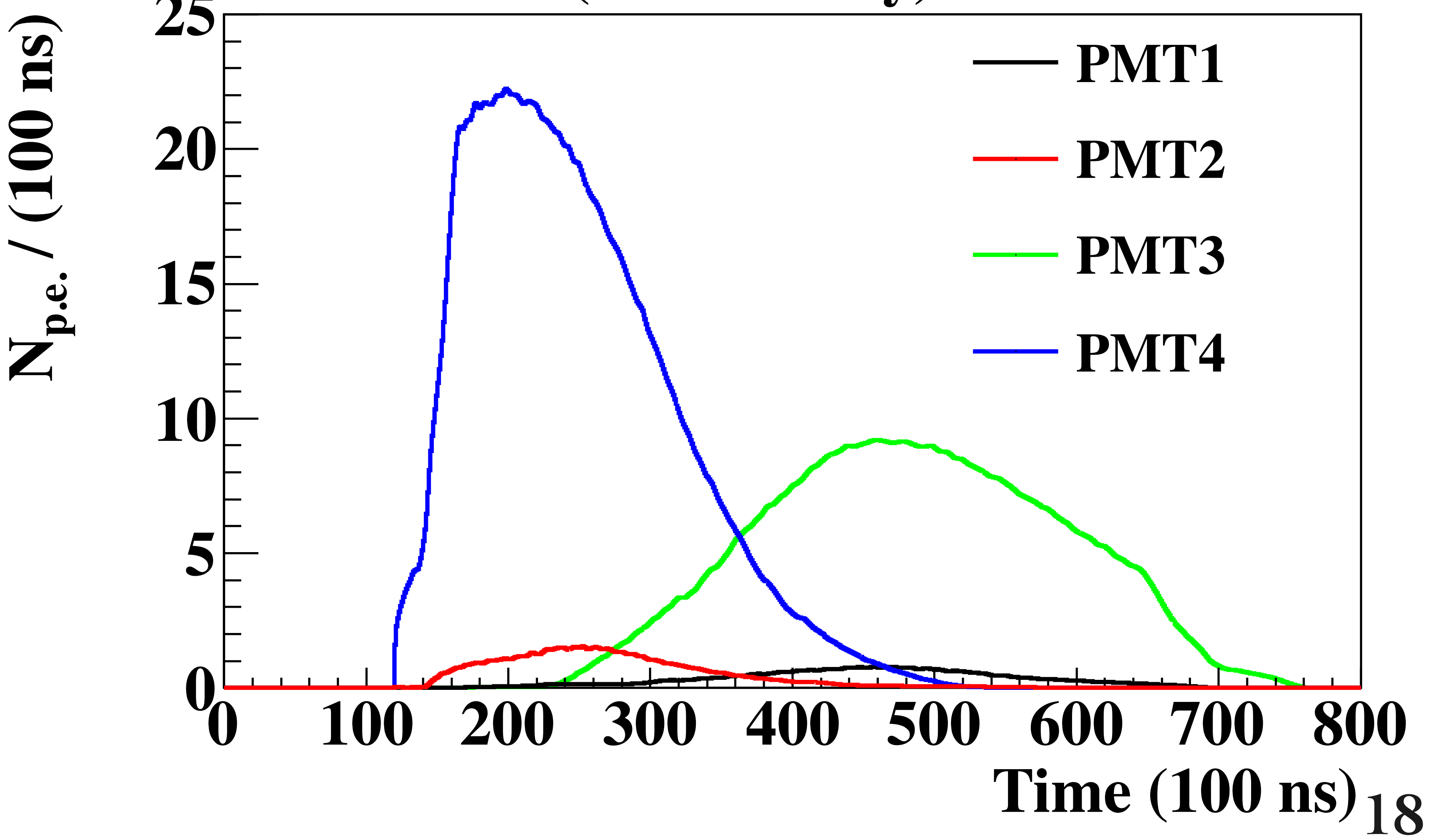
Directional characteristic (PMT2)



(PMT 4)



Simulation (Preliminary)

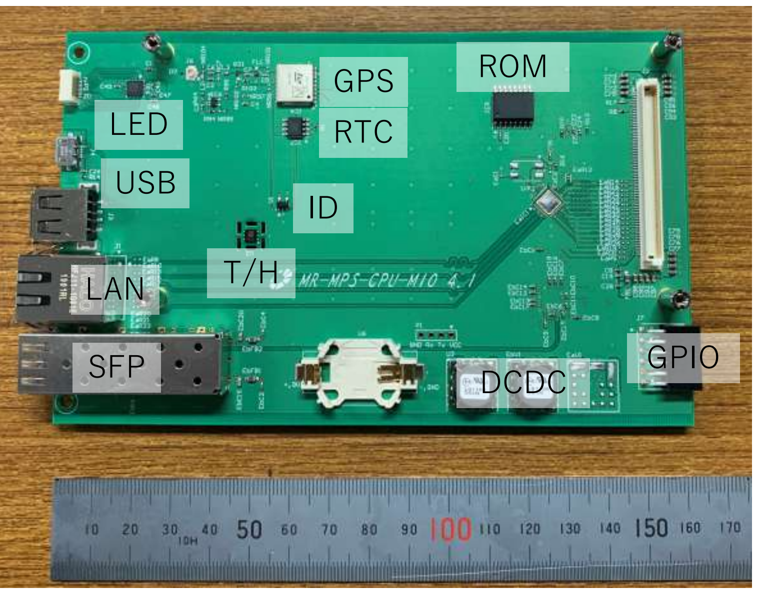


Electronics and PMT calibration in laboratory

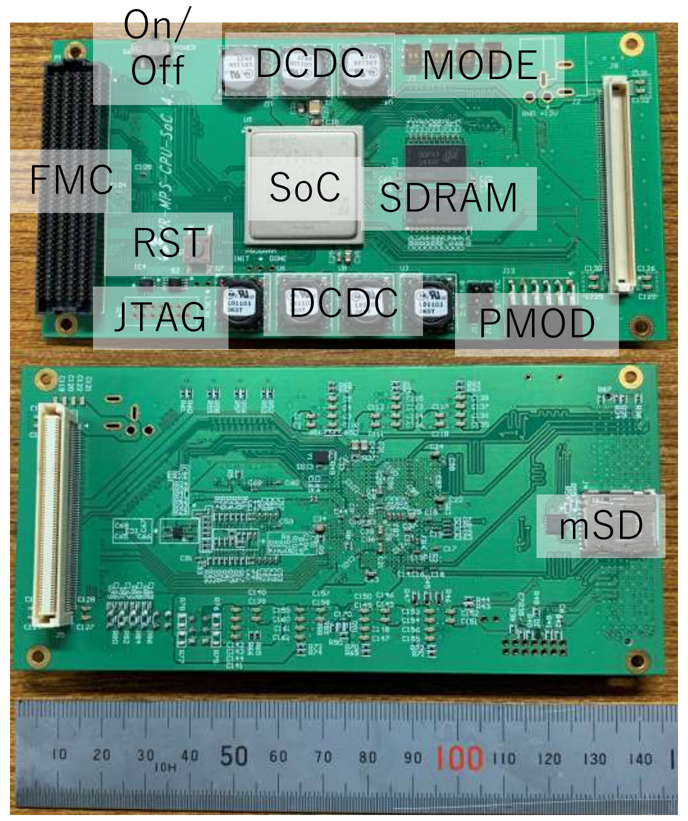
New electronics development

Dual 32ch FADC (ADS52J90), 64ch FADC
14bit 32.5 MSPS 32ch

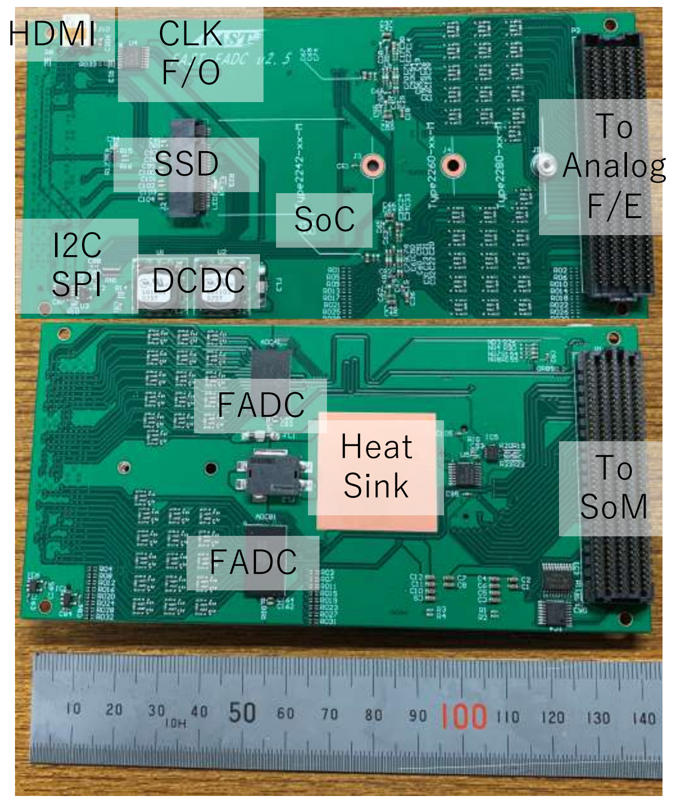
MIO



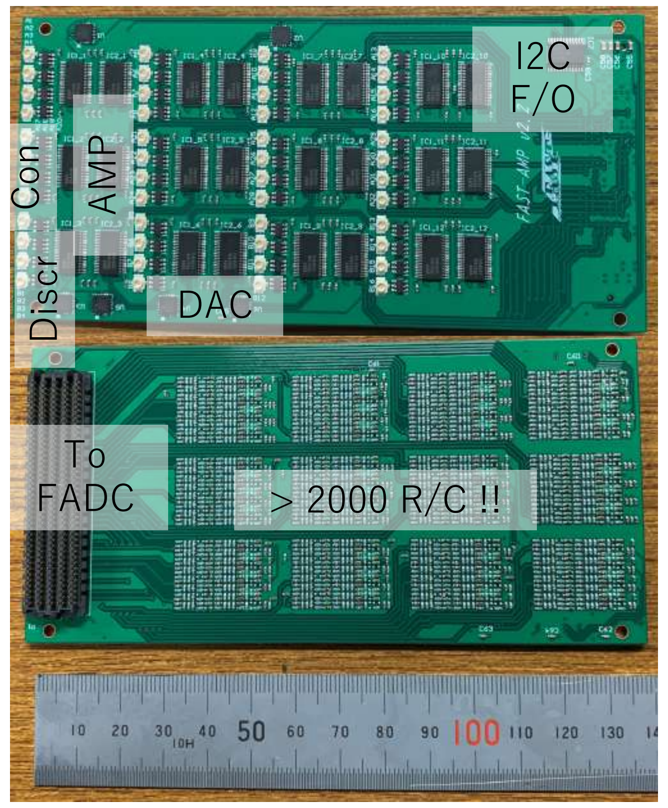
SoC



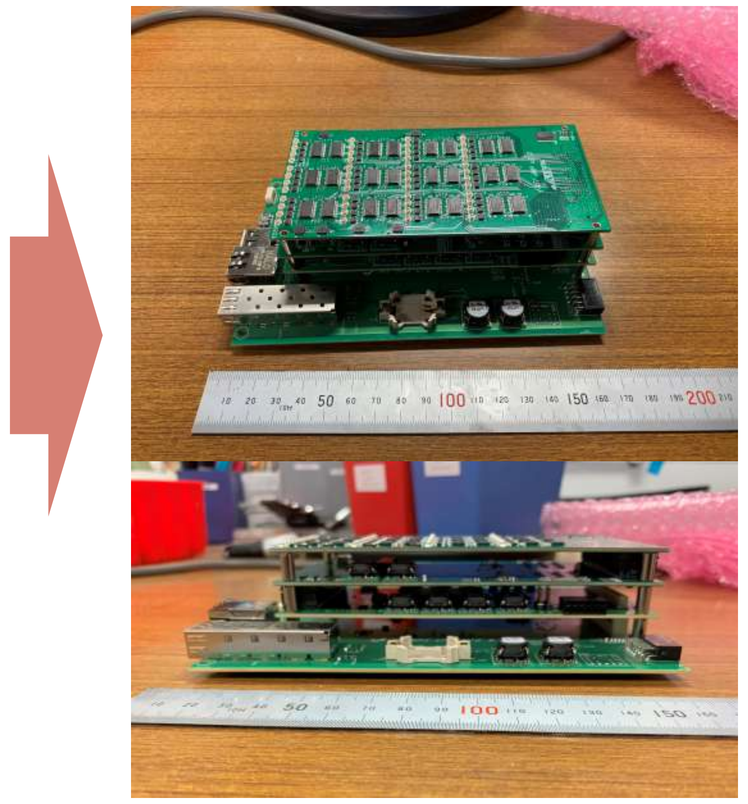
FADC



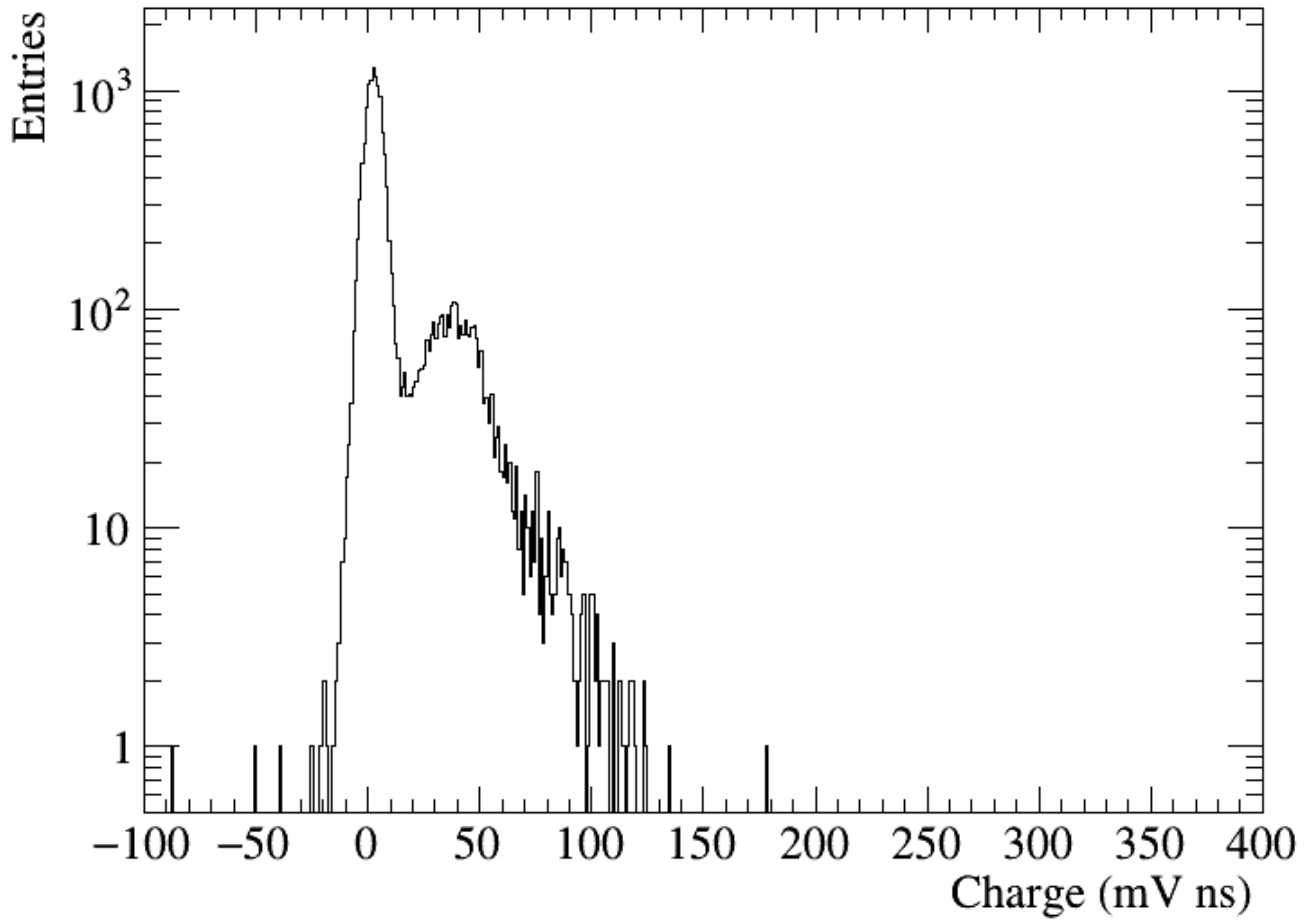
AMP



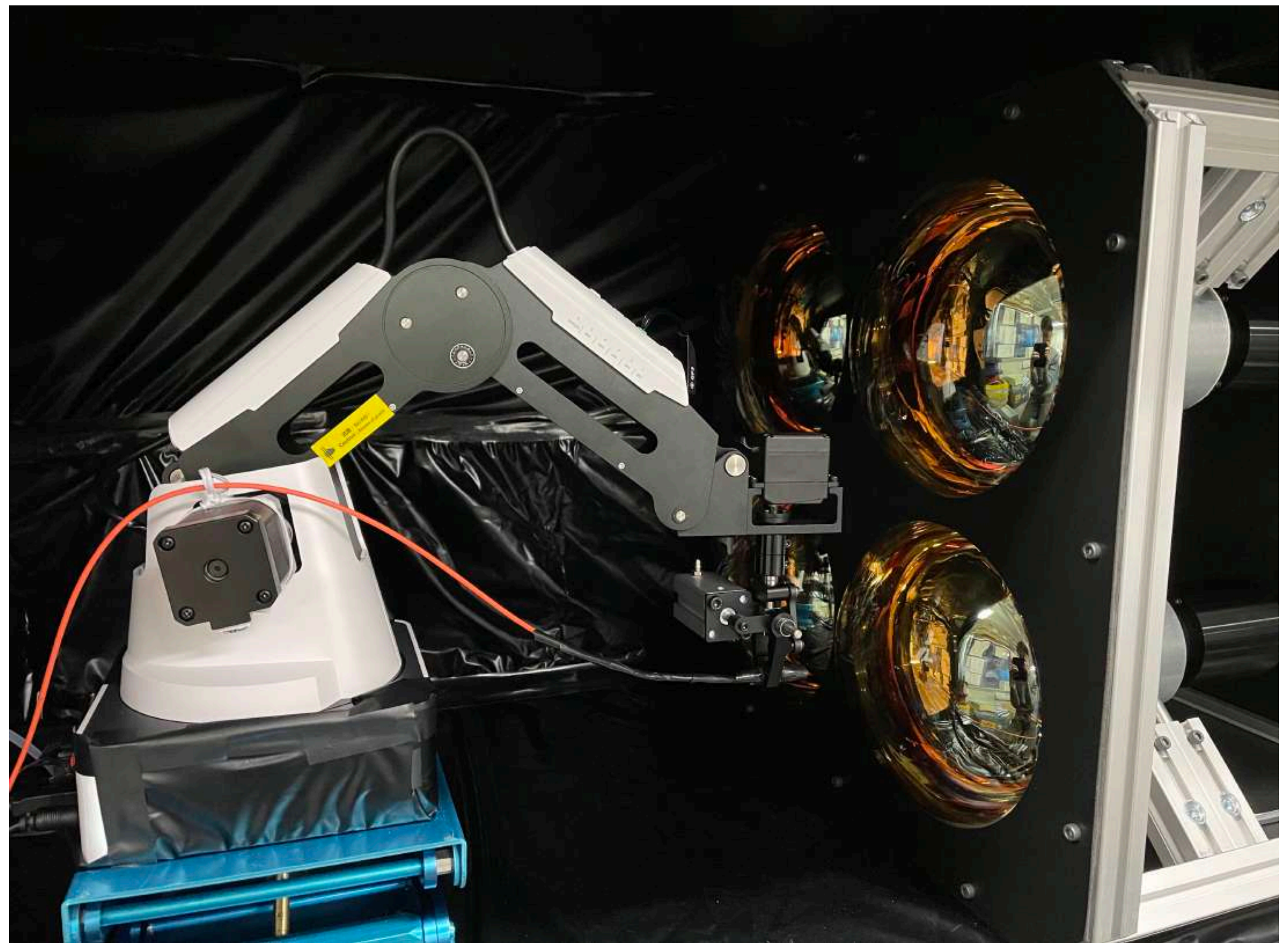
Assembly

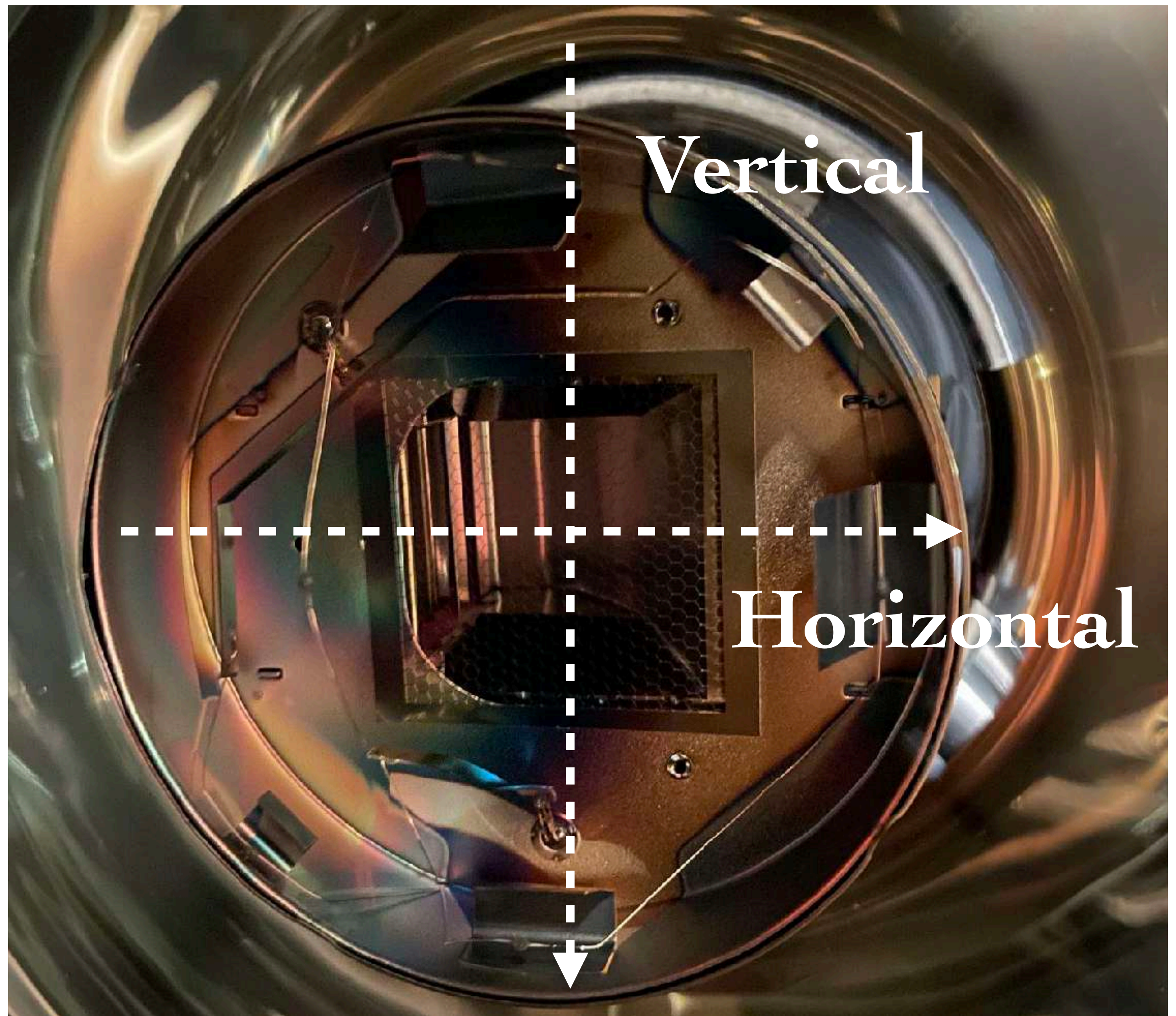


Single Photo Electron

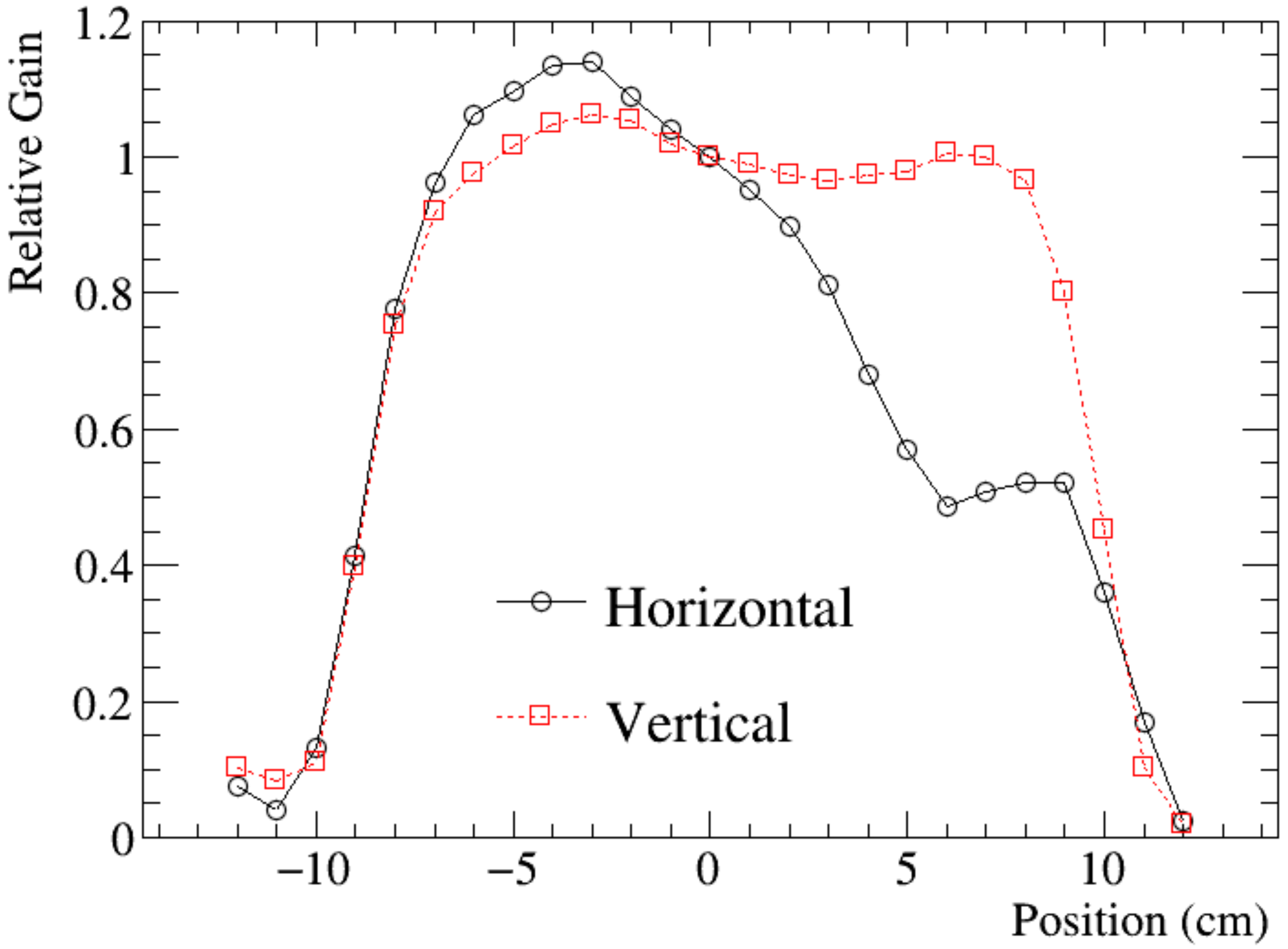


Calibration using Robot arm
(0.2 mm accuracy)



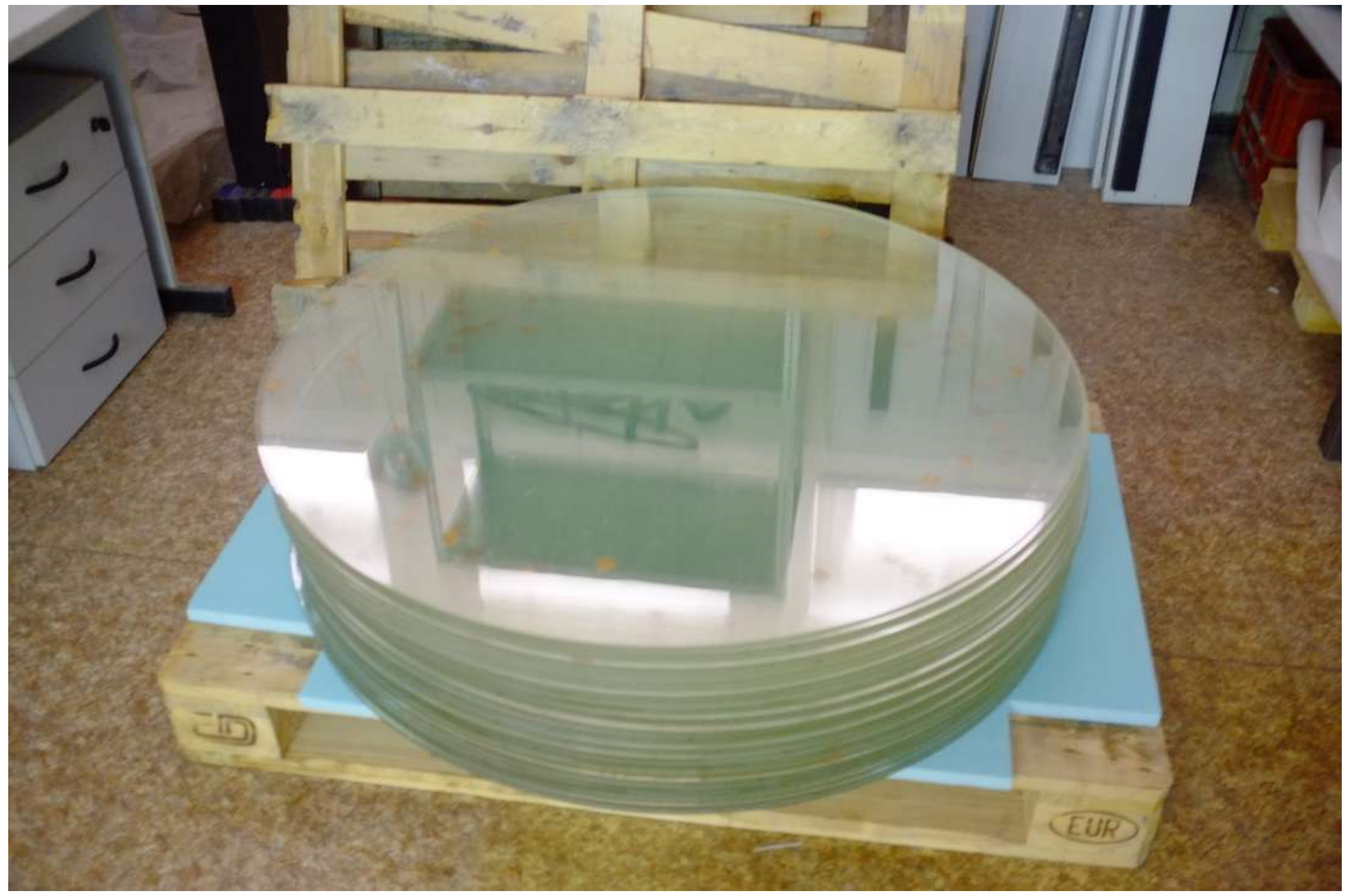


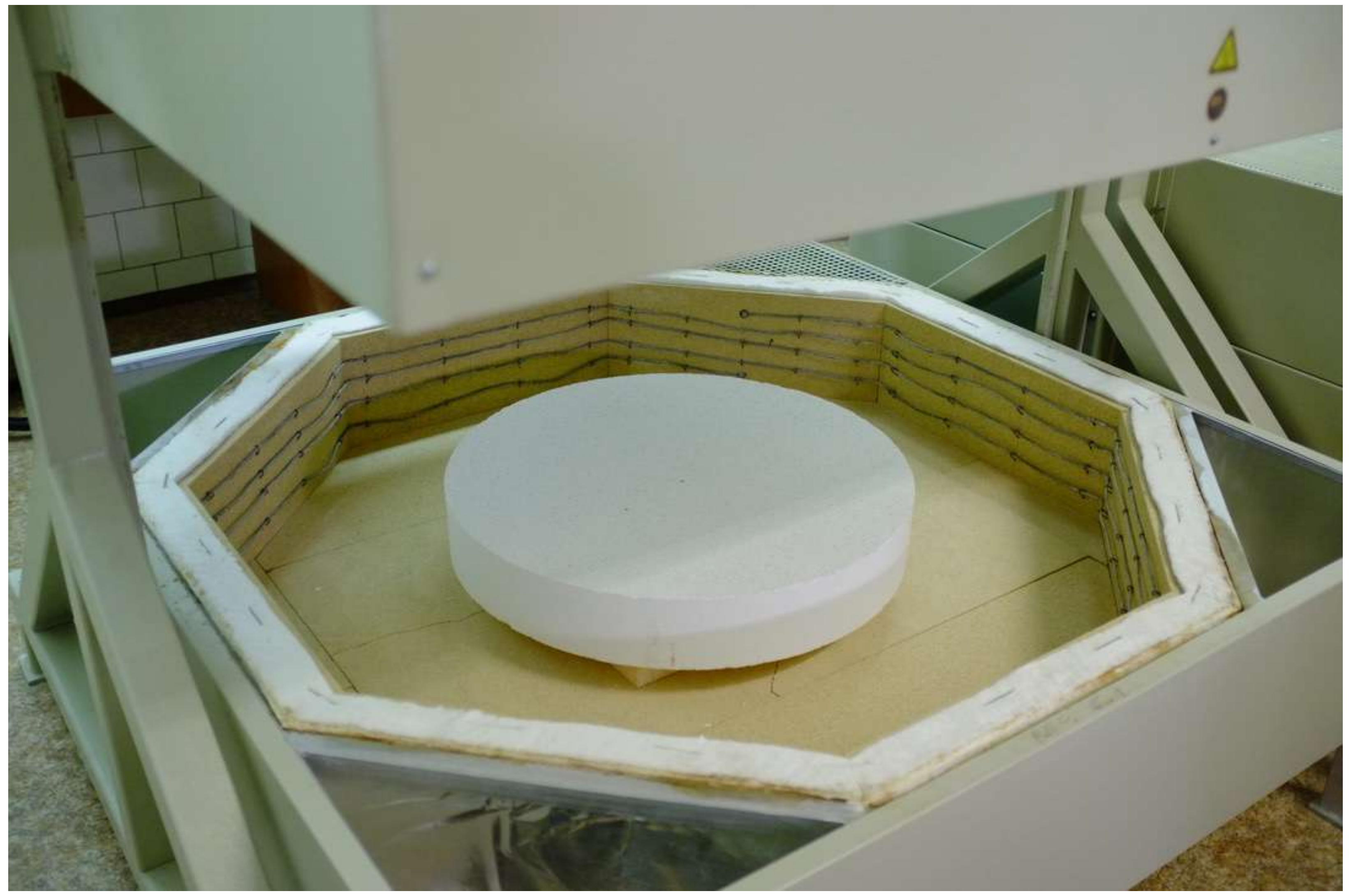
Non-uniformity

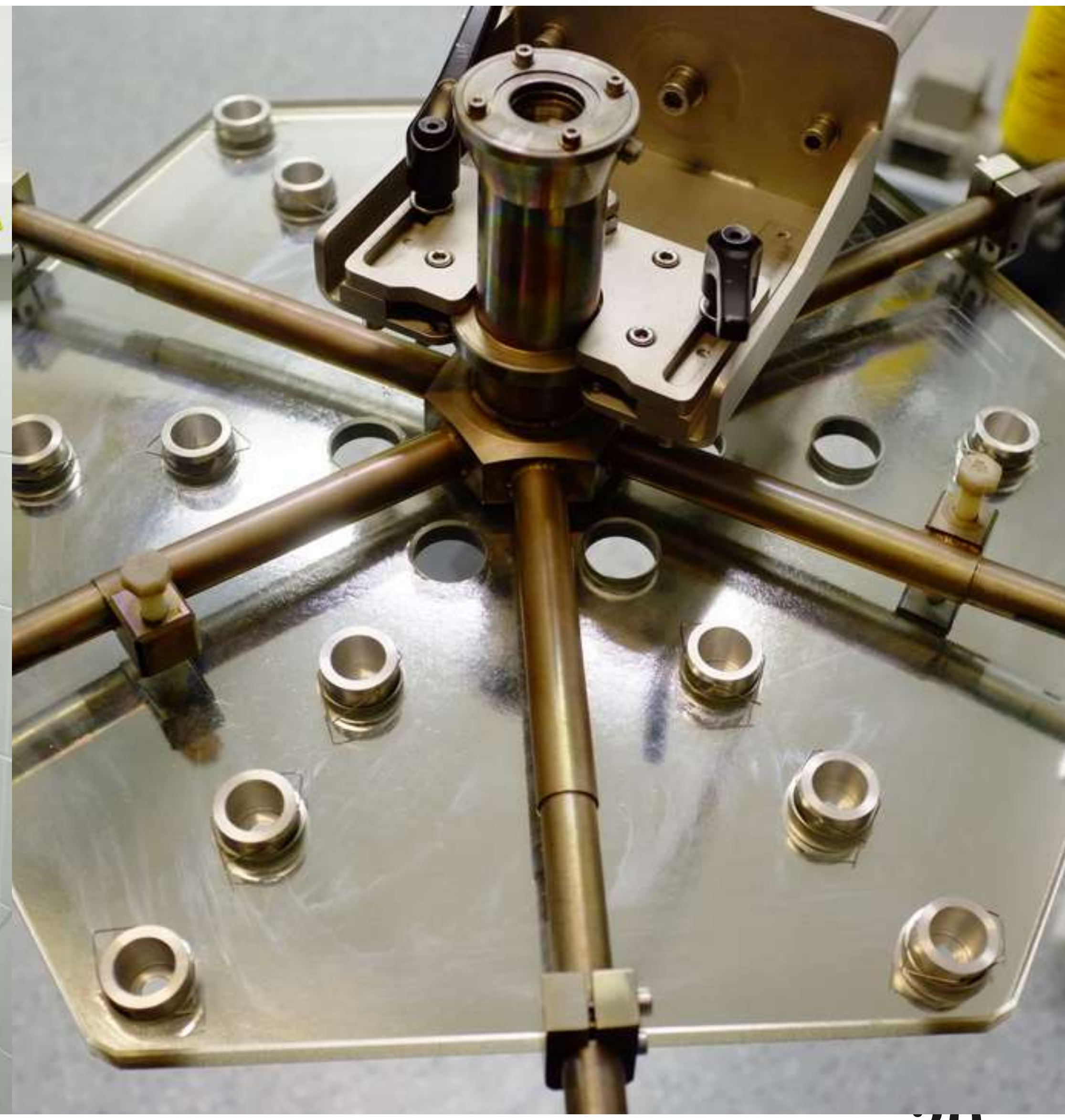


FAST
Fluorescence detector Array of Single-pixel Telescopes

Mirror production at Olomouc, Czech republic







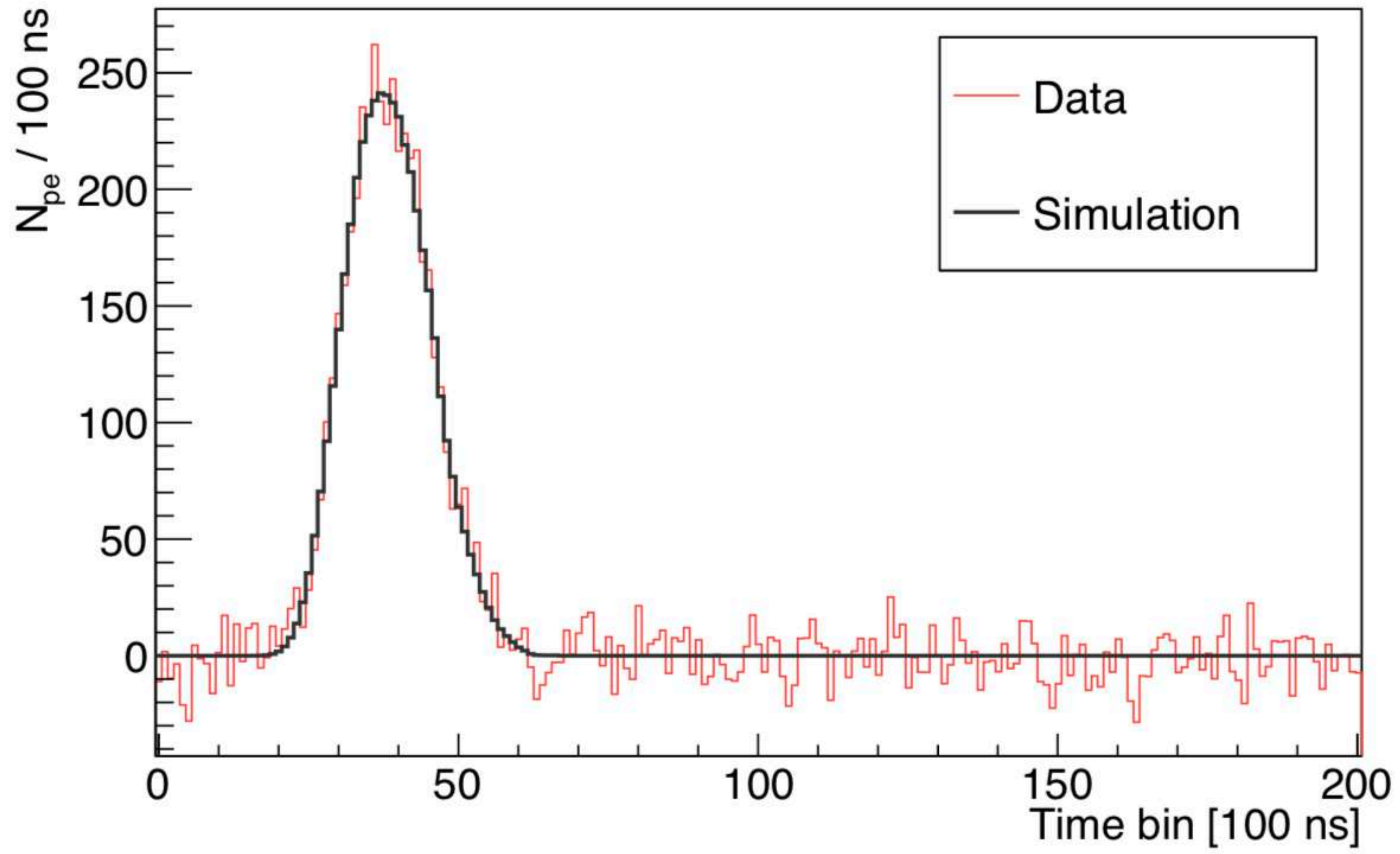
Fluorescence detector Array of Single-pixel Telescopes

Installation of the FAST prototype

Neural network first guess reconstruction

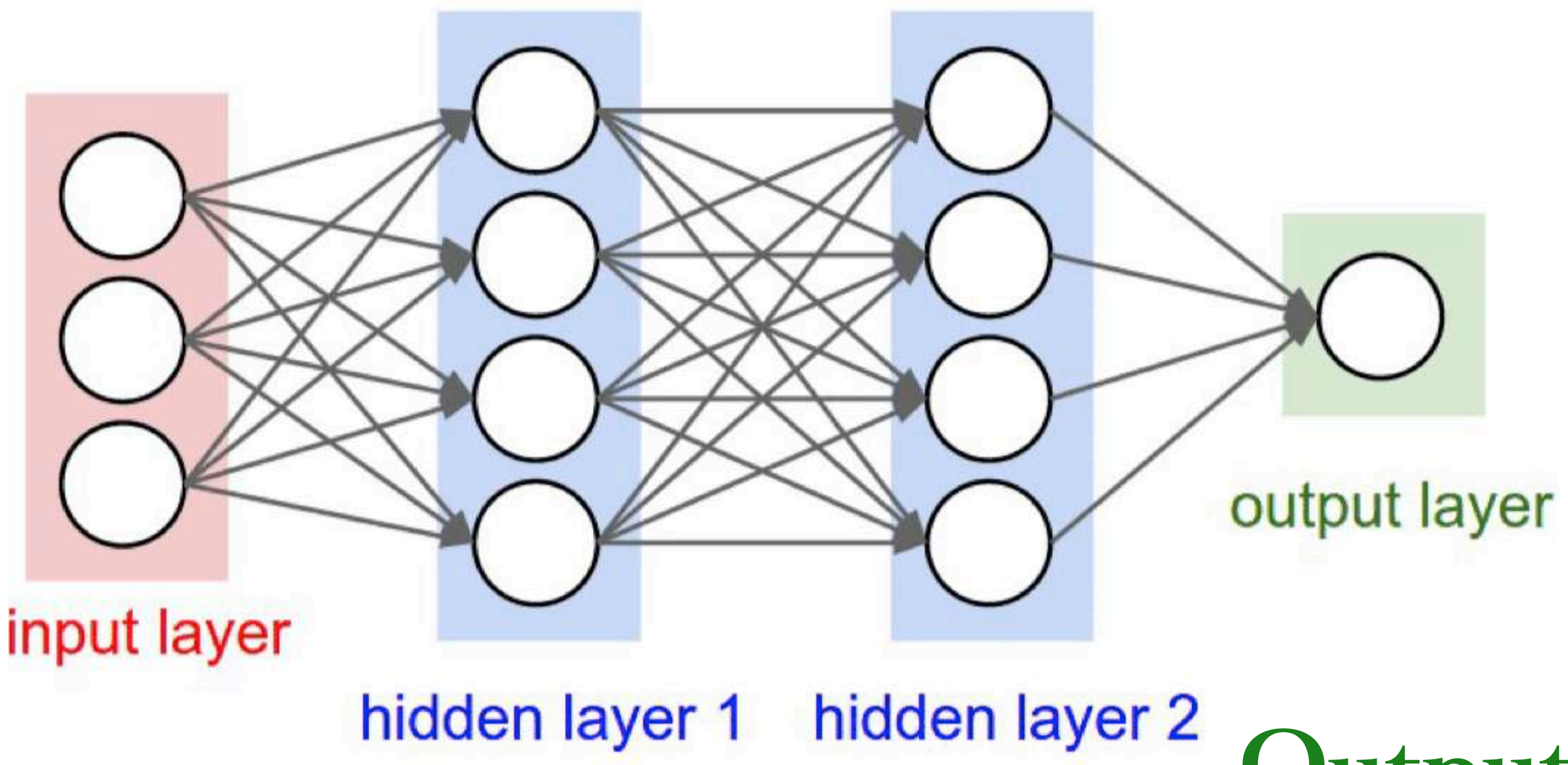
Fluorescence detector Array of Single-pixel Telescopes

Work: Justin Albury. PhD thesis (2021)



Inputs

3 feature per PMT with S/N > 5σ

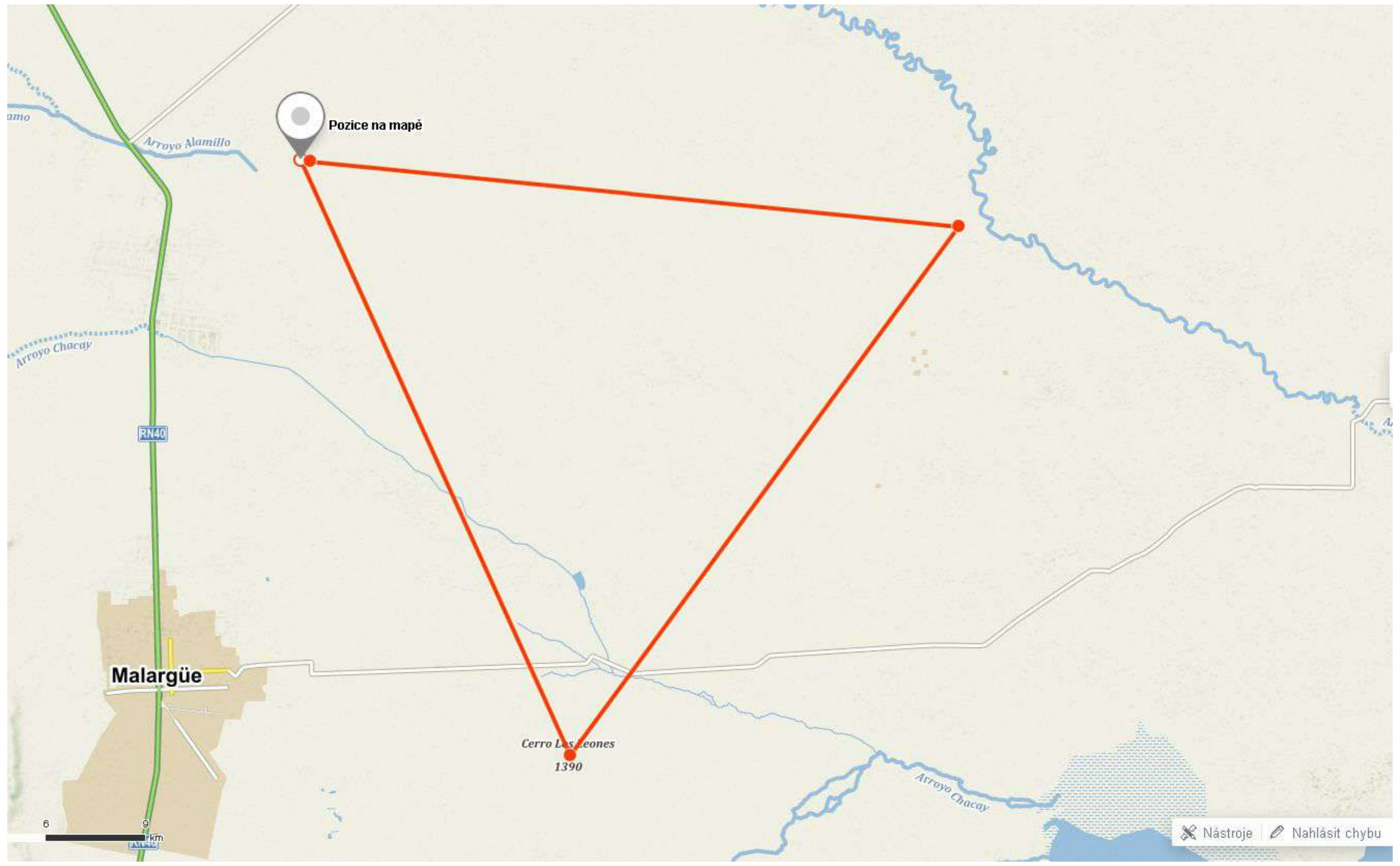


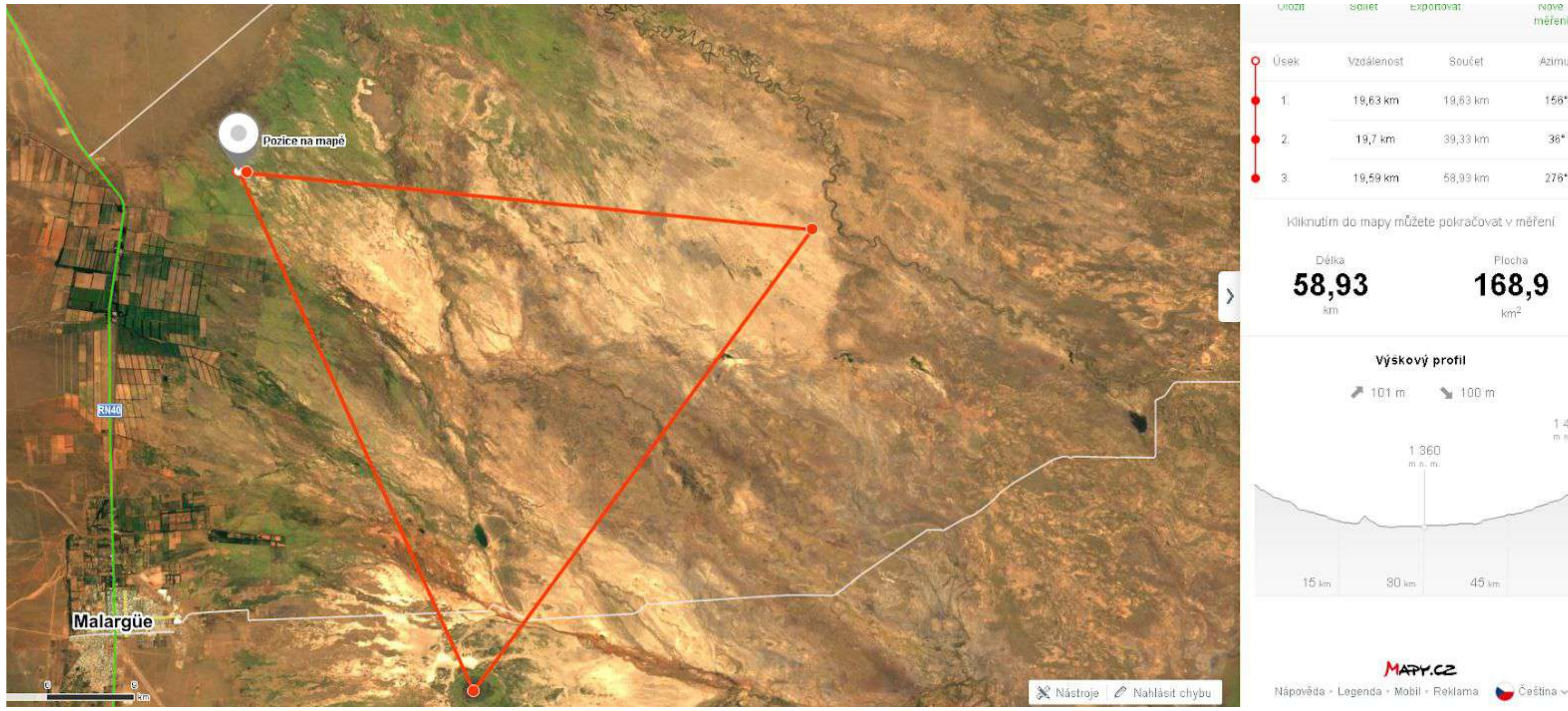
Outputs

Energy, Xmax, geometry(θ, φ, x, y)

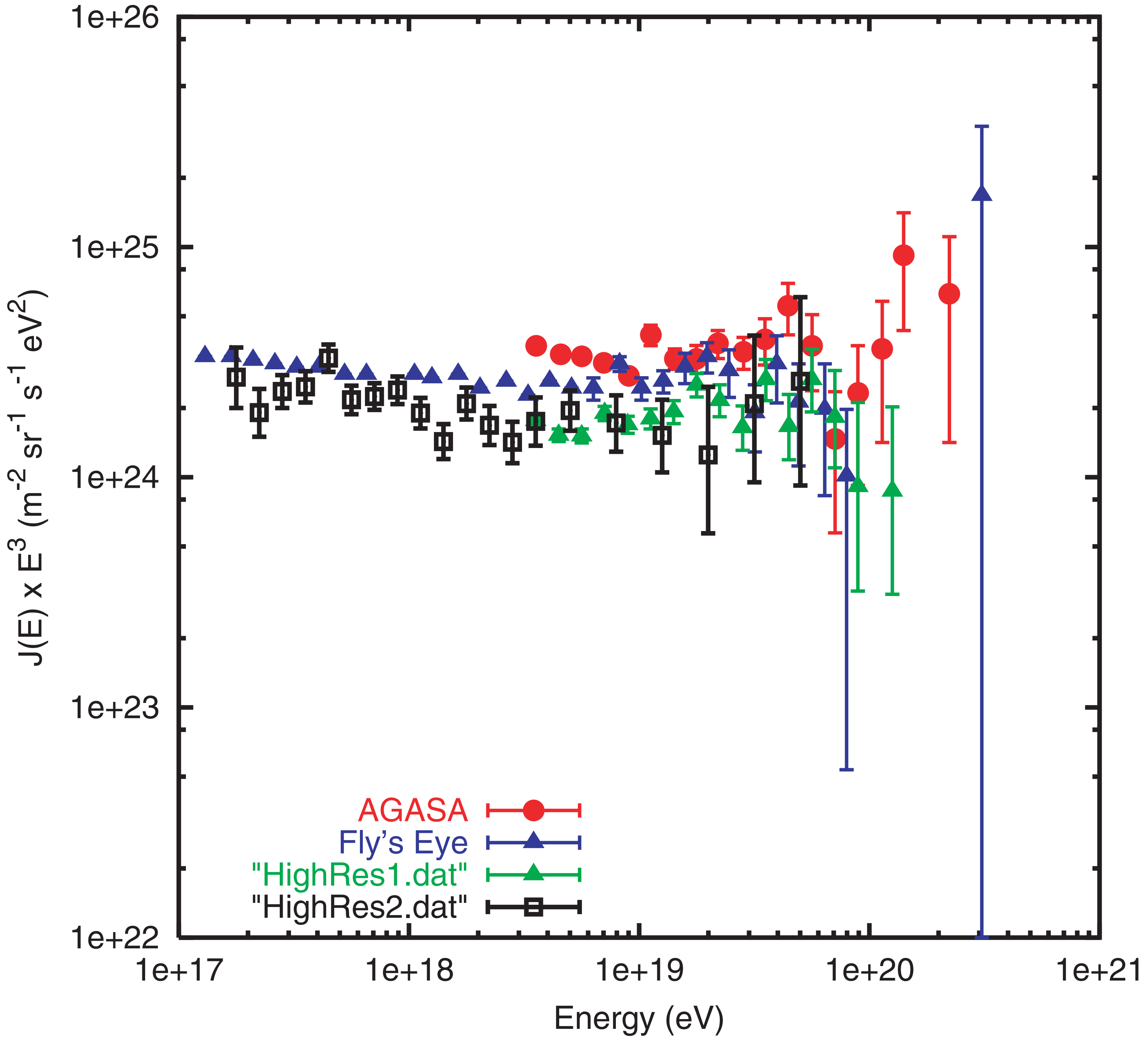
- **Top-down reconstruction (Inverse Monte Carlo)**
  - Use all available information from individual pixel traces
    - Computationally expensive
    - Need a reliable first-guess geometry
- **Neural network first guess reconstruction**
  - 3 input per PMT: **total signal, centroid time and pulse hight**
    - Kares/Tensorflow in Python, two hidden layers
  - 6 outputs: $X_{\max}$, energy, geometry (θ, φ, x, y)
    - Very prompt reconstruction

Installation site survey

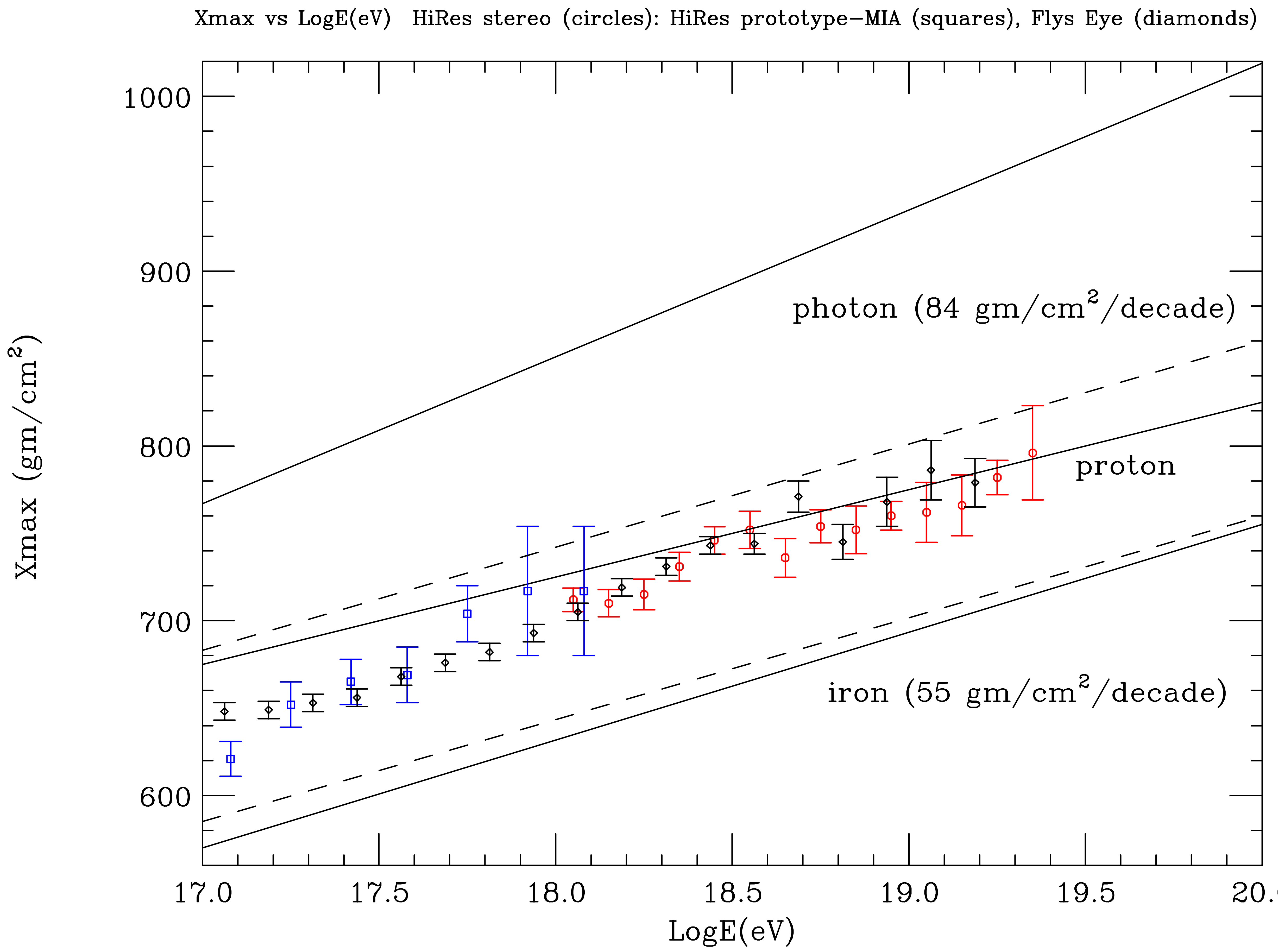


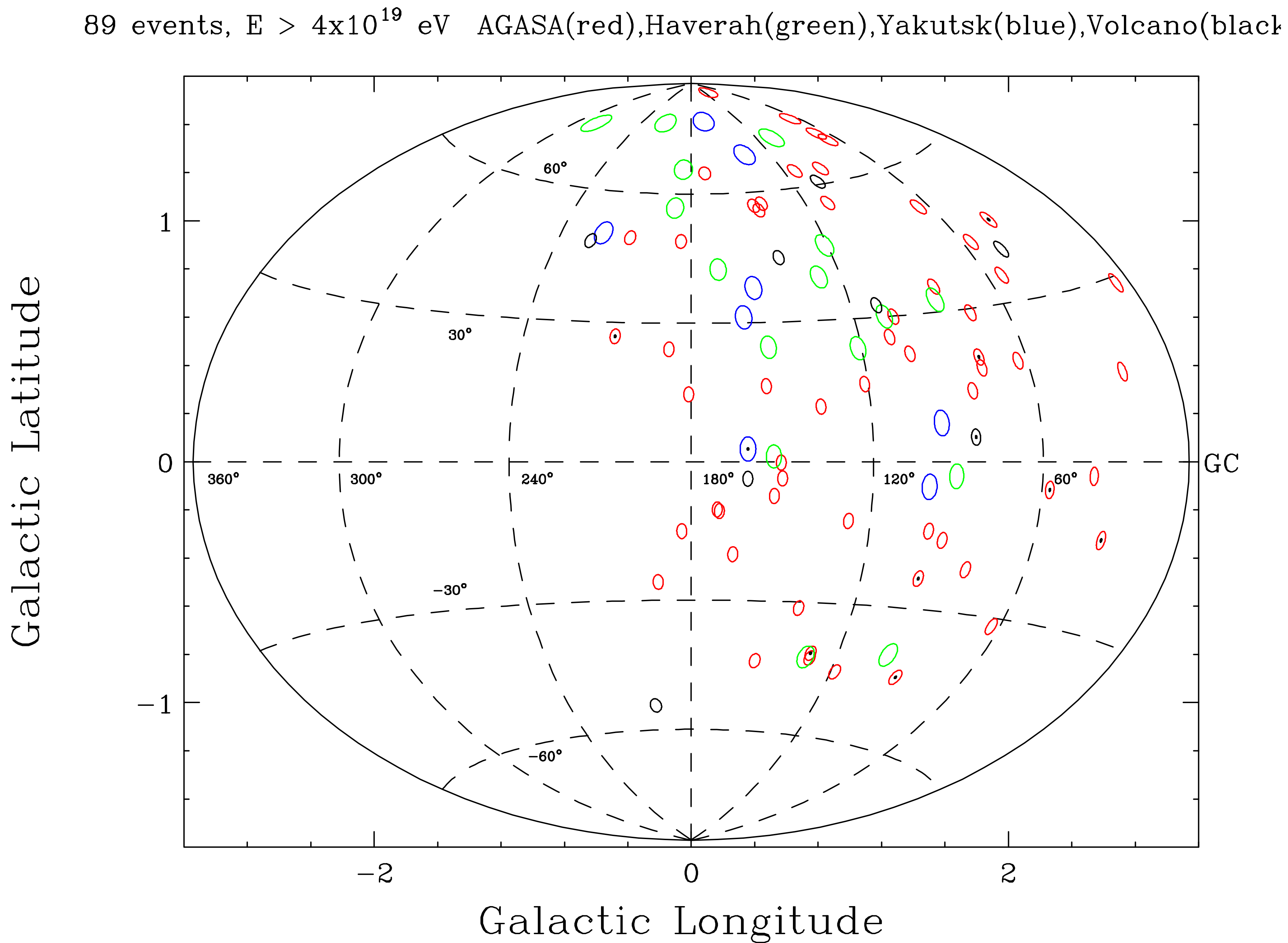


~20 years ago...



F W Stecker, J. Phys. G: Nucl. Part. Phys. 29 R47 (2003)



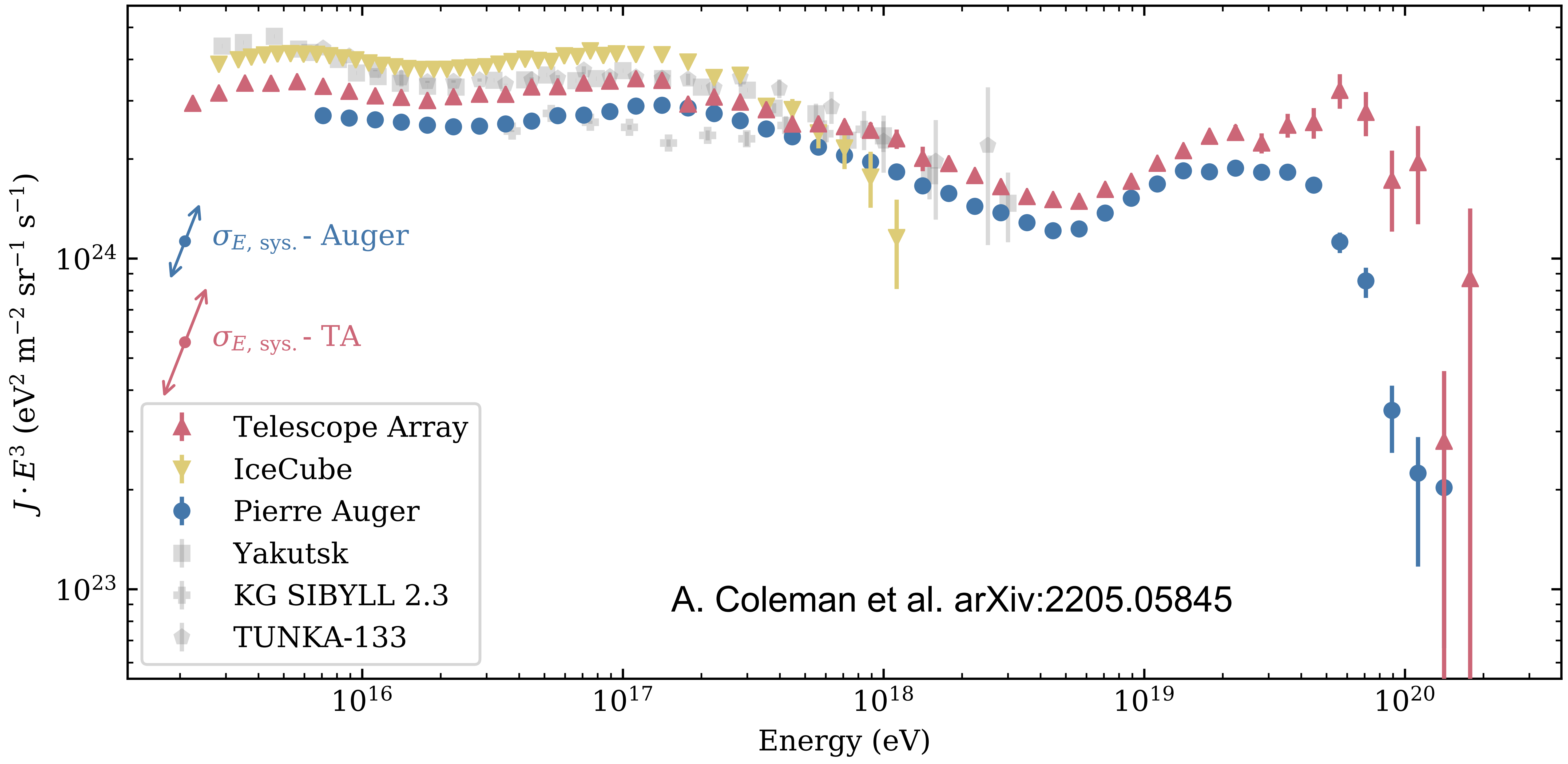


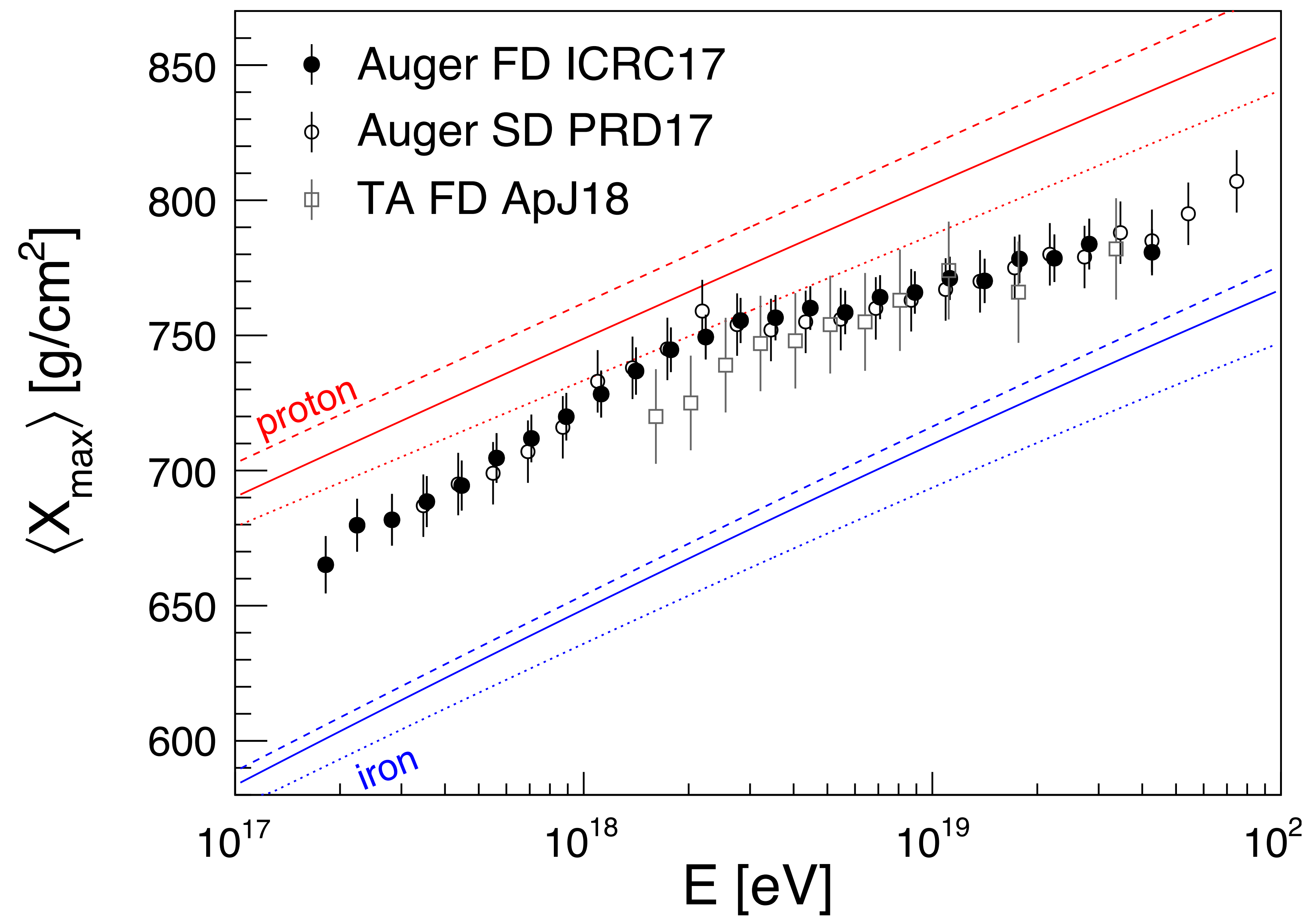
$E > 40$ EeV

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

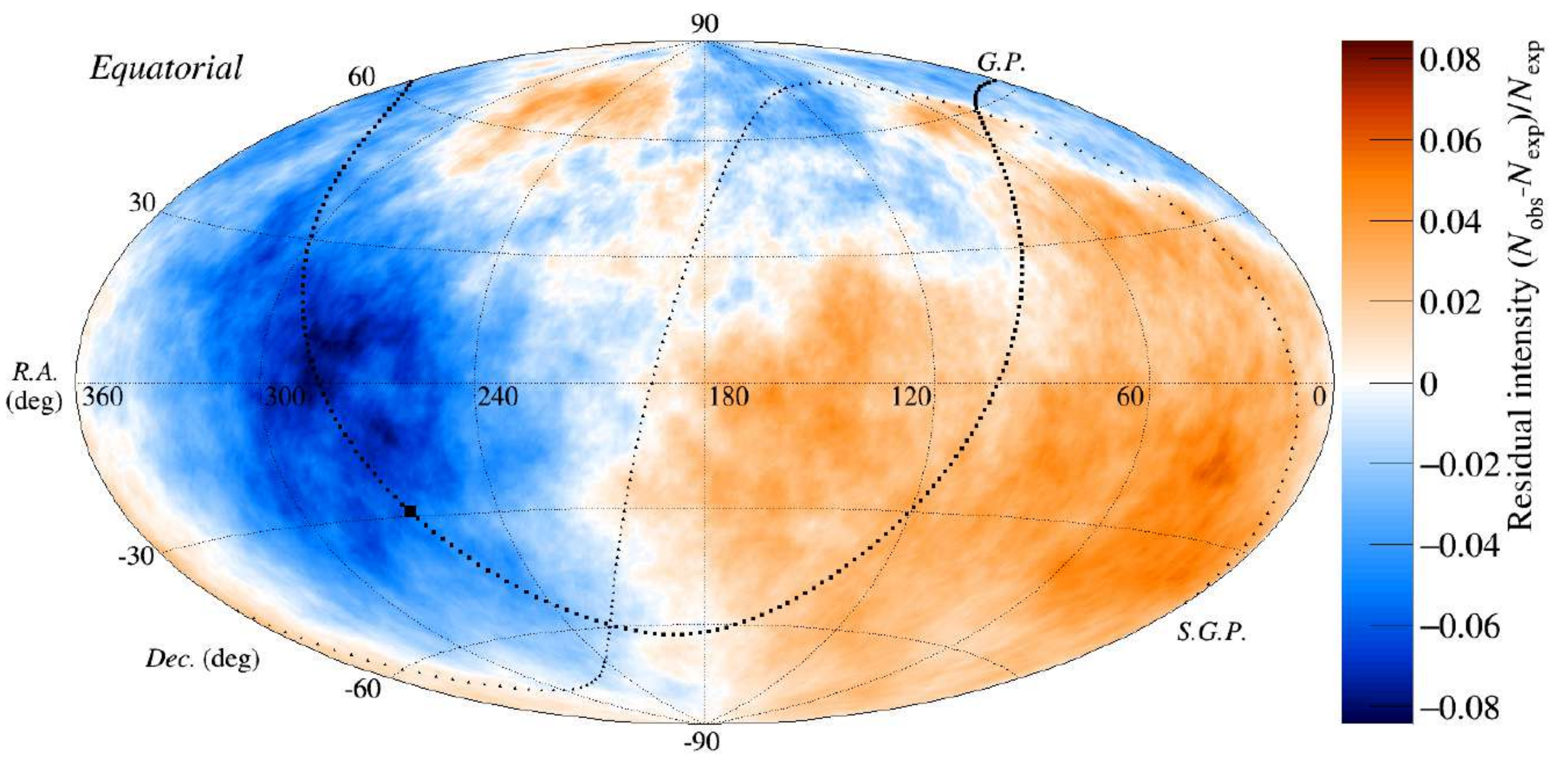
Recent results

R.A. Batista et al.,
Front.Astron.Space Sci.
6 (2019) 23

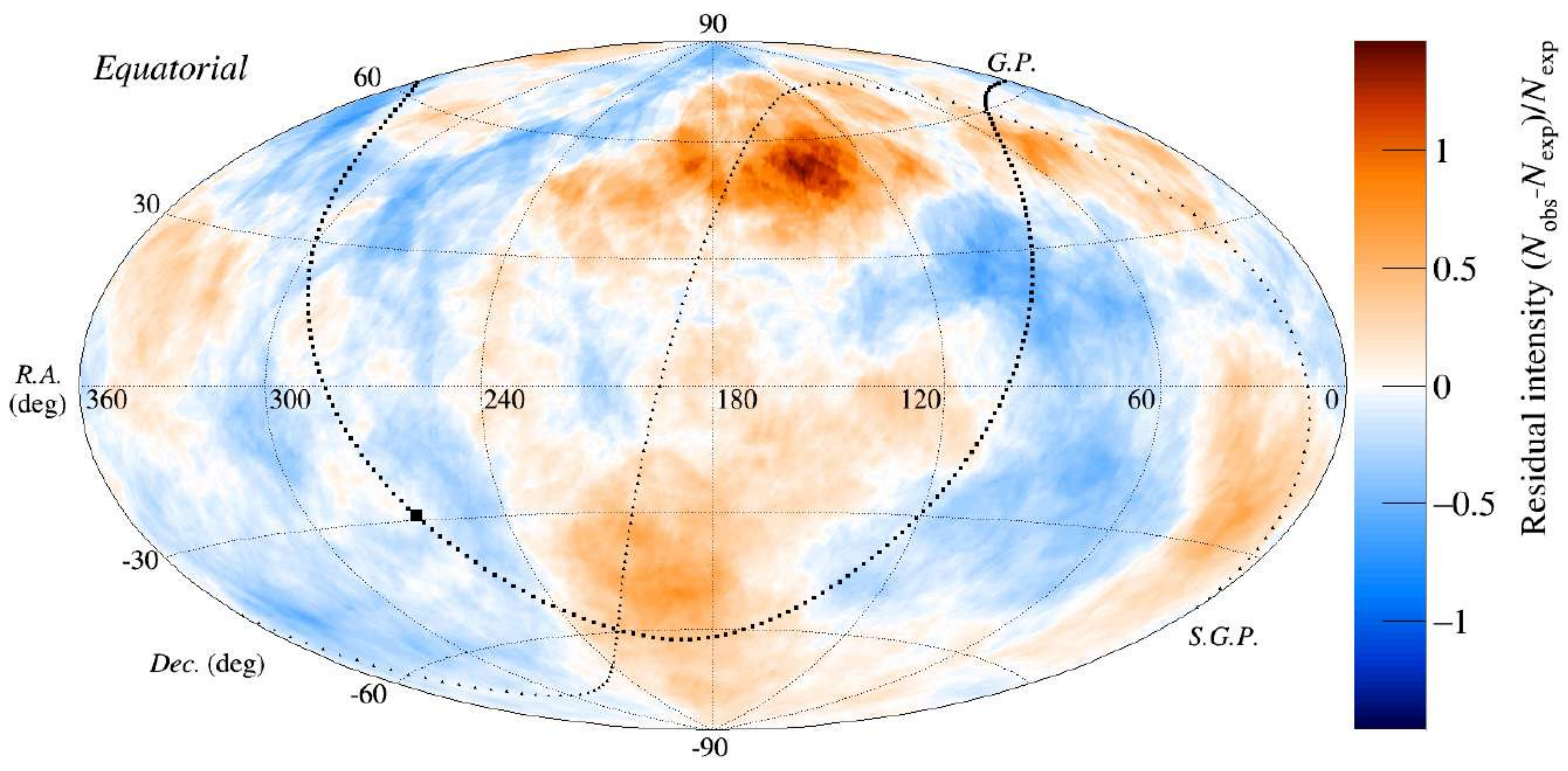


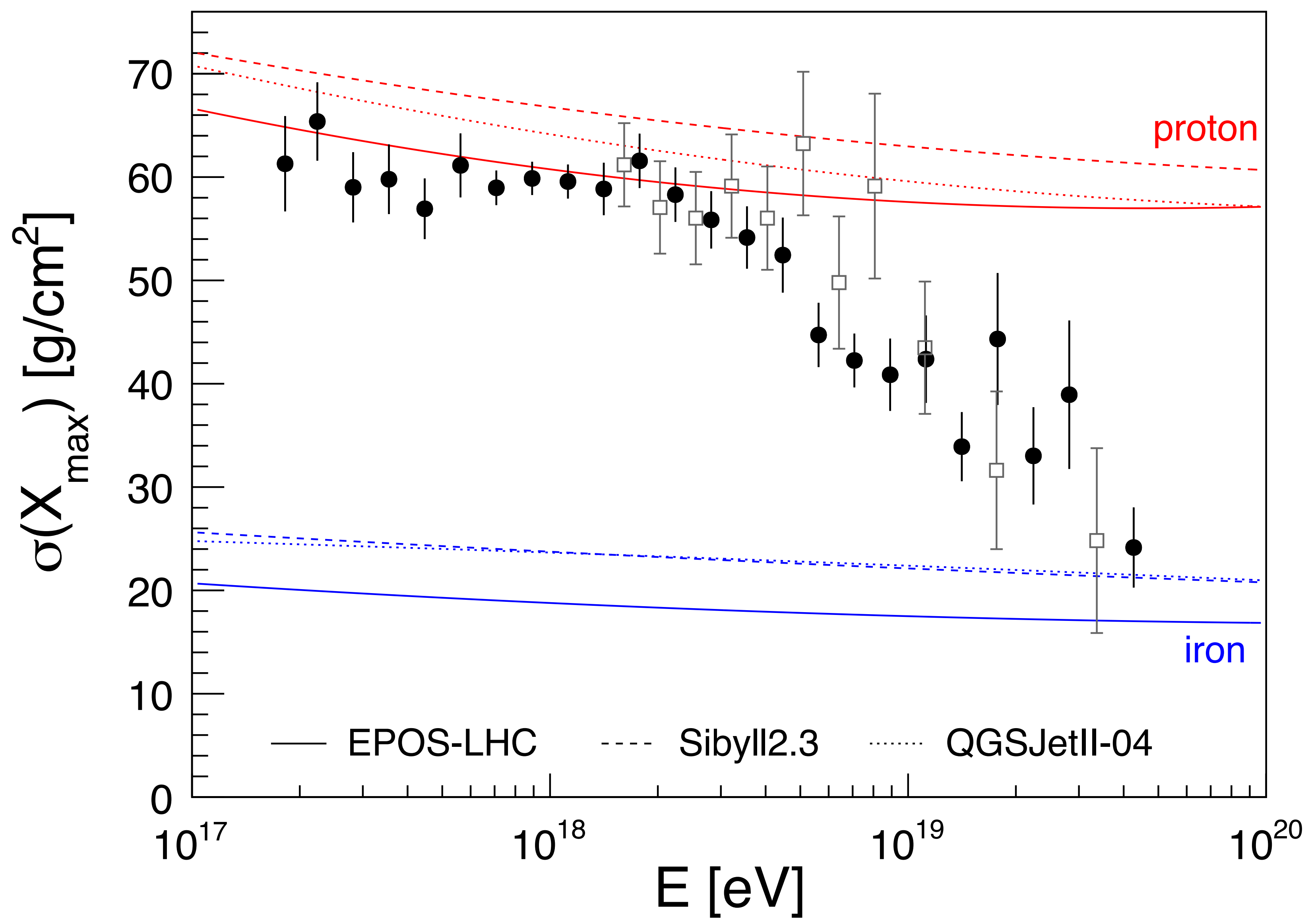


Ankle (E ~ 10 EeV)



Cutoff (E ~ 50 EeV)





T. Fujii et al., PoS (ICRC2021) 402