Latest results of ultra-high-energy cosmic ray measurements with prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST)

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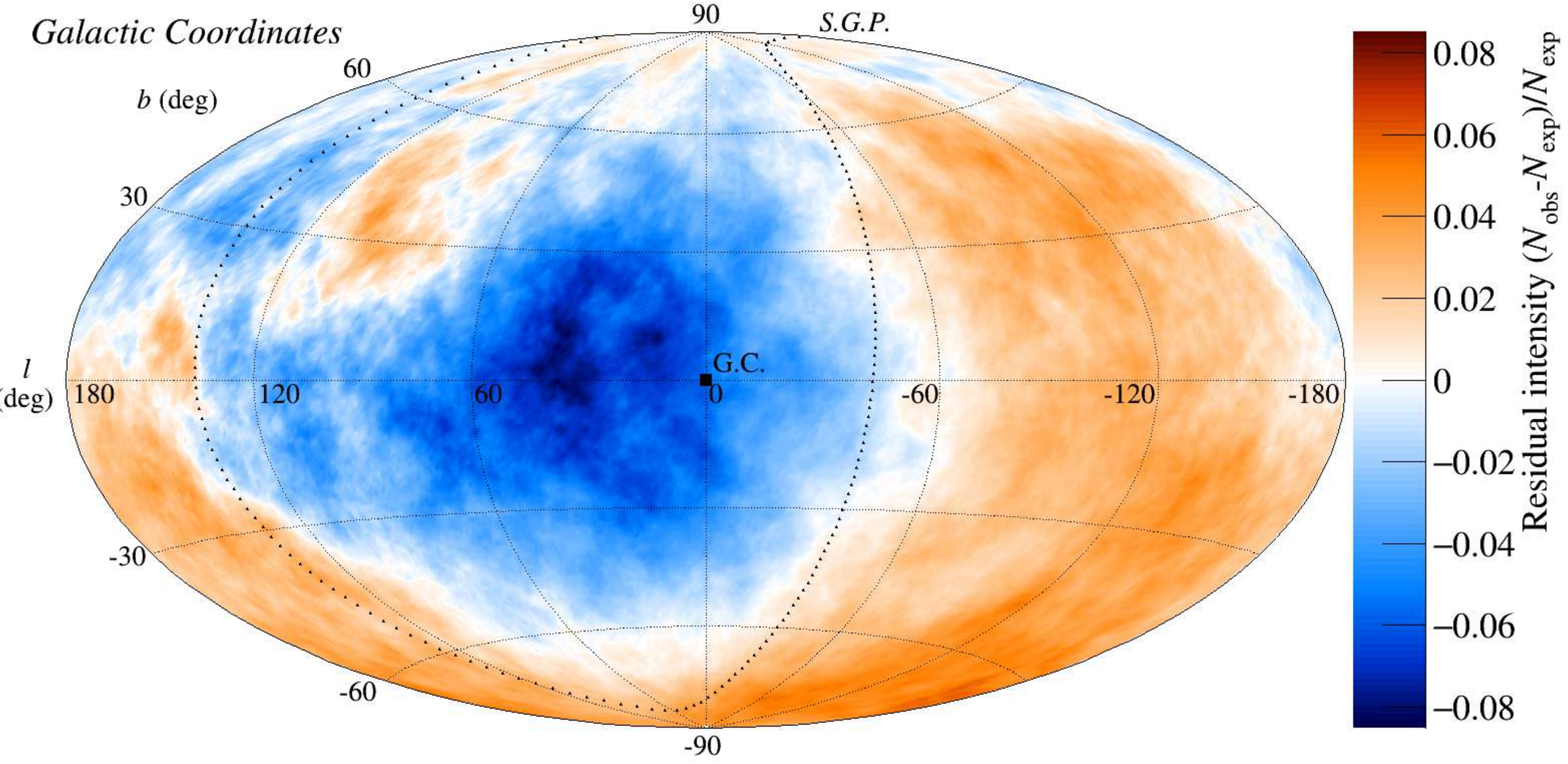
(FAST Collaboration)

ICRC 2021, July 21th, 2021

Ultra-high-energy cosmic ray (UHECR) sky

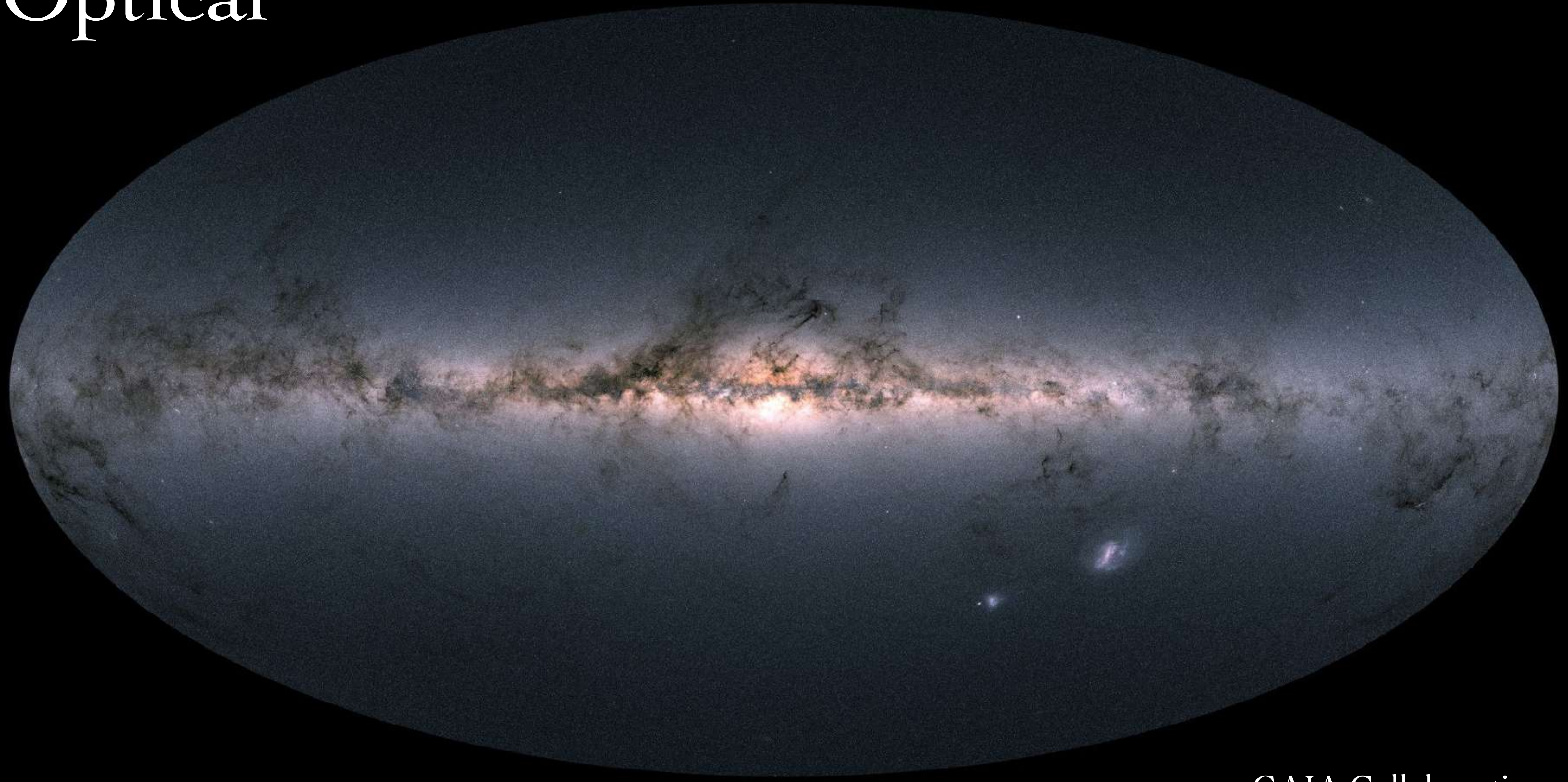
"Ankle" energies (E_{Auger}>8.86 EeV, E_{TA}>10 EeV)



→ Extragalactic cosmic rays

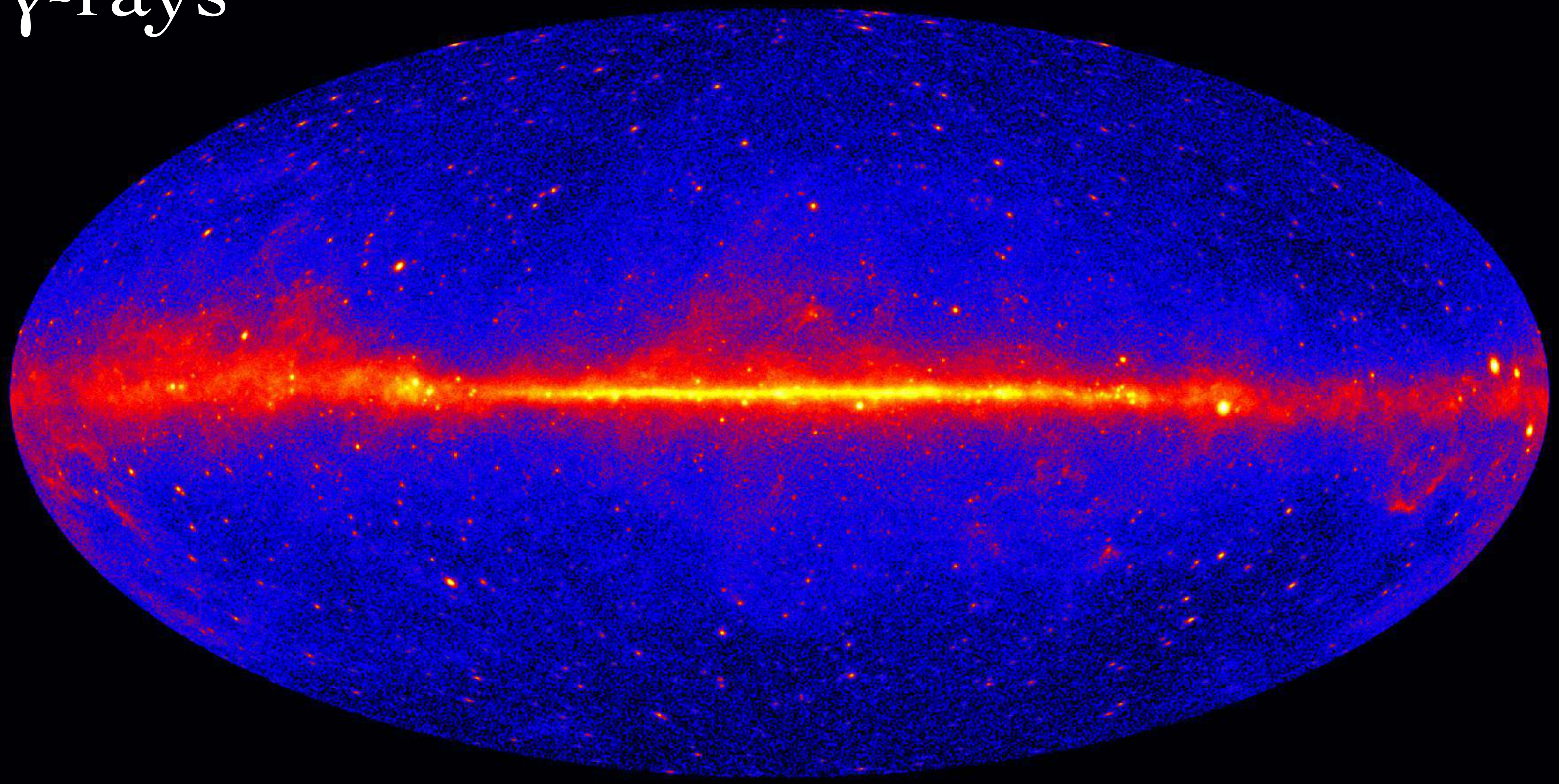
J. Biteau, TF et al., EPJ Web of Conferences 210, 01005 (2019)
A. di Matteo, TF et al., PoS ICRC2019 (2020) 439, using a different color contour

Optical



GAIA Collaboration

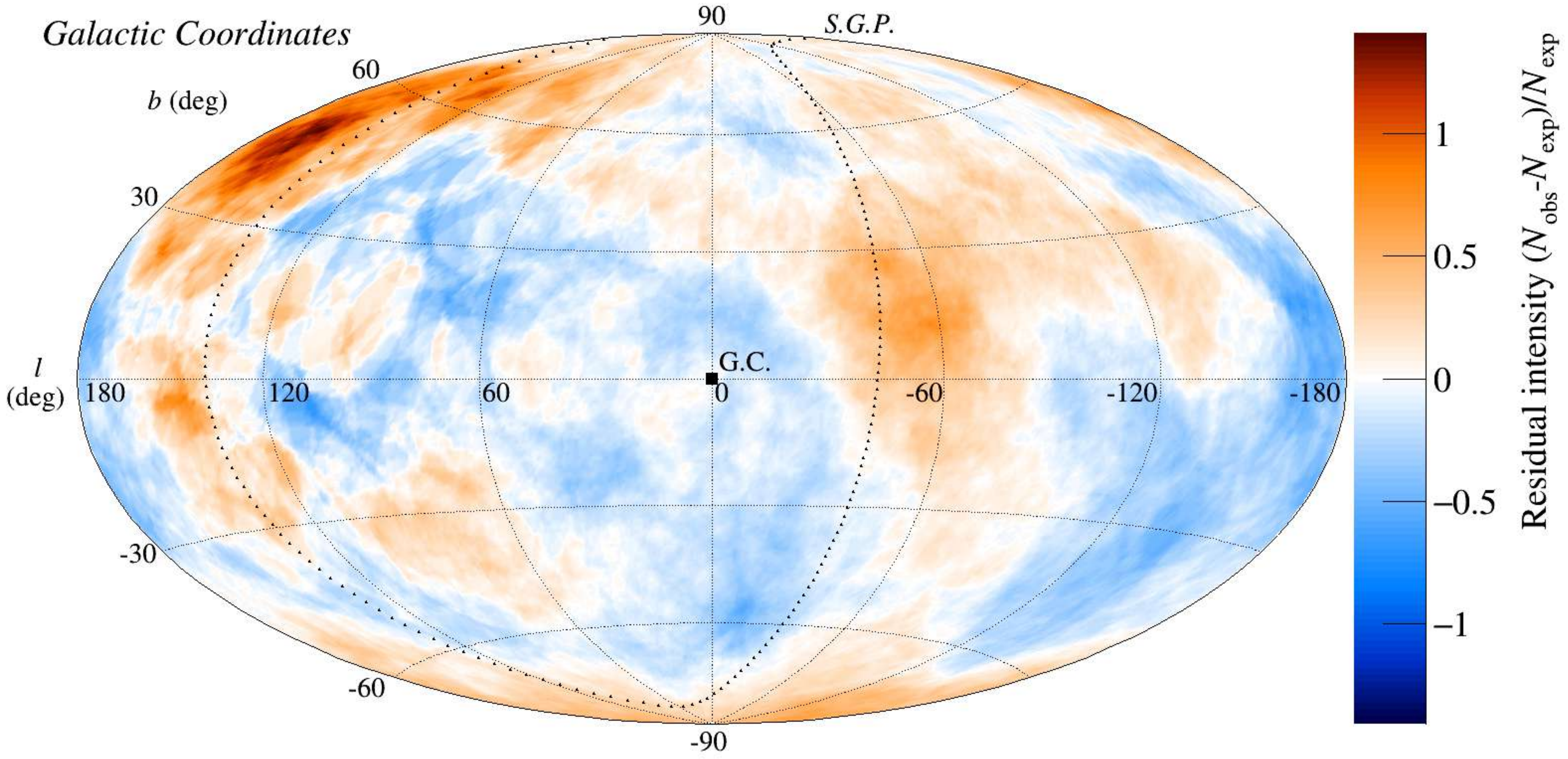
γ-rays

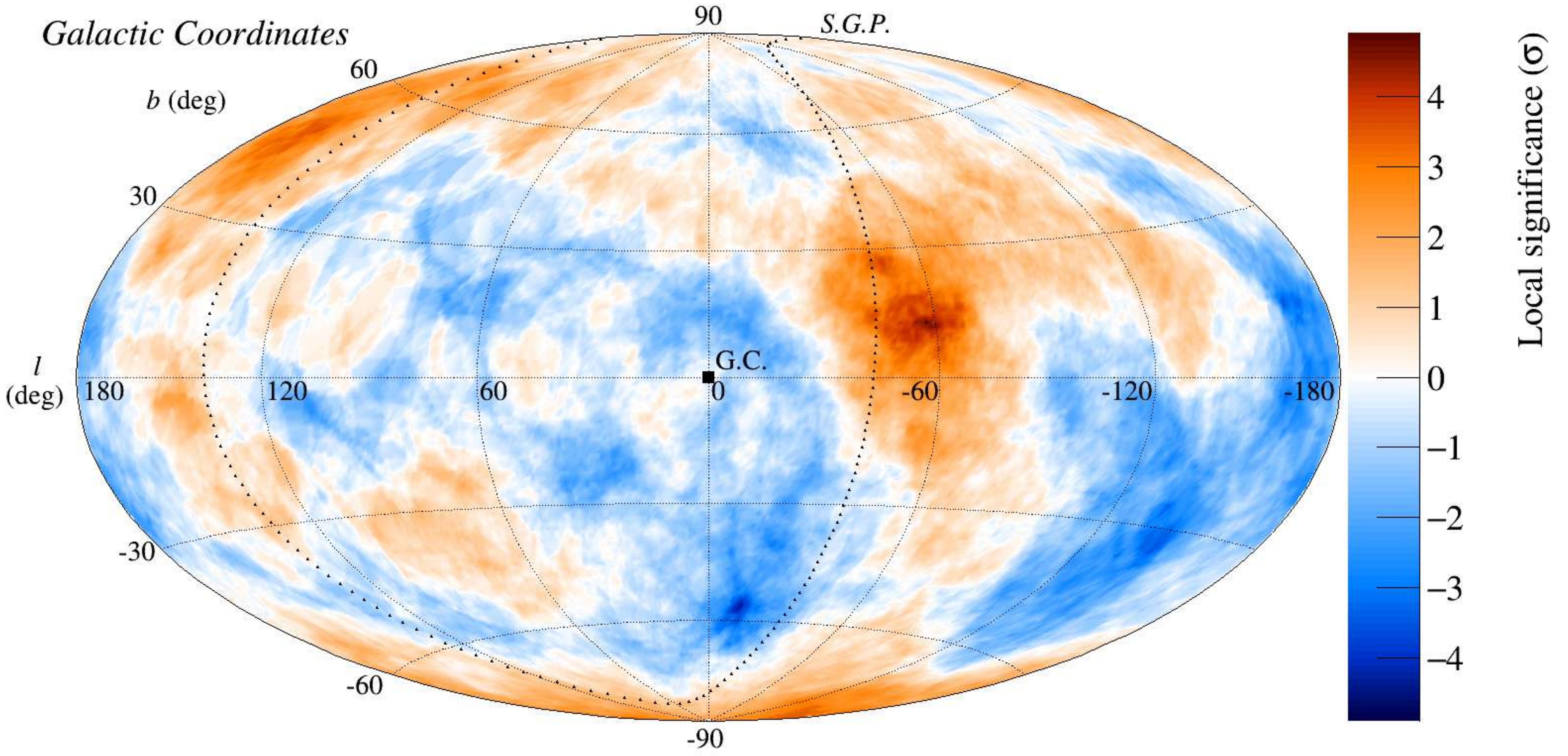


NASA/DOE/Fermi Collaboration

UHECR sky above cutoff

"Cutoff" energies (E_{Auger}>40 EeV: 842 events in 13.3 yr, E_{TA}>52.3 EeV: 127 events in 9 yr)





J. Biteau, TF et al., EPJ Web of Conferences 210, 01005 (2019)
A. di Matteo, TF et al., PoS ICRC2019 (2020) 439, using a different color contour

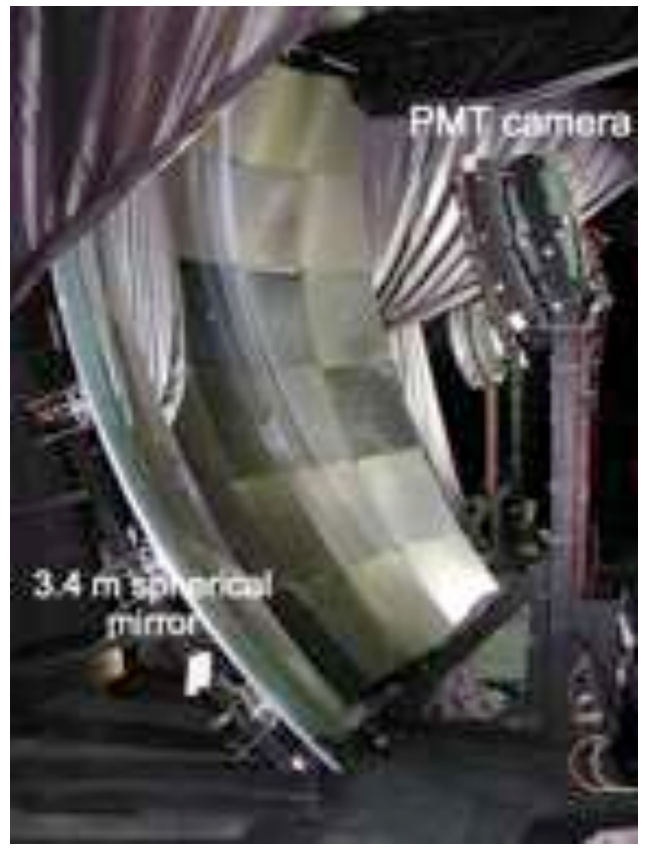
- Intriguing intermediate anisotropies: Active galactic nuclei, Starburst galaxies
  - No excess from the Virgo cluster, ***Virgo scandal***
- Challenges to mass composition and galactic/extragalactic magnetic fields

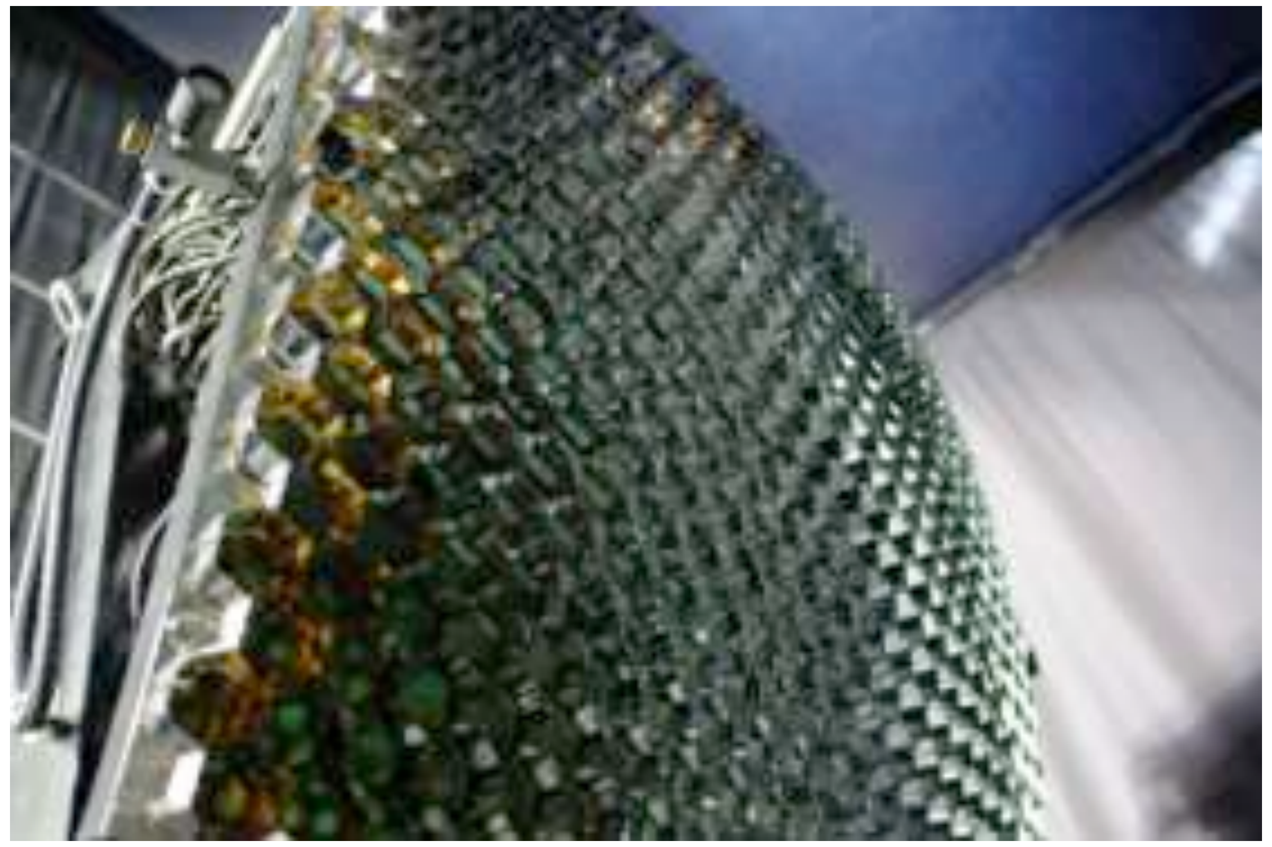
→ Need more statistic with mass composition sensitivity to identify UHECR sources

FAST: Fluorescence detector Array of Single-pixel Telescopes

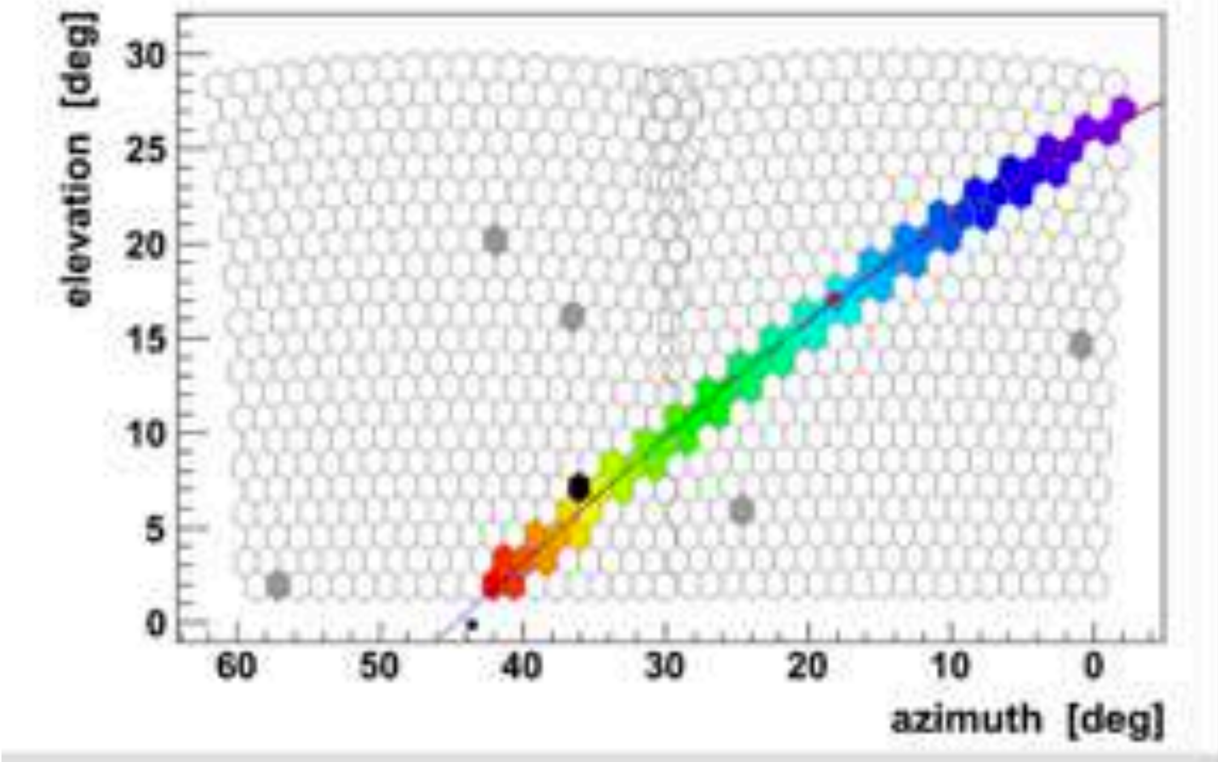
- Target : > $10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrino and gamma rays
  - Huge target volume ⇒ Fluorescence detector array

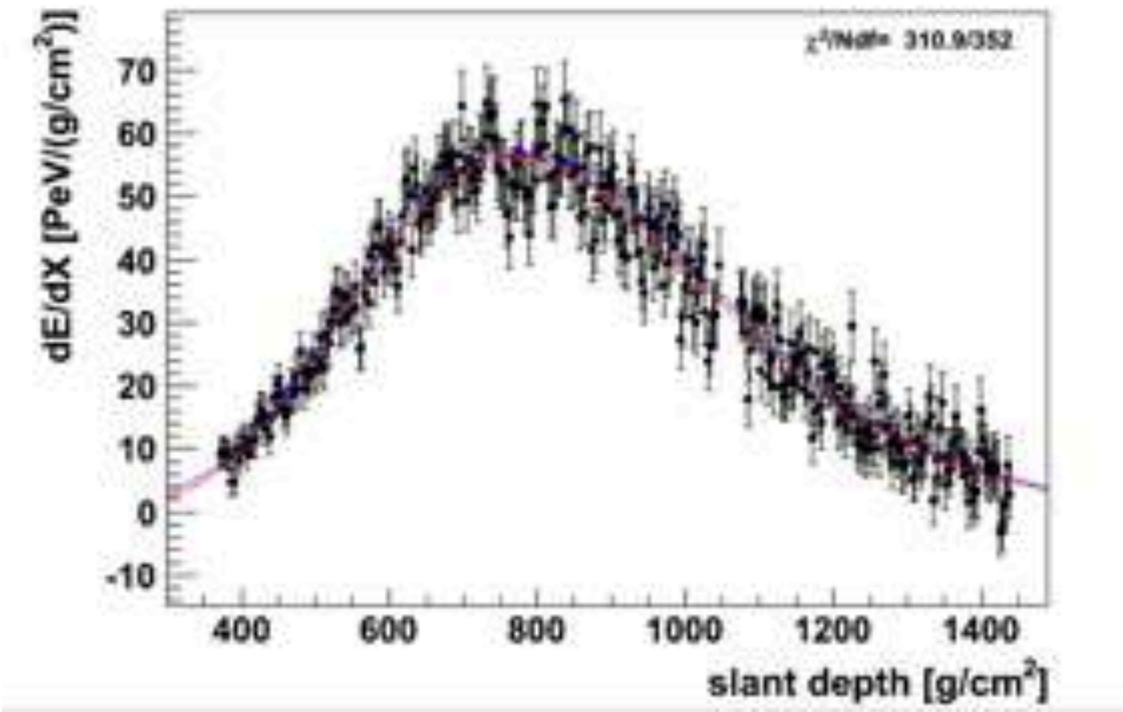
Fine pixelated camera



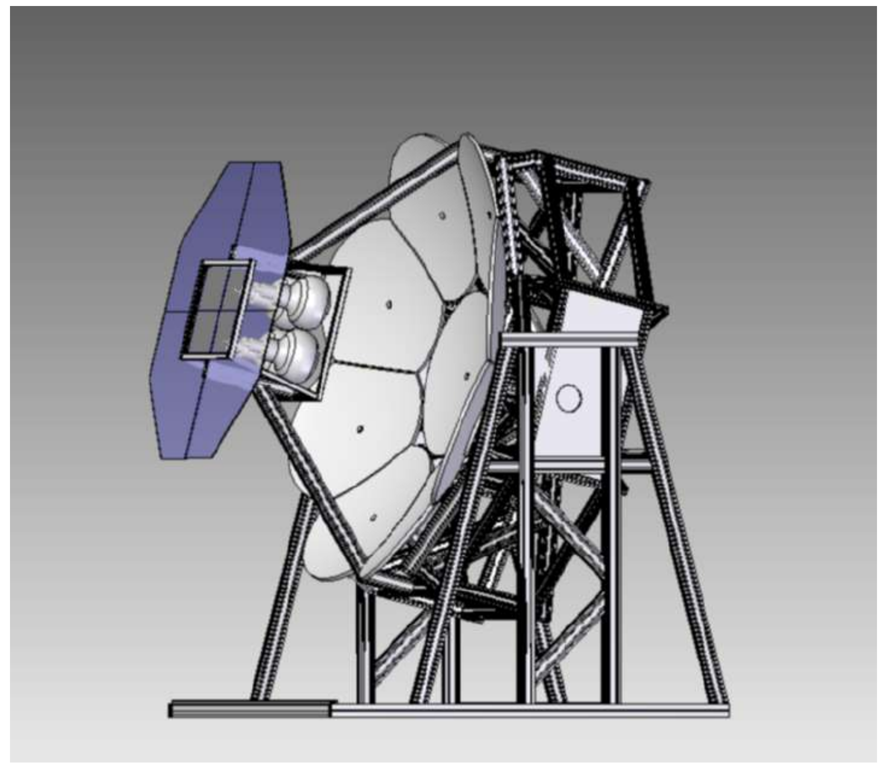


Too expensive to cover a huge area

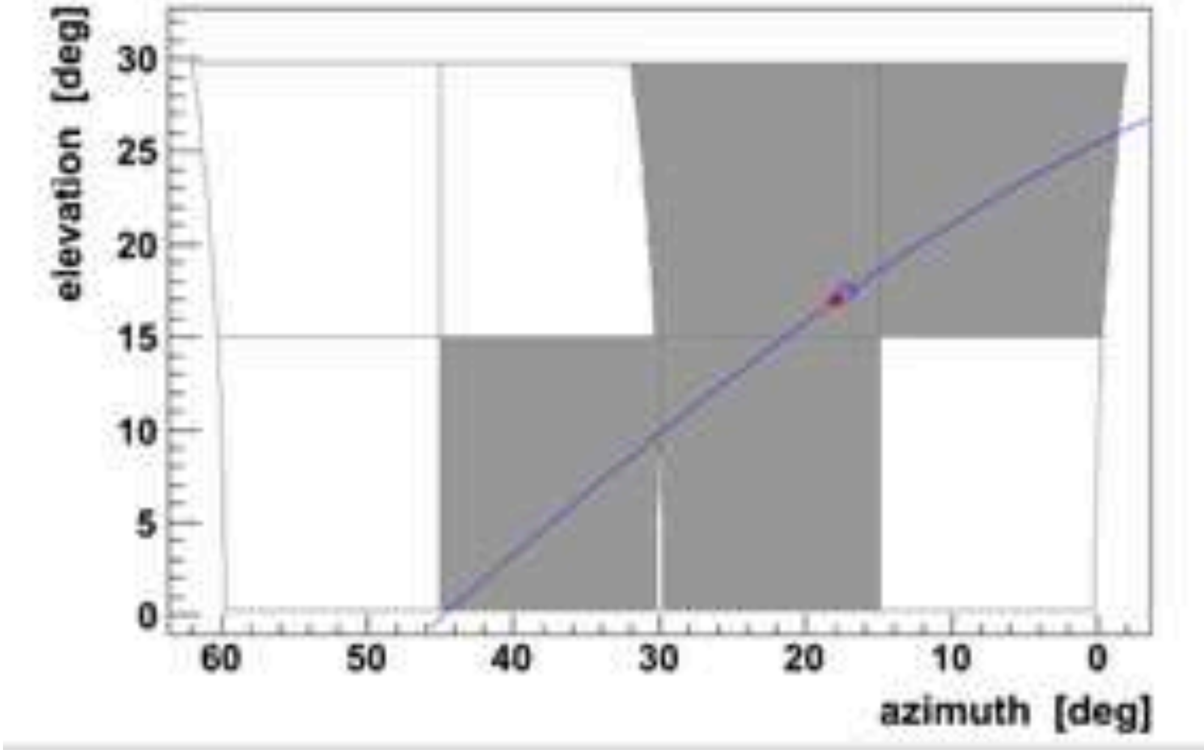


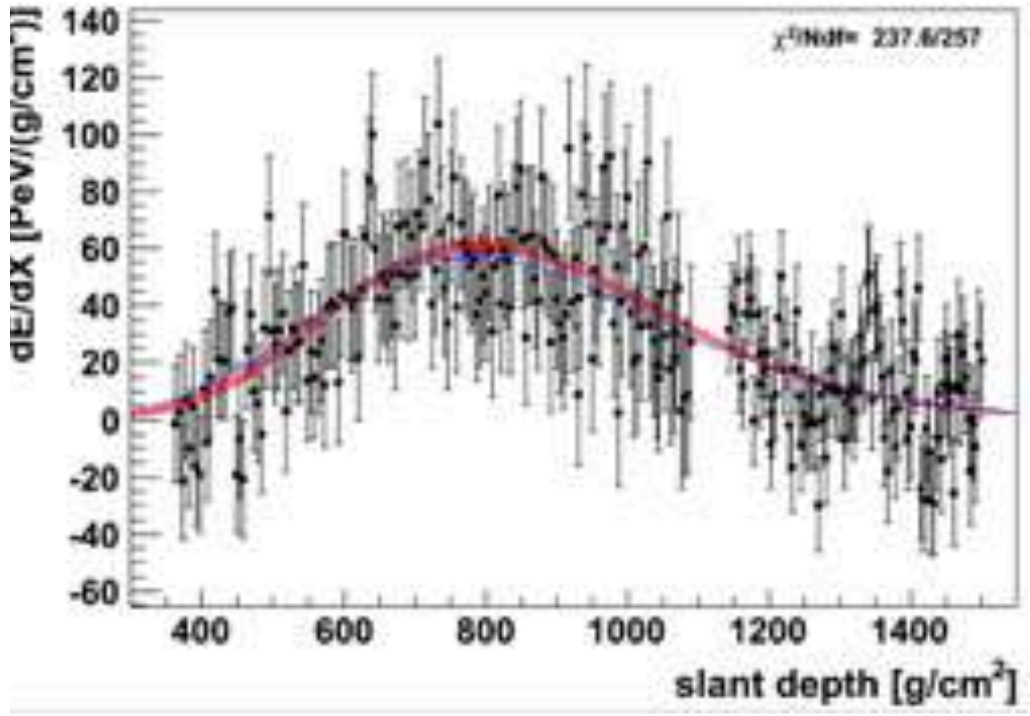


Smaller optics and single or few pixels

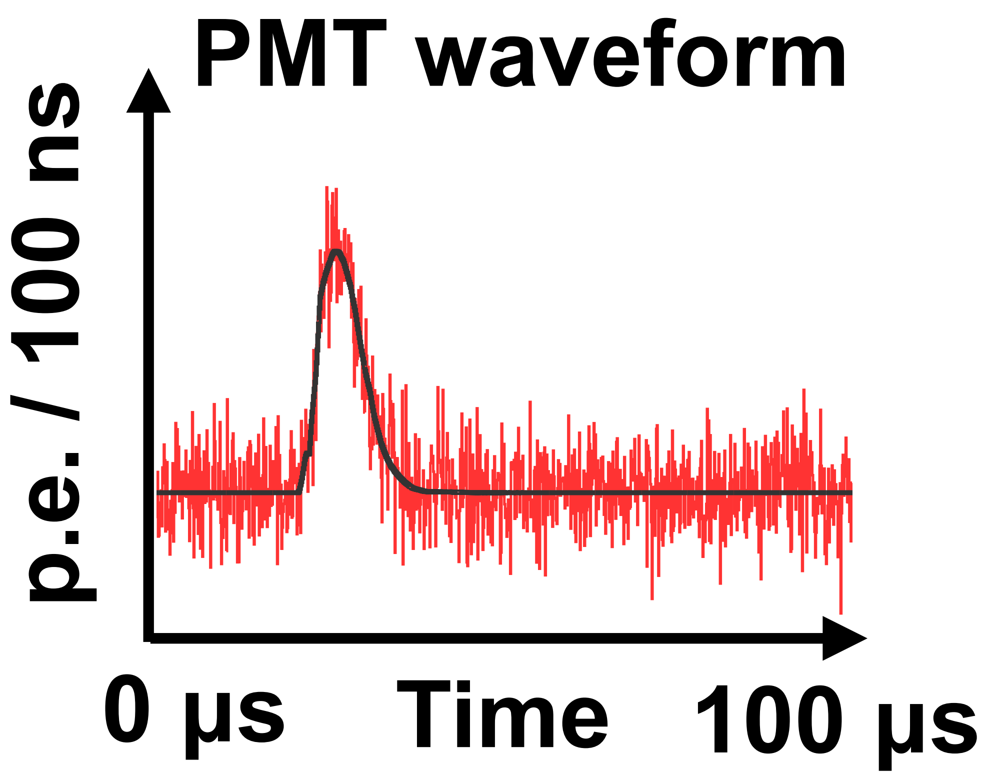


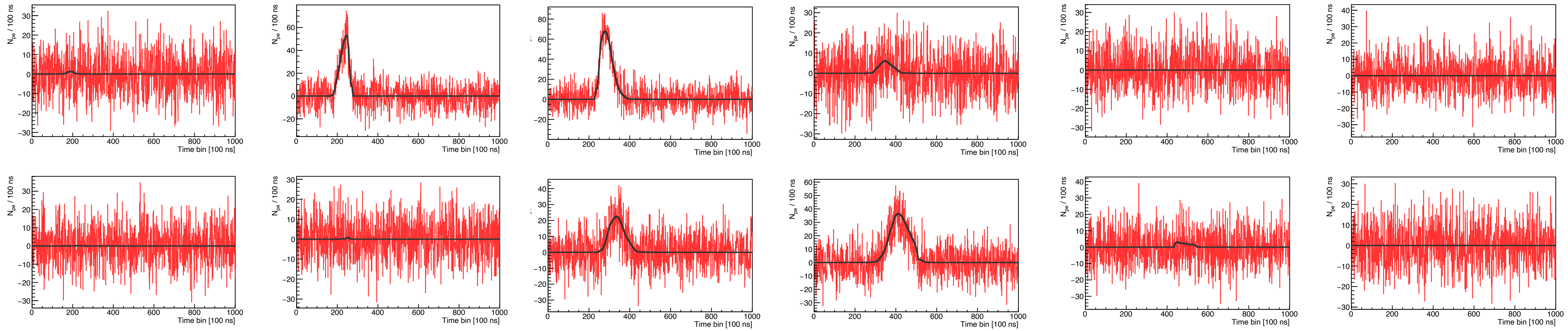
Low-cost and simplified telescope

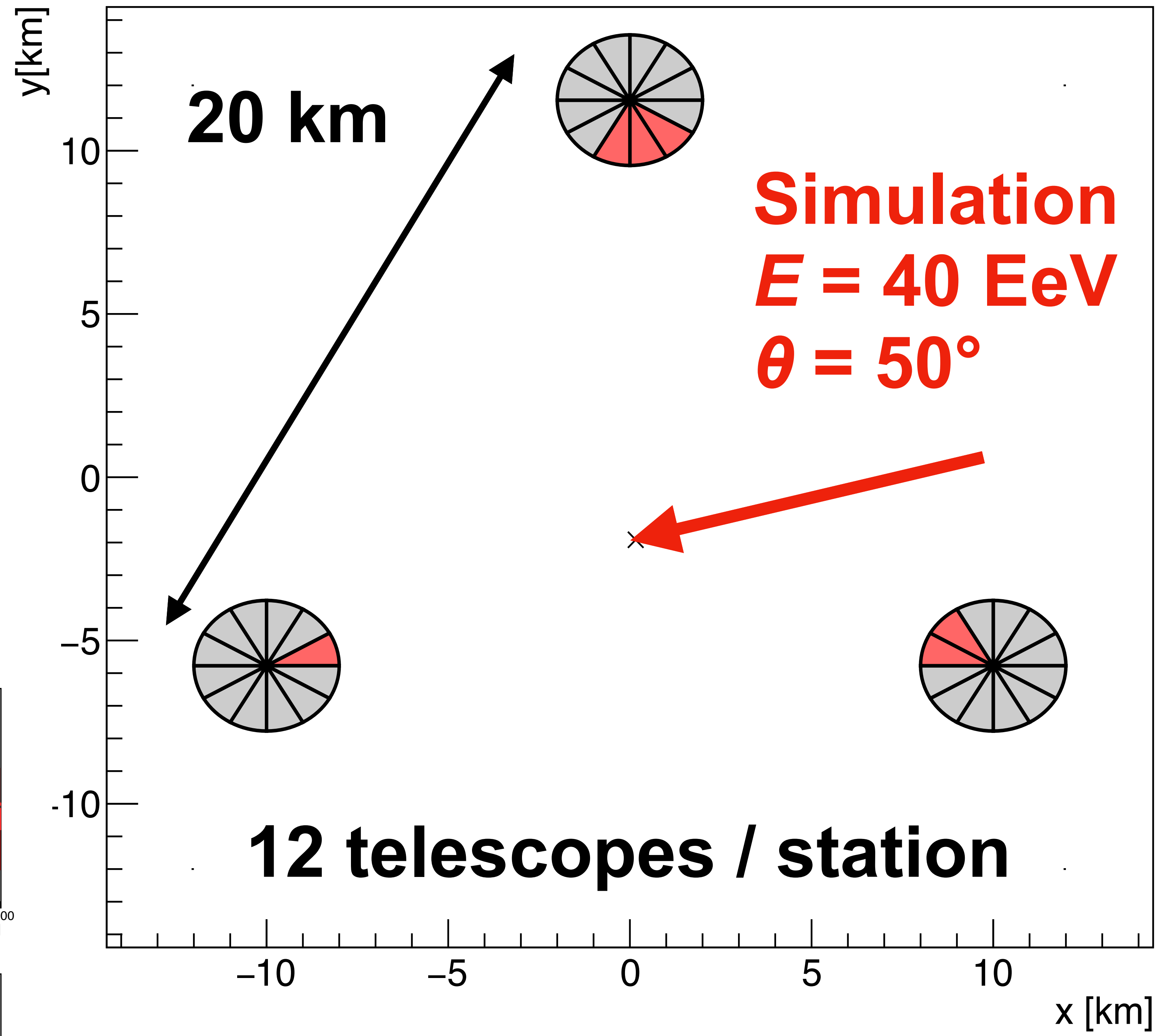




Fluorescence detector Array of Single-pixel Telescopes

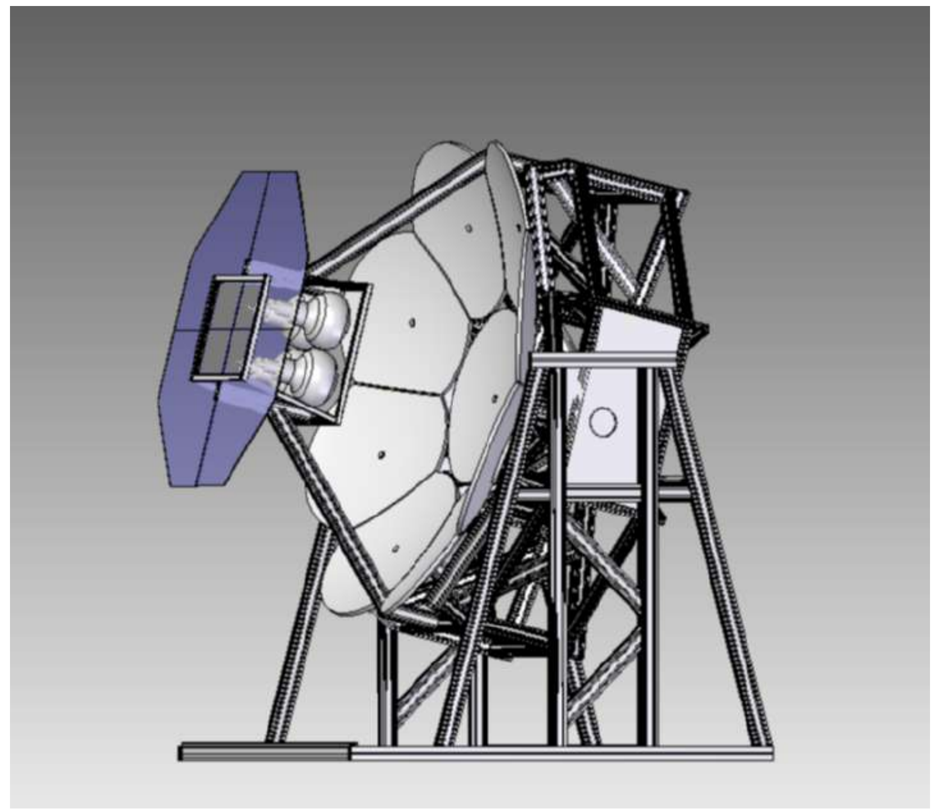






500 stations

→ 150,000 km^2

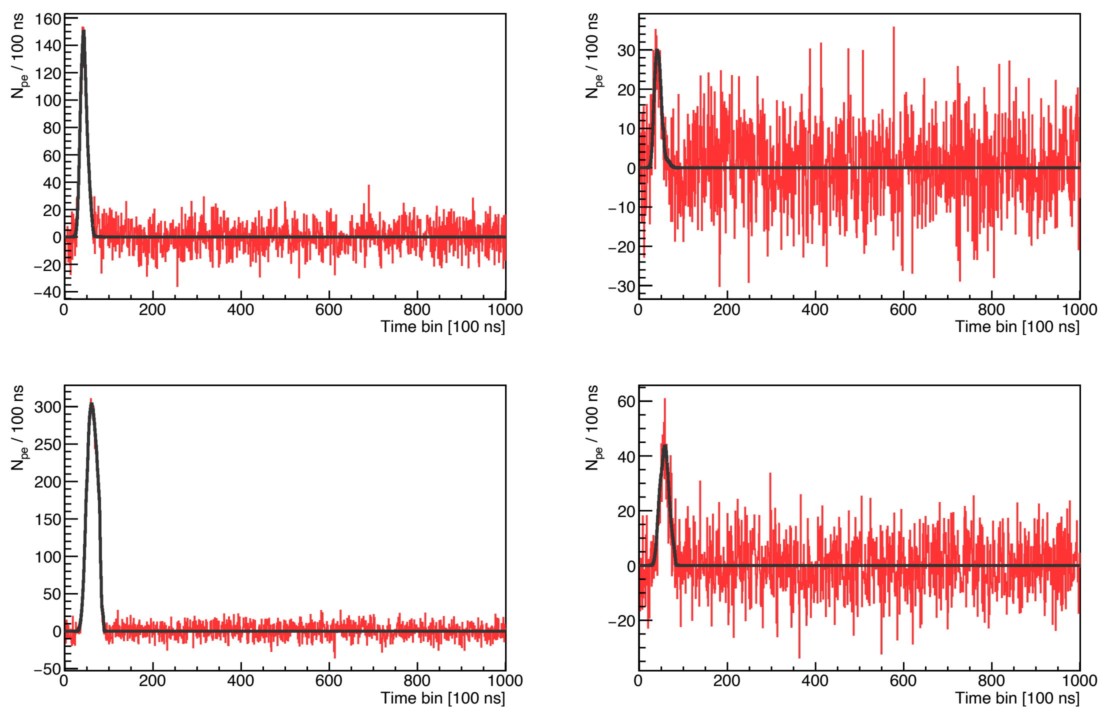


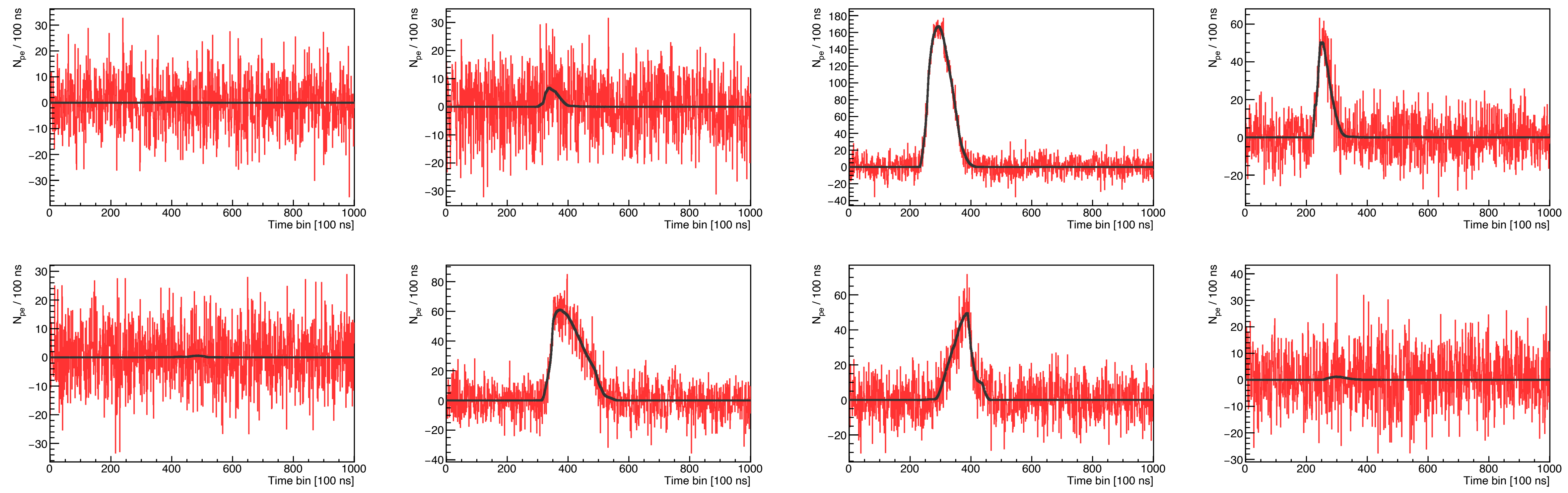
FAST telescope

4 PMTs (20 cm diameter)

1 m^2 aperture (UV filter)

Segmented mirror in 1.6 m diameter





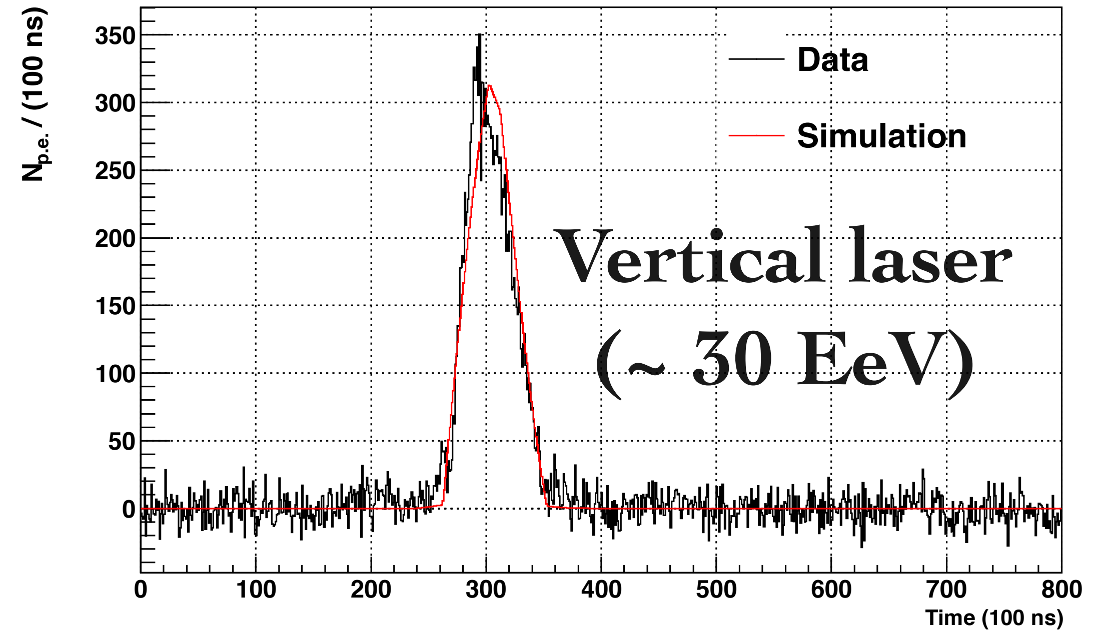
Fluorescence detector Array of Single-pixel Telescopes

Field measurements to validate the FAST concept

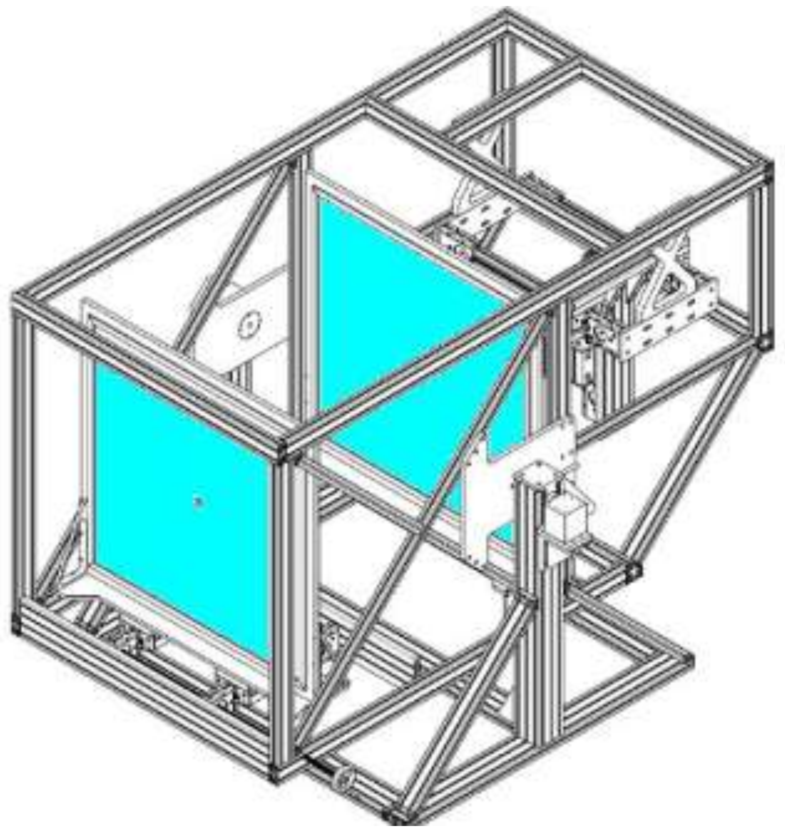
Feb. 2012

A conceptual design for a large ground array of Fluorescence Detectors

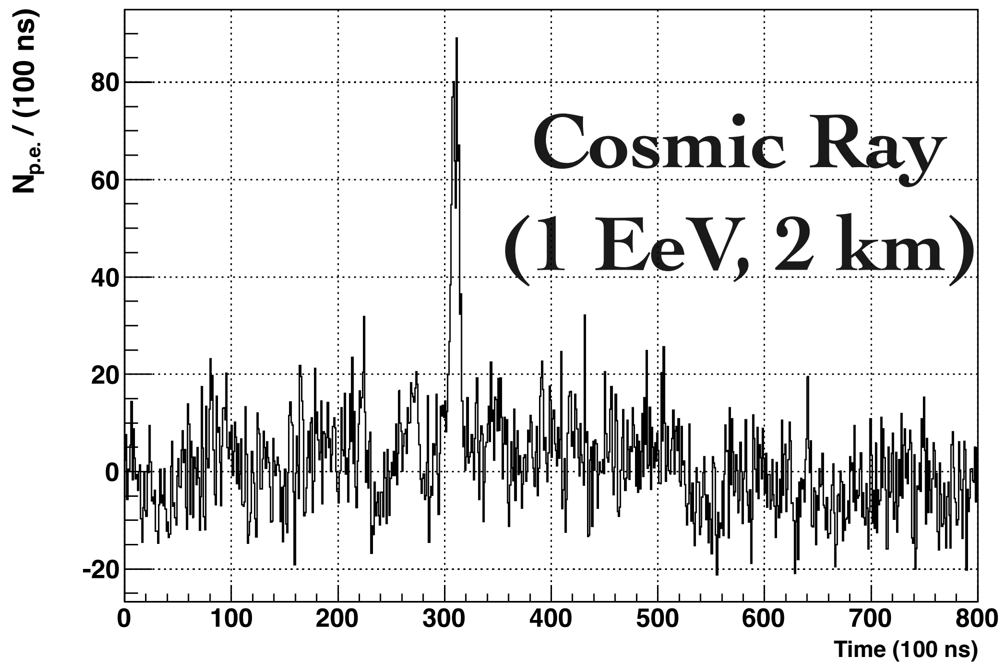
P. Privitera in UHECR 2012



Apr. 2014



EUSO-TA optics
+
Single-pixel camera



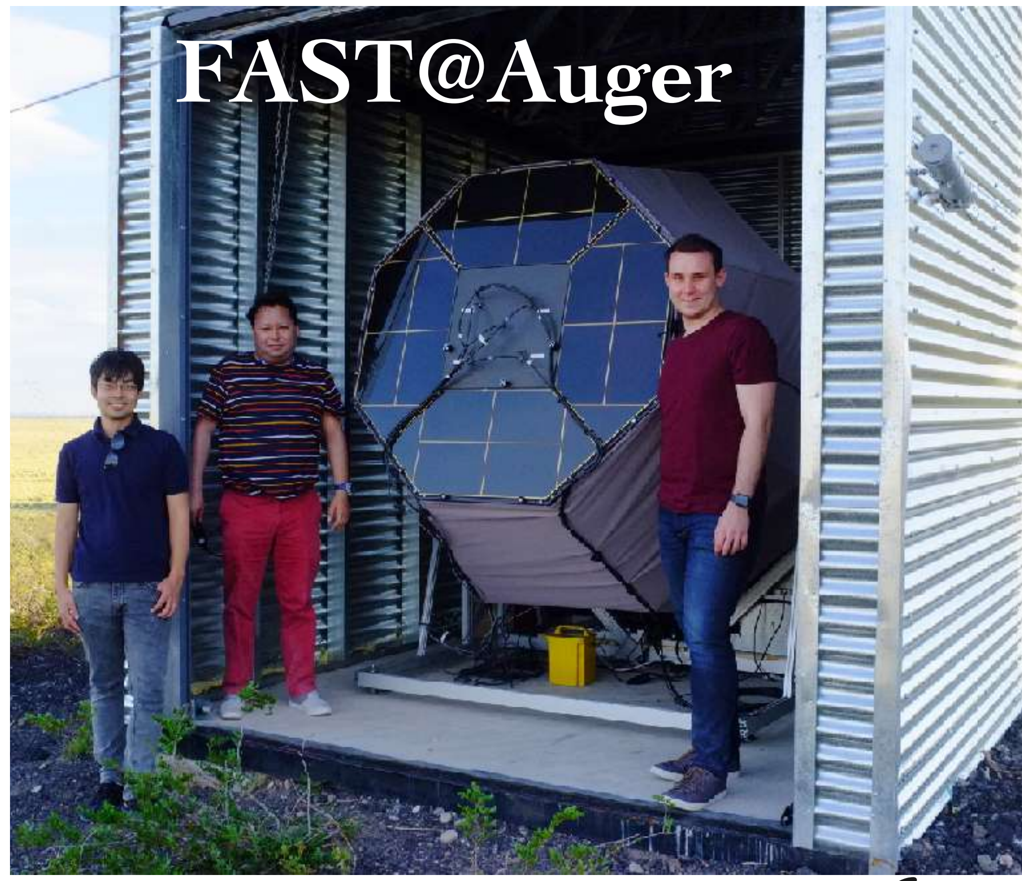
T. Fujii et al., Astroparticle Physics *74* (2016) 64-72

Oct. 2016

Sep. 2017

Oct. 2018
@TA

Apr. 2019
@Auger



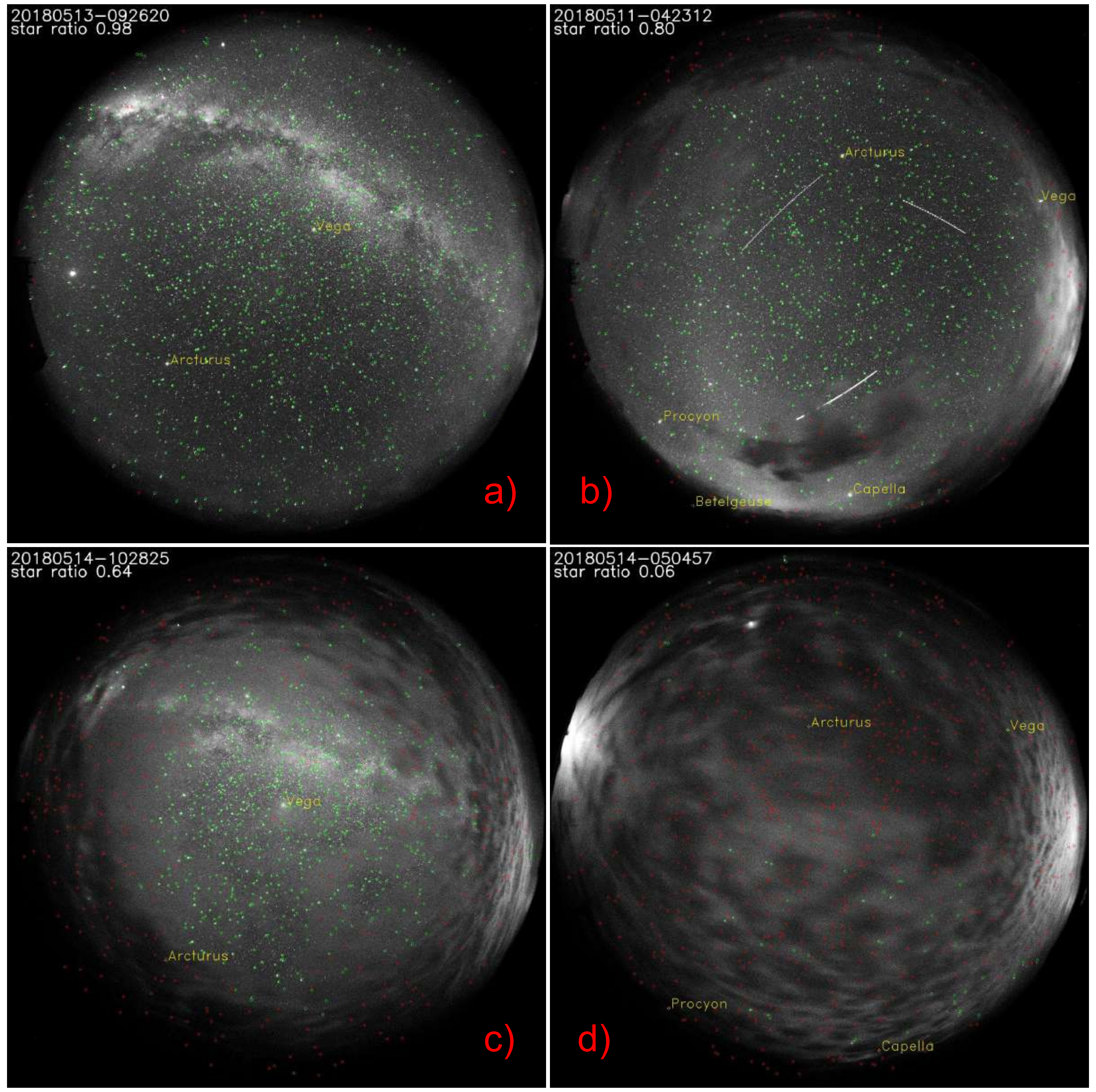
D. Mandat et al., JINST 12, T07001 (2017)

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

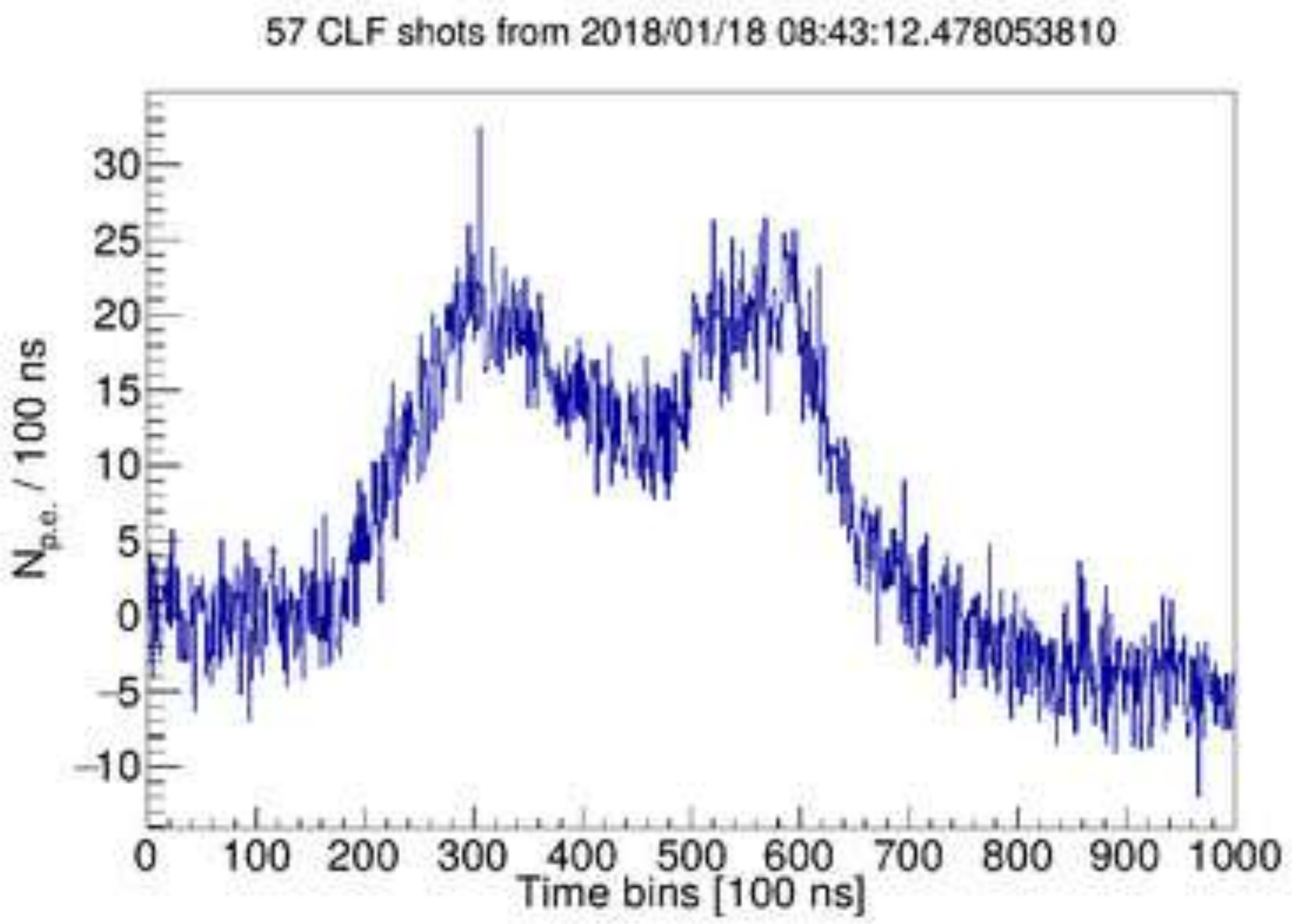
Atmospheric monitoring studies

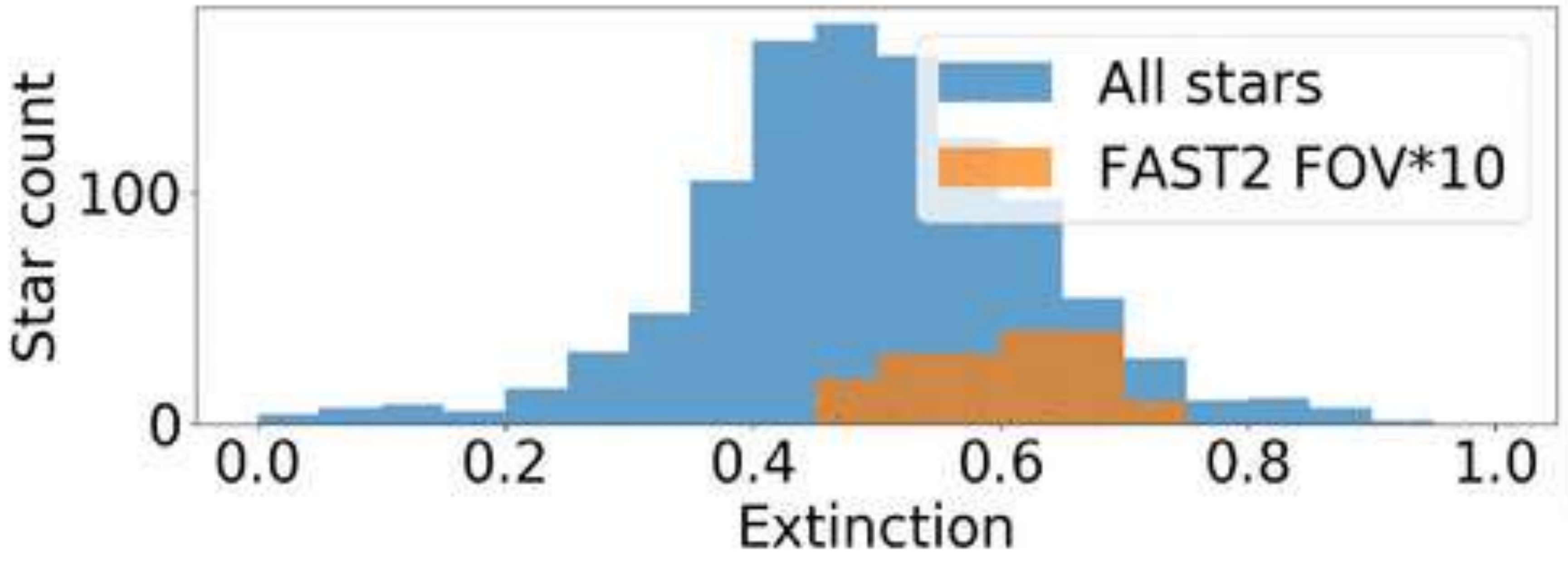
L. Chytka et al. (FAST Collaboration), JINST 15 T10009 (2020)

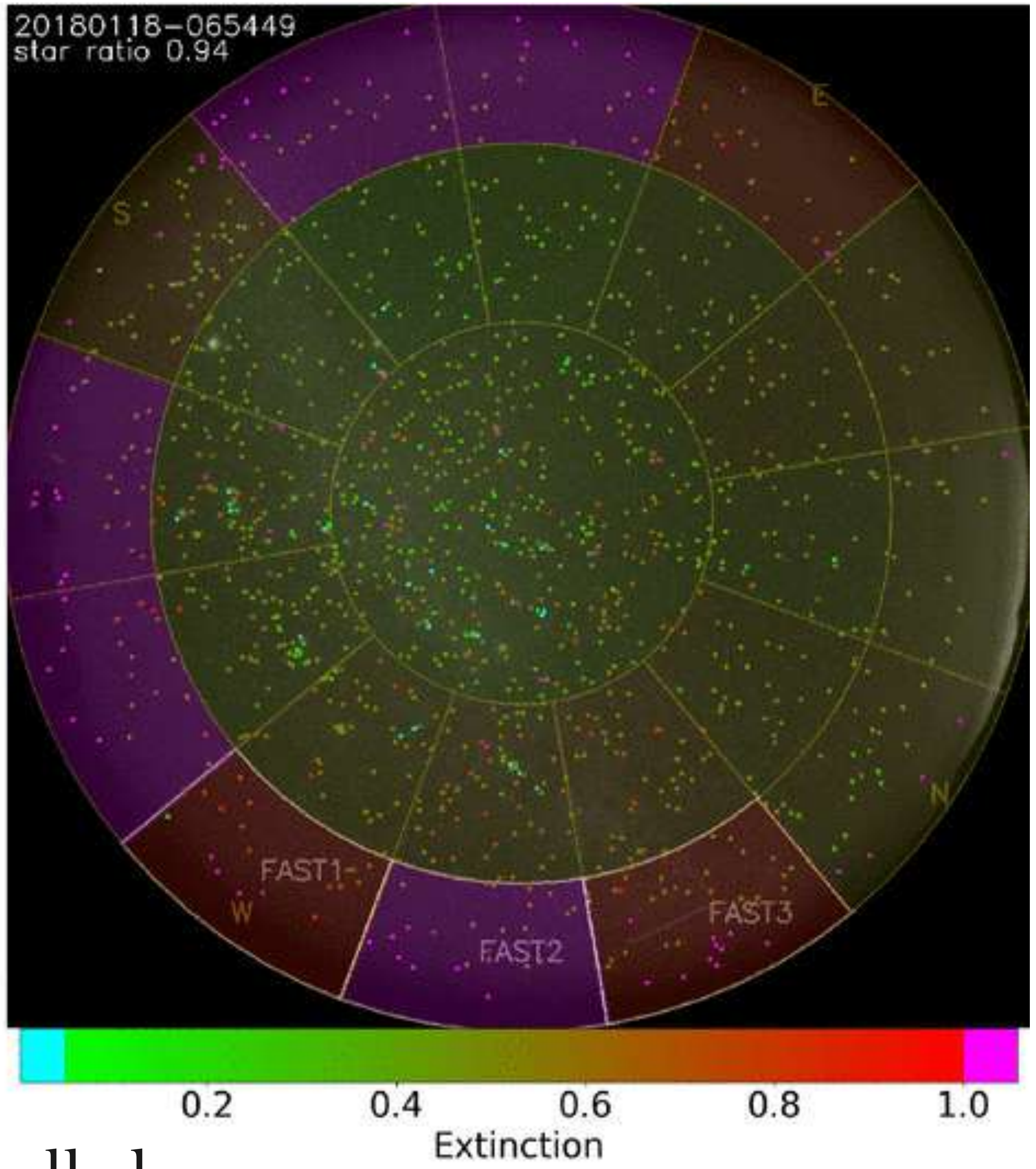
Automated all-sky camera



A distant laser detected with FAST



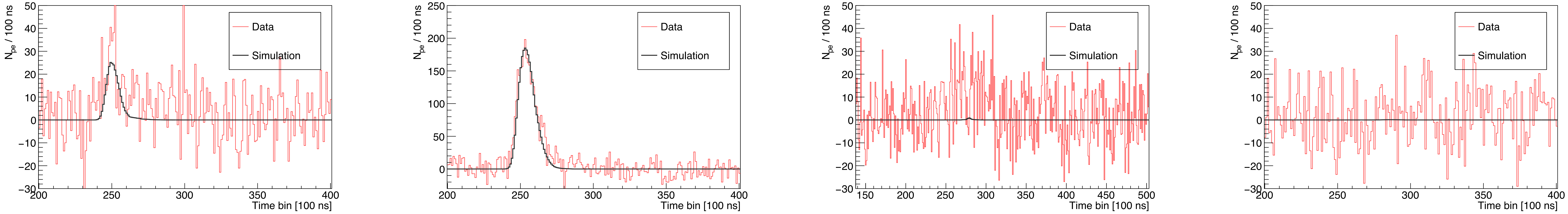




Star extinctions measured with all sky camera

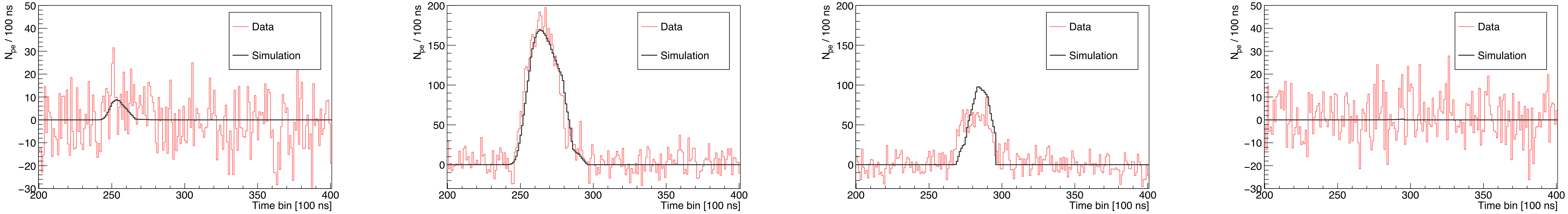
Cherenkov dominated event with "top-down" reconstruction

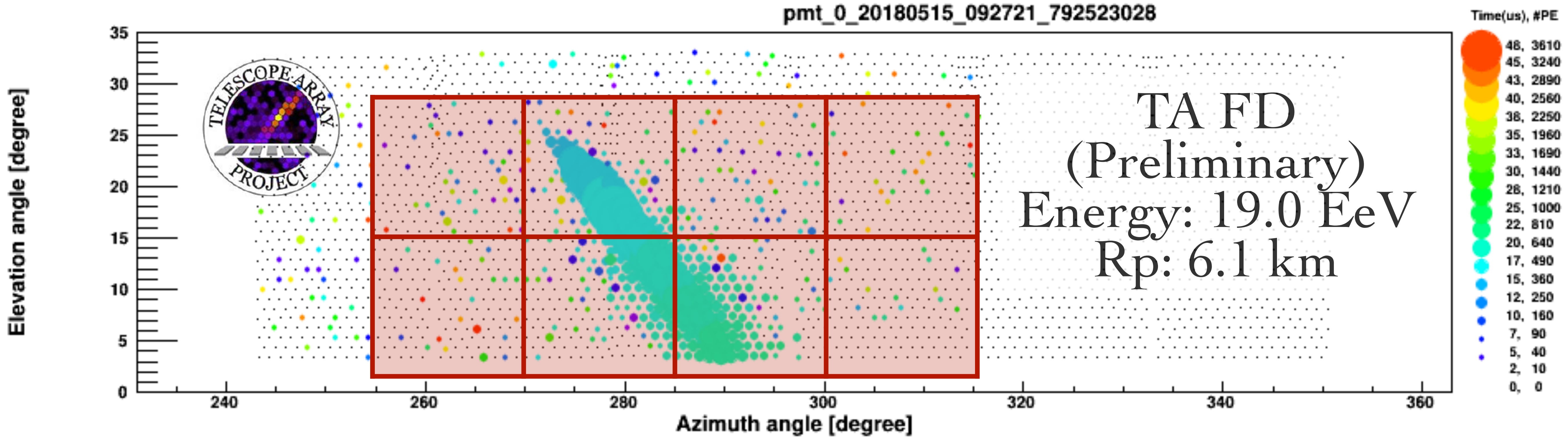
Fluorescence detector Array of Single-pixel Telescopes



FAST waveforms + Expected signals from top-down reconstruction

(Data, Simulation by the best-fit parameters)



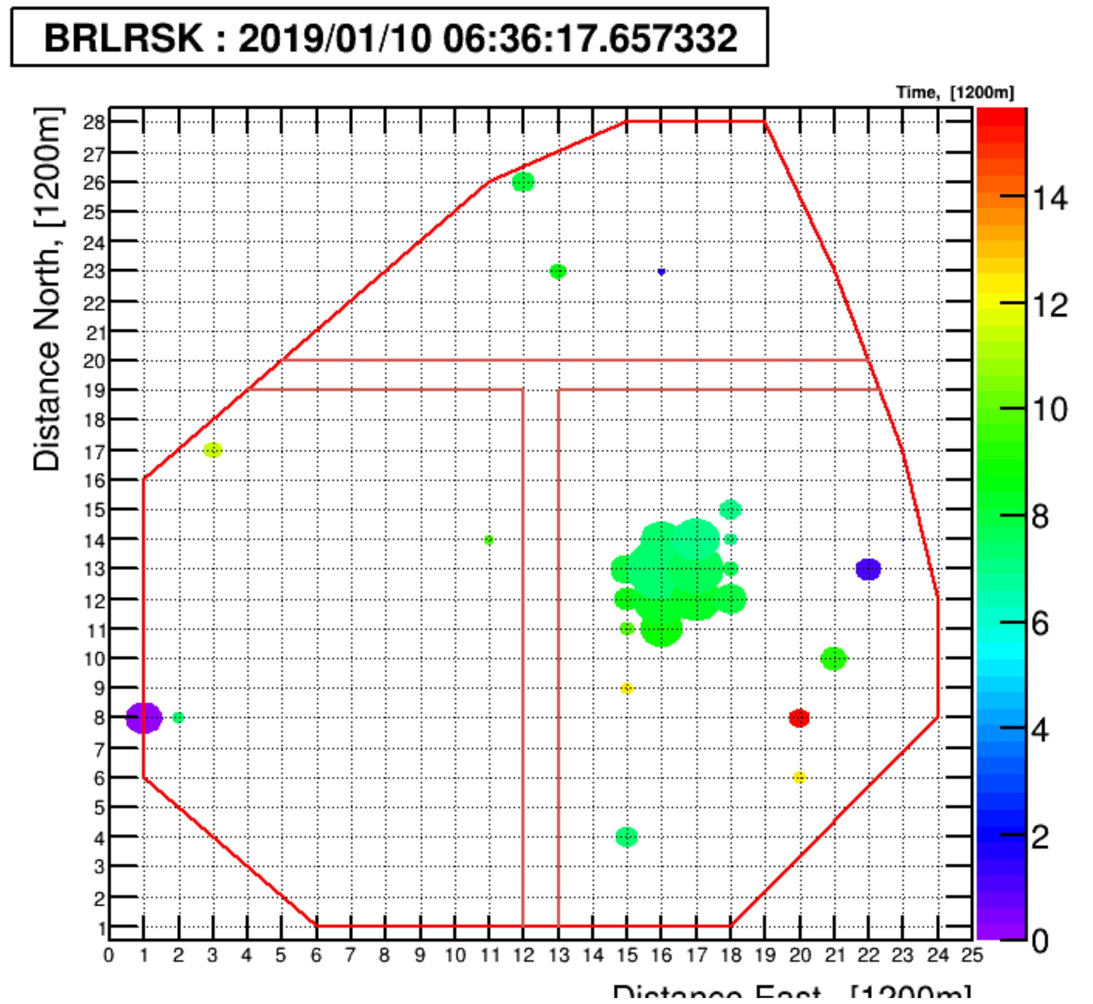


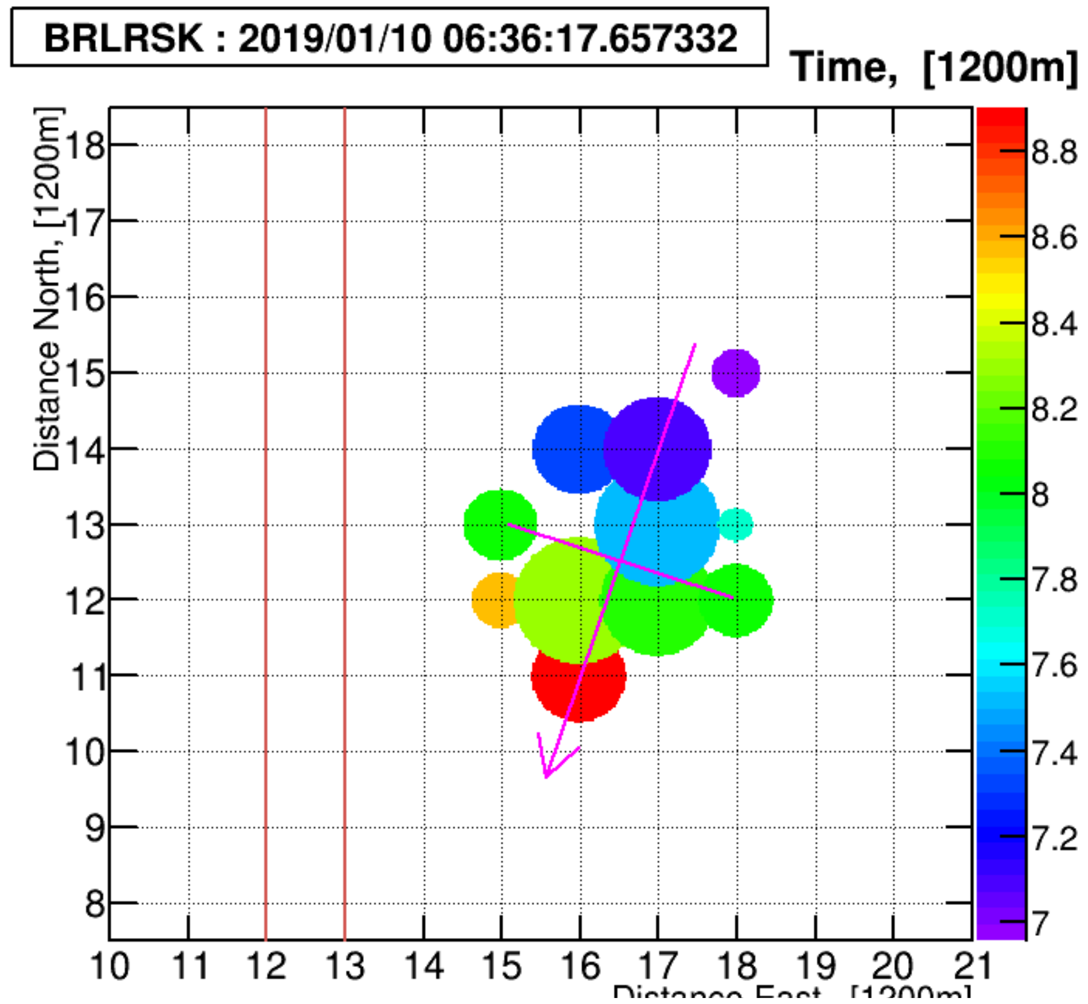
FAST top-down reconstruction (Preliminary)

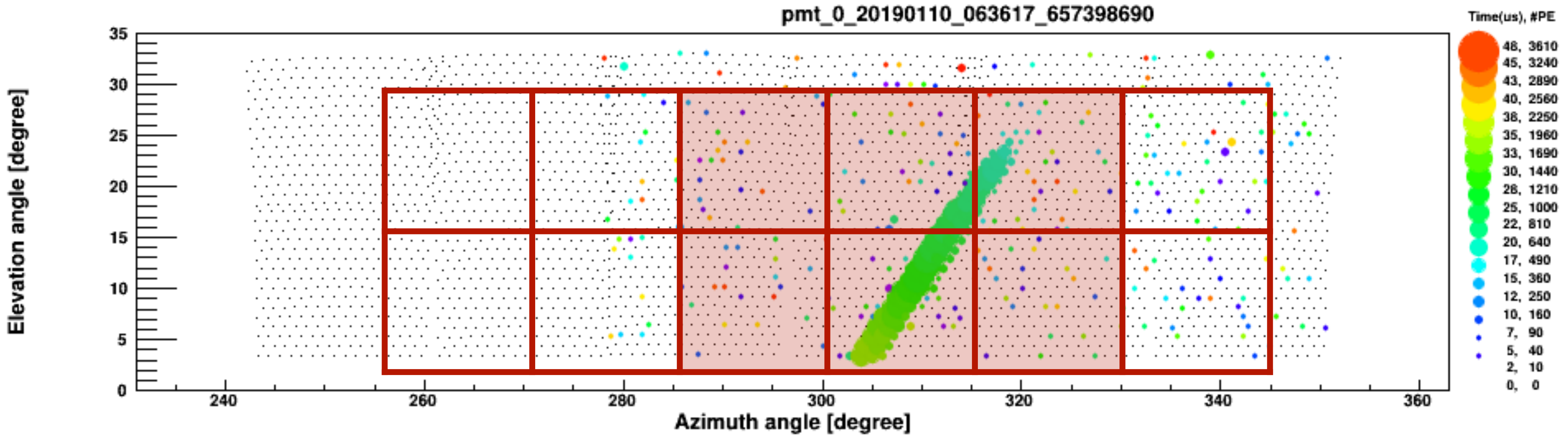
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
59.8 deg	-96.7 deg	7.9 km	-9.0 km	842 g/cm^2	17.3 EeV

Fluorescence dominated event

TA result







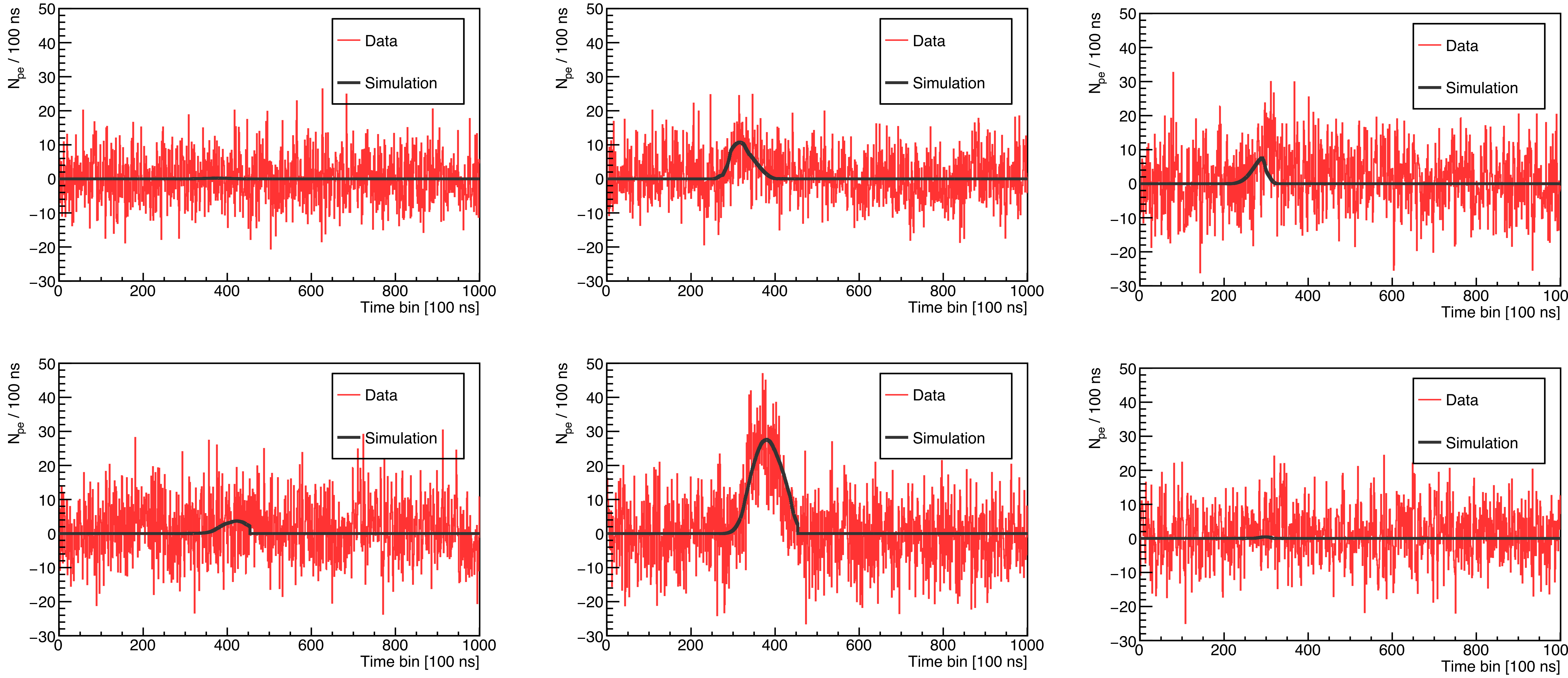
TA SD (Preliminary)

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

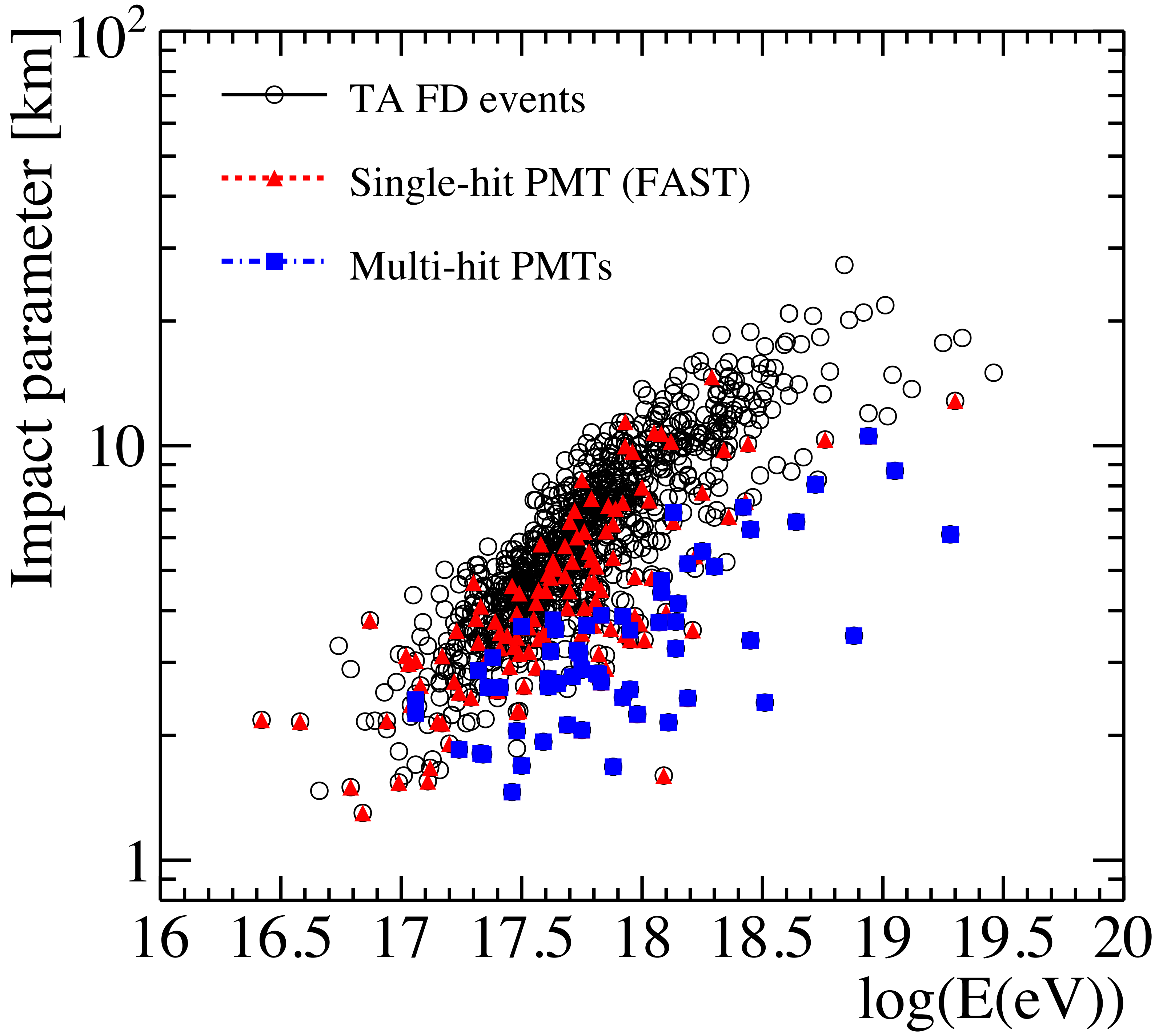


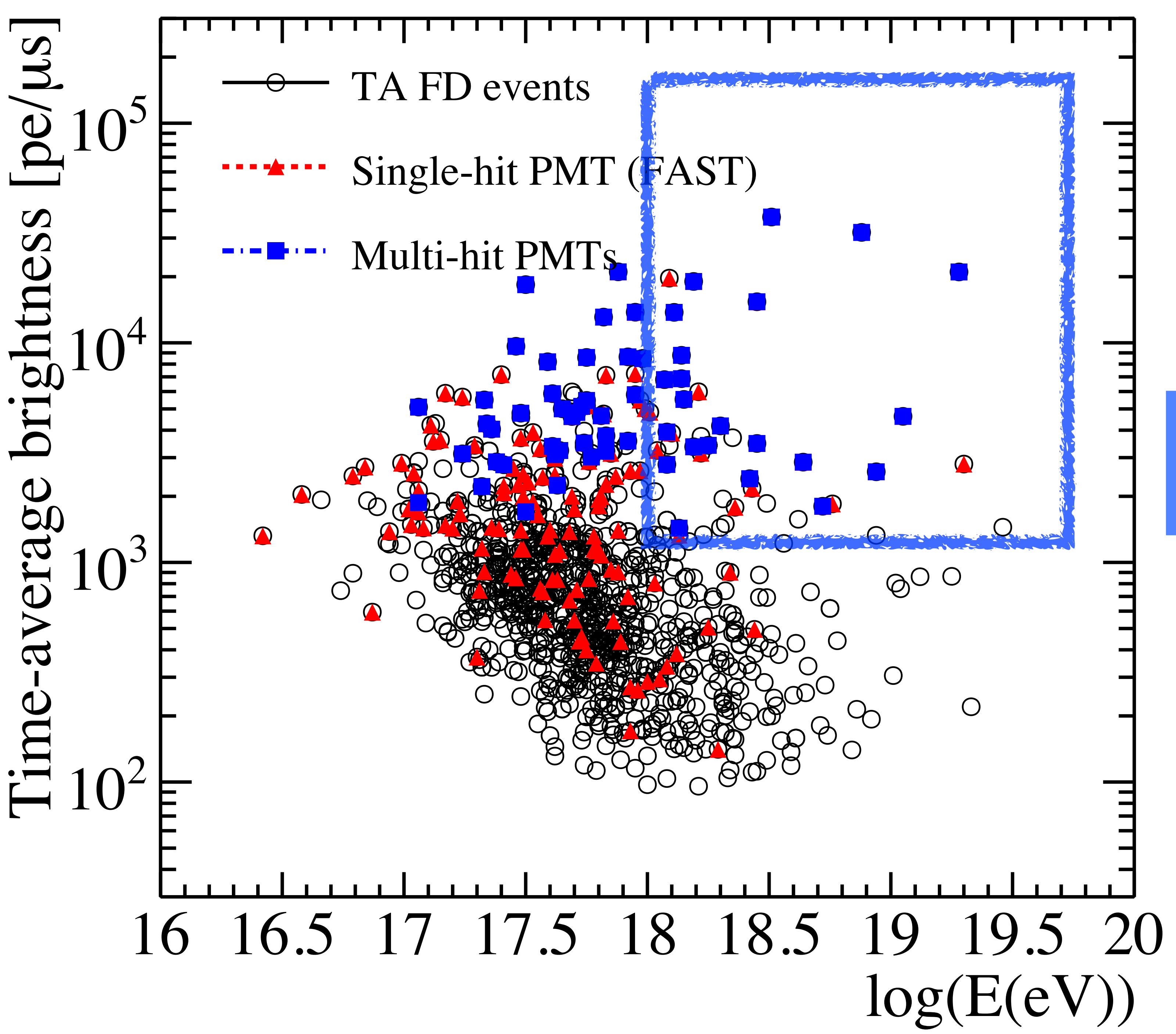
FAST top-down reconstruction (Preliminary)

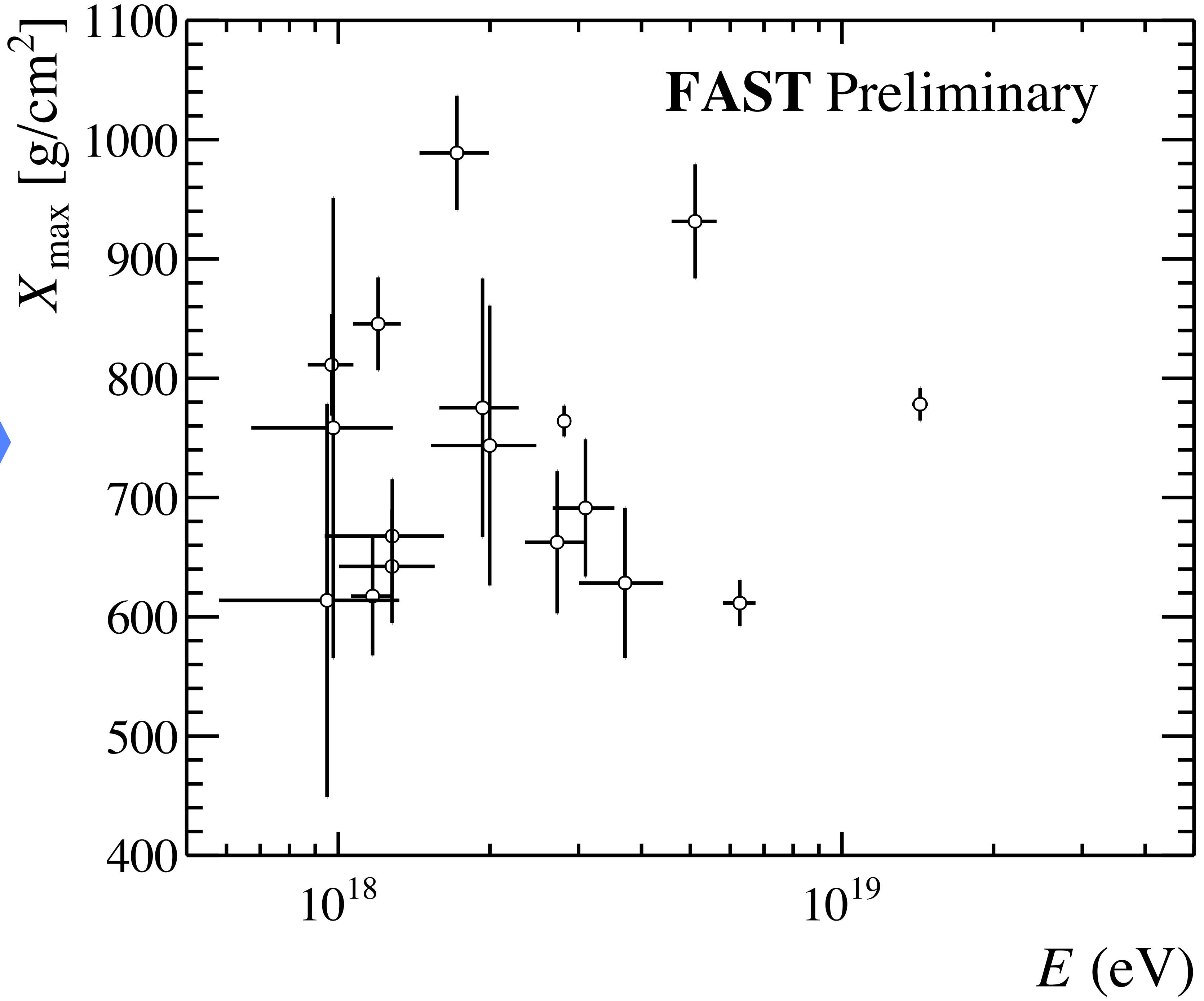
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
33.9 deg	19.3 deg	4.6 km	-4.7 km	808 g/cm^2	18.8 EeV

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





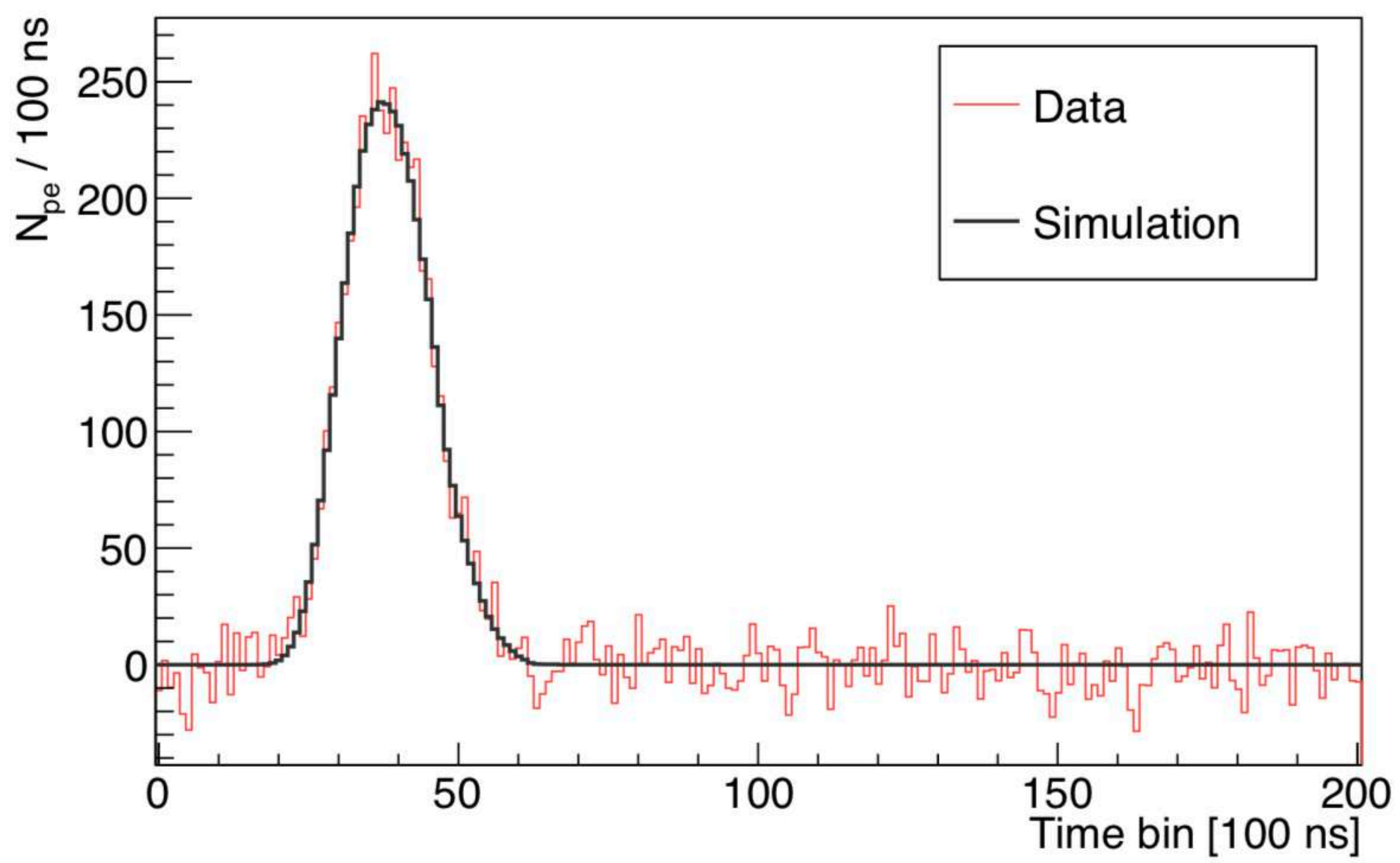


- Use **top-down reconstruction** for **events with multi-hit PMTs above 1 EeV**
  - First-guess geometry given from the TA FD

Fluorescence detector Array of Single-pixel Telescopes

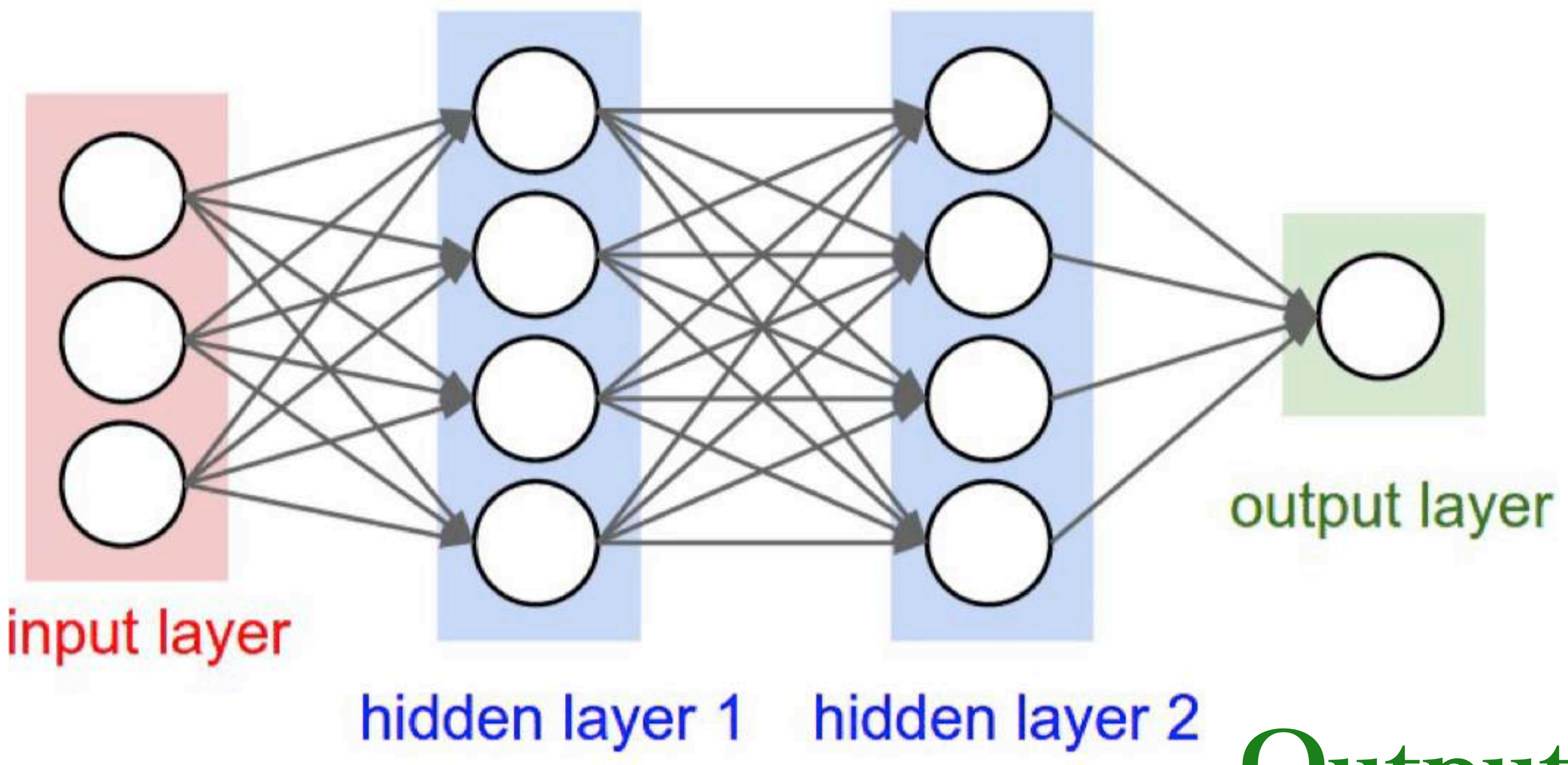
Updates on reconstruction methods

Work: Justin Albury



Inputs

3 feature per PMT with S/N > 5σ



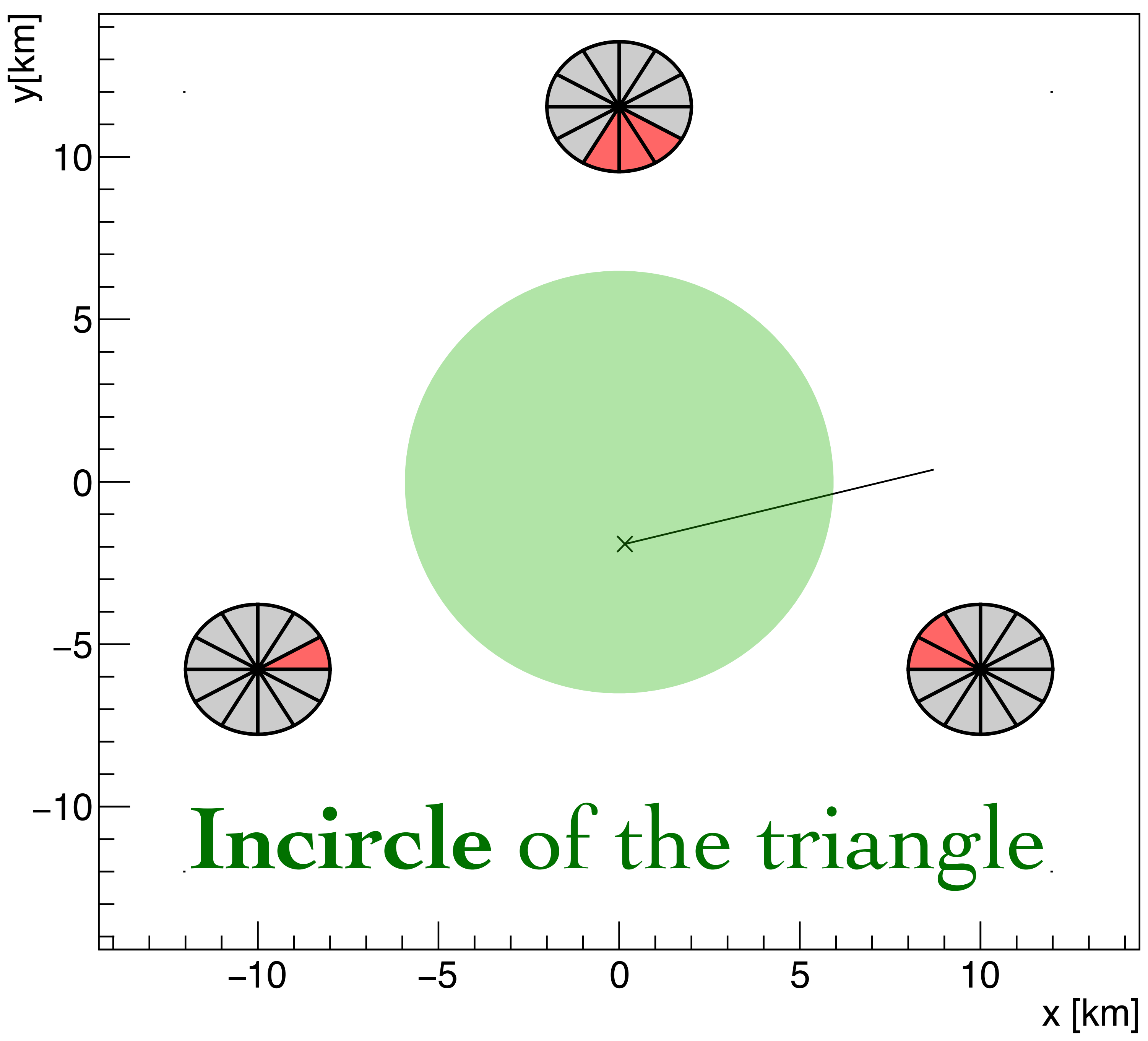
Outputs

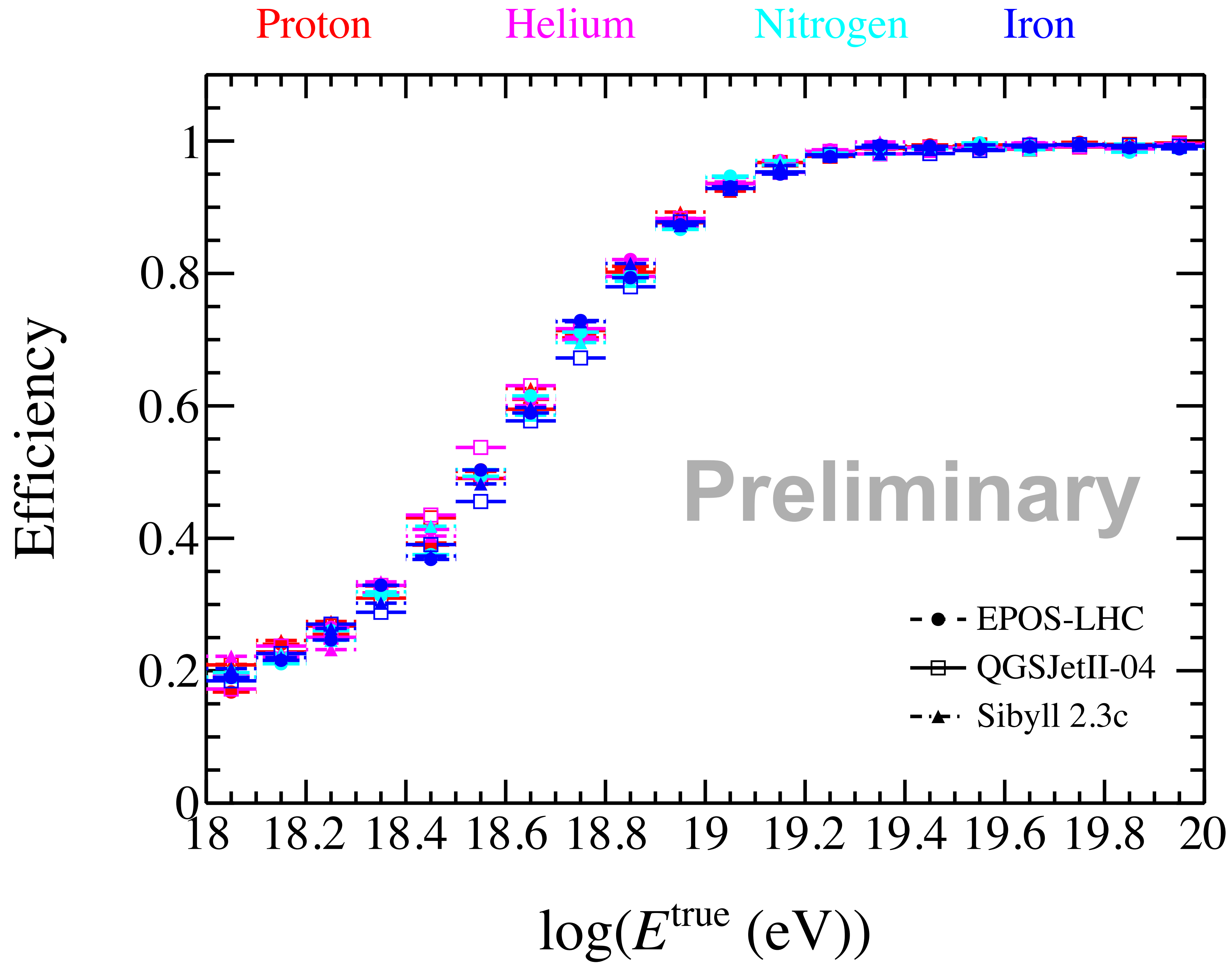
Energy, Xmax, geometry(θ, φ, x, y)

- Top-down reconstruction
  - 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 fast reconstruction

Performance with the FAST array

- **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)





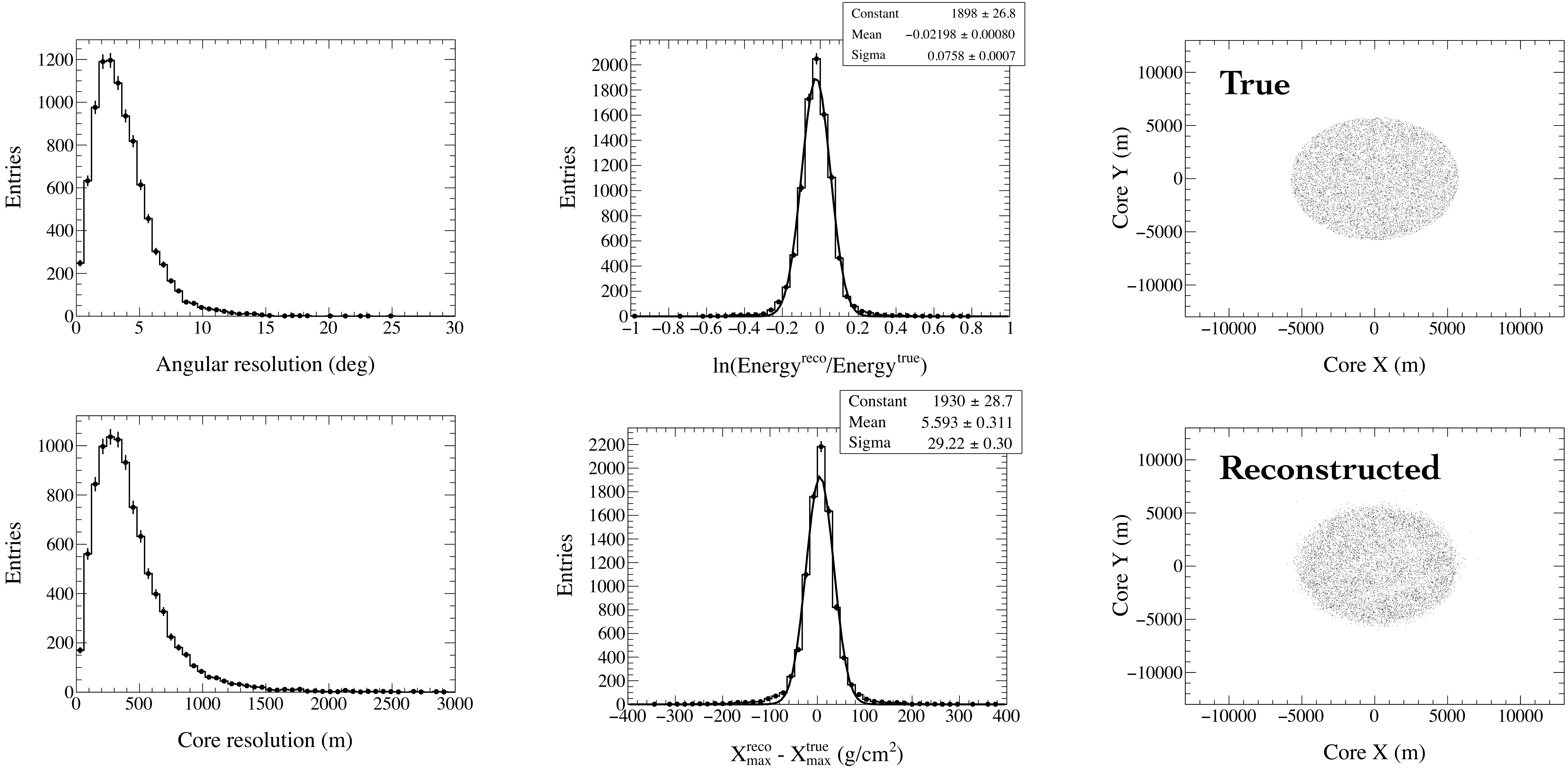
$$\epsilon = \frac{N_i(E^{\mathrm{true}}_{\mathrm{trigger}})}{N_i(E^{\mathrm{true}}_{\mathrm{thrown}})}$$

3-fold trigger efficiency

100% above $10^{19.3}$ eV

FAST
Fluorescence detector Array of Single-pixel Telescopes

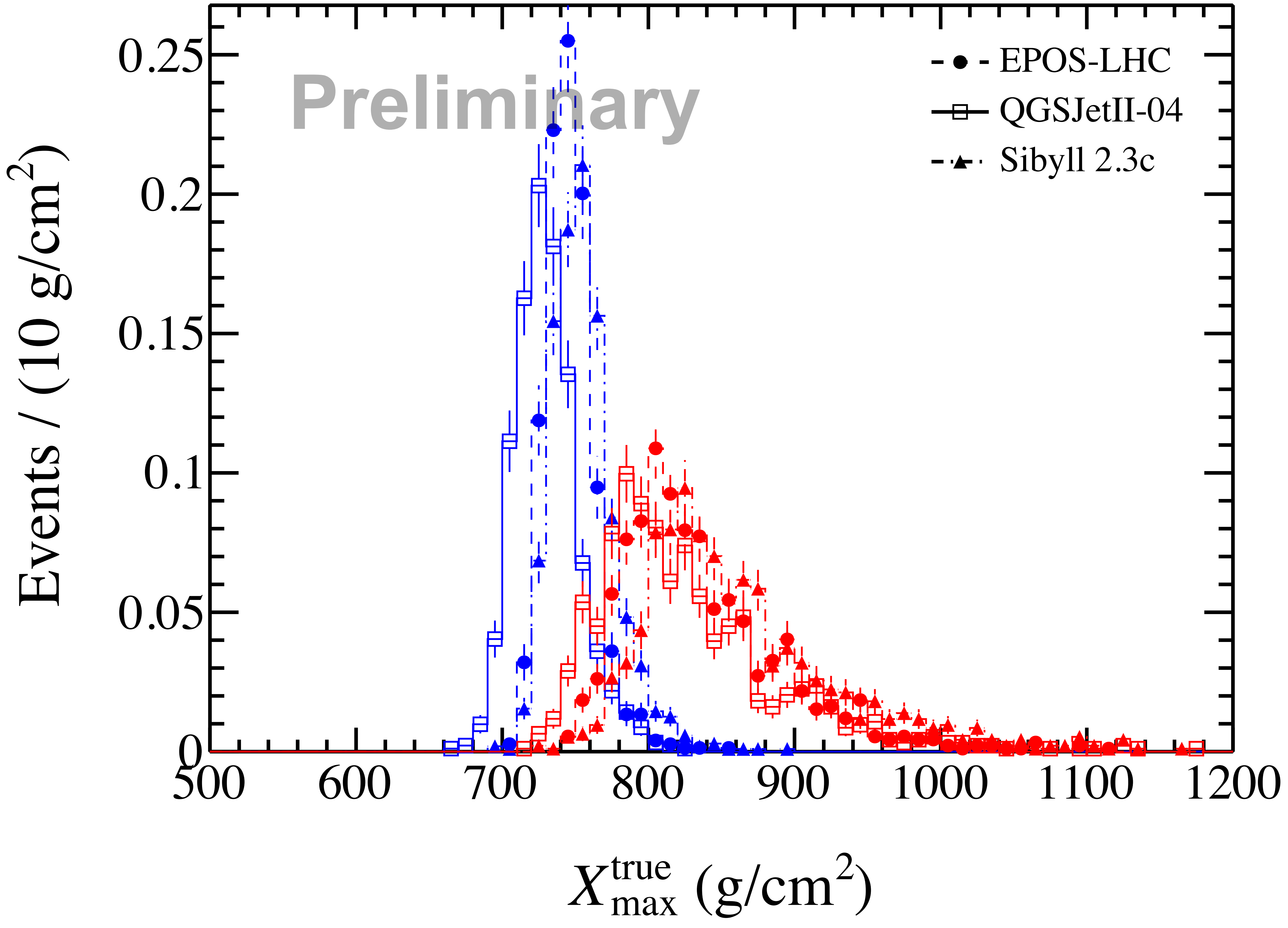
Resolution at 40 - 50 EeV (Proton, EPOS-LHC)



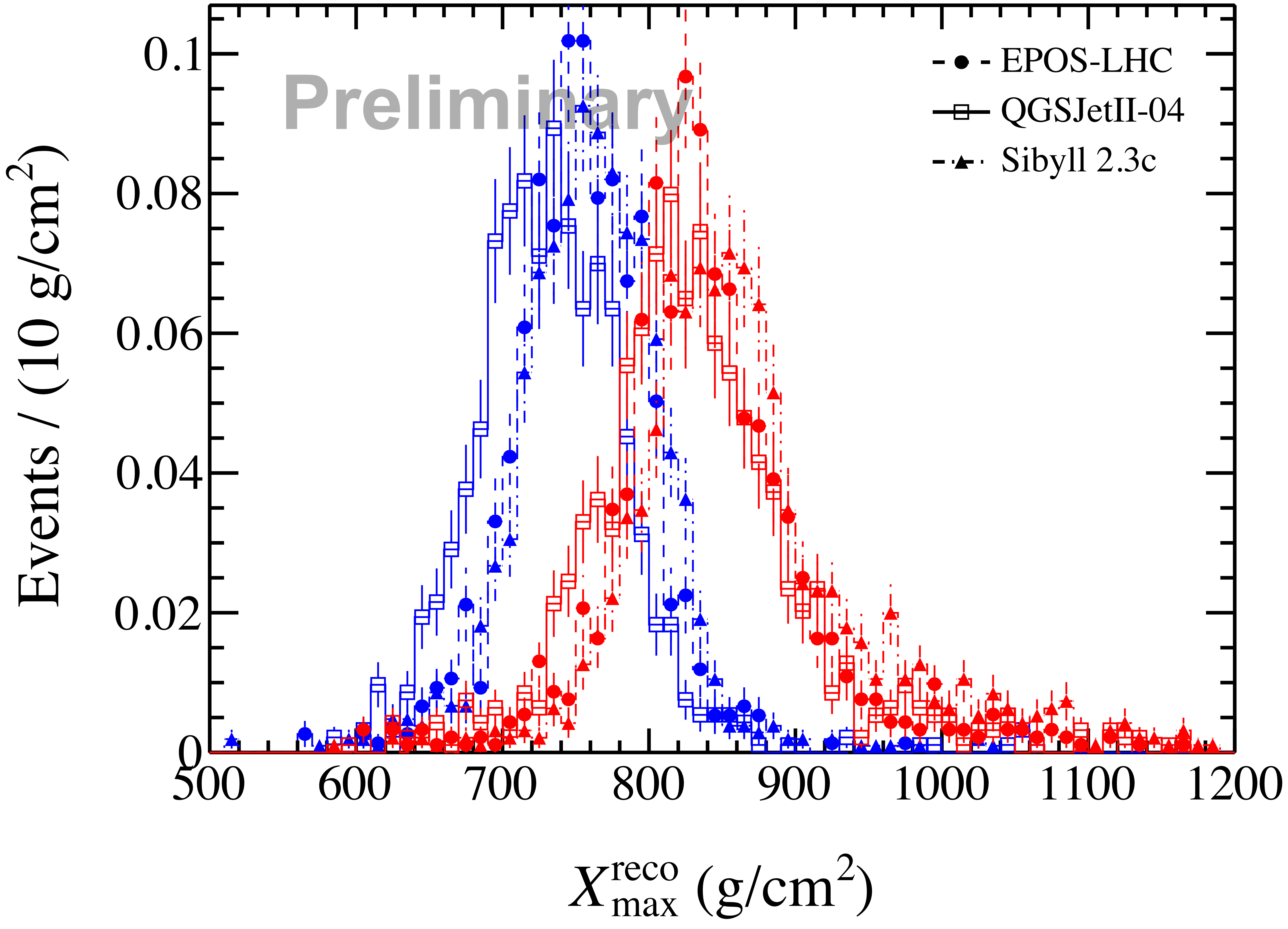
- Arrival direction: 4.2 degrees, Core: 465 m, Energy: 8% Xmax: 30 g/cm² (without quality cuts)

Reconstructed Xmax distributions at 40 - 50 EeV

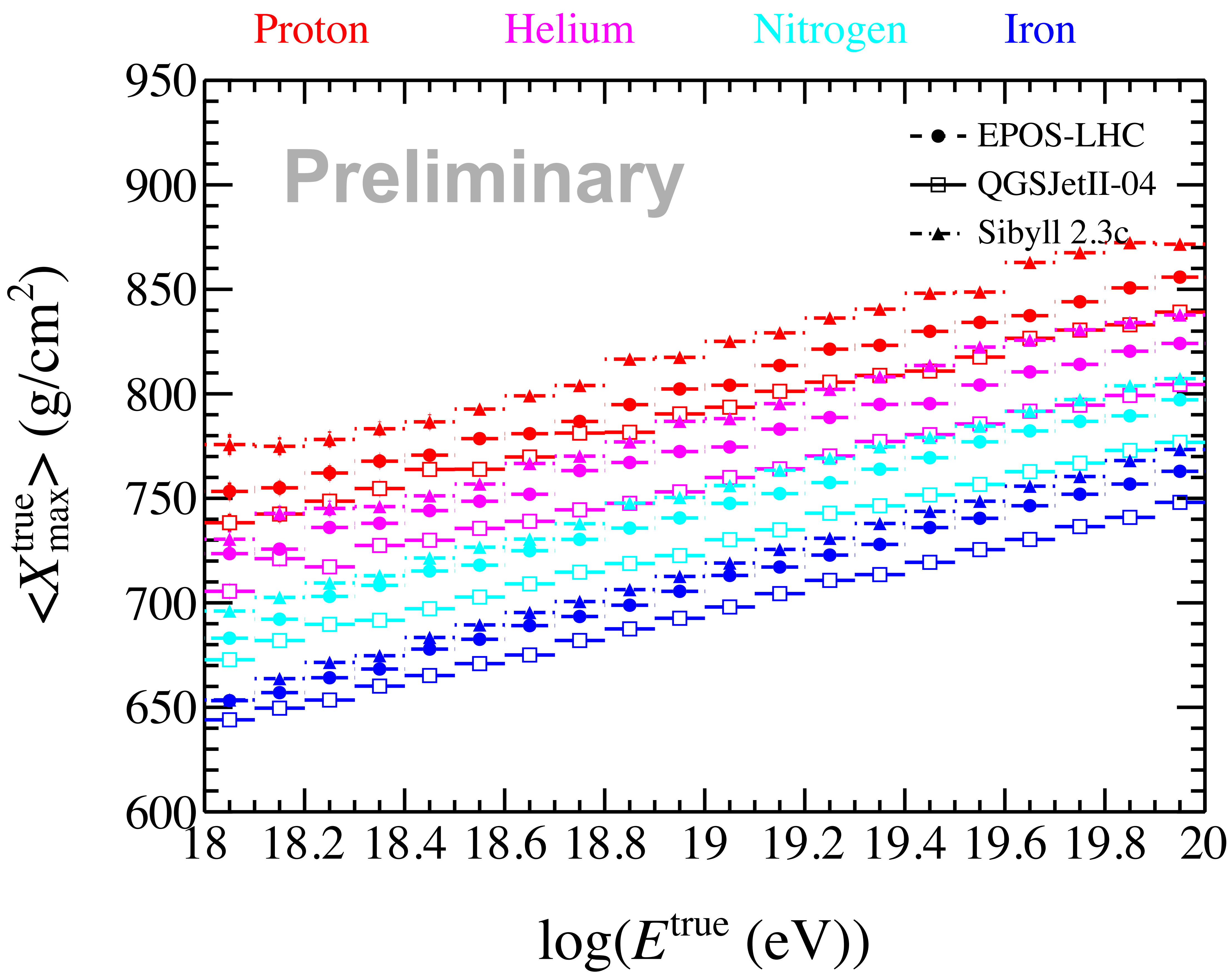
True

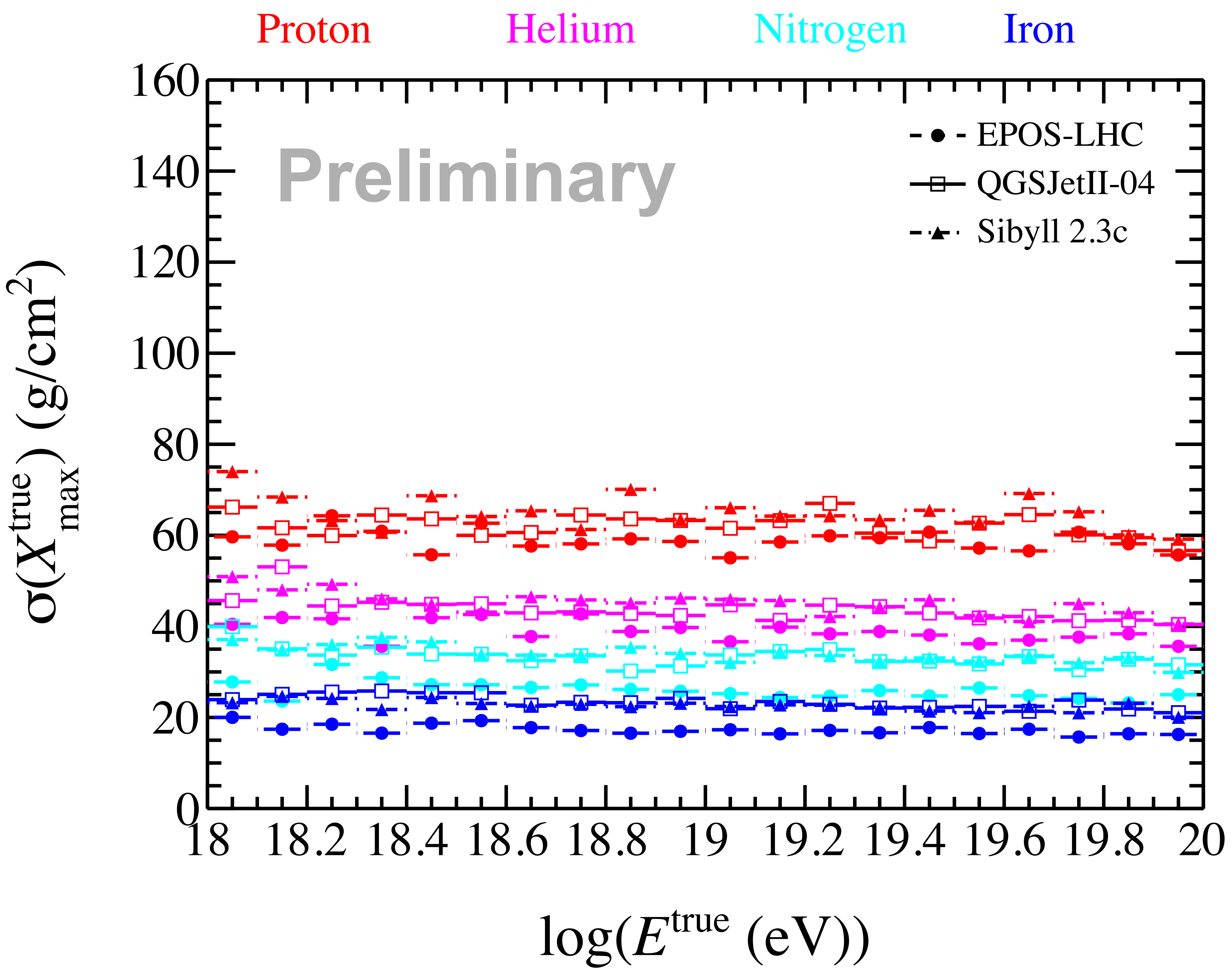


Reconstructed

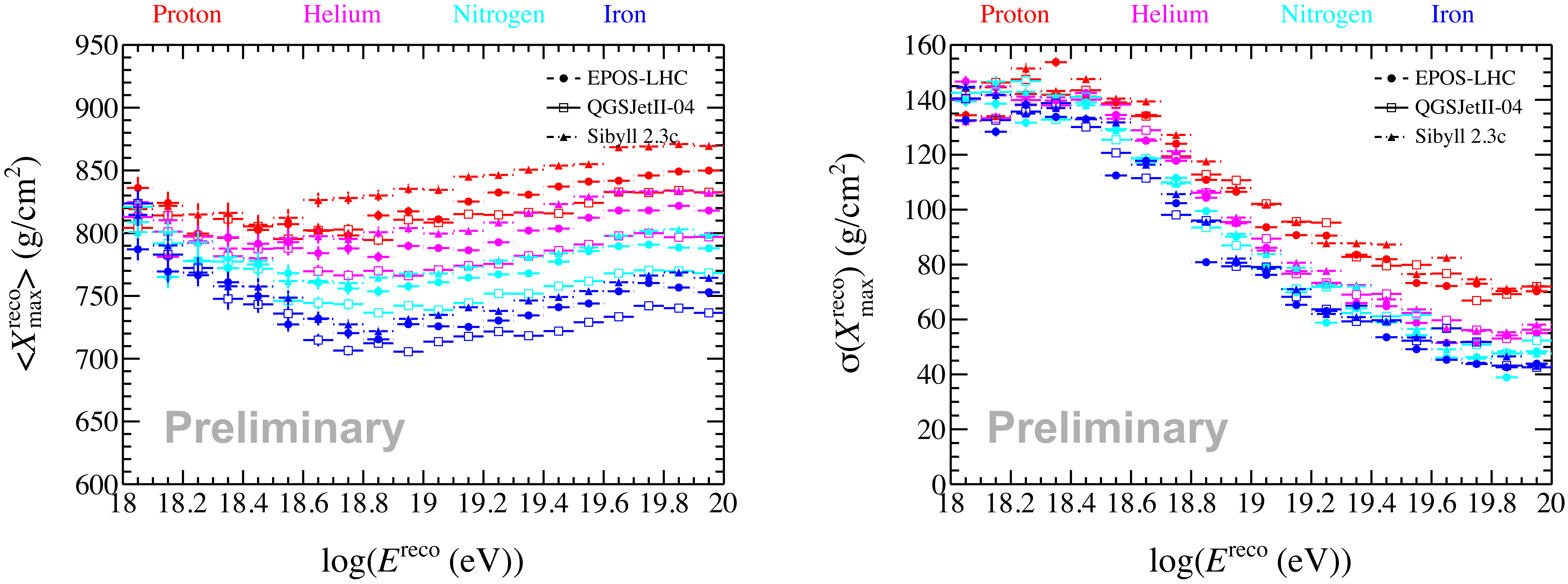


True Xmax rails





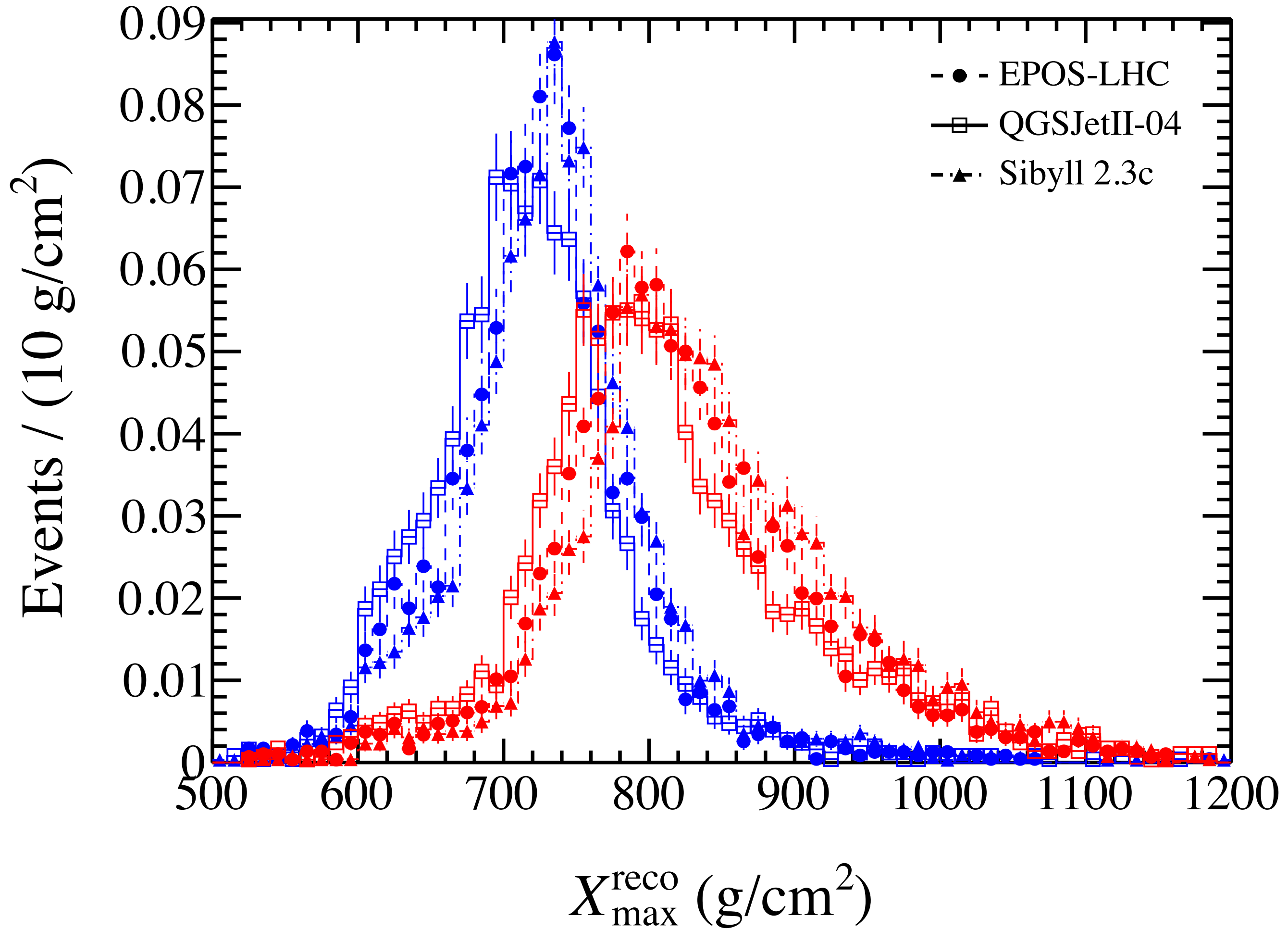
Reconstructed Xmax rails



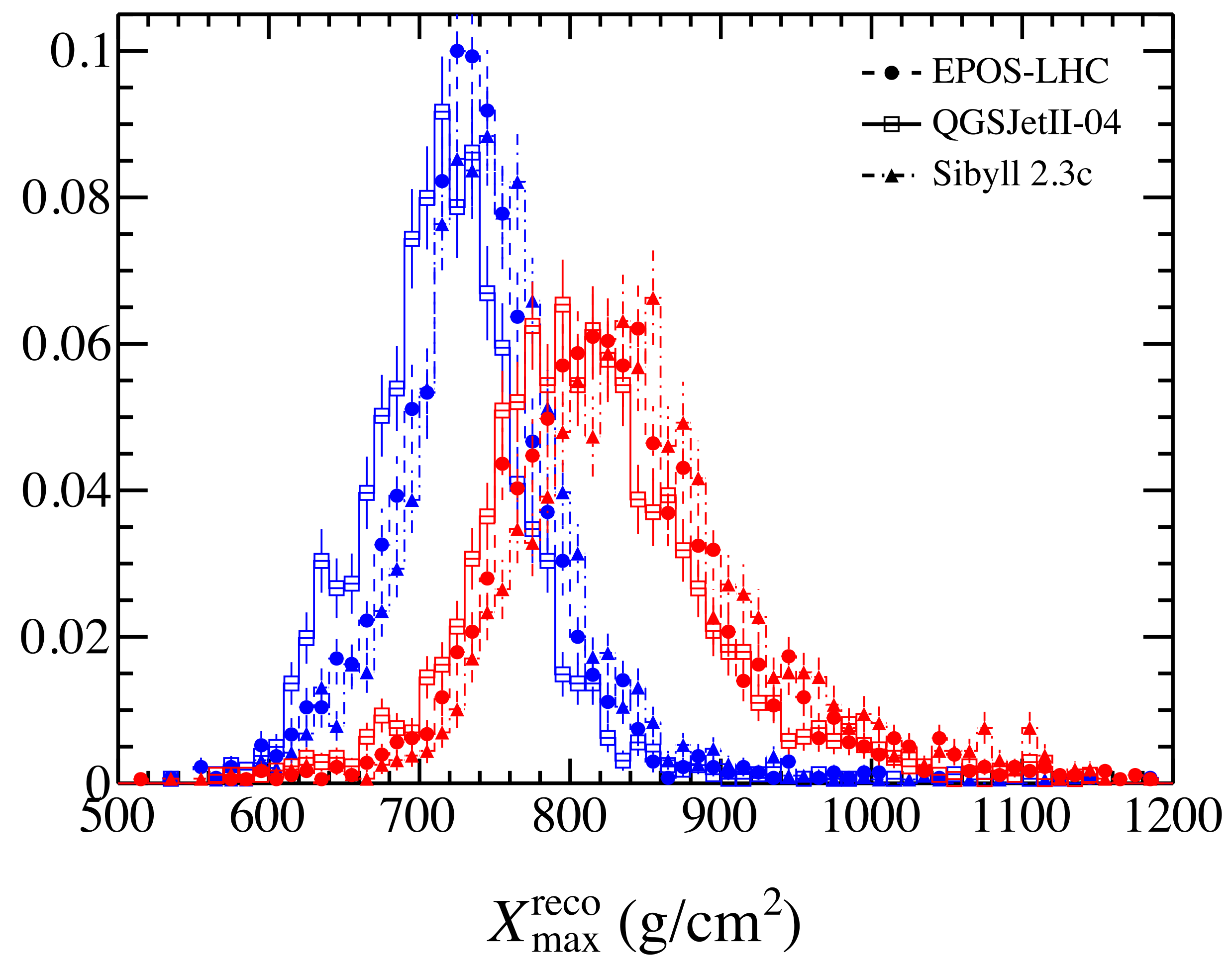
FAST
Fluorescence detector Array of Single-pixel Telescopes

Reconstructed Xmax distributions (Preliminary)

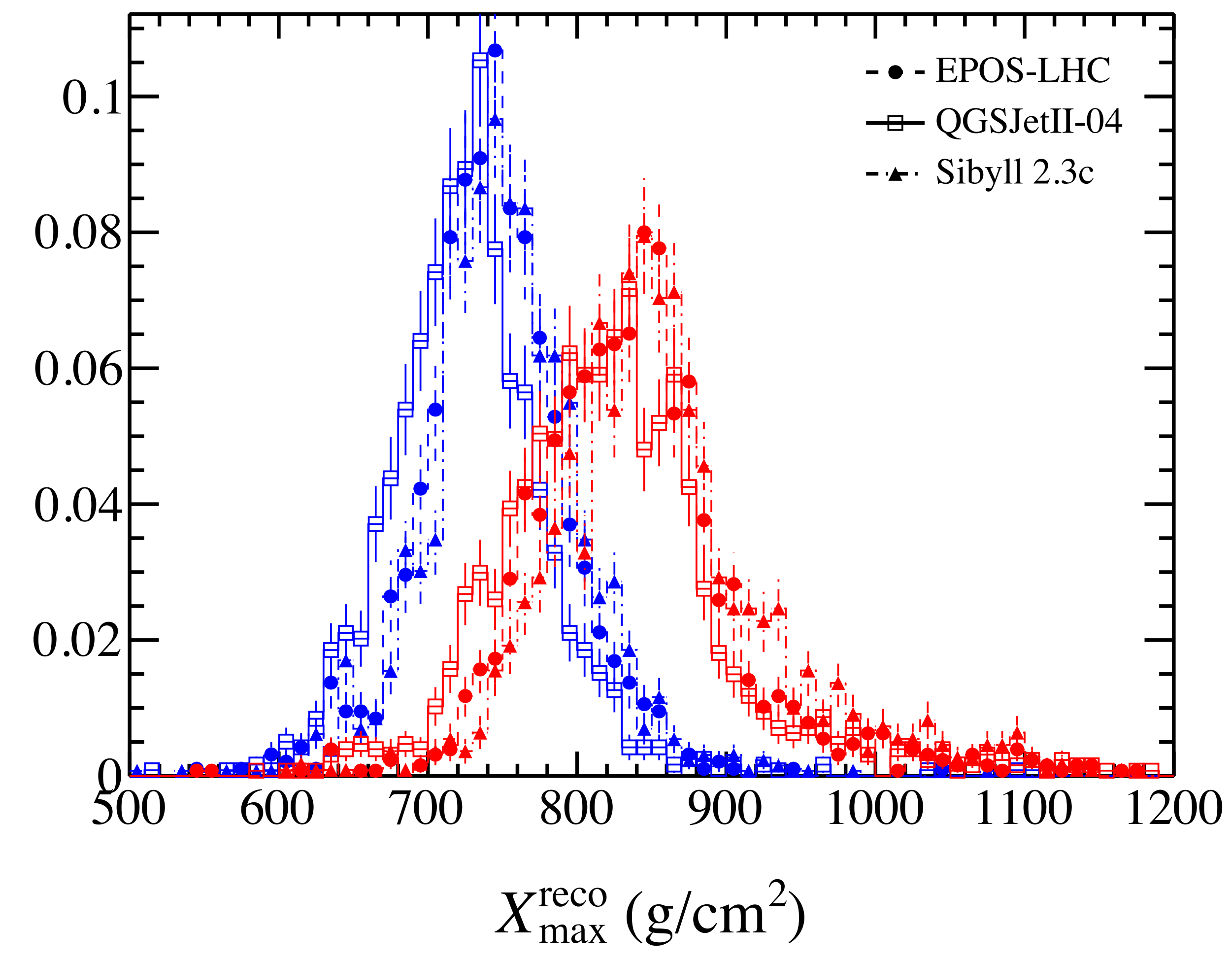
10 - 20 EeV



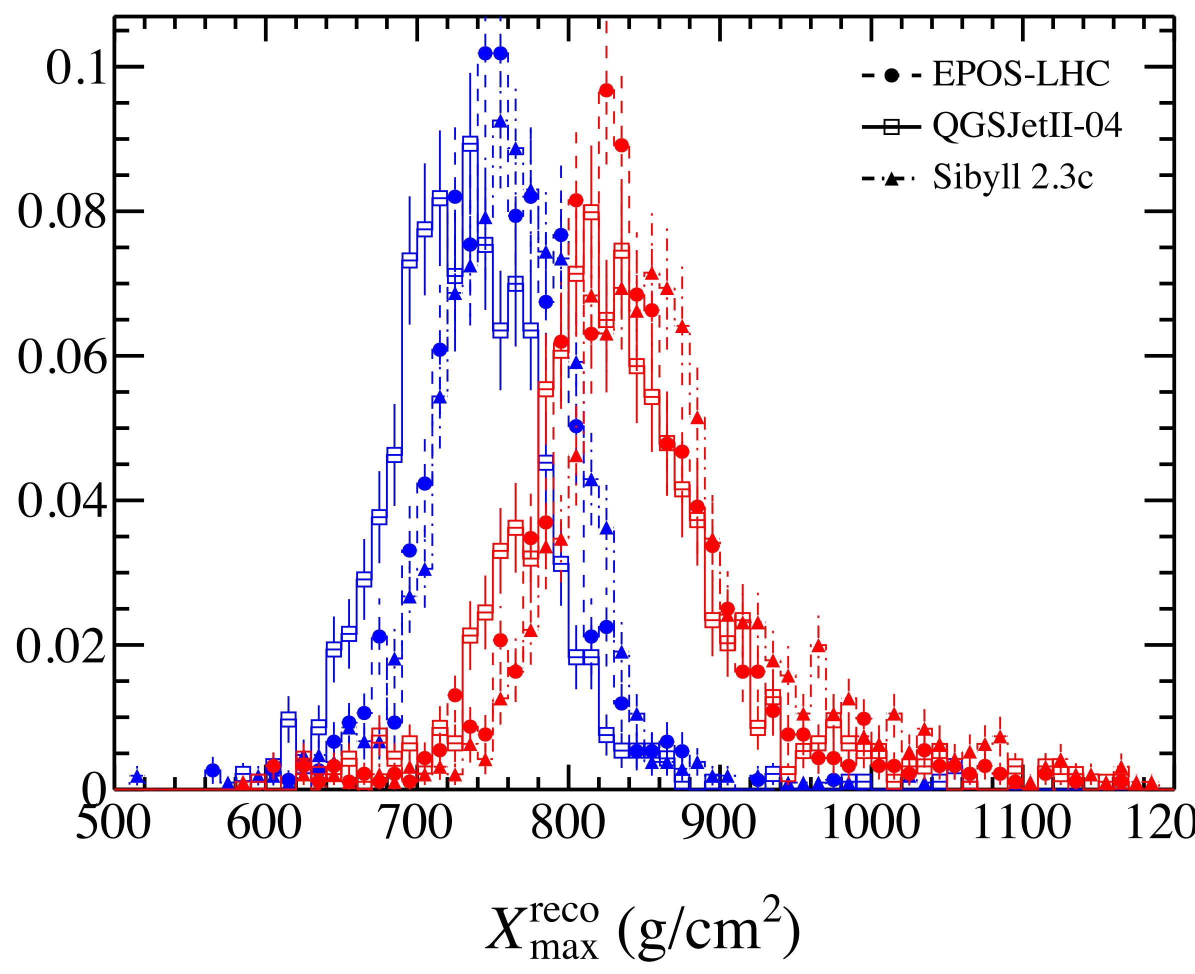
20 - 30 EeV



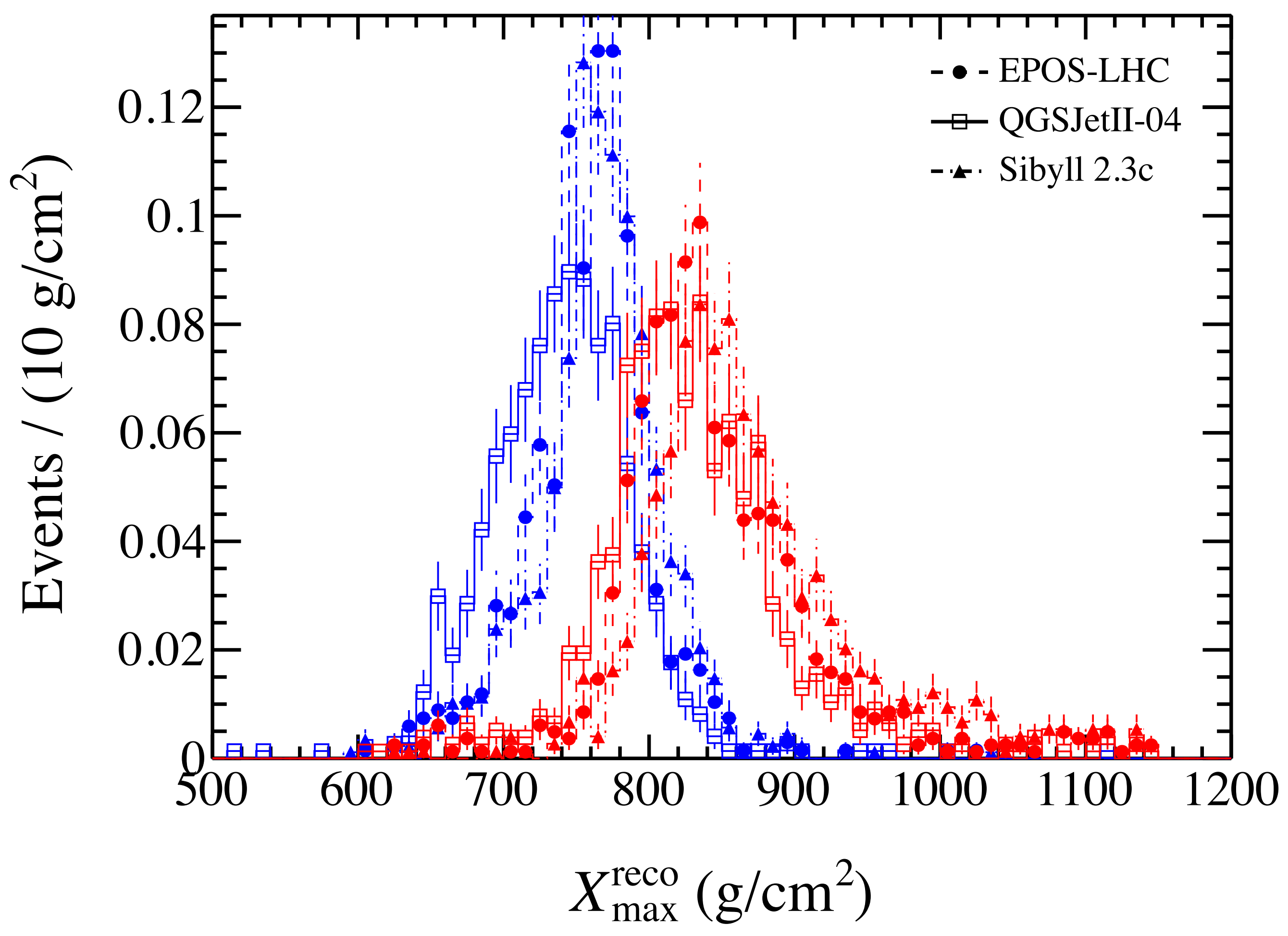
30 - 40 EeV



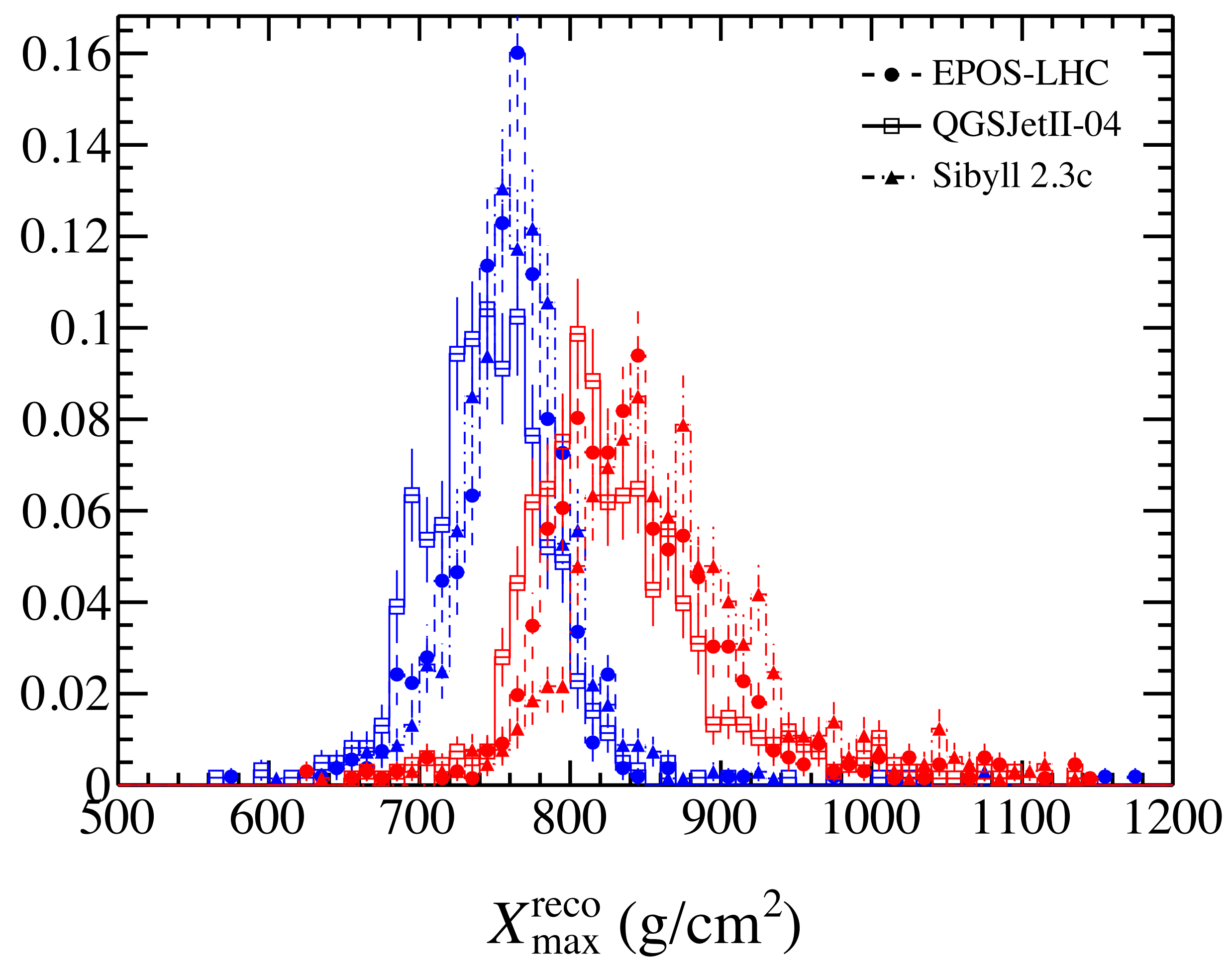
40 - 50 EeV



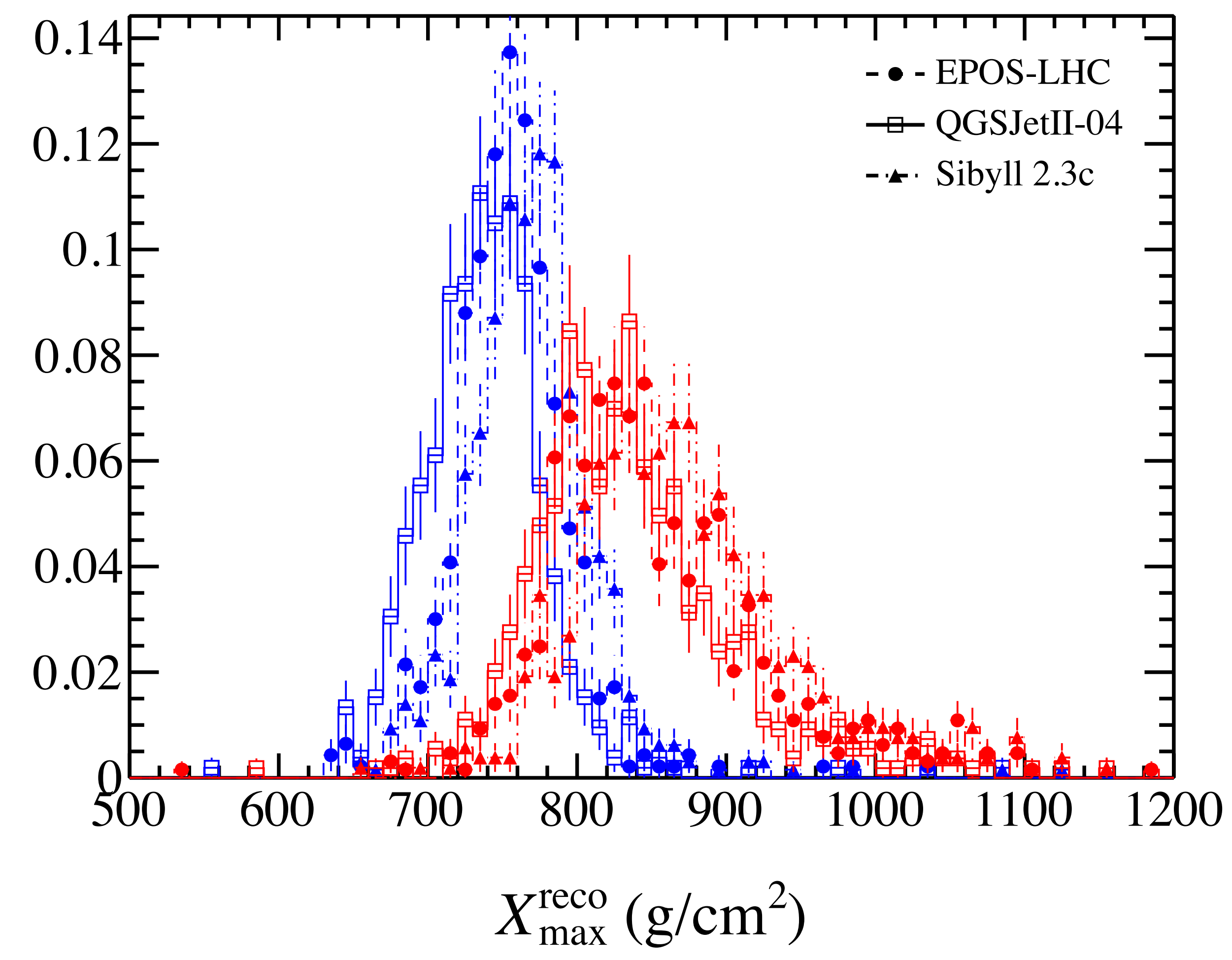
50 - 60 EeV



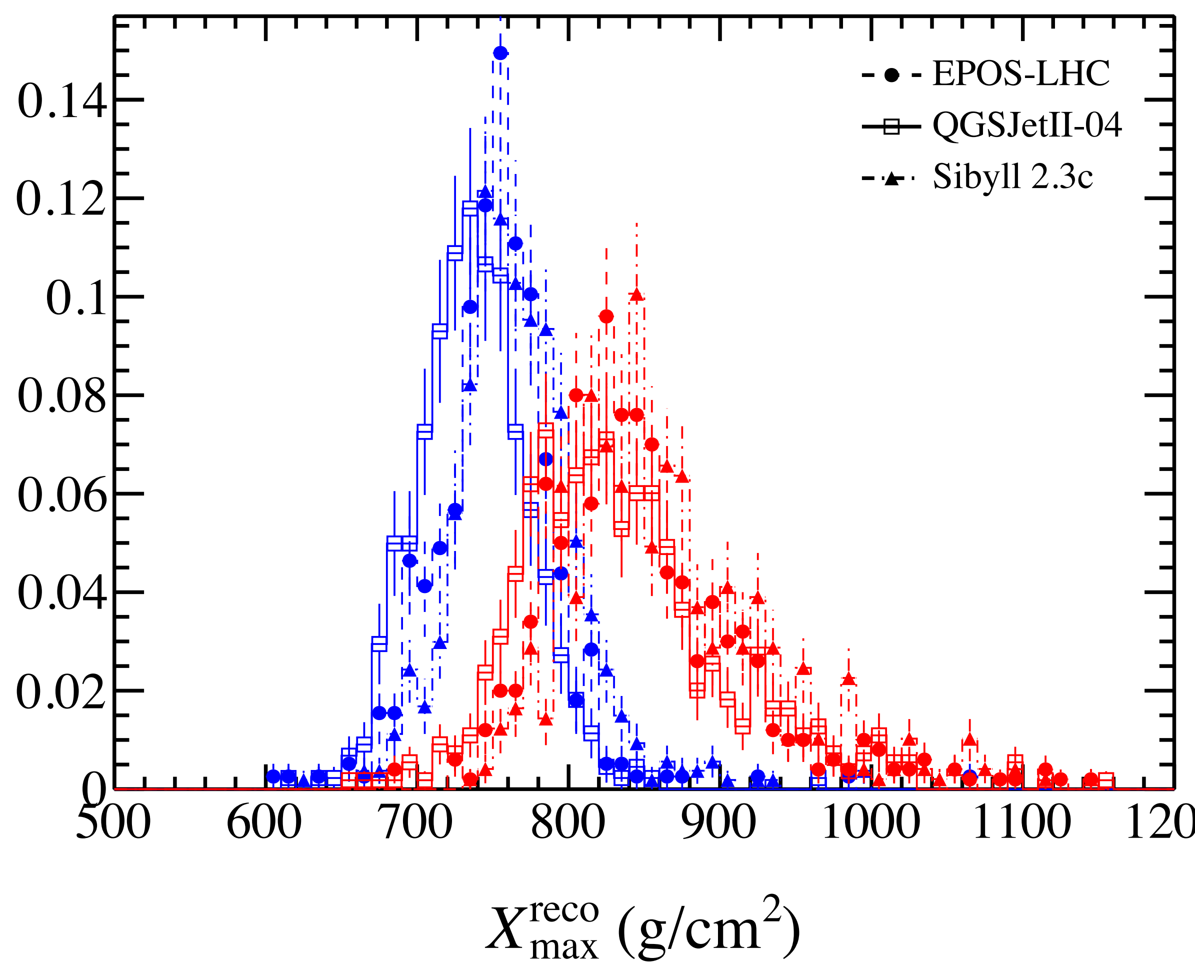
60 - 70 EeV



70 - 80 EeV



80 - 90 EeV



A lot of remaining works to optimize quality cuts, neural network, trigger condition....

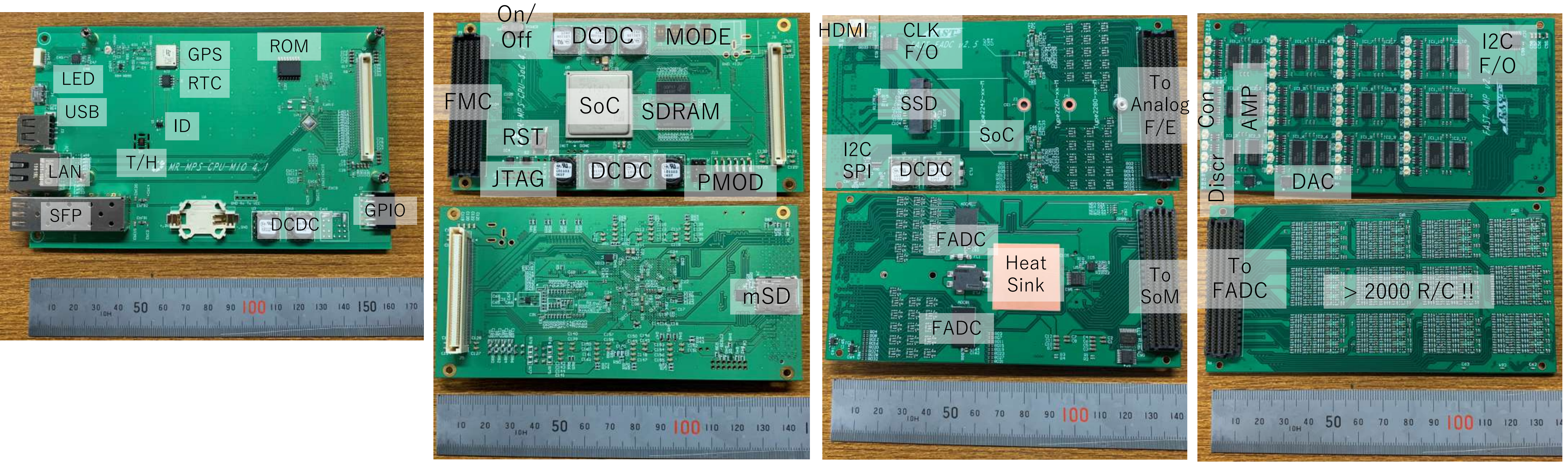
Fluorescence detector Array of Single-pixel Telescopes

Electronics and PMT calibration in laboratory

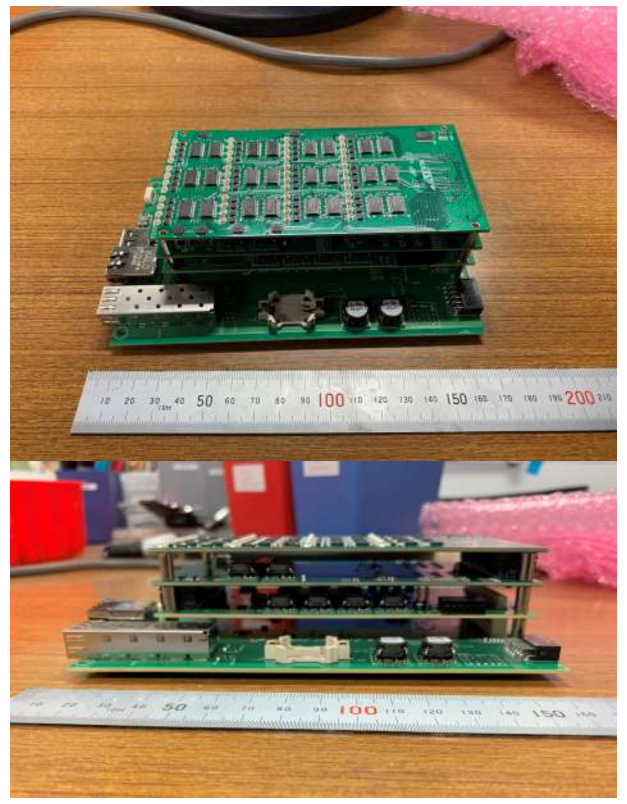
New electronics development

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

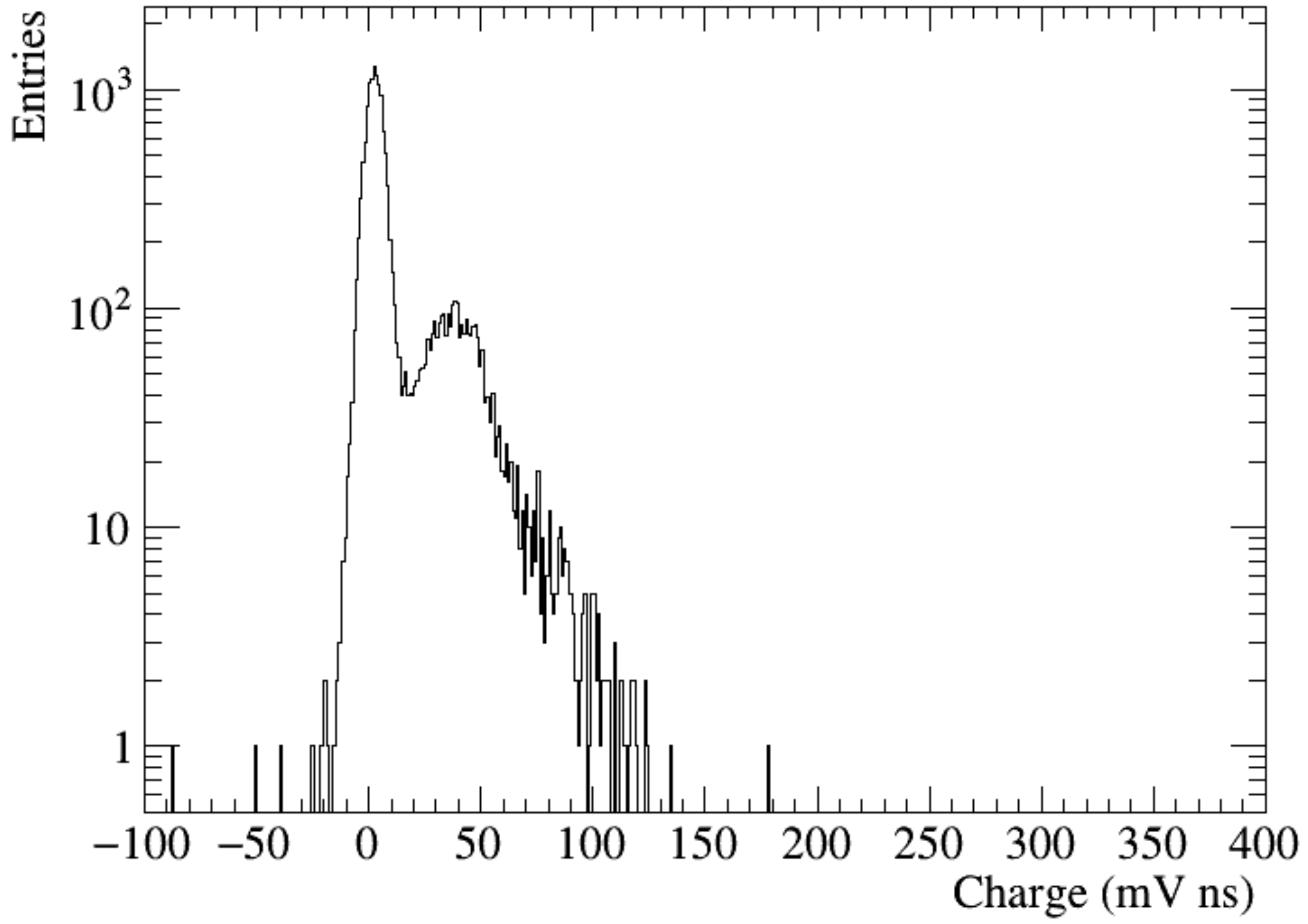
MIO SoC FADC AMP



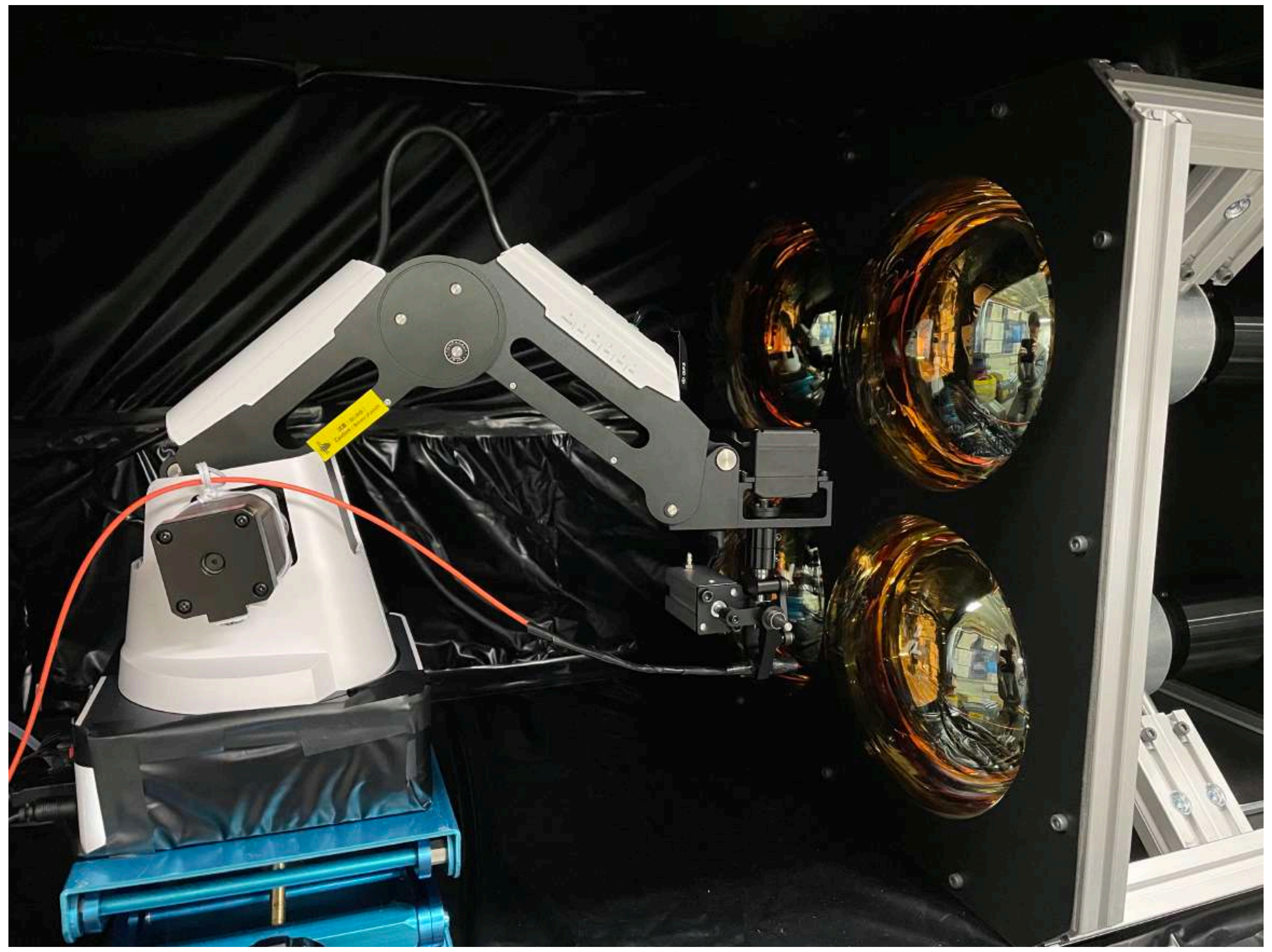
Assembly!

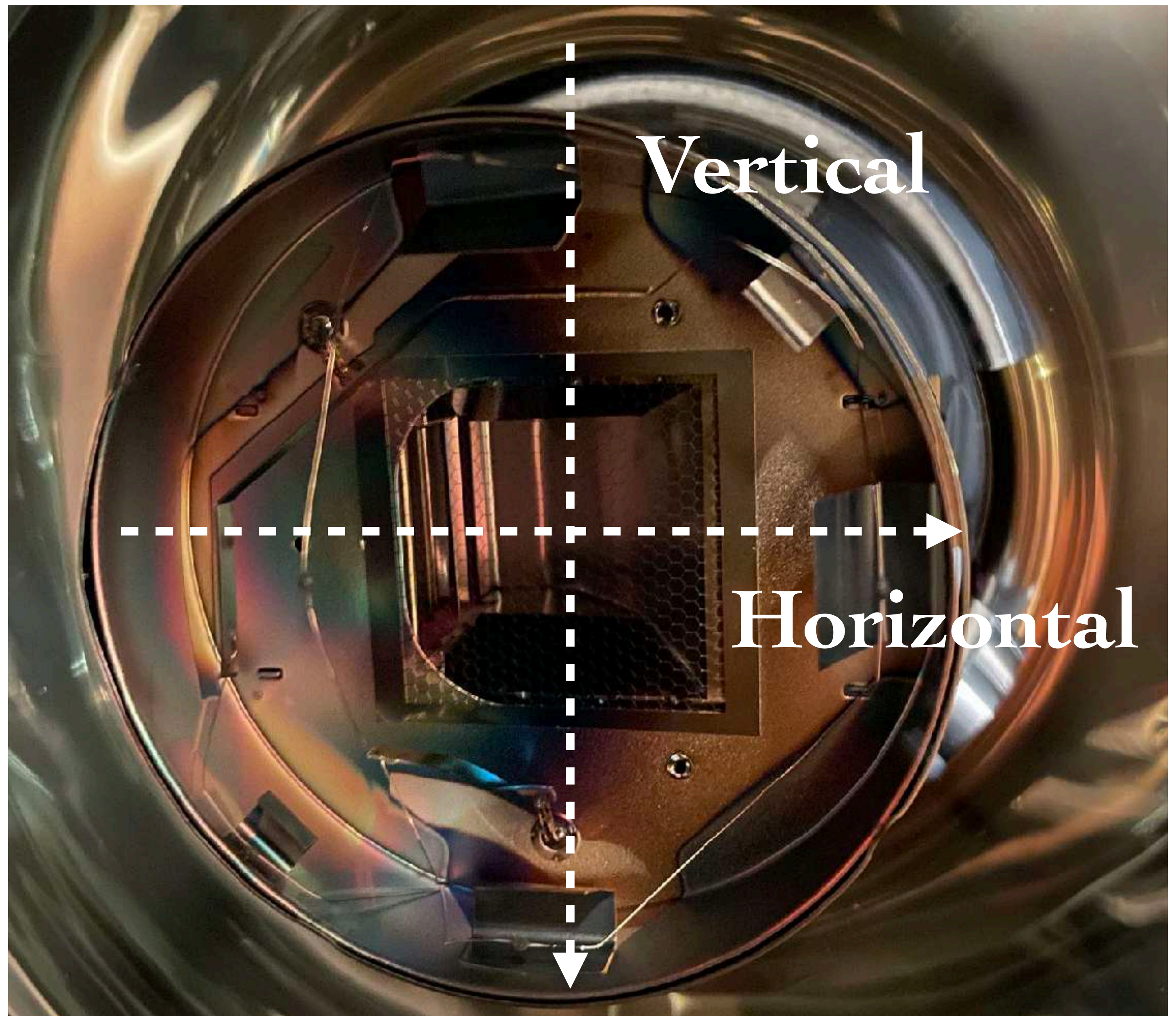


Single Photo Electron

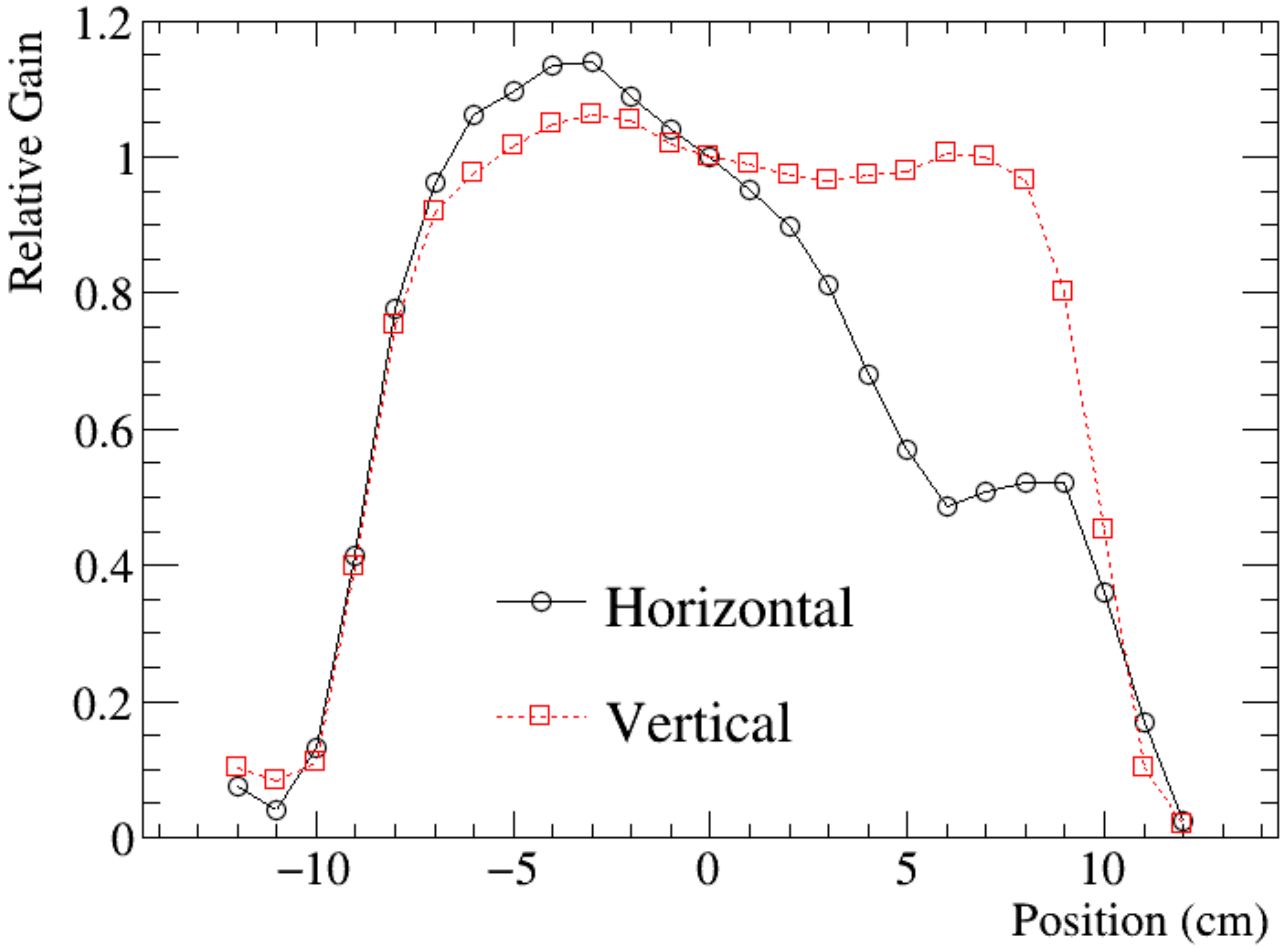


Robot arm (0.2 mm accuracy)





Non-uniformity

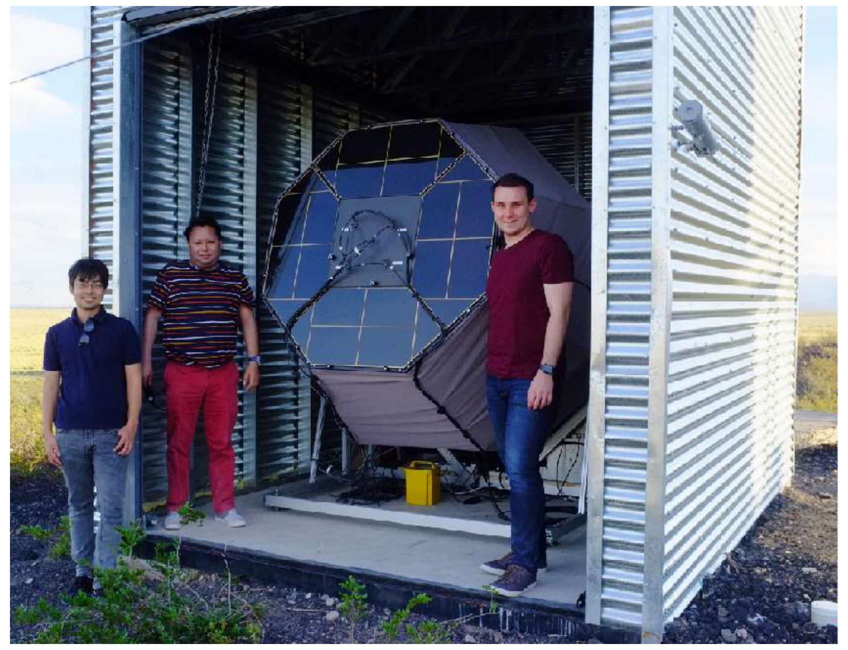


Summary and future plan

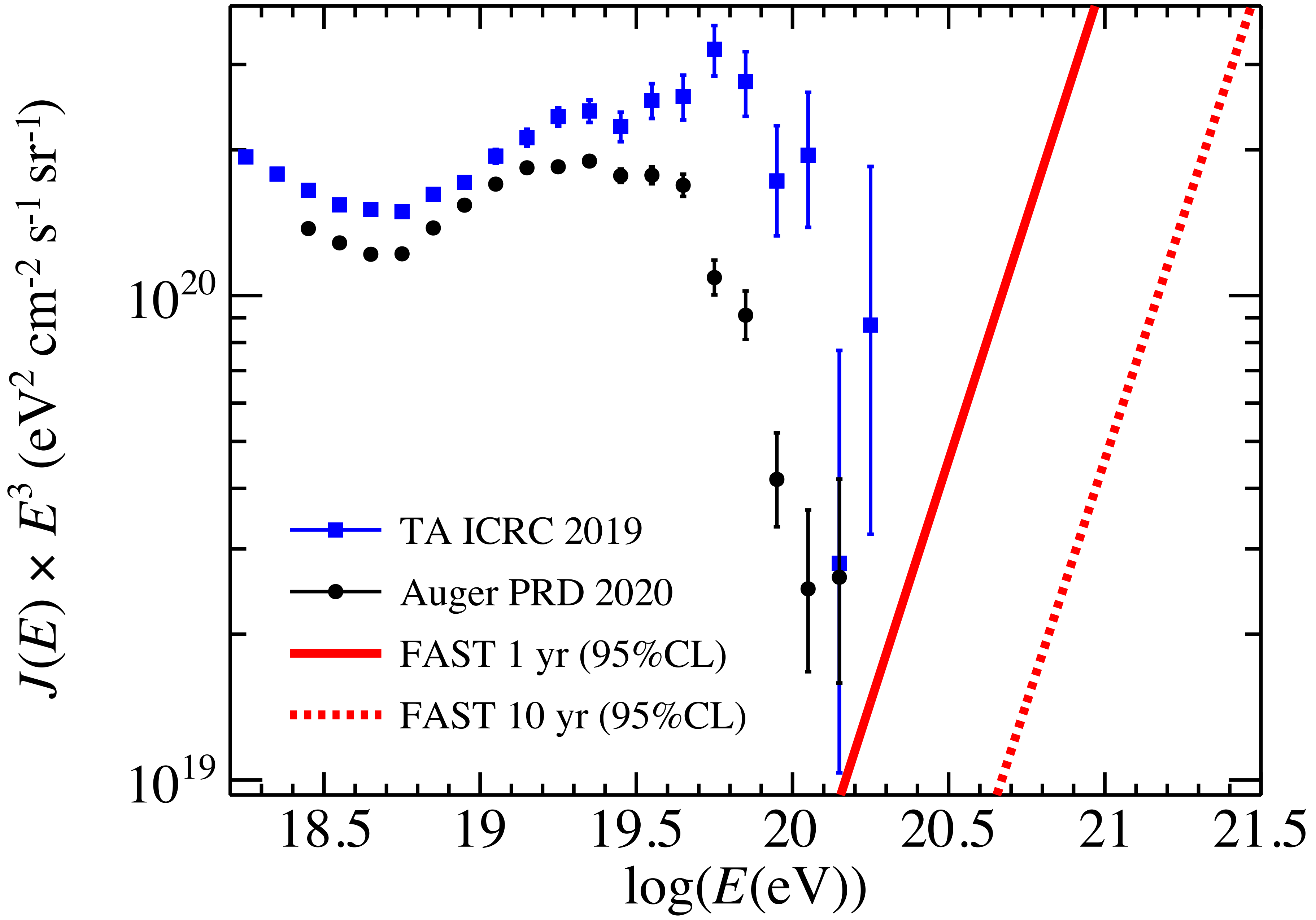
- Fluorescence detector Array of Single-pixel Telescopes (FAST)
  - Low-cost fluorescence telescope array
  - Promising concept as next-generation cosmic ray observatory to fulfill requirements
  - Anisotropy with mass composition sensitivity
- Preliminary performance estimation
  - 100% efficiency above $10^{19.3}$ eV
  - Preliminary resolution of neural network reconstruction at 40 EeV
    - Arrival direction: 4.2 deg, Core: 465 m
    - Energy: 8%, Xmax: 30 g/cm^2 ($\Delta \ln A \sim 1$)
- 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