TA実験サイトでの新型大気蛍光望遠鏡による極高エネルギー宇宙線観測

Observing ultra-high energy cosmic rays with new fluorescence detectors at Telescope Array site

Toshihiro Fujii (OMU, NITEP, toshi@omu.ac.jp)

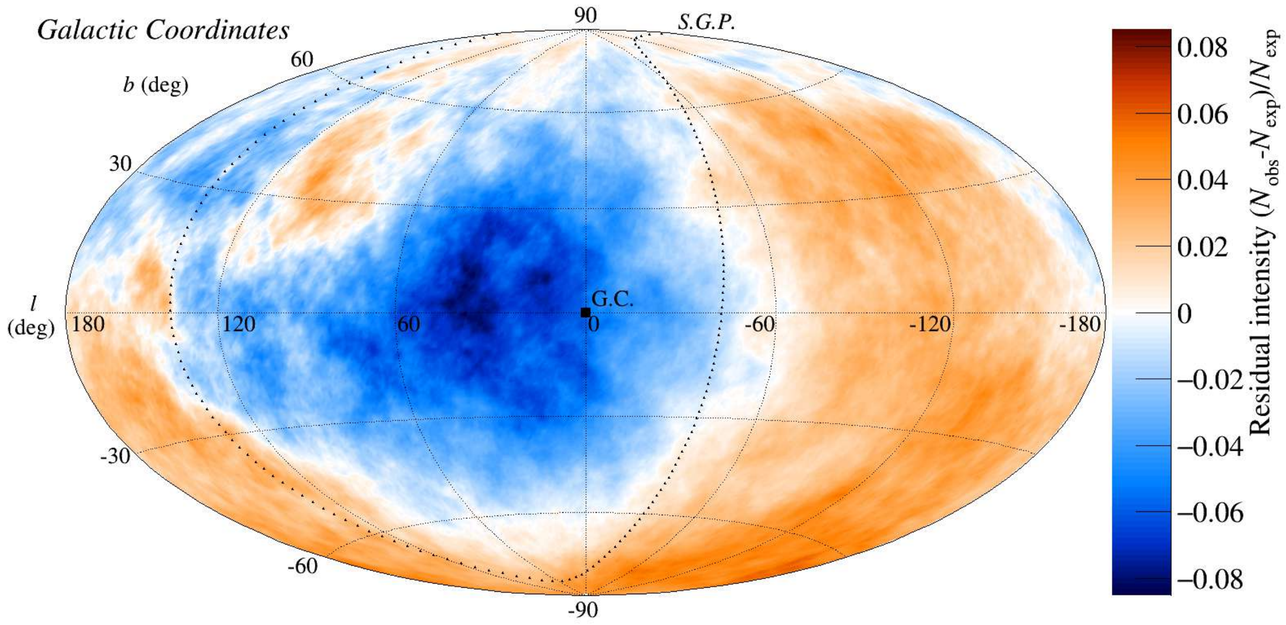
Justin Albury, Jose Bellido, Fraser Bradfield, Ladislav Chytka, John Farmer, Petr Hamal, Pavel Horvath, Miroslav Hrabovsky, Hiromu Iwasaki, Vlastimil Jilek, Jakub Kmec, Jiri Kvita, Max Malacari, Dusan Mandat, Massimo Mastrodicasa, John Matthews, Stanislav Michal, Hiromu Nagasawa, Hiroki Namba, Marcus Niechciol, Libor Nozka, Miroslav Palatka, Miroslav Pech, Paolo Privitera, Shunsuke Sakurai, Francesco Salamida, Petr Schovanek, Radomir Smida, Zuzana Svozilikova, Stan Thomas, Akimichi Taketa, Kenta Terauchi, Petr Travnicek, Martin Vacula (FAST Collaboration)

February 21, 2024, ICRR Inter-University Research Program FY2023

GRADUATE SCHOOL OF SCIENCE OSAKA METROPOLITAN UNIVERSITY 1880

OMU Osaka Metropolitan University

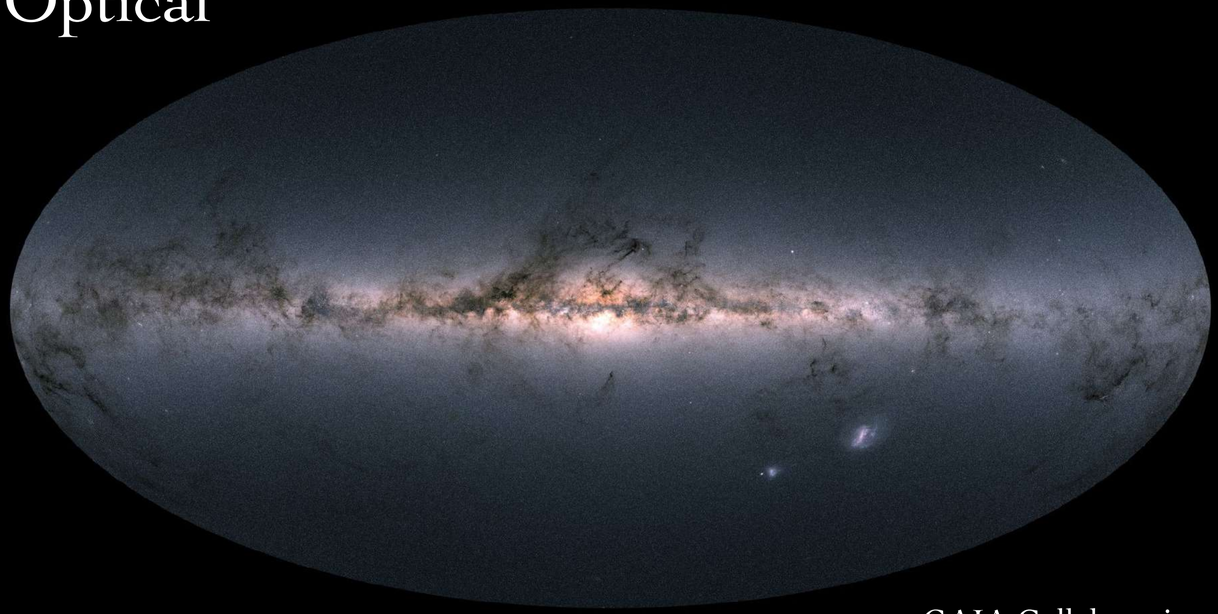
Skymap of ultra-high energy cosmic rays above 10^{19} eV



→ “Extragalactic” cosmic rays

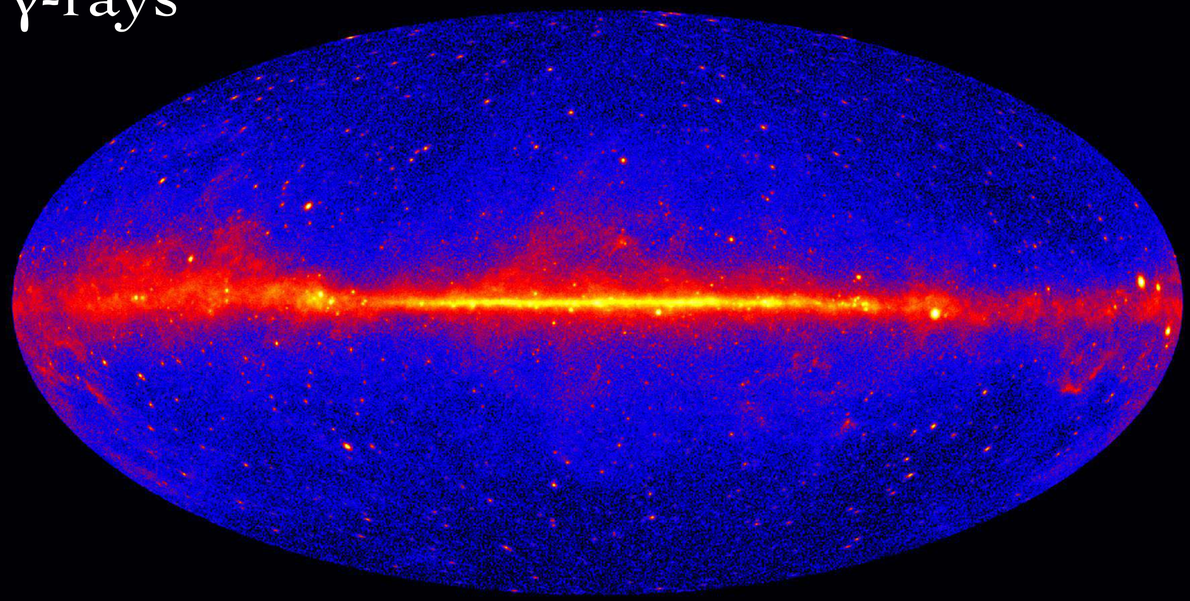
J. Biteau, TF et al., EPJ Web of Conferences 210, 01005 (2019)

Optical



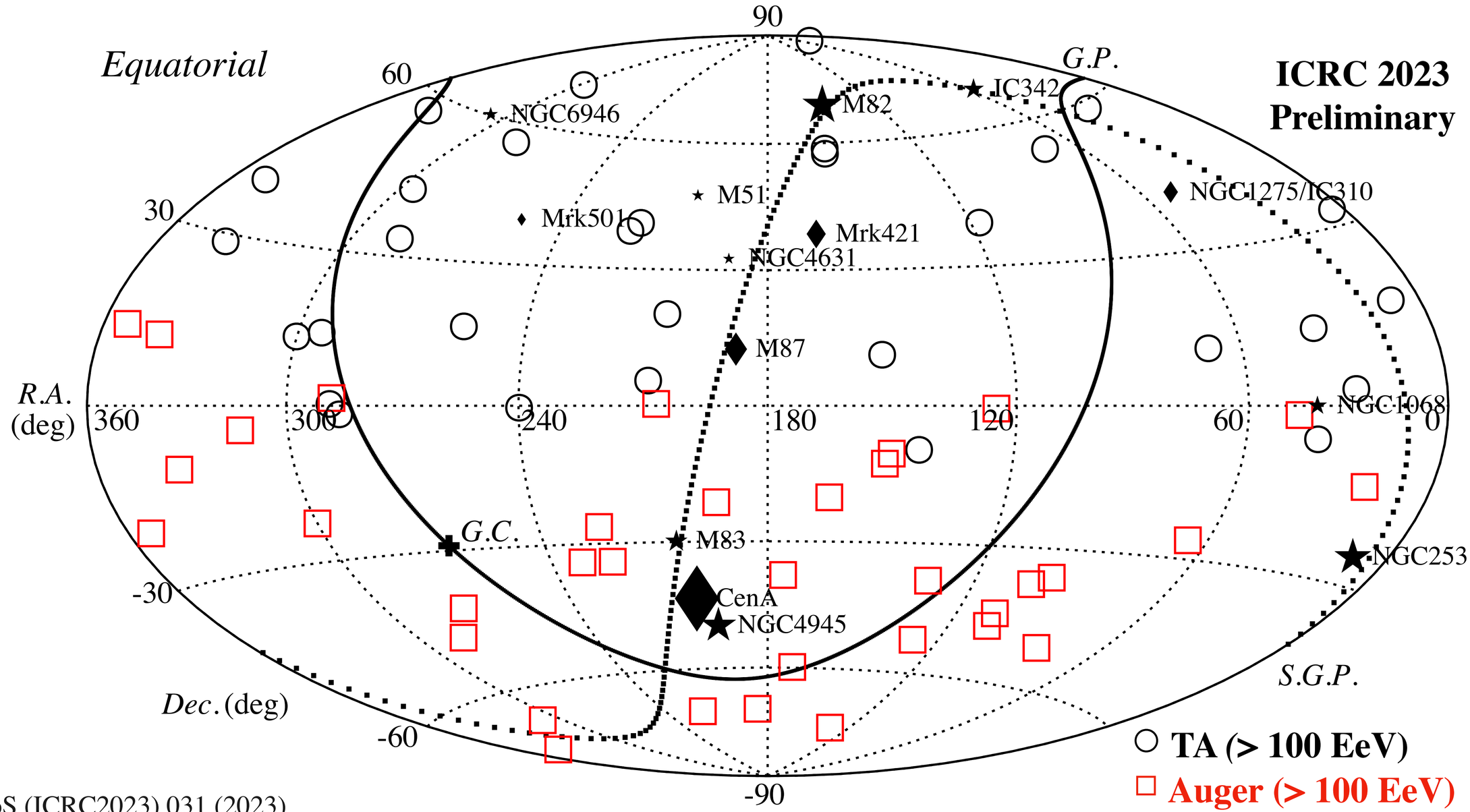
GAIA Collaboration

γ-rays



NASA/DOE/Fermi Collaboration

Need more statistics above 10^{20} eV



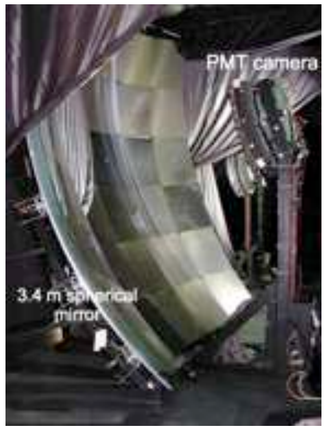
T. Fujii, PoS (ICRC2023) 031 (2023)

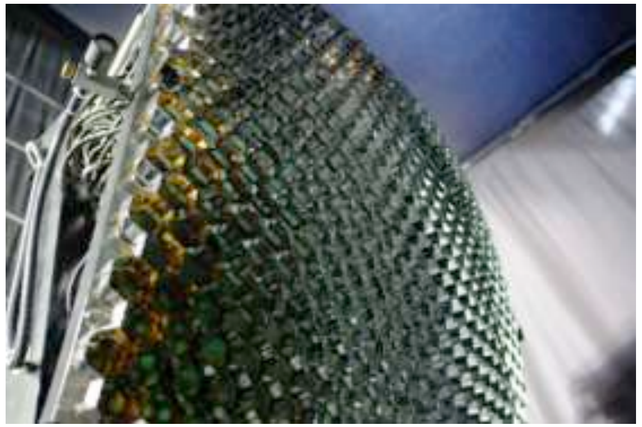
EAST Fluorescence detector Array of Single-pixel Telescopes

EAST
Fluorescence detector Array of Single-pixel Telescopes

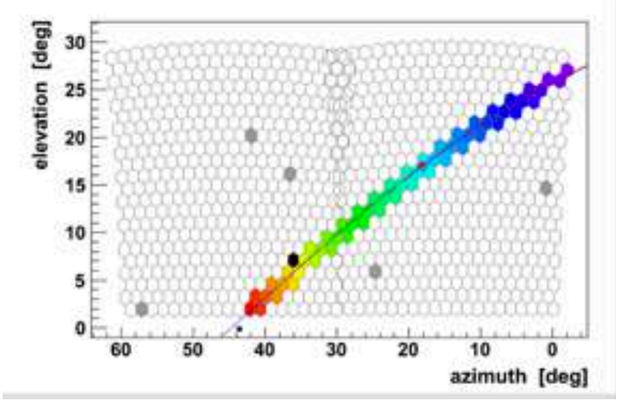
- **Target : > $10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrino and gamma rays**
  - **Huge target volume ⇒ Fluorescence detector array**

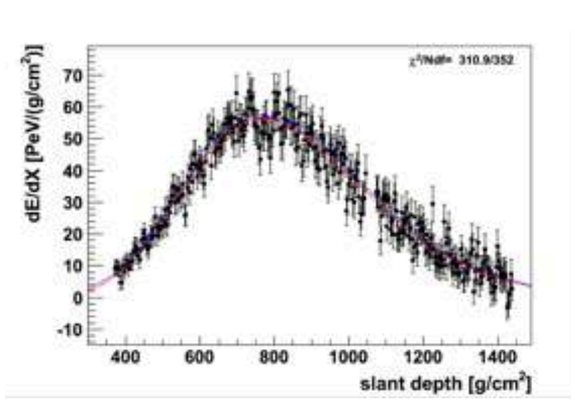
Fine pixelated camera



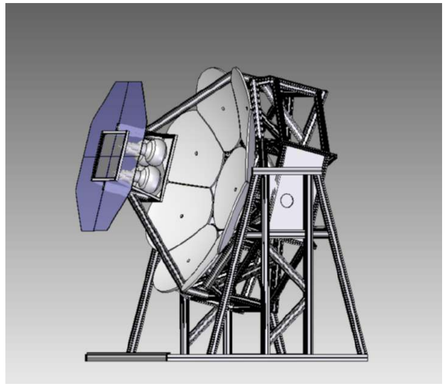


Too expensive to cover a huge area

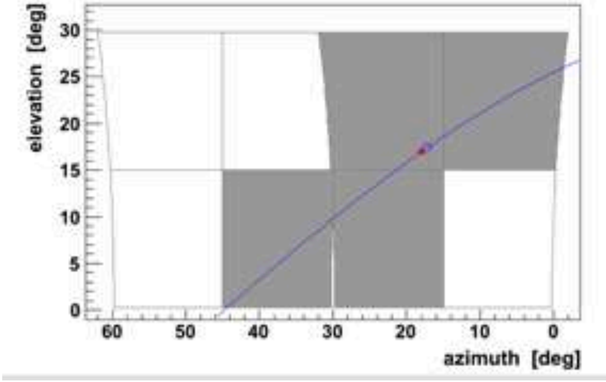


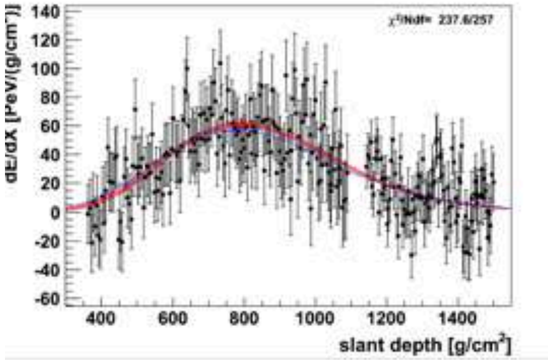


Smaller optics and single or few pixels



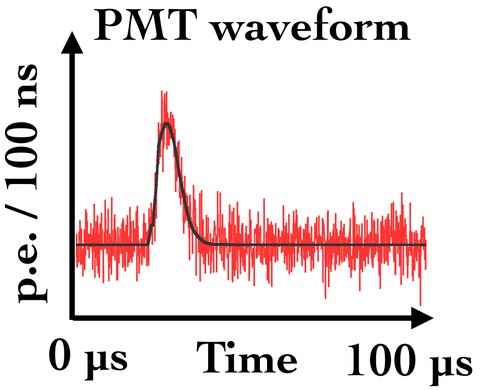
Low-cost and simplified telescope

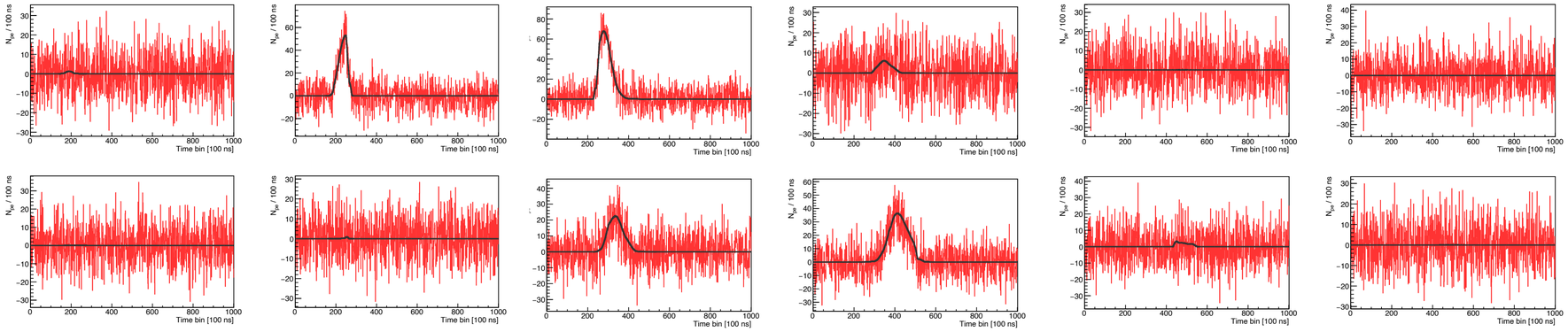


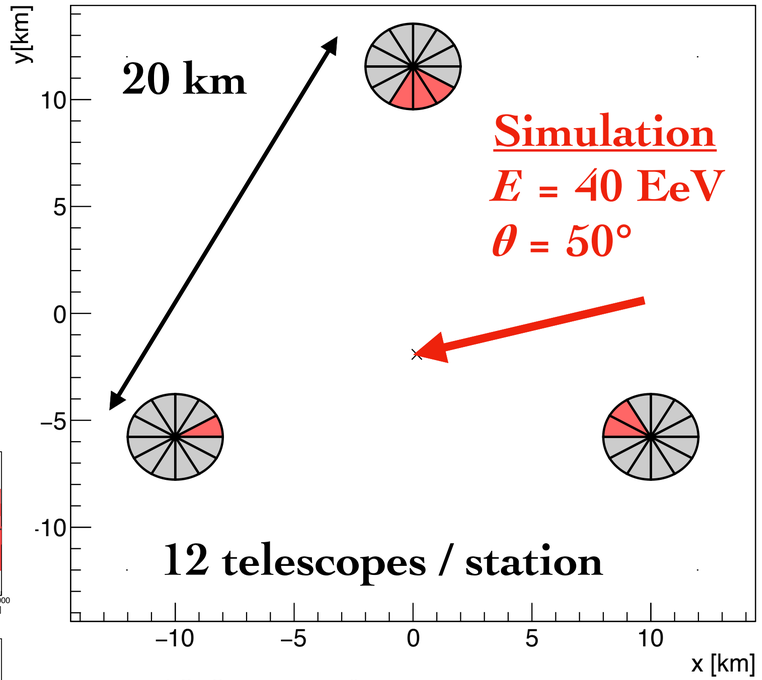


FAST Fluorescence detector Array of Single-pixel Telescopes

Fluorescence detector Array of Single-pixel Telescopes

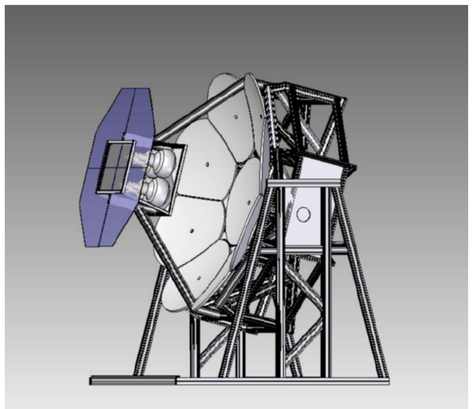






500 stations

→ 150,000 km²



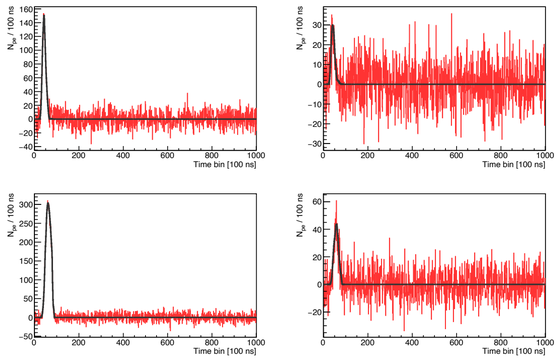
FAST telescope

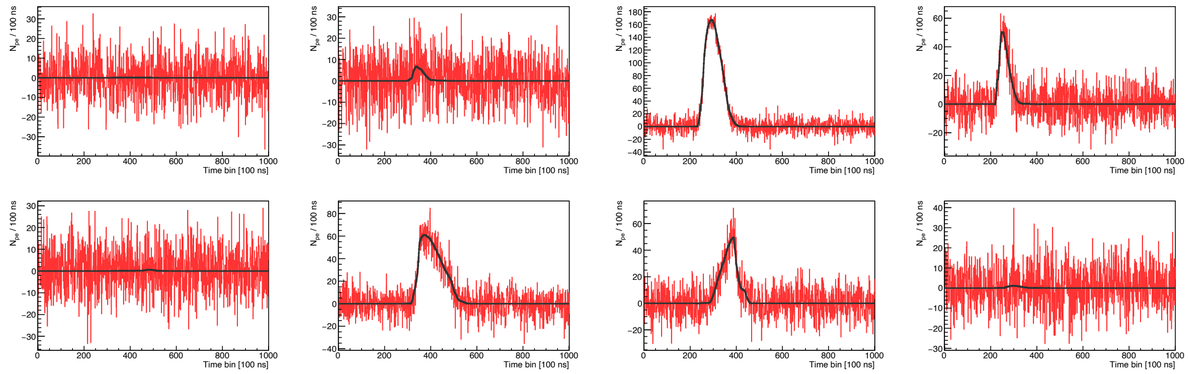
4 PMTs (20 cm diameter)

1 m² aperture (UV filter)

Segmented mirror

in 1.6 m diameter



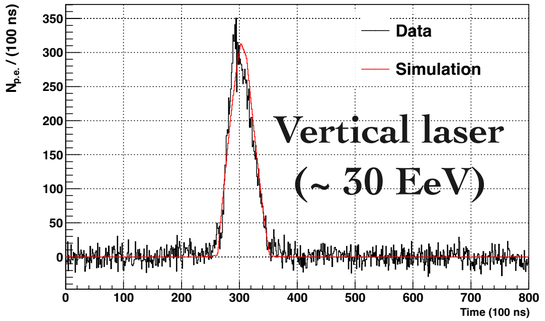


Validations of the FAST concept

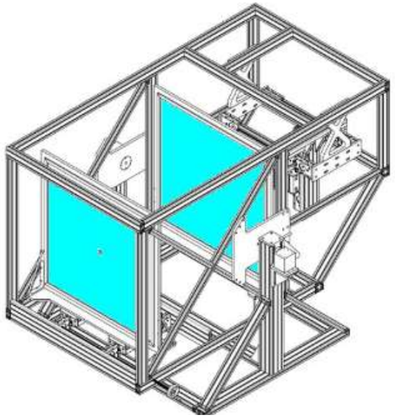
Feb. 2012

A conceptual design for a large ground array of Fluorescence Detectors

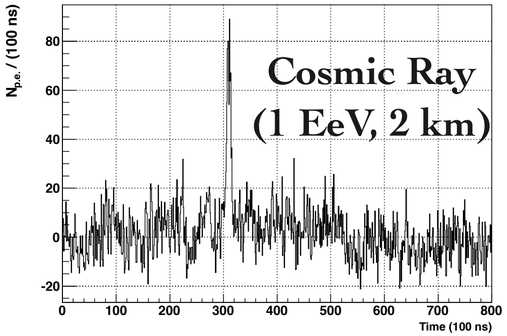
P. Privitera in **UHECR 2012**



Apr. 2014



EUSO-TA optics
+
Single-pixel camera



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

Oct. 2016

Sep. 2017

Oct. 2018

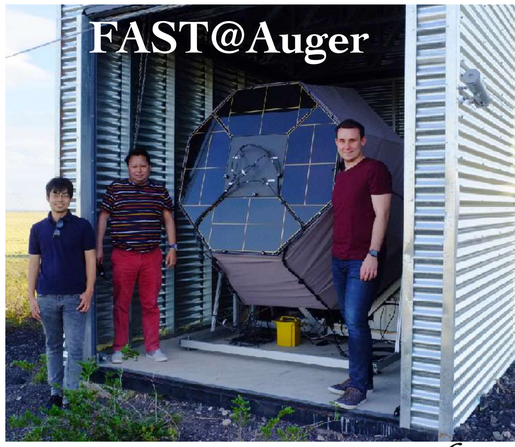
@TA

Apr. 2019

Jun. 2022

@Auger

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

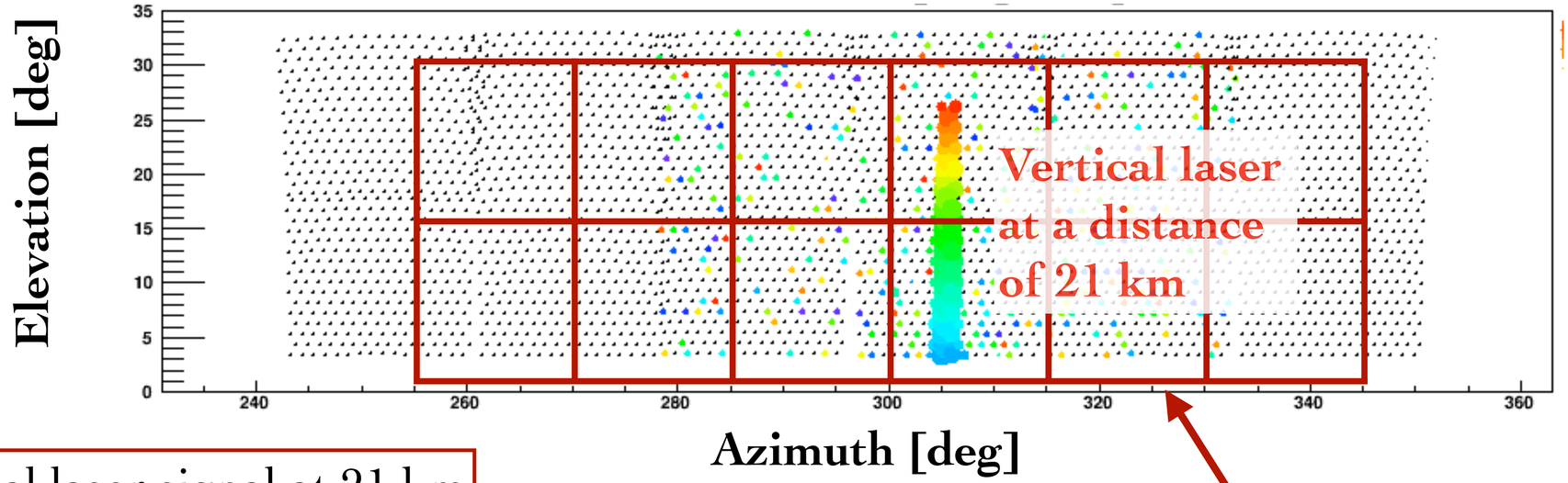


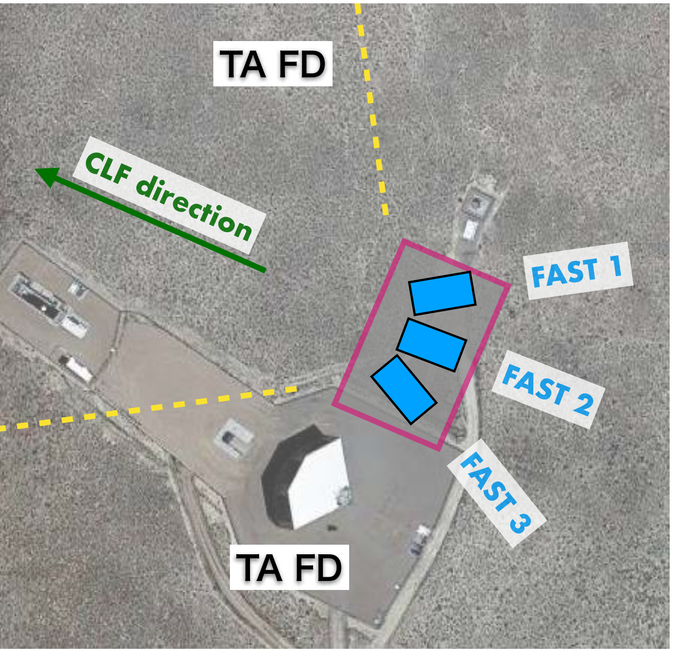
M. Malacari et al., Astroparticle Physics 119 (2020) 102430

FAST@TA observations

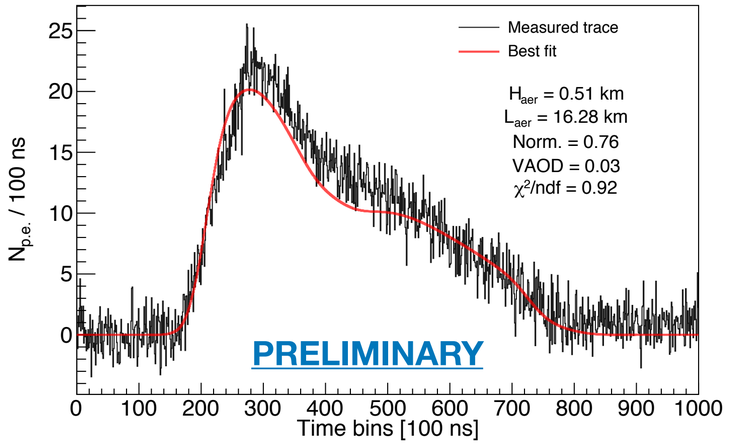
- Remote controlling observation
- Synchronized operation with external triggers from Telescope Array fluorescence detector (TA FD)
- 80% FoV of TA FD

TA FD FoV (12 telescopes, 33°×108°)

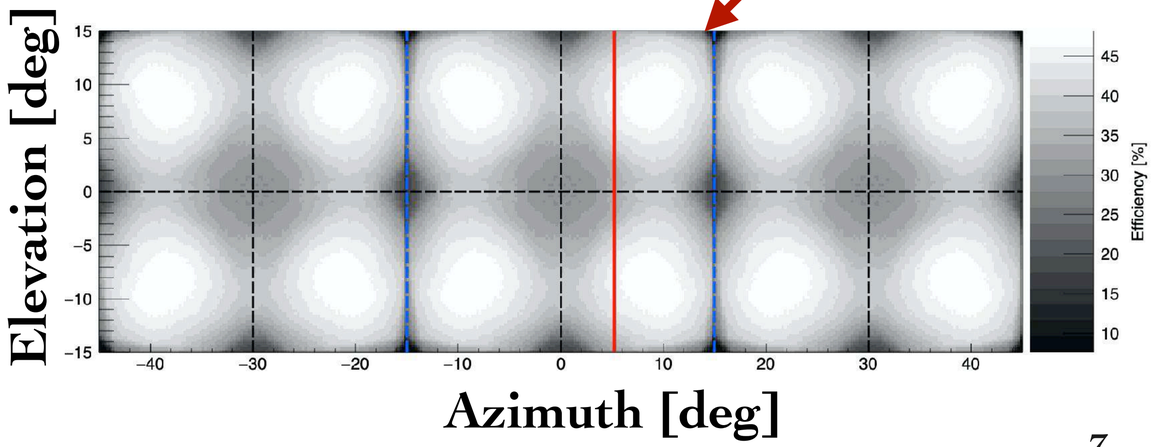




Vertical laser signal at 21 km (280 shot average)

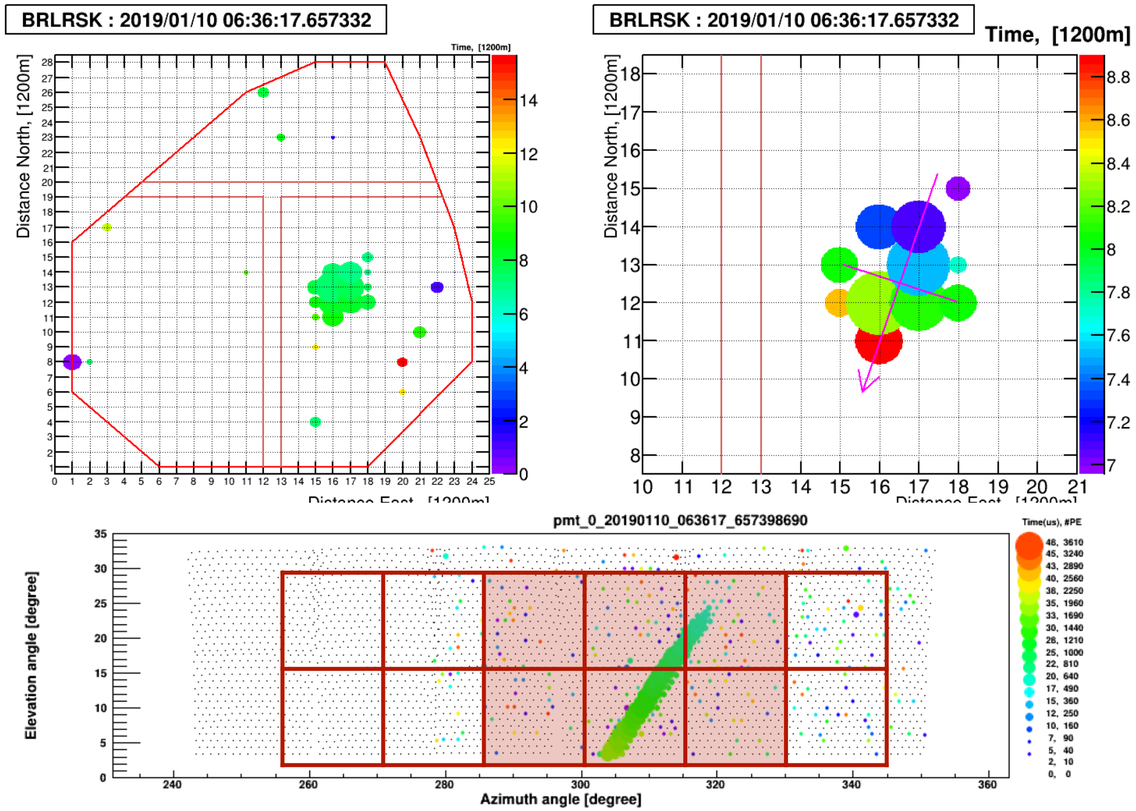


FAST FoV (3 telescopes, 30°×90°)

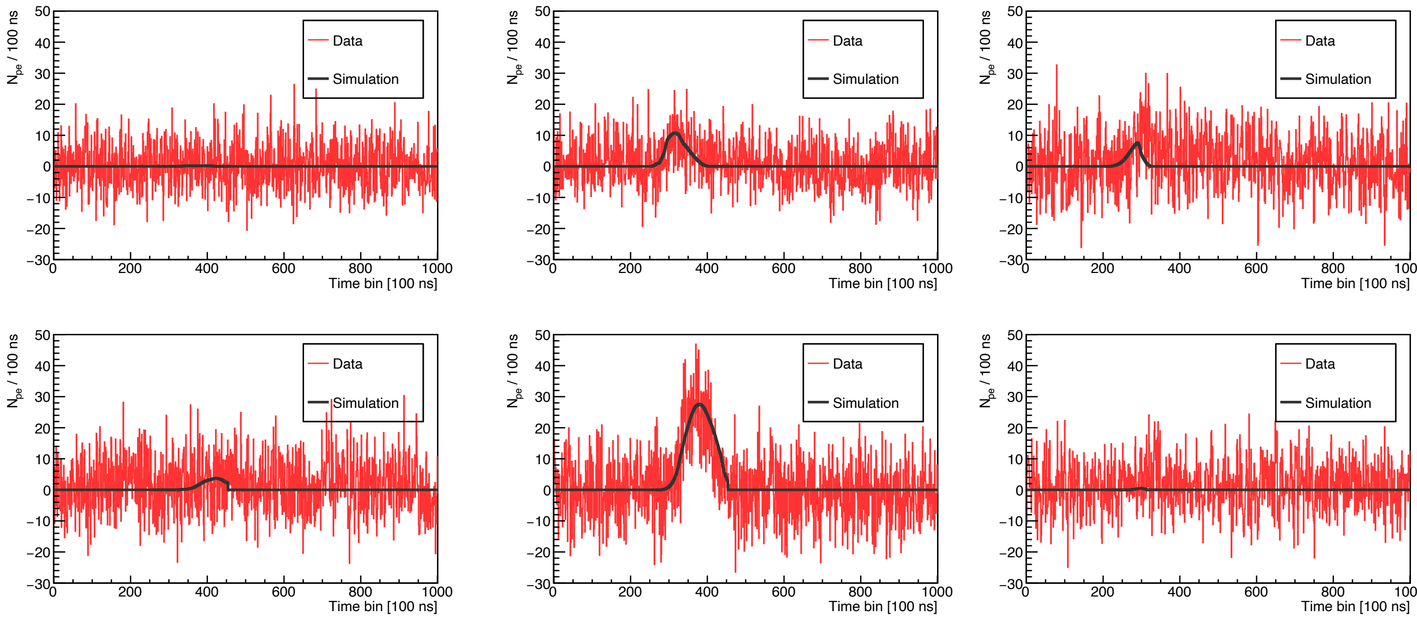


Example of FAST@TA event

TA result



FAST 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 mono (Preliminary)

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

FAST top-down reconstruction (Preliminary)

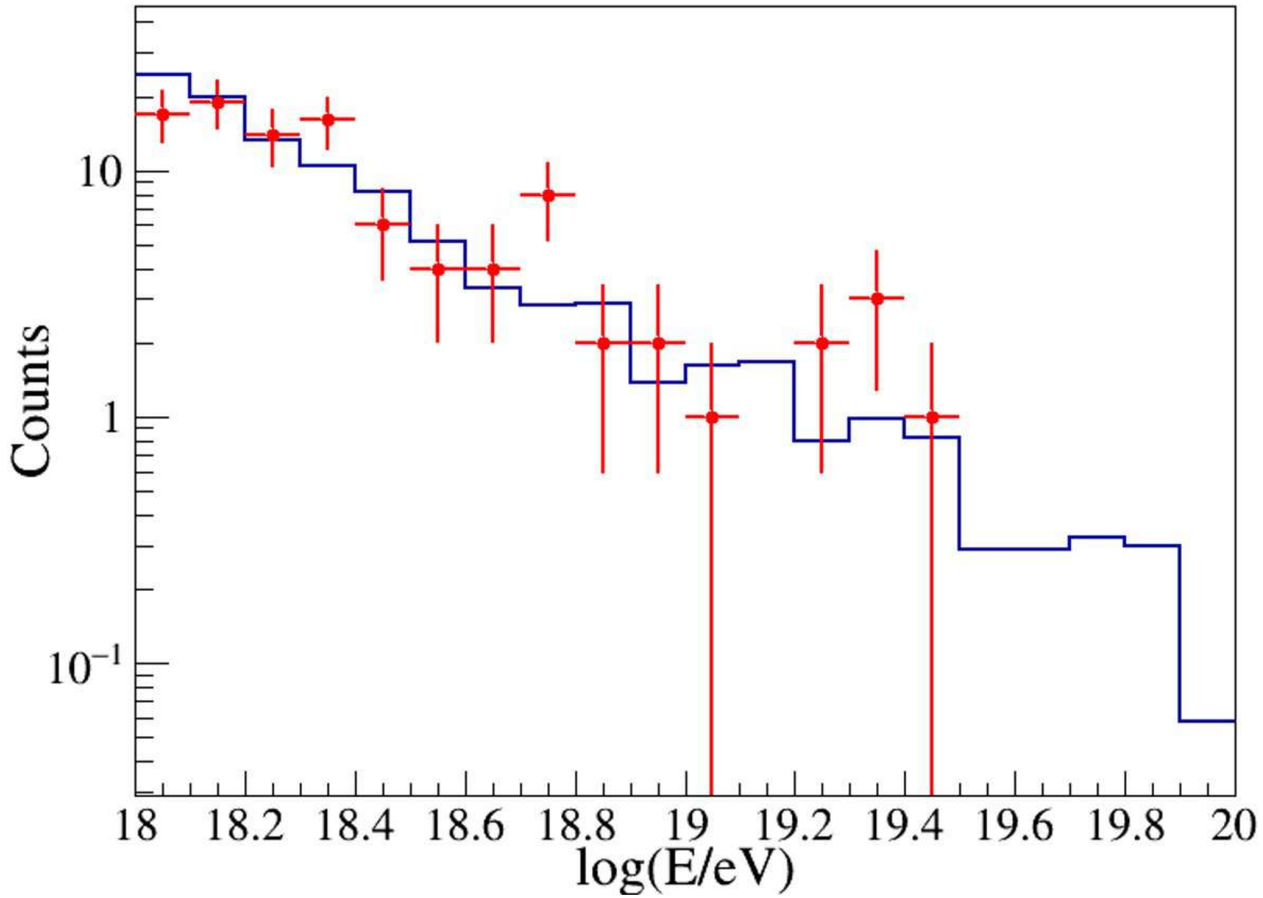
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
33.9 deg	19.3 deg	4.6 km	-4.7 km	808 g/cm^2	18.8 EeV

Data analysis of FAST@TA

Work: Fraser Bradfield

Data

MC simulation



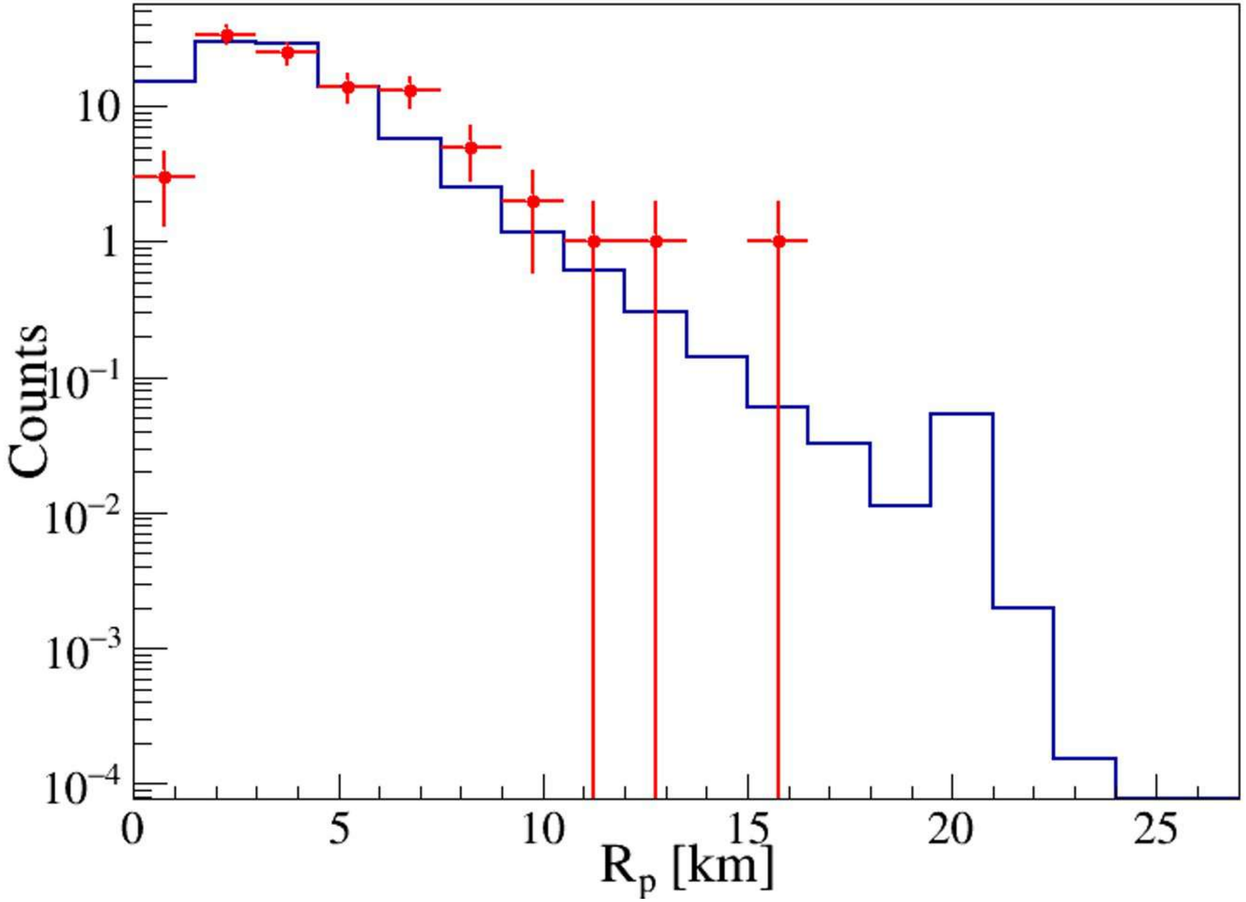
- Period: 2018/03/19 - 2023/02/25
- **Significant signal events with FAST** in the TA monocular reconstructed events
  - Total 336 events (**102 events above 10^{18} eV**)
  - Expected distributions estimated from **FAST detector Monte Carlo (MC) simulation**
  - Trigger condition: **>2 PMTs with S/N>6**
- **Data parameters are TA monocular reconstructed results**
  - Histogram of MC simulation was rescaled to be the same area of the Data

Data/MC comparison

Work: Fraser Bradfield

Data

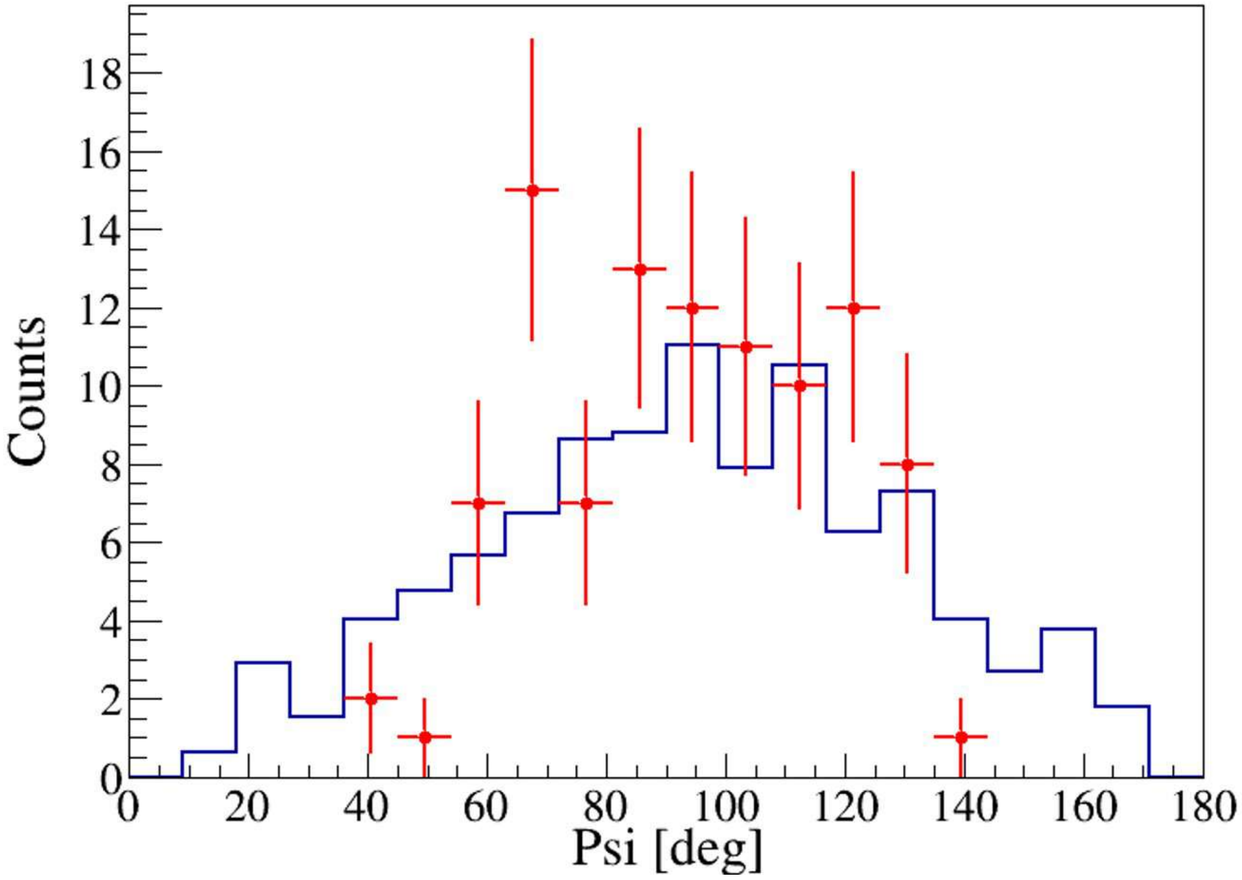
MC simulation



Impact parameter

Data

MC simulation



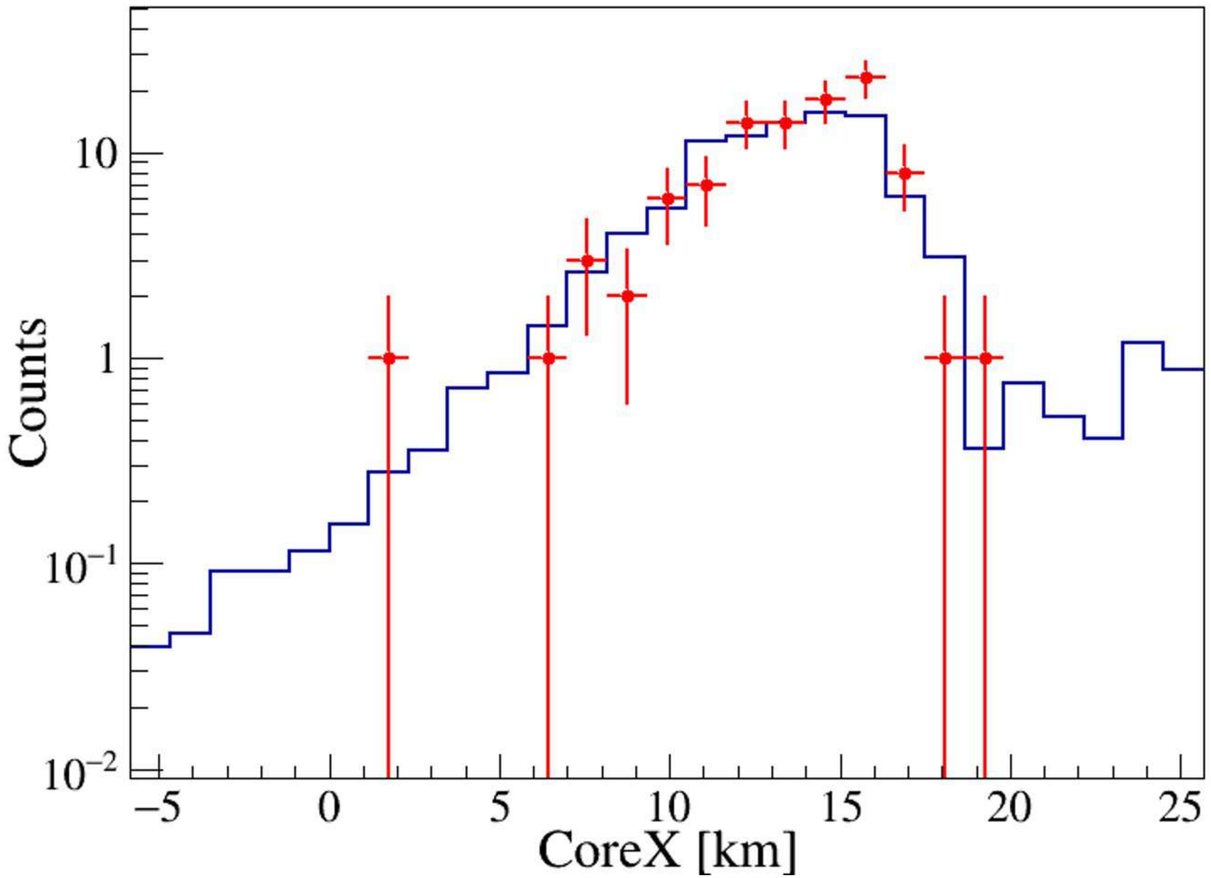
Angle in shower detector plane

Data/MC comparison

Work: Fraser Bradfield

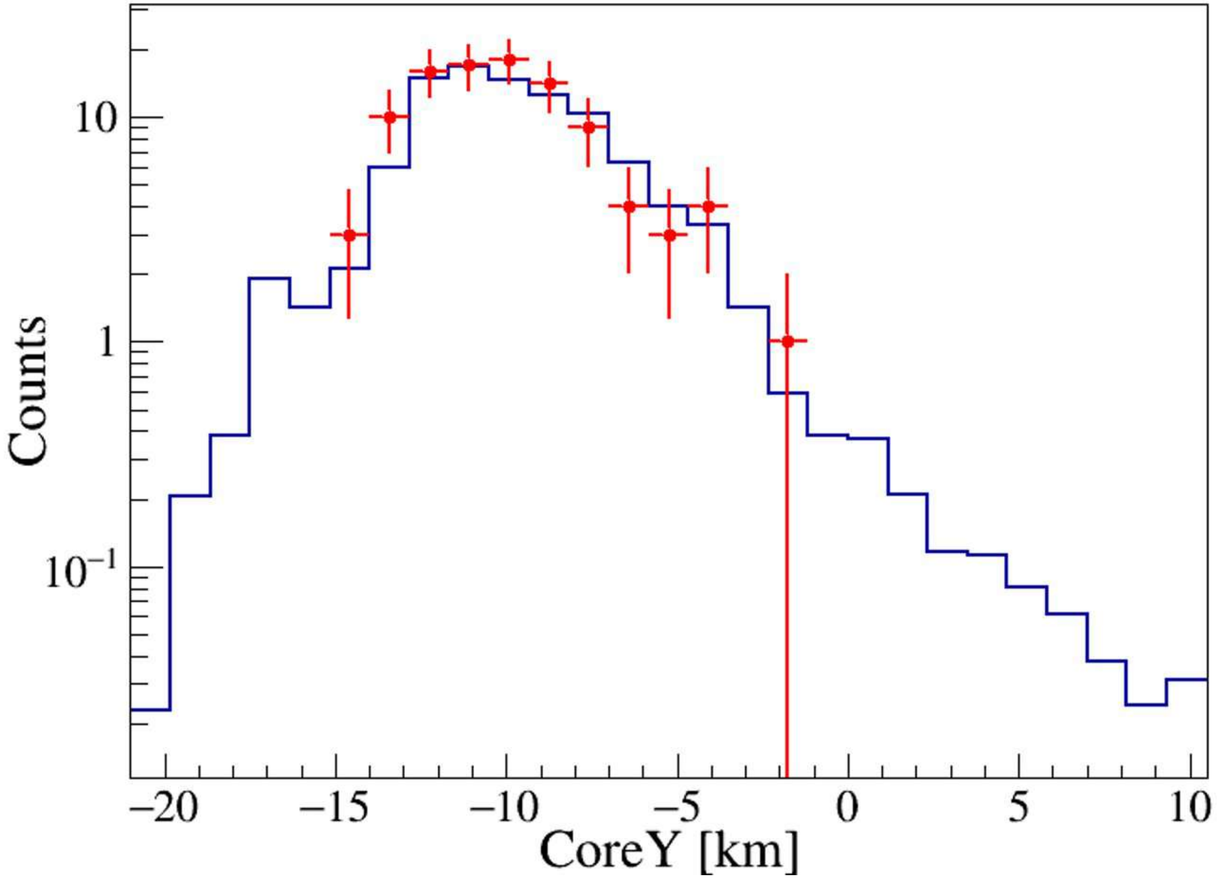
Data

MC simulation



Data

MC simulation

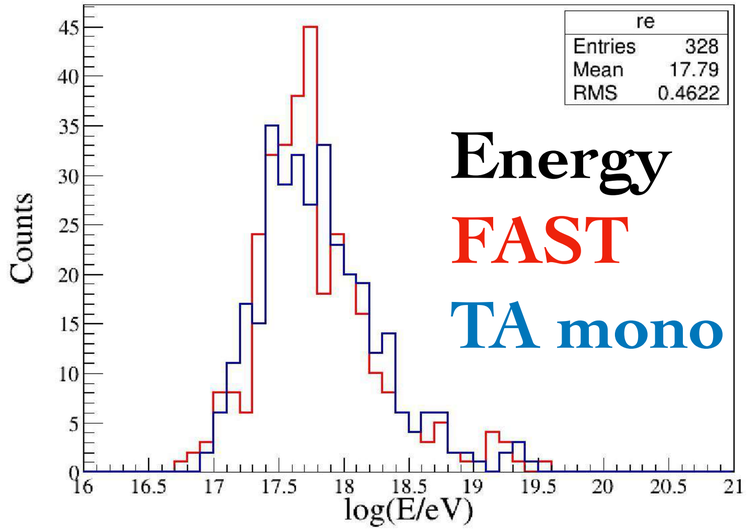


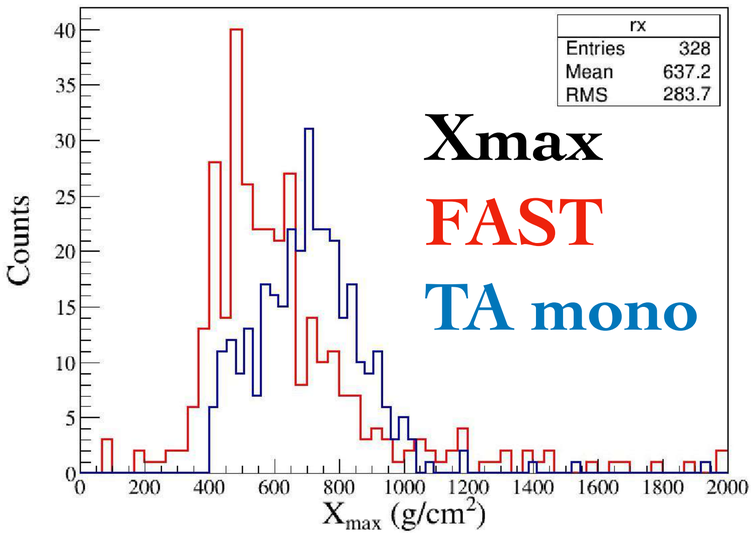
FAST location (17 km, -12 km)

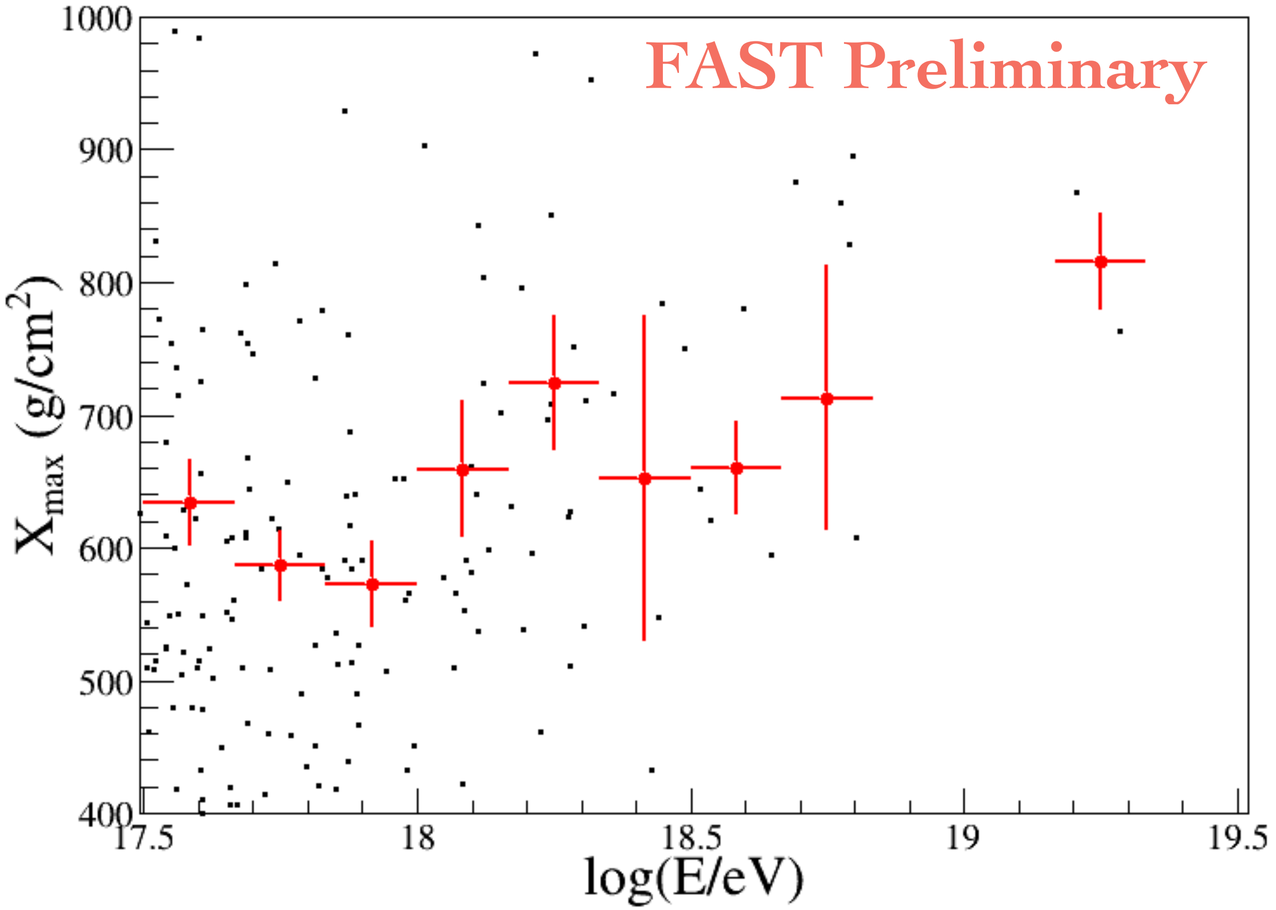
FAST top-down reconstruction

- Reconstructing **geometry, Xmax & Energy** using TA mono reconstructed geometry as initial guess

Work: Fraser Bradfield







Need to understand the bias on Xmax, and study quality cuts

FAST
Fluorescence detector Array of Single-pixel Telescopes

まとめと今後

- TAサイトに設置した3基の新型大気蛍光望遠鏡 (FAST) を使って、到来する極高エネルギー宇宙線の観測運用を続けている
  - **TAとFASTの同時検出された宇宙線を使って性能評価**
    - 10^{18} eV以上のエネルギーの**102事象**の宇宙線が、TAとFASTの同時検出された
      - FASTの検出器シミュレーションから期待されるパラメータ分布と、実際に検出された分布はおおむね誤差の範囲内で一致している
  - **FASTで検出された波形を使って、宇宙線の情報を再構成した**
    - 質量組成に感度の高い空気シャワーの最大発達深さを推定
    - 今後も観測とデータ解析を継続し、検出器の理解や物理解析を進めていく

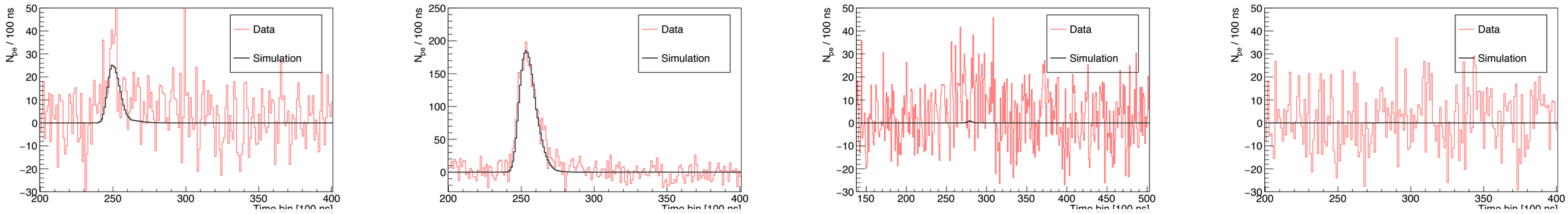
- **研究費20万円＋新任教員50万円は、米国ユタへの海外旅費や国内旅費として使用した**

Backup


SPOLEČNÁ LABORATOŘ OPTIKY
UNIVERZITY PALACKÉHO A FYZIKÁLNÍHO ÚSTAVU AV ČR
FZU
ČÁSTICOVÁ FYZIKA
STRATEGIE AV21

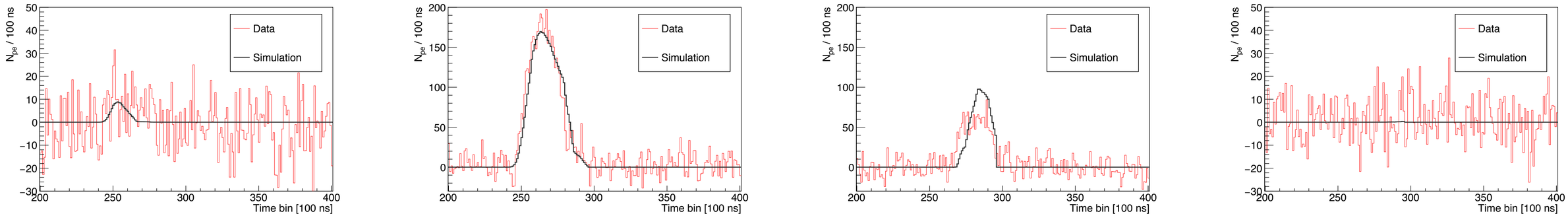
Example of FAST@TA event (Cherenkov dominated)

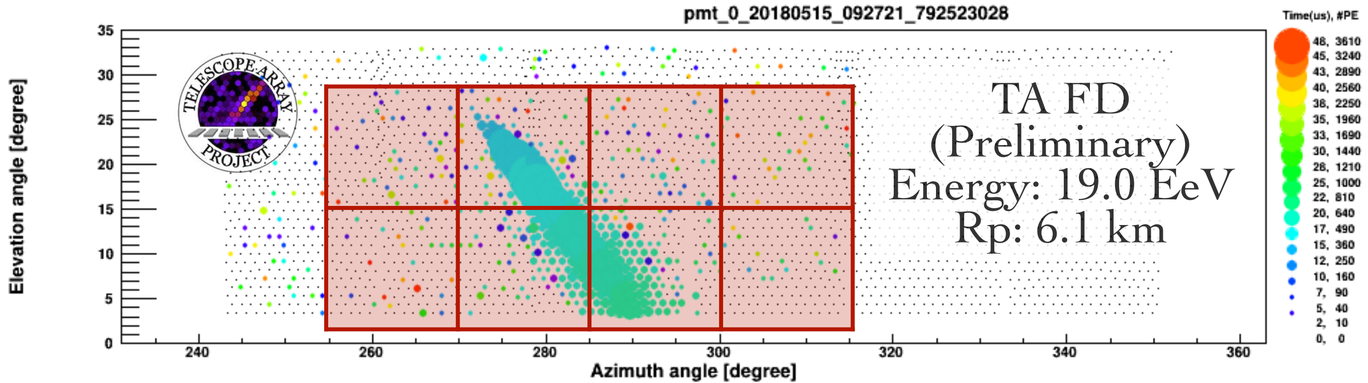
Fluorescence detector Array of Single-pixel Telescopes



FAST measured waveforms + Simulated signals from top-down reconstruction (Data, simulation by the best-fit parameters)

Fluorescence detector Array of Single-pixel Telescopes

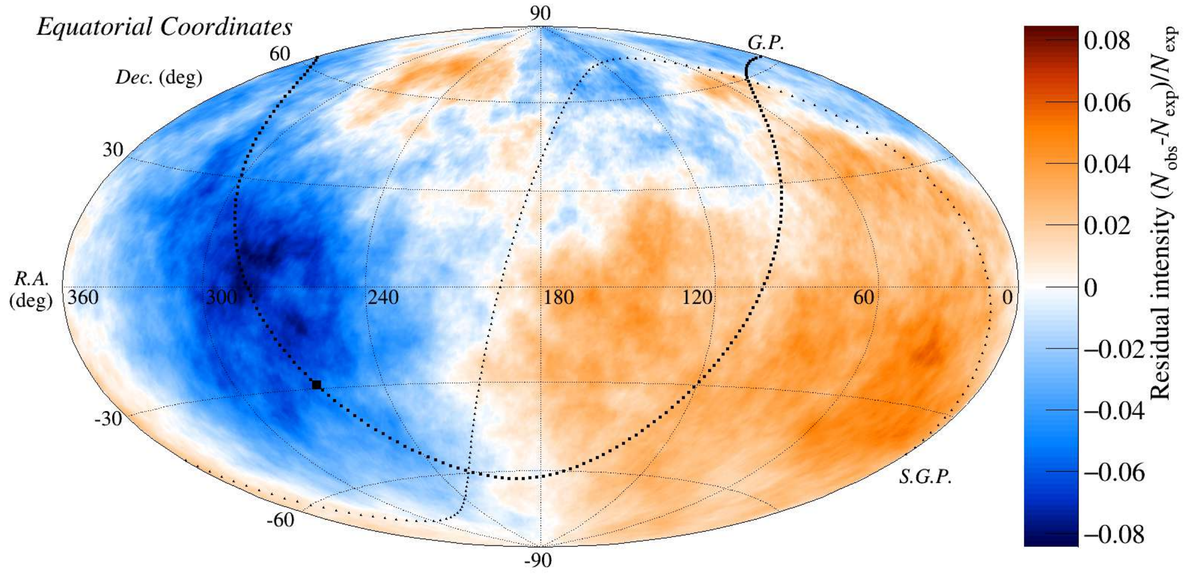




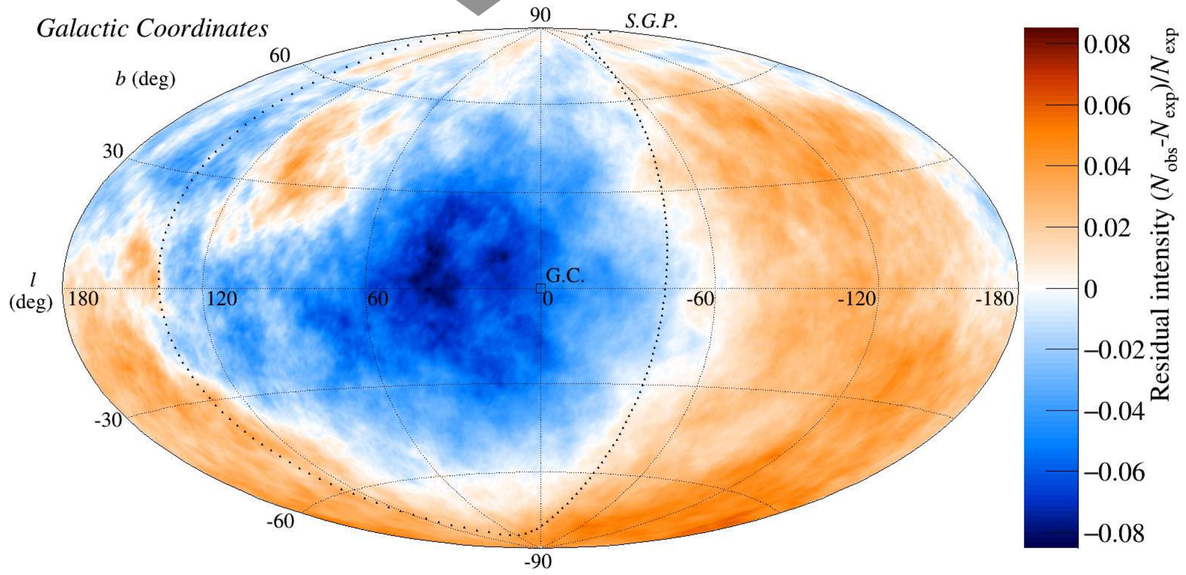
FAST top-down reconstruction (Preliminary)

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

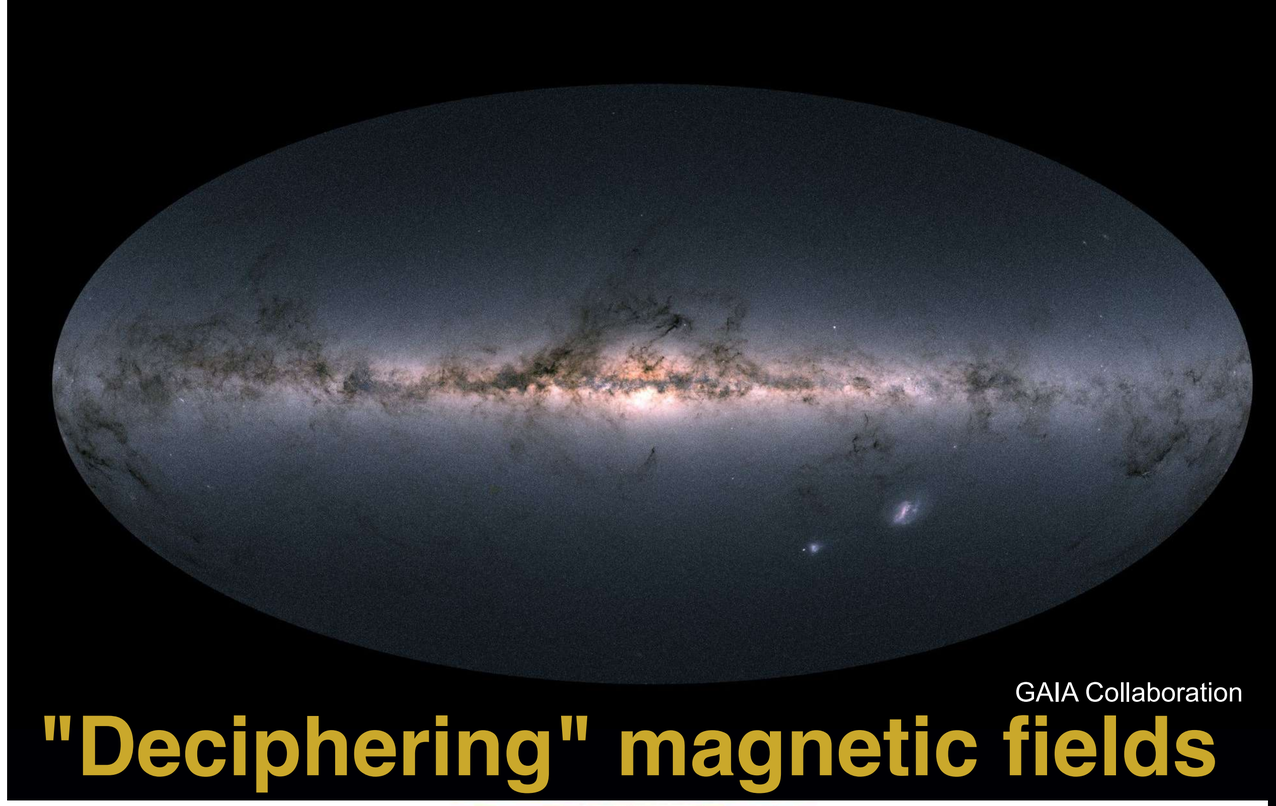
10 EeV skymap



Converted to **Galactic coordinates**



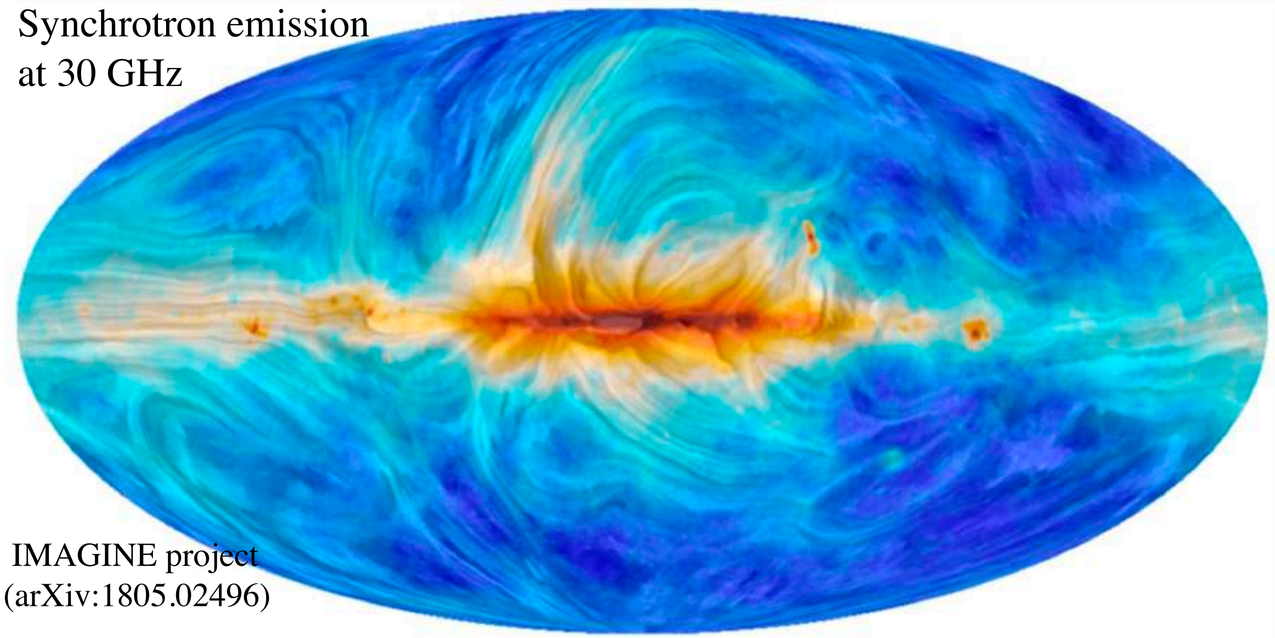
T. Fujii, PoS (ICRC2021) 402 (2021)



GAIA Collaboration

"Deciphering" magnetic fields

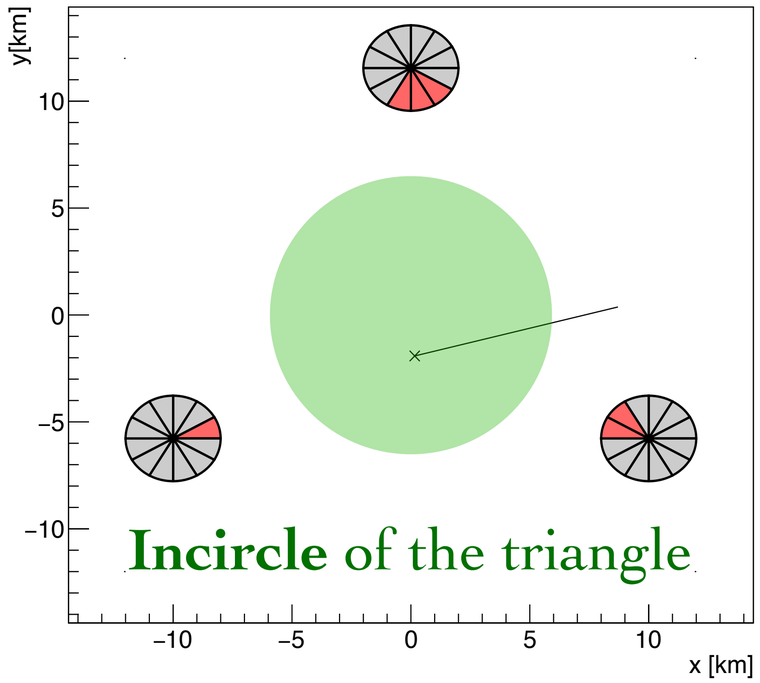
Synchrotron emission
at 30 GHz

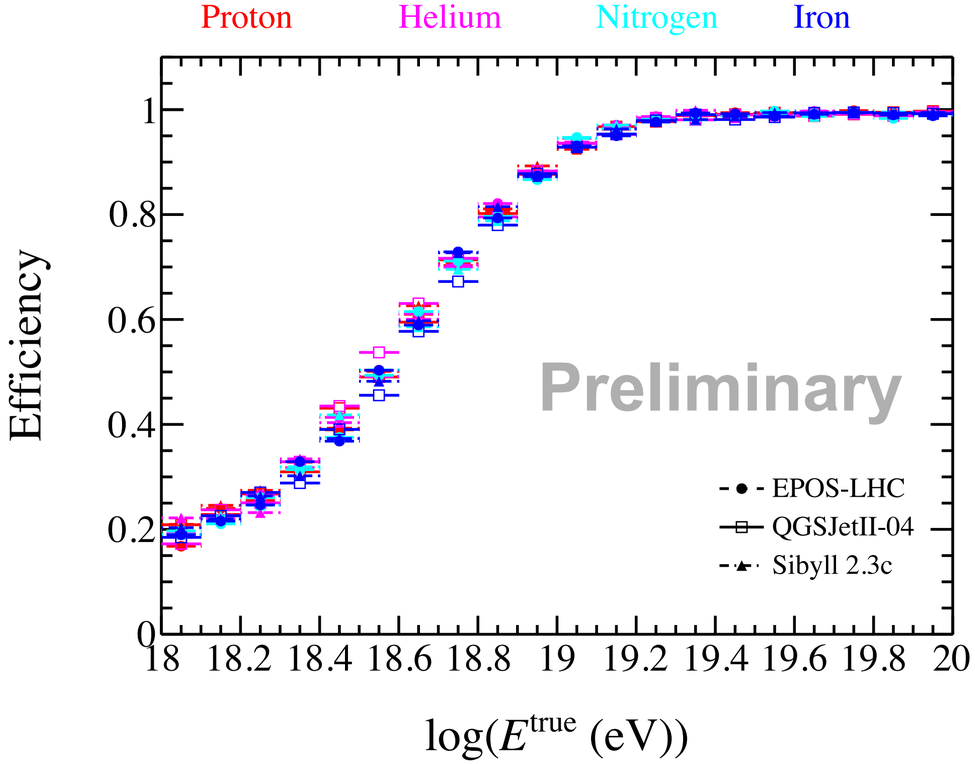


IMAGINE project
(arXiv:1805.02496)

First guess reconstruction with a 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)





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

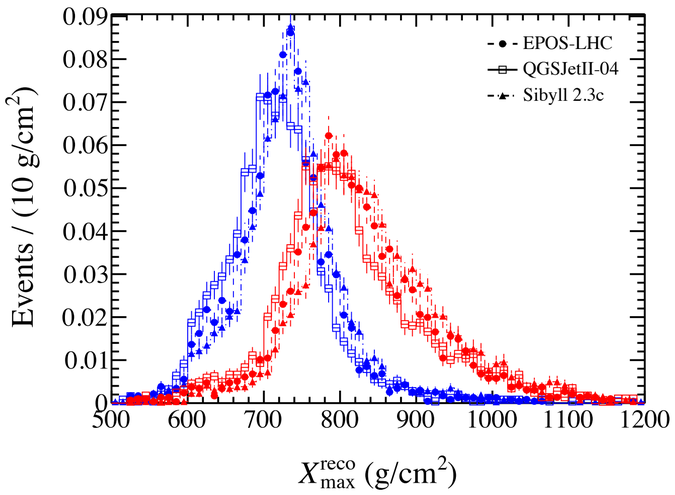
3-fold trigger efficiency

100% above 20 EeV

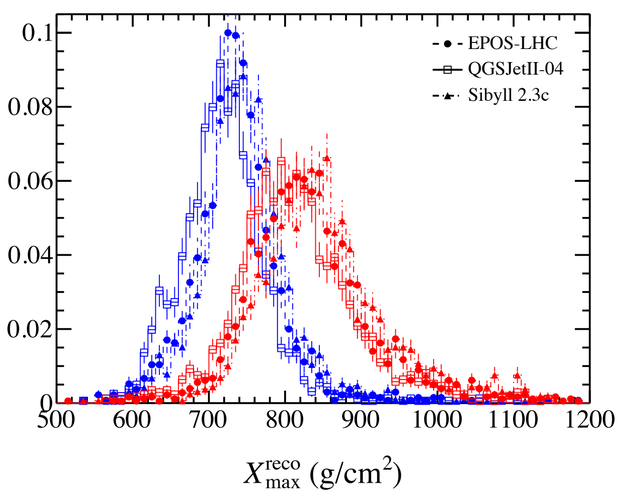
EASTT
Fluorescence detector Array of Single-pixel Telescopes

Reconstructed X_{max} distributions

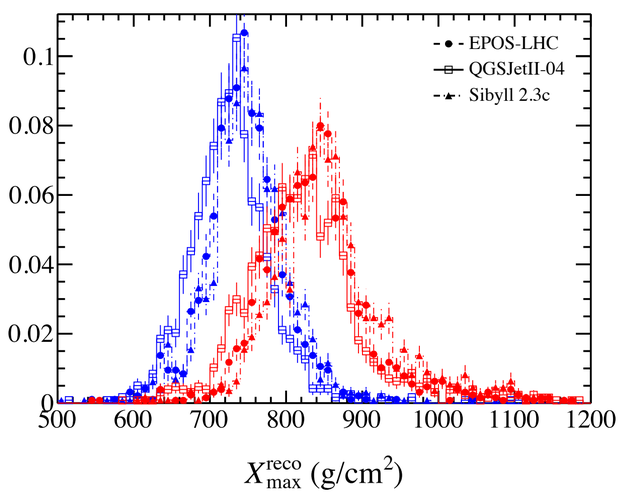
10 - 20 EeV



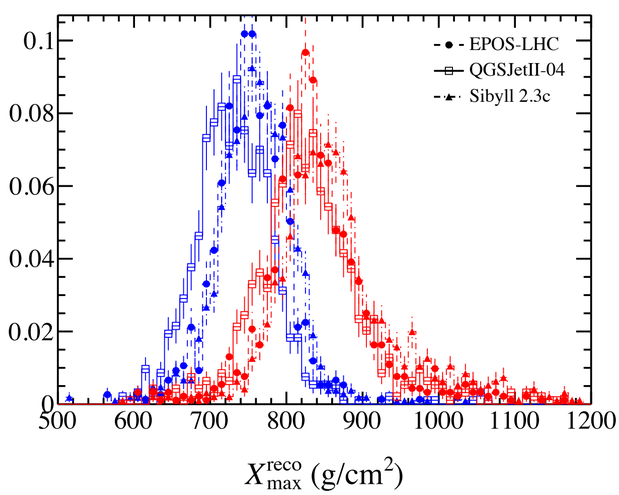
20 - 30 EeV



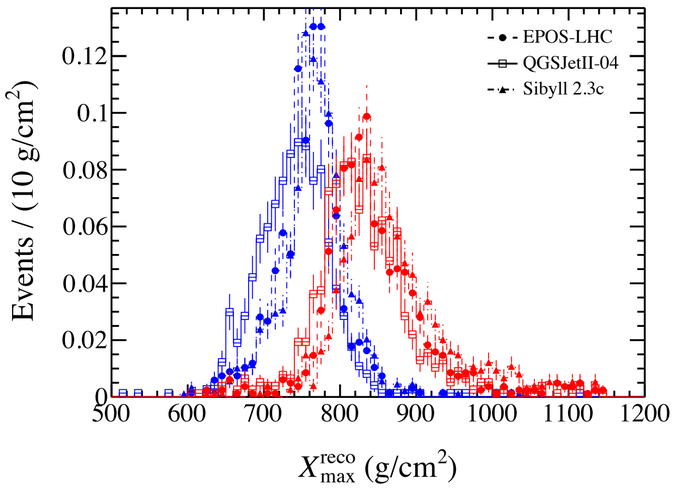
30 - 40 EeV



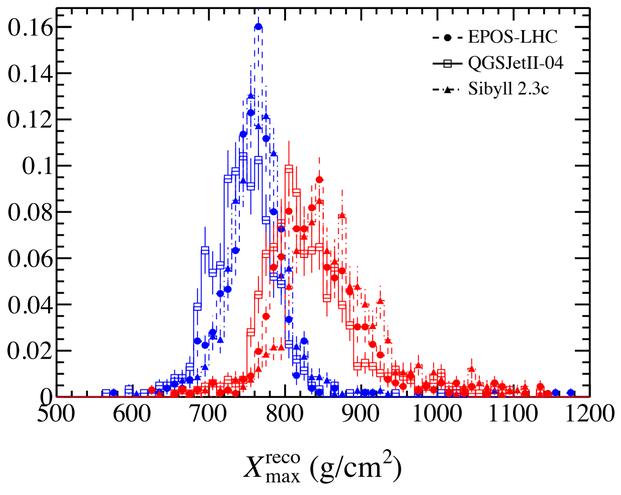
40 - 50 EeV



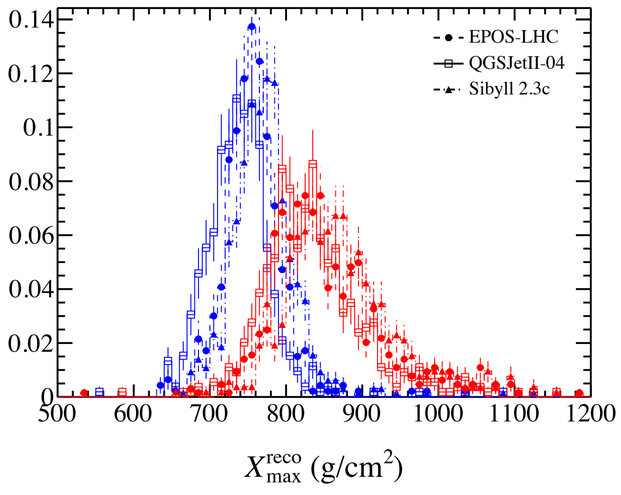
50 - 60 EeV



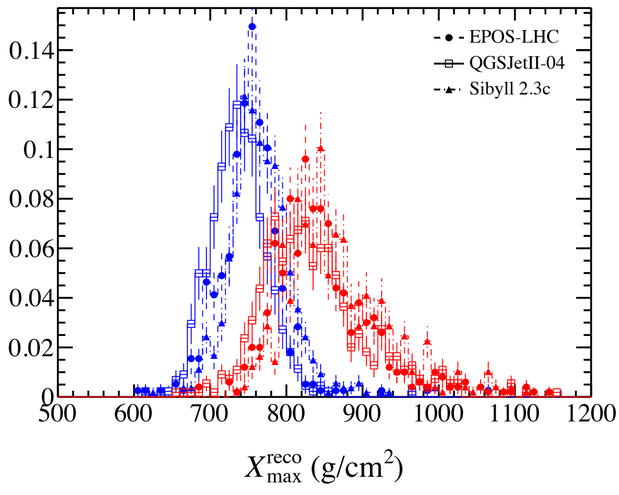
60 - 70 EeV



70 - 80 EeV

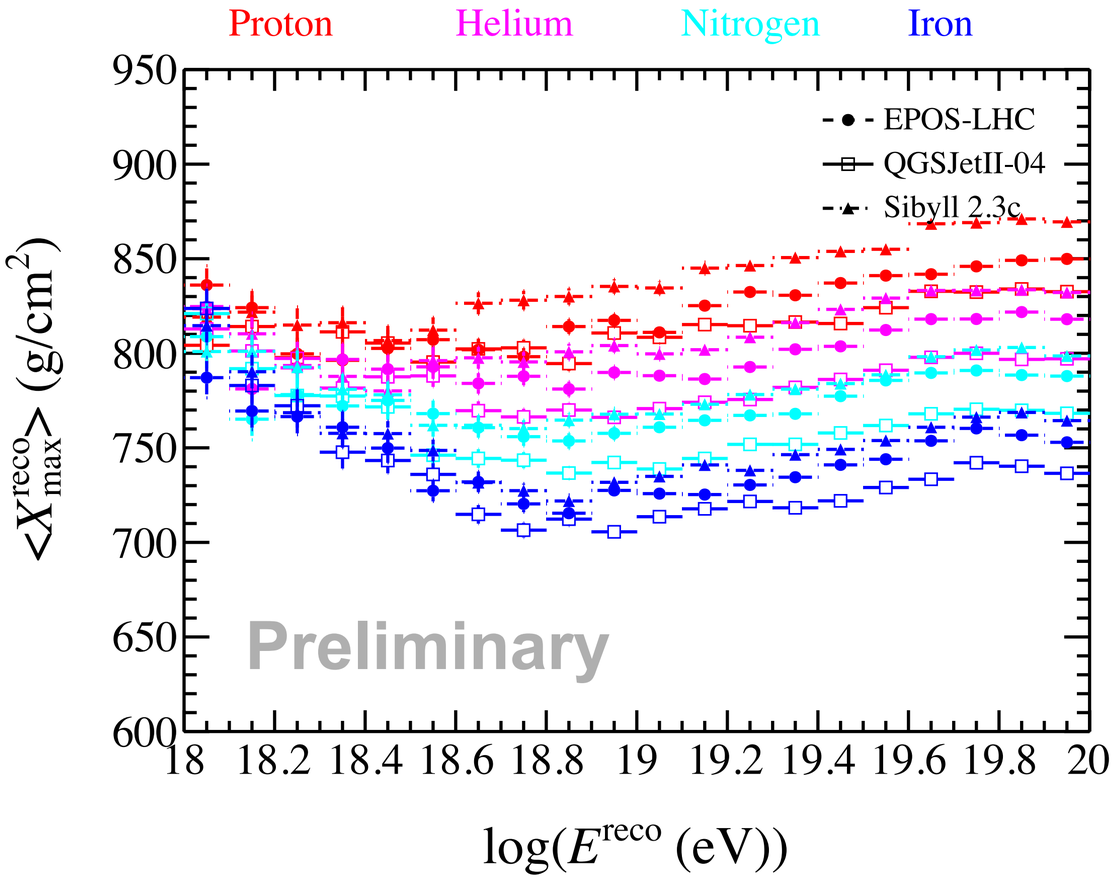


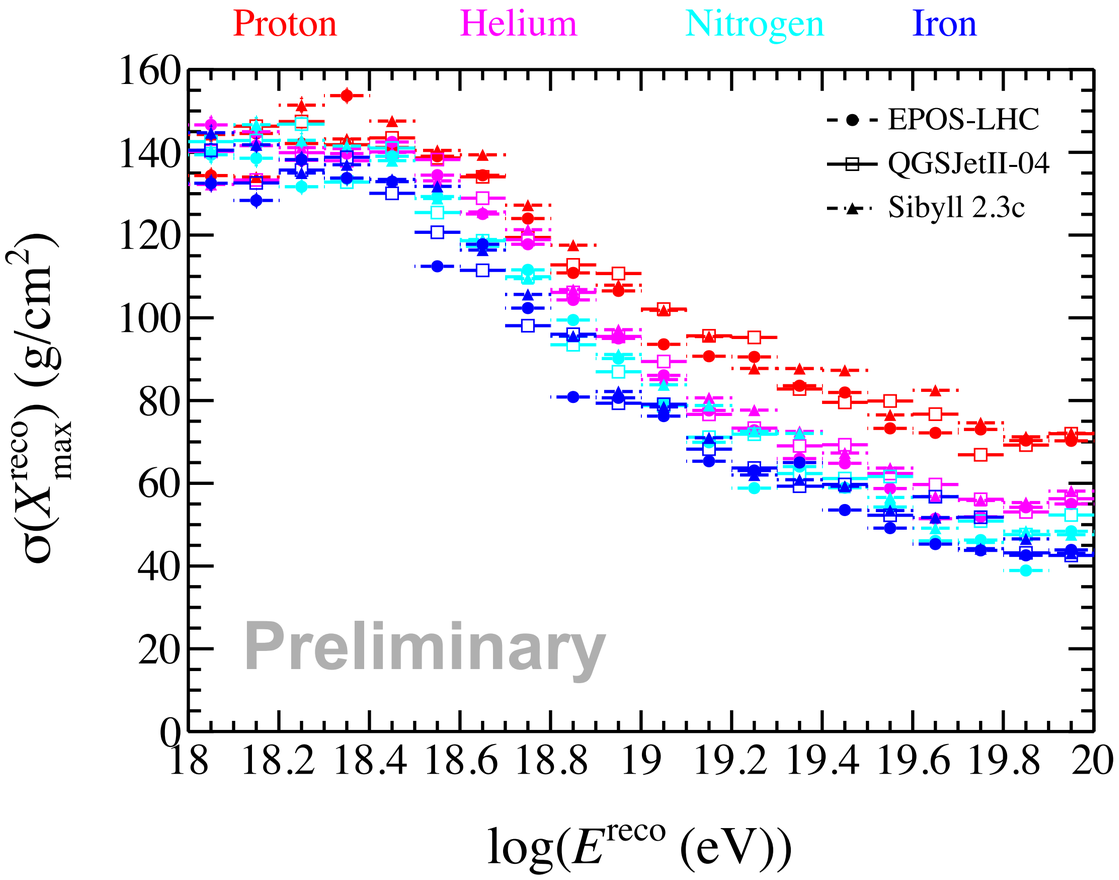
80 - 90 EeV



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

Reconstructed X_{max} rails



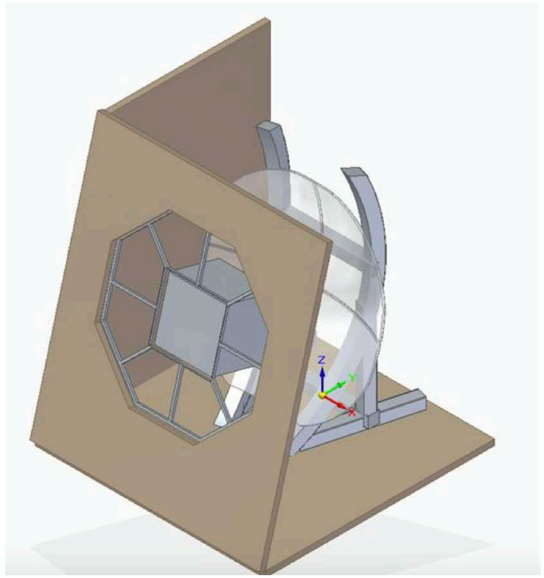


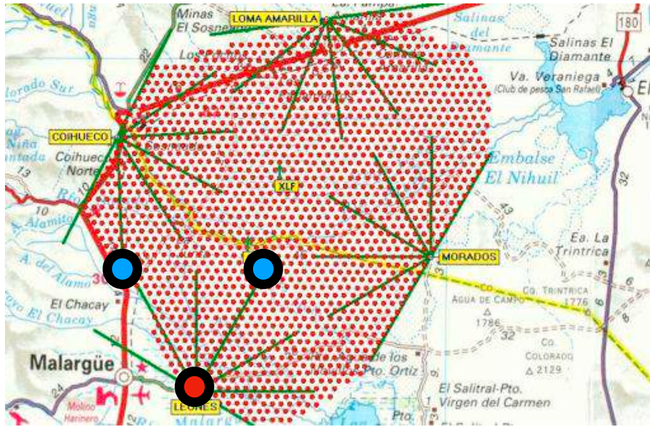
Next challenge: stand-alone operation of FAST array

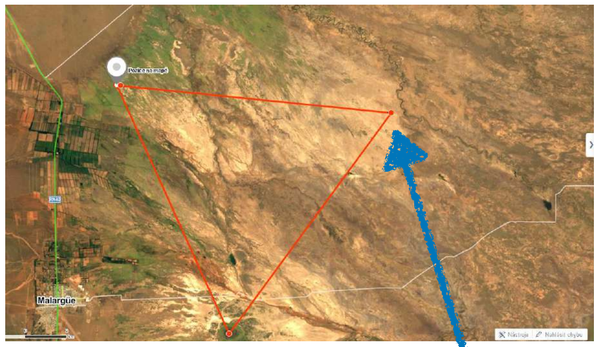
EAST
Fluorescence detector Array of Single-pixel Telescopes

Robust enclosure

Optimization of optics using 4 mirrors

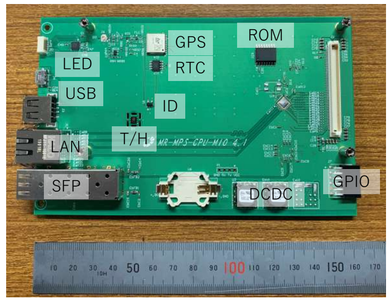




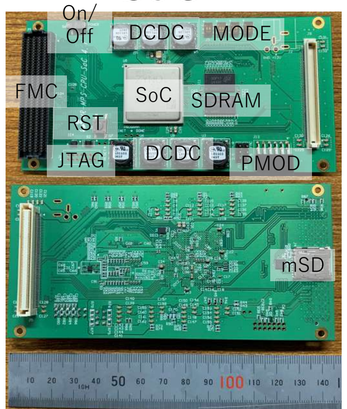


New electronics development

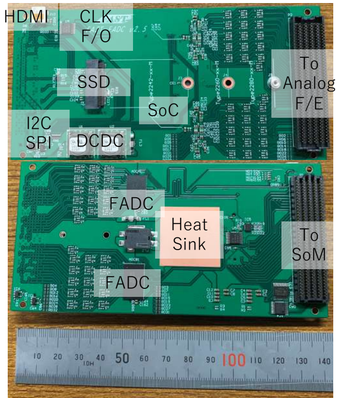
MIO



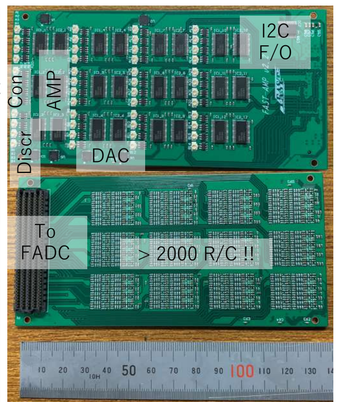
SoC



FADC



AMP



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