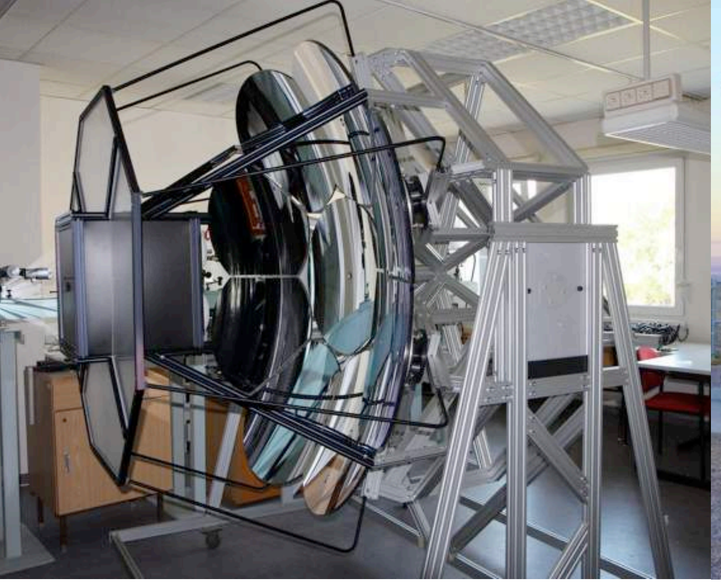


Observing ultra-high energy cosmic rays with prototypes of the Fluorescence detector Array of Single-pixel Telescopes (FAST) in both hemispheres

Toshihiro Fujii (Hakubi Center for Advanced Research, Kyoto University, fujii@cr.scphys.kyoto-u.ac.jp)
Justin Albury, Jose Bellido, Ladislav Chytka, John Farmer, Petr Hamal, Pavel Horvath, Miroslav Hrabovsky, Jiri Kvita, Max Malacari, Dusan Mandat, Massimo Mastrodicasa, John Matthews, Stanislav Michal, Xiaochen Ni, Libor Nozka, Miroslav Palatka, Miroslav Pech, Paolo Privitera, Petr Schovanek, Francesco Salamida, Radomir Smida, Stan Thomas, Petr Travnicek, Martin Vacula (FAST Collaboration)

25th July 2019, ICRC 2019, Madison, USA

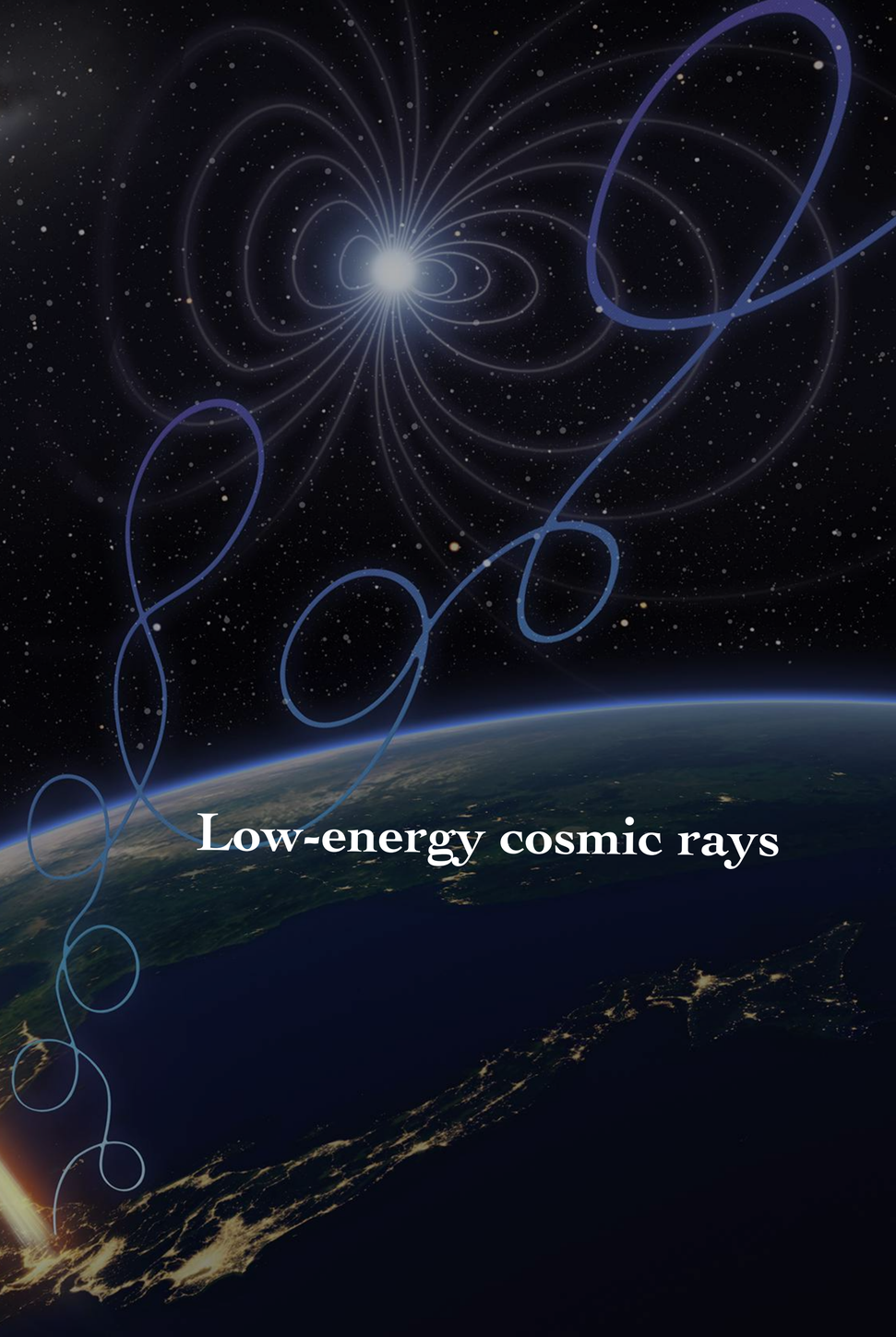
FAST
Fluorescence detector Array of Single-pixel Telescopes

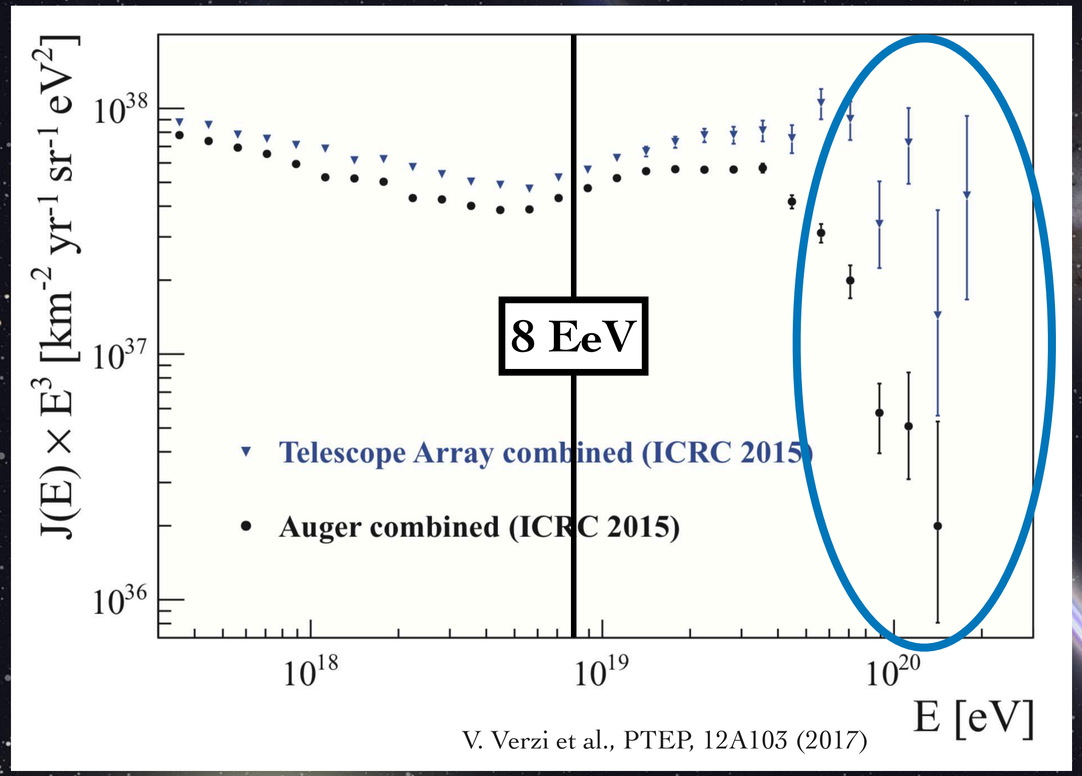
ICRC2019 36th International Cosmic Ray Conference - Madison, WI, USA
THE ASTROPARTICLE PHYSICS CONFERENCE

Ultra-high energy cosmic rays (UHECR), 10^{20} eV

- Less deflection in galactic/extragalactic magnetic fields
- Related with extremely energetic astrophysical phenomena
- Spectrum suppression,
  - Indicate nearby sources distributed non-uniformly within ~50 Mpc

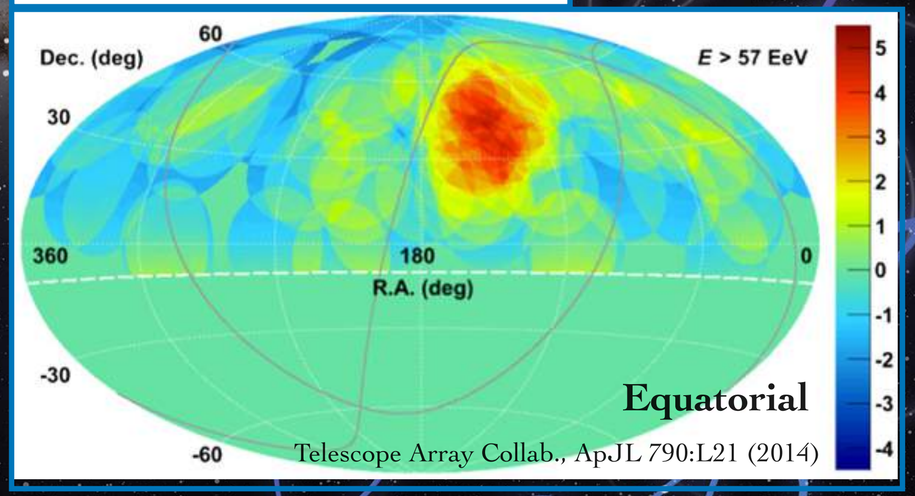
- Correlation between UHECRs and nearby energetic sources or objects
  - Next-generation astronomy





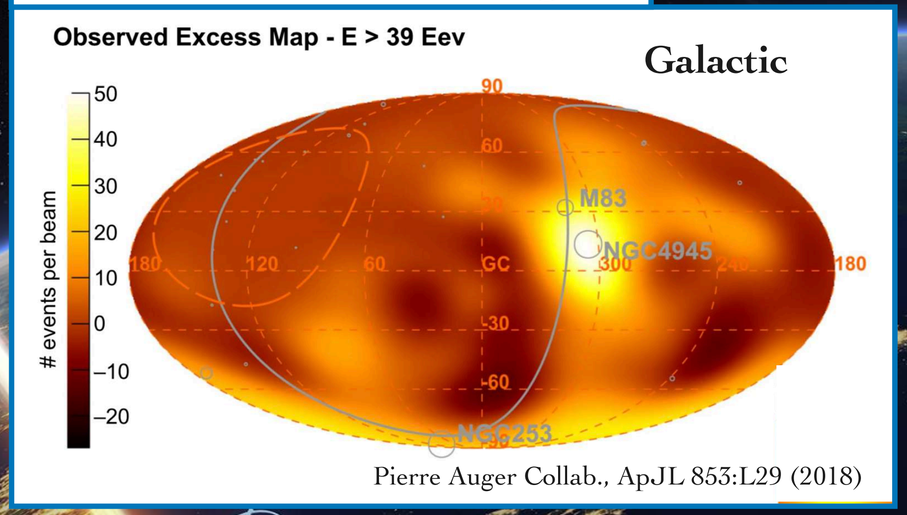
V. Verzi et al., PTEP, 12A103 (2017)

E>57 EeV, 3.4σ (TA)



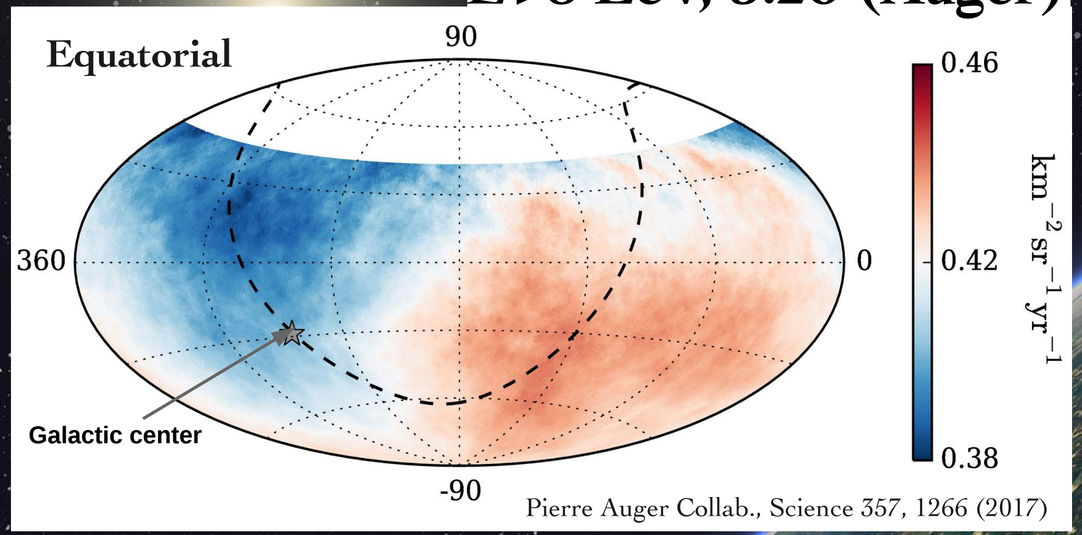
Telescope Array Collab., ApJL 790:L21 (2014)

E>39 EeV, 4.0σ (Auger)



Pierre Auger Collab., ApJL 853:L29 (2018)

E>8 EeV, 5.2σ (Auger)



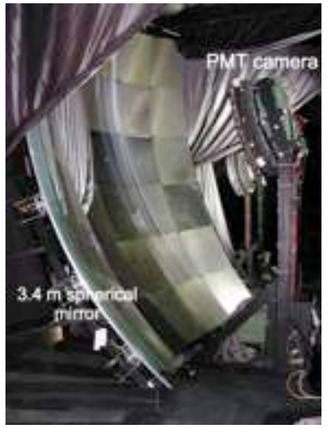
Pierre Auger Collab., Science 357, 1266 (2017)

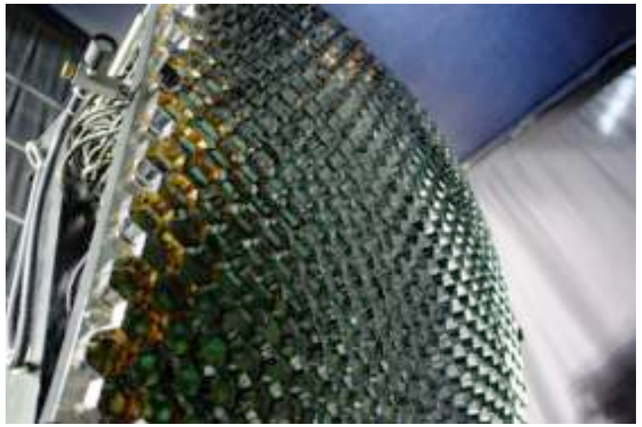
No conclusive results on UHECR sources...

EAST Fluorescence detector Array of Single-pixel Telescopes

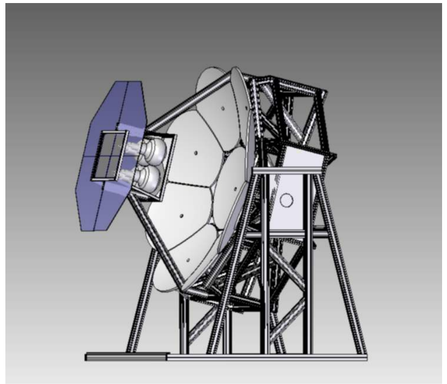
- Target : > $10^{19.5}$ eV, ultra-high energy cosmic rays (UHECR) and neutral particles
  - Huge target volume ⇒ Fluorescence detector array

Fine pixelated camera

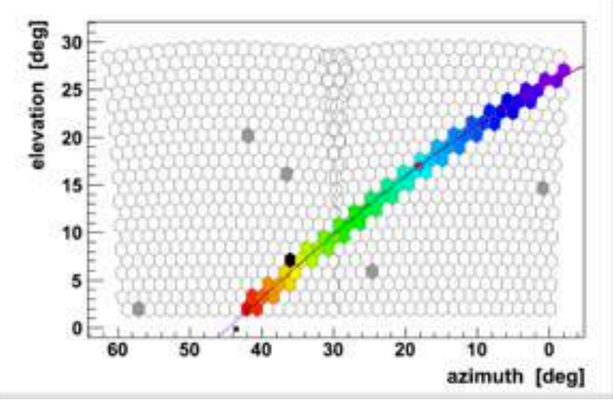


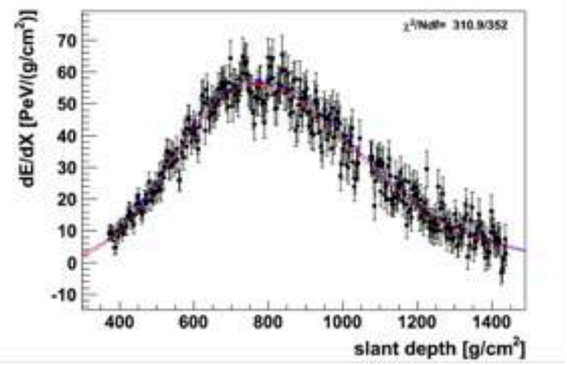


Smaller optics and single or a few pixels

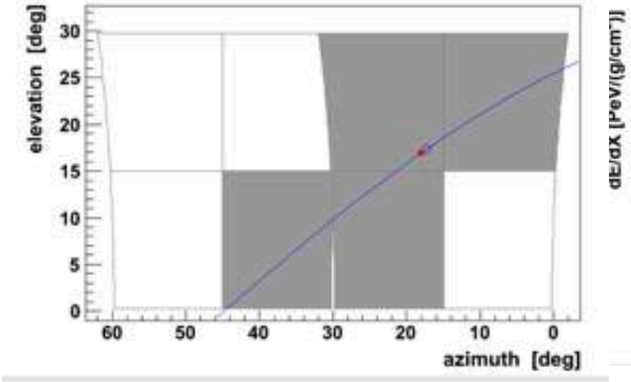


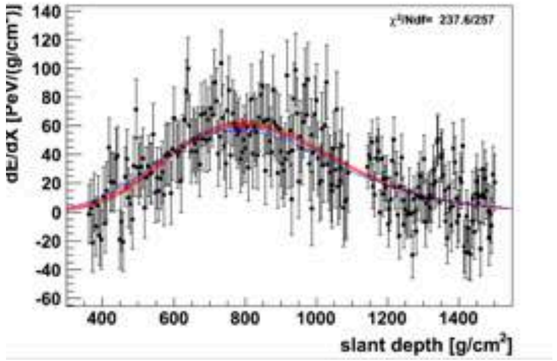
Too expensive to cover a huge area





Low-cost and simplified telescope

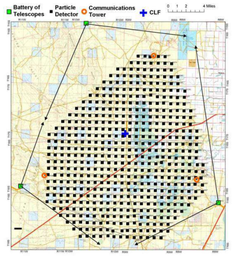




FAST Fluorescence detector Array of Single-pixel Telescopes

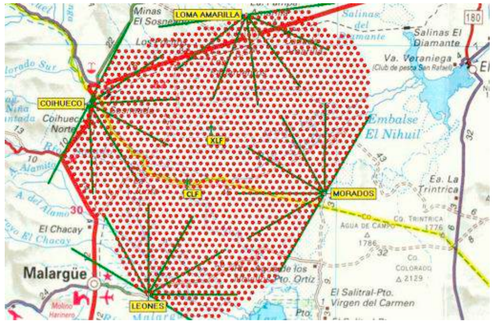
Telescope Array (TA) Pierre Auger Observatory (Auger)

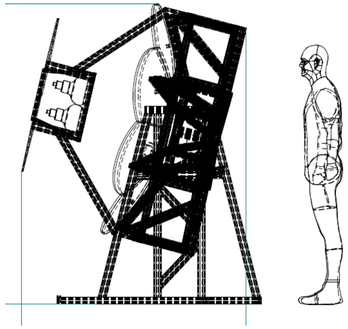
Reference: T. Fujii et al., Astropart.Phys. 74 (2016) 64-72

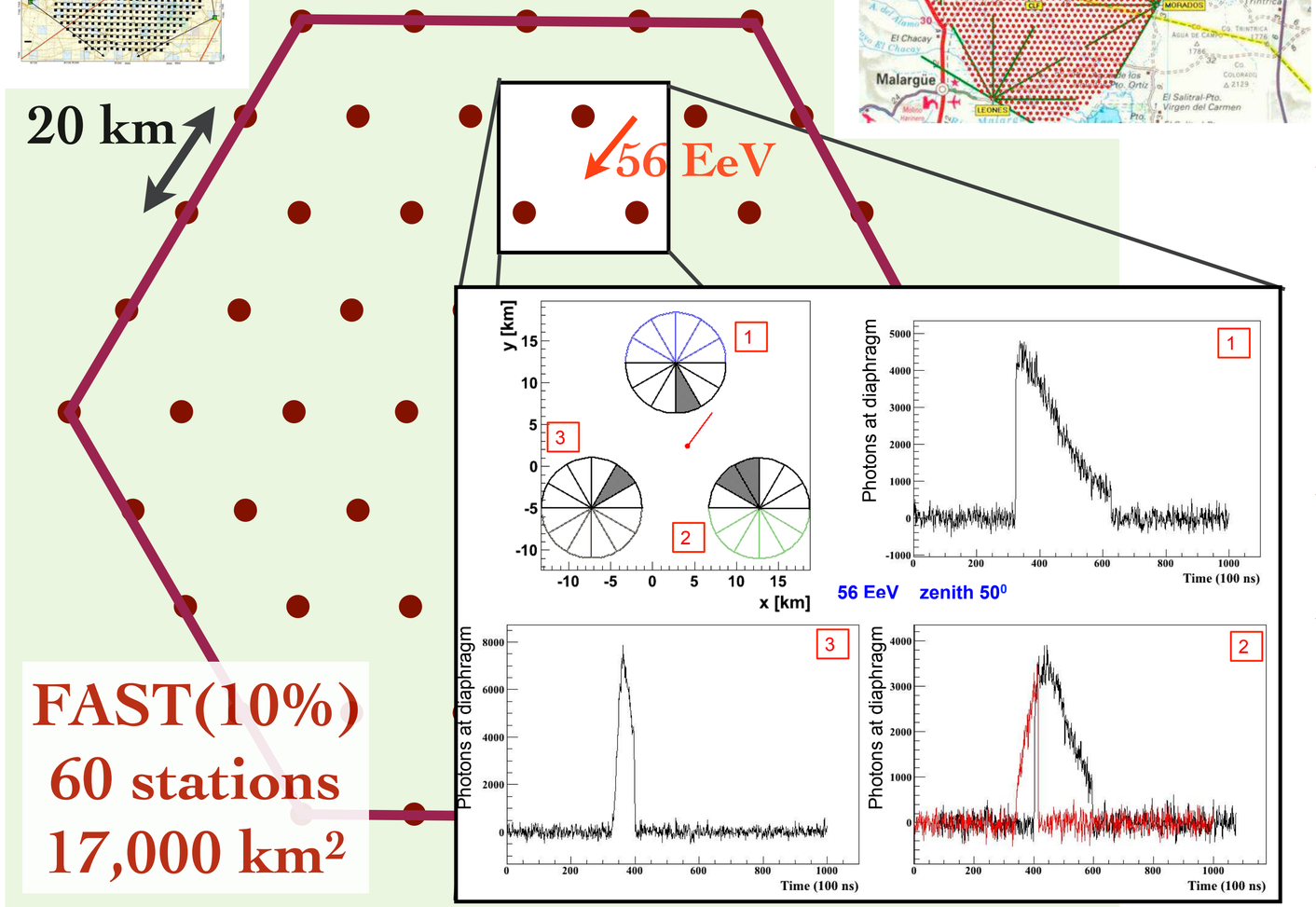


700 km²

3000 km²







- Each telescope: 4 PMTs, 30°×30° field-of-view (FoV)
  - **Reference design: 1 m² aperture, 15°×15° FoV per photo-multiplier tube (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 km²**

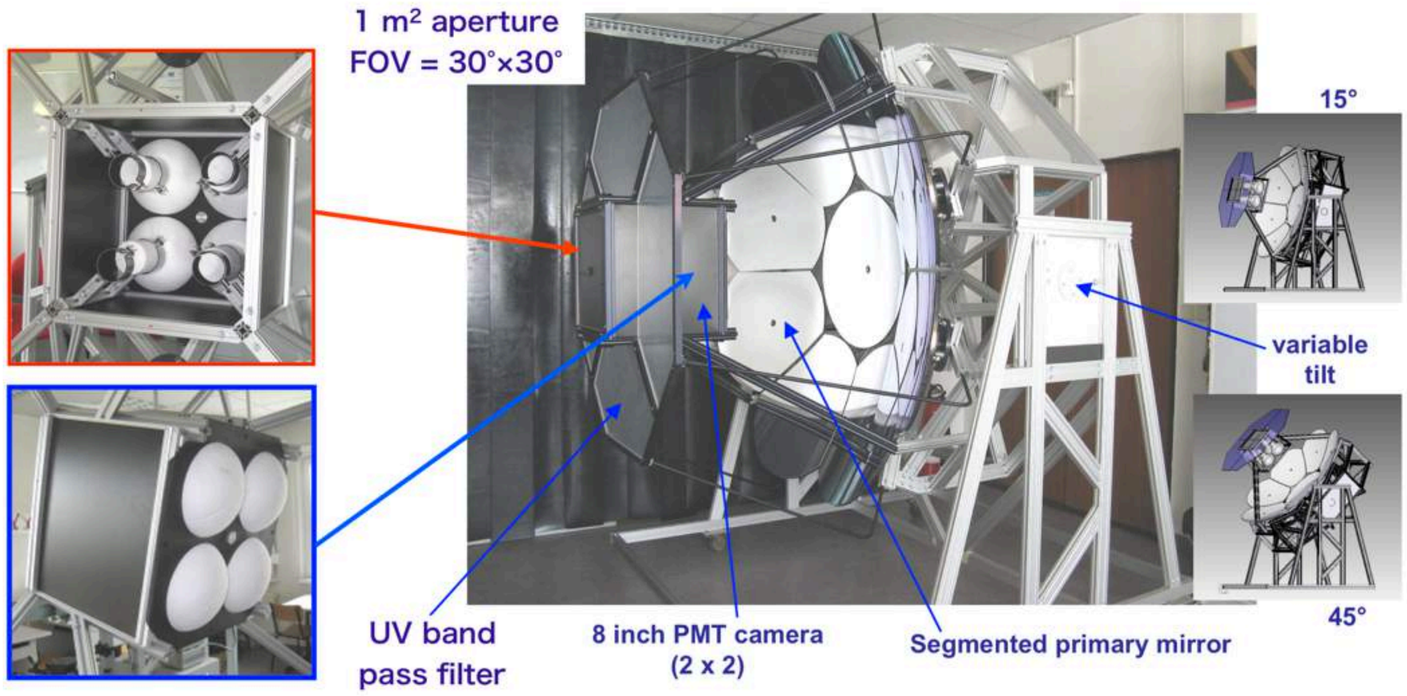
5 years: 5100 events (E > 57 EeV),

650 events (E > 100 EeV)

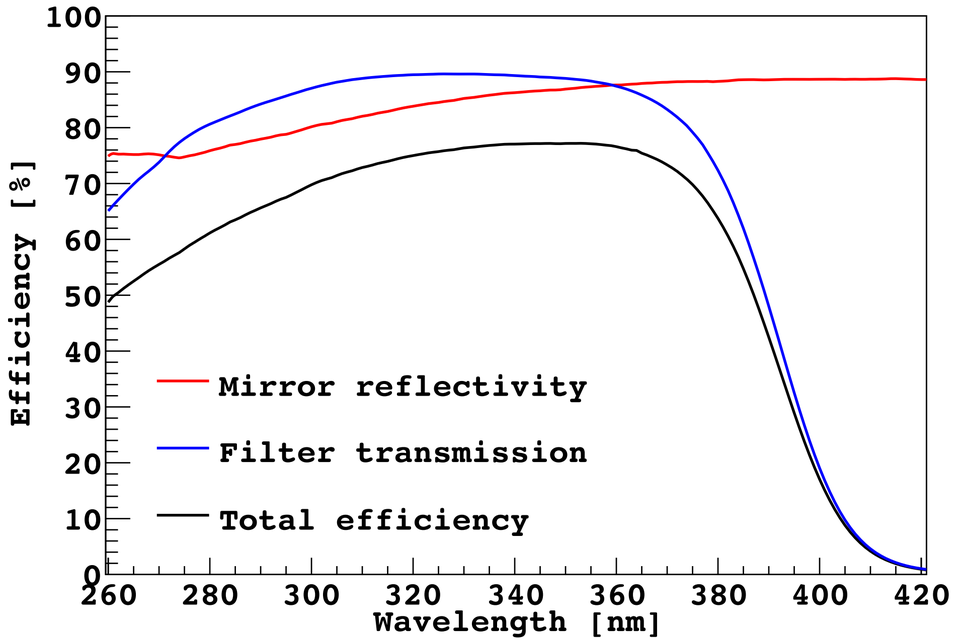
- Directional anisotropy on arrival directions, energy spectrum, mass composition

1. Detector development for future project
2. Cross-calibration of Energy and X_{max} scales in current UHECR observatories.

FAST fluorescence prototypes in TA



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

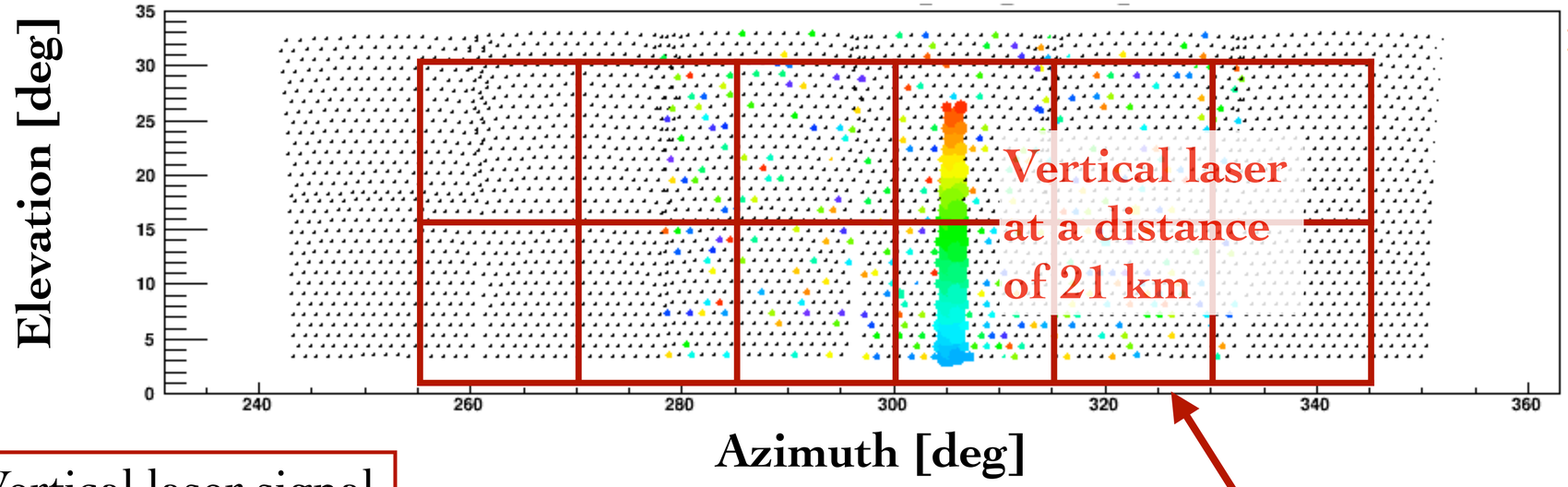


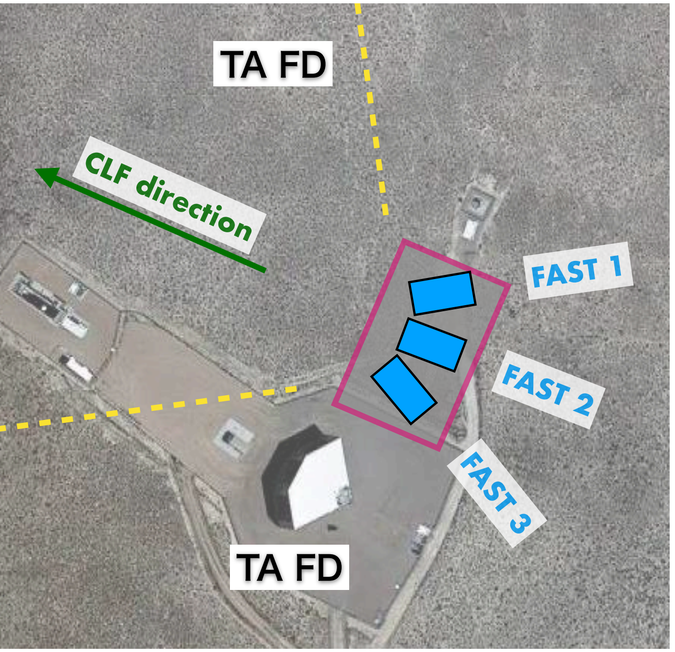
- 4 PMTs (20 cm, 8 dynodes R5912-03MOD, base E7694-01)
  - 1 m² aperture of the UV band-pass filter (ZWB3), segmented mirror of 1.6 m diameter
- Total 3 telescopes installed at TA site by October 2018
  - Total **545 hours** by June 2019

FAST observation set-up

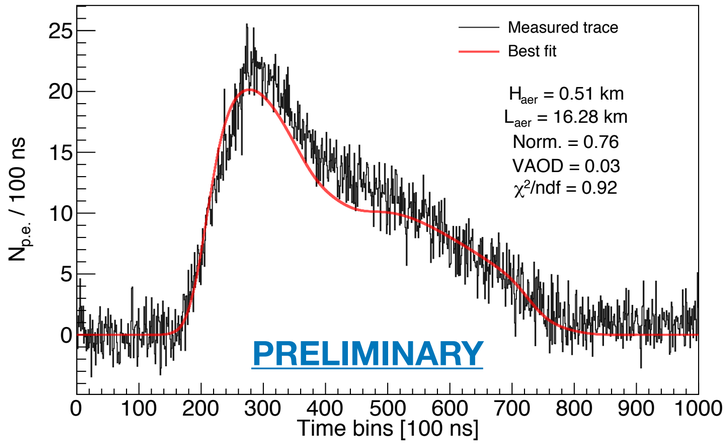
- Remote controlling observation
- Synchronized operation with external triggers from Telescope Array fluorescence detector (TA FD)
- 80% FoV of TA FD

TA FD FoV (12 telescopes, 33°×108°)

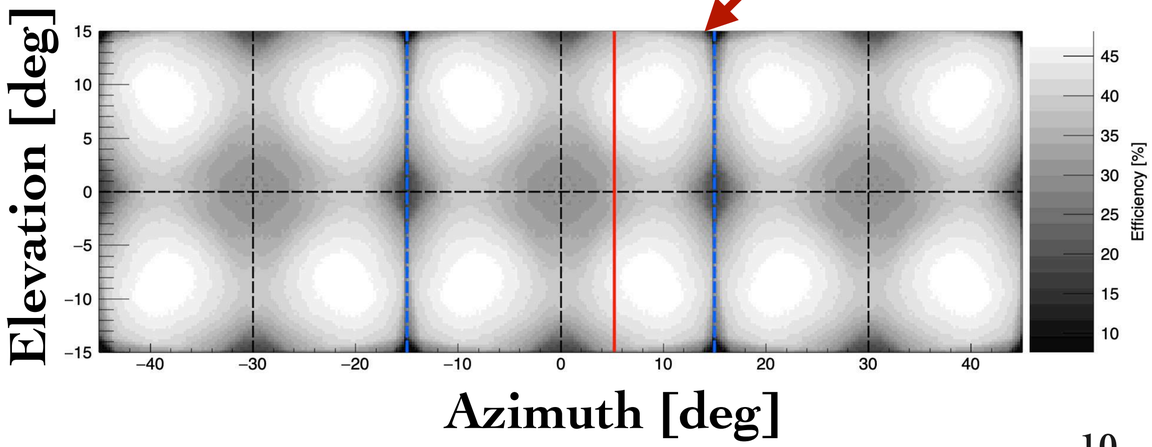




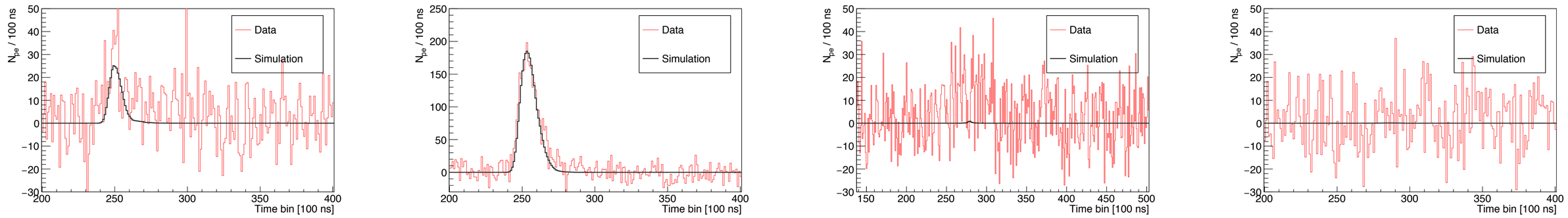
Vertical laser signal (280 shot average)



FAST FoV (3 telescopes, 30°×90°)

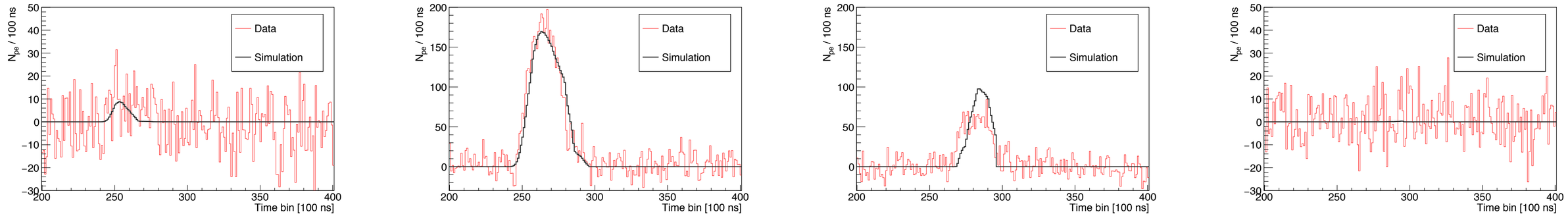


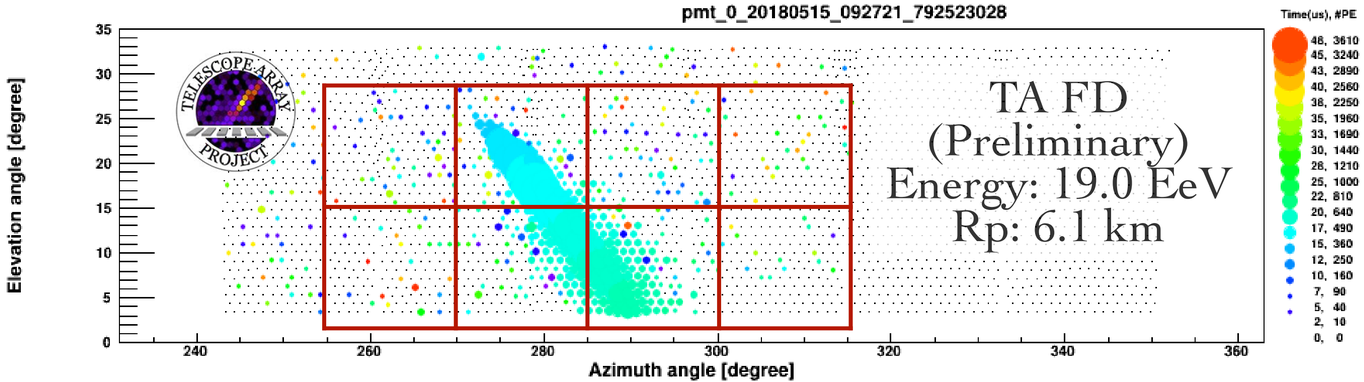
UHECR signal and reconstruction



FAST waveform + expected signal from top-down reconstruction

(Data, simulation by the best-fit parameters)



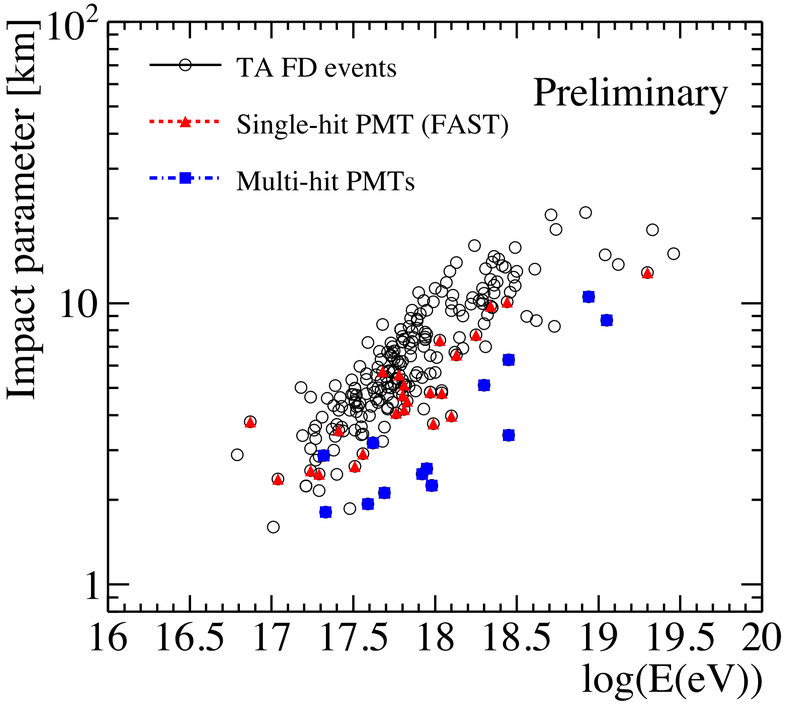


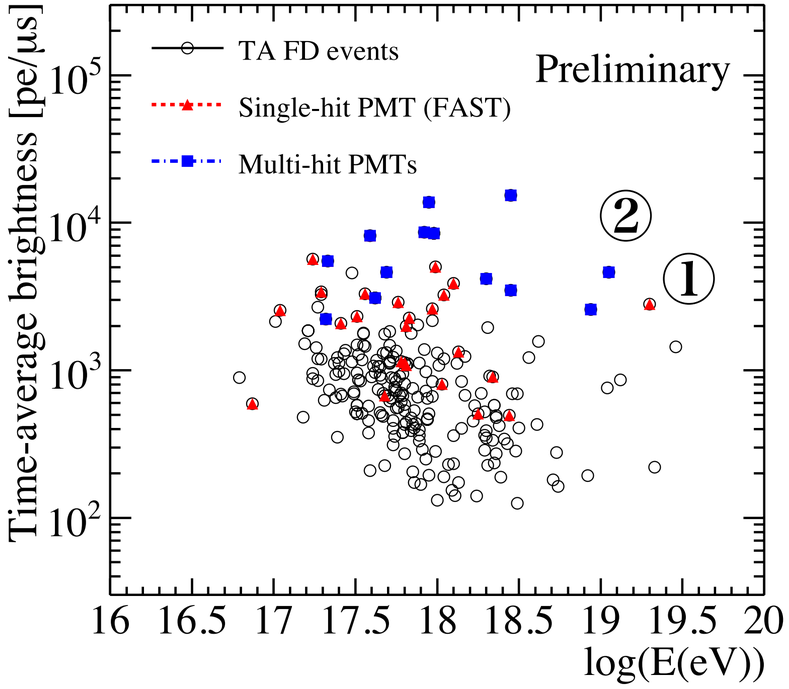
FAST top-down reconstruction (Preliminary)

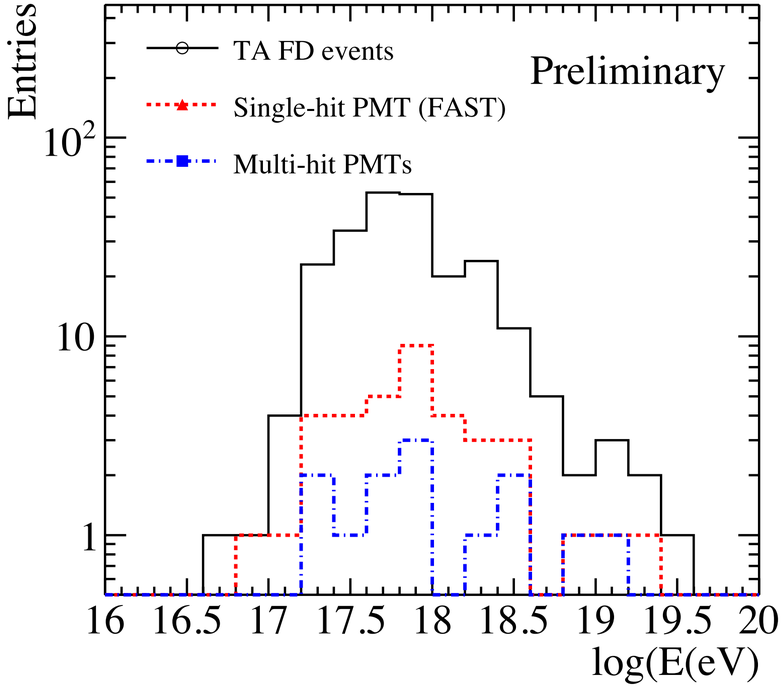
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
59.8 deg	-96.7 deg	7.9 km	-9.0 km	842 g/cm^2	17.3 EeV

Coincidence shower search between TA FD and FAST

- Data period: 2018/Oct/06 - 2019/Jan/14, 52 hours with **3 FAST prototypes**
- Event number: **236** (TA FD) -> **37** (significant signals with FAST, S/N > 6σ, Δt > 500 ns)
  - The shower parameters are reconstructed by TA FD monocular analysis.



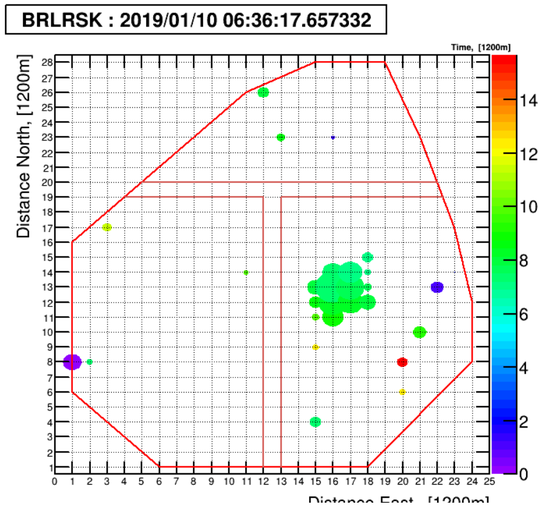


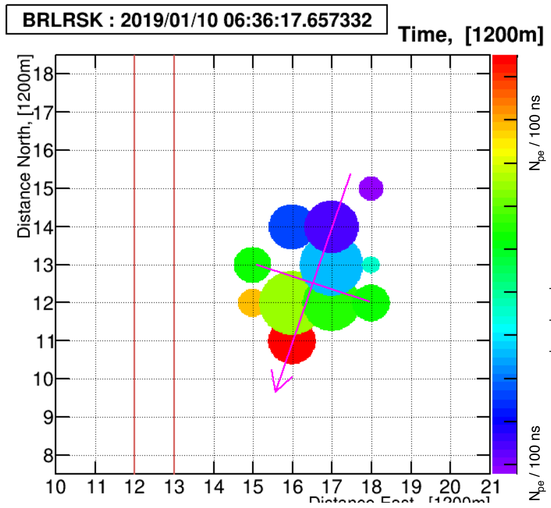


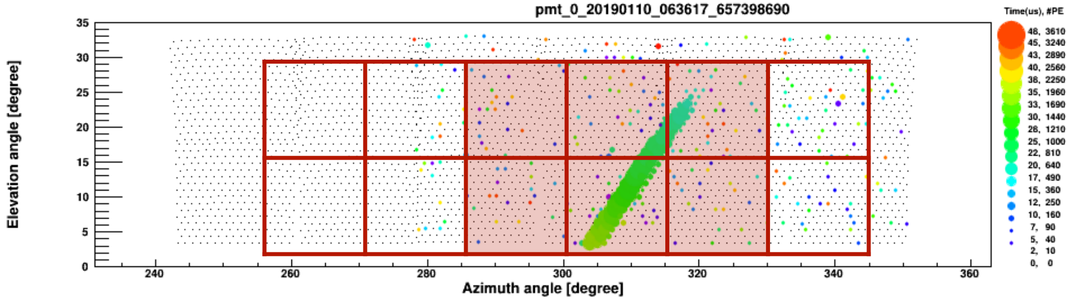
- Maximum detectable impact parameter: **~20 km at $10^{19.5}$ eV** with brighter signal showers
  - 2 events above 10 EeV in 52 hours → **~25 events/year** (15% duty cycle)

① Highest energy event

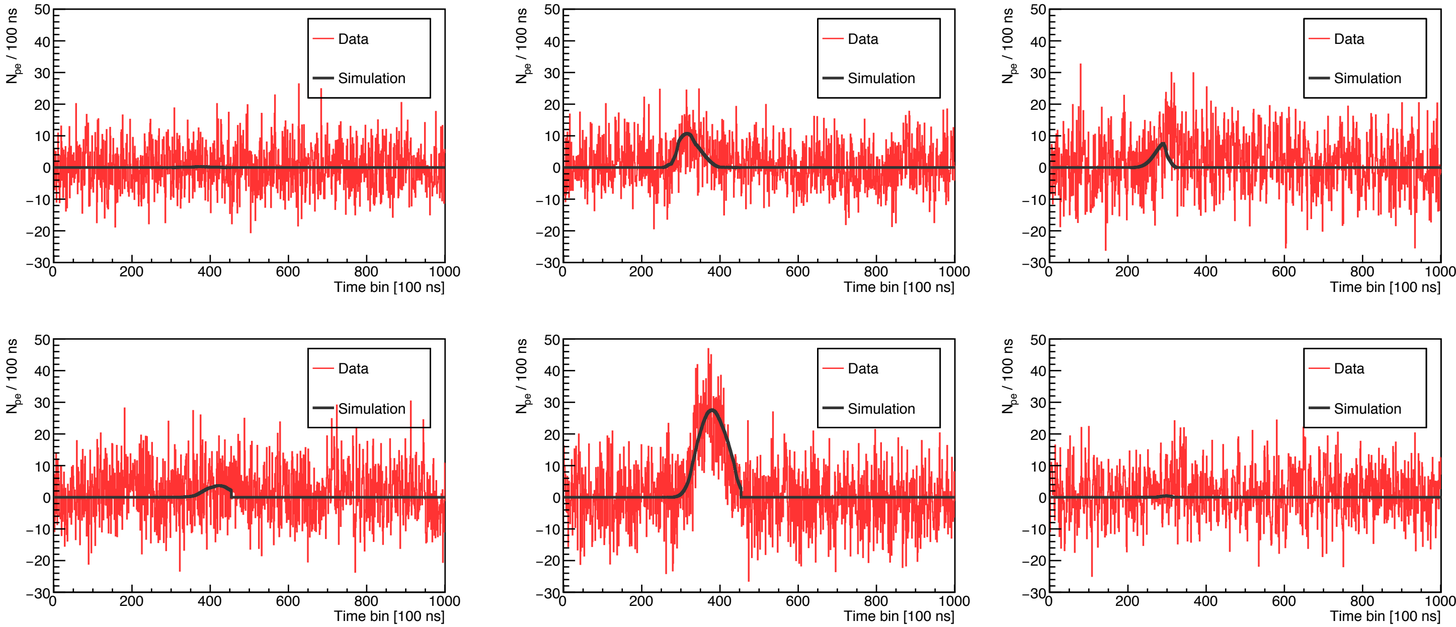
TA data







FAST data



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)

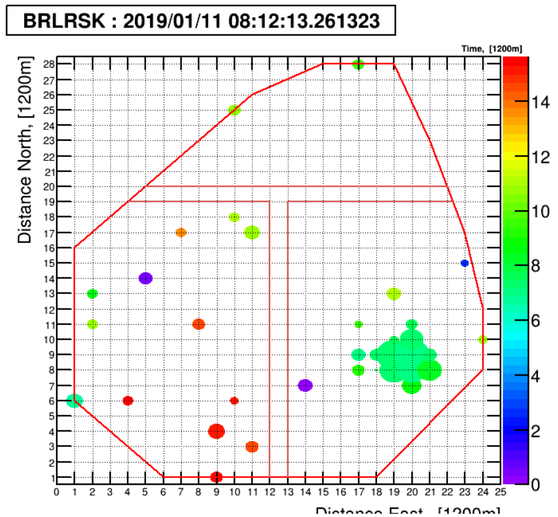
33.2 deg	35.8 deg	6.1 km	-5.3 km	20.0 EeV

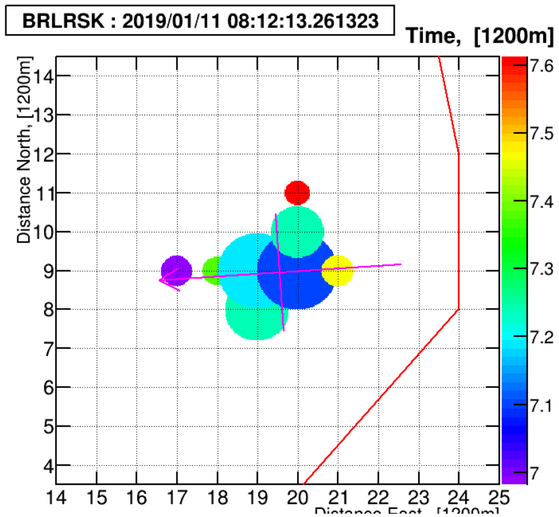
FAST top-down reconstruction (Preliminary)

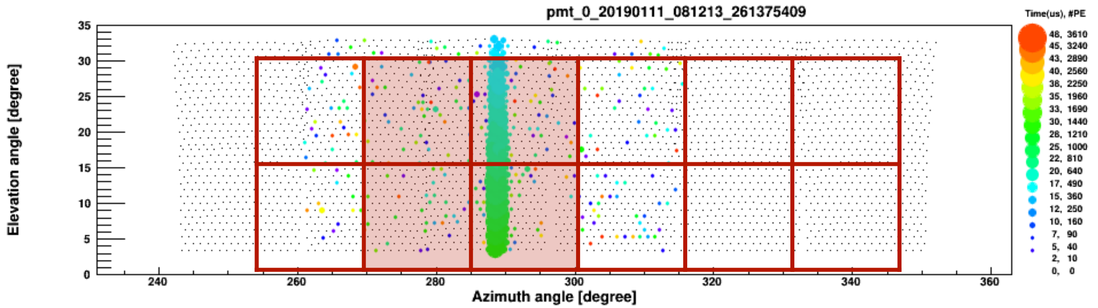
Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
33.9 deg	19.3 deg	4.6 km	-4.7 km	808 g/cm^2	18.8 EeV

② Second highest energy event

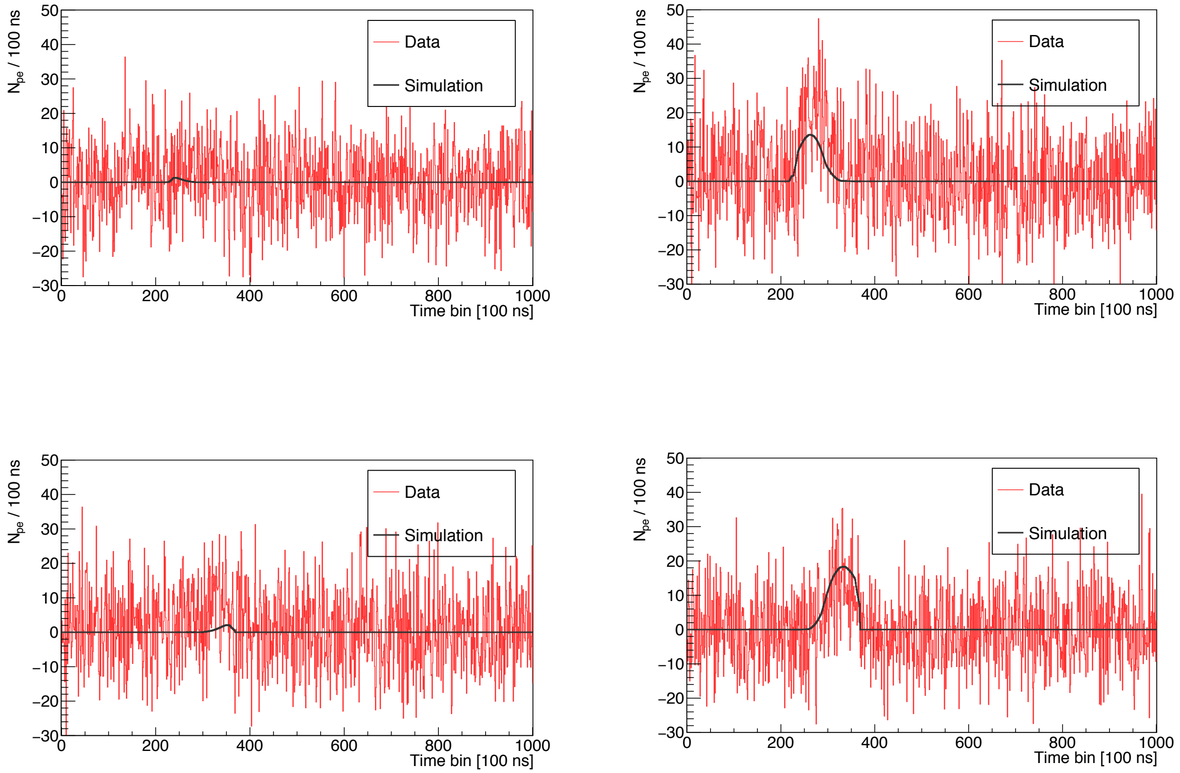
TA data







FAST data



TA SD (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Energy
4.5 deg	88.3 deg	8.8 km	-9.2 km	12.3 EeV

TA FD (Preliminary)

5.2 deg	106.0 deg	8.7 km	-9.3 km	11.2 EeV

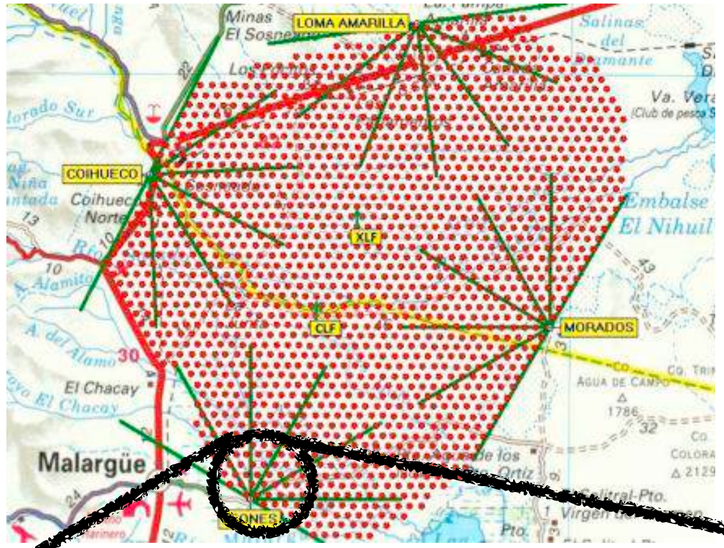
FAST top-down reconstruction (Preliminary)

Zenith	Azimuth	Core(X)	Core(Y)	Xmax	Energy
3.3 deg	110.5 deg	8.7 km	-9.2 km	830 g/cm^2	10.3 EeV

Installation of 1st FAST prototype in Auger

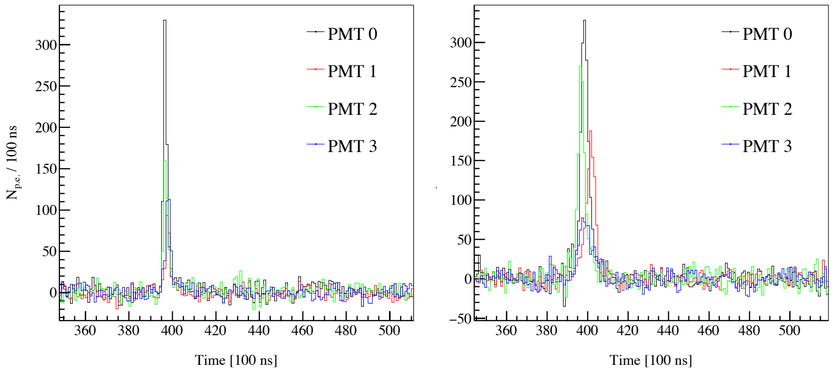
FAST
Fluorescence detector Array of Single-pixel Telescopes

Pierre Auger Observatory
Malargue, Argentina

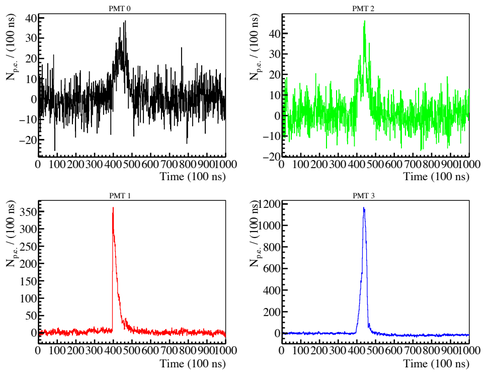


Start observation from April 11th, 2019

Cherenkov signal



Horizontal laser signal



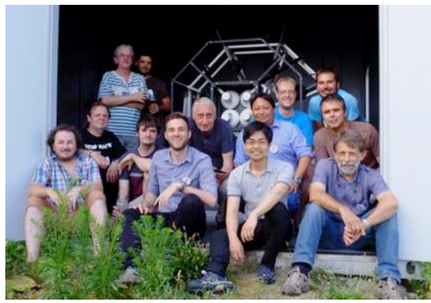
Summary and future plans

- **Fluorescence detector Array of Single-pixel Telescopes (FAST)**
  - **10×statistics** compared to Auger and TA×4 **with X_{max}**
  - **Directional anisotropy on arrival direction, energy spectrum and mass composition**

- Installed total 3 telescopes at Telescope Array site and 1st telescope in the Pierre Auger Observatory
  - Stable observation with remote controlling
  - UHECR detections, and their reconstruction method implemented.

- We will continue to operate the telescopes and search for UHECR in coincidence with current observatories.
  - A resolution study with the full FAST array
  - Developing new electronics, and preparing for stand-alone operation

http://www.fast-project.org

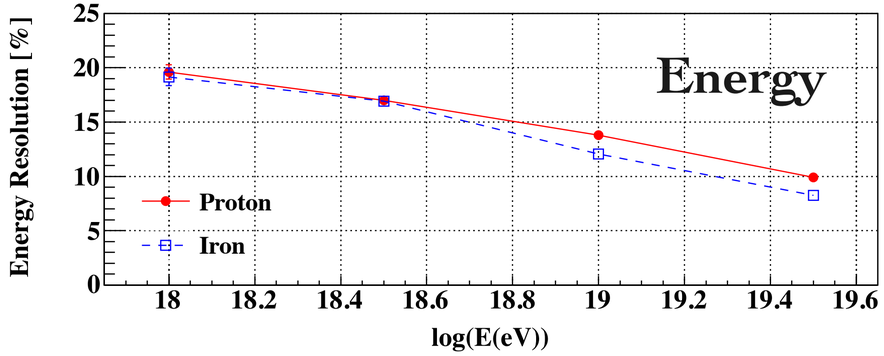


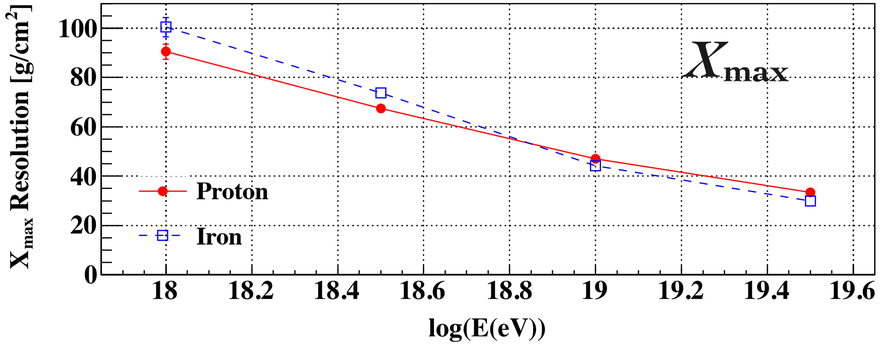
New collaborators are welcome!

Backup

Application of the FAST prototypes

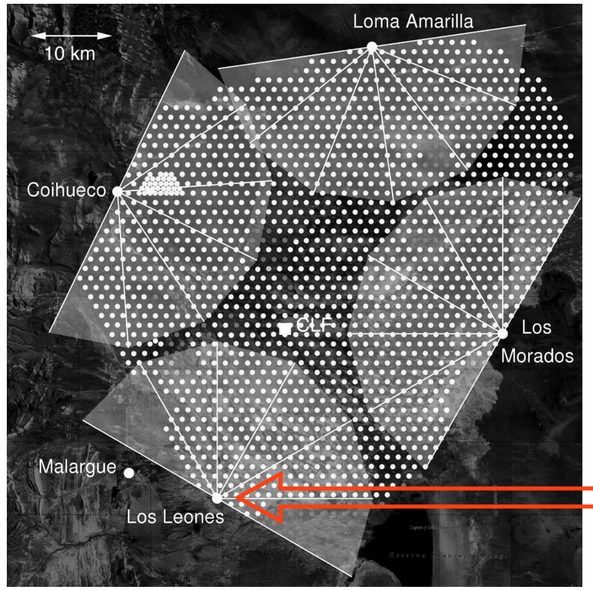
- Install the FAST prototypes at Auger and TA for a study of systematic uncertainties and a cross calibration.
- Profile reconstruction with geometry given by surface detector array (1° in direction, 100 m in core location).
  - Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
  - Independent check of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



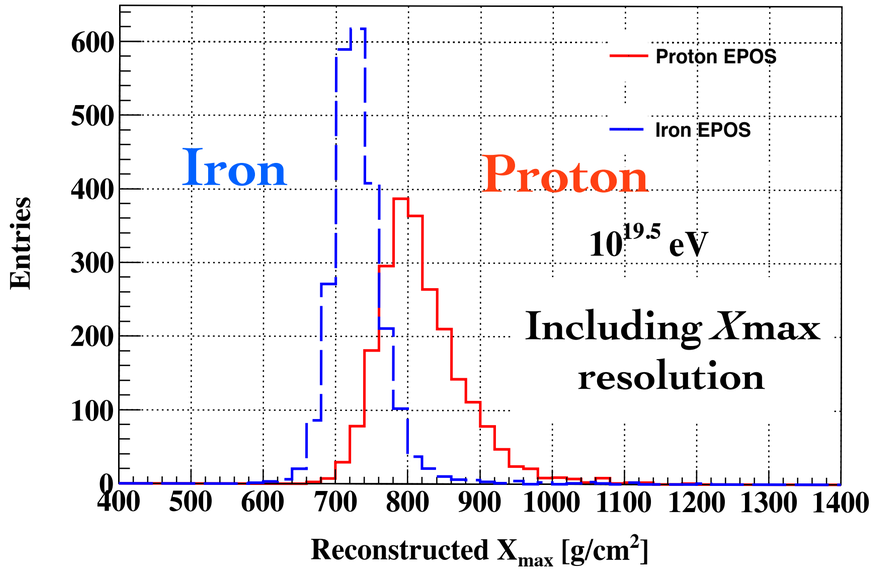


T. Fujii et al., Astropart.Phys., *74*, pp64-72 (2016)

Pierre Auger Observatory

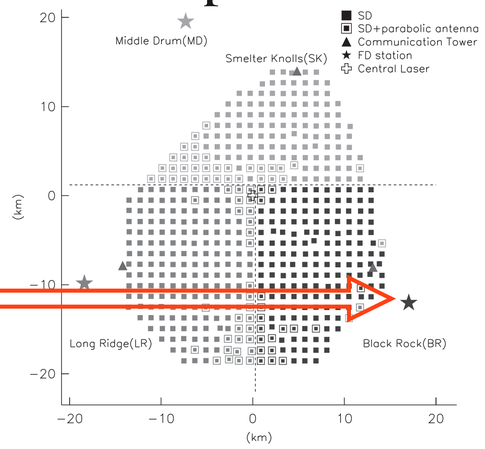


Auger collab., NIM-A (2010)



Identical simplified FD

Telescope Array Experiment

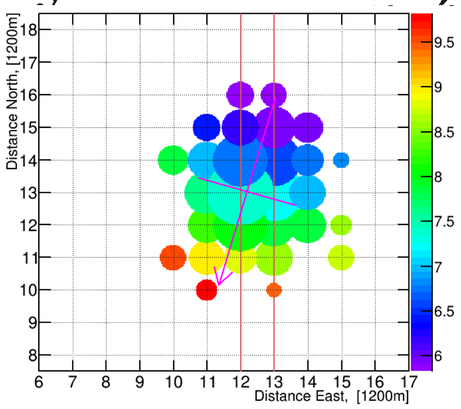


TA collab., NIM-A (2012)

Data analysis and simulation study

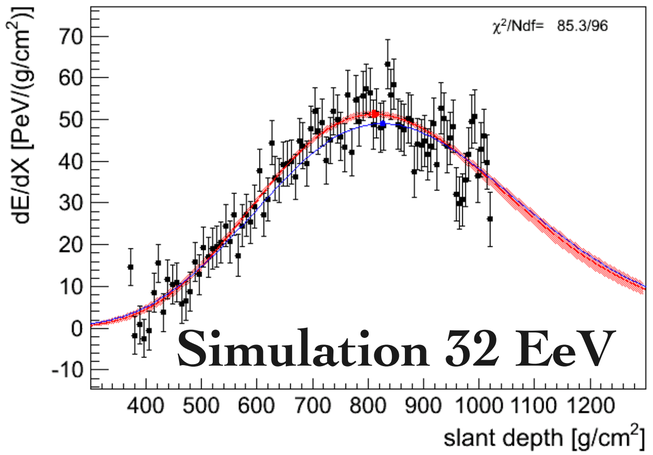
FAST hybrid reconstruction

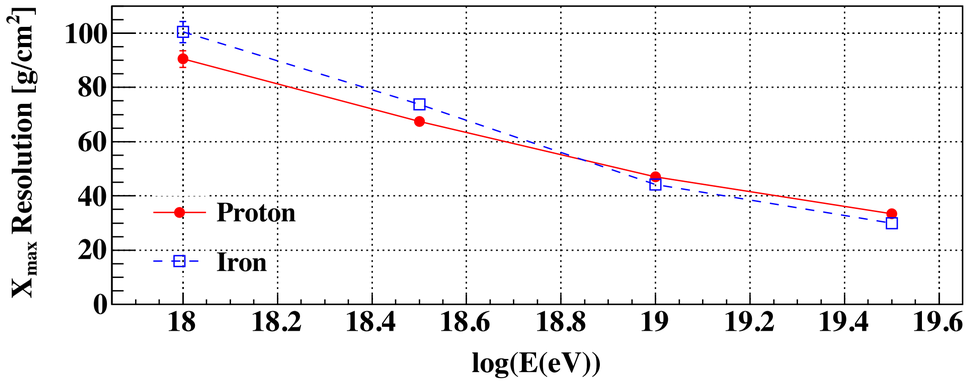
Geometry (given by TASD or FD)



+

Shower Profile (FAST)

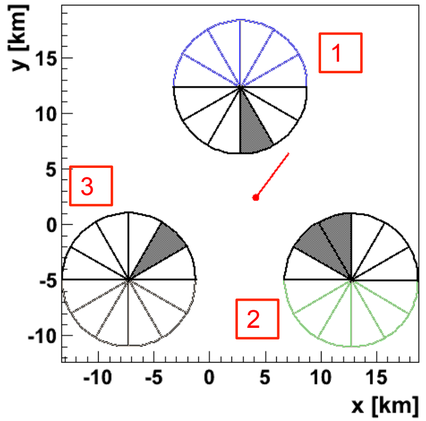


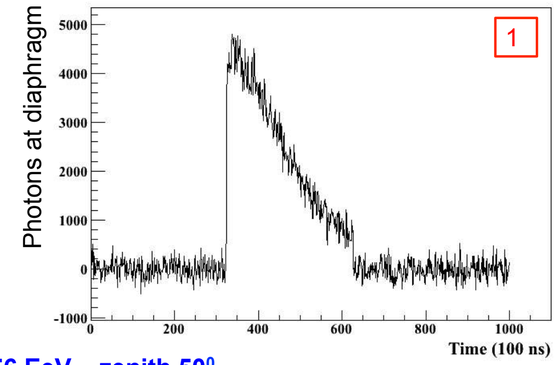


- Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
- Independent cross-check of energy and Xmax scale with simplified FD.

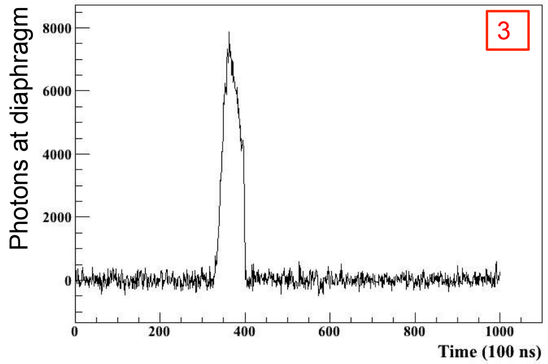
FAST reconstruction

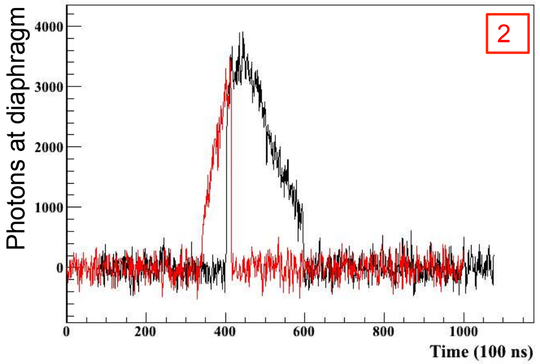
57 EeV Simulation





56 EeV zenith 50^0



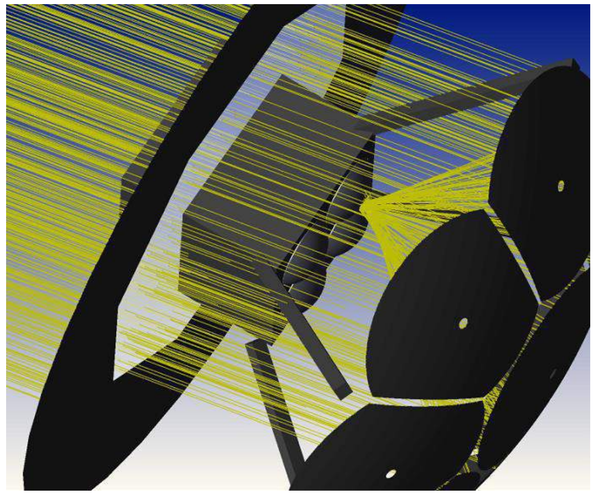


- Fluorescence detector array with a 20 km spacing.
- Reconstruct geometry and profile

Data/MC comparison with vertical UV laser

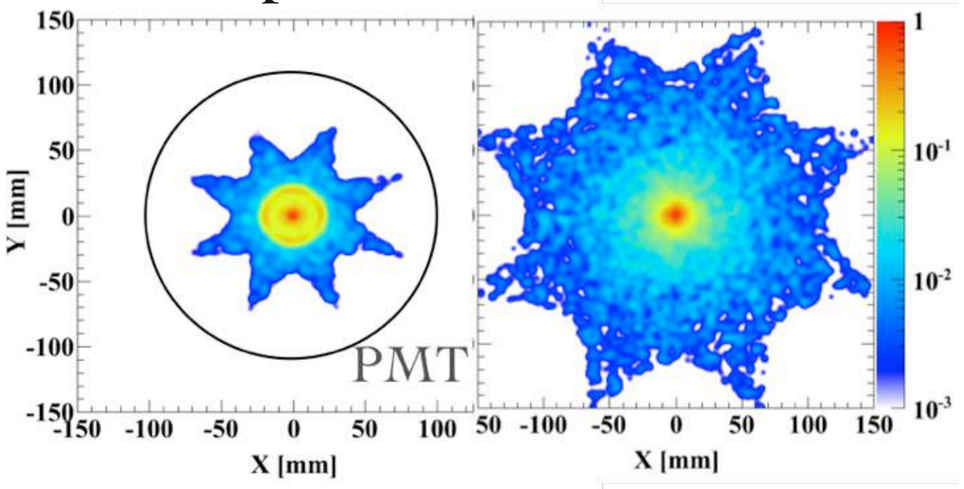
Fluorescence detector Array of Single-pixel Telescopes

Work: Miroslav Pech, Max Malacari

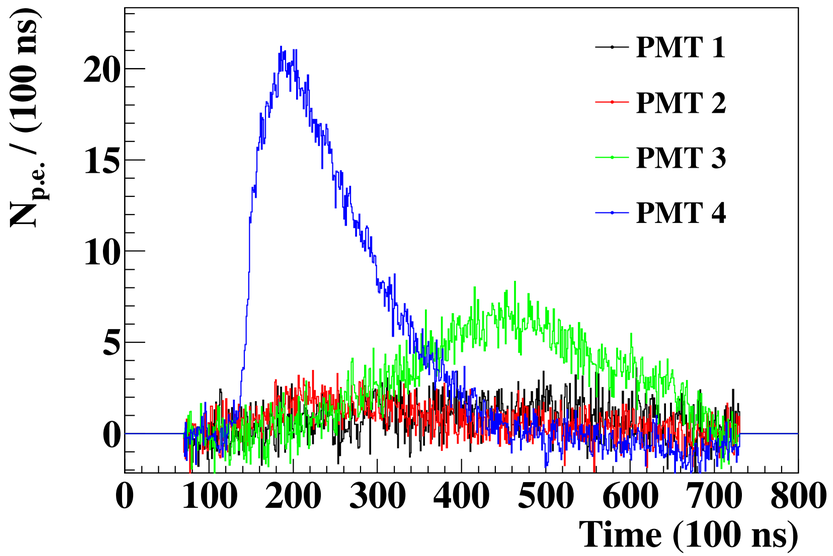


Spot-size

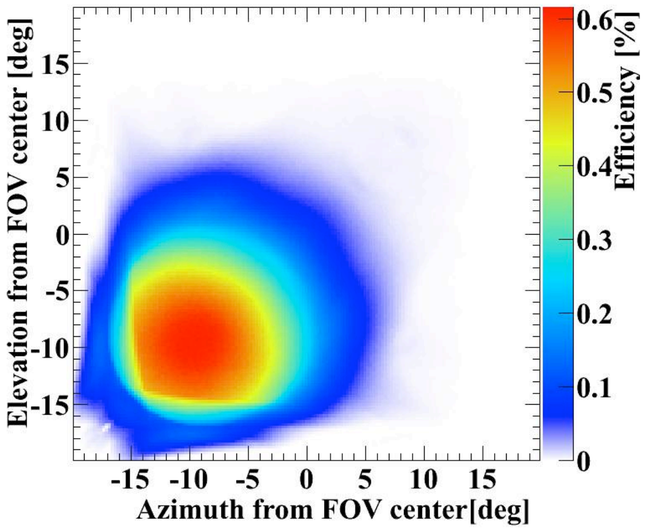
focal plane 50 mm offset



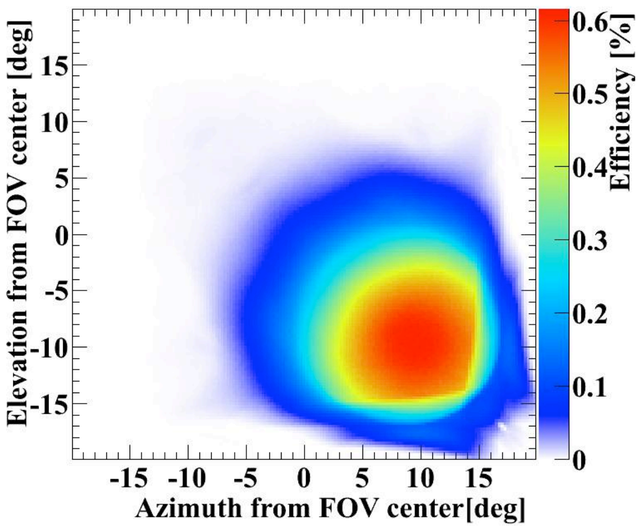
A UV vertical laser at 21 km away

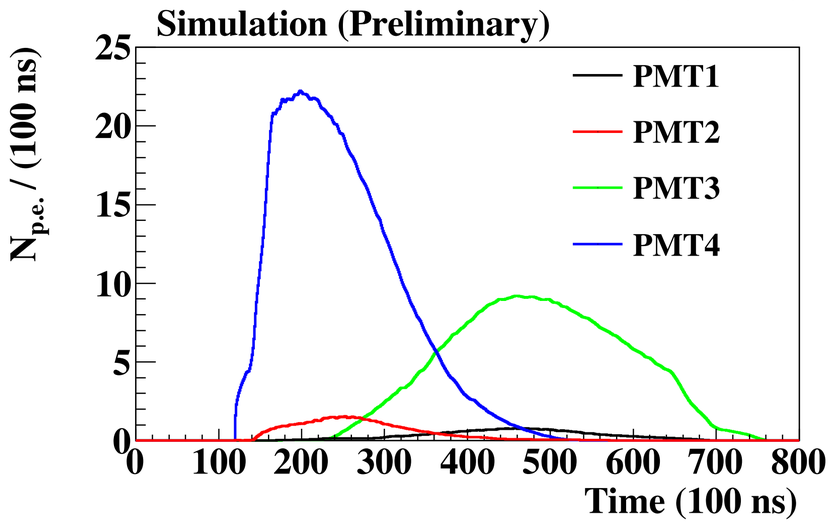


Directional characteristic (PMT2)



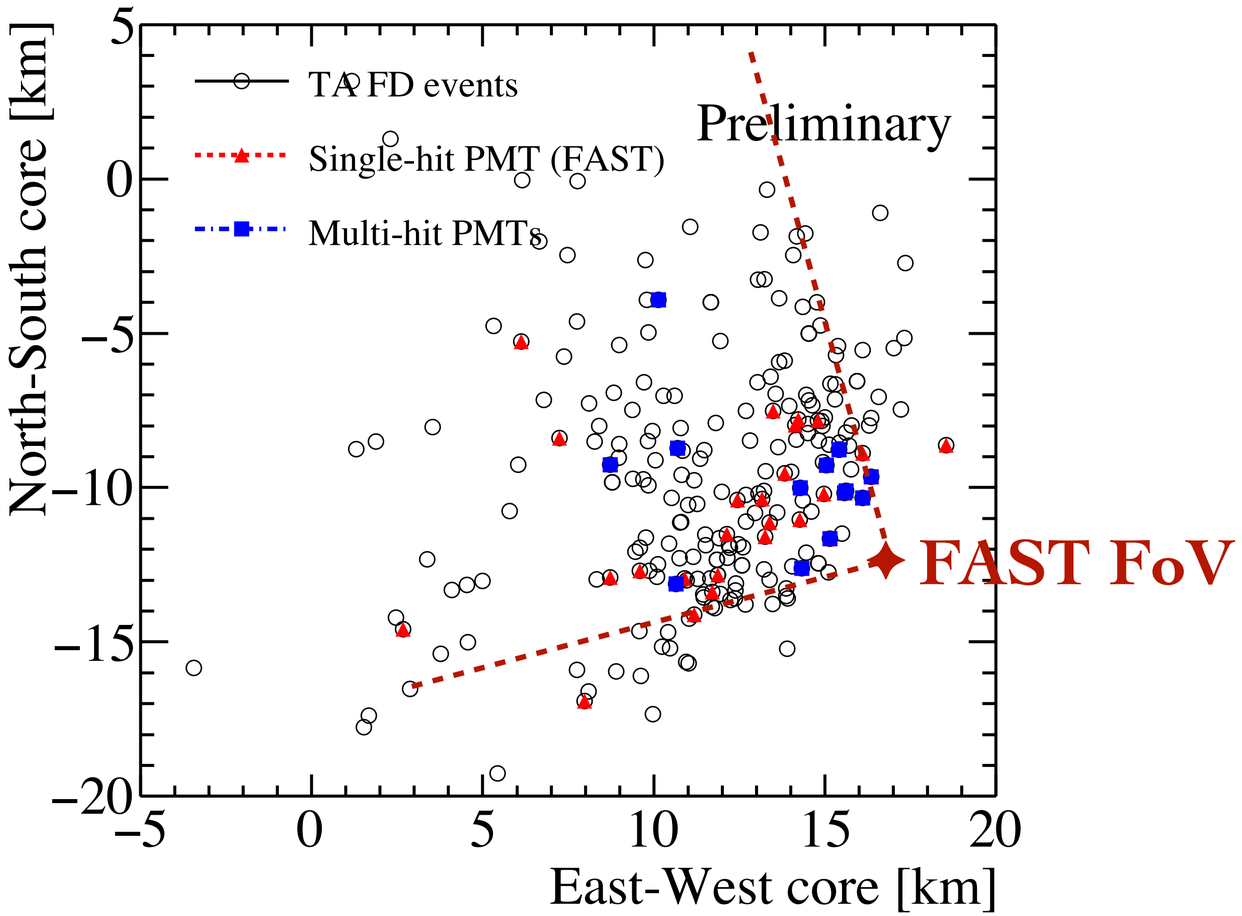
(PMT 4)

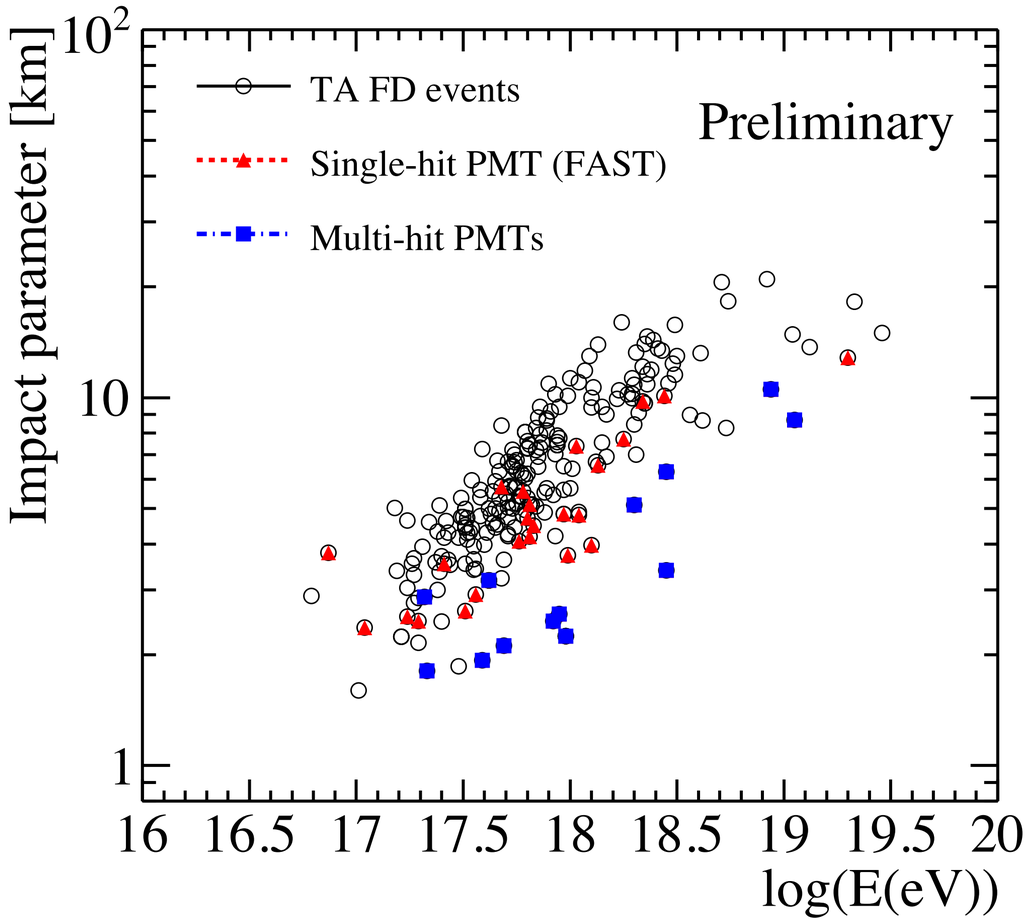




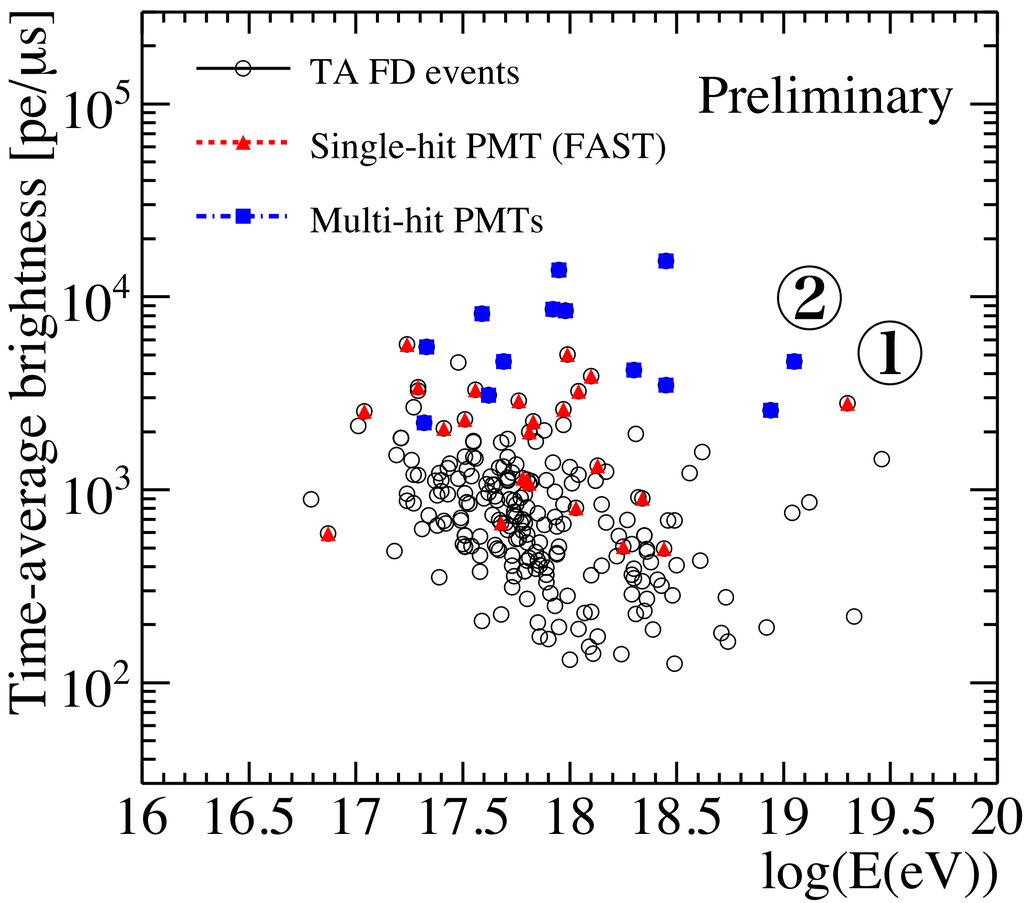
Coincidence shower search between TA FD and FAST

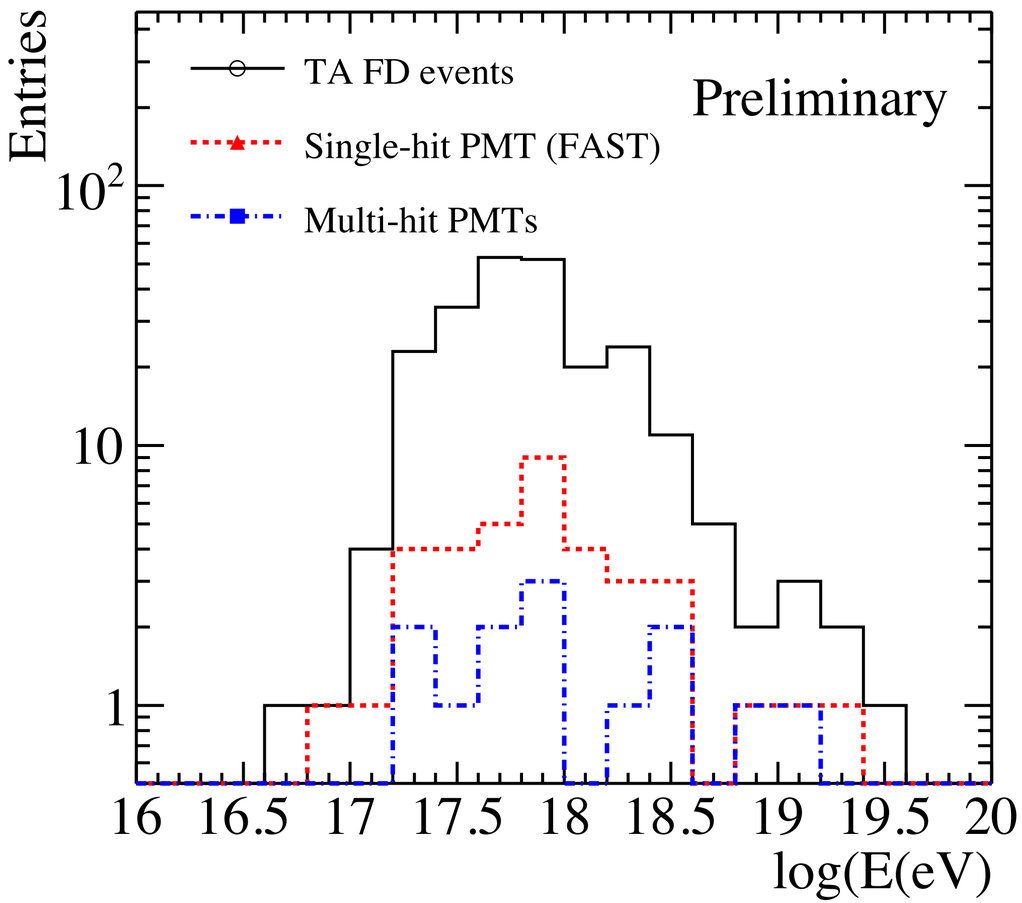
- Data period: 2018/Oct/06 - 2019/Jan/14, 52 hours, **3 FAST prototypes**
- Event number: **236** (TA FD) -> **37** (significant signals with FAST, S/N > 6σ, Δt > 500 ns)
  - The shower parameters are reconstructed by TA FD.





Coincidence showers between TA FD and FAST



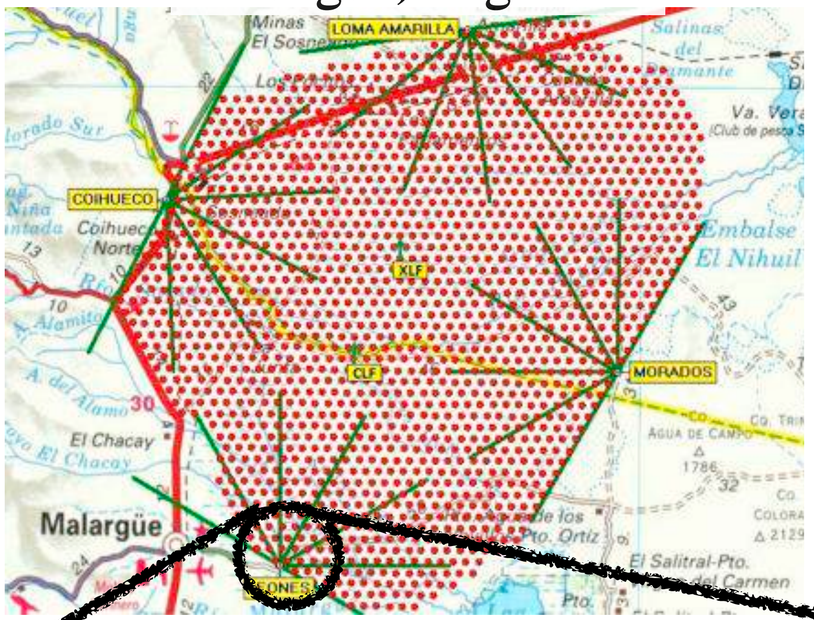


- Maximum detectable impact parameter, **~20 km at $10^{19.5}$ eV**, with brighter signal showers
- 2 events above 10 EeV in 52 hours → **~25 events/year** (15% duty cycle)

Installation of 1st FAST prototype in Auger

FAST
Fluorescence detector Array of Single-pixel Telescopes

Malargue, Argentina



Top-down reconstruction

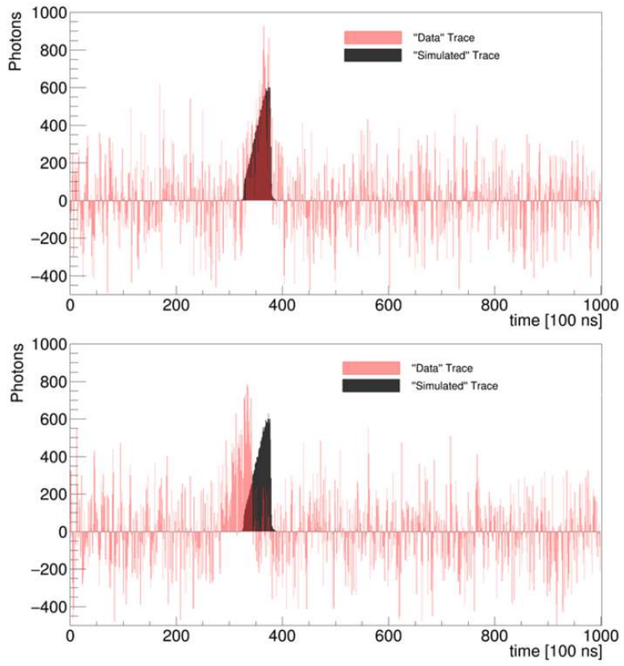
Top-Down Reconstruction

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

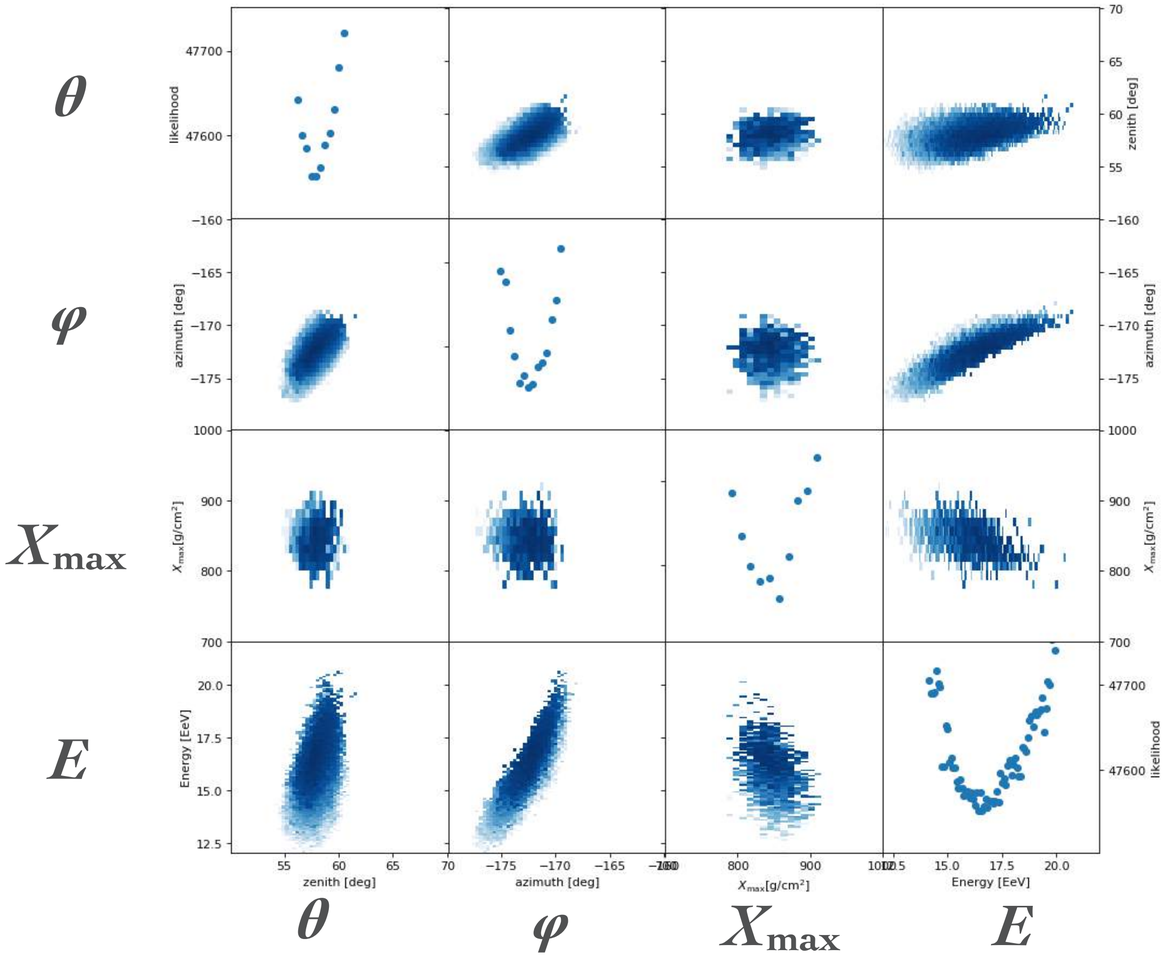
Data **Expected(θ,φ,x,y,E,$X_{\max}$)**

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

- A is a scale factor for shower energy



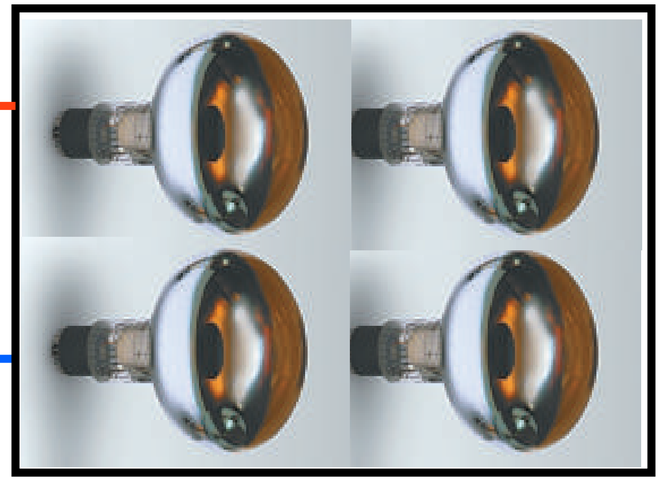
Work: Justin Albury, Jose Bellido



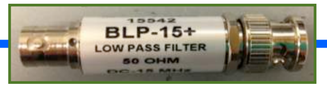
DAQ system

High voltage power supply, N1470 CAEN

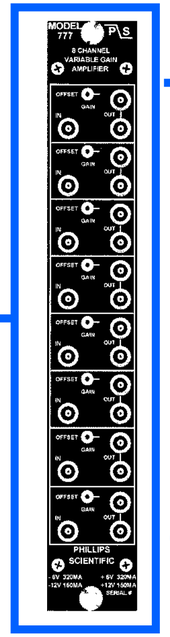
FAST Camera,
PMT R5912-MOD (8 dynodes)
Base E7694-01 (AC coupling),
HAMAMATSU



Gain
$= 5\times10^4$



15 MHz low pass filter



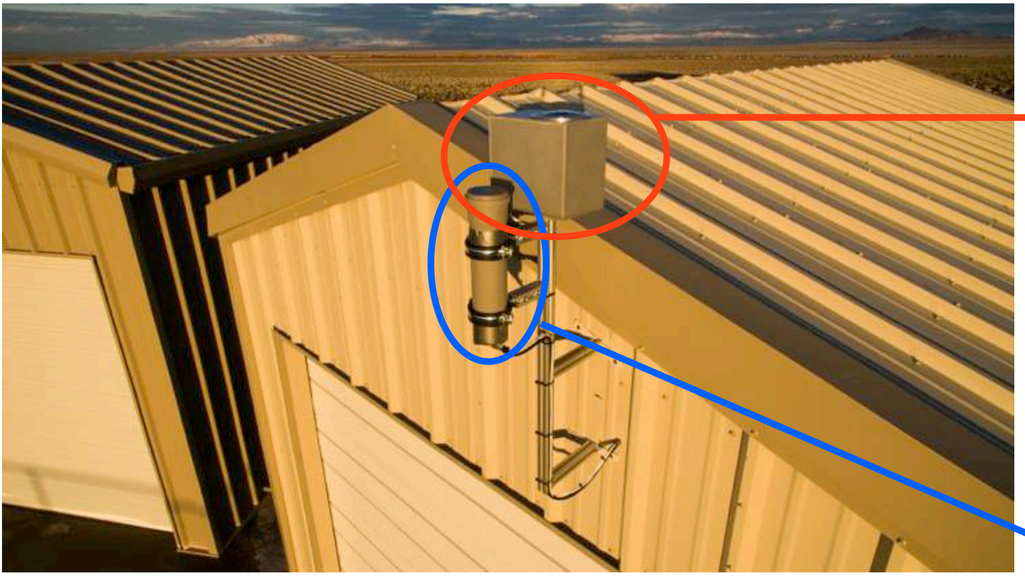
50x Amplifier Phillips Scientific 777

Portable VME Electronics
- FADC 50 MHz sampling, SIS3350
- GPS board, Hytec GPS2092
- Single board PC, GE 7865

Real-time night sky monitoring

Fluorescence detector Array of Single-pixel Telescopes

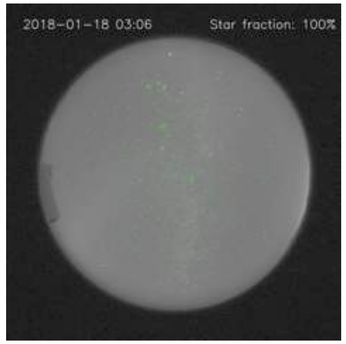
Work: Dusan Mandat, Ladislav Chytka

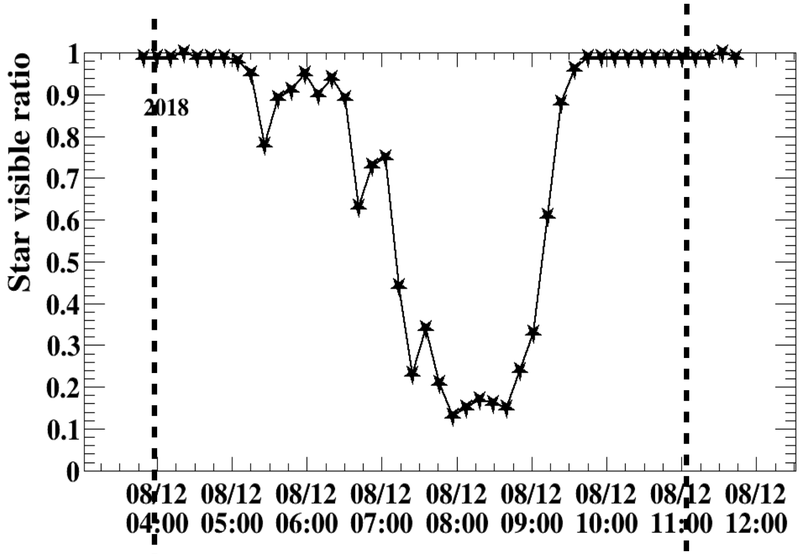


All sky camera

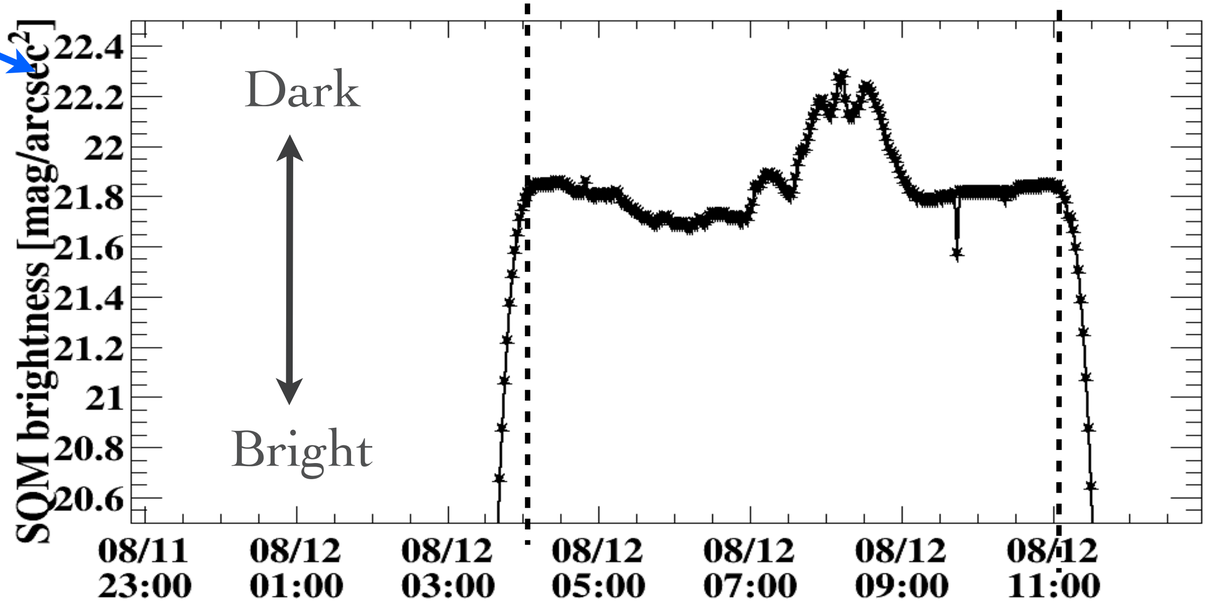
Cloudy

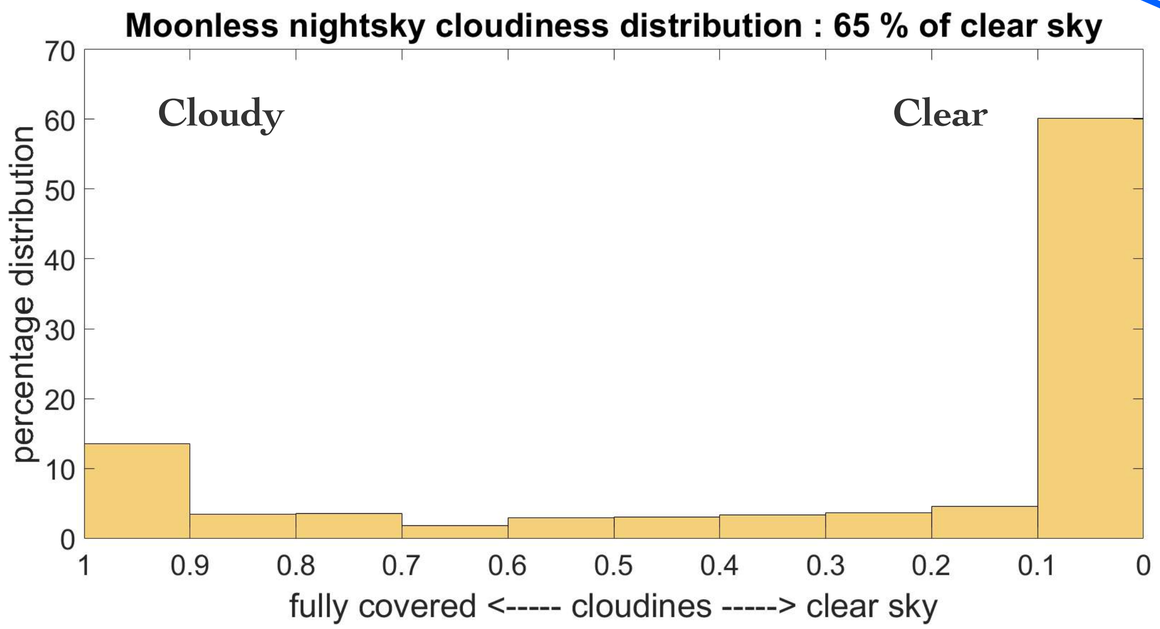
Clear





Sky quality monitor



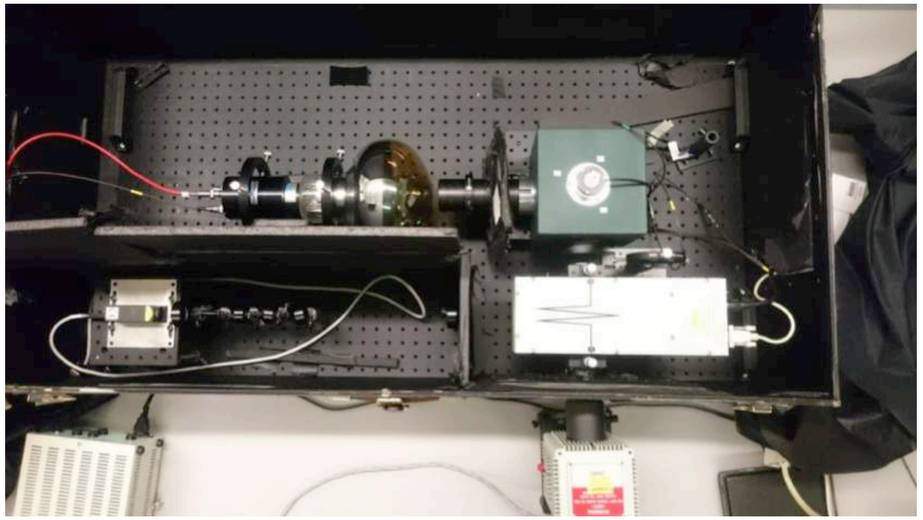


Calibrations for FAST

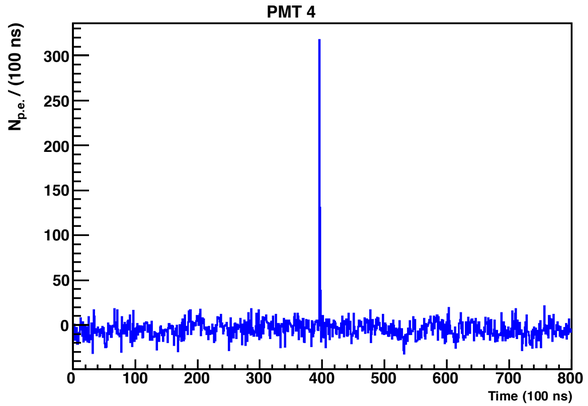
Fluorescence detector Array of Single-pixel Telescopes

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

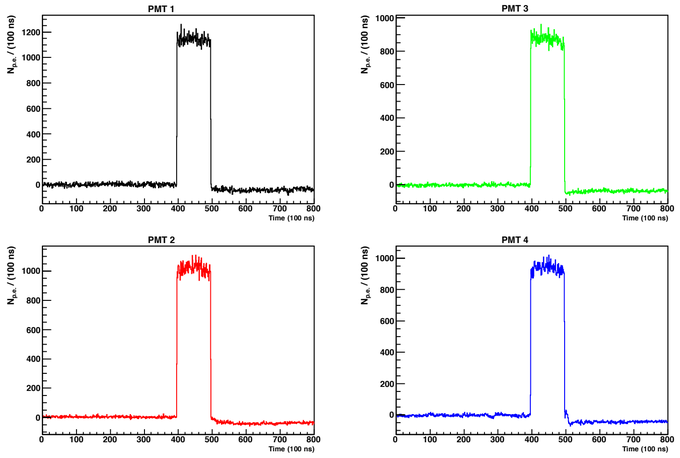
Absolute calibration in laboratory



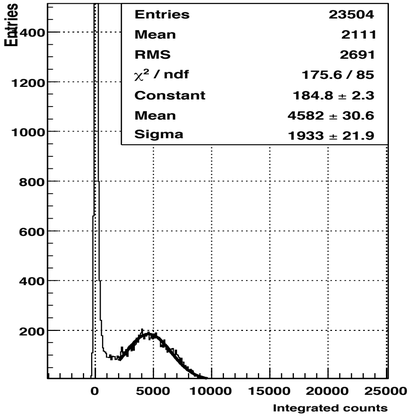
YAP pulser ($YAlO_3$:Ce scintillator + ^{241}Am source) attached on each PMT surface



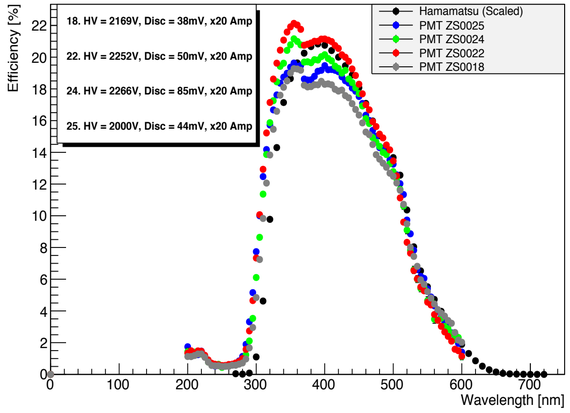
Ultraviolet LED illuminating the front of the camera

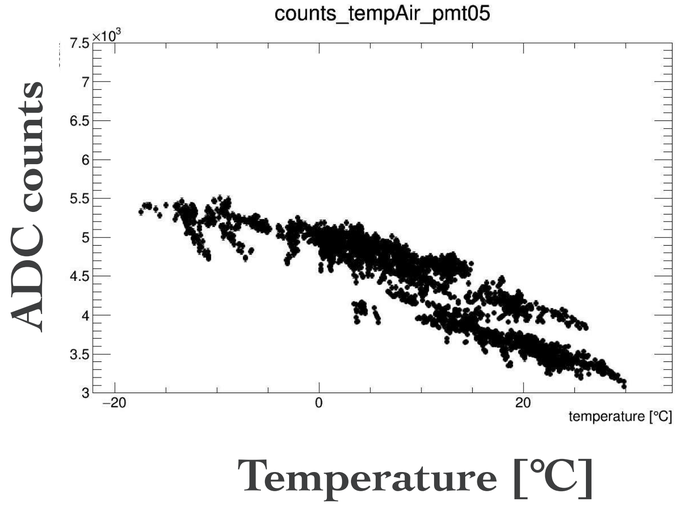


Single photo electron

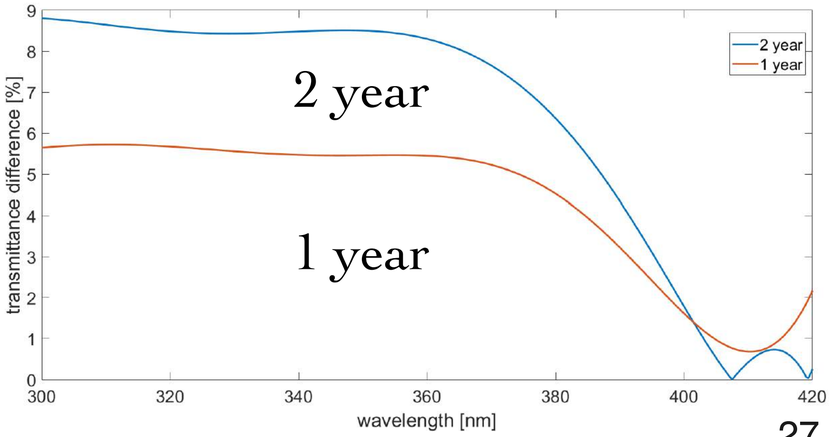


Detection efficiency

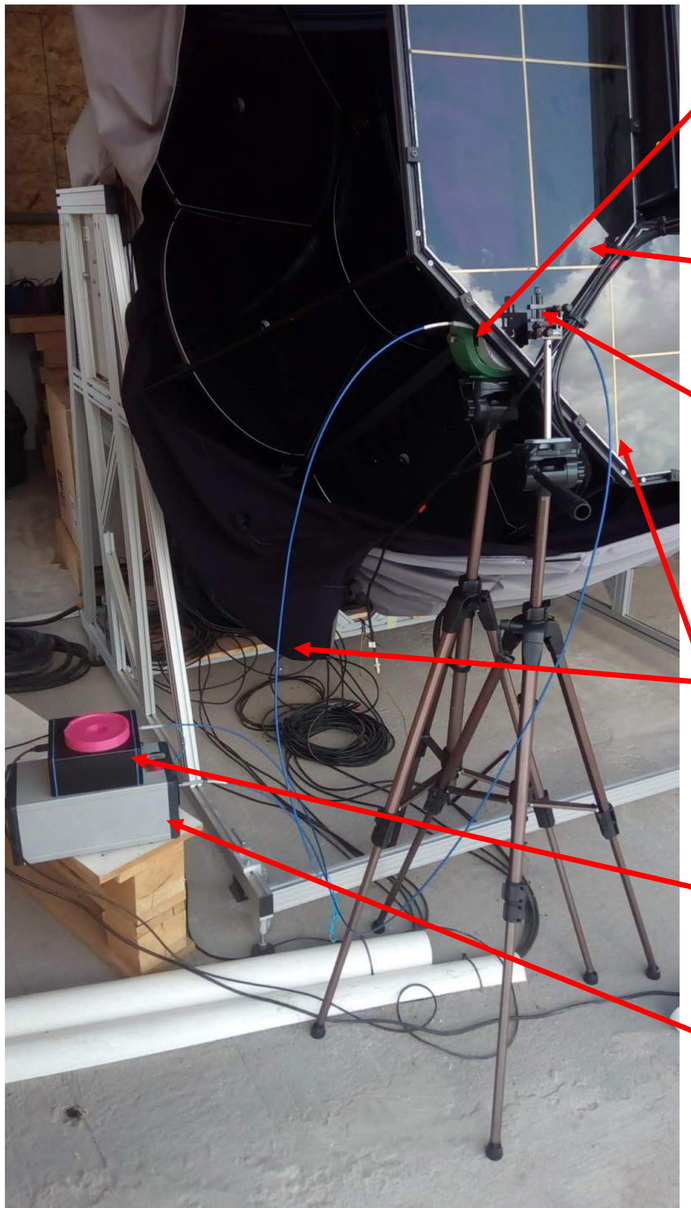




Filter transmittance difference



Filter transmittance measurement at site



Intergrating sphere :
AvaSphere-80-Refl

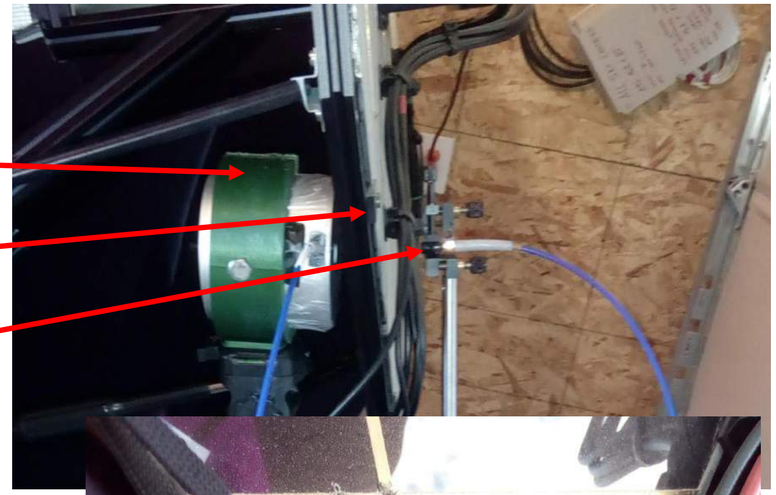
UV filter

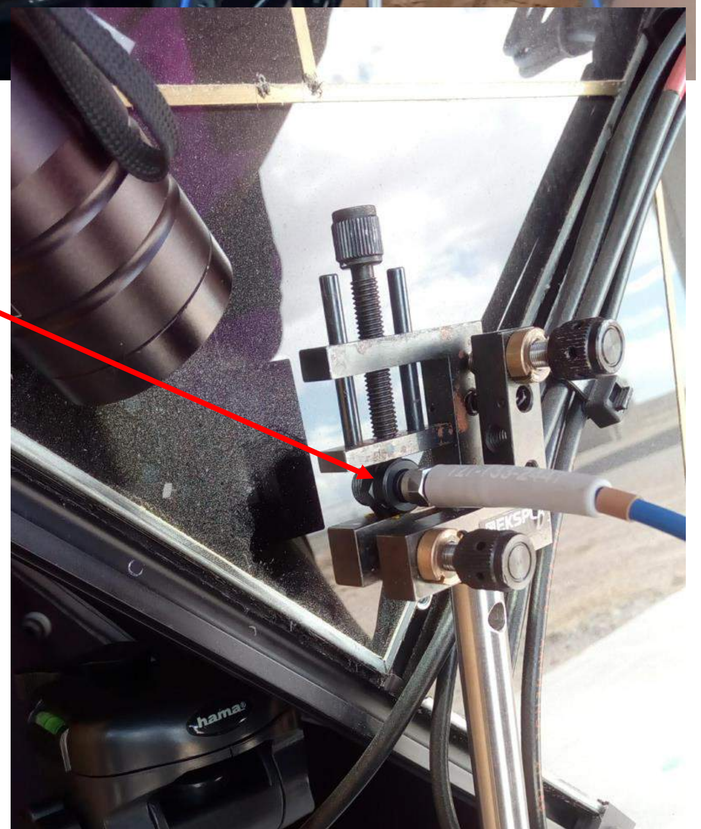
Colimator

Optical Fiber :
FC-XX800-2

Spectrophotometr :
AvaSpec-ULS2048L-USB2-UA-RS

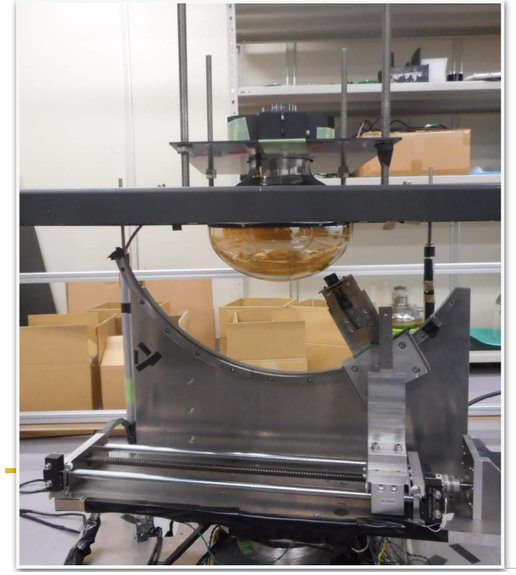
Deuterium/halogen lamp 78W
deuterium, 5W halogen

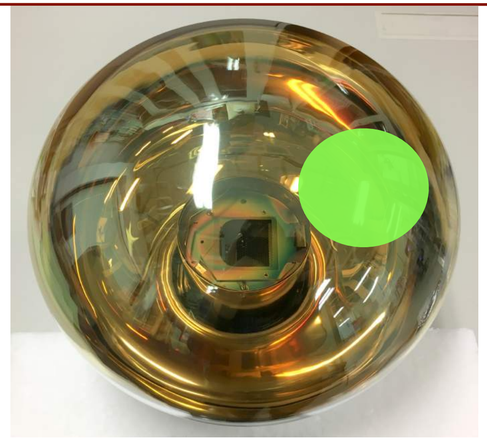


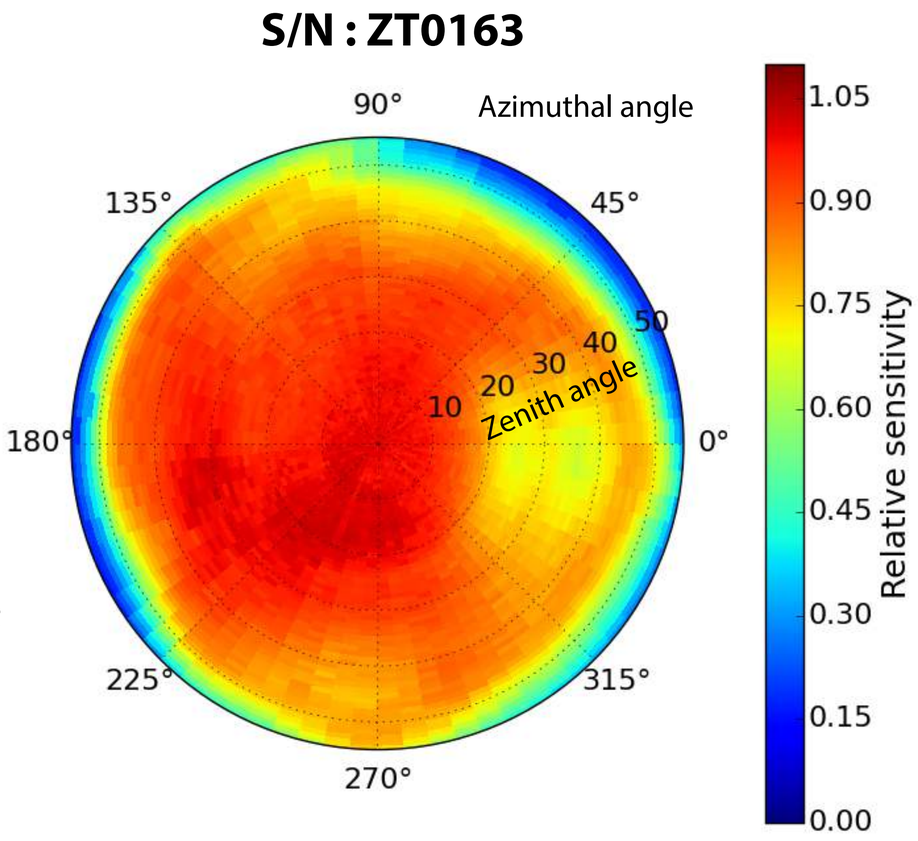


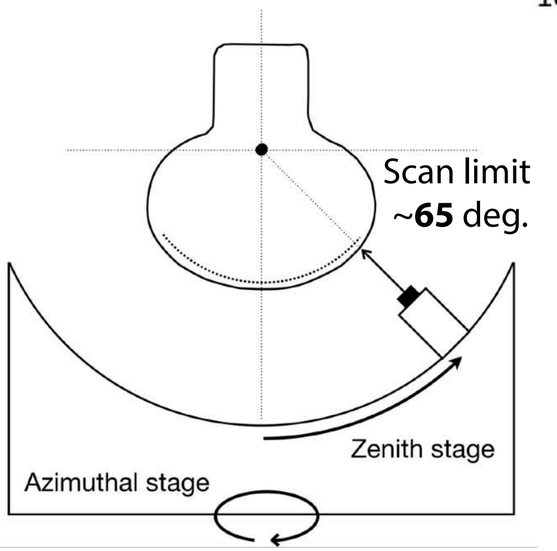
Non-uniformity on PMT surface

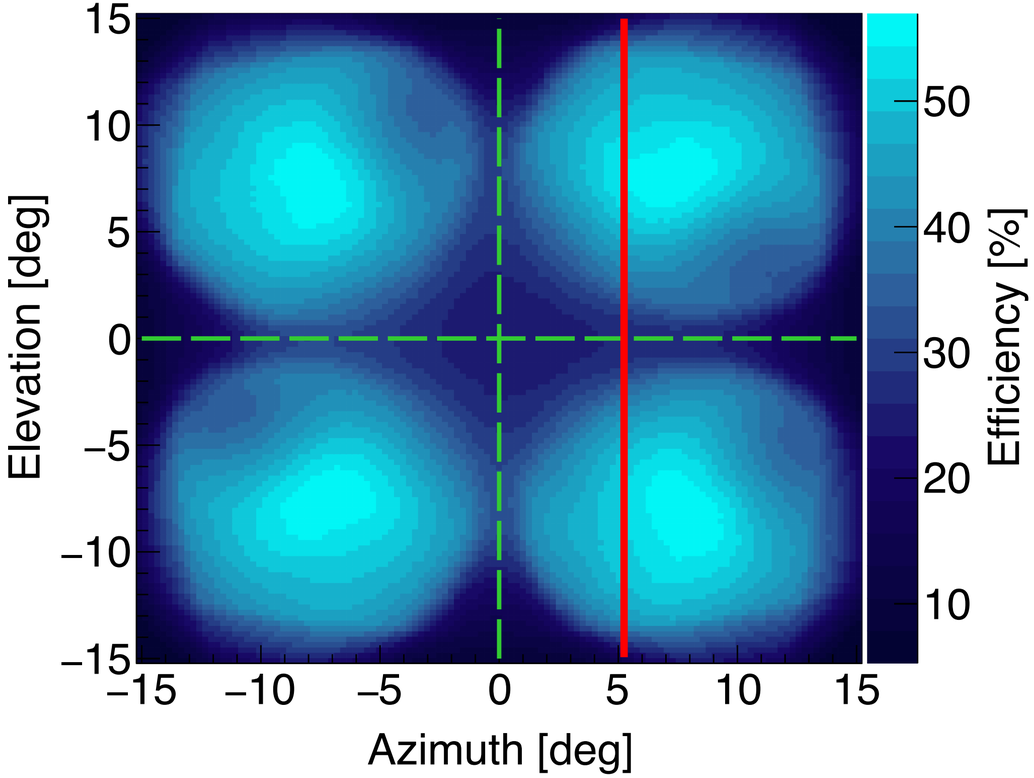
By a courtesy of the IceCube group in Chiba University, especially thank to **Dr. Yuya Makino**





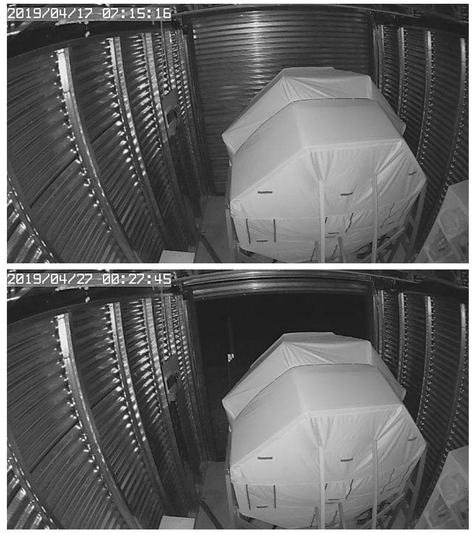




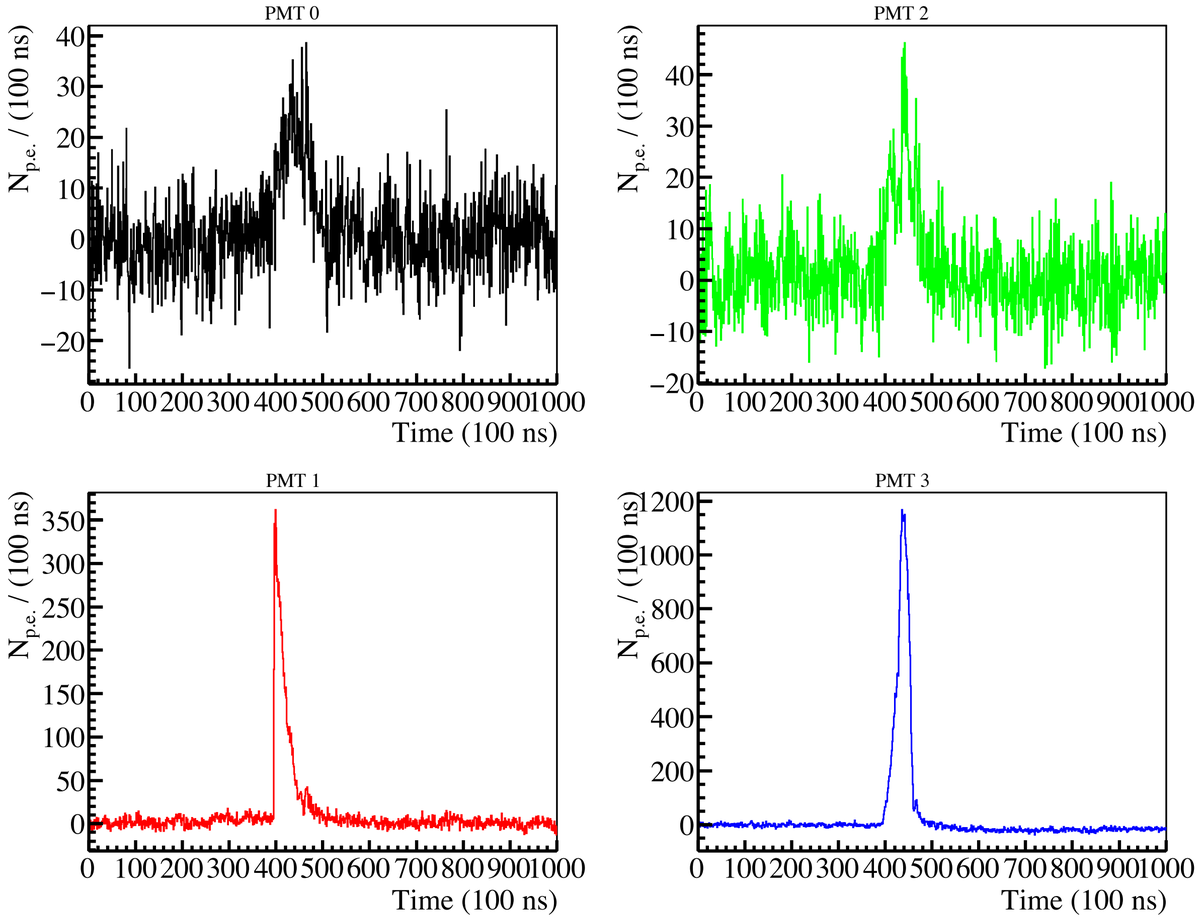


Signal detections from laser and showers

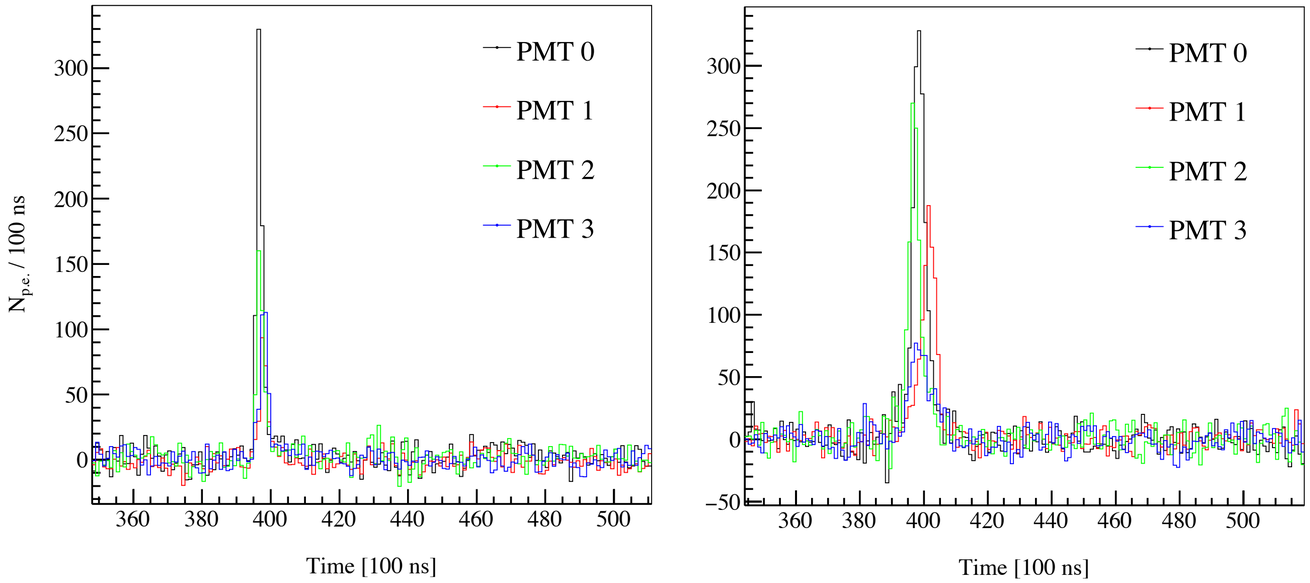
- 85 hour observation time
- Remote controlling observation
- Commissioning by self-trigger mode



A horizontal laser shot toward FAST telescope from 26 km away.



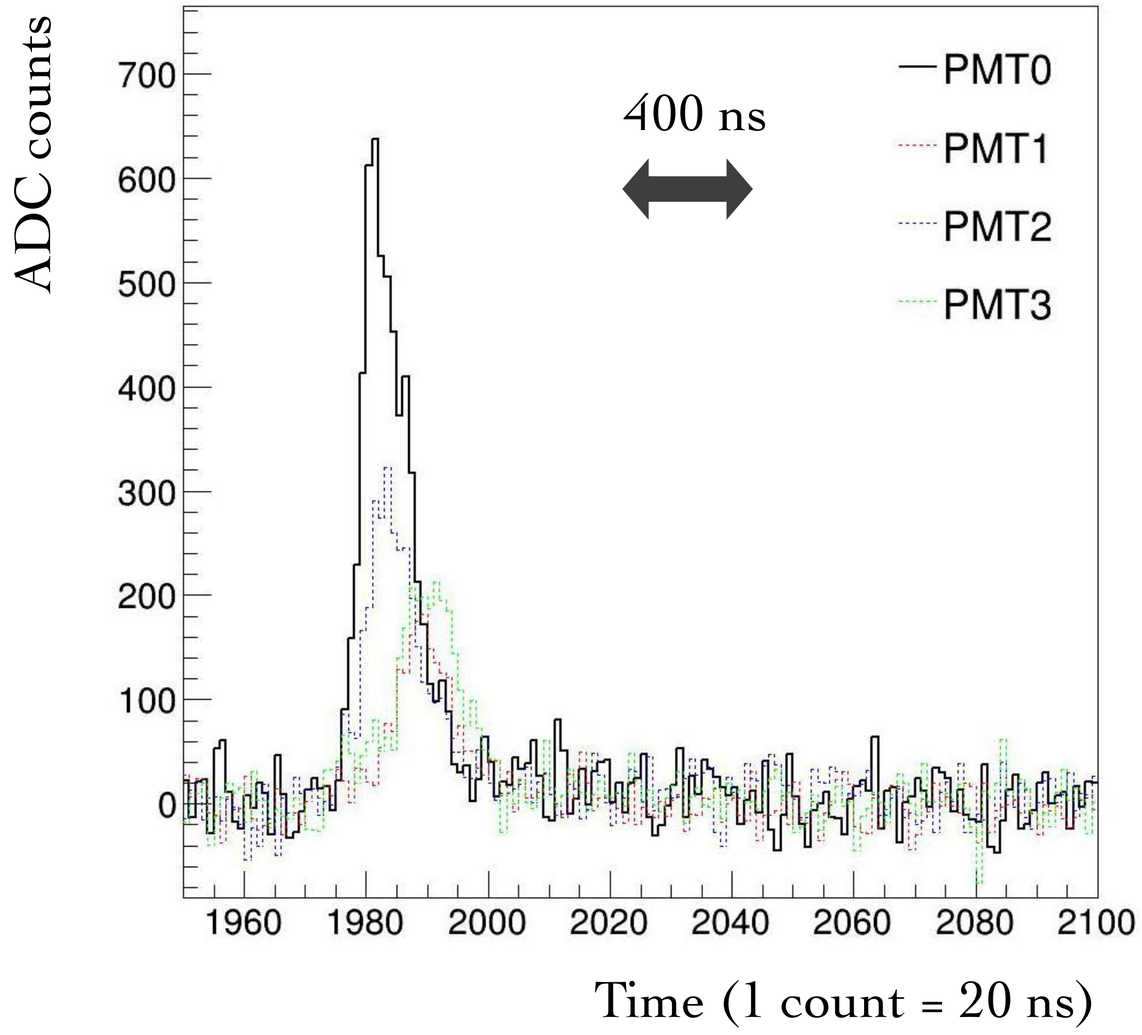
Cherenkov dominated signals

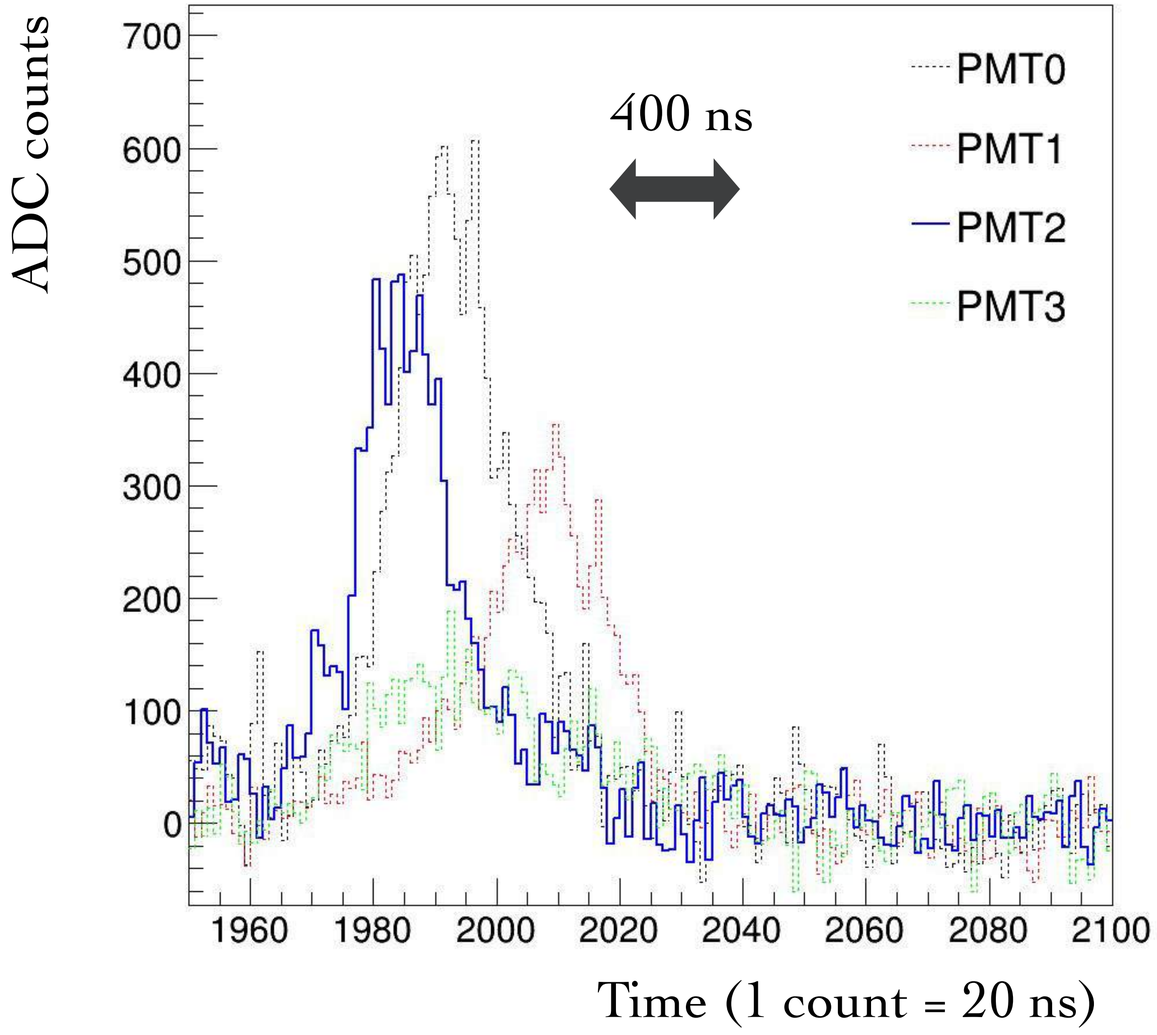


Cosmic ray events (Cherenkov)

Fluorescence detector Array of Single-pixel Telescopes

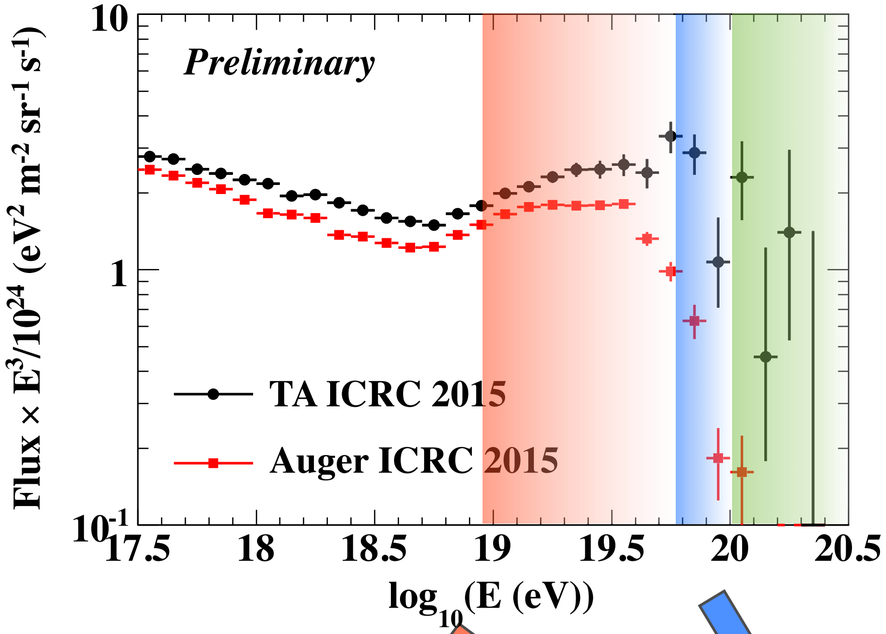
Work: Petr Hamal, Jiri Kvita

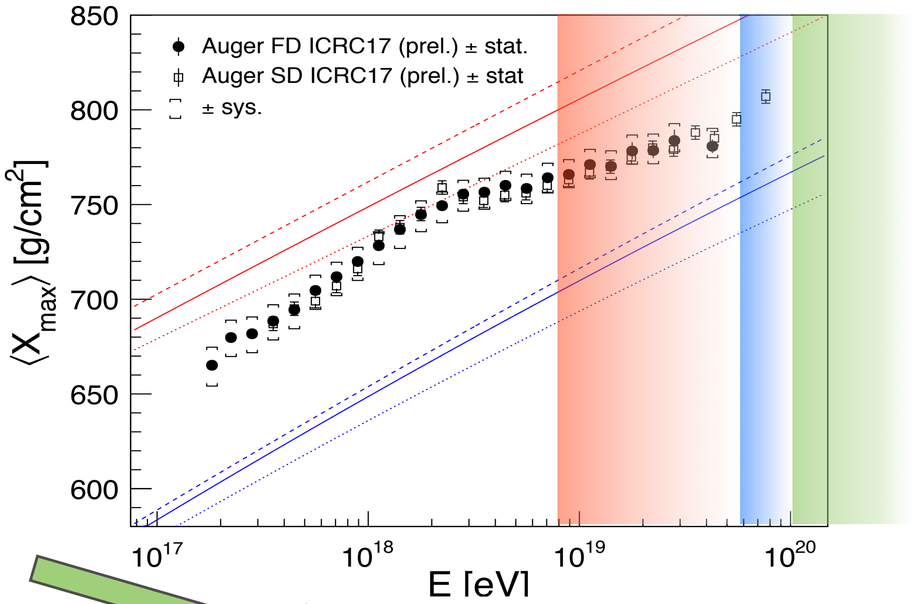




Results of energy spectrum, mass composition and anisotropy

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

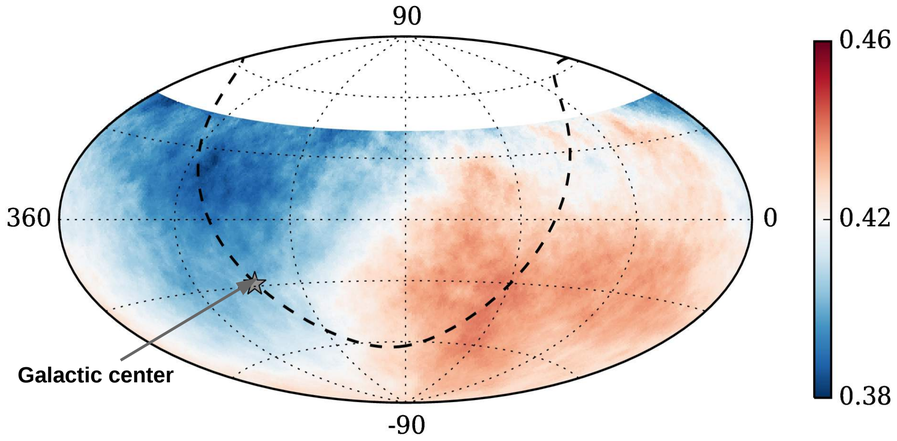




P. Sanchez-Lucas et al., Proc of ICRC 2017
Pierre Auger collab., Phys.Rev.D 96,122003 (2017)

E > 8 EeV

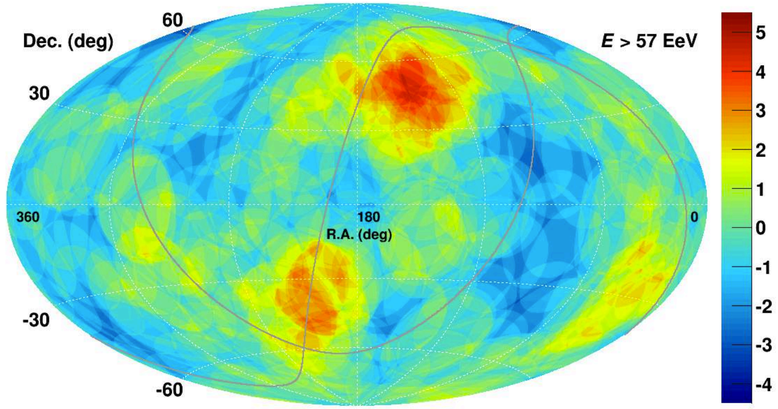
Pierre Auger Collab. Science 357, 1266 (2017)



Increase dipole amplitude above 4 EeV
arXiv:1808.03579

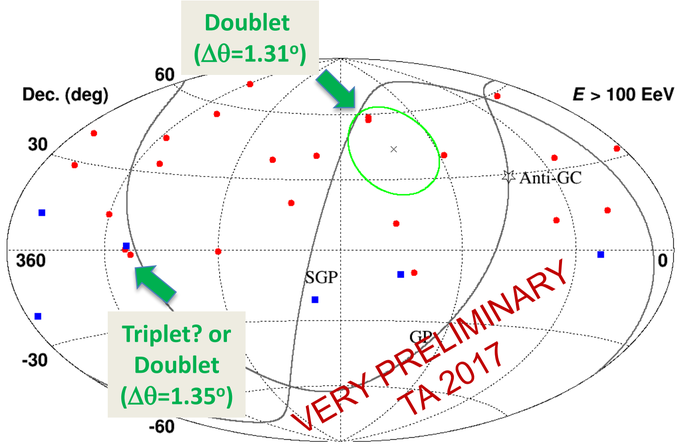
E > 57 EeV

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)

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

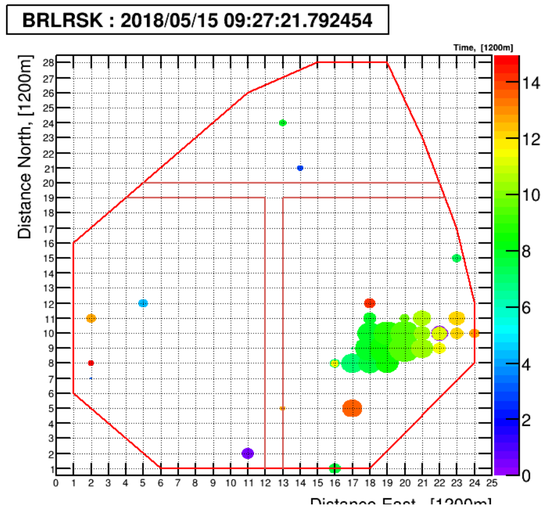
In space (100×exposure): POEMMA

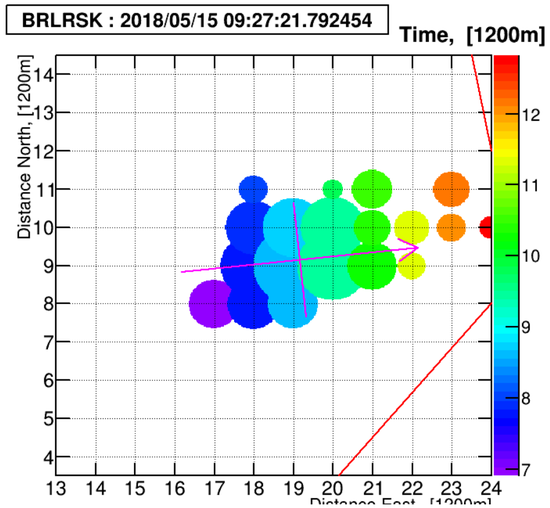
Ground (10×exposure with high quality events): FAST

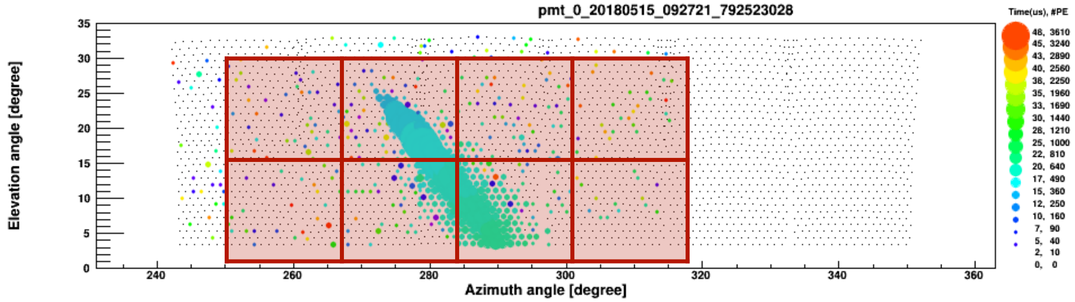
FAST
Fluorescence detector Array of Single-pixel Telescopes

Cherenkov dominated event (2 telescopes)

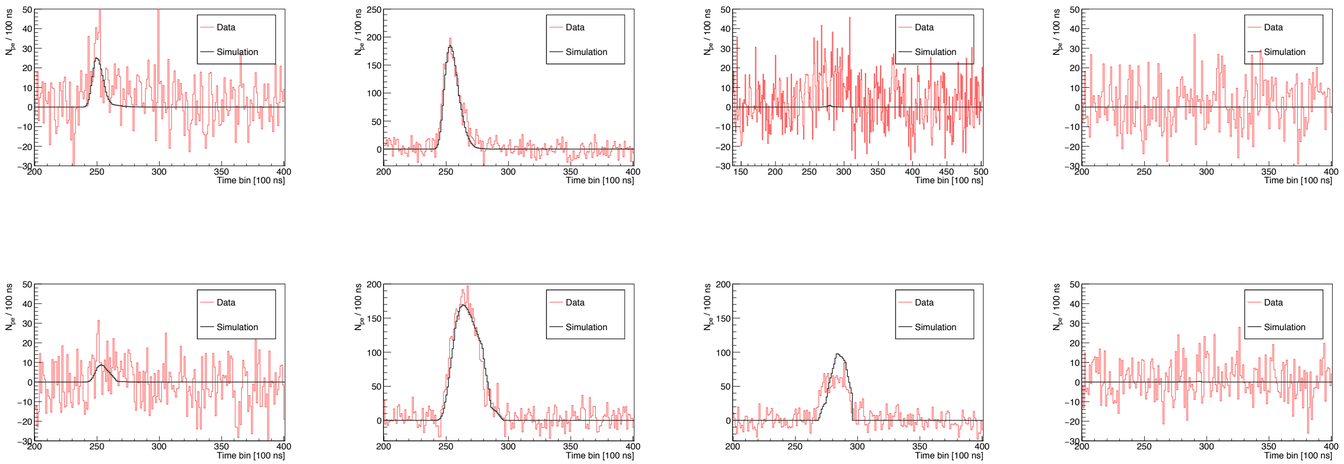
TA data







FAST data



FAST reconstruction:

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

Reconstructing the highest event

Fluorescence detector Array of Single-pixel Telescopes

Work: Justin Albury, Jose Bellido

Top-Down Reconstruction

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

Data **Expected(θ,φ,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