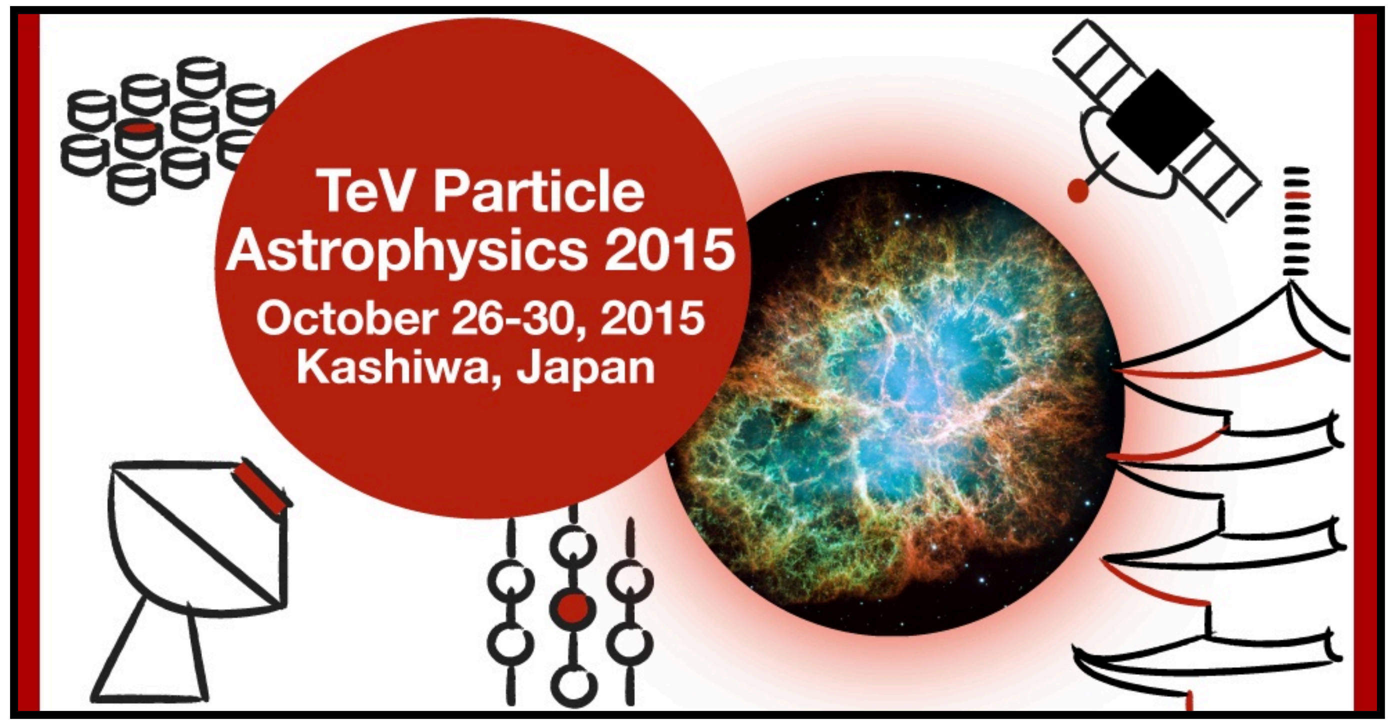
Fluorescence detector Array of Single-pixel Telescopes (FAST) project

Fluorescence detector Array of Single-pixel Telescopes



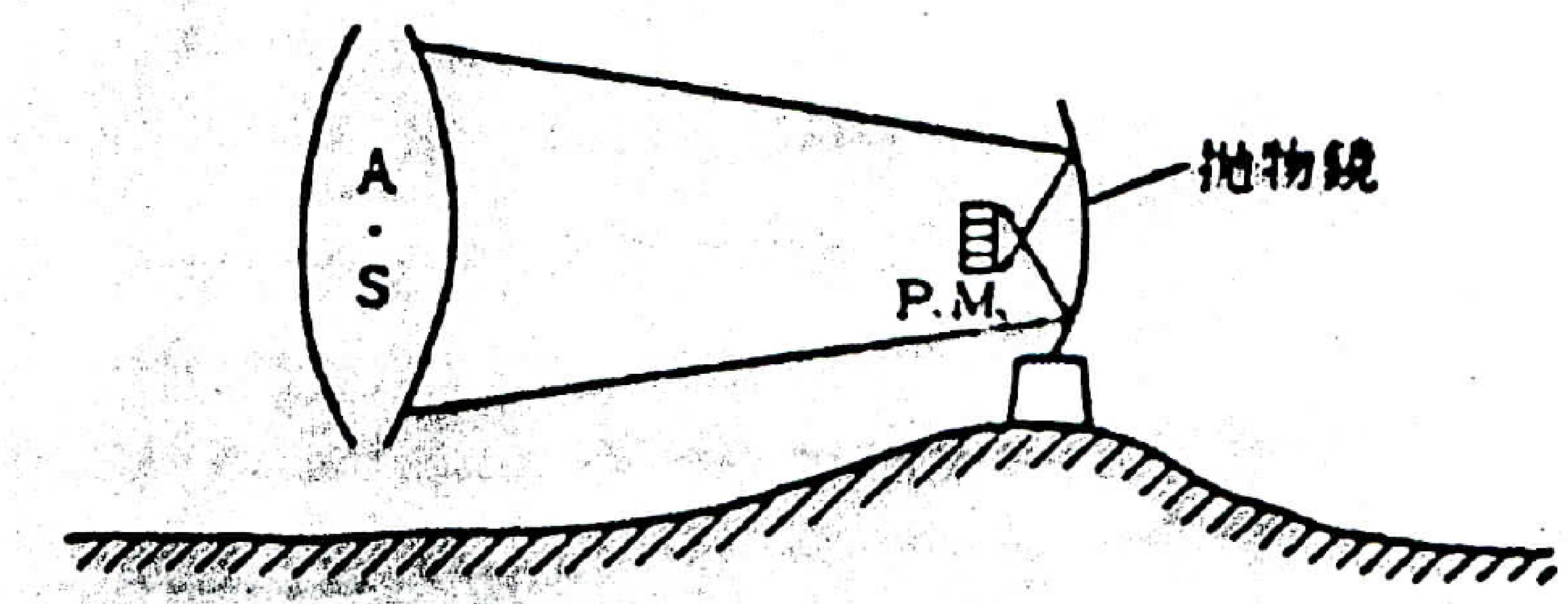
Toshihiro Fujii for the FAST collaboration

KICP, University of Chicago

ICRR, University of Tokyo

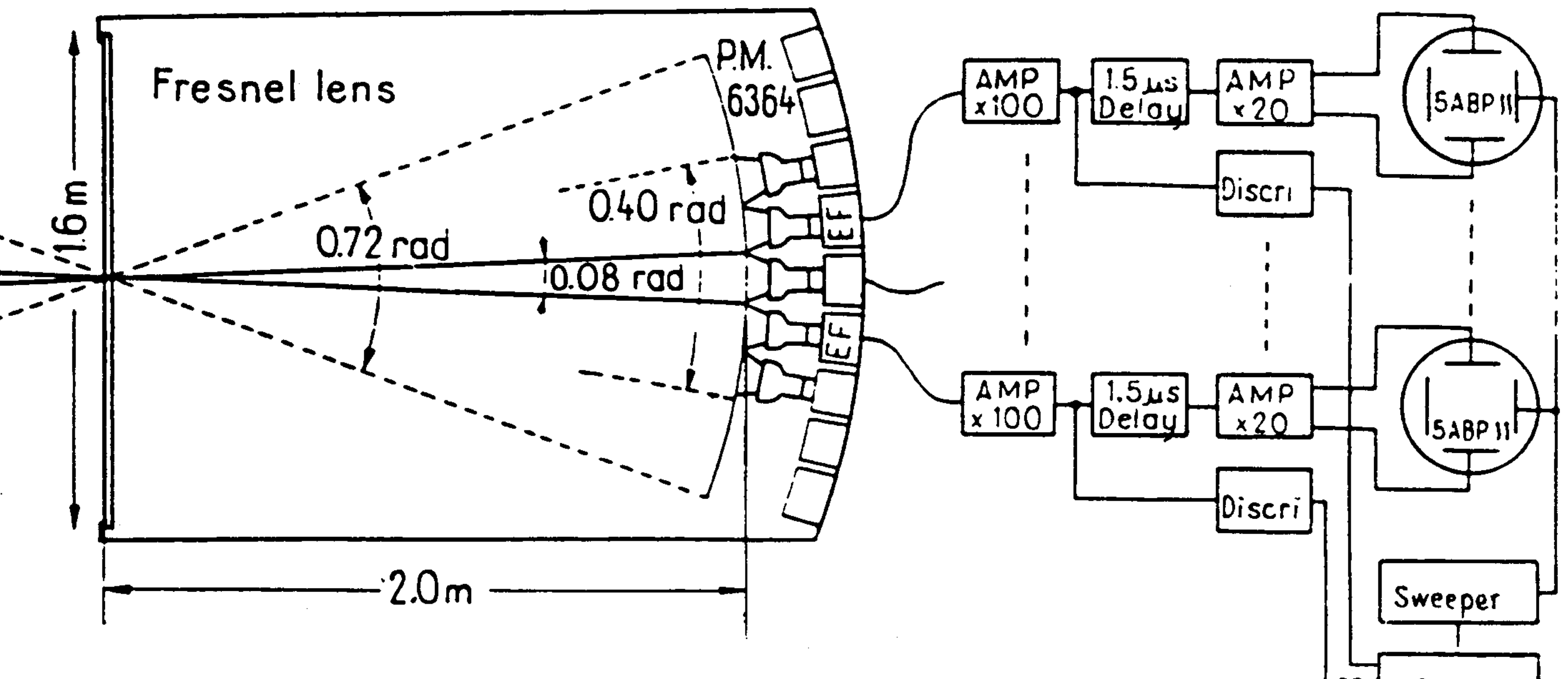
fujii@kicp.uchicago.edu

History of Fluorescence Technique

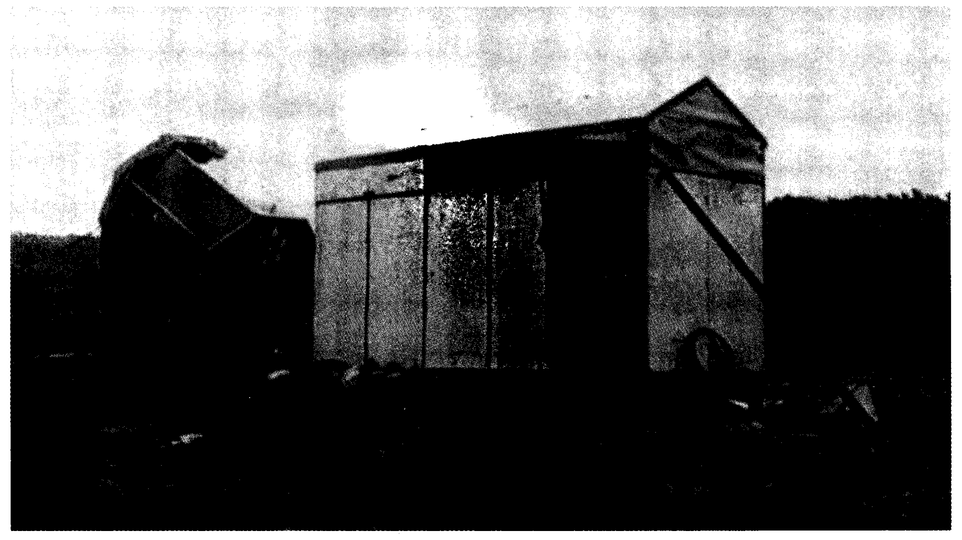


第3図 1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

Fresnel lens + PMTs



第７図　TOKYO-1の構造スケッチと回路ブロックダイアグラム



第８図　ＴＯＫＹＯ－１の設置写真

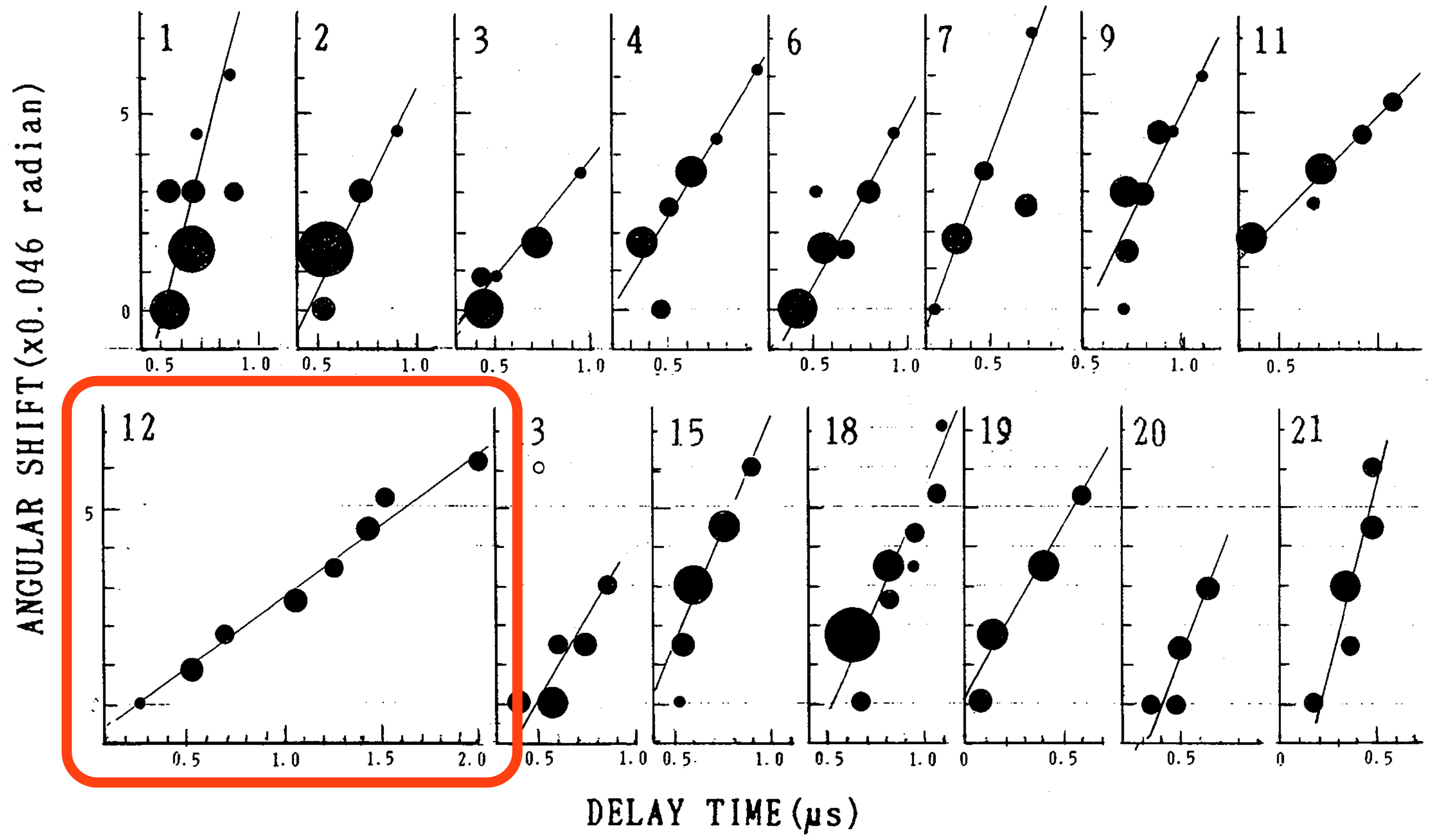
- ✦ In 1958, proposal of fluorescence technique (Suga, Oda, @Norikura symposium)
  - ✦ Many photomultiplier tubes on the focal plane of Fresnel lens/mirror to observe fluorescence light.
  - ✦ Observe longitudinal profile including Xmax to be sensitive to the mass composition of cosmic ray.
- ✦ In 1969, first detection of fluorescence light by TOKYO-1 (Tanahashi et al. @Doudaira Observatory, Japan)

Reference: 空気シャワー観測による宇宙線研究の歴史 永野元彦, 大気の蛍光観測による宇宙線実験の始まり 棚橋五郎

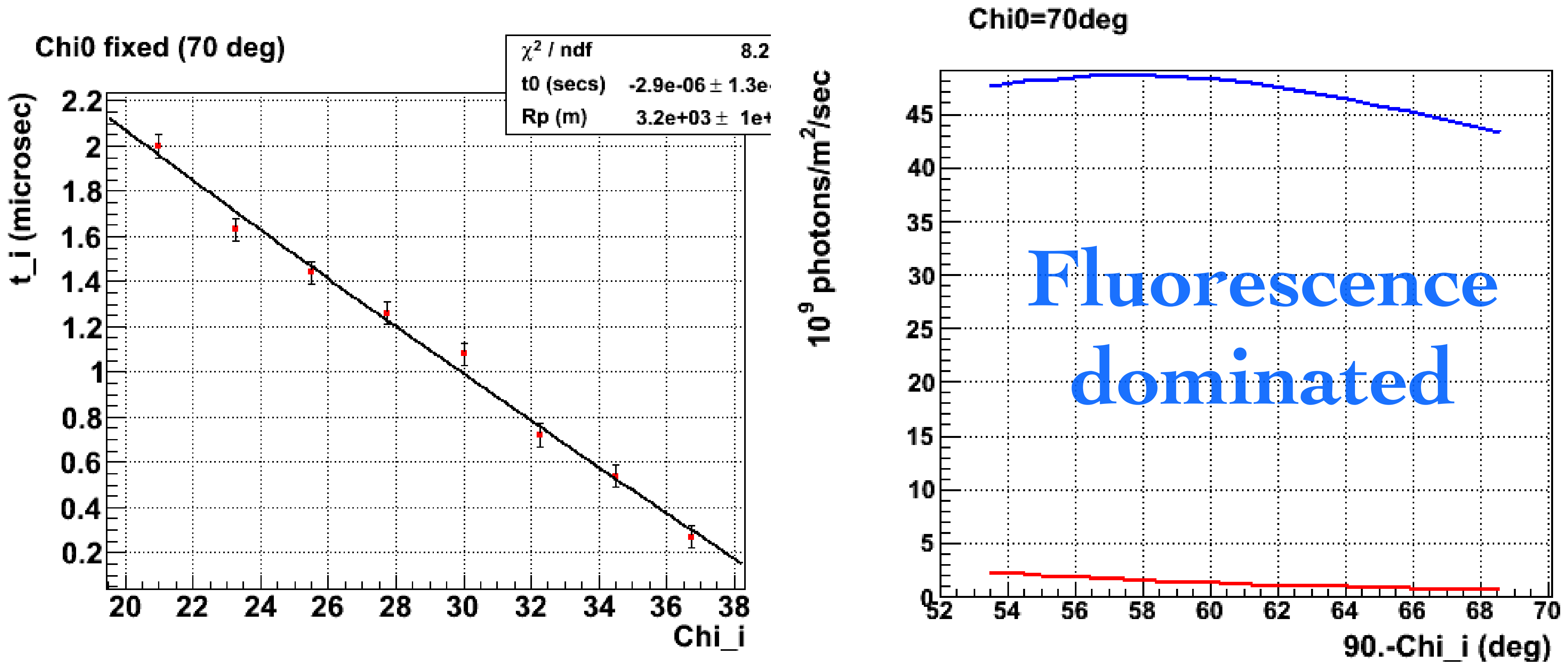
Fluorescence detector Array of Single-pixel Telescopes

First Detection of Shower by Fluorescence Technique

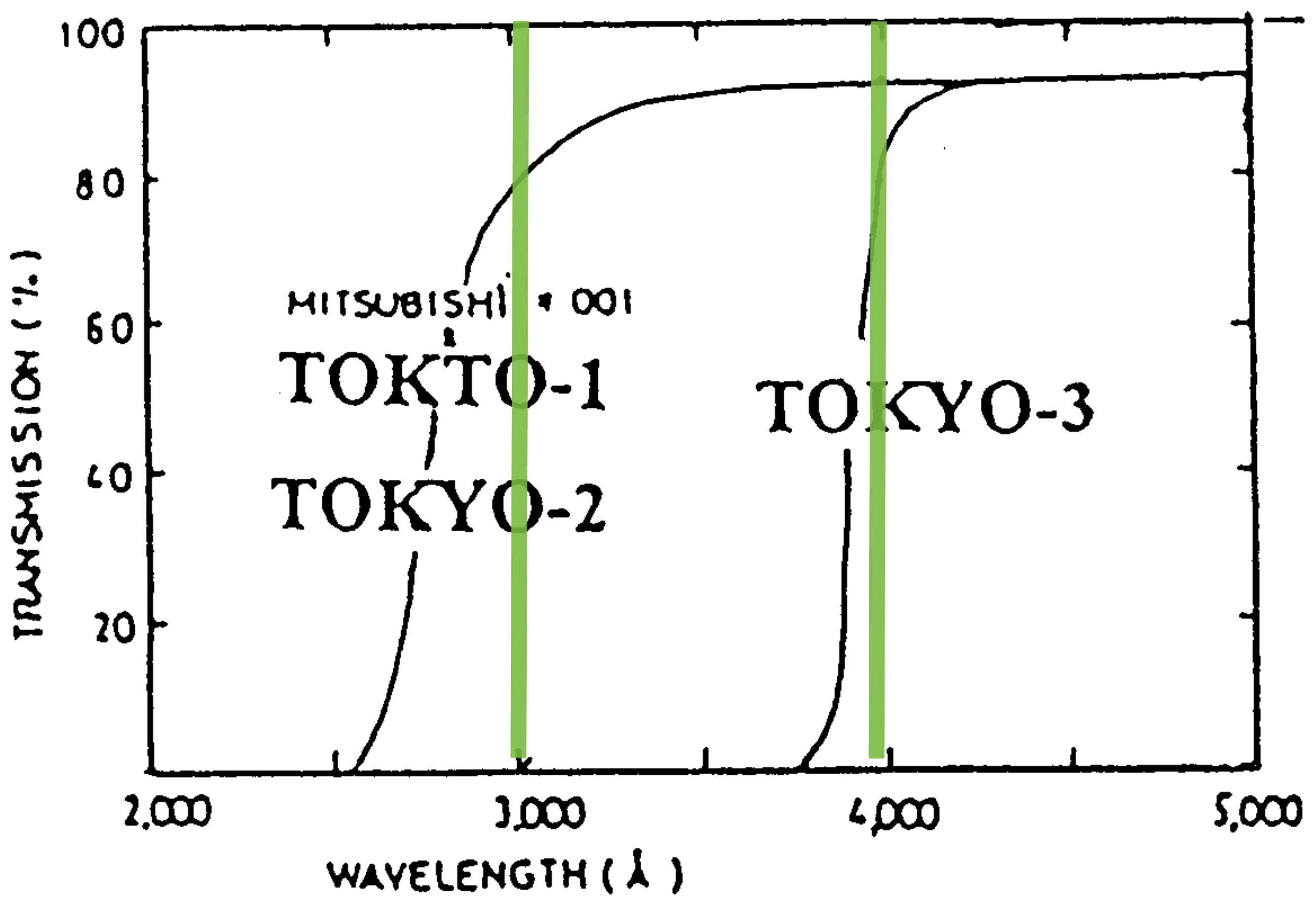
Candidates observed by TOKYO-1 (1969)



Re-analysis by B. Dawson et al. (2011)



- Long signal duration and the similar amount of light (No. 12)
- The event is consistent with the fluorescence-dominated shower with **5×10^{18} eV, 680 g/cm^2** (B. Dawson, arXiv:1112.5686).
- In the upgrade detector of TOKYO-3, the 4 m^2 lens was unfortunately UV protected one.
- Fly's Eye experiment , Telescope Array experiment, Pierre Auger Observatory established fluorescence technique and reported physics results.
- **Era to develop optimized and economical fluorescence detector.**



第６図　プラスチックレンズの光透過性能
（TOKYO-1,TOKYO-2,TOKYO-3）

M. Ave et al. / Astroparticle Physics 28 (2007) 41–57

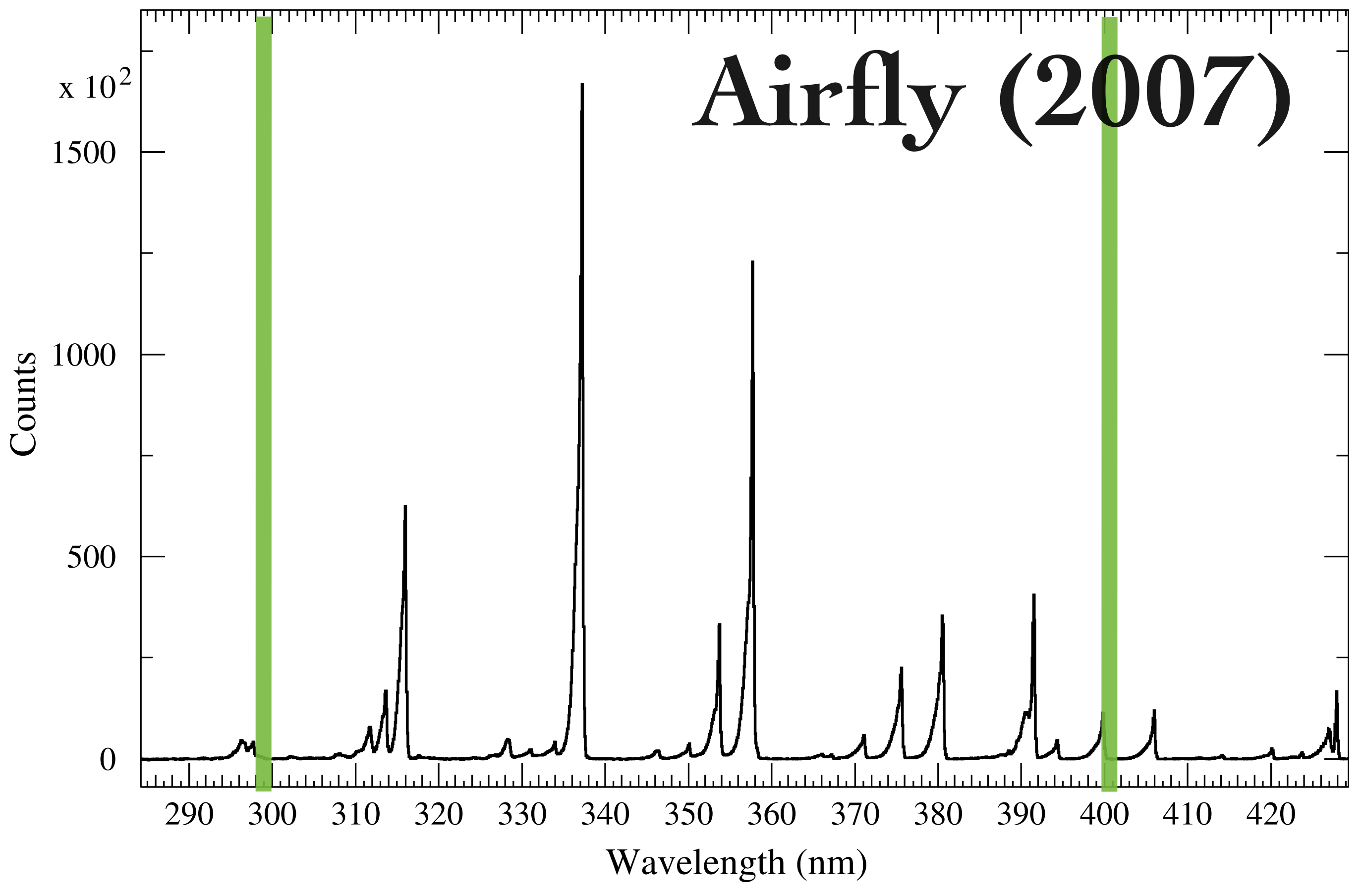


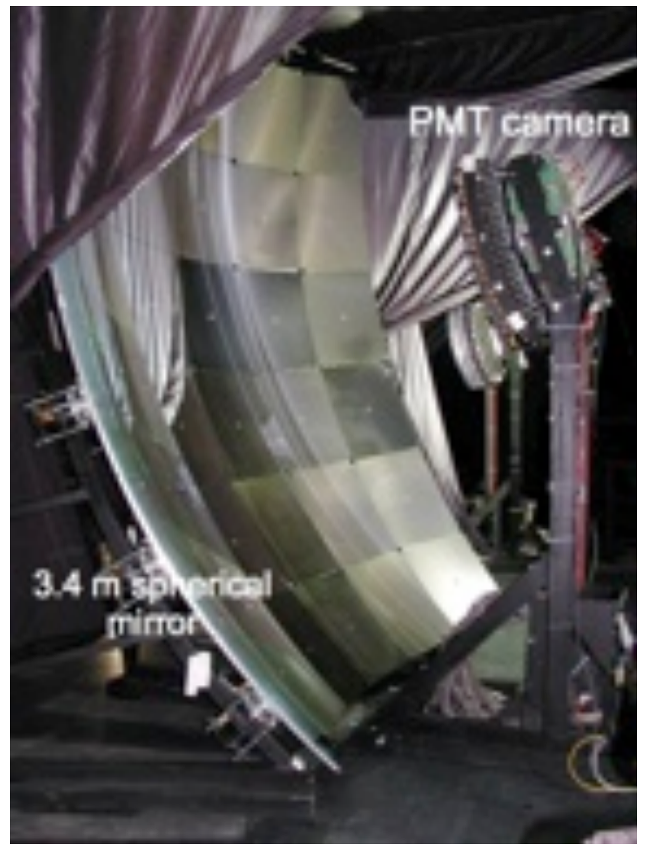
Fig. 4. Measured fluorescence spectrum in dry air at 800 hPa and 293 K.

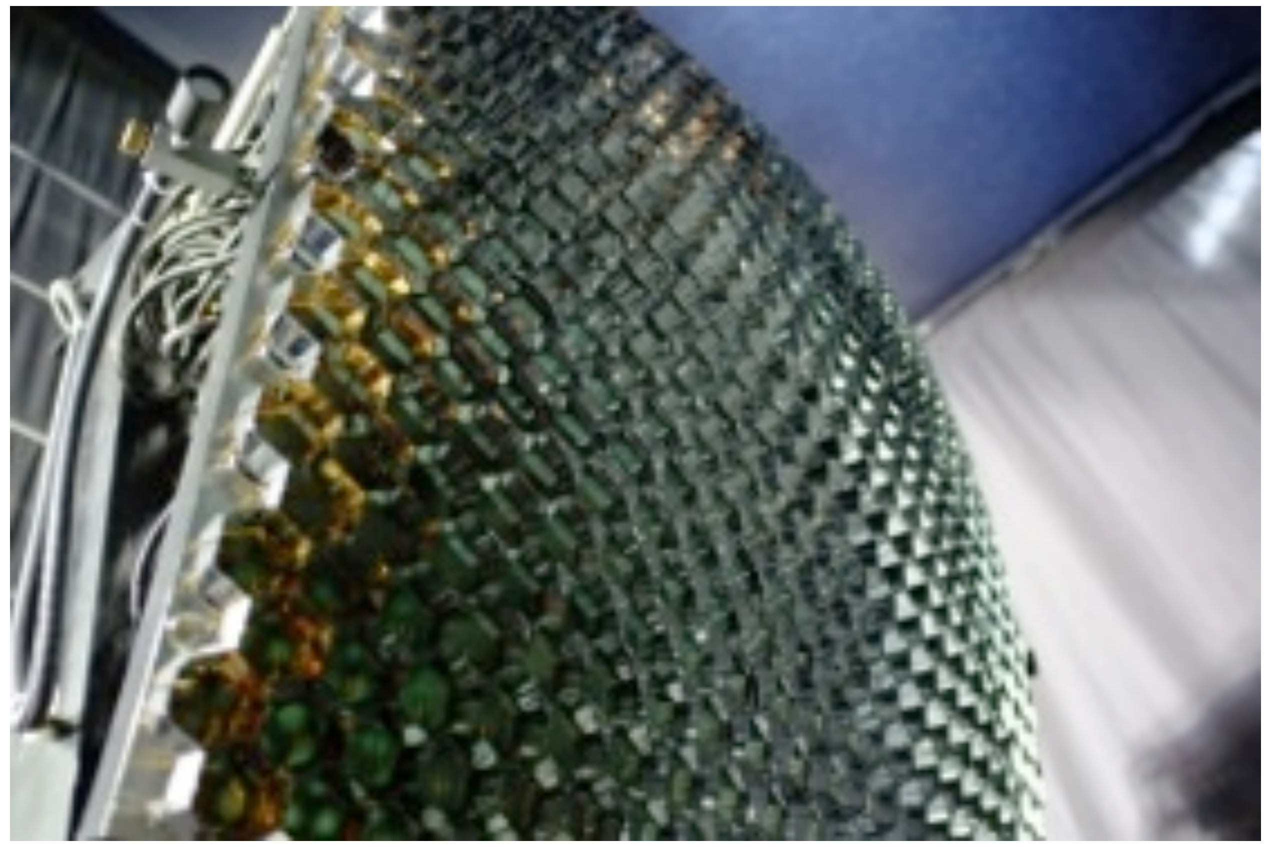
FAST Fluorescence detector Array of Single-pixel Telescopes

Fluorescence detector Array of Single-pixel Telescopes

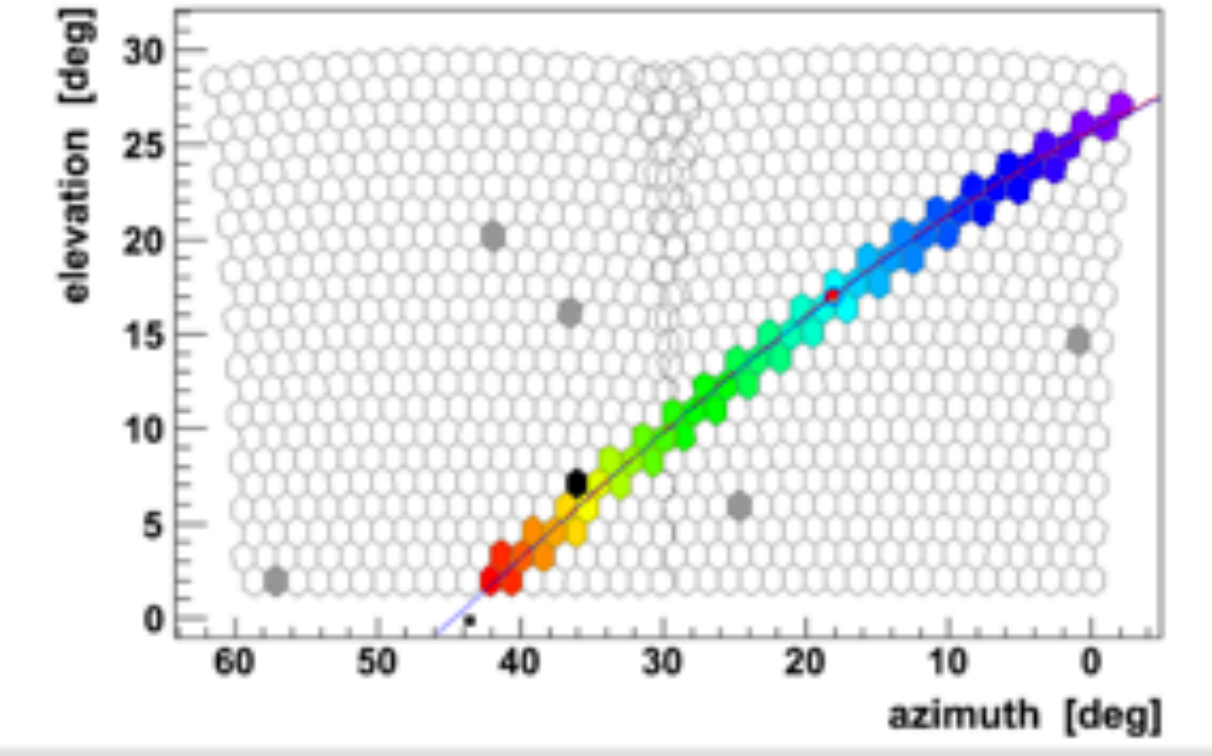
- ✦ Target : > $10^{19.5}$ eV, ultra-high energy cosmic rays (UHECR) and neutral particles
- ✦ Huge target volume ⇒ Fluorescence detector array

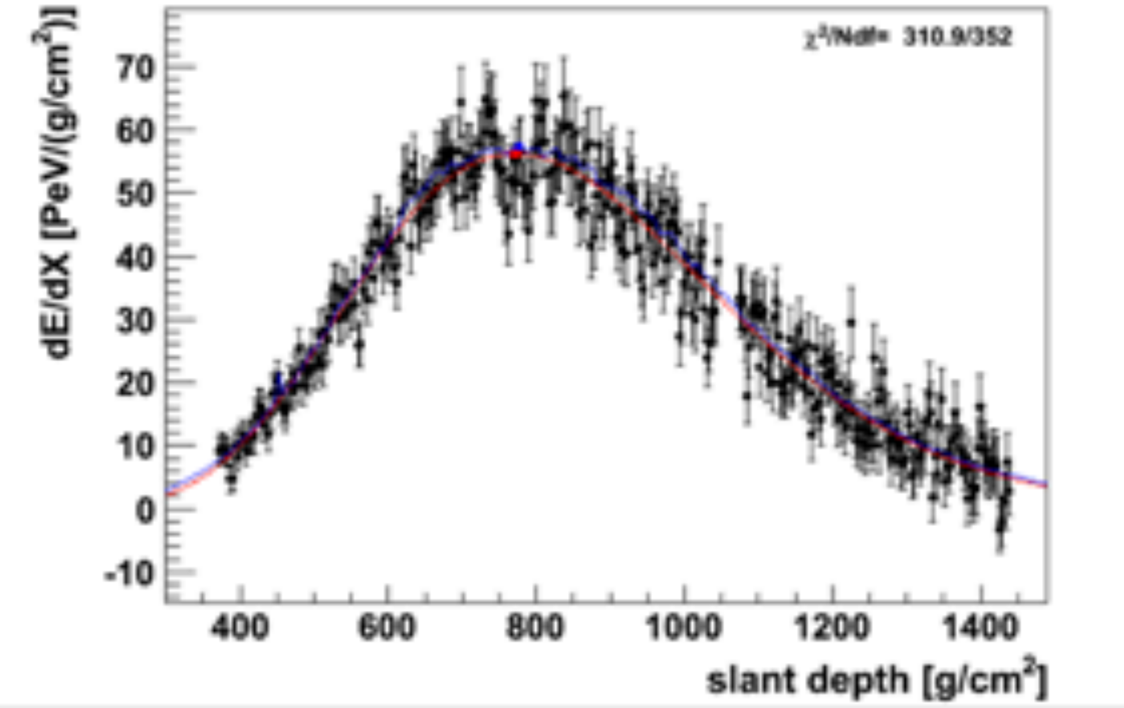
Fine pixelated camera



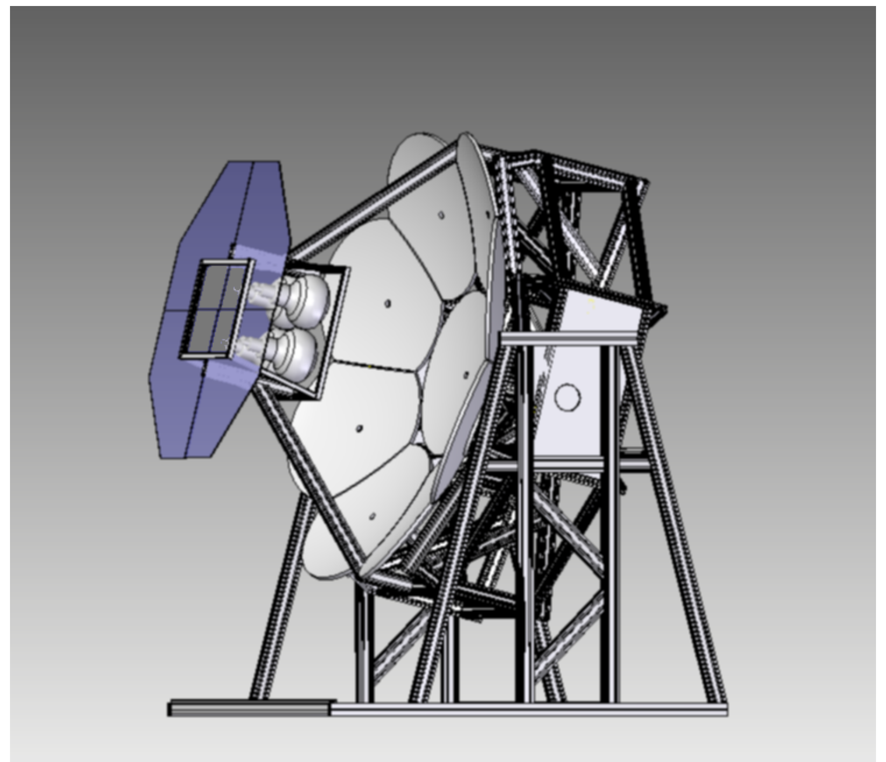


Too expensive to cover a huge area

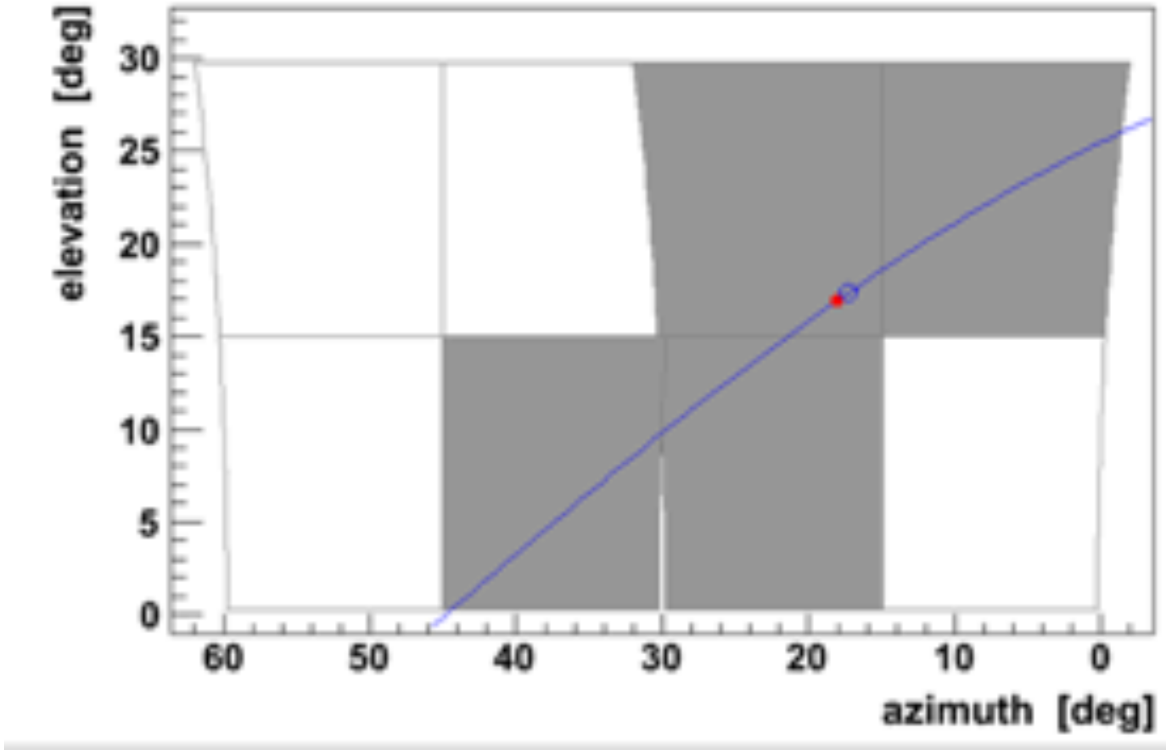


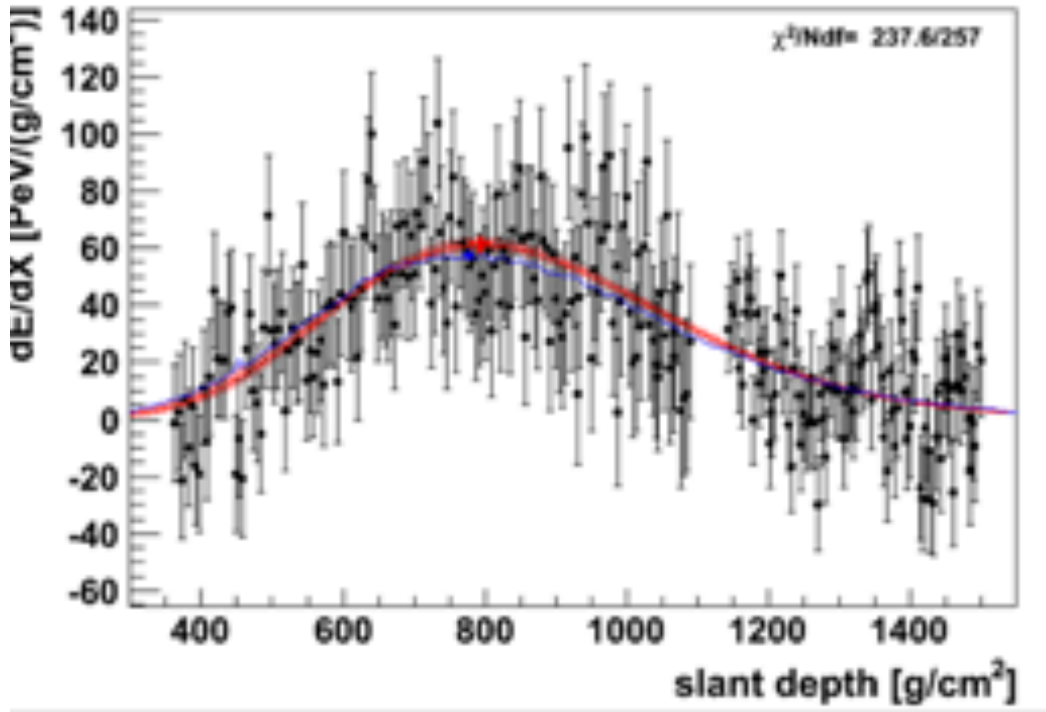


Single or few pixels and smaller optics

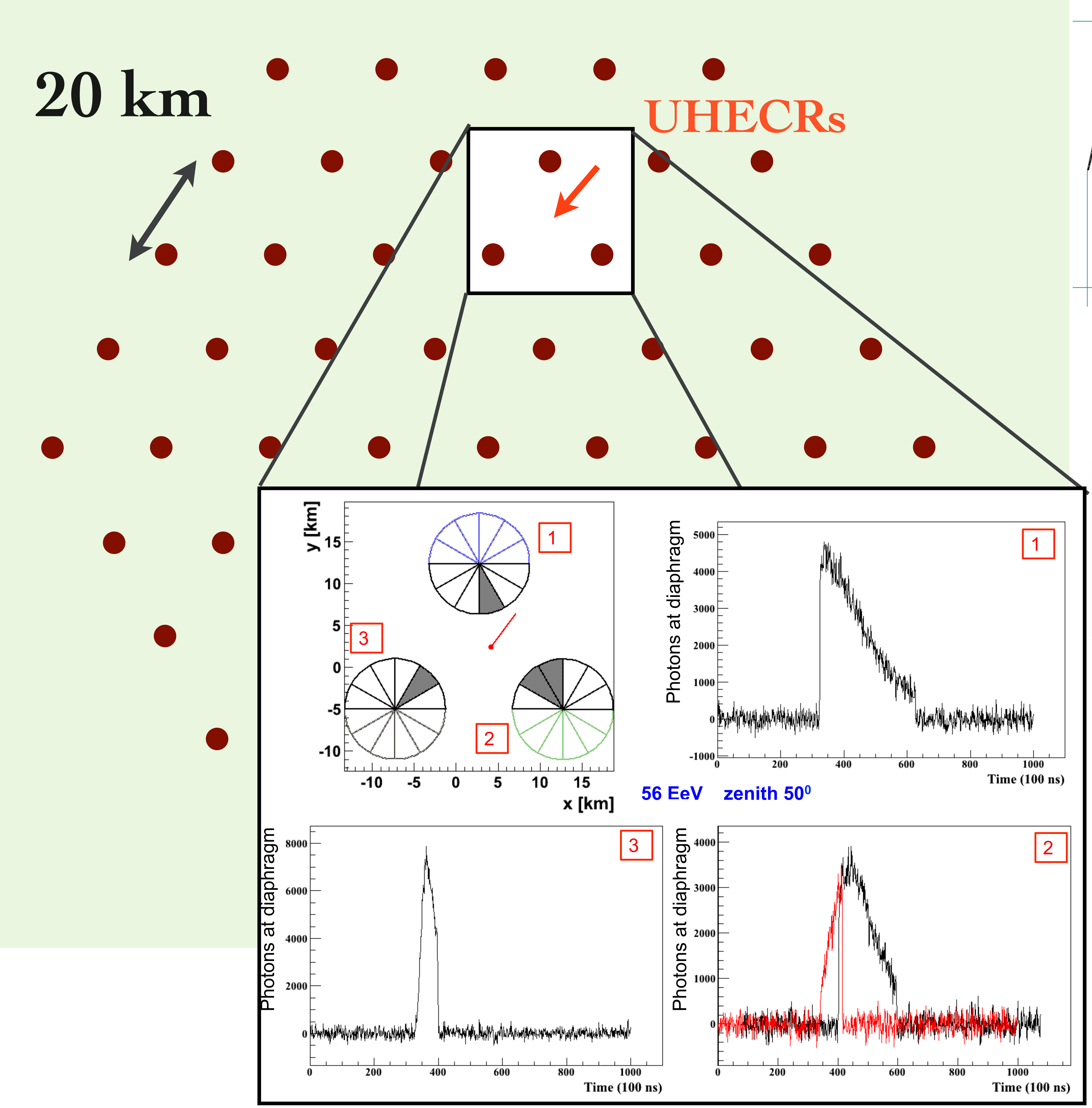


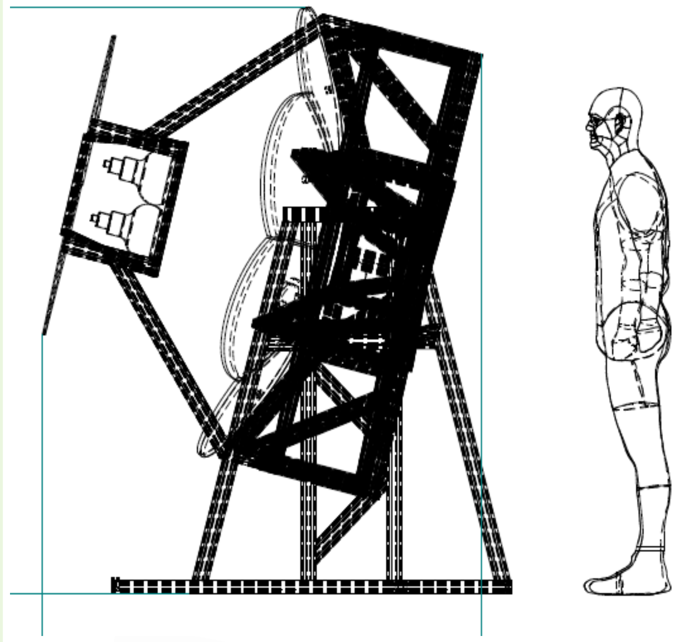
Low-cost and simplified/optimized FD

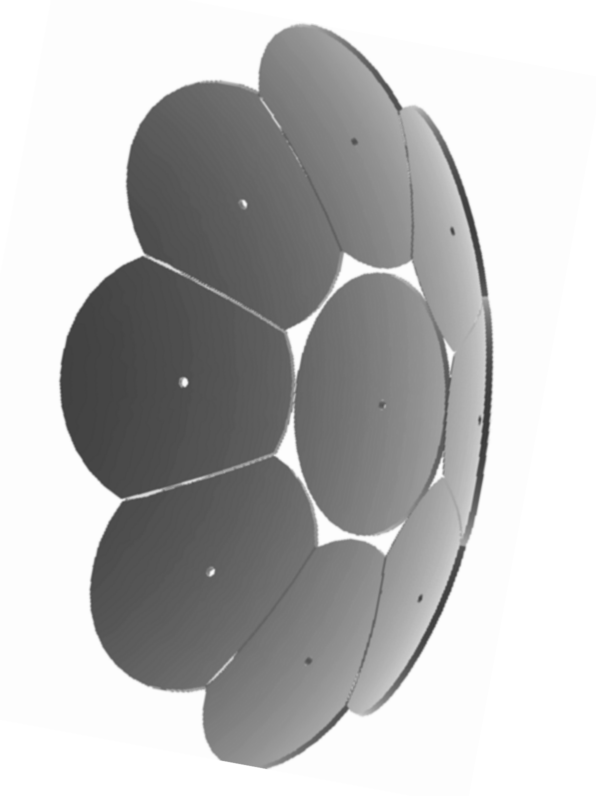


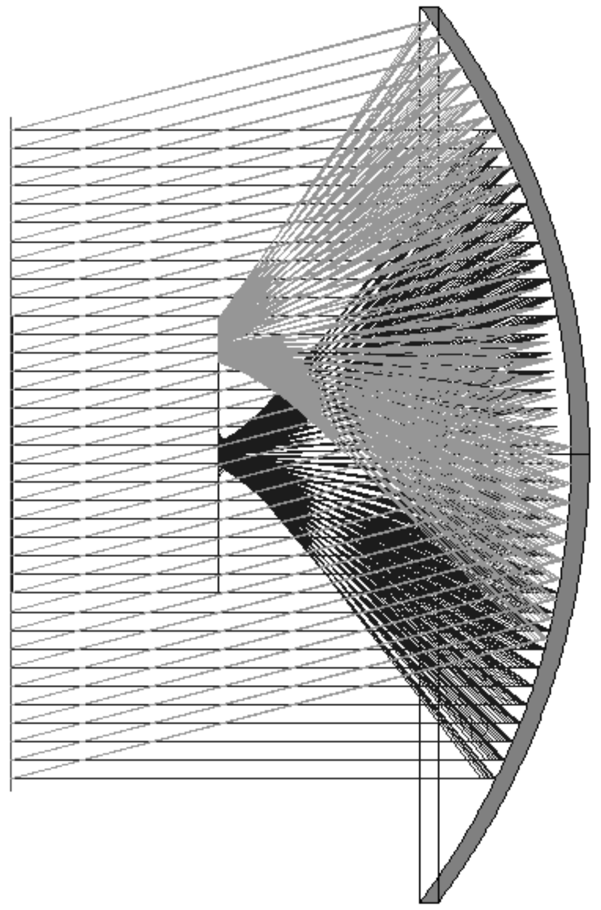


FAST Fluorescence detector Array of Single-pixel Telescopes







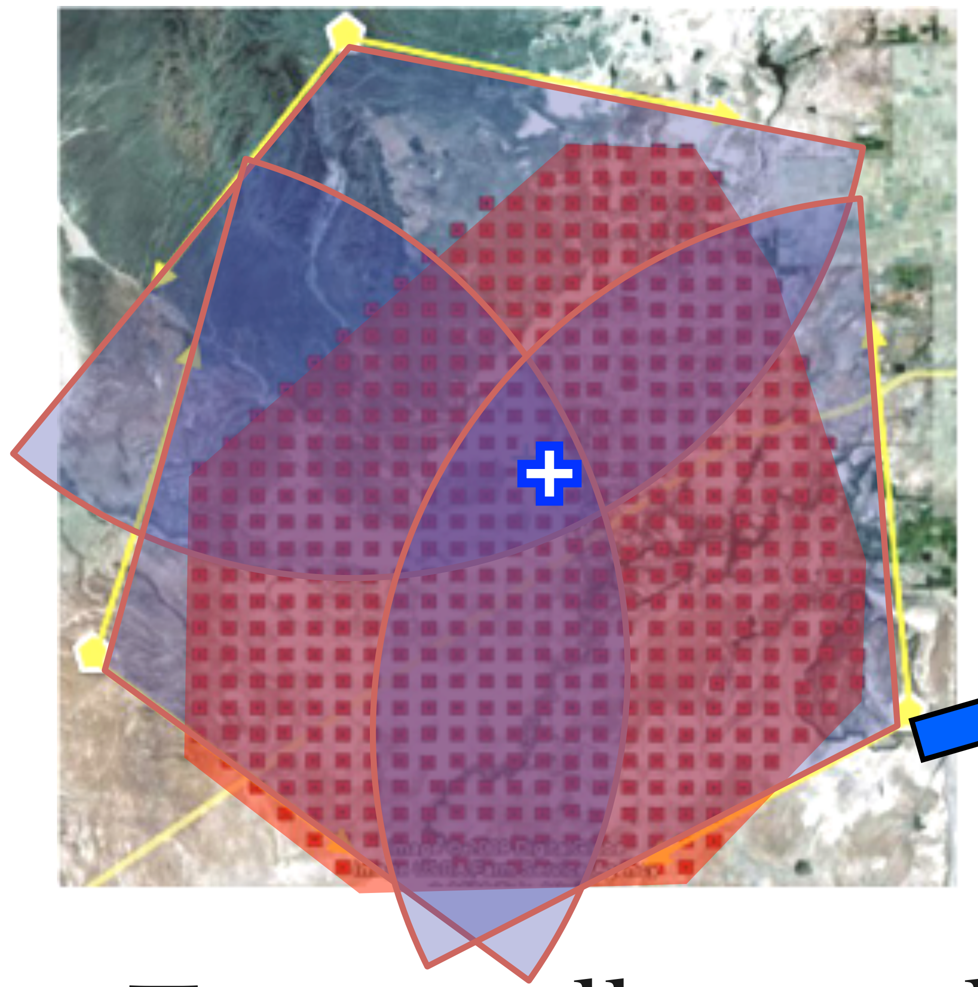


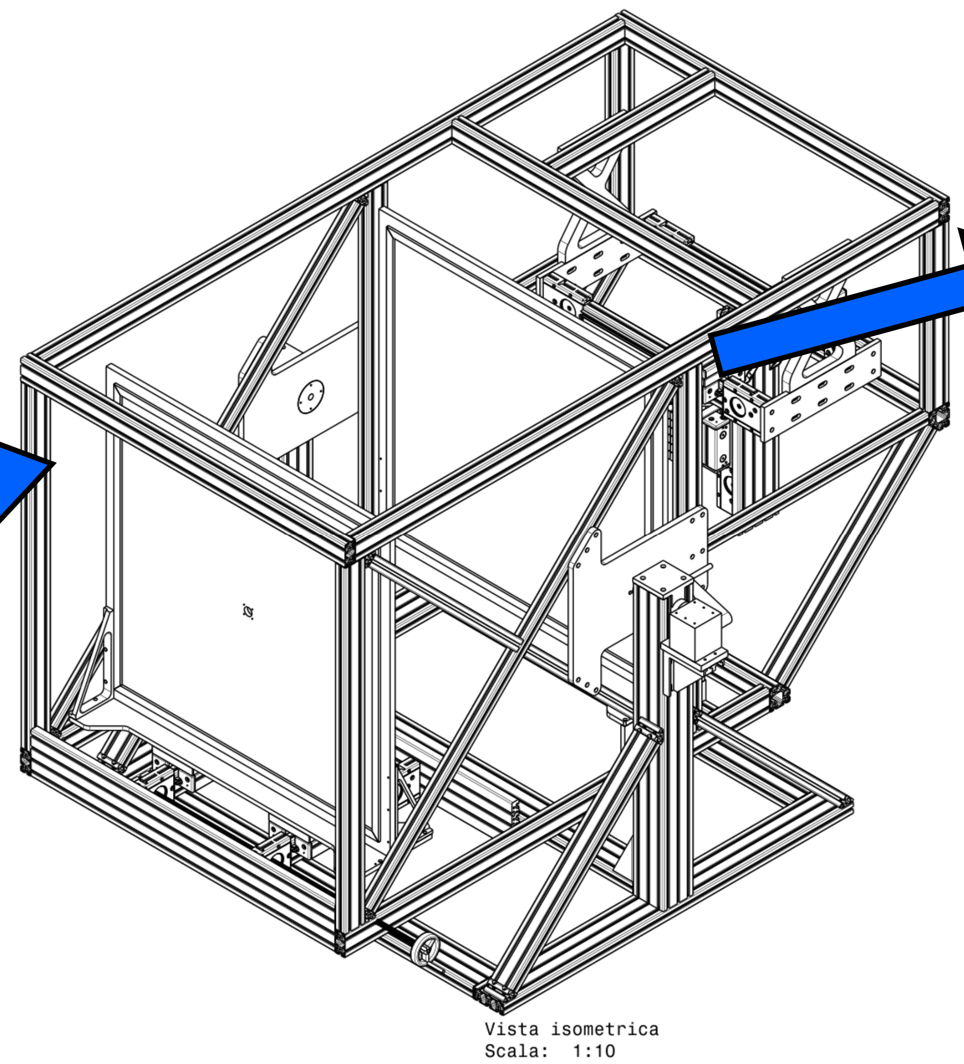
- Each telescope: 4 PMTs, 30°×30° field of view (FoV).
  - **Reference design: 1 m^2 aperture, 15°×15° FoV per PMT**
- Each station: 12 telescopes, 48 PMTs, 30°×360° FoV.
- Deploy on a triangle grid with **20 km** spacing, like **"Surface Detector Array"**.
- If 127 stations are installed, a ground coverage is ~ 40,000 km^2.
- Geometry: Radio, SD, coincidence of three stations being investigated.

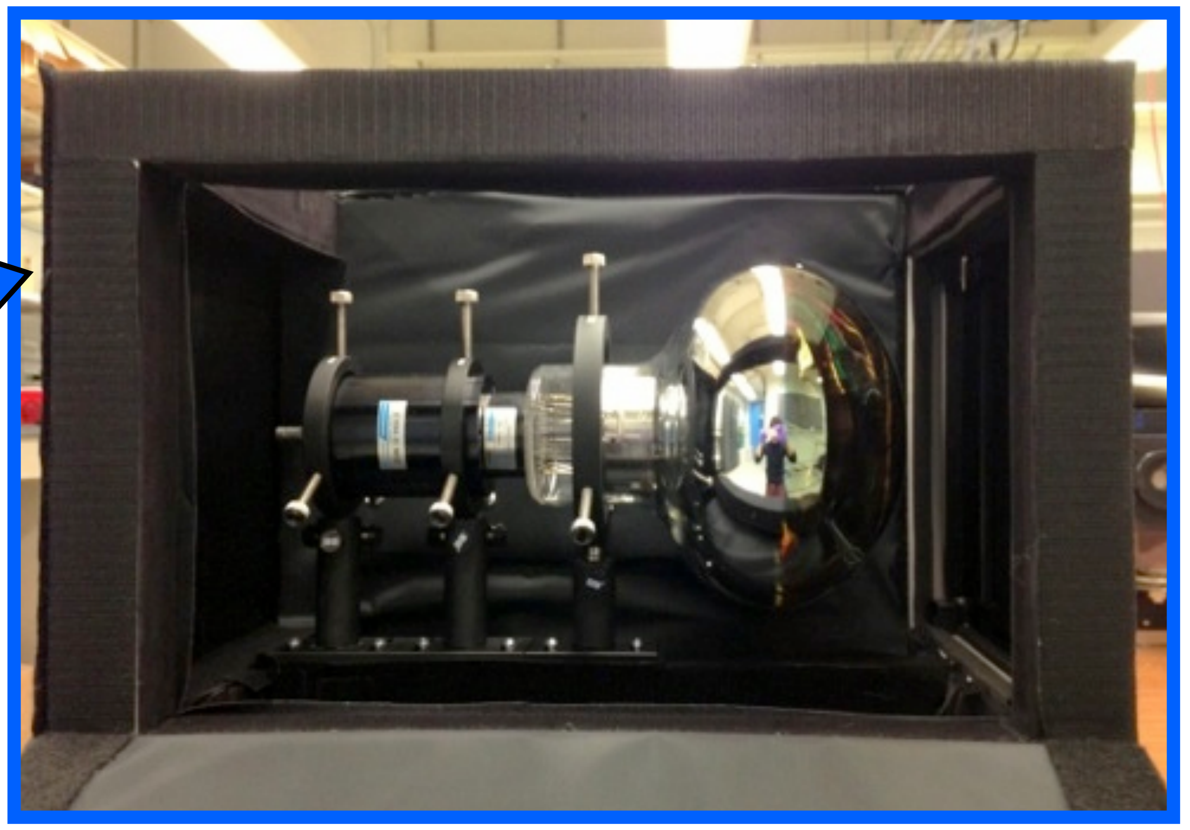
FAST
Fluorescence detector Array of Single-pixel Telescopes

Window of Opportunity at EUSO-TA

Telescope Array site **Black Rock Mesa station** **EUSO-TA telescope** **FAST camera**







- 8 inch PMT (R5912-03, Hamamtsu)
- PMT base (E7694-01, Hamamatsu)
- Ultra-violet band pass filter (MUG6, Schott)

- Temporally use the EUSO-TA optics at the TA site.
  - Two Fresnel lenses (+ 1 UV acrylic plate in front for protection)
  - **1 m^2 aperture, 14°×14° FoV ≒ FAST reference design.**
- Install FAST camera and DAQ system at EUSO-TA telescope.
- Milestones: Stable observation under large night sky backgrounds, UHECR detection with external trigger from TAFD.

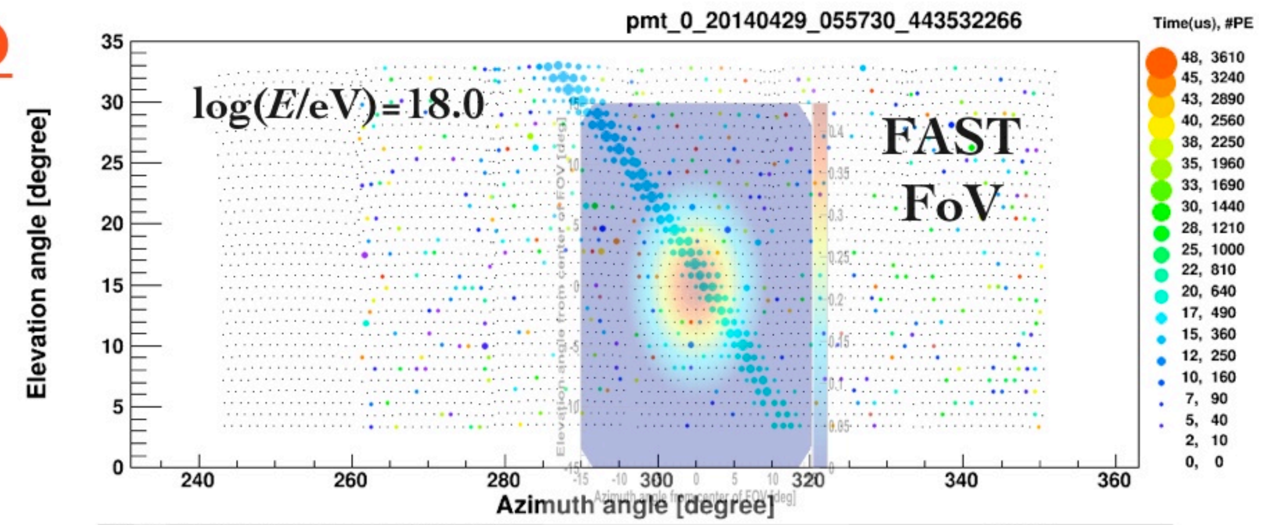

1
2
3
4
5
6
7
8
9
Start observation

FAST
Fluorescence detector Array of Single-pixel Telescopes

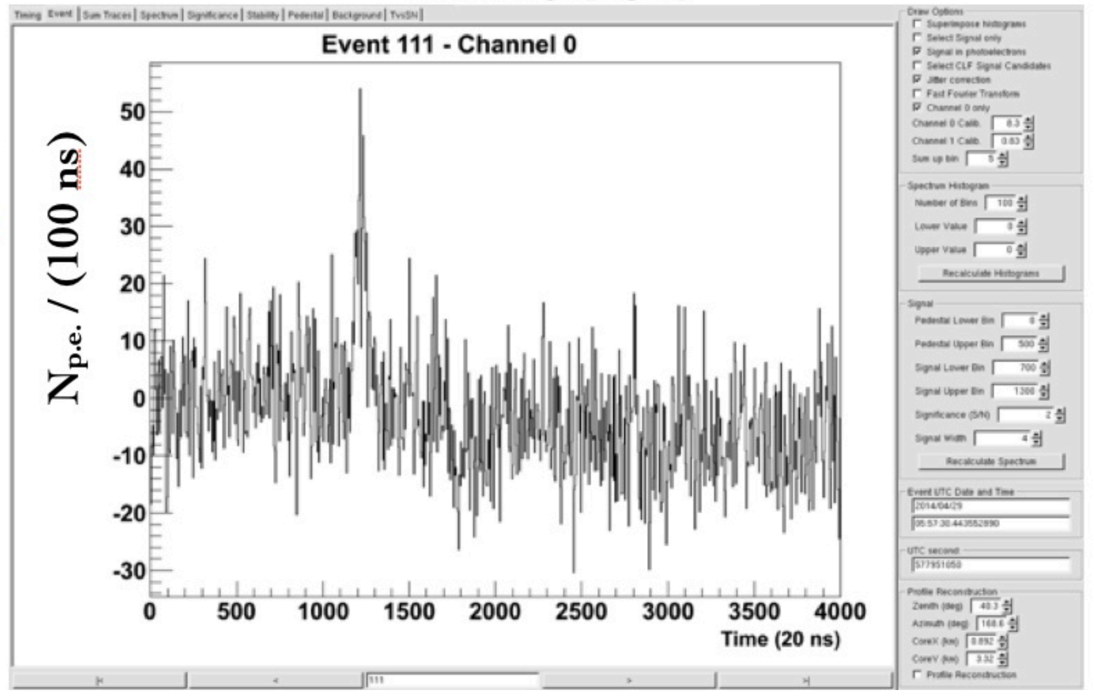
Results on the First Field Observation

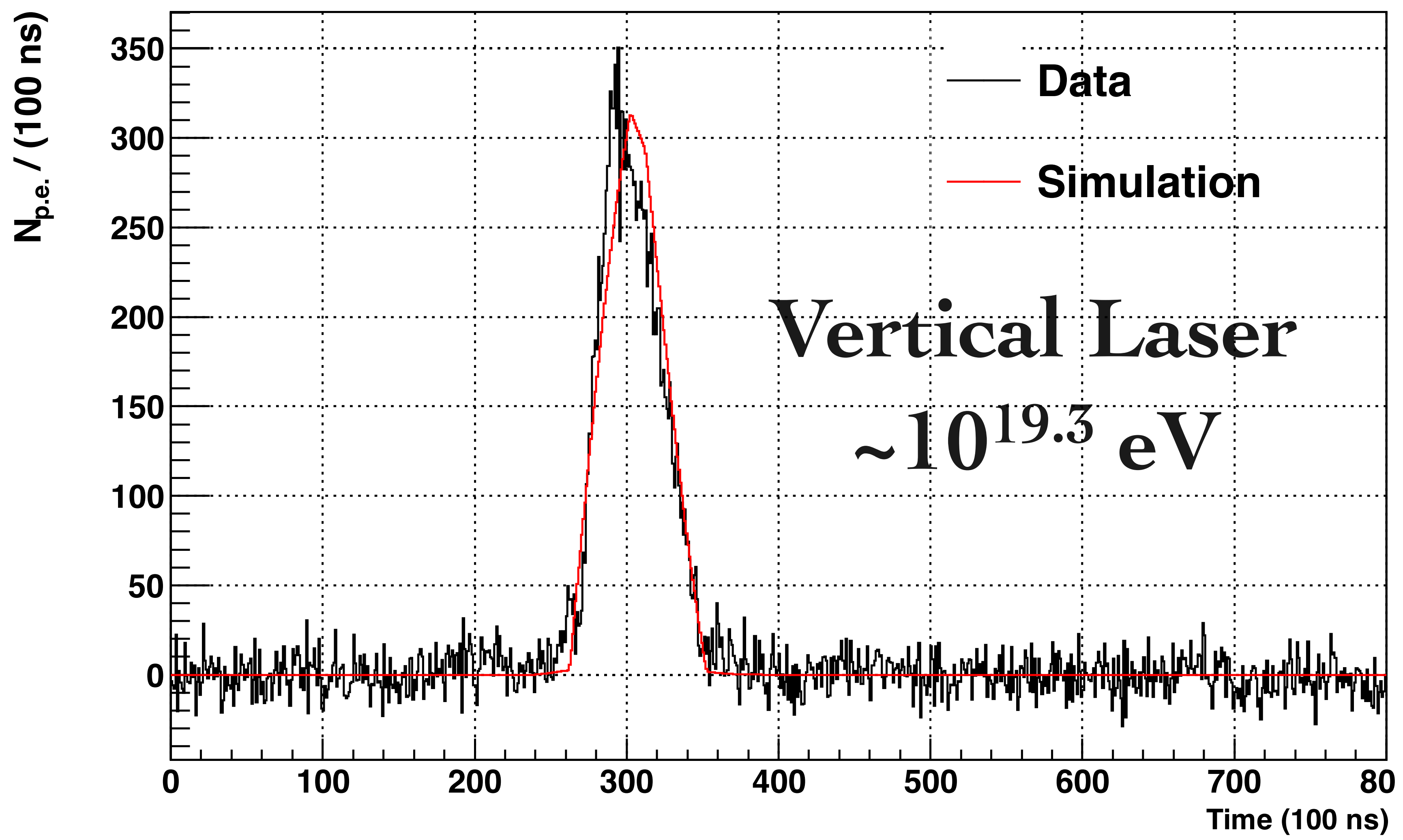
- Data set: April and June 2014 observation, 19 days, 83 hours
  - Very stable observation under large night sky backgrounds
- Laser detection to confirm a performance of the prototype
- UHECR search : 16 candidates coincidence with TA-FD
- Very successful example among Telescope Array, JEM-EUSO Pierre Auger Collaborations.

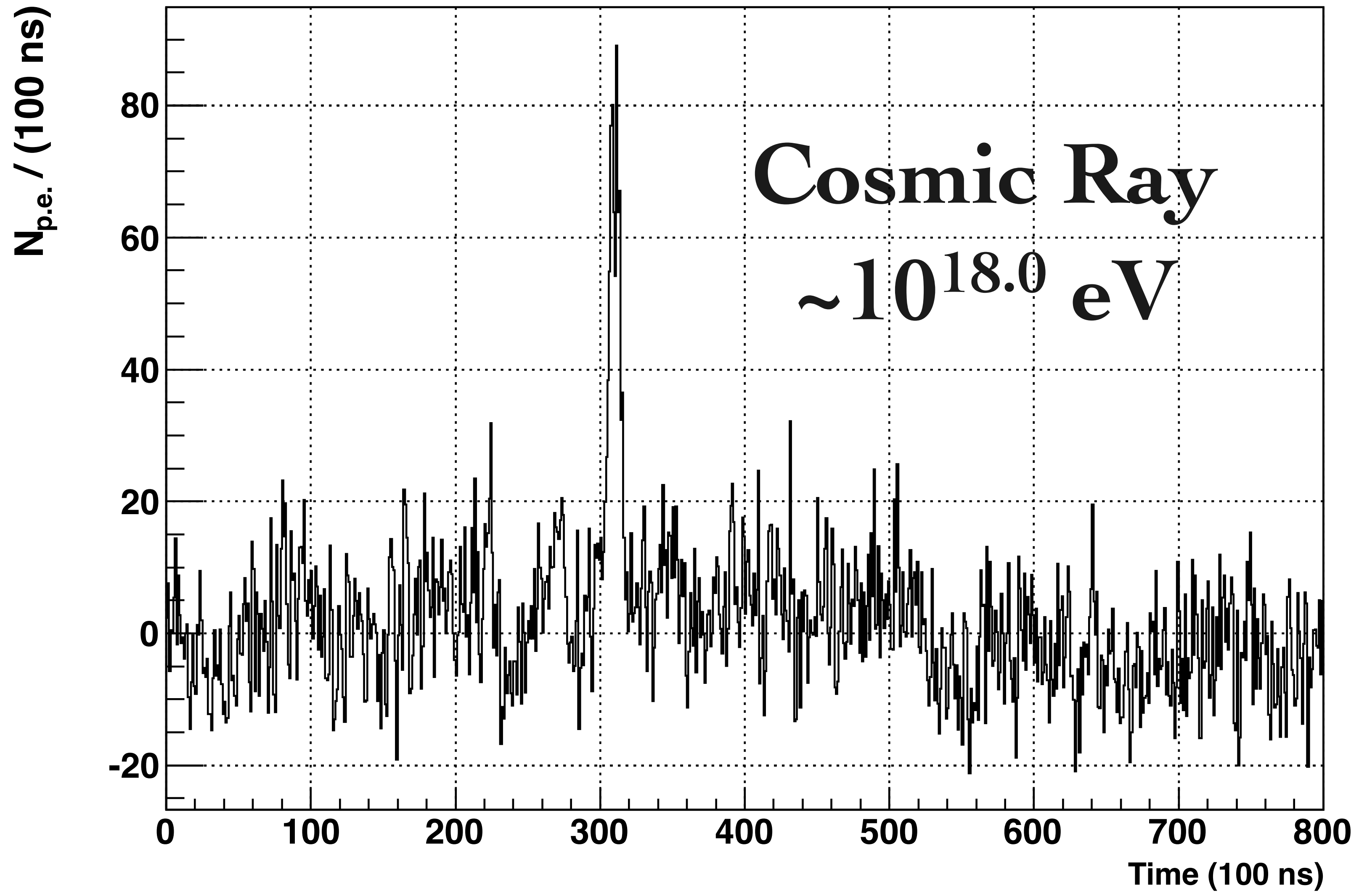
TAFD

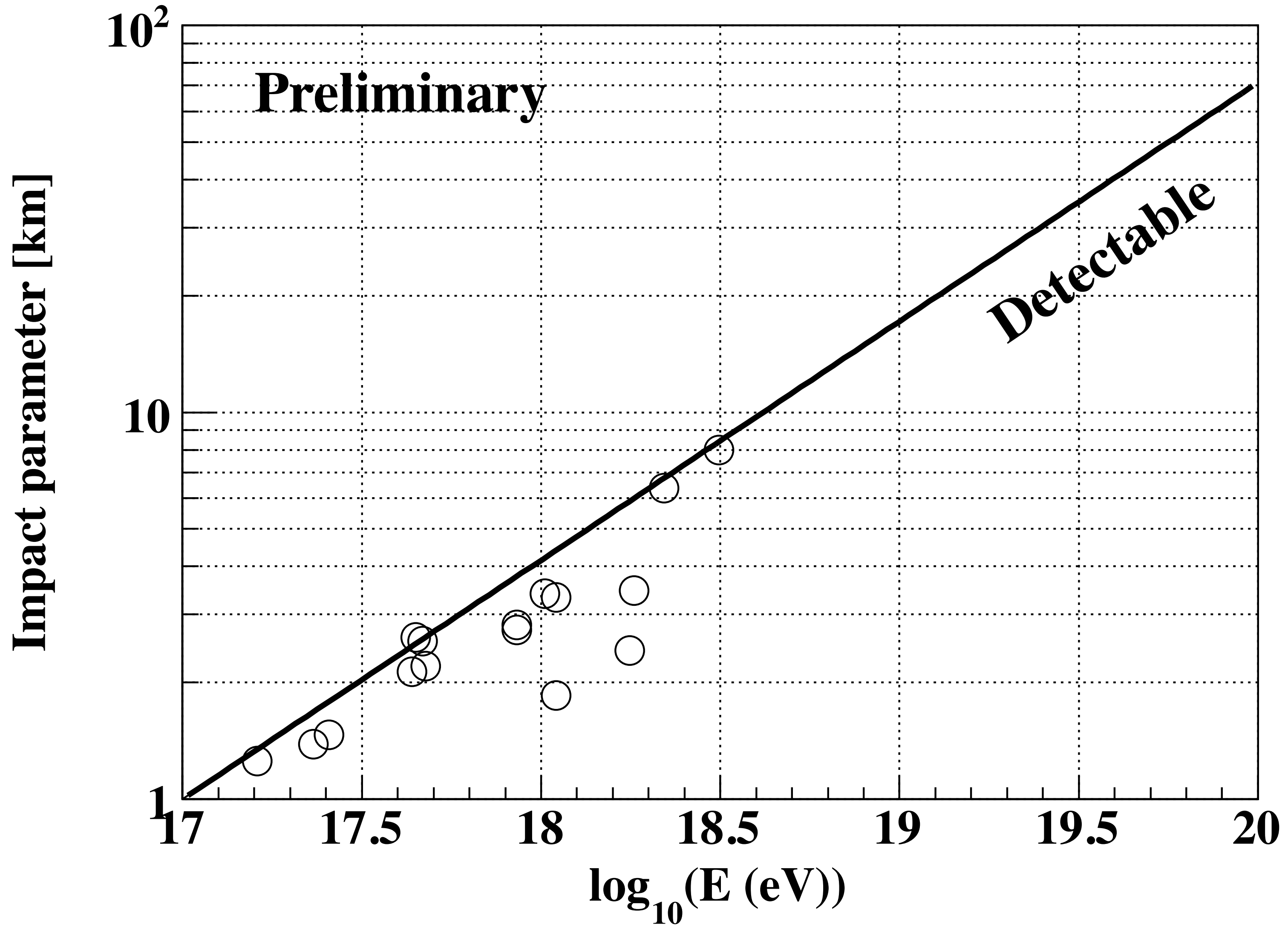


FAST





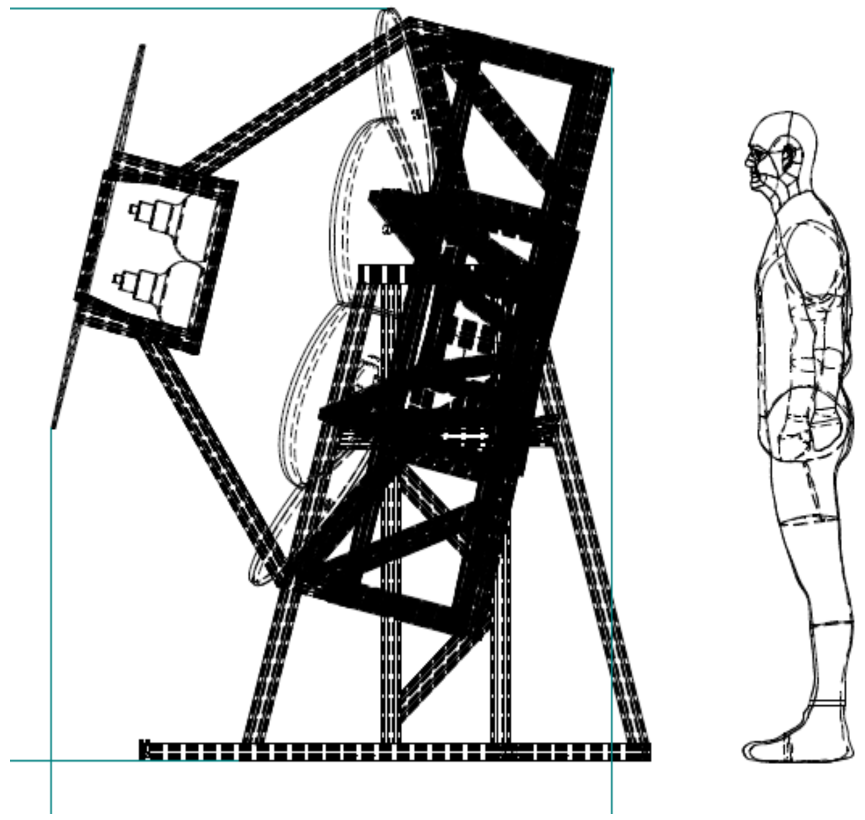


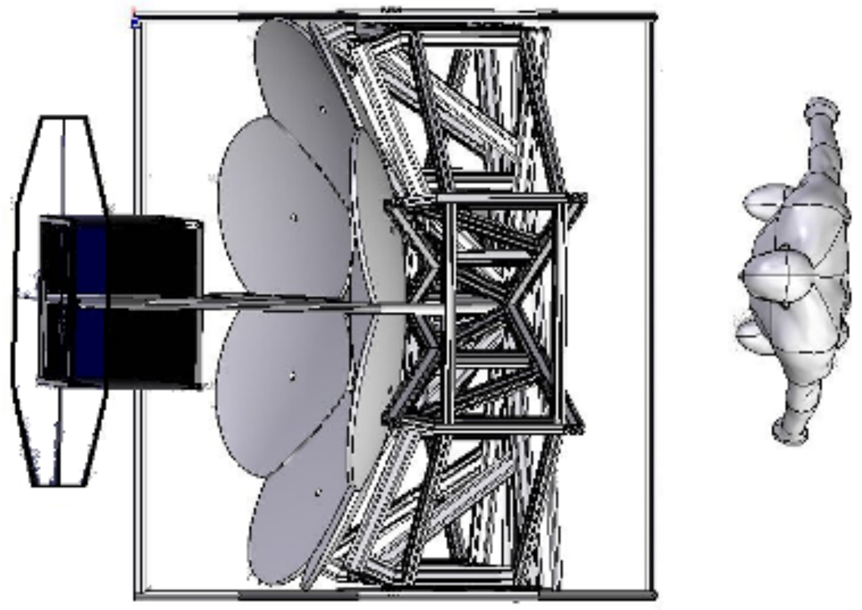


Accepted for publication in Astroparticle Physics arXiv: 1504.00692

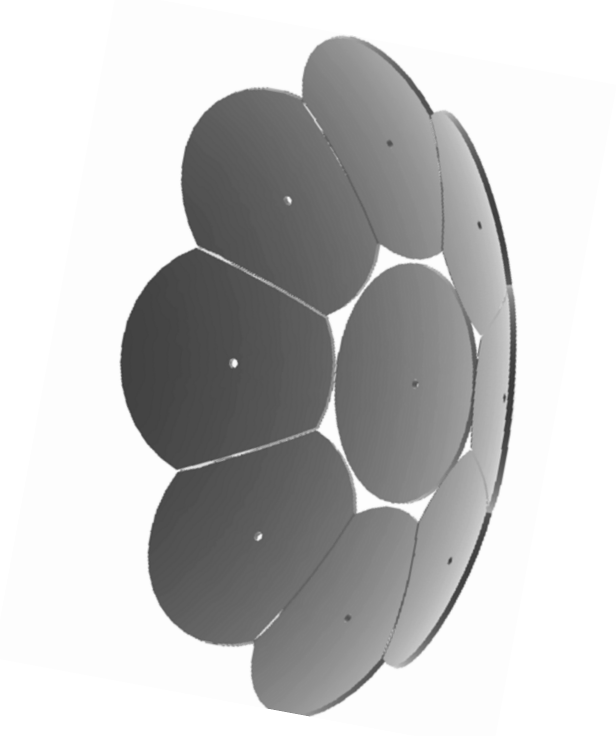
New FAST Prototype being Constructed

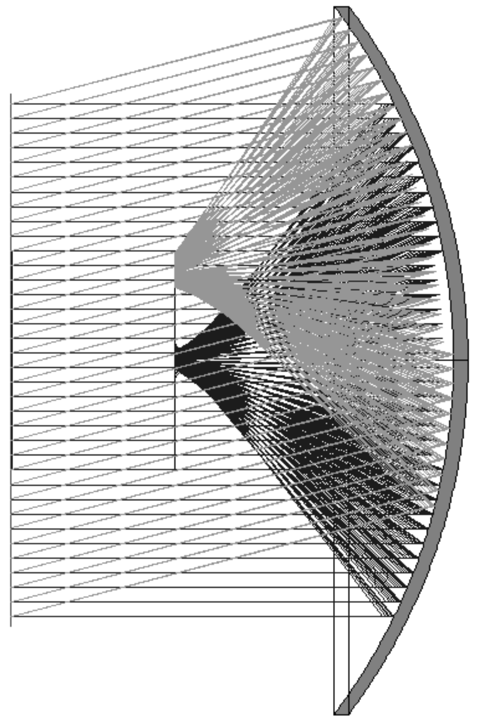
- Confirmed milestones by EUSO-TA Telescope
  - Stable operation under high night sky backgrounds.
  - UHECR detection.
- Next milestones by new FAST prototype
  - Establish the FAST sensitivity.
  - Detect a shower profile including *Xmax* with FAST

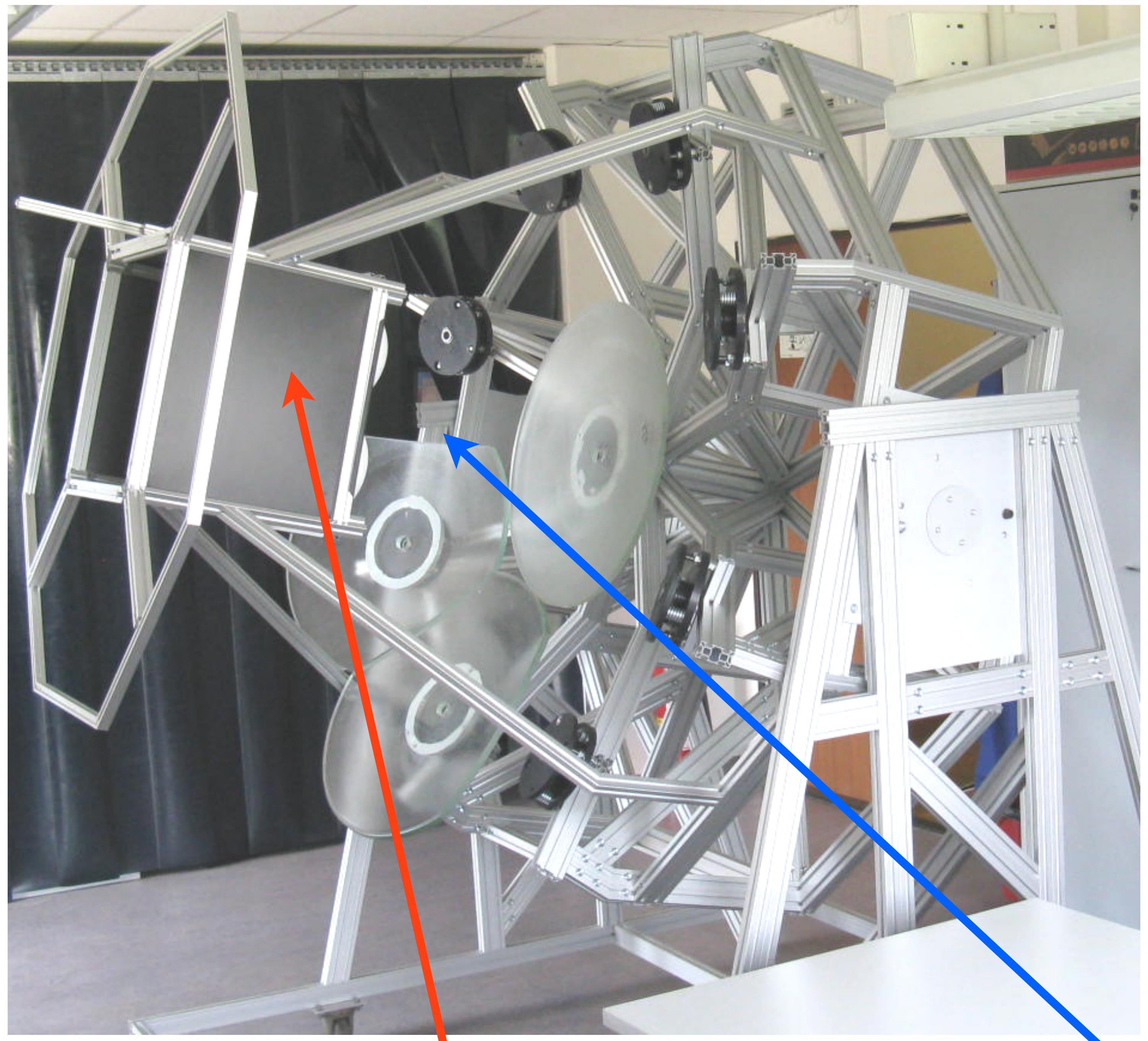


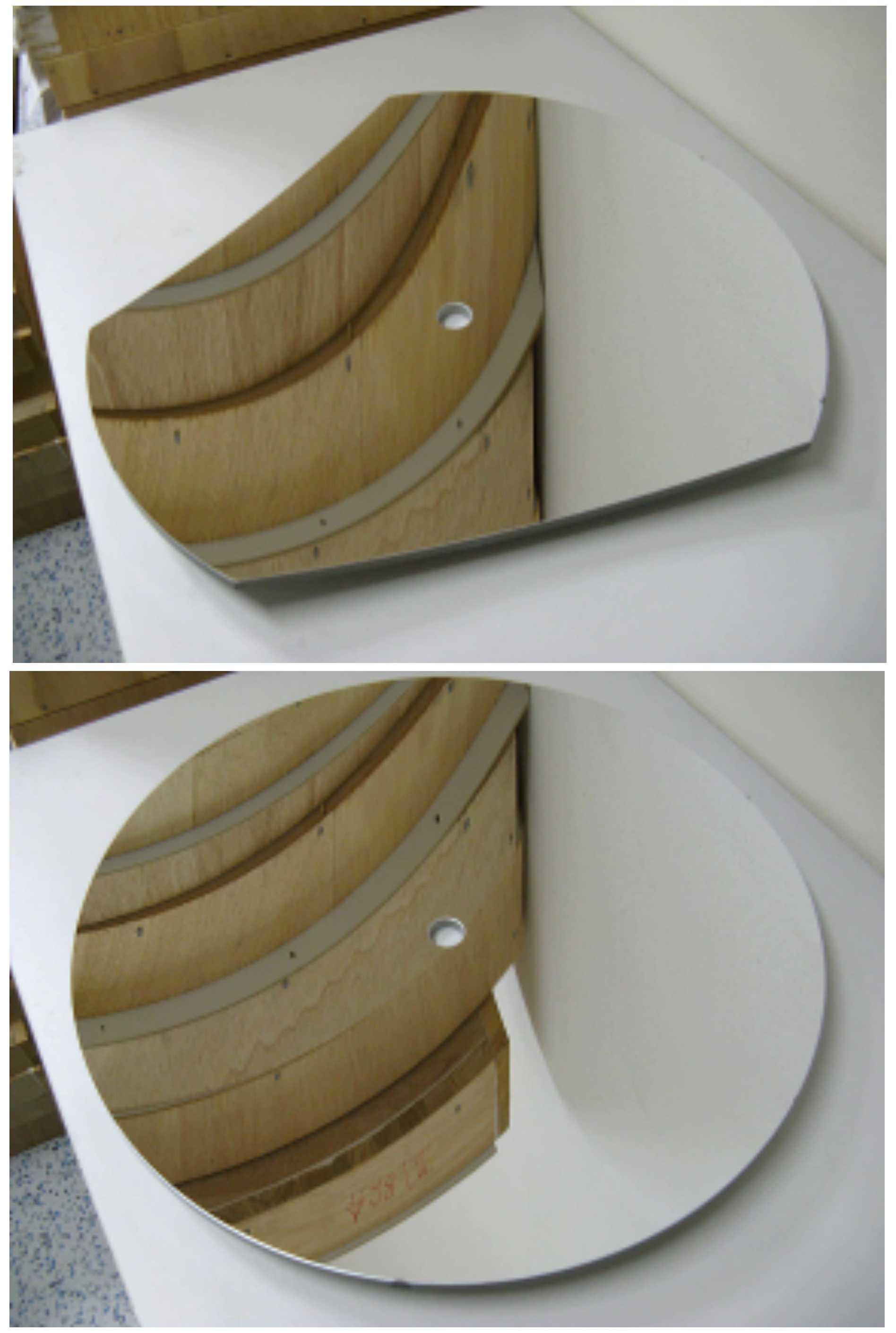


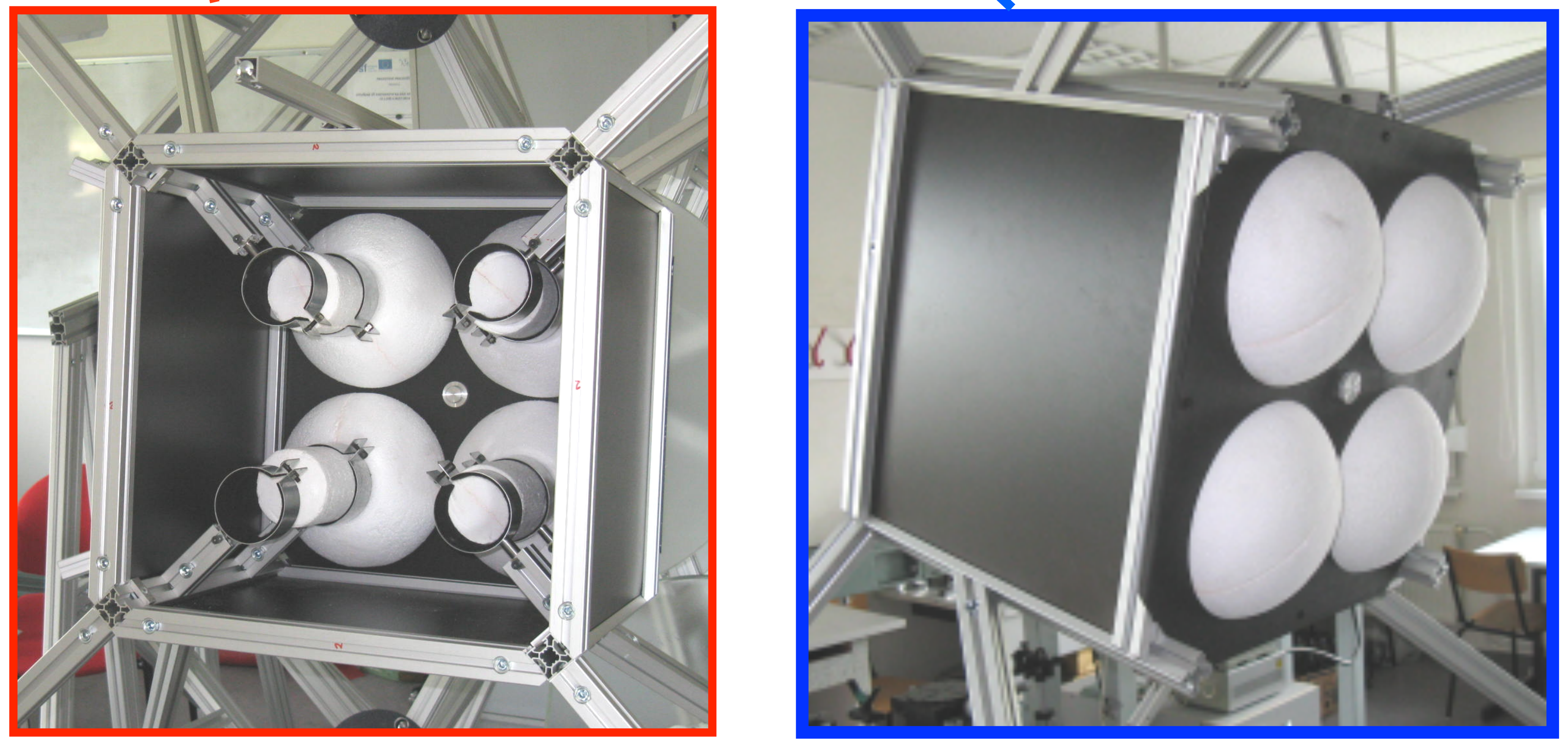
4 PMTs, 30°×30° FoV







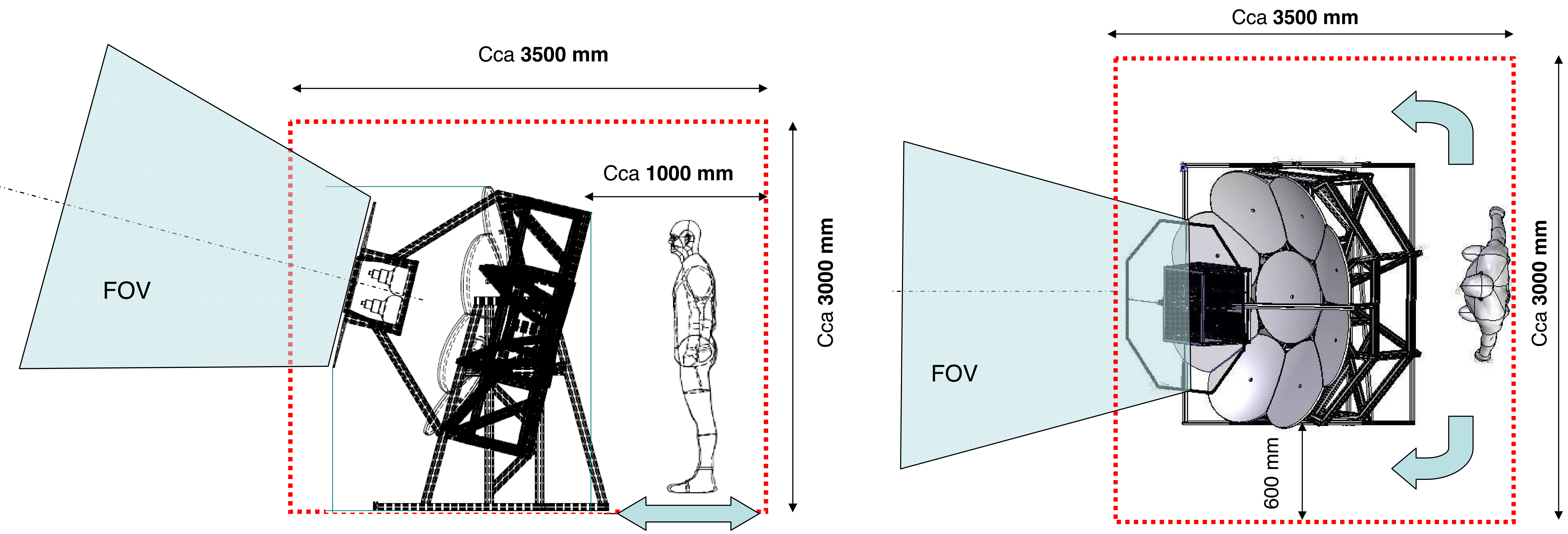




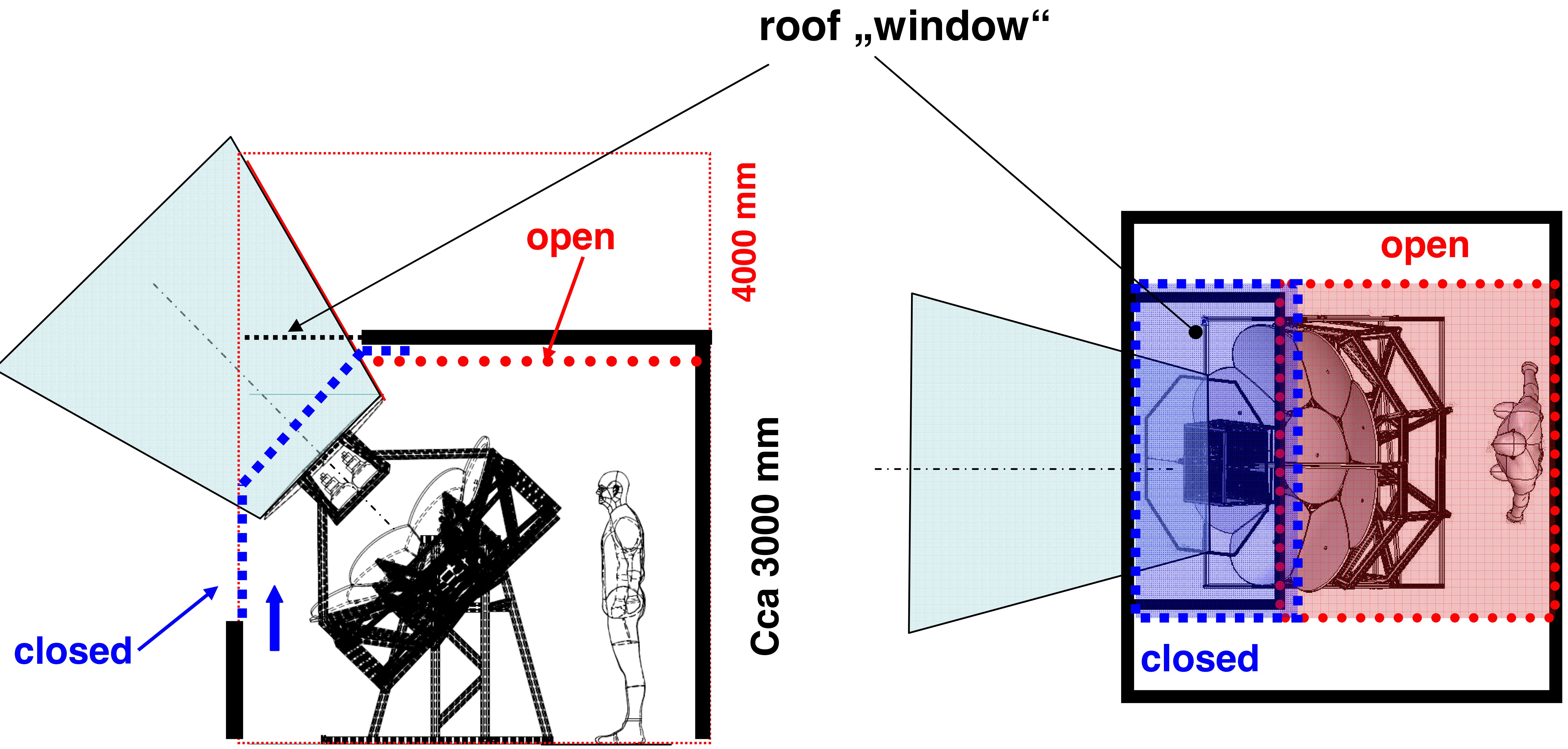
Joint Laboratory of Optics in Olomouc, Czech Republic

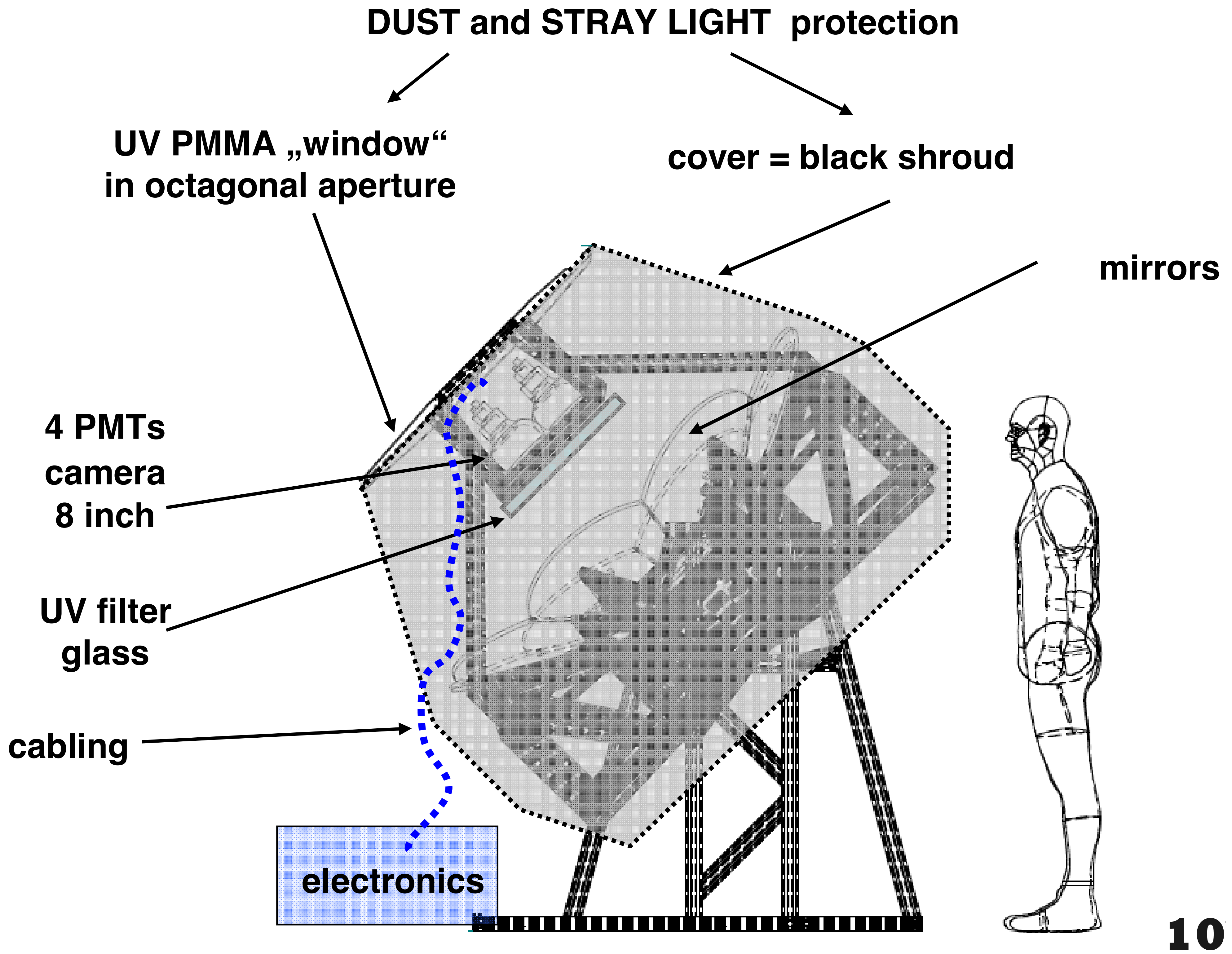
FAST
Fluorescence detector Array of Single-pixel Telescopes

Design of Hut and Shutter

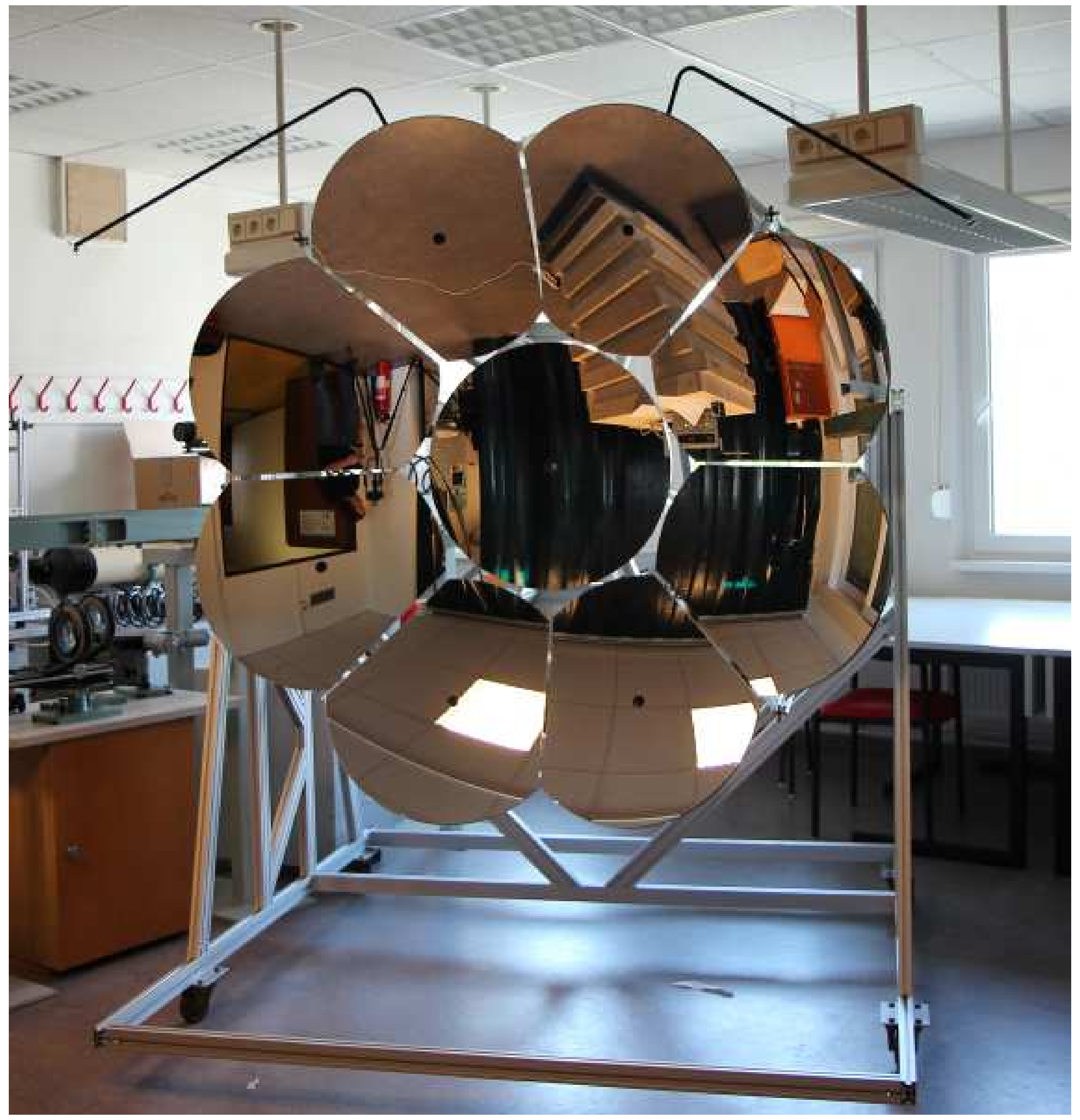


- ✦ Adjustable elevation 15° or 45°, like HEAT and TALE, to enlarge the FoV of the current FD.
- ✦ Robust design for maintenance free and stand-alone observation.





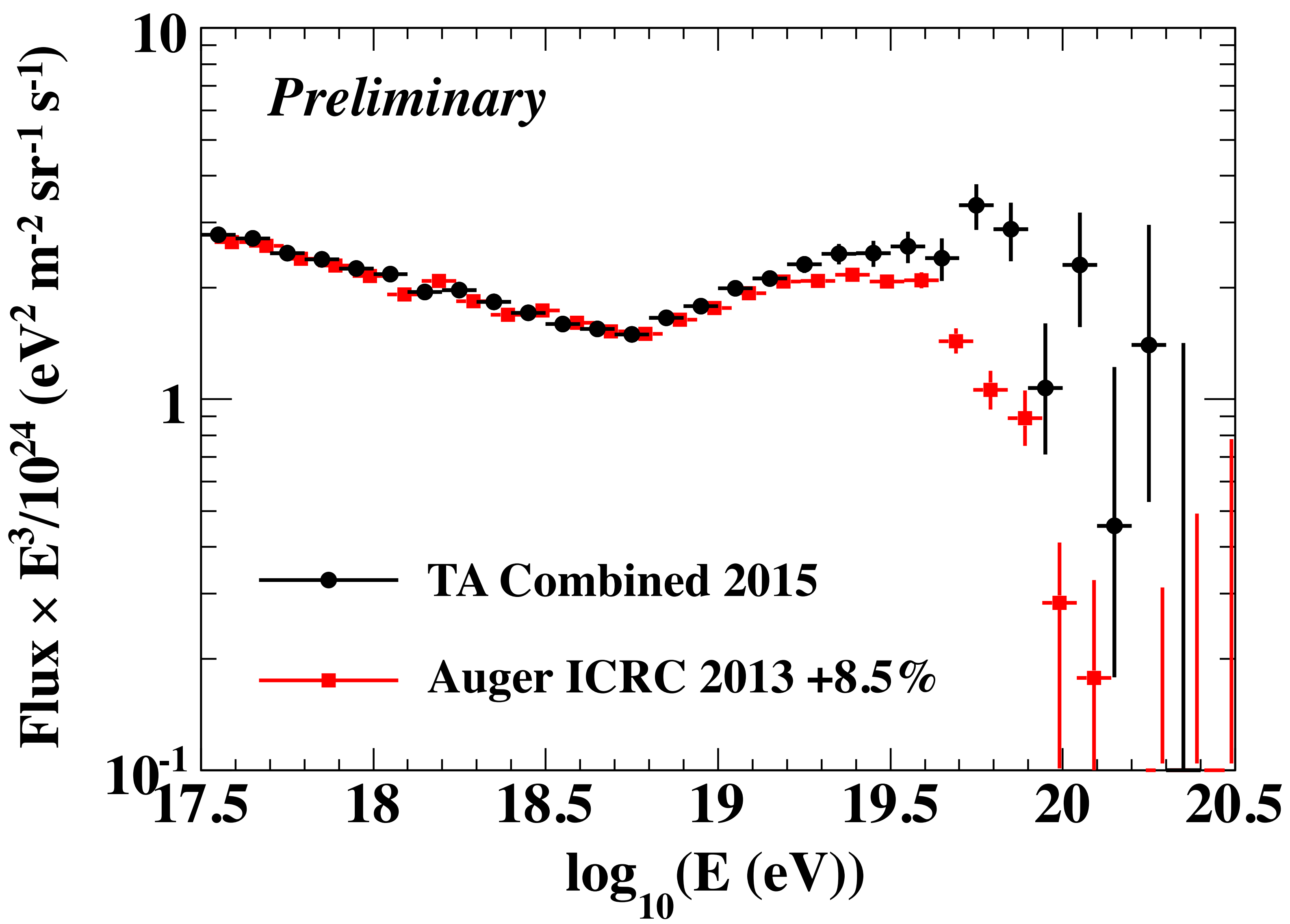
Today's FAST Prototype

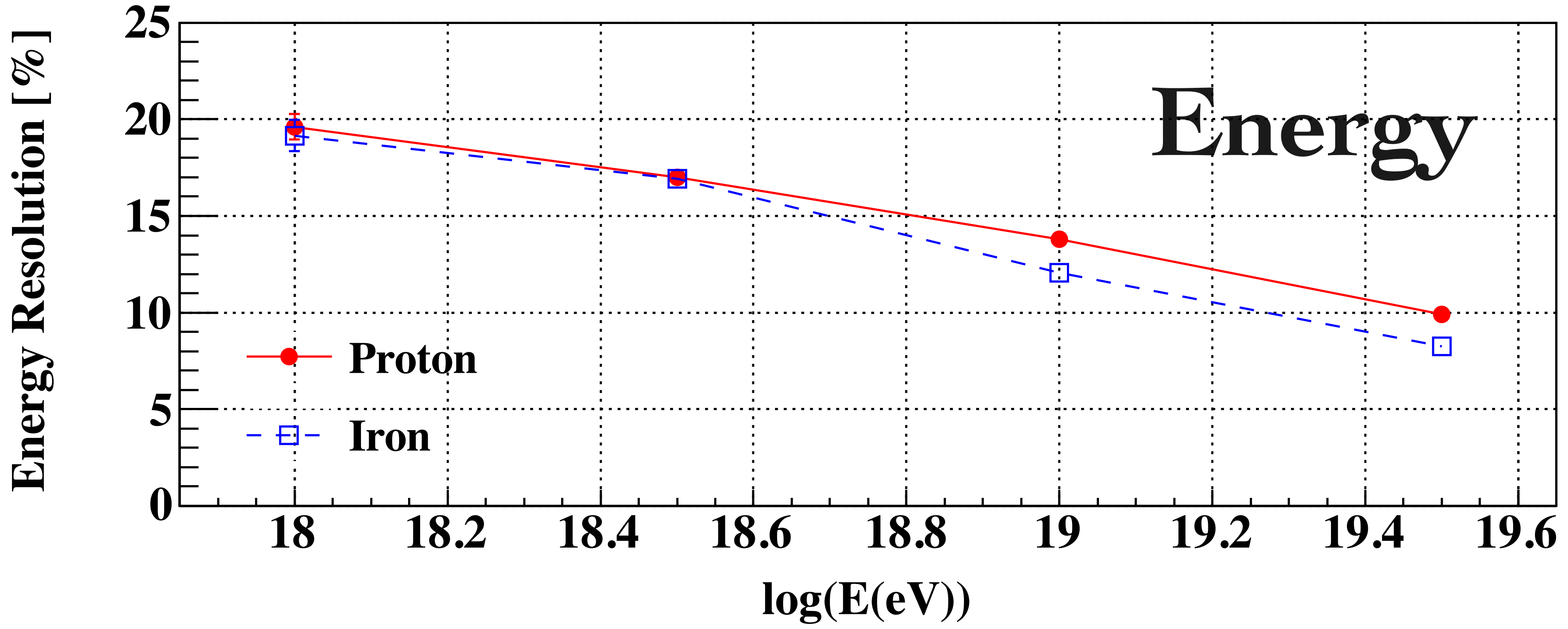


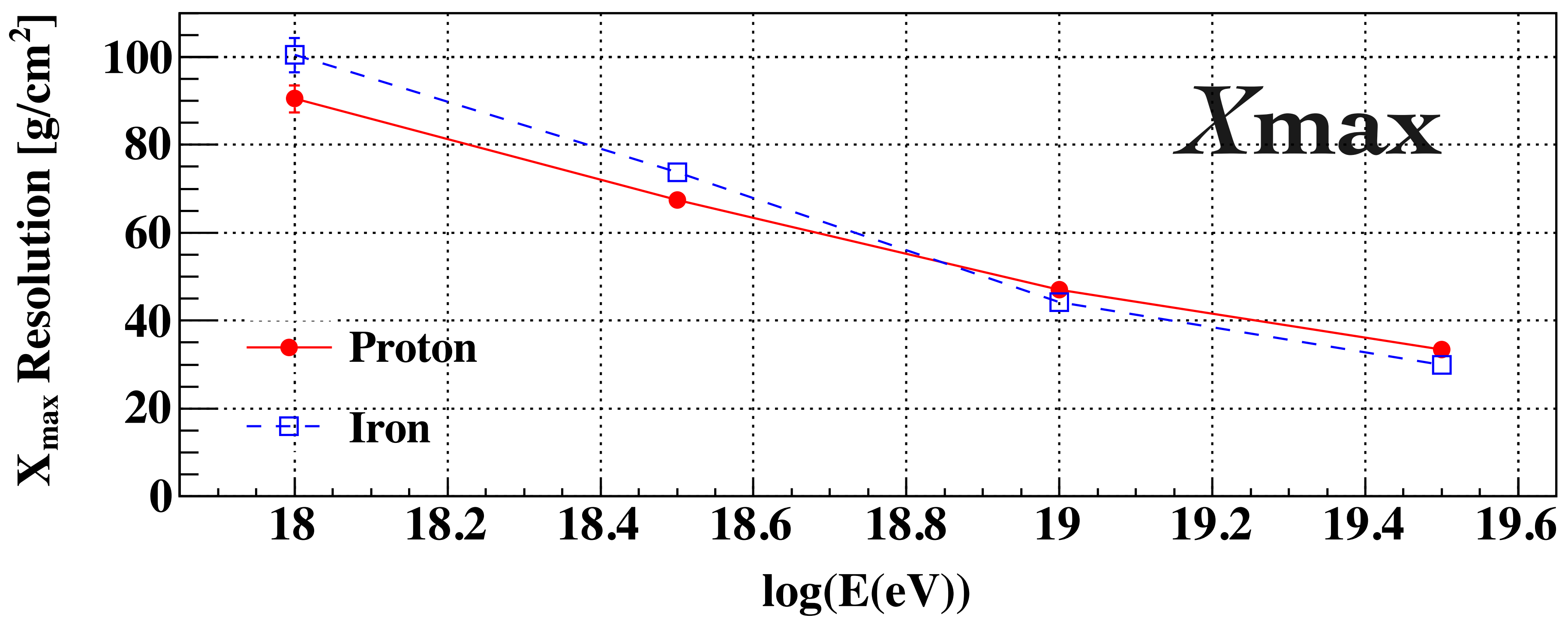
Possible Application of FAST Prototype

Fluorescence detector Array of Single-pixel Telescopes

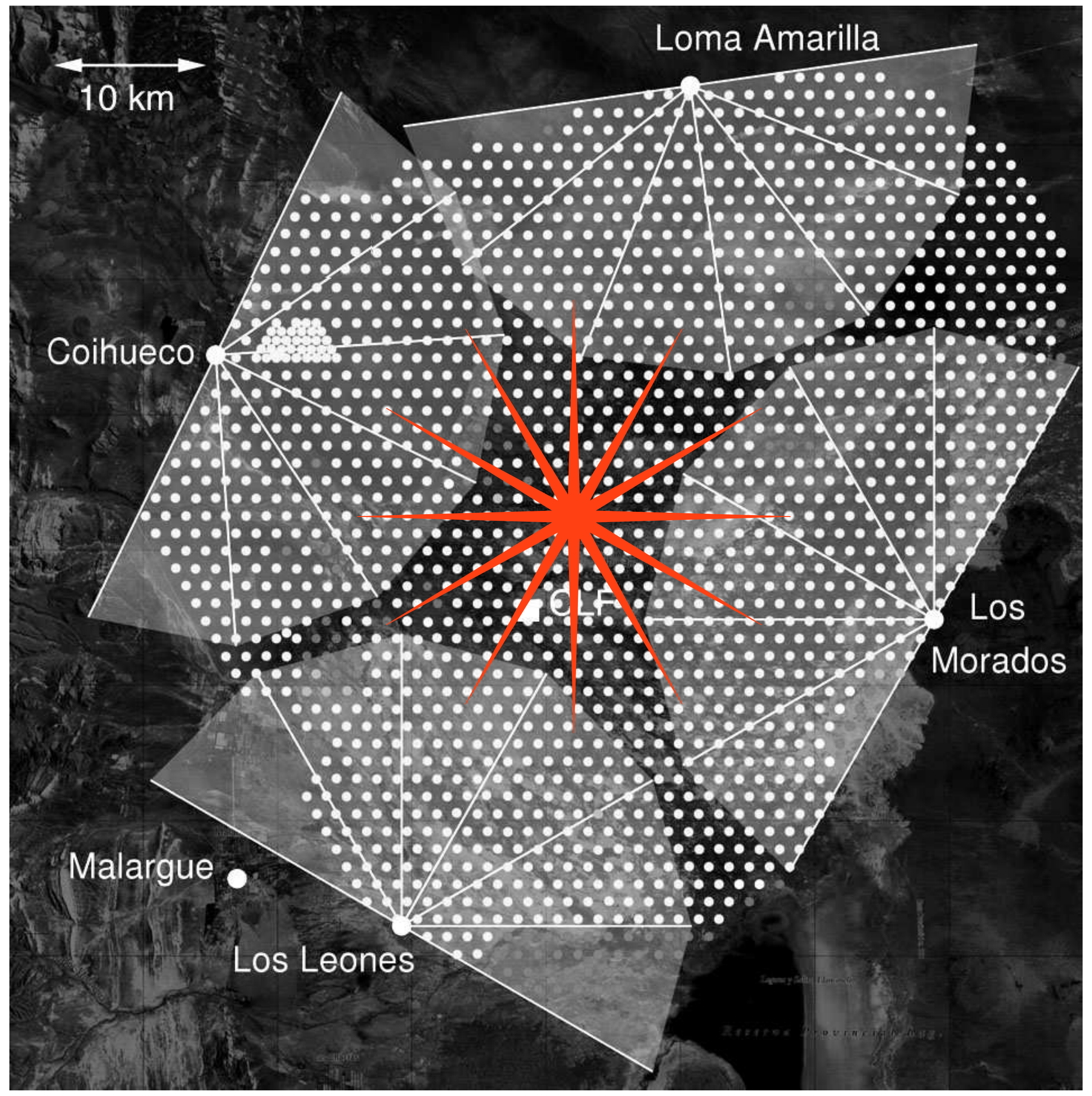
- Install FAST at Auger and TA for a cross calibration.
- Profile reconstruction with geometry given by SD (smearing gaussian width of 1° in direction, 100 m in core location).
  - Energy: 10%, Xmax : 35 g/cm^2 at $10^{19.5}$ eV
  - Independent check of **Energy and Xmax** scale between Auger and TA





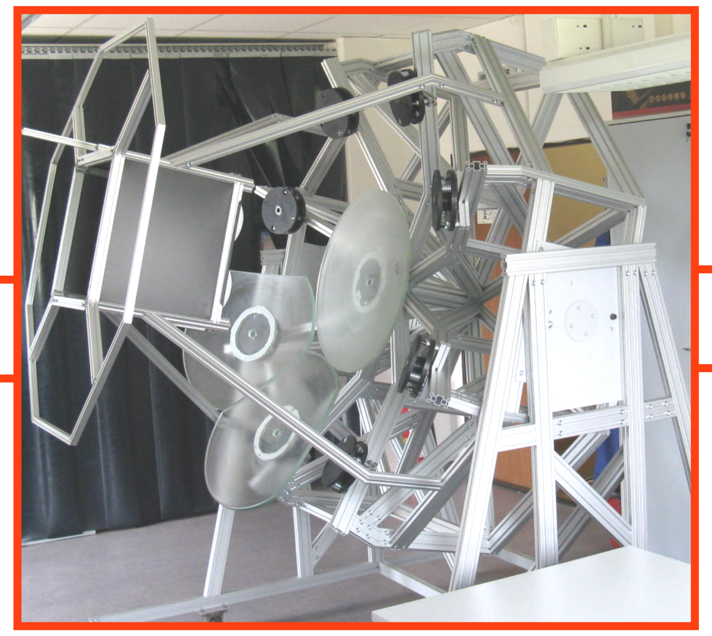


Pierre Auger Observatory

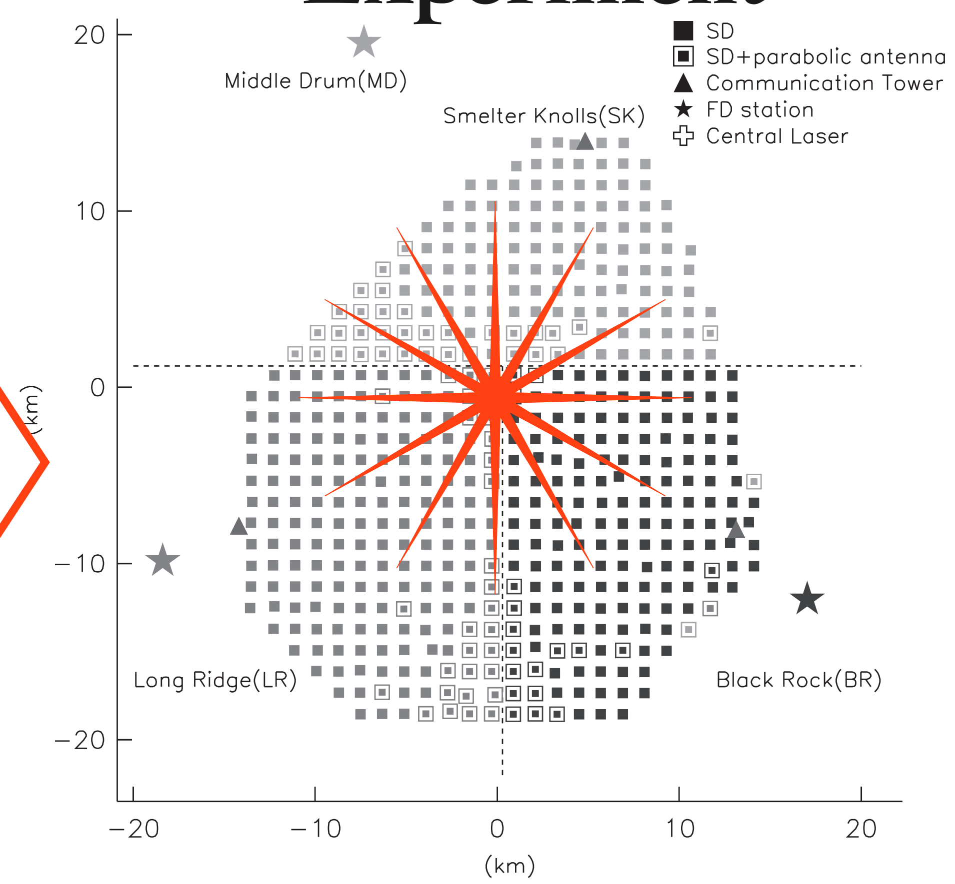


Pierre Auger Collaboration, NIM-A (2010)

Identical simplified FD



Telescope Array Experiment



Telescope Array Collaboration NIM-A (2012)

FAST
Fluorescence detector Array of Single-pixel Telescopes

Physics Goal and Future Prospects

Origin and Nature of Ultra-high Energy Cosmic Rays (UHECRs) and Particle Interactions at the Highest Energies

5 - 10 years

Exposure and Full Sky Coverage
TA×4 + Auger
JEM-EUSO : pioneer detection from space and sizable increase of exposure

Detector R&D
Radio, SiPM,
Low-cost Fluorescence Detector (FD)

"Precision" Measurements
AugerPrime
Low energy enhancement (Auger infill+HEAT+AMIGA, TALE+TA-muon+NICHE)

10 - 20 years

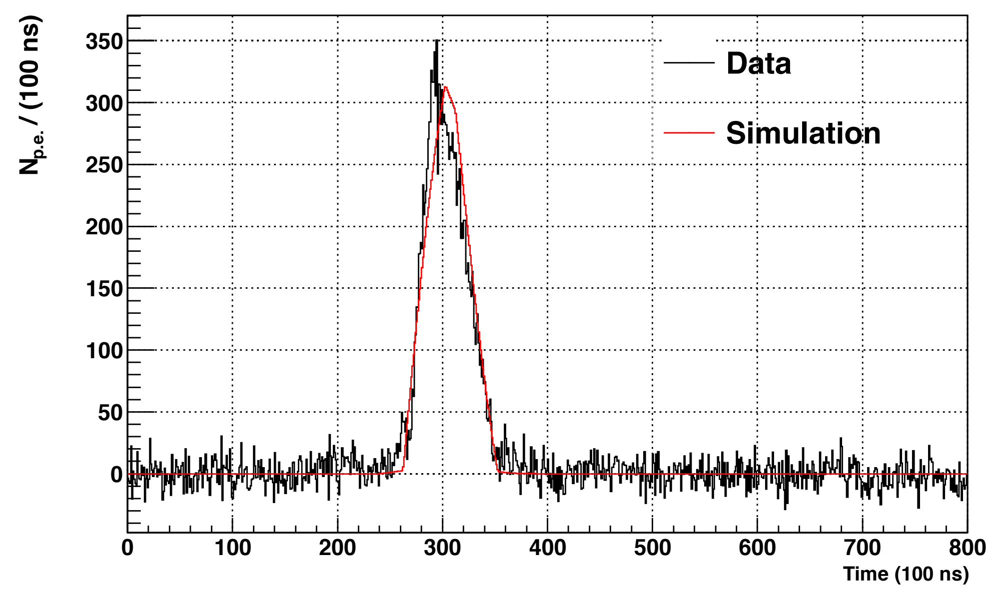
Next Generation Observatories
In space (100×exposure): Super-EUSO
Ground (10×exposure with high quality events): FAST
Fluorescence detector Array of Single-pixel Telescopes

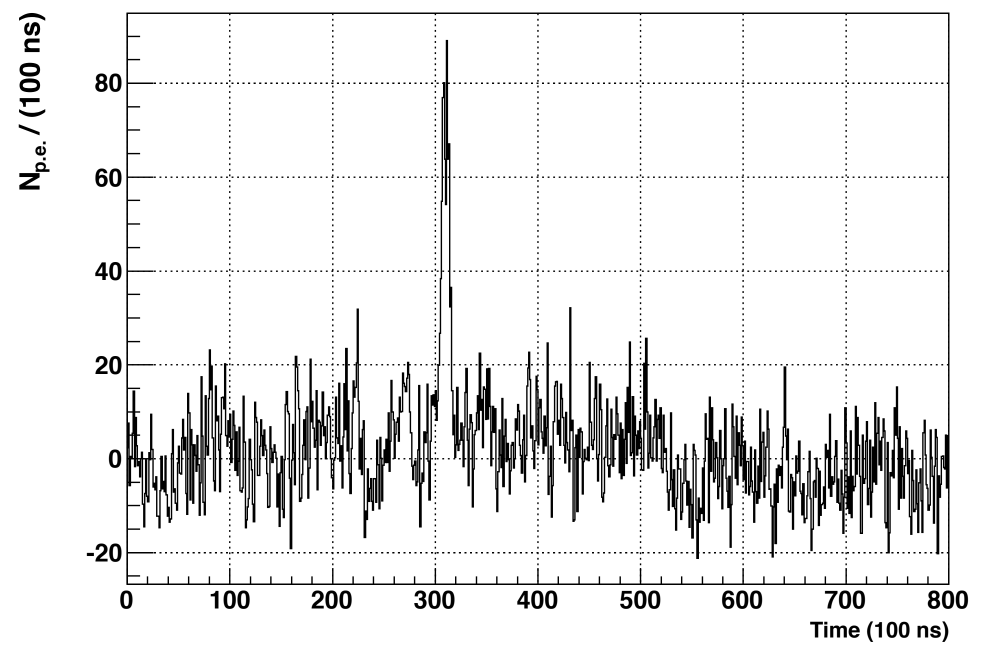
FAST
Fluorescence detector Array of Single-pixel Telescopes

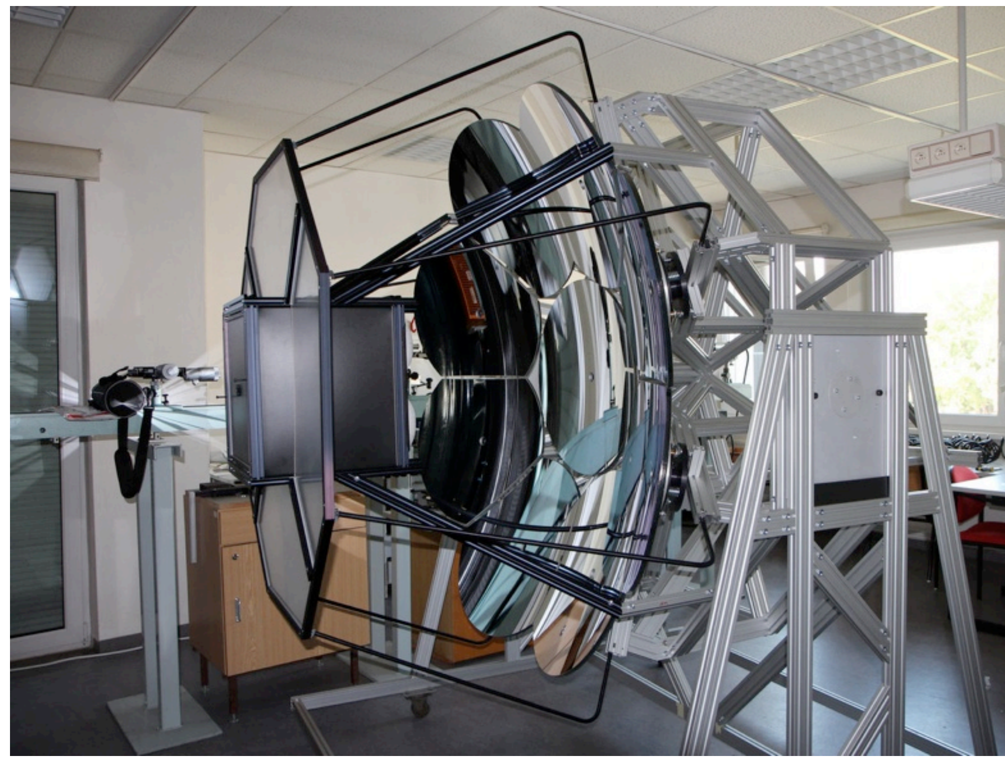
Summary and Future Plans

- **Era to develop optimized and economical fluroescence detector**
- **Fluorescence detector Array of Single-pixel Telescopes**
    - Deploy the detector array consisting of fluorescence detector optimized to observe UHECRs.
    - Next-generation observatory on the ground.
    - Increase statistics of UHECRs above $10^{19.5}$ eV by a order of magnitude to clarify origins of UHECRs, establish UHECR astronomy and detect UHE neutral particles.
- This concept was confirmed by the test measurement using EUSO-TA optics.
- New full-scale FAST prototype is being constructed, and almost completed.
- New collaborator is welcome.

FAST
Fluorescence detector Array of Single-pixel Telescopes



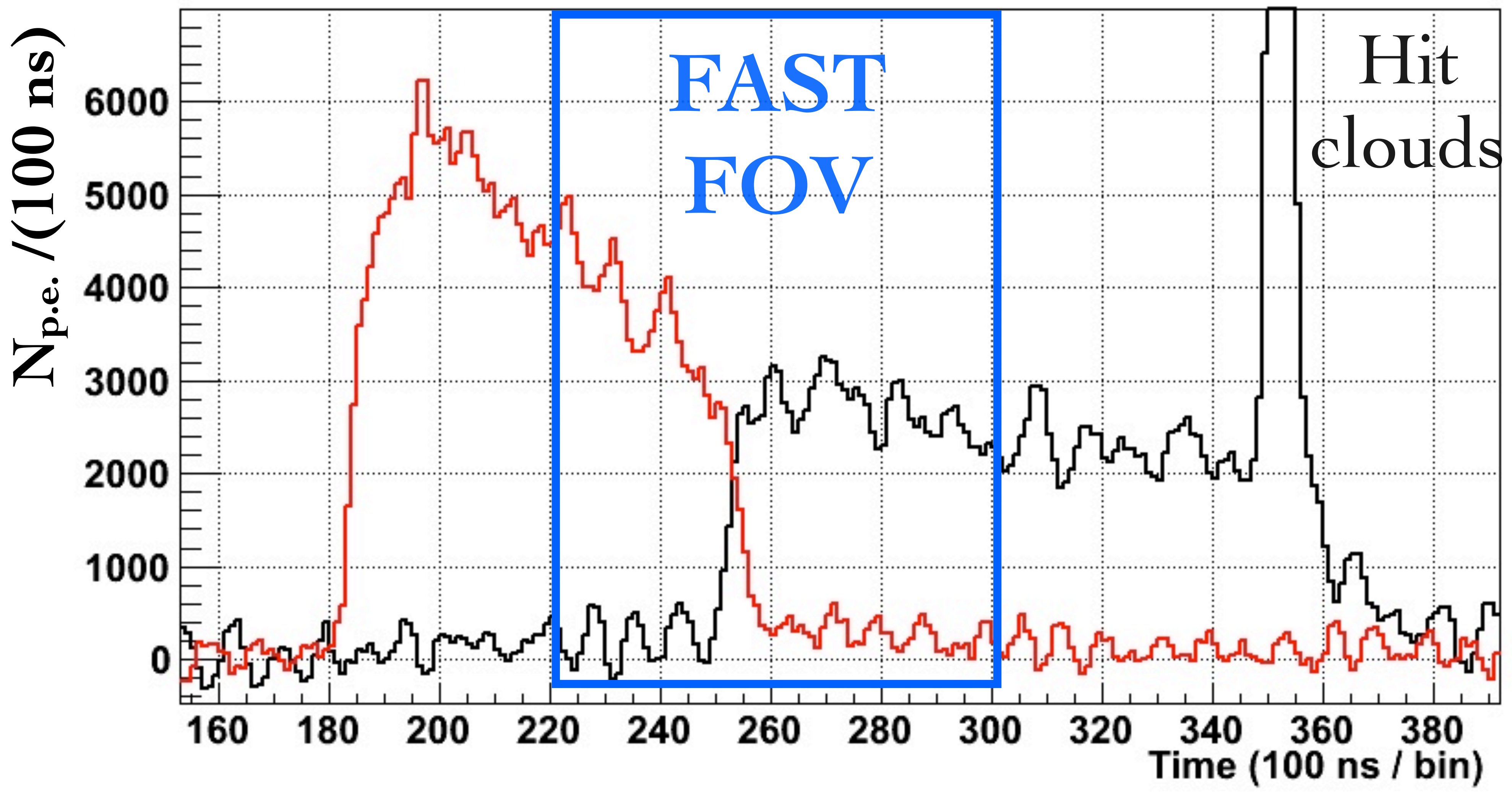




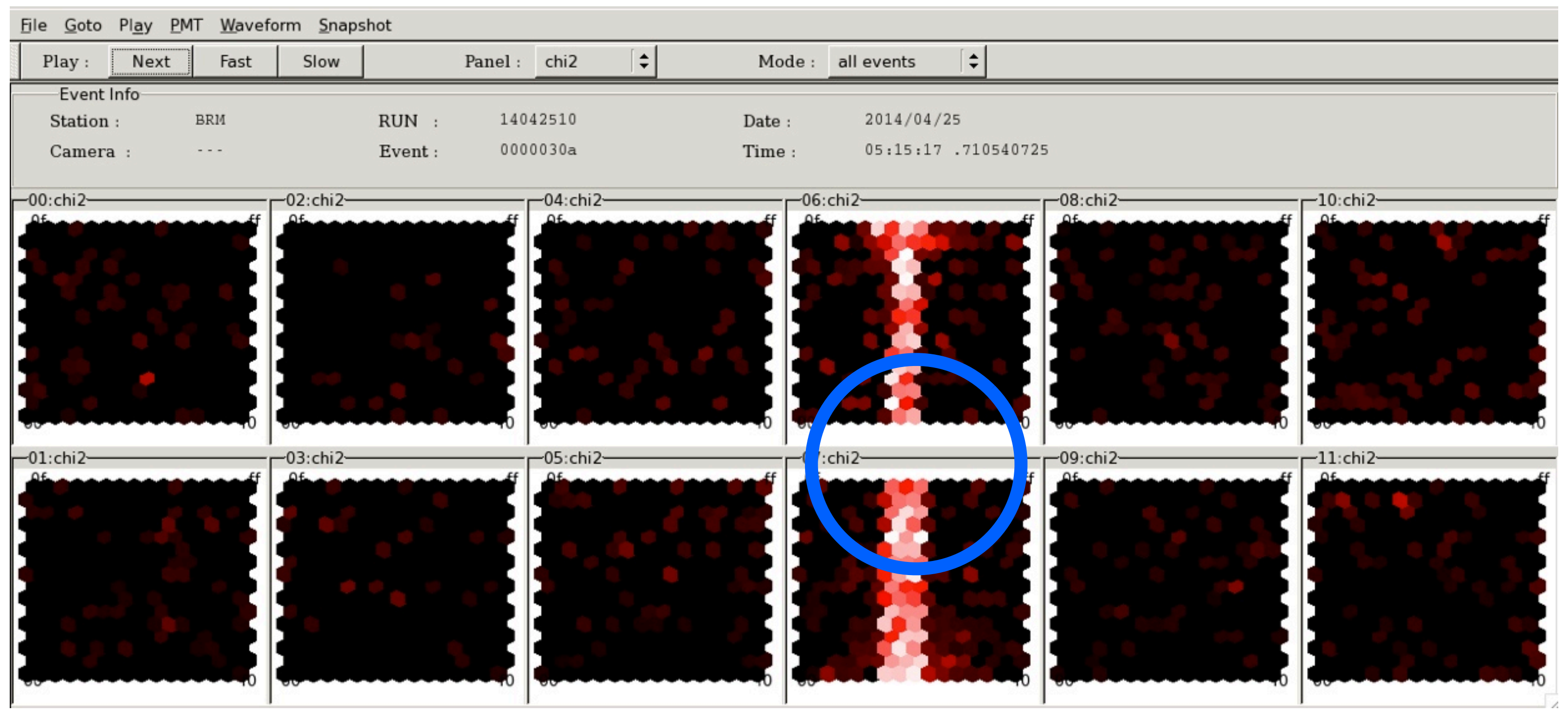
Backup

Fluorescence detector Array of Single-pixel Telescopes

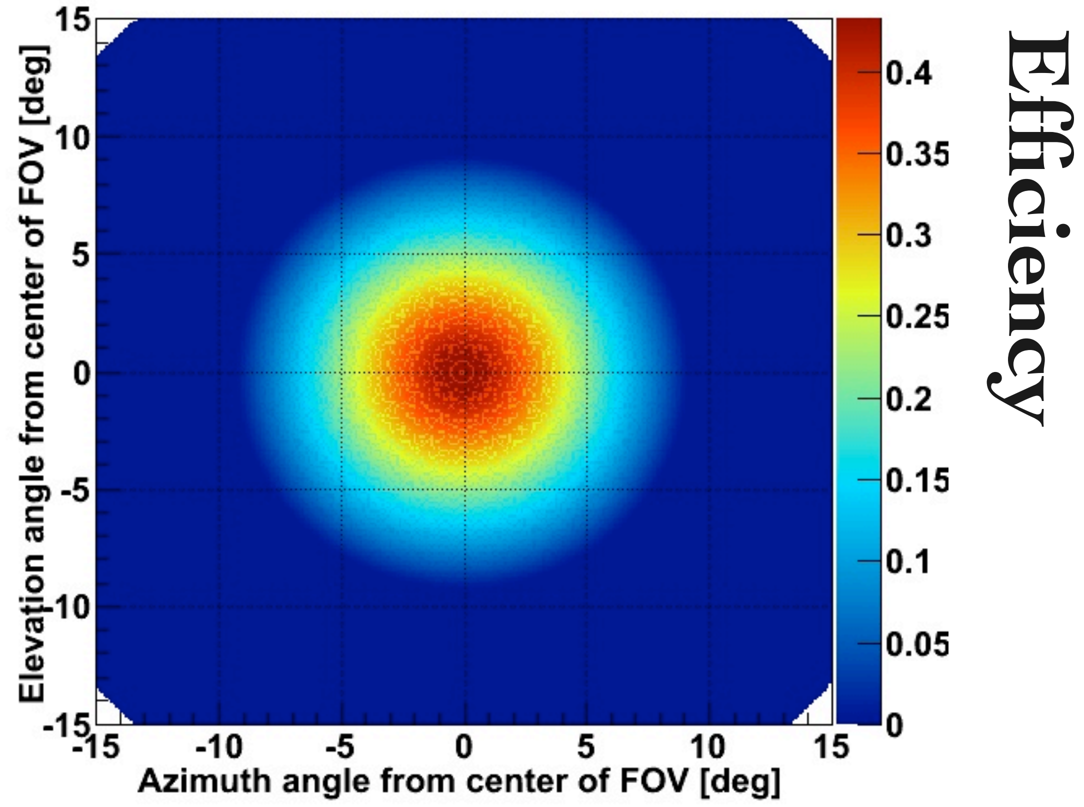
Laser Signal to Check Performance

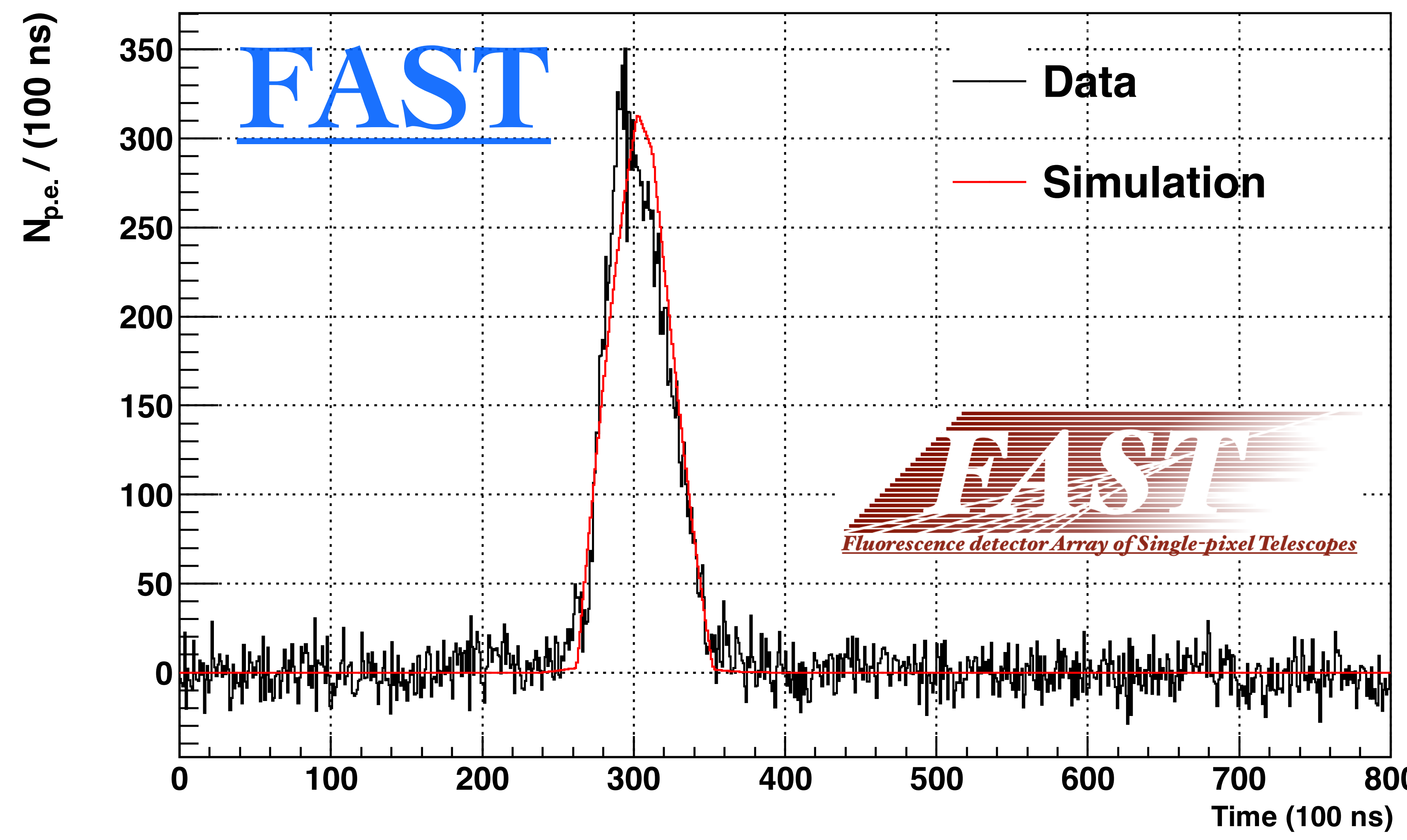


TAFD



Directional sensitivity by RayTrace of EUSO-TA telescope



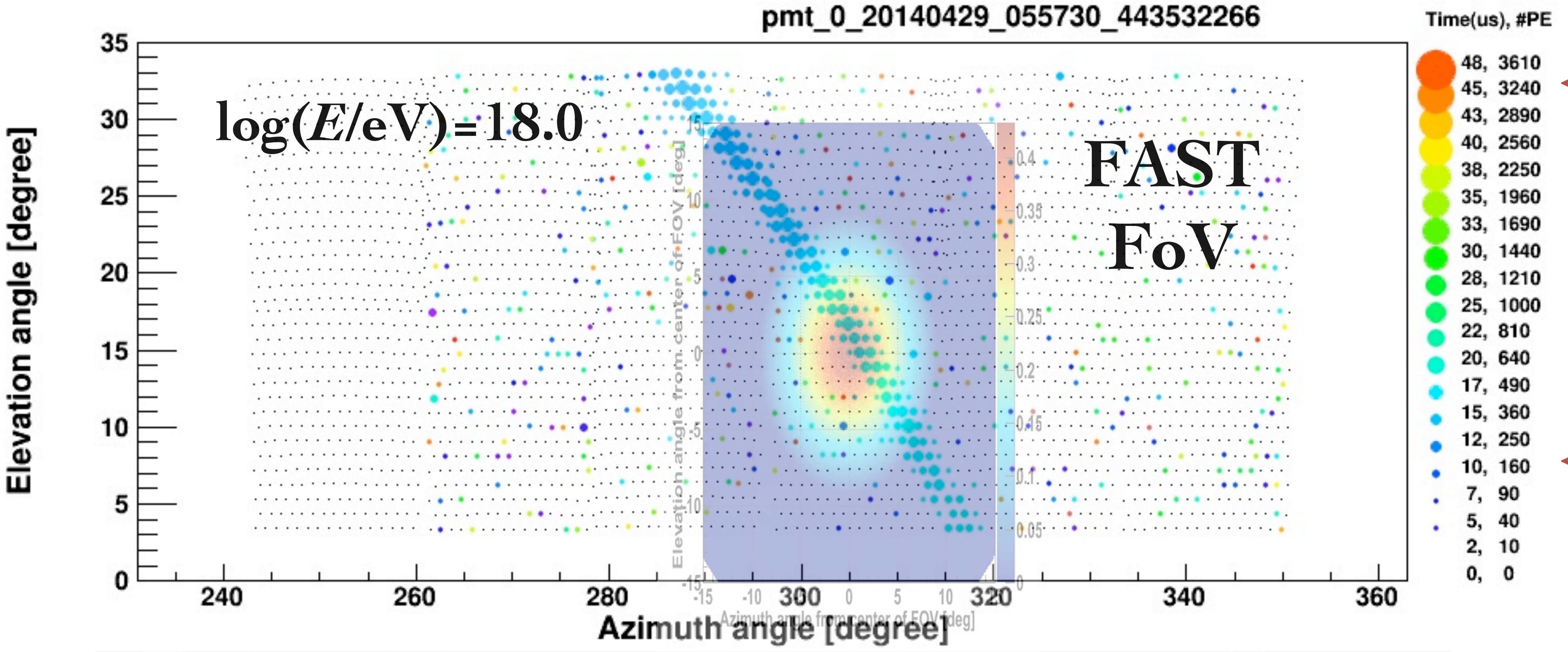


- Vertical Ultra-Violet laser at 6 km from FAST ≒ ~$10^{19.2}$ eV
- Expected signal TAFD/FAST: (7 m^2 aperture × 0.7 shadow × 0.9 mirror) / (1 m^2 aperture × 0.43 optics efficiency) ~10
  - TAFD Peak signal : ~3000 p.e. / 100 ns
  - FAST Peak signal : ~300 p.e. / 100 ns. All shots are detected significantly.
- Agreement of signal shape with simulation.

UHECR Signal Search

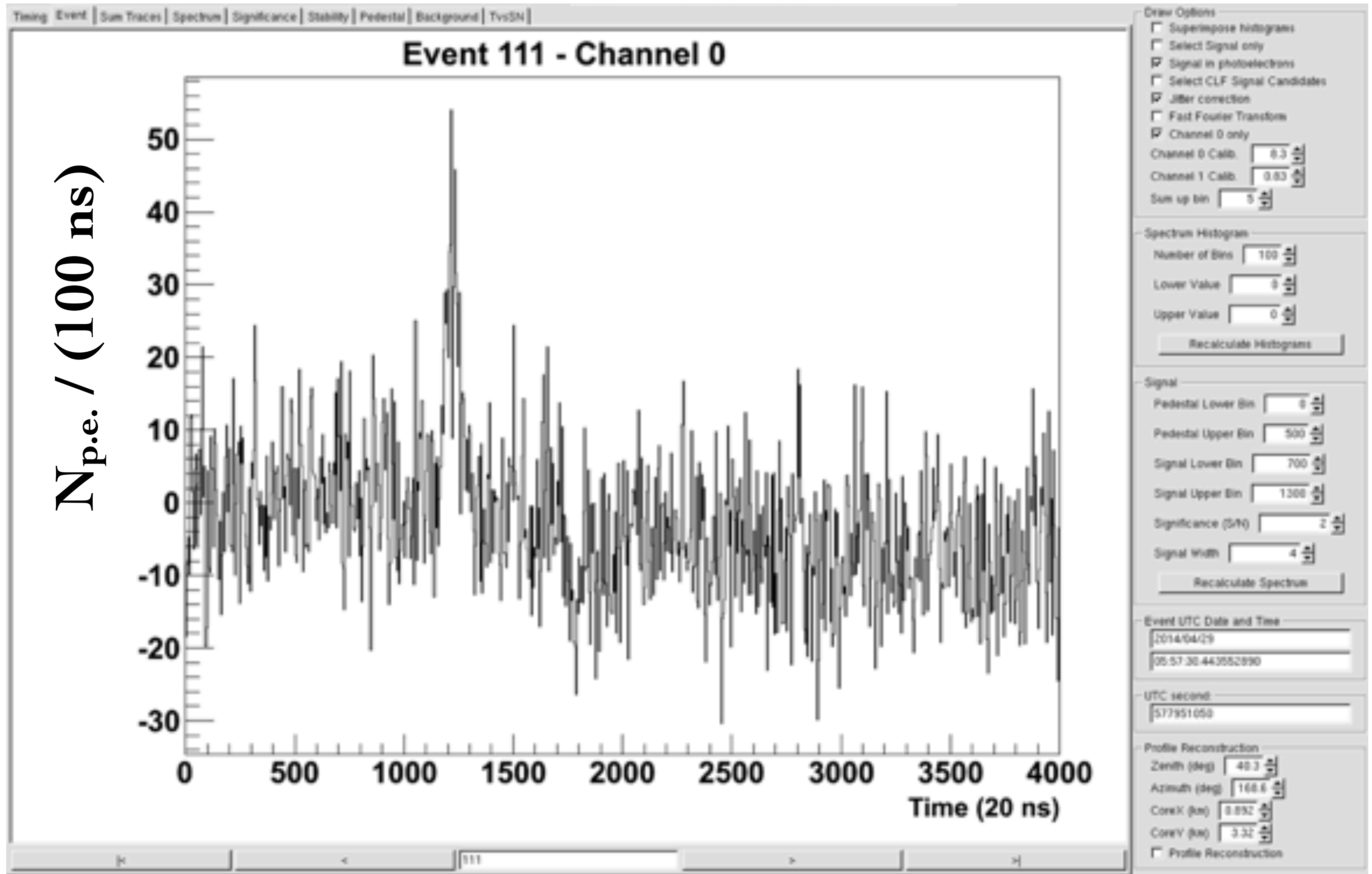
Fluorescence detector Array of Single-pixel Telescopes

TAFD



FAST

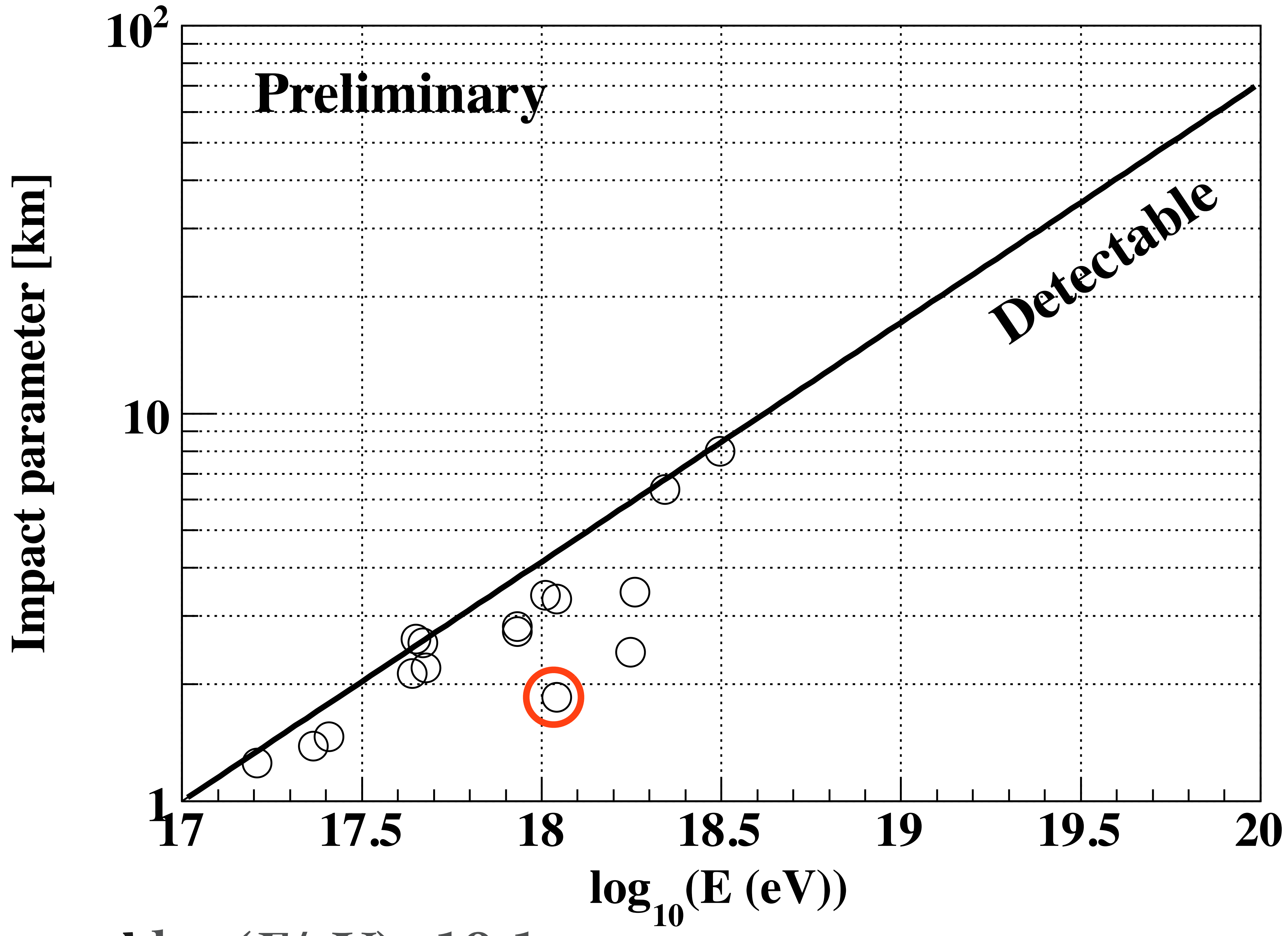
Fluorescence detector Array of Single-pixel Telescopes

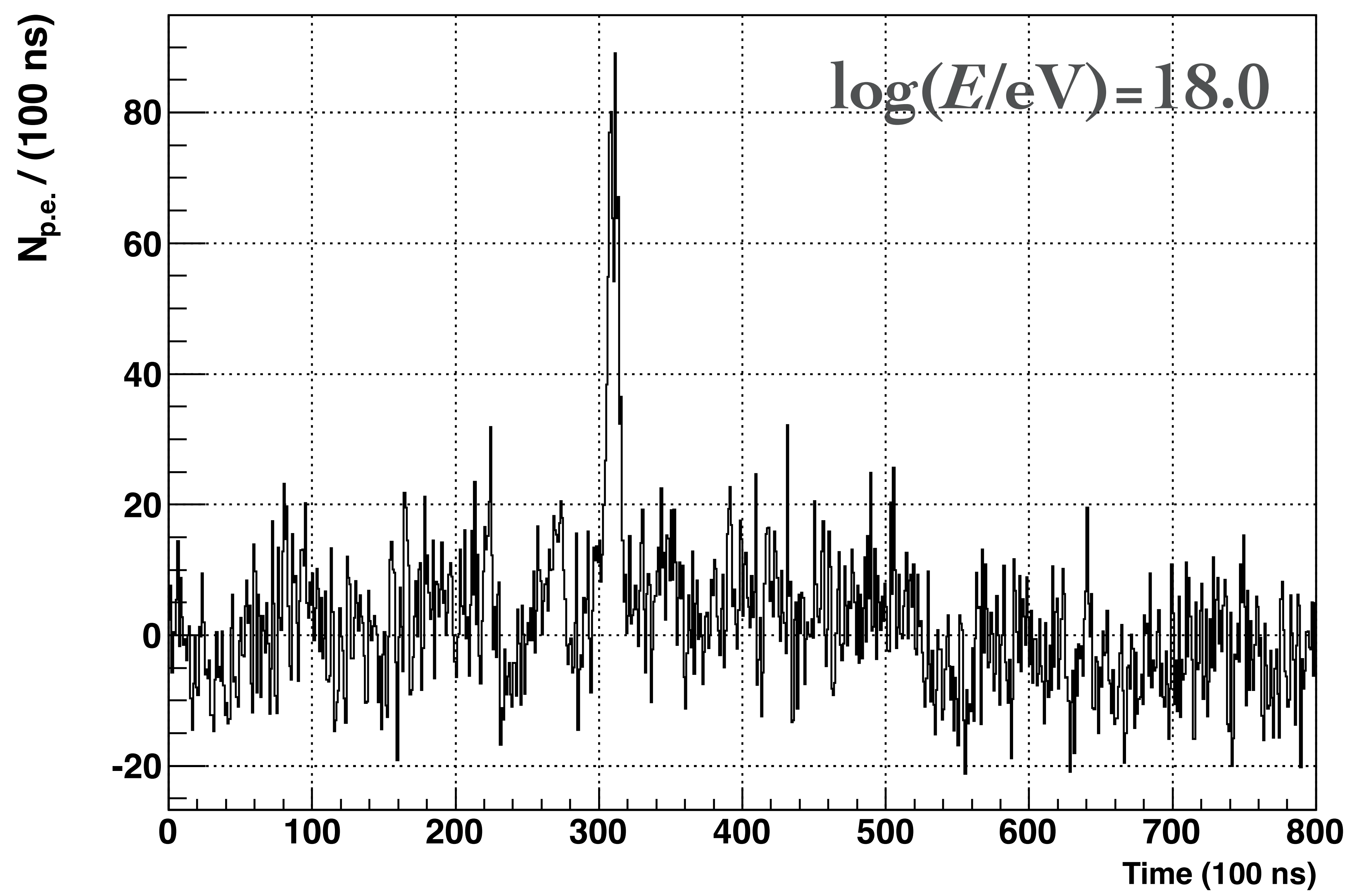


- Data set: April and June 2014 observation, 19 days, 83 hours.
  - Stable observation.
- We searched for UHECR signal in coincidence between FAST and TAFD.
  1. Search for TAFD signal crossing the field of view (FoV) with FAST.
  2. Search for a significant signal (>5σ) with FAST waveform at the same trigger.
- **16 candidates found.**
- Low energy showers as expected.

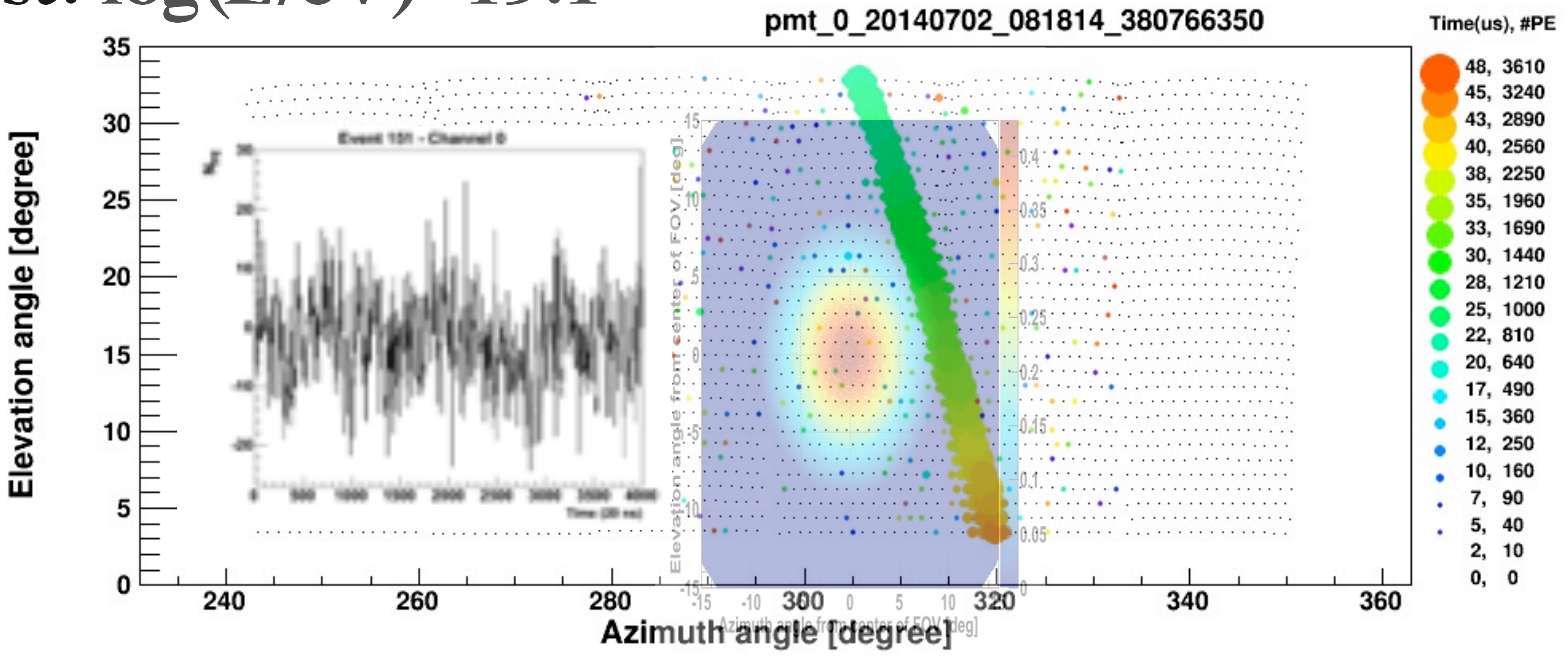
Fluorescence detector Array of Single-pixel Telescopes

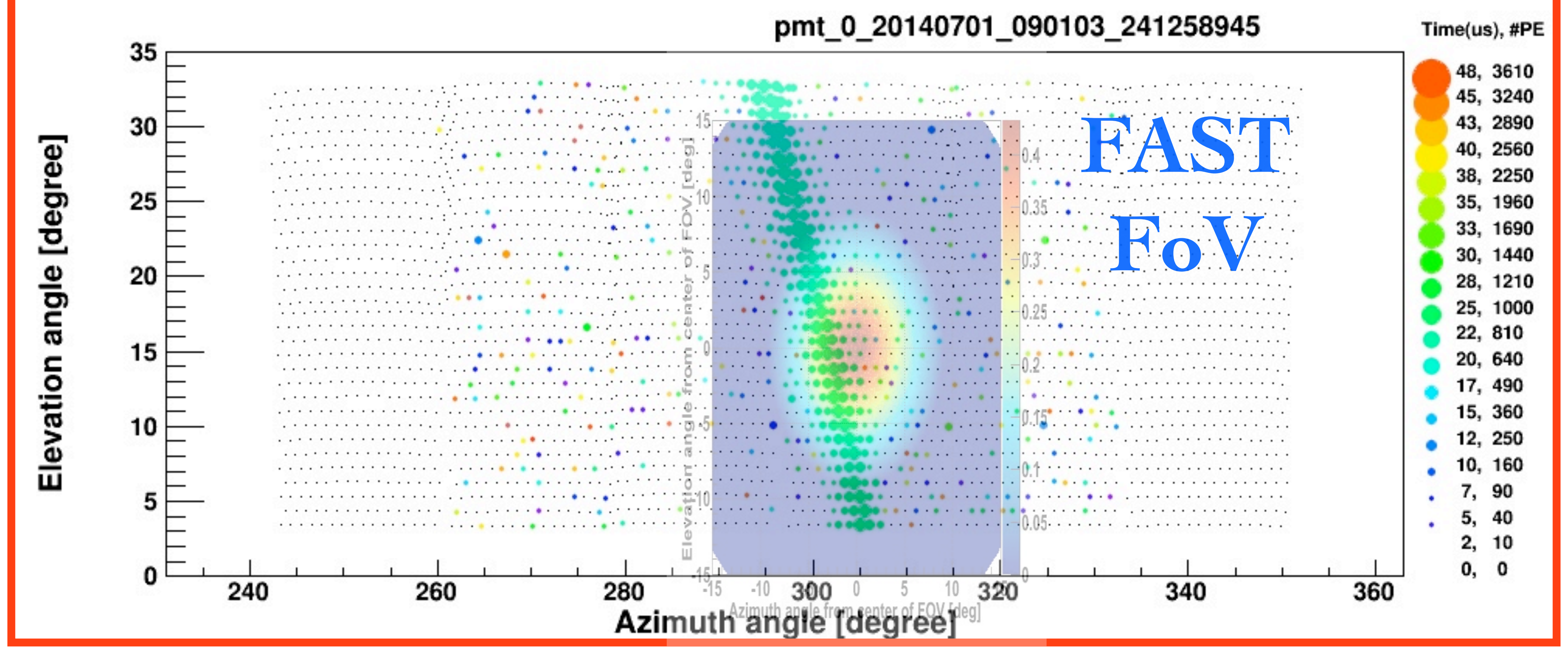
Distance vs Energy (from TAFD) for Candidates



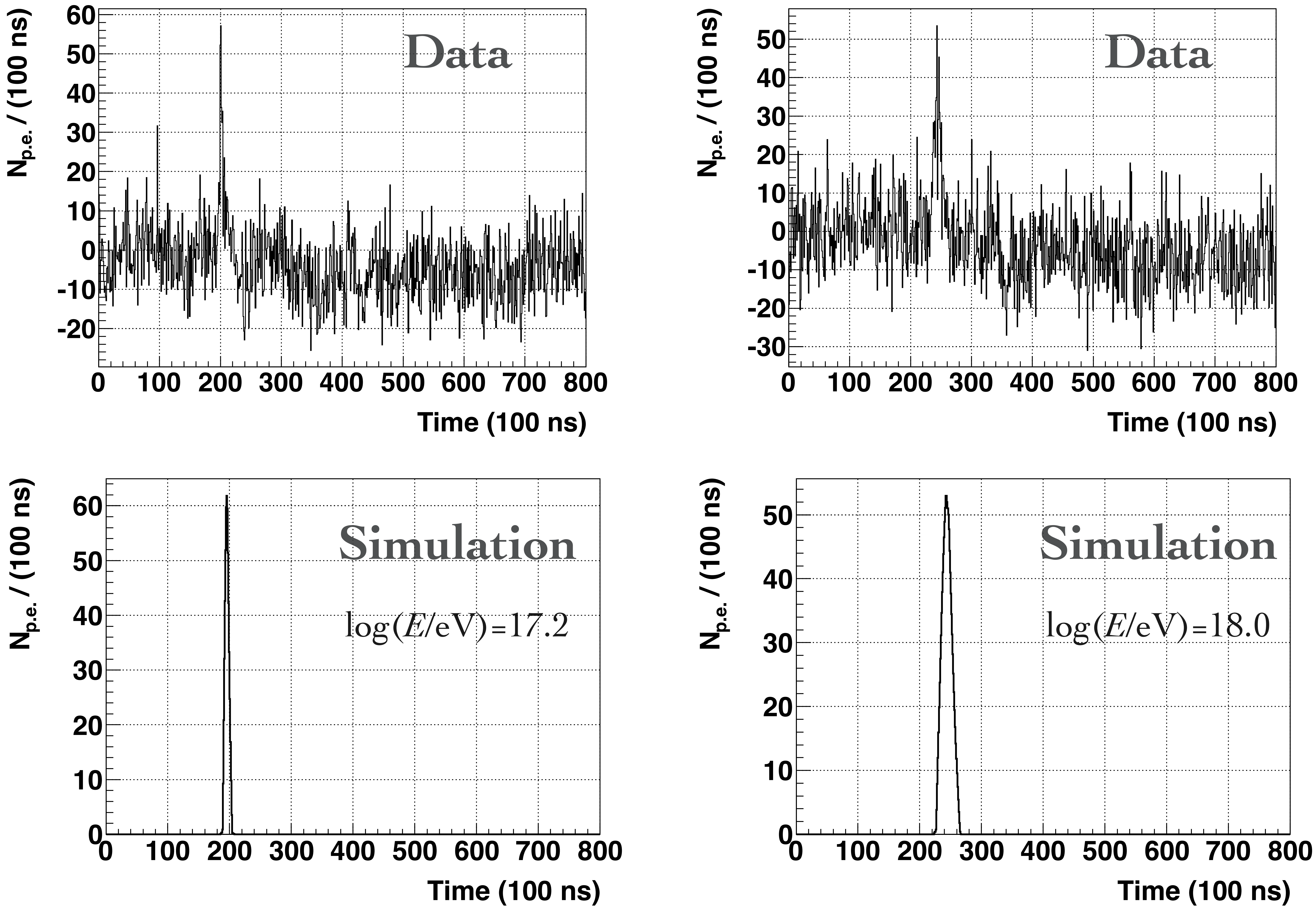


Almost! log(*E*/eV)=19.1





Comparison to Expected Signal from UHECRs



- Geometry, Energy and *X*max was reconstructed by the TAFD monocular analysis.
- Based on these information, we calculate expected signal by FAST prototype.
- Size, shape and width are consistent with expectation.
  - A signal location is fluctuated within the TAFD trigger frame of 12.8 μs.

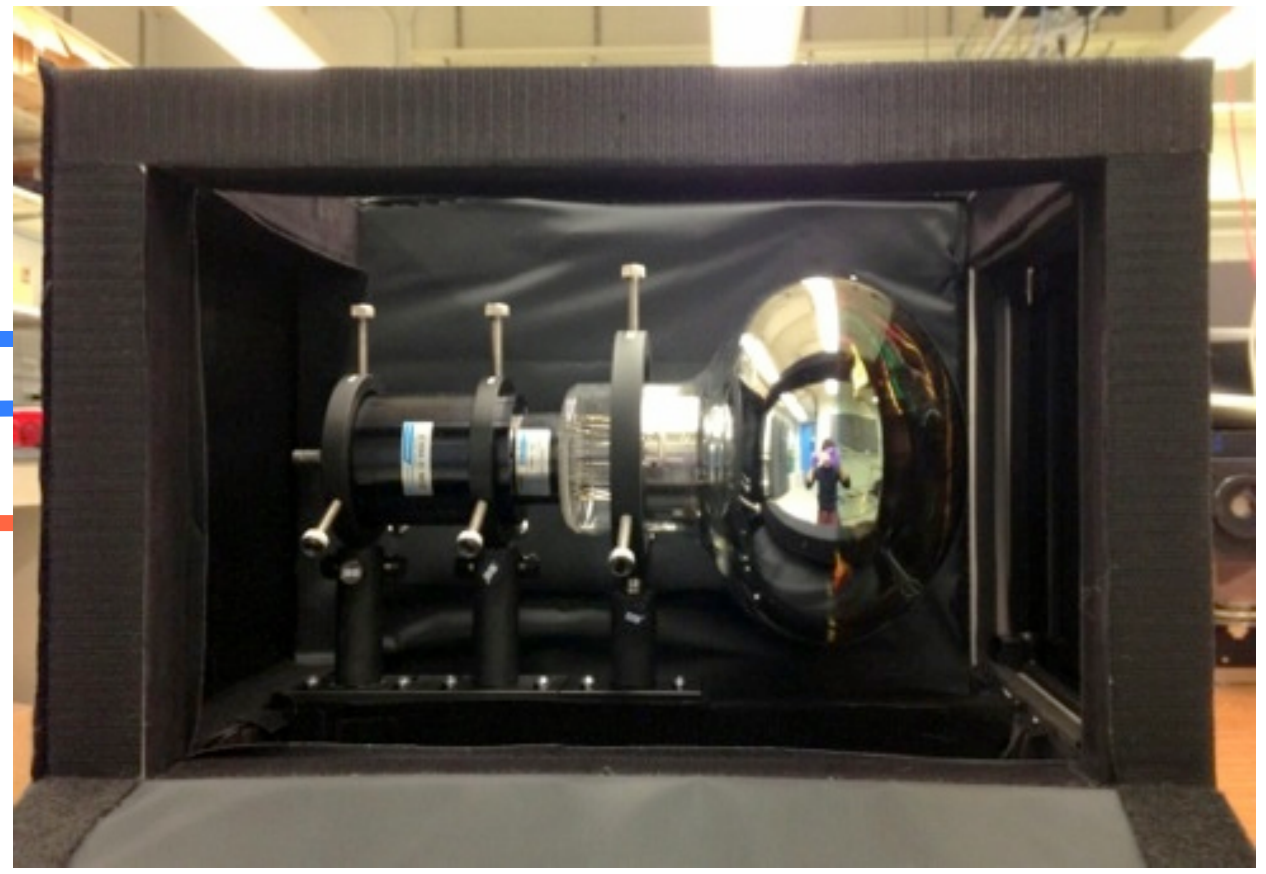
FAST DAQ System

Fluorescence detector Array of Single-pixel Telescopes

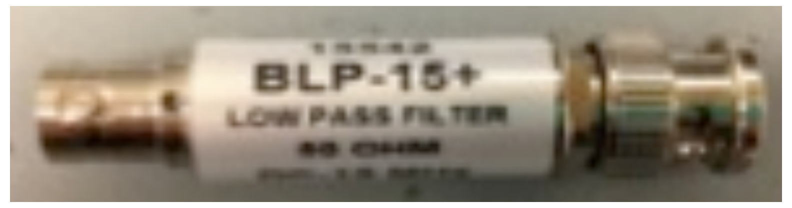
TAFD external trigger, 3~5 Hz

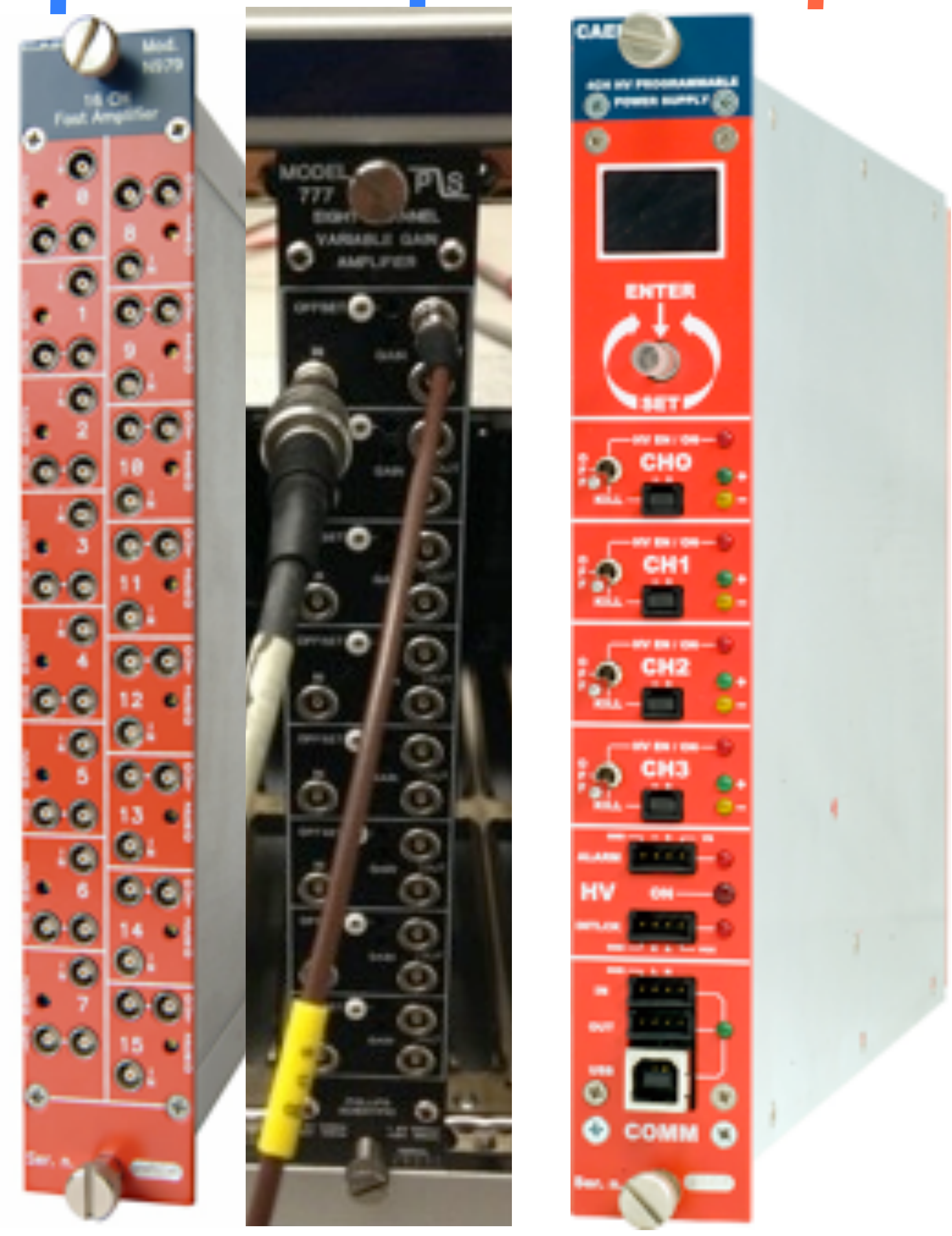
Anode & dynode Signal

Camera of FAST



15 MHz
low pass filter





High Voltage power supply,
N1470 CAEN

All modules are remotely controlled through wireless network.

Portable VME Electronics
- Struck FADC 50 MHz sampling, SIS3350
- GPS board, HYTEC GPS2092

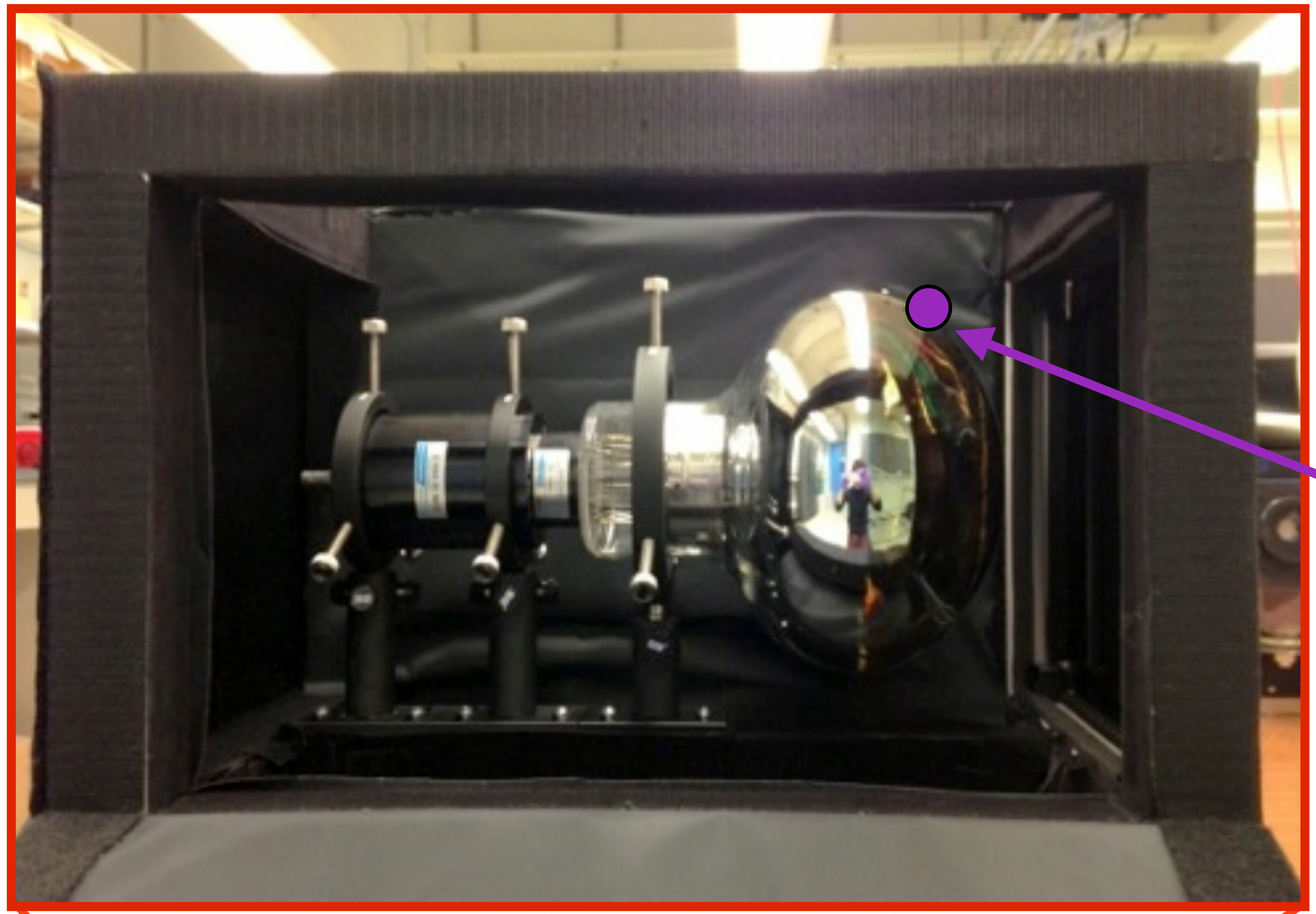
Amplifiers
R979 CAEN
Signal×10

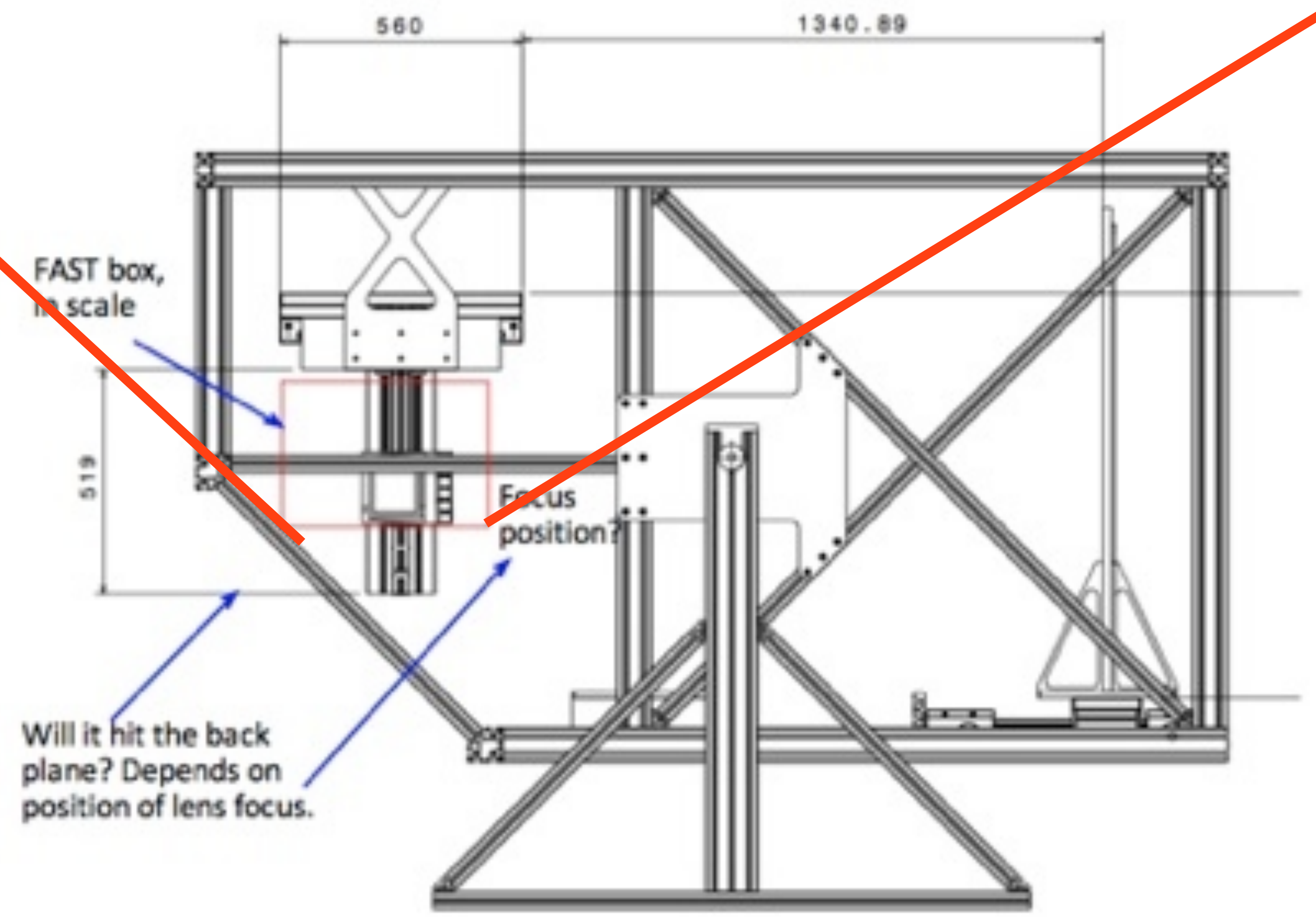
777,Phillips scientific
Signal×50

Fluorescence detector Array of Single-pixel Telescopes

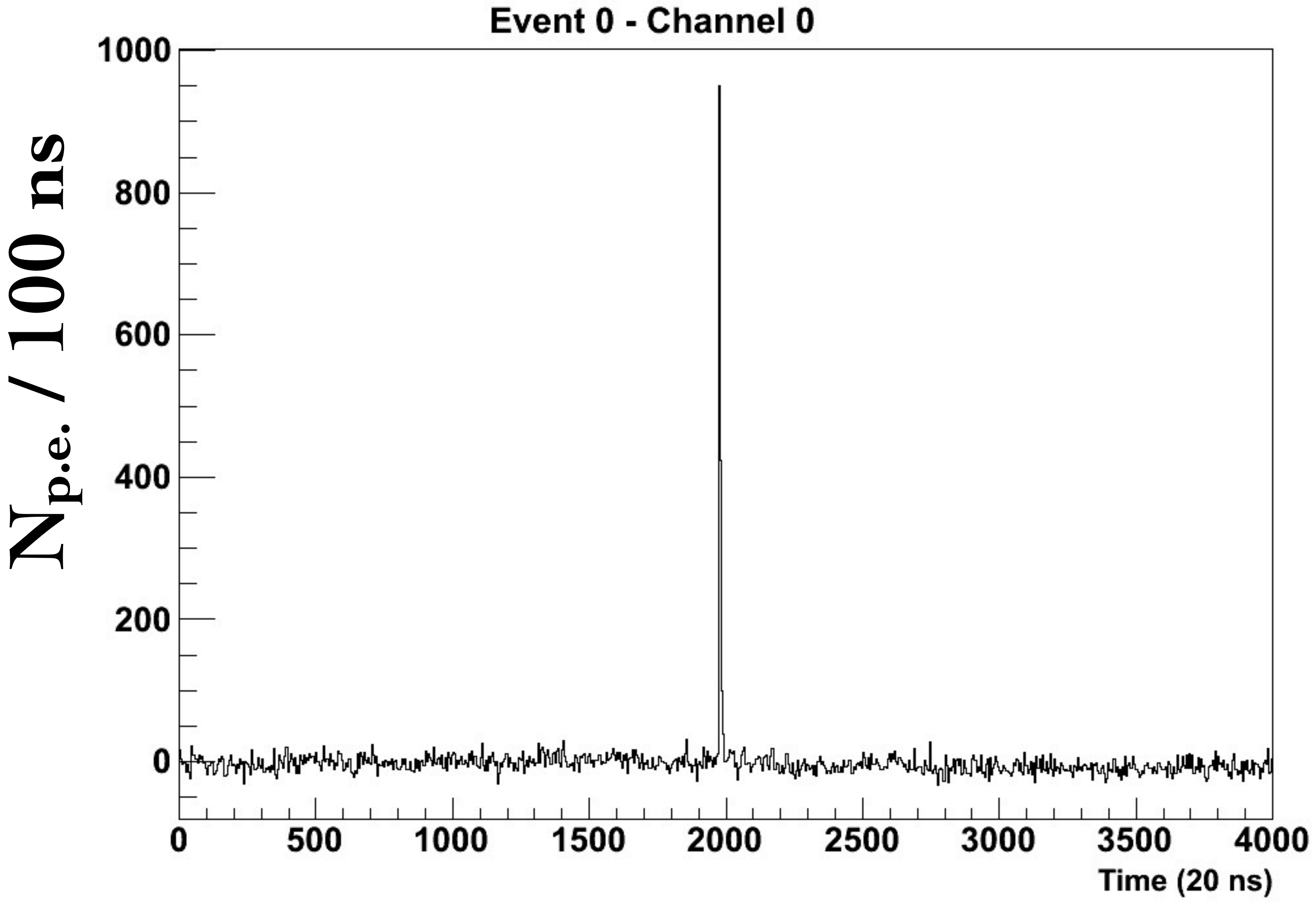
FAST
Fluorescence detector Array of Single-pixel Telescopes

Camera of FAST





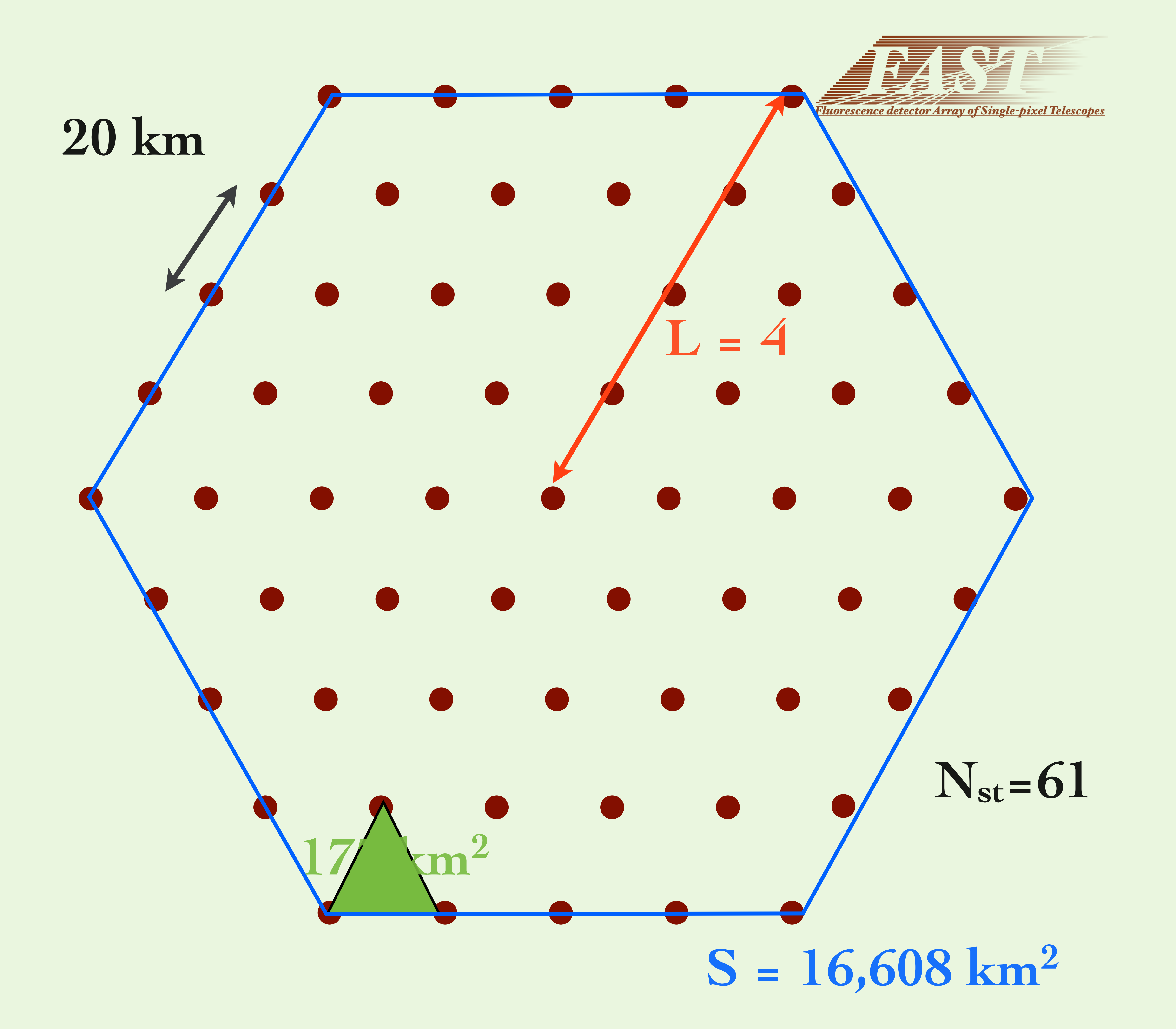
- PMT 8 inch R5912-03
- E7694-01(AC coupling)
- MUG6 UV band pass filter
- YAP ($YAlO_3$: Ce) scintillator with ^{241}Am (50 Hz) to monitor gain stability.



YAP
Signal

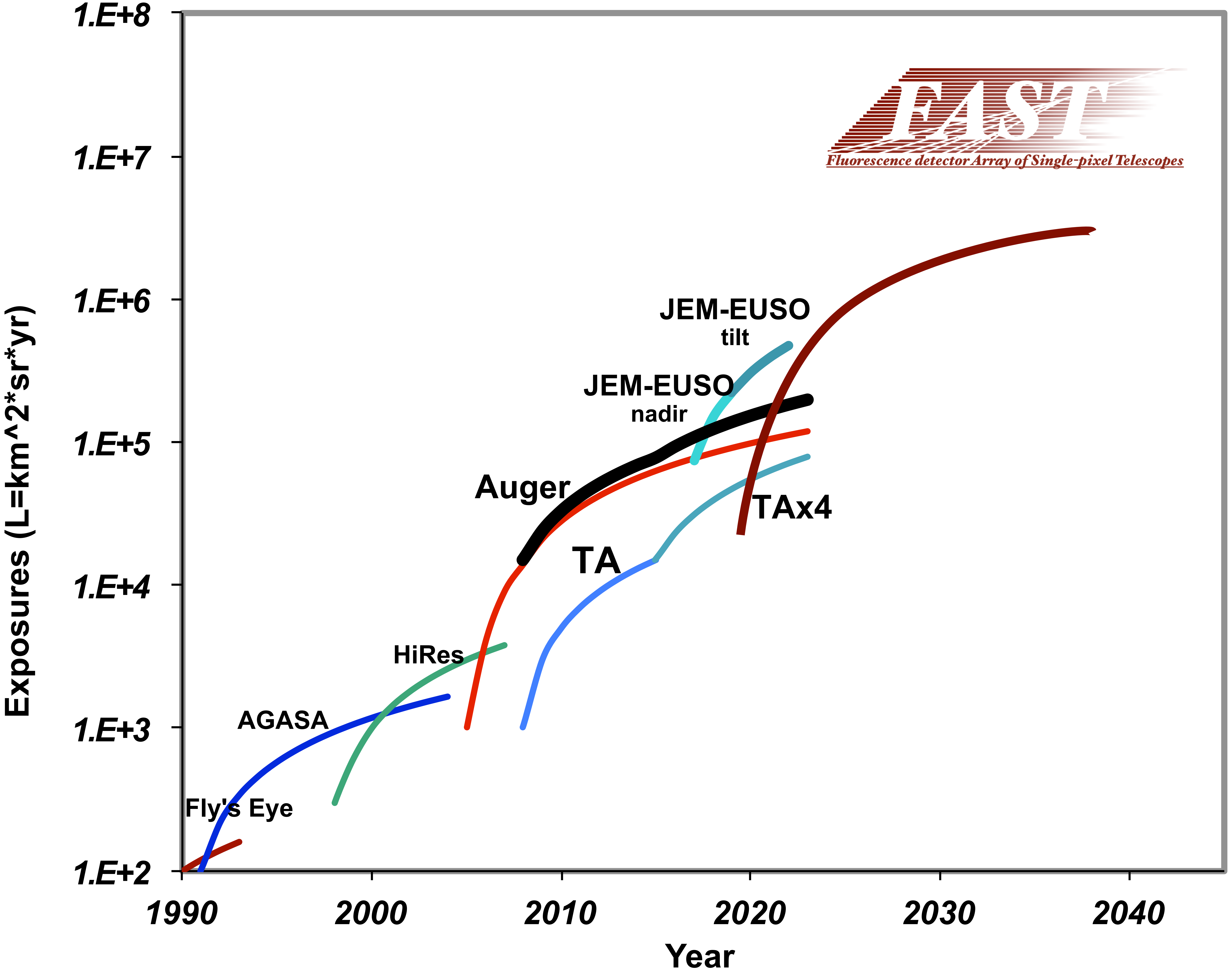
Fluorescence detector Array of Single-pixel Telescopes

Coverage and the number of FAST stations

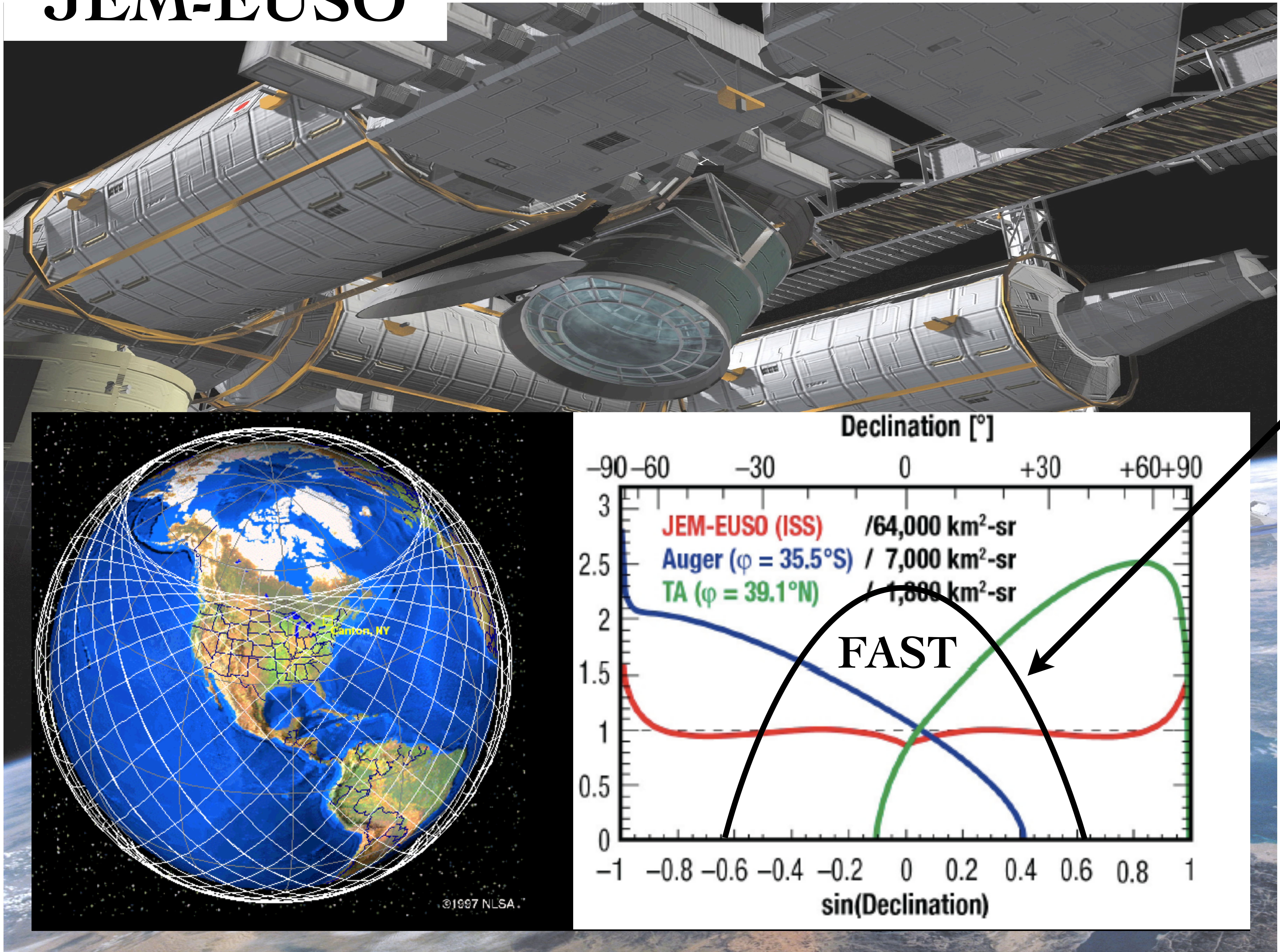


L	N_st	S [km^2]	Cost M$USD
0	1	0	0.1
1	7	1038	0.7
2	19	4152	1.9
3	37	9342	3.7
4	61	16608	6.1
5	91	25950	9.1
6	127	37368	12.7
7	169	50862	16.9
8	217	66432	21.7
9	271	84078	27.1
10	331	103800	33.1
11	397	125598	39.7
12	469	149472	46.9
13	547	175422	54.7
14	631	203448	63.1
15	721	233550	72.1
16	817	265728	81.7
17	919	299982	91.9
18	1027	336312	102.7
19	1141	374718	114.1
20	1261	415200	126.1

Expected Exposure



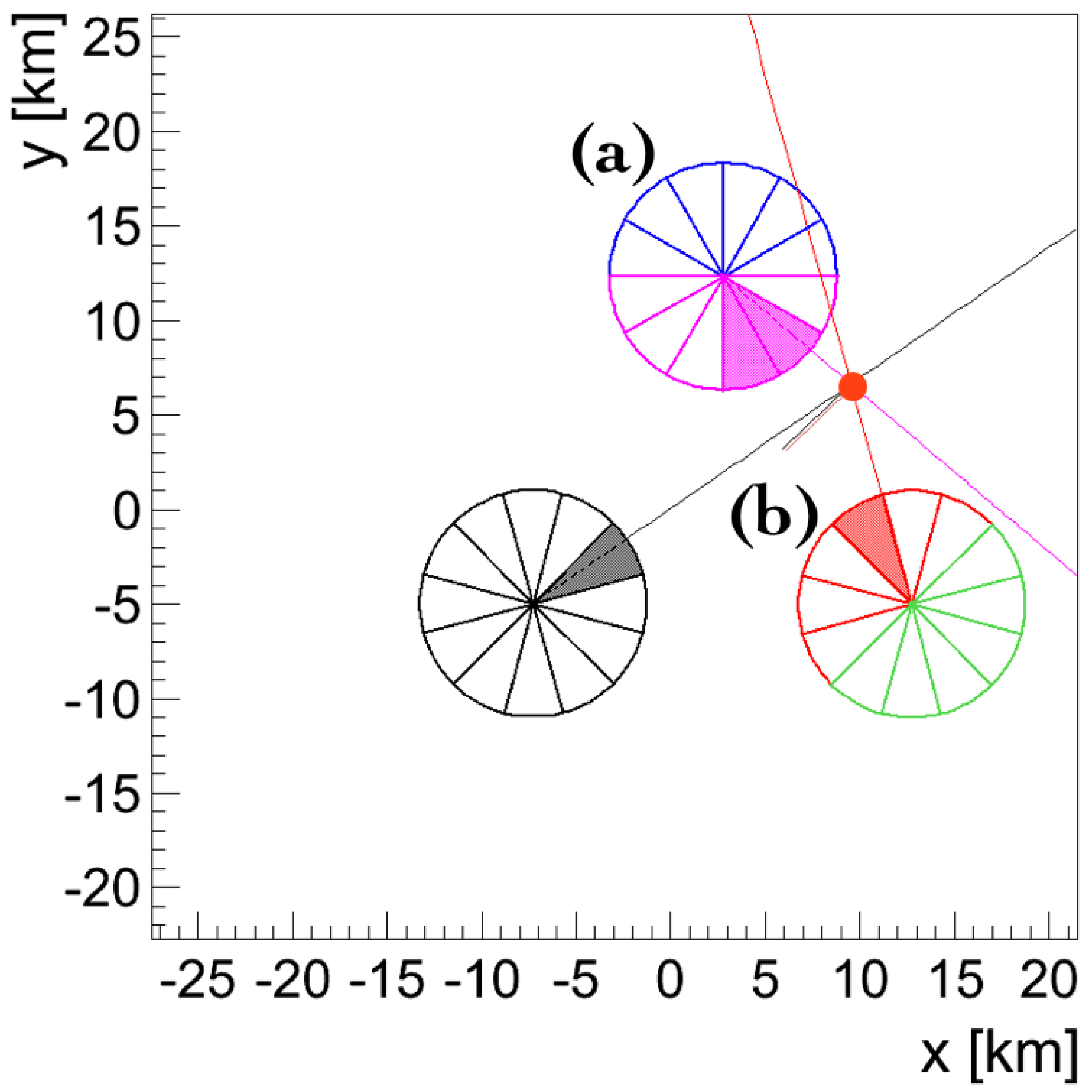
JEM-EUSO

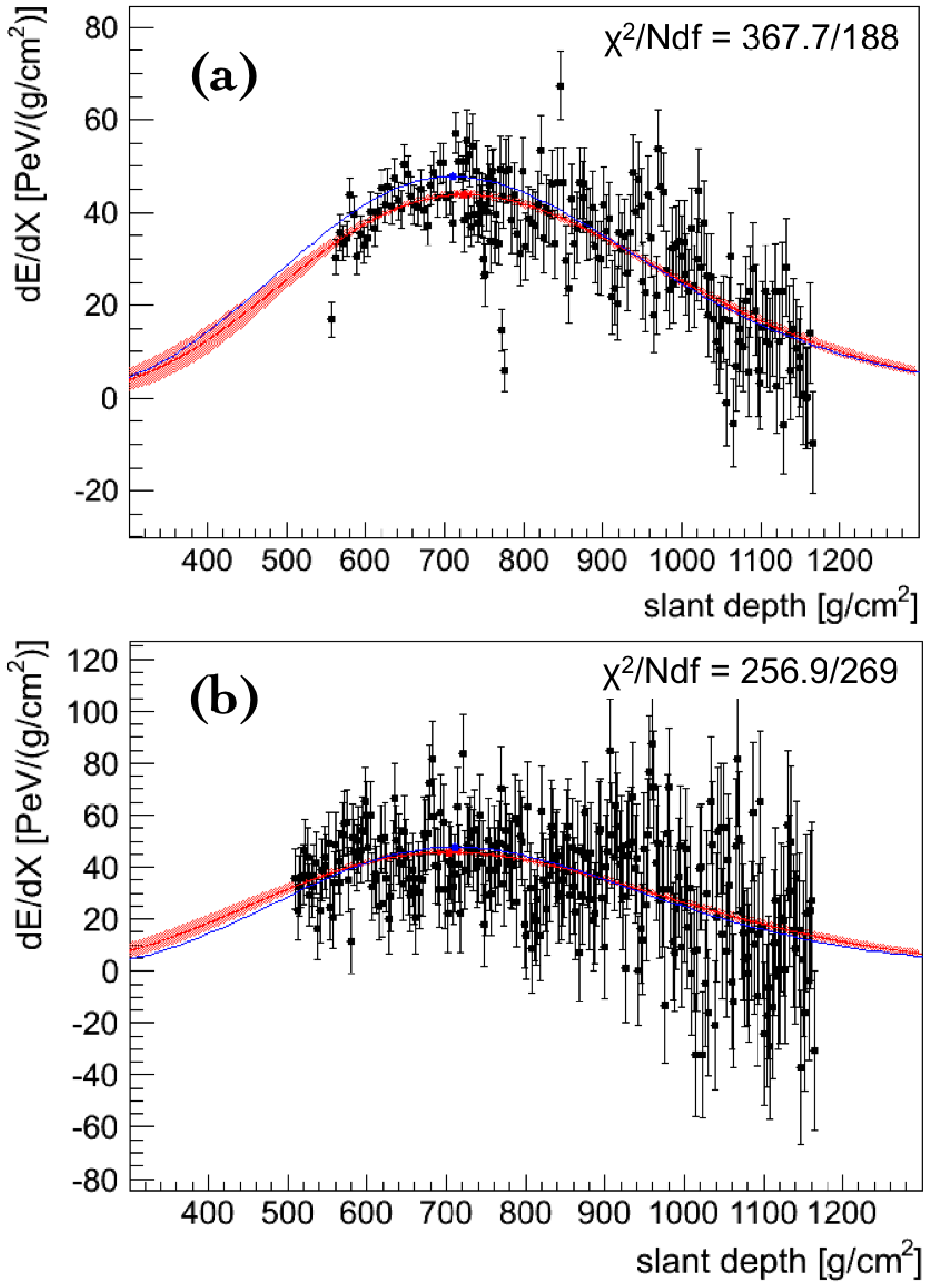


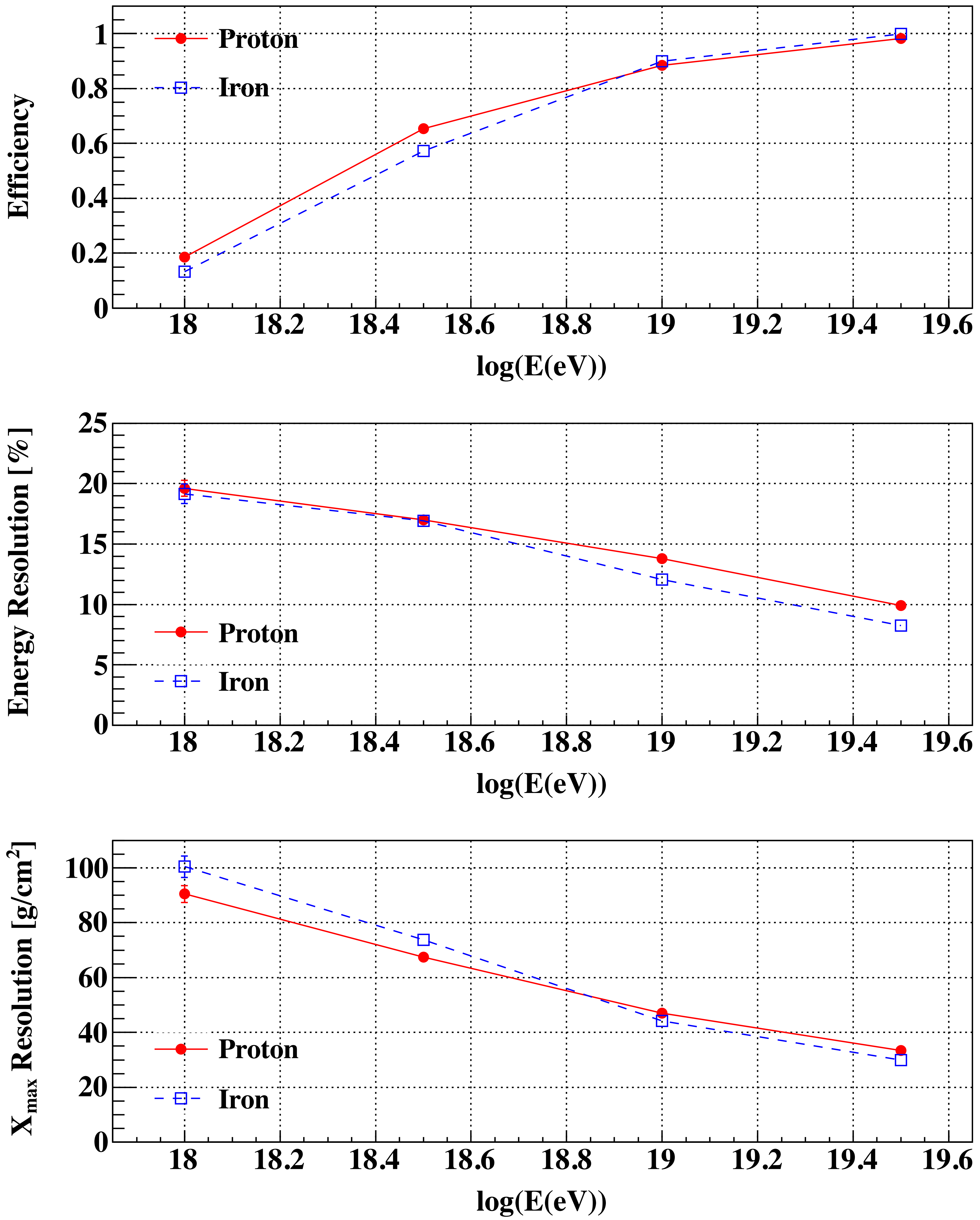
Full efficiency on ground by FAST+TA +Auger

Fluorescence detector Array of Single-pixel Telescopes

Efficiency and Resolution of FAST







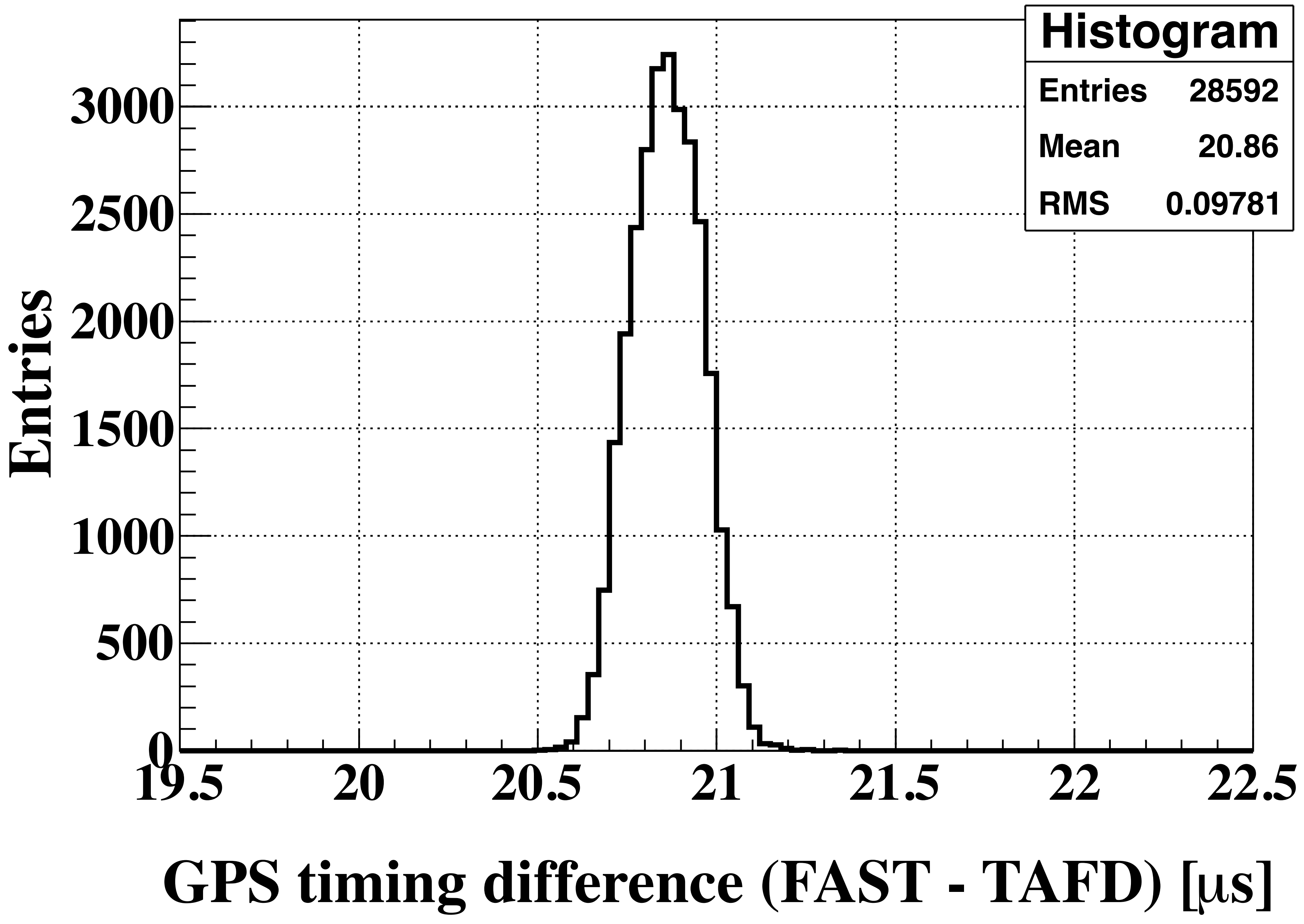
GPS Timing and CLF Signal

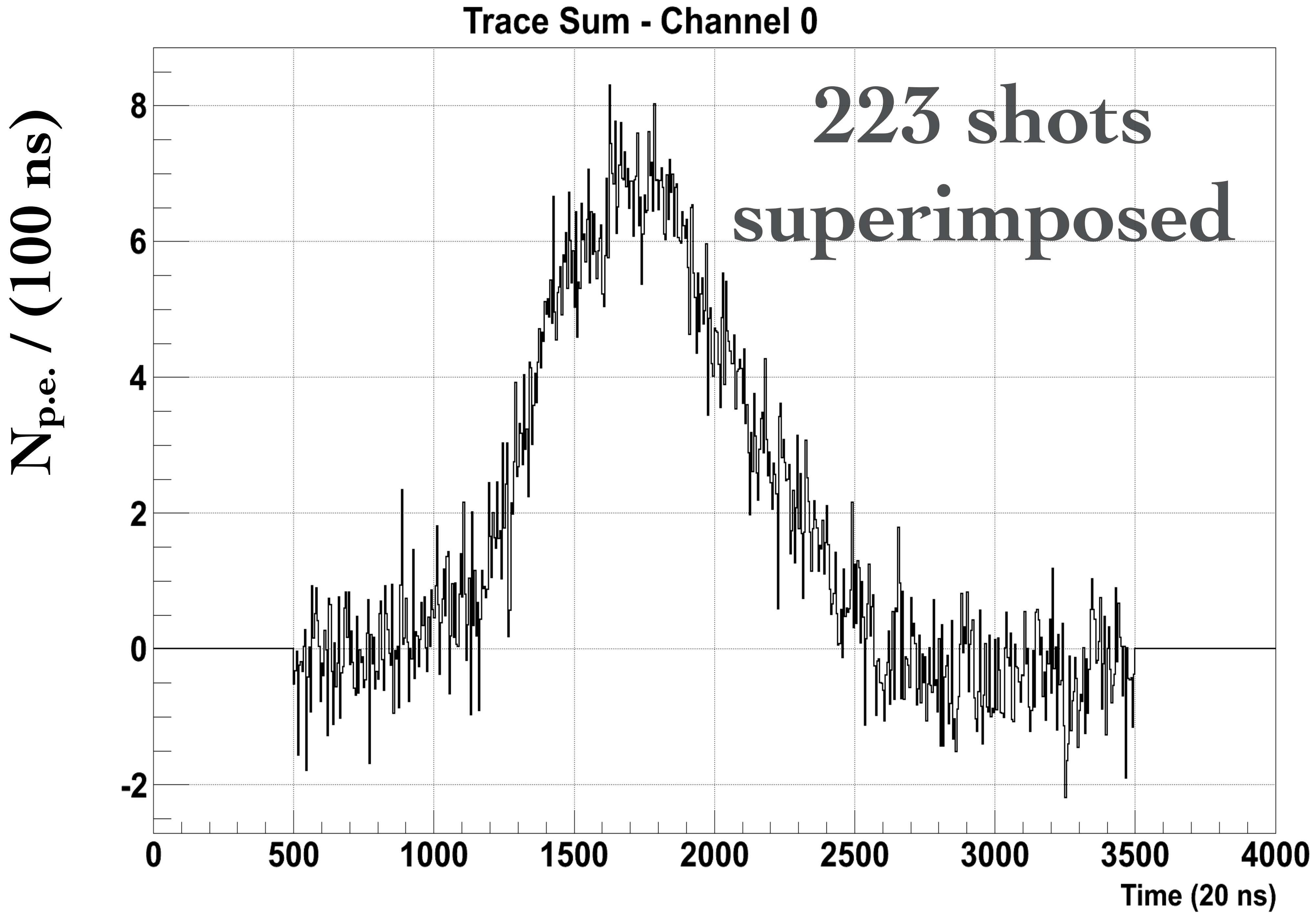
Central Laser Facility

Vertical UV laser shooting every 30 minutes,

21 km from FAST,

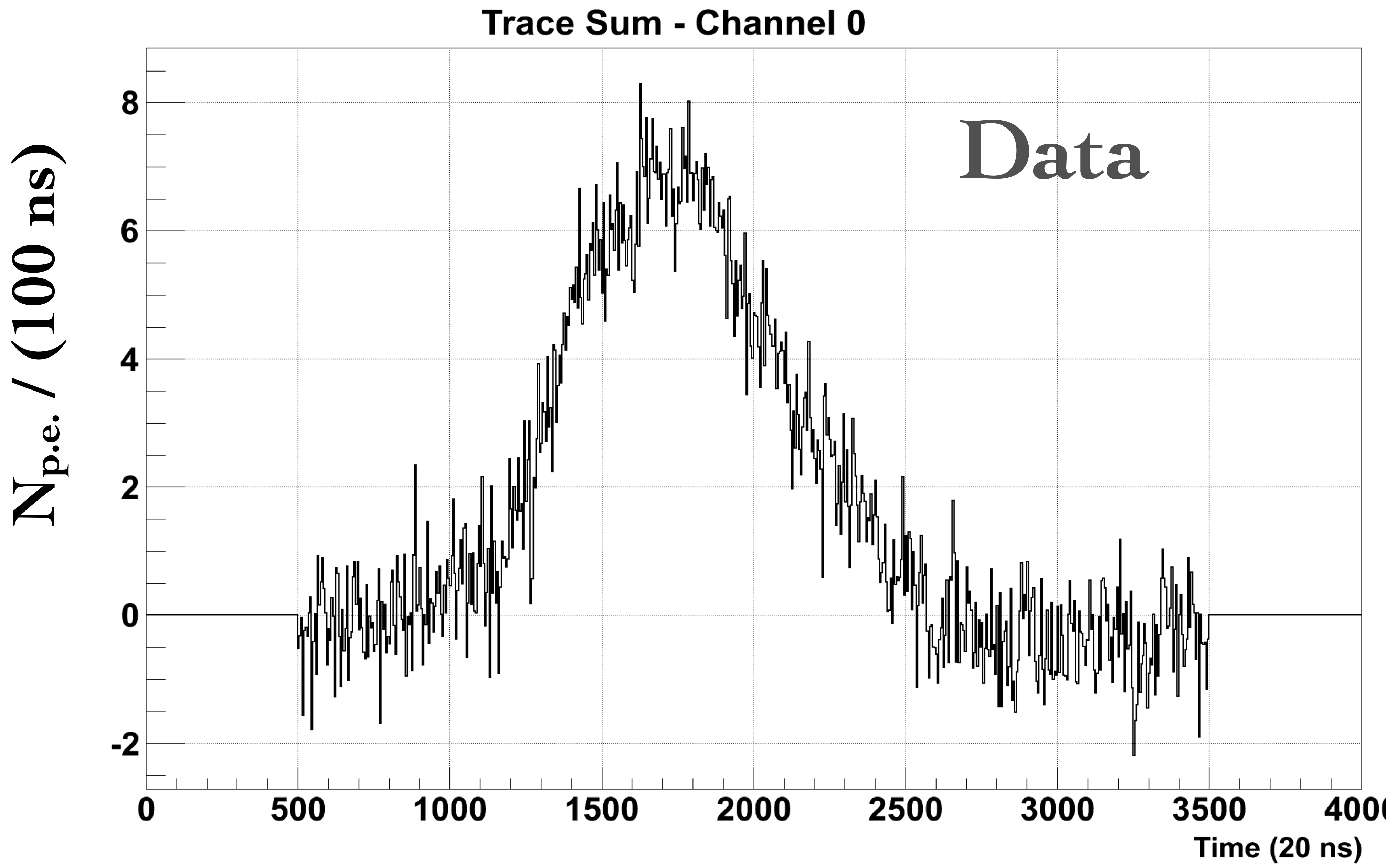
10 Hz, 2.2 mJ, 300 shots

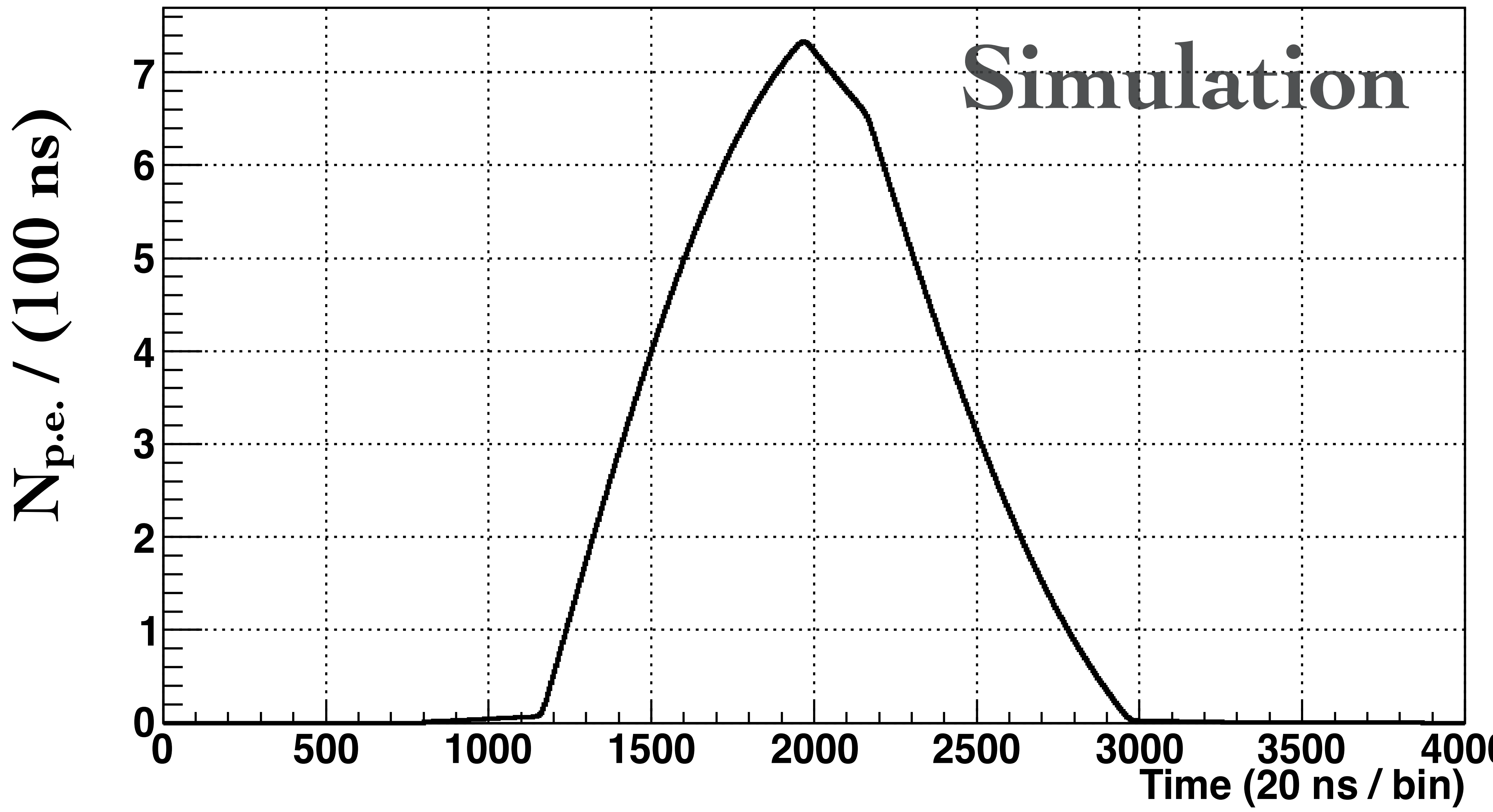




- FAST-TAFD timing resolution, 100 ns. (20.9 μs is the TAFD trigger processing time.)
- laser signal > $10^{19.2}$ eV at 21 km
- peak signal ~ 7 p.e. / 100 ns ($\sigma_{p.e.}$ = 11 p.e.) at the limit of detectability

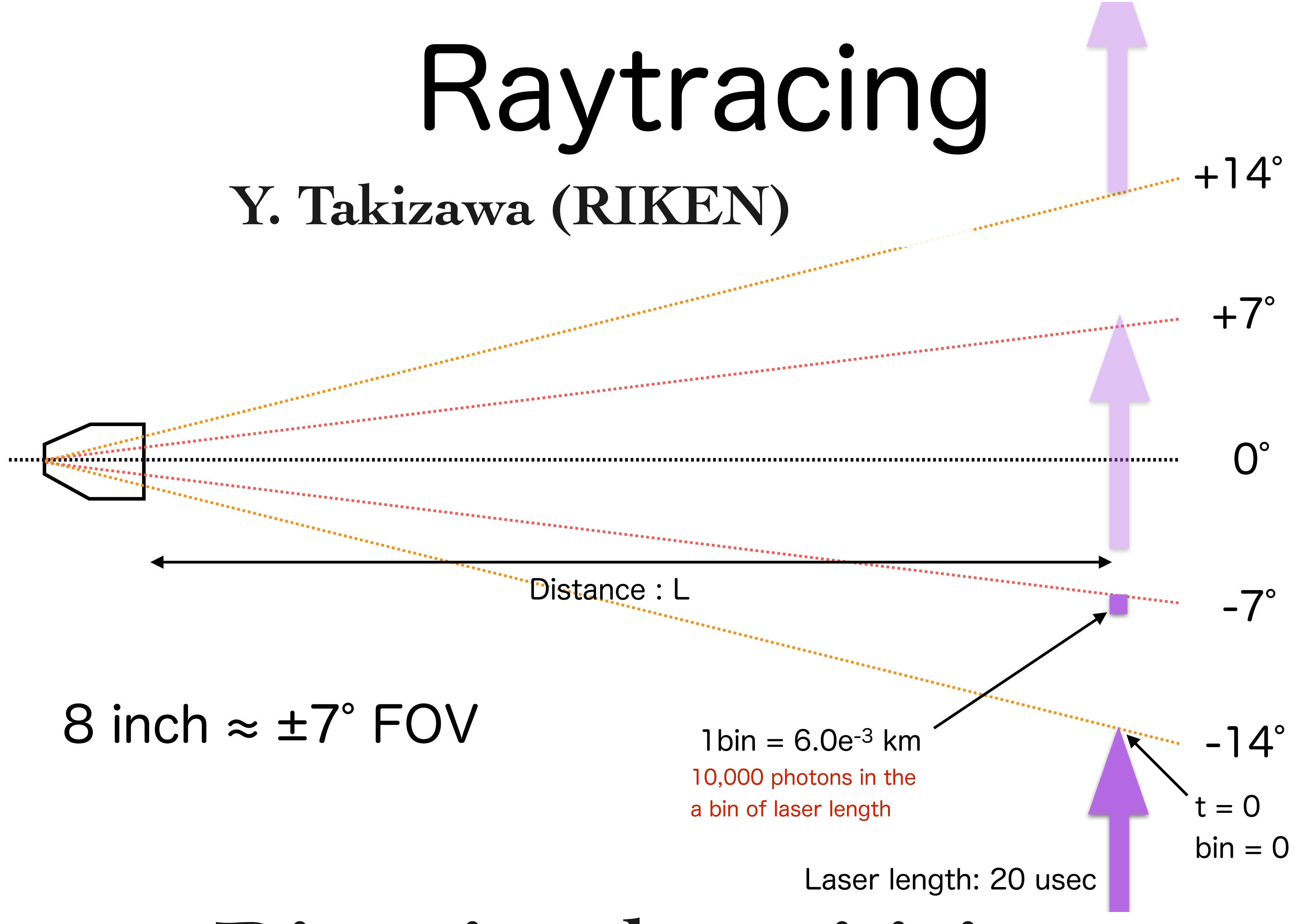
CLF Simulation



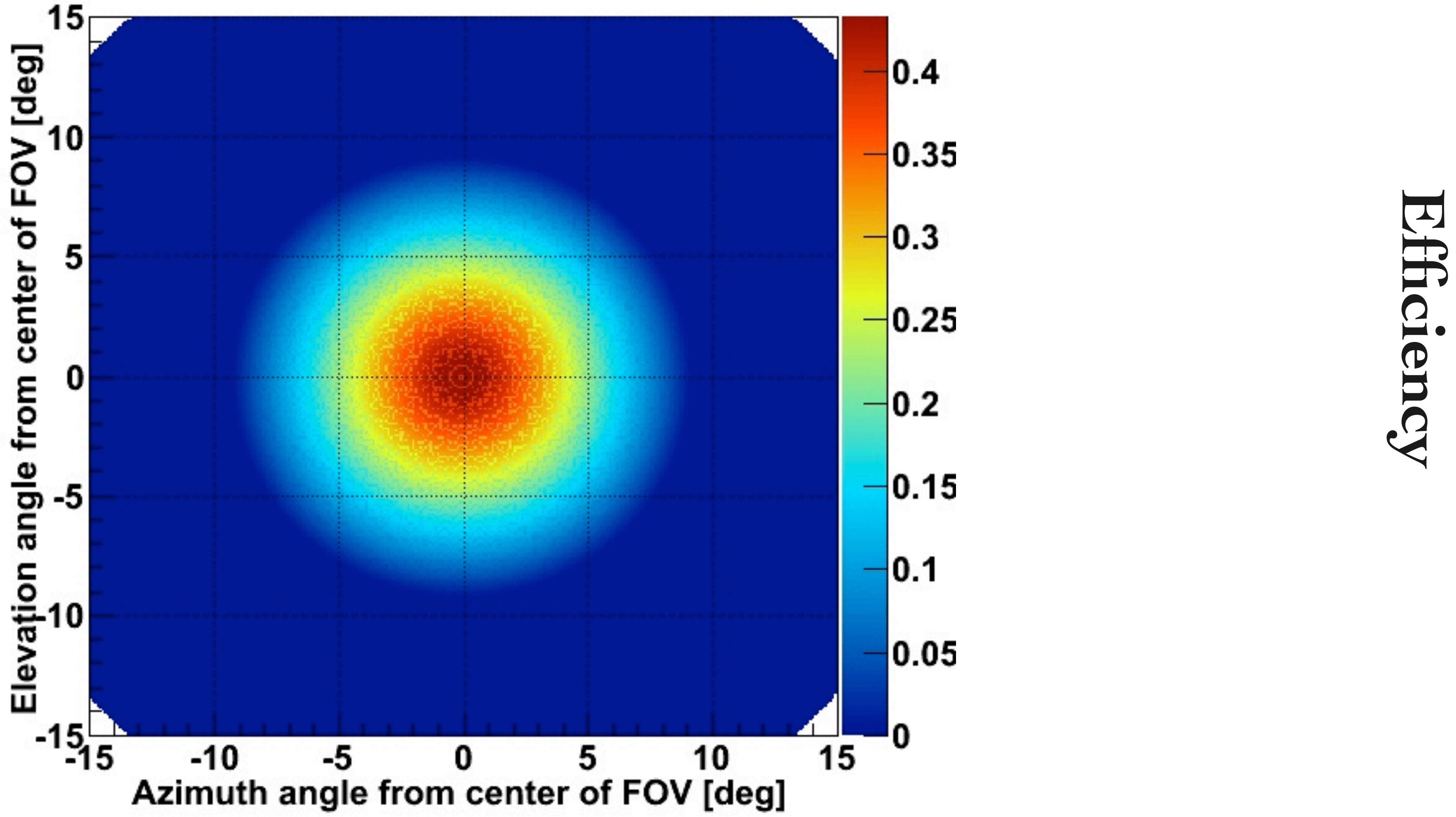


Raytracing

Y. Takizawa (RIKEN)

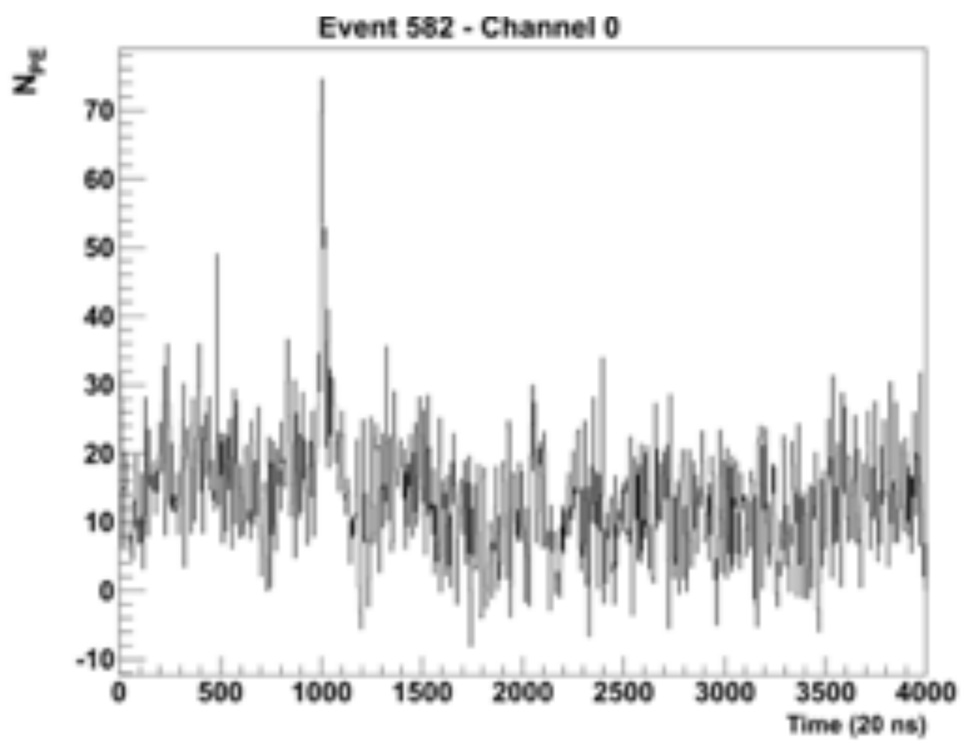


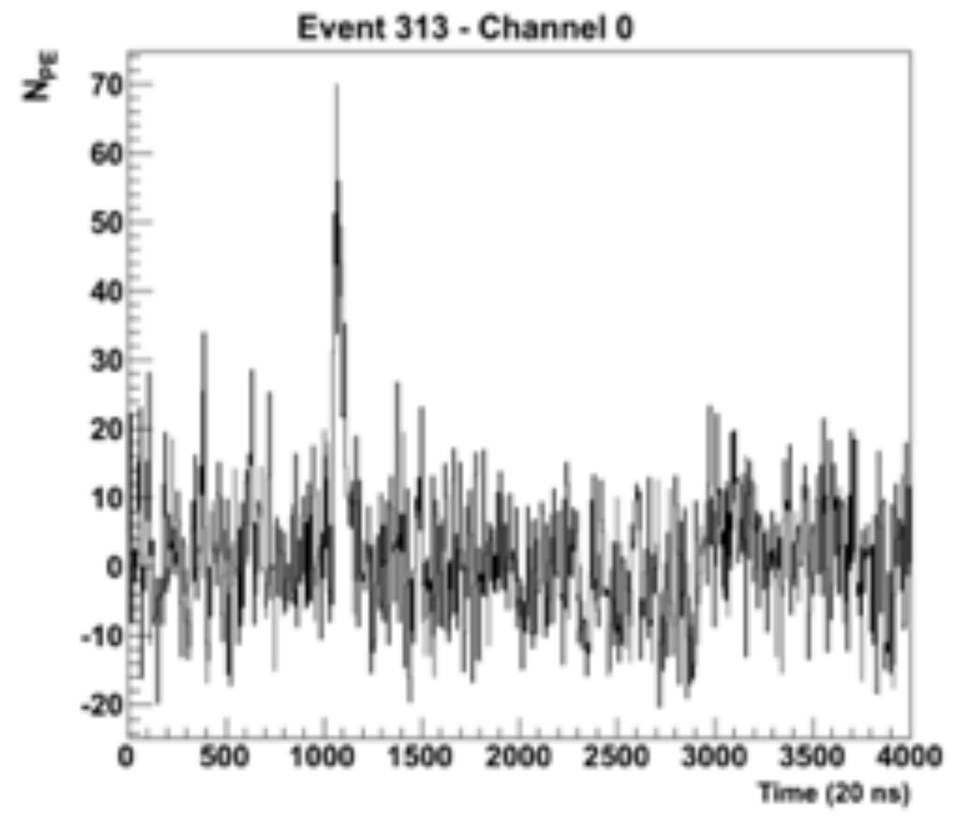
Directional sensitivity

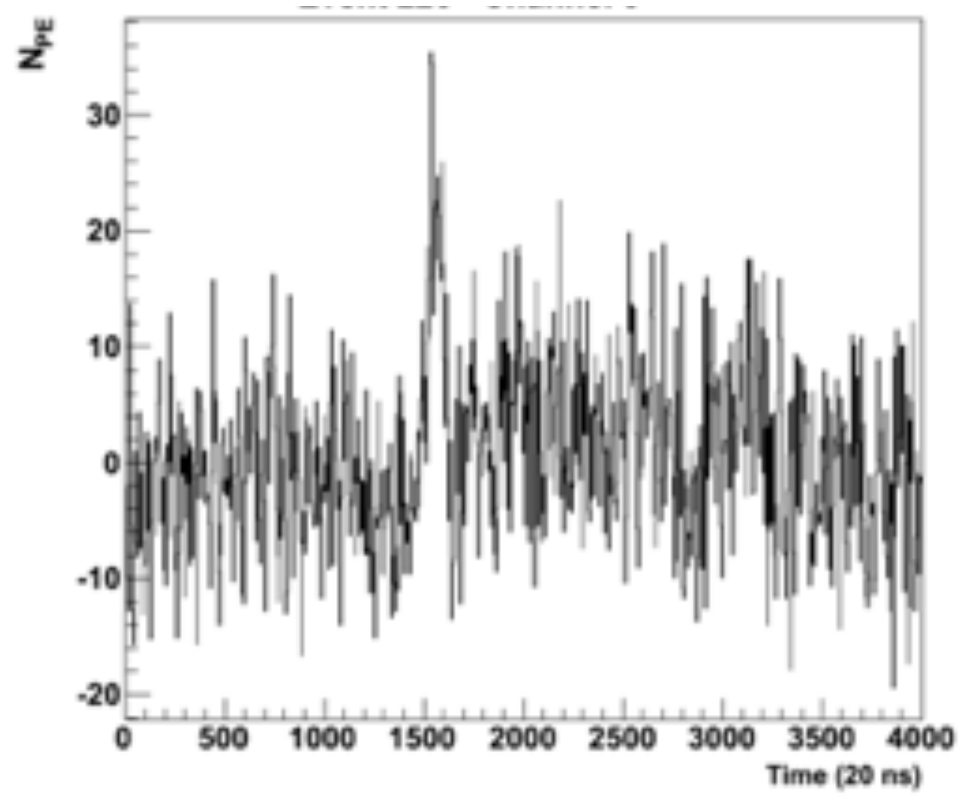


Example of Signal Candidates

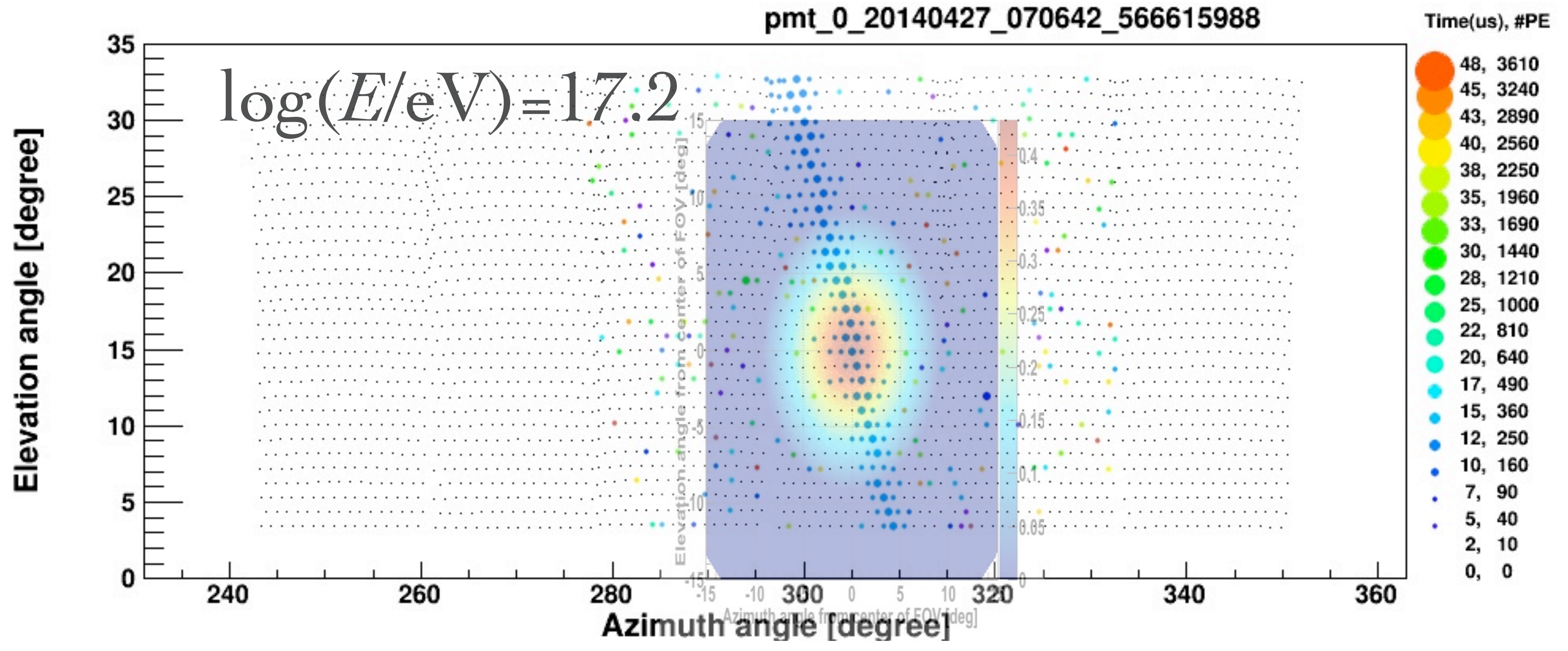
FAST

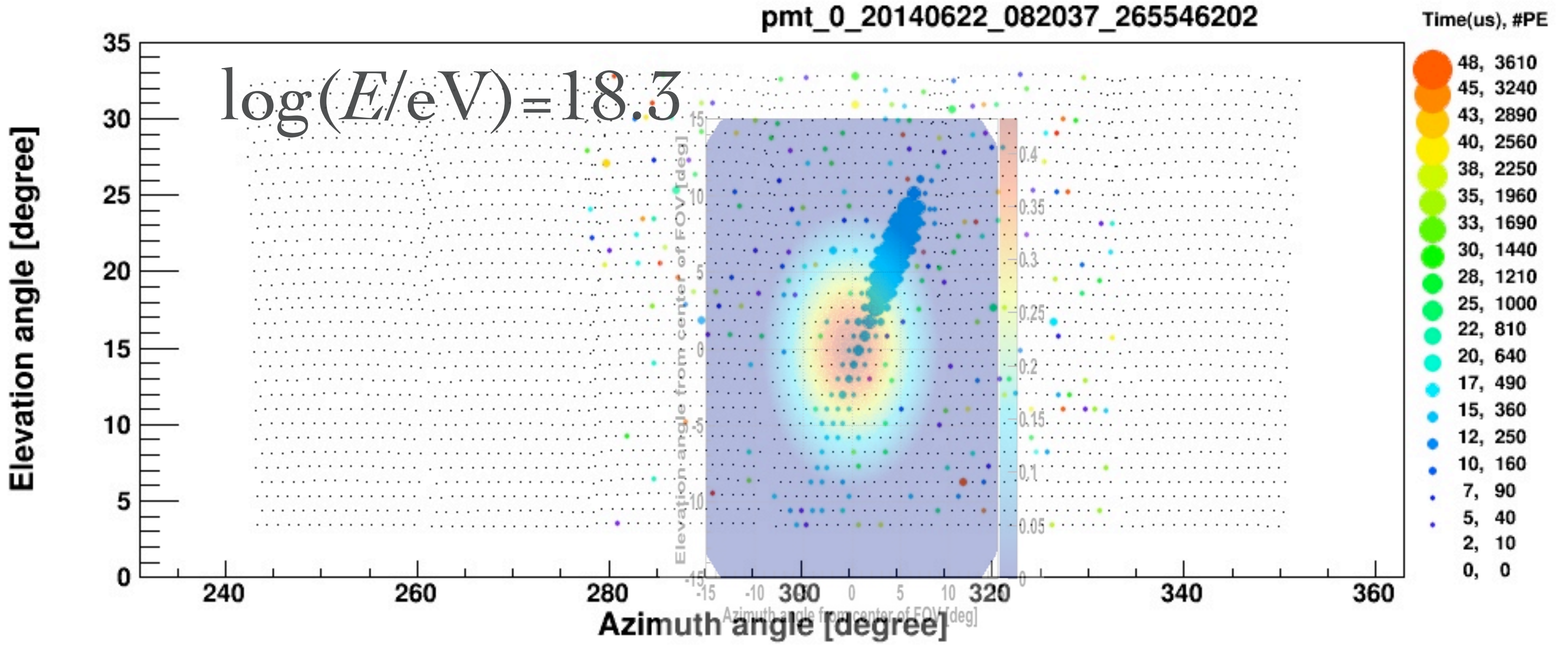


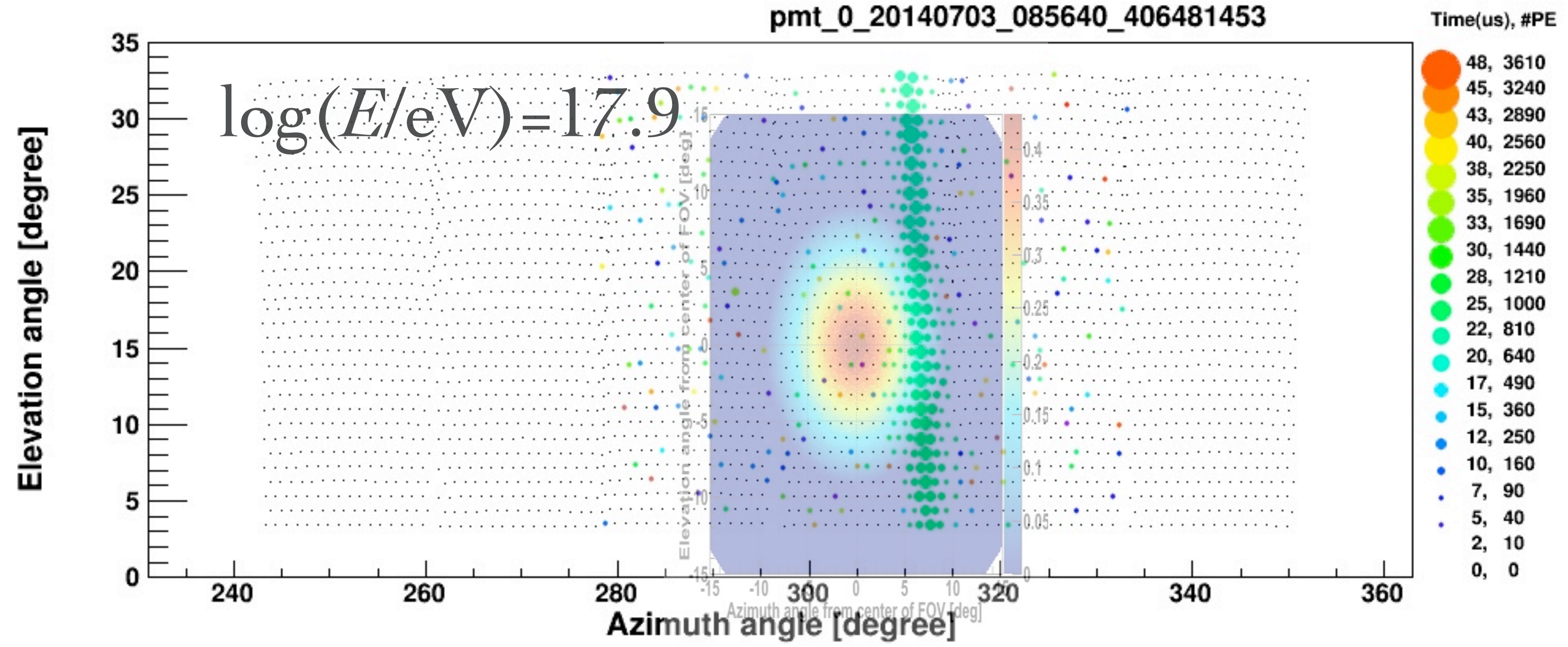




TAFD

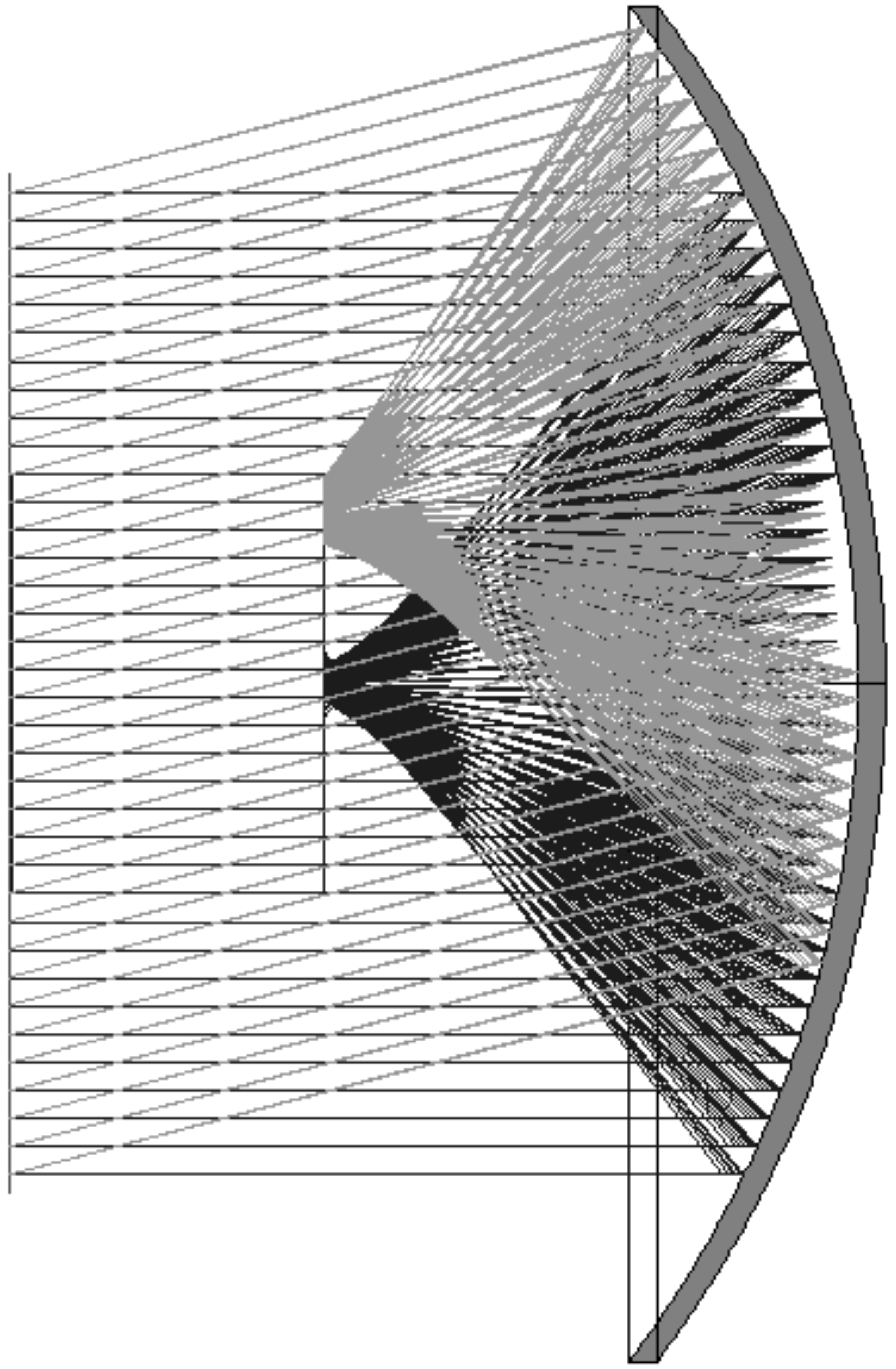




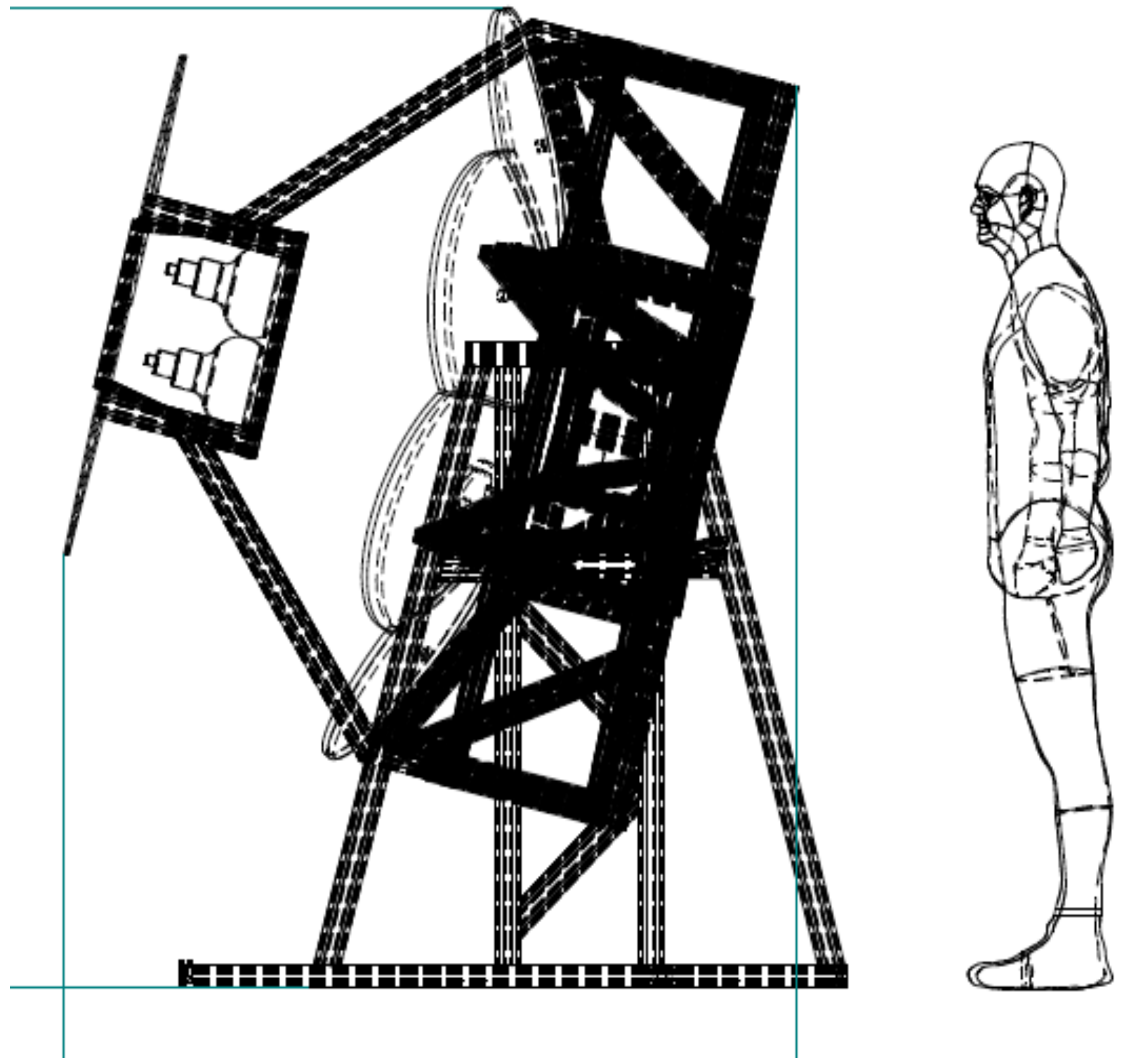


FAST
Fluorescence detector Array of Single-pixel Telescopes

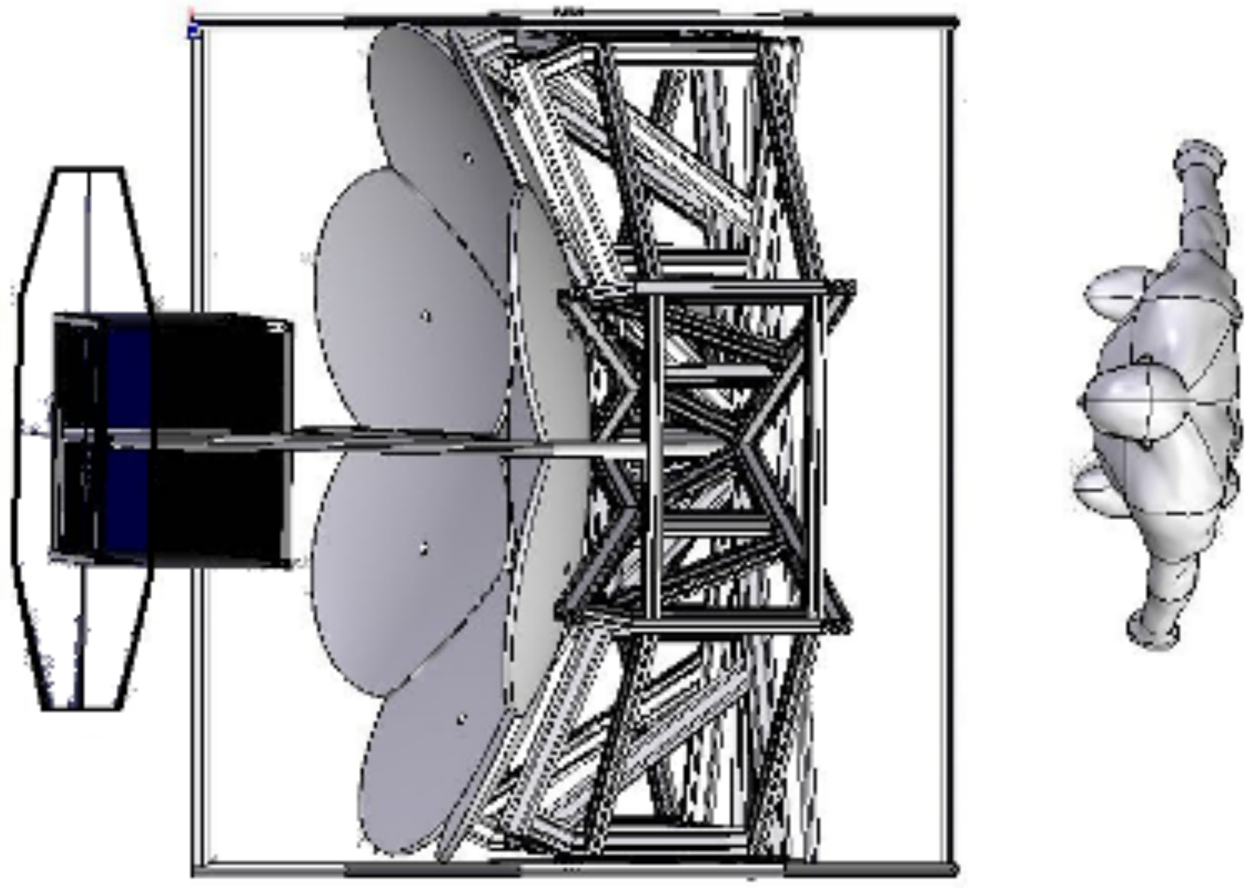
Full-scale FAST Prototype

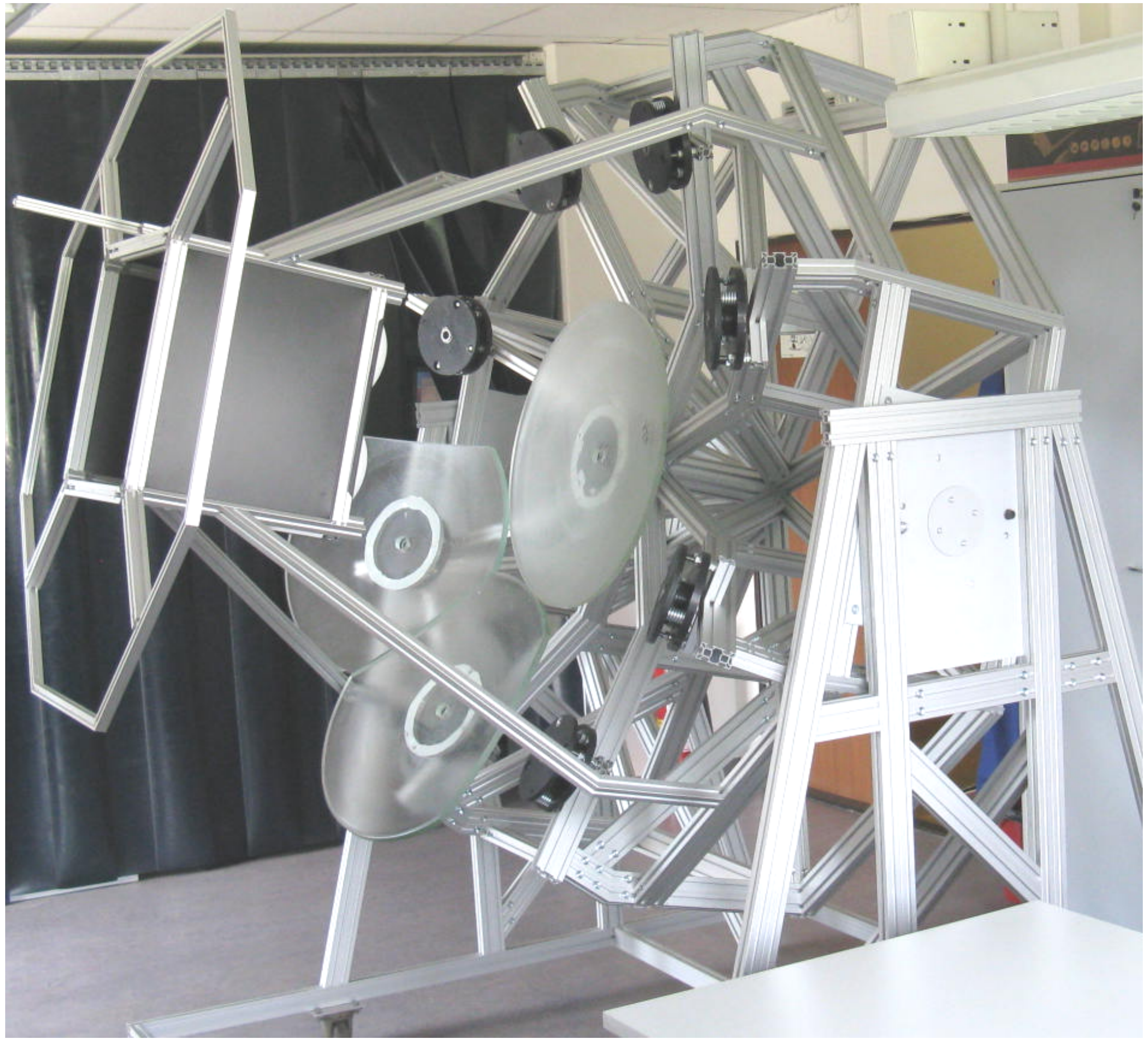


Side view



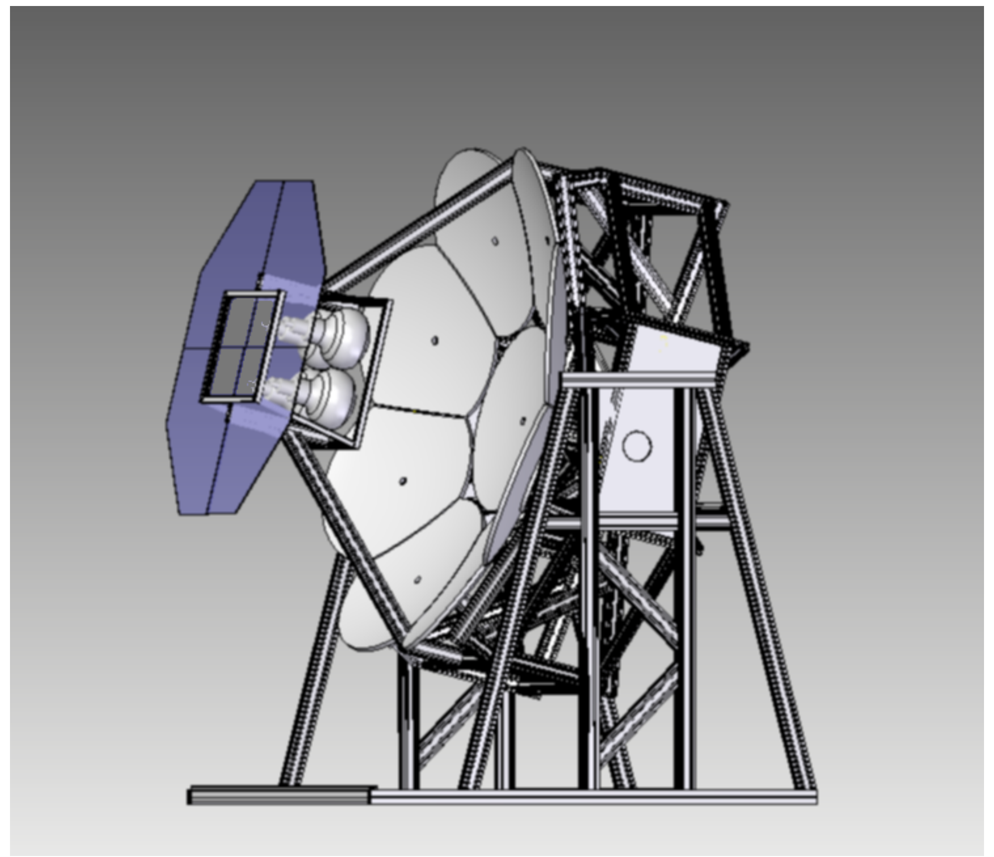
Top view

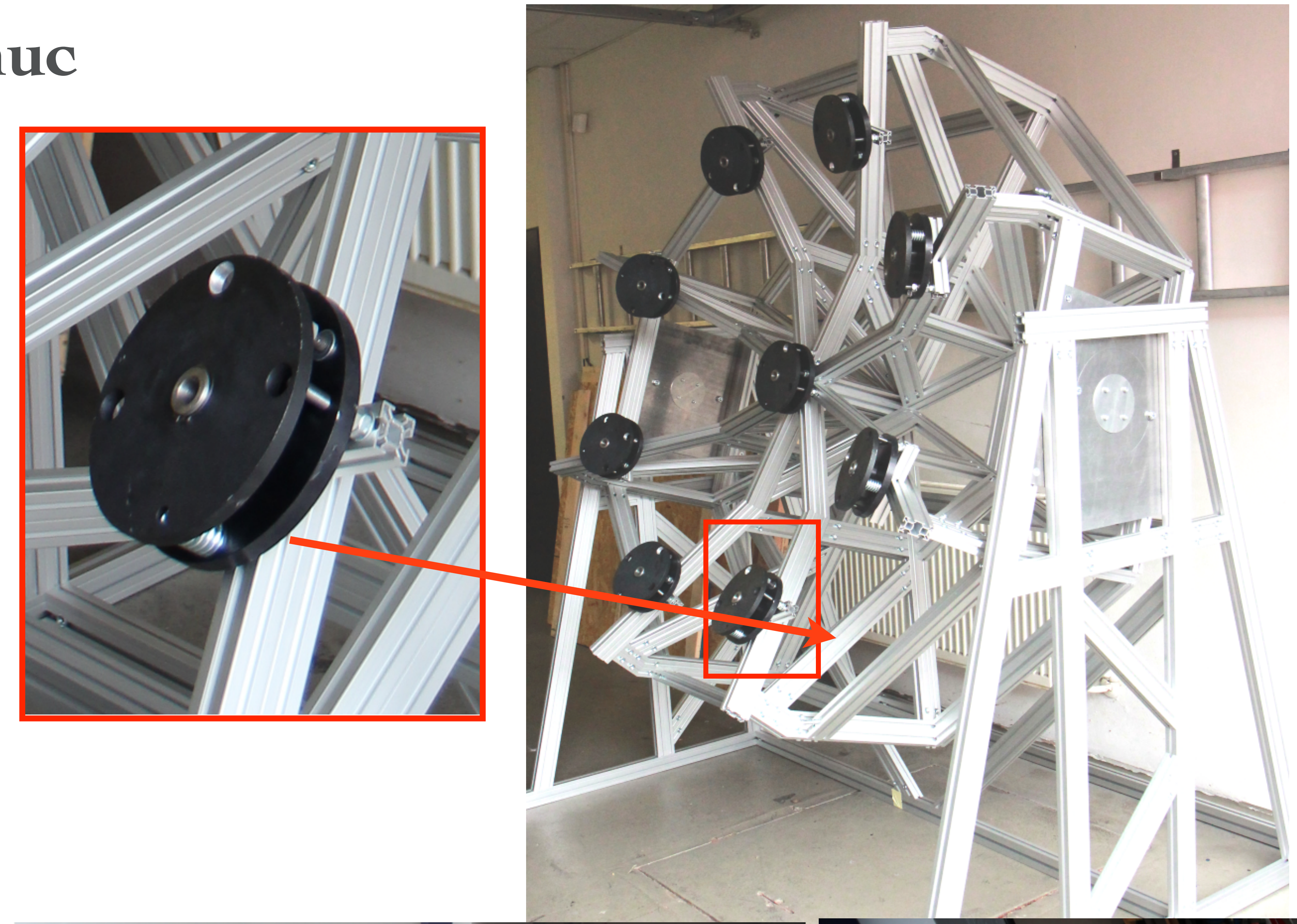




Mirror Construction

Joint Laboratory of Optics Olomuc





1 m^2 collection area, 30°×30° FoV