Latest updates and results from the Fluorescence detector Array of Single-pixel Telescopes (FAST)

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次世代研究者挑戦的研究プログラム
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Cosmic rays & Extensive Air Showers

- Cosmic rays are the **most energetic particles** in the universe
- **Ultra-high energy cosmic rays** (UHECRs) have energy $E > 10^{18.5}$ eV
- UHECRs are **very rare**! Flux of UHECRs < 1 particle / km^2 / year
- Detect via **extensive air showers (EASs)** - cascades of particles generated when cosmic rays interact with atmospheric molecules
- Measure (**reconstruct**) shower **energy**, **arrival direction**, X$_{max}$

FAST Overview

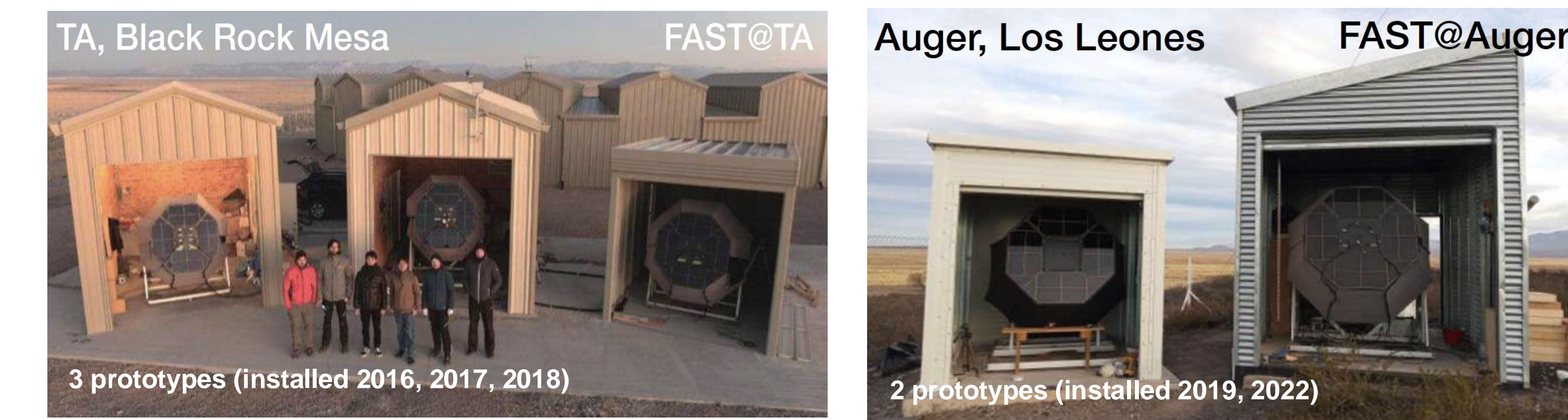### The Fluorescence detector Array of Single-pixel Telescopes
A next generation cosmic ray experiment

Design: Low-cost, easily deployable, autonomous fluorescence telescopes. Uses only 4 photomultiplier tubes (PMTs) for measuring light from EASs

Detection area: 150,000 km^2, twice the size of Hokkaido!

Four 20 cm PMTs | Segmented mirror | 1.6 m | UV filter

20 km
12 telescopes/station
x 2!
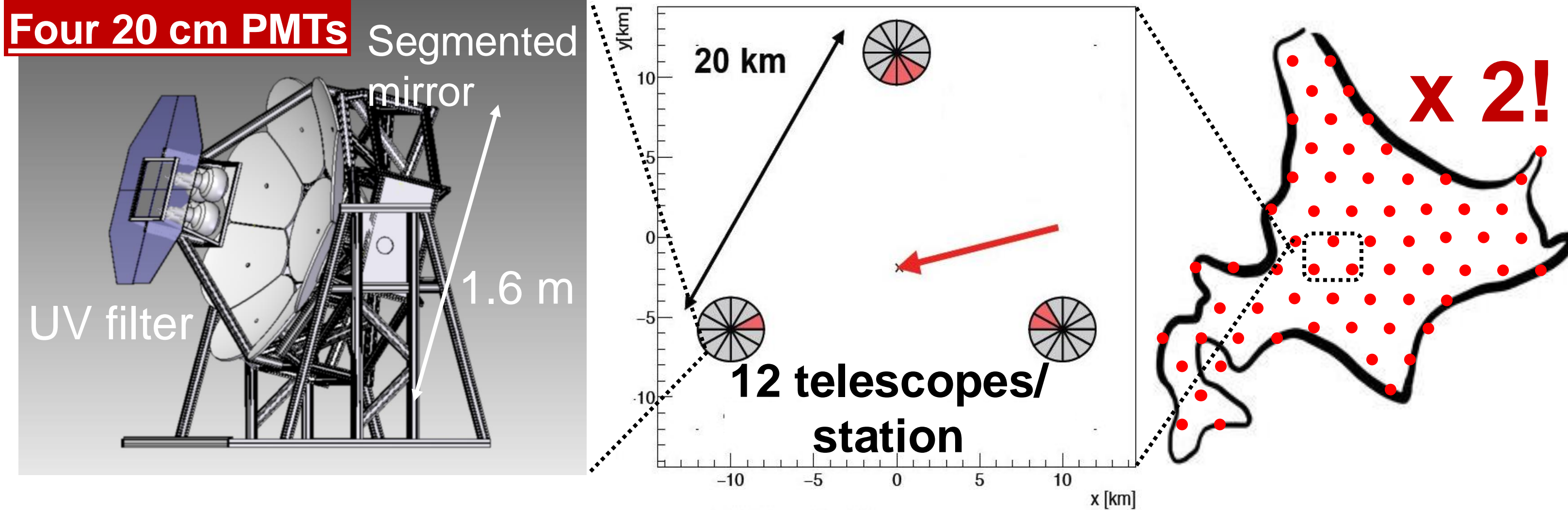
Current prototypes: Installed at current observatories, Telescope Array experiment (TA) and Pierre Auger Observatory (Auger)

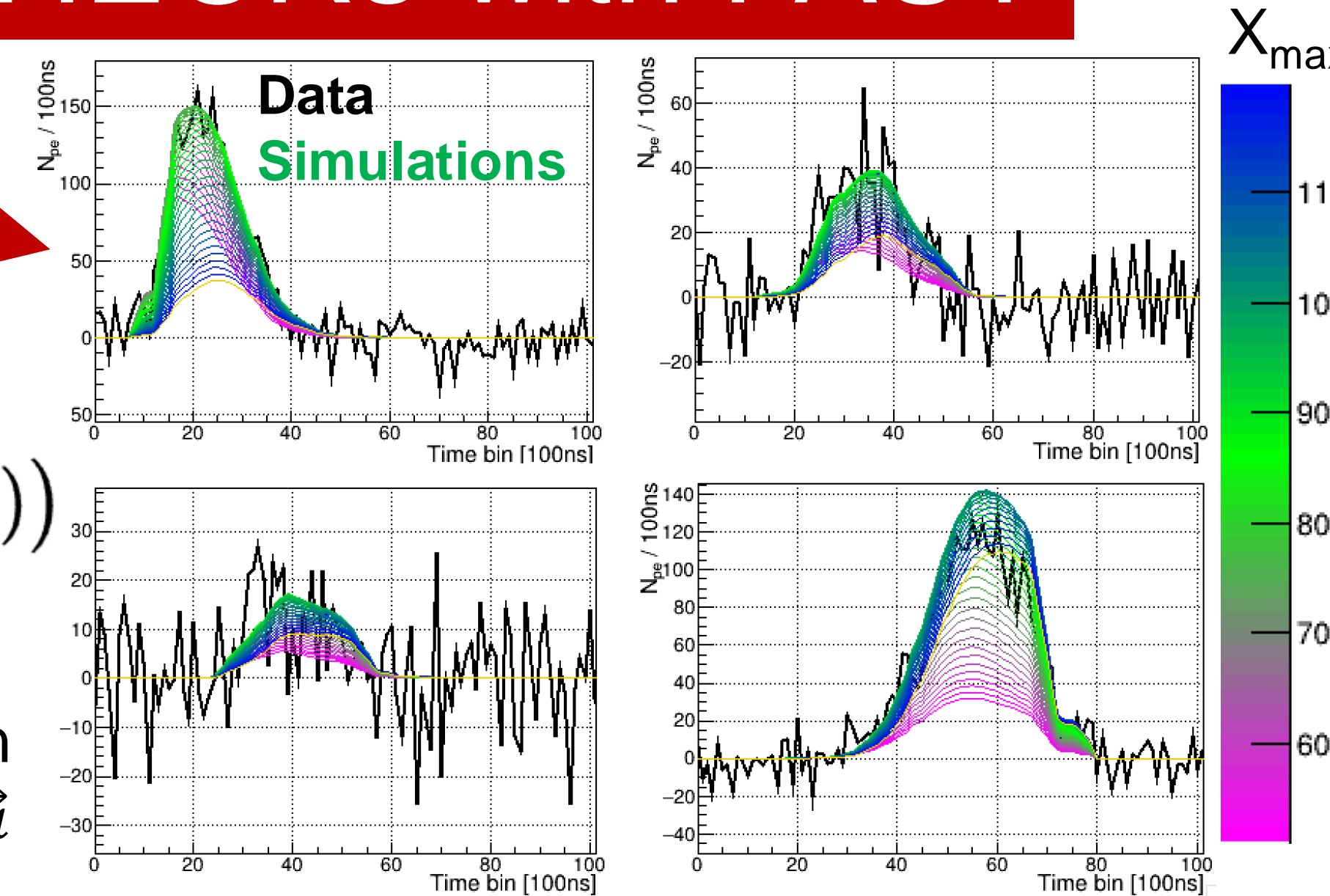TA, Black Rock Mesa — FAST@TA — 3 prototypes (installed 2016, 2017, 2018)

Auger, Los Leones — FAST@Auger — 2 prototypes (installed 2019, 2022)

Reconstructing UHECRs with FAST

Waveform matching: Compare data directly to simulations

Data / Simulations

Maximize likelihood:

$$\ln \mathcal{L}(\vec{x}|\vec{a}) = \sum_{k}^{N_{pix}} \sum_{i}^{N_{bins}} \ln\left(P_k(x_i|\vec{a})\right)$$

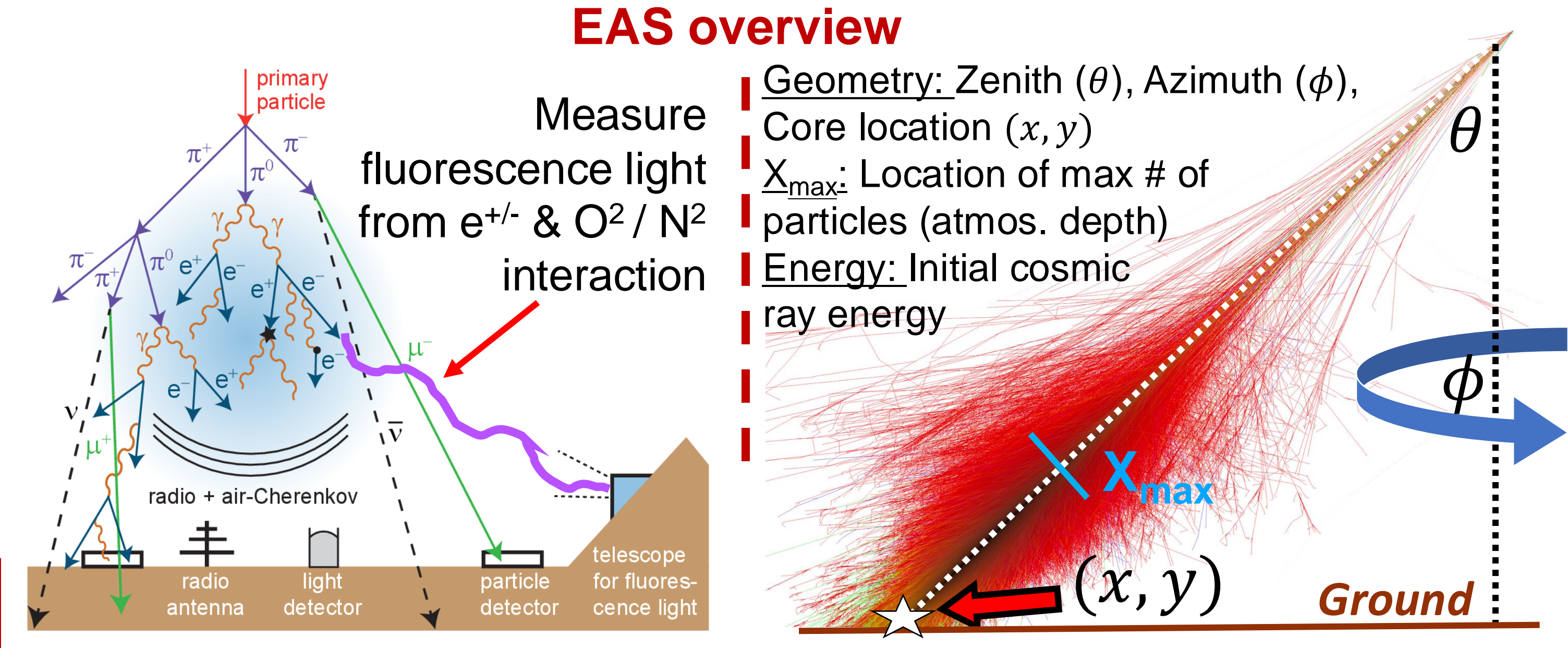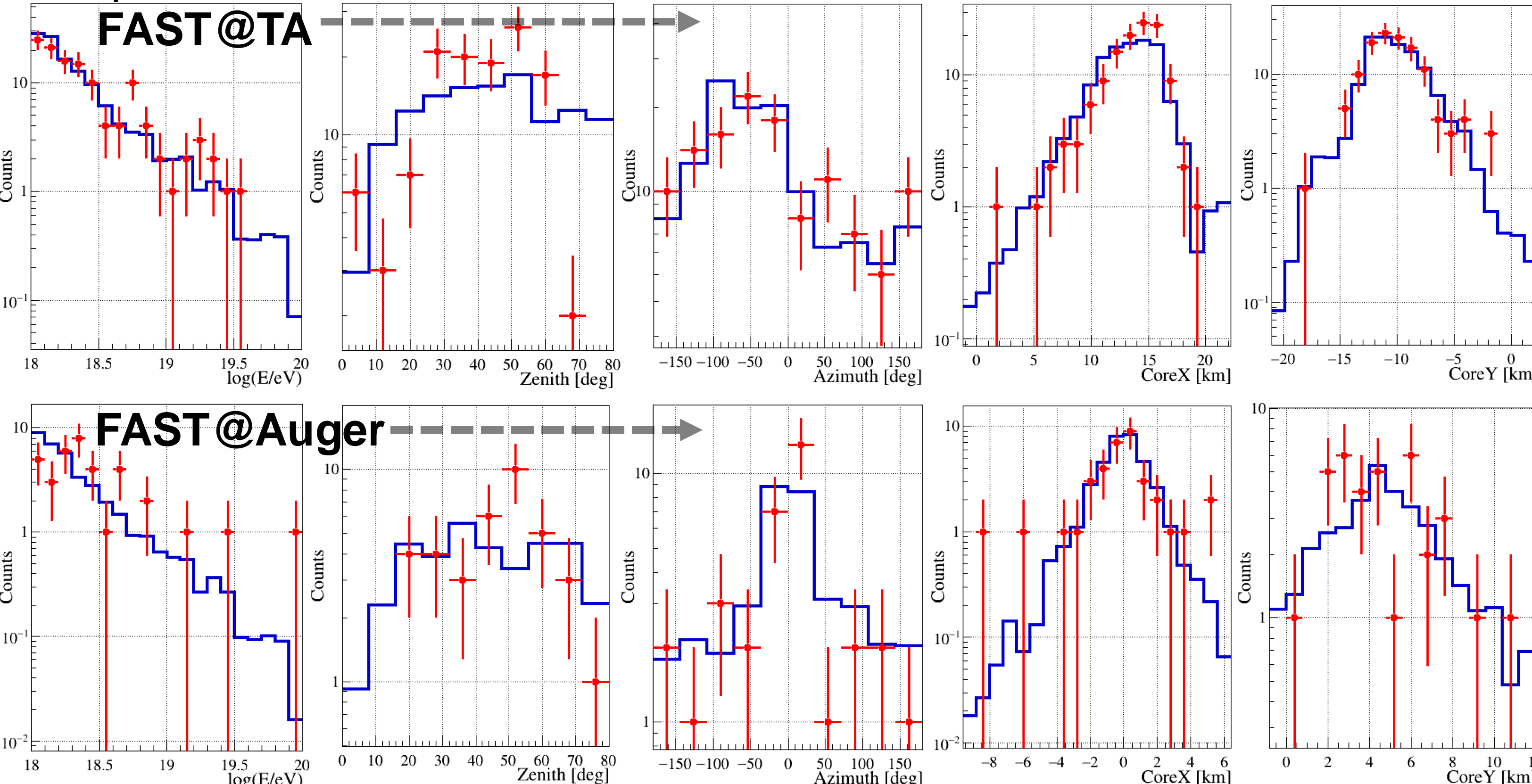Probability of observing signal x_i in bin i of PMT k given shower parameters $\vec{a}$

X$_{max}$

Coincidence event analysis

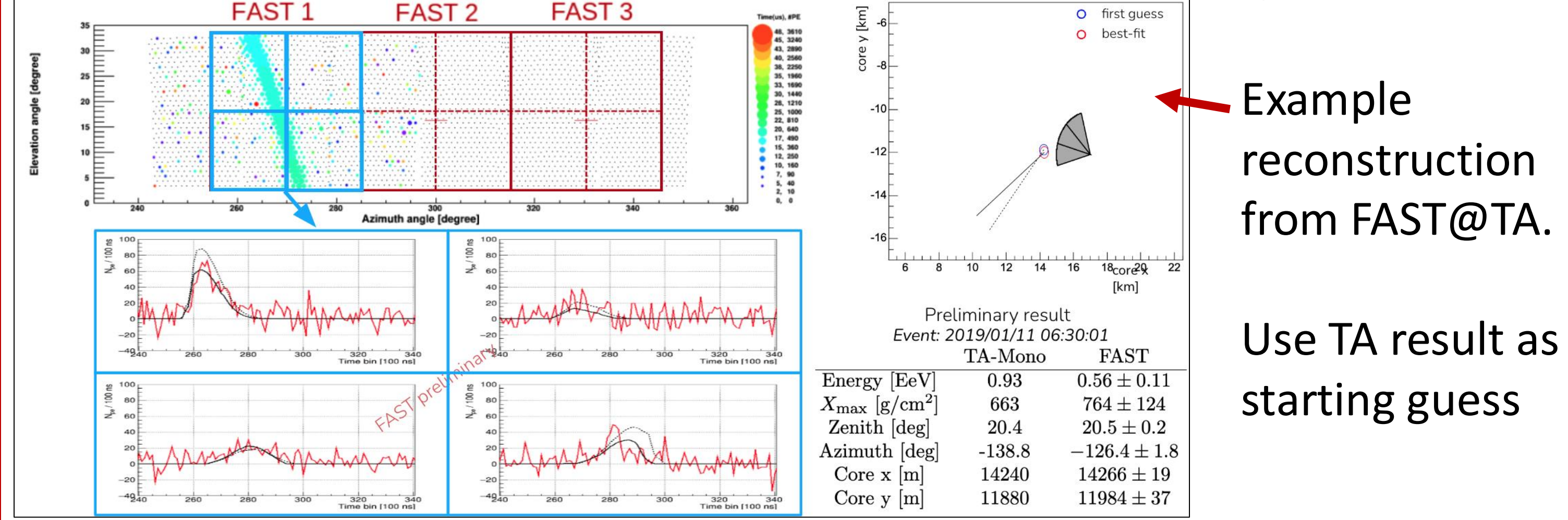**Coincidence =** cosmic ray events observed by FAST and TA/Auger

	FAST@TA	**FAST@Auger**
Analysis period	2 telescopes（2018/03 – 2018/10） 3 telescopes（2018/10 – 2023/02）	1 telescope（2022/07 – 2022/10）
Observation time	2 telescopes ~ 65 hrs 3 telescopes ~ 182 hrs	1 telescope ~ 122 hrs
Coincidence events	438	236

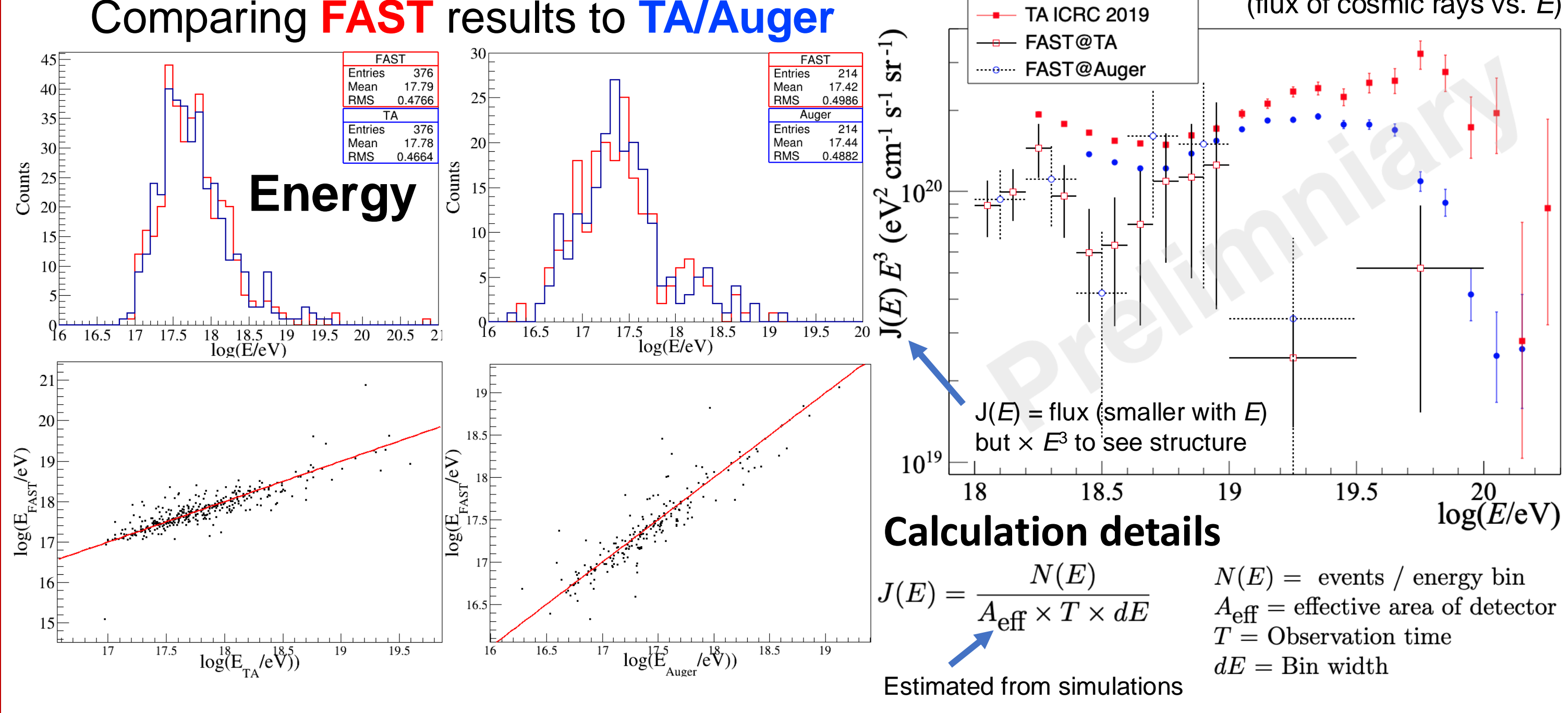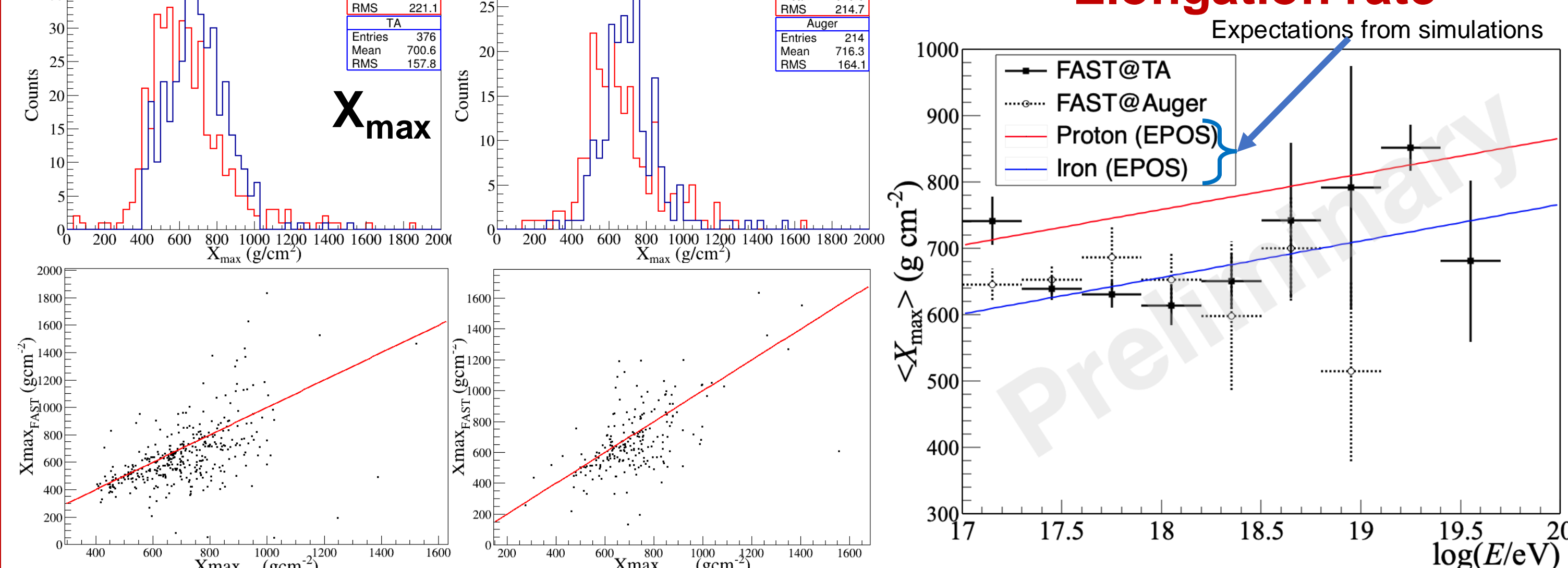Compare **TA/Auger reconstruction** to expectation from **FAST simulation**

FAST@TA

FAST@Auger

log(E/eV), Zenith [deg], Azimuth [deg], CoreX [km], CoreY [km]

EAS overview

Measure fluorescence light from $e^{+/-}$ & O^2 / N^2 interaction

primary particle

radio + air-Cherenkov
radio antenna | light detector | particle detector | telescope for fluorescence light

Geometry: Zenith (θ), Azimuth (ϕ), Core location (x, y)
X$_{max}$: Location of max # of particles (atmos. depth)
Energy: Initial cosmic ray energy

θ — X$_{max}$ — ϕ — (x, y) — *Ground*

Reconstruction results

Reconstruct coincidences with **FAST** waveform matching.

FAST 1 — FAST 2 — FAST 3

first guess / best-fit

Example reconstruction from FAST@TA.

Use TA result as starting guess.

Preliminary result
Event: 2019/01/11 06:30:01

	TA-Mono	FAST
Energy [EeV]	0.93	0.56 ± 0.11
X$_{max}$ [g/cm^2]	663	764 ± 124
Zenith [deg]	20.4	20.5 ± 0.2
Azimuth [deg]	-138.8	-126.4 ± 1.8
Core x [m]	14240	14266 ± 19
Core y [m]	11880	11984 ± 37

Comparing **FAST** results to **TA/Auger**

Energy

X$_{max}$

Energy spectrum
(flux of cosmic rays vs. E)

Auger PRD 2020 / TA ICRC 2019 / FAST@TA / FAST@Auger

$J(E)$ = flux (smaller with E) but $\times E^3$ to see structure

Calculation details

$$J(E) = \frac{N(E)}{A_{eff} \times T \times dE}$$

$N(E)$ = events / energy bin
A_{eff} = effective area of detector
T = Observation time
dE = Bin width

Estimated from simulations

Elongation rate

FAST@TA / FAST@Auger / Proton (EPOS) / Iron (EPOS)
Expectations from simulations

Elongation rate = how X$_{max}$, a measure of cosmic ray mass composition (i.e. what type of nuclei), changes with energy.

Bias in X$_{max}$ reconstruction: Smaller than Auger/TA by ~40-60 g/cm^2 – *filter degradation, PMT response, atmospheric conditions…?*

FAST@TA and FAST@Auger results agree within statistical uncertainty

Future: FAST mini-array

FAST mini-array: Install 4 more telescopes at FAST@Auger in triangle. Observe EASs from multiple locations ("**stereo**"). Increased reconstruction **accuracy** and **precision**.

2026: — Move in 2026! — 2025: — Current 2 tels.

Expected number of events per year vs. station spacing →

Installation plan:
2025: 2 telescopes, ~11km (high quality events)
2026: 2 telescopes, ~16km (increase statistics)

Stereo (≥1PMT/station) / Stereo (≥2PMT/station)
Station spacing (m)