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SST-1M
Single-Mirror
Small Size Telescope

The SST-1M stereoscopic Cherenkov telescope system

- Outline
  - The SST-1M Project
  - The SST-1M telescopes at the Ondrejov observatory
  - Telescope operation and commissioning
  - First Science results

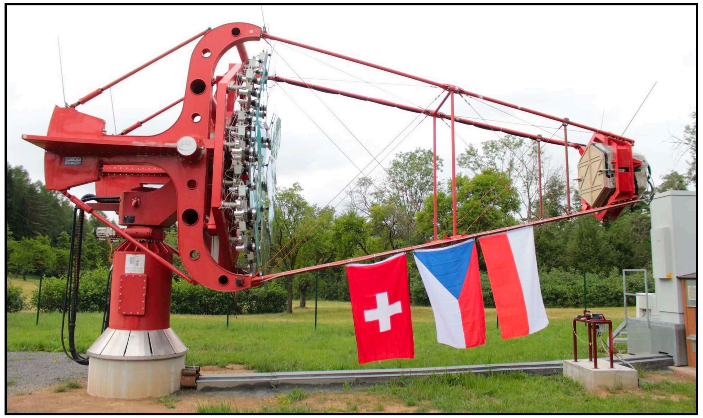
T. Montaruli on behalf of the SST-1M collaboration
CTAO-CH days, 13-14 December 2023

The SST-1M Project

- Consortium of research institutions from Czech Republic, Poland, Switzerland, Ukraine

- Initially developed for Cherenkov Telescope Array as prototypes of SSTs
  - ✦ Reviewed and satisfied all CTA requirements, nevertheless down-selection in favour of dual mirror SSTs

- Two full telescopes built and assembled:
  - ✦ One prototype
  - ✦ One pre-production
    - ◉ Improvements: camera mechanics and entrance window coating



SST-1M

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Nicolaus Copernicus Astronomical Center

CBK PAN
Centrum Badań Kosmicznych
Space Research Centre

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

AGH University of Science and Technology

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ISDC
DATA CENTRE FOR ASTROPHYSICS

JAGIELLONIAN UNIVERSITY IN KRAKOW

FZU Fyzikální ústav Akademie věd České republiky

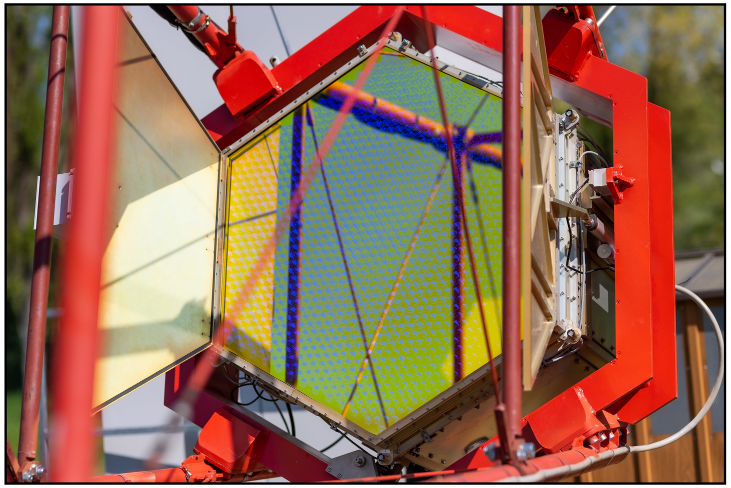
UNIWERSYTET WARSZAWSKI

asu Astronomický ústav AV ČR

Palacký University Olomouc

The SST-1M Cherenkov telescope

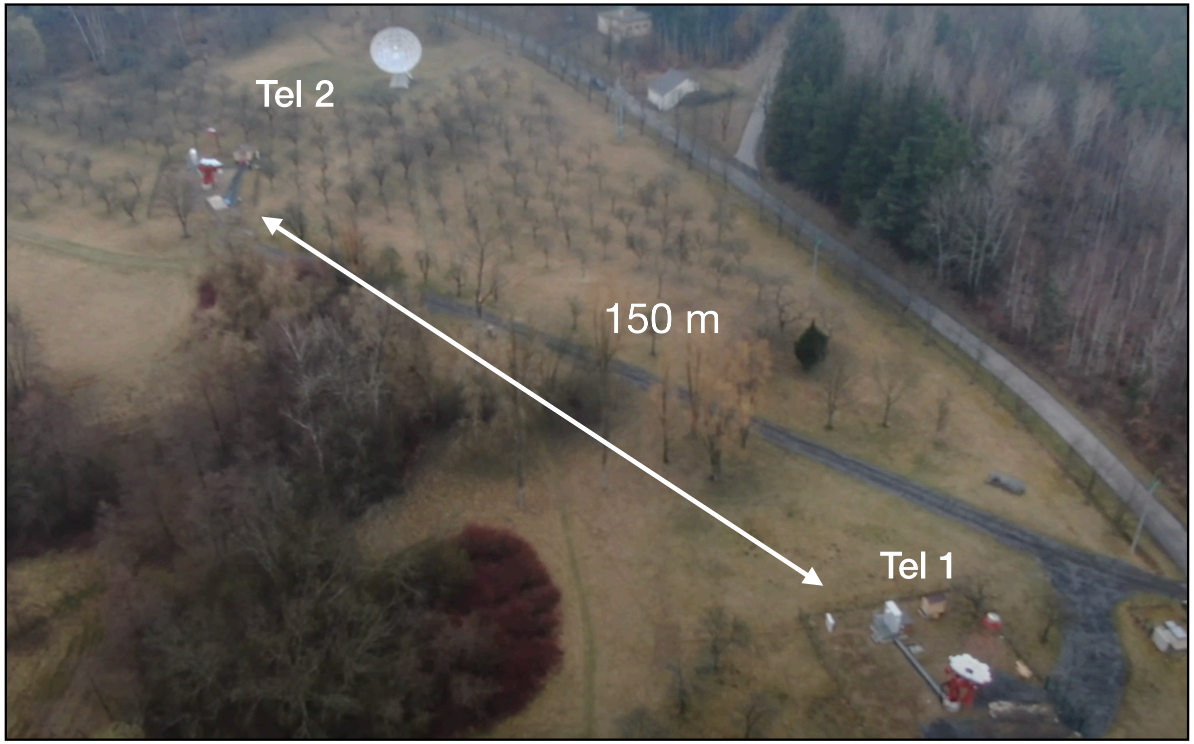
- Davies-Cotton proven optical design
  - Innovative SiPM-based camera
  - Digital electronics with fully digital trigger and readout architecture
  - Fully programmable
  - Highly performing large-area SiPMs with dedicated slow control
- Optimized for gamma-ray sensitivity above 500 GeV in stereo mode
- Lightweight (~ 8.6 t) and compact structure;
- Designed for fully robotic operation with minimal maintenance in harsh environment
- Low Cost

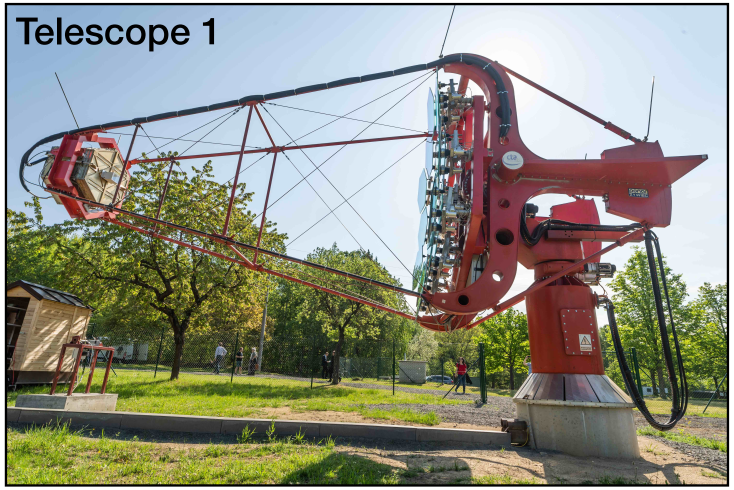


Optical properties	*Focal Length*	5600 ± 5 mm
	f/D	1.4
	Dish diameter	4 m
	Mirror Area (*)	9.42 m^2
	Mirror Effective Area(*)	6.47 m^2
	Hexagonal Mirror facets	780 ± 3 mm
	Preliminary on-axis PSF real optical parameters	0.07°
	PSF (80% of FoV@ 4° off-axis)(**)	0.21°
Camera Characteristics	*Camera (depth x width)*	60 cm x 90 cm
	Total pixel number	1296
	Pixel linear size	23.2 mm
	Pixel angular size	0.24°
	FoV	9.1°
	Photosensors PDE	> 30%
	Sampling frequency	250 MHz
	Readout rate	0.6-1 kHz
	Time Spread RMS	< 0.25 ns

The SST-1M stereoscopic telescope system

- Two telescopes, separated by ~150 m, fully deployed on the test and validation site, the Ondrejov Observatory in Czech Republic (~40 km from Prague), 550 m.a.s.l.





Simulation and analysis pipelines

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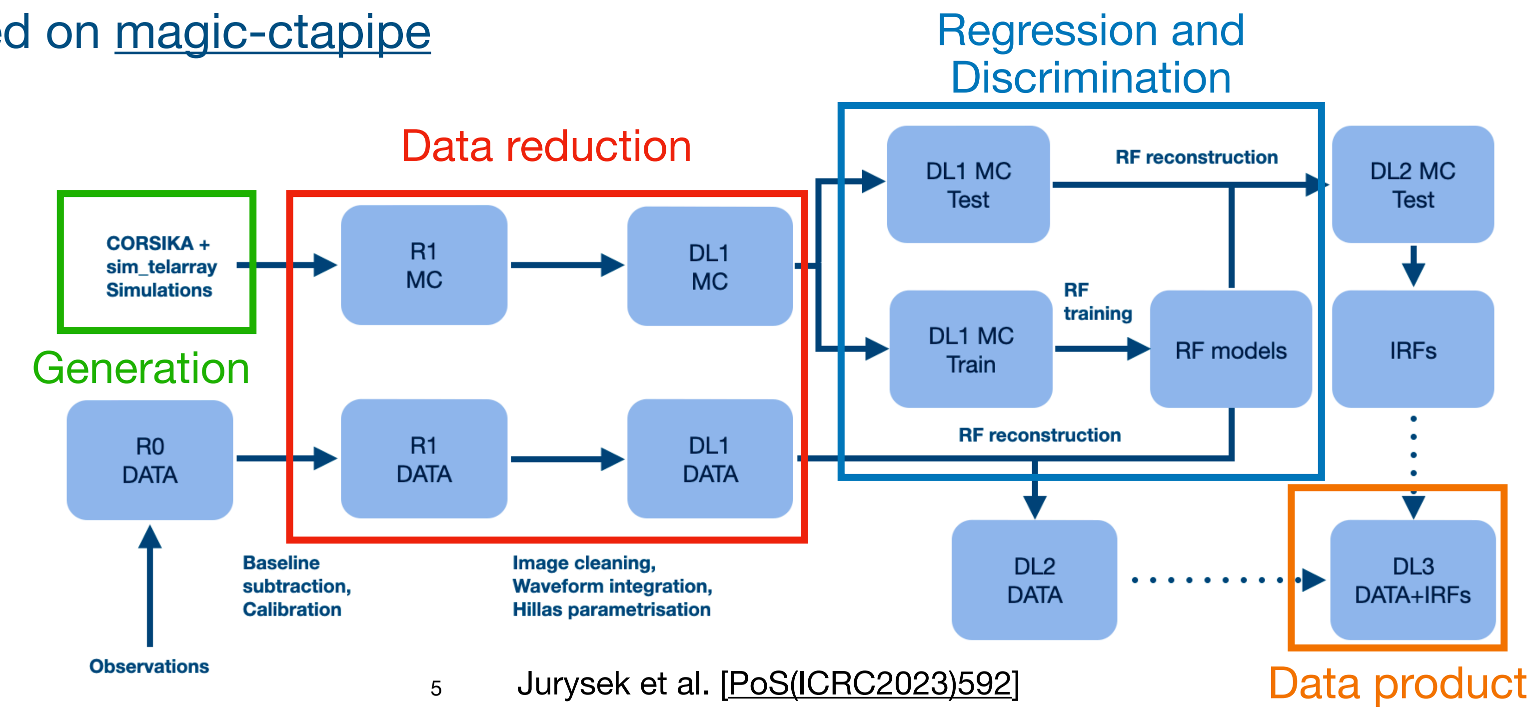
- Developed pipelines for analysing the SST-1M data: mono, stereo, MC and real data.
  - The backbone of the data analysis pipeline is ctapipe (maintained by CTAO) and inspired by lstchain (maintained by LST collaboration)
  - For calibration specific to the SST-1M telescope (SiPMs) methods derived from digicampipe (C. Alispach et al 2020 JINST 15 P11010)
  - Stereo treatment based on magic-ctapipe
- In parallel, development at UNIGE of full-event reconstruction with deep learning (CTLearn)

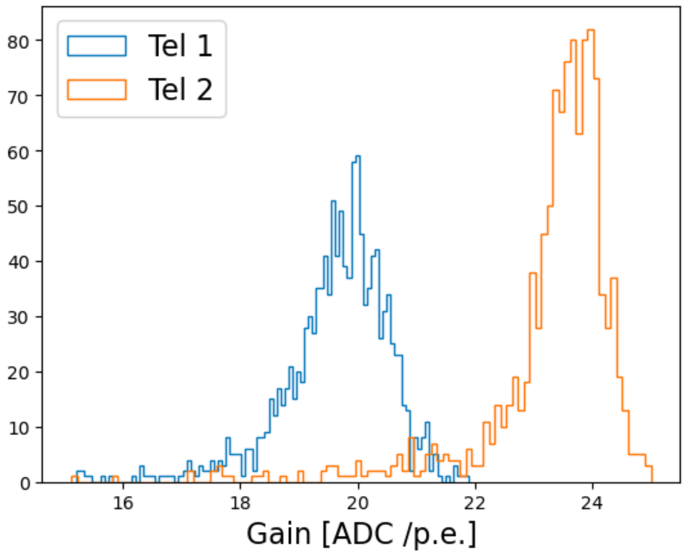


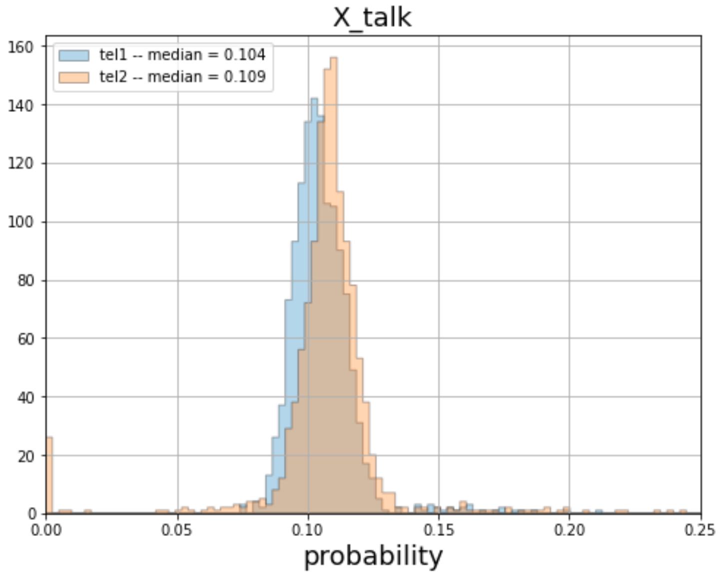
Jurysek et al. [PoS(ICRC2023)592]

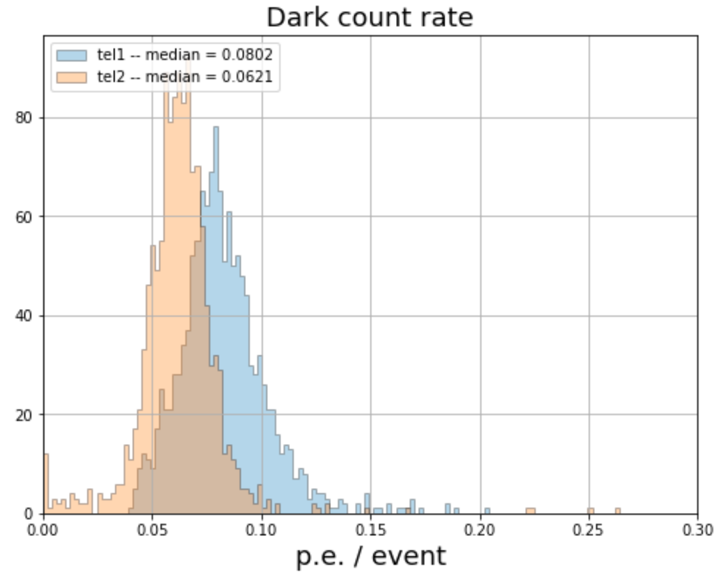
The SST-1M commissioning

Extraction of telescope parameters

- Before running any simulations, configurations must be tuned based on commissioning results:
  - Mirror reflectivity
  - Entrance window transmissivity
  - Different sources of noise:
    - Night sky background
    - Electronics
    - Sensor (DCR, optical cross talk)







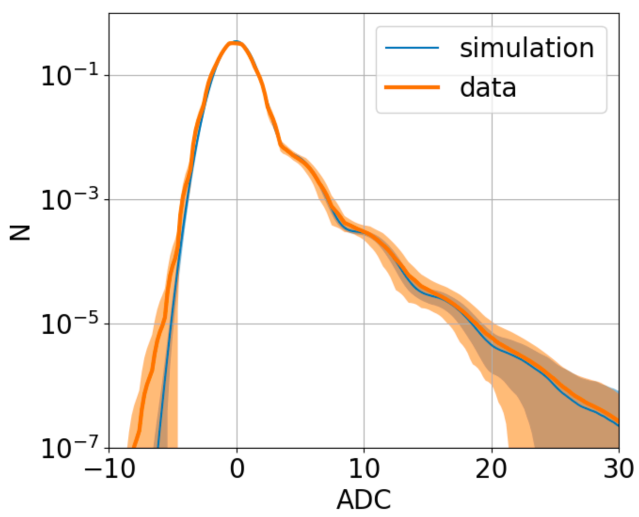
Tavernier et al. [PoS(ICRC2023)741]

Simulation and analysis pipelines

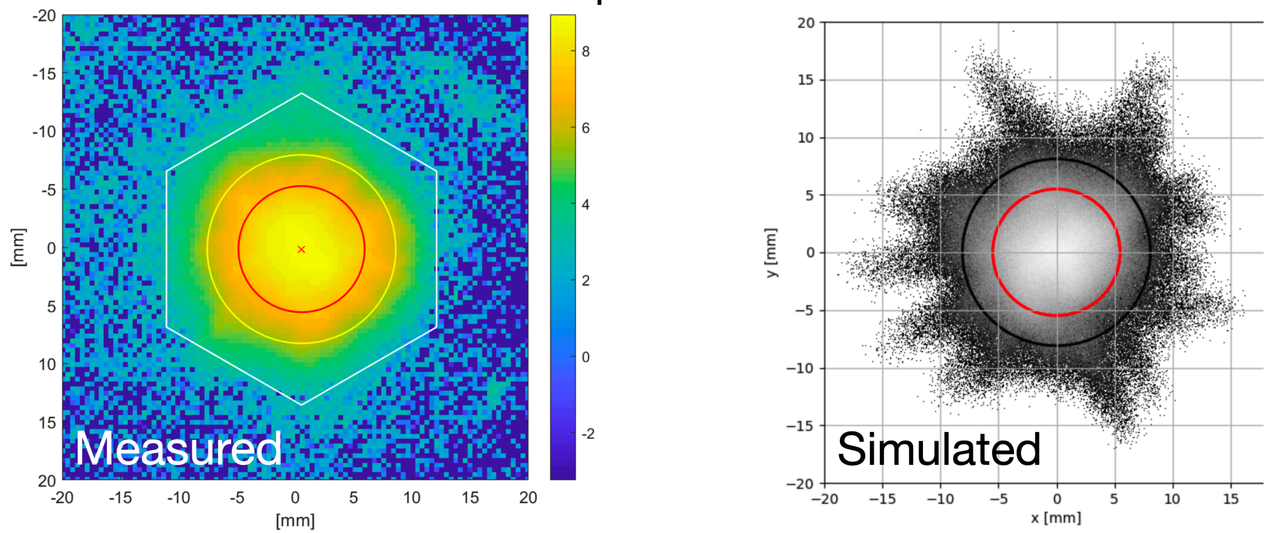
MC tuning

- Configuration parameters tuned to minimize MC/real data mismatch
  - Mirror reflectivity
  - Optical point spread function
  - Pixel characteristics: gain, noise
  - Night Sky Background level
  - …

Pixel response



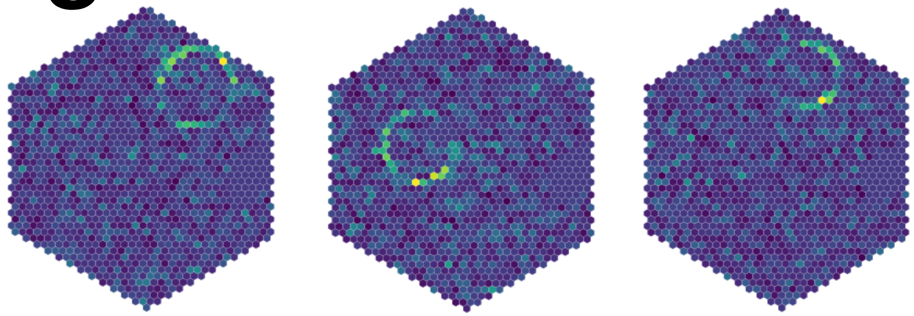
Optical PSF



Jurysek et al. [PoS(ICRC2023)592]

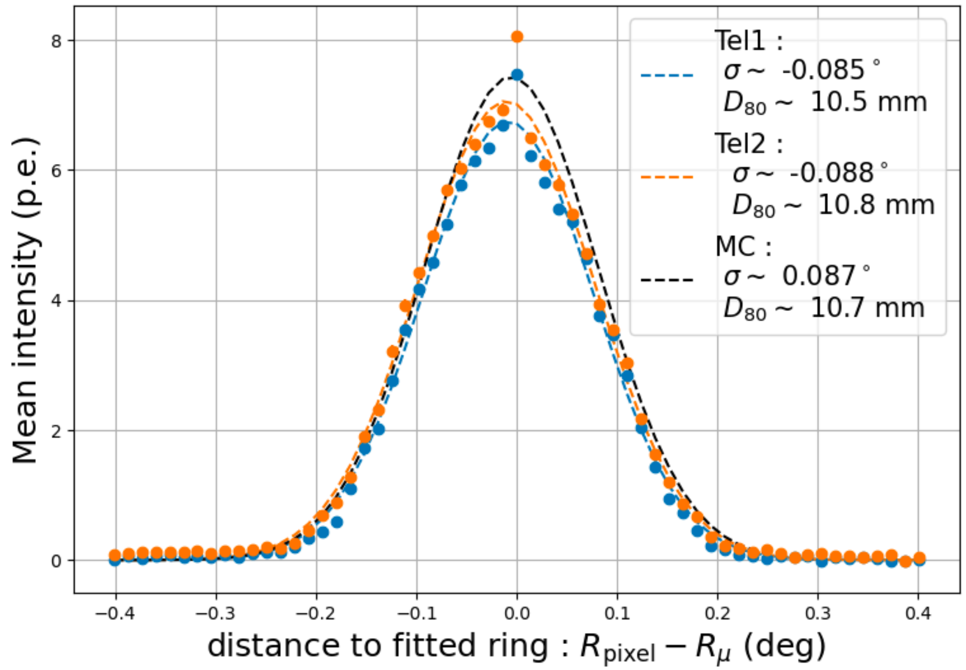
The SST-1M commissioning

Extraction of telescope parameters



- Muons are very powerful tools to calibrate the optical throughput of the telescope
  - ✦ Radius related to Cherenkov angle, i.e. muon velocity and refraction index
  - ✦ Intensity is related to optical efficiency of the telescope

- Extracted parameters for tuning the MC
  - ✦ Optical throughput
  - ✦ Optical point spread function verified with muons!

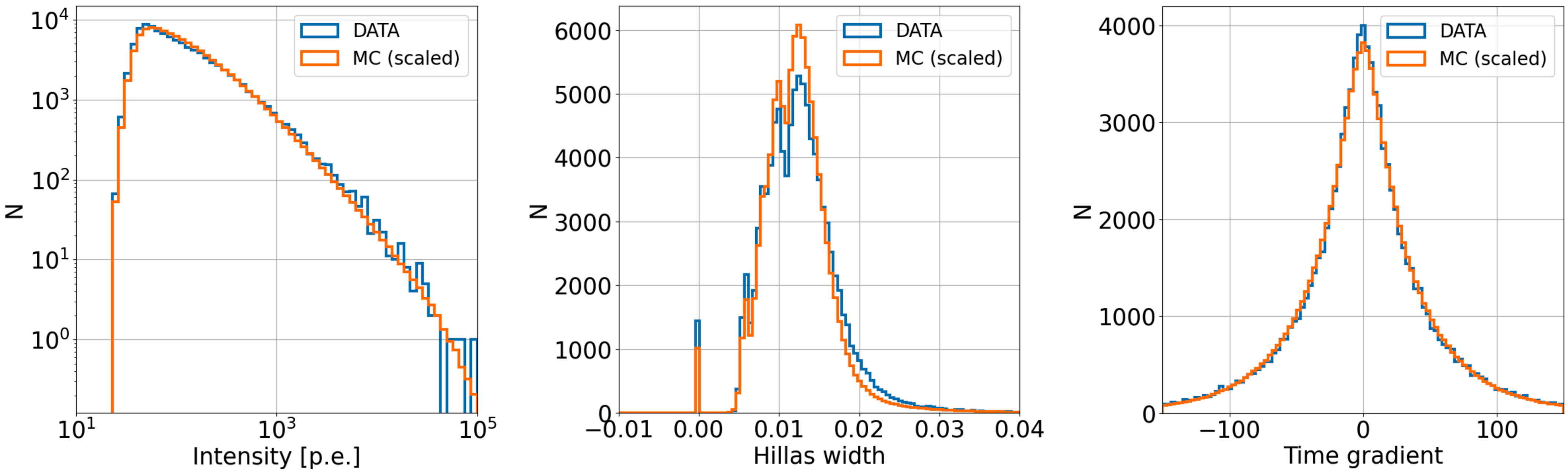


Tavernier et al. [PoS(ICRC2023)741]

Simulation and analysis

MC data comparison

- Comparison of selected Hillas parameters for data taken on June 12, 2023 at zenith angles between 18° and 22° with diffuse proton MC re-weighted on the CR spectrum.
- Distribution of MC simulated events scaled by a factor of 1.04 to account for the actual atmospheric transparency.

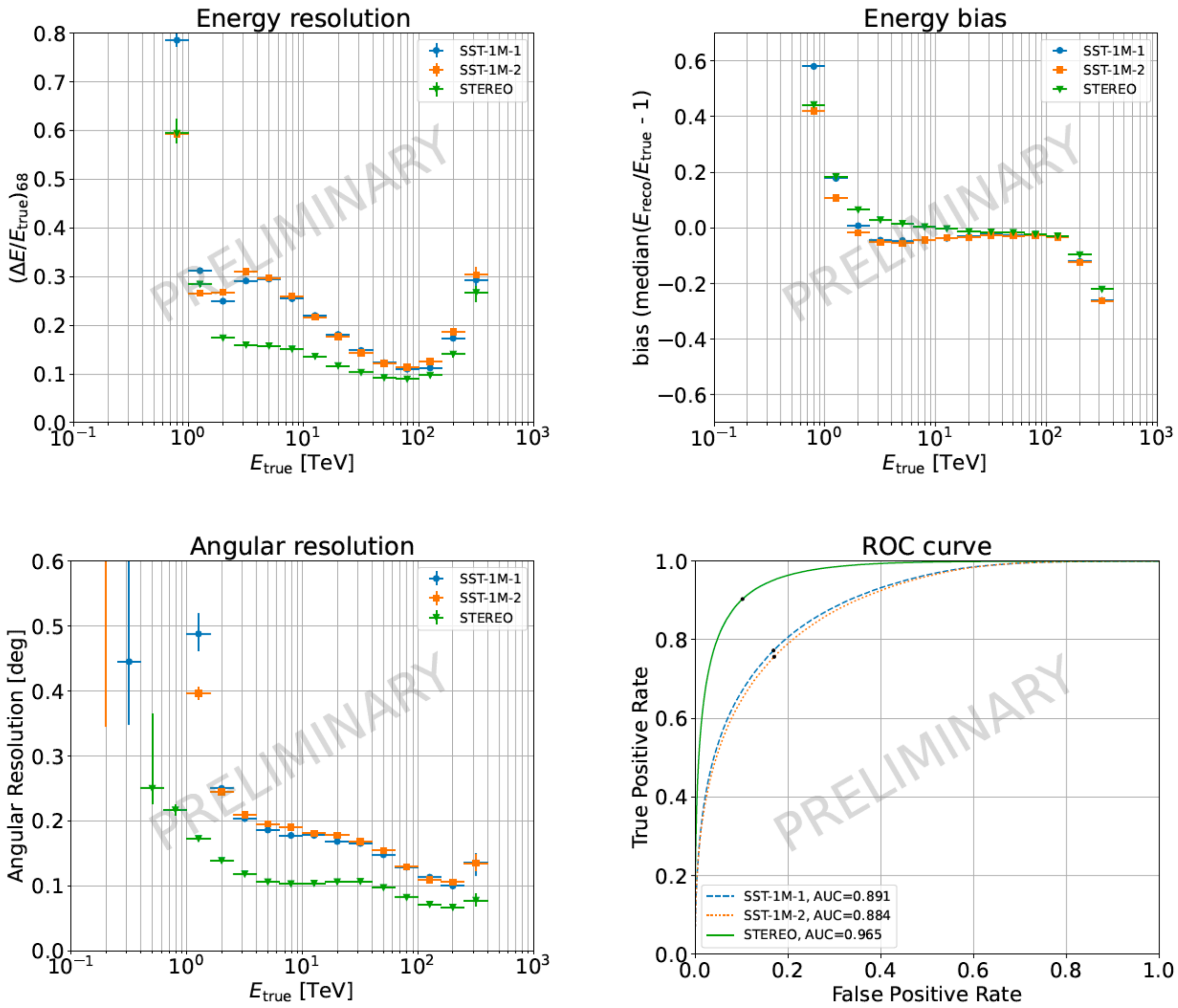


Jurysek et al. [PoS(ICRC2023)592]

Instrument response function

Ondrejov site (510 m.a.s.l)

- Low altitude of the site limits the energy threshold to ~1 TeV
- Working in stereo is key to improve performance
  - ✦ Better direction reconstruction, especially due to removal of degeneracy in shower geometry
  - ✦ Better energy resolution and lower bias due to better reconstruction of the shower geometry, in particular its impact parameter
  - ✦ Better background rejection due to better constraints on the shower geometry

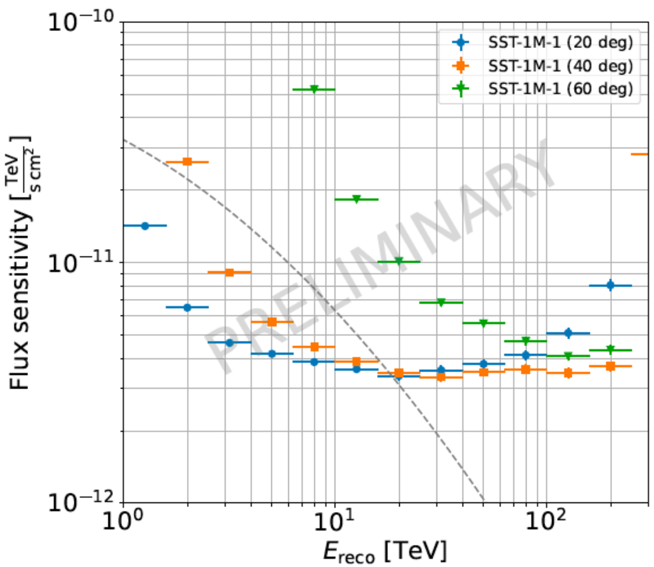


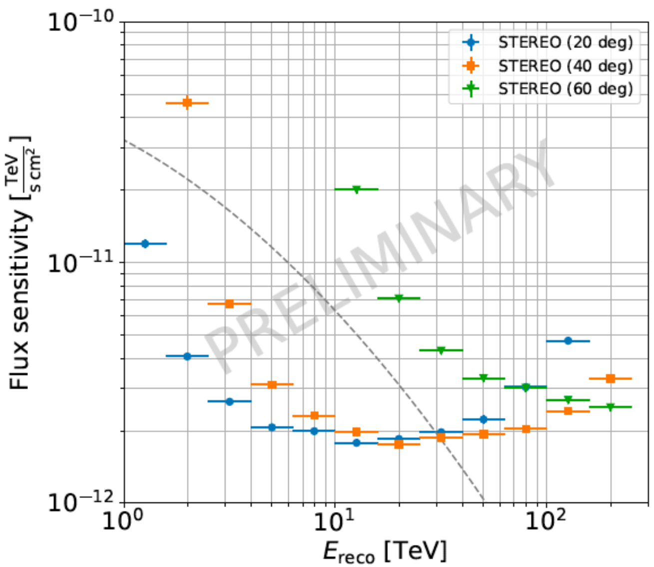
Jurysek et al. [PoS(ICRC2023)592]

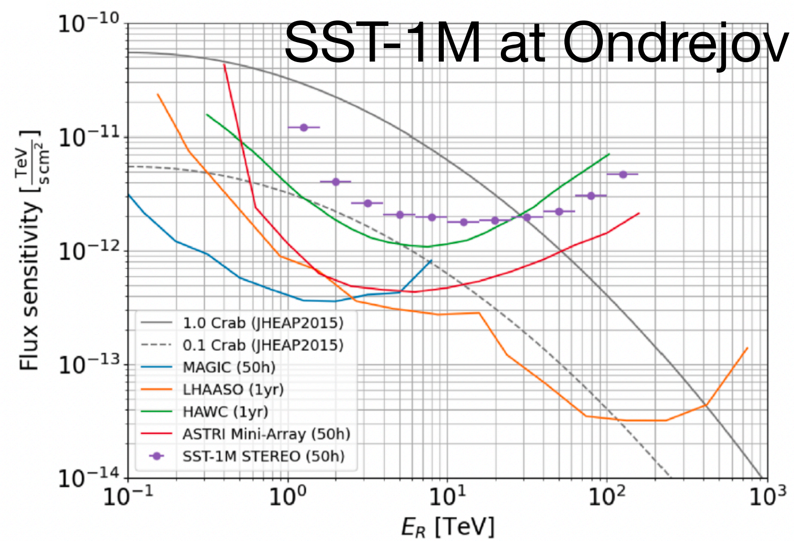
Instrument response function

Ondrejov site (510 m.a.s.l)

- Sensitivity vs. Zenith angle:
  - ✦ Improvements on direction and energy reconstruction added to a better background rejection naturally leads to better sensitivity
  - ✦ Given the low altitude, observing as close as possible to the zenith is very important !



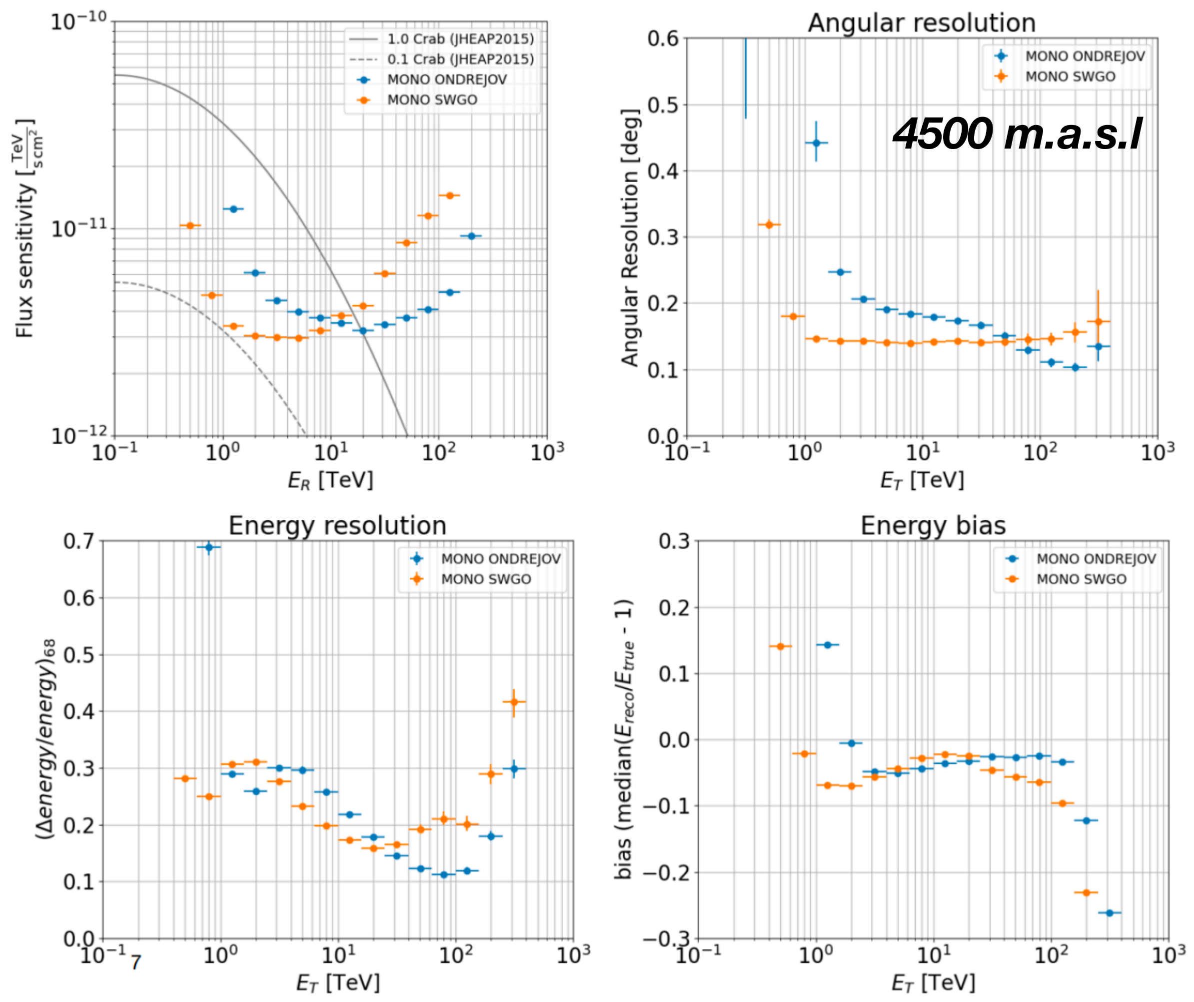




Jurysek et al. [PoS(ICRC2023)592]

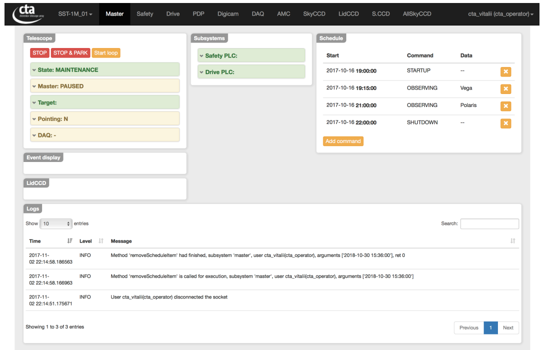
SST-1M at higher site

- Exploring different options for relocation of SST-1M
  - Hanle Observatory (India)
  - SWGO (South America)
  - …
- One common point:
  - High altitude > 4250 m.a.s.l.
- Significantly **lower energy threshold** (altitude effect and lower NSB)
- Better angular and energy resolution at lower energies compared to Ondrejov

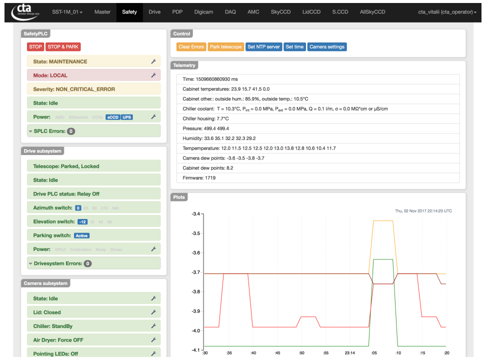


The SST-1M operation

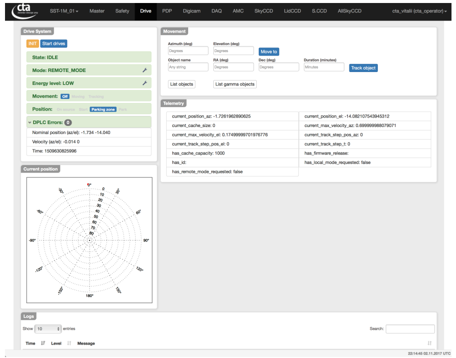
- Remote and nearly fully automatic observations



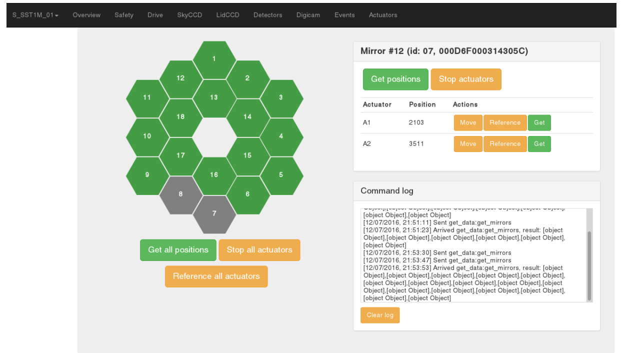
SST-1M master controller



Safety PLC subsystem



Drive system control



Active mirror control

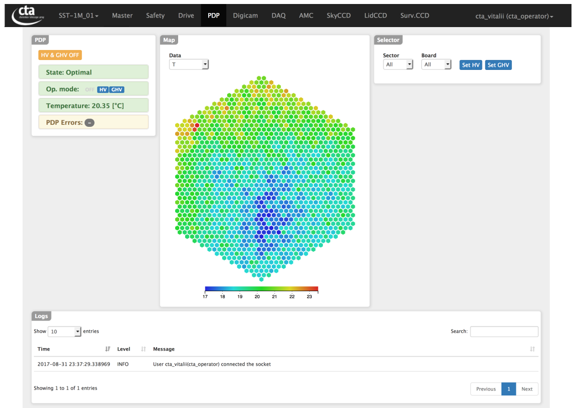
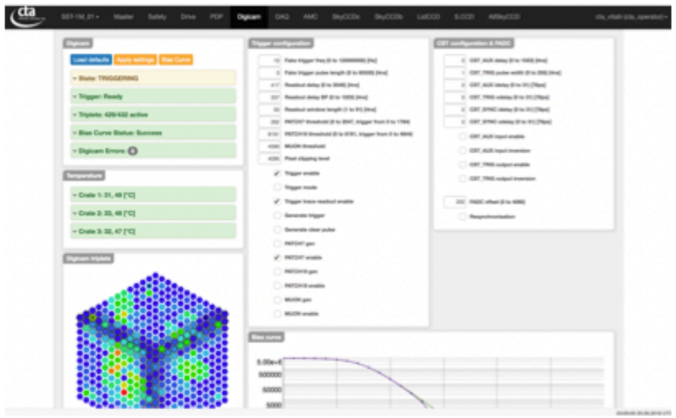
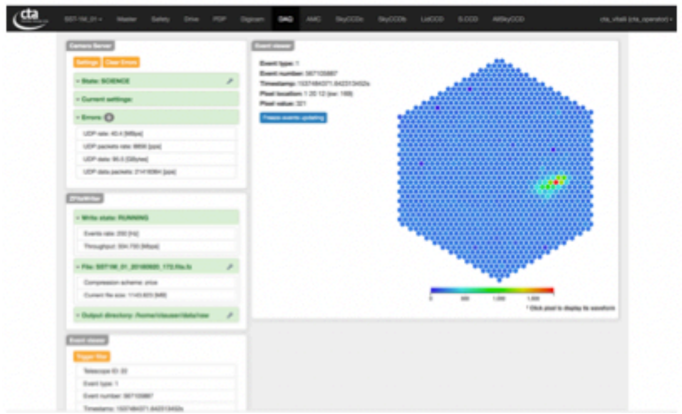


Photo detector plane control and monitoring



Digital readout configuration



DAQ control and monitoring

Stereo observations

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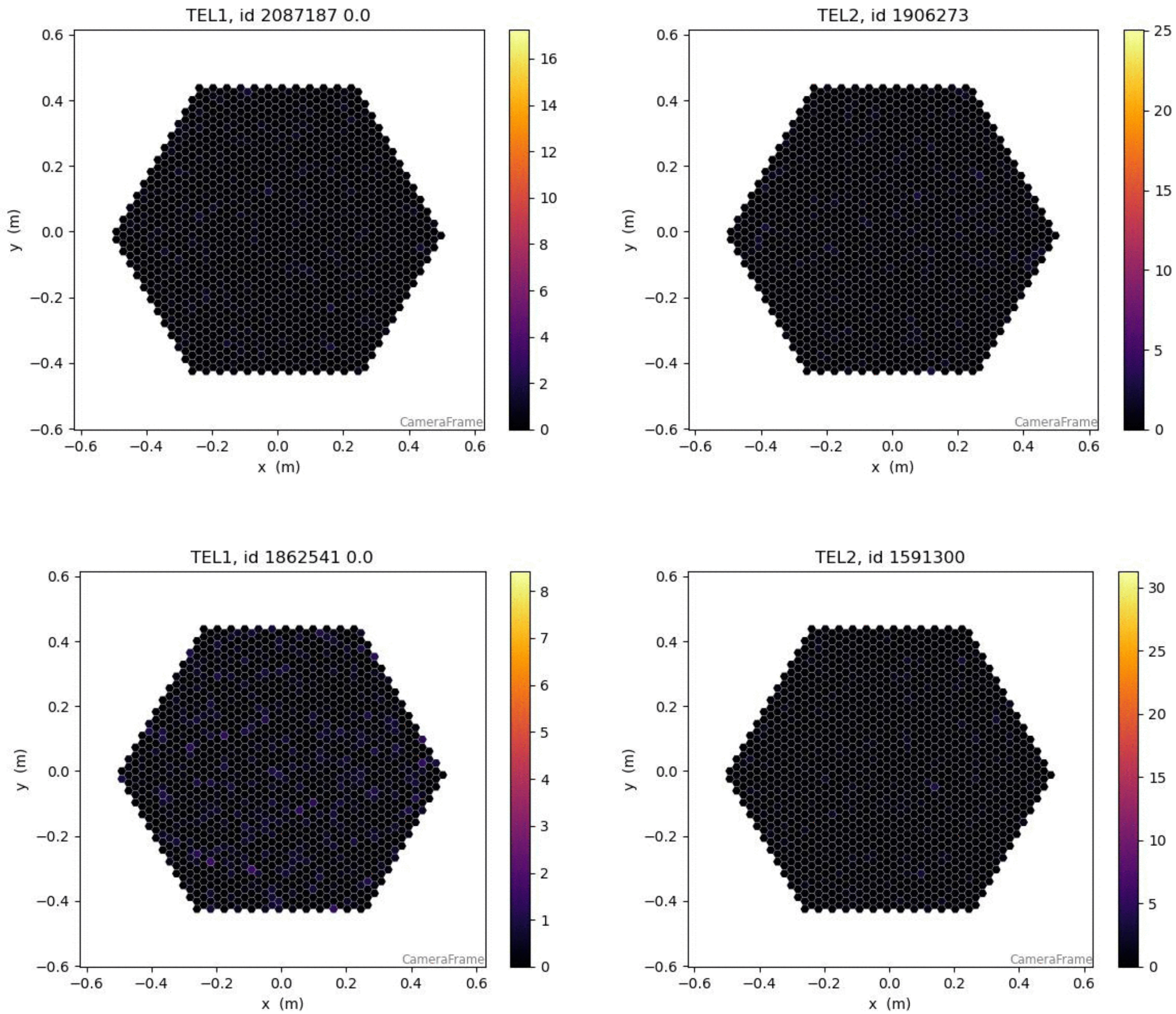
- Both cameras connected to **White Rabbit switch for synchronisation**
- System still being commissioned (missing **installation of GPS for absolute time reference**) but can already operate in stereo mode
- Stereo trigger managed by Software Array Trigger (SWAT), soon deployed with ACS



Stereo observations

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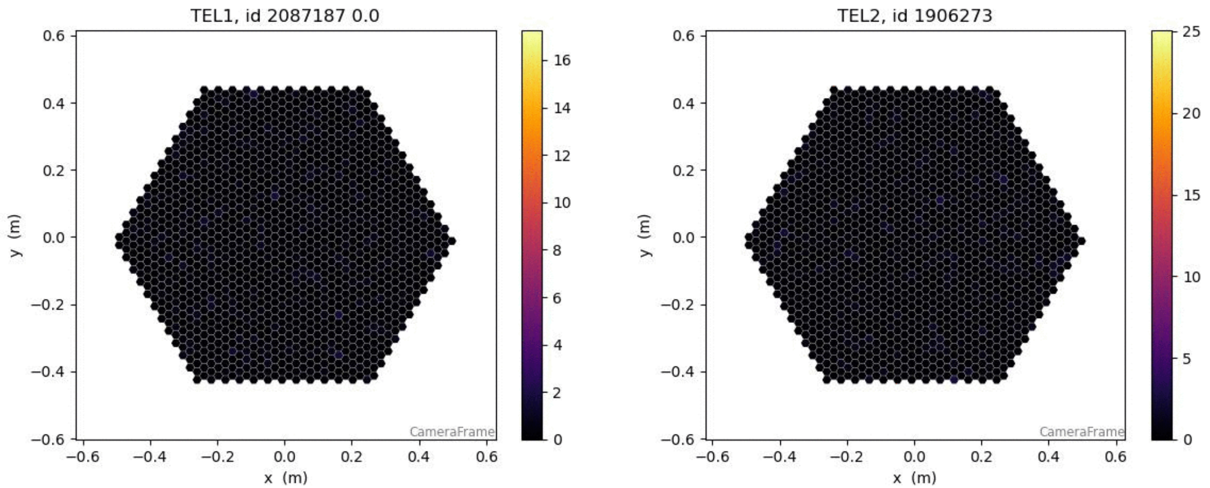
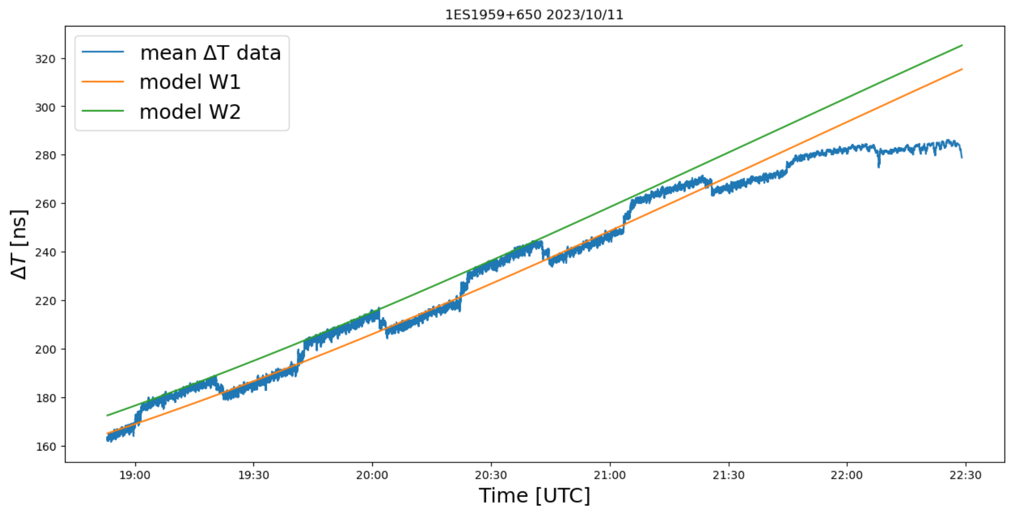
- Both cameras connected to **White Rabbit switch for synchronisation**
- System still being commissioned (missing **installation of GPS for absolute time reference**) but can already operate in stereo mode
- Stereo trigger managed by Software Array Trigger (SWAT), soon deployed with ACS
- Geometrical model well predicts the average time difference between telescopes' trigger times. Deviation with time comes from the fact that we set a maximum coincidence window of \pm 300 ns too tight for large zenith angle showers. We will implement in the SWAT an optimised coincidence window for different pointing directions as shown in the plot for various sources. This method can be transferred to CTAO.

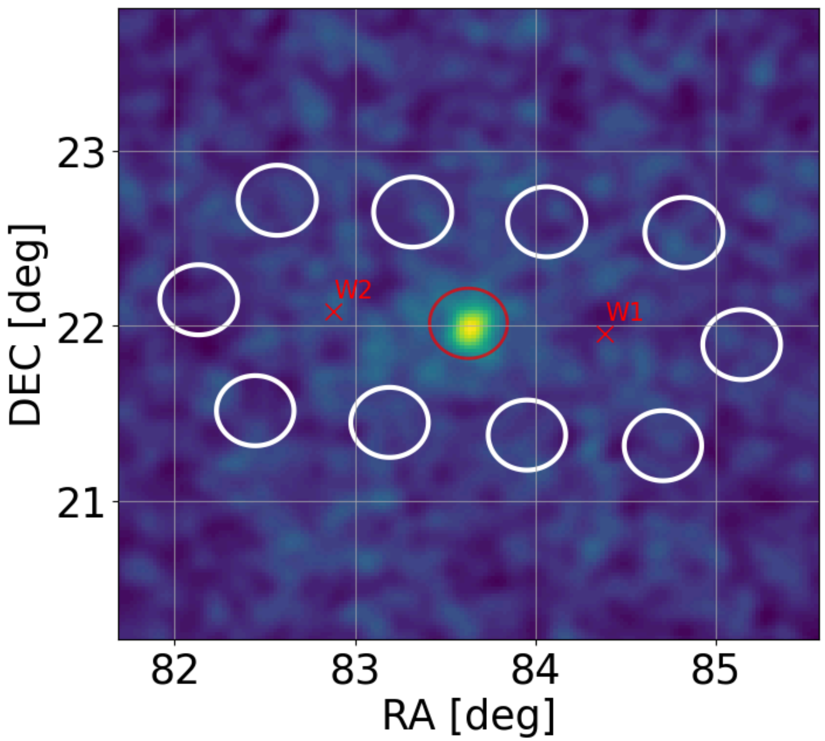


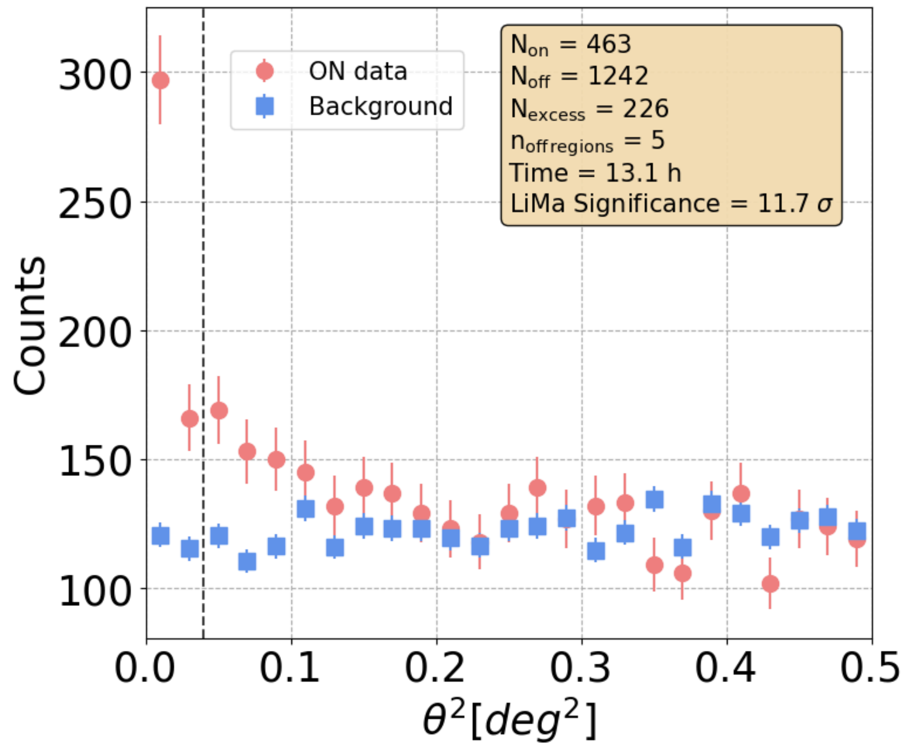


Observations

Monoscopic observation

- Crab monoscopic data set acquired with Telescope 1
- Result: 11.7 sigma in 13.1h





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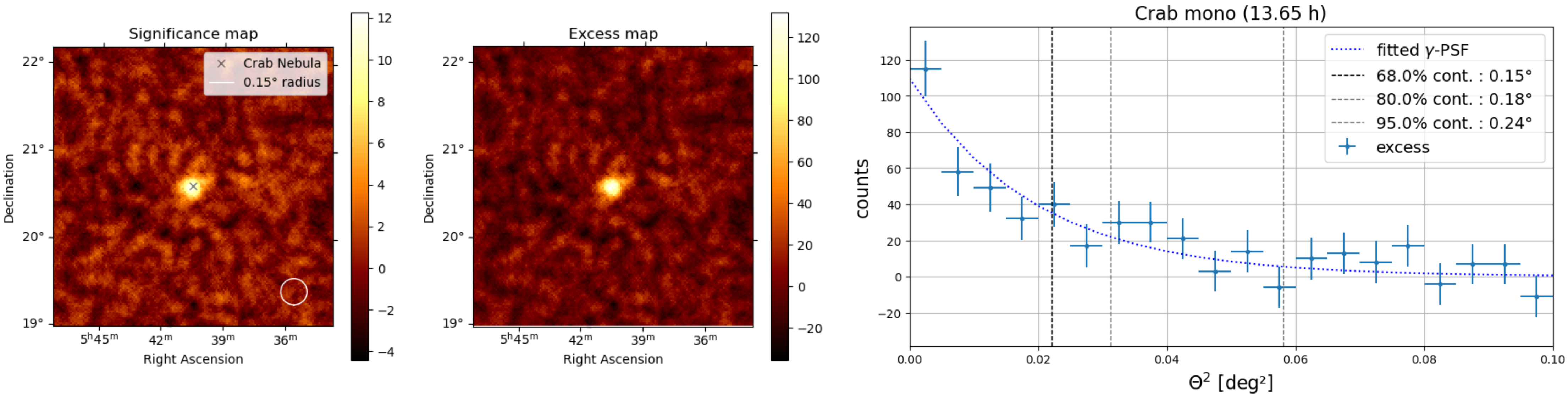
Observations

Monoscopic observation with gamma-py

- Crab monoscopic data set acquired with Telescope 1
- Result: 11.7 sigma in 13.65h



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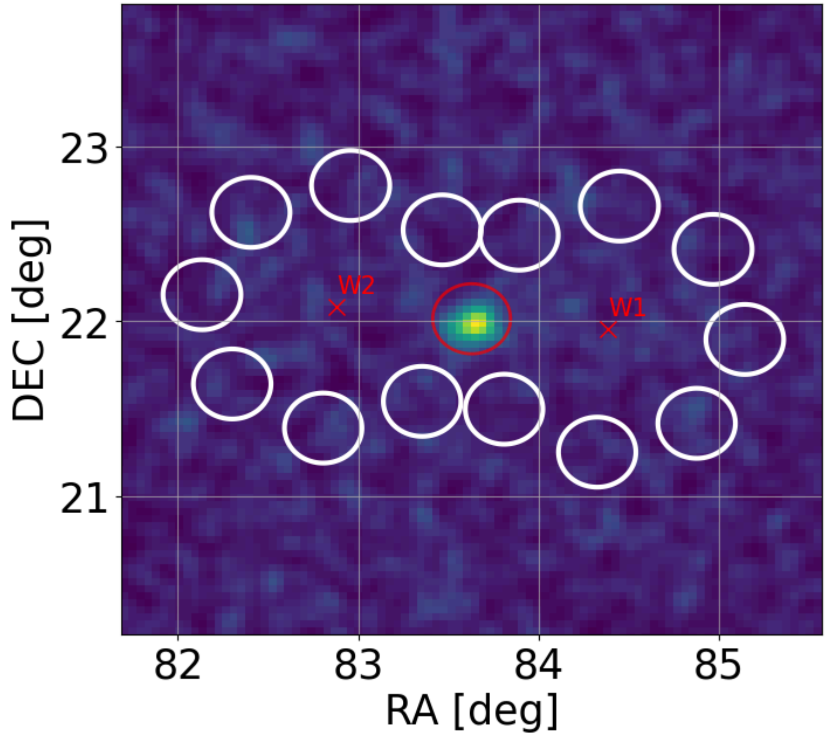
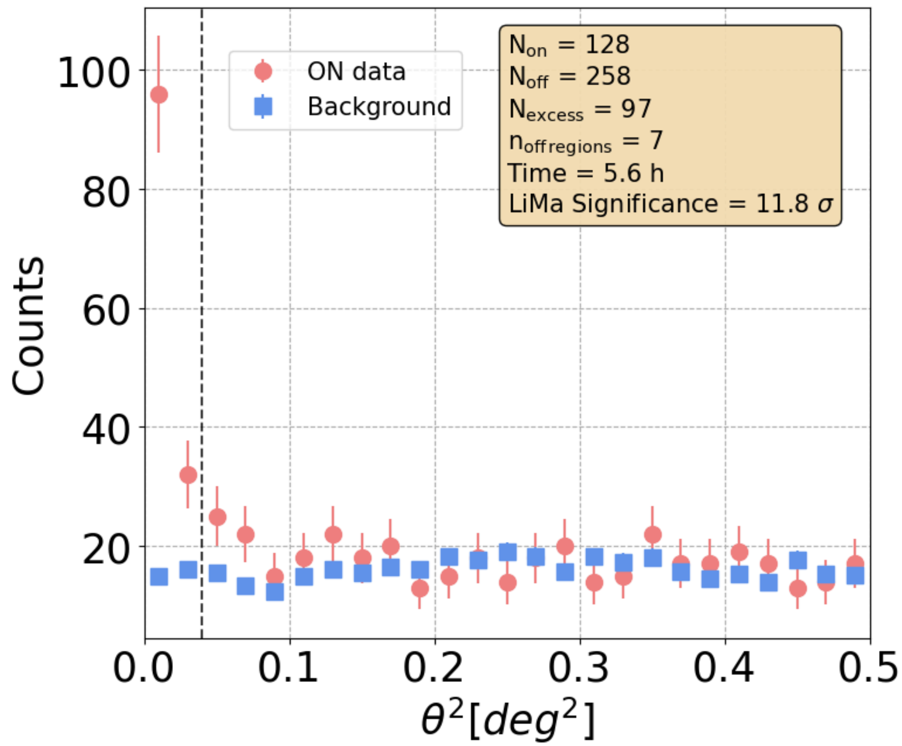
Observations

Stereoscopic observation

- 11.8 sigma in 5.6h





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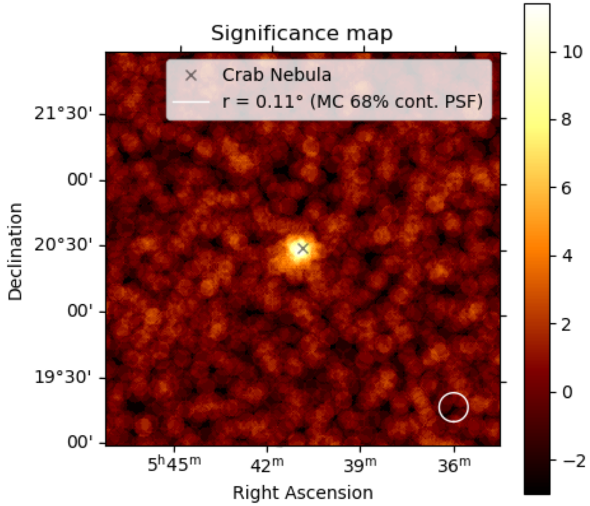
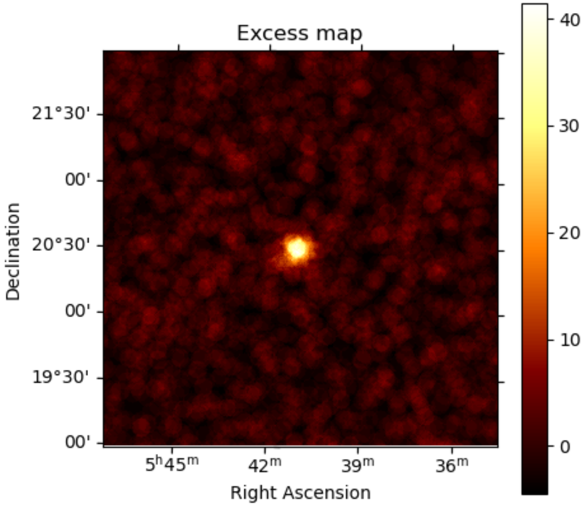
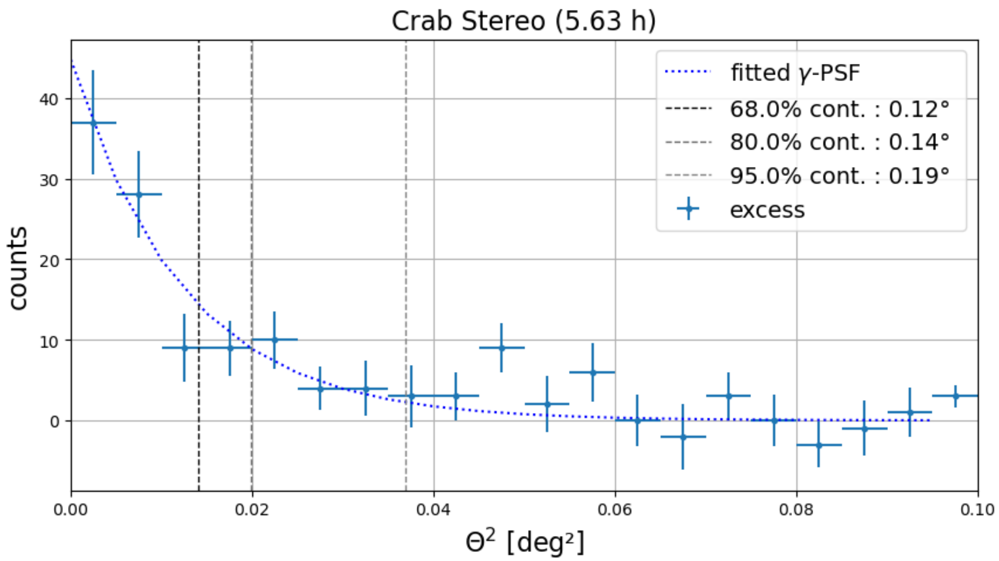
Observations

Stereoscopic observation

- 11.8 sigma in 5.63h







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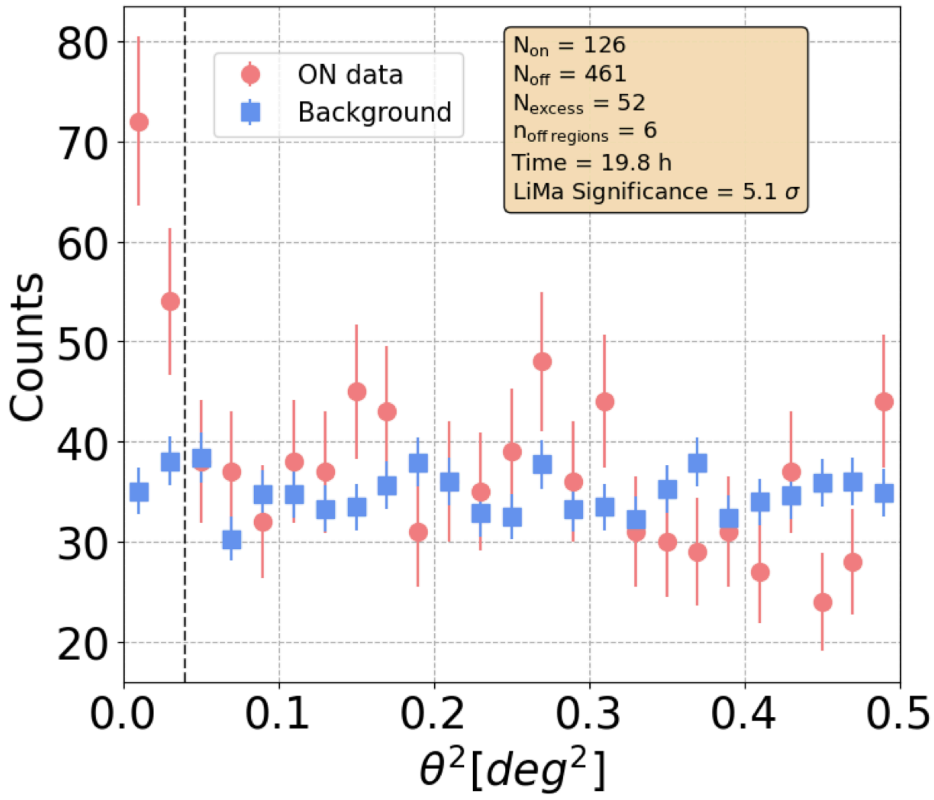
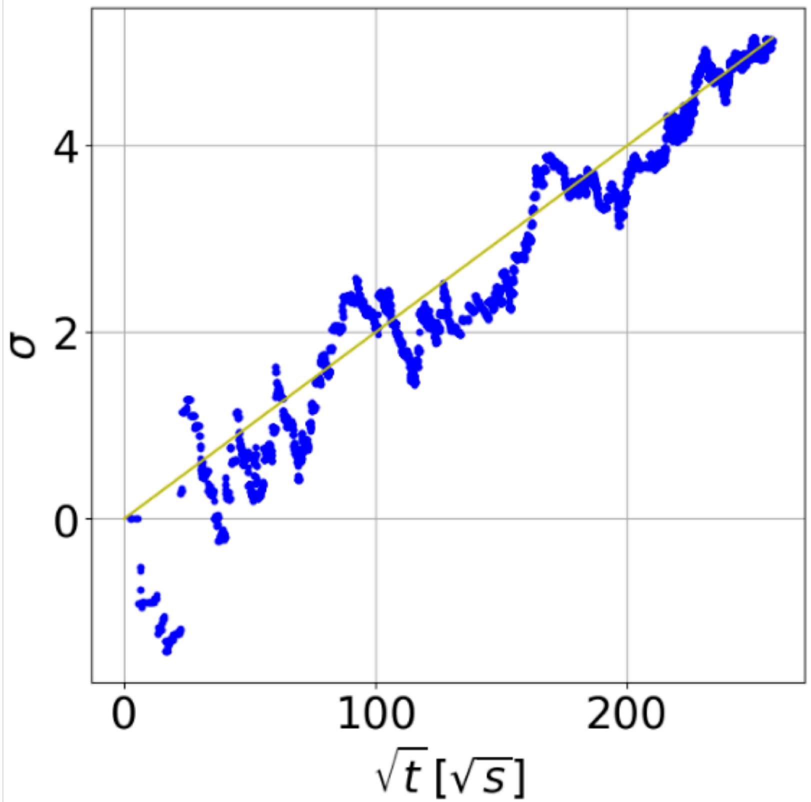
Observations

1ES1959+650

- First detection of extragalactic blazar with SST-1M !





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Conclusion and Prospects

- Finalise the commissioning for the stereo observations
  - Telescope description
  - Synchronisation
  - Fully remote and automatised telescope control

- The SST-1M concept has already proven to meet the performance requirements

- Continue with the scientific program:
  - Crab observation
  - Monitoring of the brightest blazars
    - Recent 5σ detection of extragalactic blazar 1ES1959+650
    - Accumulating data for Mrk 421, 501
  - Exploring advanced triggering and measurement methods exploiting the fully digital readout and large field of view

- The collaboration is exploring new possibilities for observation sites:
  - Two of them can only do so much …
  - … but when complementing another Cherenkov or CR observatory, they are a great asset.
- The SST-1M cameras inspired the LST Advanced camera project