

#### UNIVERSITÉ DE GENÈVE

Joint Annual Meeting of the Swiss Physical Society Austrian Physical Society 4 - 8 September 2023, Universität Basel

## The SST-1M stereoscopic Cherenkov telescope system

M. Heller on behalf of the SST-1M collaboration







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## 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

M. Heller on behalf of the SST-1M collaboration







### The SST-1M Project

- Consortium of research institutions from Czech Republic, Poland, and Switzerland
- Initially developed for Cherenkov Telescope Array as prototypes of SSTs
  - Reviewed and satisfied all CTA requirements, nevertheless an other design was selected
- Two full telescopes built and assembled:
  - One prototype
  - One pre-production
    - Improved camera mechanics and entrance window coating









Nicolaus Copernicus stronomical Center



Centrum Badań Kosmicznyc

niversity of Science and













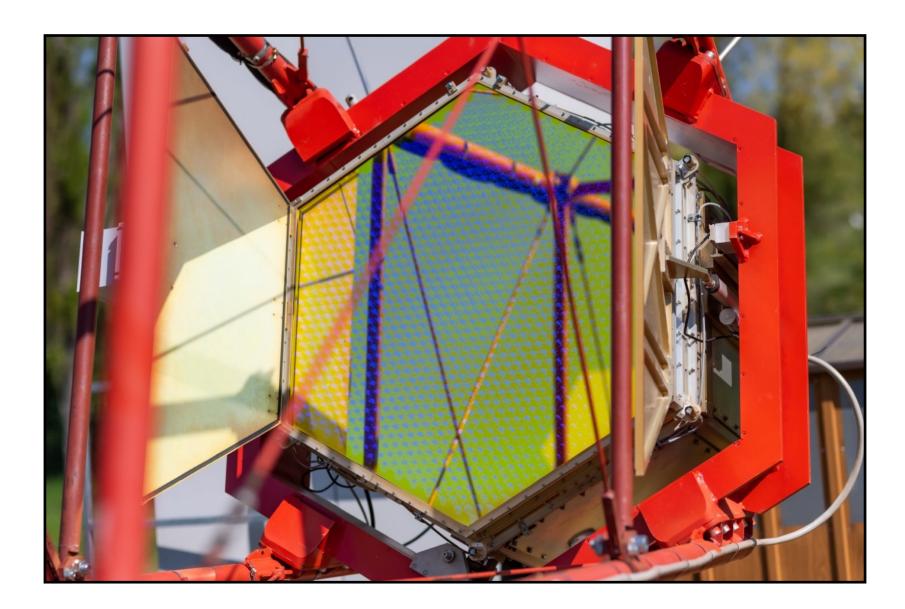
Palacký University Olomouc





### The SST-1M 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 ulletmaintenance in harsh environment
- Low Cost

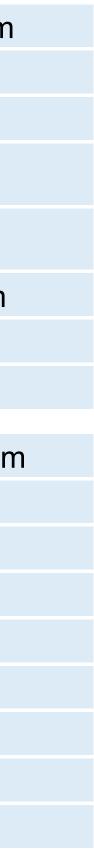






|                           | Focal Length                                    | 5600 ± 5 mm        |
|---------------------------|---|--------------------|
| ies                       | f/D   | 1.4                |
| <b>Optical properties</b> | Dish diameter                                   | 4 m                |
|                           | Mirror Area (*)                                 | 9.42 m $^{2}$      |
|                           | Mirror Effective Area(*)                        | $6.47 \text{ m}^2$ |
| otic                      | Hexagonal Mirror facets                         | 780 ± 3 mm         |
| Ö                         | Preliminary on-axis PSF real optical parameters | 0.07°              |
|                           | PSF (80% of FoV@ 4° off-axis)(**)               | 0.21°              |
|                           | Comora (donth x width)                          | 60 cm x 90 cm      |
| CS                        | Camera (depth x width)                          |                    |
| sti                       | Total pixel number                              | 1296               |
| cteristics                | Pixel linear size                               | 23.2 mm            |
|                           | Pixel angular size                              | 0.24°              |
| har                       | FoV   | 9.1°               |
| aC                        | Photosensors PDE                                | > 30%              |
| Camera Chara              | Sampling frequency                              | 250 MHz            |
|                           | Readout rate                                    | 0.6-1 kHz          |
|                           | Time Spread RMS                                 | < 0.25 ns          |
|                           | Telescope height pointing horizontally          | 4908 + 400 mm      |

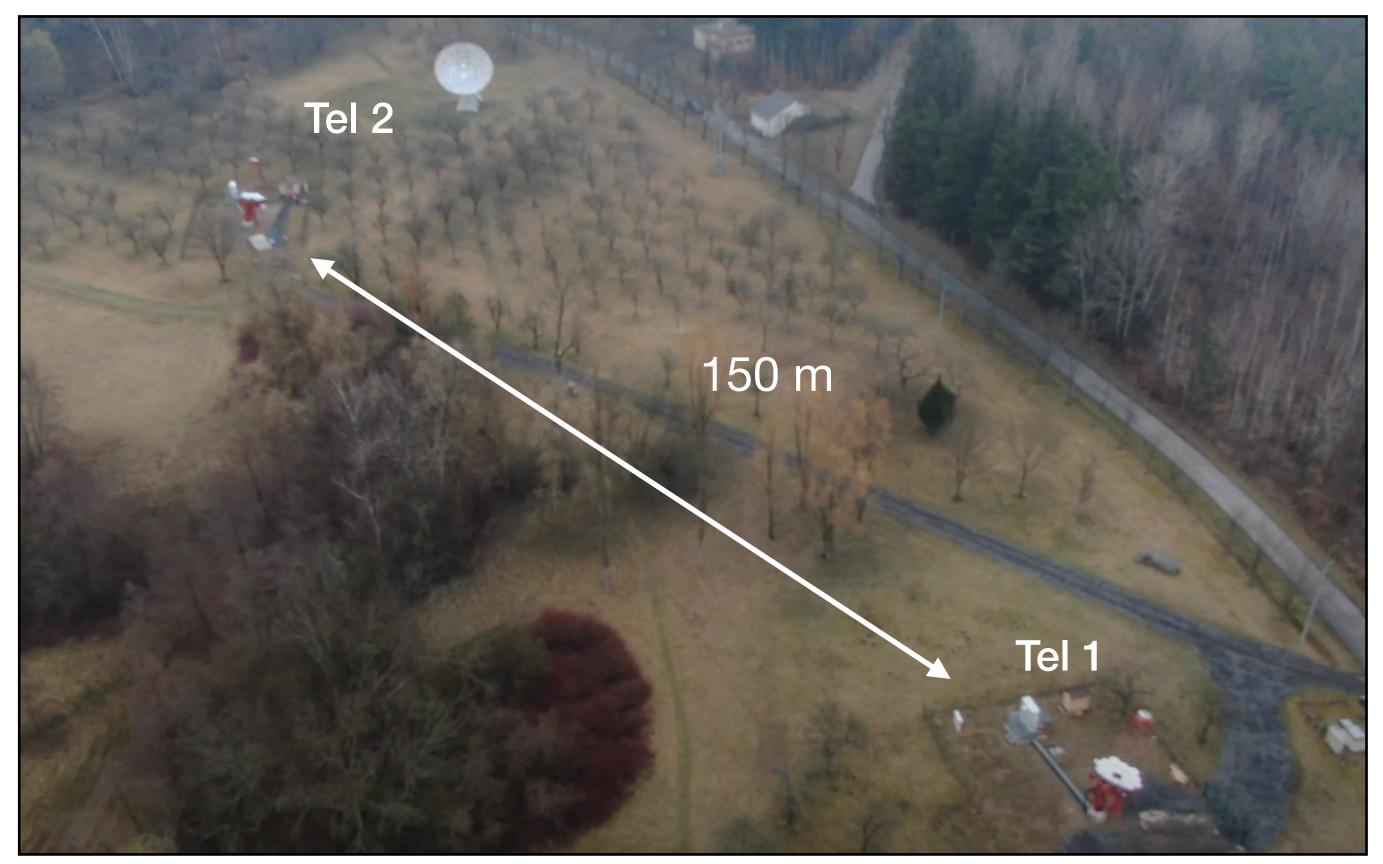
| elescope height pointing honzontally | 4906 + 400 11 |
|--------------------------------------|---------------|
| Telescope height pointing vertically | 9828 + 400 m  |





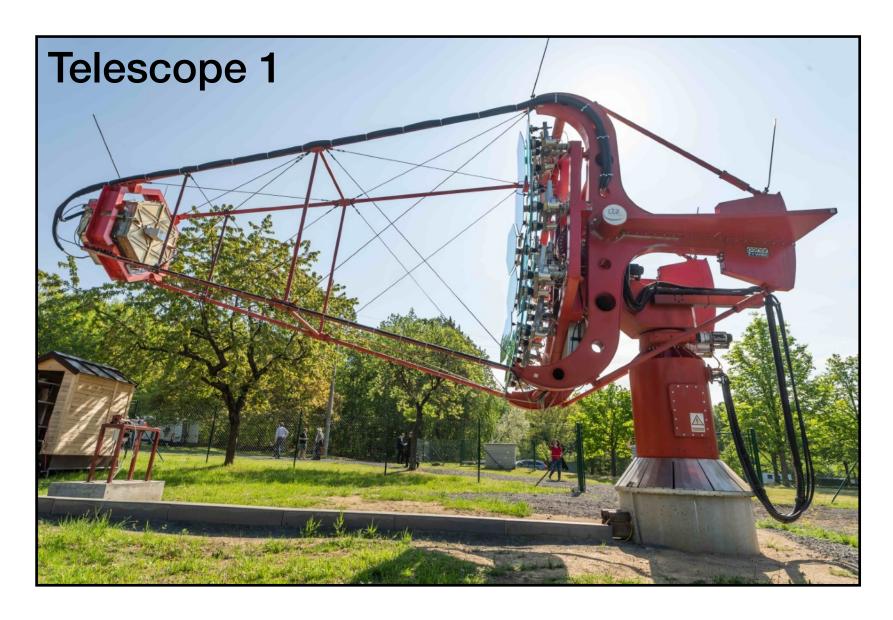
### The SST-1M stereoscopic telescope system

• 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.





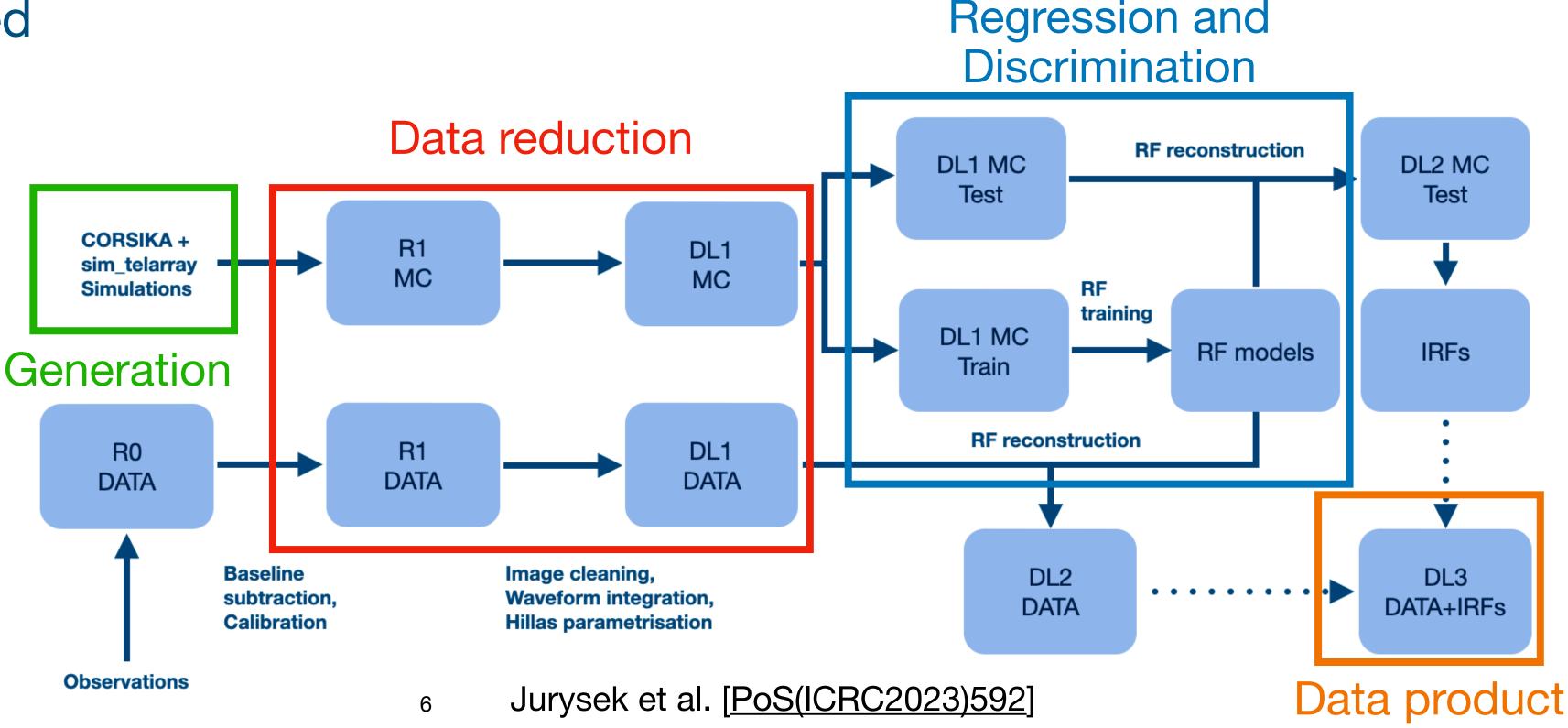






### Simulation and analysis pipelines

- Developed dedicated pipeline for the analysis of the SST-1M data: mono, stereo, MC and real data.
  - The backbone of the data analysis pipeline is <u>ctapipe</u> (maintain by CTAO) and inspired by <u>lstchain</u> (maintain by LST collaboration)
  - For calibration specific to the SST-1M telescope, methods derive from <u>digicampipe</u> (C. Alispach et al 2020 JINST 15 P11010)
  - Stereo treatment based on <u>magic-ctapipe</u>



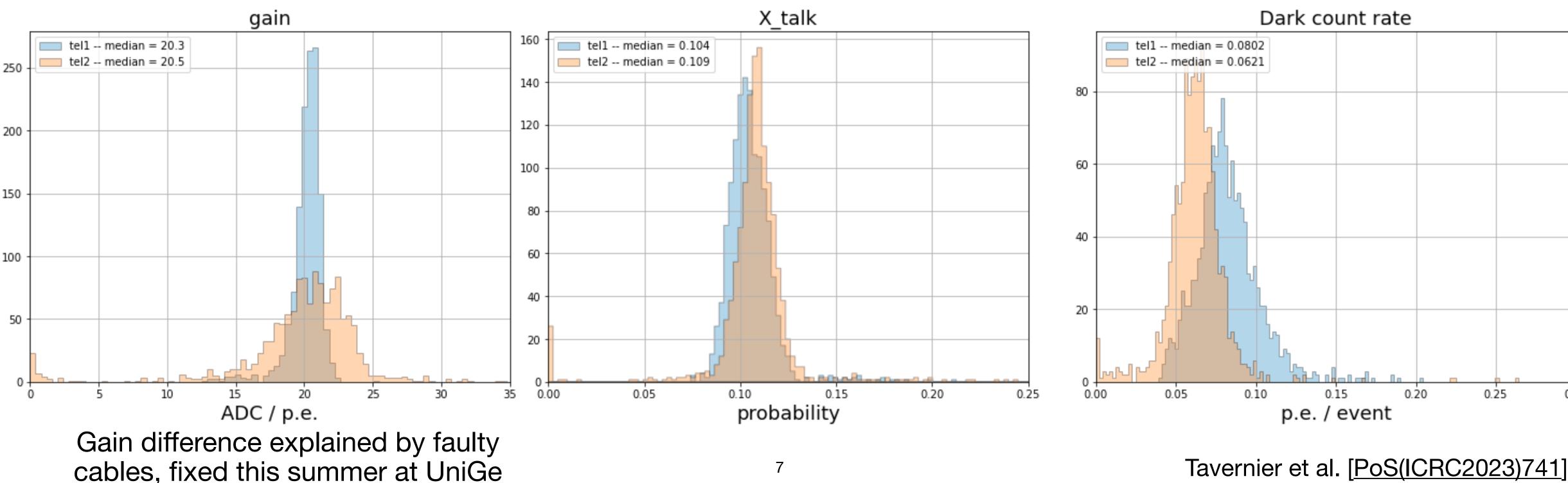




## The SST-1M commissioning

#### **Extraction of telescope parameters**

- - Mirror reflectivity
  - Entrance window transmissivity
  - Different sources of noise:
    - Night sky background
    - Electronics
    - Sensor (DCR, optical cross talk)







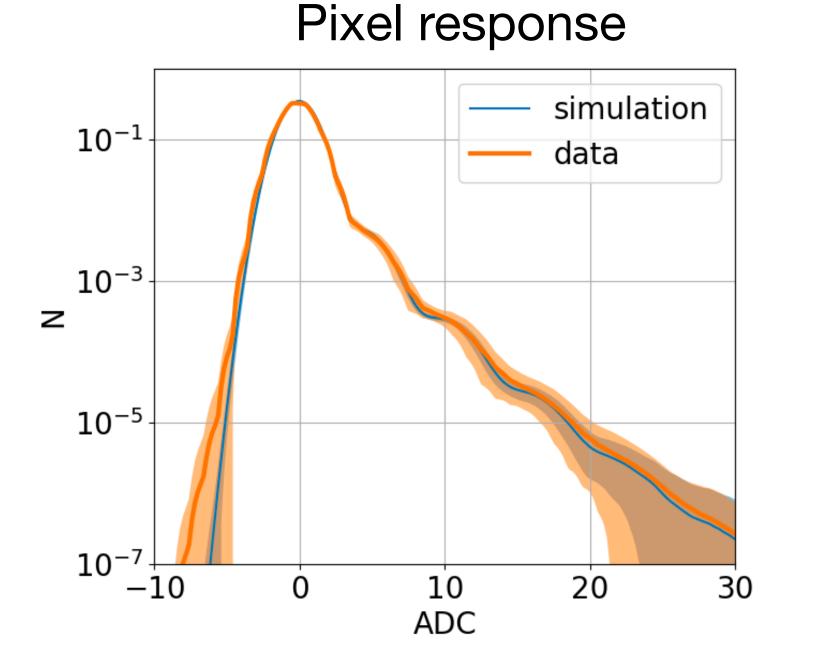
• Before running any simulation, configurations must be tuned based on commissioning results:

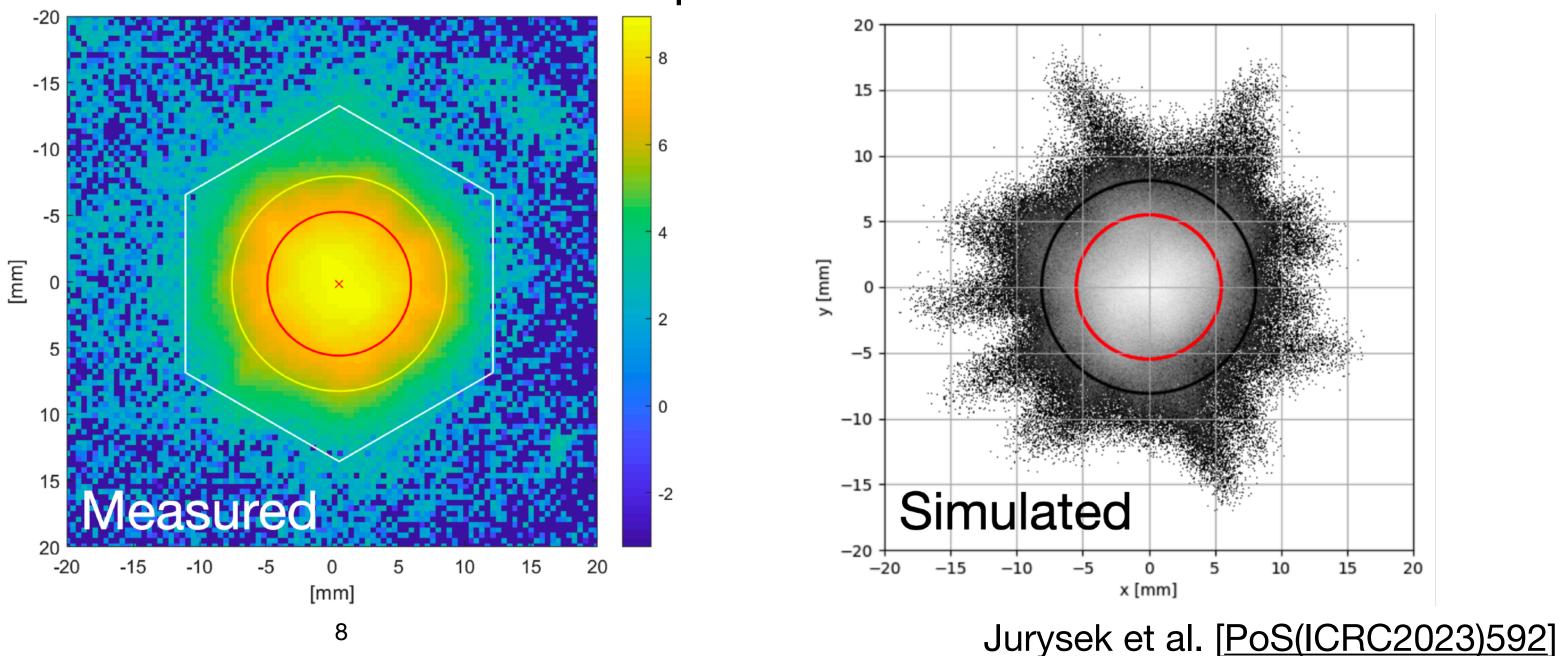


| 5 | 0.3 |    |
|---|-----|----|
| 5 | 0   | 50 |
|   |     |    |

### 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











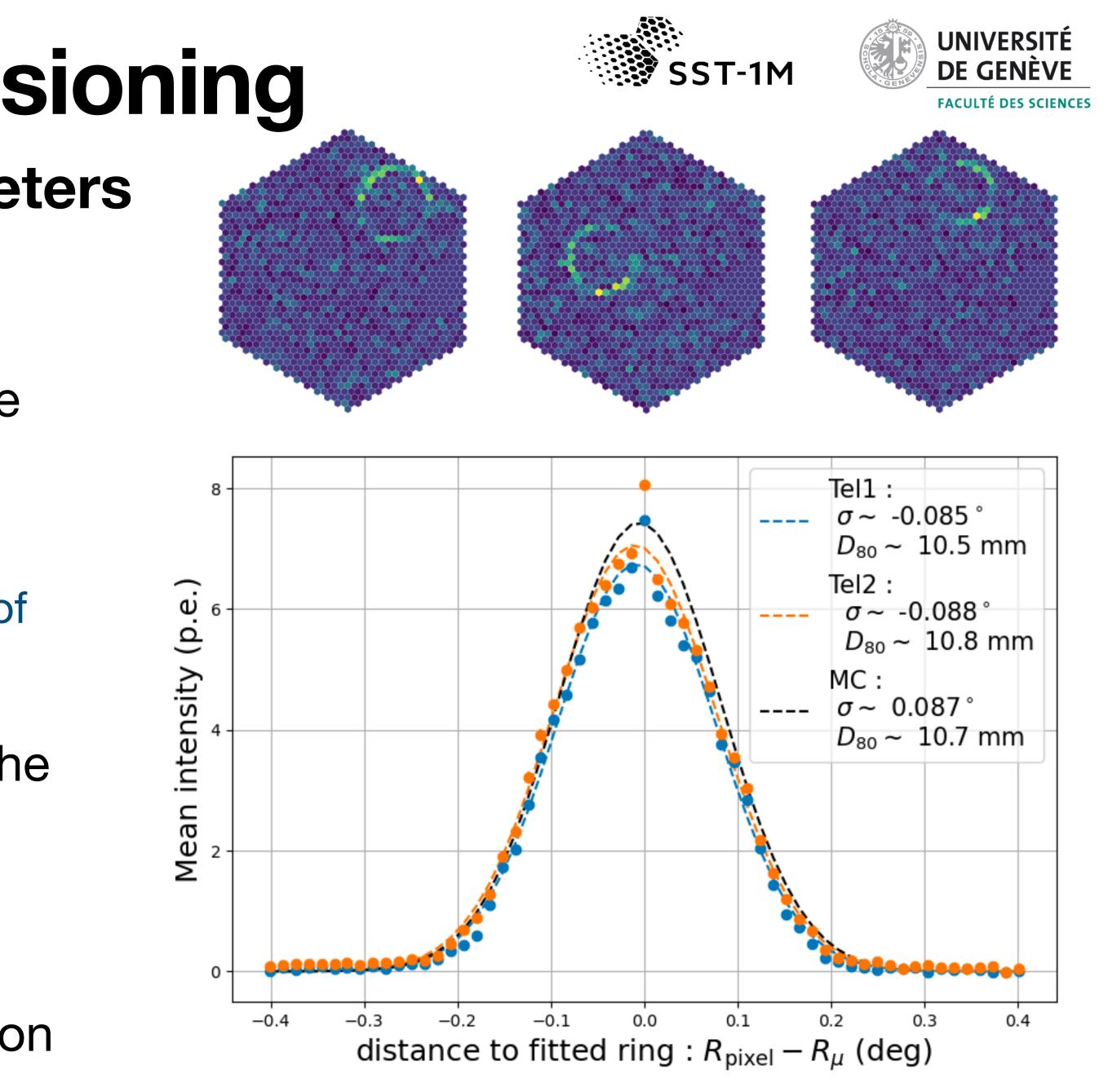
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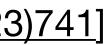
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### The SST-1M commissioning **Extraction of telescope parameters**

- 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
- Parameters extracted serve to tune the MC
  - Optical throughput
  - Optical point spread function
- Yet to be fully propagated to simulation configuration

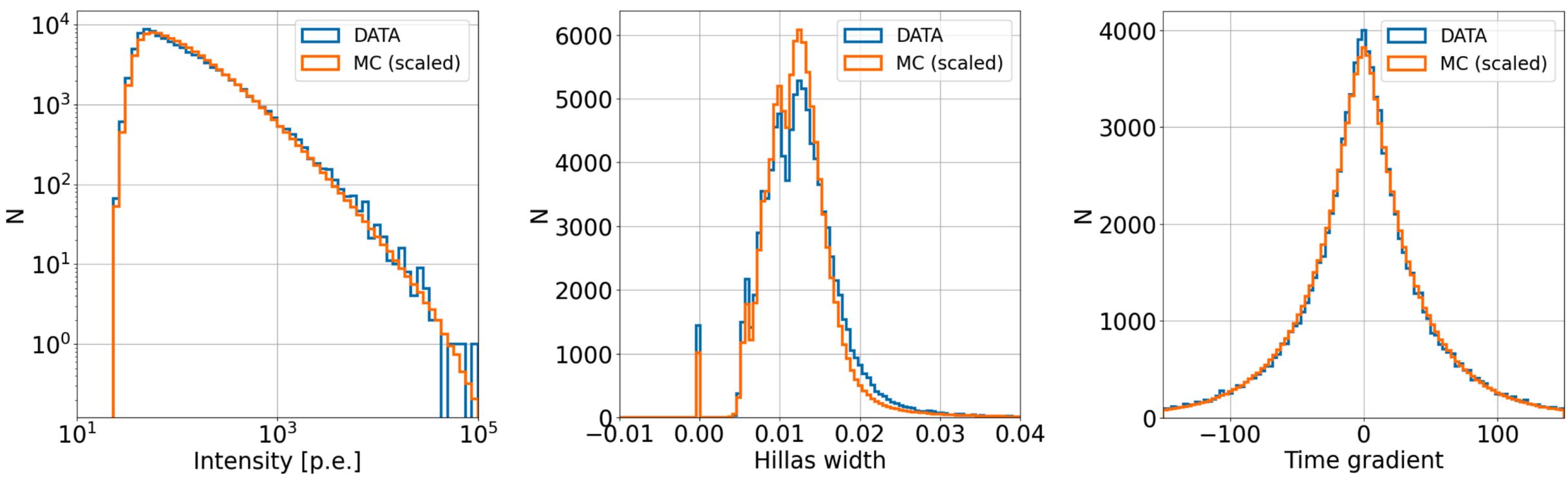


Tavernier et al. [PoS(ICRC2023)741]



### 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.



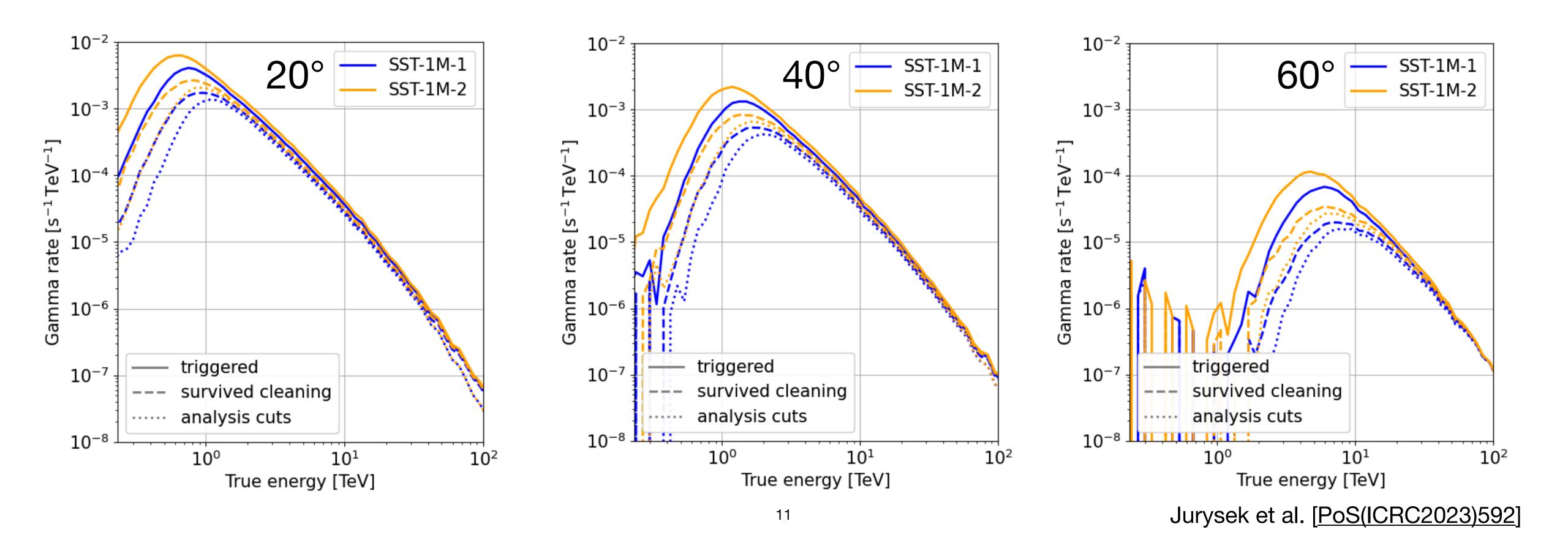






### Simulation and analysis MC tuning

with both telescopes









#### Differential rate of point-like gamma rays with Crab Nebula spectrum seen

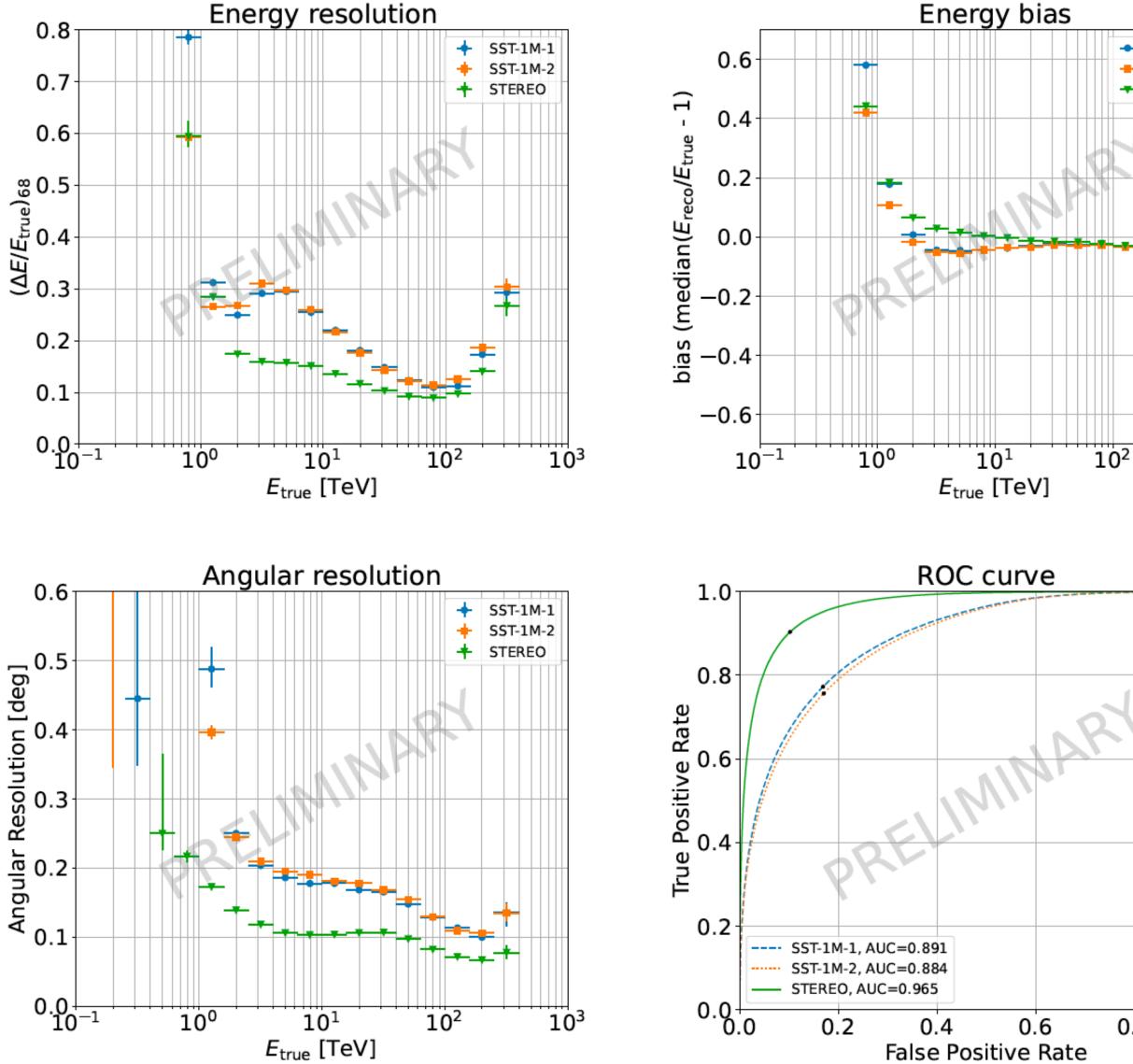
### Instrument response function

- Low altitude of the site limits the energy threshold to ~1 TeV
- Working in stereo is key to improve performance
  - Better direction reconstruction especially for "symmetric" showers
  - Better energy resolution and lower bias due to better reconstruction of the shower geometry, in particular its impact parameter
  - Better background rejection due to increase in shower features extraction



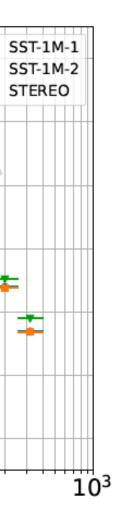


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Jurysek et al. [PoS(ICRC2023)592]



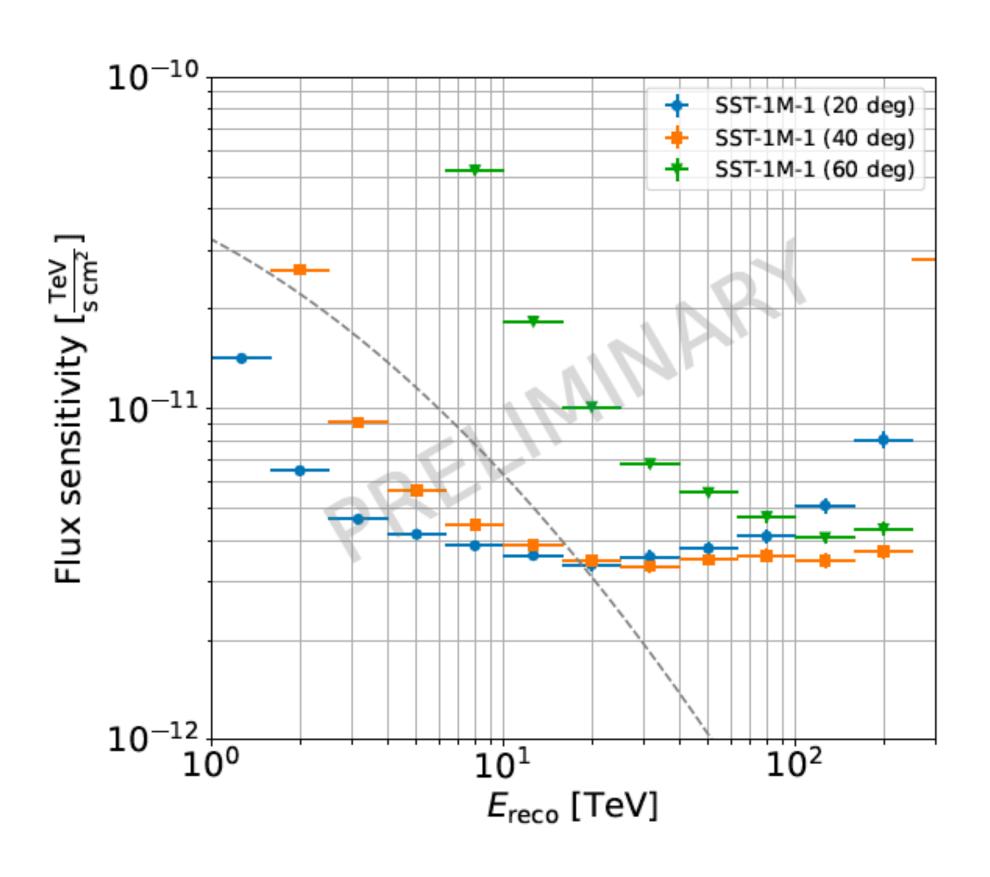






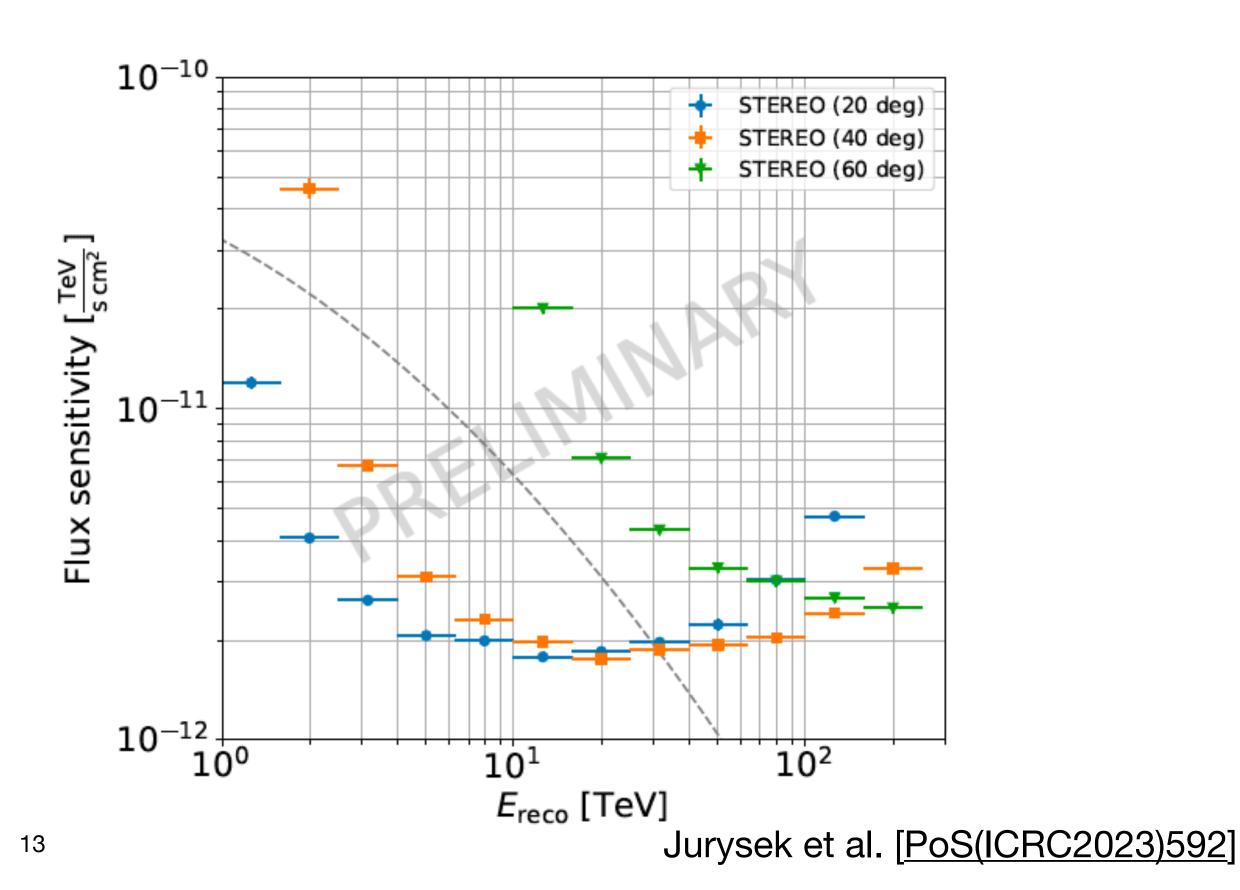
### Instrument response function **Sensitivity vs. Zenith angle**

- 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 !















## The SST-1M operation

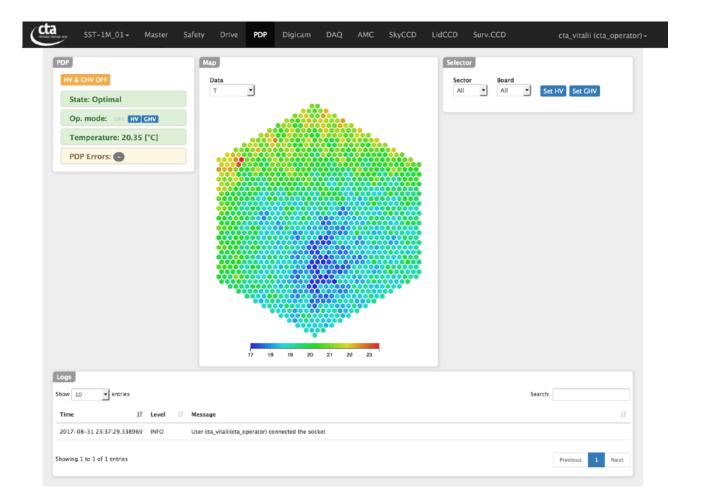
#### Remote and nearly fully automatic observations

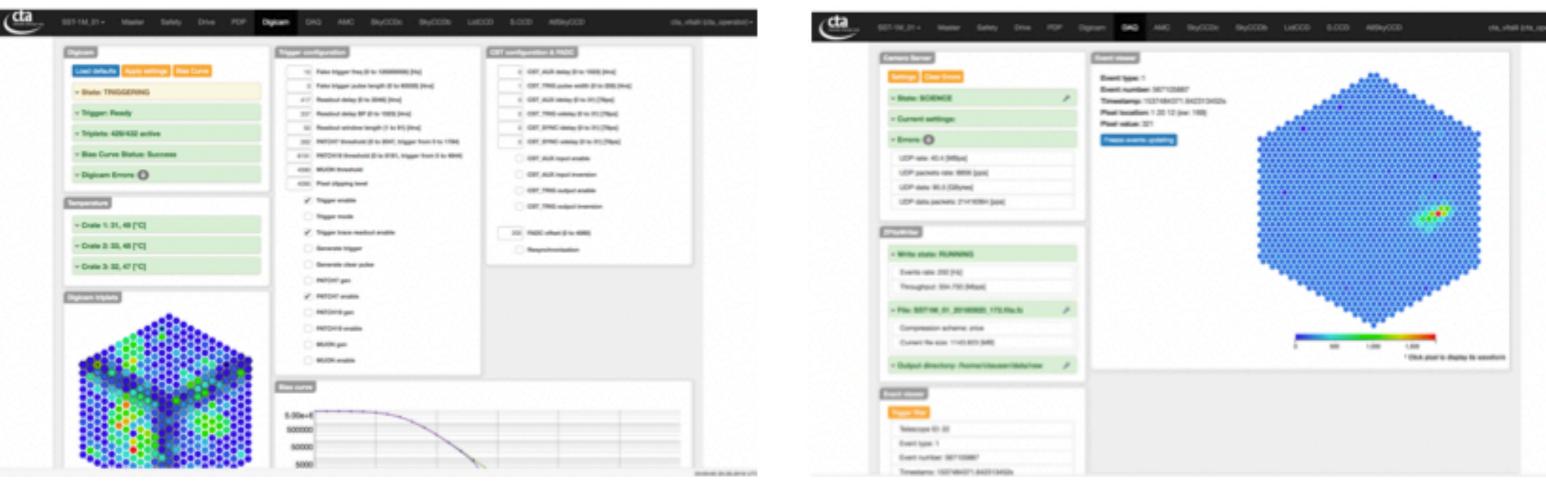
| Store Store & PANK Starts or   • State: Master:   • Master: PAUSED   • Target: • Orive PLC:   • Data 2017-10-16 18:0:00   • Data 1   • Data 2017-10-16 18:0:00   • Data 1   • Data 1   • Data <t< th=""><th>SST-1M_01 - Master Safety Drive</th><th>PDP Digicam DAQ AMC</th><th>SkyCCD LidCCD S.CCD</th><th>AllSkyCCD</th><th>cta_vitalii (cta_operator</th></t<>   | SST-1M_01 - Master Safety Drive   | PDP Digicam DAQ AMC  | SkyCCD LidCCD S.CCD | AllSkyCCD | cta_vitalii (cta_operator |  |  |  |  |
|---|-----------------------------------|----------------------|---------------------|-----------|---------------------------|--|--|--|--|
| • State: MAINTENANCE       • Drive PLC:       2017-10-16 18:00:00       STATUP       -       X         • Master: PAUSED       • Drive PLC:       2017-10-16 18:00:00       OBSERVING       Vega       X         • Pointing: N       • DAQ:-       -       X       Add command       Add command       X         • Unit display       • DAQ:-       -       •       Add command       Event       Search       Add command       X         • DAQ:-       •       *       *       *       Search       N       Add command       Event       Search       N       Add command       X       Search       N       N       N       N       N       N       N       N       N       N       N       Search       N   |                                   | Subsystems           | Schedule            |           |                           |  |  |  |  |
| • Master: PAUSED   • Master: PAUSED   • Target:   • Pointing: N   • DAQ:-   Event display   | STOP STOP & PARK Start loop       | ~ Safety PLC:        | Start               | Command   | Data                      |  |  |  |  |
| V Target:       2017-10-16 21:00:00       OBSERVING       Polaris       X         V DAQ:-       VDAQ:-       Xdd command       Xdd command         Event display       VDAQ:-       Xdd command       Xdd command         Event display       VDAQ:-       VDAQ:-       Xdd command         Event display       VDAQ:-       VDAQ:-       VDAQ:-       Xdd command         Event display       VDAQ:-       VDAQ:-       VDAQ:-       Xdd command         Event display       VDAQ:-       VDAQ:-       VDAQ:-       VDAQ:-         Event display       VDAQ:-       VDAQ:-       VDAQ:-       VDAQ:-       VDAQ:-       VDAQ:-         Event display       VDAQ:-       VDAQ:-       VDAQ:-       VDAQ:-       VDAQ:  | ~ State: MAINTENANCE              | ~ Drive PLC:         | 2017-10-16 19:00:00 | STARTUP   | - 🛛                       |  |  |  |  |
| Pointing: N   DAQ: -     Event diaplay     LidCCD     Shor 10 entries   Search:   | ✓ Master: PAUSED                  |                      | 2017-10-16 19:15:00 | OBSERVING | Vega 🗙                    |  |  |  |  |
| V DAQ: -       Sh01b0Wh       -       X         Event display       Add command       Add command         LidCCD       Image: Command Command       Sauch: Command       Image: Command Command         Show 10 = entries       Sauch: Command       Image: Command Com | v Target:                         |                      | 2017-10-16 21:00:00 | OBSERVING | Polaris X                 |  |  |  |  |
| Event display         LdCCD         LdCCD         Show 10 • entries         Saarch:         Time       IF         Level       Message         2017-11-       NFO         Nethod 'removeScheduleitern' had finished, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00], not 0         2017-11-       NFO         NFO       Method 'removeScheduleitern' is called for execution, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00]         2017-11-       NFO         User cta_vitali(cta_operator) disconnected the socket         2017-11-       NFO         User cta_vitali(cta_operator) disconnected the socket   | <ul> <li>✓ Pointing: N</li> </ul> |                      | 2017-10-16 22:00:00 | SHUTDOWN  | - 🛛                       |  |  |  |  |
| LdCCD         Show 10 ; entries       Search:         Time       IF       Level       Message         2017-11-       NFO       Method 'removeScheduleitem' had finished, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00'], ret 0       2017-11-         2017-11-       NFO       Method 'removeScheduleitem' is called for execution, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00']       ret 0         2017-11-       NFO       Method 'removeScheduleitem' is called for execution, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00']       2017-11-         2017-11-       NFO       User cta_vitali(cta_operator) disconnected the socket       2017-11-         2017-11-       NFO       User cta_vitali(cta_operator) disconnected the socket       2017-11-  | ~ DAQ: -                          |                      | Add command         |           | _                         |  |  |  |  |
| 2017-11-<br>02 22:14:58.186563       INFO       Method 'removeScheduleitem' had finished, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00'], ret 0         2017-11-<br>02 22:14:58.166963       INFO       Method 'removeScheduleitem' is called for execution, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00']         2017-11-<br>02 22:14:58.166963       INFO       User cta_vitali(cta_operator) disconnected the socket         02 22:14:51.175671       INFO       User cta_vitali(cta_operator) disconnected the socket   | Logs                              |                      |                     | Sea       | rch:                      |  |  |  |  |
| 02 22:14:58.196563         Method 'removeScheduleitem' is called for execution, subsystem 'master', user cta_vitali(cta_operator), arguments ['2018-10-30 15:36:00']           02 22:14:58.166963         User cta_vitali(cta_operator) disconnected the socket           02 22:14:51.175671         INFO   | Time ↓₹ Level ↓↑ Message          |                      |                     |           | 11                        |  |  |  |  |
| 02 22:14:58.166963<br>2017-11- INFO User cta_vitali(cta_operator) disconnected the socket<br>02 22:14:51.175671   |                                   |                      |                     |           |                           |  |  |  |  |
| 02 22:14:51.175671  |                                   |                      |                     |           |                           |  |  |  |  |
| Showing 1 to 3 of 3 entries 1 Next  |                                   | connected the sockst |                     |           |                           |  |  |  |  |
|   | Showing 1 to 3 of 3 entries       |                      |                     |           | Previous 1 Next           |  |  |  |  |

#### SST-1M master controller

| (cta         | SST-1M_01 - Ma       | ster Safety | Drive | PDP     | Digicam                       | DAQ                            | AMC                      | SkyCCD                      | LidCCD        | S.CCD          | AllSkyCC    | a;        | cta_vit      |
|--------------|----------------------|-------------|-------|---------|-------------------------------|--------------------------------|--------------------------|-----------------------------|---------------|----------------|-------------|-----------|--------------|
| SafetyPLC    |                      |             |       | Control | l.                            |                                |                          |                             |               |                |             |           |              |
| STOP         | TOP & PARK           |             |       | Clear   | Errors Pa                     | rk telescope                   | Set NTP                  | server Set                  | time Came     | ra settings    |             |           |              |
| State: N     | IAINTENANCE          |             | ×     | Telemet | ny .                          |                                |                          |                             |               |                |             |           |              |
| Mode: L      | OCAL                 |             | ×     | Tim     | e: 15096608                   | 60930 ms                       |                          |                             |               |                |             |           |              |
| Severity     | NON_CRITICAL_EF      | ROR         |       | Cab     | inet temper                   | atures: 23.9                   | 15.7 41.5 0              | .0                          |               |                |             |           |              |
| State: lo    | lle                  |             |       |         |                               |                                |                          | Itside temp.:               |               |                |             |           |              |
| Power:       |                      | aCCD UPS    | ×     |         | ler coolant:<br>ler housing:  |                                | P <sub>int</sub> = 0.0 M | IPa, P <sub>ext</sub> = 0.0 | ) MPa, Q = 0. | 1 l/m, σ = 0.0 | MΩ*cm or µS | /cm       |              |
| - SPLC E     | rrors: 0             |             |       |         | sure: 499.4<br>nidity: 33.6 3 | 499.4<br>35.1 32.2 32          | .3 29.2                  |                             |               |                |             |           |              |
| Drive subsys | item                 |             |       |         |                               | e: 12.0 11.5<br>ints: -3.6 -3. |                          | 2.0 13.0 13.8               | 12.8 10.6 10  | 4 11.7         |             |           |              |
| Telesco      | pe: Parked, Locked   |             |       |         | inet dew po                   |                                |                          |                             |               |                |             |           |              |
| State: lo    | lle                  |             |       | Firm    | ware: 1719                    |                                |                          |                             |               |                |             |           |              |
| Drive Pl     | LC status: Relay Off |             |       | Plots   |                               |                                |                          |                             |               |                |             |           |              |
| Azimuth      | n switch: 🚺 🕫 🤫      |             |       |         | -3.4 -                        |                                |                          |                             |               |                |             | Thu, 02 N | lov 2017 22: |
| Elevatio     | on switch: 💶 15 🛷    |             |       |         | ~_]                           |                                |                          |                             |               |                | F           |           |              |
| Parking      | switch: Active       |             |       |         | -3.5                          |                                |                          |                             |               |                |             |           |              |
| Power:       |                      |             | ×     |         | -3.6                          |                                |                          |                             |               |                |             |           |              |
| ~ Drivesy    | stem Errors: 🚺       |             |       |         |                               |                                |                          |                             |               |                |             |           |              |
| Camera sub   | system               |             |       |         | -3.7                          |                                |                          |                             |               |                |             |           | T            |
| State: k     |                      |             | ×     |         | -3.8                          |                                |                          |                             |               |                |             |           |              |
| Lid: Clo     |                      |             | ×     |         | -3.9                          |                                |                          |                             |               |                |             |           |              |
| Chiller:     | StandBy              |             | ×     |         | -4.0                          |                                |                          |                             | /             |                |             |           |              |
| Air Drye     | r: Force OFF         |             | ×     |         |                               |                                |                          |                             |               |                |             |           |              |
| Pointing     | LEDs: Off            |             | ×     |         | -4.1 30                       | 35                             | 40                       | :45                         | :50           | :55 23         | :14 :05     | :10       | :15          |

#### Safety PLC subsystem





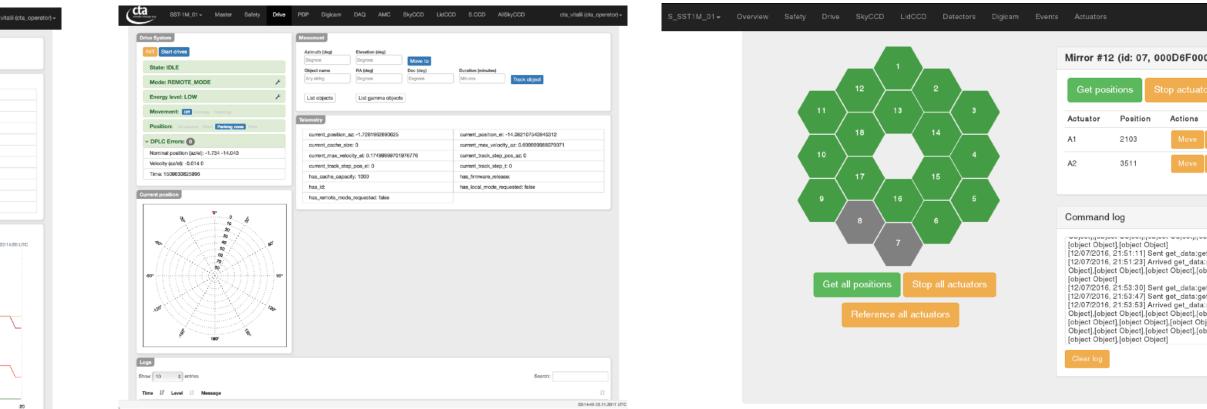
#### Photo detector plane control and monitoring

#### Digital readout configuration









#### Drive system control

#### Active mirror control

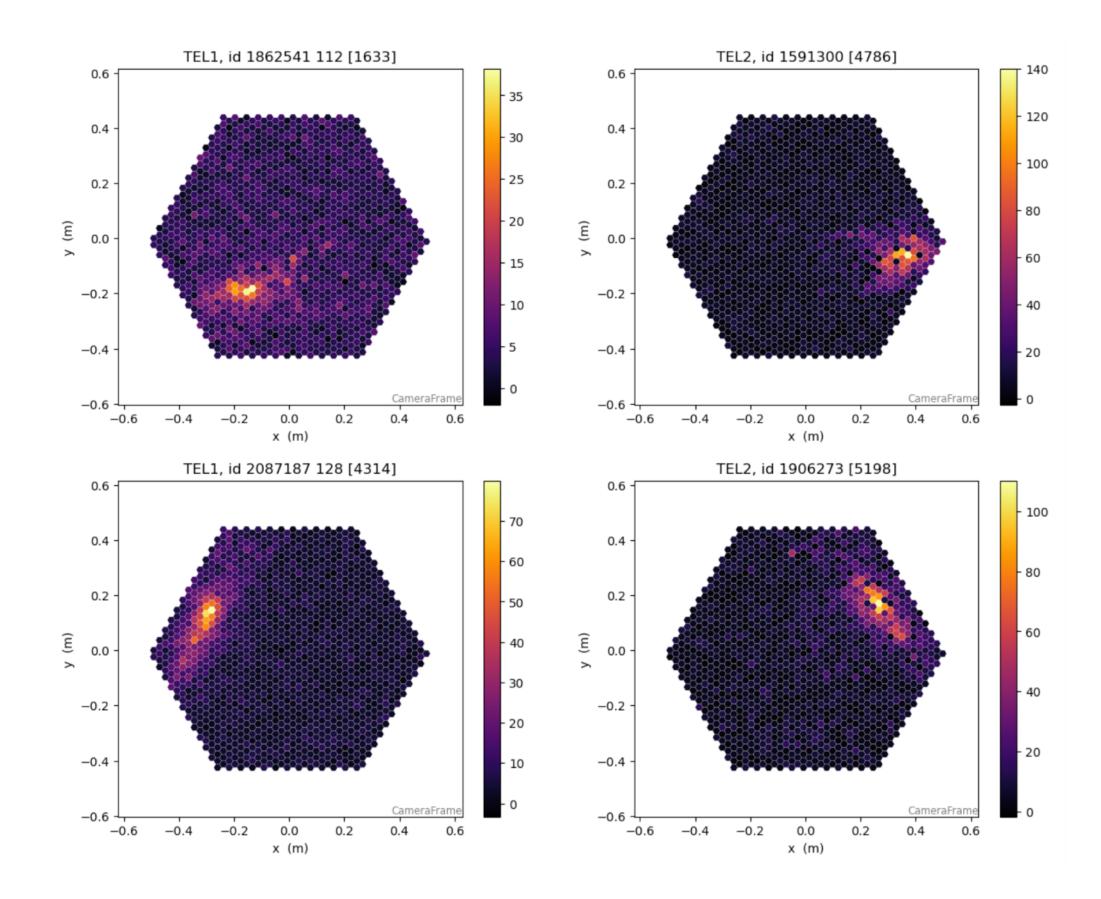
#### DAQ control and monitoring

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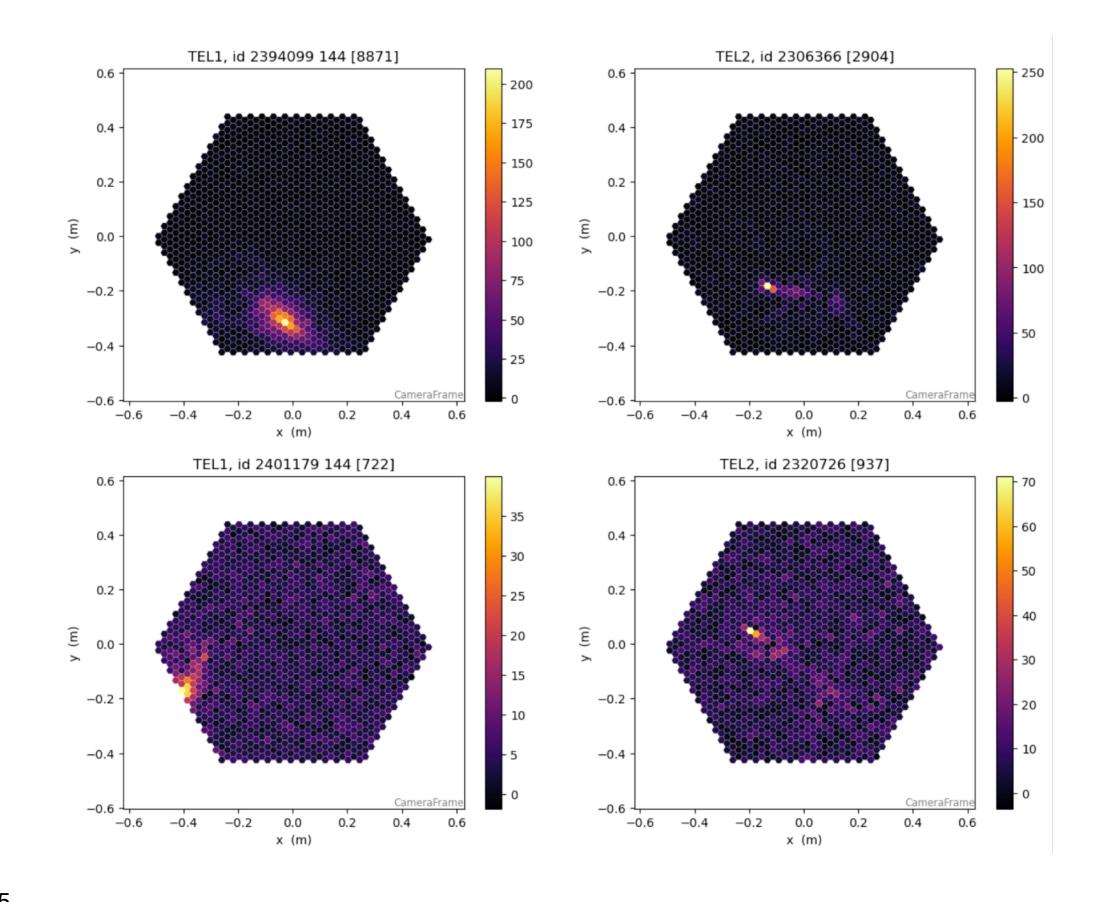
### **Stereo observations**

- commissioned
- Stereo trigger managed by Software Array Trigger (SWAT), soon deployed with ACS



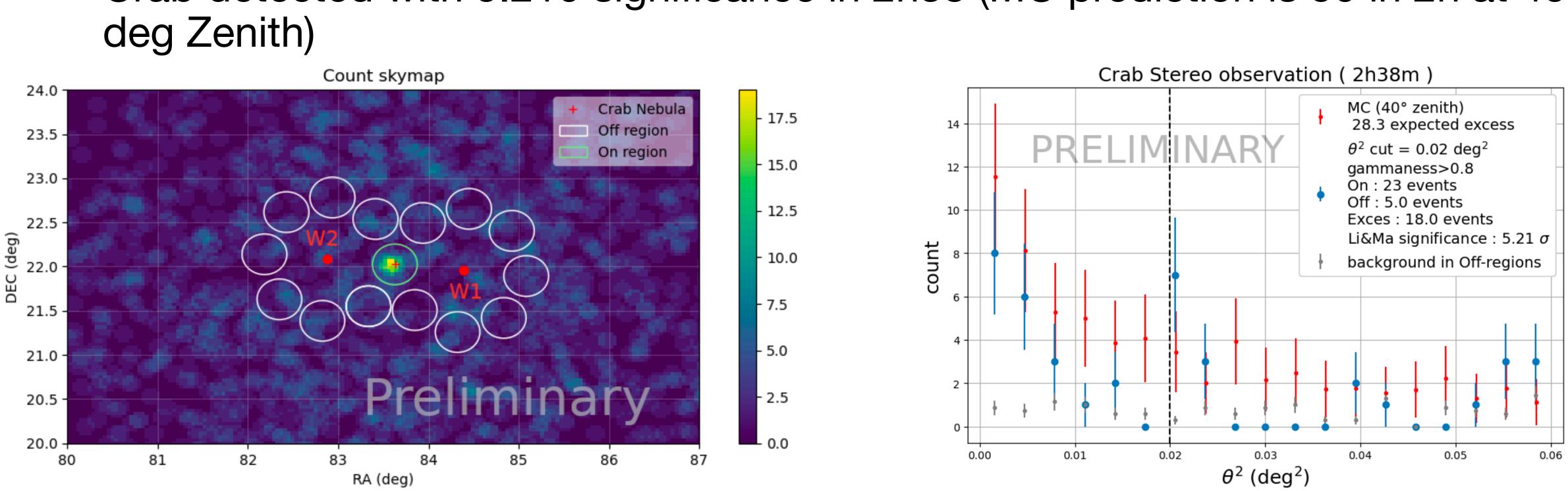


## Both cameras connected to White Rabbit switch for synchronisation, system still being



### **Observations Stereoscopic observation**

- White rabbit was not fully commissioned at the time of data taking, coincidences derived from time clustering of events
- Crab stereo data set acquired with two wobbles configuration
- deg Zenith)







# • Crab detected with 5.21 $\sigma$ significance in 2h38 (MC prediction is 5 $\sigma$ in 2h at 40

Tavernier et al. [PoS(ICRC2023)741]



### **Conclusion and Prospects**

- Finalise the commissioning for the stereo observations
  - Telescope description
  - Synchronisation
  - Fully remote and automatised telescope control
- Continue with scientific program:
  - Crab observation
  - Monitoring of the brightest blazars
    - Recent 5σ detection of extragalactic blazar 1ES1959+650
    - Accumulating data for Mrk 421, 501
  - view
- The collaboration is exploring new possibilities for observation sites:
  - Two of them can only do so much ...
  - ... but when complementing another Cherenkov of CR observatory, they are a great asset.







• The SST-1M concept has already proven to meet the performance requirements it was designed for

Exploring advanced triggering and measurements methods exploiting the fully digital readout and large field of

