cherenkov telescope array

# The Small Size Telescopes for the Cherenkov Telescope Array

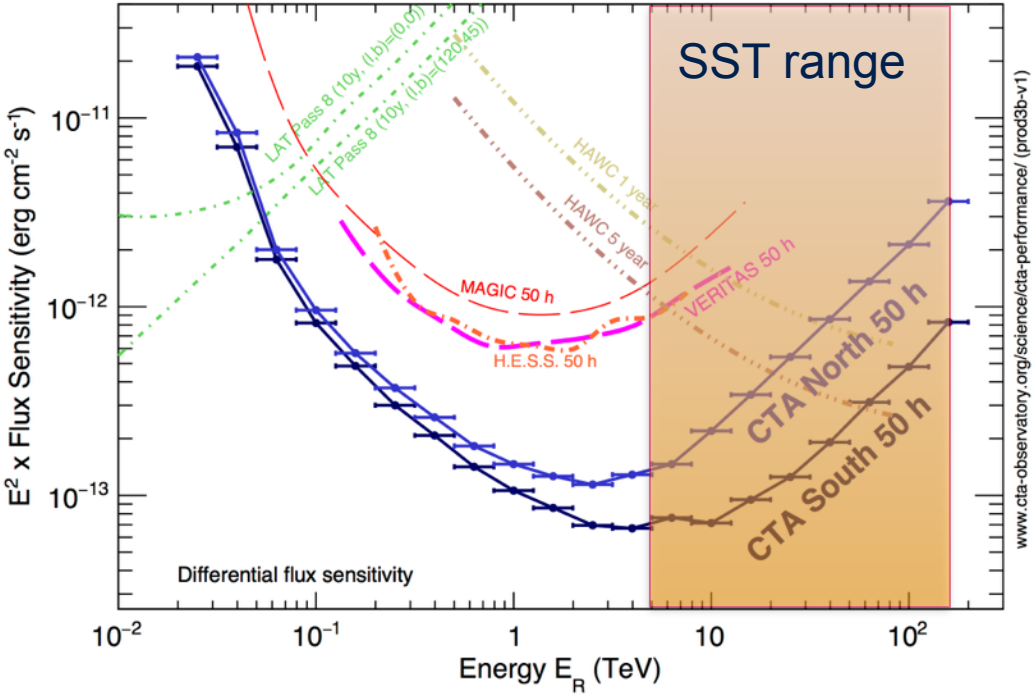
10th International workshop of Ring Imaging Cherenkov Detectors
Moscow, 29/07/2018 to 4/08/2018

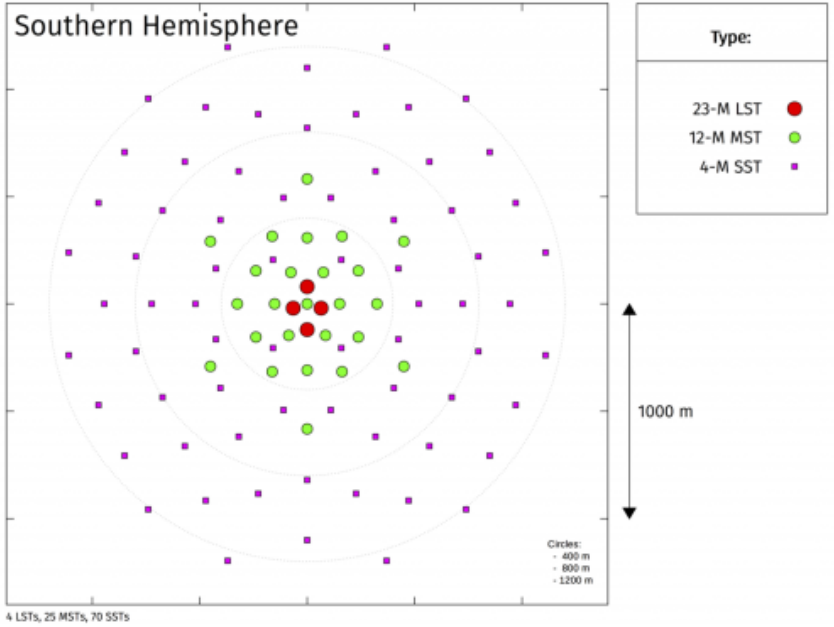
**Matthieu HELLER for the CTA consortium**

# Outline

- Why do we need Small Size Telescopes ?
- SSTs designs
  - Structure
  - Optics
  - Camera
- SSTs performance
- First light and commissioning

# Why do we need Small Size Telescopes

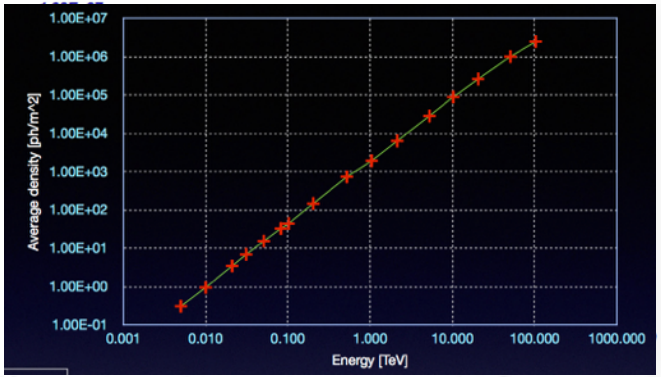


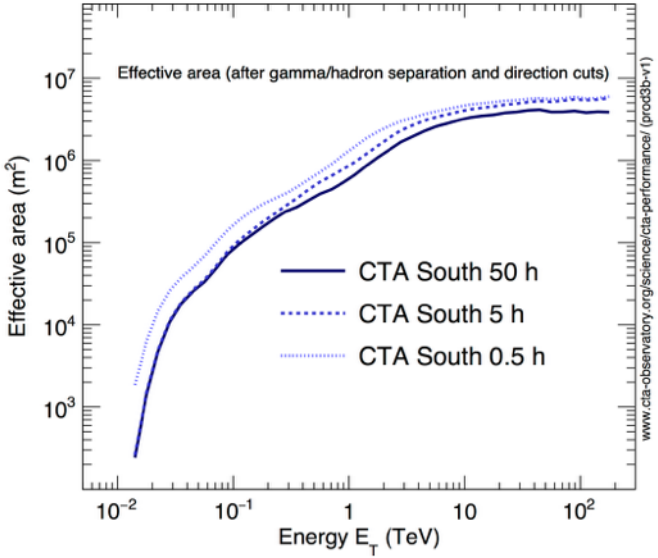




How does that translate into a telescope array: Light collection area, number of telescopes, inter telescope spacing

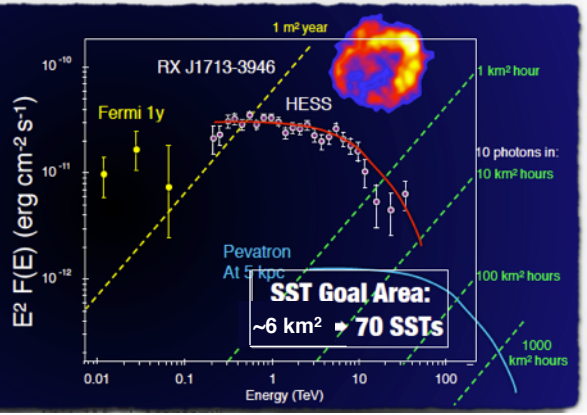
# Why do we need Small Size Telescopes

High Energy
↓
High photon density
↓
Small Dish area ~ 4m



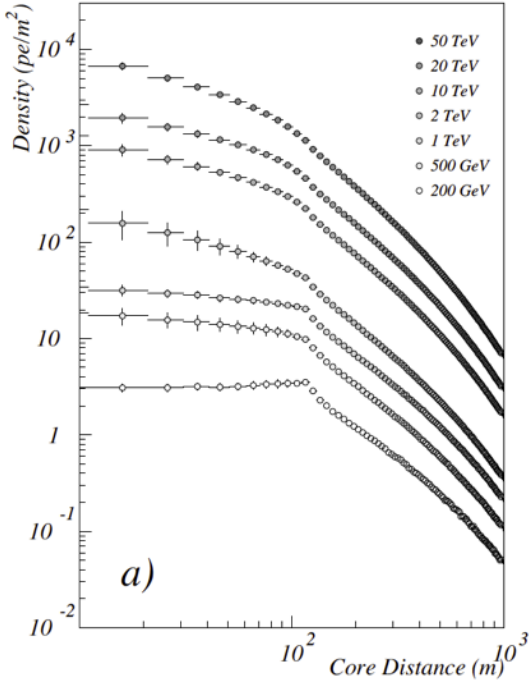




Shower Footprint
↓
Array Collection Area
↓
Number of Telescopes

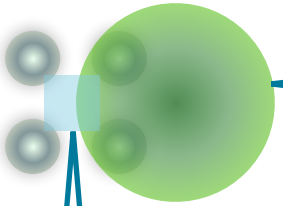



- Small telescope dish ~4 m
- Need to cover about 4.5 km² to meet SST goals, but how ?

# Why do we need Small Size Telescopes

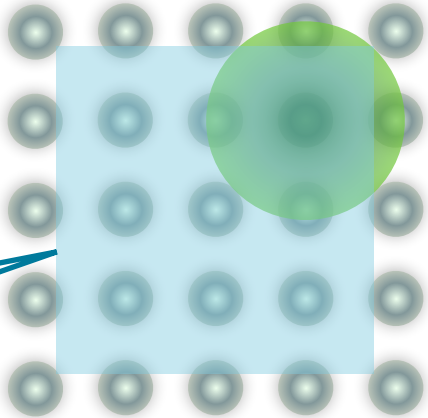



High energy showers are visible at large distances



***Light pool radius***
***R ≈ 100-150m***
***≈ typical telescope Spacing***

***Sweet spot for best triggering***
***& reconstruction…***
***most shower miss it!***



- ✓ ***Large detection Area***
- ✓ ***More Images per shower***
- ✓ ***Lower trigger threshold***

70 SST telescopes to cover ~4.5 km$^2$
Spacing of ~250 m

# The SST projects design

The ASTRI project

Astrofisica con Specchi a Tecnologia Replicante Italiana

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

MIUR

NORTH-WEST UNIVERSITY YUNIBESITI YA BOKONE-BOPHIRIMA NOORDWES-UNIVERSITEIT

Universidade de São Paulo

The Gate CHEC Telescope (GCT) project

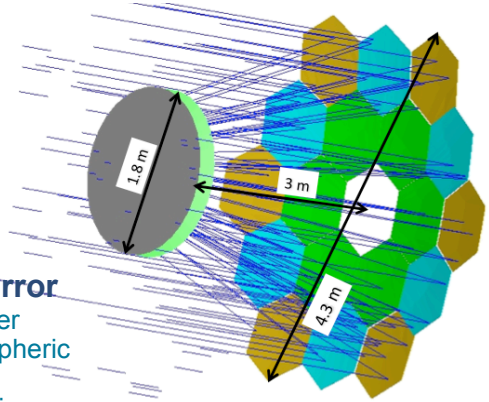
The SST-1M project

# The ASTRI structure and optics

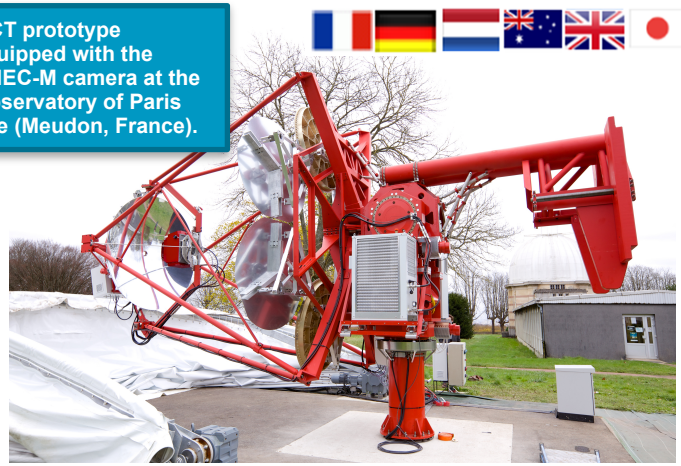

- **Telescope structure**
  - Alt-azimuthal mount
  - Height of the Telescope:
    - pointing horizontally: 7.5 m
    - pointing vertically: 8.6 m
  - Total mass: 19 t
  - Encoder precision: 2 arcsec
  - Tracking precision: < 0.1°
  - Motors & drivers: SEW
  - Control PLCs: Beckhoff

The prototype is placed at 1725 meters on the Etna volcano @ INAF-Catania mountain station in Serra La Nave

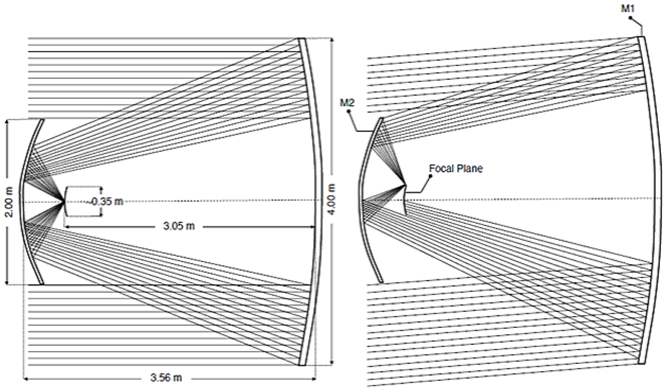
- **Schwarschild-Couder design:**
  - Average effective mirror area: **5 m²** (incl. mirror reflectivity and shadowing)
  - **FOV: 10.5°**
  - PSF @ 100% FoV diameter: 0.19°
  - **Primary mirror:**
    - 4.3 m diameter
    - 18 hexagonal aspherical panels arranged in three concentric rings
    - Cold slumping
    - Al+$SiO_2$ coating (90 % reflectivity)
  - **Secondary mirror**
    - 1.8 m diameter
    - Monolithic aspheric
    - Hot slumping
    - Al+SiO2 coating



# The GCT structure and optics



GCT prototype equipped with the CHEC-M camera at the Observatory of Paris site (Meudon, France).




- **4 m dual-mirror telescope structure**
  - **Compact** (4.1 m x 5.7 m x 8.5 m ) and light structure ( **< 11 t**)
  - Two torque motors per axis and same worm gear assembly used for elevation and azimuth axes providing **symmetry in the alt-az mount**
  - **Focal length: 2.28 m, f/D: 0.57**

- **Schwarzschild-Couder optical design**, never built before the advent of CTA, suitable for gamma-ray astronomy with the following advantages:
  - **Large FoV (>8°)**, **good angular resolution** for VHE over full FoV
  - Average effective mirror area of **4.9 m$^2$** (incl. mirror reflectivity and shadowing)
  - Reduction of the focal length  physical pixel size compact camera and structure
  - Cost-optimisation and upgradability possibilities (SiPM technology evolving rapidly)

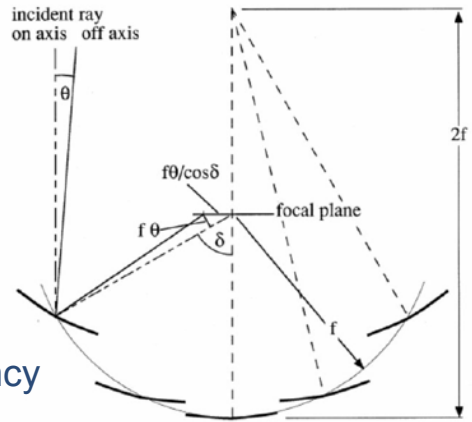
  - **GCT Primary mirror Ø 4m**
    - Tessellated in **6 identical panels**
    - Lightweight aspheric **Aluminium** mirrors (89% reflectivity, scattering to be improved with future generation)
    - Each panel is held at three points by an active mirror control system (AMC) made of 1 fixed point and 2 actuators

  - **GCT Secondary mirror Ø 2m**
    - Lightweight aspheric **Aluminium mirror** (87% reflectivity, scattering to be improved with future generation)
    - Segmented for manufacturing purposes, its six high-precision segments are bolted together and behave like a monolithic mirror

# The SST-1M structure and optics

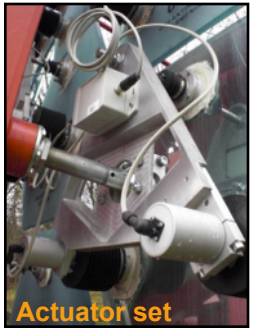

SST-1M telescope prototype at IFJ, Krakow, Poland

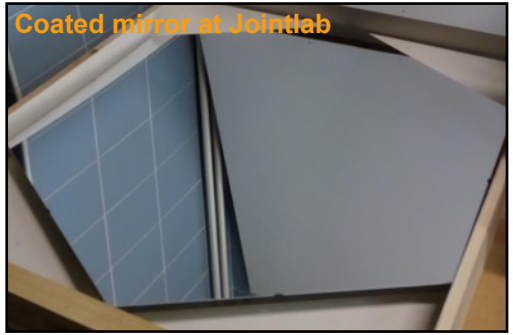
- 4 m single mirror telescope
  - Lightweight design 8.8 t
  - 5.6 m focal length, f/D = 5.6 m
  - Bearing, limit switches, slew drive and motors identical to MST structure



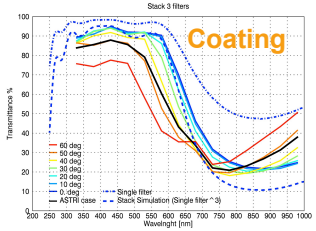

- Davies-Cotton optical design:
  - Proven design in IACT
  - Simple optics and lower optical efficiency degradation

- Mirror dish:
  - 18 hexagonal facets for an average effective mirror area of 6.46 $m^2$ (incl. mirror reflectivity and shadowing)
  - Glass substrate
  - Al-$SiO_2$ coating providing > 90% reflectivity
  - AMC system composed of 3 actuators

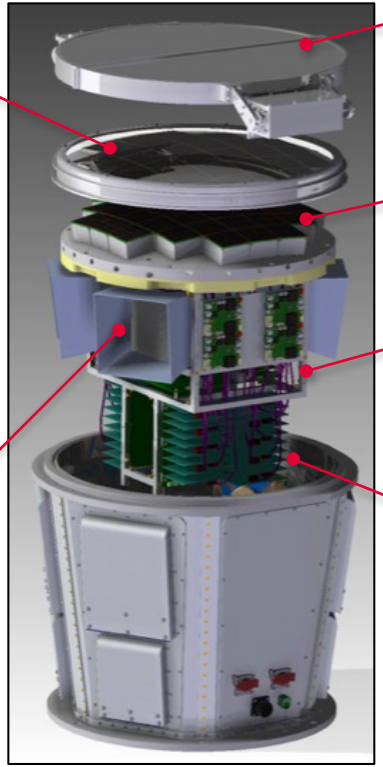

Actuator set


Coated mirror at Jointlab

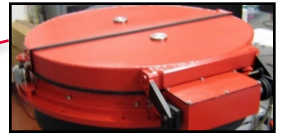
# The ASTRI camera

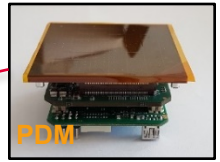







LID







Voltage distribution board

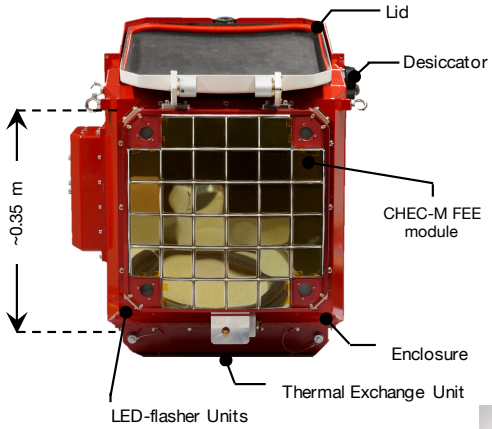
- **Front Window**
  - Stack of 3 multilayers filters to reject the red part of the NSB.
- **Thermal Control System**
  - All internal → no chiller
  - TEC based, heat pipes, sink, fans → Active control
  - ***Low power consumption < 0.5 kW***
- **Photon Detection Module**
  - SiPM → Hamamatsu LCT5 7x7mm
- **Front End Electronics**
  - Based on signal shaping not sampling
  - High gain and low gain channels
  - ***Low power consumption (0.3 W/chip)***
  - ***Low data production (0.05 Gb/s)***
- **Back End Electronics**
  - monolithic board to manage PDMs, camera trigger & ancillary devices
- **Power Supply Distribution**
  - External power supply 24V
  - Voltage distribution board → modular system to provide independent and adjustable power supply to PDM

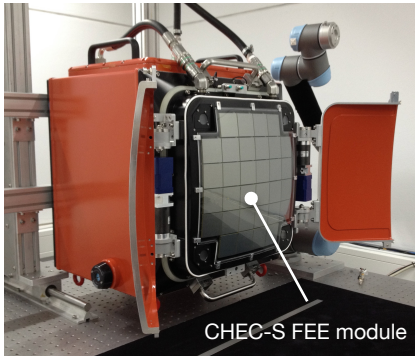
# The CHEC-M and S cameras

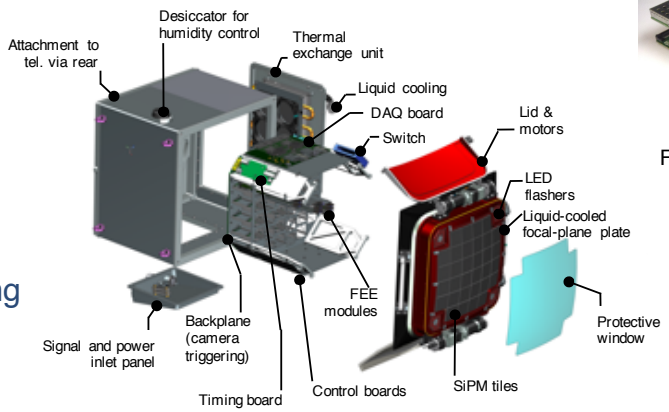
- **CHEC: Compact High Energy Camera**
  - UK, Germany, Japan, Netherlands, Australia, US
  - Prototypes:
    - CHEC-M based on MAPMs
    - CHEC-S based on SiPMs (Very close to final design)

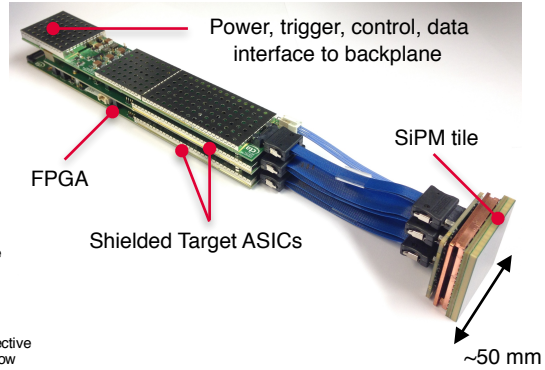
- **Philosophy**
  - High performance at low cost
    - 135 - 150 kE
    - Efficient trigger scheme, full waveforms for all pixels
  - Compatible with GCT and ASTRI

- **Key Features**
  - Compact, low power, light
    - ~0.4 m x 0.4 m x 0.4 m, 0.5 – 1 kW, ~50 kg
  - 2048 pixels (6 mm x 6 mm, 0.15°)
  - Digitisation via Target-C ASICs
    - 12 bits @1 GSa/s
    - Flexible readout window (nominally ~100 ns)
  - Triggering via Target-5TEA ASICs
  - ~1 kHz ADCs for integrated pointing monitoring
  - Integrated LED flasher calibration
  - Data: 10 Gbps fibre, Control: 1 Gbps fibre
  - White rabbit timing

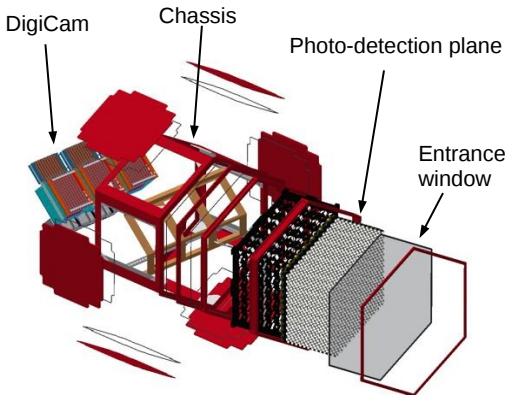


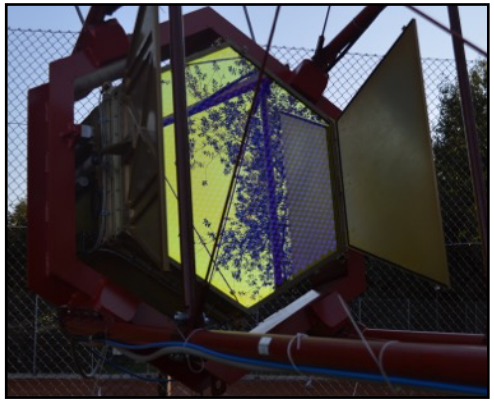



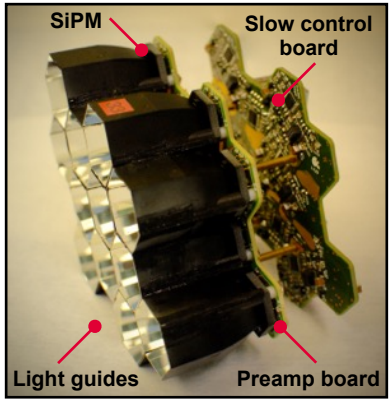



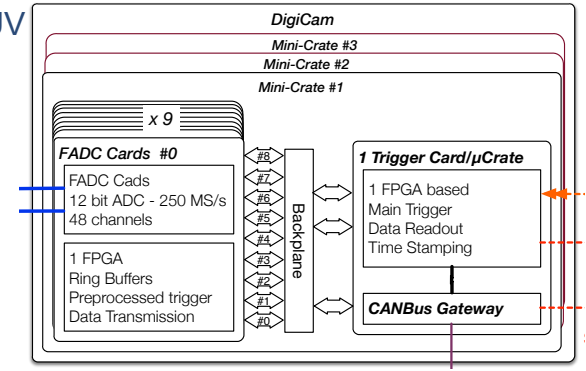
# The SST-1M camera



- **General**
  - Separation of Photo Detector Plane and Digital Readout
    - Separate mechanics and power supplies
    - Analogue signals
    - DC coupling for Night Sky Background monitoring
  - Window with AR coating and low pass filter @ 540 nm
  - Water cooled - Heat pipes on Digital board
- **Photo detection Plane and front-end**
  - 1296 pixel (0.24°) Hexagonal SiPM developed in collaboration with Hamamatsu
  - Hollow light funnel with AR coating optimised for UV
  - Discrete component preamplifier stage
  - Sensor bias voltage adjusted according to temperature
- **Backend**
  - 12 bits FADC @ 250 MS/s
  - Fully digital trigger and readout (High-speed/High-throughput)
  - Deadtime free at 600 Hz



# The SST projects performance

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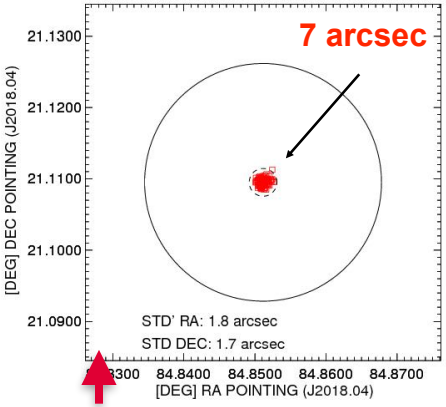
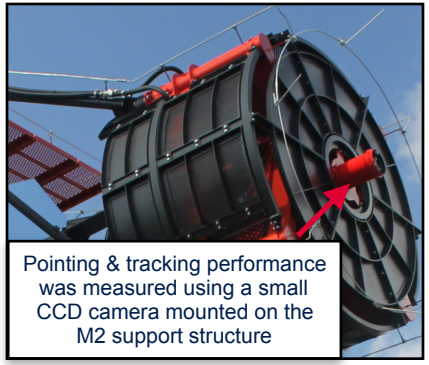
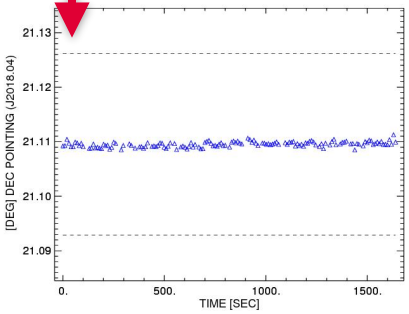
# ASTRI structure and optics performance

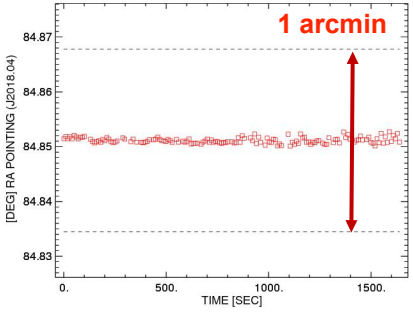


Pointing & tracking performance was measured using a small CCD camera mounted on the M2 support structure

- CTA post calibration astrometric accuracy: 7 arcsec
- CTA online astrometric accuracy: 1 arcmin

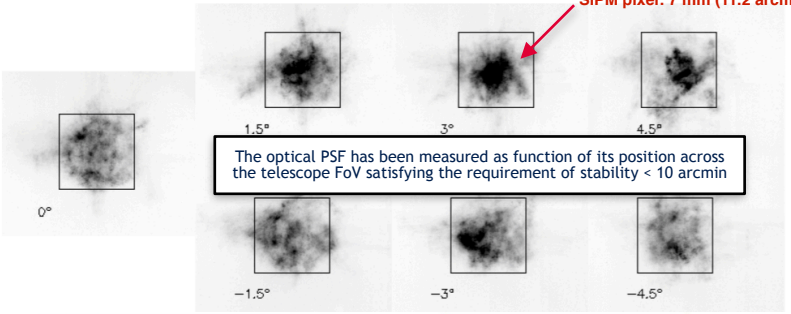


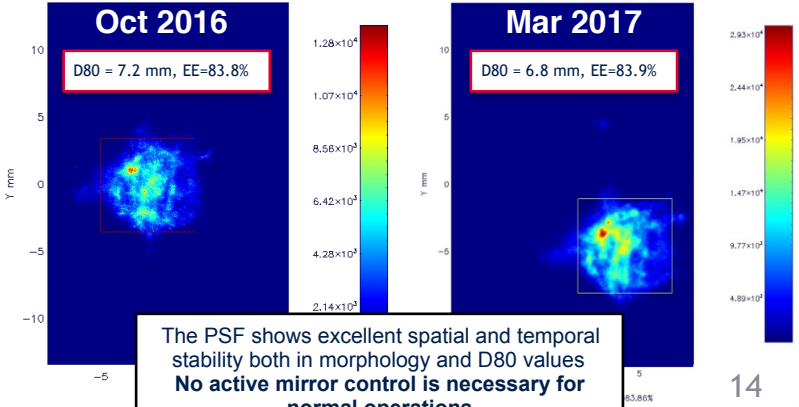

**First optical validation of a Schwarzschild Couder telescope: the ASTRI SST-2M Cherenkov telescope**

E. Giro[1,2], R. Canestrari[2], G. Sironi[2], E. Antolini[3], P. Conconi[2], C.E. Fermino[4], C. Gargano[5], G. Rodeghiero[1,6], F. Russo[7], S. Scuderi[8], G. Tosti[3], V. Vassiliev[9], and G. Pareschi[2]

SiPM pixel: 7 mm (11.2 arcmin)




The optical PSF has been measured as function of its position across the telescope FoV satisfying the requirement of stability < 10 arcmin

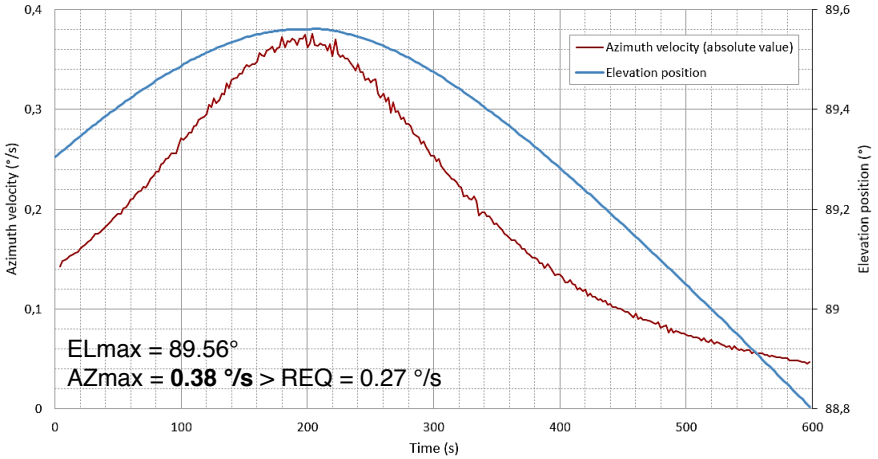


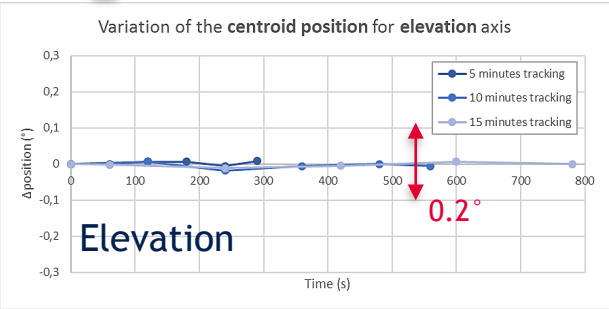

The PSF shows excellent spatial and temporal stability both in morphology and D80 values
**No active mirror control is necessary for normal operations**

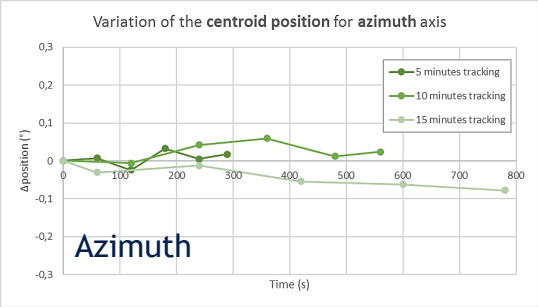
# GCT structure and optics performance

| Designation | Specification | Test result |
|---|---|---|
| Azimuth range | 510° | 523.8° |
| Maximum elevation during tracking | 89.2° | 89.6° * |
| Max slewing velocity in azimuth | 5 °/s | 6.1 °/s |
| Max slewing velocity in elevation | 2 °/s | 2.2 °/s |
| Max tracking velocity in azimuth | 0.27 °/s | 0.38 °/s |
| Max tracking velocity in elevation | 0.0039 °/s | 0.0039 °/s |
| Online Astrometric Accuracy | < 60 ’’ | 60 ’’ ** |
| Tracking precision | < 0.1° | 0.083° *** |
| Emergency stop action | < 1 s | < 1 s |
| Power consumption (Safe State) **** | 2 kW | 0.4 kW |
| Power consumption (Slewing) **** | 11 kW | 2.5 kW |

* To be able to track a source at 0.3°/s in azimuth (max speed) at 89.2° in elevation on site (latitude = 24°) the telescope must track at an elevation > 89.5° in Meudon (latitude = 48)°. Plot on the right.
** Theoretical pointing precision after applying the pointing model – to be tested
*** Worst case (in AZ°). Standard deviations are 0.026° in AZ and 0.0078° in EL.
**** With camera and chiller

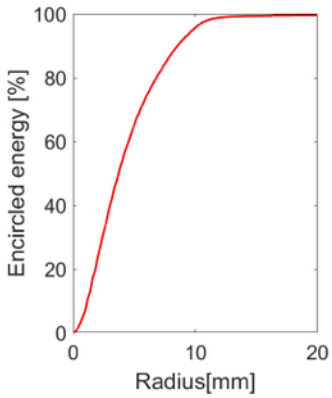


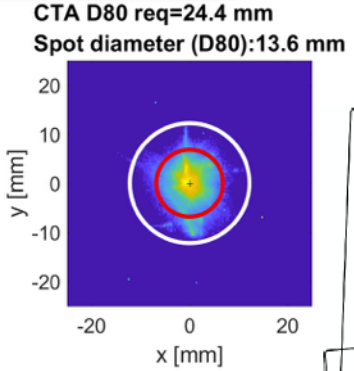



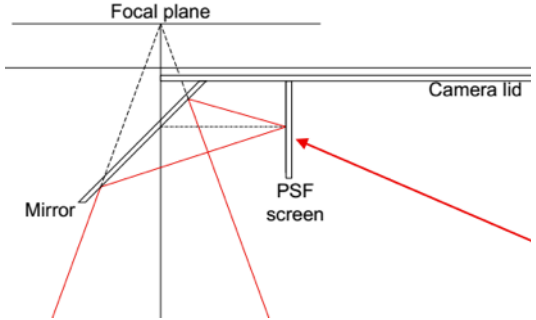



# SST-1M structure and optics performance

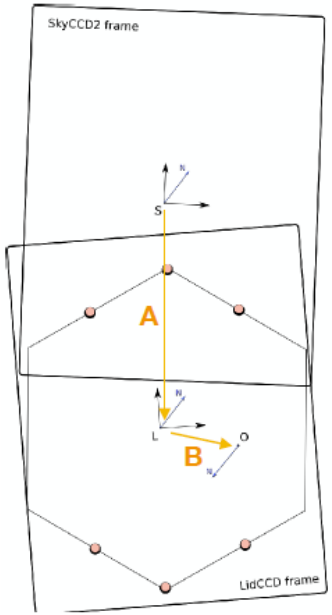
## Telescope point spread function measurements



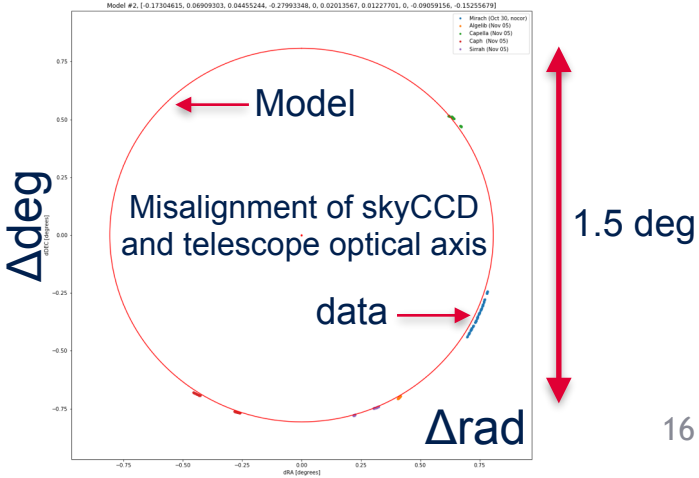




CCD cameras alignment



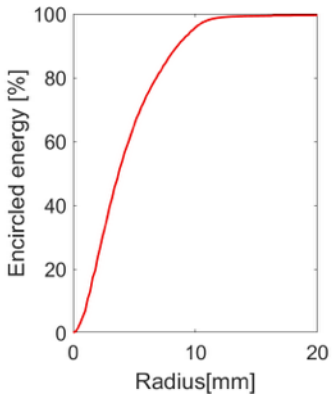

## Pointing real-time reconstruction

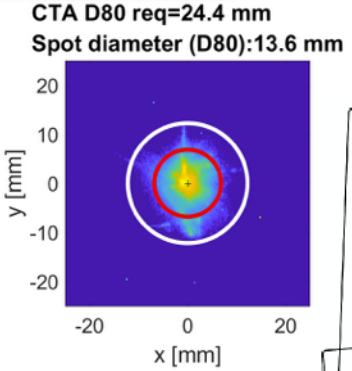
| Operation | Output | Estimated accuracy | Budget |
|---|---|---|---|
| astrometry.net | Sky CCD direction | 1 arcsec | 1 arcsec |
| 3D rotation (fixed) | Lid CCD direction | 1 arcsec | 1 arcsec |
| Translation (fixed) | Optical axis direction | 4 arcsec | 5 arcsec |
| Bending model (fixed) | Camera direction | 2 arcsec | 2 arcsec |
| LED calibration (fixed) | Light guide sky coordinate | 7 arcsec | 5 arcsec |
| **Budget** | | | **7 arcsec** |

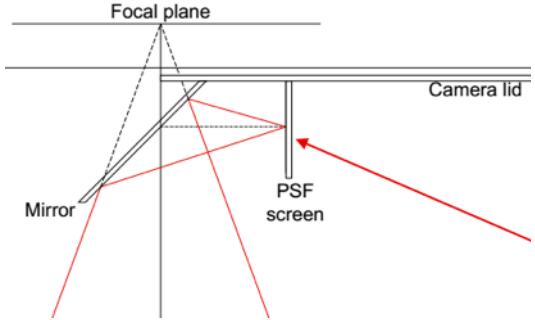


# SST-1M structure and optics performance

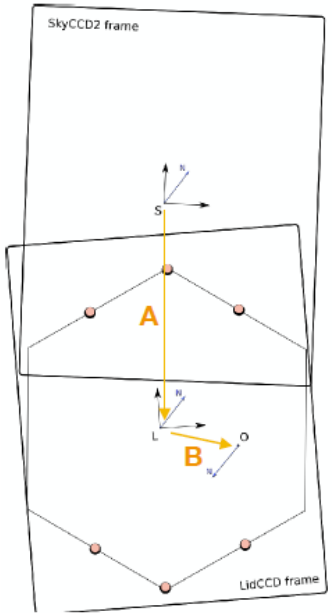
## Telescope point spread function measurements



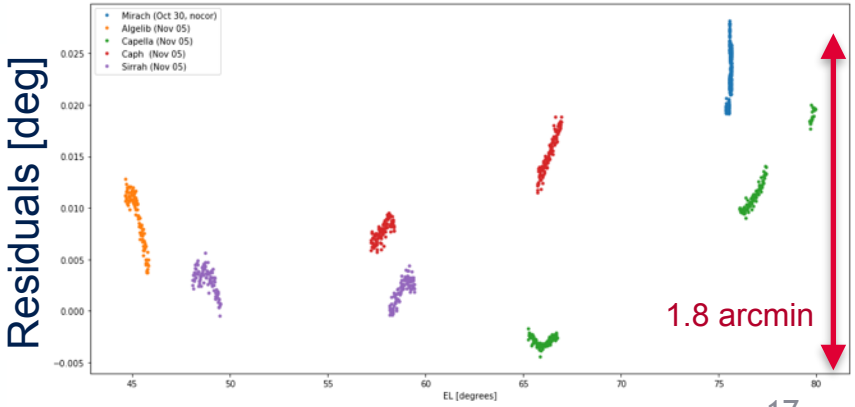




CCD cameras alignment



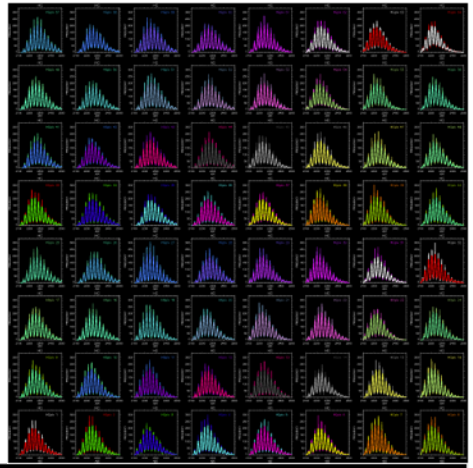

## Pointing real-time reconstruction

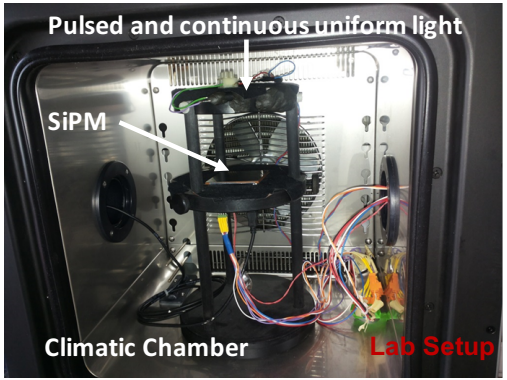
| Operation | Output | Estimated accuracy | Budget |
|---|---|---|---|
| astrometry.net | Sky CCD direction | 1 arcsec | 1 arcsec |
| 3D rotation (fixed) | Lid CCD direction | 1 arcsec | 1 arcsec |
| Translation (fixed) | Optical axis direction | 4 arcsec | 5 arcsec |
| Bending model (fixed) | Camera direction | 2 arcsec | 2 arcsec |
| LED calibration (fixed) | Light guide sky coordinate | 7 arcsec | 5 arcsec |
| **Budget** | | | **7 arcsec** |

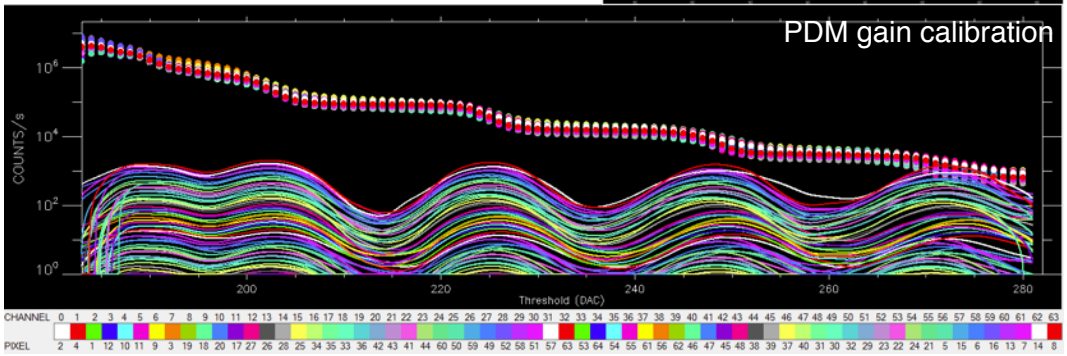


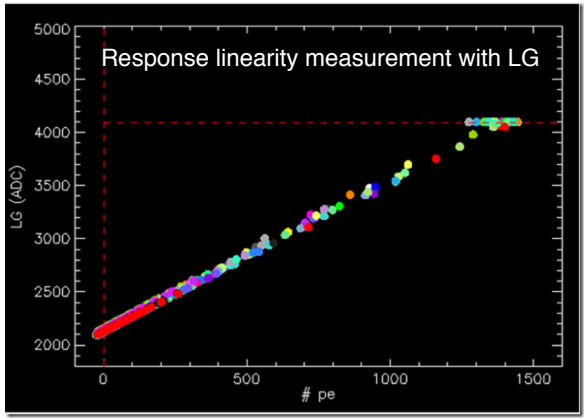
# ASTRI camera performance

- Trigger alignment within ± 1/20 pe equivalent
- Relative gain calibration
- Photoelectron equivalent
- Dynamical range up to 1350 pe





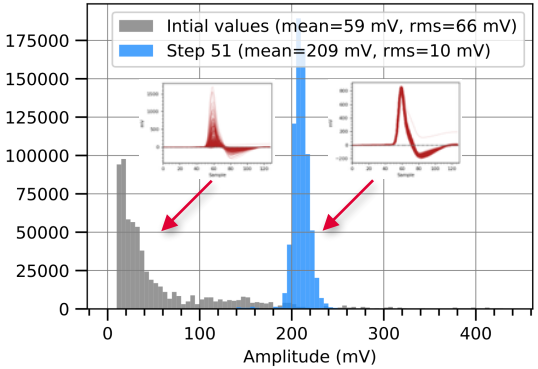



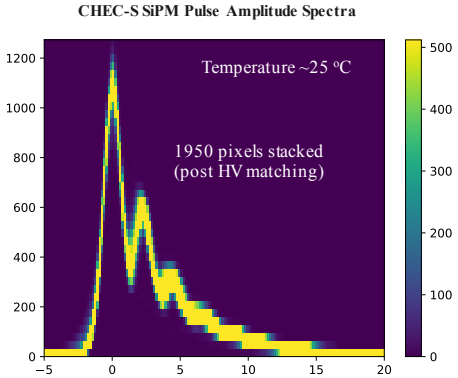



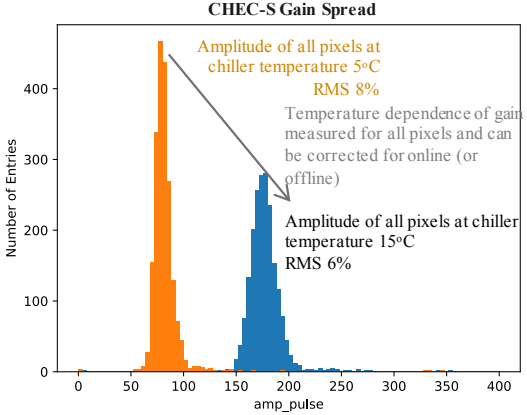
# GCT camera performance (CHEC-S)

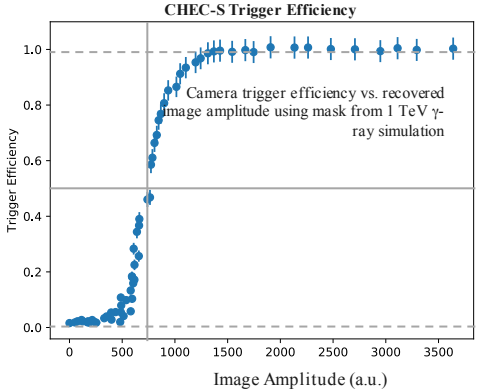
- **CHEC-M and CHEC-S tested both in lab and on-telescope**
  - SiPMs outperform MAPMTs
- **CHEC-S**
  - Single p.e. resolvable for all pixels
  - Gain spread ~8% post HV matching
    - Limitation: 1 HV per 4 pixels (i.e. can be improved)
    - Temperature dependence understood
  - Optical Cross Talk ~40% (!!)
    - >3 yr old SiPMs, Low Cross Talk from Hamamatsu will provide <10%
- **Target-C ASIC: sampling**
  - Noise: < 1 ADC count RMS
  - Signal saturation above ~500 p.e.
    - Recovery in being optimised
- **Target-T5TEA ASIC: triggering**
  - Minimum threshold: 2.5 mV (<1 pe) (expect to operate with around 10 pe threshold)

Gain flat-fielding



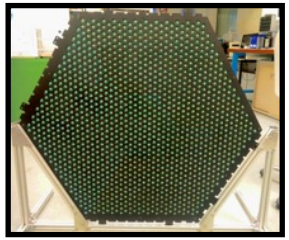



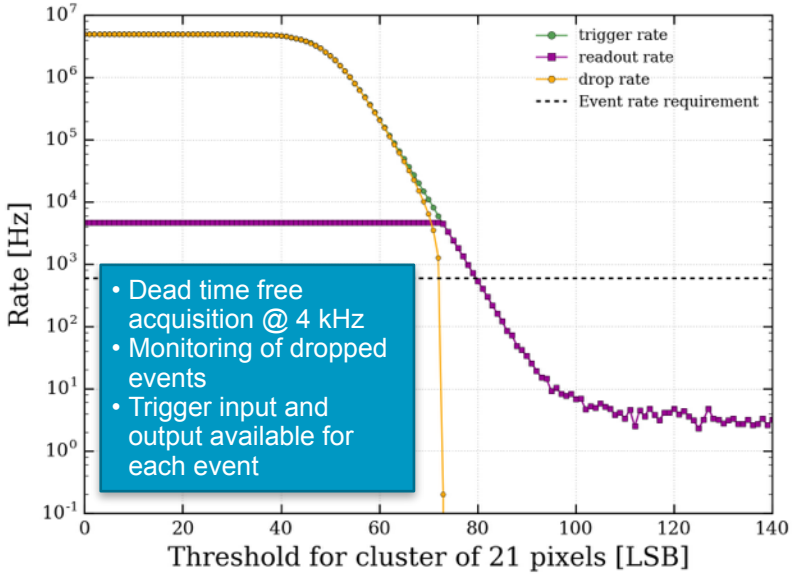



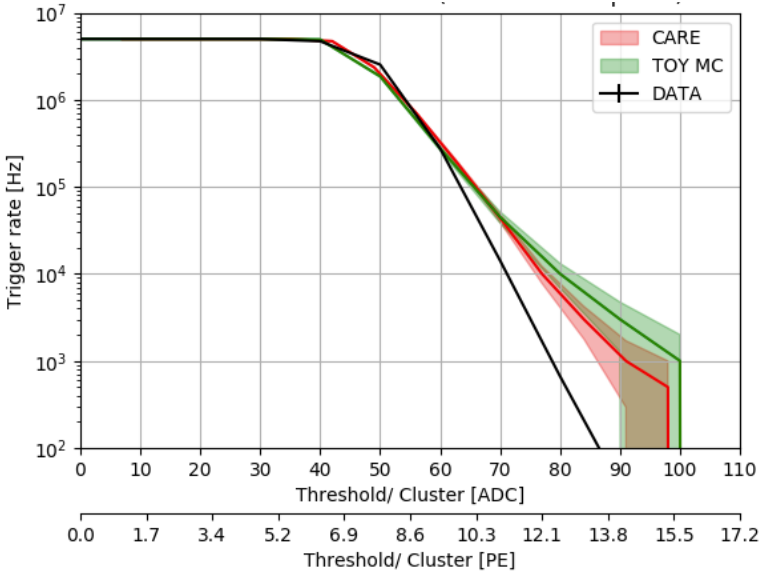
# SST-1M camera performance

- Performance assessment and camera calibration performed in the lab using dedicated setup emulating the signal and background from real observations
- Every pixel characterised (gain, oct, charge resolution, etc…)
- Trigger performance measured and compare to MC simulations



- 1 AC+1 DC led/pixel
- Each led state can be controlled individually
- AC led level / 3 pixels
- DC led level / 48 pixels
- Offset corrections possible
- Fully autonomous



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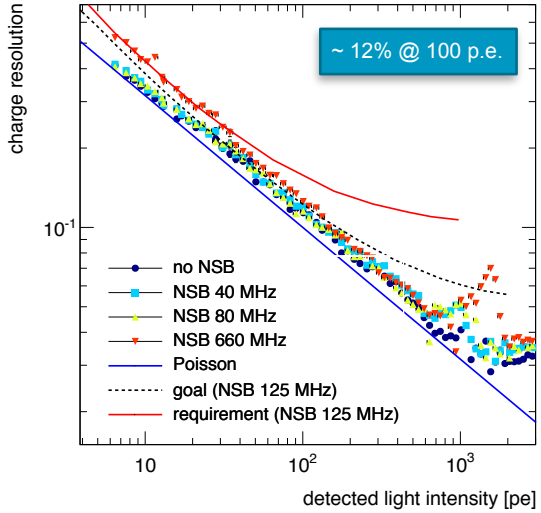
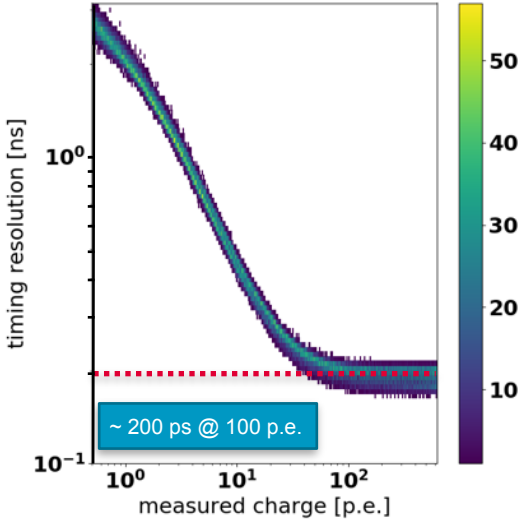
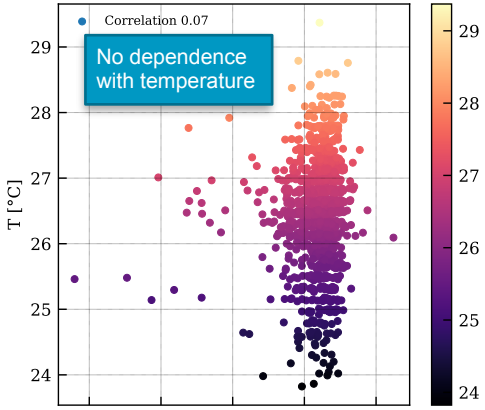
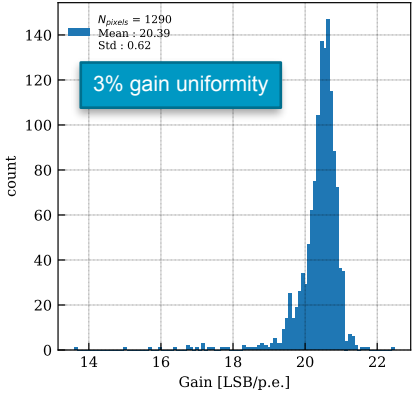


# The SST projects first lights

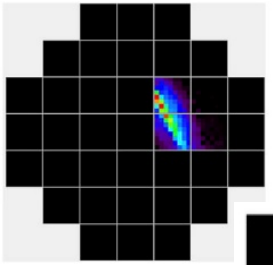
The ASTRI project

The Gate CHEC Telescope (GCT) project

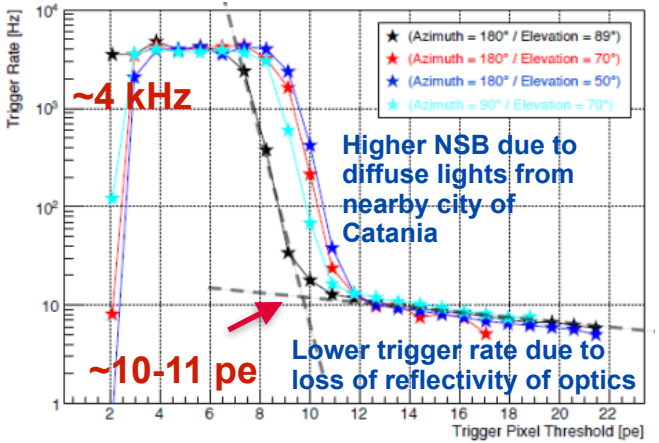
The SST-1M project

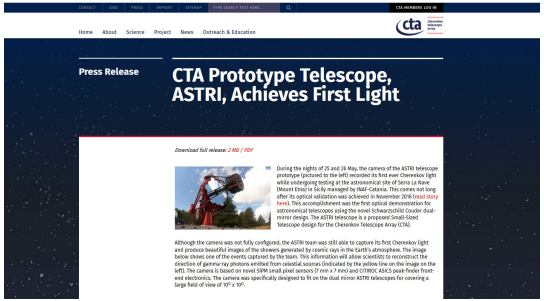
# ASTRI first light and commissioning

25th of May 2017
First Cherenkov light with the ASTRI camera



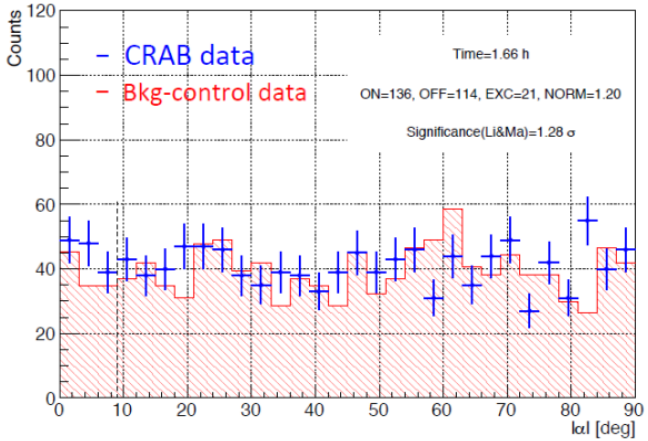
## Trigger rate vs Trigger threshold



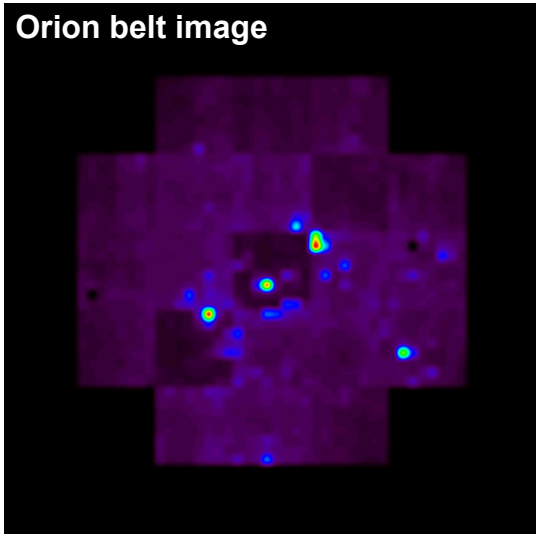




- Crab not detected after 1.66 hours of observations
- Due to low efficiency of optics 5 sigma detection of Crab in 15 h
- Not yet validated MC simulations available

## Detection alpha plot

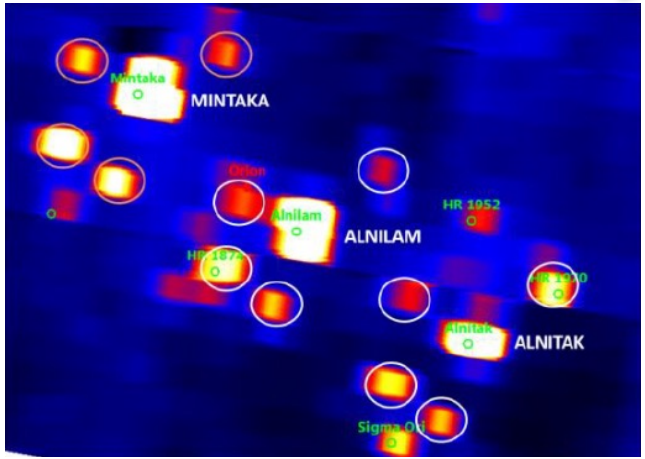


# ASTRI first light and commissioning

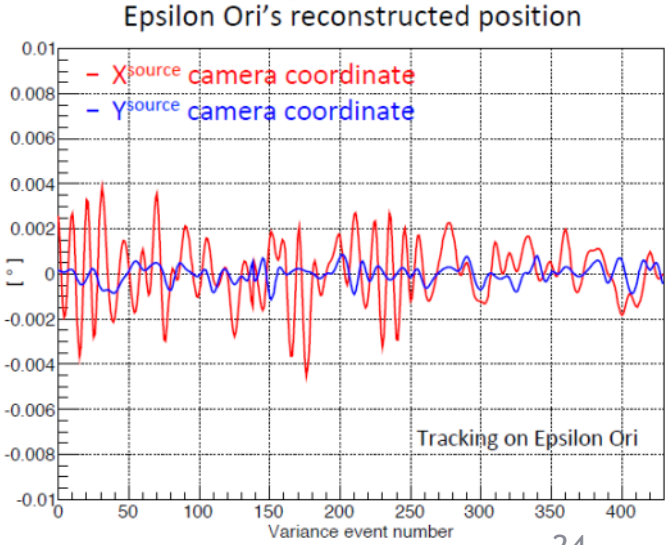



The electric signal generated by each pixel not triggered is continuously sampled and the variance of the sequence of ADC values is proportional to the photon flux.

**The acquisition of the variance data is done in parallel with the normal Cherenkov data acquisition**

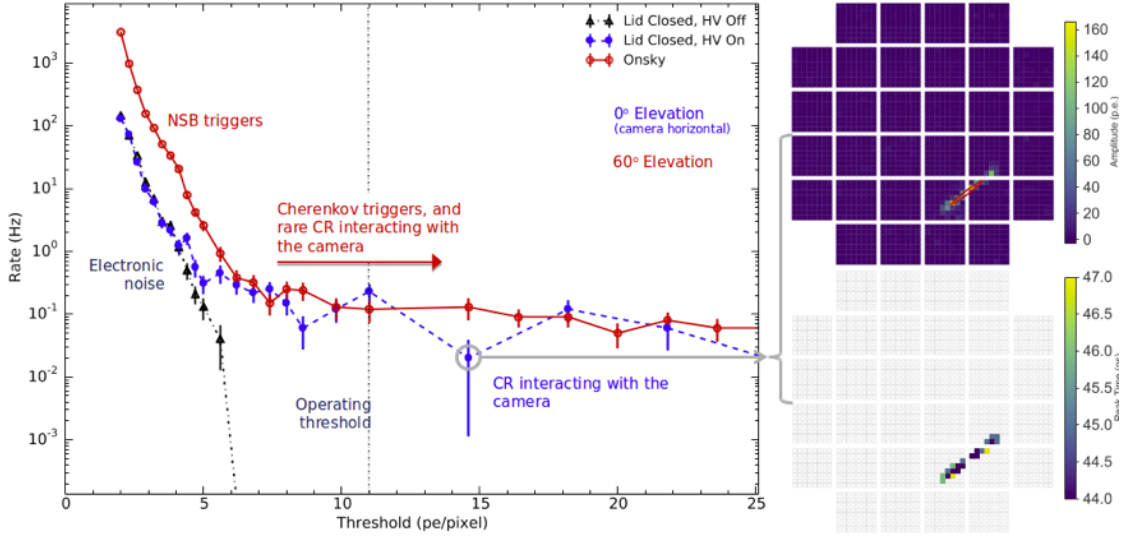


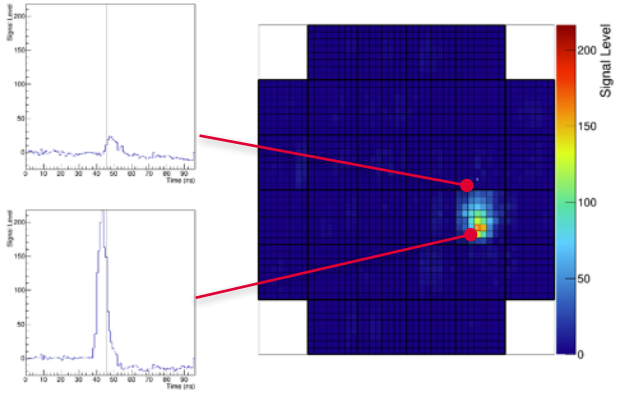

- **Measurement of Night Sky Background (NSB)**
- **Monitoring of the mirrors optical alignment**
- **Monitoring of telescope pointing accuracy**



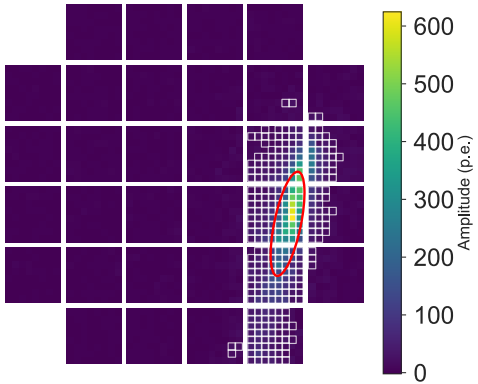
# GCT first light and commissioning (CHEC-M)

- On the **26 November 2015**, the CHEC-M camera mounted on the GATE structure recorded the first CTA atmospheric shower event
- Observation conditions in Meudon complicated due to the vicinity of the City of Lights which induce large NSB photon rate



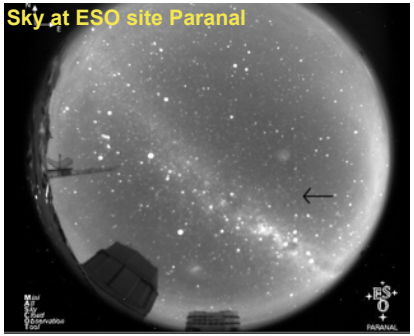

CHEC-M Recorded Cherenkov Light from Cosmic Ray

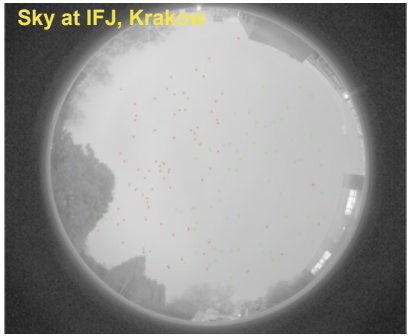


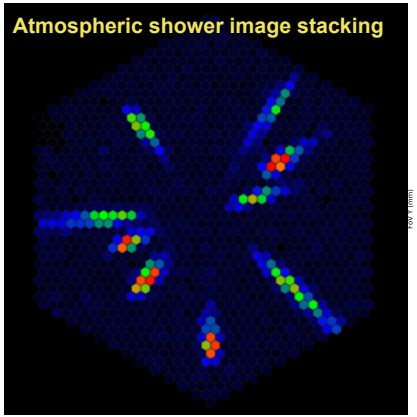
# SST-1M first light and commissioning

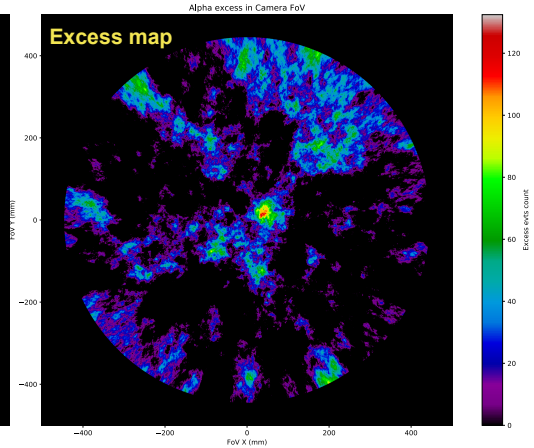
- First light achieved on **30th of August 2017**
- Site not optimal for observation as there is **> 1 GHz NSB photons per pixel**

- After **1h20 of observation pointing at the CRAB**, a 4.2σ excess of atmospheric showers pointing toward its location on the camera was observed
- New observation campaign over the summer 2018

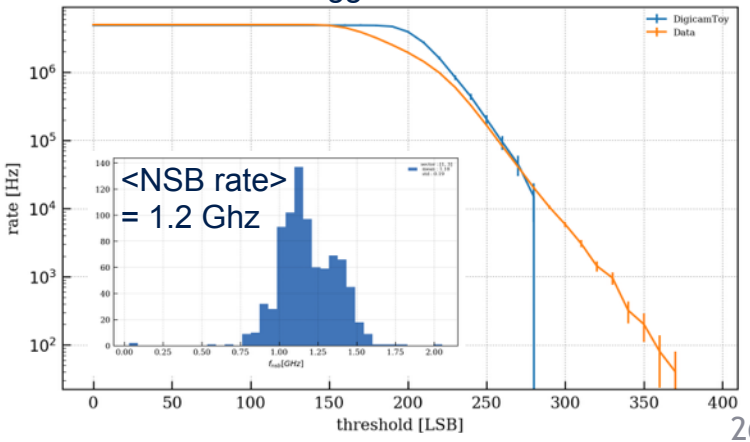



Trigger rate scan



# Conclusion

- **Three mature designs** achieved first light with their respective prototypes
- **Full performance estimation** to be confronted to CTA requirements: ongoing for the three projects
- Decision taken by the Project Office in May 2018 to adopt **only one SST design** on-site:
  - Discussions are ongoing between groups to converge to a common design for both structure and camera