The prototype Schwarzschild-Couder Telescope: a Medium-Sized Telescope for the Cherenkov Telescope Array

Elisabetta Bissaldi*

for the SCT CTA Project

*with special thanks for material to: David Williams, Wystan Benbow, Massimo Capasso, Leonardo Di Venere, Olivier Hervet, Dave Kieda, Serena Loporchio, Gernot Maier, Reshmi Mukherjee, Nepomuk Otte, Marcos Santander, and Vladimir Vassiliev

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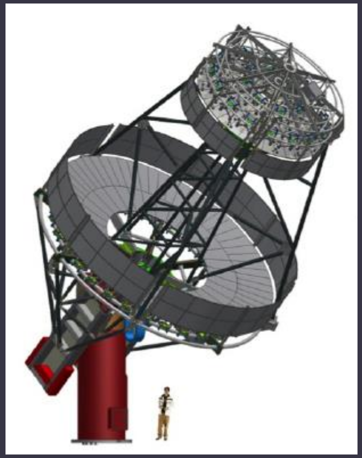
The Schwarzschild-Couder Telescope (SCT)

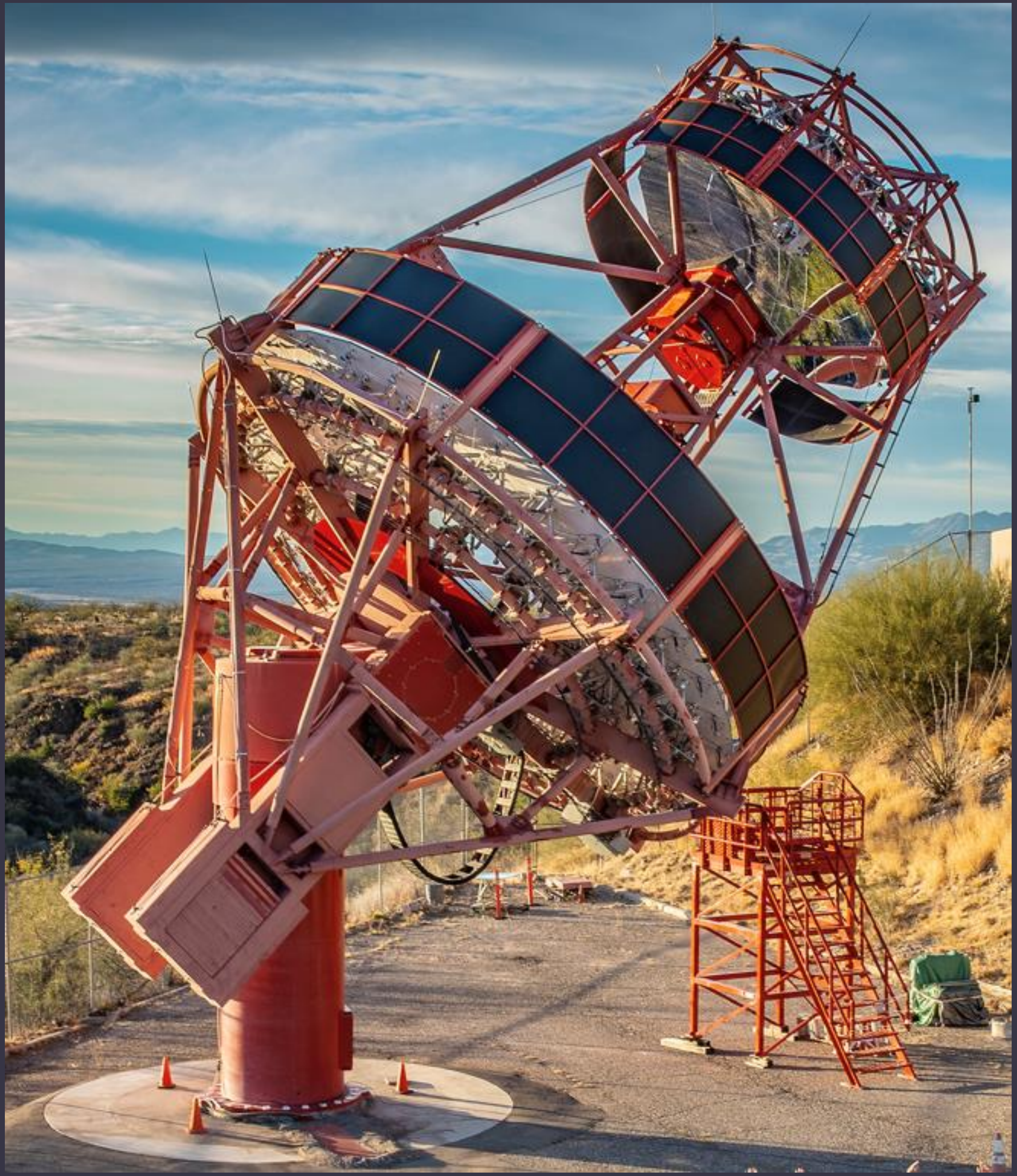
- **Candidate for a Medium-Sized Telescope for CTA**
  - With an advanced telescope optical system

- **Aplanatic dual-mirror optical system**
  - Simultaneous correction of spherical and comatic aberrations in an increased FoV
  - Demagnification of shower images
  - Minimization of astigmatism thanks to curved focal plane
  - Small focal plane plate scale enables use of state-of-the-art novel SiPM light sensors reducing camera dimension and costs
  - Significantly increase in imaging resolution

  ➔ **Main challenges**: Mechanical stability and mirror alignment

- **The prototype SCT (pSCT)**
  - Located at the Fred Lawrence Whipple Observatory in southern Arizona (USA), adiacent to the VERITAS telescopes





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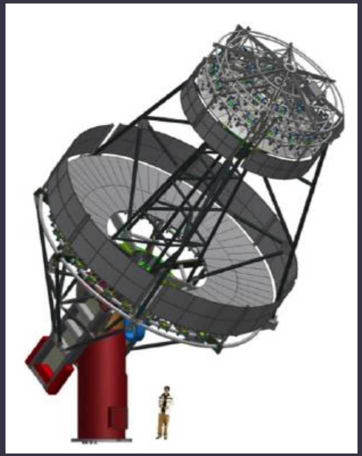


Schwarzschild Telescope (1905)

Reprinted from *Astronomische Mittheilungen der Königlichen Sternwarte zu Göttingen*, Vol. 10, pp. 3-28 (1905).

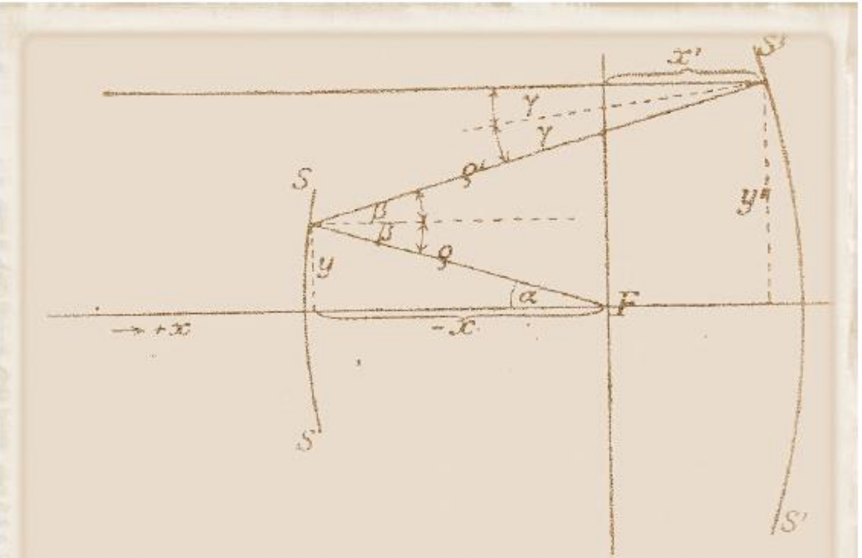
Untersuchungen zur geometrischen Optik. II.

Theorie der Spiegeltelescope.

Von

K. Schwarzschild.

Vorgelegt von F. Klein in der Sitzung vom 22. Januar 1905.



Section 5 – "de-magnifying" telescope

Found the exact solution for figures of two aspheric mirrors which corrected spherical and comatic aberrations

K. Schwarzschild, Astronomische Mittheilungen von der Koeniglichen Sternwarte zu Goettingen, 10:3-28, 1905

The pSCT is implemented with an exact Schwarzschild Aplanat: q=0.666; a=0.666, which was found to be optimal for IACT application.

V. V. Vassiliev, S. J. Fegan "Schwarzschild-Couder two-mirror telescope for ground-based gamma-ray astronomy," 2007, arXiv:0708.2741

Karl Schwarzschild (1873 -1916)

Following pSCT project development, the small-sized telescope of CTA (and ASTRI project reported at this conference) also adopted similar optical system albeit in different aplanatic configuration.

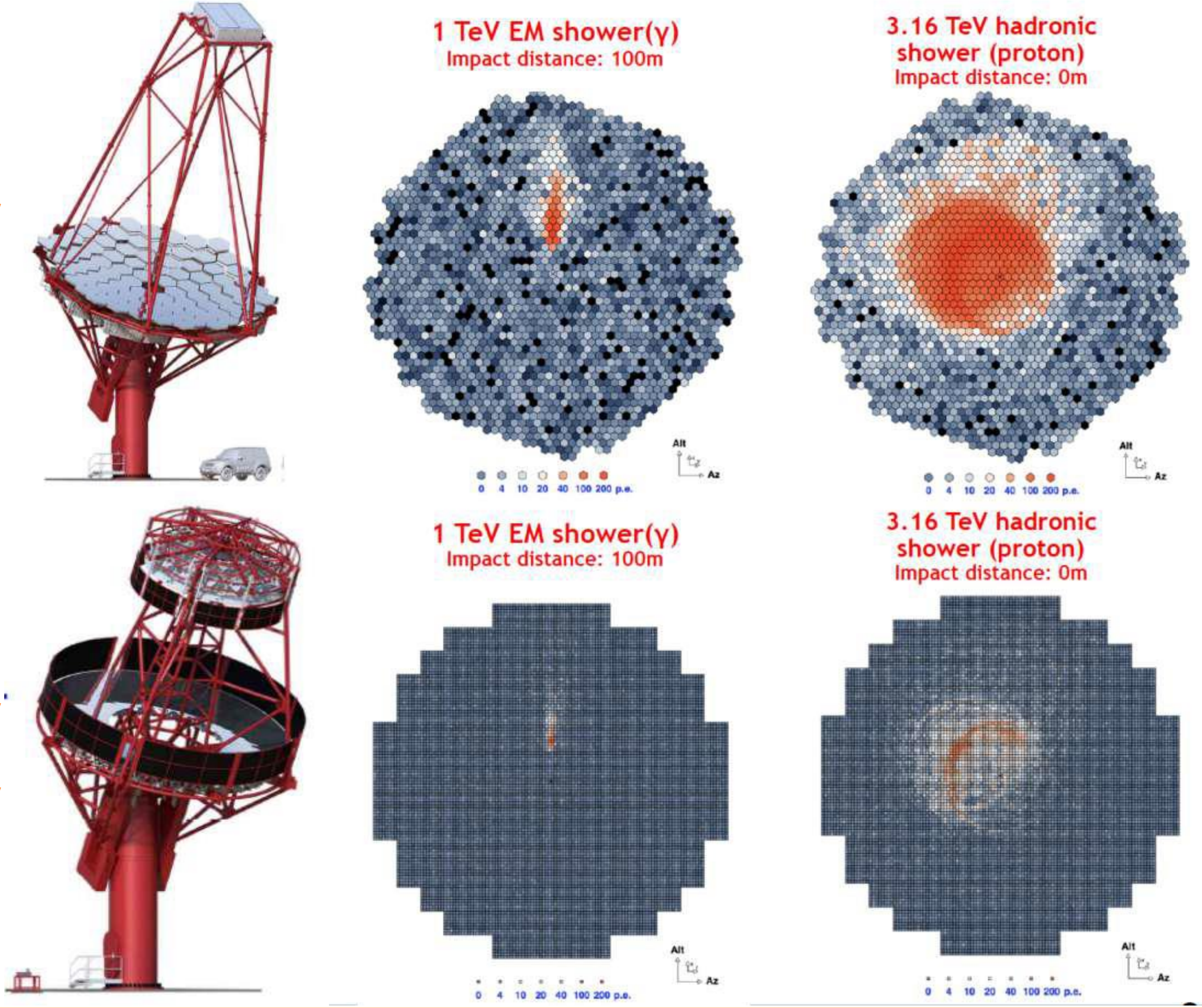
Slide by V.V. Vassiliev – SPIE 2022

The Schwarzschild-Couder Telescope (SCT)

- Superior optical angular resolution over a wide (~8°) field of view
  - Largest IACT FOV is currently < 5°
- By focusing the light on a smaller surface, it is possible to adopt state-of-the-art sensors (Silicon-photomultipliers, SiPMs) and electronics
  - Better sensitivity and reduced observation time

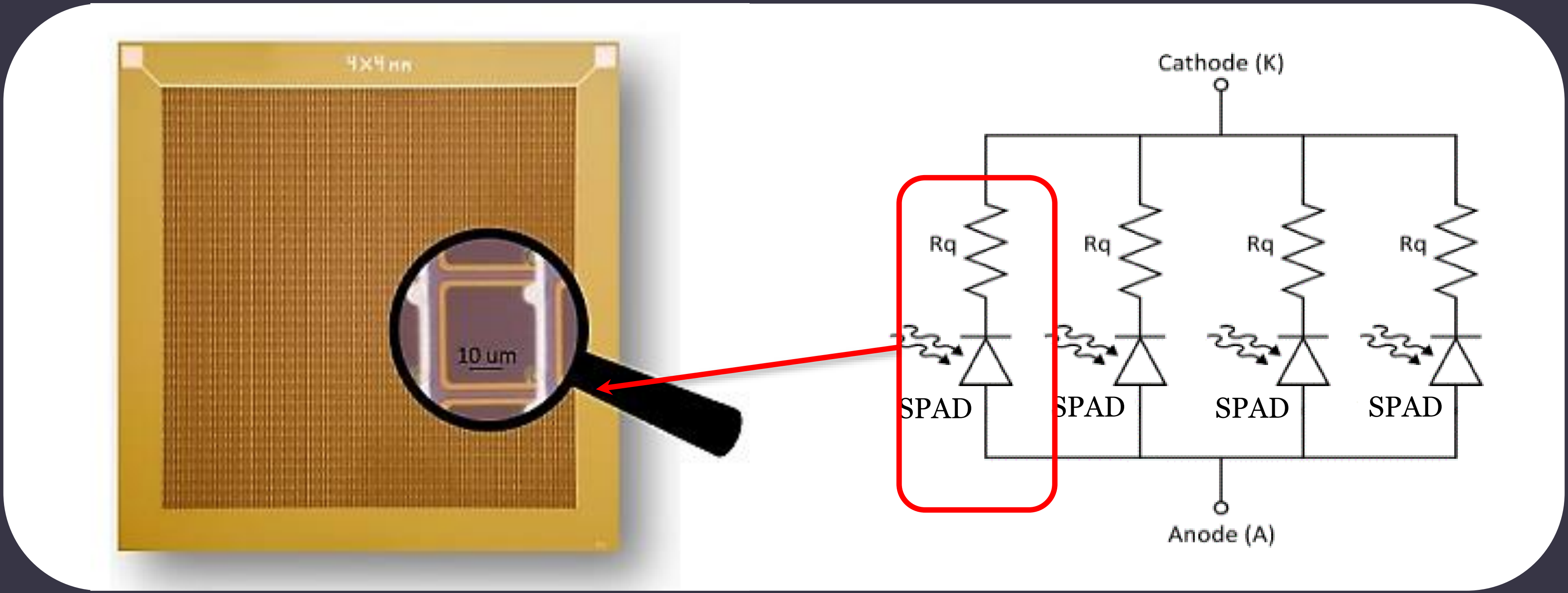
MST Single Mirror
Davies-Cotton
~2k PMTs

MST Dual Mirror
Schwarzschild-Couder
~12k SiPMs



The detectors: Silicon Photomultipliers

SiPMs: array of reverse-biased Single Photon avalanche Diodes (**SPADs**) connected in parallel



SiPM size:
from 1x1 mm^2 to 10x10 mm^2

SPAD size:
from 5 μm to 40 μm (typical)

http://advansid.com/resources/the-silicon-photmultiplier

The pSCT project

- ~30 participating Institutions
  https://cta-psct.physics.ucla.edu/institutions.html
- pSCT project major milestones:
  - 2005-2010: Advanced Gamma-Ray Imaging System (AGIS) and SCT design concept
  - 2010-2014: AA DS2010 endorsement, merging with CTA, and towards pSCT construction NSF MRI project
  - 2014-2018: pSCT Construction at FLWO
  - **17.01.2019: Inauguration of the telescope**
  - **23.01.2019: First light**
  - 12.2019: On-Axis optical alignment achieved the pre-construction estimated PSF
  - **05.2020: Significant detection of the Crab Nebula (236th AAS)**
  - 10.2020: CTA Consortium endorses development and construction of SCTs for CTAO
  - 11.2021: AA Decadal Survey 2020 Panel on Particle Astrophysics and Gravitation endorsement of US contribution to CTAO
  - 06.2022: Off-Axis optical alignment achieved and validated
  - 2018-… pSCT camera upgrade ongoing

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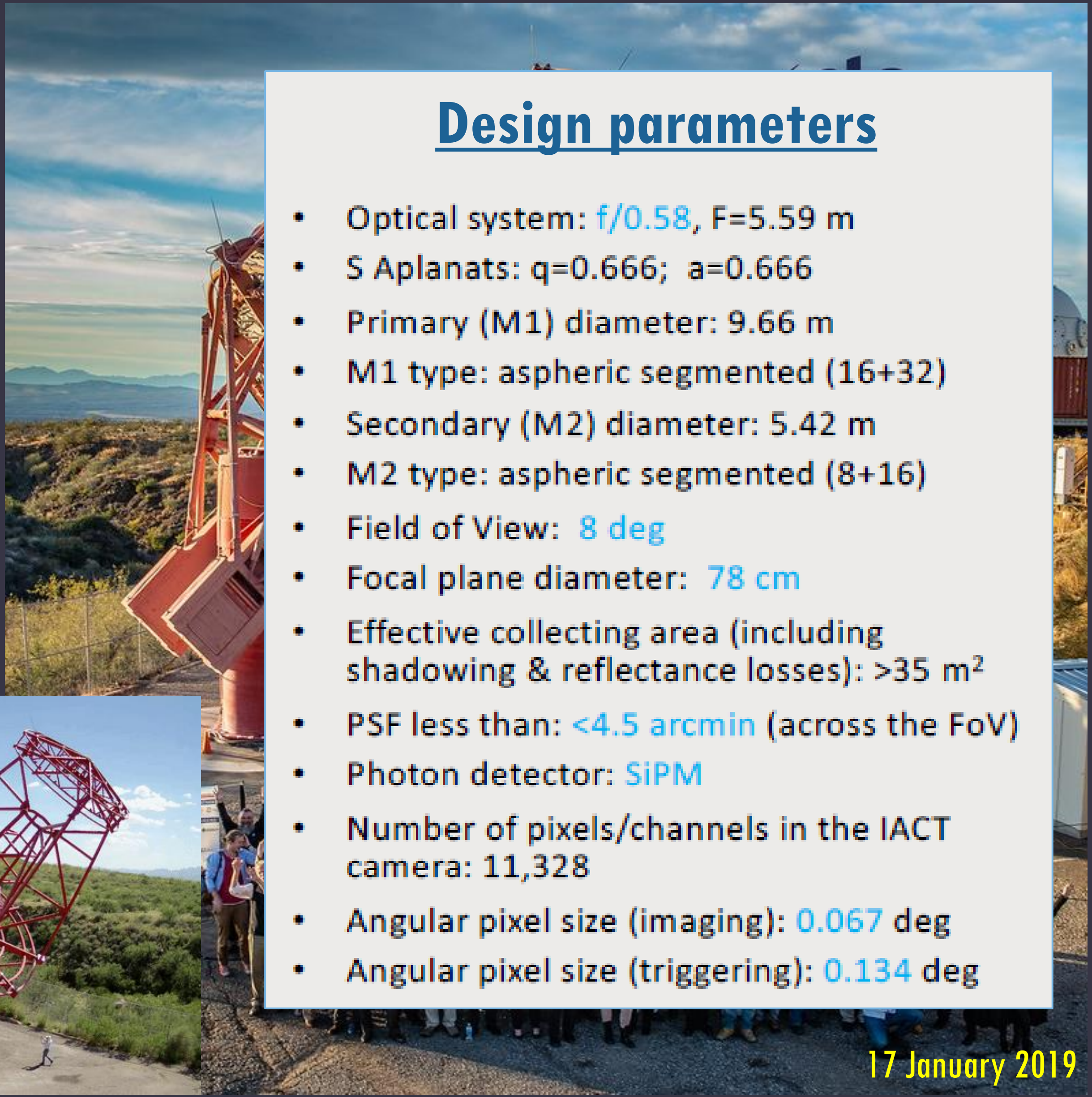


Design parameters

- Optical system: f/0.58, F=5.59 m
- S Aplanats: q=0.666; a=0.666
- Primary (M1) diameter: 9.66 m
- M1 type: aspheric segmented (16+32)
- Secondary (M2) diameter: 5.42 m
- M2 type: aspheric segmented (8+16)
- Field of View: 8 deg
- Focal plane diameter: 78 cm
- Effective collecting area (including shadowing & reflectance losses): >35 m^2
- PSF less than: <4.5 arcmin (across the FoV)
- Photon detector: SiPM
- Number of pixels/channels in the IACT camera: 11,328
- Angular pixel size (imaging): 0.067 deg
- Angular pixel size (triggering): 0.134 deg

Project scope and common CTA technologies

Initial scope of the prototype SCT project funded by the NSF MRI program and international partners DESY, INAF, INFN, and the others:

- SCT-MEC: Full telescope optical support structure (OSS) and positioning system;
- SCT-OPT: Full telescope optical system (OS);
- SCT-CAM: Prototype camera (14% of focal plane is instrumented with SiPM-based photosensors and electronics);
- SCT-AUX: Nearly complete implementation

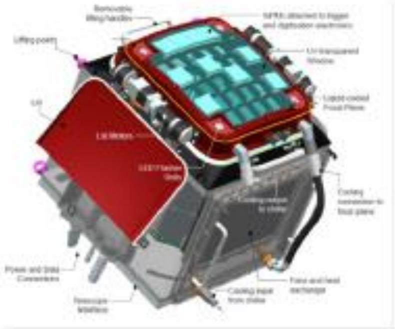
Common telescope mount and positioning systems

Common aspheric mirror fabrication technology

Combination of SCT ideas, originated in the US, with moderately expensive mirror replication technology developed at INAF de Brera and Media Lario Technologies became particularly prolific for the realization of highly aspheric segmented SCT optics.

The prototype SC-MST (pSCT) has been designed in close coordination with the DC-MST team and utilizes nearly identical telescope tower and positioning system developed originally at DESY Zeuthen.

Common SiPM-based camera electronics utilizing identical ASICs



The camera electronics based on TARGET ASIC technology, and the trigger backplane are common for both SCT and GCT-S cameras. Major camera components, such as front-end electronics modules, have been developed in fruitful collaboration with MPIK and University of Erlangen groups.

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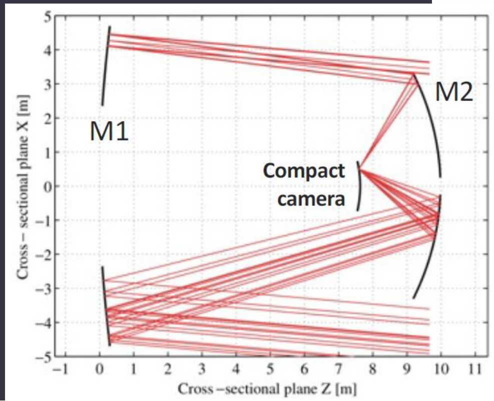
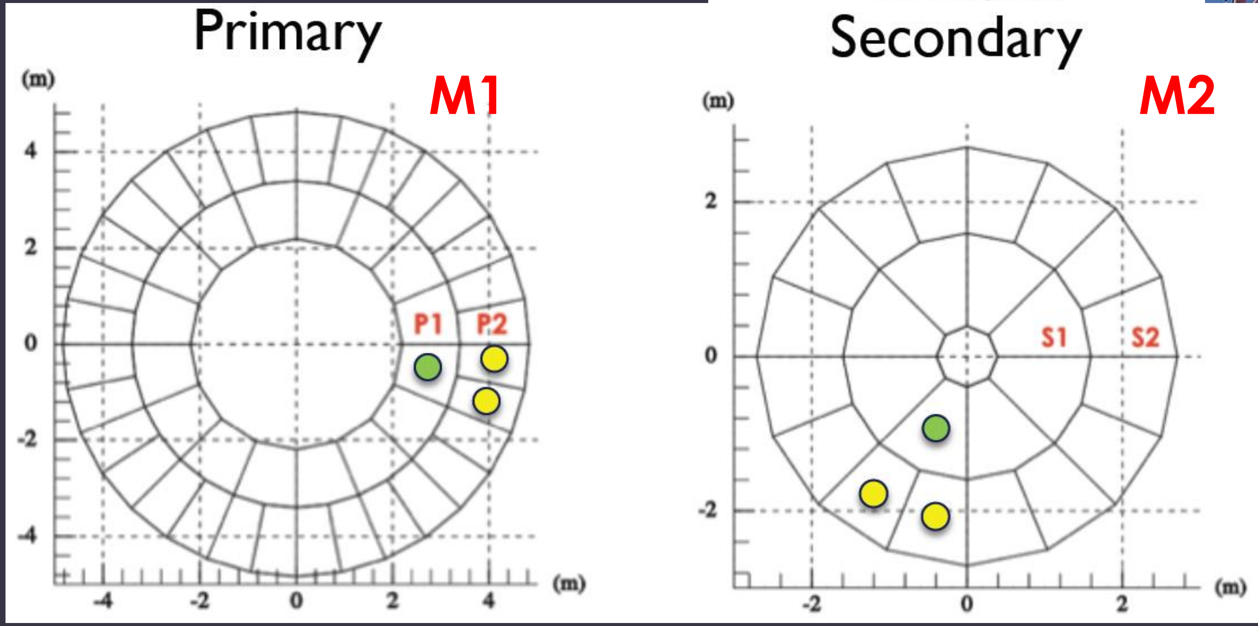
The pSCT Optical System

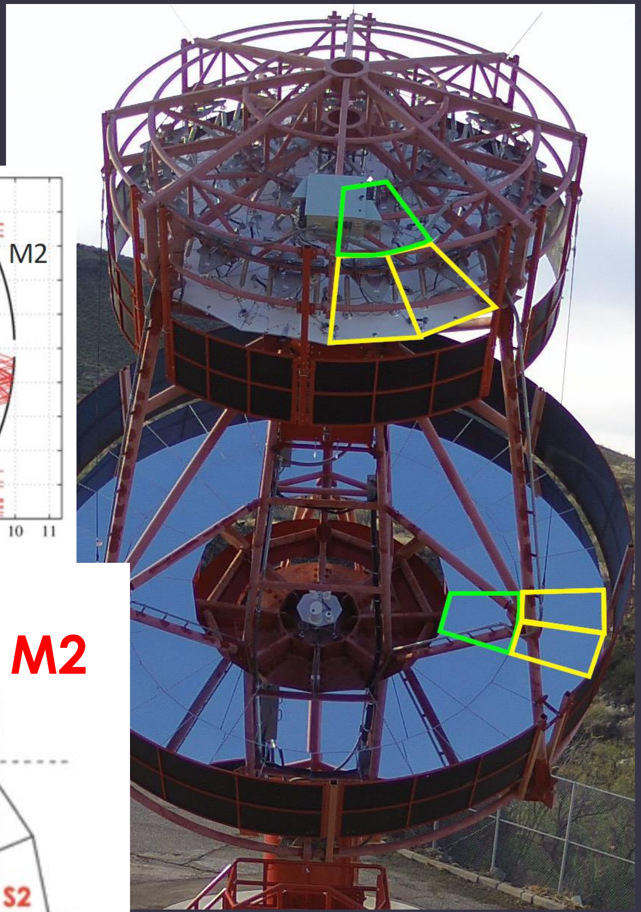
- **Primary mirror (M1)**: diameter 9.7 m, segmented into 48 mirror panels, split between 2 rings
  - 16 P1 (inner) panels + 32 P2 (outer) panels
- **Secondary mirror (M2)**: diameter 5.4 m, segmented into 24 mirror panels, split between 2 rings
  - 8 S1 (inner) panels + 16 S2 (outer) panels

➔ **Focal length: 5.586 m**



- To achieve the PSF of the Optical System in the FoV compatible with the SiPM pixel size (6mm) sub-mm and sub-mrad alignment is required



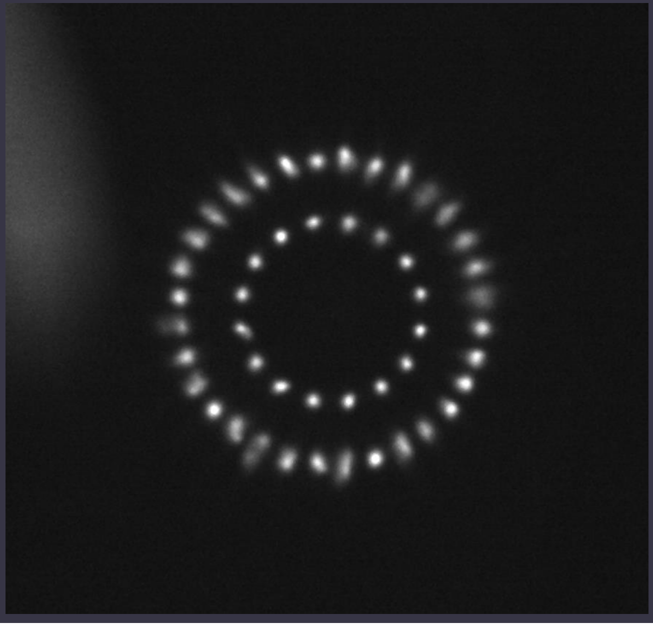


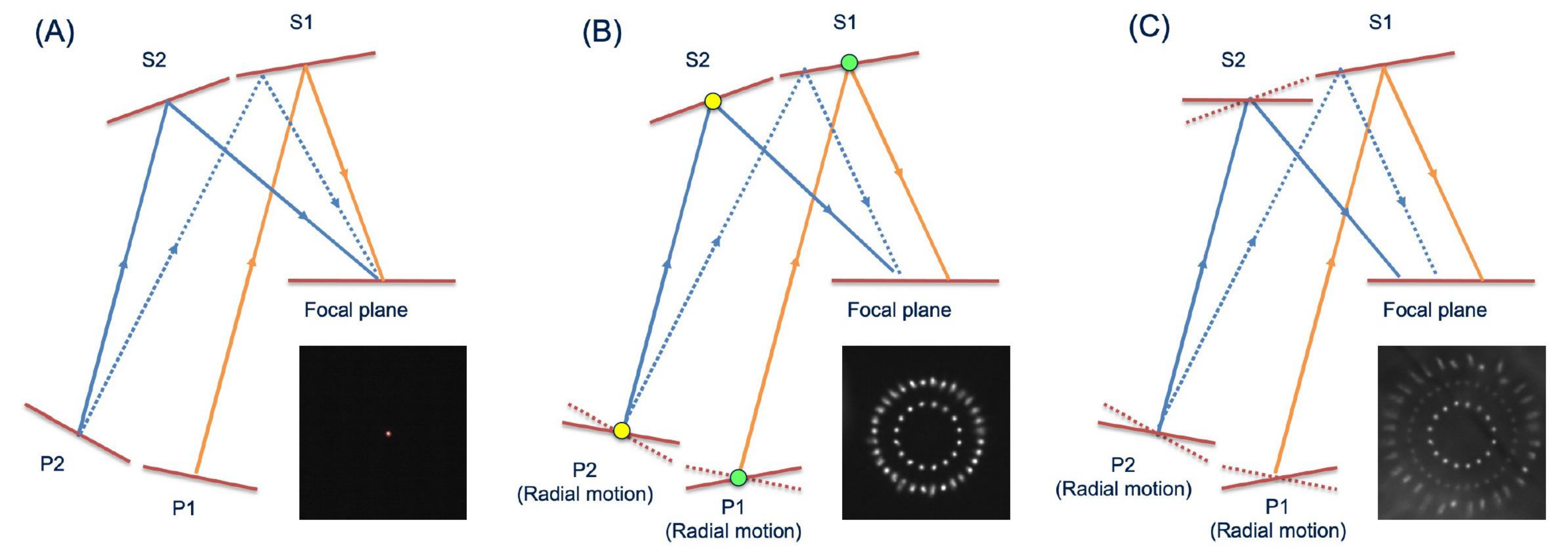
Each S1 reflects from 2 P1 (and a small fraction of 4 P2)
Each S2 reflects from 2 P2

The pSCT Optical System

Optical alignment procedure

- Process using a de-focused star projected on the focal plane
  - Alignment based on the focusing/defocusing of each pair of panels
  - Characteristics of individual images (major and minor axes and elongation) used to guide relative global positioning of M1, M2, FP
  - Creation of response matrices
  - Asynchronous functionality allows a fast alignment





Ribeiro+2021
https://doi.org/10.22323/1.395.0717

The pSCT Optical System

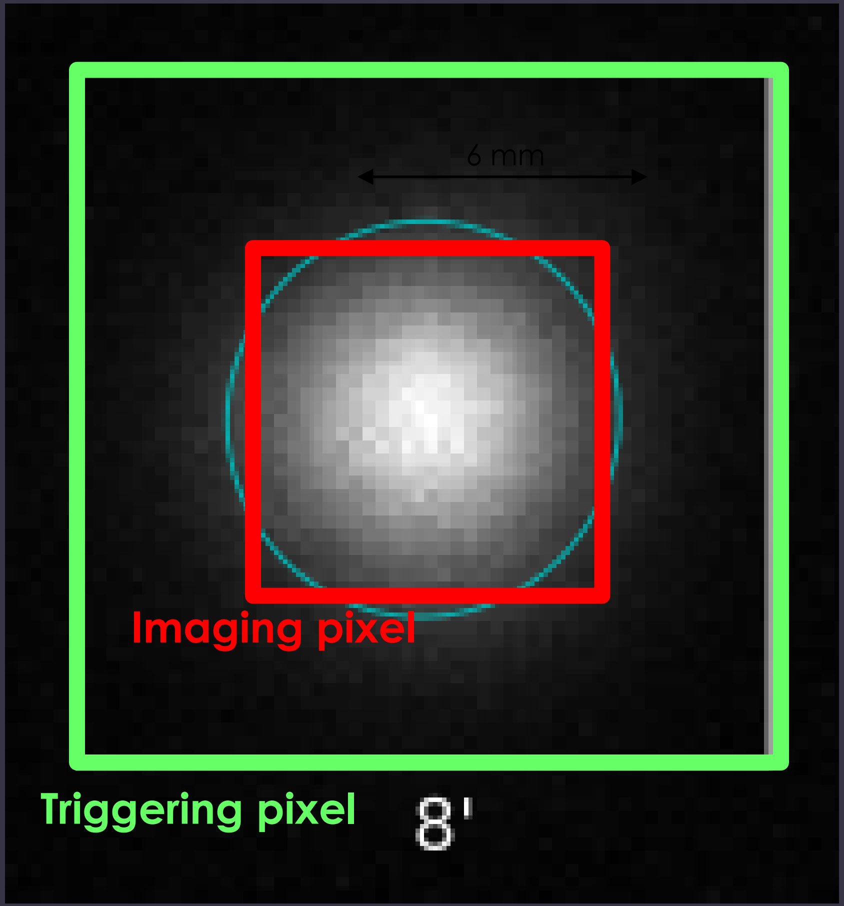
Commissioning

- Measured response of star image to panel motion
- Optimized position between M2 and FP
- Improved S1 alignment strategy

➔ **Achieved PSF design goal of 2.9 arcmin**

- New progress:
  - Precise focus of M1 panels through the "overshoot method"
  - Reduce global misalignment of M1-to-M2-to-FP by analyzing cumulative asymmetry parameters of individual images

On-axis PSF
(Arcturus, 76° elevation)



Ribeiro+2021
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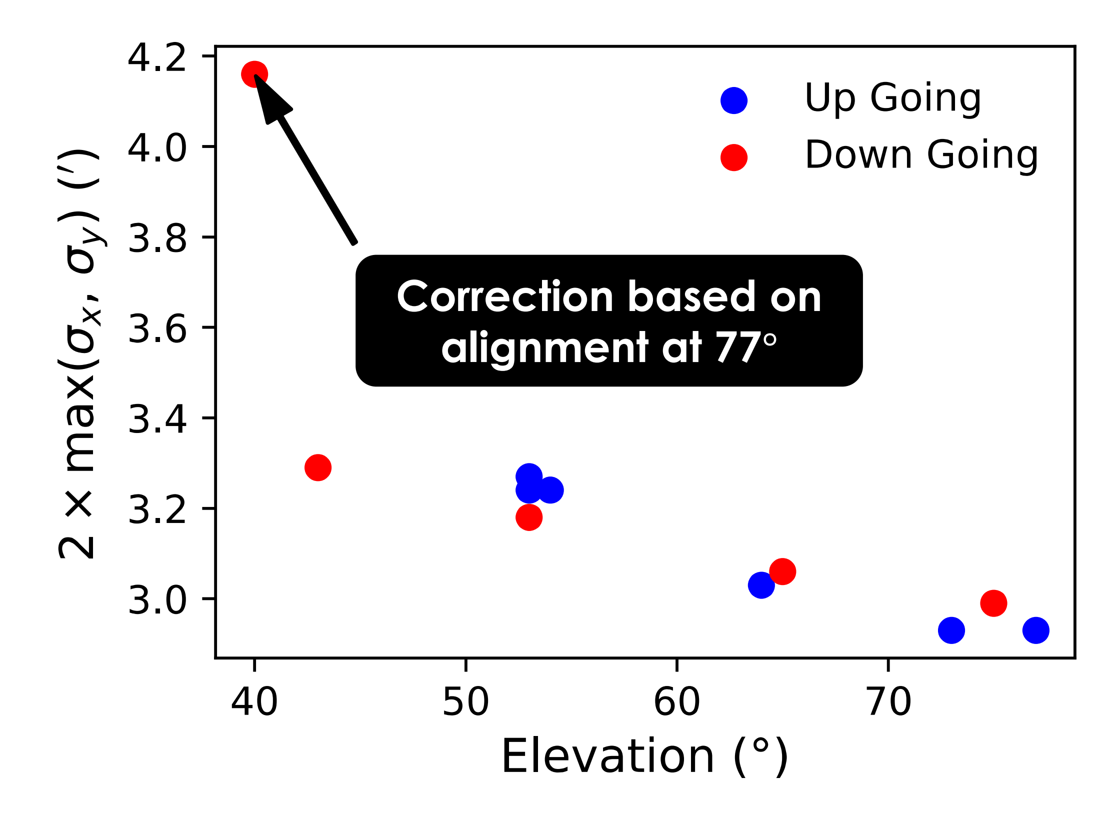
The pSCT Optical System

On-axis PSF as a function of elevation
(Arcturus, April 2021)



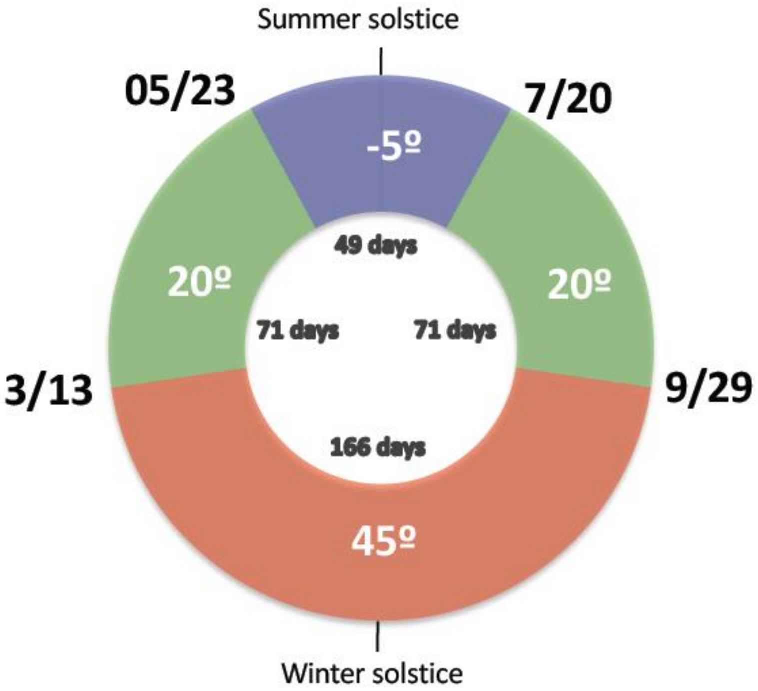
Ribeiro+2021
https://doi.org/10.22323/1.395.0717

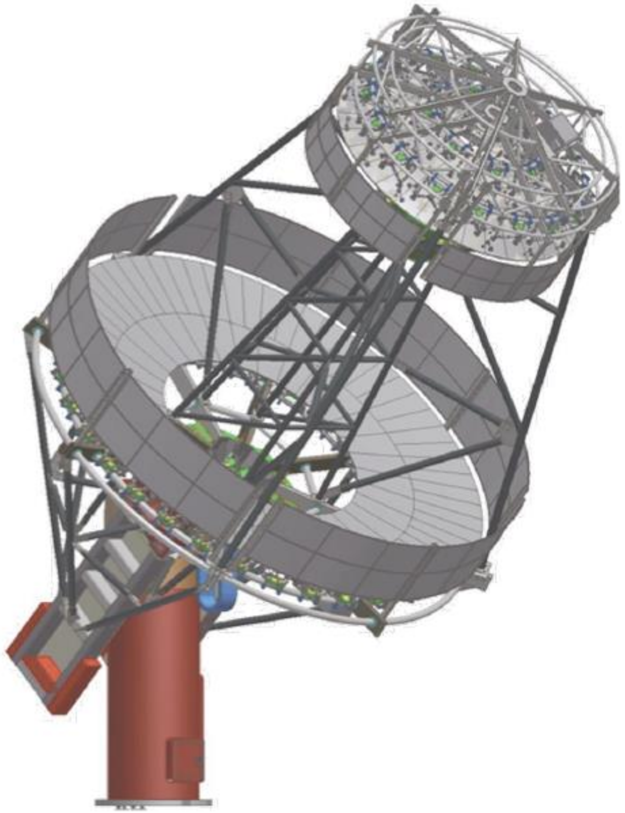
- The alignment depends on the pointing elevation
- A database of aligned panel positions is being built to allow us to maintain the PSF through the full range of elevations
- Initial studies:
  - Achieved PSF of ~3' across an elevation range of 77°-40°.
  - Negligible hysteresis: up- and down-going points overlap

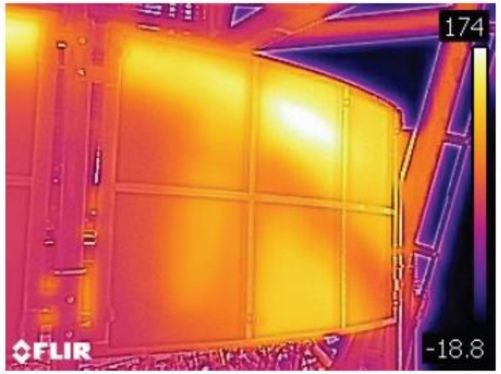
pSCT sunlight protection and stray light control

(SCT parking concept without the dome)

Parking at 3 elevation angles during the year (-5º, 20º and 45º)







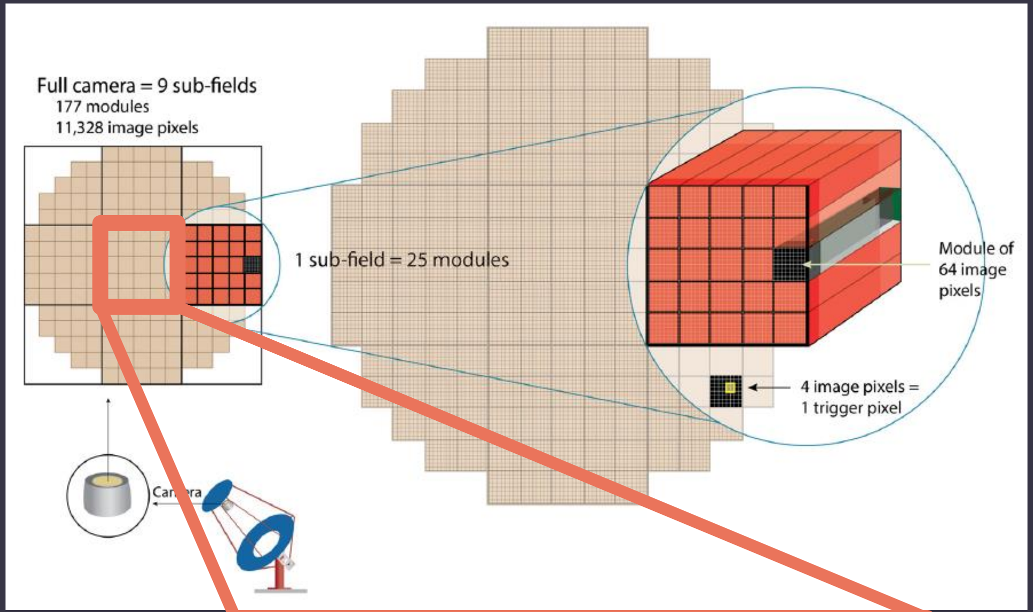
The M1 and M2 baffle system demonstrated viability of the parking concept and confirmed safety of operation.

The light reflected by M2 around noon on July 15th is intercepted by the M2 baffle. The difference in temperature between reflected light region on the baffle and the region directly illuminated by the sun (baffle on the opposite side) is 15 degrees F.

Slide by V.V. Vassiliev – SPIE 2022

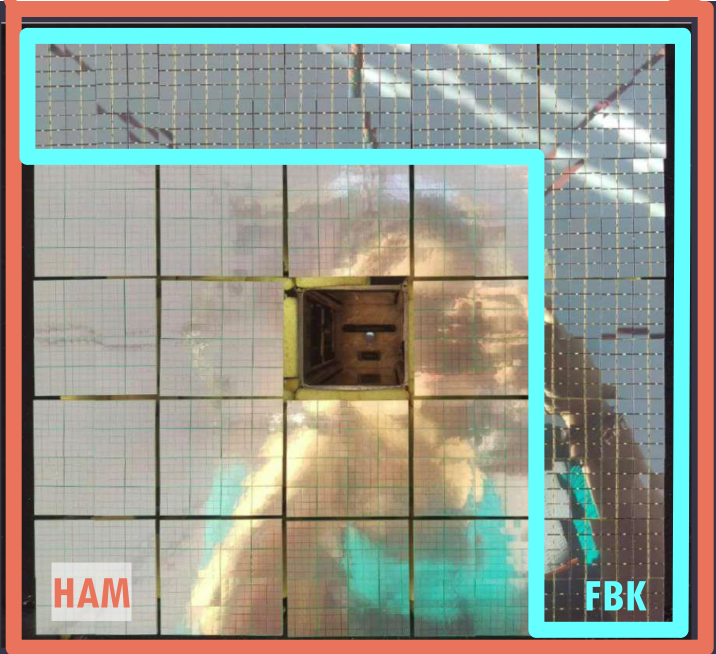
The pSCT Camera

- Located between primary and secondary mirrors
- **Modular design:**
  9 backplanes, 177 modules, 11'328 pixels
  - Camera shares common components (FEE and backplane) with the compact high energy camera (CHEC) for SSTs
  - Each module contains FEE + focal-plane module (FPM)
    - FPMs form a curved focal plane facing secondary mirror



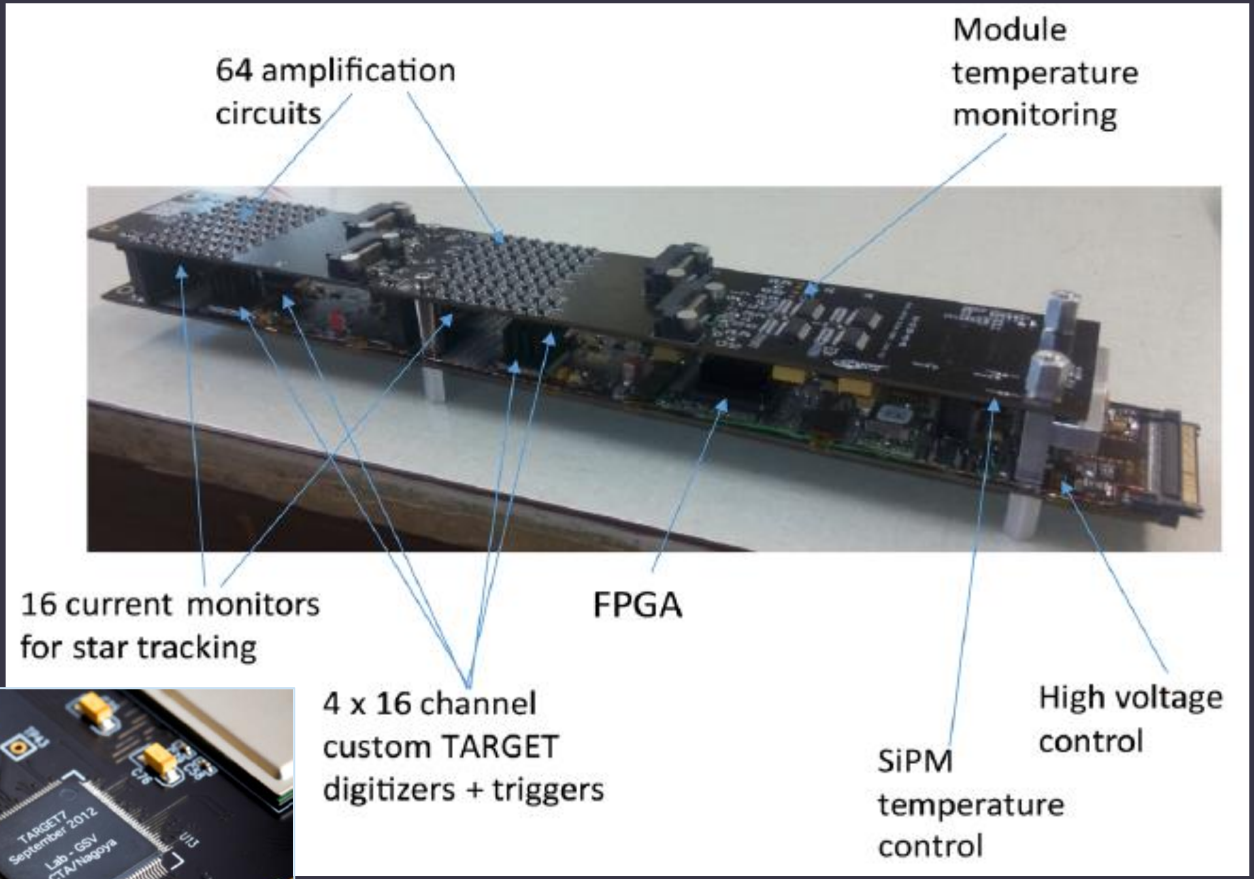
Adams+2022
https://doi.org/10.1117/1.JATIS.8.1.014007

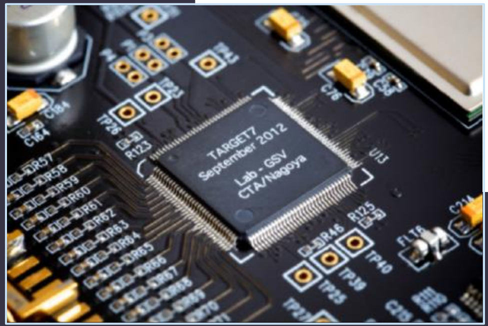
- **Current configuration:**
  25 modules, 1536 pixels, 2.68° FoV
  - Hamamatsu (S12642-0404PA-50(X), USA, 16 modules, 3x3 mm^2) + FBK (NUV-HD3, Italy, 9 modules, 6x6 mm^2) Silicon Photomultipliers (SiPMs)
    - SiPM pixels → much smaller than traditional PMTs → providing much higher resolution air shower image, reduced uncertainty in gamma-ray direction and energy resolution, better background rejection



The pSCT Camera

- Front-End Electronics (FEE) functionalities:
  - Amplification and digitization of FPM signals
  - Control of SiPM bias voltage
  - Temperature monitoring and control of FPM
  - Low-level trigger generation
  - Waveform data packaging and transfer to storage
- Electronics distributed over 2 circuit boards, primary and auxiliary
  - Primary board containing 4 TARGET7 chips
    - 7th generation TeV Array Readout with GSa/s sampling and Event Trigger)
    - Samples and digitizes 16 input channels
    - Analogue ring buffer of 16k capacitors
    - Storage of analogue waveforms @1GSa/s
    - Trigger generation





Adams+2022
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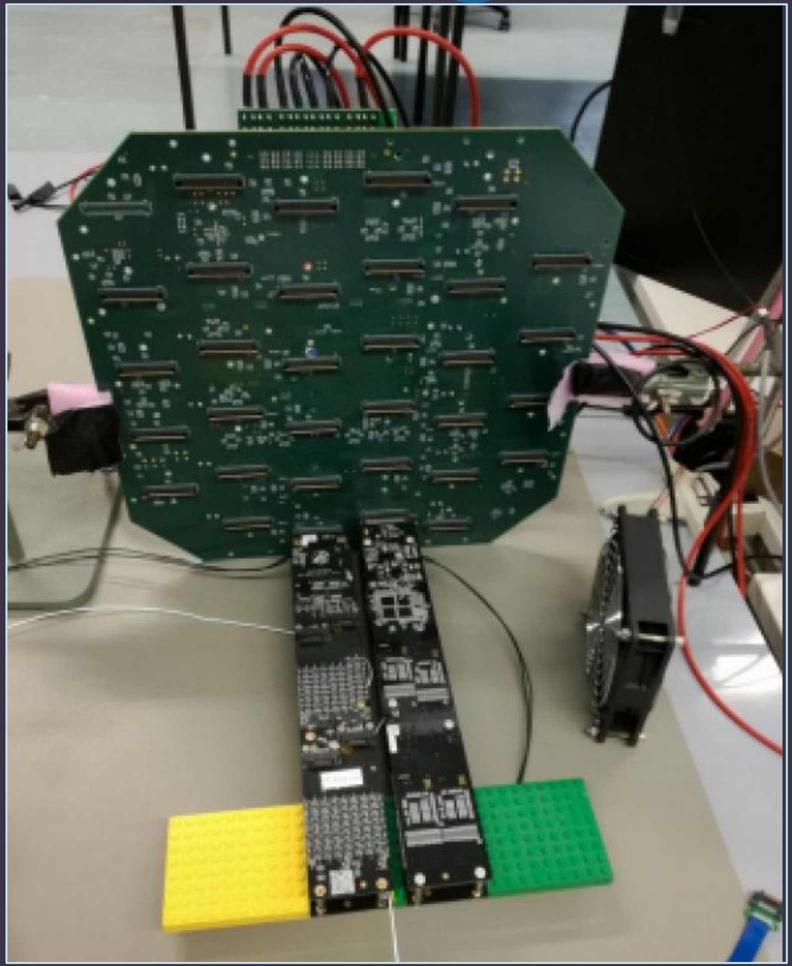
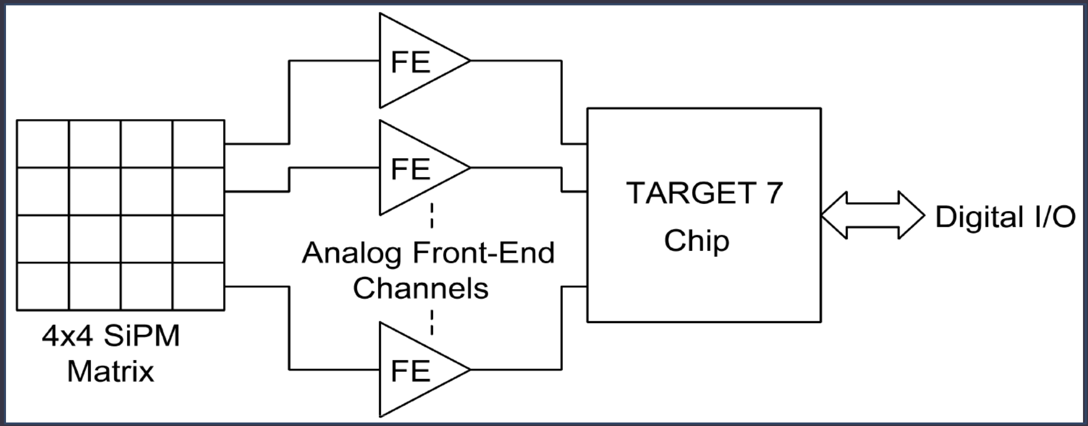
- Focal plane and camera electronics protected by a retractable shutter
- Electronics cooled by a chiller system

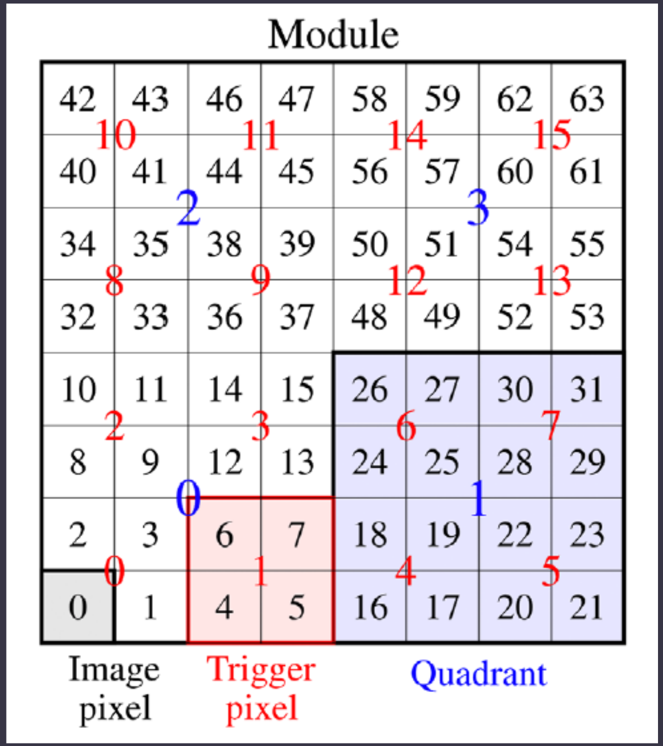
pSCT Matrices: Module readout and trigger



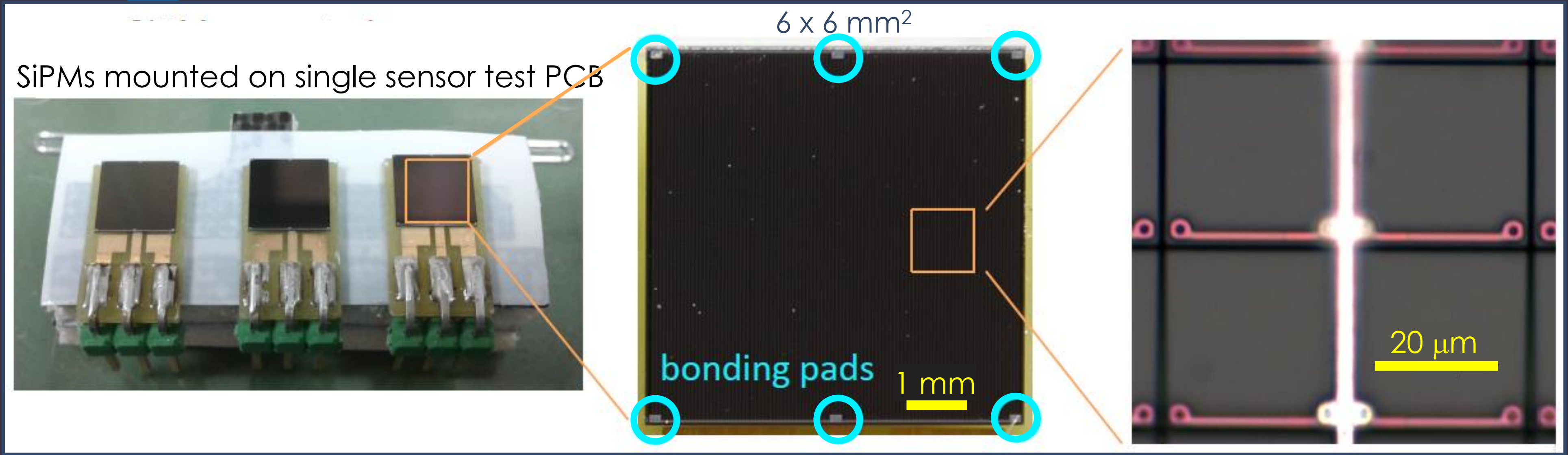
Backplane of the pSCT camera hosting 2 TARGET–7 modules



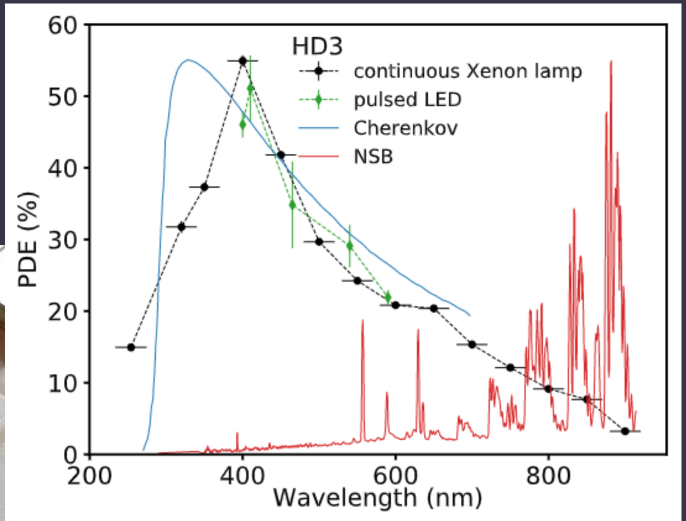
- A single FPM contains 64 **image pixels (black)**
  - 1 square group of 4 image pixels makes up **1 trigger pixel (red)**
  - ➔ Single FPM contains 16 trigger pixels
  - 1 square group of four trigger pixels makes up **1 FPM quadrant (blue)**
    - Quadrants mounted onto a printed circuit board (PCB)
- Pixels are associated with channels, trigger pixels with trigger groups, and quadrants with ASICs in the software



FBK NUV-HD SiPM sensors



- The Italian National Institute for Nuclear Physics (**INFN**) has been involved in the **development and testing** of SiPMs suitable for Cherenkov light detection in the Near Ultraviolet (NUV SiPMs)
- **NUV High-density (HD) SiPMs** produced at **Fondazione Bruno Kessler** (FBK, Trento, Italy)*
  - **Wide** dynamic range
  - **High** Fill Factor (FF)
  - **Increased** PDE
  - **Low** correlated noise

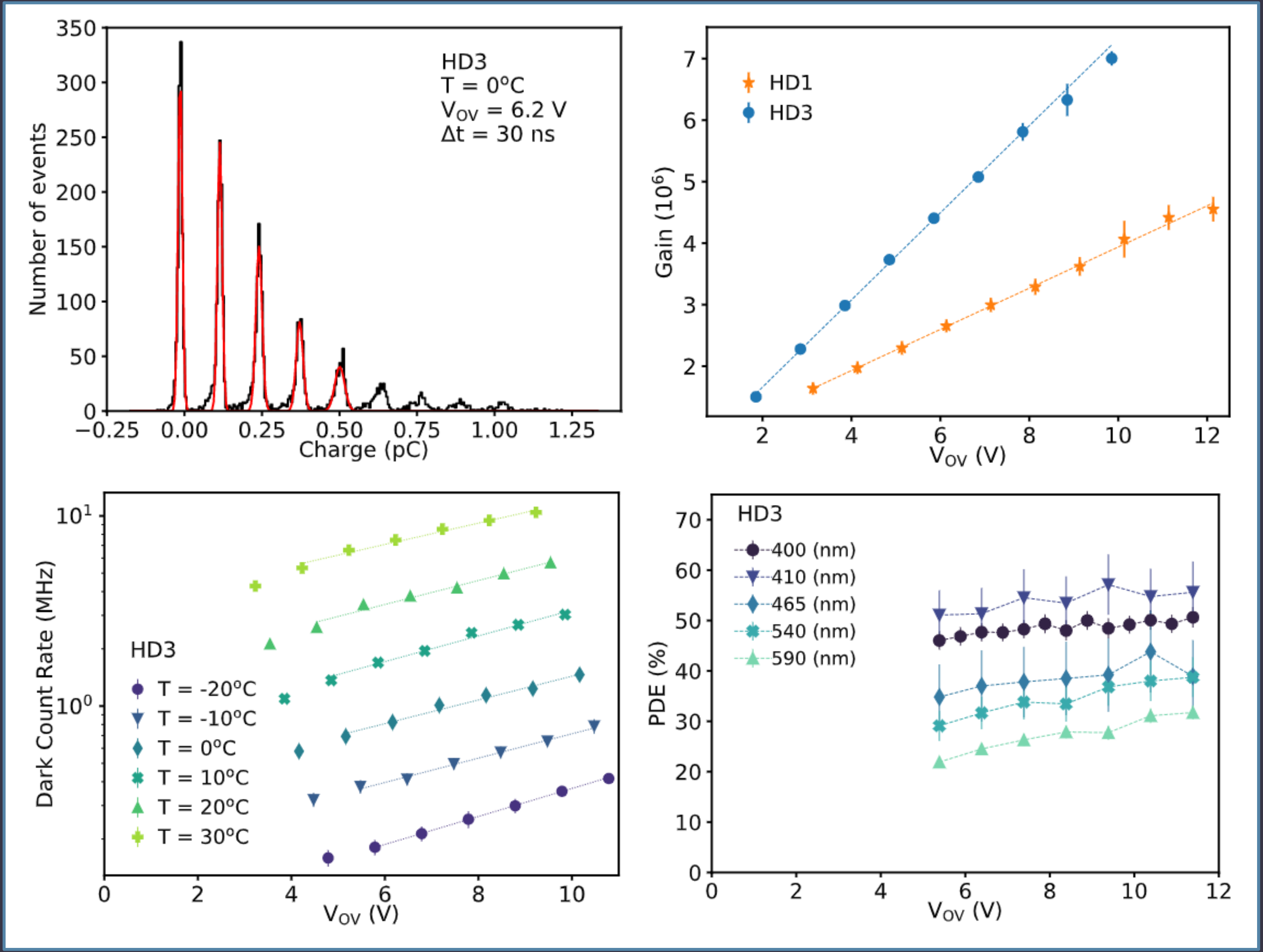


* For more information, see http://srs.fbk.eu/optimization-sipm-technology

FBK NUV-HD SiPM sensors

- Full characterization of FBK NUV-HD3 SiPMs (6x6 mm² area, 40 μm cell pitch
- Results prove excellent performance of the device in terms of gain, cross-talk probability, PDE, and SNR

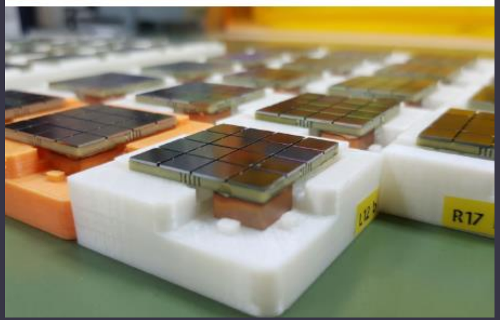
	HD3
Breakdown voltage at T = 25 °C	(26.49 ± 0.02) V
Change in V_{BD} with T	(31.1 ± 0.5) mV/°C
Quenching resistance at T=25°C	1.11 ± 0.01 MΩ
Change in R_q with T	(−10.2 ± 0.4) kΩ/°C
Saturation current at T = 25°C	(32 ± 9) pA
Gain at V_{OV} = 5 V	$\sim 4 \cdot 10^6$
Change in gain with OV	$(7.1 \pm 0.1)\ 10^5$/V
SNR at V_{OV} = 5 V	~ 7
Saturation of detected photons	$V_{OV} \geq 4$ V
Cross-talk probability at V_{OV} = 5 V	~ 20%
Change in cross-talk probability with OV	(6.1 ± 0.4)%/V
DCR at $V_{OV} \simeq 5$ V and T = 20°C	(3 ± 0.2) MHz
PDE (400 nm) at $V_{OV} \simeq 5$ V	54.9% ± 0.8%



Ambrosi+2022a
Submitted to NIMA

FBK arrays for the pSCT Camera

- 36 FBK NUV-HD3 optical units assembled, tested and characterized at INFN laboratories in Italy
- Study of performance and homogeneity in terms of breakdown voltage, gain, signal to noise ration (SNR), and dark count rate (DCR)



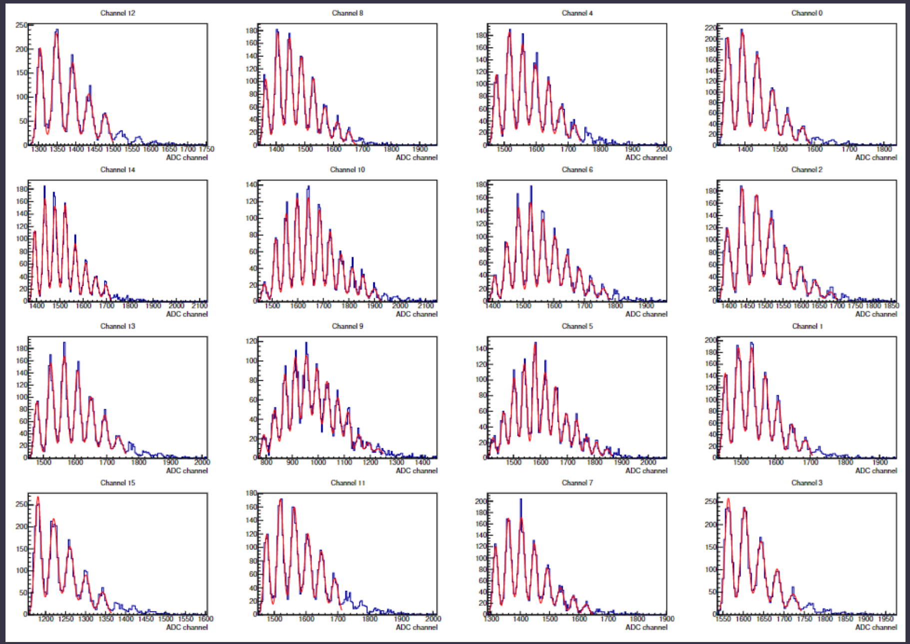
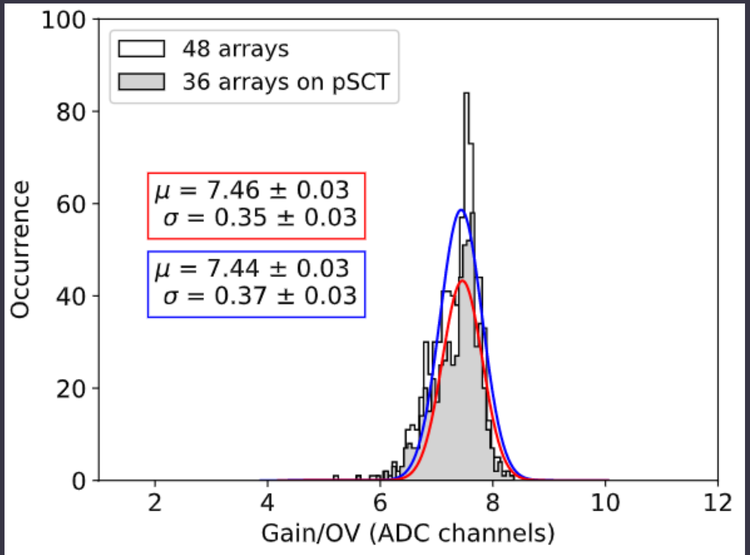
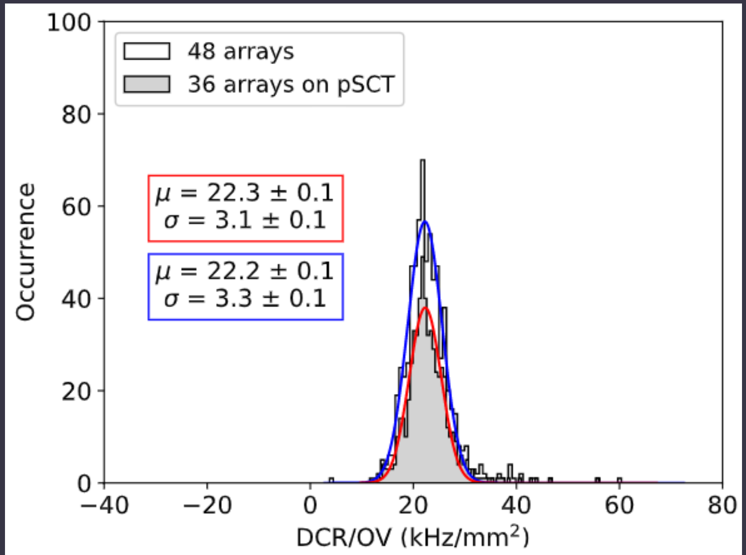


Table 1: Summary of performance of the 36 arrays installed on the pSCT camera.

	Mean	Standard deviation
V_{BD} (V) (first group)	26.33	0.05
V_{BD} (V) (second group)	26.54	0.06
Gain (ADC channels/OV unit)	7.5	0.4
SNR at OV=6.5 V	4.9	0.2
DCR (kHz/mm^2/V)	22.3	3.1

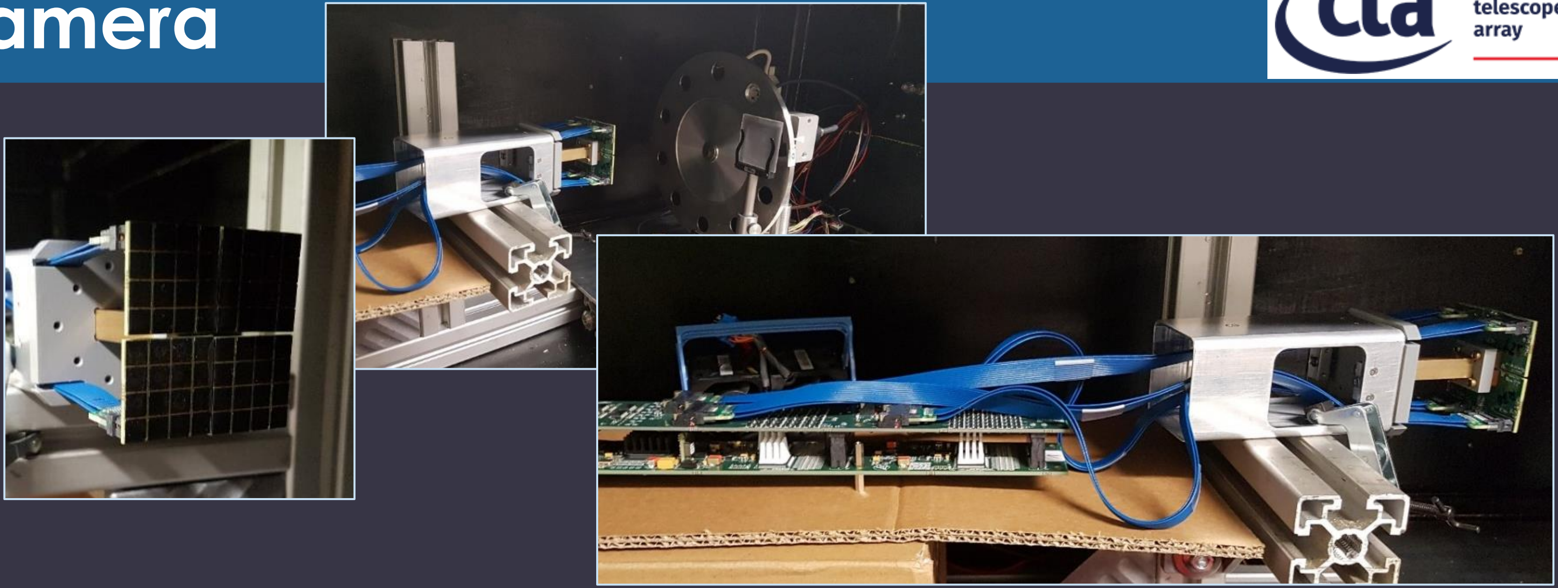
Ambrosi+2022b
Submitted to NIMA



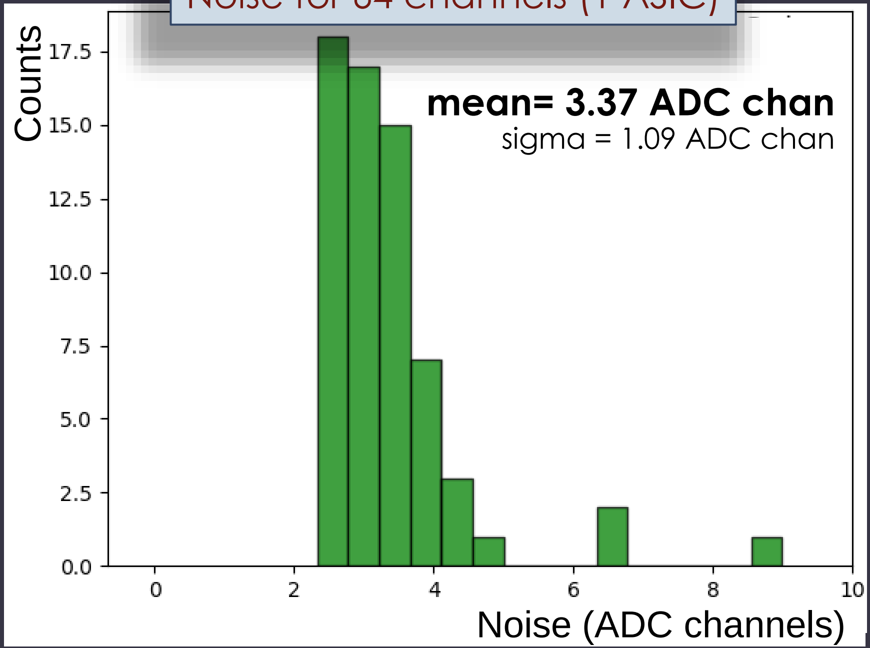


FBK arrays for the pSCT Camera

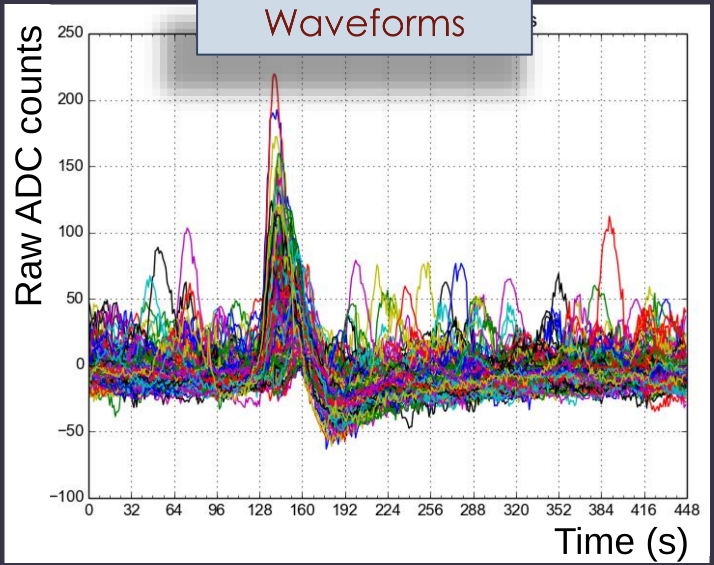
- **Quality control tests** performed with fully assembled modules
  1. Pedestals acquisition
  2. Waveform acquisition
  3. Trigger verification



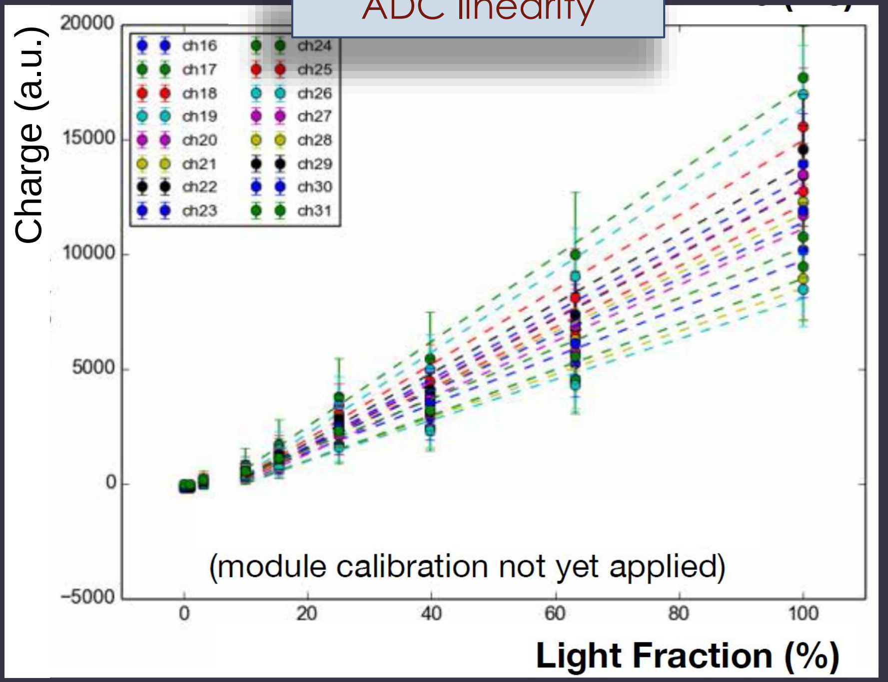
Noise for 64 channels (1 ASIC)



Waveforms

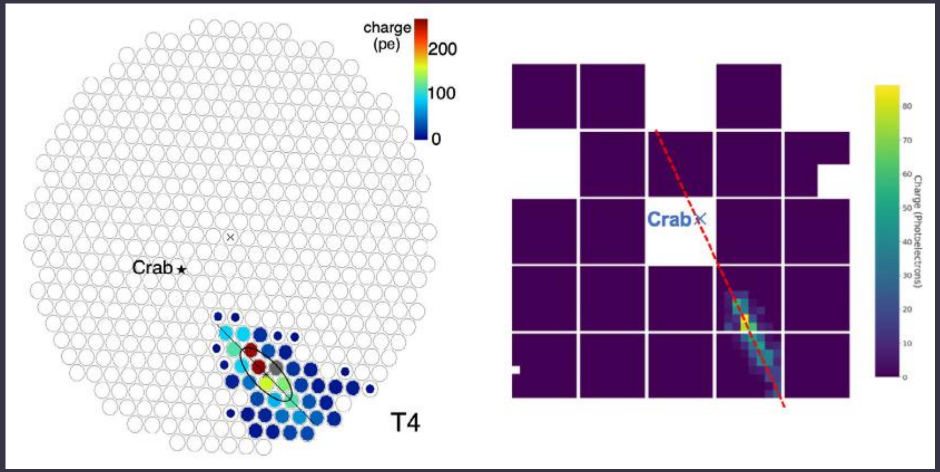


ADC linearity

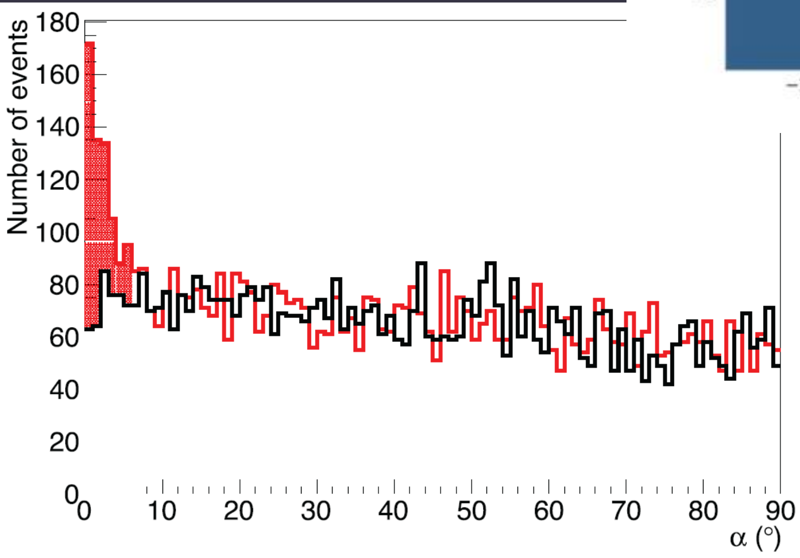


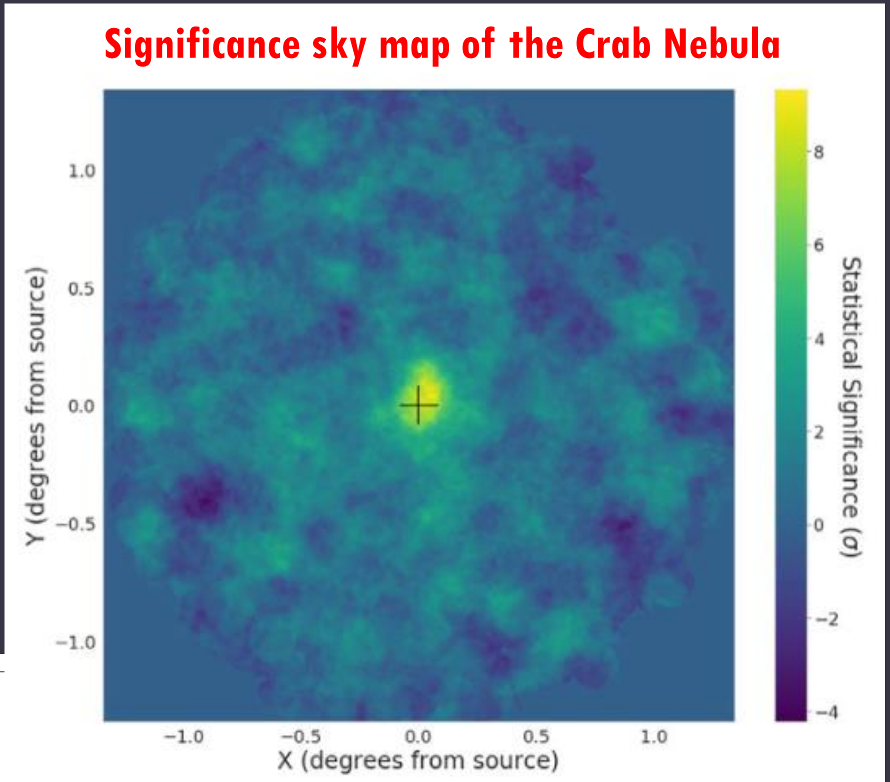
Detection of the Crab Nebula with pSCT

- The first pSCT observation campaign, conducted in January and February 2020, demonstrated the detection of gamma-ray emission from the Crab Nebula with a statistical **significance of 8.6 σ**
  - Total exposure (without correction for acquisition deadtime): 21.6 hours OFF, 17.6 hours ON
  - No full MC simulations: **VERITAS** providing independent information about nature and properties of air showers observed simultaneously - clear identification of true air shower events



Same air shower event (3.5 TeV gamma-ray reconstructed by VERITAS) observed by VERITAS T4 (left) and pSCT (right).





Adams+2021

https://doi.org/10.1016/j.astropartphys.2021.102562

Angle α between major axis of the image, and a line joining image centroid image to the location of Crab
- Red = 17 . 6 hrs ON source obs
- Black = same duration OFF source obs, after applying gamma-ray selection cuts
- Shaded region = the < 6° cut on α

pSCT Camera Upgrade

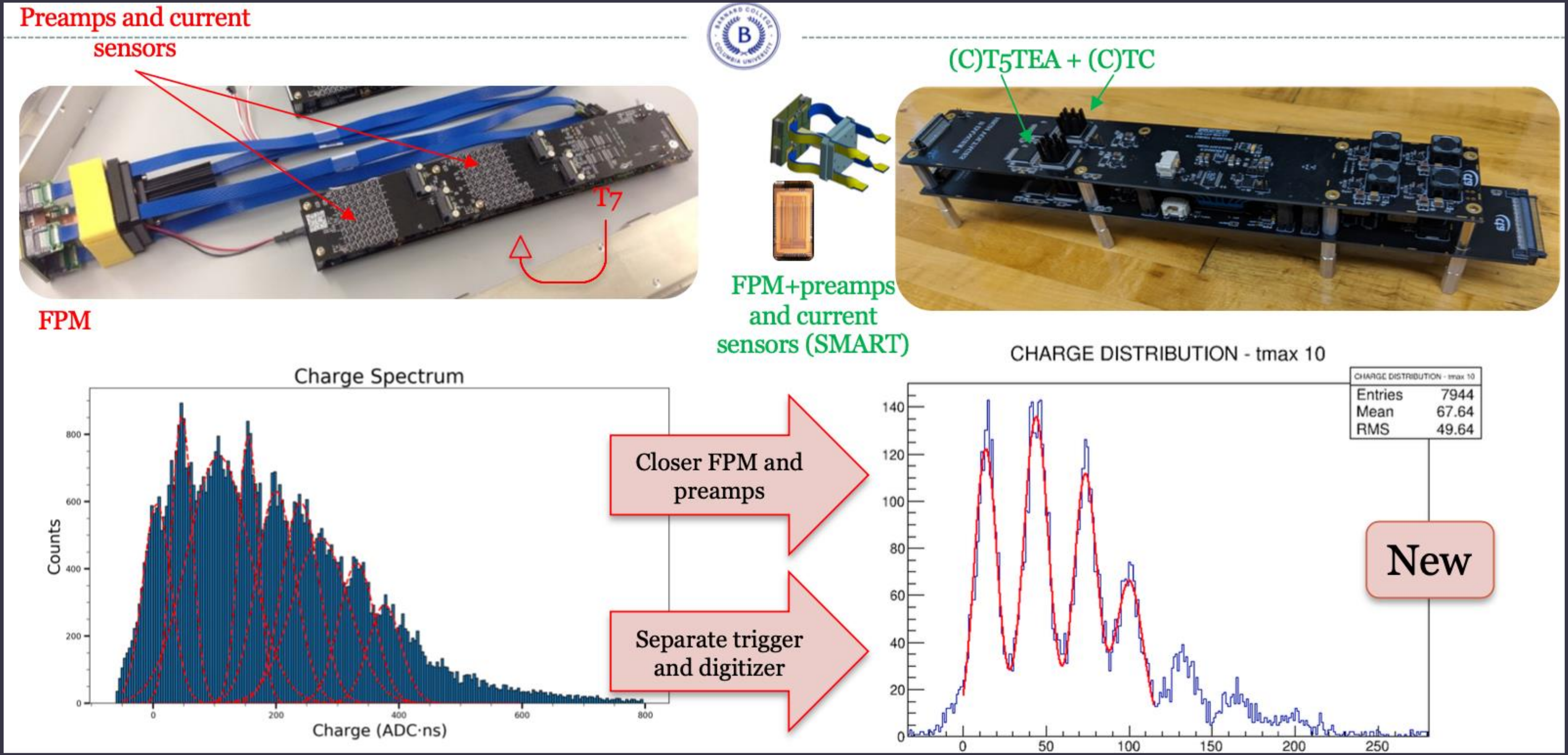
- Populate all 9 camera sectors → 177 modules – 11328 pixels
- SiPMs produced by FBK with high PDE and low optical CT
- New electronics to reduce noise
  1. **SMART ASIC**: Integrated pre-amplifier attached to SiPM boards
  2. **CTC ASIC**: 16 channels sampler (1GSa/s) and digitizer
     1. Analog buffer with 16k cells per channel → 16 μs storage depth
  3. **CT5TEA ASIC**: 16 channels trigger
     - Channels are summed in groups of 4 (16 trigger pixels per FEE modules)
     - Adjustable threshold for each group

- New DACQ boards, module cage, camera frame and redesign of the cooling system

→ **Improvement in single-photon resolution, lower minimum threshold and lower noise**

→ **Reduction of noise both on digitized signals and in the trigger circuit**

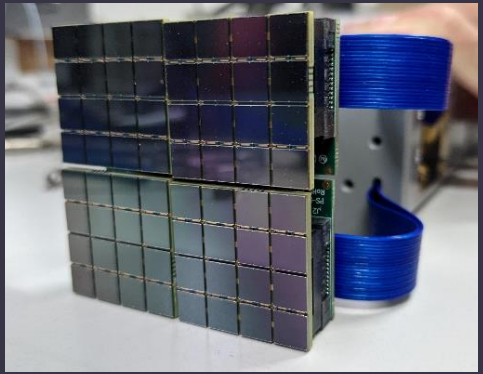
pSCT Camera Upgrade



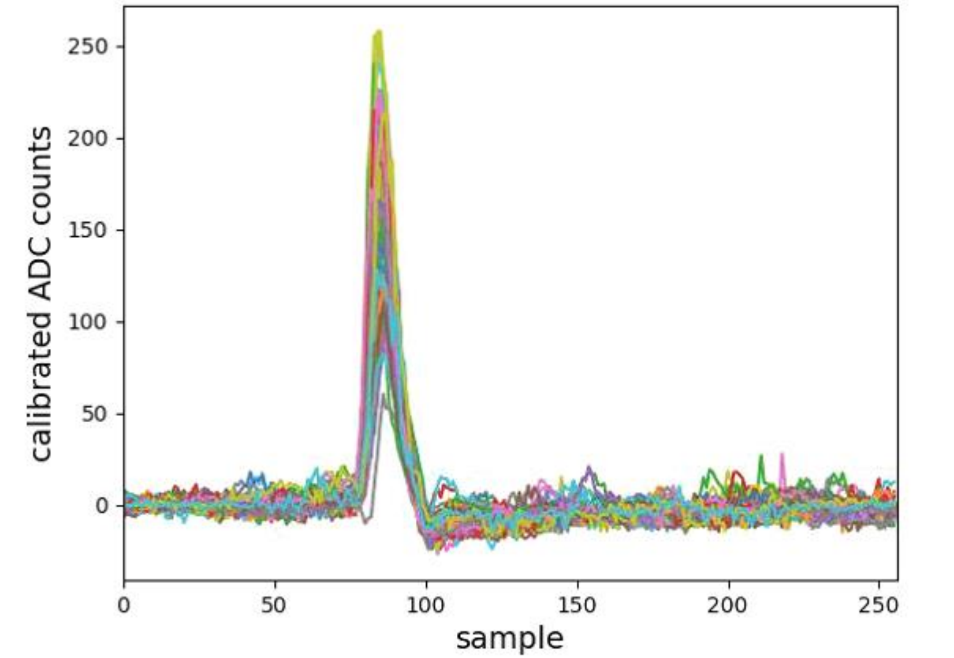
Slide by M. Capasso – SCT 2021

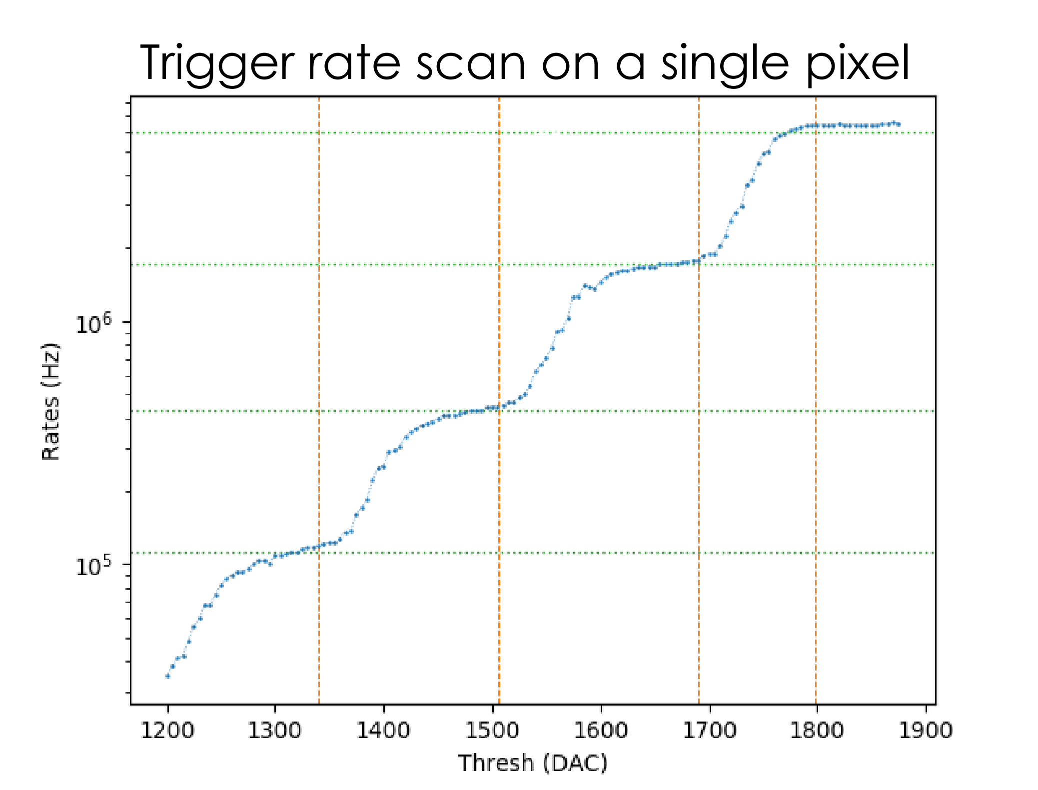
pSCT Camera Upgrade: Recent electronics tests

- Assembly and test of full chain from SiPM to FEE



Digitized waveforms

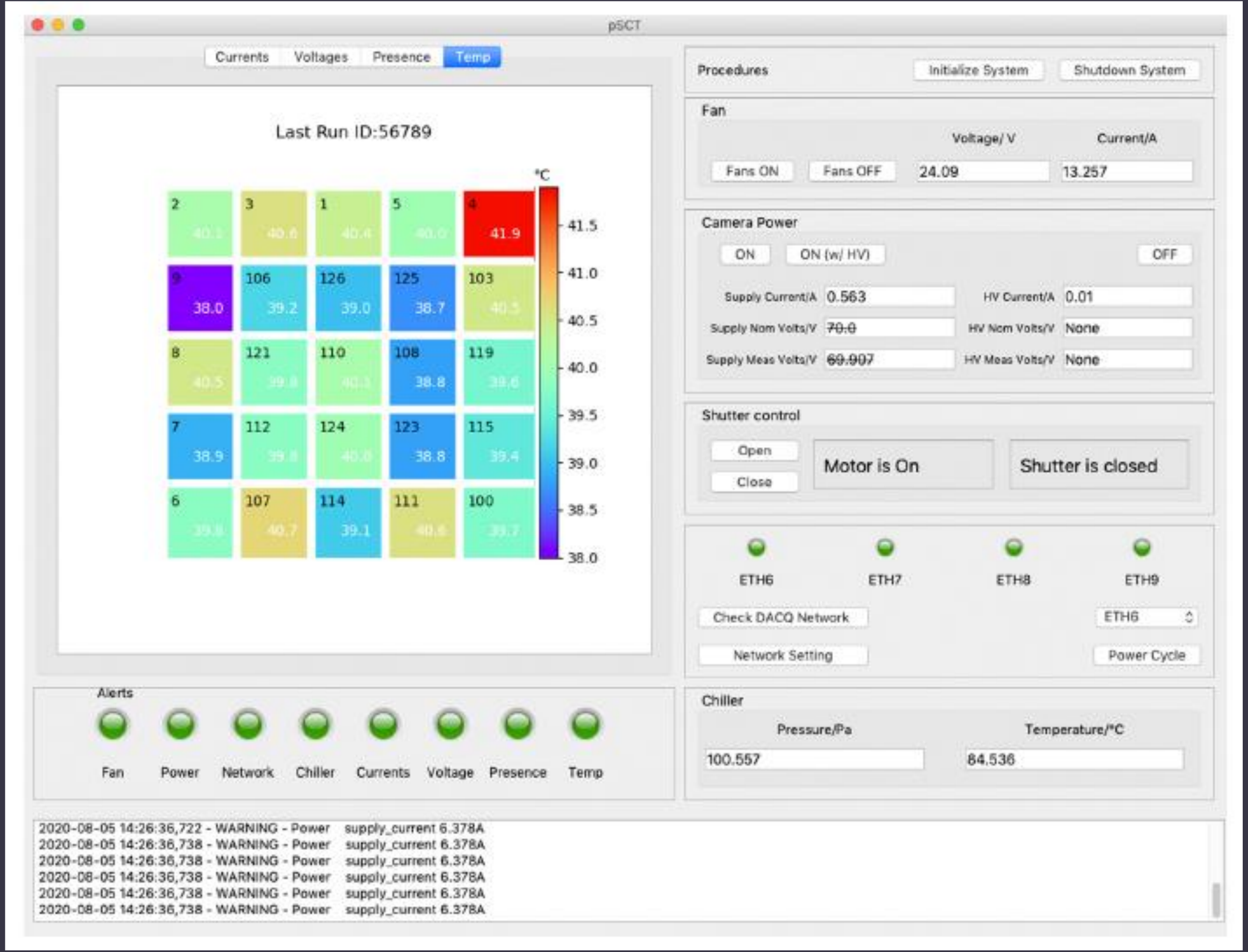




pSCT Software

- New software system in development to replace the current monitoring and data taking scripts
- A single camera control server to communicate with, monitor, and log the status of all camera hardware
  - Slow-control (SC) system
    - Powering and monitoring camera hardware components
    - SiPM temperature control
    - Creation of alerts
  - Run-control (RC) system
    - Load configuration settings of FEE modules
    - Start, monitor, and stop runs
    - Recording of the physics-level and calibration
- SC Graphical user interfaces (GUI)
  - Fully tested under observing conditions
  - Working on debugging the Run Control GUI under operating conditions

First version of the Slow Control (SC) GUI



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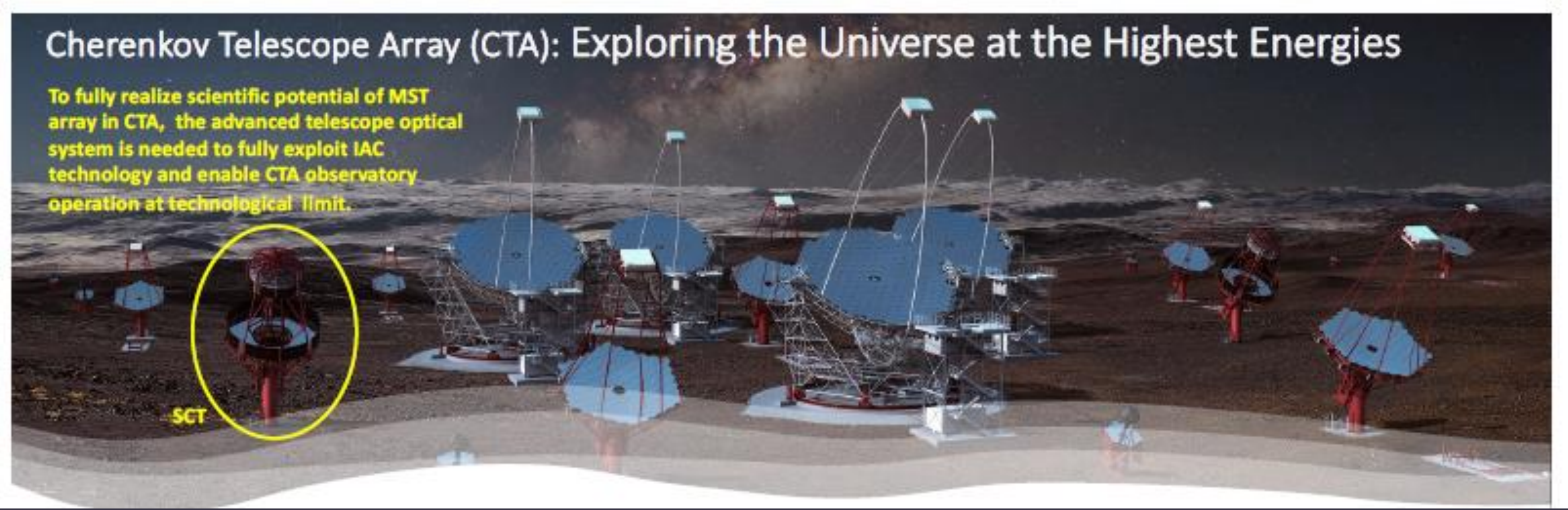
SCTs in CTAO

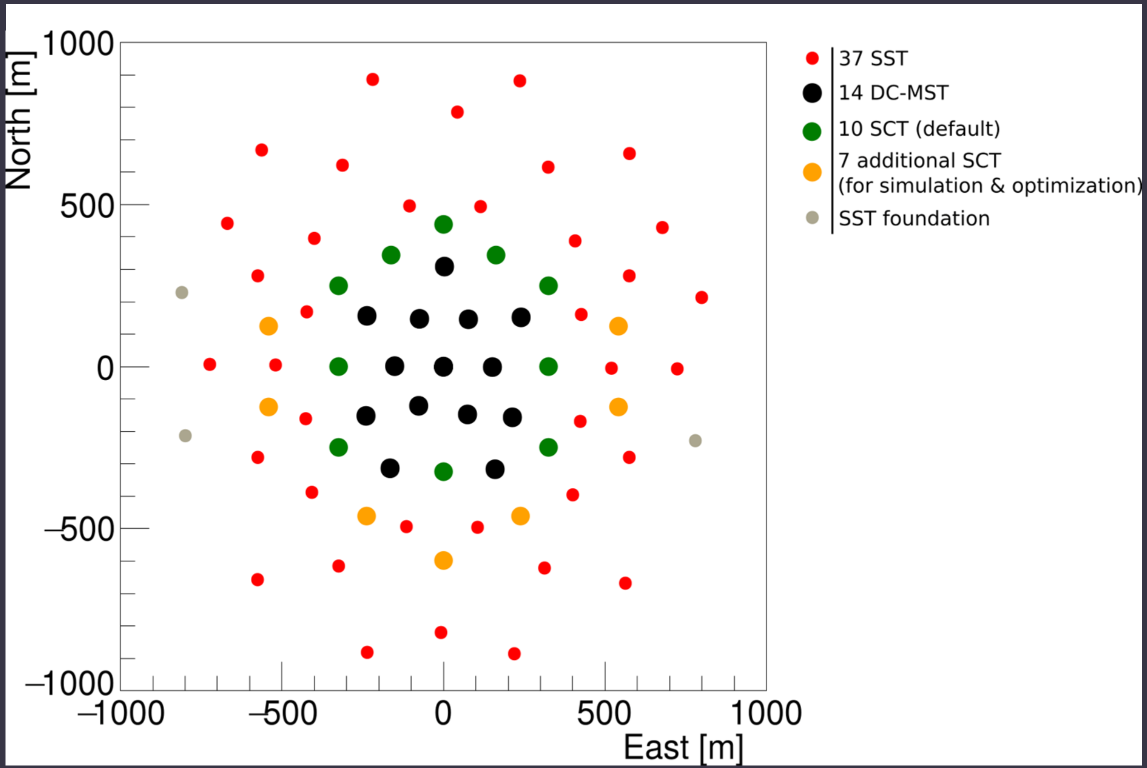
- Goal of SCT Project has always been to:
  1. Enhance the performance of CTA
  2. Complete the medium-sized telescope array at CTA-S or CTA-N (if needed)
- In the era of the Threshold Configuration: **Add 10 SCTs to CTA-S or CTA-N**
  - This was the plan presented to *and endorsed by* the U.S. Astro 2020 Decadal Survey
- In the era of the **Alpha Configuration: Add 11 SCTs to CTA-S**
  - Discussed now with CTAO management
  - Studied in simulations with Prod3b and Prod6



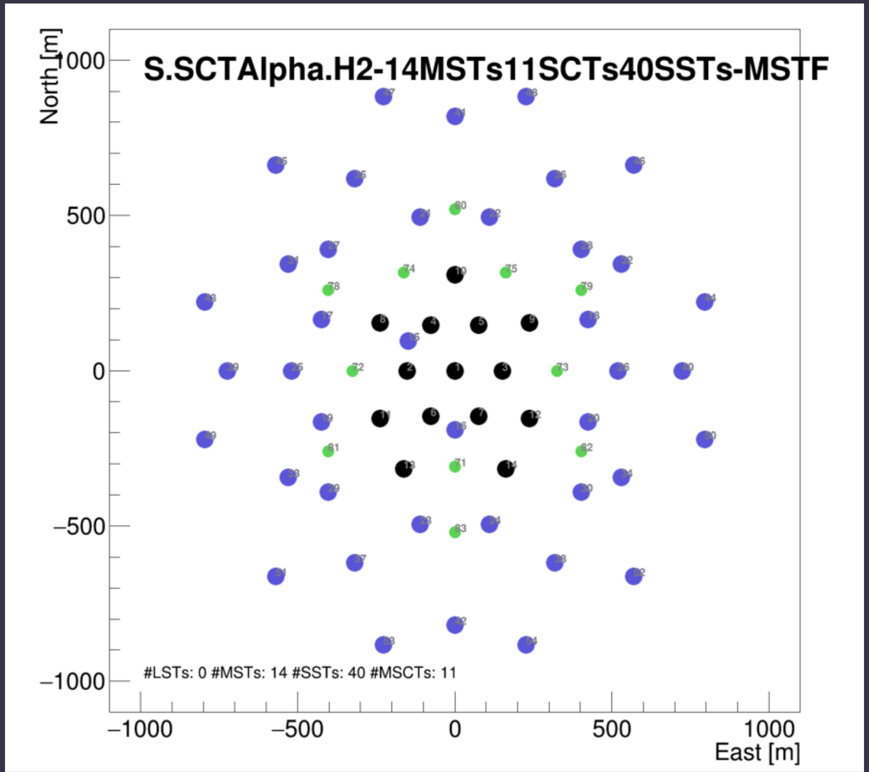
SCTs in CTA-S

- Extensive IRF studies and MST/SCT Prod3b “Alpha” comparisons on CTA Gitlab:
  - https://gitlab.cta-observatory.org/cta-science/simulations/simulation-and-performance-parallel-mode/future-extensions/prod3b-sctalpha-performance/-/tree/main/

Preliminary proposition of including SCTs in CTA-South



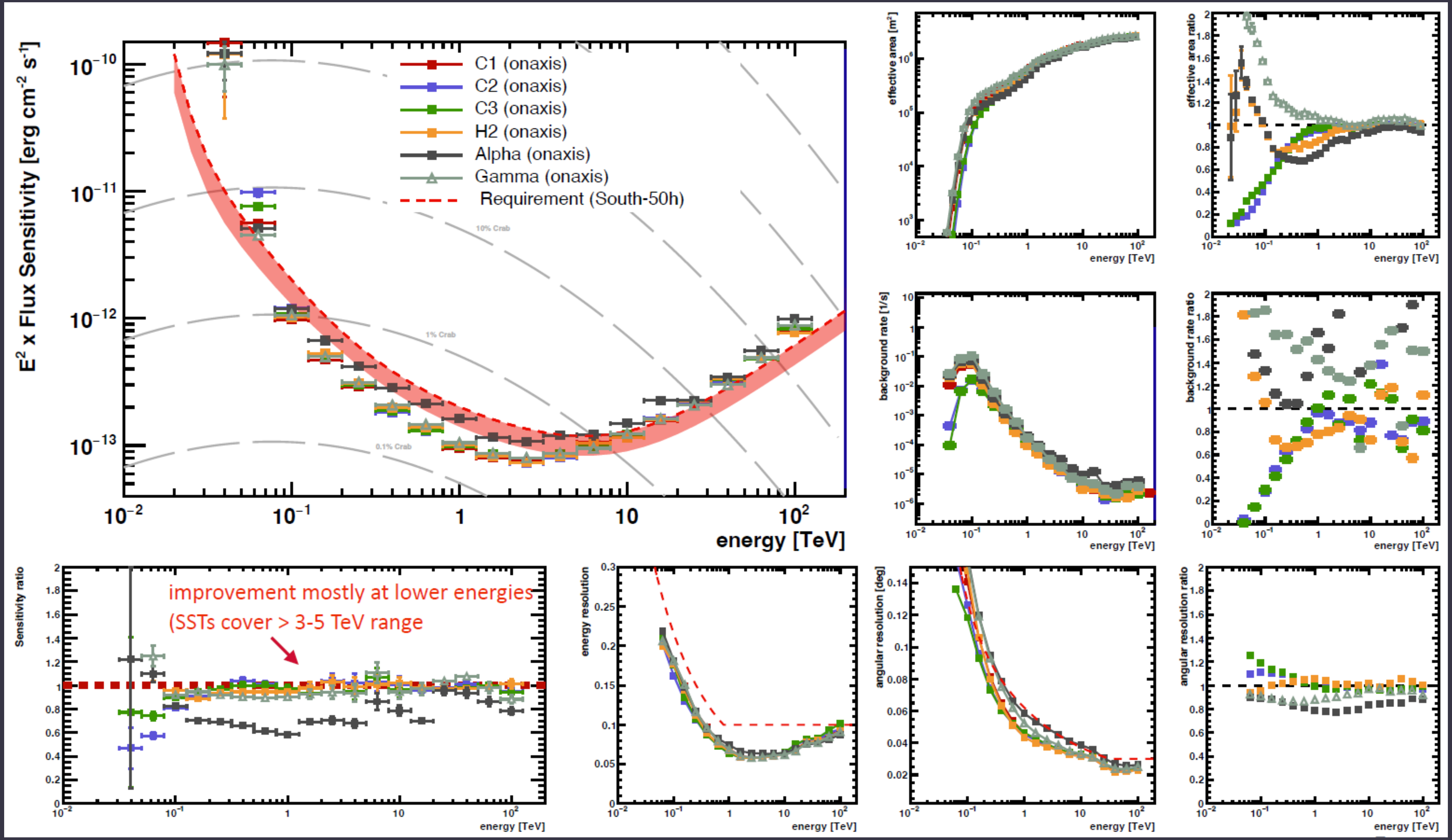
Closest configuration tested with Prod3b



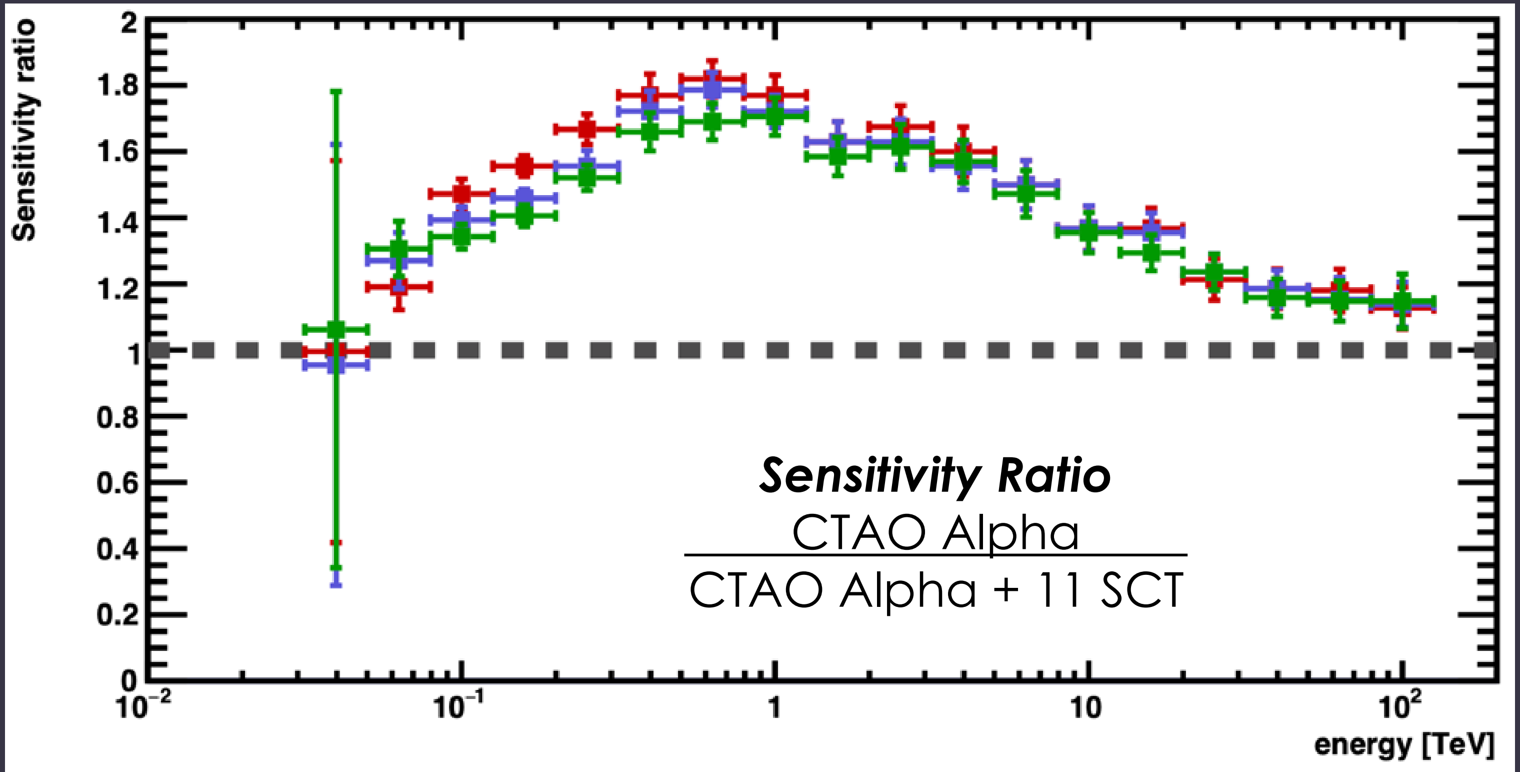
SCT Simulations

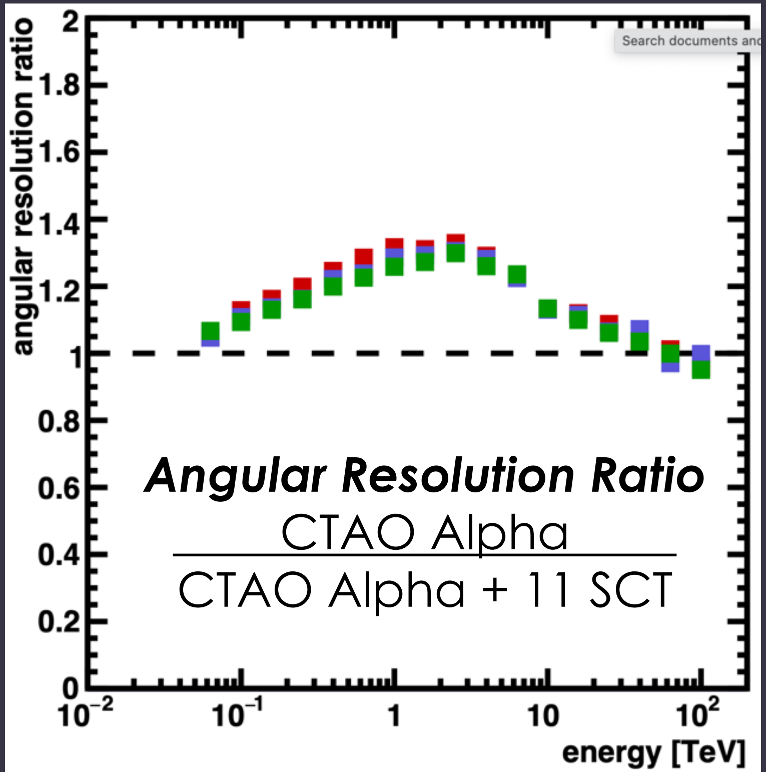
- Simulations adding 11 SCTs to the CTA-S Alpha configuration (14 MSTs + 11 SCTs)

- On-axis
- 50 hours
- 20 deg zen
- Average azimuth



SCT Simulations





- **3-4° off axis at 20° zenith angle**
  - The three colors correspond to slightly different layouts for the added SCTs
  - Note that the time needed to detect a faint source scales with the sensitivity *squared*

SCT Summary and Outlook

- **Recent results**
  - Improved optics alignment
  - First measurement of inclination-dependent PSF measurement
  - Further work on current camera to improve data analysis
  - Full-chain (FPM+SMART+FEE) measurements for camera upgrades
    - Production for full camera started
- **Next steps**
  - Continued commissioning, engineering, and operations
  - Improvements in Optical System (alignments and off-axis PSF)
  - Camera upgrade
    - Production and installation of upgraded sensors and electronics
  - Discussions with CTAO Project Office
    - Infrastucture planning and budgeting for SCT addition in CTA-S

THANK YOU!

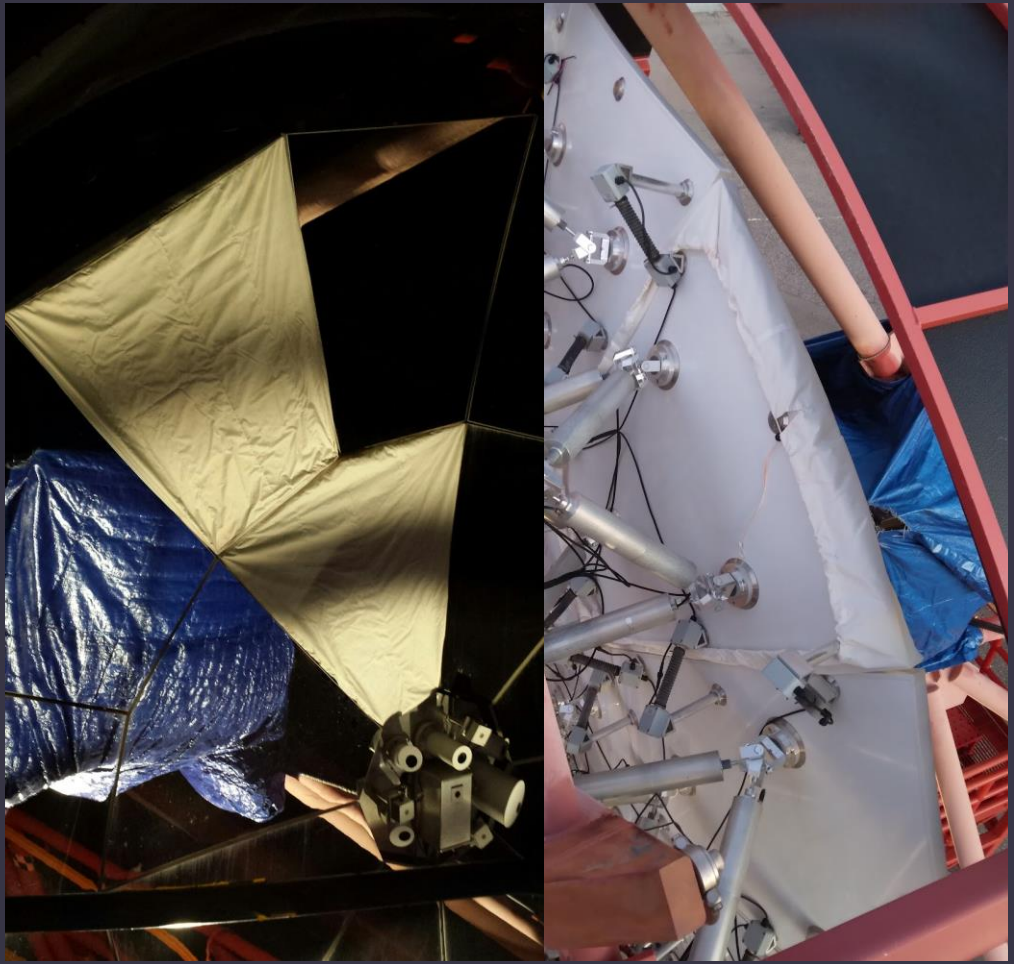
BAKCUP

Recent pSCT Activities at FLWO

47 nights of on-site technical work:
- 31 nights for optical alignment / tracking
- 14 nights for DAQ / control software
- 2 nights for camera-system testing

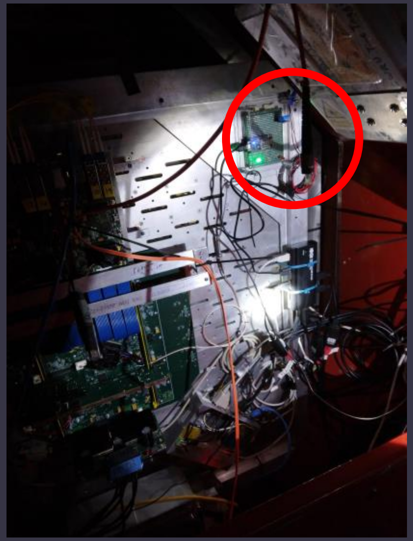
~50% of nights VERITAS operated (since Feb 1)

Fabric Covers Developed for Secondary Mirrors



Full set of 24 covers designed, prototyped & manufactured
Enables day-time technical work & 2022 camera upgrade

Environmental Monitoring Sensors Installed:
Camera & server room;
Temp., humidity, water, etc



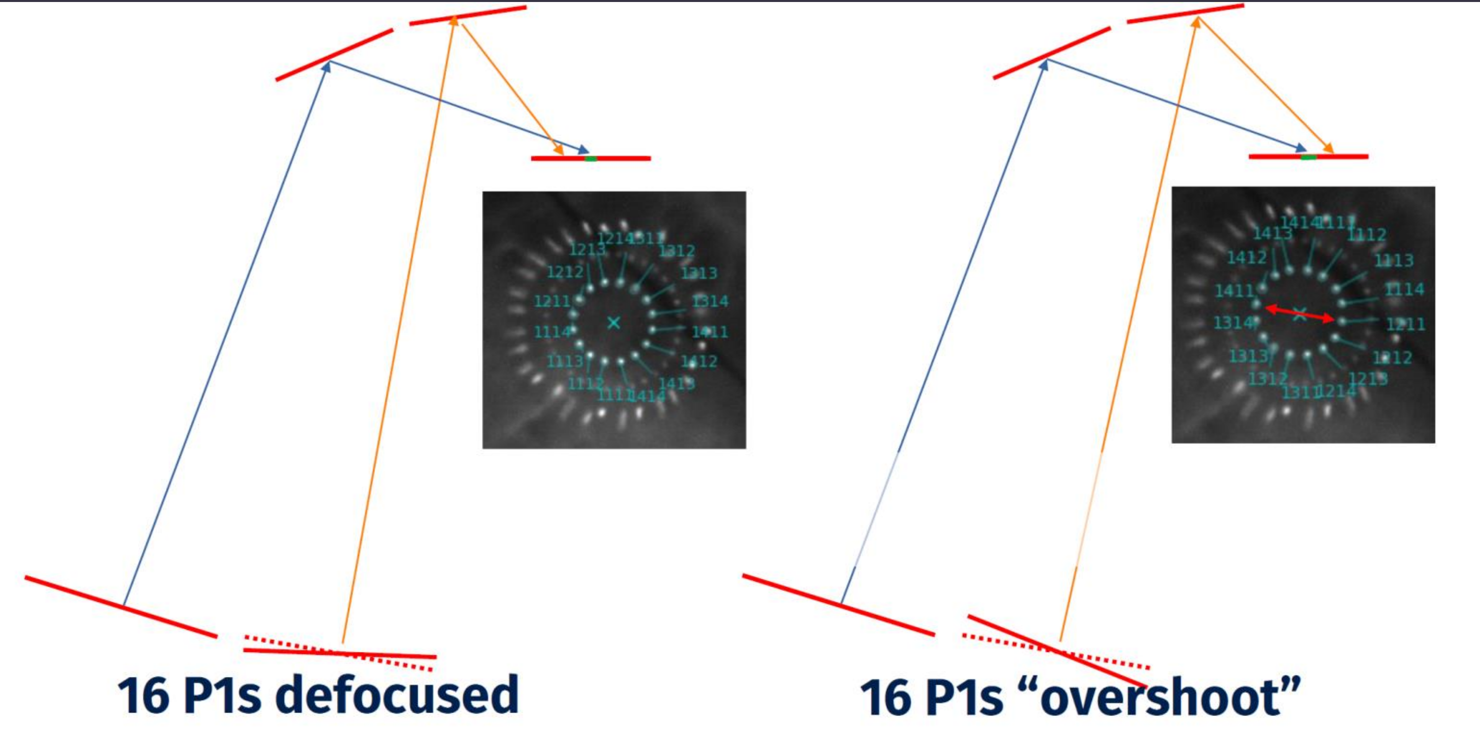
Tower Interlock Switch Installed
Prevents telescope motion when platform extended
Still need to run cable to control panel

Improved Emergency Response (total power loss):
Portable generator connects (400 V) to main drive cabinet
& not just emergency cabinet (~1 h response => ~10 min)
Thank you DESY!

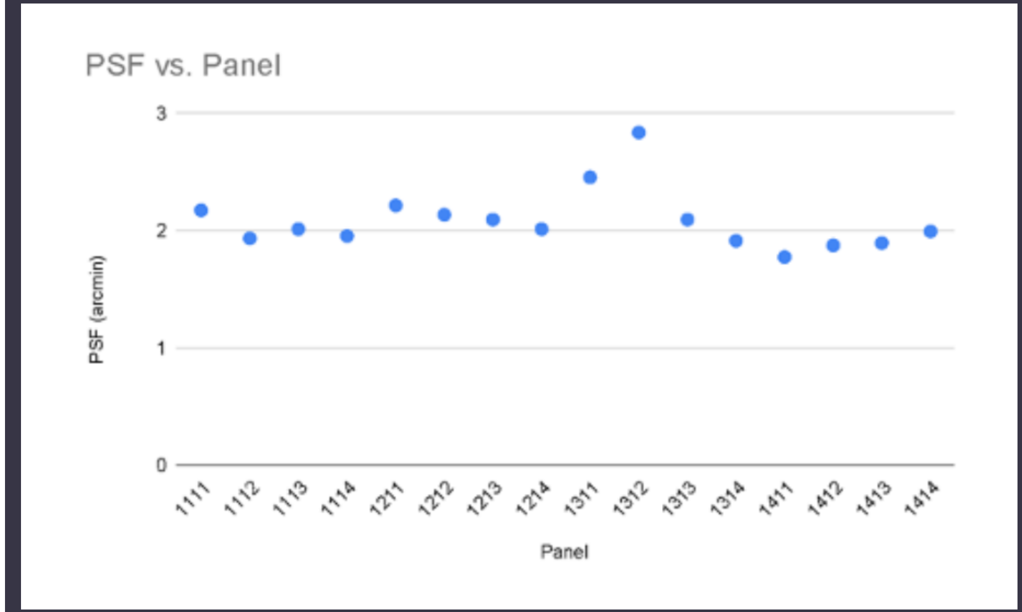
The pSCT Optics

Improved focus via overshoot method

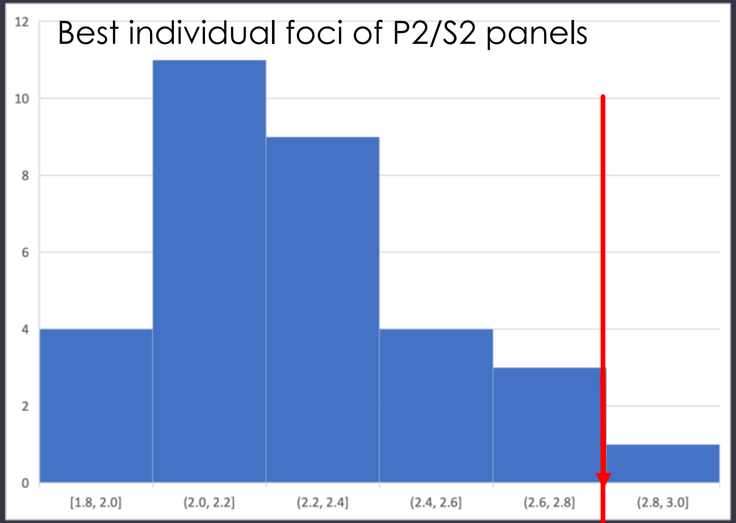
Overshoot method



P1/S1 PSF measurements

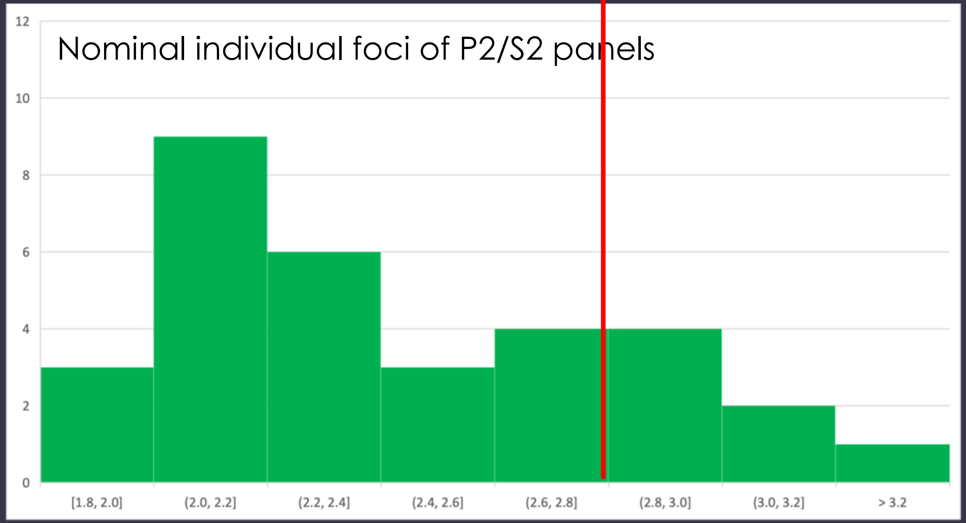


The pSCT Optics – PSF Analysis



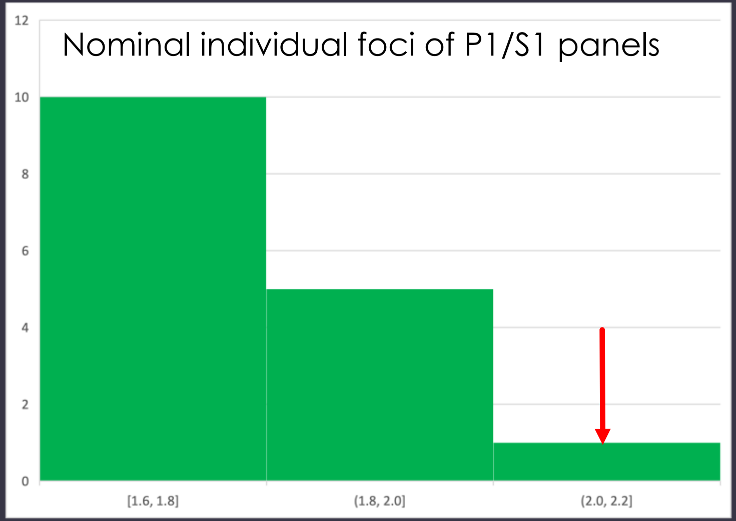
Best achieved on-axis focus of entire P2/S2 ring of 32 images is 2.8 arcmin.

PSF [arcmin]



P1/S1 and P2/S2 PSF analysis

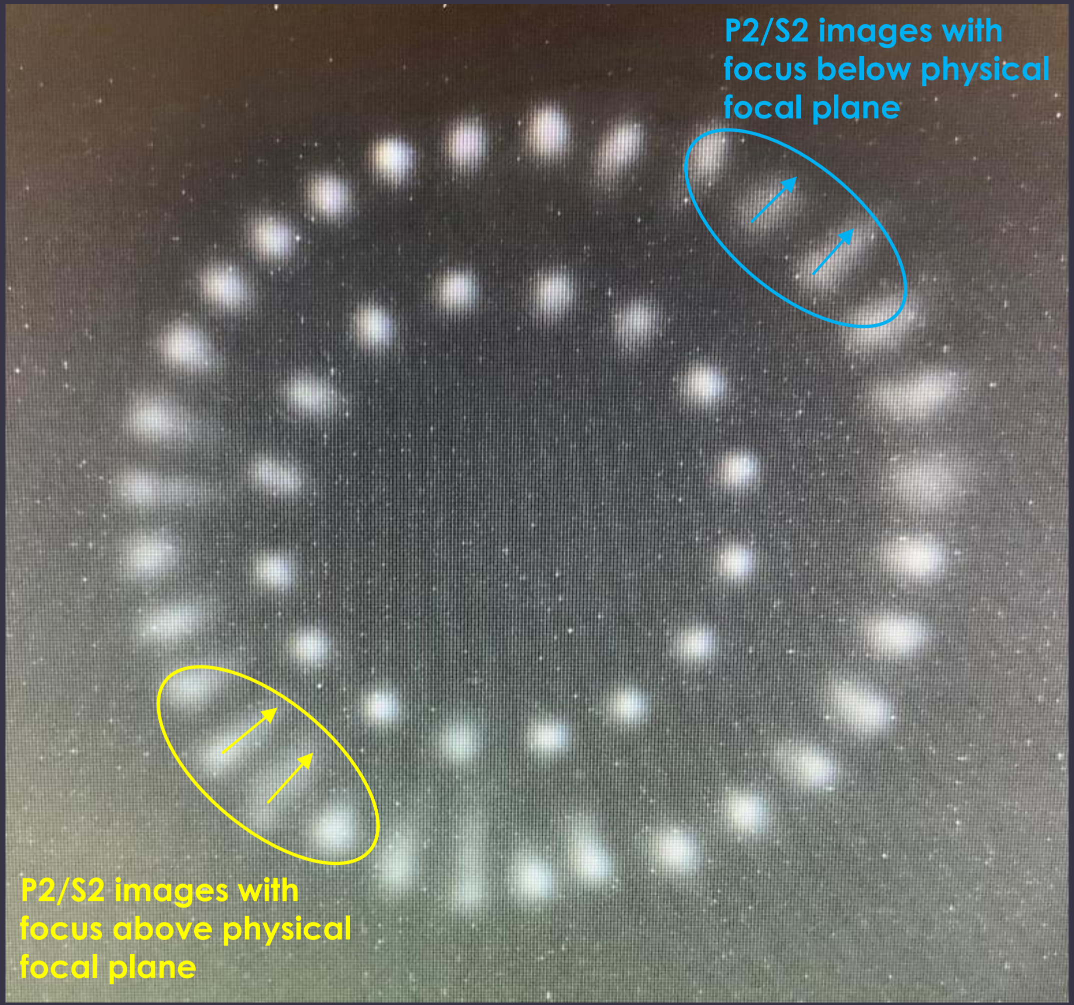
- The achieved PSF of focused P2/S2 and P1/S1 rings is comparable to the PSF of individual pairs of panels, which indicates that the alignment errors are significantly subdominant to the figure errors of individual mirror segments.
- The PSF of entire SCT is dominated by the figure errors (variations in foci) of P2/S2 pairs. The slope errors of mirrors defining PSF at the best focus are subdominant.
- The deficiencies in the fabrication accuracy of the figures of P2 panels detected during manufacturing have now been confirmed as the main limiting factor of on-axis SCT OS performance.



Best achieved on-axis focus of entire P1/S1 ring of 16 images is 2.1 arcmin.

PSF [arcmin]

The pSCT Optics – Alignment

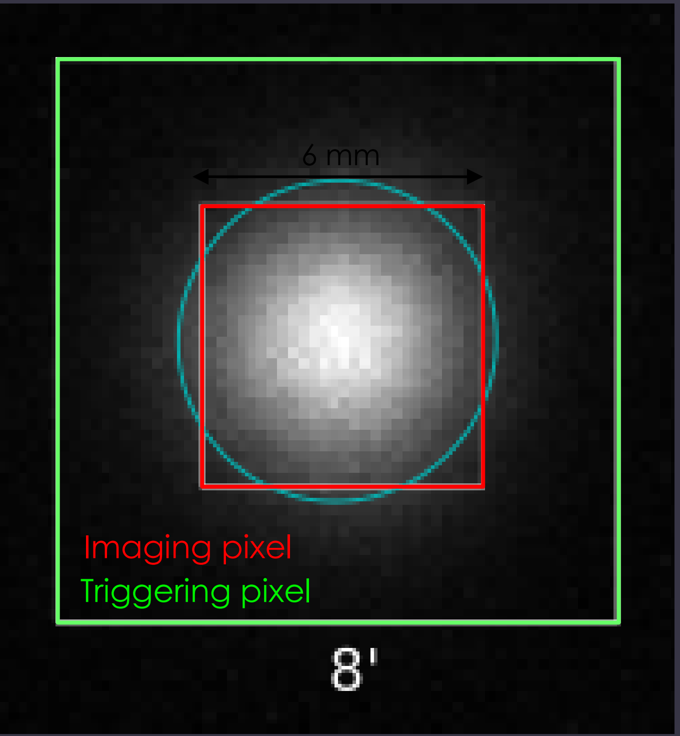


M2 & M1 global alignment

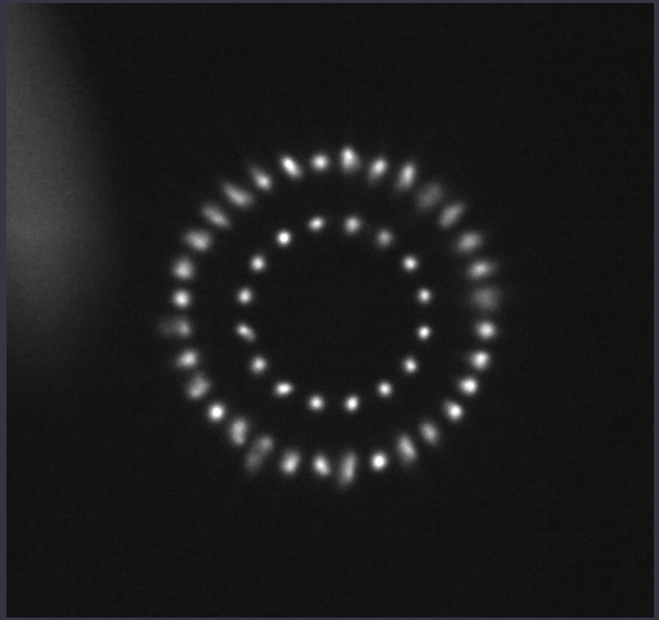
- A fast method has been developed for M2 alignment, based on the elongation structure of the P2/S2 images of pSCT OS.
- Rotation angles of M2 (Rx , Ry) are computed from the data in a single image (see example) and require two-three iterations to achieve convergence at the noise level.
  - Example shown corresponds to 2×10^{-3} rad misalignment (7.2 arcmin or 5.4 mm displacement at the edge of 2.7m M2 radius)
- Alignment accuracy achieved: $\sim 2 \times 10^{-4}$ rad (0.54 mm displacement at the edge of 2.7m M2 radius) and is limited by the distribution in PSF and focal length of individual P2/S2 pairs.
- Elevation-dependent deformations in the M2 OS structure dominating on-axis PSF degradations exceed significantly this limit and are correctable by M2 OS re-alignment (in principle)

SCT best on-axis focus and 1 degree off-axis initial result

On-axis PSF (Arcturus, 05/2022)



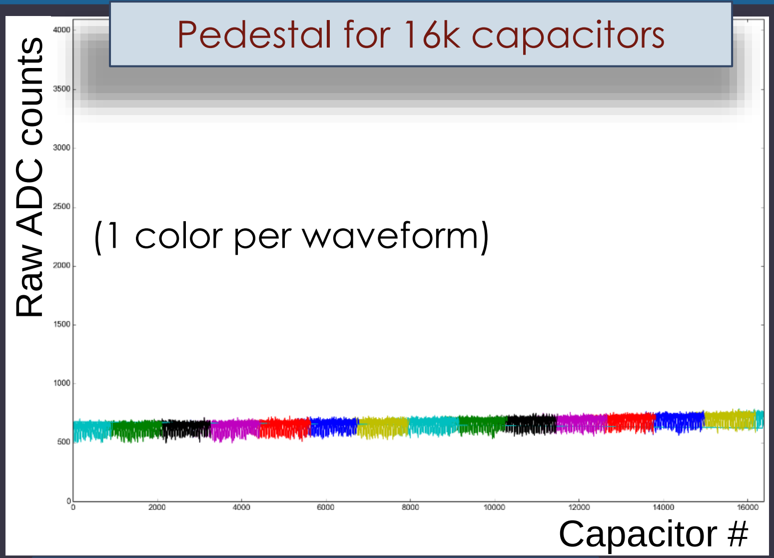
- The best SCT on-axis optical PSF of 2.6' arcminis achieved with the σ_y,σ_x determined as best fit of the Gaussian profile
- $$PSF = 2 \times \max(\sigma_y, \sigma_x)$$
- The pre-construction "acceptable" on-axis PSF: 3.6' and the "desirable" PSF: 2.6'
- >80% containment within a γ-ray imaging pixel (4'), >99.5% within a trigger pixel (8').
- Further minor improvements in the pSCT on-axis optical PSF might be possible by re-arranging individual P2 panels on the telescope (diminishing return). Ultimately, the SCT optical PSF can be improved further by reducing P2 panels figure fabrication errors; significant fraction of P2 panels have not met specifications in pSCT implementation and this parameter can be improved within current MLT technology.

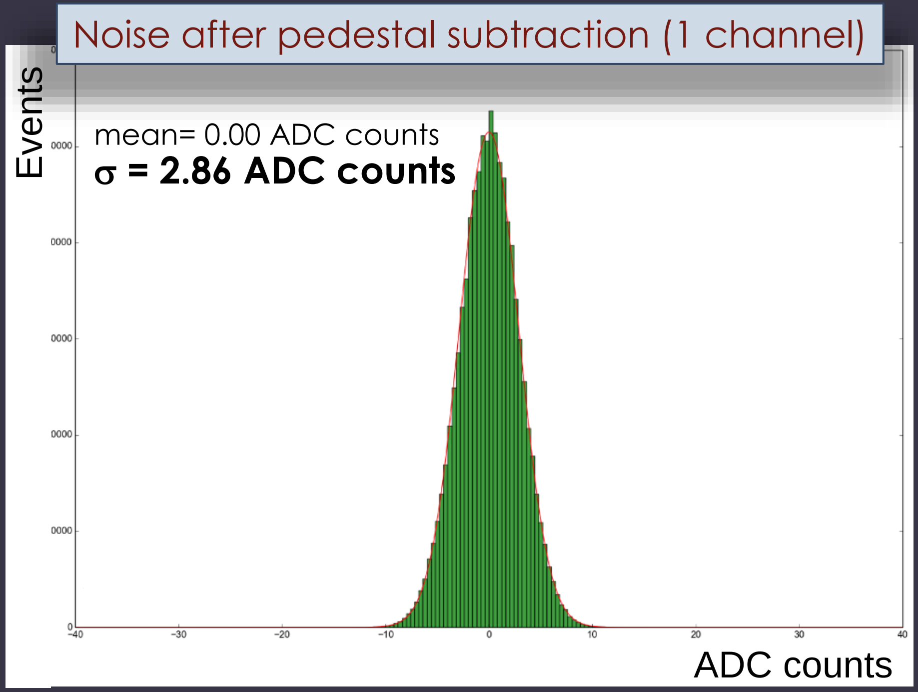


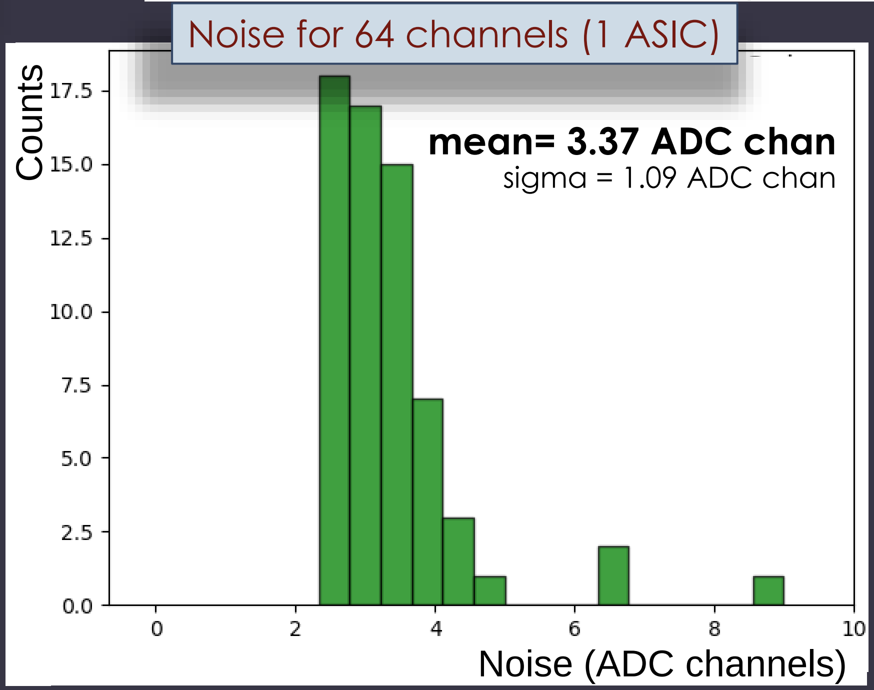
The initial work was conducted on the off-axis alignment of pSCT utilizing flat screen (no curvature to correct for astigmatism). The result achieved so far at 1 degree field angle is 3.3 +/- 0.2 arcmin measured in four perpendicular directions. A segment of the full size curved focal plane was fabricated, and test fitted to the pSCT focal plane. The work is scheduled to continue in May-June.

INFN modules for pSCT: QC and tests

1. Pedestal acquisition
   - Waveforms acquired using the **external trigger** to cover the entire buffer
   - **FBK matrices coupled** but no voltage provided
   - Pedestals studied for each capacitor (16384)

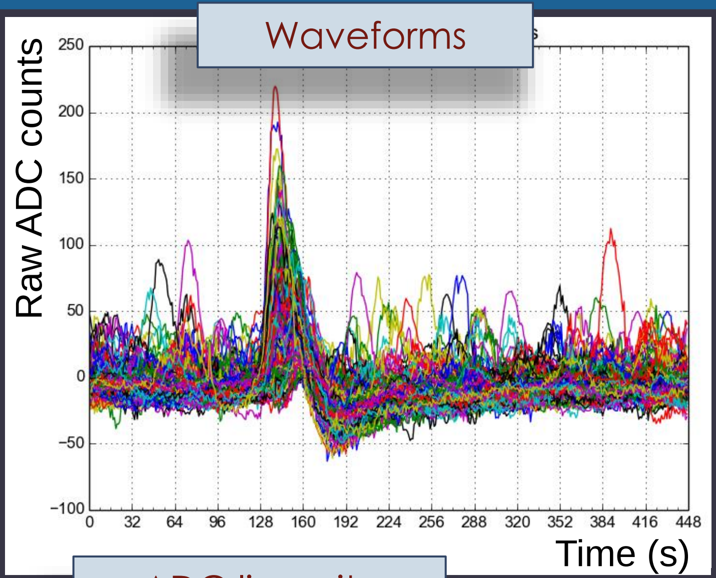


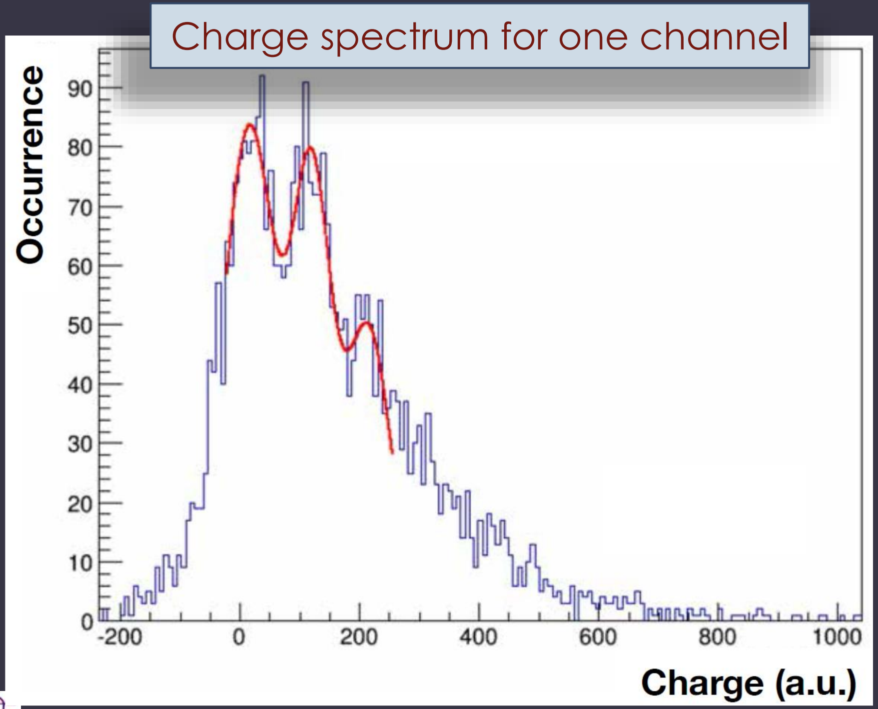


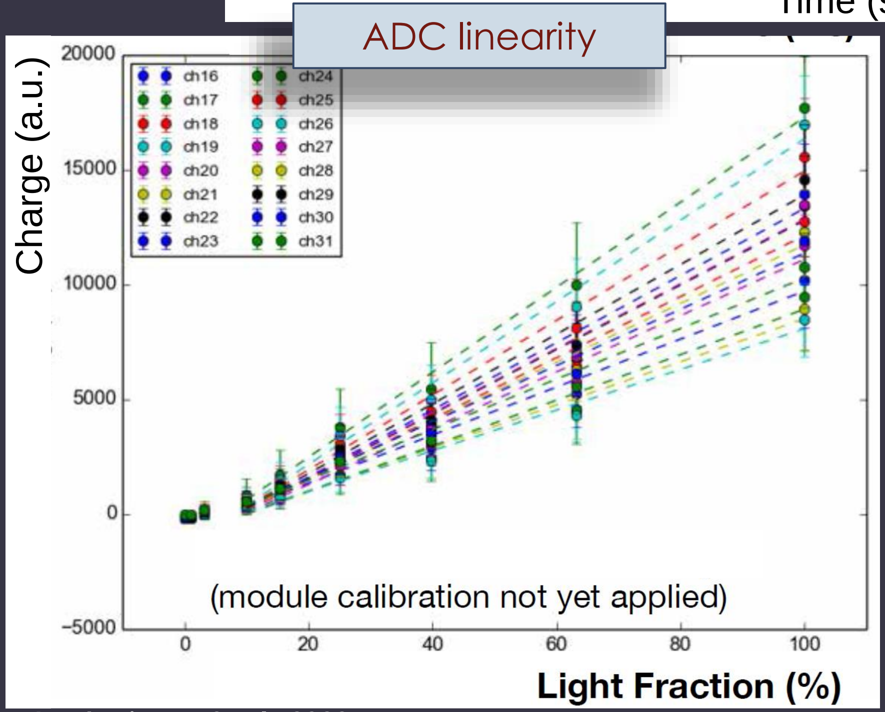


INFN modules for pSCT: QC and tests

2. Waveform acquisition
   - **Simultaneous** acquisition of ~3500 waveforms from 64 channels
   - Charge spectrum obtained with an **integration window of 16 ns**
   - Maximum amplitude distribution at different **light intensities → ADC linearity confirmed**

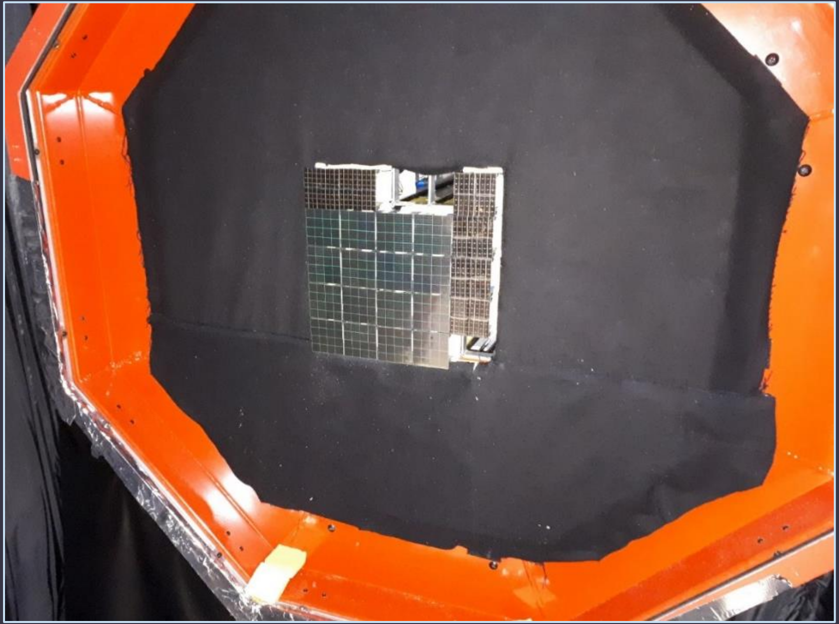


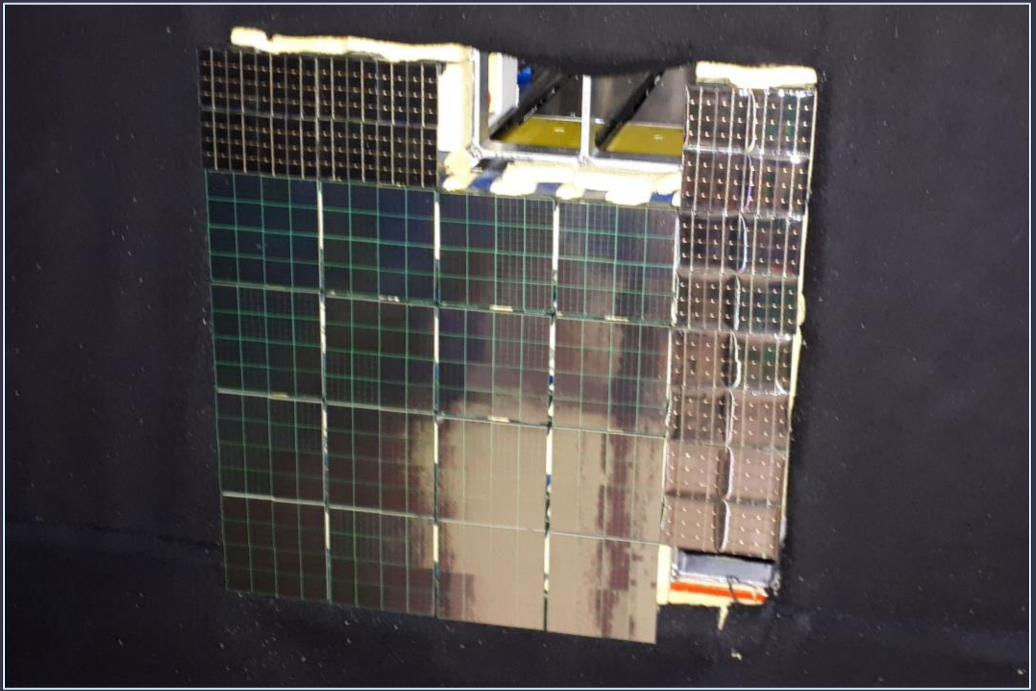




pSCT Camera Tests

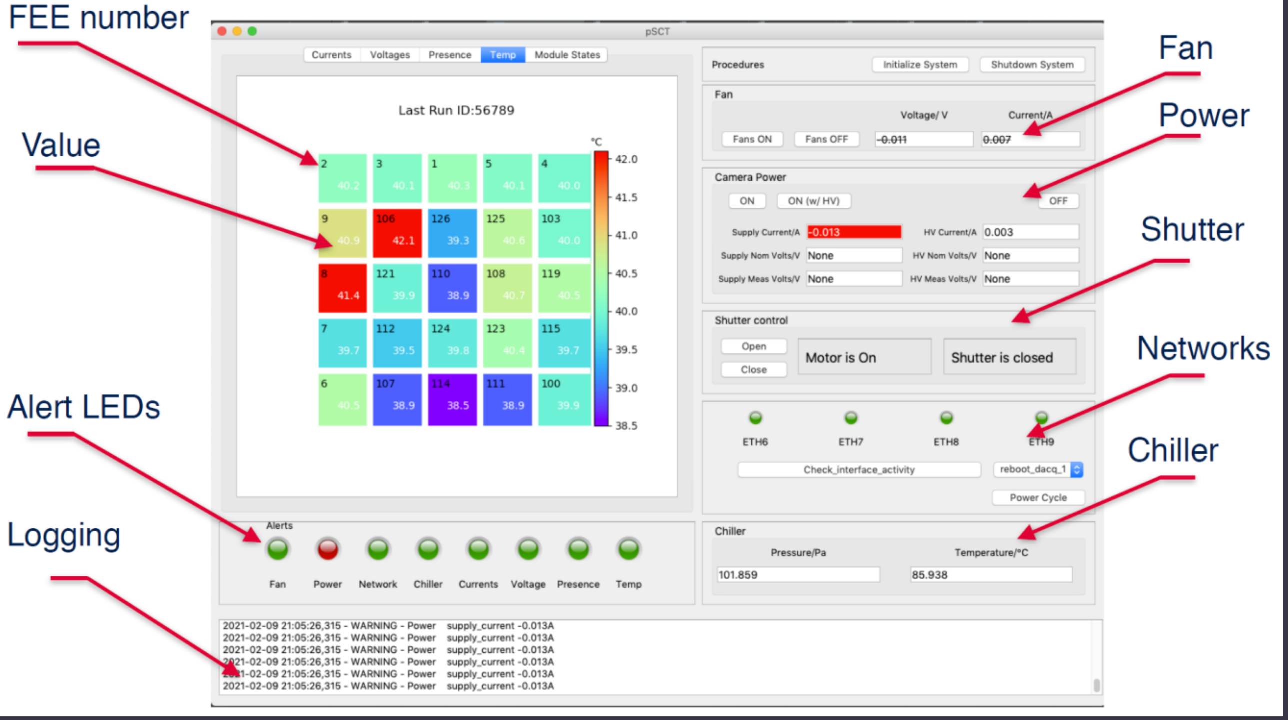
- Modules @ University of Wisconsin, Madison
  - 16 Hamamatsu modules
  - 6 FBK modules
- Modules integration (March-May 2018)



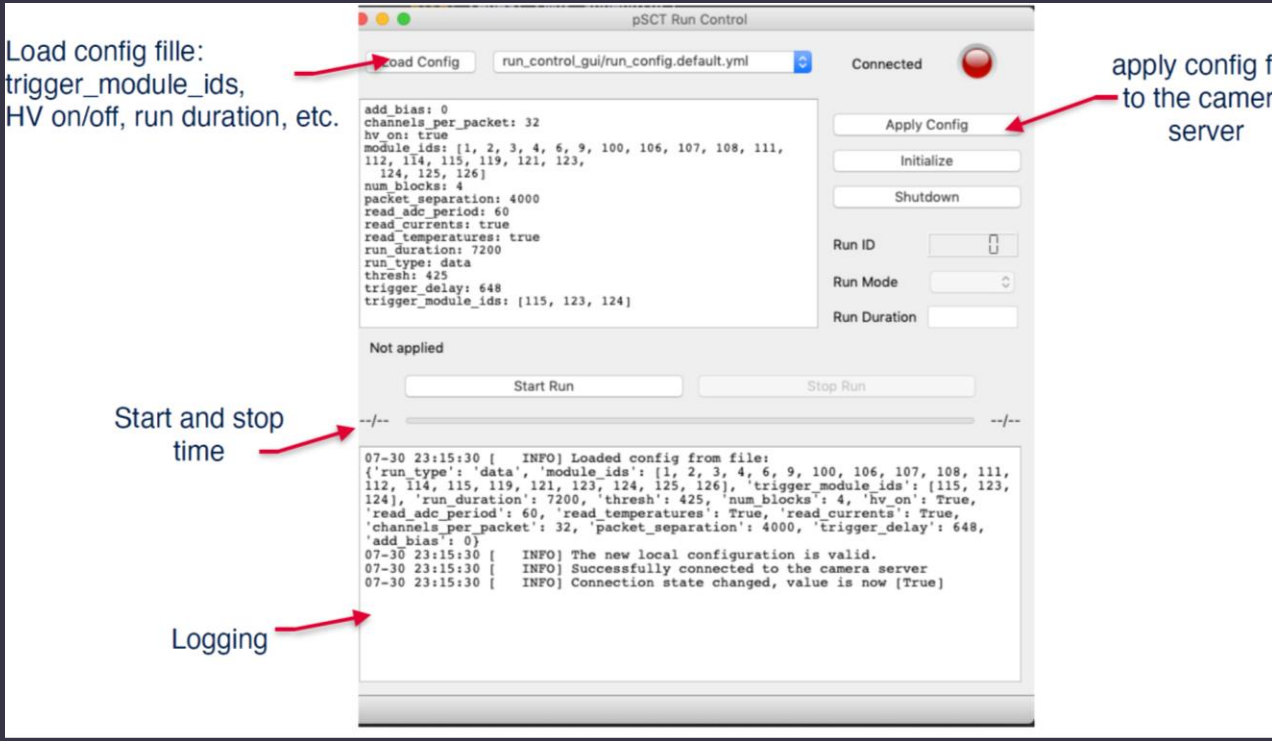


The Graphical User Interface(s)

Slow control GUI

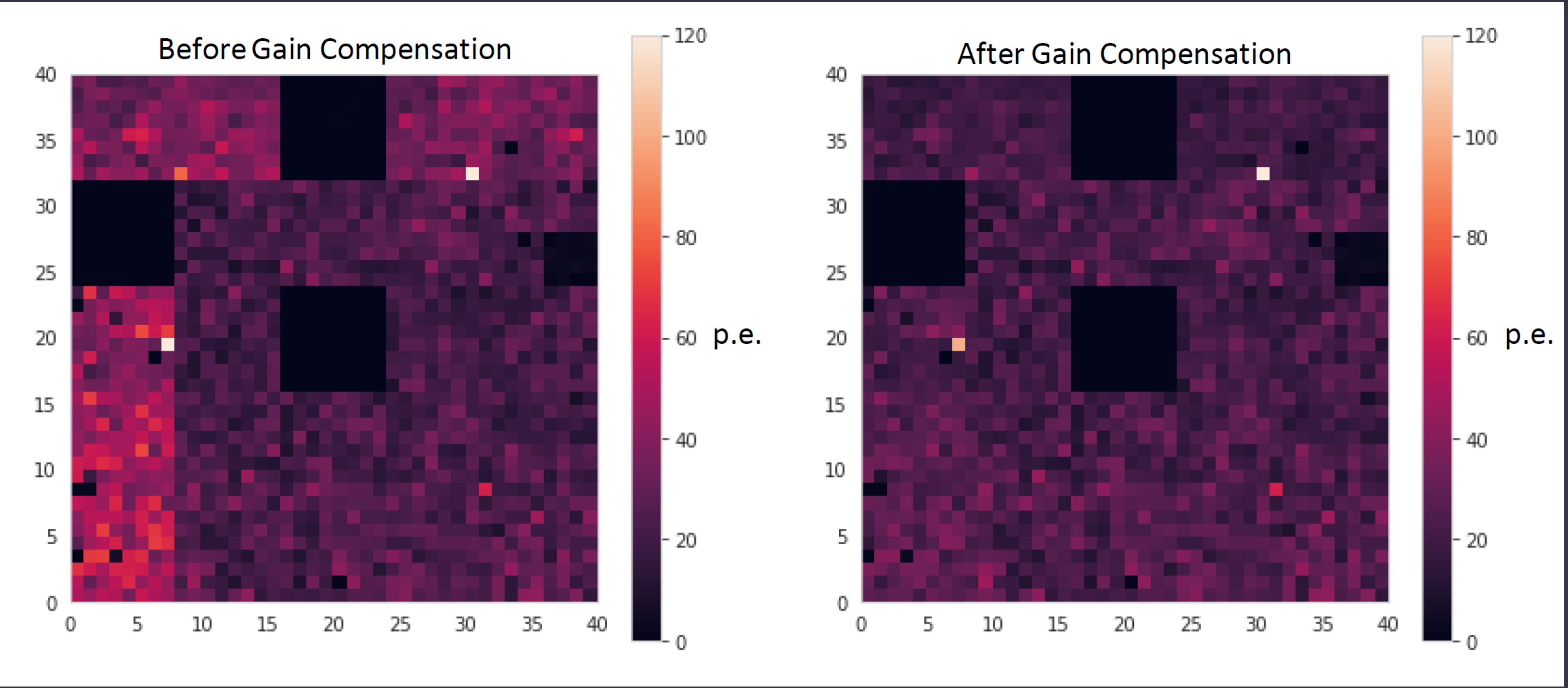


Run control GUI



Gain compensation

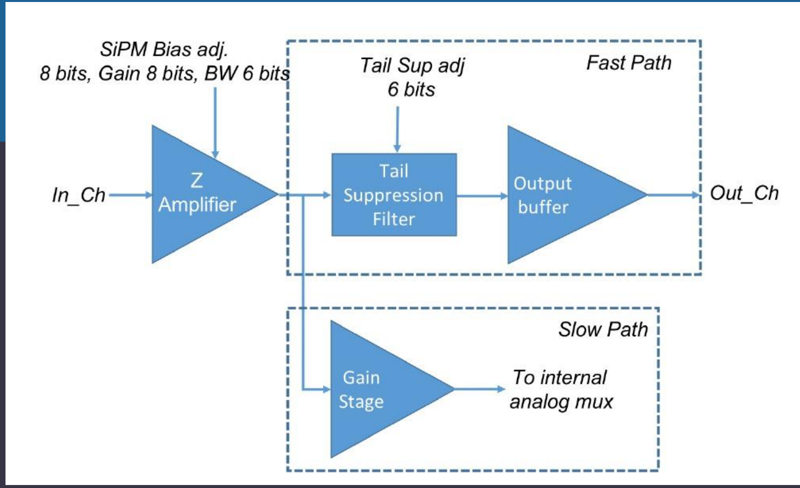
Detailed study of charge fluctuations from flasher runs to correct for the different amplification stages on INFN and US modules

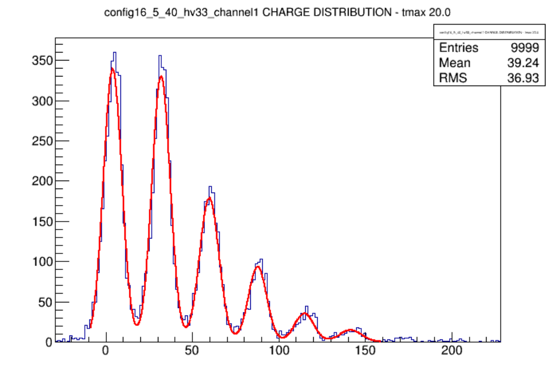


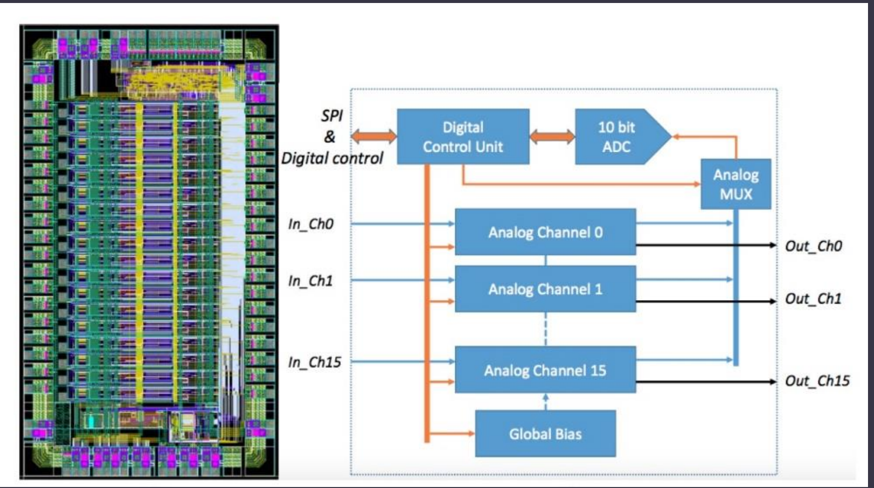
SMART ASIC

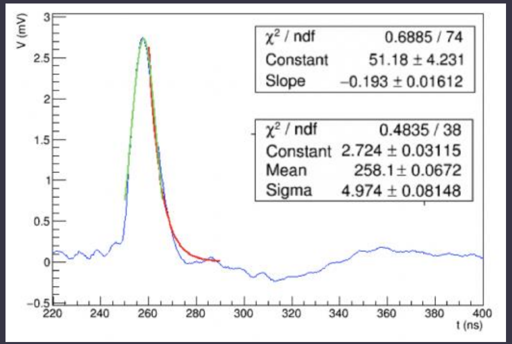
SMART: a **S**iPM **M**ultichannel **A**sic for high **R**esolution Cherenkov **T**elescopes

- 16 input channels
  - Trans-impedance amplifier
  - Fast path gain: 2-5mV/ph
  - Tail supression: pulse duration ~ 10ns
  - 20-bit global adjustment: gain (8 bits), bandwidth (6 bits), PZ (6 bits)
- Slow monitoring of SiPM current (10-bit ADC)
- 8-bit DAC for SiPM bias fine tuning (1 DAC per channel)
- 600 mV dynamic range
- 200 SMART ASICs produced and assembled for full camera









The pSCT Camera Upgrade

- **Updated Inner Camera**
  - 177 modules
  - 9 backplanes
  - Motion control
  - Heat exchanger
- **Performance**
  - Heat control
    - >6 kW water cooling capability
    - < 2°C variation across camera
  - Pitch/Yaw range > +/- 5^0
  - Optical Axis z: (electric drive)
    - > +/-40 mm movement
    - < 0.001 mm step size
  - X-Y alignment (manual)
    - > +/- 25 mm horizontal
    - > +/- 12 mm vertical
- **Timeline**
  - Fabrication & Test (Aug 2022)
  - Install on SCT (Oct 2022)
  - Operations (Jan 2023)