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

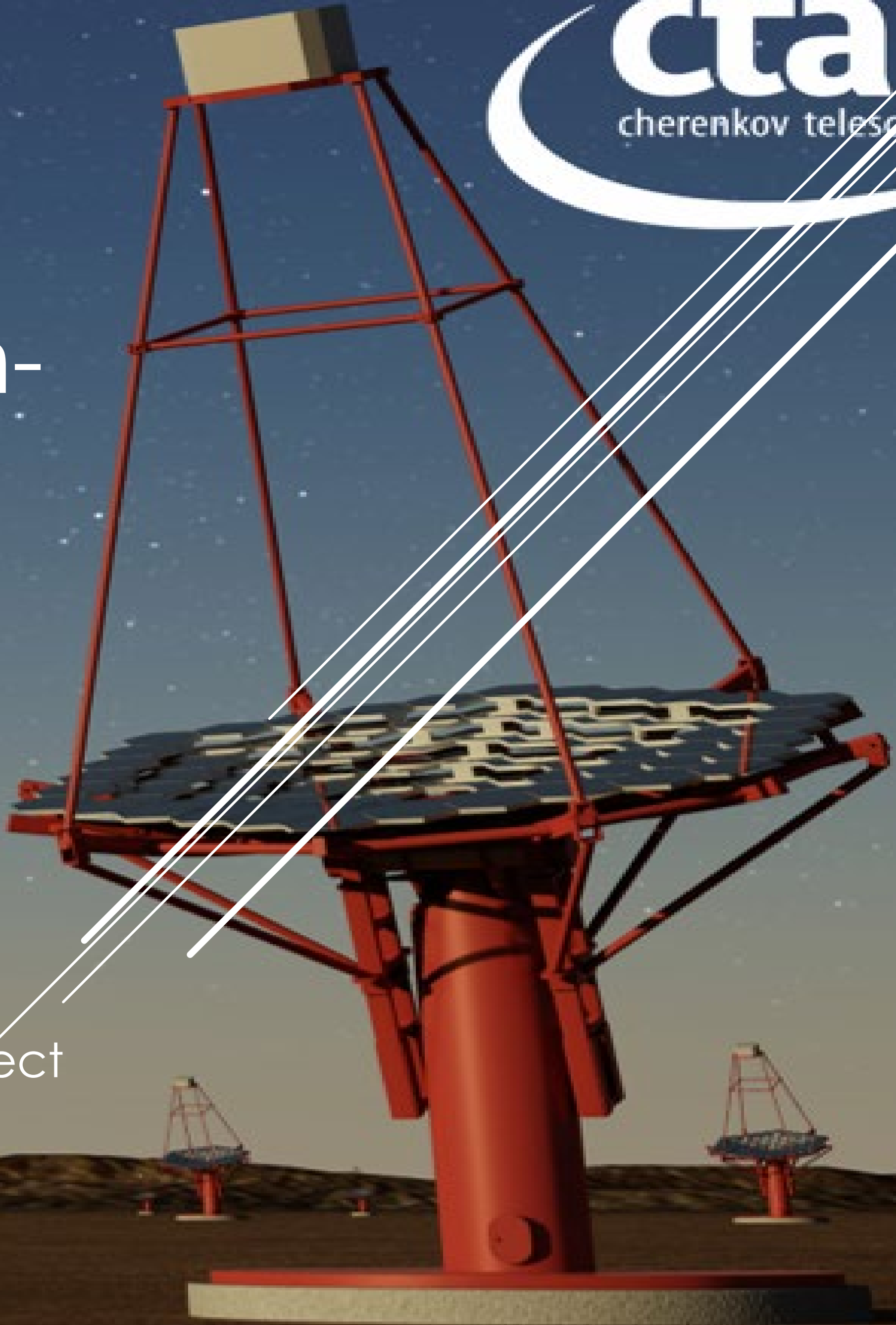
L. Di Venere

for the CTA-SCT project

University and INFN Bari

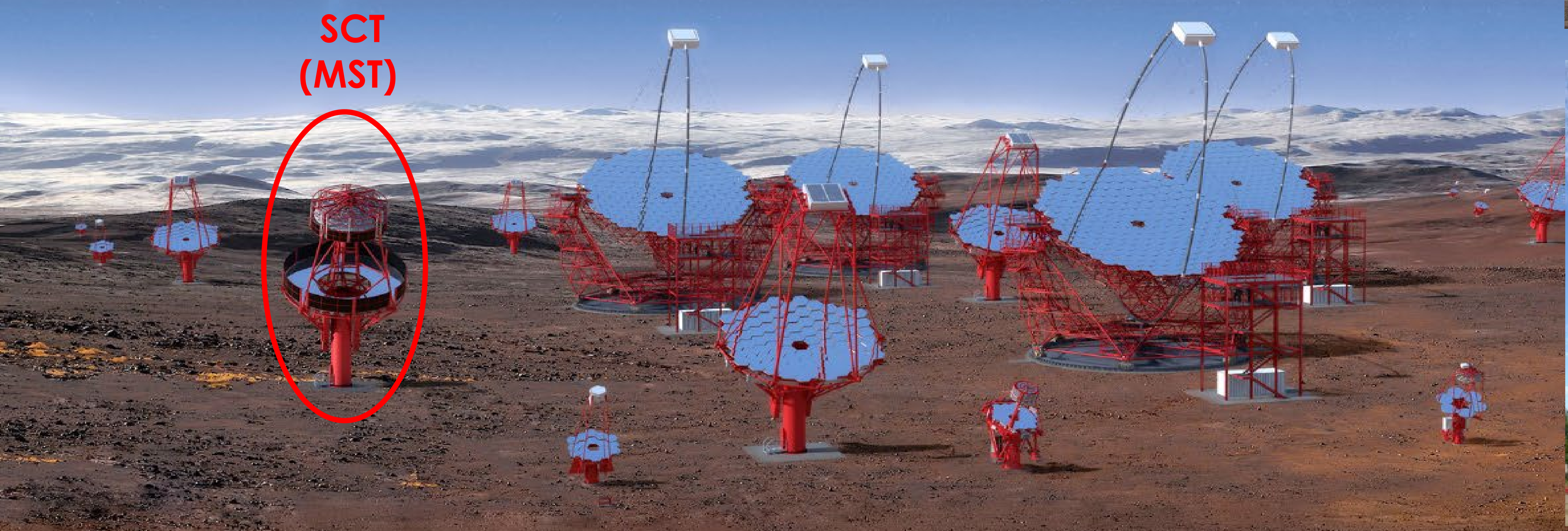
This work was conducted in the context of the CTA-SCT Project

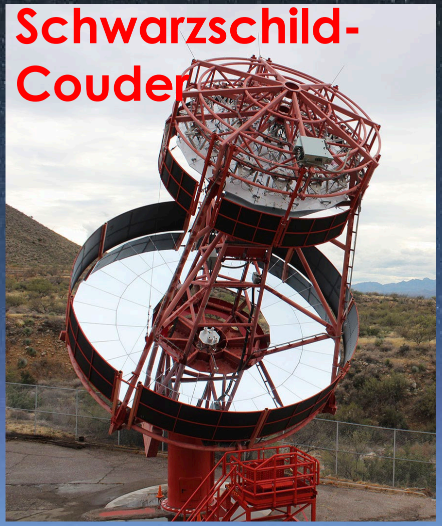
leonardo.divenere@ba.infn.it



The Cherenkov Telescope Array

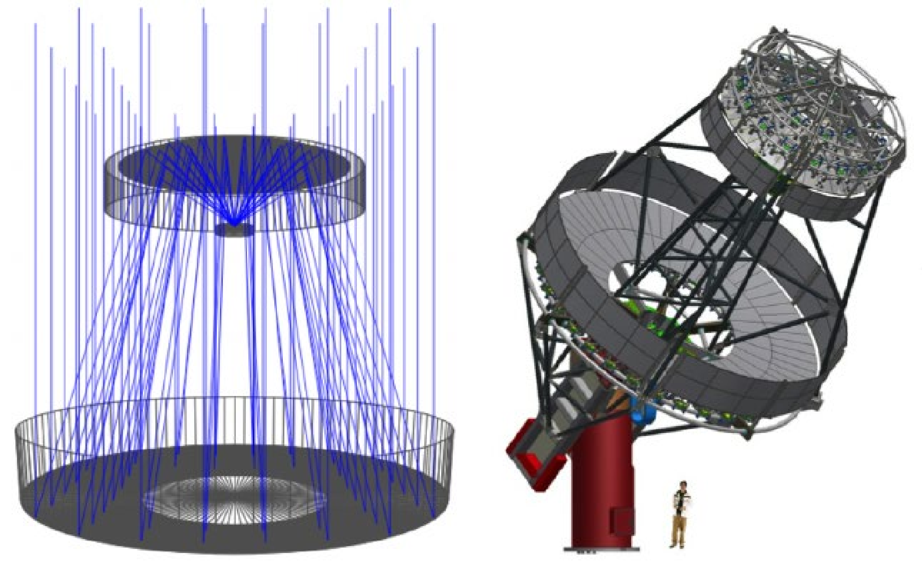
- **Schwarzschild-Couder Telescope (SCT)**
  - **A medium-sized double mirror telescope**
  - **Aim: increase sensitivity and performance of the CTA Southern Array**

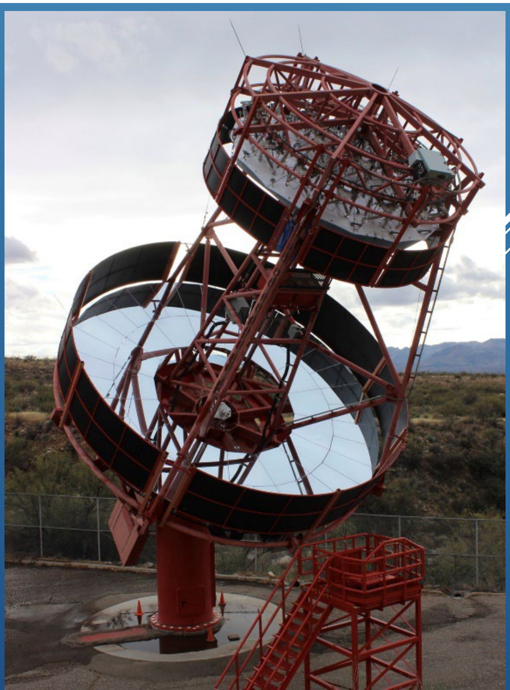




The Schwarzschild-Couder Telescope for CTA

- **Candidate for a Medium Sized Telescope for CTA**
  - **With an advanced telescope optical system**
- **Aplanatic dual mirror optical system**
  - **Correction of spherical and comatic aberrations**
  - **Increased FoV**
  - **Demagnification of shower images to be compatible with a compact high-resolution SiPM camera**
  - **Main challenges: Mechanical stability and mirror alignment**
- **First Prototype** (pSCT) inaugurated in January 2019 at the Fred Lawrence Whipple Observatory, Arizona





https://www.cta-observatory.org/project/technology/sct/

Single and dual mirror MSTs

MST Single Mirror

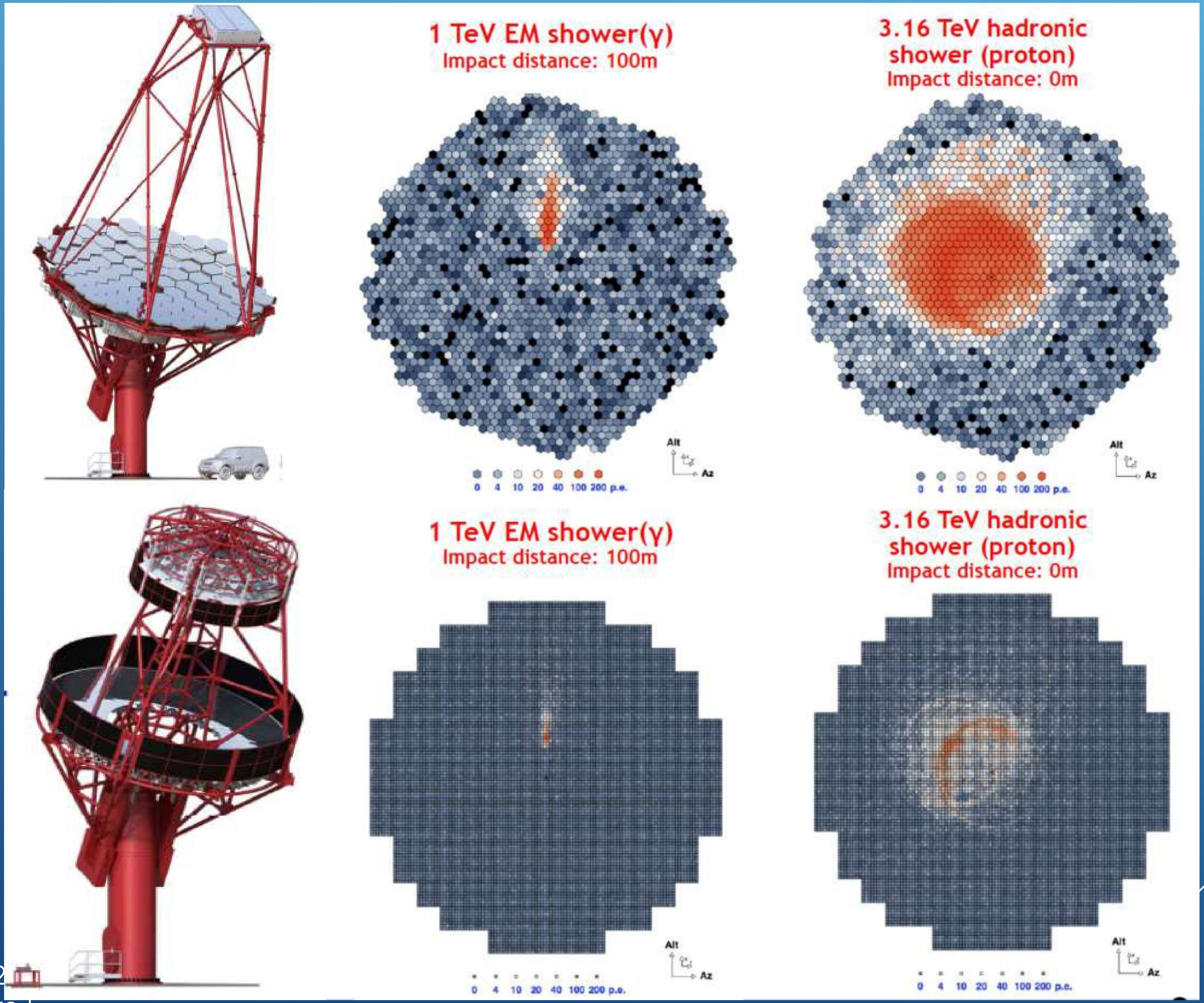
Davies-Cotton

~2k PMTs

MST Dual Mirror

Schwarzschild-Couder

~12k SiPMs



Main advantages:

- Superior optical angular resolution over a wide (~8°) field of view, especially for off-axis observations
- Better sensitivity and reduced observation time

The CTA SCT project

~30 participating Institutions

Milestones:

- 1st construction: 06-23-2015
- Inauguration: 01-17-2019
- 1st light: 01-23-2019
- December 2019: optical alignment achieving preconstruction estimated PSF
- January 2020: detection of the Crab Nebula

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

- Endorsement by the CTA Consortium for supporting the development and construction of SCTs to add to the array and complement single-mirror MSTs

Next steps:

- Ongoing (NSF/INFN funded MRI): population of the focal plane to ~11k channels with upgraded SiPMs and electronics

The CTA SCT project

~30 participating Institutions

8 June 2015

September 2016

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

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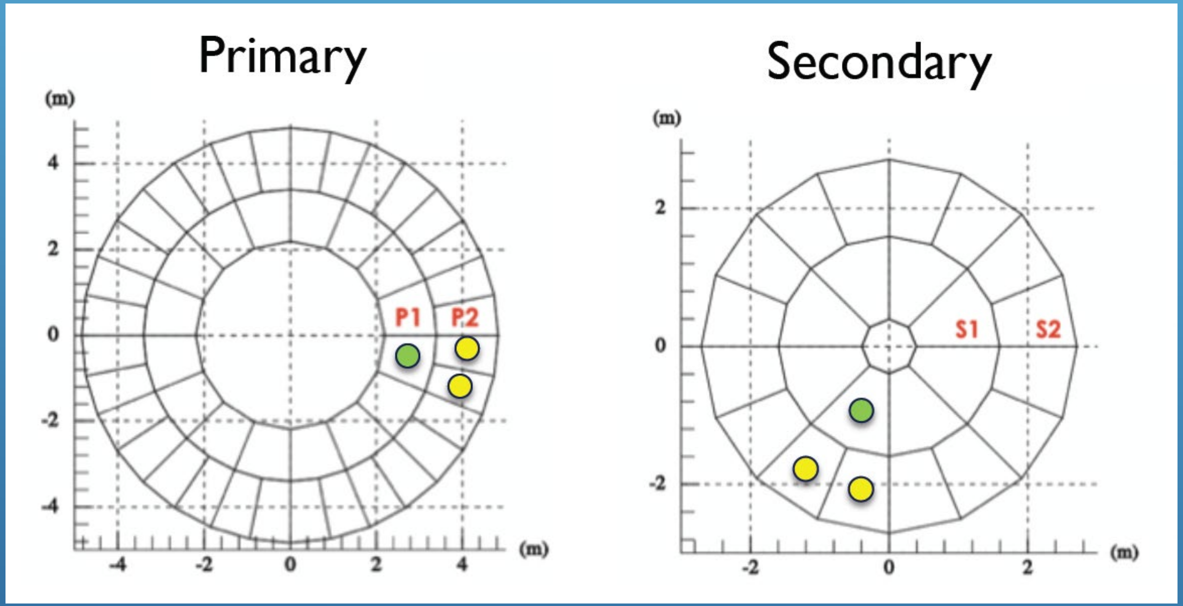
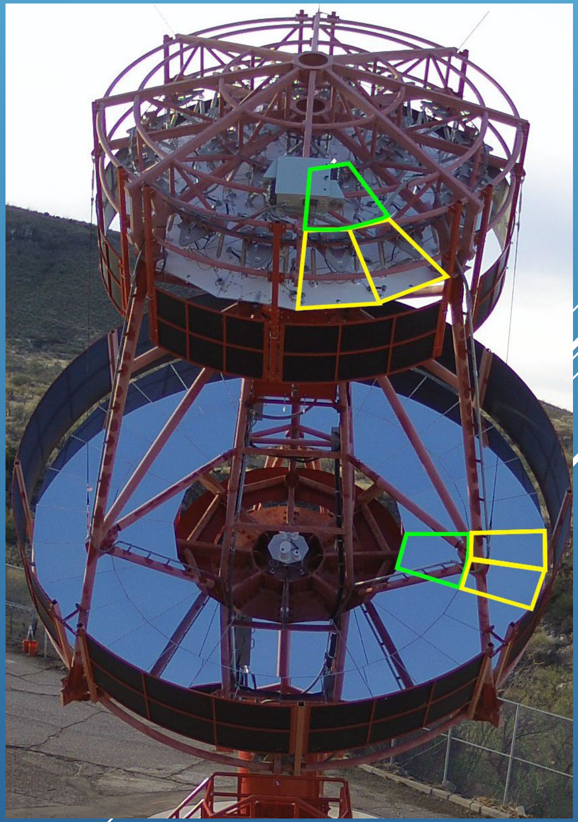
The pSCT optics

- Primary mirror (M1): diameter 9.7 m
  - 16 P1 + 32 P2 panels
- Secondary mirror (M2): diameter 5.4 m
  - 8 S1 + 16 S2 panels
- Focal length: 5.586 m

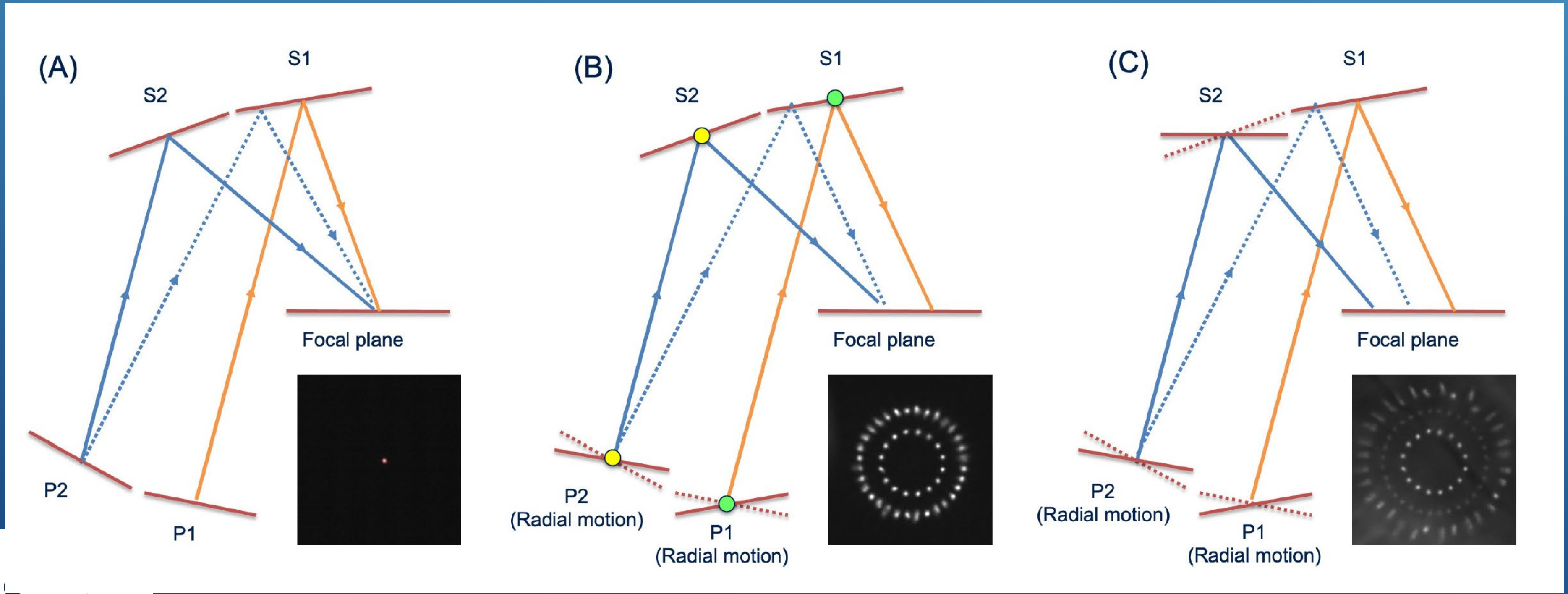




- To achieve the PSF of the Optical System in the FoV compatible with the SiPM pixel size (6mm), sub mm and sub mrad alignment is required

Optics alignment

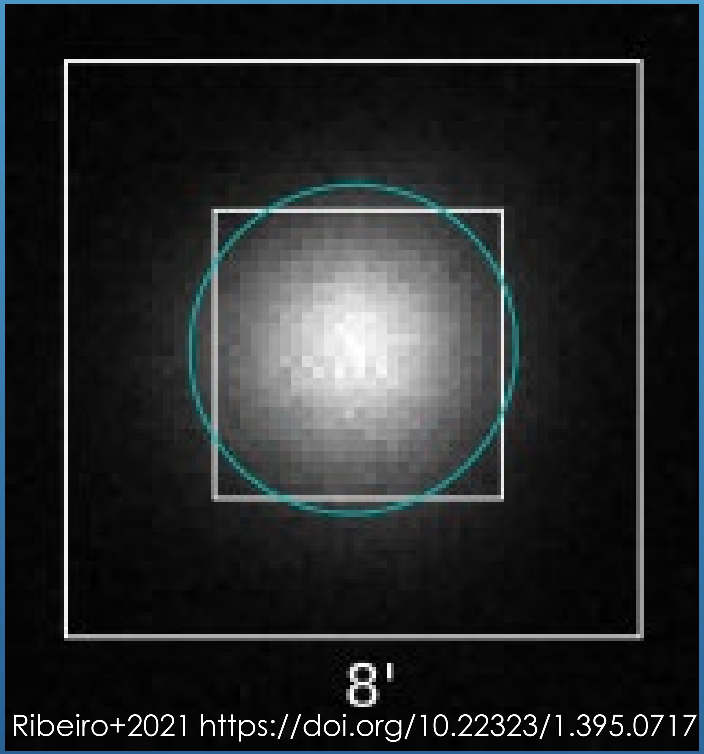
- Use a de-focused star projected on the focal plane
- Alignment based on the focusing/defocusing of each pair of panels
- Characteristics of individual images (major and minor axes and elongation) used to guide relative global positioning of M1, M2, FP
- Creation of response matrices



- Each S1 reflects from 2 P1s (and a small fraction of 4 P2s)
- Each S2 reflects from 2 P2s
- Alignment is based on the focusing/defocusing of each P1/S1 or P2/S2
- The asynchronous functionality allows a fast alignment

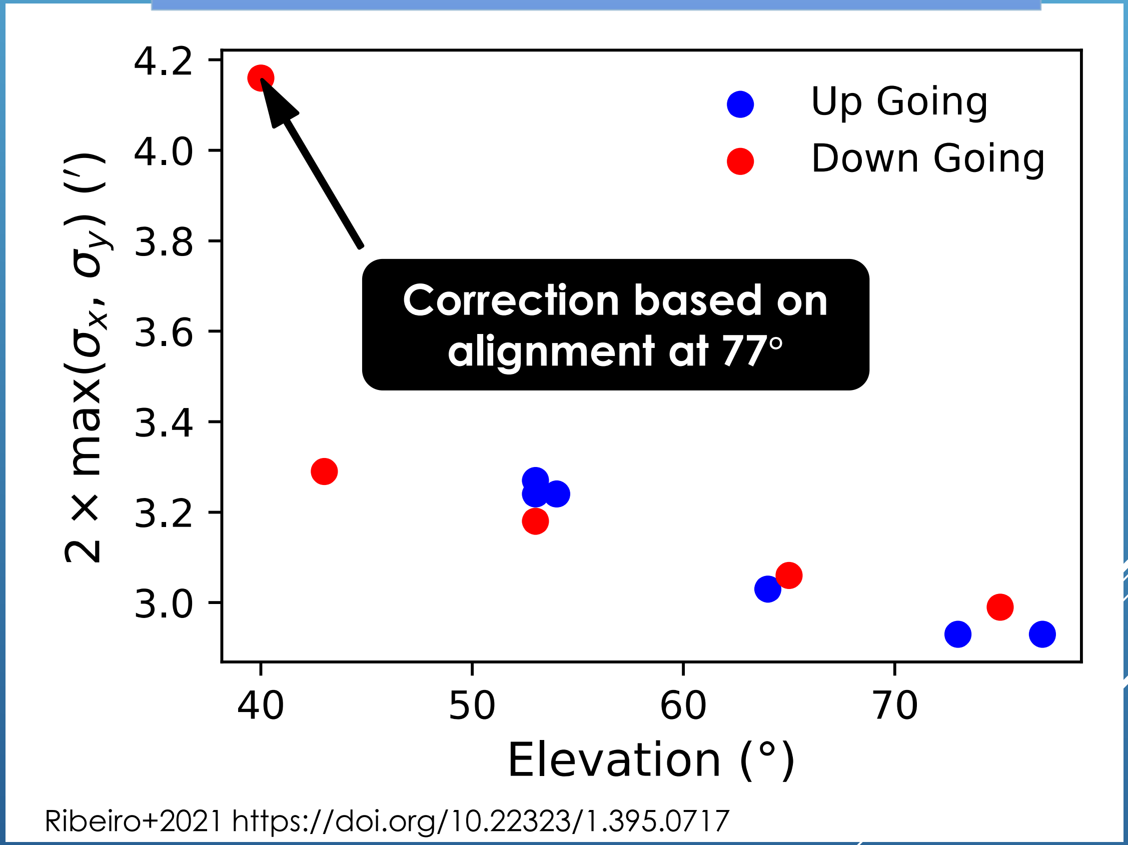
Ribeiro+2021 https://doi.org/10.22323/1.395.0717

Optics commissioning



Achieved PSF design goal of 2.9 arcmin in December 2019

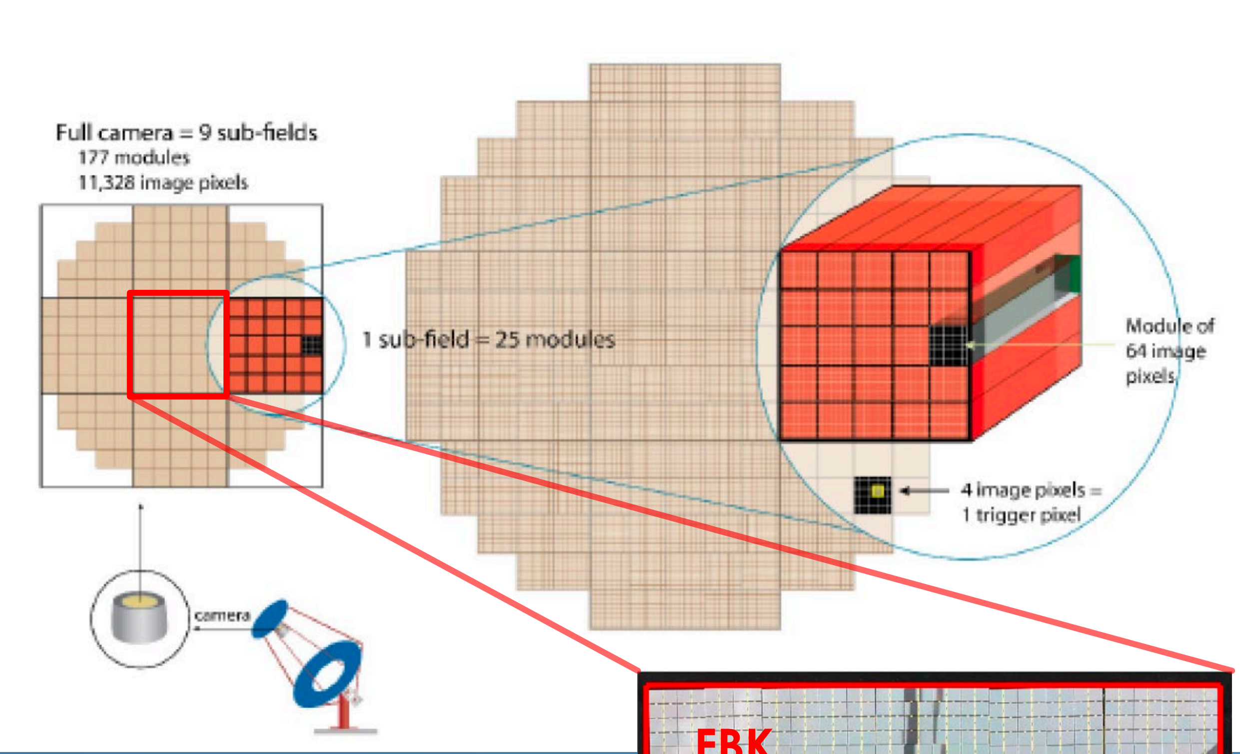
On-axis PSF as a function of elevation (Arcturus, April 2021)

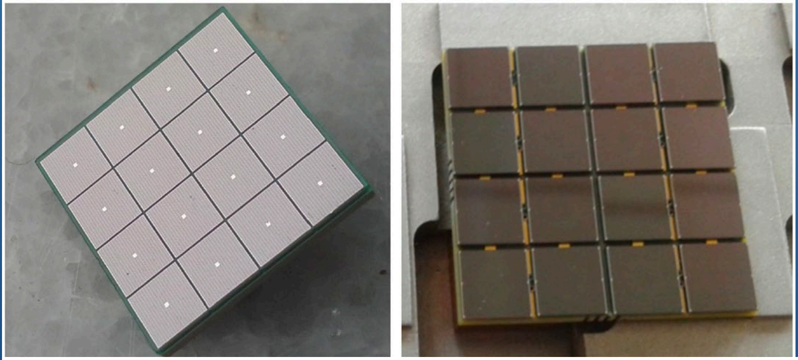


Achieved PSF of ~3’ across an elevation range of 77°-40°

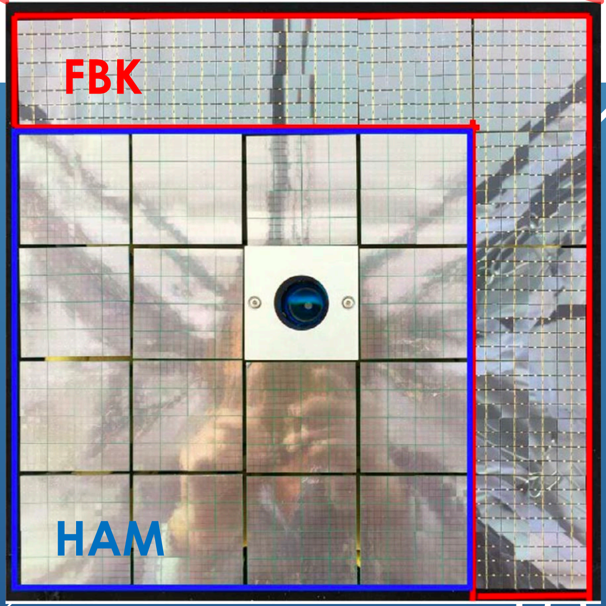
The pSCT camera

- Modular design:
  - 9 backplanes, 177 modules, 11'328 pixels
  - Each module contains focal-plane module (FPM) + Frontend electronics (FEE)
  - FPMs form a curved focal plane facing secondary mirror
- Current configuration:
  - 25 modules, 1536 pixels, 2.68° FoV
  - Hamamatsu (S12642-0404PA-50(X), USA, 16 modules, 3x3 mm2) + FBK (NUV-HD3, Italy, 9 modules, 6x6 mm2) Silicon Photomultipliers (SiPMs)
- SiPM pixels → smaller than traditional PMTs → providing much higher resolution air shower image
  - Better angular resolution
  - Better background rejection



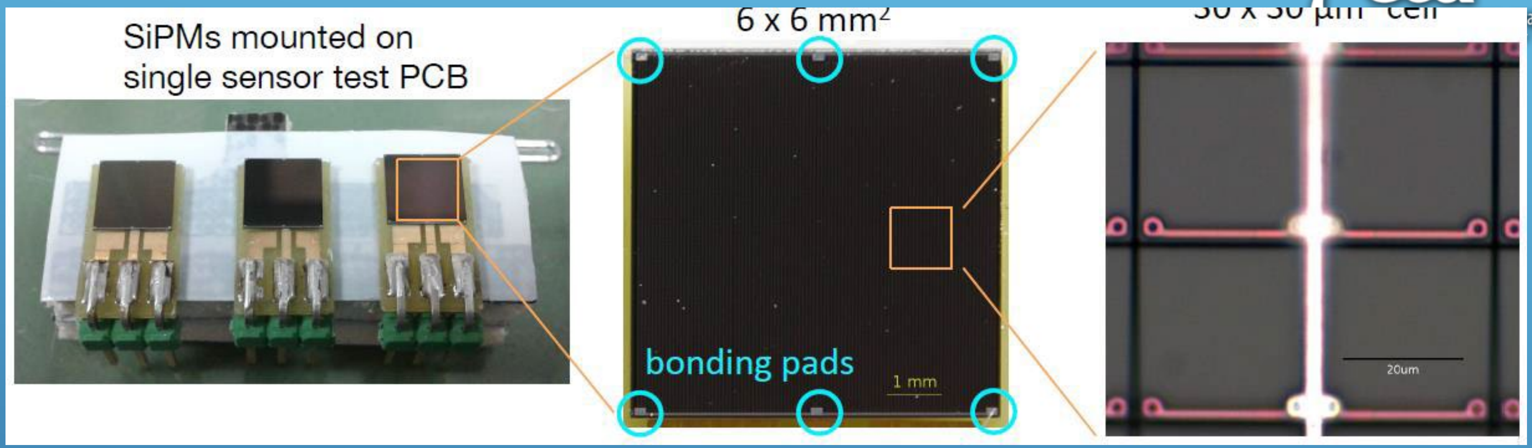


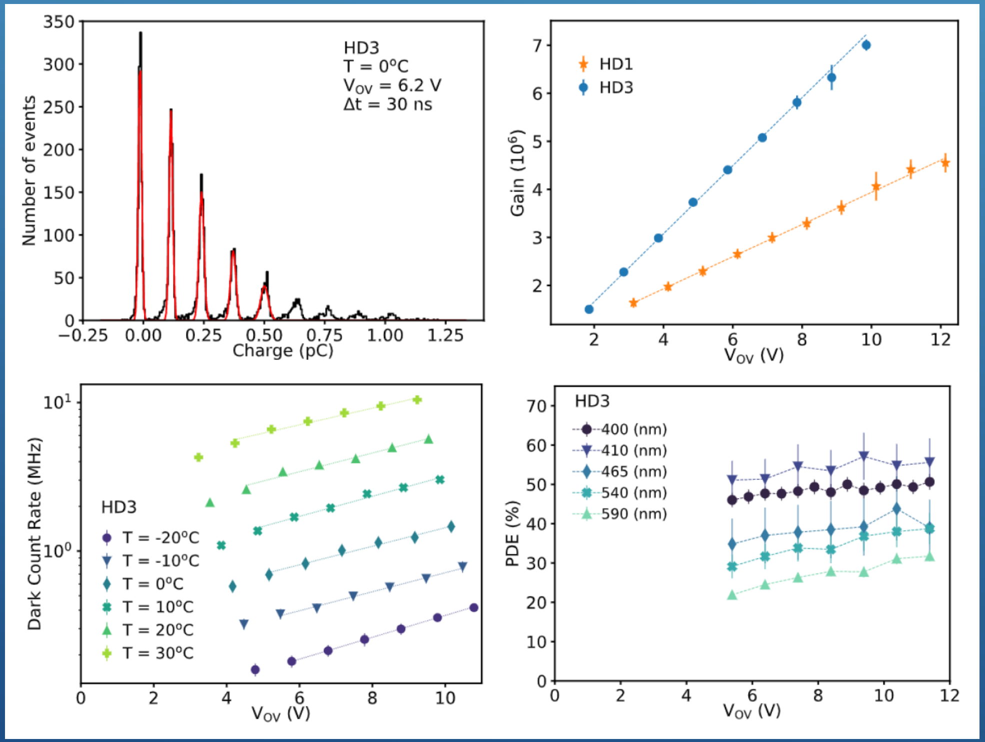
Hamamatsu MPPc FBK HD3

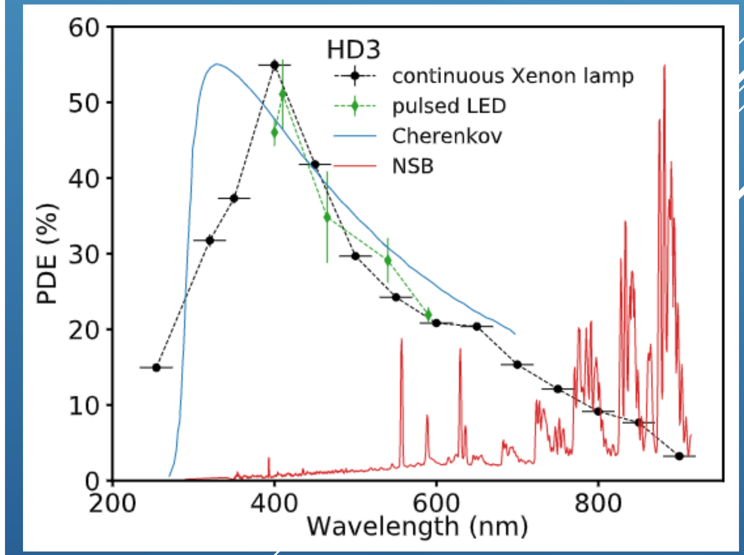


FBK NUV-HD SiPM

- INFN 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 by Fondazione Bruno Kessler (FBK, Trento, Italy)
- Main features:
  - Wide dynamic range
  - High Fill Factor (FF)
  - Increased PDE at NUV wavelengths
  - Low correlated noise
  - 40 x 40 µm² cell
  - 6 x 6 mm² area



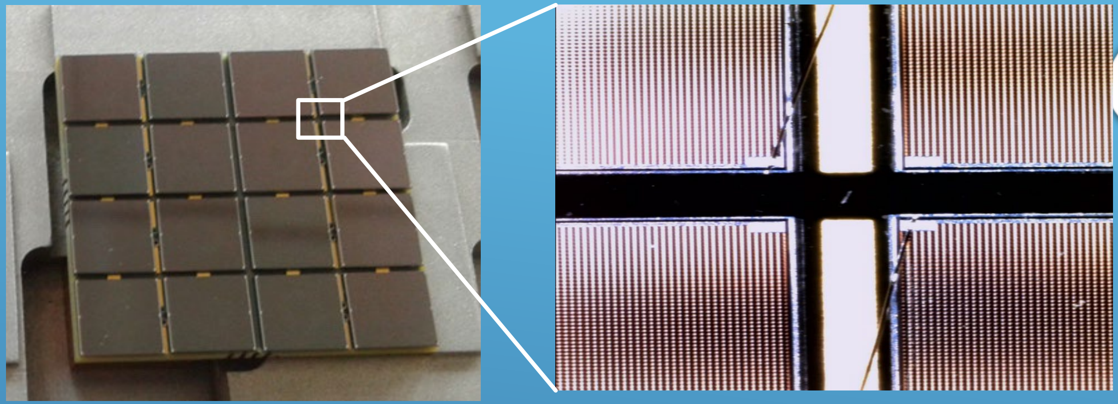


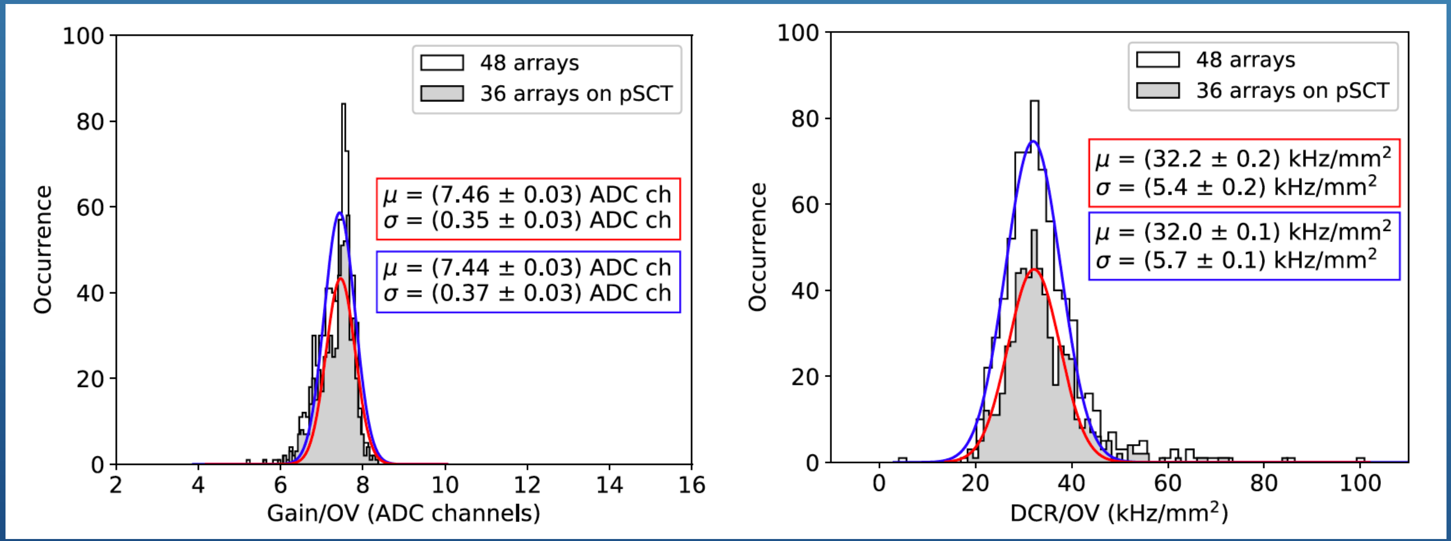


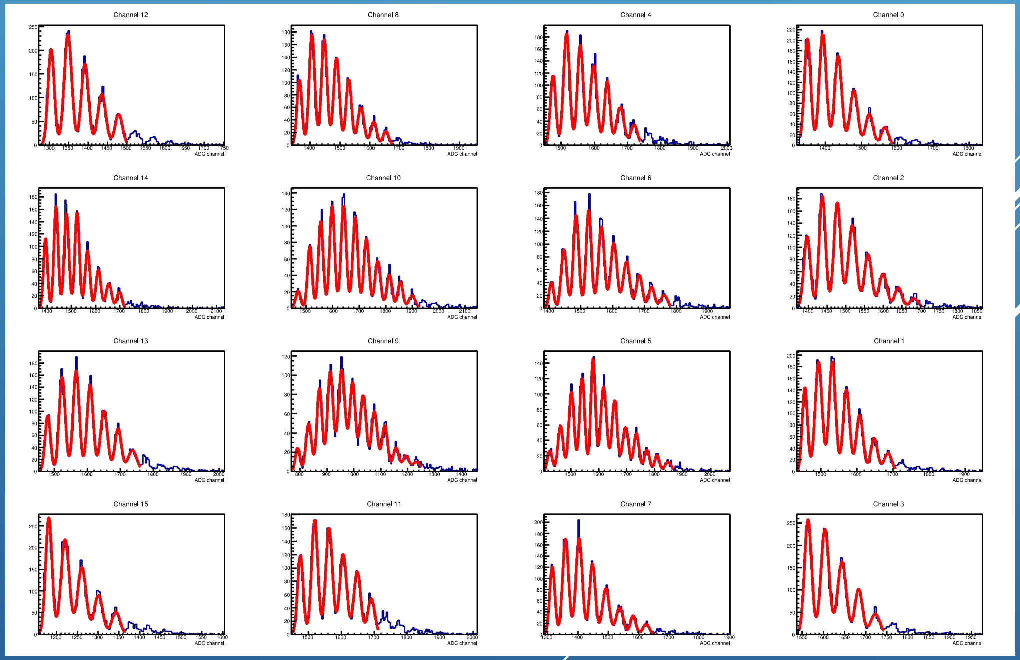
Ambrosi+2022 Submitted to NIMA

FBK NUV-HD SiPM

- 4x4 SiPM matrices assembled and tested
- 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 ratio (SNR), and dark count rate (DCR)



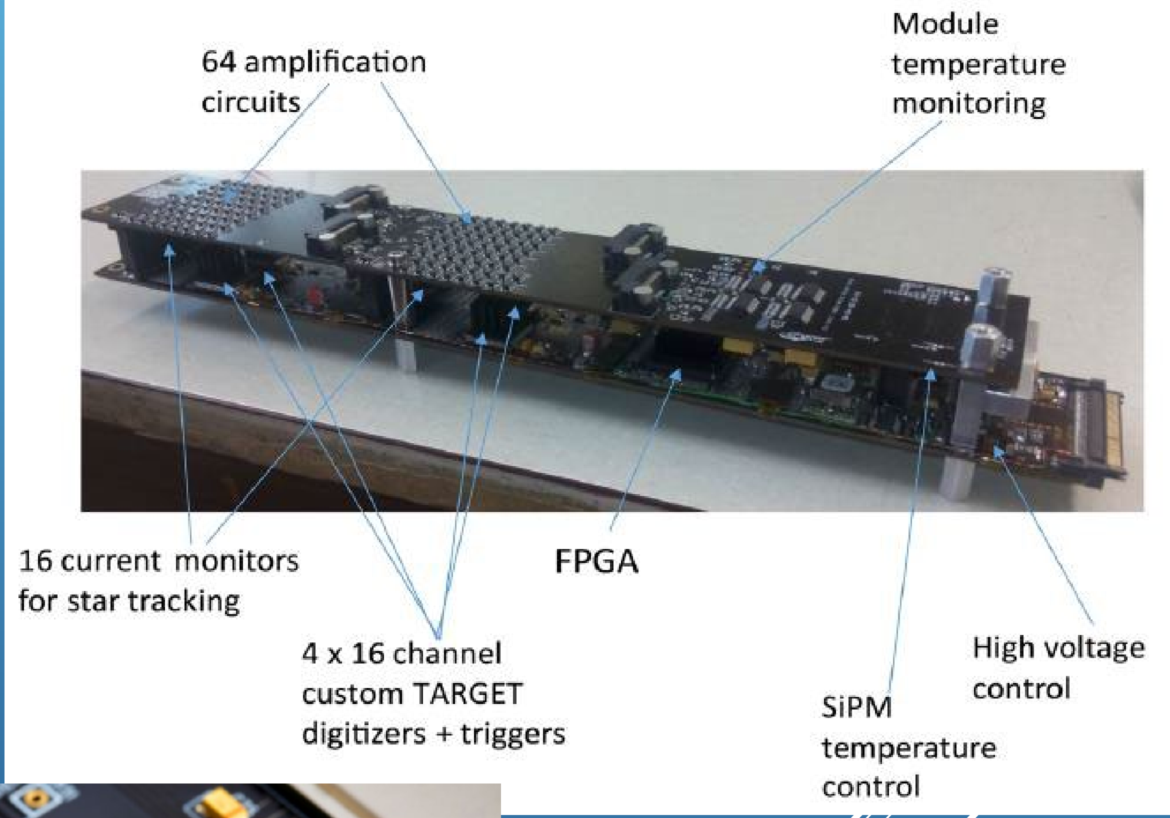


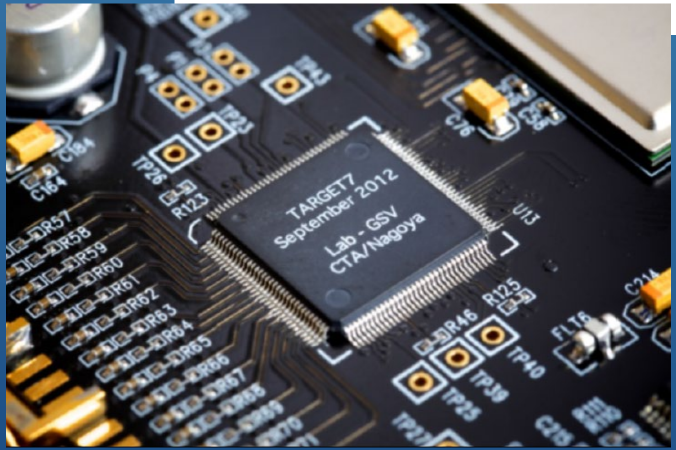


Ambrosi+2022 https://doi.org/10.1016/j.nima.2022.167359

Frontend electronics

- Front-End Electronics (FEE) functionalities:
  - Amplification and digitization of SiPM signals
  - Waveform data sampling and transfer to storage
  - Low-level trigger generation
  - Control of SiPM bias voltage
  - Temperature monitoring and stabilization of FPM
- Electronics distributed over 2 circuit boards, primary and auxiliary
- Based on 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 based on the sum of four adjacent pixels

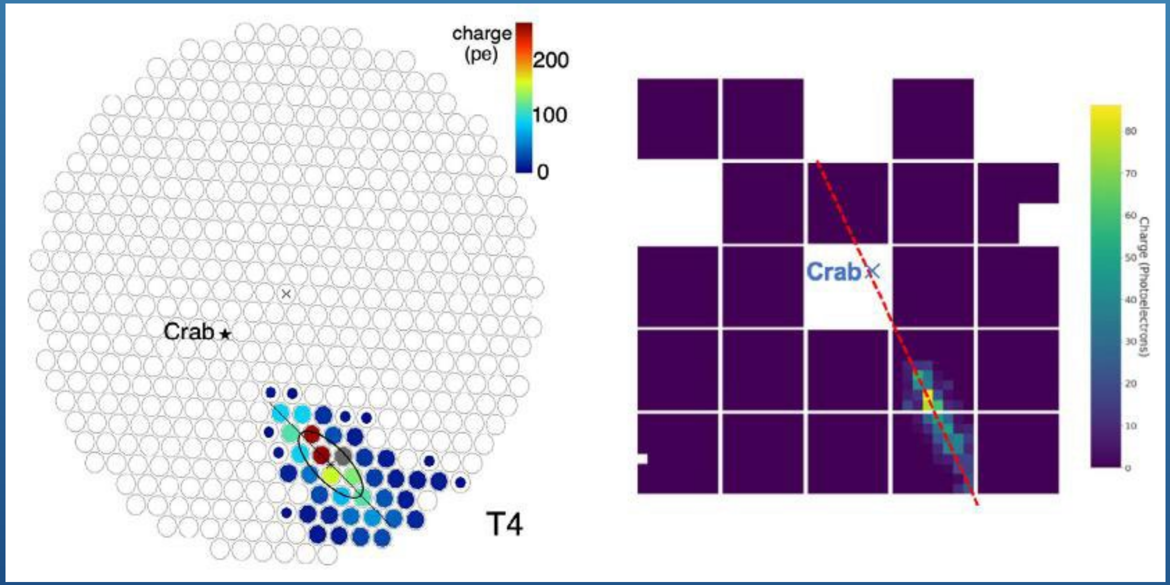


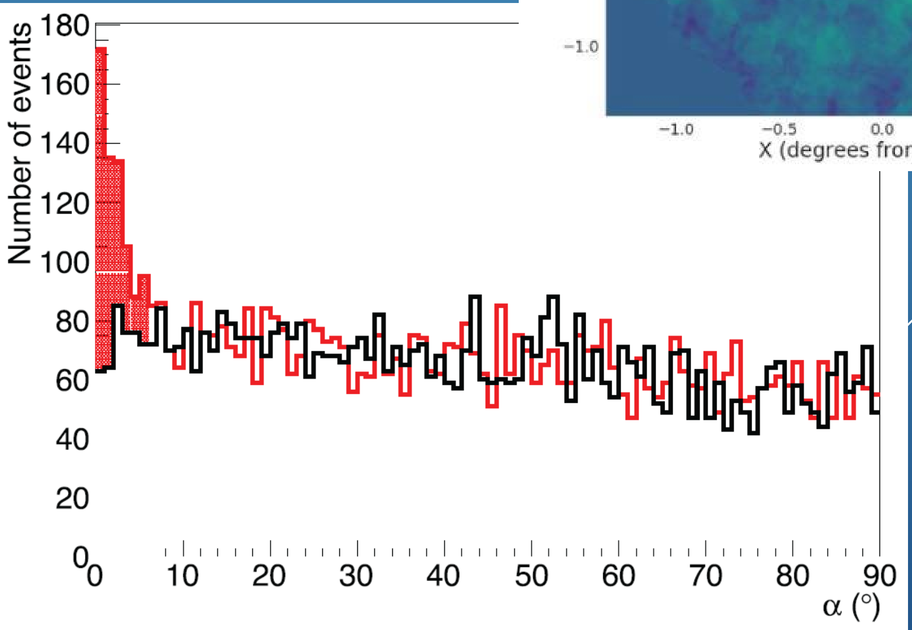


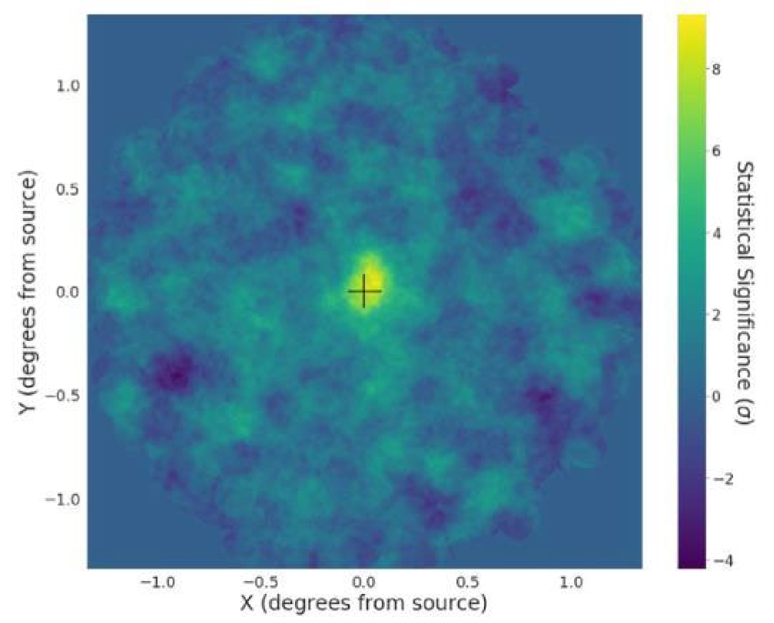
Adams+2022
https://doi.org/10.1117/1.JATIS.8.1.014007

Crab detection with pSCT

- First pSCT observation campaign conducted in January and February 2020
  - Detection of gamma-ray signal 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 → simultaneous VERITAS observations used to identify gamma-rays in shower events







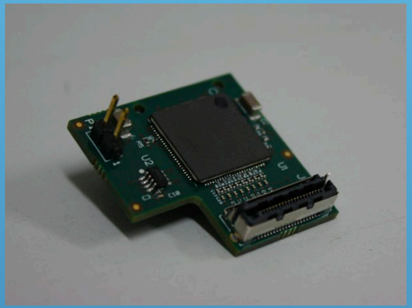
Adams+2021 https://doi.org/10.1016/j.astropartphys.2021.102562

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:
  - SMART ASIC: Integrated preamplifier attached to SiPM boards
  - CTC ASIC: 16-channel 1GSa/s digitizer
    - Analog buffer with 16k cells per channel → 16 us storage depth
  - CT5TEA ASIC: 16-channel trigger ASIC
    - Channels are summed in groups of 4 to obtain 4 trigger pixels per ASIC
    - Adjustable threshold for each group
- New backend electronics and mechanics

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

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



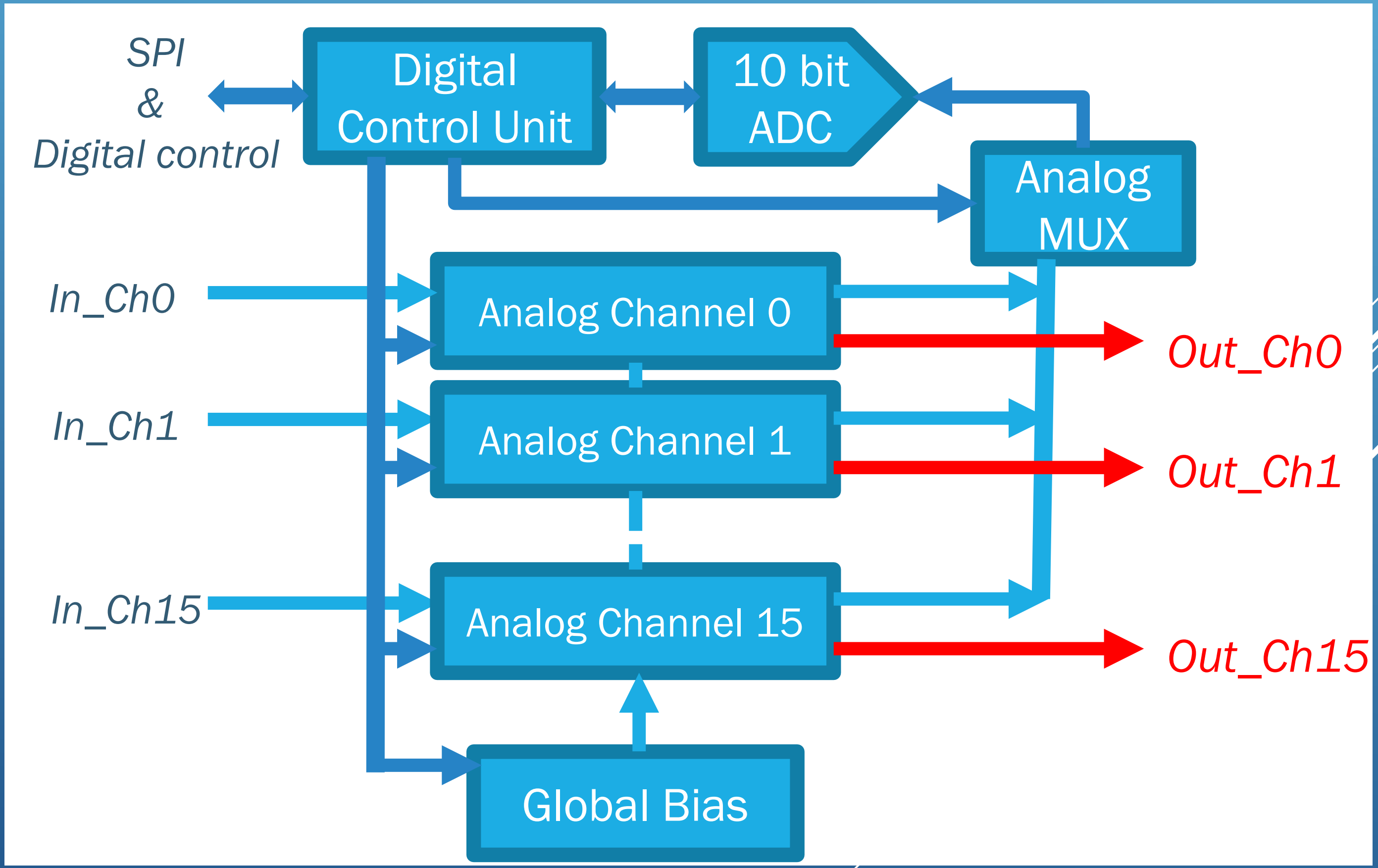
SMART ASIC

CTC+CT5TEA FEE module

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

Pre-amplifier designed for photon counting

- 16-channel trans-impedance amplifier
- 20-bit global adjustment: gain (8 bits), bandwidth (6 bits), Pole-Zero (6 bits)
- 8-bit DAC for SiPM bias fine tuning (1 DAC per channel)
- Slow monitoring of SiPM current (10-bit ADC)
- 1 MHz LVDS SPI interface

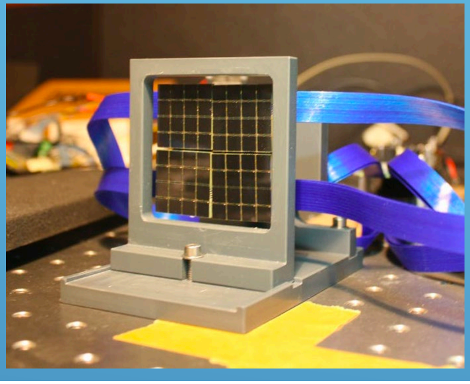


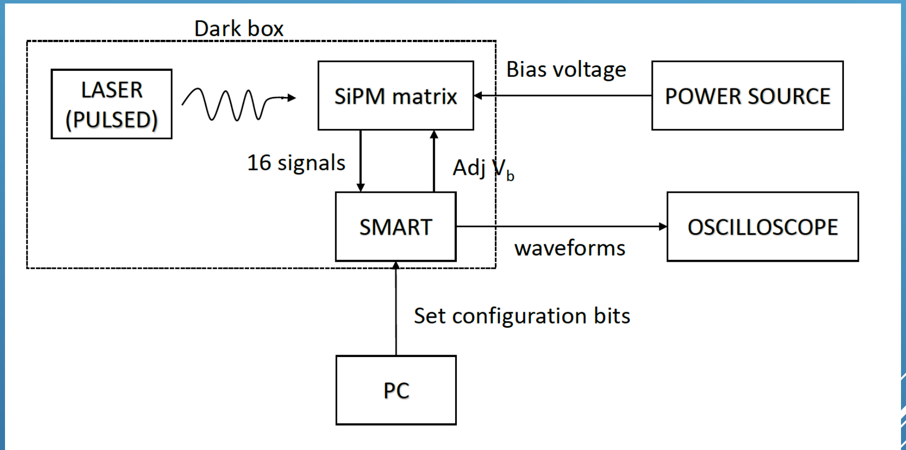
Designed by F. Licciulli & G. De Robertis at the Electronics CAD INFN Bari

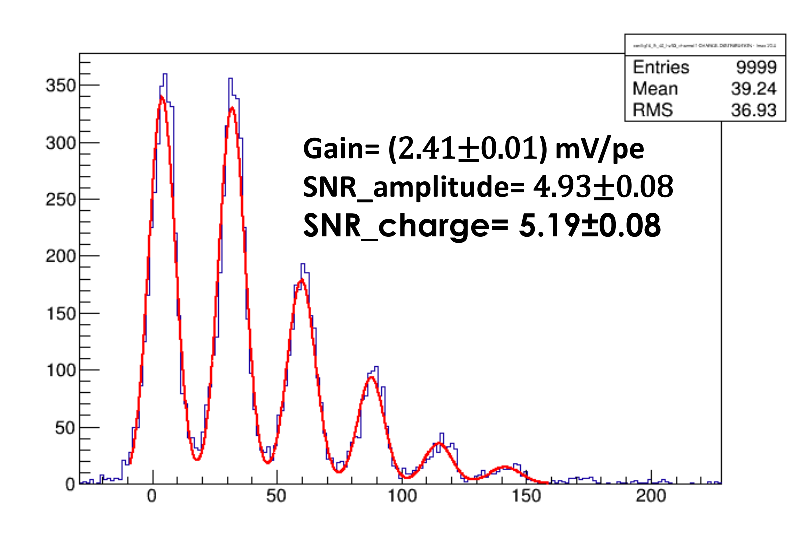
Contact: francesco.licciulli@ba.infn.it

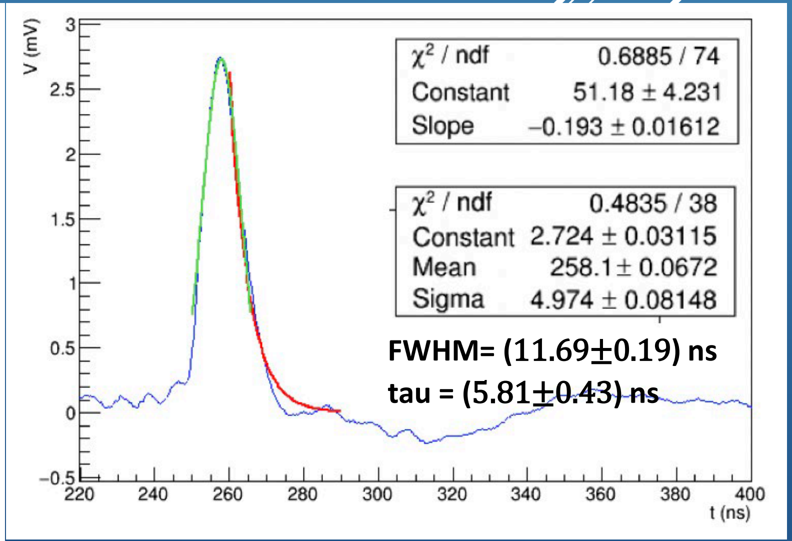
SMART laboratory tests

- Gain, signal-to-noise ratio and pulse width as a function of configuration bits
  - R : gain resistance
  - C : filtering capacitance
  - PZ: pole zero cancellation
- External PZ fixed with discrete components to match SiPM recovery time
- Output dynamic range:
  - 900 mV without external PZ
  - 600 mV with external PZ
- Approx. 800 SMART boards tested and qualified at INFN labs

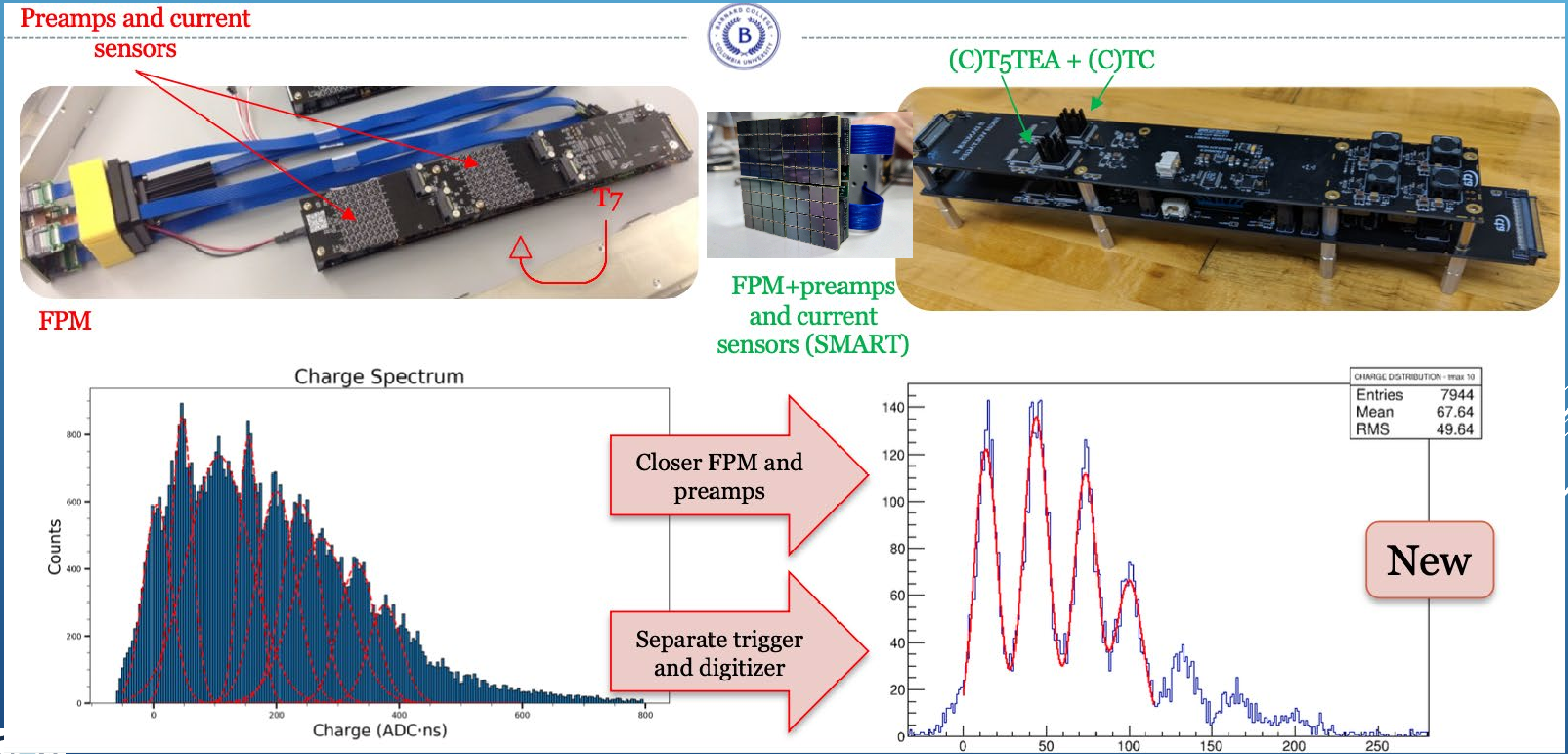






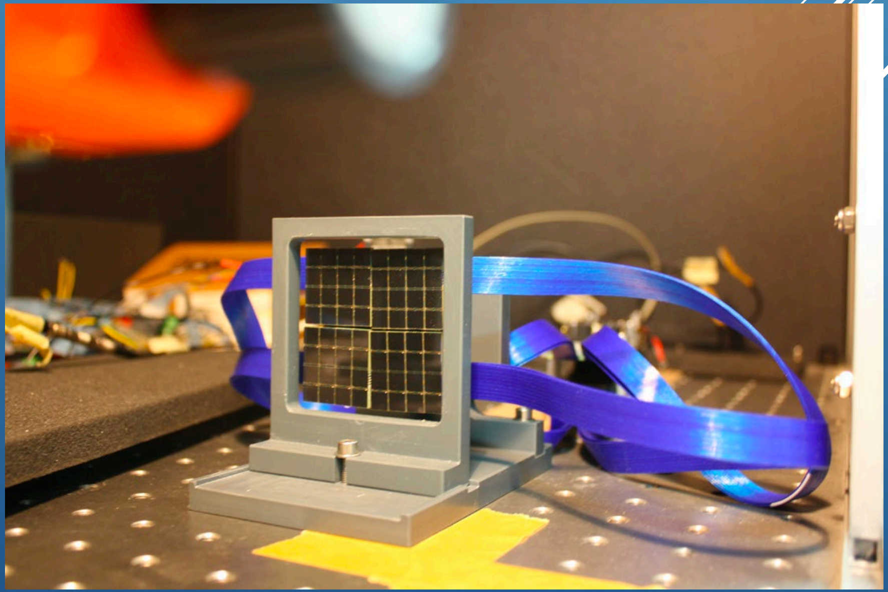


Upgraded electronics performance



SMART Quality Control tests

- About 750 ASICs produced only 7 ASICs were found to be defective(< 1%).
- The main features of the SMART were tested to check basic functionalities:
  - ADC calibration for current readout
  - Response to a laser pulse
  - Variation of pulse shape vs SMART configuration
  - Pulse amplitude variation vs DAC for fine SiPM bias tuning



Summary

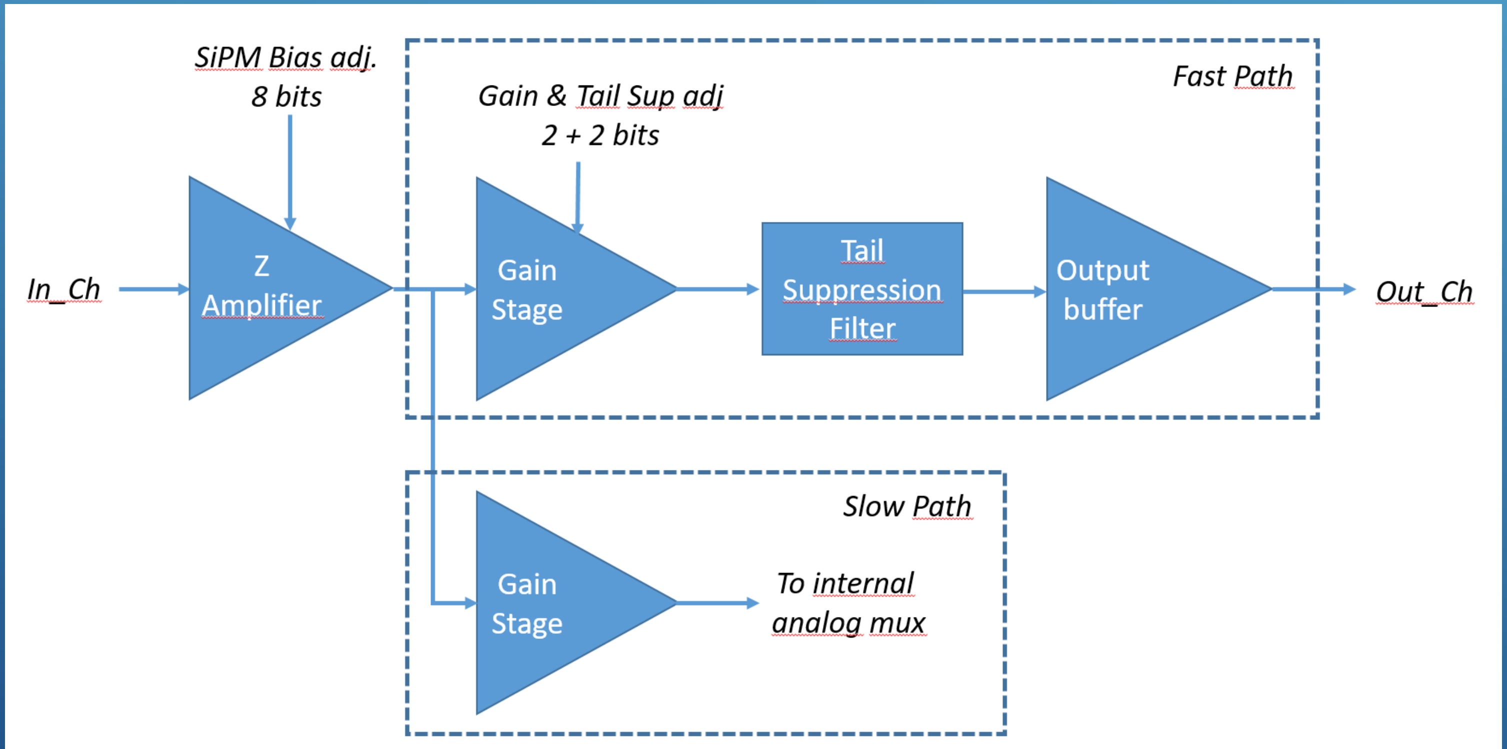
- The Schwarzschild-Couder Telescope is one of the proposed designs for the Medium-Sized Telescopes for CTA
  - Improved angular resolution and sensitivity wrt single mirror telescope
- First prototype installed at the FLWO in Arizona and inaugurated in Jan 2019
  - Optics aligned reaching pre-construction estimated PSF – Dec 2019
  - Crab detection – May 2020
- Camera upgrade ongoing
  - Full equipment of the focal plane
  - Upgraded camera electronics and mechanics to reach design performance

Acknowledgements:
https://www.cta-observatory.org/consortium_acknowledgments/


Thanks for the attention!

Backup

SMART Channel Architecture



Channel features:

- Fast path gain: 2-8 mV/ph
- Tail suppression: pulse duration ~ 10ns
- Output buffer impedance: 12.5Ω
- Current consumption: from 4.5mA to 6mA
- SiPM bias fine tuning: LSB = 12.5mV
- Slow path output & 10 bit ADC: LSB = 2MHz

Camera design