

# SiPM optical modules for the Schwarzschild- Couder Medium Size Telescopes proposed for the CTA observatory

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**and the INFN-SCT group:**

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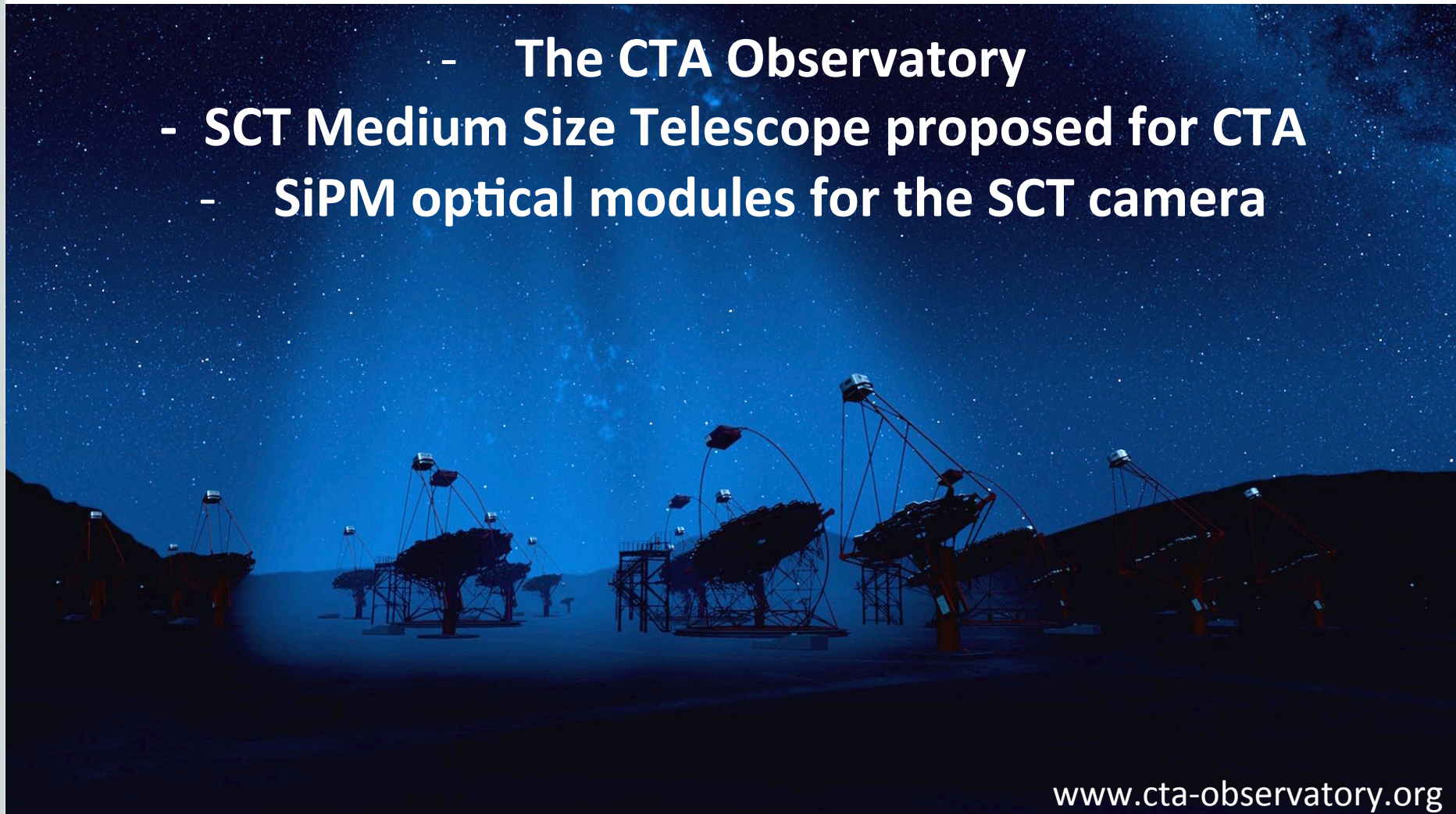
**for the CTA SCT Project**



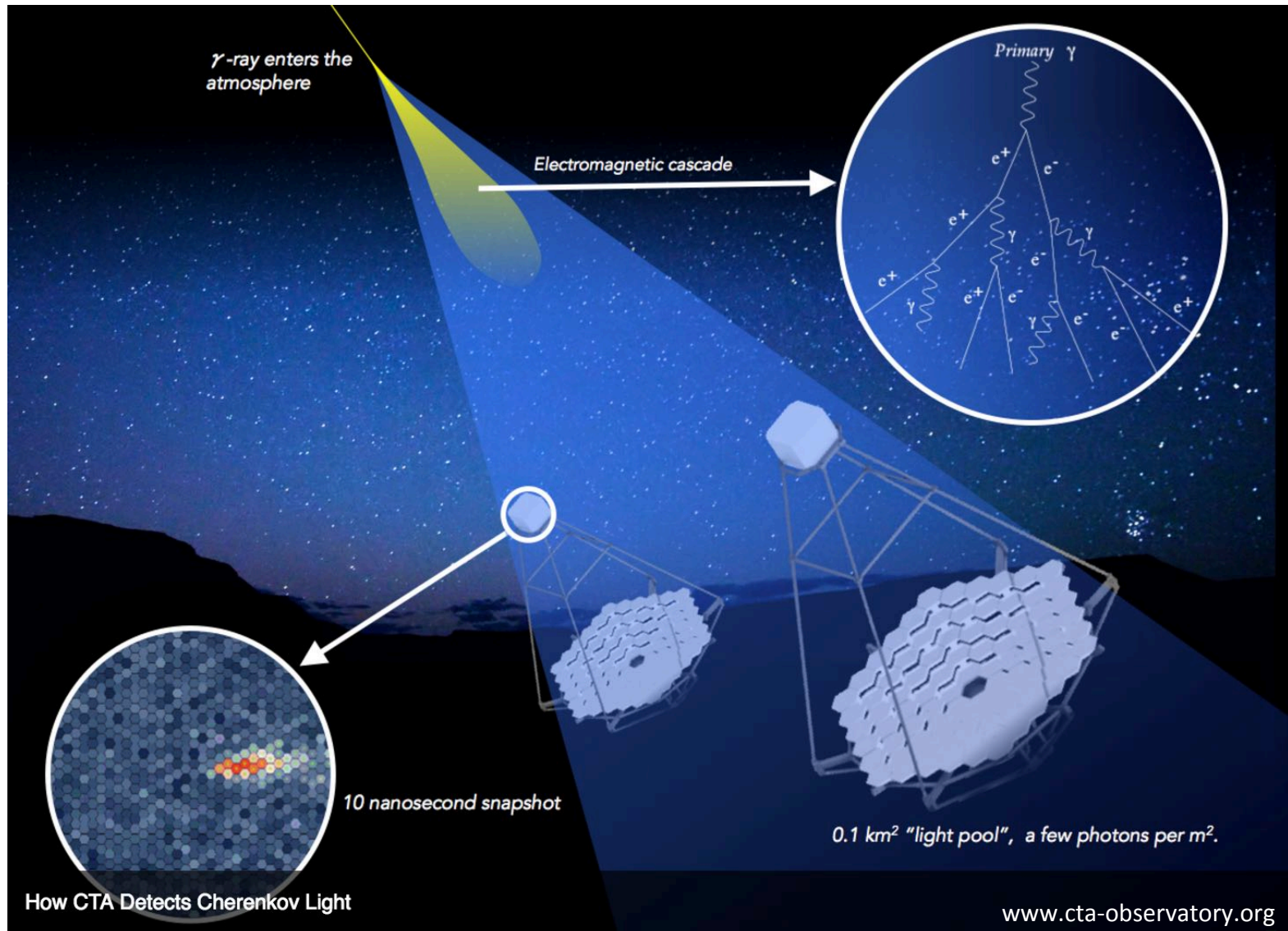


## SiPM optical modules for the Schwarzschild- Couder Medium Size Telescopes proposed for the CTA observatory

- The CTA Observatory
- SCT Medium Size Telescope proposed for CTA
- SiPM optical modules for the SCT camera

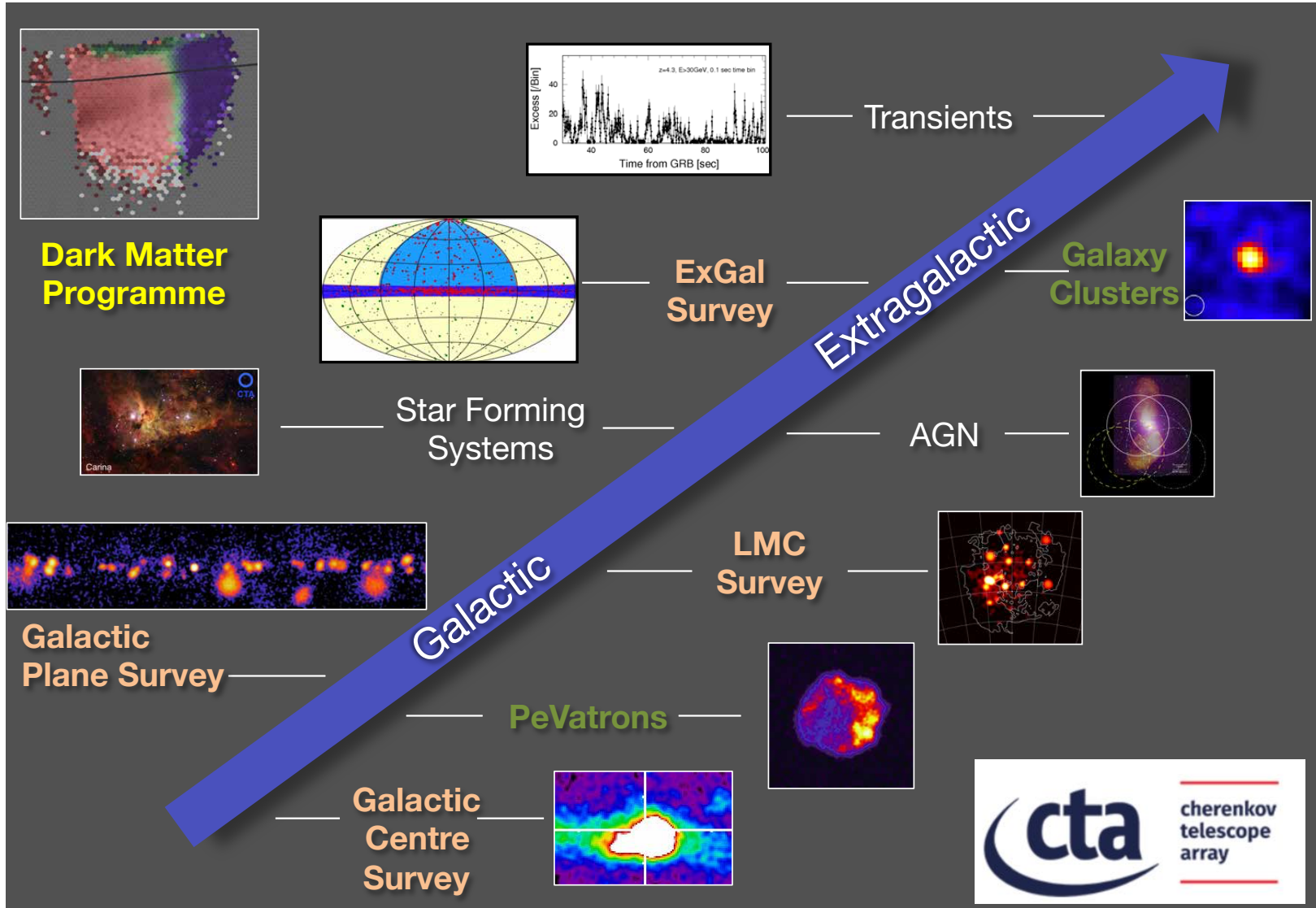


# Cherenkov Telescopes





# Exploring the Universe at the Highest energies



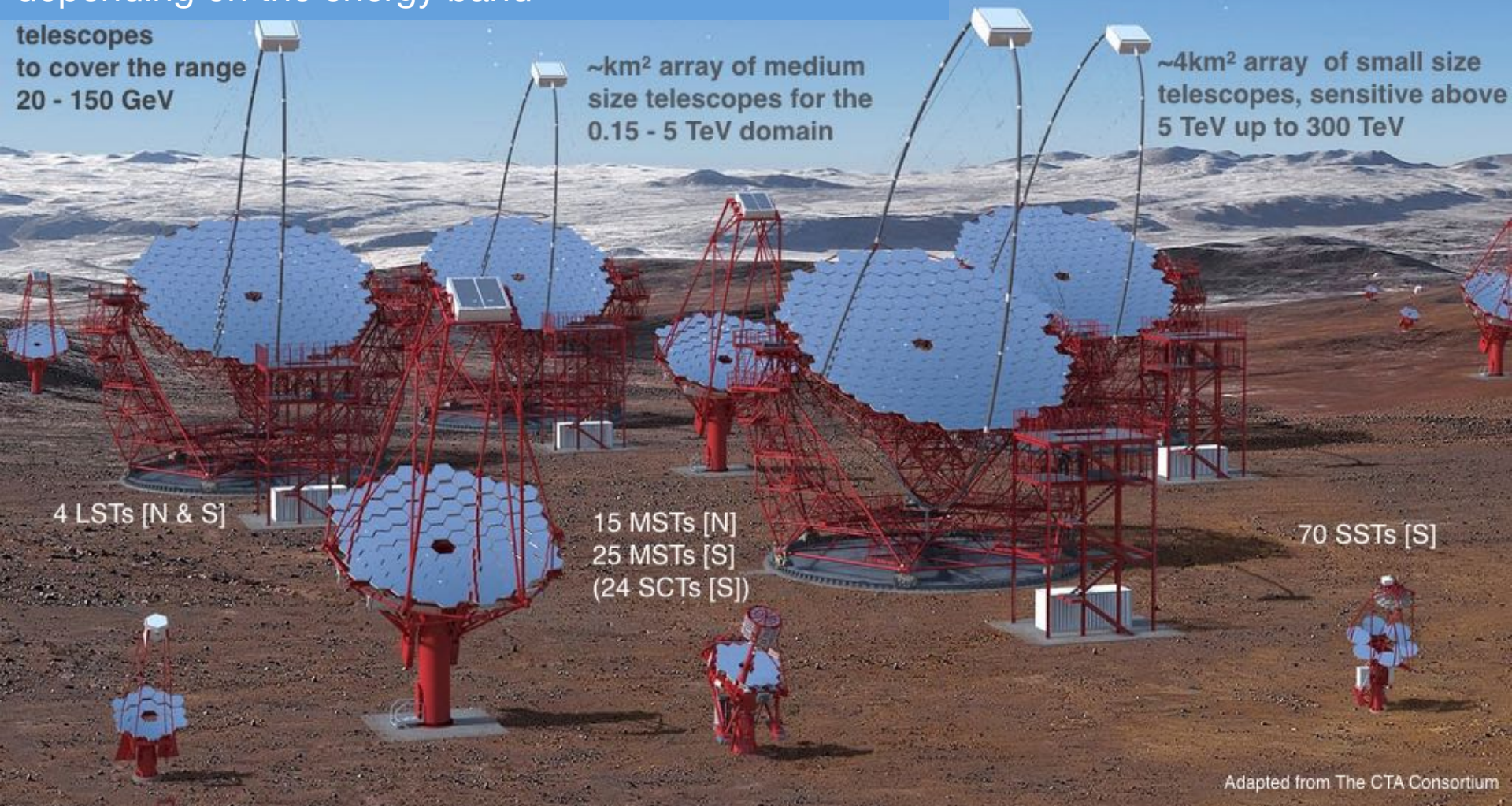


Two sites in northern and southern hemisphere for a whole-sky coverage

Operated as an open observatory

A factor of 5-10 more sensitive wrt the current IACTs depending on the energy band

# The Cherenkov Telescope Array



telescopes to cover the range 20 - 150 GeV

~km<sup>2</sup> array of medium size telescopes for the 0.15 - 5 TeV domain

~4km<sup>2</sup> array of small size telescopes, sensitive above 5 TeV up to 300 TeV

4 LSTs [N & S]

15 MSTs [N]  
25 MSTs [S]  
(24 SCTs [S])

70 SSTs [S]



# SCT Telescope

## Schwarzschild-Couder dual mirror optics Medium Size Telescope

Secondary mirror (5.4m diam)

Focal plane camera

Primary mirror (9.7m diam)



**The Fred Lawrence Whipple  
Observatory, Arizona**

**Dual mirror optics:** cancel aberration and de-magnify images, compatible with **compact high-resolution SiPM camera** -> a smaller point spread function (PSF) and **improved angular resolution**

**Mechanical stability and mirror alignment are the main challenges.**



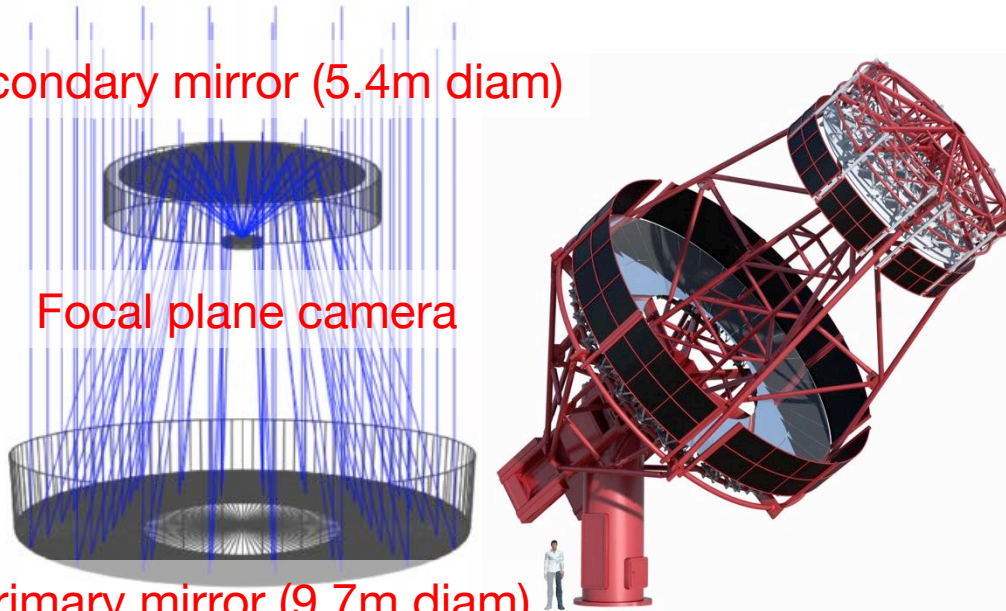
# SCT Telescope

## Schwarzschild-Couder dual mirror optics Medium Size Telescope

Secondary mirror (5.4m diam)

Focal plane camera

Primary mirror (9.7m diam)



**VERITAS site, Arizona**



22 institutes, universities and observatories



5 institutes, universities and observatories



3 institutes and universities



1 university



1 university

**SCT is the unique proposal of the innovative SC optics for the CTA Medium Size Telescope**

# Single and Dual mirror MST

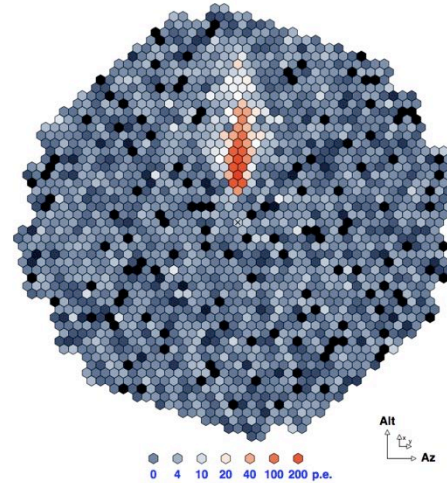
## MST

Single mirror  
Davies-Cotton

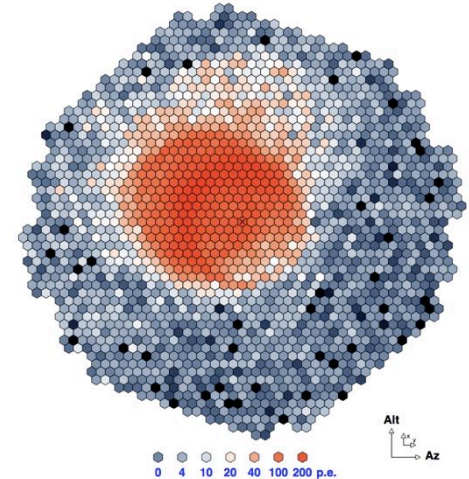
approx 2k PMTs



1 TeV  $\gamma$ -ray Shower  
Impact Distance: 100m



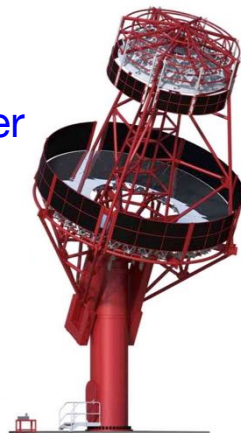
3.16 TeV Proton Shower  
Impact Distance: 0m



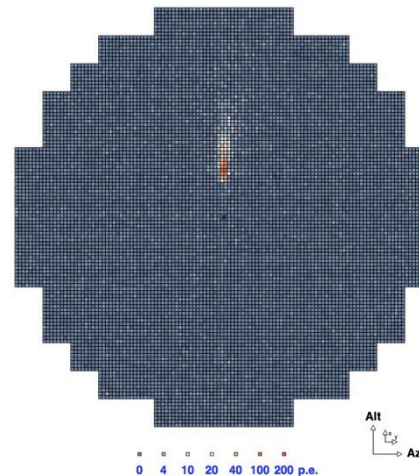
## SCT

Dual mirror  
Schwarzschild-Couder

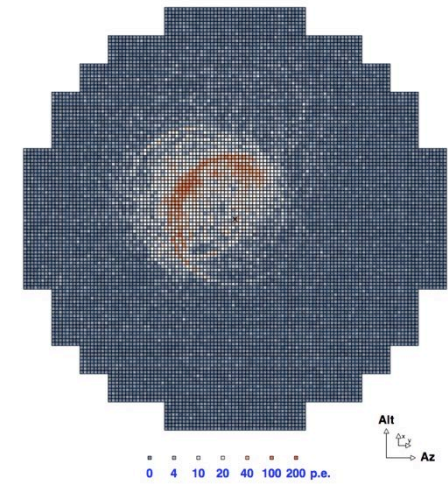
approx 12k SiPMs



1 TeV  $\gamma$ -ray Shower  
Impact Distance: 100m



3.16 TeV Proton Shower  
Impact Distance: 0m

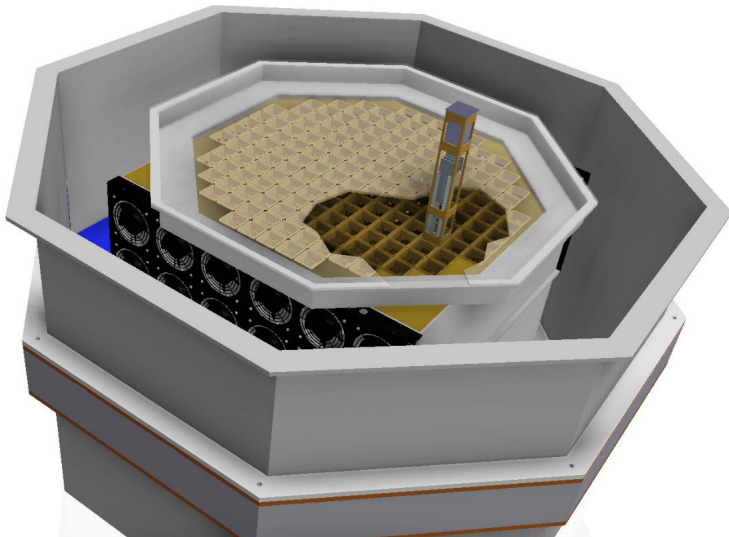




# pSCT Telescope

## Prototype demonstrator for the Medium Size SCT solution

**0.4m<sup>2</sup> active area per telescope**



8° field of view, 81 cm diameter

Prototype main goals:

- Demonstrate the **performances of the optical system**
- Gain experience with the **optical alignment** and **operation of the SiPM camera**

- Excellent optical resolution, small plate scale of dual-mirror telescope well matched to fine pixelation supported by silicon photomultipliers and TARGET readout electronics
- 11,328 6x6 mm<sup>2</sup> pixels (temperature-stabilized silicon photomultipliers)
- Pixel size 0.067° (high-resolution imaging)
- Readout directly behind focal plane
- 1 GSa/s, 10 bits effective (TARGET 7)
- 3 kW power budget

pSCT project has been awarded with a grant of the National Science Foundation  
INFN is in charge for the assembly of a complete focal plane equipped with FBK  
NUV-HD and the FEE modules

"MRI Consortium: Development of a WideField-of-View Camera for the  
Schwarzschild-Couder Gamma Ray Telescope," is under the direction of Reshmi  
Mukherjee, Nepomuk Otte, Brian Humensky, Francesco Giordano, Justin A.  
Vandenbroucke

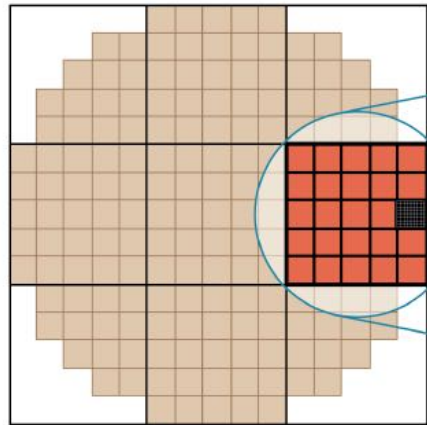
It starts September 1 , 2018 and ends August 31, 2021

This award is expected to total \$2,195,309

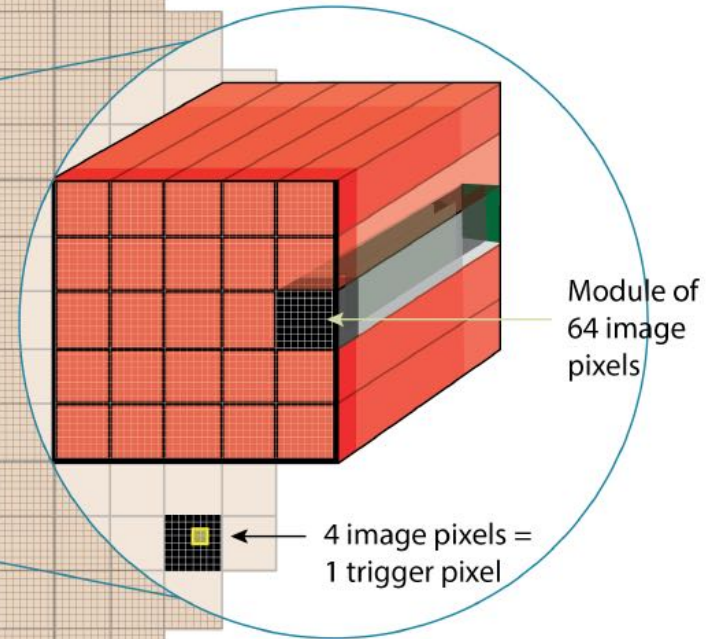


# Focal Plane camera

Full camera = 9 sub-fields  
 177 modules  
 11,328 image pixels

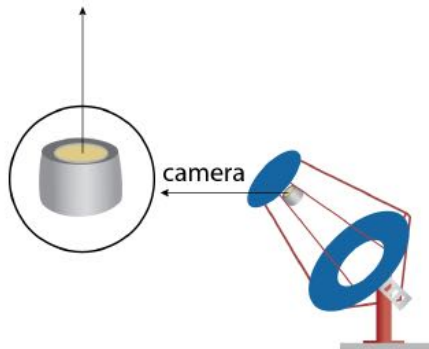


1 sub-field = 25 modules

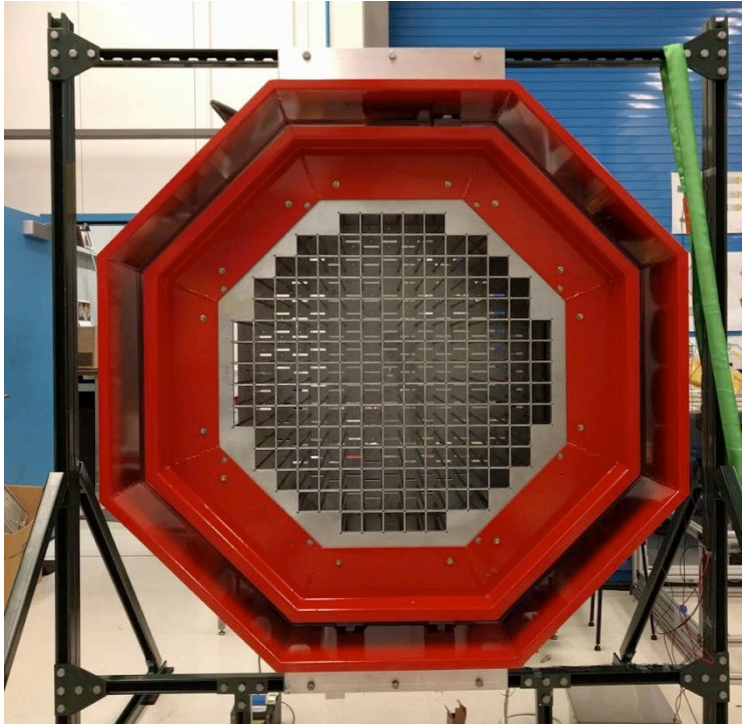


Module of 64 image pixels

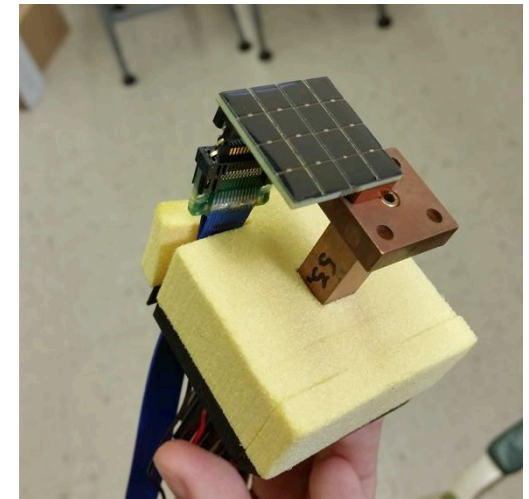
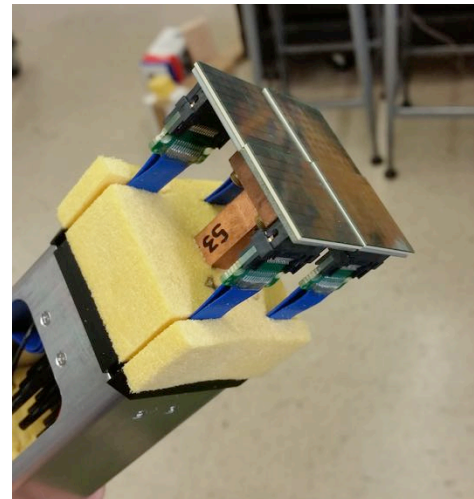
4 image pixels = 1 trigger pixel



pSCT camera frame in Univ. of Wisconsin



- Originally planned with Hamamatsu MPPC modules
- Possible upgrade with **FBK NUV-HD SiPM** modules

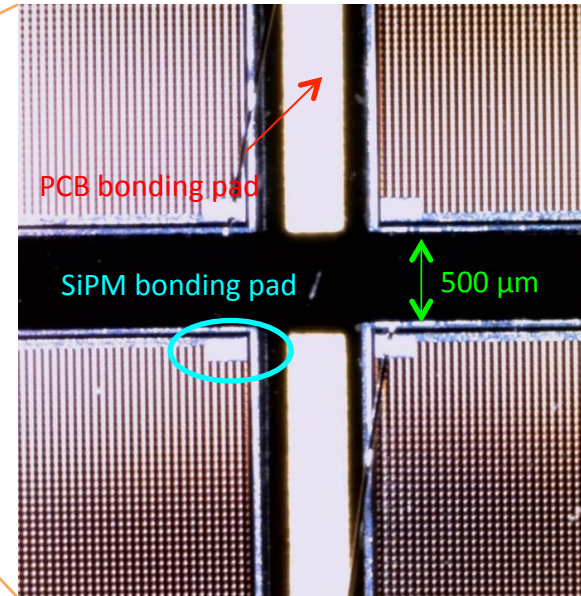
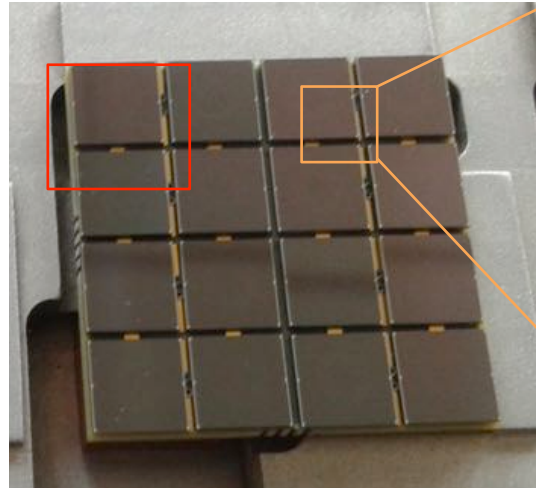


US Hamamatsu module INFN FBK prototype

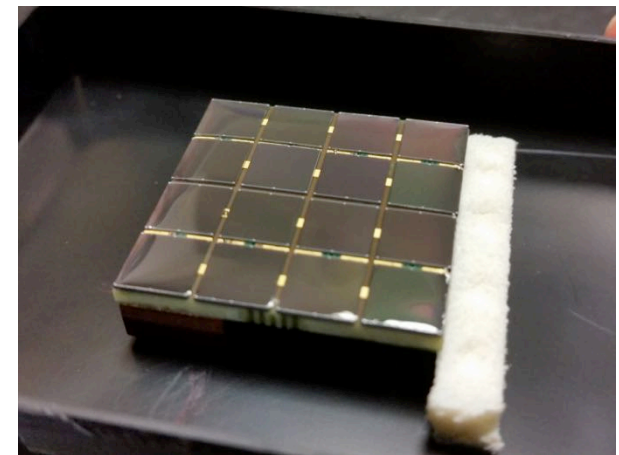
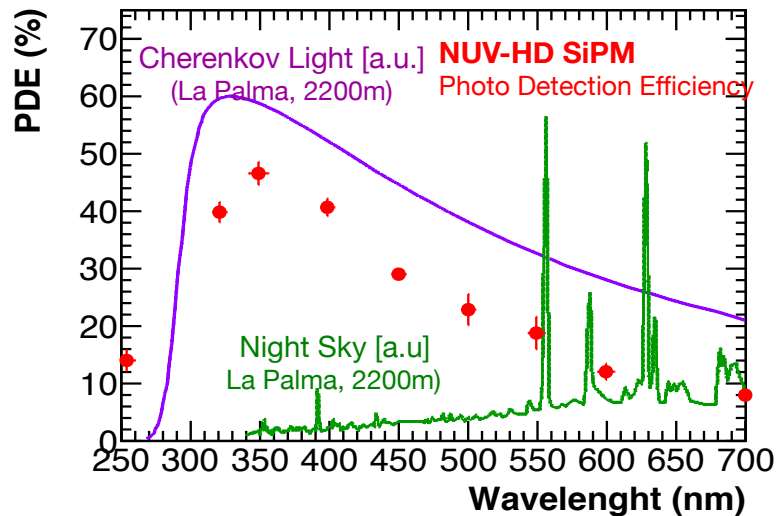


# pSCT module upgrade (FBK)

6x6mm<sup>2</sup>



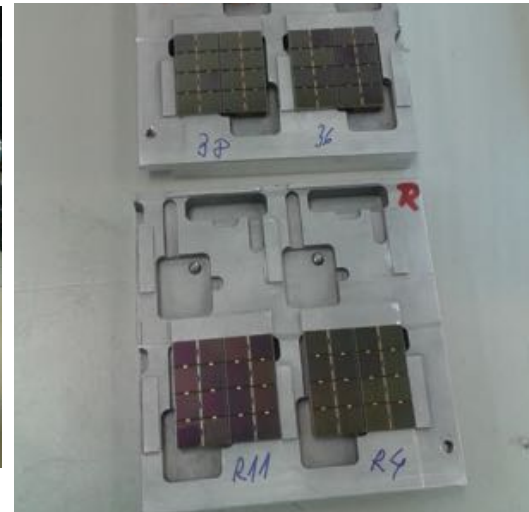
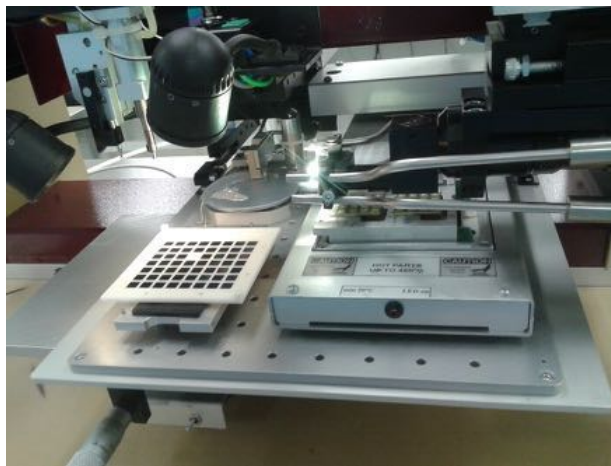
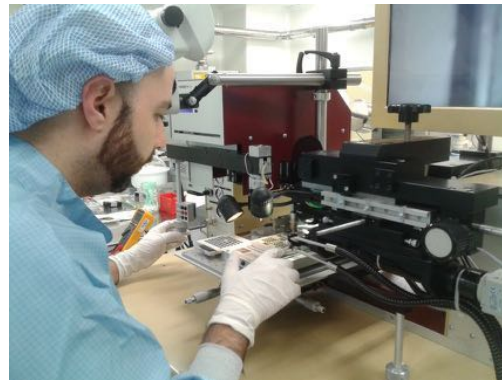
27x27mm<sup>2</sup> PCBs are equipped with 16 SiPMs to cover uniformly the exposed area





PCB modules are assembled with SiPM sensors in the laboratories of INFN.

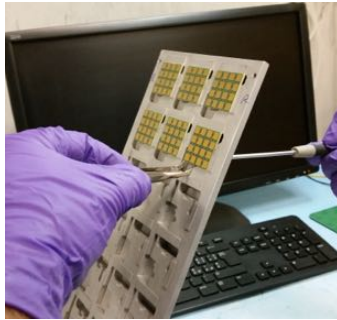
R&D activities in 2016/2017 (INFN and Univ. of Perugia, IT).



# SiPM module assembly and tests

After quality checks, SiPMs are wire-bonded and the PCBs are protected with UV-transparent epoxy layer

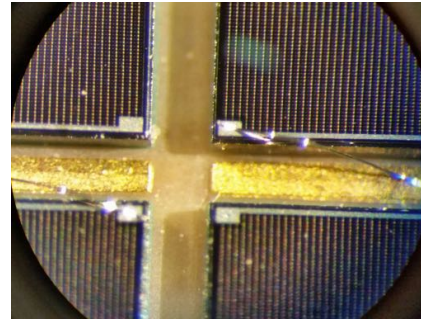
Placement in bonding&transport jig



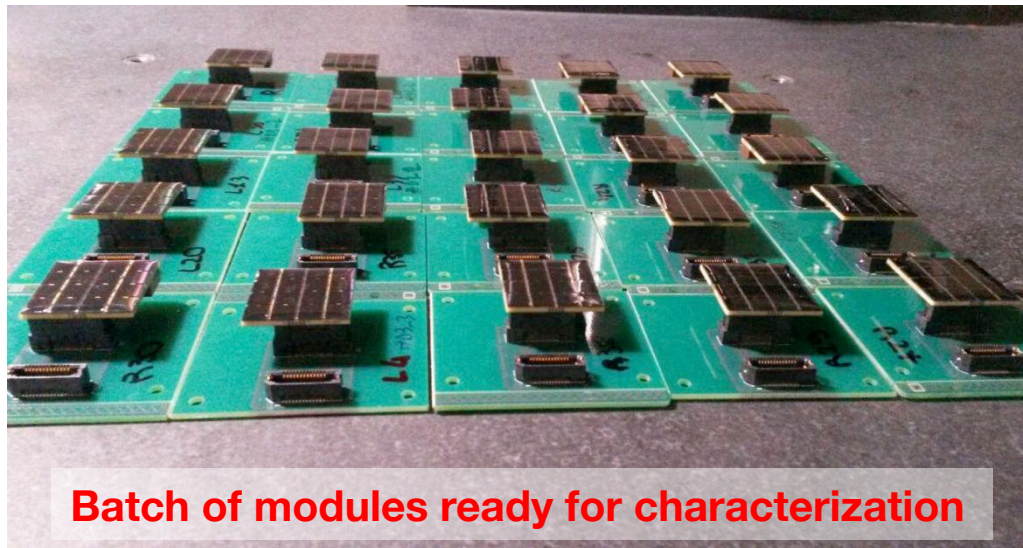
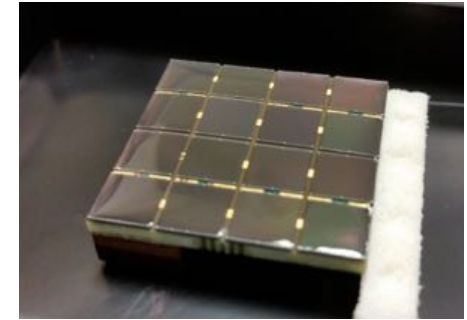
Bonding (approx. 15 mins/matrix)



Bonding with 20 $\mu$ m Al/Si wire

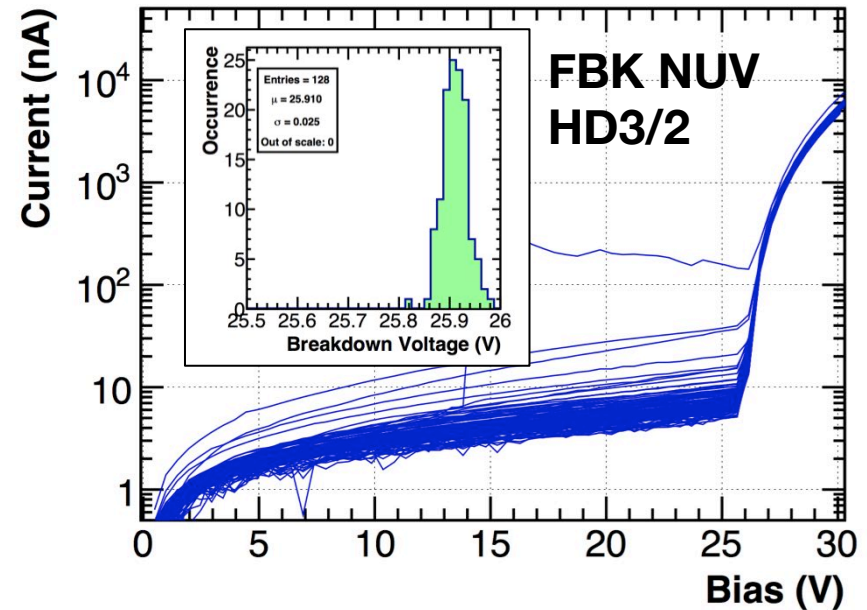
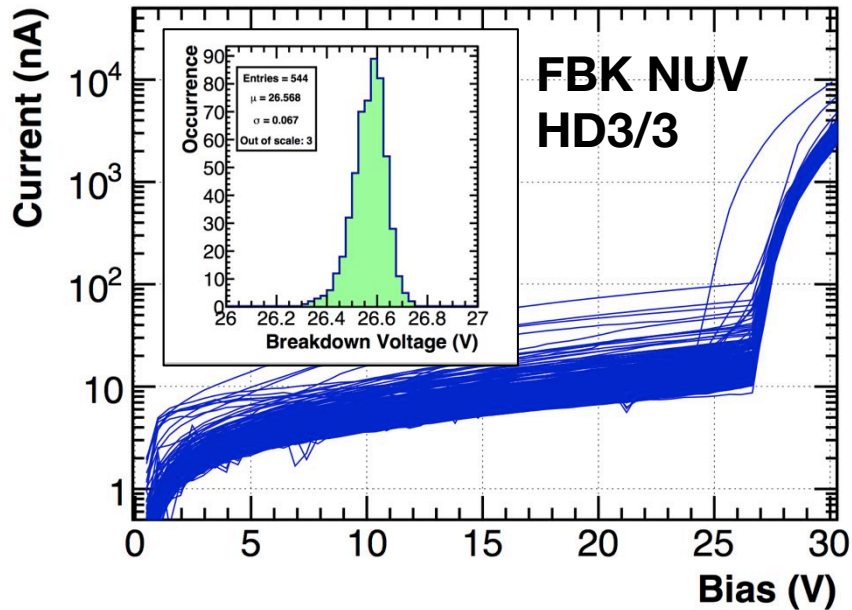


Dispensing of UV-transparent protecting epoxy



**Batch of modules ready for characterization**





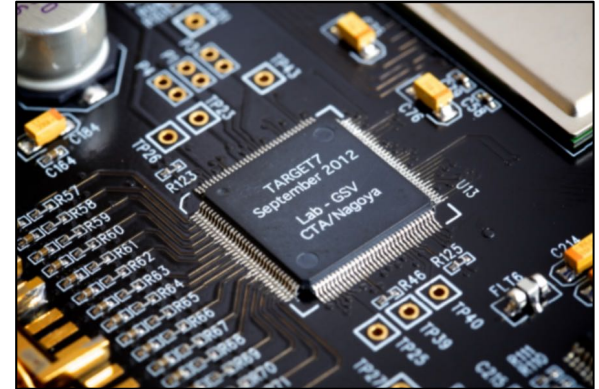
2017/2018:

- 100 units assembled (including prototypes and mechanicals)
- 56 units tested electrically
- **36 units selected to equip 9 modules for the pSCT camera.**

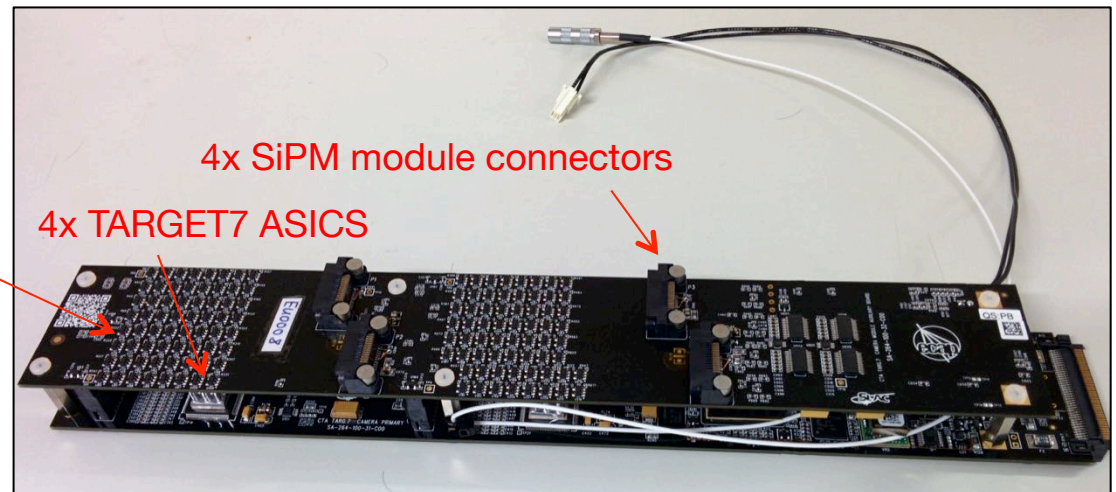
# SiPM module readout

Module signal readout using “TeV Array Readout with GS/s sampling and Event Trigger” (TARGET7) board

- **Compact chip for high density channel camera**
- 16 input channels
- Analogue ring buffer of 16384 capacitors
- Switched Capacitors Array
- Storage of **analogue** waveforms in a limited period of time @ 1GSa/s sampling frequency

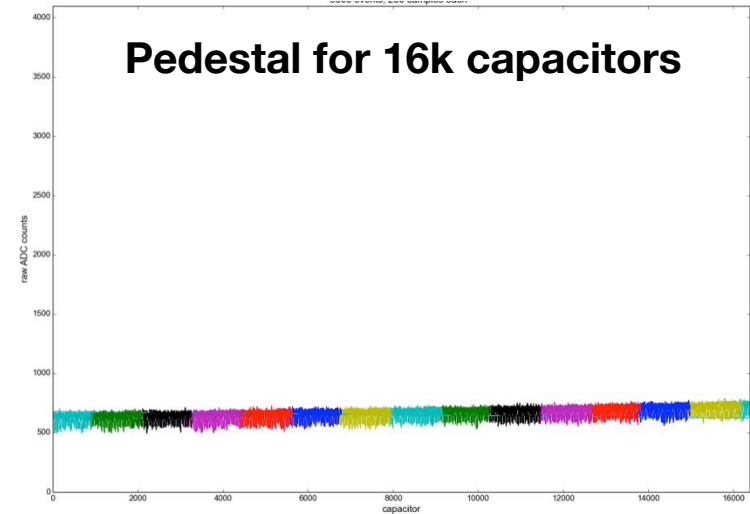


Pre-amplifier stage  
pulse shaping  
pole zero cancellation network

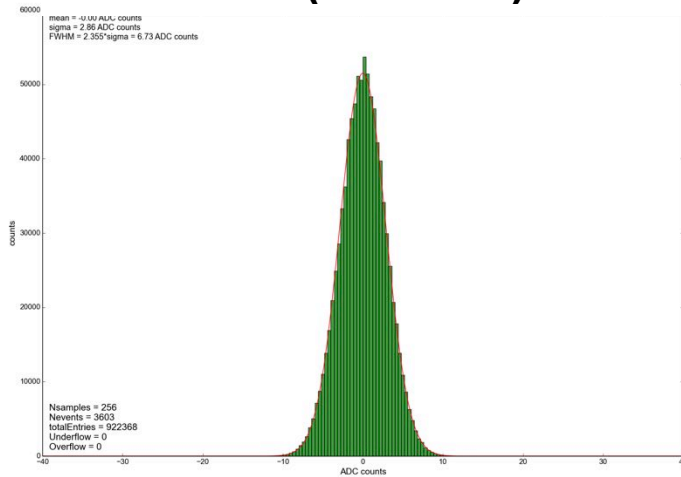




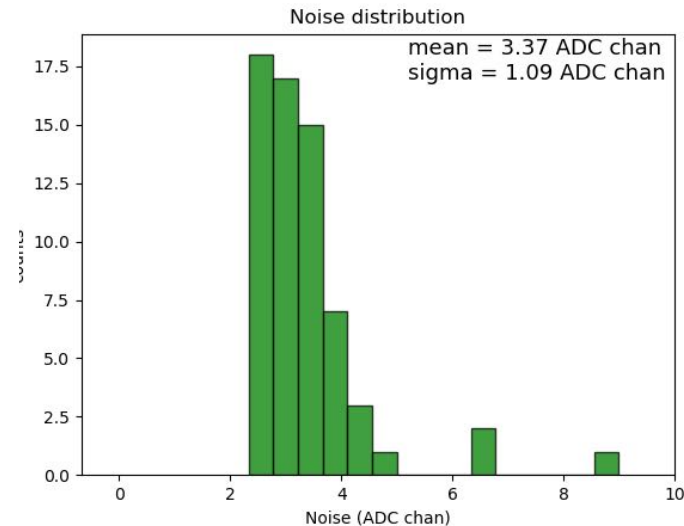
- 5 TARGET 7 modules produced in IT
- 4 TARGET 7 modules processed to adapt FEE to FBK SiPMs
- Quality controls in INFN Pisa+Bari including
  - **Pedestal calibration**
  - Waveform acquisition (laser)
  - Trigger verification



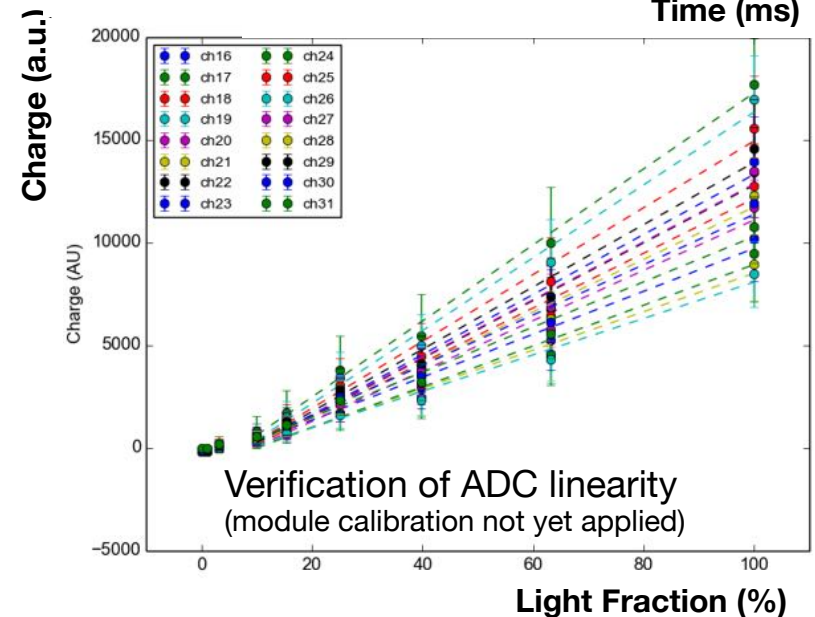
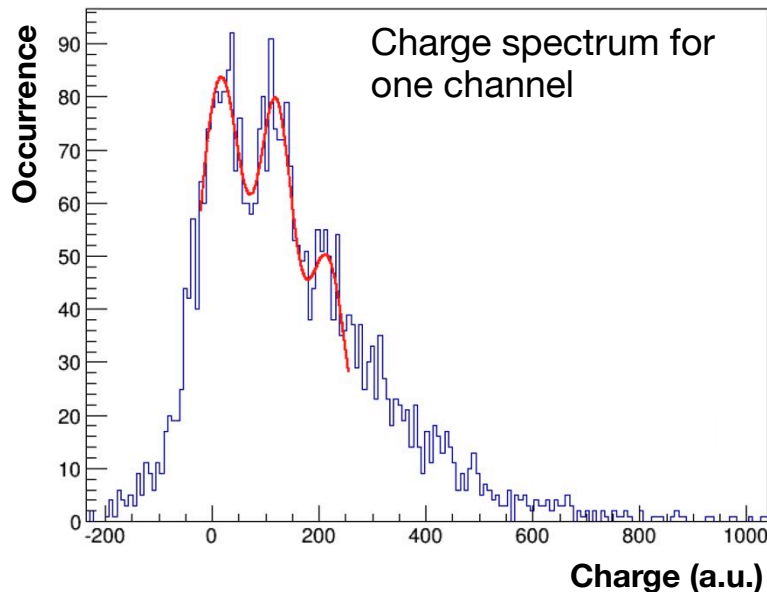
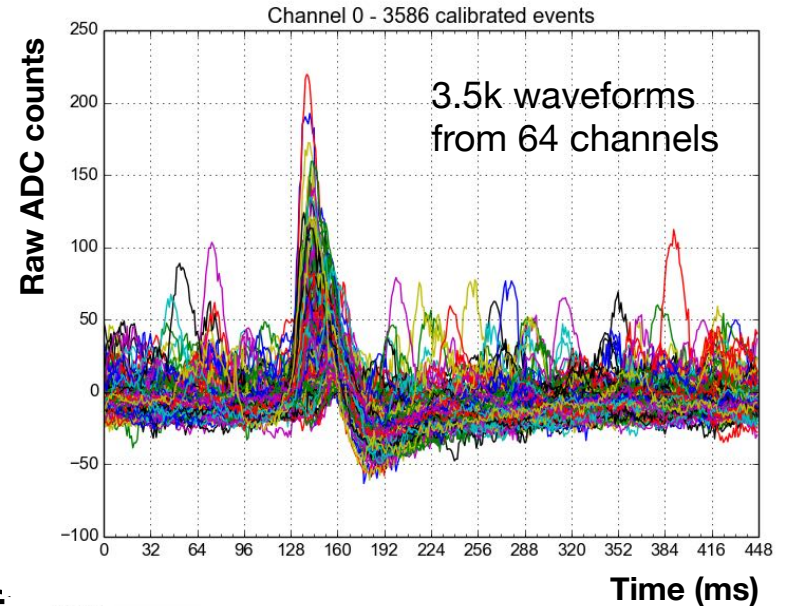
## ADC after pedestal subtraction (1 channel)



## Noise for 64 channels (1 ASIC)

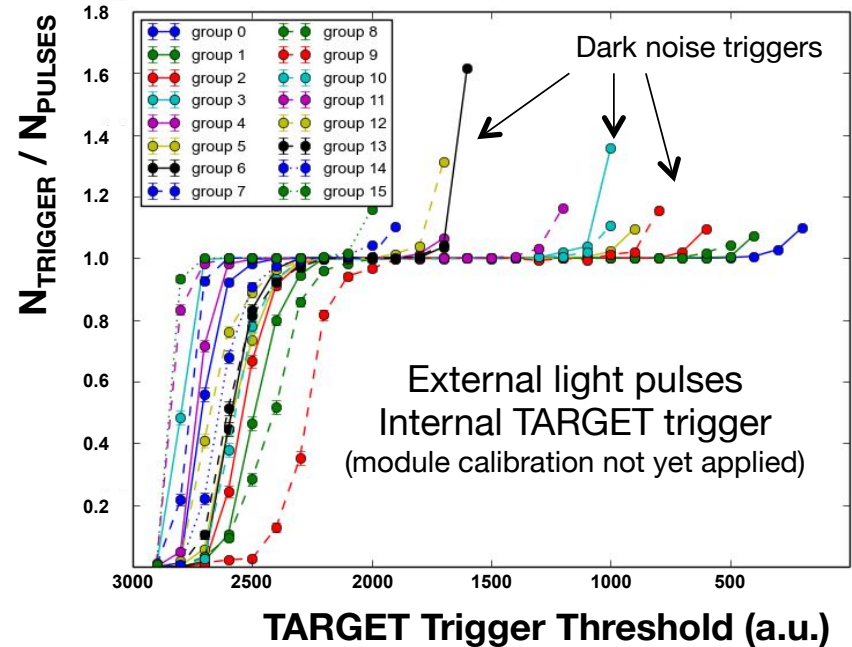


- 5 TARGET 7 modules produced in IT
- 4 TARGET 7 modules processed to adapt FEE to FBK SiPMs
- Quality controls in INFN Pisa+Bari including
  - Pedestal calibration
  - **Waveform acquisition (laser)**
  - Trigger verification





- 5 TARGET 7 modules produced in IT
- 4 TARGET 7 modules processed to adapt FEE to FBK SiPMs
- Quality controls in INFN Pisa+Bari including
  - Pedestal calibration
  - Waveform acquisition (laser)
  - **Trigger verification**



**All measurements repeated on 9 fully assembled modules**  
4 FEE channels out of 576 channels failed the tests (99% yield)

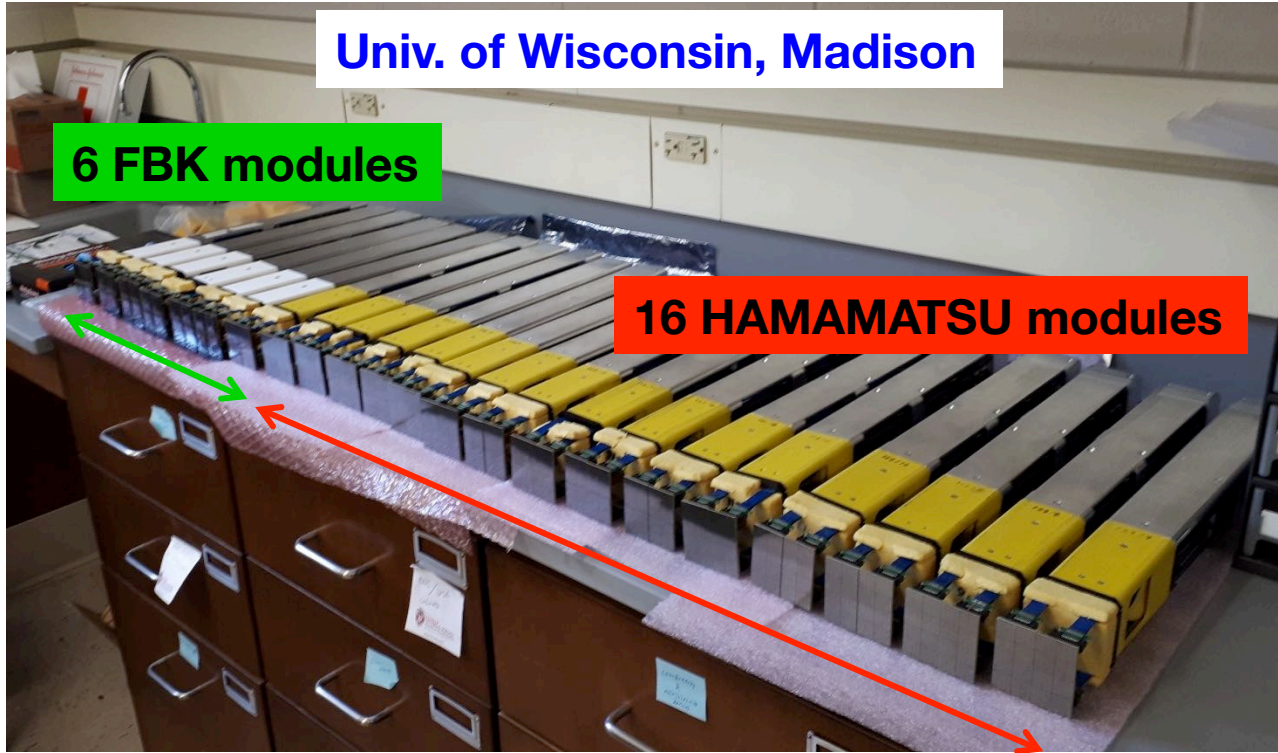
**9 board smade for integration on the pSCT camera**

# Camera tests

Univ. of Wisconsin, Madison

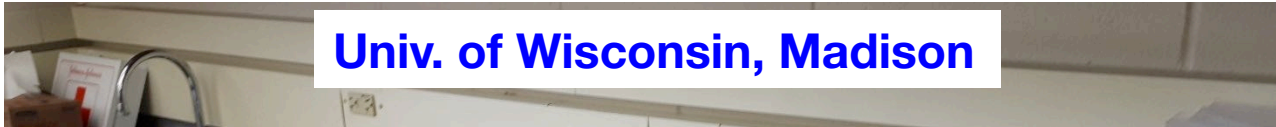
6 FBK modules

16 HAMAMATSU modules



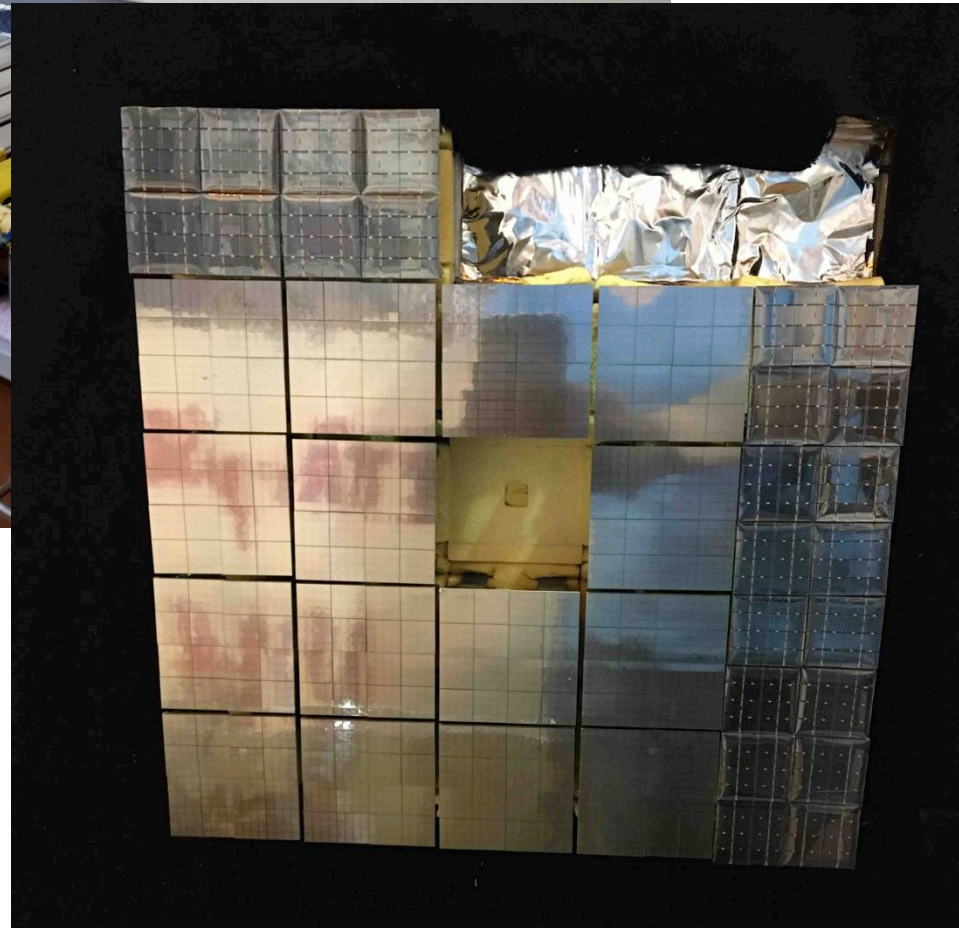
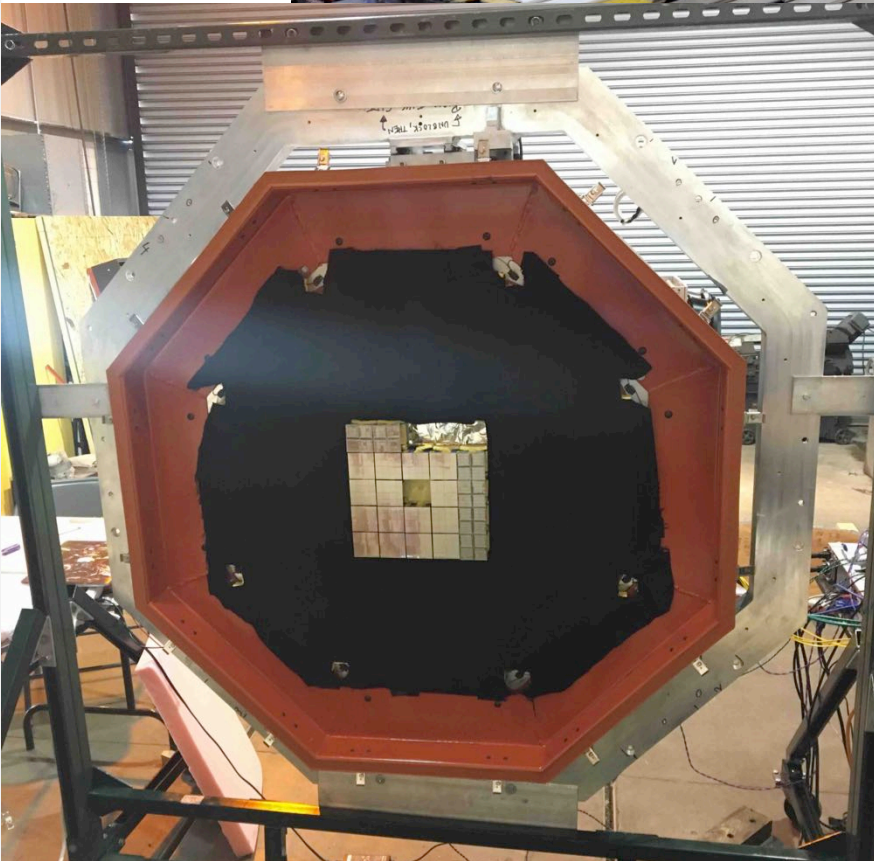


# Camera tests



Univ. of Wisconsin, Madison

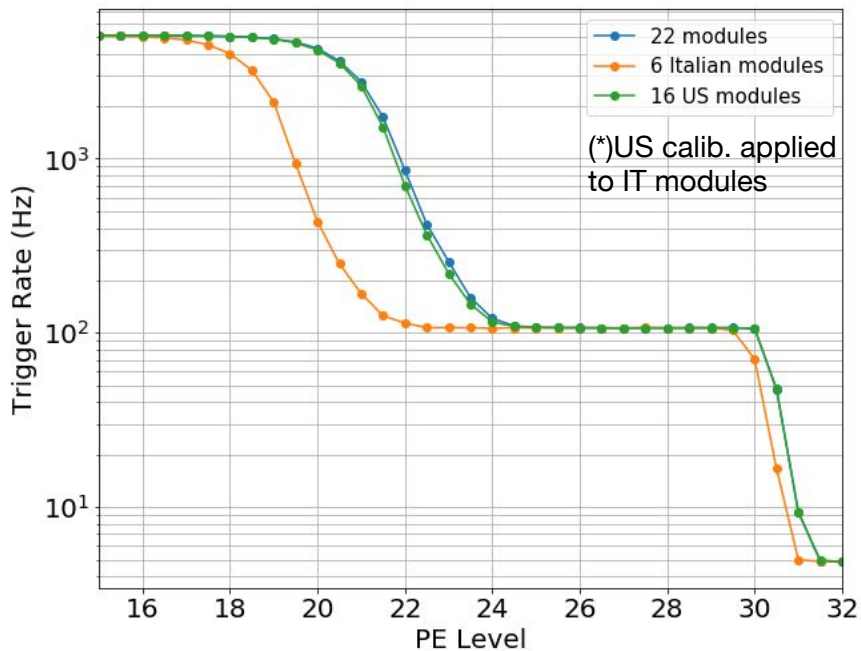
15 US + 6 INFN modules integrated (1408 total pixels)



# Camera tests

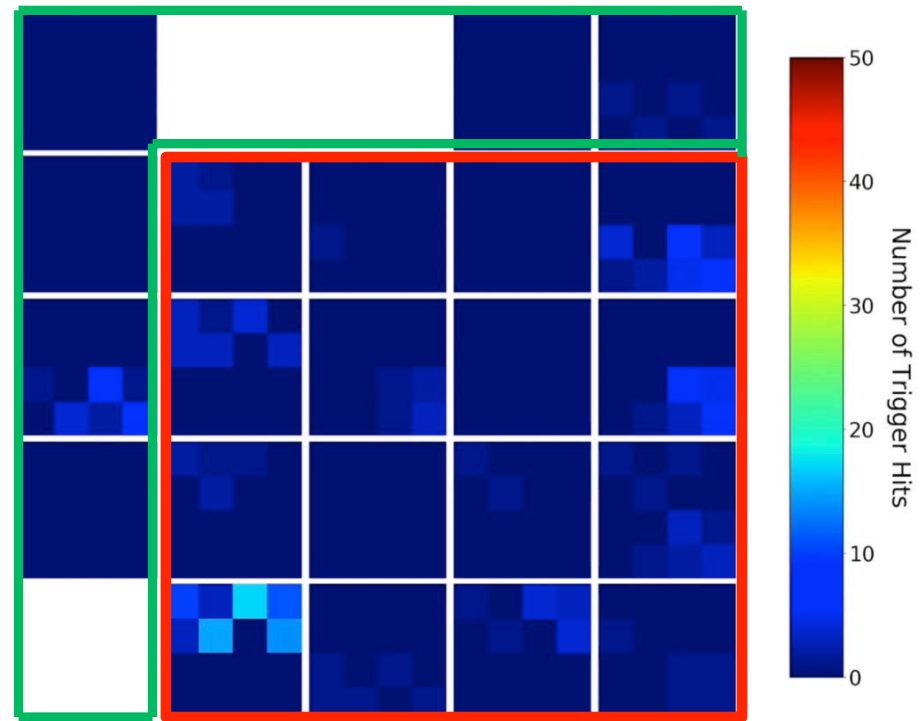
LED flashed at 100 Hz, camera self triggered (using TARGET 7 internal trigger)  
 Trigger applied to analog sum of 4 pixels (equivalent to 5.5 pe per pixel)

Nominal operating point: 1 kHz readout at 22 photoelectron threshold



Study of noise occupancy and comparison to waveform-based images is underway

18.0 PE Threshold **INFN modules**



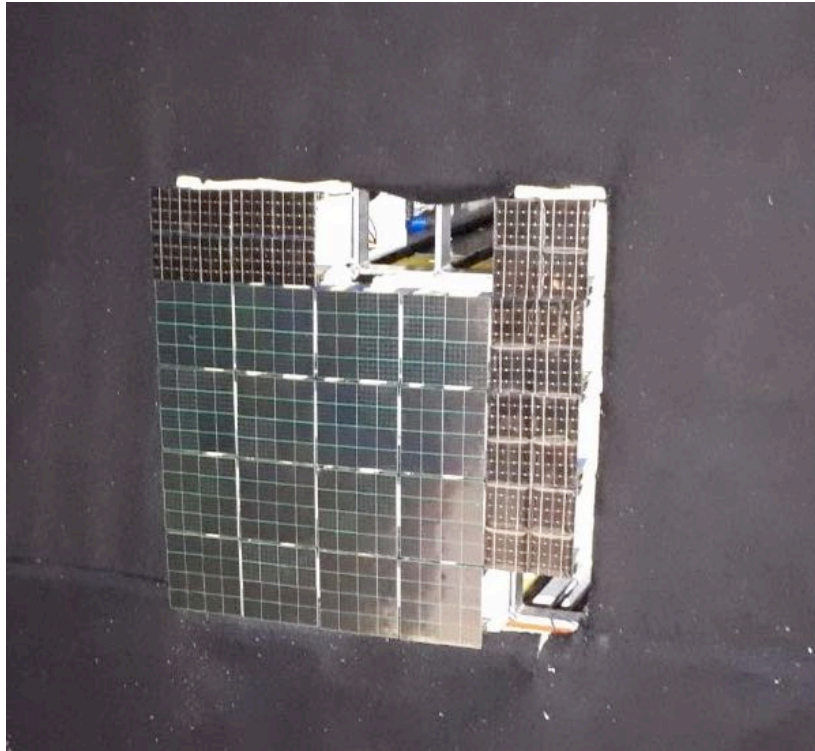
**US modules**



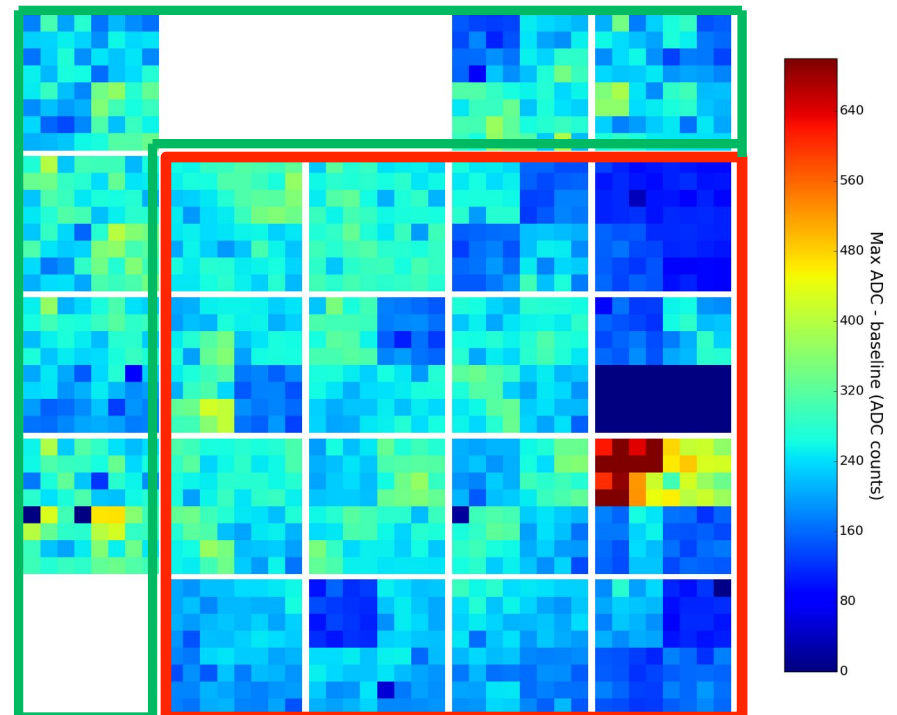
# Camera tests

LED flashed at 100 Hz, camera self triggered (using TARGET 7 internal trigger)  
Raw, uncalibrated ADC amplitudes (INFN divided by 2 for gain compensation)

Further characterization of the camera after installation on the telescope



**INFN modules**



**US modules**



### Main Installation milestones:

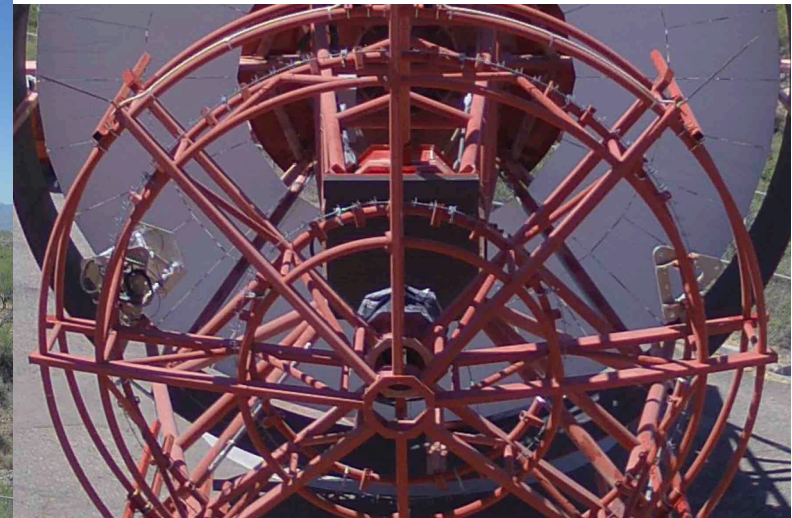
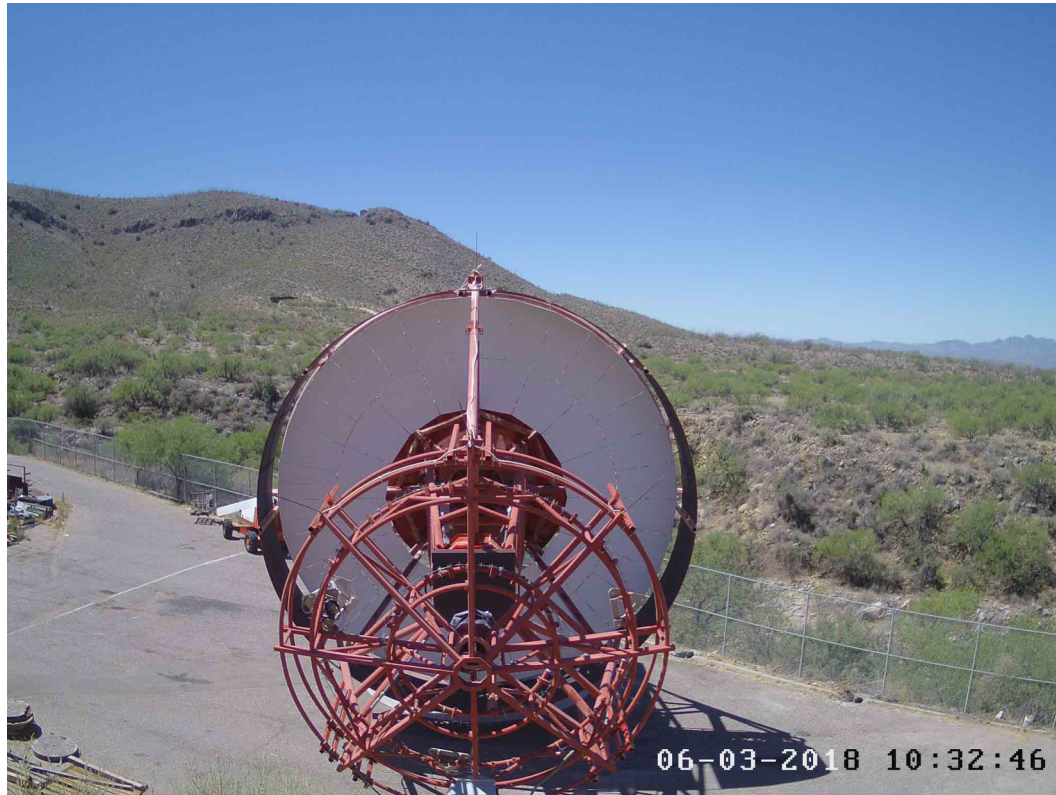
- Primary mirror installation: done
- Camera commissioning (primary mirror only): done
  - Secondary mirror installation: done
- Camera commissioning (complete optics): Fall 2018
- Integration of one additional camera sector (25 modules): End of 2018 / 2019

Image credits: B. Humensky & J. Vandenbroucke



# Camera Installation

**Camera lift and successfully installed on 30 May 2018**



pSCT webcam: <http://cta-psct.physics.ucla.edu/>

# Camera Installation

**Secondary mirror installation completed on 15<sup>th</sup> August 2018**

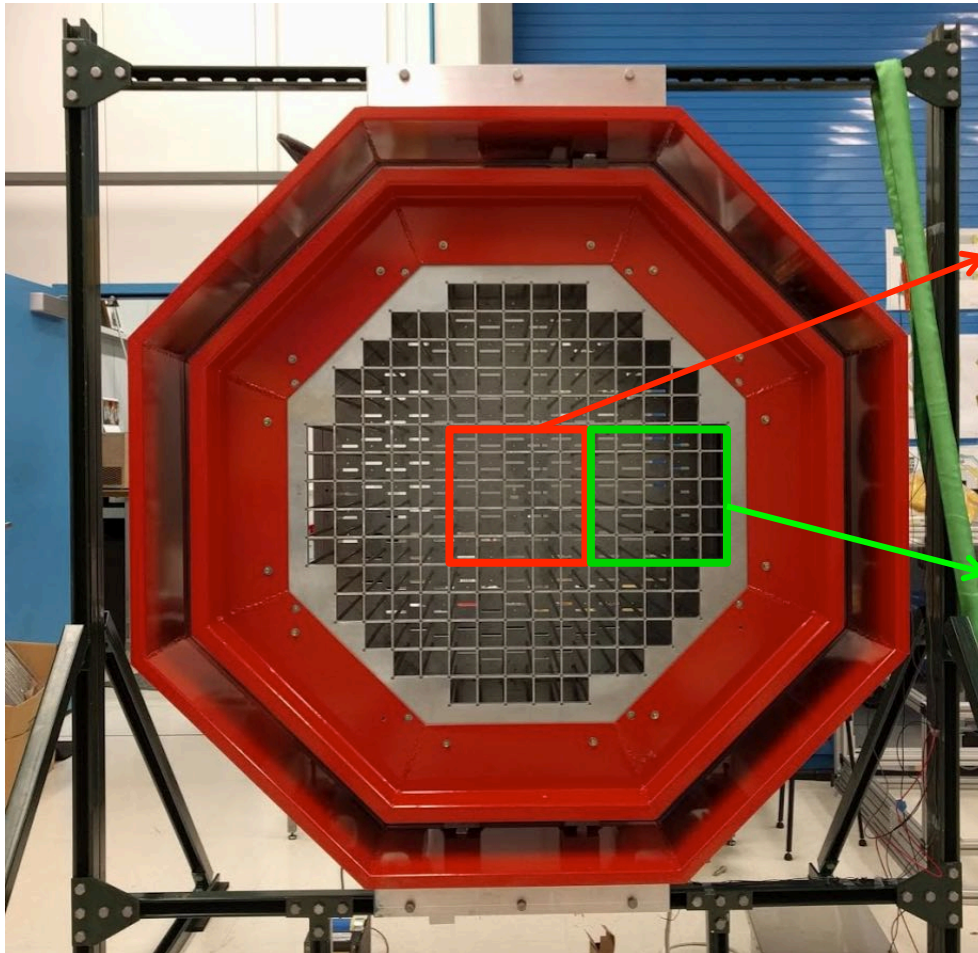


pSCT webcam: <http://cta-psct.physics.ucla.edu/>



# Module integration pt. II

One additional quadrant (25 modules, 1600 pixels) scheduled to be integrated with FBK SiPMs and upgraded electronics by end of 2018.



25 modules equipped & in commissioning  
(9 FBK NUV-HD, 16 Hamamatsu)

25 modules to be equipped  
(25 FBK NUV-HD)

## Assembly, packaging and tests of optical modules based on FBK SiPMs

- 6 modules installed in the pSCT camera, 3 additional modules foreseen
- - One additional quadrant (25 modules, 1600 pixels) scheduled to be integrated with FBK SiPMs and upgraded electronics by end of 2018.

This award starts September 1 , 2018 and ends August 31, 2021.

