CTA Small-sized Telescopes and Technical Challenges for Wide-FOV Cameras and Optical Systems

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名古屋大学 NAGOYA UNIVERSITY

ISEE Institute for Space–Earth Environmental Research

cta cherenkov telescope array

oxon@mac.com

Small-Sized Telescopes (SSTs)

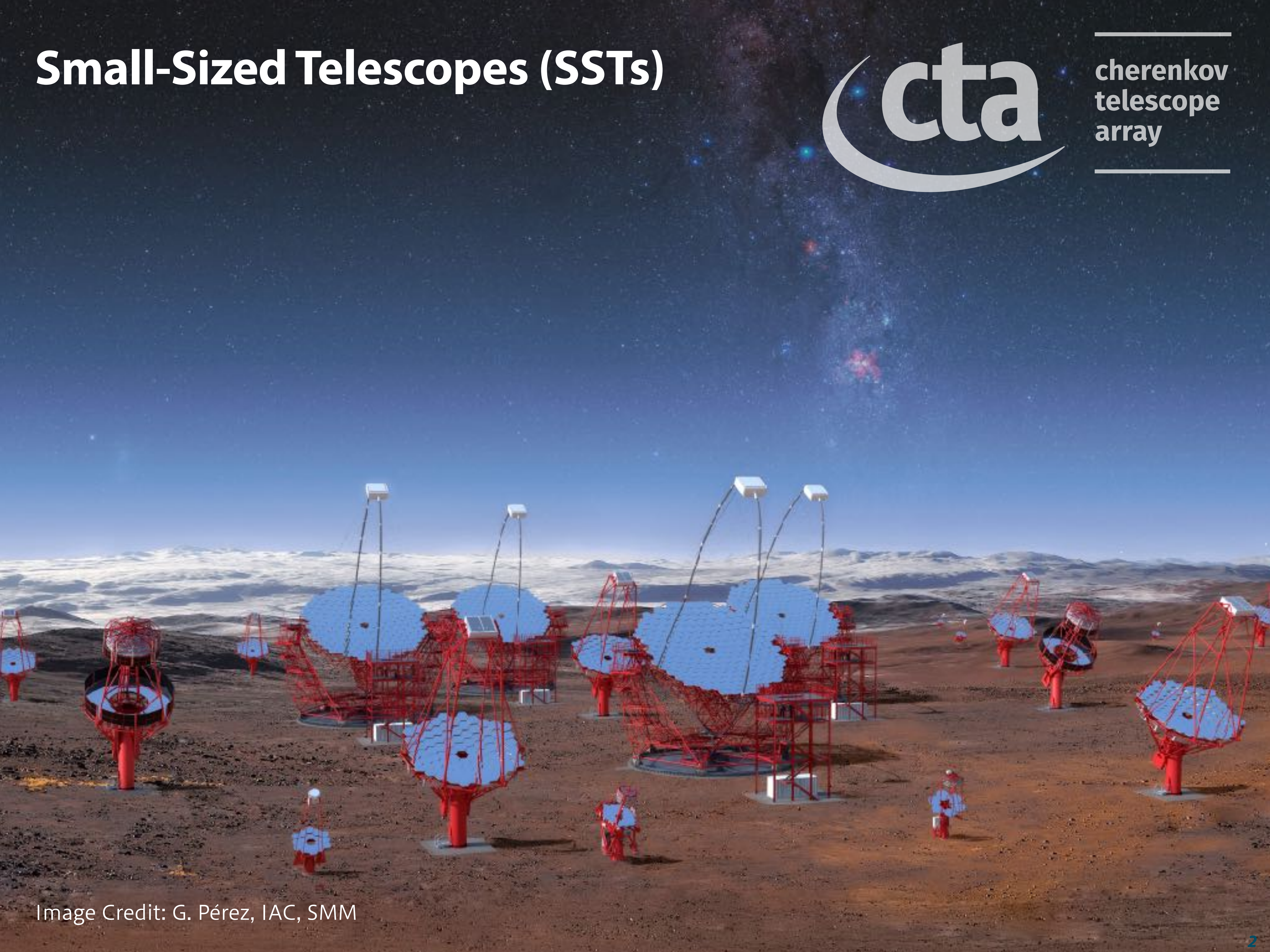

Image Credit: G. Pérez, IAC, SMM

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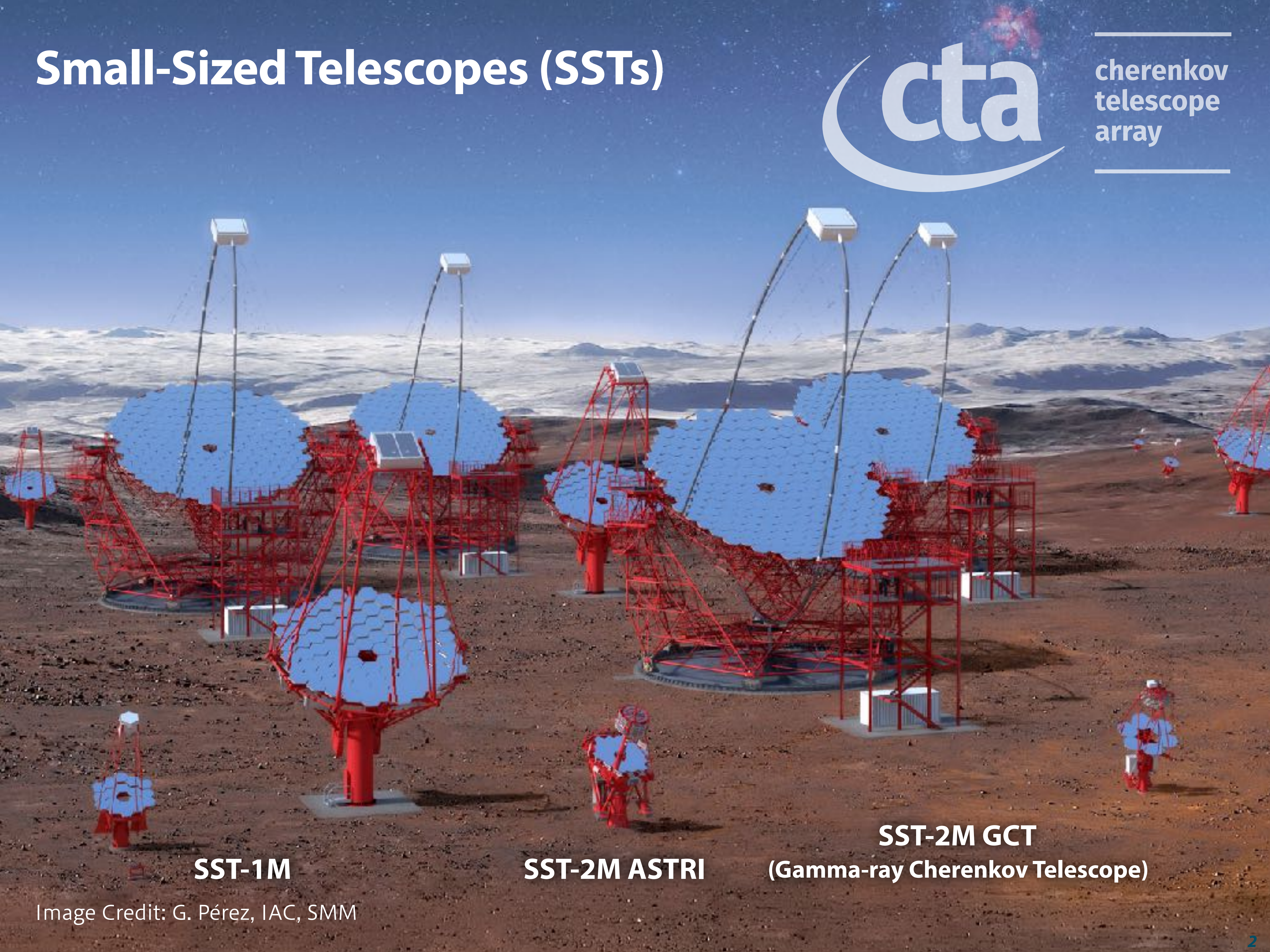
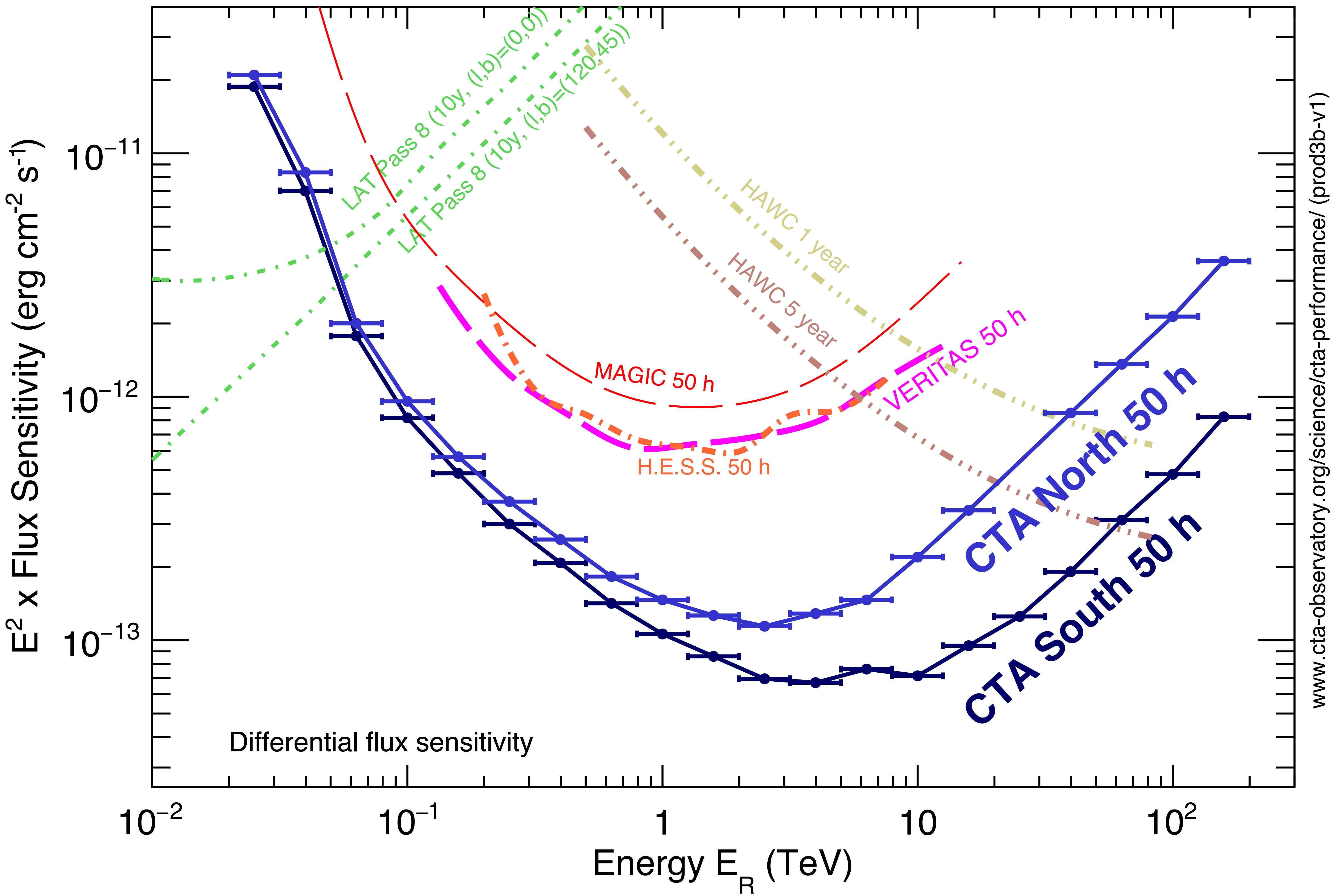


Image Credit: G. Pérez, IAC, SMM

High-energy Frontier by CTA SSTs

CTA Consortium arXiV:1709.07997



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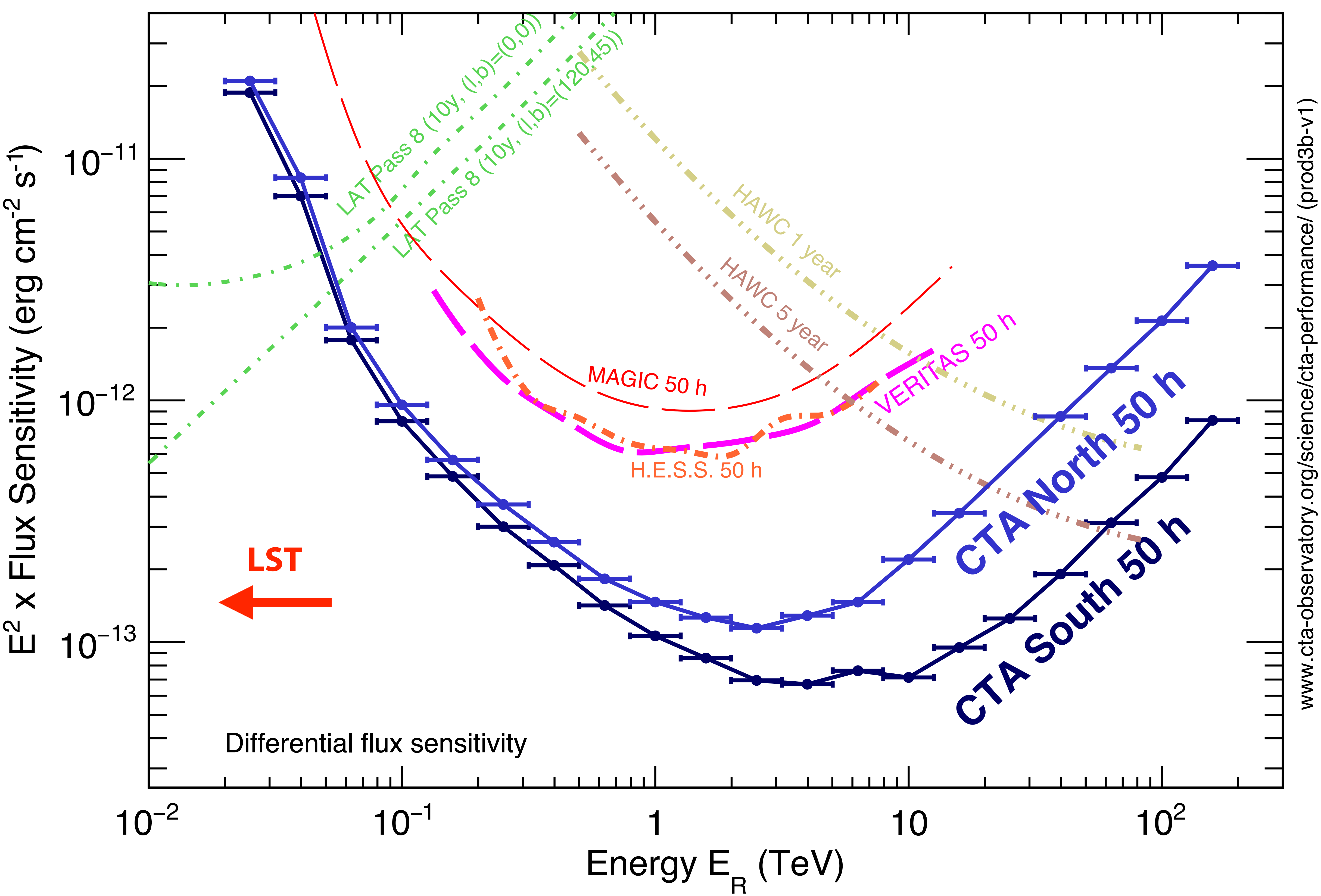

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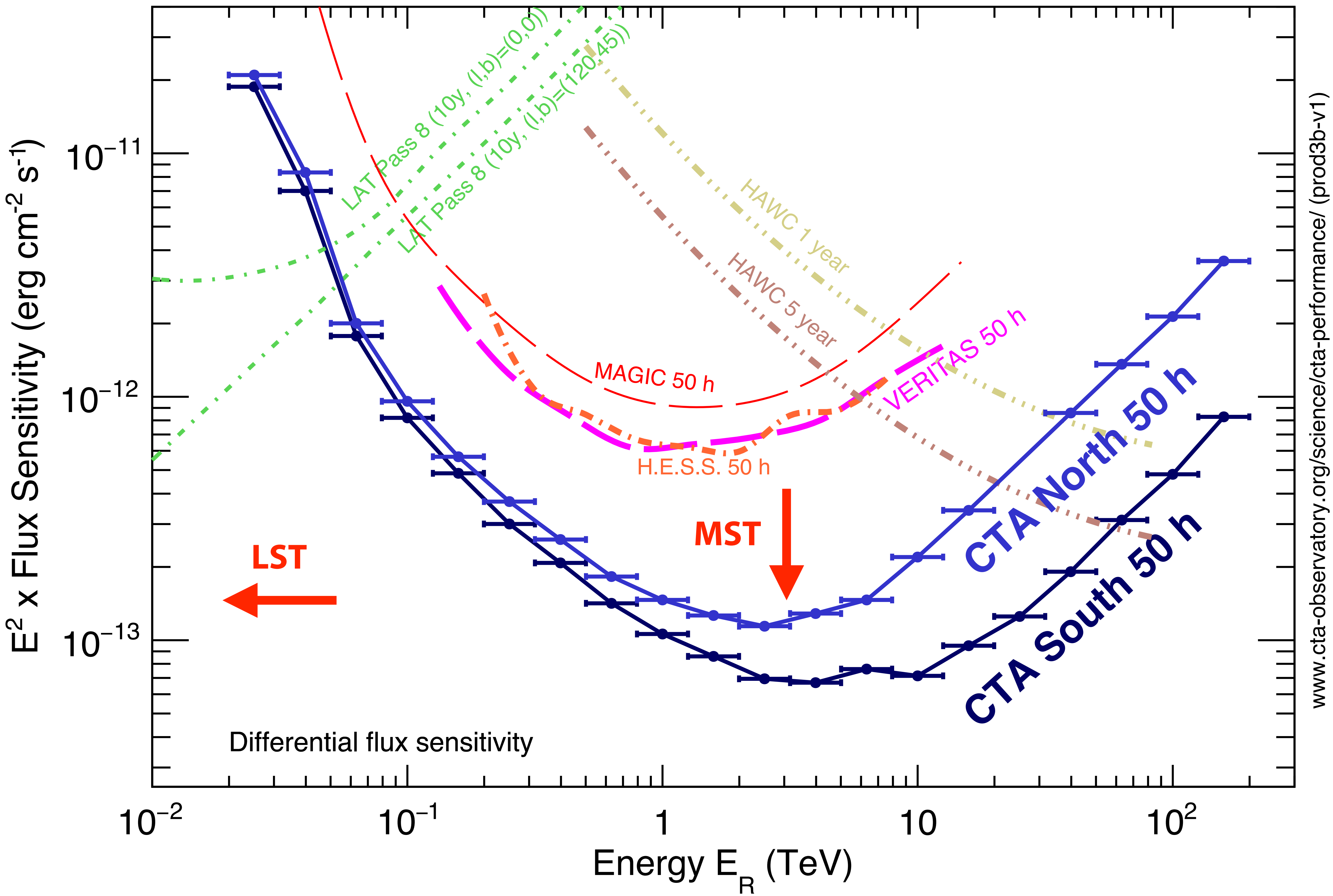

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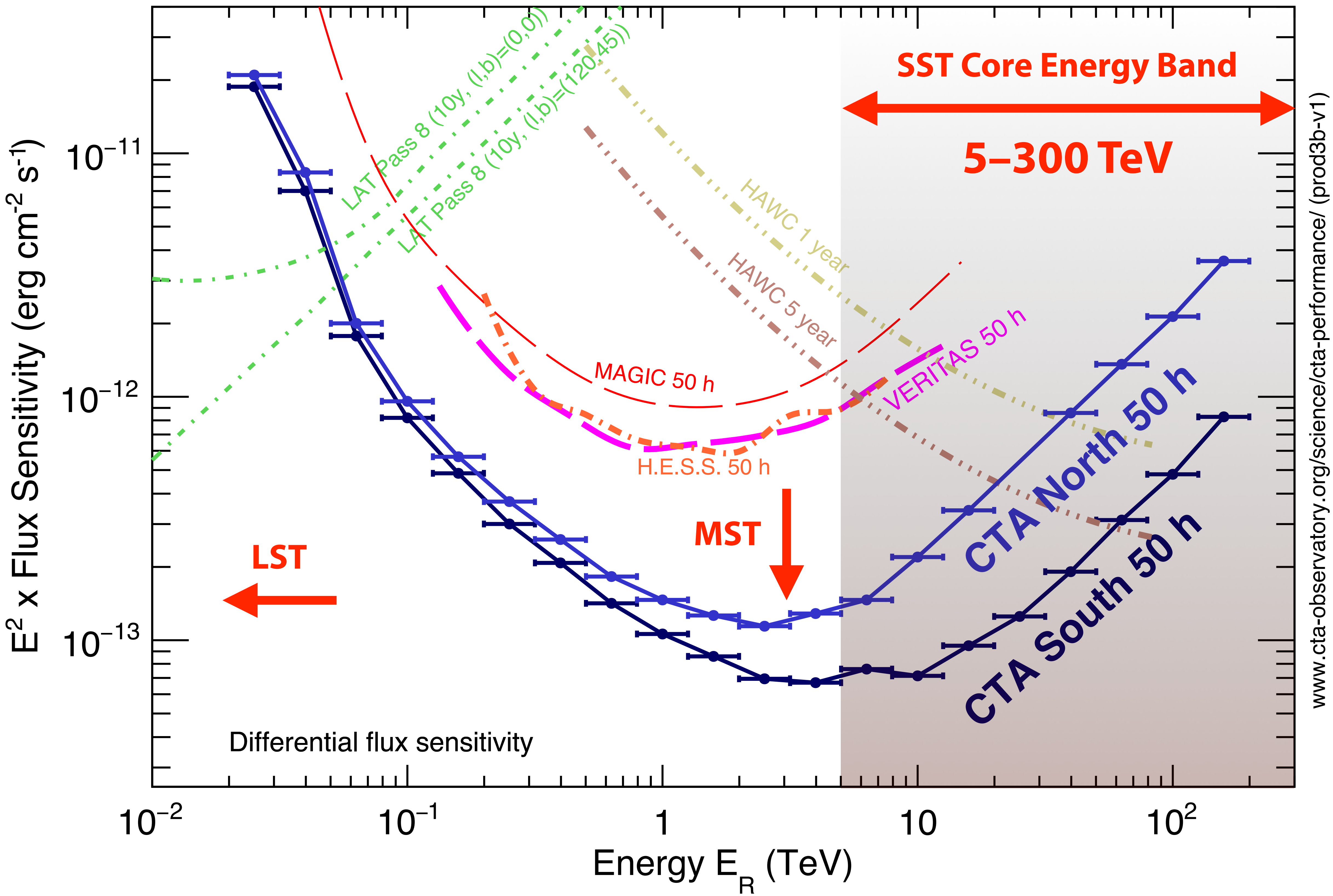

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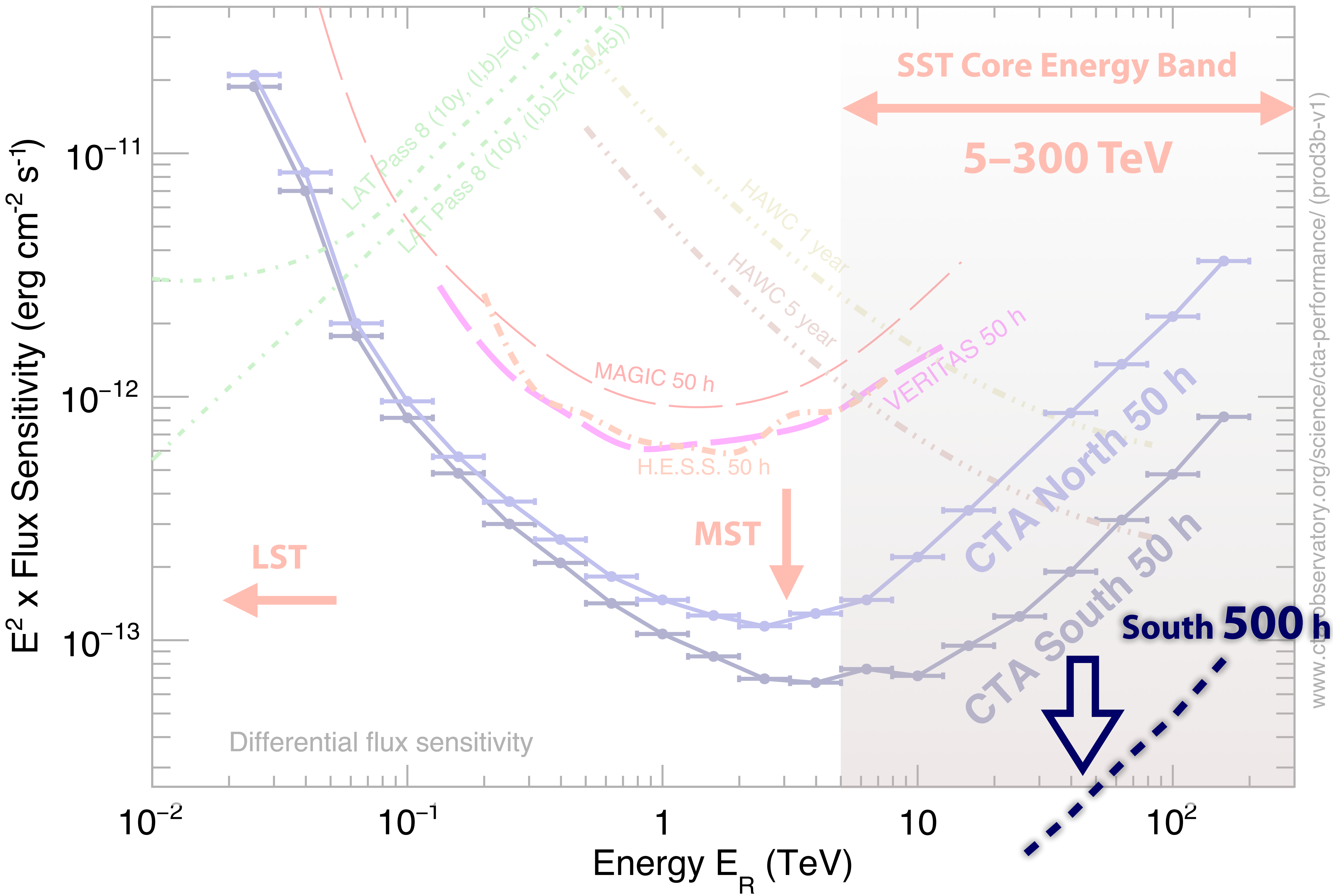
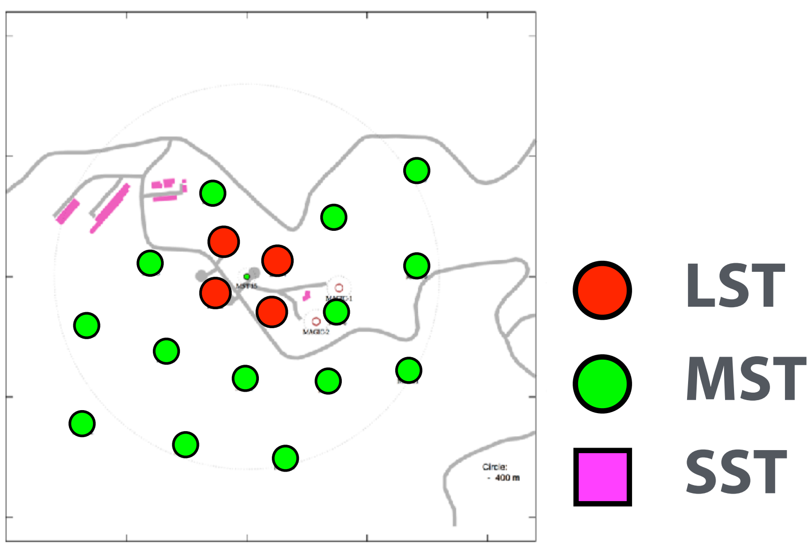
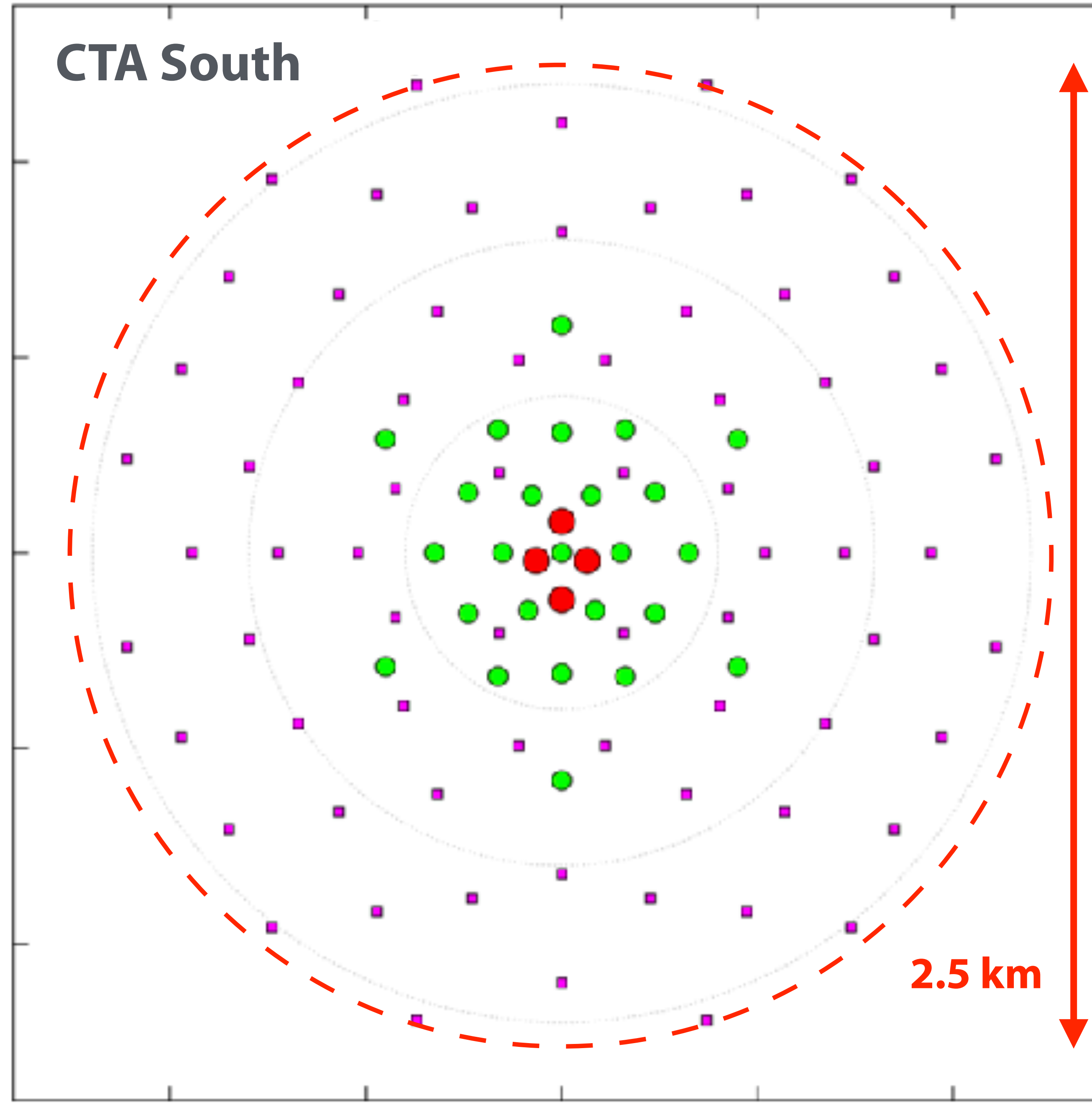


Baseline Layout of CTA with 70 SSTs

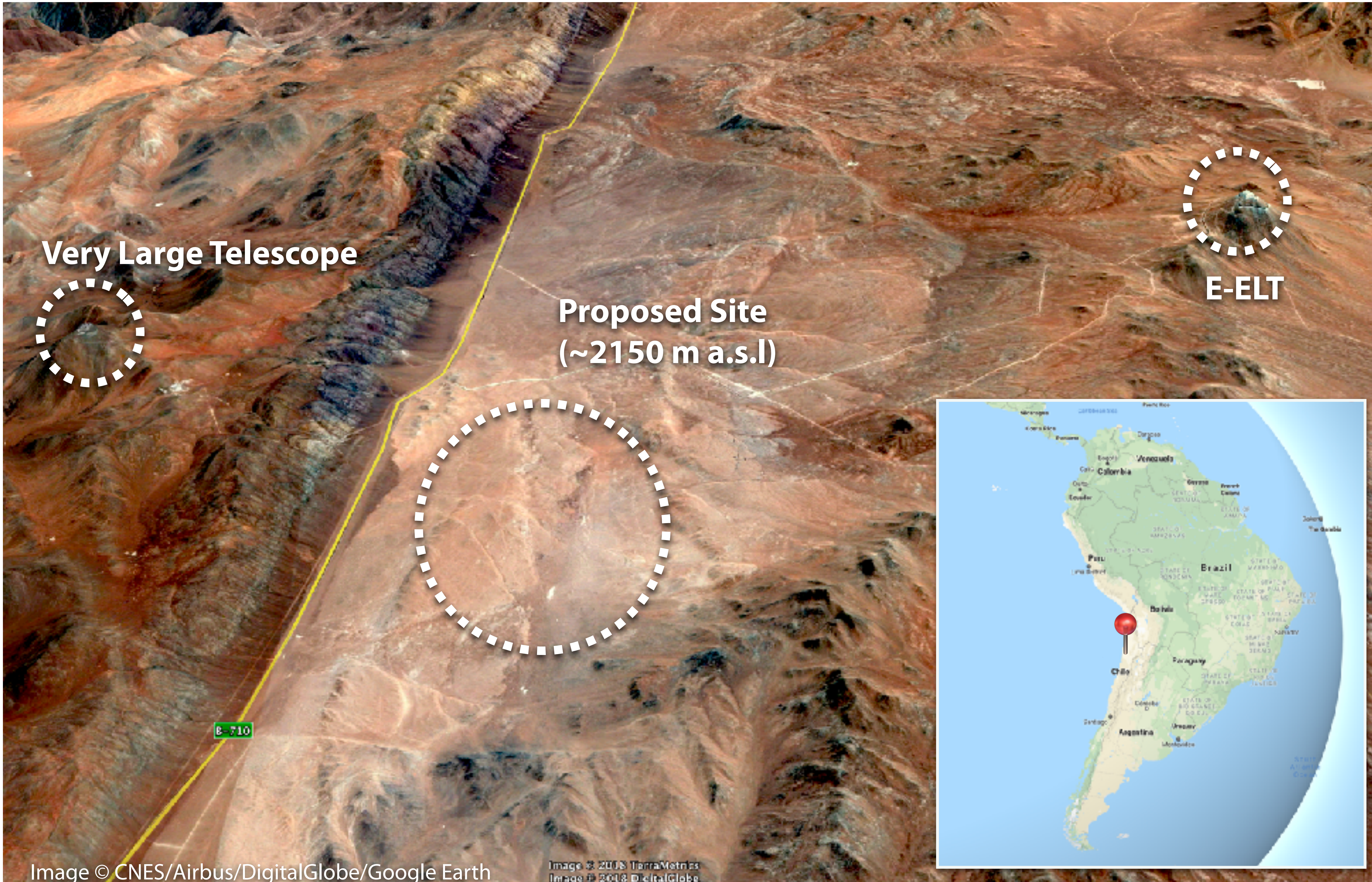
CTA North



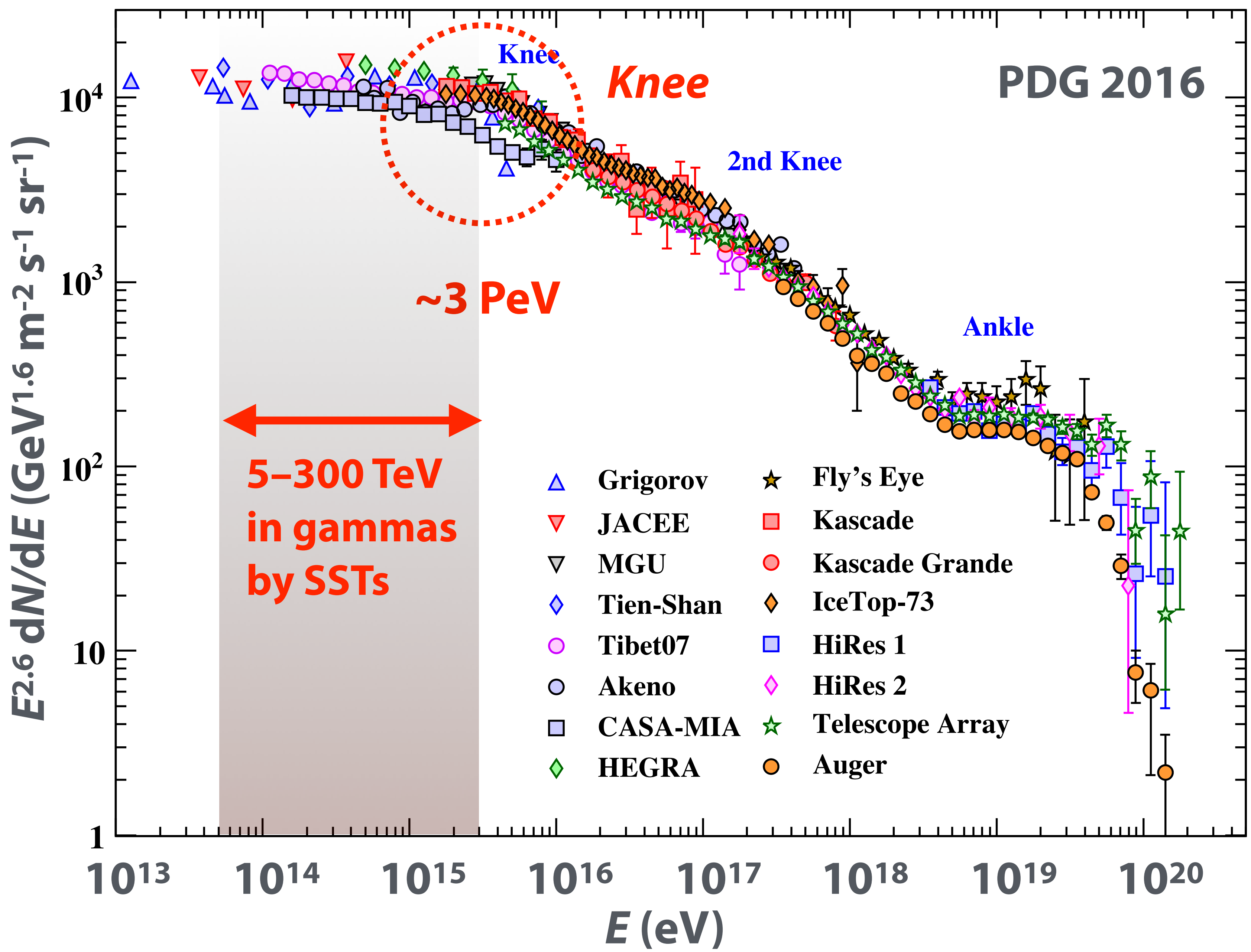


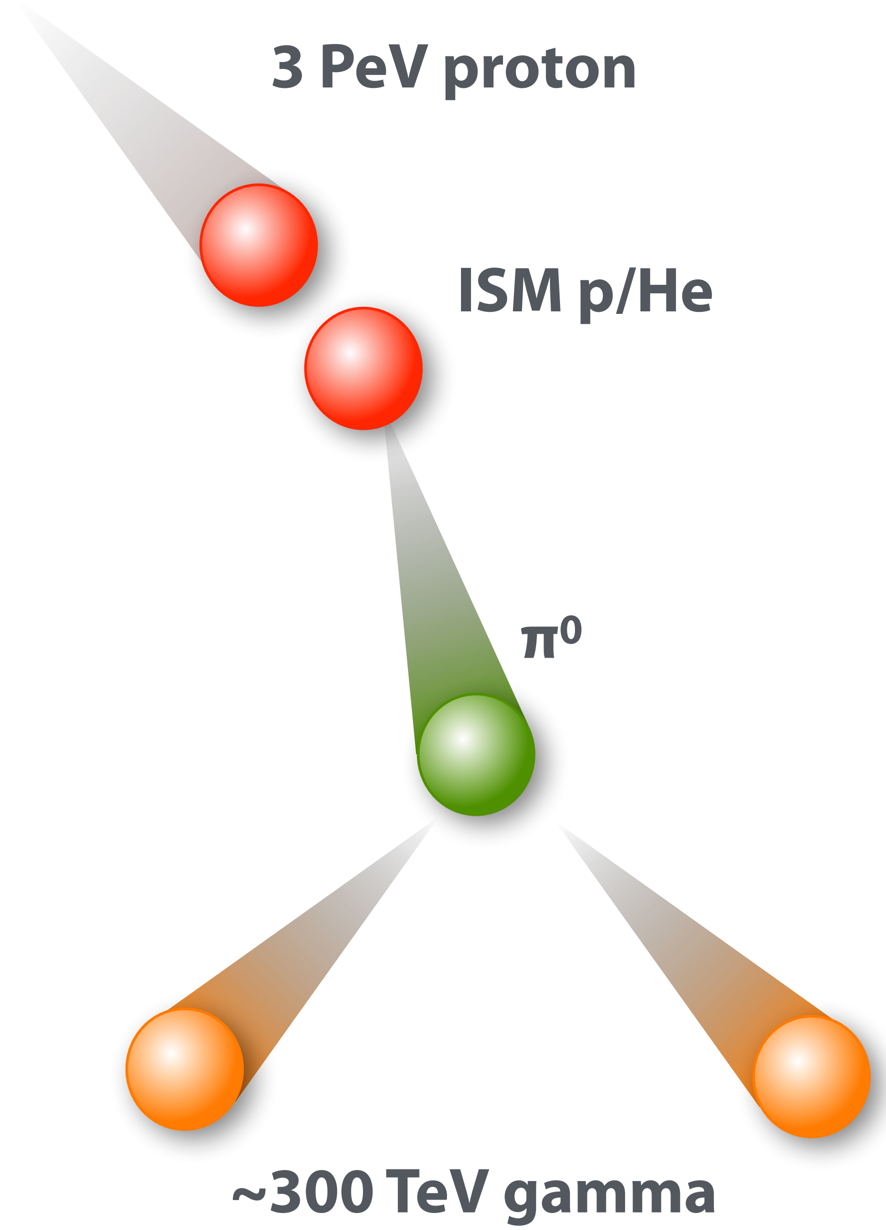
- Achieves a vast effective area of **~5 km²** with **70** SSTs
- Extends the highest-energy frontier to **300 TeV** and beyond

Southern Site – Paranal, Chile



PeVatron: Galactic PeV Cosmic-ray Accelerator

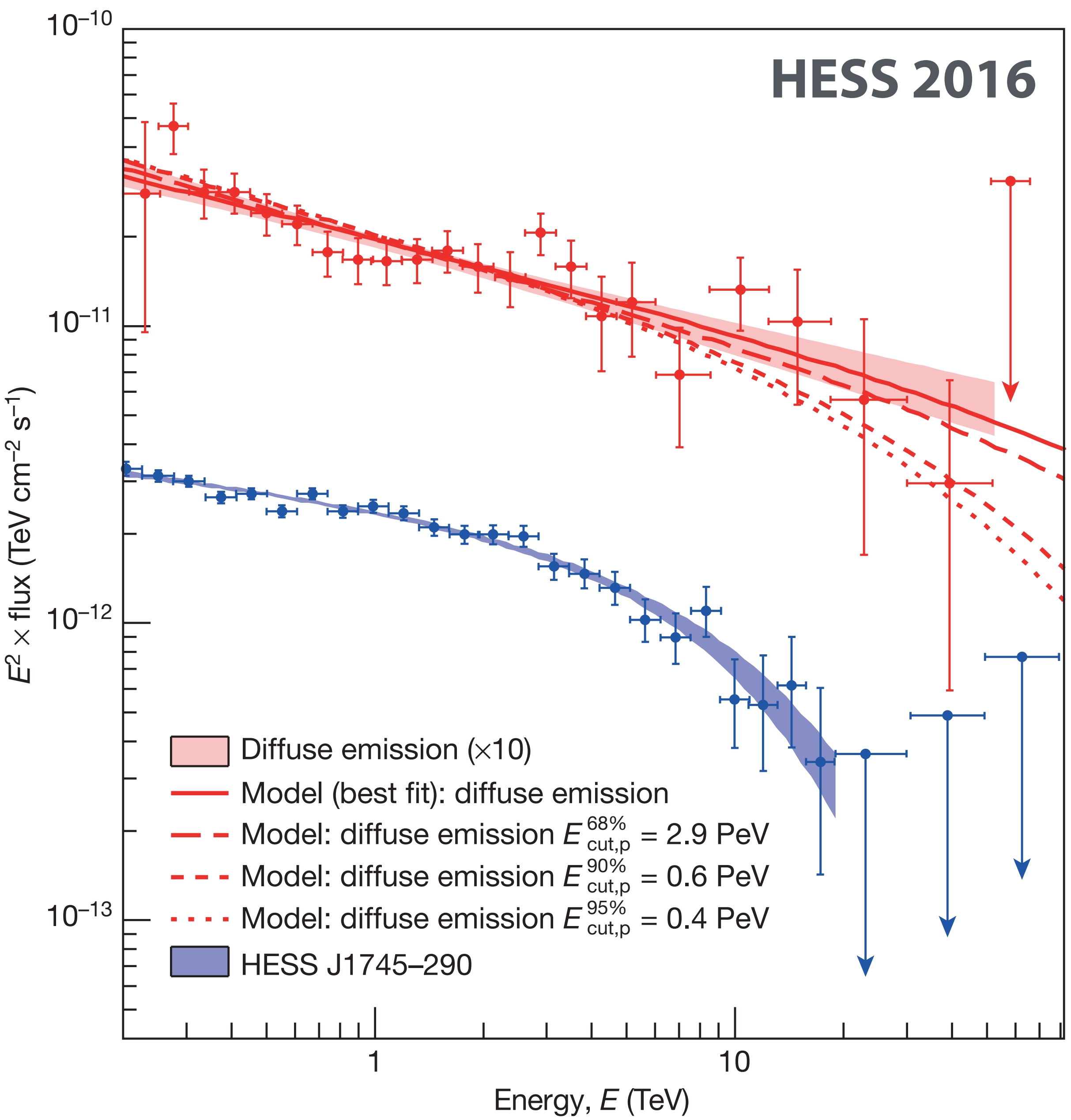


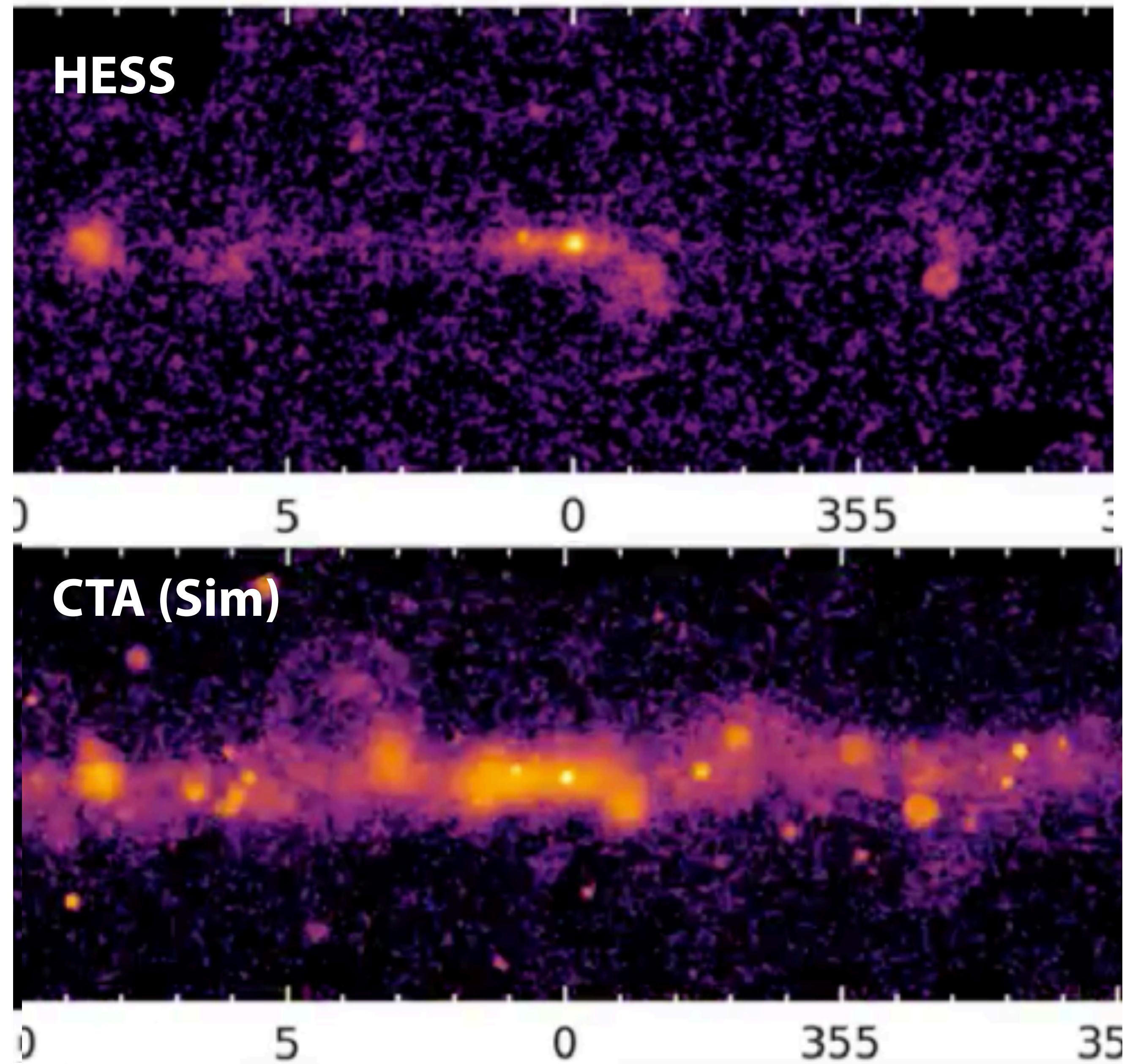


- Where do PeV cosmic rays come from? Need localization and identification
- ~3 PeV cosmic-ray protons → ~300 TeV gamma rays through π^0 decays

CTA Key Science Projects for PeVatron Search

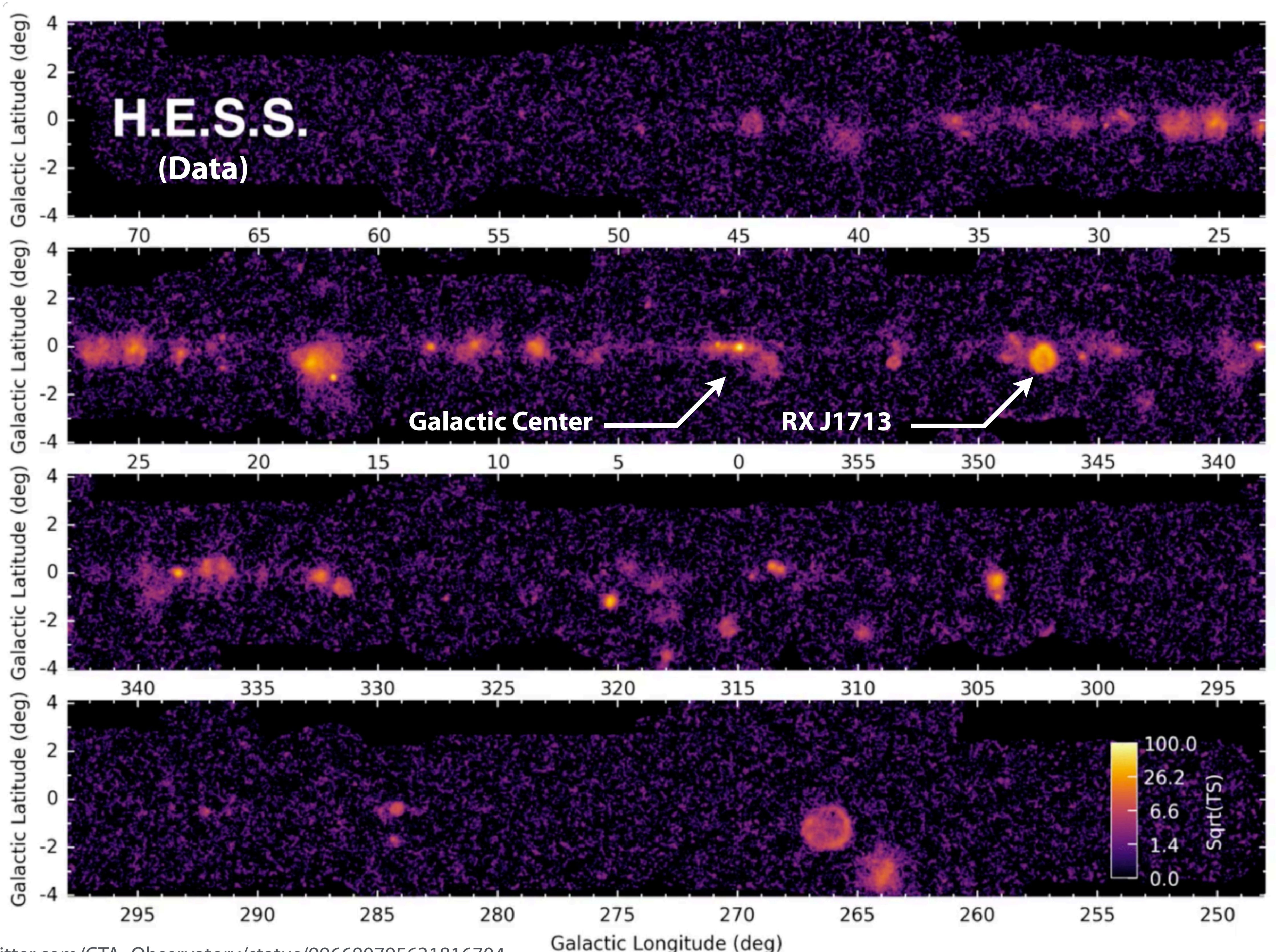
Galactic Center





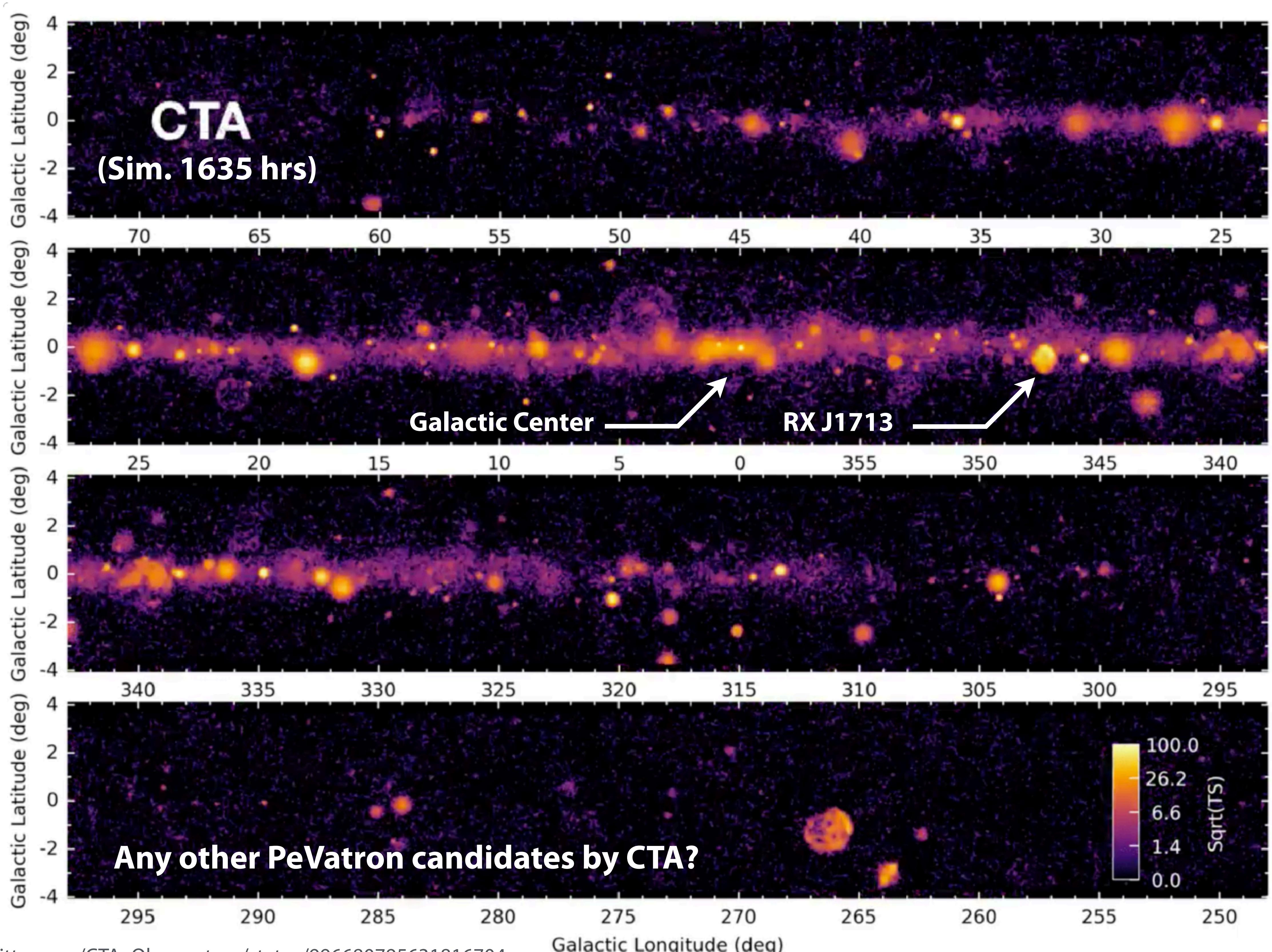
- Galactic center region is the best PeVatron candidate so far (possible CR cutoff energy of a few PeV)
- Deep survey of ~800 hours is planned (inc. dark matter search)

Galactic Plane Survey (GPS)



https://twitter.com/CTA_Observatory/status/996680795631816704

Galactic Plane Survey



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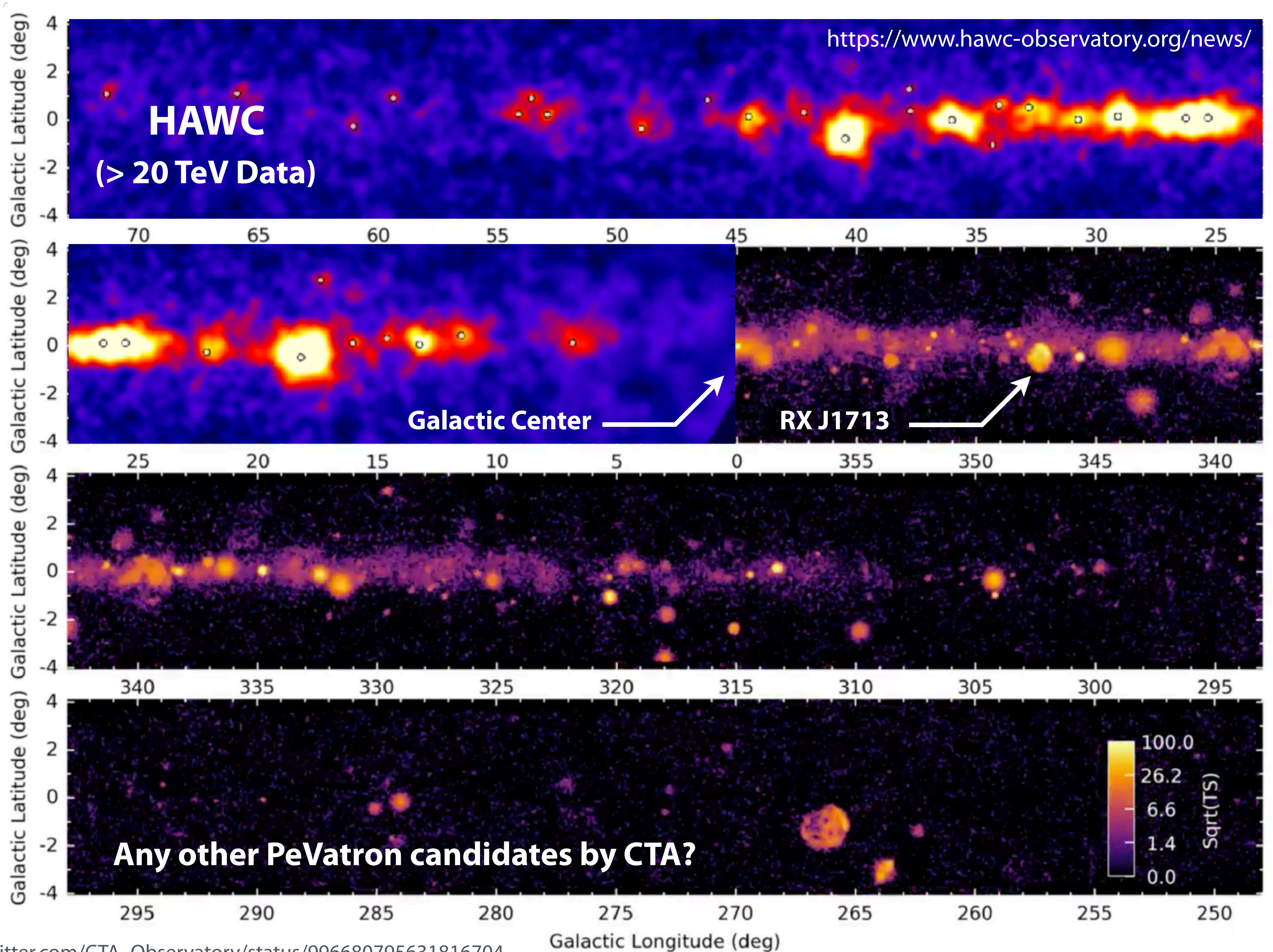

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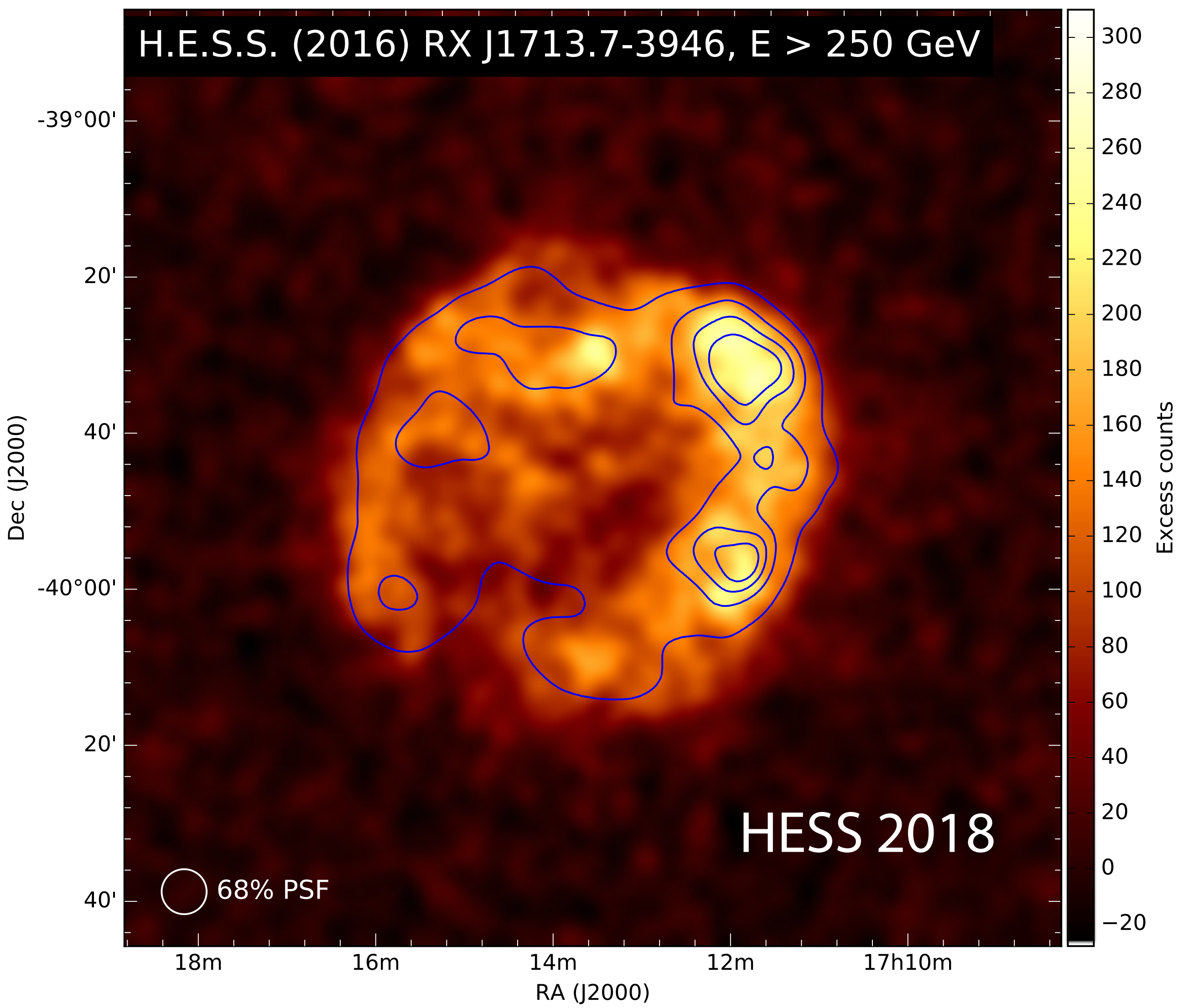
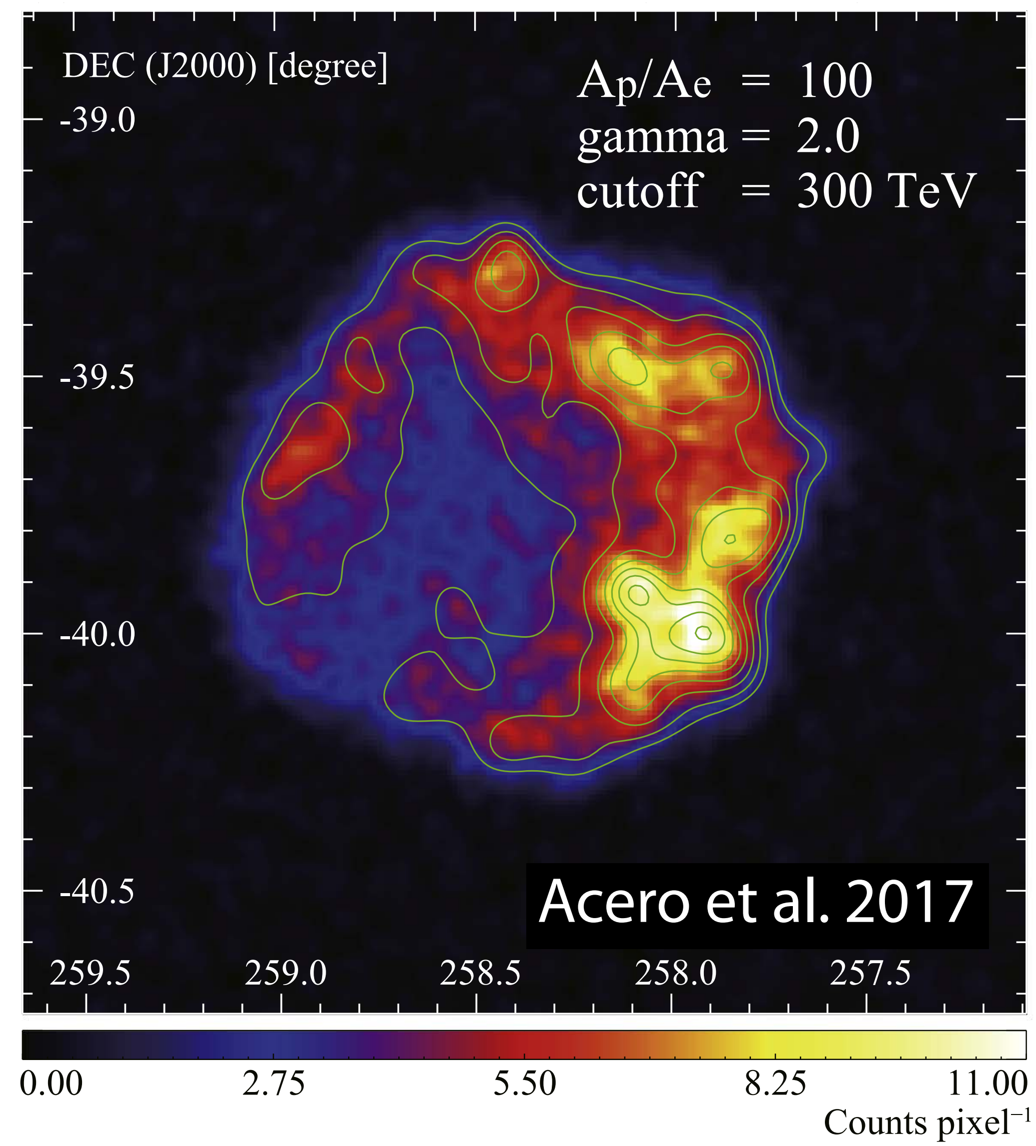
Young Supernova Remnants (SNRs)

HESS ~160 hrs



CTA ~50 hrs (sim)

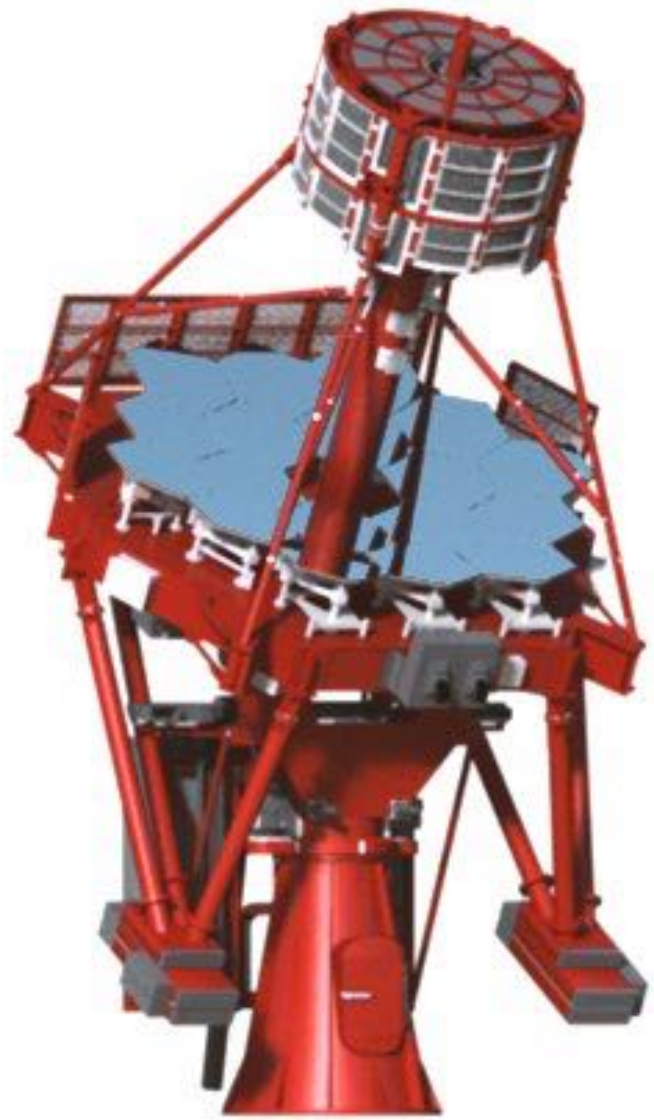


- 50-hrs exposure for RX J1713.7-3946 and other candidates each after GPS
- More photons in > 10 TeV region to study spectral cutoff and hadronic component
- Higher angular resolution and sensitivity may be able to reveal escaping cosmic rays
- Need a longer exposure by SSTs to collect more photons in > 10 TeV

SST Design Proposals

Image Credit: G. Pérez, IAC, SMM

SST-2M GCT



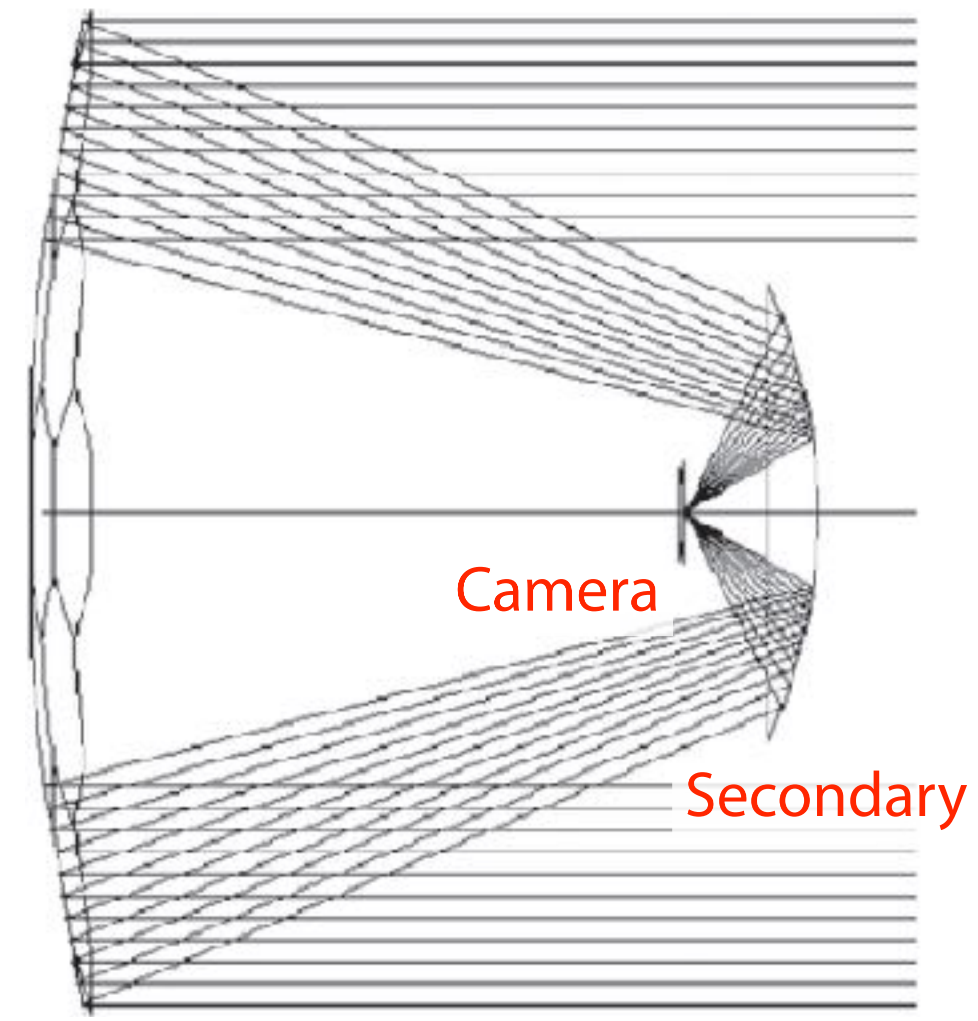
SST-2M ASTRI

SST-1M

- Need 70 SSTs with less expensive technologies (4-m optics & compact camera)
- Large FOV (8–10°) to detect gamma rays with large core distances (~5 km^2 with ~300 m separation)
- SiPM cameras with 1296–2368 pixels and compact front-end electronics

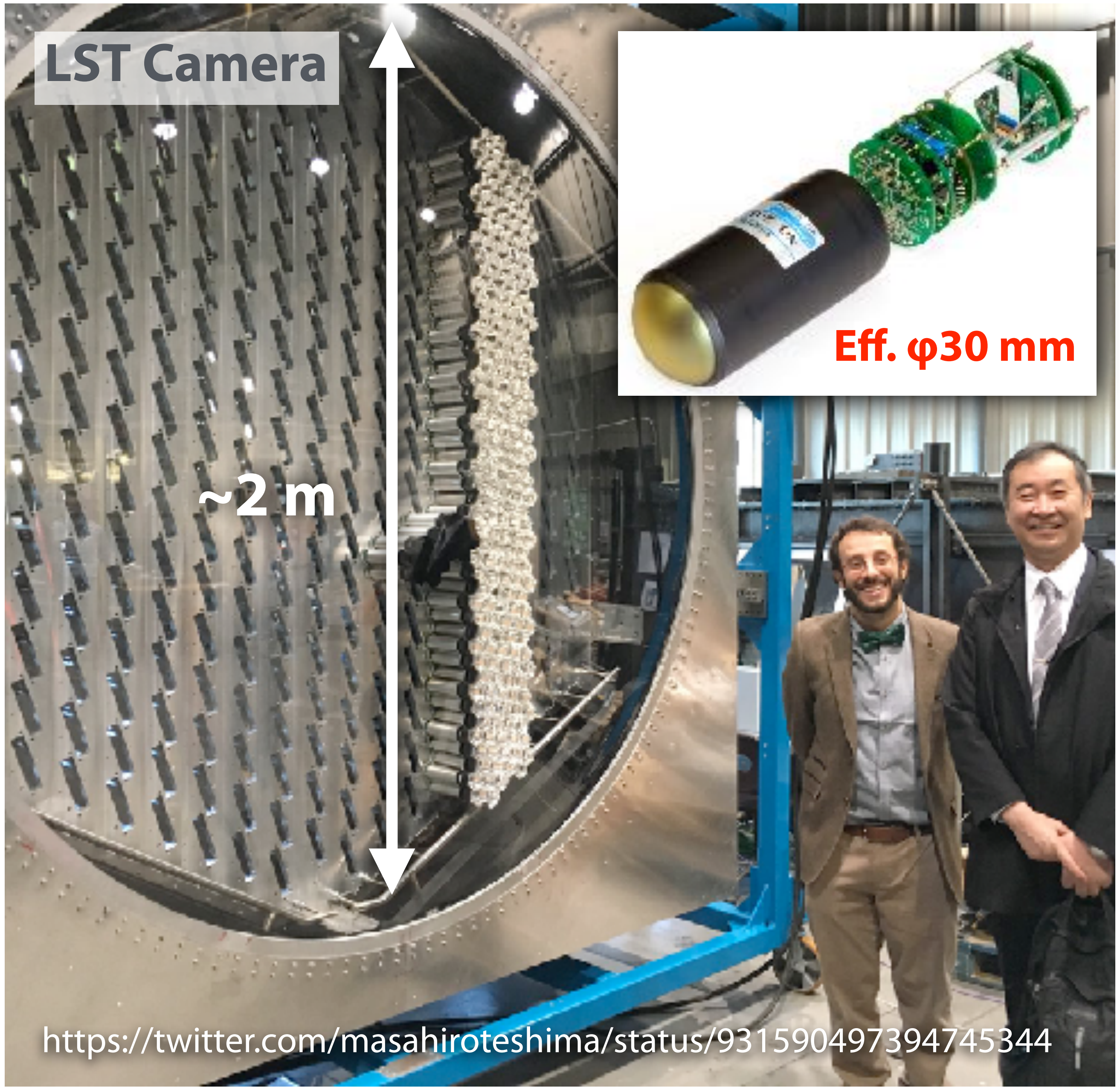
Optical Systems for >8° FOV

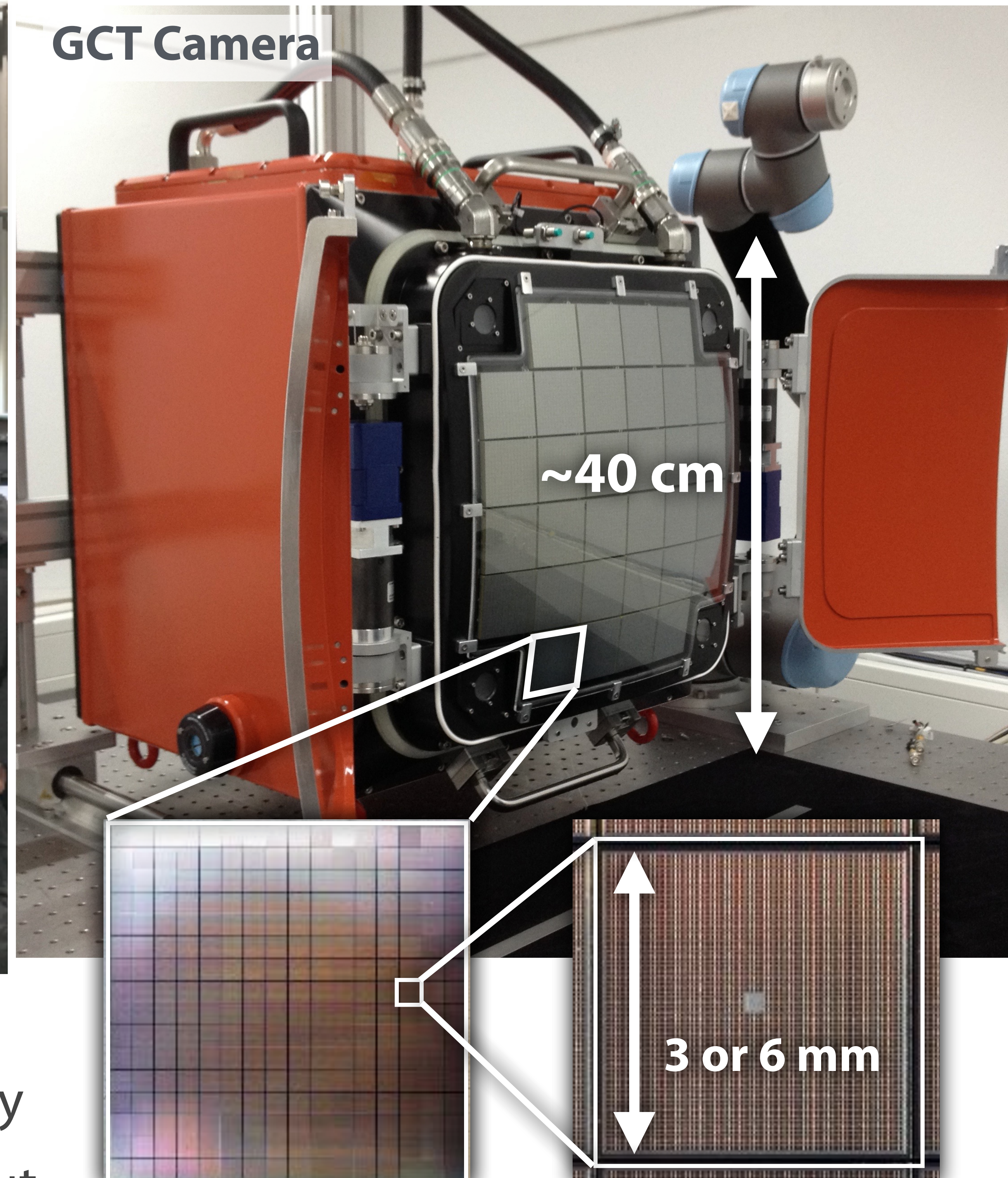
Schwarzschild–Couder
(ASTRI and GCT)



Rodeghiero+ 2016

SiPM Cameras

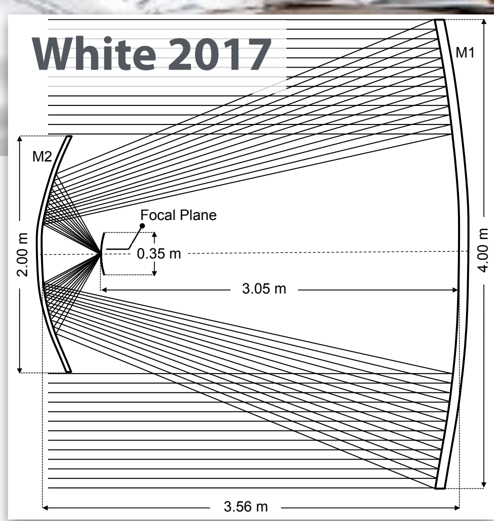


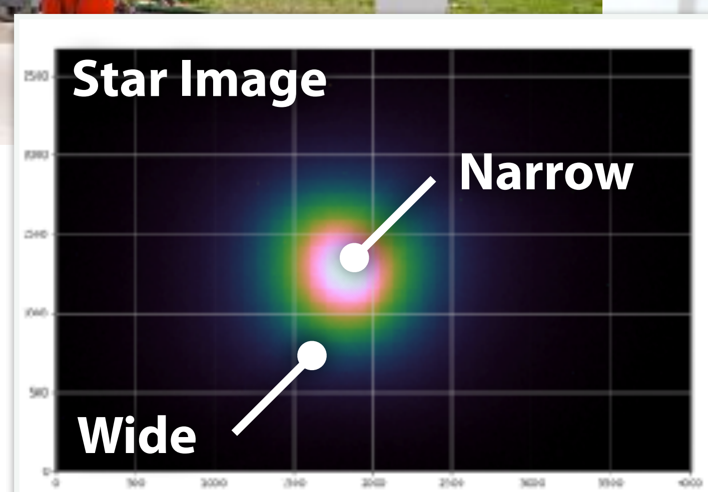


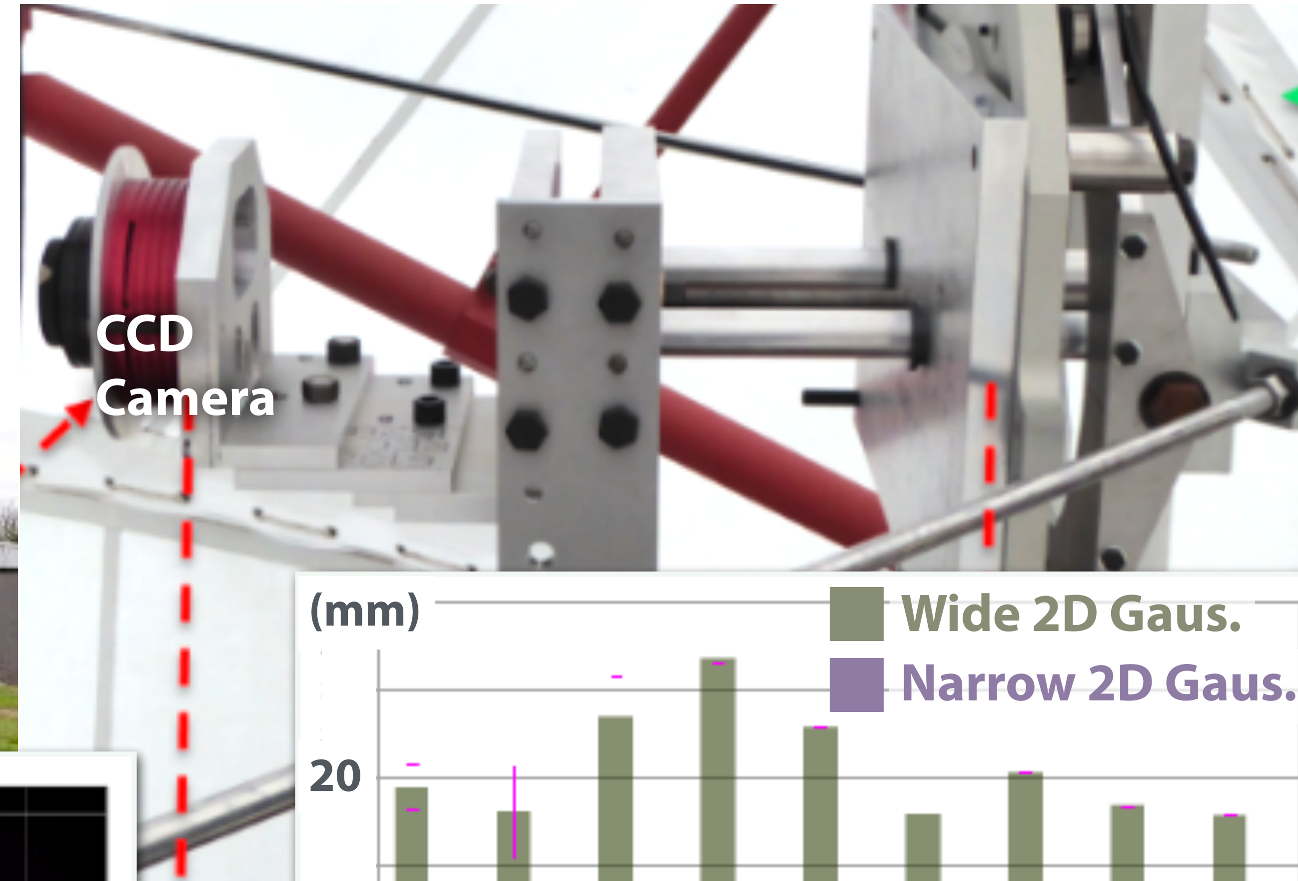
- Use of SiPMs enables us to build compact cameras with high pixel density
- Dedicated compact and modular readout
- Very NSB tolerant and long SST-only observations (> 5 TeV) are possible

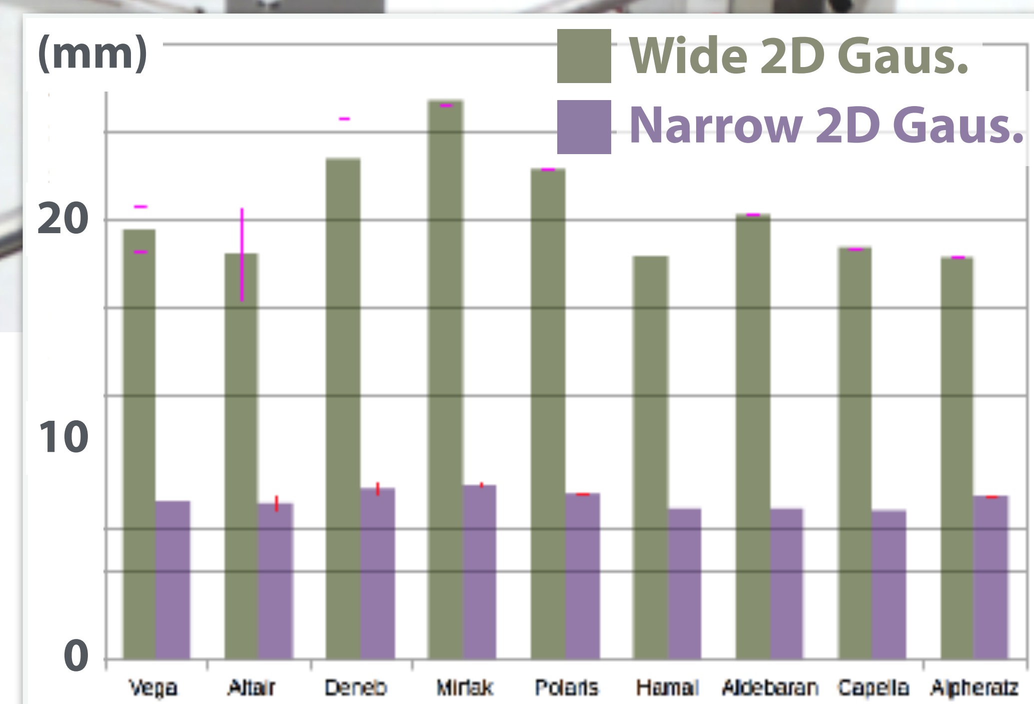
SST-2M GCT (Gamma Cherenkov Telescope)

GCT Prototype Telescope @ Paris Observatory



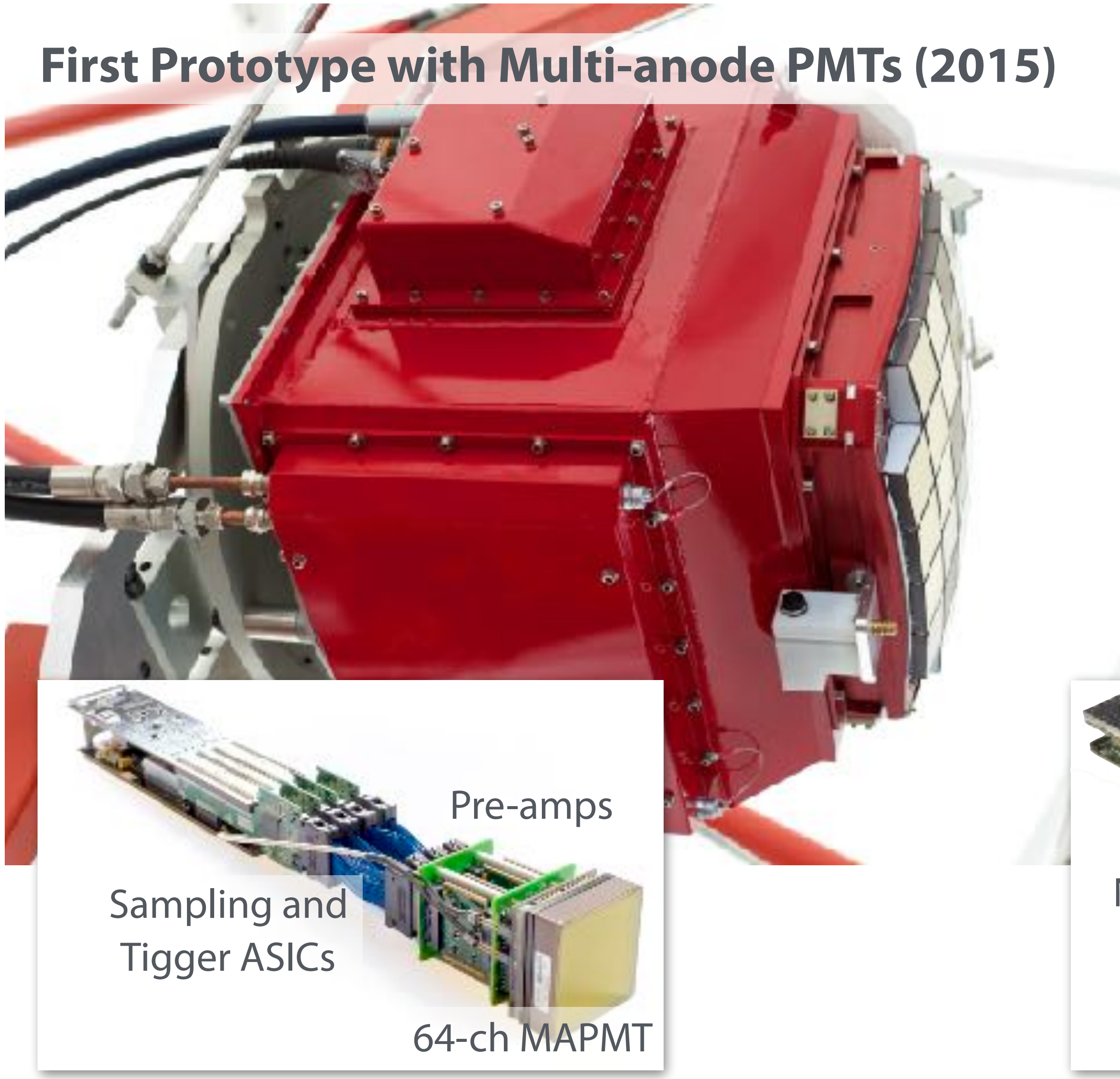


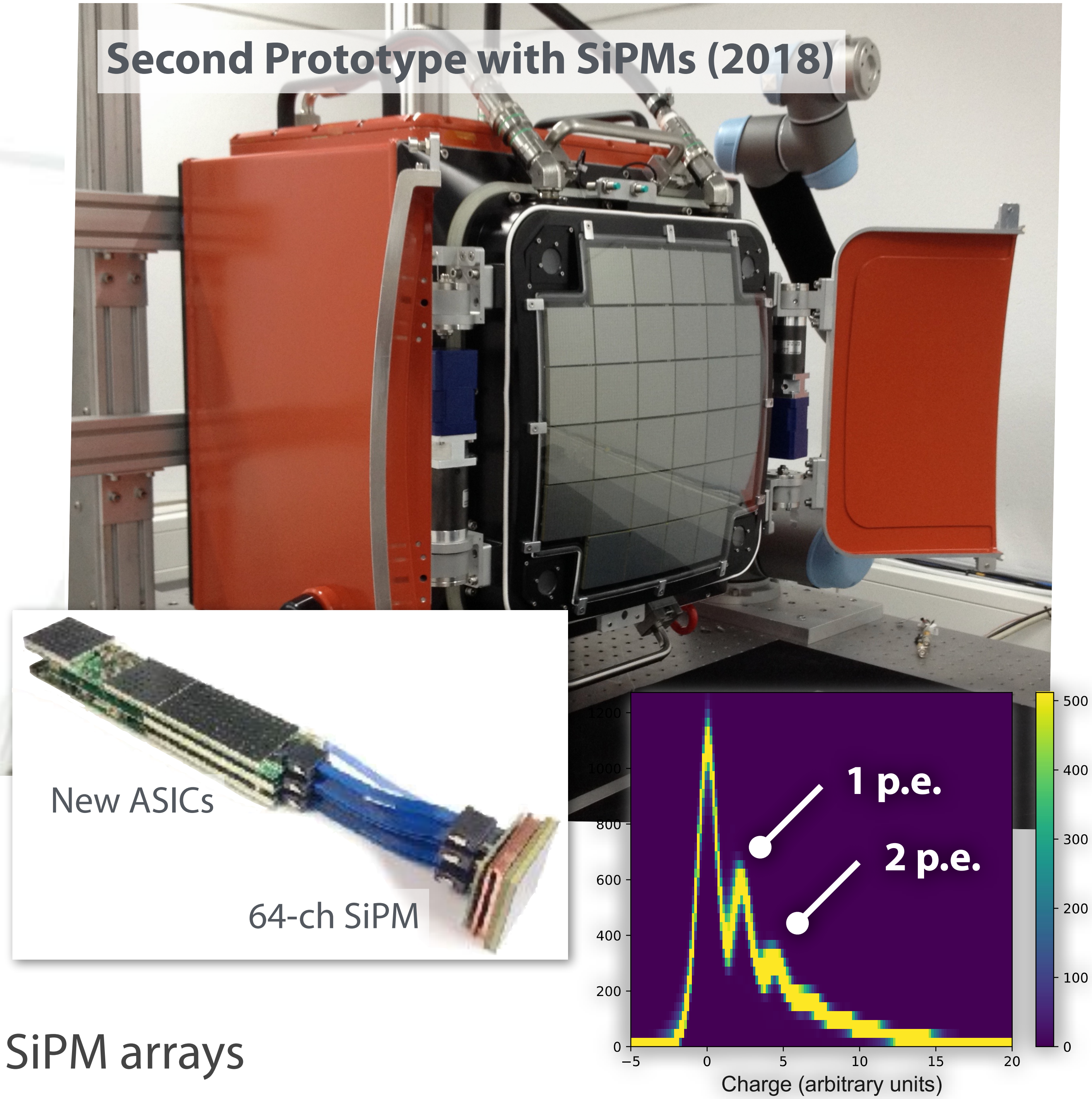




- Built at Meudon site of the Paris Observatory's (very bright sky)
- 6 segmented aspherical primary mirrors and semi-monolithic secondary (aluminum)
- Star images by a CCD camera show 6–7 mm PSF size (narrow component) while wide component (scattering by micro roughness) is being improved with new Al mirrors

SST-2M GCT Camera

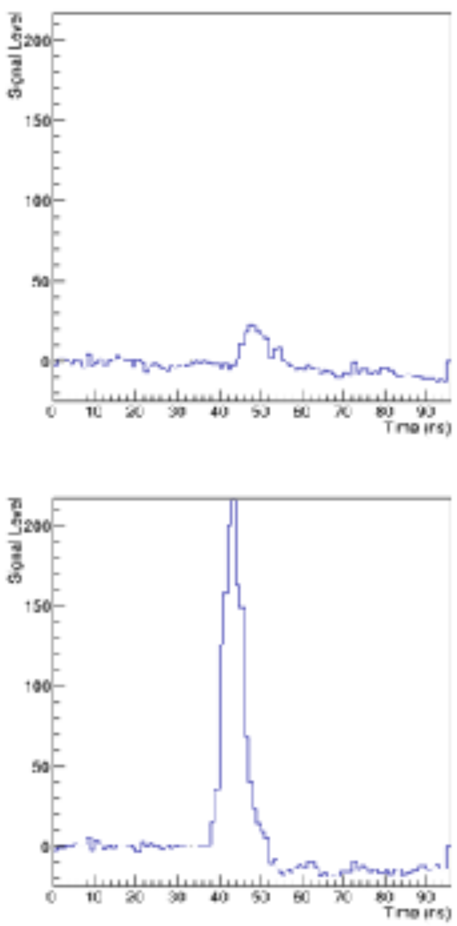


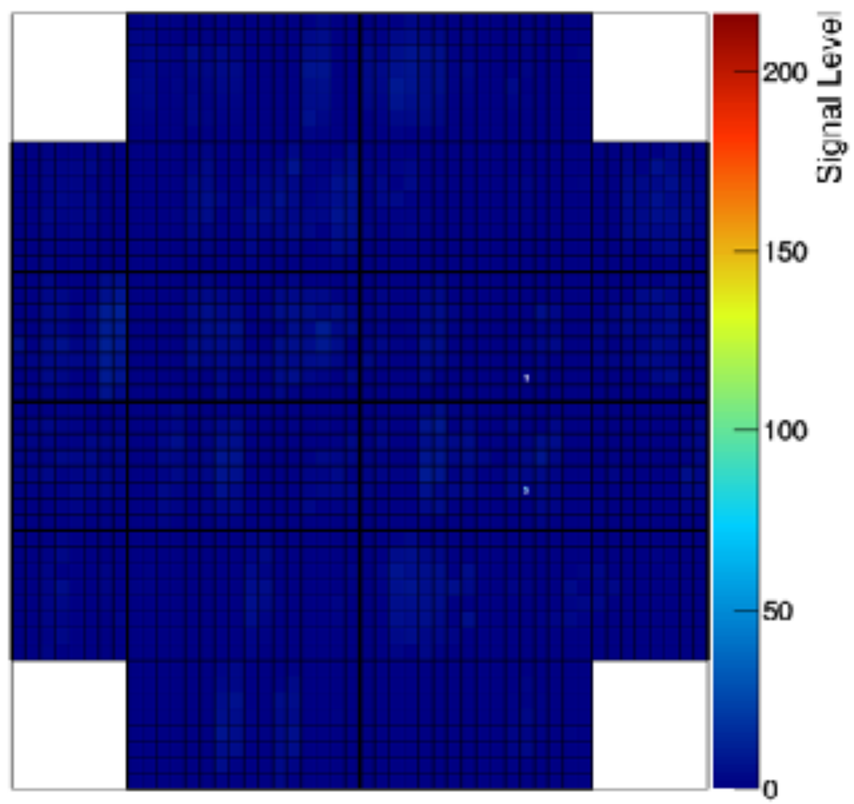


- Updated the first prototype camera with SiPM arrays
  - Better photon detection efficiency, uniform pixel gain, and better charge resolution
  - New sampling and trigger ASICs for better dynamic range, lower noise, improved trigger efficiency, etc
- Lab tests and on-telescope observations

GCT First Light

https://www.cta-observatory.org






Press Release

CTA Prototype Telescope Achieves First Light

Download full release: 1 MB / PDF

On 26 November 2015, a prototype telescope proposed for the Cherenkov Telescope Array, the Gamma-ray Cherenkov Telescope (GCTFigure1), recorded CTA's first ever Cherenkov light while undergoing testing at l'Observatoire de Paris in Meudon, France. The GCT is proposed as one of CTA's Small-Size Telescopes (SSTs), covering the high end of the CTA energy range, between about 1 and 300 TeV (tera-electronvolts). Another SST prototype, the ASTRI telescope, captured the first optical image in May 2015 with its diagnostic camera.

Photo credits: Akira Okumura

- CTA's first ever Cherenkov images taken on Nov 26, 2015
- CR hadron observations with the first camera and telescope prototype at Paris Observatory
- The second camera to be tested on the ASTRI telescope prototype in 2019

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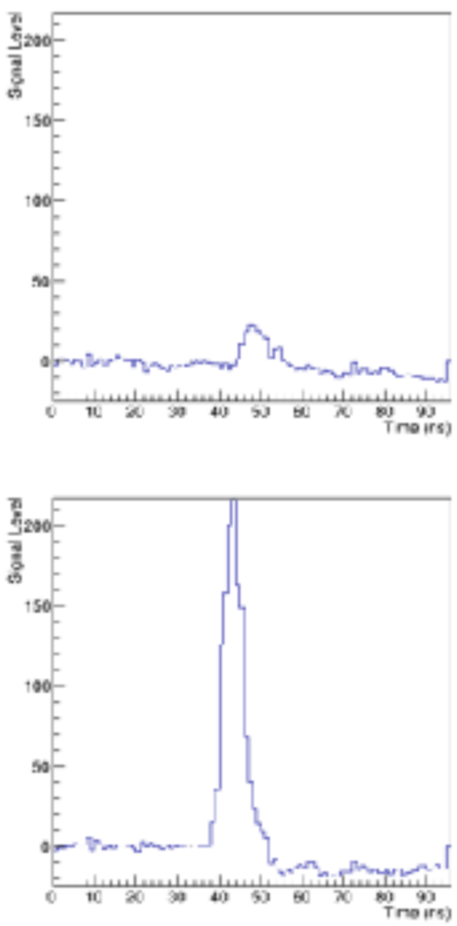

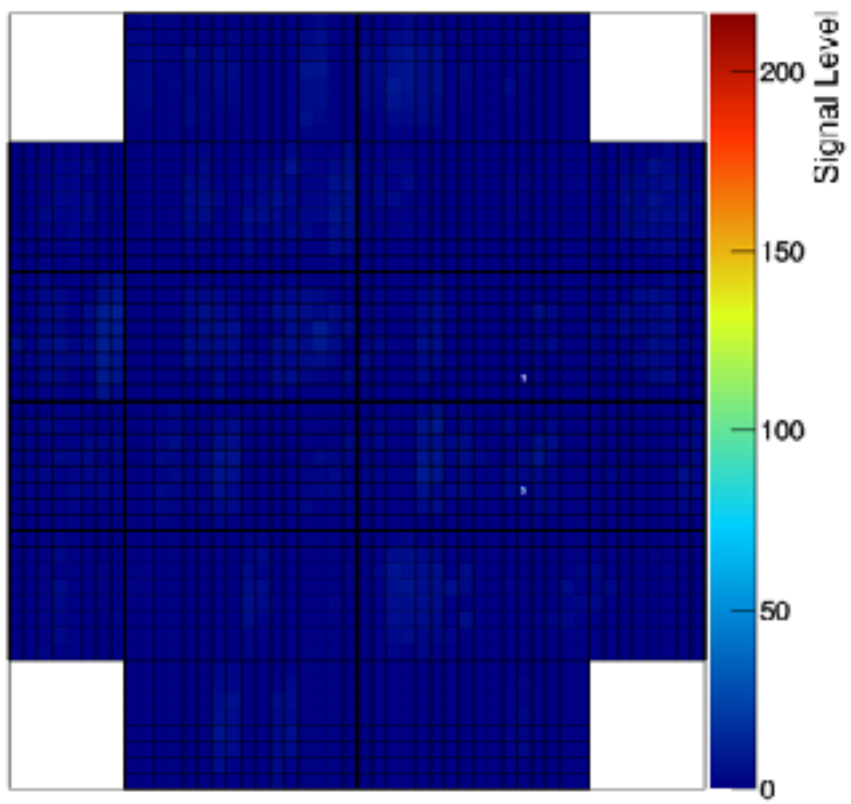

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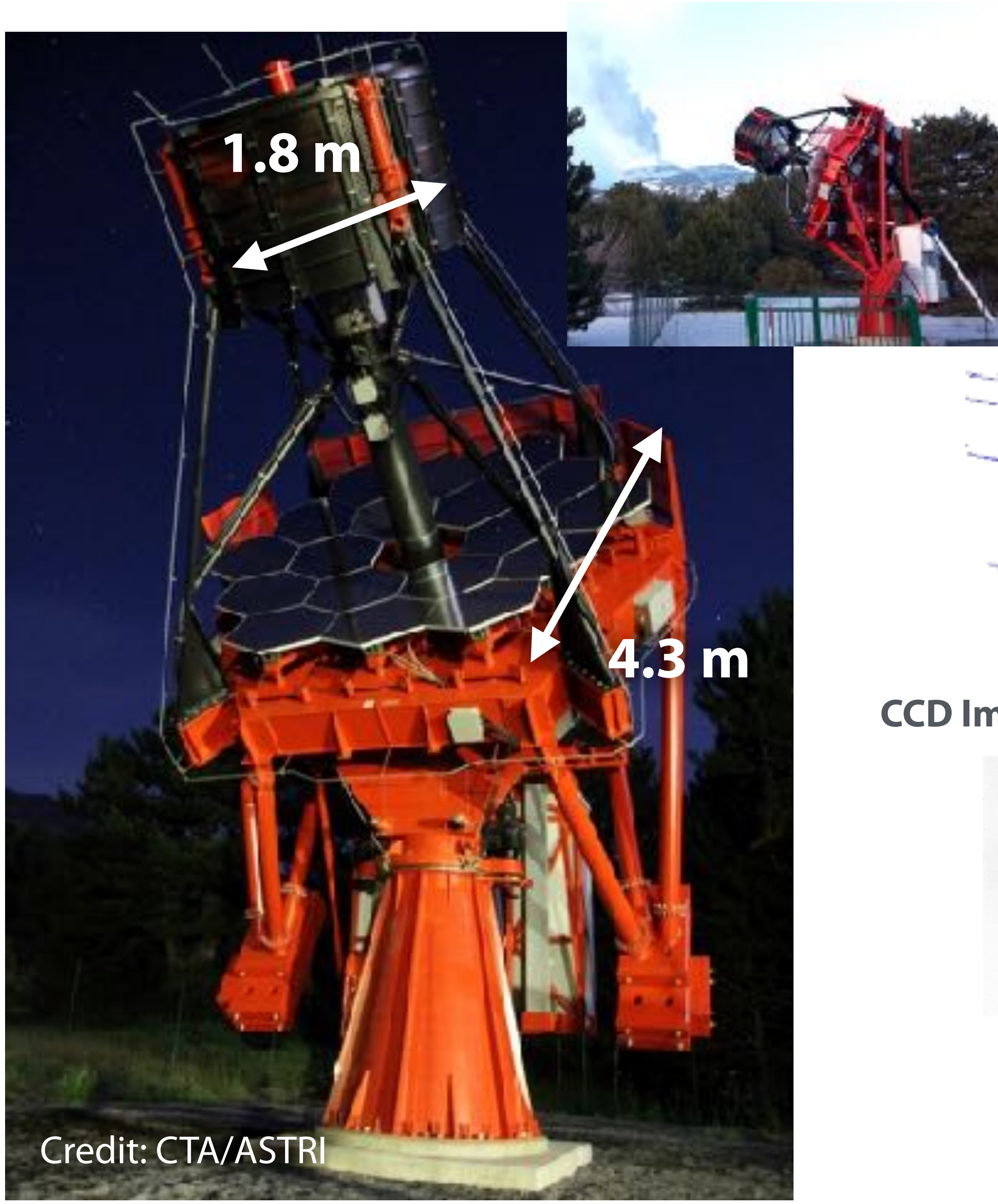
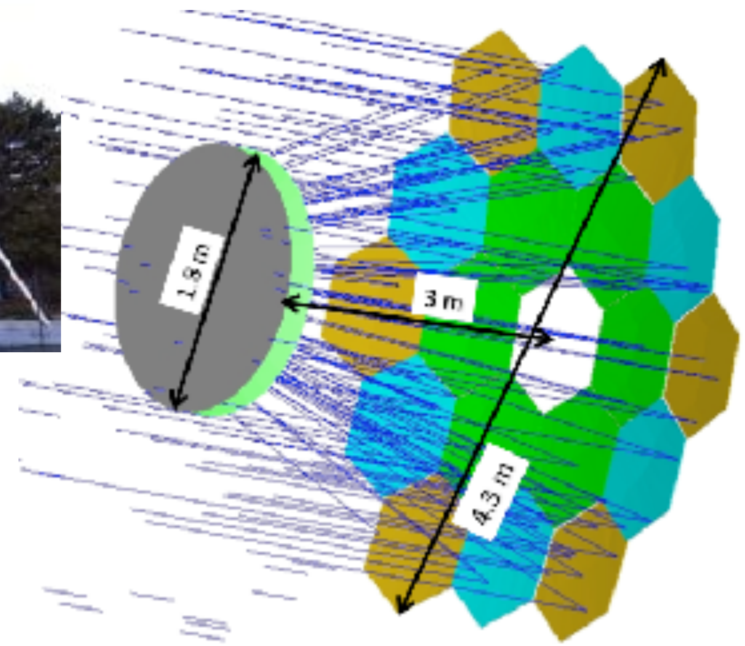
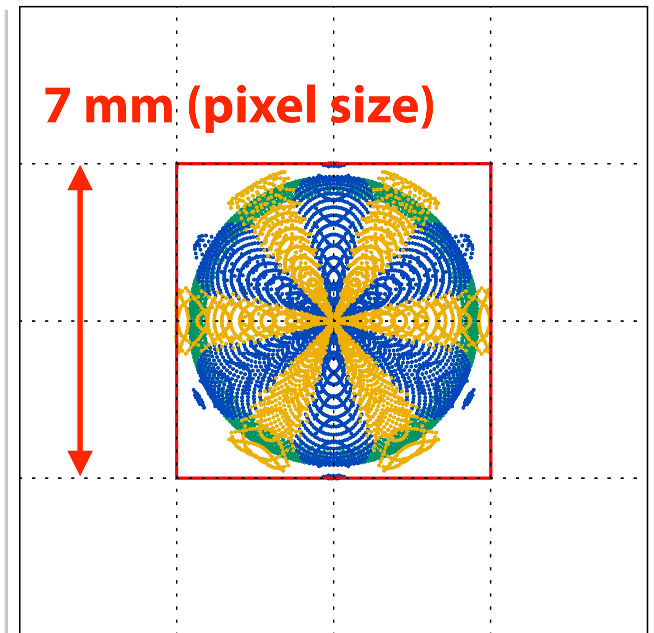
mirror replication technology

SST-2M ASTRI (Astrofisica con Specchi a Tecnologia replicante Italiana)

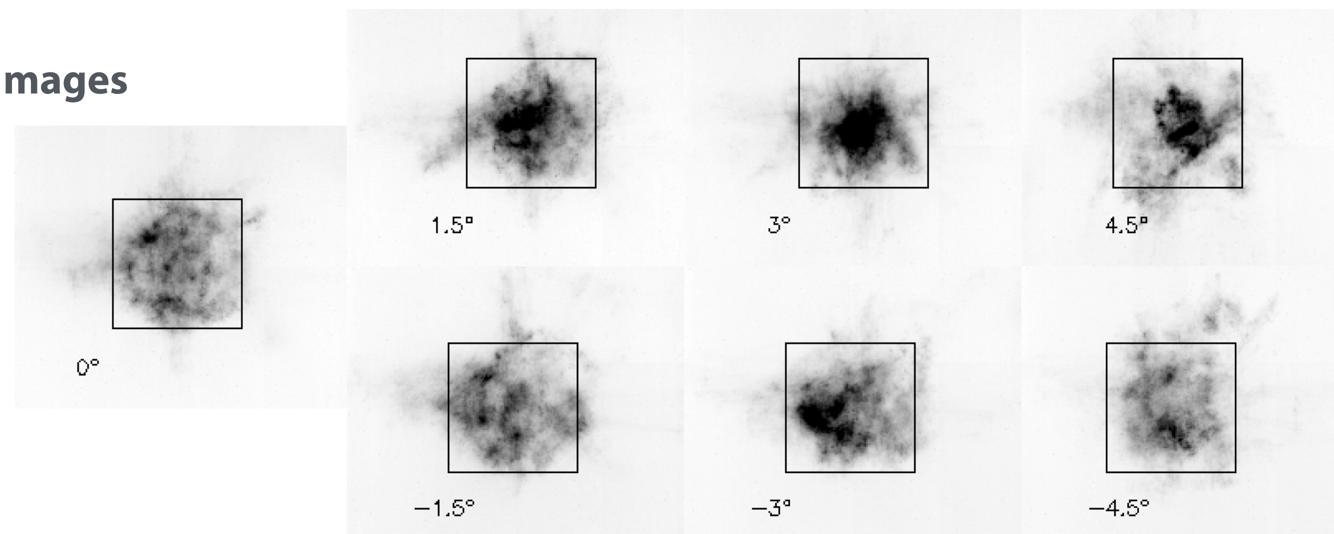




On-axis Simulation



CCD Images

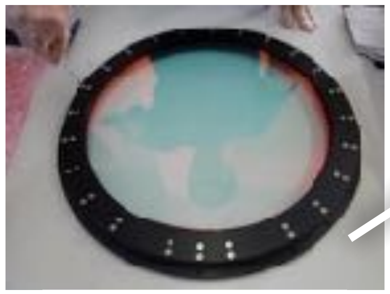


Giro+ 2017

- Built at INAF-Catania mountain station on Mt. Etna (very active volcano)
- 18 segmented aspherical primary mirrors + monolithic aspherical secondary
- ASTRI prototype telescope is the first realization of the Schwarzschild–Couder optics with full mirror configuration

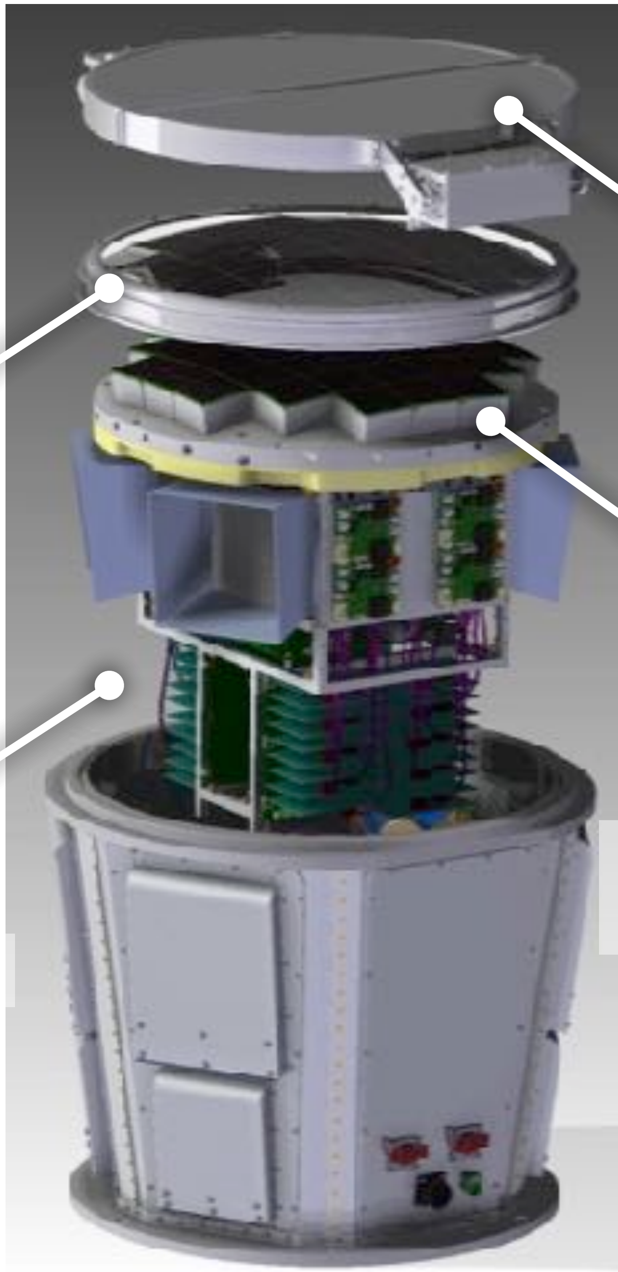
SST-2M ASTRI Camera

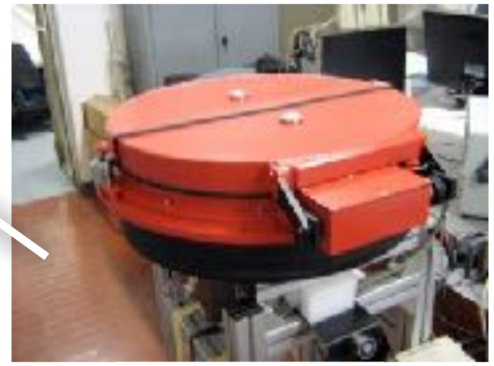
Image credit: CTA/ASTRI



Front Window

Backend Electronics

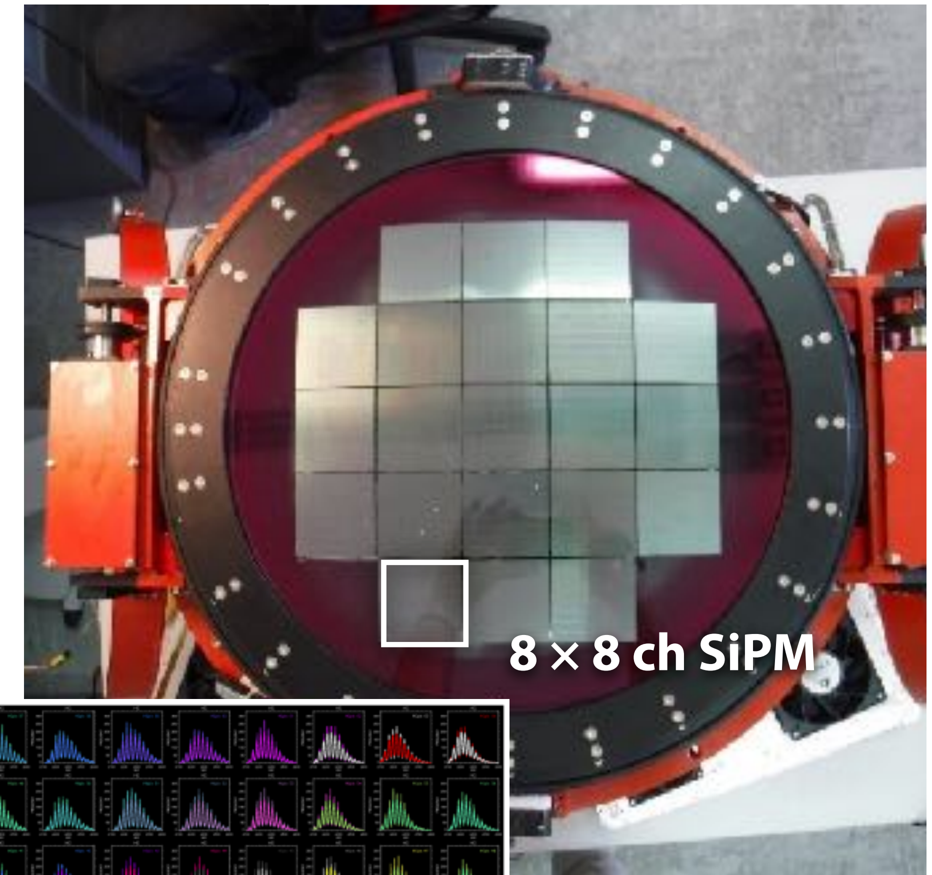


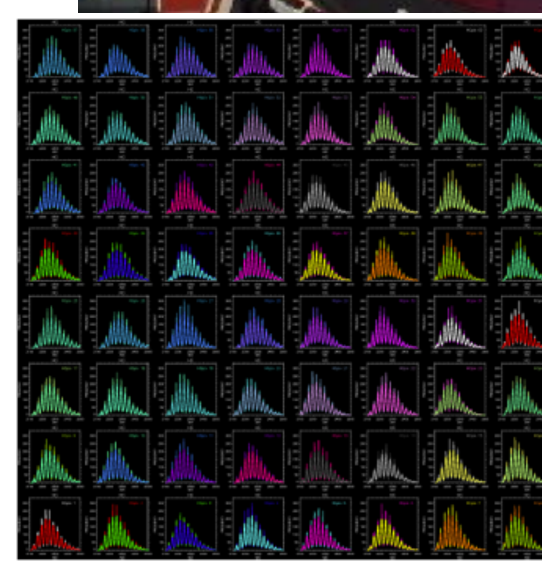


Camera Lids

Photon Detection Module
(SiPM and frontend)

Prototype Camera





Pulse height distribution
of a single SiPM array

- 8 × 8 ch MPPC × 37 = 2368 MPPC pixels at the focal plane
- Dedicated SiPM-readout ASICs (CITIROC) used in front-end electronics
- Compatible design with SST-2M GCT

ASTRI First Light

https://www.cta-observatory.org

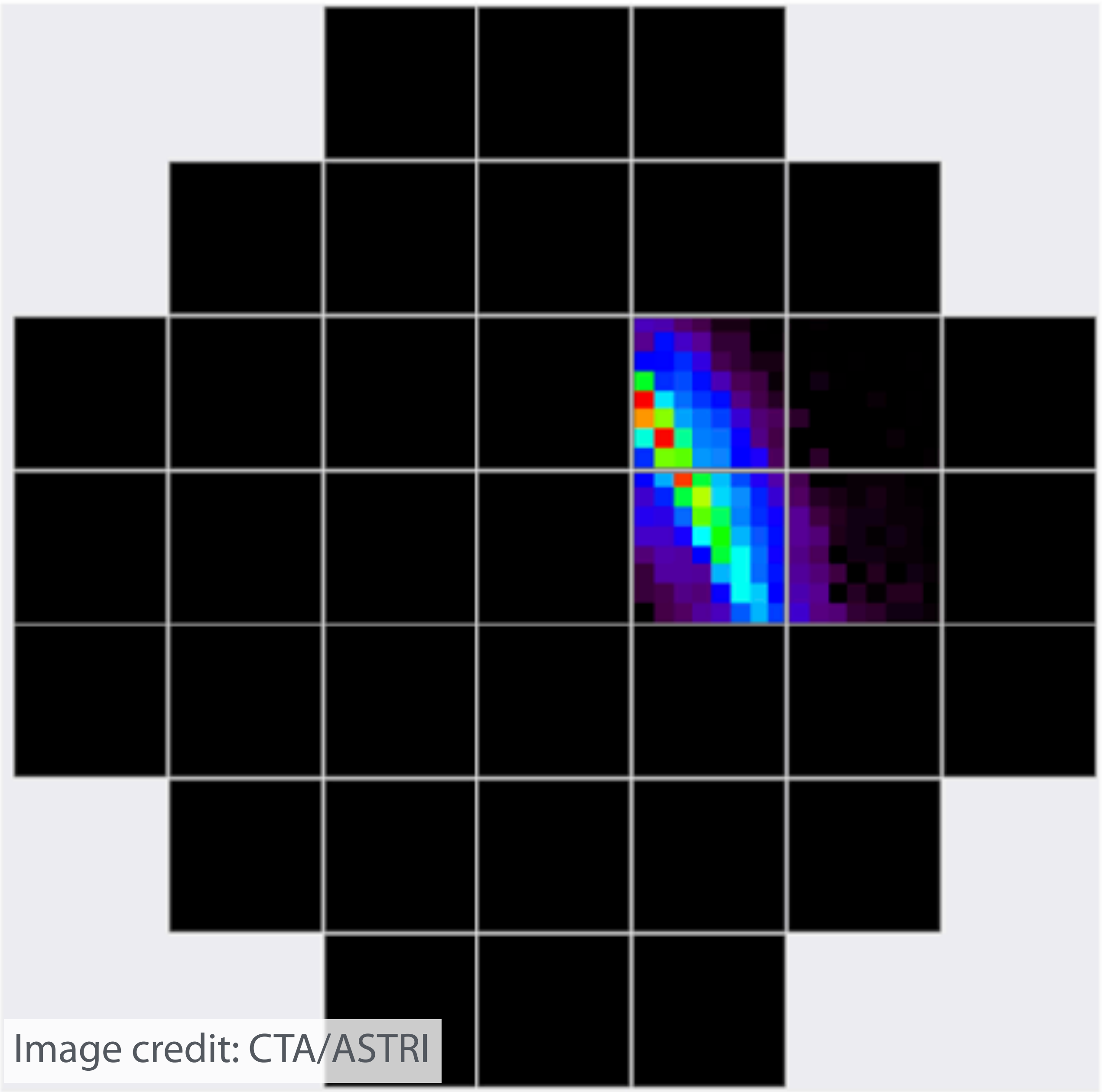
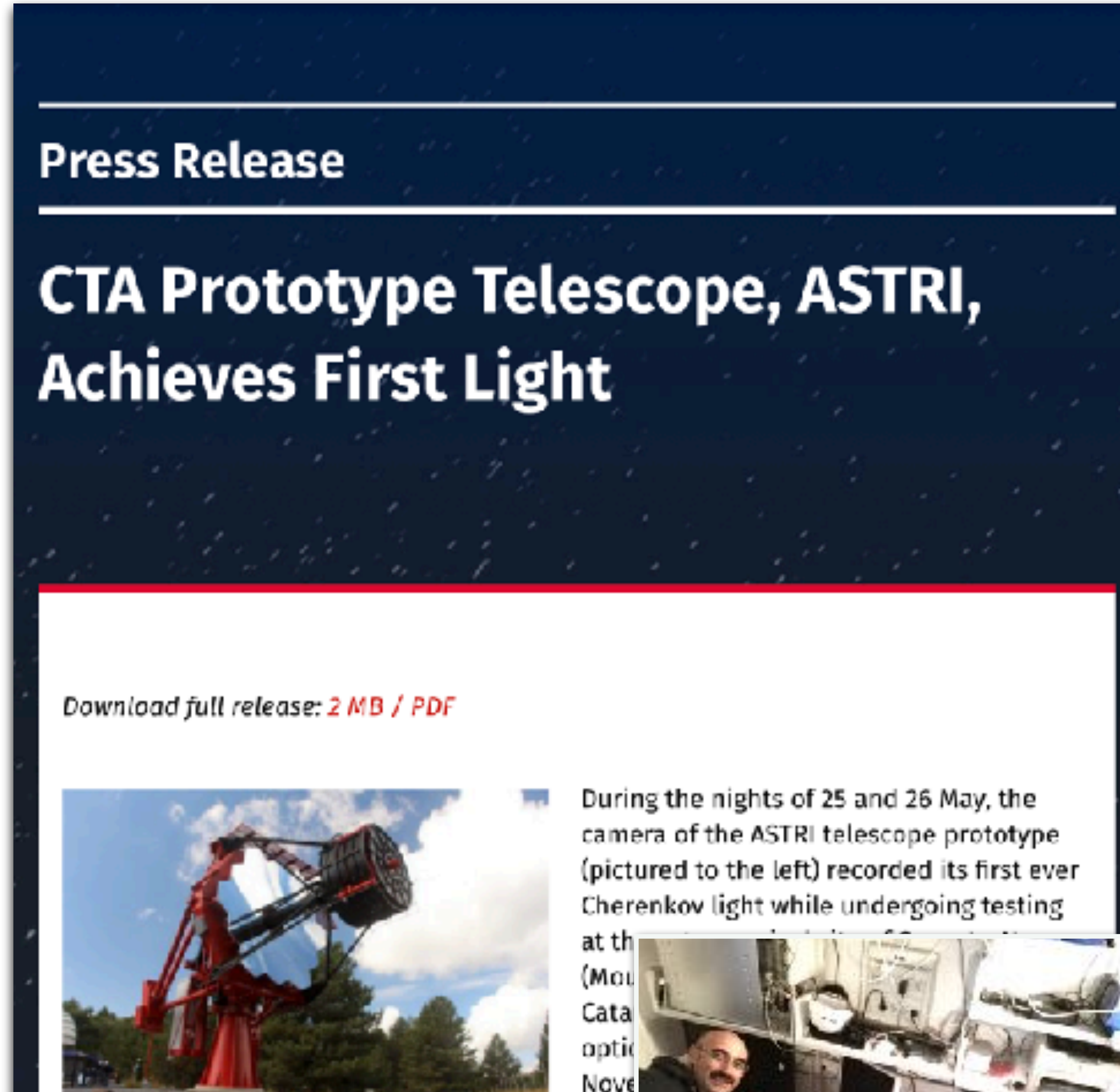


Image credit: CTA/ASTRI



Press Release

CTA Prototype Telescope, ASTRI, Achieves First Light

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During the nights of 25 and 26 May, the camera of the ASTRI telescope prototype (pictured to the left) recorded its first ever Cherenkov light while undergoing testing at th
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- Achieved first light of air-shower images on May 25, 2017
- Also able to image stars by measuring pixel amplitude variance (proportional to star flux)

ASTRI First Light

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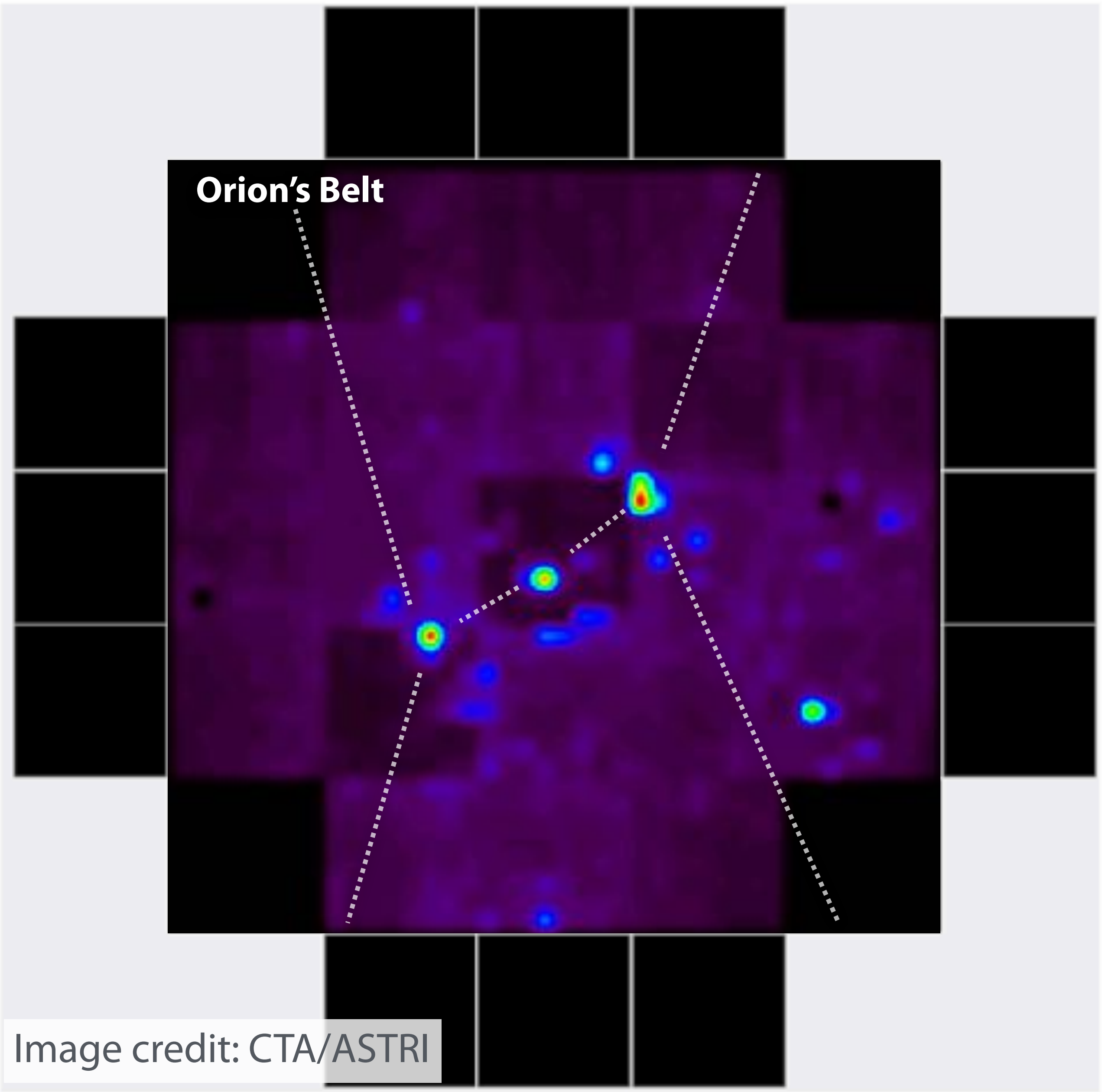

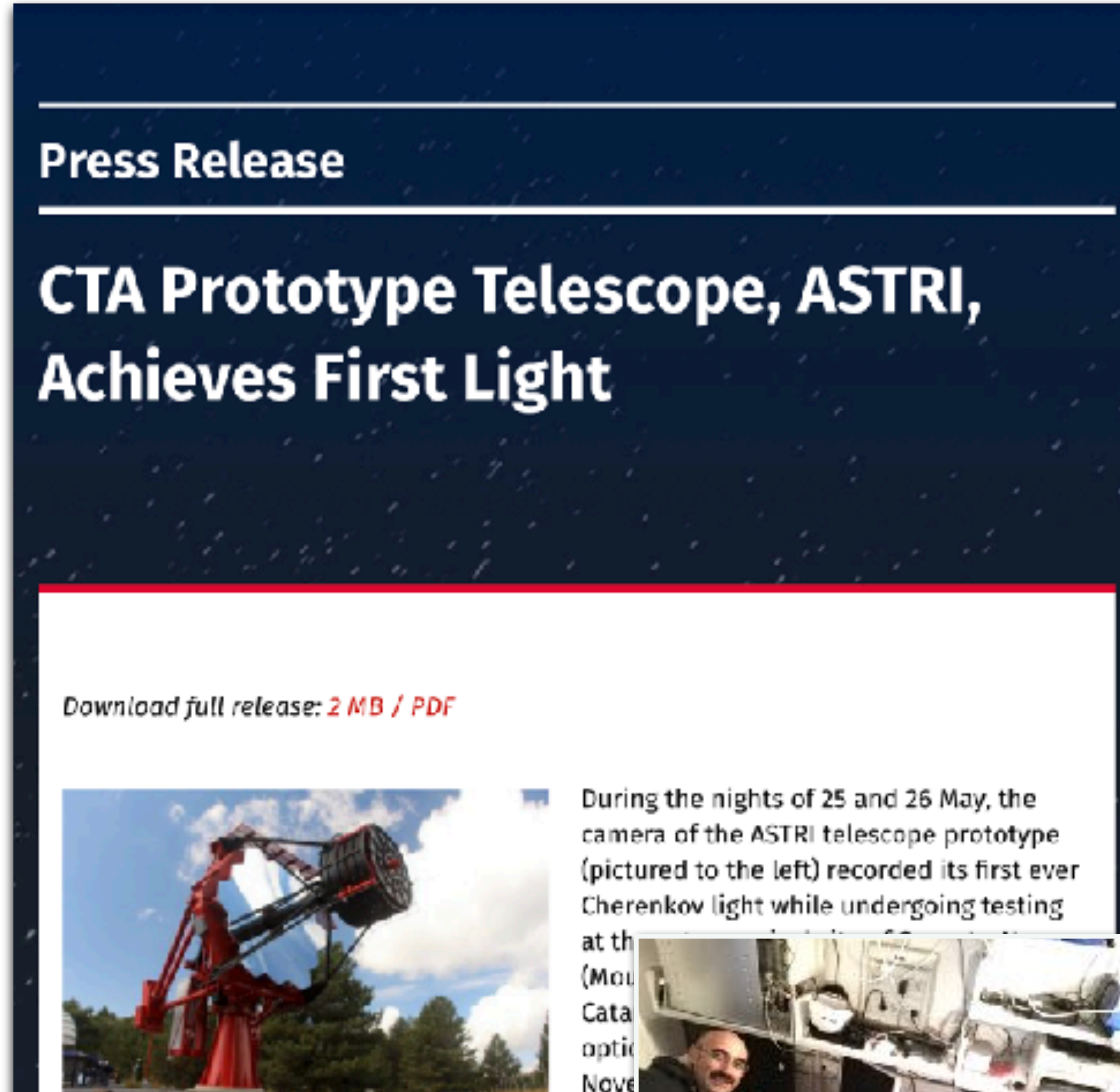

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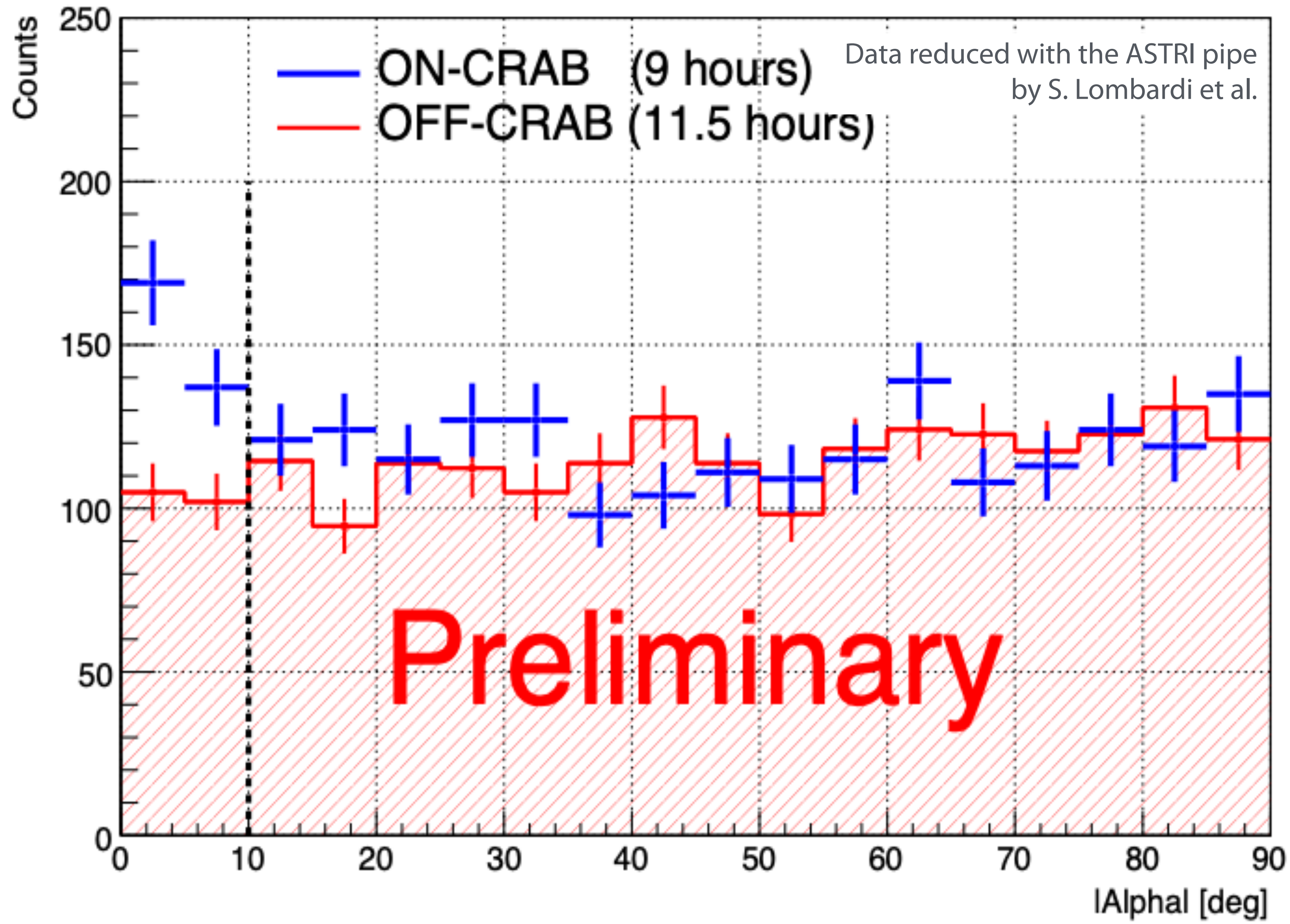
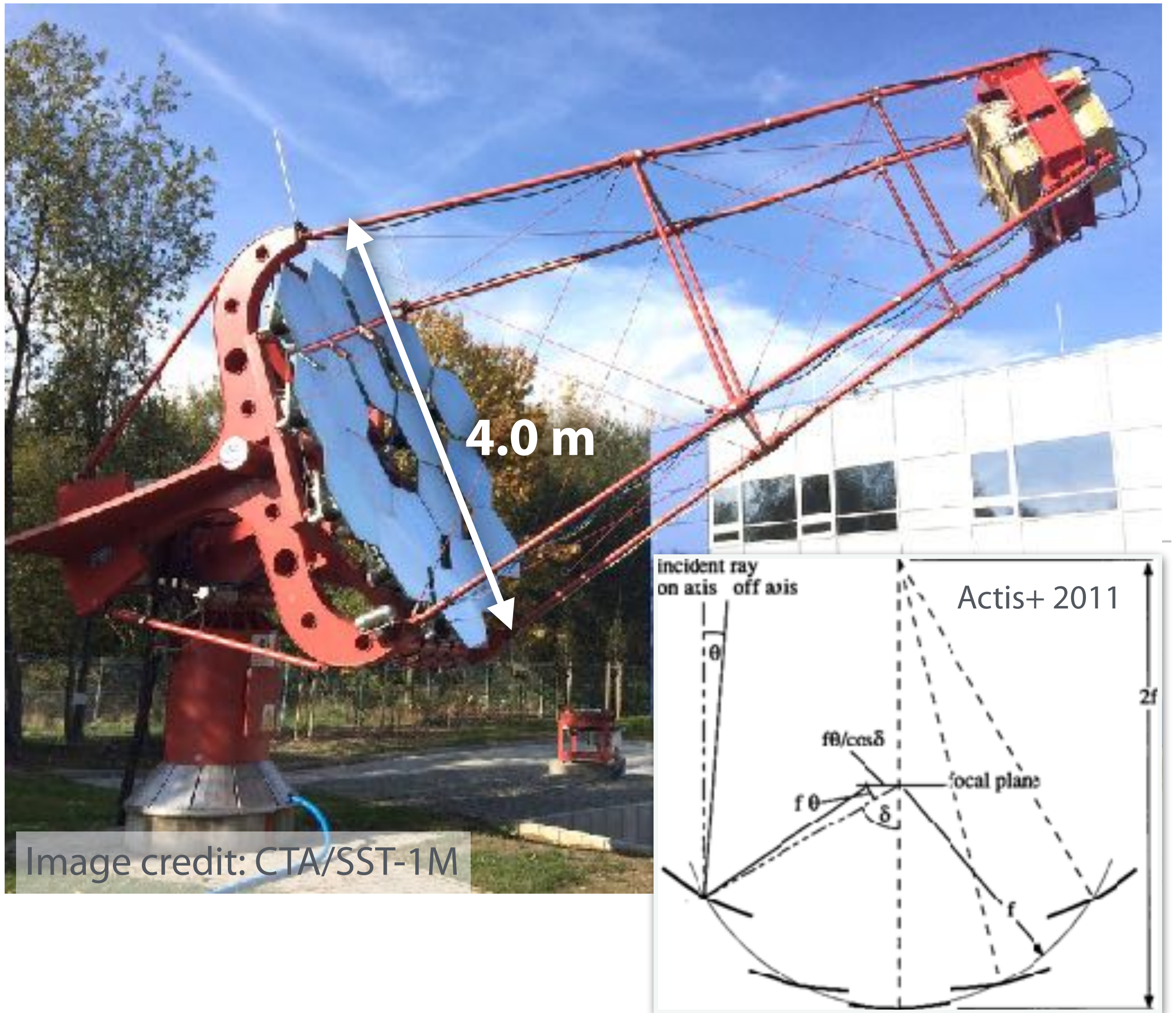
ASTRI Crab Observations

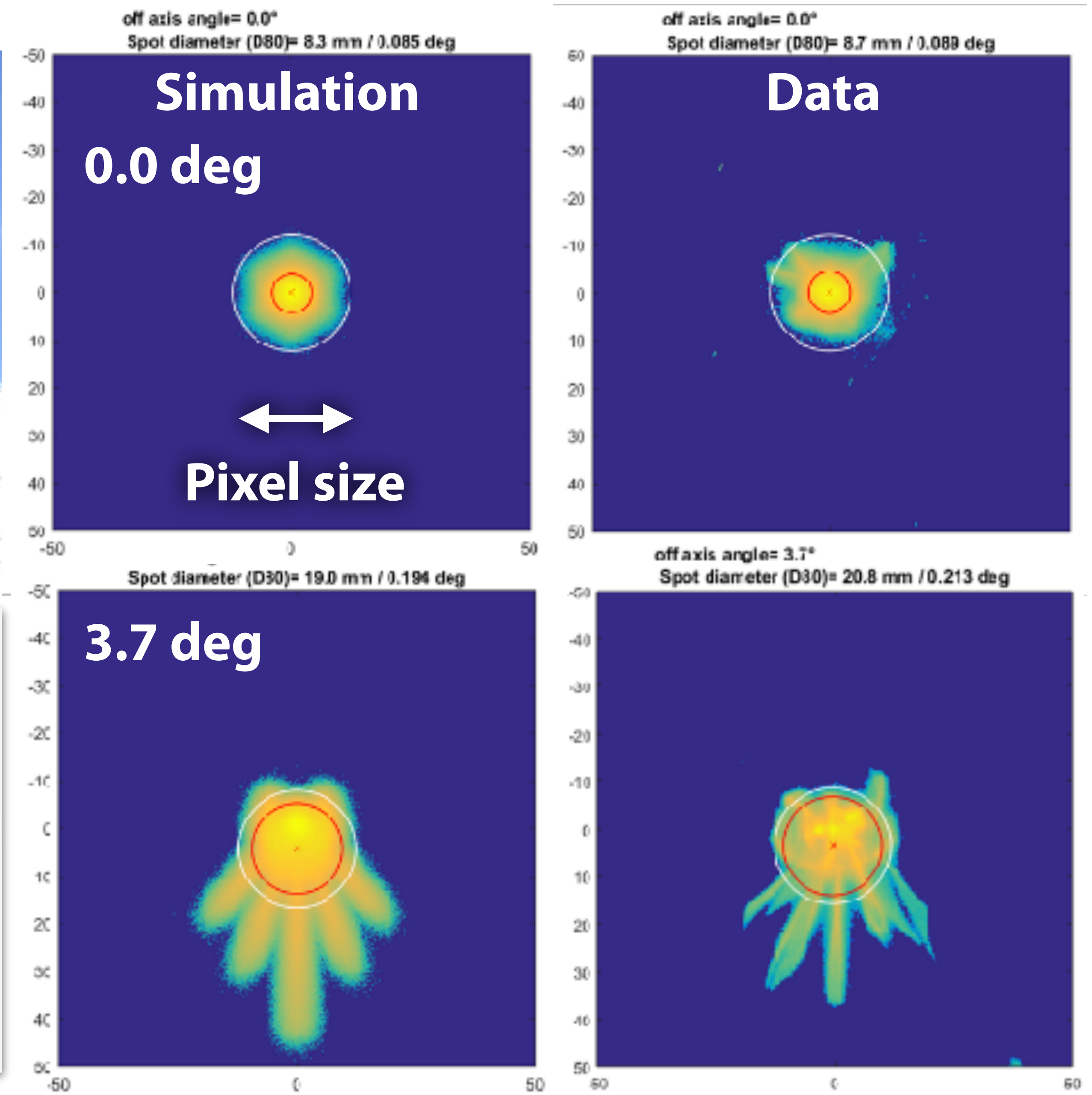
From the presentation by G. Pareschi at
the pSCT Inauguration Workshop Jan 16, 2019



- More than 5σ significance with 9-hour on-source observations
- First detection of a gamma-ray source with a dual-mirror Cherenkov telescope

SST-1M



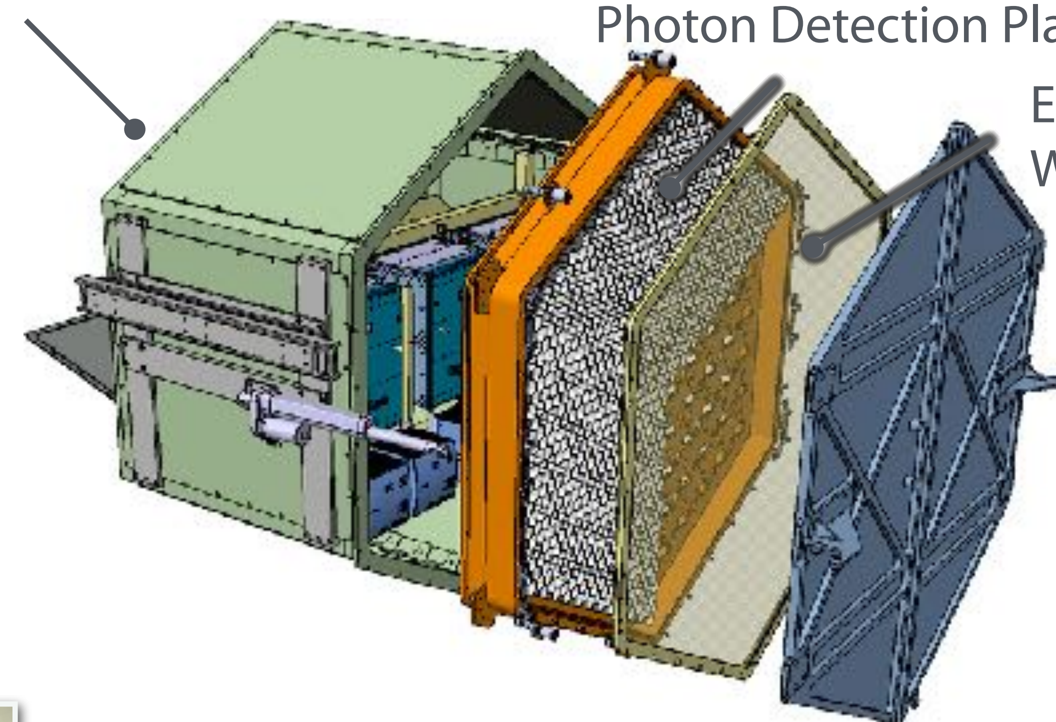


- Conventional Davies–Cotton optics with 18 segmented spherical mirrors (less expensive than Schwarzschild–Couder)
- Fully automated system installed at IFJ, Krakow, Poland
- Optical performance has been verified with star images

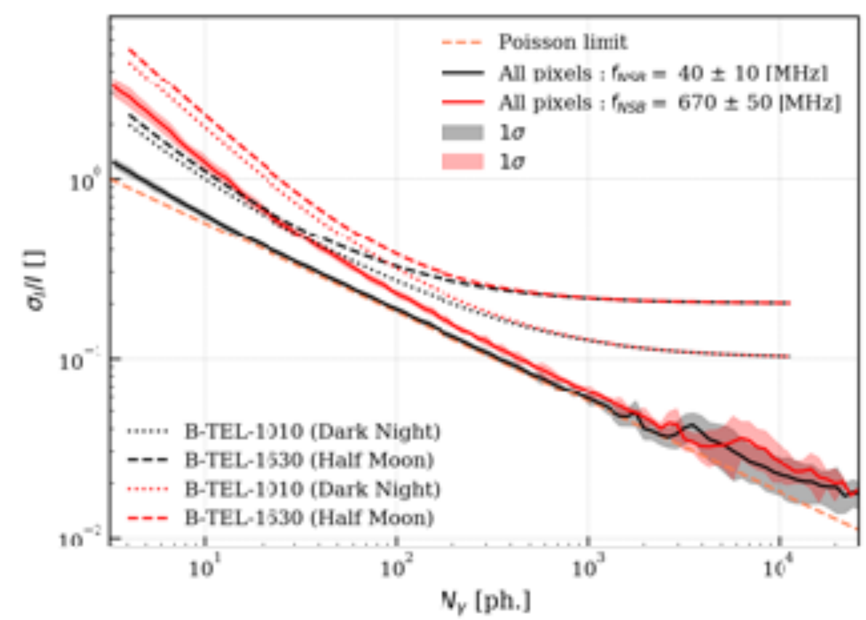
SST-1M Camera

Photon Detection Plane Module

Image credit: CTA/SST-1M



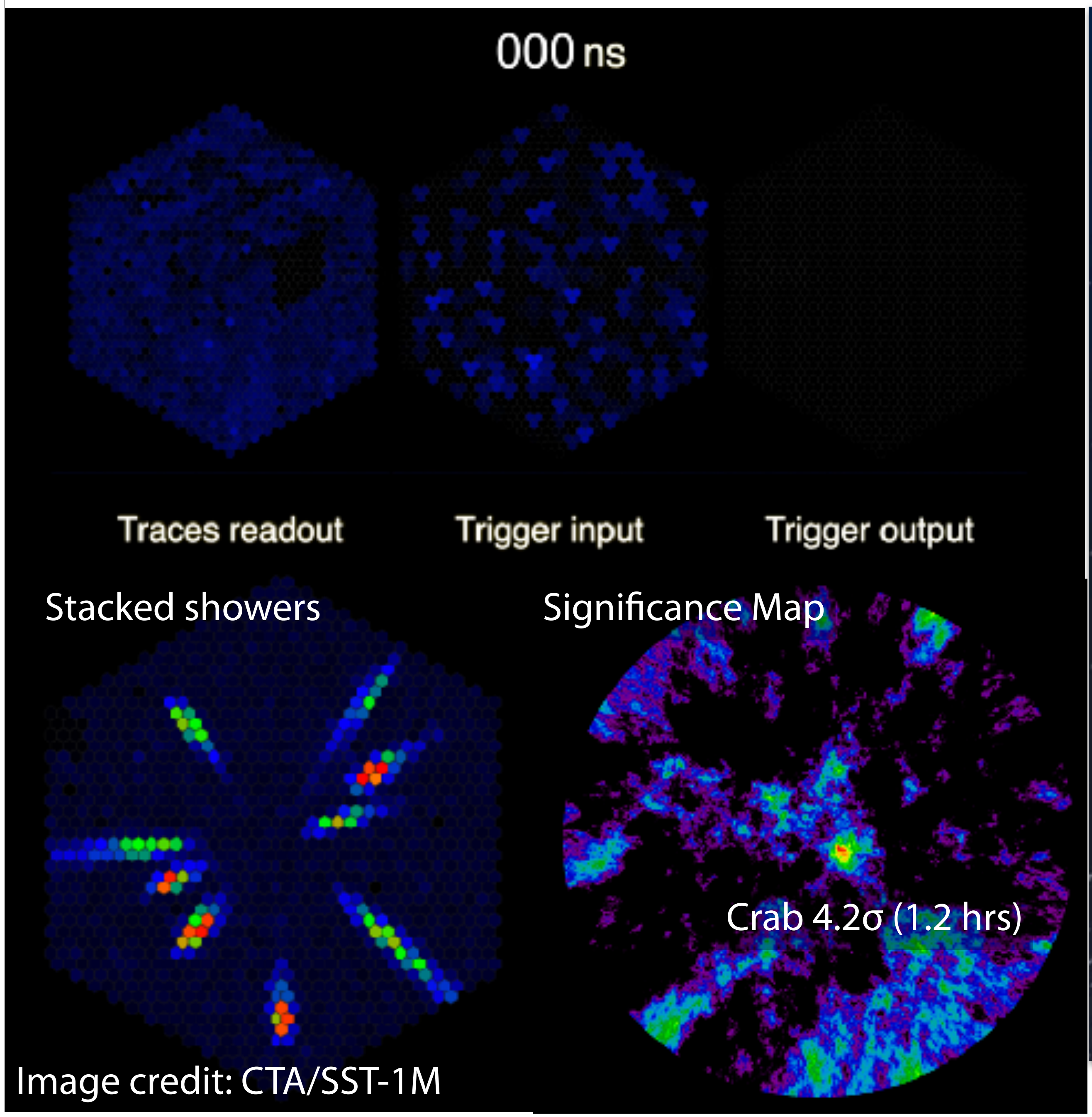
Measured Charge Resolution



- Dead-time free fully digital camera (DigiCam)
- 8.9° FOV with 1296-pixel SiPMs and light concentrators
- Not compatible with SST-2Ms but use similar technologies with MST FlashCam

SST-1M First Light

https://www.cta-observatory.org



Announcement

CTA Prototype Telescope, the SST-1M, Catches its First Glimpse of the Sky

On Thursday, 31 August, 2017, a prototype telescope proposed for the Cherenkov Telescope Array (CTA), the SST-1M, recorded its first events while undergoing testing at the Institute of Nuclear Physics Polish Academy of Sciences (IFJ-PAN) in Krakow, Poland. The SST-1M is proposed as one of CTA's Small-Sized Telescopes (SSTs), which will cover the high end of CTA's energy range, between about 1 and 300 TeV (tera-electronvolts).

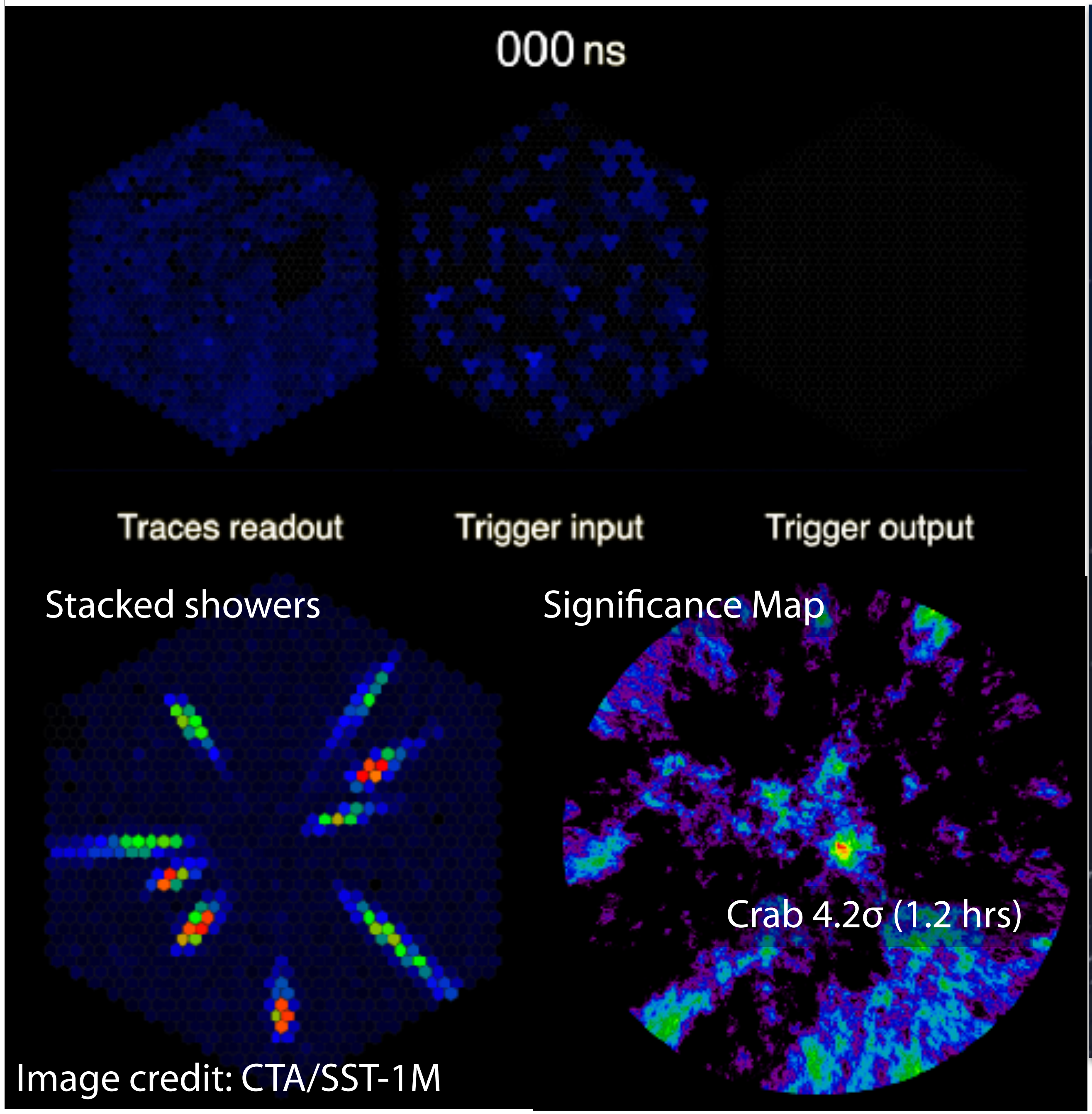
A crew in Krakow worked for two days to install the camera on the telescope and spent another two days monitoring it to ensure it could be safely switched on in the high humidity conditions. Watch the camera installation in the video below.

SST-1M Camera Installation

- Achieved first light on Aug 31, 2017
- Prototype detected the Crab nebular with 4.2σ excess in test observations
- New observation campaigns are ongoing from 2018

SST-1M First Light

https://www.cta-observatory.org



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CTA Prototype Telescope, the SST-1M, Catches its First Glimpse of the Sky

On Thursday, 31 August, 2017, a prototype telescope proposed for the Cherenkov Telescope Array (CTA), the SST-1M, recorded its first events while undergoing testing at the Institute of Nuclear Physics Polish Academy of Sciences (IFJ-PAN) in Krakow, Poland. The SST-1M is proposed as one of CTA's Small-Sized Telescopes (SSTs), which will cover the high end of CTA's energy range, between about 1 and 300 TeV (tera-electronvolts).

A crew in Krakow worked for two days to install the camera on the telescope and spent another two days monitoring it to ensure it could be safely switched on in the high humidity conditions. Watch the camera installation in the video below.

SST-1M Camera Installation

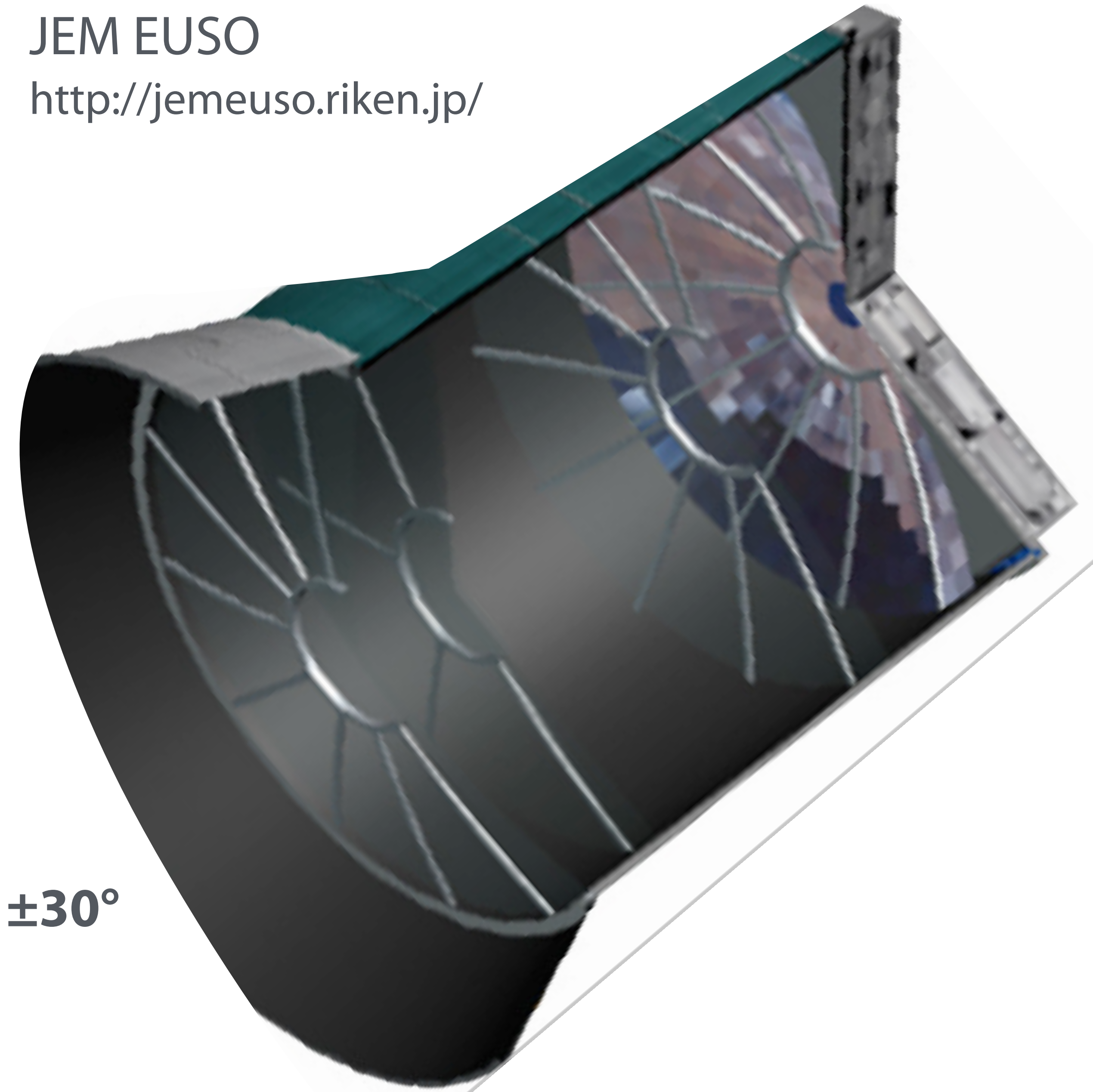
- Achieved first light on Aug 31, 2017
- Prototype detected the Crab nebular with 4.2σ excess in test observations
- New observation campaigns are ongoing from 2018

Wide FOV Camera and Optics

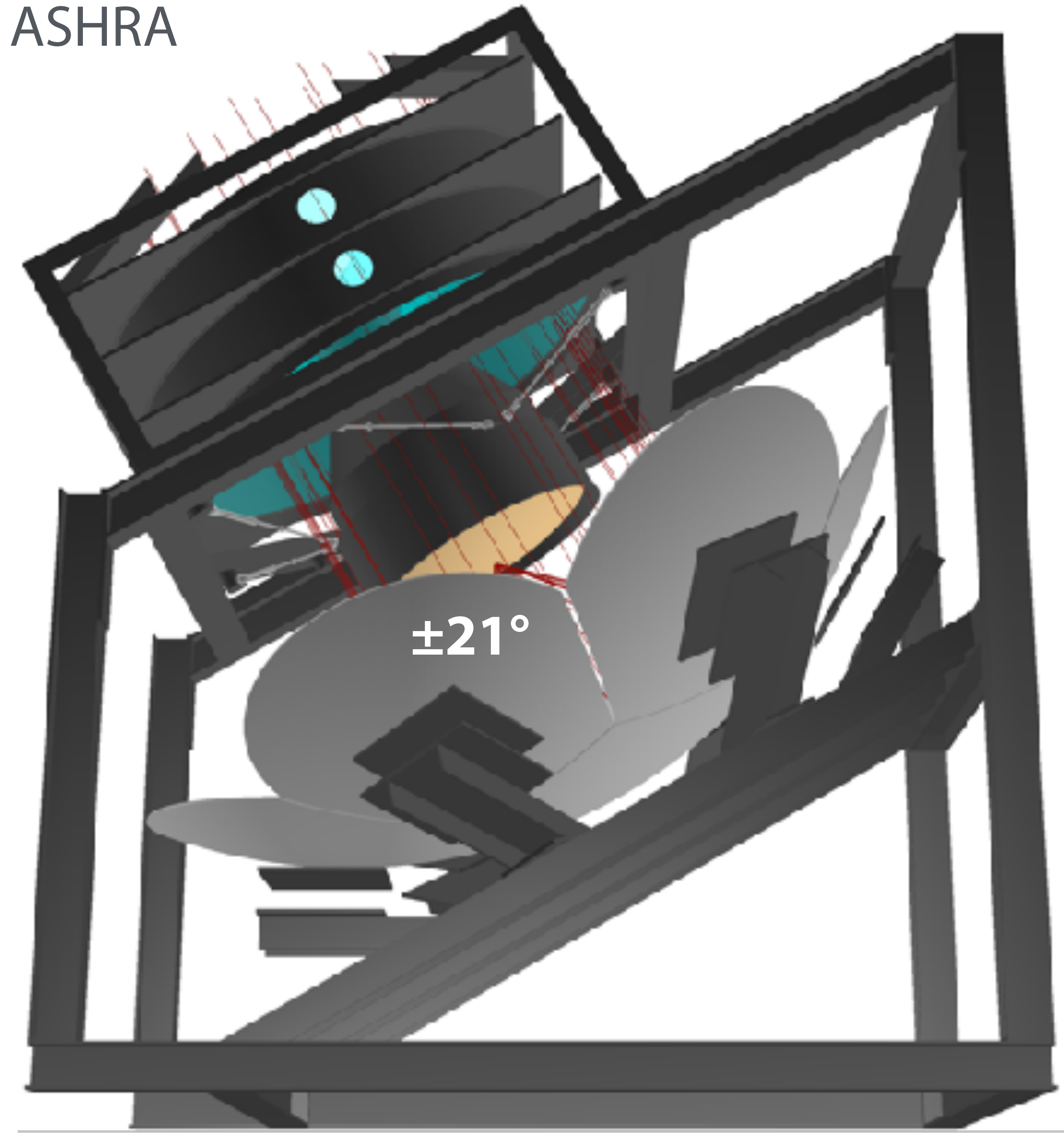
Wide FOV Telescopes (~50 deg)

JEM EUSO

http://jemeuso.riken.jp/



ASHRA

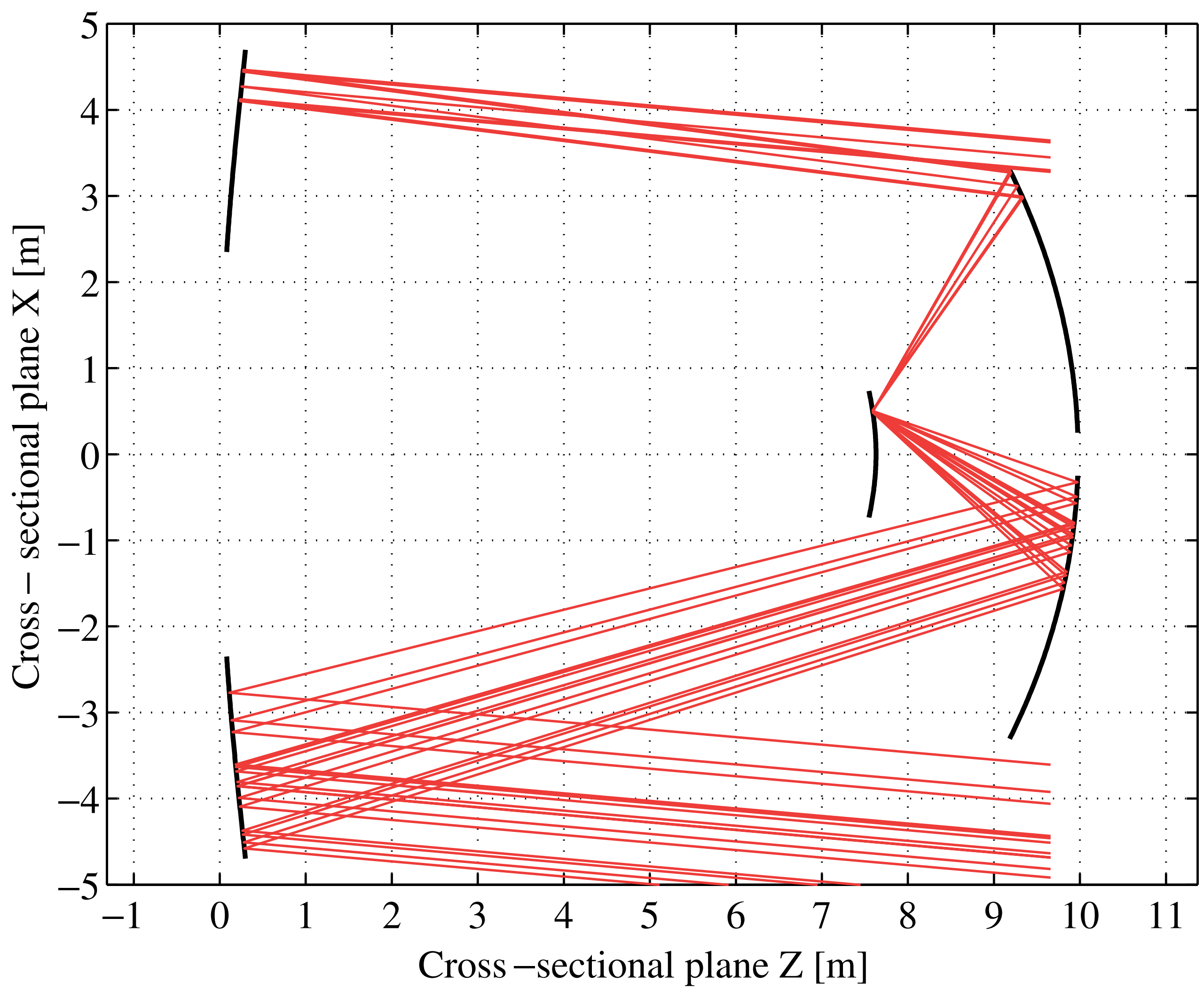


Okumura et al. (2016)

- Concepts of wide FOV and high angular resolution are usually trade-off
- New ideas and technologies are often brought for long exposure or survey
- But not scalable for large Cherenkov telescopes (5–20 m) or pointing observations

Schwarzschild–Couder (SC) Optical System

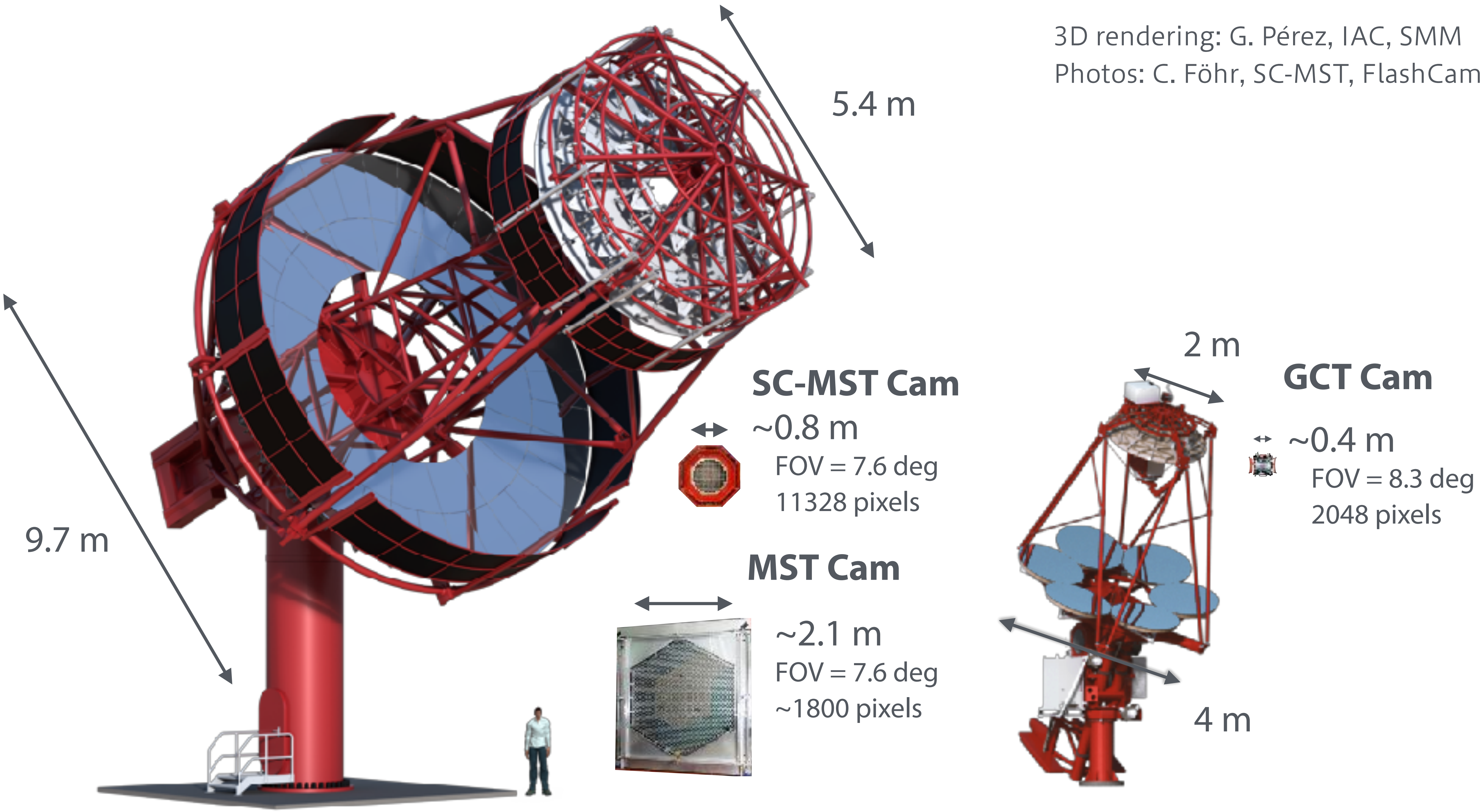
Vassiliev et al. (2007)



Prototype-SC-MST Inauguration, Jan 2019

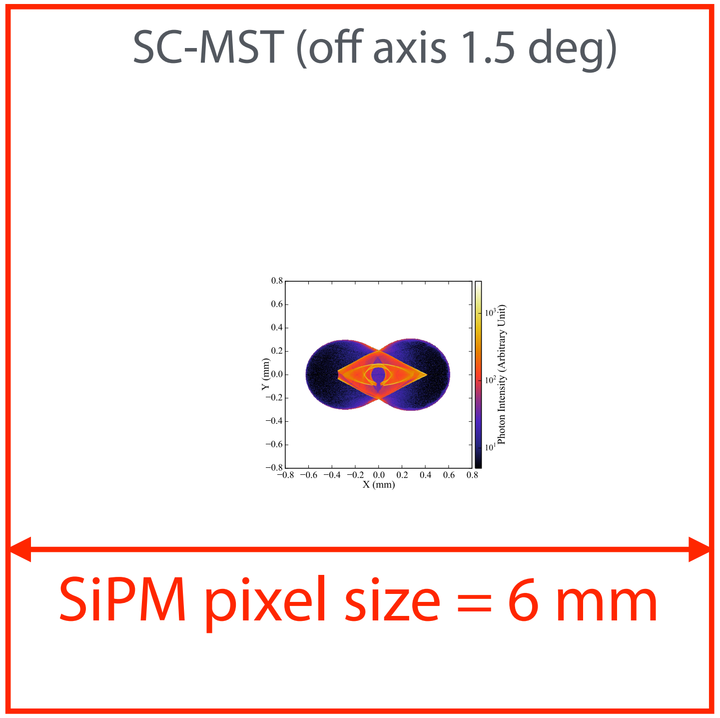
- Proposed for future Cherenkov telescopes achieving a wider FOV (~3 deg → ~10 deg) with smaller pixels (0.1–0.2 deg → ~0.05 deg)
- Two aspherical segmented mirrors and (a)spherical focal plane
- In CTA proposed for SC Medium-sized Telescopes (SC-MST) and two SST designs

SC-MST and SC-SST

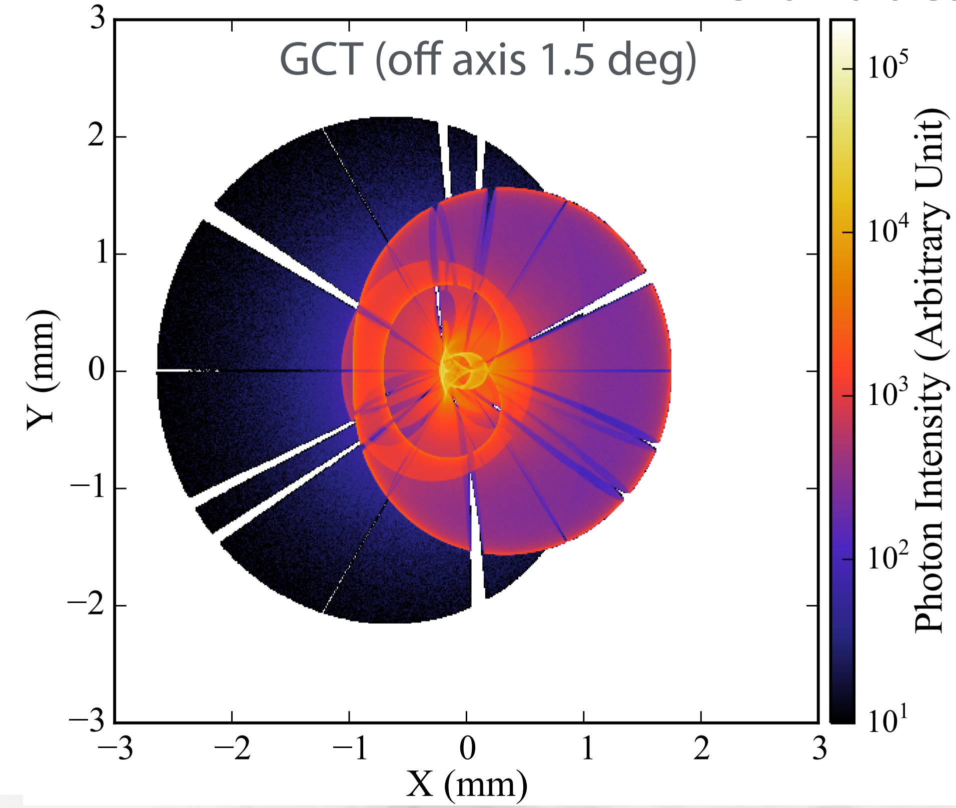


- Schwarzschild–Couder (SC) enables more compact cameras and finer pixels than those of conventional Cherenkov telescopes
- Compact and modular electronics and photodetectors developed by SC-MST and SC-SST (GCT) teams

PSF Simulation and Measurement

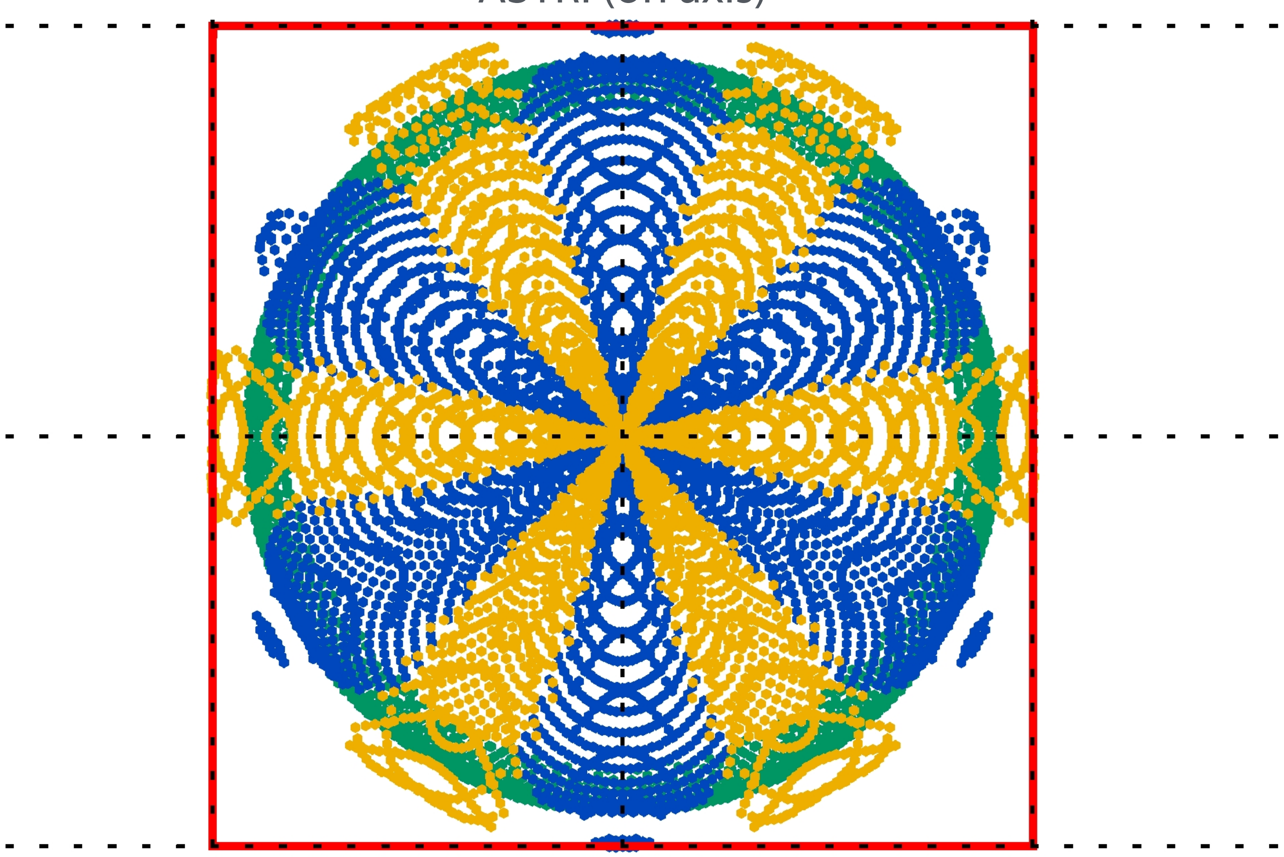


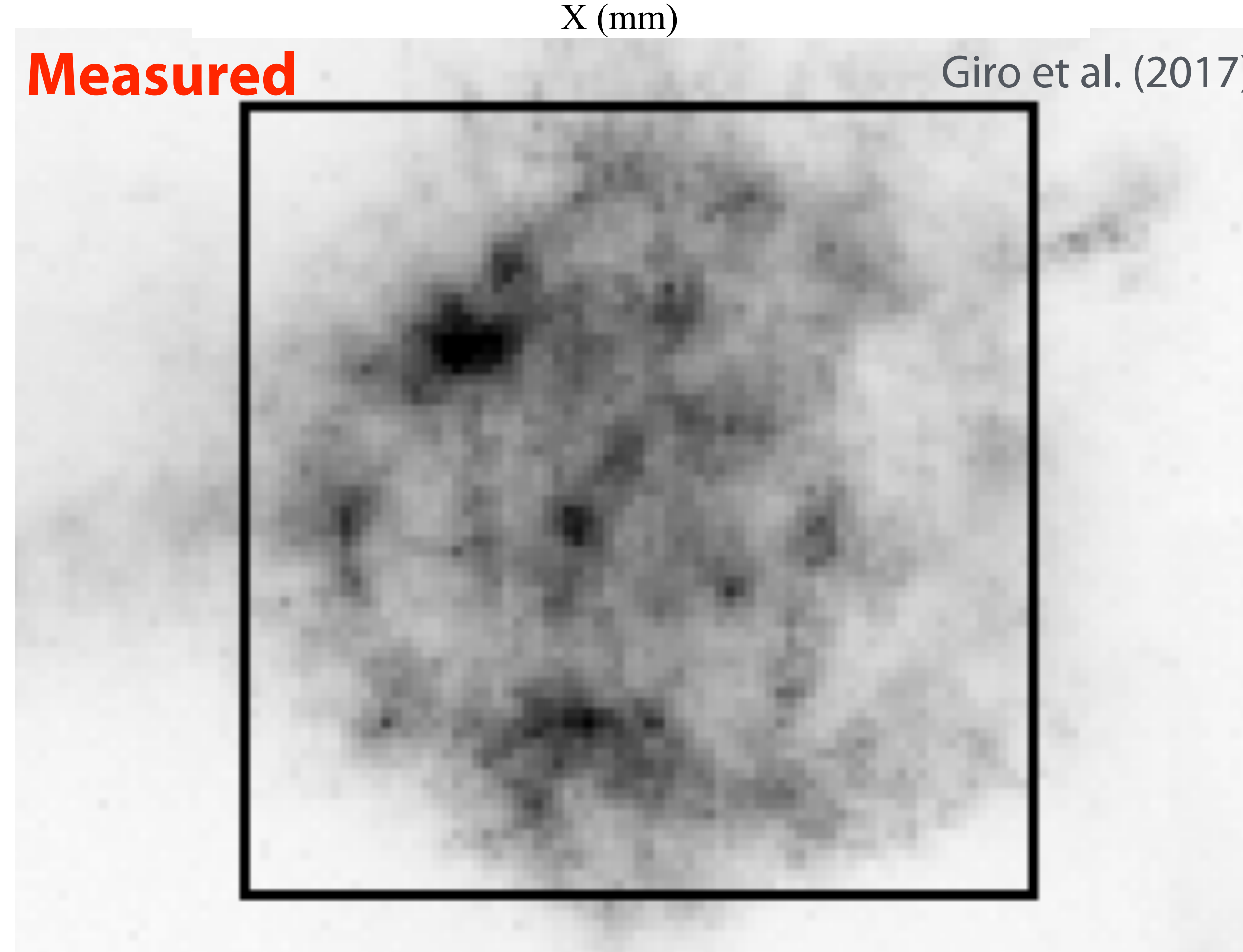
Okumura et al. (2016)



NB: Aberration more obvious at 4 deg

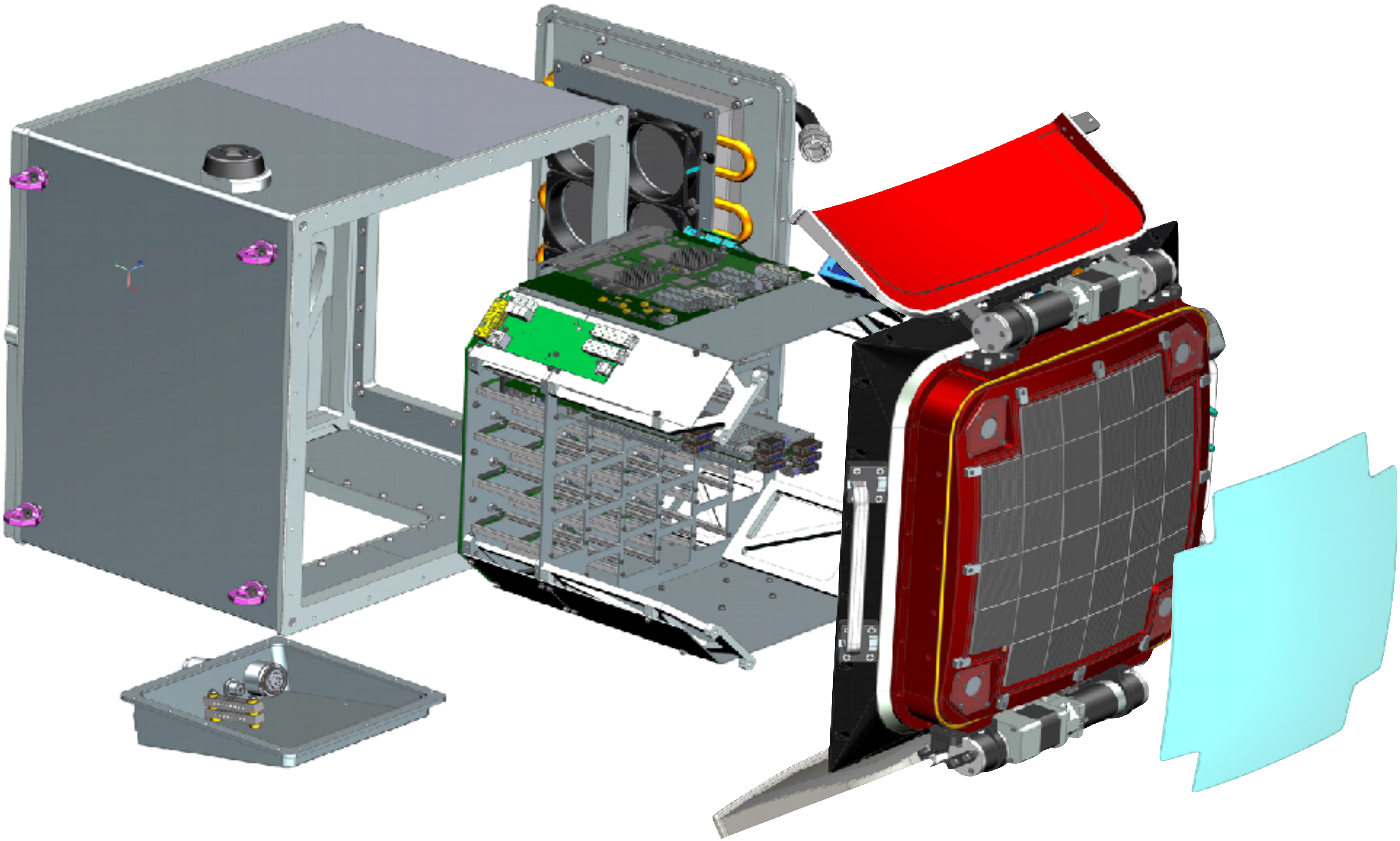
ASTRI (on axis)





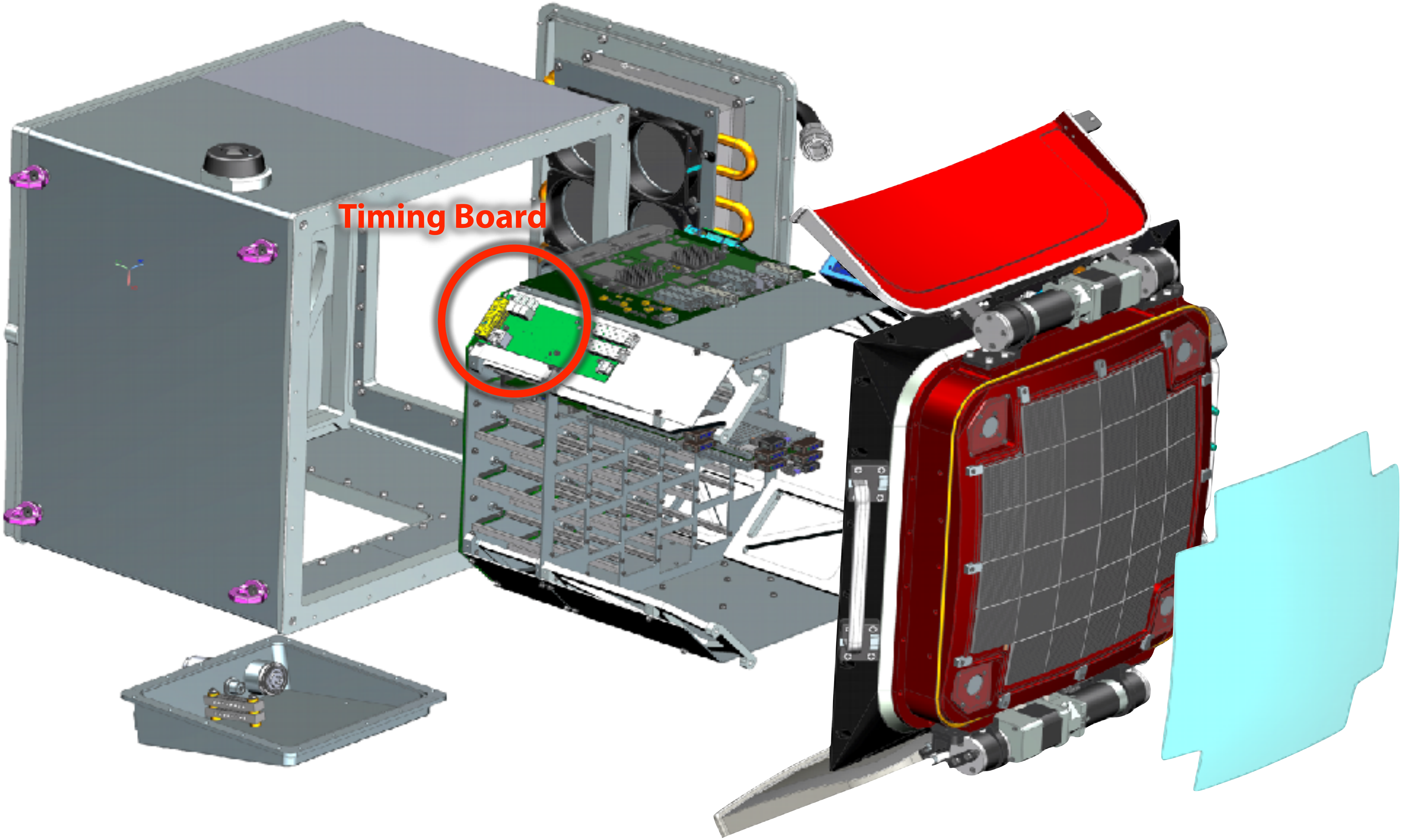
Giro et al. (2017)

SC-SST (GCT) Camera



3D CAD by D. Ross (taken from R. White 2017)

SC-SST (GCT) Camera



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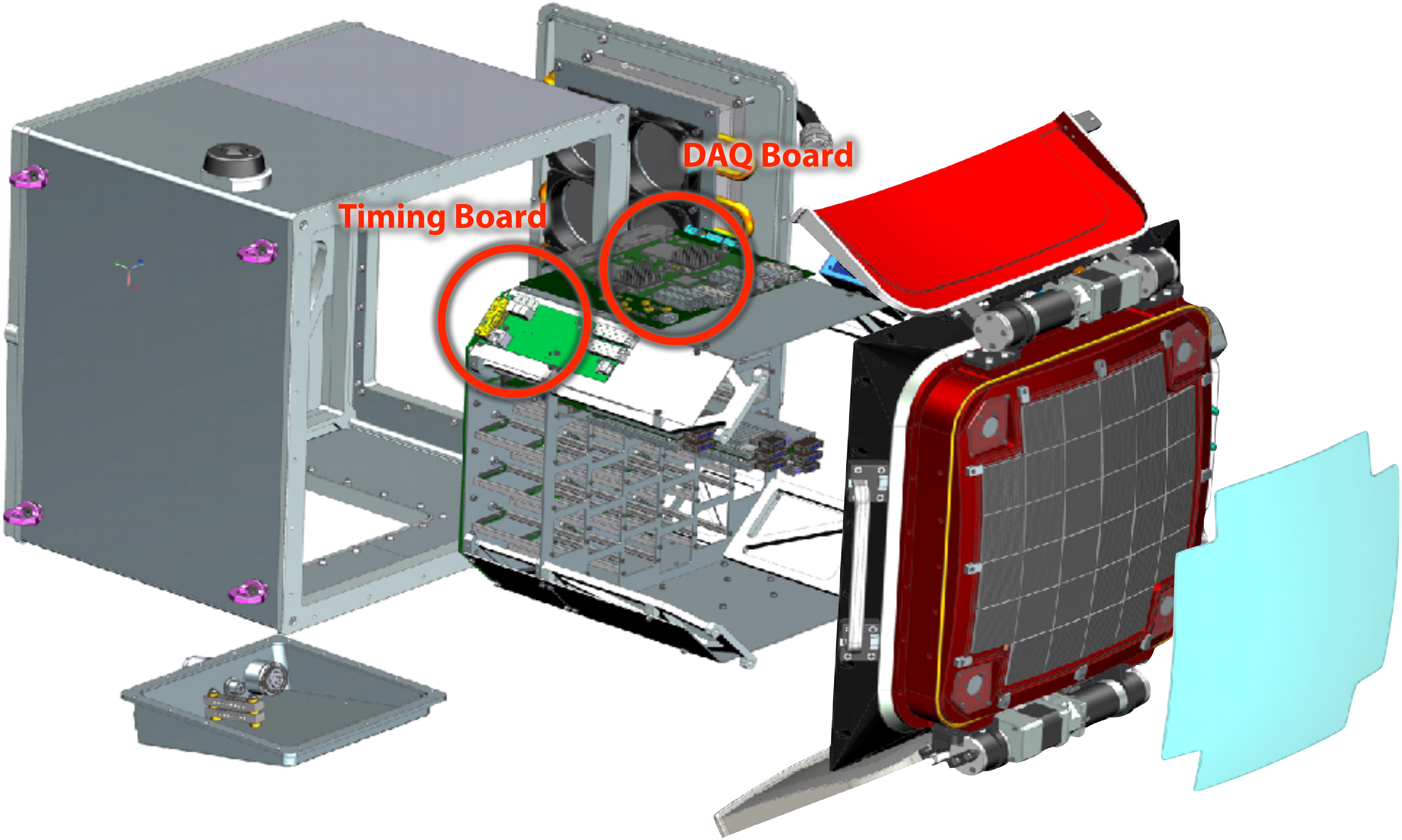

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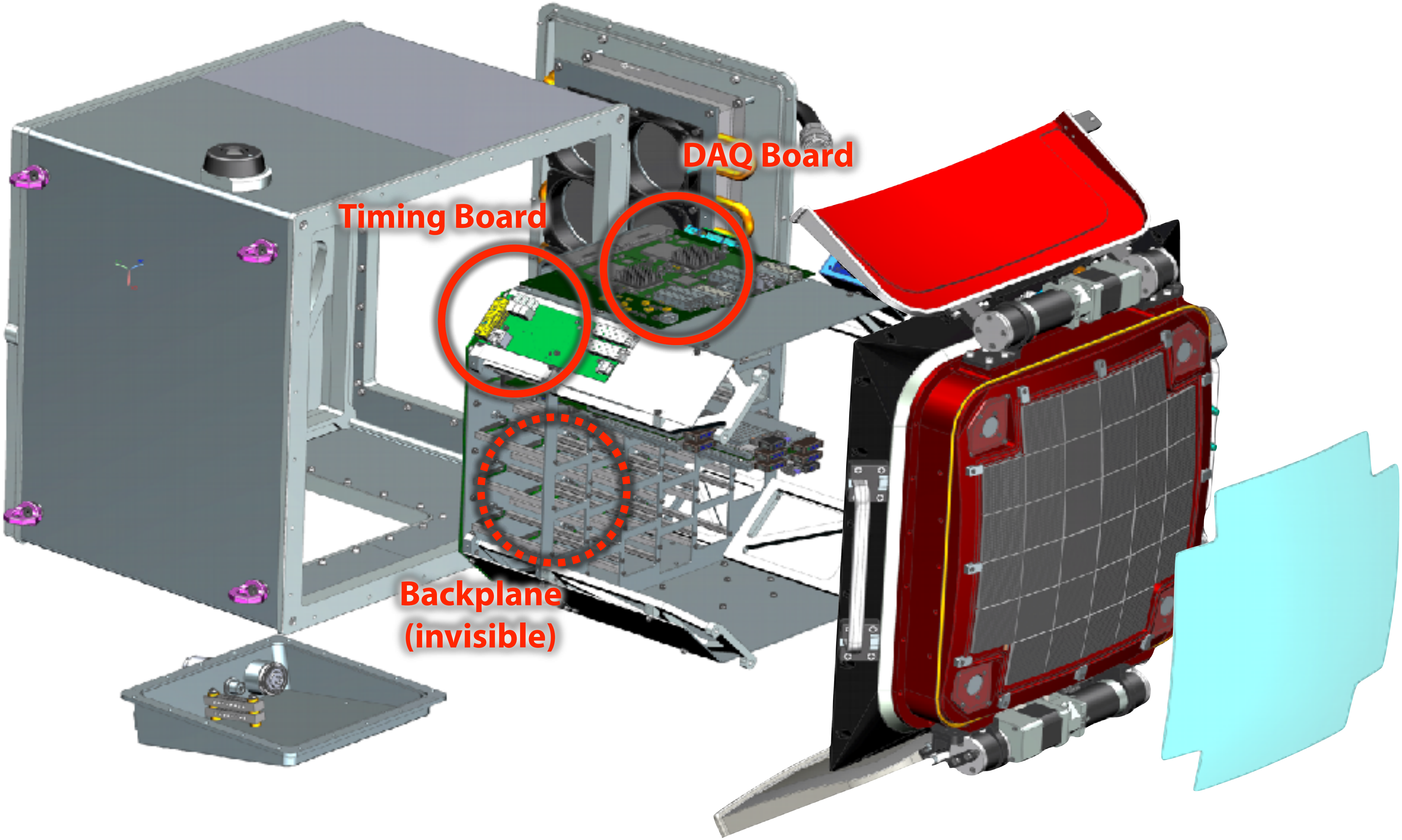

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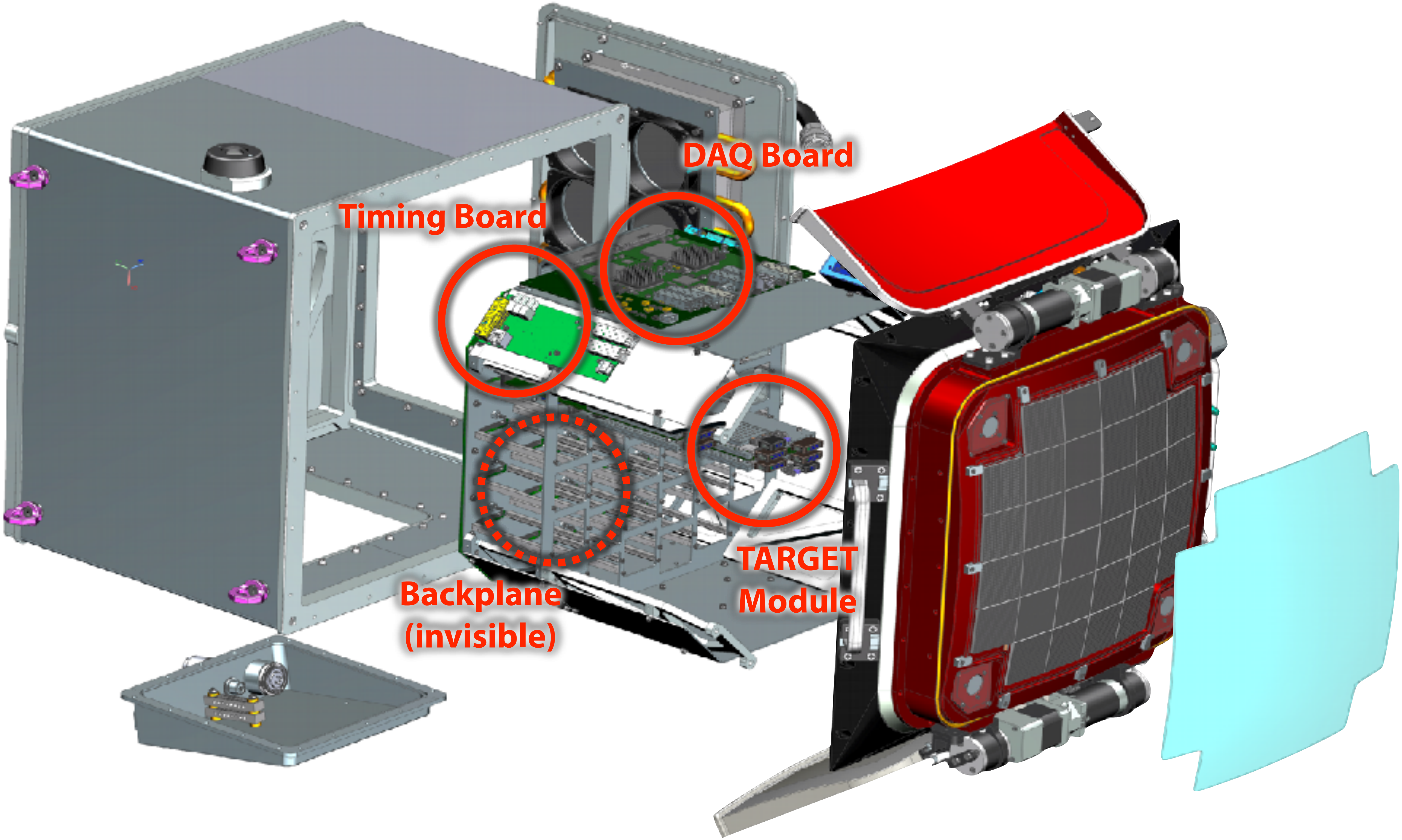

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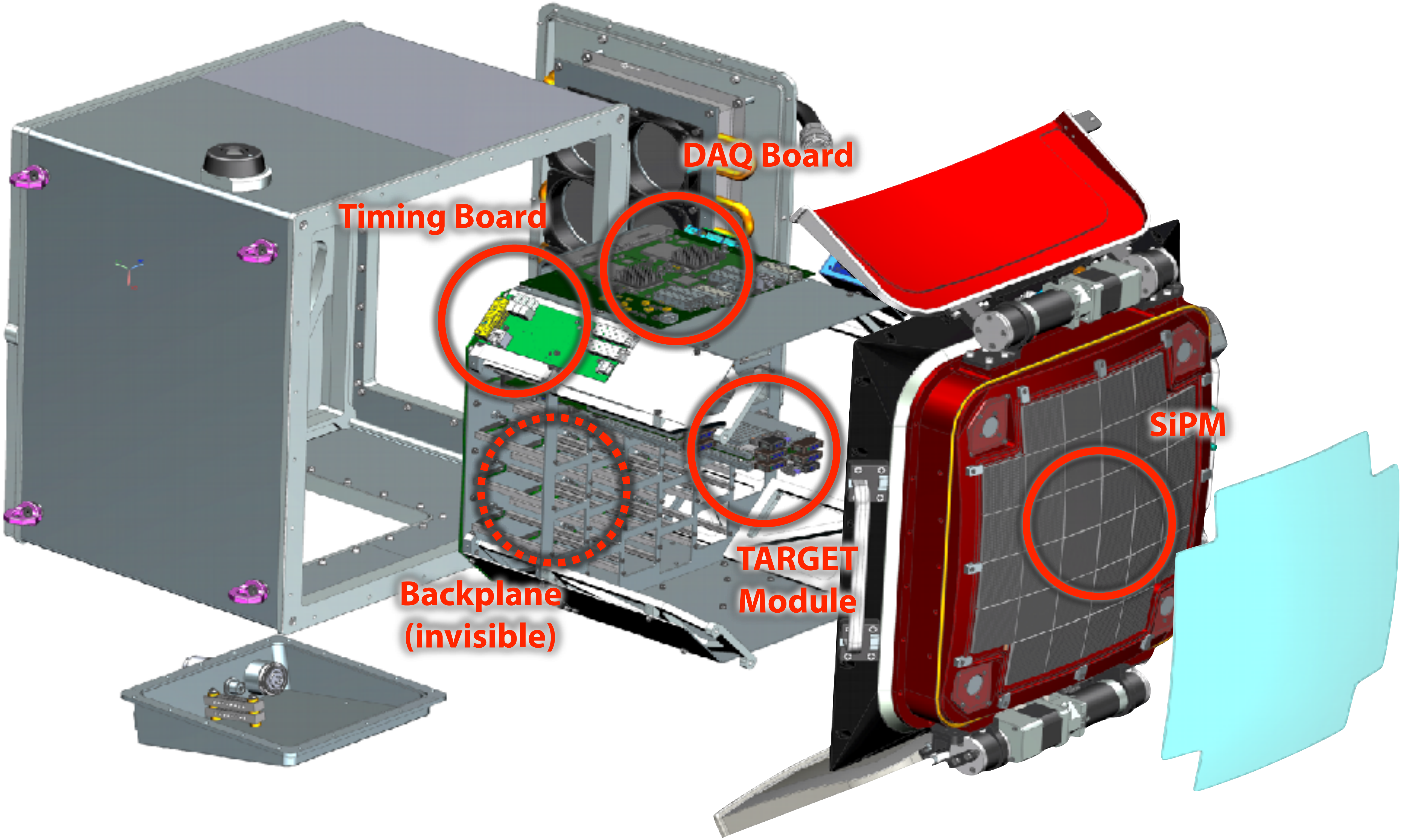

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SiPM

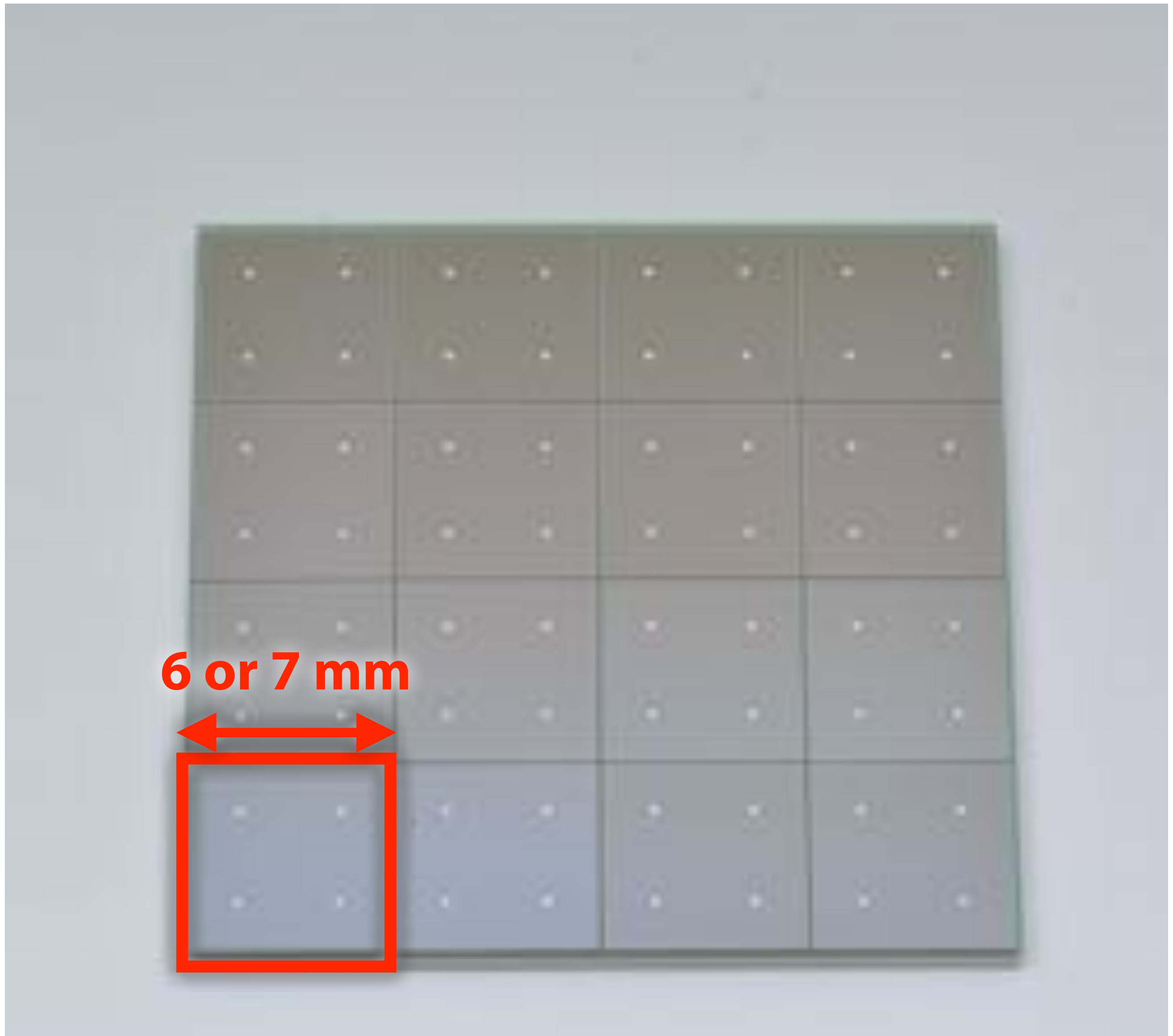
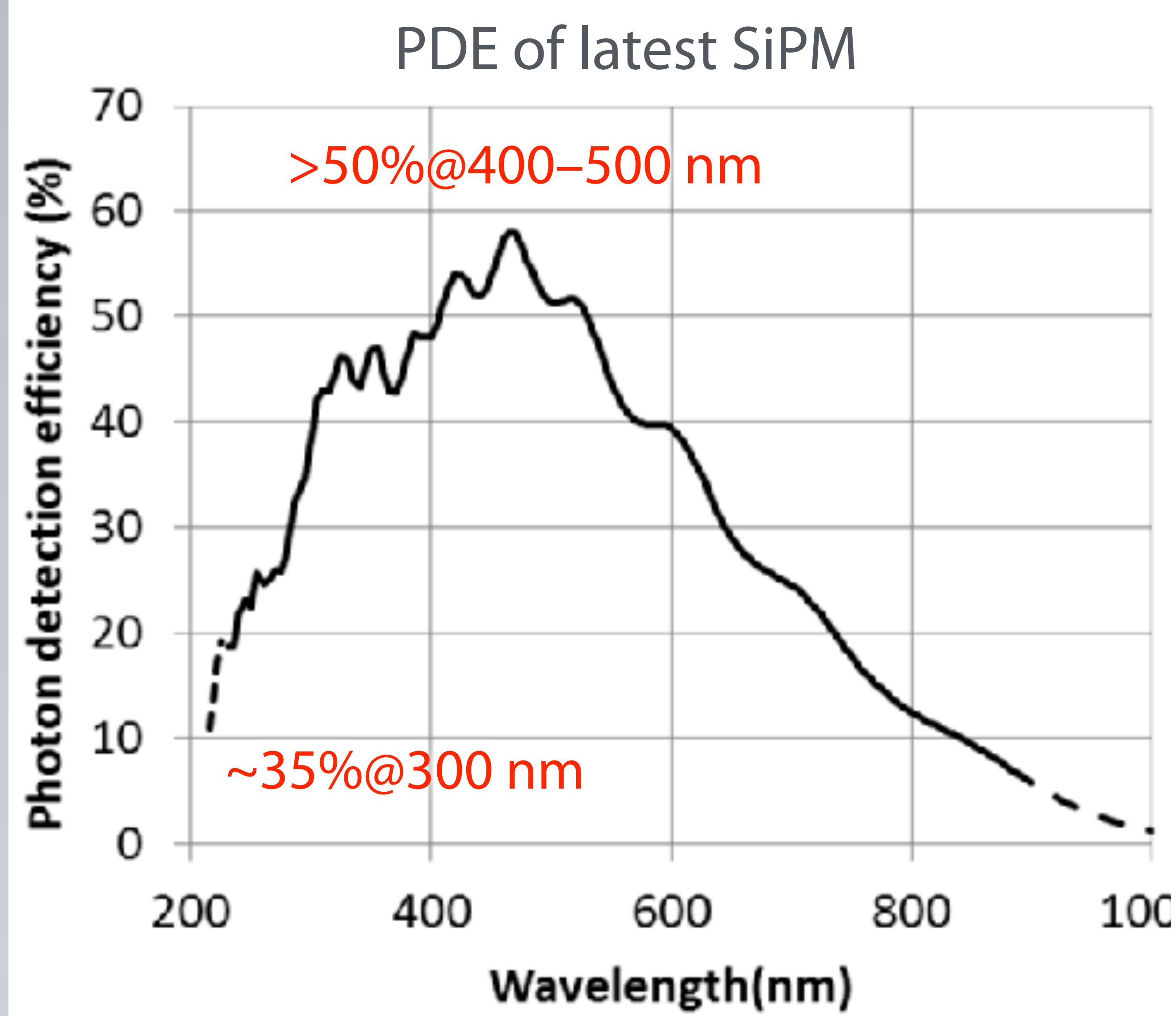


Photo by Hamamatsu Photonics

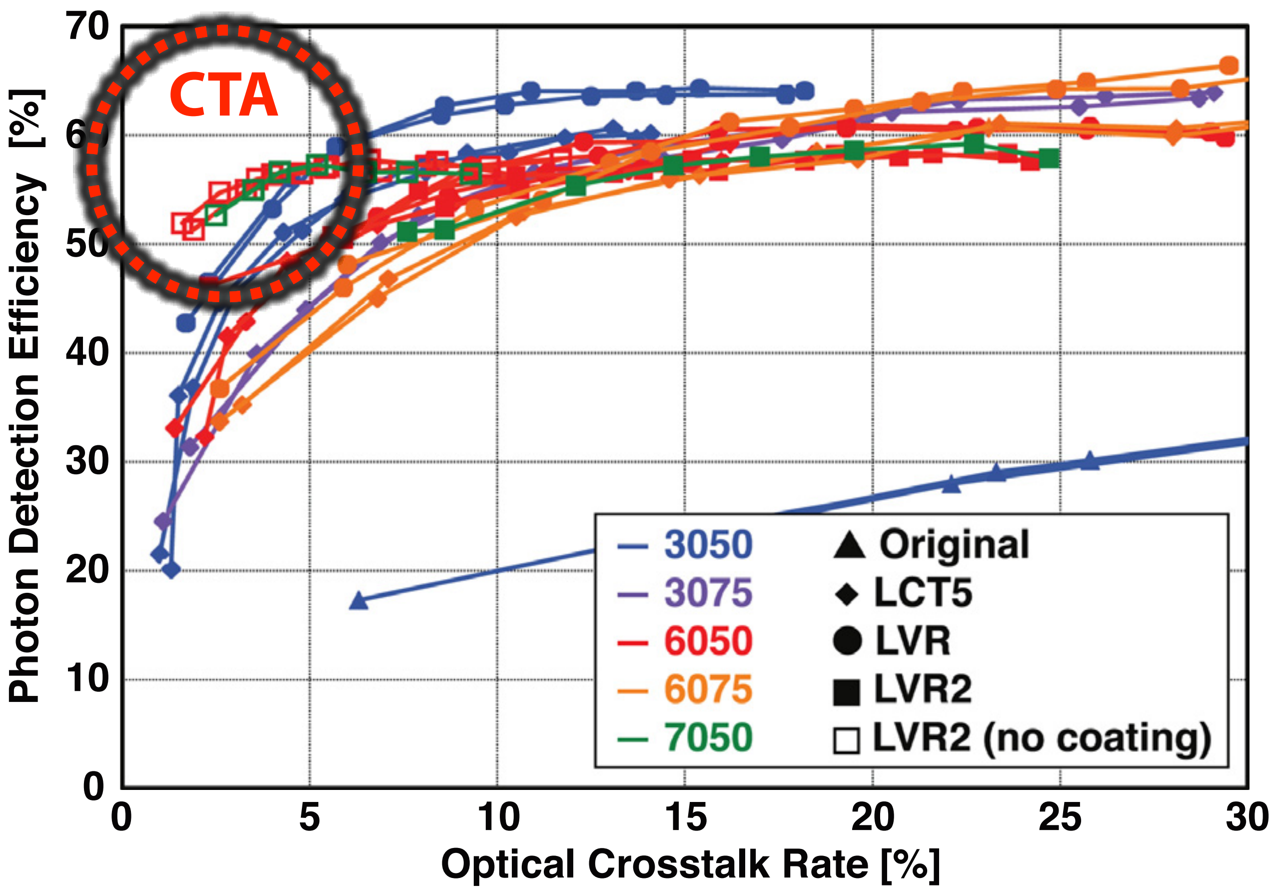


From Hamamatsu S14521-8648 spec sheet

- Compact, light weight, low voltage (~50 V), excellent 1-p.e. resolution and PDE
- Suitable for compact and fine-resolution Cherenkov cameras
- Low enough optical crosstalk (<5%) and UV sensitivity by removing protection resin

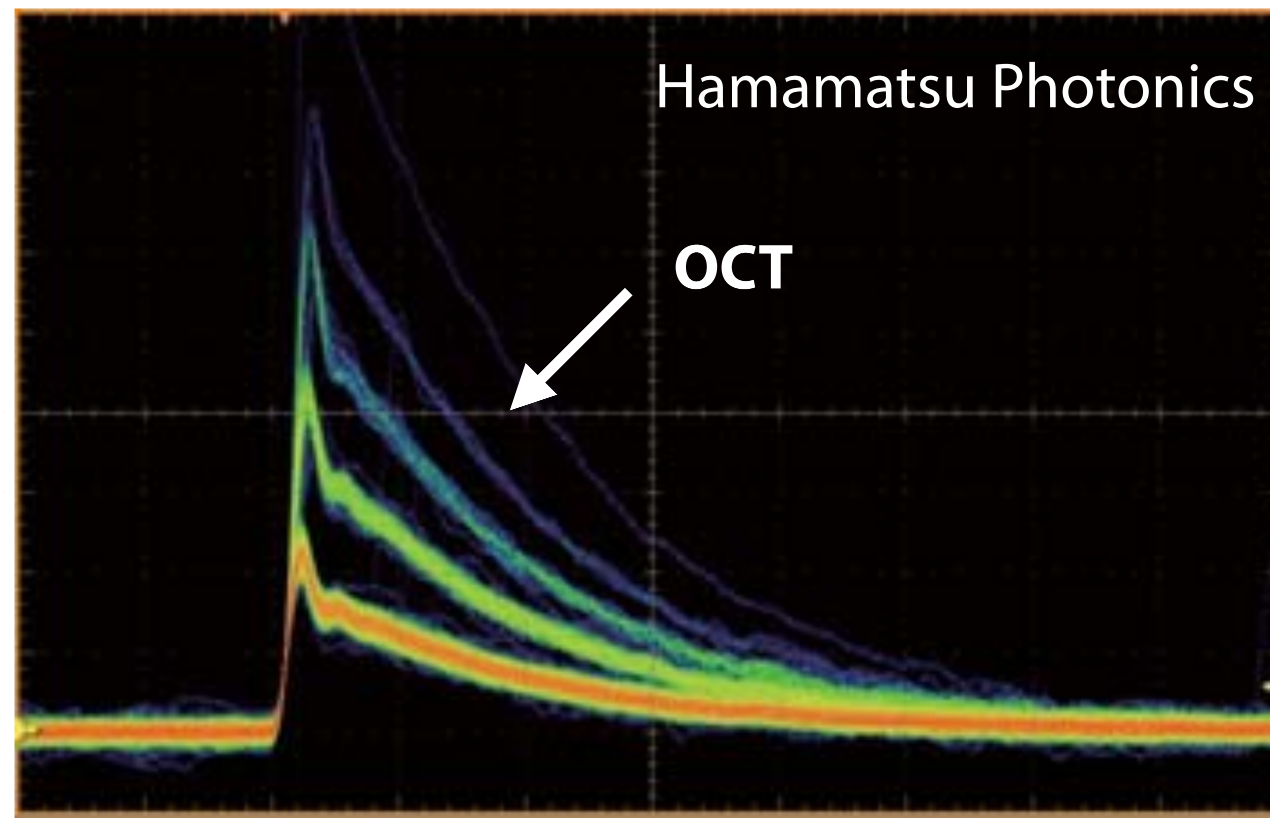
Optical Crosstalk (OCT)

PDE (405 nm) v.s. OCT at various operation voltages

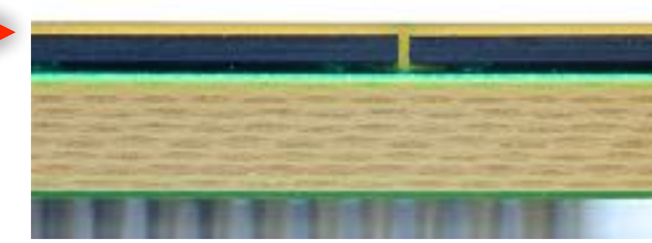


Asano et al. (2018)

Old type SiPM (around 2013)

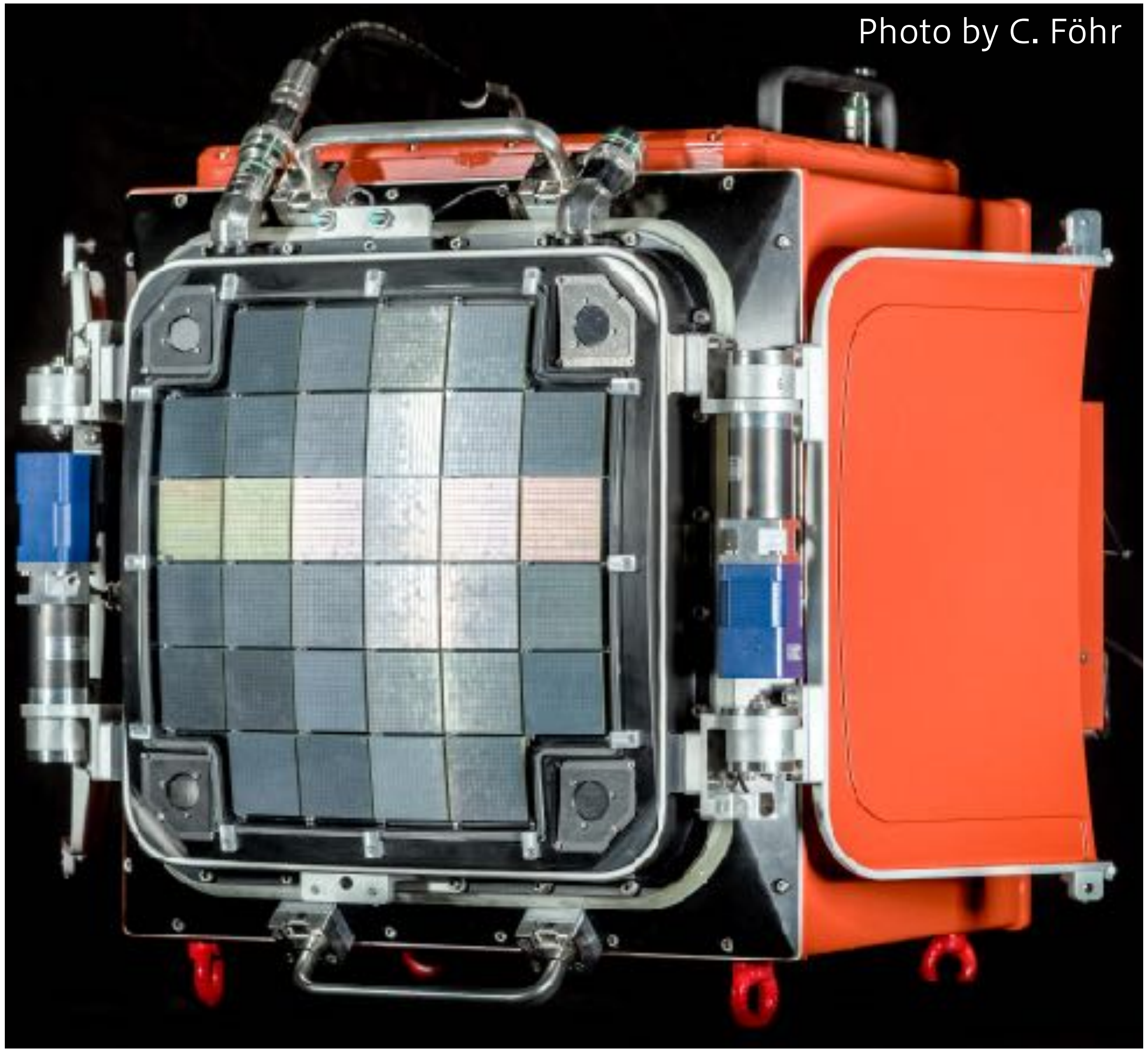


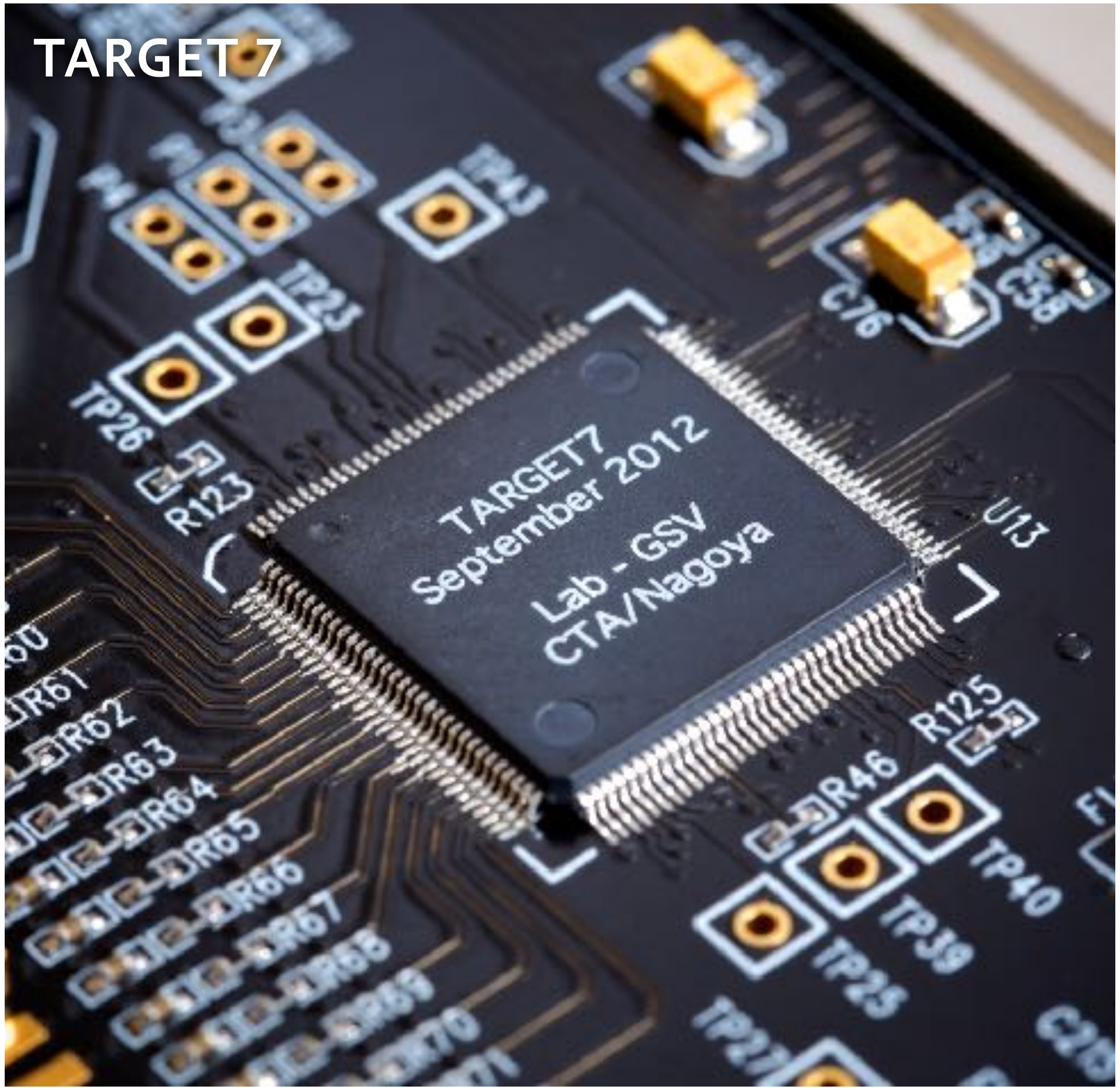
resin coating



- Single photons detected by a SiPM often behave like multi-p.e. signal
- Was a critical drawback of SiPMs, but recent products for CTA have very low OCT rate (< 5%) (Hamamatsu LVR2 generation, resin removal) with high PED being kept
- OCT to neighboring pixels was also reduced by removing the resin coating

TARGET ASIC Family

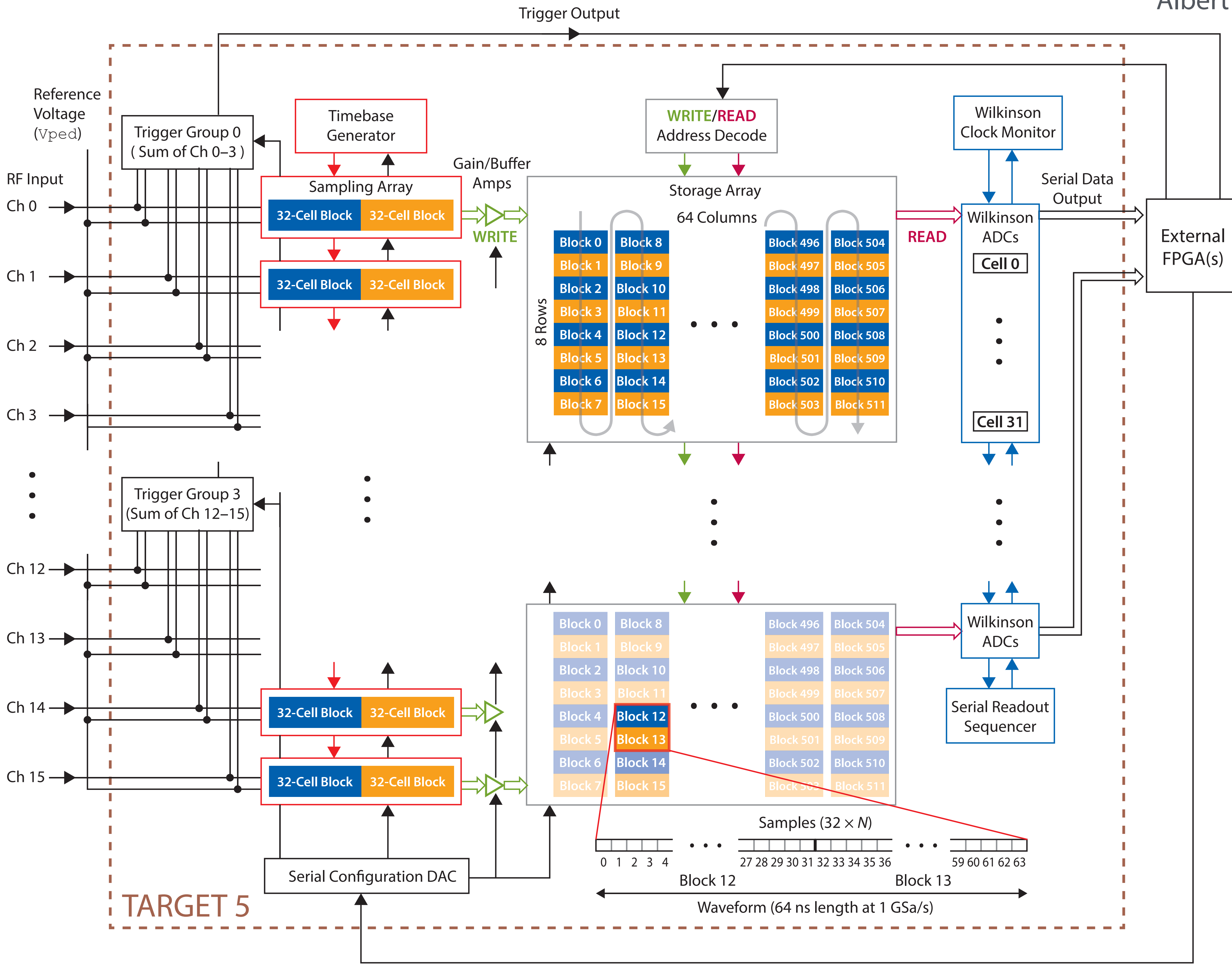




- Application specific integration circuit (ASIC) for compact and modular Cherenkov cameras (designed by Gary Varner @ Univ. Hawaii)
- 16-ch waveform sampling (1 GSa/s) and trigger (~2.4 mV thd) on a single or separate chips, bandwidth of 500 MHz, ~2 (V) / 11 bits dynamic range
- ~20 USD per channel (w/o SiPM) in CTA mass production

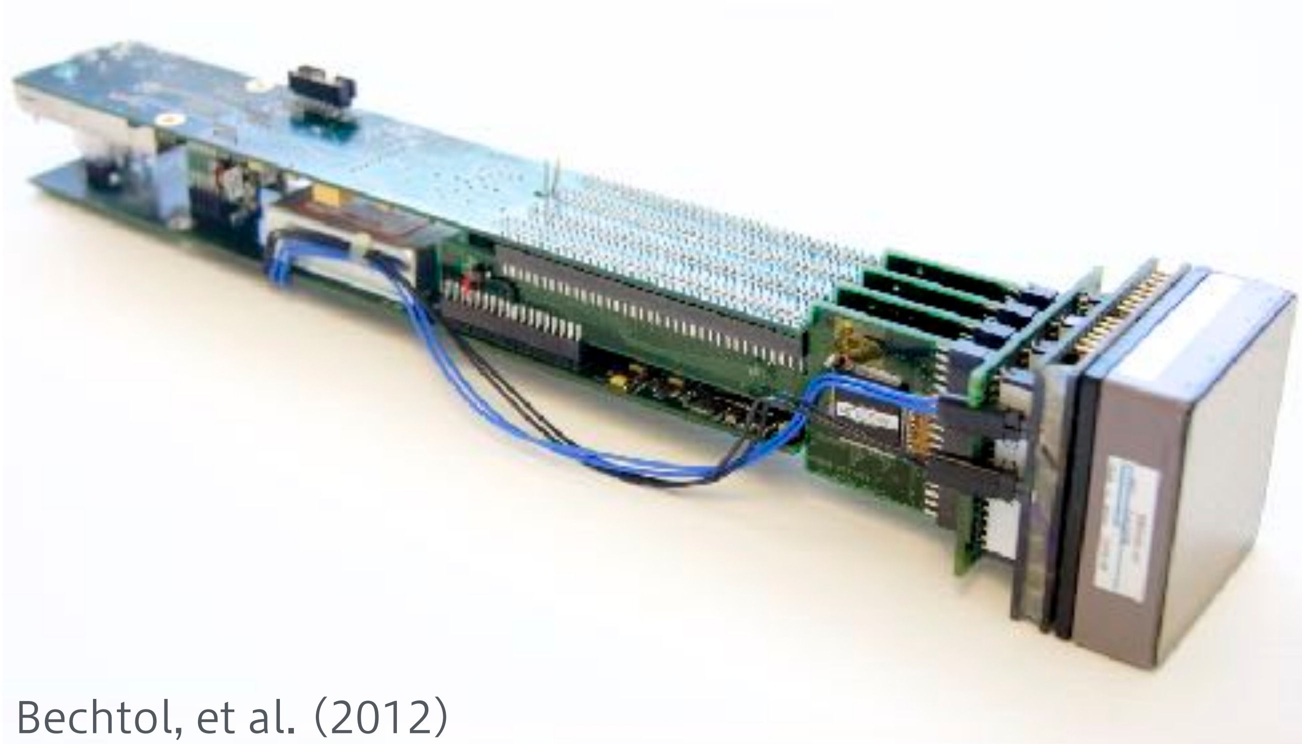
TARGET Quicklook

Albert et al. 2015



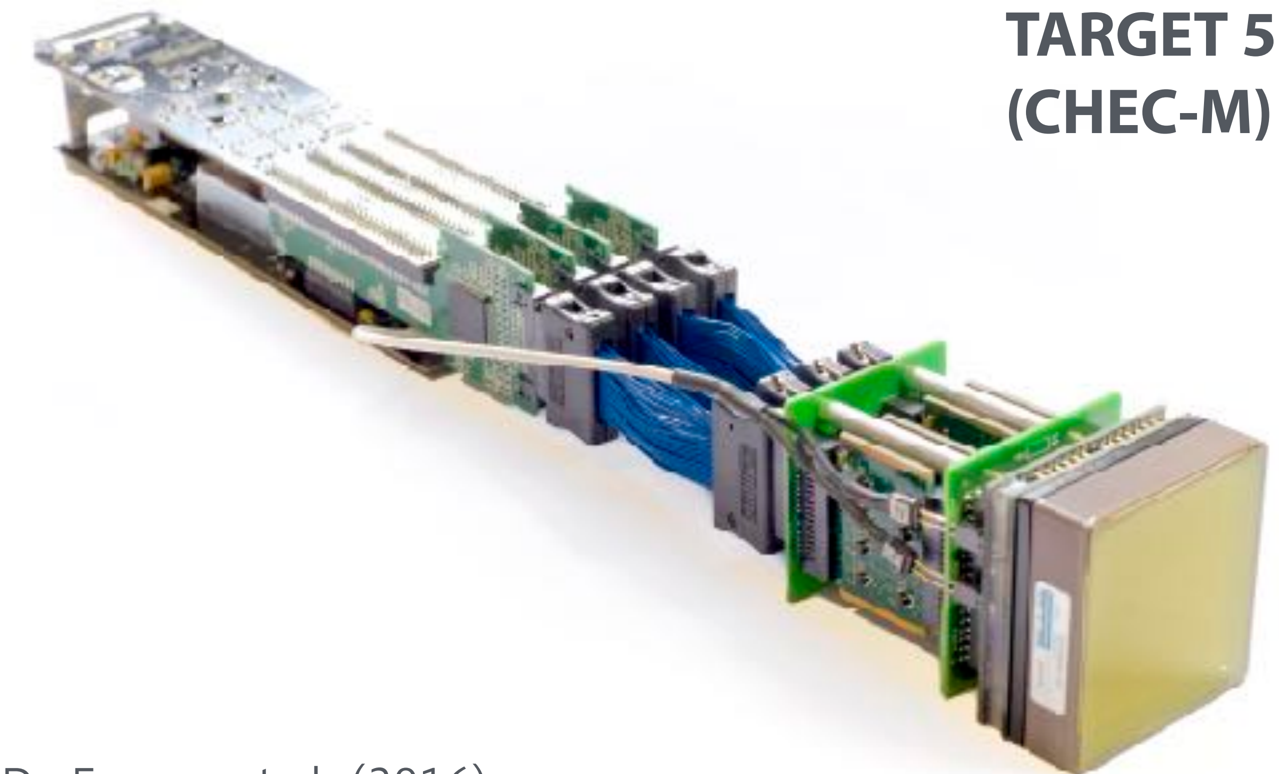
History of TARGET Camera Modules

TARGET 1



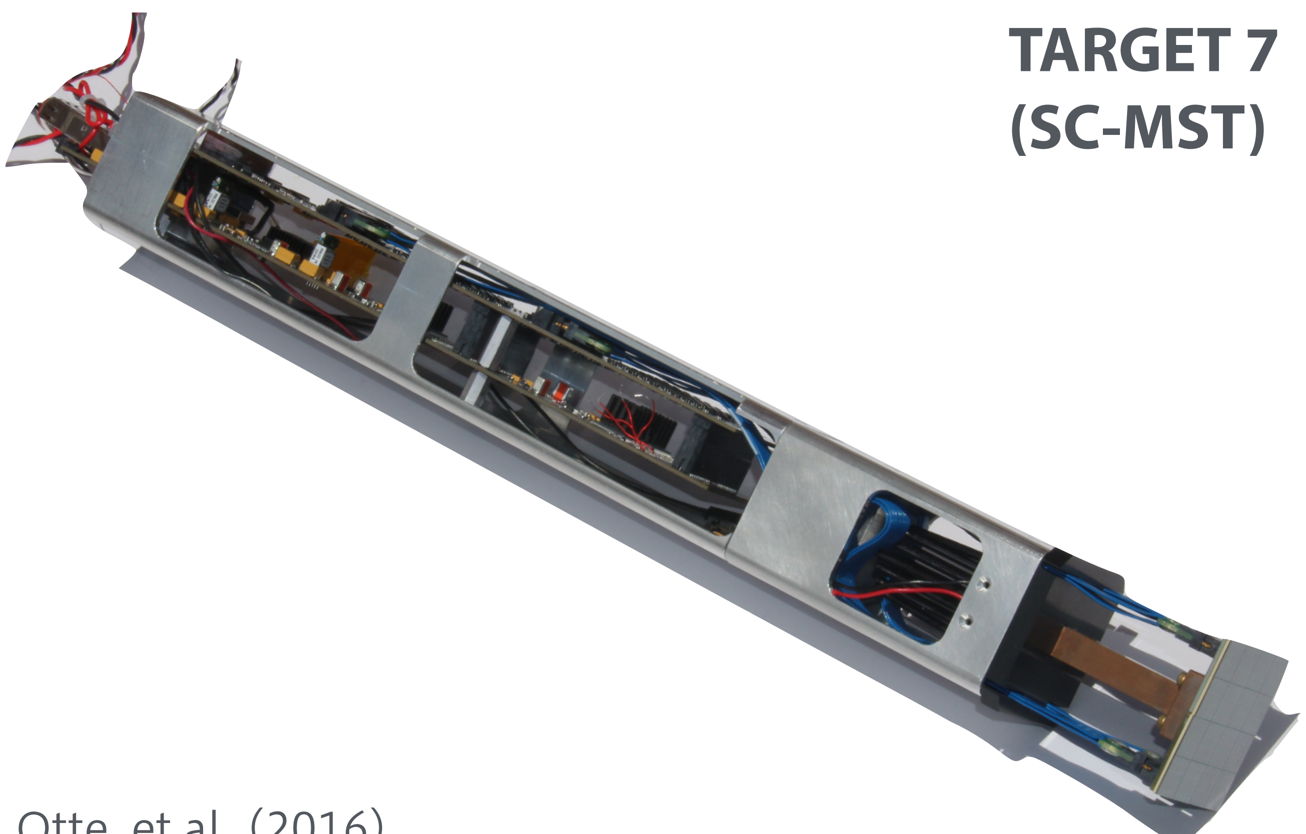
Bechtol, et al. (2012)

TARGET 5 (CHEC-M)



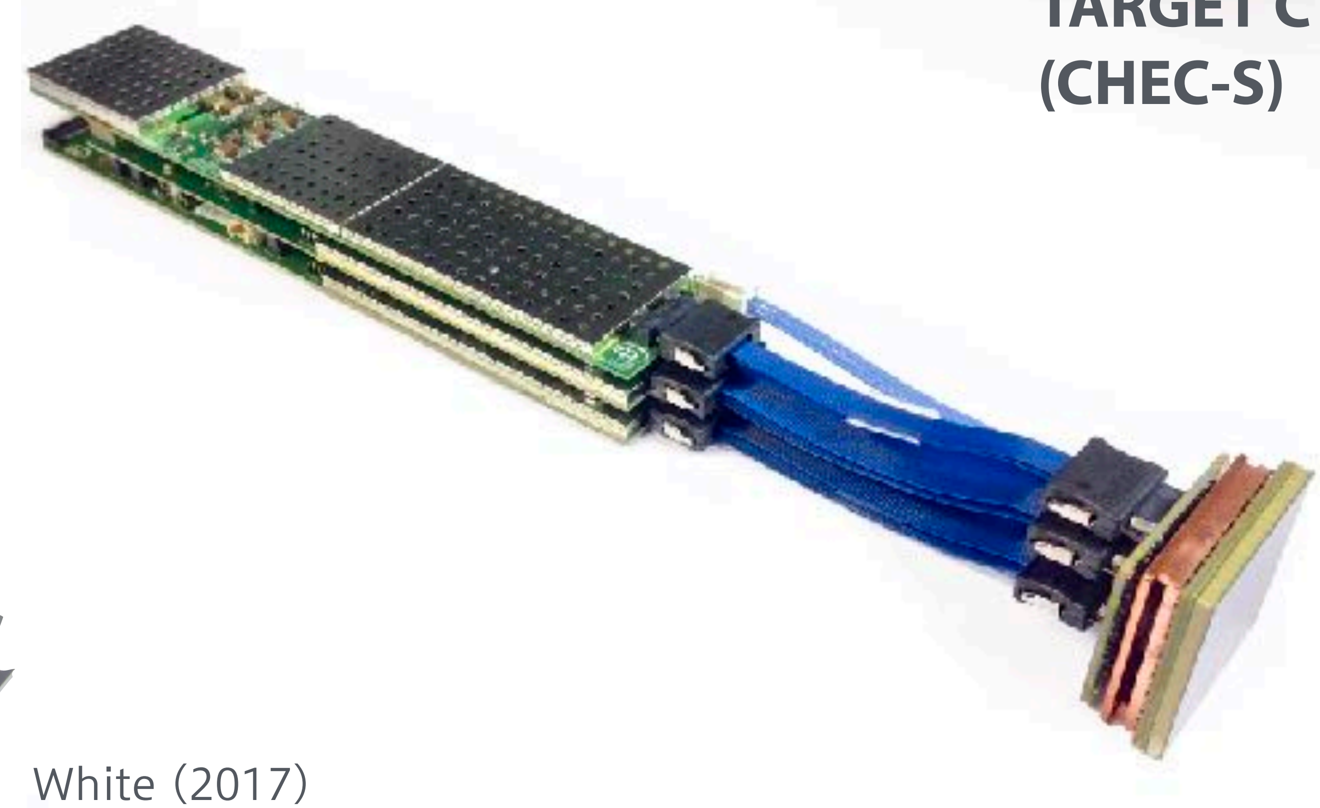
De Franco, et al. (2016)

TARGET 7 (SC-MST)



Otte, et al. (2016)

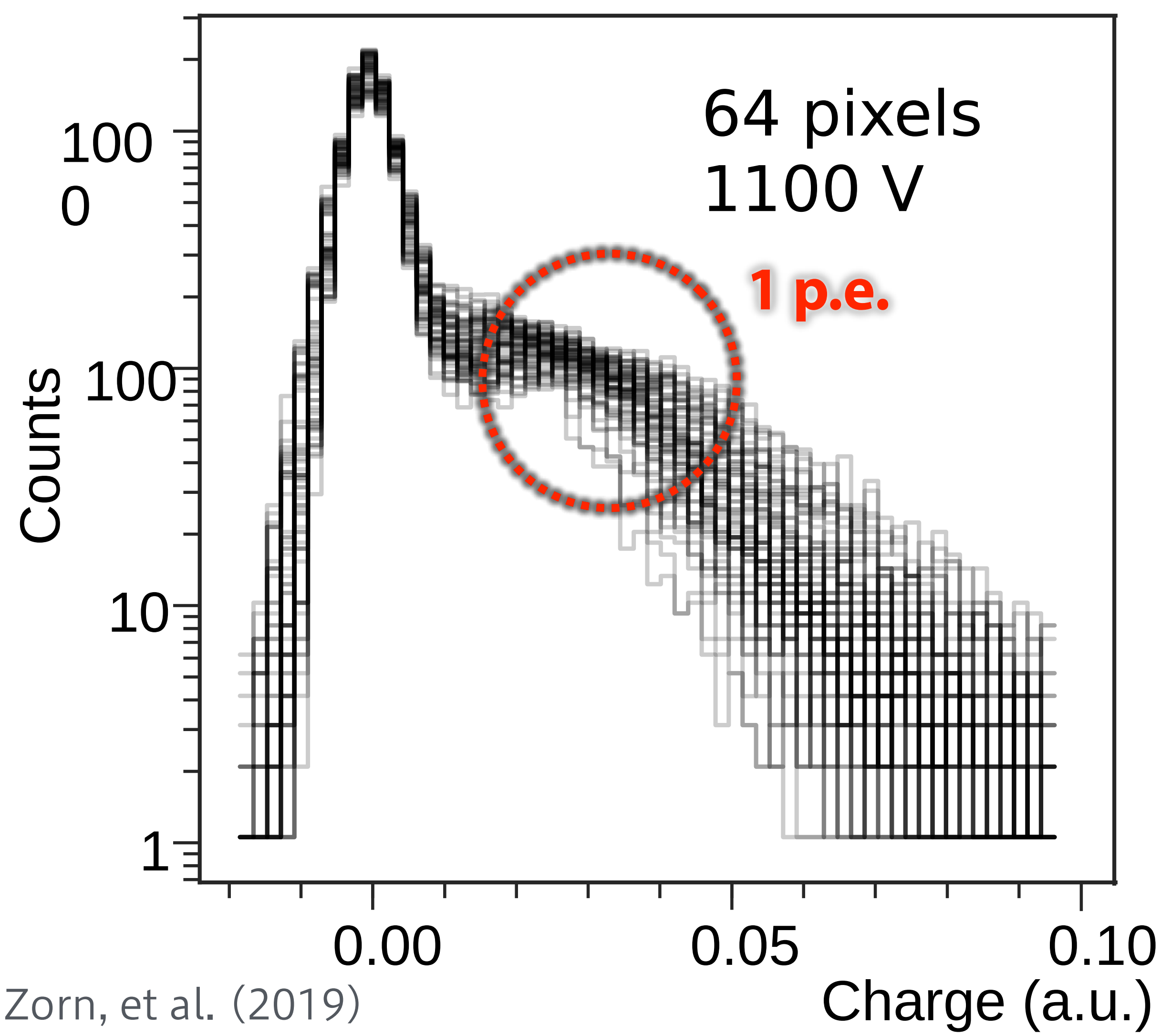
TARGET C (CHEC-S)



White (2017)

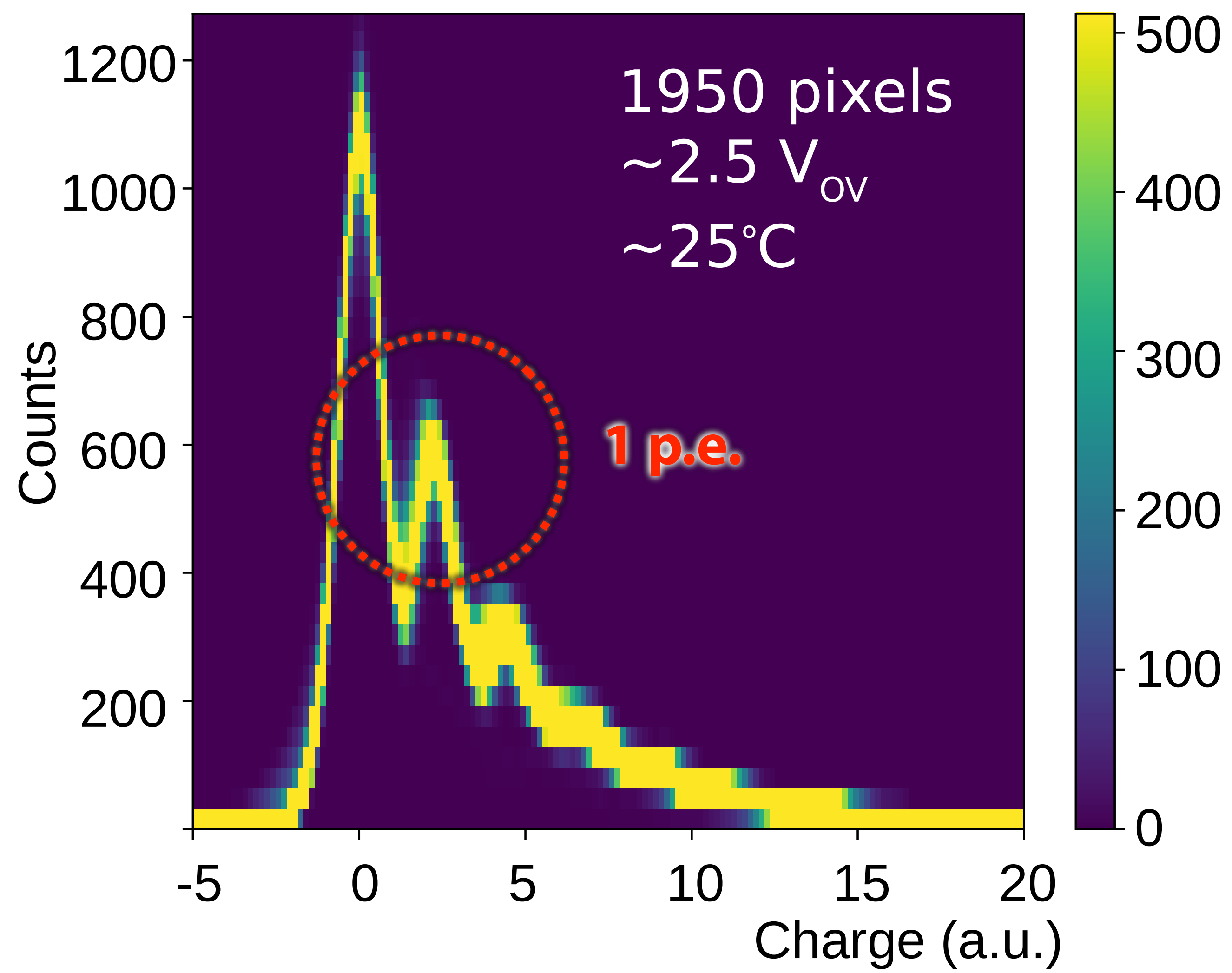
Performance Example

MAPMT-based Prototype (with TARGET 5)



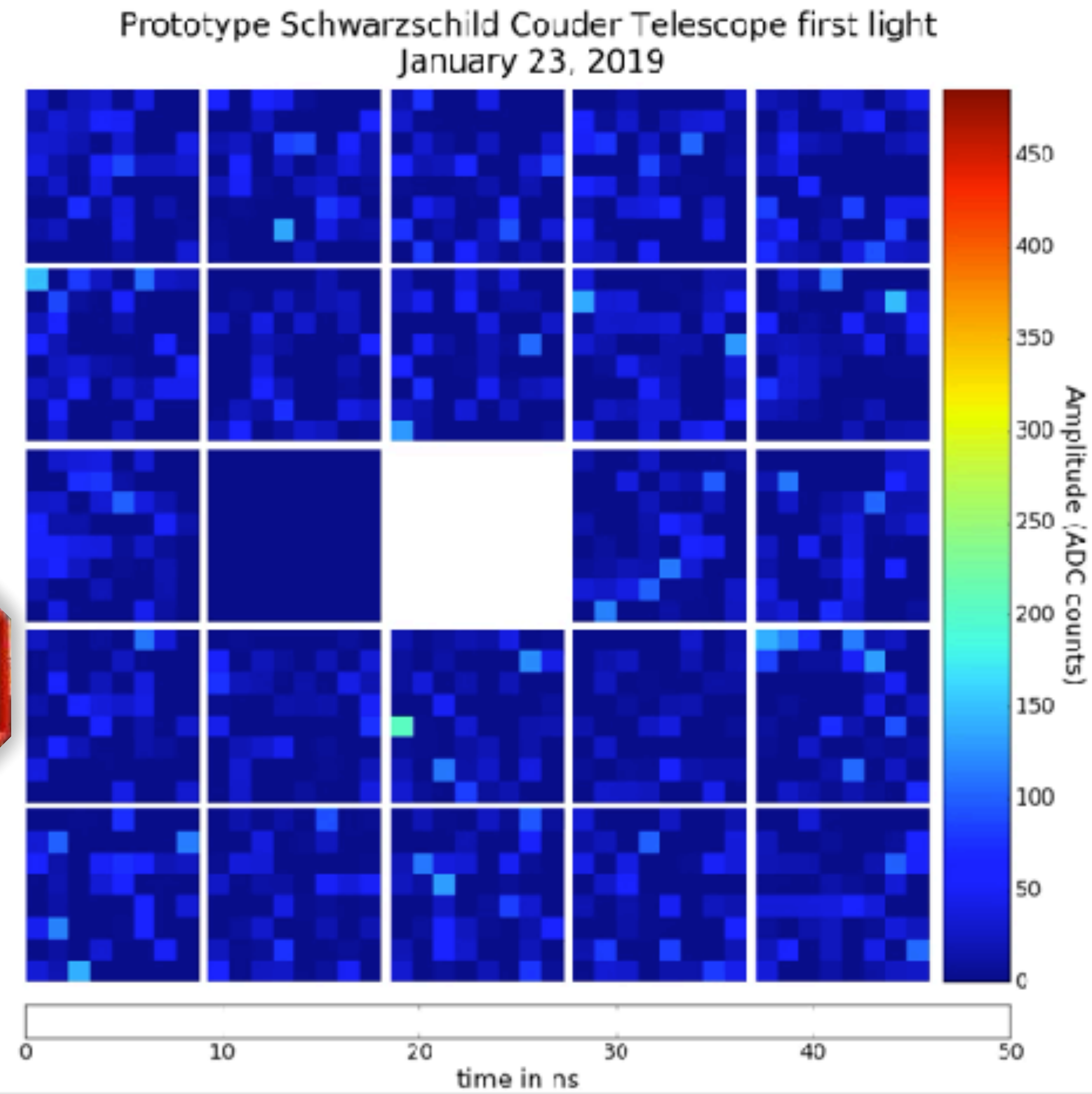
Zorn, et al. (2019)

SiPM-based Prototype (with TARGET C)



- MAPMTs: bad 1-p.e. peak, ~50% gain non-uniformity, fragile, require high voltage ~1000 (V)
- SiPMs: much better 1-p.e. separation, uniformity, light-weight, low voltage ~50 (V)

Schwarzschild–Couder MST First Light on Jan 23



- Completion of the aspherical primary and secondary mirrors in 2018
- Achieved first light with a partially populated SiPM camera on Jan 23, 2019
- Seven times large area will be populated to cover the full 8-deg FOV

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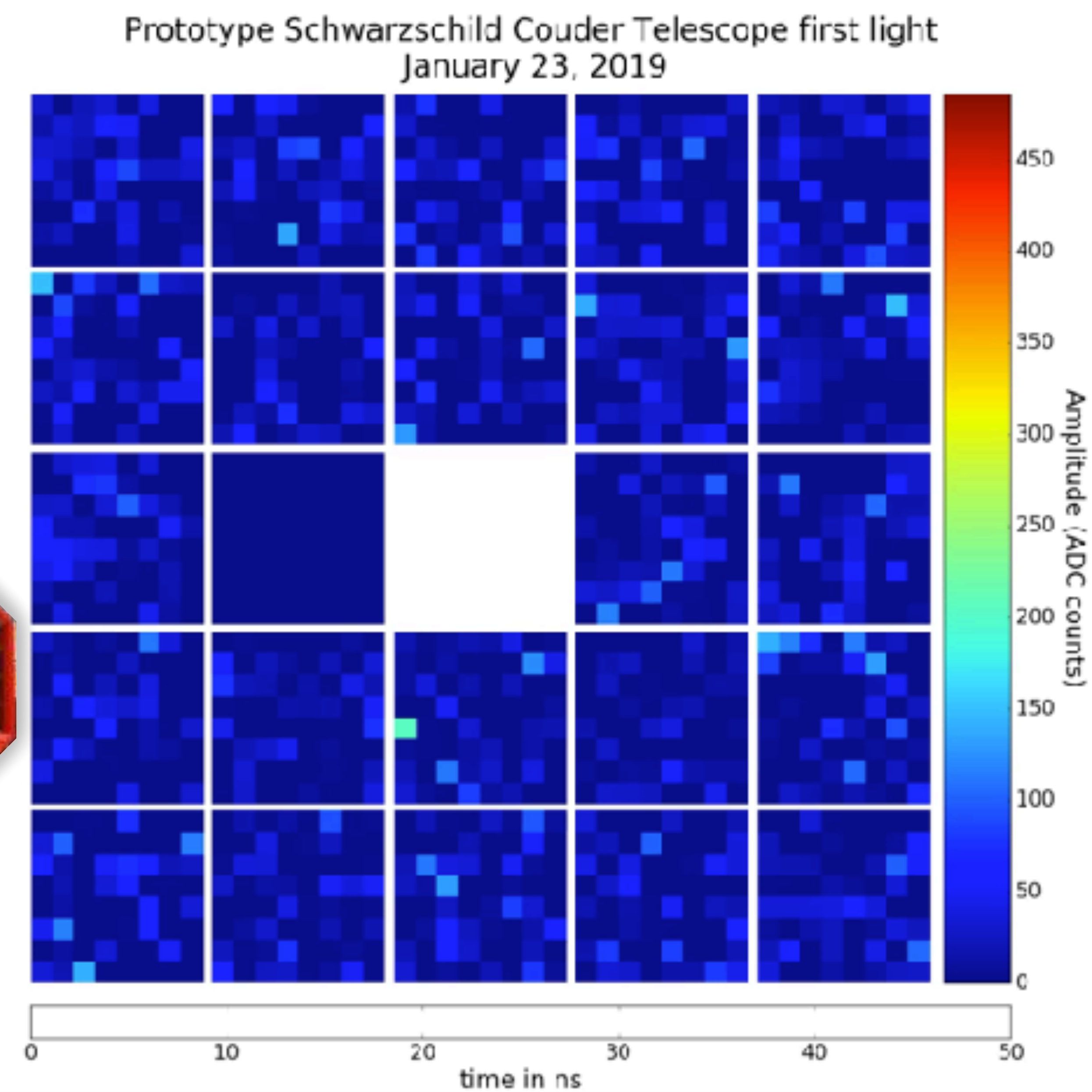

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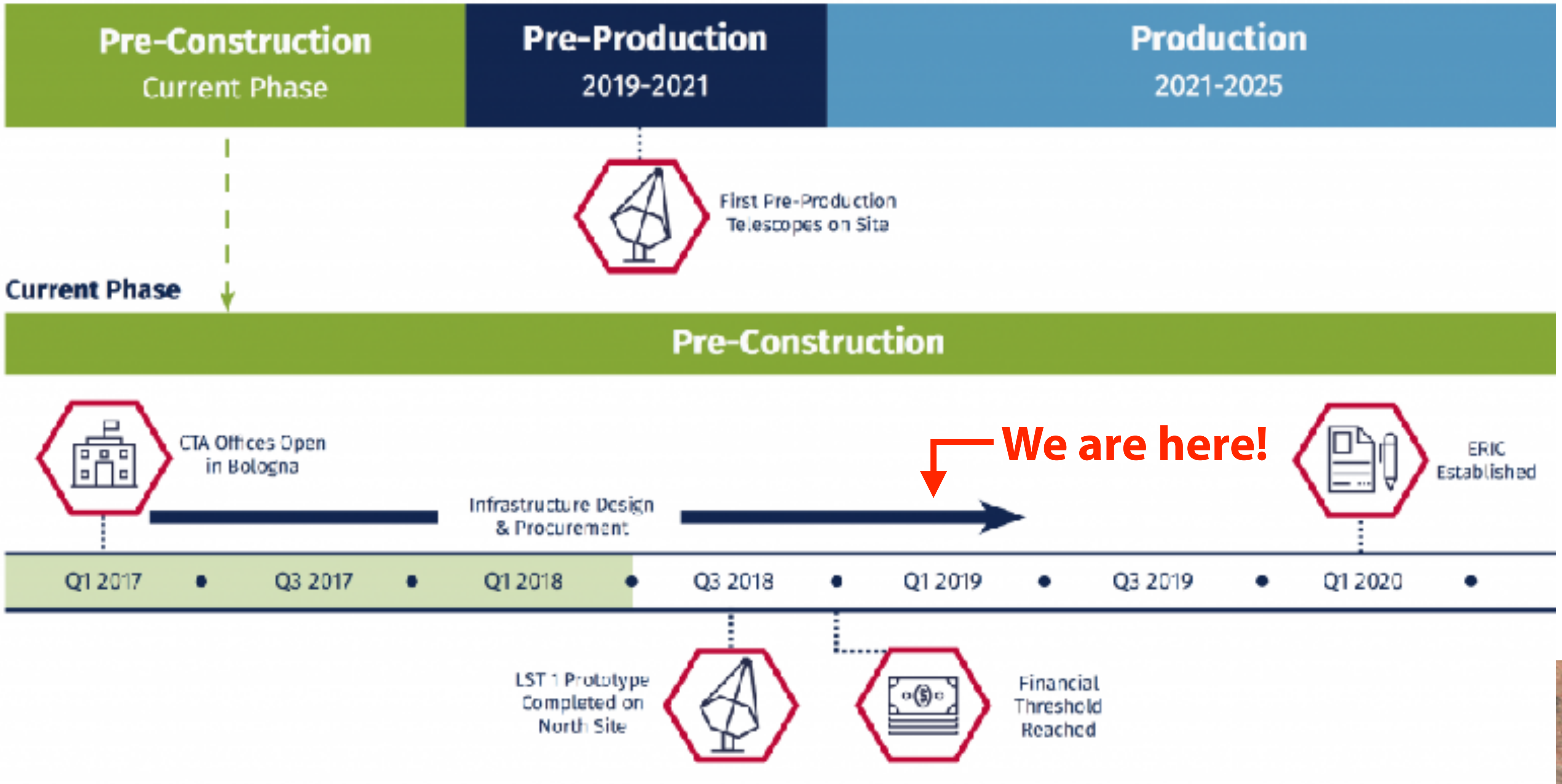
SST Harmonization

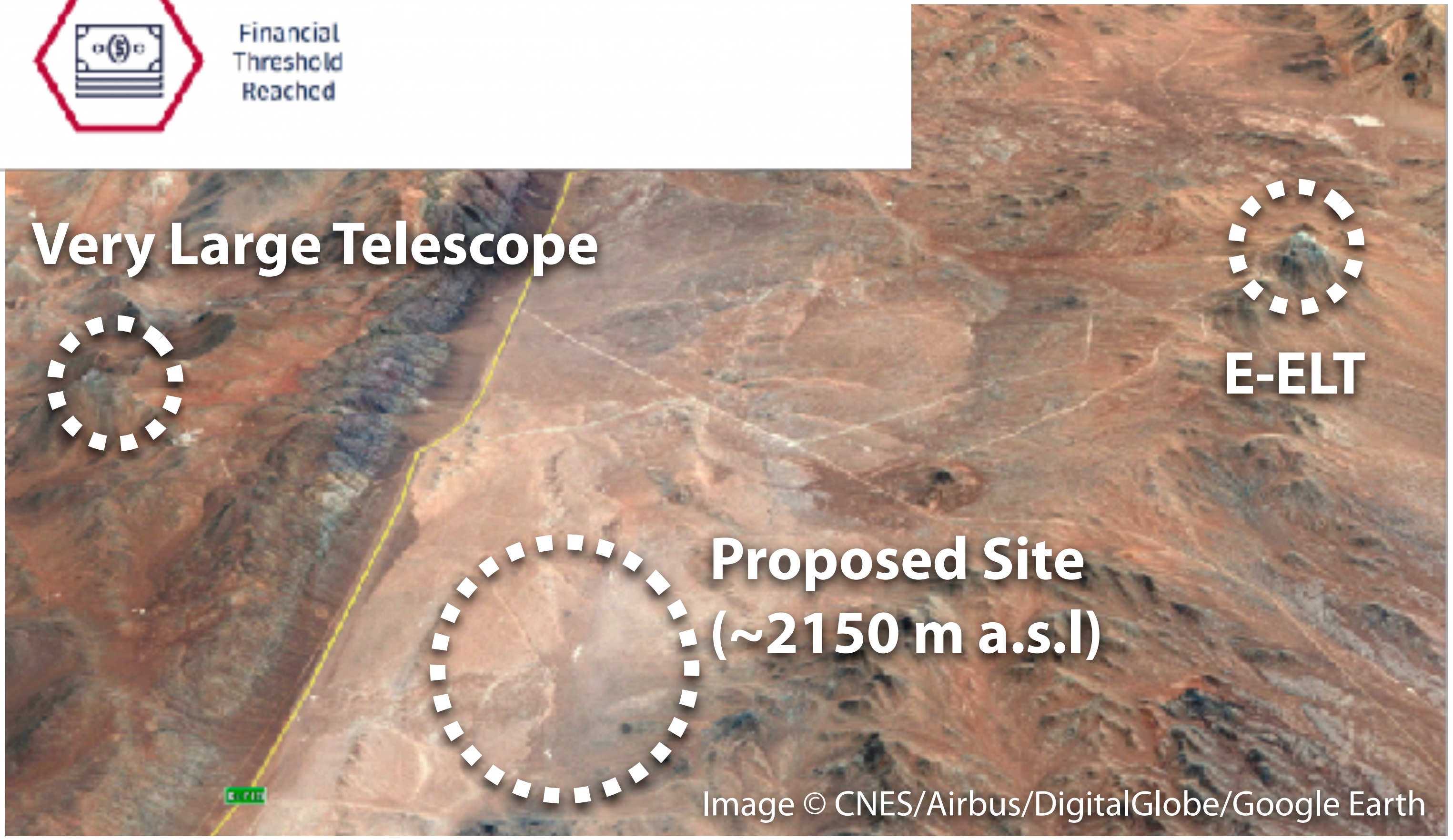
- Three different approaches are matured and have verified the concept of SSTs
- But it is time to consolidate the optics and camera designs before SST pre-production phase
- “SST harmonization” process started in May 2018 to simplify the southern array with easier maintainability and less construction cost

- Final SST design proposals have been submitted Oct 2018
- Review and evaluation of “the” final SST design will follow in 2019

Timeline



- Site hosting agreement for CTA south **signed**



ASTRI Mini Array

- 9 ASTRI telescopes proposed (and approved by INAF) to be built as ASTRI Mini Array in parallel to the SST harmonization
- Stereo imaging, array trigger, array control etc. will be thoroughly tested
- ASTRI and GCT cameras can be mounted

Summary

- CTA Small-Sized Telescopes will explore the highest-energy gamma-ray frontier from the ground
  - Core energy coverage of 5–300 TeV
  - 70 telescopes in CTA South
  - Wide-FOV optical system and SiPM camera
  - PeVatrons and cosmic-ray origins
- Three SST designs; GCT, ASTRI, and SST-1M
  - Verified their functionalities in labs and by first light
  - Harmonization process is ongoing
  - Bigger single SST group will be formed and quickly move toward pre-production and completion
- New technologies developed in the CTA SSTs and Schwarzschild–Couder-MST will also help realization of future telescopes and observatories