Development Status of CTA Small-Sized Telescopes

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Nagoya University

"The extreme Universe viewed in very-high-energy gamma rays 2023"
Feb 19–20, 2024 @ Kashiwa Campus, Univ. Toyo

名古屋大学
NAGOYA UNIVERSITY

ISEE Institute for Space–Earth Environmental Research

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

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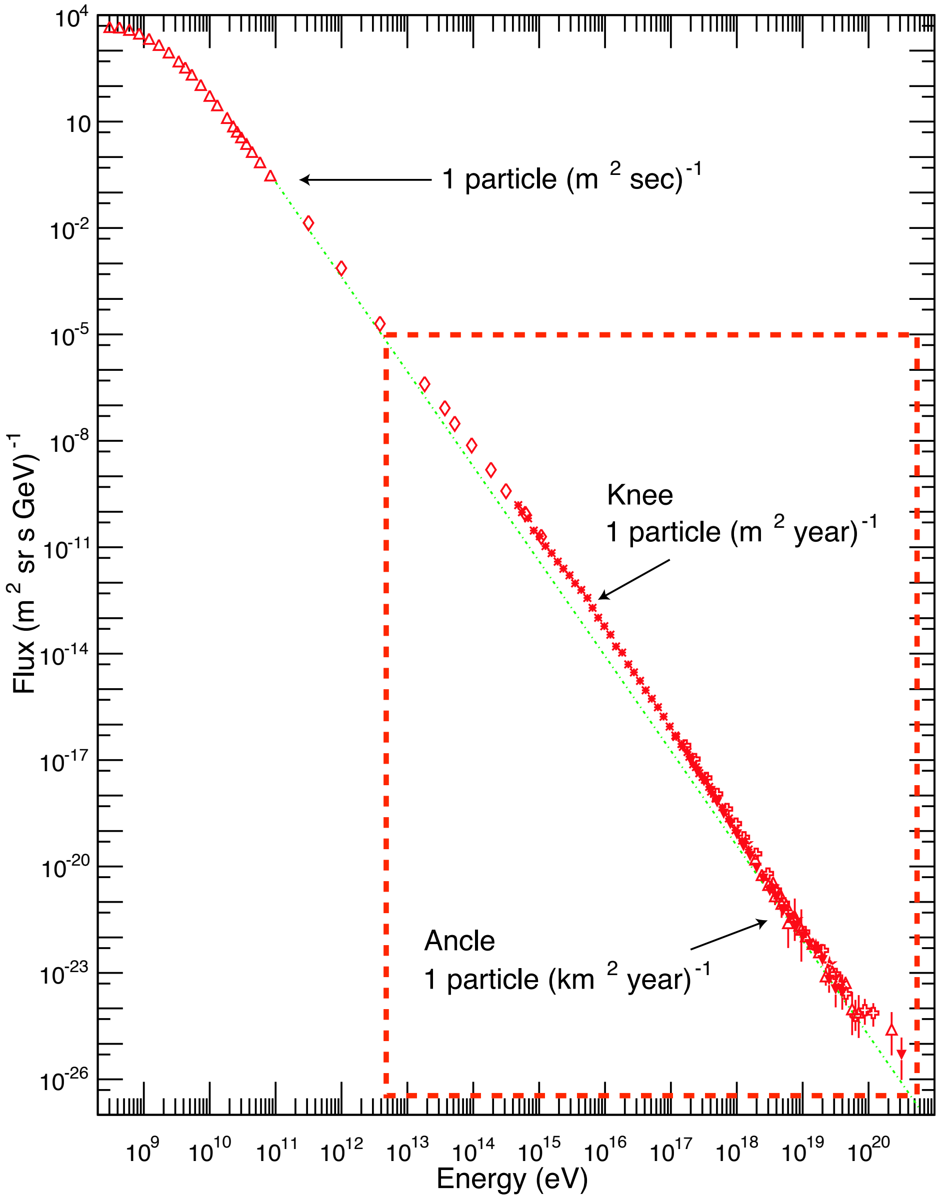
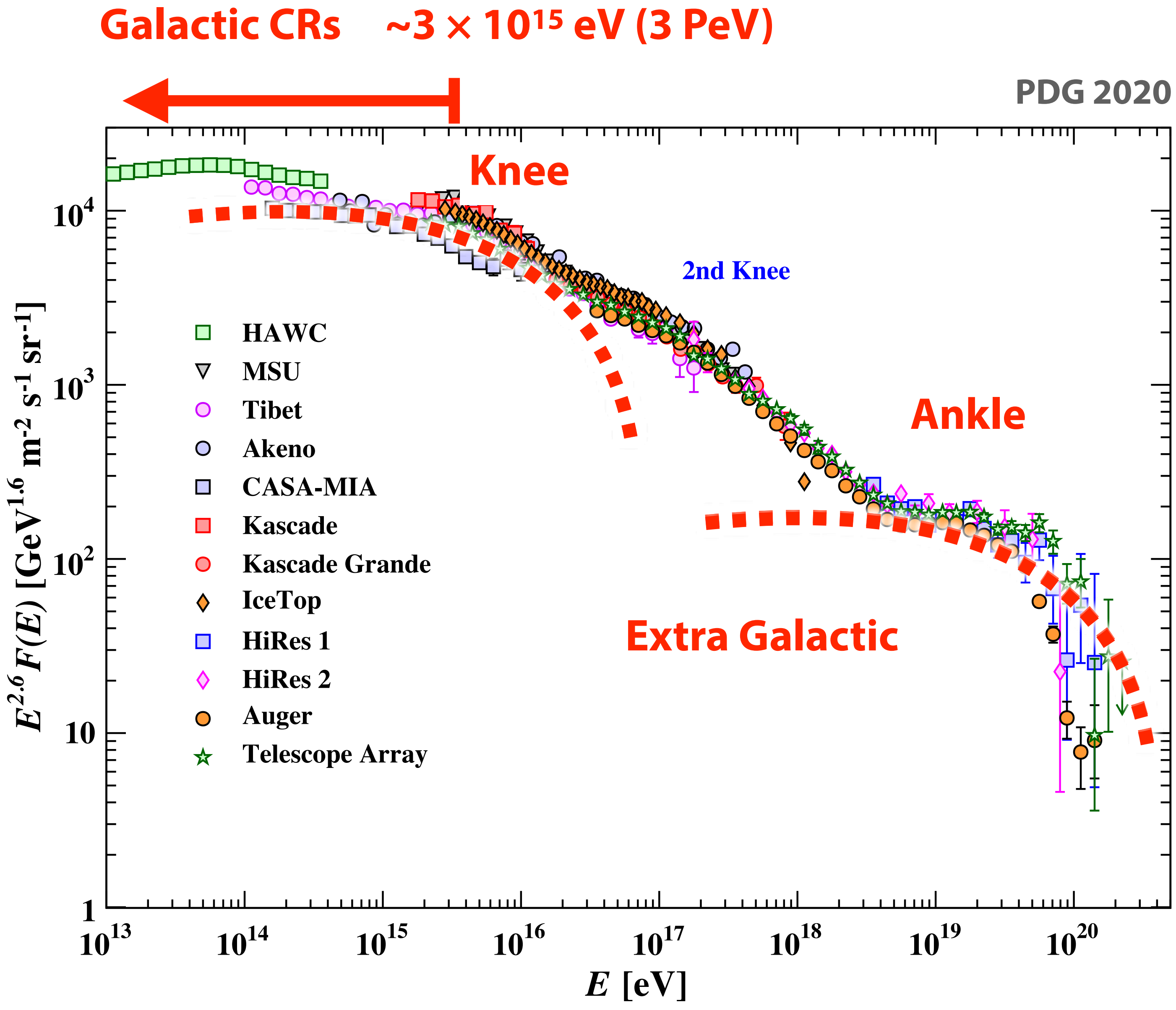
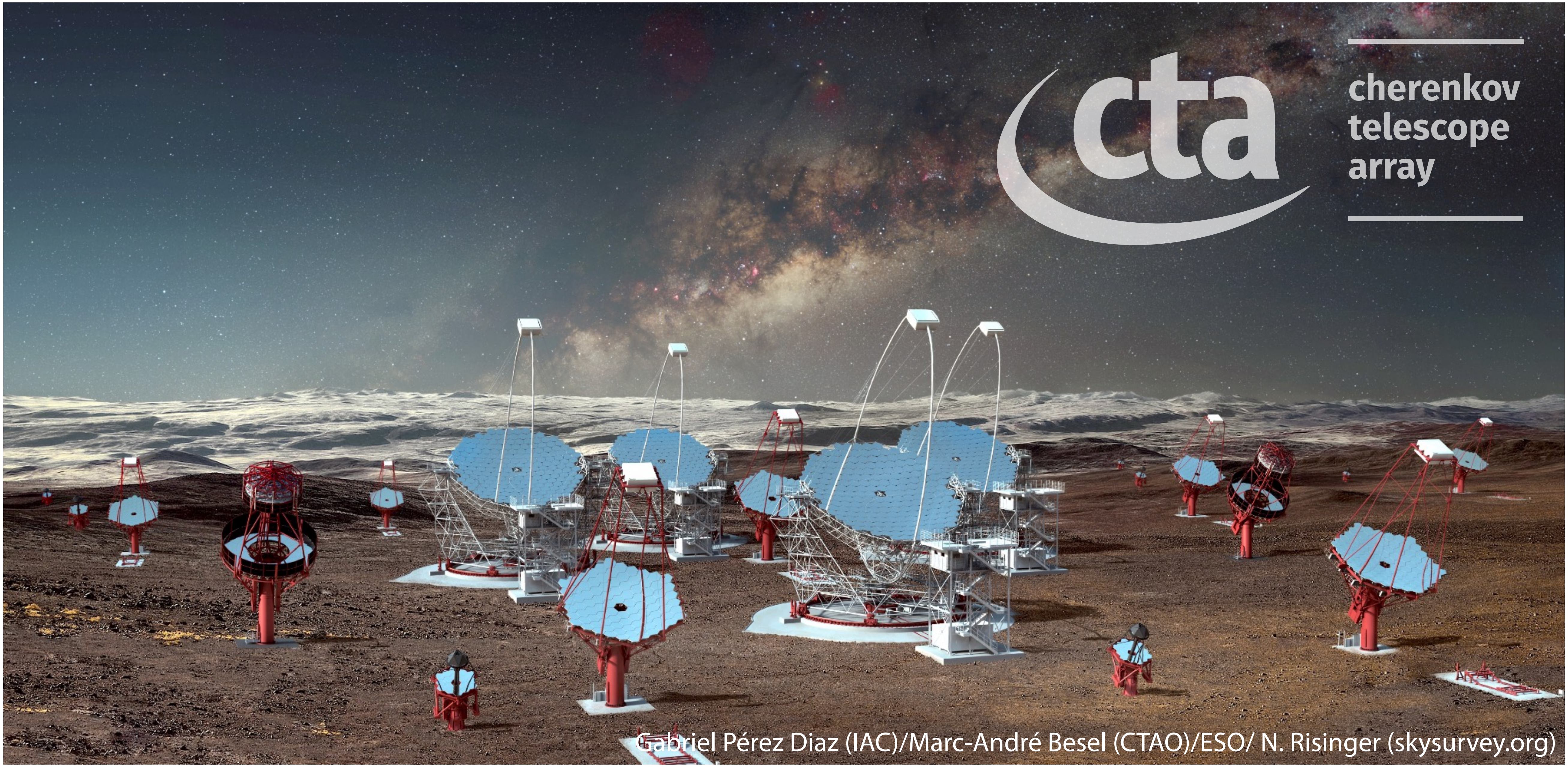
(Hadronic) Cosmic-ray Spectrum at Earth


Modified Cronin+ (1997)



- ~10^8 eV (~100 MeV) to > 10^{20} eV, with a power law of $dN/dE = E^{-2.7}$ to $E^{-3.0}$
- Almost uniformly distribute over the sky (due to the magnetic fields)
- What is the origin (PeVatron) of Galactic CRs (< ~3 PeV)?
  Supernova remnants? Galactic center? $E^{-2.1}$ at the source?

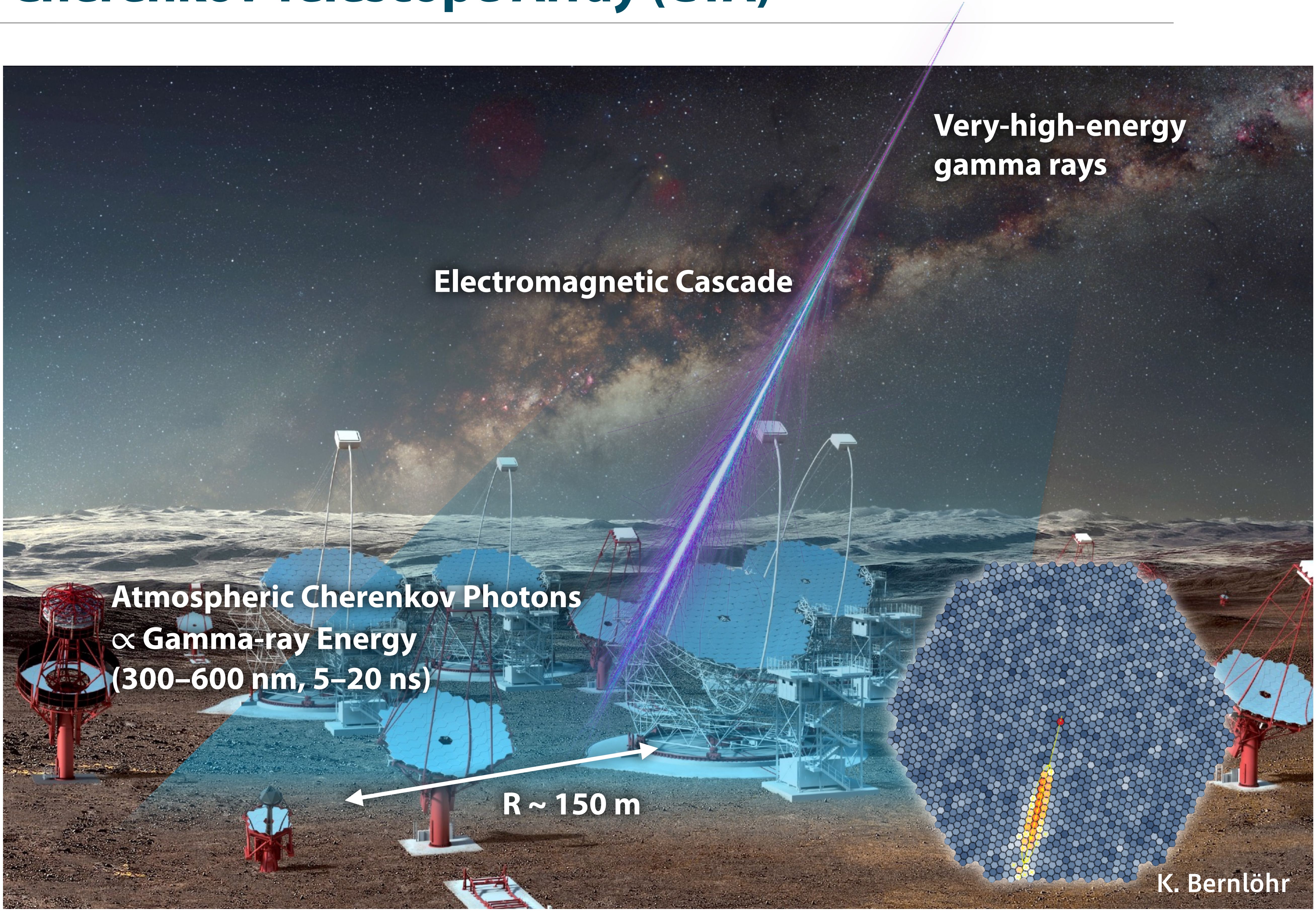
Cherenkov Telescope Array (CTA)



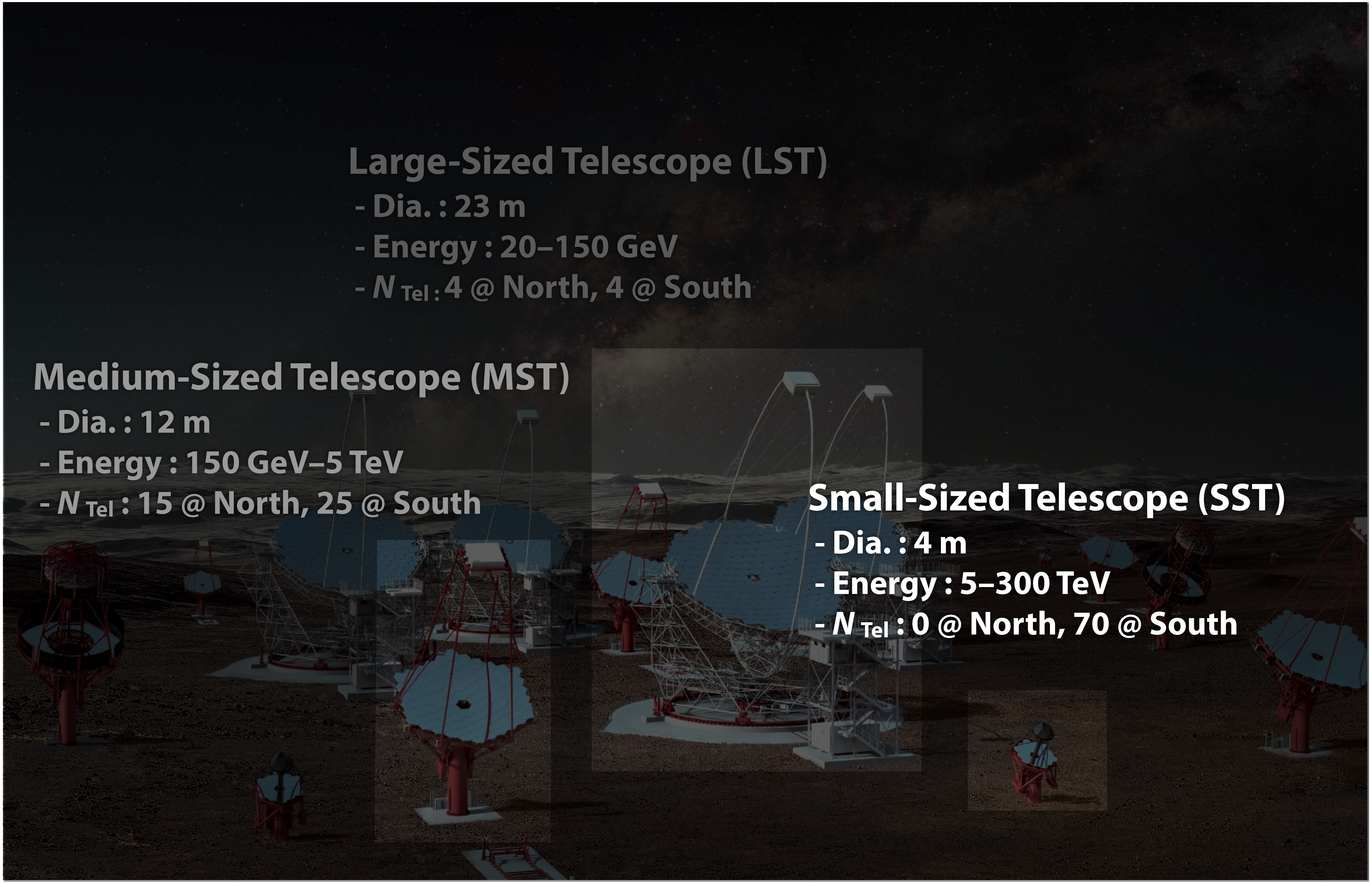
Gabriel Pérez Diaz (IAC)/Marc-André Besel (CTAO)/ESO/ N. Risinger (skysurvey.org)

- Next-generation ground-based gamma-ray observatory with ×10 better sensitivity
- Covering 20 GeV–300 TeV with 3 telescope designs
- High angular resolution of 0.02–0.05° above 10 TeV

Cherenkov Telescope Array (CTA)



Cherenkov Telescope Array (CTA)



Large-Sized Telescope (LST)

- Dia. : 23 m
- Energy : 20–150 GeV
- N_{Tel} : 4 @ North, 4 @ South

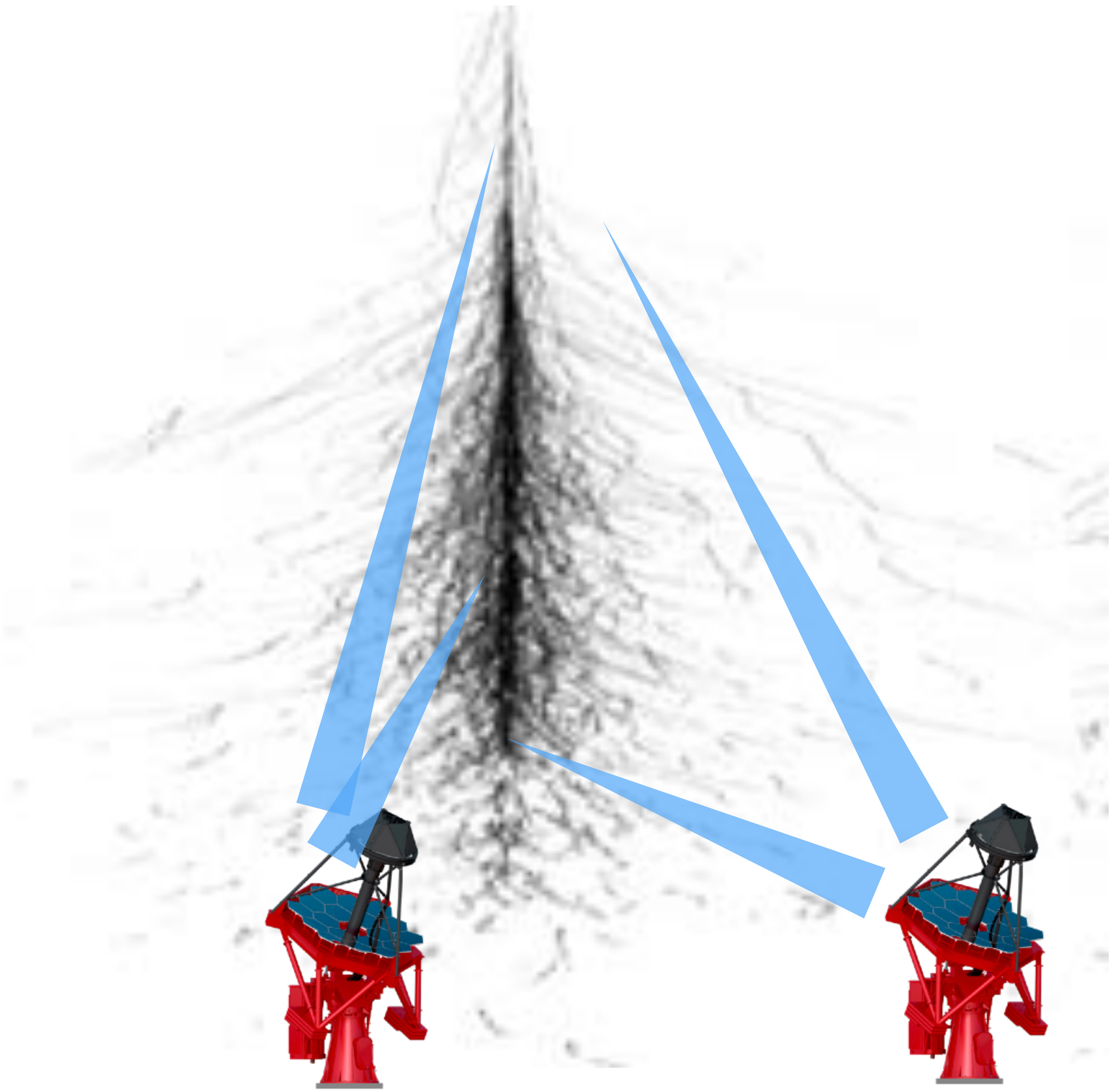
Medium-Sized Telescope (MST)

- Dia. : 12 m
- Energy : 150 GeV–5 TeV
- N_{Tel} : 15 @ North, 25 @ South

Small-Sized Telescope (SST)

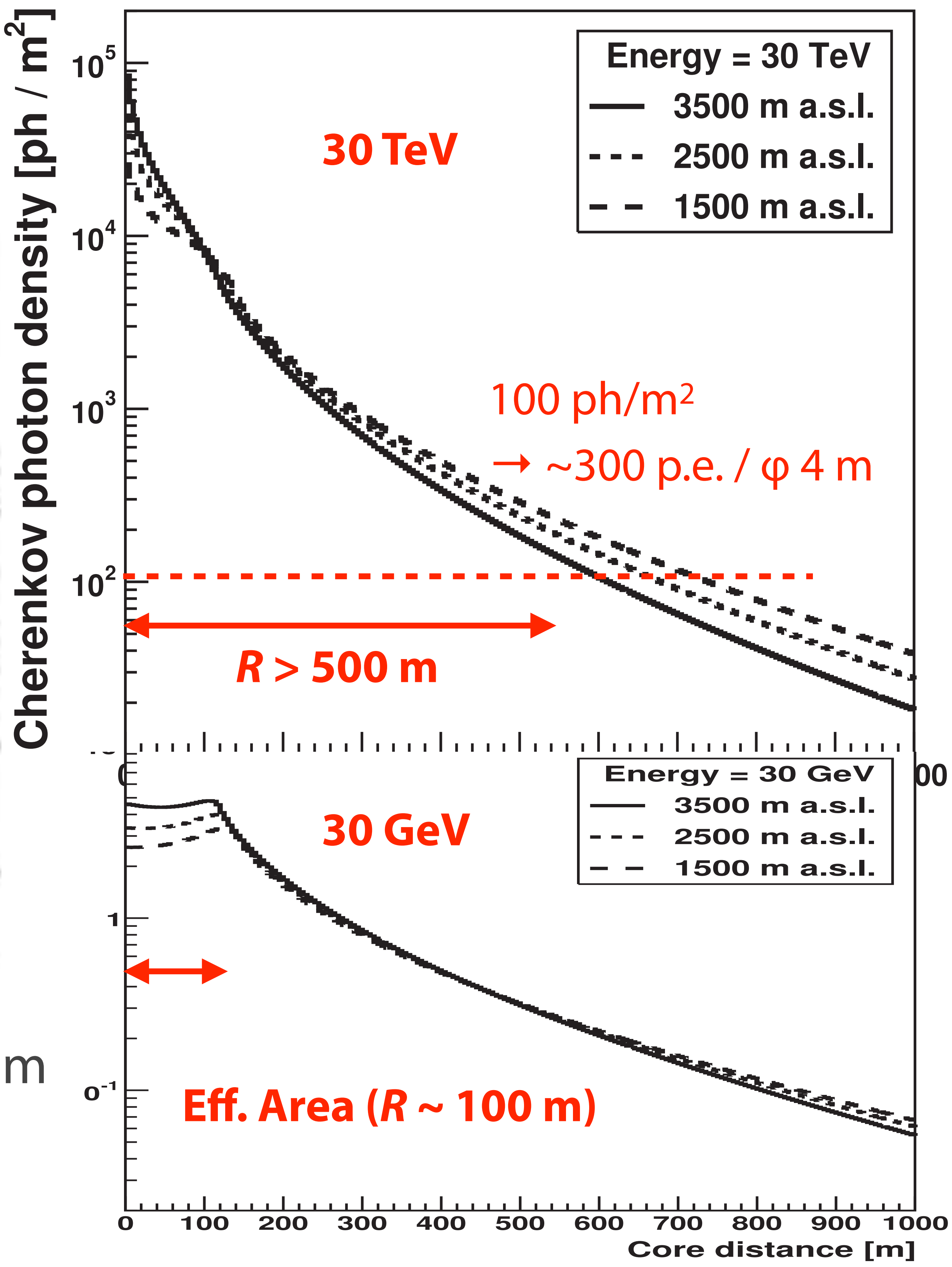
- Dia. : 4 m
- Energy : 5–300 TeV
- N_{Tel} : 0 @ North, 70 @ South

Effective Area for > 10 TeV Photons



- Long tail of Cherenkov photons > 500 m
- Large FOV is required due to scattered electrons

Hassan et al. 2009



30 TeV

100 ph/m^2

→ ~300 p.e. / φ 4 m

R > 500 m

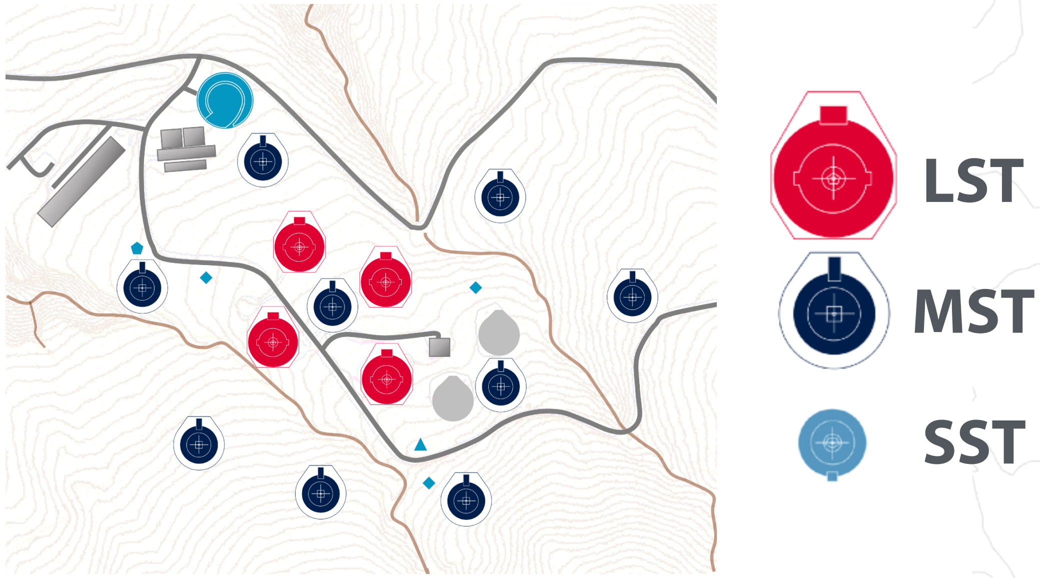
30 GeV

Eff. Area (*R* ~ 100 m)

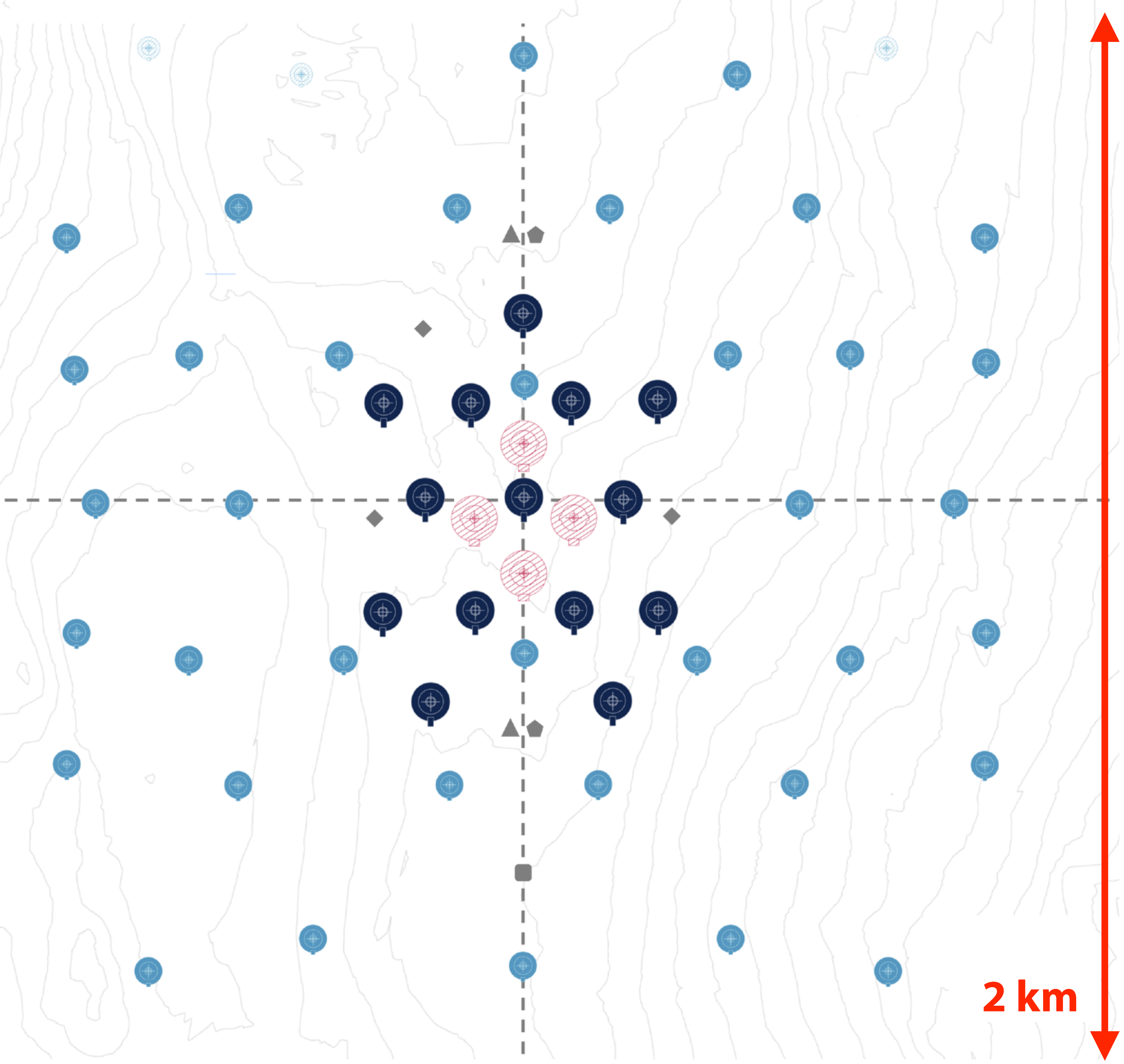
CTA Northern & Southern Sites (Initial Configuration)

CTA North: La Palma, Spain


Image Credit: G. Pérez, IAC, SMM



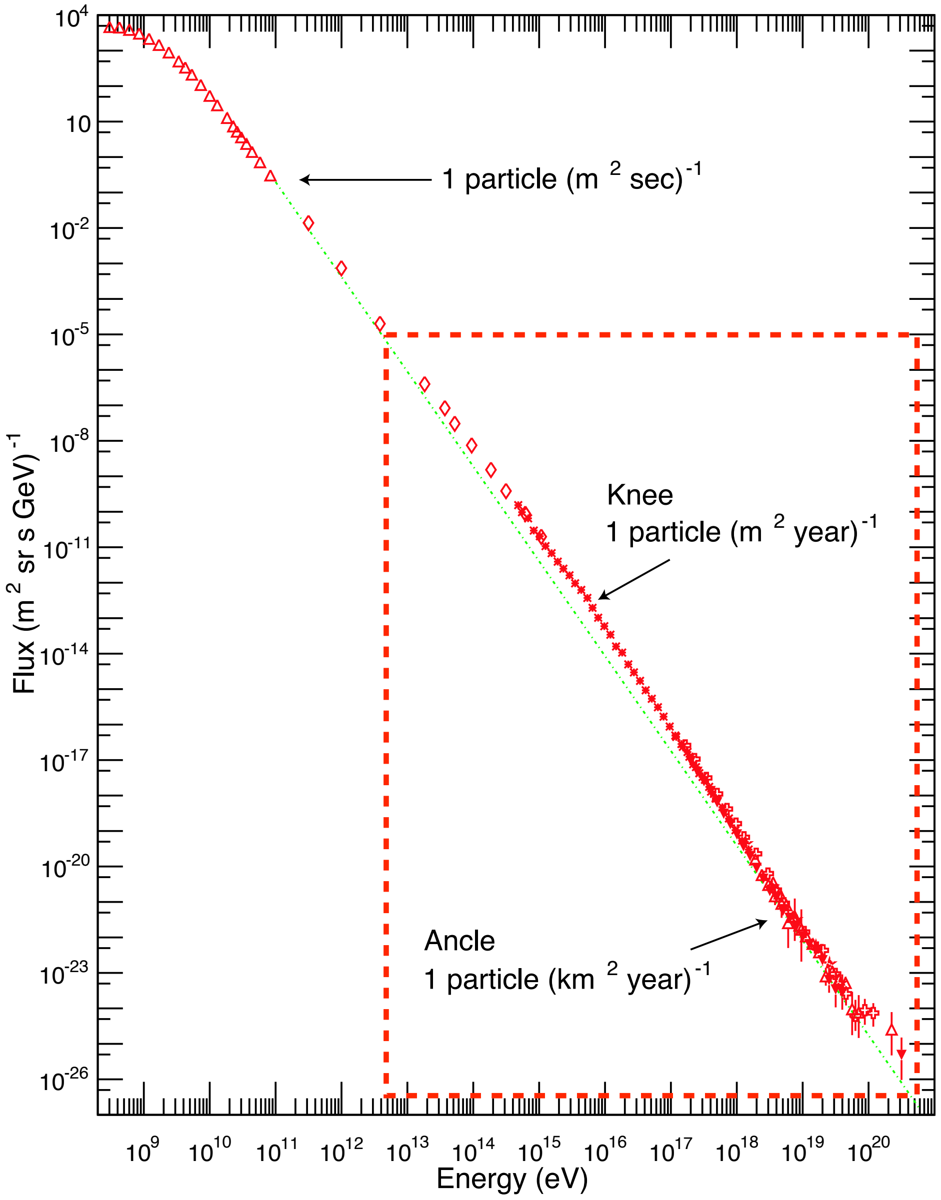
CTA South: Paranal, Chile



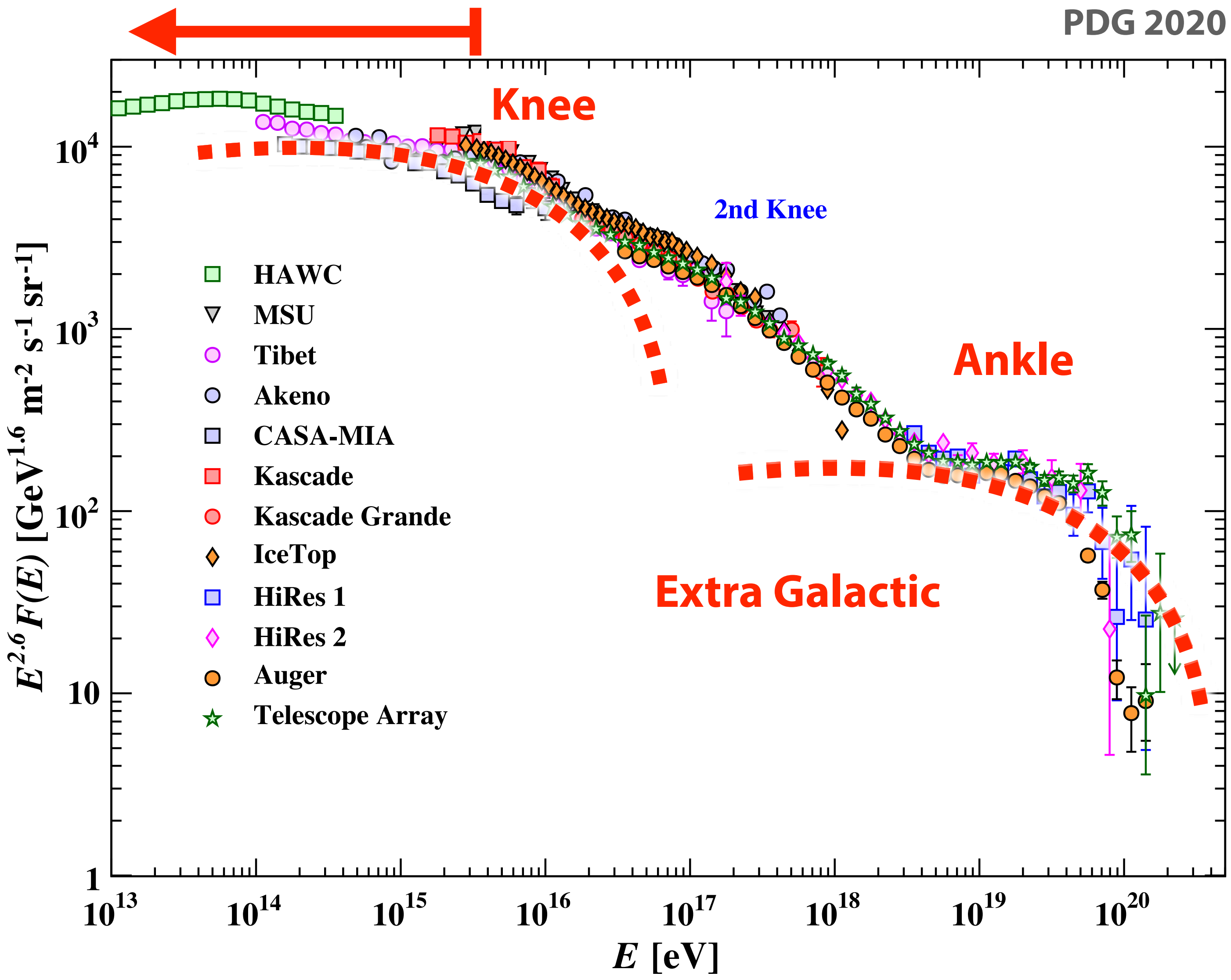
- Wide energy coverage of 20 GeV–300 TeV with three telescope sizes
- Spread over a few km^2 area to catch Cherenkov photons anywhere in the circle
- Construction phase to start with 4 LSTs + 9 MSTs (north) and 14 MSTs + 37 SSTs (south)

(Hadronic) Cosmic-ray Spectrum at Earth

Modified Cronin+ (1997)



Galactic CRs **~3 × 10^{15} eV (3 PeV)**



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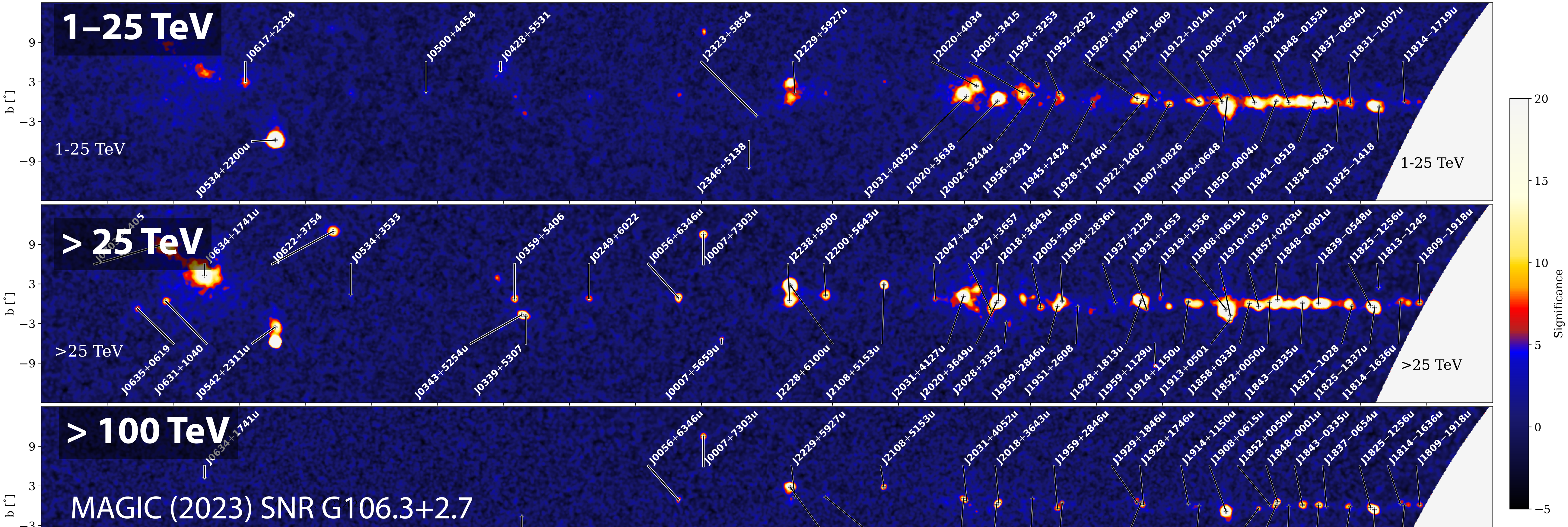
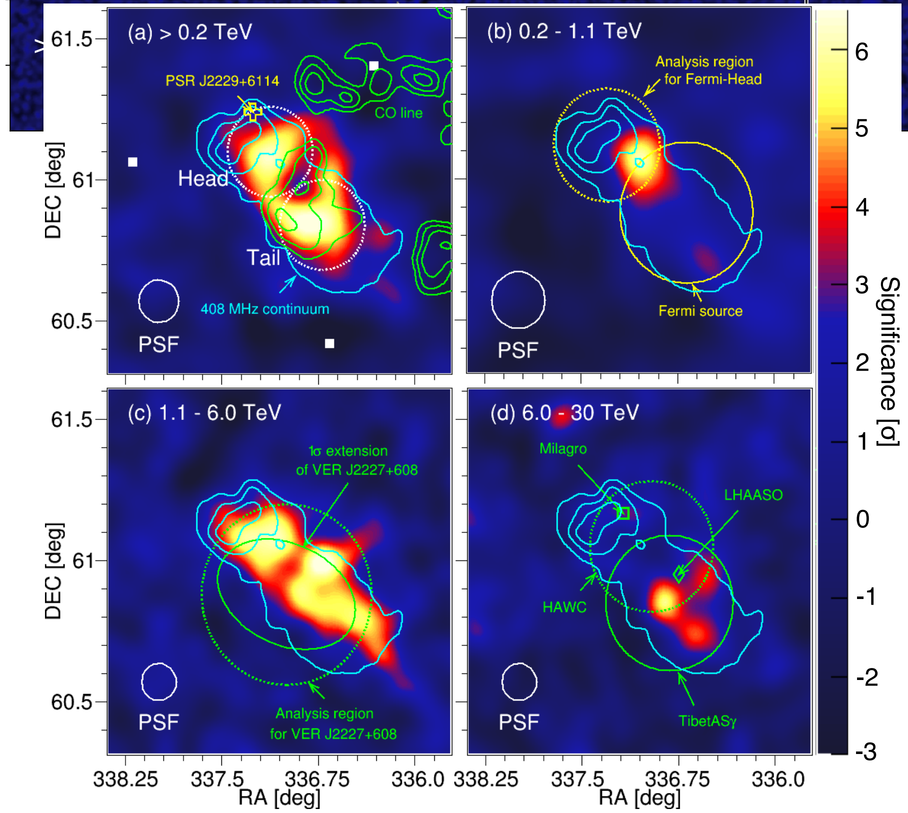
LHAASO Sources

LHAASO (2023) 2305.17030

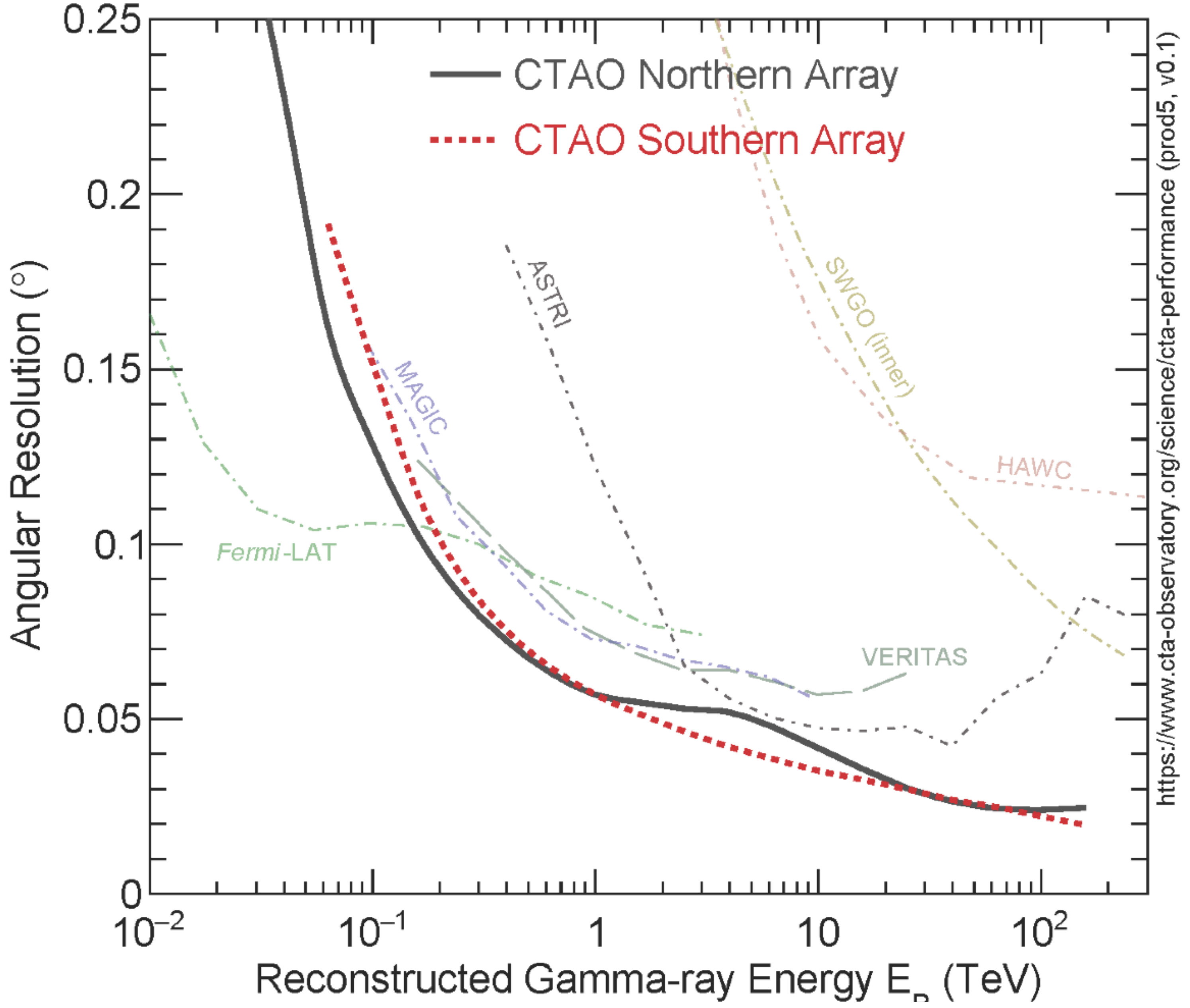


MAGIC (2023) SNR G106.3+2.7



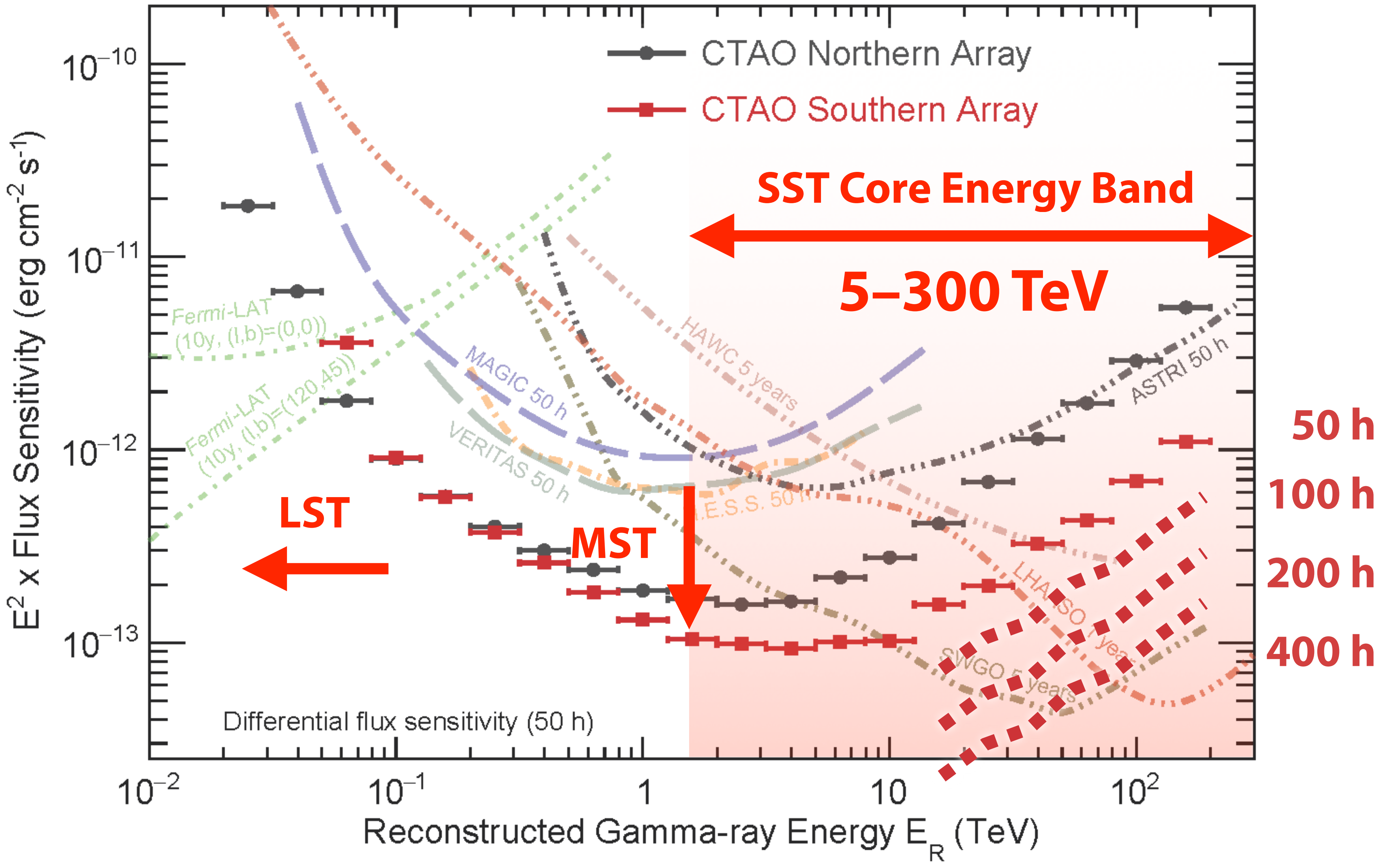
- **Northern** array-type surface detectors are exploring the PeV band
- LHAASO found 43 sources >100 TeV (> 4σ)
- What can Cherenkov telescopes do?

Angular Resolution



- Roughly 5 to 10 times better angular resolution than particle detector arrays
- Improvement of SST analysis will bring further better resolution down to 0.01° at 100 TeV

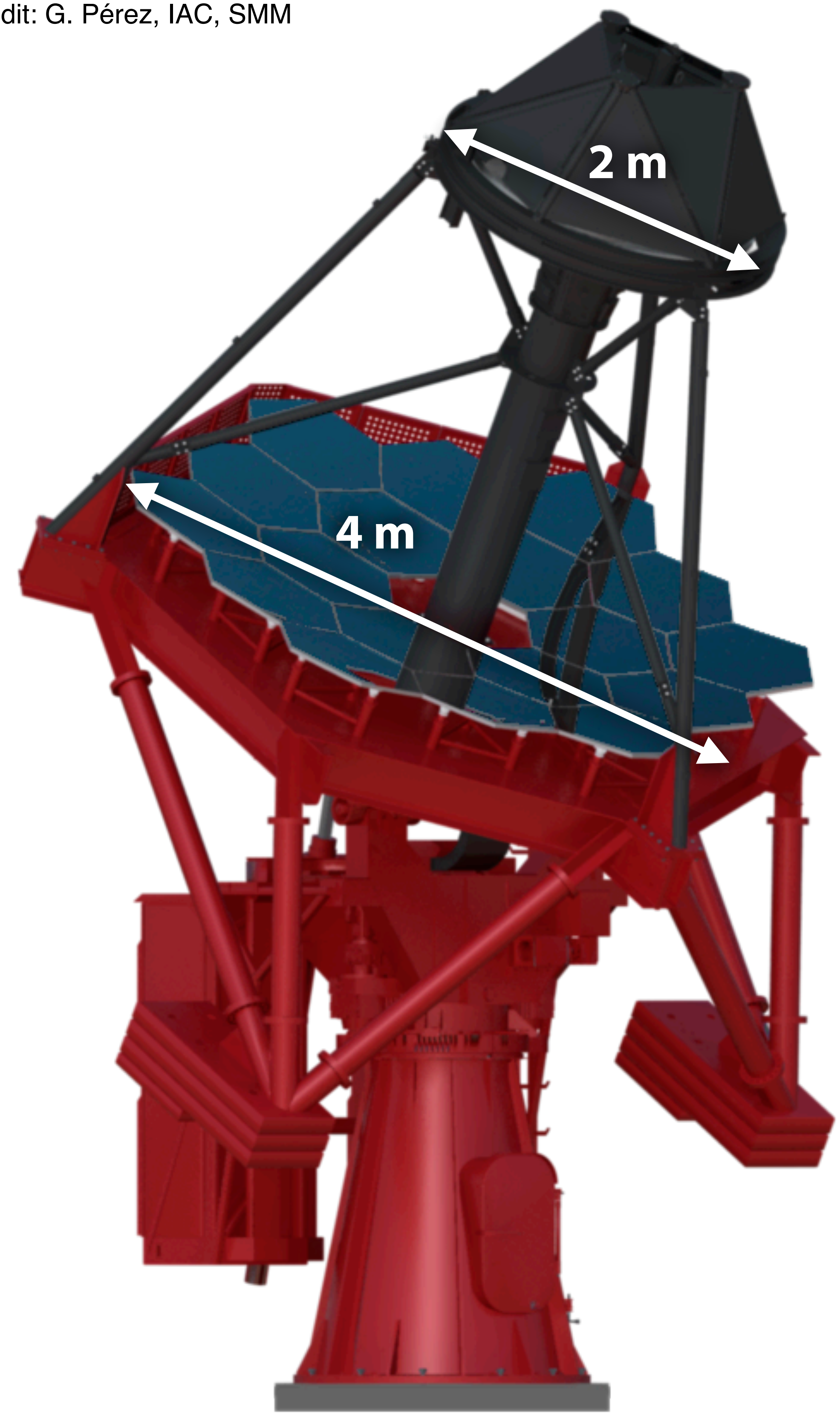
High-energy Frontier by CTA SSTs (Initial Configuration)

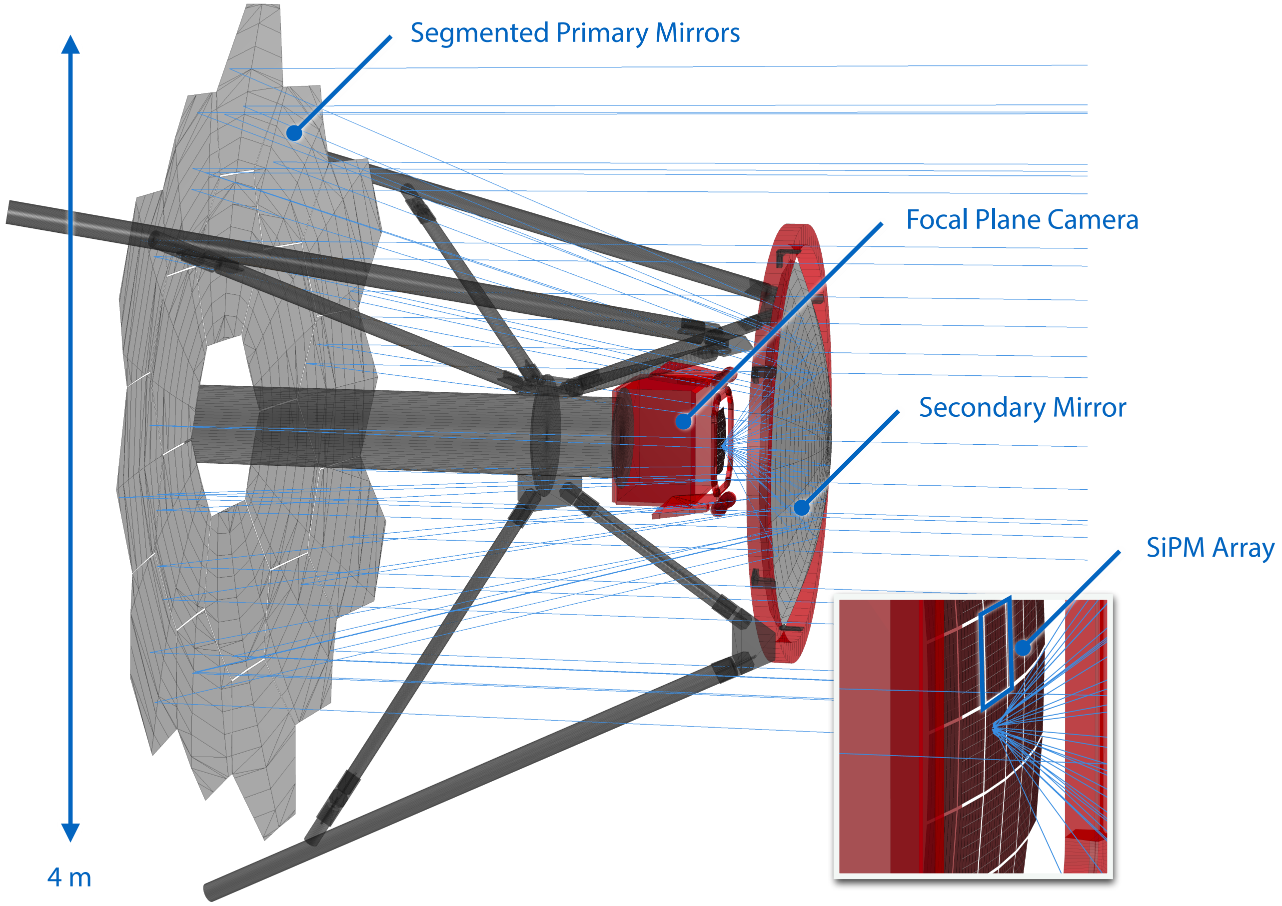


https://www.cta-observatory.org/science/cta-performance (prod5, v0.1)

- Covering up to 100–300 TeV is a key for PeVatron search
- Long observations of selected candidates (e.g., Gal. Center) with better ang. reso.
- Observations under bright moon conditions will double the duty cycle

Small-Sized Telescopes (SSTs)





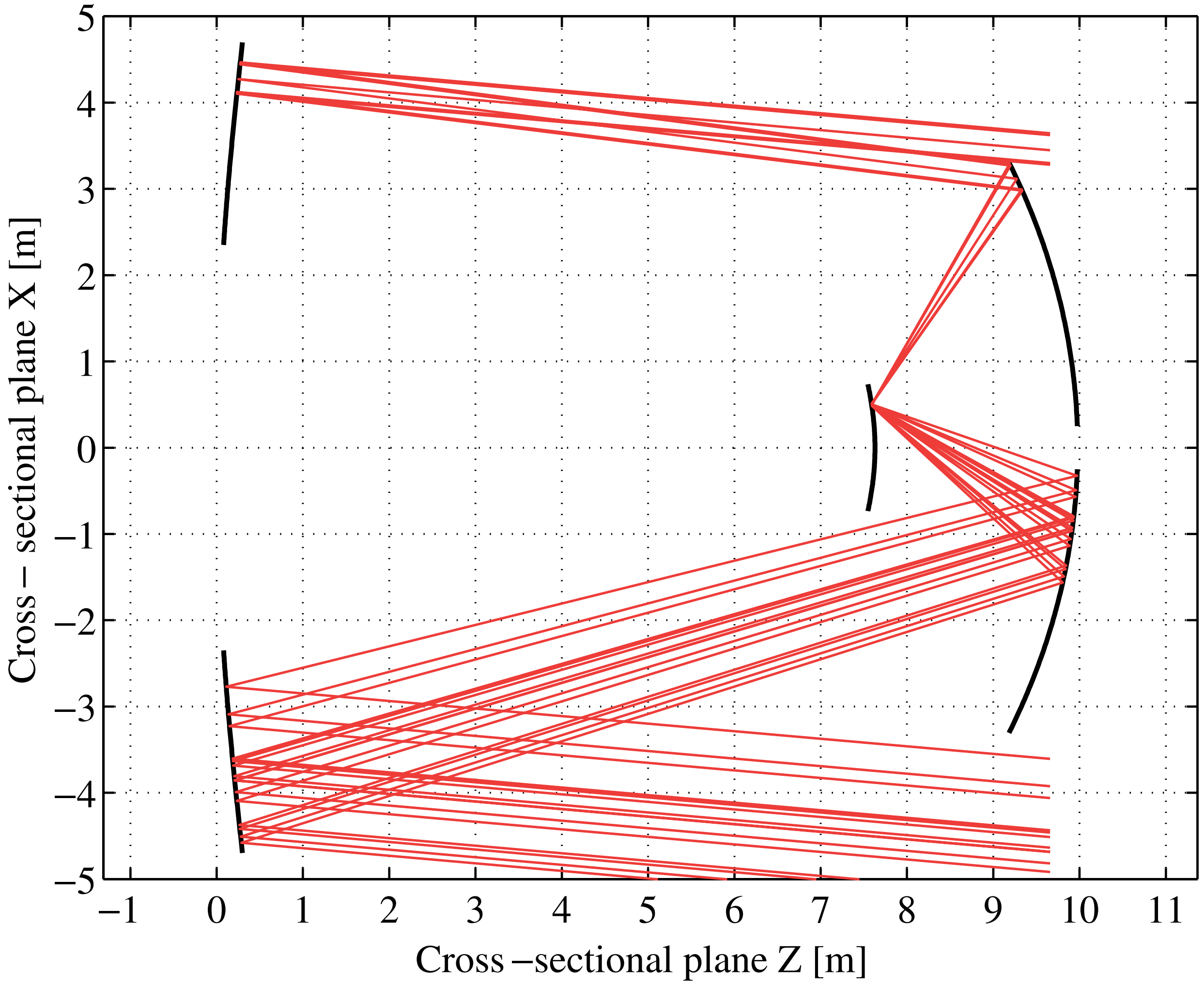
- Schwarzschild–Couder optical system
  - 4 m aspherical primary mirrors (segmented)
  - 2 m monolithic secondary mirror (monolithic)
  - ~0.15° PSF diameter over ~9° FOV
- Compact focal-plane camera
  - 2048 SiPM pixels to form 300 mm focal plane
  - 32 × 64-ch camera modules with dedicated ASICs
  - Large contributions from Nagoya University

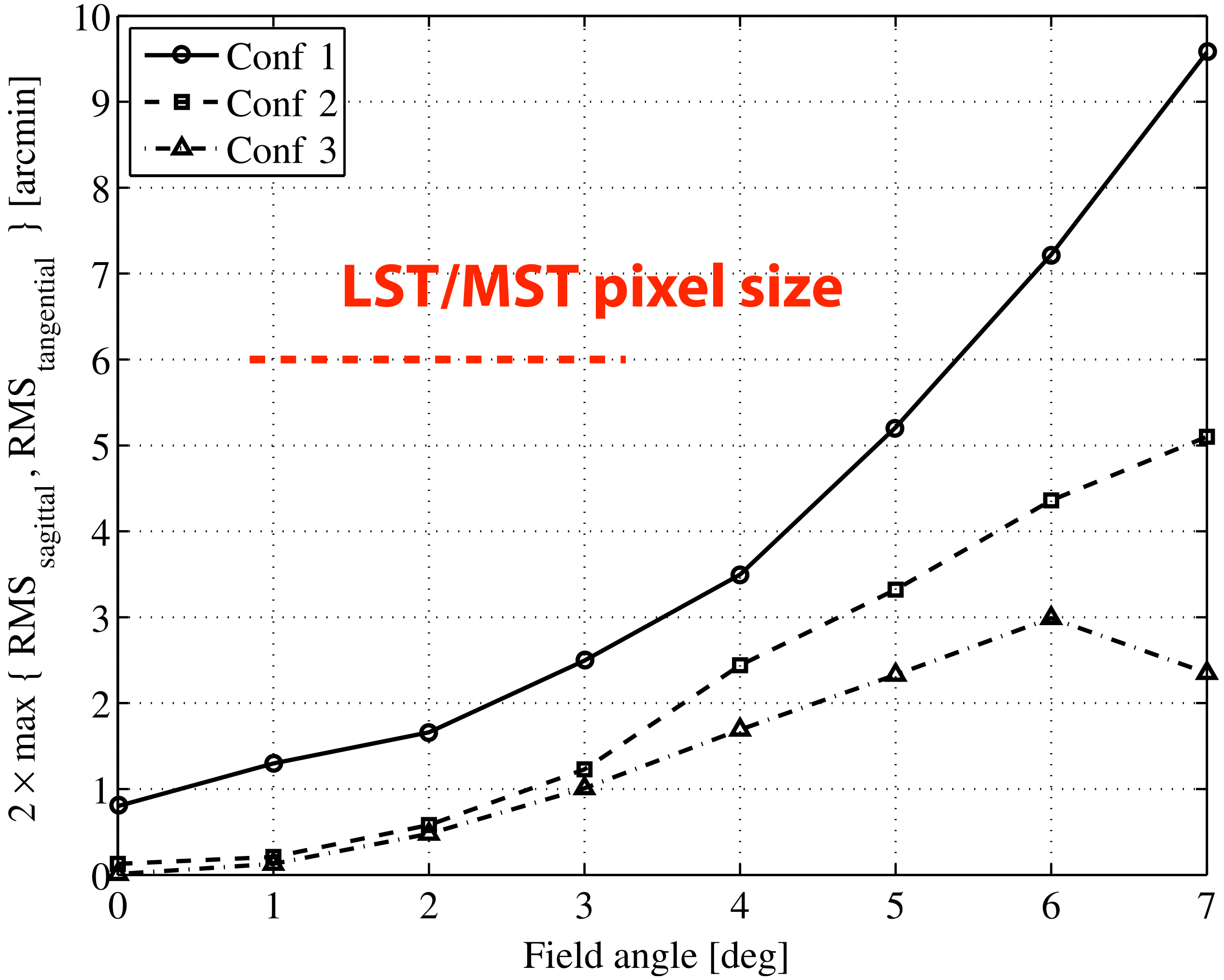
What Instruments Do We Need?

- Telescope
  - Small diameter telescopes (~4 m) to detect 1–300 TeV gamma rays
  - Wide field of view (~9 deg) with good angular resolution (~0.1 deg) over the FOV
- Camera
  - Fine SiPM pixels with ~2000 ch readout
  - Compact camera diameter to reduce the SiPM cost
  - Multichannel high-density electronics for 1 GHz sampling (1 ns) and digitization

Schwarzschild–Couder Configuration

Vassiliev+ (2007)

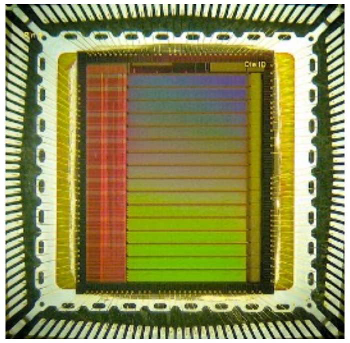




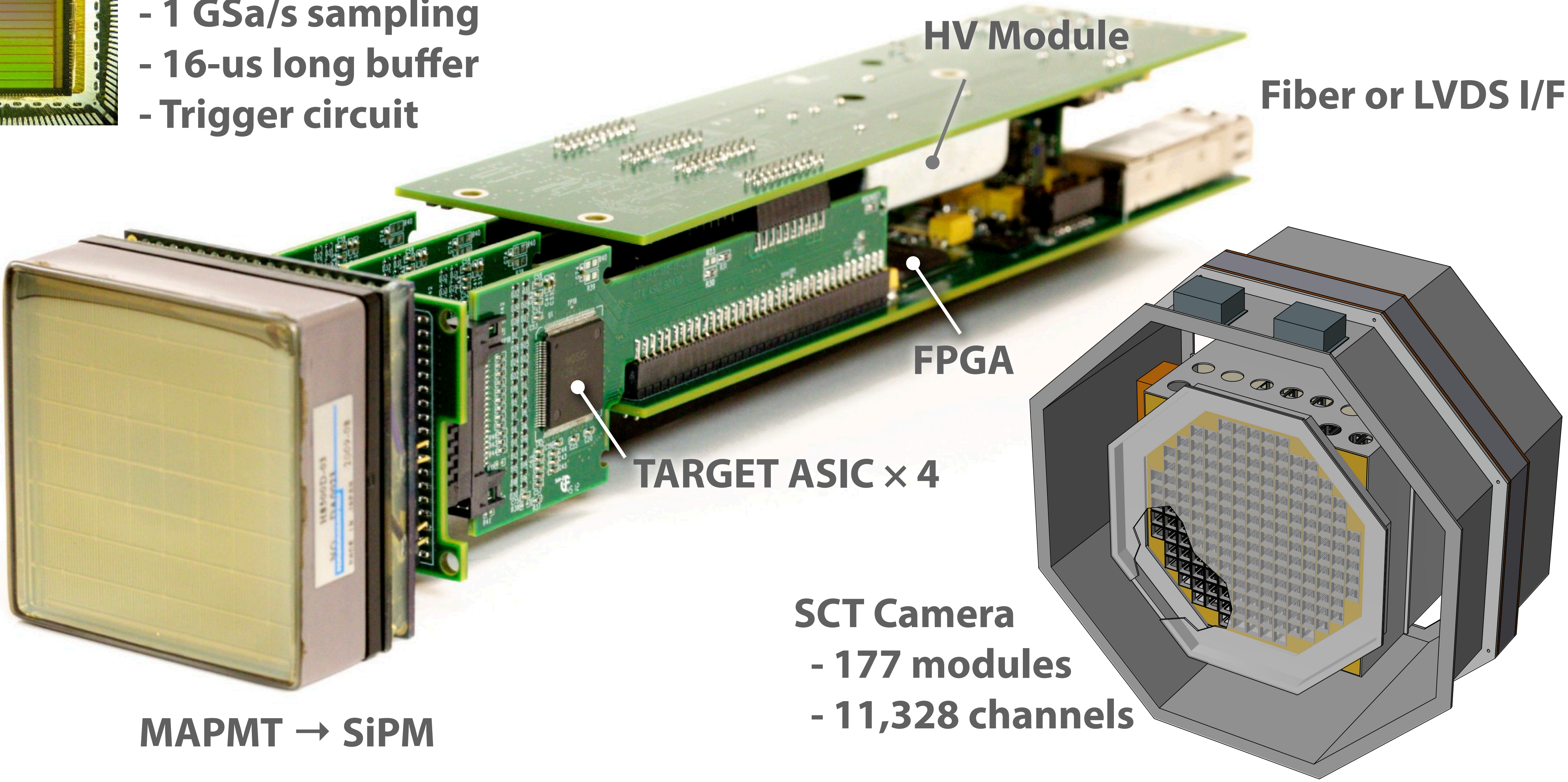
LST/MST pixel size

- **Aspherical** primary and **secondary** mirrors to achieve wide FOV and better resolution at the same time
- Wider FOV brings fast survey and wider effective area for higher-energy photons
- Finer shower-image resolution (→ higher sensitivity) and compact camera (→ less expensive) are expected
- Proposed by the CTA US group first for MSTs

TARGET (TeV Array Readout with GSa/s sampling and Event Trigger)



TARGET ASIC (designed by G. Varner @ U. Hawaii)
- 16 channels readout
- 1 GSa/s sampling
- 16-us long buffer
- Trigger circuit



HV Module

Fiber or LVDS I/F

FPGA

TARGET ASIC × 4

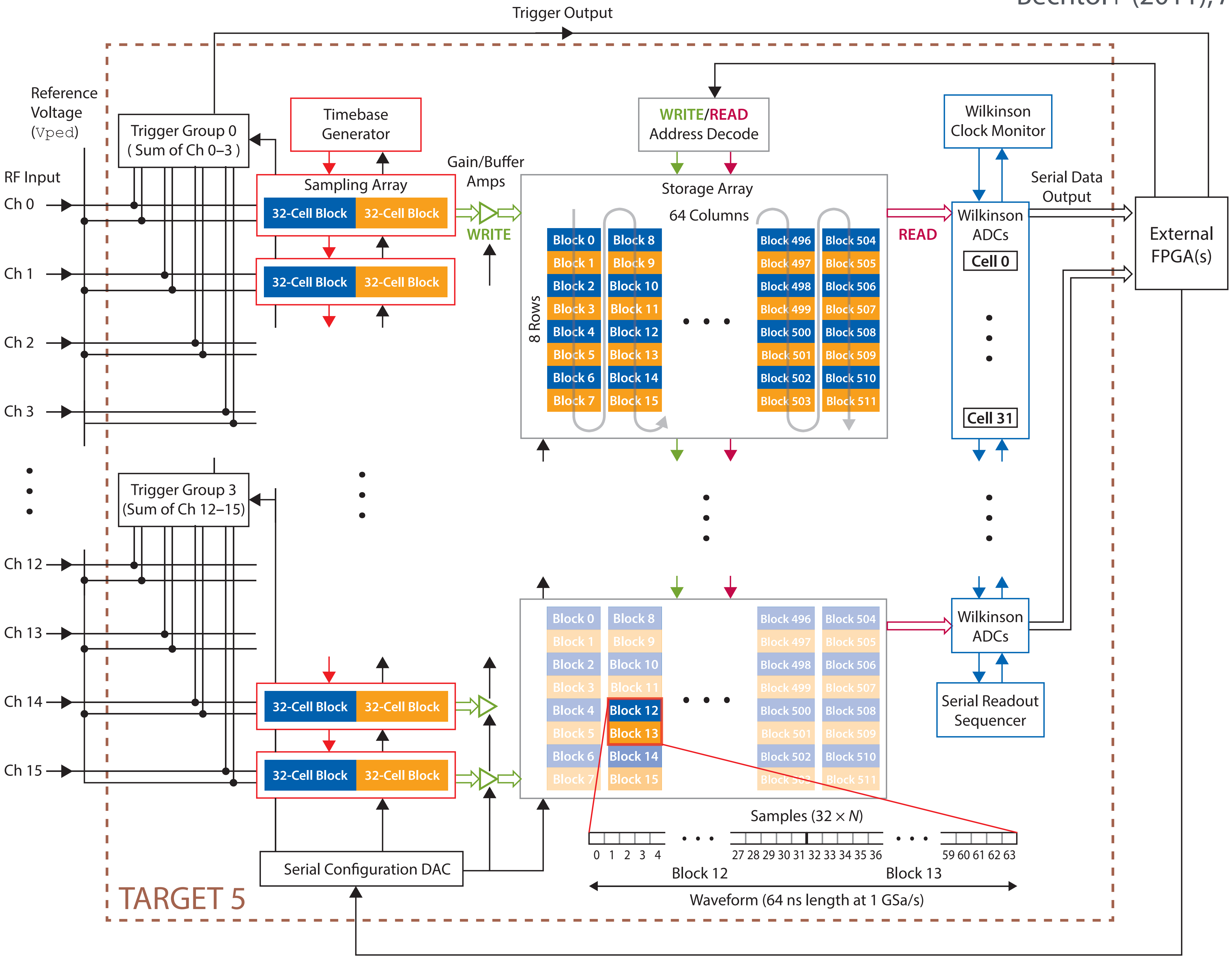
SCT Camera
- 177 modules
- 11,328 channels

MAPMT → SiPM

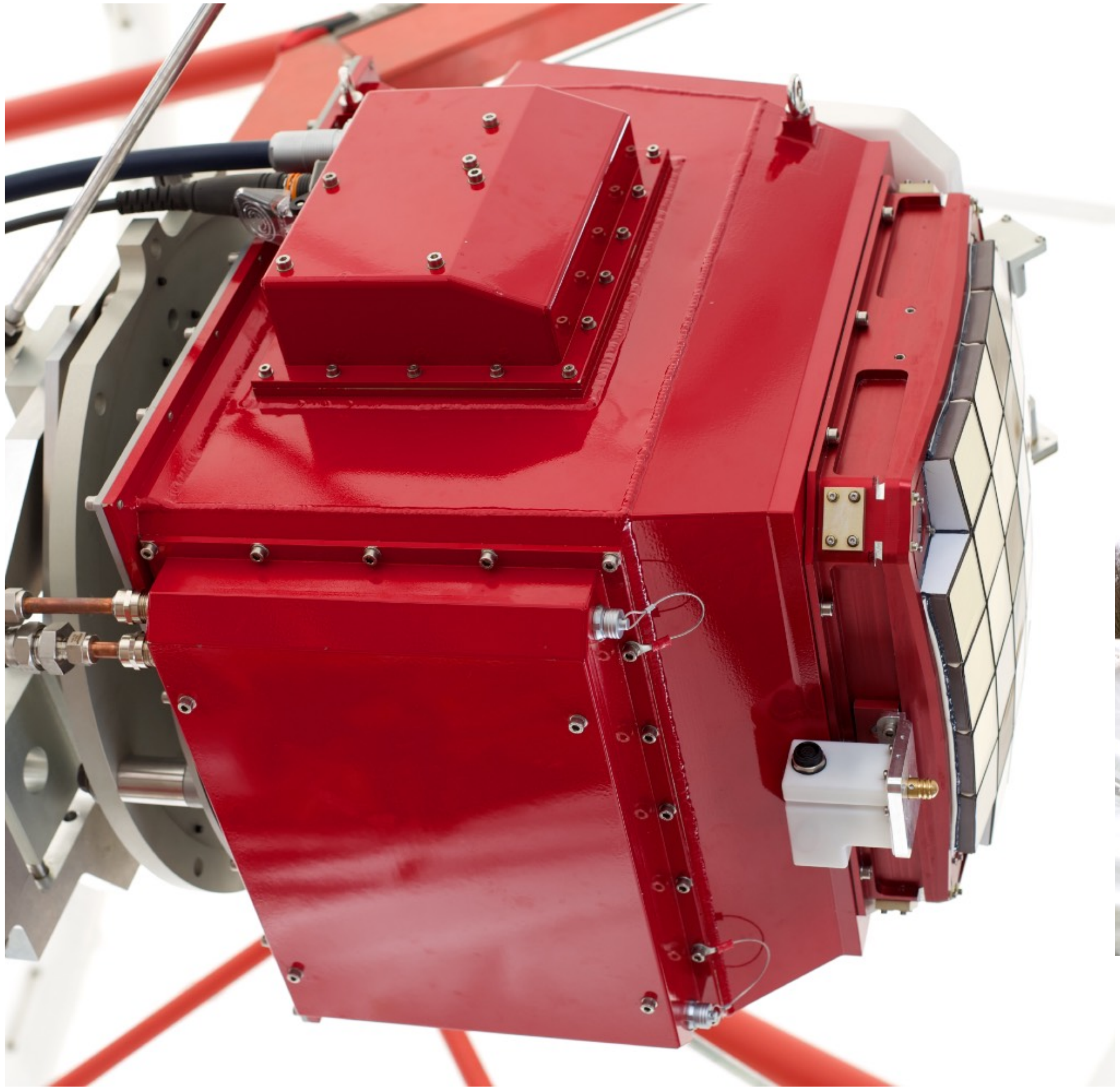
- Application specific integrated circuit (ASIC) for CTA
- Developed TARGET 1 for concept validation (Bechtol et al. 2012)
- TARGET 5 (w/ gain adjustment) for MAPMTs, TARGET 7 for MPPCs (Albert et al. 2017)

TARGET Diagram

Bechtol+ (2011), Albert+ (2017)



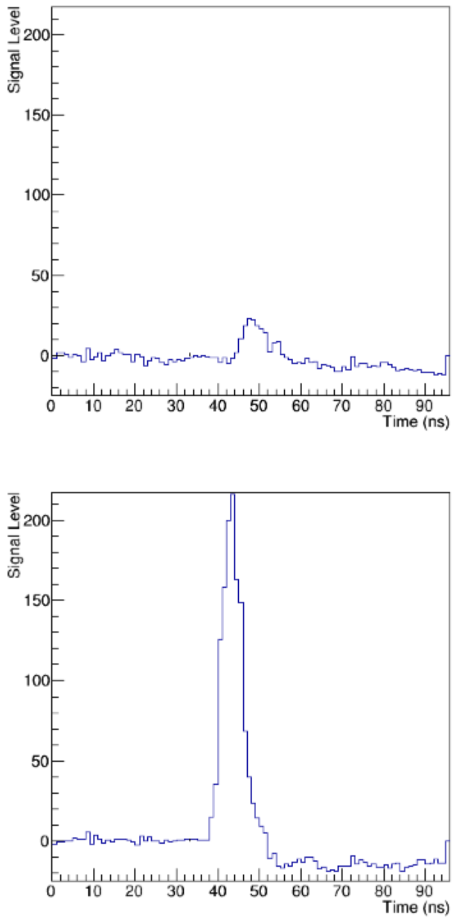
First SST Camera Prototype (w/ MAPMTs)

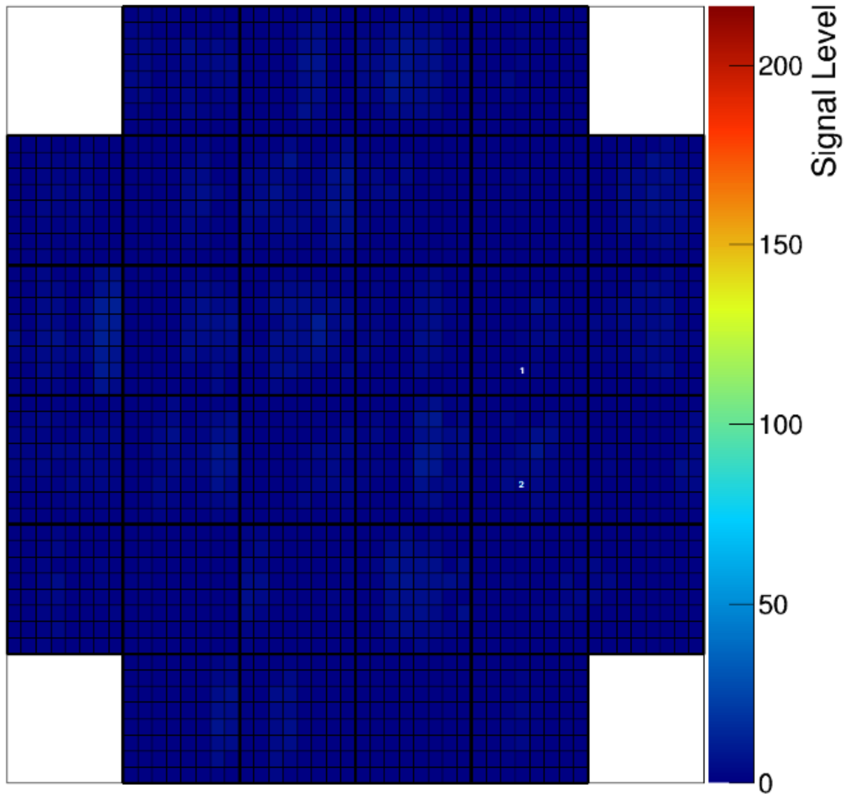


- TARGET 5 ASICs and 32 MAPMTs (2048 channels)
- Mounted on a French telescope prototype (incomplete)
- CTA's first ever Cherenkov images (near Paris!) in 2015

Cherenkov Shower

https://www.cta-observatory.org





Press Release

CTA Prototype Telescope Achieves First Light

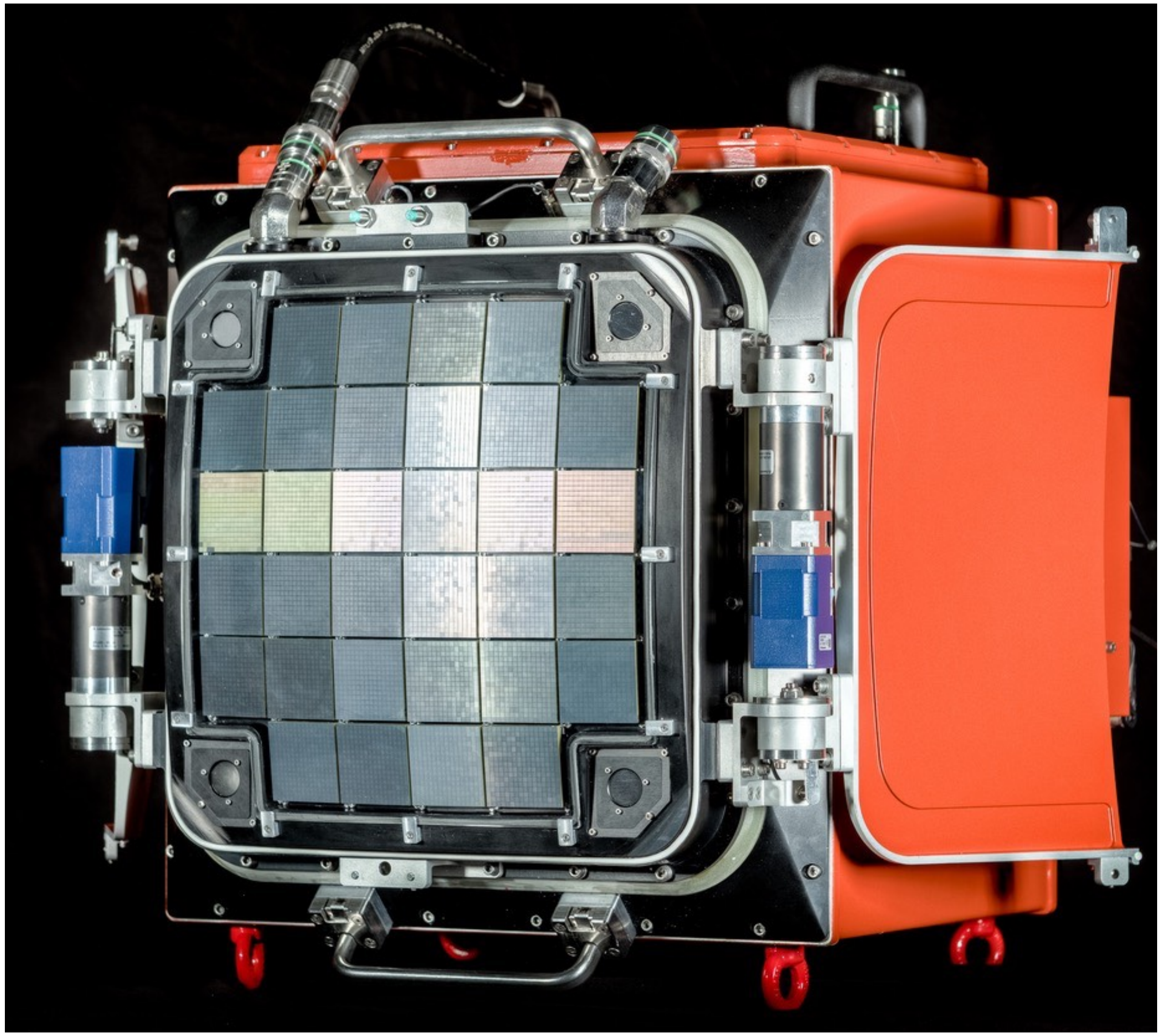
Download full release: 1 MB / PDF

On 26 November 2015, a prototype tel
the Gamma-ray Cherenkov Telescope
while undergoing testing at l'Observa
as one of CTA's Small-Size Telescopes
between about 1 and 300 TeV (tera-el
telescope, captured the first optical ir

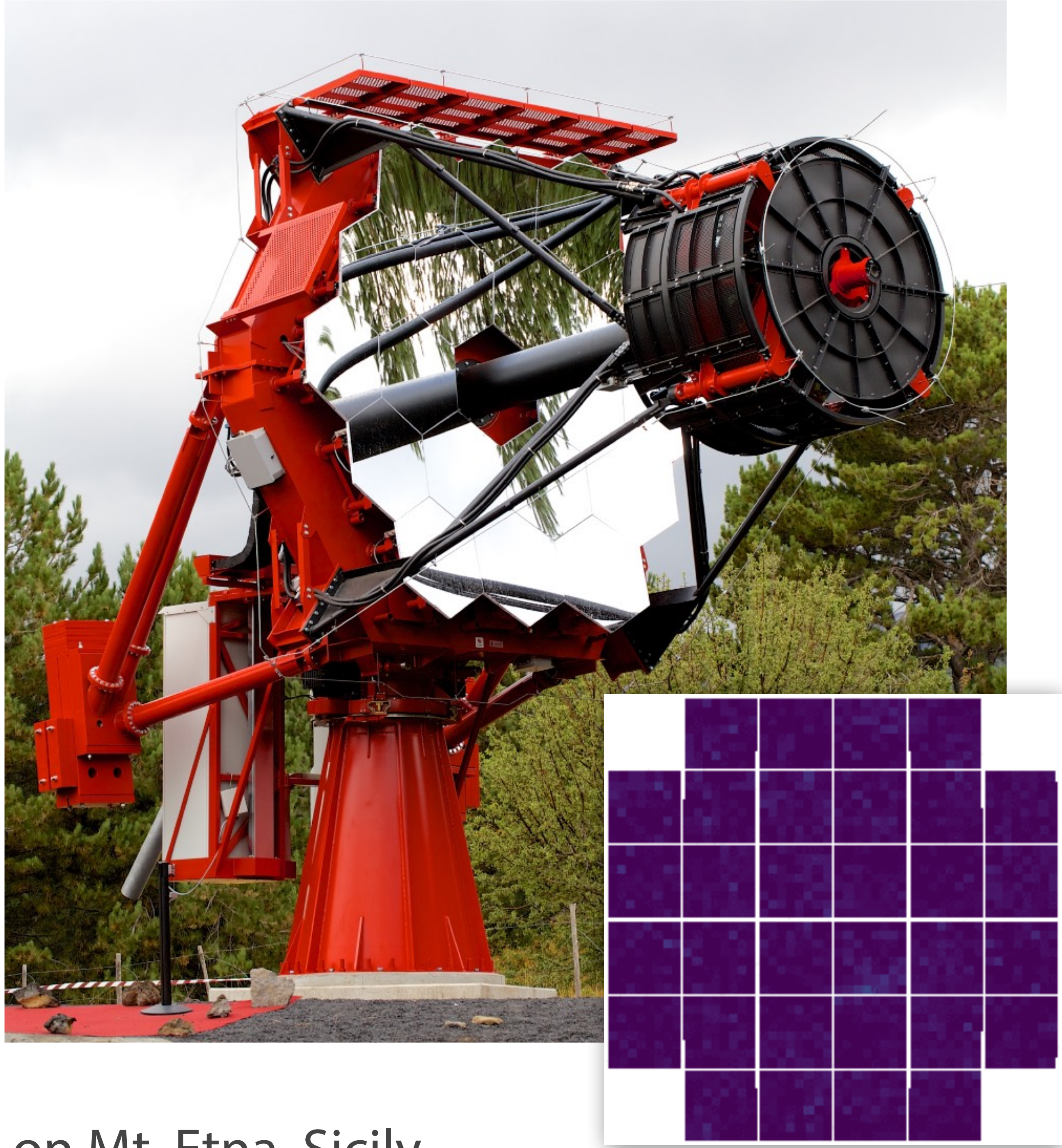
Photo credits: Akira Okumura

- Trigger, data acquisition, data analysis, module calibration etc.
- First images taken on Nov 26, 2015
- Could not join the shift as my second son was born on Oct 26, 2015

Second SST Camera Prototype (w/ SiPMs)



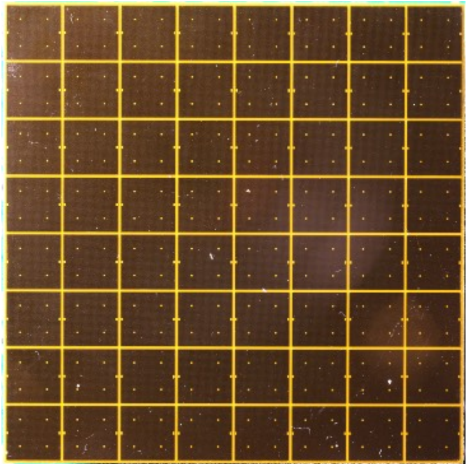
Credit: Christian Föhr (MPIK)

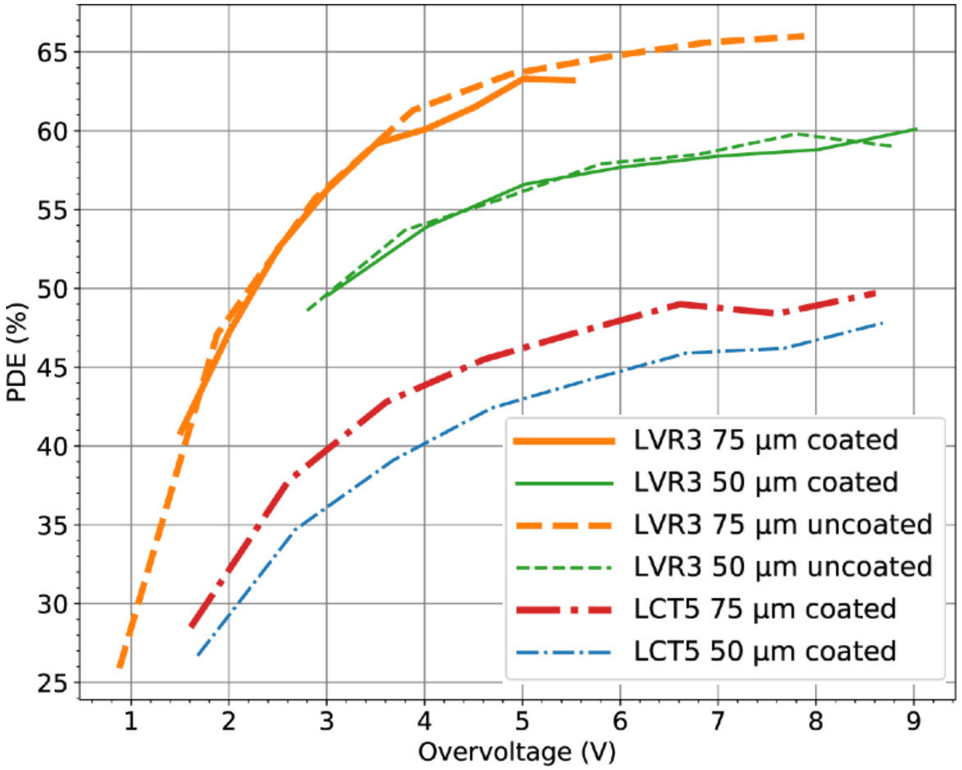


- TARGET 7 ASICs and 32 SiPMs (2048 ch)
- Mounted on an Italian telescope prototype on Mt. Etna, Sicily
- First light in 2019, and later volcano activity
- SST “Harmonization” process chose our camera design in 2019

SiPM Advantage

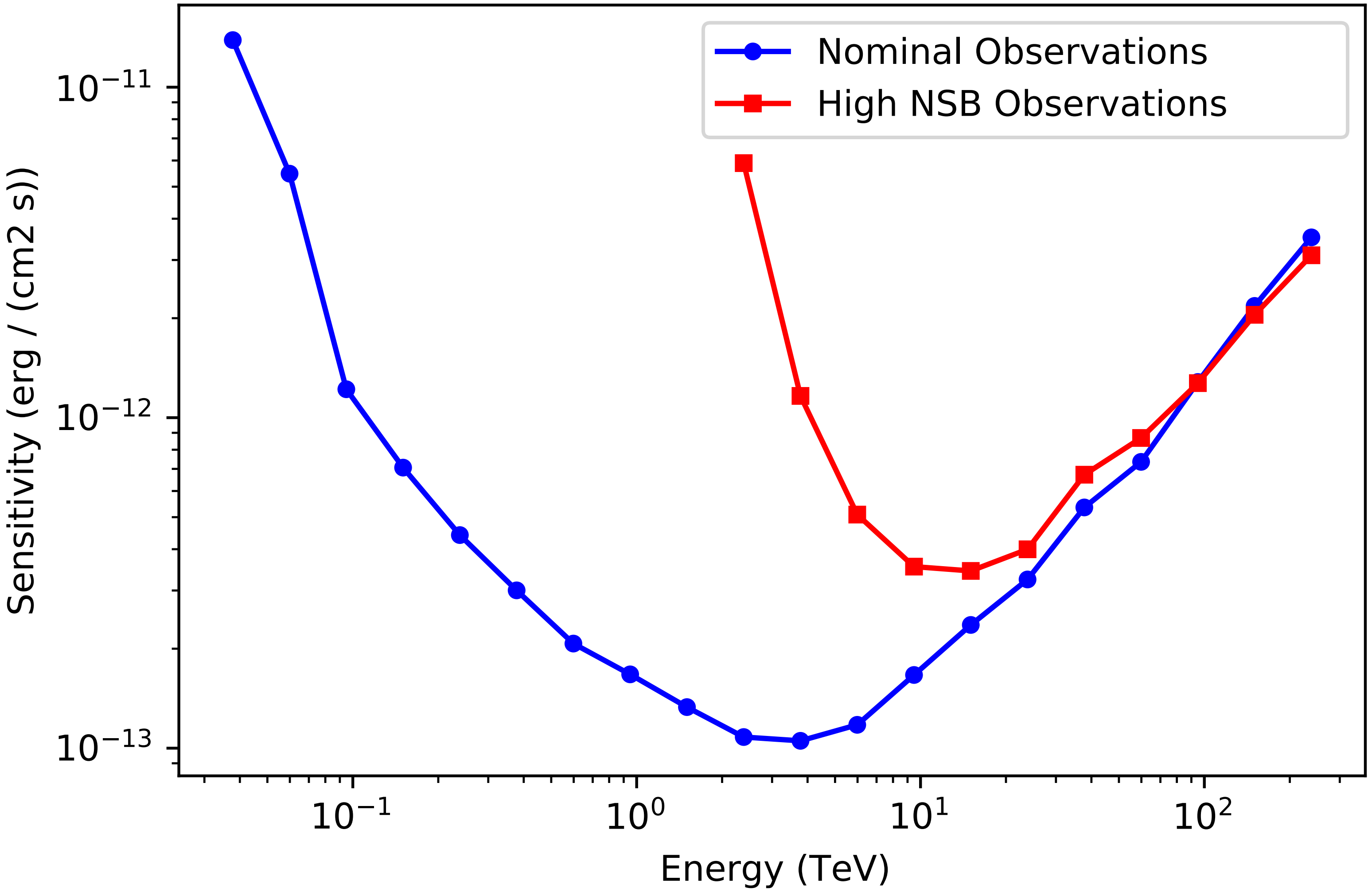
Hamamatsu S14521-1720





Depaoli et al. (2024)

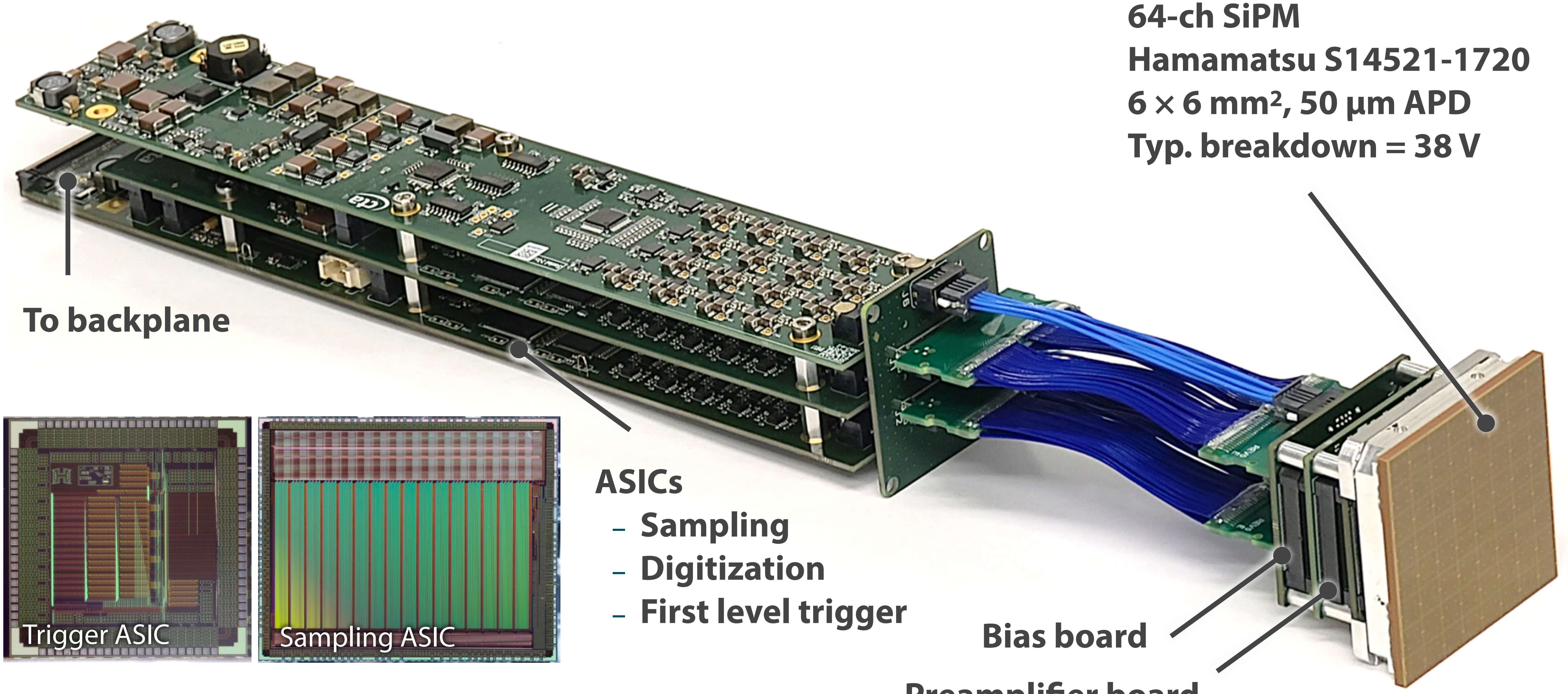
CTA (2023)



- Latest SiPMs for SSTs (LVR3, 50 µm, uncoated) have as high as >55% PDE
- Optical crosstalk rate was successfully reduced by removing the resin coating
- SSTs will be operated under high night sky background conditions

Camera Module

D. Depaoli (ICRC2023)

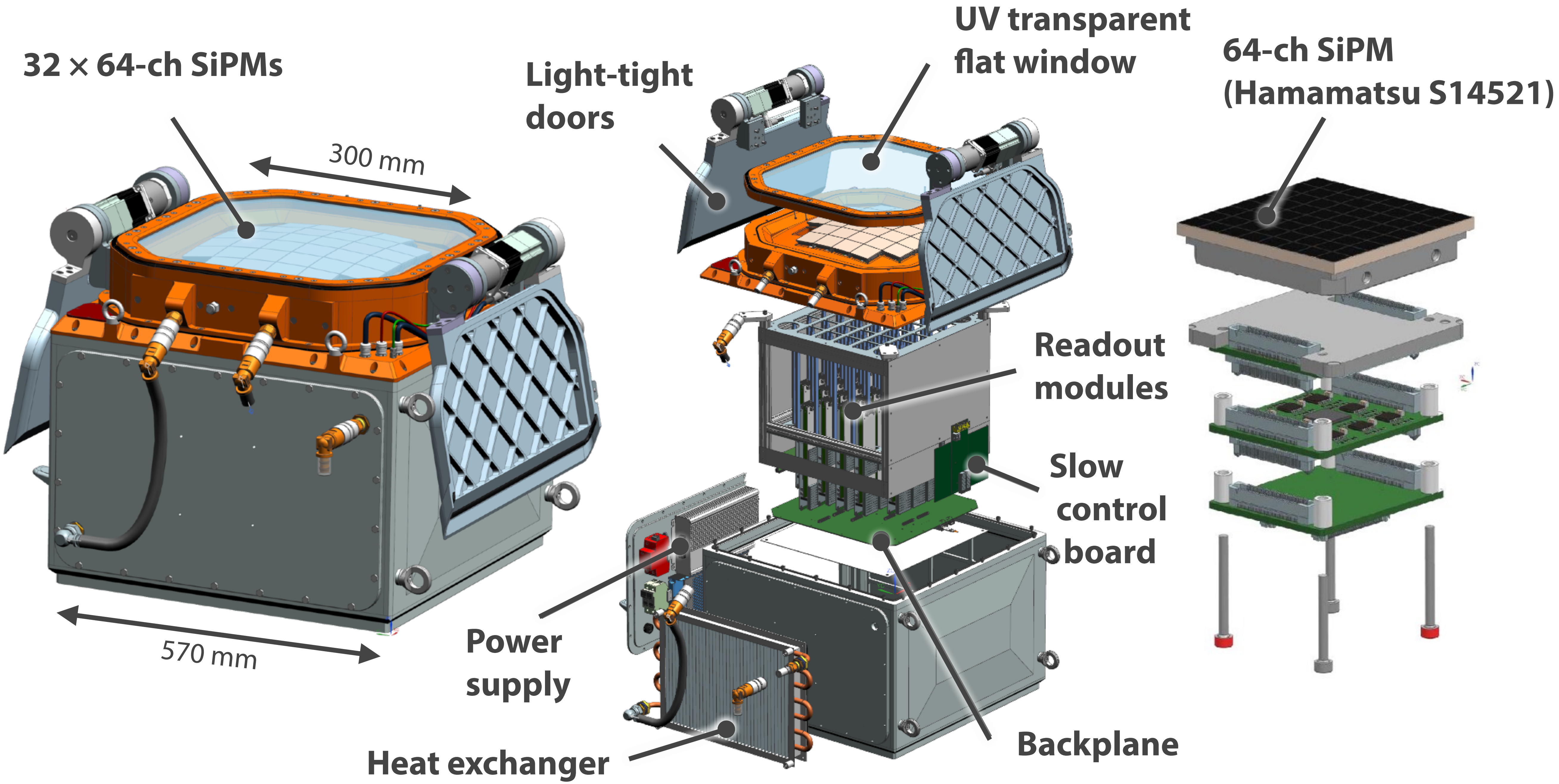


64-ch SiPM
Hamamatsu S14521-1720
6 × 6 mm², 50 µm APD
Typ. breakdown = 38 V

ASICs
- **Sampling**
- **Digitization**
- **First level trigger**

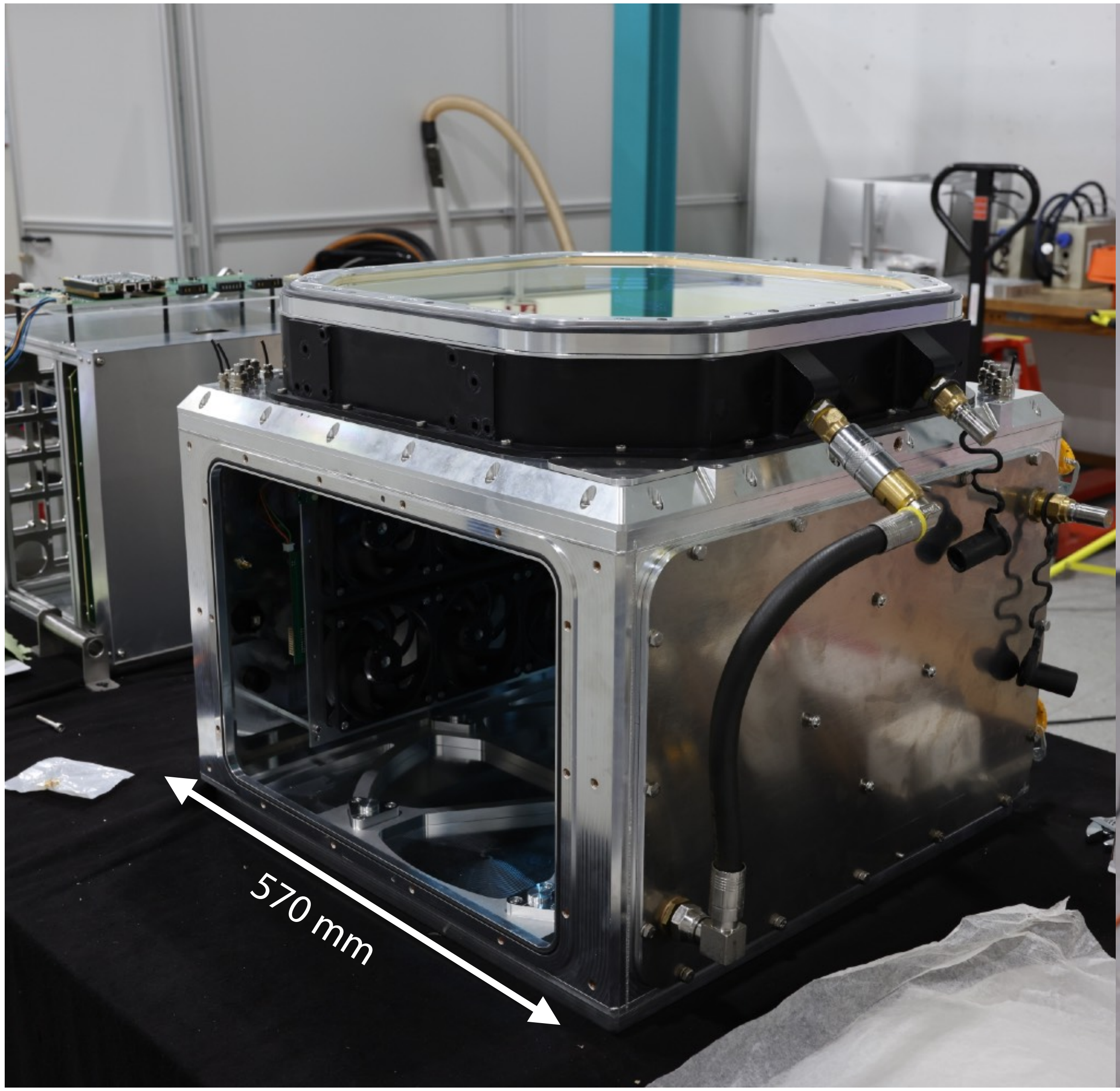
- Started with the first TARGET ASIC (16-ch sampling and trigger), and 64-ch MAPMTs in 2009
- Latest module uses 4 × sampling ASIC (TARGET-CTC) and 4 × trigger ASIC (TARGET-CT5TEA)
- UV-sensitive and uncoated low-optical-crosstalk 64-ch SiPMs

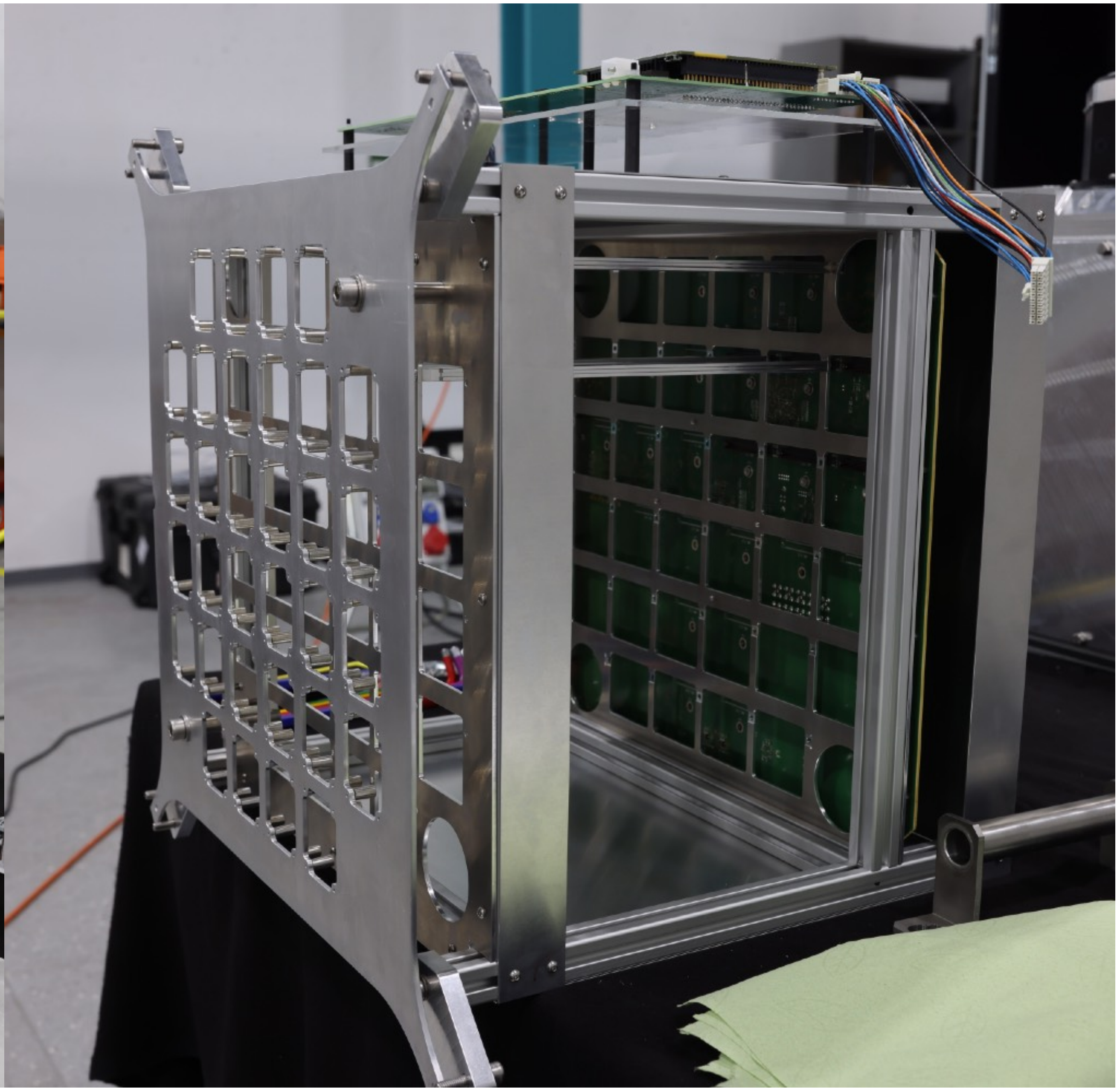
(Almost) Final Design



- The same concept: 32 × 64-ch SiPMs to form the spherical focal plane, read and triggered by dedicated ASICs (TARGET series), and controlled by backplane
- After the experience of two prototypes, the design is being finalized now

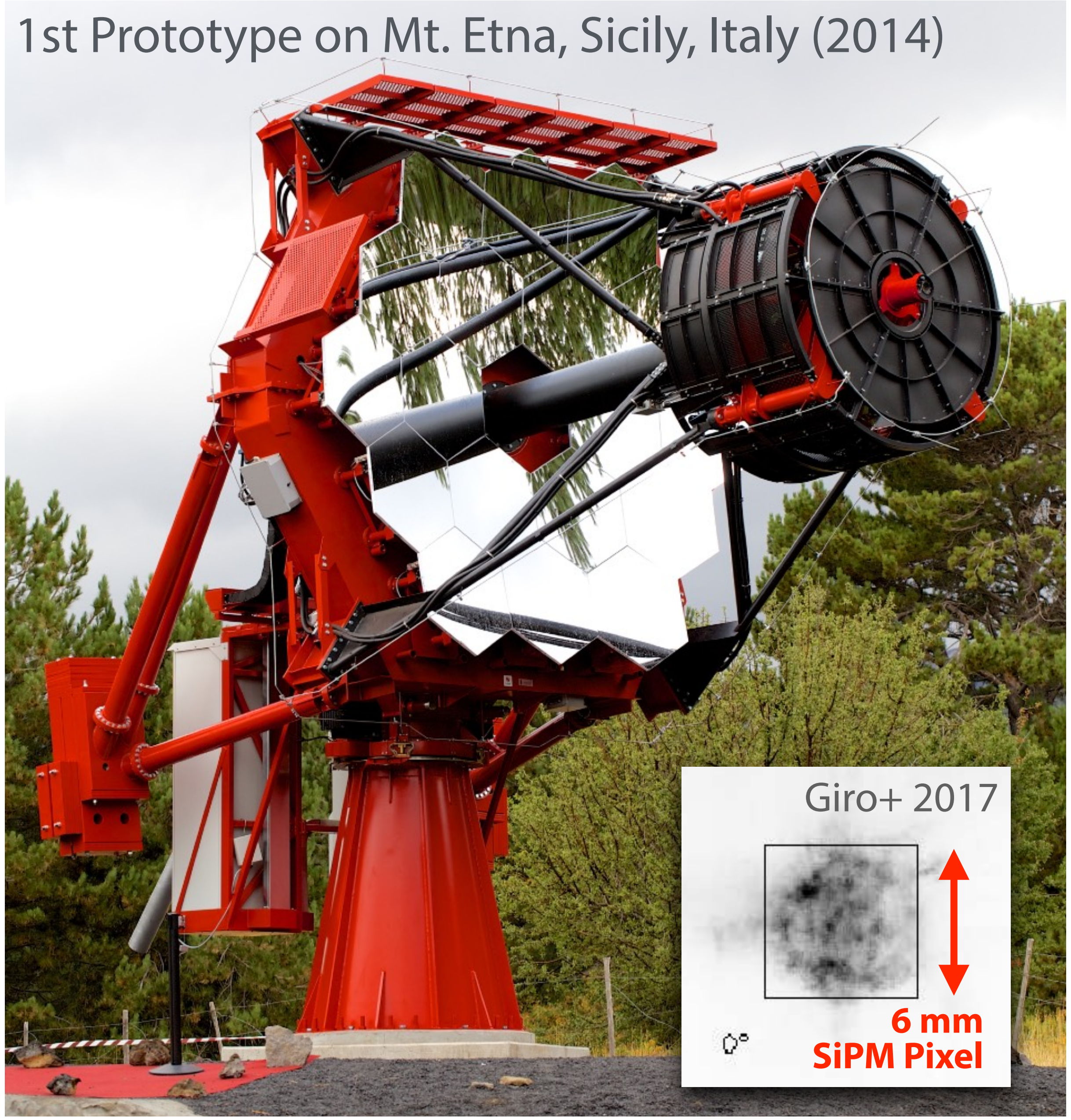
Quarter Camera @ MPIK, Heidelberg

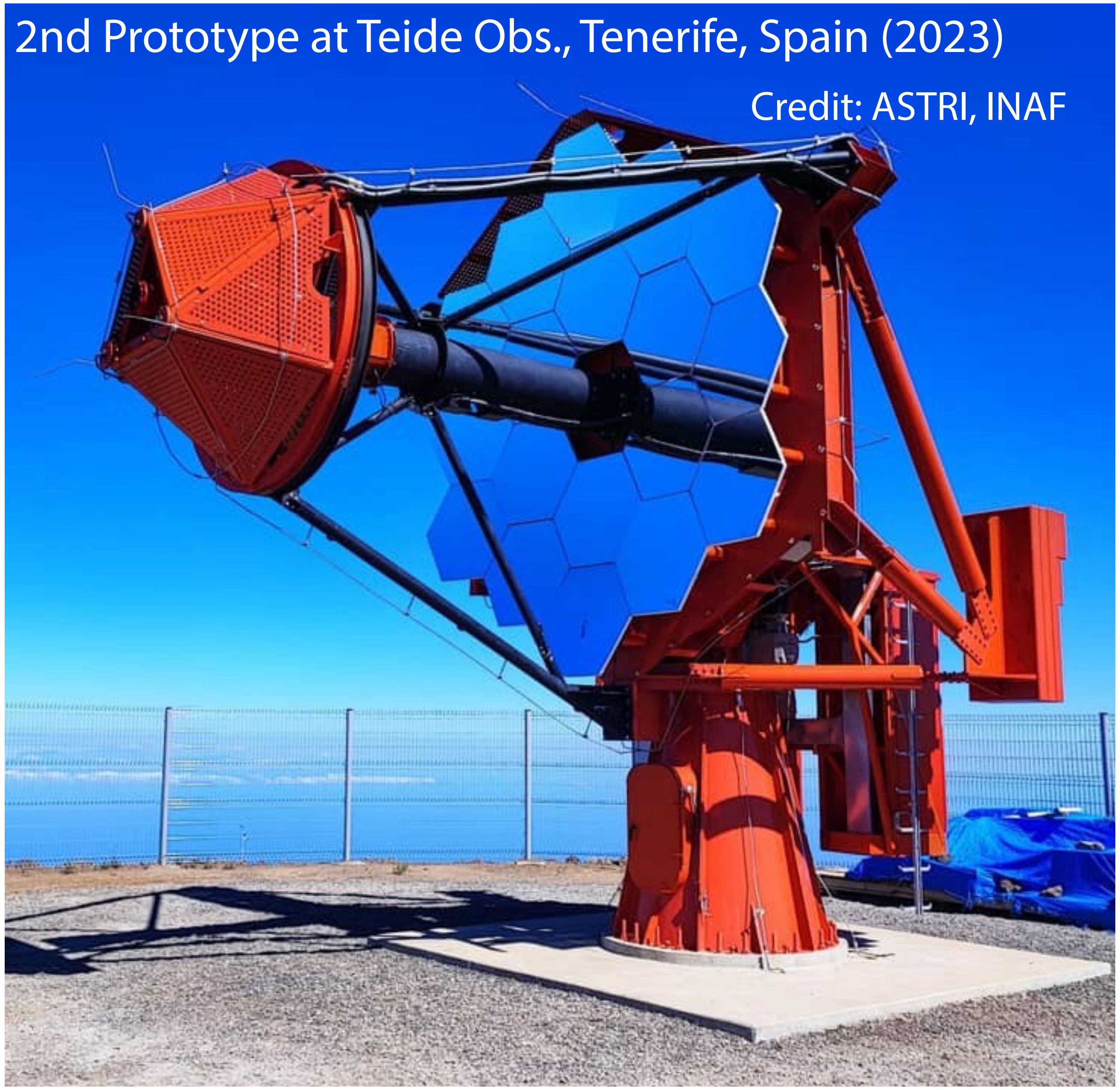




- Quarter camera will have only 8 camera modules (512 of 2048 pixels)
- Mechanical, thermal, and electrical tests started this summer in parallel to stand-alone module tests
- Tests and debugging to finish this year, then a full camera (first camera) will be built in 2024–2025
- Mounting test on a telescope at the Tide Observatory in October

Status of the SST Optical System

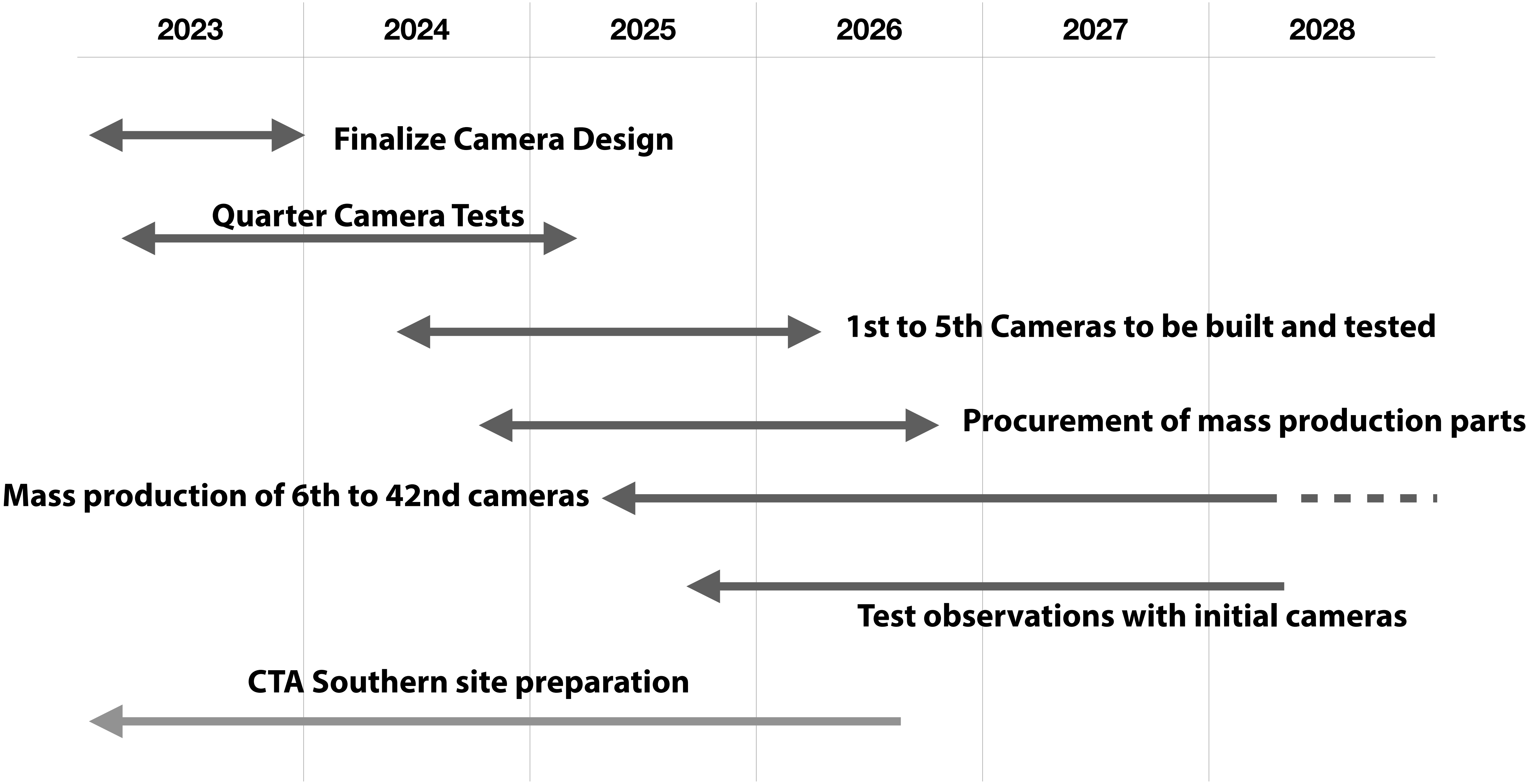

1st Prototype on Mt. Etna, Sicily, Italy (2014)


2nd Prototype at Teide Obs., Tenerife, Spain (2023)

Credit: ASTRI, INAF

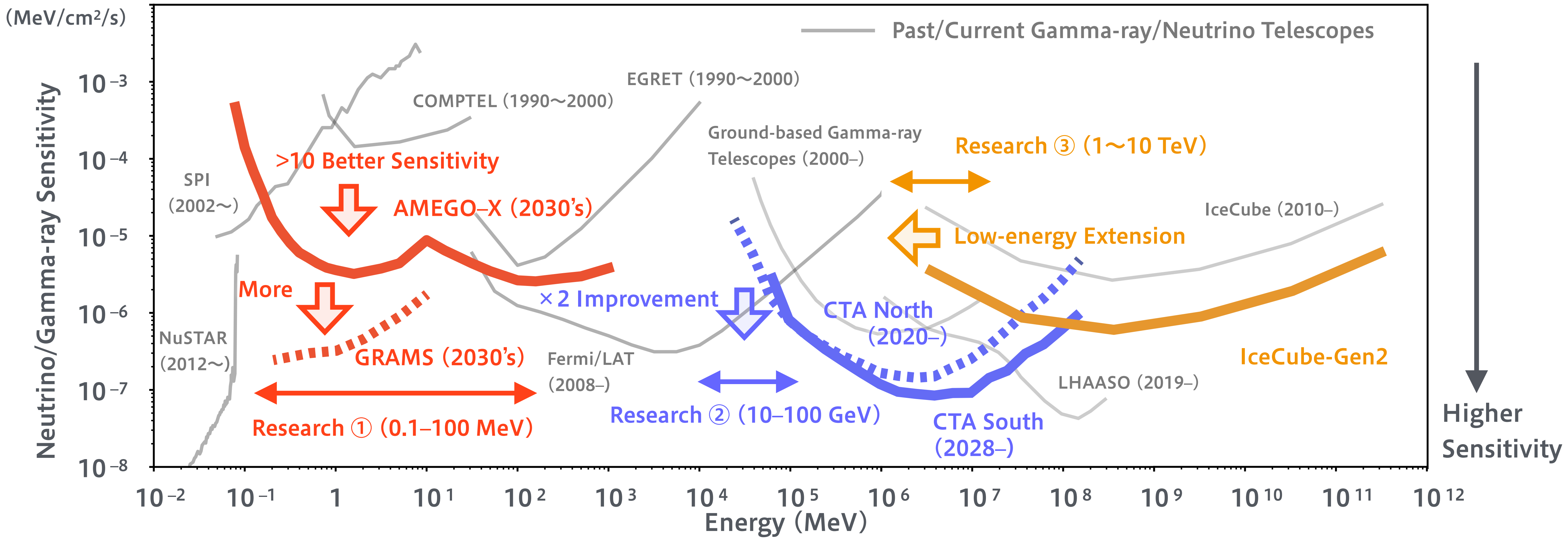
- The optical performance of the Schwarzschild–Couder system validated
- **ASTRI mini-array** (9 SST-like systems) to be built at Teide Observatory
- Optics and array control will be tested and validated before SST construction in ~2026

Tentative Schedule



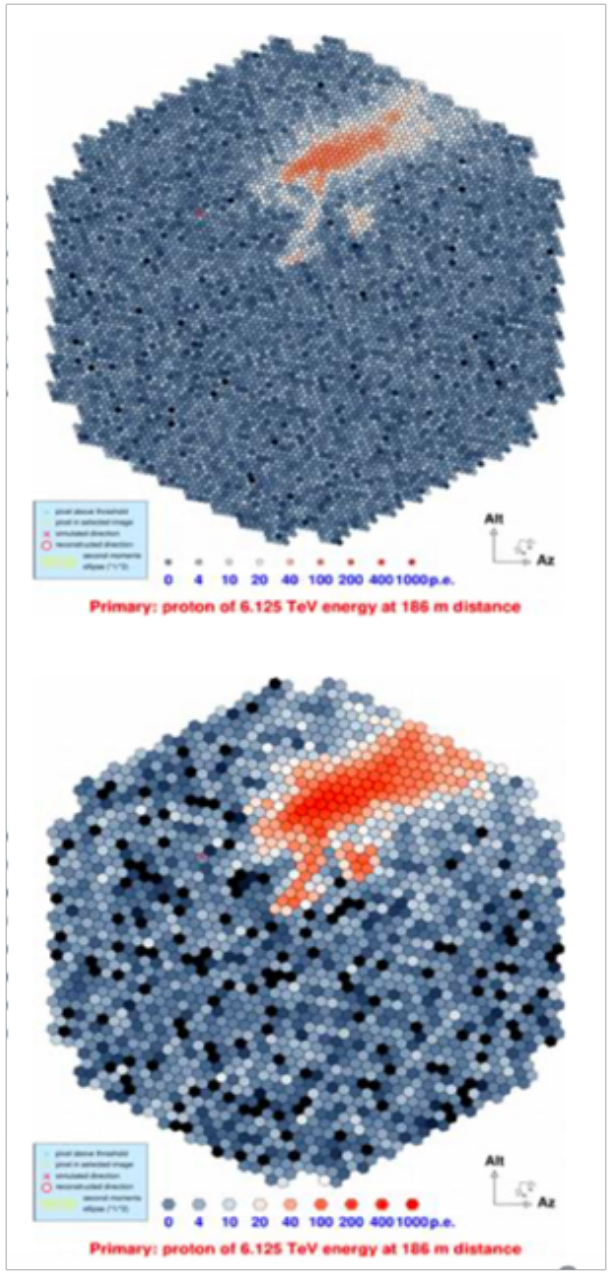
- Quarter camera in 2023–2024, 1st camera in 2024–2025, …
- Once the 1st camera is ready, we will start test observations in 2025
- Must produce and test a new camera a month from 2025

Wide High-Energy Coverage by Neutral Particles

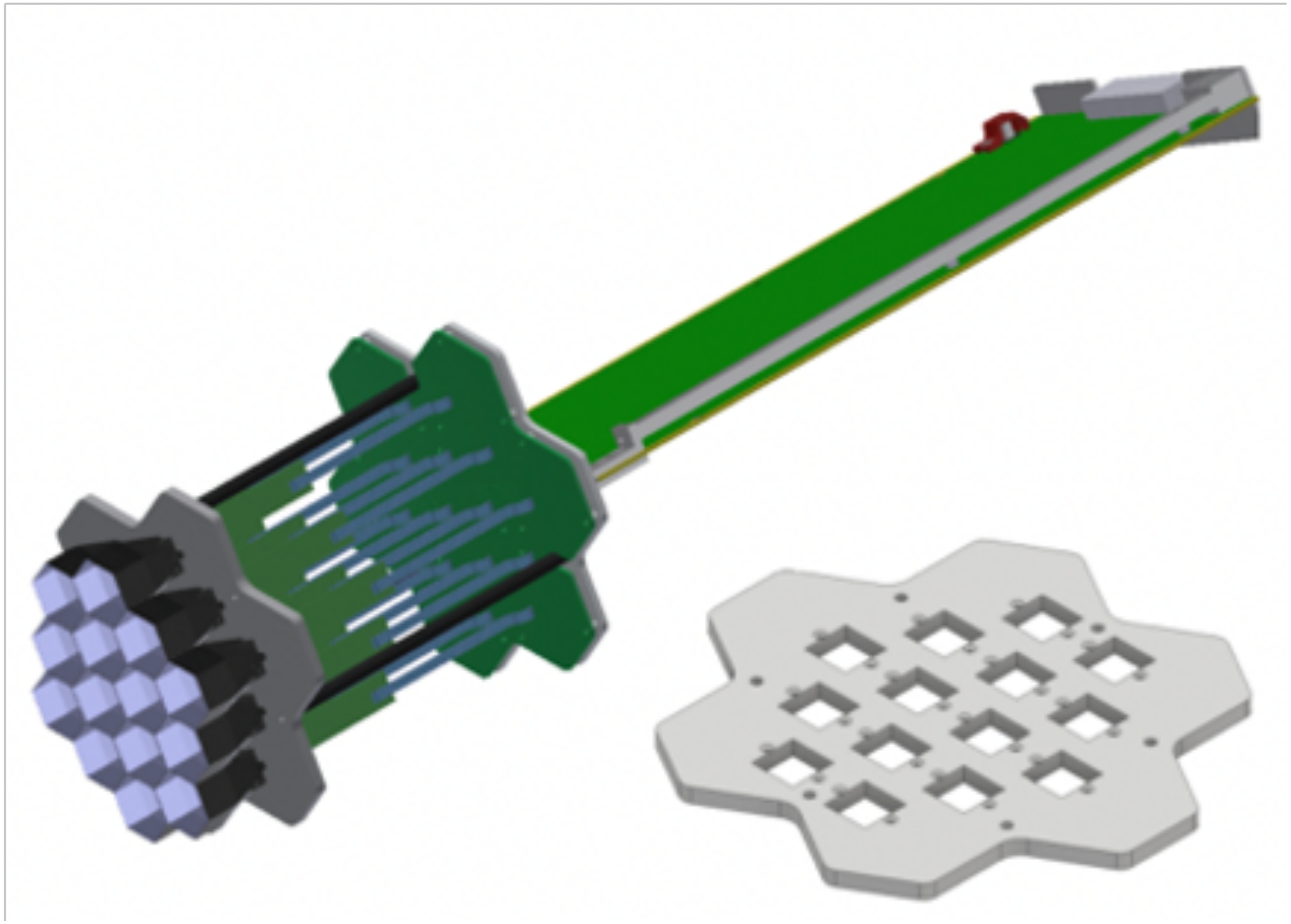


- **Neutral** keV/MeV/GeV/TeV/PeV regions are covered by different techniques and by gamma rays and neutrinos
- Need to **fill the sensitivity gaps** and to **extend the energy coverages** for future multimessenger astrophysics (2030–)

SiPMs for CTA LSTs

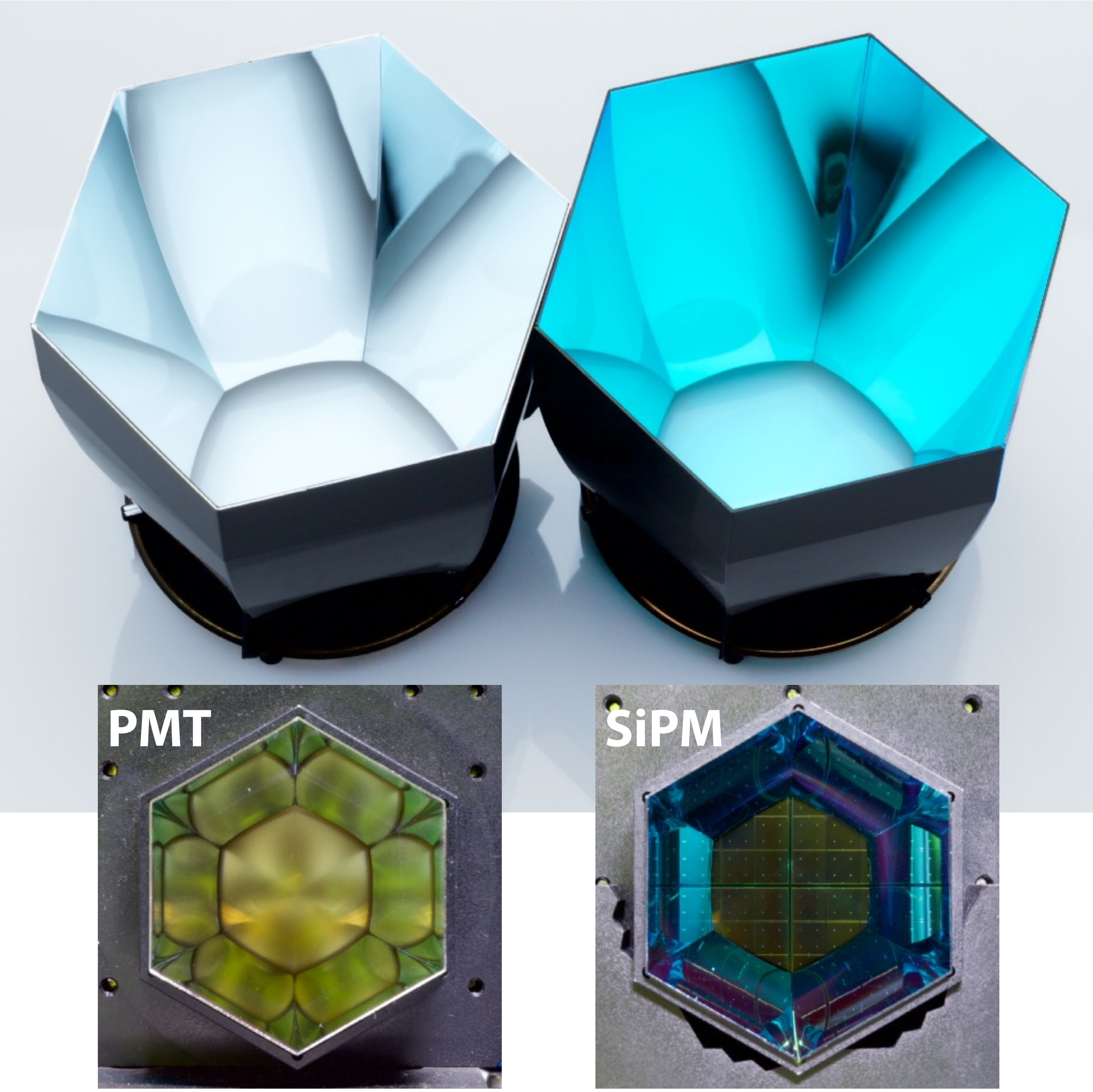


with T. Saito (ICRR), T. Yamamoto (Konan)

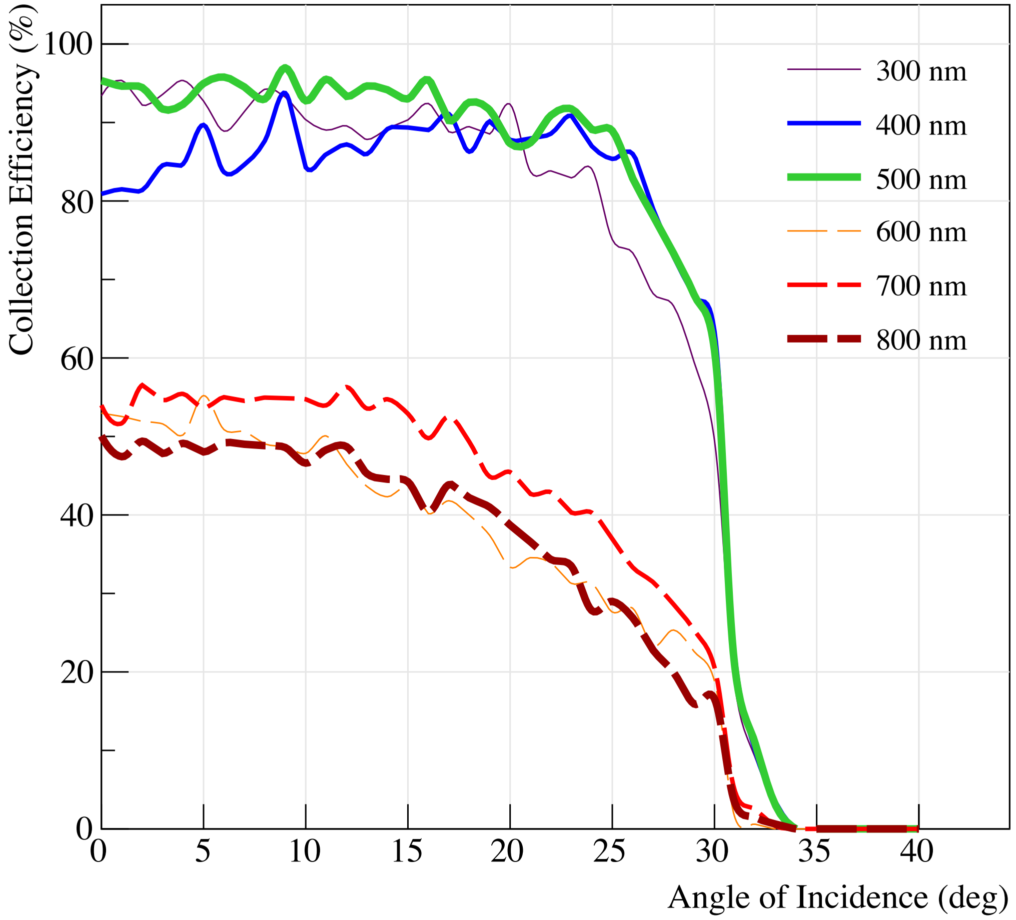


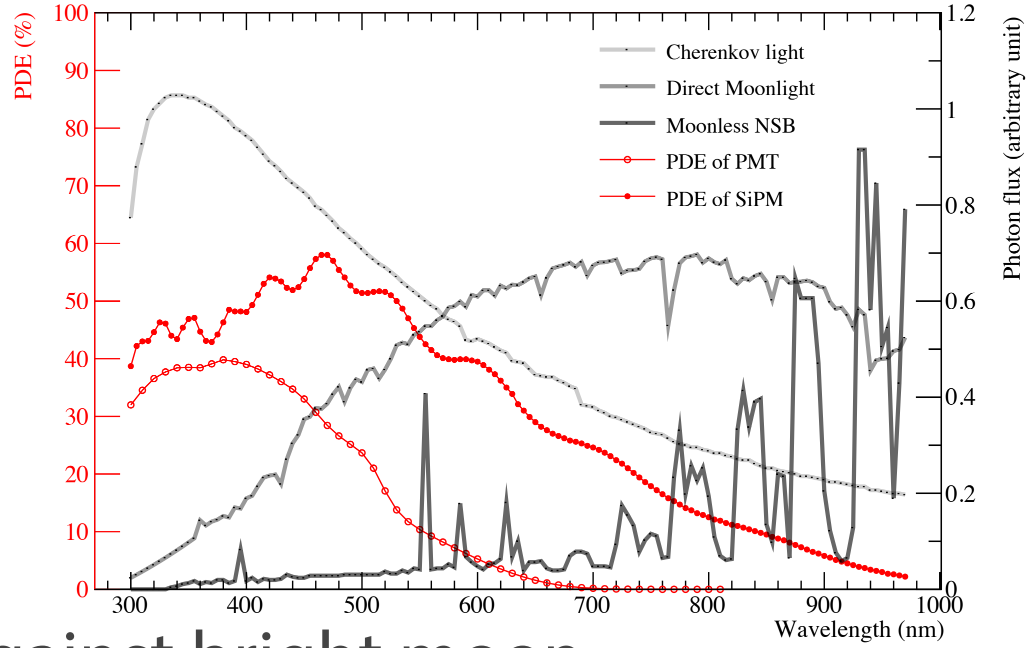
- Compact pixelization will fully exploit the LST optics resolution and improve the signal to noise ratio
- Better angular resolution for gamma-ray events is expected
- Highly tolerant against bright moon sky

Multilayer Coating



Okumura et al. (ICRC2023)





- SiPMs will bring better PDE and tolerance against bright moon
  → Lower energy threshold, longer observation time, and finer pixels
- Novel absorptive 8-layer coating achieved by additional thin (~10 nm) Al layer

Summary

- CTA SSTs will be in charge of the highest-energy band observations
- >10 years have past since the early development stage and finally the first SST of the **final** design is coming in 1–2 year
- Searching southern PeVatrons together with ALPACA and SWGO will start bring new results from late 2020s

- SiPM technology can be used for LSTs and other projects in the future