Status of the Schwarzschild-Couder Telescope project: Exploring an innovative technology for gamma-ray astrophysics

TeVPA, Chicago

Reshmi Mukherjee (Barnard College, Columbia University) for the CTAO SCT group

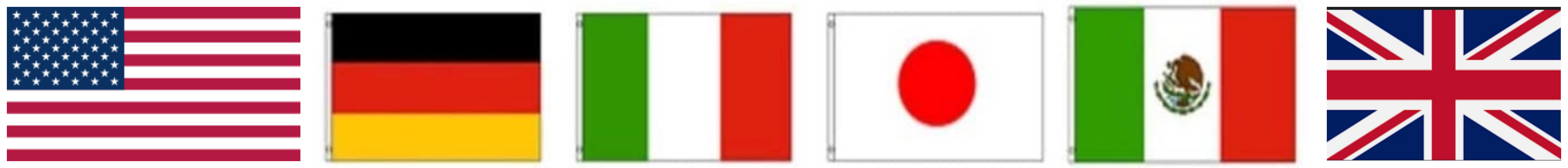
Outline

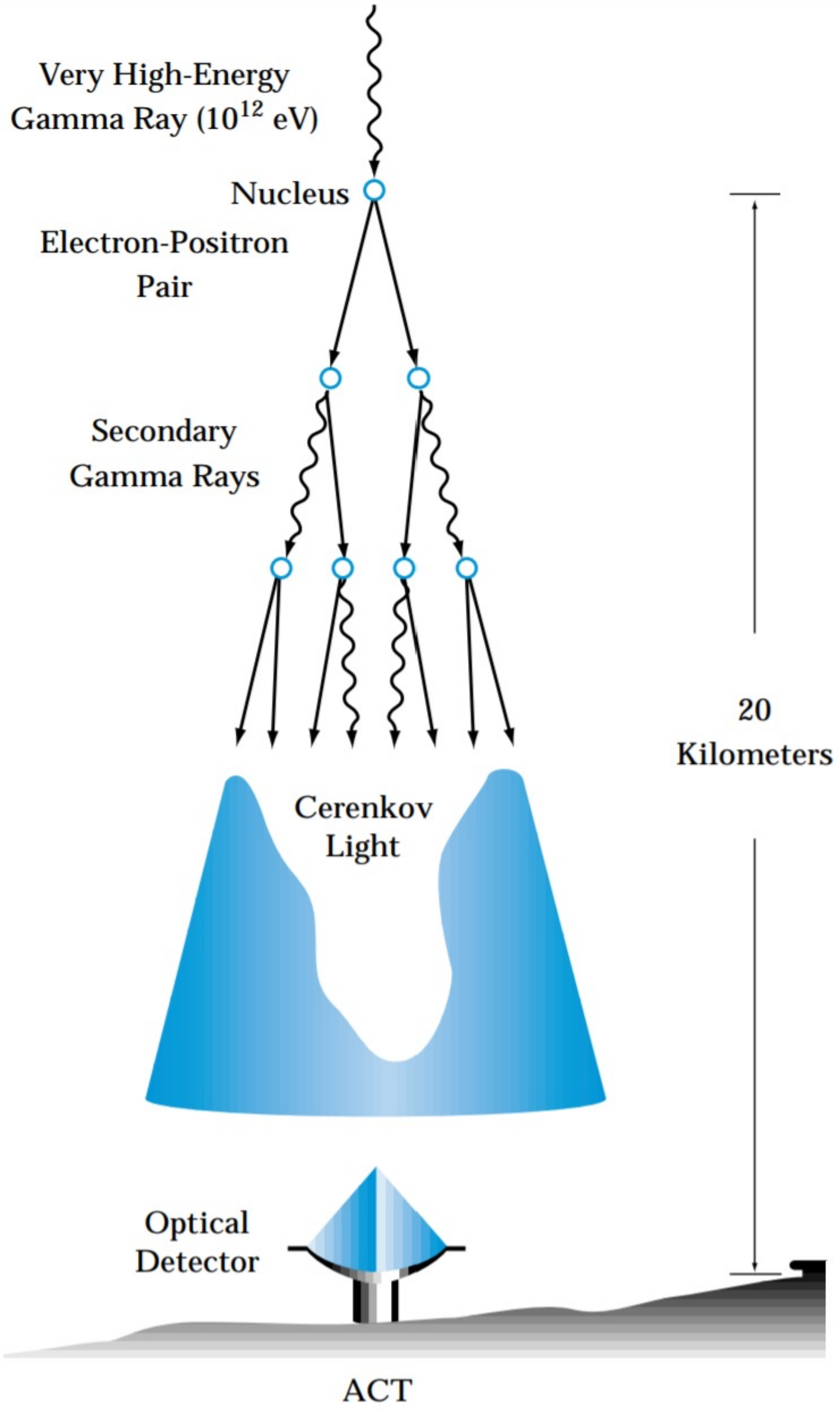
- Introduction to CTAO
- Need for new IACT technology
- Design of Schwarzschild-Couder Telescope (SCT)
- Performance of SCT
- Expected improvement to CTAO science
- Current status and future plans

pSCT funded by 3 NSF MRI awards

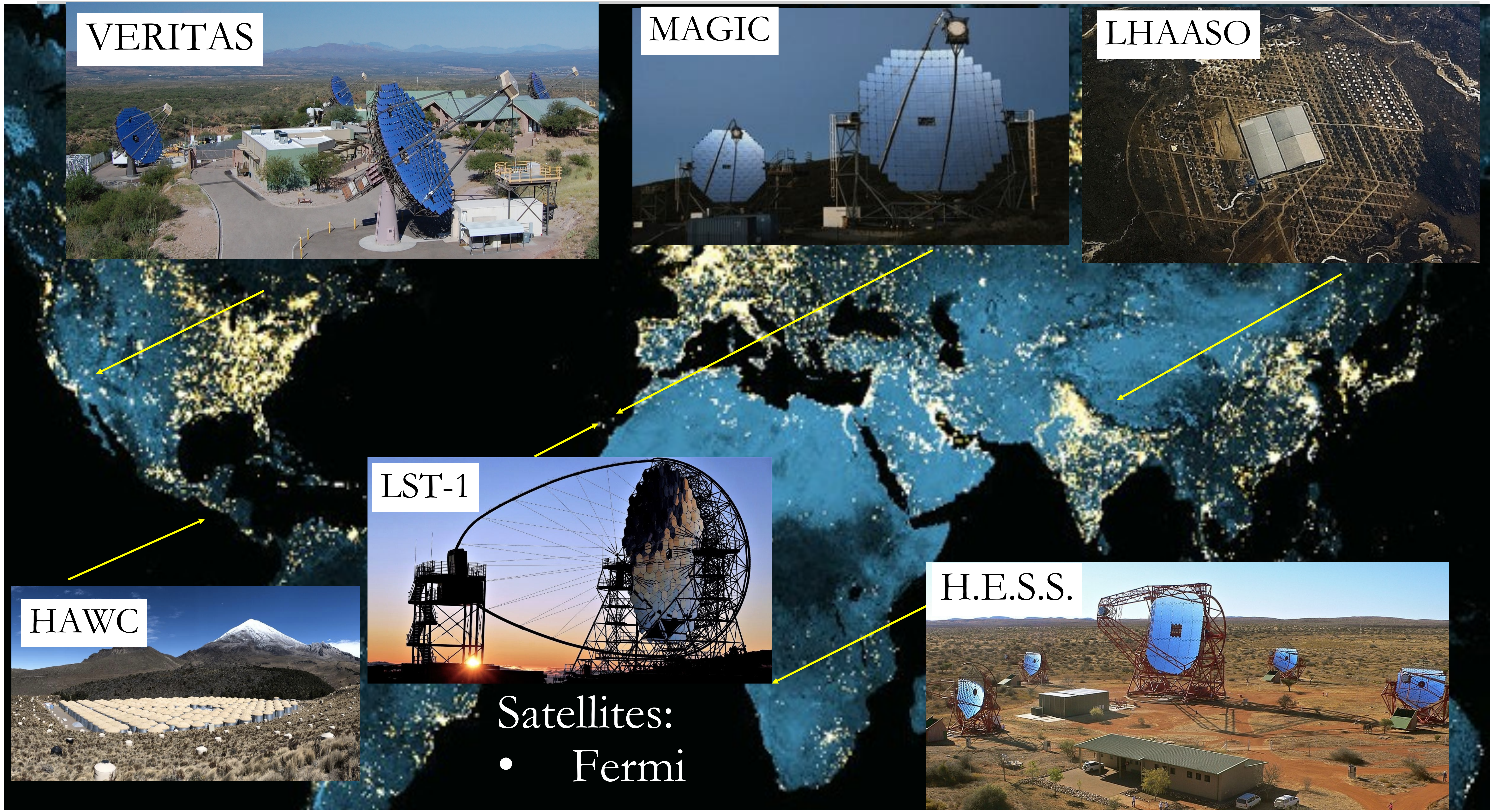
- SCT Telescope MRI (2012-2018)
- SCT Camera upgrade MRI (2018-2025)
- SCT/MST Optical Alignment MRI (2023-2026)

+ Multiple International Partners





Current Gamma-ray Instruments



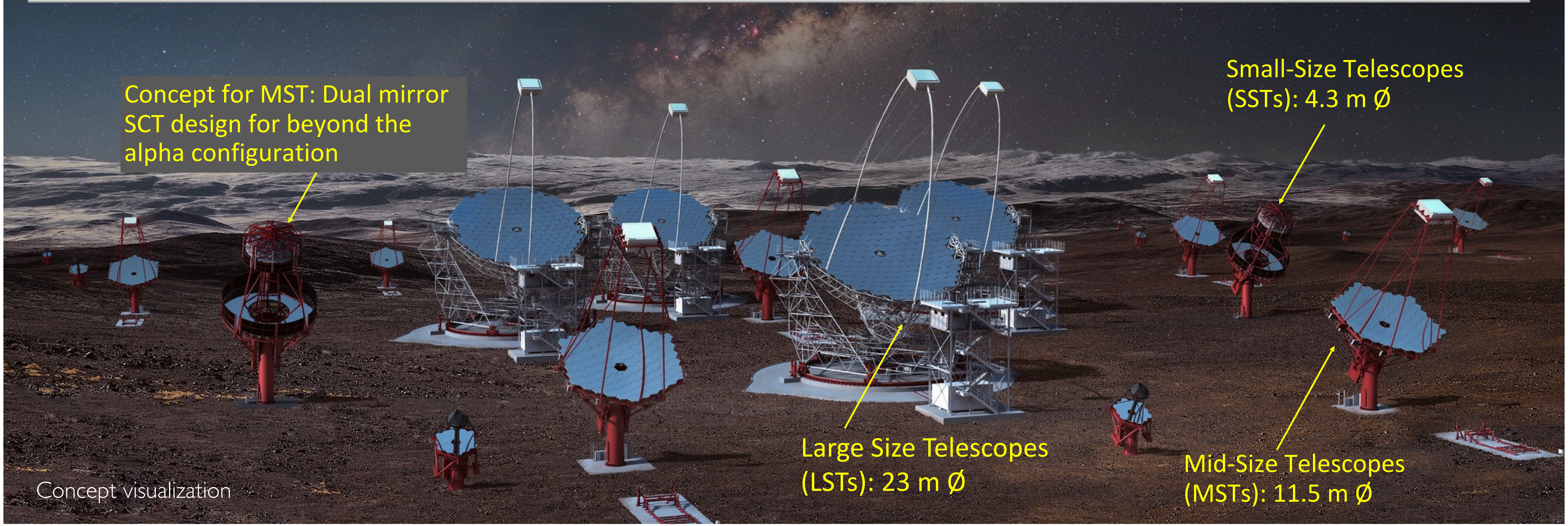
National Geographic Night Sky Map

The Status of CTAO

CTAO

- Next-generation Cherenkov Telescope Array Observatory. Consortium: 1,500 members, from over 150 institutes in 25 countries
- Originally envisioned: ~ 100 telescopes of 3 different sizes
- Alpha configuration (defined 2022): (Southern Array: 14 MSTs + 37 SSTs; Northern Array: 4 LSTs + 9 MSTs)
- Expected to improve sensitivity by ~ factor 10 compared to existing facilities (H.E.S.S., MAGIC, VERITAS)
- Extend energy coverage: ~ 10 GeV - >100 TeV
- Alpha config. Expected to be fully operational ~ 2028-29

See talk by Manuel Meyer



Need for fine angular resolution

- At lower energies (< 1 TeV), the telescope operates in a background dominated regime
  - Gamma-ray showers: clean and narrow
  - Hadronic showers: broad and messy
- The angular resolution has a major impact on gamma-ray sensitivity
- Transverse angular size of the gamma-ray shower core is ~ 1 minute of arc
- Current generation IACT instruments have pixel size of 9 arcmin (far from optimal!)

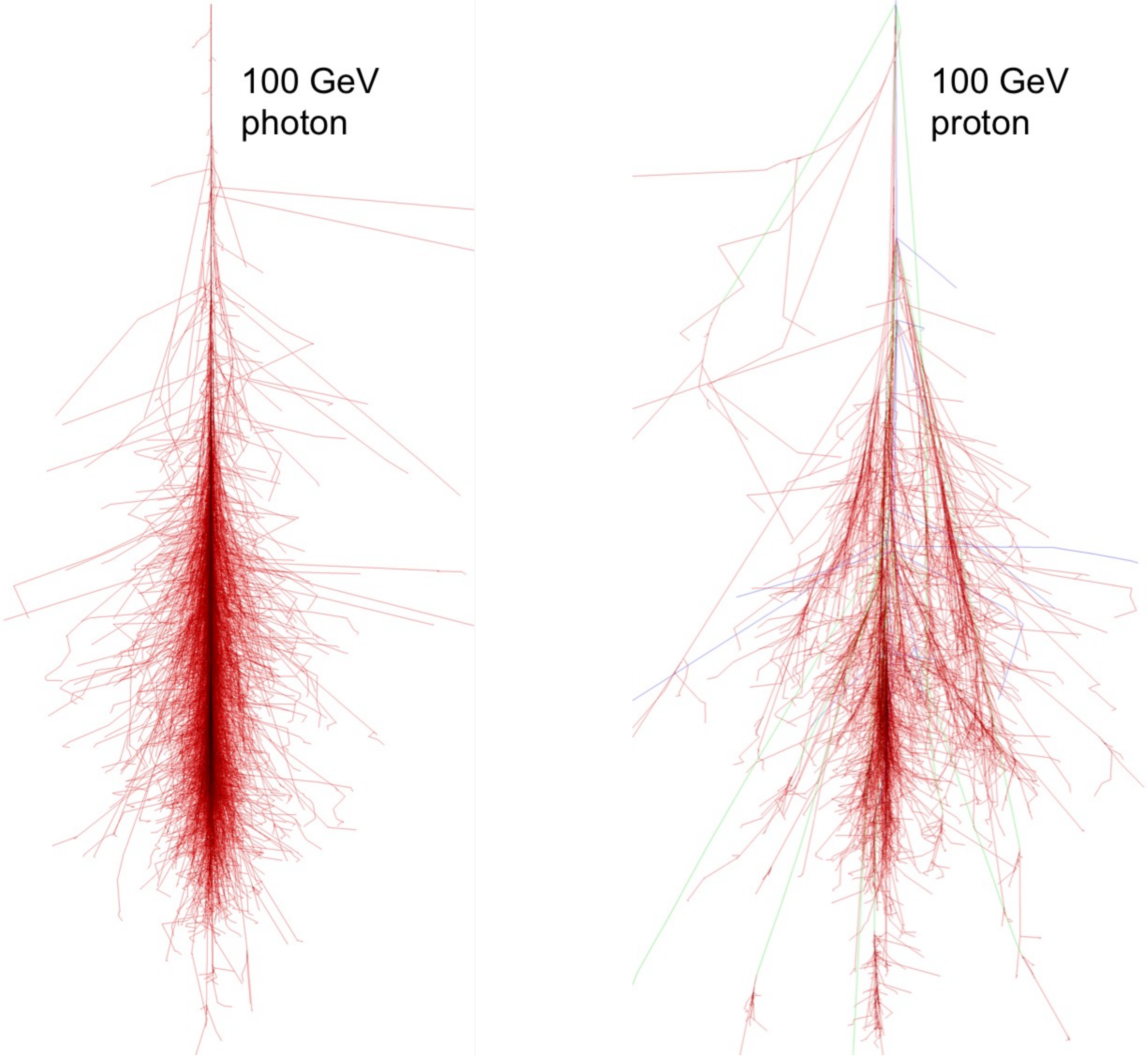
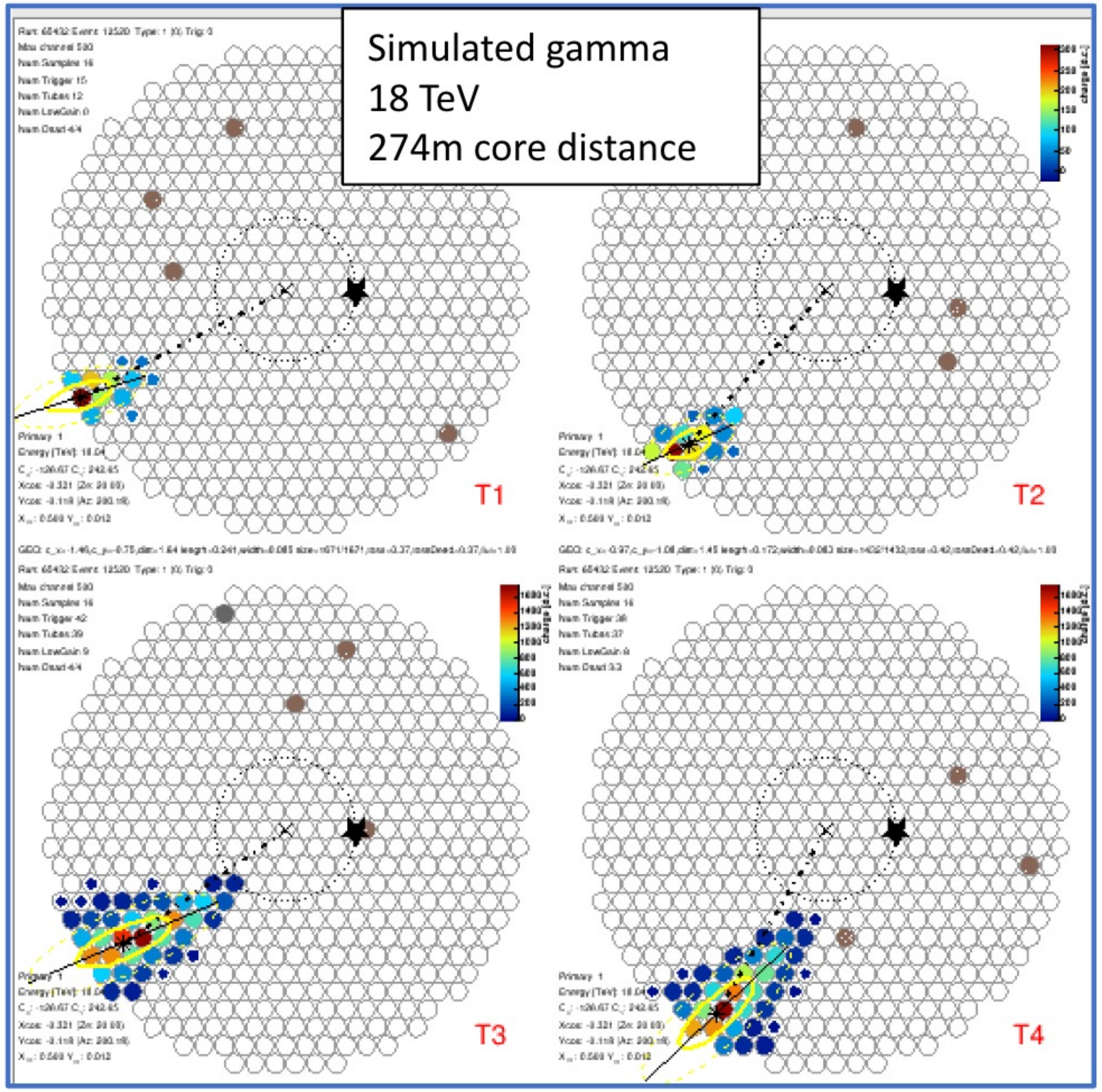


Image from: J. Holder arXiv:1510.05675

Need for large field of view

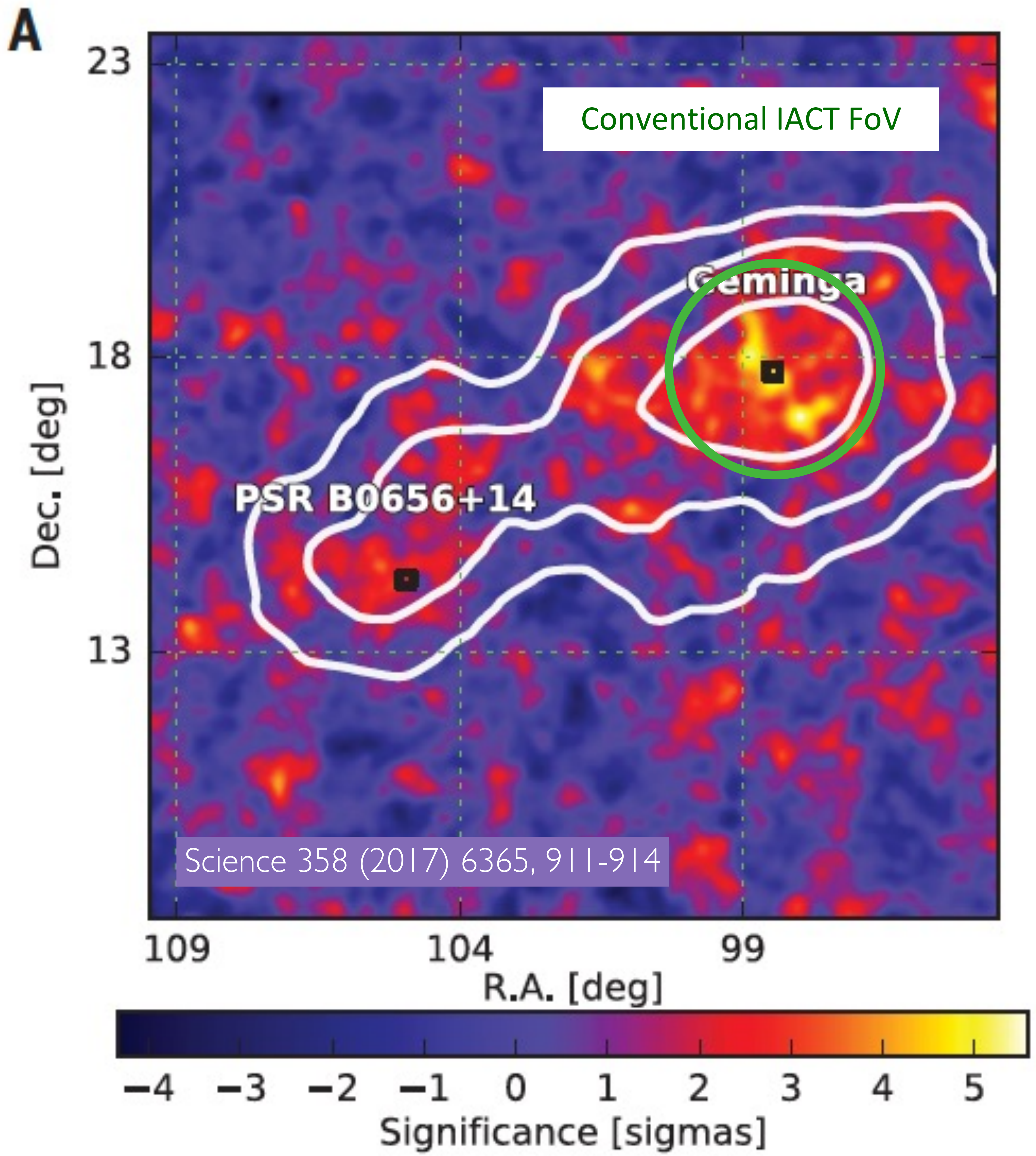
- At high energies, images at large core distance are truncated by the camera FoV
- Conventional IACTs have a FoV* ~ 4 deg
- Need a large FoV without degradation of sensitivity at large offset angle



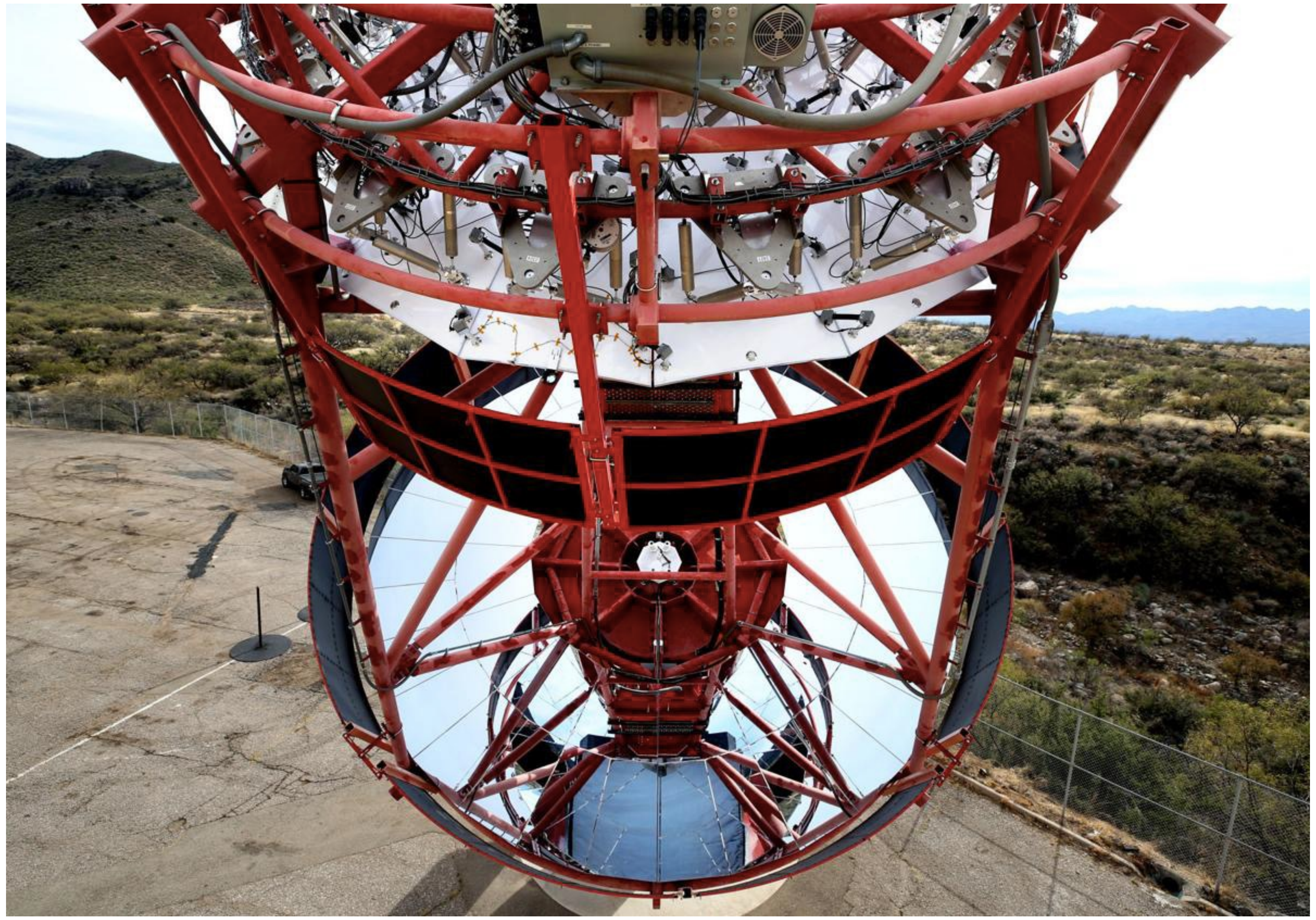
* FoV: field of view

Need for large field of view

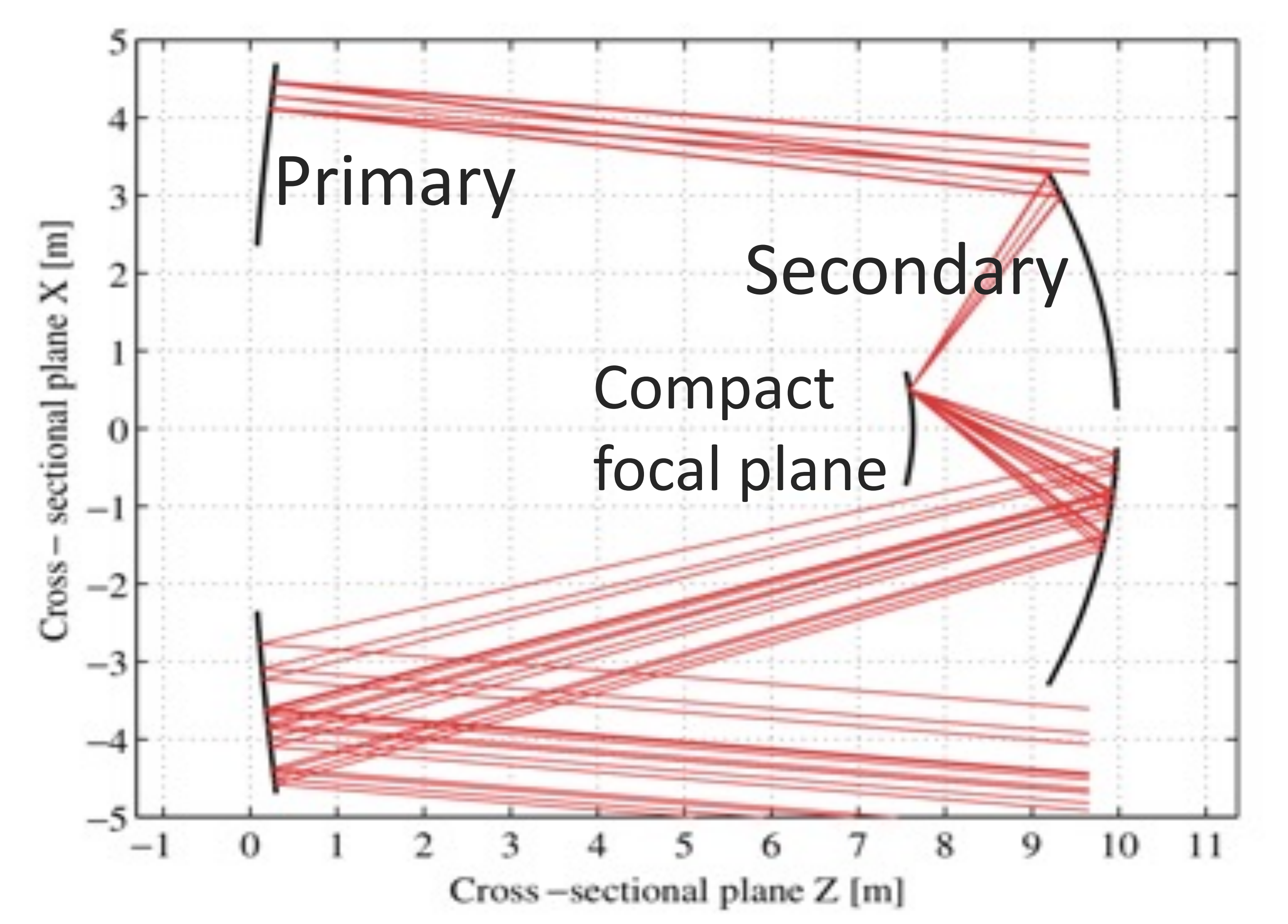
- Conventional IACTs maintain good PSF up to an offset angle of ~ 2 deg
- For sources with large extension (e.g. Geminga halo radius > 5 deg), analyses are difficult without a γ-ray free background region in FoV
  - TeV halos are key for understanding positron excess
  - Ideally, contain Geminga halo emission in a single pointing
- To improve angular resolution by ~3x and field of view by ~3x, need:
  - A camera with ~ 10^5 pixels
  - Note → current IACTs have ~ 10^3 pixels



The Schwarzschild-Couder Telescope (SCT)



- Aplanatic dual mirror optical system: Correction of spherical and comatic aberrations + Increased FoV
- Minimization of astigmatism, thanks to curved focal plane
- Demagnification of shower images → compatible with a compact high-resolution SiPM camera



V.Vassiliev et al. Astroparticle Physics 28 (2007) 10

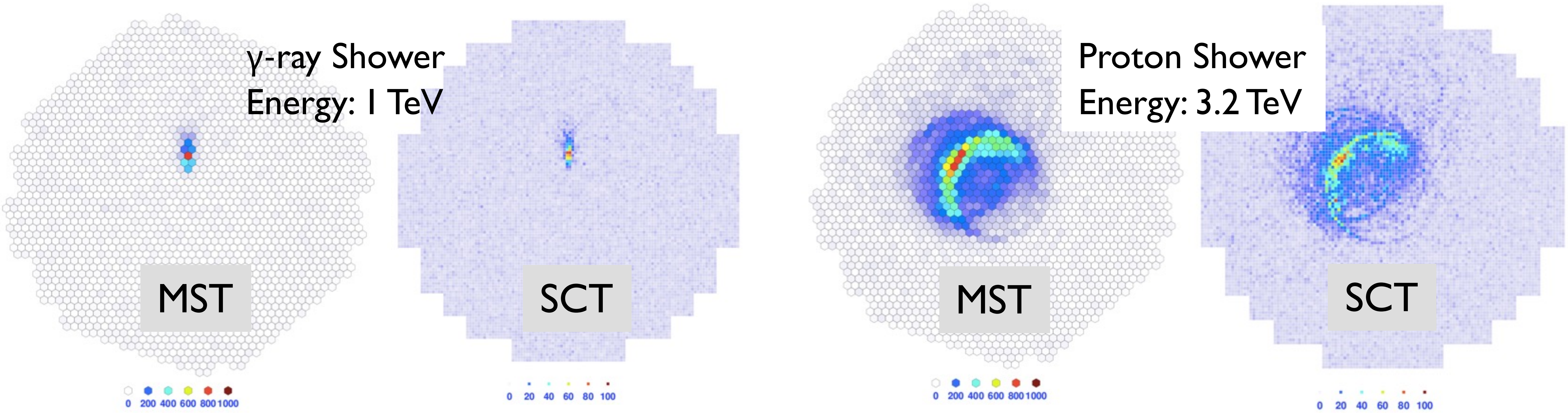
- By focusing the light on a smaller surface, the technique enables the use of state-of-the-art sensors (SiPMs) and electronics
- Better sensitivity and reduced observation time

Key Characteristics of the prototype (p)SCT

- **Dual-mirror design:**
    - Correct for spherical and comatic aberrations
    - Small plate scale
    - Large field of view
    - Large telescope aperture
- **Compact high-resolution camera:**
    - Silicon photomultipliers
    - 11328 pixels
    - Each pixel 0.067°(6 mm) square (PSF 0.05-0.07 °)
    - 8° field of view
- R&D funded by NSF + international partners happening in the US
- US contribution aims for best enhancement of CTAO science capabilities depending on the available US funding. Favored strategy at present: Add SCTs to Southern Array

The pSCT at the FLWO, Arizona

The SCT: big eyes with a sharper view



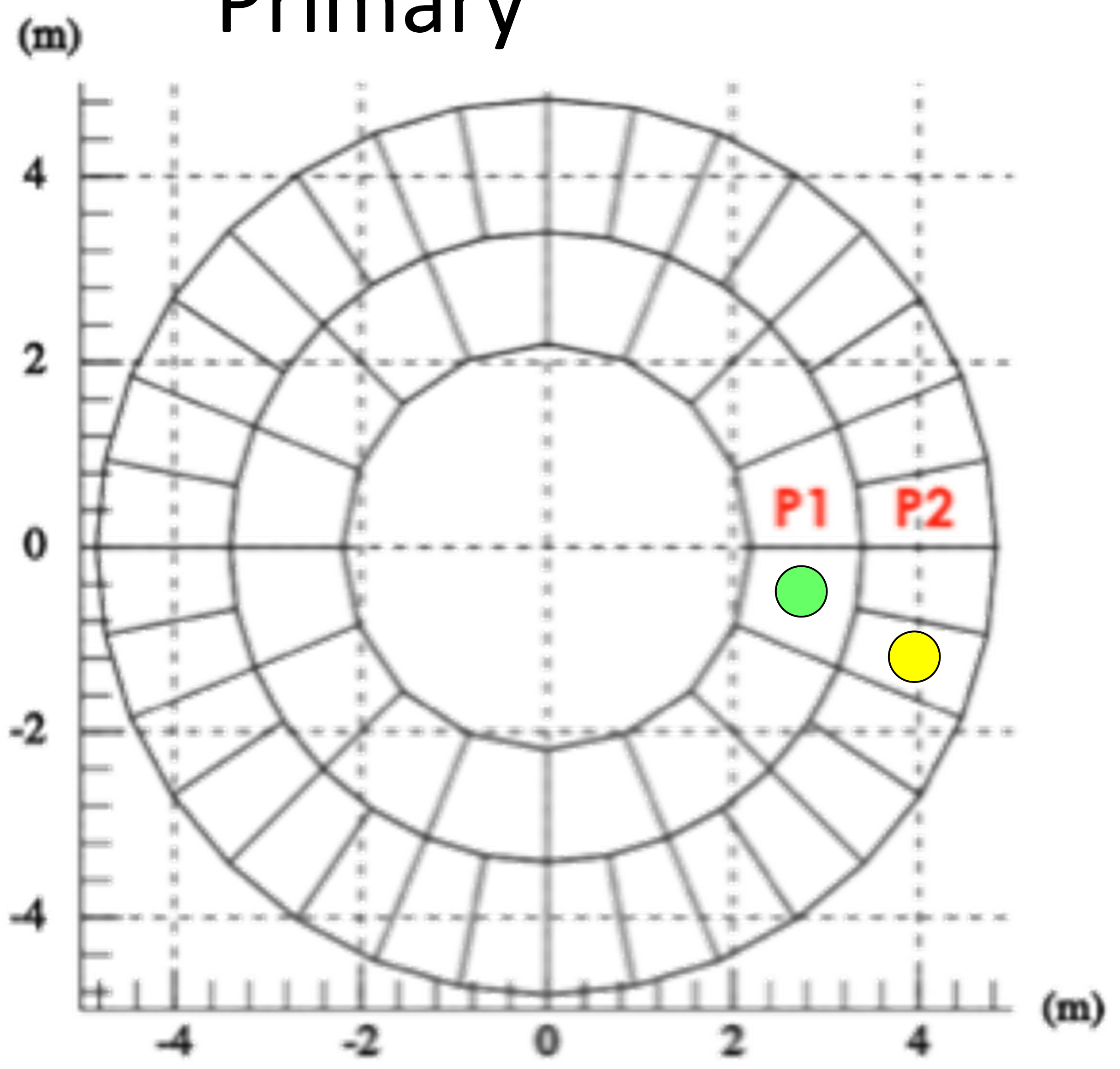
DC-MST Images
7.7° field of view, 0.17° pixels
1,855 channels

SCT Images
8° field of view, 0.067° pixels
11,328 channels`

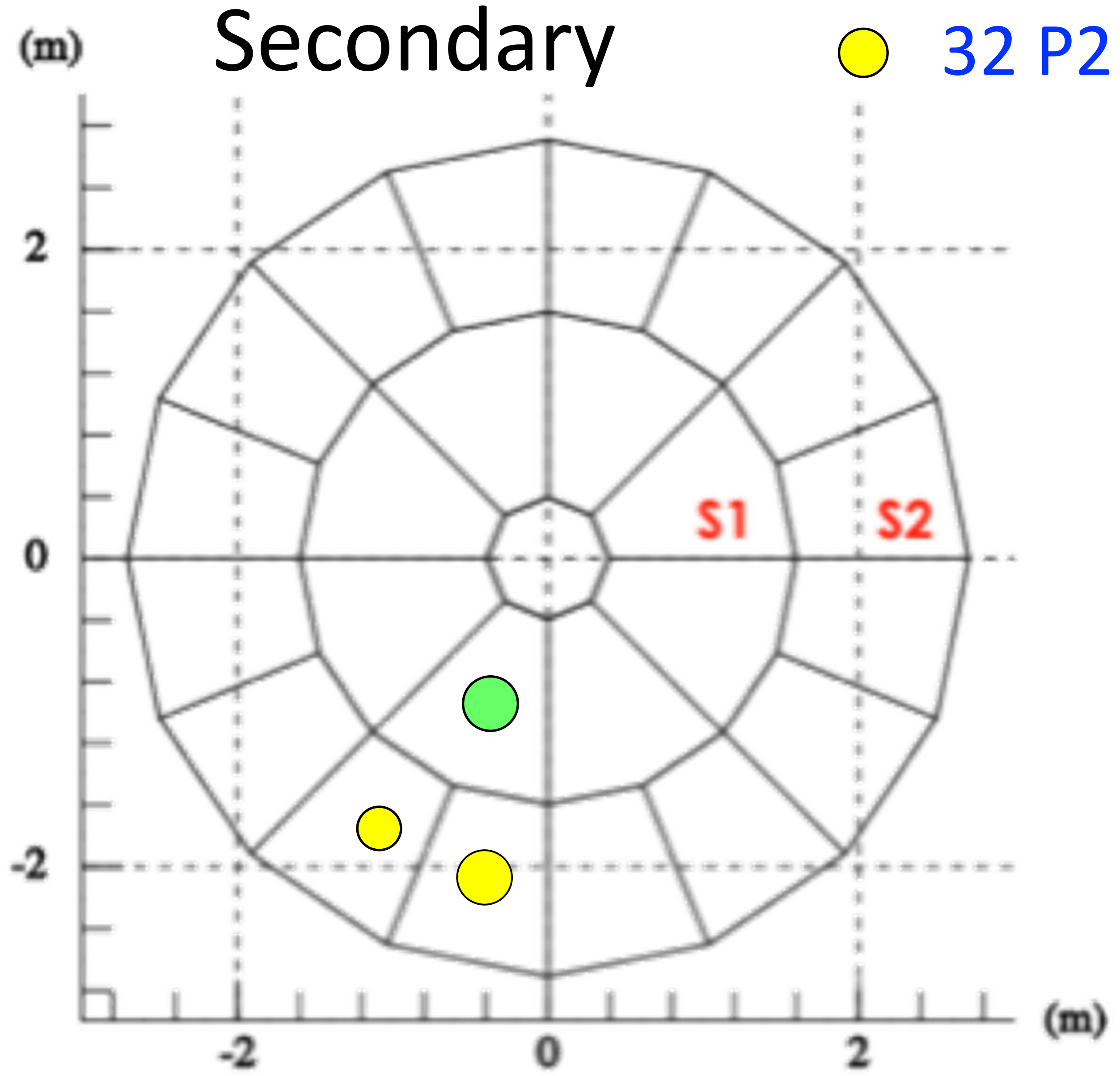
- Superior optical angular resolution over a wide (~8°) field of view
- MST Single Mirror Davies-Cotton ~2k PMTs
- MST Dual Mirror Schwarzschild- Couder ~12k SiPMs
- Better gamma-ray PSF across the FoV for morphology, survey, and transients

pSCT: The Optical System

Primary

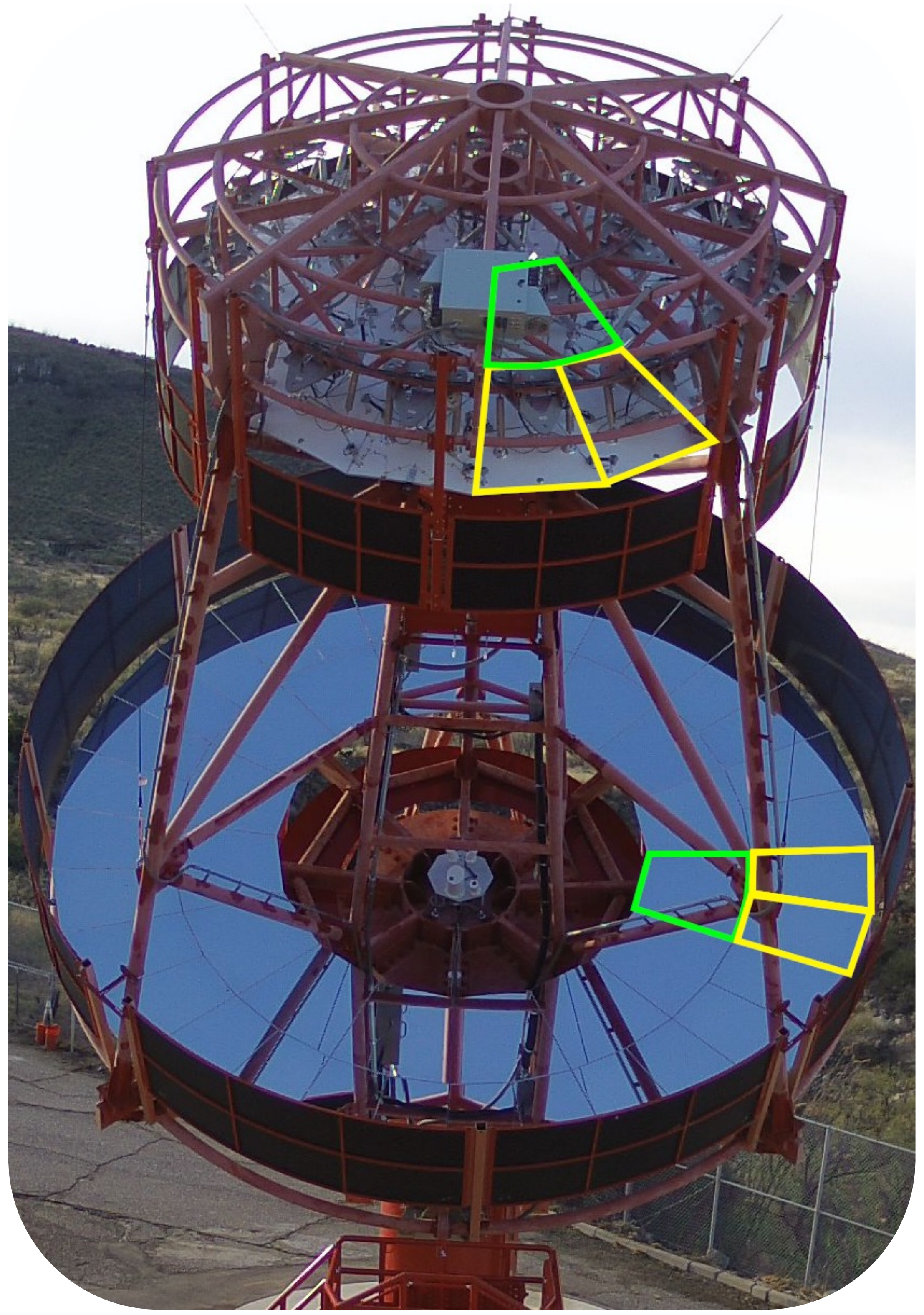


Secondary



16 P1 and 8 S1

32 P2 and 16 S2



https://cta-psct.physics.ucla.edu/

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Verification of the Optical System of the 9.7-m Prototype Schwarzschild-Couder Telescope
https://arxiv.org/pdf/2010.13027.pdf

Primary mirror: radius 4.83 m

- segmented into 48 panels
- inner-ring panel (P1) area 1.33 m^2
- outer-ring panel (P2) area of 1.16 m^2

Secondary mirror: radius 2.71 m

- Segmented into 24 panels
- inner-ring (S1) and outer ring (S2) area 0.94 m^2, each

Alignment for the pSCT optical system

- Stewart platform to control optics
- 3 steps for the commissioning alignment of the pSCT optical system
  - Laboratory calibration of Mirror-Panel Edge Sensors (MPESs)
  - Alignment using MPESs
  - Alignment using defocused images of stars

https://cta-psct.physics.ucla.edu/

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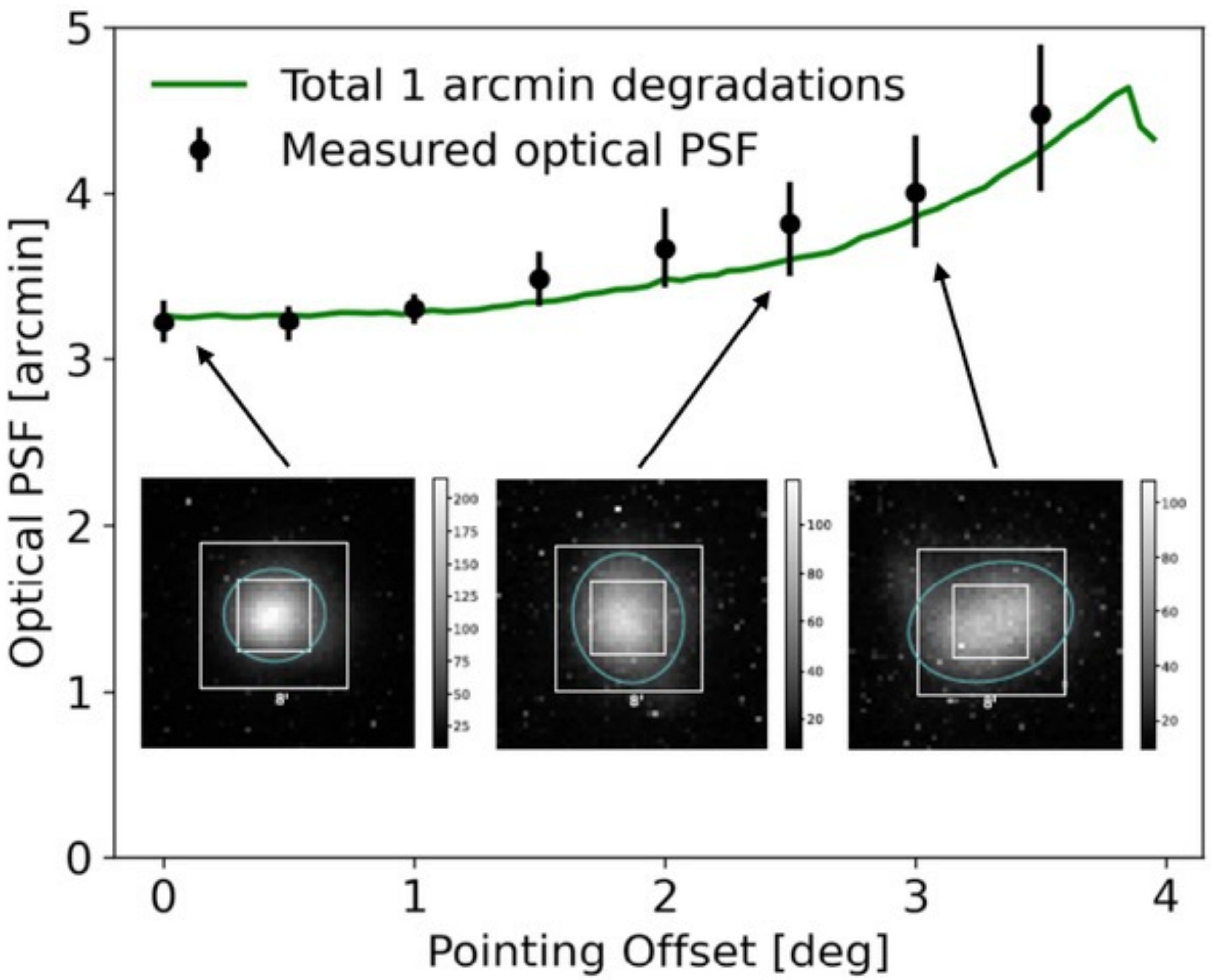
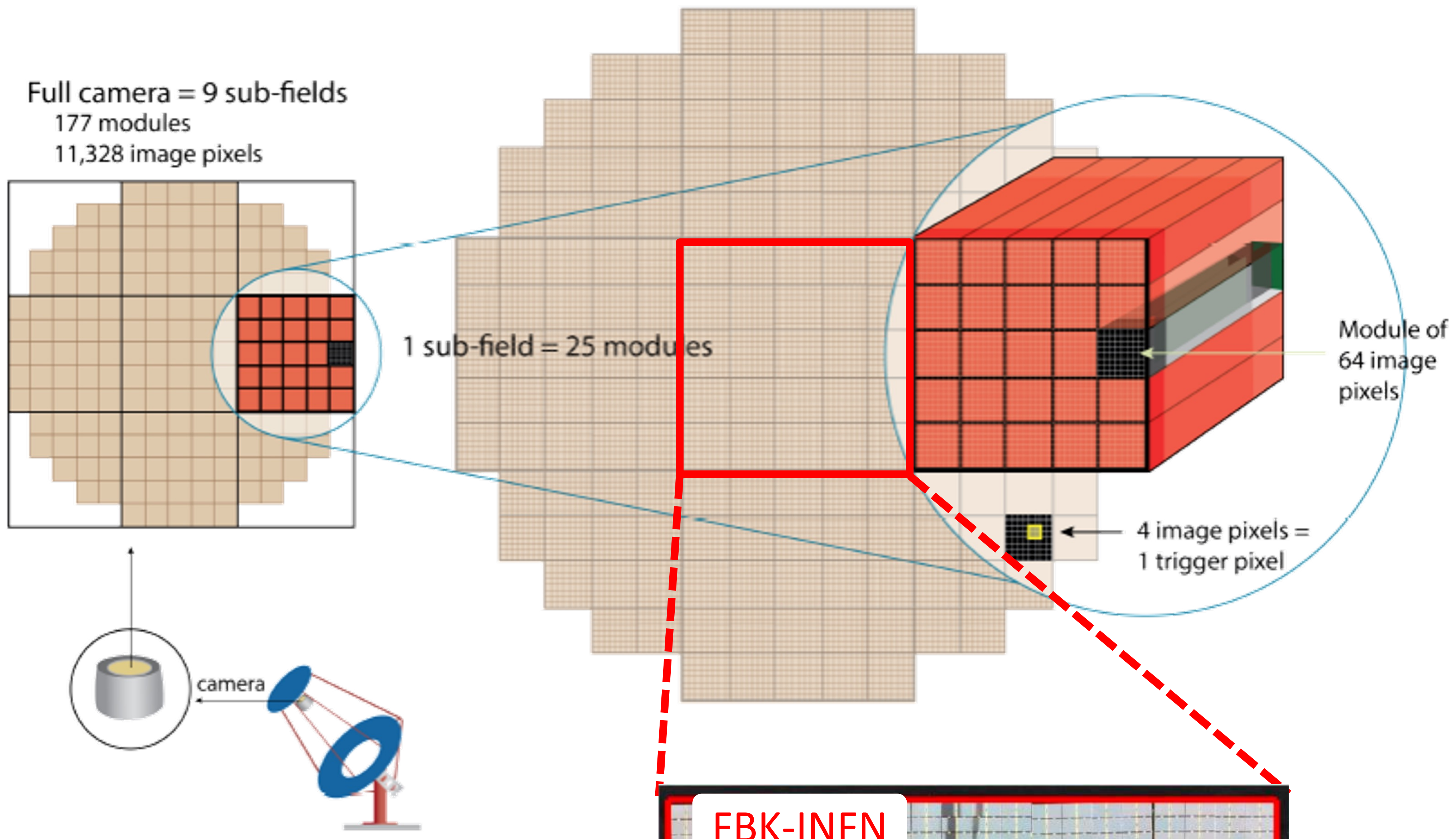
Optical performance

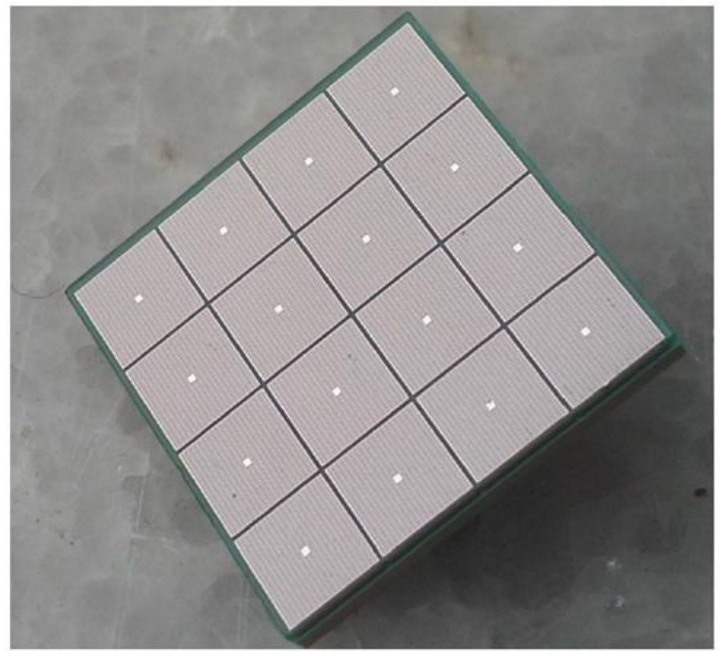
- The full alignment of the optical system across the 8-deg FoV was initially completed in 2022
- The optical PSF is ~ 3.2 arcmin on-axis and ~ 4.2 arcmin at 3.5-deg off-axis.
- Good PSF is maintained across the 8-deg FoV!



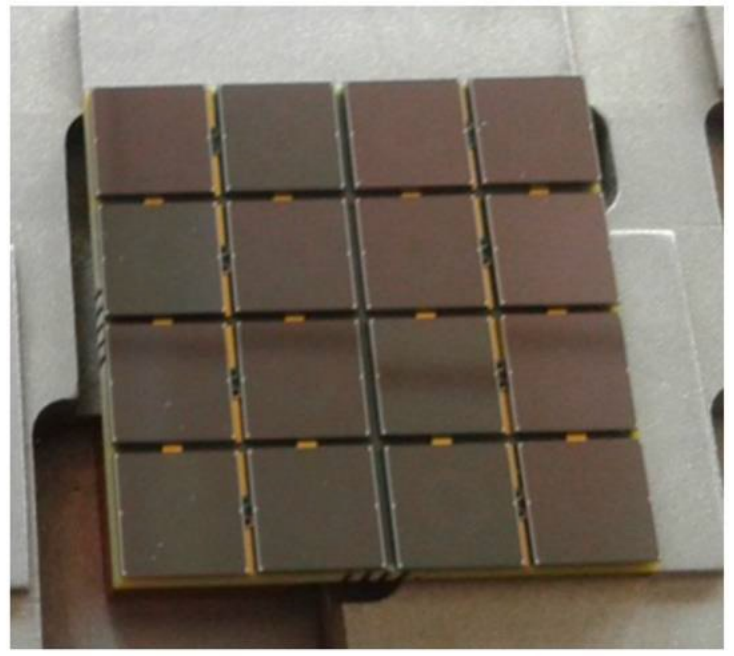
pSCT Camera

- **SiPM pixels** provide much higher-resolution air shower image
  - **Better angular resolution**
  - **Better background rejection**
- **Modular design**
  - 9 sectors (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
- **Pre-upgrade 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 mm^2) Silicon Photomultipliers (SiPMs)

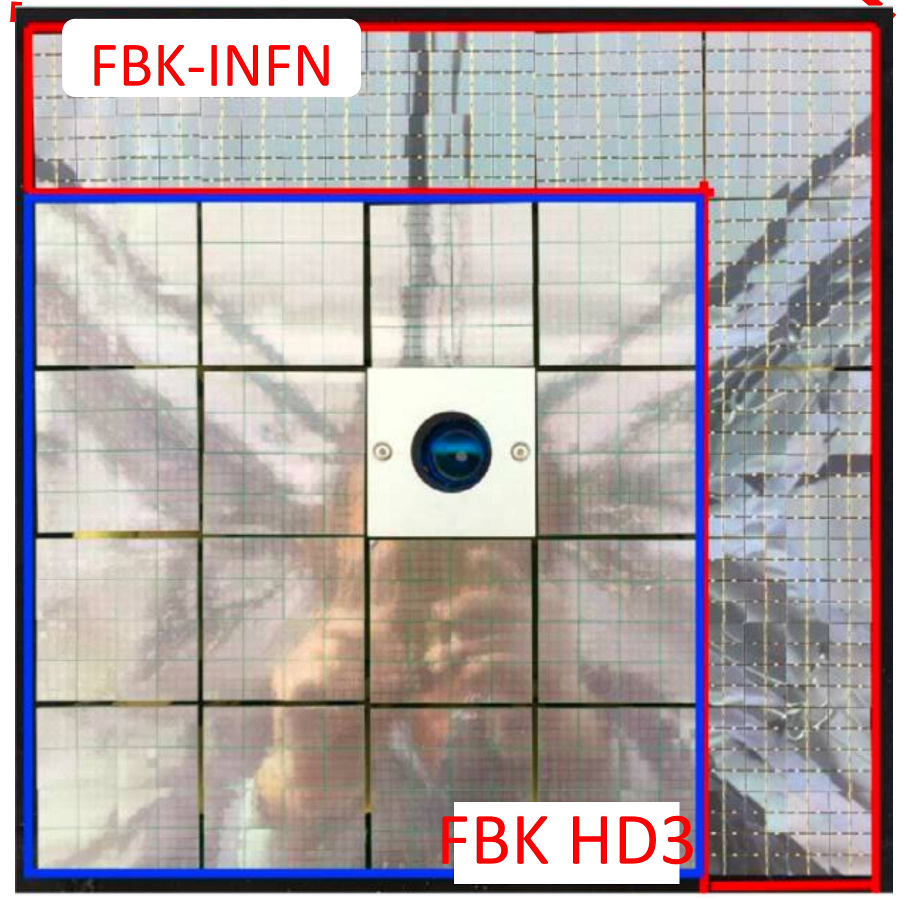




Hamamatsu MPPC FBK



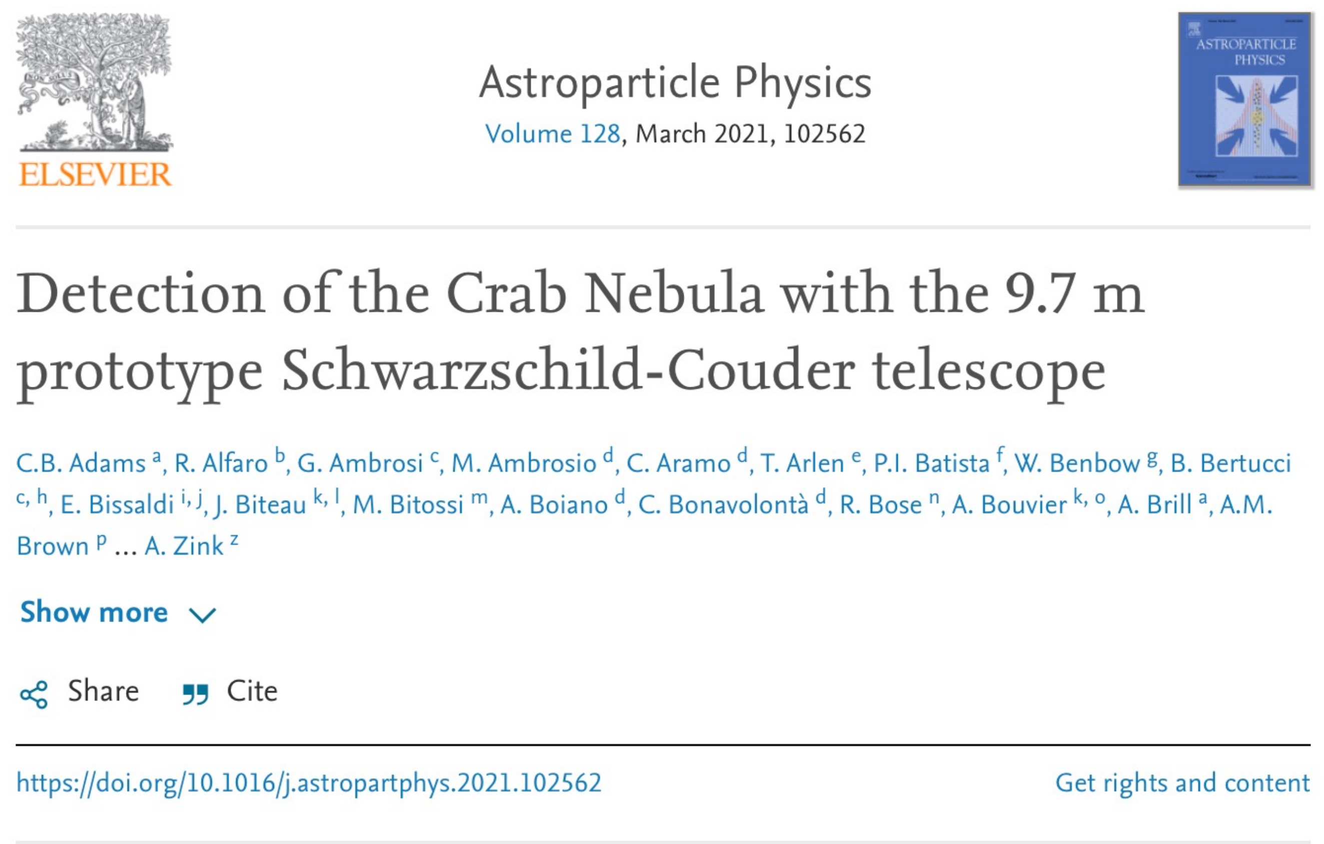
FBK HD3



~2.7° FOV, 0.067° image pixel

Detection of Crab Nebula

- Crab Nebula is detected at 8.6σ in 2019 with a partial camera
- A major milestone for the demonstration of the viability of SCT technology for CTAO
- The co-location of SCT project with VERITAS observatory at FLWO and simultaneous operation of both instruments has been critical ingredient of this success!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Astroparticle Physics
Volume 128, March 2021, 102562

Detection of the Crab Nebula with the 9.7 m prototype Schwarzschild-Couder telescope

C.B. Adams [a], R. Alfaro [b], G. Ambrosi [c], M. Ambrosio [d], C. Aramo [d], T. Arlen [e], P.I. Batista [f], W. Benbow [g], B. Bertucci [c, h], E. Bissaldi [i, j], J. Biteau [k, l], M. Bitossi [m], A. Boiano [d], C. Bonavolontà [d], R. Bose [n], A. Bouvier [k, o], A. Brill [a], A.M. Brown [p] ... A. Zink [z]

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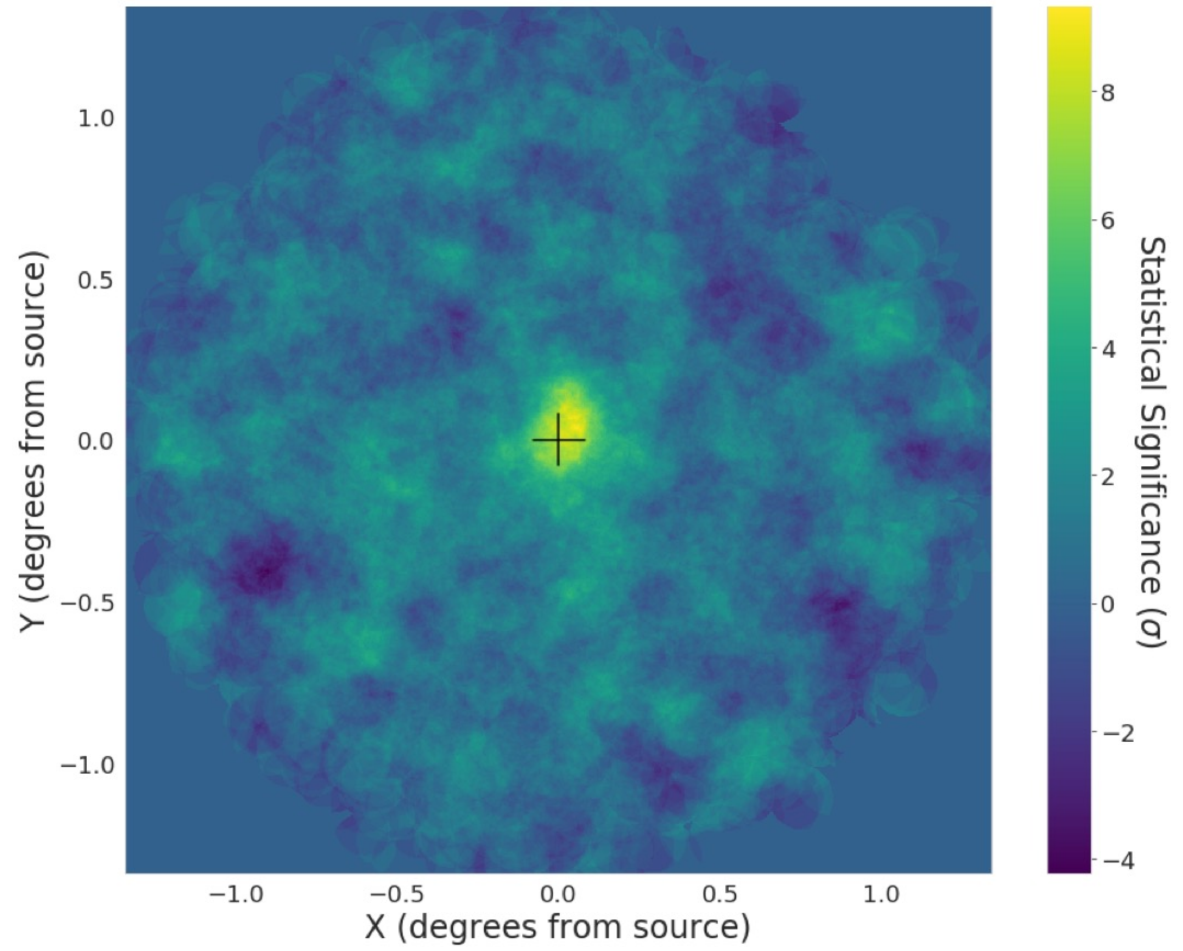
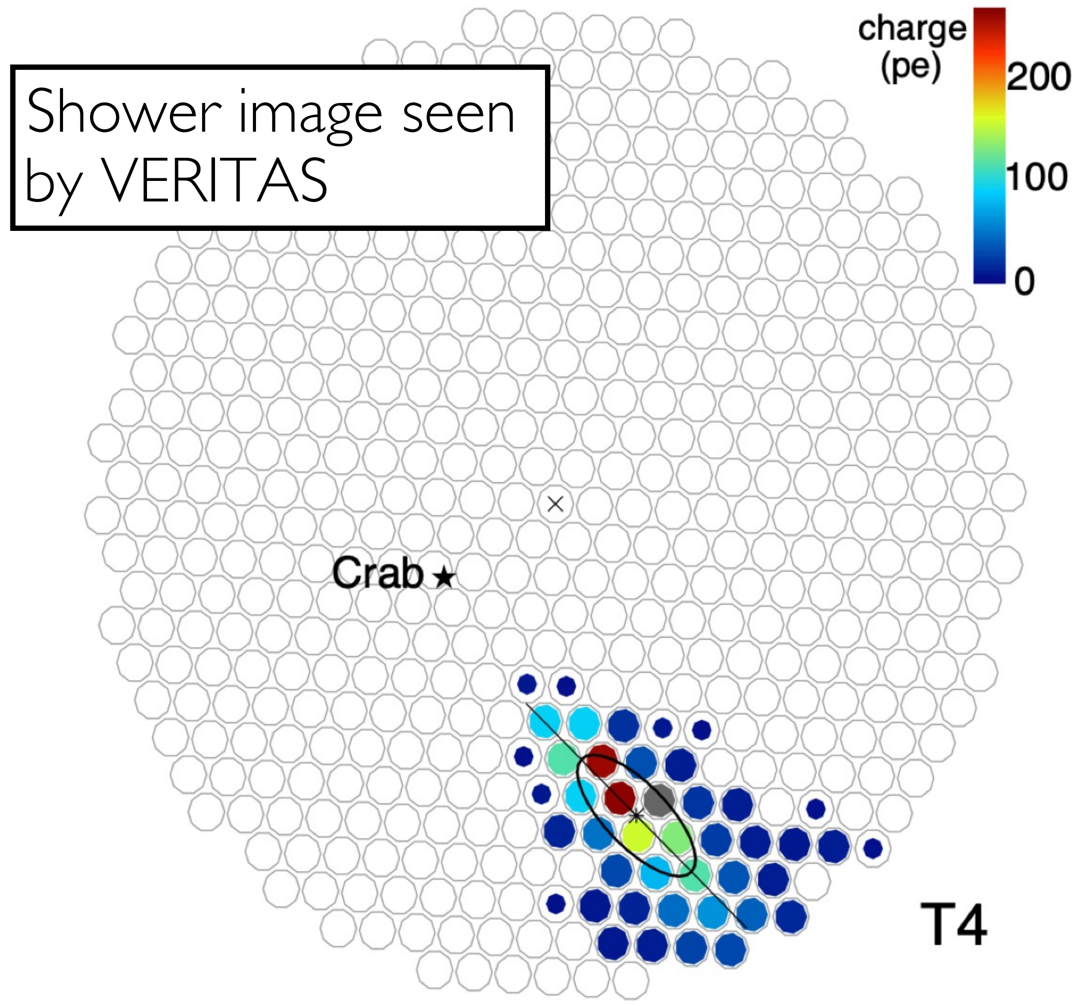
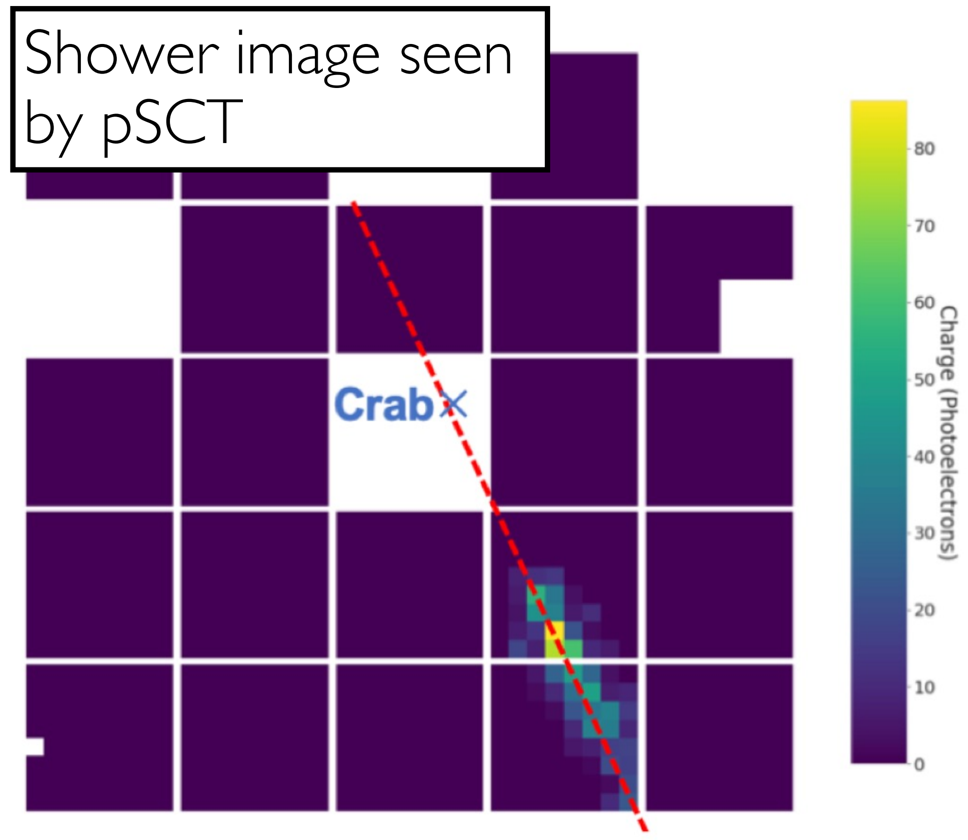






Upgrading the pSCT Camera

- Populate all 9 camera sectors: 177 modules, 11328 pixels
- SiPMs produced by FBK with high PDE and low optical cross talk

- 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 μs 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

SMART ASIC

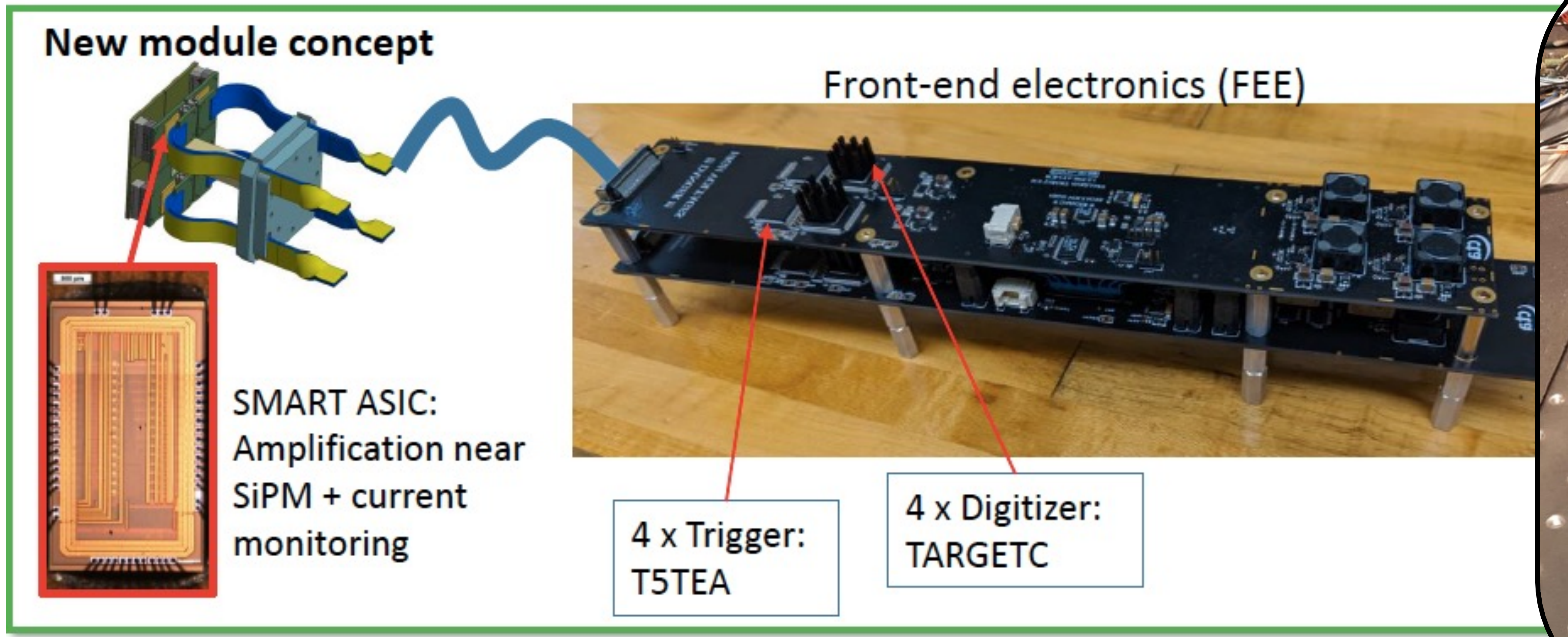
CTC+CT5TEA FEE module

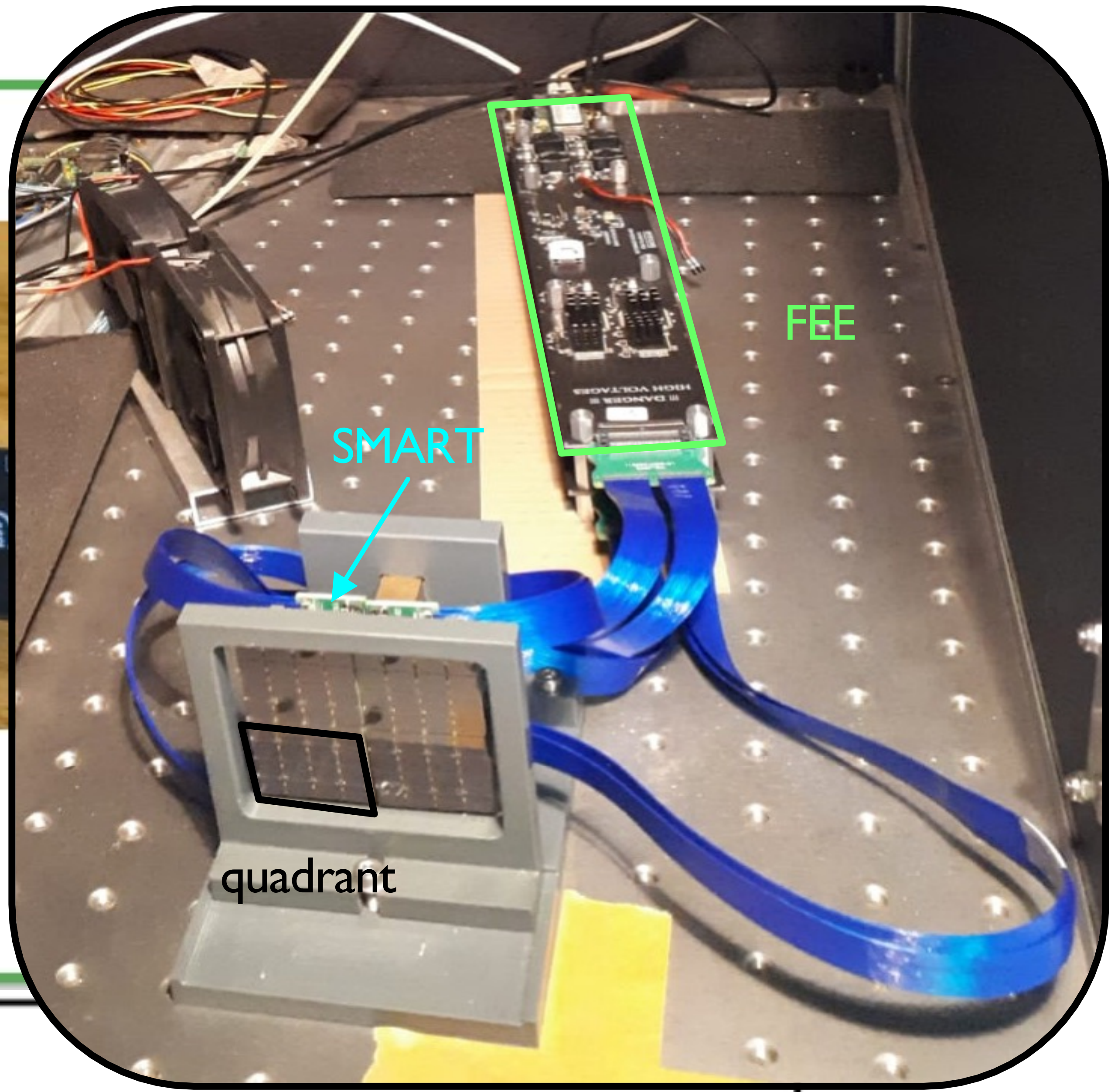
- New backend electronics and mechanics

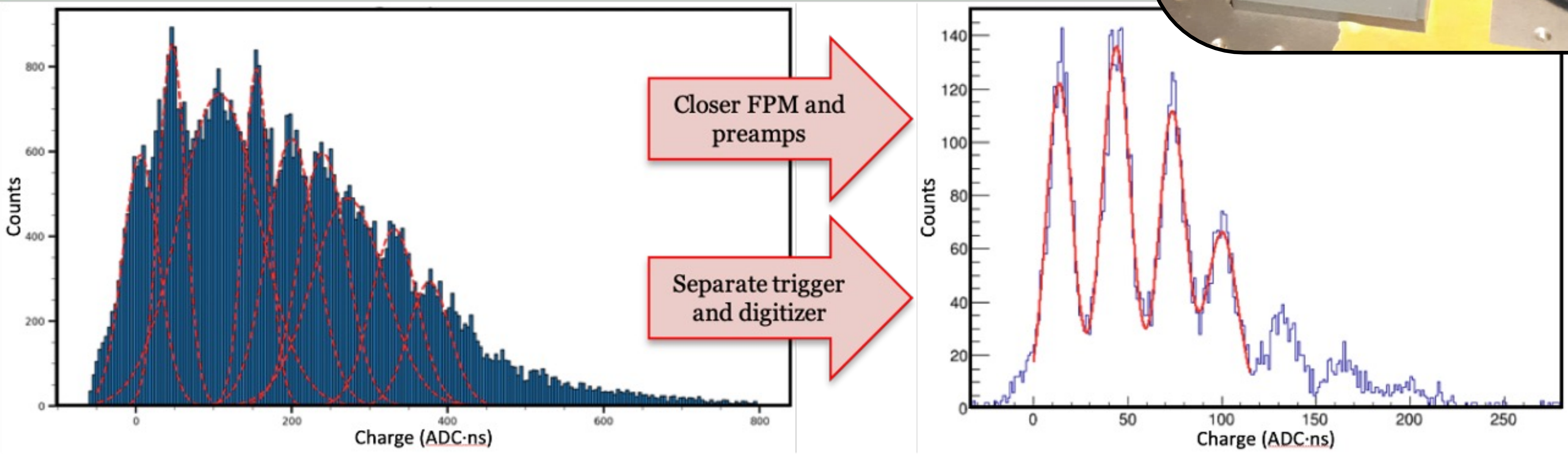
→ Improvement in single photon resolution, lower minimum threshold and lower noise

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

Upgraded pSCT Electronics - Performance

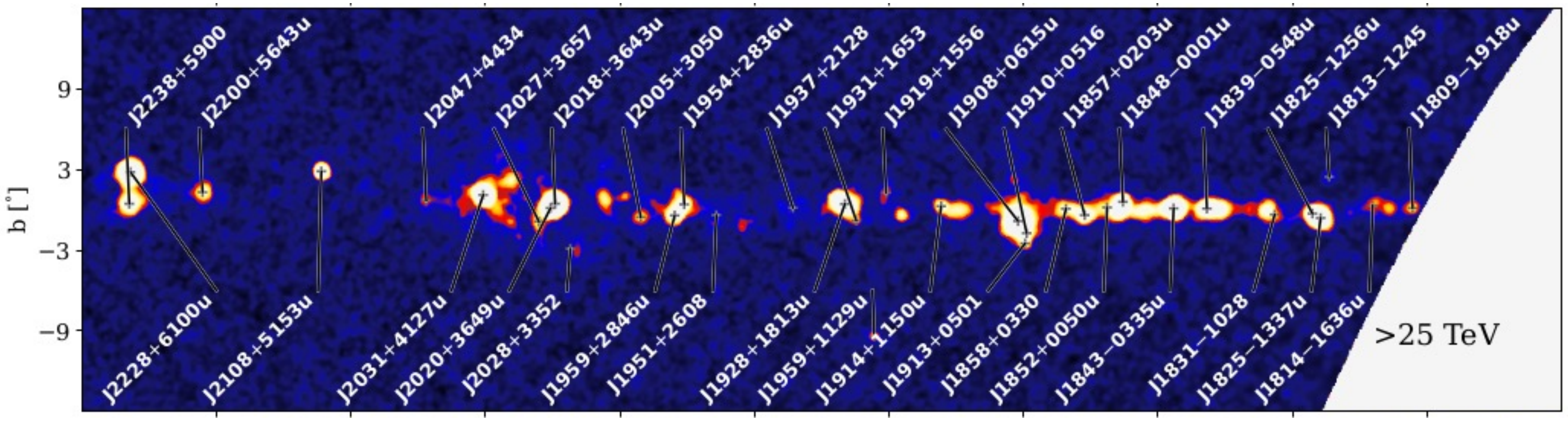






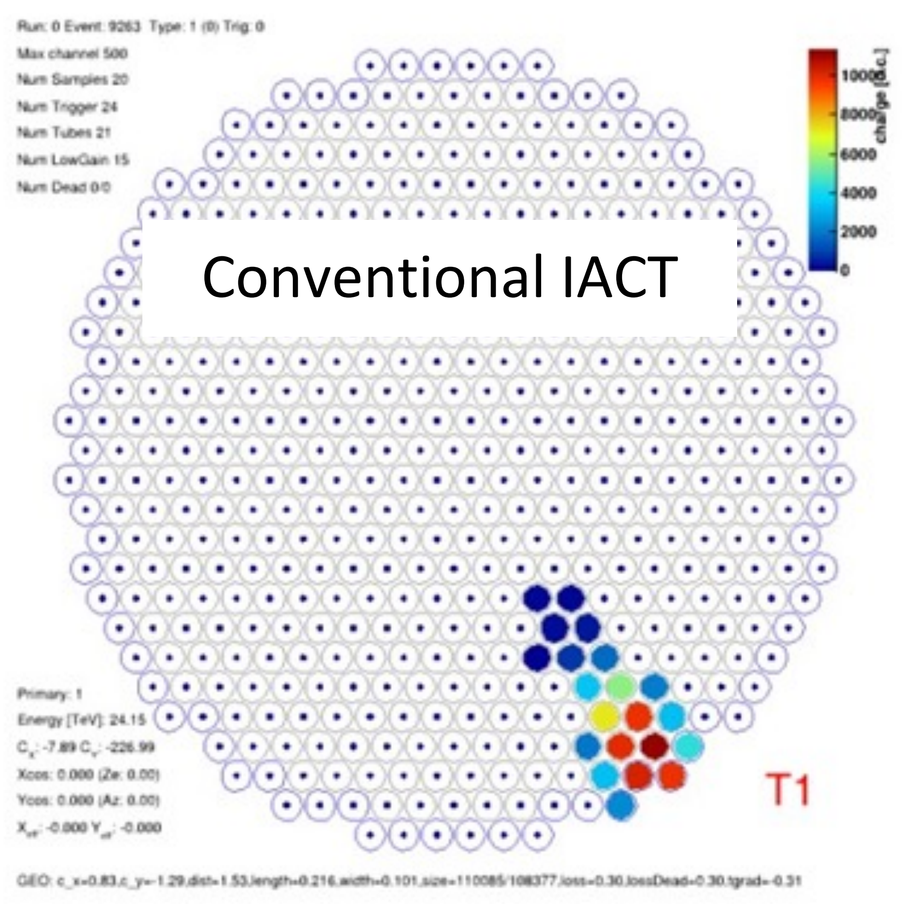
Detecting high-energy sources

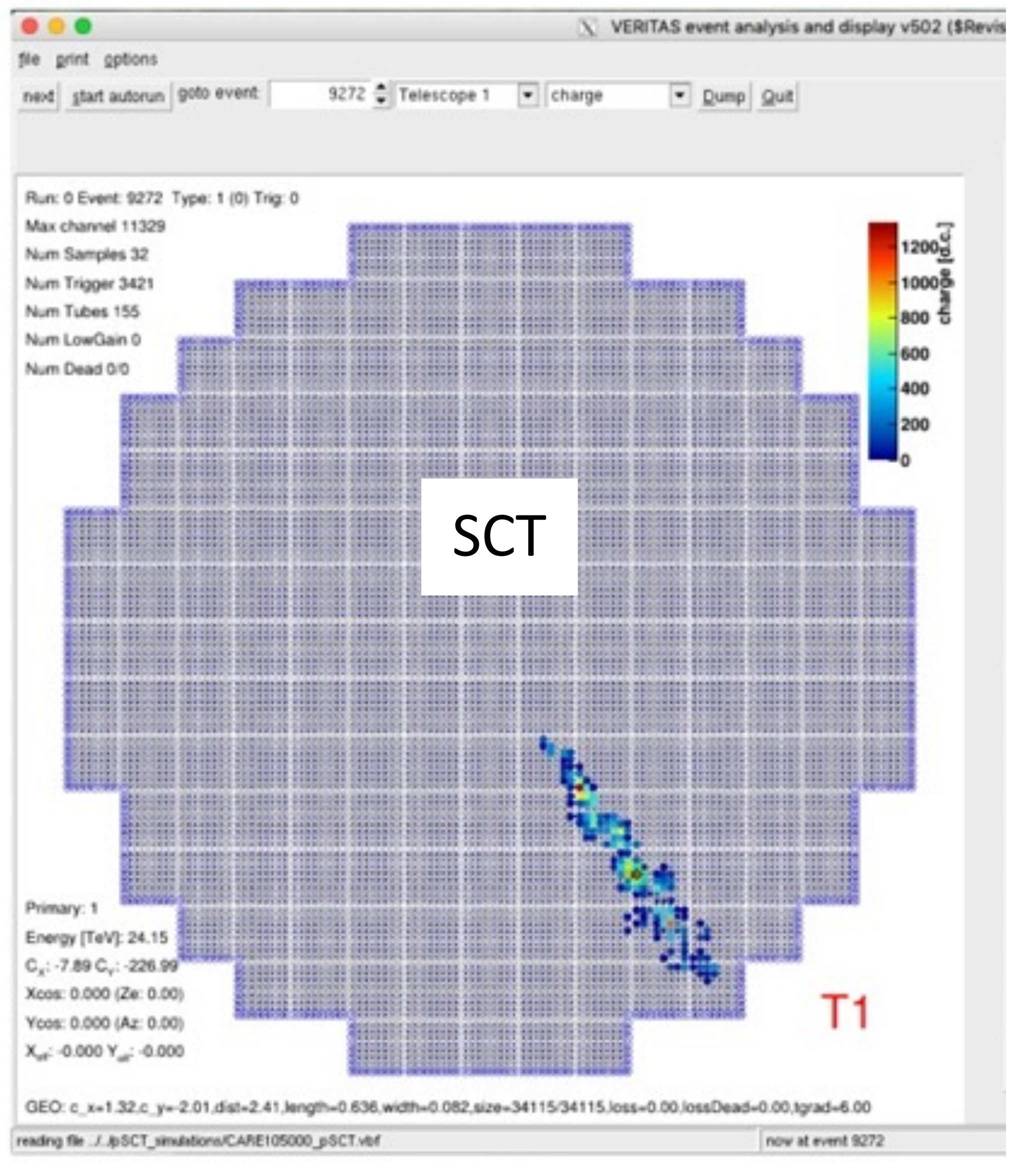
- First Catalog of LHAASO sources opens a new territory of gamma-ray astronomy with 43 UHE sources (>100 TeV)
- Good PSF maintained over 8-deg FoV would allow energy reconstruction of high-energy events (that would be truncated in conventional IACT FoV) and improve high-energy sensitivity



Astrophys.J.Suppl. 271 (2024) 1, 25

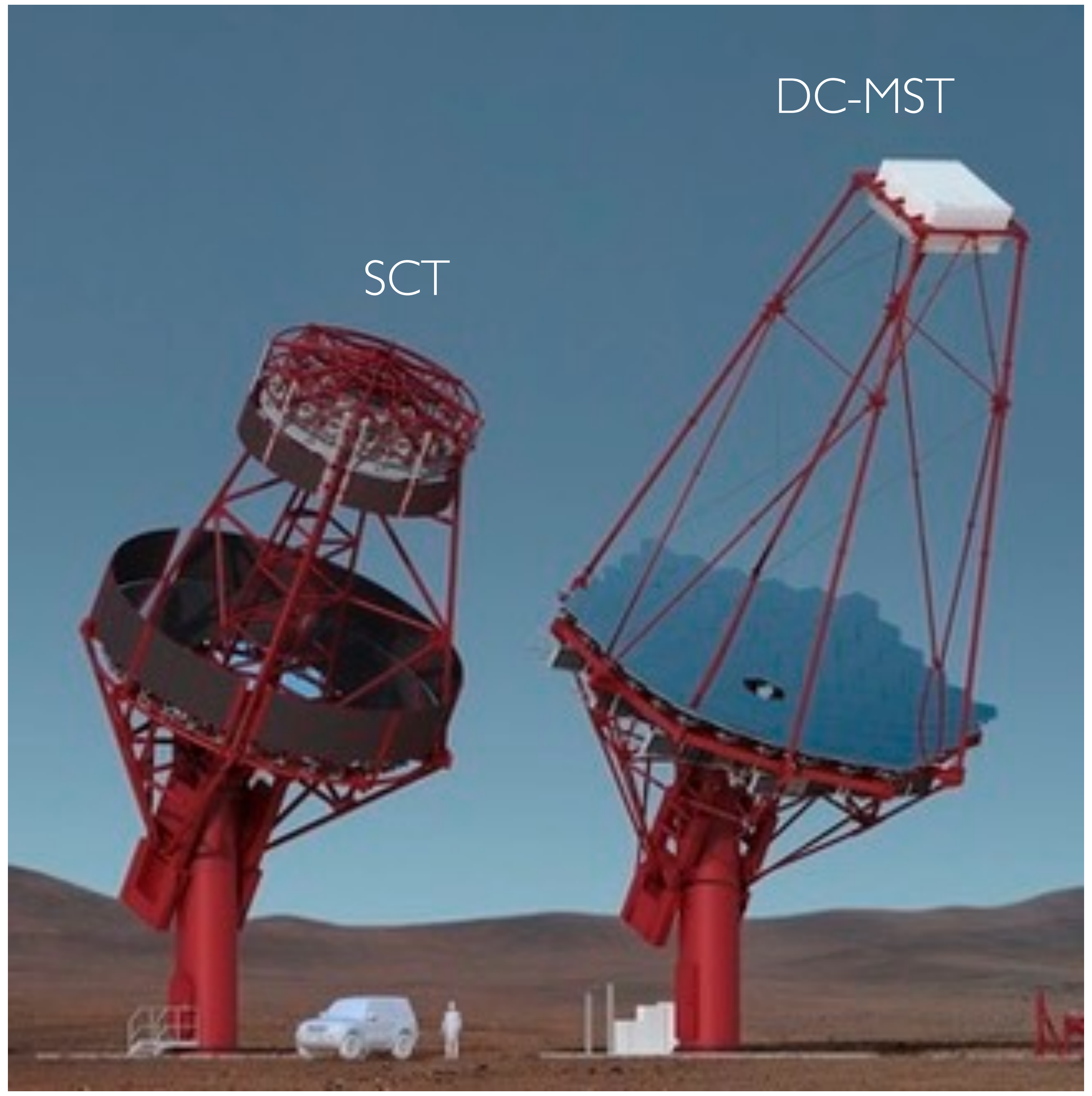
E = 24.15 TeV
C_x = -7.89 m, C_y = -226.99 m

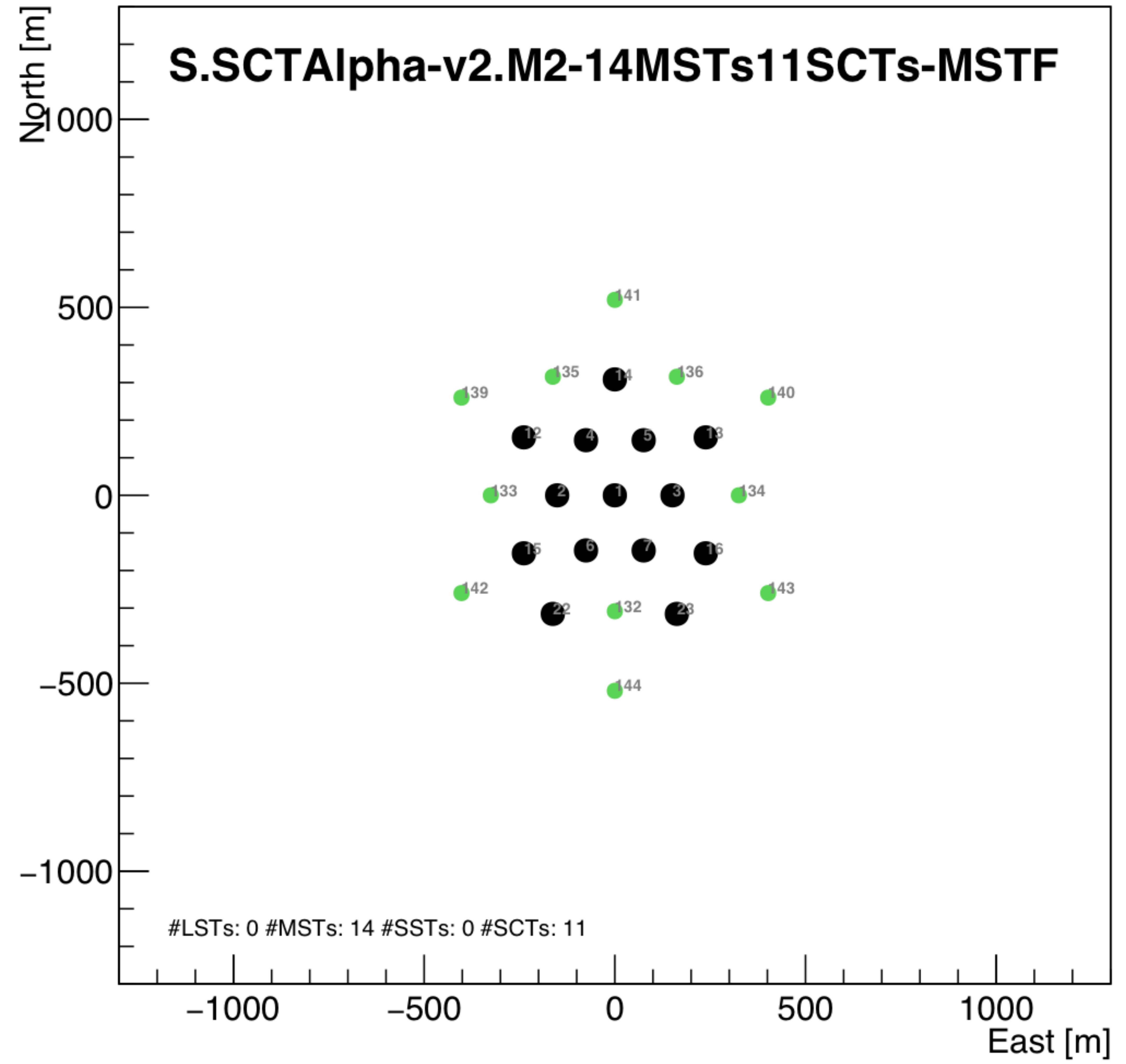




CTA South configuration

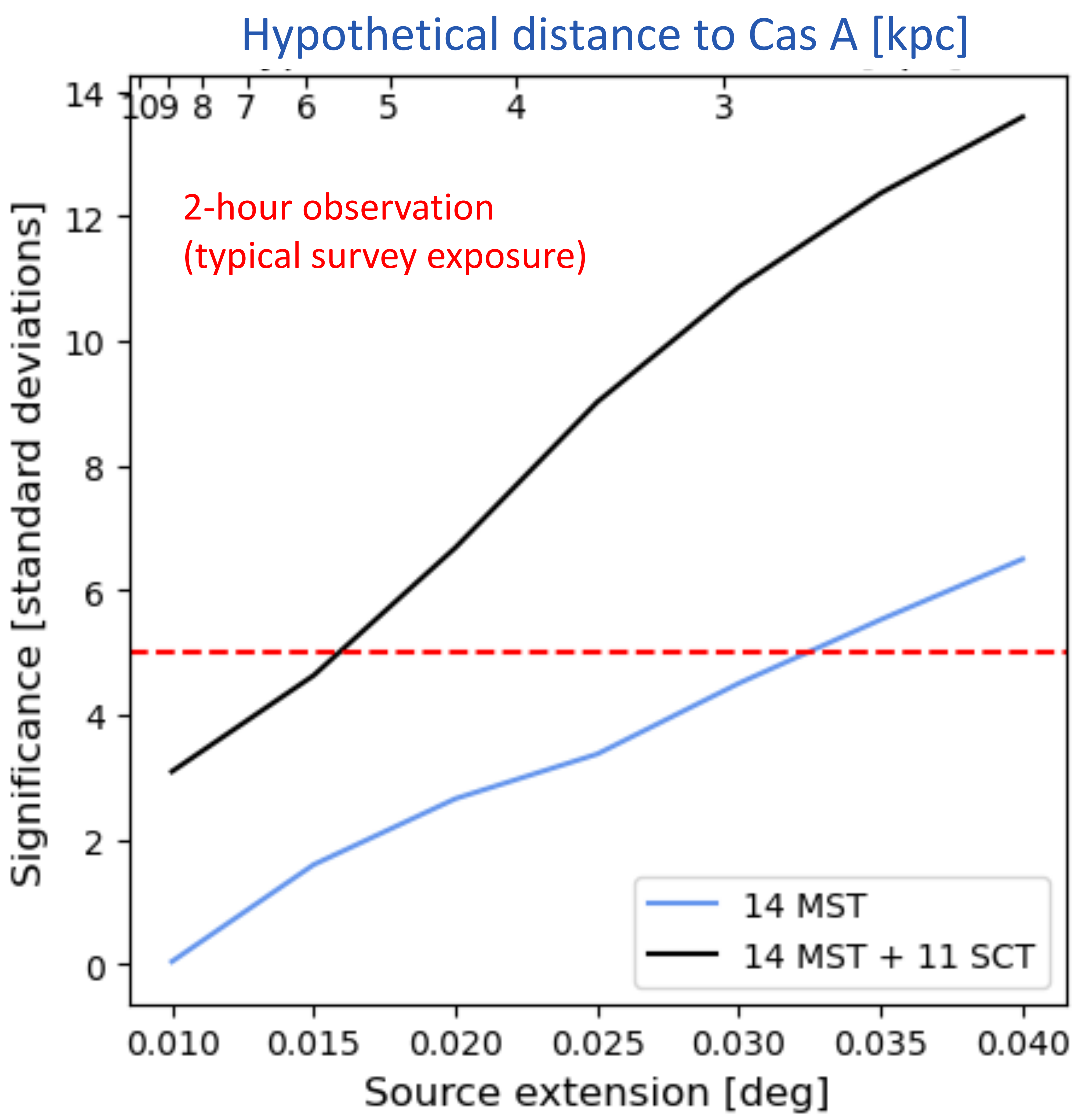
- Nominal CTA South alpha configuration includes 14 DC-MSTs (black dots)
- We consider + 11 SCTs (green dots) configuration as a hypothetical enhancement exercise





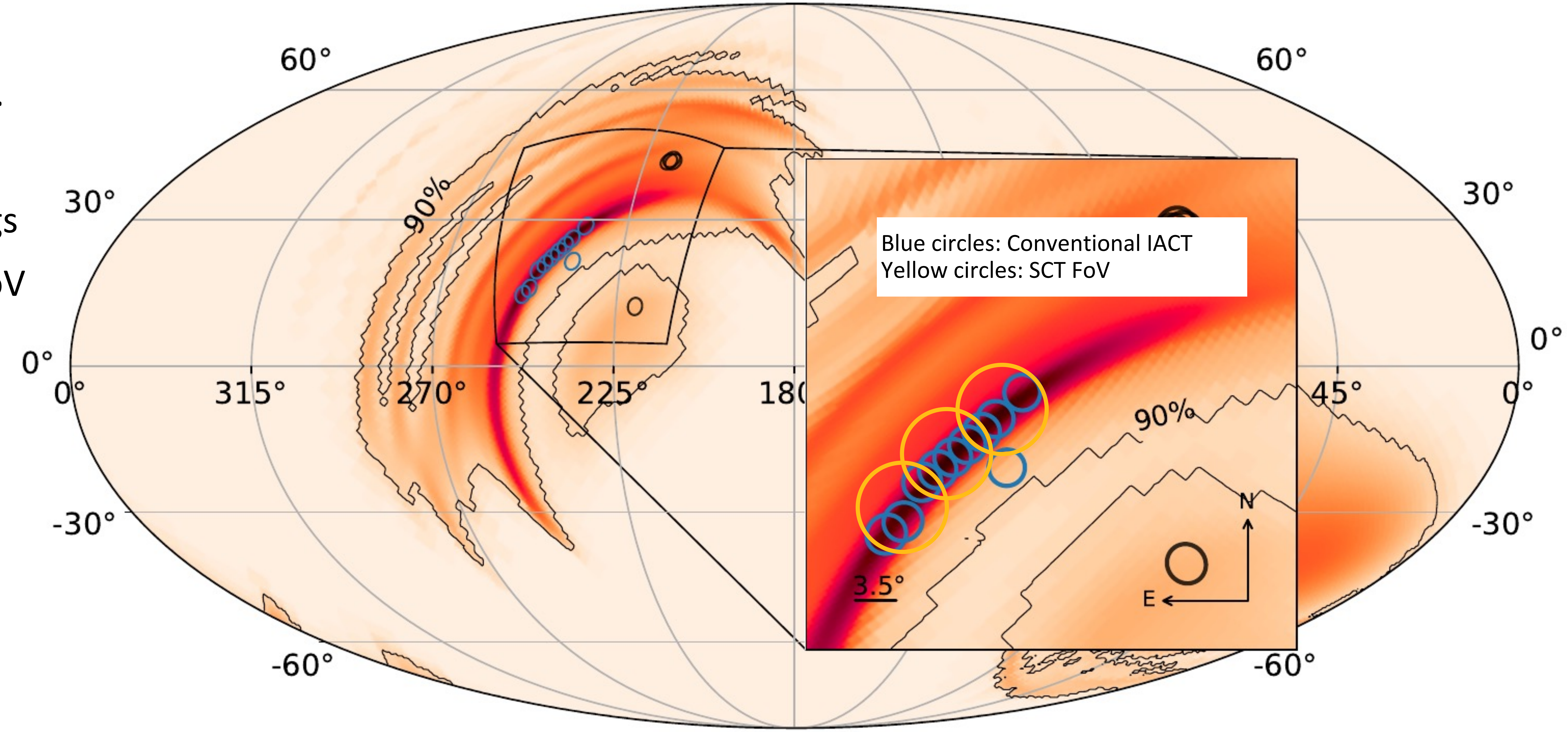
Gamma-ray performance

- The addition of 11 SCTs to CTA will improve the ability in resolving sources with small extensions
- Simulation of γ-ray emission from a source similar to Cas A, placed at different distances, is used to test the capability of detecting the source extension
- The ability to resolve a radius = 1’ source means that CTA and NuSTAR/XMM/Chandra can observe a source at different wavelength with a similar angular-size scale



Detecting transient sources

- Transient events with poor localizations (e.g. GW and GRB events) require multiple pointings
- SCT with large FoV can cover a large sky region with fewer pointing and shorter time



Conclusion

- The Schwarzschild-Couder Telescope is one of the proposed designs for the Medium-Sized Telescopes for CTAO
- SCT design achieves 3.2 arcmin optical PSF across 8-deg FoV:
  - Dual-mirror optics
  - High-resolution SiPM
- Expected improvement to CTAO includes detecting transient events, resolving source confusion, detecting PeVatrons, and large-extent sources
- The SCT group has constructed a prototype with functioning optical system and camera
  - Detected Crab Nebula
  - Upgrading to full camera by 2025
  - Ongoing: Instrumentation of the focal plane to 11k+ channels with upgraded SiPMs and front end electronics
  - 2025: Expected completion of pSCT camera upgrade to full 8° field of view
- Thank you to NSF and international partners for their support!

NSF INFN Istituto Nazionale di Fisica Nucleare DESY.

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

Thank you

We gratefully acknowledge financial support from the agencies and organizations listed here:
https://www.ctao.org/for-scientists/library/acknowledgments/

The development of the pSCT was made possible by funding provided through the NSF-MRI program under awards PHY-1229792, PHY-1229205, and PHY-1229654.

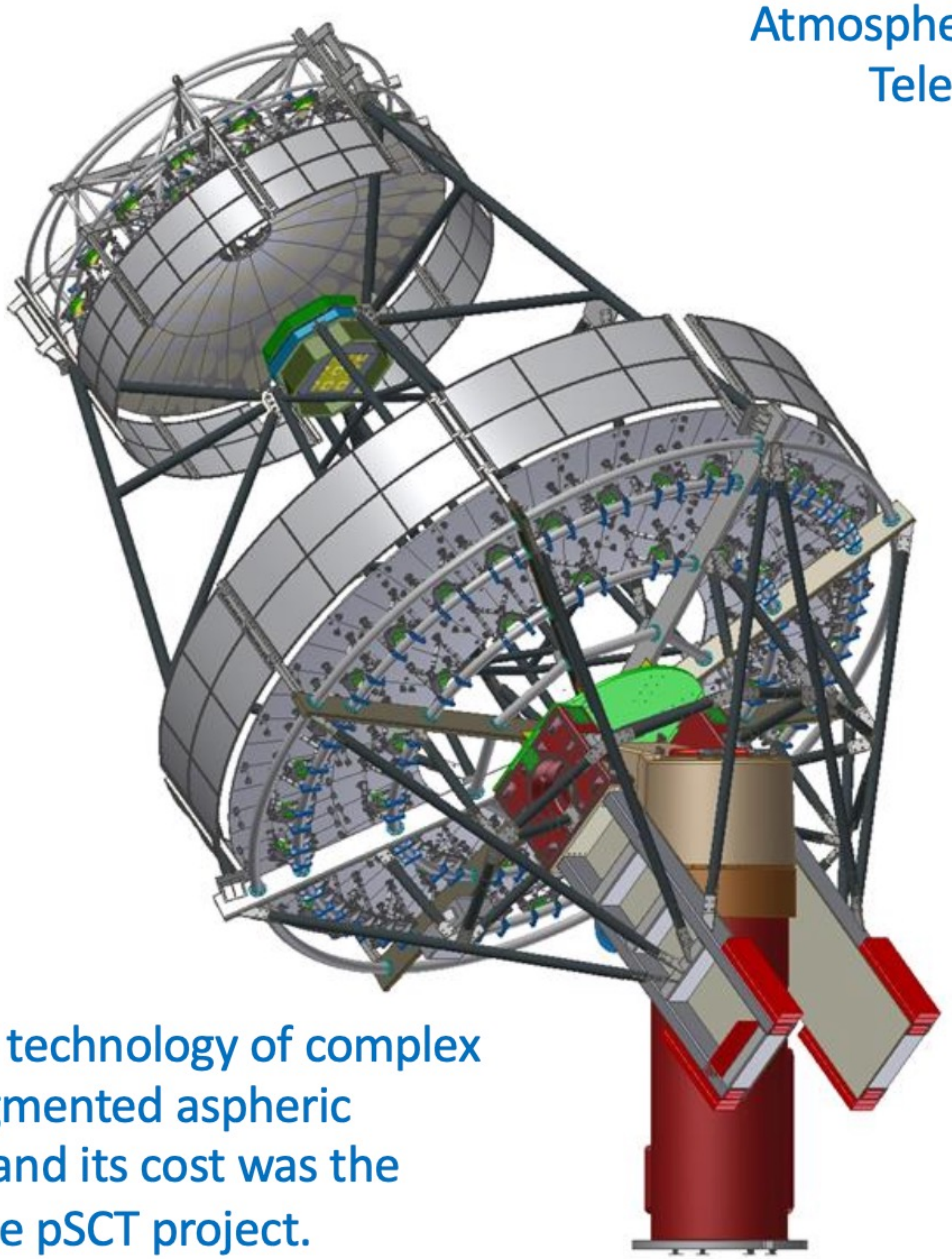
Acknowledgements:https://www.cta-observatory.org/consortium_acknowledgments/

Extras

pSCT 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

The design is unique for Imaging Atmospheric Cherenkov Telescopes (IACTs)

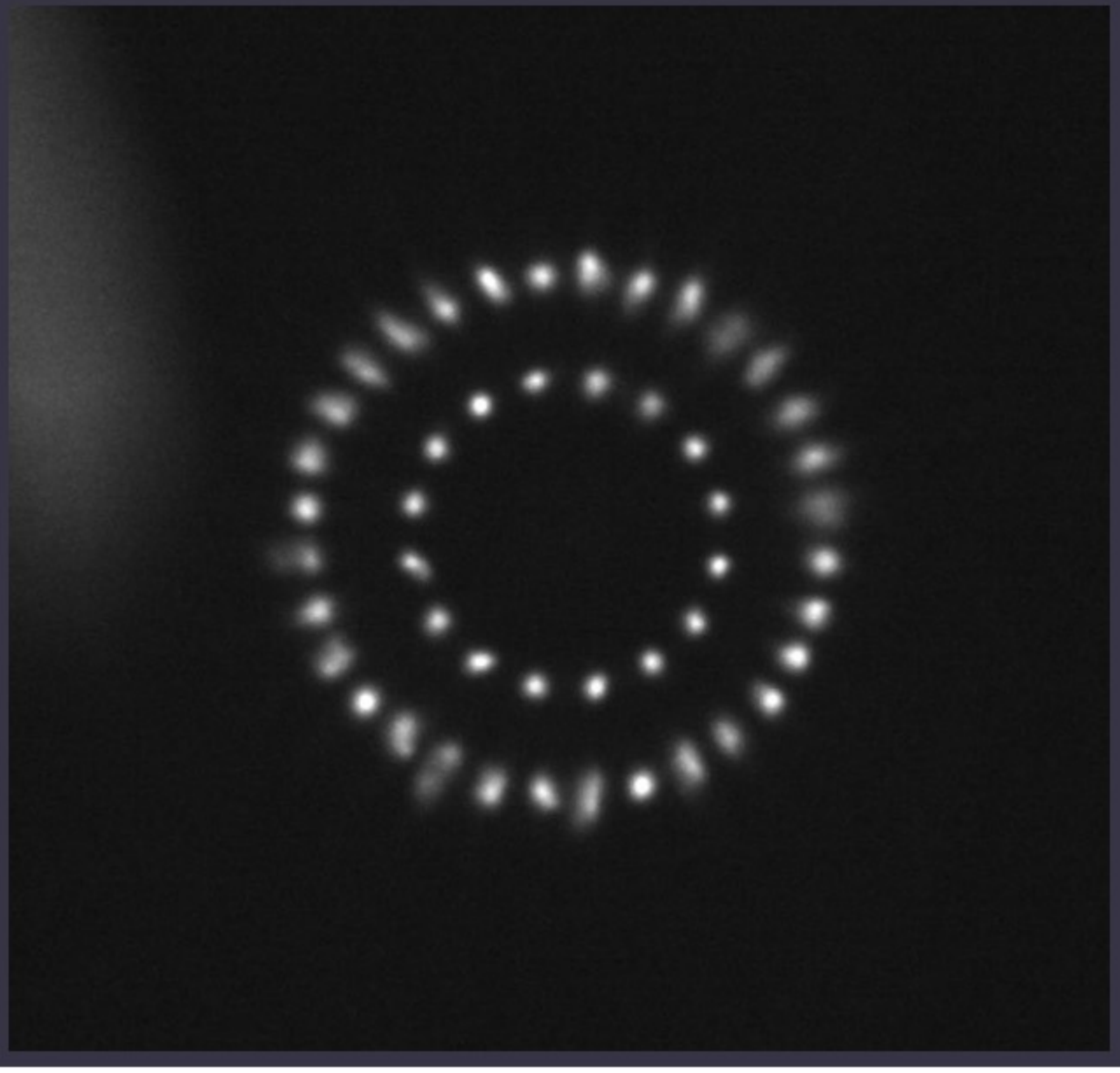


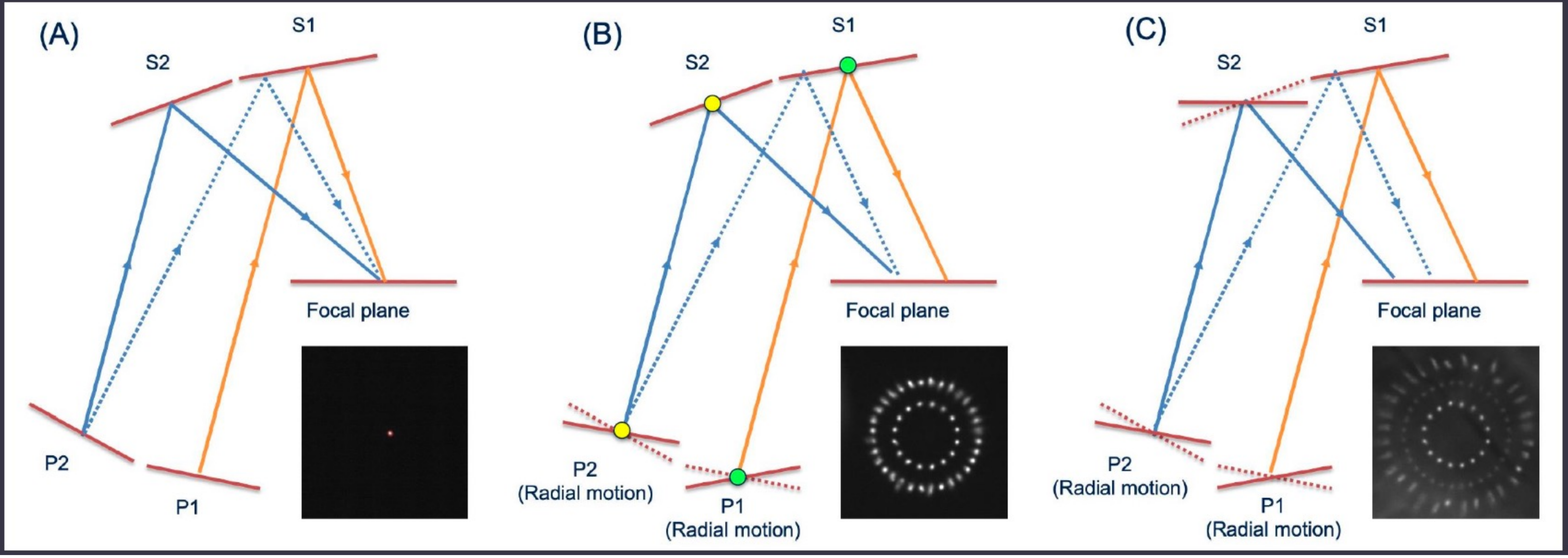
The fabrication technology of complex dual-mirror segmented aspheric optical system and its cost was the major risk of the pSCT project.

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





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