Schwarzschild-Couder Telescope: An innovative technology for gamma-ray astrophysics

2nd CTAO Science Symposium

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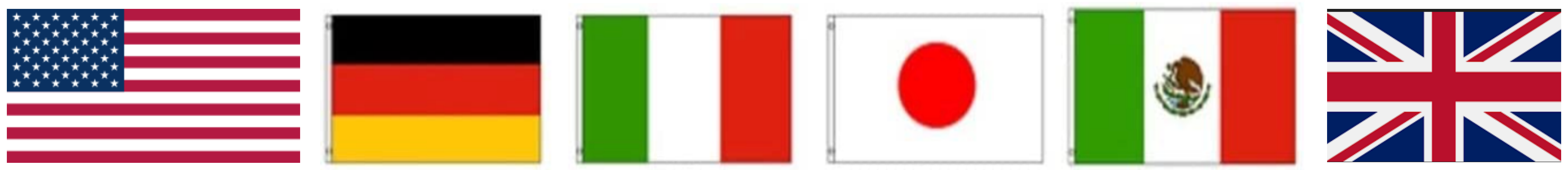
Outline

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

Instrument 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



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: fat 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!)

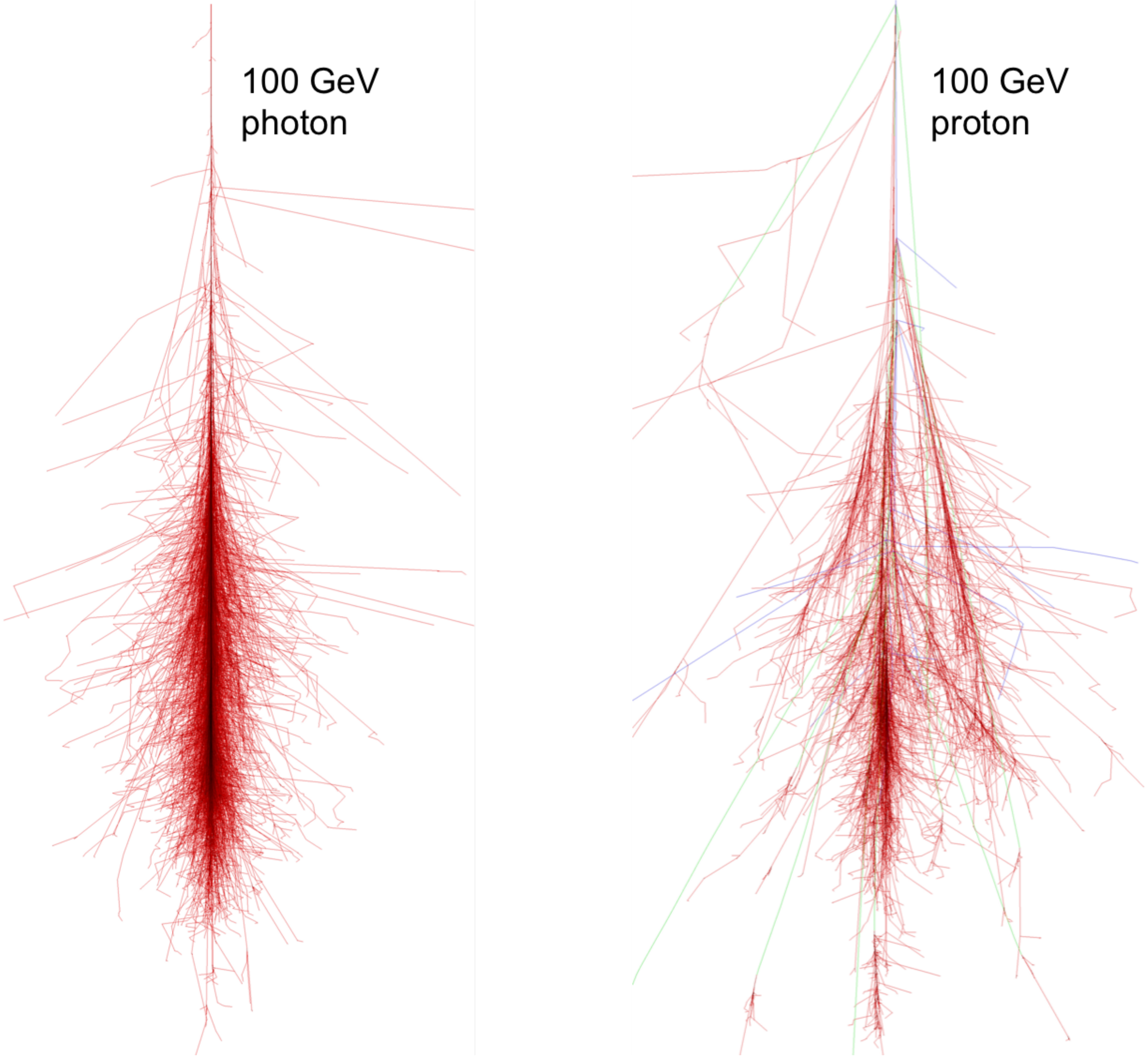
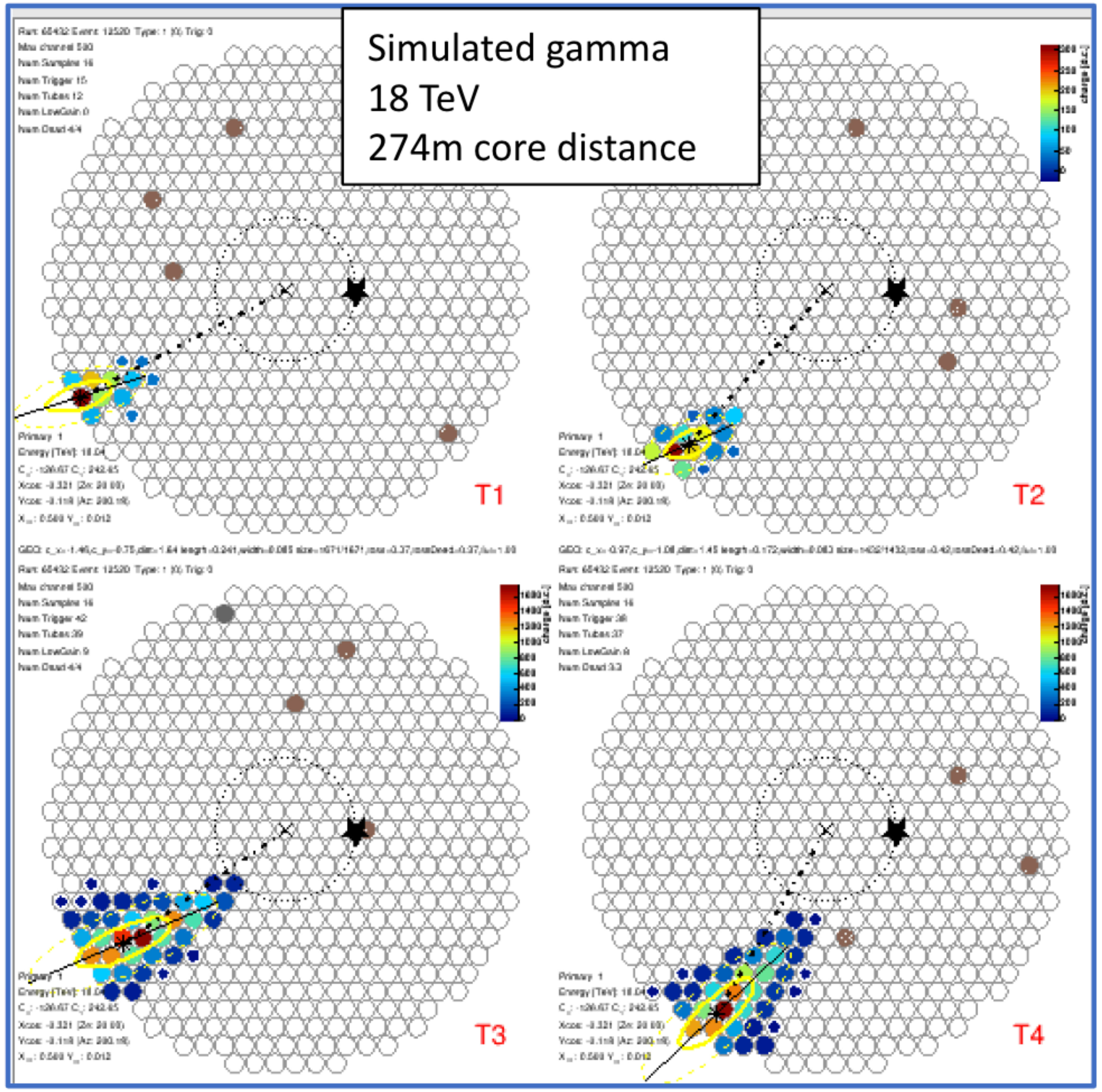


Image from: https://ar5iv.labs.arxiv.org/html/1510.05675

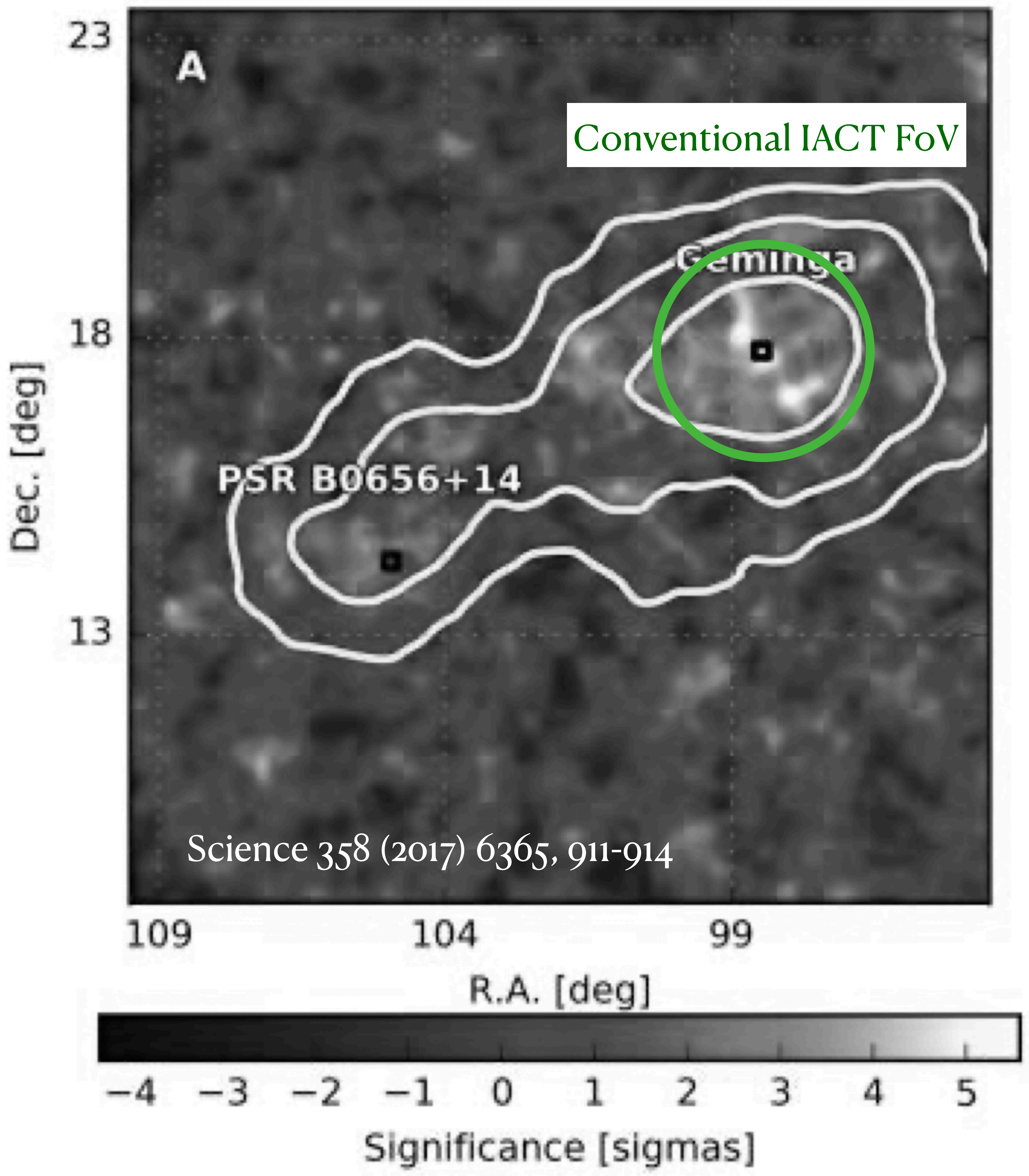
Need for large field of view

- 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



Need for large field of view

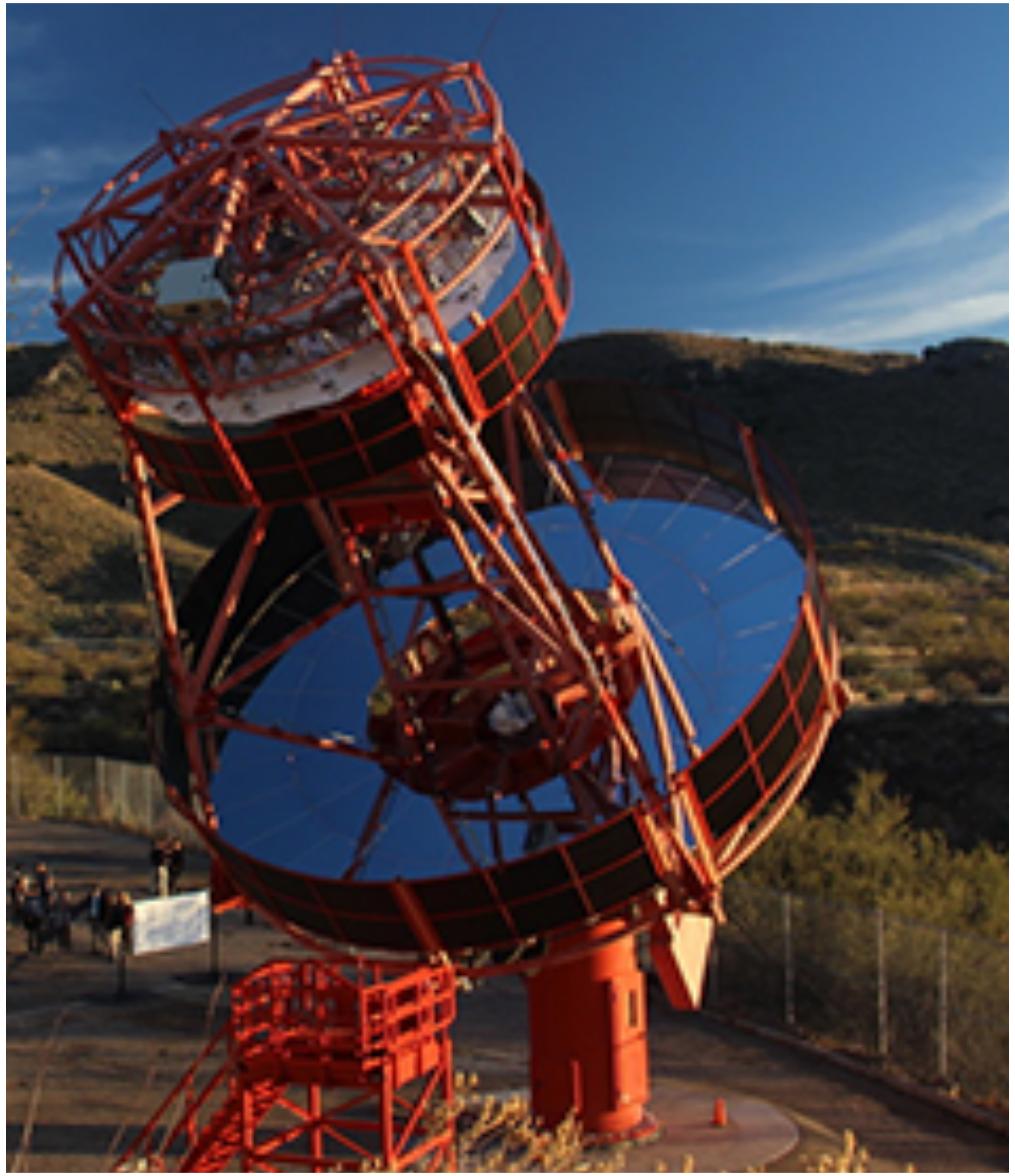
- Conventional IACTs maintain good PSF up to an offset angle of ~ 2 deg.
- For sources with large extension (e.g. Geminga halo radius > 5 deg), analyses are difficult without γ-free background region in FoV.
- To improve angular resolution by ~3x and field of view by ~3x:
    - A camera with ~10^5 pixels
    - Current IACTs have ~10^3 pixels



Science 358 (2017) 6365, 911-914

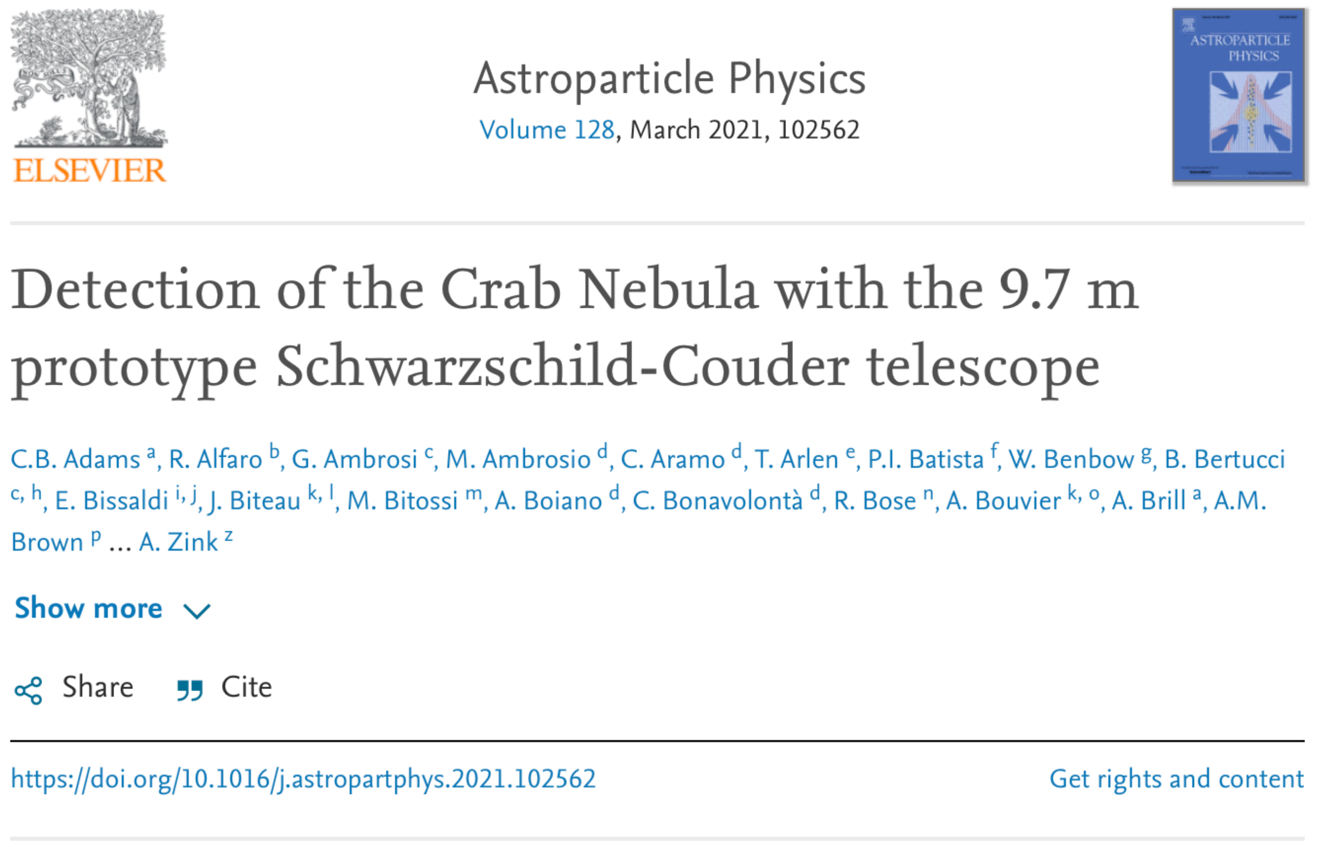
Schwarzschild-Couder telescope (SCT)

- 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



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 CTA.
- 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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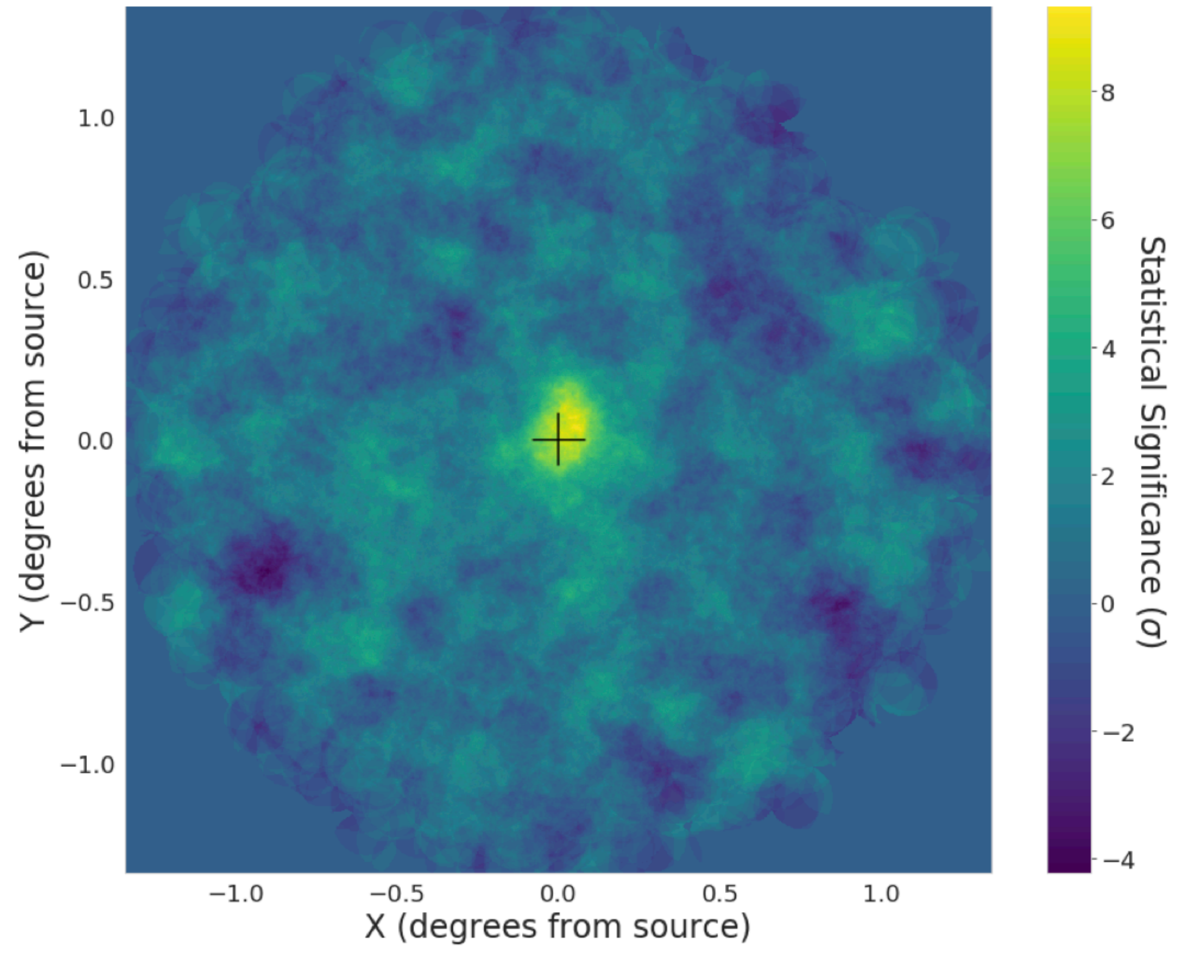
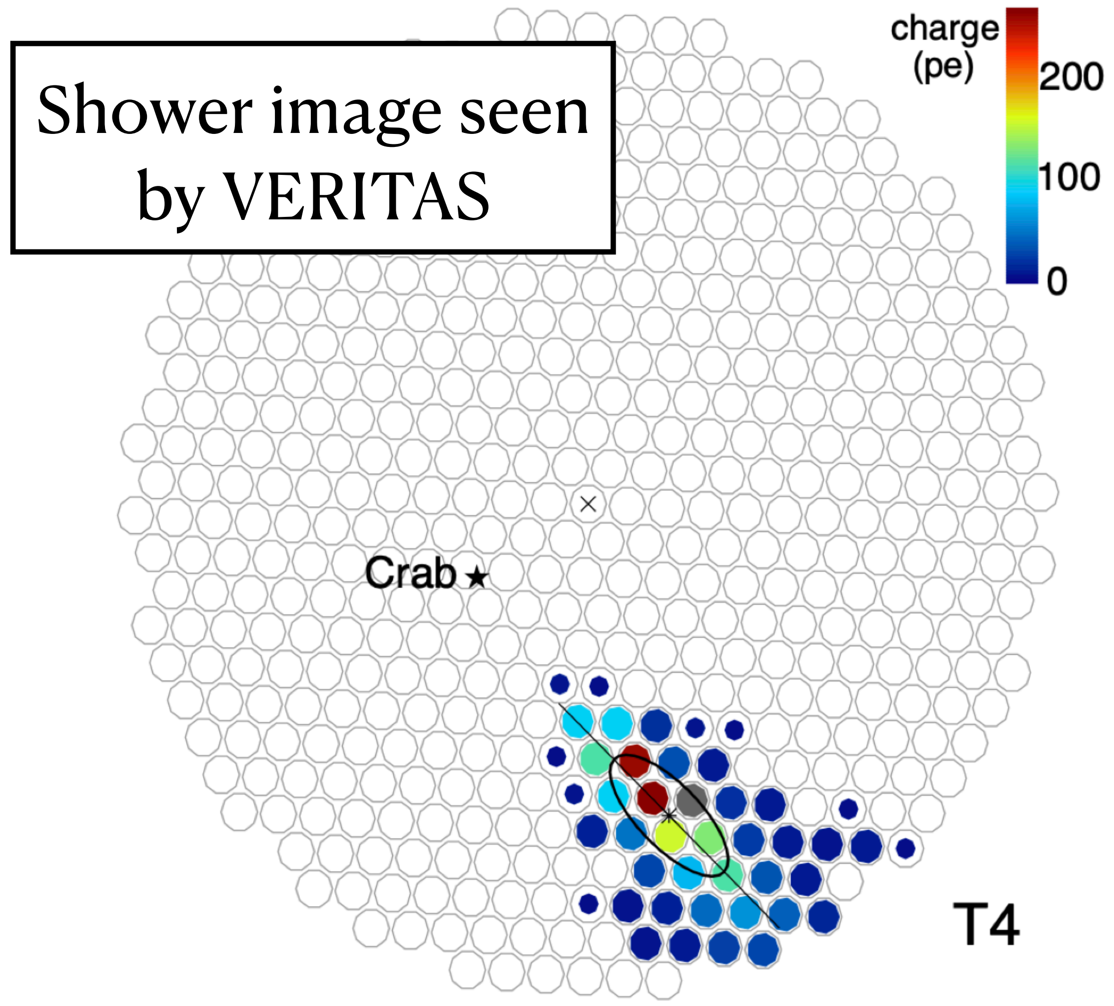
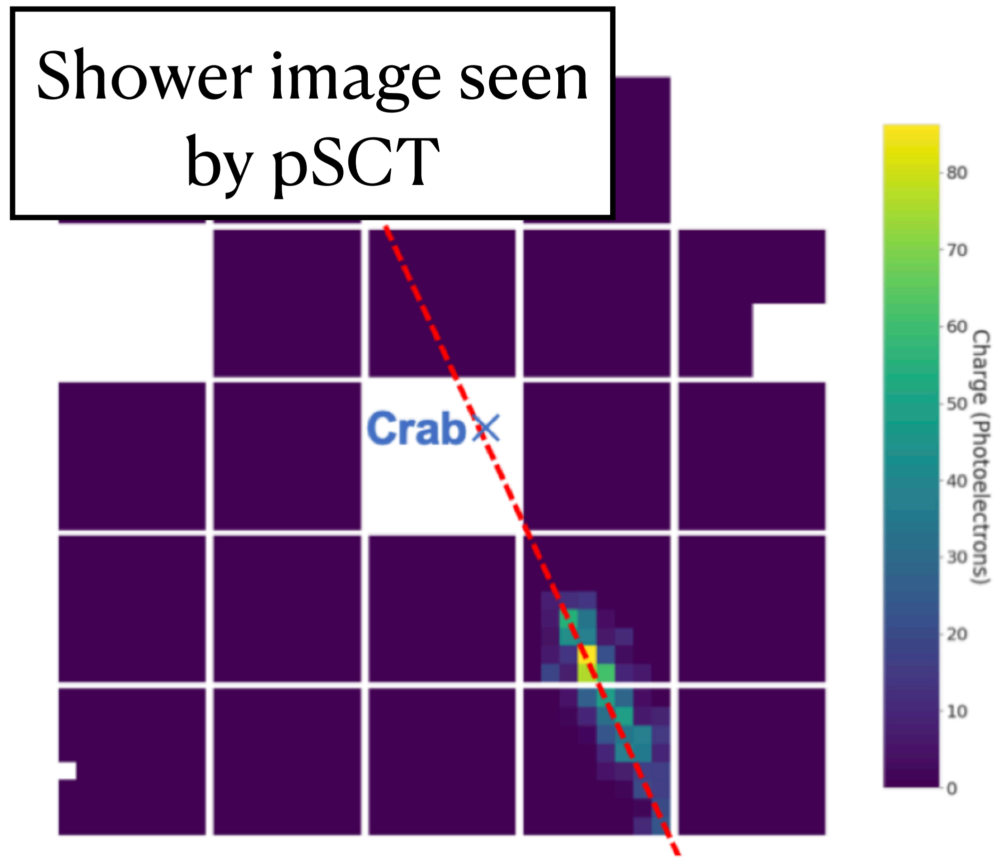
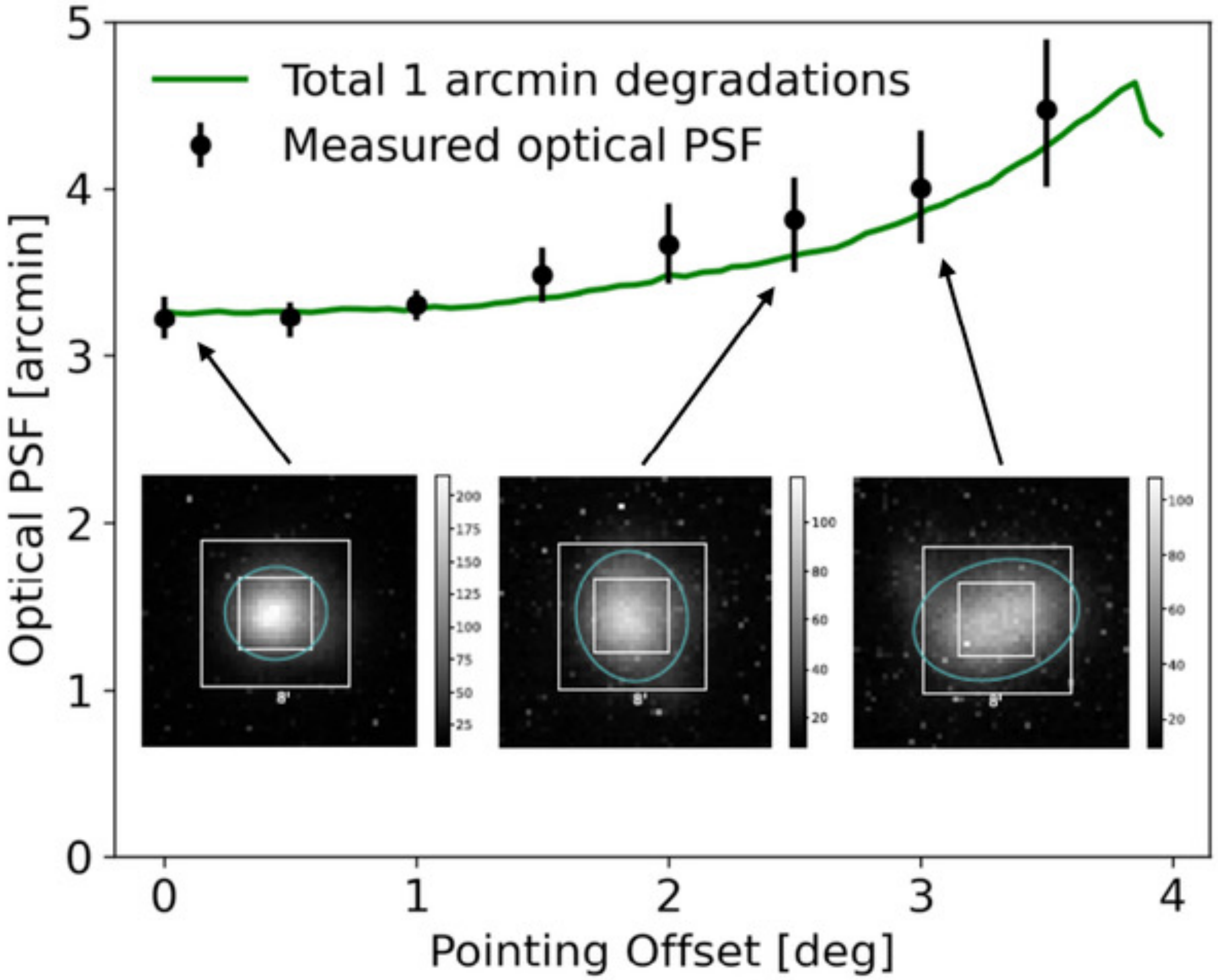






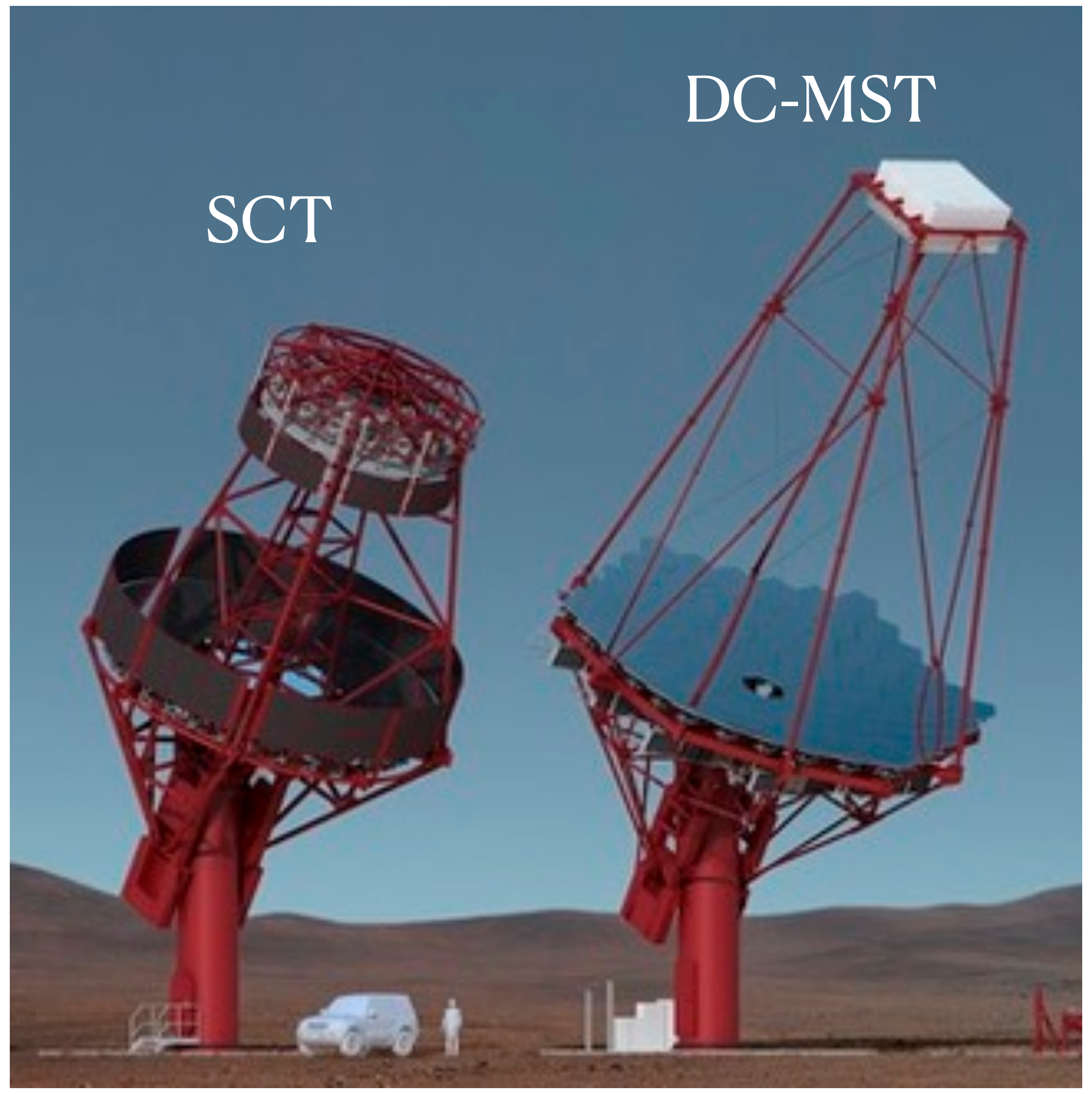
Optical performance

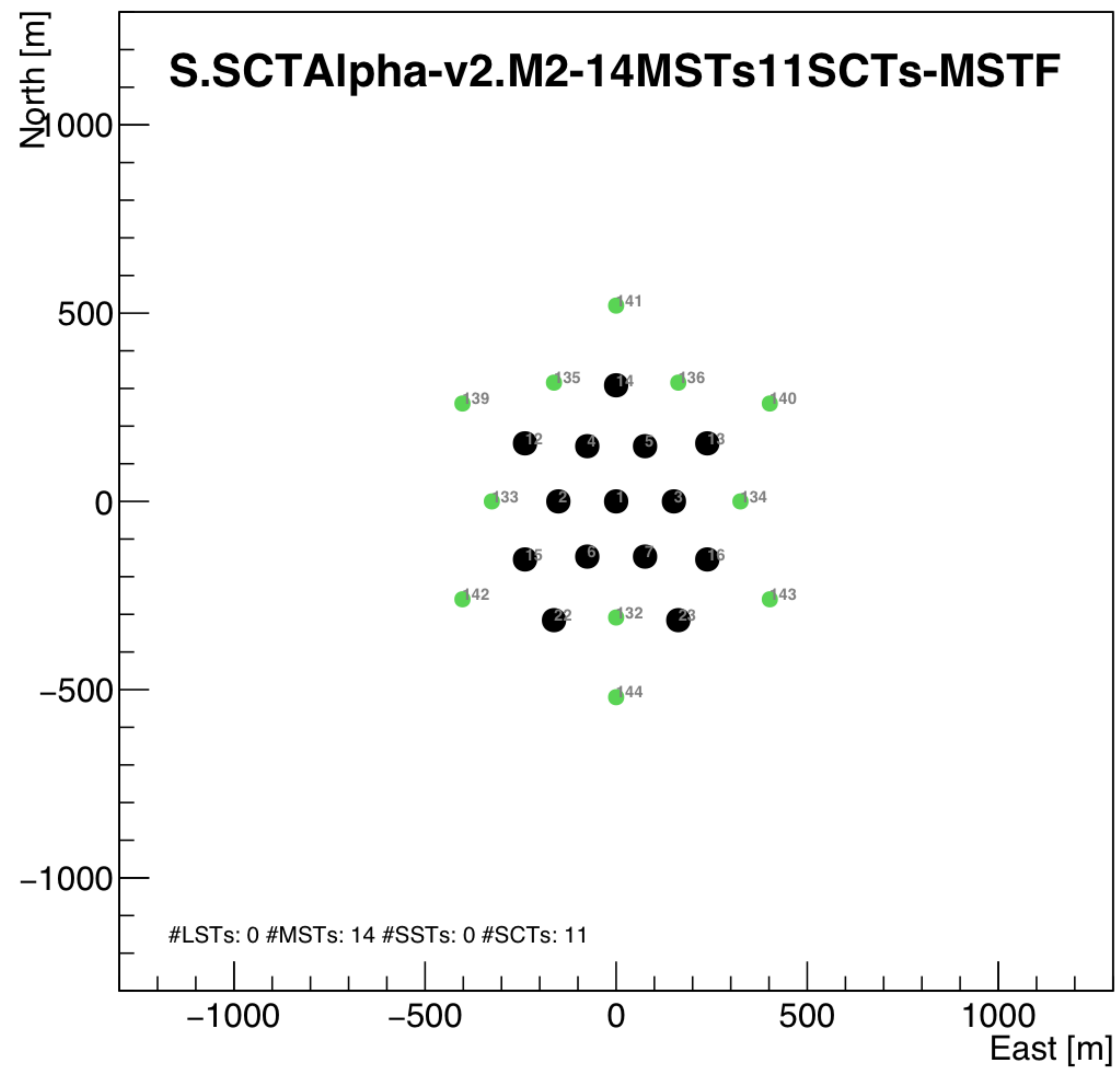
- The full alignment of the optical system across the 8-deg FoV was initially completed in 2022
- The optical PSF is ~ 3.2 arcmin on-axis and ~ 4.2 arcmin at 3.5-deg off-axis.
- Good PSF is maintained across the 8-deg FoV!



CTA South configuration

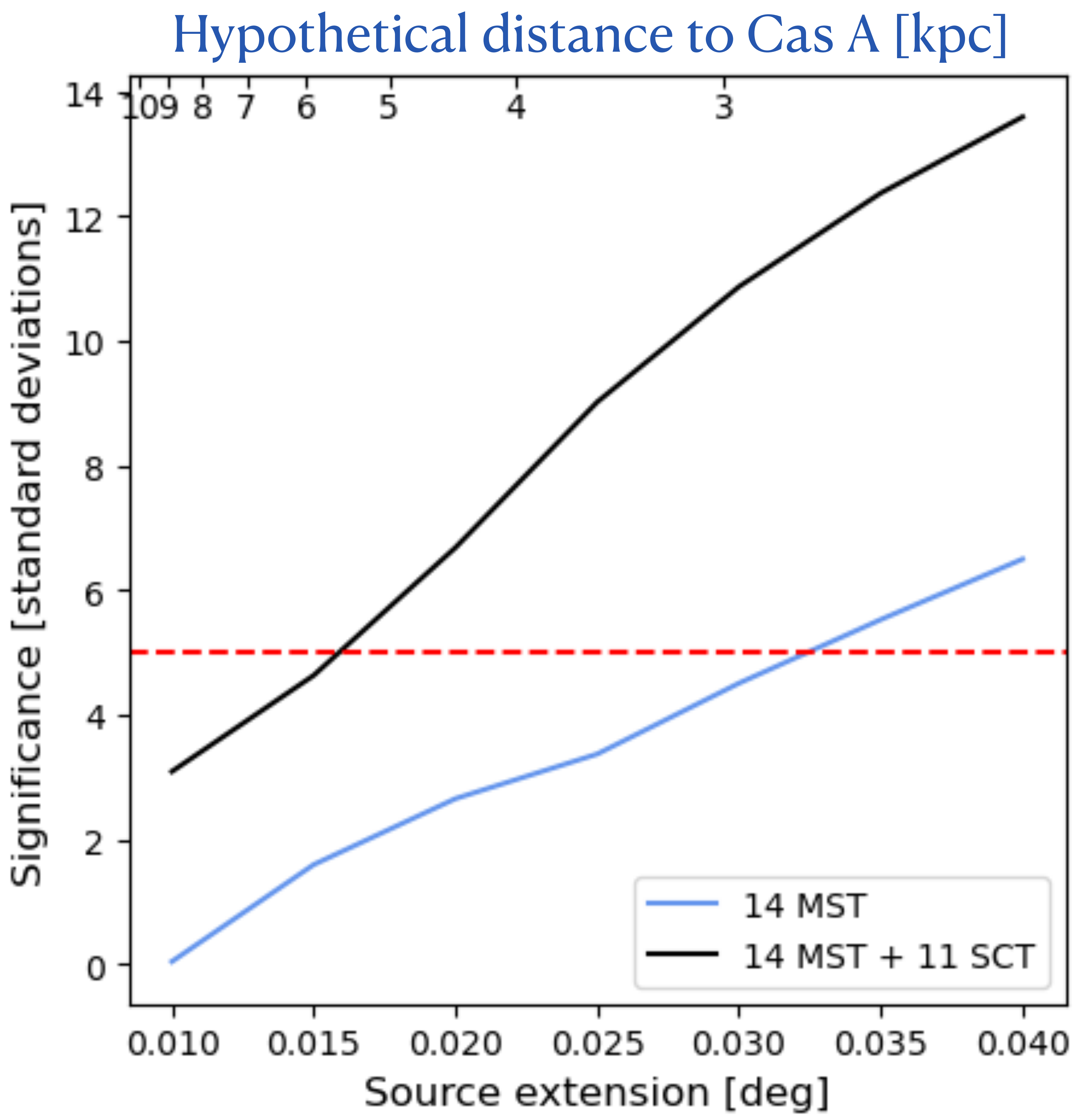
- Nominal CTA South alpha configuration includes 14 DC-MSTs (black dots)
- We consider + 11 SCTs (green dots) configuration as a hypothetical enhancement exercise





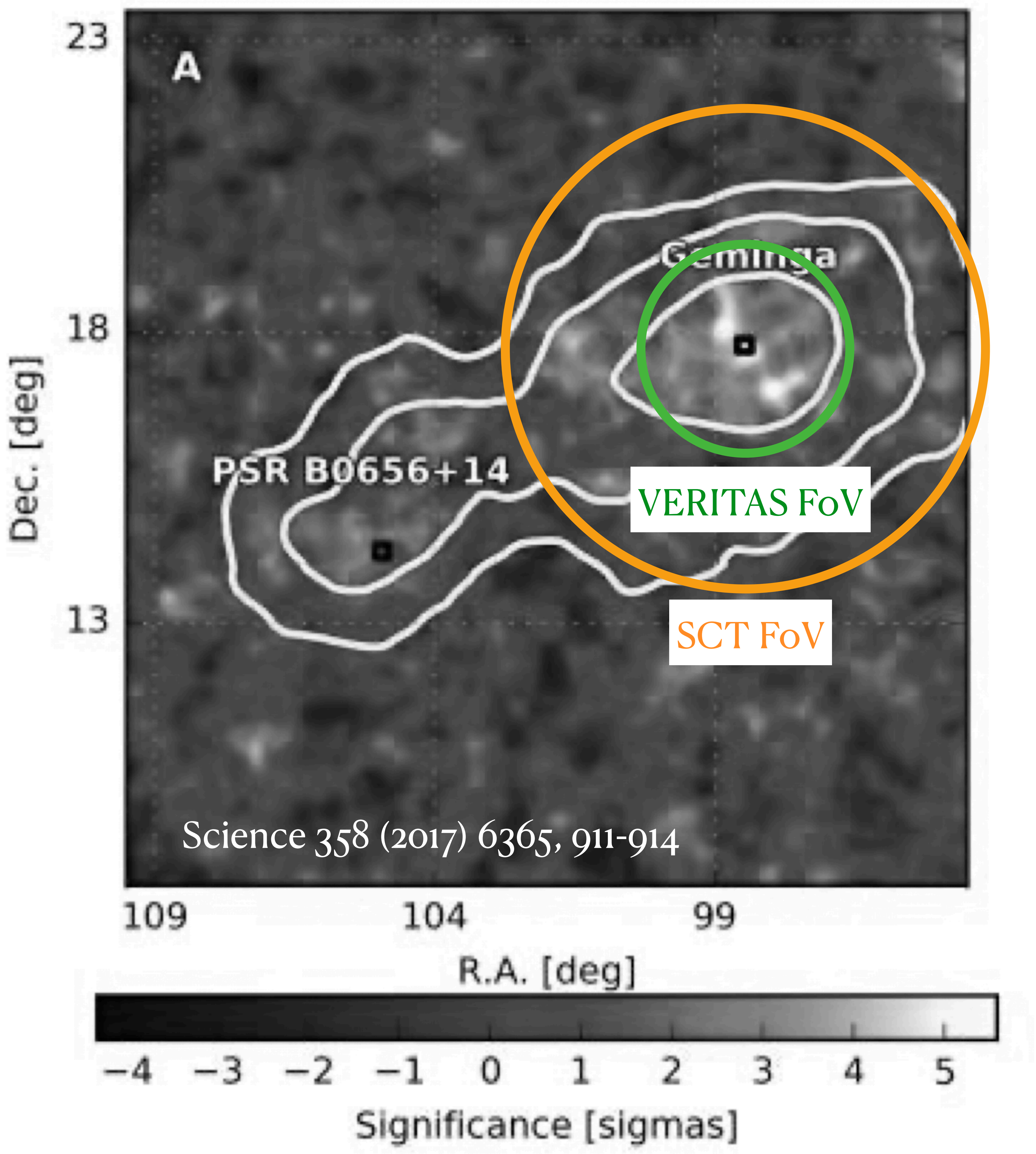
Gamma-ray performance

- 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 a 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.



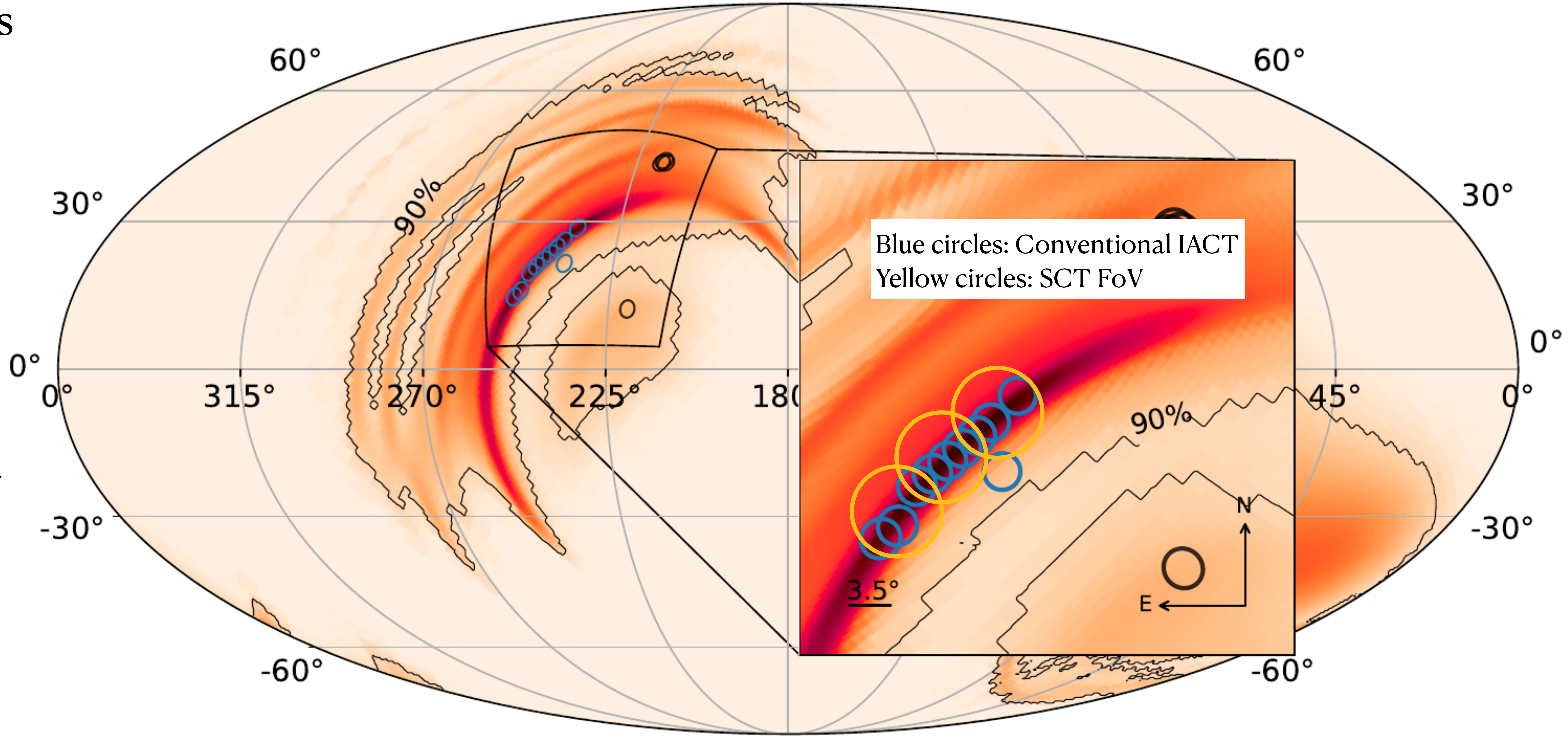
Detecting extended sources

- TeV halos are key for understanding positron excess.
- Analyses for extended sources are difficult without γ-free background region in FoV.
- SCT provides good PSF maintained across the 8-deg FoV
  - Contain Geminga halo emission in a single pointing
  - γ-ray-free region in the FoV available for background modeling



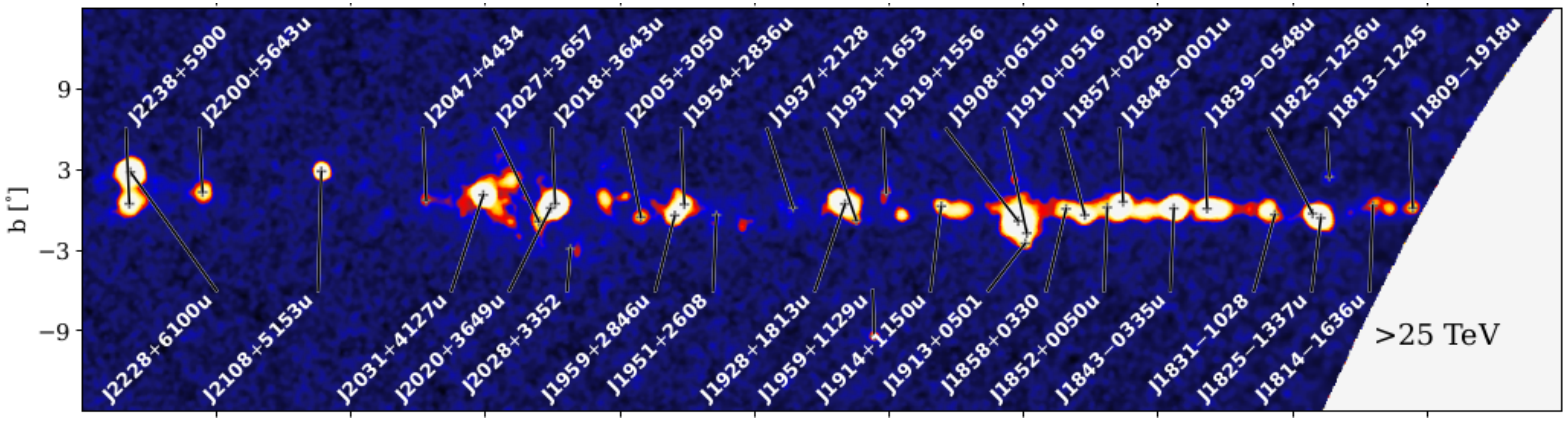
Detecting transient sources

- 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 pointings and shorter time.



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.



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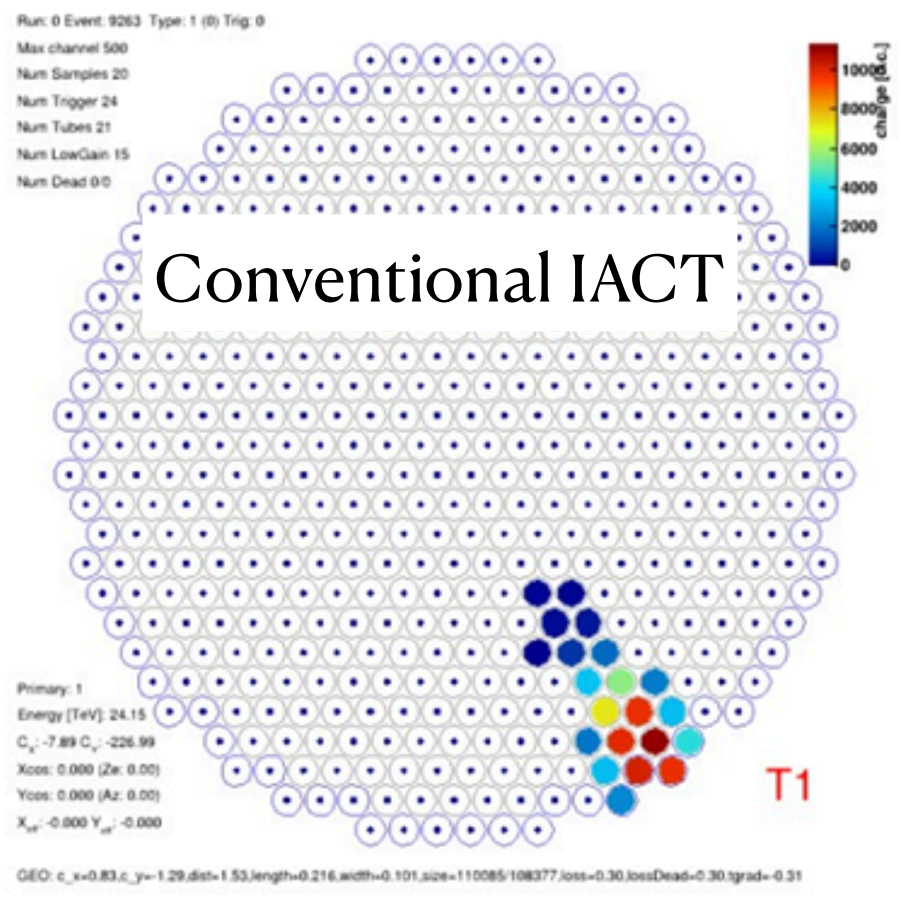
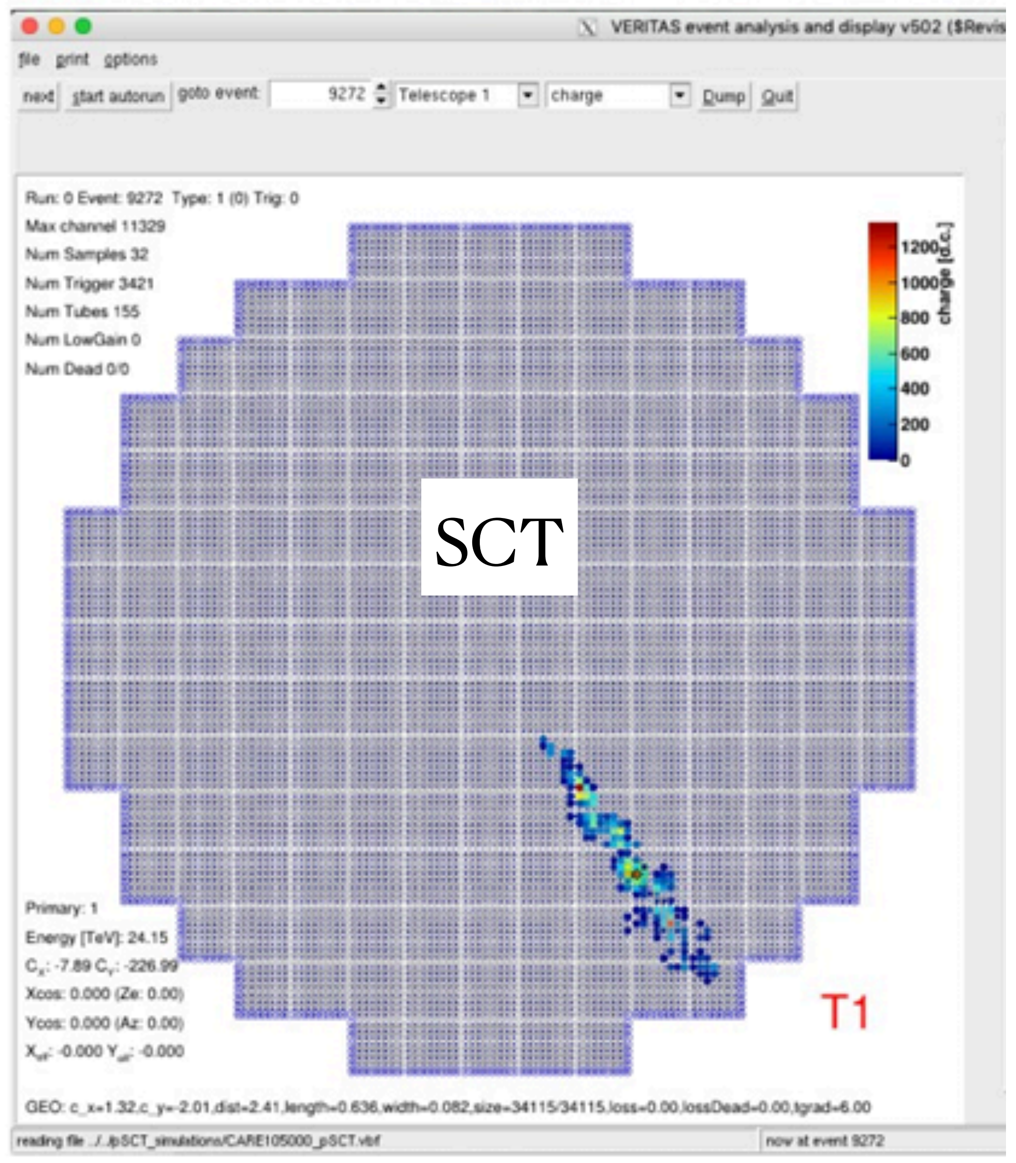
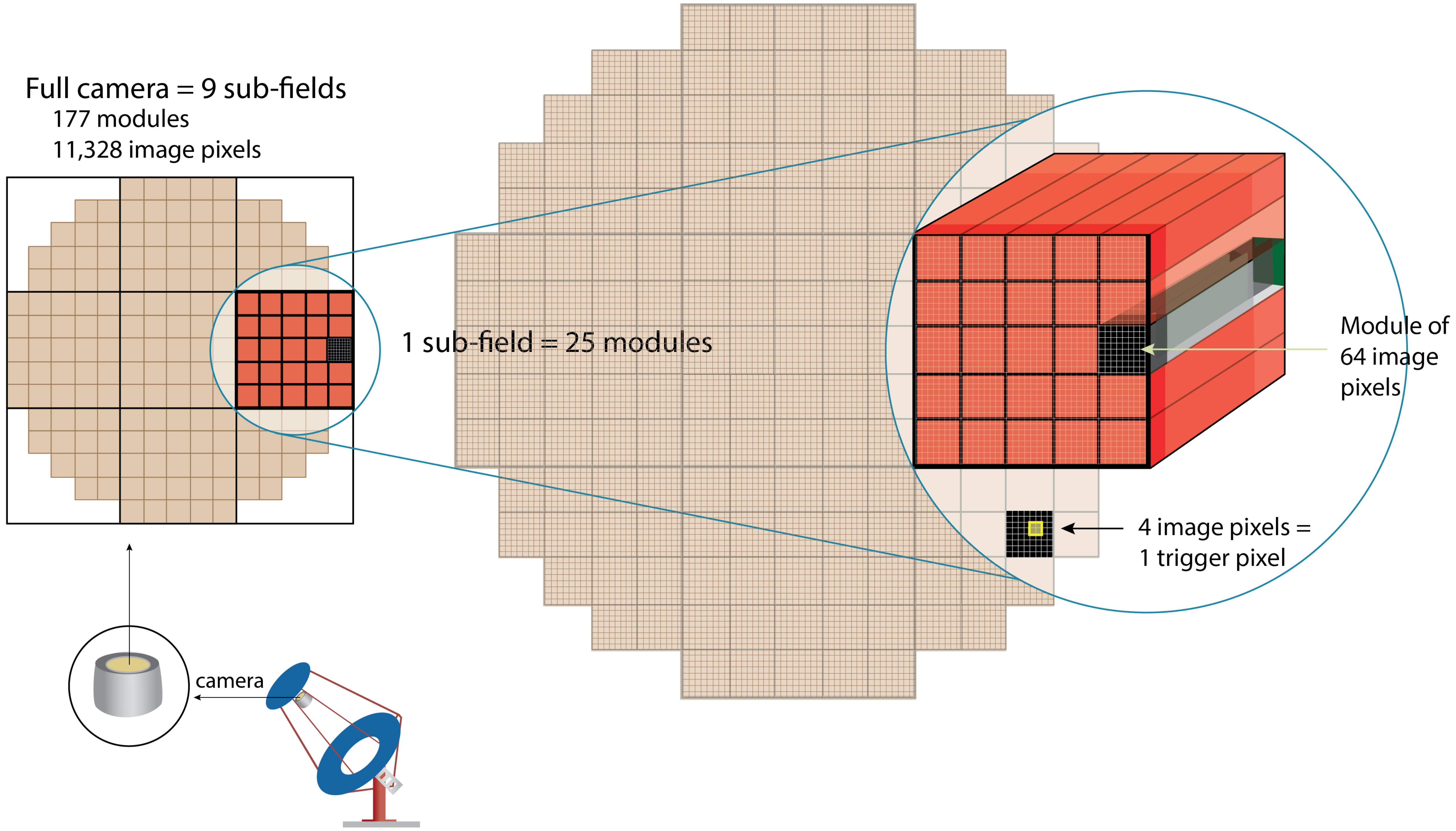
E = 24.15 TeV
C_x = -7.89 m, C_y = -226.99 m



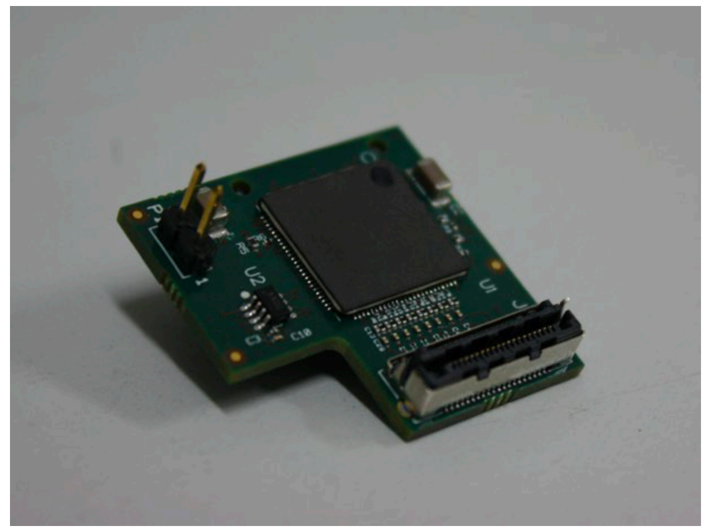


Camera upgrade

- Populate all 9 camera sectors: 177 modules, 11328 pixels
  - Increase field of view x7
- Upgraded electronics
  - Improvement in single photon resolution,
  - lower minimum threshold and lower noise



Hierarchical, modular design based on silicon photomultipliers and waveform sampling TARGET chips

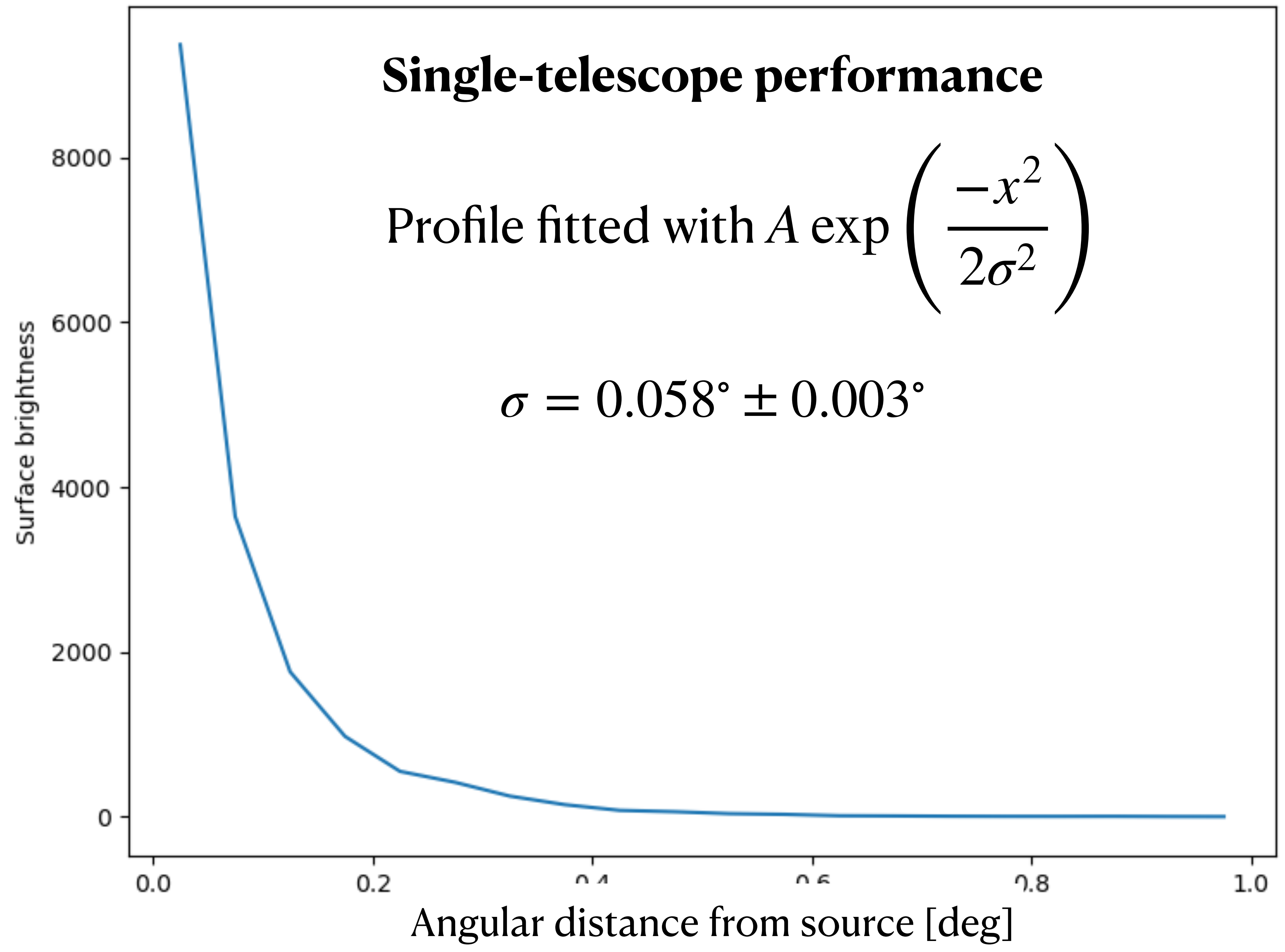


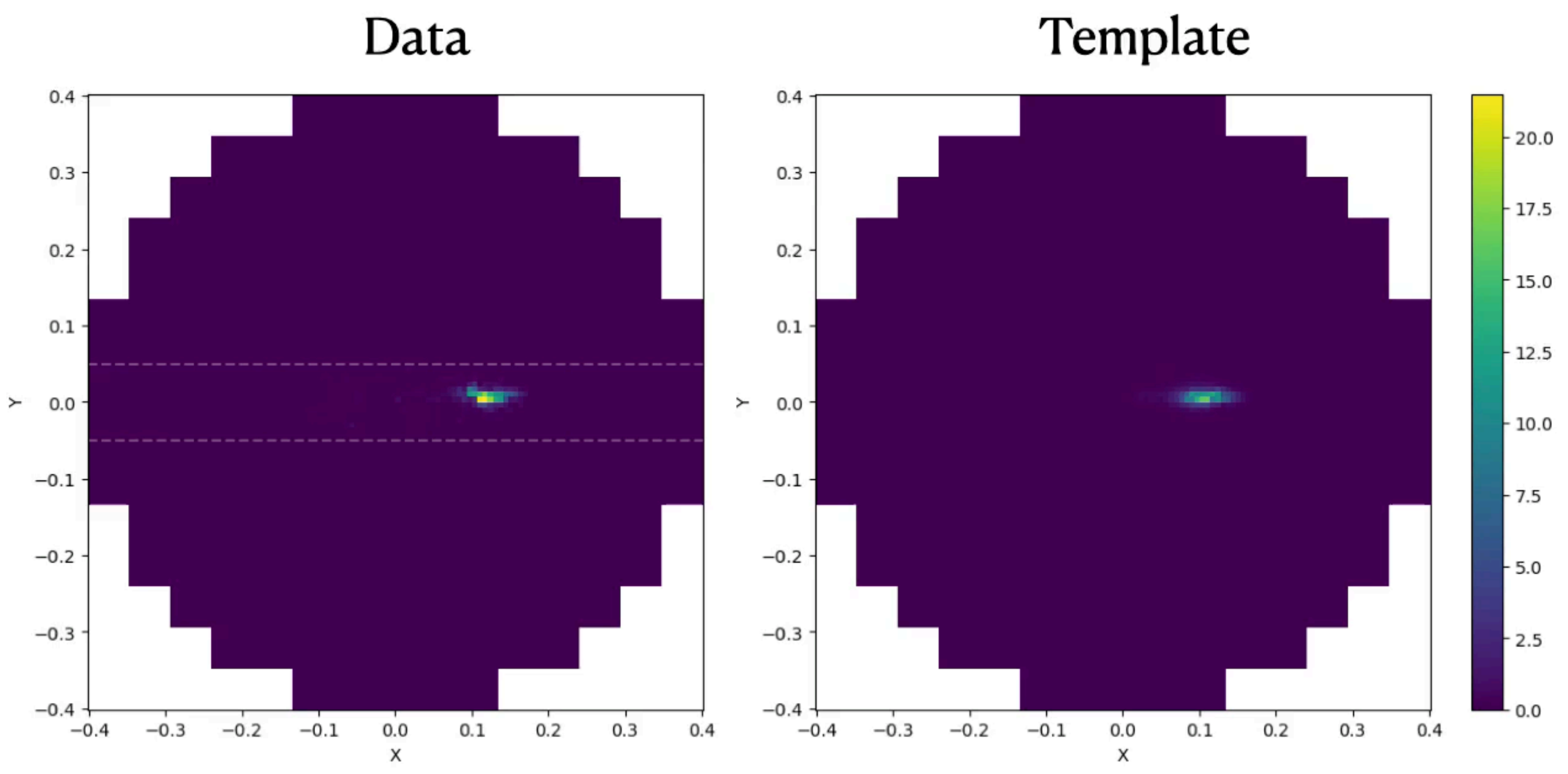
SMART ASIC:
Integrated preamplifier attached to SiPM boards

CTC+ CT5TEA FEE module:
16 us storage depth
4 trigger pixels per ASIC
Adjustable threshold for each group

Reconstruction algorithm

- We are developing a new reconstruction algorithm that could maximize the advantage of SCT's high-angular resolution and timing information.
- Idea is to use Single Value Decomposition to analyze γ-ray shower images in simulation and build time-dependent image template using principle components.
- The initial result looks promising.
- Simulation study with Prod6 in the future to fully characterize SCT performance.

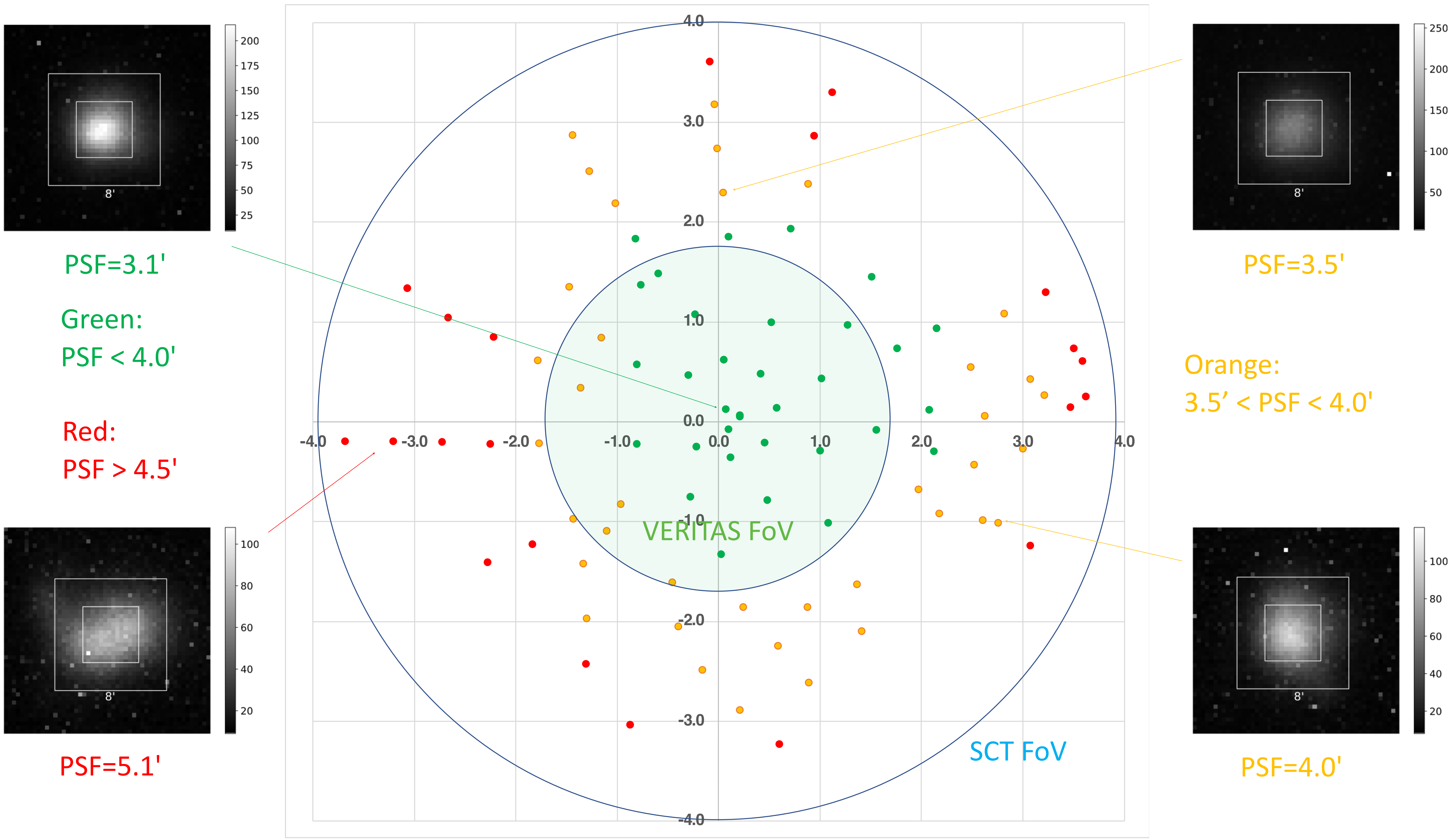




Conclusion

- SCT design achieves 3.2 arcmin optical PSF across 8-deg FoV:
  - Dual-mirror optics
  - High-resolution SiPM
- Expected improvement to CTA includes detecting transient events, resolving source confusion, detecting PeVatron, and large-extent sources
- The SCT group has constructed a prototype with functioning optical and camera
  - Detected Crab Nebula
  - Upgrading to full camera in this year
- Thank you to NSF and international partners for their support!

Backup



PSF=3.1'
Green:
PSF < 4.0'
Red:
PSF > 4.5'
PSF=5.1'
VERITAS FoV
SCT FoV
PSF=3.5'
Orange:
3.5' < PSF < 4.0'
PSF=4.0'
8'