Prototype Telescopes of the Cherenkov Telescope Array

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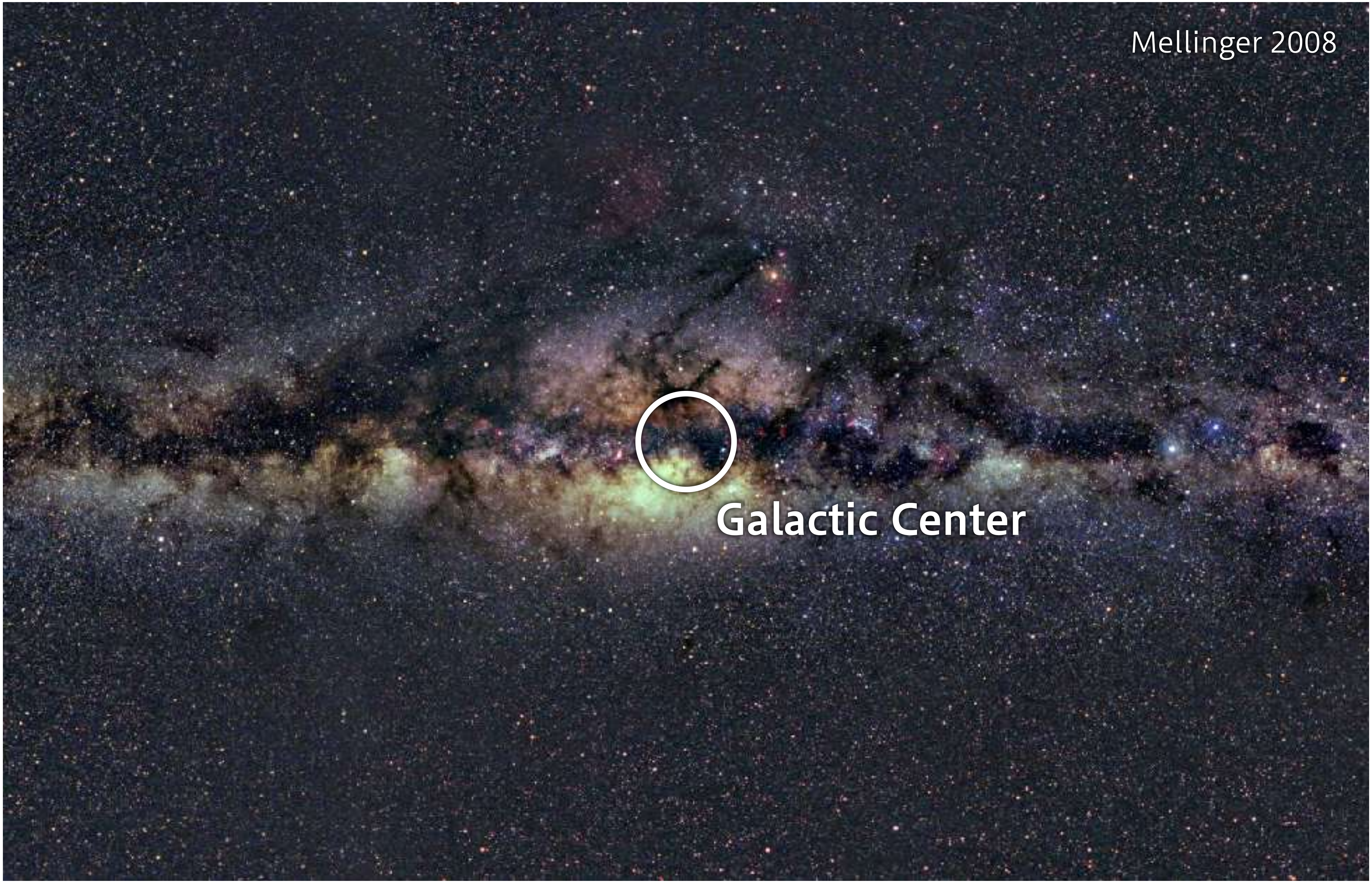
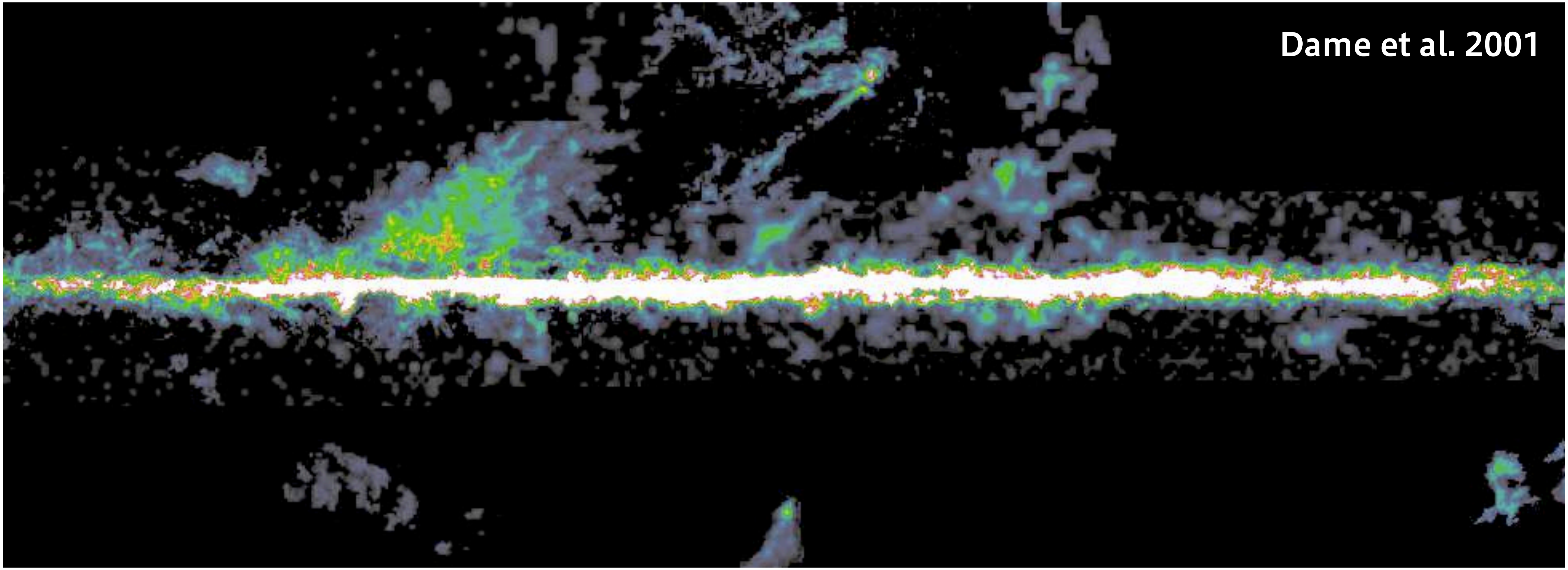
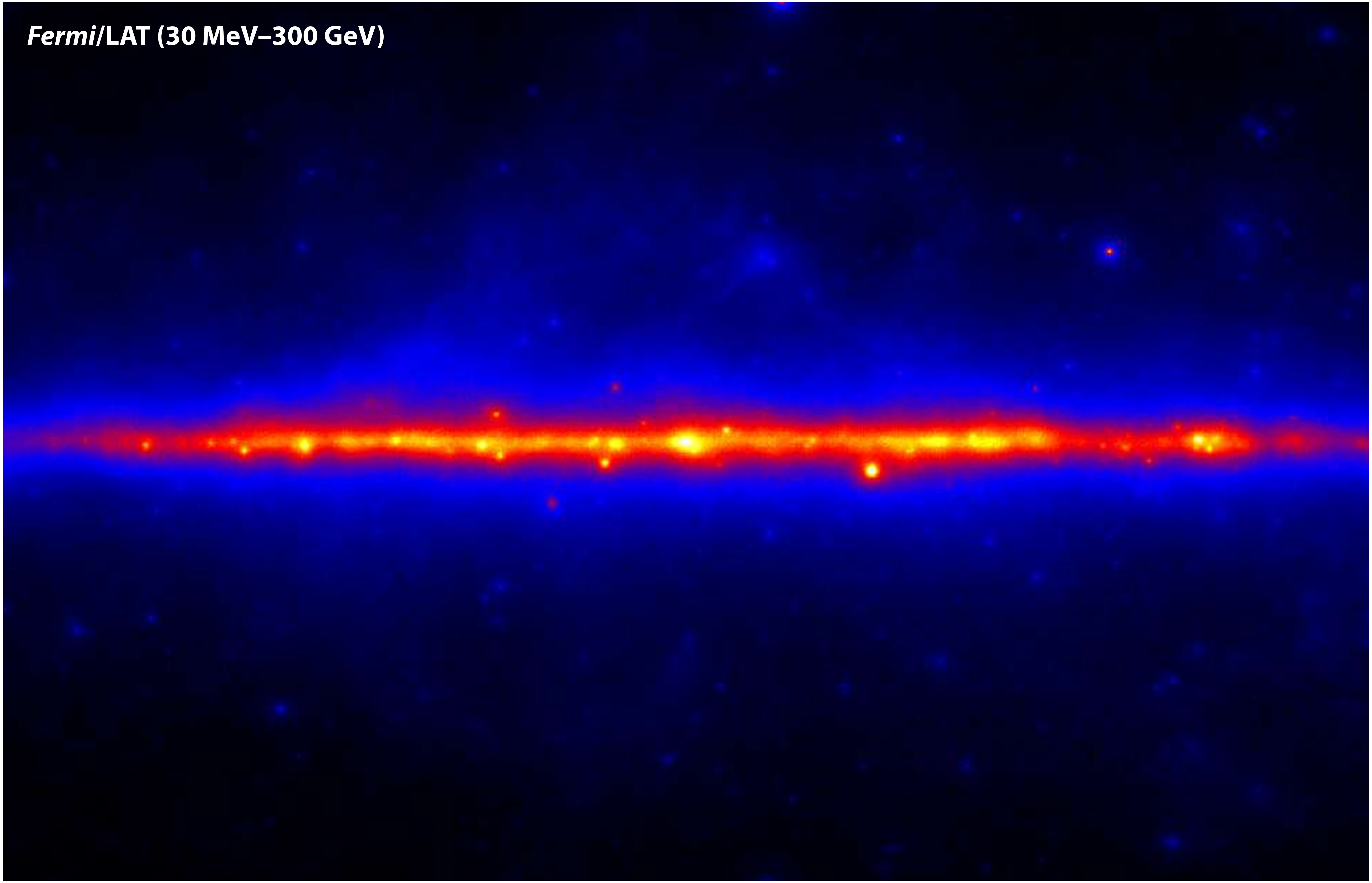
Milky Way by Optical Photons



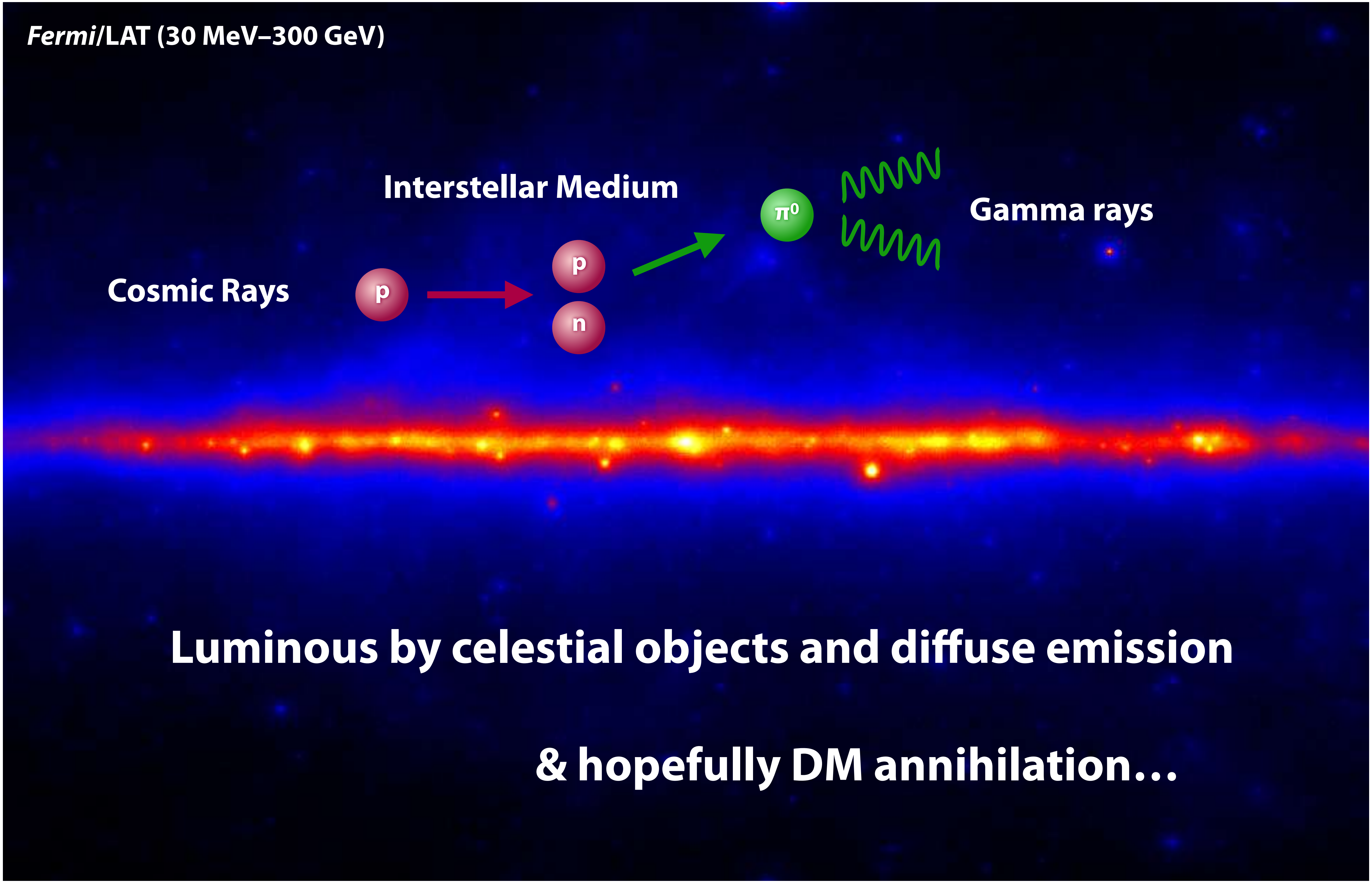
Milky Way by Radio (CO 115 GHz Emission Line)



Milky Way by Gamma Rays

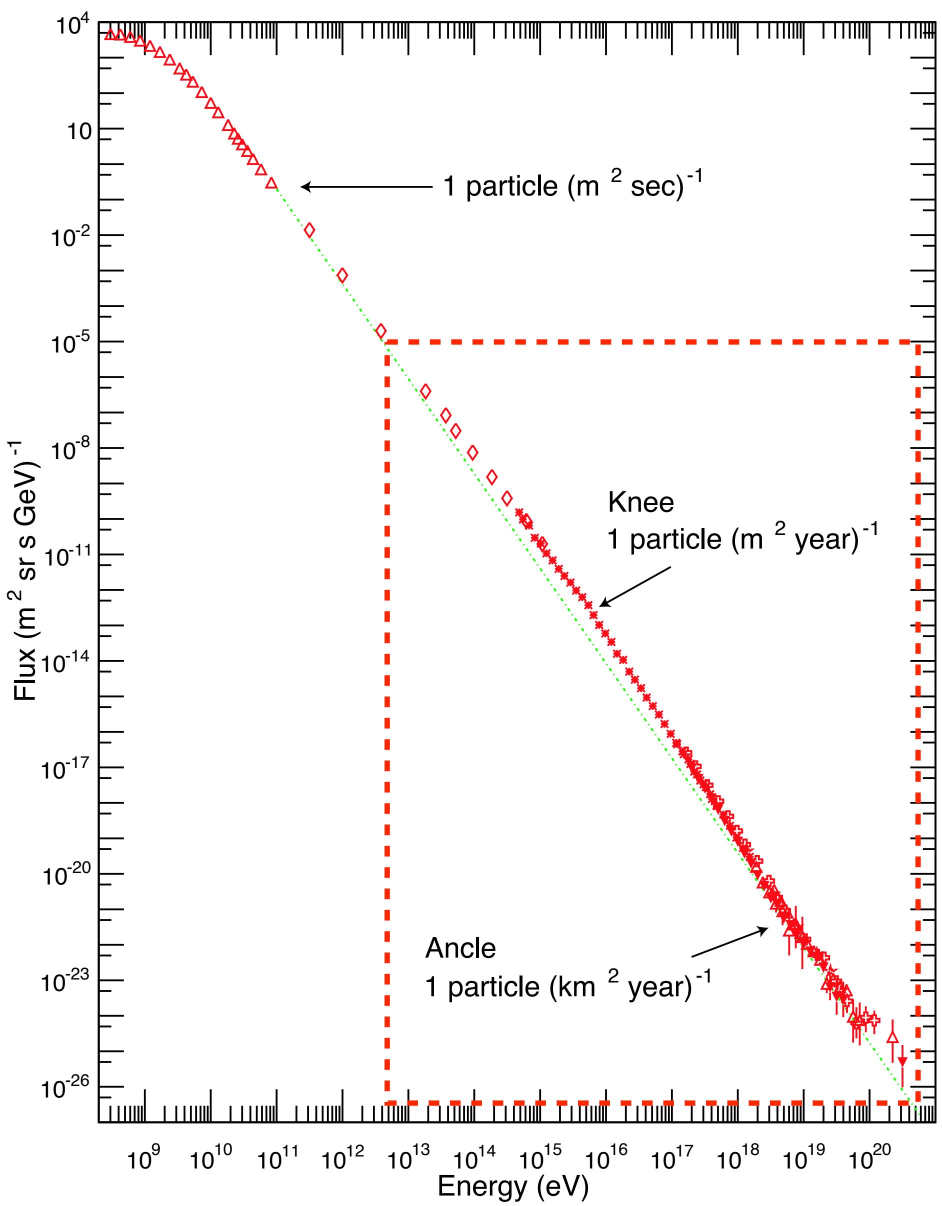


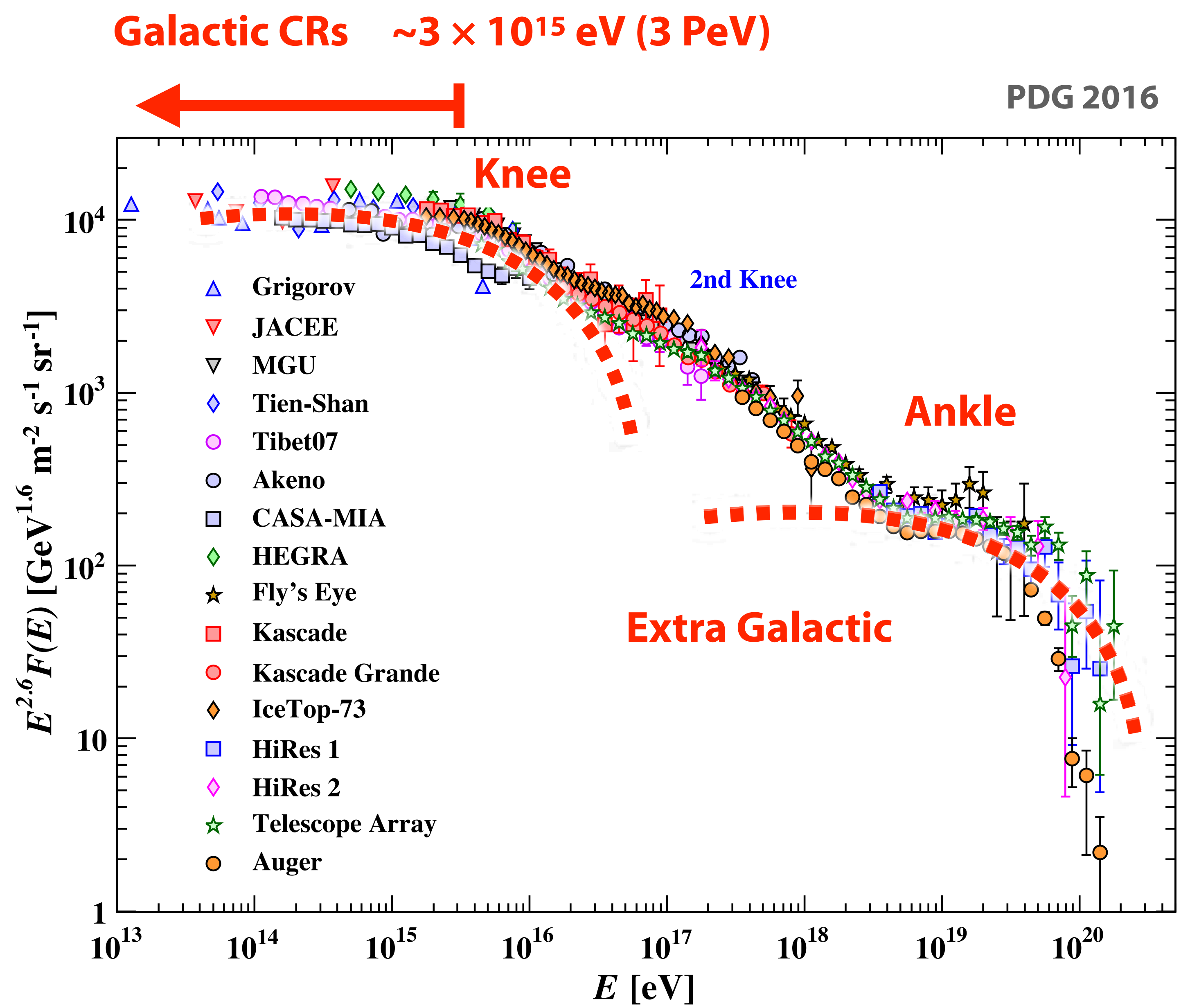
Milky Way by Gamma Rays



Cosmic-ray Hadron Spectrum

Modified Cronin+ (1997)

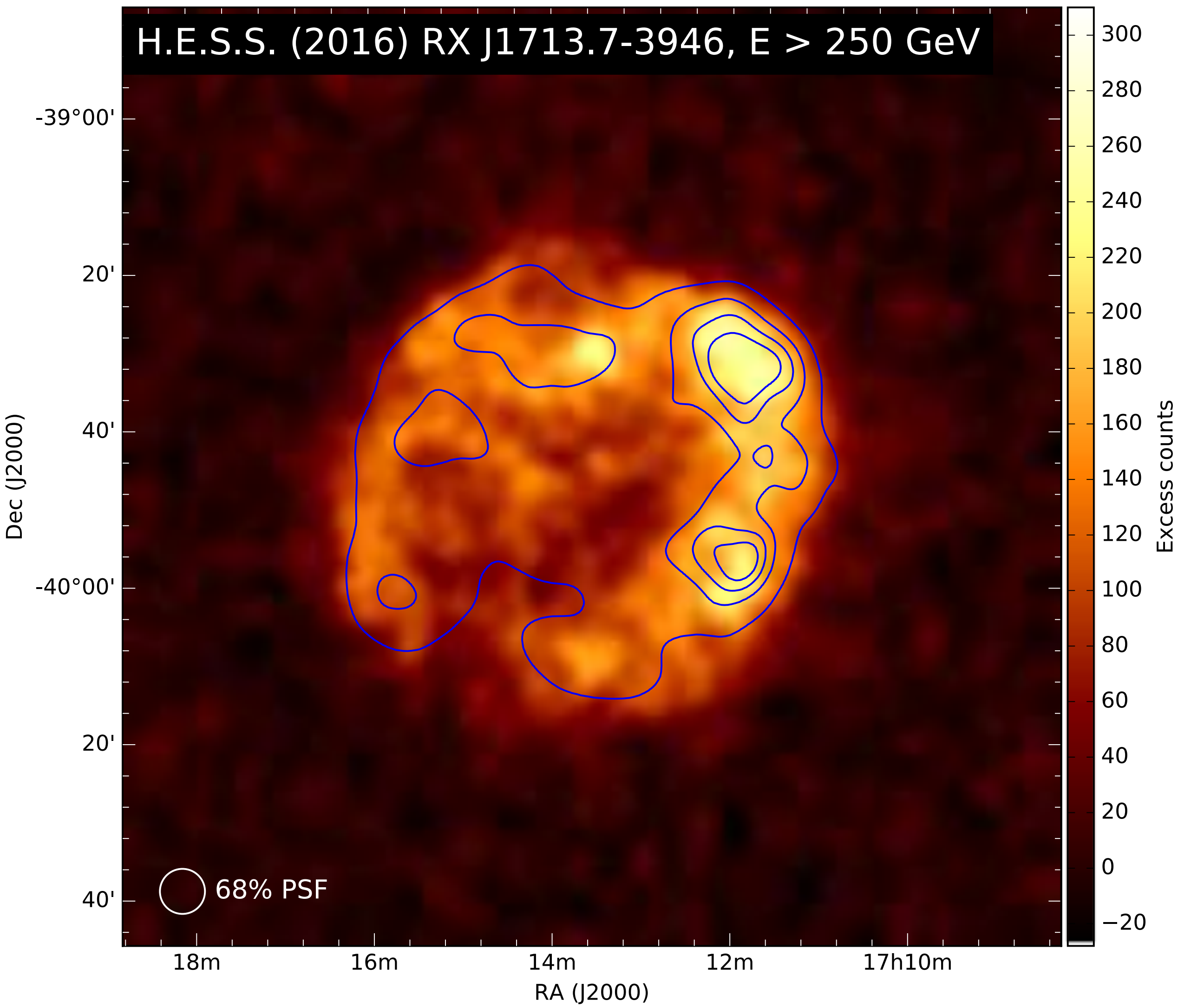




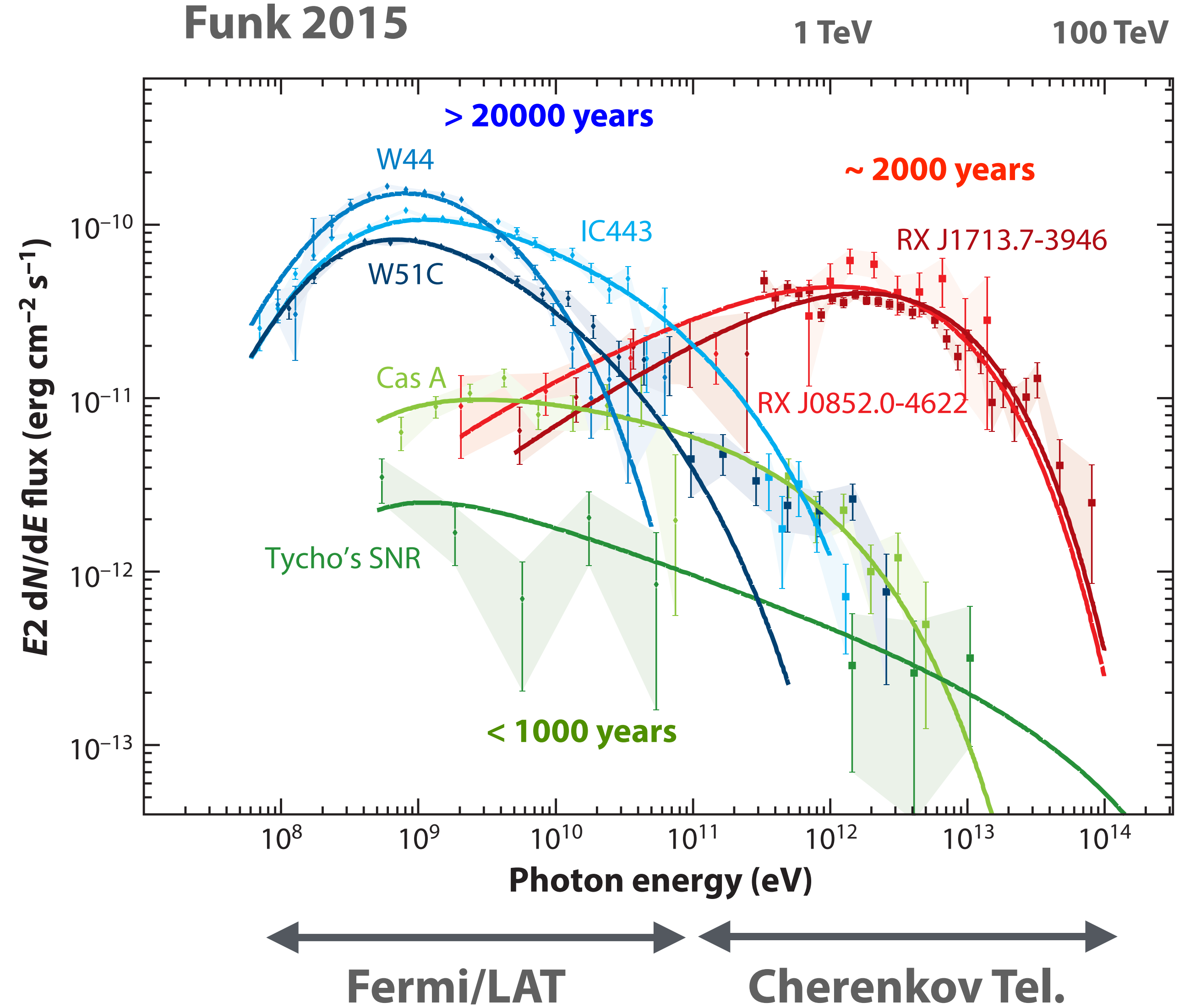
- $\sim 10^8$ eV ($\sim$100 MeV) to > 10^{20} eV, with a power law of $dN/dE = E^{-2.7}$ to $E^{-3.0}$
- What is the origin (PeVatron) of Galactic CRs (< ~3 PeV)? Supernova remnants? Galactic center?

Supernova Remnants (SNRs)

H.E.S.S. 2018



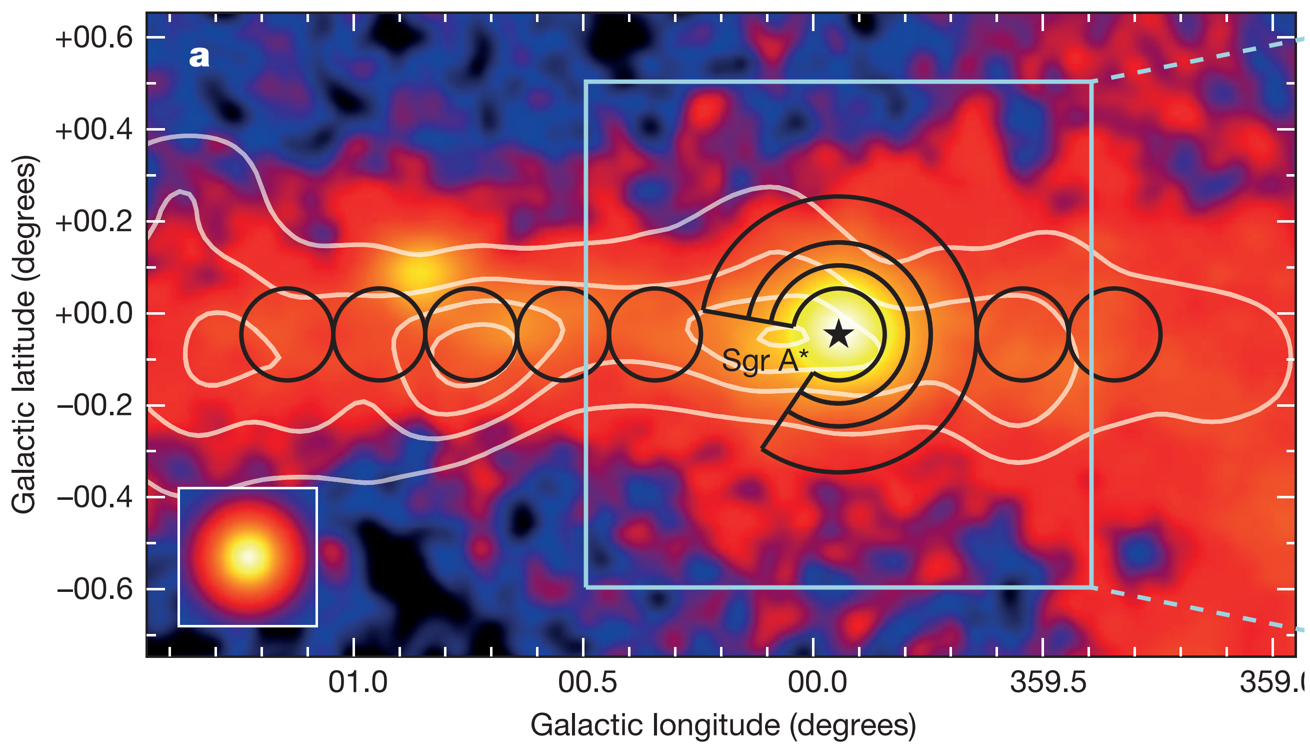
Funk 2015

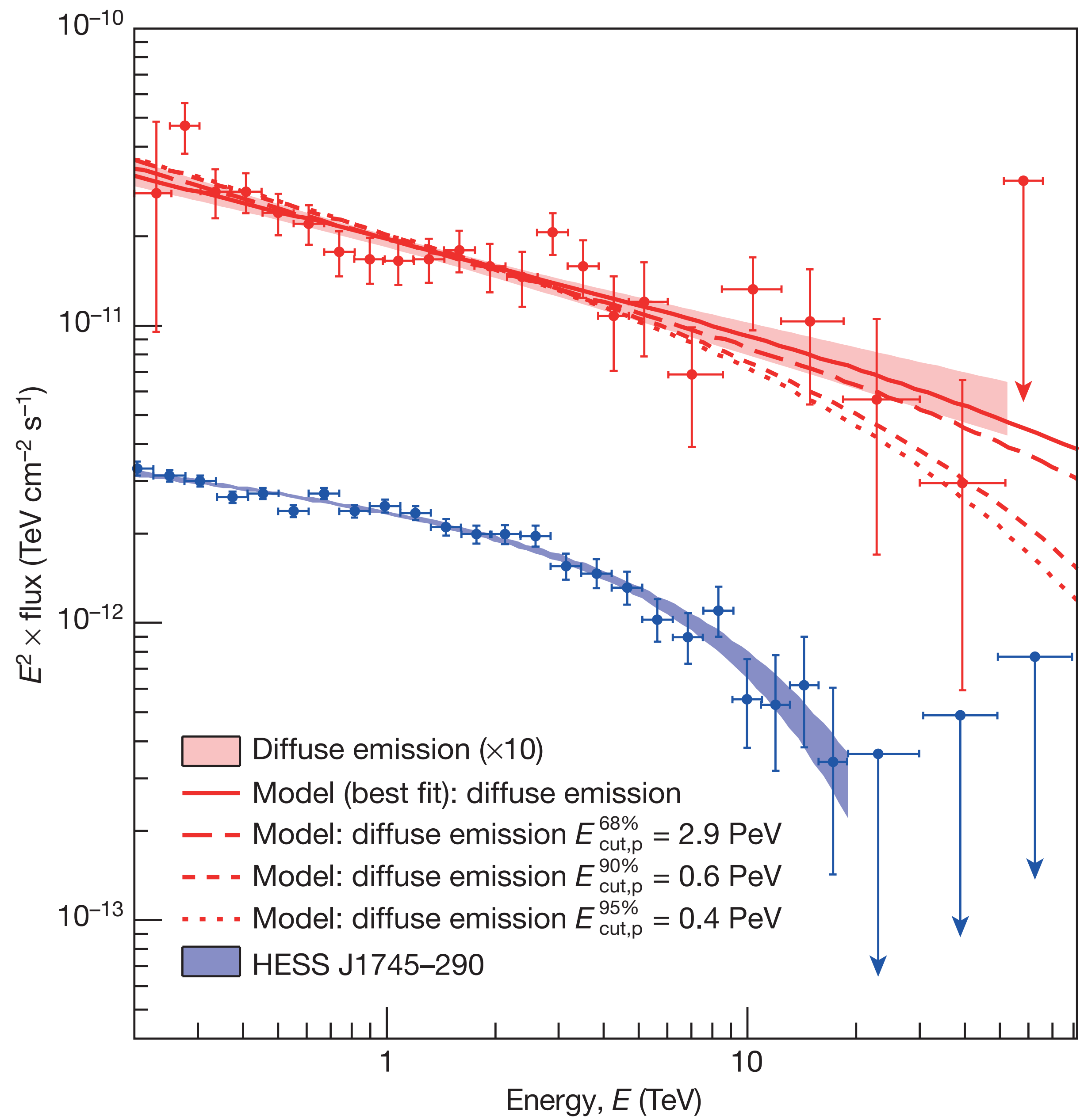


- Correlation between gamma emission and interstellar gas, and spectral shape consistent with π^0
- LST SNRs; W44/W51C/IC443 are thought to be proton accelerators, but no PeV source is found so far
- RX J1713.7–3946: > 10 TeV spectrum, but cutoff below 100 TeV → not a PeVatron

Galactic Center Region

H.E.S.S. (2016)

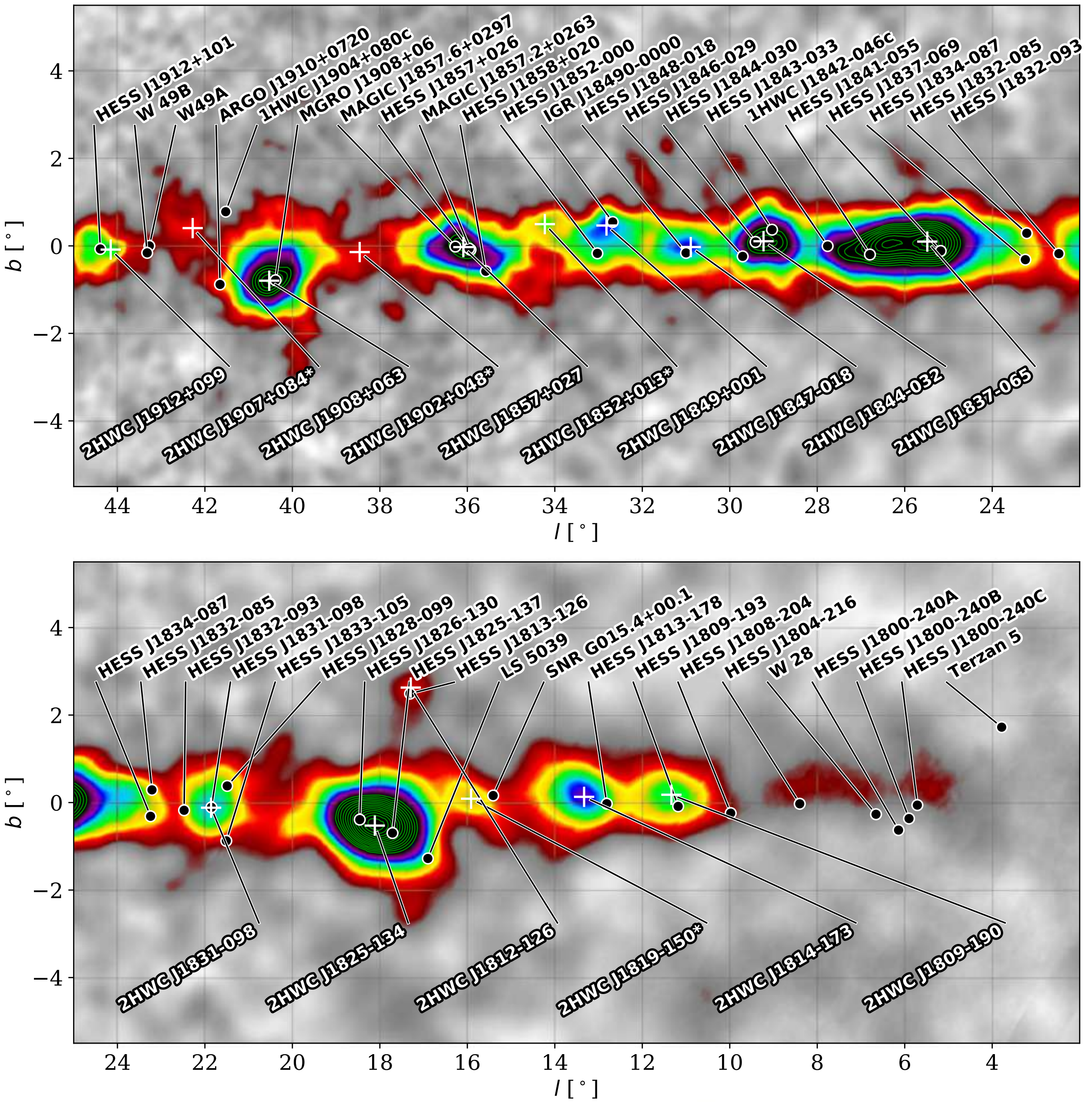




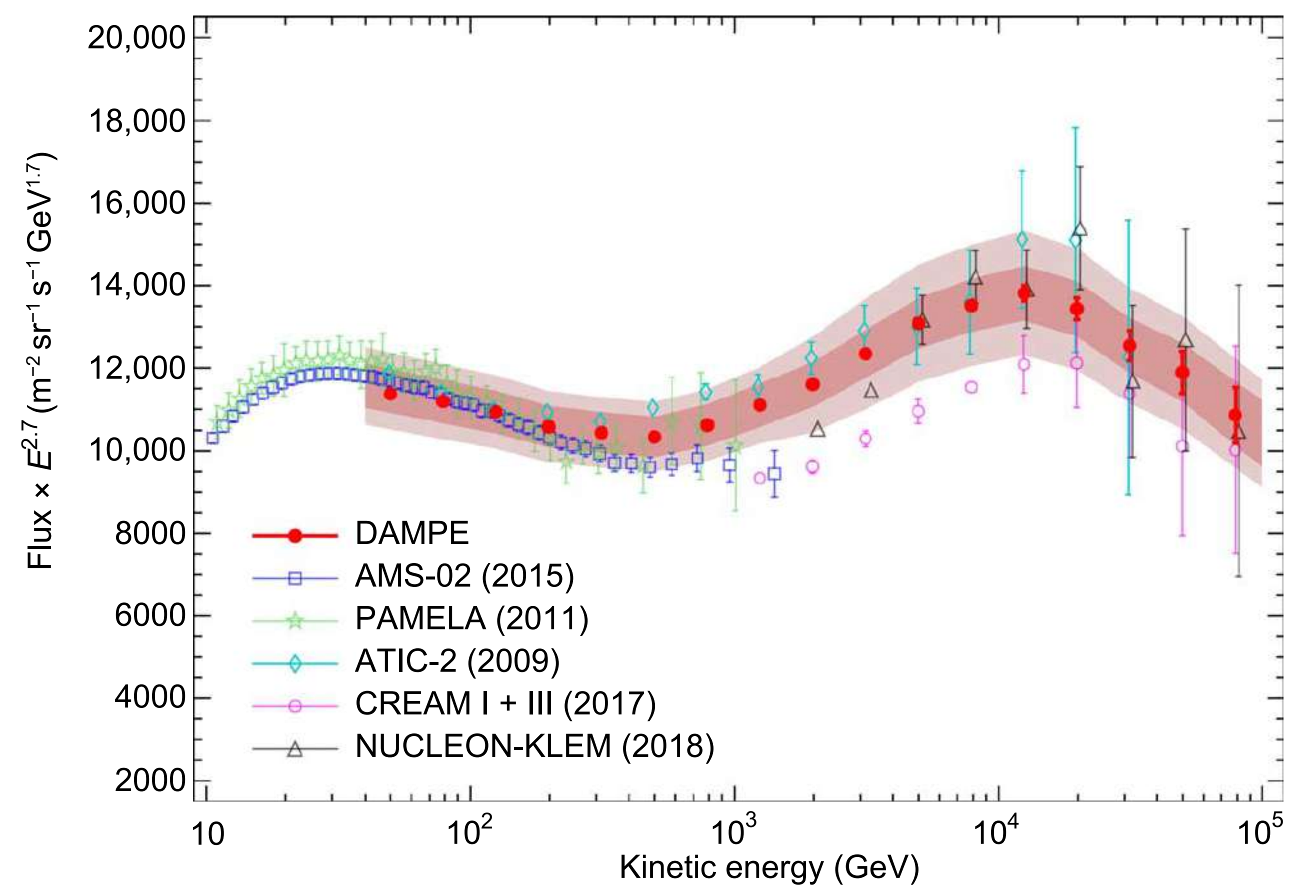
- Massive black hole ($4 \times 10^6\ M_\odot$) at Sgr A* (bright radio source)
- Point source HESS J1745–290 at Str A* and diffuse gamma-ray emission
- Diffuse component has a cutoff energy of 2.9 PeV (68% conf.) → PeVatron?

Other Recent Gamma/CR Observations (1)

HAWC (2017)



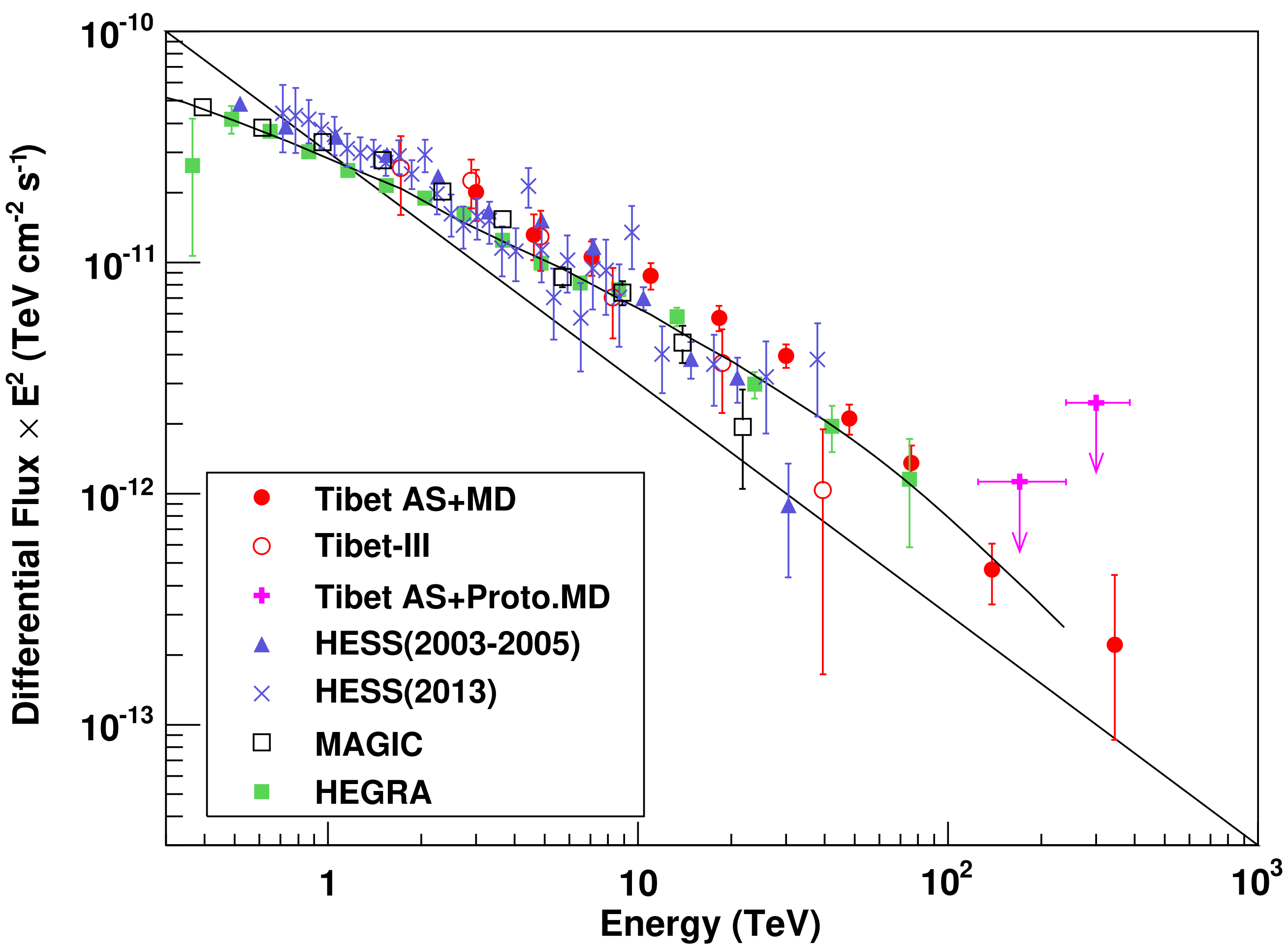
DAMPE (2019)



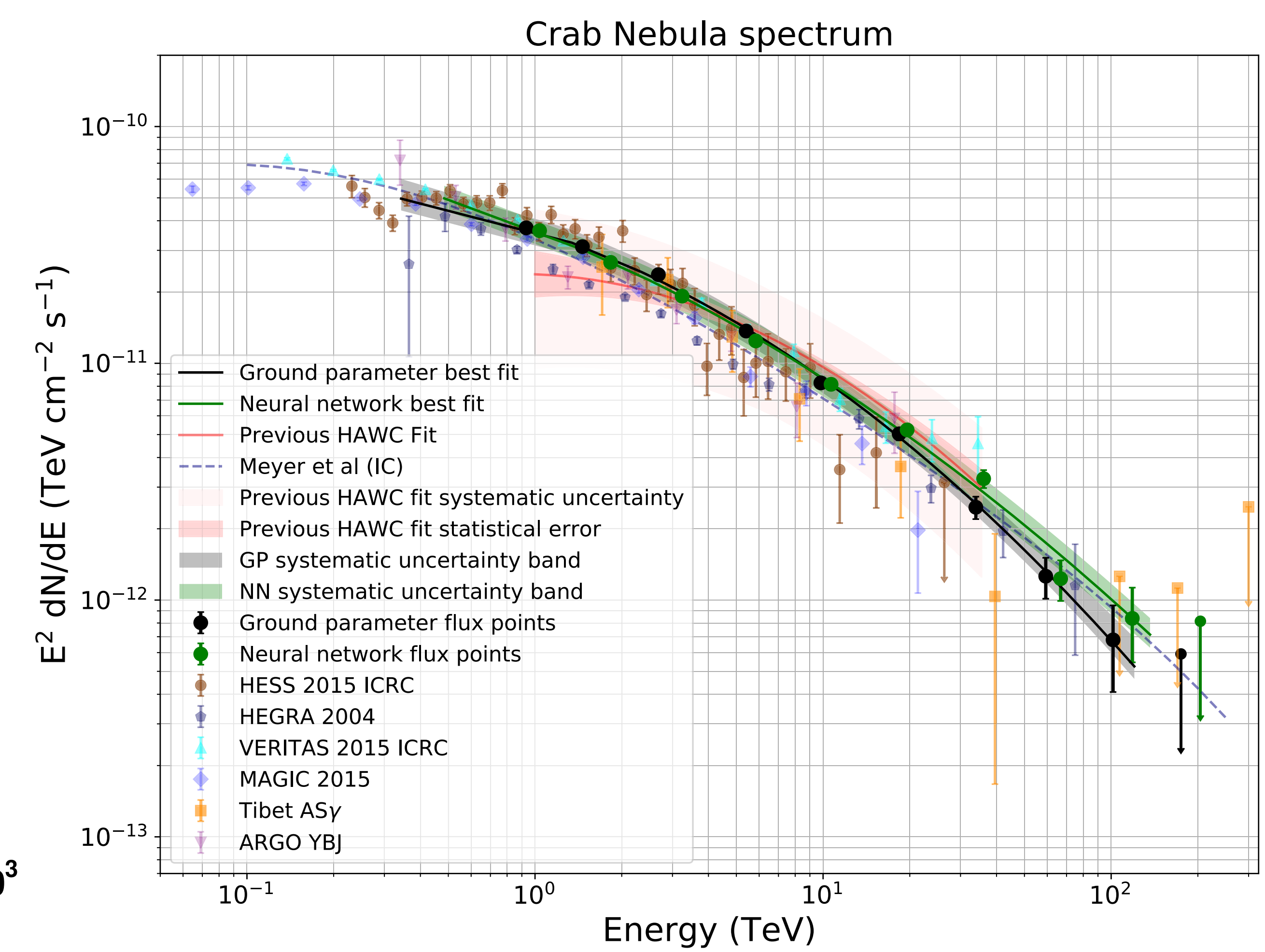
- Sources found in > ~10 TeV Sky by HAWC are not completely identical with H.E.S.S. sources (< ~10 TeV)
  → Are we observing mixture of multiple PeVatrons?
- DAMPE and other satellite measurements revealed spectrum hardening and softening in 1–100 TeV
  → Galactic CRs are originated from different accelerator object types?

Other Recent Gamma/CR Observations (2)

Tibet (2019)

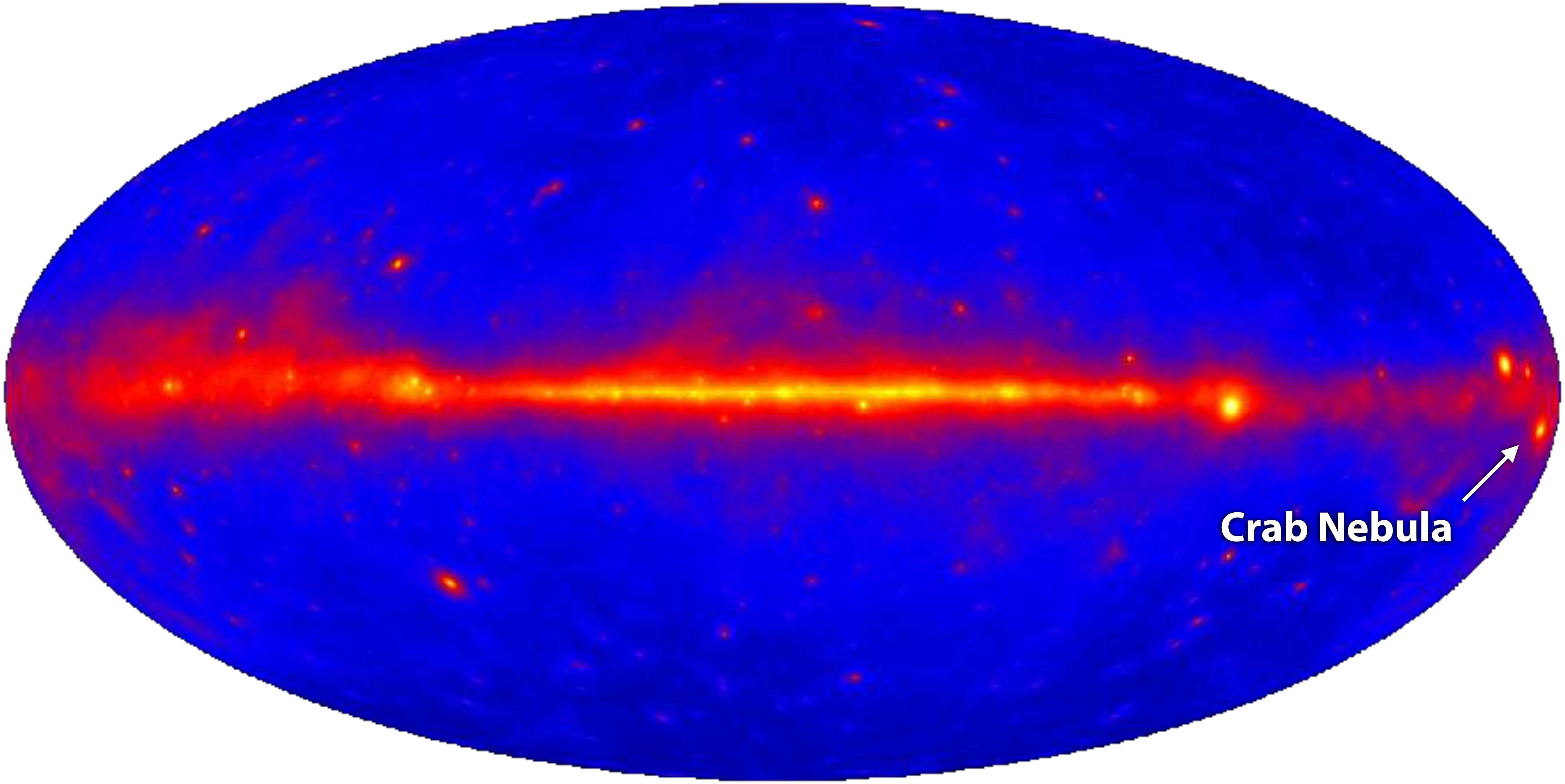


HAWC (2019)



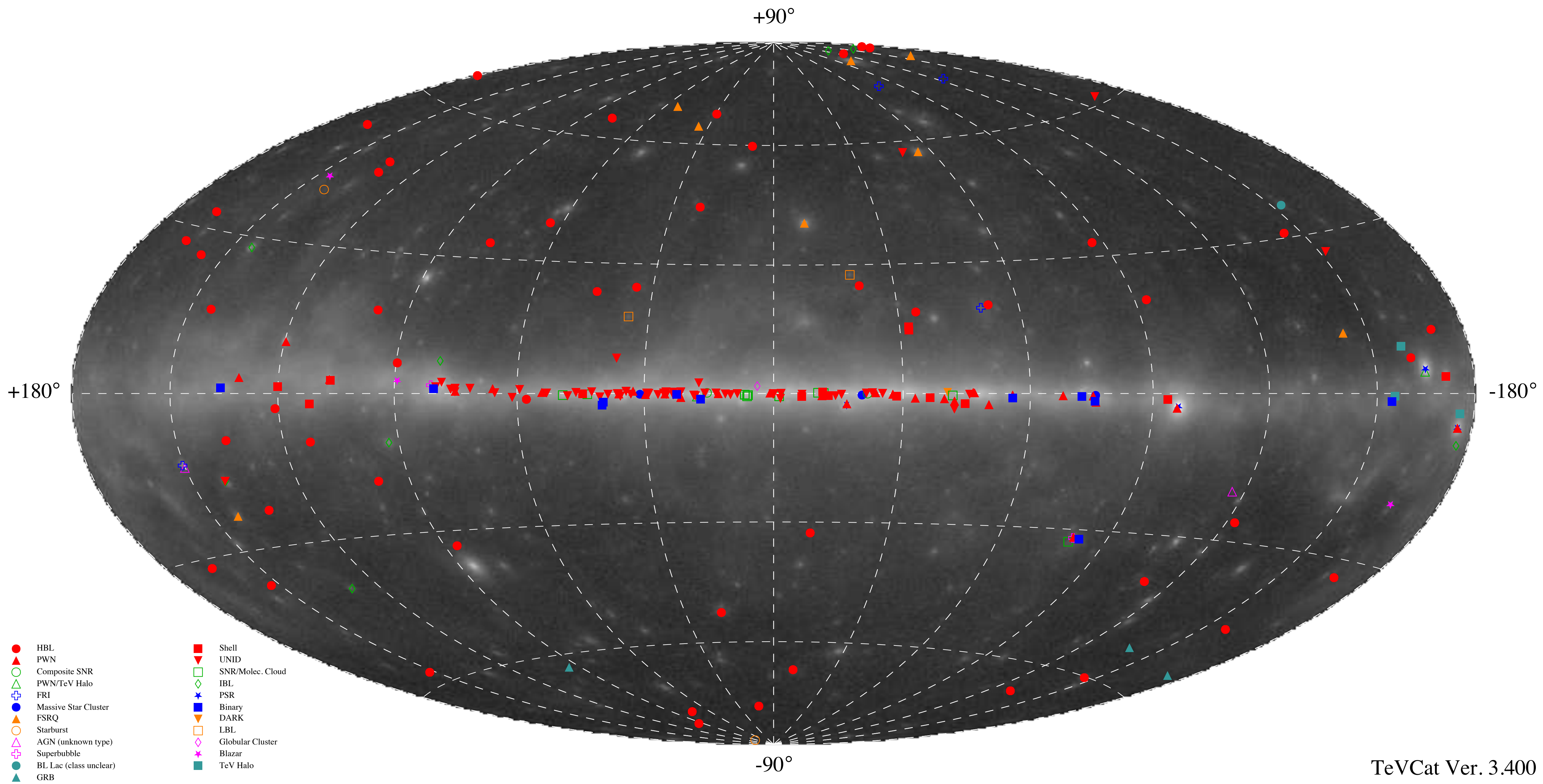
- 100 TeV 超のガンマ線は、かに星雲 (Crab Nebula) でようやく見えてきたばかり (チェレンコフ望遠鏡ではそこまで長時間 Crab を観測しない)
- Crab では電子加速による逆コンプトン散乱なので、宇宙線陽子の PeV までの加速の証拠ではない
-

Fermi/LAT All-sky Map (30 MeV–300 GeV)

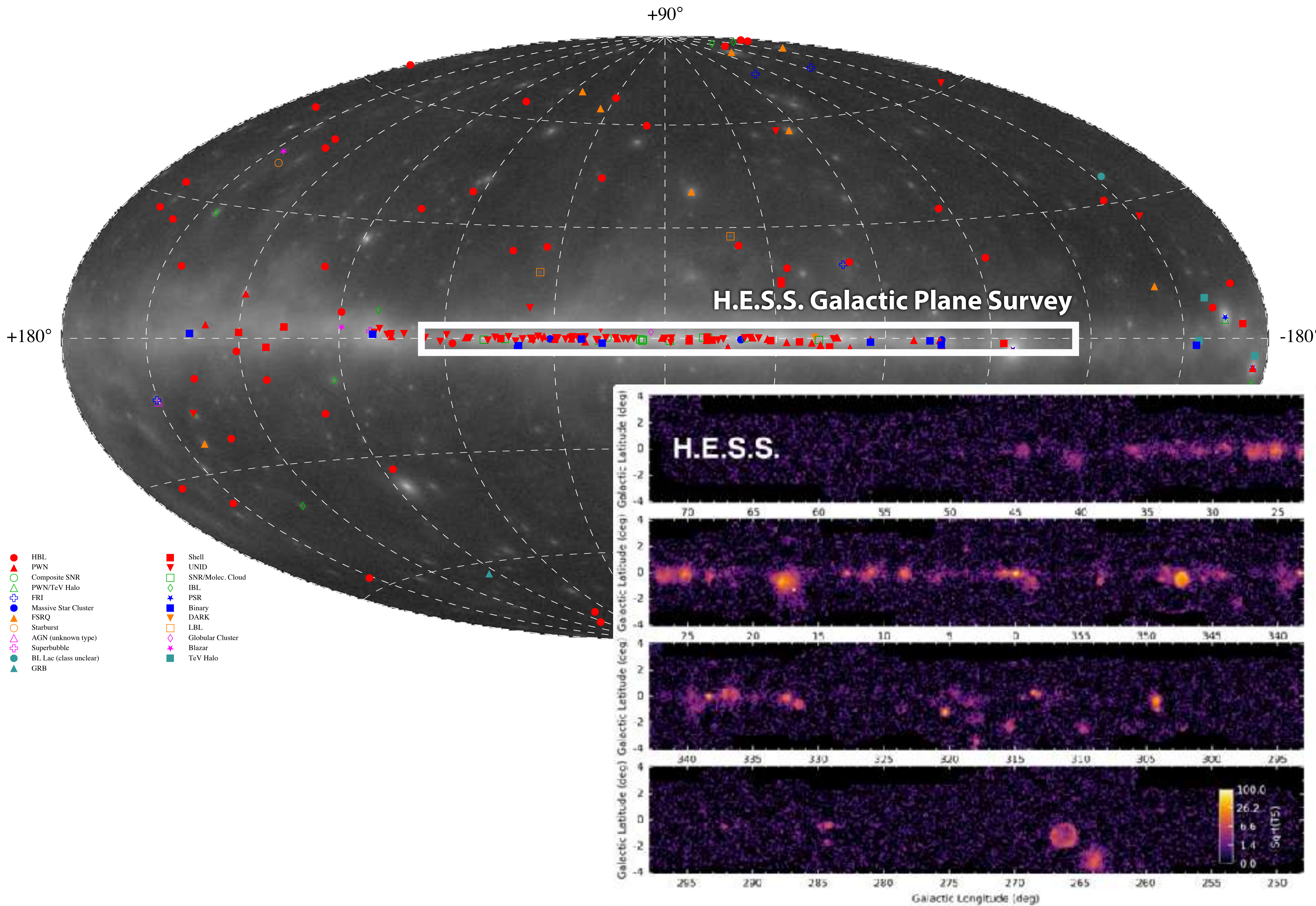


- Where do cosmic-ray protons come from? One of the biggest issues in CR physics
- Supernova remnants? Galactic Center? Any other sources?

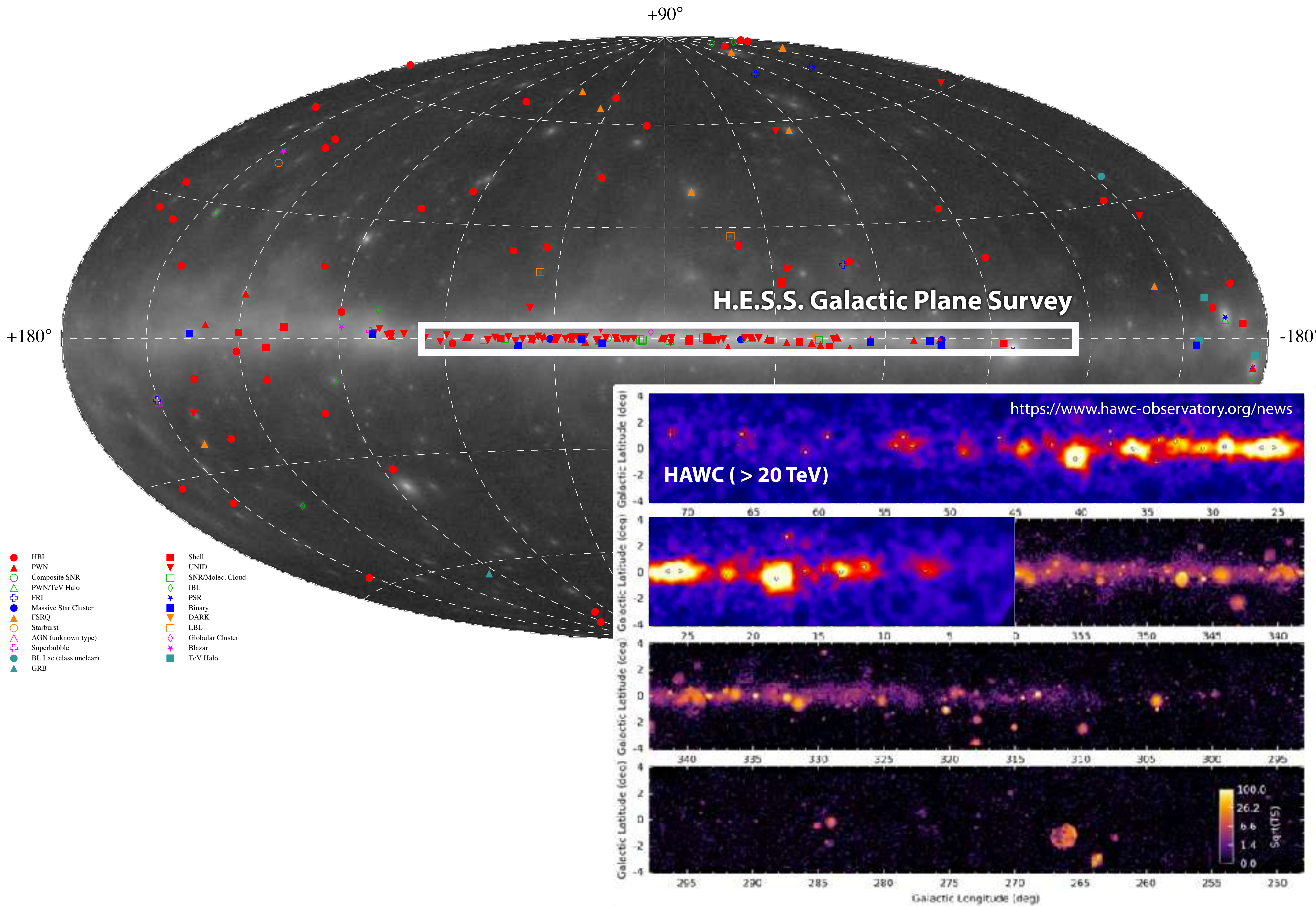
TeV Source Map



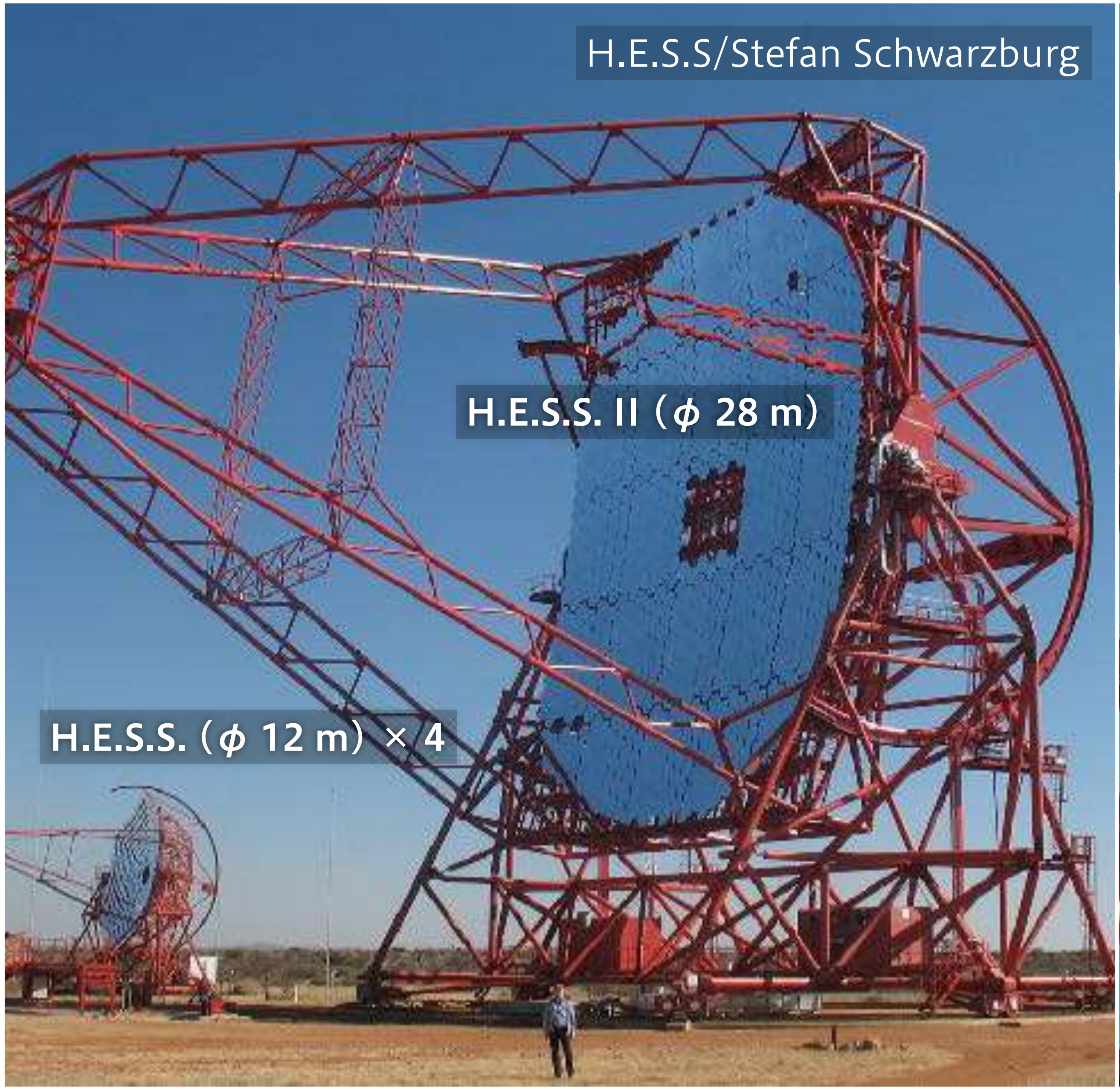
TeV Source Map



TeV Source Map



Imaging Atmospheric Cherenkov Telescopes (100 GeV–10 TeV)



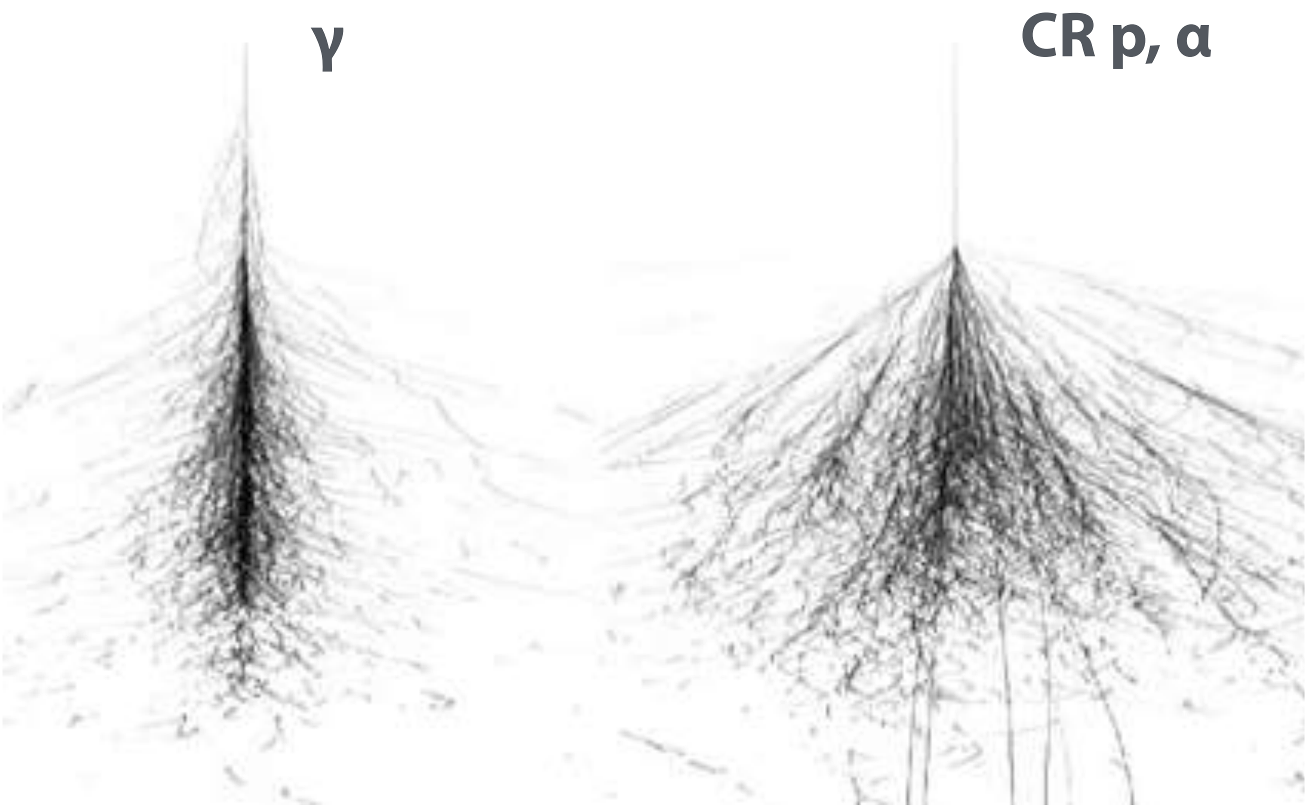
- 3–30 m diameter mirrors to detect atmospheric Cherenkov photons (300–500 nm) in moonless nights
- H.E.S.S. (@Namibia, 4 × 12 m & 1 × 28 m), MAGIC (@La Palma, 2 × 17 m), VERITAS (@Arizona, 4 × 10 m)
- Wide effective area, high energy resolution (< 20%), high angular resolution (< 0.1°), but narrow field of view (< 5°) and low operation coverage (ave. ~4 hours/day)

Other Techniques

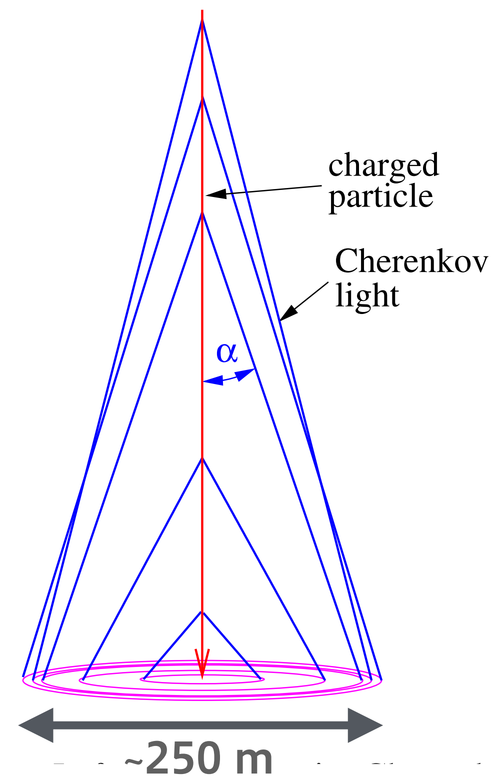
- 30 MeV–300 GeV, all-sky survey, high angular and energy resolution, but small effective area (~1 m^2)
- HAWC, Tibet ASγ, LHAASO (ground-based particle detectors)
  - High energies > 1 TeV, wide effective area, wide FOV, and 24 hour/d, but low angular and energy resolution

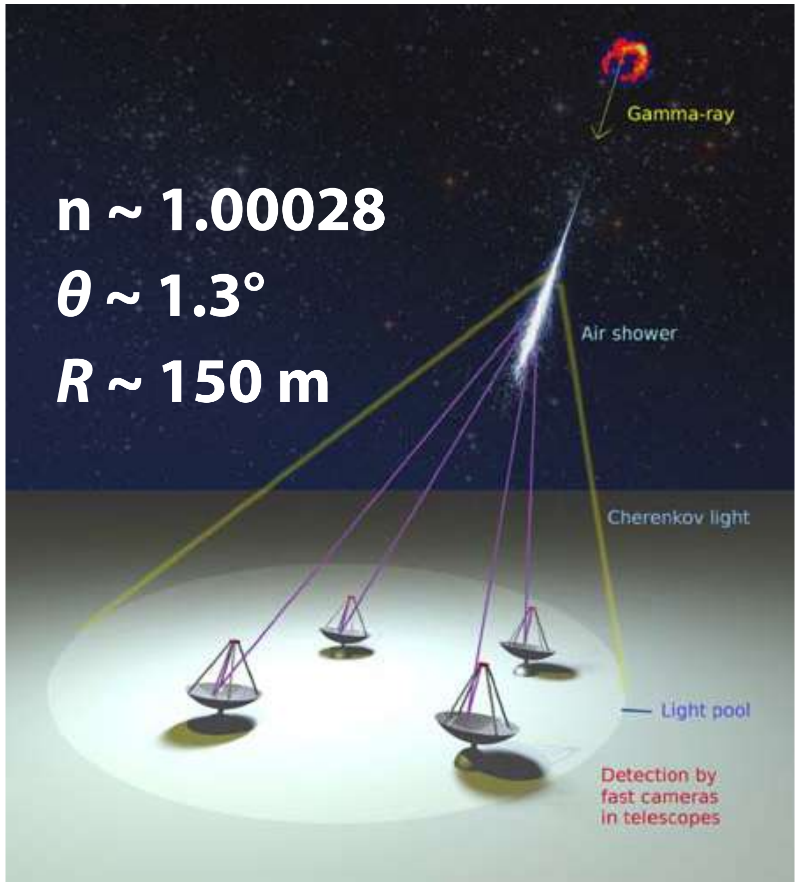
Atmospheric-Cherenkov Observation

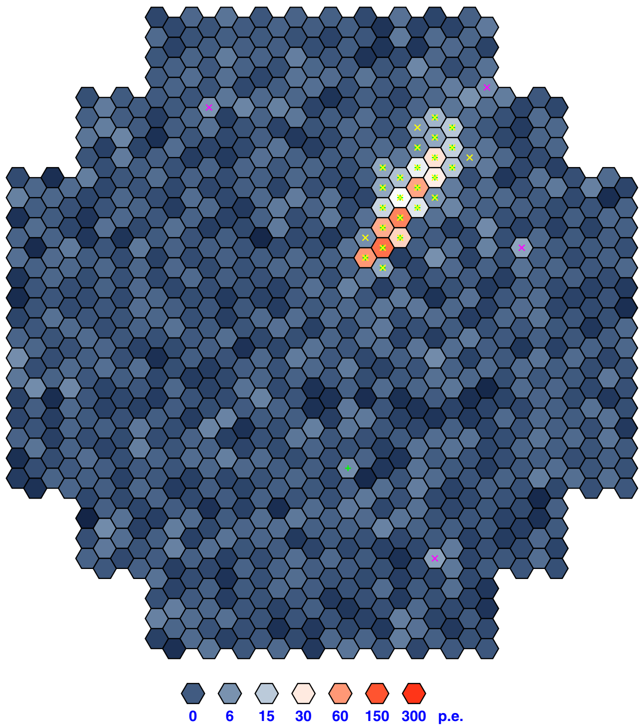
Völk and Bernlöhr 2009



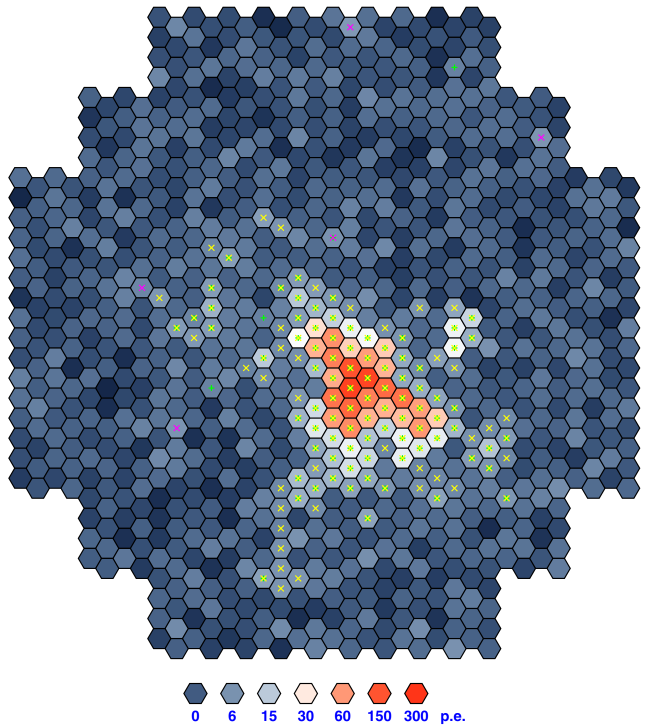
Gamma shower | Hadronic shower



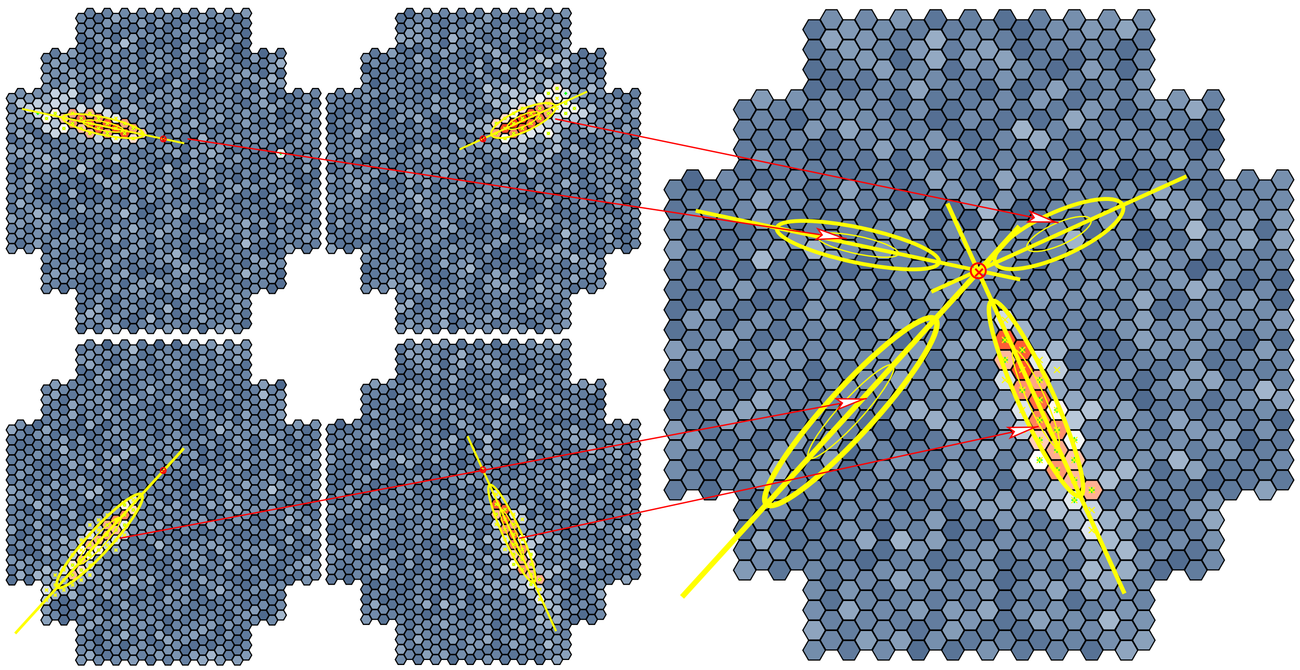




1.0 TeV gamma shower



2.6 TeV proton shower



Cherenkov Telescope Array (CTA)

cta
cherenkov
telescope
array

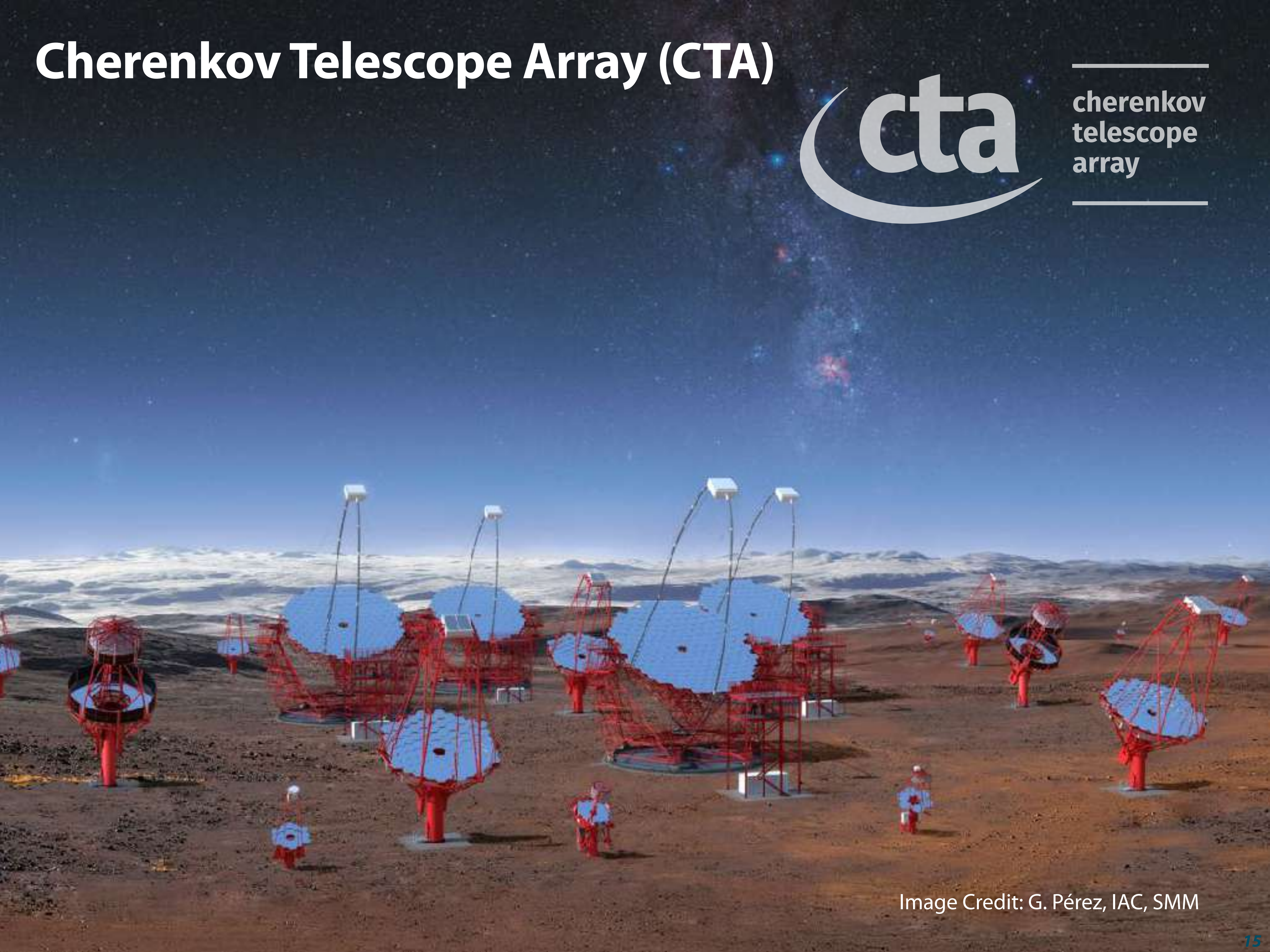


Image Credit: G. Pérez, IAC, SMM

Cherenkov Telescope Array (CTA)

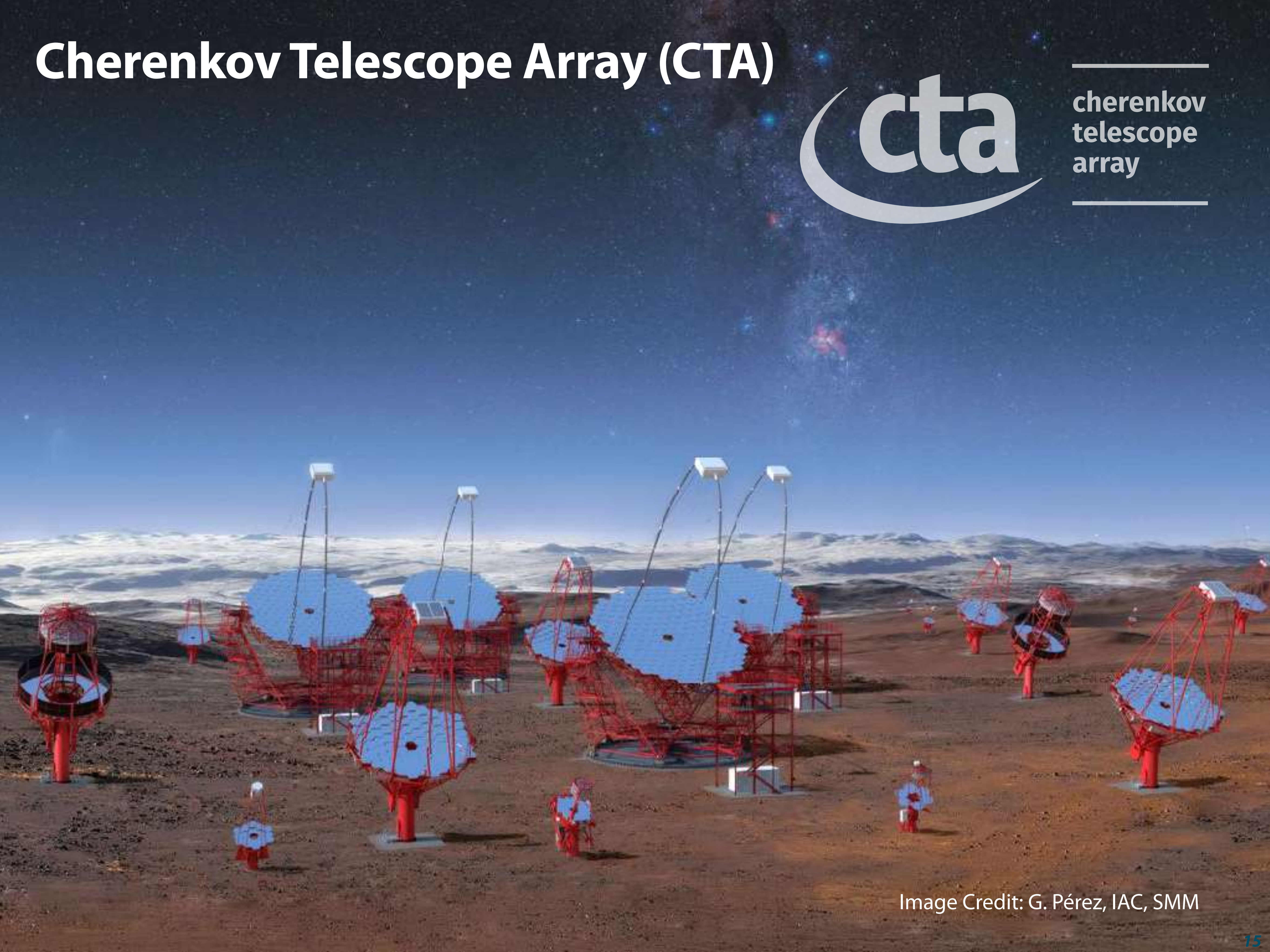


Image Credit: G. Pérez, IAC, SMM

Cherenkov Telescope Array (CTA)

cta
cherenkov
telescope
array

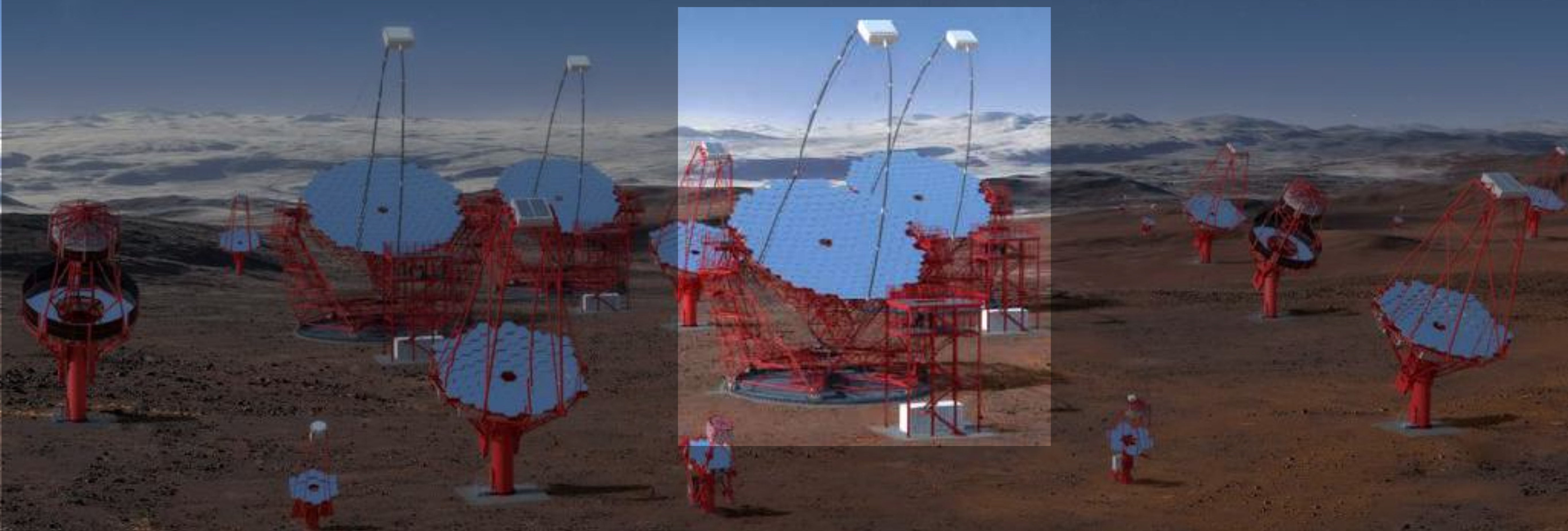
Image Credit: G. Pérez, IAC, SMM

Cherenkov Telescope Array (CTA)

cherenkov telescope array

Large-Sized Telescope (LST)

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



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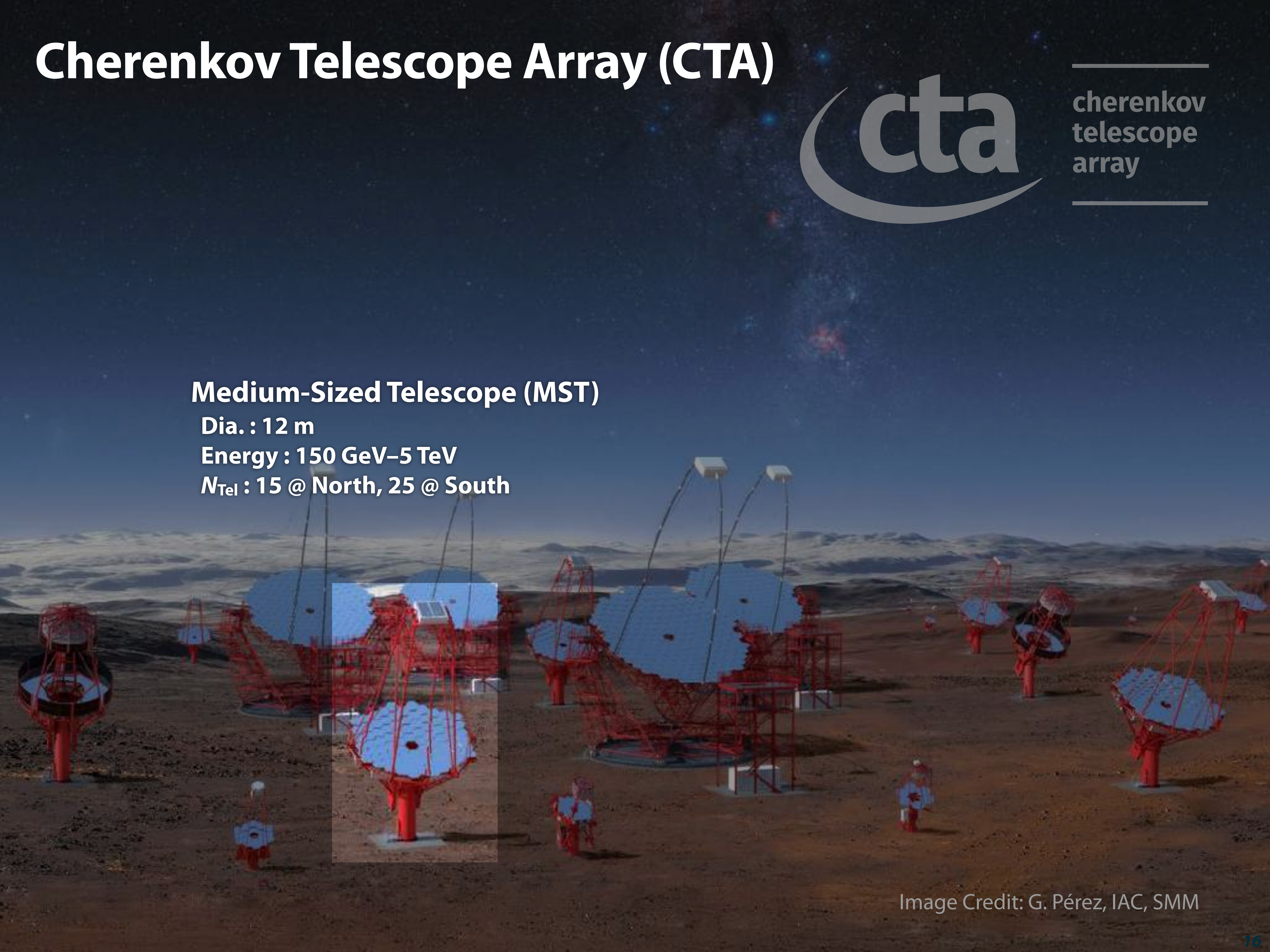
Cherenkov Telescope Array (CTA)

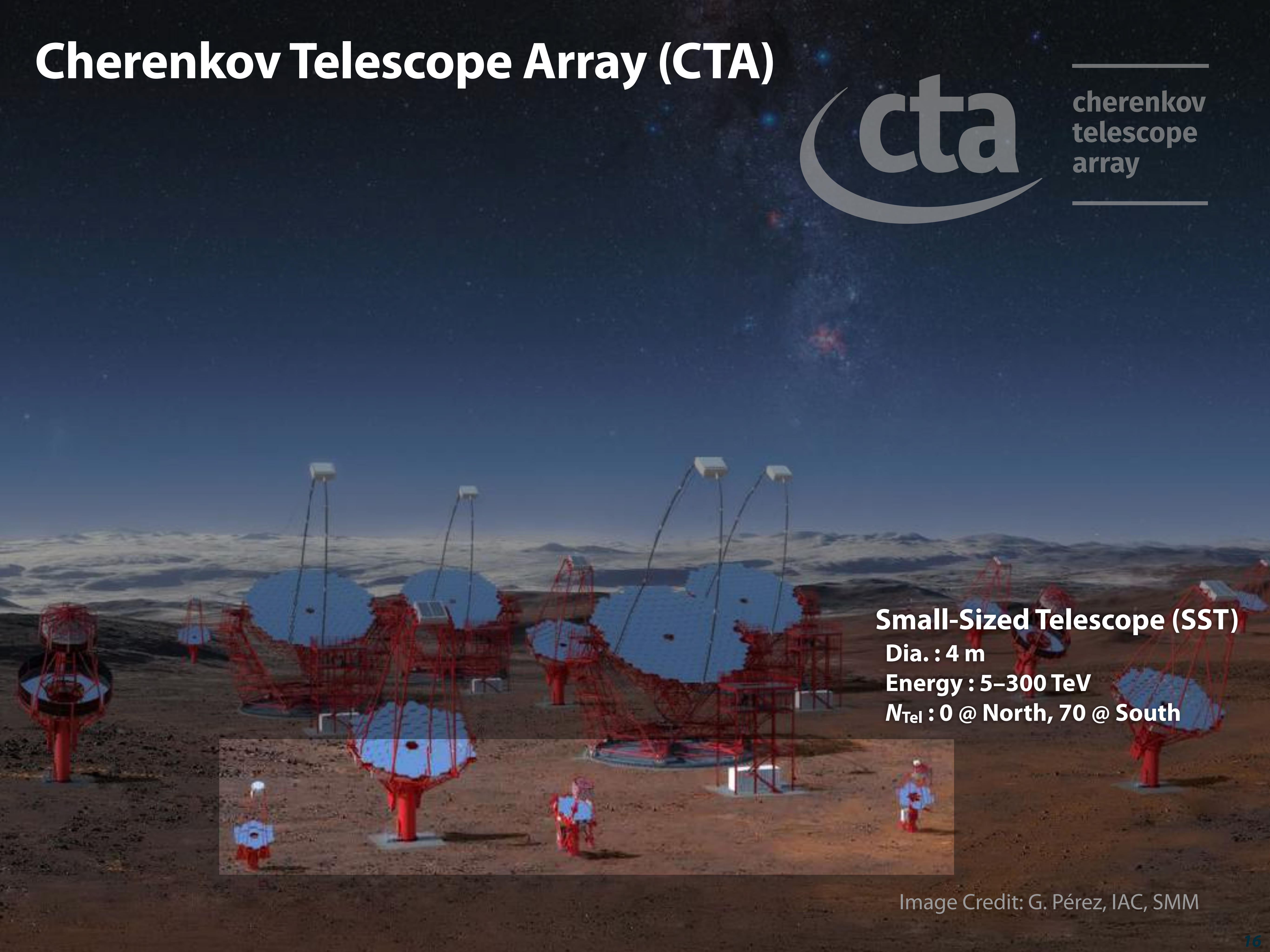
cherenkov
telescope
array



Medium-Sized Telescope (MST)

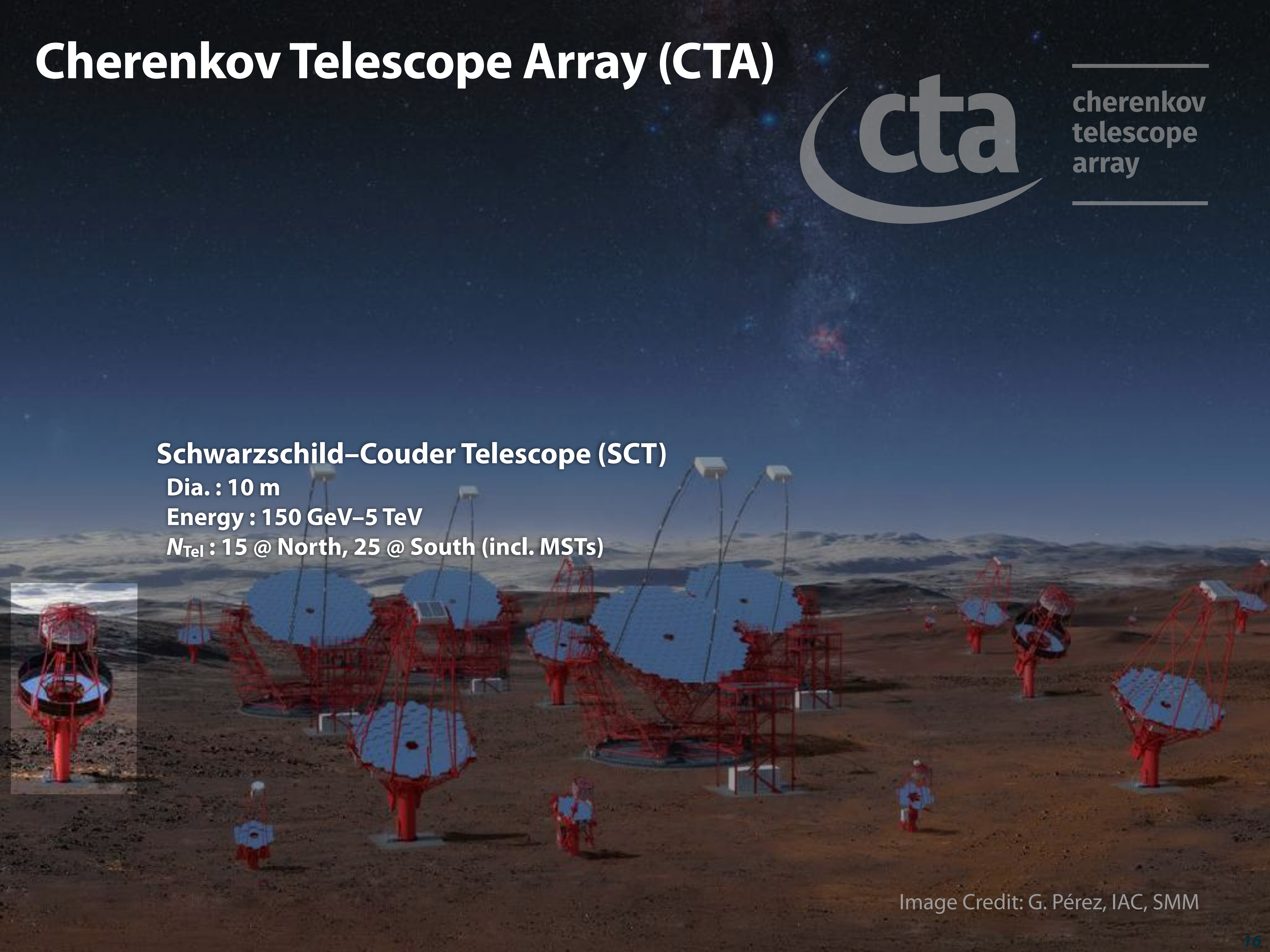
Dia. : 12 m
Energy : 150 GeV–5 TeV
N_{Tel} : 15 @ North, 25 @ South

Image Credit: G. Pérez, IAC, SMM


Cherenkov Telescope Array (CTA)
cta
cherenkov
telescope
array
Small-Sized Telescope (SST)
Dia. : 4 m
Energy : 5–300 TeV
N_{Tel} : 0 @ North, 70 @ South
Image Credit: G. Pérez, IAC, SMM

Cherenkov Telescope Array (CTA)

cta
cherenkov
telescope
array



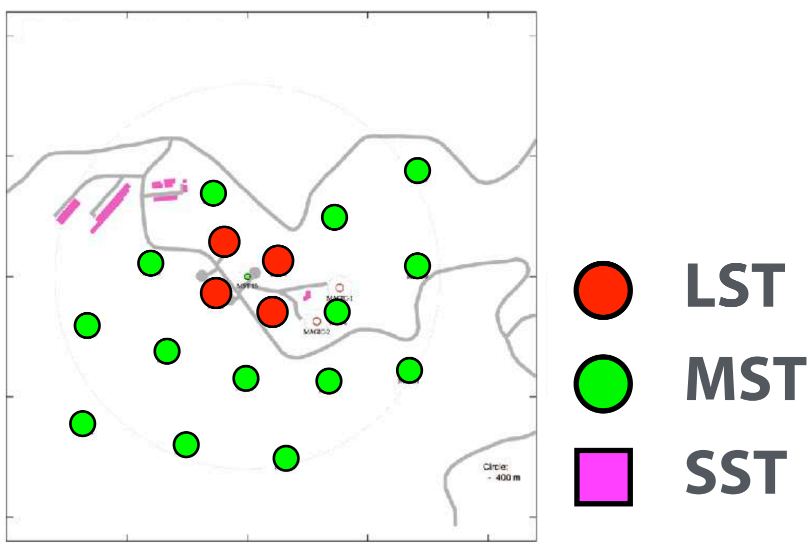
Schwarzschild–Couder Telescope (SCT)

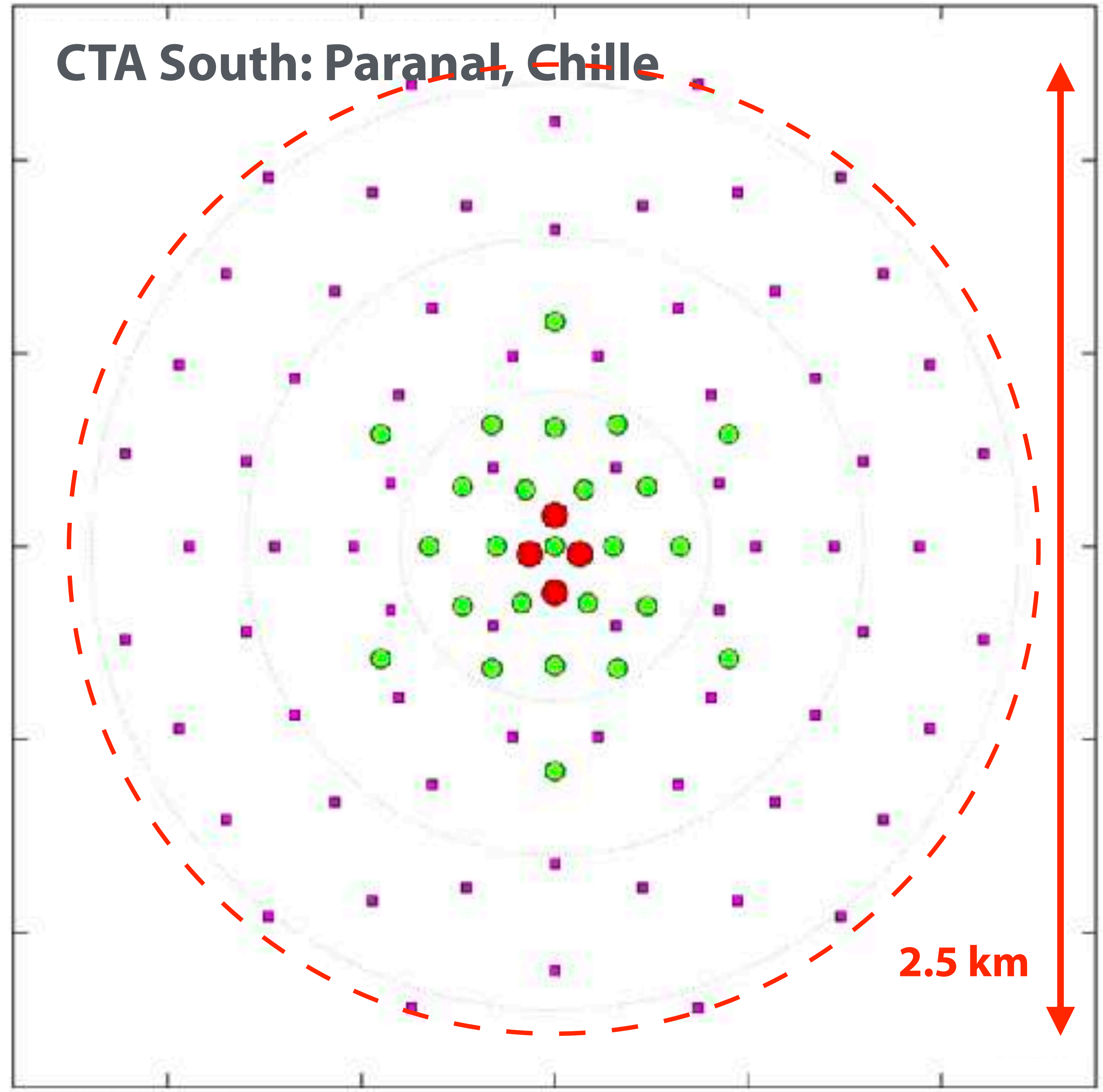
- Dia. : 10 m
- Energy : 150 GeV–5 TeV
- N_{Tel} : 15 @ North, 25 @ South (incl. MSTs)

Image Credit: G. Pérez, IAC, SMM

CTA Northern & Southern Sites

CTA North: La Palma, Spain

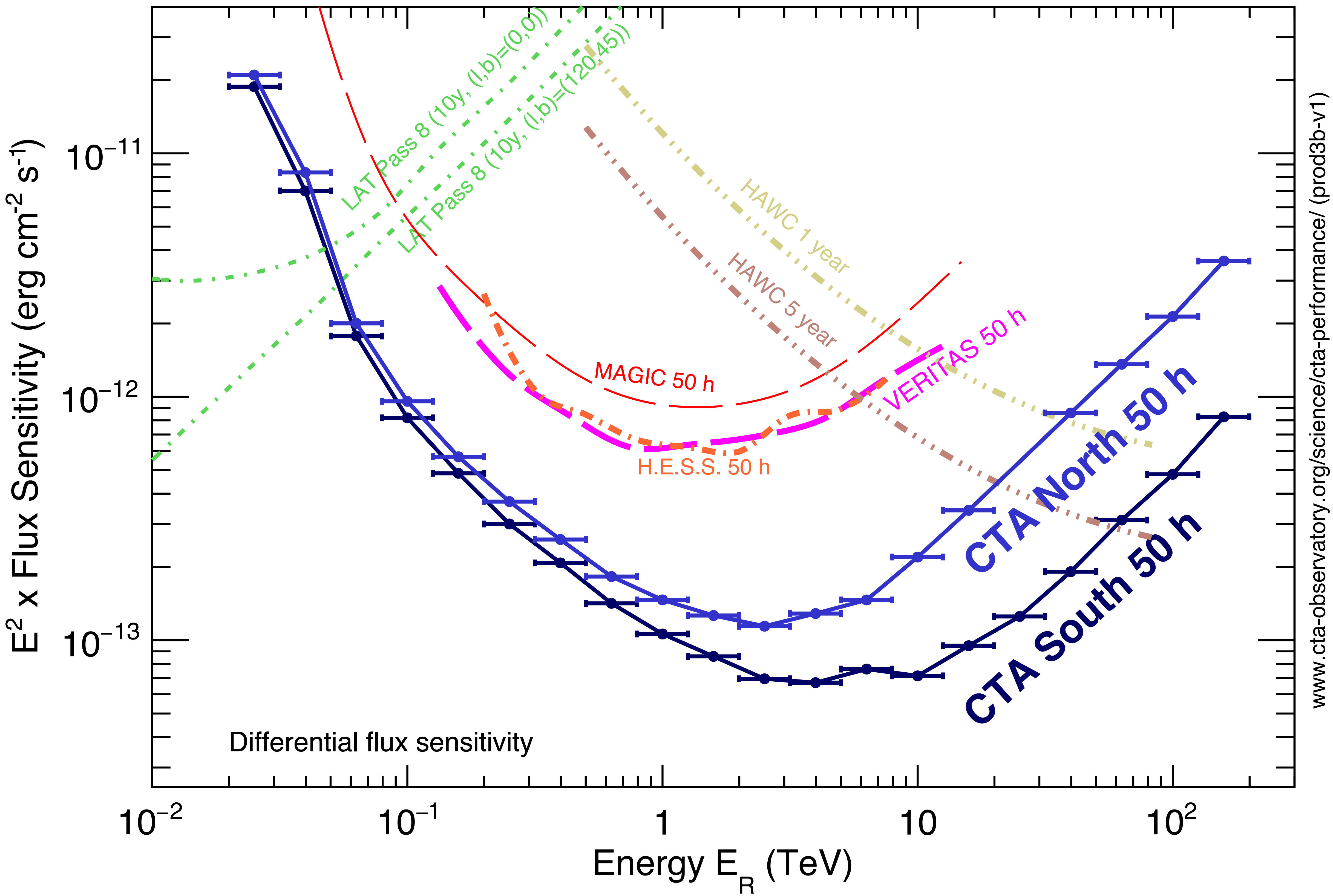




- Wide energy coverage of 20 GeV–300 TeV with three telescope sizes
- Spread over ~5 km^2 area to catch Cherenkov photons anywhere in the circle

High-energy Frontier by CTA SSTs

CTA Consortium arXiV:1709.07997



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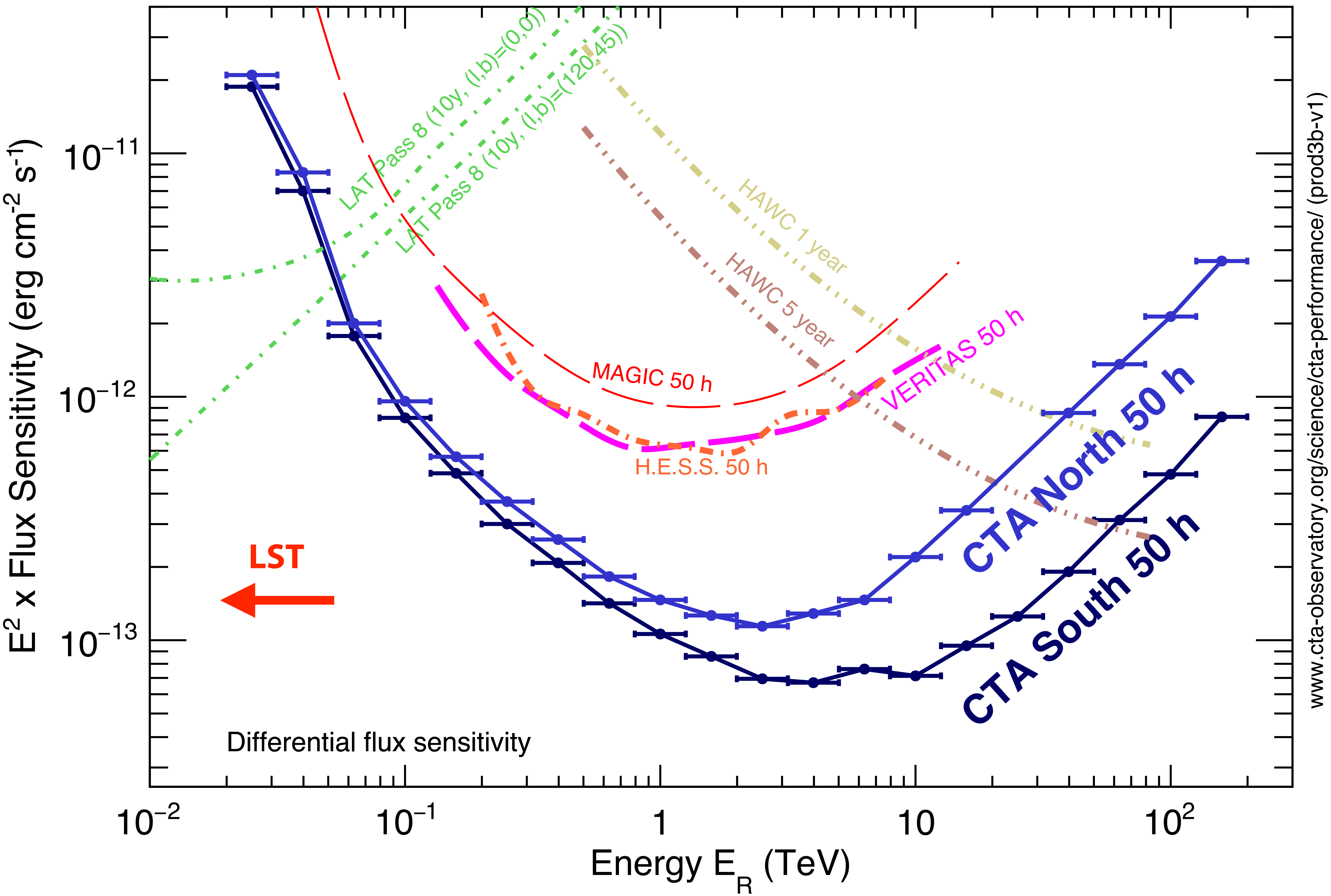

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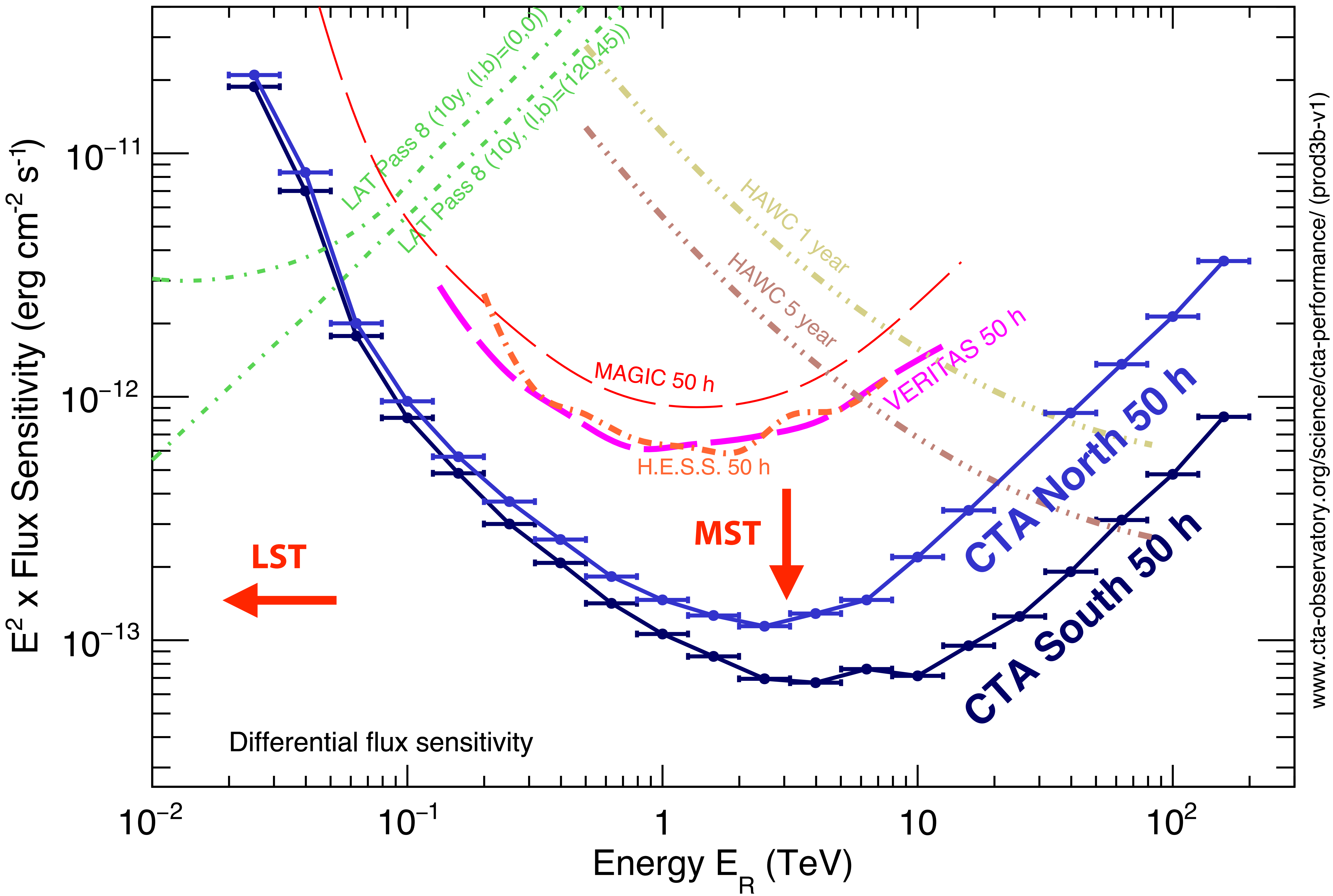

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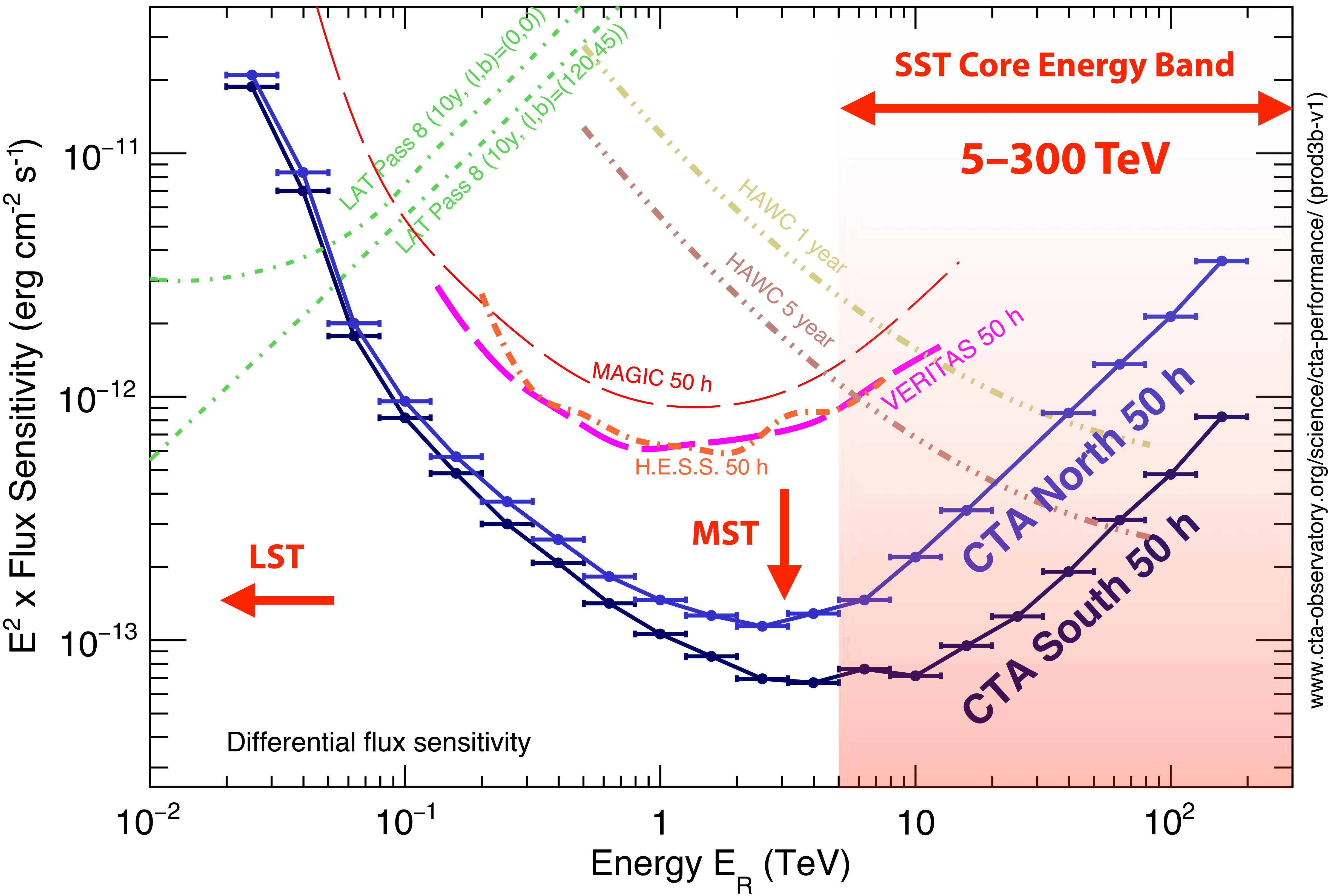

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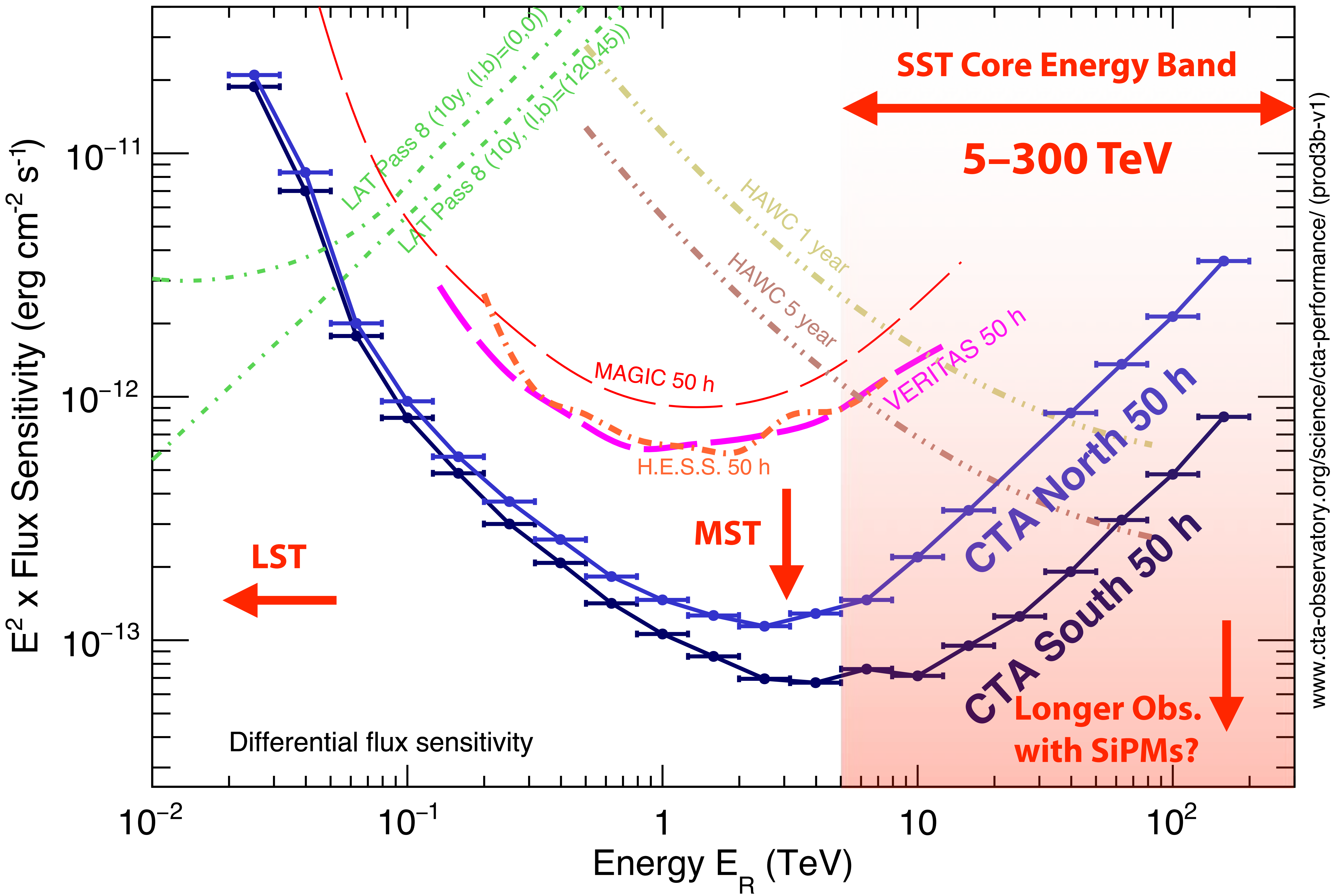
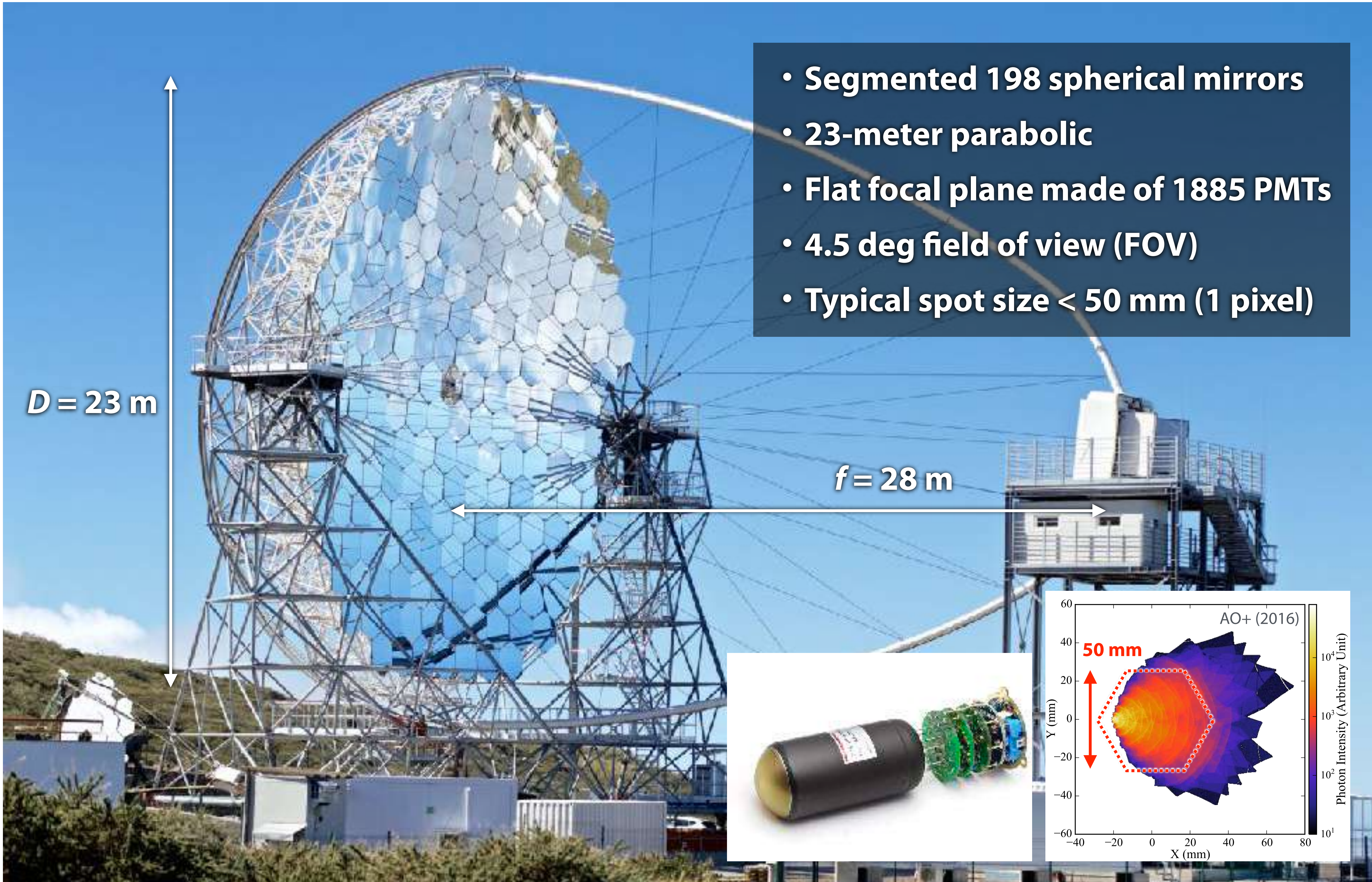
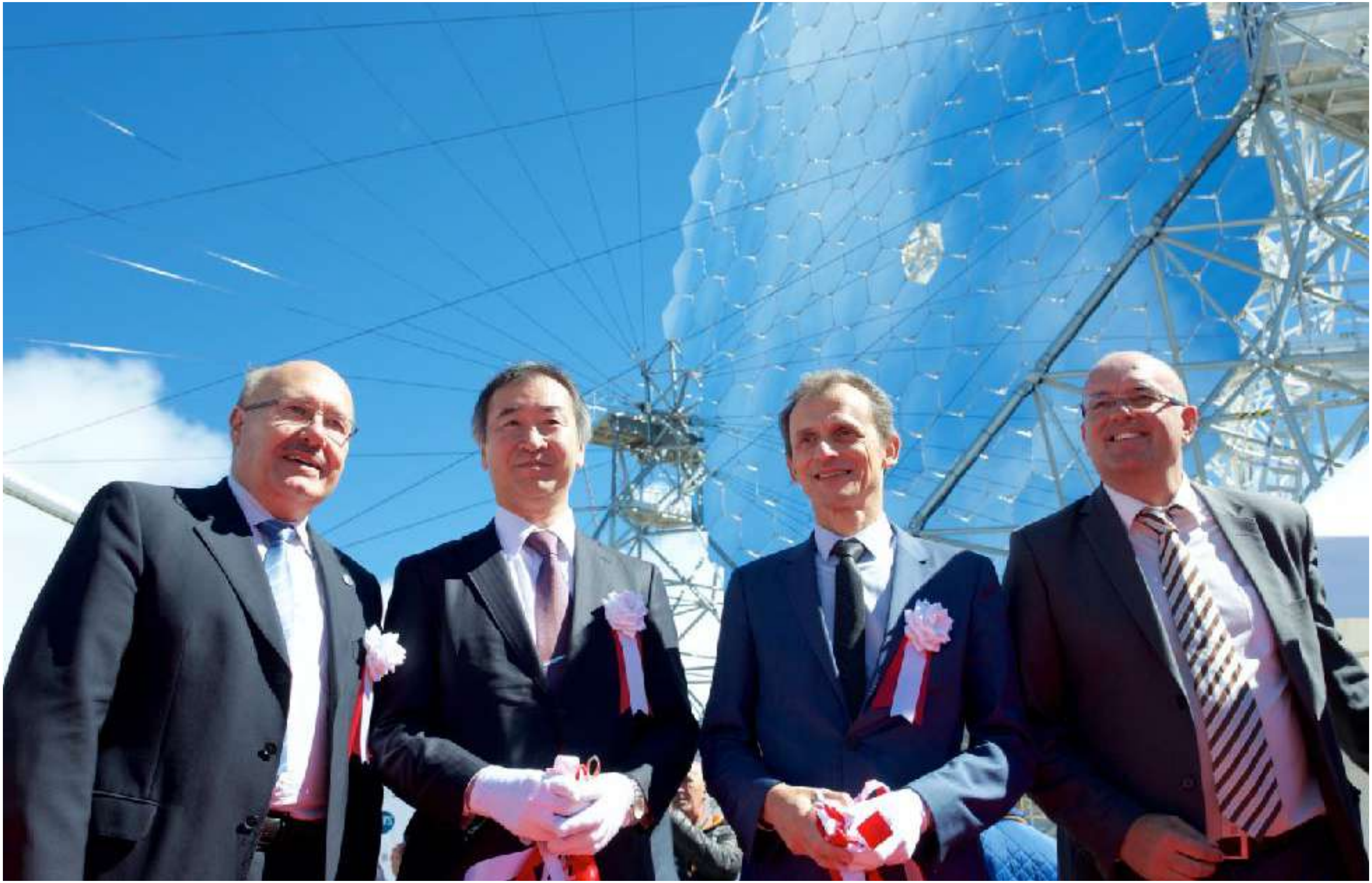


Large-Sized Telescopes (LSTs)

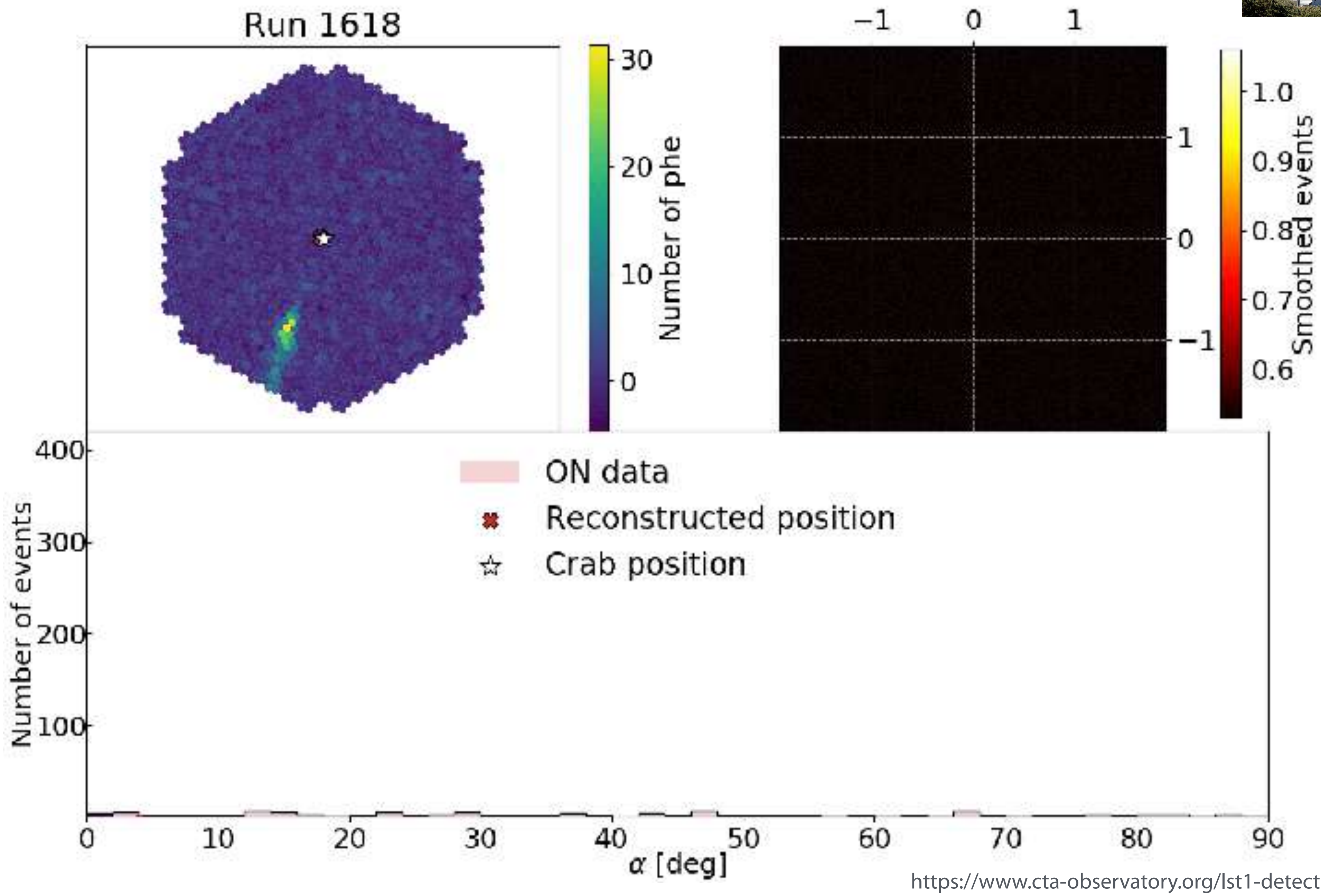
- Segmented 198 spherical mirrors
- 23-meter parabolic
- Flat focal plane made of 1885 PMTs
- 4.5 deg field of view (FOV)
- Typical spot size < 50 mm (1 pixel)



The First LST Inaugurated in Oct 2018



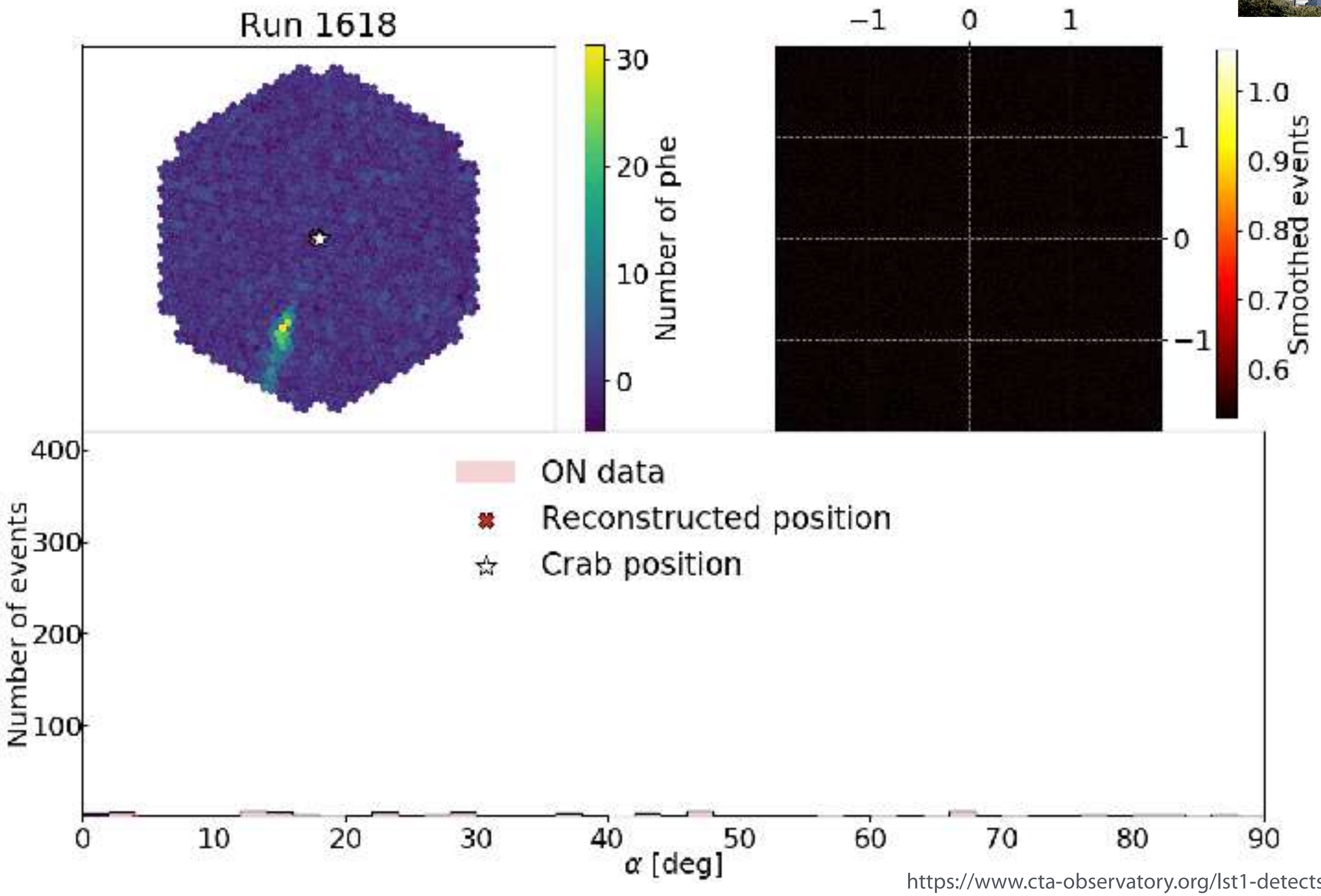
LST Crab Observations: Significant Detection



https://www.cta-observatory.org/lst1-detects-first-gamma-ray-signal/

- Inauguration in Oct 2018, first light in Dec 2018
- Significant Crab Nebular detection in Nov 2019
- Verification that the LST 1 is working well (no physics result yet)

LST Crab Observations: Significant Detection



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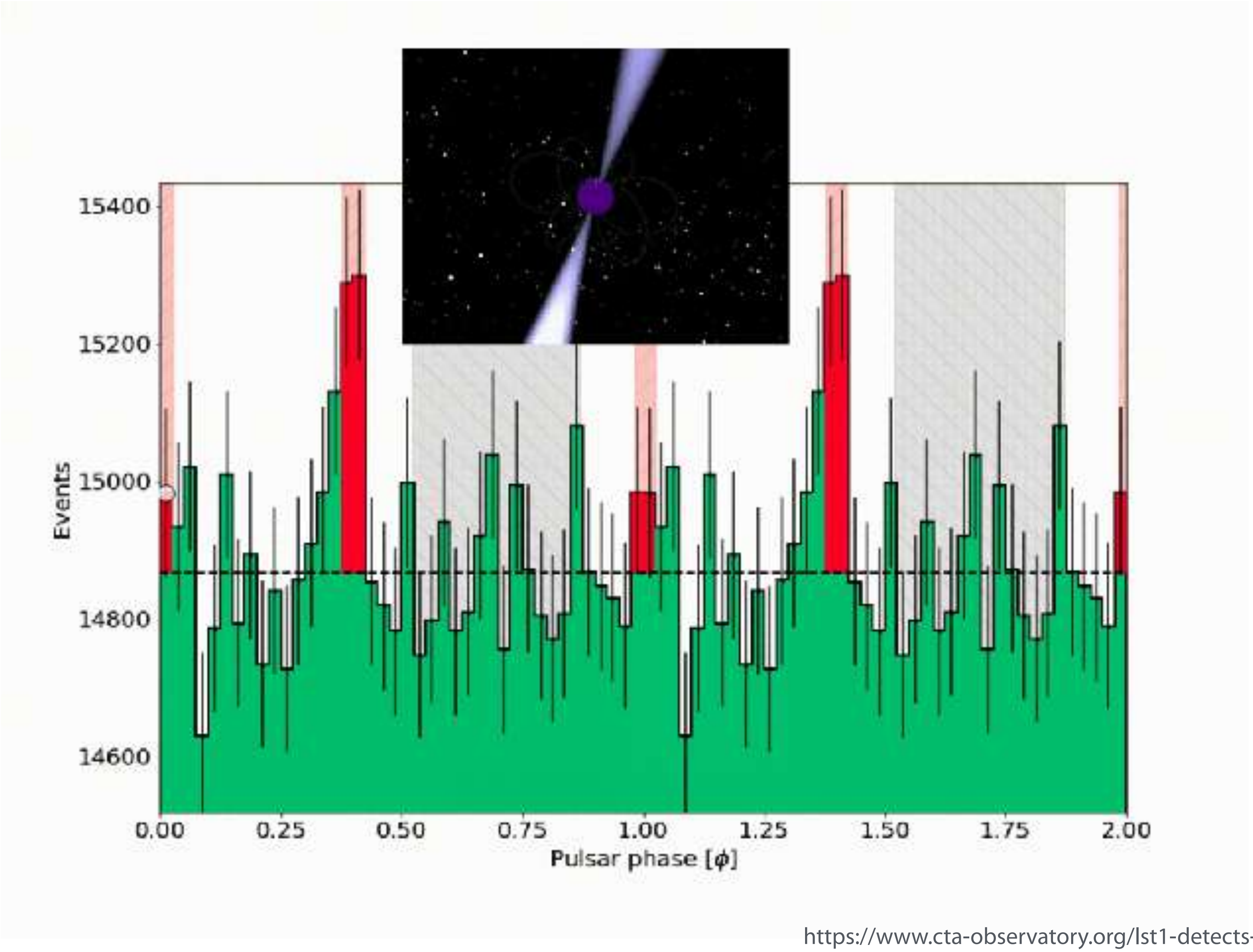
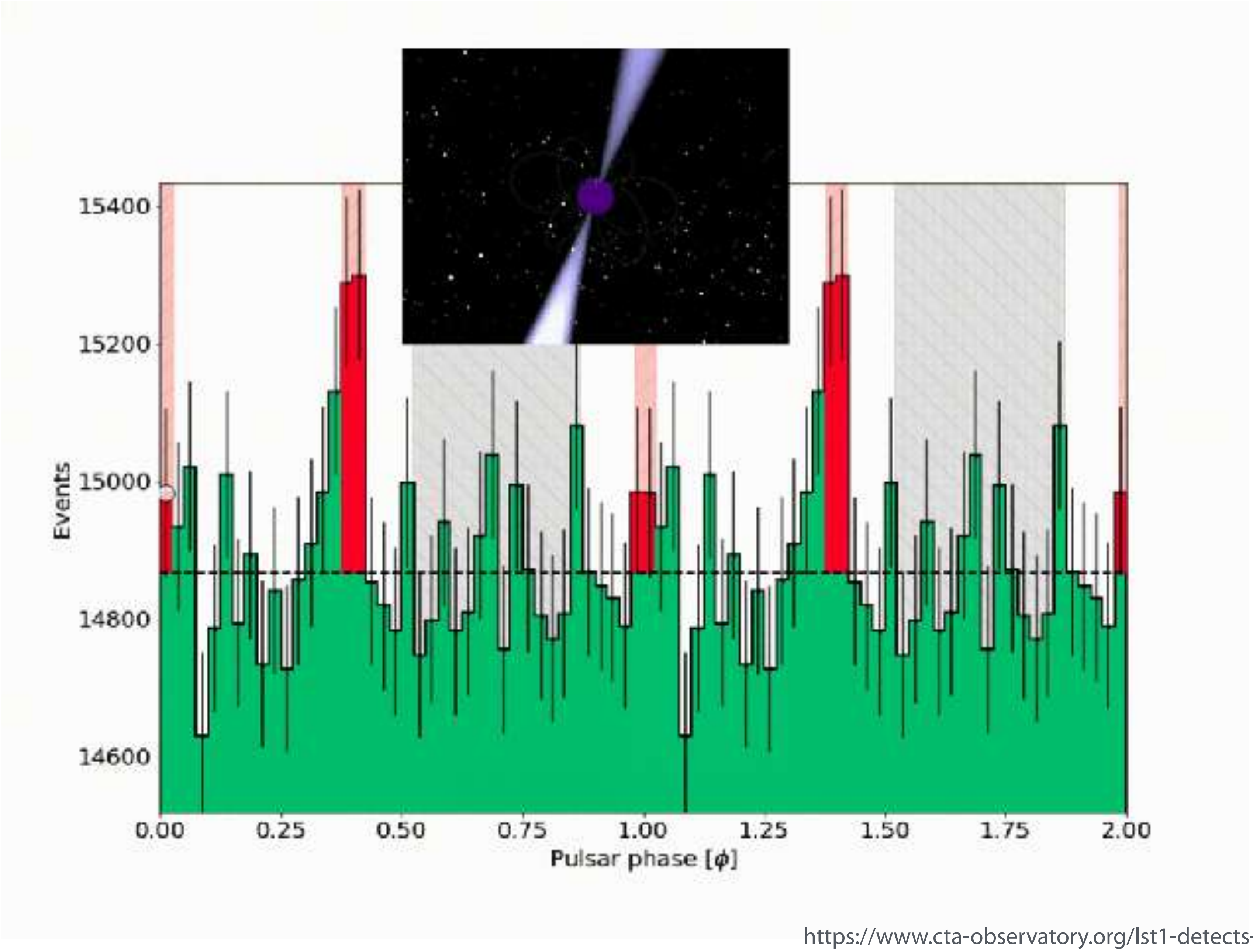
LST Crab Observations: Crab Pulsation



https://www.cta-observatory.org/lst1-detects-vhe-emission-from-crab-pulsar/

- Another verification web-released on Jun 22, 2020
- Low-energy detectability was performed
- Suffering from the COVID-19 situation, but the on-site operation started again

LST Crab Observations: Crab Pulsation



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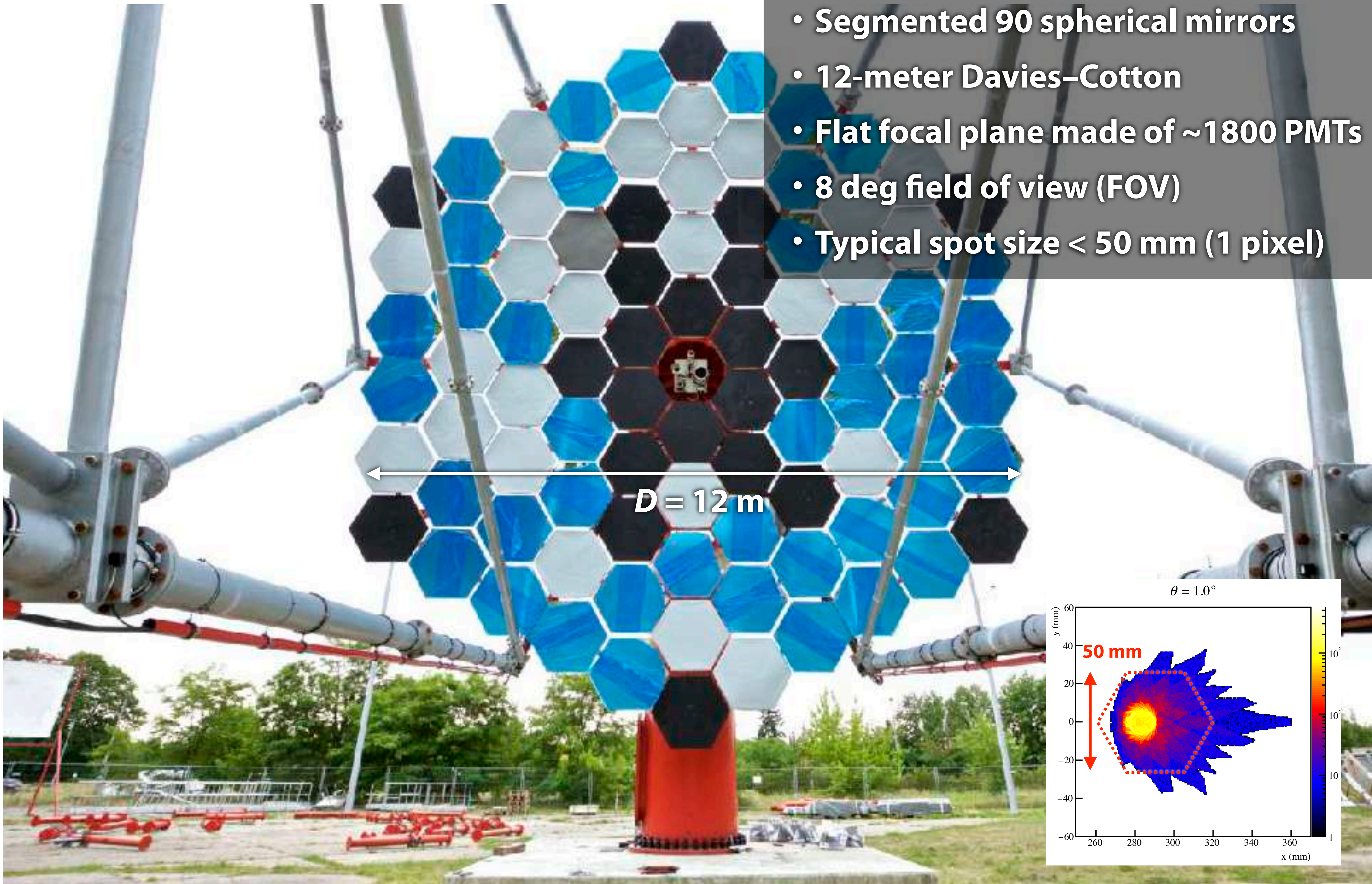
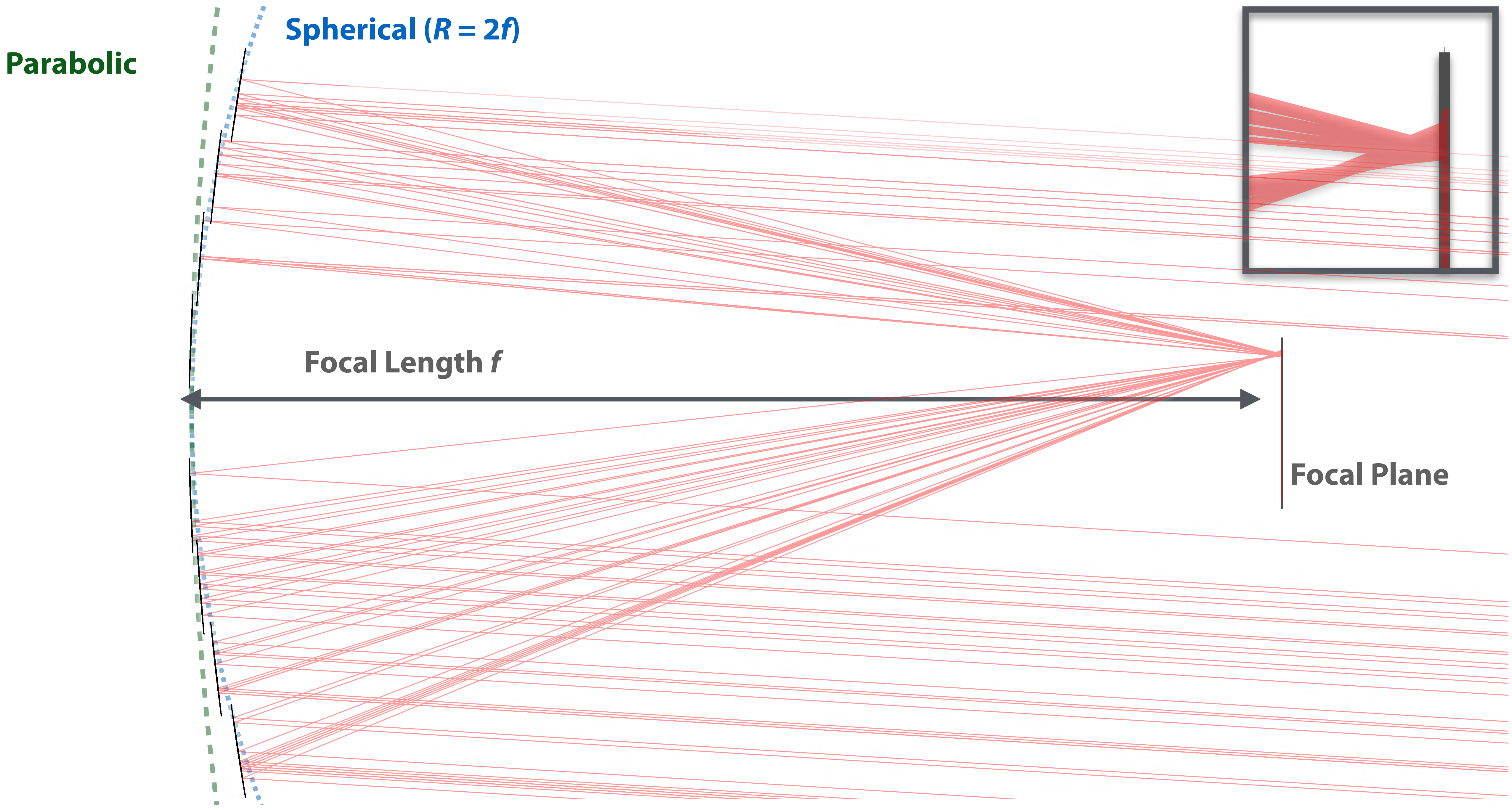
Medium-Sized Telescopes (MSTs)

- Segmented 90 spherical mirrors
- 12-meter Davies–Cotton
- Flat focal plane made of ~1800 PMTs
- 8 deg field of view (FOV)
- Typical spot size < 50 mm (1 pixel)



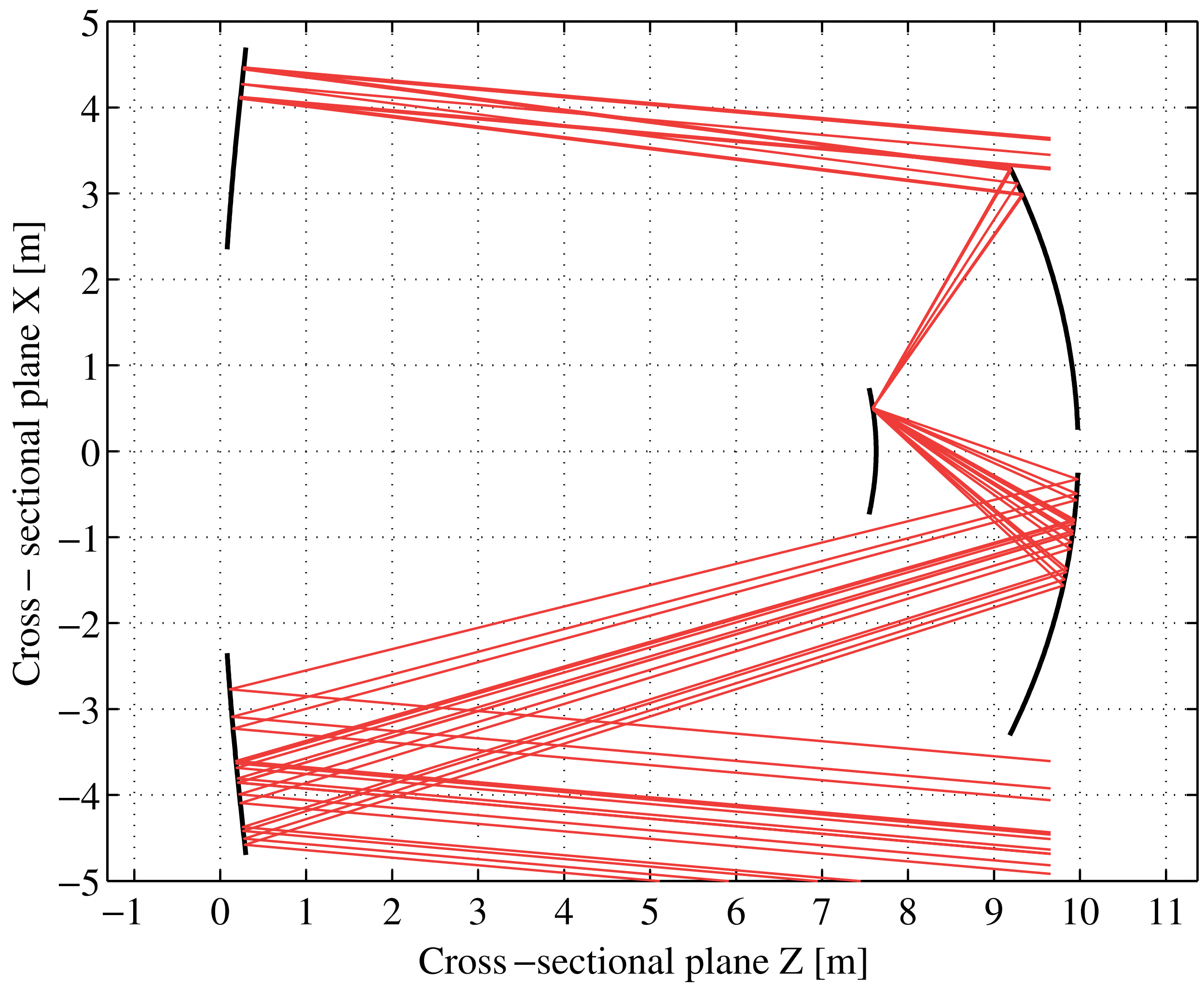
Davies–Cotton Configuration

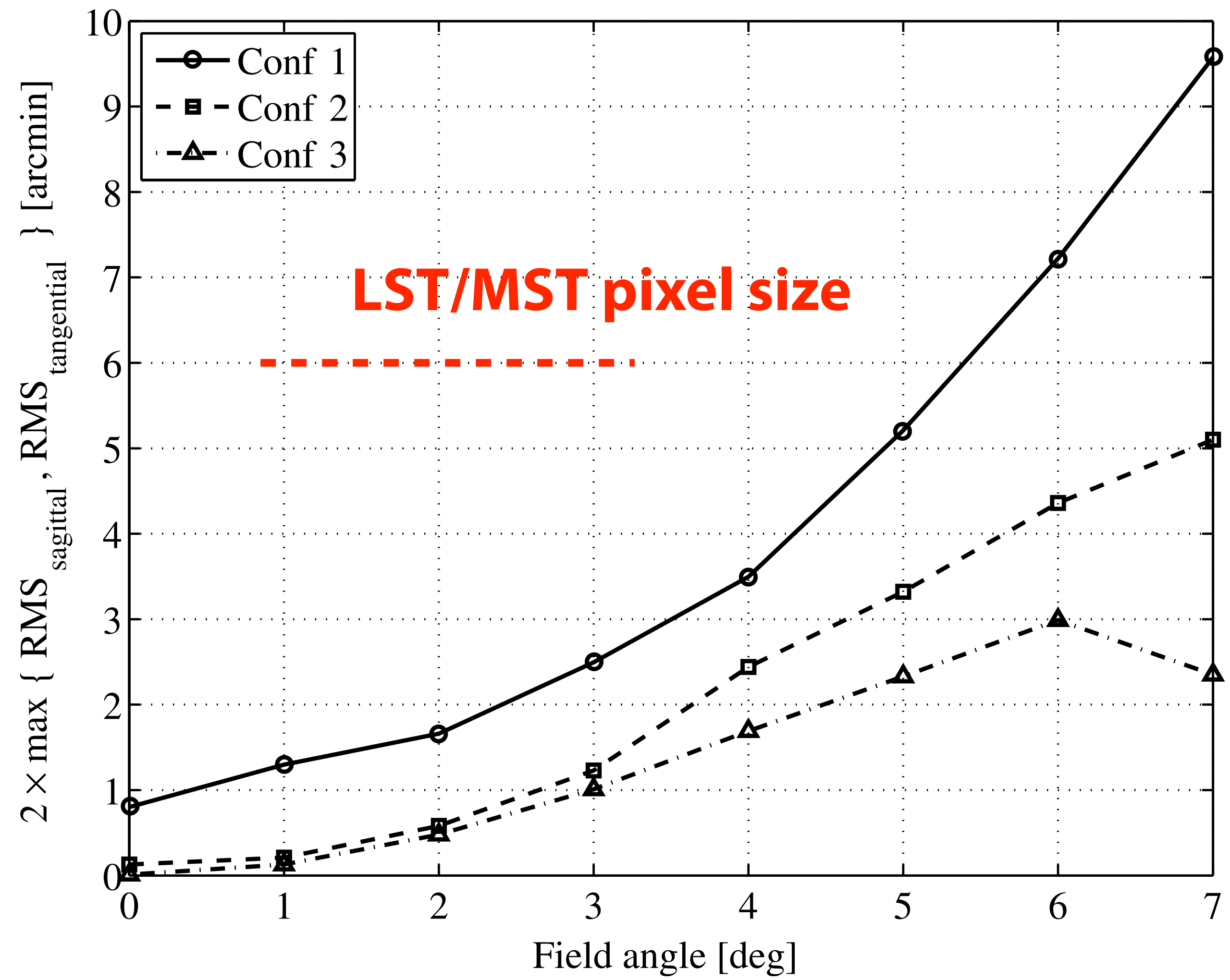


- Another standard optics design in Cherenkov telescopes
- Initially proposed for solar power plants, thus no good resolution

Schwarzschild–Couder Configuration

Vassiliev+ (2007)



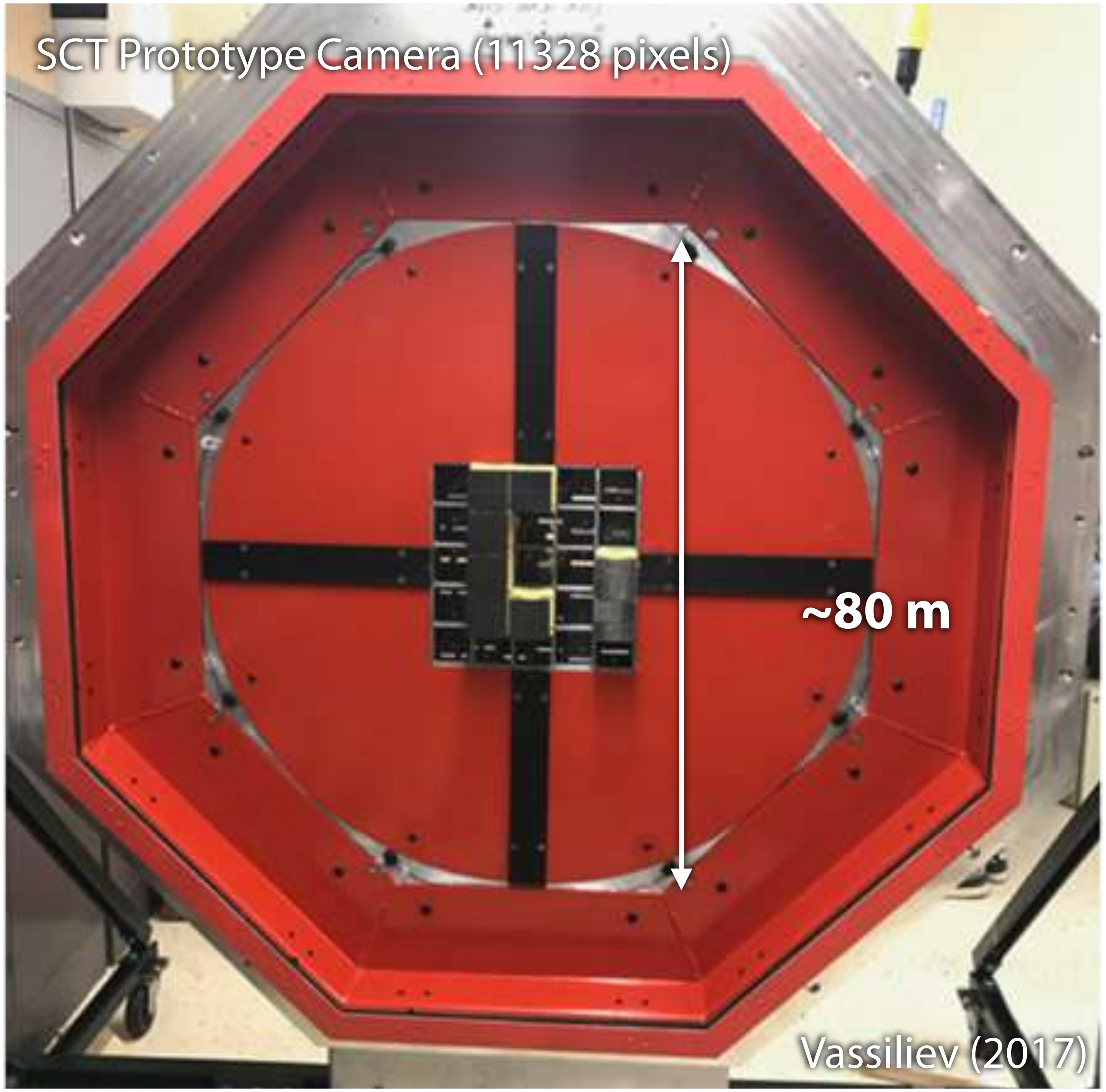


- **Aspherical** primary and **secondary** mirrors to achieve wide FOV and better resolution at the same time
- Wider FOV brings fast survey and wider effective area for higher-energy photons
- Finer shower-image resolution (→ higher sensitivity) and compact camera (→ less expensive) are expected
- Proposed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

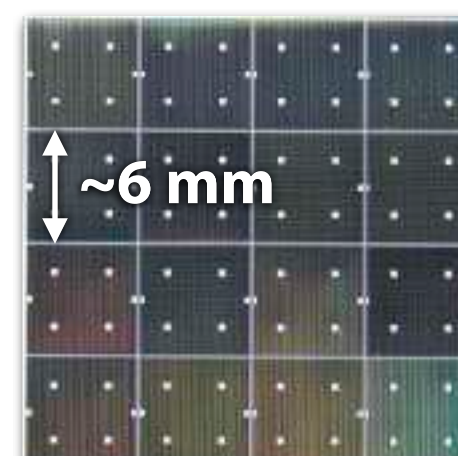
Schwarzschild–Couder Proposals for CTA

- Schwarzschild–Couder MST (SCT) with 10-meter diameter for MST extension
  - US, Italy, Germany, Mexico, and ISEE/KMI
  - H. Tajima and A. O. have been working in SCT since ~2010
- 4-meter SC SST × camera design was selected the final SST design from three proposals in June 2019
  - ISEE/KMI mainly involve in the camera development (SiPM, electronics, software) and optics simulation

Need Compact Cameras with SiPMs

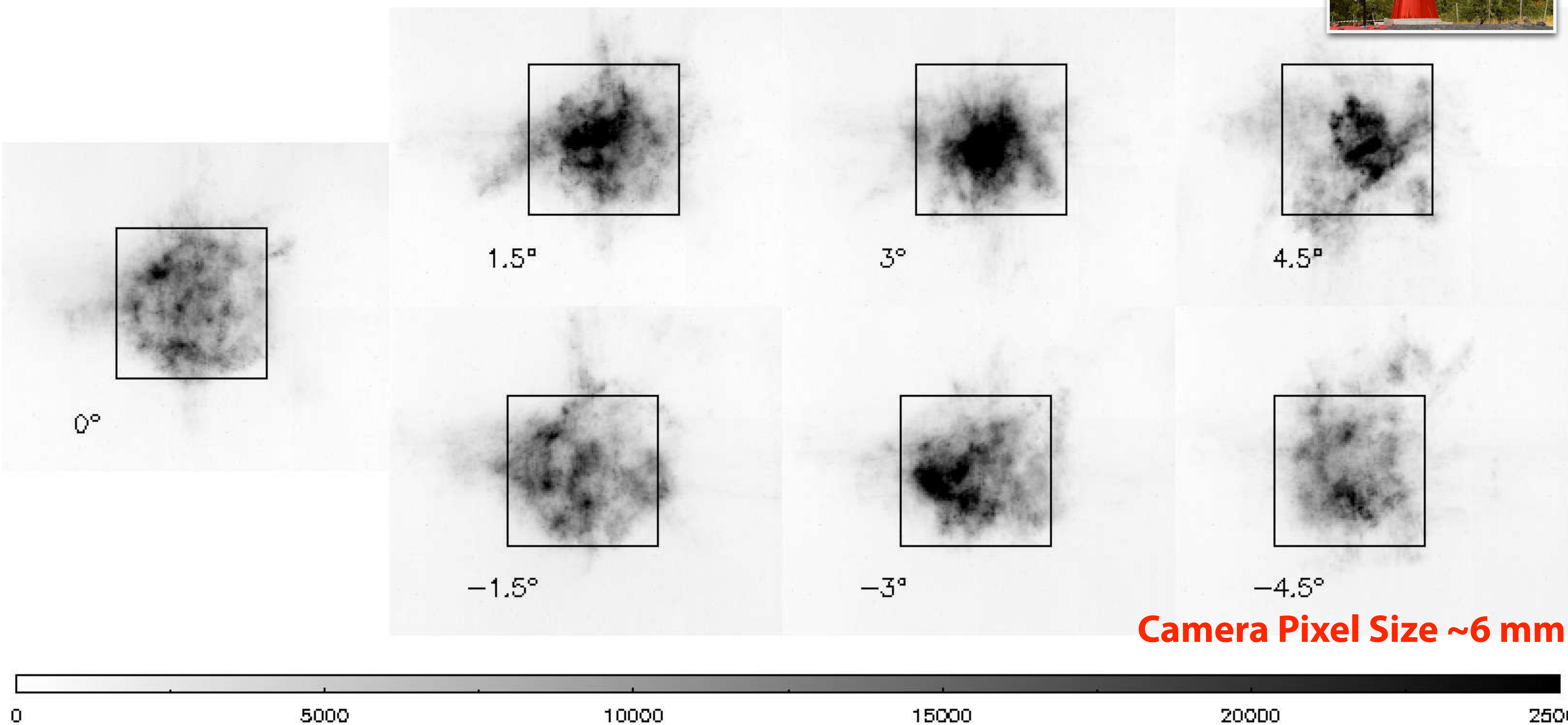


- The concave secondary mirrors make the plate scales (≡ 1/*f*) large and enable us to build compact cameras
- Silicone photomultipliers (SiPMs) are used instead of conventional photomultipliser tubes (PMTs)



SST Optical System

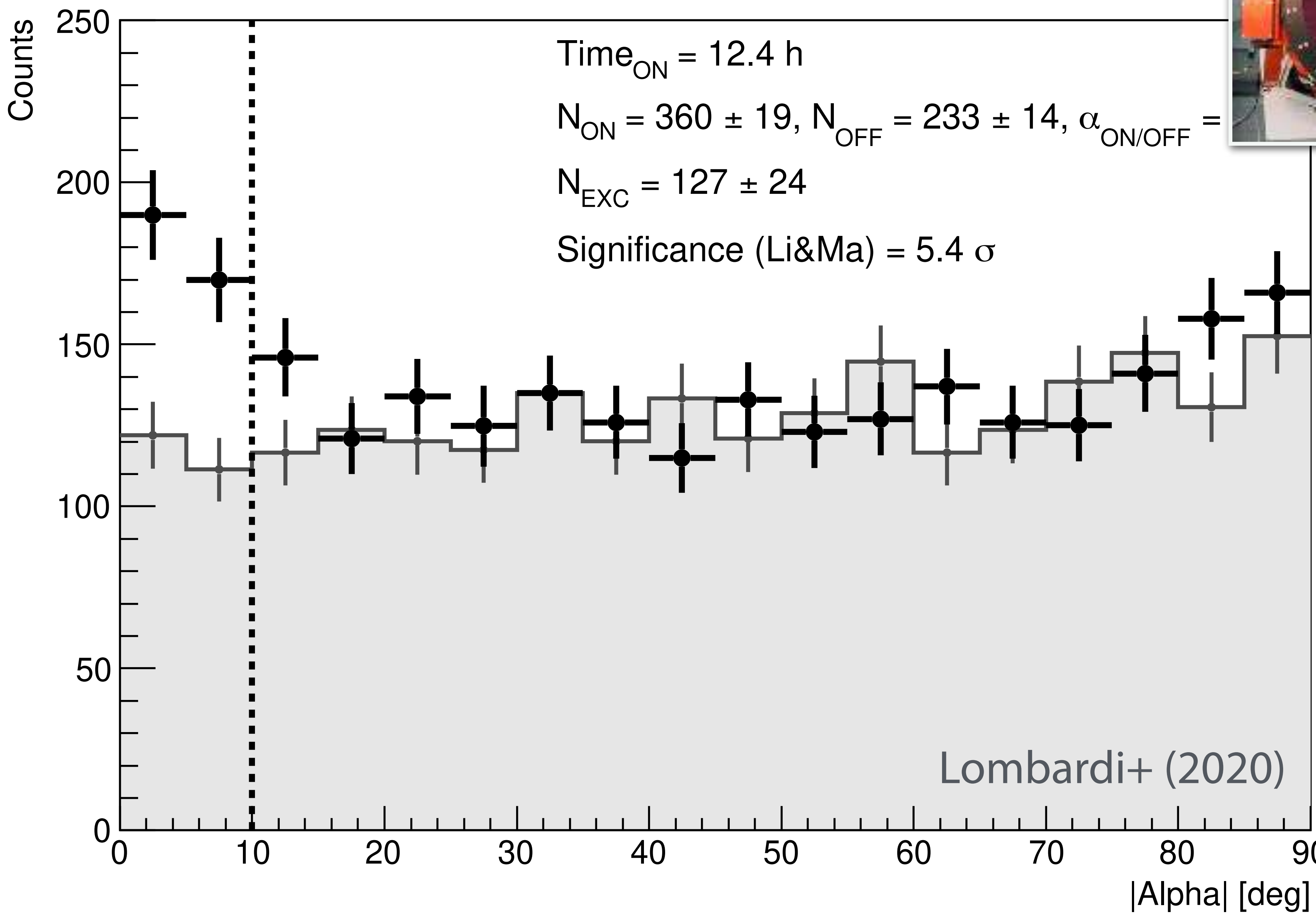
Giro+ (2017)

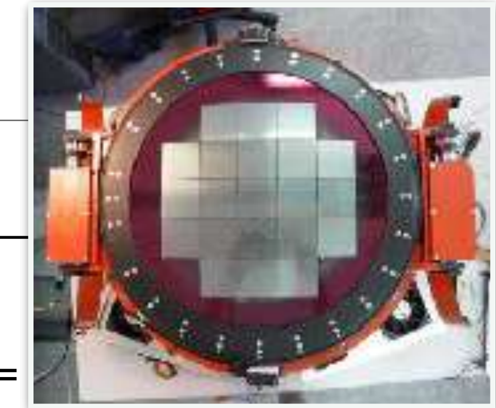


Camera Pixel Size ~6 mm

- Achieved good enough optical resolution matching the SST pixel size
- First realization of the Schwarzschild–Couder configuration ever

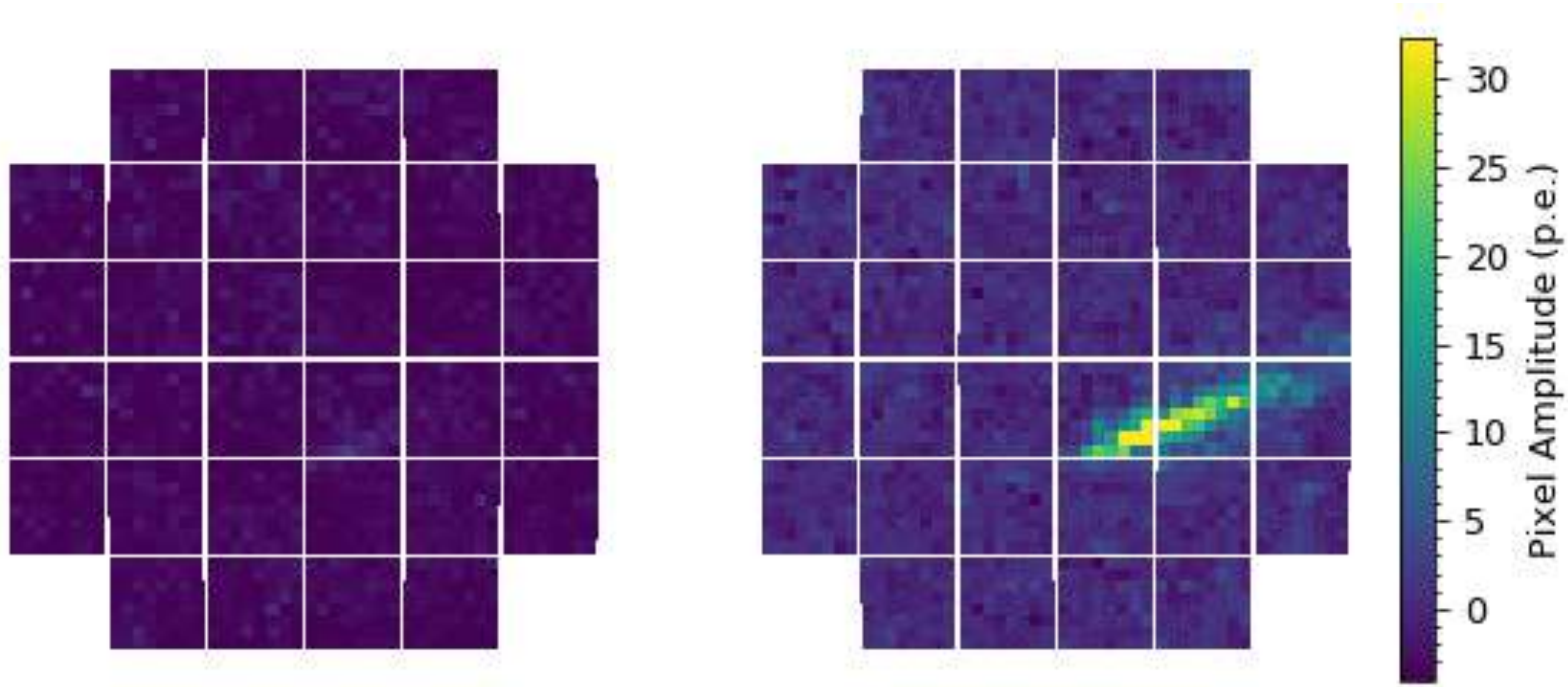
SST Crab Observations: Detection at 5.4 σ





- “Italian” camera successfully detected gamma-ray signal from the Crab Nebula
- Combination of the Schwarzschild–Couder and a SiPM camera verified

Another (Our) SST Camera Test Observations



https://www.cta-observatory.org/chec-achieves-first-light-on-astri/

- "Our" camera also succeeded in air-shower observations on the same prototype telescope (replaceable with the Italian camera)
- Additional test observations canceled due to mirror re-coating and COVID-19

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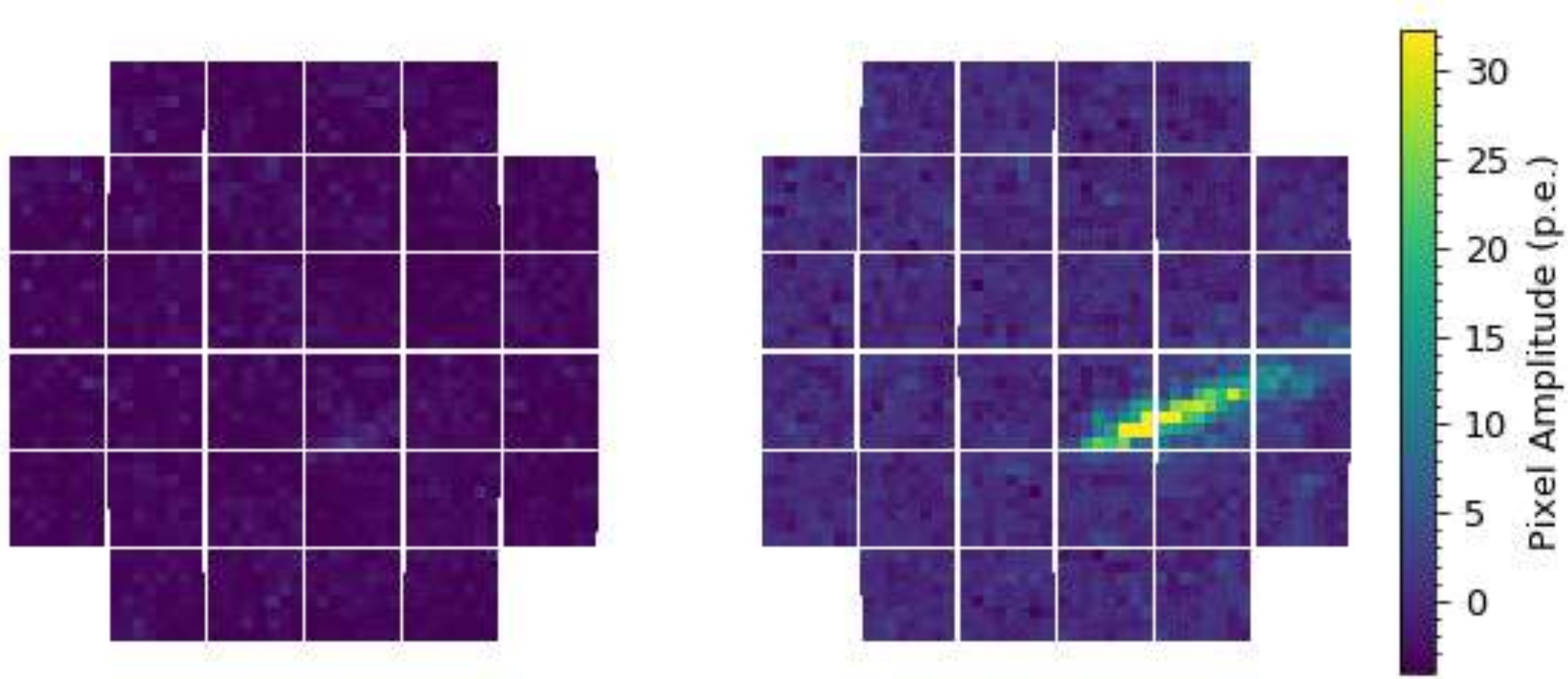

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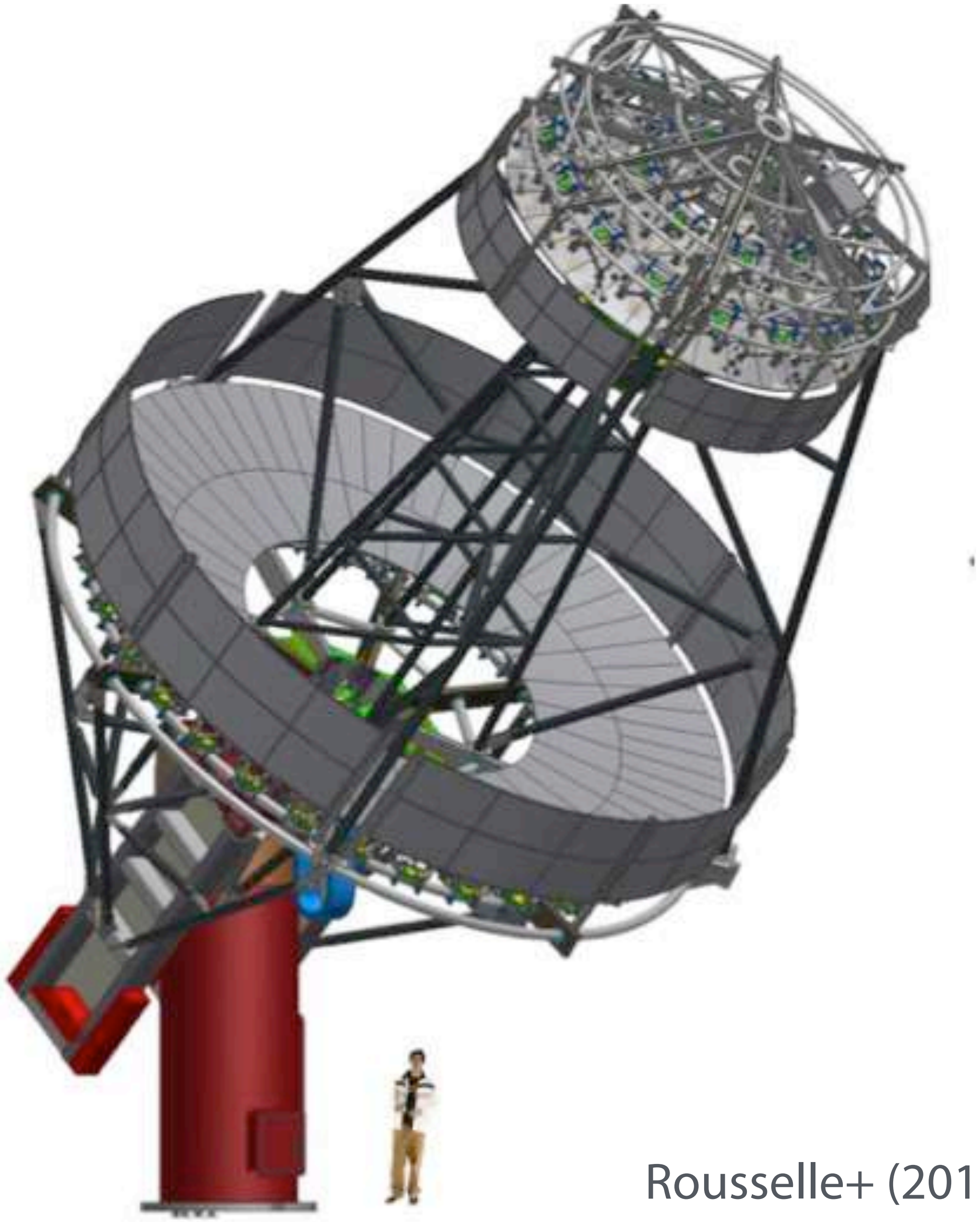
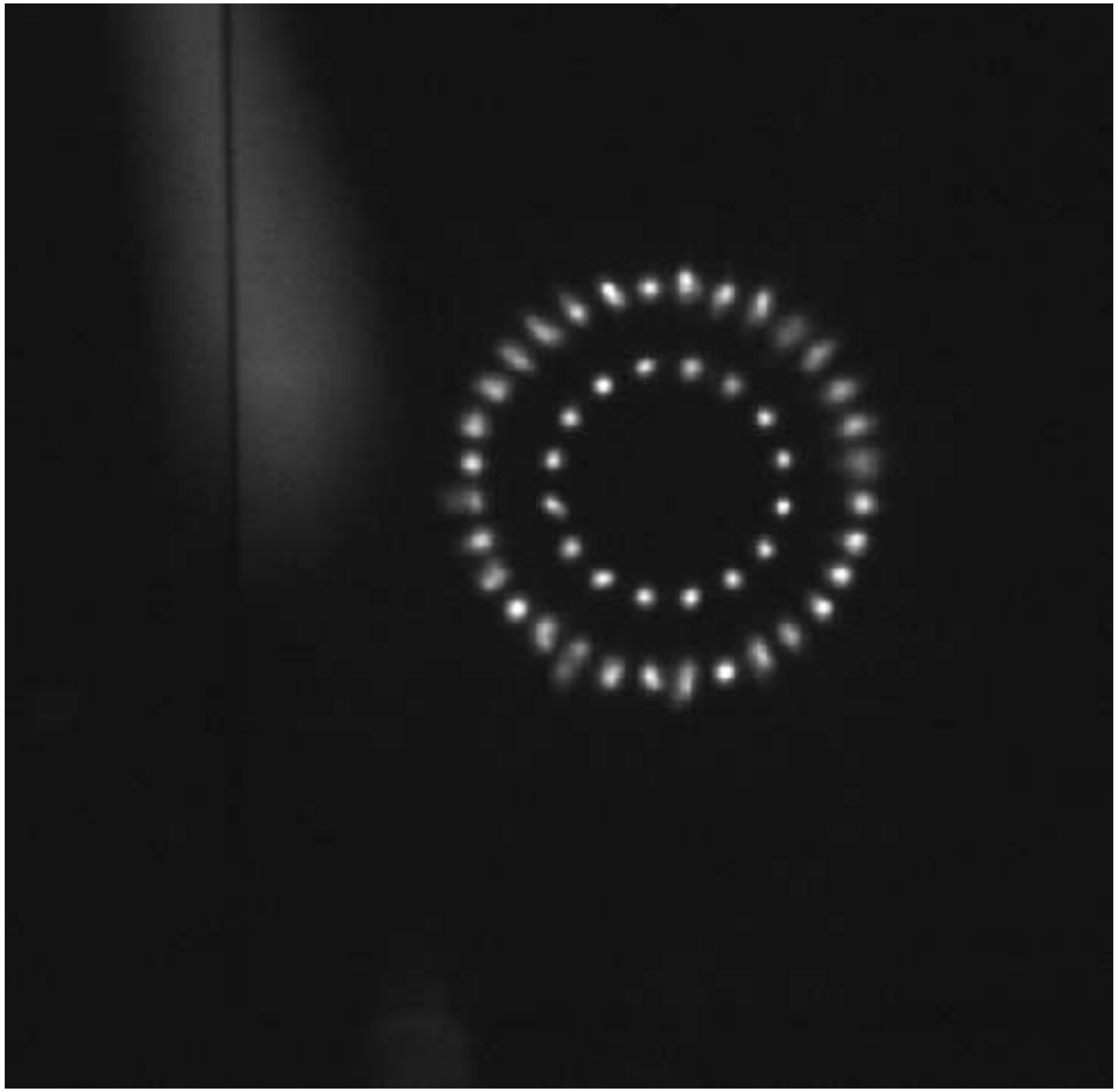
Schwarzschild–Couder MST Optical System



Rousselle+ (2015)



- > 2 times wider than the SST optical system
- More number of segmented mirrors, thus more complex
- Optical alignment was successfully finished

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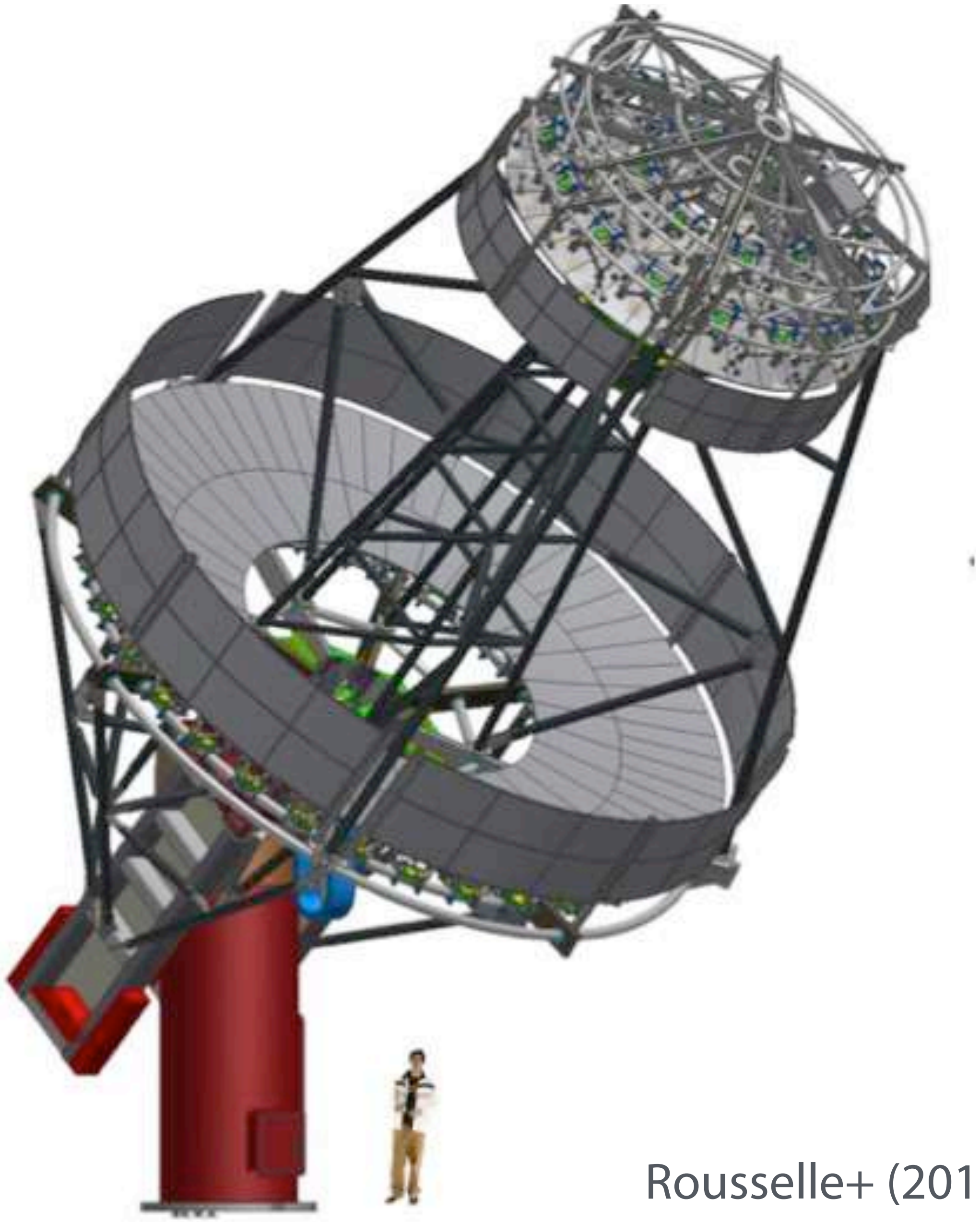

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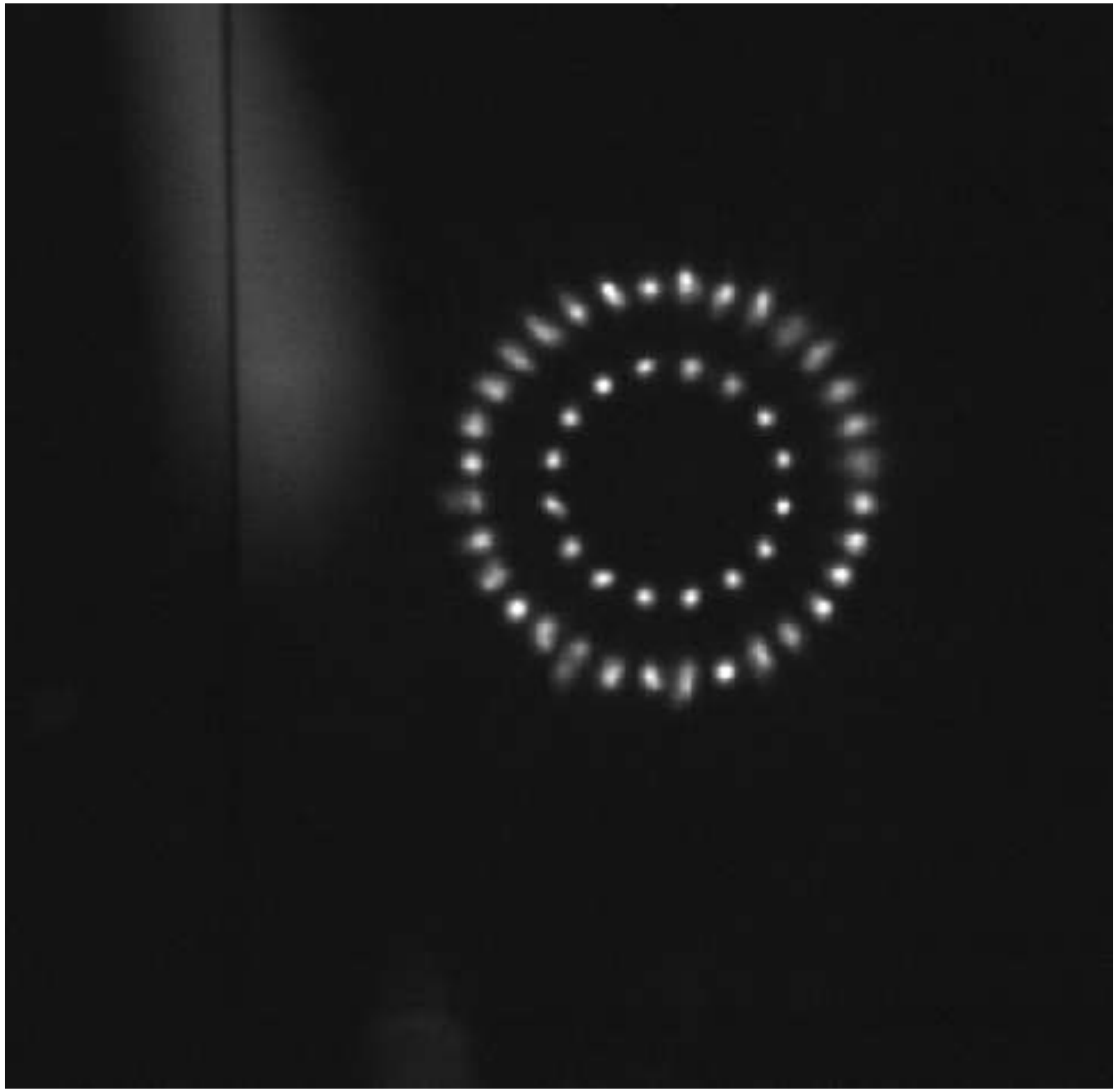

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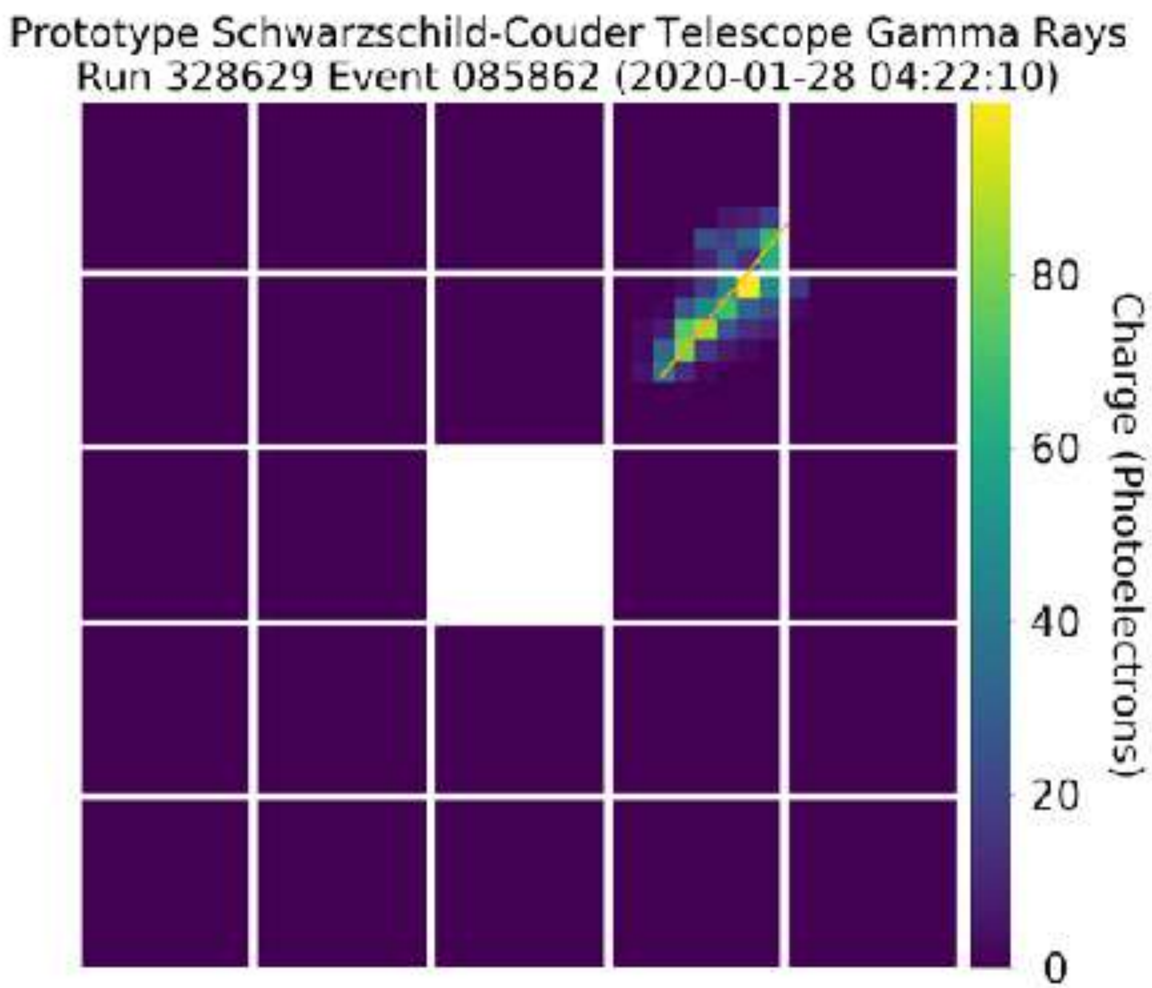
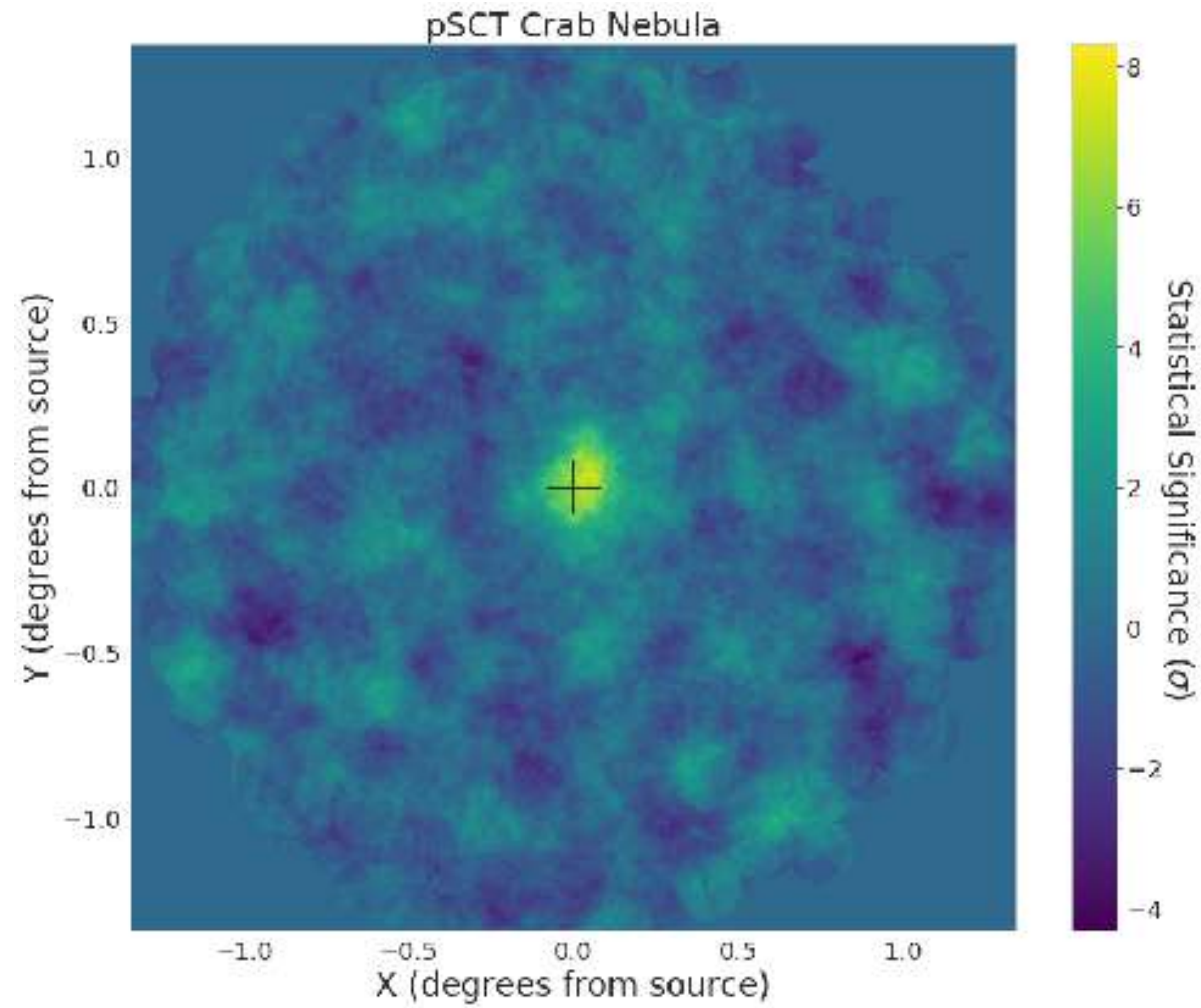
Crab Observations by Prototype Schwarzschild–Couder





- Crab Nebular detection at 8.3σ, while the prototype FOV is still limited
- Also see KMI topics http://www.kmi.nagoya-u.ac.jp/eng/blog/2020/06/03/prototype-cta-telescope-detects-gamma-rays-from-the-crab-nebula/

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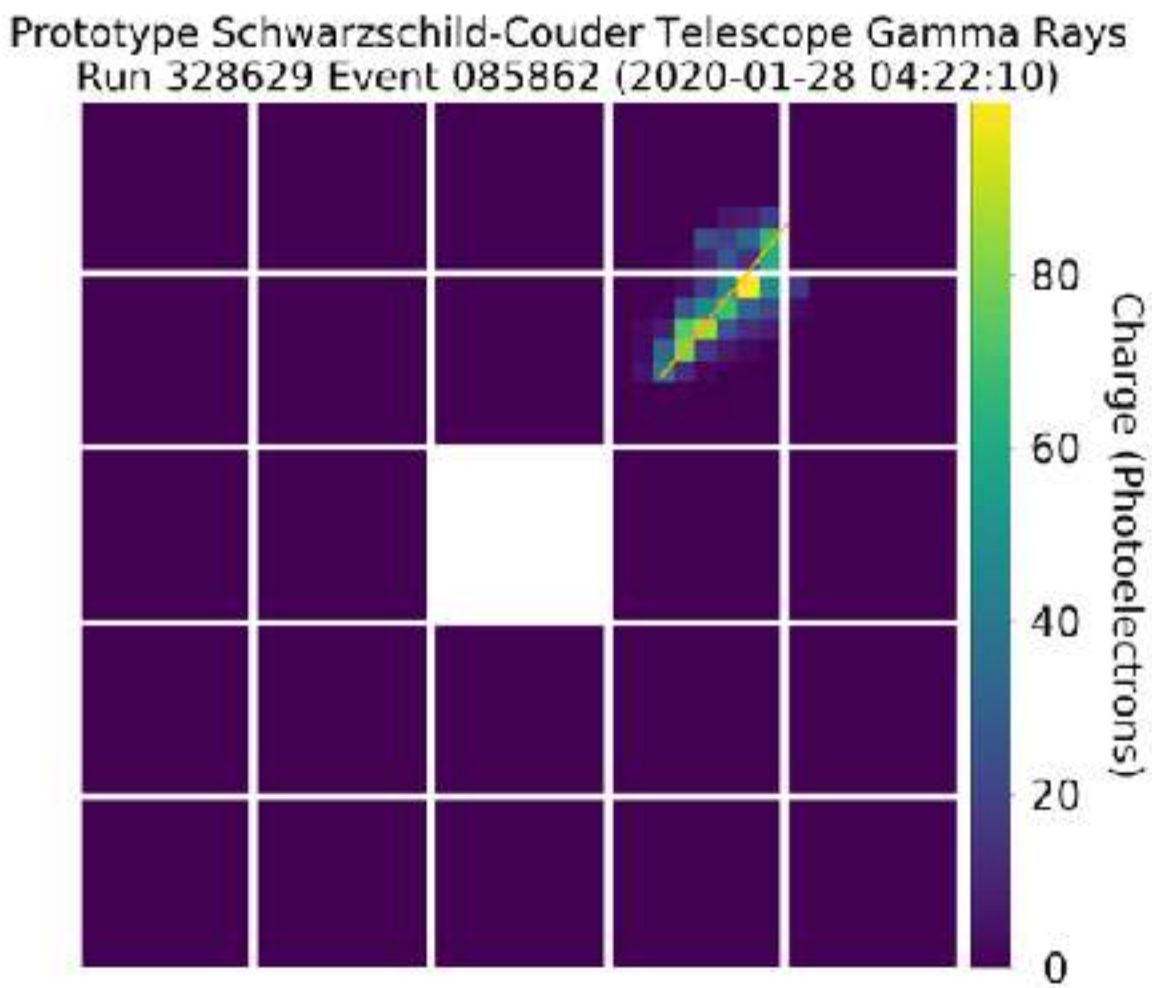

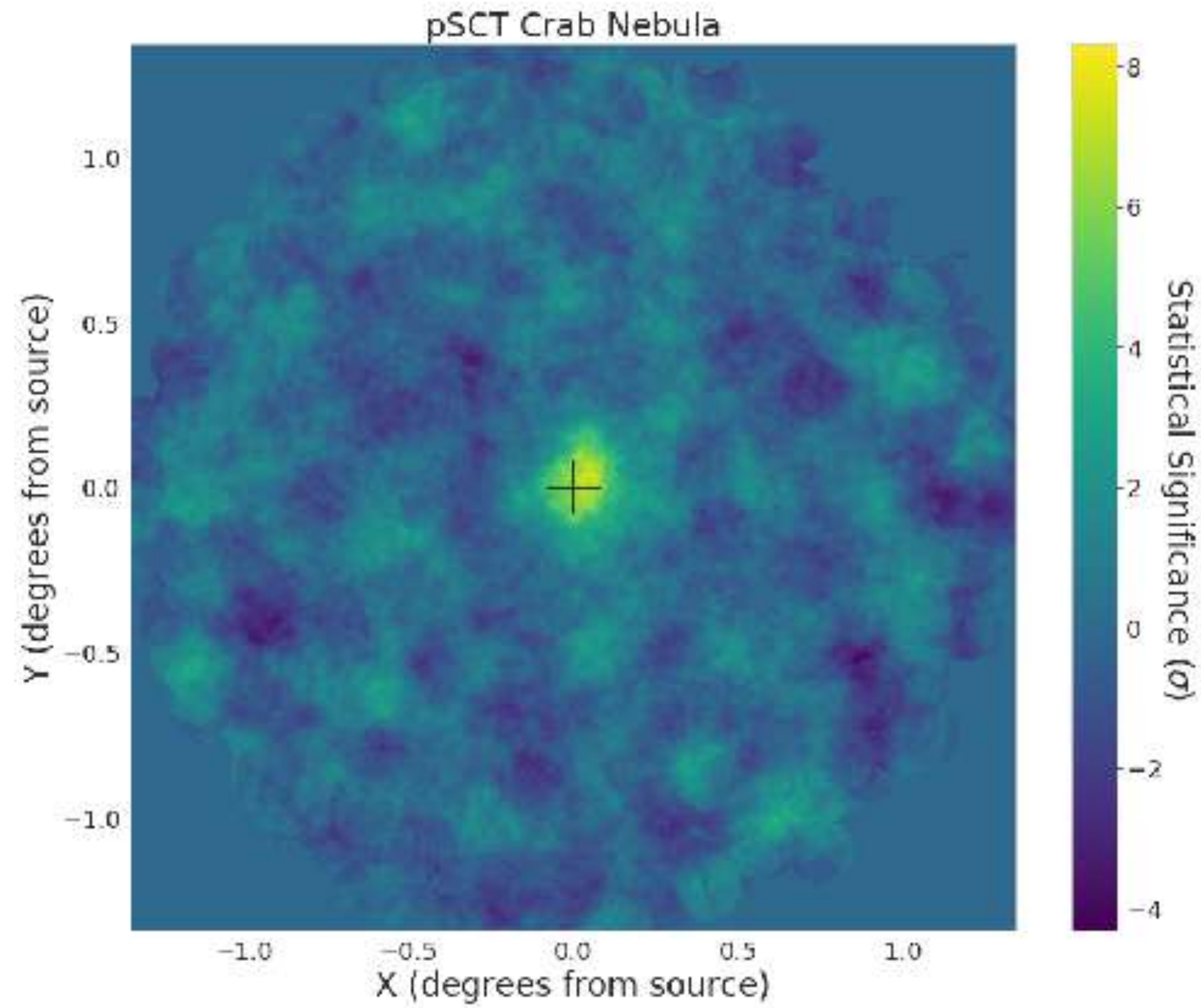

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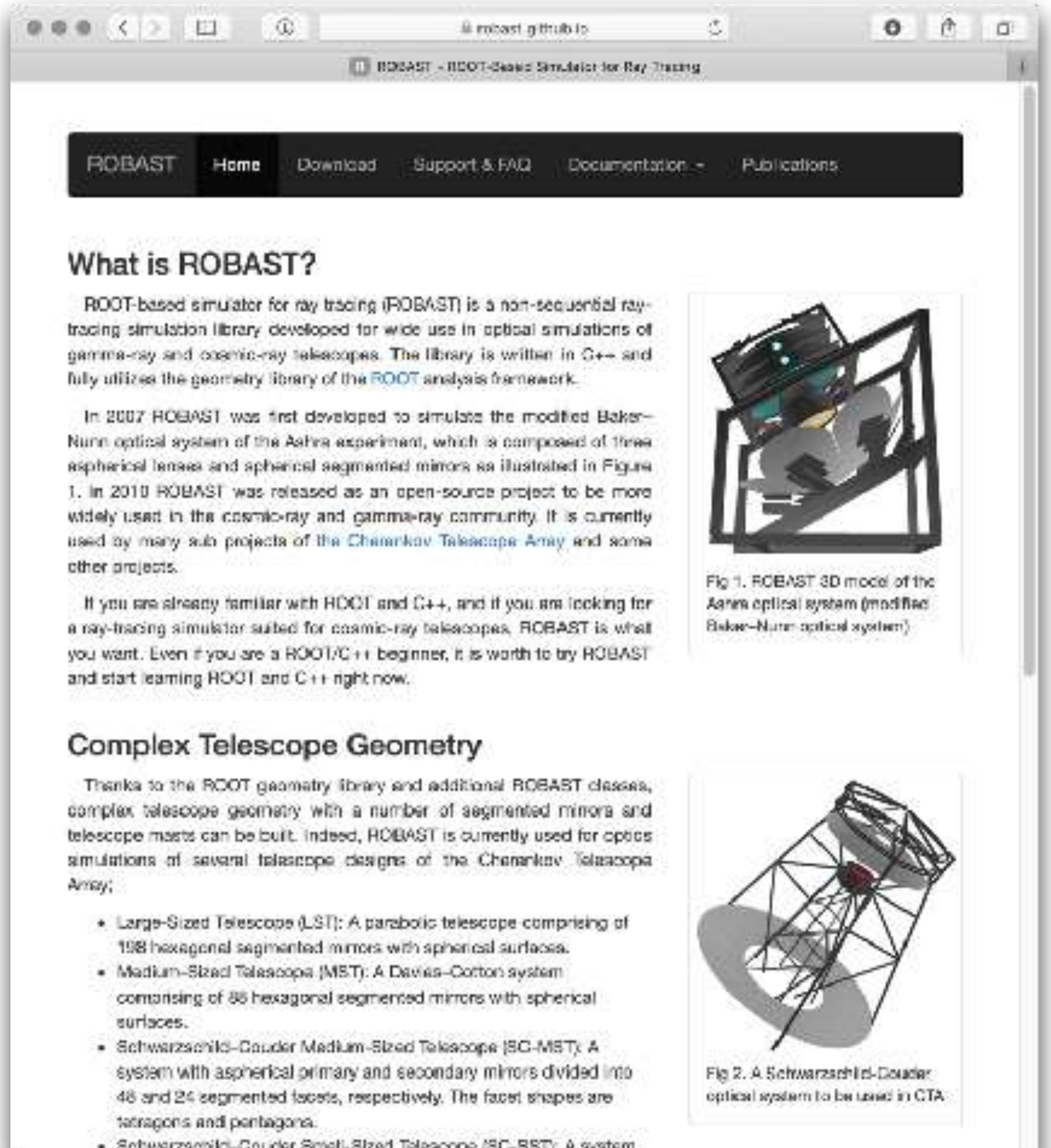
Ad: ROBAST

https://robast.github.io


robast.github.io
ROBAST - ROOT-Based Simulator for Ray Tracing

ROBAST | Home | Download | Support & FAQ | Documentation | Publications

What is ROBAST?

ROOT-based simulator for ray tracing (ROBAST) is a non-sequential ray-tracing simulation library developed for wide use in optical simulations of gamma-ray and cosmic-ray telescopes. The library is written in C++ and fully utilizes the geometry library of the ROOT analysis framework.

In 2007 ROBAST was first developed to simulate the modified Baker–Nunn optical system of the Ashra experiment, which is composed of three aspherical lenses and spherical segmented mirrors as illustrated in Figure 1. In 2010 ROBAST was released as an open-source project to be more widely used in the cosmic-ray and gamma-ray community. It is currently used by many sub projects of the Cherenkov Telescope Array and some other projects.

If you are already familiar with ROOT and C++, and if you are looking for a ray-tracing simulator suited for cosmic-ray telescopes, ROBAST is what you want. Even if you are a ROOT/C++ beginner, it is worth to try ROBAST and start learning ROOT and C++ right now.

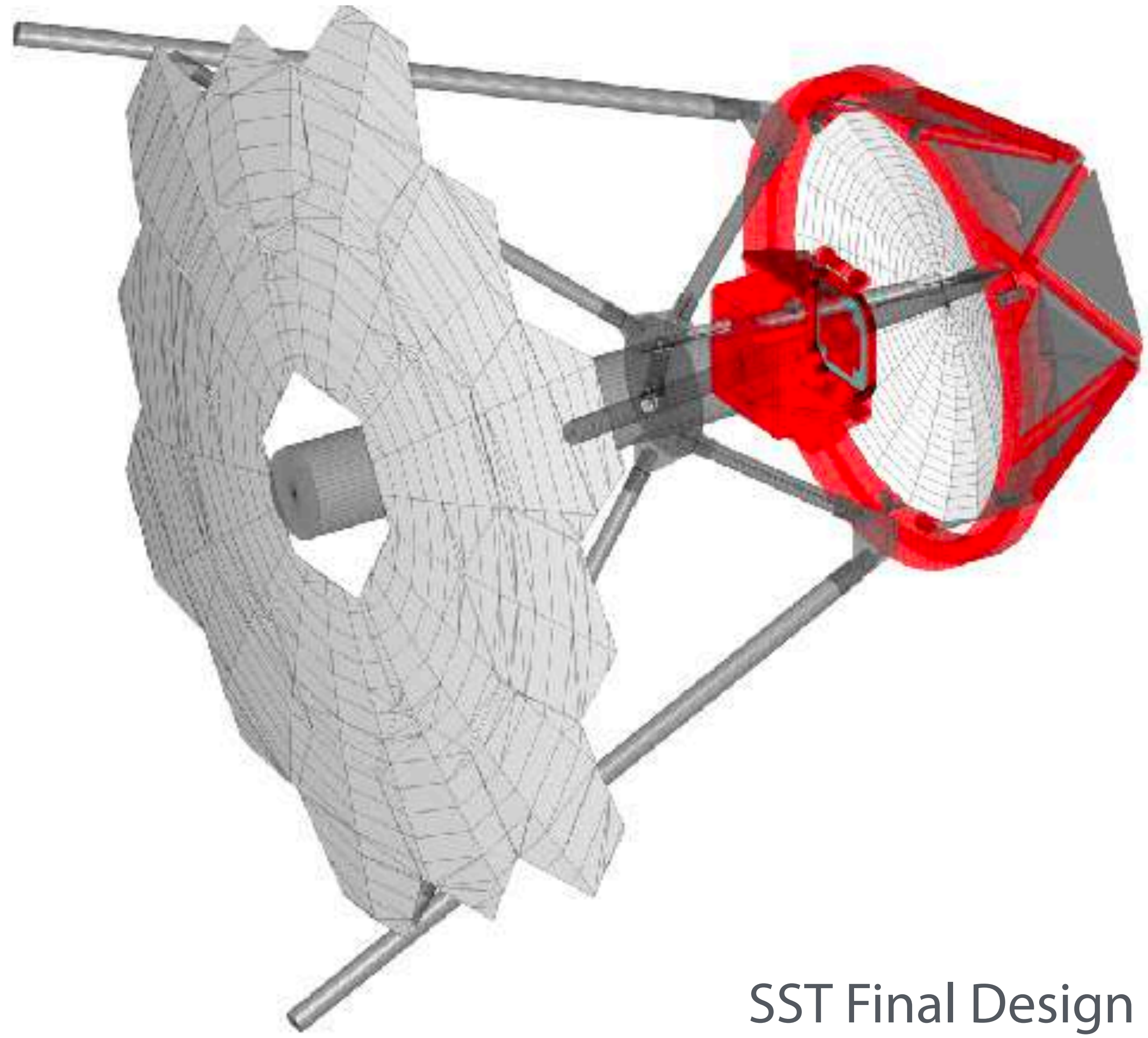
Fig 1. ROBAST 3D model of the Ashra optical system (modified Baker–Nunn optical system)

Complex Telescope Geometry

Thanks to the ROOT geometry library and additional ROBAST classes, complex telescope geometry with a number of segmented mirrors and telescope masts can be built. Indeed, ROBAST is currently used for optics simulations of several telescope designs of the Cherenkov Telescope Array;

- Large-Sized Telescope (LST): A parabolic telescope comprising of 198 hexagonal segmented mirrors with spherical surfaces.
- Medium-Sized Telescope (MST): A Davies–Cotton system comprising of 86 hexagonal segmented mirrors with spherical surfaces.
- Schwarzschild–Couder Medium-Sized Telescope (SC-MST): A system with aspherical primary and secondary mirrors divided into 48 and 24 segmented facets, respectively. The facet shapes are tetragons and pentagons.
- Schwarzschild–Couder Small-Sized Telescope (SC-SST): A system

Fig 2. A Schwarzschild-Couder optical system to be used in CTA

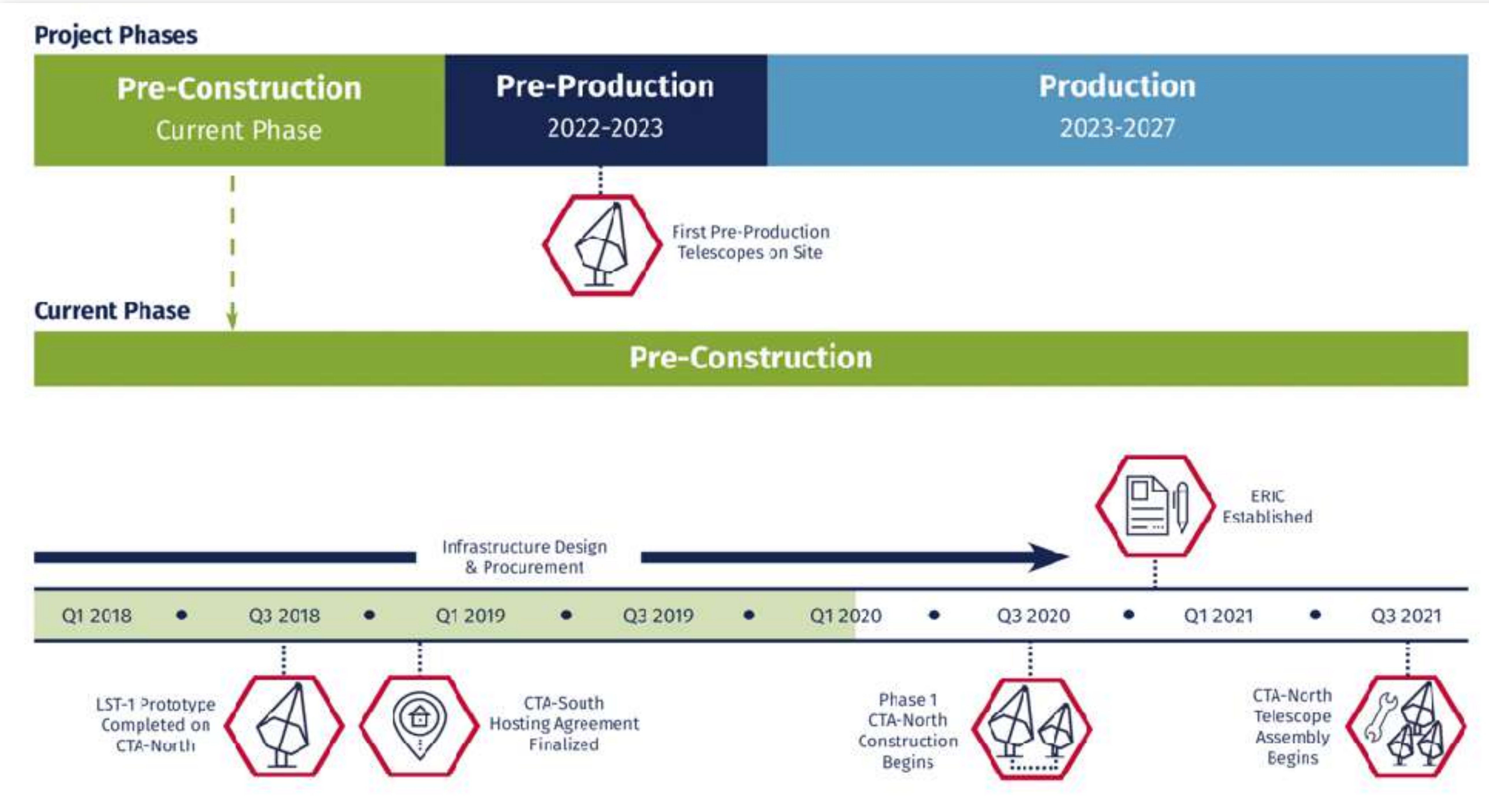


SST Final Design

- ROOT-based ray-tracing simulator for CR telescopes and photodetectors (optical photons only)
- Used in all CTA telescope and Winston cone simulations and some other future projects (see. [Okumura+ 2016](#))
- Some of KMI (exp.) members may be interested in it for photodetector or multilayer simulations

CTA Schedule

https://www.cta-observatory.org/project/status/



Summary and Prospects

- CTA Small-sized Telescopes are built to search Galactic PeVatrons (the PeV CR origin)
- CTA prototype telescopes successfully constructed and verification process are ongoing
- Schwarzschild–Couder configuration and SiPM ideas were also verified in prototypes

- Some early physics results will come in early 2020s and full array completion will be in 2027
- P.S. Try using ROBAST