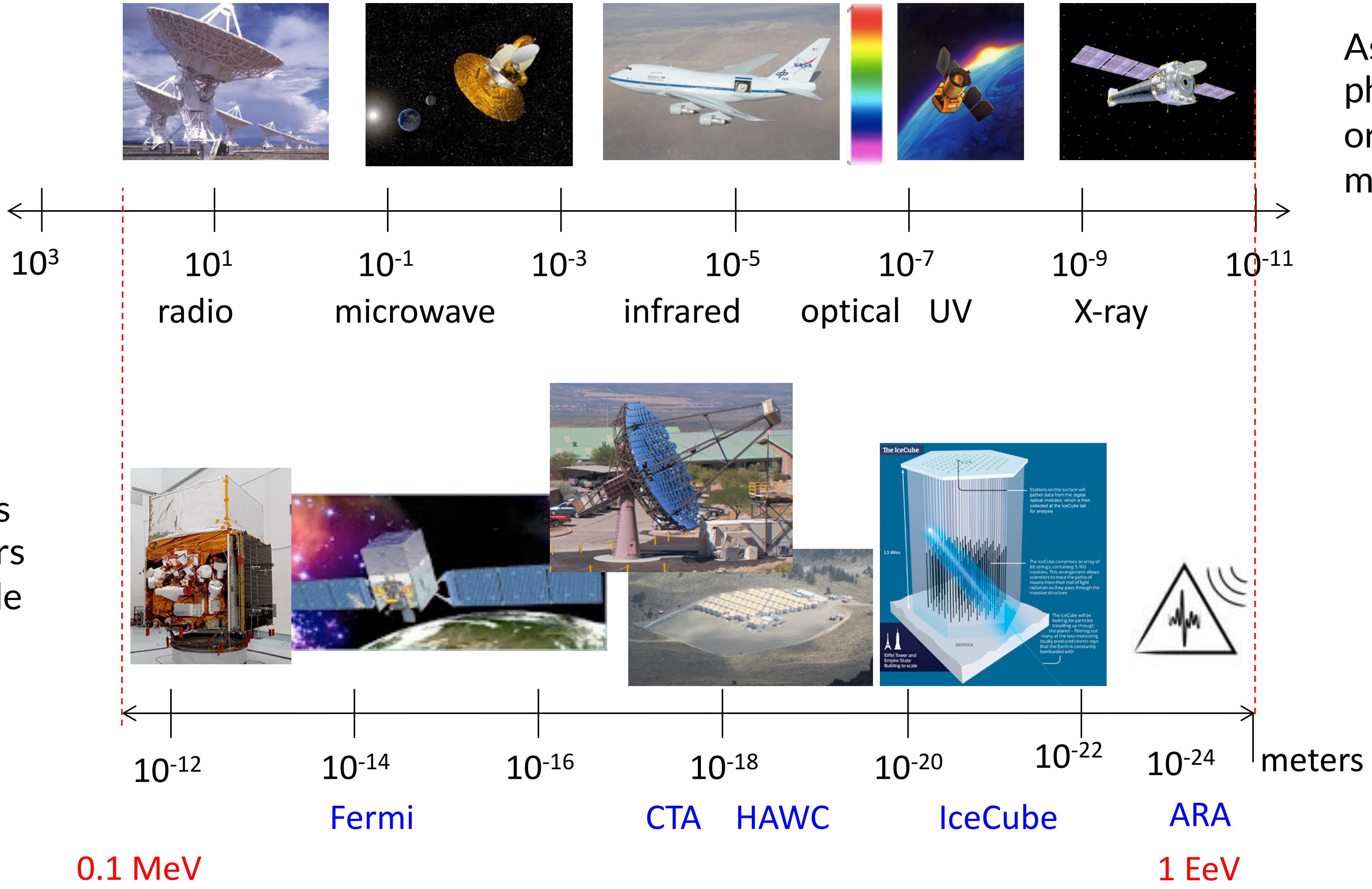
Cherenkov Telescope Array

A New Era in Astrophysics

Brent Mode
18 June 2020
For the IceCube Bootcamp

Motivations for TeV Gamma Ray Astronomy

Astroparticle Physics and Gamma Rays

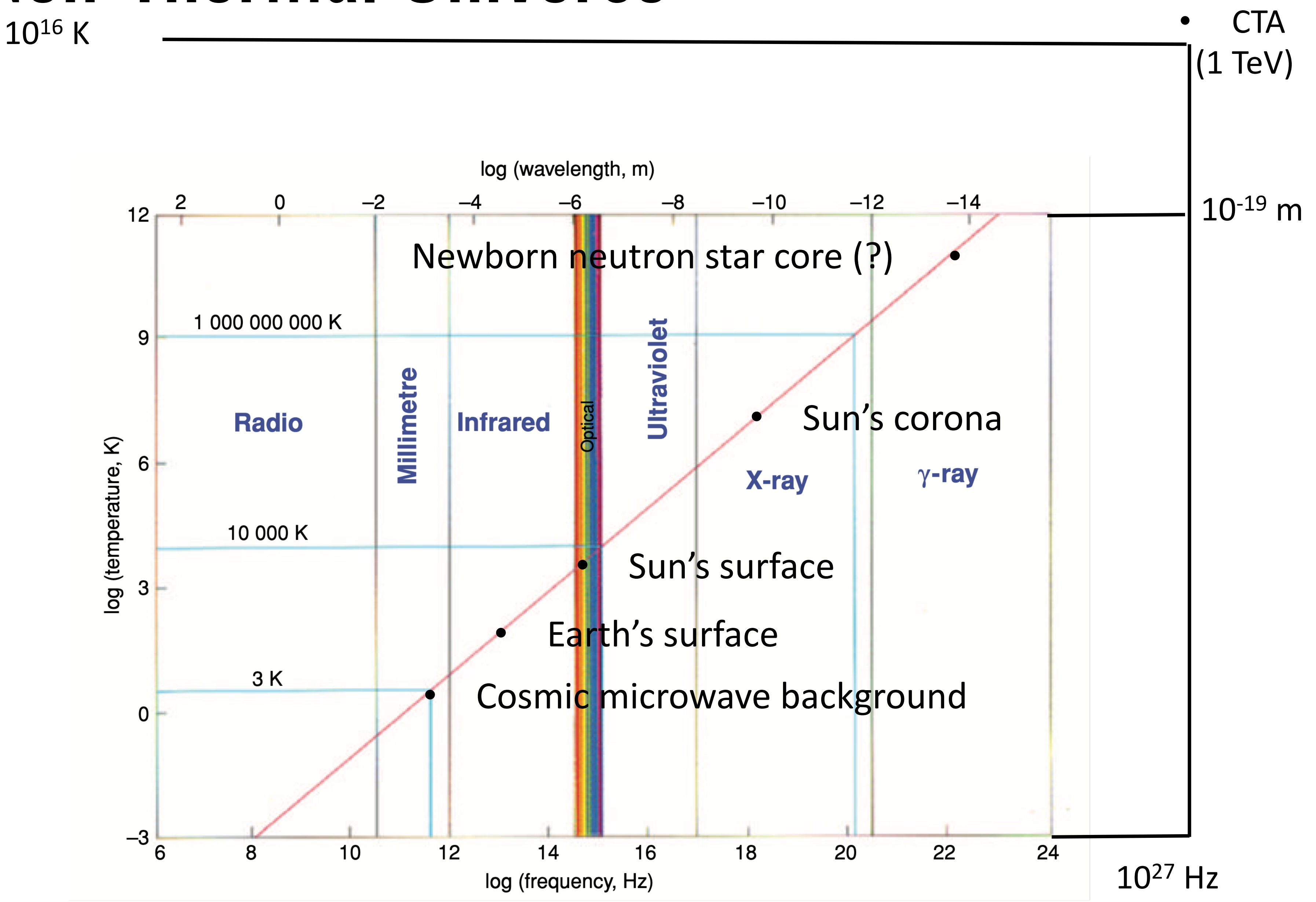


Astroparticle physics over 13 orders of magnitude

Gamma rays over 9 orders of magnitude

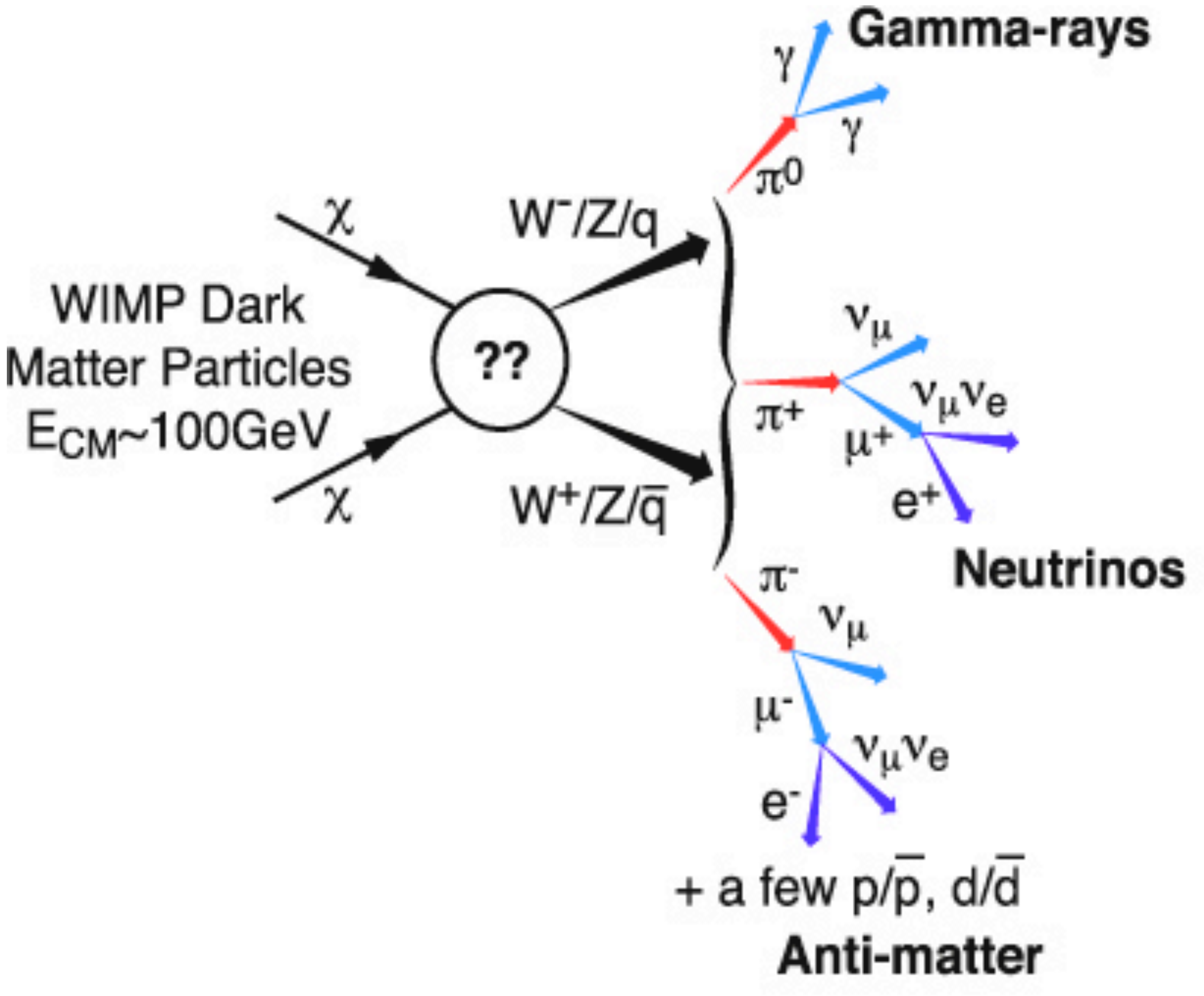
The Thermal v. Non-Thermal Universe

- Black body radiation is responsible for much of the low energy light in the universe
- Even some gamma rays can come from very high energy thermal events
- Most gamma rays will come from non-thermal processes, as the associated black body temperature peaked at 1 TeV is 10 quadrillion K

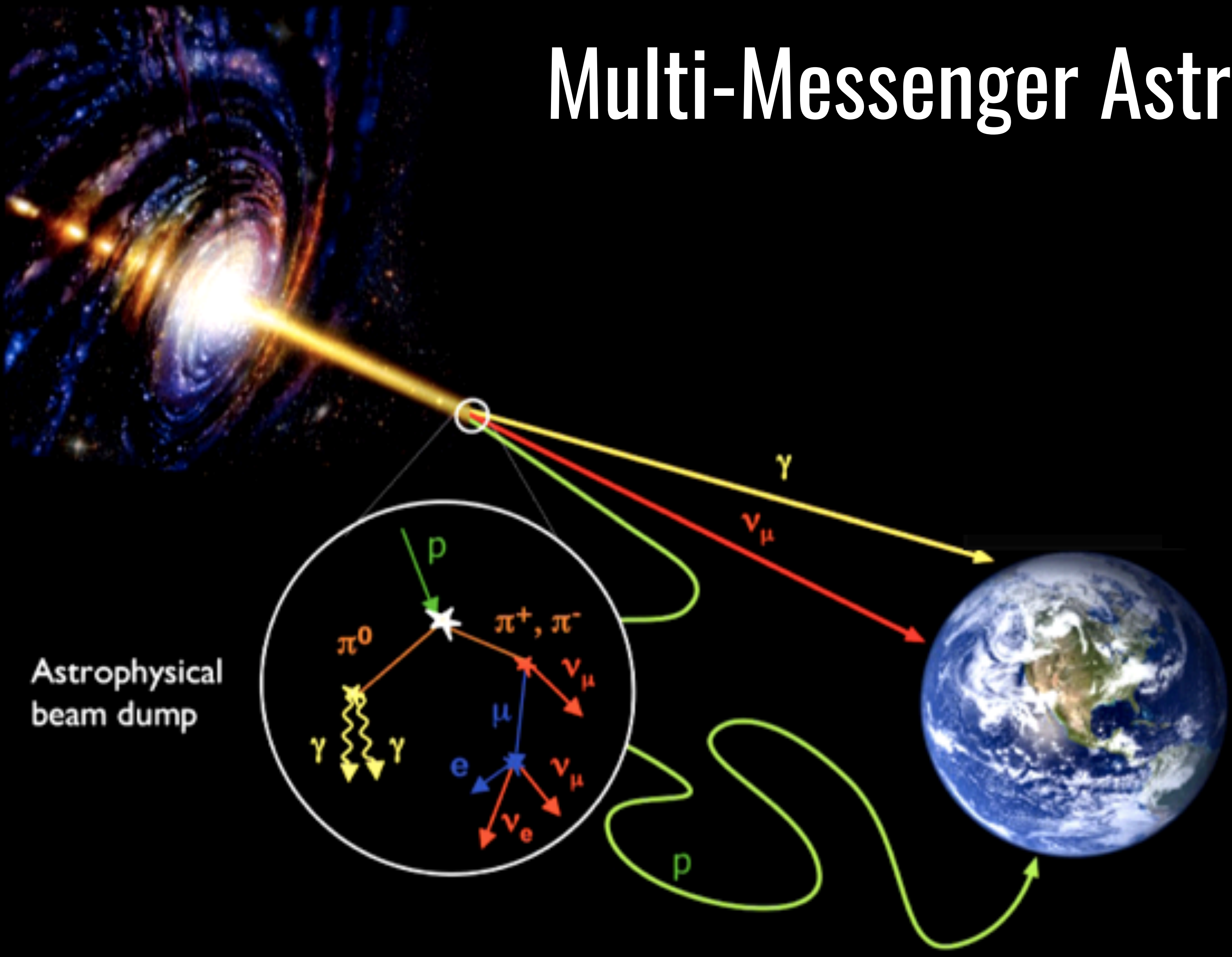


Possible Gamma Ray Production from Dark Matter

- A possible fifth non-thermal source of gamma rays is exotic particle decay or interaction, like dark matter
- This gives rise to the indirect detection sector of the dark matter search
- It is complementary with the direct detection and accelerator production approaches
- This approach has the benefit of being potentially sensitive to more than one broad class of dark matter models

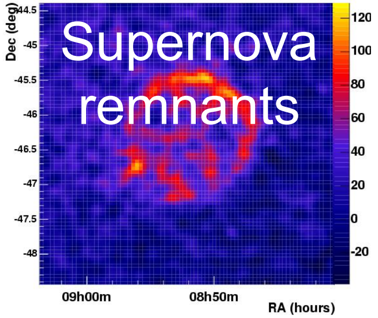


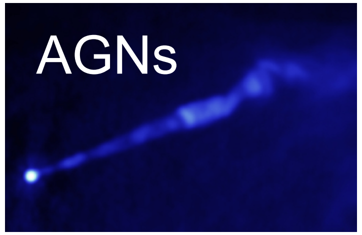
Multi-Messenger Astronomy

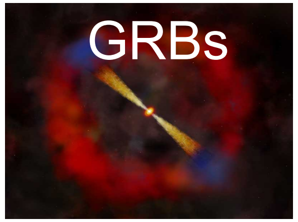


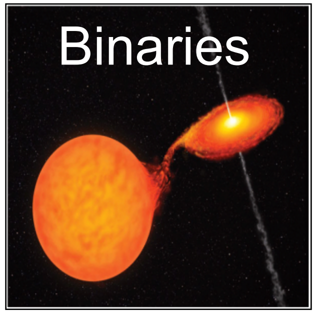
- Using photons, neutrinos, cosmic rays, and gravitational waves, we can study astrophysical sources and transient objects much more thoroughly than ever before
- Different astrophysical sources emit different particles and at different energies, allowing for multi-instrument, coordinated observations

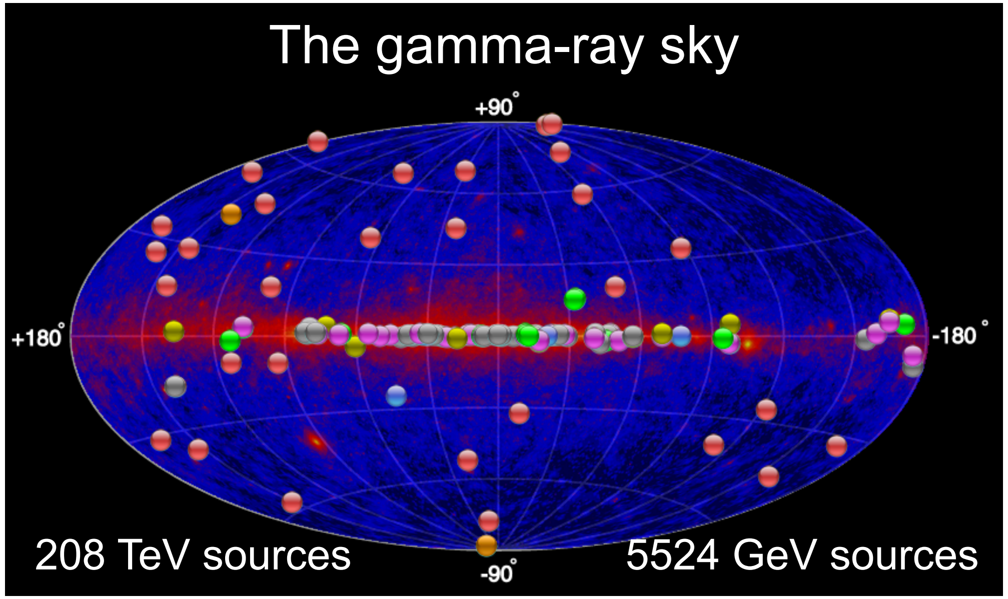
Physics with TeV Gamma Ray Telescopes

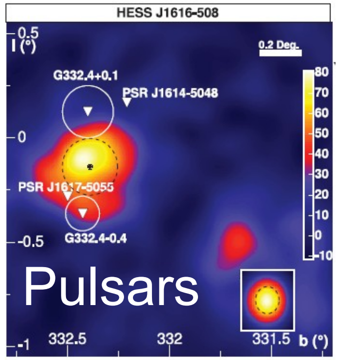


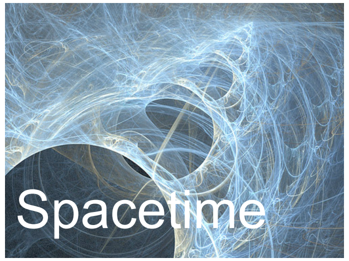




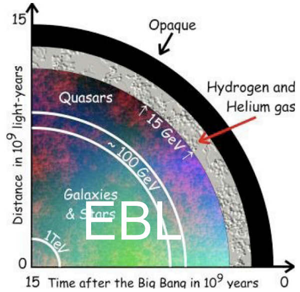








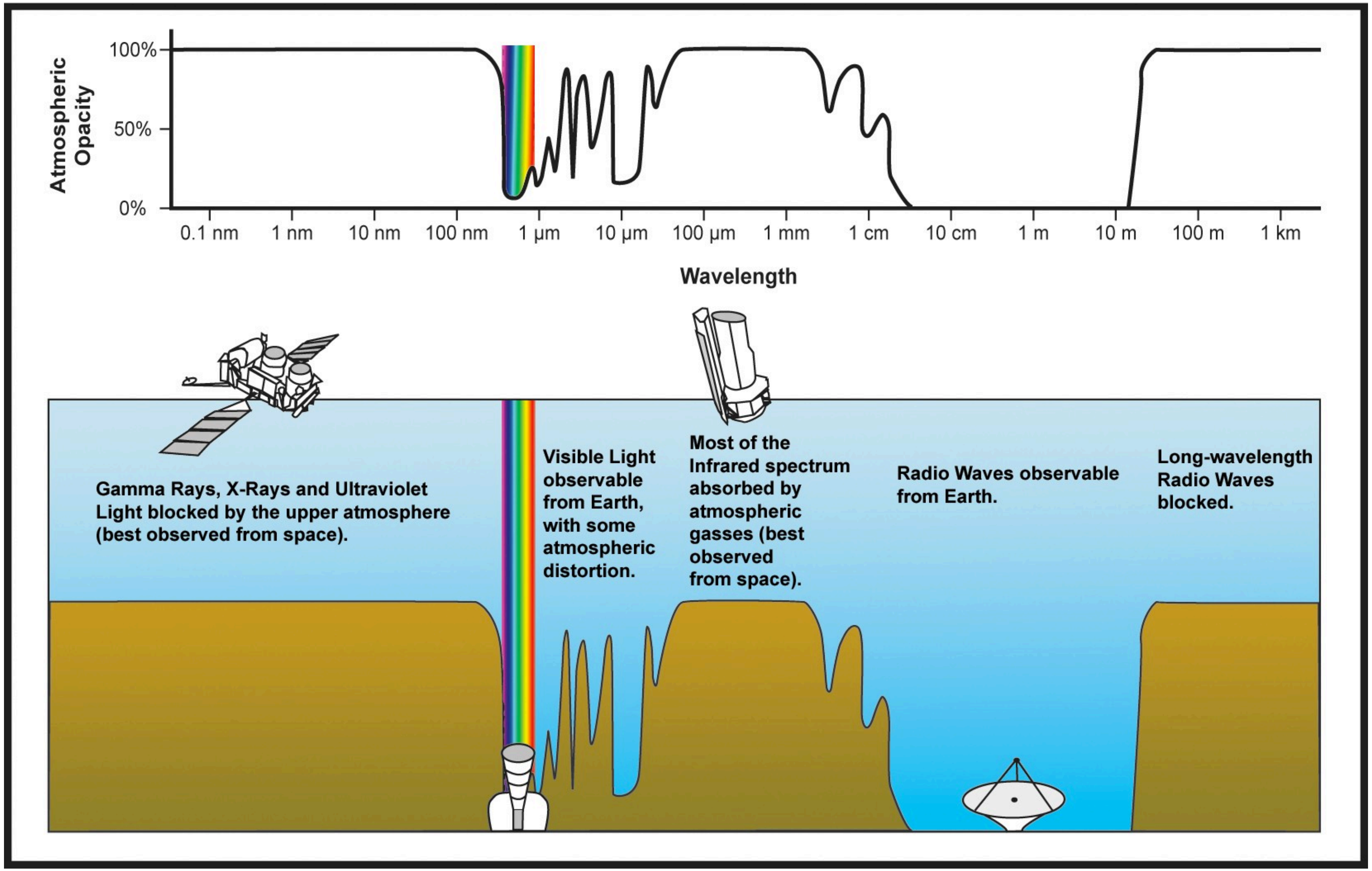
Axions, …



Imaging Atmospheric Cherenkov Telescopes

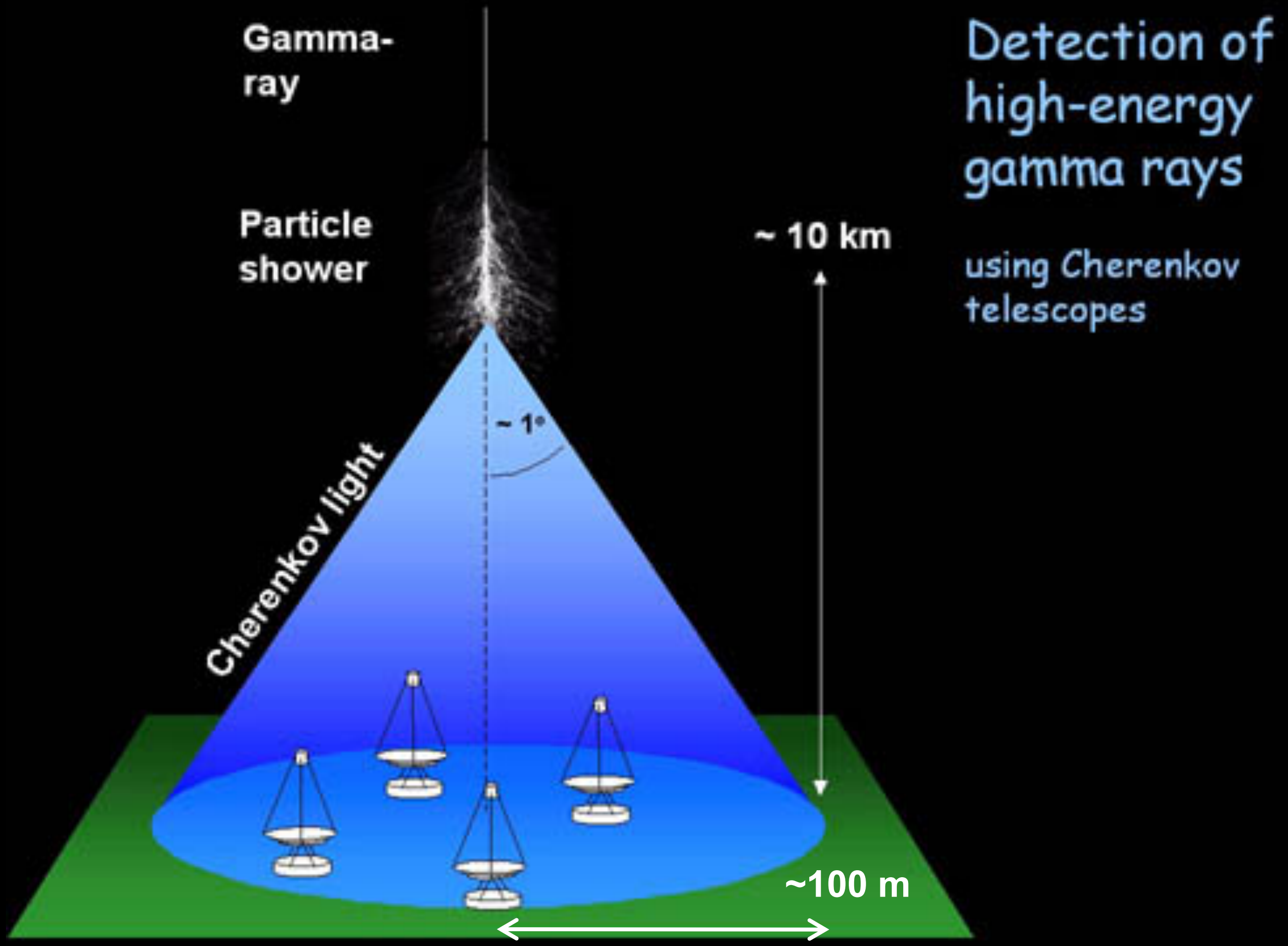
A technique for TeV gamma-ray astronomy

The Atmosphere is Opaque to Gamma Rays



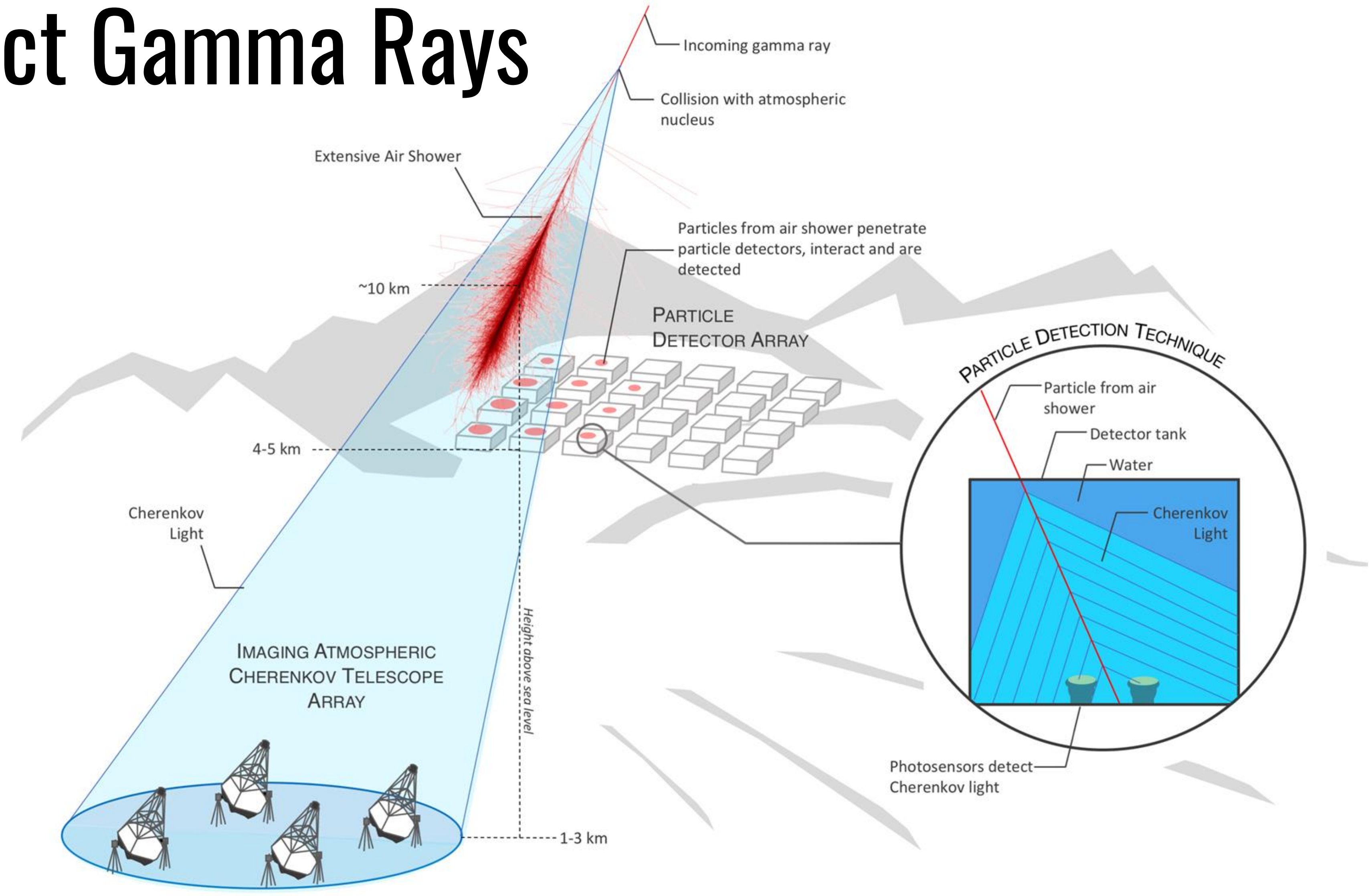
Atmospheric Cherenkov Radiation

- Optical frequency (blue) light
- Very short (few ns) exposure to limit night sky background
- Cherenkov cone very narrow, ~1°:
- $\theta = \arccos \frac{1}{n\beta}$
- 1000-1500 hours per year (dark, good weather)



Two Ways to Detect Gamma Rays

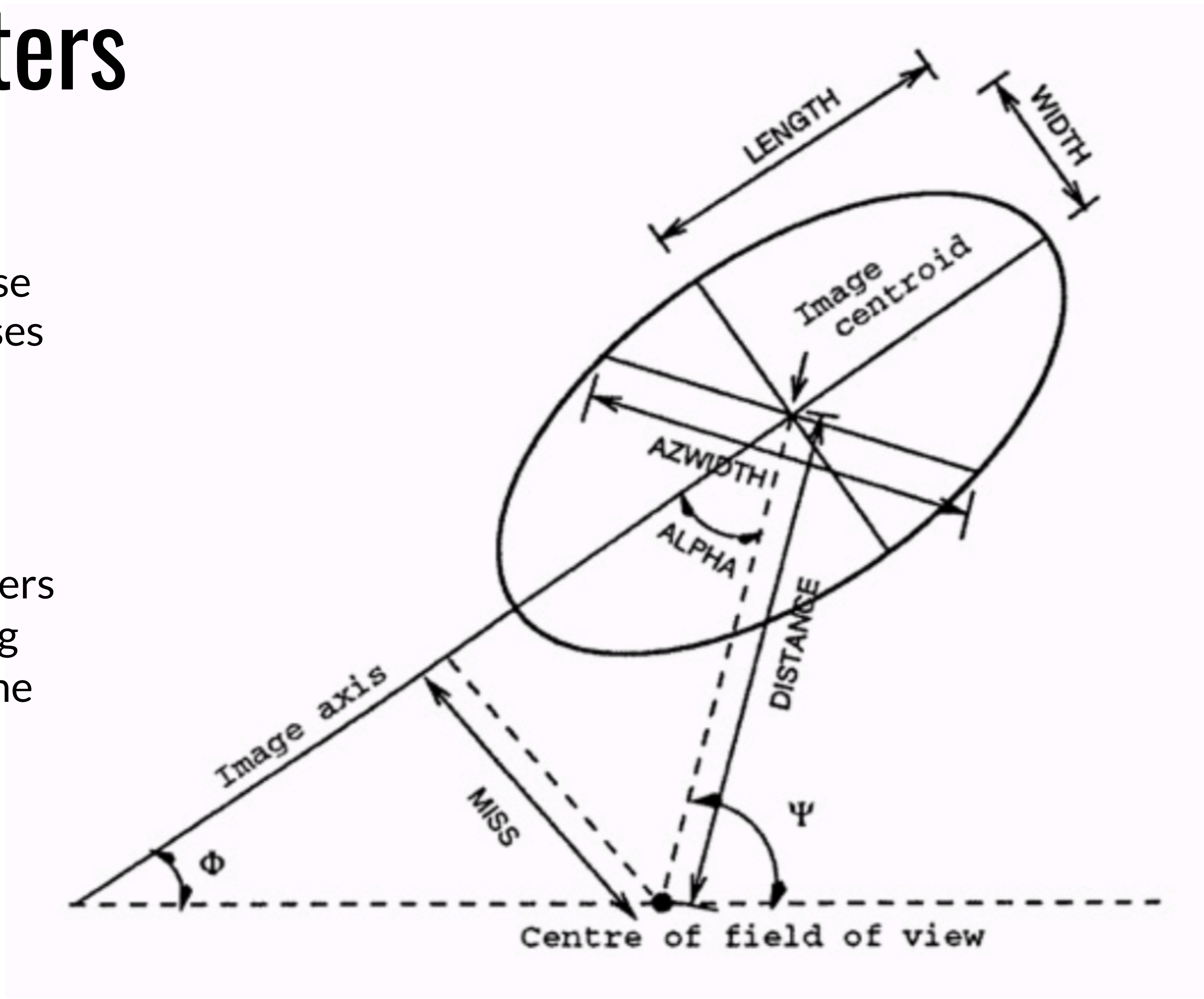
- CTA detects the Cherenkov light produced by the particles in the air shower
- HAWC and SWGO (will) detect Cherenkov light produced in water tanks by particles in the air shower
- IACTs have better angular resolution but a much smaller FOV



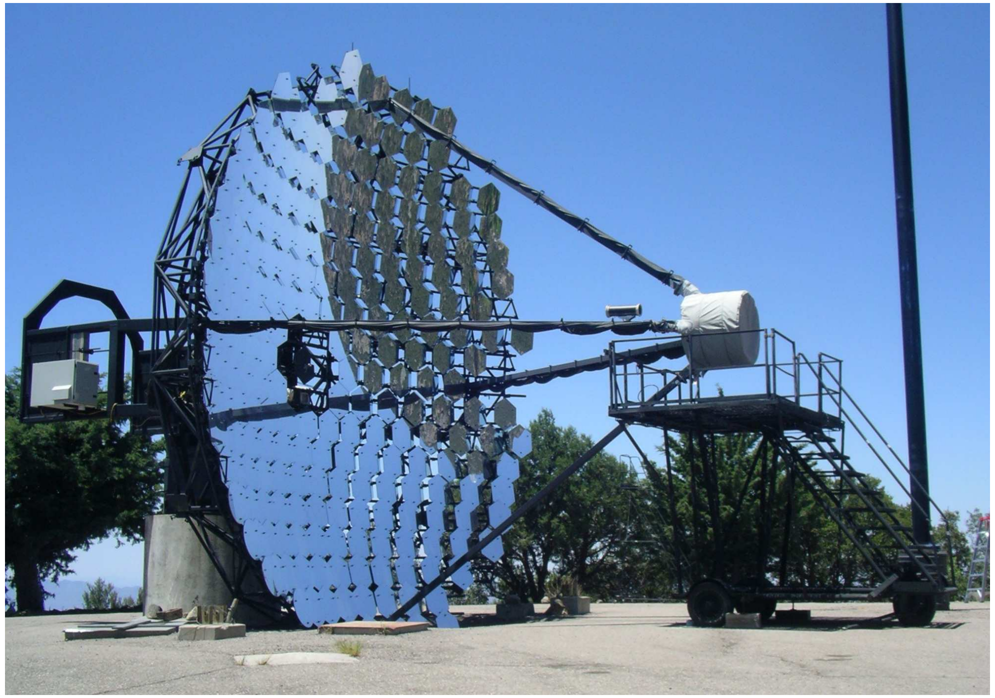
Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Hillas Parameters

- Parameterization of an ellipse
- Since air showers form ellipses on an IACT camera, this is useful for analysis
- Length and width are particularly useful for identifying gamma ray showers
- Alpha is useful for identifying showers that originated in the direction of the source (if on source)

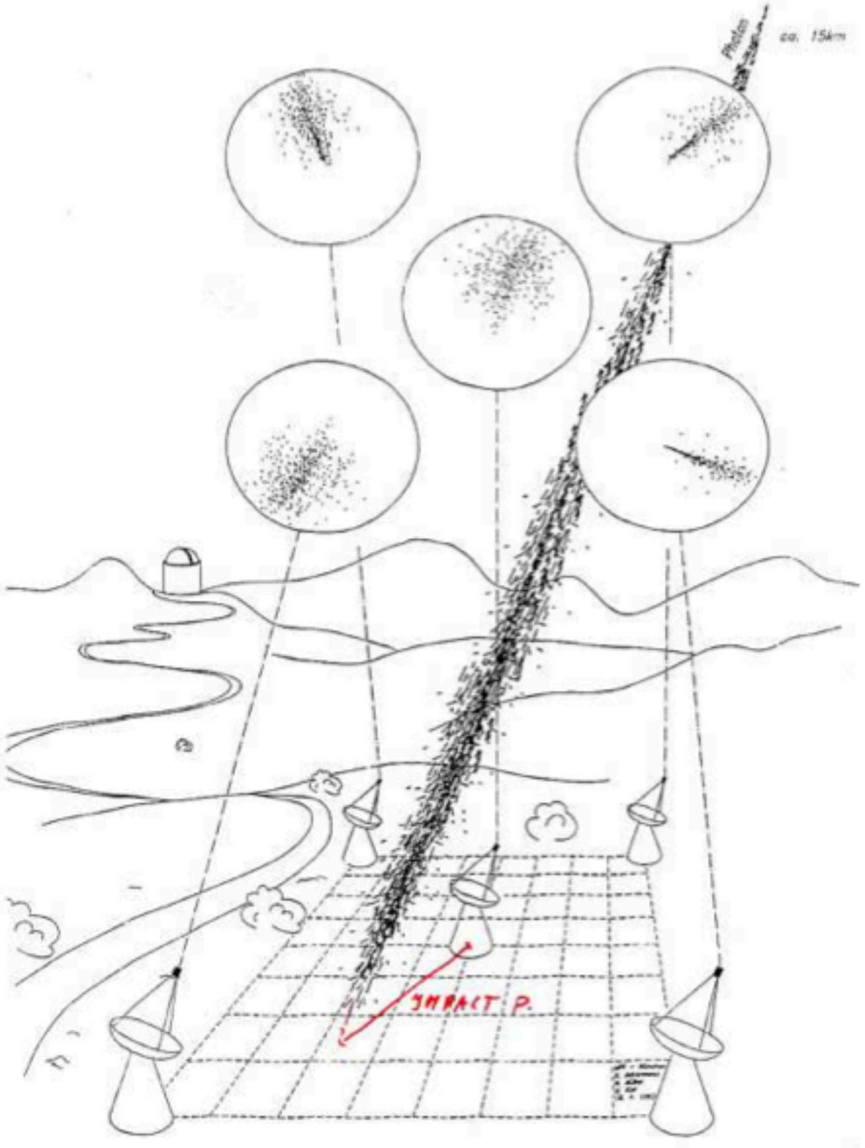


First IACT: Whipple 10 m Telescope at FLWO

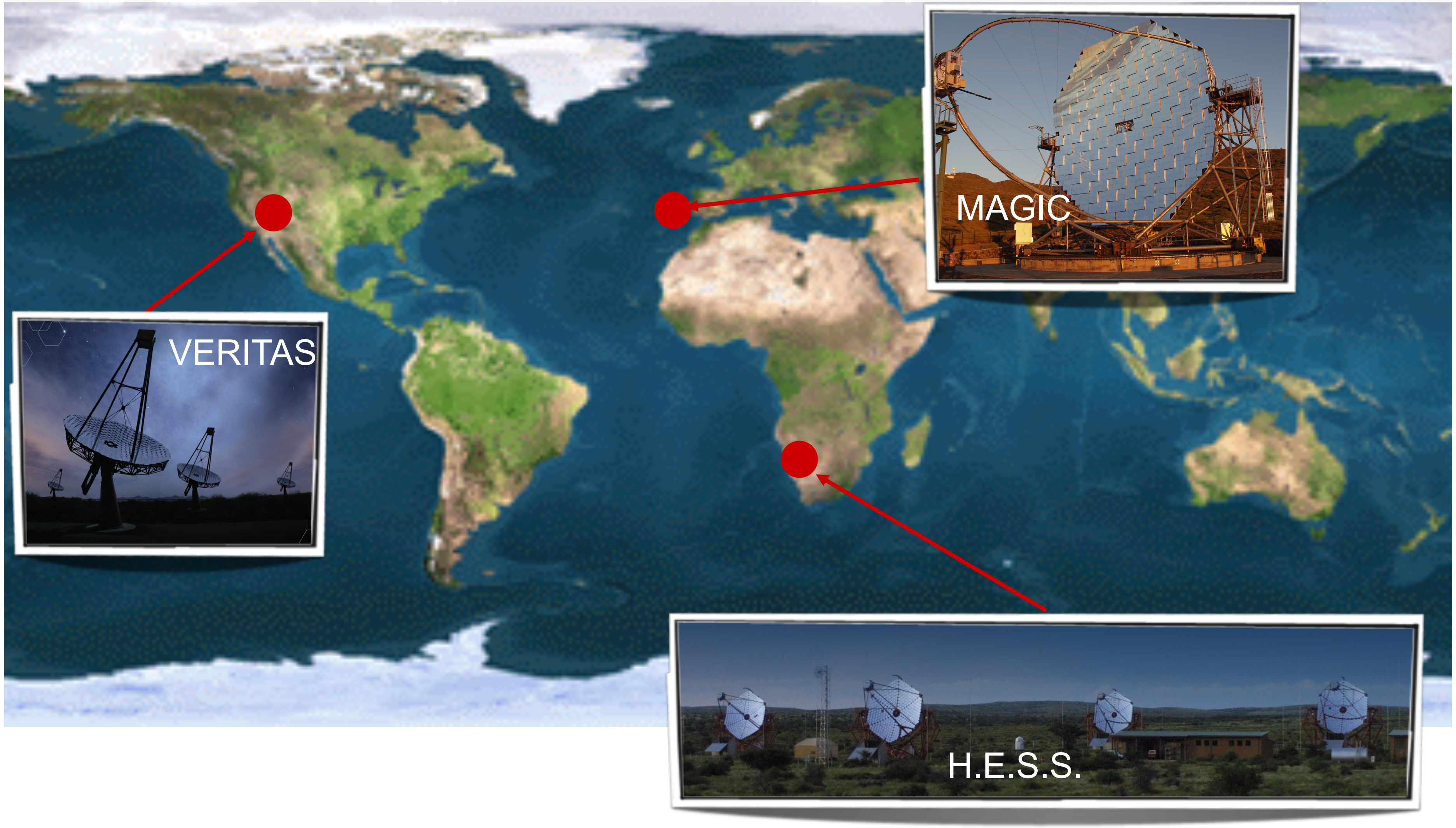


- Pioneer imaging atmospheric Cherenkov telescope
- Discovered the first very-high energy (TeV) astronomical sources
  - Crab Nebula: 1989 (in UV in 1996)
  - Markarian 421 (1992): a nearby blazar
  - Markarian 501 (1997): another nearby blazar

Two Telescopes are Better Than One



Current Generation of Stereo IACTs




View from MAGIC


H.E.S.S.

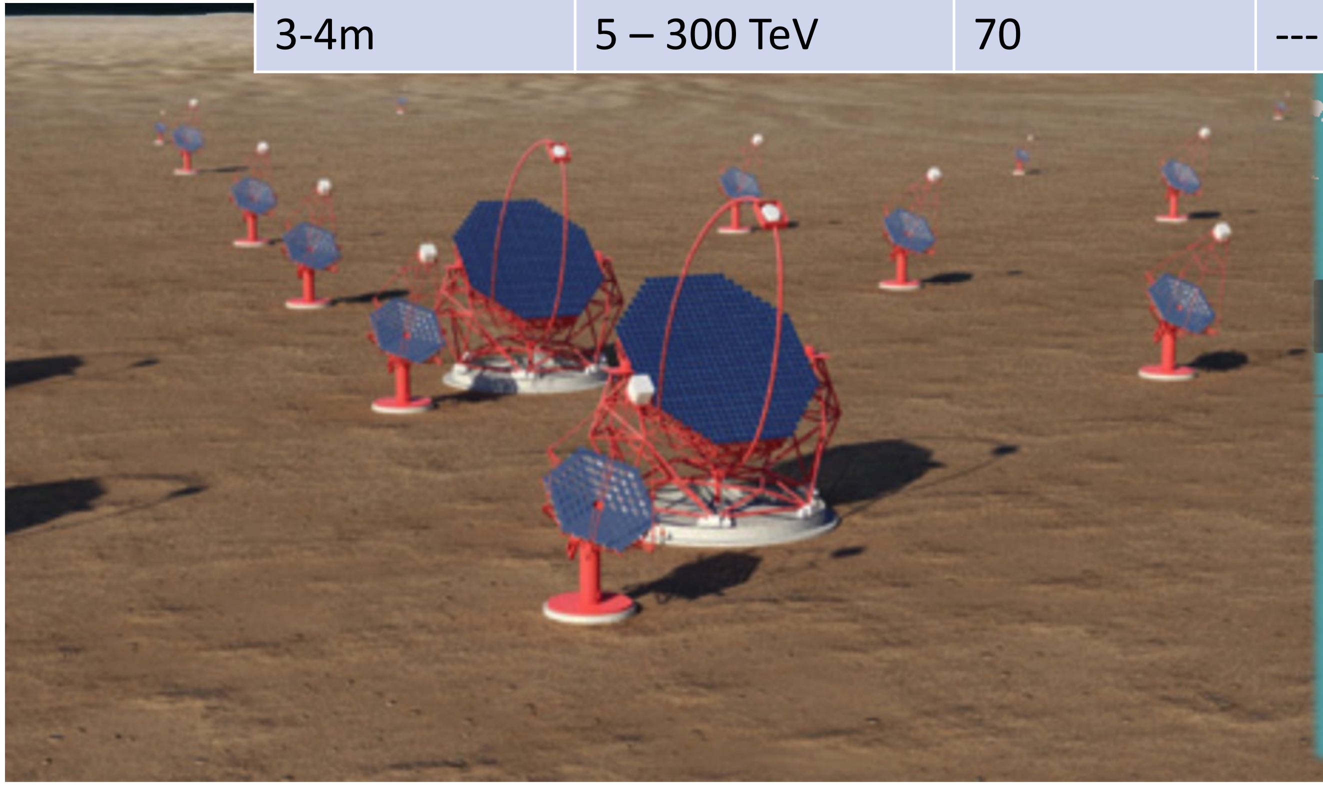

VERITAS

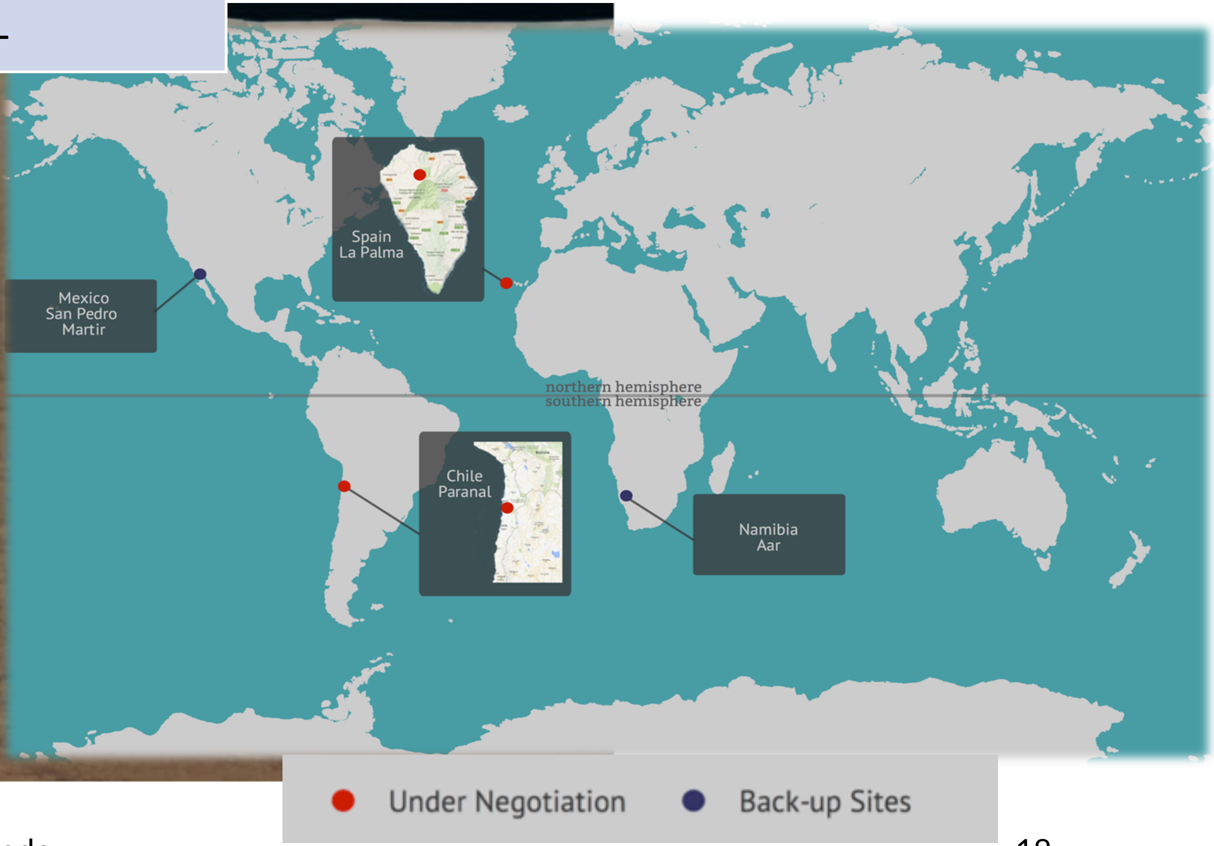
The Cherenkov Telescope Array

Cherenkov Telescope Array

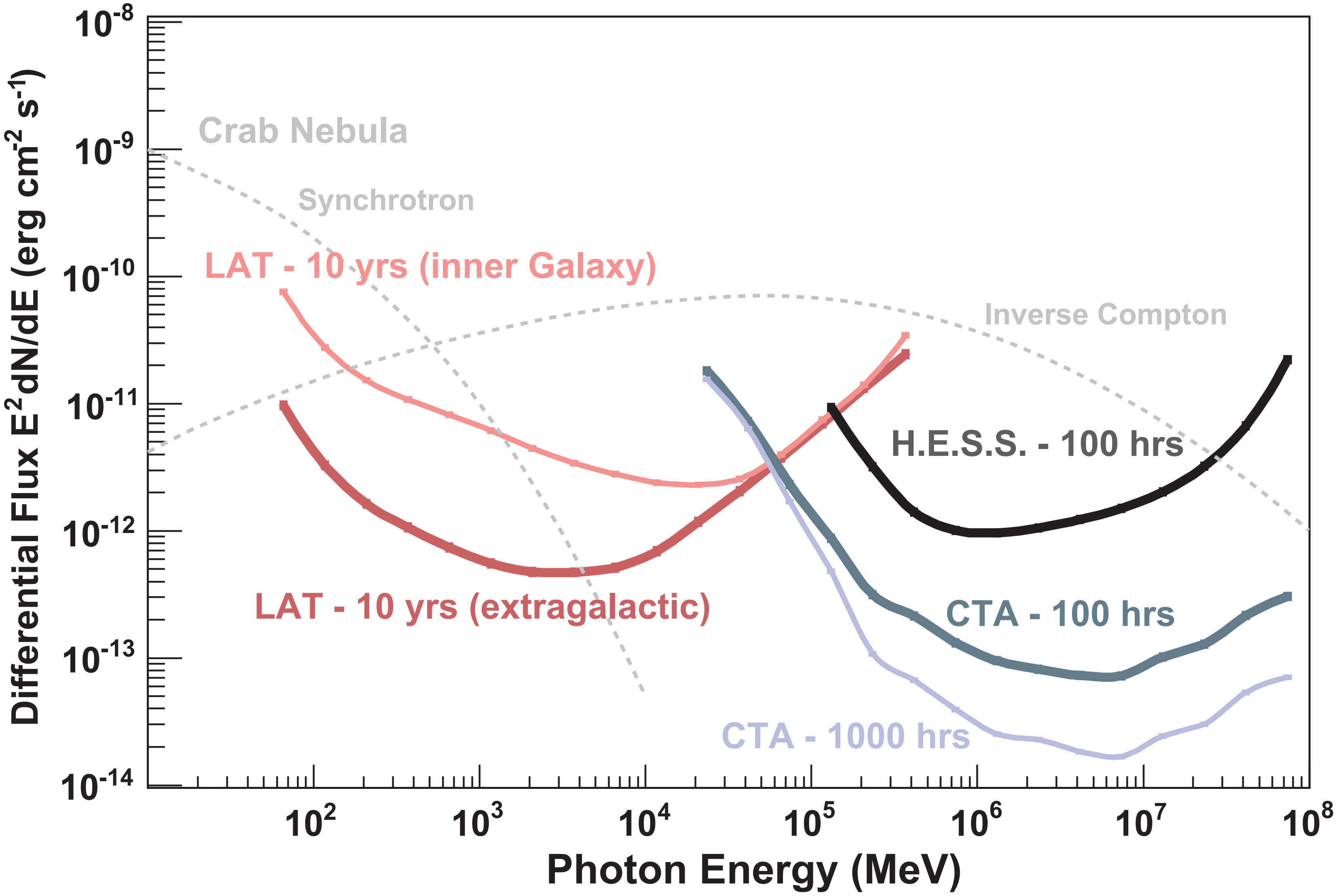
Telescope size	Energy range	South array	North array
23m	20GeV – 1 TeV	4	4
9-12m	100Gev – 10TeV	25	15
3-4m	5 – 300 TeV	70	---

2 arrays of differently sized telescopes looking for gamma ray induced air showers

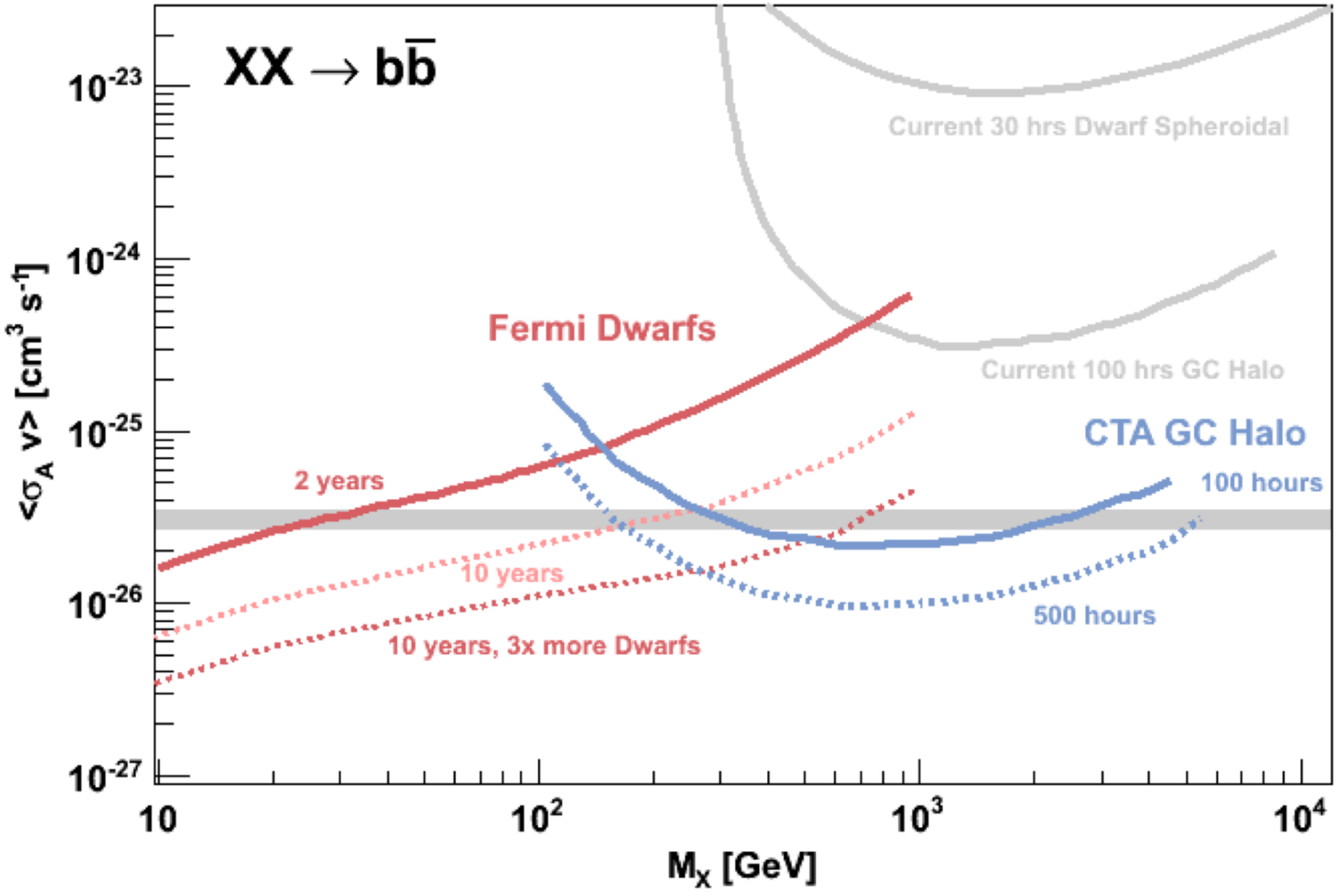




CTA v. Fermi LAT

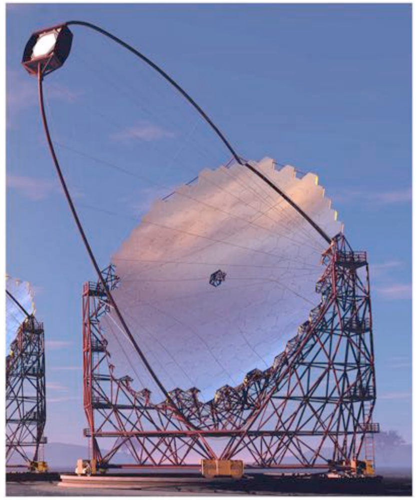


Fermi Dwarfs and CTA GC Will Cover Entire Mass Range Down to Thermal Cross Section



CTA Telescopes and Prototype Locations

Large, Canary Islands



LST

Medium (1 mirror), Germany

MST

Medium (2 mirror), Arizona

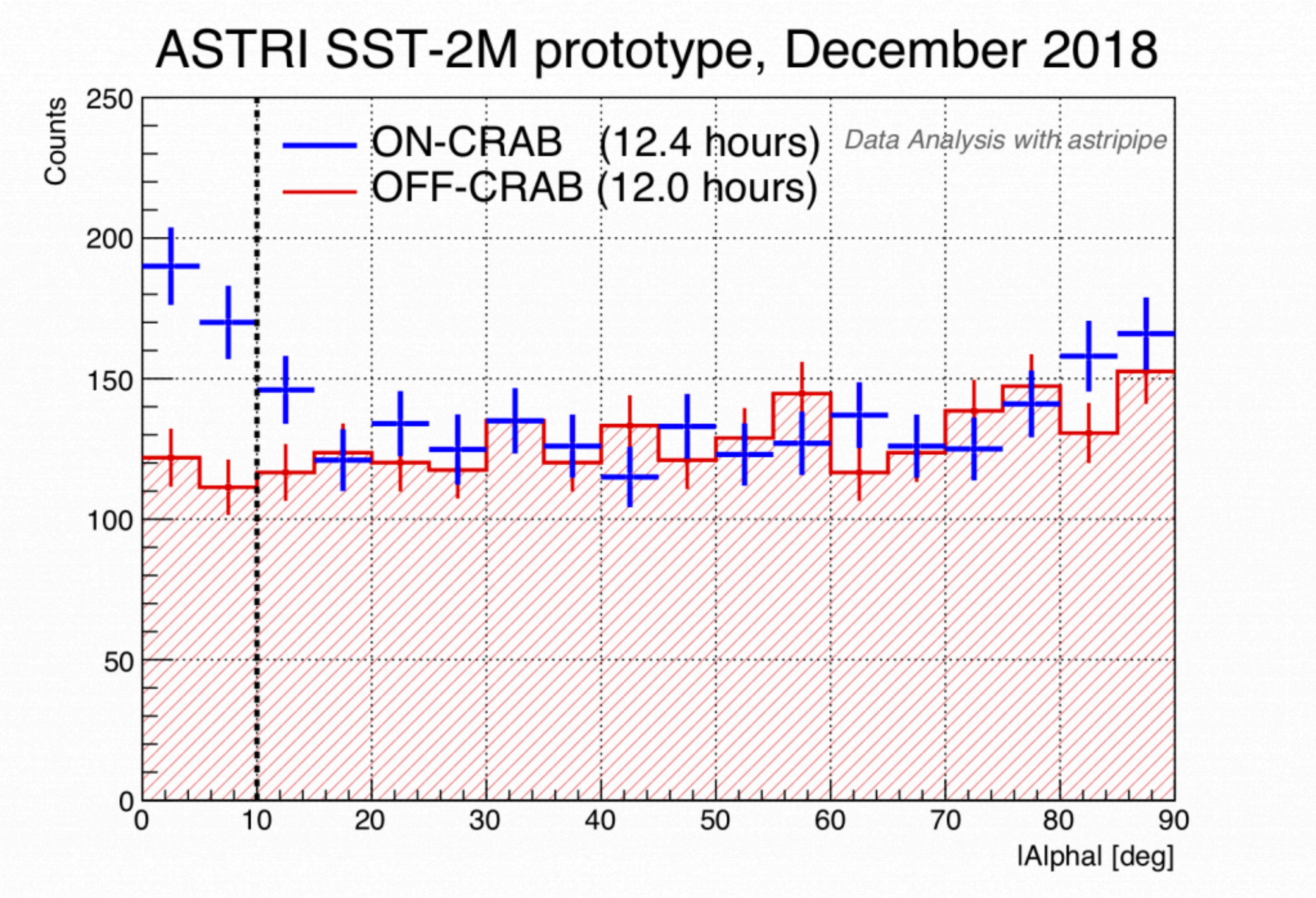
SCT

Small:

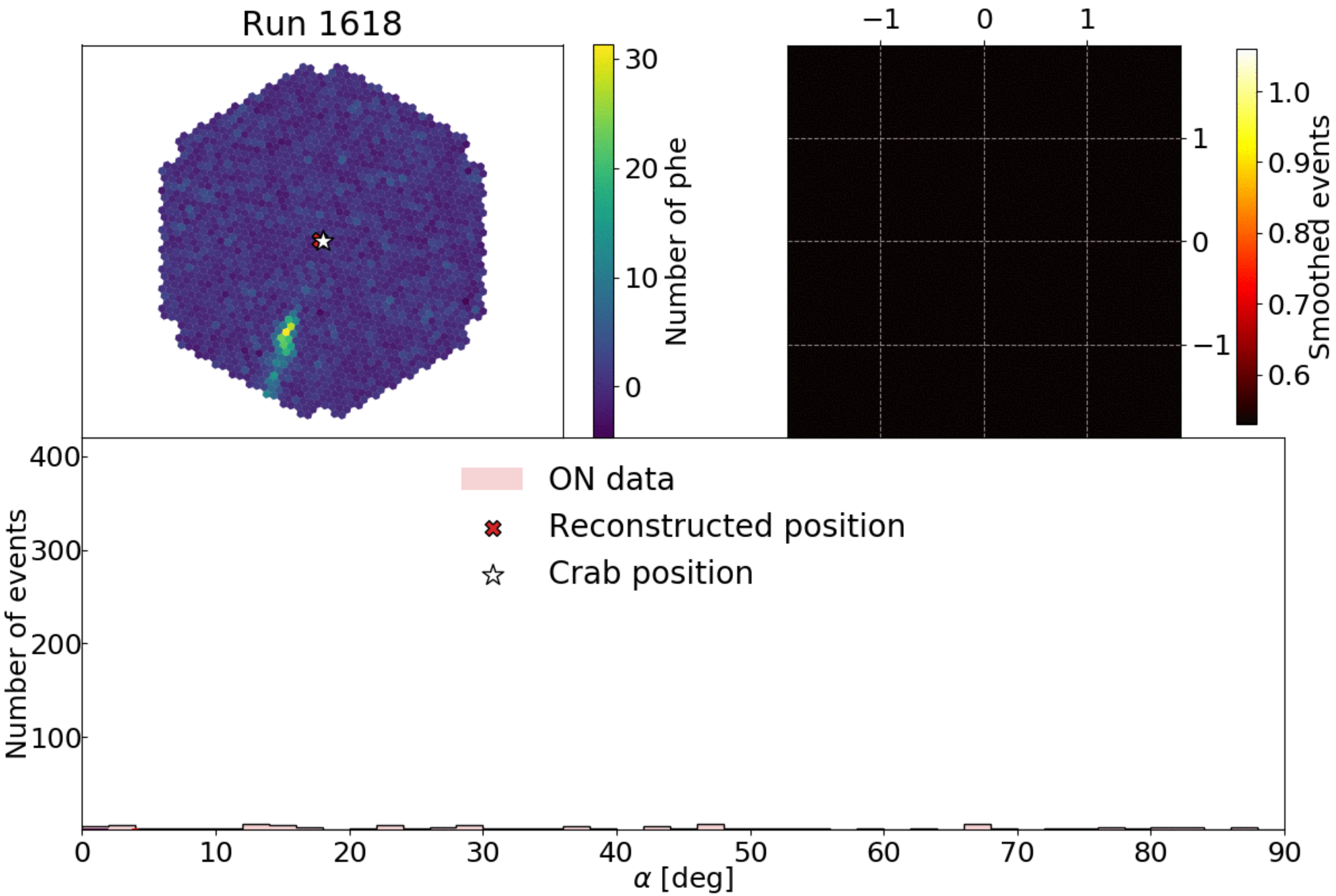
2 mirror, Sicily

SST

SST Prototype Detects Crab Nebula



LST Prototype Detects Crab Nebula



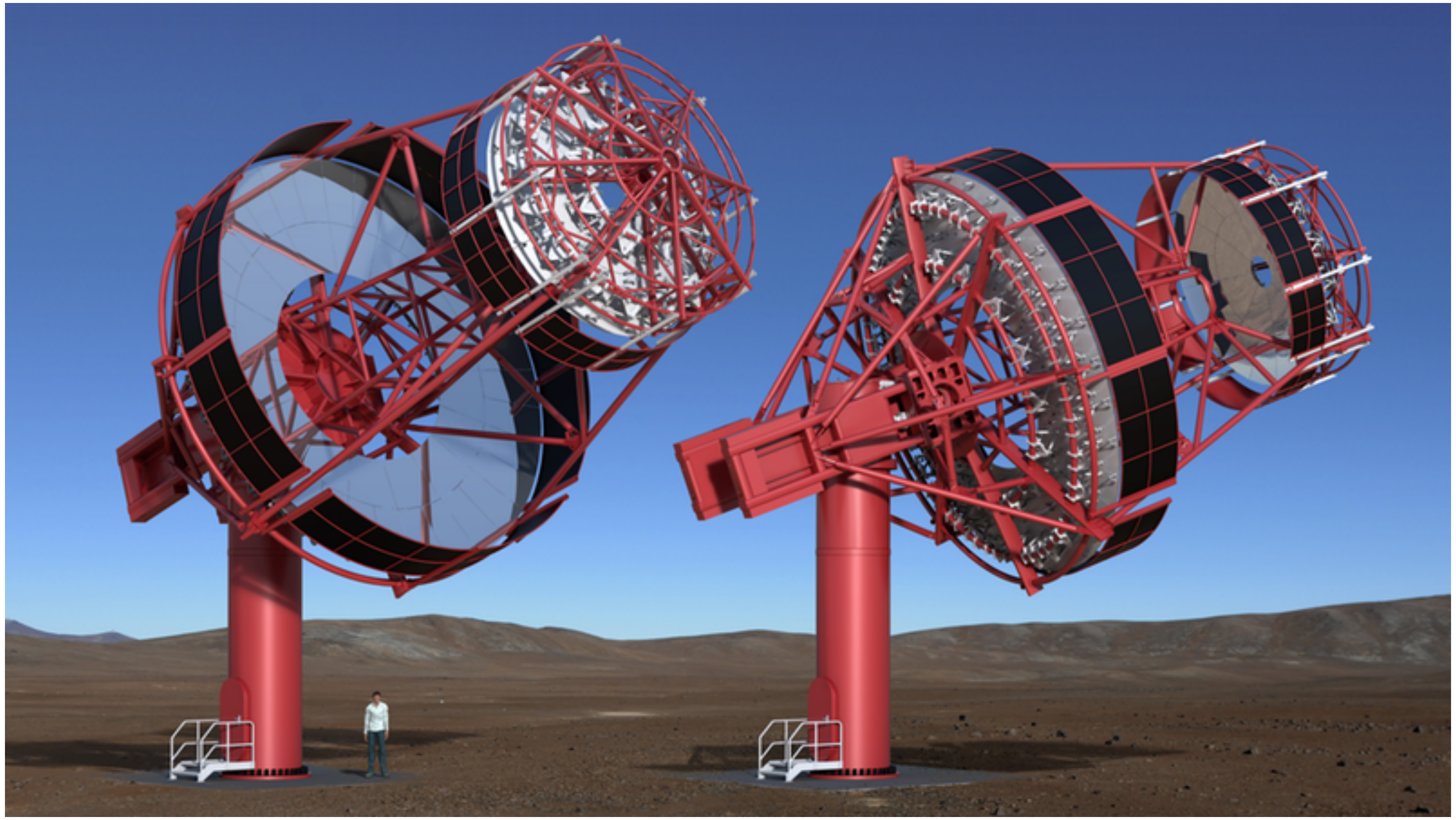
CTA @ WIPAC:
Commissioning the pSCT

pSCT: Prototype Schwarzschild-Couder Telescope

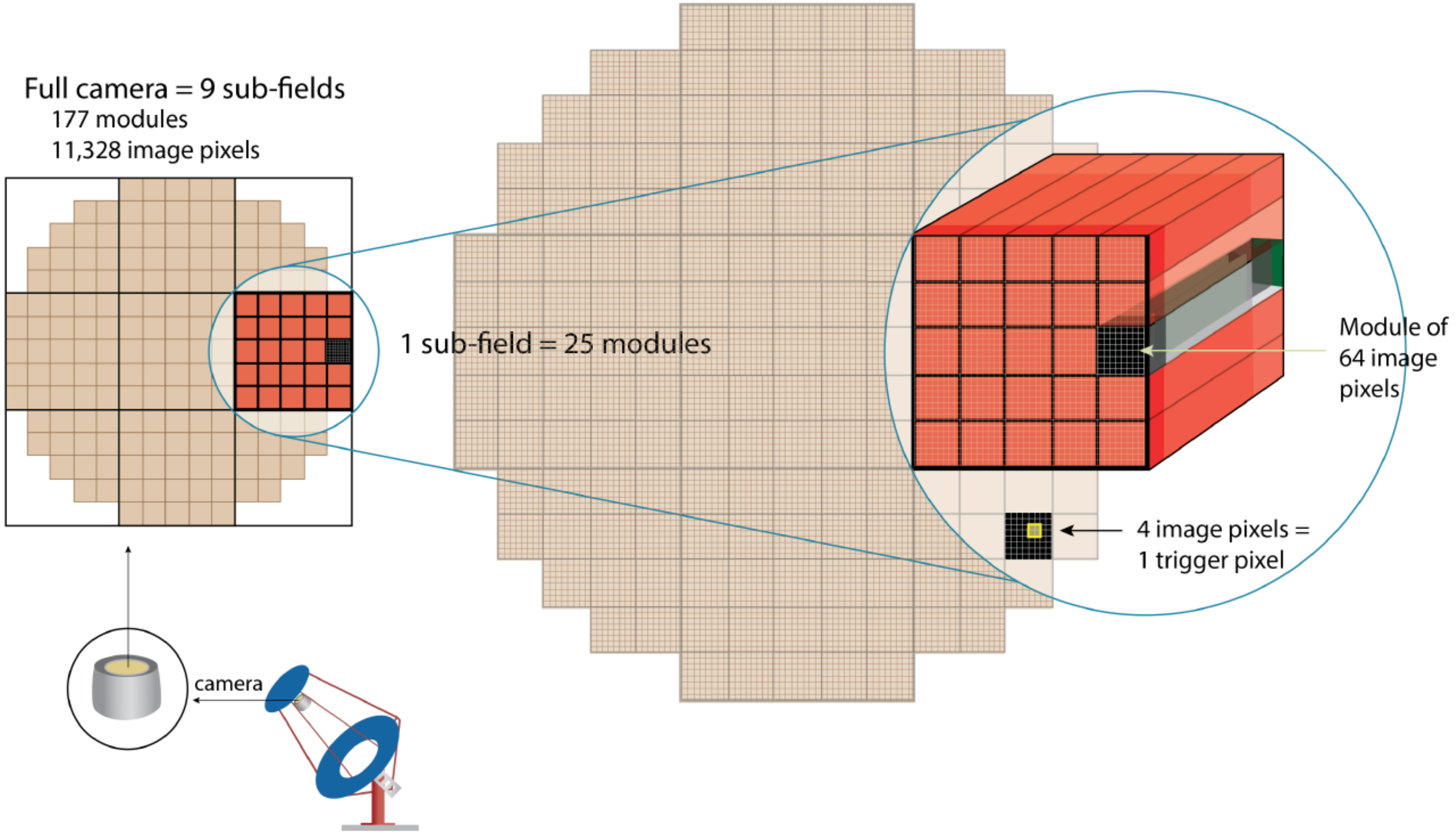
- **Use two mirrors instead of one:**
- Advantages:
  - Telescope can be more compact
  - Has wider field of view
  - Better resolution

- Need special technique for a-spherical mirror shaping:
  - optimized for maximum resolution and field of view

- Need fast, high-resolution camera:
  - possible through new developments in SiPM and ASIC technology

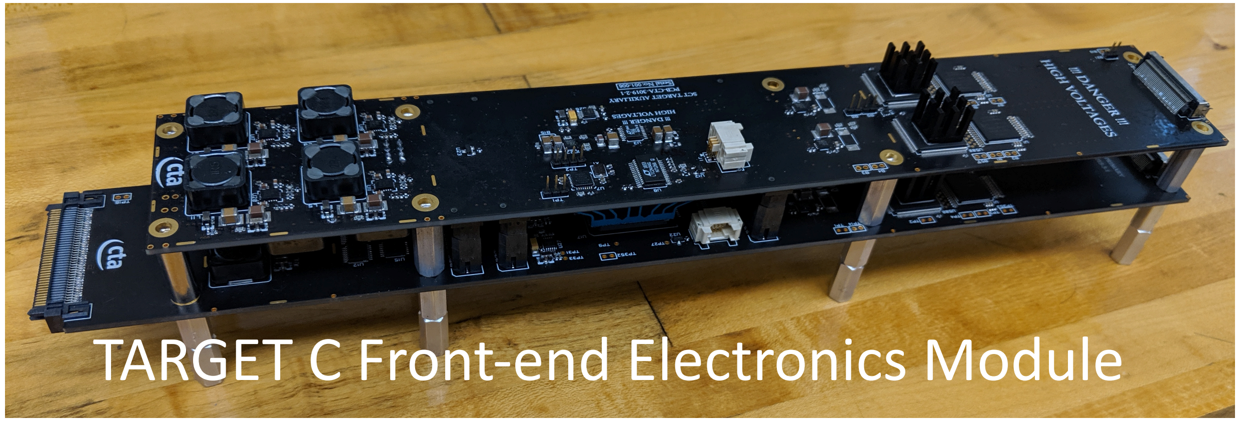


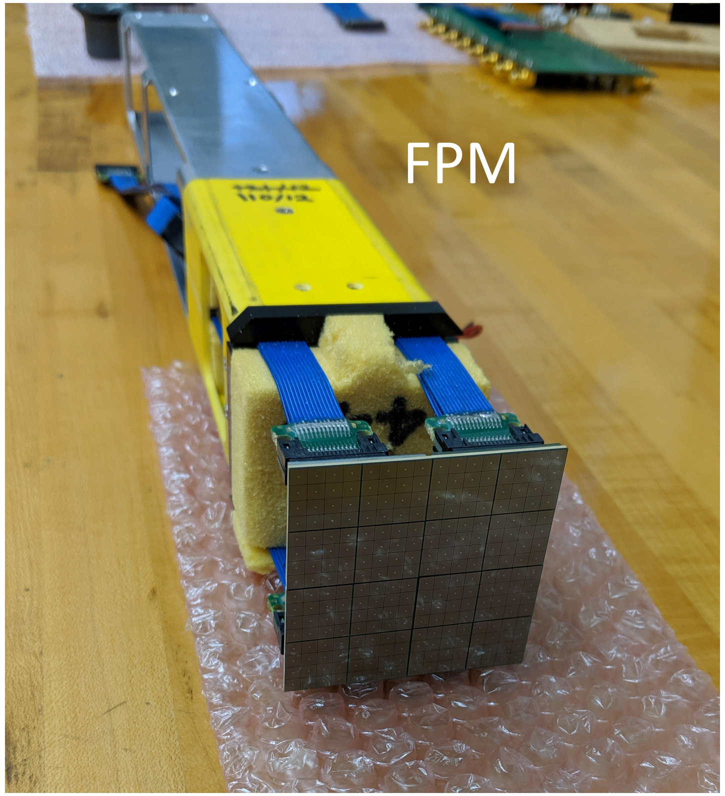
pSCT Camera Organization



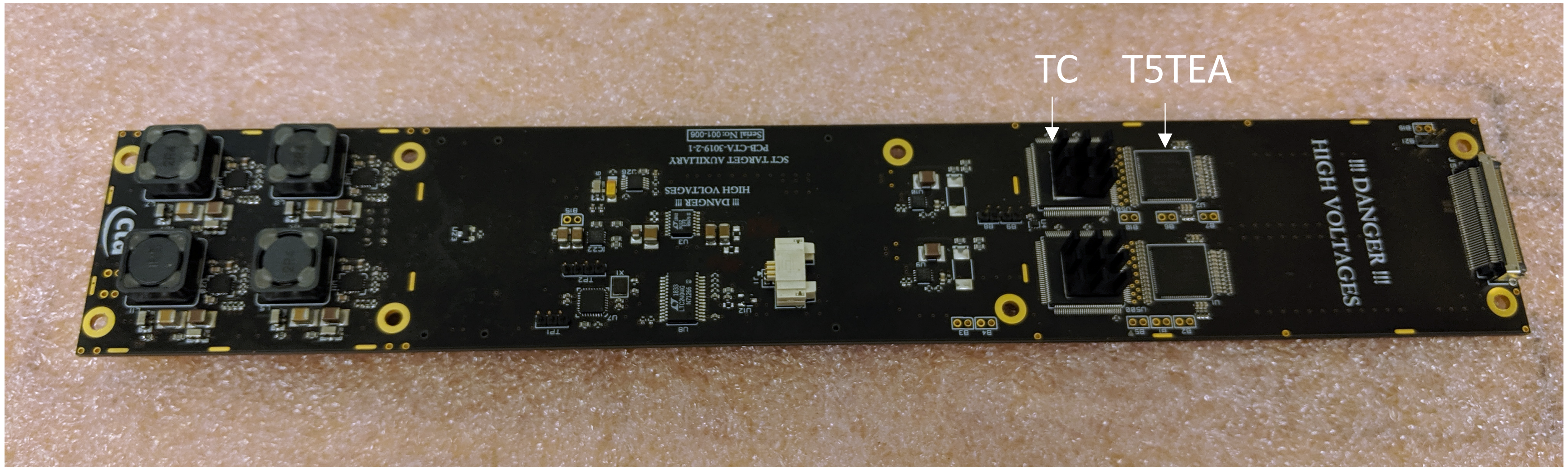
pSCT at WIPAC

- UW group has been heavily involved with the development of the pSCT camera and its commissioning
- Also involved with the upgrade of the pSCT camera to full FOV, validation of new electronics modules

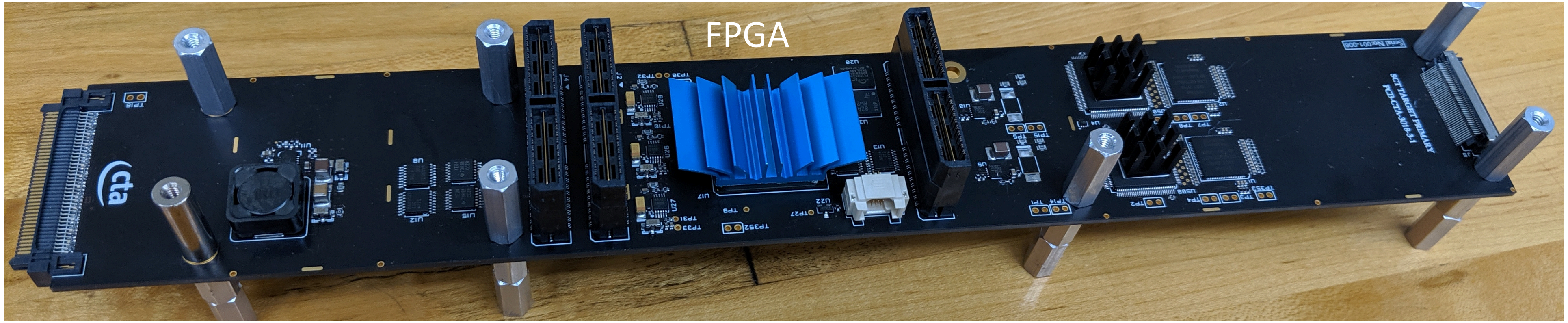




TARGET C Module

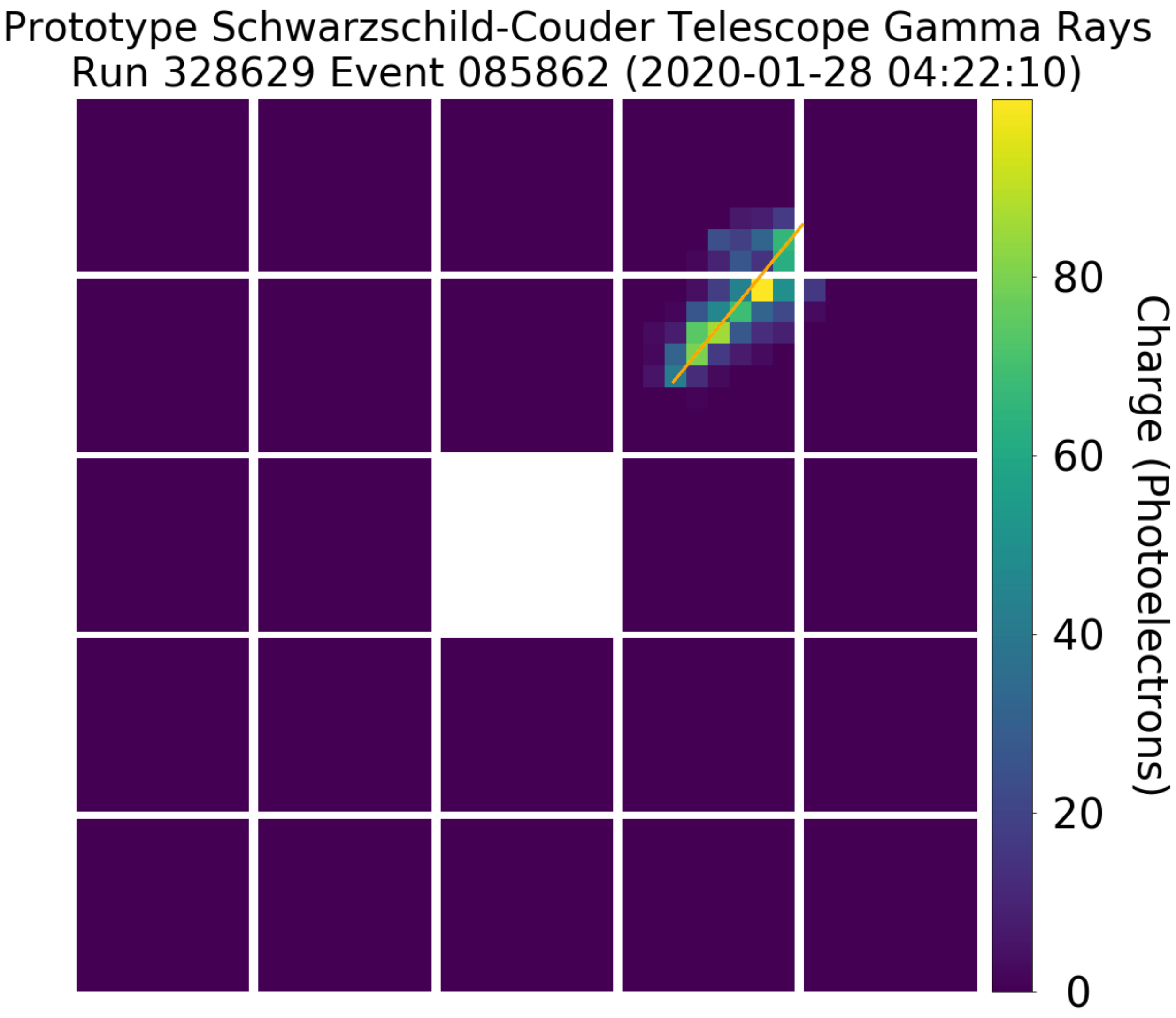


Signal Input

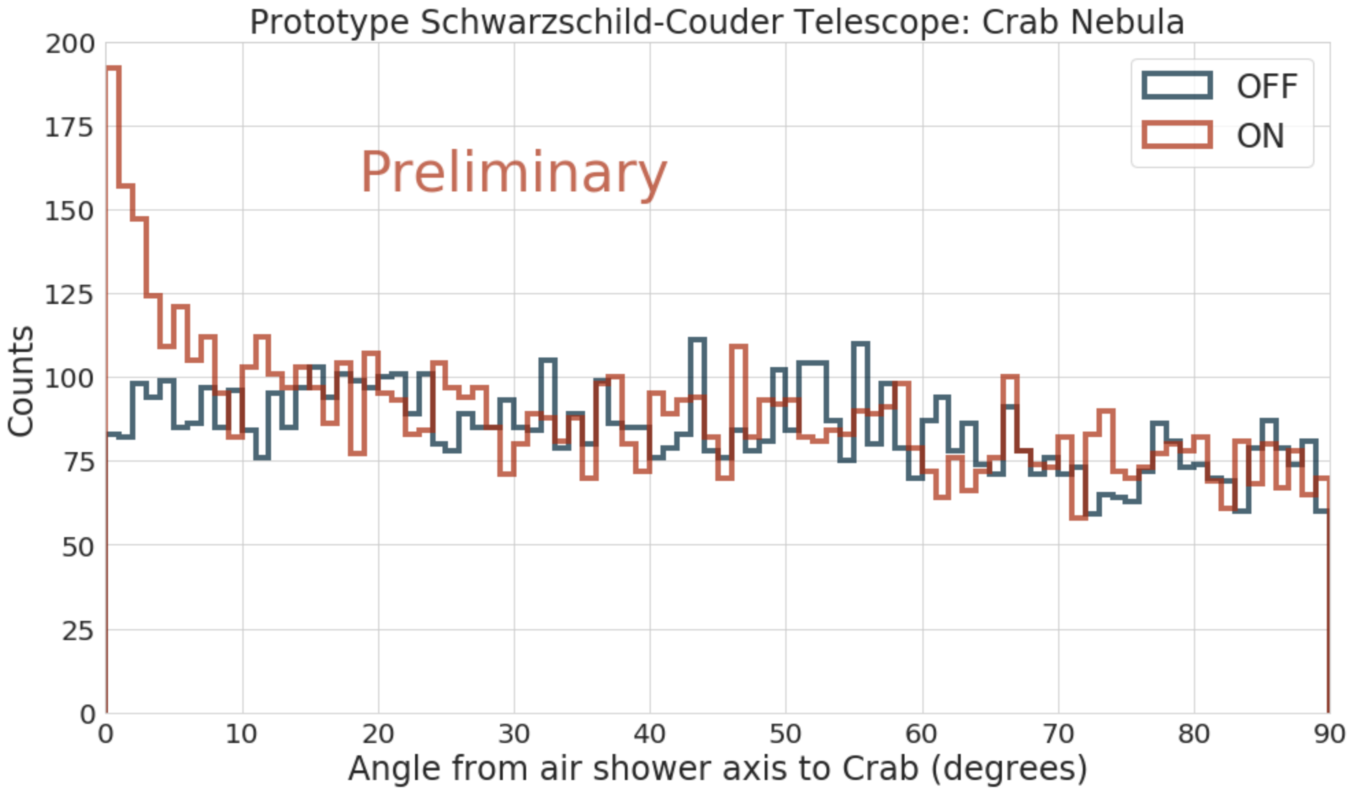


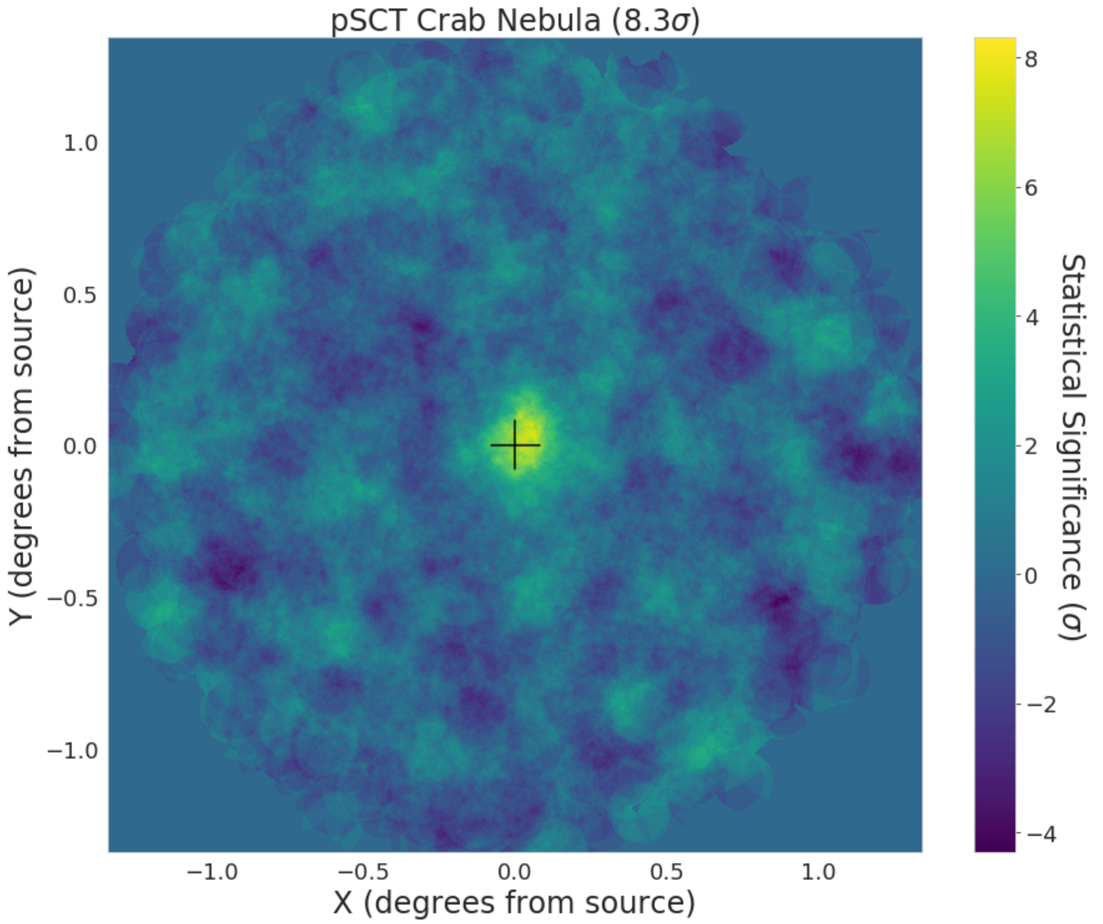
To Backplane

pSCT Images of All 18 Tagged Gamma Rays (after image cleaning)



pSCT Detection of Crab Nebula



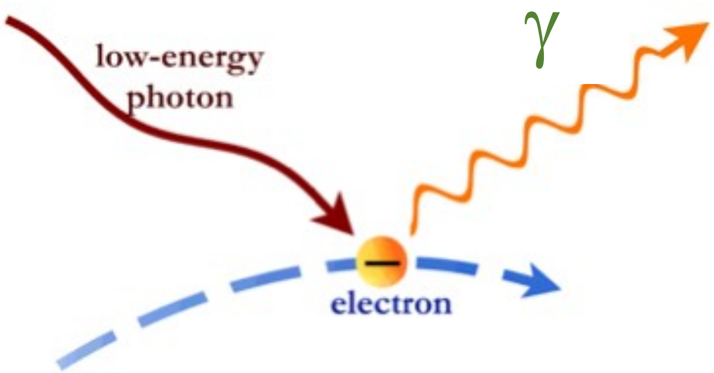


Backup Slides

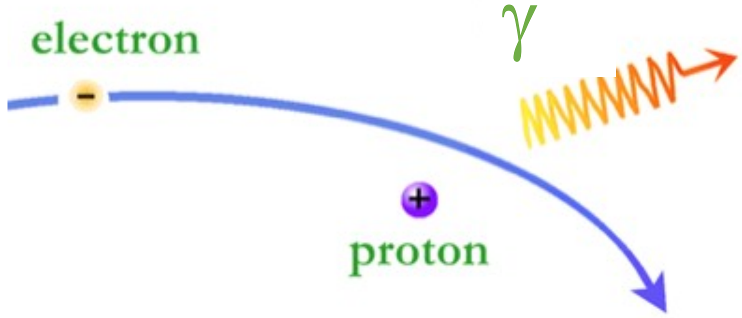
Non-thermal Mechanisms of Gamma Ray Production

- Production of gamma rays in particle physics can occur through a variety of mechanisms
- Each of these processes can create gamma rays in astrophysical sources
- Inverse Compton scattering is a particularly important source of astrophysical gamma rays

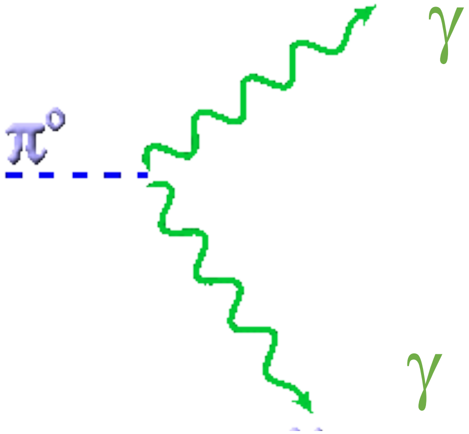
(1) Synchrotron (electromagnetic)



(2) Inverse Compton (electromagnetic)

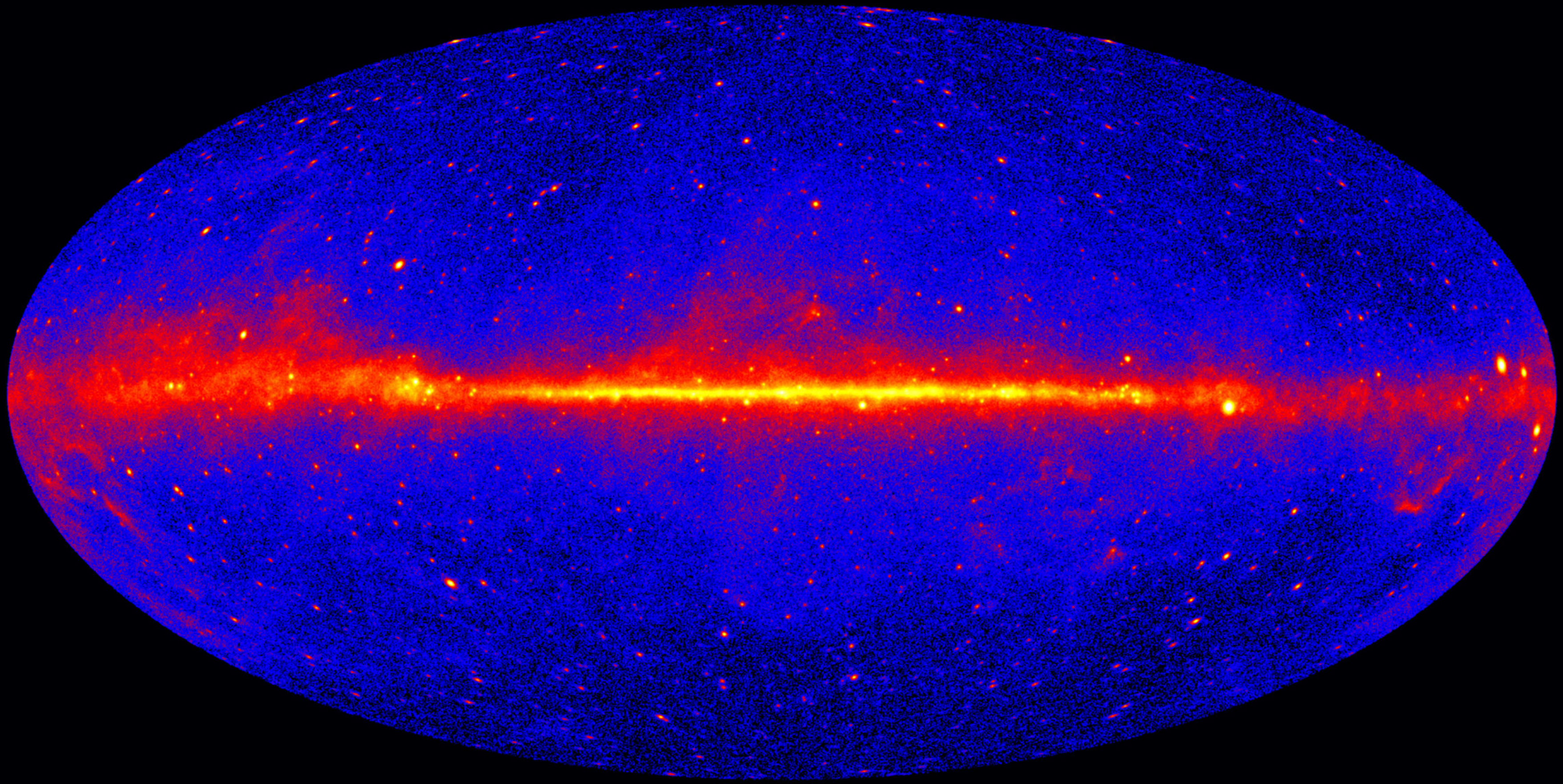


(3) Bremsstrahlung (electromagnetic)



(4) Pion decay (hadronic)

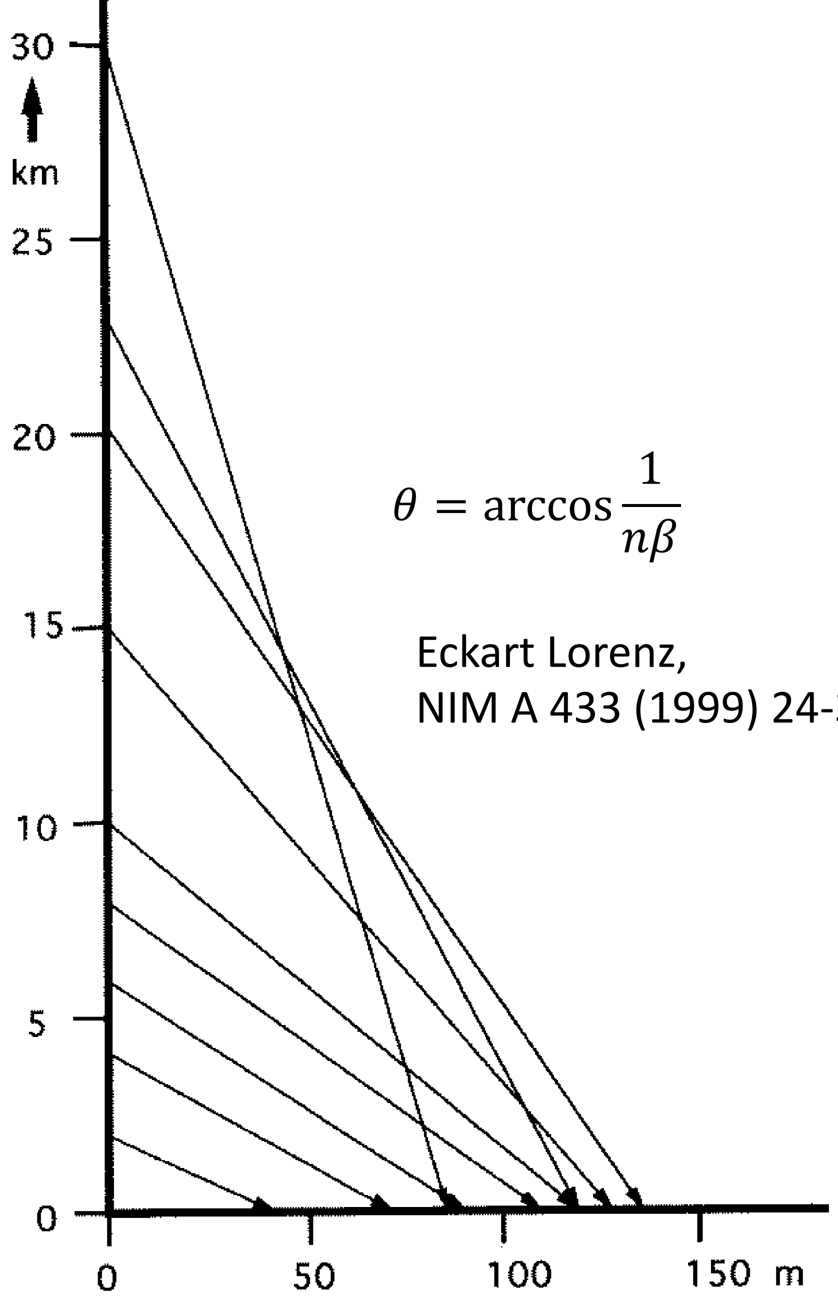
The Universe in >1 GeV Gamma Rays



Fermi Large Area Telescope

Cherenkov Light Pool from Vertical Shower

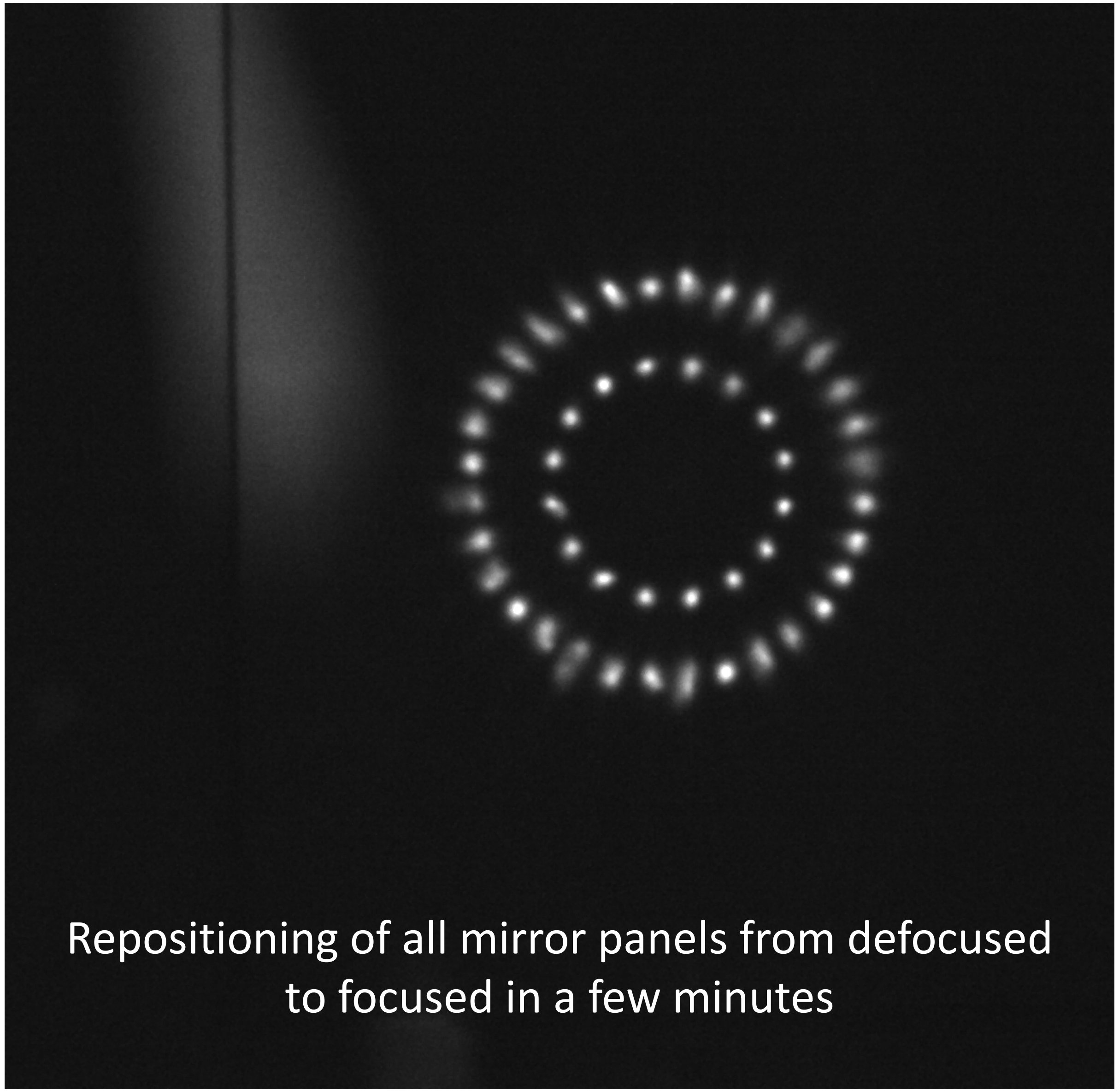
- At high altitude, density is small, index of refraction is close to 1, and Cherenkov angle is small
- Towards ground level, each of these increases
- Light pool of radius ~120-140 m on ground



$$\theta = \arccos \frac{1}{n\beta}$$

Eckart Lorenz,
NIM A 433 (1999) 24-33

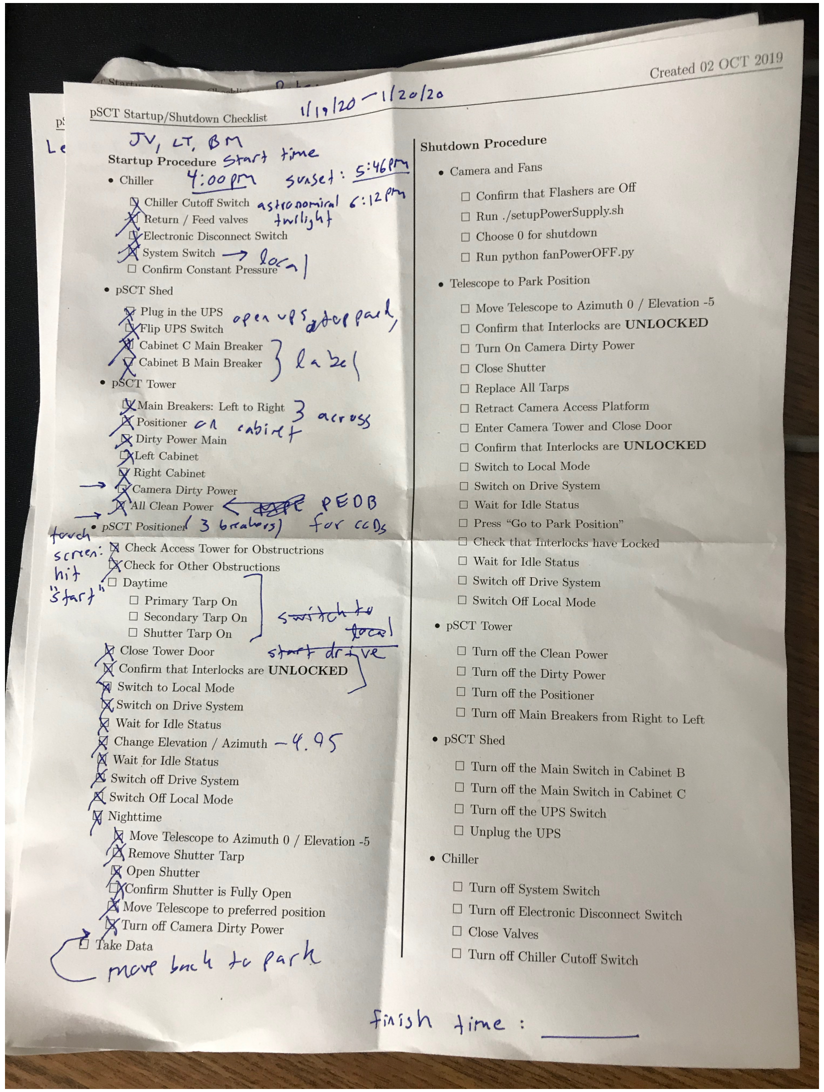
Alignment of Optical System



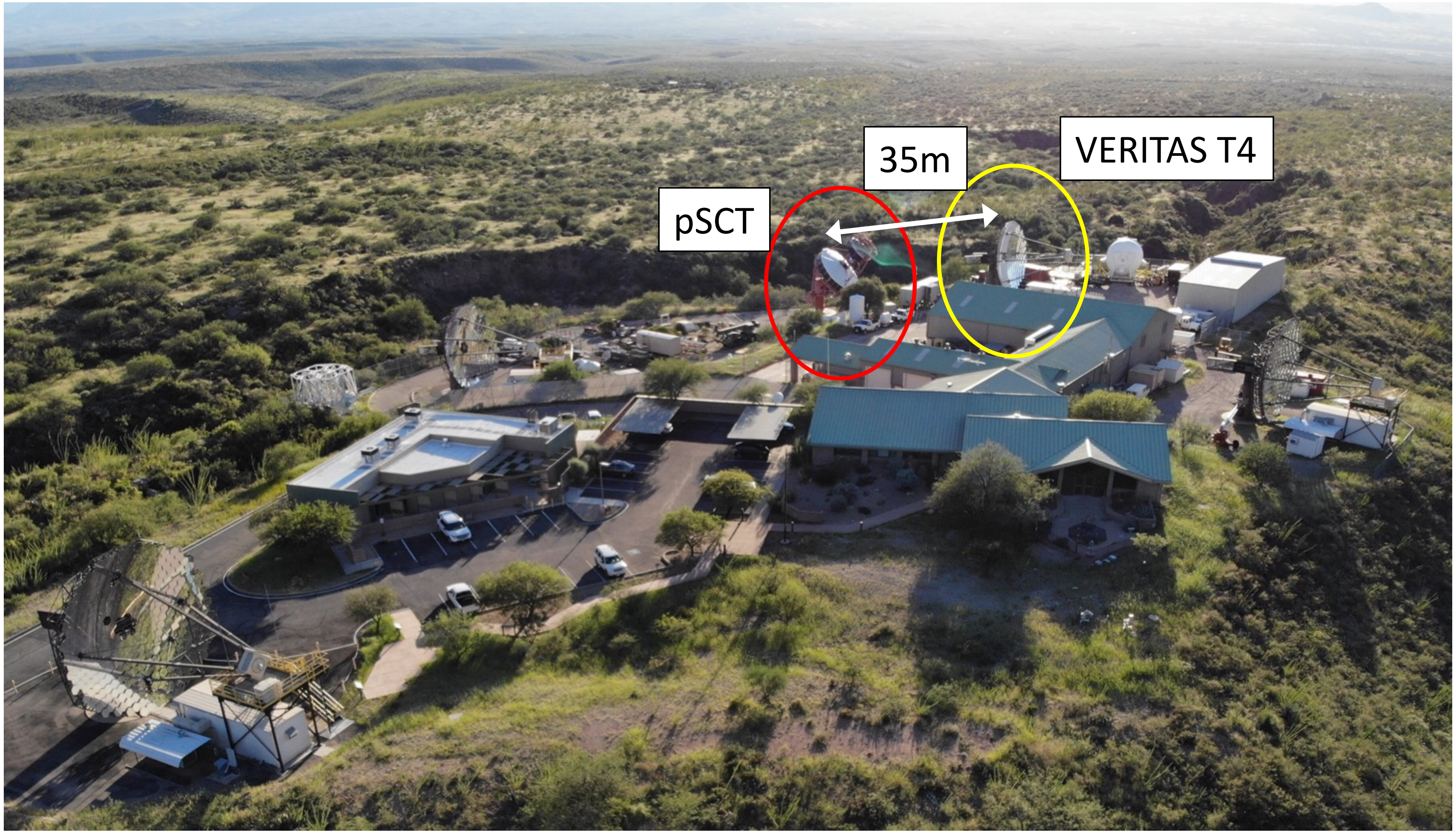
Crab Observations

- The pSCT observed the Crab Nebula from 18 January – 26 February 2020
- Data taken in ON source and OFF source modes for simple background estimation
- Coincident data taking with VERITAS when possible

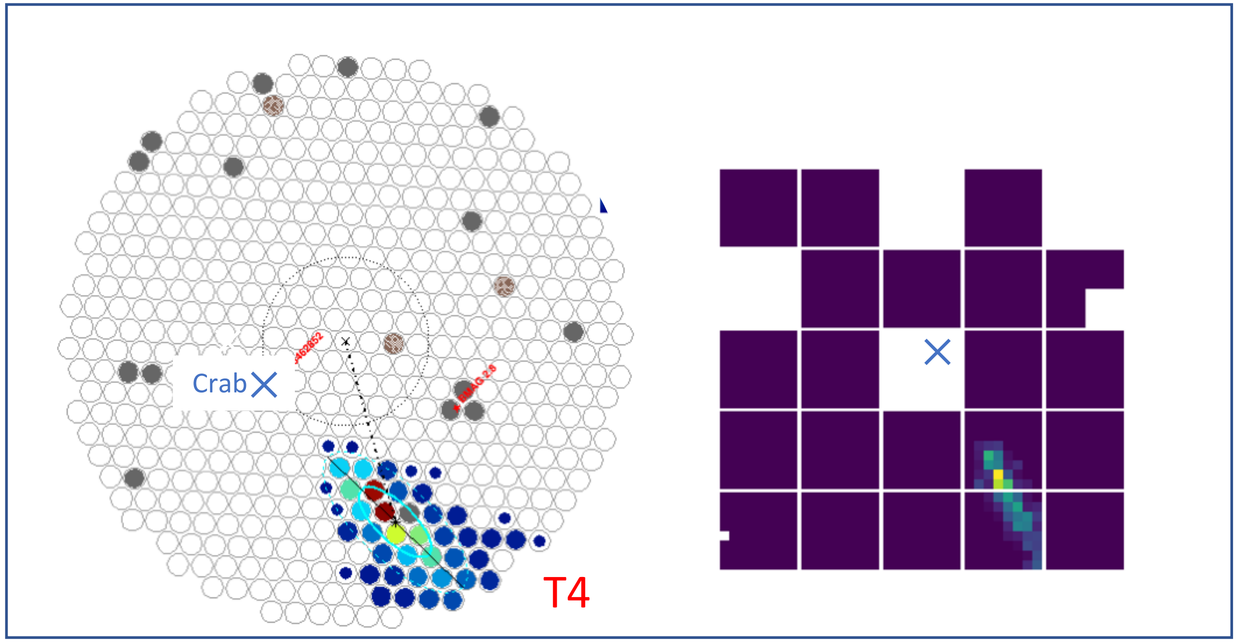
Startup/Shutdown Checklist

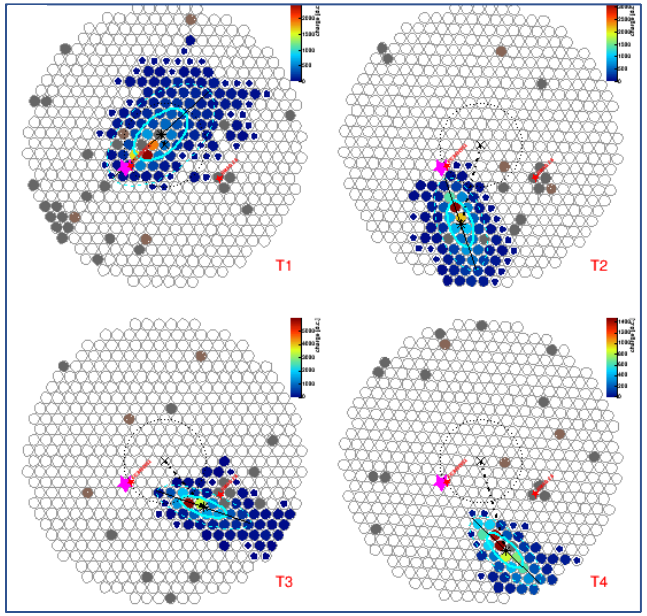


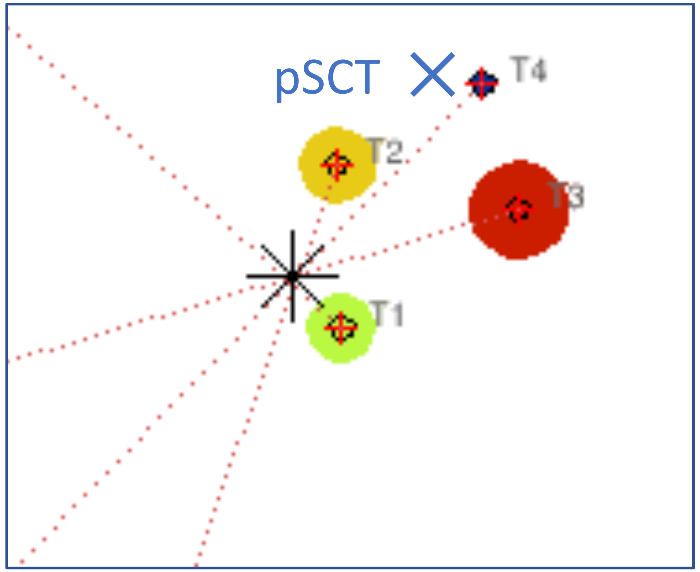
The pSCT is near VERITAS Telescope 4: 2 telescopes can detect the same showers, with similar viewing angle



A 3.5 TeV gamma ray detected by both pSCT and VERITAS

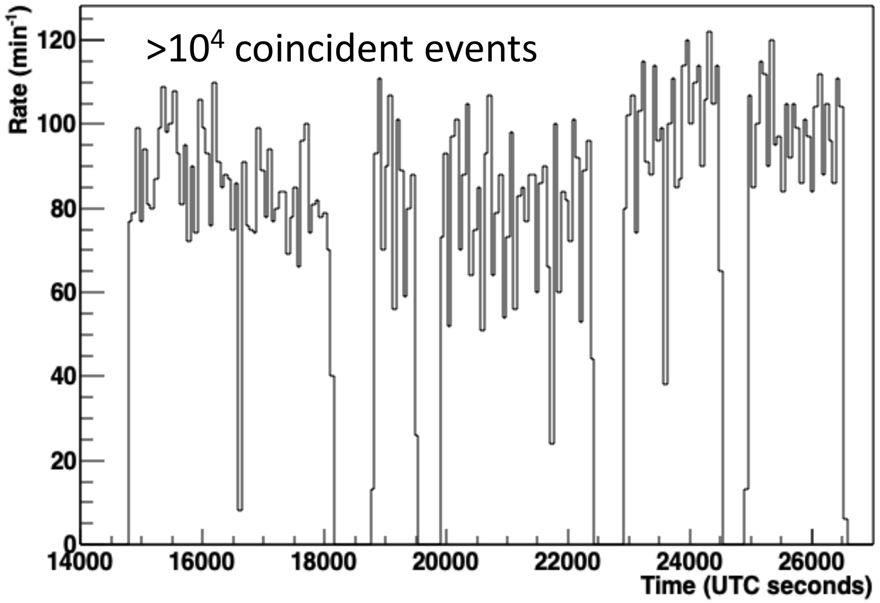






Crab observations: simultaneous observing with VERITAS

Rate of showers detected by both VERITAS and pSCT



- pSCT commissioning and Crab observations January–March 2020
- Simultaneous with VERITAS Crab observations whenever possible
- VERITAS-pSCT shower matching offline: negligible accidental coincidence (<1 μs precision)
- Three-hour joint Crab dataset for developing pSCT cuts with VERITAS-tagged gamma/hadron

Image Cleaning

- Algorithm used in M. Wood et al. (2015) scans a circular aperture over each pixel and identifies image pixels compared to background noise (shown at right)
- This was developed to be a more optimal image cleaning strategy for SiPM-based cameras
- Noise events identified previously are used to find average "noise signal" in each pixel
- Signal is compared to noise signal to clean shower candidate images since it encapsulates pixel-pixel noise differences and is less biased than an empirical flat cutoff value

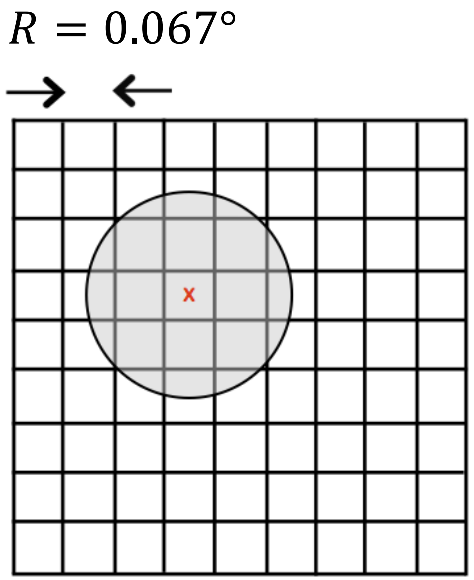
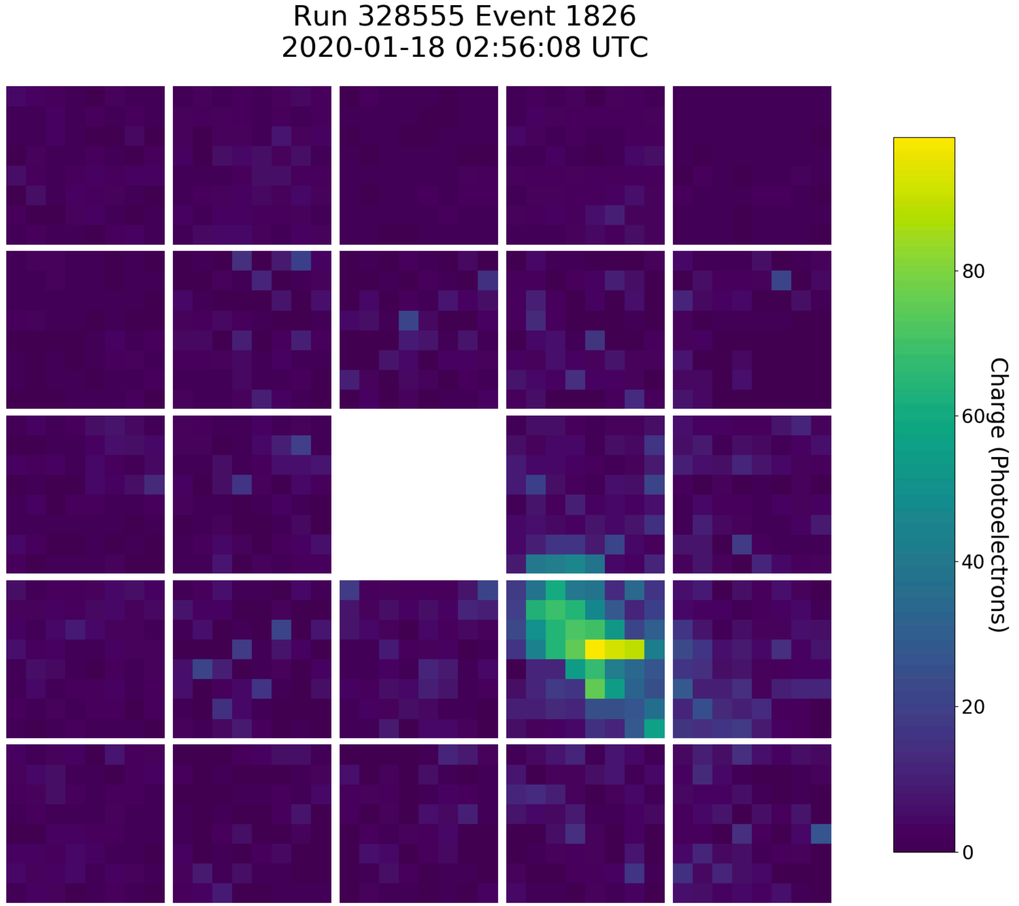


Image Cleaning – Aperture Method

Raw data



Cleaned image