

# Cherenkov Telescope Array

## A New Era in Astrophysics

Brent Mode

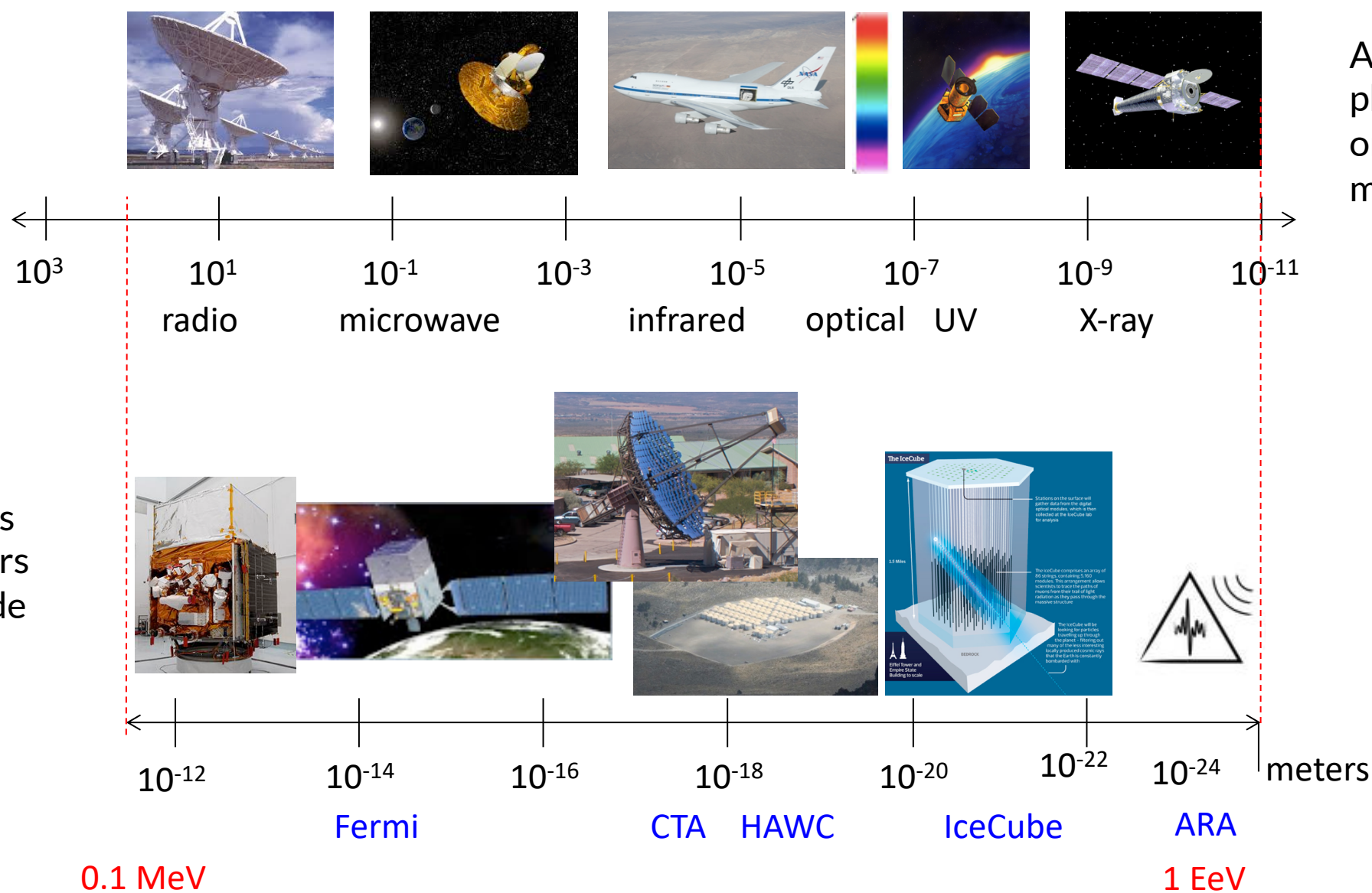
18 June 2020

For the IceCube Bootcamp



# Motivations for TeV Gamma Ray Astronomy

# Astroparticle Physics and Gamma Rays



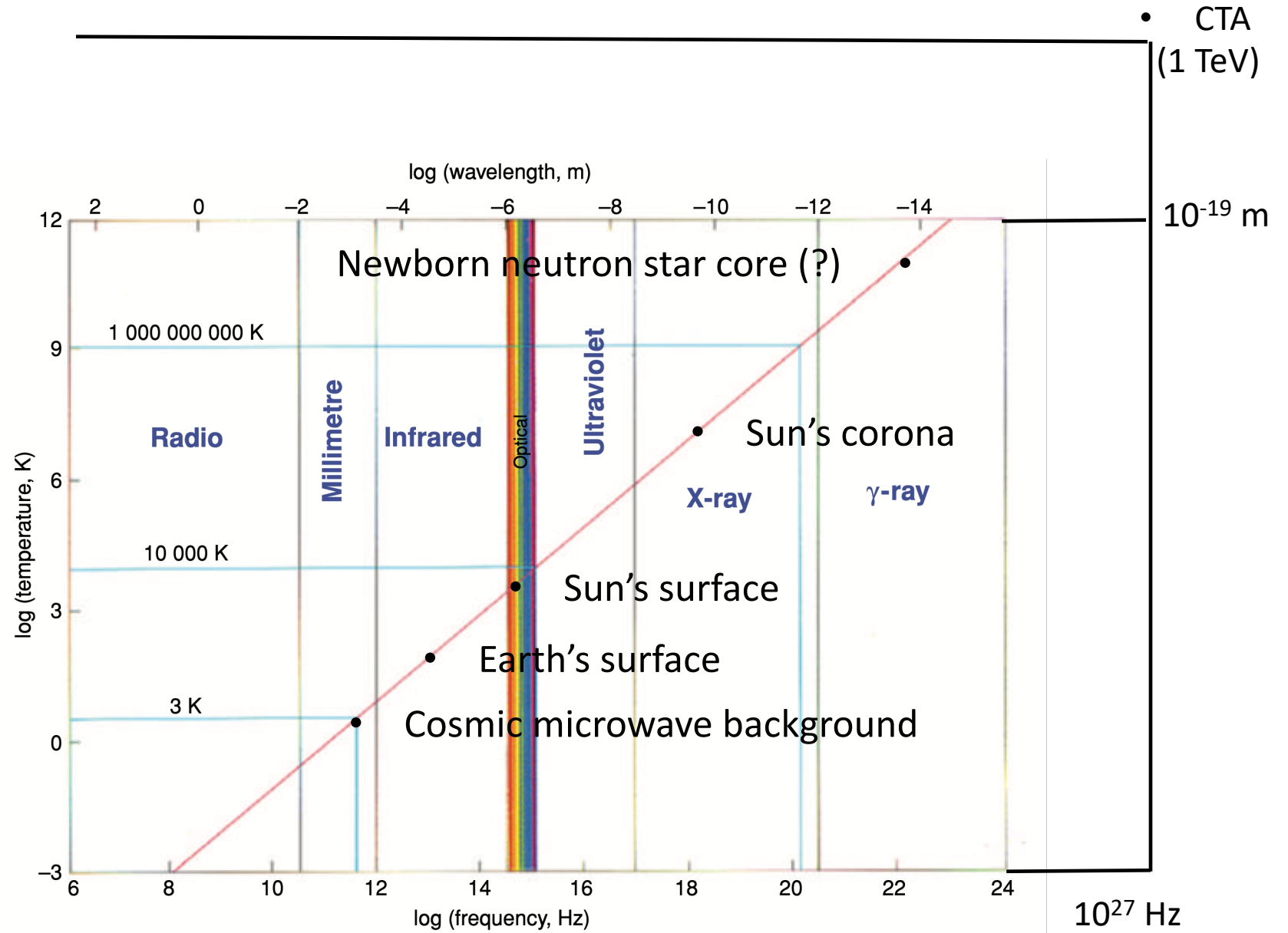
Astroparticle physics over 13 orders of magnitude

Gamma rays over 9 orders of magnitude

# The Thermal v. Non-Thermal Universe

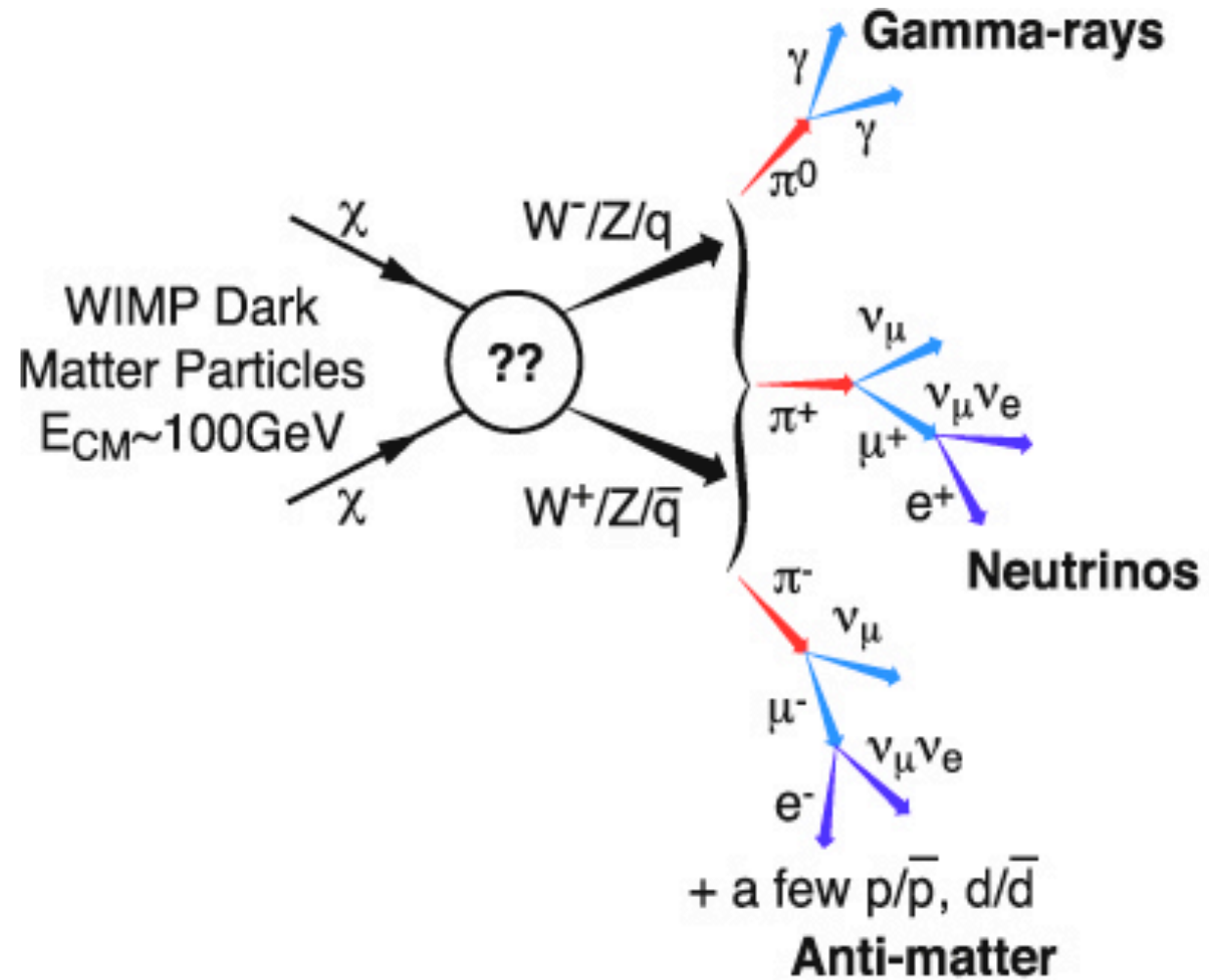
$10^{16}$  K

- 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

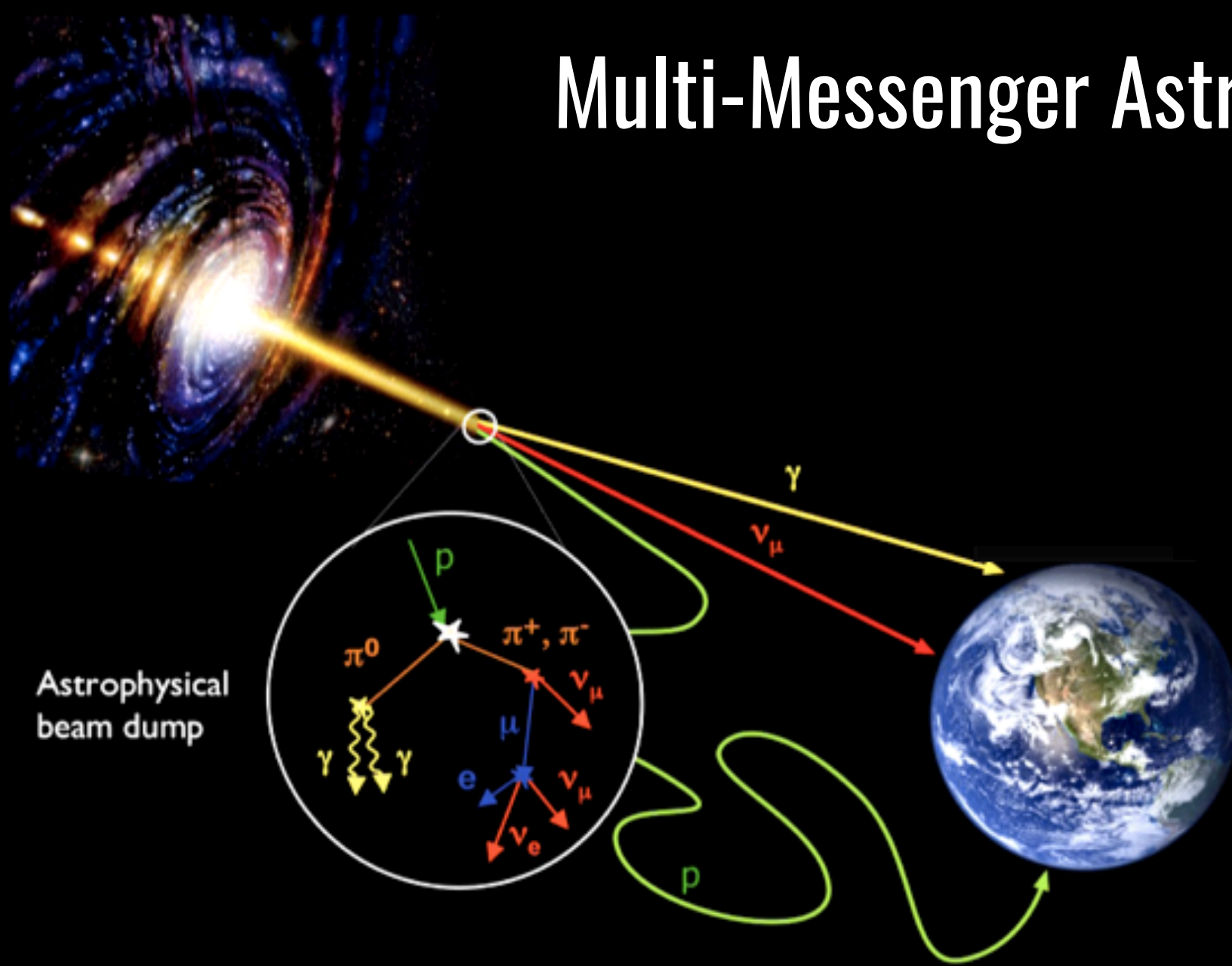


# Possible Gamma Ray Production from Dark Matter

- 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

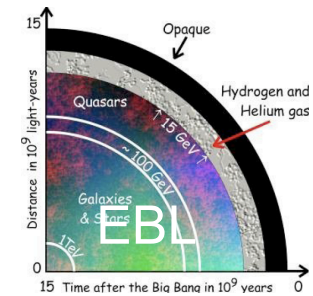
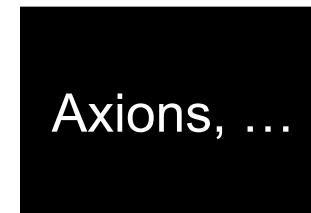
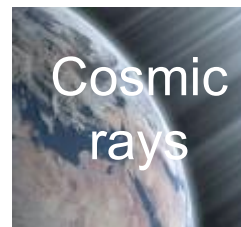
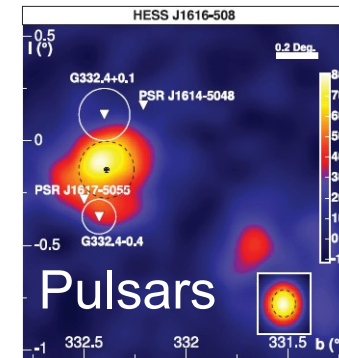
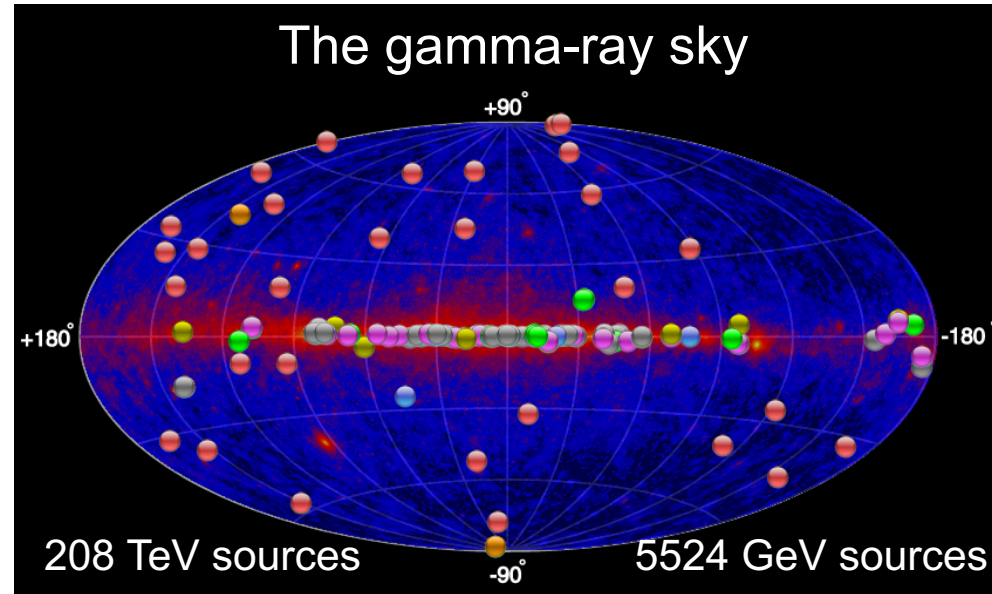
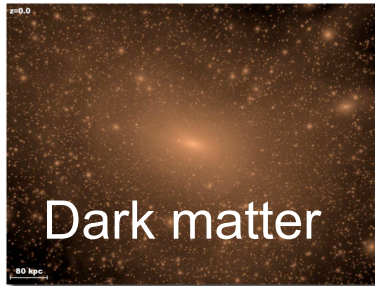
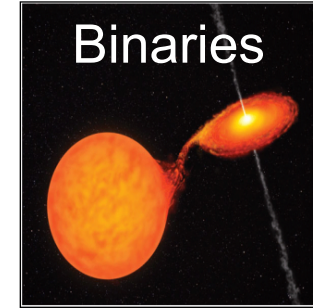
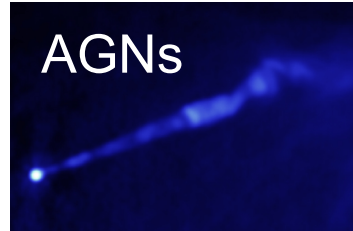
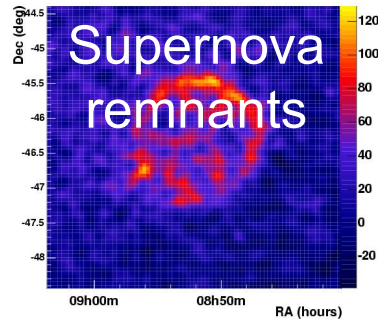


# Multi-Messenger Astronomy



- 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

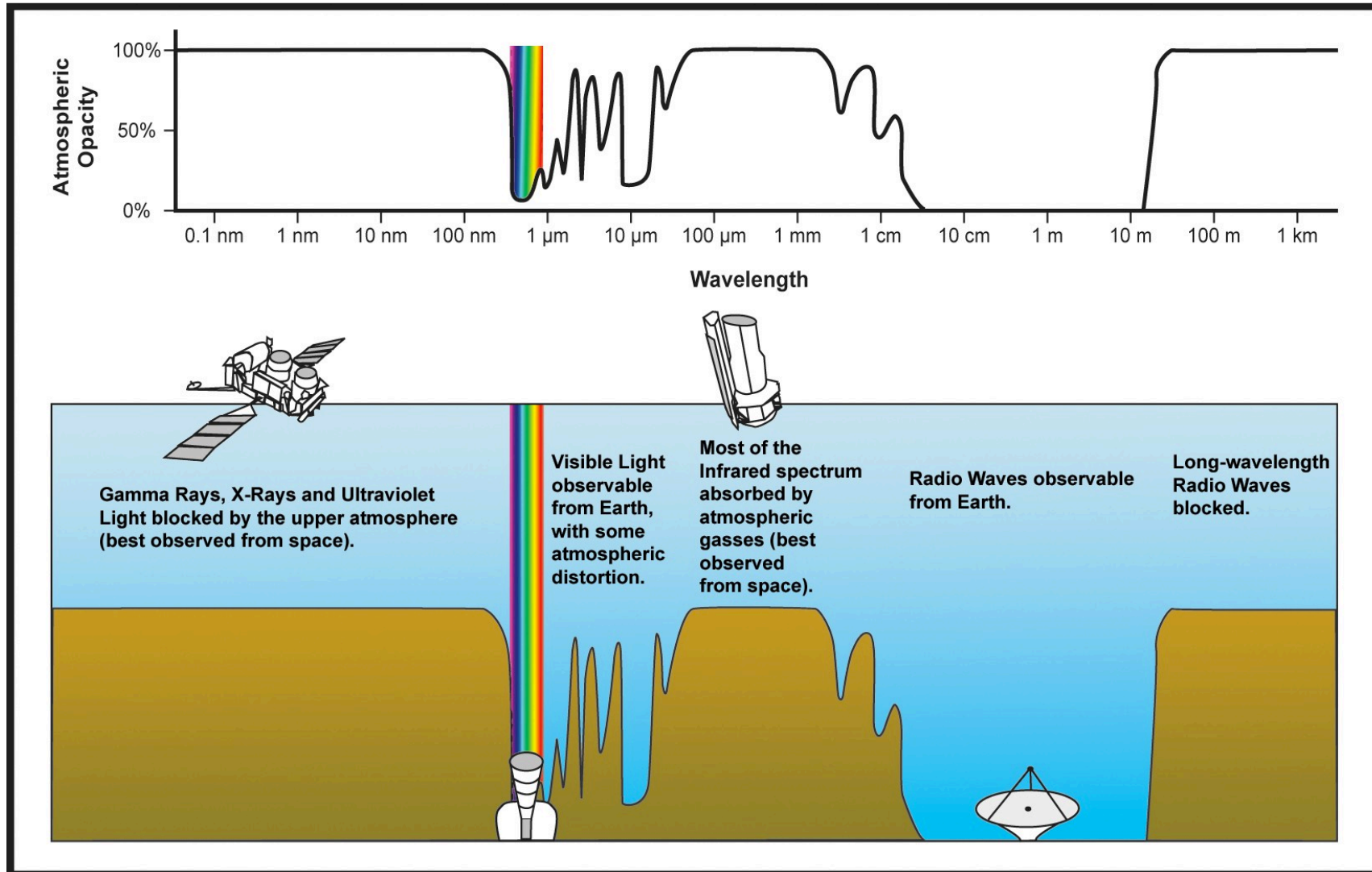


# Imaging Atmospheric Cherenkov Telescopes

A technique for TeV gamma-ray astronomy

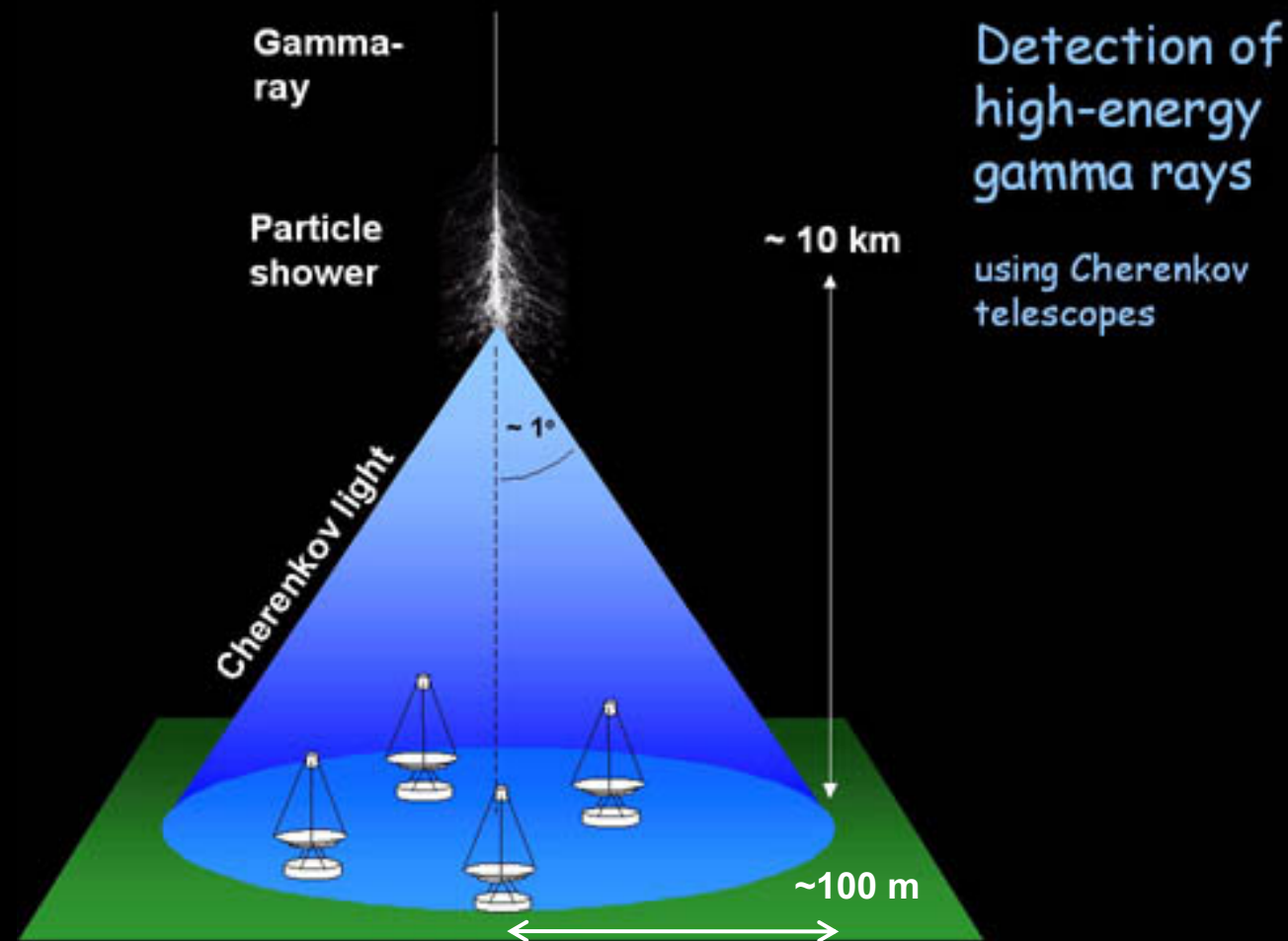


# The Atmosphere is Opaque to Gamma Rays



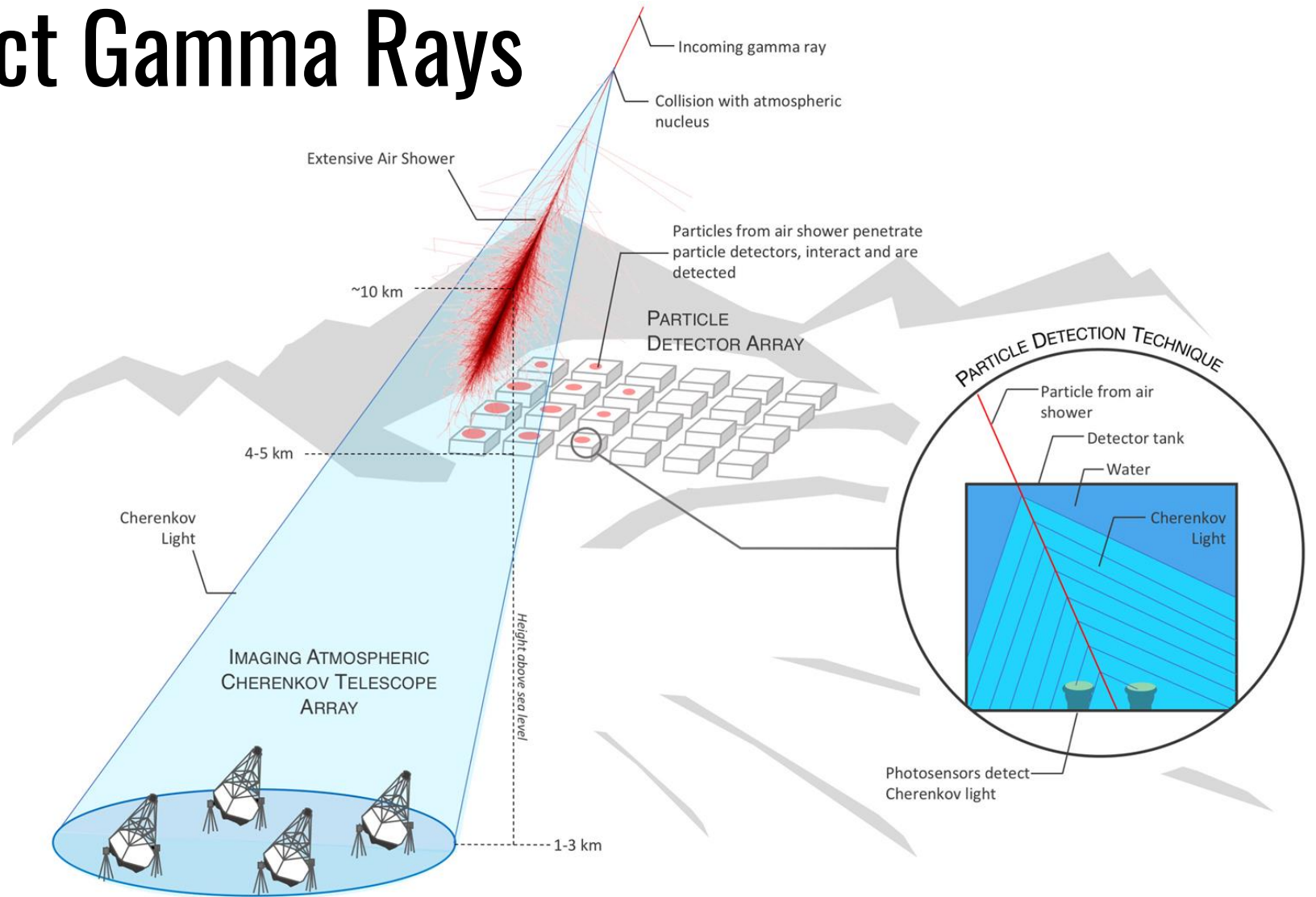
# Atmospheric Cherenkov Radiation

- Optical frequency (blue) light
- Very short (few ns) exposure to limit night sky background
- Cherenkov cone very narrow,  $\sim 1^\circ$ :
- $\theta = \arccos \frac{1}{n\beta}$
- 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

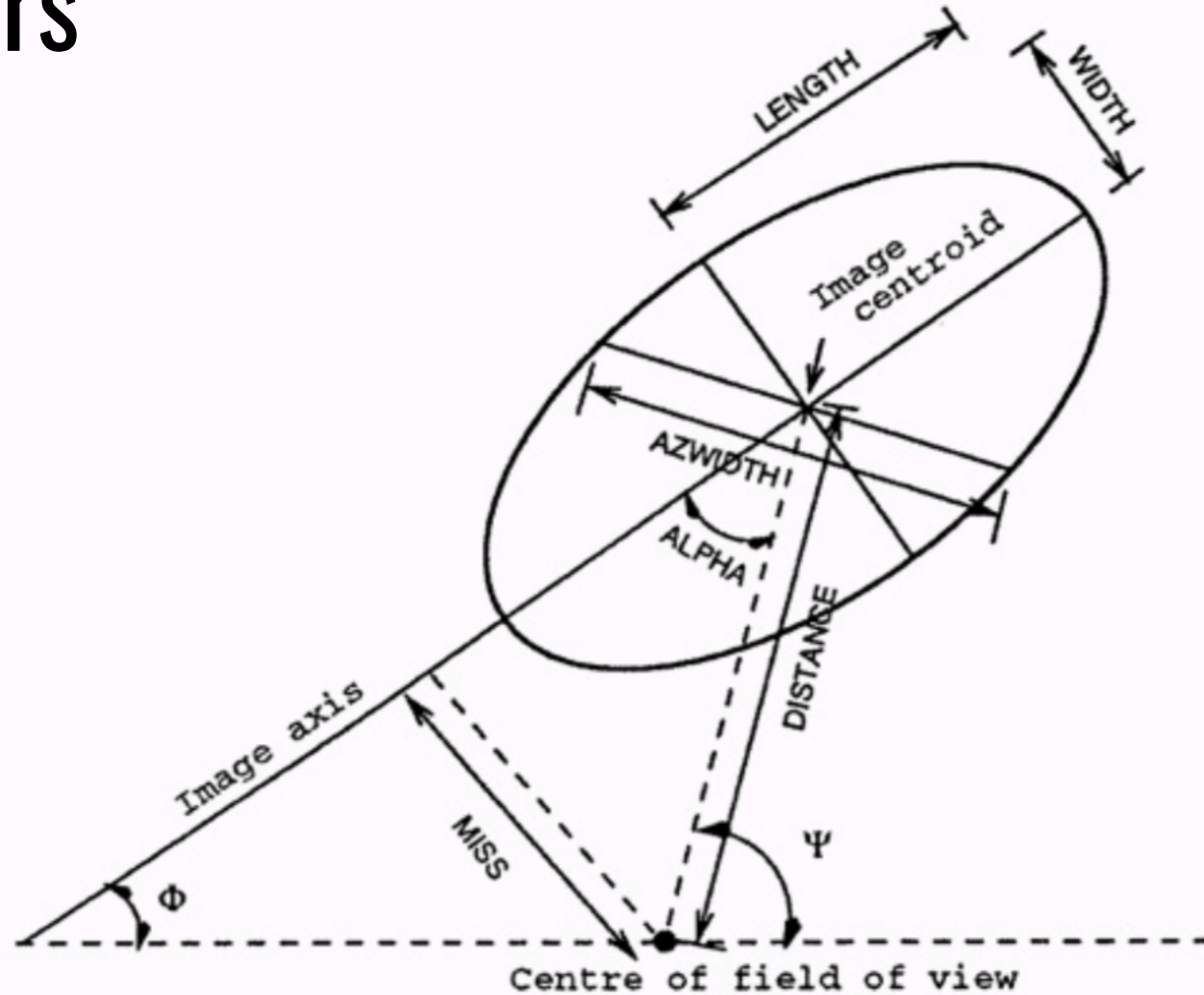


Shower image, 100 GeV  $\gamma$ -ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, <https://www-zeuthen.desy.de/~jknapp/js/showerimages.html>

Not to scale

# 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)

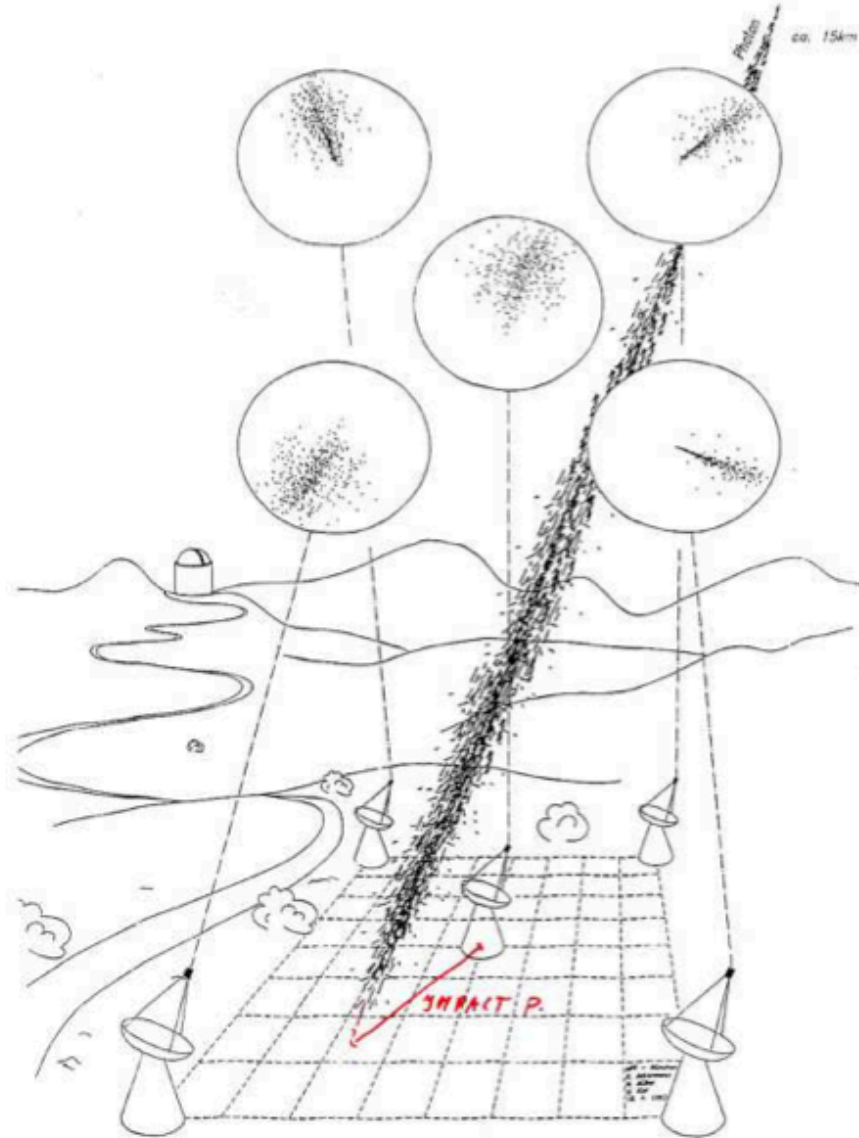


# First IACT: Whipple 10 m Telescope at FLWO



- 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



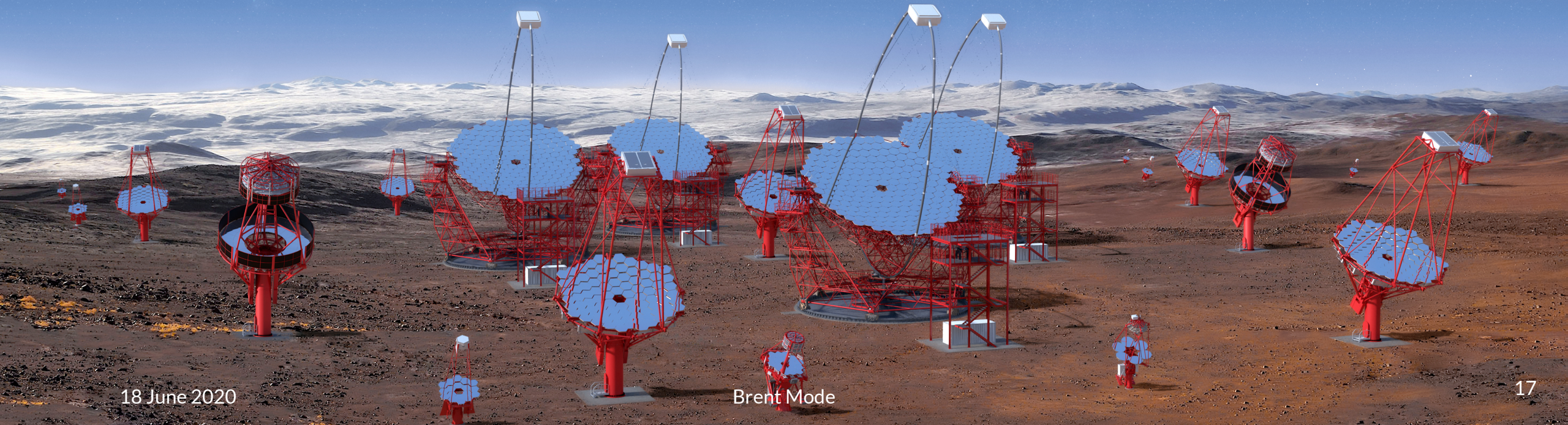
H.E.S.S.



VERITAS



# The Cherenkov Telescope Array



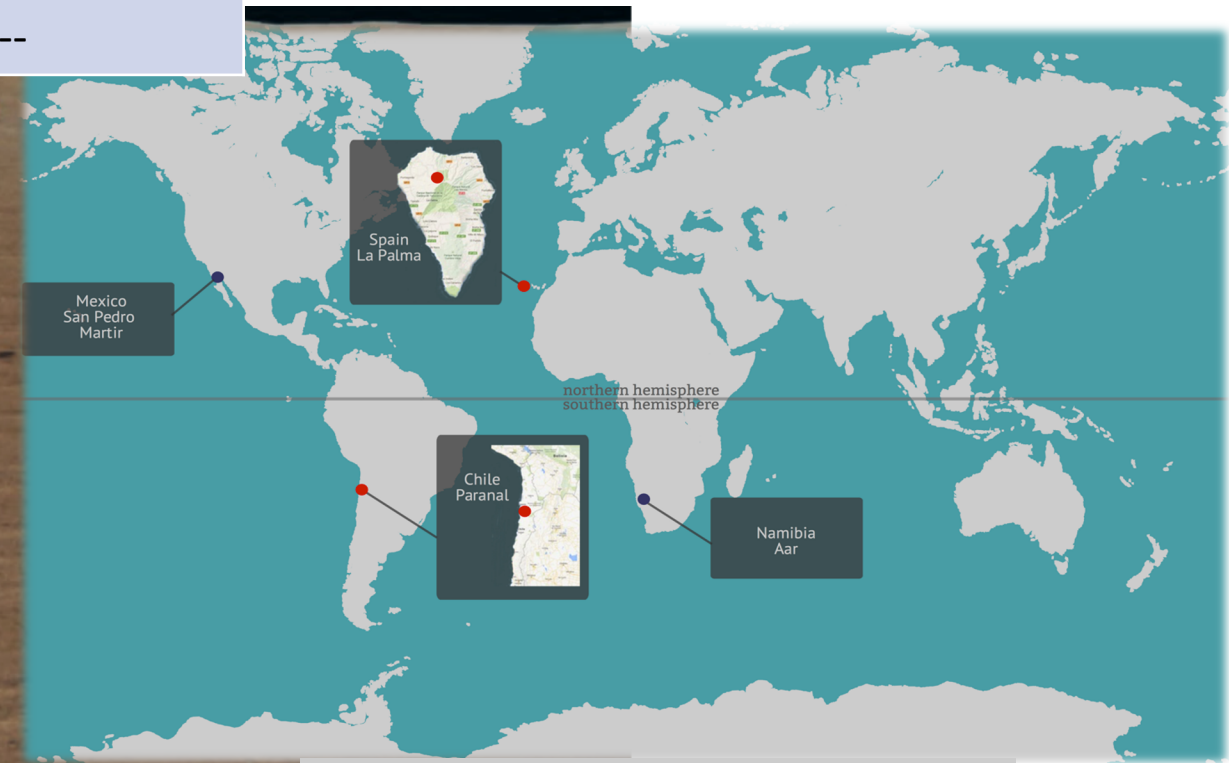
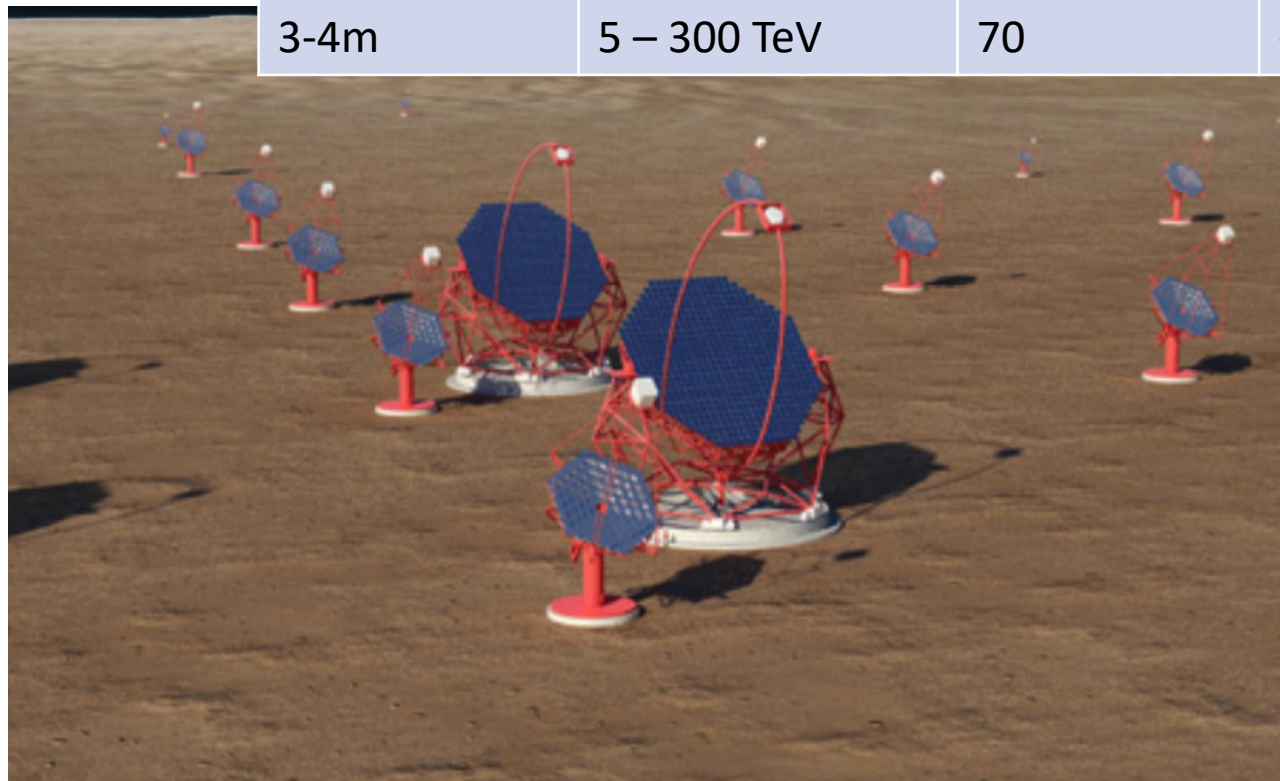
18 June 2020

Brent Mode

# Cherenkov Telescope Array

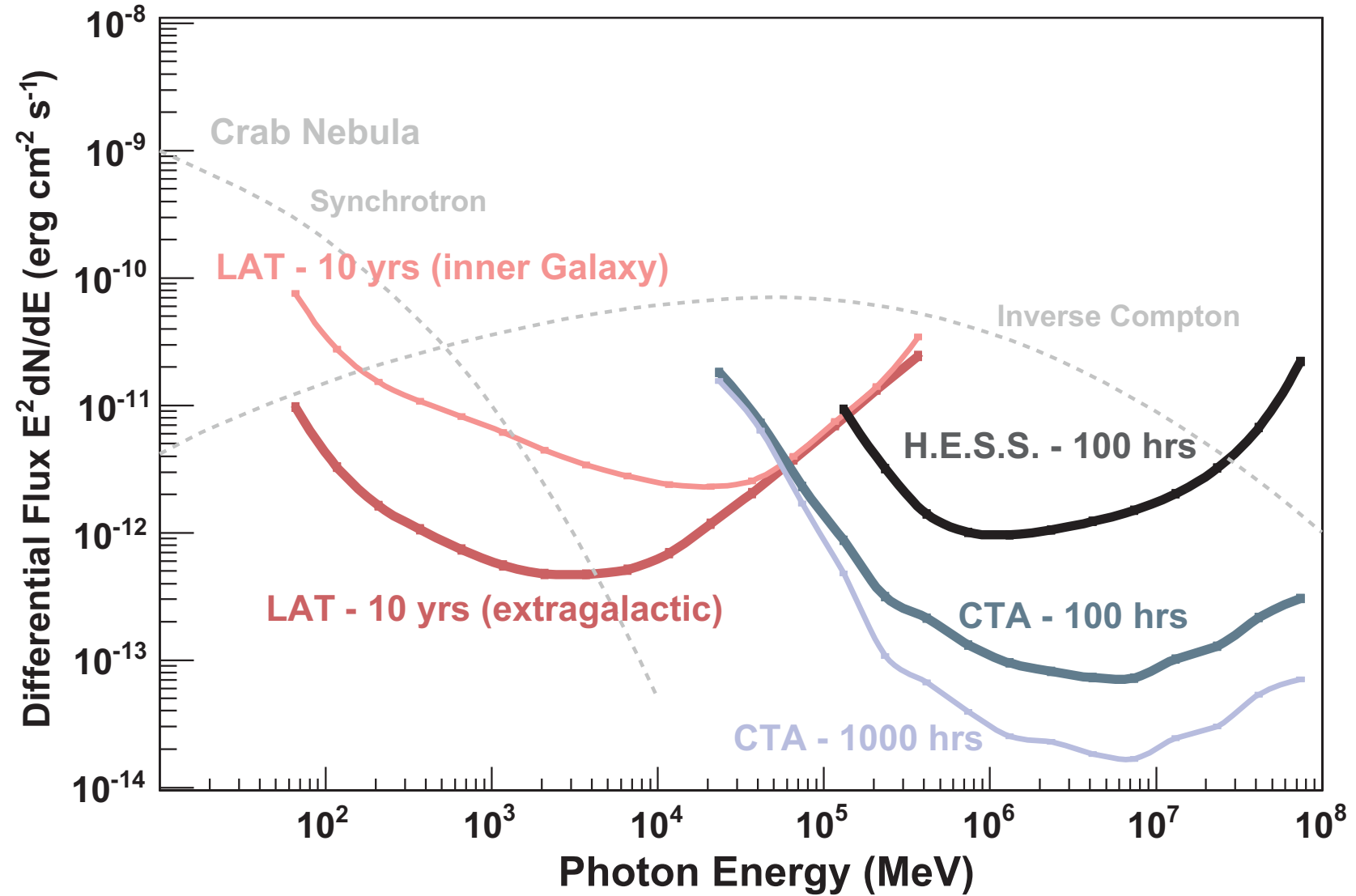
Telescope size	Energy range	South array	North array
23m	20GeV – 1 TeV	4	4
9-12m	100Gev – 10TeV	25	15
3-4m	5 – 300 TeV	70	---

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

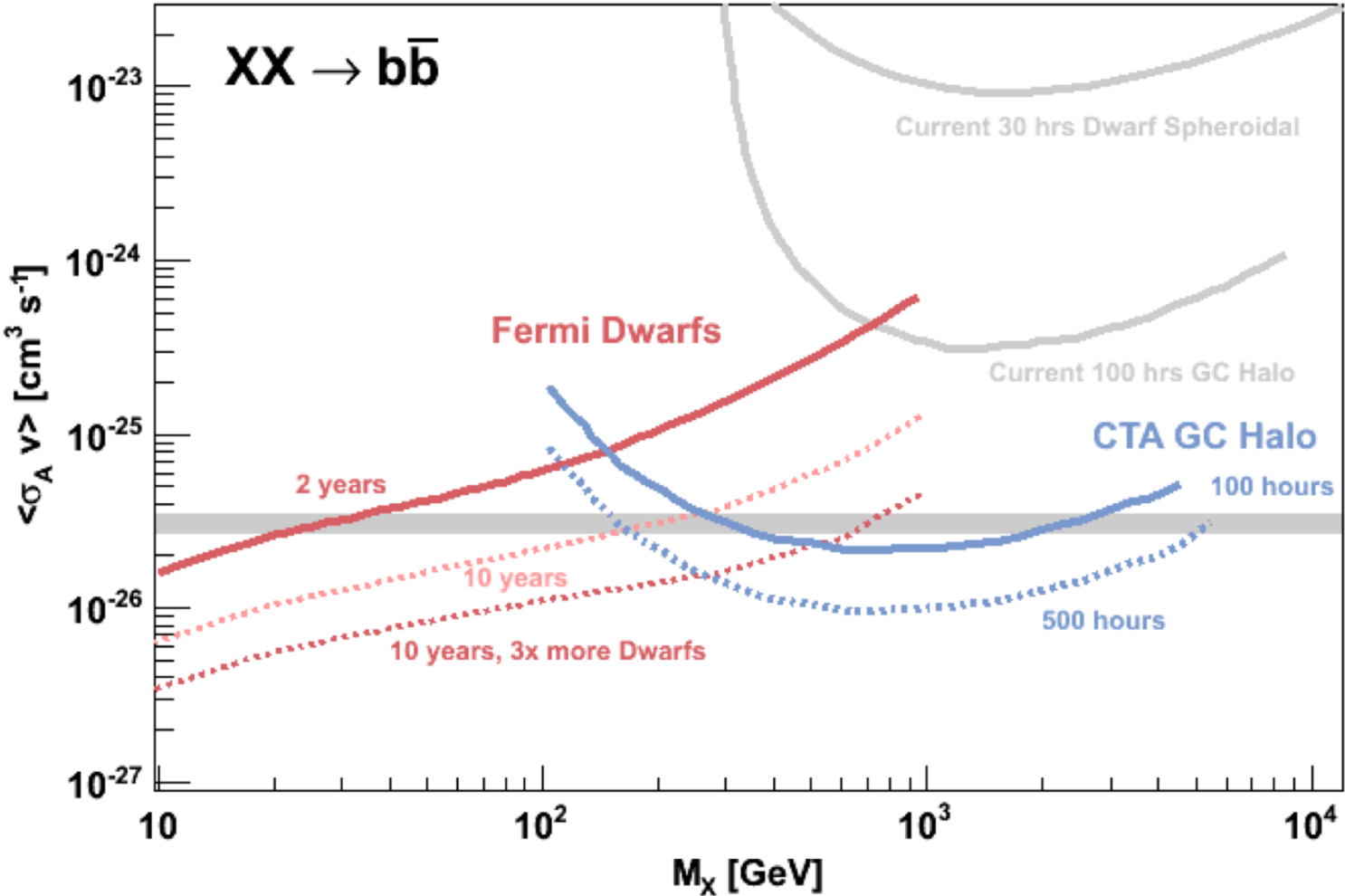


● Under Negotiation ● Back-up Sites

# CTA v. Fermi LAT

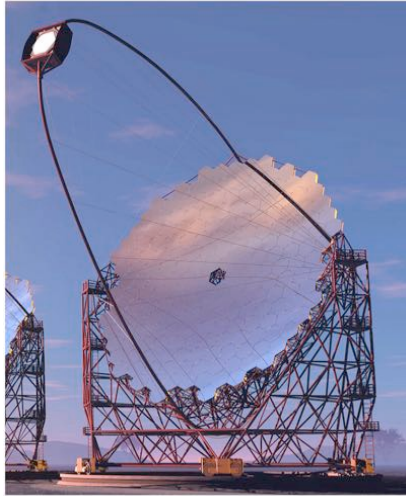


# Fermi Dwarfs and CTA GC Will Cover Entire Mass Range Down to Thermal Cross Section



# CTA Telescopes and Prototype Locations

Large, Canary Islands



LST

Small:

Medium (1 mirror), Germany



MST

2 mirror, Sicily



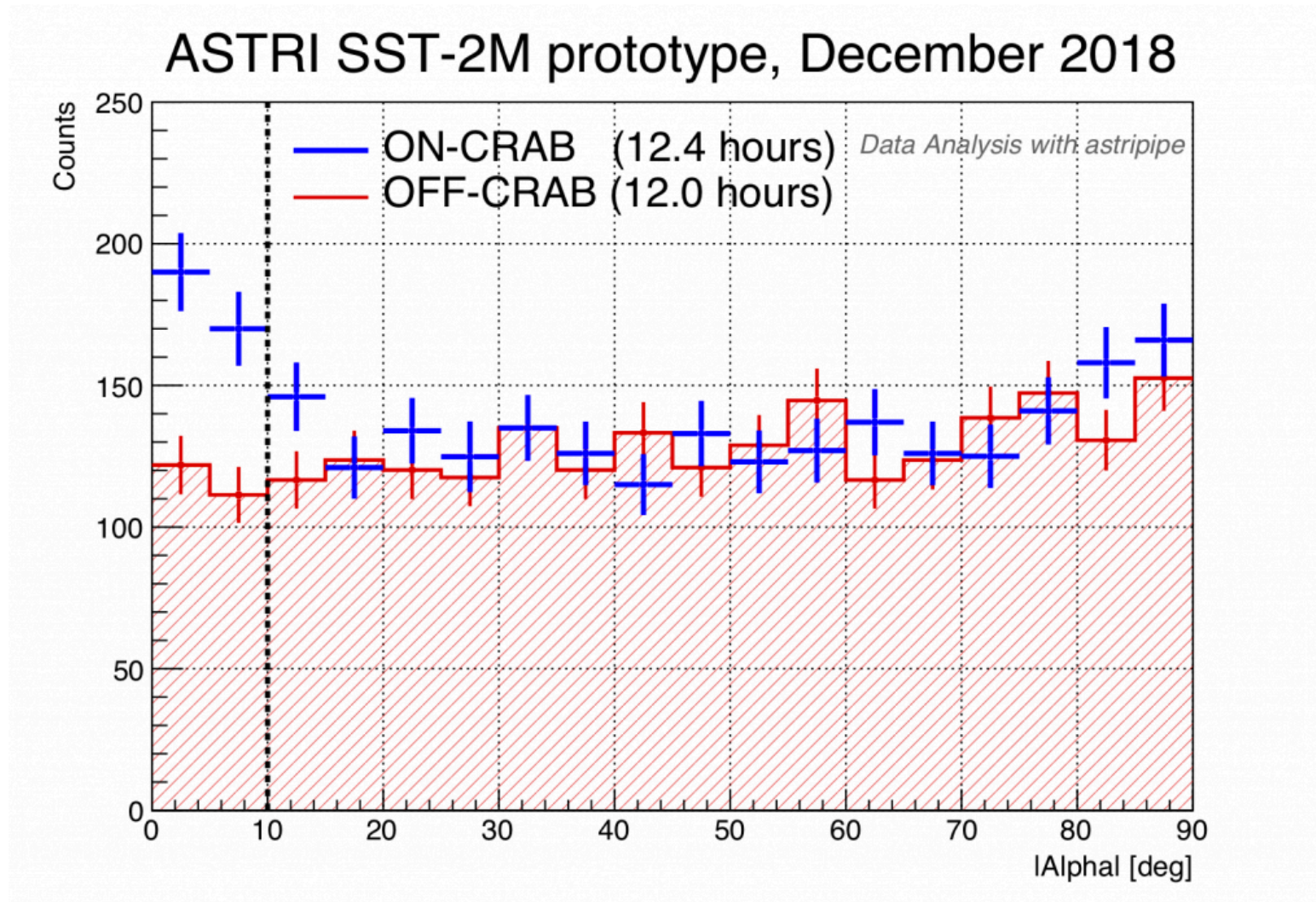
SST

Medium (2 mirror), Arizona

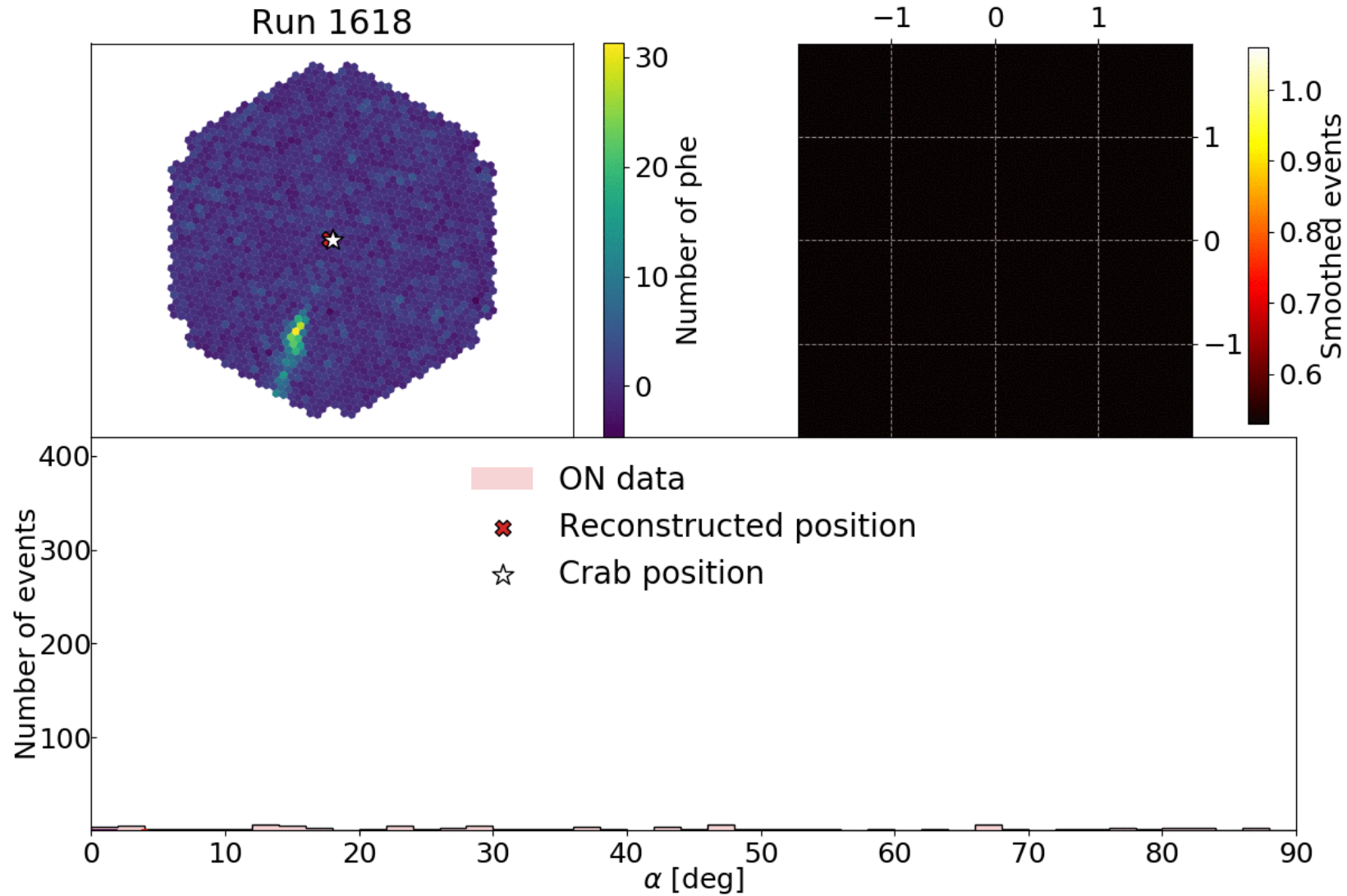


SCT

# SST Prototype Detects Crab Nebula



# LST Prototype Detects Crab Nebula



# CTA @ WIPAC: Commissioning the pSCT



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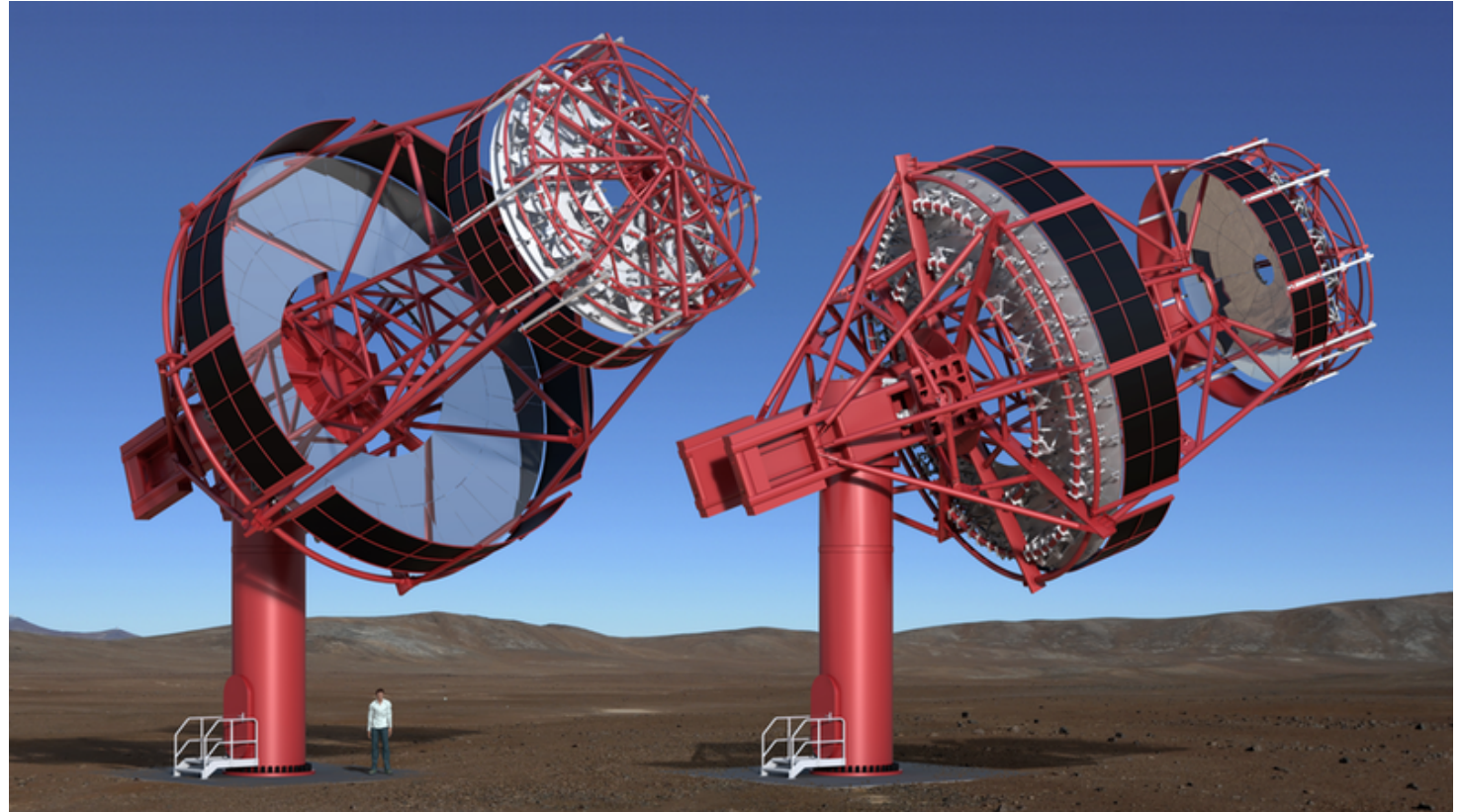
Brent Mode

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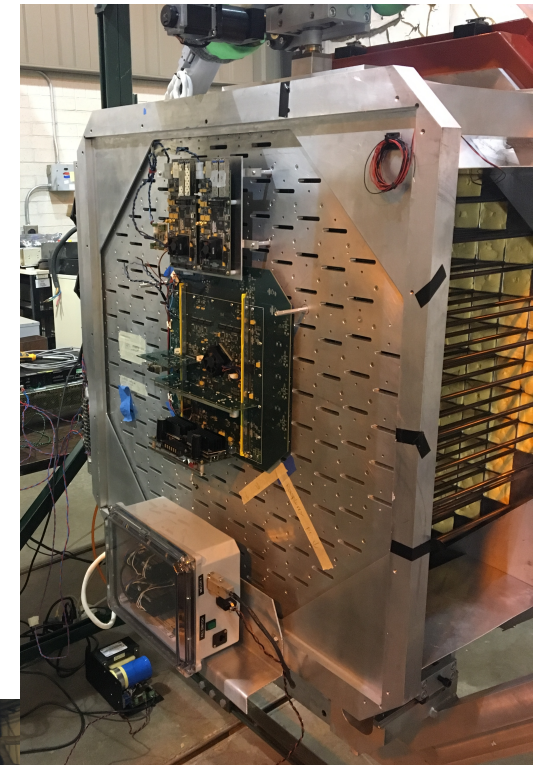
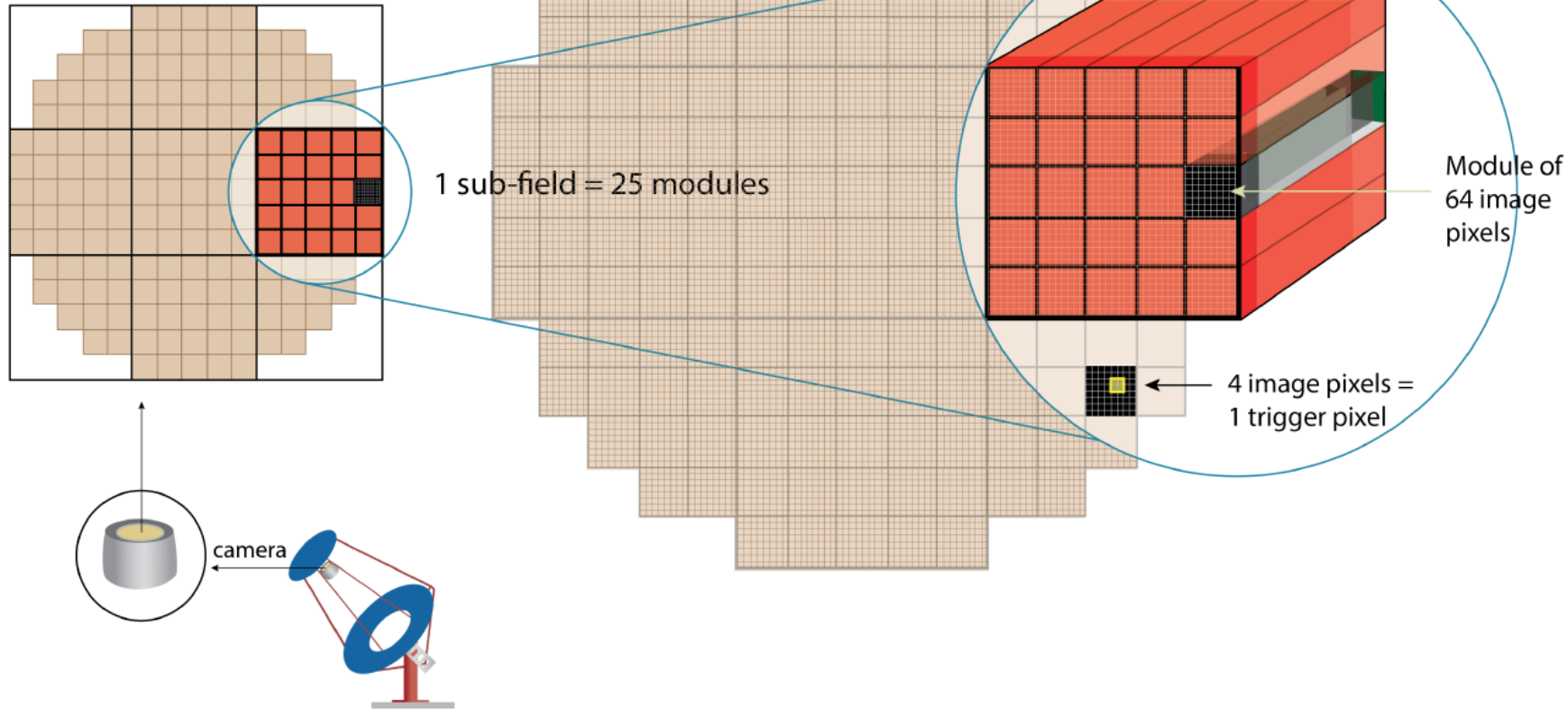
# pSCT: Prototype Schwarzschild-Couder Telescope

- **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



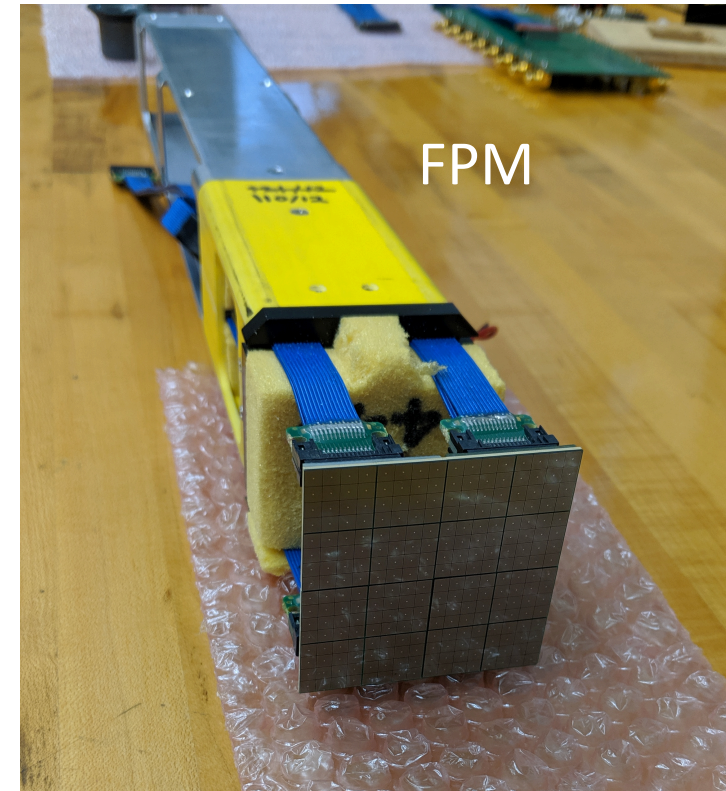
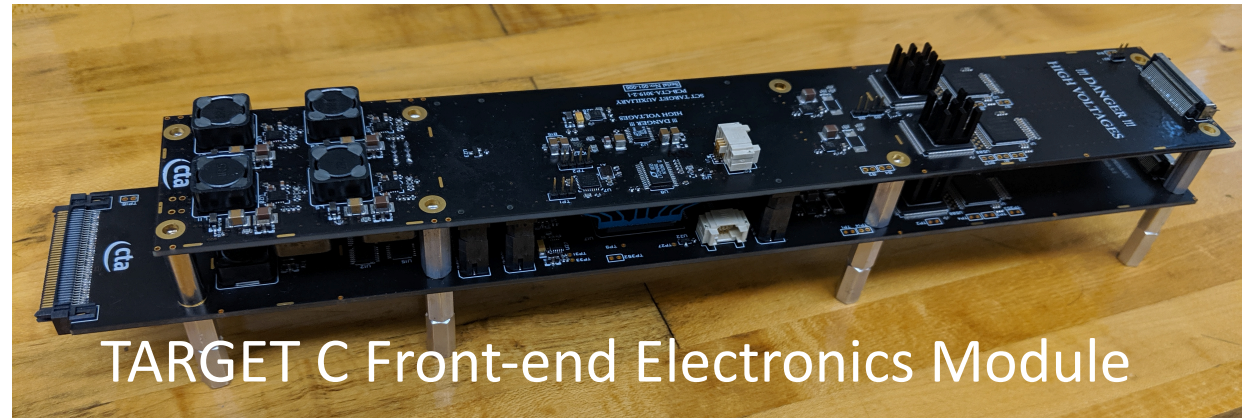
# pSCT Camera Organization

Full camera = 9 sub-fields  
177 modules  
11,328 image pixels

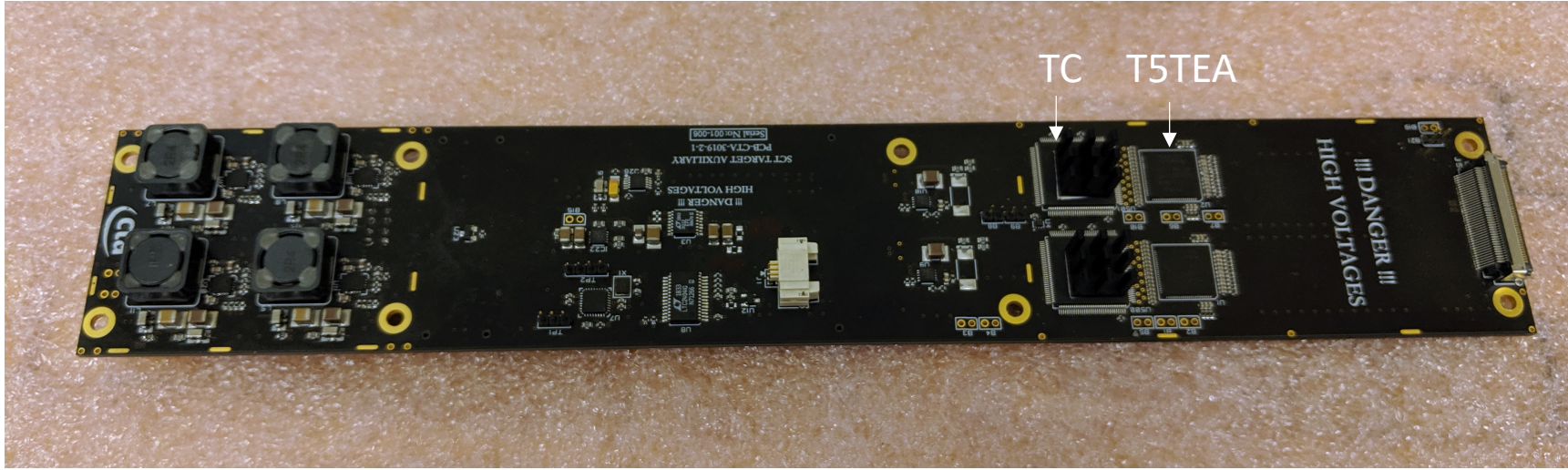


# pSCT at WIPAC

- 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

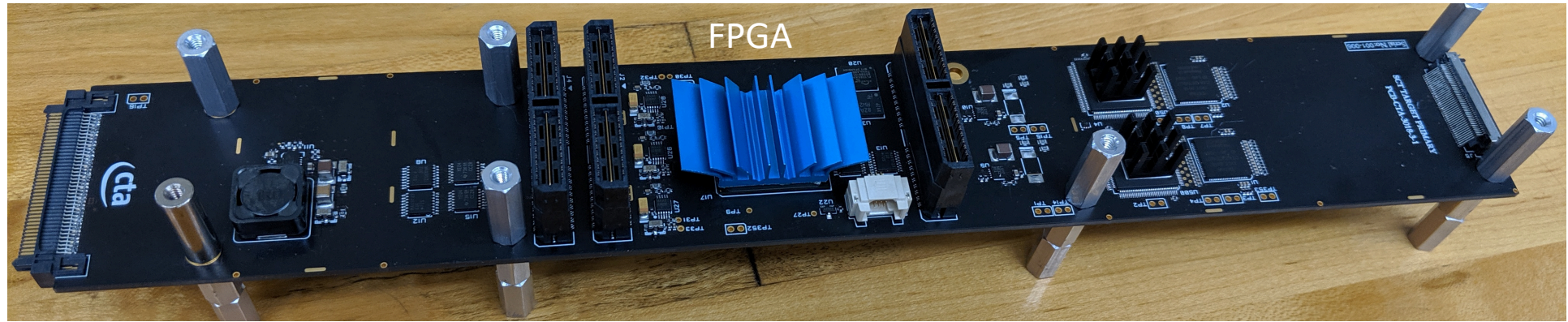


# TARGET C Module



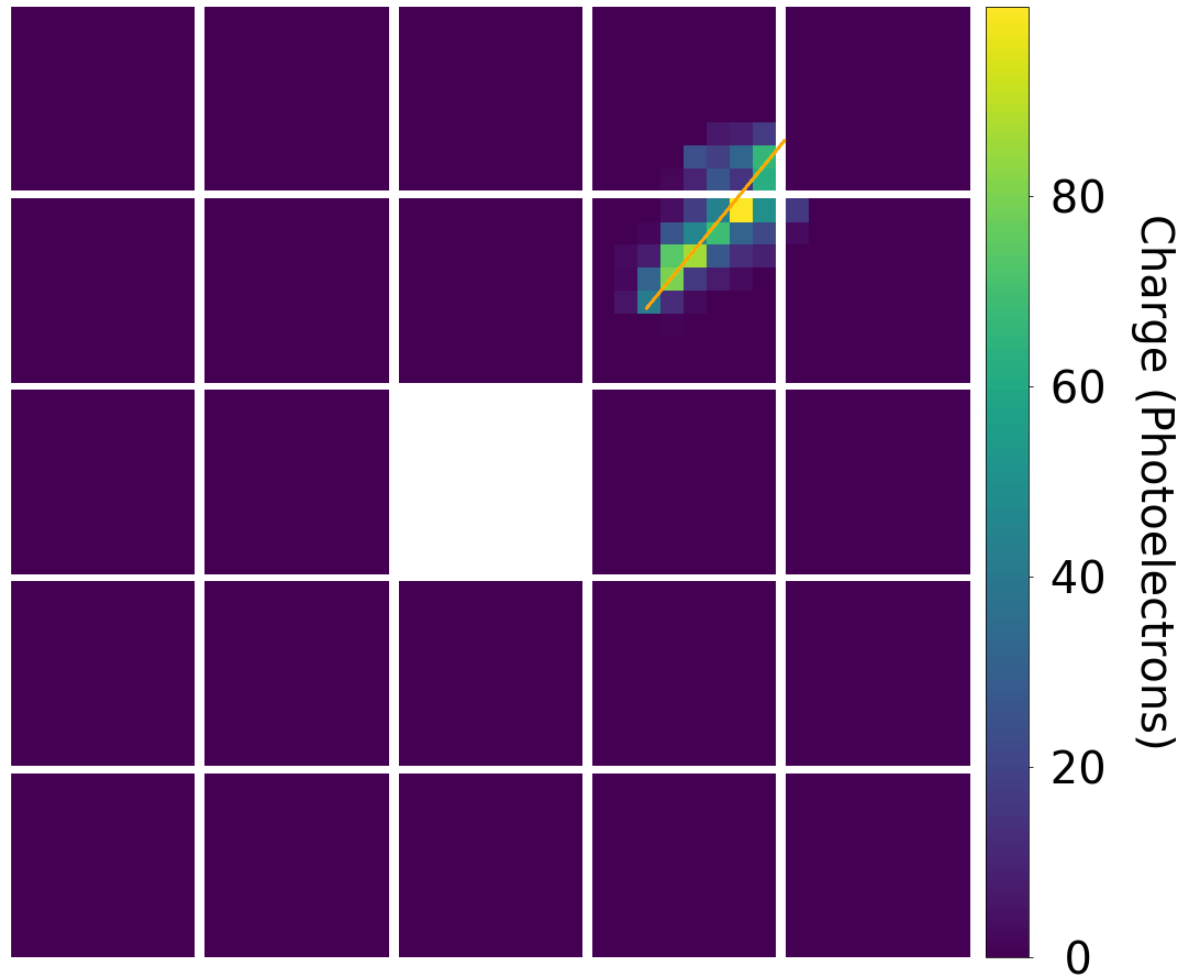
← Signal Input

To Backplane →

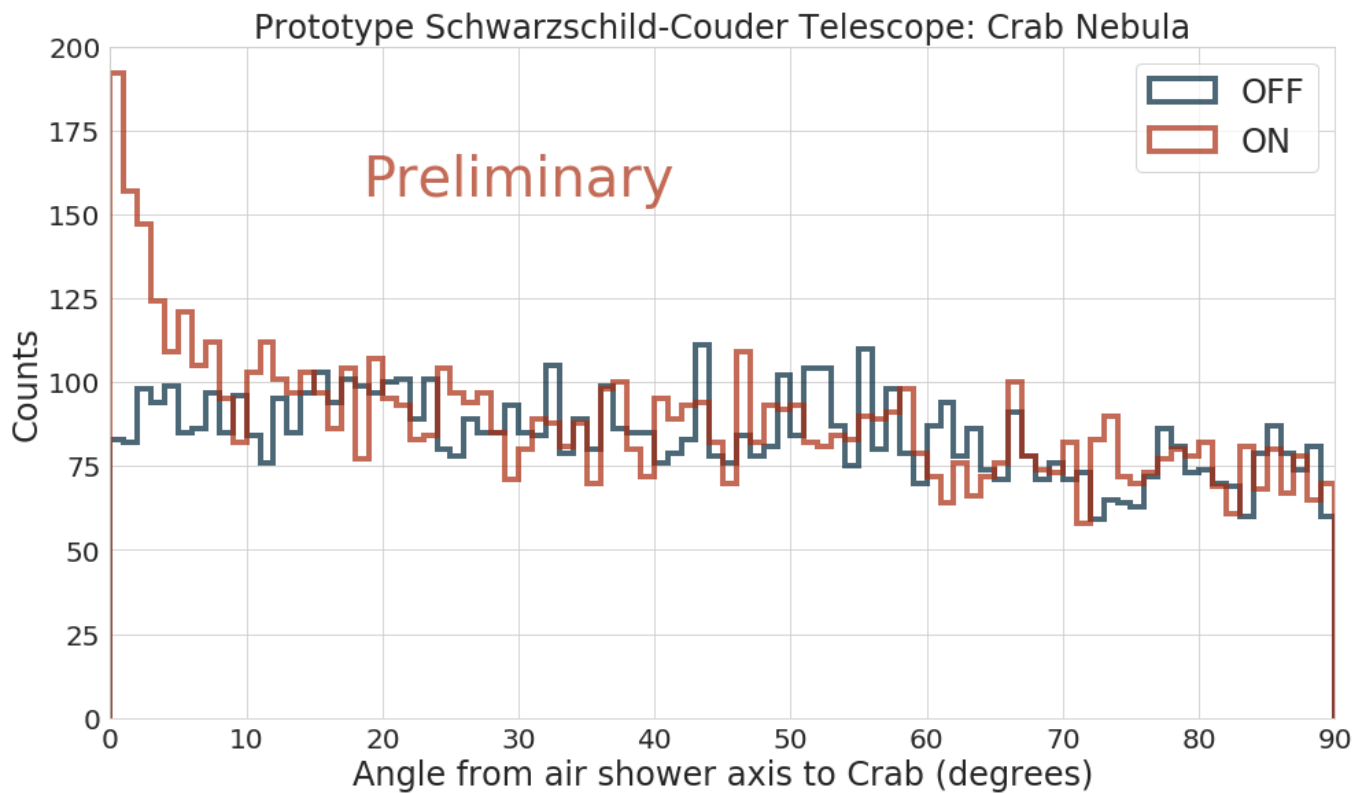


# pSCT Images of All 18 Tagged Gamma Rays (after image cleaning)

Prototype Schwarzschild-Couder Telescope Gamma Rays  
Run 328629 Event 085862 (2020-01-28 04:22:10)

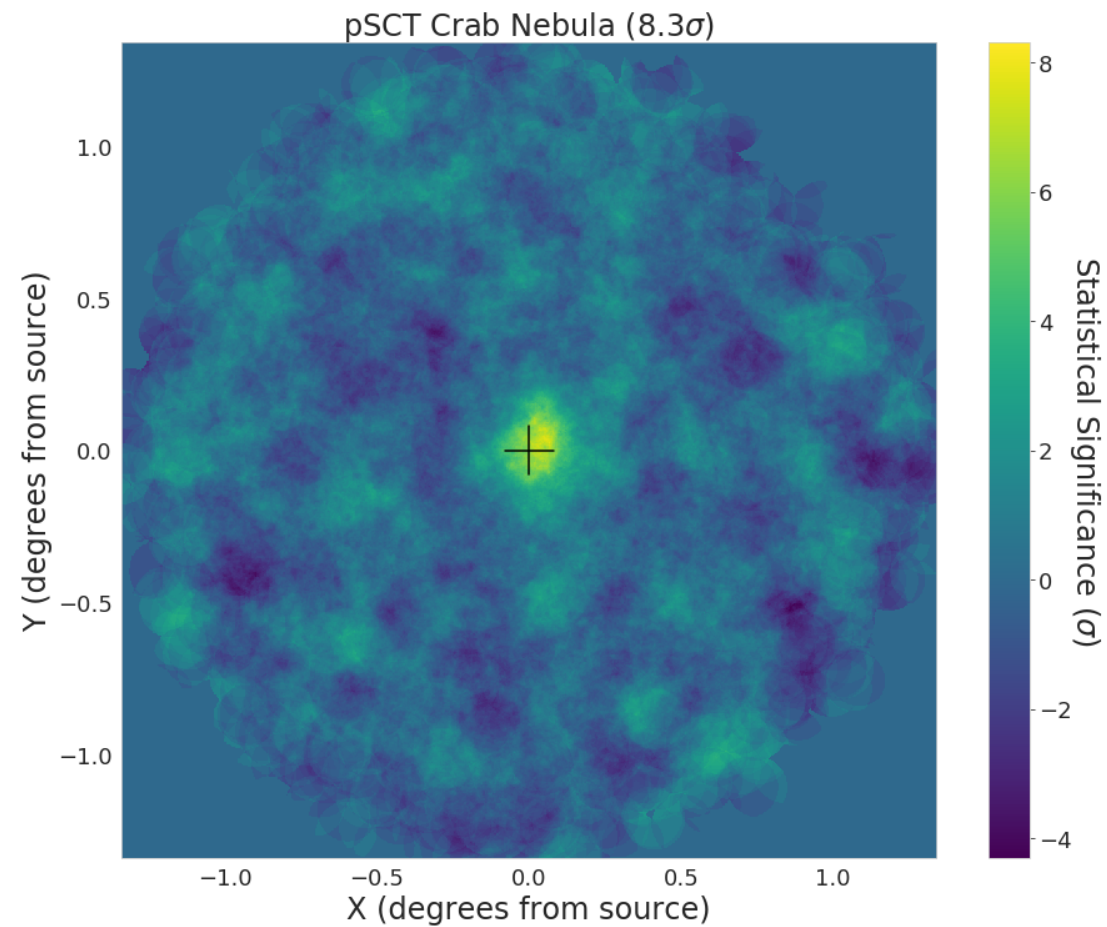


# pSCT Detection of Crab Nebula



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Brent Mode



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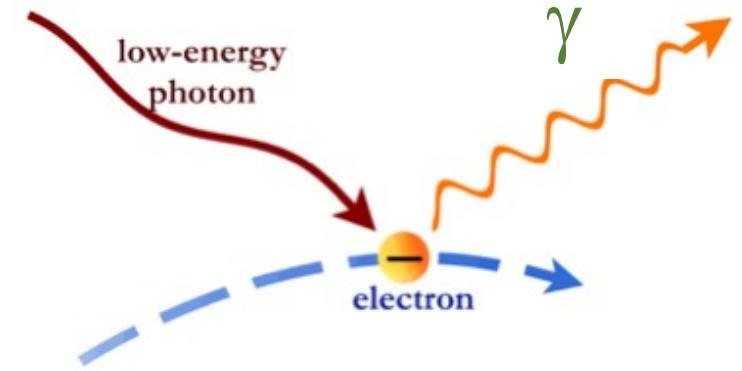
# Backup Slides

# Non-thermal Mechanisms of Gamma Ray Production

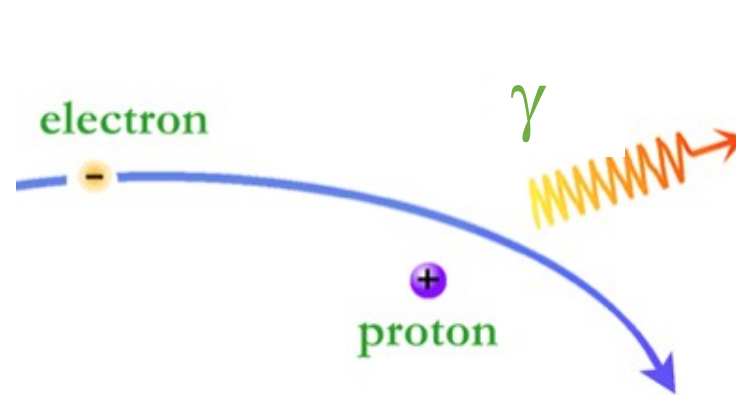
- Production of gamma rays in particle physics can occur through a variety of mechanisms
- Each of these processes can create gamma rays in astrophysical sources
- Inverse Compton scattering is a particularly important source of astrophysical gamma rays



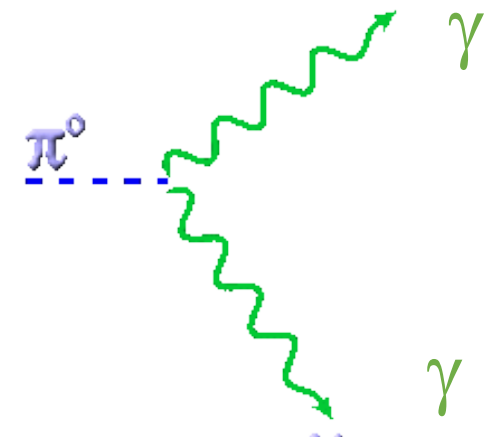
(1) Synchrotron (electromagnetic)



(2) Inverse Compton (electromagnetic)



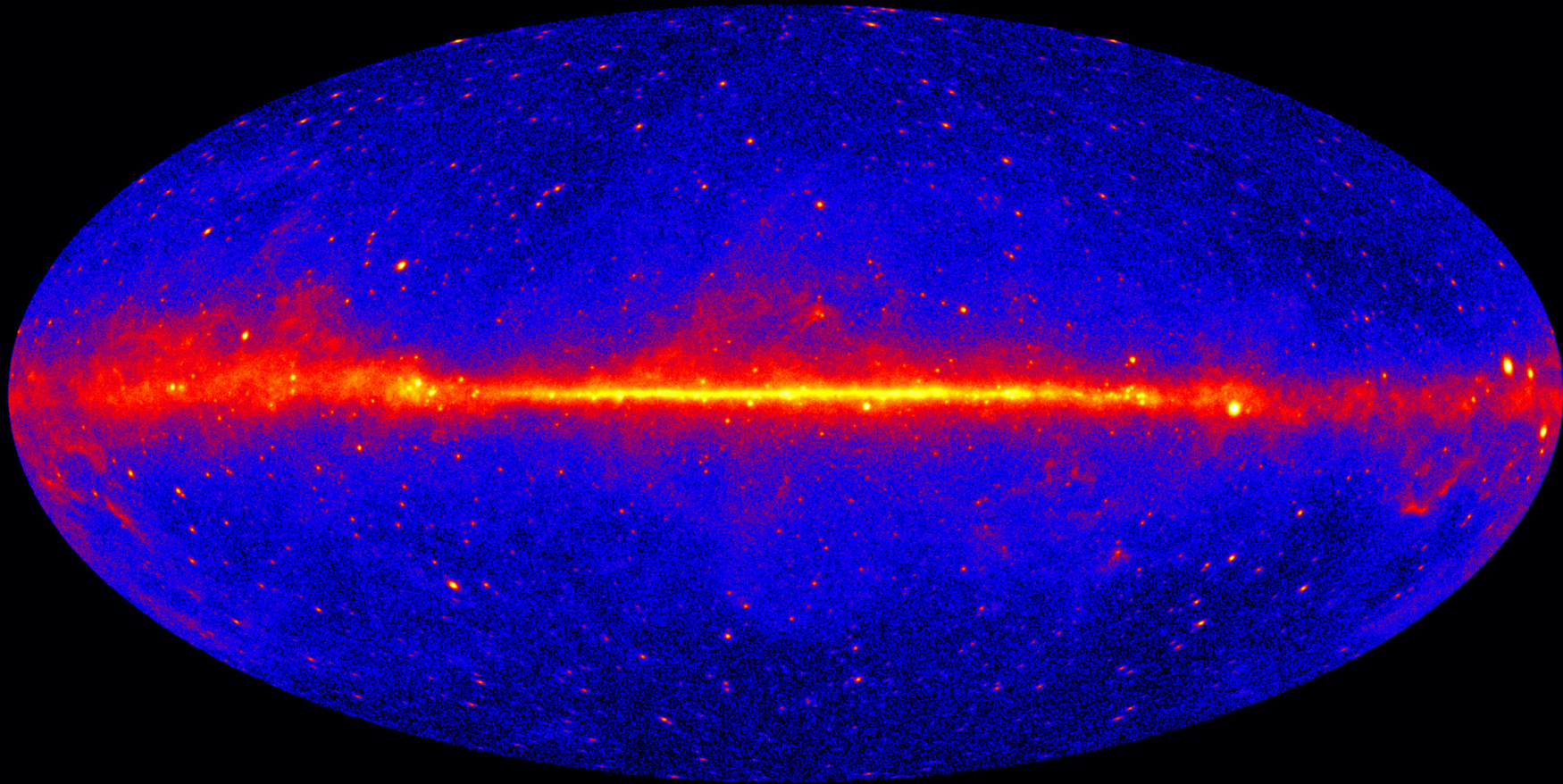
(3) Bremsstrahlung (electromagnetic)



(4) Pion decay (hadronic)



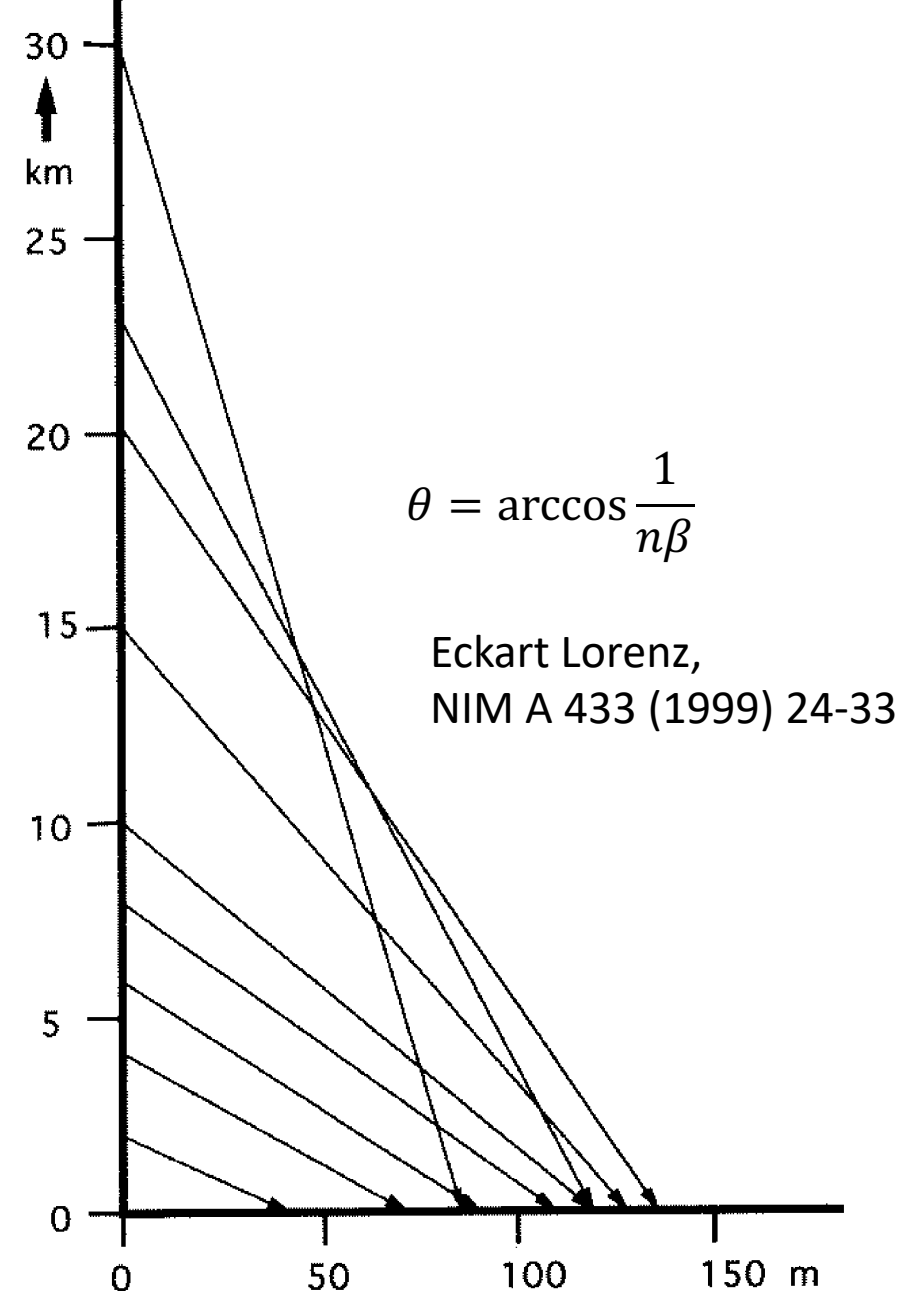
# The Universe in $>1$ GeV Gamma Rays



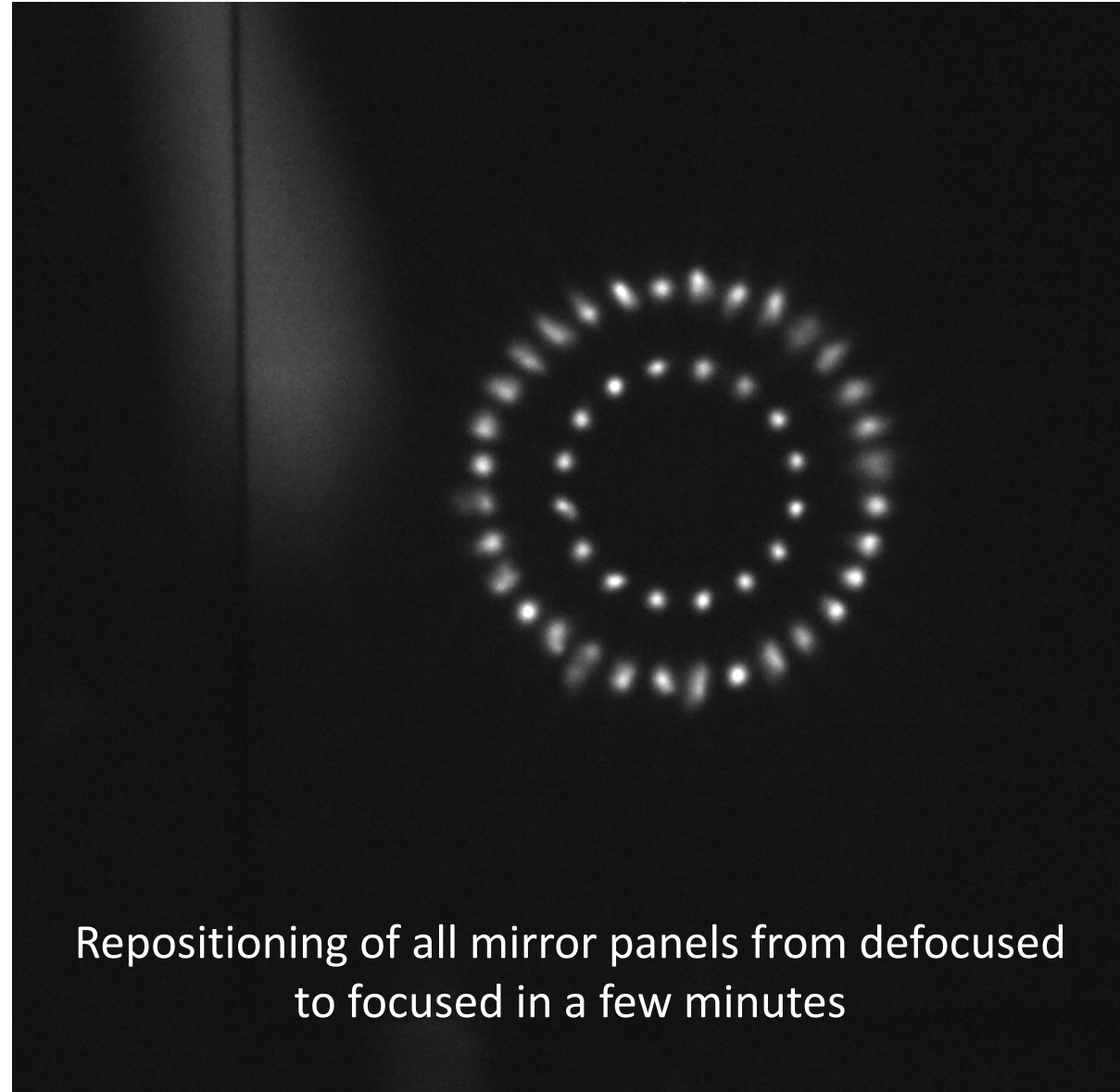
Fermi Large Area Telescope

# 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



# Alignment of Optical System



Repositioning of all mirror panels from defocused  
to focused in a few minutes

# 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

Created 02 OCT 2019

pSCT Startup/Shutdown Checklist 1/18/20 - 1/20/20

JV, LT, BM

Startup Procedure Start time

- Chiller 4:00pm sunset: 5:46pm  
 Chiller Cutoff Switch  
 Return / Feed valves astronomical twilight  
 Electronic Disconnect Switch  
 System Switch → local  
 Confirm Constant Pressure
- pSCT Shed  
 Plug in the UPS open UPS door park  
 Flip UPS Switch  
 Cabinet C Main Breaker } label  
 Cabinet B Main Breaker }
- pSCT Tower  
 Main Breakers: Left to Right } across  
 Positioner on cabinet  
 Dirty Power Main  
 Left Cabinet  
 Right Cabinet  
 Camera Dirty Power  
 All Clean Power ← PEOB  
touch screen: hit start  
 pSCT Positioner (3 breakers) for cables  
 Check Access Tower for Obstructions  
 Check for Other Obstructions  
 Daytime  
 Primary Tarp On  
 Secondary Tarp On  
 Shutter Tarp On  
 Close Tower Door  
 Confirm that Interlocks are UNLOCKED  
 Switch to Local Mode  
 Switch on Drive System  
 Wait for Idle Status  
 Change Elevation / Azimuth -4.95  
 Wait for Idle Status  
 Switch off Drive System  
 Switch Off Local Mode  
 Nighttime  
 Move Telescope to Azimuth 0 / Elevation -5  
 Remove Shutter Tarp  
 Open Shutter  
 Confirm Shutter is Fully Open  
 Move Telescope to preferred position  
 Turn off Camera Dirty Power  
 Take Data  
move back to park

Shutdown Procedure

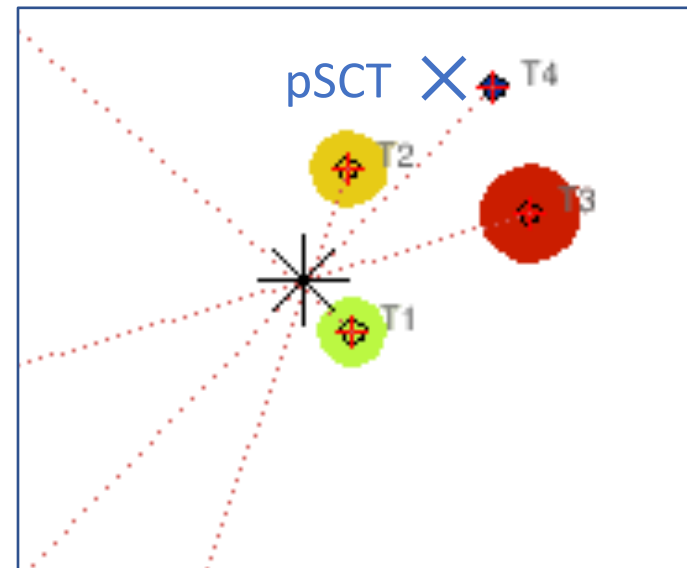
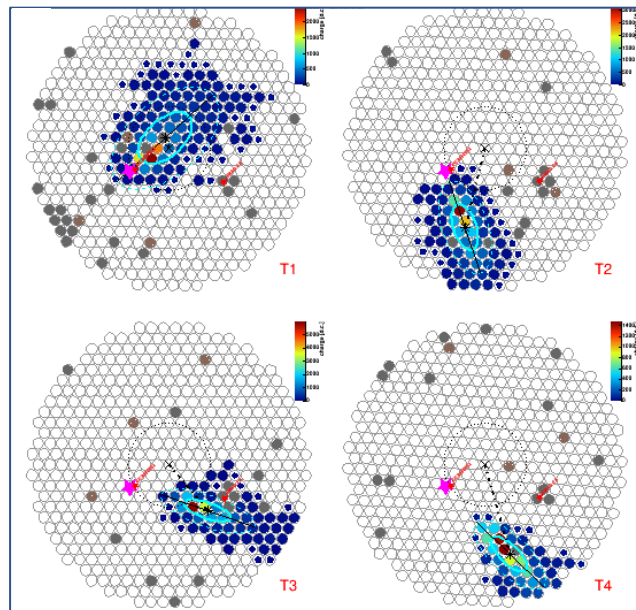
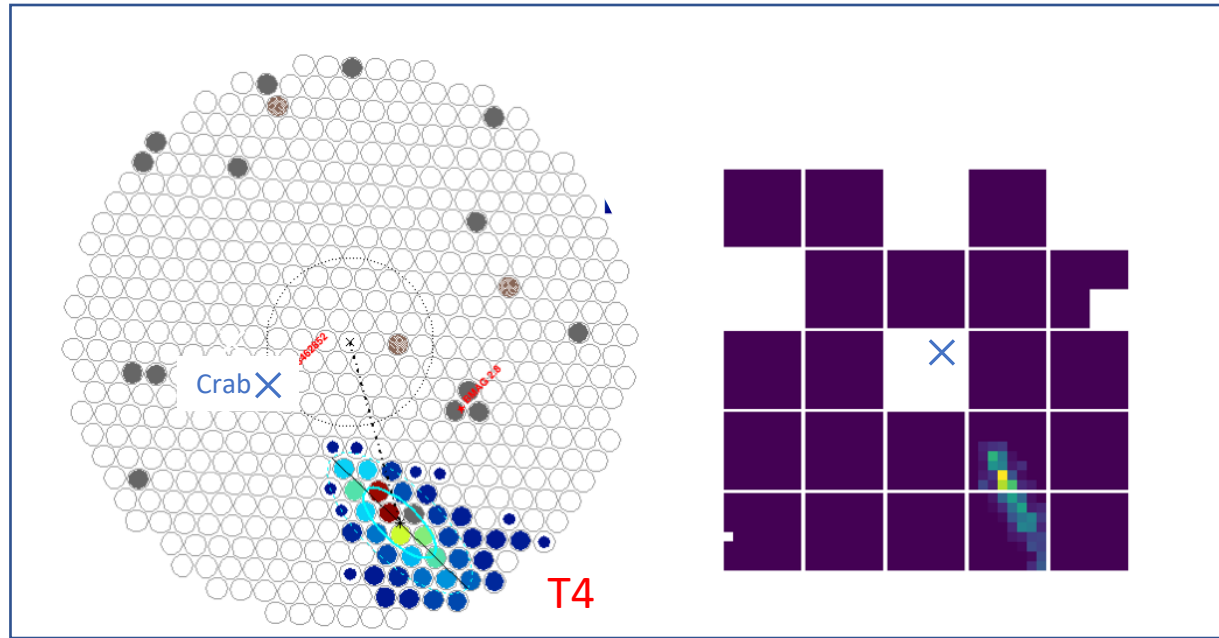
- Camera and Fans  
 Confirm that Flashers are Off  
 Run ./setupPowerSupply.sh  
 Choose 0 for shutdown  
 Run python fanPowerOFF.py
- Telescope to Park Position  
 Move Telescope to Azimuth 0 / Elevation -5  
 Confirm that Interlocks are UNLOCKED  
 Turn On Camera Dirty Power  
 Close Shutter  
 Replace All Tarps  
 Retract Camera Access Platform  
 Enter Camera Tower and Close Door  
 Confirm that Interlocks are UNLOCKED  
 Switch to Local Mode  
 Switch on Drive System  
 Wait for Idle Status  
 Press "Go to Park Position"  
 Check that Interlocks have Locked  
 Wait for Idle Status  
 Switch off Drive System  
 Switch Off Local Mode
- pSCT Tower  
 Turn off the Clean Power  
 Turn off the Dirty Power  
 Turn off the Positioner  
 Turn off Main Breakers from Right to Left
- pSCT Shed  
 Turn off the Main Switch in Cabinet B  
 Turn off the Main Switch in Cabinet C  
 Turn off the UPS Switch  
 Unplug the UPS
- Chiller  
 Turn off System Switch  
 Turn off Electronic Disconnect Switch  
 Close Valves  
 Turn off Chiller Cutoff Switch

finish time: \_\_\_\_\_

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

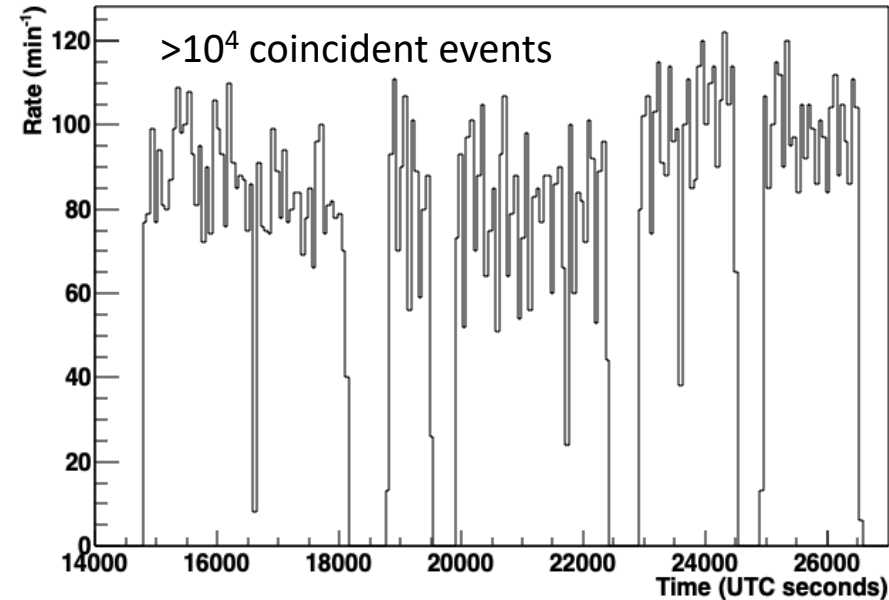


# A 3.5 TeV gamma ray detected by both pSCT and VERITAS



# Crab observations: simultaneous observing with VERITAS

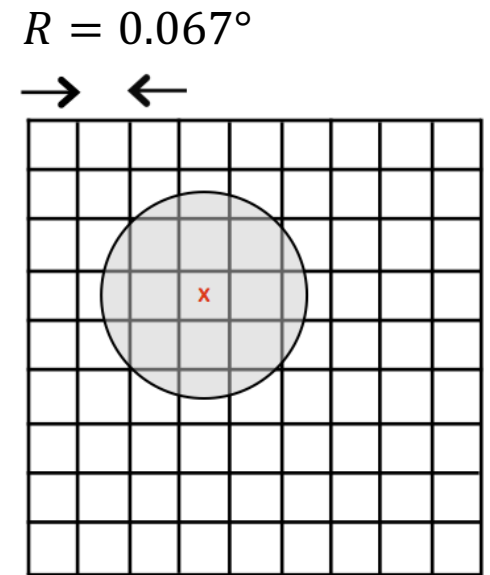
Rate of showers detected by both VERITAS and pSCT



- pSCT commissioning and Crab observations January–March 2020
- Simultaneous with VERITAS Crab observations whenever possible
- VERITAS-pSCT shower matching offline: negligible accidental coincidence ( $< 1 \mu\text{s}$  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

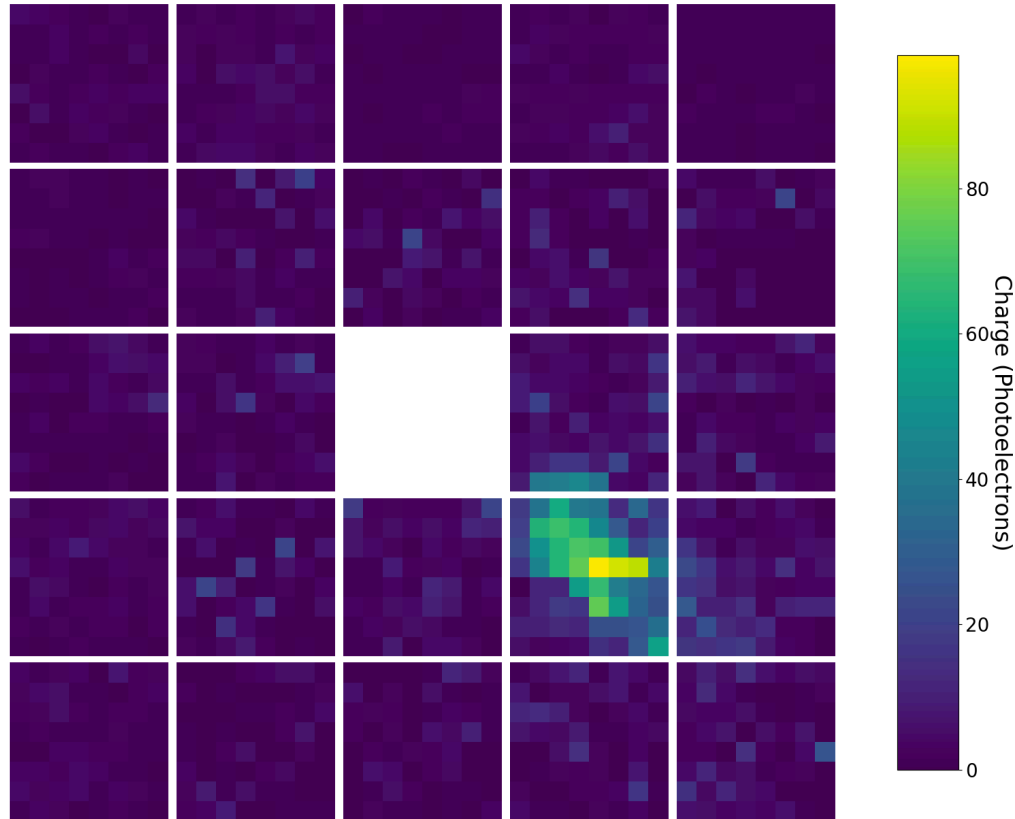




# Image Cleaning – Aperture Method

Raw data

Run 328555 Event 1826  
2020-01-18 02:56:08 UTC



Cleaned image

Run 328555 Event 1826  
2020-01-18 02:56:08 UTC

