UNIVERSITY OF LEICESTER

School of Physics and Astronomy

Techniques for Very High Energy (VHE) Gamma-ray Astronomy

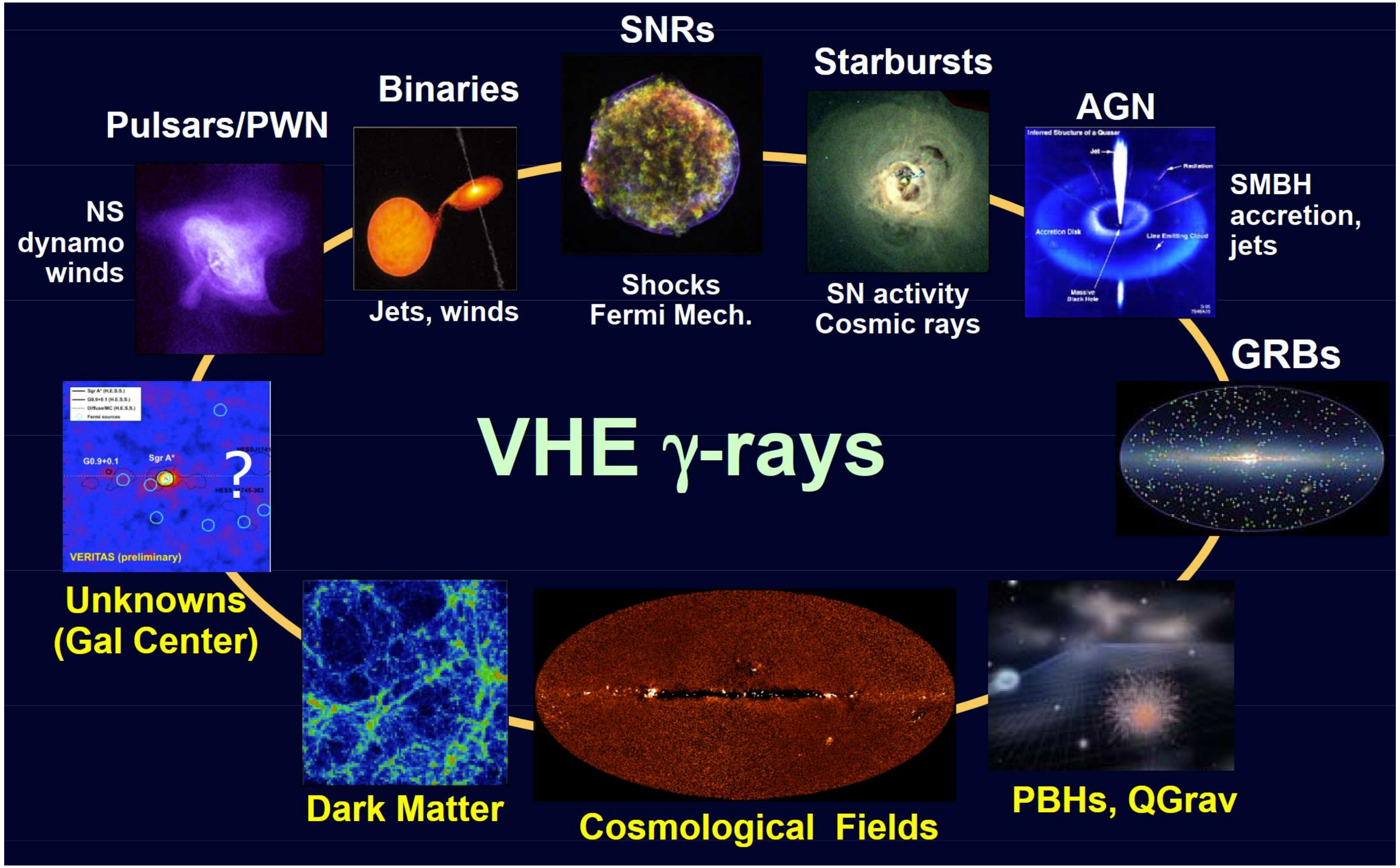
Jon Lapington

PSD13: 13th International Conference on Position Sensitive Detectors – September 3-8, 2023

Outline

- Why do VHE Gamma-ray astronomy?
- VHE Gamma-ray astronomy techniques
- Water Cherenkov detectors
- The Southern Widefield Gamma-ray Observatory
- Imaging Air Cherenkov detectors
- The Cherenkov Telescope Array
- The future of Gamma-ray astronomy in the UK

Why do VHE Gamma-ray astronomy?



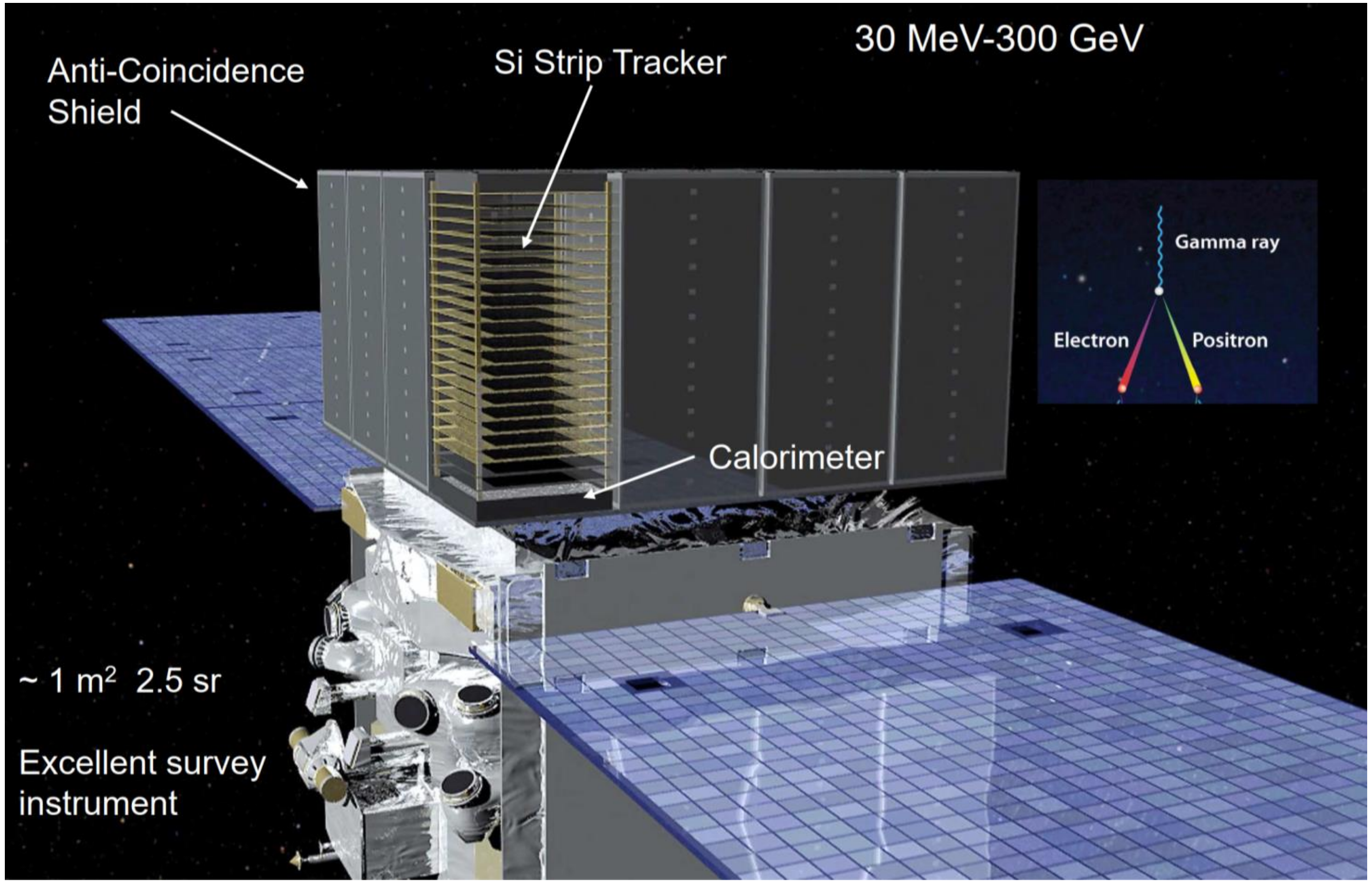
Key Science Questions

GeV and TeV gamma-ray sources are ubiquitous in the universe and probe extreme particle acceleration, and the subsequent particle interactions and propagation.

1. How are the bulk of cosmic ray particles accelerated in our Galaxy and beyond? (one of the oldest surviving questions of astrophysics)
2. Can we understand the physics of jets, shocks & winds in the variety of sources we see, including pulsars, binaries, AGN, starbursts, and GRBs?
3. How do black holes of all sizes efficiently accelerate particles? How are the structures (e.g. jets) formed and how is the accretion energy harnessed?
4. What do high-energy gamma rays tell us about the star formation history of the Universe, intergalactic radiation fields, and the fundamental laws of physics?
5. What is the nature of dark matter, and can we map its distribution through its particle interactions?
6. What new unexpected phenomena will be revealed by exploring the non-thermal Universe?

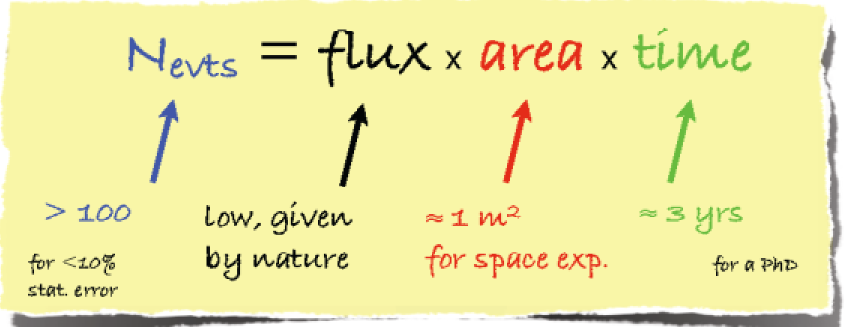
VHE Gamma-ray astronomy techniques

- Observing from space e.g. Fermi Large Area Telescope



VHE Gamma-ray astronomy techniques

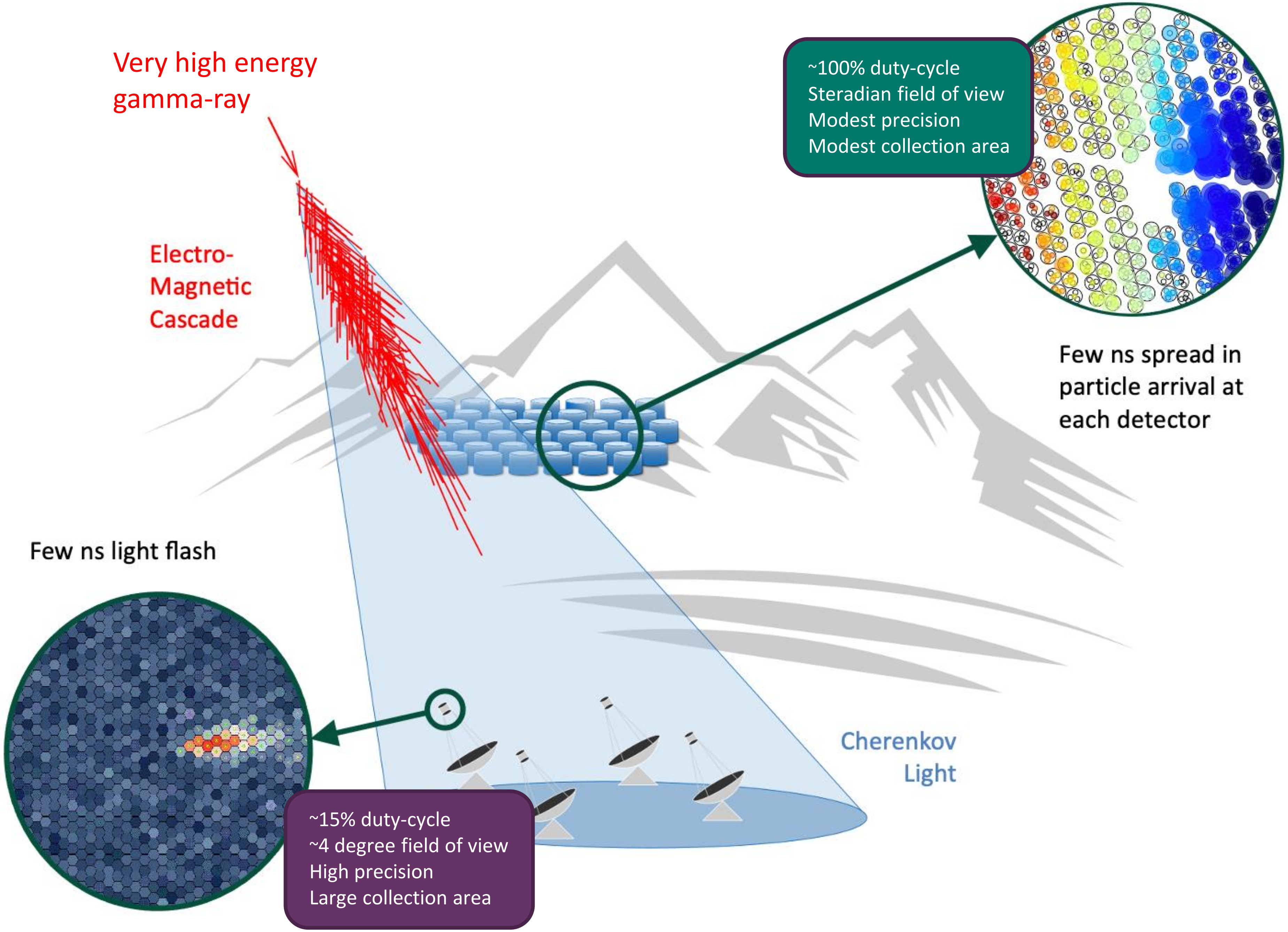
- Observing from space e.g. Fermi Large Area Telescope



Steeply falling spectrum:

x10 increase in Energy → flux divides by 100-500

- Large effective area needed for detectable VHE signals - not possible in space
- Natural detector: the Earth's atmosphere



Very high energy gamma-ray

Electro-Magnetic Cascade

~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area

Few ns spread in particle arrival at each detector

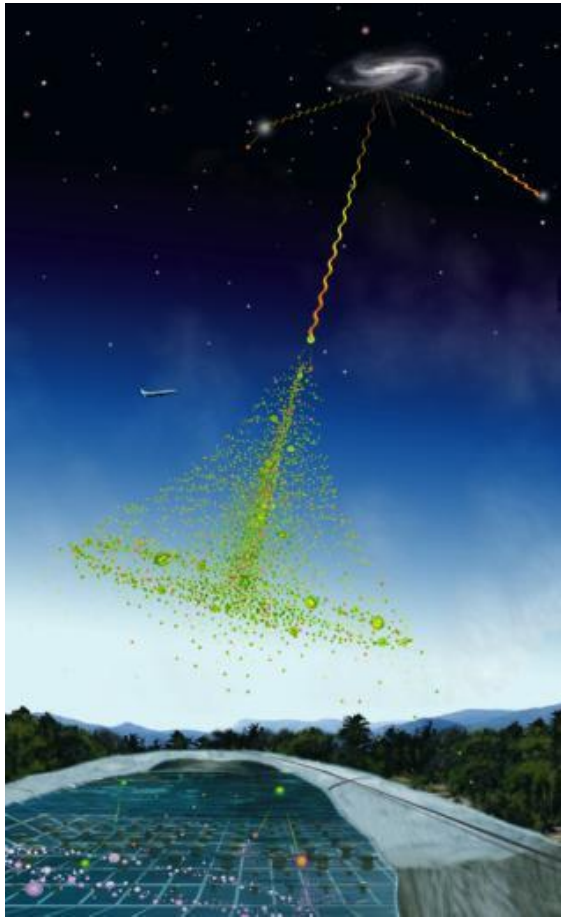
Few ns light flash

Cherenkov Light

~15% duty-cycle
~4 degree field of view
High precision
Large collection area

Water Cherenkov Detectors

- Detect the secondary particle shower directly
- Need to be at high altitude
- Wide Field of View with TeV sensitivity
- Continuously operating (> 90% duty cycle)
- Unbiased search for transients → multi messenger observations
- Major Water Cherenkov Observatories
  - Milagro Gamma Ray Observatory
  - High Altitude Water Cherenkov (HAWC)
  - Large High Altitude Air Shower Observatory (LHAASO)
  - Southern Widefield Gamma-ray Observatory (SWGO)



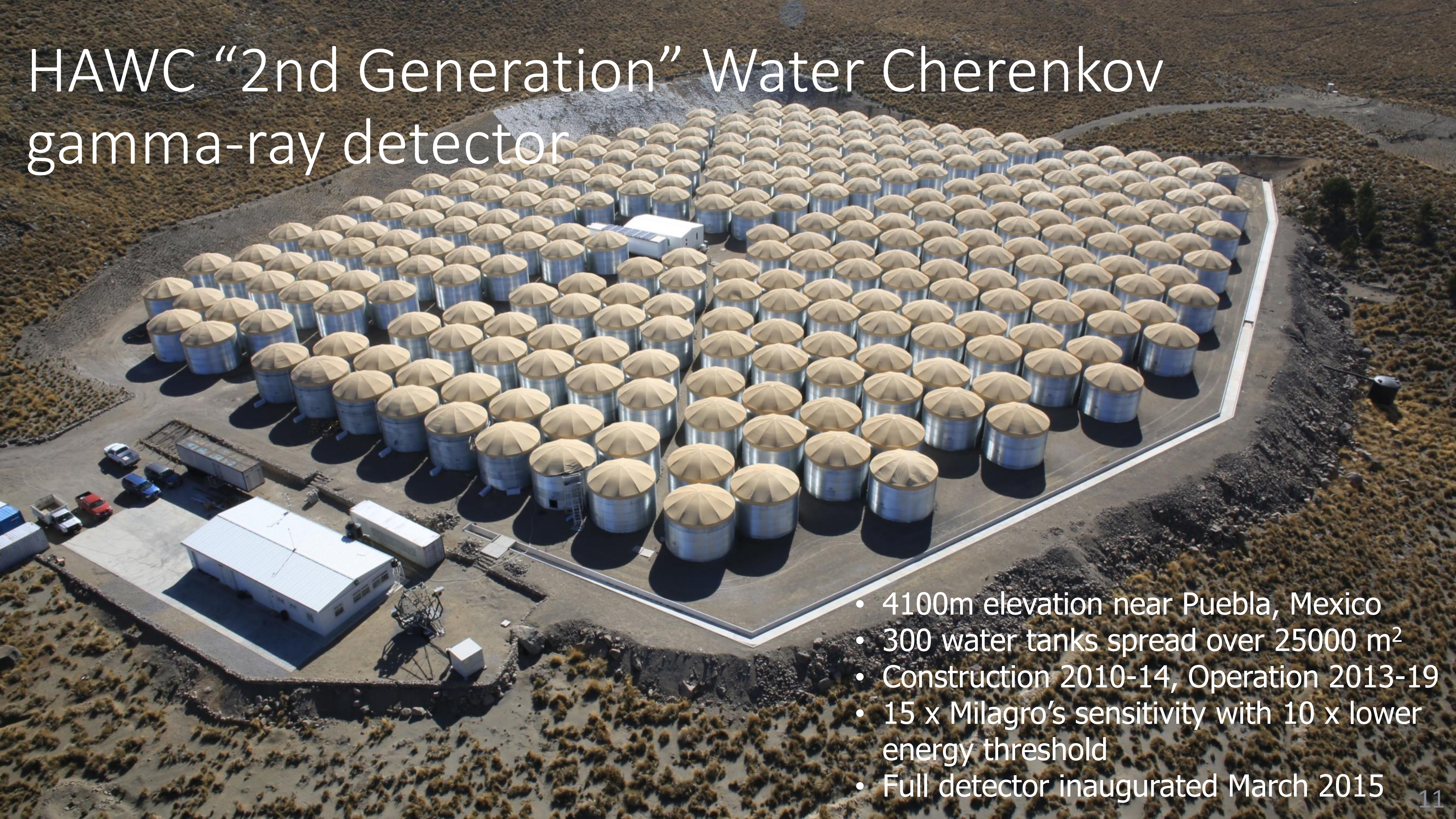
©Aurore Simonnet

Milagro “1st Genersation” Water Cherenkov TeV Observatory

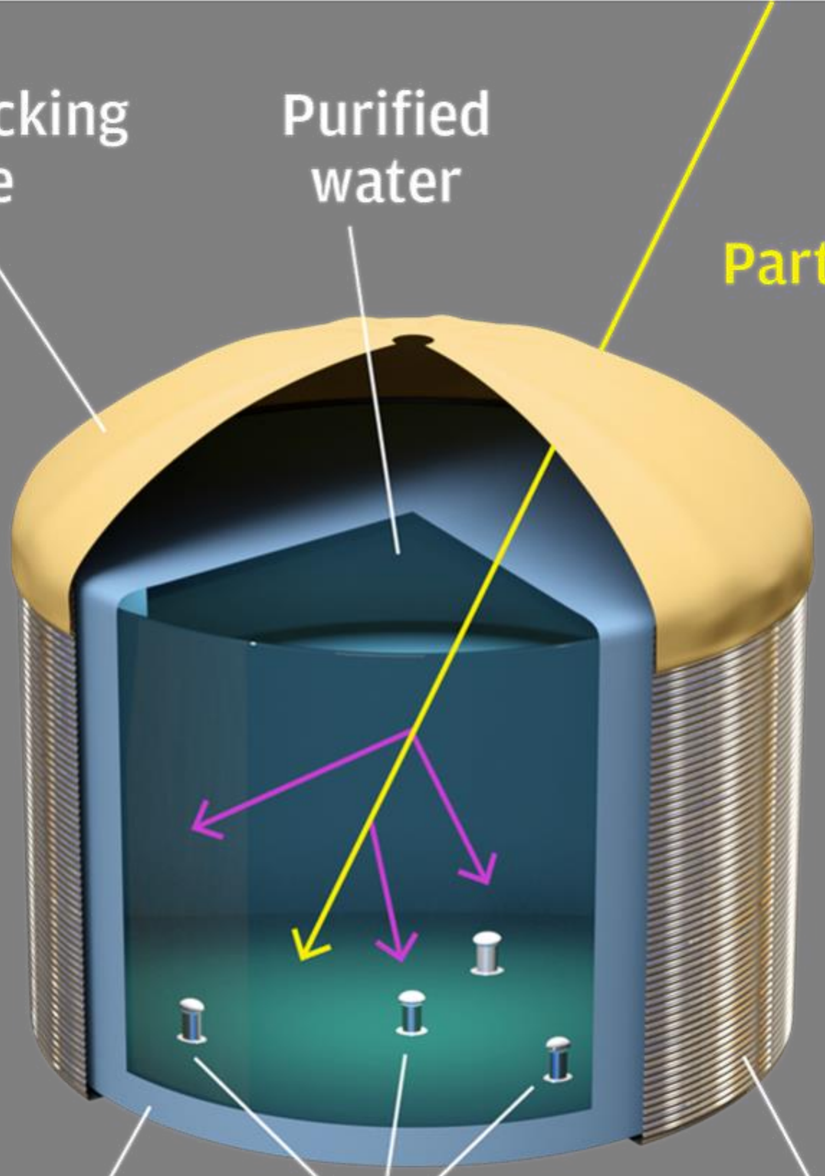
- 2650m elevation near Los Alamos, NM
- Covered pond of 4000 m^2
- Operated 2000-2008
- Detected new Galactic sources, Galactic plane, cosmic ray anisotropy, and put upper limits on prompt emission from gamma-ray bursts

- 4800 m^2 pond surrounded by 40000 m^2 array of outriggers
- Operated from 2000-2008
- Operated 2004-2008 with outriggers (2x sensitivity)

HAWC “2nd Generation” Water Cherenkov gamma-ray detector



- 4100m elevation near Puebla, Mexico
- 300 water tanks spread over 25000 m^2
- Construction 2010-14, Operation 2013-19
- 15 x Milagro’s sensitivity with 10 x lower energy threshold
- Full detector inaugurated March 2015



Light-blocking dome

Purified water

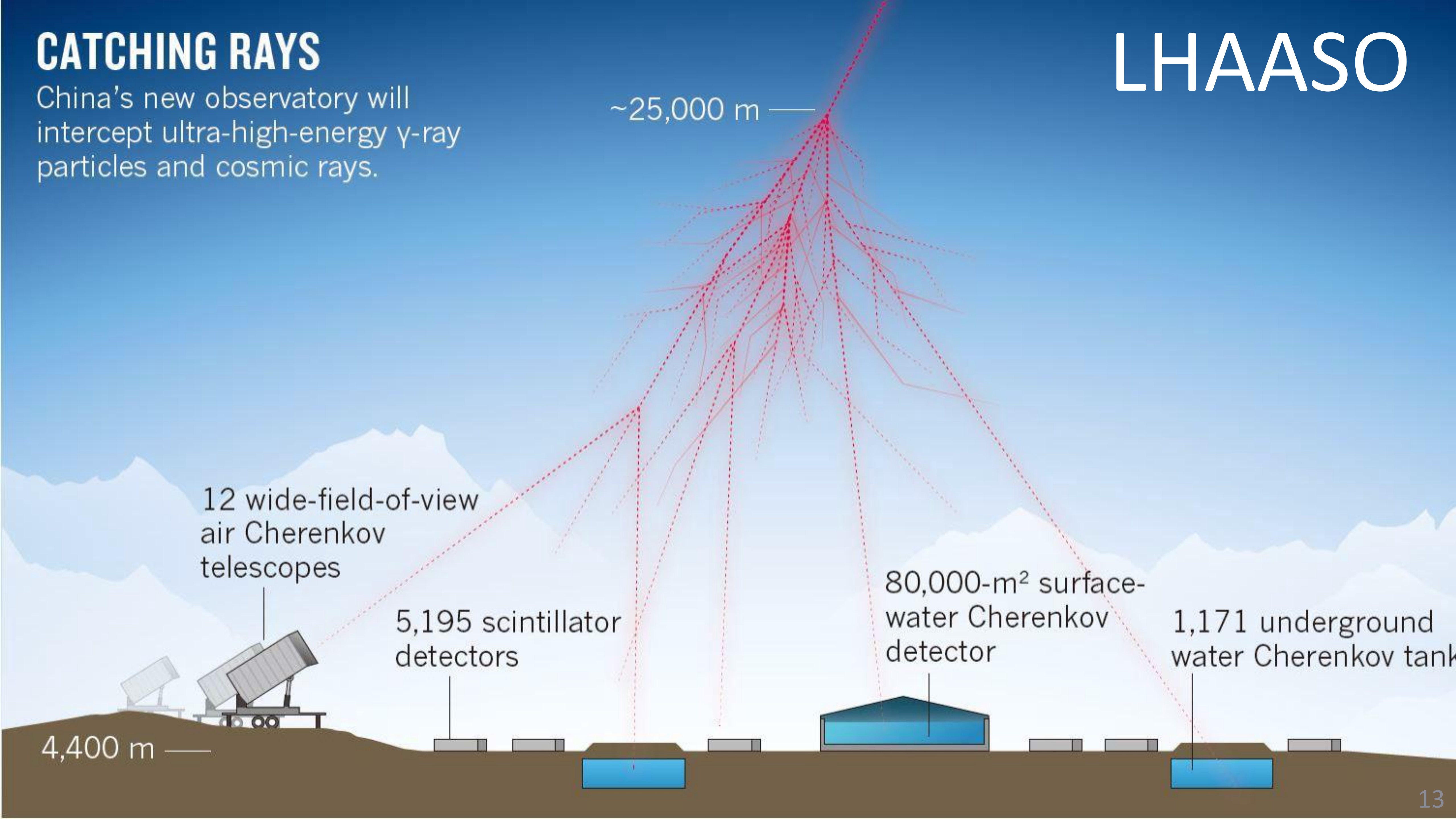
Particle path

Watertight liner

Photosensors

Steel water tank

LHAASO



CATCHING RAYS

China's new observatory will intercept ultra-high-energy γ-ray particles and cosmic rays.

LHAASO

LHAASO

LHAASO Discovery of Pevatrons

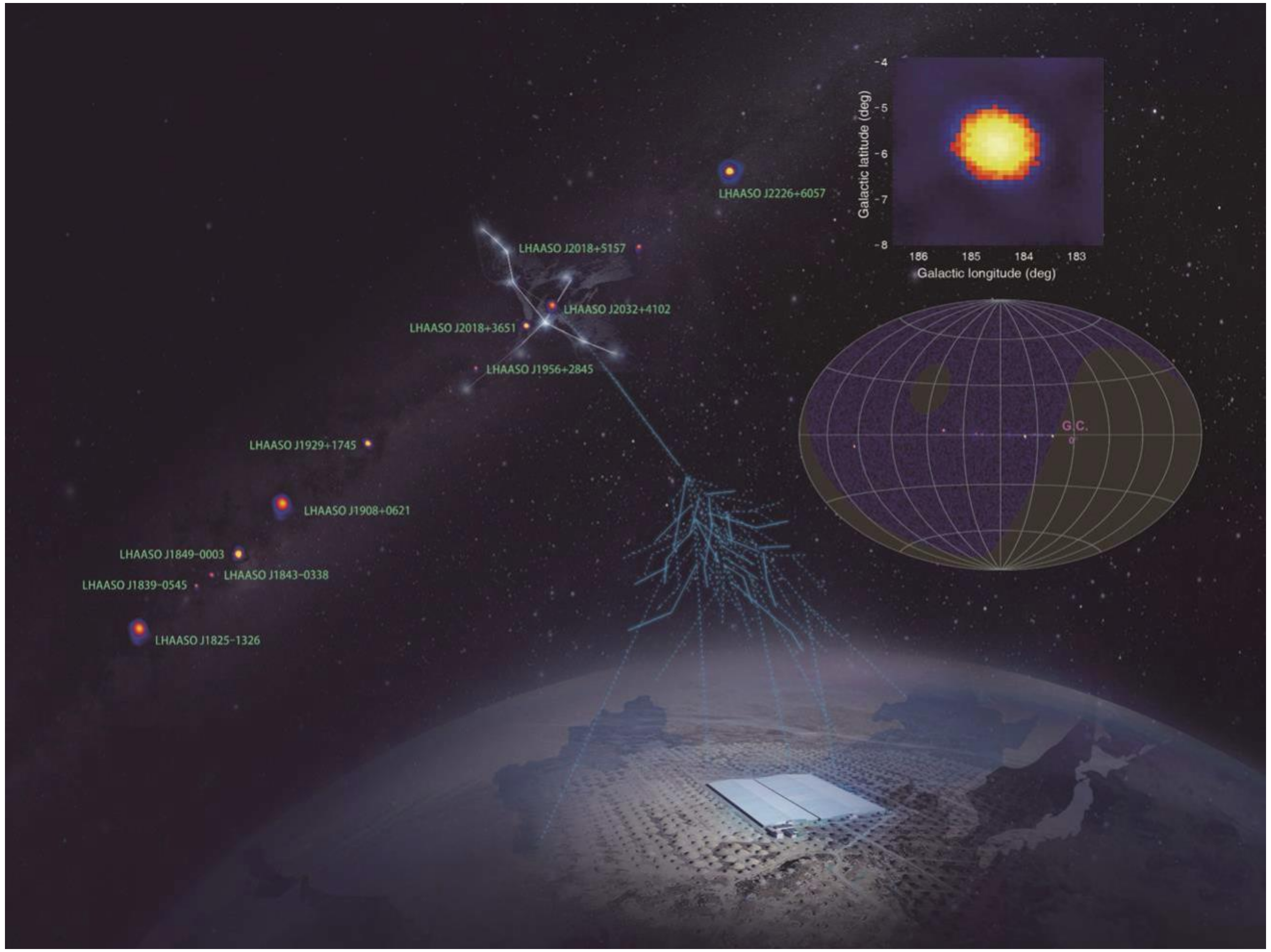
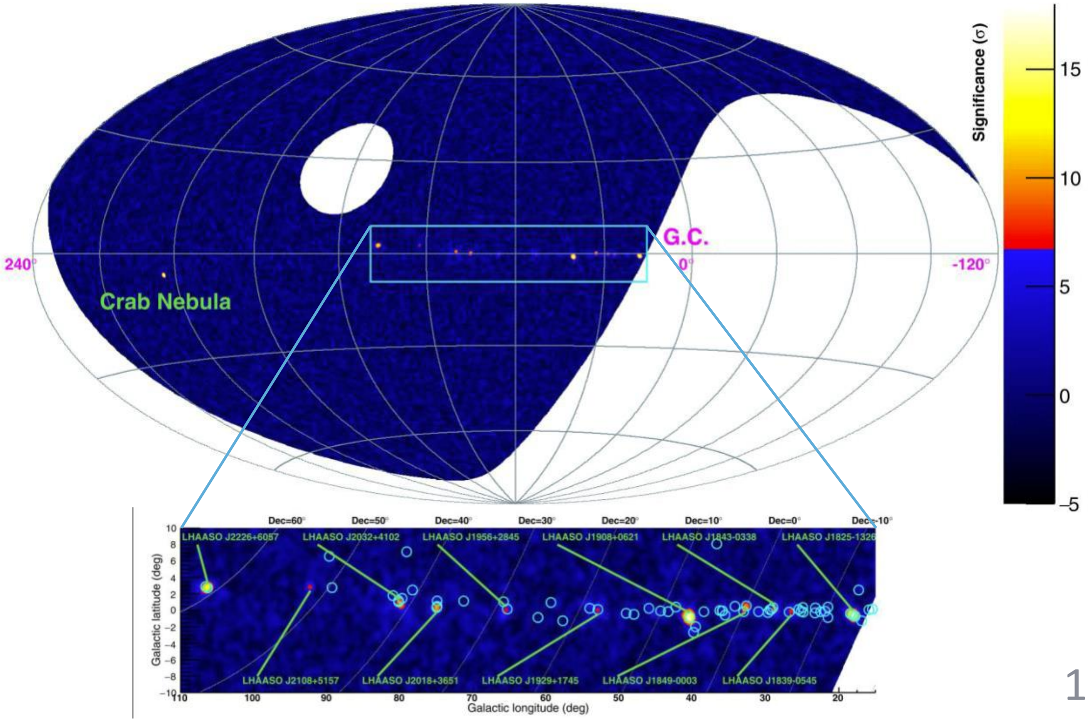
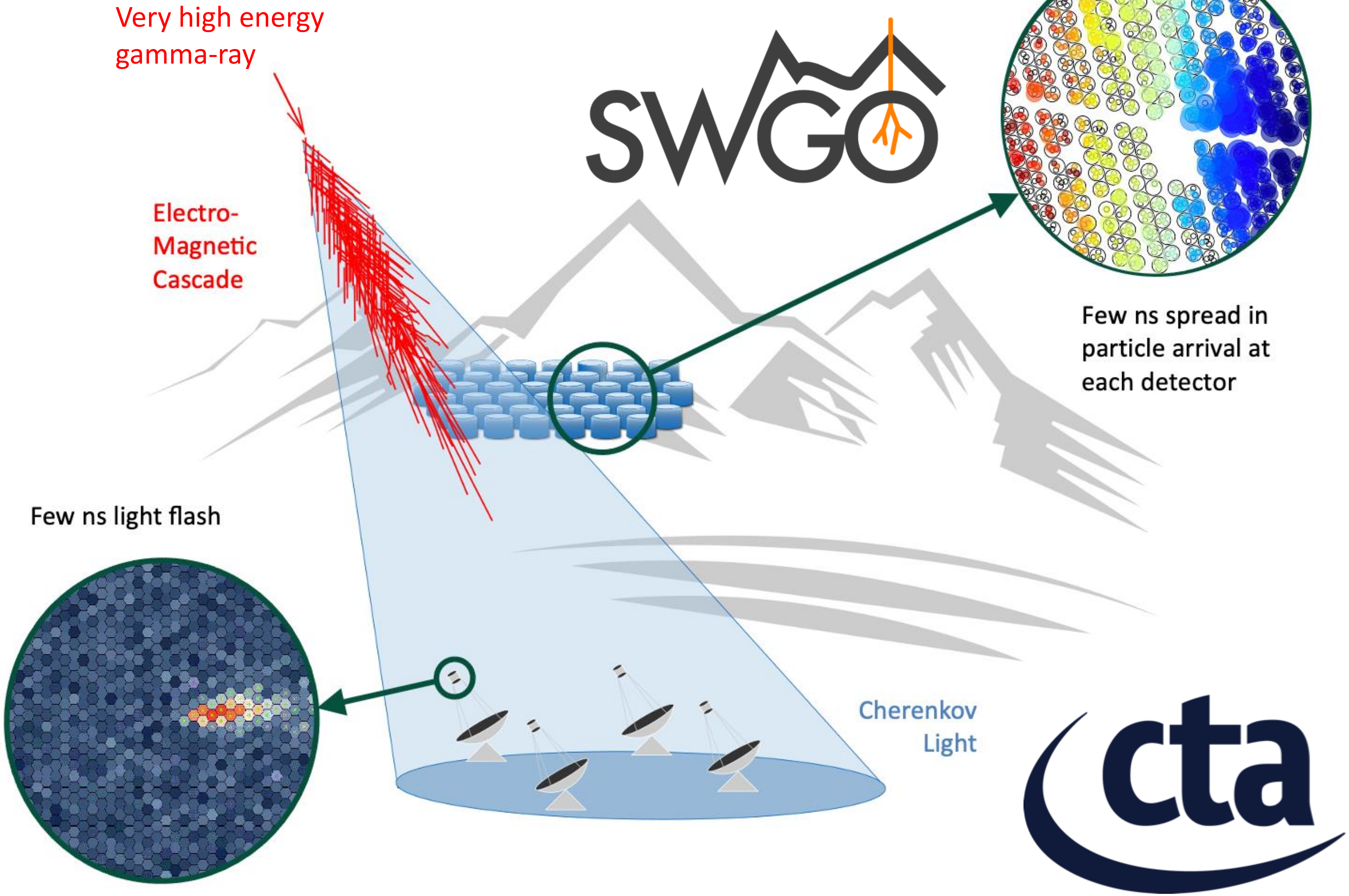
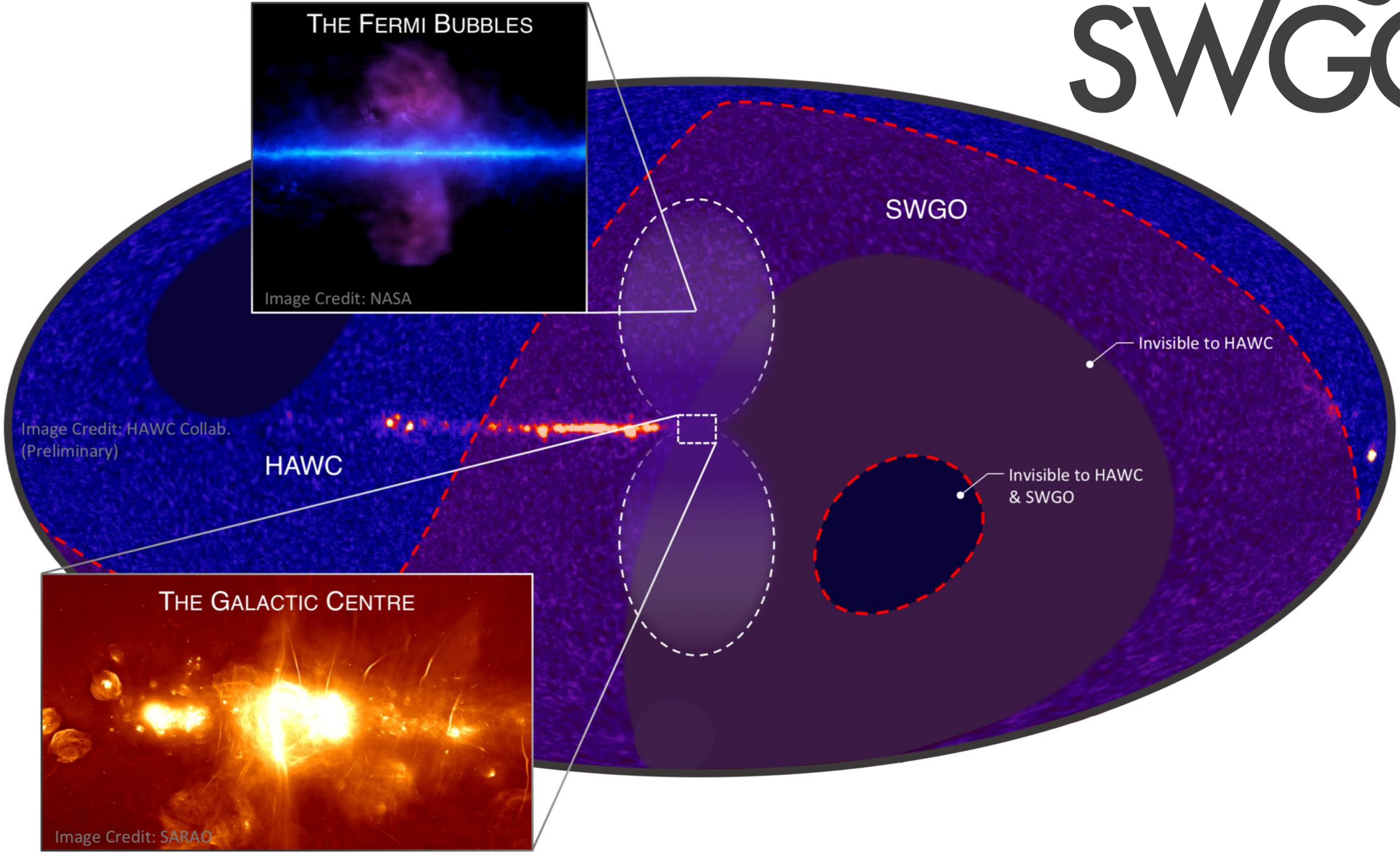


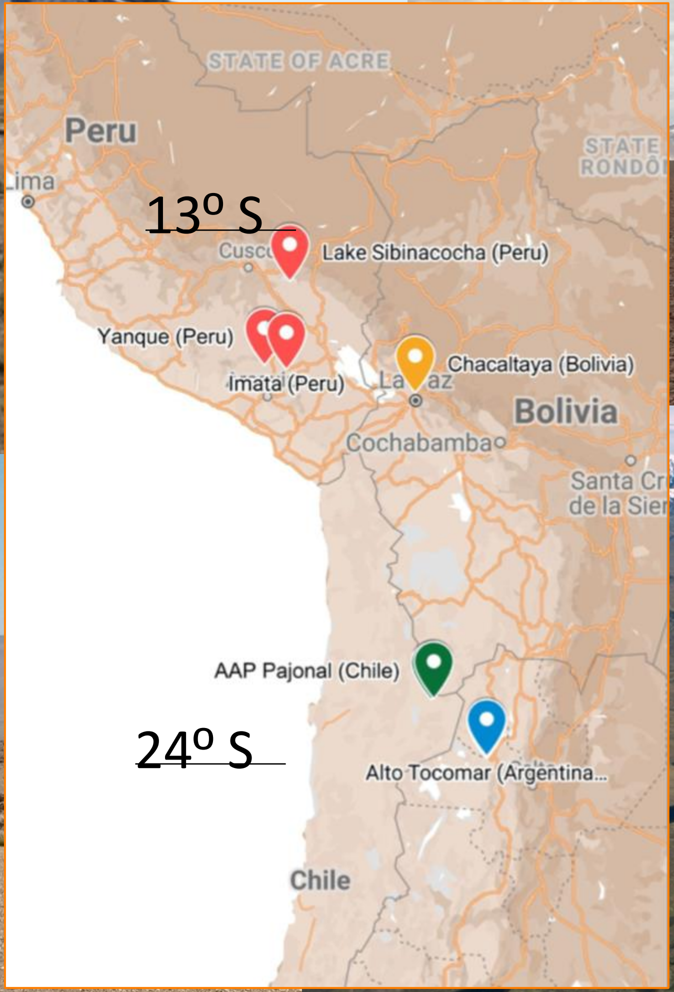
Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

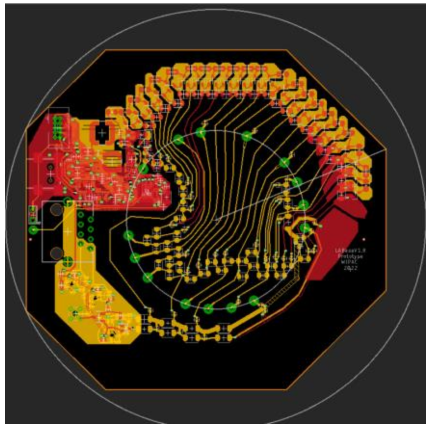



Very high energy gamma-ray
Electro-Magnetic Cascade
Few ns spread in particle arrival at each detector
Few ns light flash
Cherenkov Light

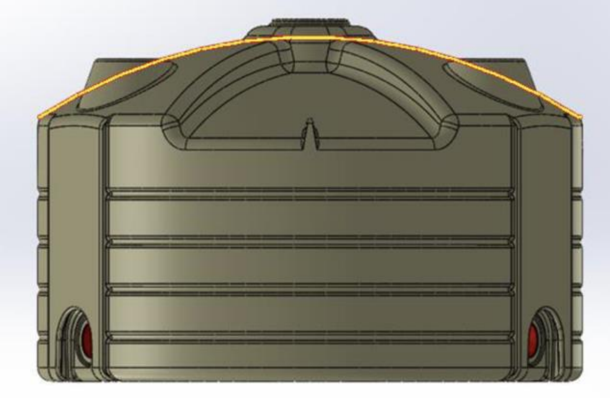

THE FERMI BUBBLES
Image Credit: NASA
SWGO
Invisible to HAWC
Image Credit: HAWC Collab.
(Preliminary)
HAWC
Invisible to HAWC
& SWGO
THE GALACTIC CENTRE
Image Credit: SARAO

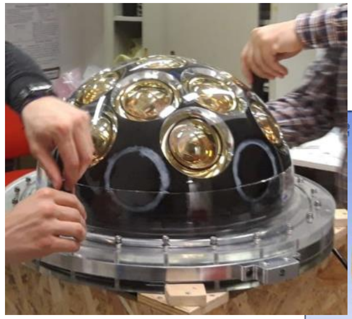


Site shortlisting: September 2022
Site team visits: October 2022
Preferred Site identified: Autumn 2023
On-site prototyping activities: from 2022

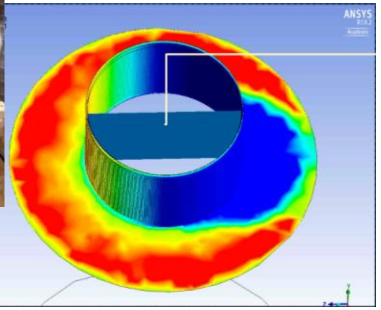


- **WCD Unit**
  - **Lake**
    - Natural Lake
    - Artificial Lake/Pond
  - **Tank**
    - Steel Tank
    - Rotomolded Plastic



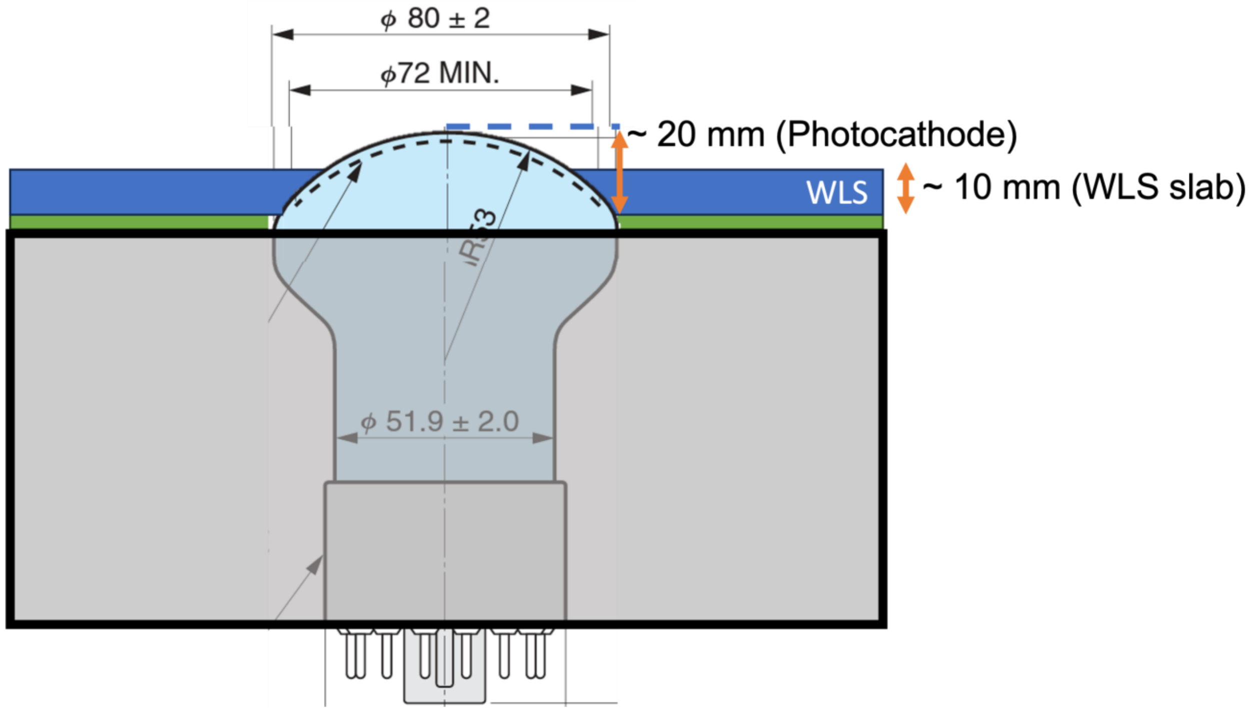


*cooperation with KM3NeT, MoU in prep.

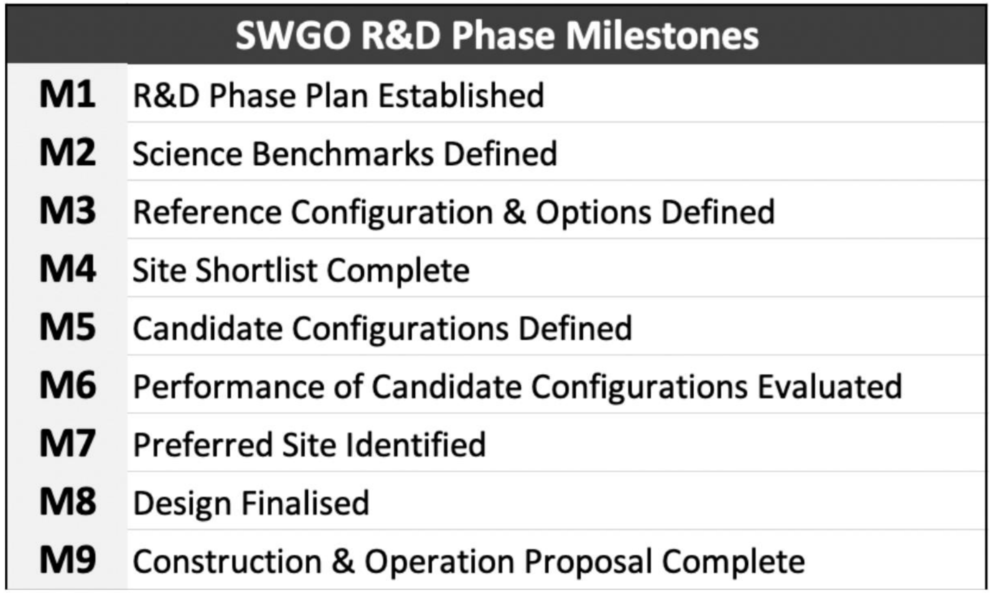


SWGO – UK developments

- Wavelength Shifting (WLS) materials
  - Reduce costs by using a smaller PMT
  - WLS material to recover lost efficiency
  - However WLS degrades time resolution
  - Use for muon veto tank only – CR rejection
- Calibration light systems
  - Heritage from CTA “flashers”



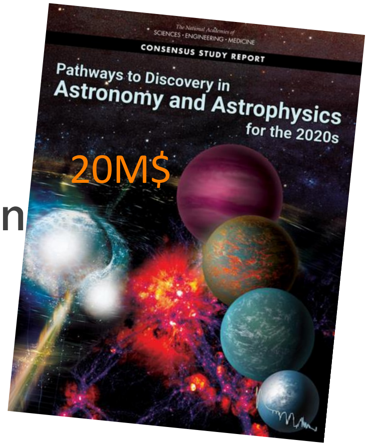
Status & Plan



	SWGO R&D Phase Milestones	
✓	**M1**	R&D Phase Plan Established
✓	**M2**	Science Benchmarks Defined
✓	**M3**	Reference Configuration & Options Defined
	M4	Site Shortlist Complete
✓	**M5**	Candidate Configurations Defined
	M6	Performance of Candidate Configurations Evaluated
	M7	Preferred Site Identified
	M8	Design Finalised
	M9	Construction & Operation Proposal Complete

- SWGO partners
  - 47 institutes in 12 countries*
  - + supporting scientists

- R&D Phase
  - Kick off meeting Nov 2019
  - Expected completion 2023
    - ✓ Site and Design Choices made
  - Then:
- Preparatory Phase
  - Detailed construction plan
  - **Engineering Array**
- (Full) Construction Phase
  - 2026+



The National Academies of SCIENCES · ENGINEERING · MEDICINE

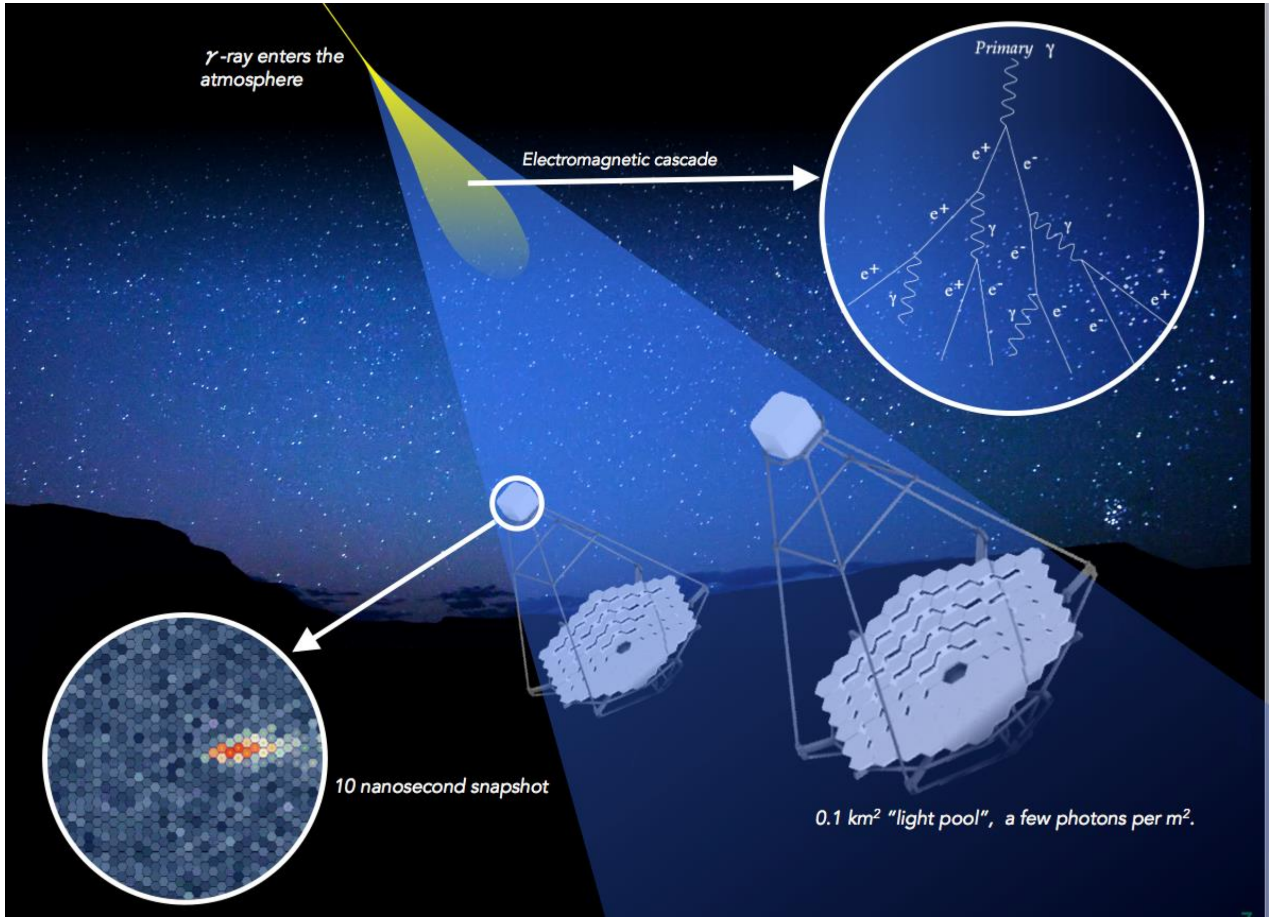
CONSENSUS STUDY REPORT

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

20M$

Imaging Air Cherenkov Detectors

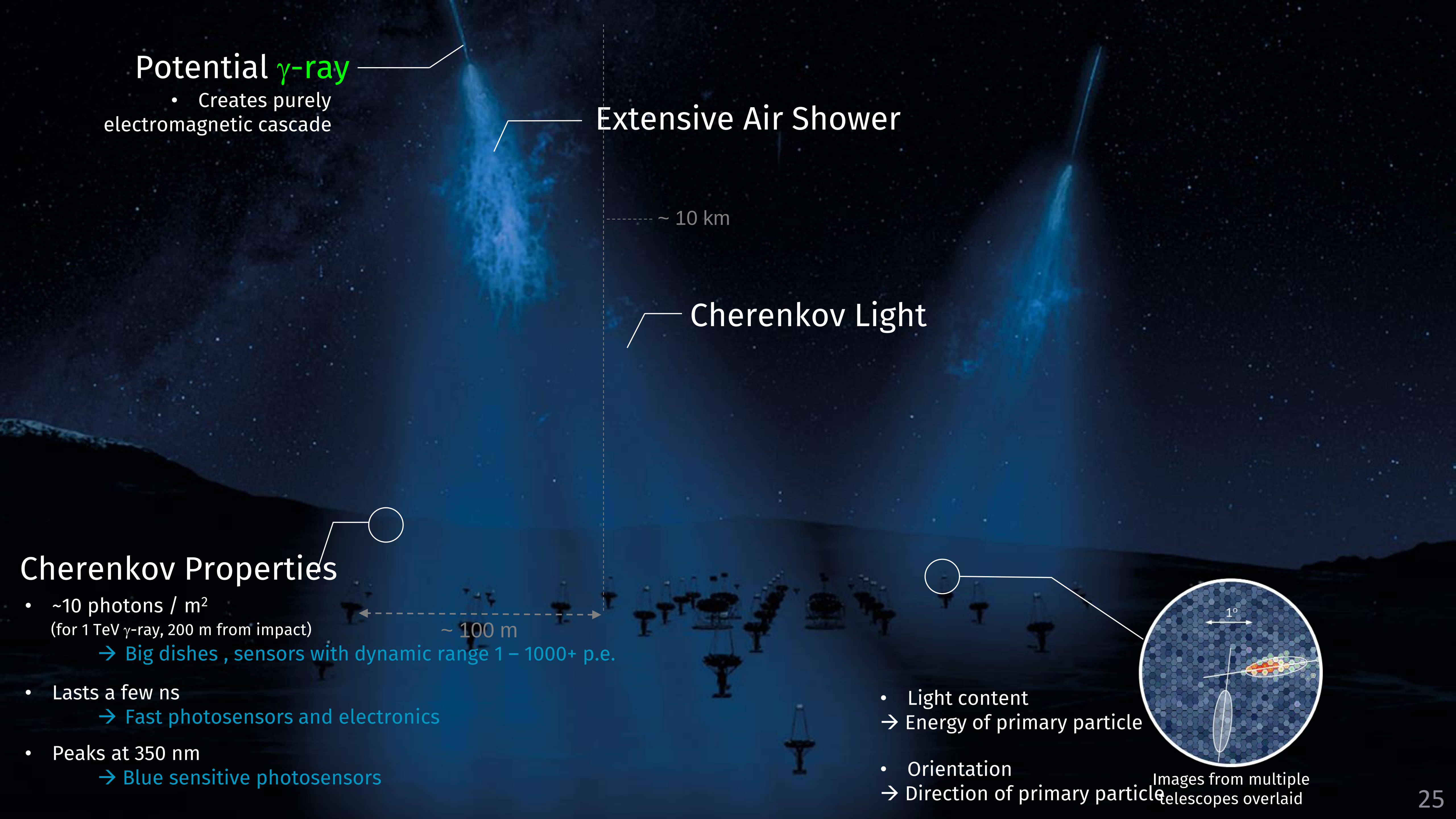
- Large collection area
- Excellent Background Rejection
- Low Duty Cycle/Small Aperture
  - ~15% duty-cycle
  - ~4 degree field of view
  - Surveys of limited regions of sky
- High precision
  - High angular resolution
  - High Resolution Energy Spectra
  - TeV sensitivity



- Creates purely electromagnetic cascade

Cherenkov Properties

- ~10 photons / m^2
  (for 1 TeV γ-ray, 200 m from impact)
  → Big dishes , sensors with dynamic range 1 – 1000+ p.e.
- Lasts a few ns
  → Fast photosensors and electronics
- Peaks at 350 nm
  → Blue sensitive photosensors



Potential γ-ray

- Creates purely electromagnetic cascade

Extensive Air Shower

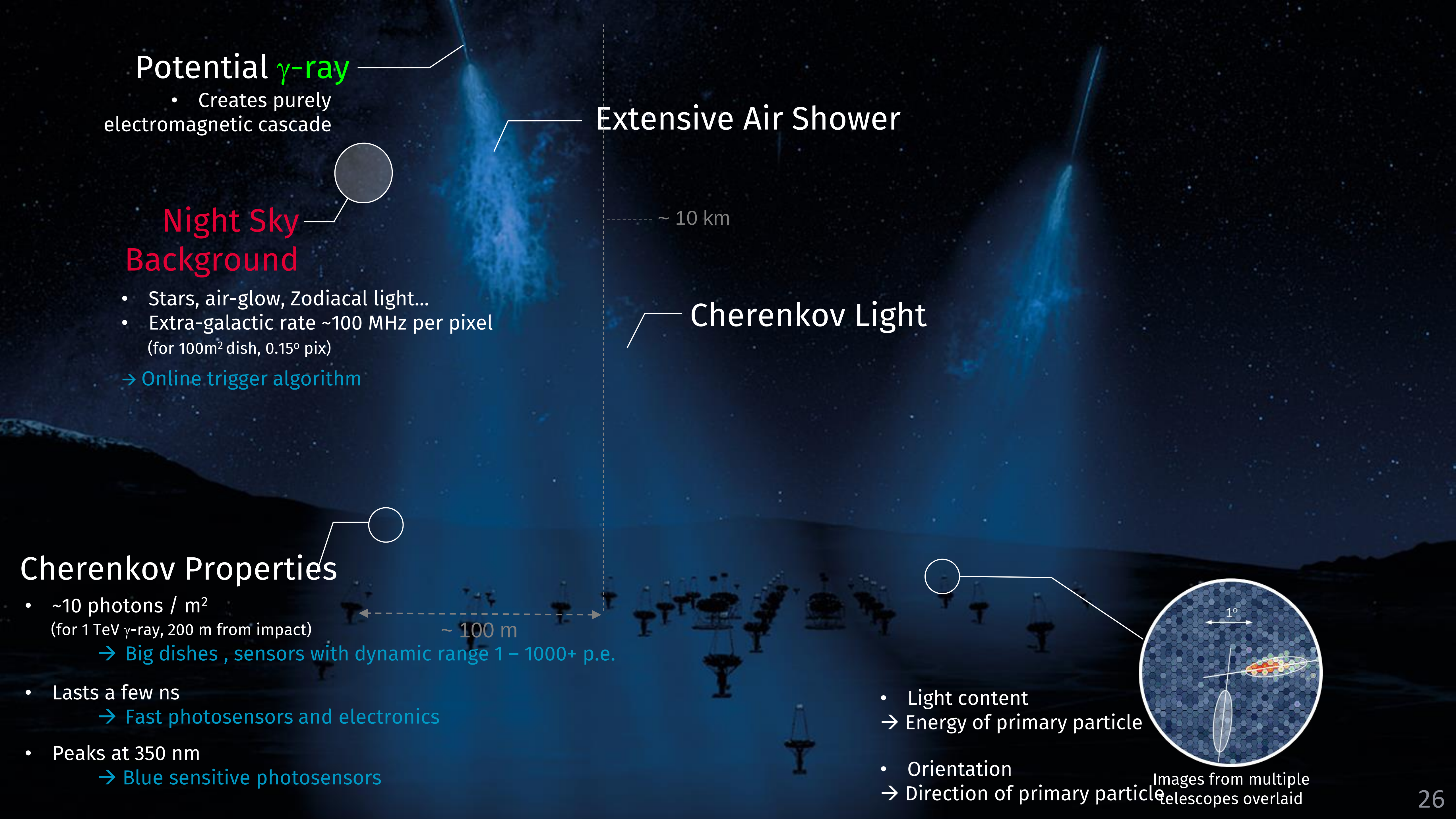
Cherenkov Light

Cherenkov Properties

- ~10 photons / m^2
  (for 1 TeV γ-ray, 200 m from impact)
  → Big dishes , sensors with dynamic range 1 – 1000+ p.e.
- Lasts a few ns
  → Fast photosensors and electronics
- Peaks at 350 nm
  → Blue sensitive photosensors

- Light content
  → Energy of primary particle
- Orientation
  → Direction of primary particle

Images from multiple telescopes overlaid



Potential γ-ray

- Creates purely electromagnetic cascade

Extensive Air Shower

Night Sky Background

- Stars, air-glow, Zodiacal light…
- Extra-galactic rate ~100 MHz per pixel (for 100m^2 dish, 0.15° pix)

→ Online trigger algorithm

Cherenkov Light

Cherenkov Properties

- ~10 photons / m^2 (for 1 TeV γ-ray, 200 m from impact)
  → Big dishes , sensors with dynamic range 1 – 1000+ p.e.
- Lasts a few ns
  → Fast photosensors and electronics
- Peaks at 350 nm
  → Blue sensitive photosensors

- Light content
  → Energy of primary particle
- Orientation
  → Direction of primary particle

Images from multiple telescopes overlaid

Potential γ-ray

- Creates purely electromagnetic cascade

Night Sky Background

- Stars, air-glow, Zodiacal light…
- Extra-galactic rate ~100 MHz per pixel (for 100m^2 dish, 0.15° pix)

→ Online trigger algorithm

Extensive Air Shower

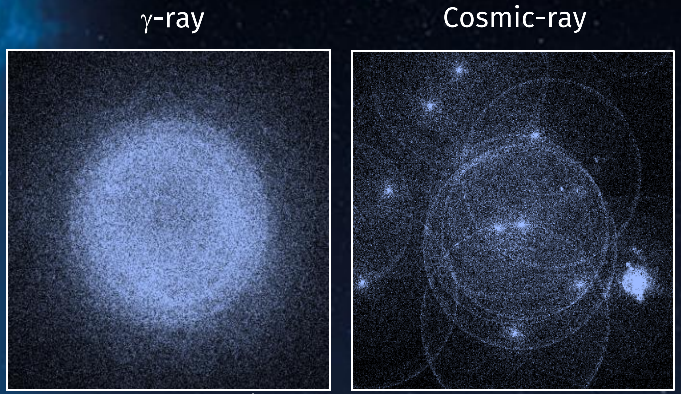
~ 10 km

Cherenkov Light

Potential Cosmic-ray

- Dominates γ-ray rate, even after NSB is reduced
- Complex cascade
- Irregular images in the camera

→ Offline image analysis



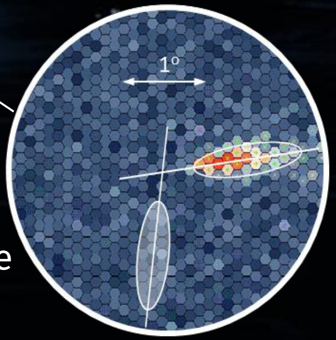
Cherenkov light pool on the ground

Cherenkov Properties

- ~10 photons / m^2 (for 1 TeV γ-ray, 200 m from impact)
  → Big dishes , sensors with dynamic range 1 – 1000+ p.e.
- Lasts a few ns
  → Fast photosensors and electronics
- Peaks at 350 nm
  → Blue sensitive photosensors

~ 100 m

- Shape
  → γ/CR discrimination
- Light content
  → Energy of primary particle
- Orientation
  → Direction of primary particle



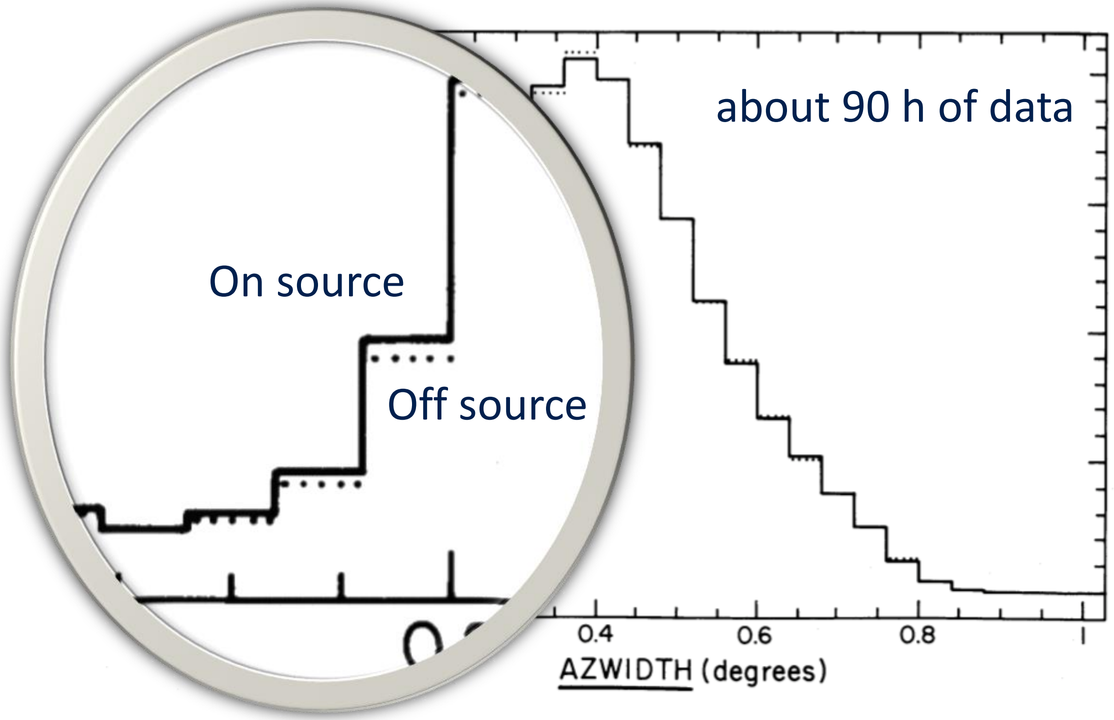
Images from multiple telescopes overlaid

GROUND-BASED GAMMA RAY ASTRONOMY 1989

Whipple Telescope 1968

T. Weekes et al., ApJ 342 (1989) 379

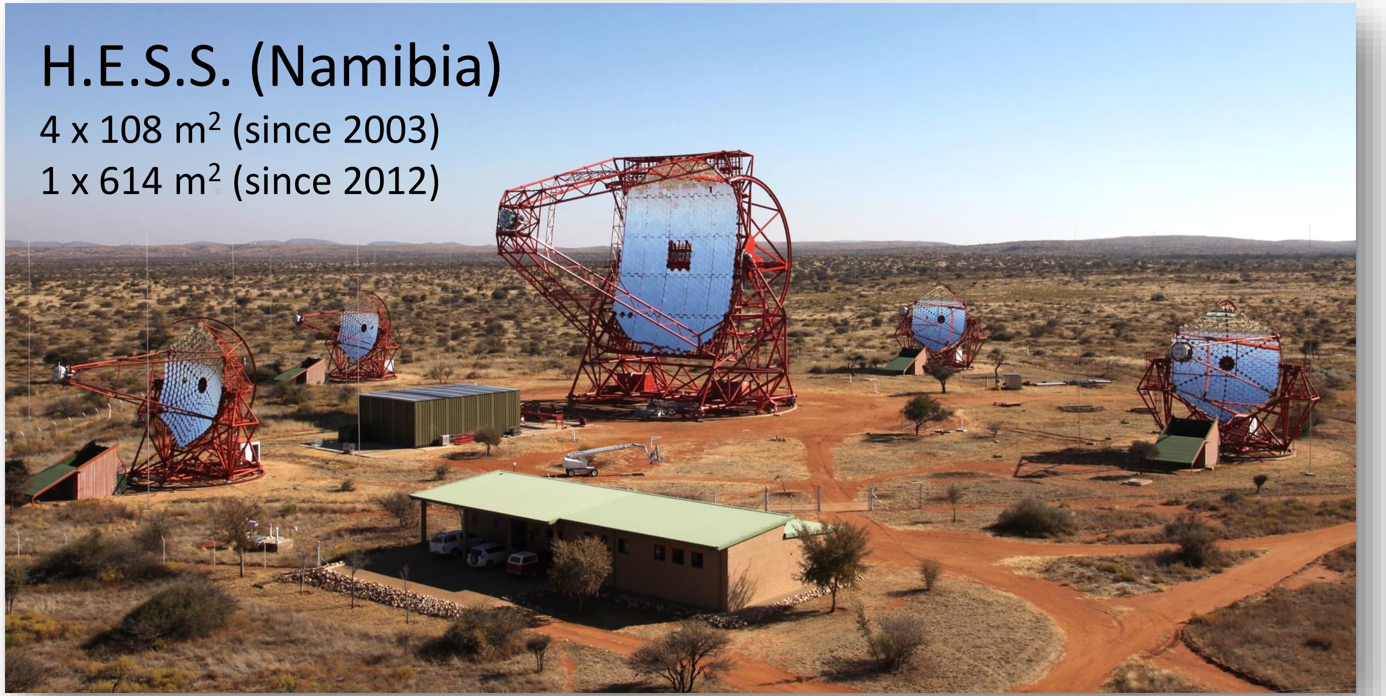
“Observation of TeV Gamma Rays from the Crab Nebula using the Atmospheric Cerenkov Imaging Technique”



about 90 h of data

On source

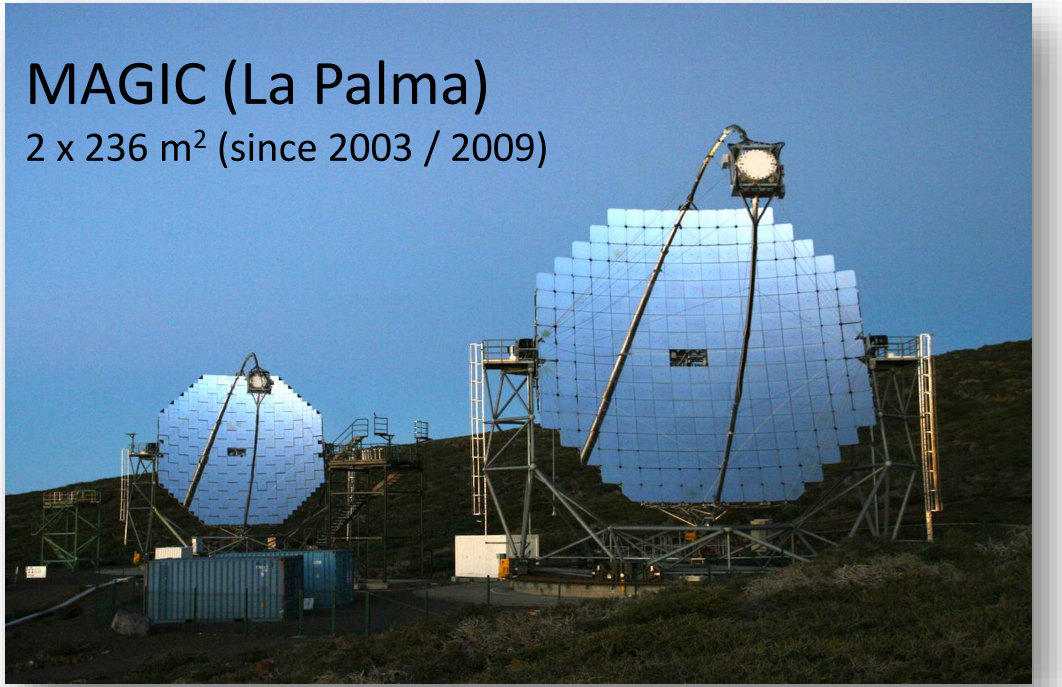
Off source



H.E.S.S. (Namibia)

4 x 108 m^2 (since 2003)

1 x 614 m^2 (since 2012)

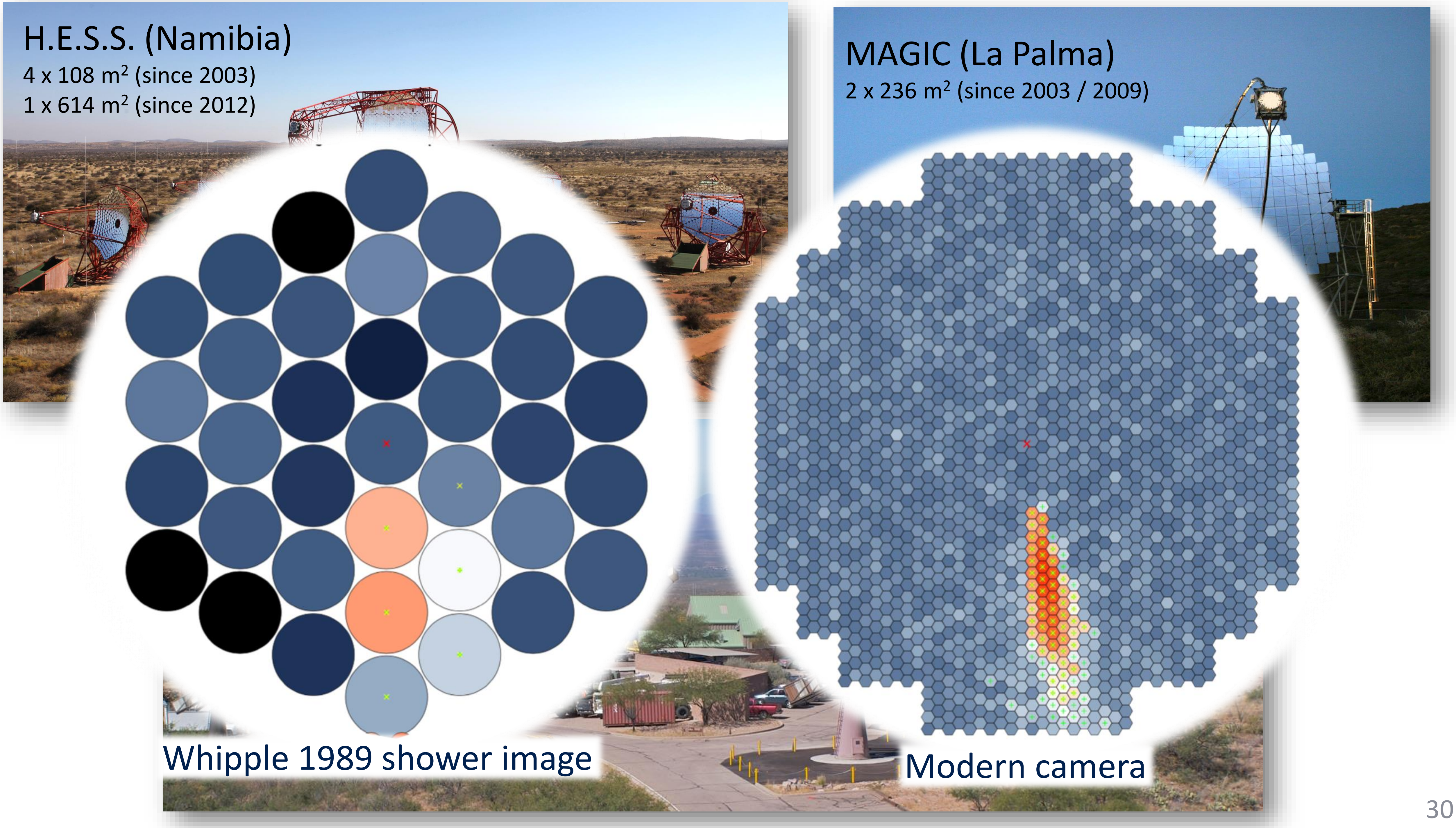


MAGIC (La Palma)

2 x 236 m^2 (since 2003 / 2009)

VERITAS (Arizona)

4 x 110 m^2 (since 2007)



H.E.S.S. (Namibia)

4 x 108 m^2 (since 2003)
1 x 614 m^2 (since 2012)

MAGIC (La Palma)

2 x 236 m^2 (since 2003 / 2009)

Whipple 1989 shower image

Modern camera

The Cherenkov Telescope Array

The next big step

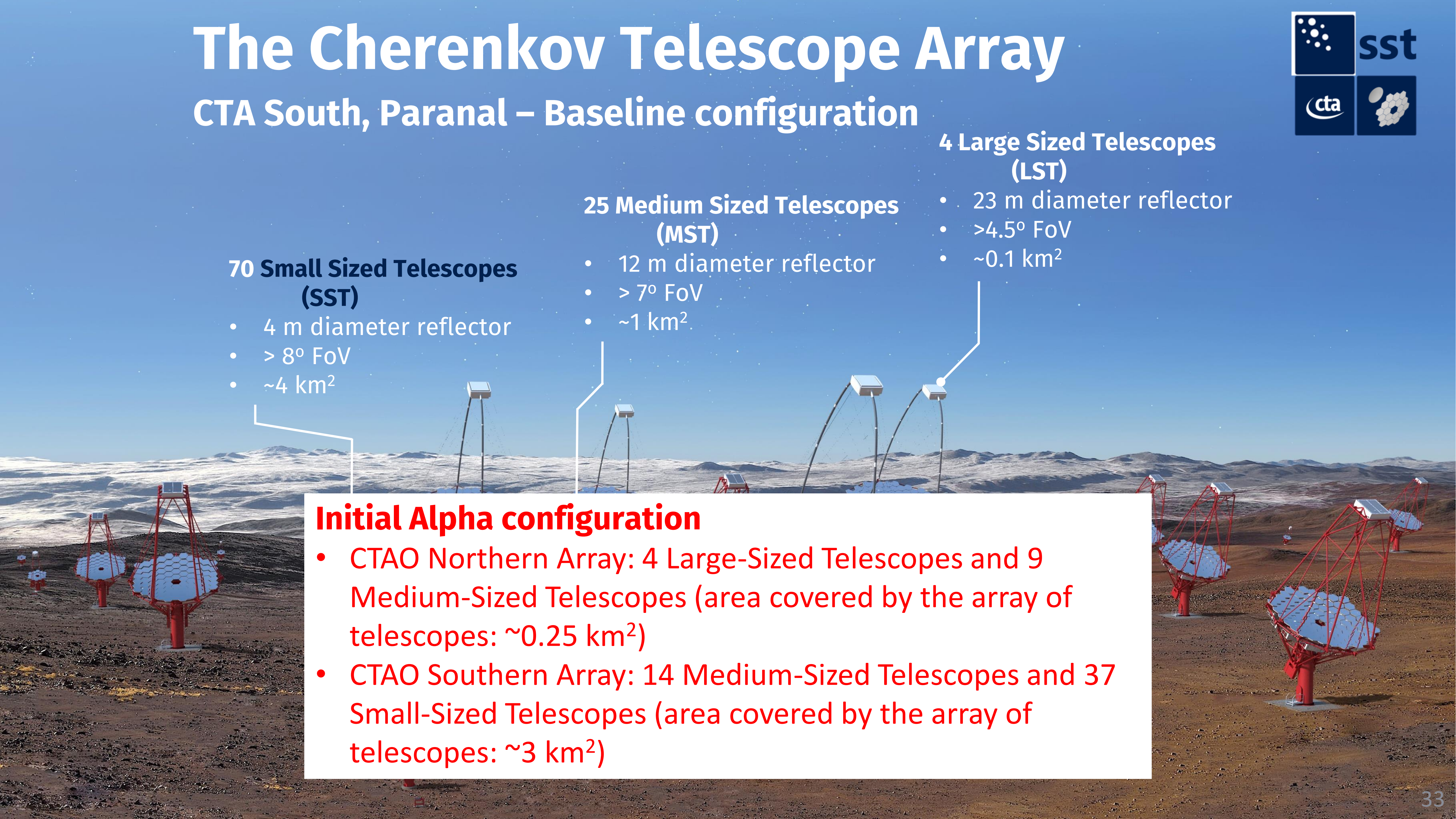
- World’s first VHE gamma-ray observatory
- Explores top 4-5 decades in energy - 20 GeV to 300 TeV
- Factor of 10 improvement in sensitivity compared to current telescopes
- Full sky coverage
- Large community of users

The Cherenkov Telescope Array

La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google

The Cherenkov Telescope Array

CTA South, Paranal – Baseline configuration



70 Small Sized Telescopes (SST)
- 4 m diameter reflector
- > 8° FoV
- ~4 km^2

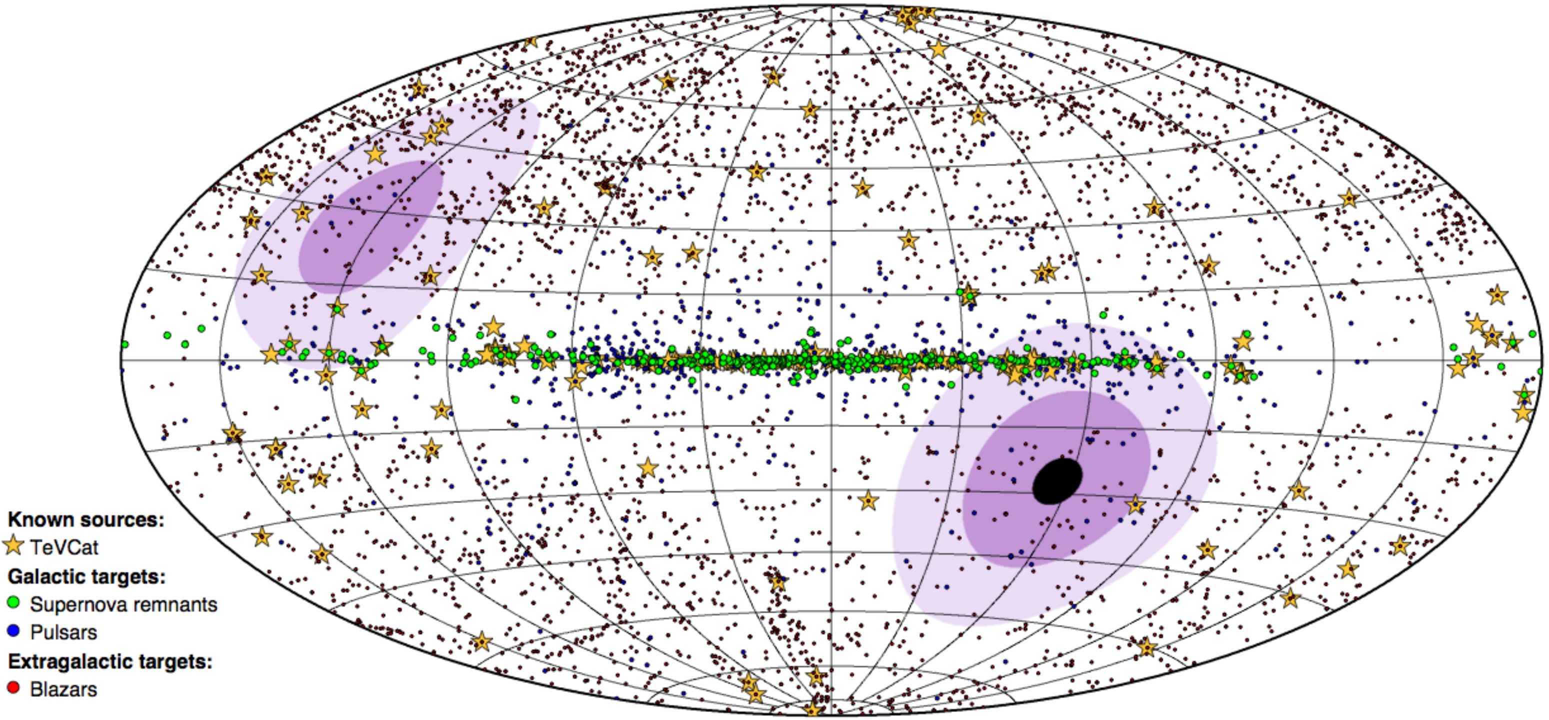
25 Medium Sized Telescopes (MST)
- 12 m diameter reflector
- > 7° FoV
- ~1 km^2

4 Large Sized Telescopes (LST)
- 23 m diameter reflector
- >4.5° FoV
- ~0.1 km^2

Initial Alpha configuration
- CTAO Northern Array: 4 Large-Sized Telescopes and 9 Medium-Sized Telescopes (area covered by the array of telescopes: ~0.25 km^2)
- CTAO Southern Array: 14 Medium-Sized Telescopes and 37 Small-Sized Telescopes (area covered by the array of telescopes: ~3 km^2)

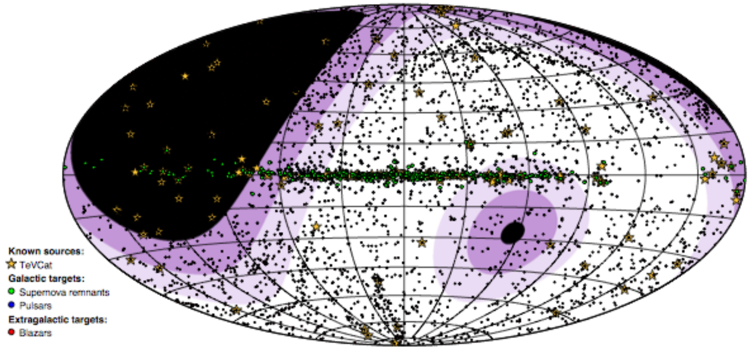
CTA Science:
Full-sky Coverage

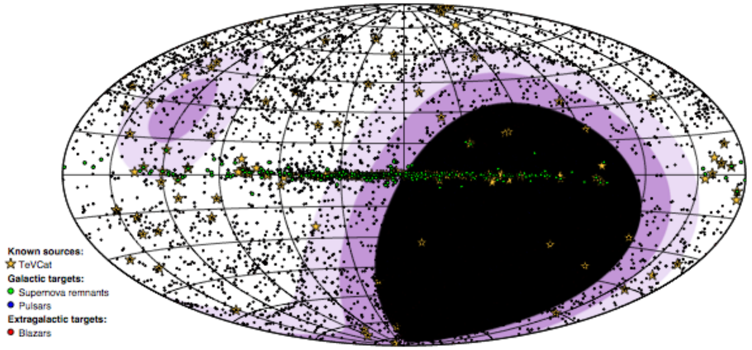
North+South



>60º zenith
45º-60º
30º-45º

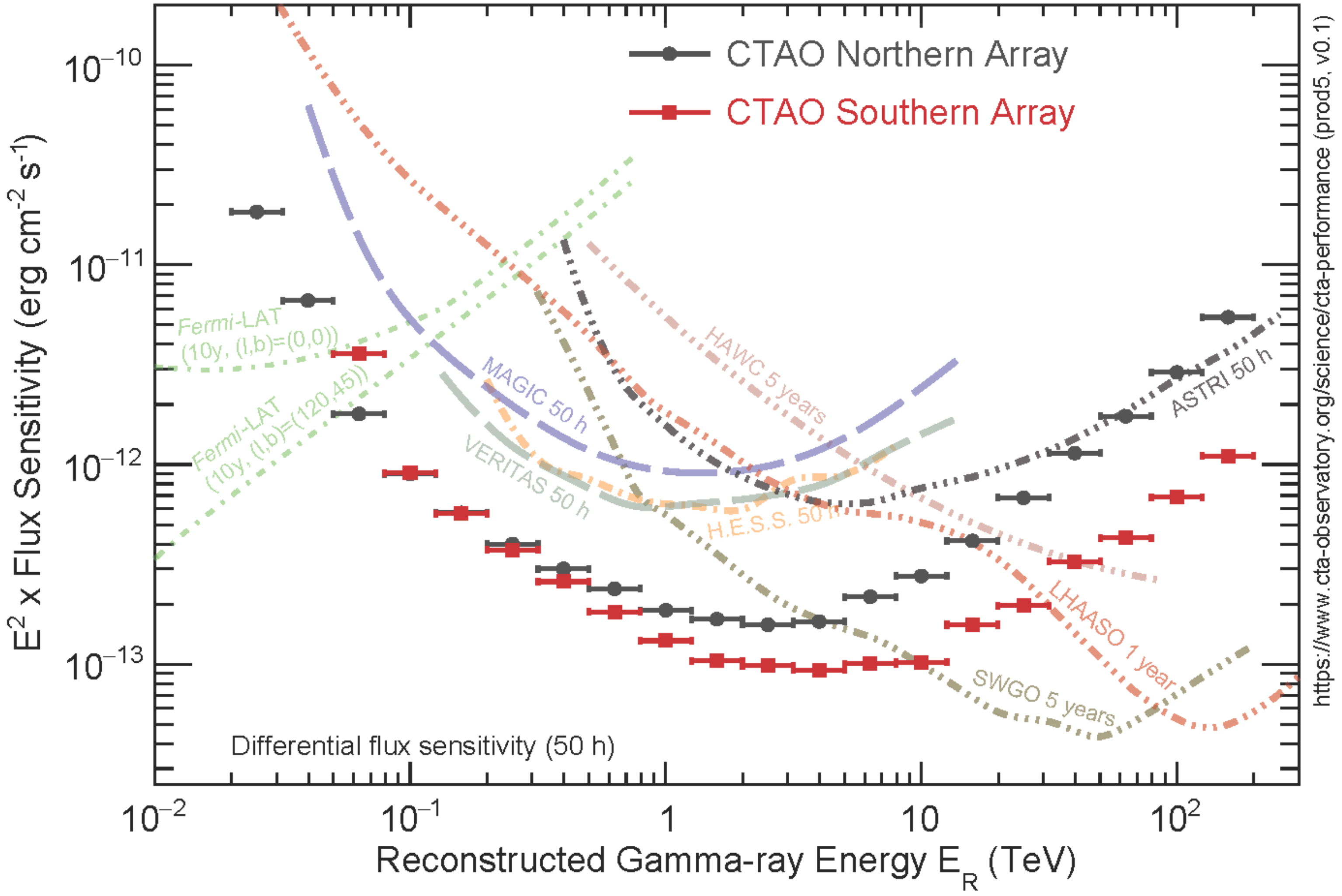
South





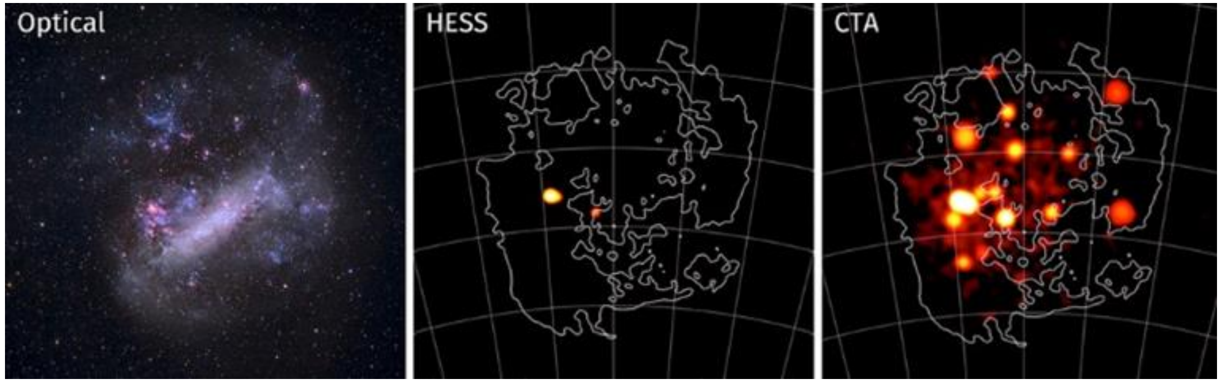
North

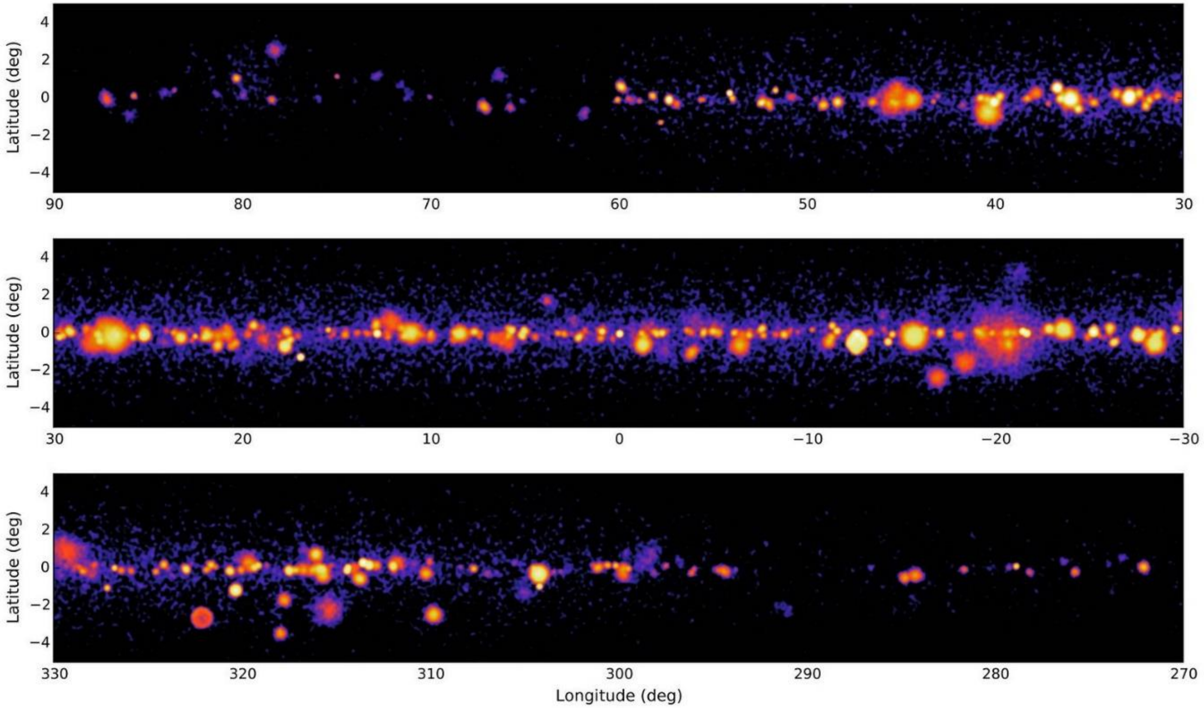
CTA Science:
Improved Sensitivity



CTA Science:
Improved Sensitivity

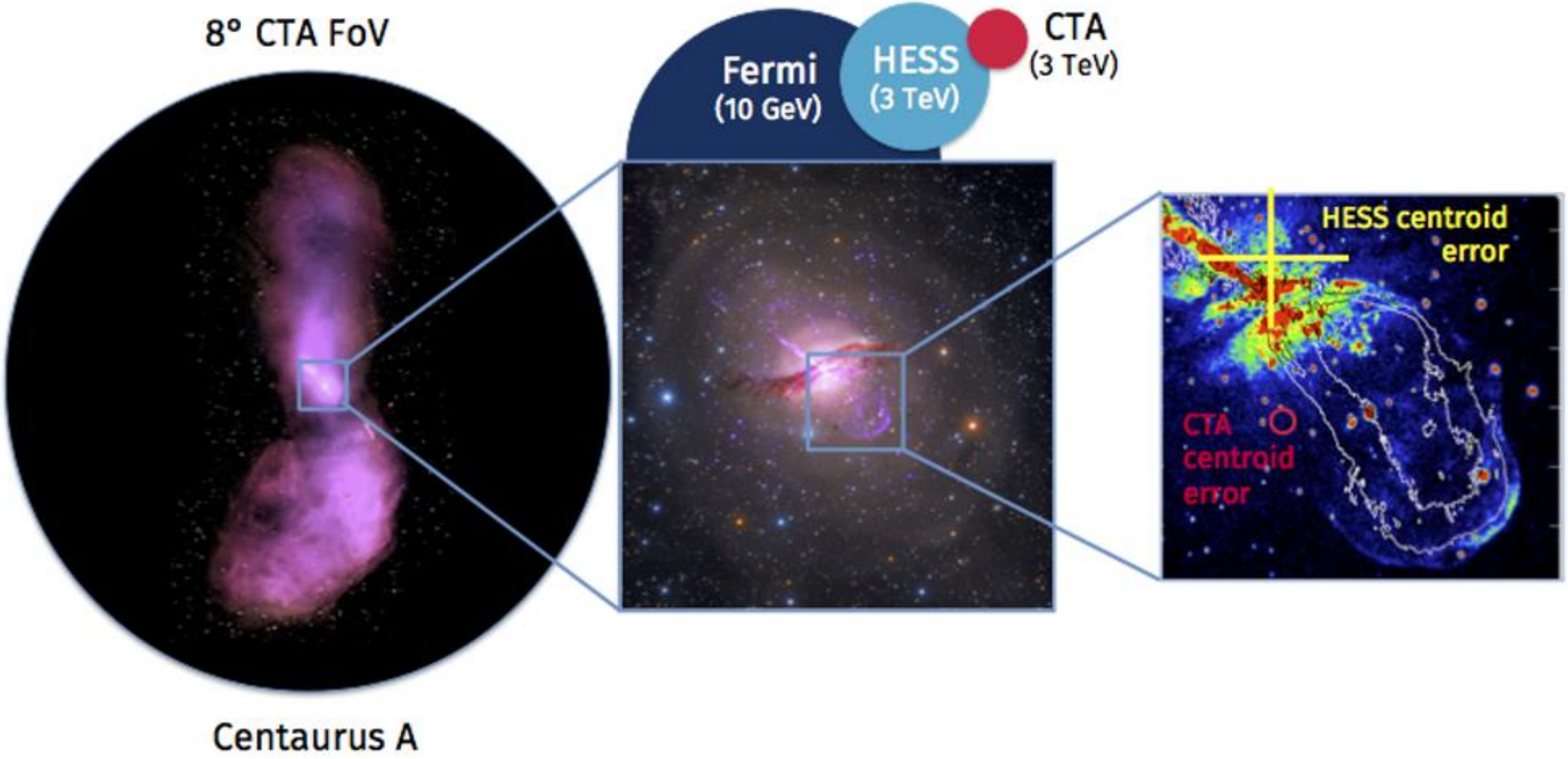
LMC and Galactic Plane observations will provide many more detections





Expect an increase of a factor of ~10 in the source catalogue.

CTA Science:
Improved Angular Resolution

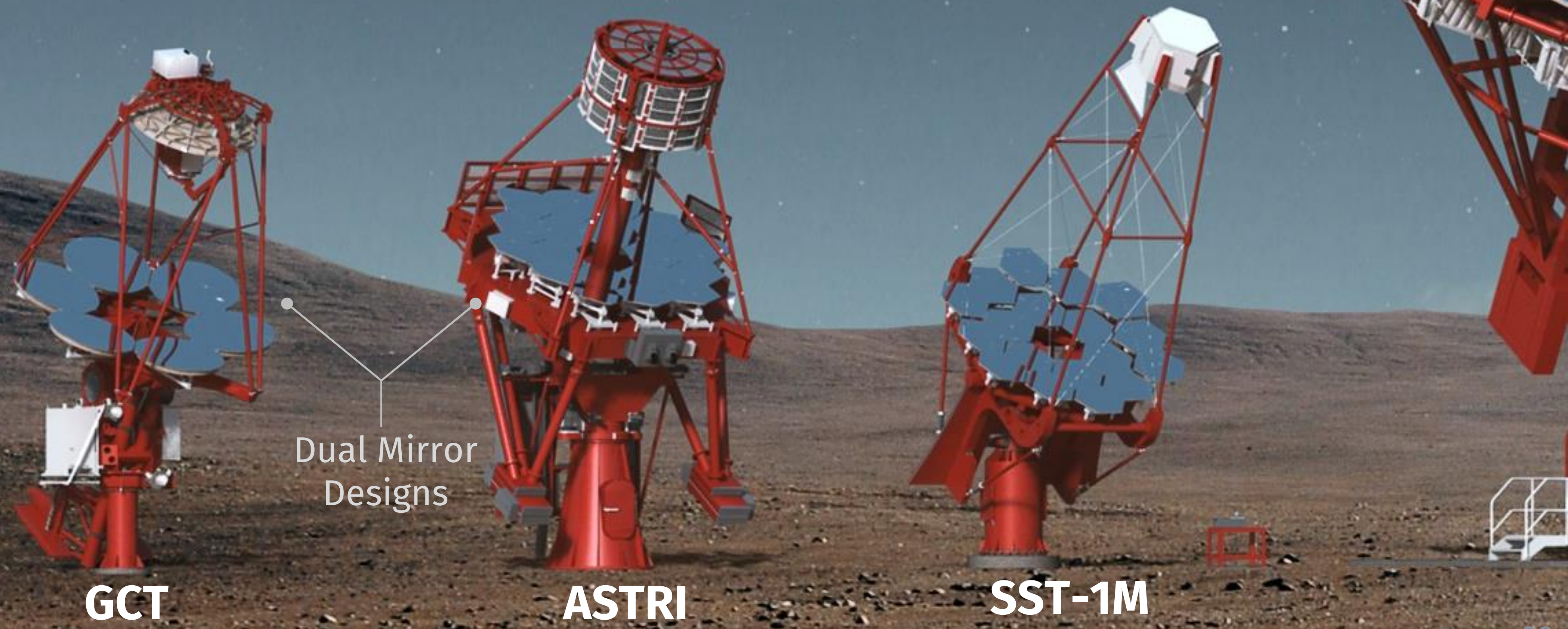


The best angular resolution of any instrument above 100 keV

Small-Sized Telescope (SST)

Three SST Designs Proposed

- Dual mirror (SST-2M) design allows use of a compact camera
    - Short focal length → reduced plate scale → small camera and pixels
    - Candidate sensors: MAPMTs, SiPMs
- Technical challenges
    - Curved focal plane (R_c = 1.0 m)
    - High density readout electronics required
    - Low cost



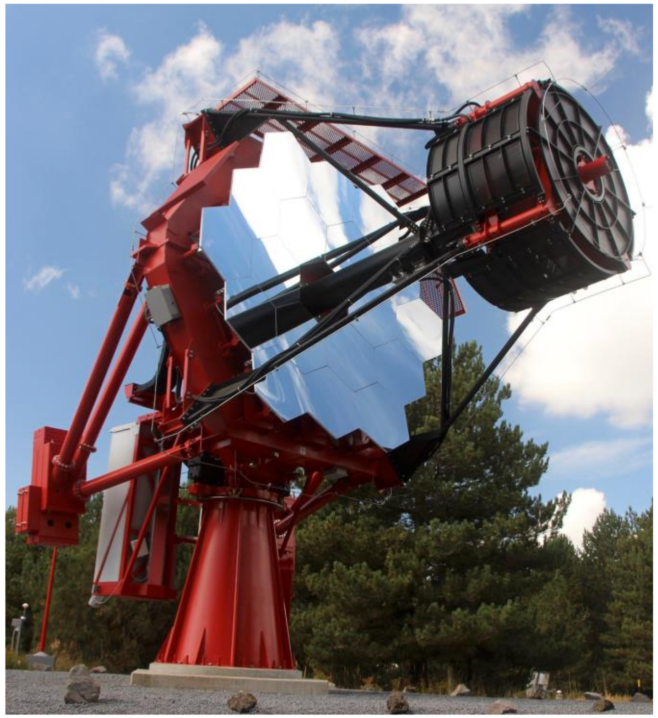
Three Prototype SSTs Developed

- Prototypes for all SSTs (telescopes and cameras) exist
  → The dual-mirror telescope prototypes provided
  a test-bed for the Compact High Energy Camera (CHEC)

Meudon, France

GCT

Serra La Nave, Italy



ASTRI

Krakow, Poland

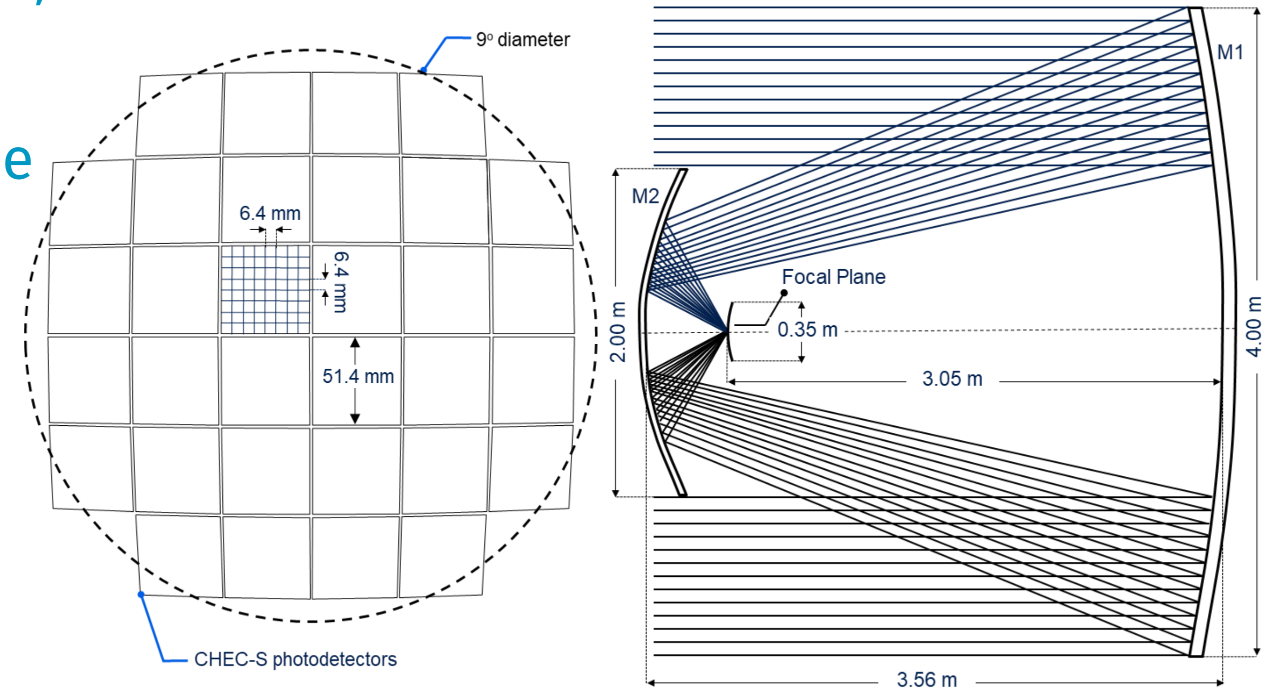
SST-1M

CTA Small-Sized Telescope

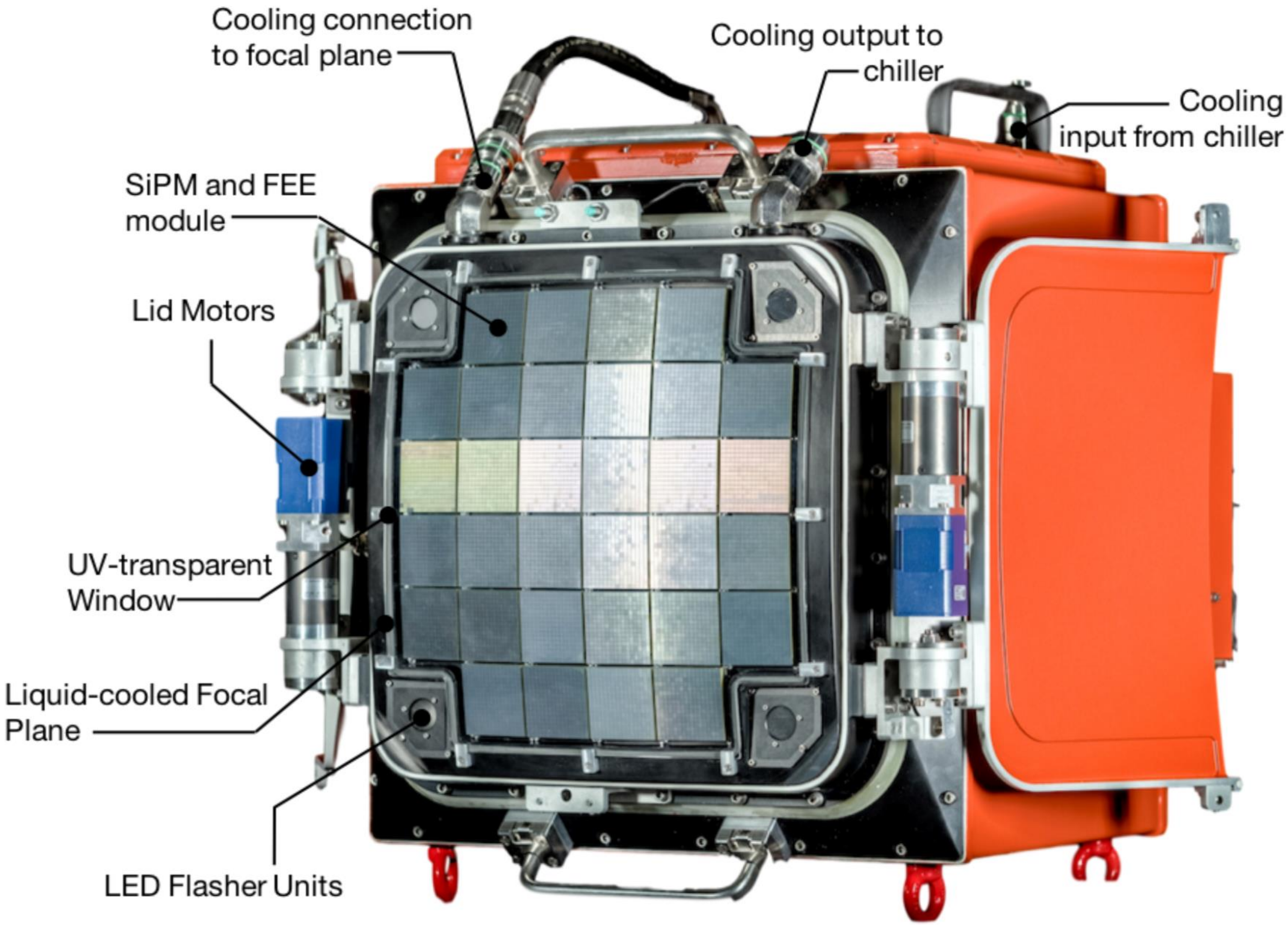
CTA-SST dual-mirror design

- CTA-SST dual-mirror (SST-2M) telescopes
  - Uses Schwarzschild-Couder optics, as first proposed for IACTs by Vassiliev
  - SST-2M telescopes designed to be compatible with same camera
  - Small plate scale enables use of smaller, lower cost camera – CHEC

- SST design drivers:
  - High performance at low cost
  - Ease of production and maintenance

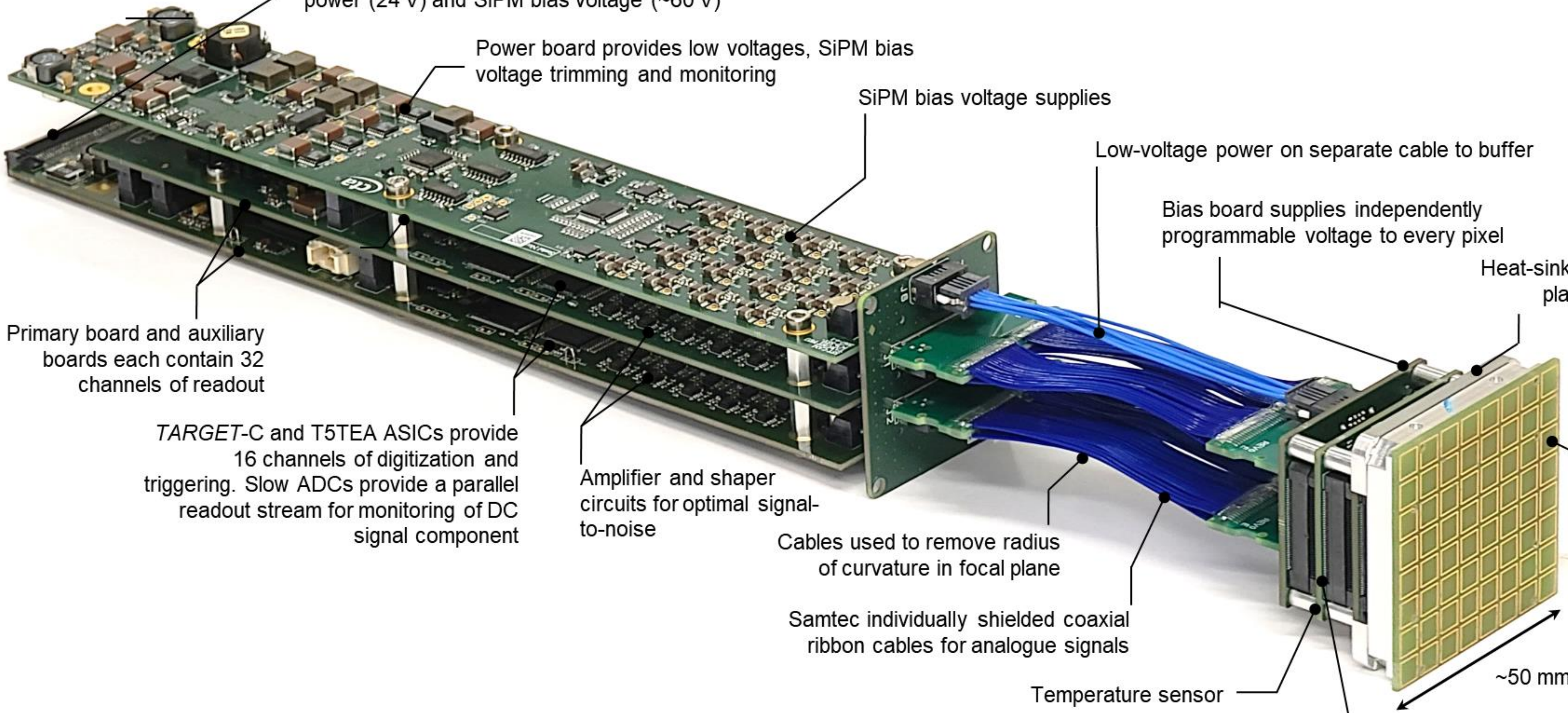


Prototyping the Compact High-Energy Camera
CHEC-S



Prototyping the Compact High-Energy Camera

CHEC-S



Connection to the backplane: raw data, trigger, clock signals, electronics power (24 V) and SiPM bias voltage (~60 V)

Power board provides low voltages, SiPM bias voltage trimming and monitoring

SiPM bias voltage supplies

Low-voltage power on separate cable to buffer

Bias board supplies independently programmable voltage to every pixel

Heat-sink to focal plane plate

Primary board and auxiliary boards each contain 32 channels of readout

TARGET-C and T5TEA ASICs provide 16 channels of digitization and triggering. Slow ADCs provide a parallel readout stream for monitoring of DC signal component

Amplifier and shaper circuits for optimal signal-to-noise

SiPM Tile (dummy)

Cables used to remove radius of curvature in focal plane

Samtec individually shielded coaxial ribbon cables for analogue signals

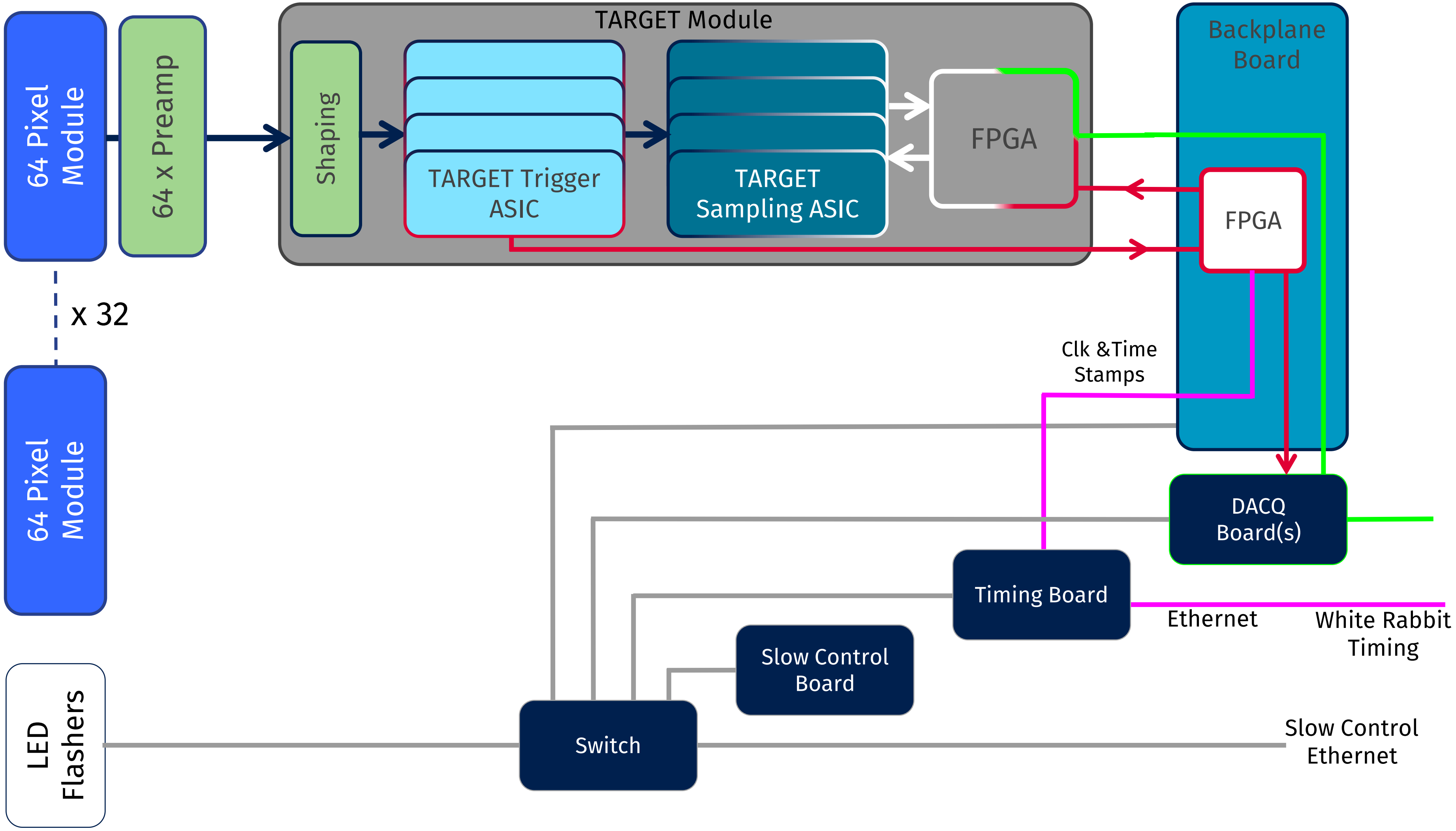
~50 mm

Temperature sensor

Buffer circuits for noise immunity

Prototyping the Compact High-Energy Camera

Camera Architecture



CHEC Field Trials - 2019

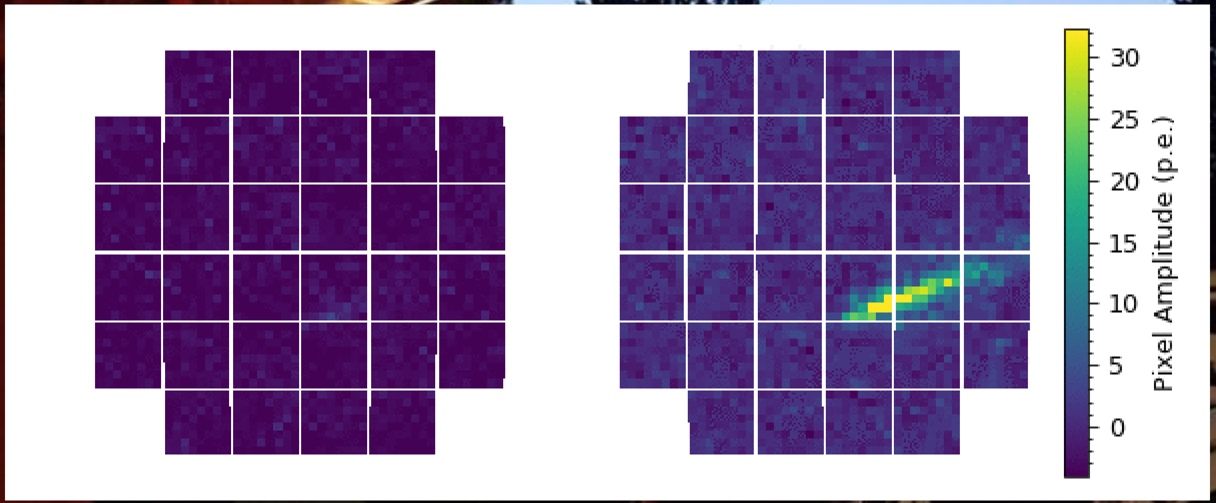
An obvious place to put a telescope!

CHEC-S Field Trials Success!

Sicily, Southern slope of Mt. Etna at Serra La Nave

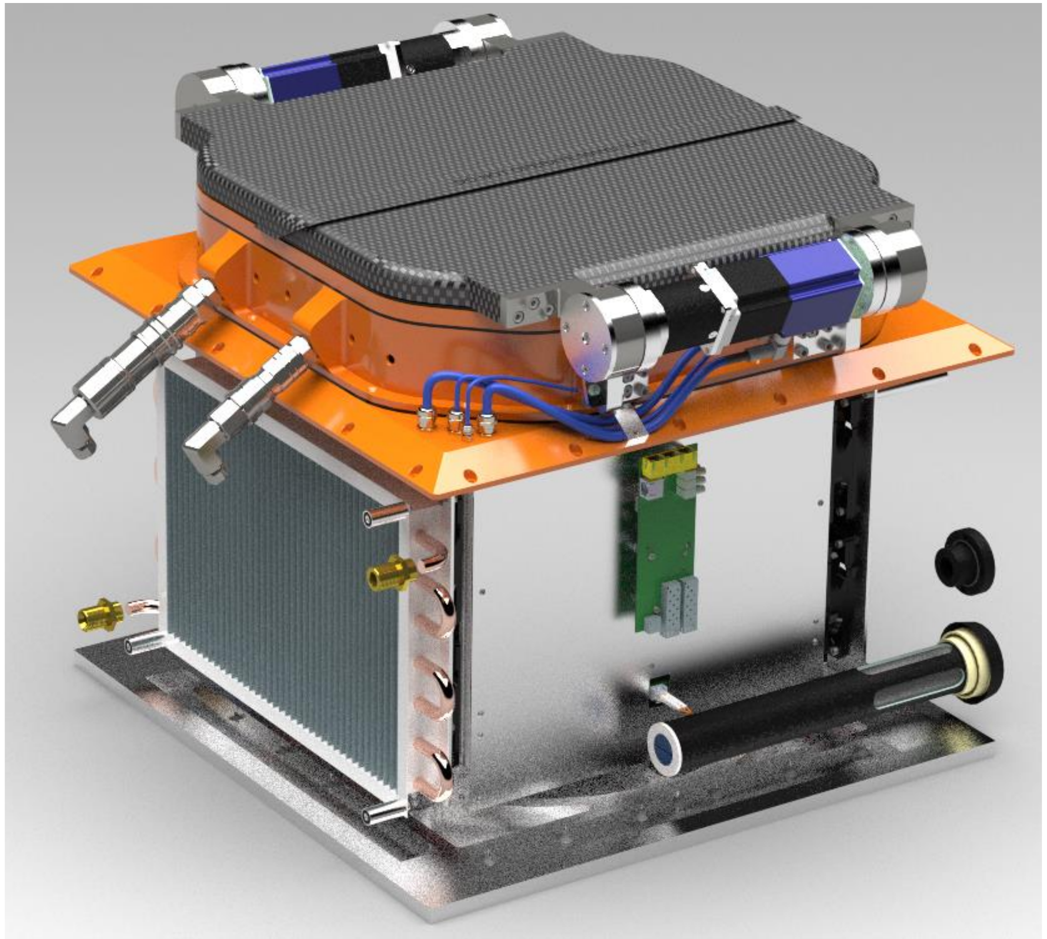
Hosted by INAF-Catania

1750 m asl



SST Camera
Selection

- Following 2019 CTAO Harmonization review
  - CHEC selected as baseline SST Camera
  - ASTRI selected as baseline telescope
- SST Camera Key Features
  - Fine pixellation, ~9° FoV
  - SiPMs with Target ASIC readout
    - 5x lower cost than MST/LST per pixel
    - Higher detector efficiency
  - Efficient trigger scheme
  - Full waveform readout
- Now focused on an iteration to ensure
  - Ease of production
  - High quality
  - Ease of installation
  - Low maintenance needs



SST Camera

UK Involvement

- The UK has been central in the design of the SST Camera
- Design for production is completed and being proven
- The finalization of the CTAO ERIC is imminent
- Construction of the first 42 SSTs will begin in 2024

A future of Gamma-ray astronomy in the UK?

- CTA and SWGO strongly supported by PAAP, however ..
- UK involvement in CTAO
  - STFC have ceased funding the UK elements of the CTA SST
  - Loss of Front-End Electronics to UK industry worth >£3M
  - Jeopardises funding of the CTA Small-Sized Telescope programme
  - UK participation in CTA Key Science Projects in jeopardy

- UK involvement in SWGO – Durham, Leicester, Oxford
  - Application of wavelength-shifting materials
    → reduce PMT size and costs
  - Calibration “flasher” systems
  - Worry that UK funding bodies will be similarly shortsighted

Thank you for your attention