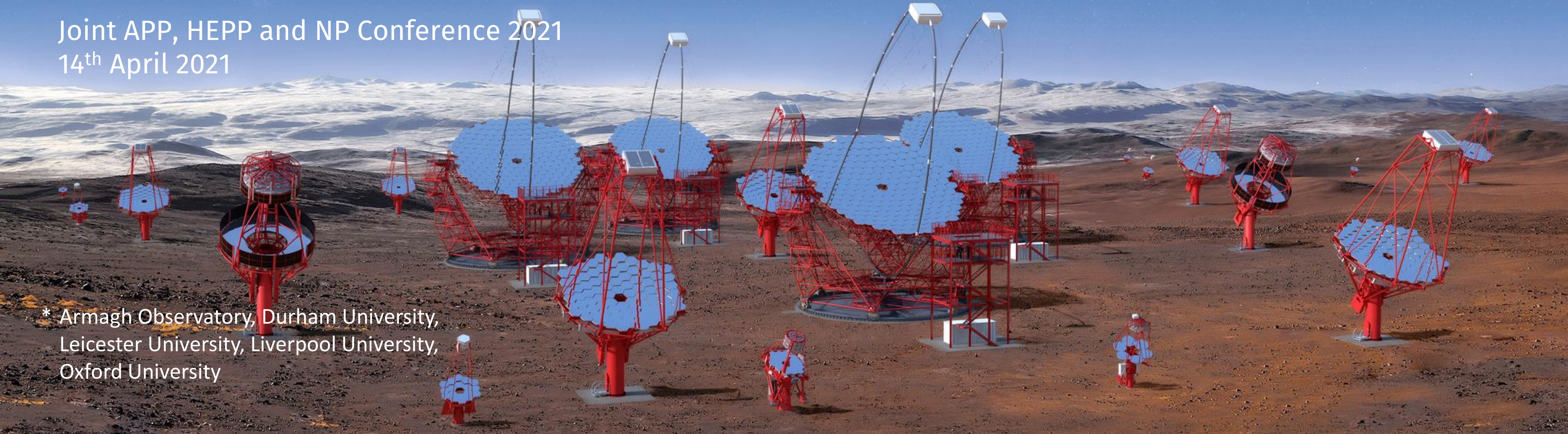
Very High Energy Gamma-ray Astronomy with the Cherenkov Telescope Array

Jon Lapington
On behalf of the UK-SST Camera Project*

Joint APP, HEPP and NP Conference 2021
14th April 2021



* Armagh Observatory, Durham University, Leicester University, Liverpool University, Oxford University

Outline

- Introduction
- The Cherenkov Telescope Array
- The Small-Sized Telescope
- Prototyping CHEC
- SST Camera Project
- CTA Observatory Status
- CTA UK Science Community

Introduction

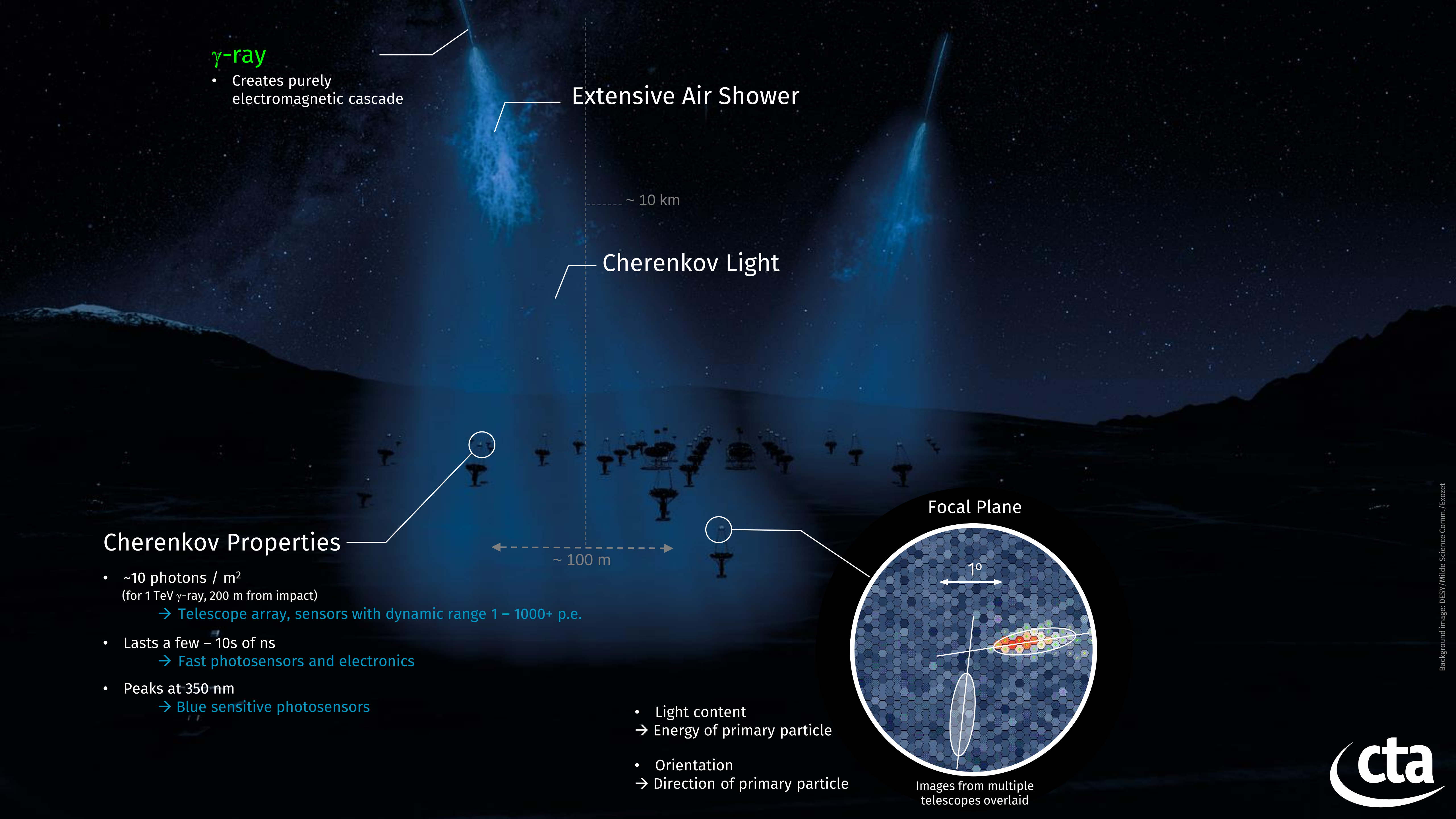
γ-ray

- Creates purely electromagnetic cascade

Cherenkov Properties

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

Background image: DESY/Milde Science Comm./Exozet



γ-ray
- Creates purely electromagnetic cascade

Extensive Air Shower

Cherenkov Light

Cherenkov Properties

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Focal Plane

Images from multiple telescopes overlaid

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

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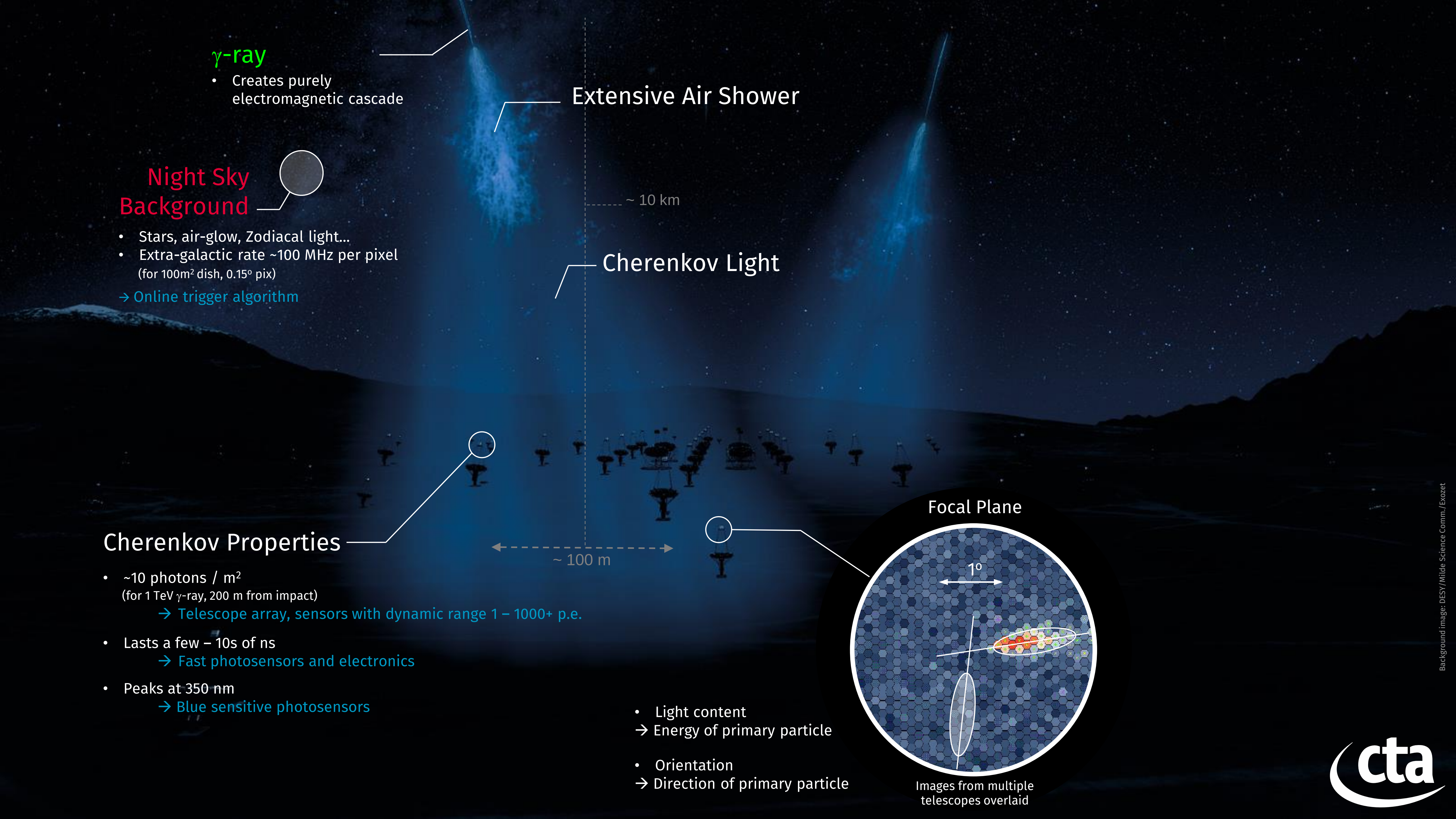

γ-ray

- Creates purely electromagnetic cascade

Extensive Air Shower

Night Sky Background

- Stars, air-glow, Zodiacal light…
- Extra-galactic rate ~100 MHz per pixel
  (for 100m² dish, 0.15° pix)

→ Online trigger algorithm

Cherenkov Light

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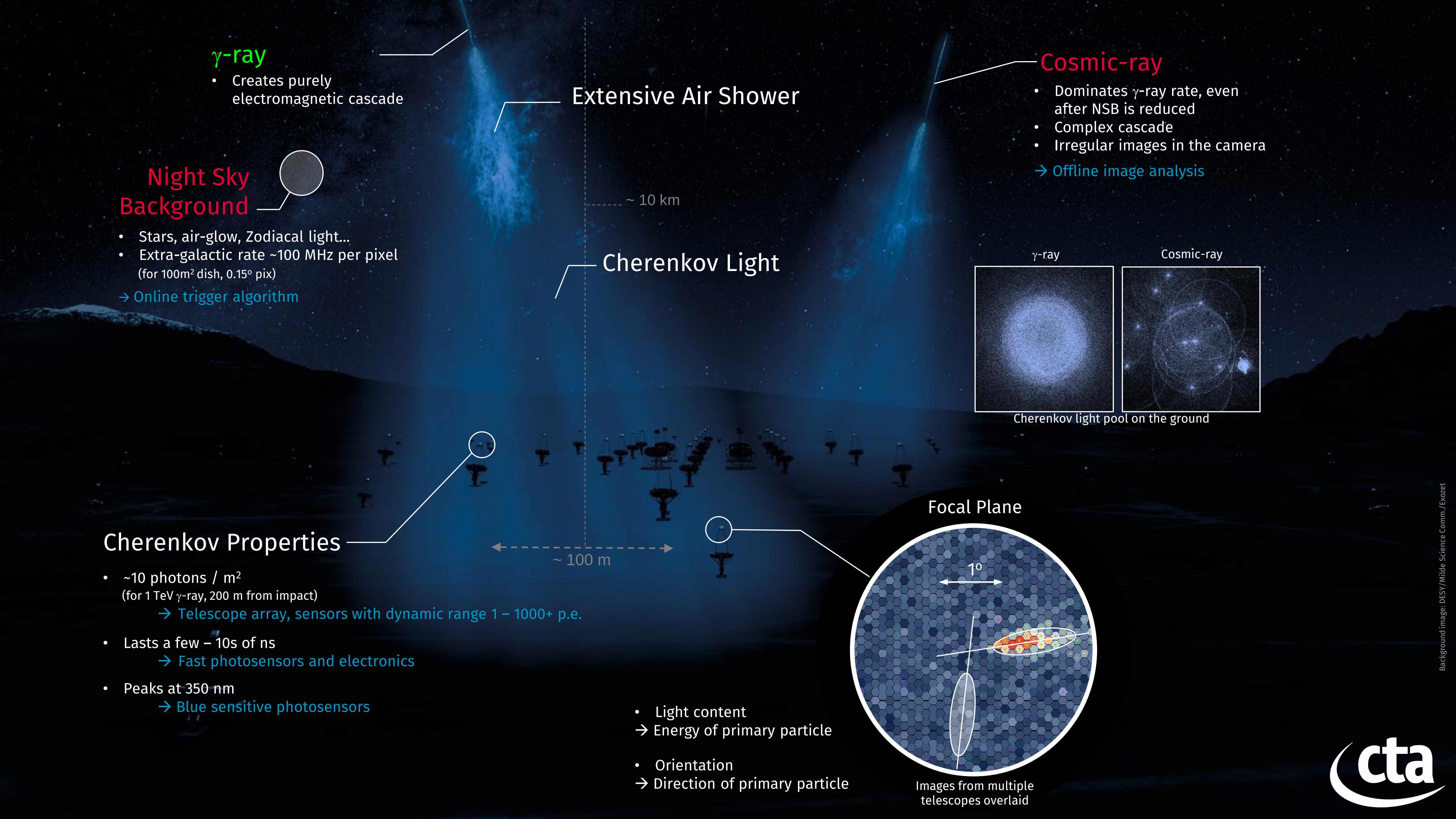

γ-ray

- Creates purely electromagnetic cascade

Extensive Air Shower

Cosmic-ray

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

→ Offline image analysis

Night Sky Background

- Stars, air-glow, Zodiacal light…
- Extra-galactic rate ~100 MHz per pixel (for 100m² dish, 0.15° pix)

→ Online trigger algorithm

Cherenkov Light

Cherenkov light pool on the ground

Cherenkov Properties

- ~10 photons / m² (for 1 TeV γ-ray, 200 m from impact)
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Focal Plane

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Images from multiple telescopes overlaid

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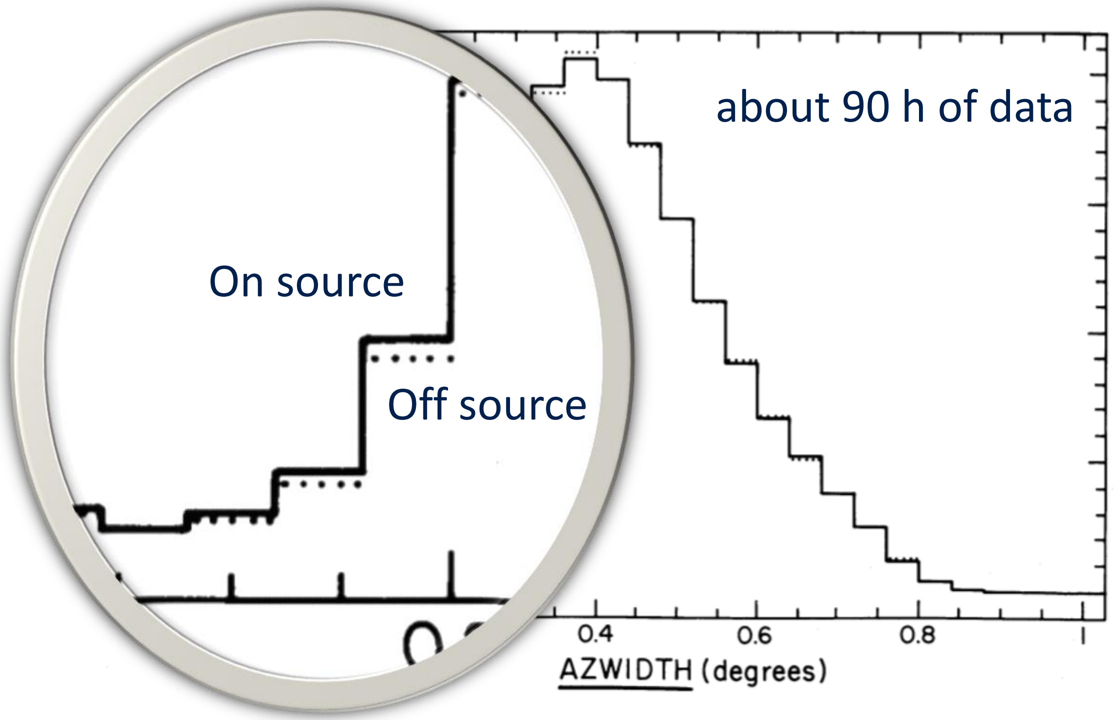
GROUND-BASED GAMMA RAY ASTRONOMY 1989

Whipple Telescope 1968

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

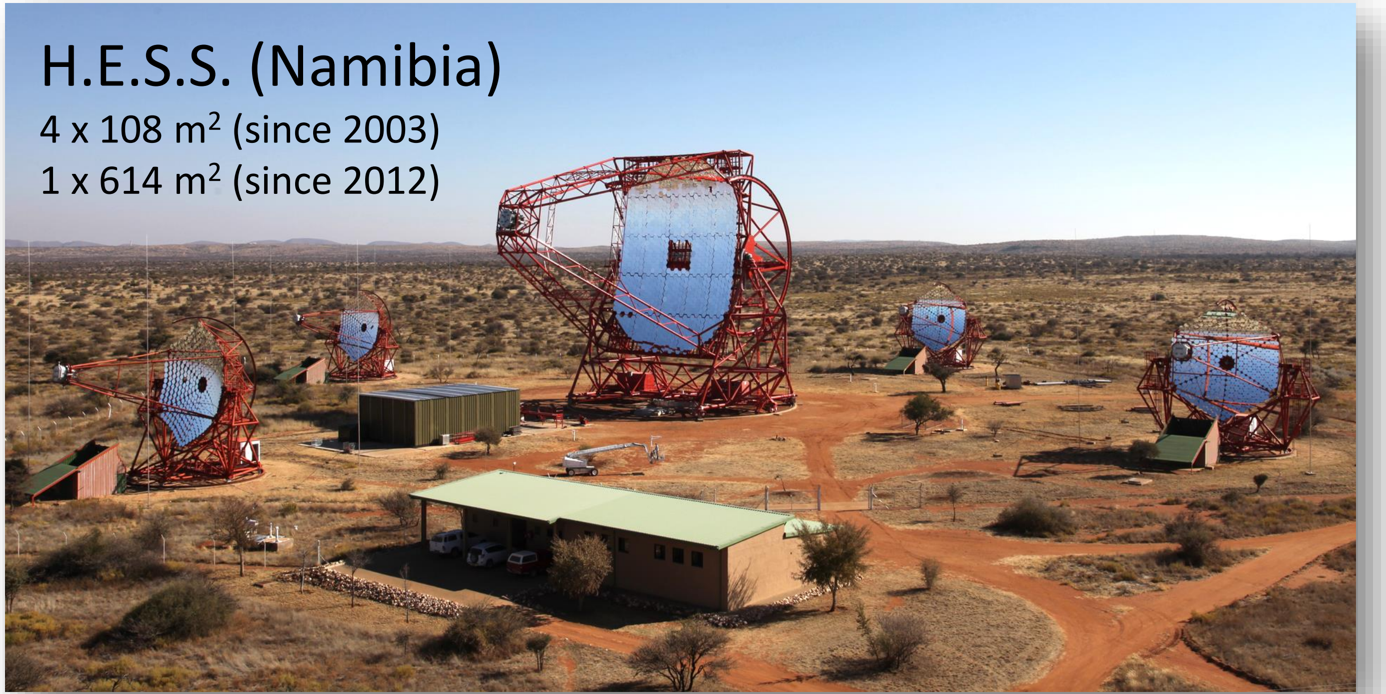
“Observation of TeV Gamma Rays from the Crab Nebula using the Atmospheric Cerenkov Imaging Technique”



about 90 h of data

On source

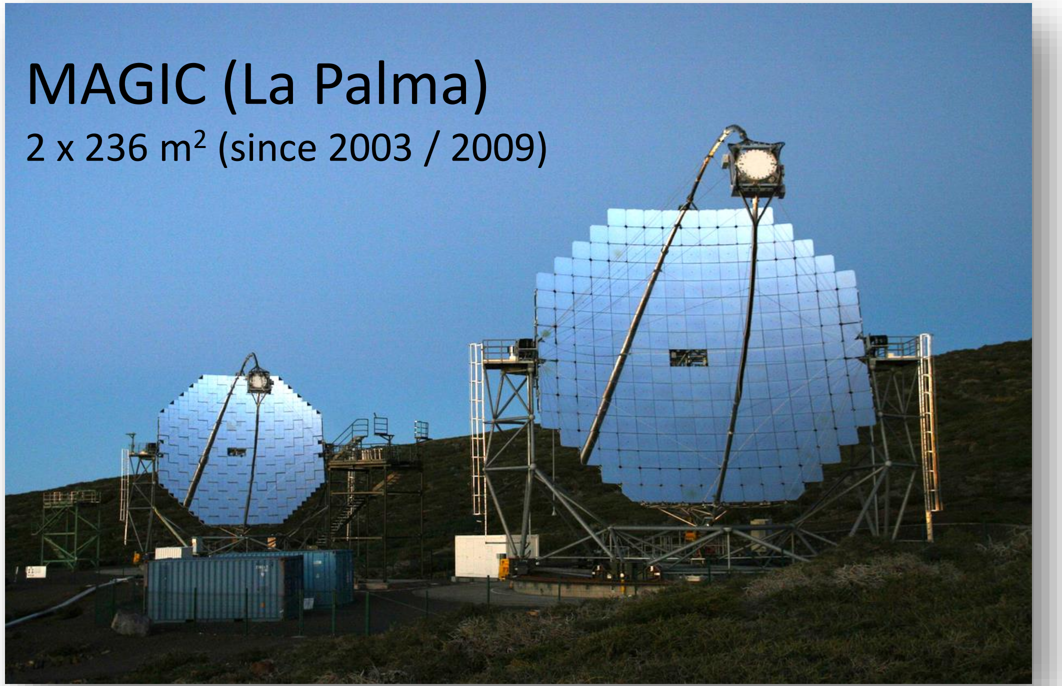
Off source



H.E.S.S. (Namibia)

4 x 108 m^2 (since 2003)

1 x 614 m^2 (since 2012)

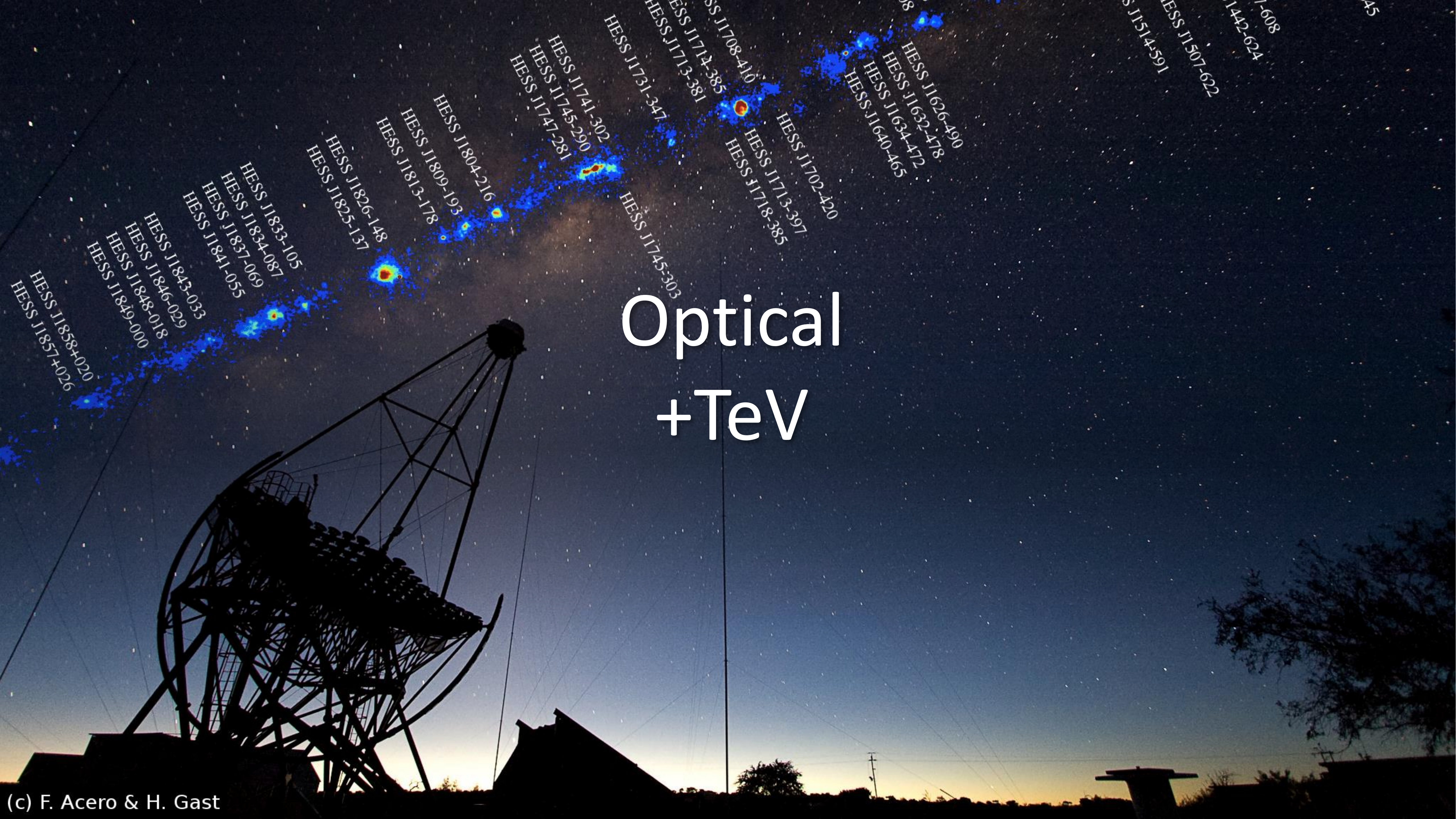


MAGIC (La Palma)

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

VERITAS (Arizona)

4 x 110 m^2 (since 2007)

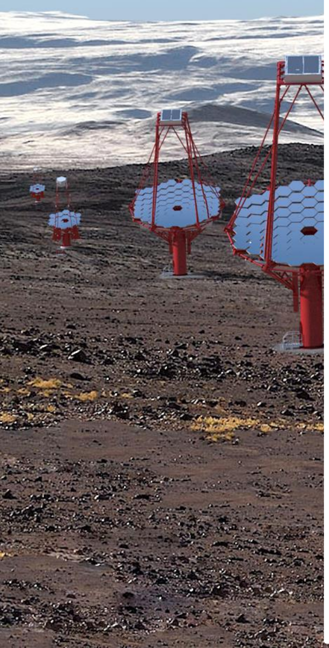


Optical
+TeV

(c) F. Acero & H. Gast

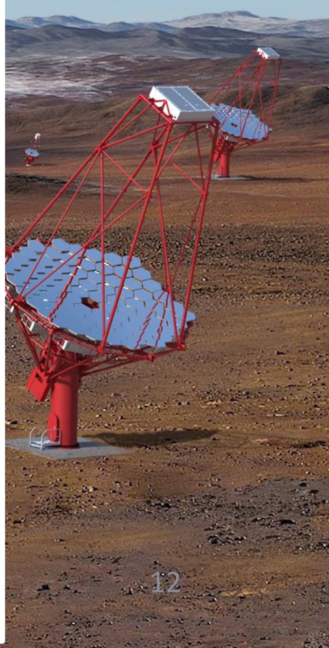
The Cherenkov Telescope Array

The Cherenkov Telescope Array



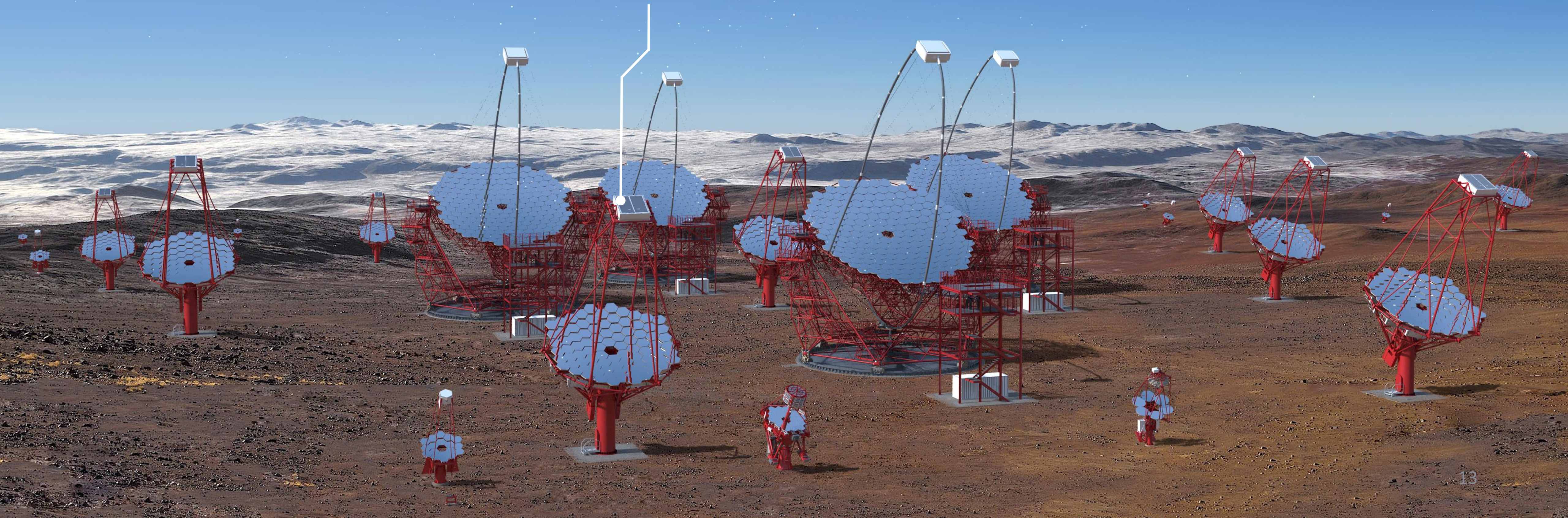
La Palma Map: ©2015 Google, Inst. Geogr. Nacional
Paranal Map: ©2015 Google

● Array Sites ● Headquarters ● Science Data Management Centre



The Cherenkov Telescope Array

CTA South, Paranal

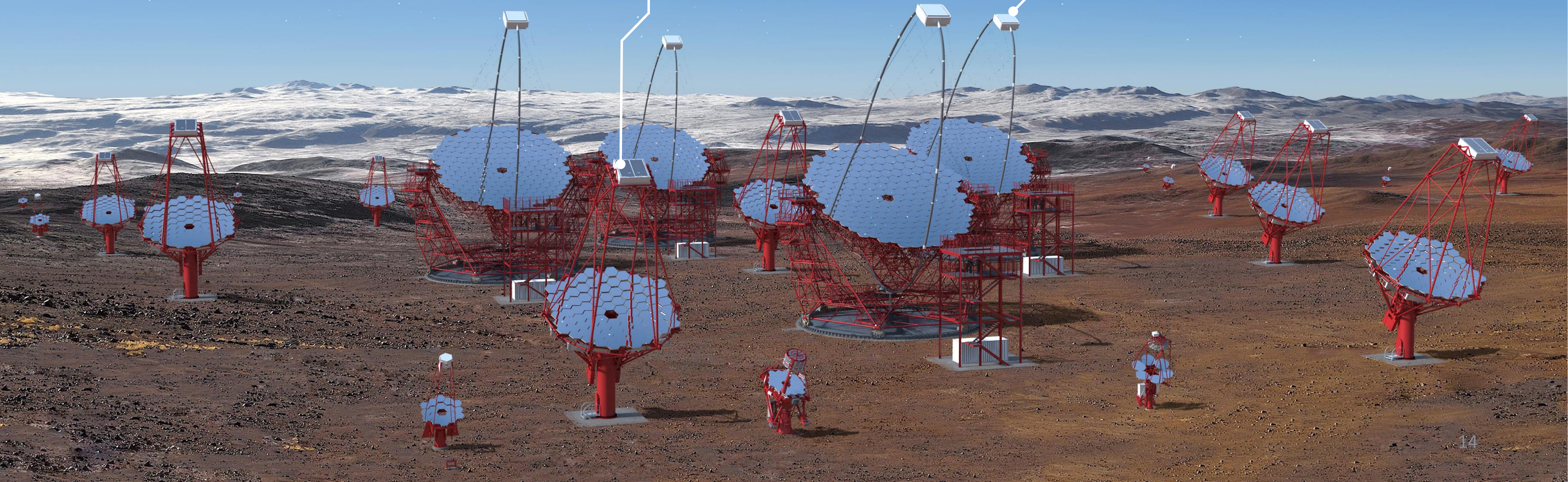


25 Medium Sized Telescopes (MST)

- 12 m diameter reflector
- > 7^o FoV
- ~1 km^2

The Cherenkov Telescope Array

CTA South, Paranal



25 Medium Sized Telescopes (MST)

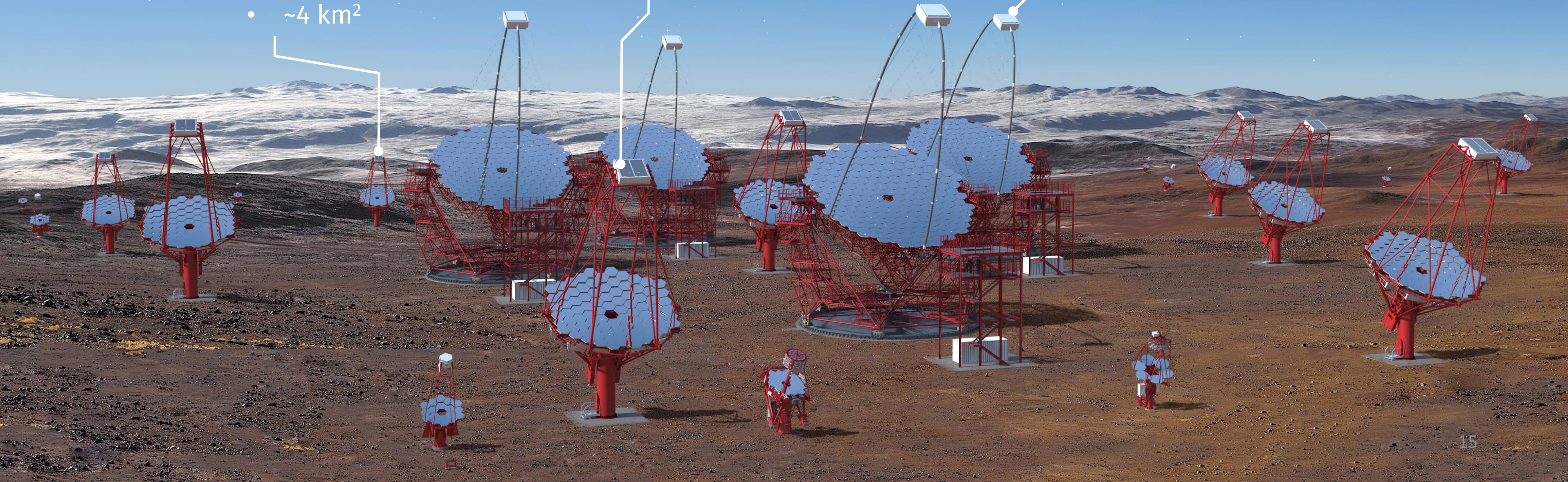
- 12 m diameter reflector
- > 7º FoV
- ~1 km²

4 Large Sized Telescopes (LST)

- 23 m diameter reflector
- >4.5º FoV
- ~0.1 km²

The Cherenkov Telescope Array

CTA South, Paranal



4 Large Sized Telescopes (LST)

- 23 m diameter reflector
- >4.5^o FoV
- ~0.1 km^2

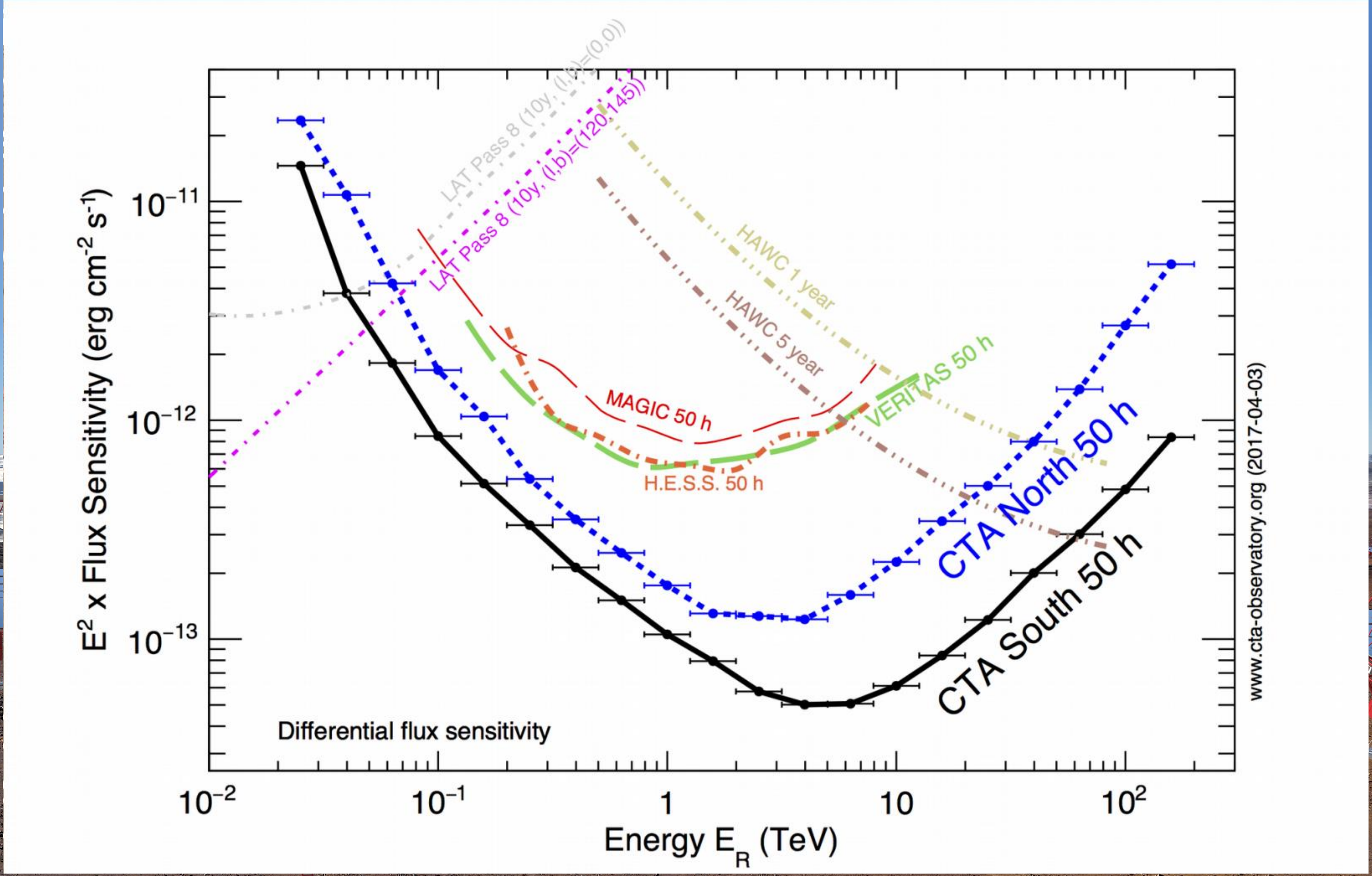
25 Medium Sized Telescopes (MST)

- 12 m diameter reflector
- > 7^o FoV
- ~1 km^2

70 Small Sized Telescopes (SST)

- 4 m diameter reflector
- > 8^o FoV
- ~4 km^2

The Cherenkov Telescope Array



The Small-Sized Telescope

SST Camera

Requirements

- Small-Sized telescopes
  - Large area coverage essential for (rare) highest energy showers (to 300 TeV)
  - Good event quality (resolution, background rejection) requires telescope separation not too large → many units → low unit cost
  - High telescope-multiplicity events provide the highest resolution events of CTA at around 10 TeV
- SST Camera Design Implications
  - Large impact distance measurements → wide field of view, large time gradients
  - Wide field of view without compromising on pixel size/image resolution implies many pixels → low-cost individual pixels
  - Large time gradients → digitization in wide time window – flexibility for optimal offline extraction of time and intensity information

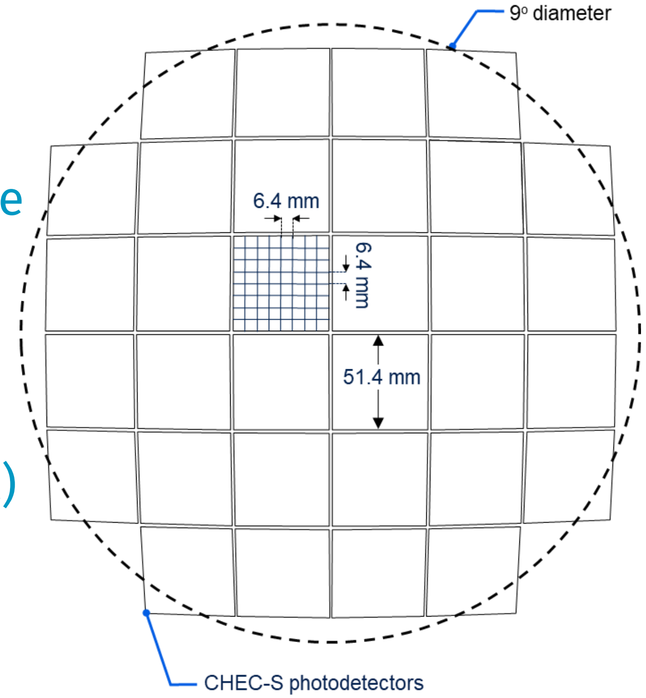
CTA Small-Sized Telescope

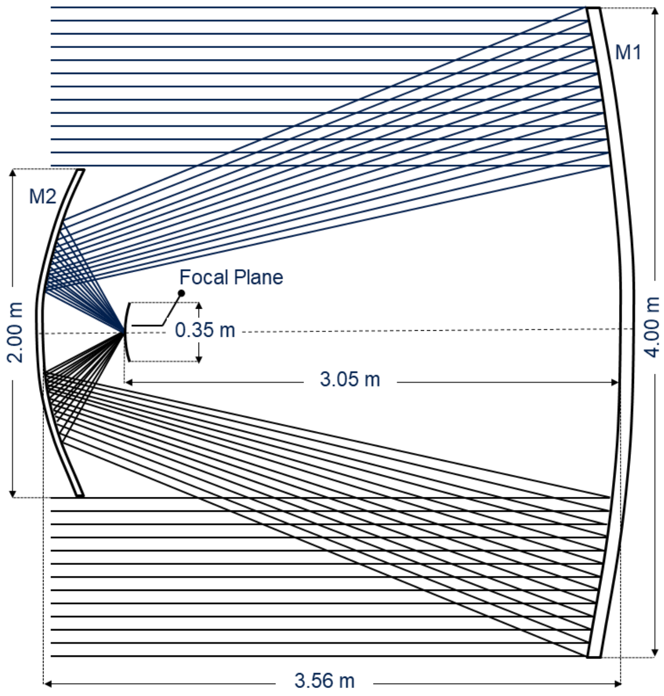
UK Involvement

- CTA-UK groups have been involved in the SST concept from the beginning
  - The UK provided the basic optical design on which CTA-SST dual-mirror (SST-2M) telescopes are based
  - UK pushed to ensure all SST-2M optical designs are compatible with a single camera
  - The UK camera was deliberately designed to be compatible with all SST-2M telescopes

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

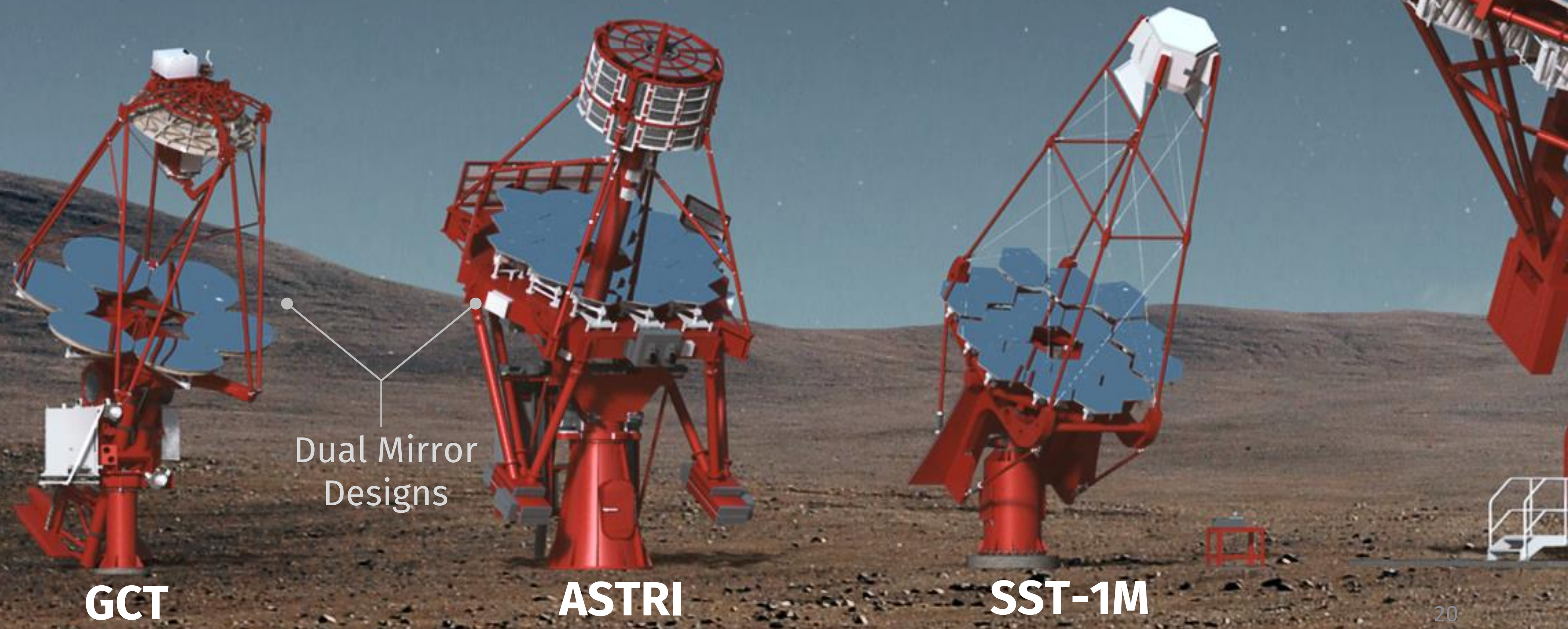
- Design allows a smaller, cheaper camera
  - → Compact High Energy Camera (CHEC)
  - → CHEC largely developed in the UK





Proposed SSTs

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



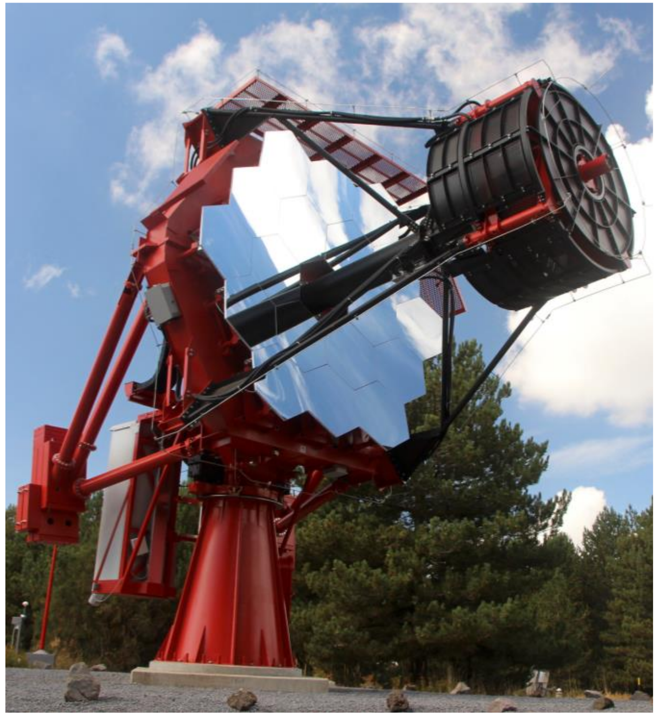
Prototype SSTs

- Prototypes for all SSTs (telescopes and cameras) exist
  - → The dual-mirror telescope prototypes provided an excellent test- bed for CHEC

Meudon, France

GCT

Serra La Nave, Italy



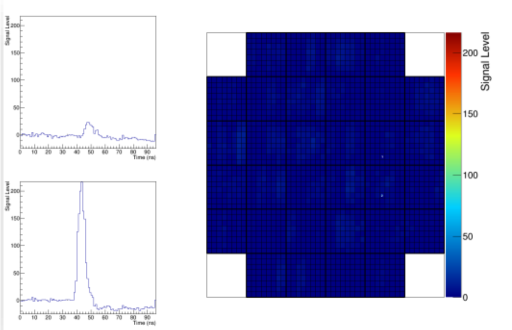
ASTRI

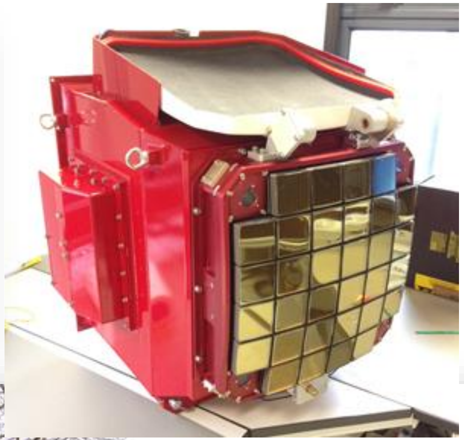
Krakow, Poland

SST-1M

ASTRI and GCT

Competing SST-2M designs





GCT

GATE telescope

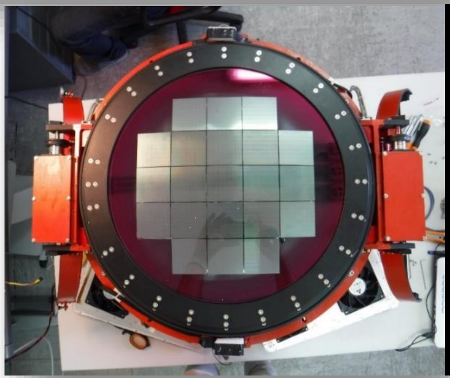
CHEC-M camera

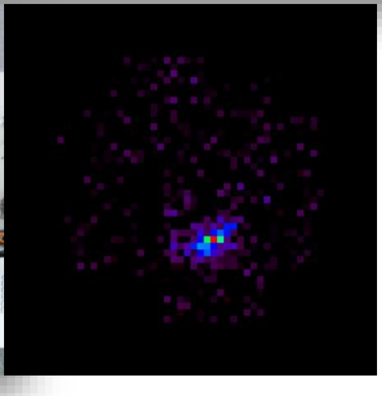
Paris-Meudon

November 2015 – first ever Cherenkov light for a CTA prototype

ASTRI telescope and camera

Serra La Nave Observatory Sicily

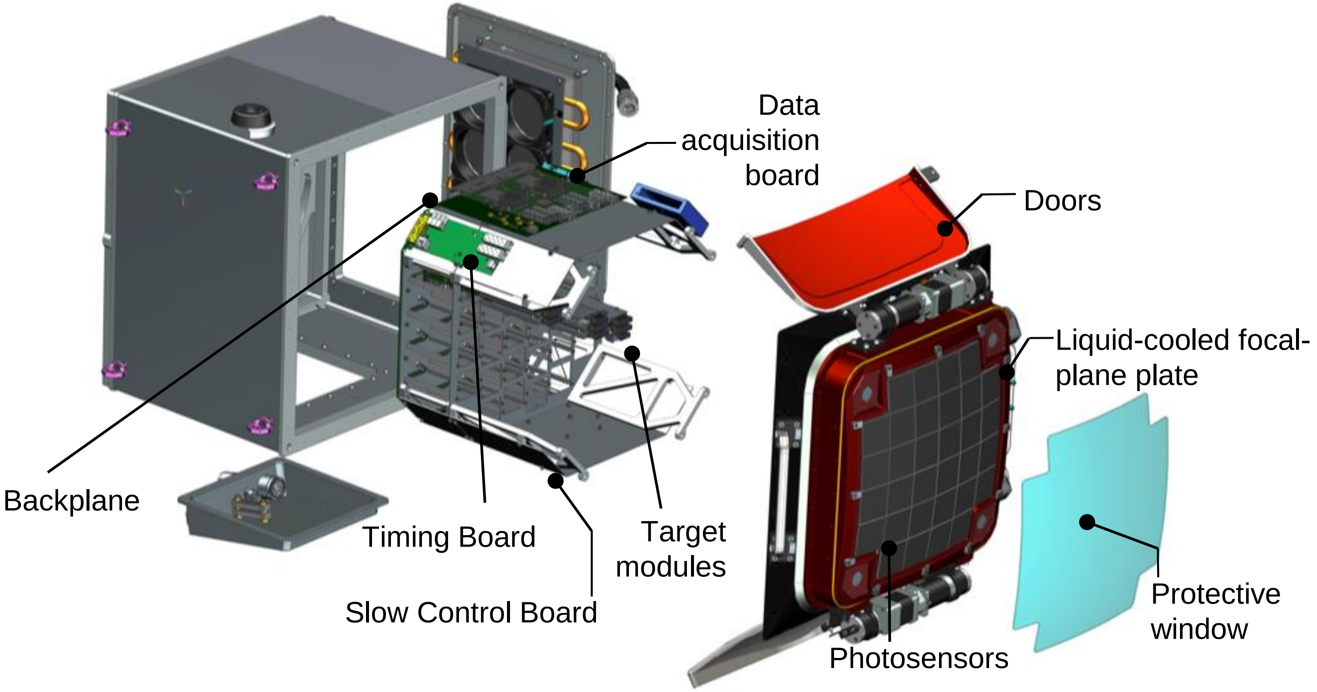




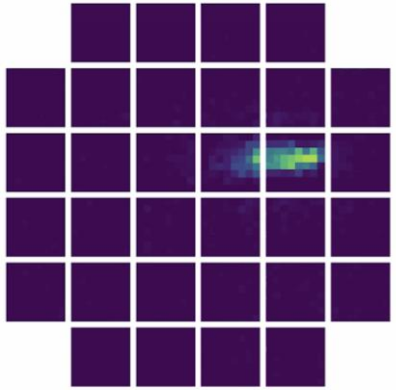
Prototyping CHEC

Prototyping CHEC
Overview

- CHEC-M & CHEC-S
  - Same fundamental architecture
  - Different photosensor technologies
- Tested in the lab and on-telescope
  - CHEC-M on GATE (GCT)
  - CHEC-S on ASTRI



CHEC-M on GCT: first light for any CTA prototype

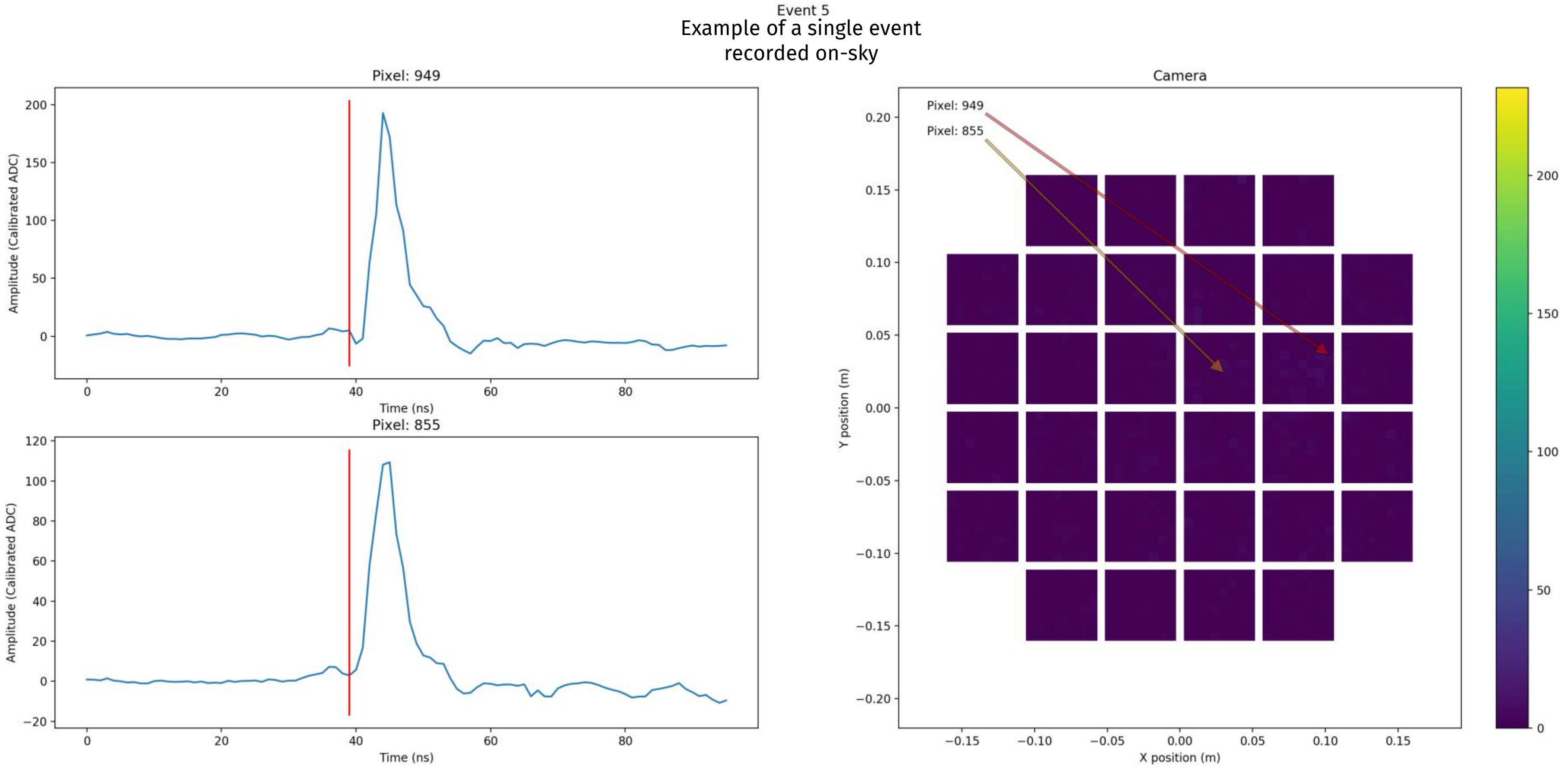


CHEC-M

On-Telescope Tests in Meudon

- Cherenkov Images
  - Successful self-triggering on Cherenkov events (cosmic rays – no γ-rays)
  - First light for any CTA prototype

Example of a single event recorded on-sky



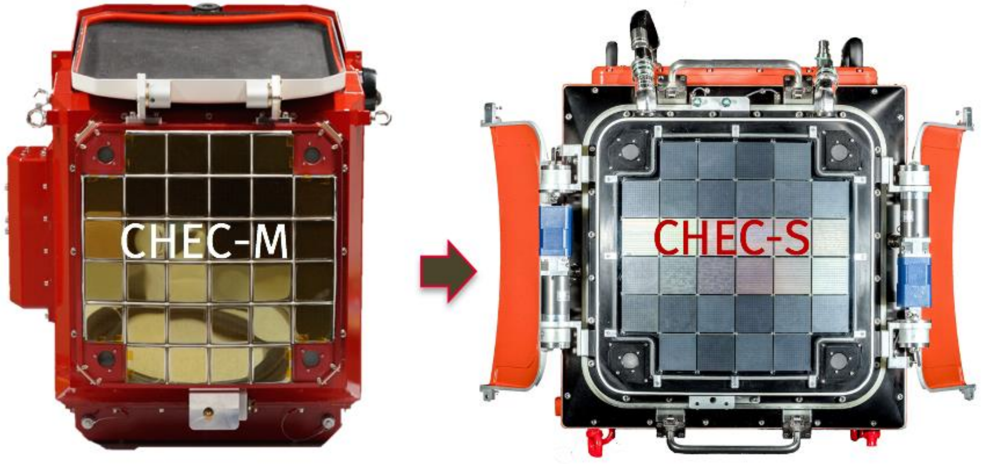
Prototyping CHEC

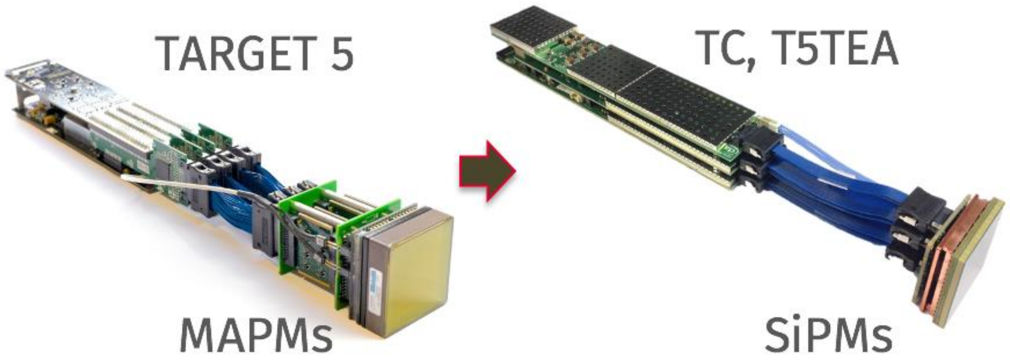
Evolution

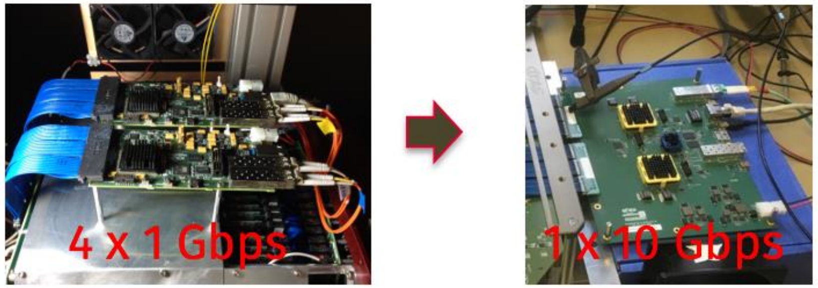
- CHEC-M
    - MAPMs
    - TARGET 5
    - 1 Gbps DACQ boards
    - Wash U. Backplane

  → Proof of principle of many aspects (e.g. triggering and readout), limited by ASIC performance and MAPM gain spread
- CHEC-S
    - SiPMs
    - Liquid cooling
    - TARGET C and TARGET T5TEA
    - In-Project Backplane
    - 10 Gbps XDACQ
    - Slow signal chain for pointing

  → Most CTA requirements met, performance limited by SiPMs and thermal control

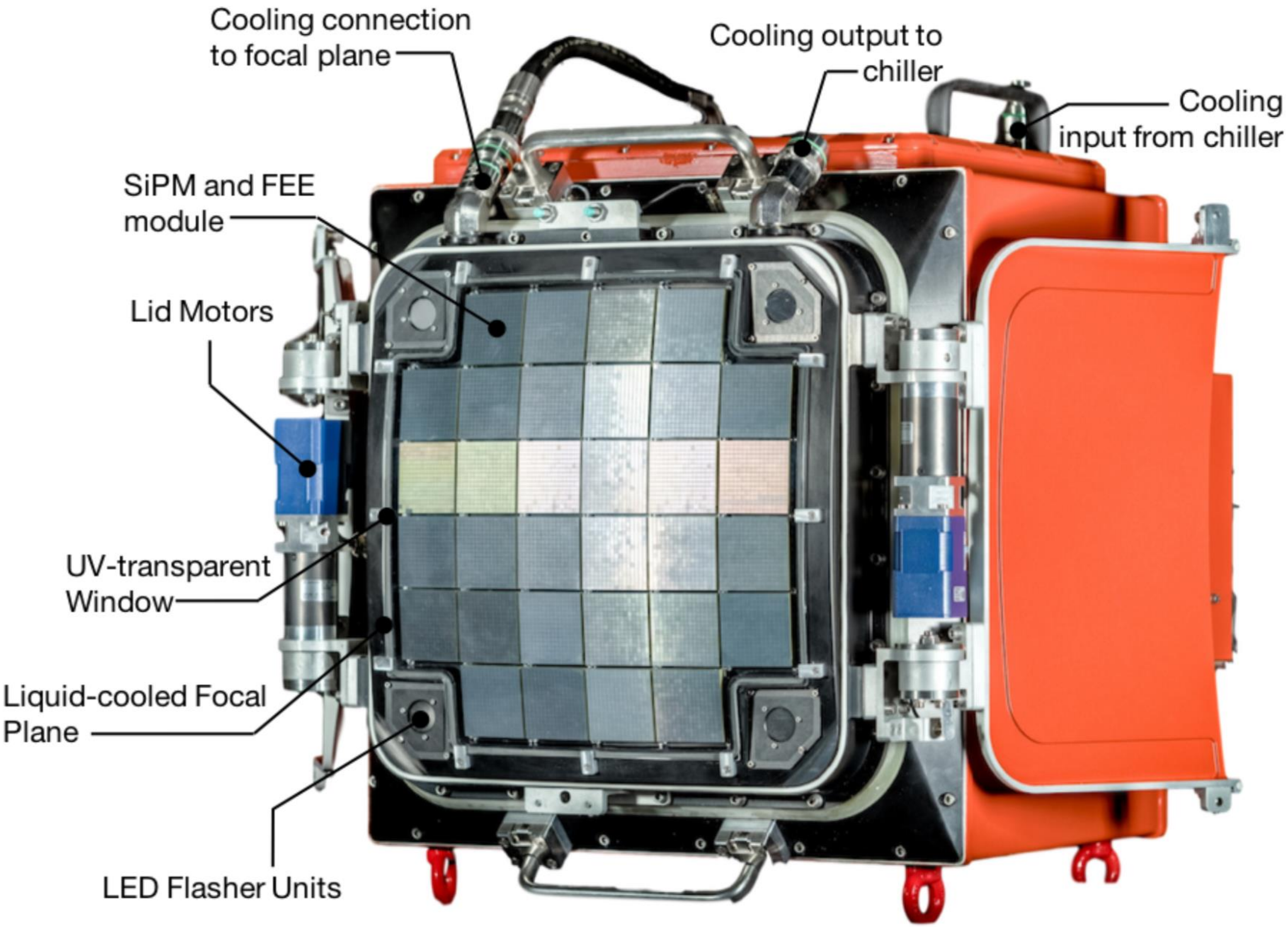






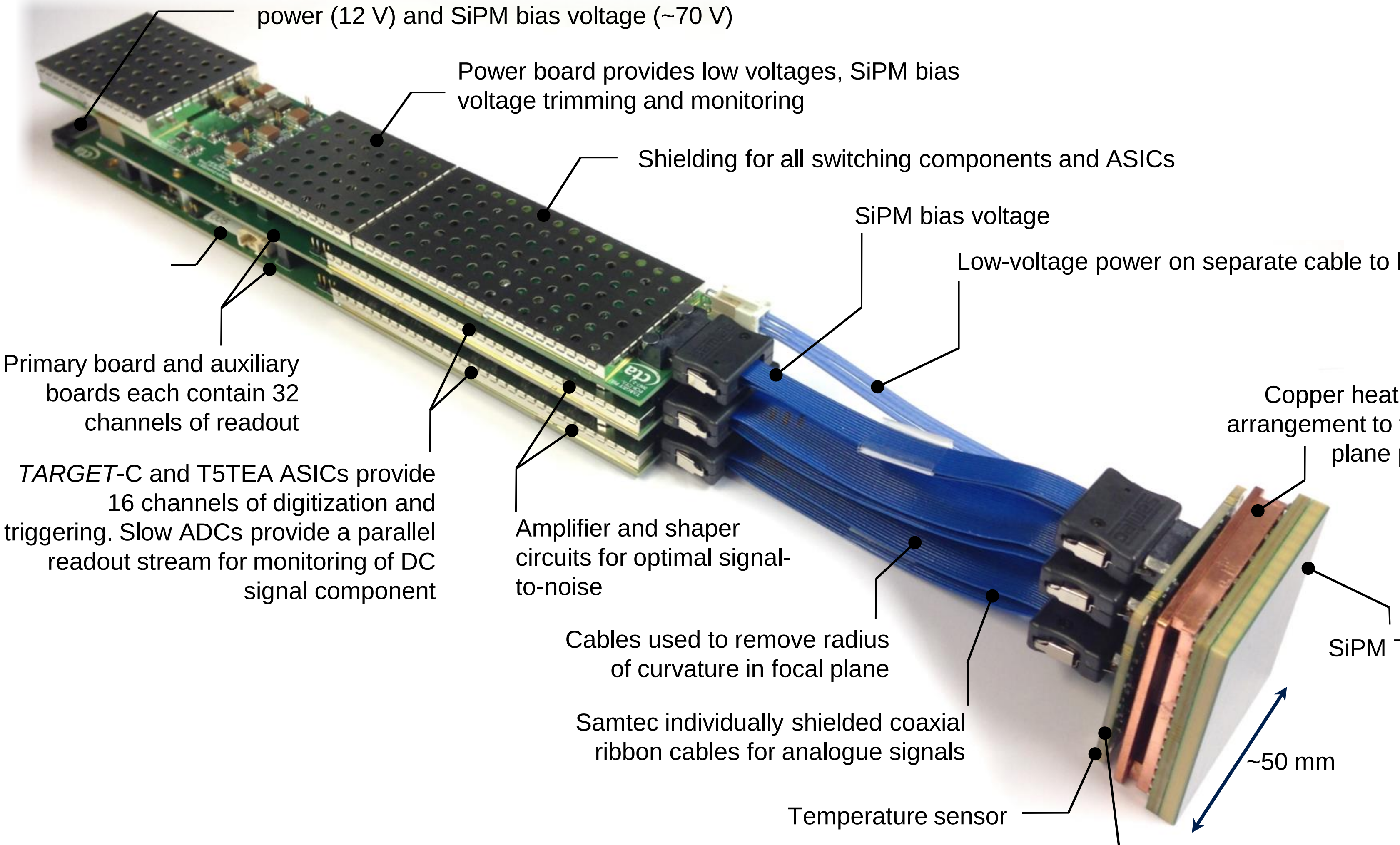
Prototyping CHEC

CHEC-S



Prototyping CHEC

CHEC-S



Connection to the backplane: raw data, trigger, clock signals, electronics power (12 V) and SiPM bias voltage (~70 V)

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

Shielding for all switching components and ASICs

SiPM bias voltage

Low-voltage power on separate cable to buffer

Primary board and auxiliary boards each contain 32 channels of readout

Copper heat-sink arrangement to focal plane plate

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

Cables used to remove radius of curvature in focal plane

Samtec individually shielded coaxial ribbon cables for analogue signals

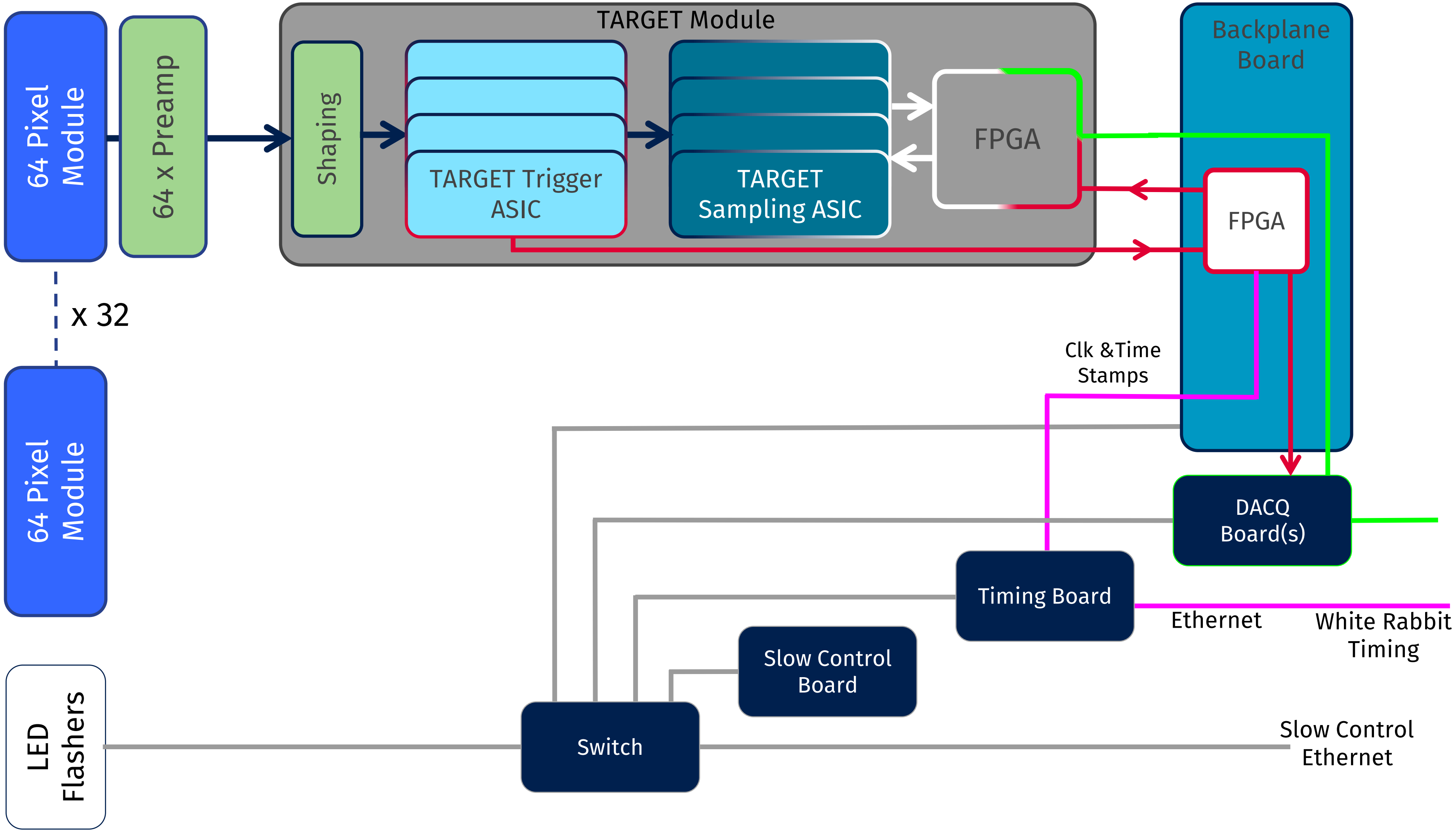
~50 mm

Temperature sensor

Buffer circuits for noise immunity

Prototyping CHEC

Camera Architecture



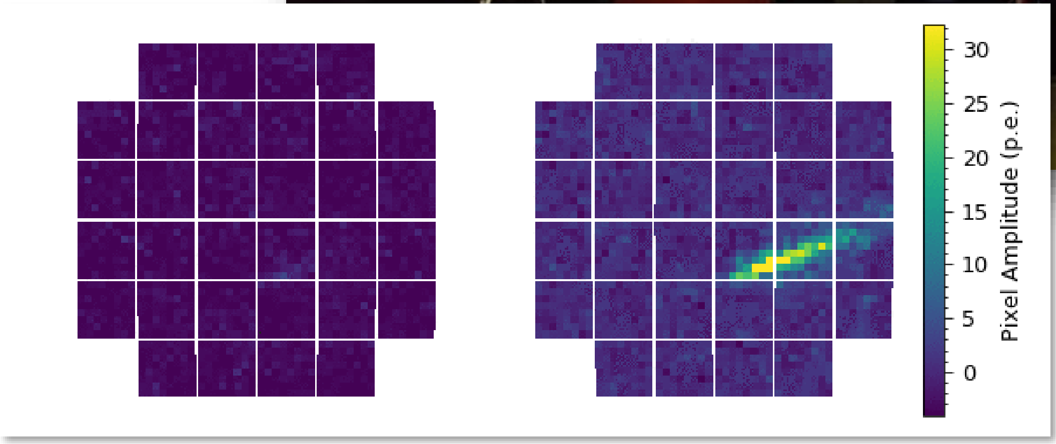
ASTRI-CHEC Campaign

Field trials - 2019

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

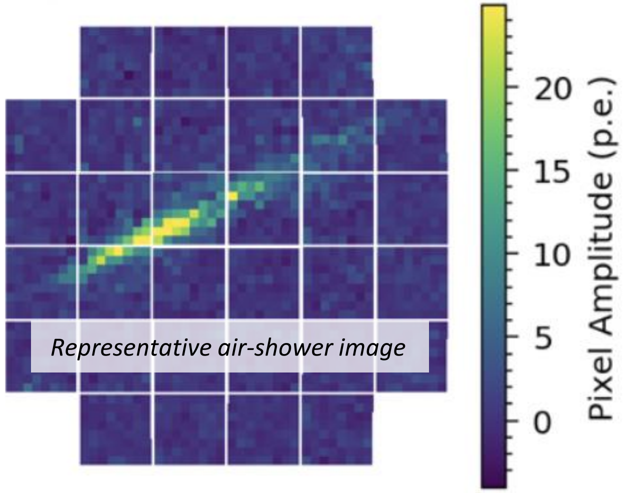
Hosted by INAF-Catania

1750 m asl

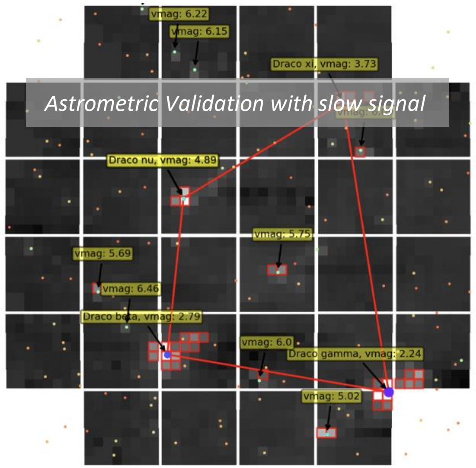


ASTRI-CHEC Campaign
Field trials - 2019

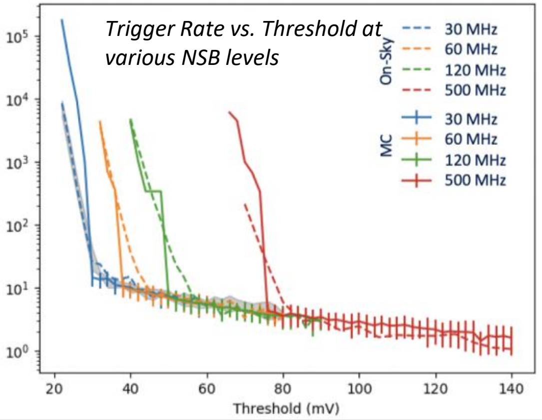
- CHEC-S installed on ASTRI in 2019
  - Interfaces prepared before arrival and verified
  - First light ~48 hours after arrival onsite
  - Images in focus without additional camera alignment
  - On-sky data a good match to MC expectations
  - Continuous calibration performed in parallel to observations
    - Astrometric verification via slow signal
    - Photosensor calibration via interleaved LED flashes
  - On-telescope operations fully exercised



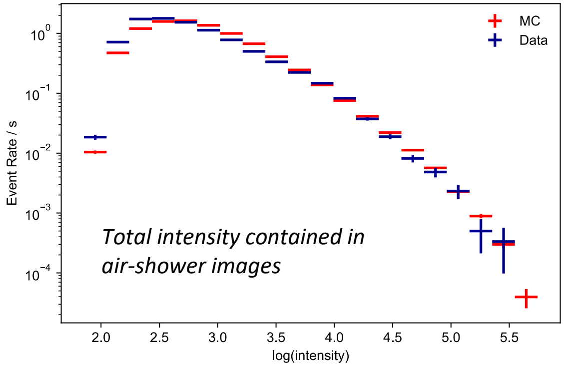
Representative air-shower image



Astrometric Validation with slow signal



Trigger Rate vs. Threshold at various NSB levels

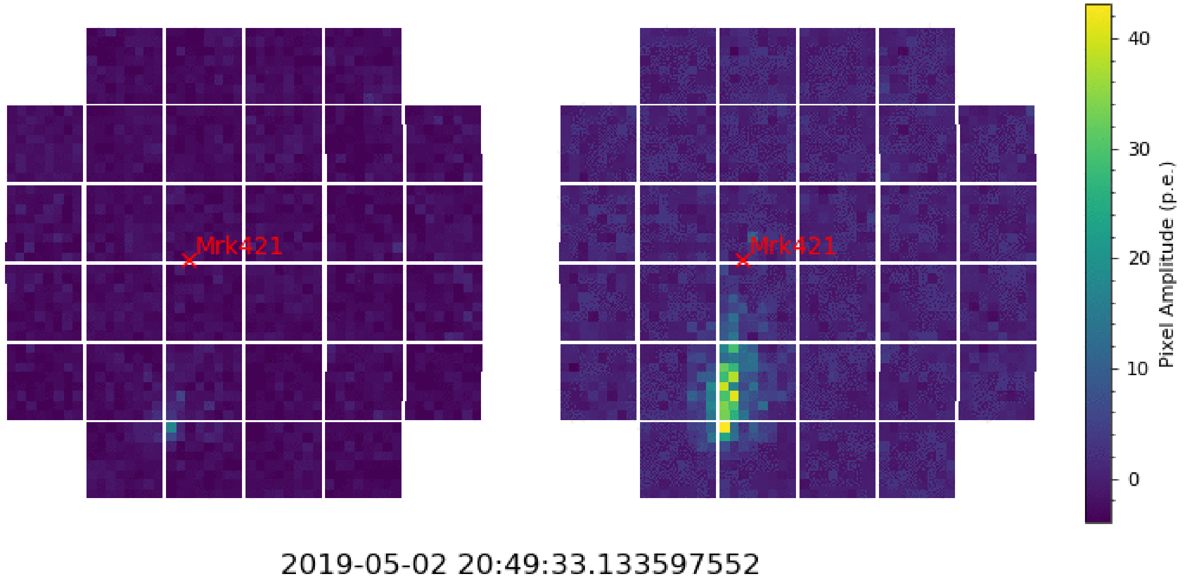


Total intensity contained in air-shower images

ASTRI-CHEC Campaign

Field trials - 2019

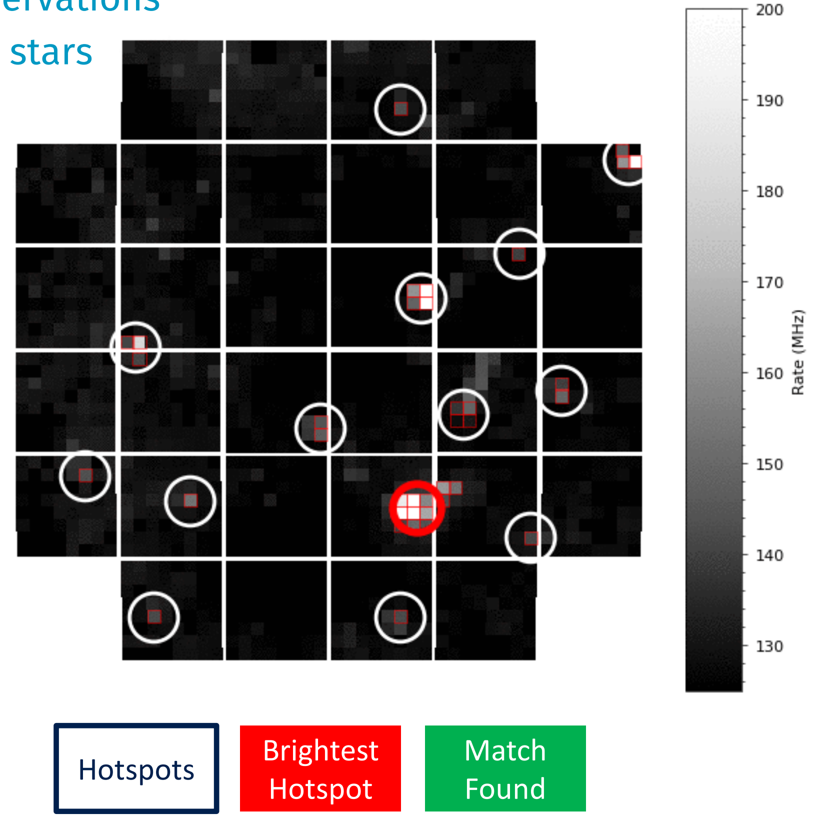
- Observation strategy during CHEC-on-ASTRI campaign: Wobble Mode
  - Pointing direction is offset from the source by 1 degree
  - Observations alternate between offsets on different sides of the source
- Priority of campaign: Test on-telescope operation of camera and compatibility with ASTRI structure - **SUCCESS**
- Gamma-ray source observation: Sensitivity limited by mirror reflectivity

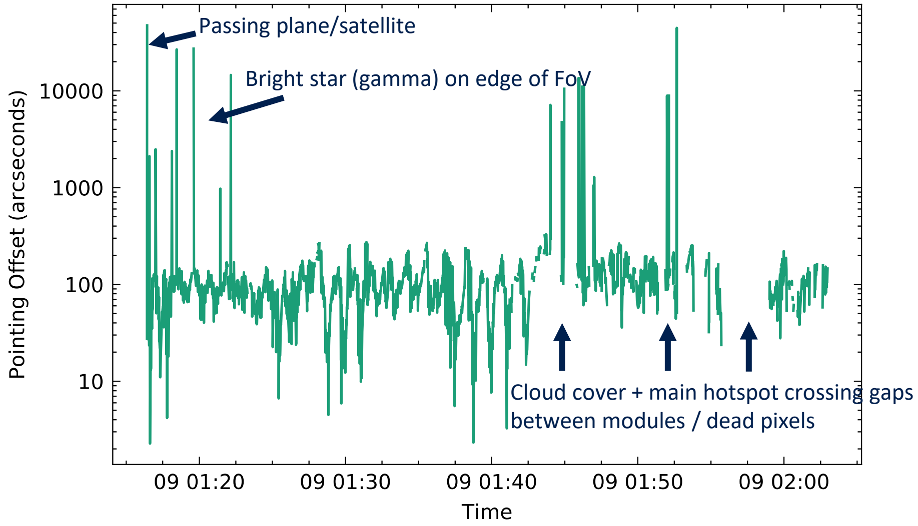


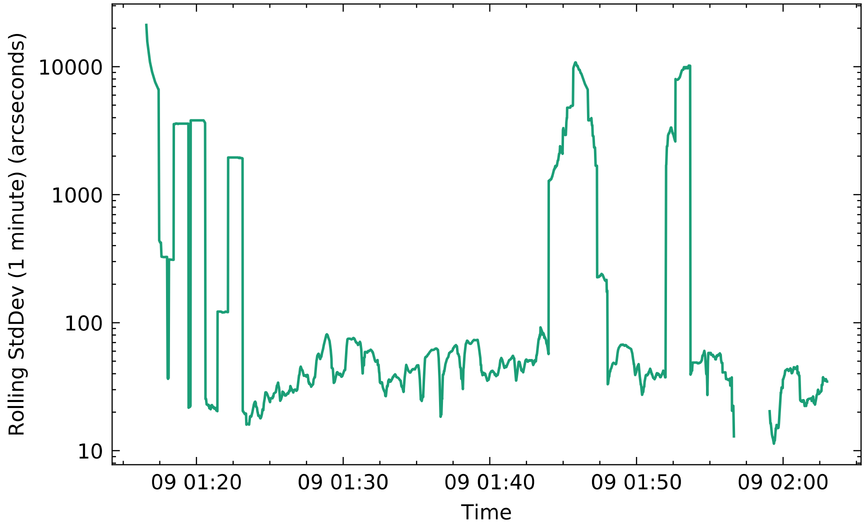
Cherenkov showers pointed towards source position (as reported by ASTRI-Horn SQL database)

CHEC-S on ASTRI
Field trials - 2019

- Slow signal – Predicted pointing accuracy
  - Utilise timing information as star crosses pixel boundary
  - Simulations: 4-5 arcseconds
  - Requires ~10 stars in FoV
  - Up to 30 stars expected in a typical FoV (Vmag < 9)
- Can be used for
  - NSB level during observations
  - Disabling pixels with stars present
  - Telescope pointing
  - PSF across FoV



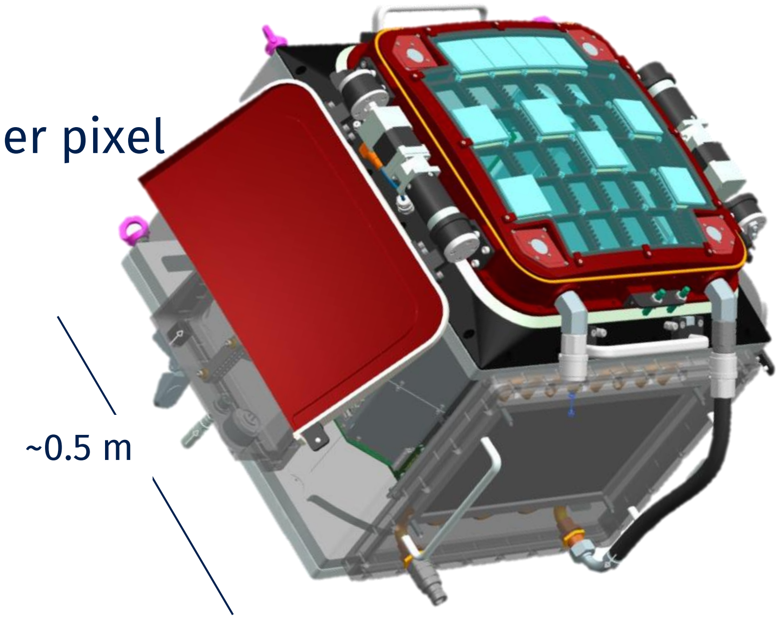




SST Camera Project

SST Camera
Selection

- Following 2019 CTAO Harmonization review
  - CHEC selected as baseline for the SST Camera
  - ASTRI selected as the baseline telescope structure
- SST Camera Key Features
  - Fine pixellation, ~9° FoV
  - SiPMs with Target ASIC readout
    - Costs a factor of 5 lower 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



6 mm pixel
2048 pixels

32 Photosensor modules → ~9° FoV

~0.5 m

50 kg
Liquid cooling (<1kW)

SST Camera
Design Finalization

Many lessons learnt from CHEC protypes

- Assembly concept
  - Involves removing SiPMs to access Target Modules
    - Risk of SiPM damage
  - Involves inserting Target Modules through focal plane
    - Risk of TM damage

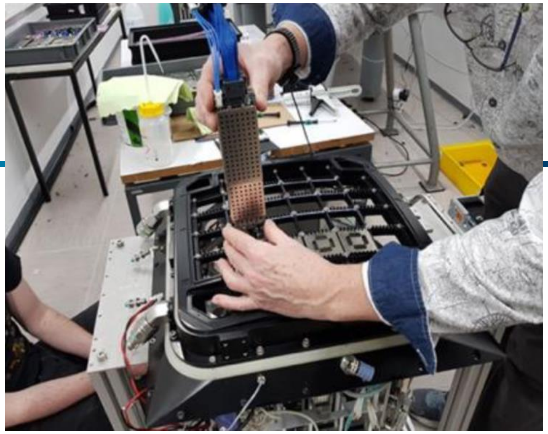
    New camera assembly scheme – SOLVED BOTH
- SiPMs
  - Optical Cross Talk (40%)
    - Limits trigger performance and charge reconstruction

    Latest LVR3 SiPM devices utilized – SOLVED
  - Control (Bias voltage resolution)
    - Limits trigger uniformity

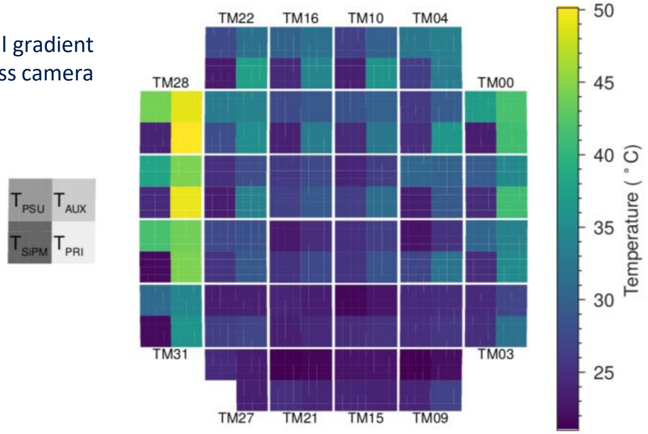
    Per pixel bias redesign - SOLVED
- Cooling capacity
  - Adequate for SiPMs (FPP worked well)
  - But large gradient across TMs (> 20 °C)
    - Limits charge reconstruction (ASIC temperature dependence)

    Cooling system upgrade – SOLVED
- LED Flasher concept
  - Relies on reflection from M2
  - Hard to calibrate in the lab

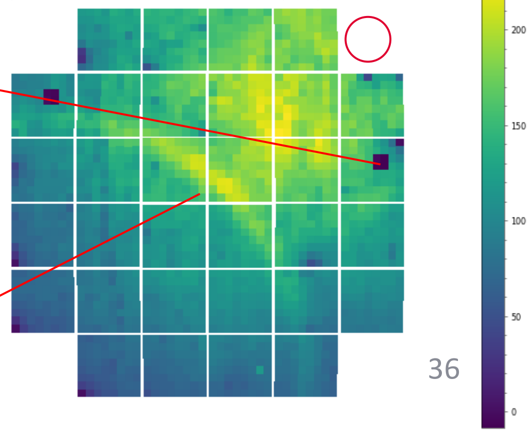
  New Flasher circuit design and placement – SOLVED BOTH


TM insertion

Thermal gradient across camera



Example flash from LED unit 0 (top right) on ASTRI

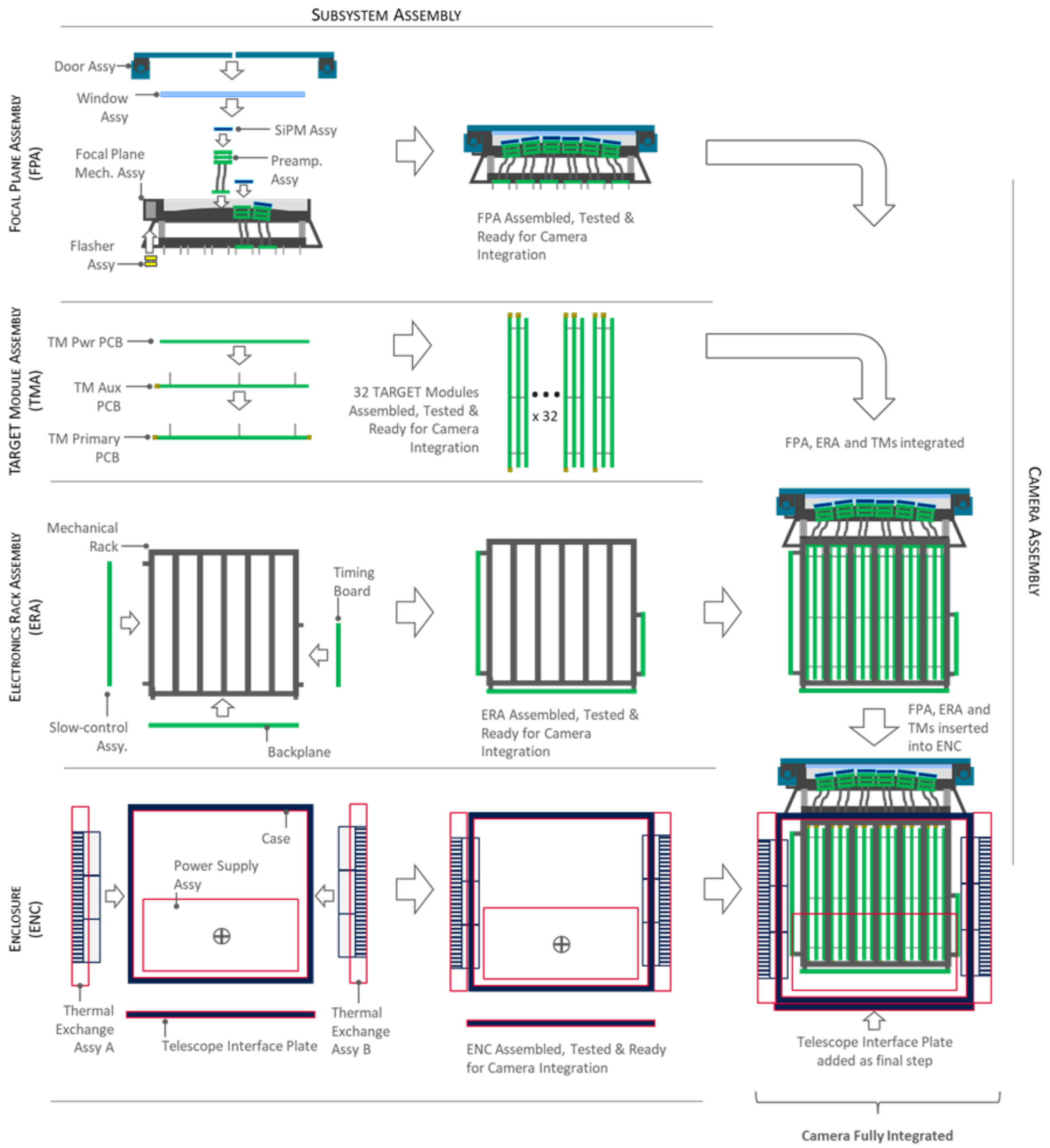


Known disabled HV blocks

M2 artefact

Camera Series Production

Modular assembly



Camera Series Production (SST Camera Project)

Timeline

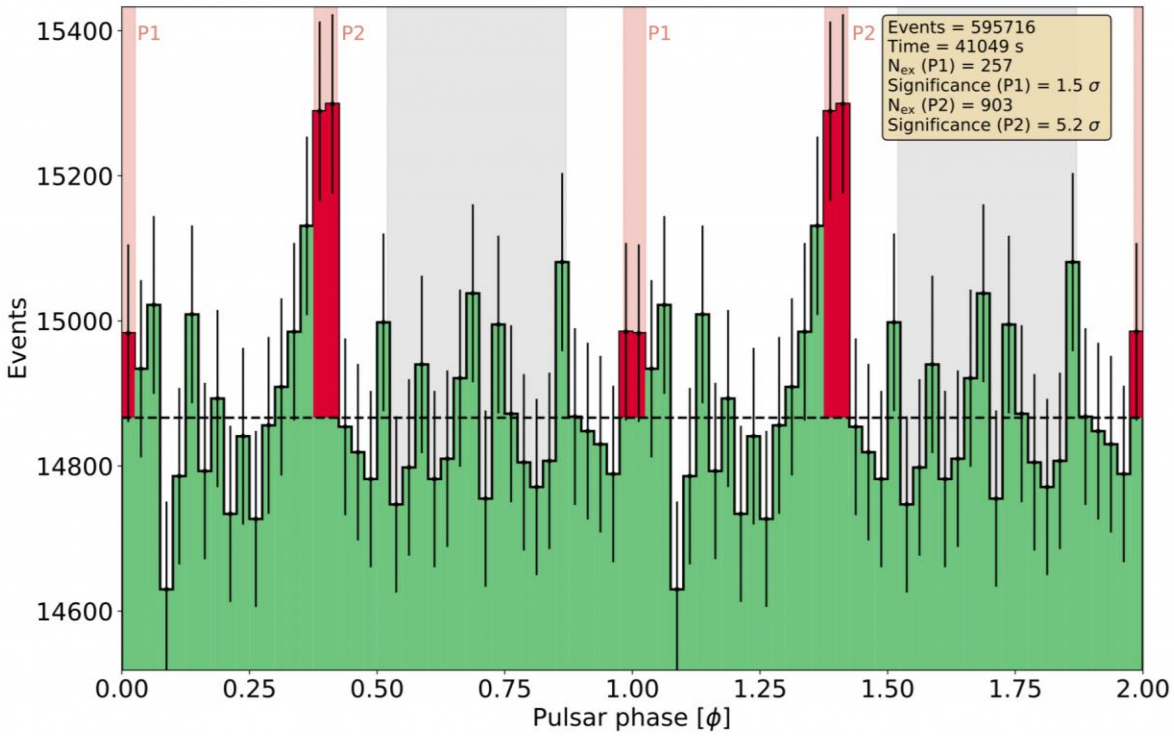
- Series production can begin once:
  - Camera design is accepted by CTAO
  - IKC Agreements are signed
- UK camera production in parallel and proportionate to MPIK production
- Camera production to be ramped up in increasing batches
  - improve manufacturing efficiency, optimize processes, iron out teething troubles
- Likely schedule:
  - SST Design Consolidation Phase – completion mid 2022
  - ERIC finalization – Early 2022 → agreement on IKCs
  - UK Production Phase (5 year) begins Q2 2022
  - First SSTs onsite – beginning Q3 2023
  - SST array (Phase 1) completion - 2026

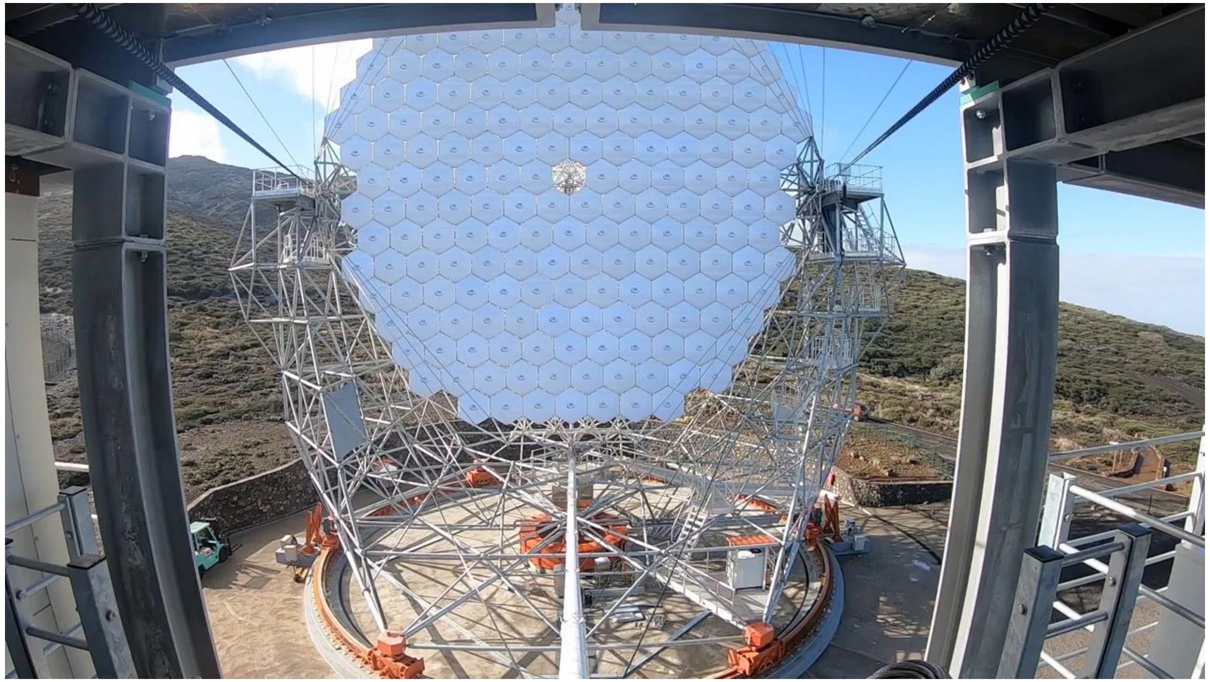
SST Camera Project

- Strong and tightly knit international team
- Now working on final camera design iteration after prototyping and down-selection
- Close links between MPIK, Germany (project lead organisation) and UK group
- MPIK Director (Hinton) – ex-lead of UK-CTA project
- SST Camera Project lead (White) – ex-manager of UK-CTA project
- UK SST Project is thoroughly embedded within the SST Camera Project

CTA Observatory Status

CTA Observatory
LST Prototype on La Palma





Phasogram of Crab Pulsar as measured by the LST-1. The pulsar is known to emit pulses of gamma rays during phases P1 and P2. Credit: LST Collaboration

The construction of the LST prototype, LST-1, was completed in October 2018 at the Observatorio del Roque de los Muchachos in La Palma.

CTA Observatory
In-kind Contributions

- CTAO GmbH is in the process of becoming a European Research Infrastructure Consortium (ERIC)
  - Being negotiated by Board of Governmental Representatives
  - ERIC Step 1 application submitted March 2019
  - ERIC legal framework finalisation – ~1 year timescale from now
- In-kind Contribution (IKC) agreements
  - Once ERIC starts IKC agreements defined and signed
  - Member voting rights and data access dependent on IKC value
  - Necessary Cost Book approved
- CTA cost
  - Estimated CTA Phase 1 overall cost, Total 320-325M€
  - UK IKC likely to be ~3M€


Board of Governmental Representatives at INAF Headquarters, May 2018

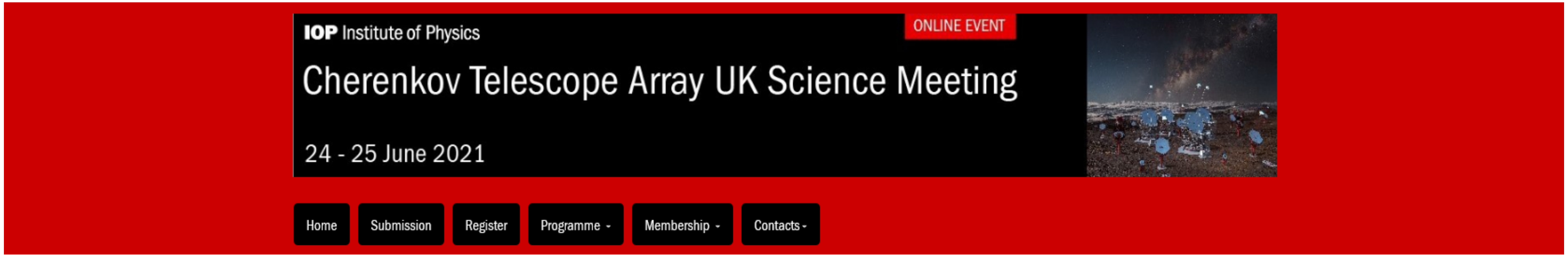
CTA UK Science Community

CTA Science

UK Community

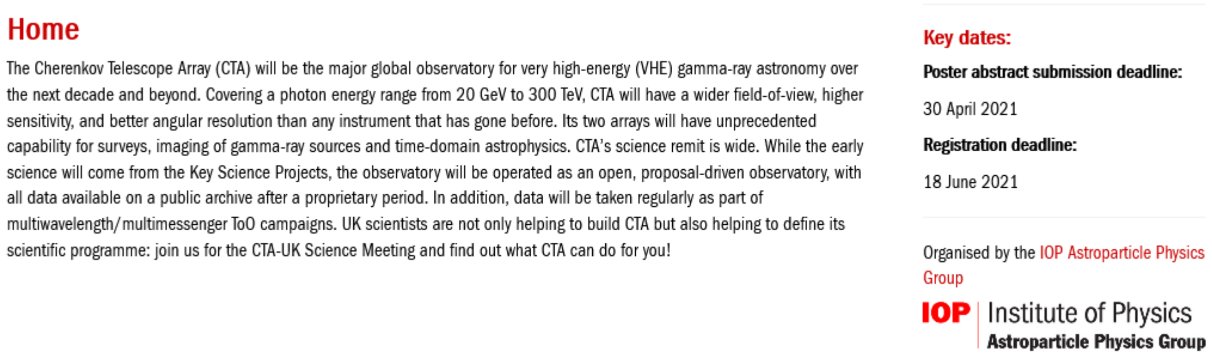
- CTA science - good alignment with UK science community interests:
  - Dark matter
  - Beyond the Standard Model physics
  - Very-high-energy cosmic rays
  - Multi-wavelength astrophysics of pulsars, supernova remnants and AGN
  - Transients and multi-messenger astrophysics
- Strengths and synergies with:
  - UK gravitational wave community
  - GRB follow-up community
  - Swift and the future SVOM mission
  - Longer-term science involvement in Einstein Probe
  - UK lead roles in SKA and Rubin Observatory projects
- UK science return from CTA
  - Likely to be proportionally much larger than anticipated ~1% IKC investment.

CTA Science
UK Community



Cherenkov Telescope Array UK Science Meeting

24 - 25 June 2021



Home

The Cherenkov Telescope Array (CTA) will be the major global observatory for very high-energy (VHE) gamma-ray astronomy over the next decade and beyond. Covering a photon energy range from 20 GeV to 300 TeV, CTA will have a wider field-of-view, higher sensitivity, and better angular resolution than any instrument that has gone before. Its two arrays will have unprecedented capability for surveys, imaging of gamma-ray sources and time-domain astrophysics. CTA's science remit is wide. While the early science will come from the Key Science Projects, the observatory will be operated as an open, proposal-driven observatory, with all data available on a public archive after a proprietary period. In addition, data will be taken regularly as part of multiwavelength/multimessenger ToO campaigns. UK scientists are not only helping to build CTA but also helping to define its scientific programme: join us for the CTA-UK Science Meeting and find out what CTA can do for you!

Key dates:

Poster abstract submission deadline:

30 April 2021

Registration deadline:

18 June 2021

Organised by the IOP Astroparticle Physics Group

IOP | Institute of Physics
Astroparticle Physics Group

- Two-day CTA-UK Science meeting
  - 24–25 June 2021
  - International and UK speakers from over a dozen institutes
  - Free registration
  - Virtual poster session - with prizes!

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Thank you for your attention