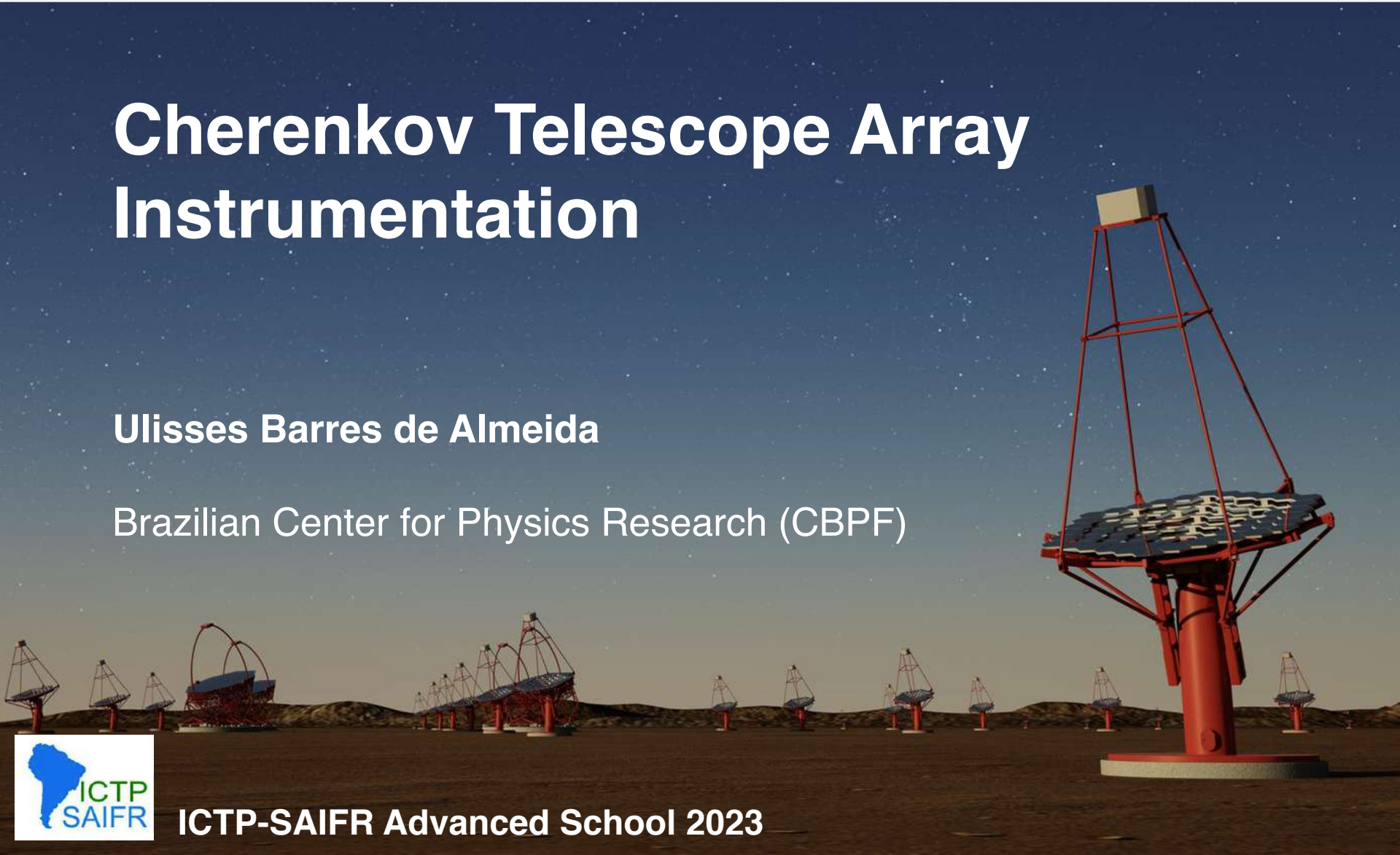
Cherenkov Telescope Array Instrumentation

Ulisses Barres de Almeida

Brazilian Center for Physics Research (CBPF)



ICTP-SAIFR Advanced School 2023

cherenkov telescope array

Imaging Atmospheric Cherenkov Instruments

The Cherenkov Telescope Array

Telescope types: MST, SCT (SST) and LST

The LST-1 prototype

Complementarity between IACTs and EASs

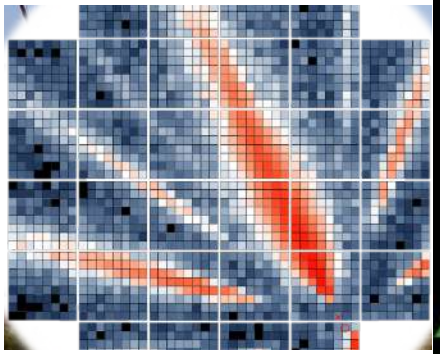
EASs and the SWGO

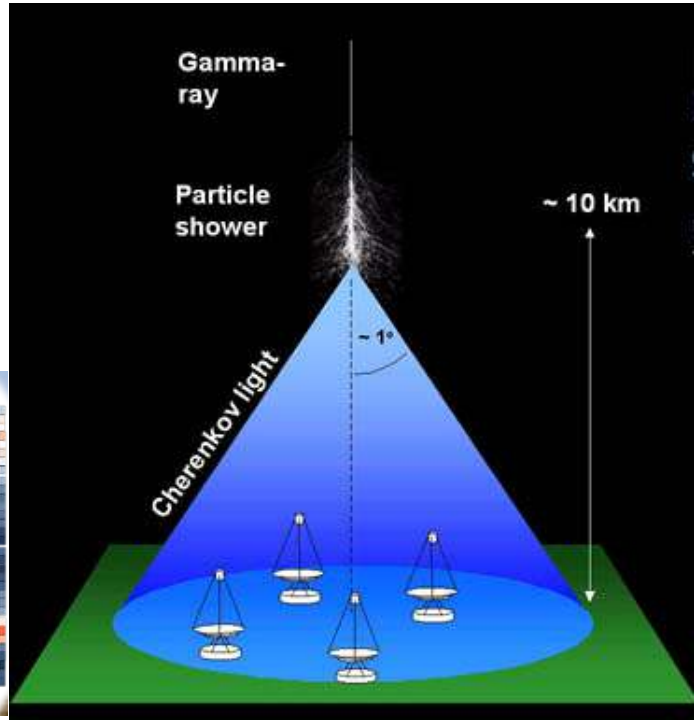
Imaging Atmospheric Cherenkov Instruments

- **IAC Technique** is based on the indirect detection of the blue Cherenkov light from EASs
  - The pulse is few ns short
  - Short exposure limits NSB
  - Cherenkov light emitted in narrow Cherenkov cone

$$\theta = \cos^{-1}\frac{1}{n\beta} \sim 1^{o}$$

  - **Strengths:**
    - Large effective areas of showers (10^5 m^2)
    - Achieves a low-E threshold
    - Good angular (few-‘) and energy resolution
  - **Limitation:**
    - Duty cycle of 1500 h/year
    - Only dark nights.

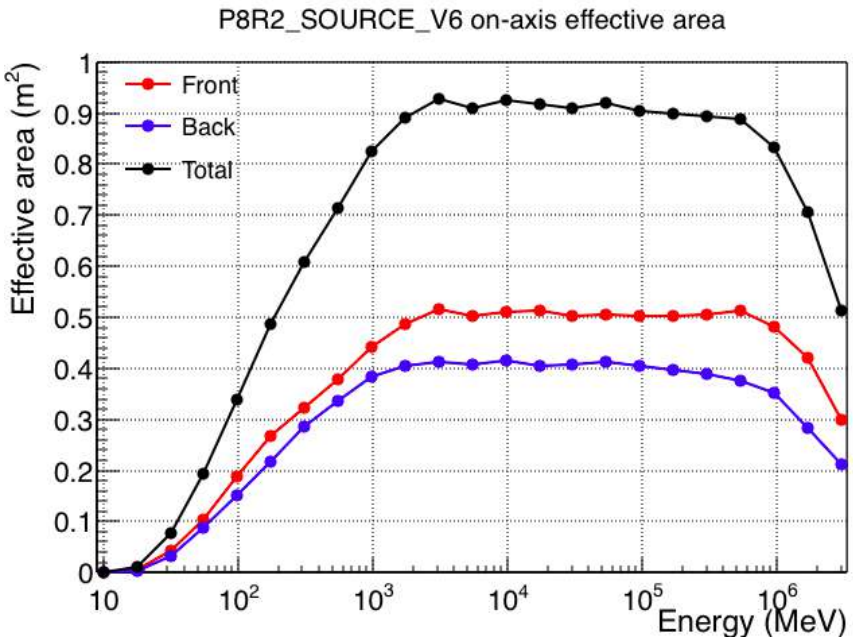




Imaging Atmospheric Cherenkov Instruments

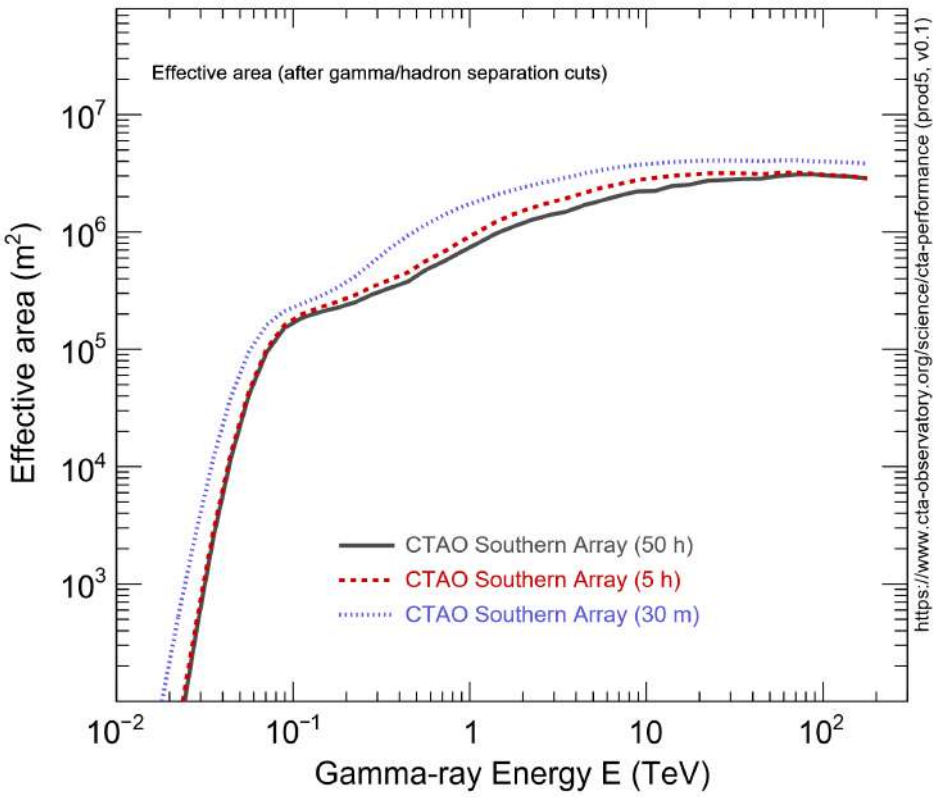
Imaging Atmospheric Cherenkov Instruments: Effective Areas

Fermi Large Area Telescope



1 m^2

Cherenkov Telescope Array

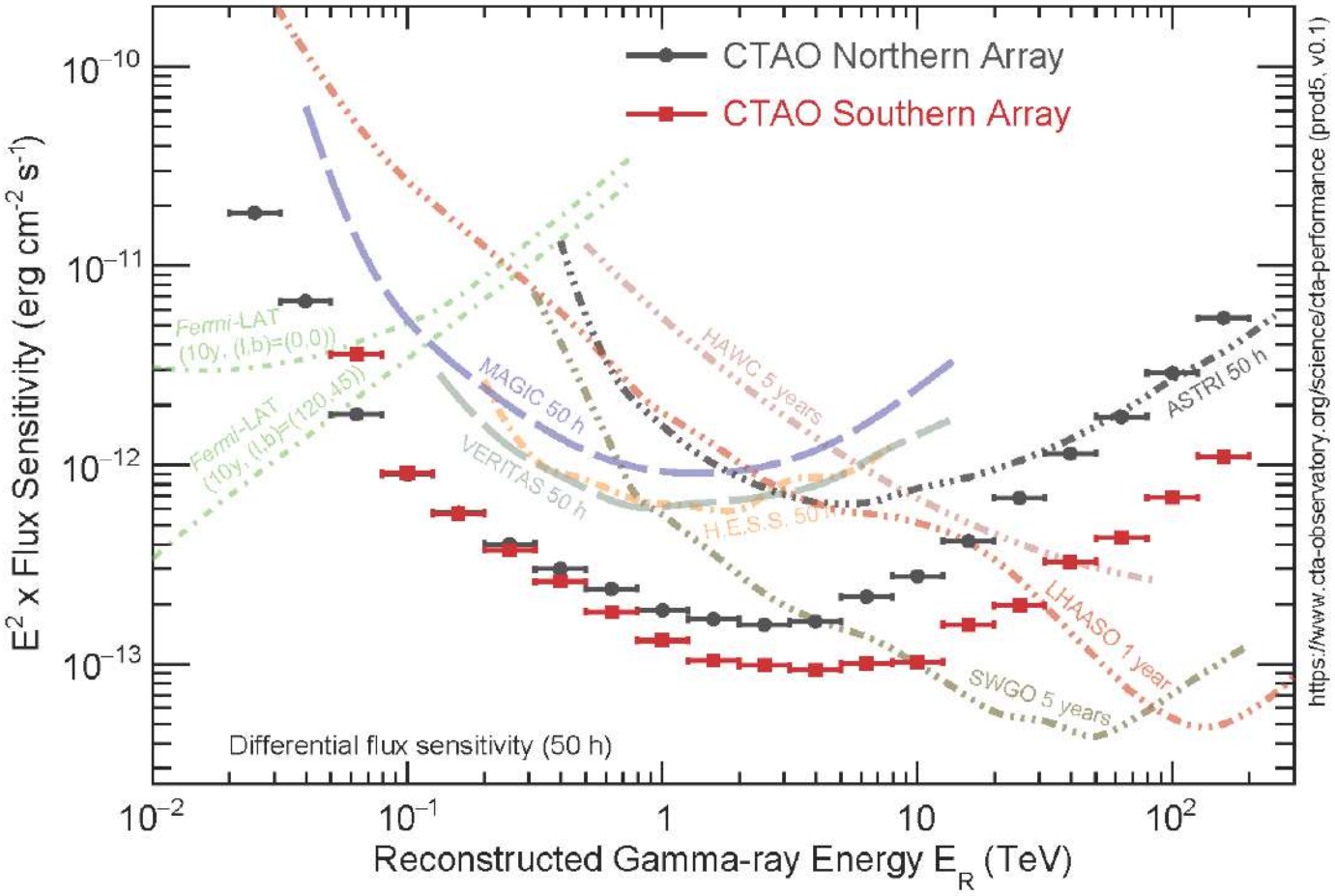


10^6 m^2

Imaging Atmospheric Cherenkov Instruments: Sensitivity (point source)

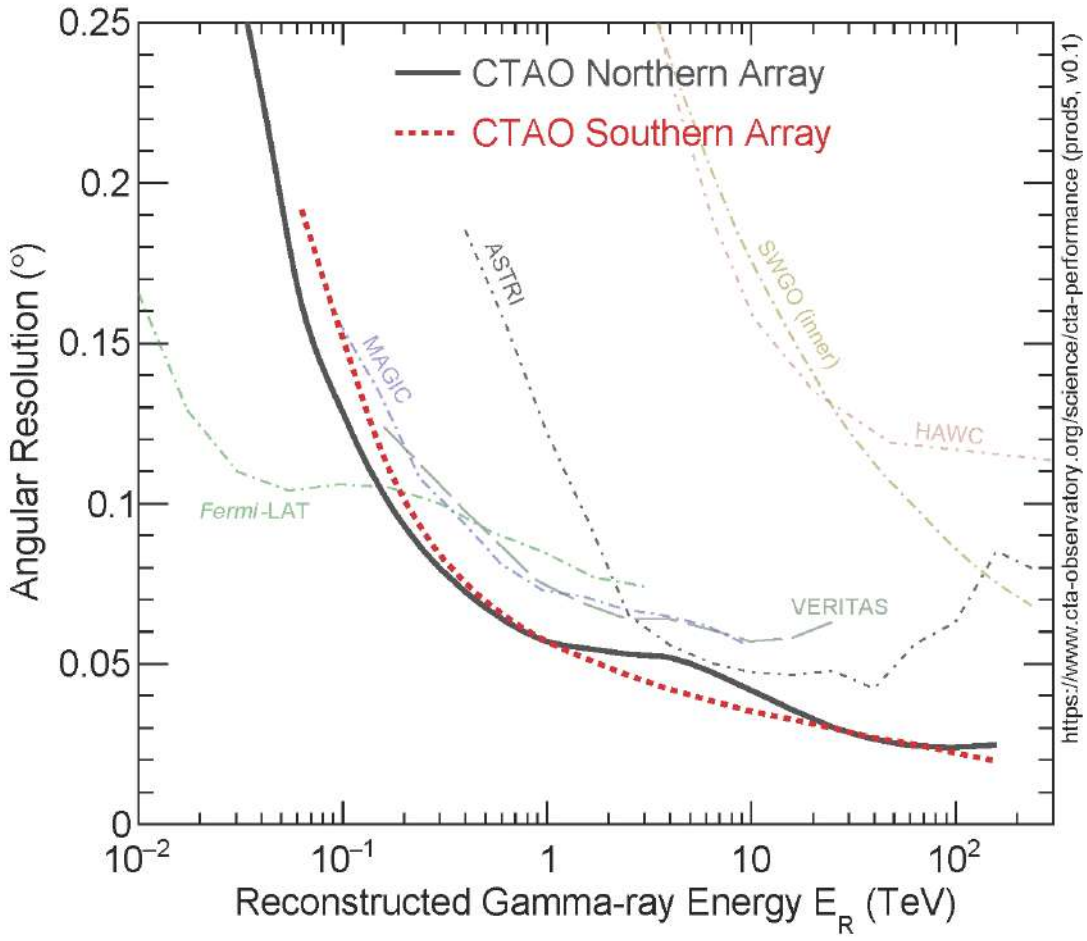
Intensity of Cherenkov Image → photon energy

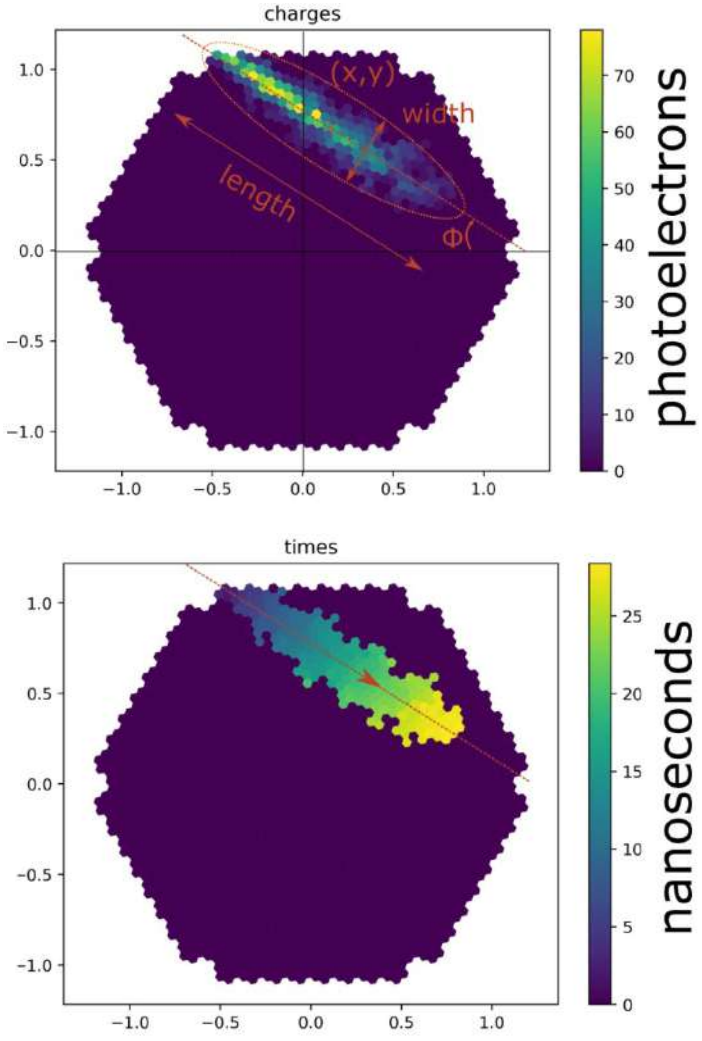
Shape of Cherenkov Image → background rejection



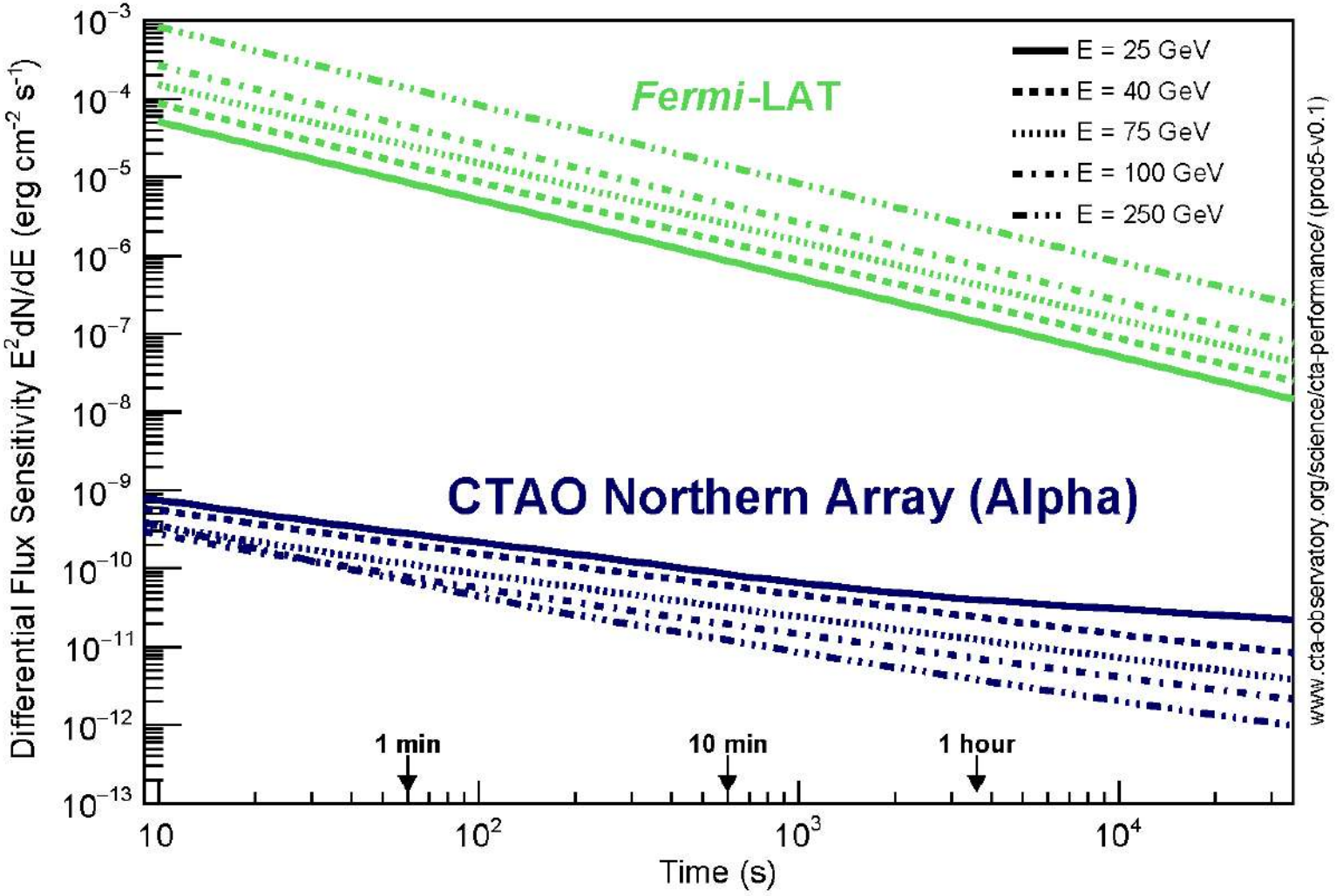
Imaging Atmospheric Cherenkov Instruments: Angular Resolution

Geometry of Cherenkov Image (Stereoscopy) → photon direction

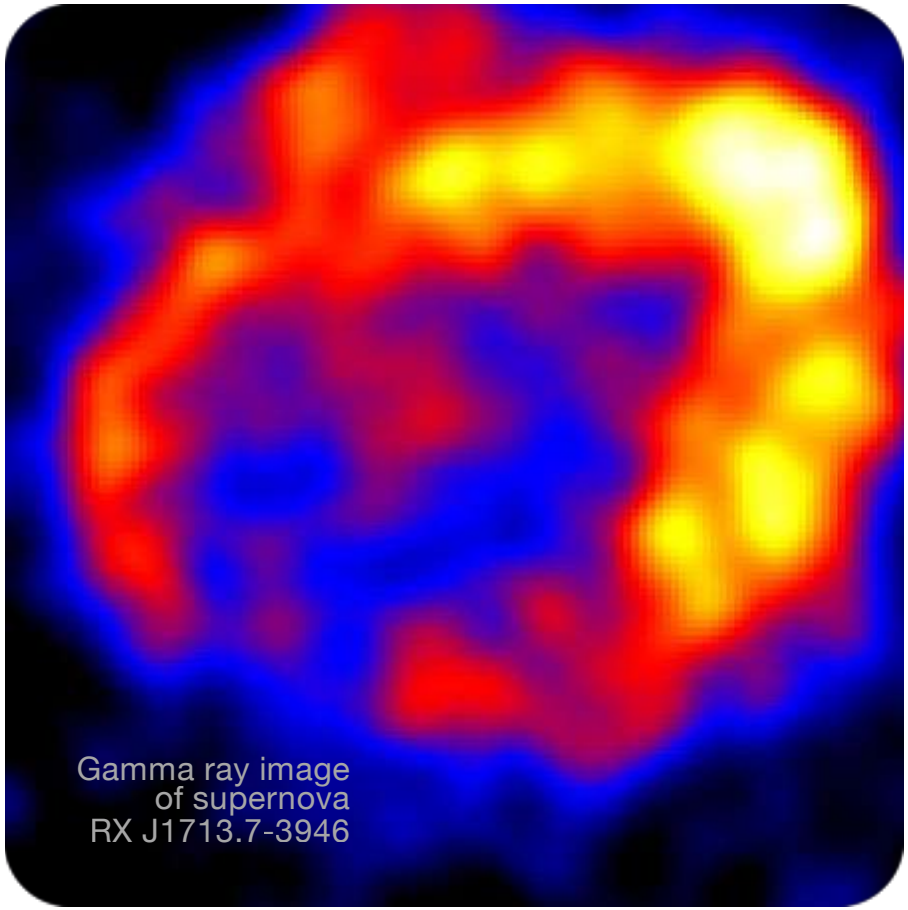




Imaging Atmospheric Cherenkov Instruments: Time domain



Status of Ground-Based Gamma-ray Astronomy



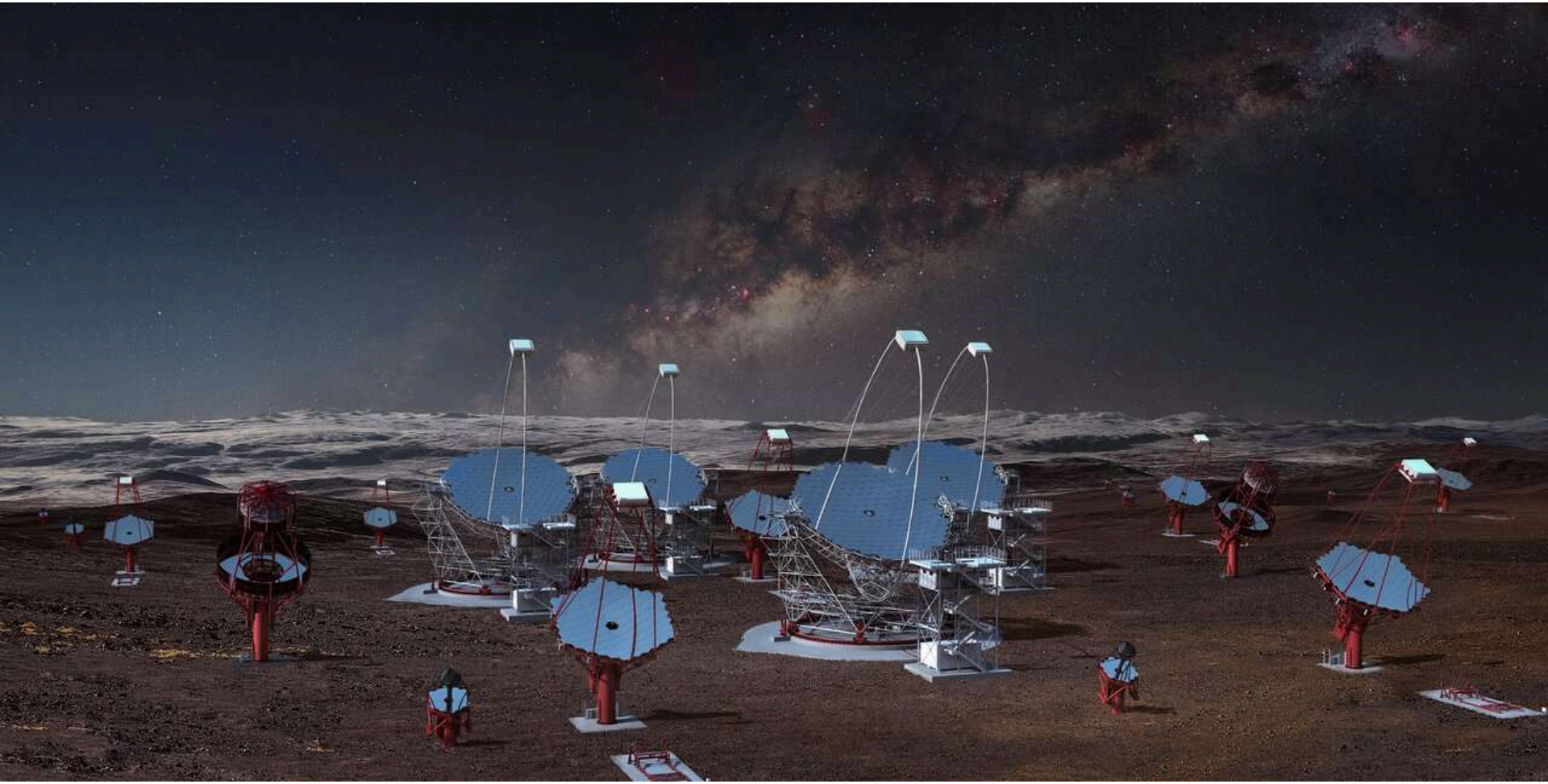
Cherenkov Astronomy has reached the status of "real astronomy"

- good-resolution skymaps, ~ 5'
- 200+ sources detected
- spectra from c. 30 GeV to 30 TeV
- times resolved light curves down to minute timescales

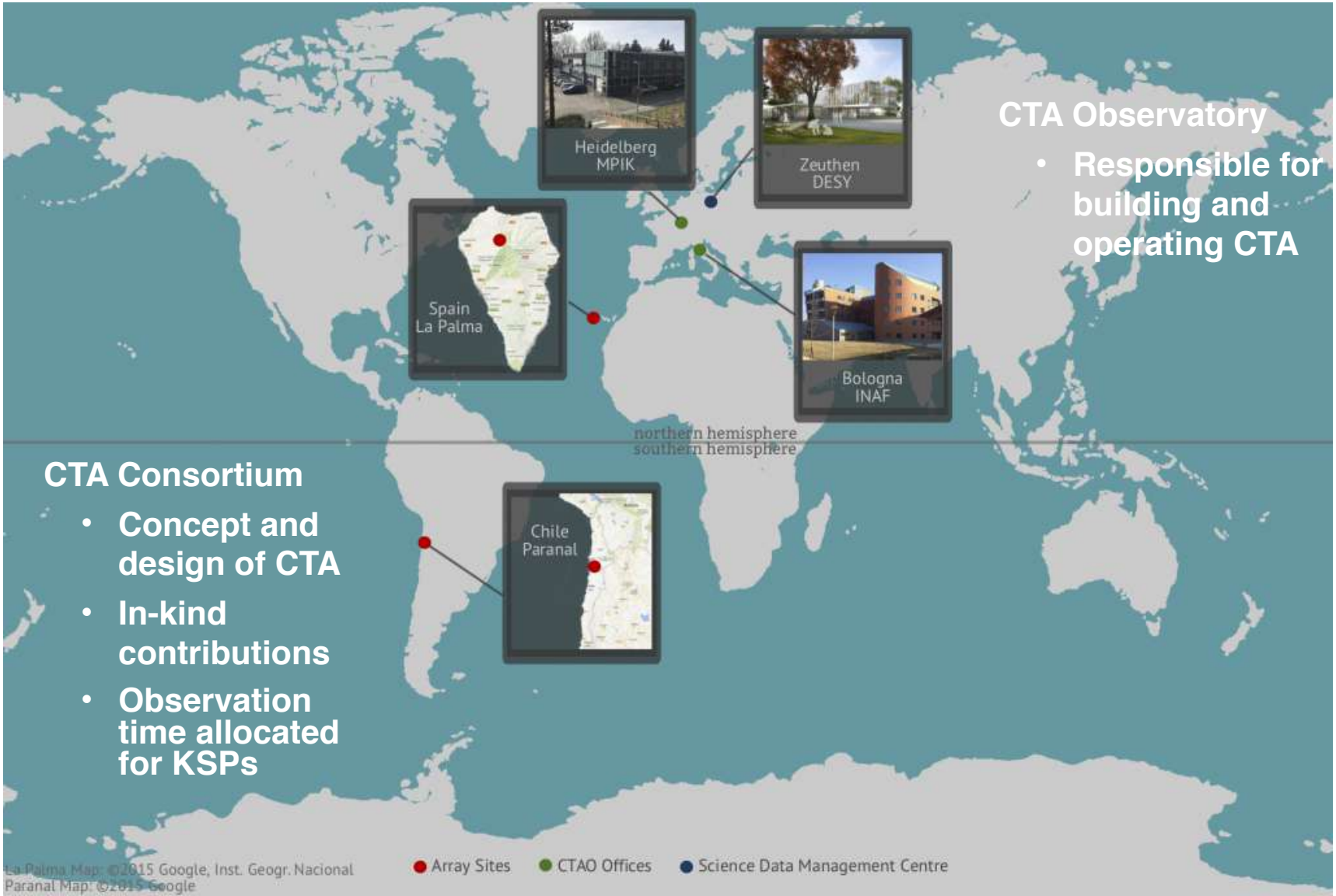
The recipe of the success?

- efficient gamma-hadron separation + stereoscopy
- large light collection, mirror areas 100+ m^2
- sensitive cameras, small-pixel sizes ~ 0.2°
- large field of view of several degrees

The Cherenkov Telescope Array



The (infra-)structure of CTA



CTA Observatory

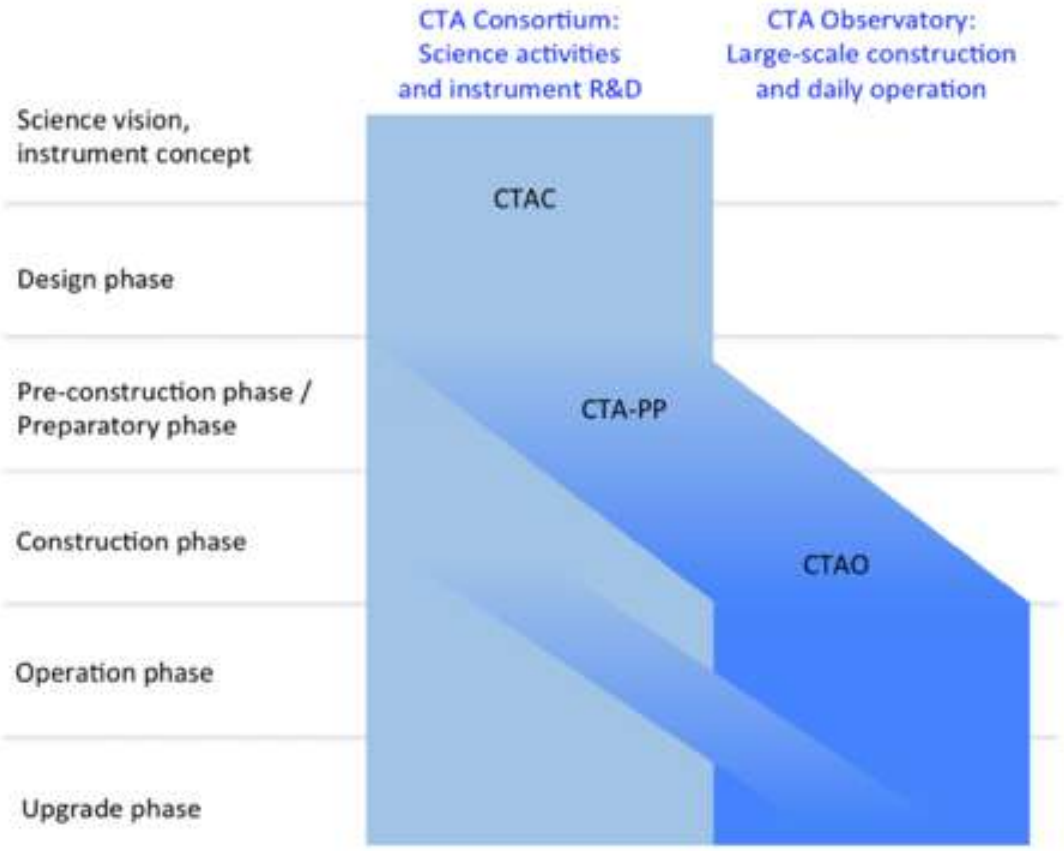
- Responsible for building and operating CTA

CTA Consortium

- Concept and design of CTA
- In-kind contributions
- Observation time allocated for KSPs

A next generation Cherenkov Observatory

Status and observatory planning…



From:
Concept for CTA
construction and operation
WH 2011/12

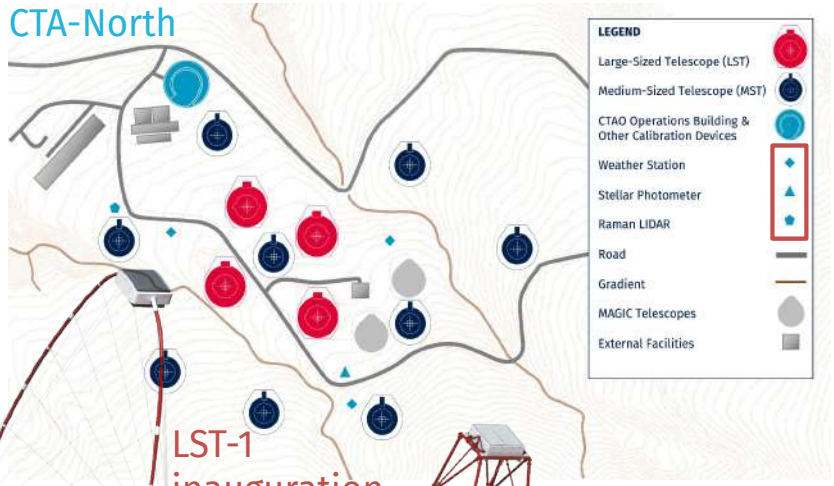
- CTA as open observatory
- Regular AOs
- Proposals evaluated by TAC
- Observations carried out in queue mode
- Fully calibrated photon lists and analysis tools provided to observers
- Data open after proprietary period of 1 year

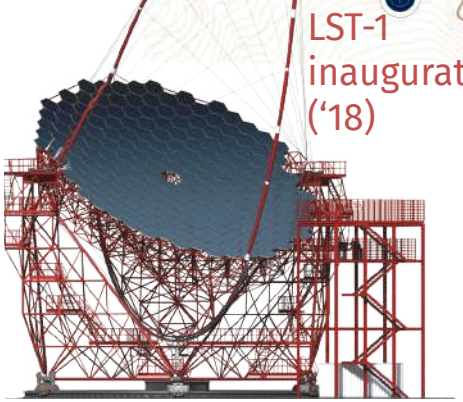
The CTA alpha-configuration

Science-based optimization

North: extragalactic oriented (high-E/z absorption)

CTA-North





LST-1 inauguration (‘18)

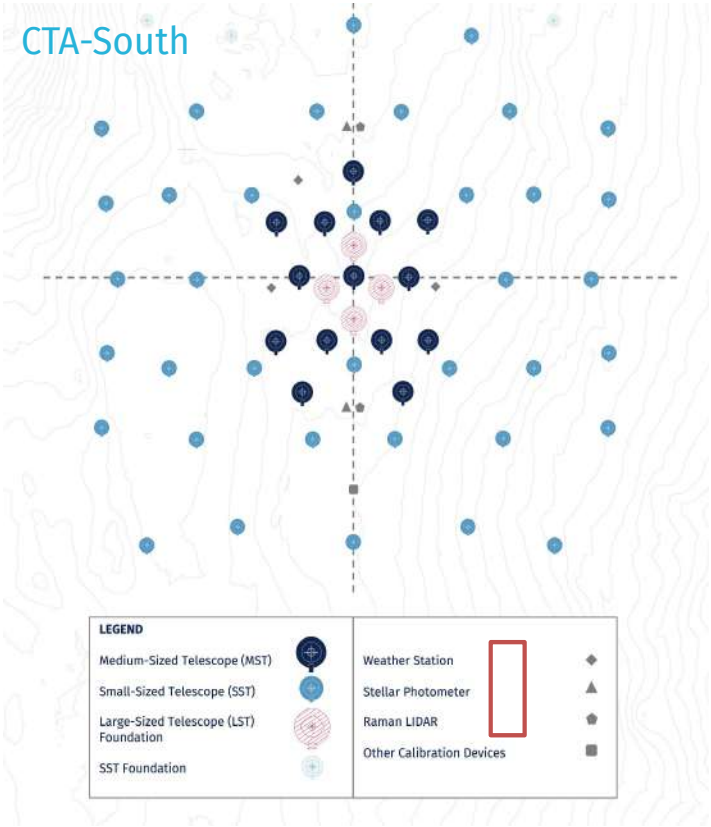
MST camera agreement (‘20)

Single SST design (‘18-19)

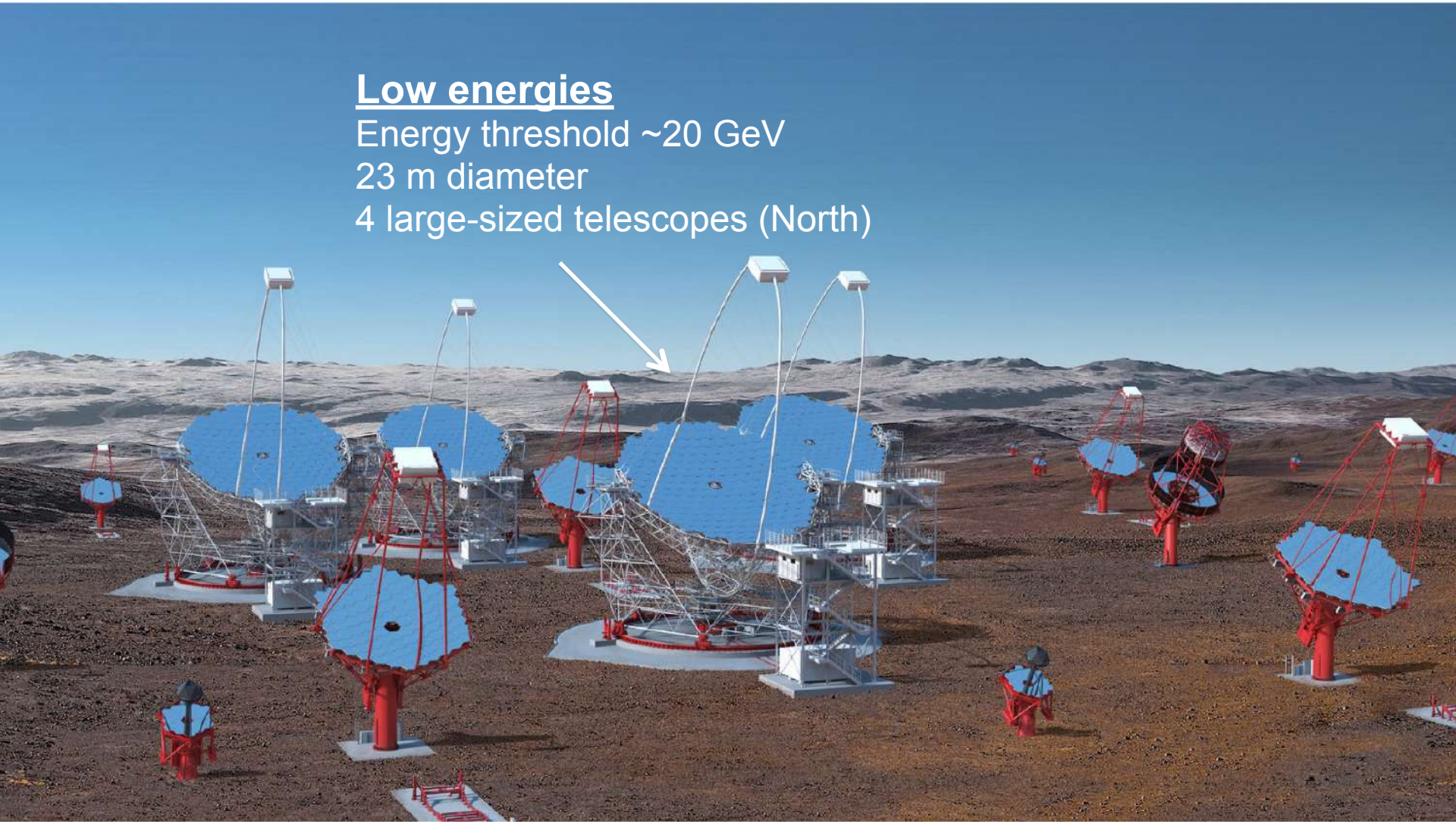
Shower-based optimization

LSTs ~20-200 GeV, MSTs 0.2-2 TeV, SSTs >2 TeV

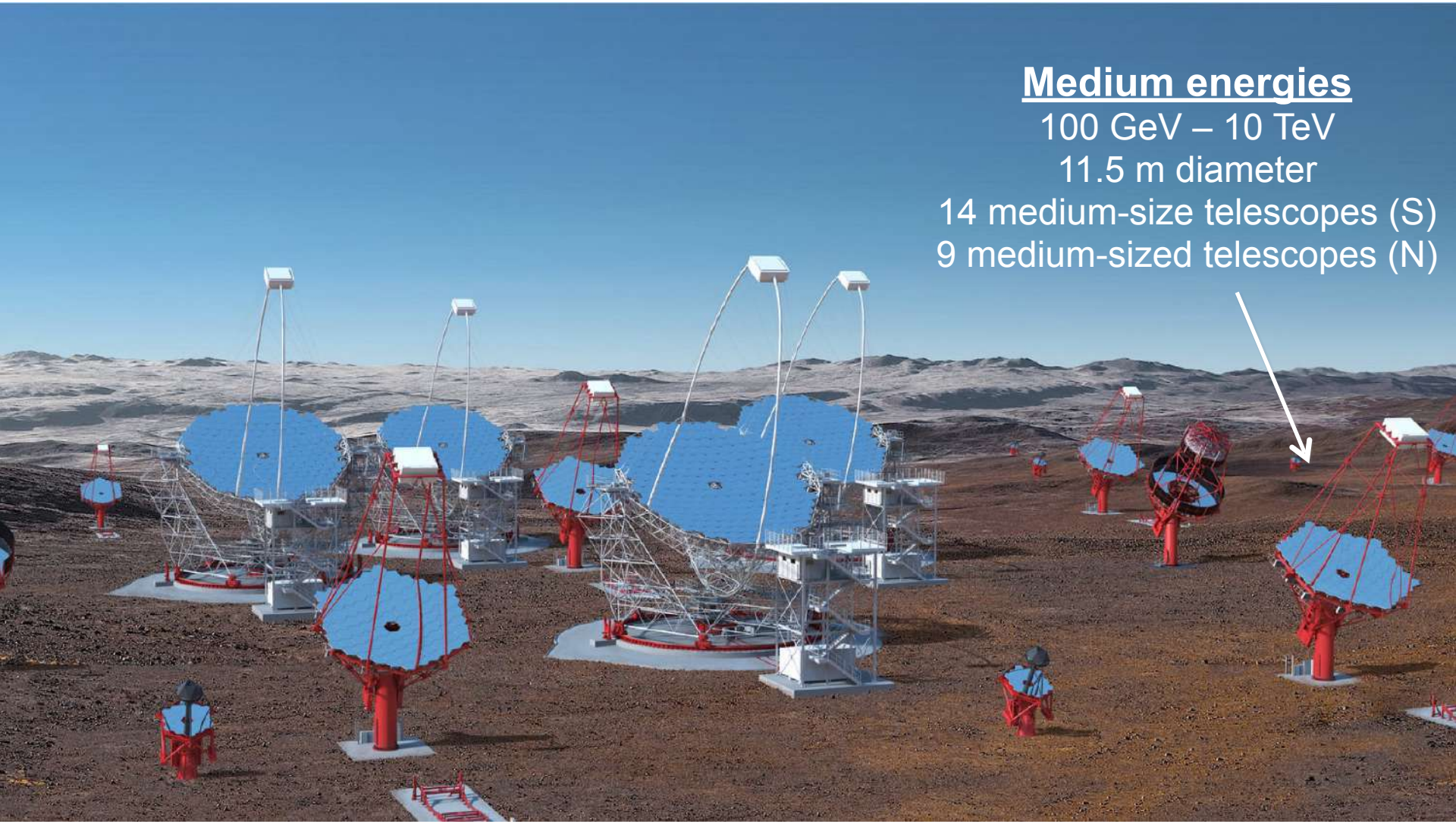
CTA-South



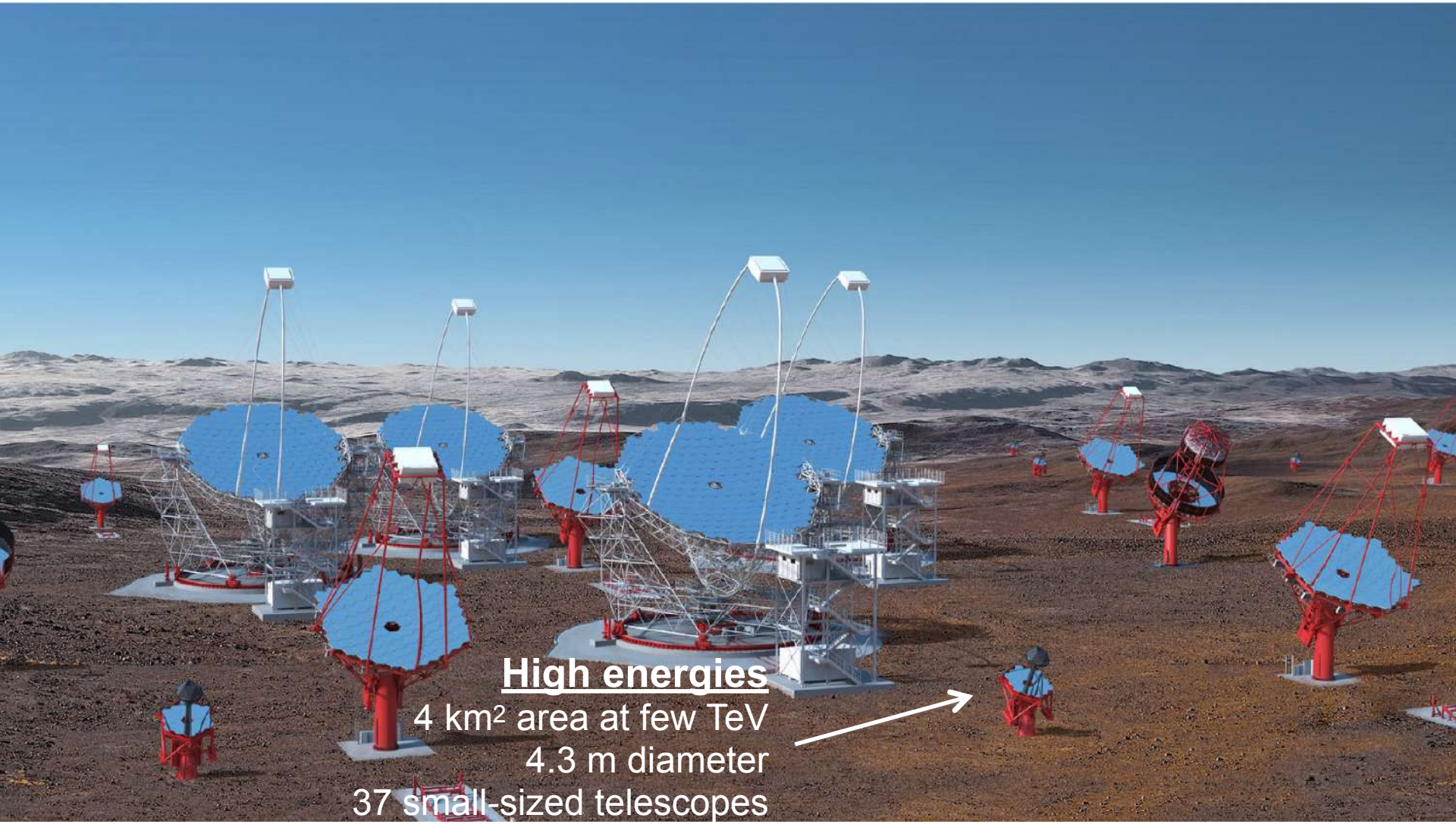
Cherenkov Telescope Array: Instrumentation



Cherenkov Telescope Array: Instrumentation



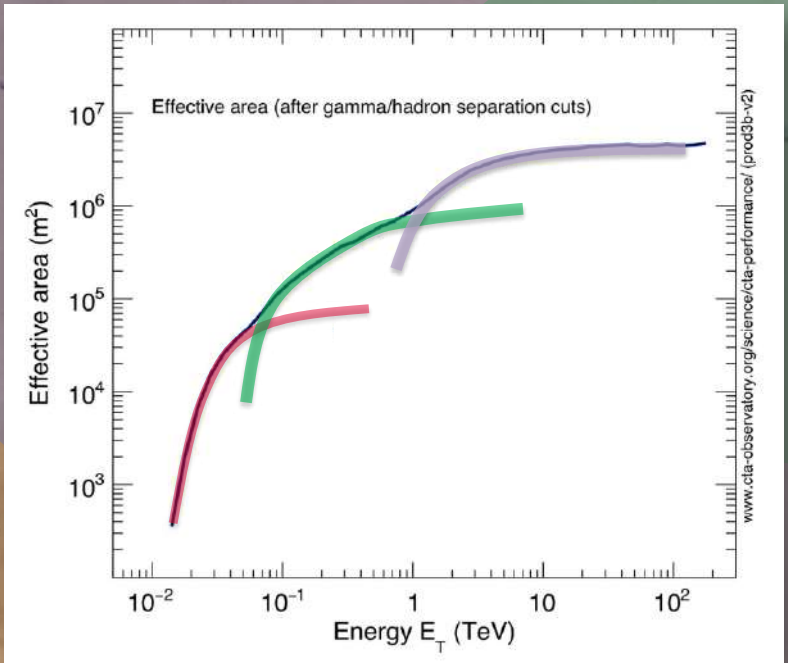
Cherenkov Telescope Array: Instrumentation



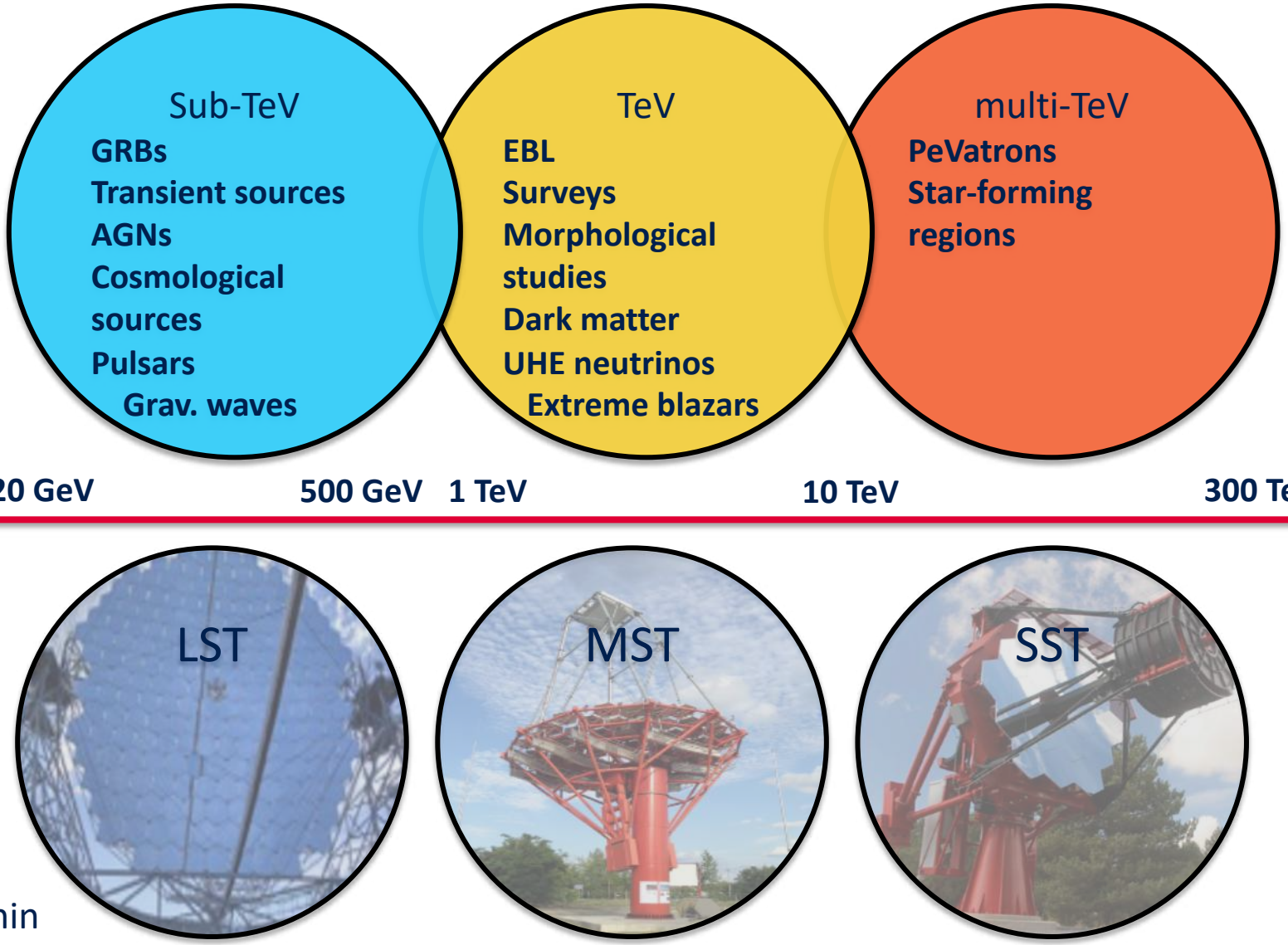
Cherenkov Telescope Array: Instrumentation

10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

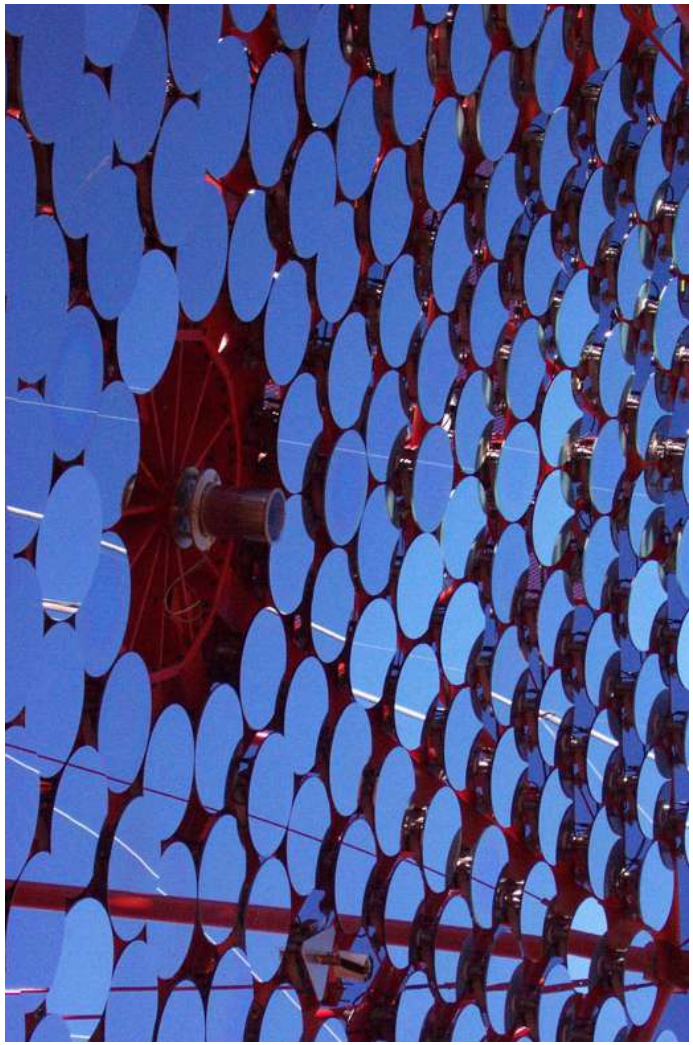
70 x 4 m ∅ Small Size Telescopes (SST) (South)

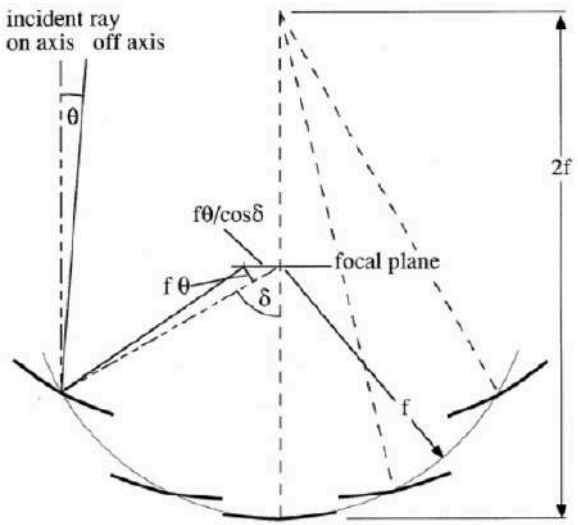


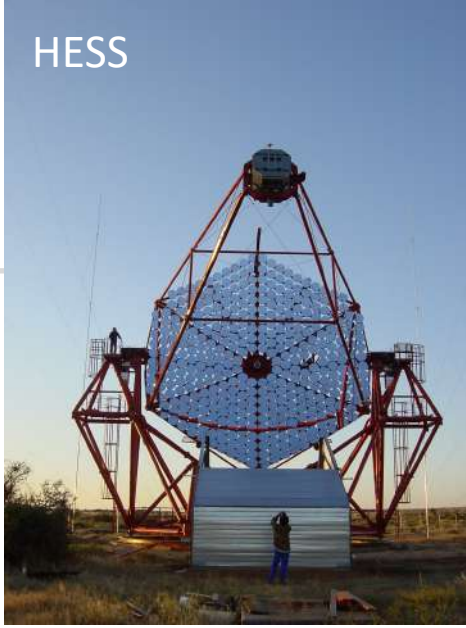
CTA:Science & Instrumentation across VHE spectrum



The Davies-Cotton Optical Design

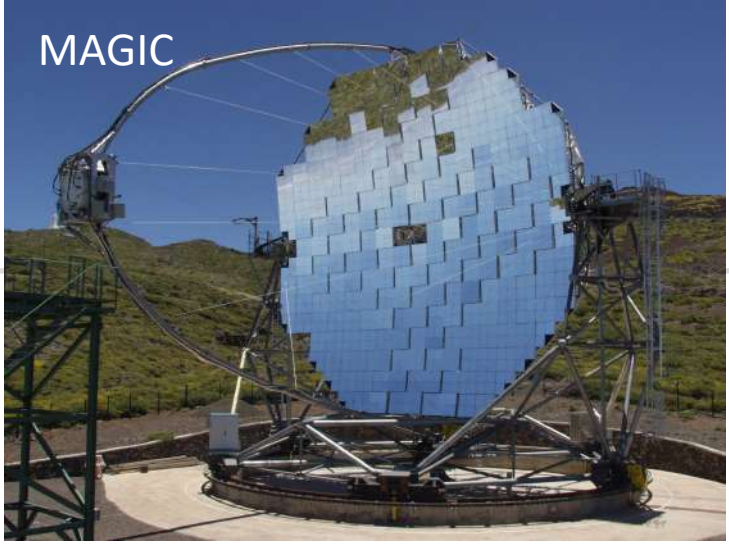


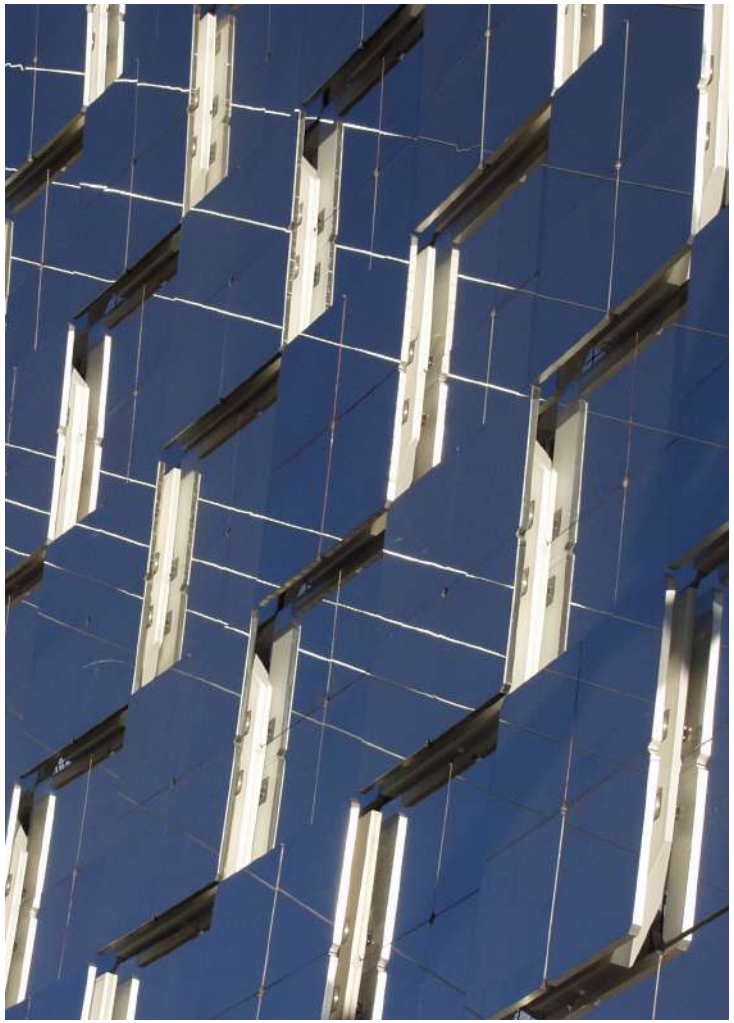




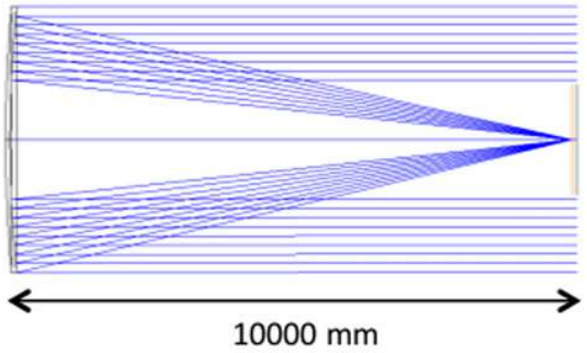
- Inherited from early solar concentrators
- Spherical identical facets mirrors (RoC = 2R)
- Mounted on spherical mount with RoC = R
- Mount and facets have same focal length, but orientation at 2f
- Not synchronous (by a few ns)
- Small off-axis aberrations
- Provides good compromise of PSF over entire FoV

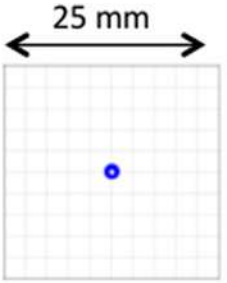
The MAGIC Parabolic Design



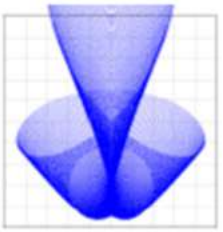


- Dish and mirro segments are parabolic
- Isochronicity
- Small on-axis aberrations
- Better on-axis angular resolution (than DC)
- LARGER off-axis aberrations (than DC)





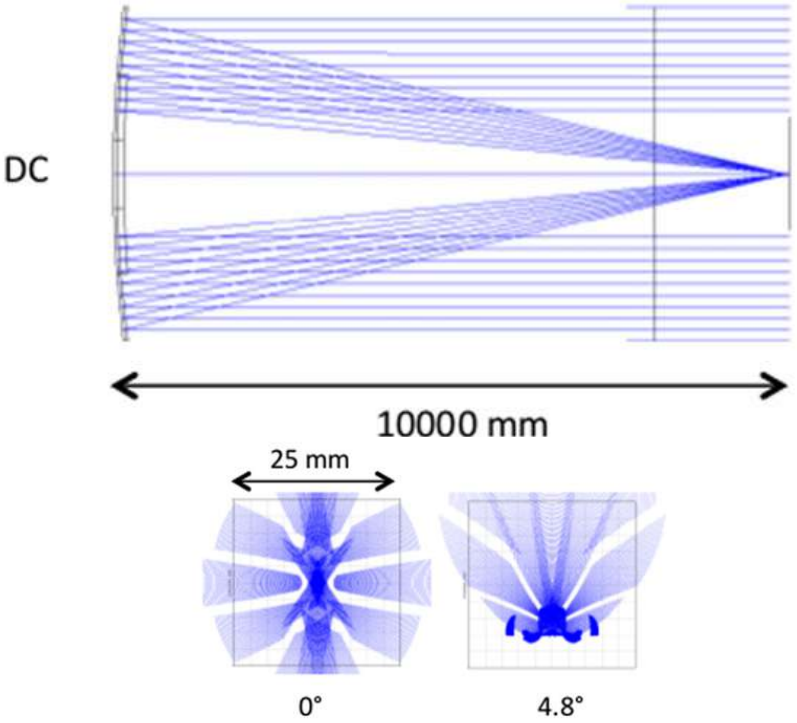
On-axis



Off-axis

The CTA Medium-Sized Telescope

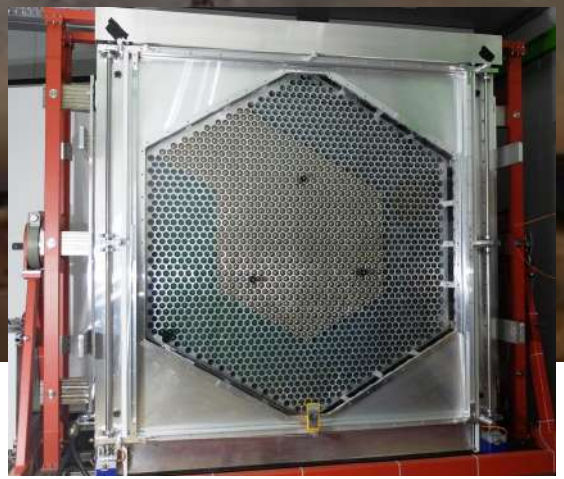
Prototype operated in Berlin-Adlershof for several years;
Two PMT cameras: NectarCAM and FlashCam (N/S split)



- Inherited from early solar concentrators
- Spherical facets mirrors (2RoC)
- Mounted on a modified spherical mount for reduction of aberrations
- Orientation at 2f
- Slight deformation to improve isochronicity

CTA Medium-Sized Telescope: Flashcam

FlashCam unit in routine operation on HESS II telescope since one year



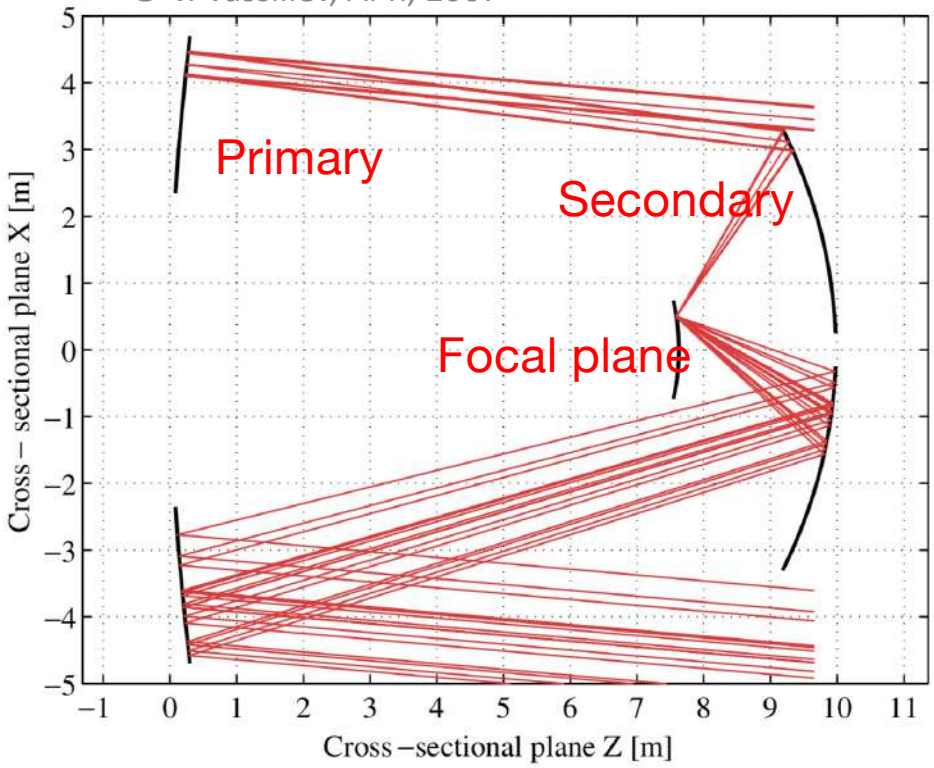
8 degrees FoV
1800 pixels
0.17 deg/pixel

The Schwarzschild-Couder dual-mirror telescope, SCT

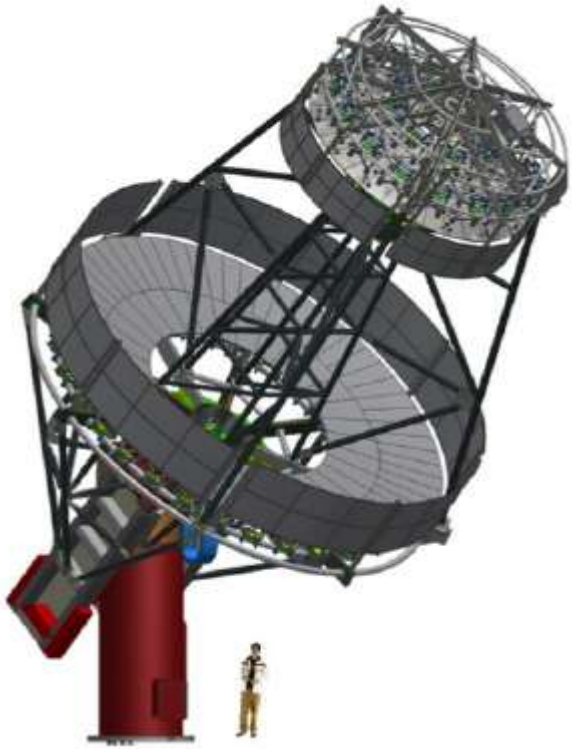
The Scharzschild-Couder dual-mirror telescope

- **New medium-size dual-mirror telescope technology for CTA**
  - **9.7 m primary mirror & 5.4 m segmented second mirror**
  - **Aspherical primary mirror (*)**
  - **De-magnifying aspherical secondary mirror (**)**
  - **(*) + (**) = Optical system corrects spherical and comatic aberrations**

© V. Vassiliev, APh, 2007

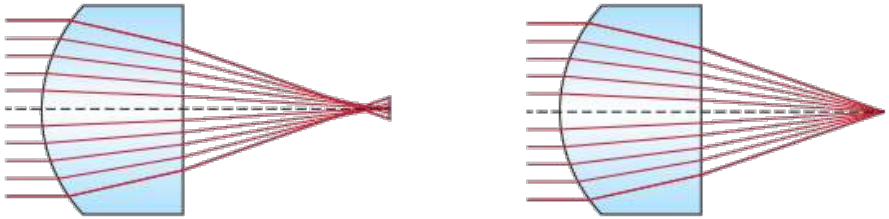


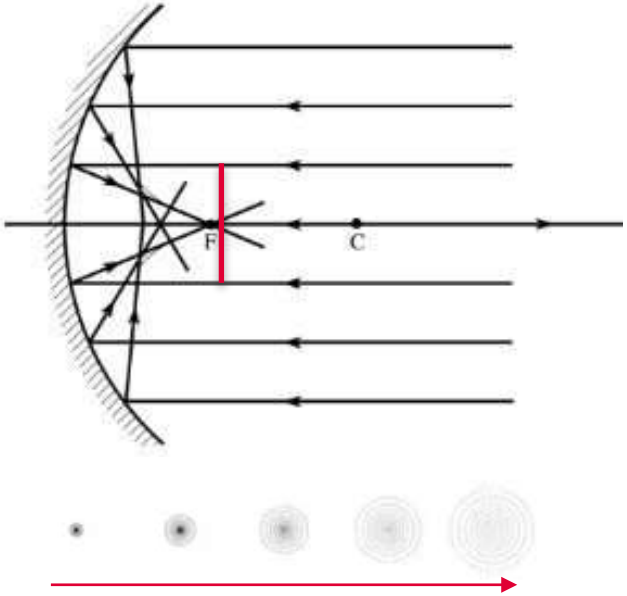
© D. Nieto+ 2015 (pSCT)



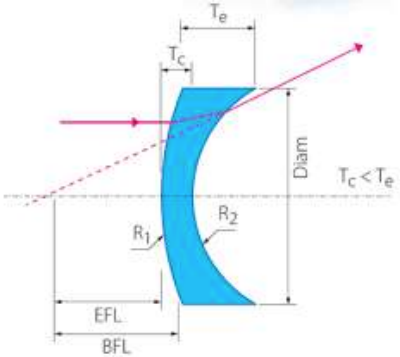
Aberrations

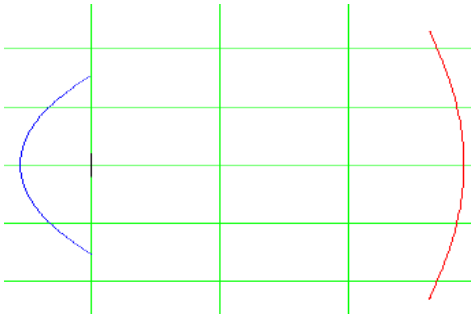
- **Spherical aberration**
  - **Intrinsic defect of spherical mirrors**
  - Correct by aspherical mirror geometry





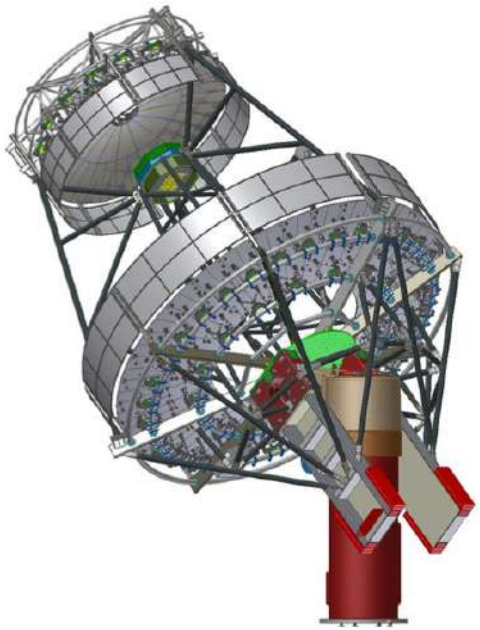
- **Comatic aberration**
  - **Non-spherical surface**
  - Correct by the combined use of the two aplanatic mirrors





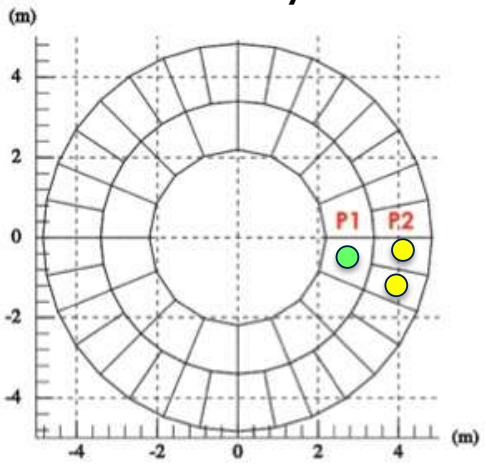
The Scharzschild-Couder dual-mirror telescope

- **New medium-size dual-mirror telescope technology for CTA**
  - **9.7 m primary mirror & 5.4 m segmented second mirror**
  - **Aspherical primary mirror (*)**
  - **De-magnifying aspherical secondary mirror (**)**
  - **(*) + (**) = Optical system corrects spherical and comatic aberrations**
  - Improved optical angular resolution over wide (8º) FoV
  - Small focal plane : small camera with high-resolution (0.067 degree per pixel)
    - Modern dense, highly integrated photo-detectors (SiPM) and electronics
  - On-axis PSF ~ 2.9'
  - **Optics impact improved sensitivity:**
    - Improved gamma-ray angular resolution
    - Improved background rejection (image shape)

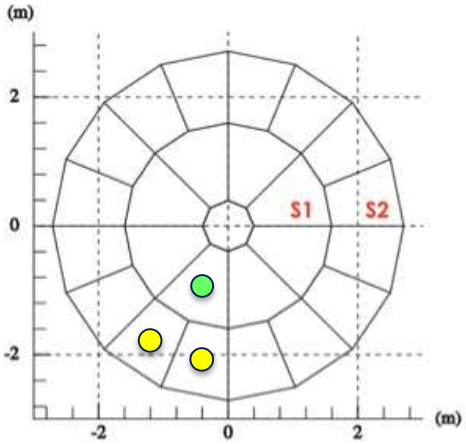


The SCT optical system

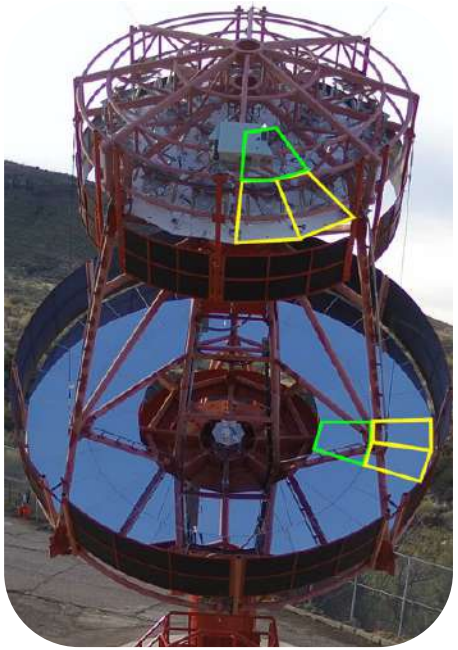
Primary



Secondary



16 P1 and 8 S1
32 P2 and 16 S2



https://cta-psct.physics.ucla.edu/

- Two aplanatic aspherical segmented surfaces.
- Primary and secondary segmented mirrors in total of 72 individually controlled panels

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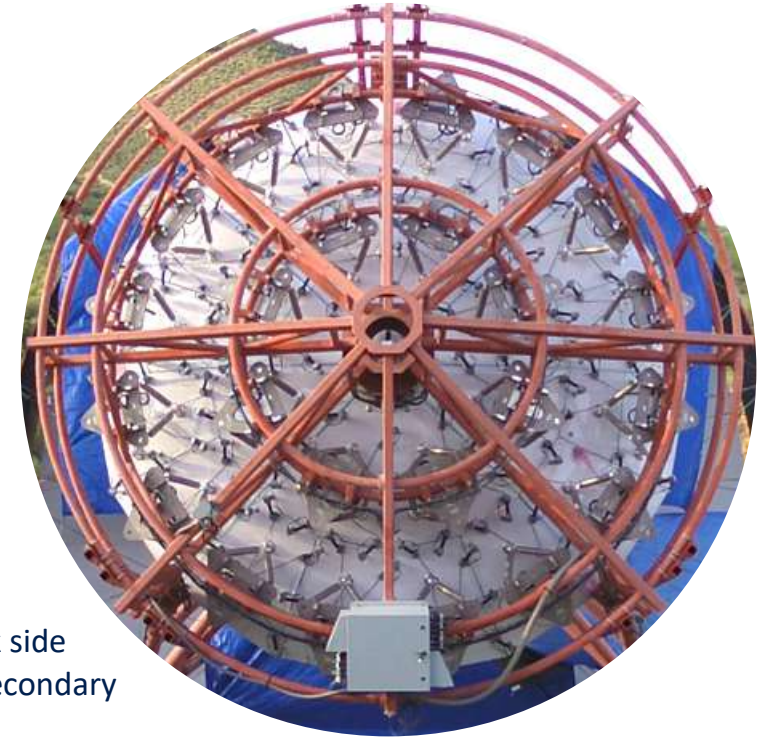
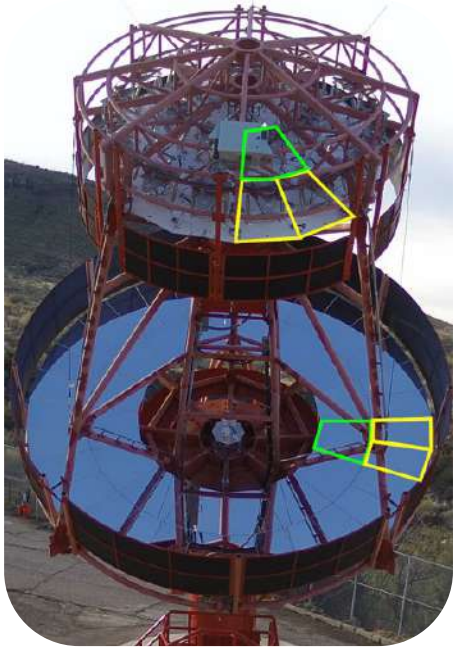
Verification of the Optical System of the 9.7-m Prototype Schwarzschild-Couder Telescope
https://arxiv.org/pdf/2010.13027.pdf

The SCT optical system



Back side
of secondary



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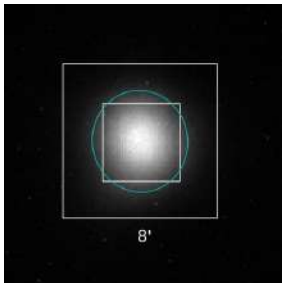

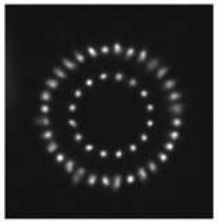

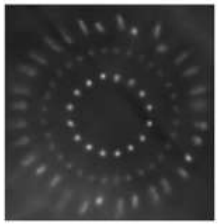

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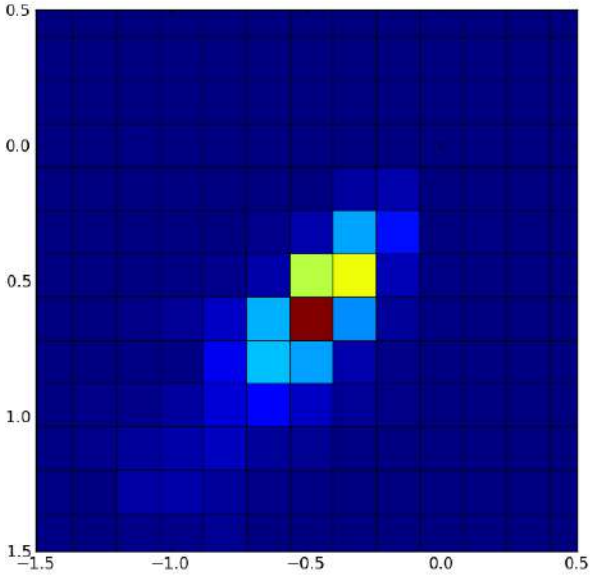
Verification of the Optical System of the 9.7-m Prototype Schwarzschild-Couder Telescope
https://arxiv.org/pdf/2010.13027.pdf

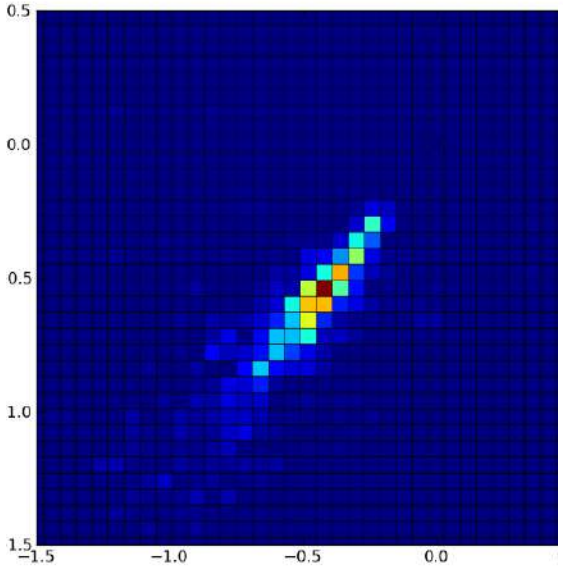
- Actuators system for mirror alignment

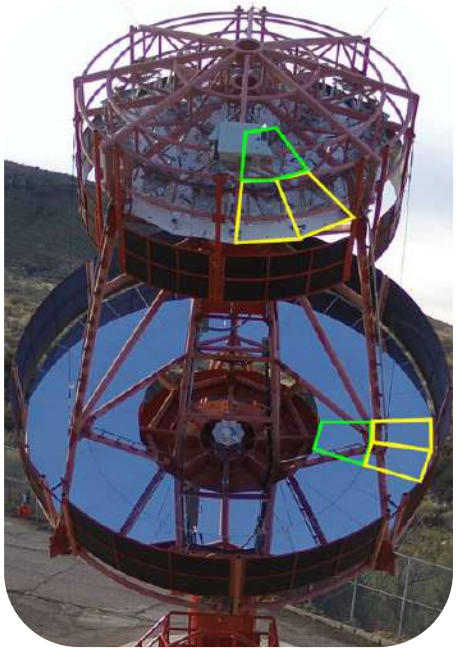
The SCT optical system

1 mirror telescope (~2k 0.17°pixels)

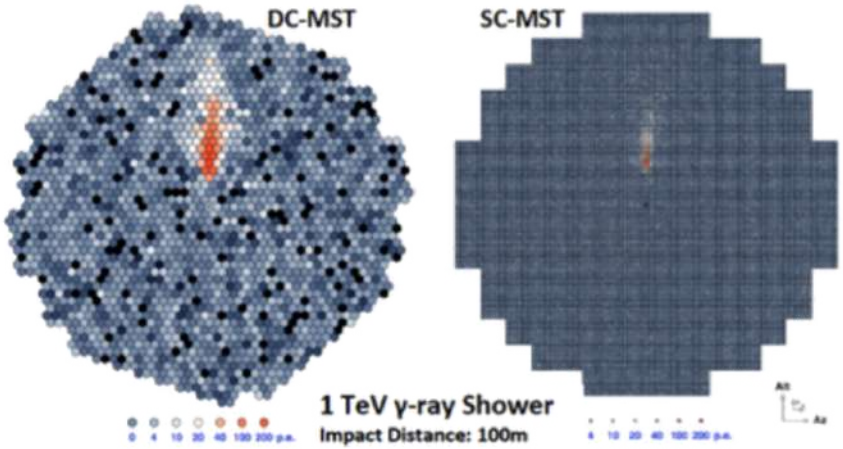


2 mirror telescope (~11k 0.07° pixels)





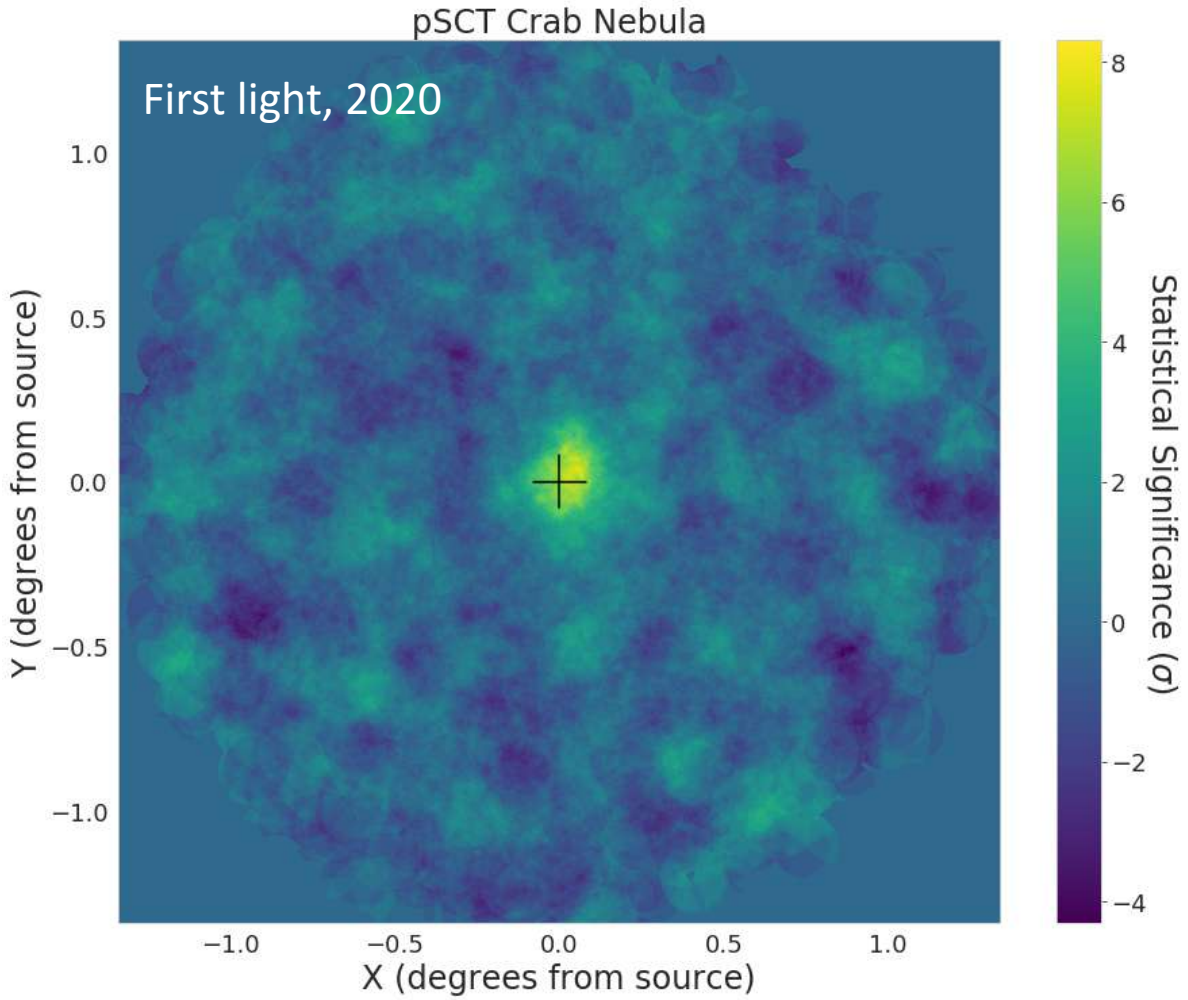
https://cta-psct.physics.ucla.edu/



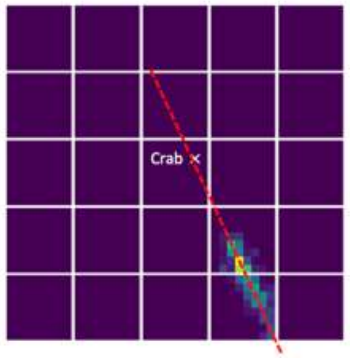
SPIE. DIGITAL LIBRARY

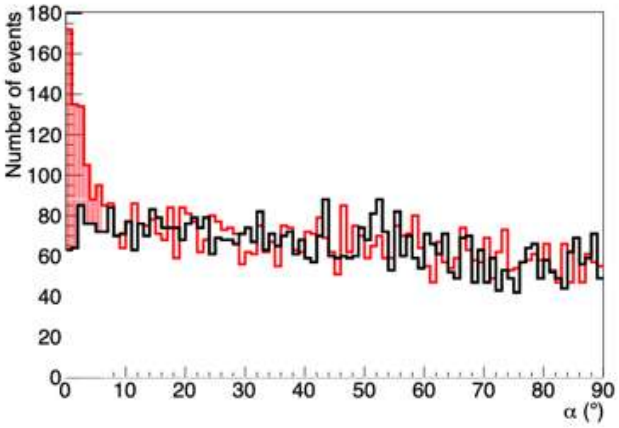
Verification of the Optical System of the 9.7-m Prototype Schwarzschild-Couder Telescope
https://arxiv.org/pdf/2010.13027.pdf

The pSCT dual-mirror telescope



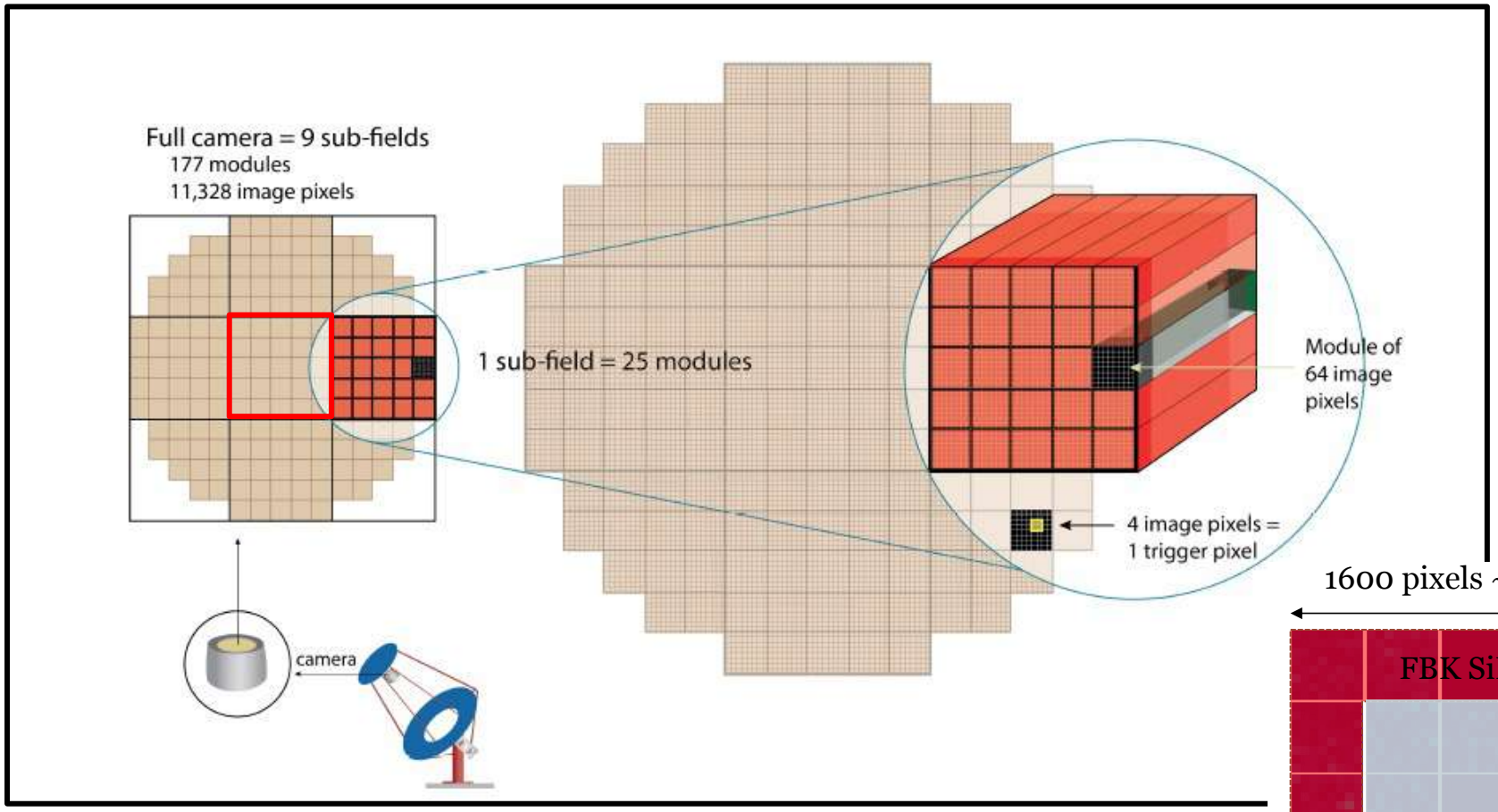
- Prototype pSCT Telescope constructed at Whipple Observatory

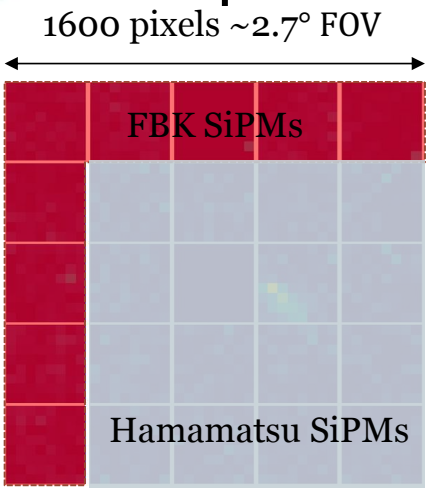




"Crab detection establishes innovative dual-mirror technology for gamma-ray astronomy"
C. B. Adams et al., Astroparticle Physics 128 (2021) 102562

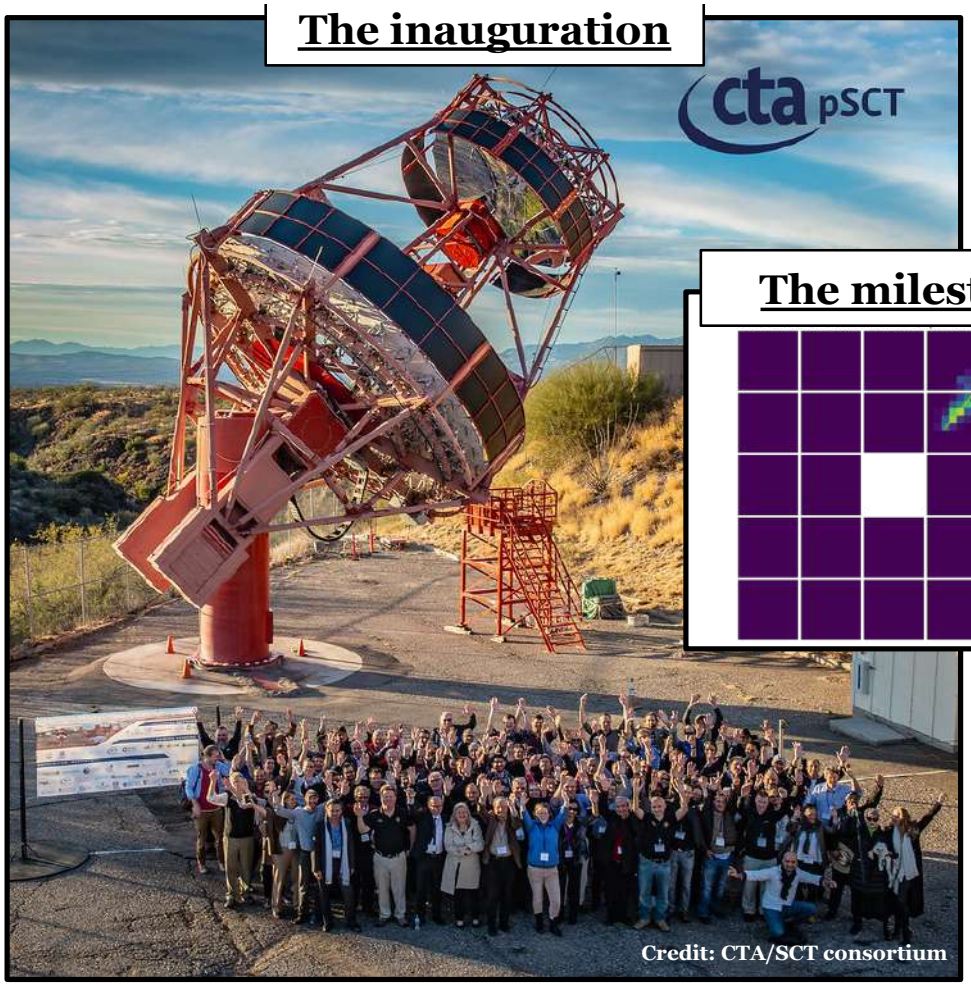
The pSCT camera





https://doi.org/10.1117/1.JATIS.8.1.014007

Status of the pSCT project

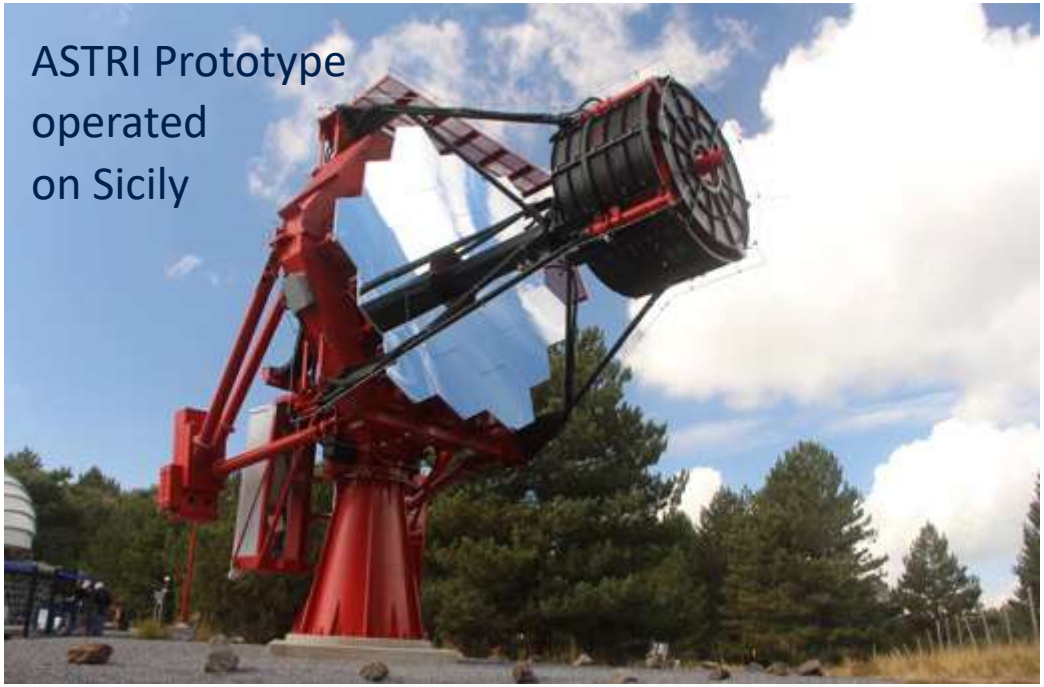


- ~30 institutions https://cta-psct.physics.ucla.edu/institutions.html
- Milestones:
  - 1st construction: 06-23-2015
  - Inauguration: 01-17-2019
  - 1st light: 01-23-2019
  - December 2019: optical alignment achieving pre-construction estimated PSF
  - May 2020: significant detection of the Crab Nebula (presented at 236th AAS) https://doi.org/10.1016/j.astropartphys.2021.102562
  - Endorsement by the CTA Consortium for supporting the development and construction of SCTs to add to the array and complement single-mirror MSTs
- Next steps:
  - Ongoing (funded MRI): population of the focal plane to ~11k channels with upgraded SiPMs and electronics

© Massimo Capasso

CTA ASTRI Small-sized Telescope

- Dual-mirror design with SiPM camera



10 degrees FoV
2350 pixels
0.19 deg/pixel

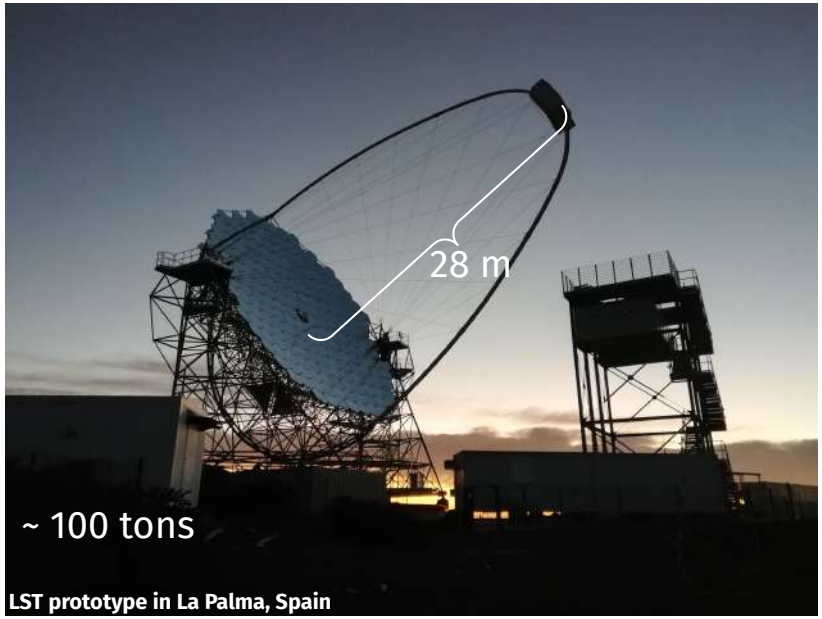
CHEC Camera

The CTA Large Size Telescope (LST)

The CTA Large Size Telescope (LST)

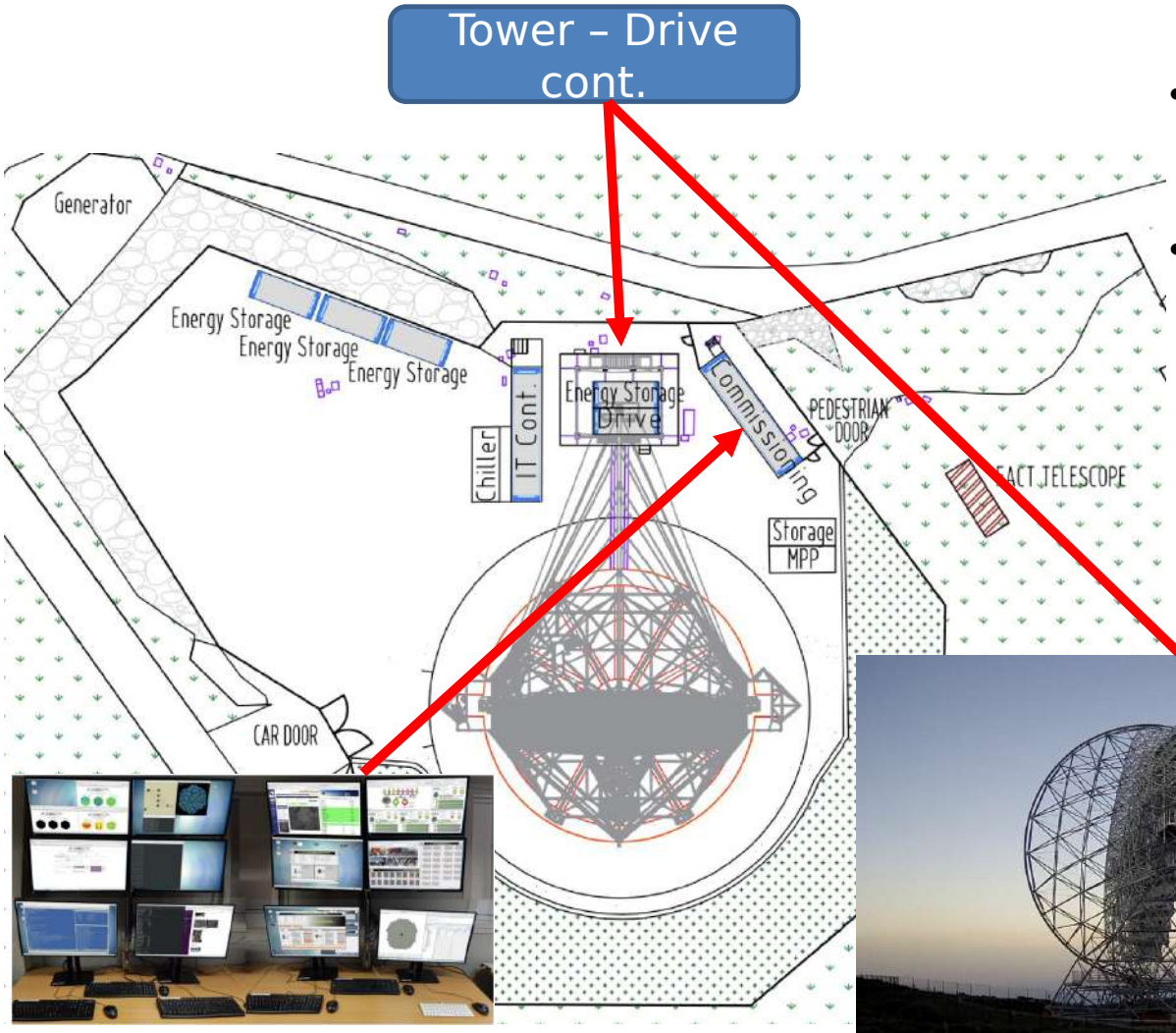
- **A CTA telescope** designed to detect lower energy gamma-rays
  - Will drive the CTA performance in the range 20 to 200 GeV
  - **Prepared for transient science**
    - Fast positioning in 30 sec to follow-up burst alerts
    - Field of view of 4.5º
    - Optimised for extragalactic science, such as AGNs and GRBs
  - **LST1 is taking data since November 2019**

drone picture taken during LST-1 inauguration, October 2018



LST prototype in La Palma, Spain

The CTA Large Size Telescope (LST)



- Profit from available infrastructure at the ORM at IAC
- Added
  - Power line
  - Diesel generator
  - Onsite IT center
  - Commissioning container
  - Storage and tools container

The CTA Large Size Telescope (LST)

Structure	
Alt-Azimuth Mount on a circular rail	
Tubular Structure in CFRP & Steel	
Full Telescope Weight	100 tons
Time for a 180 deg azimuth movement	<20 s
Pointing precision	<14”
Optics – Parabolic mirror	
Primary Mirror Diameter	23 m
Focal Length	28 m
Effective area including shadowing	368 m²
Camera	
Field of View	4.5°
Number of Pixels	1855
Pixel size	0.1°
Photo Sensor	PMT
Signal sampling rate	1 GHz

Despite Volcanoes…

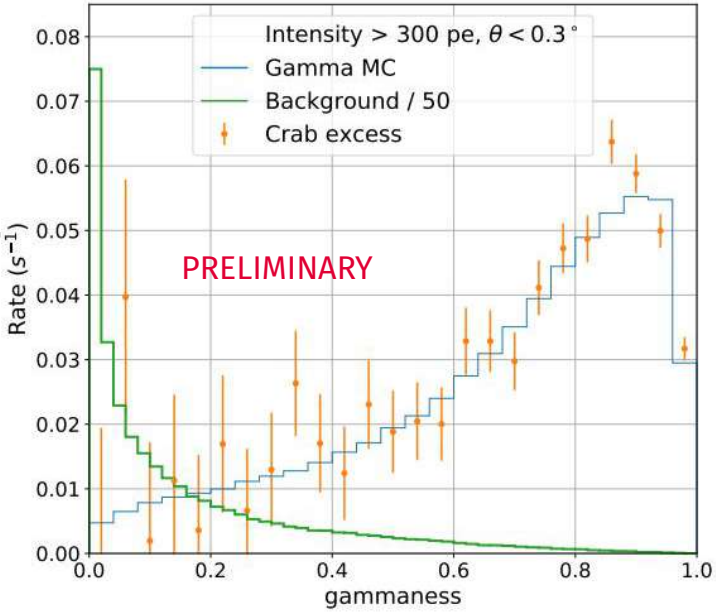
The eruption of the Cumbre Vieja block all operations from the end of September up to January

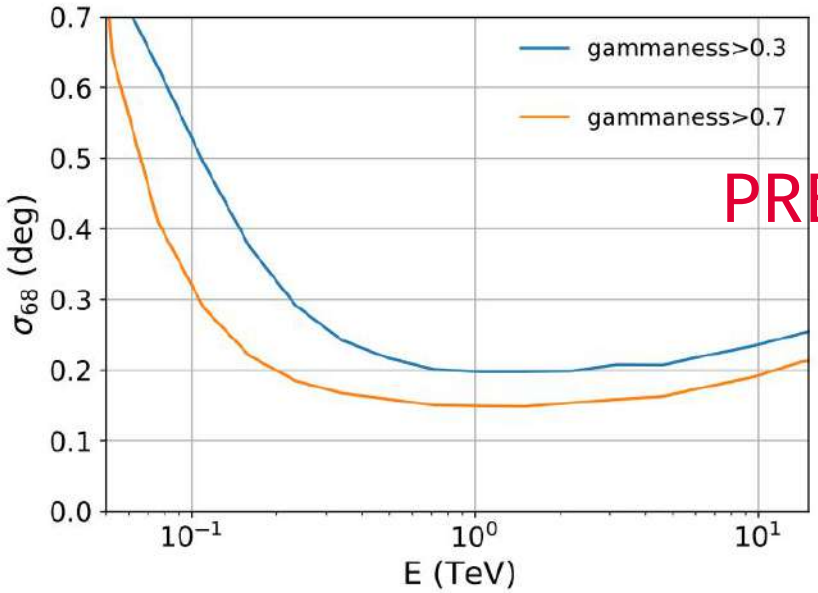
Operations are back to normal since February with no impact on the scientific performance

LST1 observations

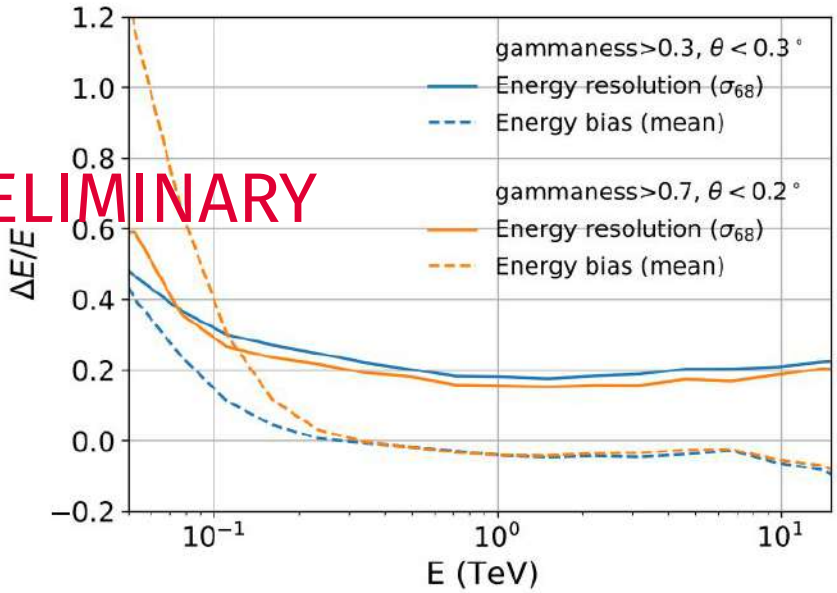
Crab Nebula Observations

- Tune Monte Carlo and improve analysis steps.
- “Gammaness” is a measure of how gamma-like and event is, used for background rejection





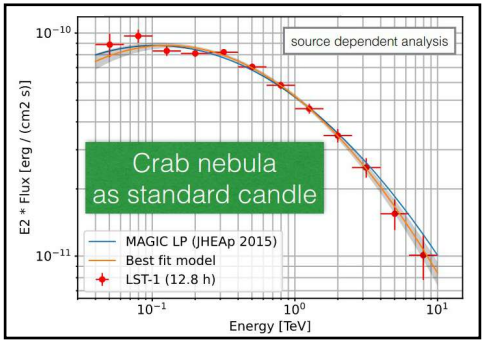
PRELIMINARY

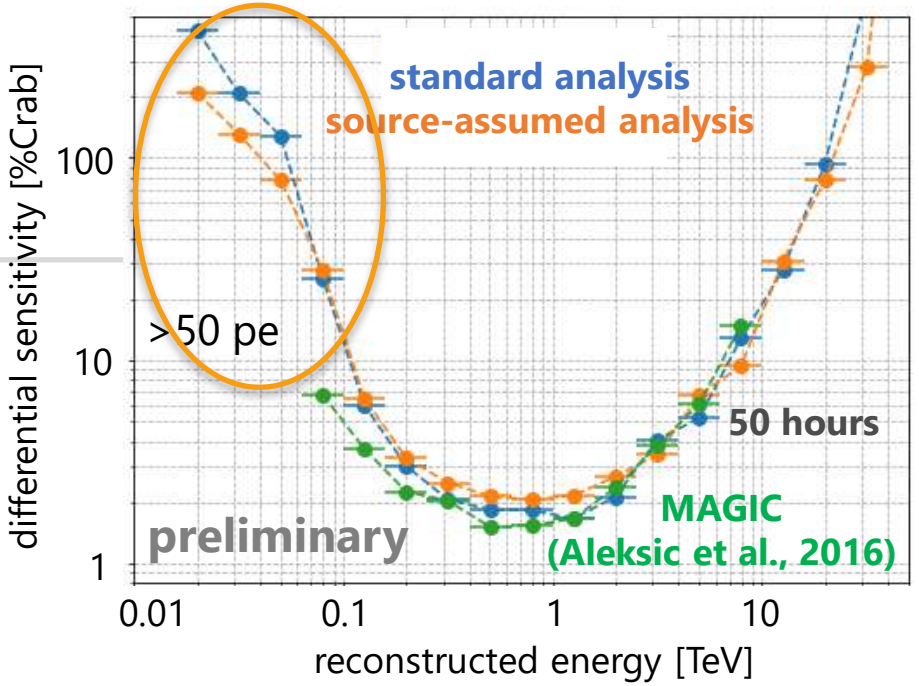


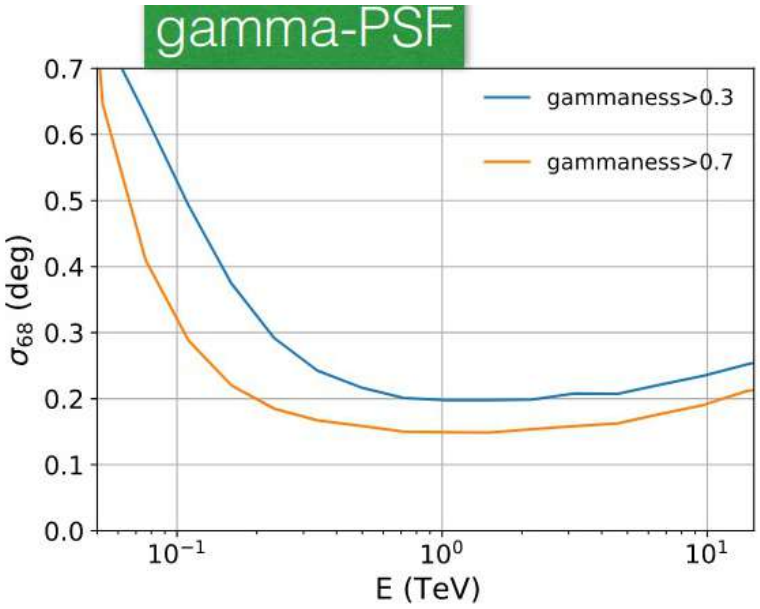
Angular and Energy resolution of LST1 using tuned MC to Crab Data and source independent analysis.

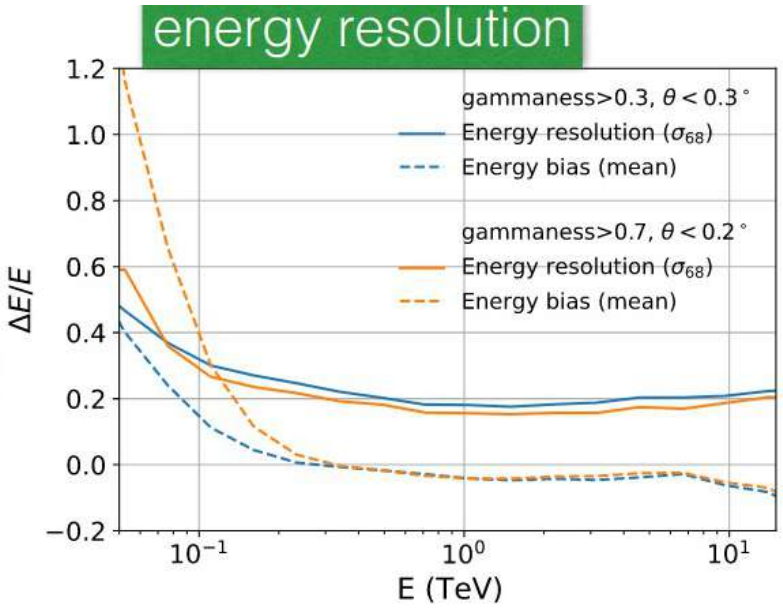
LST1 observations

Performance diagnostics





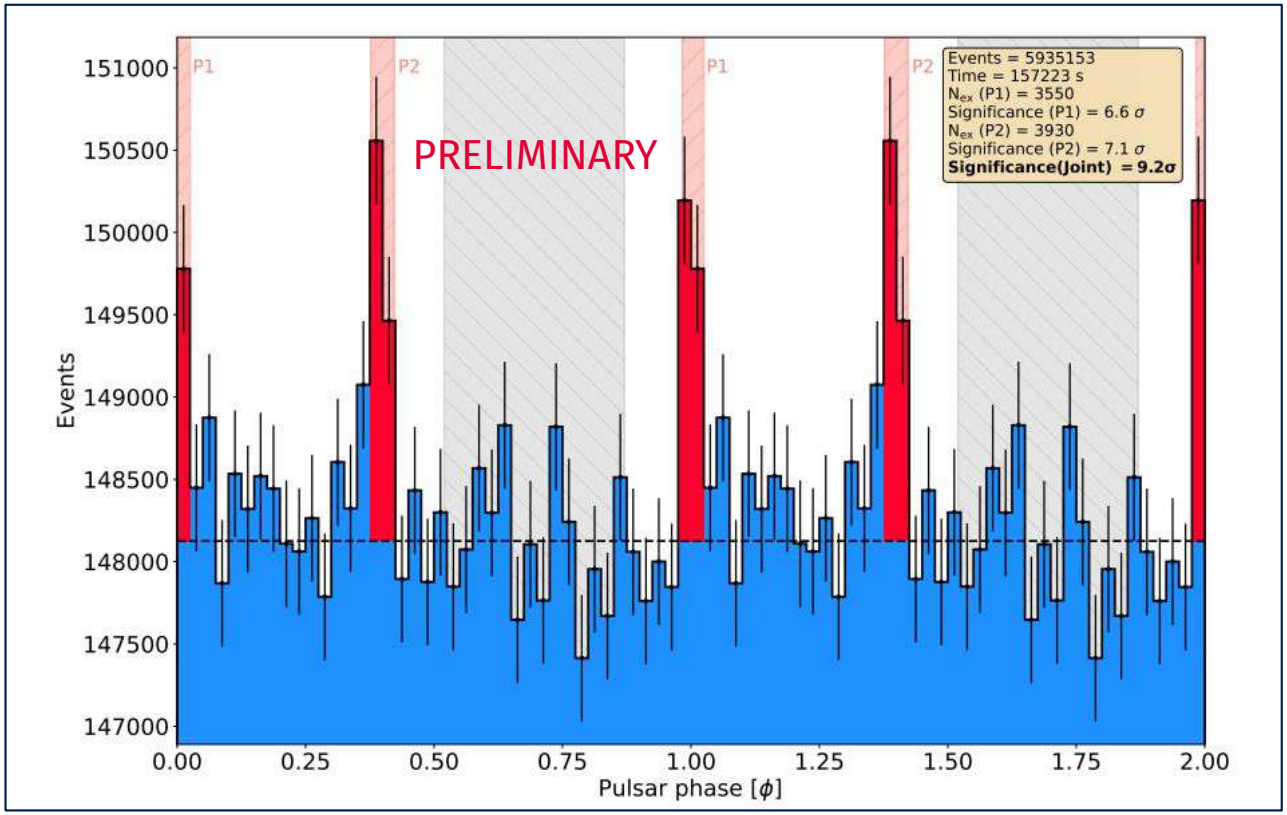




LST1 observations

Crab Pulsar

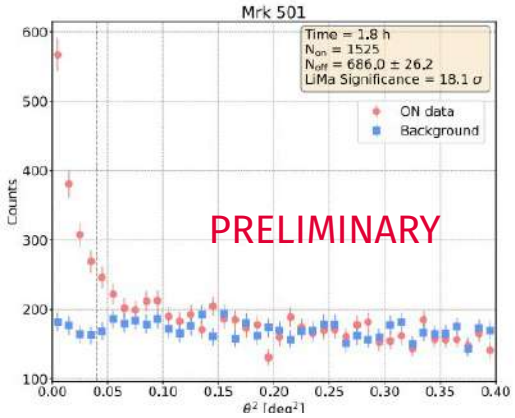
- Rotating neutron star P = 33 ms
- LST first observations in Jan-Fev and Nov ’20
- Successful detection of P1 and P2 pulses

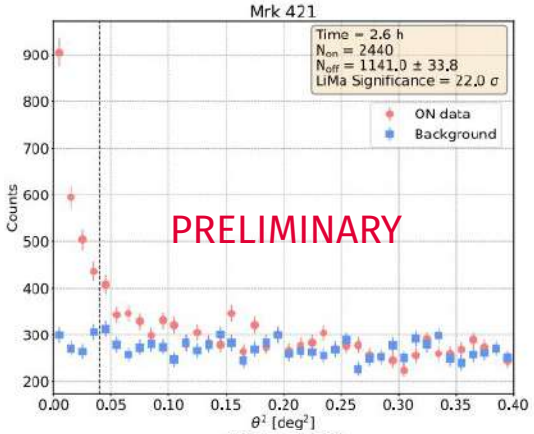


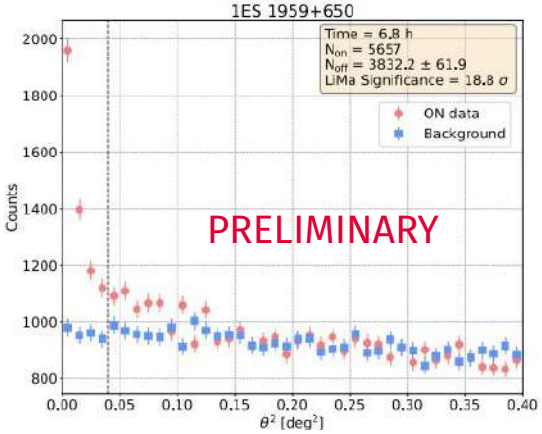
LST1 observations

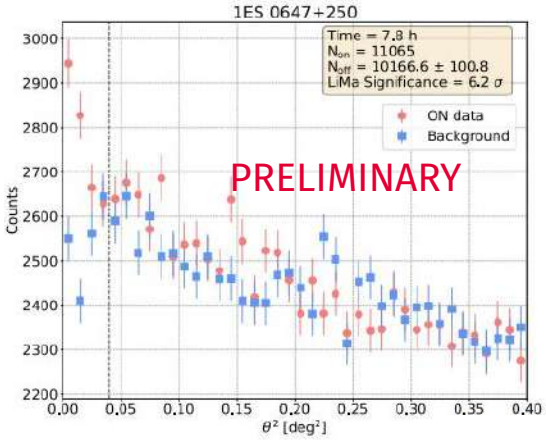
Active Galactic Nuclei

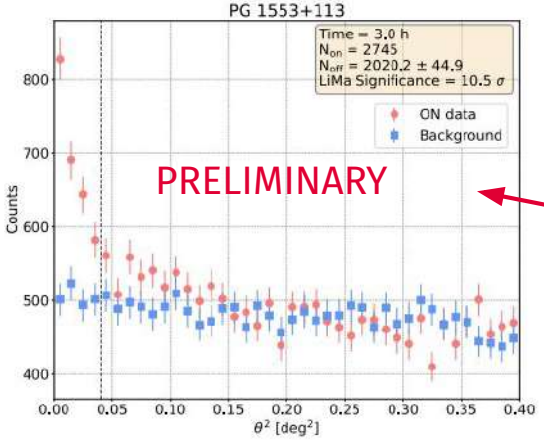
- LST1 observed and successfully detected a number of these objects











Most distant source detected by the LST1 (redshift ~ 0.5).

C. Priyadarshi, A. Baquero

LST1 observations

Active Galactic Nuclei

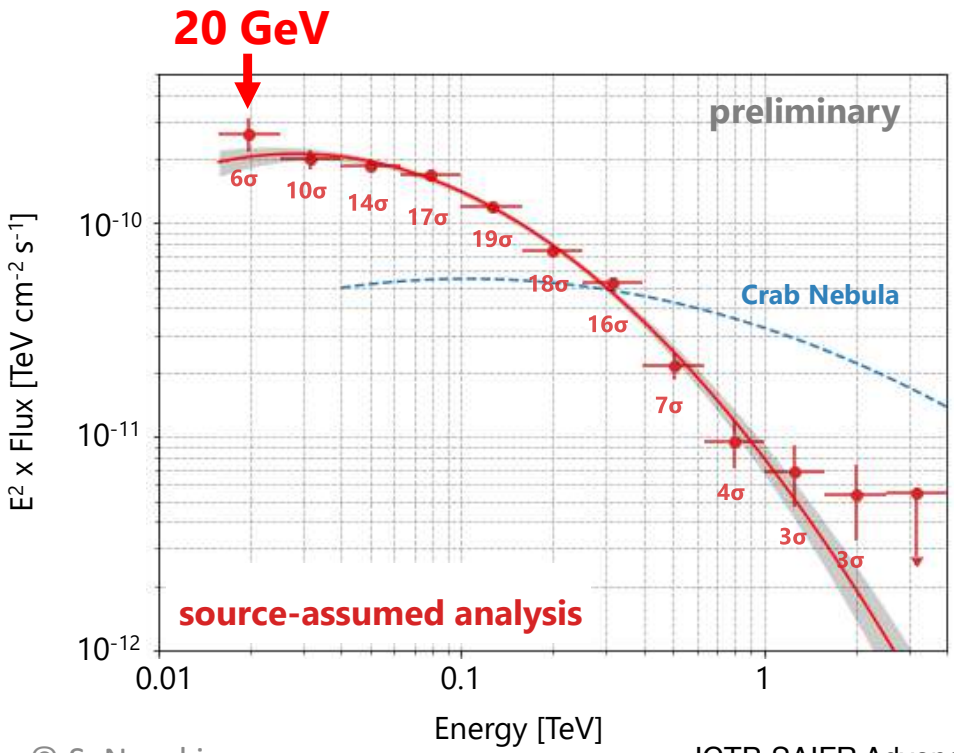
- In particular, the detection of a flare from BL Lac in 2021 resulted in the first Atel from a CTA instrument on 13th July


[Previous | Next | ADS]

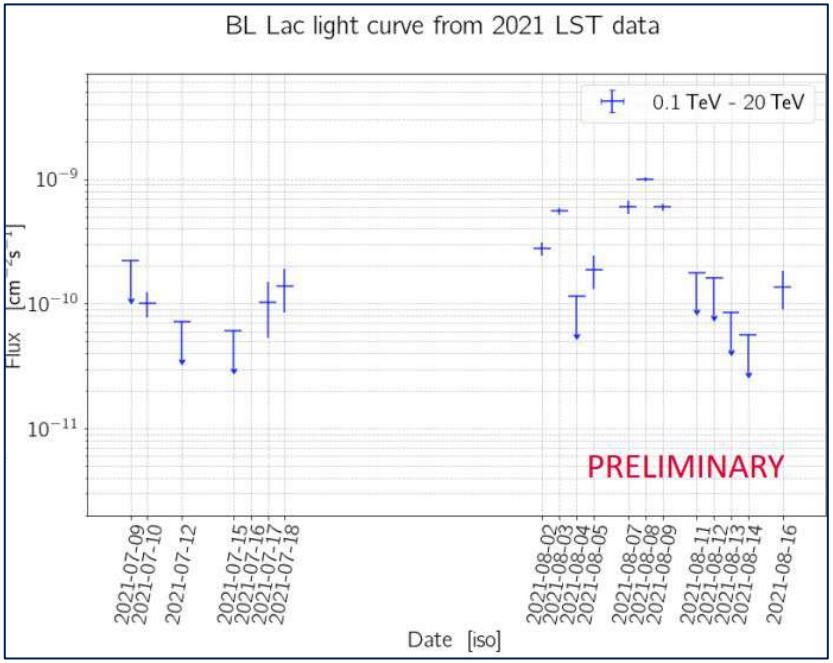
Detection of very-high-energy gamma-ray emission from BL Lac with the LST-1

ATel #14783; Juan Cortina for the CTA LST collaboration
on 13 Jul 2021; 21:03 UT
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)

Related
14854 BL Lac still in optical high state
14839 AGILE detection of enhanced gamma-ray activity from the blazar BL Lac
14826 Detection of flaring very-high-energy gamma-ray emission from BL Lacertae with the MAGIC telescopes
14820 BL Lac reaches a new optical all-time maximum
14783 Detection of very-high-energy gamma-ray emission from BL



Light curve of summer 2021 observations:



LST1 observations

Active Galactic Nuclei

- In particular, the detection of a flare from BL Lac in 2021 resulted in the first Atel from a CTA instrument on 13th July

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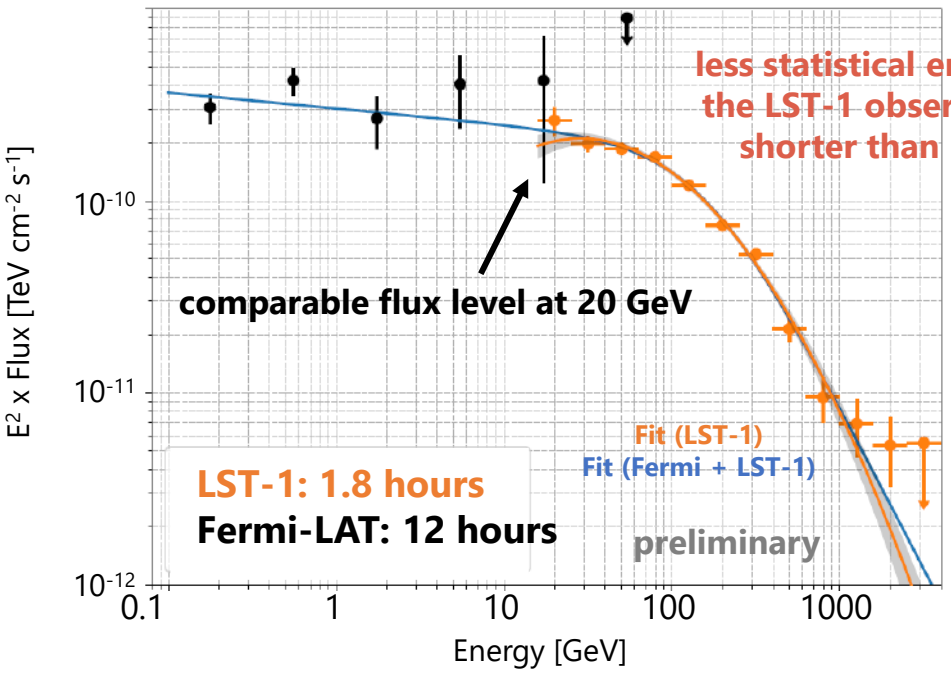

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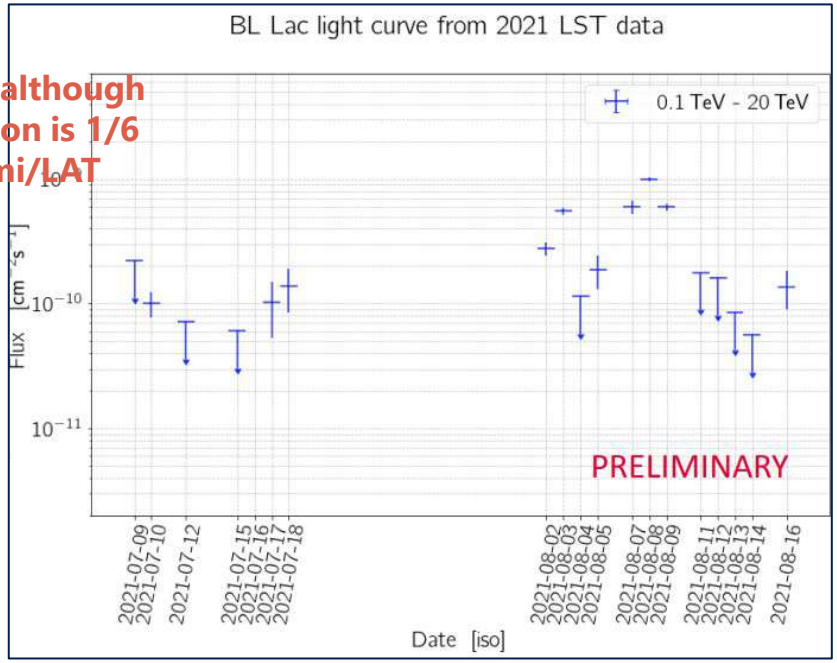
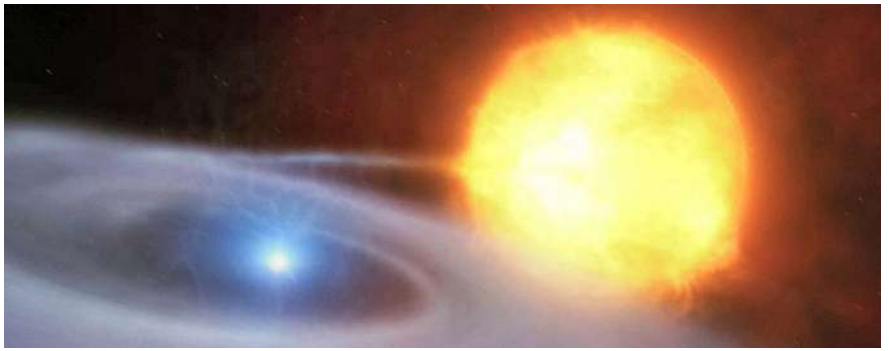


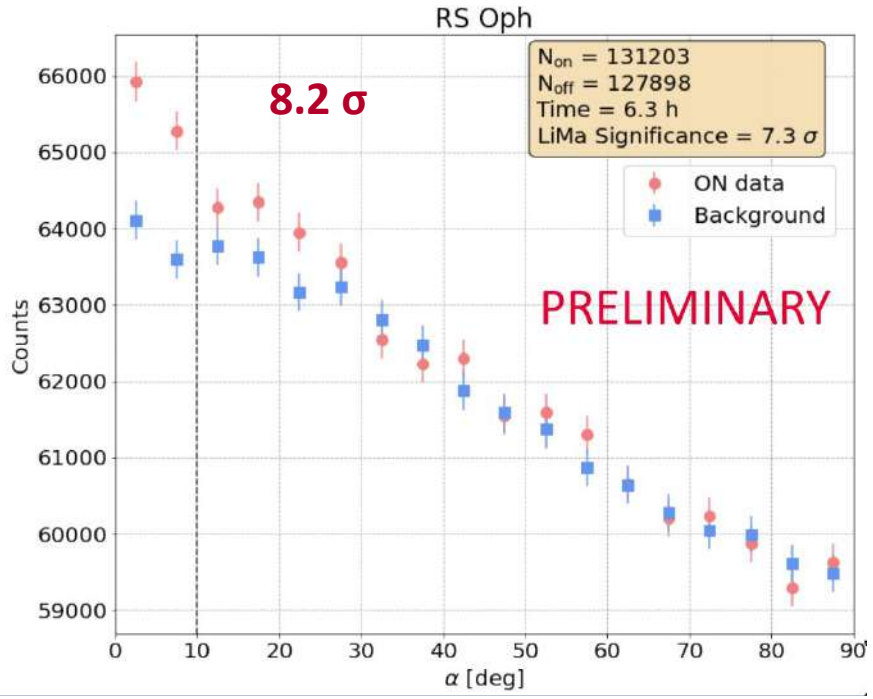
LST1 observations

Novae RS Ophiuchi

- Recurrent nova composed of a WD and a Red Giant
- It erupts ~ 15 years after accumulation of material on the WD from giant companion → thermonuclear explosion
- Eruption of 8th August 2021 followed by LST (6.3 hours)

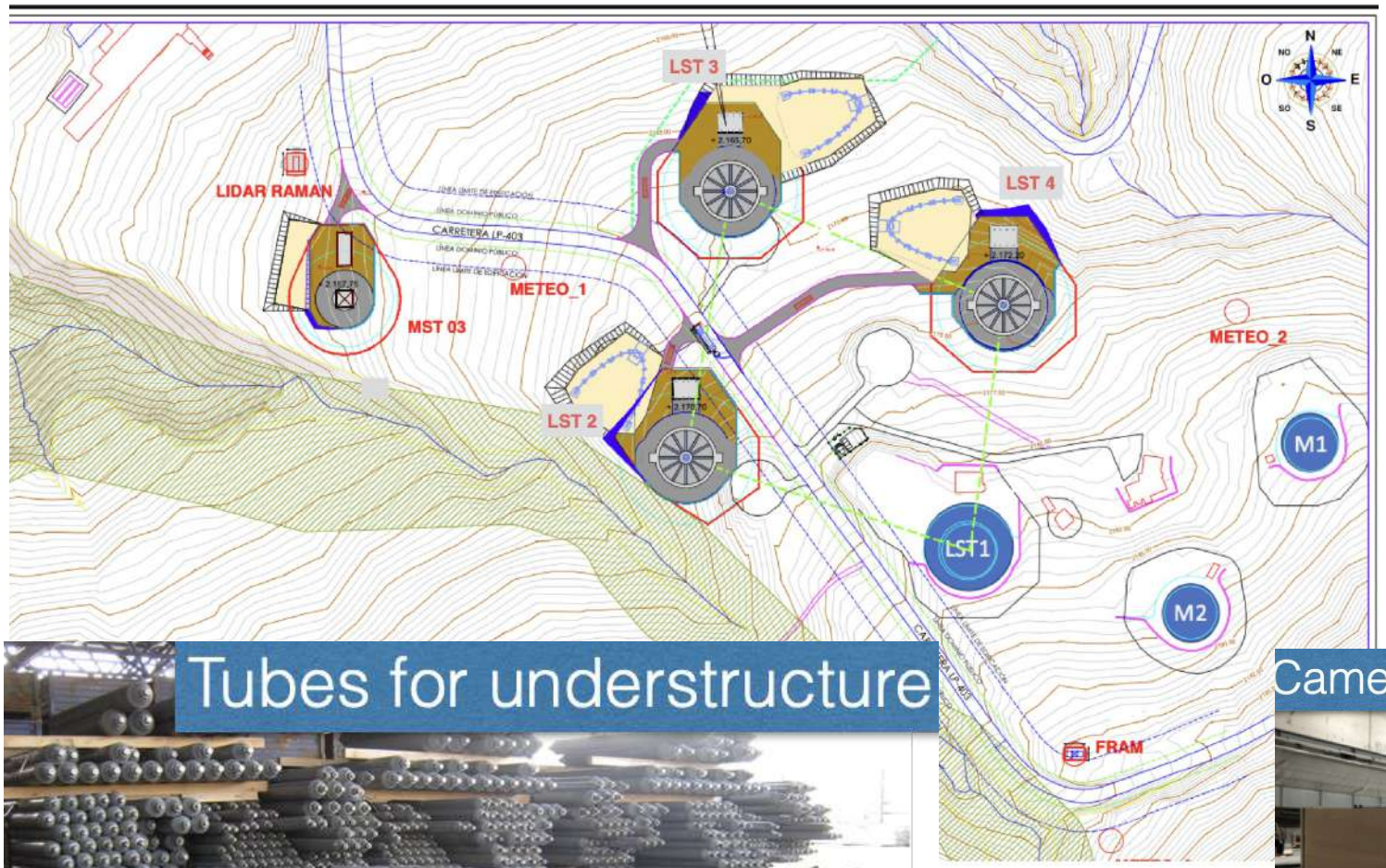
A competitive instrument for transient observations

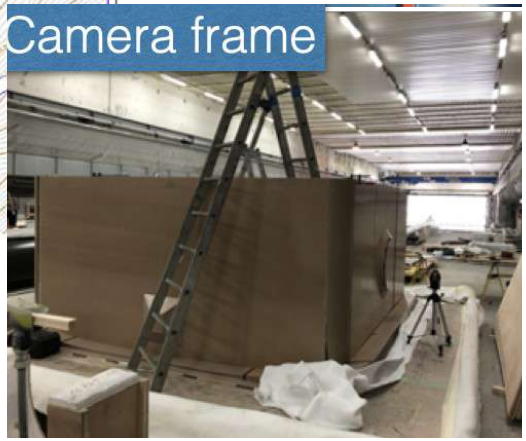




The construction of LST 2-4

Components are all on the way or ready!

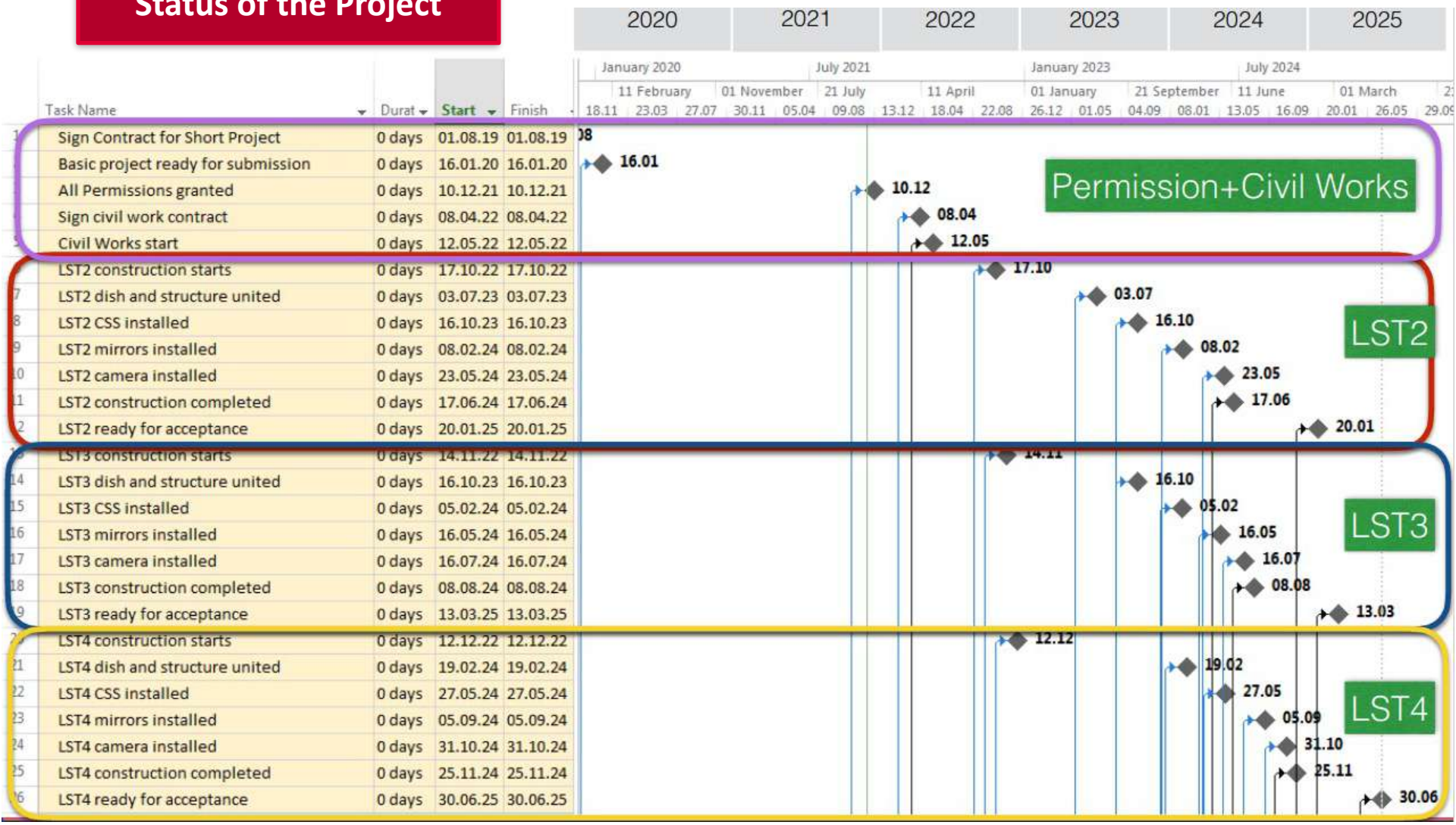




The construction of LST 2-4

Components are all on the way or ready!

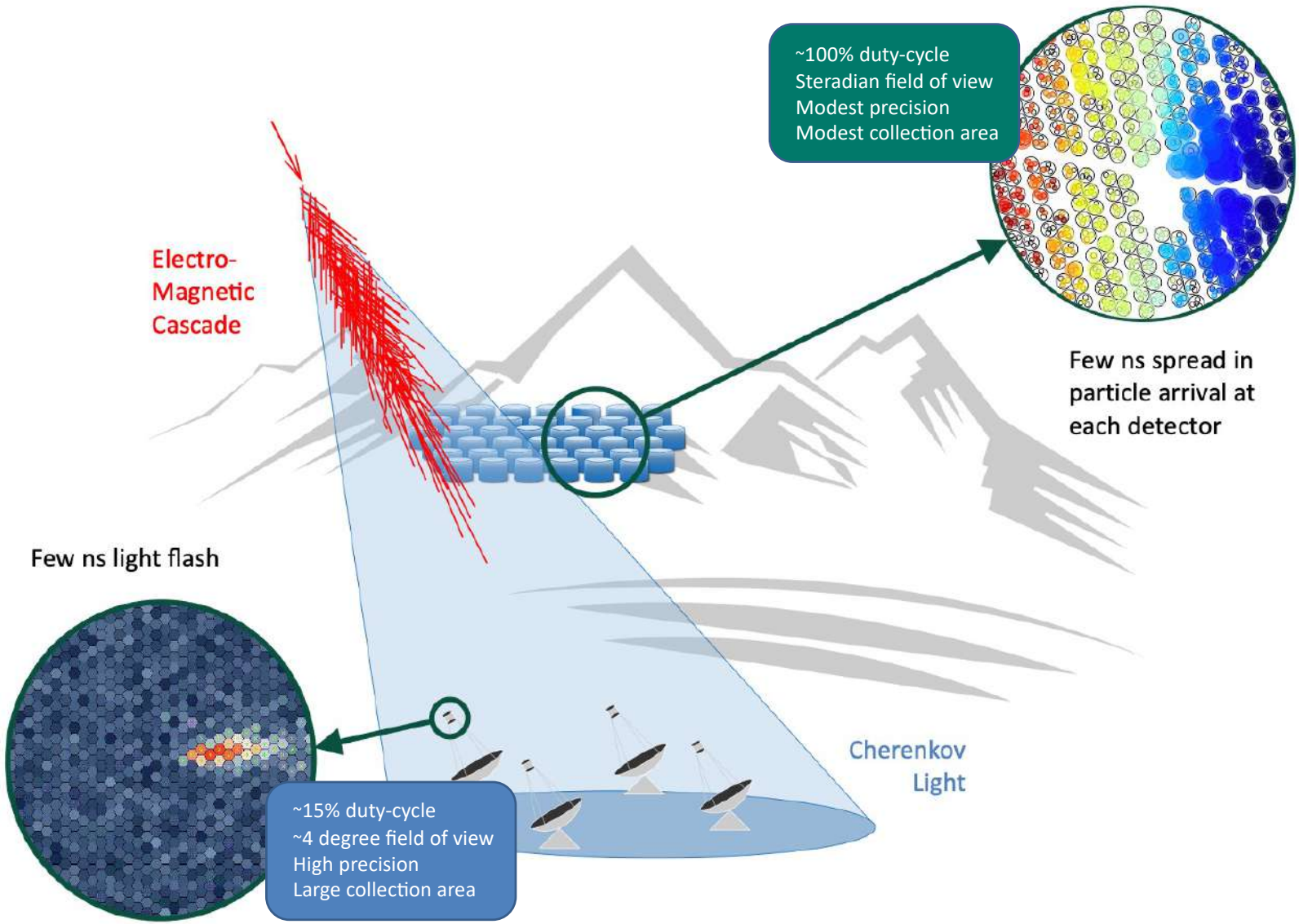
Status of the Project



	Task Name	Durat	Start	Finish
1	Sign Contract for Short Project	0 days	01.08.19	01.08.19
2	Basic project ready for submission	0 days	16.01.20	16.01.20
3	All Permissions granted	0 days	10.12.21	10.12.21
4	Sign civil work contract	0 days	08.04.22	08.04.22
5	Civil Works start	0 days	12.05.22	12.05.22
6	LST2 construction starts	0 days	17.10.22	17.10.22
7	LST2 dish and structure united	0 days	03.07.23	03.07.23
8	LST2 CSS installed	0 days	16.10.23	16.10.23
9	LST2 mirrors installed	0 days	08.02.24	08.02.24
10	LST2 camera installed	0 days	23.05.24	23.05.24
11	LST2 construction completed	0 days	17.06.24	17.06.24
12	LST2 ready for acceptance	0 days	20.01.25	20.01.25
13	LST3 construction starts	0 days	14.11.22	14.11.22
14	LST3 dish and structure united	0 days	16.10.23	16.10.23
15	LST3 CSS installed	0 days	05.02.24	05.02.24
16	LST3 mirrors installed	0 days	16.05.24	16.05.24
17	LST3 camera installed	0 days	16.07.24	16.07.24
18	LST3 construction completed	0 days	08.08.24	08.08.24
19	LST3 ready for acceptance	0 days	13.03.25	13.03.25
20	LST4 construction starts	0 days	12.12.22	12.12.22
21	LST4 dish and structure united	0 days	19.02.24	19.02.24
22	LST4 CSS installed	0 days	27.05.24	27.05.24
23	LST4 mirrors installed	0 days	05.09.24	05.09.24
24	LST4 camera installed	0 days	31.10.24	31.10.24
25	LST4 construction completed	0 days	25.11.24	25.11.24
26	LST4 ready for acceptance	0 days	30.06.25	30.06.25

SWGO
The Southern Wide-field Gamma-ray Observatory

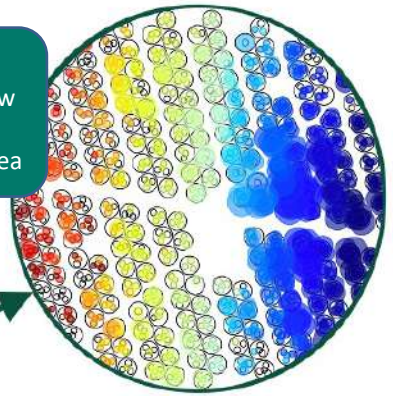
CTA Complementarity: Extensive Air Shower Arrays

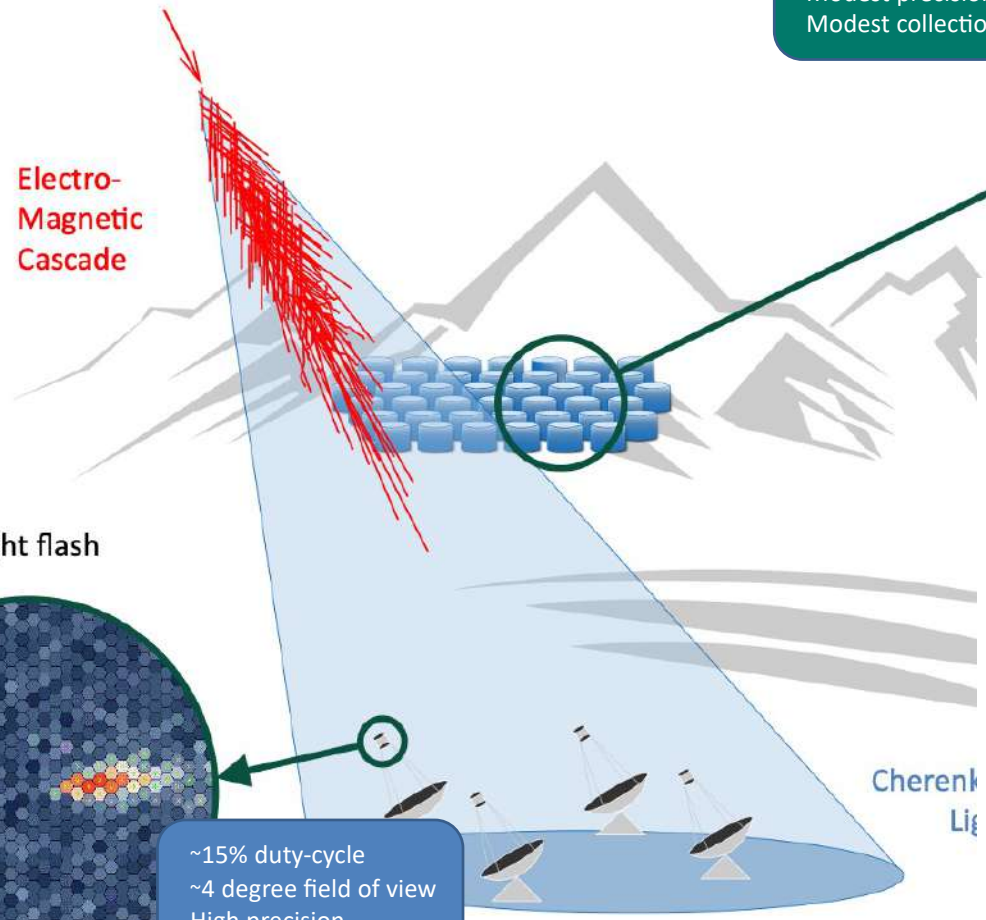


CTA Complementarity: Extensive Air Shower Arrays

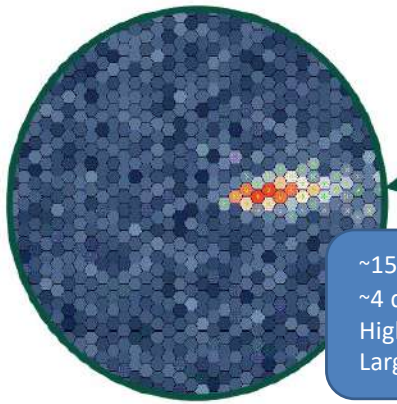
The Southern Wide-field Gamma-ray Observatory

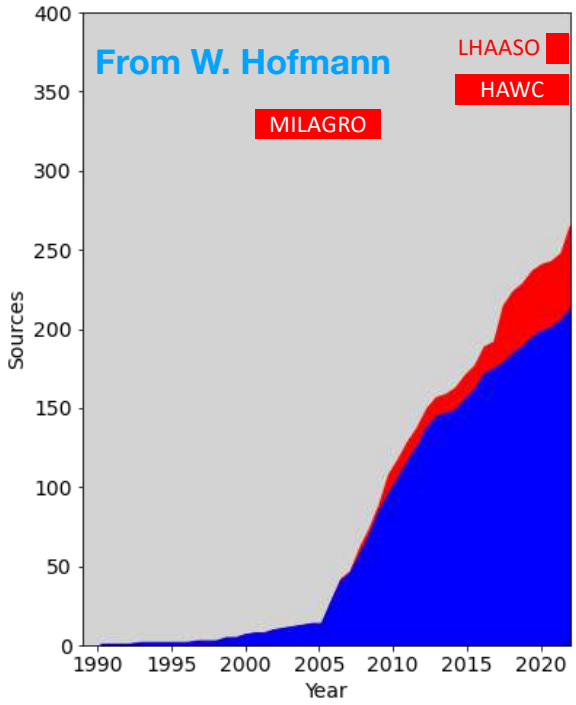
~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area



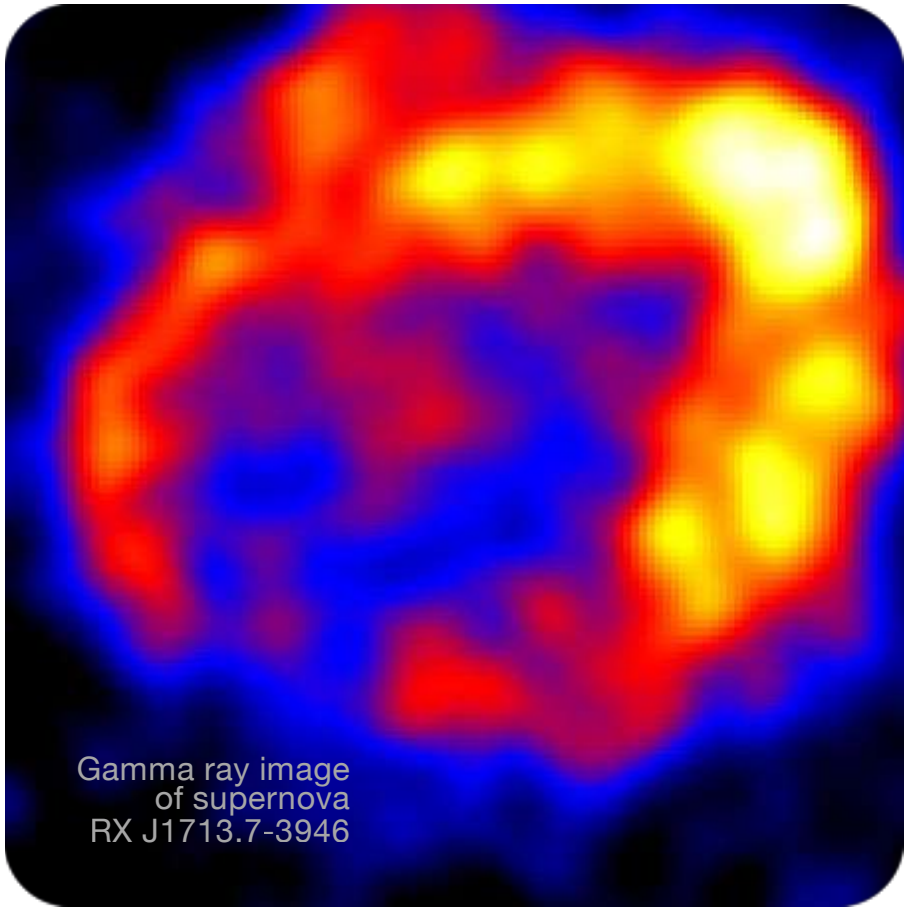


~15% duty-cycle
~4 degree field of view
High precision
Large collection area





Status of Ground-Based Gamma-ray Astronomy



Cherenkov Astronomy has reached the status of "real astronomy"

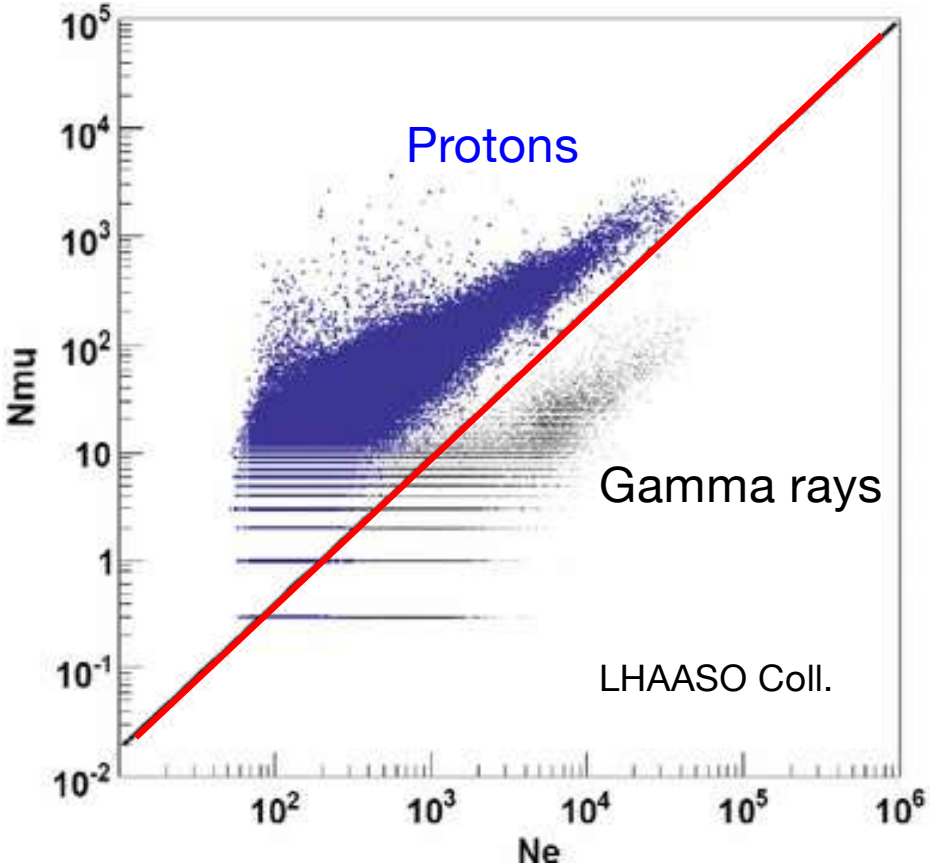
- good-resolution skymaps, ~ 5'
- 200+ sources detected
- spectra from c. 30 GeV to 30 TeV
- times resolved light curves down to minute timescales

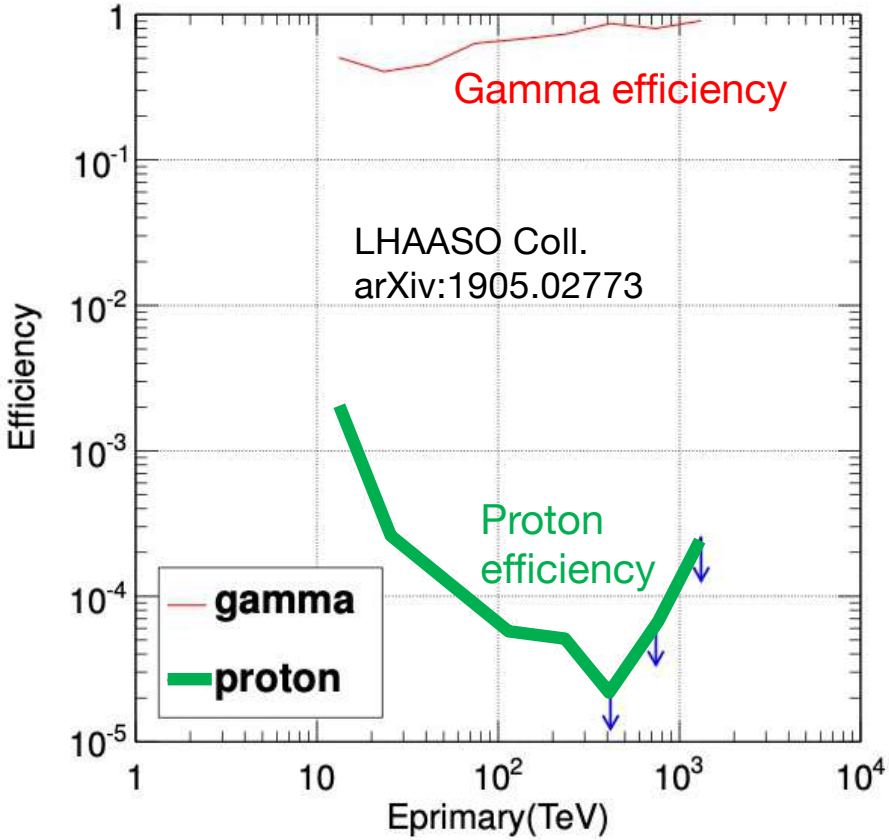
The recipe of the success?

Also for ground-particle arrays…

- very-high altitude arrays, > 4 km a.s.l.
- dense / calorimetric measurement of the EAS particles
- large array areas >> shower footprint
- Large muon effective areas

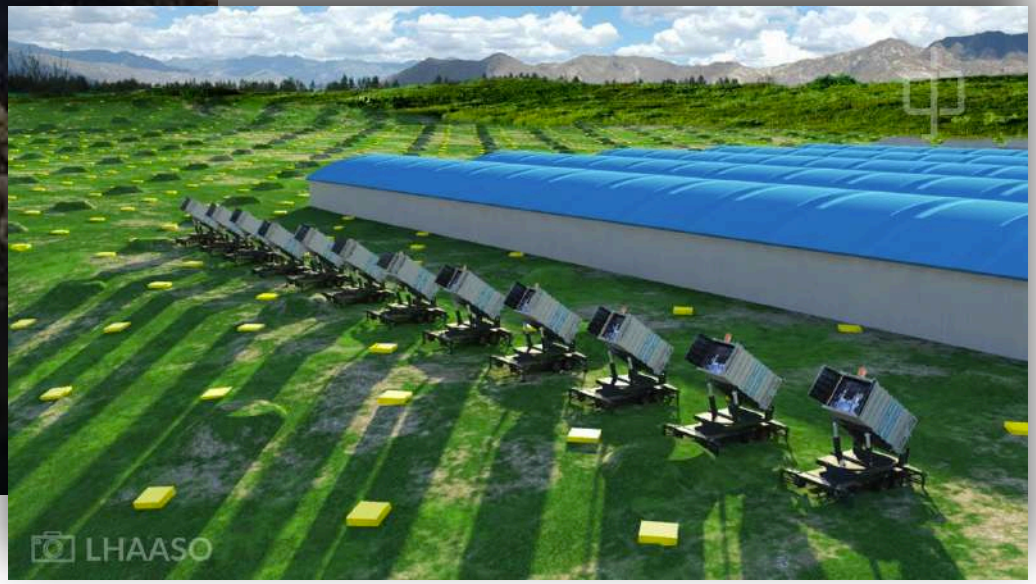
Large muon detection areas



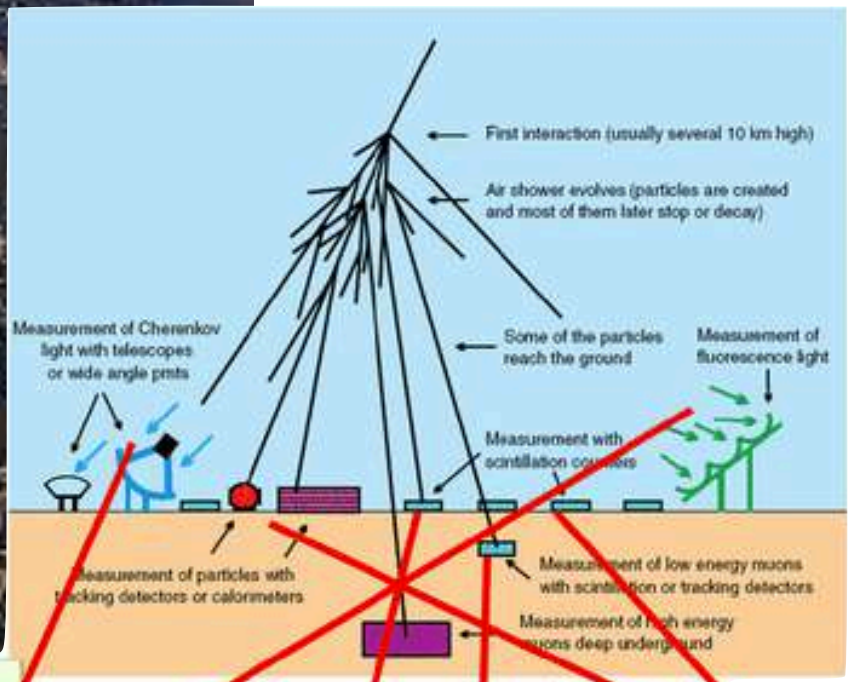


Large High Altitude Air Shower Observatory

LHAASO
高海拔宇宙线观测站



Large High Altitude Air Shower Observatory

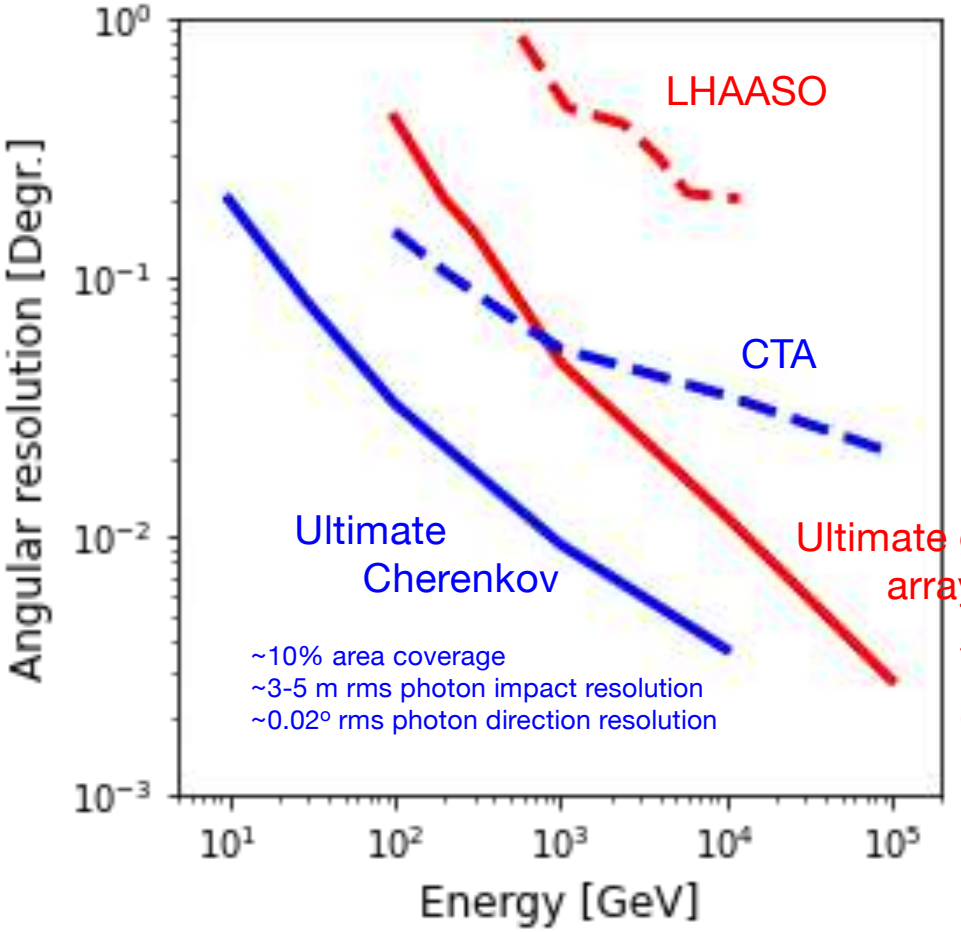


WFCTA:
12 telescopes
1024 pixels each

KM2A:
5195 EDs
1171 MDs

WCDA:
3000 cells

Limitations of the Techniques



W. Hofmann

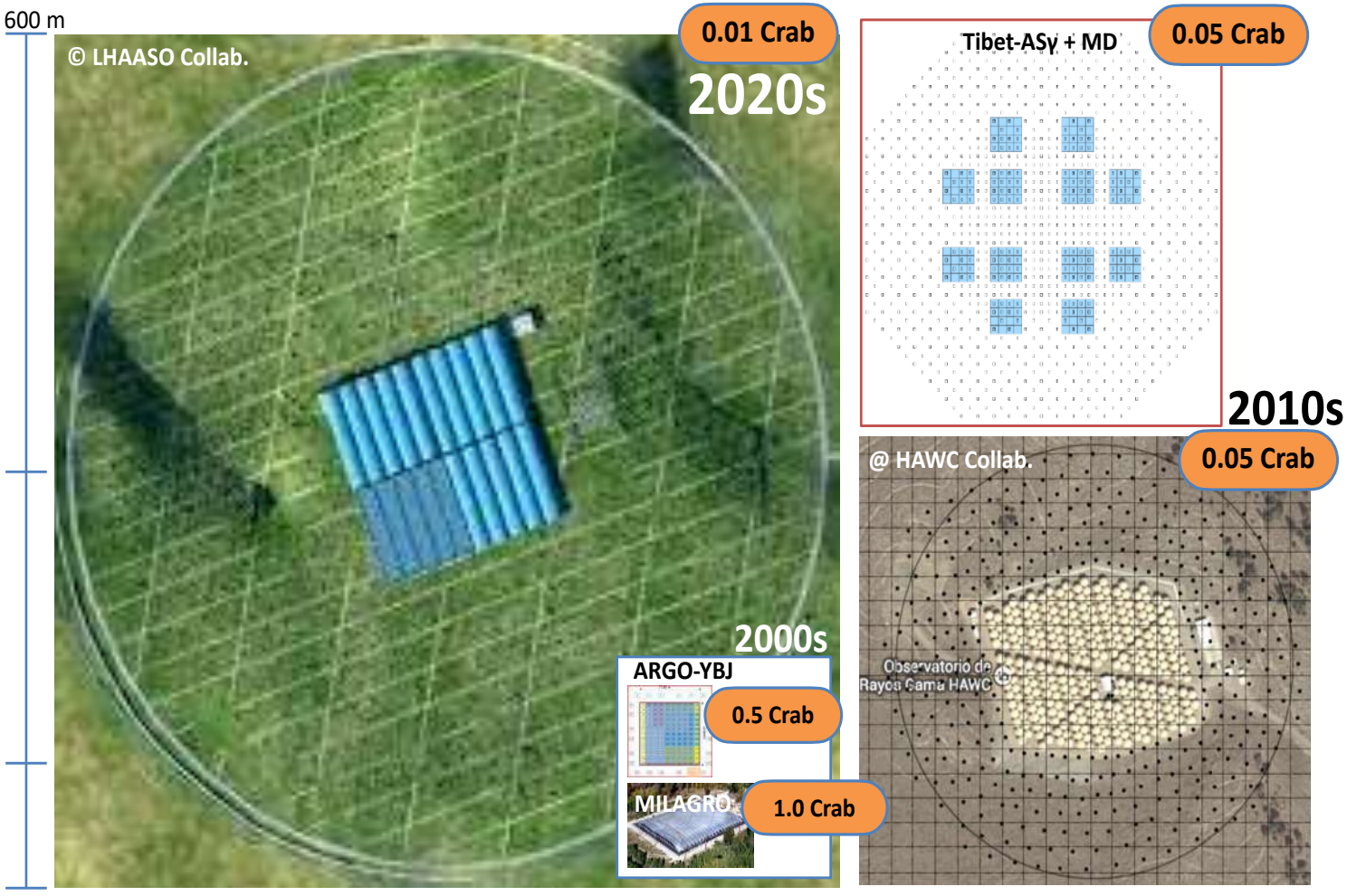
Performance Limits for Cherenkov Instruments
astro-ph/0603076

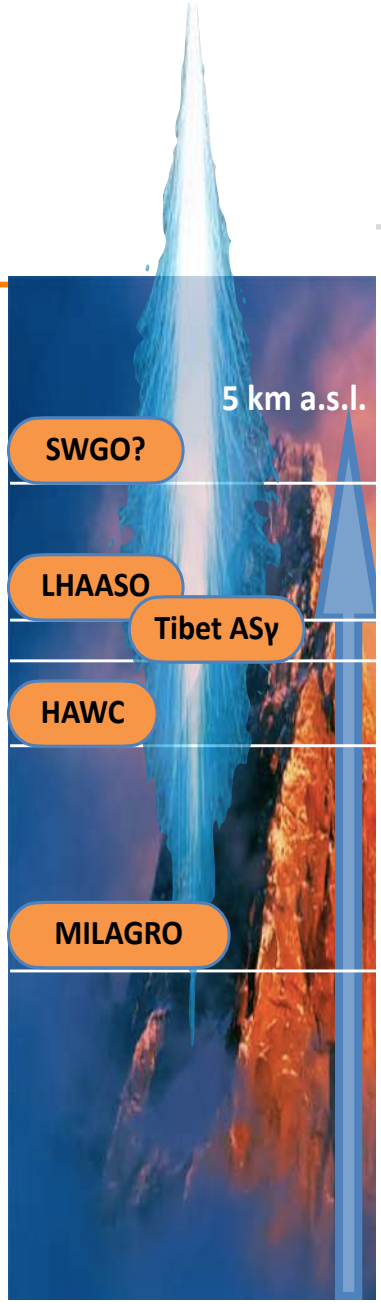
On angular resolution limits for air shower arrays
Astroparticle Physics 123 (2020) 102479

few 10% particle detection eff. above 100 MeV
100 ps time resolution
(Converter + RPC array + WC)

Thanks to W. Hofmann

Larger and higher...

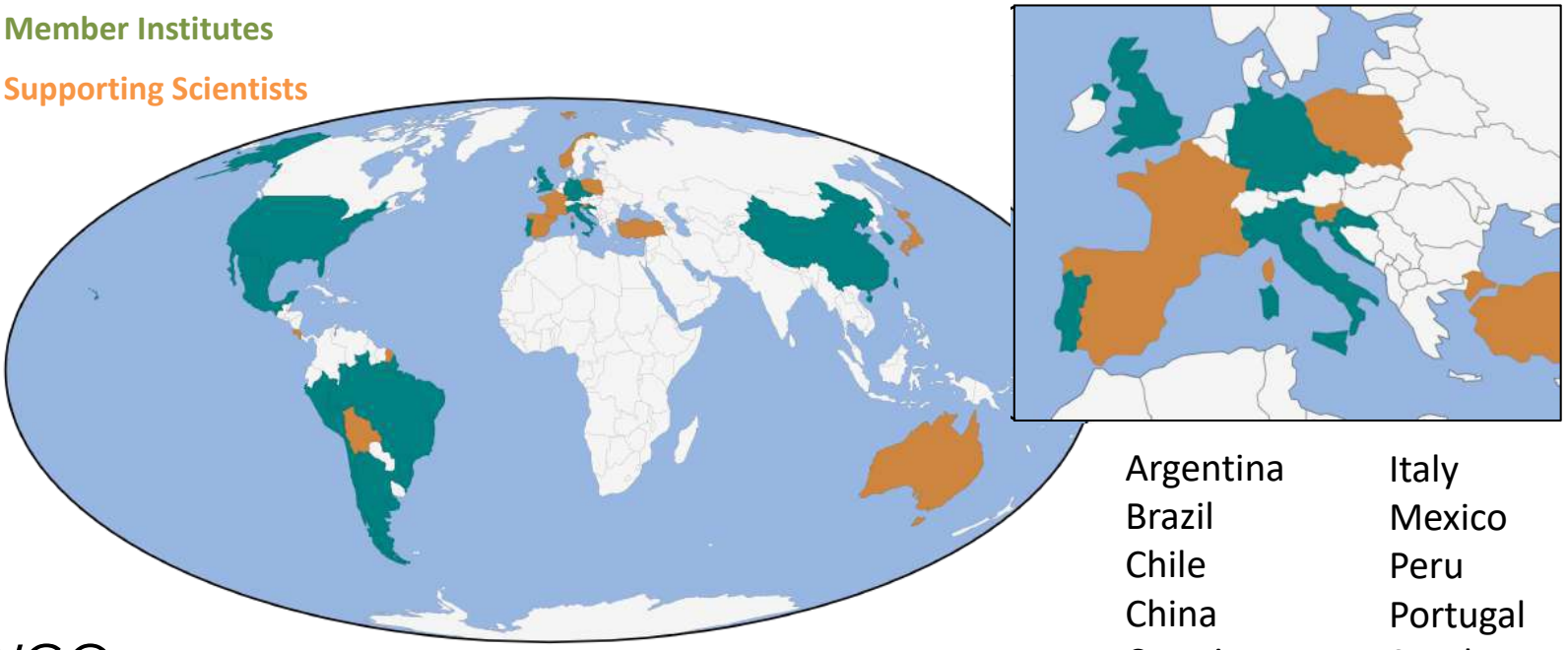




The SWGO Collaboration

SWGO
The Southern Wide-field Gamma-ray Observatory

Member Institutes
Supporting Scientists

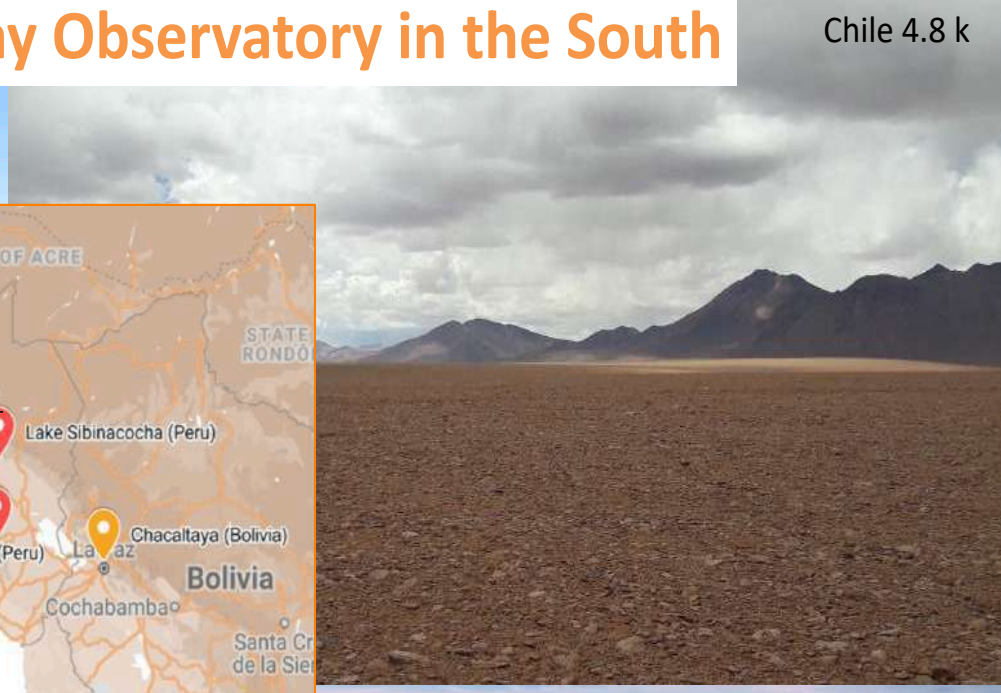


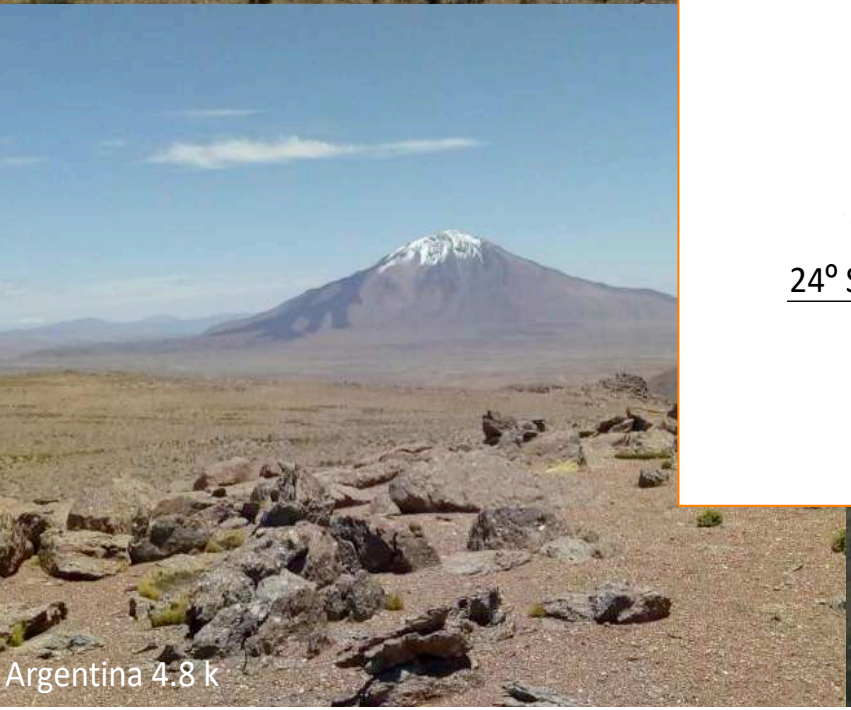
- SWGO partners
  - → 14 countries, 66 institutes*
  - → + supporting scientists

Argentina
Brazil
Chile
China
Croatia
Czech Republic
Germany
Italy
Mexico
Peru
Portugal
South Korea
United Kingdom
United States

- R&D Phase
  - → Kick off meeting Oct 2019
  - → Expected completion 2024
    - ✓ Site and Design Choices made
- Preparatory Phase
  - → Detailed construction planning
  - → **Engineering Array**
- (Full) Construction Phase
  - → 2026+

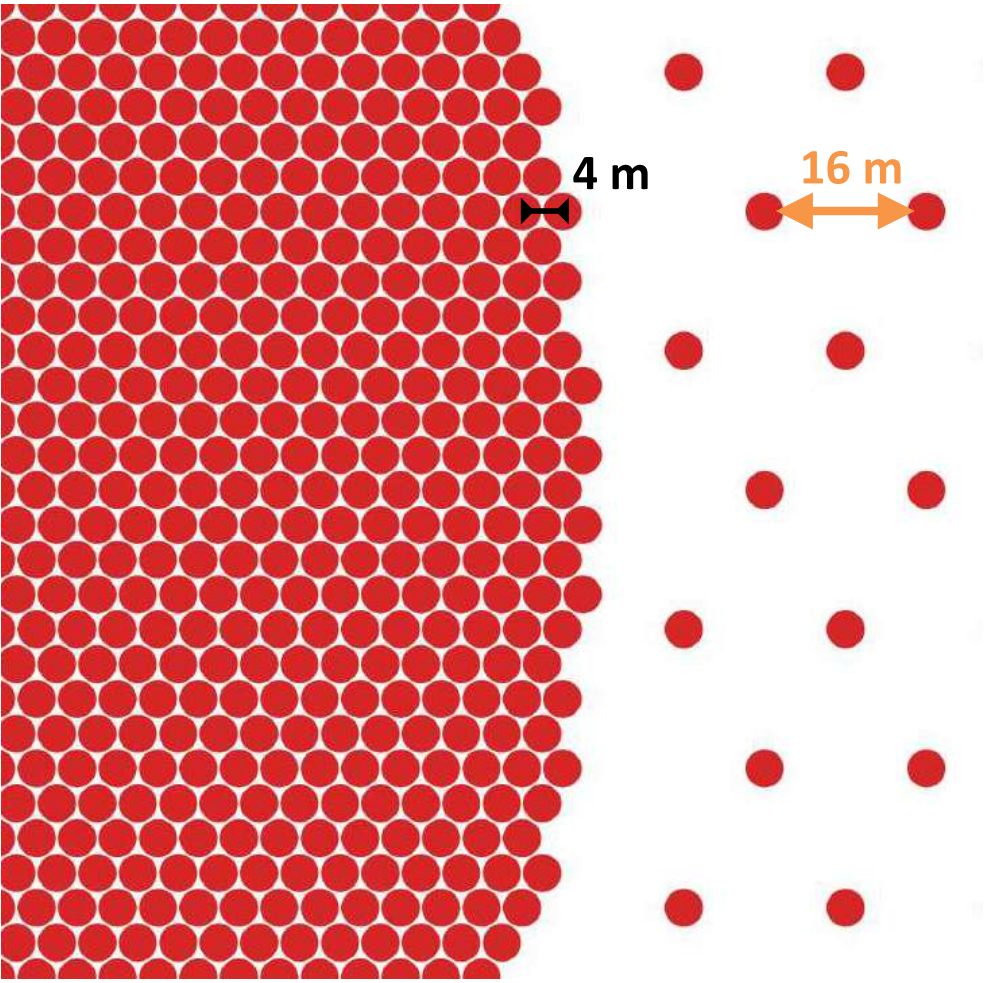
A Wide-field Gamma-ray Observatory in the South





The SWGO Detector Concept

The Southern Wide-field Gamma-ray Observatory

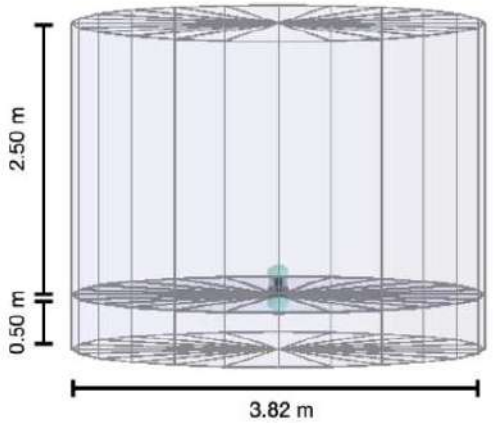


Core: Ø 320 m, FF = 80%
5,700 WCD units

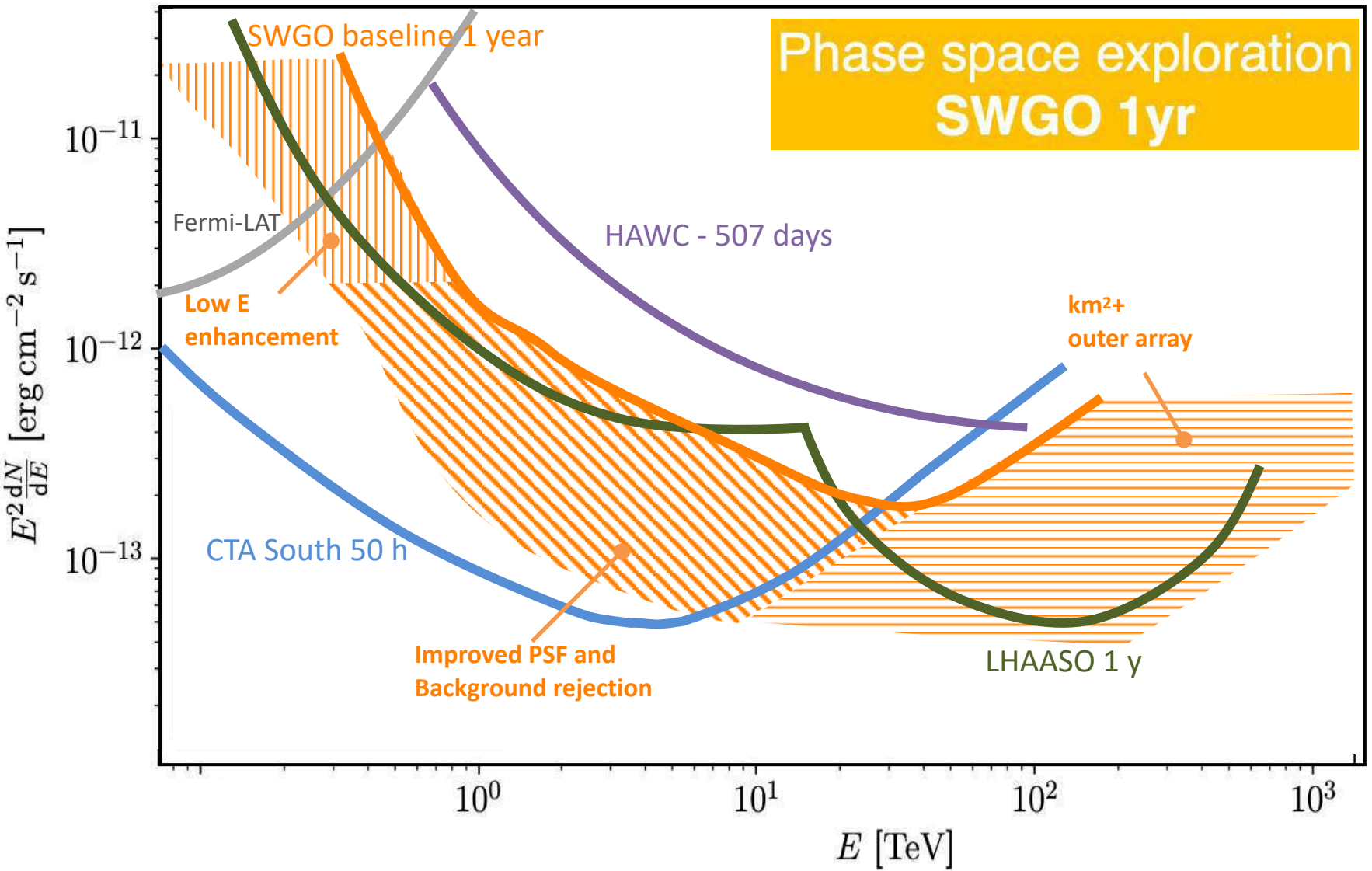
Outer: Ø 600 m, FF = 5%
880 WCD units

Altitude: 4,700 m a.s.l.

✧ muon counting

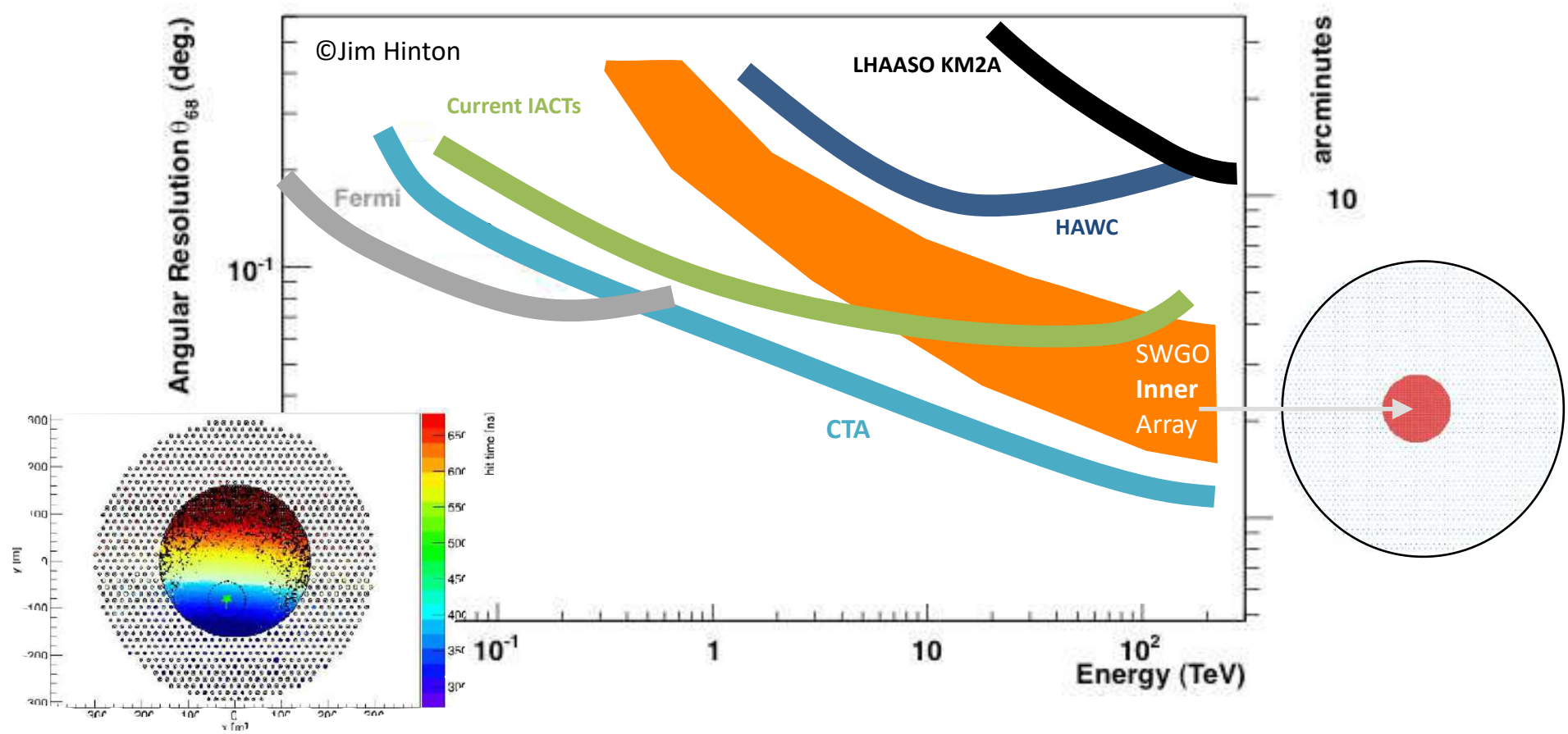


The SWGO Detector Concept



The SWGO Detector Concept

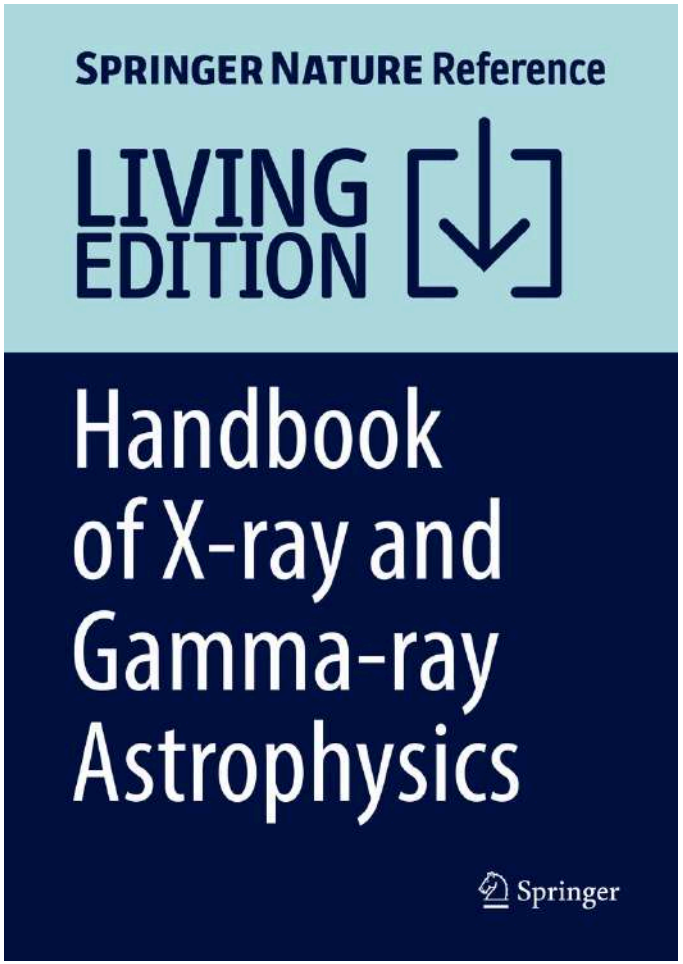
The Southern Wide-field Gamma-ray Observatory



END

Thank you very much!

https://www.cta-observatory.org



https://link.springer.com/referencework/10.1007/978-981-16-4544-0?page=1#toc