



cherenkov
telescope
array

The Cherenkov Telescope Array

Status and perspectives

Francesco Longo

On behalf of the CTA Consortium and the CTA Observatory

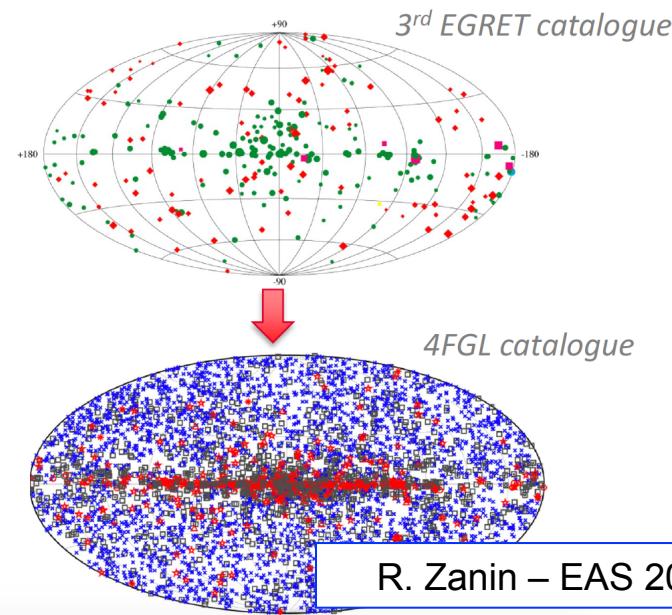
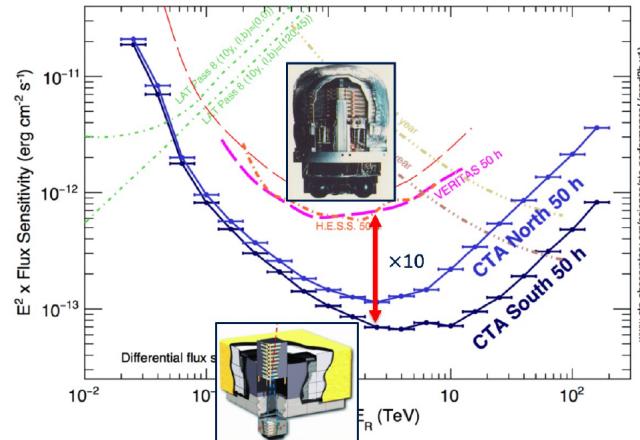
Vulcano workshop – September 2022

Take away messages ...



Conclusions

- CTAO will be the first gamma-ray ground-based observatory, openly delivering data to the community
- CTAO will usher in a new era in VHE Astrophysics
 - Rich science program answering many open questions
 - Large new discovery space



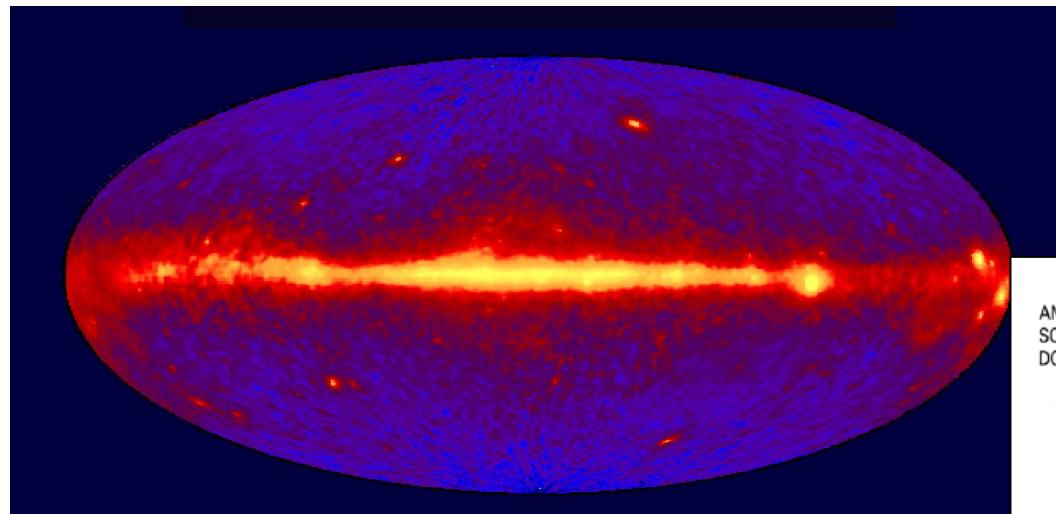
R. Zanin – EAS 2022



Summary

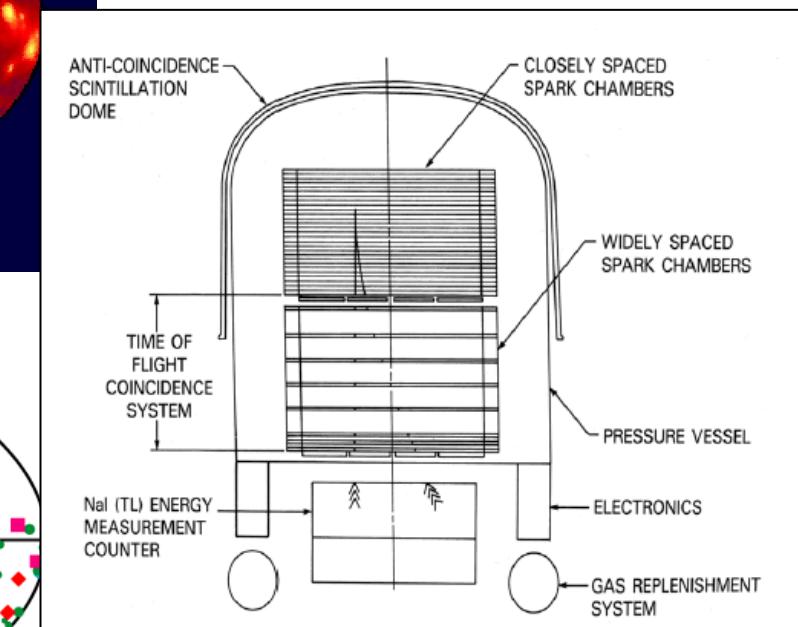
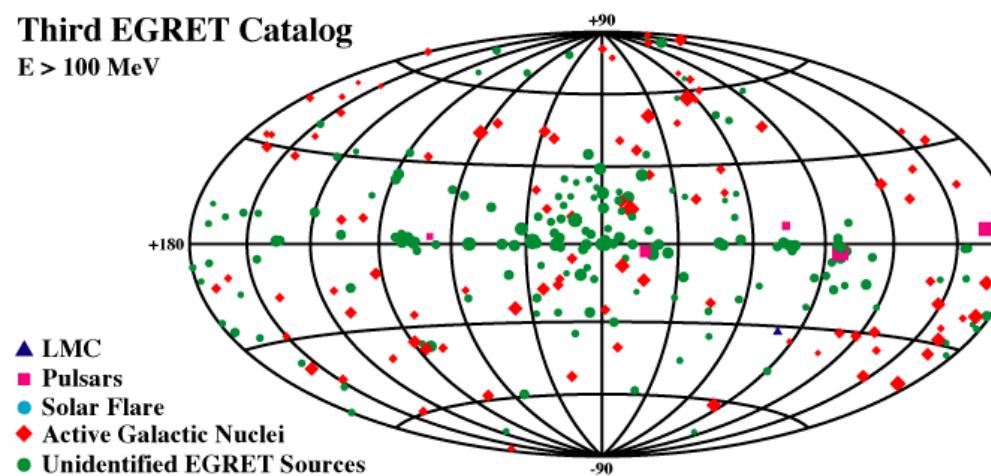
- Lessons learned by Fermi/LAT...
- The Cherenkov Telescope Array
- The actual status of the array
- Key Science Topics
- Opportunities ...

The EGRET era (1991-2000)

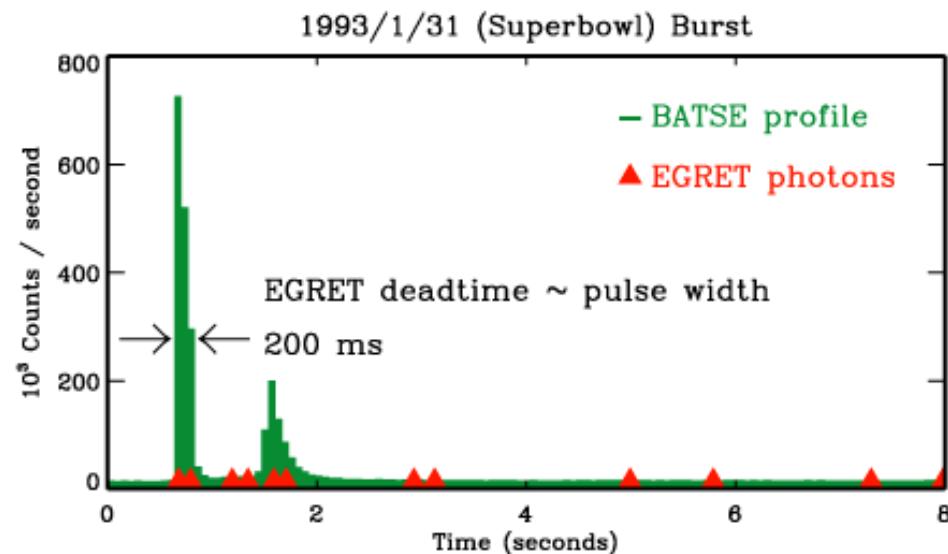


Third EGRET Catalog

$E > 100$ MeV

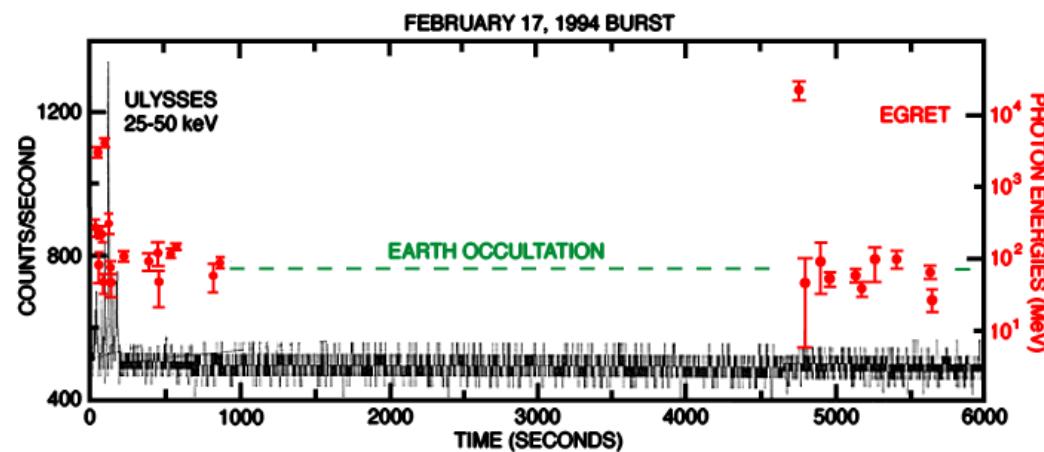


GRBs in the EGRET era

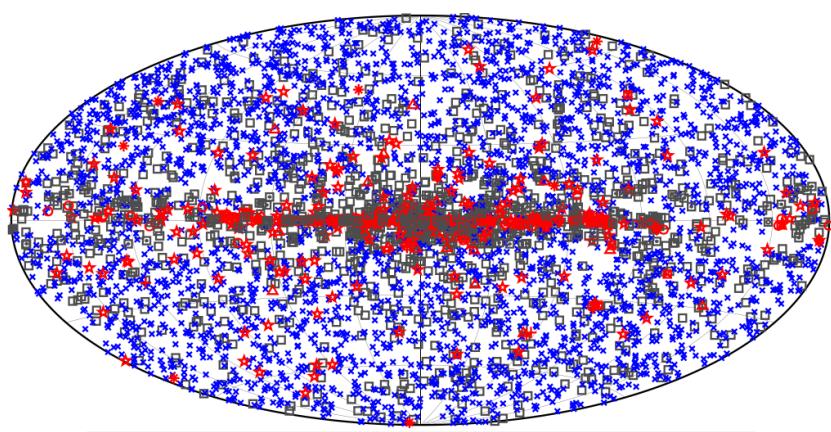
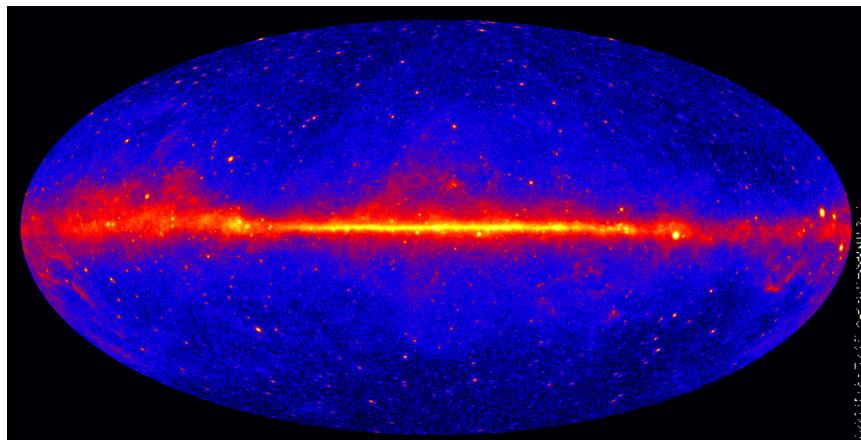


Hurley et al. 1994

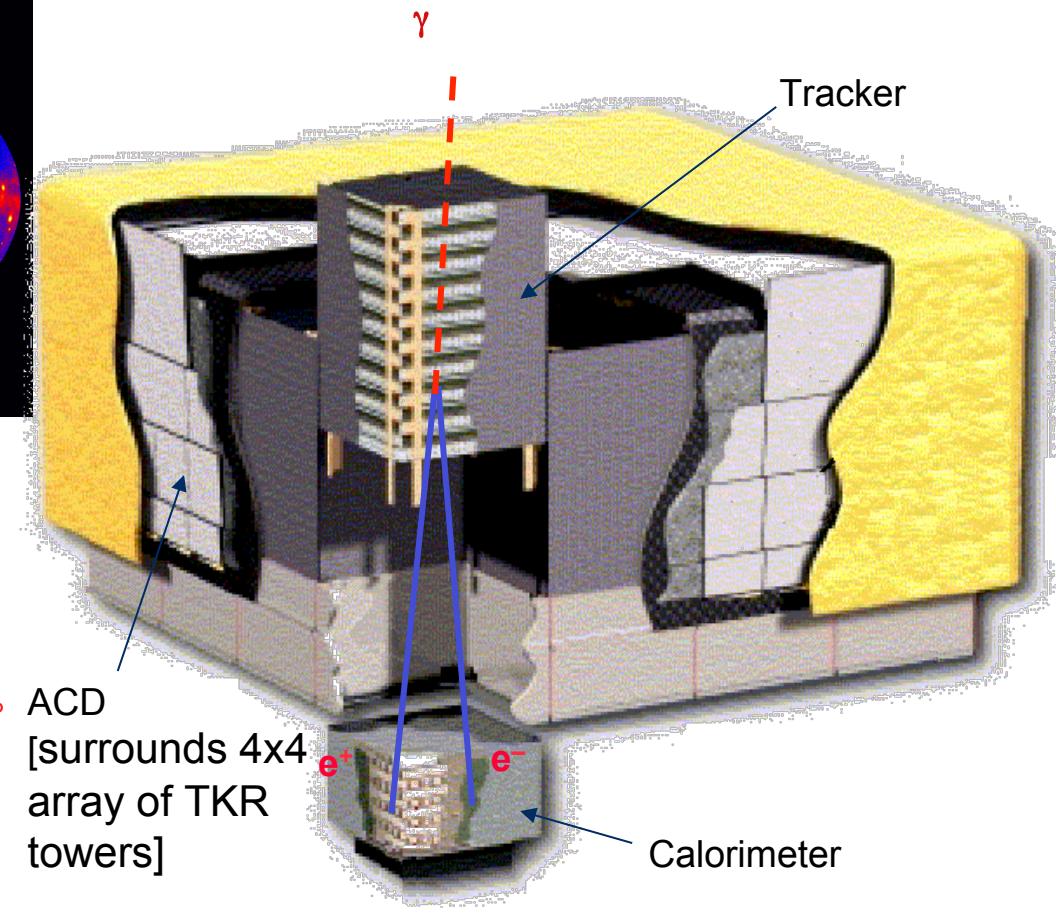
Kouveliotou et al 1994
Sommer et al. 1994



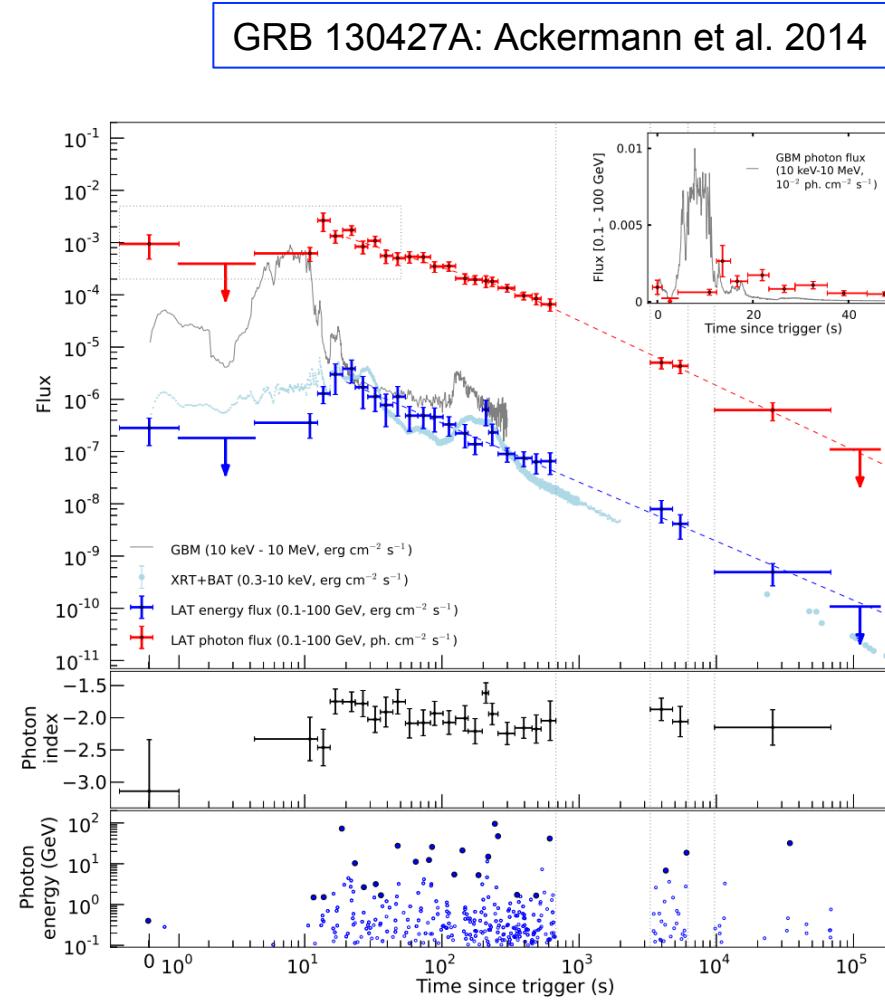
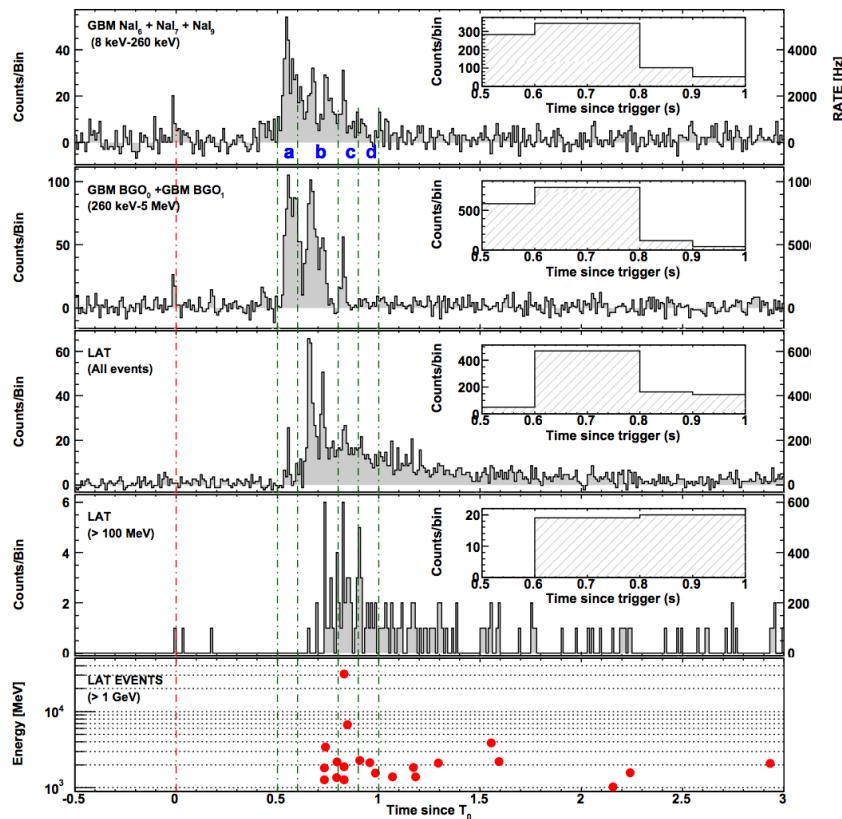
The Fermi/LAT era (2008-...)



□ No association	■ Possible association with SNR or PWN	* AGN
★ Pulsar	△ Globular cluster	* Starburst Galaxy
▣ Binary	+ Galaxy	◊ PWN
* Star-forming region	□ Unclassified source	○ SNR
		◆ Nova



GRBs in the Fermi era



Performance comparison



LAT Specifications & Performance

Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area ¹	> 8000 cm ²	1500 cm ²
Field of View	> 2 sr	0.5 sr
Angular Resolution ²	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution ³	< 10%	10%
Deadtime per Event	< 100 μs	100 ms
Source Location Determination ⁴	< 0.5'	15'
Point Source Sensitivity ⁵	< 6×10^{-9} cm ⁻² s ⁻¹	~ 10^{-7} cm ⁻² s ⁻¹

¹ After background rejection

² Single photon, 68% containment, on-axis

³ 1-σ, on-axis

⁴ 1-σ radius, flux 10^{-7} cm⁻² s⁻¹ (>100 MeV), high |b|

⁵ > 100 MeV, at high |b|, for exposure of one-year all sky survey, photon spectral index -2

Astronomy with IACTs

TeV Astronomy is an indirect technique

- The large effective areas provided by the air-showers (10^5 m^2) improve photon statistics at extreme energies
- Lowest achievable energy threshold of few 10s GeV
- Pointing instruments, good angular resolution ($\sim 0.1^\circ$)

γ -ray enters the atmosphere

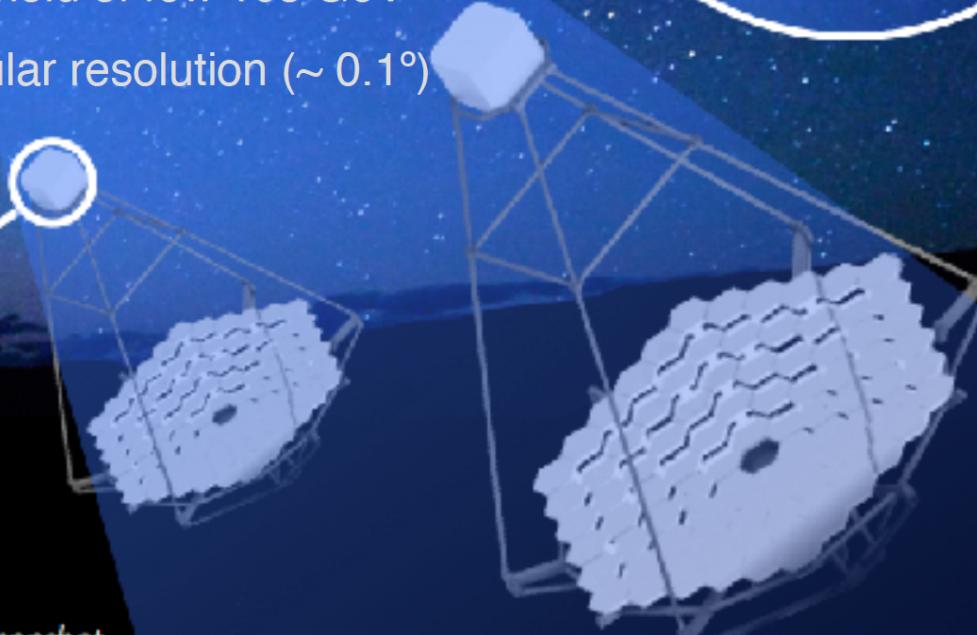
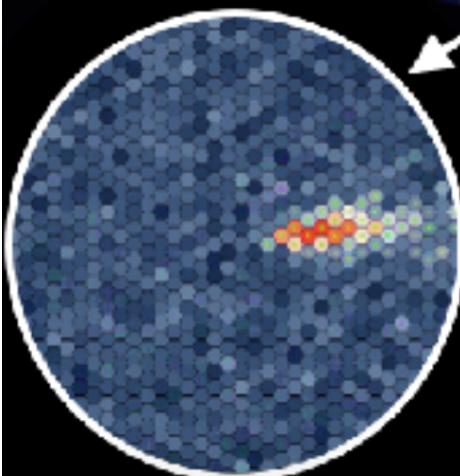
Electromagnetic cascade

Primary γ



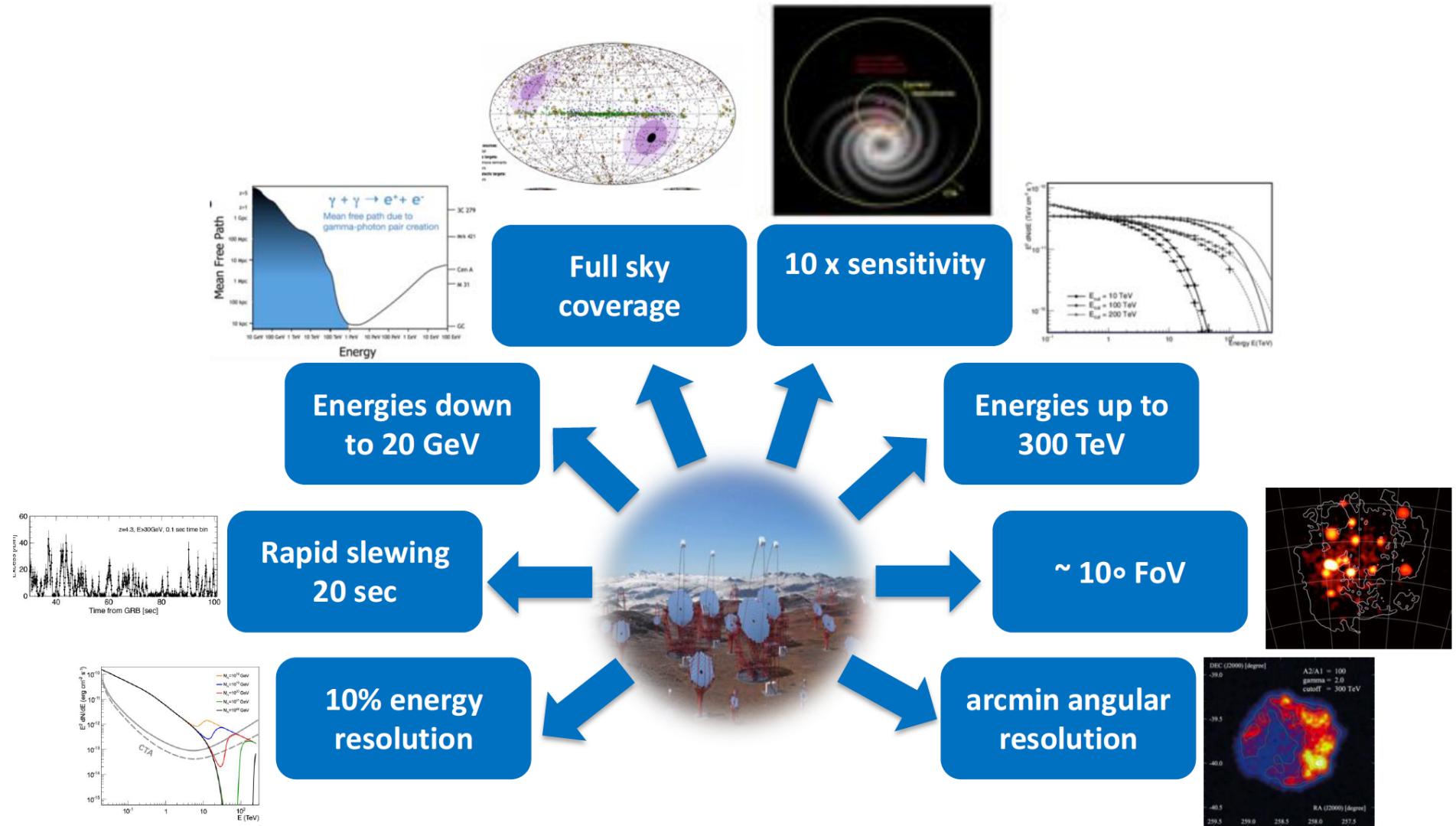
10 nanosecond snapshot

0.1 km^2 "light pool", a few photons per m^2 .

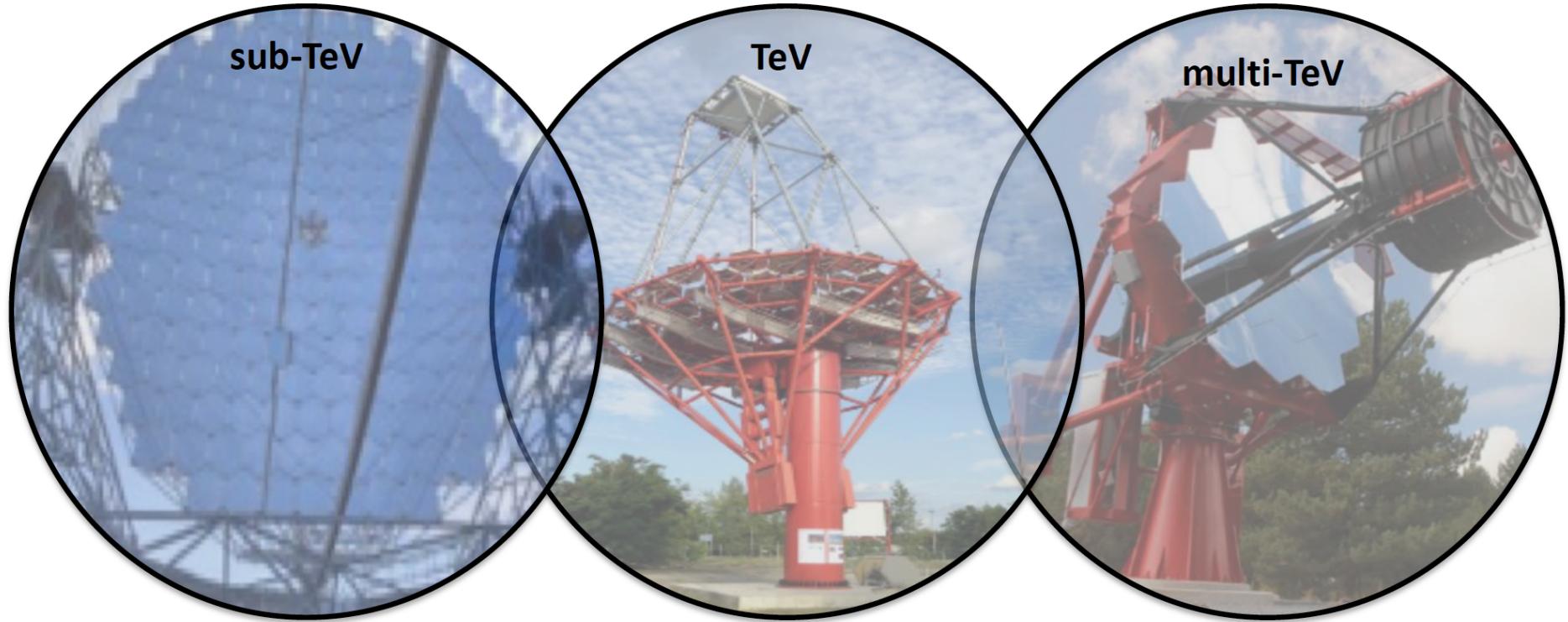


- **The first ground-based gamma-ray observatory**
 - serve large user community data & science tools in fair way
 - **Proposal driven observatory**
- **30 yr of lifetime**
 - Significant effort for maintenance and operations costs optimization
- **One legal entity: CTAO GmbH in the process to become an ERIC with HQ in Bologna (Italy)**
- **Two Telescope arrays, one Observatory**
 - Inter-site coordination
 - Uniform approach to scientific operations
- **The Science Data Mgmt Center in Zeuthen (Germany)**

Design drivers

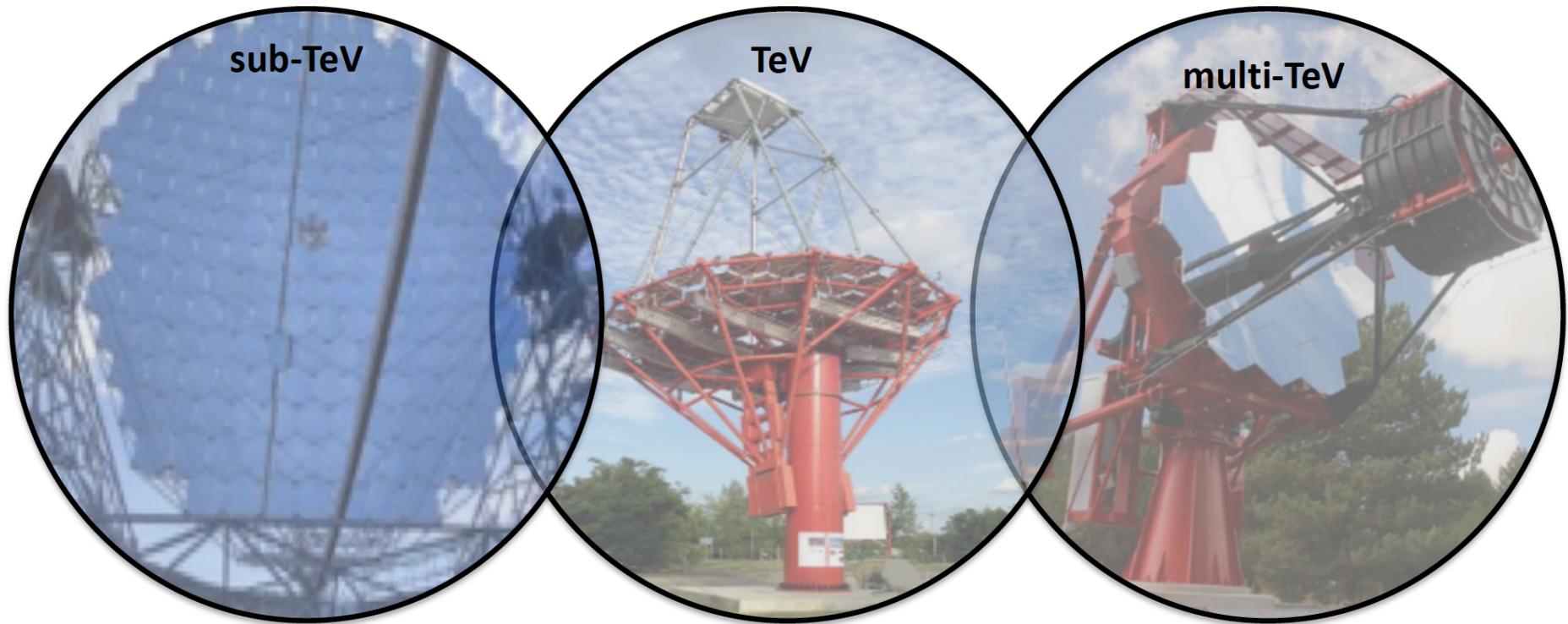


Science cases and design



- Parabolic optical design
 - 23 m mirror diameter
 - PMT camera
- Davies-Cotton optical design
 - 12 m mirror diameter
 - PMT camera
- Schwarzschild-Couder optical design
 - 4 m dual mirror
 - SiPM T camera

Science cases and design



- Lowest energies (tens of GeV)
→ **cosmological sources**
 - deepest sensitivity ever
 - arcmin angular resolution
 - large FoV
 - Deepest sensitivity for short timescale phenomena
→ **Time domain unexplored**
- Surveys & precision studies
- R.Zanin – TeVPa 2019
- Precision measurements in a still little explored energy range
 - **100 TeV range unexplored**
 - **precision studies**

The CTA Sites



A Global Observatory...



Toward the construction ...



The Data Center



SDMC – Groundbreaking Ceremony



- On 2 March, a ceremony was held at DESY Zeuthen for the laying of the SDMC ground stone
 - With dignitaries of the Science Ministries (Federal and Regional), DESY, CTAO, the local community and staff from DESY & CTAO



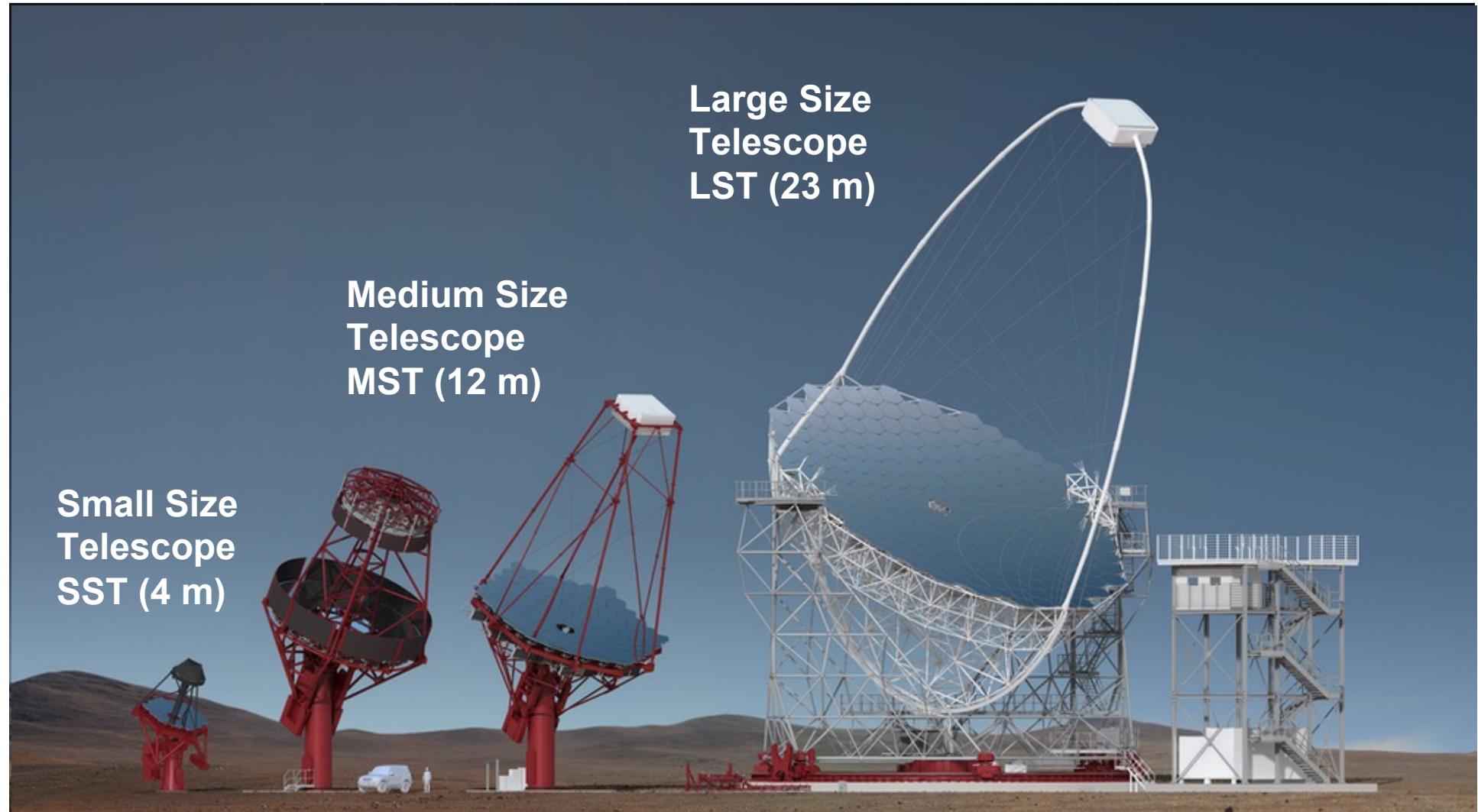
Credit and Copyright:
Heinle, Wischer und Partner, Freie Architekten, Berlin

(image rights: DESY / www.marco-urban.de)

The CTA Telescopes

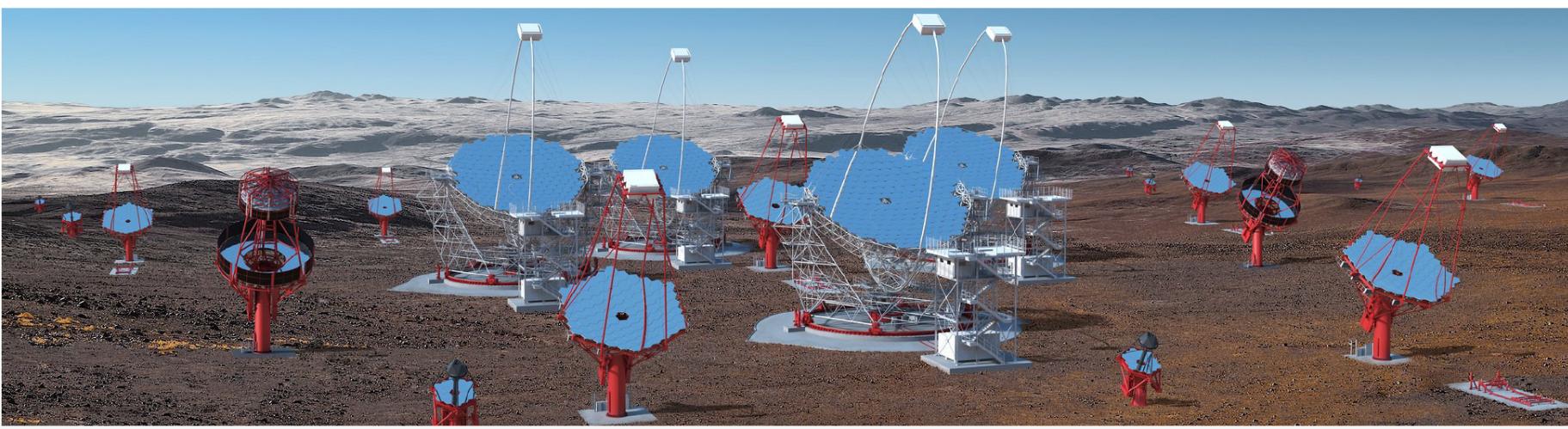
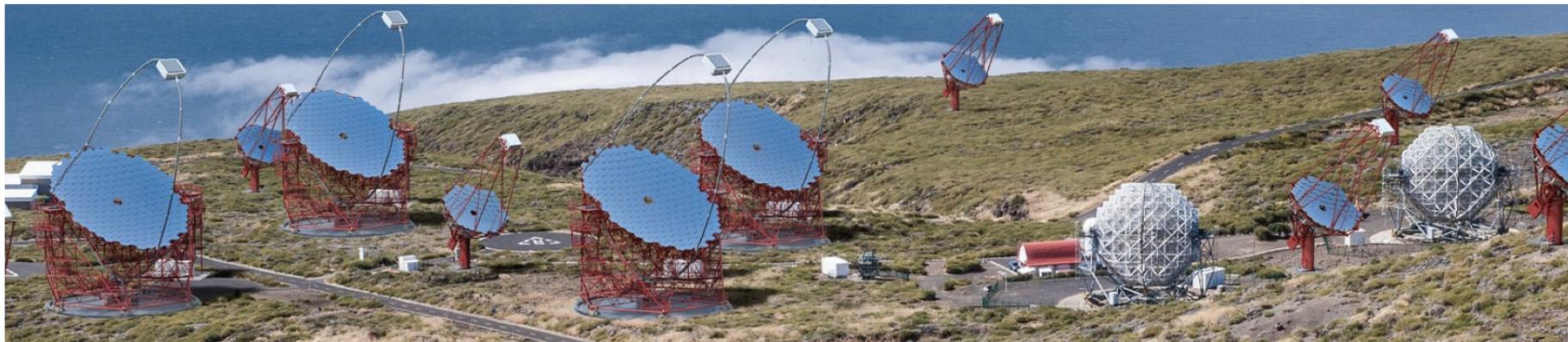


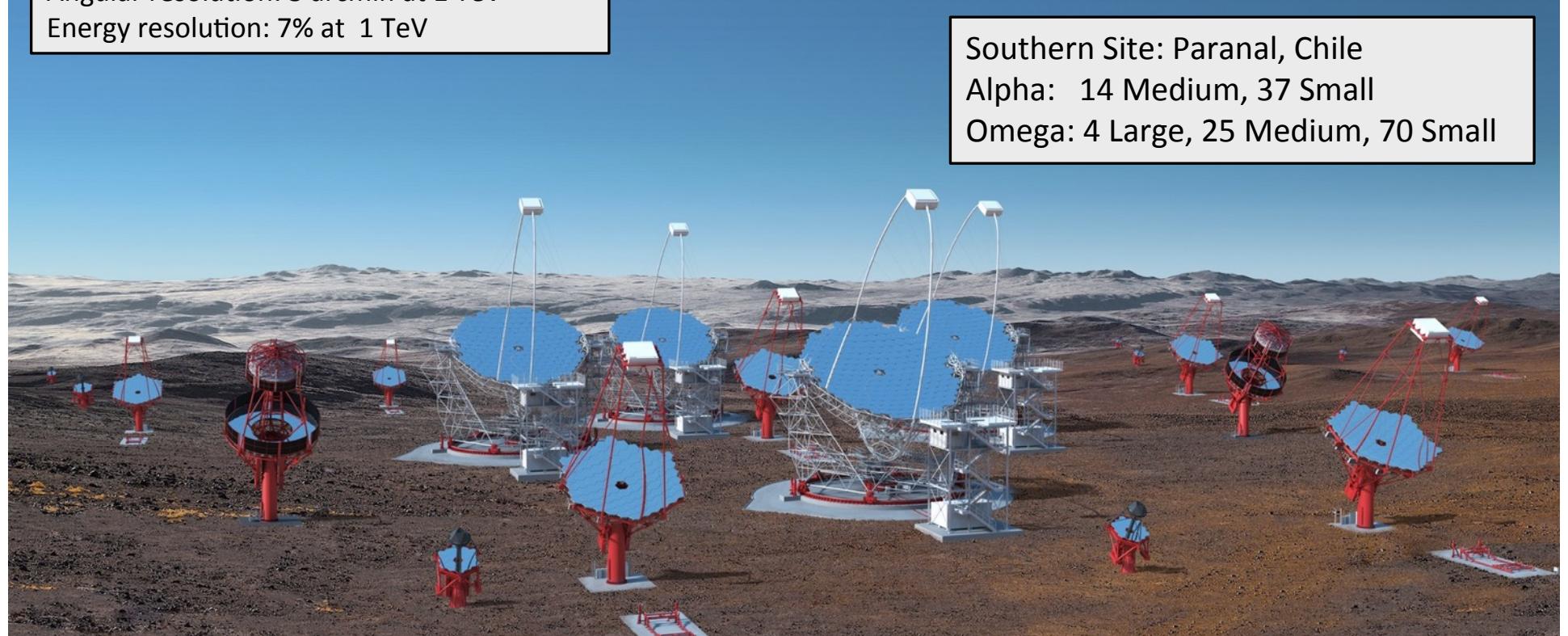
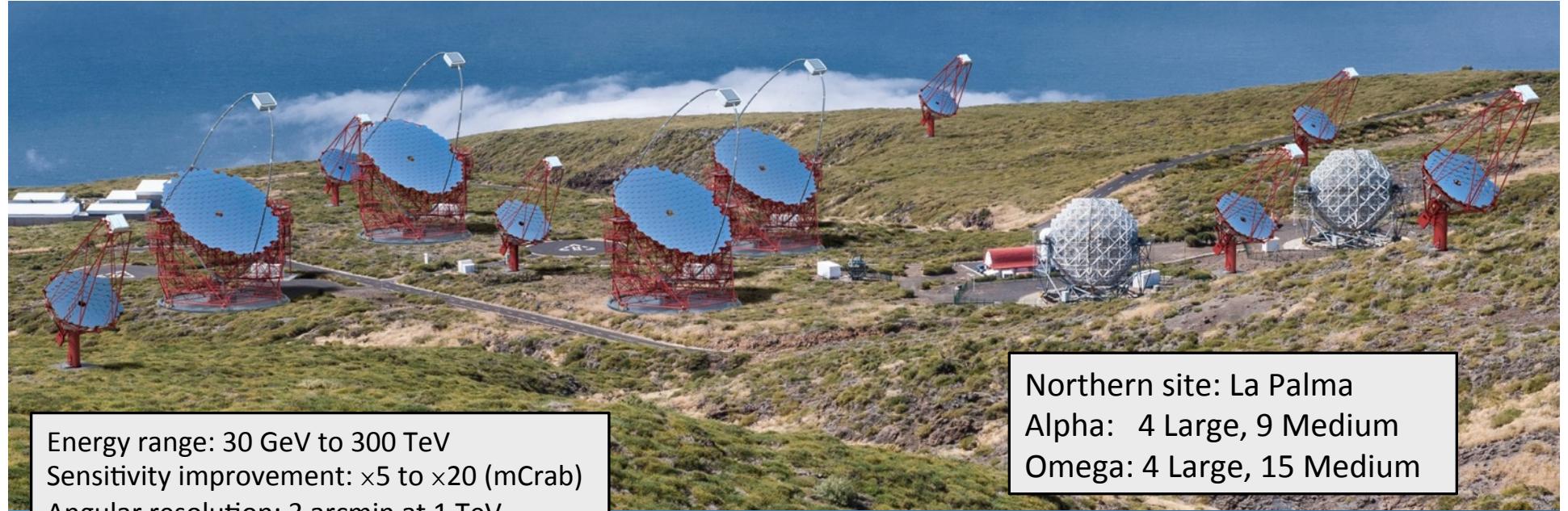
A Hybrid Observatory...



CTA North & CTA South

Alpha		CTA Construction
Northern Array	Number of LSTs	4
	Number of MSTs	9
Southern Array	Number of LSTs	0
	Number of MSTs	14
	Number of SSTs	37
Total		74





CTA Alpha Layout

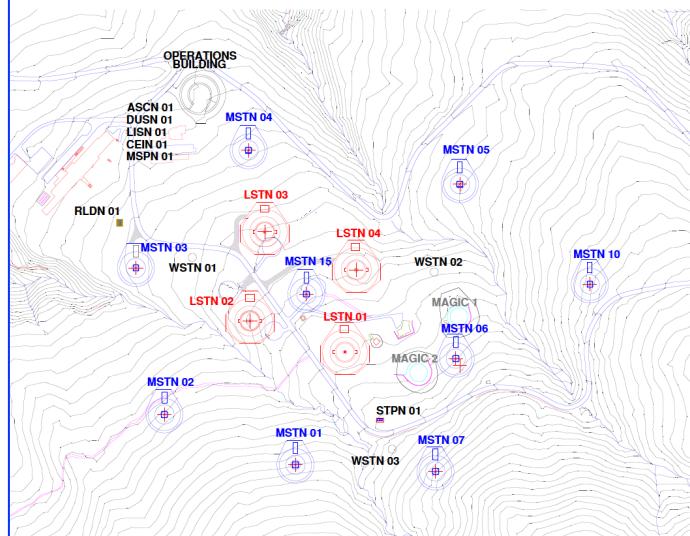


The two initial CTAO arrays: the Alpha Configuration



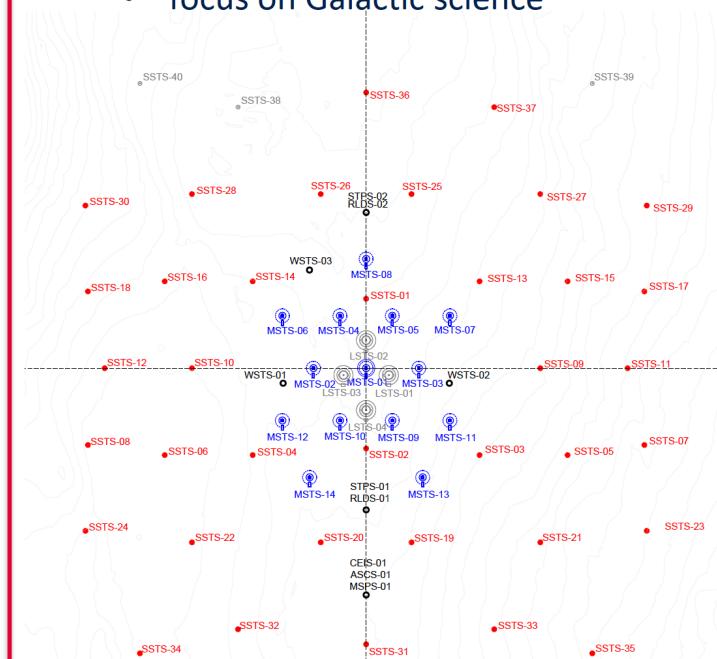
CTAO Northern Array

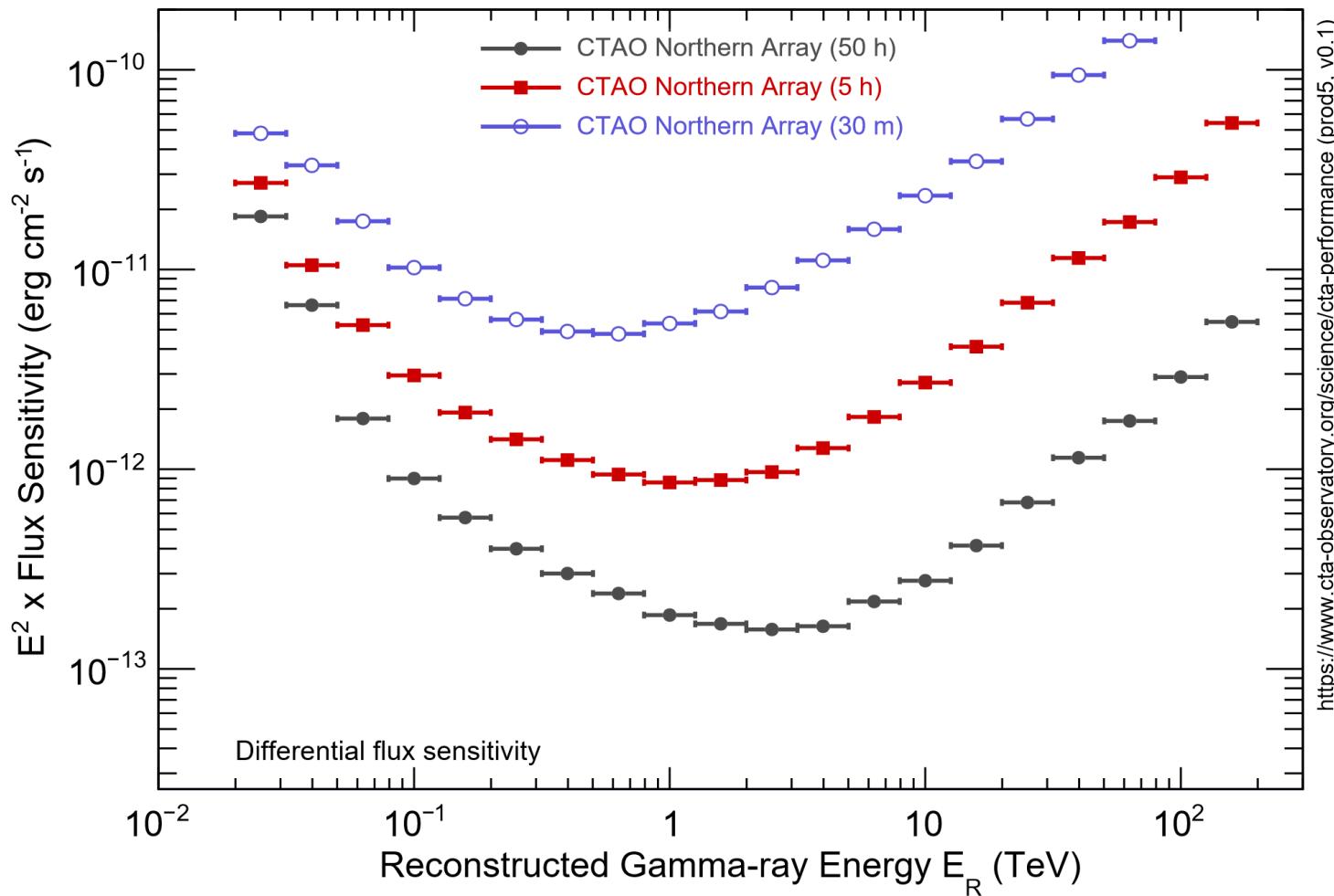
- 4 LSTs + 9 MSTs
- 0,25 km² footprint
- focus on extra-Galactic science

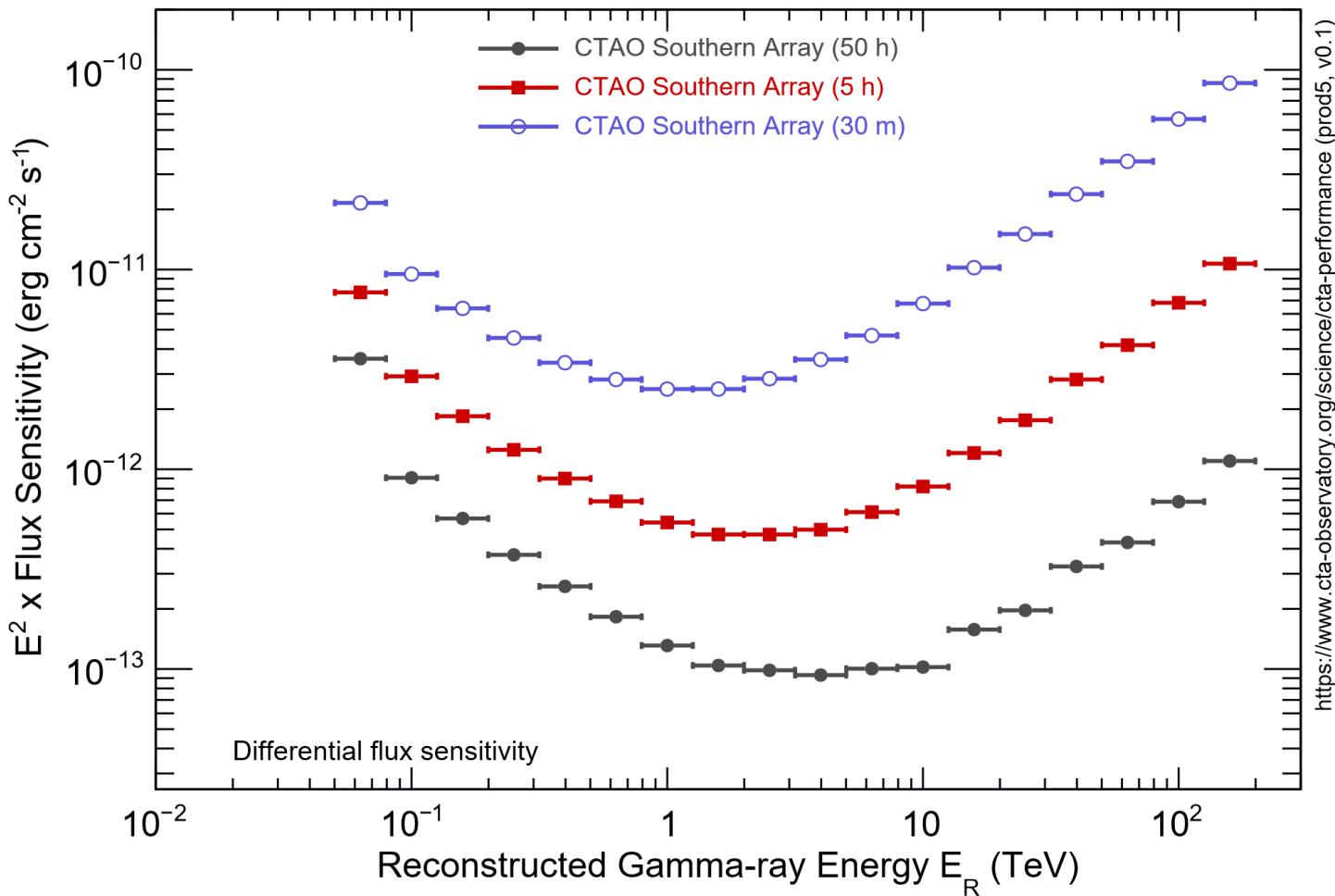


CTAO Southern Array

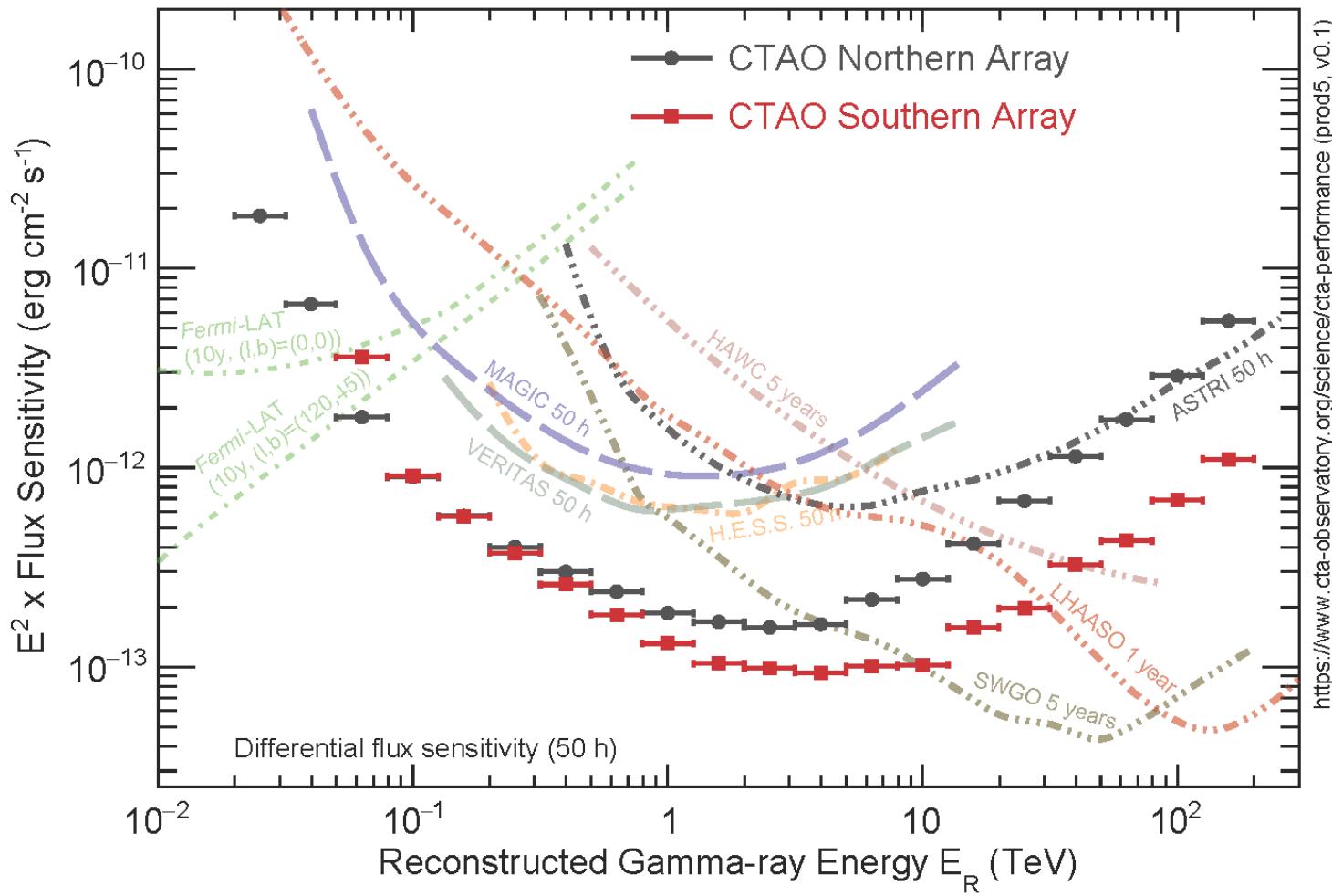
- 14 MSTs + 37 SSTs
- 3 km² footprint
- focus on Galactic science



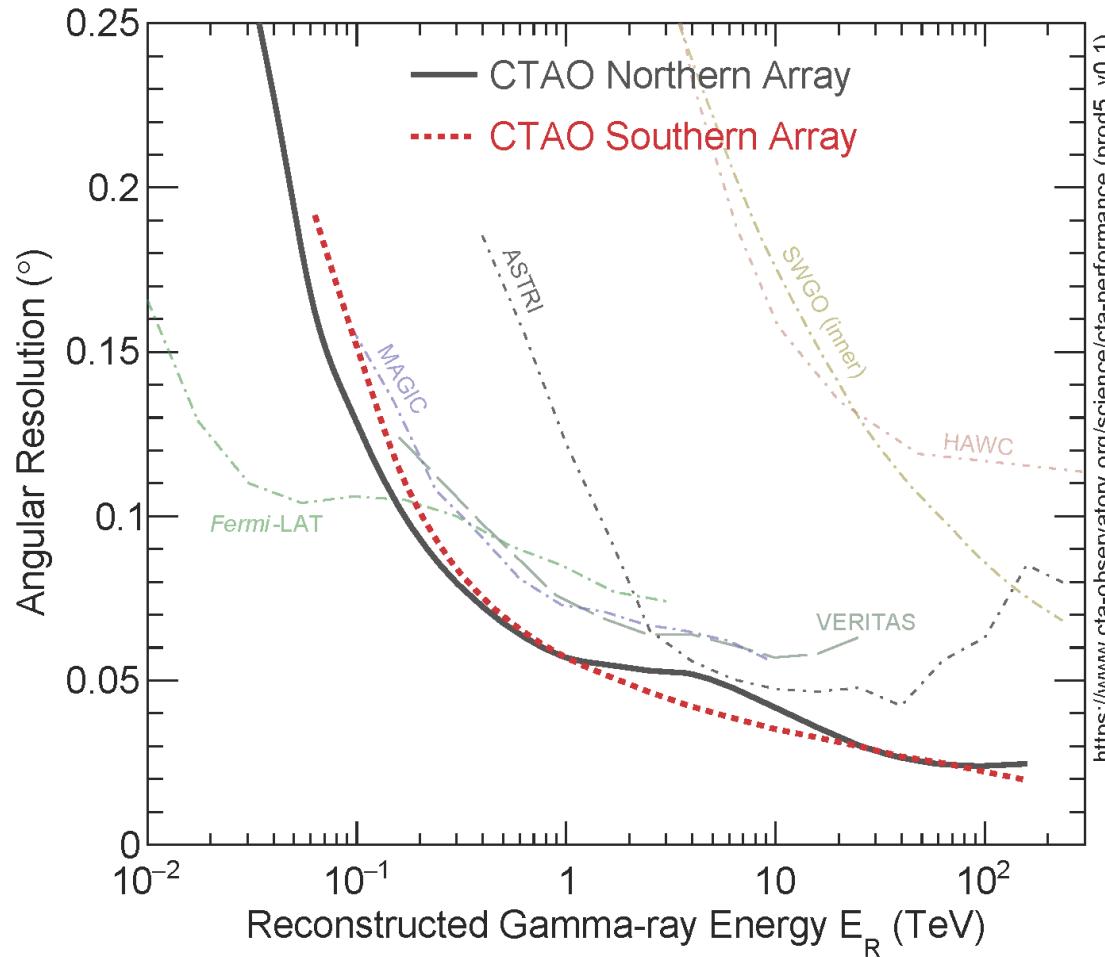




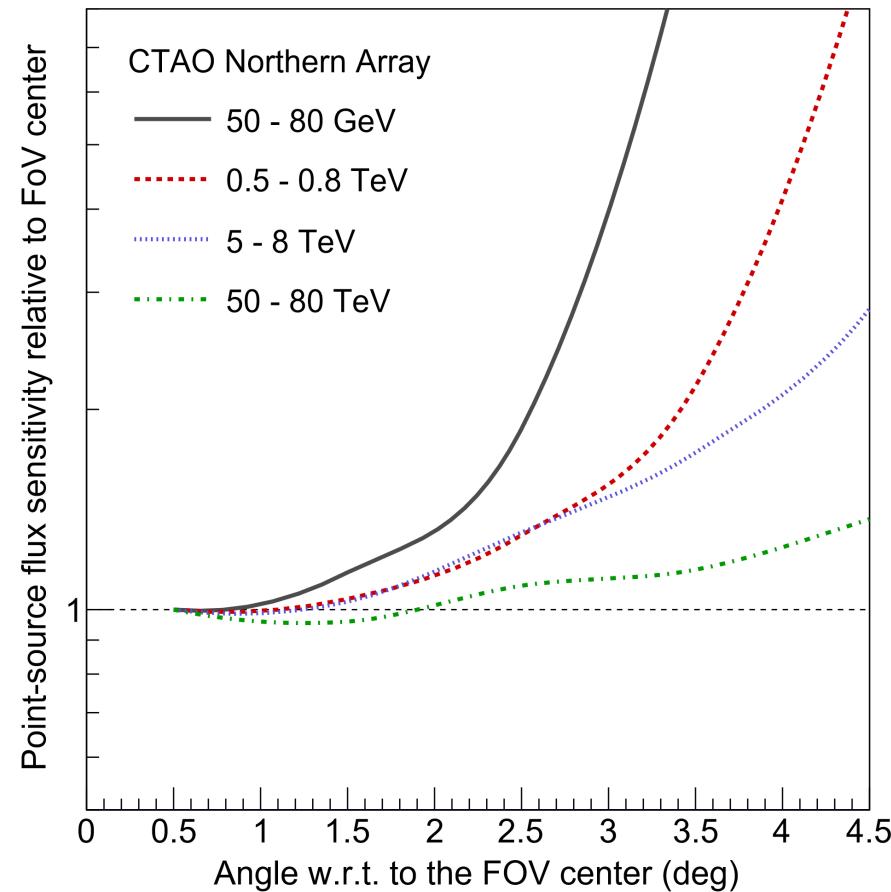
CTA performance



CTA performance



CTA performance



The CTA Telescopes

LST-1 La Palma



SST - ASTRI



MST-SCT

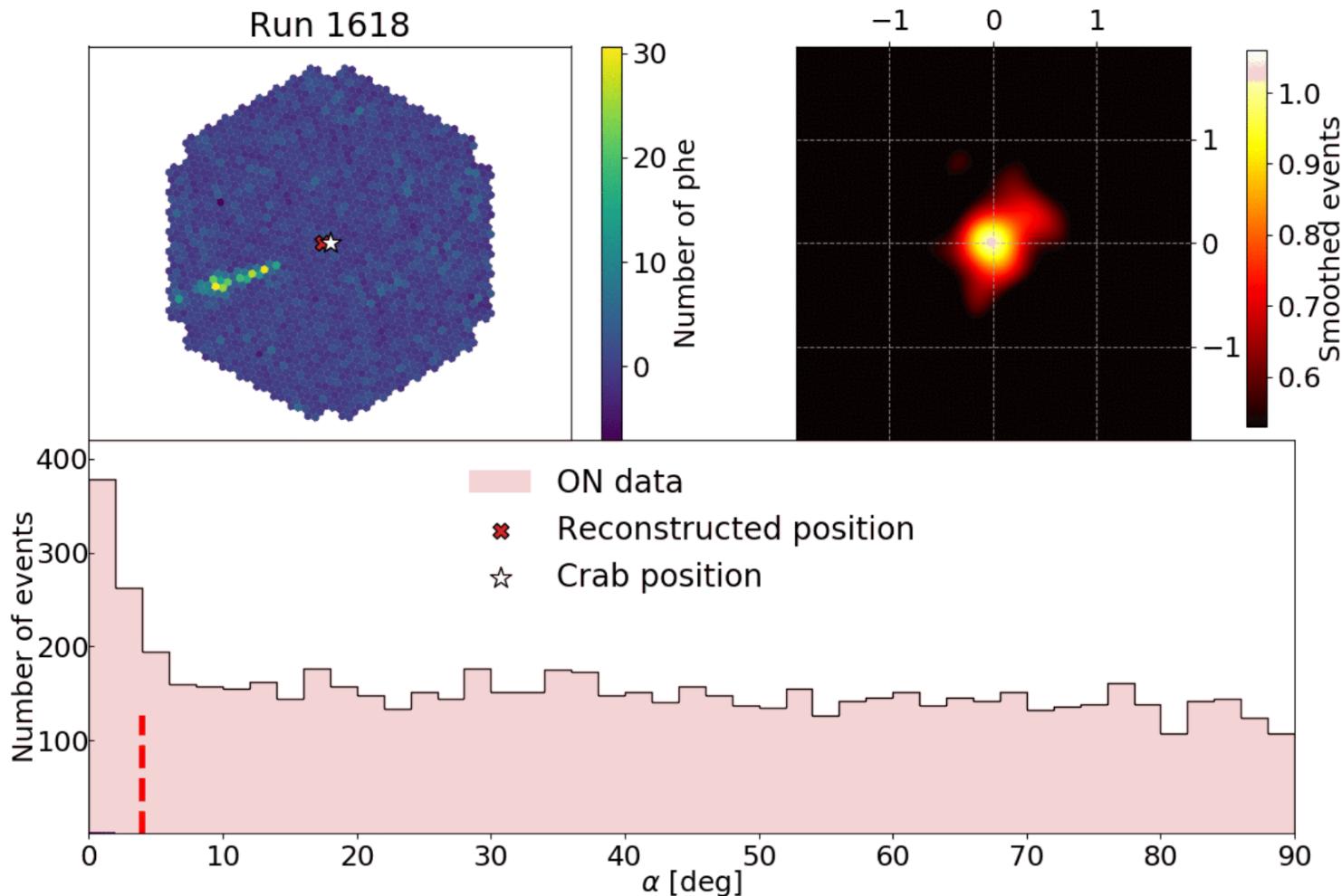


MST

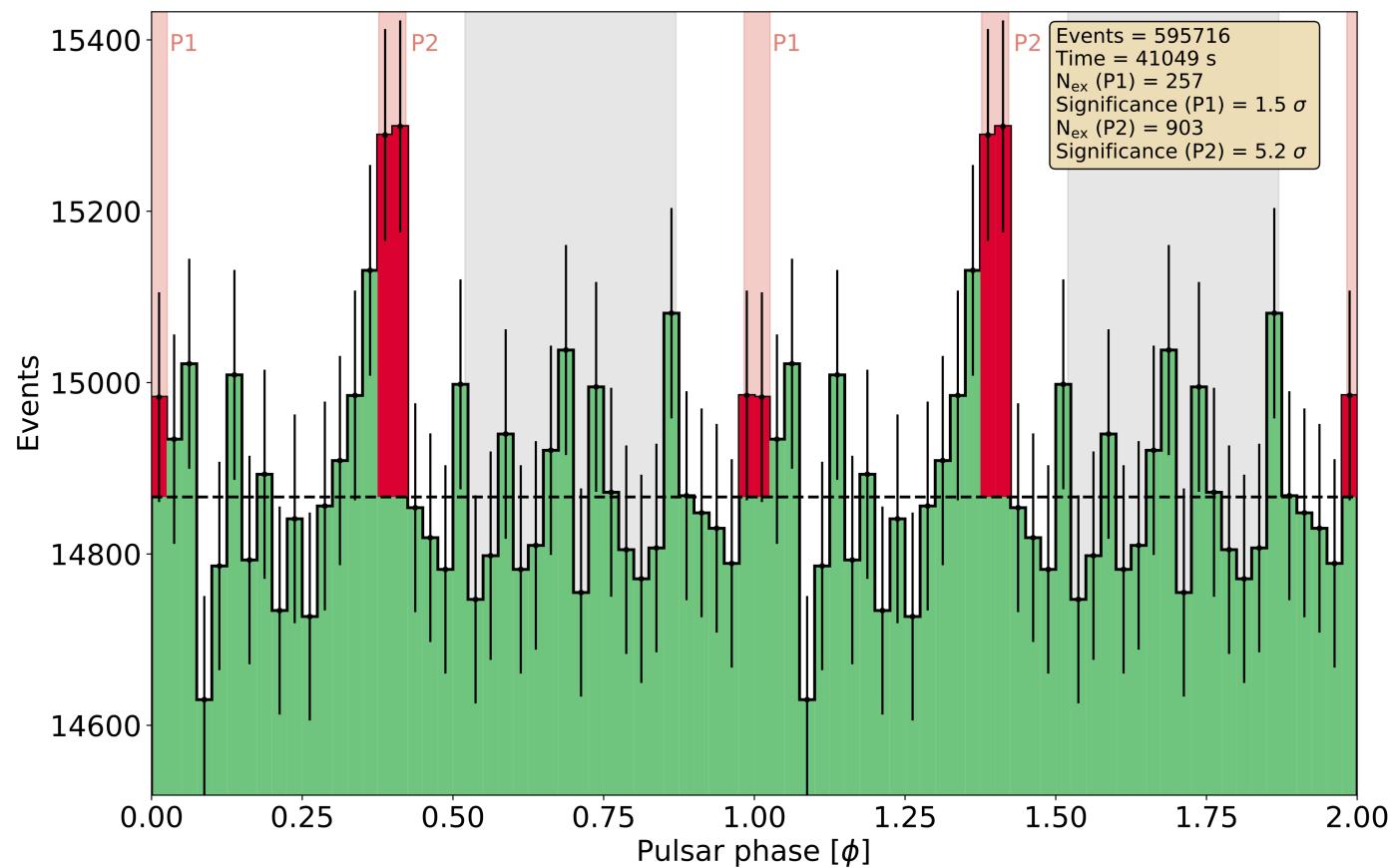


U.Barres – COSPAR 2020

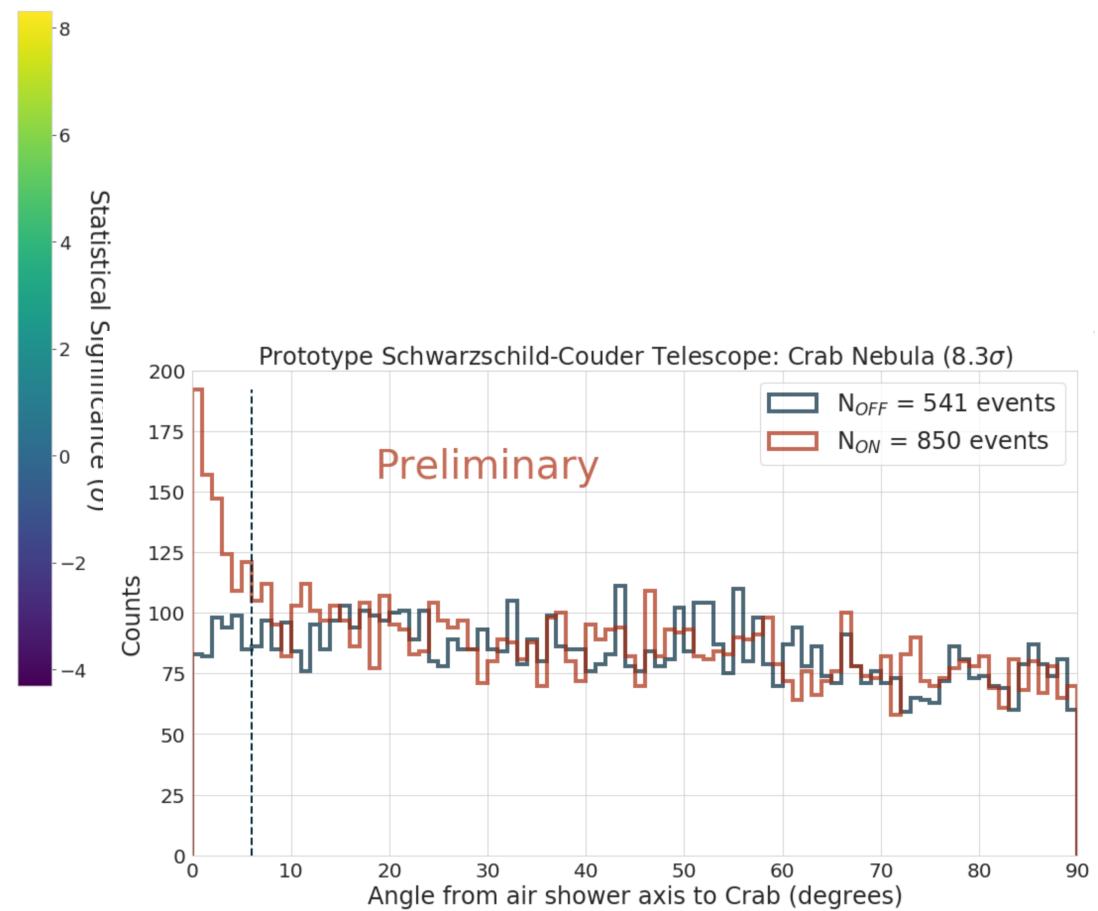
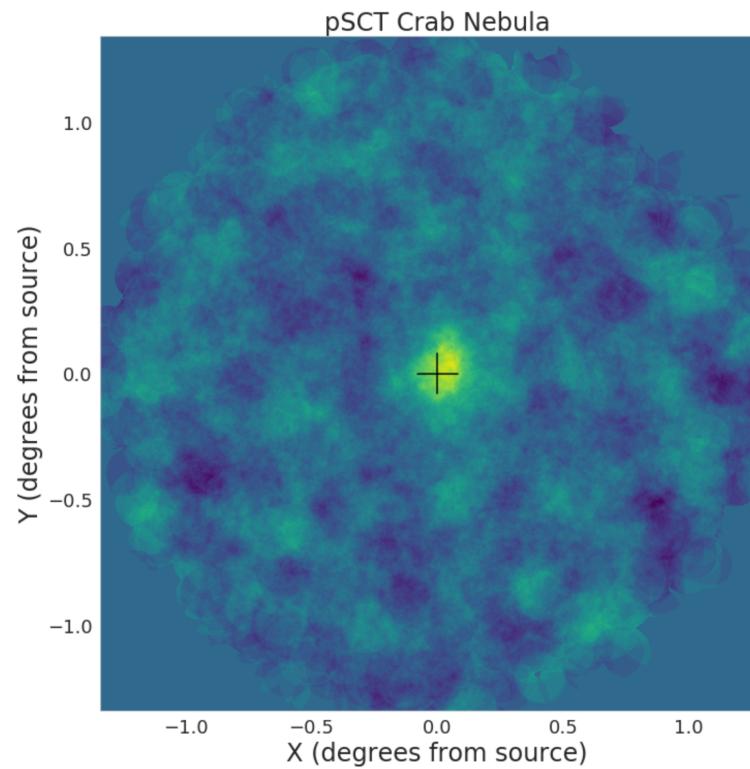
CTA telescopes – first results



CTA telescopes – first results



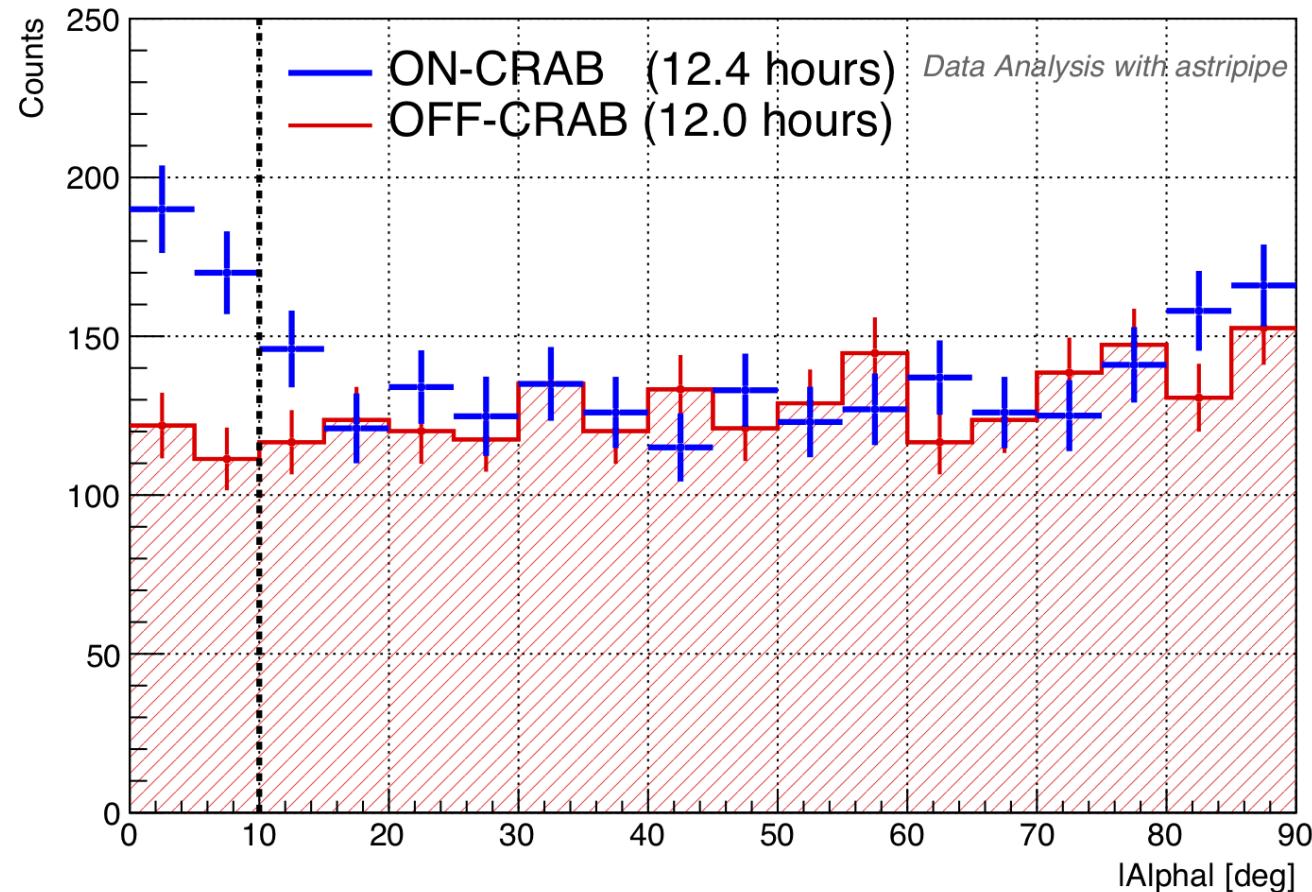
CTA telescopes – first results



CTA telescopes – first results



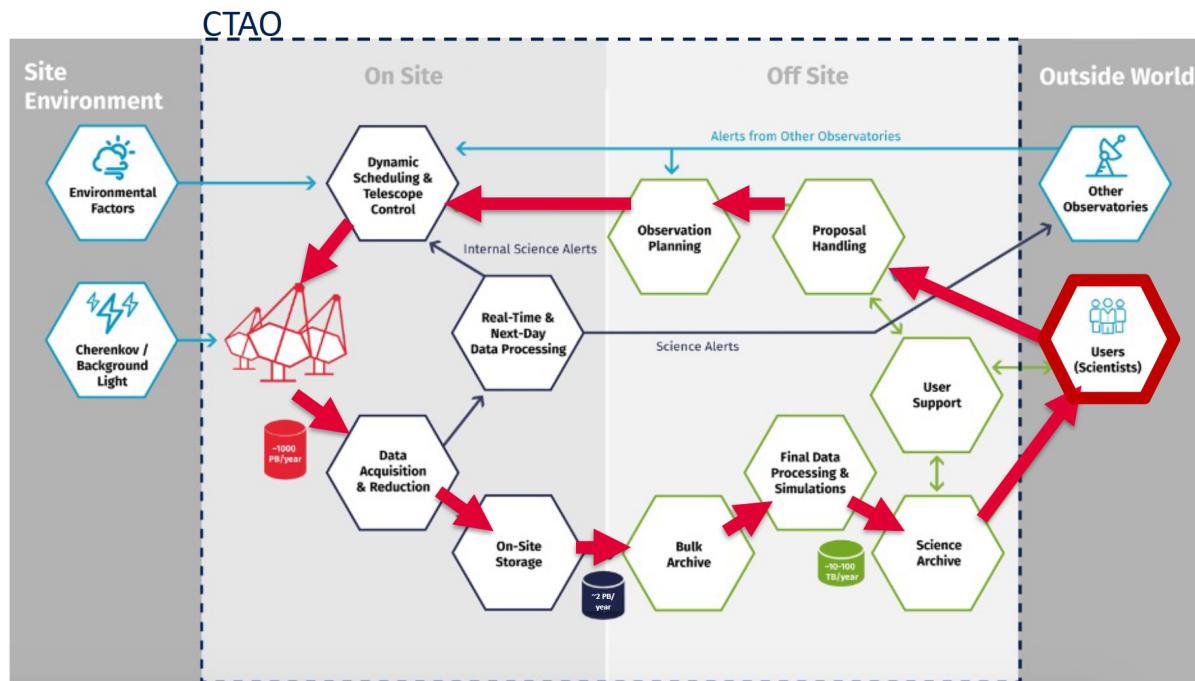
ASTRI SST-2M prototype, December 2018



CTA as an observatory

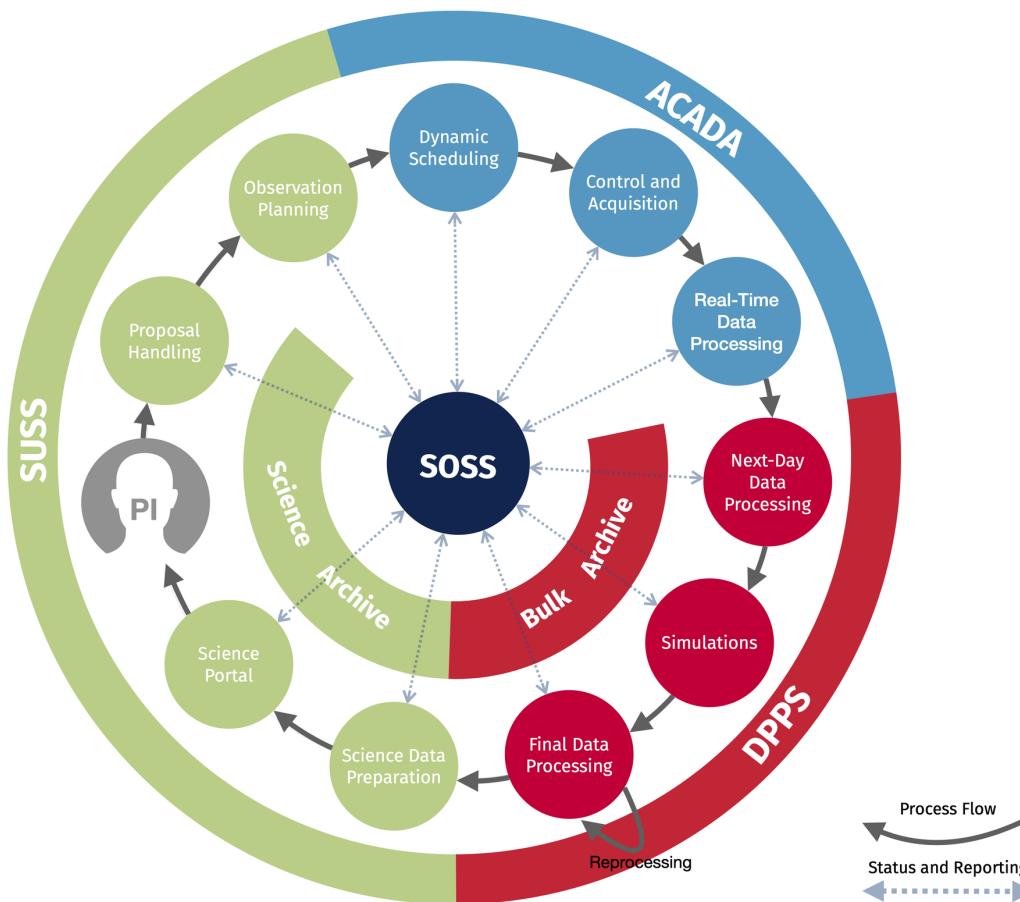


CTA Observatory



- **Proposal driven observatory:** standard proposals & long and large proposals (including Key Science Projects)
- **Proposals evaluated on scientific merits** by a Time Allocation Committee

CTAO computing



CTAO time allocation

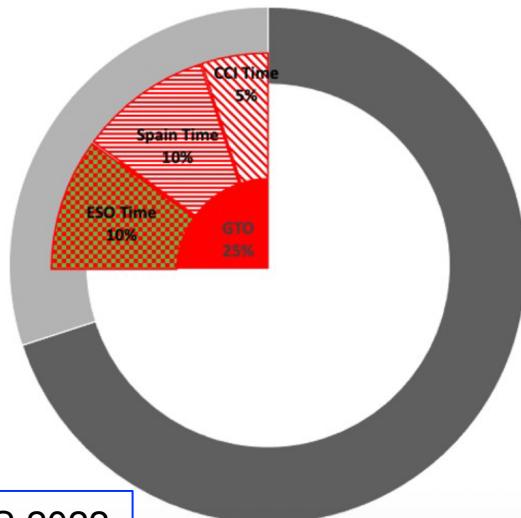


CTAO is an ESO programme

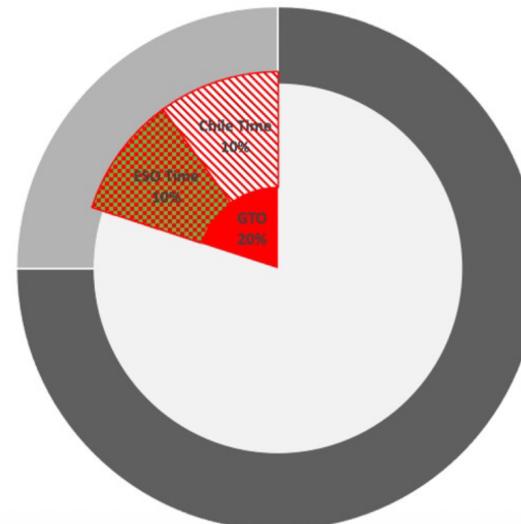


- An ESO scientist can apply for ESO time in response to an announcement of opportunity call (once per year)
- ESO time foresees 10% of the overall observing time equally distributed between the two arrays

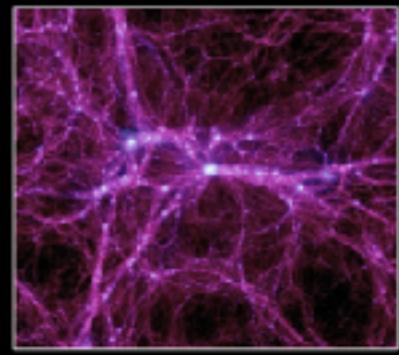
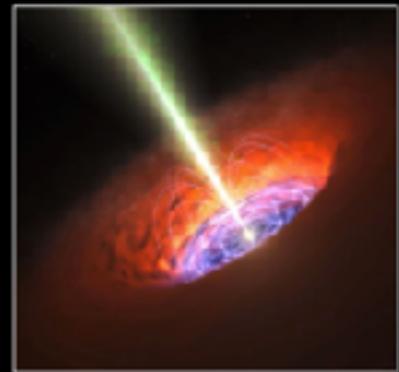
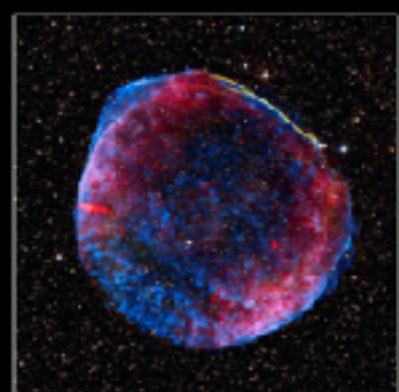
CTAO Northern Array



CTAO Southern Array



Astrophysics with IACTs



- **COSMIC PARTICLE ACCELERATION**

What are the sites and mechanisms of particle acceleration in the cosmos?

- **EXTREME ASTROPHYSICAL ENVIRONMENTS**

The physics of neutron stars, black holes and their energetic environments, such as relativistic jets, winds and stellar explosions.

- **FUNDAMENTAL PHYSICS FRONTIERS**

Probing the nature of Dark Matter, the existence of axion-like particles, and Lorentz invariance violation



cherenkov
telescope
array

The Science of CTA

CTA will target major science questions in high-energy astrophysics, through a large observational programme.

Sky Surveys

- Galactic and X-Gal Scan
- Dark Matter Programme
- Magellanic Clouds

Deep Targeted Observations

- PeVatrons
- Star-forming Systems
- Radio Galaxies & Clusters

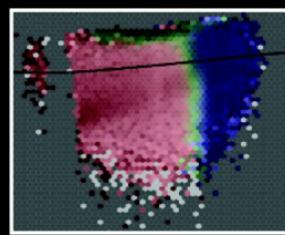
Follow-ups of Transient and Multi-messenger events

Monitoring of Variability notably of AGN

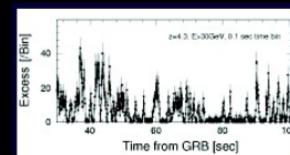
A Census of particle accelerators across all cosmic scales



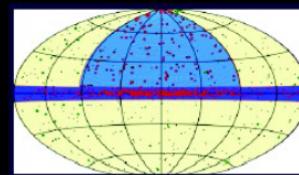
KEY SCIENCE PROJECTS



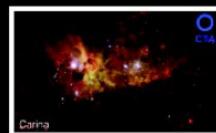
Dark Matter
Programme



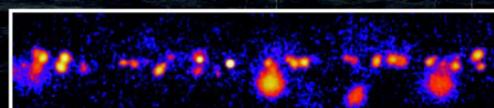
Transients



ExGal
Survey



Star Forming
Systems



Galactic
Plane Survey

Galactic

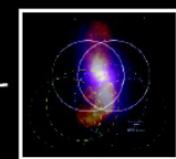
PeVatrons

Galactic
Centre

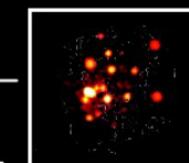
Extragalactic



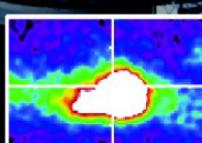
Galaxy
Clusters



AGN



LMC
Survey



U.Barres – COSPAR 2020

Science with CTA



CTA will have important synergies with many of the new generation of major astronomical and astroparticle observatories. Multi-wavelength and multi-messenger approaches combining CTA data with those from other instruments will lead to a deeper understanding of the broad-band non-thermal properties of target sources, elucidating the nature, environment, and distance of gamma-ray emitters. Details of synergies in each waveband are presented.

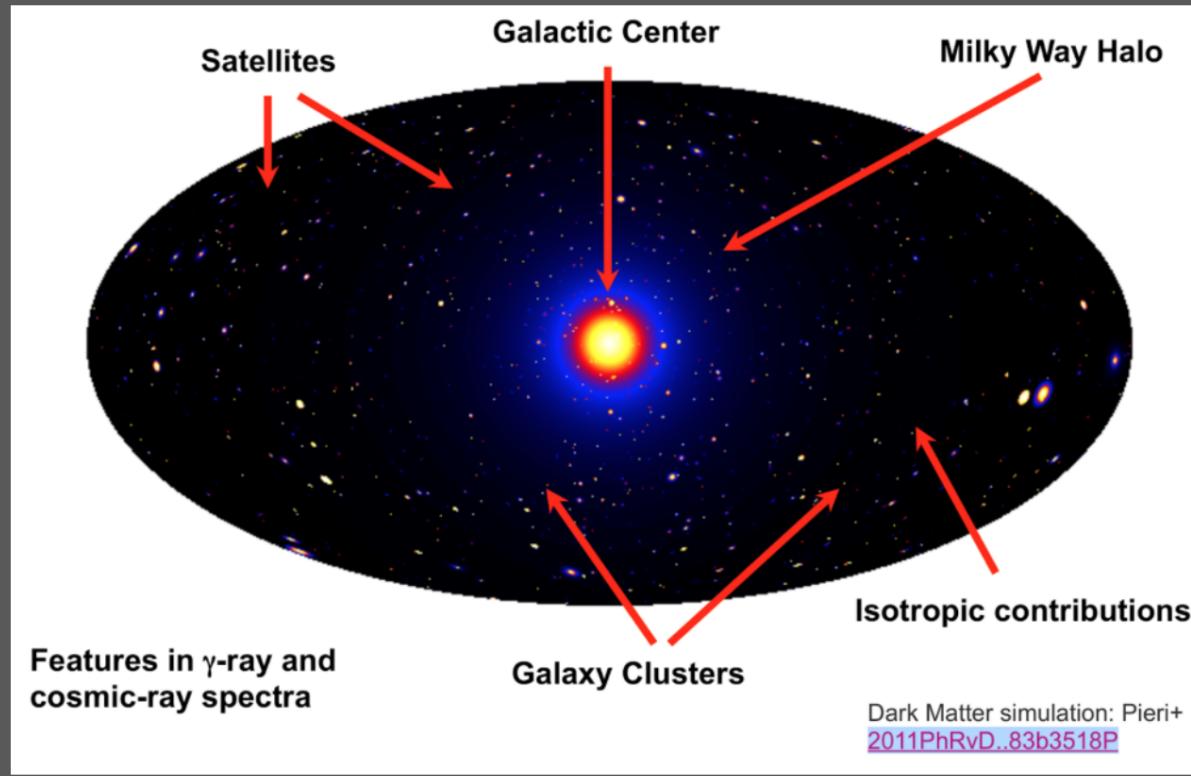
<https://arxiv.org/abs/1709.07997>



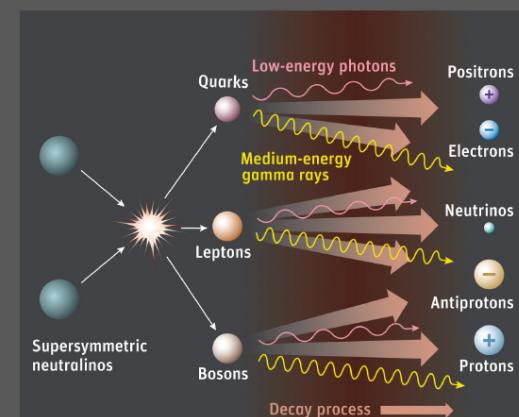
The Dark Matter Programme



Gamma-rays trace annihilating Dark Matter



- Weakly-interacting massive particles (WIMPs)
- Candidate with masses at TeV-scale, ideal for CTA searches
- Annihilation and decay of DM-particles to give out spectral signatures in gamma-rays such as continuum edges and line-emissions features

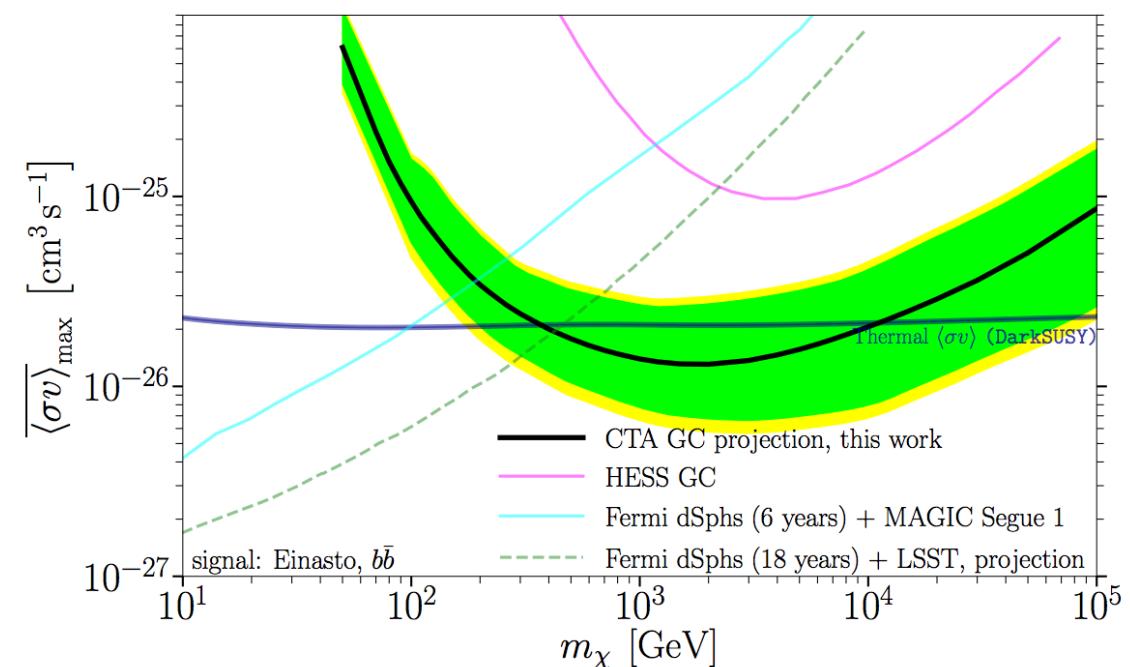


The Dark Matter Programme



Comparison with other experiments

- The GC and Halo provide the most promising sites for CTA Dark Matter searches
- Over 500 h planned observation time at the GC
- CTA will complement data from direct DM detection and other indirect experiments in the energy range of 10s of TeV



U.Barres – COSPAR 2020

arXiv:2007.16129

Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre

arXiv:2007.16129v2 [astro-ph.HE] 30 Jan 2021

Abstract. We provide an updated assessment of the power of the Cherenkov Telescope Array (CTA) to search for thermally produced dark matter at the TeV scale, via the associated gamma-ray signal from pair-annihilating dark matter particles in the region around the Galactic centre. We find that CTA will open a new window of discovery potential, significantly extending the range of robustly testable models given a standard cuspy profile of the dark matter density distribution. Importantly, even for a cored profile, the projected sensitivity of CTA will be sufficient to probe various well-motivated models of thermally produced dark matter at the TeV scale. This is due to CTA’s unprecedented sensitivity, angular and energy resolutions, and the planned observational strategy. The survey of the inner Galaxy will cover a much larger region than corresponding previous observational campaigns with imaging atmospheric Cherenkov telescopes. CTA will map with unprecedented precision the large-scale diffuse emission in high-energy gamma rays, constituting a background for dark matter searches for which we adopt state-of-the-art models based on current data. Throughout our analysis, we use up-to-date event reconstruction Monte Carlo tools developed by the CTA consortium, and pay special attention to quantifying the level of instrumental systematic uncertainties, as well as background template systematic errors, required to probe thermally produced dark matter at these energies.

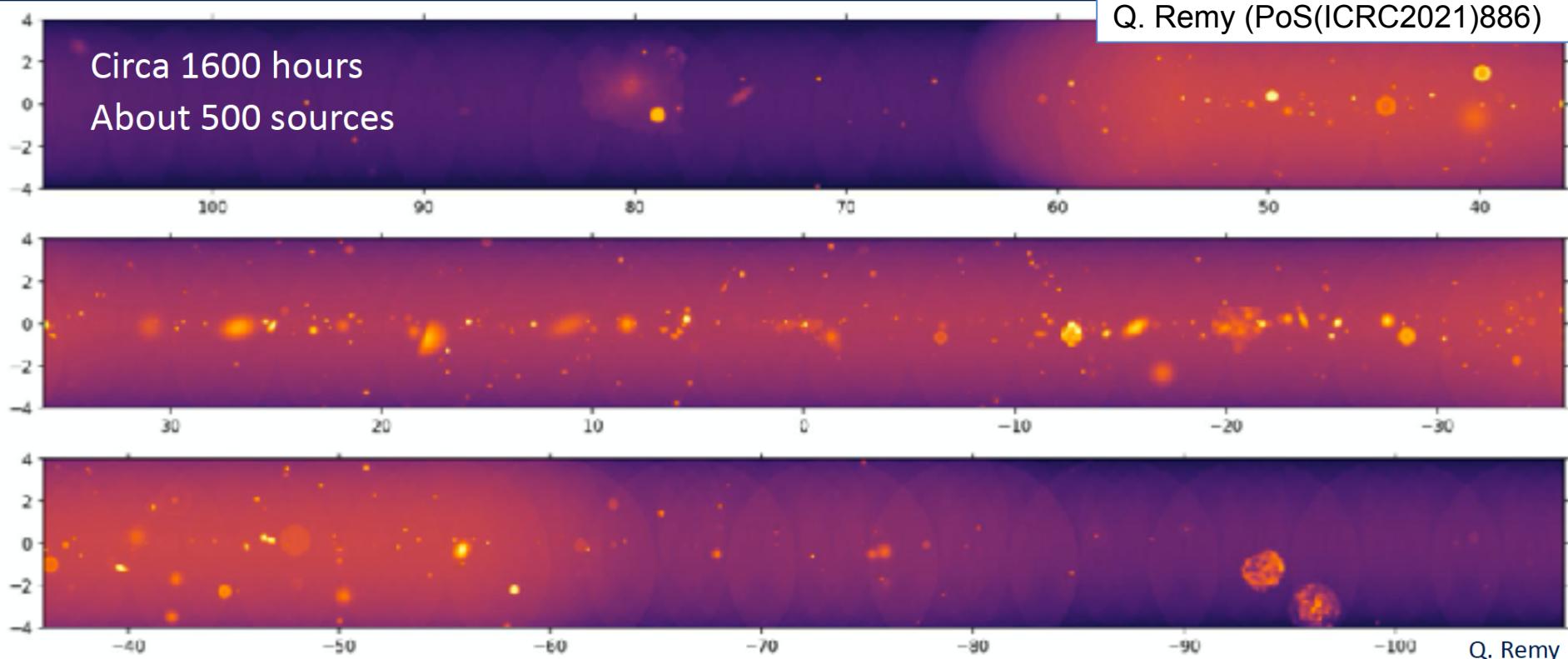
<https://arxiv.org/abs/2007.16129>



cherenkov
telescope
array

CTA Galactic Science

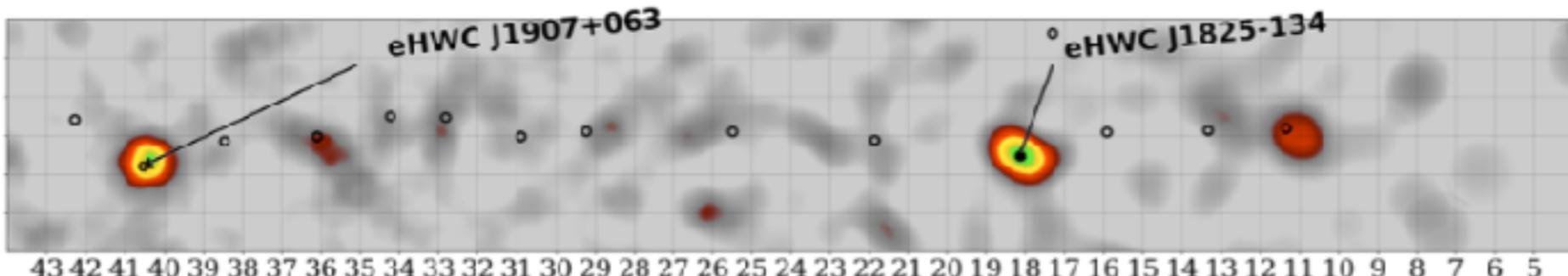
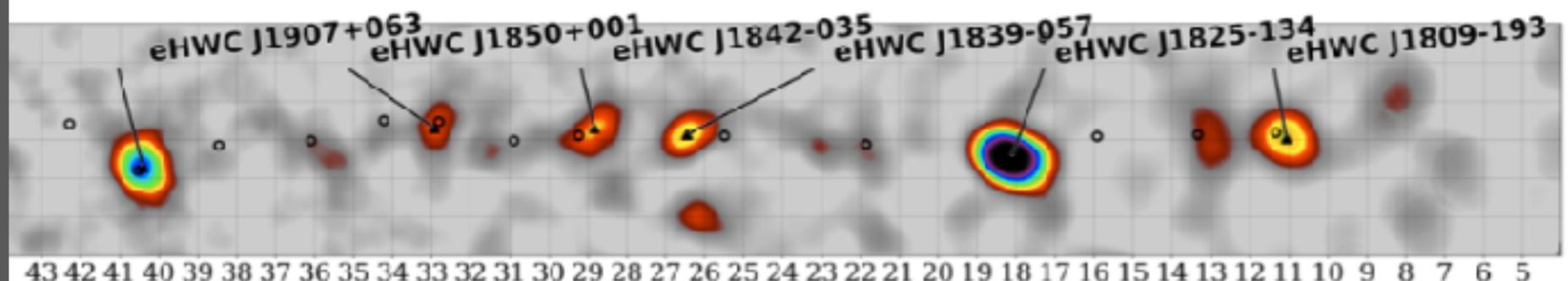
- Survey speed about 300x greater than H.E.S.S.
- Much deeper reach, to scan the entire galaxy for PWNe and SNRs, as opposed to the few-kpc reach of current instruments.



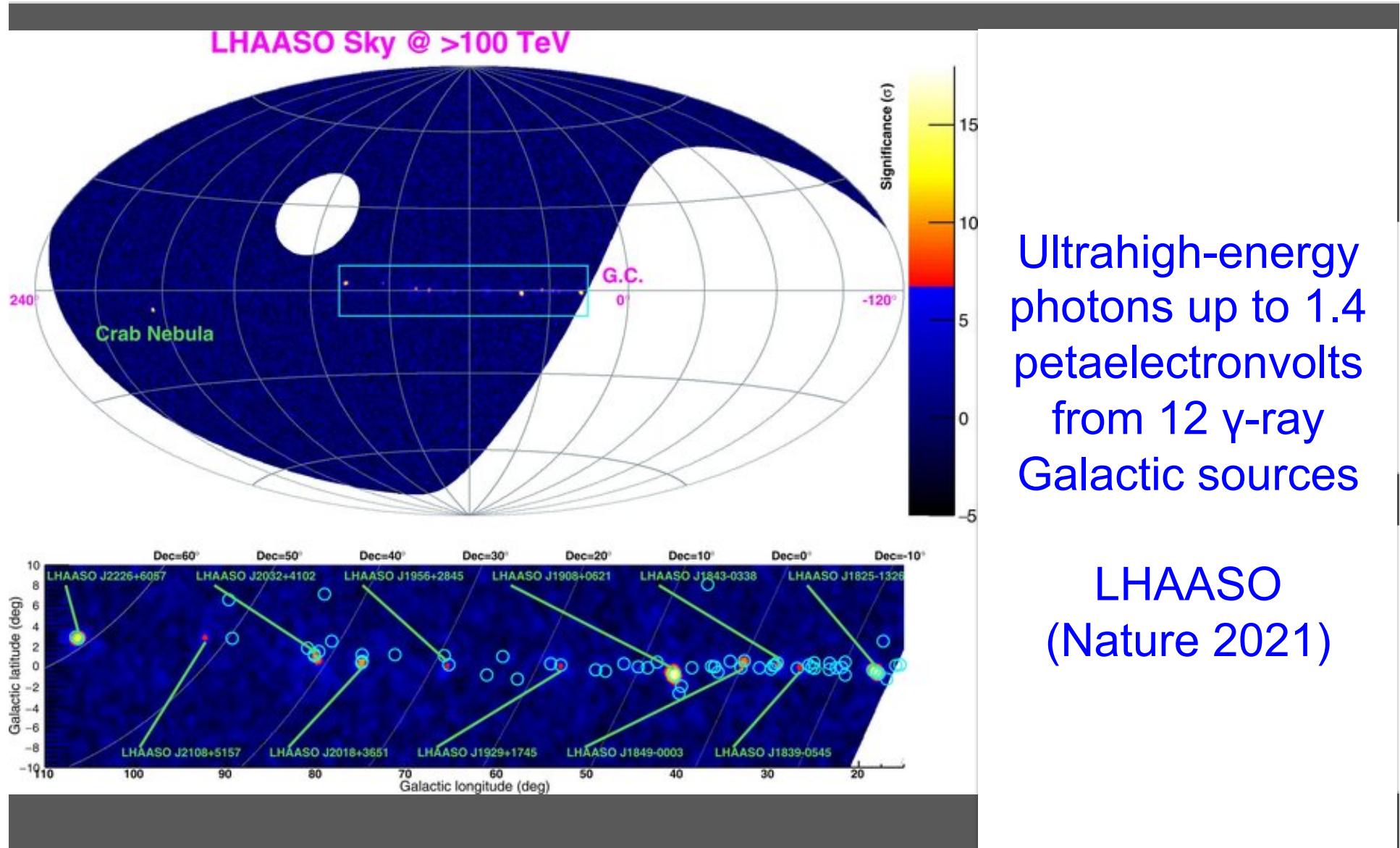
PeVatrons: the extreme energy frontier



HAWC (arXiv:1909.08609) has opened a window into the PeVatron frontier that can be extensively probed and expanded by CTA



PeVatrons: the extreme energy frontier



CTA's Prospects for AGN

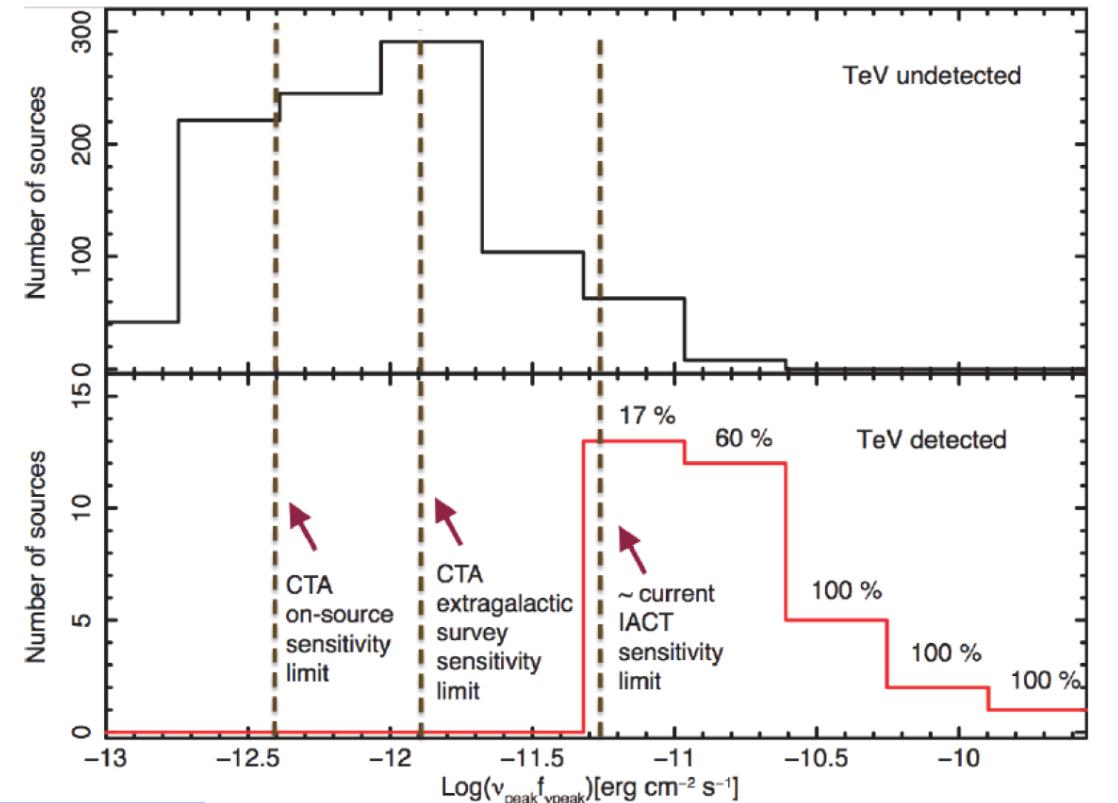
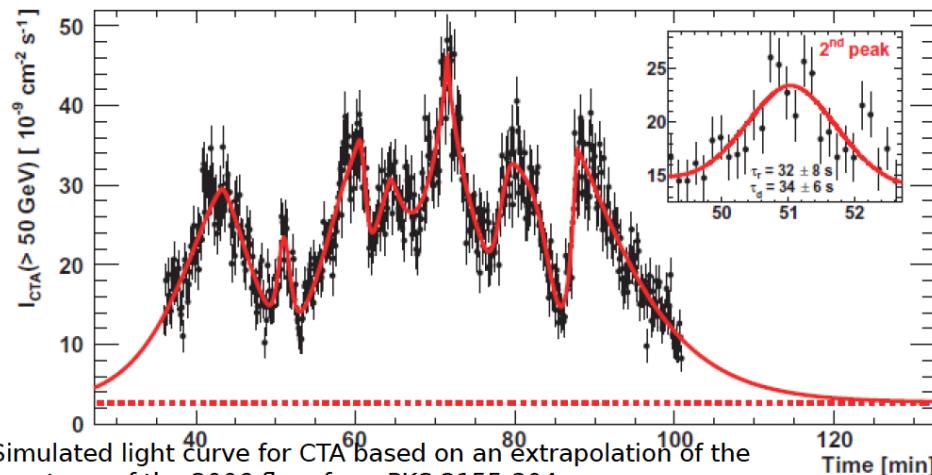
CTA will detect many 100s of AGN to $z \sim 2$

FoV up to 10 degrees → several AGN in FoV at same time.

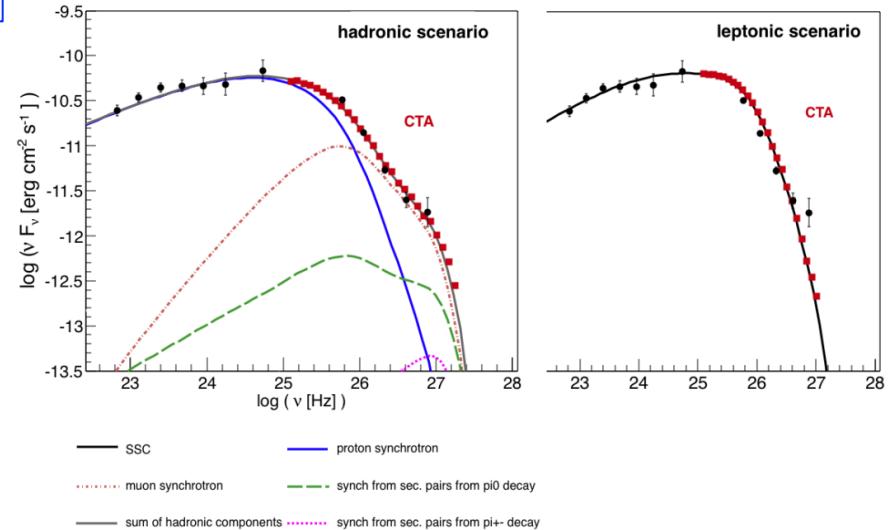
Light curve details down to sub-minutes.

Spectral resolution to reveal sub-components:

- Hadronic (synchrotron from protons, muons, + secondaries)
- Leptonic (SSC)



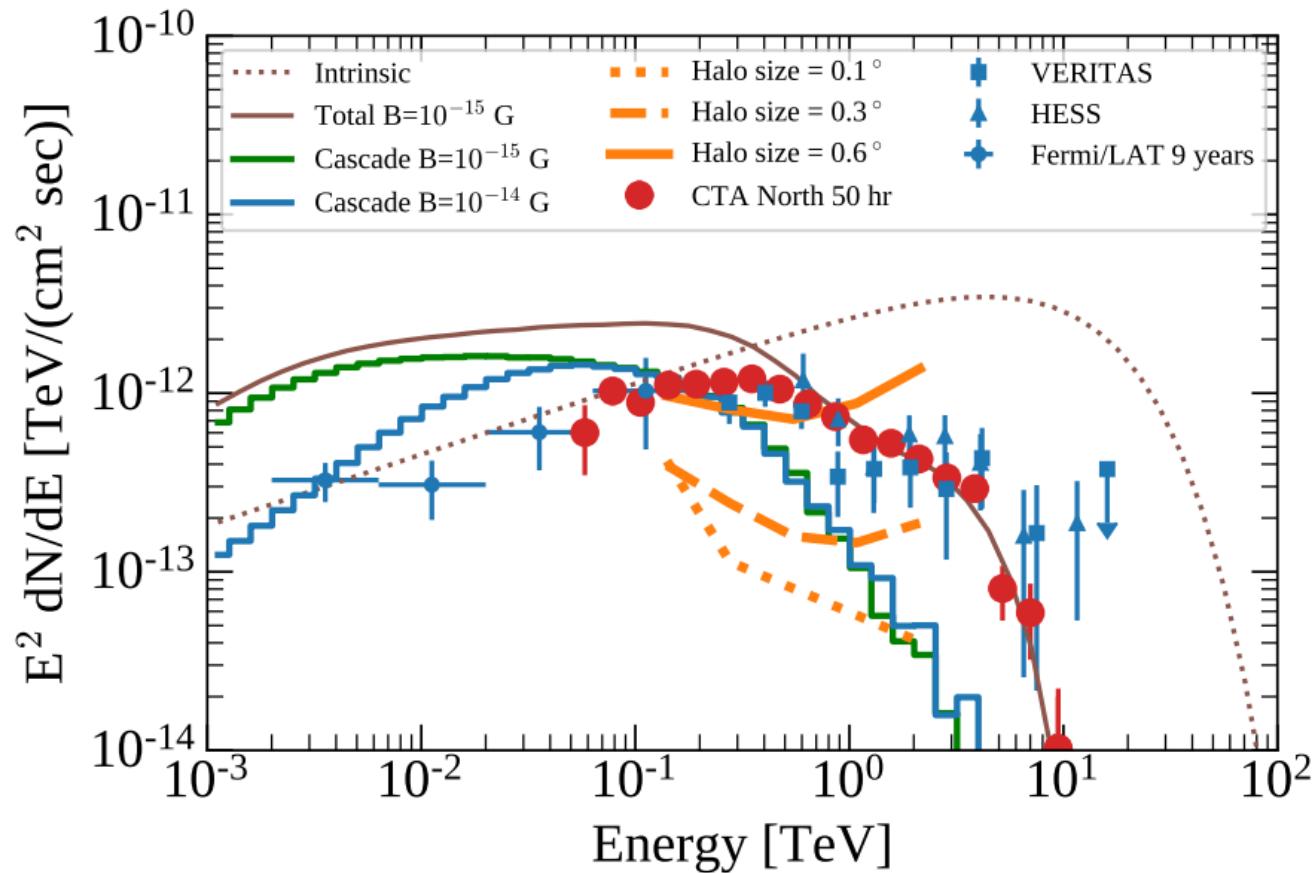
G. Rowell – COSPAR 2020



Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation

Abstract. The Cherenkov Telescope Array (CTA), the new-generation ground-based observatory for γ -ray astronomy, provides unique capabilities to address significant open questions in astrophysics, cosmology, and fundamental physics. We study some of the salient areas of γ -ray cosmology that can be explored as part of the Key Science Projects of CTA, through simulated observations of active galactic nuclei (AGN) and of their relativistic jets. Observations of AGN with CTA will enable a measurement of γ -ray absorption on the extragalactic background light with a statistical uncertainty below 15% up to a redshift $z = 2$ and to constrain or detect γ -ray halos up to intergalactic-magnetic-field strengths of at least 0.3 pG. Extragalactic observations with CTA also show promising potential to probe physics beyond the Standard Model. The best limits on Lorentz invariance violation from γ -ray astronomy will be improved by a factor of at least two to three. CTA will also probe the parameter space in which axion-like particles could constitute a significant fraction, if not all, of dark matter. We conclude on the synergies between CTA and other upcoming facilities that will foster the growth of γ -ray cosmology.

Cosmology and Fundamental Physics





cherenkov
telescope
array

The new window of VHE Gamma-ray Bursts

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; **Razmik Mirzoyan on behalf of the MAGIC Collaboration**
on 15 Jan 2019; 01:03 UT

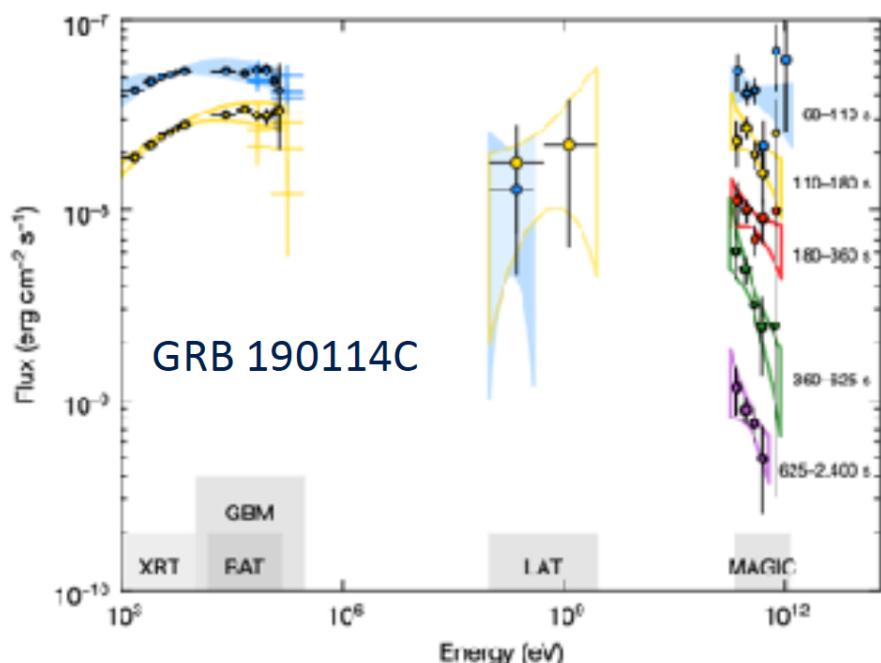
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-RAT alert. we started



Three long GRBs detections announced in the past two years:

GRB 180720B ($z=0.65$)

GRB 190114C ($z=0.42$)

Afterglow detected > 300 GeV
Huge statistics (1000s gammas)
Sub-minute timescale spectra

GRB 190829A ($z=0.08$)

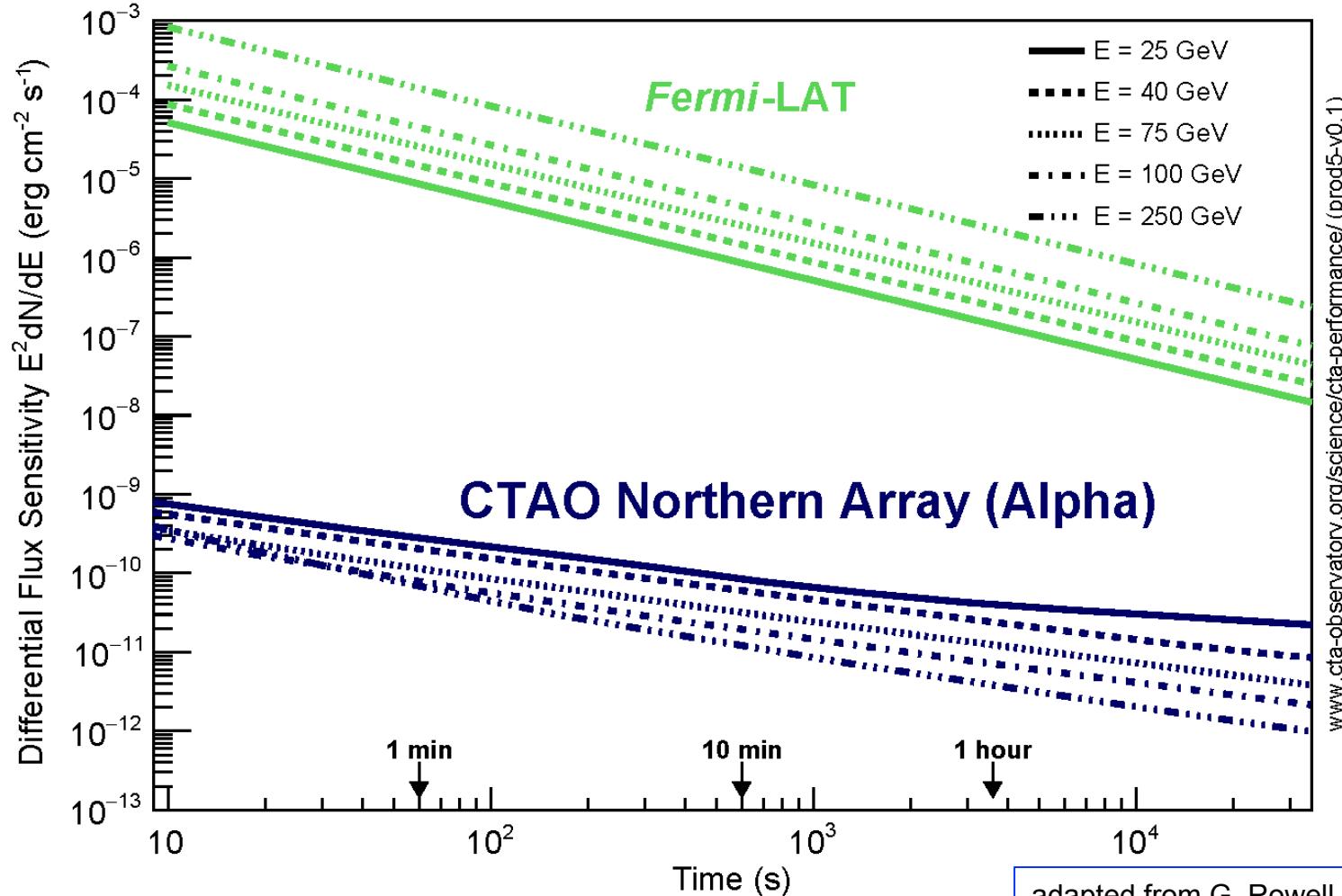
+ GRB 201216C ($z = 1.1$)

Strong MWL and MM synergies for spectral and variability studies

U.Barres – COSPAR 2020

Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)



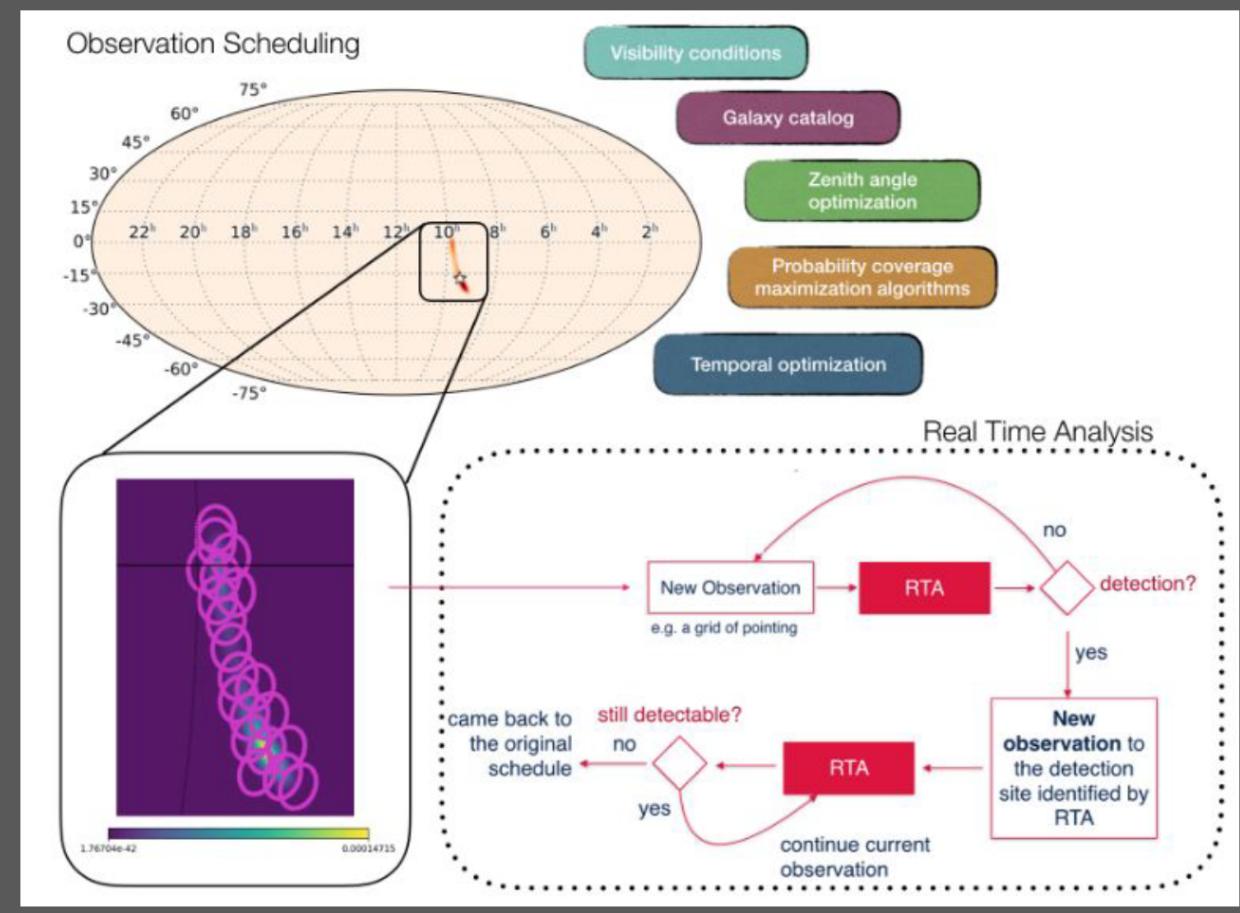
CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range
→ GRBs, AGN, giant pulses, FRBs, GW, SGR bursts.....

Gravitational wave follow-ups



CTA will represent an important improvement on the follow-up of gravitational wave events

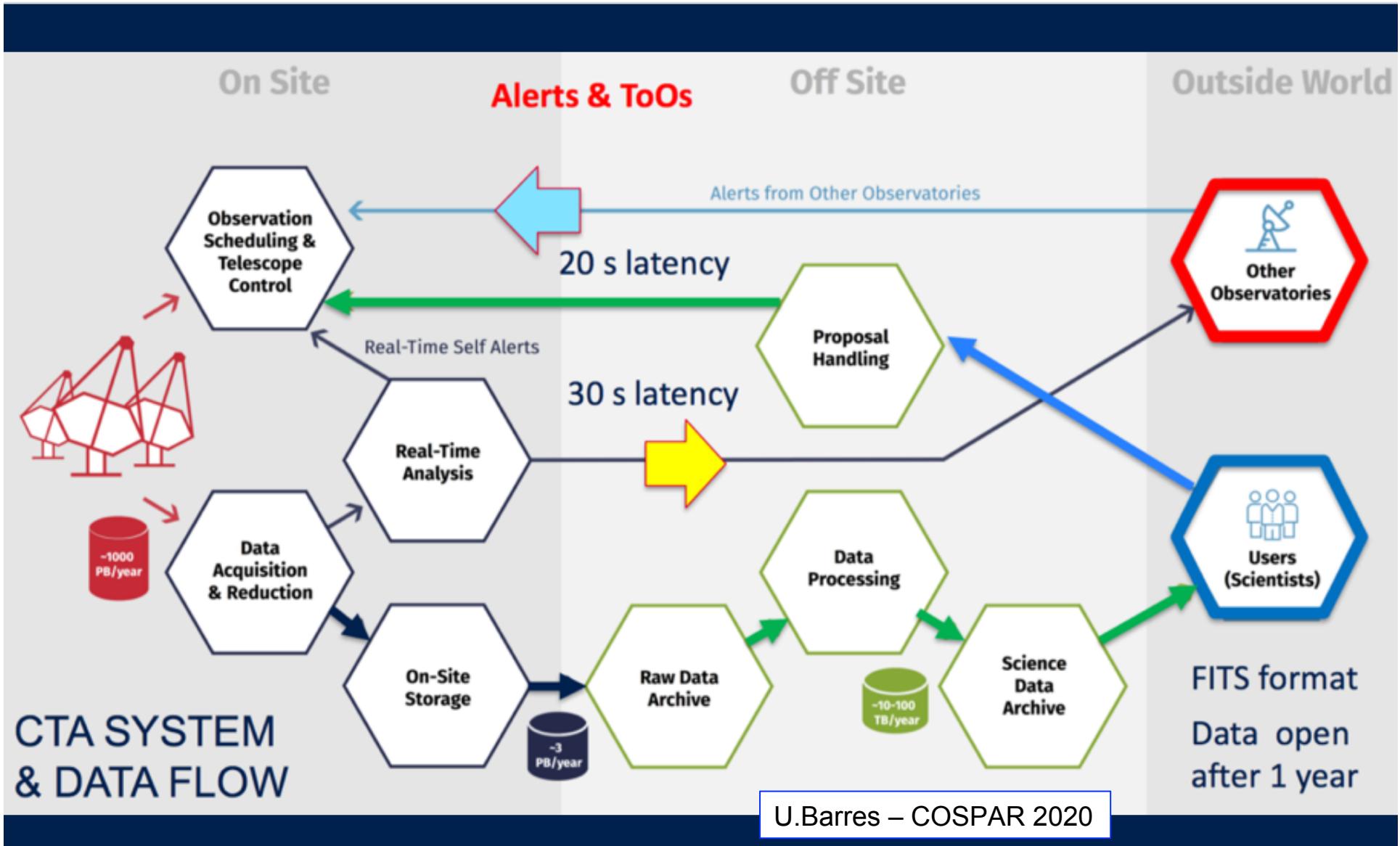
- Larger field of view of 5°
- 7° means quicker scan of GW error regions
- An optimised pointing strategy will be used to efficiently cover the sky area of the GW signal





cherenkov
telescope
array

CTA Transients Science



The 1st CTAO Science Data Challenge



CTAO Science Data Challenge(s)



- **CTAO Science Data Challenge (SDC):**
source and large-scale structure finding/characterization data challenges
on simulated science-ready (DL3) data products*
- **A series of SDCs with increasing complexity both on the sky realism side
and on the foreseen goals**

The 1st CTAO Science Data Challenge



CTAO SDCs: general goals



1. **to allow the broad science community to get familiar with the CTAO data products and the CTAO Science Analysis Tools (SATs)**
2. **to serve as a test-bed for driving forward new algorithms and new technologies** (like machine-learning) for source and large-scale structure detection/identification in the context of the source confusion
3. **to serve as intermediate step in the verification process of software packages** that will be used during Observatory operations and data models and formats
4. **to foster the production of good documentation** to be used for users' support

The 1st CTAO Science Data Challenge



CTAO SDCs: phases



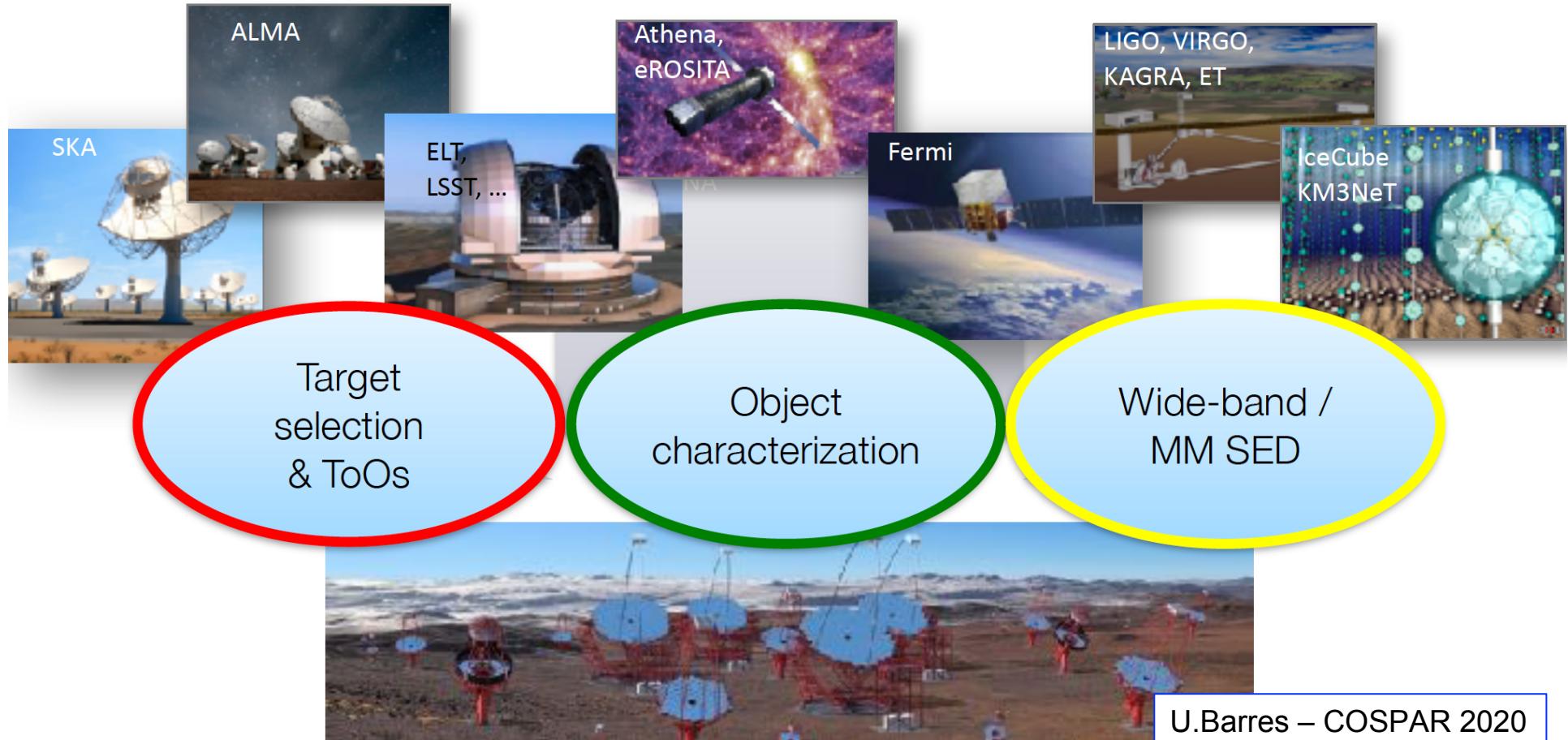
Each SDC consists of 4 phases:

- **Phase 1: definition**
 - definitions of goals, science cases and technical needs
- **Phase 2: preparation**
 - preparation and running of the simulations
- **Phase 3: execution**
 - starts with the opening of the challenge;
 - users can download and explore the data,
 - users can submit their results
- **Phase 4: closing-out**
 - starts when the challenge is closed;
 - it foreseen the scrutiny and score of the submitted results, the nomination of the winners;
 - it includes the writing-up of a closing-out document (peer-reviewed paper under discussion)

MWL and Multi-Messenger Perspectives



Synergies with astrophysical facilities...



External Needs Matrix



cherenkov
telescope
array

G. Rowell – COSPAR 2020

✓ = important ✓ = critical

Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	✓	✓	✓	✓	✓	✓	✓	✓		✓
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	✓	✓	✓		✓		✓	✓		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	✓	✓	✓	✓	✓		✓	✓	✓	
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.						✓	✓			✓
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	✓	✓	✓	✓	✓	✓	✓	✓		✓
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	✓	✓	✓	✓	✓	✓	✓			✓
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	✓	✓	✓		✓		✓			
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.		✓				✓	✓			✓
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						✓				✓

Conclusions

- CTA will open a new era in VHE astrophysics
 - A rich science program to answer key scientific questions
 - A VHE observatory !
- Clear MM and MWL synergies
- A new Data Challenge is being organised

