The Cherenkov Telescope Array

General Introduction to Science Topics

Francesco Longo

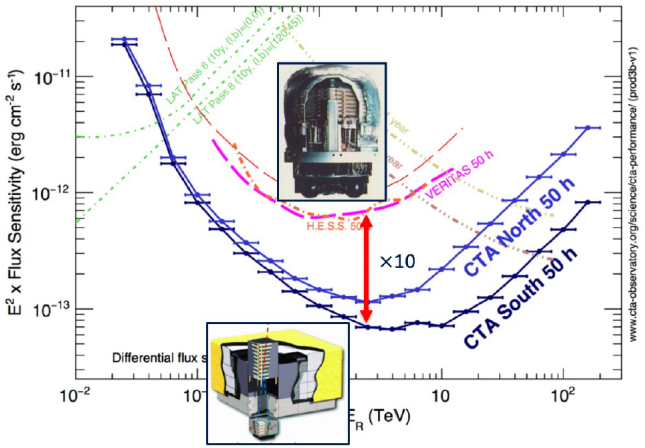
On behalf of the CTA Consortium and the CTA Observatory

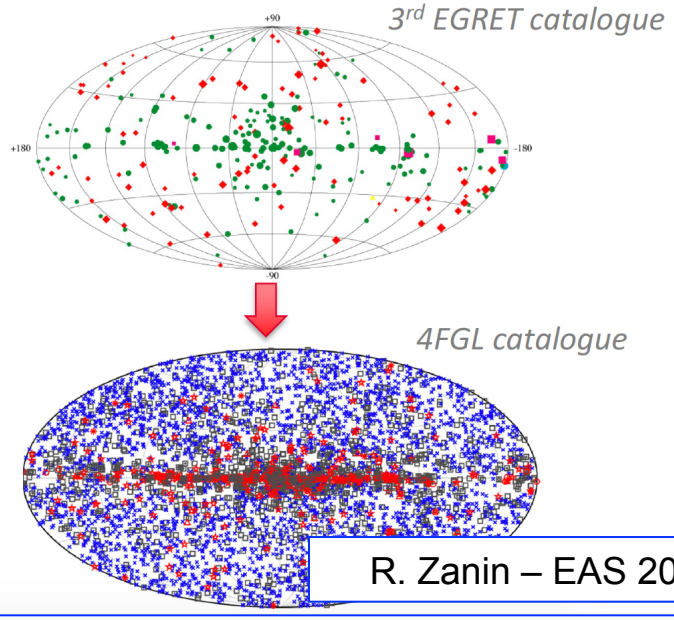
Sexten Summer school – July 2022

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

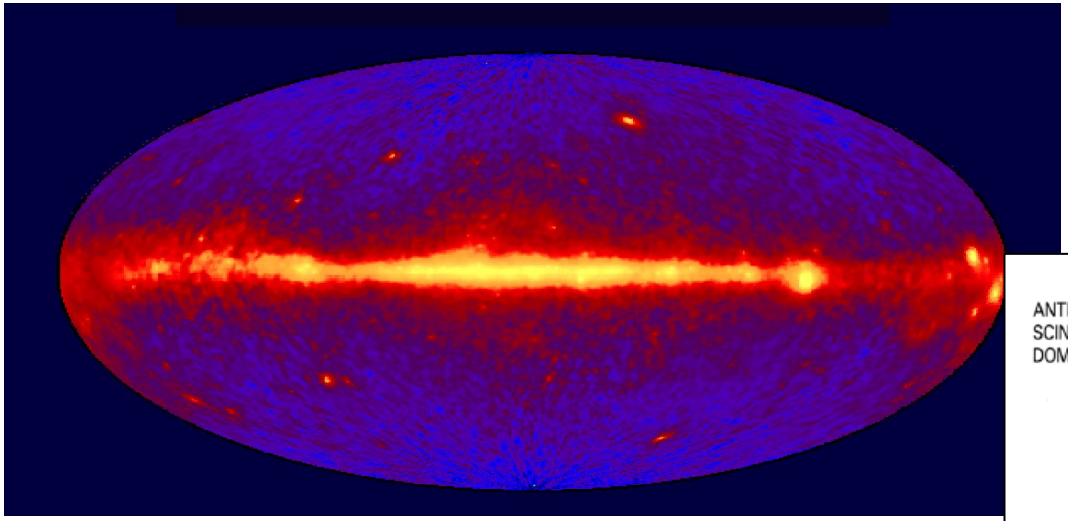


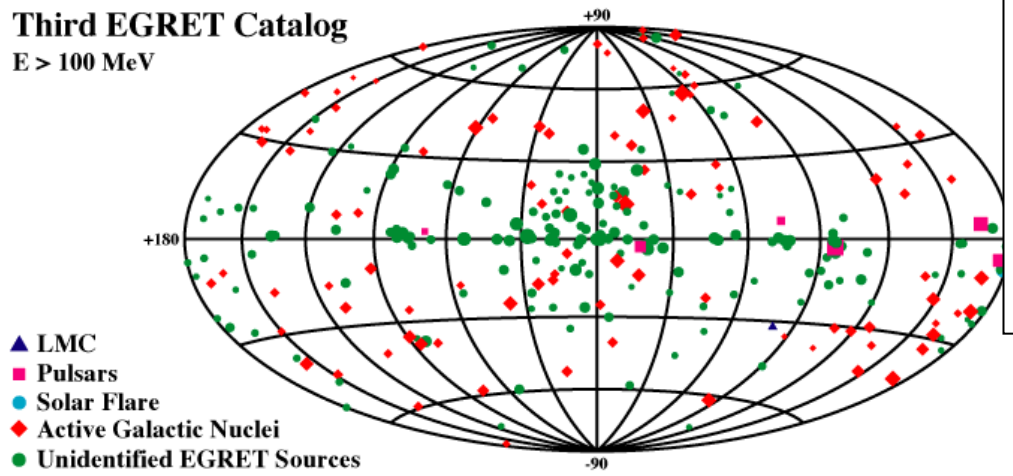


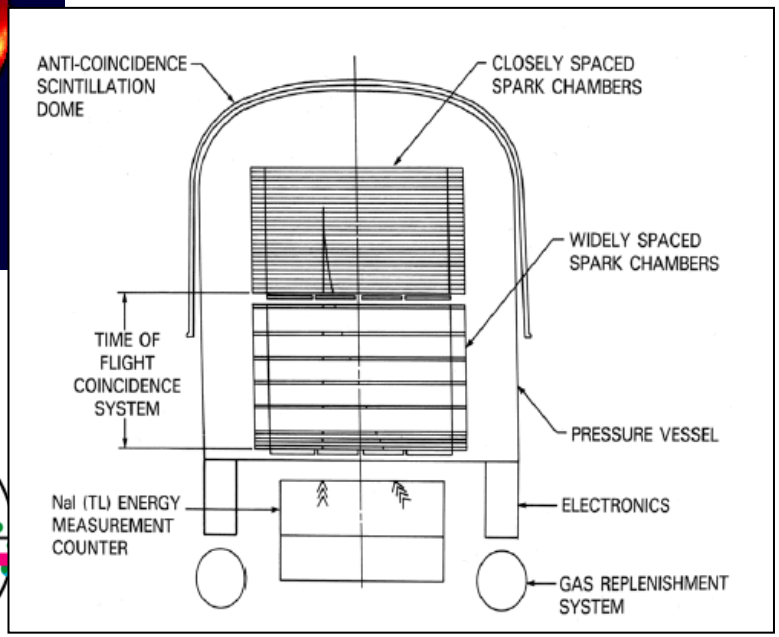
Summary

- Lessons learned by Fermi/LAT…
- The Cherenkov Telescope Array
- Key Science Topics
- Opportunities …

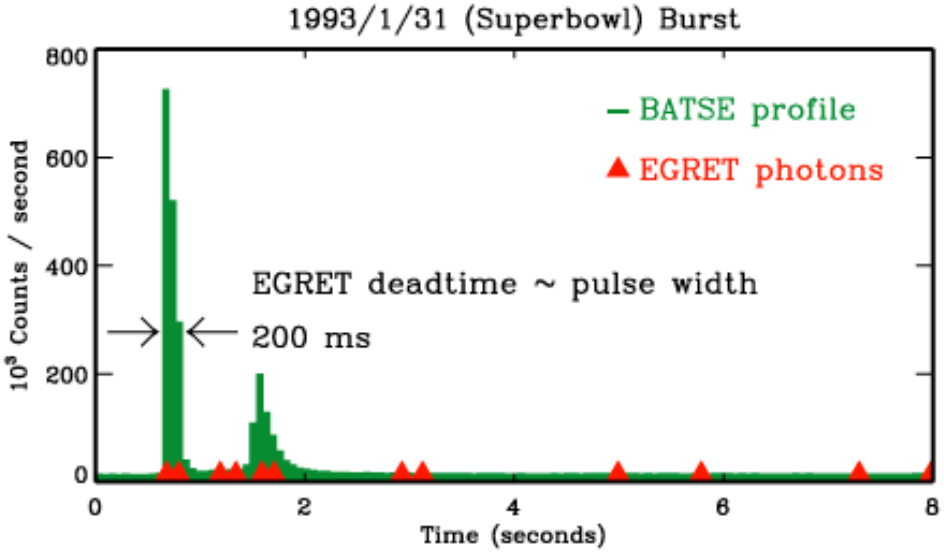
The EGRET era (1991-2000)

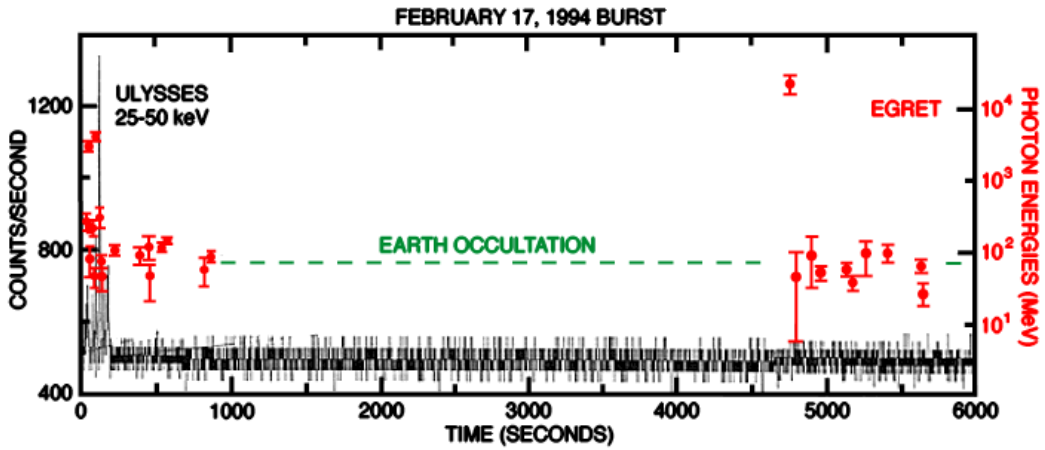




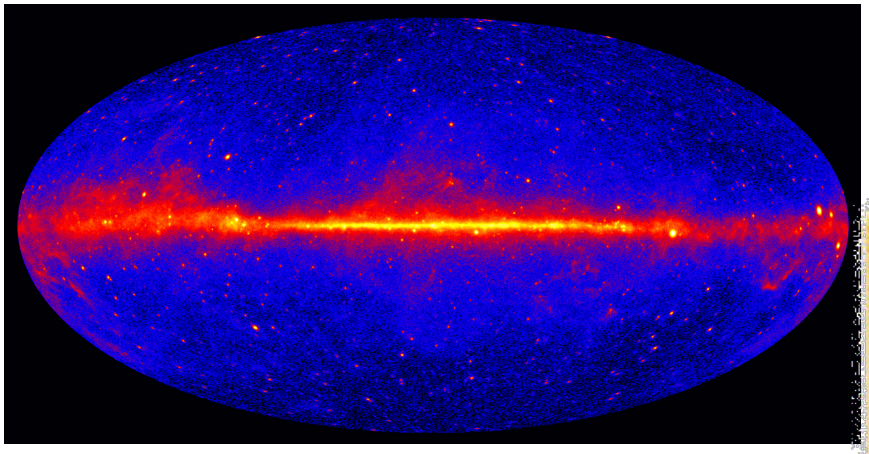


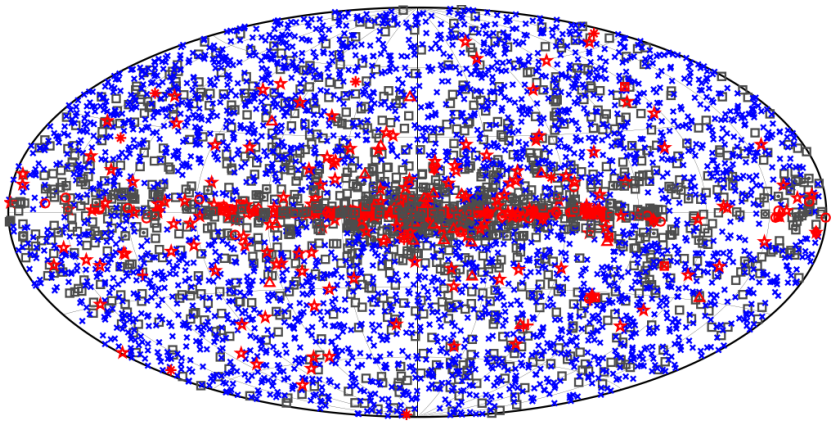
The EGRET era

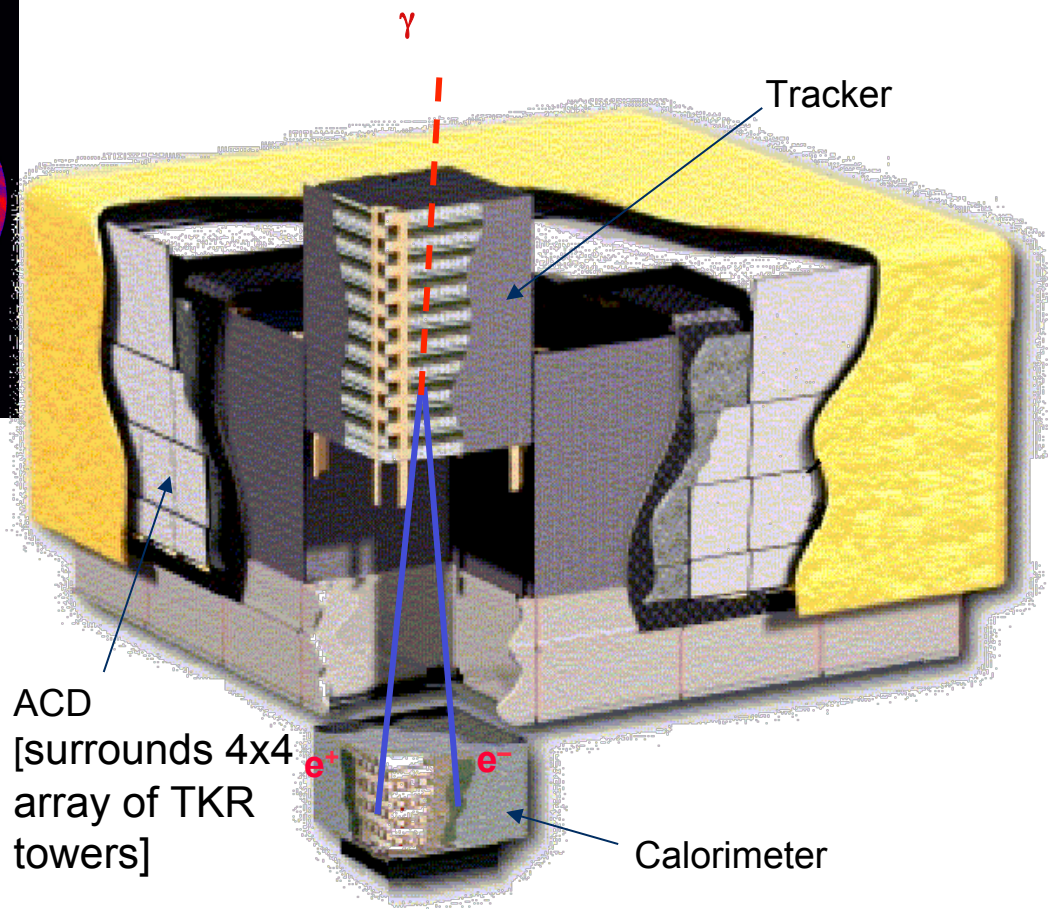




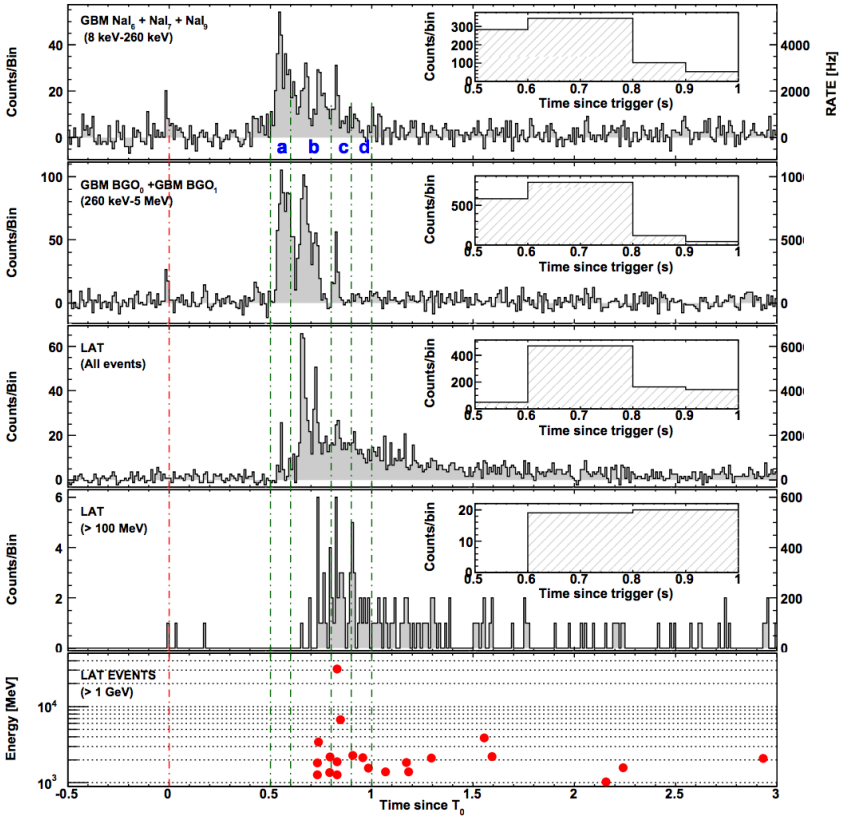
The Fermi/LAT era (2008-...)







The Fermi era



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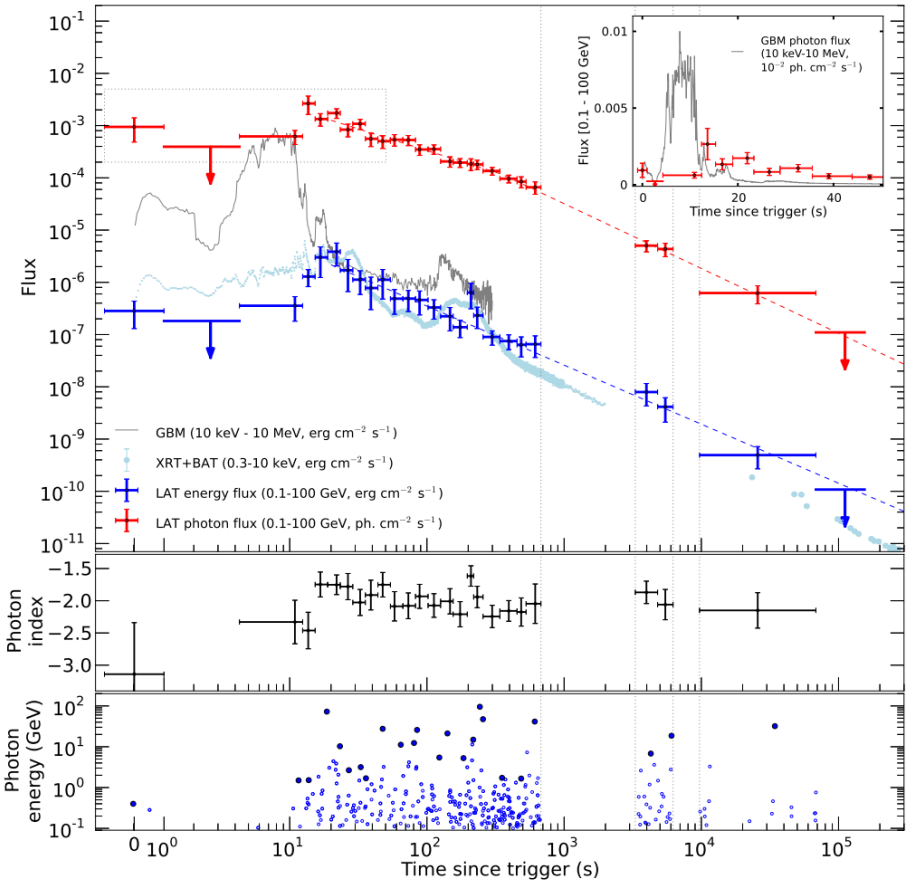


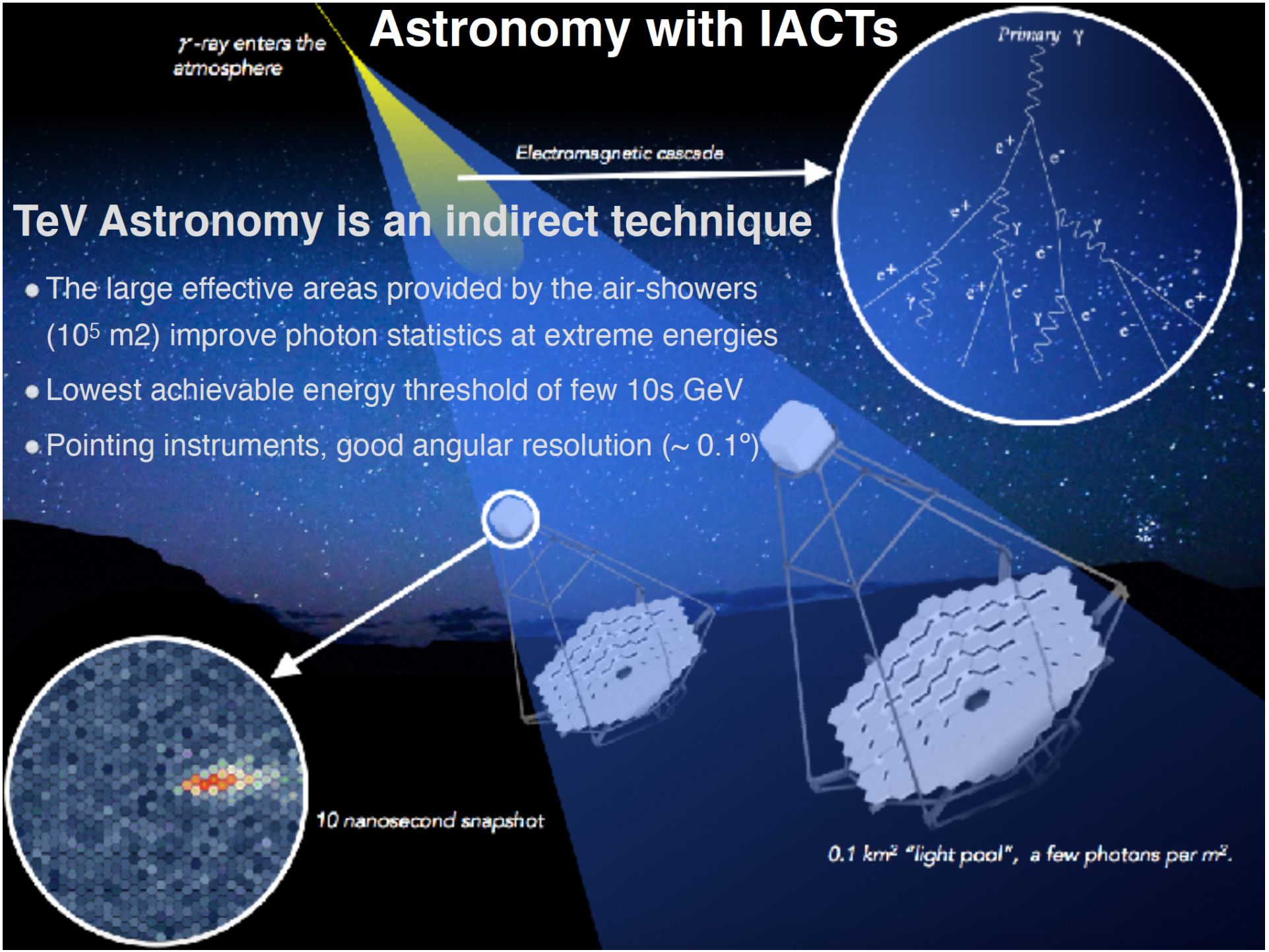
Performance comparison

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 x 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



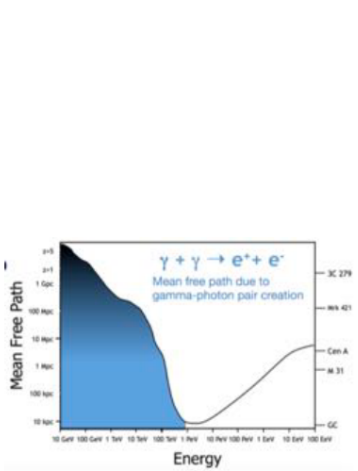
TeV Astronomy is an indirect technique

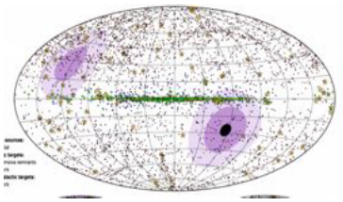
- The large effective areas provided by the air-showers (10^5 m2) improve photon statistics at extreme energies
- Lowest achievable energy threshold of few 10s GeV
- Pointing instruments, good angular resolution (~ 0.1°)

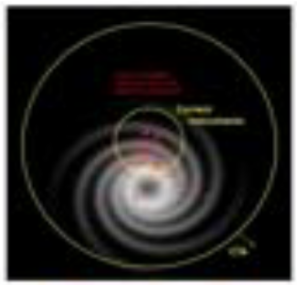
A next generation Cherenkov Observatory

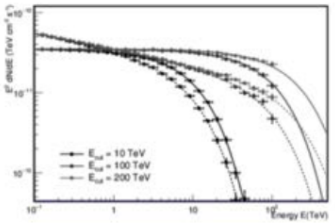
- **Cherenkov Telescope Array :** the next-generation Imaging Atmospheric Gamma-ray Observatory
  - Broadest energy range amongst IACTs: 20 GeV to 300 TeV
  - The first Open Observatory in the field
  - Full-Sky Coverage
    - Northern Site at the Canary Islands, Spain
    - Southern Site at the Chilean Andes, in Cerro Paranal
  - **CTA Observatory**
    - Headquarters in Bologna, Italy and Data Center in Zeuthen, Germany
    - Responsible for building and operating CTA
  - **CTA Consortium**
    - Responsible for the concept and design of CTA
    - Will provide in-kind contributions to the Observatory

Design drivers







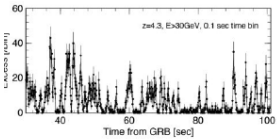


Full sky coverage

10 x sensitivity

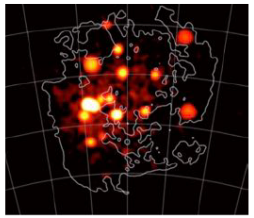
Energies down to 20 GeV

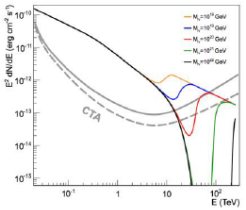
Energies up to 300 TeV



Rapid slewing 20 sec

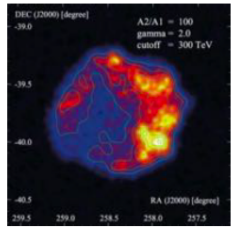
~ 10◦ FoV



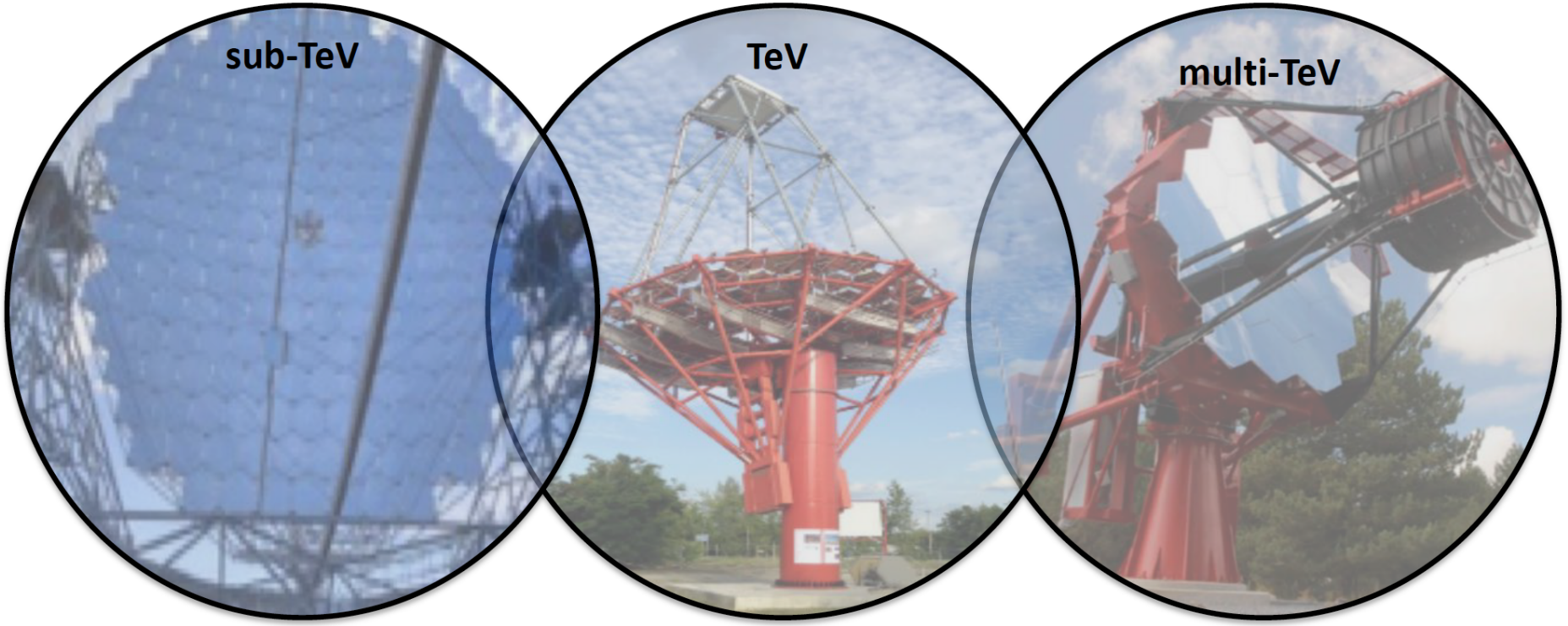


10% energy resolution

arcmin angular resolution



Science cases and design



- Lowest energies (tens of GeV)
  → **cosmological sources**
- Deepest sensitivity for short timescale phenomena
  → **Time domain unexplored**

- deepest sensitivity ever
- arcmin angular resolution
- large FoV

- Surveys & precision studies

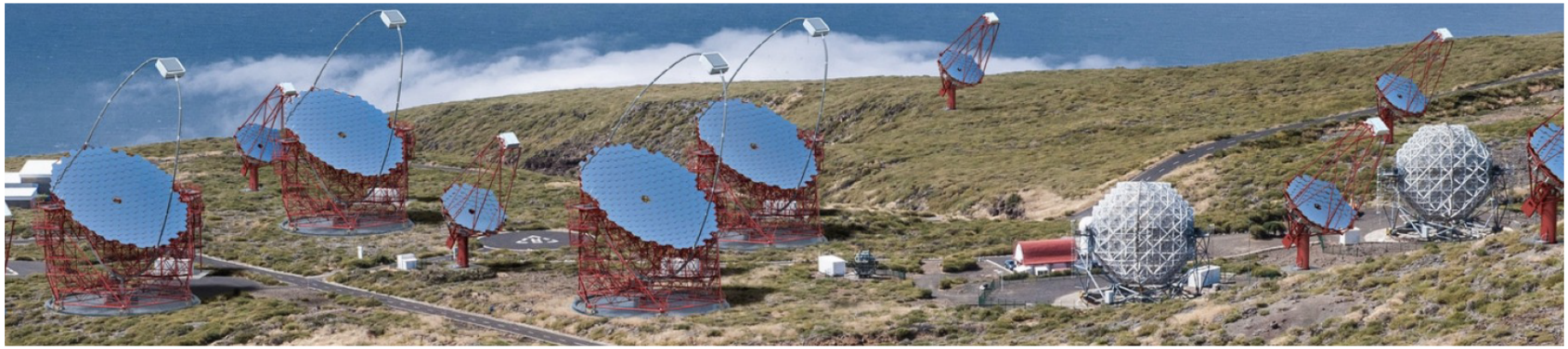
- Precision measurements in a still little explored energy range

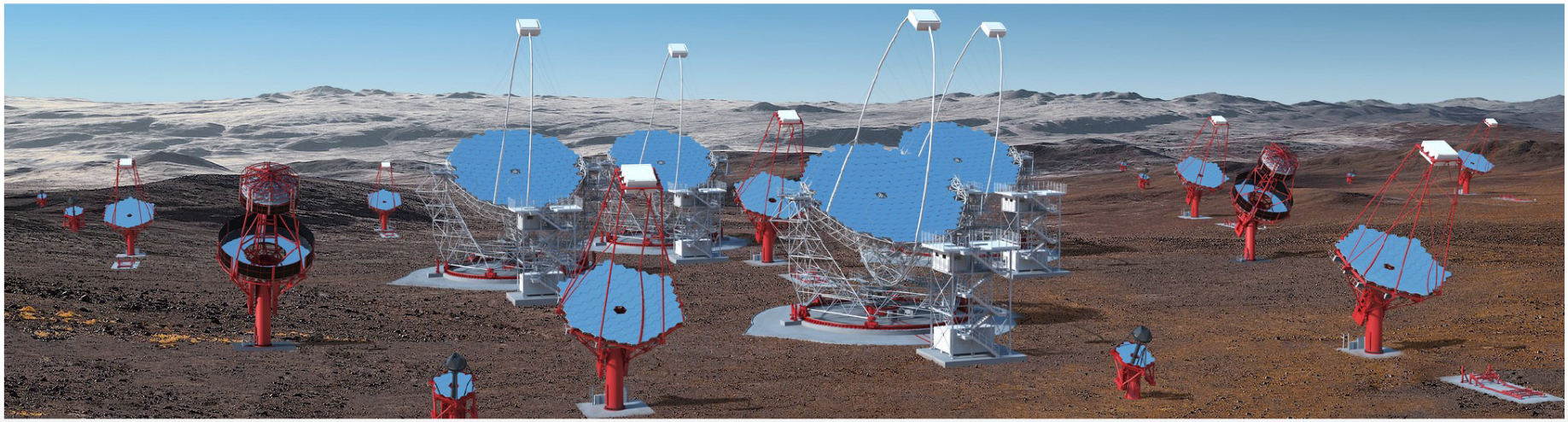
- **100 TeV range unexplored**
- **precision studies**

R.Zanin – TeVPa 2019

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



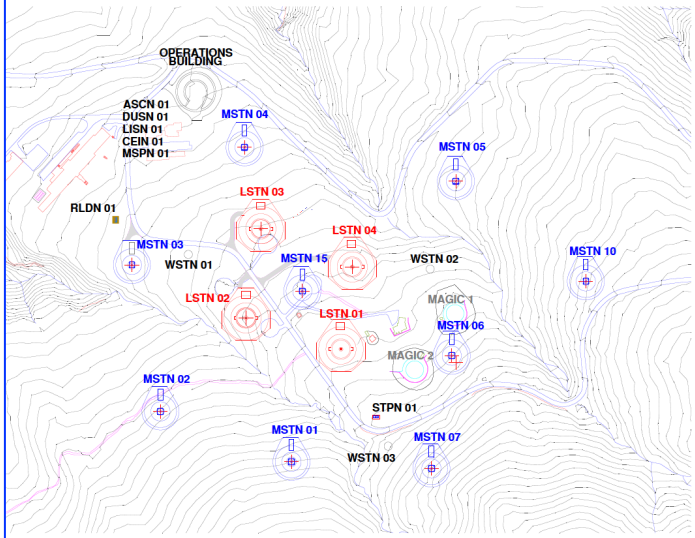


CTA Alpha Layout

The two initial CTAO arrays: the Alpha Configuration

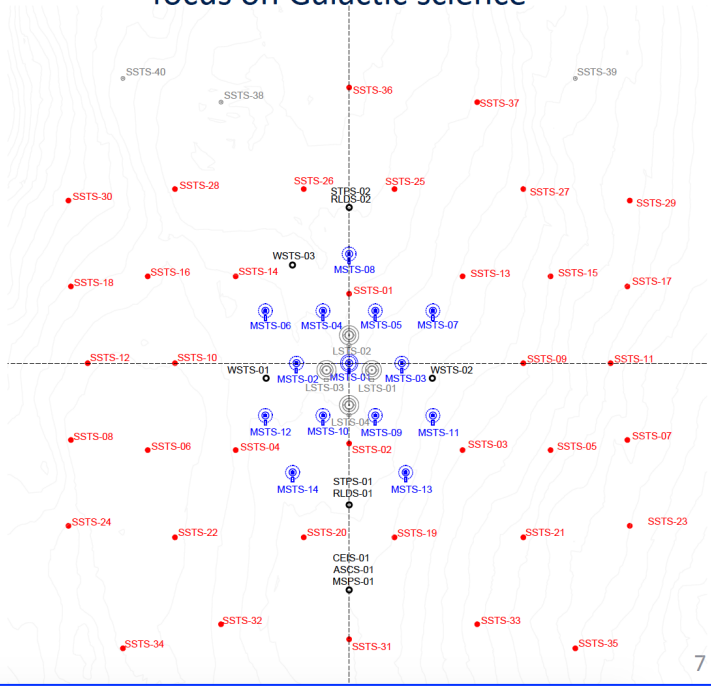
CTAO Northern Array

- **4 LSTs + 9 MSTs**
- 0,25 km^2 footprint
- focus on extra-Galactic science



CTAO Southern Array

- **14 MSTs + 37 SSTs**
- 3 km^2 footprint
- focus on Galactic science



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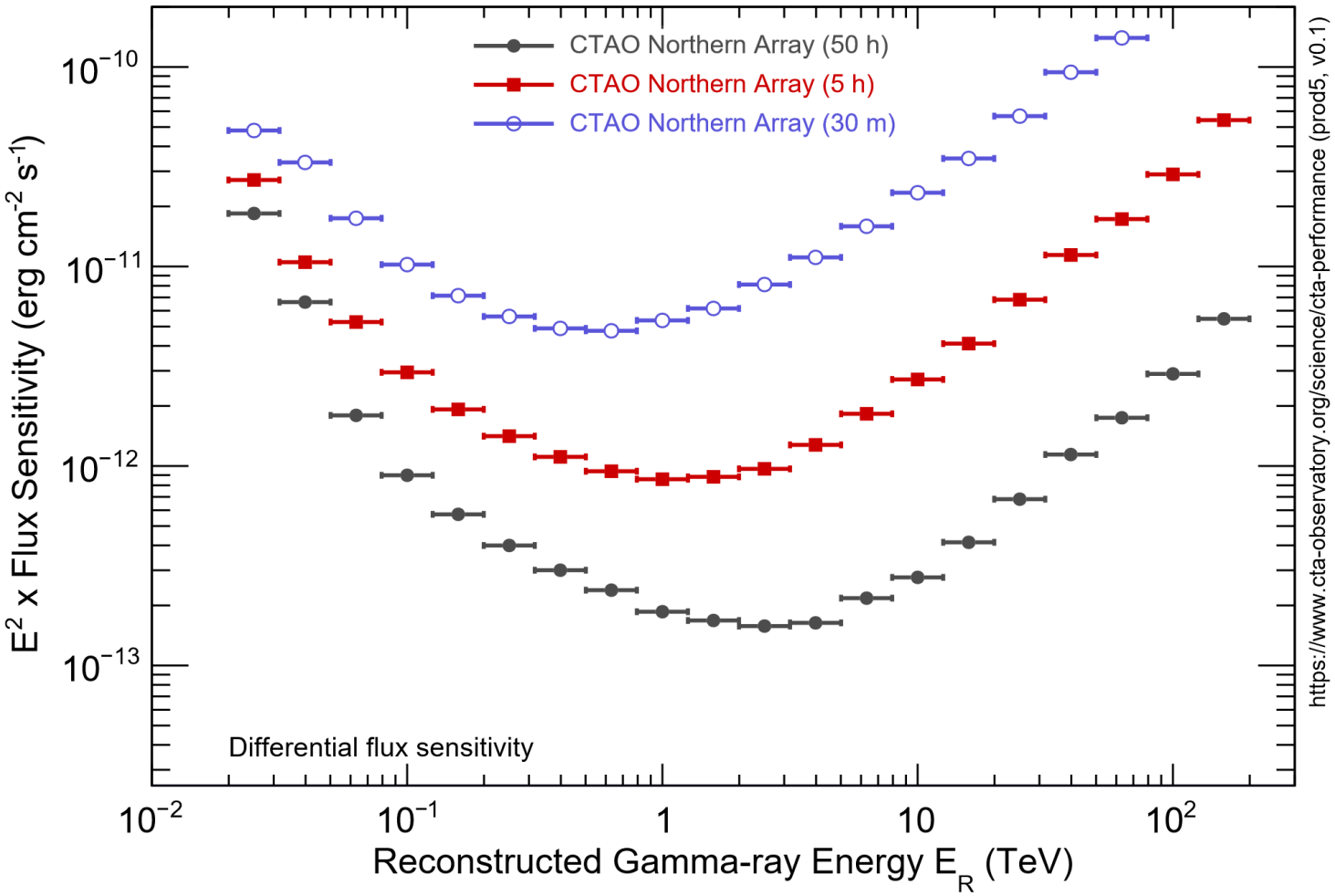
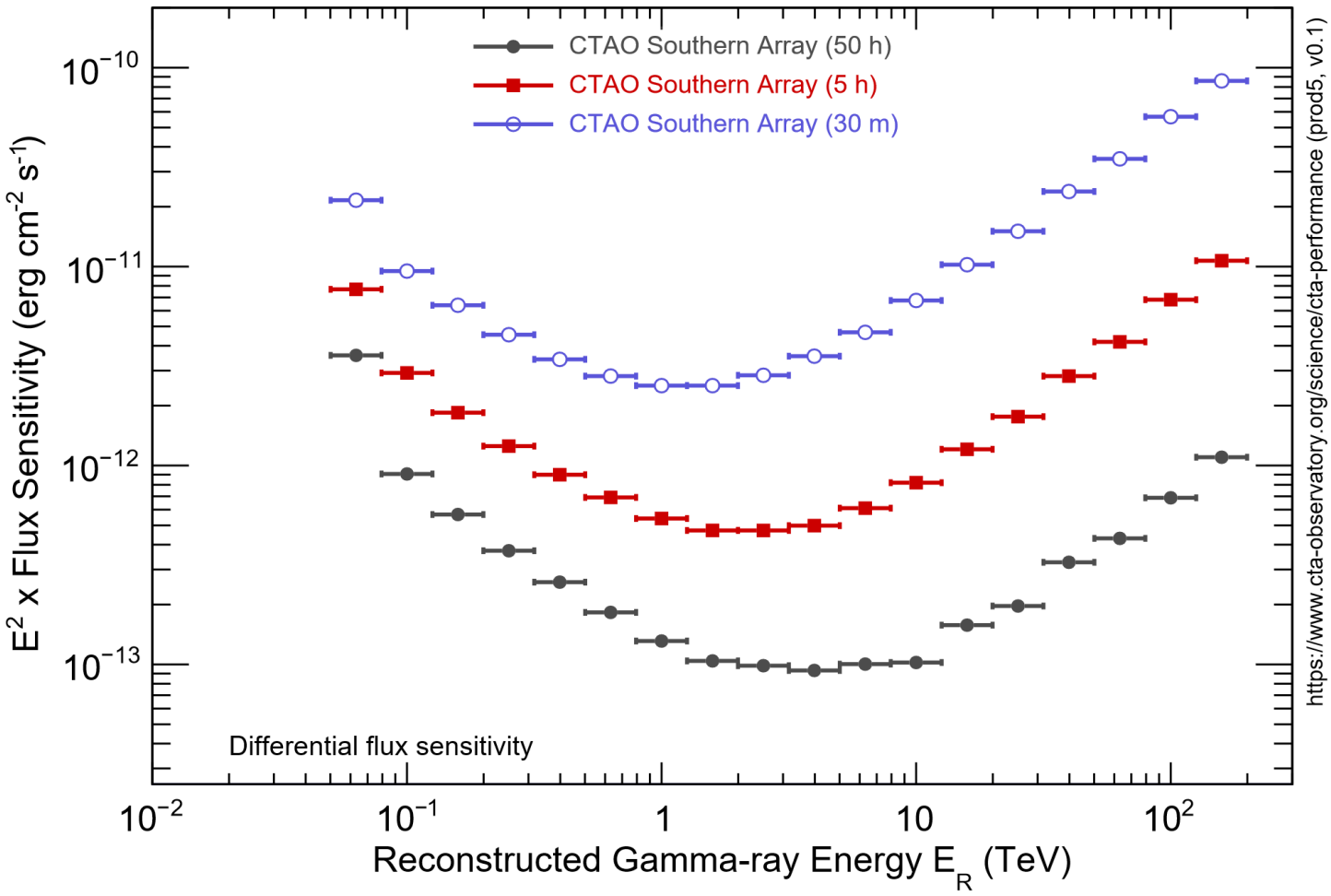
CTA - North



https://www.cta-observatory.org/science/cta-performance/

CTA – South



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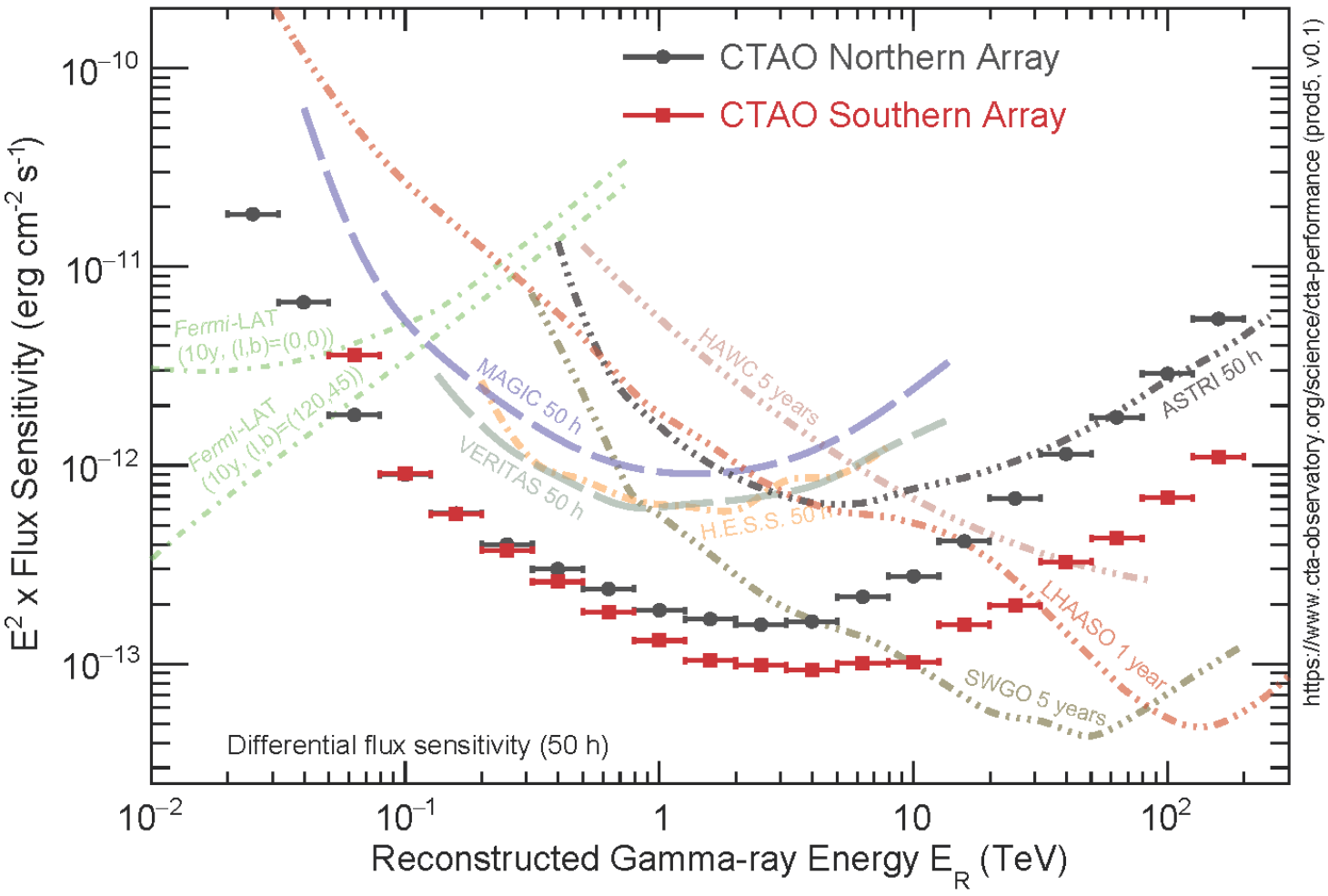
CTA performance



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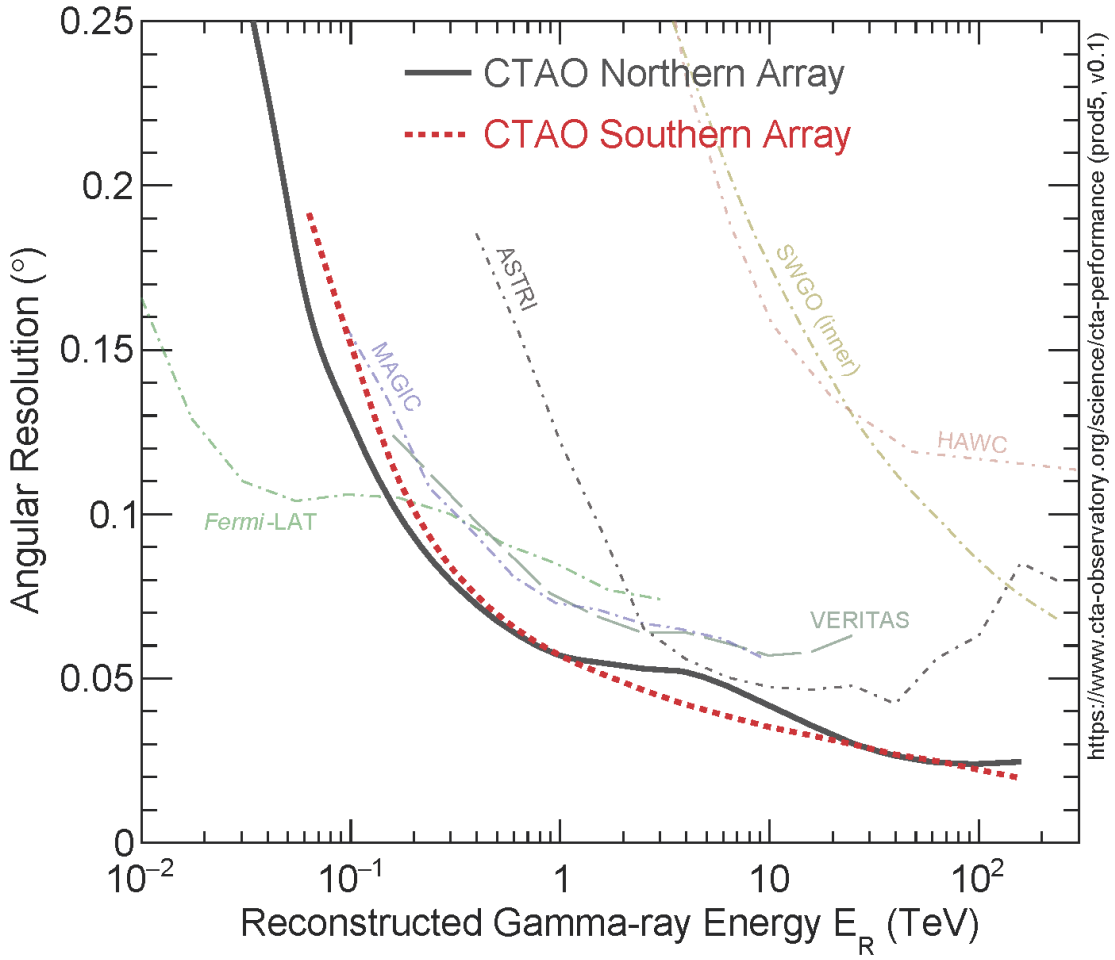
CTA performance



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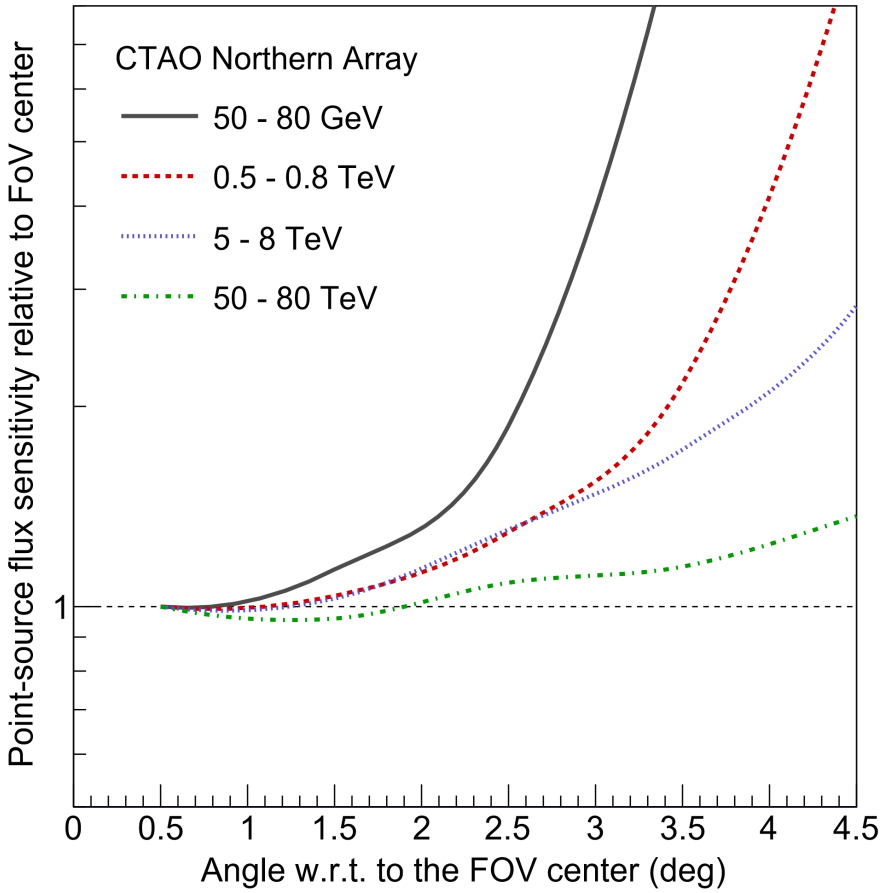
CTA performance



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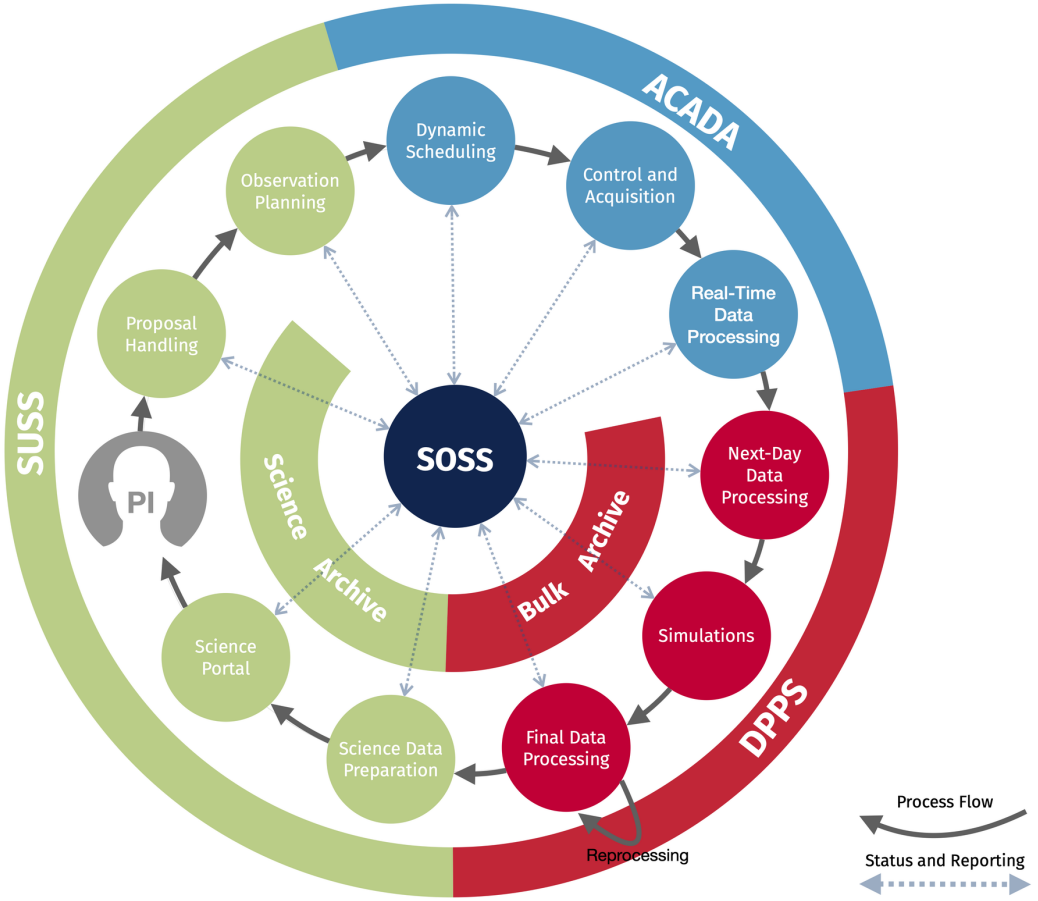
CTAO computing



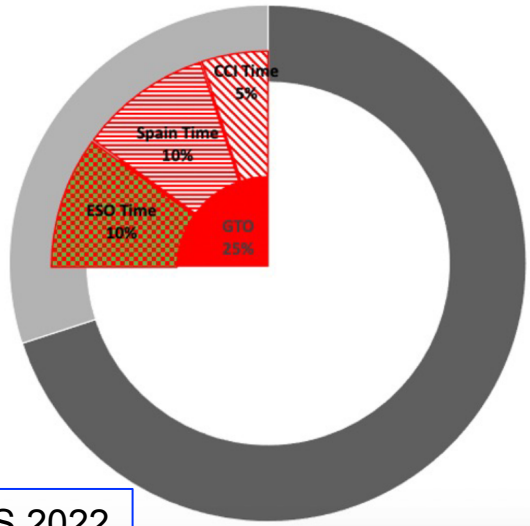
https://www.cta-observatory.org/project/technology/computing/

CTAO time allocation

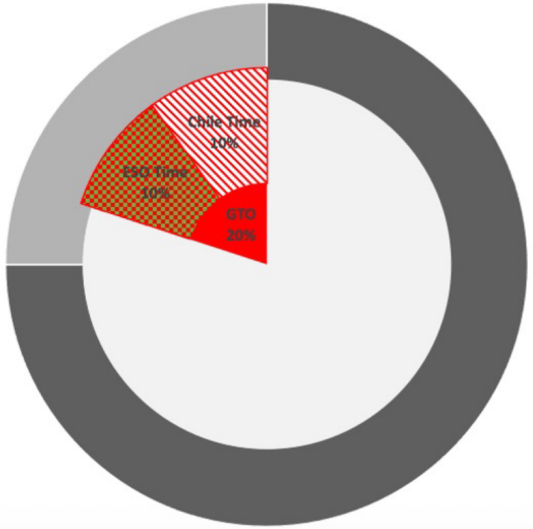
CTAO is an ESO programme

- 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



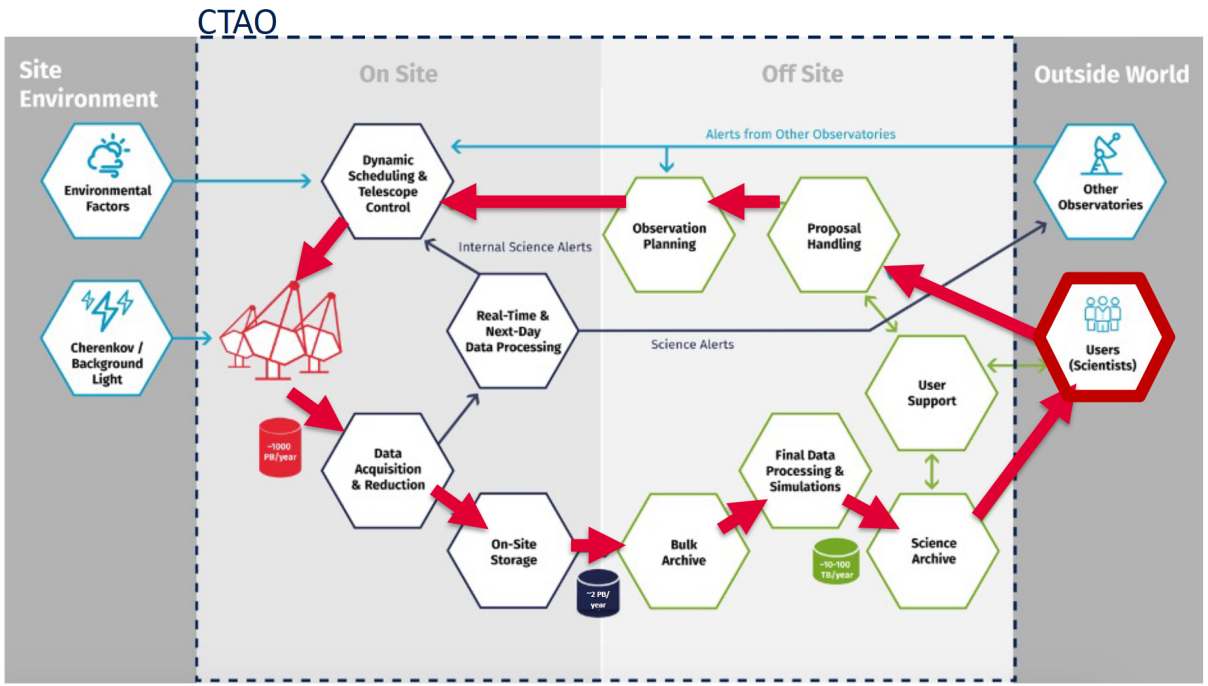
CTAO Southern Array



R. Zanin – EAS 2022

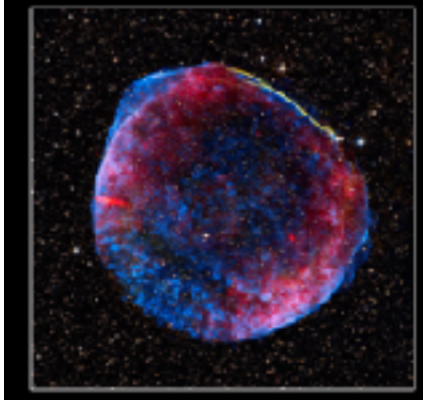
CTA as an observatory

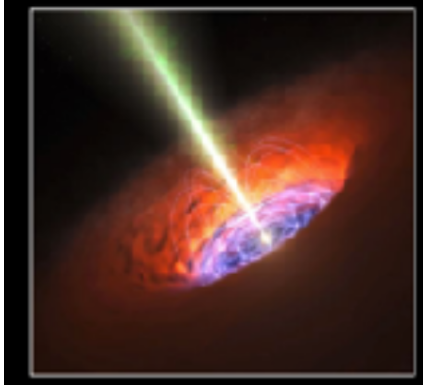
CTA Observatory

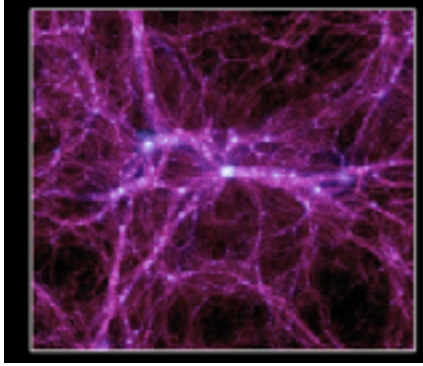


- **Proposal driven observatory**: standard proposals & long and large proposals (including Key Science Projects)
- **Proposals evaluated on scientific merits** by a Time Allocation Committee

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

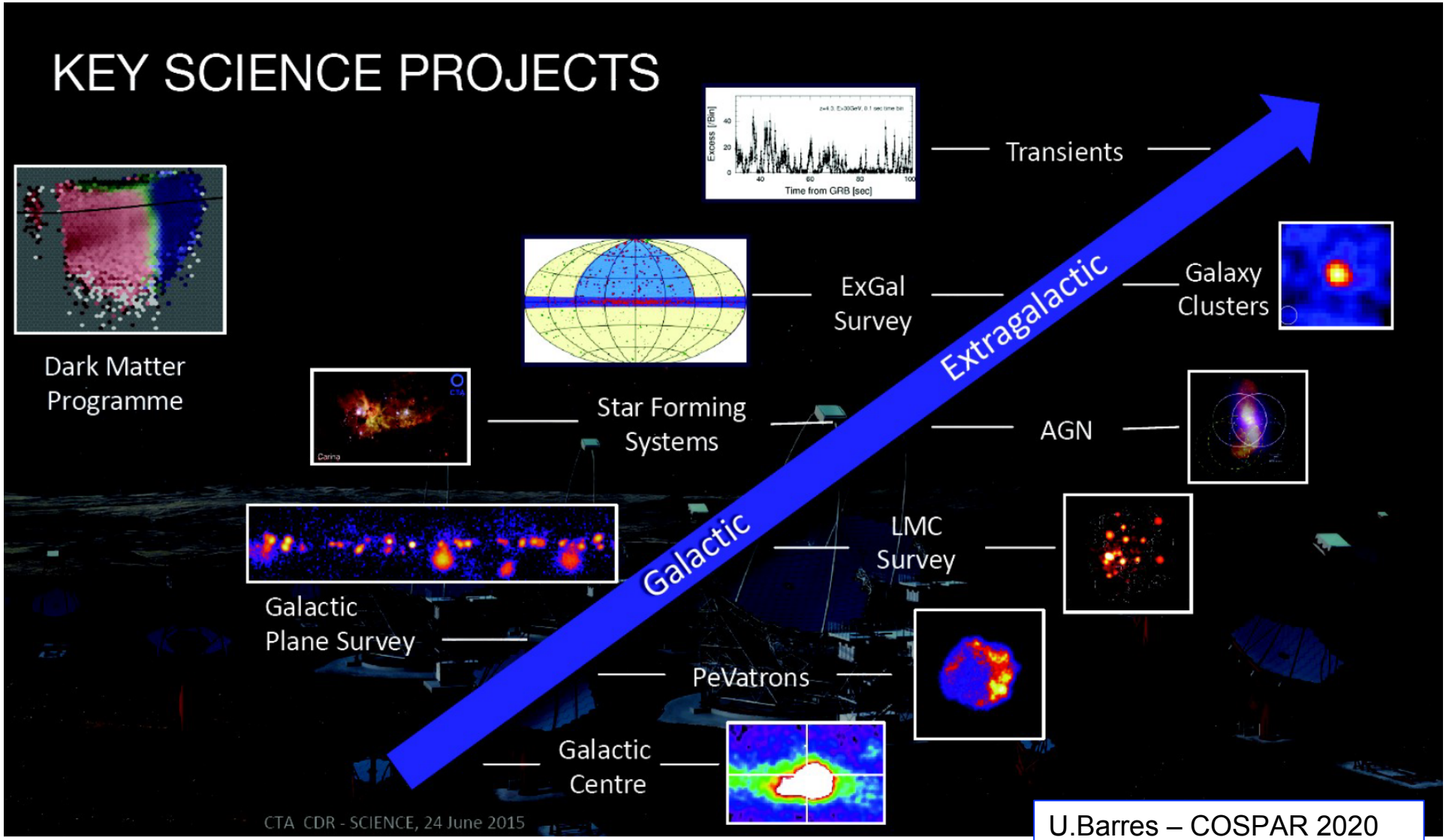
Deep Targeted Observations

- 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



U.Barres – COSPAR 2020

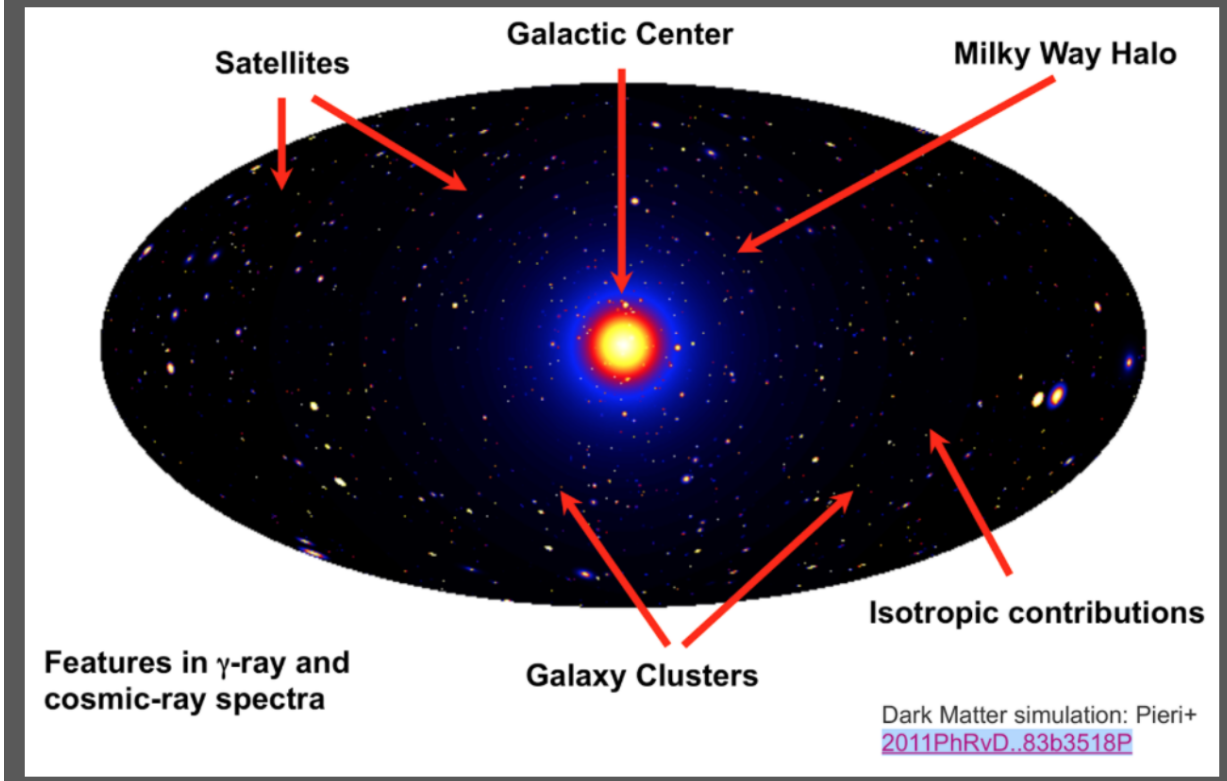
Science with CTA

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.

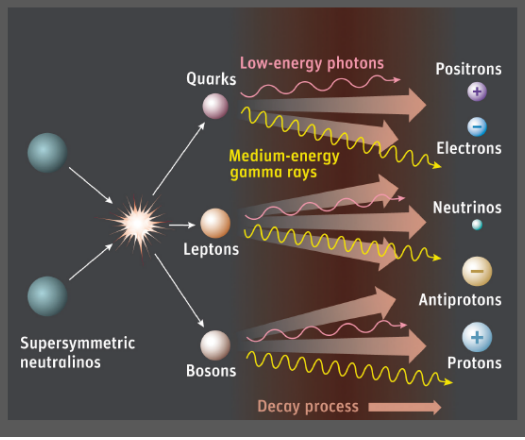
https://arxiv.org/abs/1709.07997

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



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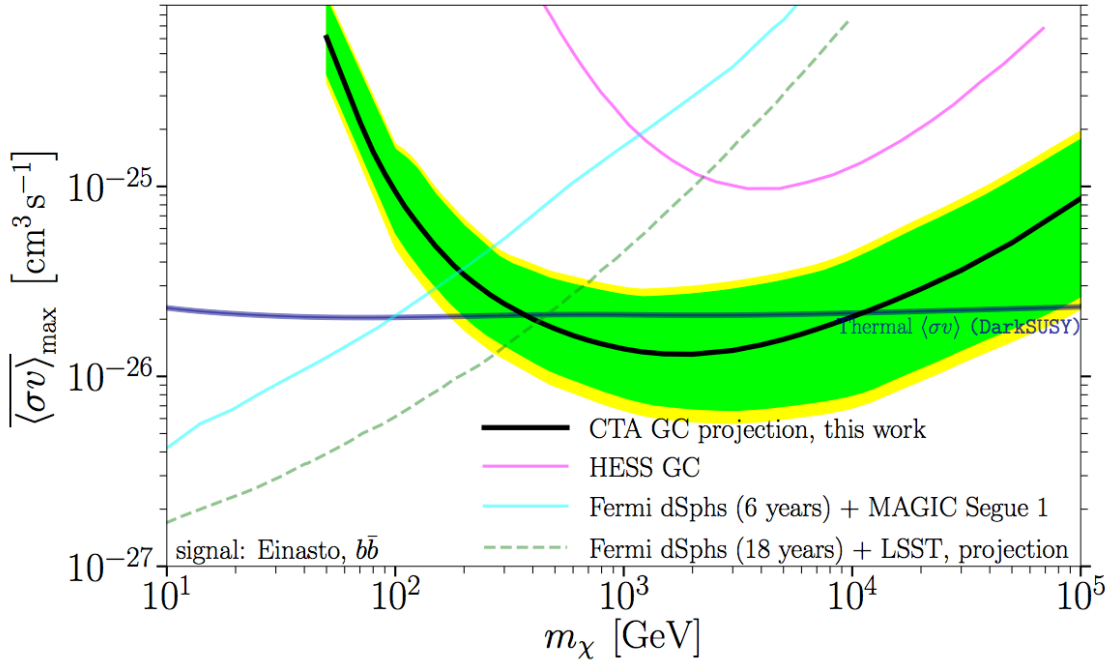
The Dark Matter Programme

- 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

Comparison with other experiments



U.Barres – COSPAR 2020

arXiv:2007.16129

Dark Matter with CTA

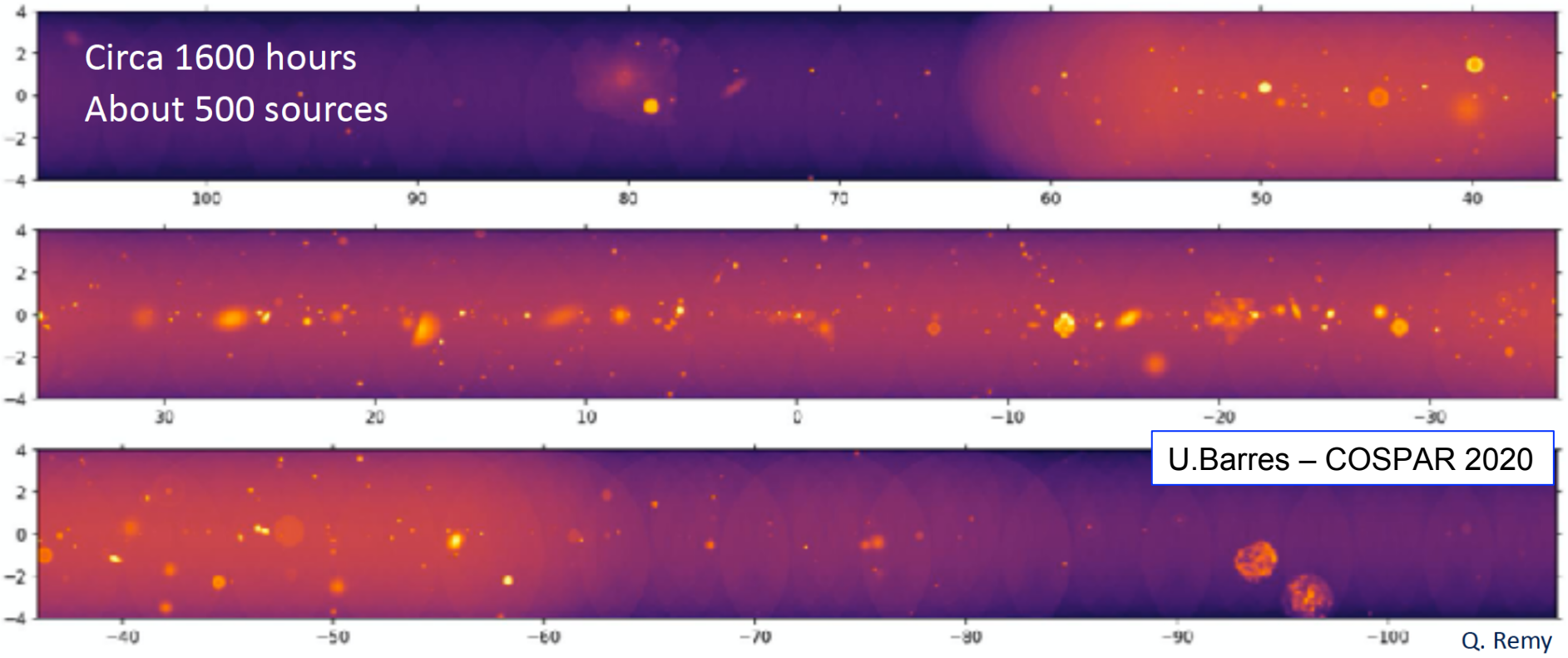
Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre

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

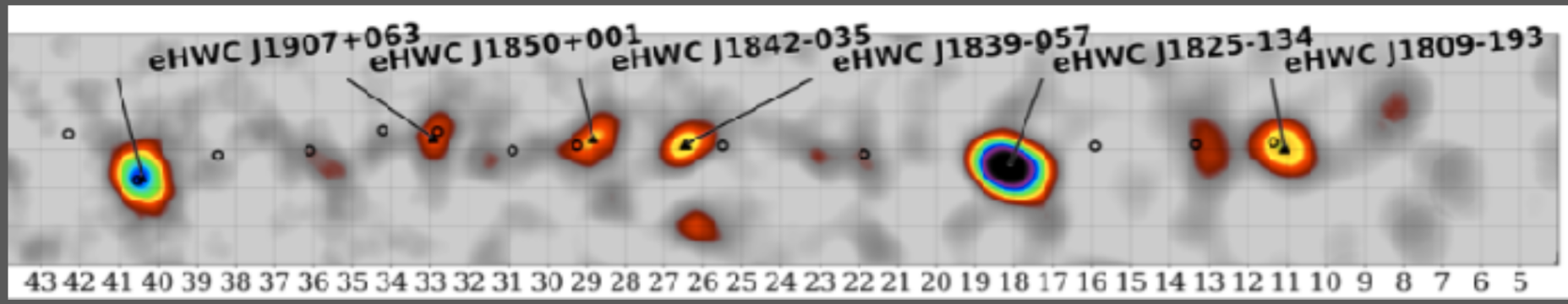
CTA Galactic Science

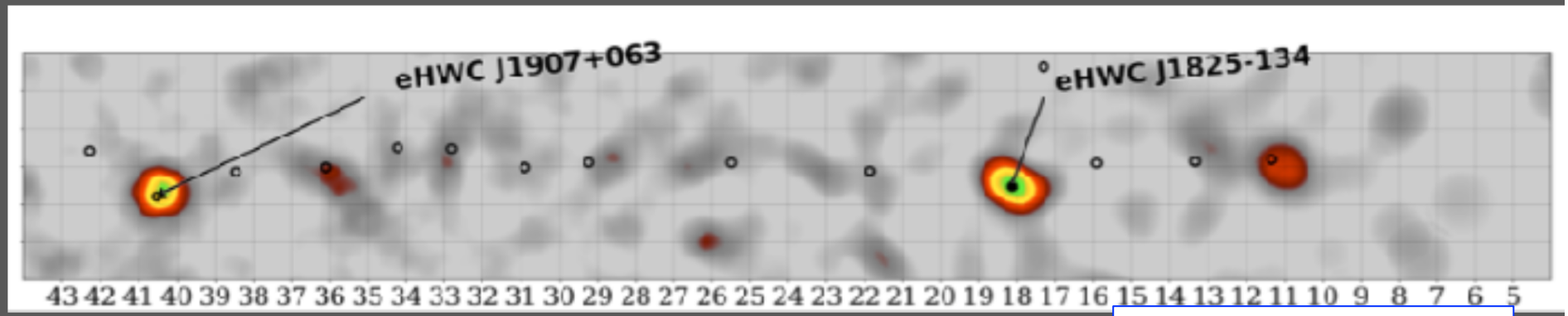
- Survey speed about 300x greater than H.E.S.S.
- Much deeper reach, to scan the entire galaxy for PWNe and SNRs, as opposed to the few-kpc reach of current instruments.



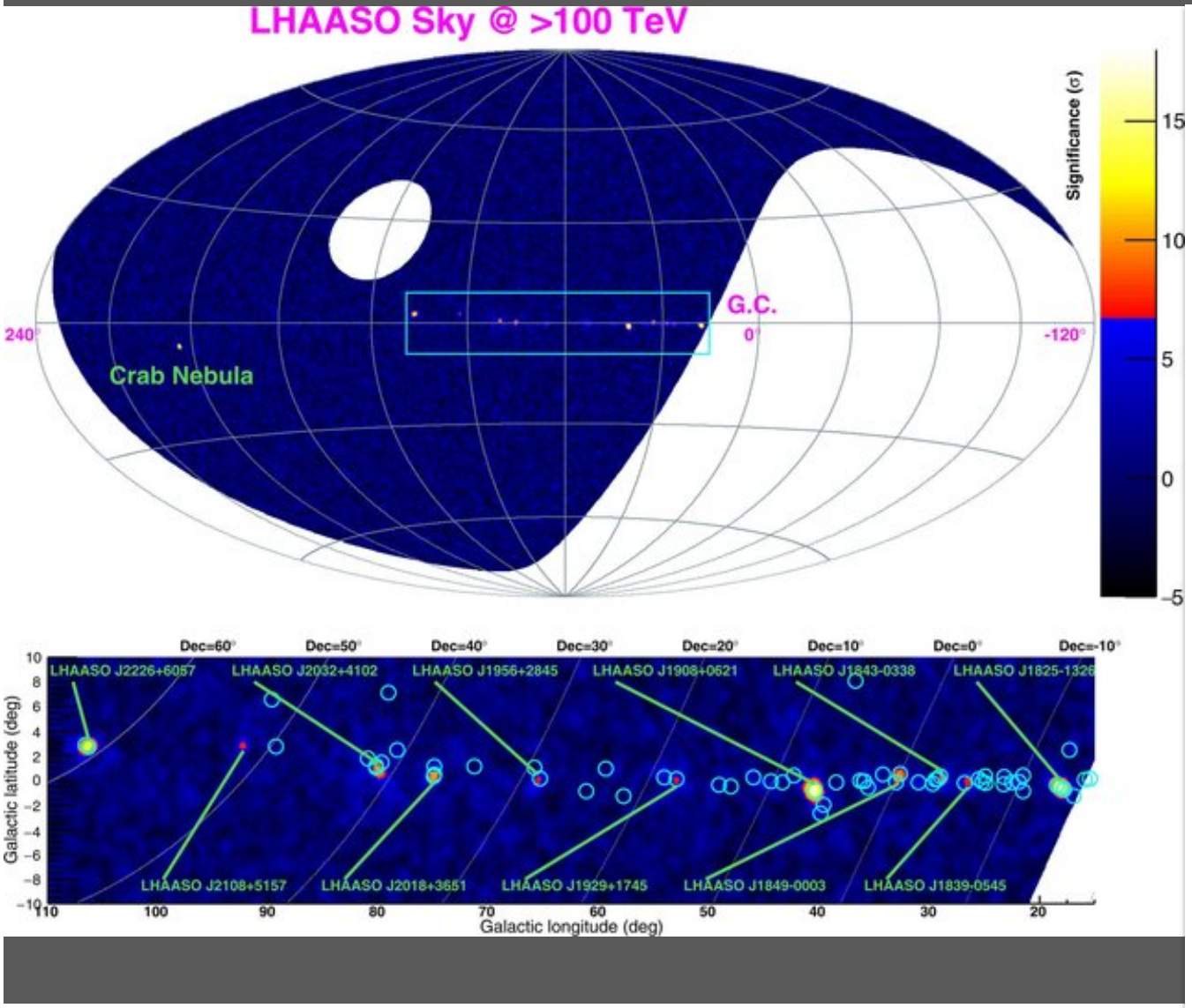
PeVatrons: the extreme energy frontier

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



Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

LHAASO (Nature 2021)

CTA's Prospects for AGN

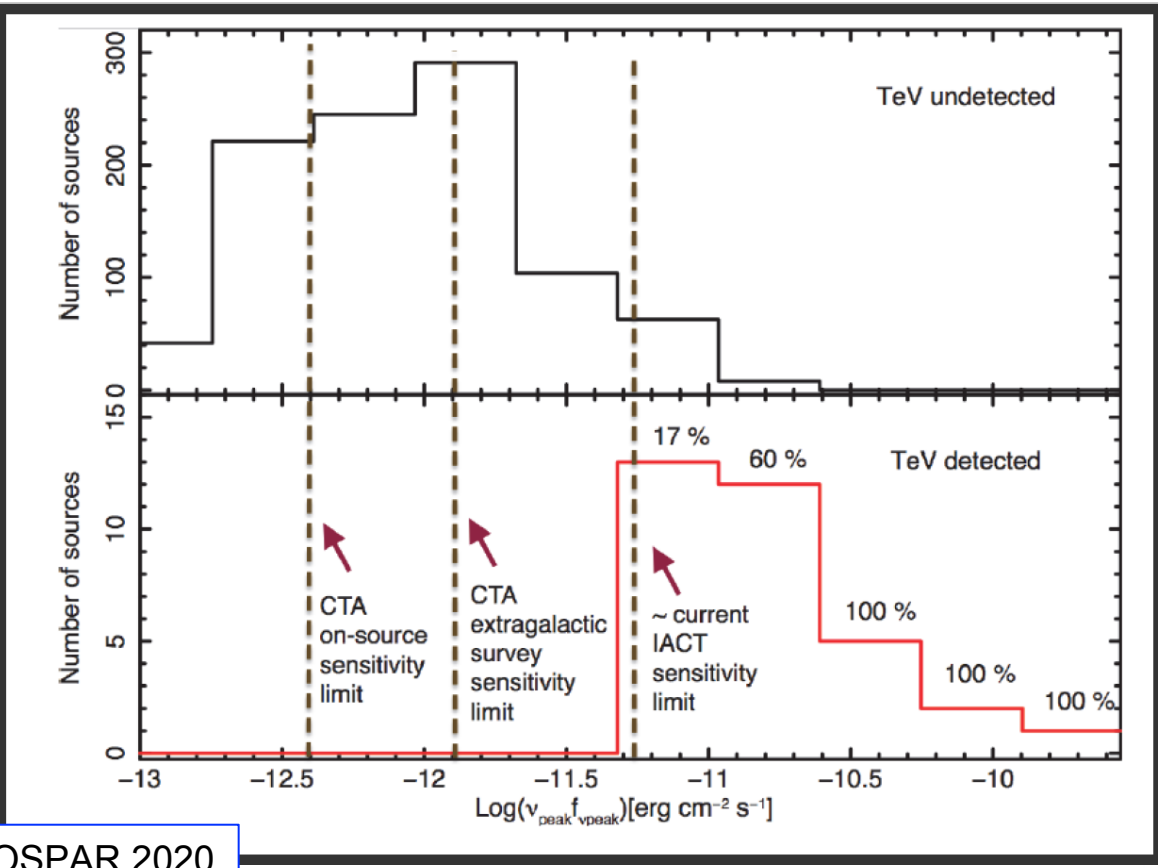
CTA will detect many 100s of AGN to z~2

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)



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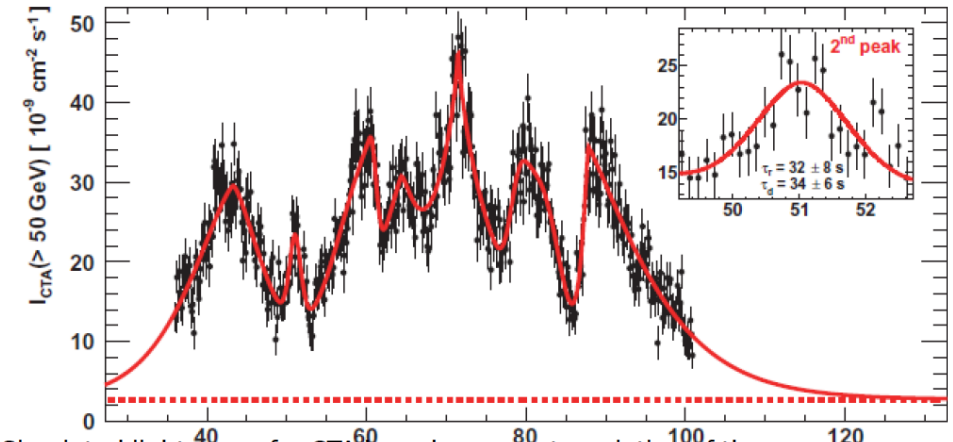
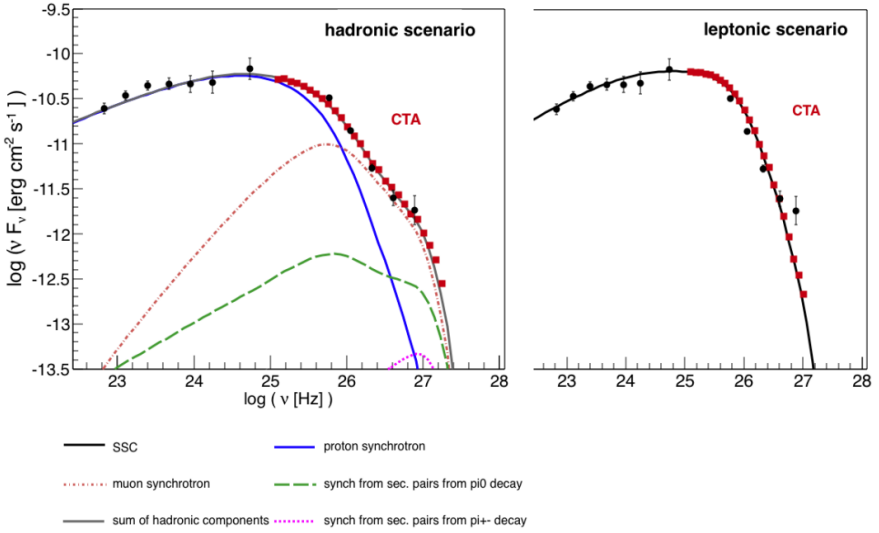


Simulated light curve for CTA based on an extrapolation of the spectrum of the 2006 flare from PKS 2155-304



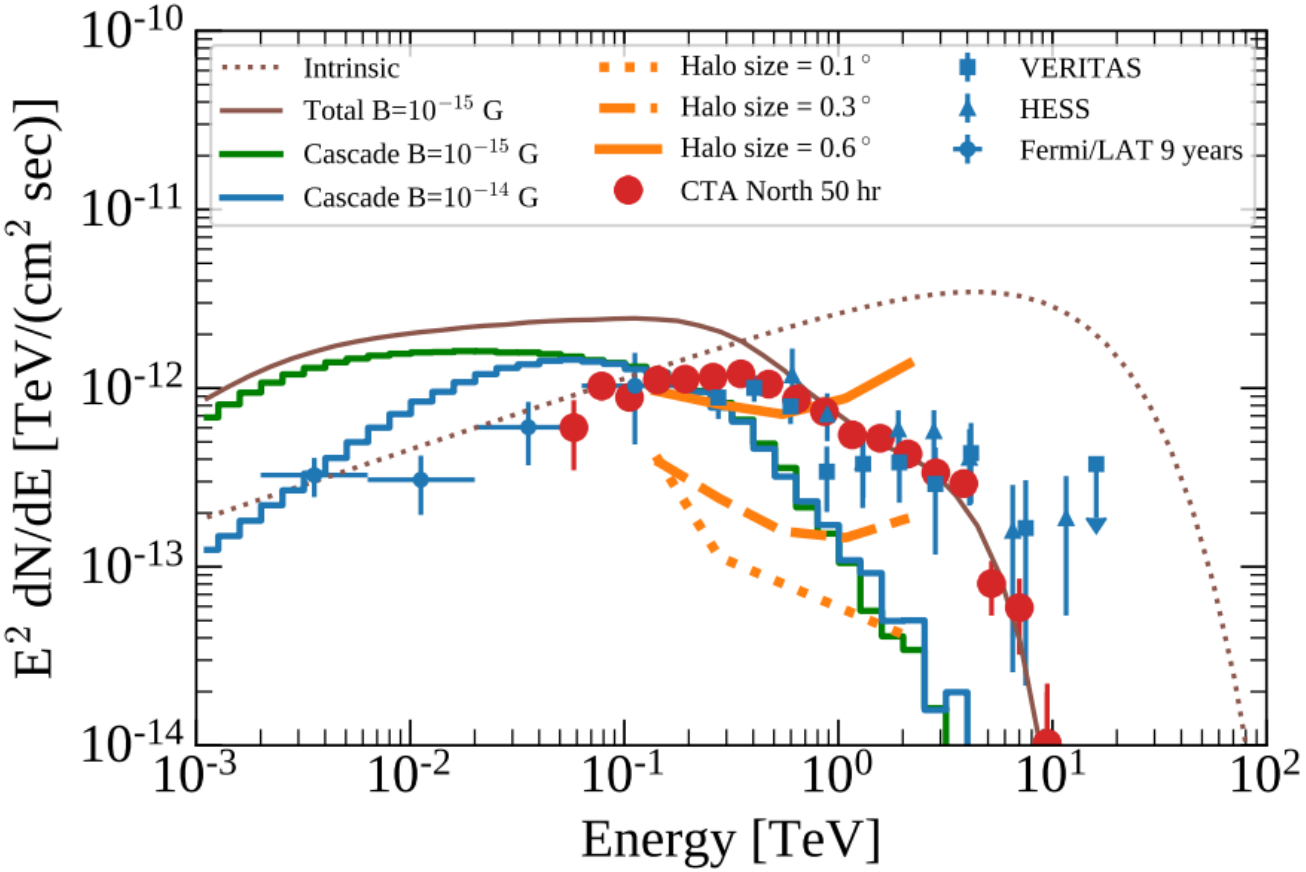
Cosmology and Fundamental Physics

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.

https://arxiv.org/abs/2010.01349

Cosmology and Fundamental Physics



https://arxiv.org/abs/2010.01349

The new window of VHE Gamma-ray Bursts

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

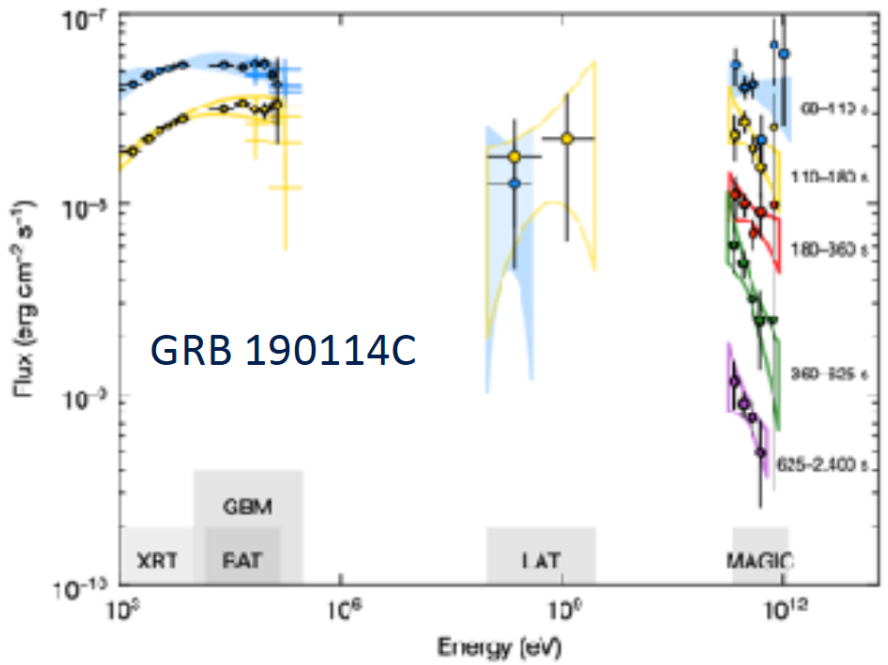
ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration*** *on **15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

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-BAT 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

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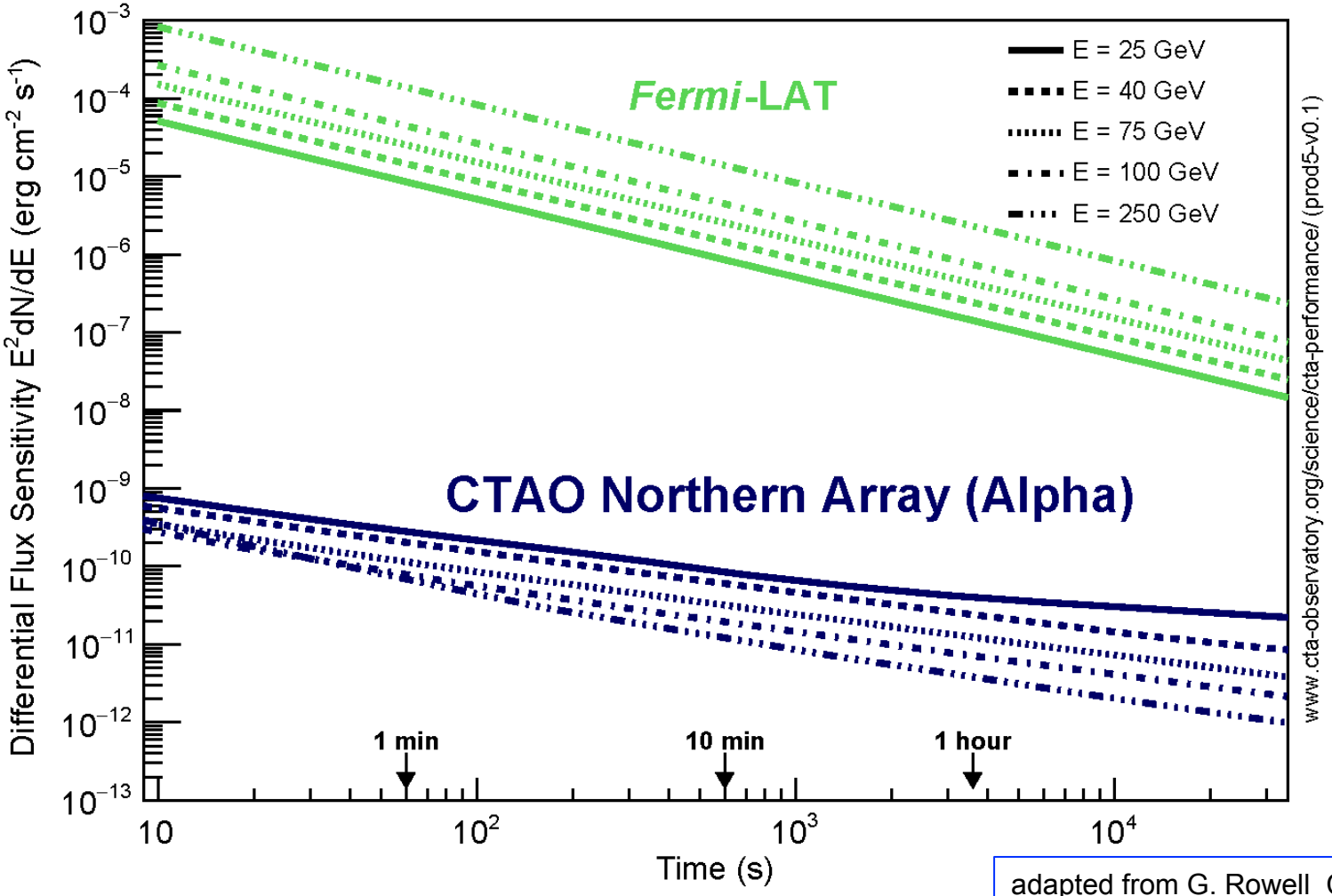
Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)



adapted from G. Rowell COSPAR2020

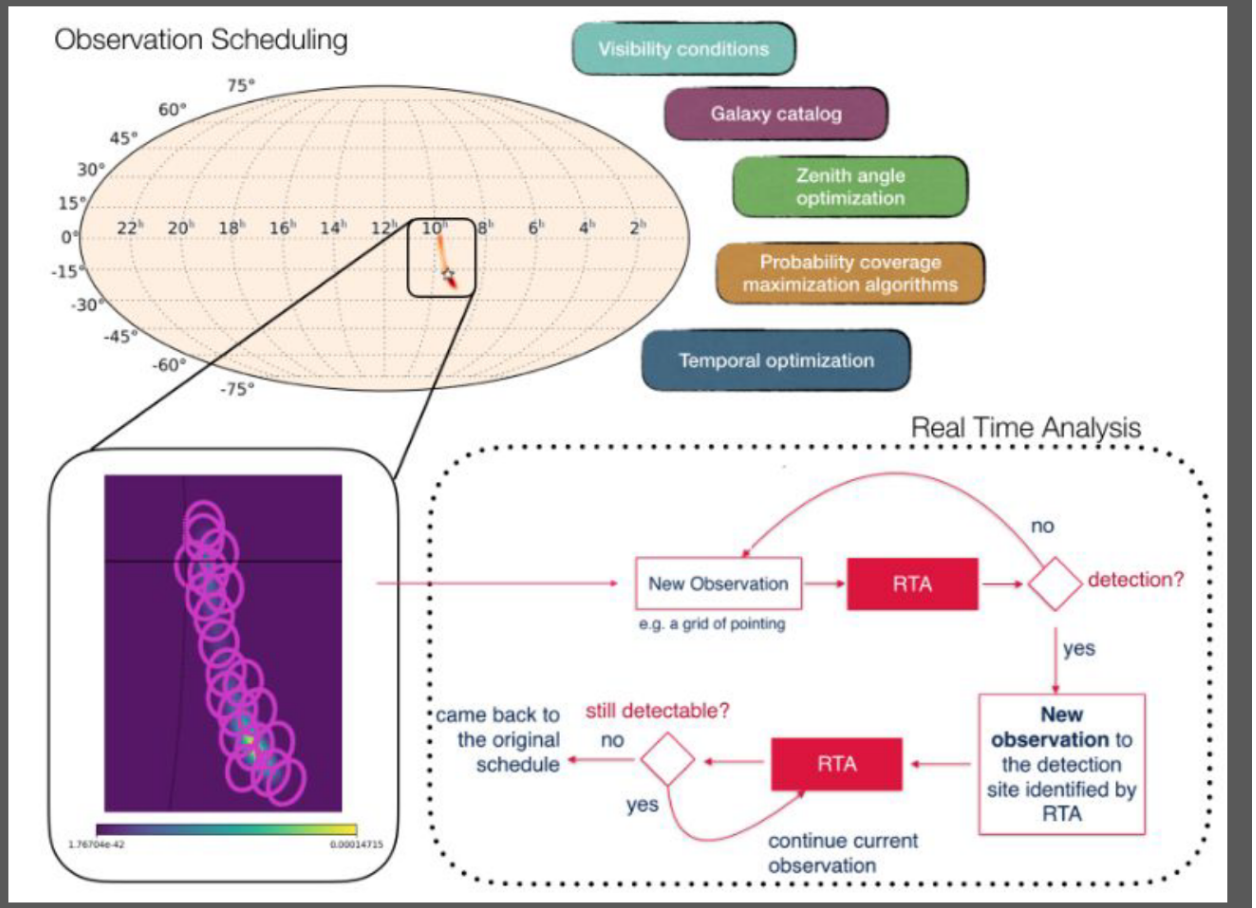
CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range

→ 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



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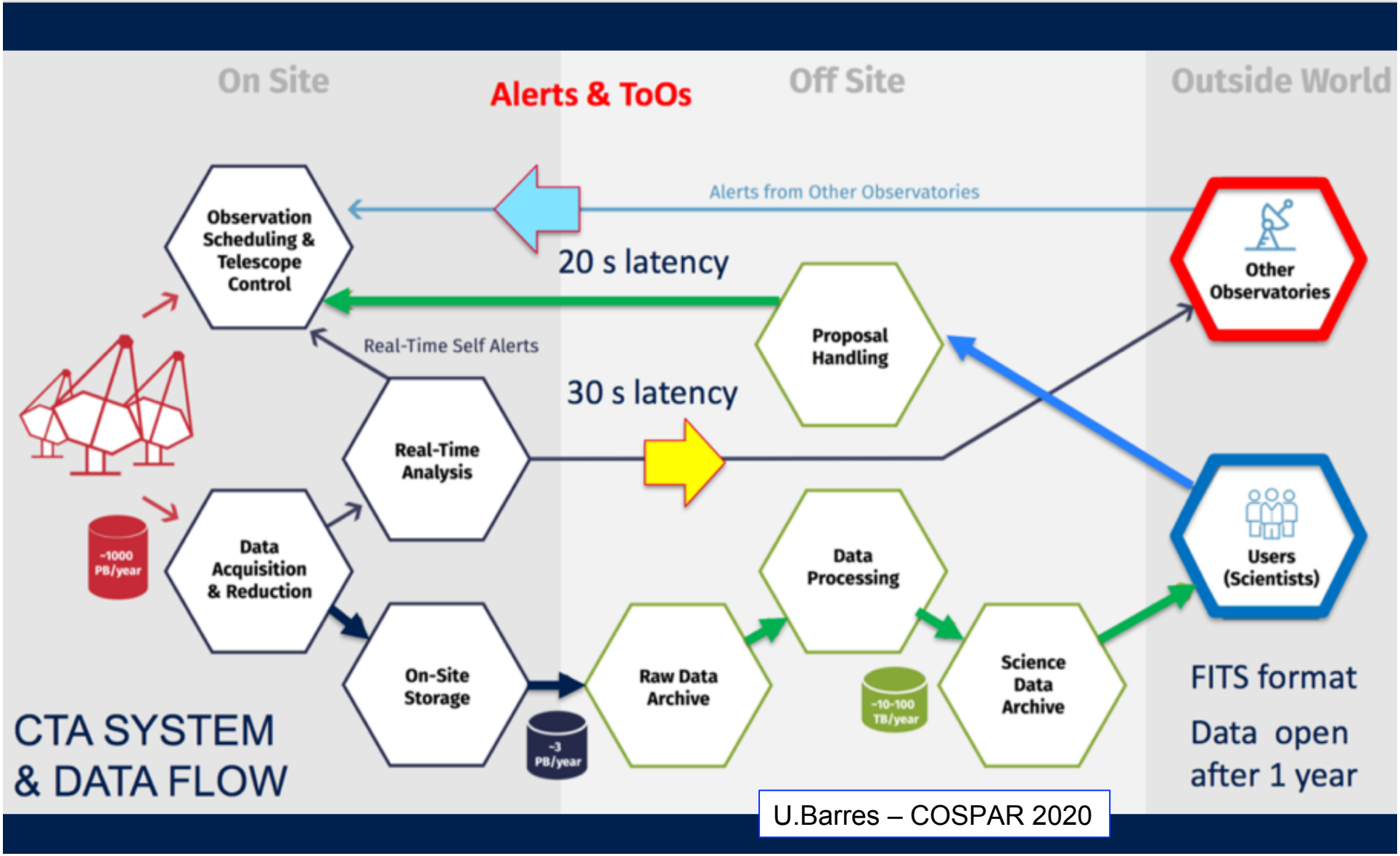
CTA Transients Science



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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 commuity 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

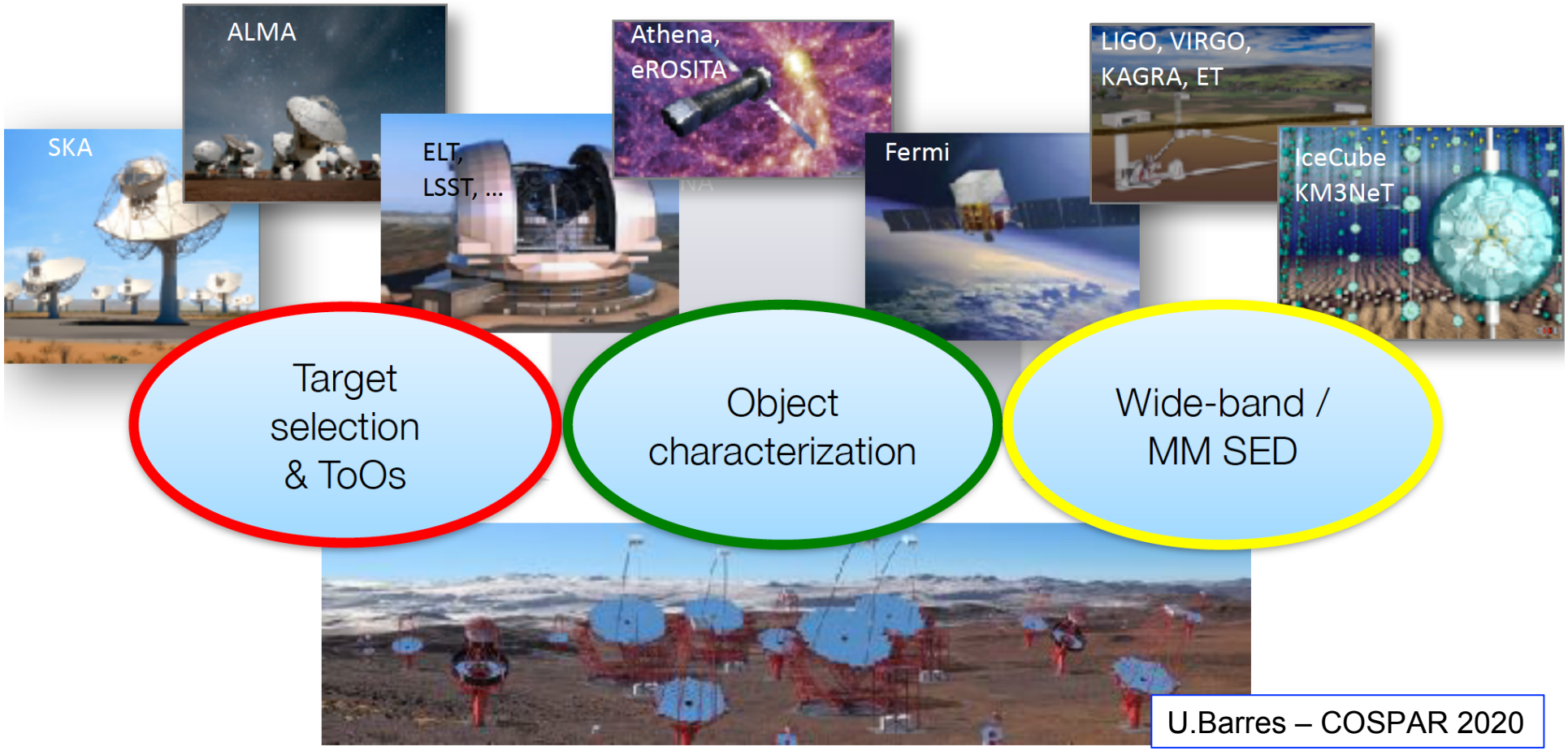
CTAO SDCs: phases

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

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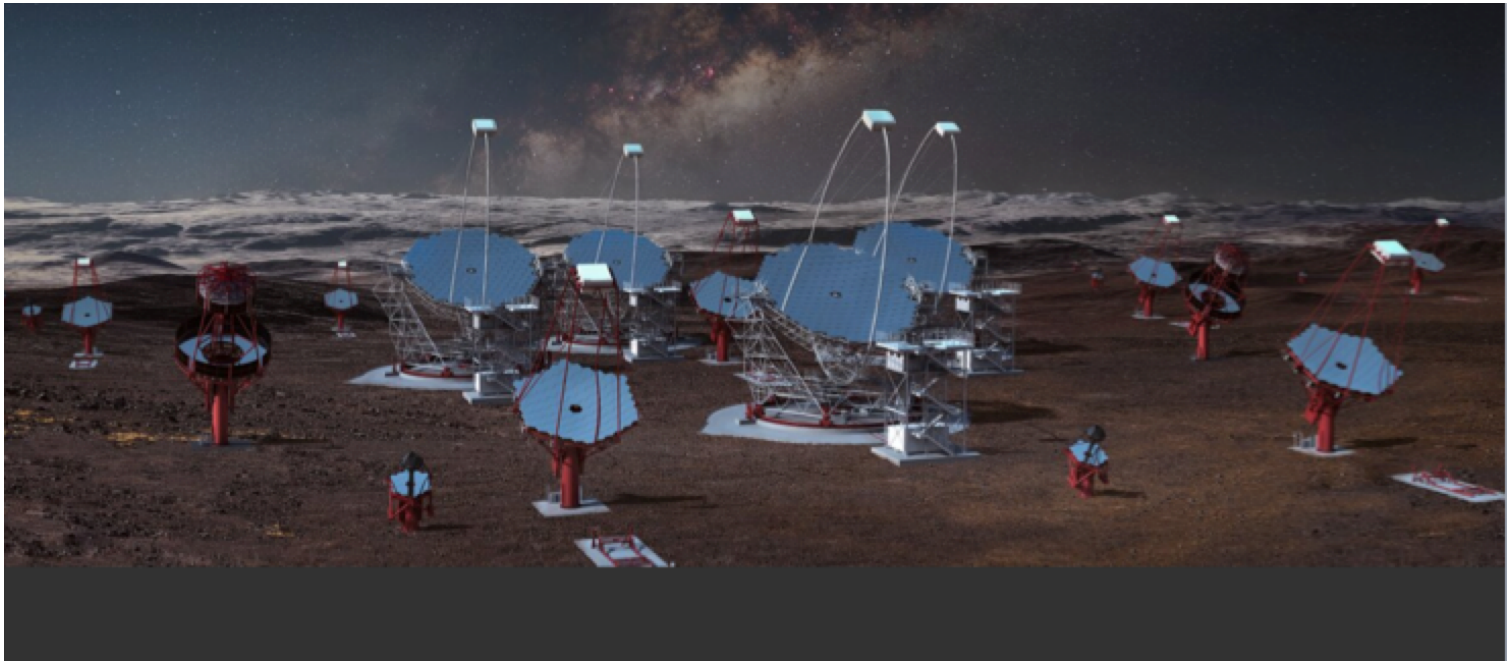
✓ = important ✓ = critical

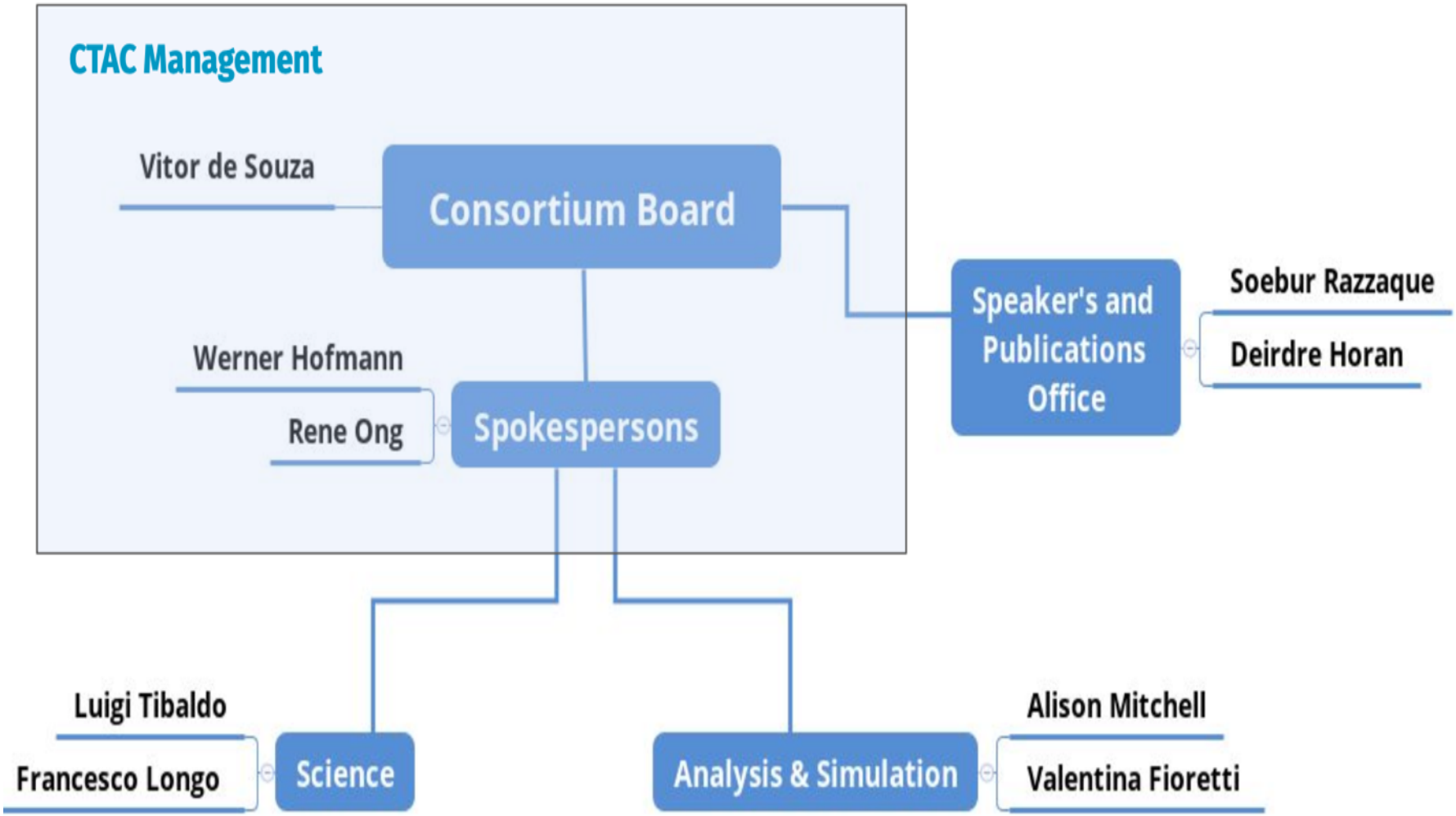
Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	✓	✓	✓	✓	✓	✓	✓	✓		✓
(Sub)Millimetre	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



CTAC Organisation



Science Working Group