CTAO
Cherenkov Telescope Array Observatory

An overview of CTAO Science

Francesco Longo

Francesco Longo, University of Trieste and INFN, Trieste
francesco.longo@ts.infn.it
francesco.longo@cta-observatory.org

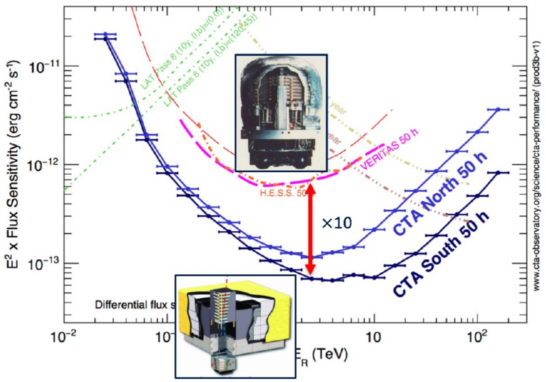
CTAO

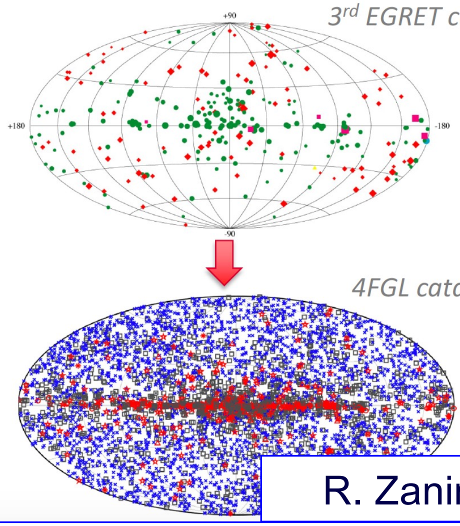
1. Lesson Learned from Fermi
2. Introduction to VHE Astrophysics
3. What is CTAO?
4. Main Scientific objectives
5. What’s next?

Take home 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





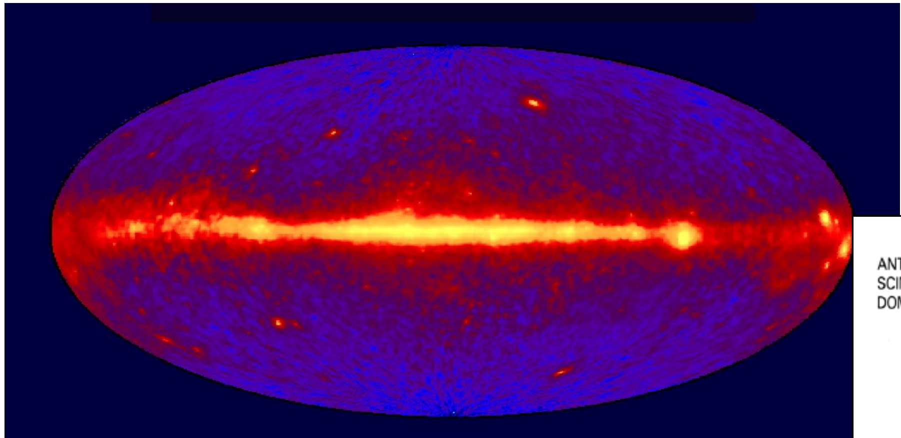
3rd EGRET catalogue

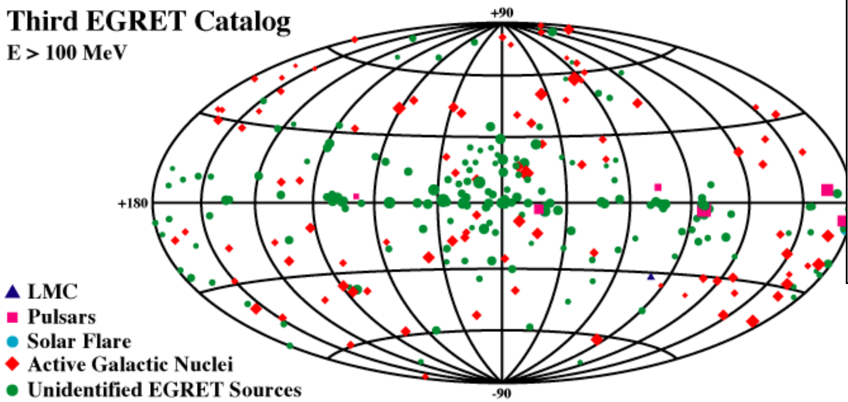
4FGL catalogue

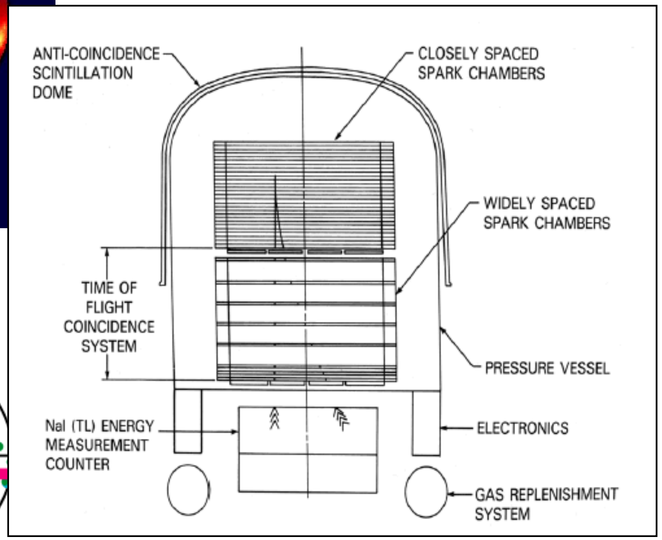
R. Zanin – EAS 2022

Lesson learned from Fermi

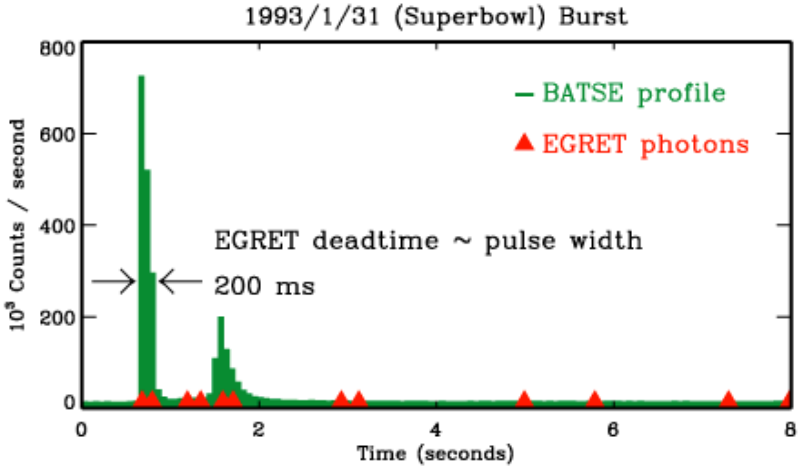
The EGRET era (1991-2000)





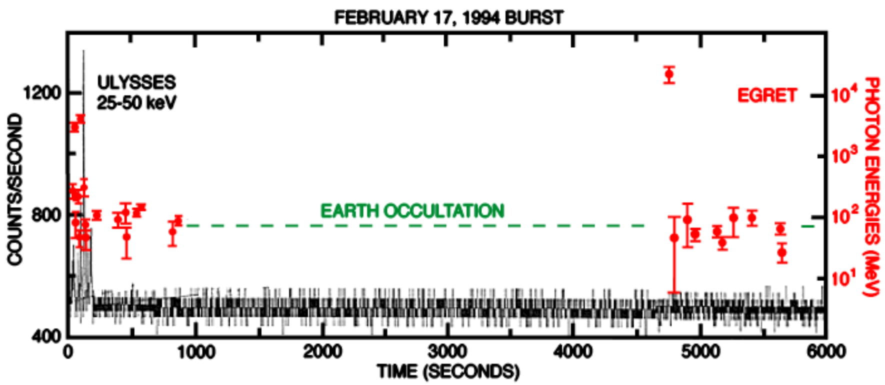


GRBs in the EGRET era

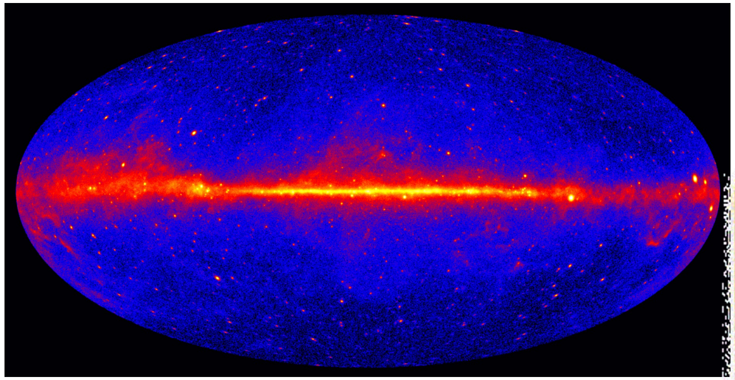


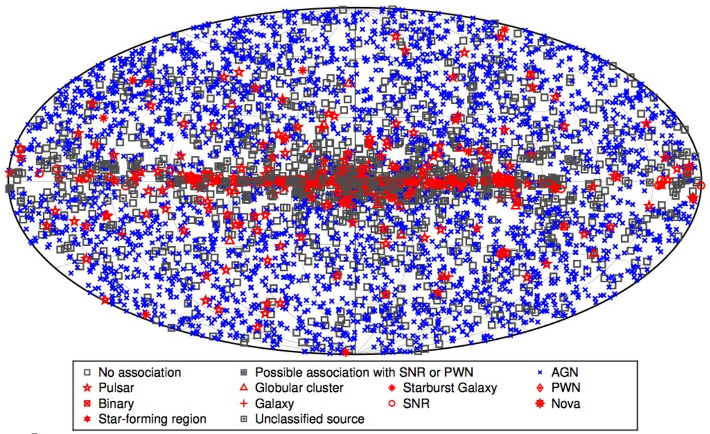
Kouveliotou et al 1994
Sommer et al. 1994

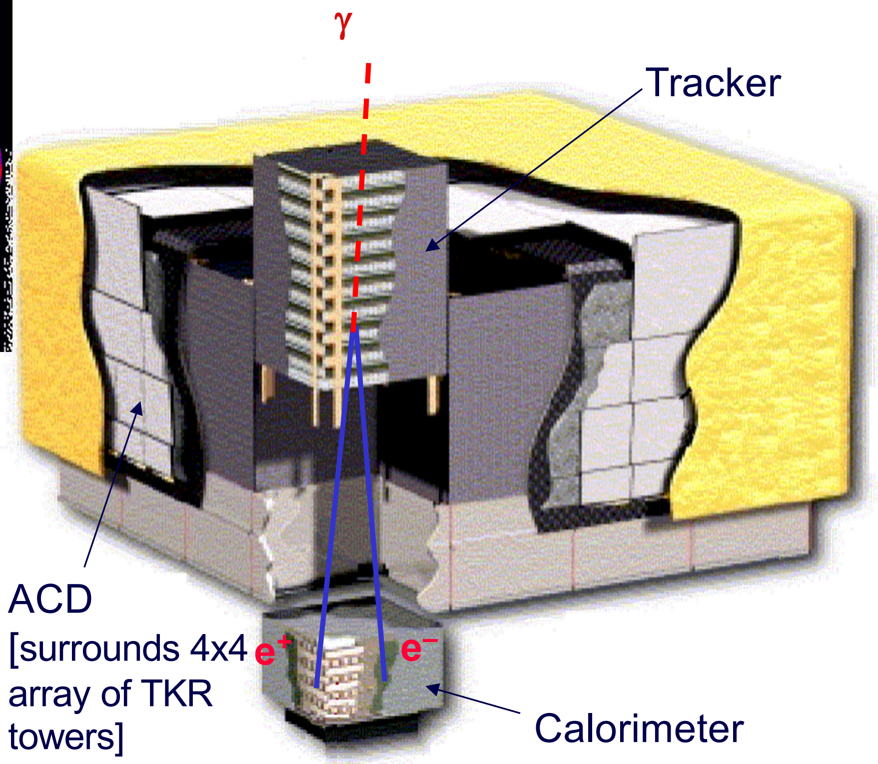
Hurley et al. 1994



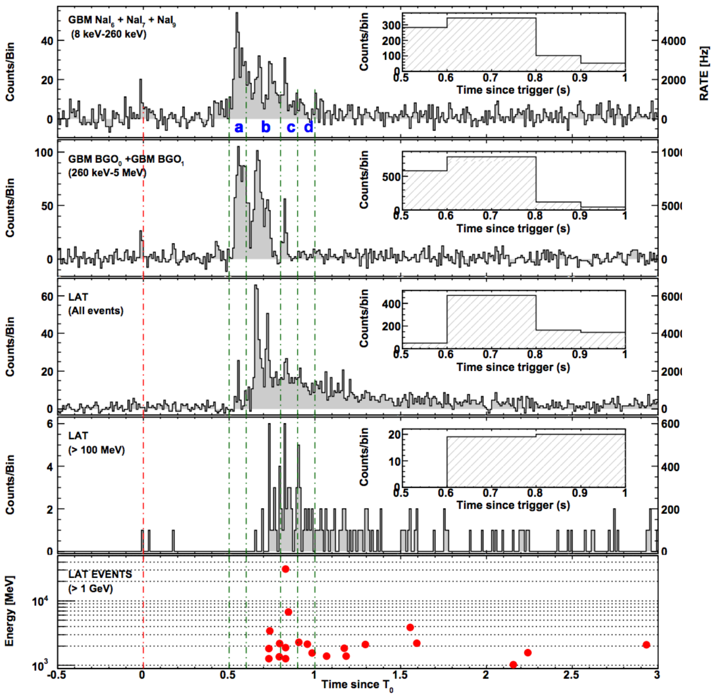
The Fermi/LAT era (2008-…)





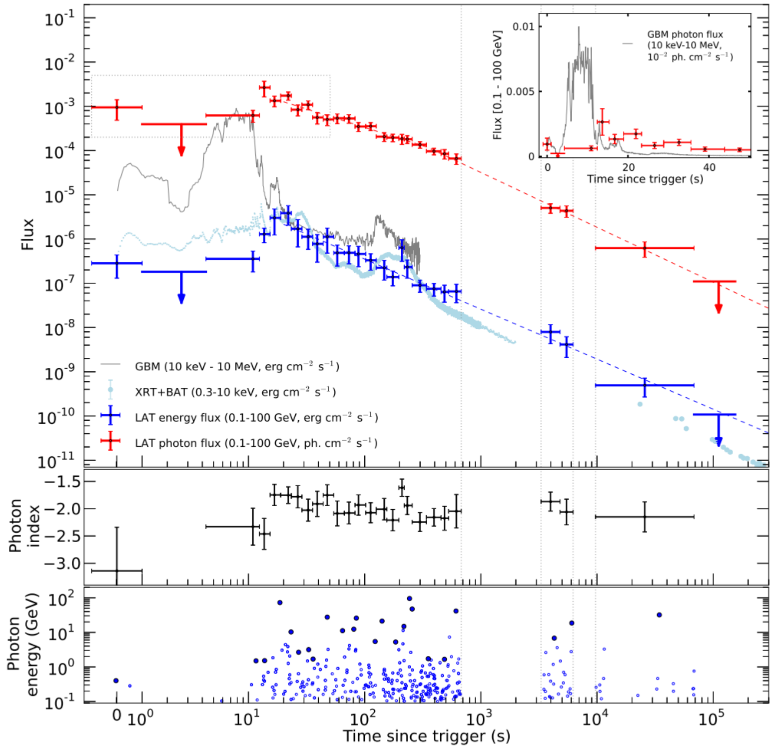


GRBs in the Fermi era



GRB 090510: Ackermann et al 2010

GRB 130427A: Ackermann et al. 2014

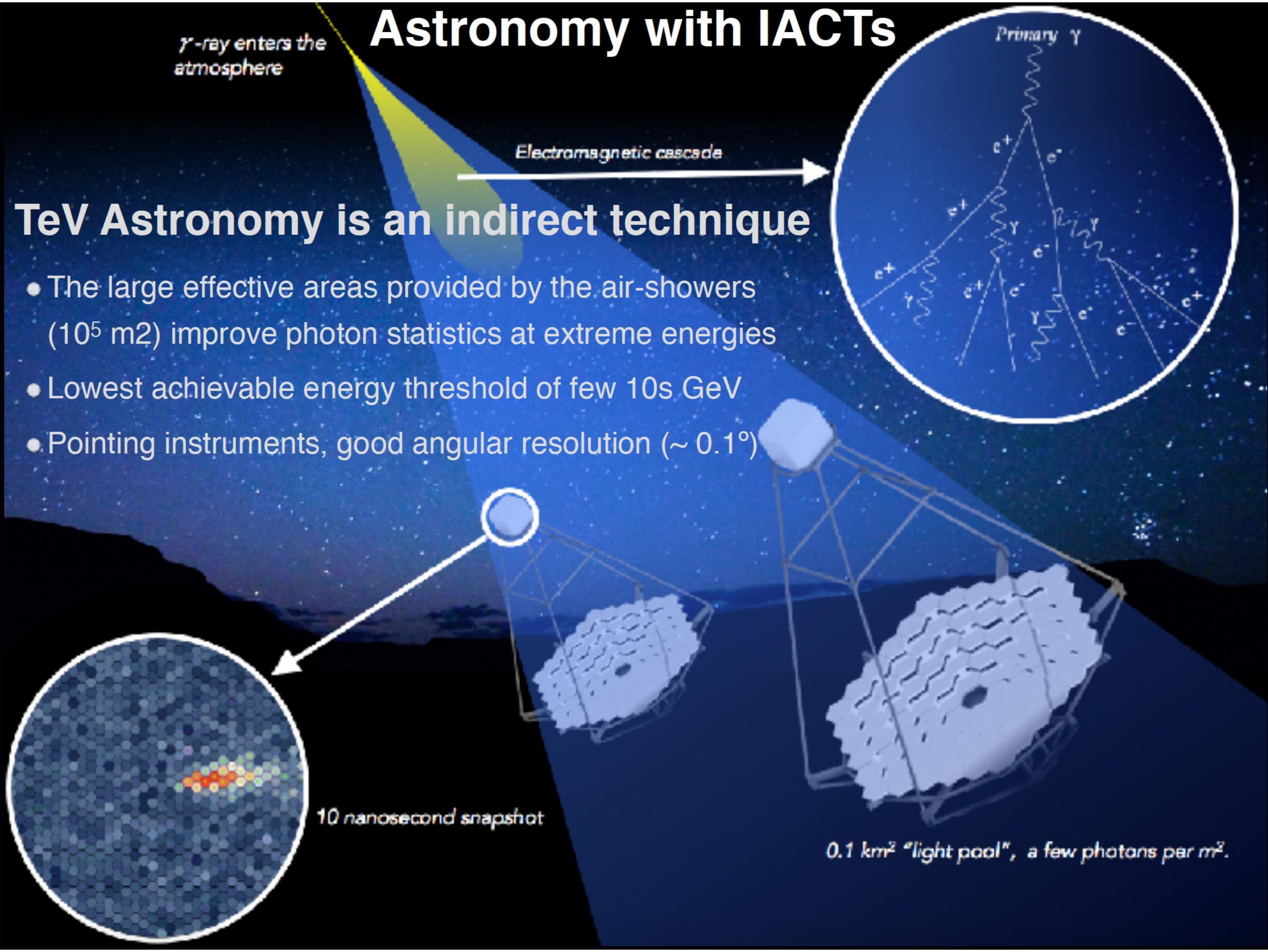


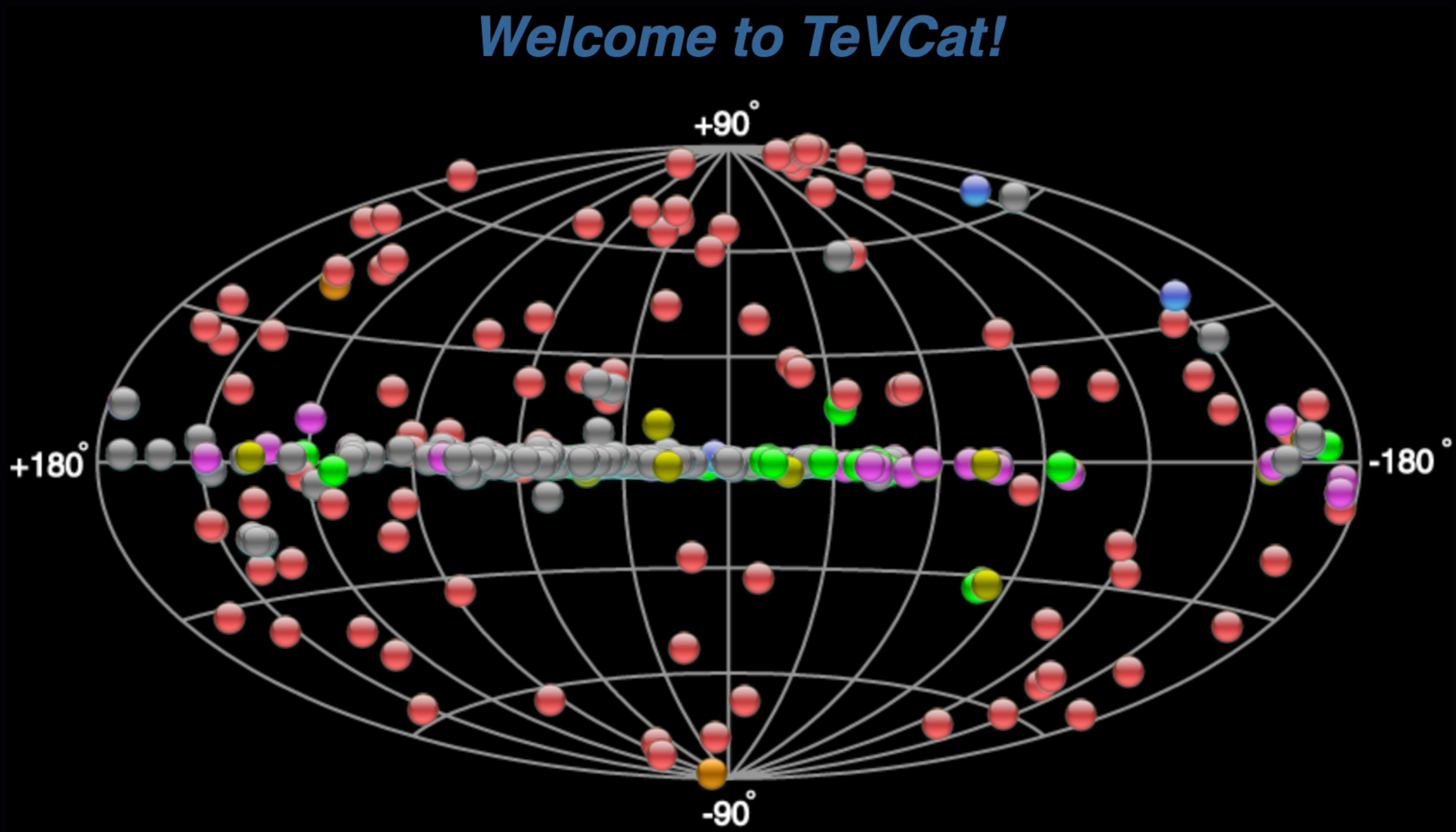
VHE Astrophysics

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°)

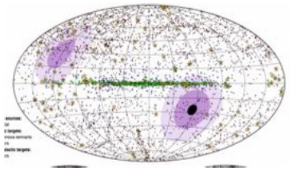


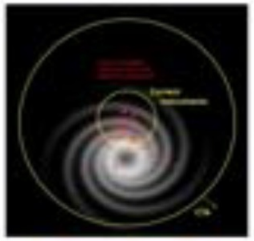


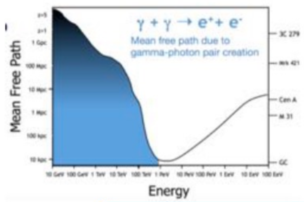
http://tevcat.uchicago.edu/

The Cherenkov Telescope Array Observatory

Design drivers

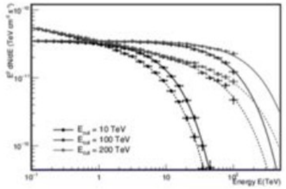






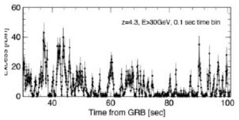
Full sky coverage

10 x sensitivity



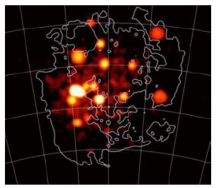
Energies down to 20 GeV

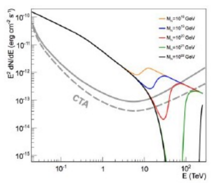
Energies up to 300 TeV



Rapid slewing 20 sec

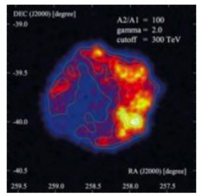
~ 10° FoV





10% energy resolution

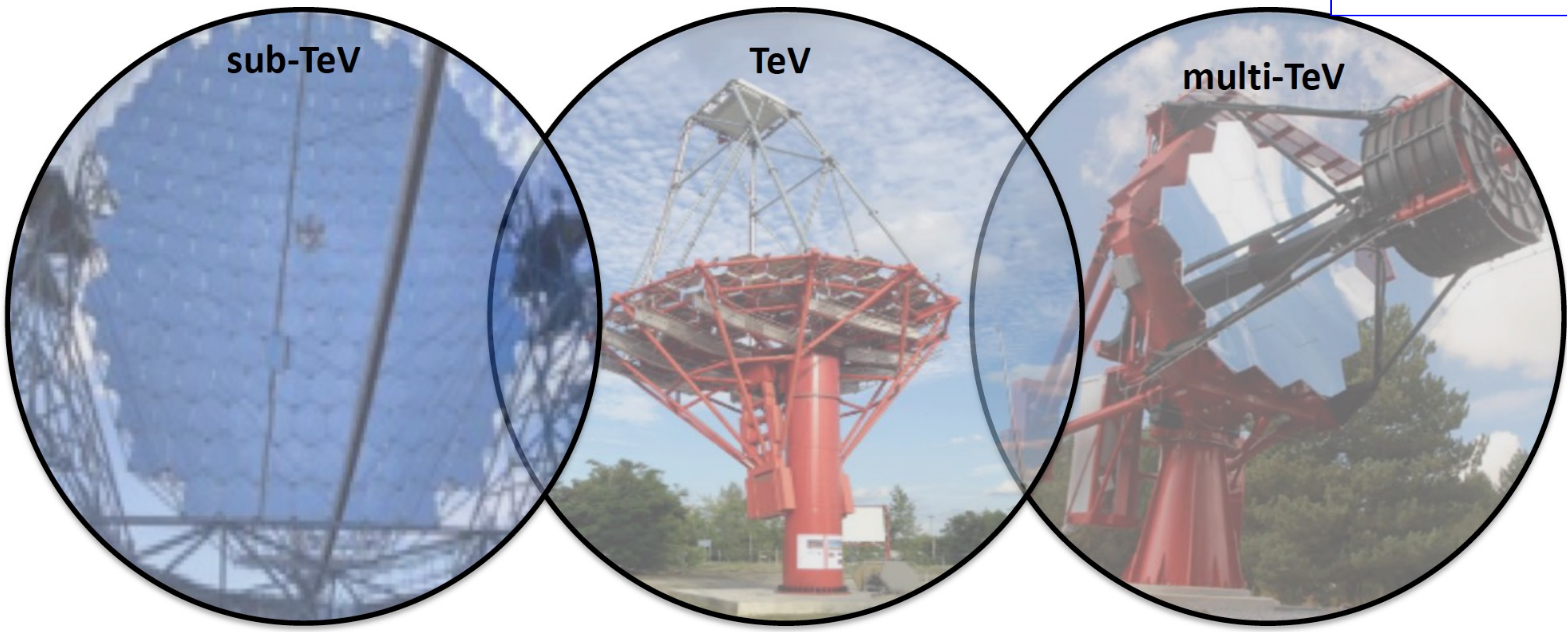
arcmin angular resolution



R.Zanin – TeVPa 2019

Science cases and design

R.Zanin – TeVPa 2019



- 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

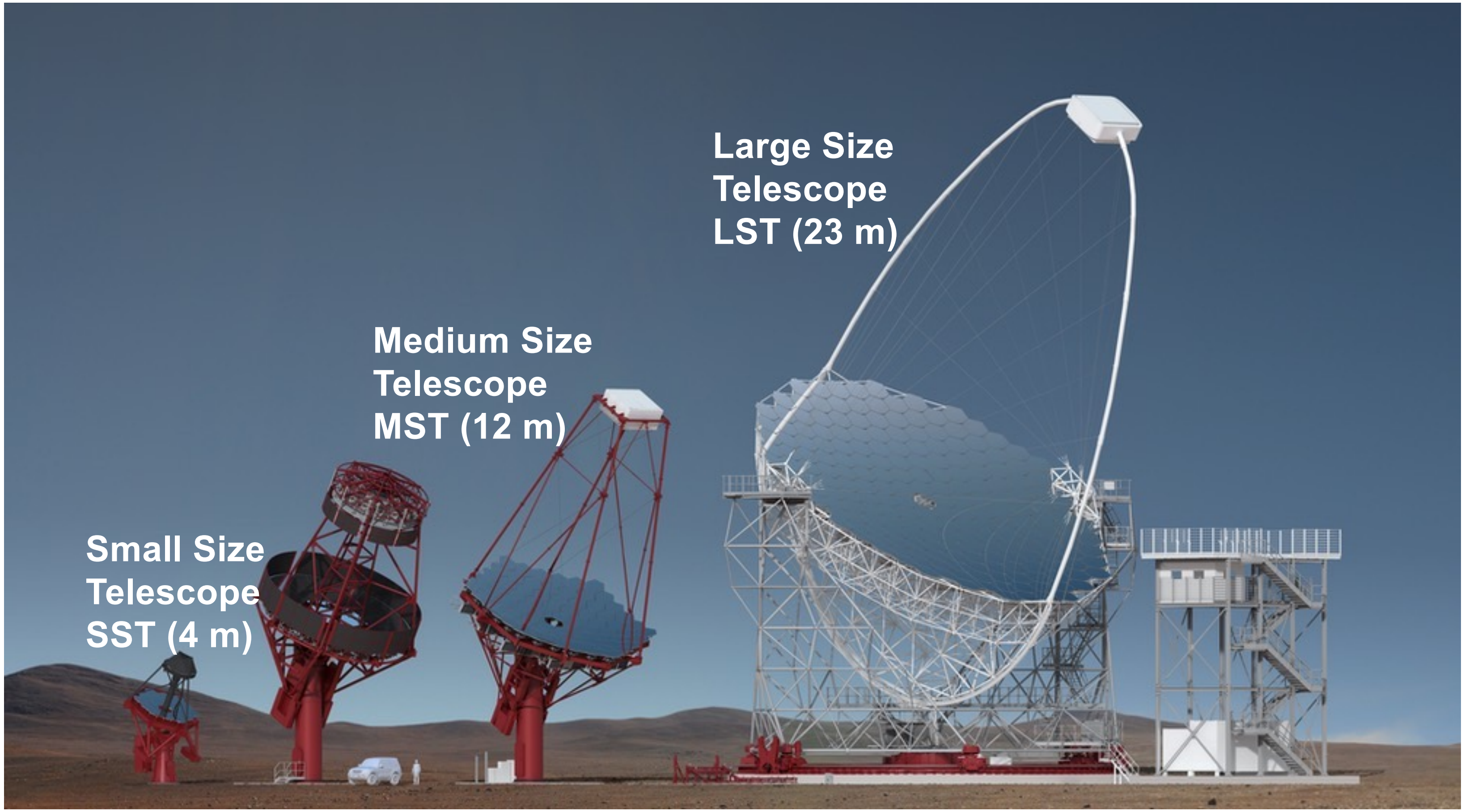
- **100 TeV range unexplored**
- **precision studies**

The CTA Sites

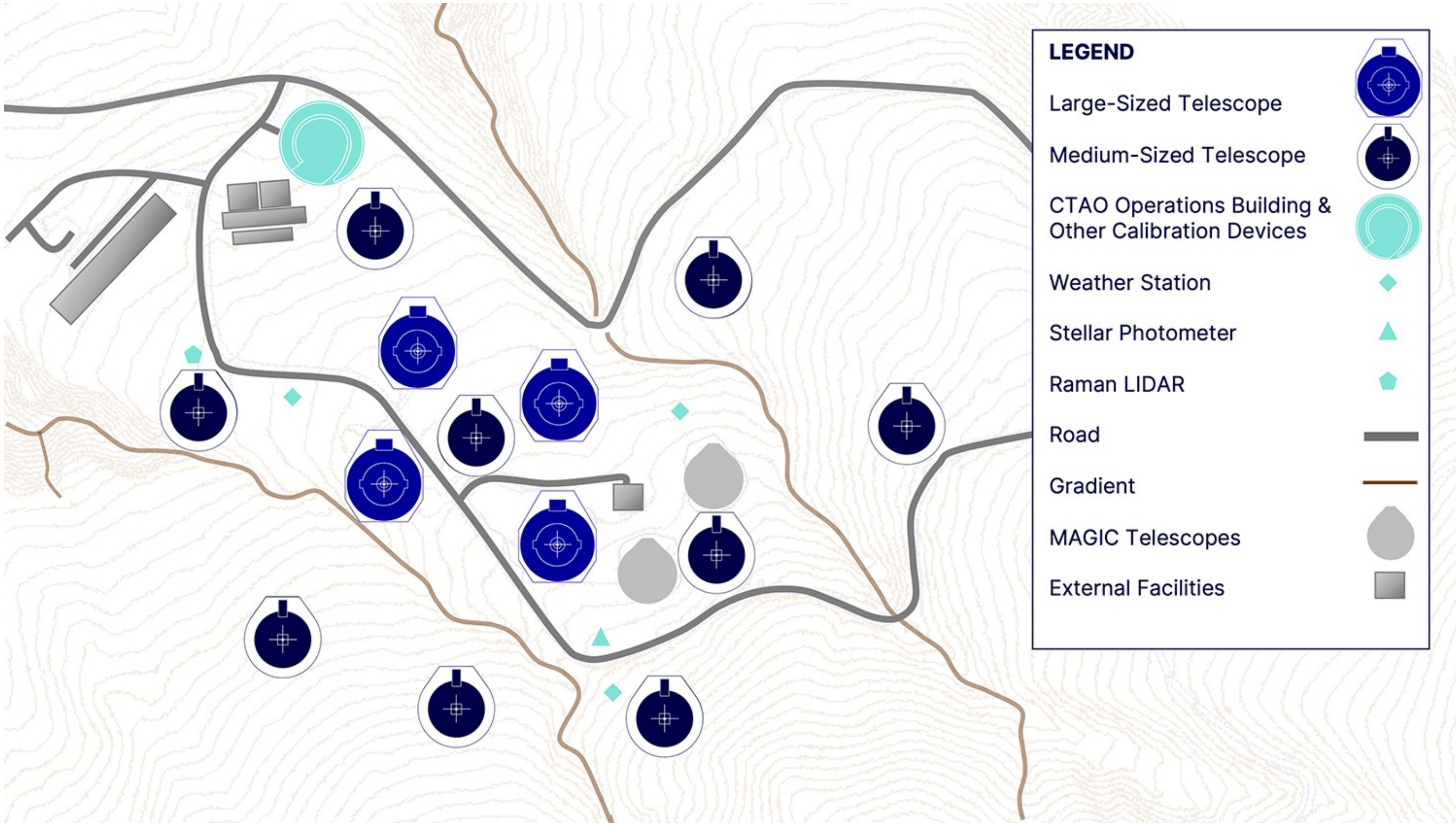
A Global Observatory…

U.Barres – COSPAR 2020

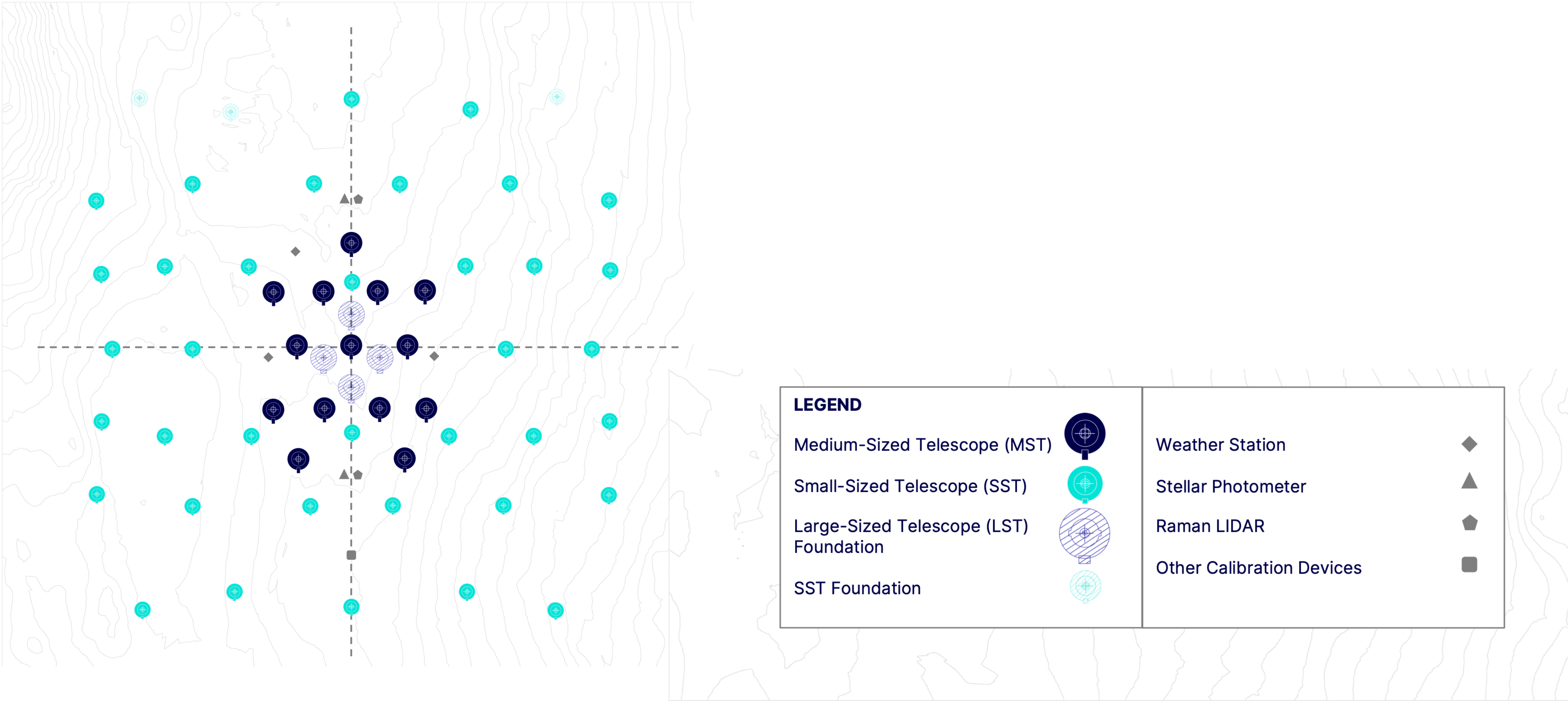
CTAO telescope types



CTAO Alpha Layouts

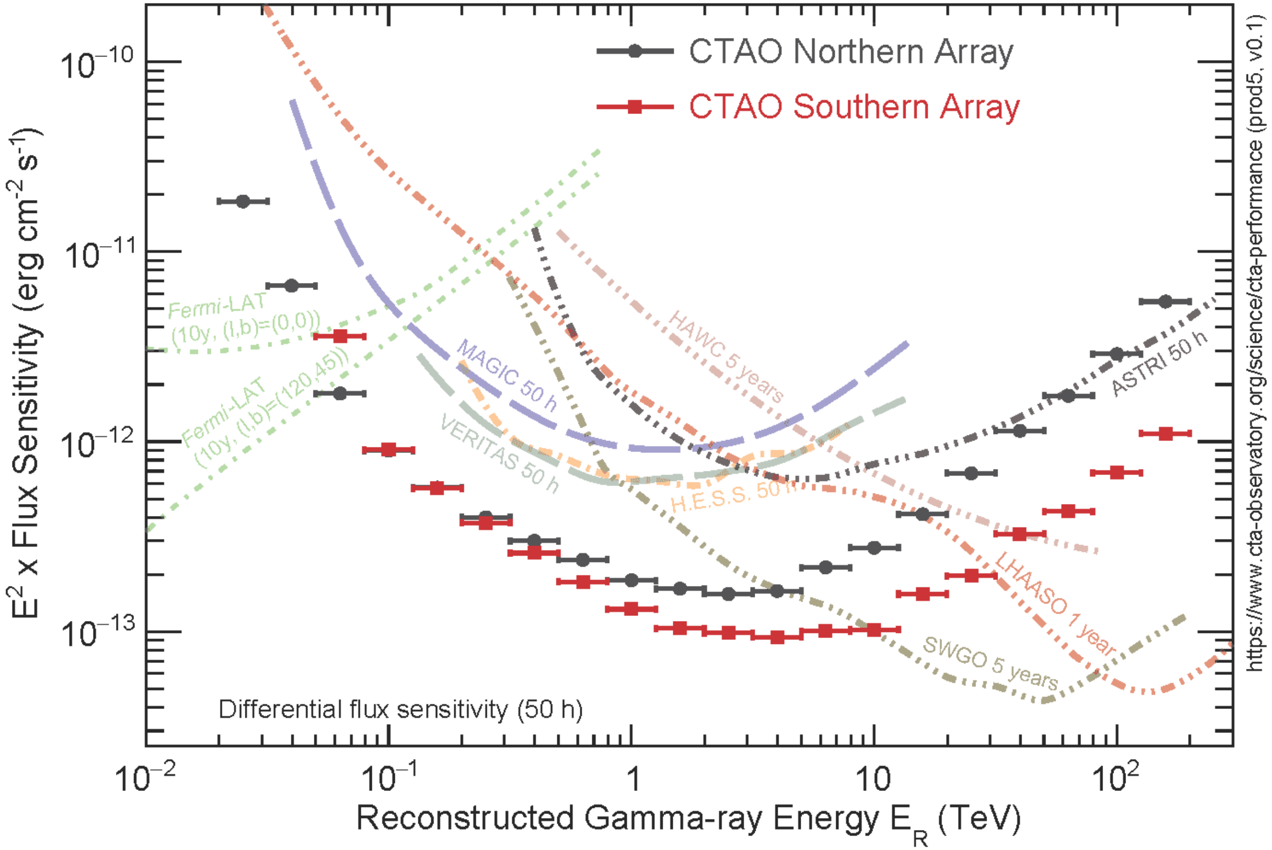


CTAO Alpha Layouts



CTAO – performance

https://www.ctao.org/for-scientists/performance/



CTAO

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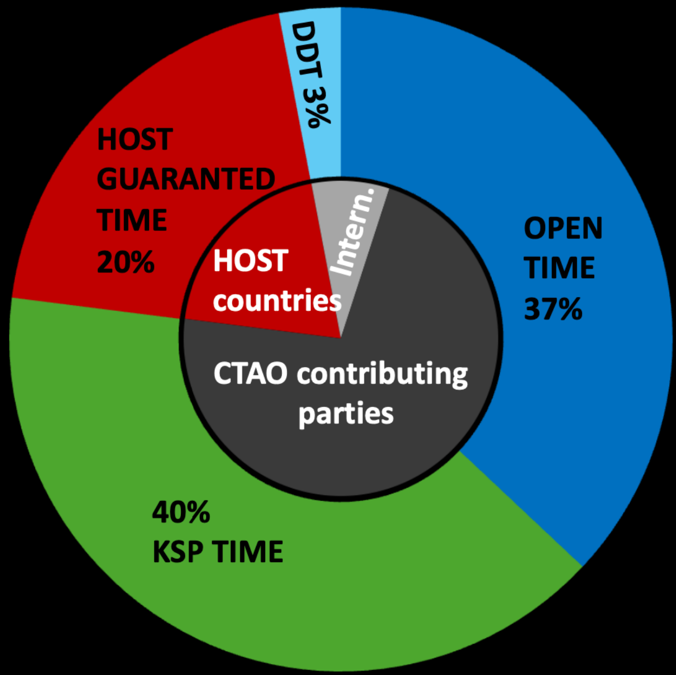
Access to CTAO data

In operation phase access is regulated by he already approved access policy



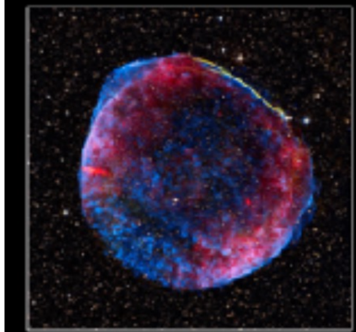
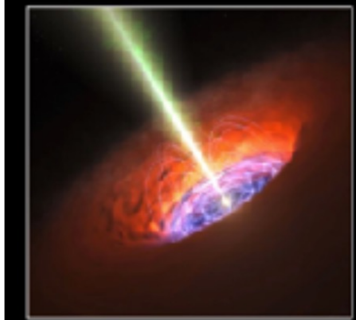
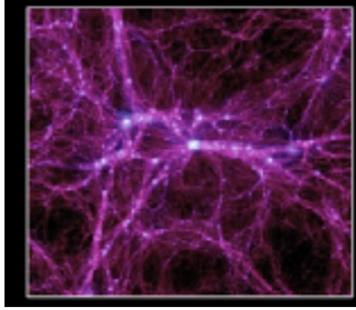
integrated over 10 yr

R.Zanin – 2nd CTAO Symposium 2024

Science topics

Astrophysics with IACTs

CTAO

- **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

CTAO

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

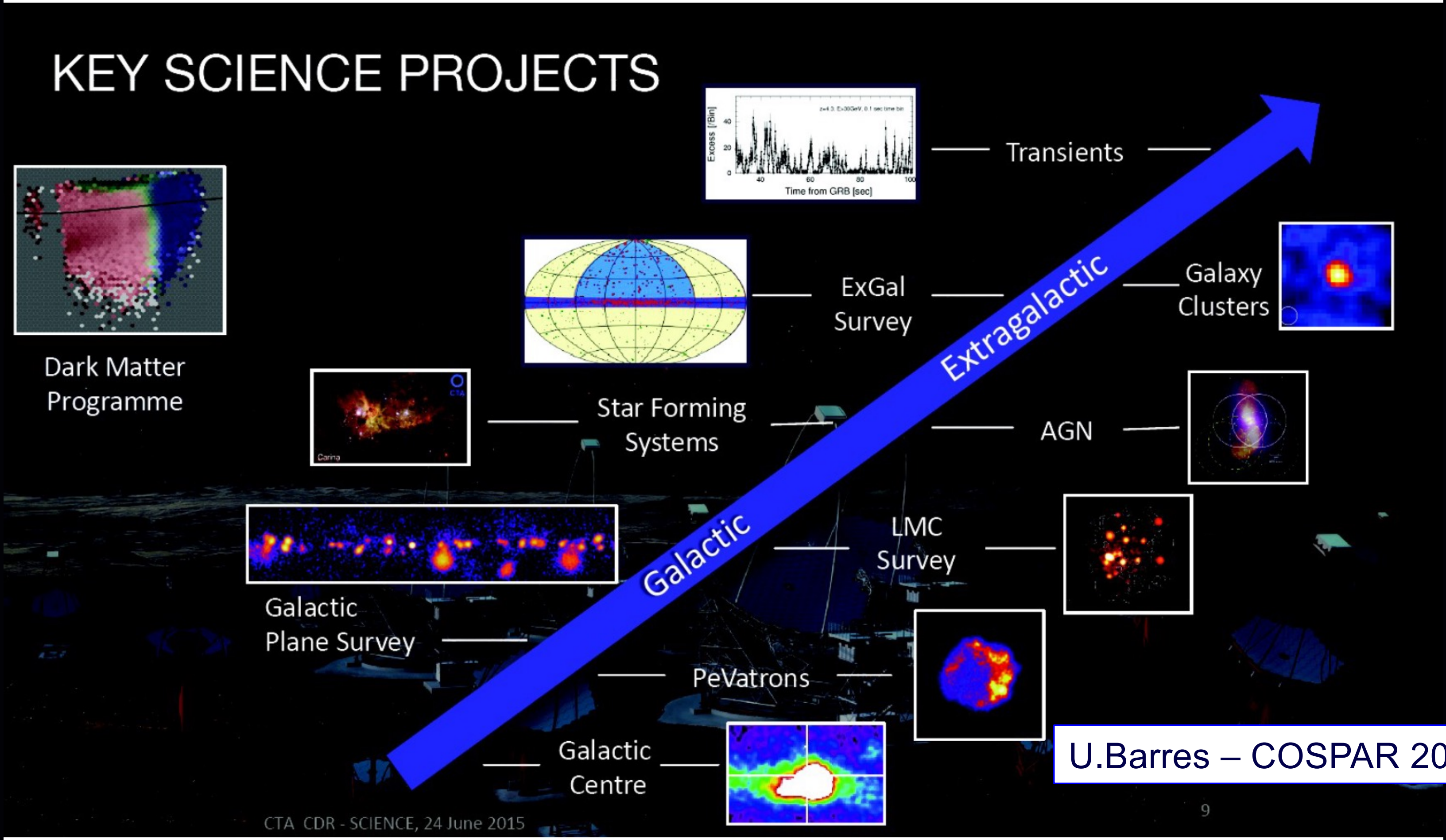
Deep Targeted Observations

- 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



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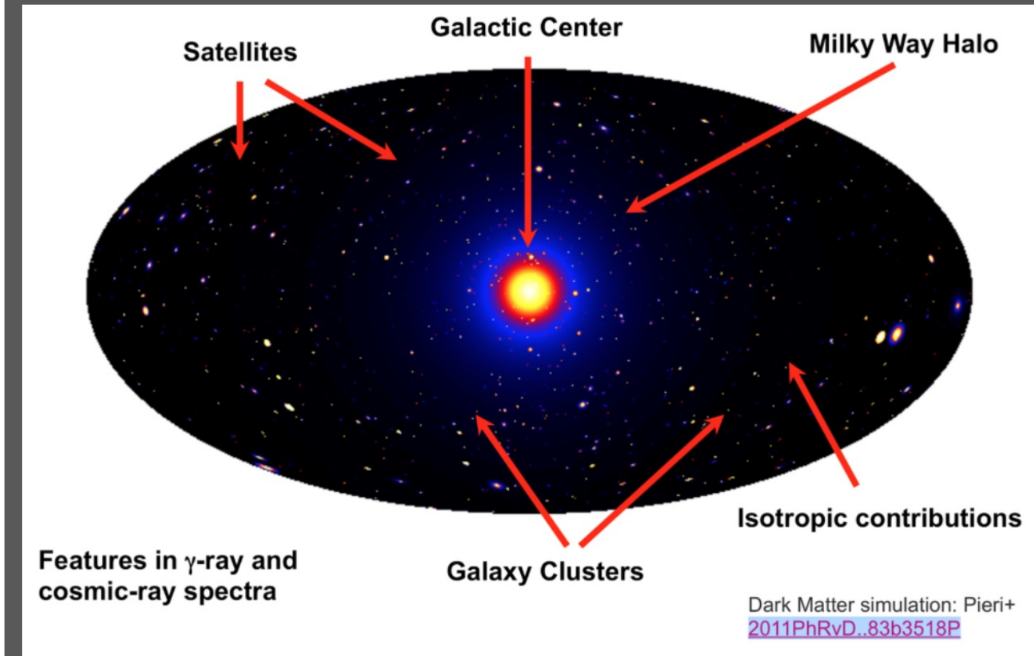
Science with CTAO

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



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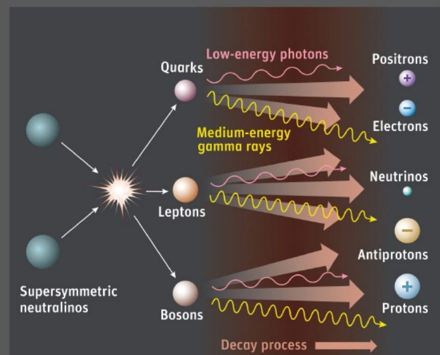
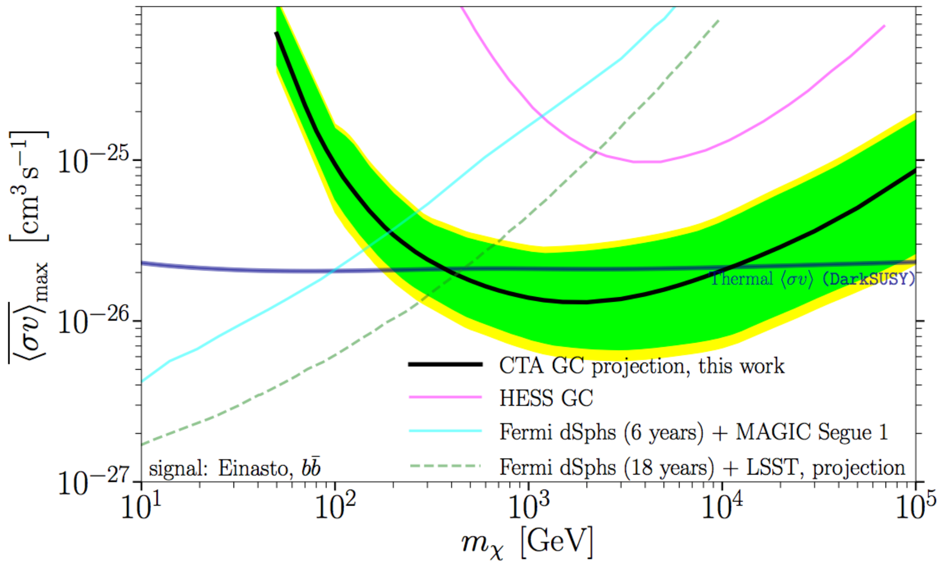
- Weakly-interacting massive particles (WIMPs)
- Candidate with masses at TeV-scale, ideal for CTA searches
- Annihilation and decay of DM-particles to give out spectral signatures in gamma-rays such as continuum edges and line-emissions features



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

Dark Matter with CTAO

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

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

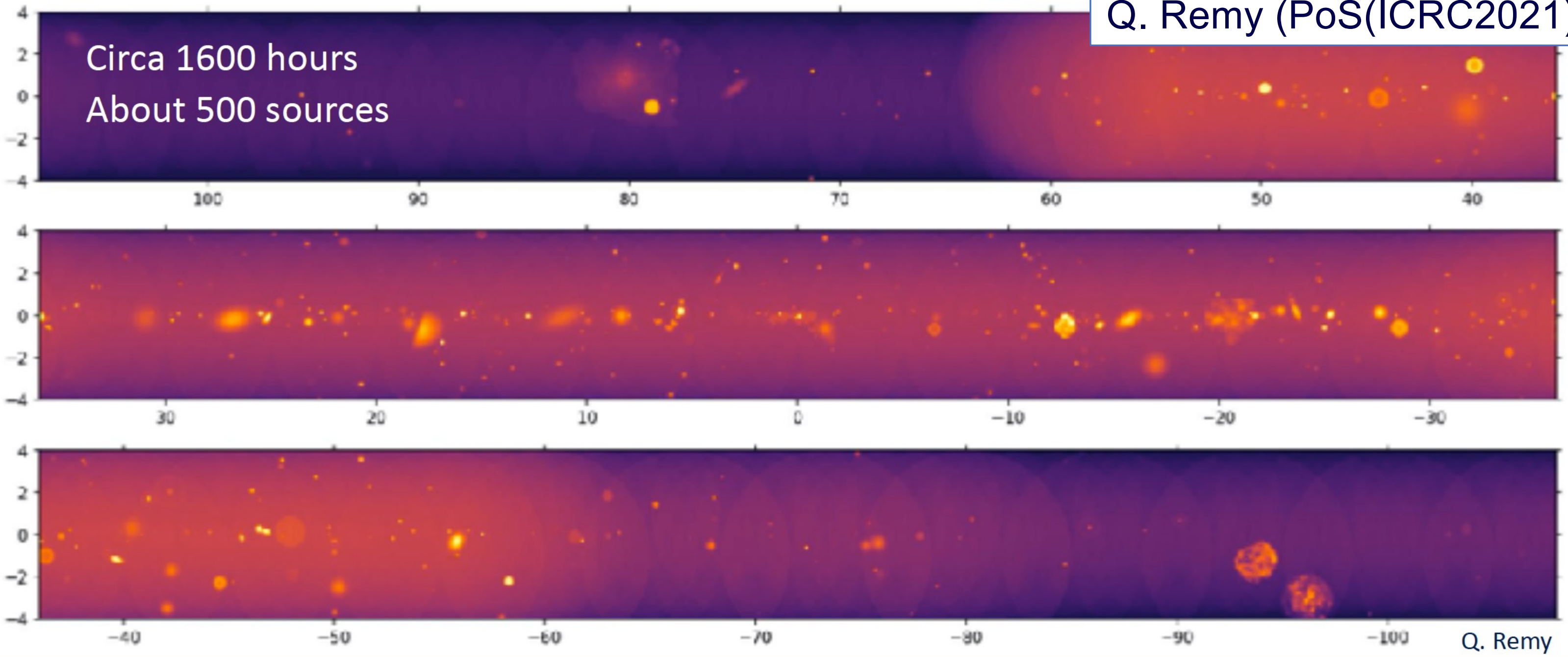
Abstract. We provide an updated assessment of the power of the Cherenkov Telescope Array (CTA) to search for thermally produced dark matter at the TeV scale, via the associated gamma-ray signal from pair-annihilating dark matter particles in the region around the Galactic centre. We find that CTA will 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

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.

Q. Remy (PoS(ICRC2021)886)



Galactic Science with CTAO

Prospects for a survey of the Galactic plane with the Cherenkov Telescope Array

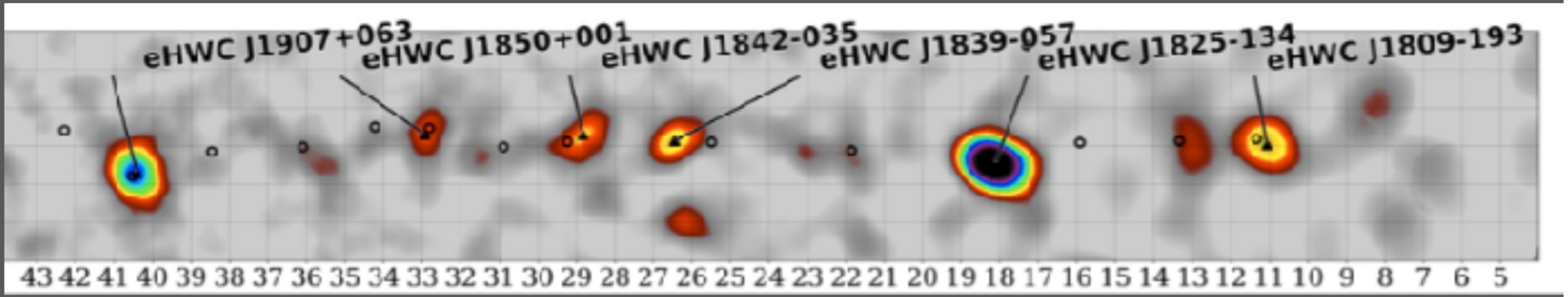
arXiv:2310.02828v2 [astro-ph.HE] 16 Jul 2024

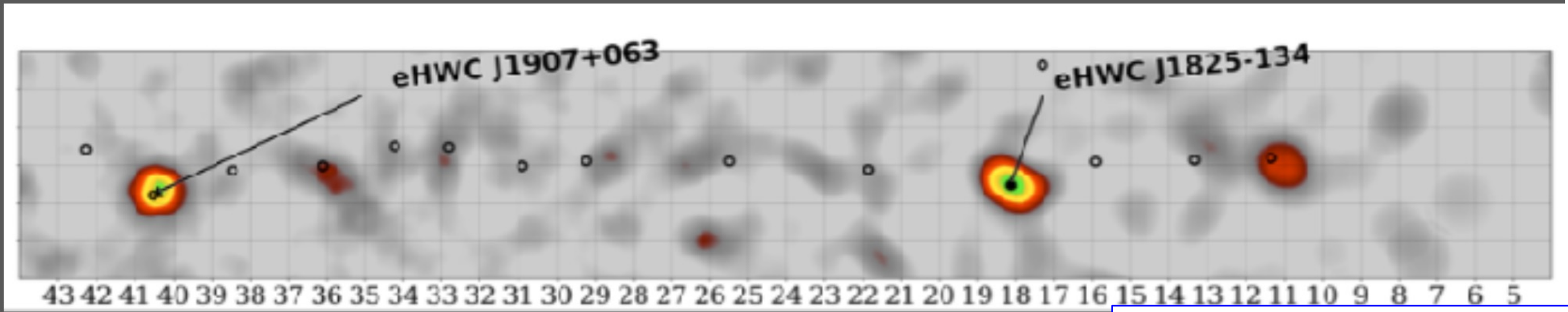
Abstract. Approximately one hundred sources of very-high-energy (VHE) gamma rays are known in the Milky Way, detected with a combination of targeted observations and surveys. A survey of the entire Galactic Plane in the energy range from a few tens of GeV to a few hundred TeV has been proposed as a Key Science Project for the upcoming Cherenkov Telescope Array Observatory (CTAO). This article presents the status of the studies towards the Galactic Plane Survey (GPS). We build and make publicly available a sky model that combines data from recent observations of known gamma-ray emitters with state-of-the-art physically-driven models of synthetic populations of the three main classes of established Galactic VHE sources (pulsar wind nebulae, young and interacting supernova remnants, and compact binary systems), as well as of interstellar emission from cosmic-ray interactions in the Milky Way. We also perform an optimisation of the observation strategy (pointing pattern and scheduling) based on recent estimations of the instrument performance. We use the improved sky model and observation strategy to simulate GPS data corresponding to a total observation time of 1620 hours spread over ten years. Data are then analysed using the methods and software tools under development for real data. Under our model assumptions and for the realisation considered, we show that the GPS has the potential to increase the number of known Galactic VHE emitters by almost a factor of five. This corresponds to the detection of more than two hundred pulsar wind nebulae and a few tens of supernova remnants at average integral fluxes one order of magnitude lower than in the existing sample above 1 TeV, therefore opening the possibility to perform unprecedented population studies. The GPS also has the potential to provide new VHE detections of binary systems and pulsars, to confirm the existence of a hypothetical population of gamma-ray pulsars with an additional TeV emission component, and to detect bright sources capable of accelerating particles to PeV energies (PeVatrons). Furthermore, the GPS will constitute a pathfinder for deeper follow-up observations of these source classes. Finally, we show that we can extract from GPS data an estimate of the contribution to diffuse emission from unresolved sources, and that there are good prospects of detecting interstellar emission and statistically distinguishing different scenarios. Thus, a survey of the entire Galactic plane carried out from both hemispheres with CTAO will ensure a transformational advance in our knowledge of Galactic VHE source populations and interstellar emission.

https://arxiv.org/abs/2310.02828

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

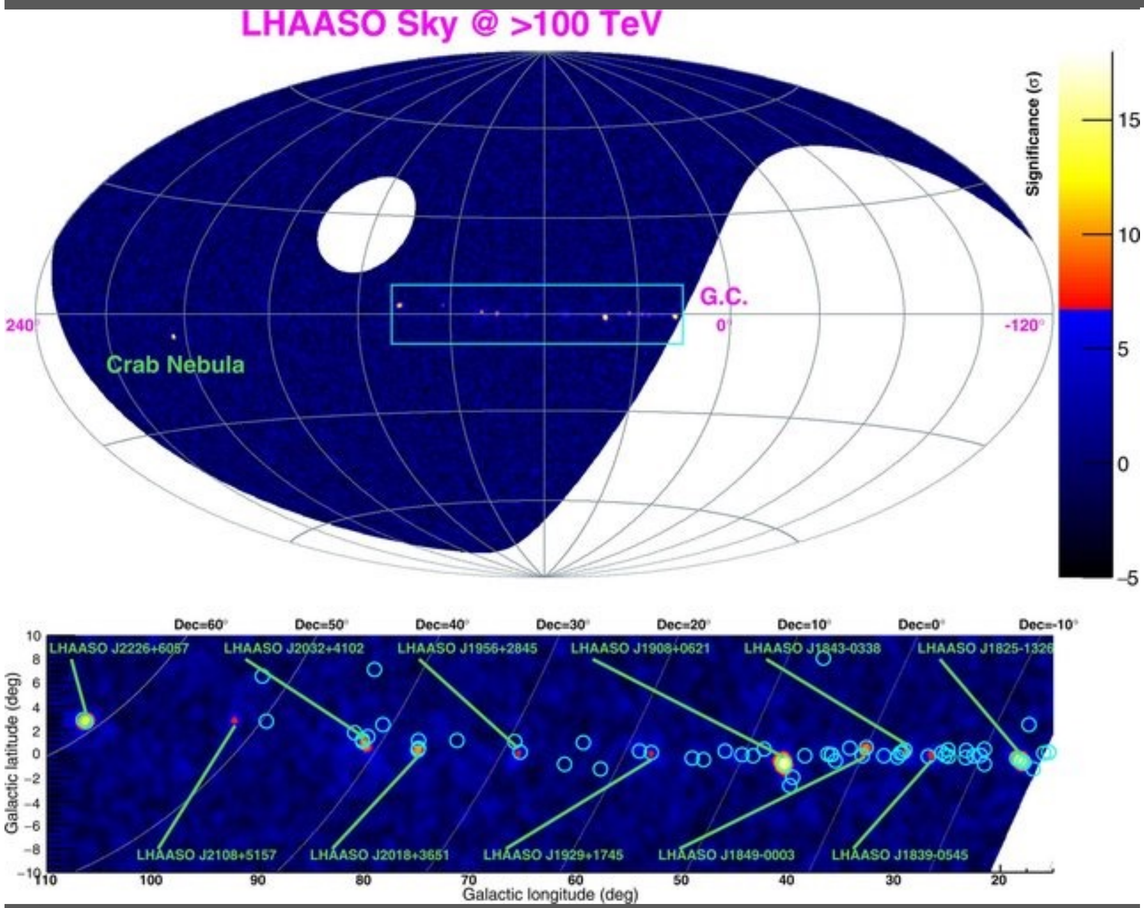




U.Barres – COSPAR 2020

PeVatrons: the extreme energy frontier

CTAO



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

LHAASO (Nature 2021)

Pevatron Science with CTAO

Sensitivity of the Cherenkov Telescope Array to spectral signatures of hadronic PeVatrons with application to Galactic Supernova Remnants

The Cherenkov Telescope Array Consortium[1], E.O. Angüner[a,b], G. Spengler[c], H. Costantini[b], P. Cristofari[d], T. Armstrong[b], L. Giunti[e]

[a]*TÜBİTAK Research Institute for Fundamental Sciences, 41470 Gebze, Kocaeli, Turkey*
[b]*Aix-Marseille Université, CNRS/IN2P3, CPPM, 163 Avenue de Luminy, 13288 Marseille cedex 09, France*
[c]*Department of Physics, Humboldt University Berlin, Newtonstr. 15, 12489 Berlin, Germany*
[d]*LUTH, GEPI and LERMA, Observatoire de Paris, CNRS, PSL University, 5 place Jules Janssen, 92190, Meudon, France*
[e]*Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France*

Abstract

The local Cosmic Ray (CR) energy spectrum exhibits a spectral softening at energies around 3 PeV. Sources which are capable of accelerating hadrons to such energies are called hadronic PeVatrons. However, hadronic PeVatrons have not yet been firmly identified within the Galaxy. Several source classes, including Galactic Supernova Remnants (SNRs), have been proposed as PeVatron candidates. The potential to search for hadronic PeVatrons with the Cherenkov Telescope Array (CTA) is assessed. The focus is on the usage of very high energy γ-ray spectral signatures for the identification of PeVatrons. Assuming that SNRs can accelerate CRs up to knee energies, the number of Galactic SNRs which can be identified as PeVatrons with CTA is estimated within a model for the evolution of SNRs. Additionally, the potential of a follow-up observation strategy under moonlight conditions for PeVatron searches is investigated. Statistical methods for the identification of PeVatrons are introduced, and realistic Monte–Carlo simulations of the response of the CTA observatory to the emission spectra from hadronic PeVatrons are performed. Based on simulations of a simplified model for the evolution for SNRs, the detection of a γ-ray signal from in average 9 Galactic PeVatron SNRs is expected to result from the scan of the Galactic plane with CTA after 10 hours of exposure. CTA is also shown to have excellent potential to confirm these sources as PeVatrons in deep observations with $O(100)$ hours of exposure per source.

Keywords: Gamma rays: general, Cosmic rays, Galactic PeVatrons, (Stars:) supernovae: general, Methods: data analysis, Methods: statistical

https://arxiv.org/abs/2303.15007

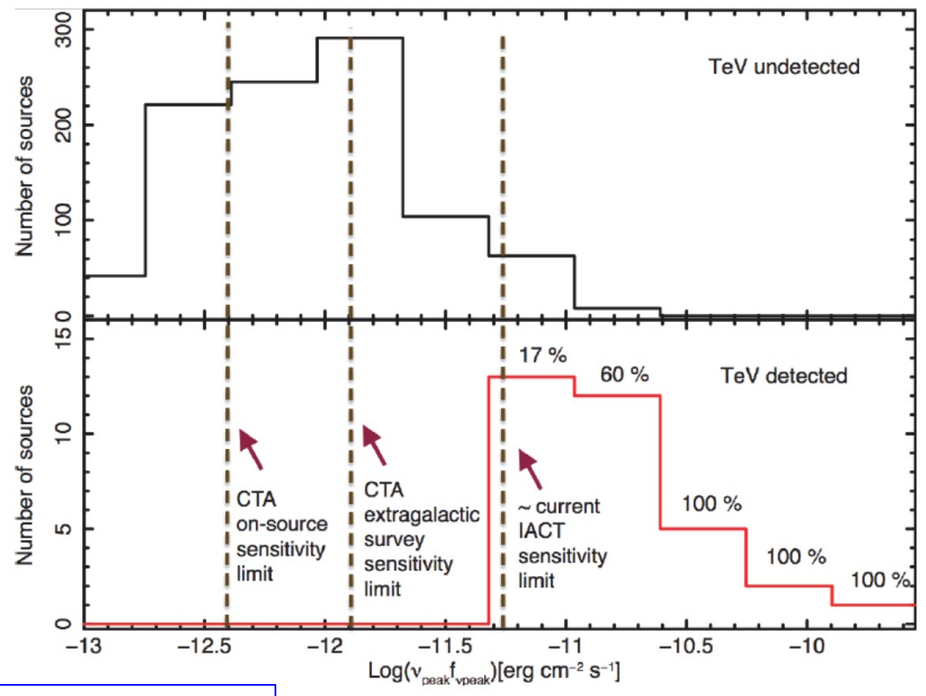
CTA's Prospects for AGN

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

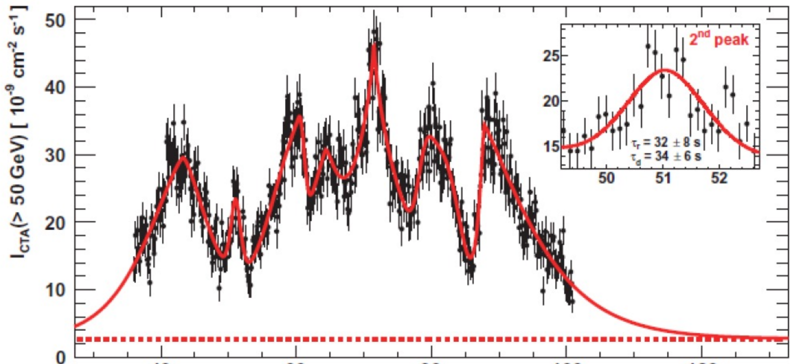
FoV up to 10 degrees → several AGN in FoV at same time.

Light curve details down to sub-minutes.

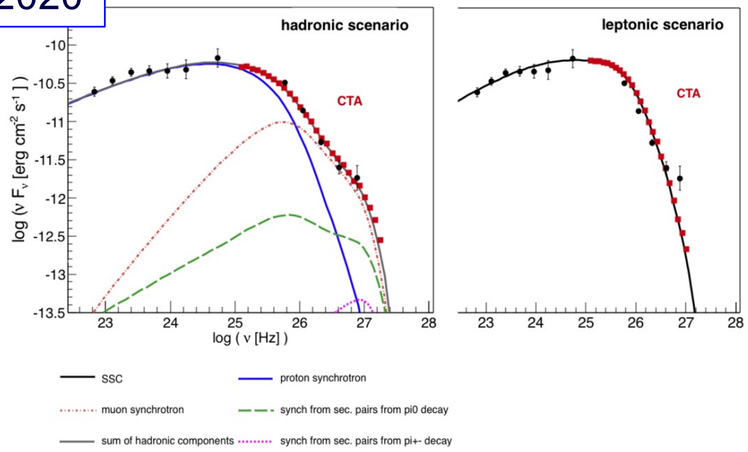
Spectral resolution to reveal sub-components:
- Hadronic (synchrotron from protons, muons, + secondaries)
- Leptonic (SSC)



G. Rowell – COSPAR 2020



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

The new window of VHE Gamma-ray Bursts

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

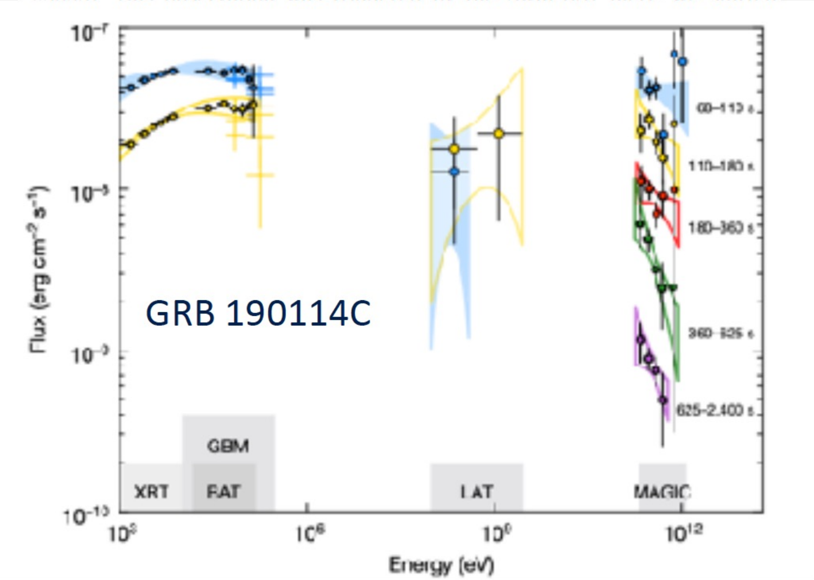
ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
on ***15 Jan 2019; 01:03 UT***
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

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)

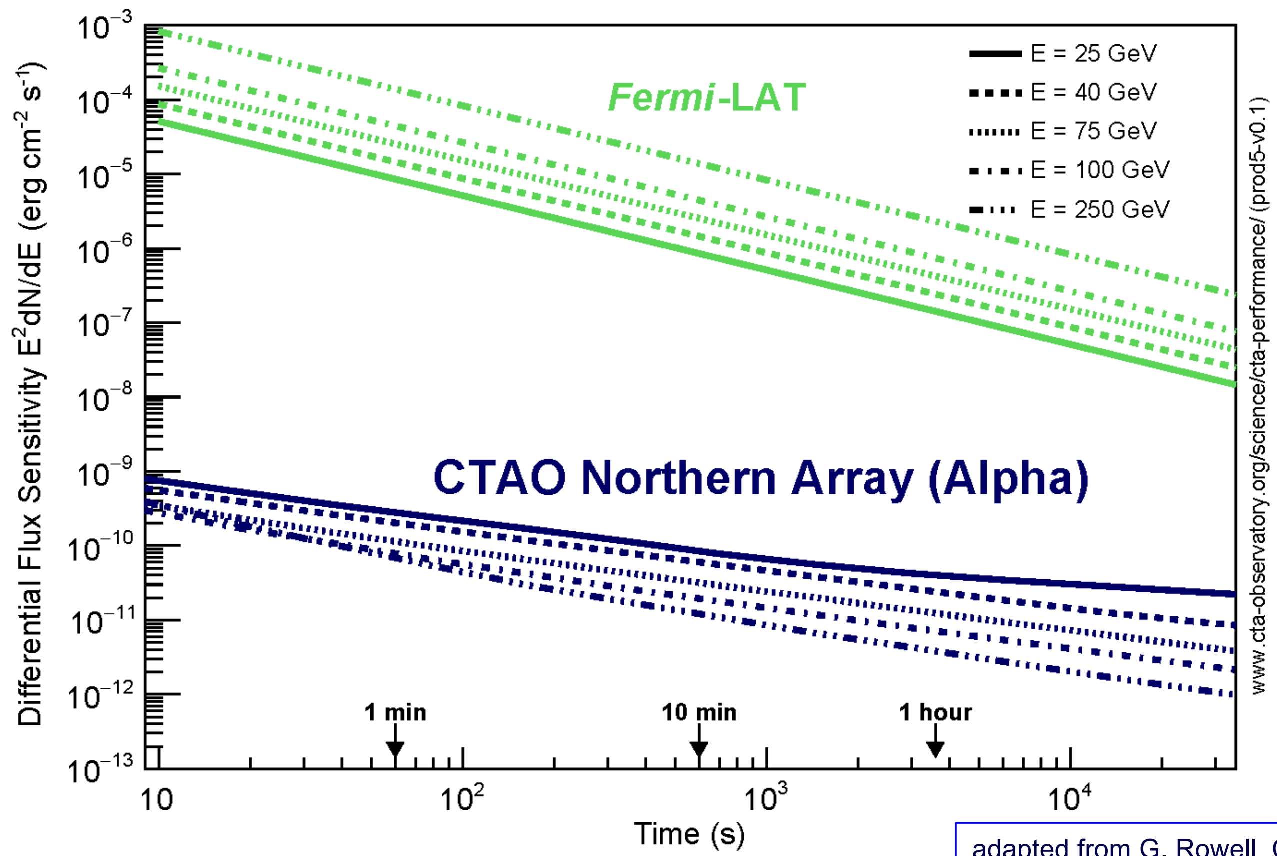
+ GRB 201216C (z = 1.1)

Strong MWL and MM synergies for spectral and variability studies

U.Barres – COSPAR 2020

Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)

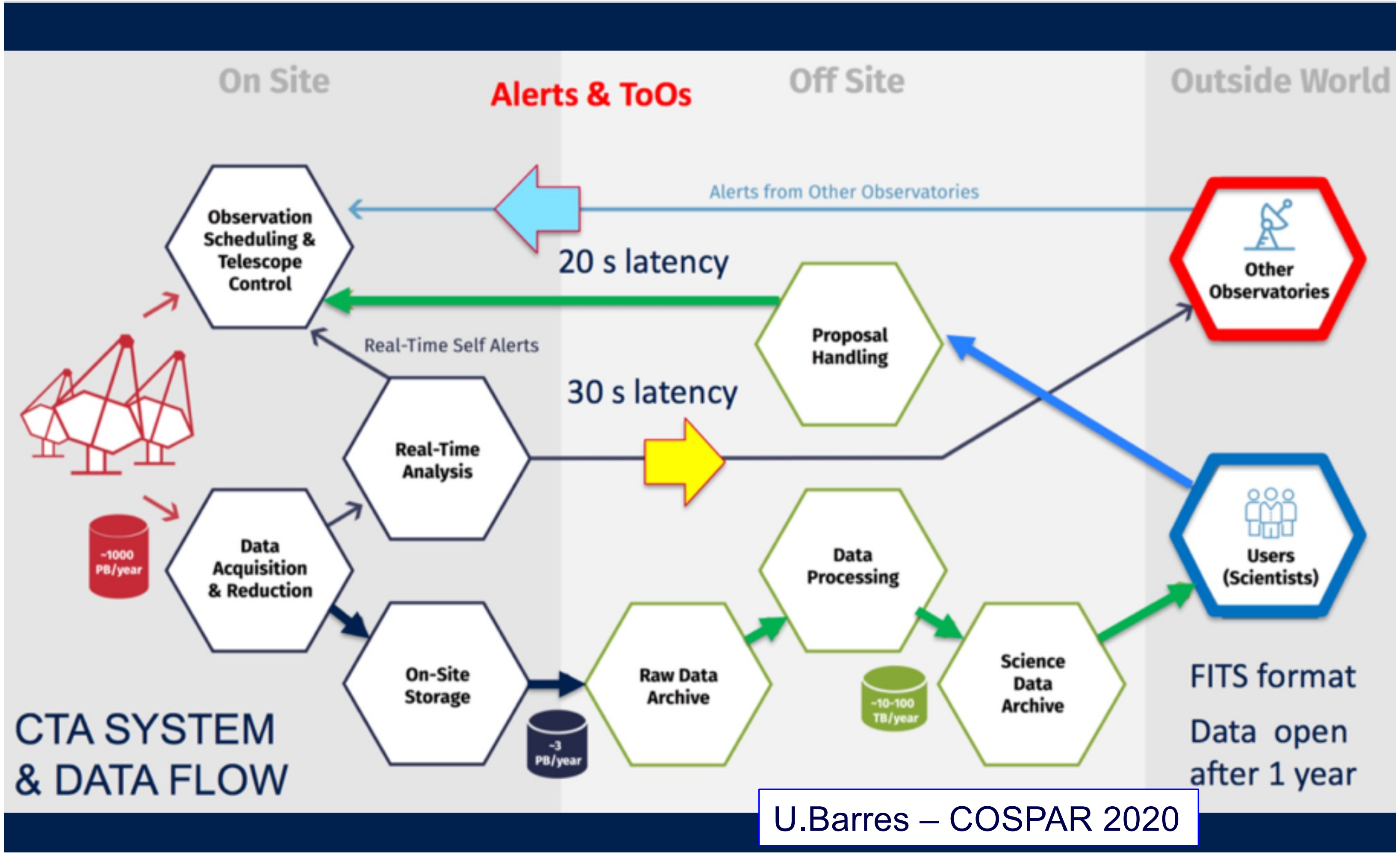


adapted from G. Rowell COSPAR2020

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

→ GRBs, AGN, giant pulses, FRBs, GW, SGR bursts......

CTA Transients Science



Transient Science with CTAO

Galactic transient sources with the Cherenkov Telescope Array

ABSTRACT

A wide variety of Galactic sources show transient emission at soft and hard X-ray energies: low-mass and high-mass X-ray binaries containing compact objects (e.g., novae, microquasars, transitional millisecond pulsars, supergiant fast X-ray transients), isolated neutron stars exhibiting extreme variability as magnetars as well as pulsar wind nebulae. Although most of them can show emission up to MeV and/or GeV energies, many have not yet been detected in the TeV domain by Imaging Atmospheric Cherenkov Telescopes. In this paper, we explore the feasibility of detecting new Galactic transients with the Cherenkov Telescope Array (CTA) and the prospects for studying them with Target of Opportunity observations. We show that CTA will likely detect new sources in the TeV regime, such as the massive microquasars in the Cygnus region, low-mass X-ray binaries with low-viewing angle, flaring emission from the Crab pulsar-wind nebula or other novae explosions, among others. We also discuss the multi-wavelength synergies with other instruments and large astronomical facilities.

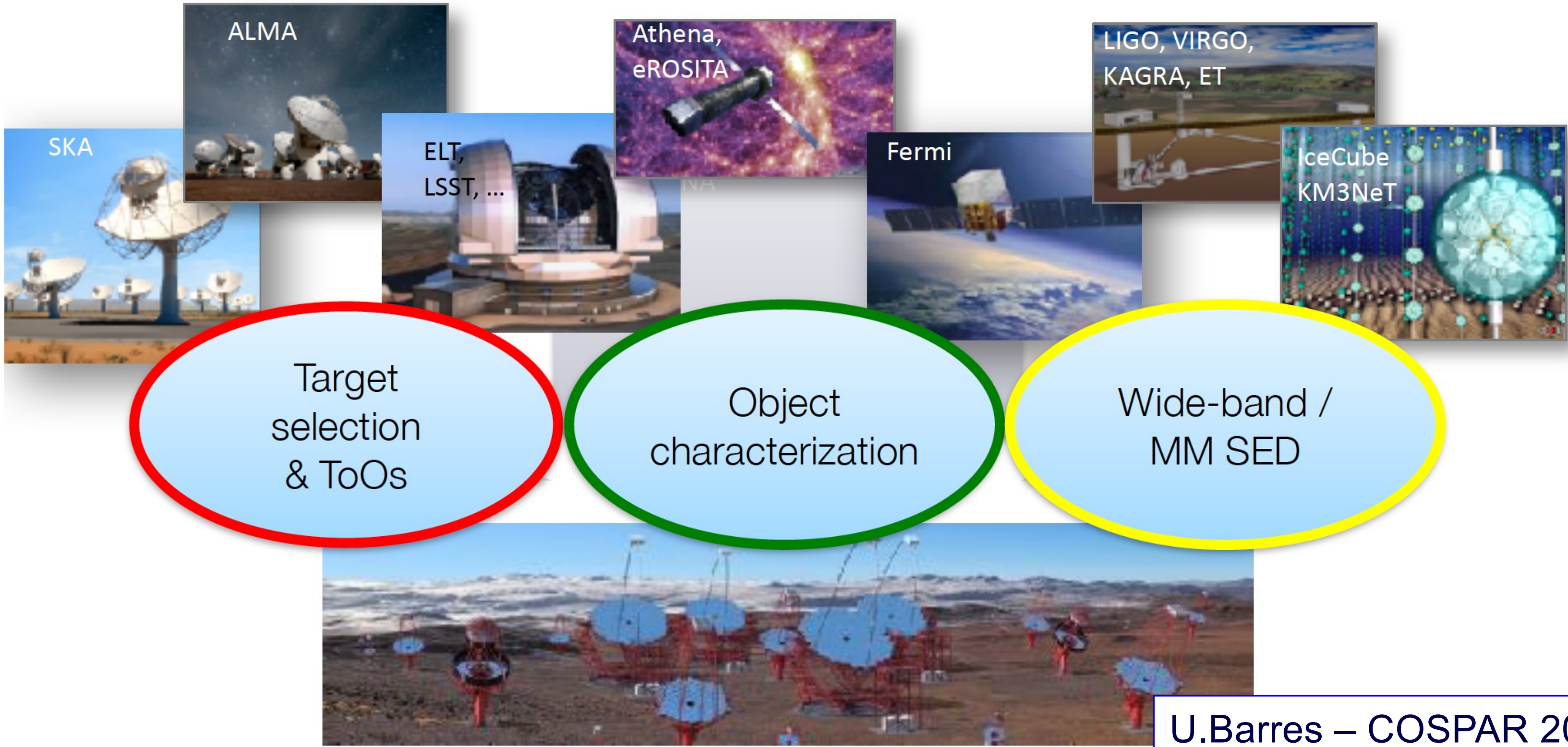
Key words: gamma-rays:general – transients – binaries: general – pulsars:general – stars:novae – stars:magnetars

https://arxiv.org/abs/2405.04469

What's next?

MWL and Multi-Messenger Perspectives

Synergies with astrophysical facilities…



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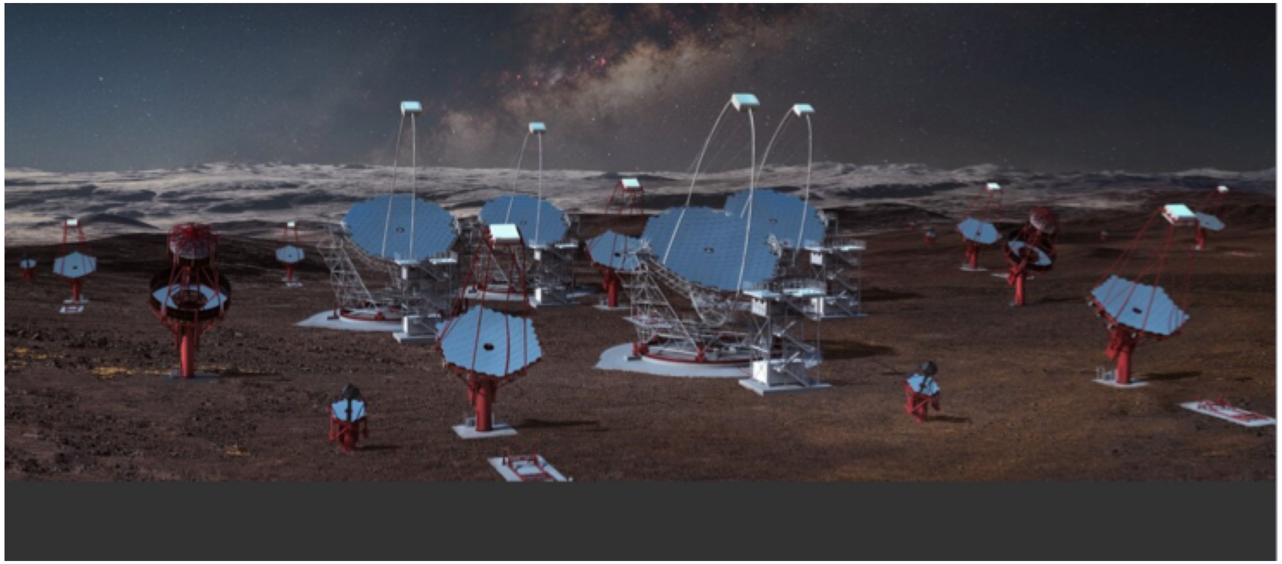
Conclusions

- CTAO 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
- The First VHE observatory !



Thank you

CTAO

www.ctao.org