VHE Science Review – CTAO perspective

Status, science and tech

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1 CTAO

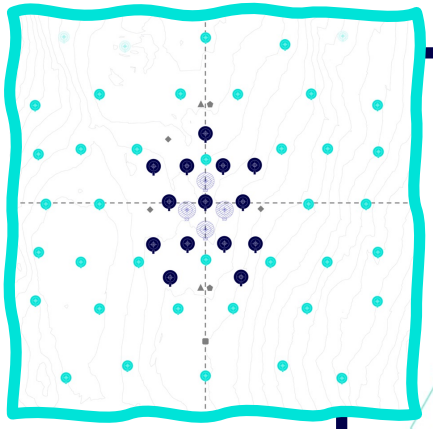
2 CTAO science

3 VLBI-CTAO synergies

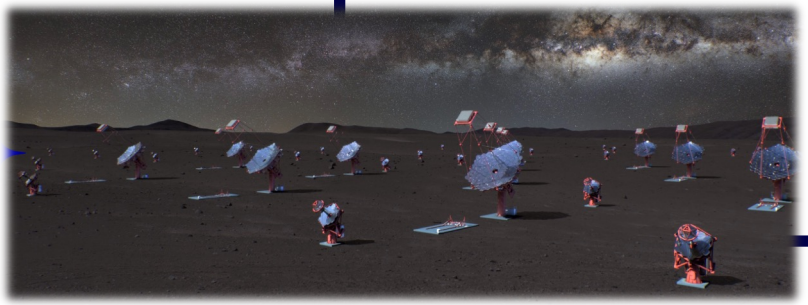
1 CTAO. What’s in the project.

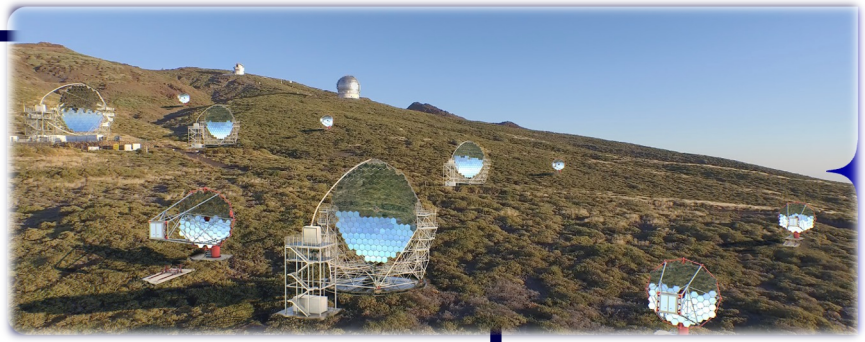
Alpha Configuration

One observatory: two arrays. North (ORM), South (ESO Paranal)

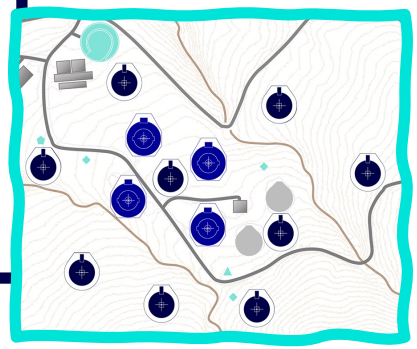


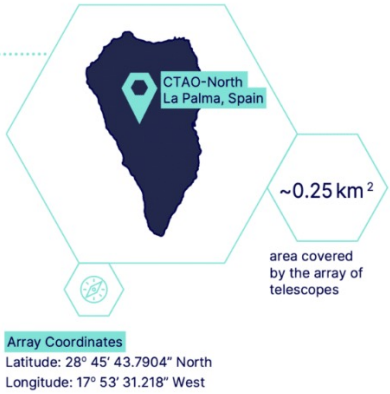
CTAO Southern Array
14 MSTs
37 MSTs

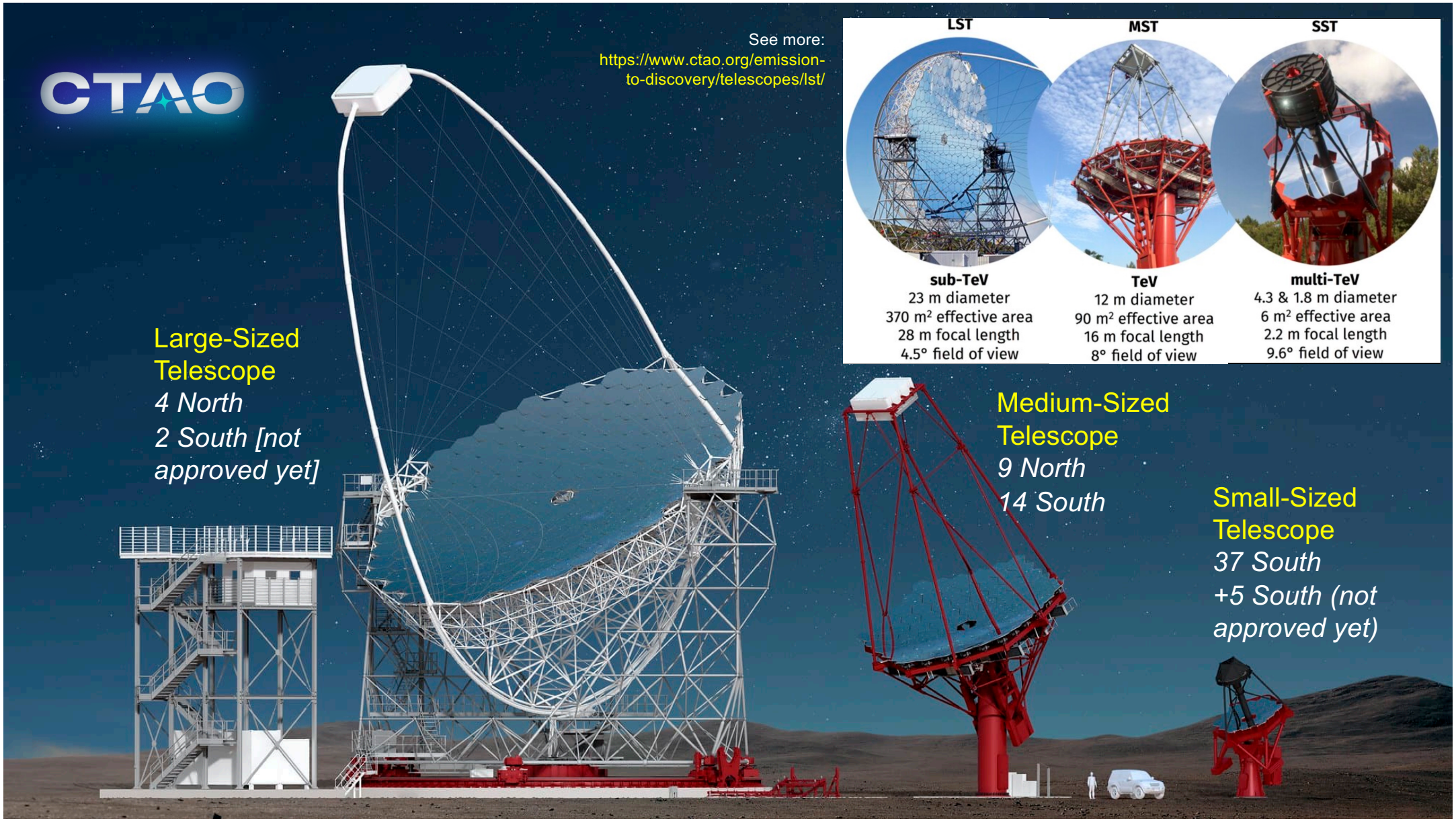




CTAO Northern Array
4 LSTs
9 MST






CTAO
See more:
https://www.ctao.org/emission-to-discovery/telescopes/lst/
LST
MST
SST
sub-TeV
23 m diameter
370 m² effective area
28 m focal length
4.5° field of view
TeV
12 m diameter
90 m² effective area
16 m focal length
8° field of view
multi-TeV
4.3 & 1.8 m diameter
6 m² effective area
2.2 m focal length
9.6° field of view
Large-Sized Telescope
4 North
2 South [not approved yet]
Medium-Sized Telescope
9 North
14 South
Small-Sized Telescope
37 South
+5 South (not approved yet)

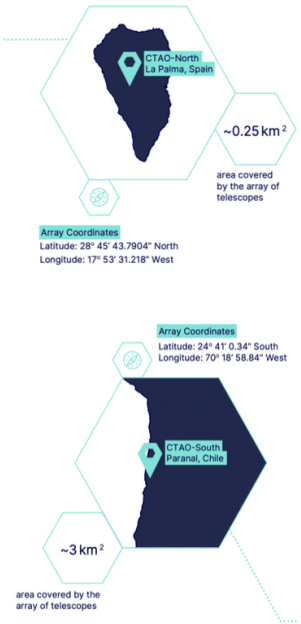
Status

Buckle seat belts…finally about to start!

The CTAO ERIC is established (European Research Infrastructure Center) on 7th Jan 2025

- **Headquarter**: Bologna [here]
- **Science Data Management Center:** DESY Zeuthen

APPROVED



2028	2029	2030	2031	2032
Early Science OP 1	Early Science OP 2	Early Science OP 3	OP1	
4x LST 1x MST	4x LST 5x MST	4x LST 9x MST	4x LST 9x MST	
Observatory Release 2	Observatory Release 3	Observatory Release 4	Official Start of Operations	
Verified in 2028 AO Call in 2029	Verified in 2029 AO Call in 2030	Verified in 2030 AO Call in 2031	AO Call in 2032	
2x MST 5x SST	TBD	14x MST 37x SST	14x MST 37x SST	

Complete!

Open-Observatory

A novelty in the field

Current generation:
H.E.S.S., MAGIC, VERITAS
operated as experiments:

- Proprietary data format
- Private data access
- Limited guest observation program

DATA FORMAT

- CTAO has defined a data format (DL3) compliant with VODF and subscribed by HE, VHE + nu communities
- CTAO science analysis tools based on gammapy [www.gammapy.org]

https://vodf.readthedocs.io/

VODF
very-high-energy open data format

https://gammapy.org/

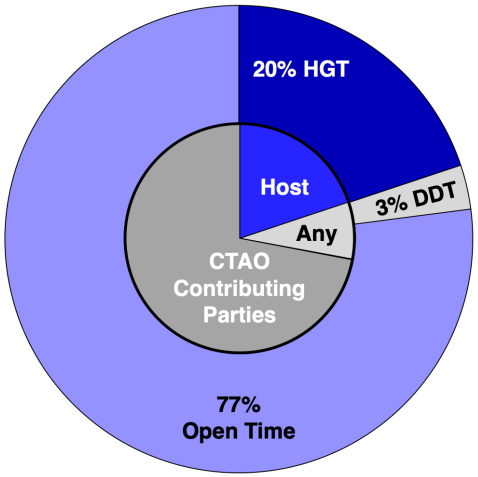
A Python package for gamma-ray astronomy

OBSERVING TIME

<10y: KSP + HGT + DDT/Open*

>10y: HGT + DDT/Open*

*8% to non contributing parties



DATA ACCESS

<1y proprietary period

>1y shared via CTAO Science Data Portal

CTAO Science Framework

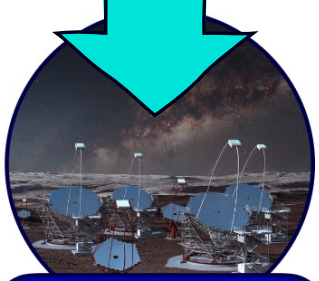
In prep: Verification and Validation Science Cases with Community Involvement

CTAO Construction

- Roads, data centers, foundations, infrastructure
- CTAO Software

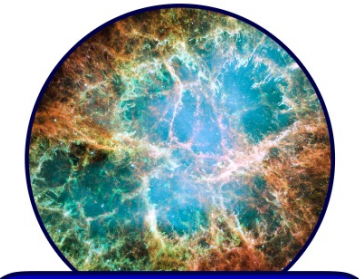
IKC Construction

- Telescopes
- Array Common Elements
- Commission of array elements
- CTAO software



Array Commissioning

- Integration, verification, and validation of array elements and software
- Science verification of intermediate array configurations



Early Science

- Public call for proposals
- Guaranteed observing time for Contributors to construction project

Steady State Operations

- Full Alpha configuration
- Normal Operations begin
- KSP begins

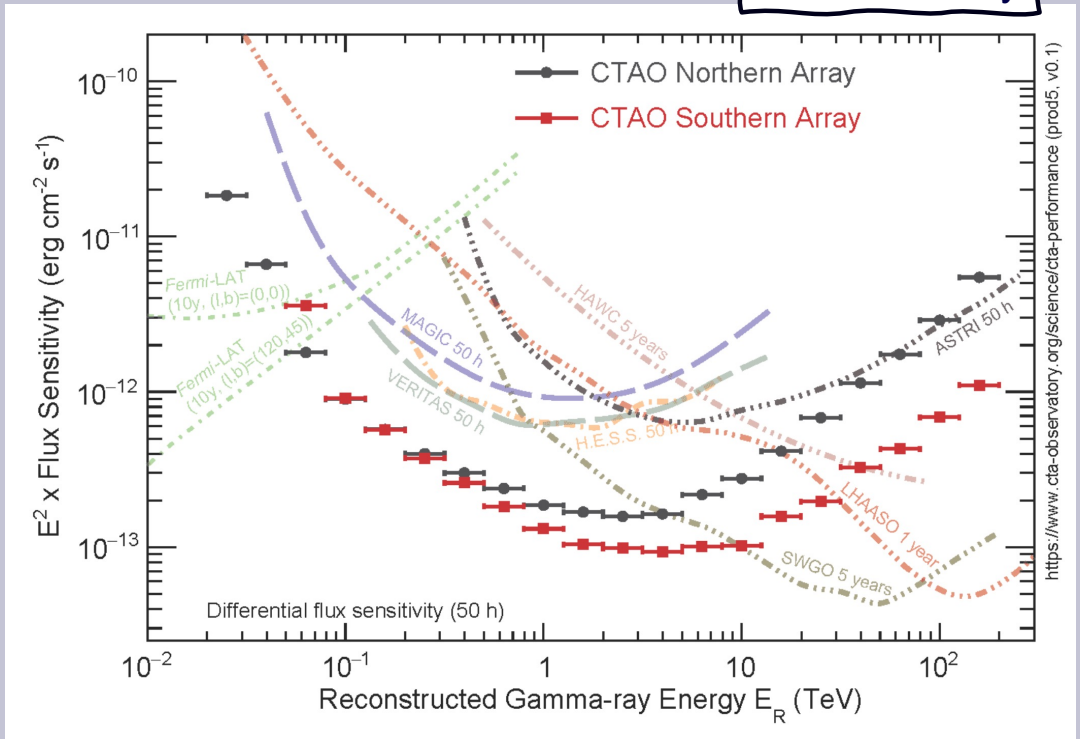
Now | 2027 - 2029 | 2028 - 2030 | 2030+

Science Data Challenge in Q4 2026

- Fully open and blind
- Get external acquainted with CTAO data
- Award!

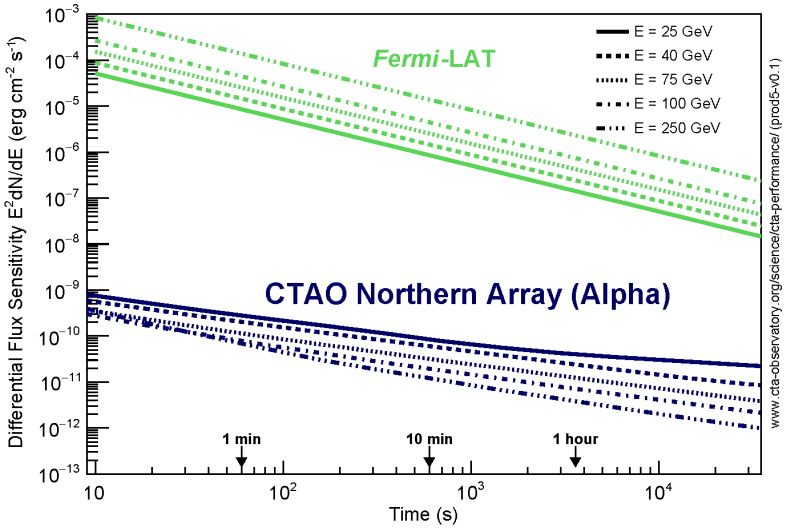
Performance and context: sensitivity

Flux sensitivity



- Complements Fermi-LAT (LE) and LHAASO (HE)
- 10x sensitivity than prev. generation
- More sensitive instrument between 0.1-30 TeV

Transient sensitivity

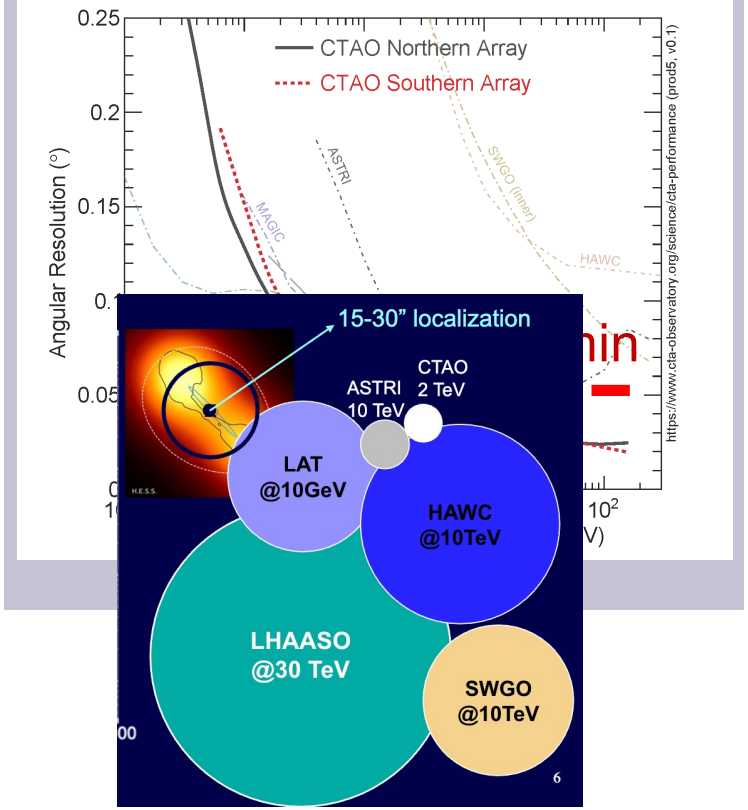


- Unbeaten transient sensitivity!
- Orders of magnitudes more sensitive for duration below 1h
- Cons: field of view of <10deg

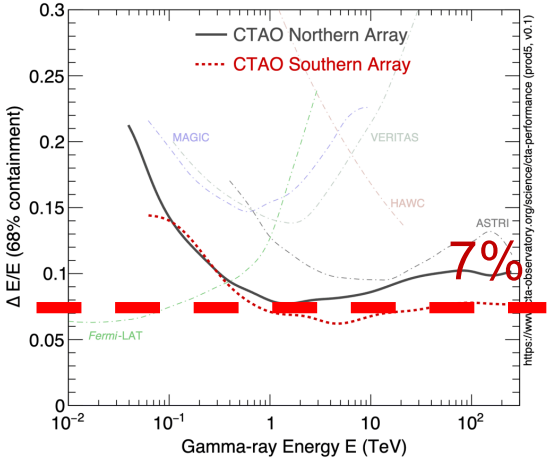
Not only sensitivity

The quantum leap from previous generation

Angular Resolution

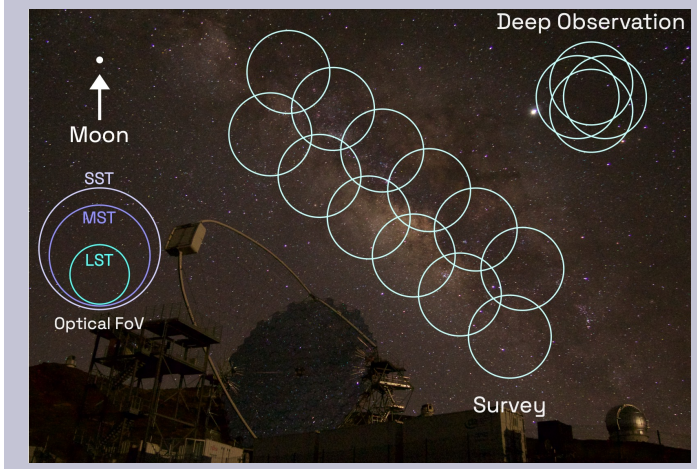


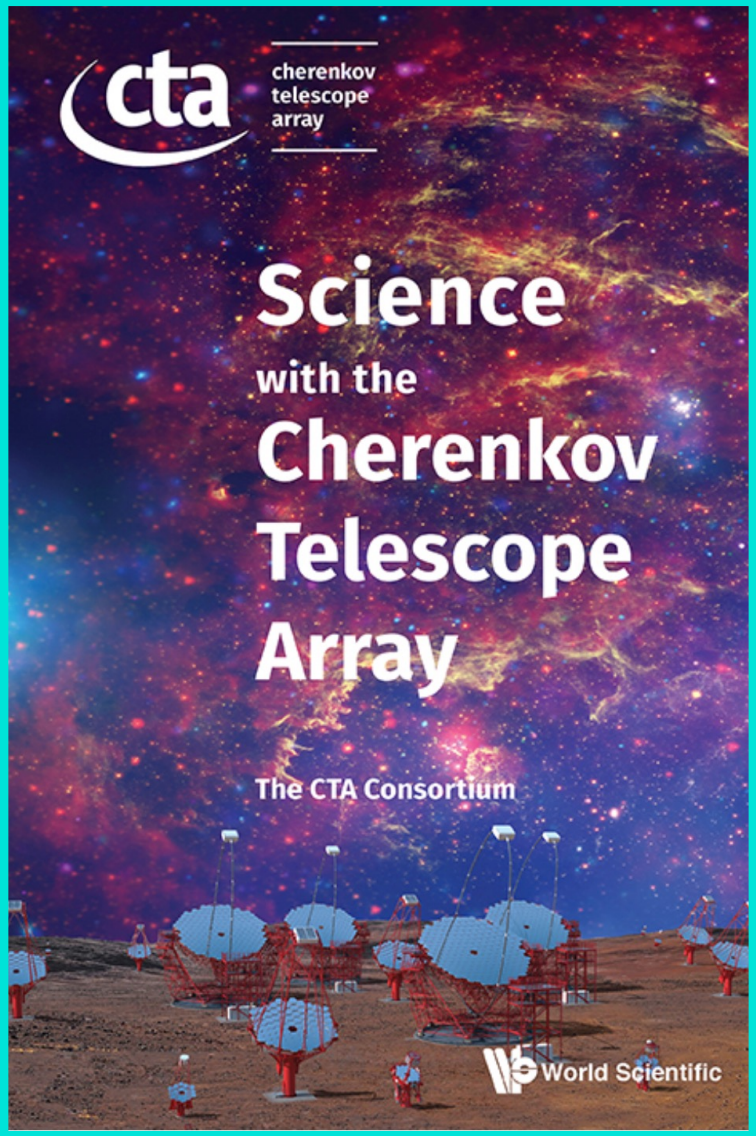
Energy Resolution



Under investigation:
- Subarrays obs.
- Divergent obs.

Obs. Modes and Field of view





← 2019

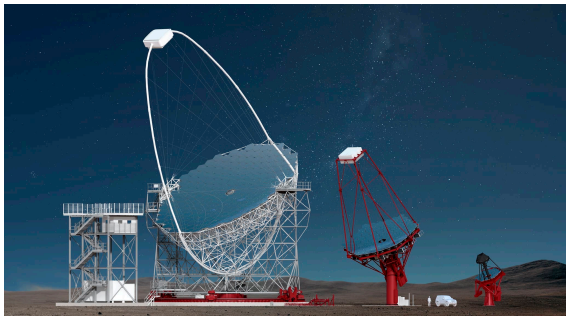
2 Science with CTAO

Science with the Cherenkov Telescope Array

https://doi.org/10.1142/10986 | March 2019
Pages: 364
By (author): The CTA Consortium

Now, to science

Next generation.



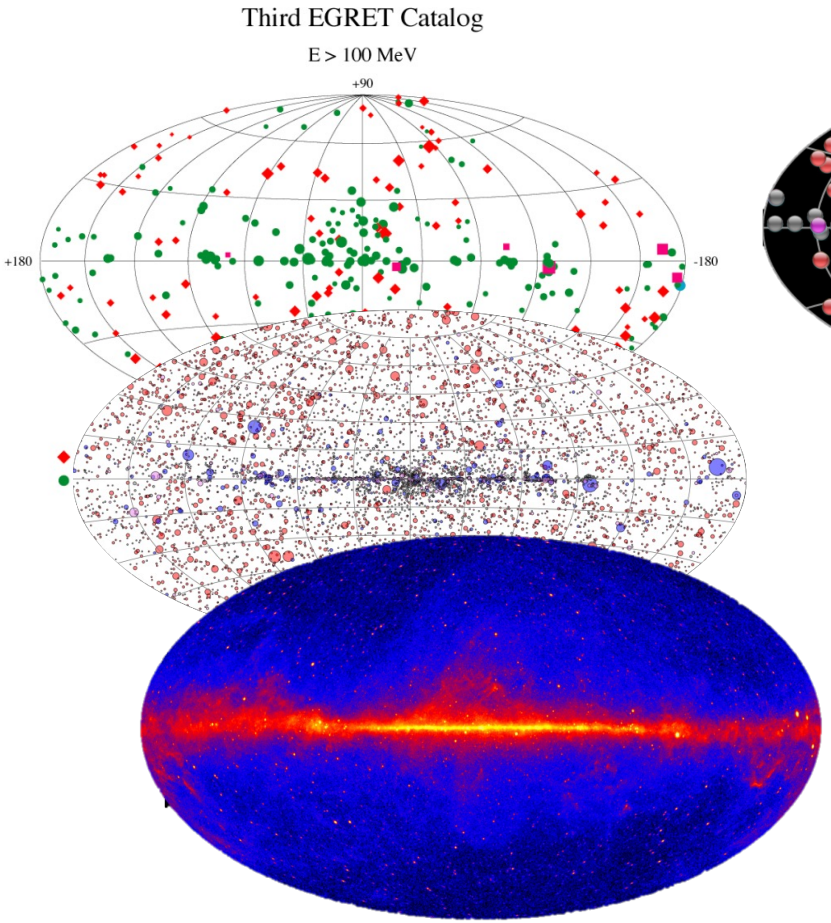
CTA's quantitative improvement

Quantity	Pre-CTA (H.E.S.S./MAGIC/VERITAS)		CTA expected
Energy range	0.05–20 TeV	~2x	0.02–300 TeV
Flux sensitivity	10^{-12}–10^{-11} erg cm^{-2} s^{-1}	~10x	10^{-13}–10^{-14} erg cm^{-2} s^{-1}
Energy resolution	15–20 %	~3x	5–10 %
Angular resolution	0.1°	~5x	0.02°
Temporal resolution	minutes	~5x	tens of seconds

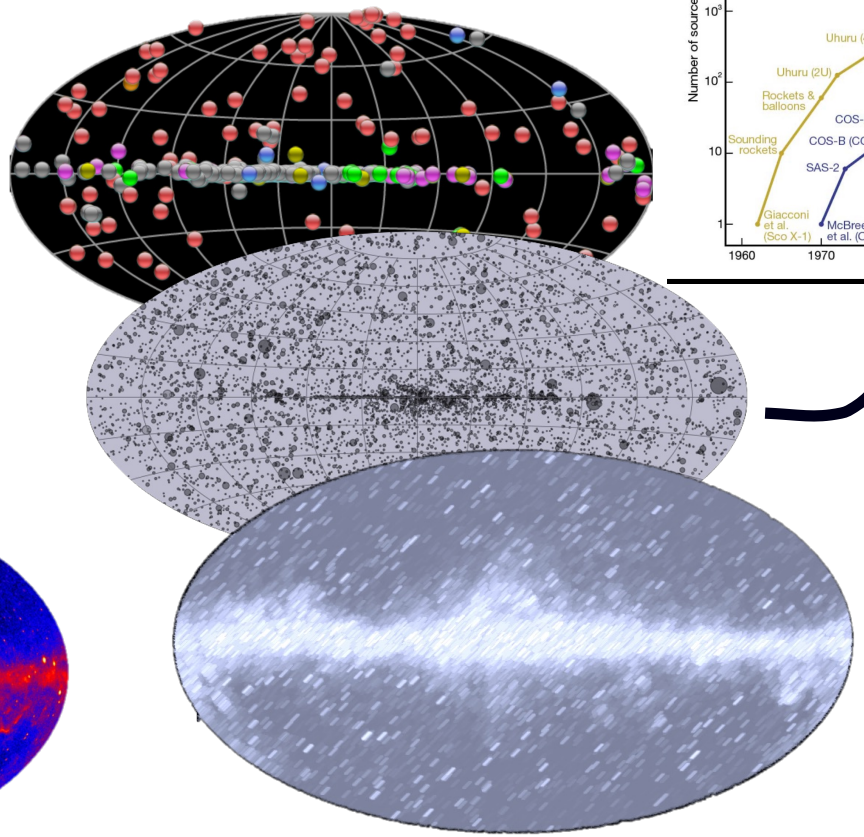
How this will shape CTAO science?

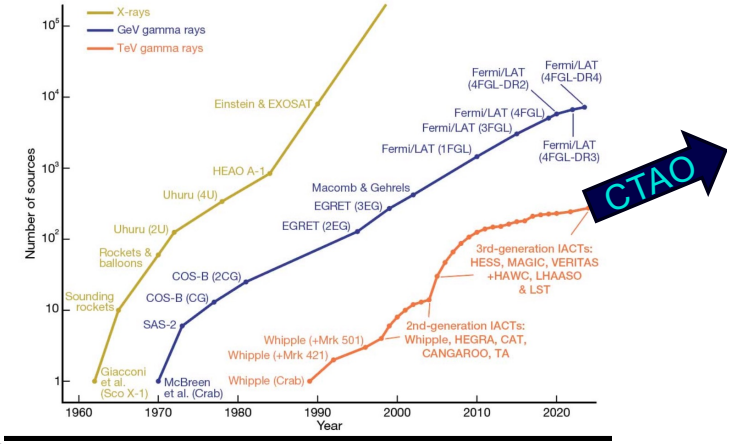
A revolution is coming

High-Energy



CTAO VHE





Kifune plot

CTAO science themes

- Understanding the Origin and Role of Relativistic Particles in the Universe
- Probing Extreme Environments
- Exploring Frontiers in Physics

Theme 1

Understanding the Origin and Role of Relativistic Particles in the Universe

- **Galactic PeVatrons**

  Identify sources capable of *accelerating cosmic rays to PeV* energies.

  Key targets: Galactic Center, young supernova remnants (SNRs),+.

- **Supernova Remnants (SNRs) and the Origin of Cosmic Rays**

  Study *acceleration, diffusion, and escape* of particles.

  Combine CTA data with Fermi, radio, and X-ray observations.

- **Pulsar Wind Nebulae (PWNe)**

  Examine leptonic acceleration, cooling, and nebular structure.

- **Binary Systems**

  Investigate *particle acceleration* in compact binaries, microquasars.

- **Star-forming Systems**

  Explore *collective acceleration* in starburst regions and OB associations.

- **Cosmic-Ray Diffusion and Propagation**

  Probe *cosmic-ray transport* through molecular clouds and diffuse emission.

Theme 2

Probing Extreme Environments

- **Active Galactic Nuclei (AGN)**
  Study particle acceleration, jet formation, B-field and variability.
  Profound transient and multi-w program
- **Radio Galaxies and Misaligned AGN**
  Test jet models and large-scale VHE emission.
- **Gamma-Ray Bursts (GRBs)**
  Explore prompt and afterglow VHE emission; Lorentz factor limits; new physics.
- **Pulsars and Magnetospheres**
  Search for VHE pulsed emission; constrain emission zones.
- **The Galactic Center Environment as a whole**
  Study diffuse gamma-ray emission, potential PeVatron, and dark matter.
- **Clusters of Galaxies**
  Probe cosmic-ray confinement, cluster energetics and intracluster medium heating.

Theme 3

Exploring Frontiers in Physics

- **Dark Matter Searches**

  WIMP *annihilation/decay* from Galactic Center, dwarf spheroidals, galaxy clusters.

- **Lorentz Invariance Violation (LIV)**

  Use GRBs and AGN flares to test quantum-gravity effects through *time-delay and threshold effects*

- **Axion-like Particles (ALPs)**

  Search for photon–ALP mixing through *irregularities in spectra and photon-recovery*.

- **Cosmic-Ray Electron Spectrum**

  Measure *local spectrum* up to tens of TeV to test nearby sources.

  Expected performance in *heavier CRs*

- **Extragalactic Background Light (EBL)**

  Constrain EBL density through *attenuation of AGN and GRB spectra.*

- **Cosmology and Intergalactic Magnetic Fields (IGMF)**

  Study pair cascades and delayed emission to probe IGMF strength

New: Intensity Interferometry

Key Science Projects (KSPs)

Ideas put forward by CTAO Consortium

- KSP will be awarded to the CTAO Science Collaboration consisting of contributors to the construction project
- Common ideas:
  - Long/multi-y observations (300+h),
  - Several science cases,
  - Coherent analysis fashion

FURTHER READINGS

- **Galactic Centre**: Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre JCAP 01 (2021) 057
- **Galactic Plane Survey**: Prospects for a survey of the galactic plane with the Cherenkov Telescope Array JCAP 10 (2024) 081

Galactic transient sources with the Cherenkov Telescope Array Observatory, MNRAS 540 (2025) 1, 205

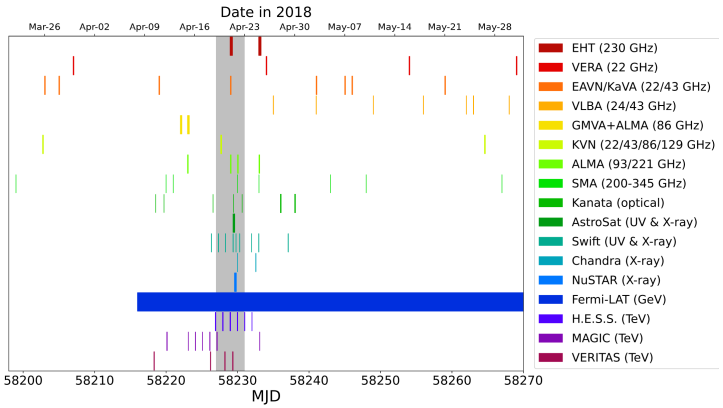
- **Large Magellanic Cloud**: Sensitivity of the Cherenkov Telescope Array to TeV photon emission from the Large Magellanic Cloud MNRAS 523 (2023) 4, 5353
- **Dark Matter Programme:** Prospects for γ-ray observations of the Perseus galaxy cluster with the Cherenkov Telescope Array JCAP 10 (2024) 004, Dark matter line searches with the Cherenkov Telescope Array JCAP 07 (2024) 047, Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation JCAP 02 (2021) 048, **Prospects for dark matter observations in dwarf spheroidal galaxies with the Cherenkov Telescope Array Observatory** MNRAS 2025

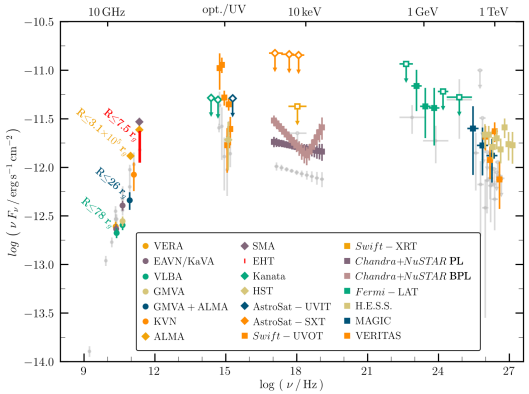
3 Physics cases with VLBI synergies

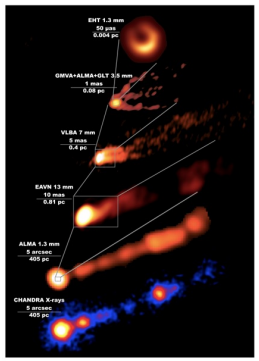
0. VLBI and IACTs so far, e.g:

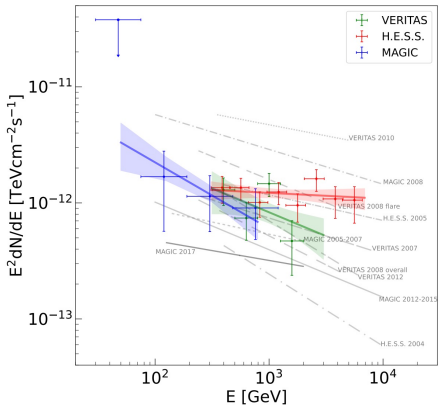
No specific MOUs between VLBI and IACTs (to my knowledge)

Broadband multi-wavelength properties of M87 during the 2018 EHT campaign including a very high energy flaring episode★









Coordinated campaigns to understand origin of VHE emission

Astrophysics > High Energy Astrophysical Phenomena

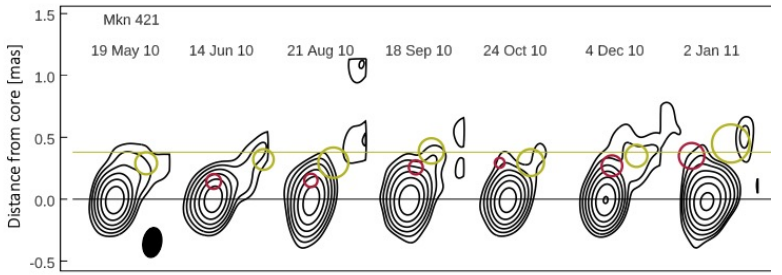
[Submitted on 10 Sep 2025]

Time-Dependent Modeling of the Sub-Hour Spectral Evolution During the 2013 Outburst of Mrk 421

Astrophysics > High Energy Astrophysical Phenomena

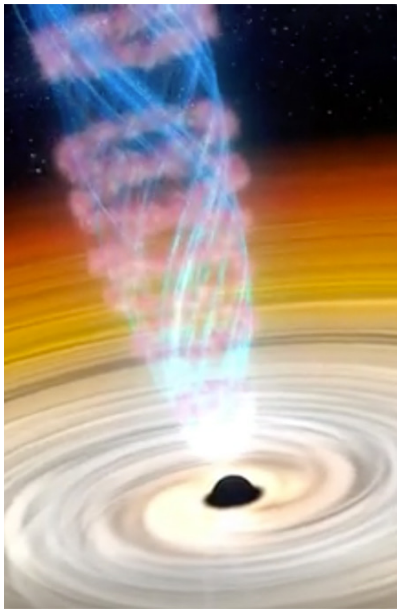
[Submitted on 7 Jan 2025]

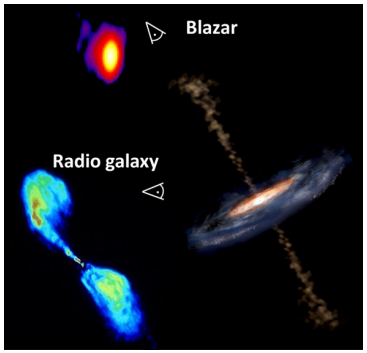
Characterization of Markarian 421 during its most violent year: Multiwavelength variability and correlations



Knots localization (VLBA)
Dopple factor crisis

1/ AGN Jets and Relativistic Outflows





Physical overlap:

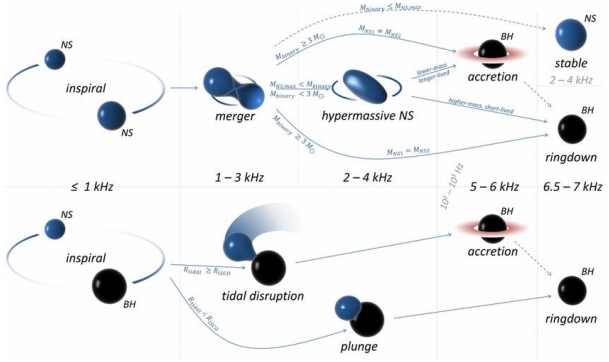
Both CTAO and VLBI probe the innermost regions of AGN jets — CTAO via γ-ray emission (inverse Compton, hadronic interactions), and VLBI via synchrotron radio emission tracing the jet base.

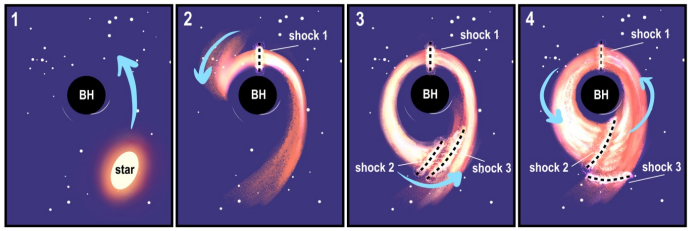
Synergies:

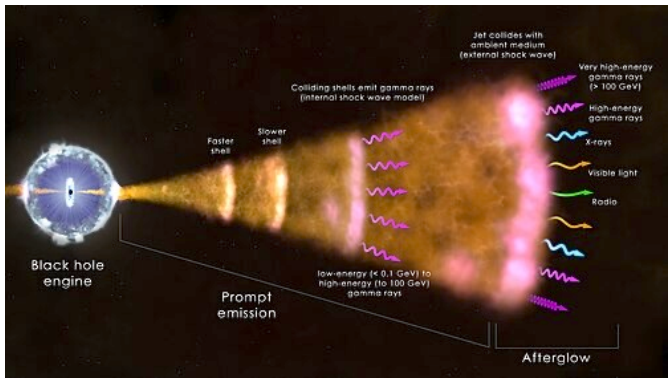
- **Multi-zone modeling**
  VLBI resolves the *structure* of the jet (knots, core shifts, collimation, magnetic field), CTAO measures the *energetic output* (variability, high-energy spectrum).
- **Time-domain**
  Simultaneous VLBI and CTAO observations of γ-ray flares can identify where in the jet γ rays originate (core vs downstream knot).
- **Magnetic field diagnostics**
  VLBI polarimetry constrains magnetic field geometry; CTAO spectral and temporal behavior constrains particle acceleration efficiency in those fields.

Class	Jet	CTAO–VLBI Synergy Focus
Blazars	Aligned	Variability, flare correlation, Doppler boosting, emission zone localization
Radio galaxies	Misaligned	Spatially resolving the TeV region, jet collimation, magnetohydrodynamics near the core

2/ All Transients and Variable Sources







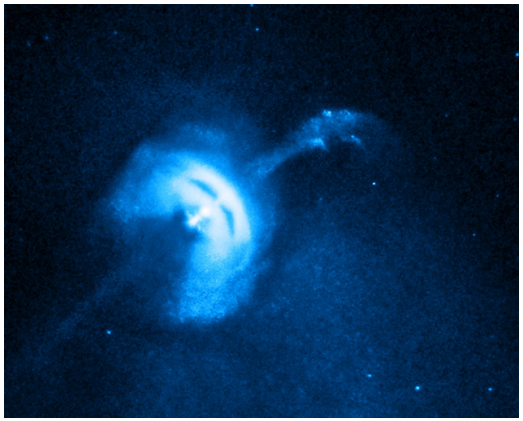
Targets:

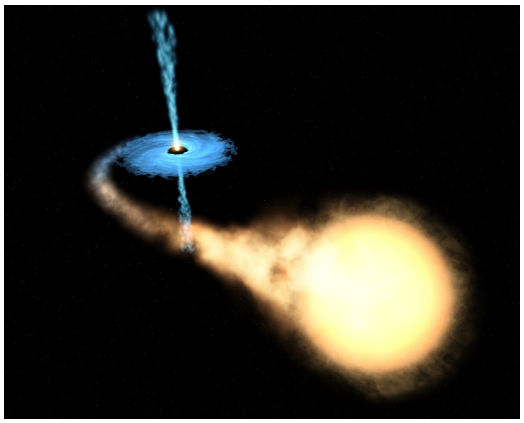
Blazars, TDEs, GRBs, compact binaries, novae, magnetars.

Synergies:

- **Localization:**
  Combining VLBI and CTAO both helps *pinpoint* the emission region and identify multi-messenger counterparts.
- **Jet formation**
  Combining VLBI and CTAO one gets temporal sequence of jet launch and particle acceleration.
- **Follow-up network**
  CTAO alerts could trigger VLBI campaigns (especially e-EVN or ngVLA) to study the evolution of the source on timescales of days–weeks.

3. Galactic Compact Objects





Targets:

Pulsar wind nebulae, X-ray binaries, magnetars, nova

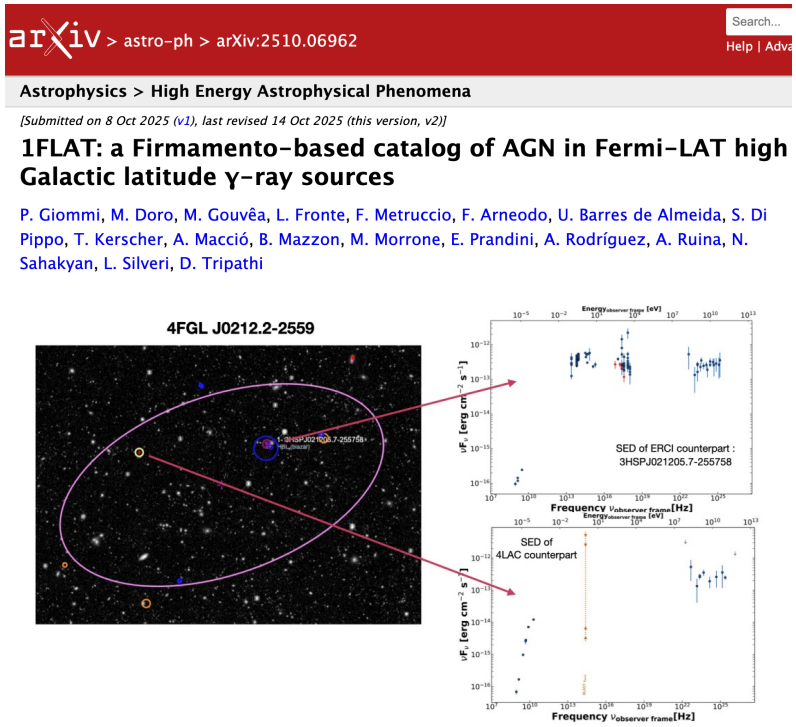
Synergies:

VLBI detects compact radio outflows or structural changes in binaries during outbursts.

CTAO detects high-energy γ rays from inverse Compton or hadronic processes.

→ Jointly probe **shock acceleration regions**, **magnetization**, and **particle escape**.

4. Astrometric and Environmental Studies



arXiv > astro-ph > arXiv:2510.06962

Search... Help | Adva

Astrophysics > High Energy Astrophysical Phenomena

[Submitted on 8 Oct 2025 (v1), last revised 14 Oct 2025 (this version, v2)]

1FLAT: a Firmamento-based catalog of AGN in Fermi-LAT high Galactic latitude γ-ray sources

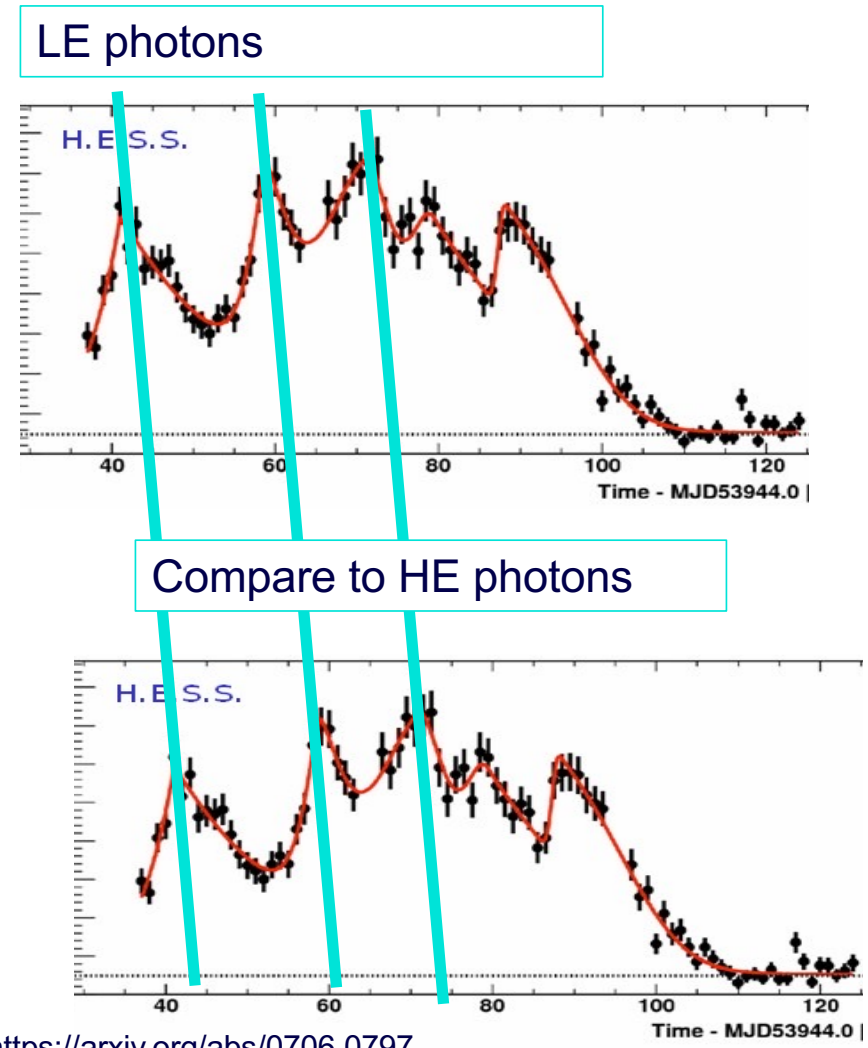
P. Giommi, M. Doro, M. Gouvêa, L. Fronte, F. Metruccio, F. Arneodo, U. Barres de Almeida, S. Di Pippo, T. Kerscher, A. Macció, B. Mazzon, M. Morrone, E. Prandini, A. Rodríguez, A. Ruina, N. Sahakyan, L. Silveri, D. Tripathi

Figure 5. Example of a 4FGL proposed counterpart that is not confirmed by *f*, which proposed a second blazar. The 4FGL counterpart (lower SED on the right) has a strong radio but has no infrared, optical or X-ray flux, the SED of the 3HSPJ021205.7-255758, the *f* counterpart, clearly fits well with that of an HSP counterpart.

- VLBI provides **astrometry** of radio counterparts to γ-ray sources → improved source association and population studies.
  [see, e.g. 1FLAT catalog, https://arxiv.org/abs/2510.06962]

- VLBI studies of interstellar scattering, **absorption**, or Faraday rotation give environmental information crucial for *interpreting γ-ray attenuation and propagation* in galactic targets.

5. Fundamental Physics, e.g:



https://arxiv.org/abs/0706.0797

- **Lorentz invariance tests**

  Combining high-precision VLBI timing (e.g., in AGN flares) with CTAO timing of TeV photons can set limits on energy-dependent speed of light variations.

  VLBI supports LIV studies by improving source localization, timing accuracy, and emission-region characterization for γ-ray transients observed by CTAO.

- **Multi-messenger :** CTAO–VLBI synergy enhances counterpart identification for neutrino or gravitational-wave events.

CTAO-VLBI Coordination – Take Home

- **CTAO/VLBI observing campaigns:** coordinated programs already exist → they should be extended for CTAO northern and southern sites. This will be done basically through proposals
- **Alerts:** CTAO monitoring campaigns or flare detection could trigger VLBI
- **Data synergy:** CTAO light curves and VLBI imaging can be cross-correlated to trace jet evolution.

CONCLUSION

Complementarity in scale and synergic: CTAO probes particle populations (GeV–TeV electrons/protons), VLBI probes structure and magnetic fields — together they constrain jet energetics and composition.

Thanks