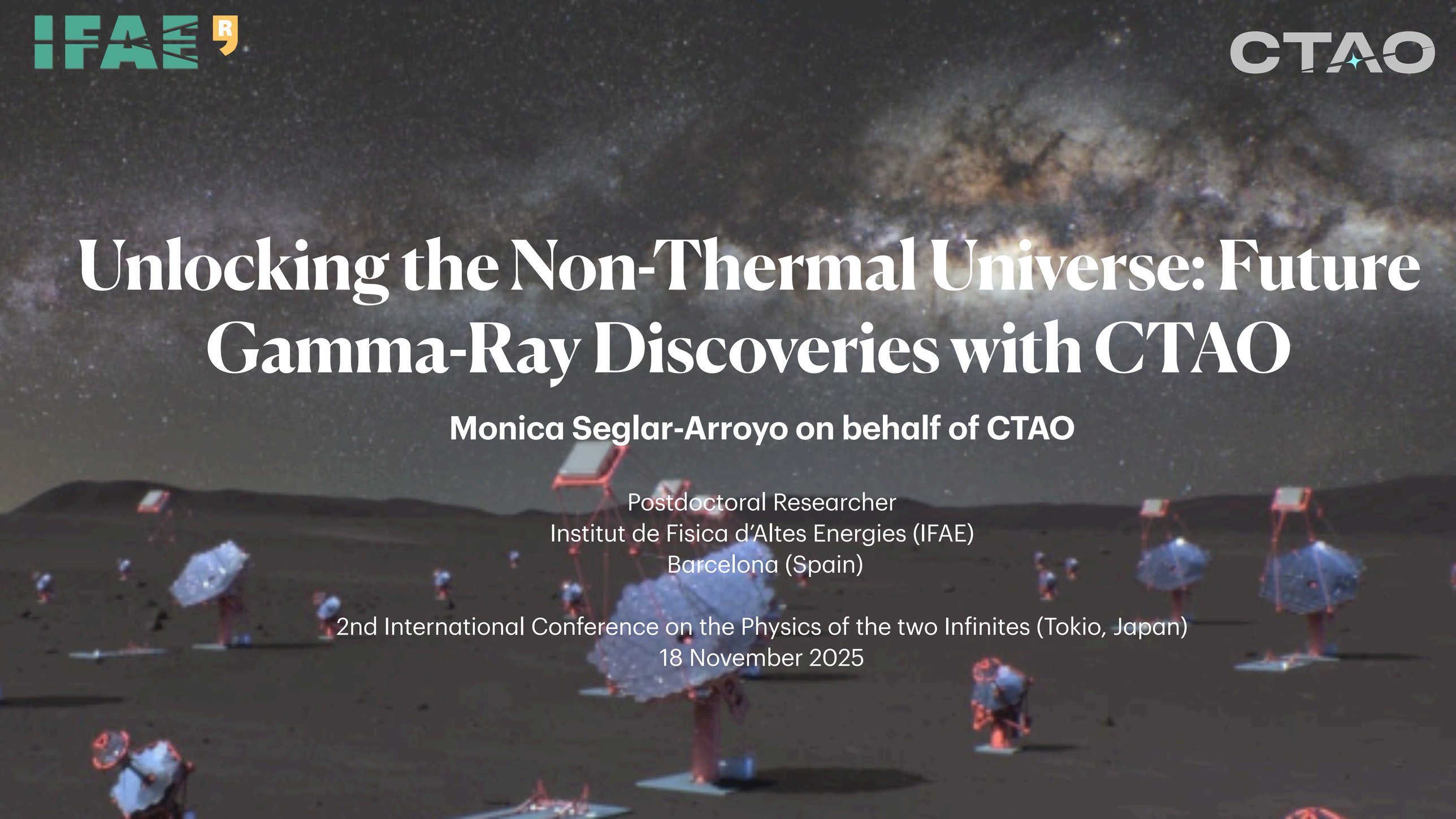


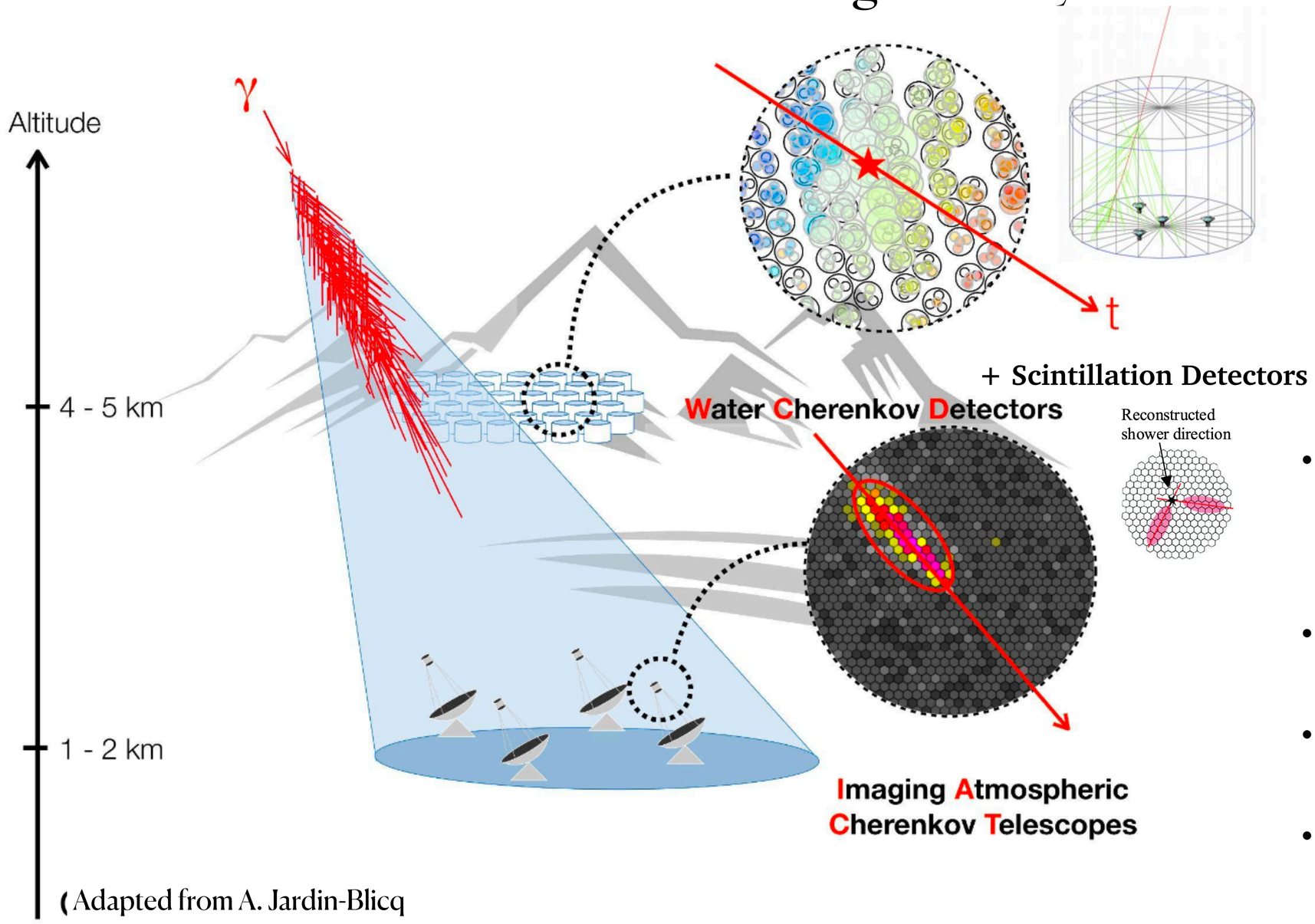
Unlocking the Non-Thermal Universe: Future Gamma-Ray Discoveries with CTAO

Monica Seglar-Arroyo on behalf of CTAO

Postdoctoral Researcher
Institut de Fisica d'Altes Energies (IFAE)
Barcelona (Spain)

2nd International Conference on the Physics of the two Infinites (Tokio, Japan)
18 November 2025

The VHE* gamma-ray band



- Photons are produced in acceleration processes (leptonic/hadronic) or via exotic mechanisms (dark matter annihilation/ decay)
- Photon are detected indirectly via the particles of the shower
- Complementary view of the gamma-ray sky via WCDs and IACTs!
- VHE energy range in these slides: 20GeV-300TeV

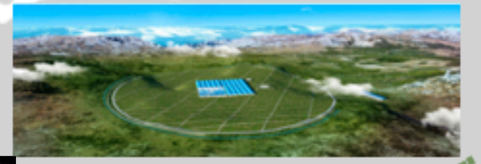
The VHE* gamma-ray band

Currently observing

Under construction

VERITAS

MAGIC



ASTRI

CTAO-N
(LST-1)

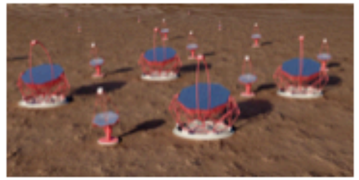
LHAASO
LACT

HAWC

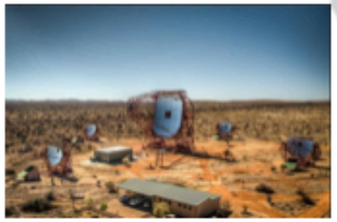
ALPACA

SWGO

CTAO-S



HESS



Mix of various generations of instruments currently studying the gamma-ray sky!

Check yesterday's talk by Armand Fiasson

A view into the current gamma-ray sky

Galactic: galactic center, pulsars, binaries, microquasars, novas, SNR, PWN, PeVatrons, halos, diffuse emission

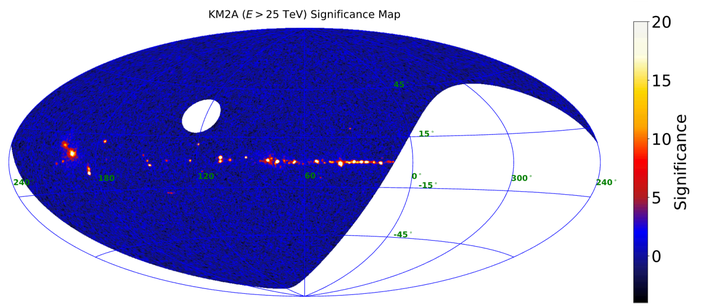
Extragalactic: AGN zoo, GRBs

Fundamental: Dark matter, IGMF, EBL, LIV, Ho..

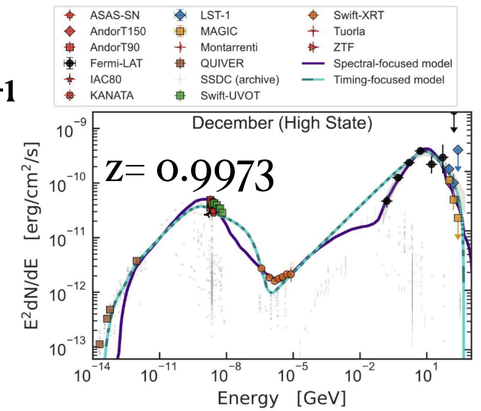
Multi-messenger and multi-wavelength connection

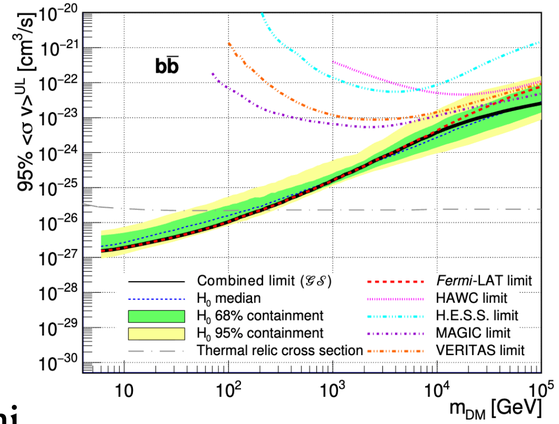
Check D. Kerszberg's talk on Wednesday

Galactic Plane, PeVatrons, Halos, LHAASO

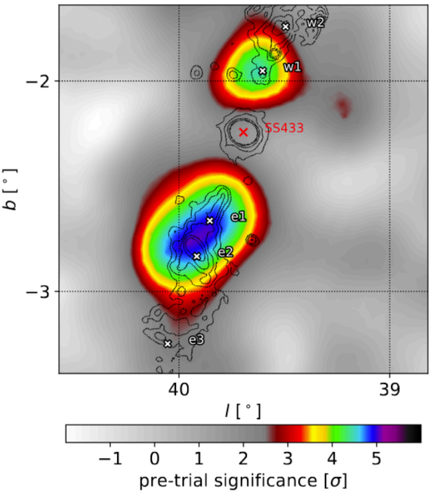


OP313, LST-1

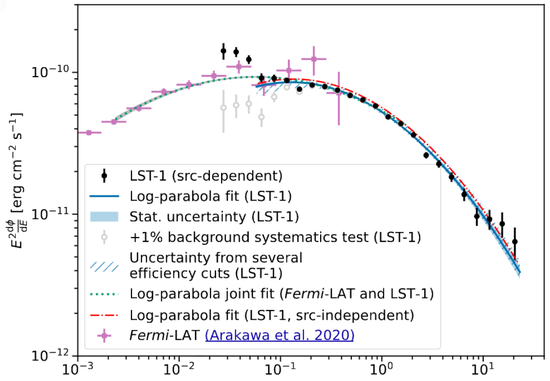




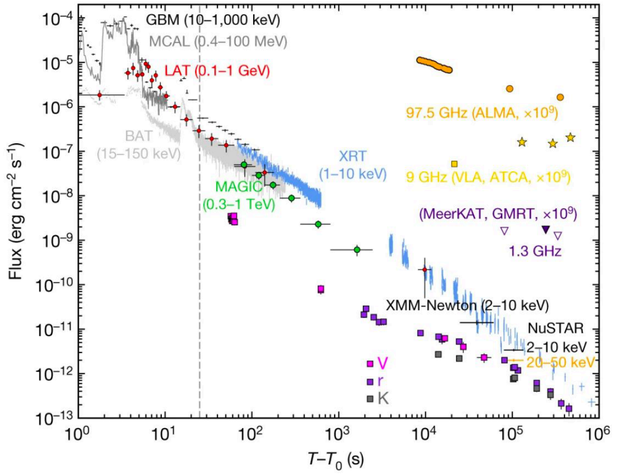
SS433, HAWC



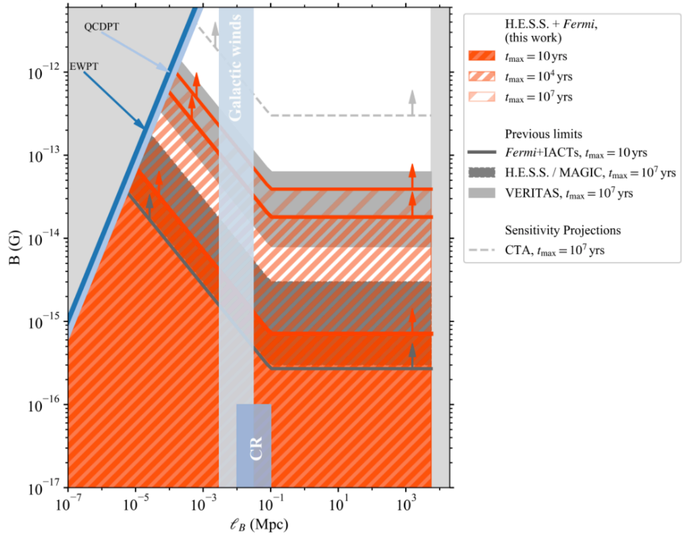
Crab Nebula, LST-1



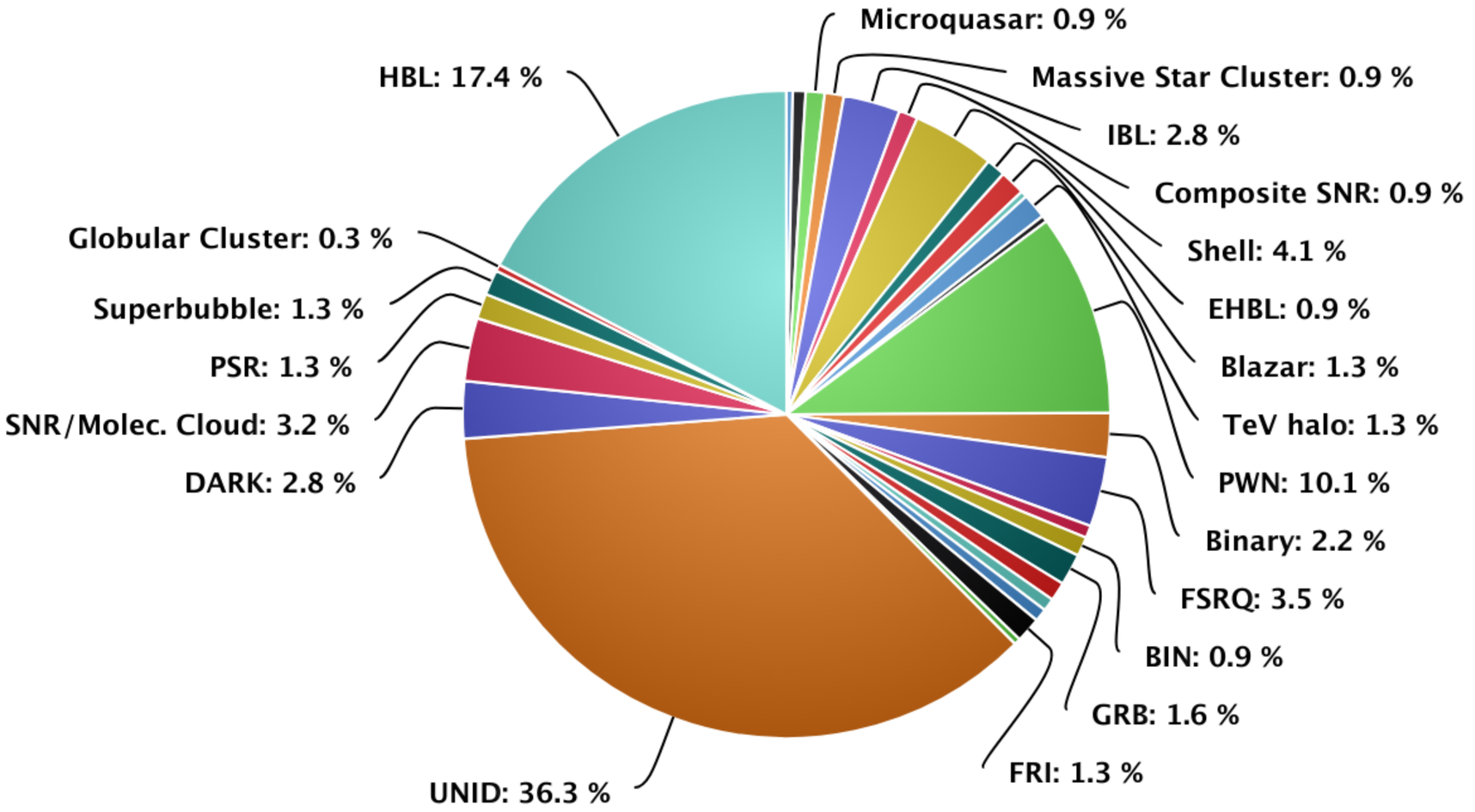
GRB190114C, MAGIC



IGMF, H.E.S.S. + Fermi



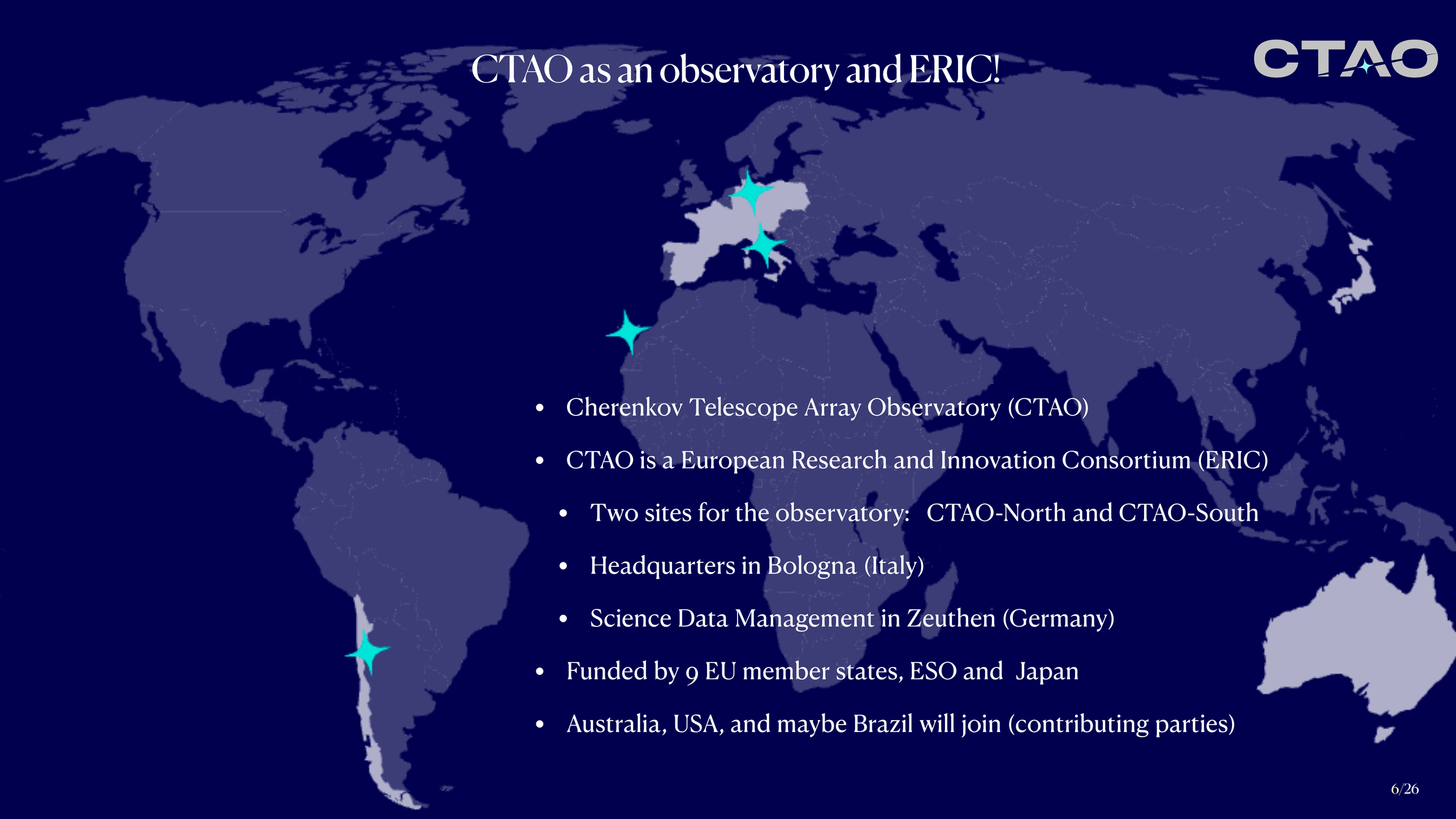
A view into the current gamma-ray sky: TeVCat



- 317 sources as of today
- Blazars (FSRQ, EHBL,HBL, IBL, LBL) are the most numerous TeV sources!
- Recent highlights: 90 new sources in the galactic plane from LHAASO (Cao et al. 2024))
- Novas, microquasars, GRBs as *recent* TeV sources!

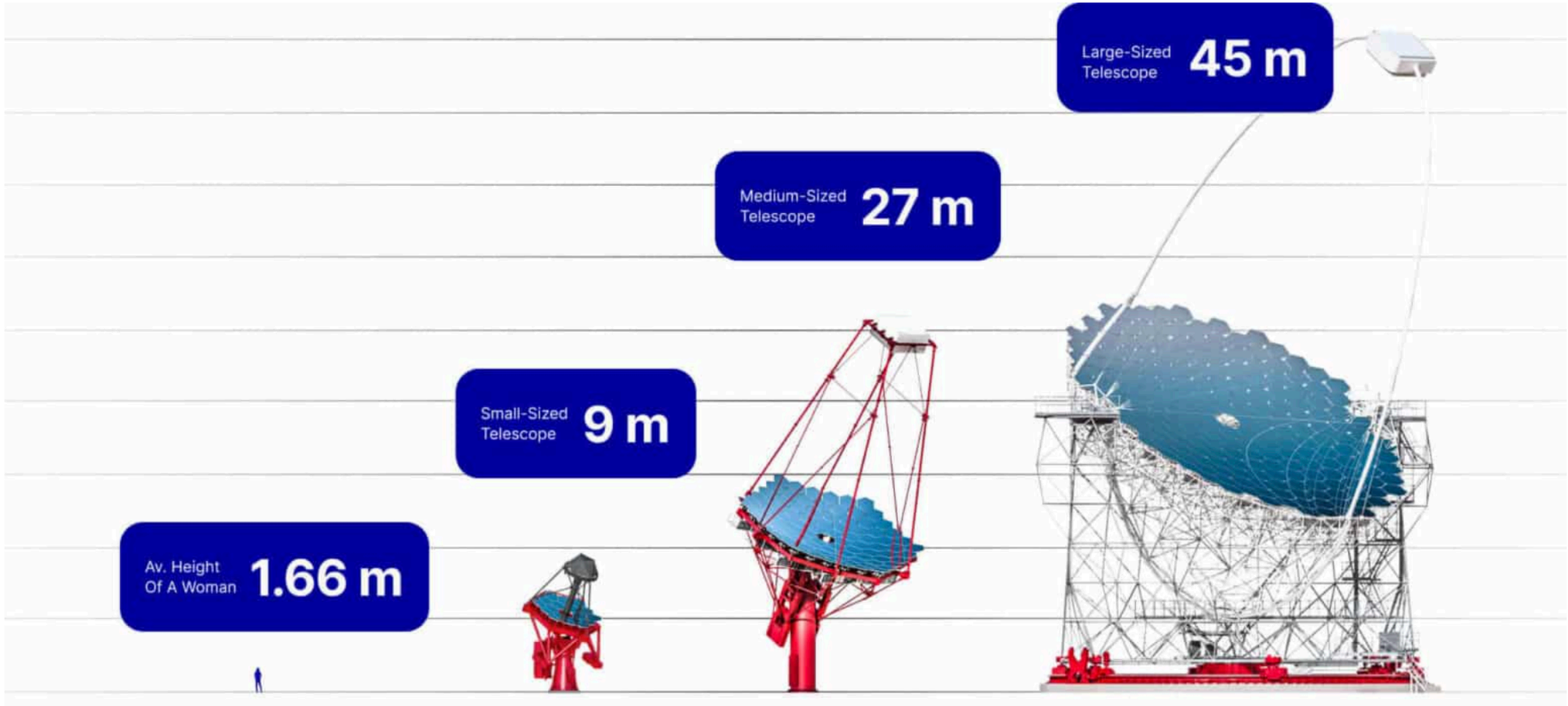
https://tevcat2.tevcat.org

CTAO as an observatory and ERIC!



- Cherenkov Telescope Array Observatory (CTAO)
- CTAO is a European Research and Innovation Consortium (ERIC)
  - Two sites for the observatory: CTAO-North and CTAO-South
  - Headquarters in Bologna (Italy)
  - Science Data Management in Zeuthen (Germany)
- Funded by 9 EU member states, ESO and Japan
- Australia, USA, and maybe Brazil will join (contributing parties)

Three different designs for the telescopes

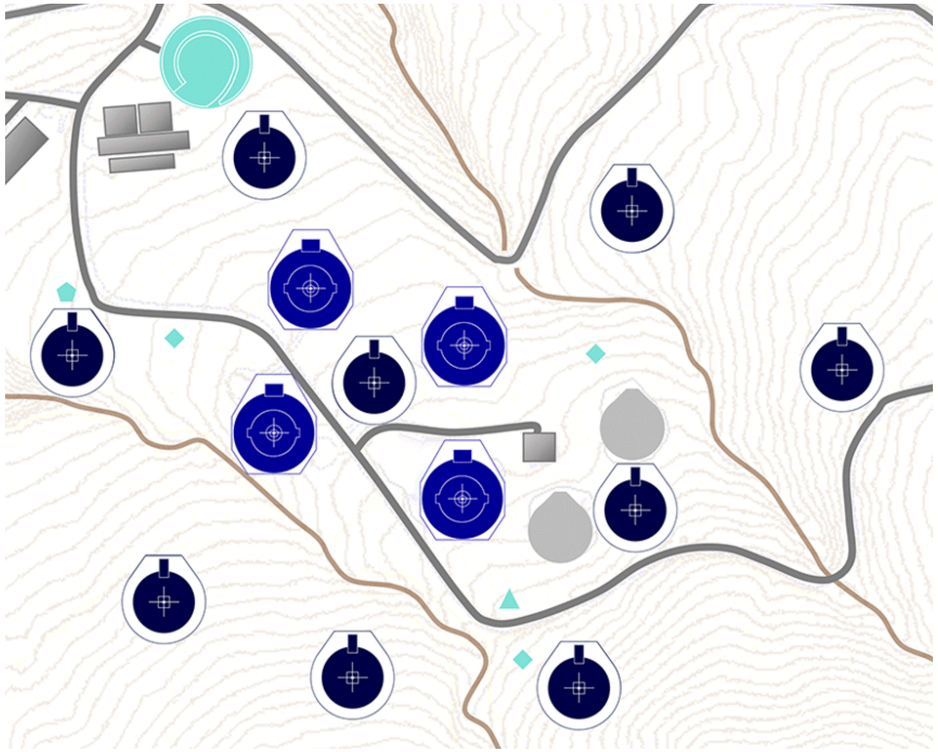


Small-Sized Telescope (SST)	Medium-Sized Telescope (MST)	Larged-Sized Telescope (LST)	
4.3 m reflector	12 m reflector	23 m reflector	Size
9° FoV	8° FoV	4.3° FoV	Field of View
5-300 TeV	0.150-5 TeV	0.2- 150 GeV	Energy range where telescope dominates

The Cherenkov Telescope Array Observatory

CTAO-North (La Palma, Spain): 4 LST and 9 MST

Alpha configuration

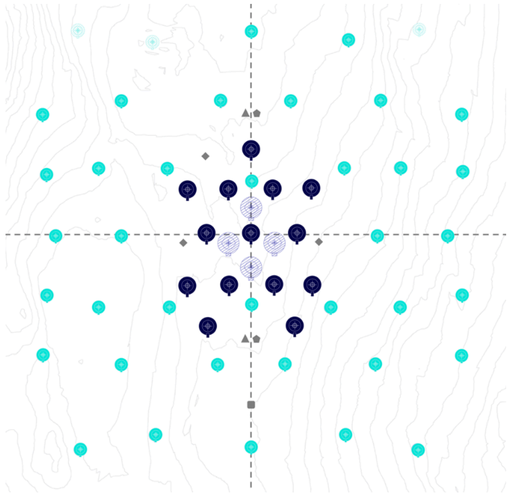


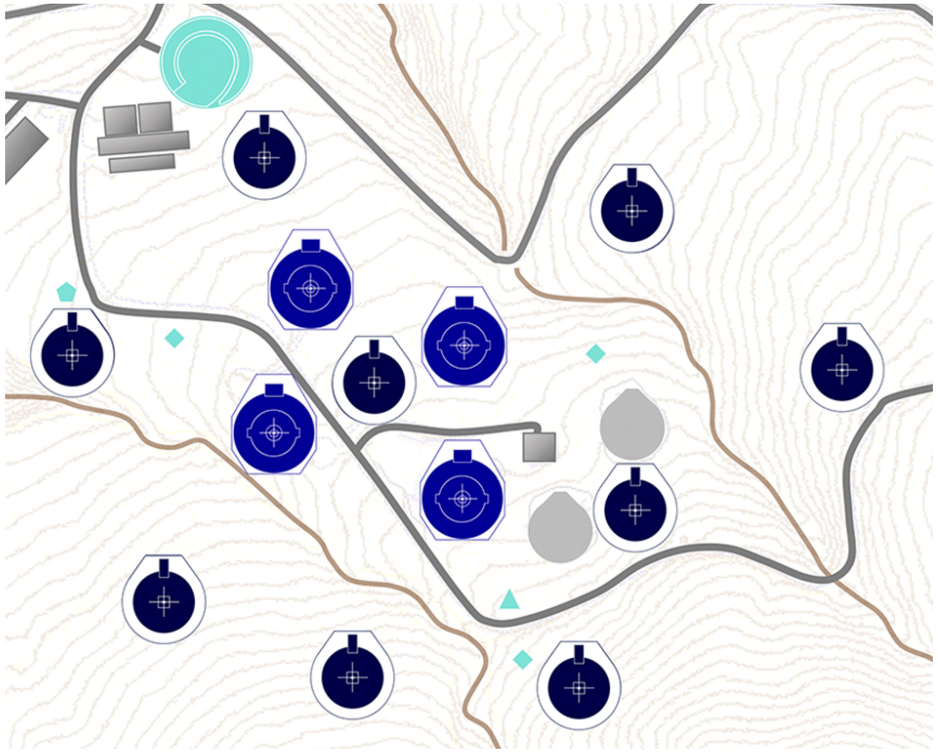
The Cherenkov Telescope Array Observatory

CTAO-North (La Palma, Spain): 4 LST and 9 MST

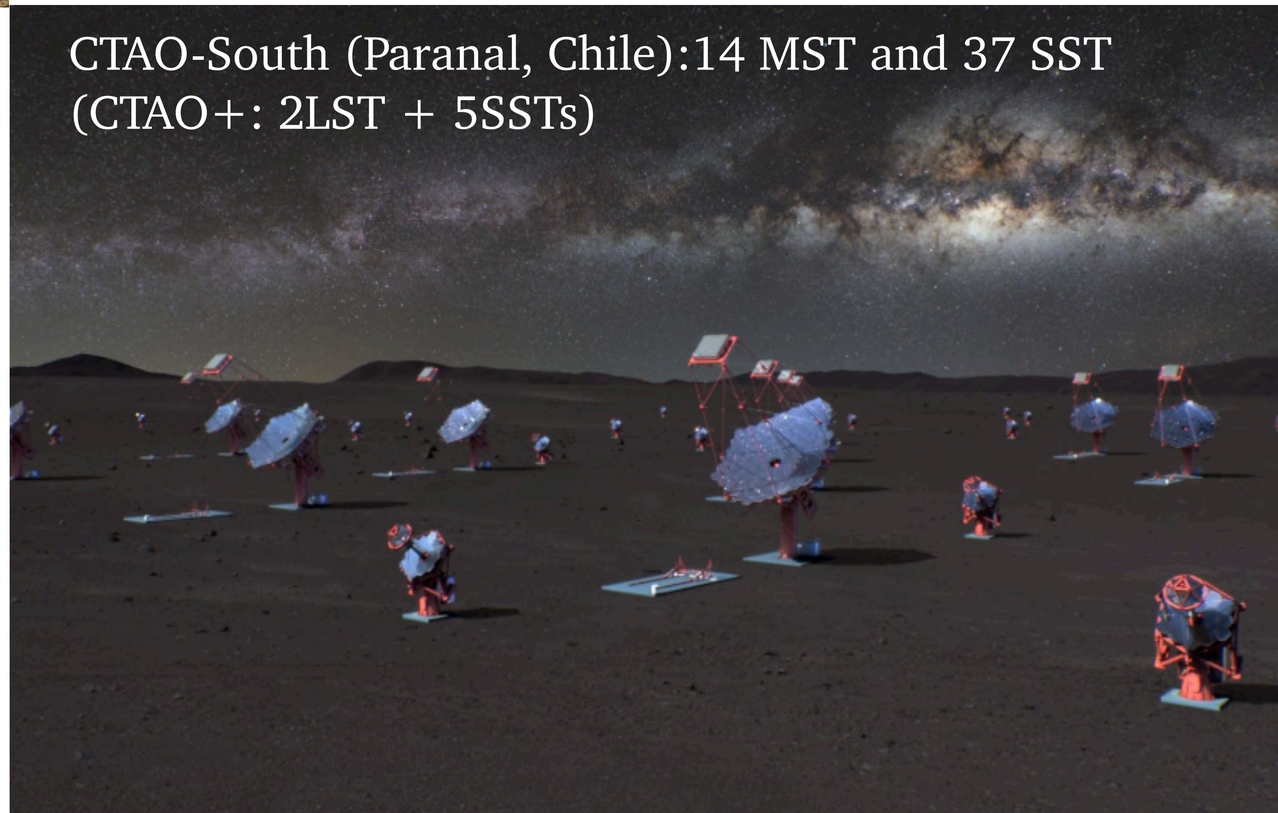
Alpha configuration

CTAO

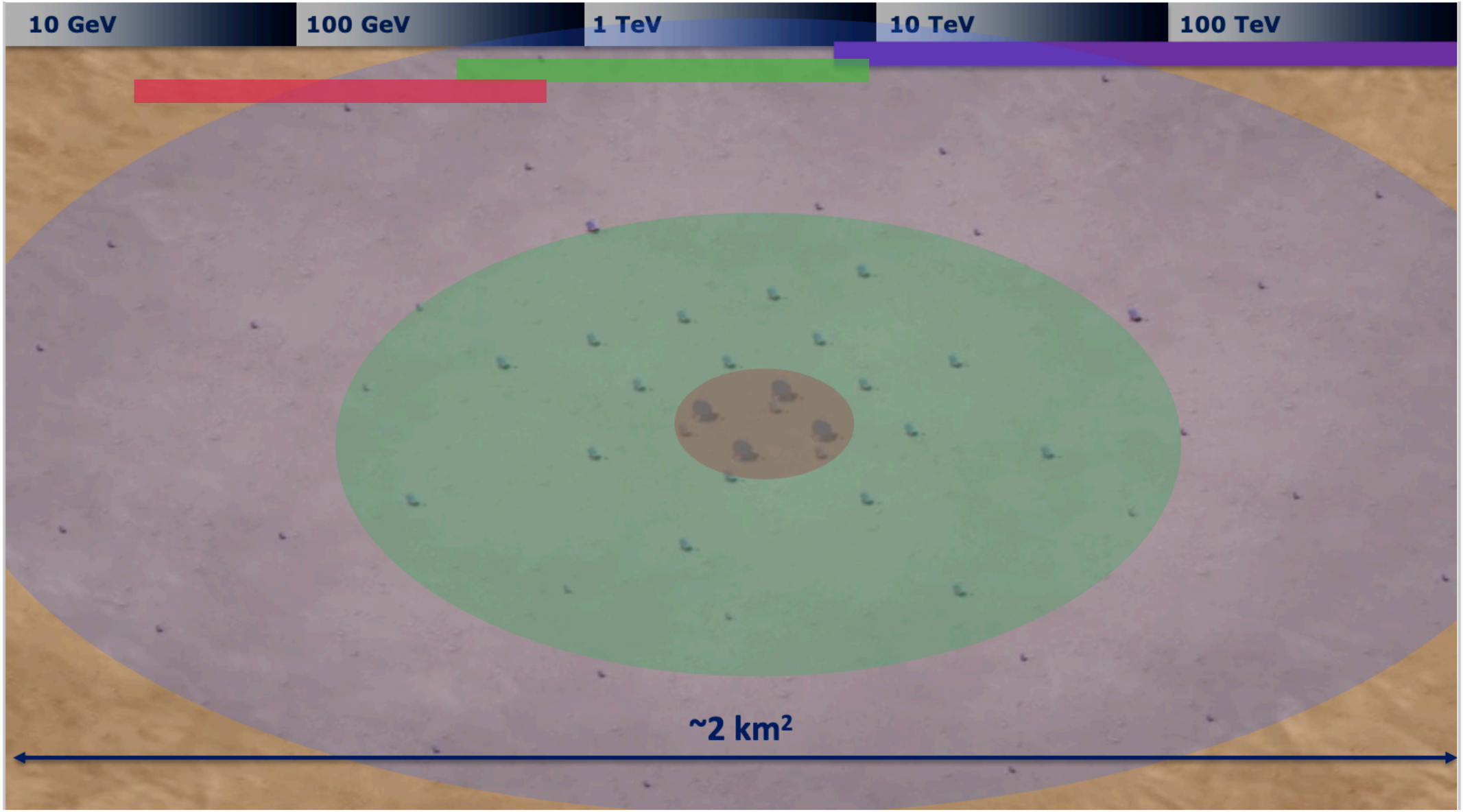




CTAO-South (Paranal, Chile):14 MST and 37 SST
(CTAO+: 2LST + 5SSTs)



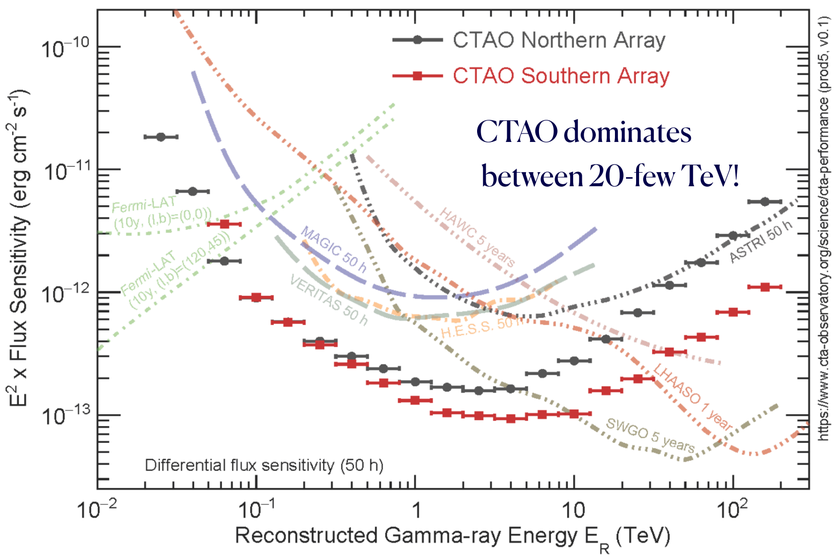
3-telescope design



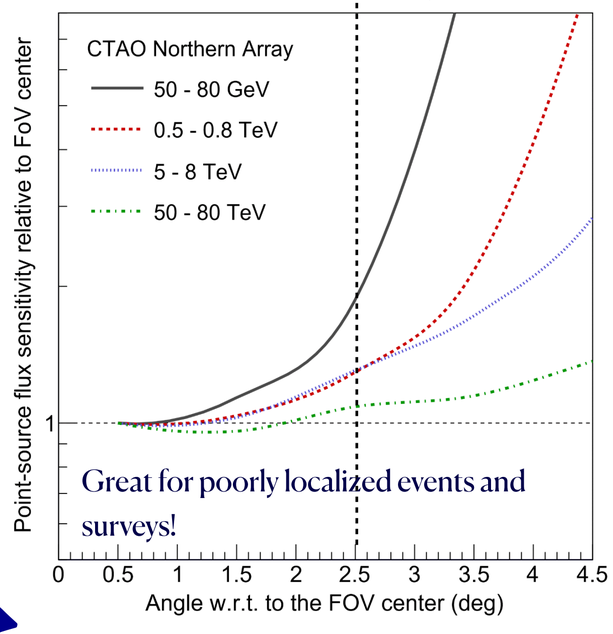
Credit: R. Zanin /CTAO

CTAO performance in a nutshell

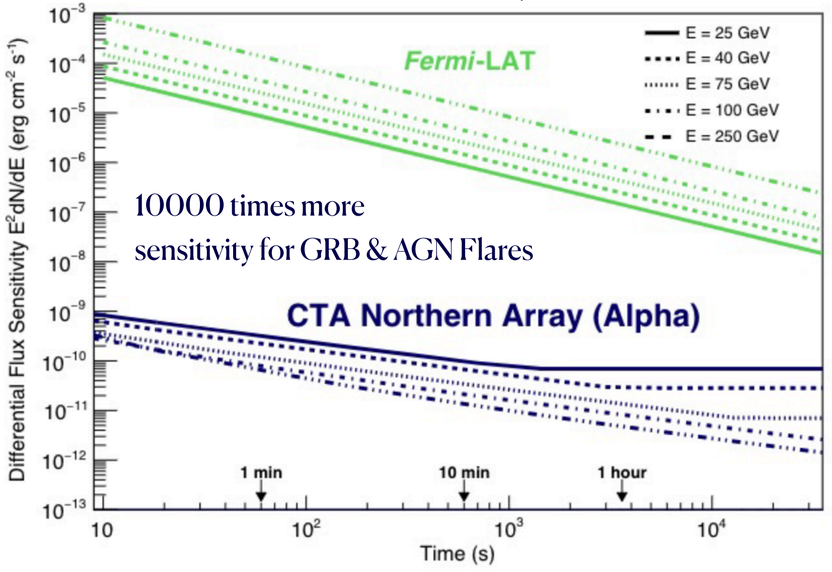
Flux sensitivity



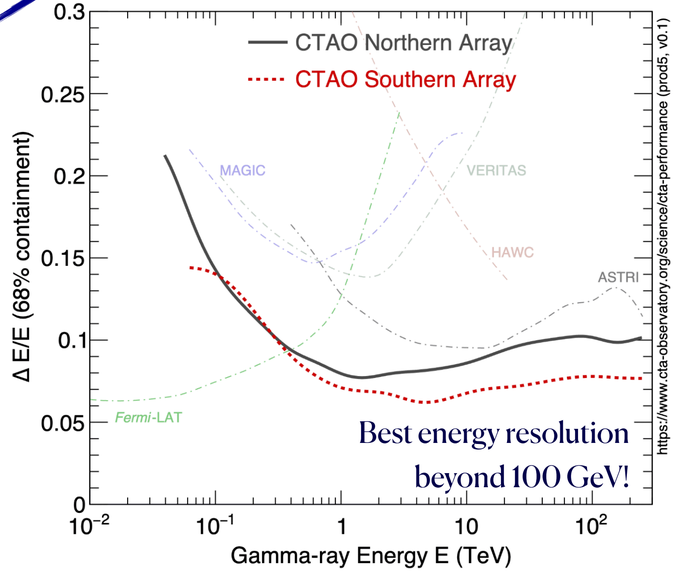
Off-axis sensitivity



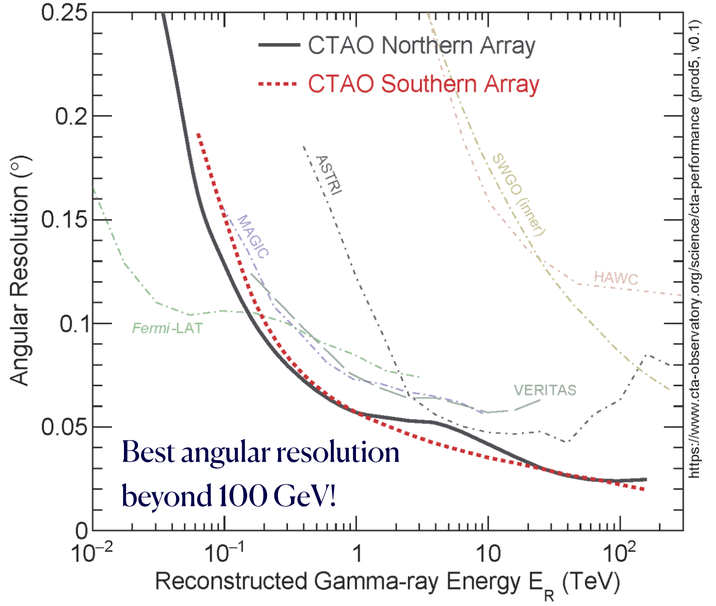
Differential sensitivity vs. Time



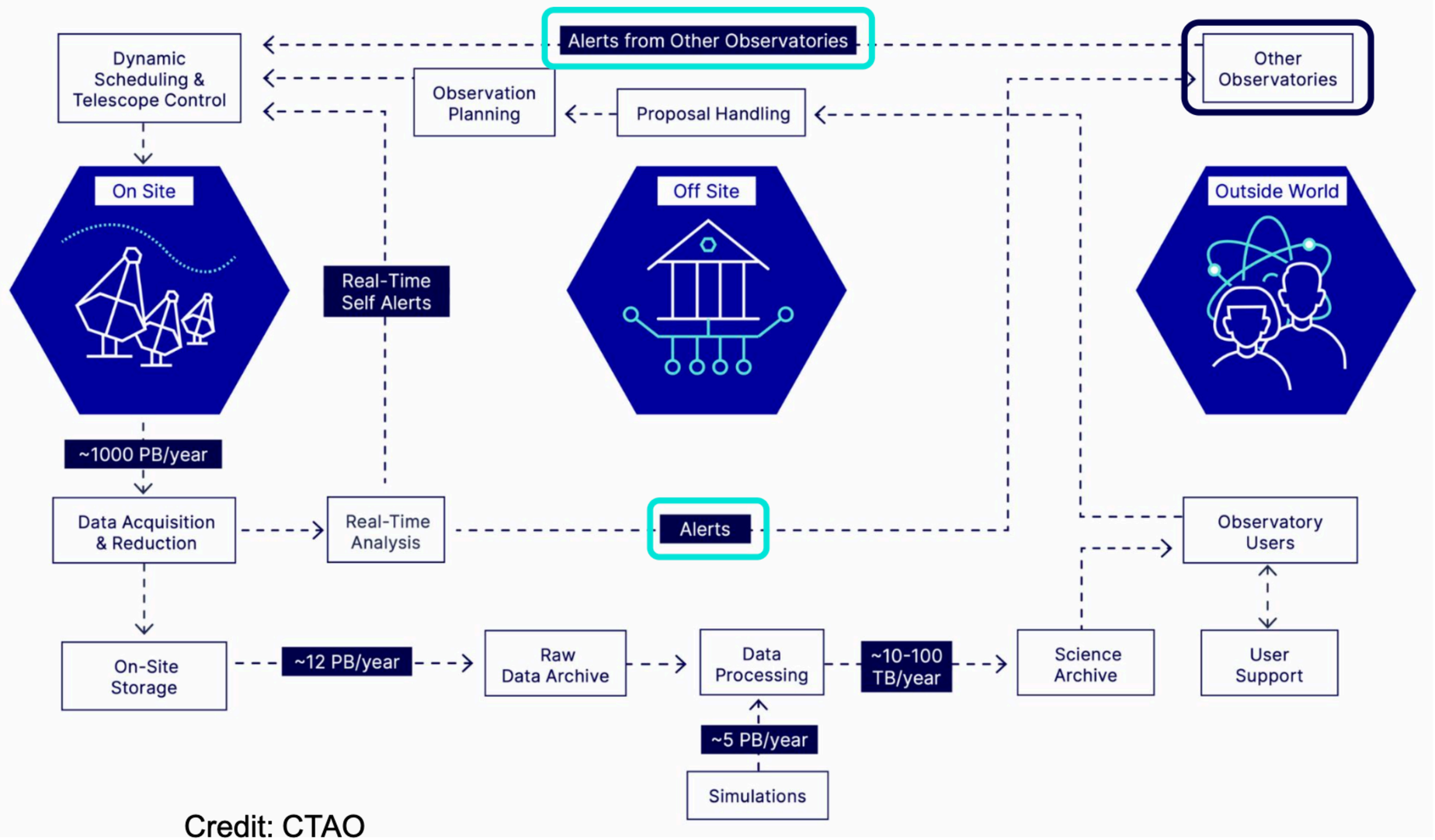
Energy resolution



Angular resolution



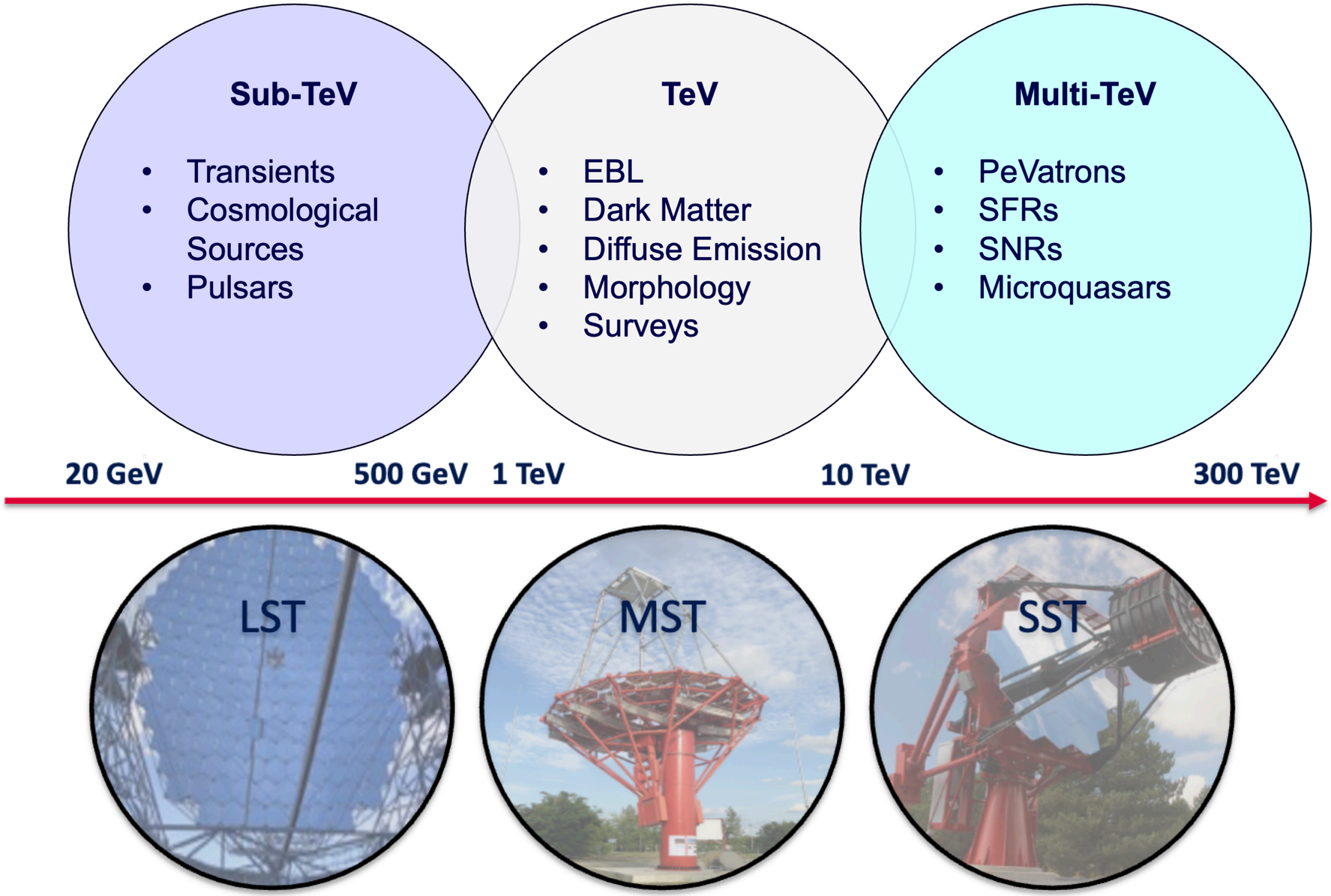
CTAO as part of the MWL/MM observatory ecosystem



- External alerts will be handled in <**50 s**
- Internal Alerts handled and issue in ~**30 s thanks to RTA**

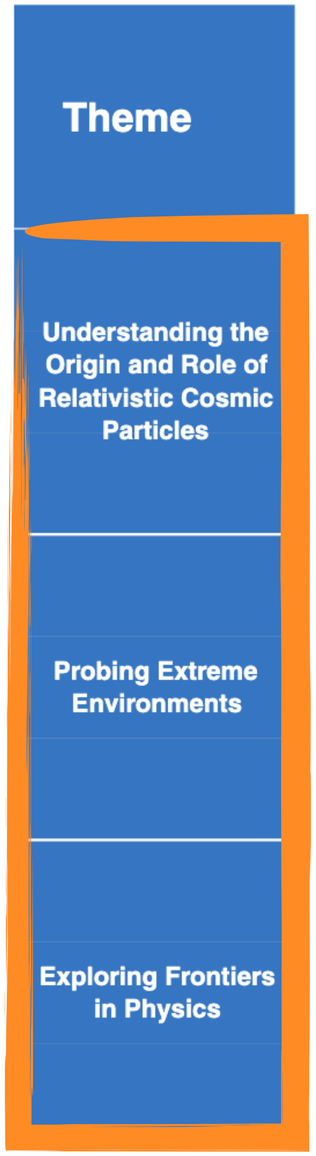
- Communication with other observatorios
  - Private streams: MoUs, emails/automated protocols
  - Public streams: GCNs and brokers (e.g. LSST brokers)

A renewed view of the gamma-sky



Credit: R. Zanin, D. Green

3 main themes



CTAO Science Book, 2017

From questions to KSP

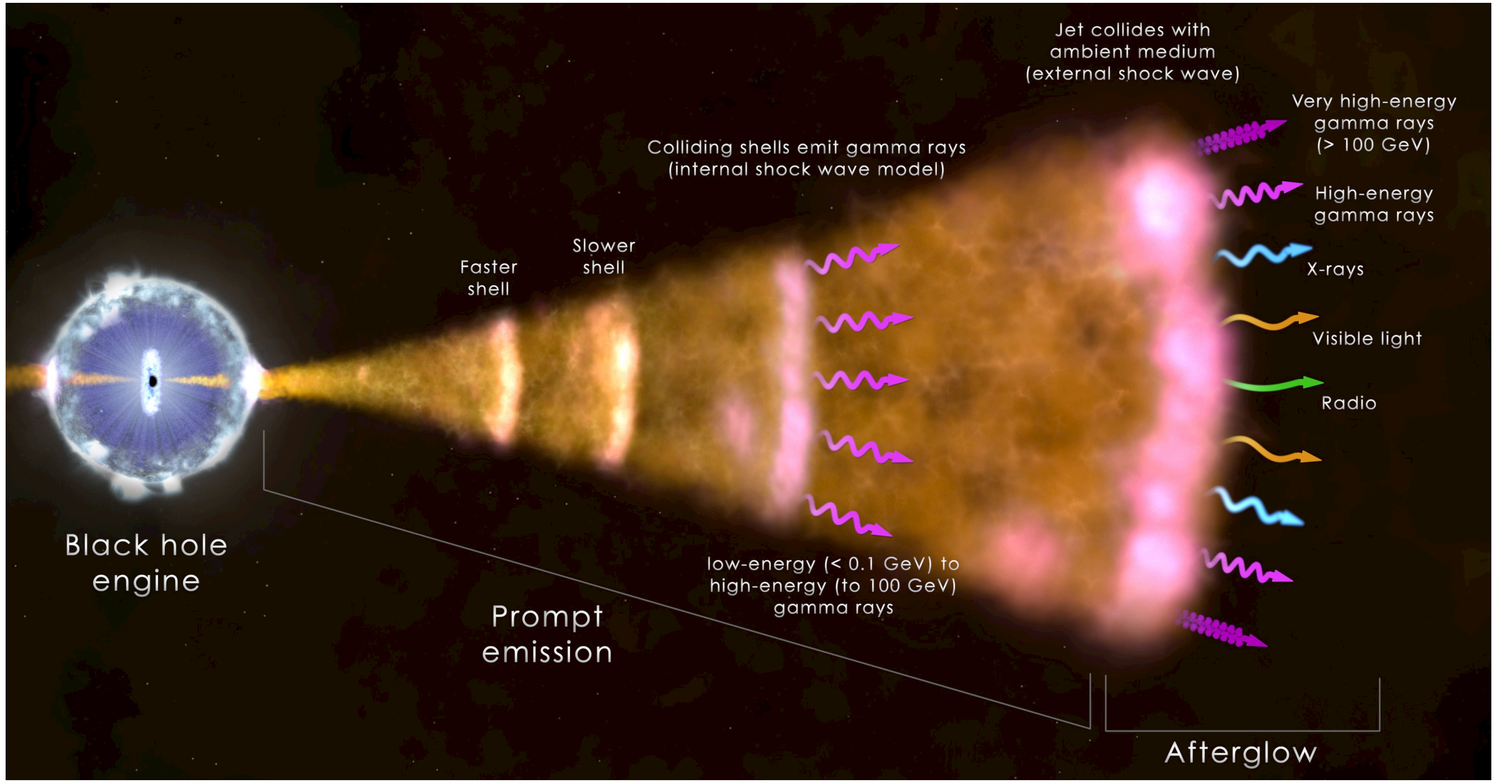
Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

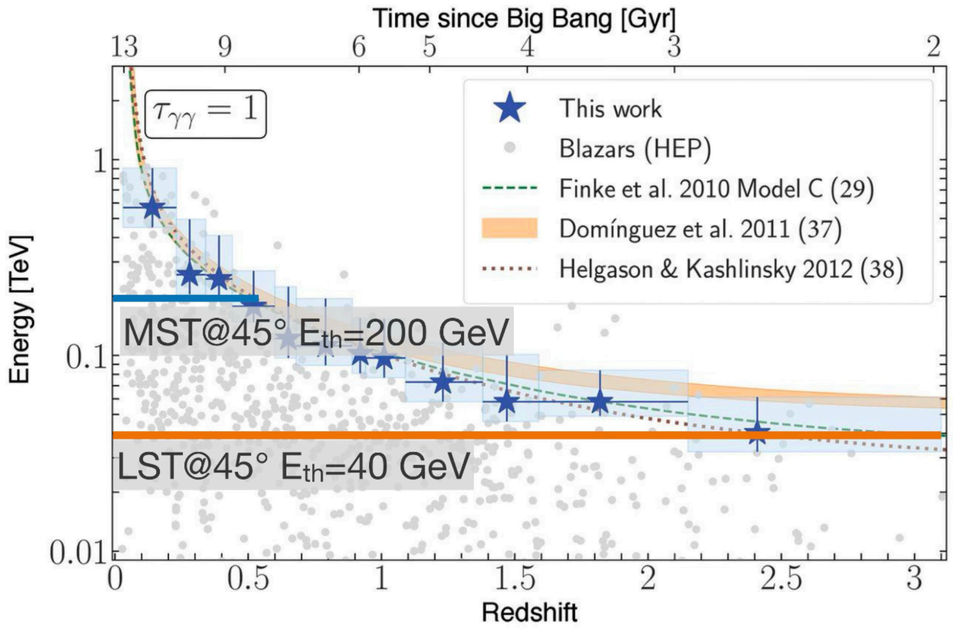
CTAO Science Book, 2017

Observing the transient sky

- Deep understanding of GRB and transient phenomena as KSP!
  - ~mCrab sensitivities, reach of z~2-4 for GRBs: low energy range is crucial
  - Relatively large FoVs of telescopes! => suited for localised and poorly localised transients (case of GRBs, GW, neutrinos!)
  - Real time analysis assured by the SAG system

Key to be fast, optimised and MWL/MM coordinated!





From D. della Volpe @ICRC 2025, for blazars

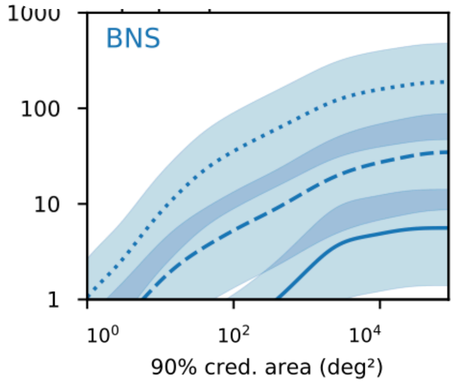
sGRB detections from BNS mergers

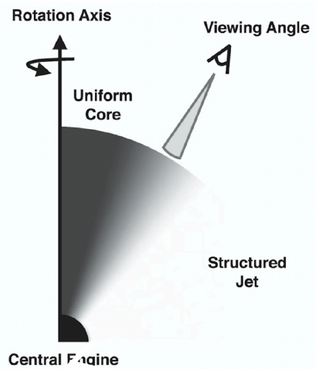
- **GW: 2307 binary neutron star (BNS) mergers** (Petrov, P et al., *Astrophys.J.* 924 (2022) 2, 54)
  - 4 interferometers in O5 (LHVK): 2 aLIGO 330Mpc, AdV 150–260Mpc. KAGRA~130Mpc
  - Homogeneous and isotropic distribution

- **GRBs:** Phenomenological set of short GRB simulations
  - Assume that **all launch** a jet: gaussian structure in energy and Lorentz factor.

- Link via **distance**, **viewing angle** and the **mass of the BNS**
  - **Viewing angle** given by the orbital inclination of the binary
  - **Jet core angle :** from sGRB distribution, ~14deg (A&A , 52:43–105, 2014.)

- $\mathbf{E_{iso}}$ from short GRB distribution in Ghirlanda et al. A&A, 594:A84, Oct 2016
- **Lightcurve**: temporal decay and luminosity at TeV similar to that in soft X-rays.
- **Spectrum**: EBL- absorbed GRB spectrum, power-law with photon index of -2.2. External medium ~0.1cm^{-3}



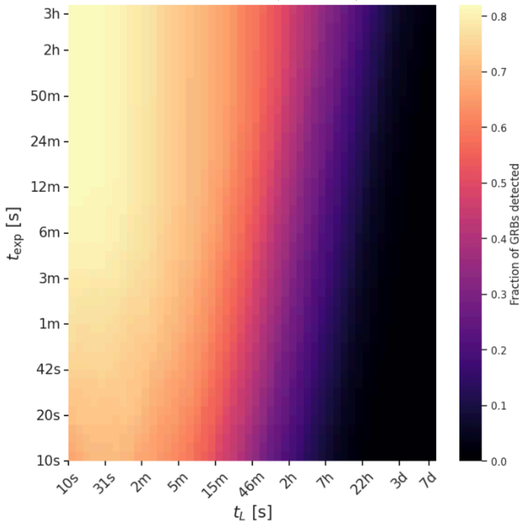


From Abbot et al, 848:L13 (27pp), 2017

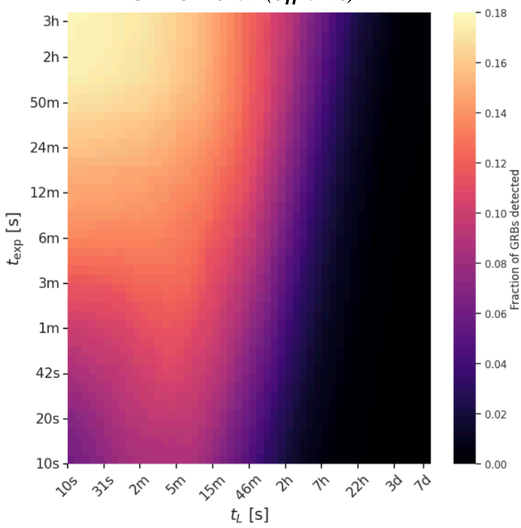
- **Main conclusions on-axis:**
  - 10s exposures **are enough** for detection
  - Turning point at 15', detectability~ 0 after a day

- **Main conclusions off-axis:**
  - Detectability **notably** decreases
  - Detection not directly at ~seconds of delays
  - Minimum exposures of ~3 min

CTAO North (on-axis)



CTAO North (off-axis)



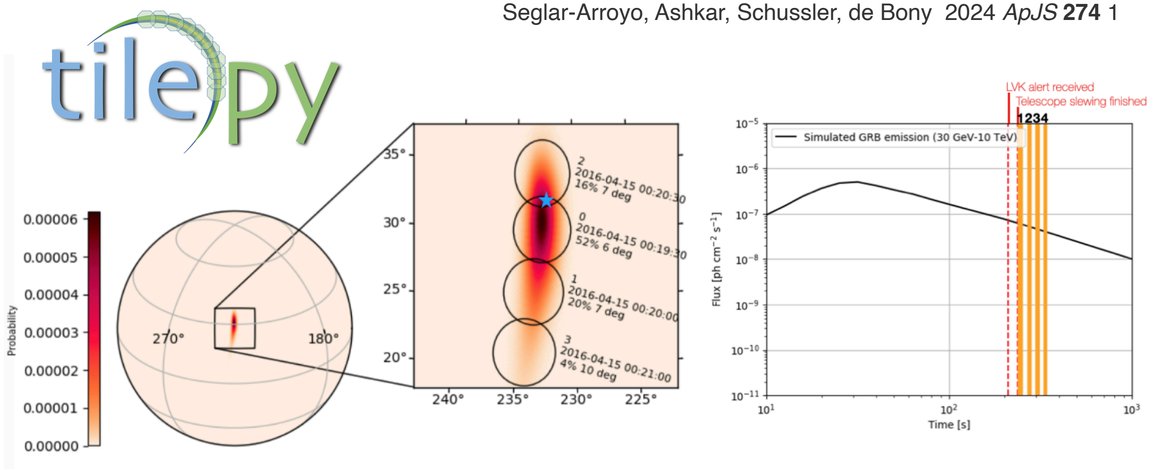
Green, Patricelli, Nava, Schüssler, Seglar-Arroyo, Stamerra et al. (CTAO Consortium paper), *expected end Nov 2025*

Simulating tiling observations and RTA

- Gravitational waves are *sometimes* poorly localised: ranges between few square degrees and thousands of degrees!
  - **No problem! Let's figure it out**

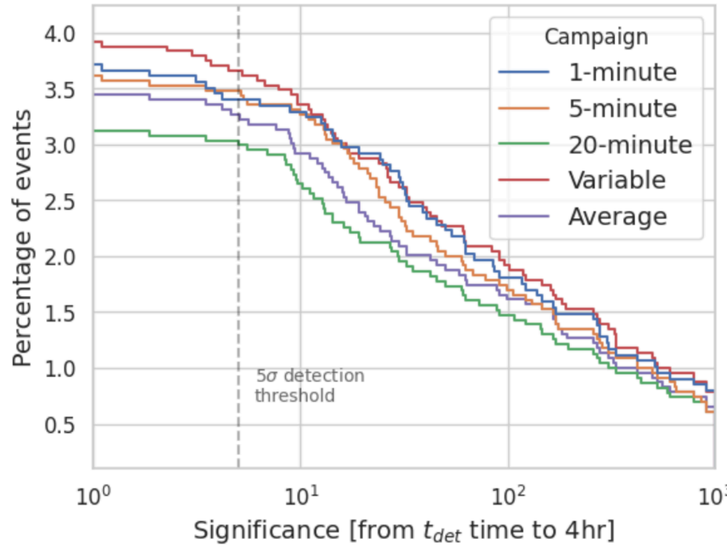
- Tiling strategies to cover the uncertainty region fast!
- Tested various strategies to unveil covered/detected ratios
- All considerations embedded: duty cycle, visibilities, evolving sky...

Seglar-Arroyo, Ashkar, Schussler, de Bony 2024 *ApJS* **274** 1



	1-minute	5-minute	20-minute	Variable	Average
Percent (%)					
Percent Covered	70.0	65.9	62.9	6.7	44.7
Percent Detected [4hr campaign]	4.7	5.1	4.8	4.9	4.5

- We explore the significance distribution reached in **a realistic scenario**:
  - **Self-triggering via RTA happens when 5 sigma is achieved:** observation scheduled are stopped and source is monitored until the end of the campaign.
  - **Boost of significance** obtained, which enables a much better scientific outcome of the observing campaign!

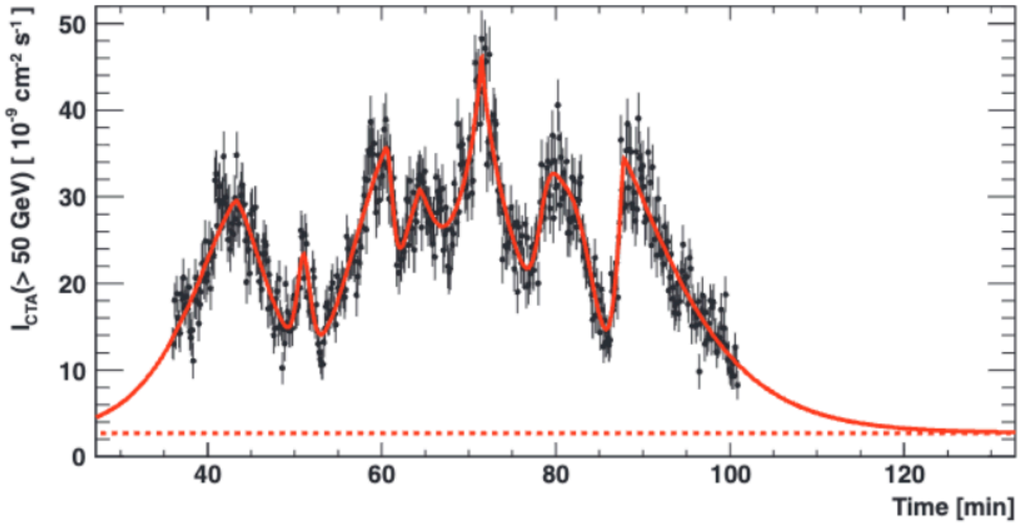


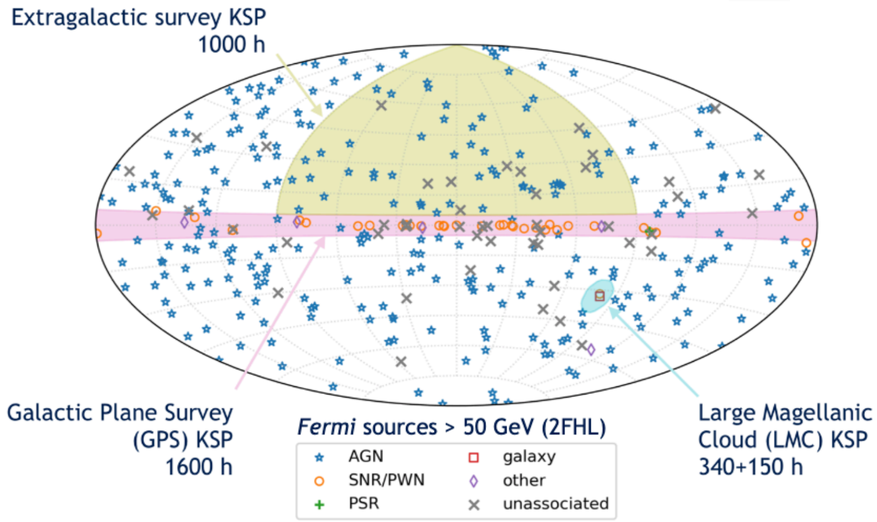
Green, Patricelli, Nava, Schüssler, Seglar-Arroyo, Stamerra et al. (CTAO Consortium paper), *expected end Nov 2025*

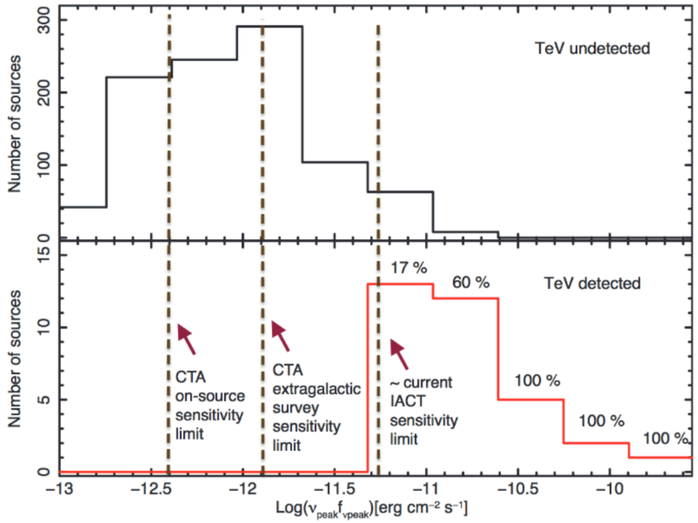
The extragalactic sky survey

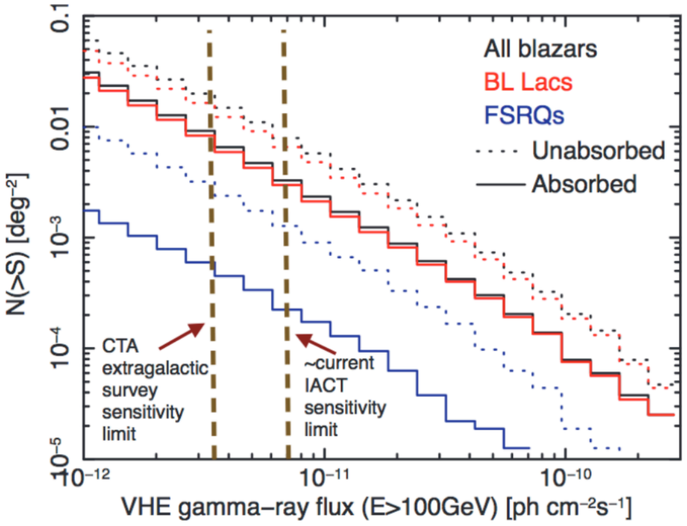
- Extragalactic survey (KSP): blindly survey 25% of the sky.
- Serendipitous detection of AGNs and GRBs!
- Usually, observation follow a triggering for high flux in other wavelengths (optical, X-ray, gamma-ray)
- Construct high resolution map of the extragalactic sky, unbiased
- Increase the number of detections of startbust galaxies, radio galaxies
- Detect new type of sources/probe further regions of the blazar sequence (extreme blazars)
- Probe ultra-fast variability !

Simulated PKS 2155-304 LC, CTAO Science Book 2017





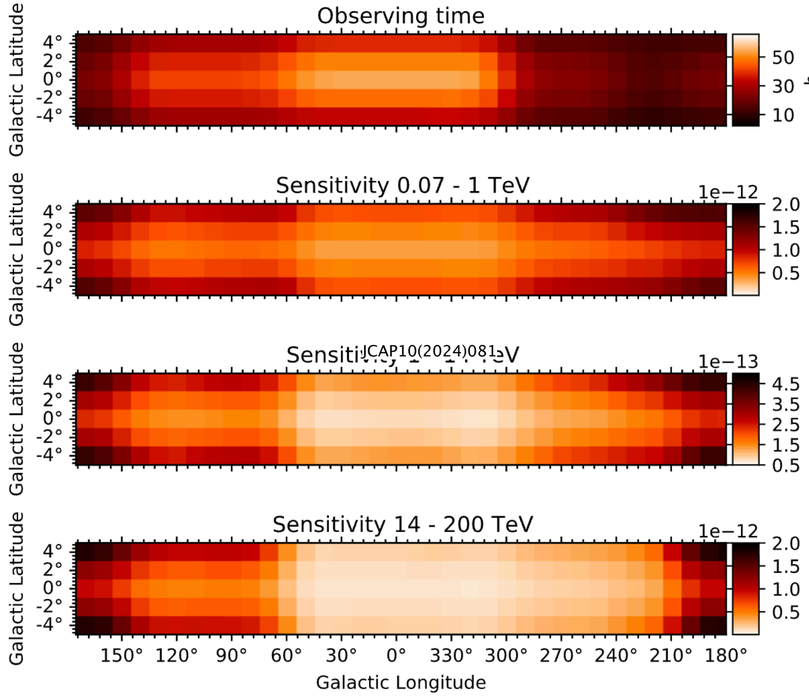


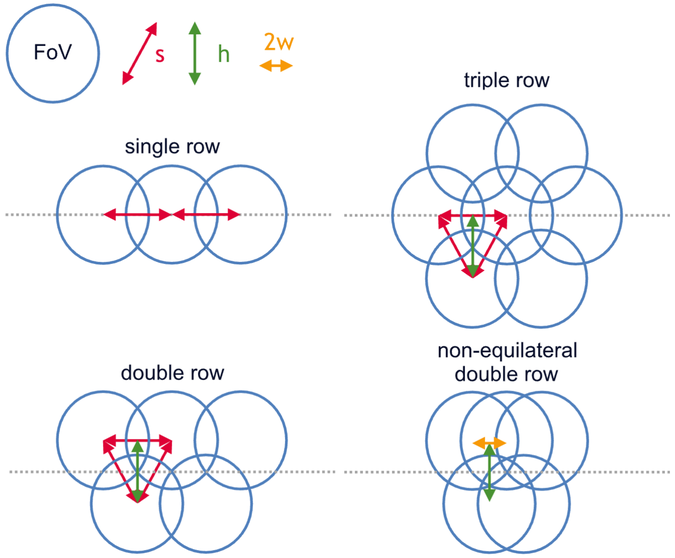


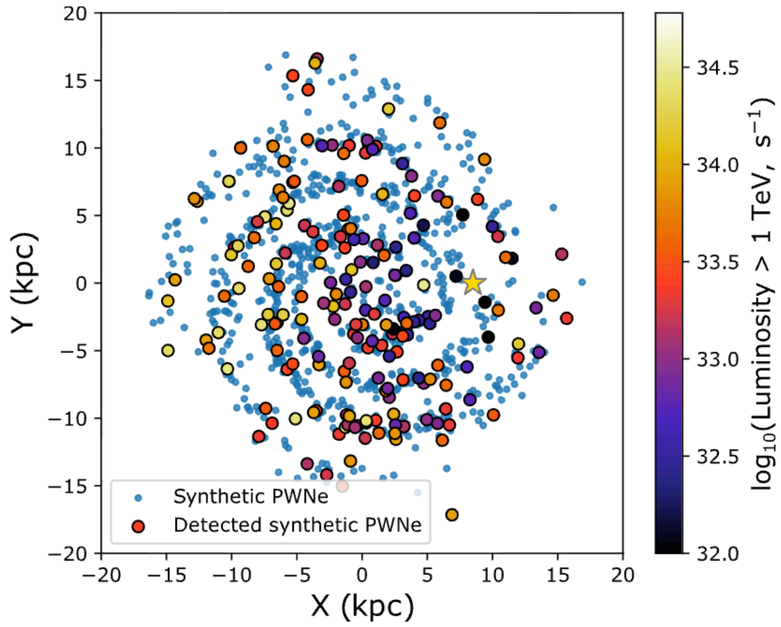
CTAO AGN Populations paper in preparation

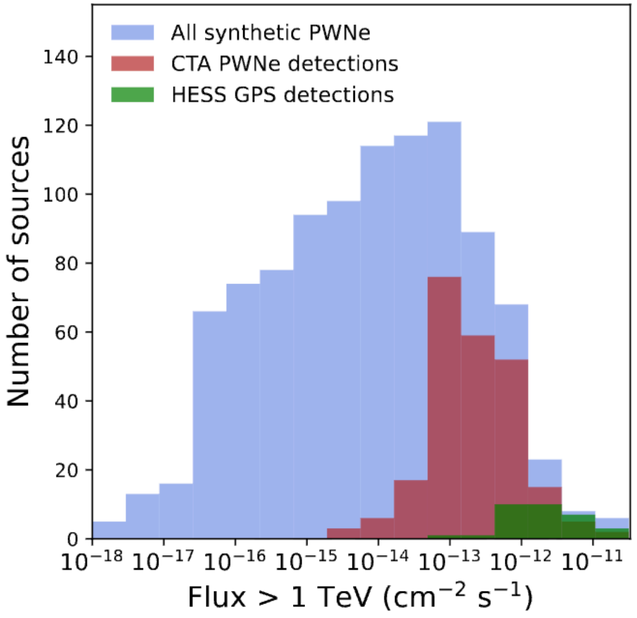
Galactic plane survey

- Galactic Plane Survey: **systematic survey which will bring potential increase of source of factor 5 to ~300-500** (for an instrument achieving a sensitivity of 1–3 mCrab)
- Benefit from the large energy range, reaching 300 TeV for SSTs!
- Benefit from the North and South coverage!
- Specific observations strategies proposed. New strategies include large zenith obs!
- Connection with many other KSP as Galactic Center, Pevatrons, Transients





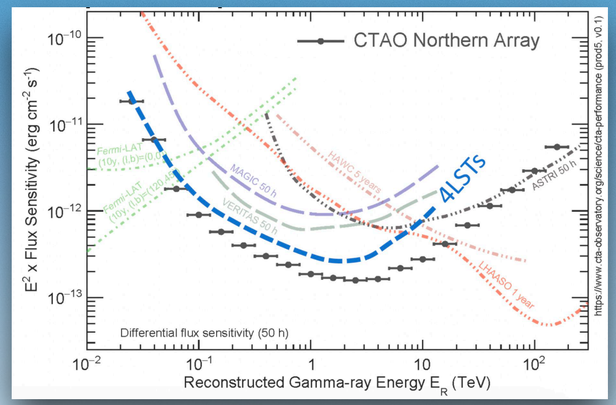




CTAO Consortium, JCAP10(2024)081

The Large Sized Telescope-1

- LST-1 has collected already >2000 h data!
- **The other 3 LSTs: advanced construction stage: commissioning starts 2026**
- **A transient catcher machine!**
  - **4.5 deg FoV**: coverage of broad sky regions
  - Fast repointing (<20 seconds)
  - Light structure: **fast slewing (180 deg /20 s)**

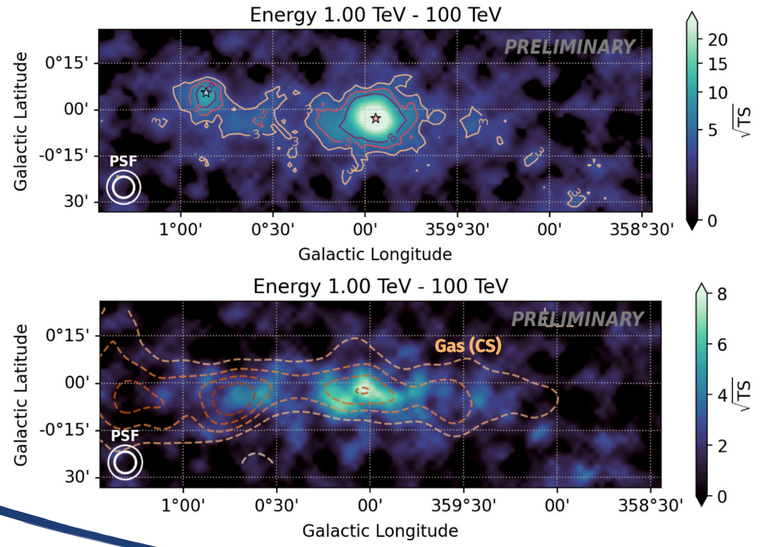


D. Sanchez

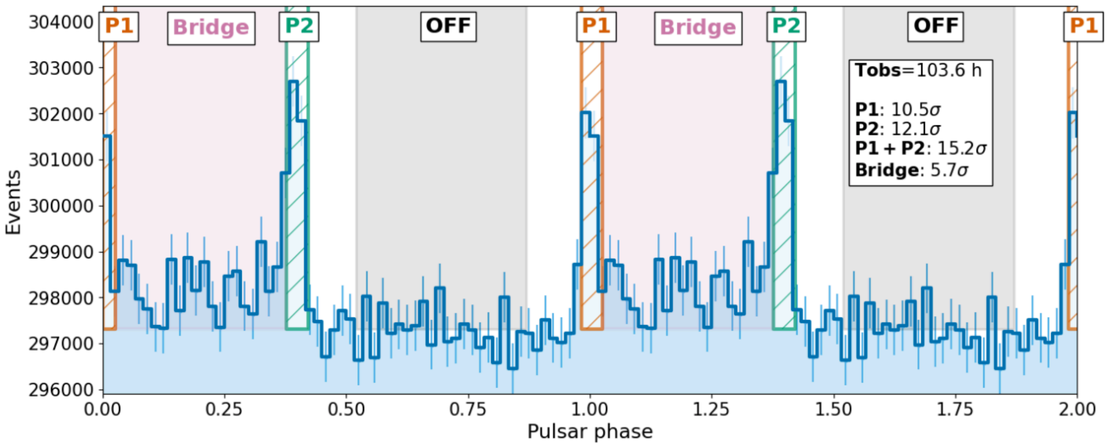
LST-1 is already producing great science!

+ New methodologies. e.g observing modes: tilings, drift scans, large zenith angle!

Abe, et al. PoS(ICRC2025), 542

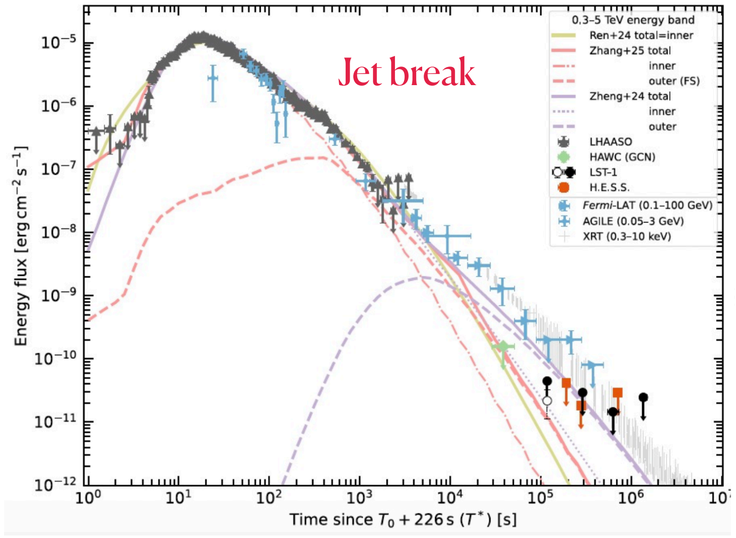


Crab Pulsar + bridging the gap with Fermi-LAT!



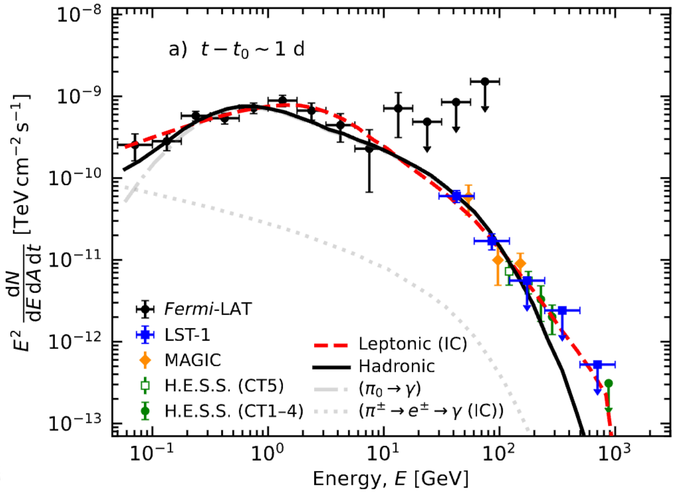
Abe et al. (LST Coll.), A&A, 690, A167 (2024)

GRB 221009A: 4.1 sigma, to+ 1.33 days



K. Abe *et al* 2025 *ApJL* **988** L42

RS Ophiuchi: proton acc. favoured

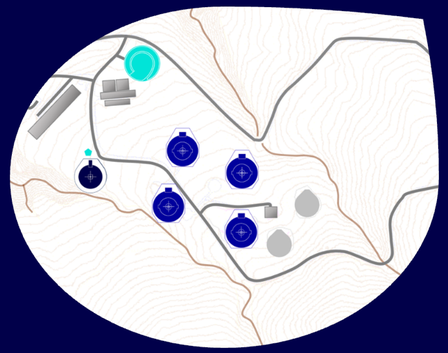


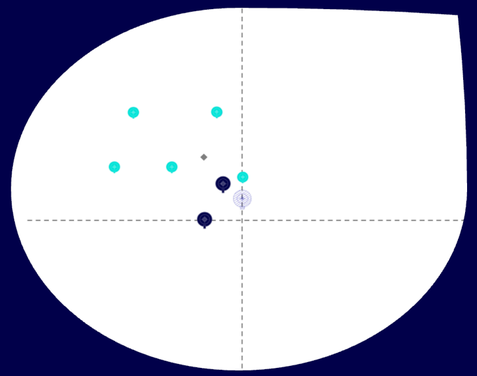
Abe, K., et al.,Astronomy & Astrophysics 695 (2025): A152.

Intermediate configuration ~2028

3 years from today

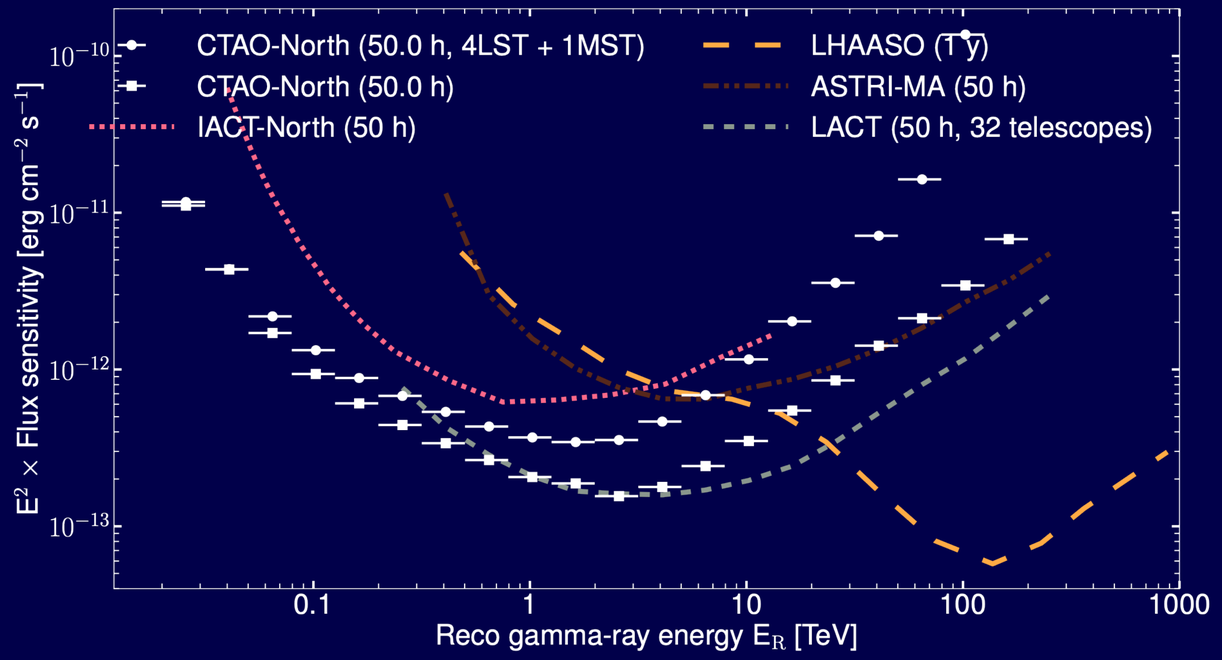
- Incremental array configurations that become progressively available to the community





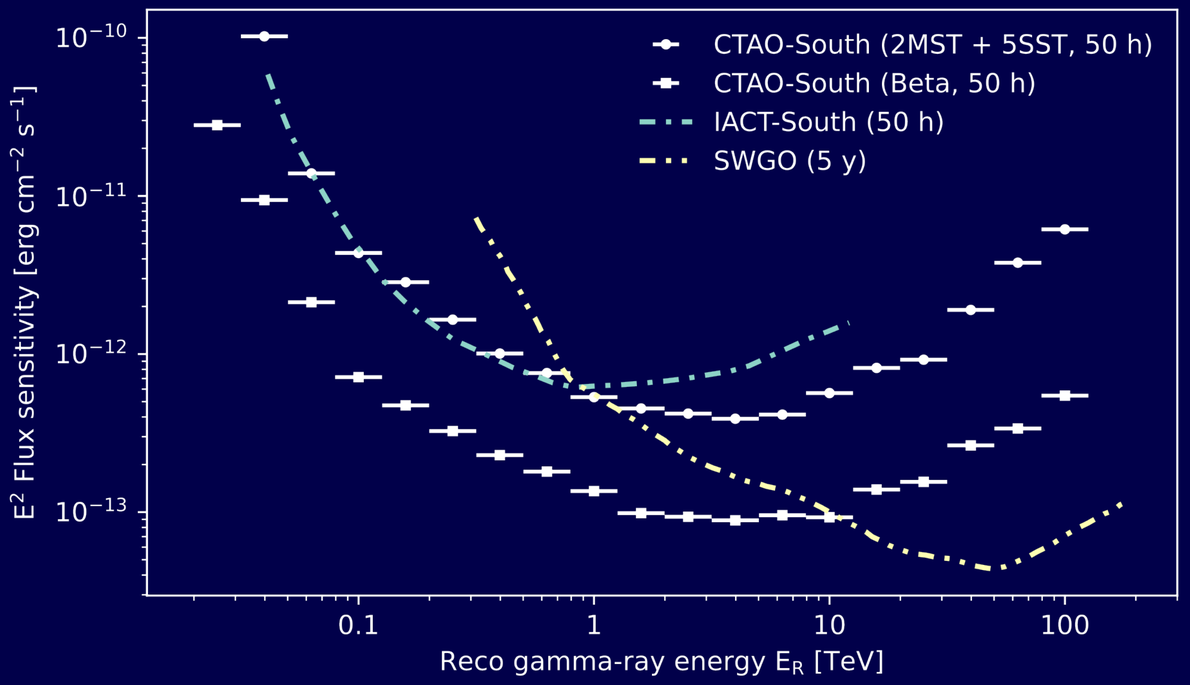
CTAO-North

4 LST + 1 MST



CTAO-South

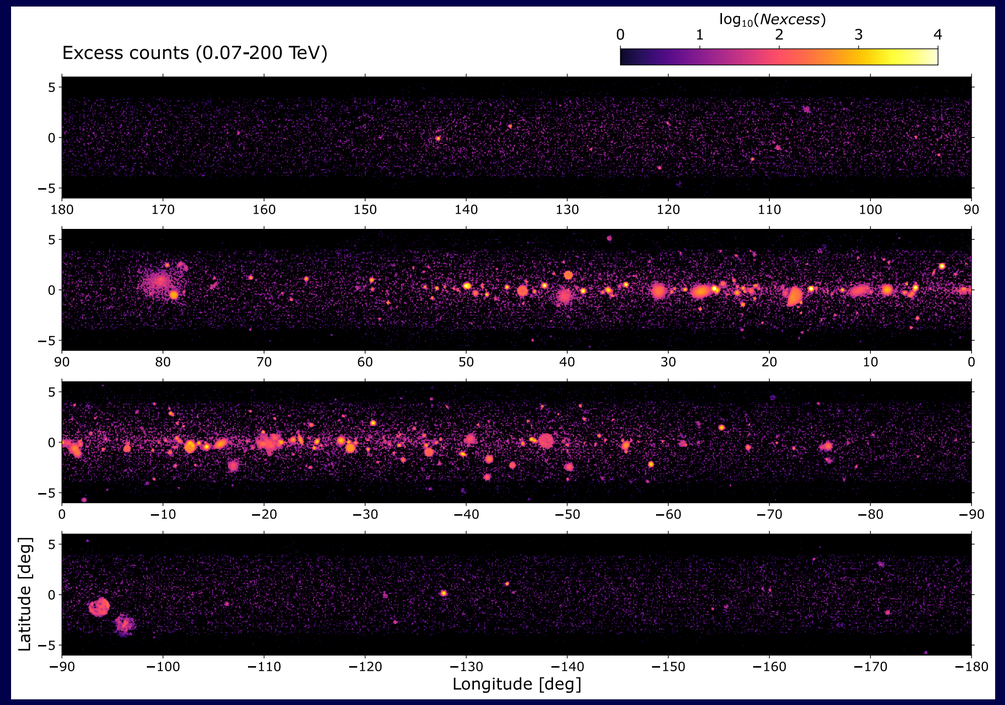
2 MST + 5 SST



Credit: D. Green/CTAO

CTAO news!

- Science Data Challenge
- Seven years of simulated CTAO observations provided as science-ready datasets
- Fully open and blind !!



- CTAO School in May 2026!
- Focus of school :Time-domain astrophysics and Galactic science
- Application deadline is November 30th!
- https://school.ctao.org/

CTAO SCHOOL

Welcome to the 2026 Edition!
The school will run from **12 to 22 May**, and is designed for **PhD students and postdoctoral researchers** eager to begin or further explore CTAO **science, technology, and data analysis.**

See you in La Palma, Spain

2026

Stay tuned: Release end 2026

Credit: D. Green/CTAO

Conclusion

- The exploration of the gamma-ray sky has basically just started!

- CTAO is set to be a revolutionary experiment, opening a new era in VHE astrophysics
  - First γ-ray ground-based observatory!
  - Intermediate configuration expected for 2028-2029!
  - In the meantime, LST is taking data :D

- Many new insights expected in various fields:
  - astrophysics, astroparticle, cosmology, fundamental!

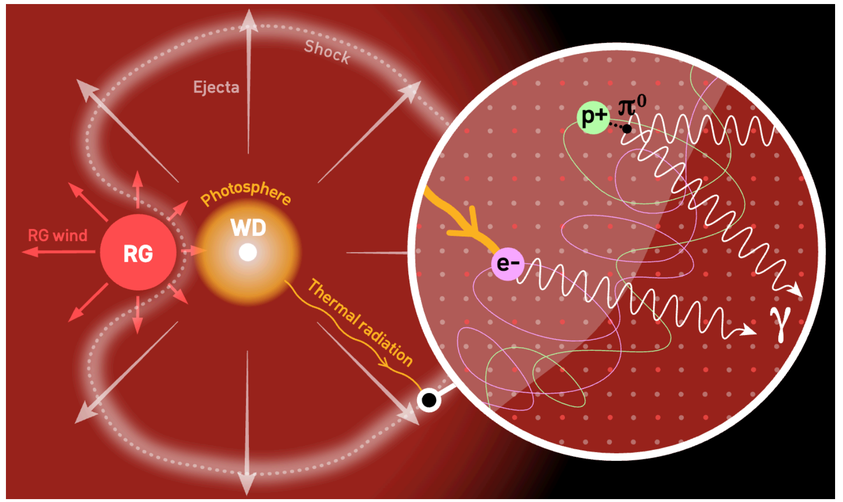

Thanks for your attention!

Back-up

The galactic gamma-ray transient sky

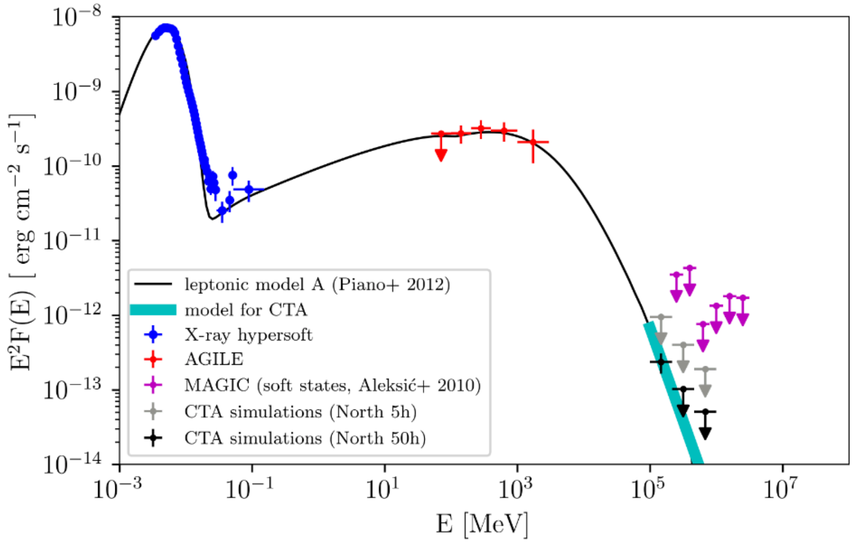
Many new possible galactic transients in the TeV regime!

- massive microquasars in the Cygnus region (Cygnus X-1 and Cygnus X-3)
- low-mass X-ray binaries with low-viewing angle
- novae explosions
- flaring emission from the Crab PWN

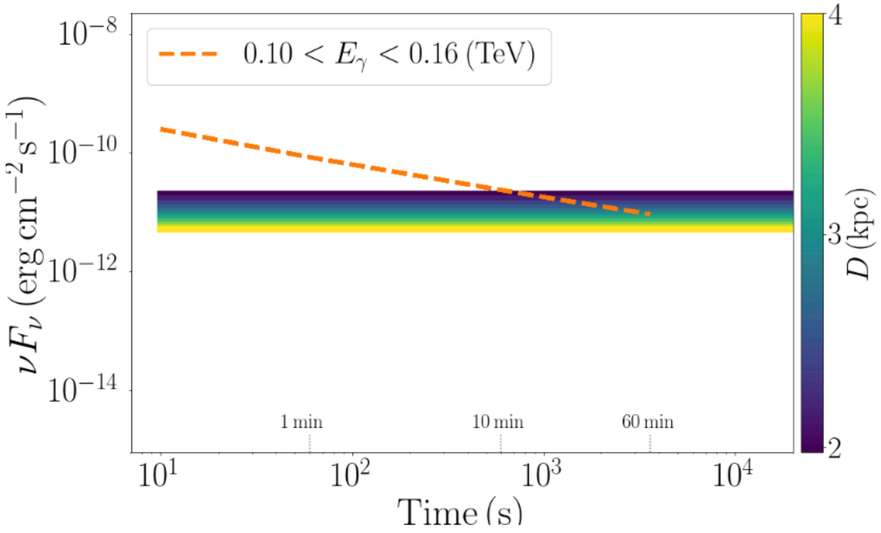


RS Oph, from Nature Astronomy ,volume **6**, p 689–697 (2022)

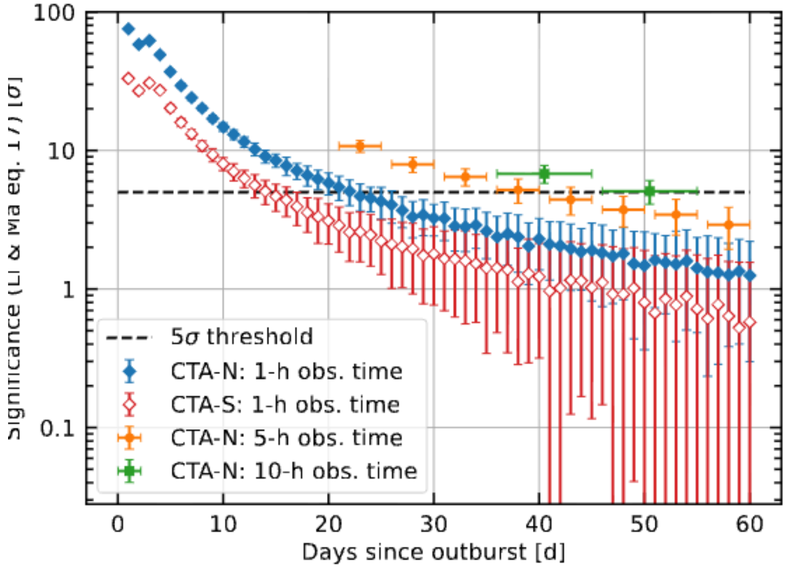
Cygnus X-3



BH-LMXB based on MAXI J1820+070



RSOphiuchi



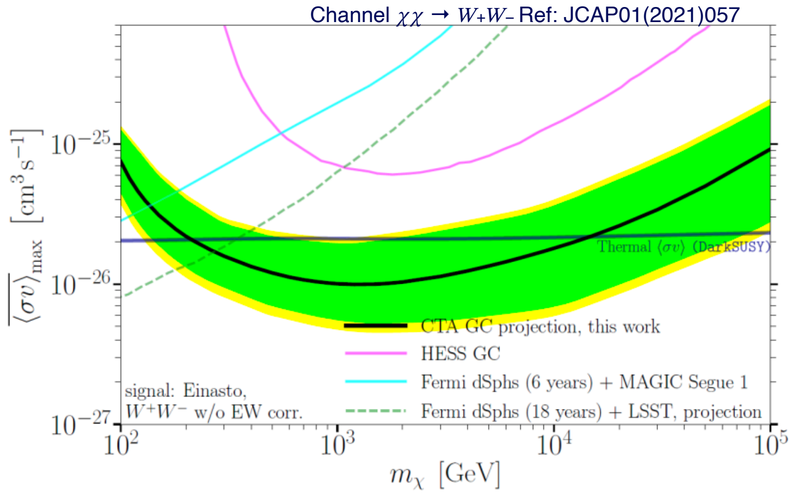
CTAO Consortium, MNRAS, Volume 540, Issue 1, June 2025, Pages 205-238

Fundamental physics

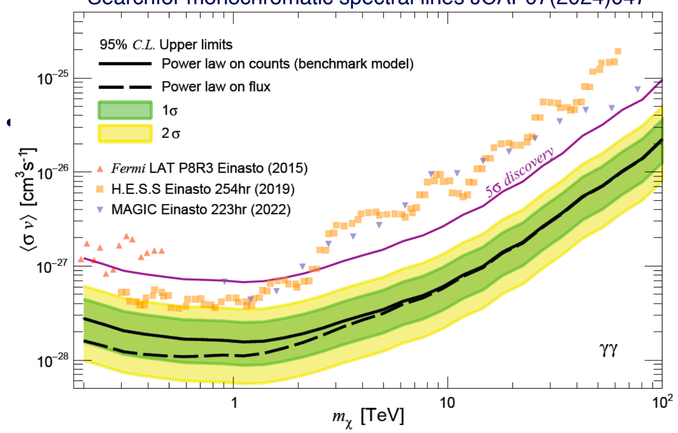
Dark matter searches:

- diffuse emission (GC, LMC, Perseus cluster)
- lines (GC, dwarf spheroidal galaxies)

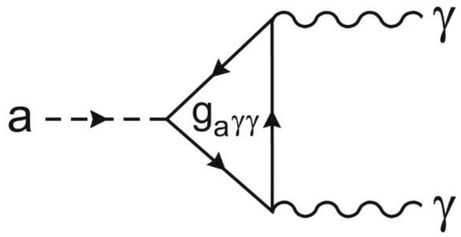
Channel $\chi\chi \to W^+W^-$ Ref: JCAP01(2021)057

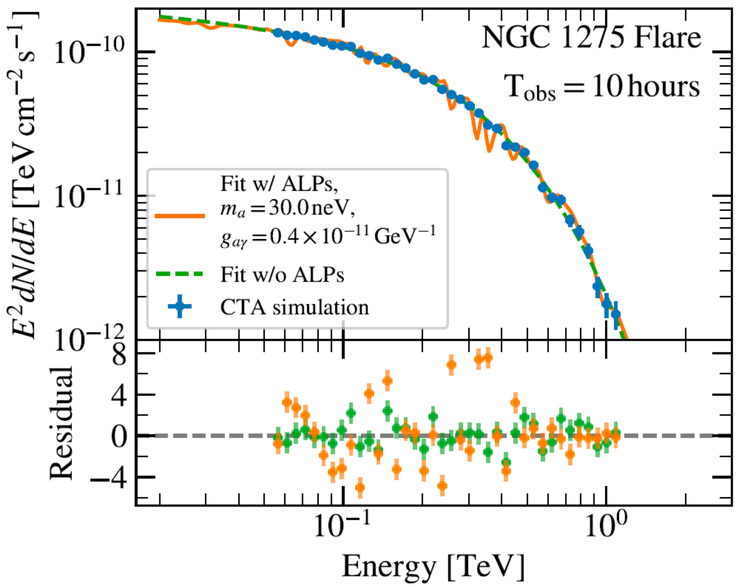


Searchfor monochromatic spectral lines JCAP07(2024)047



- Axion-like particles: pseudo-scalar particles coupling to photons.Inprint on observed gamma-ray spectra

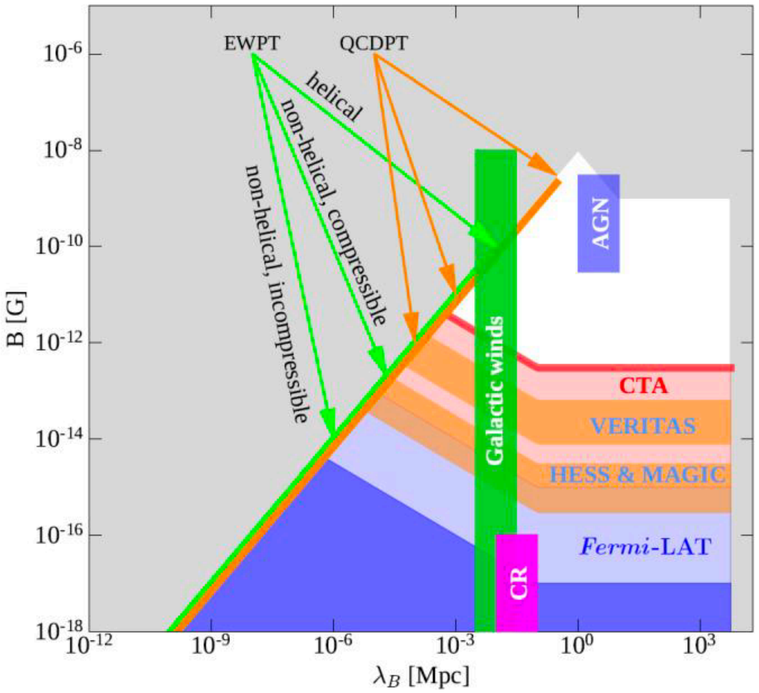




Fundamental physics with AGNs and GRBs:

- Extragalactic Background light (EBL)
- Lorent Invariance Violation (LIV)
- Intergalactic Magnetic Fields (IGMF)

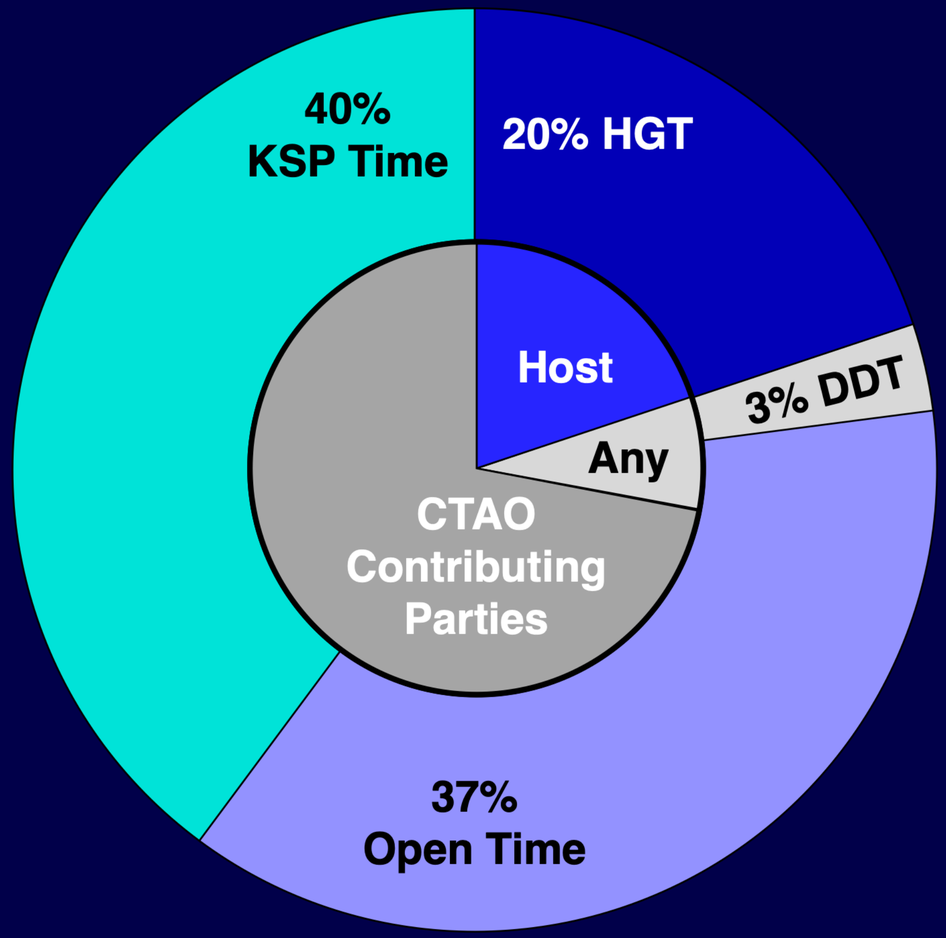
JCAP02(2021)048



Types of Observing Time

- Seve Proposals will be evaluated on their scientific merit in a double-blind fashion
- Data will have a proprietary period of 1 year
- After which the data will be public
- 8% of time is for any scientist either through DDT or Open Time

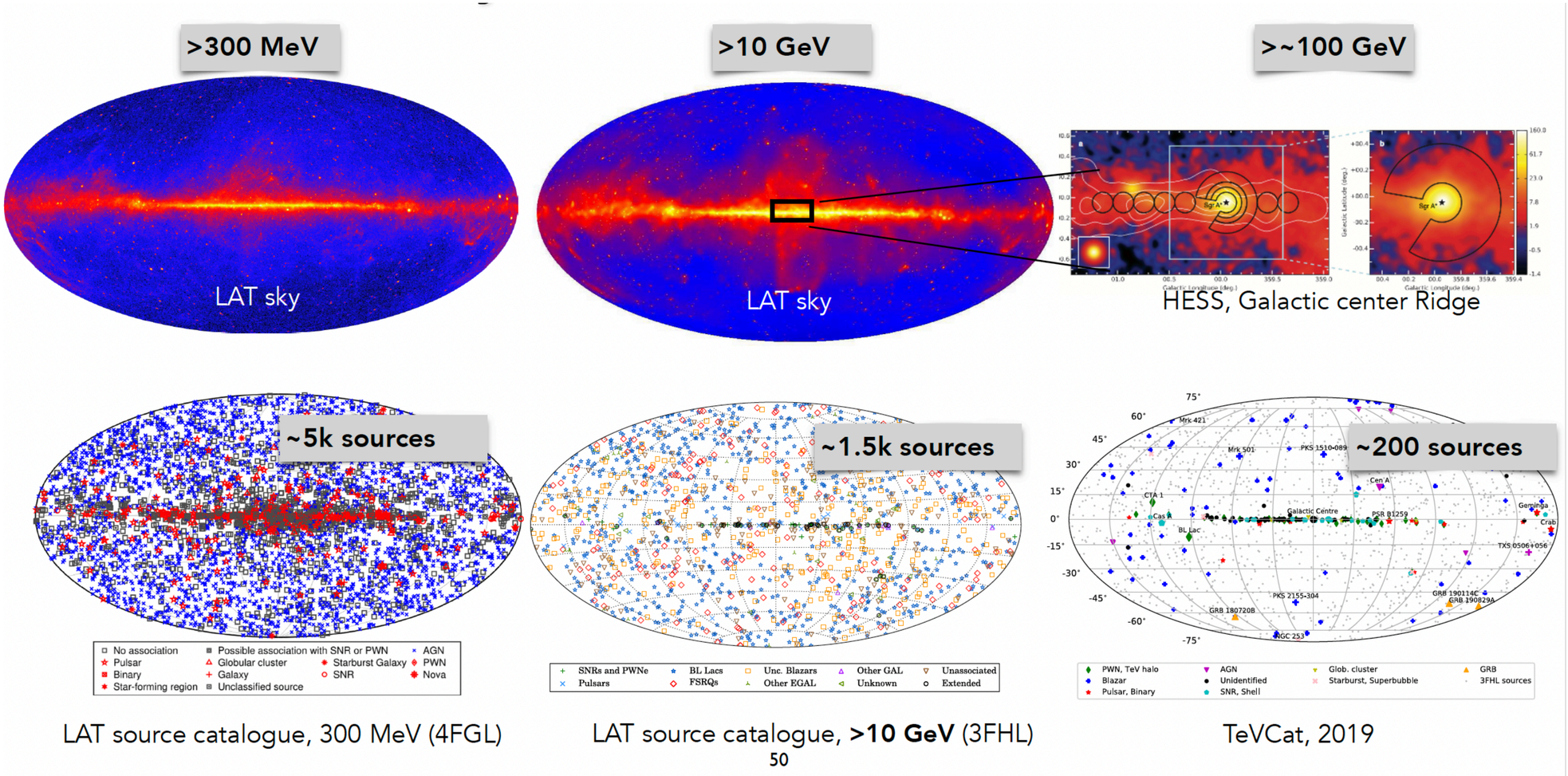
- HGT – Host Guarantee Time (Spain, Chile, ESO)
- DDT – Director's Discretionary Time
- KSP – Key Science Projects



Integrated over 10 years

Credit: D. Green/CTAO

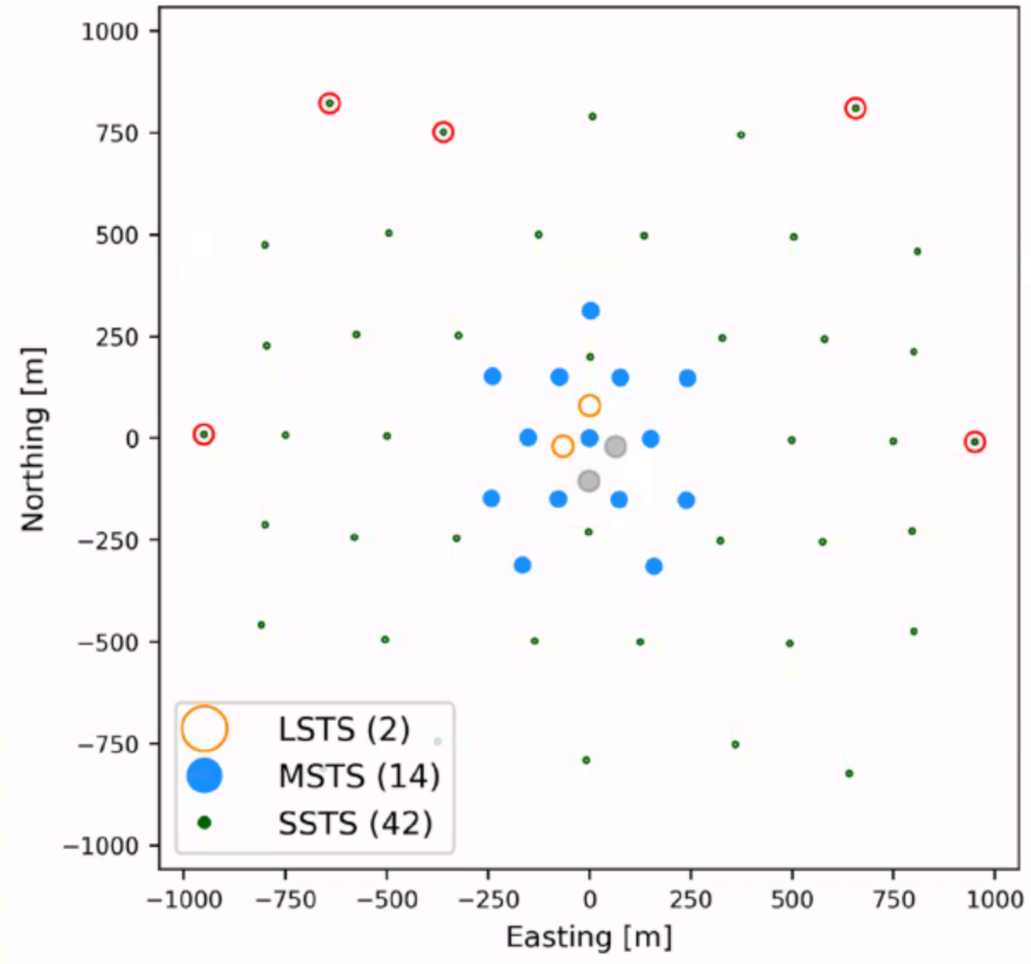
The GeV to the TeV energy range

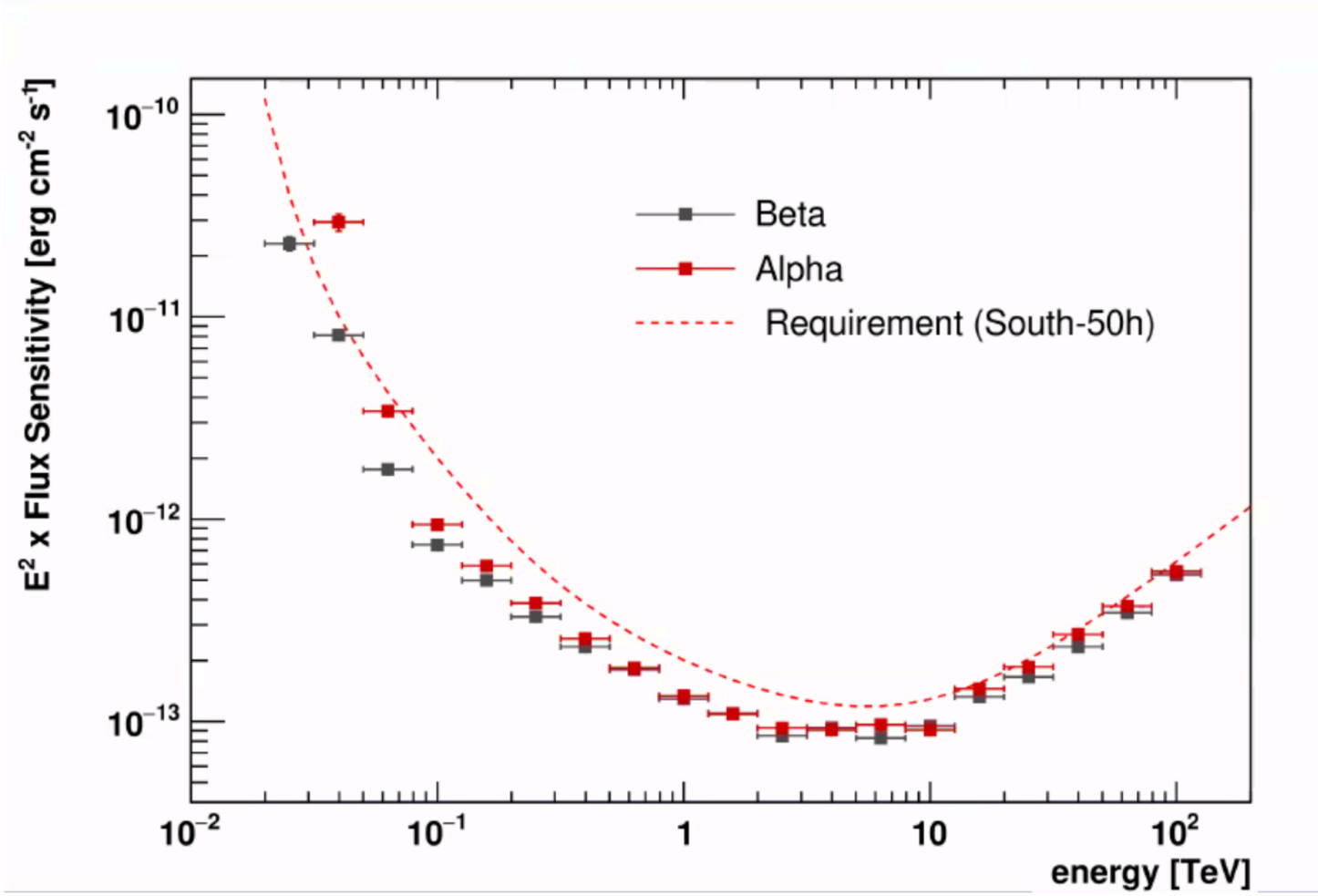


50

Credit: Zaharijas,TeVPA 2025

Beta





Credit: R. Zanin /CTAO