CTAO
Cherenkov Telescope Array Observatory

CTAO a new window for the multi-messenger and multi-wavelength astronomy

Roberta Zanin (CTAO Project Scientist) and Antonio Stamerra (INAF) on behalf of the CTAO Science Department

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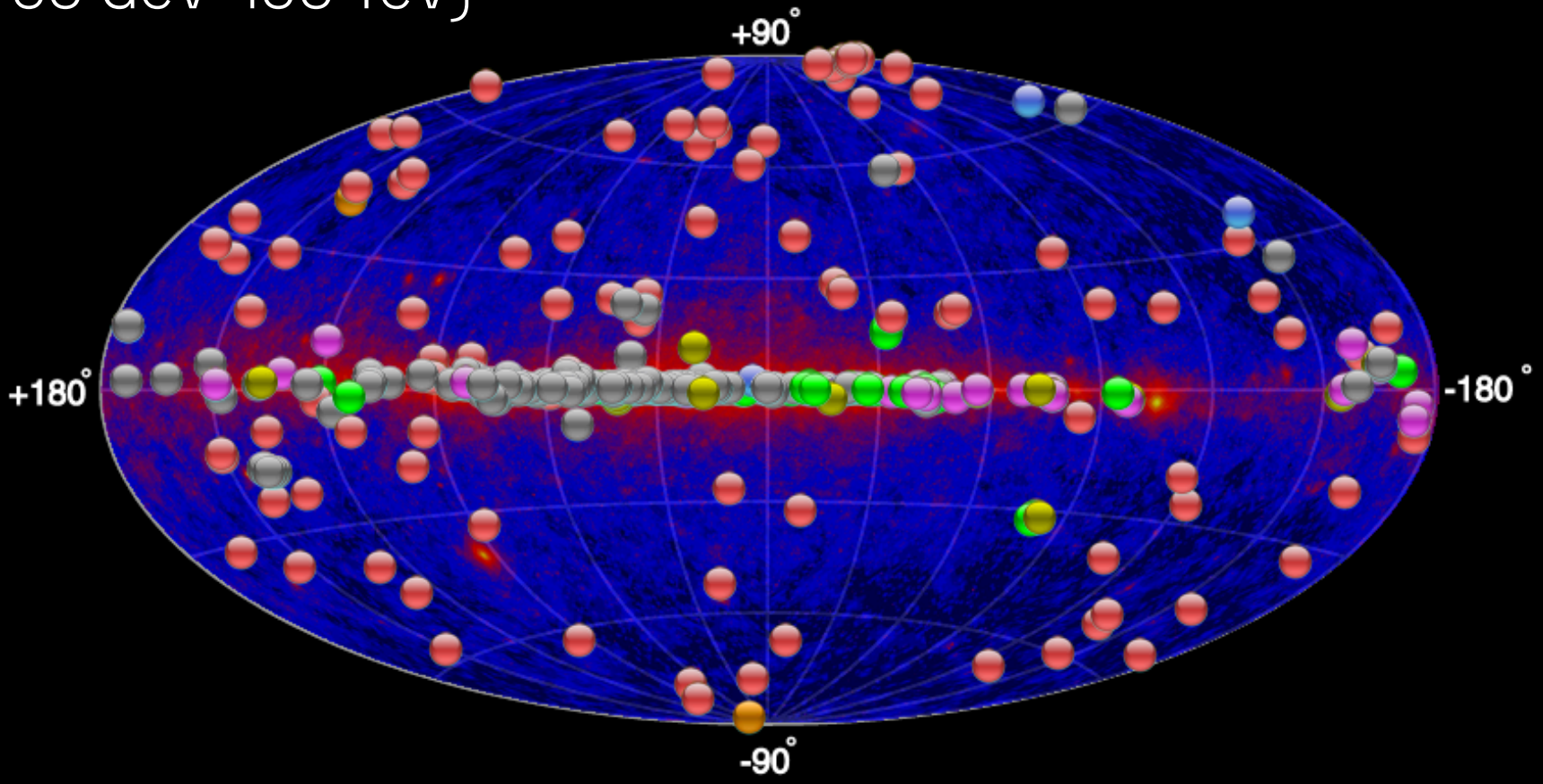
Celebrating 20 years of Swift Discoveries - Firenze - 24-28 March 2025

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

TeV observations in a multi-wavelength and multi-messenger context

The TeV gamma-ray sky

(E>~50 GeV-100 TeV)



Source Types

- TeV Halo PWN/TeV Halo PWN
- Binary XRB PSR Gamma BIN
- HBL IBL GRB FRI FSRQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

Most of these TeV sources are variable (minutes-to-months)

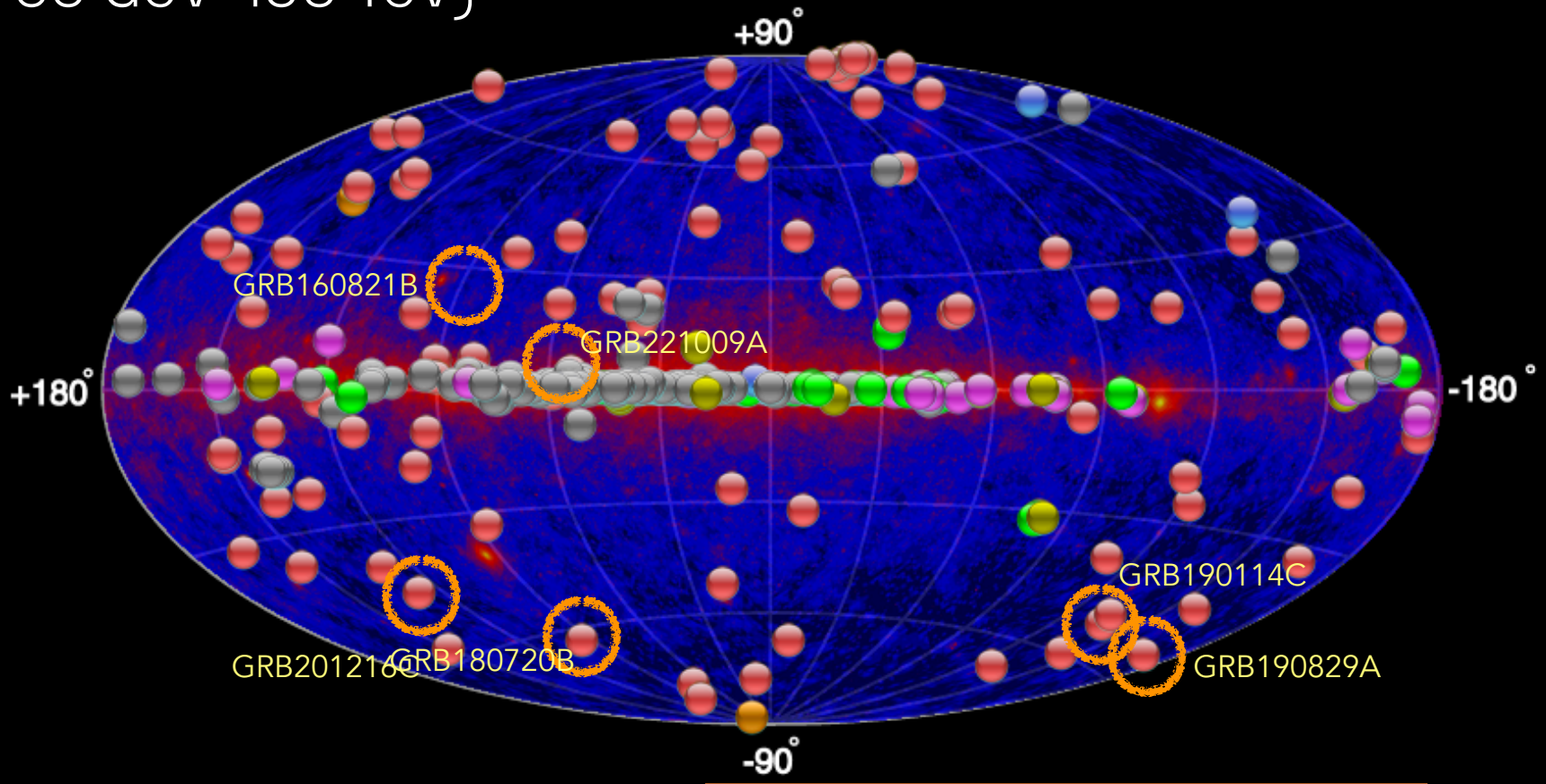
308 sources in total

93 are AGN-blazars/radiogalaxies

5 Gamma-RAY Burst GRB

http://tevcat.uchicago.edu

The TeV gamma-ray sky
(E>~50 GeV-100 TeV)



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5 Gamma-RAY Burst GRB

http://tevcat.uchicago.edu

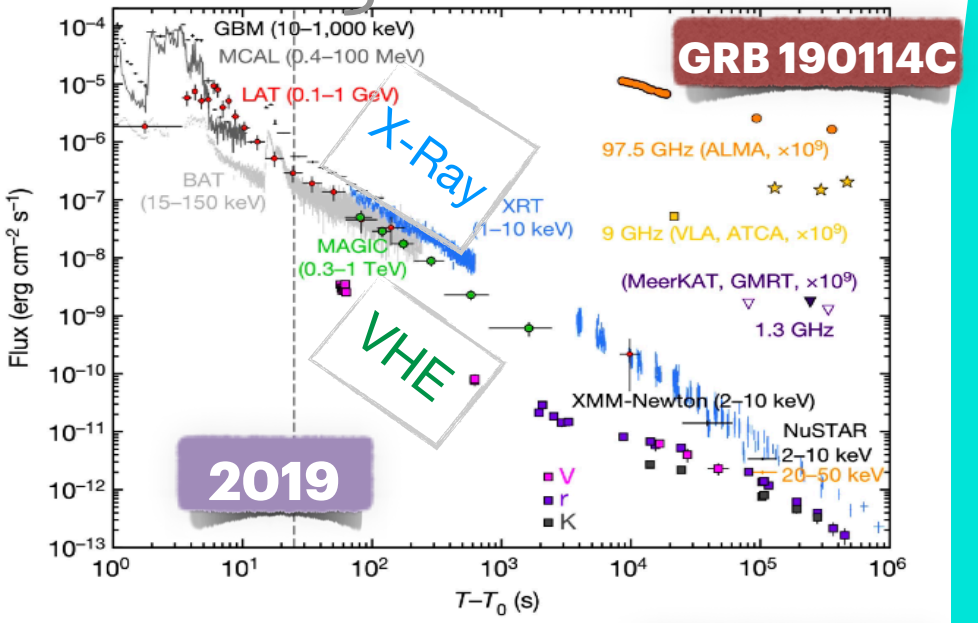
GWs and GRBs at TeV energies

★ Detection of the TeV (afterglow) emission

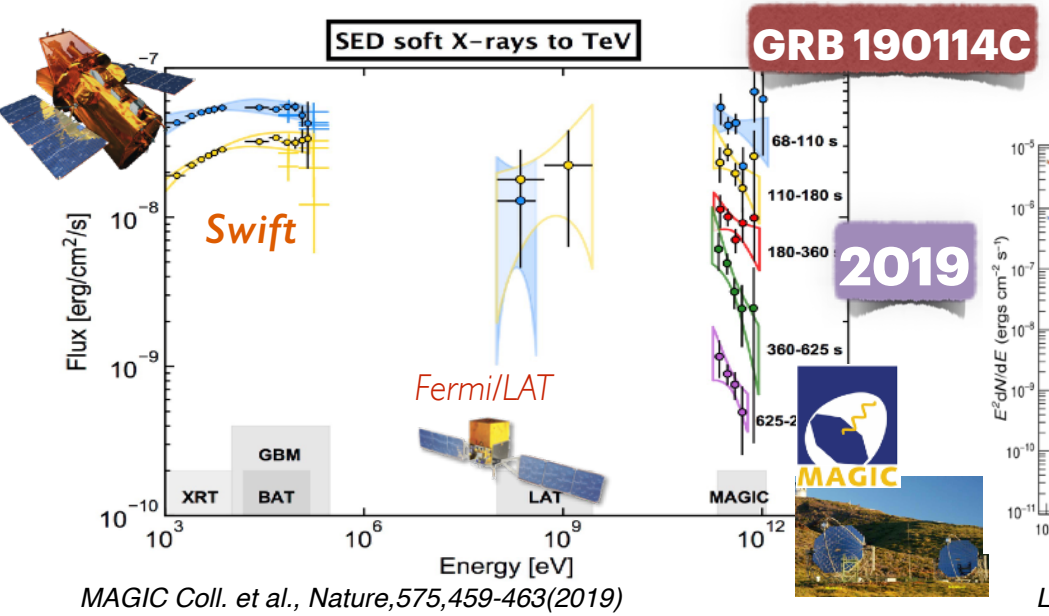
✓ GRB engine accelerates photons up to TeV
Gamma rays up to 12 TeV from the GRB 221009A!

✓ Energy budget and time evolution similar to the optical-X-ray component: *TeV flux follows closely the X-ray flux*

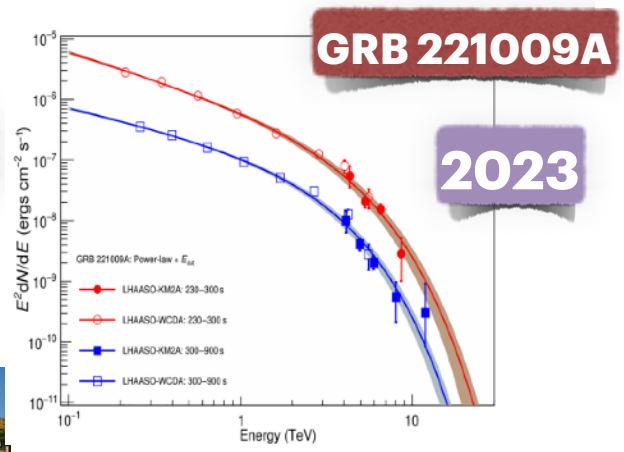
lightcurve



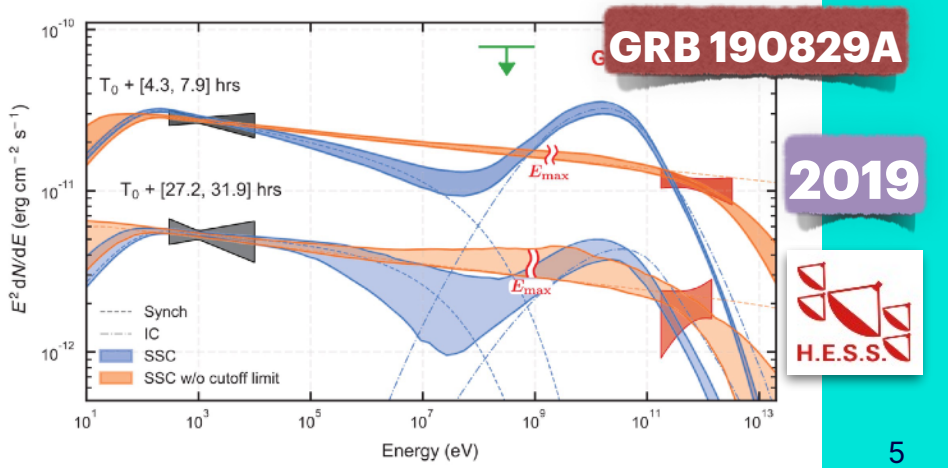
S E D



MAGIC Coll. et al., Nature,575,459-463(2019)

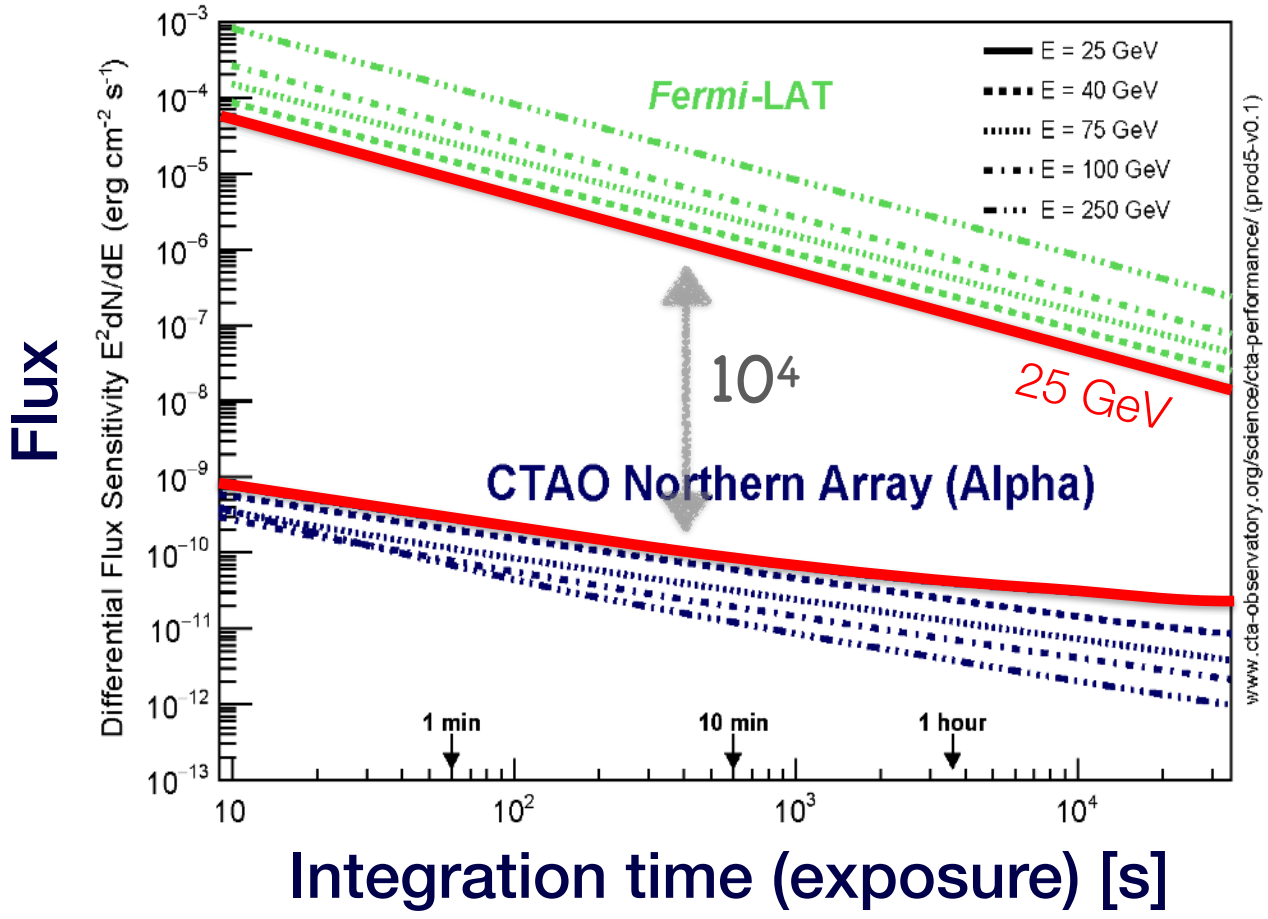


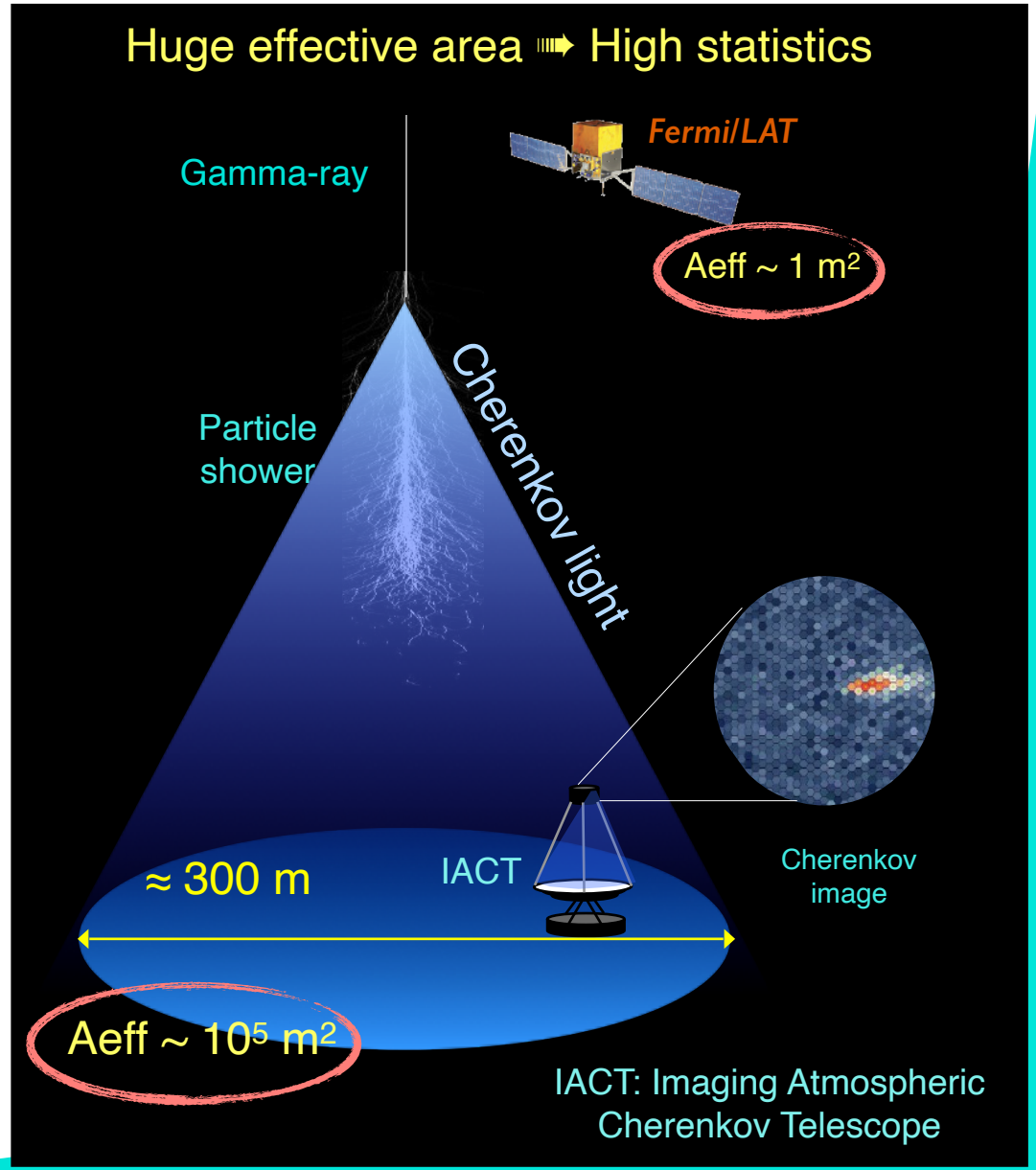
LHAASO Coll. et al., Science,9,46 (2023)



H.E.S.S. Coll., Science, 372 (2021)

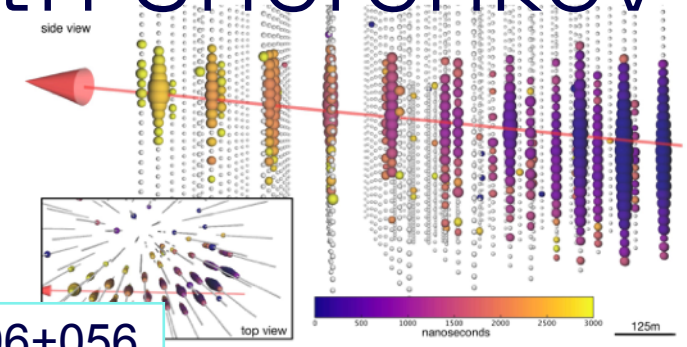
Cherenkov telescopes are most sensitive to transient and flaring sources



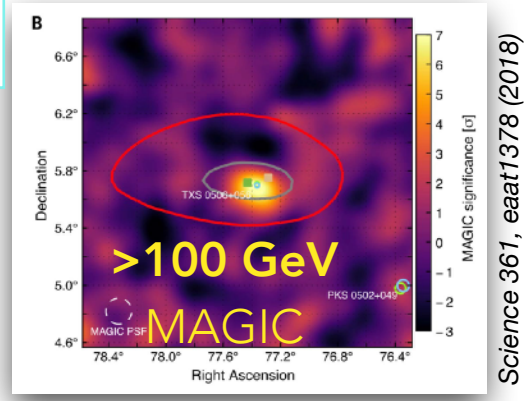


https://www.ctao.org/for-scientists/performance/

Constraining the neutrino sources with Cherenkov telescopes

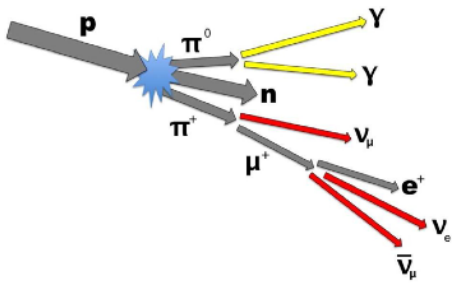


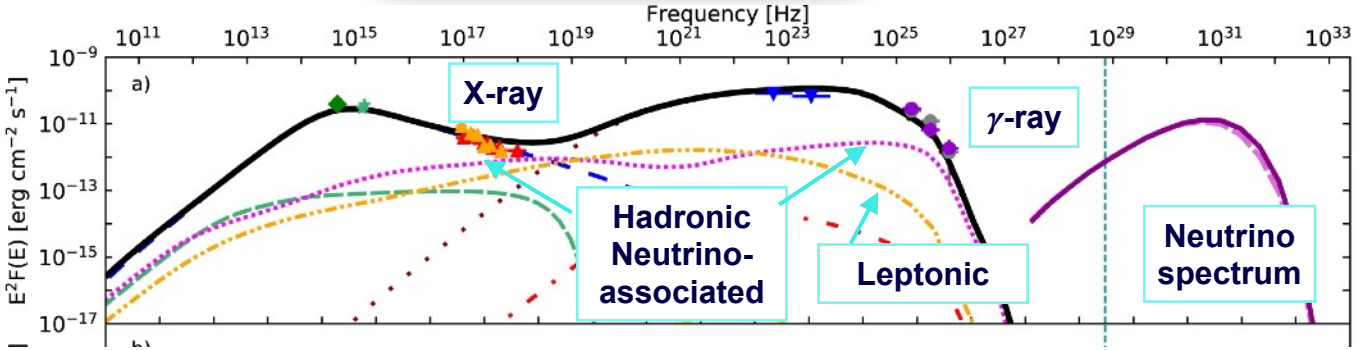
TXS0506+056 associated to IC170922A



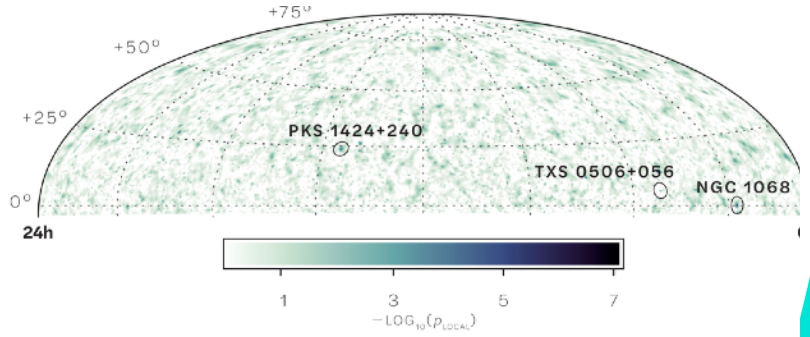
Science 361, eaat1378 (2018)

The interplay between X-ray and TeV emissions are key to constrain neutrino driven models

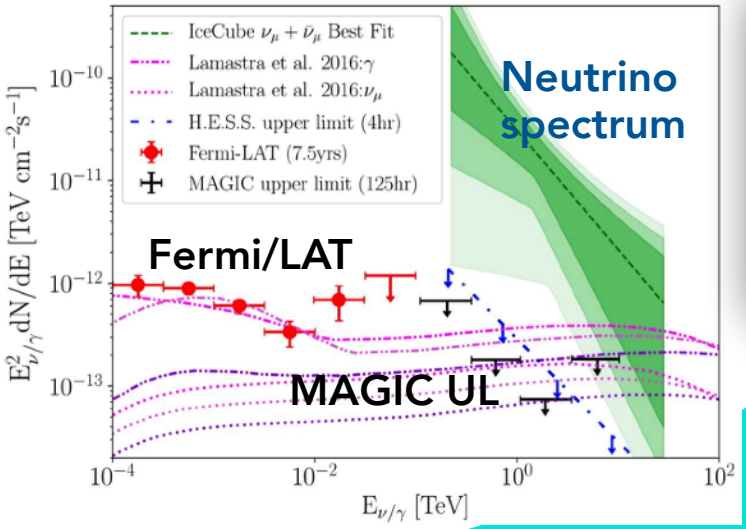


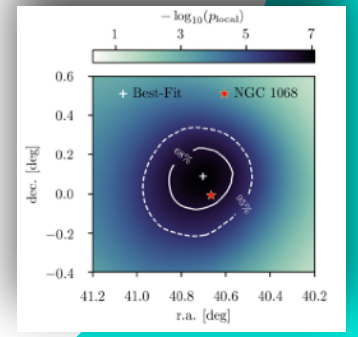


NGC1068 first evidence of neutrino emission from a AGN



Icecube coll., 2022 Science 378





*V. A. Acciari et al 2019 ApJ **883** 135*

IACTs in the Swift era

PennState Mission Operations Center for *Swift*

Home | Target of Opportunity | Observations | BAT | XRT | UVOT

Swift Target of Opportunity Requests

Target of Opportunity (TOO) requests allow for the community to request Swift

Submit a new TOO request

TOO request for 3C 279

Submit a New ToO for this Source

ToO ID	353
Requester	Stamerra
Time Submitted	2007-01-13 00:43:44
Urgency	Medium Urgency (days to a week)
Object Name	3C 279
Type or Classification	AGN Flare
GRB Discovery Instrument	n/a

Celebrating 20 years of Swift Discoveries

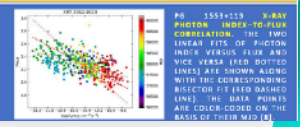
March 24 – 28, 2025
Firenze Fiera - Palazzo degli Affari

Unveiling the periodic variability patterns of the X-ray emission from the blazar PG 1553+113

by Tommaso Aniello – Associate scientist INAF Osservatorio Astronomico di Roma – PhD graduated in Astronomy, Astrophysics and Space Sciences
tommaso.aniello@inaf.it

...si, A. Lamastra, R. Middei, M. Perri, F. G. Saturni, A. Stamerra, F. Verrecchia)

...15H 55M 43.0S, DEC = +11° 11' 24" AND WAS DISCOVERED AS A BLUE STELLAR ...1982. IN THE EARLY 1980S, IT WAS CLASSIFIED AS A BL LAC OBJECT DUE TO ITS ...SO DETECTED AS AN X-RAY SOURCE AND AS A TEV Γ-RAY EMITTER. ...0.5 ([1]), SHOWS EVIDENCE OF A PERIODICITY (T ~ 2.2 YR) IN THE Γ-RAY BAND ...BAND:[2];[3];[4]).



1 of 1

Swift's Role in Shaping MAGIC's Multiwavelength High-energy Astrophysics

Jahanvi
University of Udine-INFN Trieste
On behalf of the MAGIC Collaboration

MAGIC: MAJOR ATMOSPHERIC GAMMA IMAGING CHERENKOV TELESCOPES

INFN TRIESTE

Introduction to MAGIC [1]

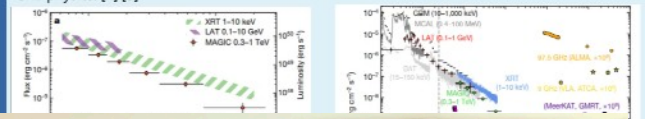
- First light: 2004
- Location: La Palma, Canary Island
- No. of telescopes: 2
- Mirror: 17 m diameter each
- Field of view: 3.5°
- Trigger area: 4.30 deg²
- Angular resolution: ~0.1°
- Energy range: ~30 GeV to tens of TeV
- Repositioning speed = 27s /180° for fast follow-up observations
- Automatic repositioning in case of alerts

Fig. 1: MAGIC looking at the ... (Image credit: Josue Fried...

Why MAGIC needs Multiwavelength (MWL) support?

Gamma-ray observations alone provide limited context, so MWL data—from X-rays t... and radio—is essential. Many gamma-ray sources (e.g., AGNs and GRBs) emit via ... and inverse-Compton processes, with the synchrotron peak often in the X-ray ... inverse-Compton scattering produces VHE gamma-rays. X-ray data are crucial b... offer complementary insights into the source's environment and dynamics, helpin...

2) GRB190114C (2019): The first GRB detected at TeV energies, showing clear inverse Compton emission. Triggered by instruments including Fermi-GBM, Fermi-LAT, and Swift-BAT, Swift's X-ray/UV data confirmed the synchrotron origin of the lower-energy component, while MAGIC's TeV observations provided direct evidence of inverse Compton scattering. Combined MWL data support a synchrotron self-Compton (SSC) model, advancing our understanding of GRB physics. [4] [5]



The Swift Perspective of Very High Energy Sources Observed with VERITAS

VERITAS is one of the world's most sensitive detectors of astrophysical very high energy (VHE; E> 100 GeV) gamma rays. The array is located in southern Arizona, USA and is made up of four 12-m imaging atmospheric Cherenkov telescopes (IACTs

Amy Furniss (UC Santa Cruz)
27 March 2025 11:15
Florence, Italy
Celebrating 20 years of Swift Discoveries

The ASTRI Mini-Array at the time of multi-messenger astronomy

G. Pareschi[1] & S. Vercellone[1], for the ASTRI Project[2]
[1]INAF – Osservatorio Astronomico di Brera
[2]http://www.astri.inaf.it/en/library/

ABSTRACT
The ASTRI Mini-Array is currently being installed in Tenerife at the Teide Observatory to explore the gamma-ray sky in the 1–200 TeV energy range with unmatched angular resolution (a few arcminutes) across a wide field of view (10.5 degrees). The array consists of nine imaging atmospheric Cherenkov telescopes (IACTs), each equipped with a 4-meter diameter dual-mirror system featuring a Schwarzschild-Couder-like optical configuration, functioning as an aplanatic system, and an innovative compact camera which utilizes Silicon photomultipliers sensors. This contribution briefly overviews the ASTRI Mini-Array project layout, capabilities, and scientific objectives. The ASTRI Mini-Array can play an important role in multi-messenger astronomy to better understand Galactic and extragalactic astrophysical aspects, combining the information inferred by other observational facilities. In this respect, a parallel observation program with ASTRI Mini-Array and *Swift* already started.

ASTRI MINI-ARRAY STATUS

ASTRI-1 (see Fig. 1), the first telescope of the ASTRI Mini-Array [1,2], has been acquiring data at the Teide Observatory since October 2024. Four ASTRI telescopes will be

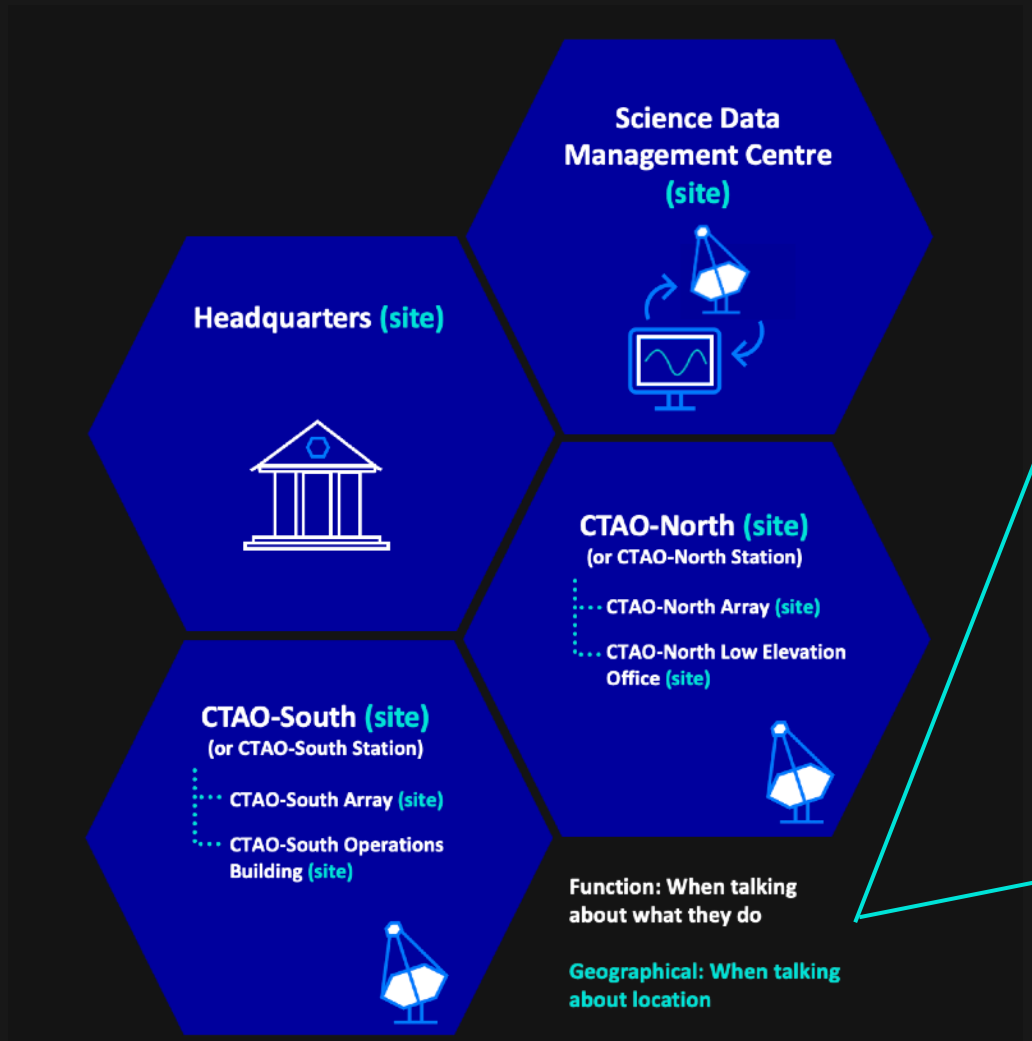
ASTRI MINI-ARRAY PERFORMANCE

Fig. 3 shows the ASTRI Mini-Array differential sensitivity both for 50h and 5σ compared with those of current IACTs and of the planned CTAO and for deeper exposures (200h/500h, 5σ) compared with current WCDs. The ASTRI Mini-Array will improve the current IACT sensitivity at energies greater than a few TeVs and will be

Check poster session for further connections between TeV and X-ray studies

The Cherenkov Telescope Array Observatory

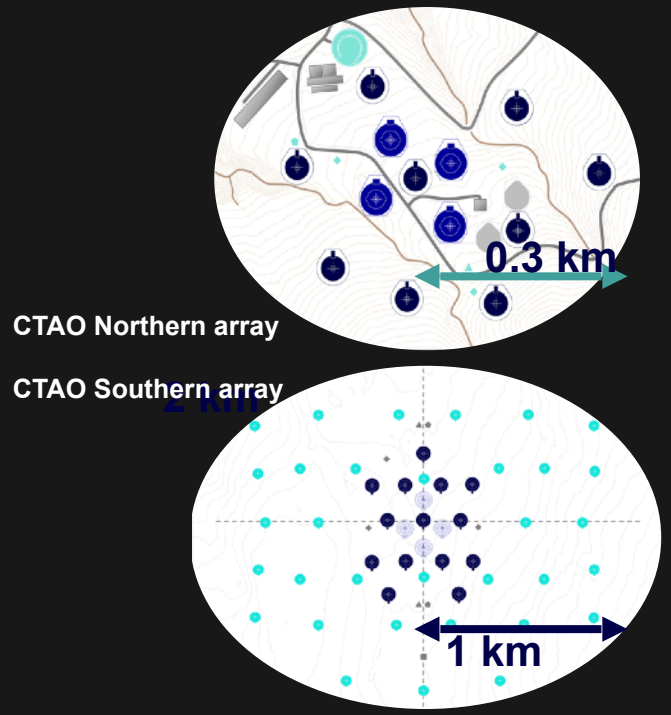
CTAO: a distributed facility

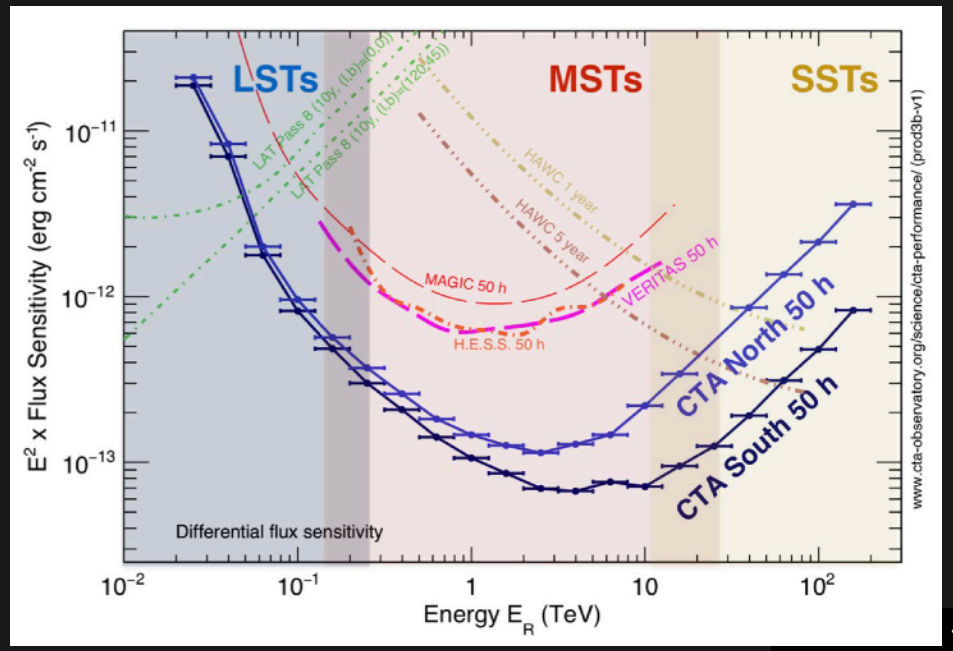


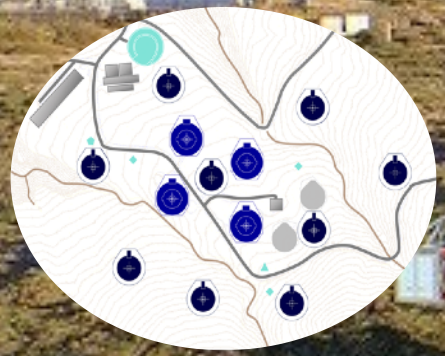
CTAO: a diverse array

- Extended energy range (20 GeV-300 TeV) with telescopes of 3 sizes.
- Improved sensitivity, up to 5-10 times than current IACTs.
- Improved angular resolution (3′) and energy resolution (7% @1 TeV).

	LST	MST	SST
Mirror ⌀	~23m	~11.5m	~4m
FoV	~4.3deg	~7.5deg	~9deg

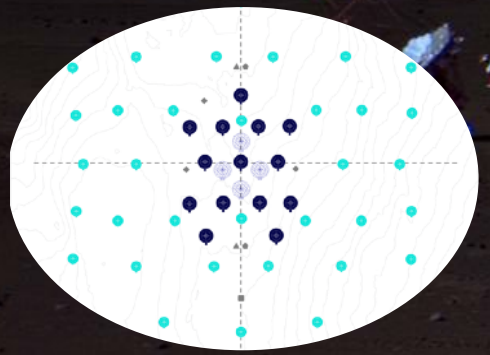




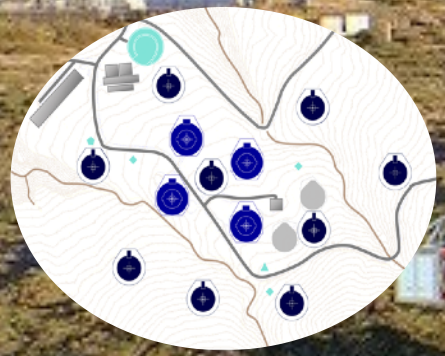


Northern site: La Palma
13 telescopes: 4 Large, 9 Medium

Southern Site: Paranal, Chile
51 telescopes: 14 Medium, 37 Small



Alpha configuration



Northern site: La Palma
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Southern Site: Paranal, Chile
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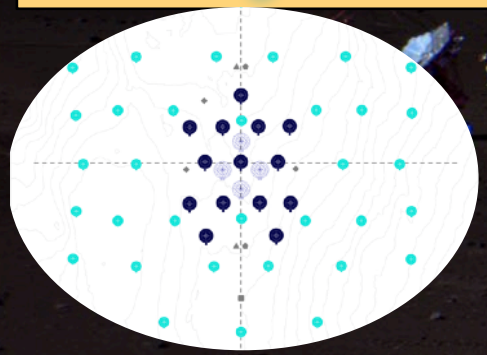
+ 2 Large + 5 SST*



*CTA+ Italian project NRRP

Improved Alpha configuration


North site: LST-1(4) Telescope(s) at La Palma (Spain)


The CTAO team

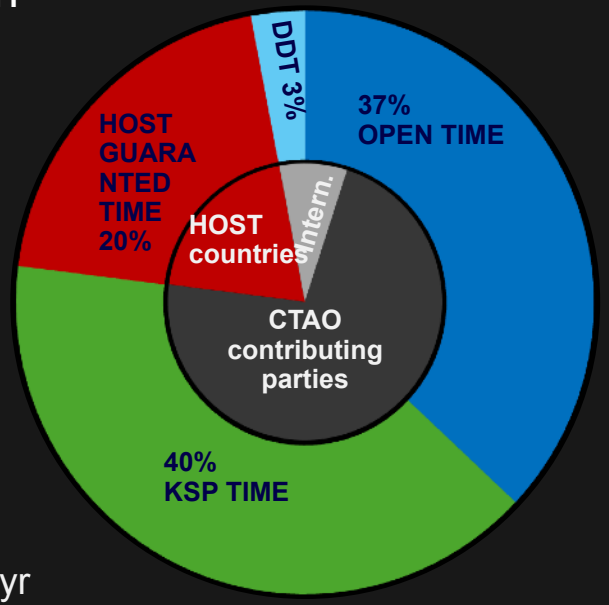

South site: Atacama (Chile)


Computing Center at DESY (Germany)

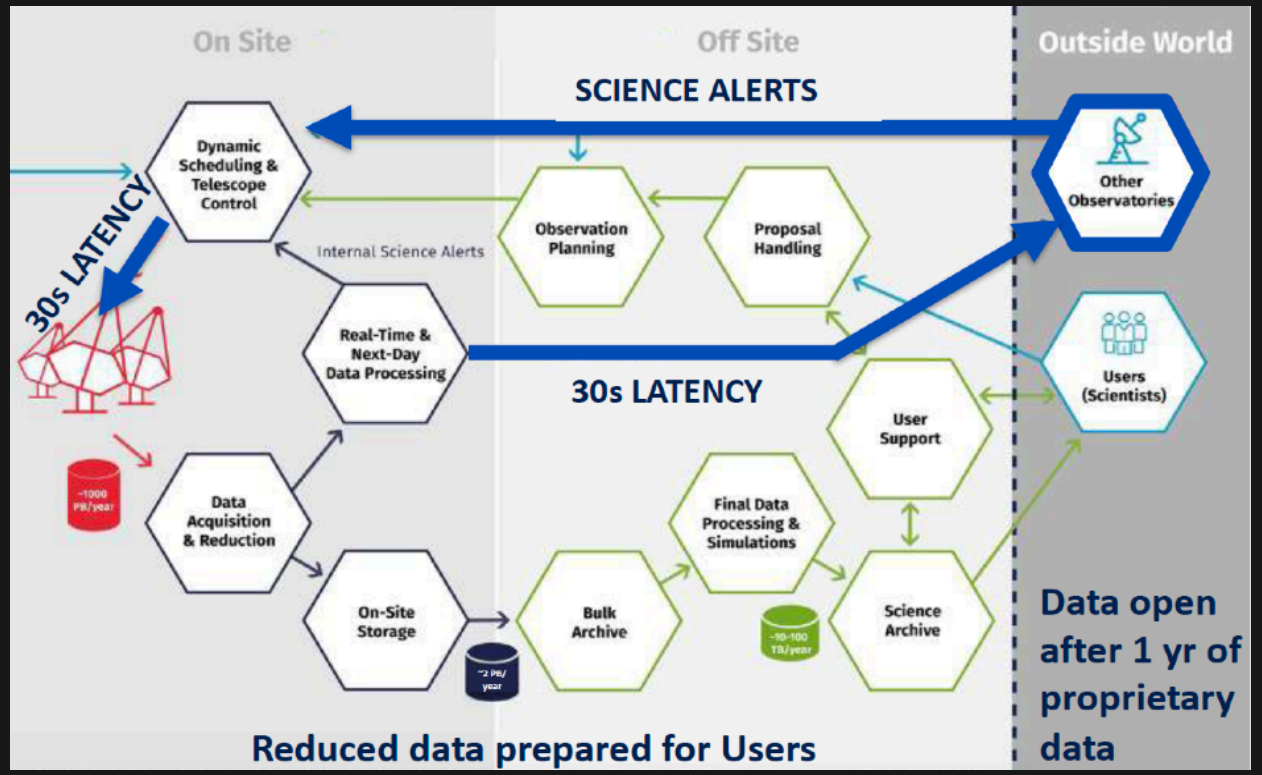
An astronomical observatory

An open proposal-driven observatory

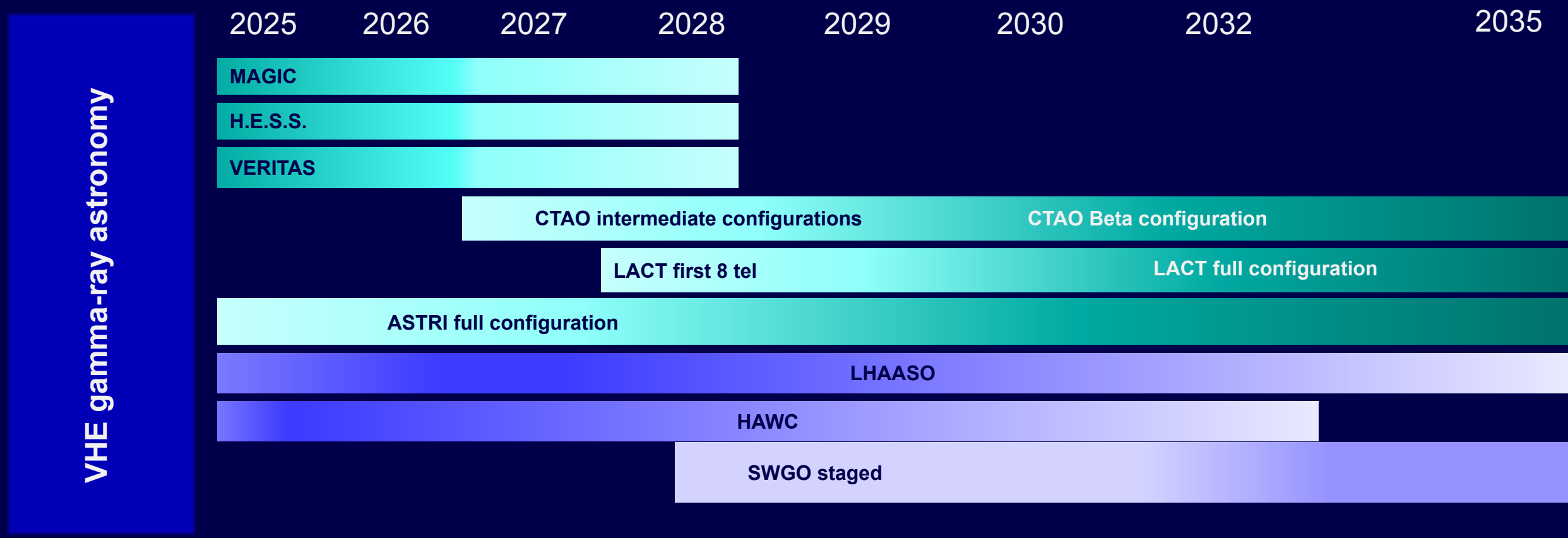
- Proposals will be evaluated only on their scientific merit
- Data with a proprietary period of 1 yr after that fully open



integrated over 10 yr

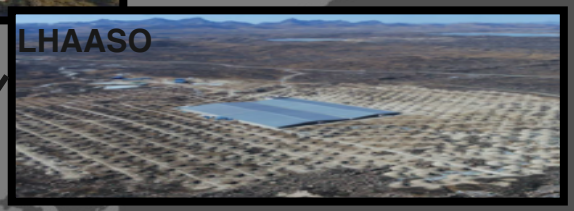


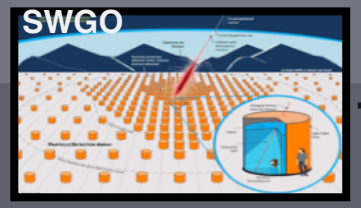
CTAO in the TeV landscape



The end dates of the facilities are just indicative: the fate of these instruments is currently under discussion

CTAO in the TeV landscape



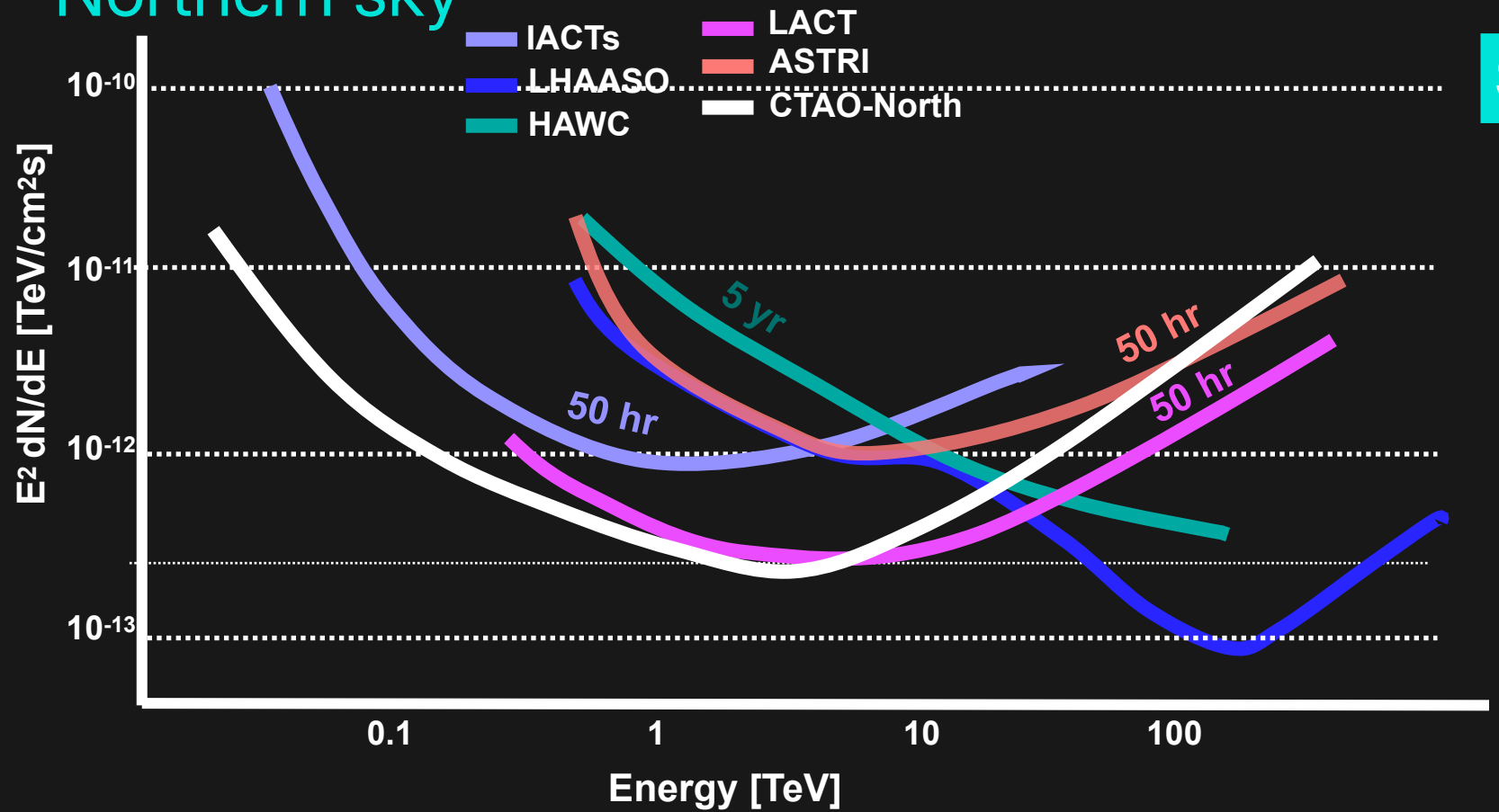


Galactic equator

ASTRONET Roadmap 2022-2035

CTAO Performance

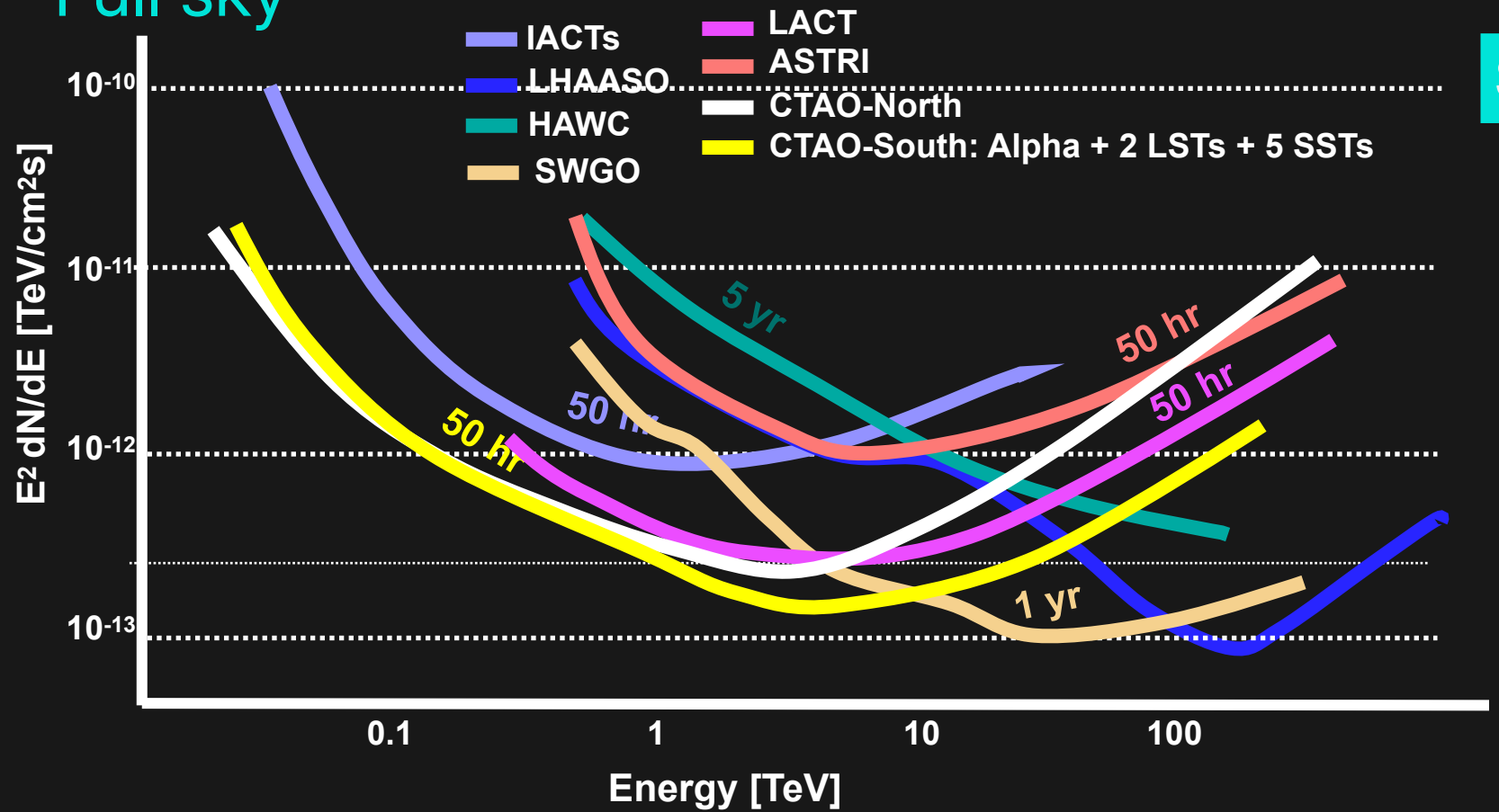
Northern sky



Sensitivity

CTAO Performance

Full sky

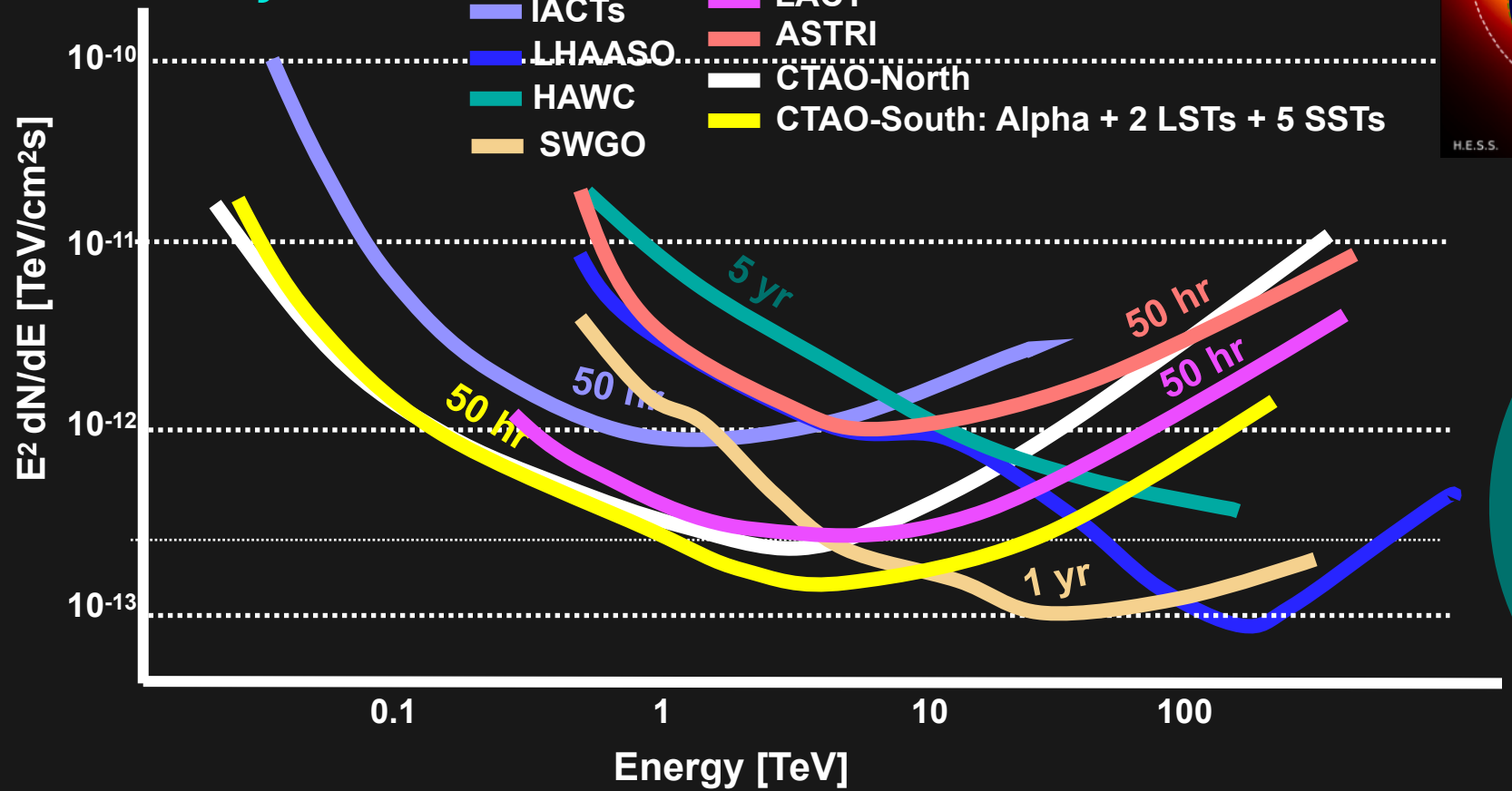


Sensitivity

CTAO Performance

Full sky

Sensitivity



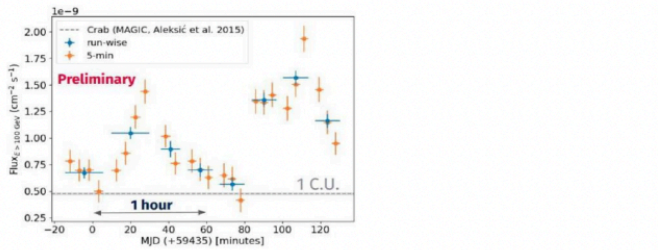
Angular resolution

Early-Science with CTAO

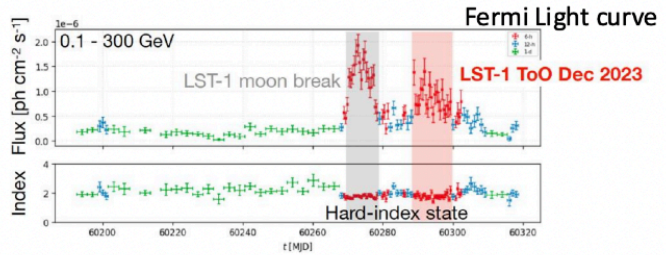
The prototype LST-1 is already producing science

2024 – LST1 performance paper

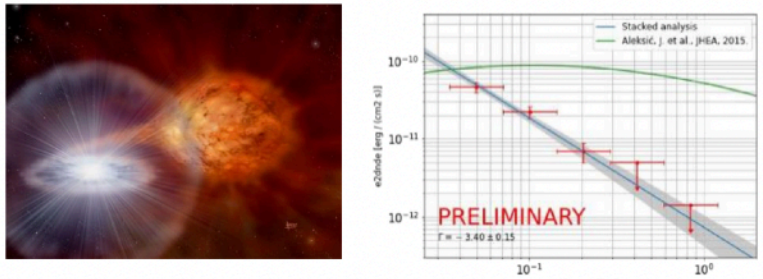
BL Lac intranight fast variability (a few min)



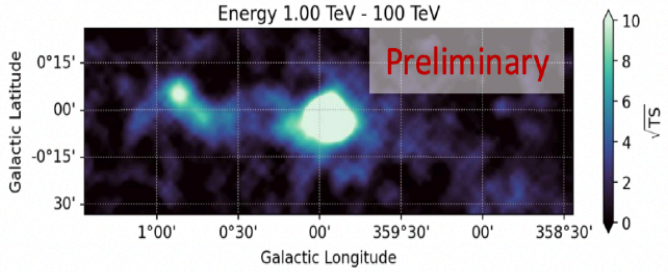
OP313: discovery of the most distant VHE AGN



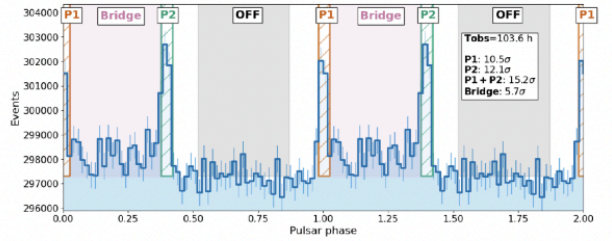
Symbiotic Nova RS Ophiuchi



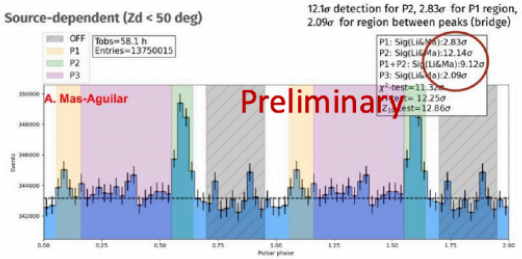
Galactic Center 39hrs (Sgr A*, diffuse)



Crab pulsar above 20GeV



Geminga pulsar above 15GeV



Credits to M. Teshima & the LST collaboration

Towards the first CTAO data

Intermediate array configurations

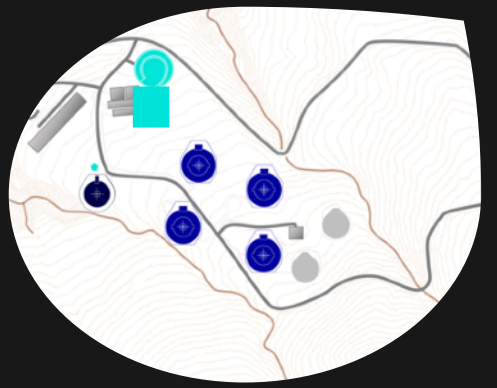
CONCEPT

Intermediate array configurations: incremental array configurations that become progressively operative

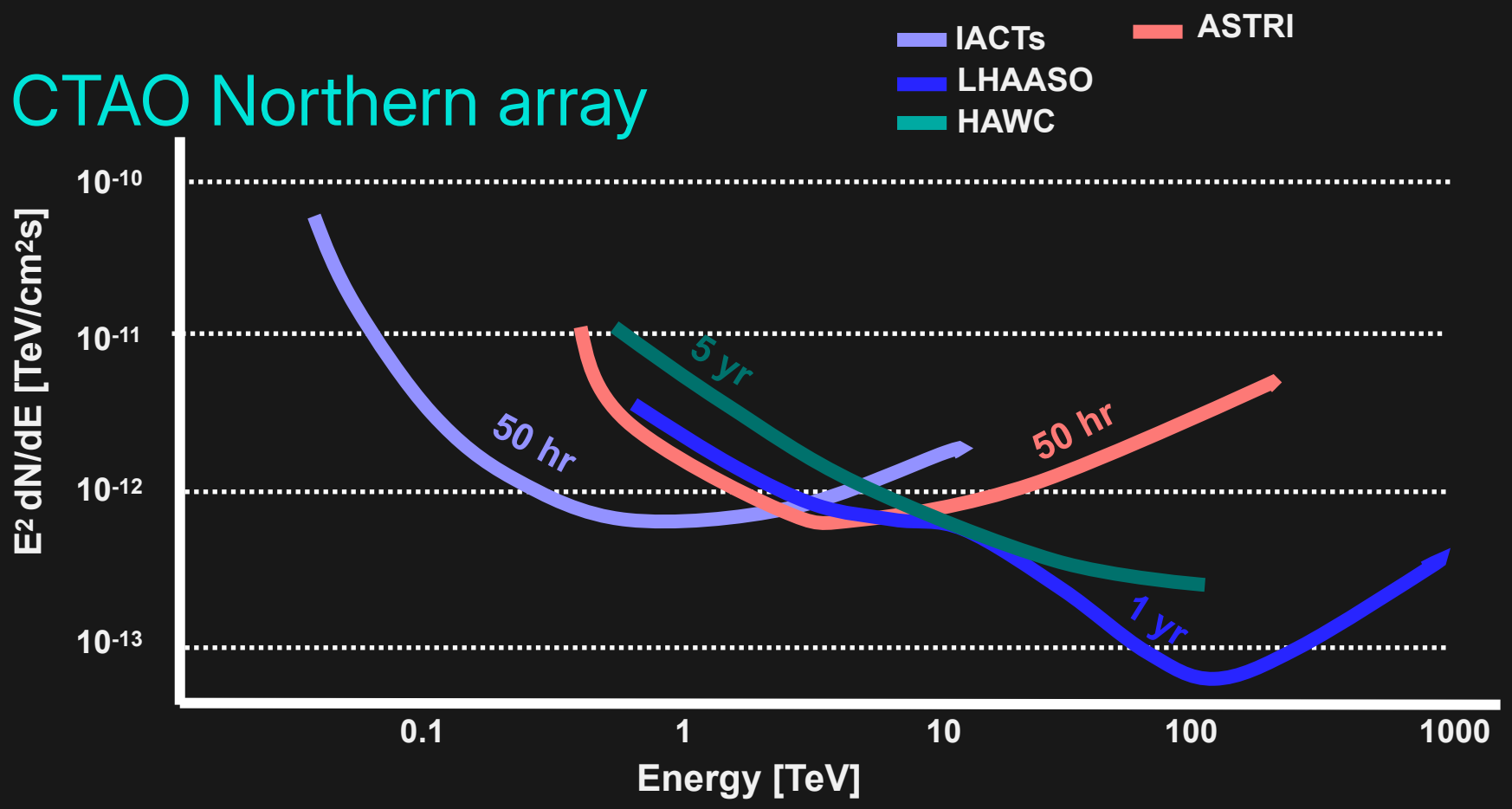
- array elements fully integrated with the intermediate releases of the software packages
- array elements include telescopes but also calibration devices and atmospheric characterization instruments

MID-PERIOD PLAN (3 yr long) BASED ON THE CONSTRUCTION SCHEDULE
built accounting for the inputs of the in-kind contribution teams

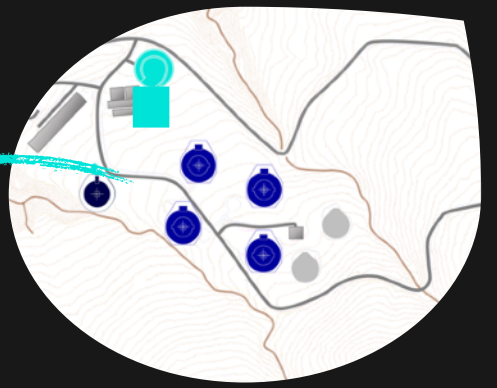
In 3 years from now



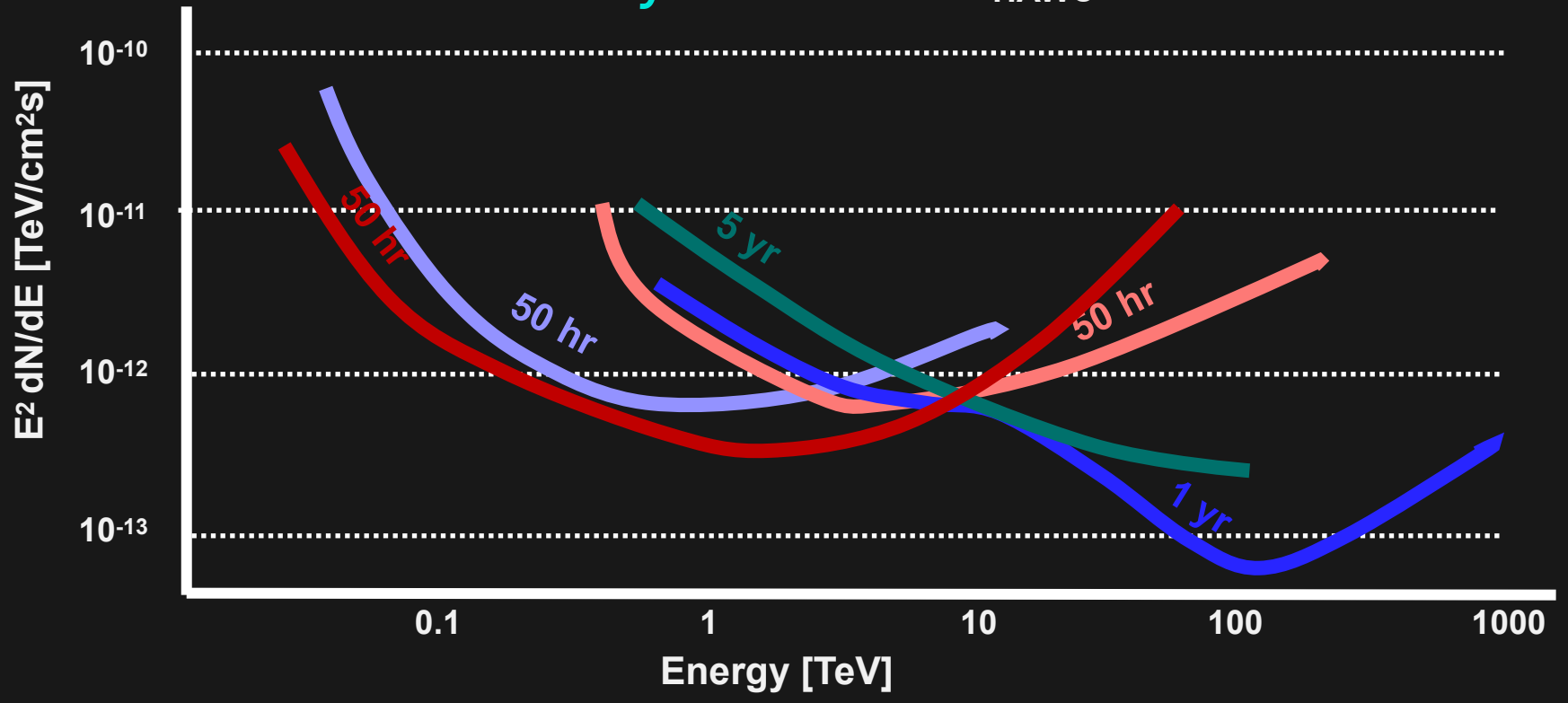
CTAO Northern array



In 3 years from now



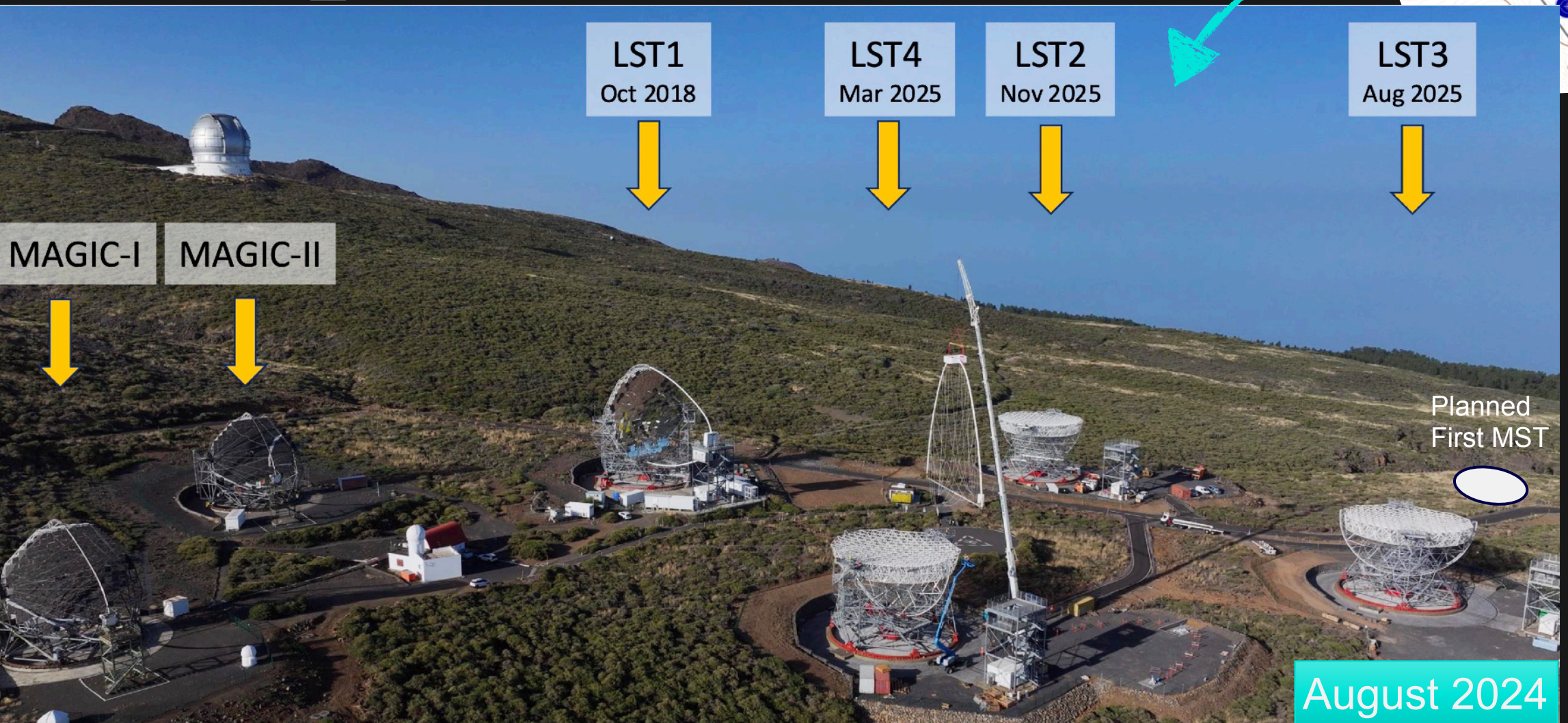
CTAO Northern array



With respect to current IACT arrays:

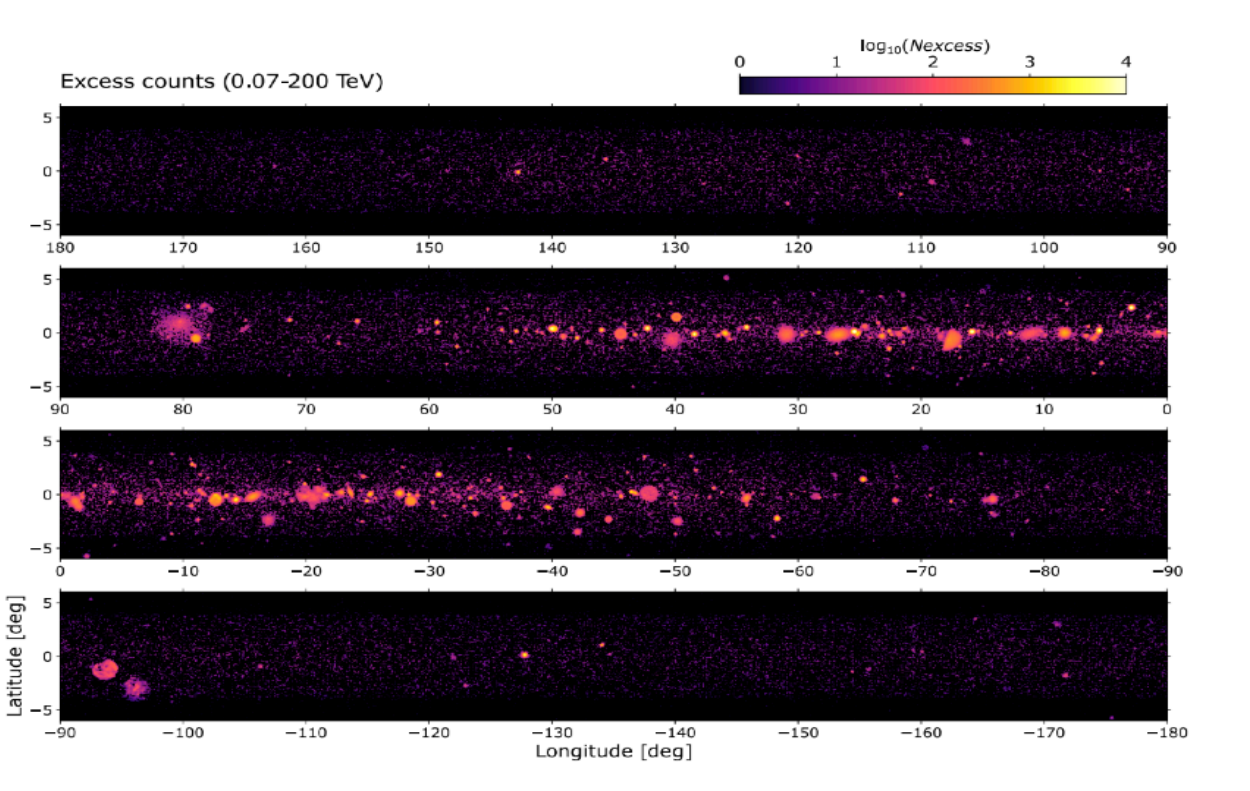
- Sensitivity up to a factor of two better
- Angular resolution up to 40% improvement

In 3 years from now



Science Data Challenge

Blind and open! … coming soon



- 7 yr of simulated CTAO observations provided as science-ready data sets (DL3)
- Goal #1: allow the gamma-ray community as well as the broad astronomical community to explore the CTAO scientific capabilities
- Goal #2: allow the users to familiarize with the technicalities of the analysis as well as with the CTAO science analysis tools, based on gammapy

Key Takeaways

- ✓ Several complementary ground-based instruments will drive the advancements in gamma-ray astronomy in the (tens of) GeV to PeV range in the near future.
- ✓ CTAO is a key player, enhancing:
  - ✓ **sensitivity** (more sources, high-precision spectral measurements).
  - ✓ **angular resolution** (morphological studies).
  - ✓ **Field of view** (galactic and extragalactic surveys).
  - ✓ **Energy range**, from 20 GeV (expanding the explored volume of the Universe) to 300 TeV.
- ✓ CTAO is well suited to time-domain astronomy studies in a multi-frequency and multi-messenger context.
- ✓ The first CTAO data is expected within the next three years, with performance capabilities already twice as good as existing facilities.
  - ✓ Transient phenomena will be explored at maximum capability within the next three years.

https://www.ctao.org

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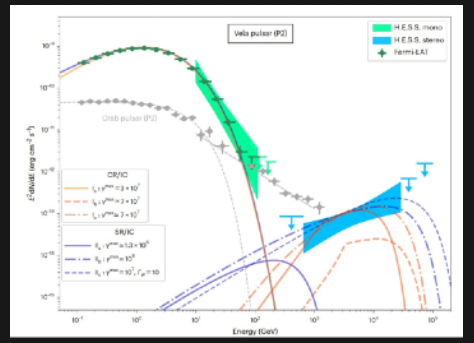
Eager to hear your feedback and to involve you in the SDC next year!

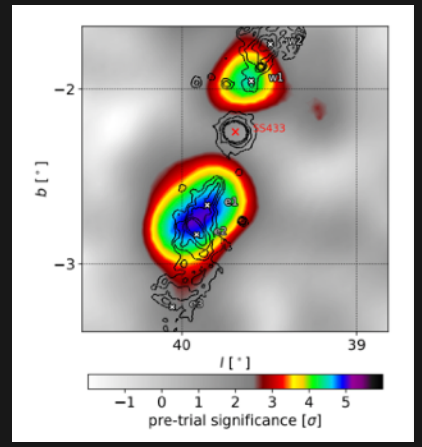
https://www.ctao.org

Science cases of the VHE astronomy

H.E.S.S. coll. Nature 2023



HAWC coll. Nature 2018



sub-TeV

- Transients
- Cosmological sources
- Pulsars

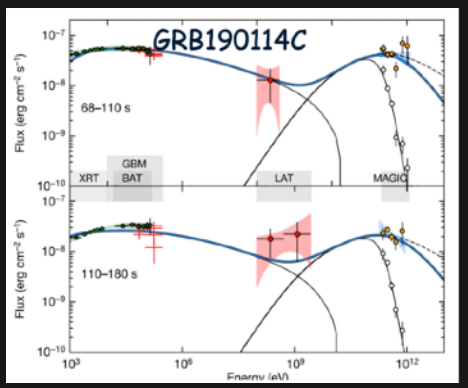
TeV

- EBL
- Dark Matter
- diffuse emission
- morphological studies
- surveys

multi-TeV

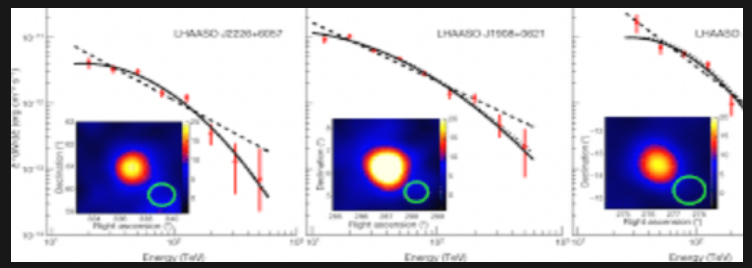
- PeVatrons
- SFRs

MAGIC coll. Nature 2020

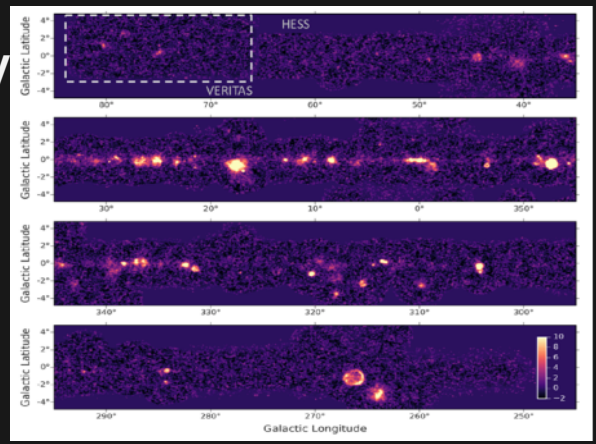


20 GeV 500 GeV 1 TeV 10 TeV 300 TeV

LHAASO coll. Nature 2021



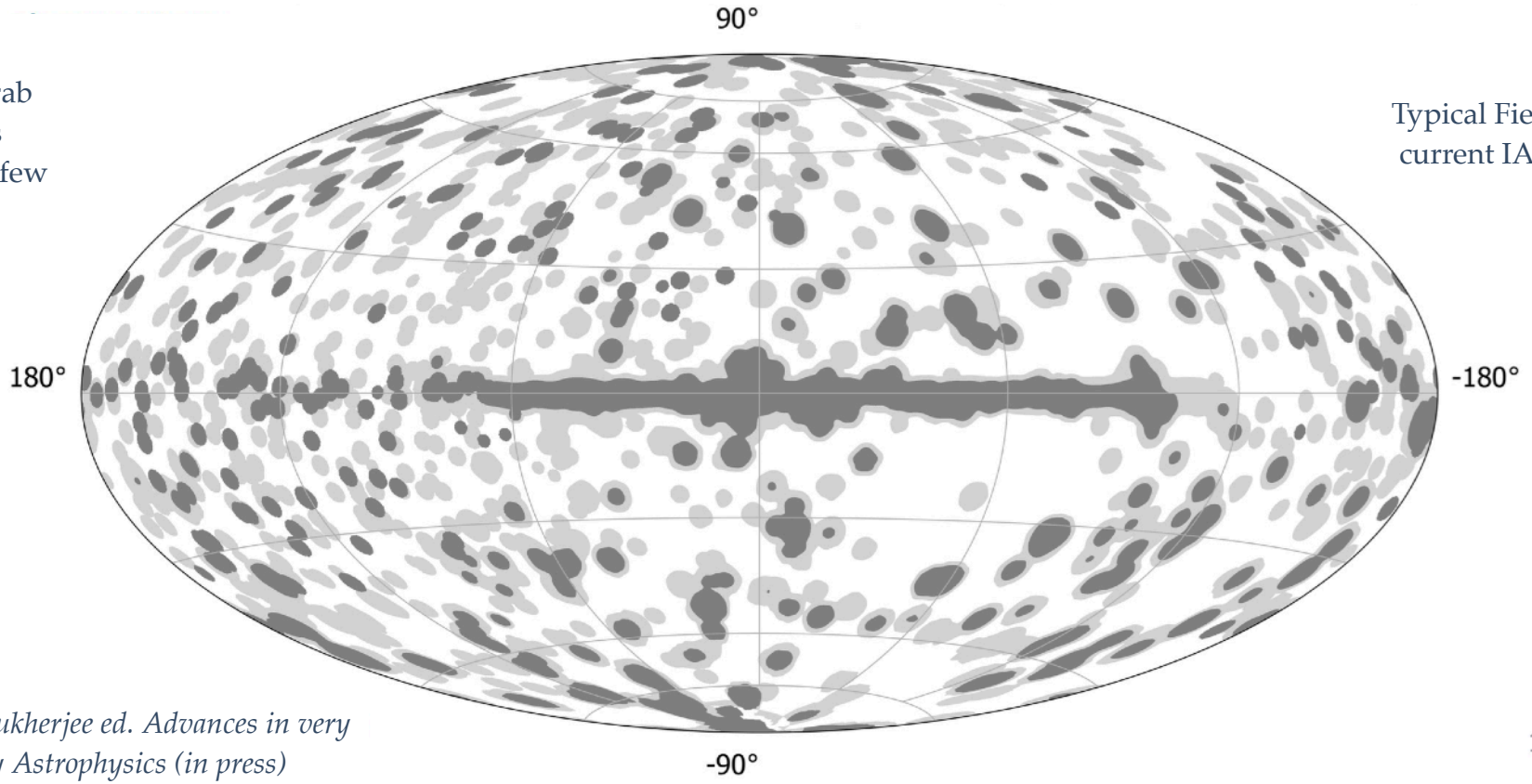
GPS VERITAS + H.E.S.S.



Why an extragalactic survey at TeV energies?

- The extragalactic TeV sky is biased due to non-uniform observations, primarily driven by target-based monitoring and triggers on flaring sources in other wavelengths.

Sensitivity ~1% Crab
~10^{-12} erg/cm^2/s
Typical exposures: few to tens of hours



Typical Field of View of current IACTs: 3-5 deg

R. Zanin&R. Mukherjee ed. Advances in very high energy Astrophysics (in press)

1

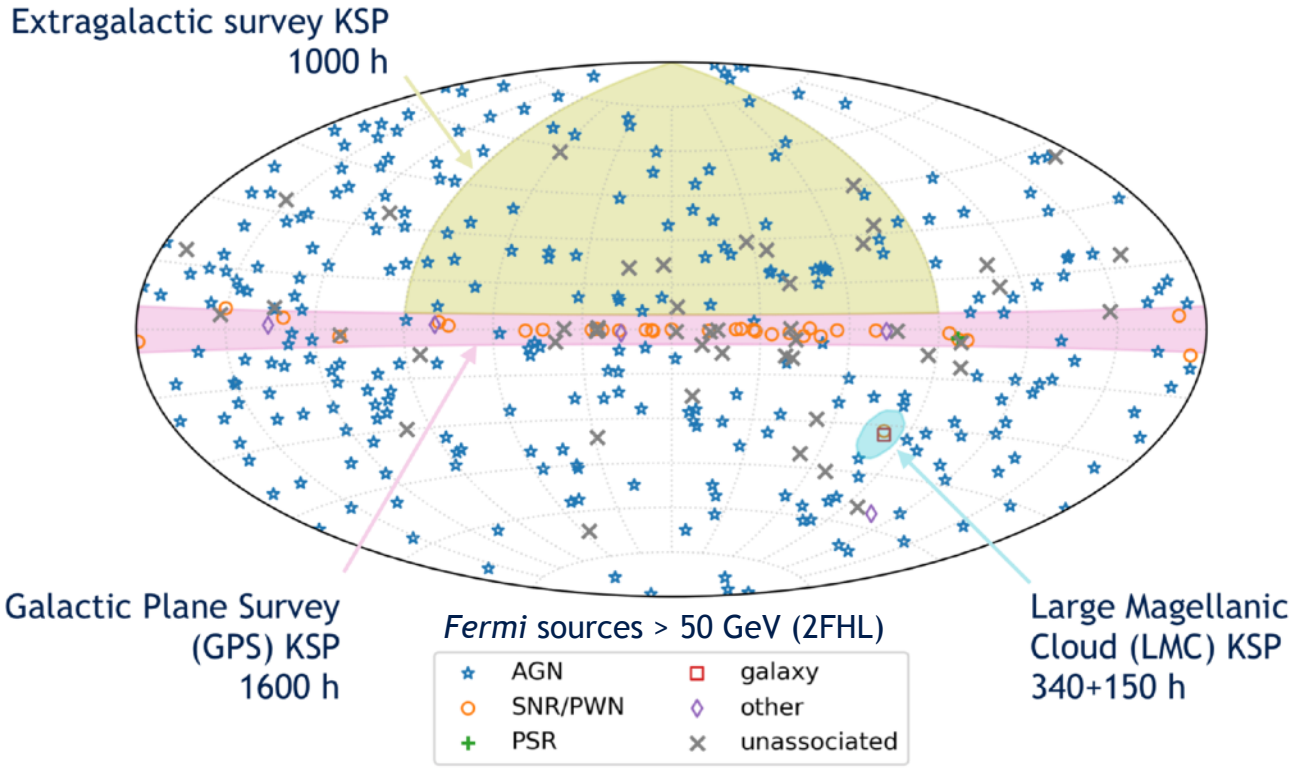
Planned surveys with the Cherenkov Telescope Array Observatory CTAO

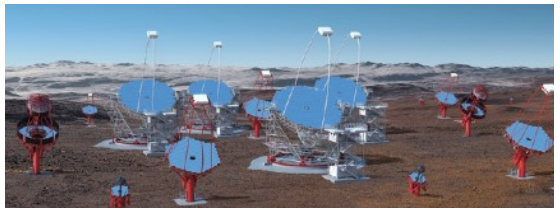
- Unbiased survey on 1/4 of the sky, 1000 hours. Sensitivity 6 mCrab (~3x10^{12} ph/cm^2/s >125 GeV)

✓ derive the LogN-LogS and Luminosity function of TeV blazars

✓ Detect sources in flaring state —> Duty cycle

✓ Serendipitous new sources; extreme blazars; exotic:dark sources; GRB

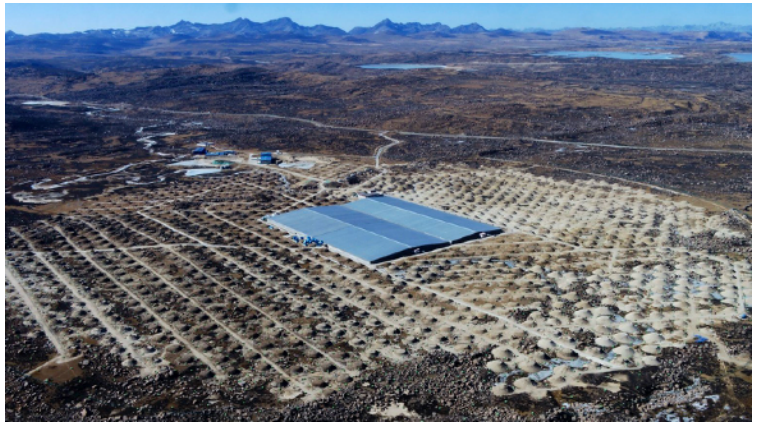


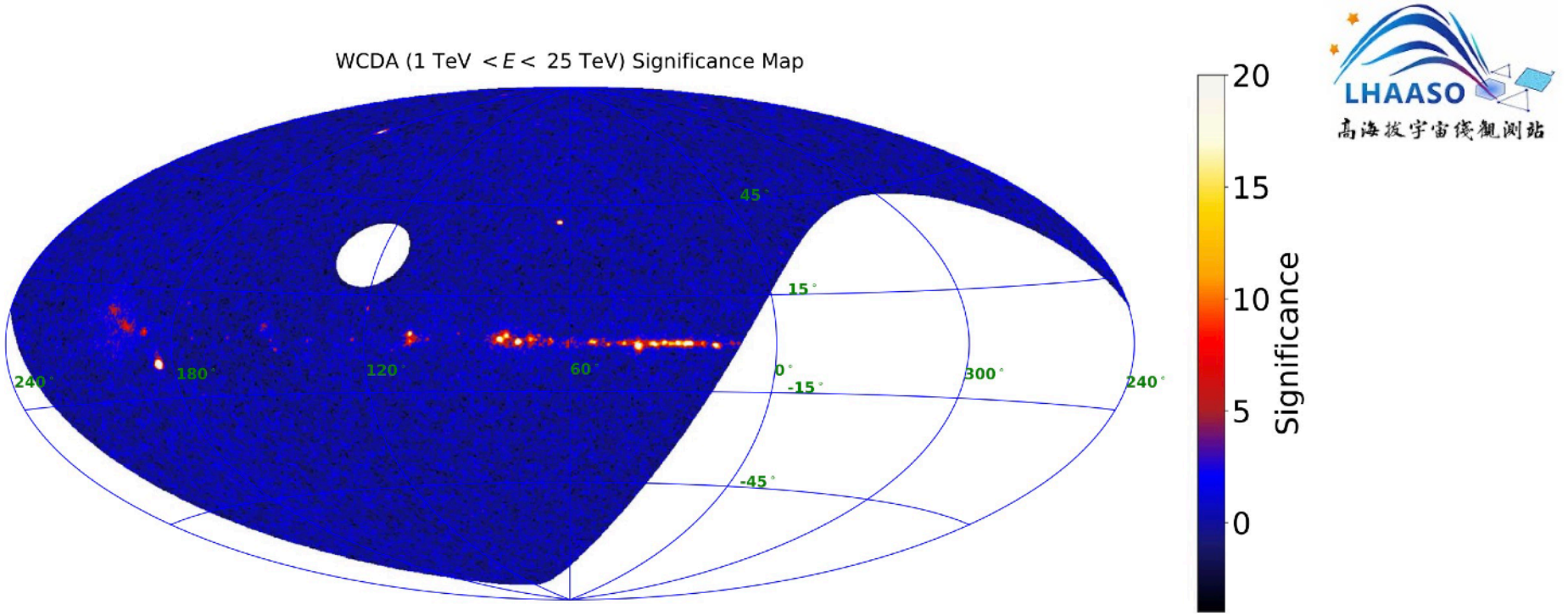


Field of view of CTAO telescopes: ~8 deg

Why an extragalactic survey at TeV energies?

- 1st LHAASO catalogue with exposure: 1.5 yrs
  - 90 sources; 4(5) blazars
- Limiting flux ~1% Crab at >1 TeV
- Severe EBL absorption
  - WCDA: >1 TeV, KM2A: >25 TeV



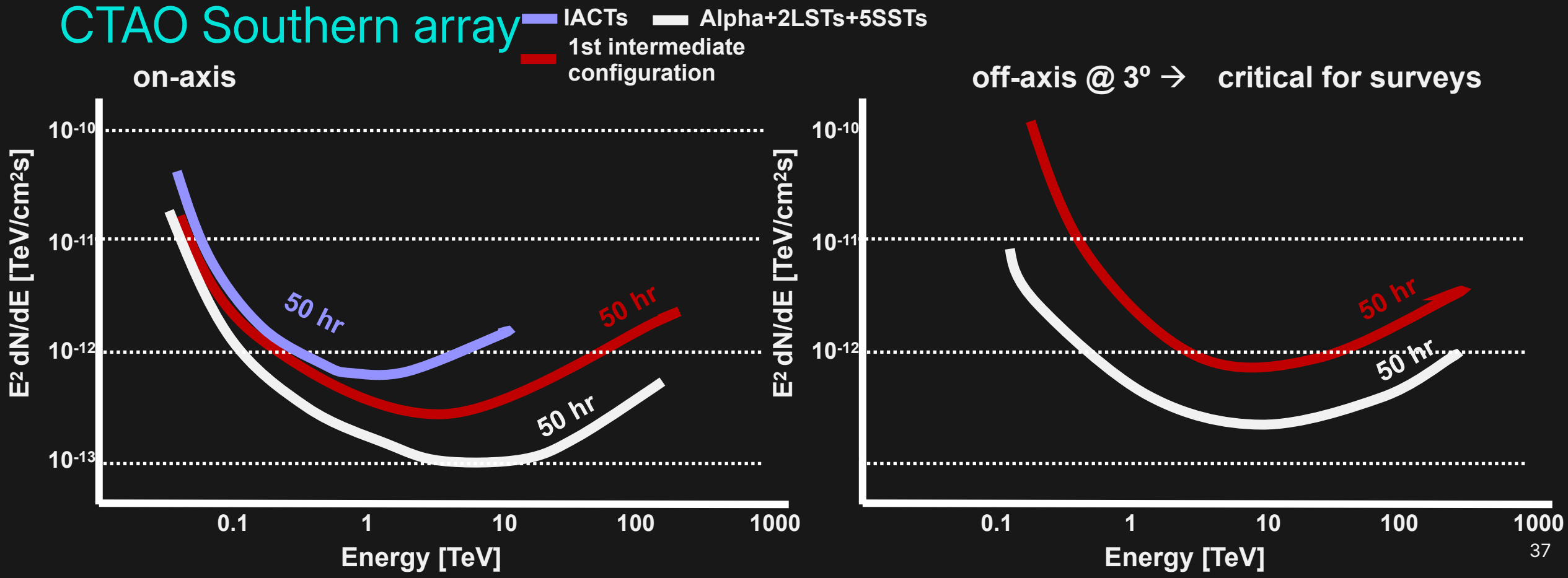


*Zhen Cao et al 2024 ApJS **271** 25*

In 3 years from now

@10 TeV
- as good as LHAASO
- 80% better than ASTRI

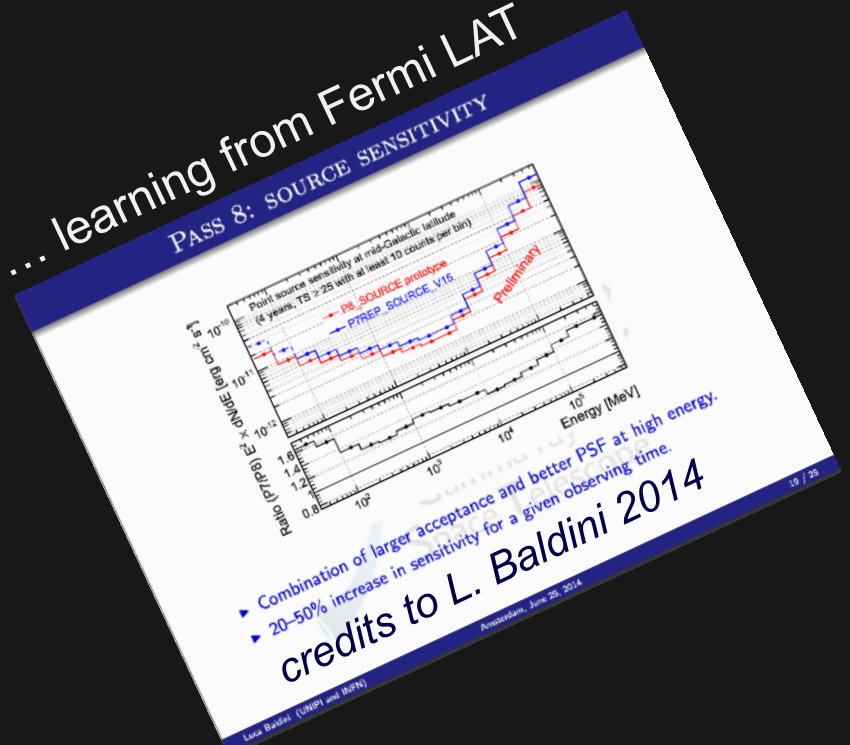
CTAO Southern array

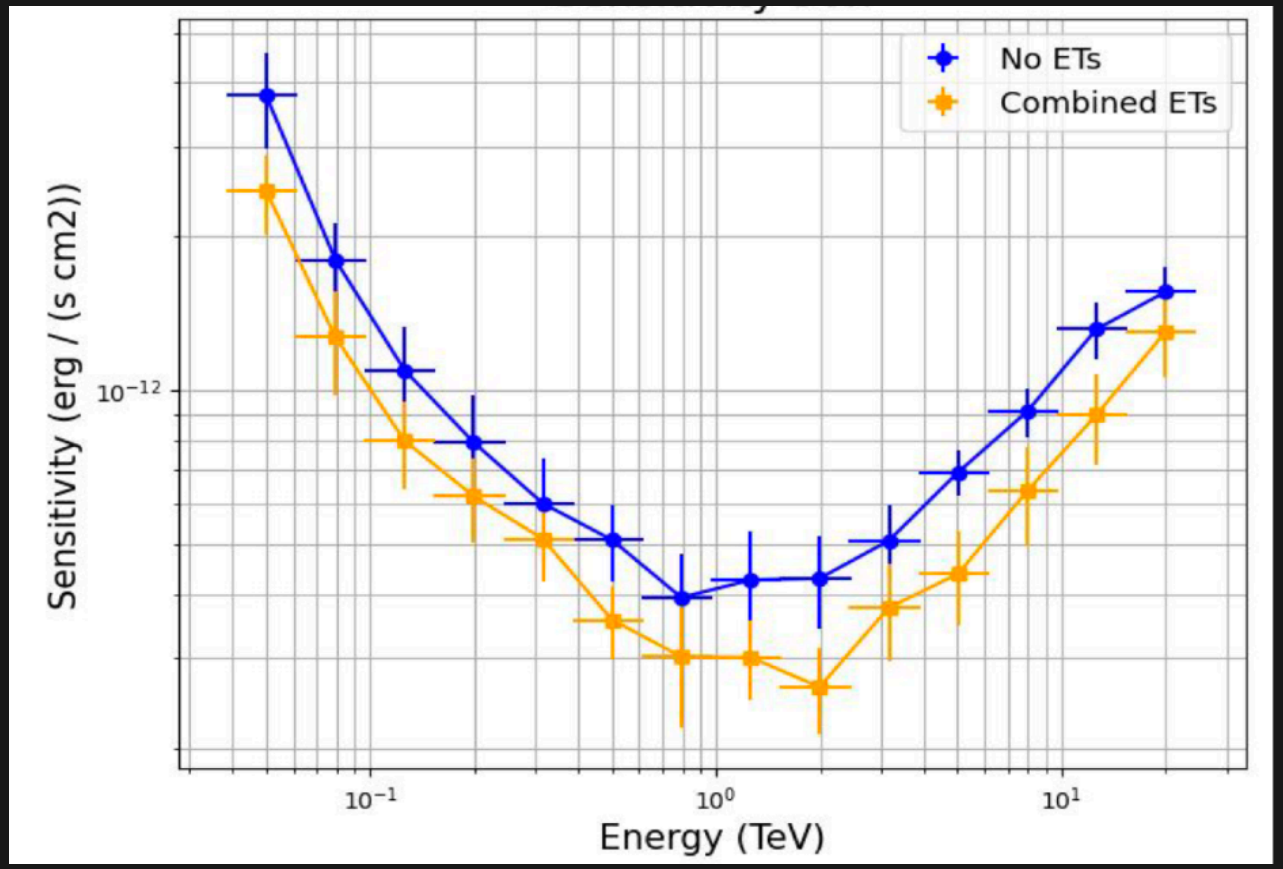


Non la metterei a meno che non abbia senso 'politicamente'

Improved Alpha configuration

Introducing the concept of the event types





credits to J. Bernete-Medrano et al

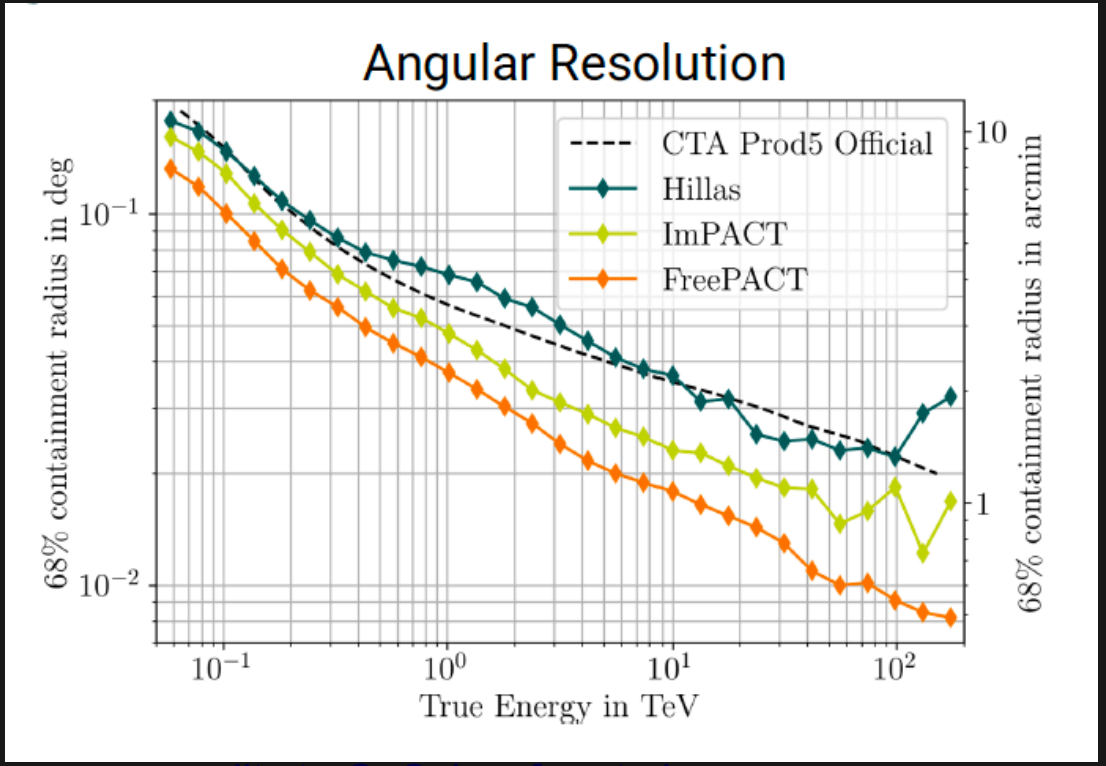
Improved Alpha configuration

exploiting the machine-learning

There is more room

... using a hybrid likelihood, machine-learning algorithm

What does this imply for science?

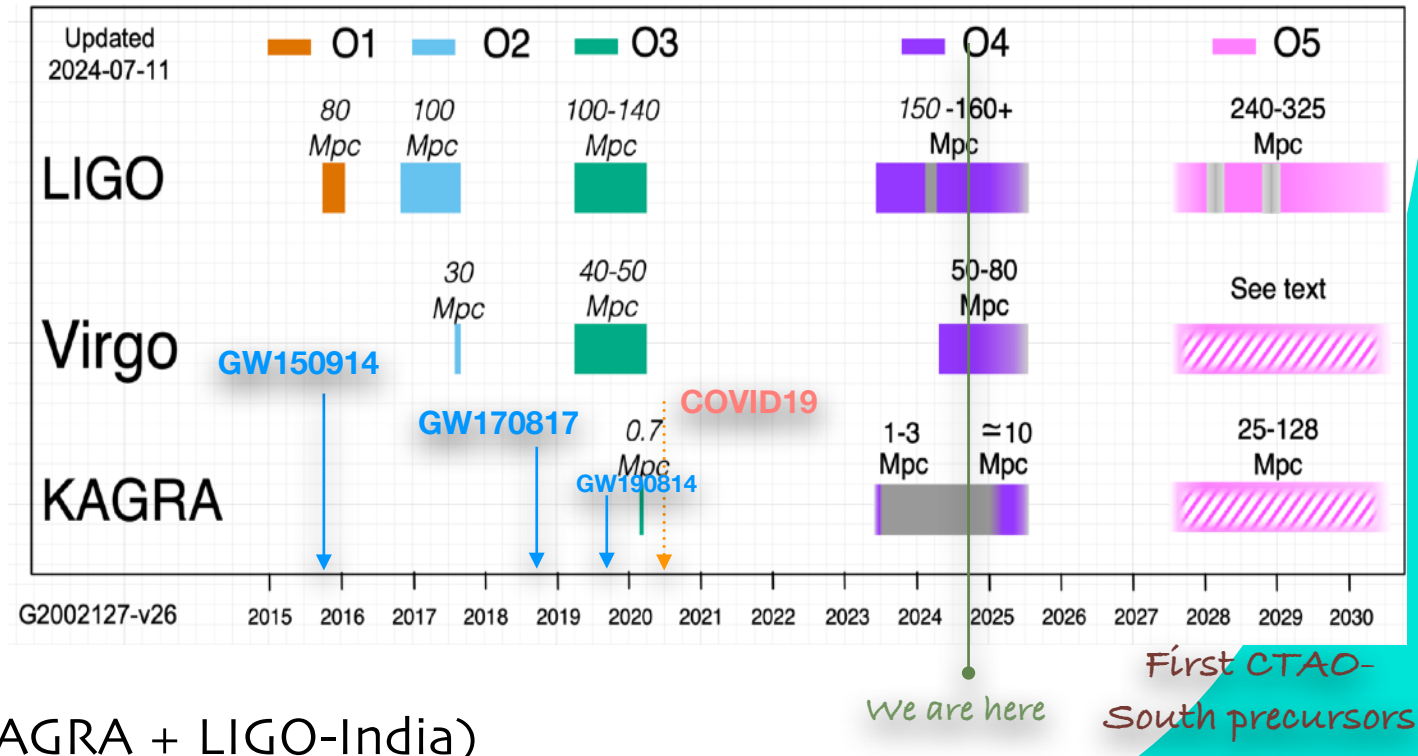


Credits to G. Schwefer et al.

GW interferometers - scientific runs

- Run 01 (2x LIGO)
  Sept 2015 - Jan. 2016
  First GW (BH-BH) event!
- Run 02 (LIGO + VIRGO)
  2016-2017; 6 months; Virgo: Aug. 2017
  First e.m. counterpart of BNS merger!
- Run 03 (LIGO + VIRGO) -advan. phase
  February 2019; 1 year - O3a / O3b
  First NS-BH events!
  March 27th: stop due to COVID19...
- **Run O4 - (LIGO+VIRGO+KAGRA)**
  Started 24 May 2023 until 2025, June 9th
- **Run O5** - AdV+ phase (LIGO+VIRGO+KAGRA + LIGO-India)
  2027-2030

https://observing.docs.ligo.org/plan/

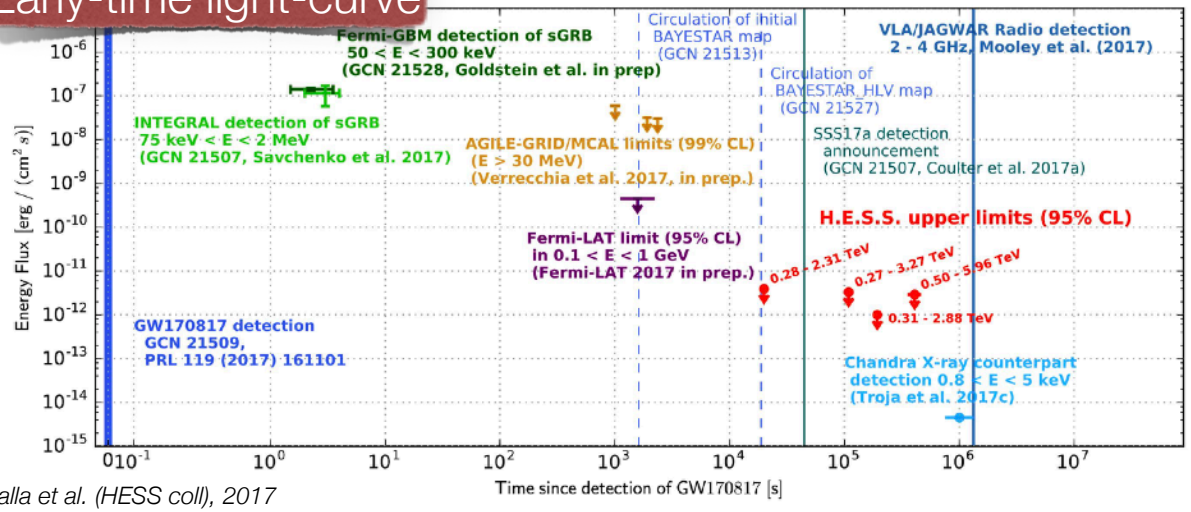


Run O5 matches the current CTAO timeline

Gravitational Wave counterparts at TeV energies

No detection of GeV-TeV emission from the counterpart of GW170817/GRB170817A

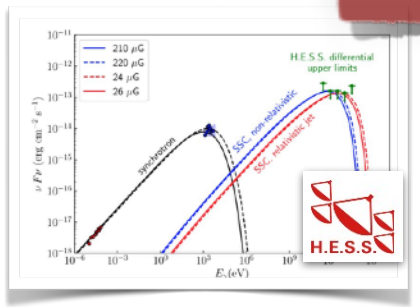
Early-time light-curve



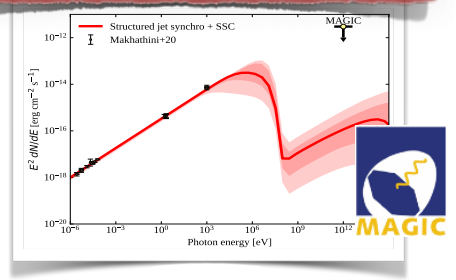
Abdalla et al. (HESS coll), 2017

SED and spectral models

@~200 days from T0

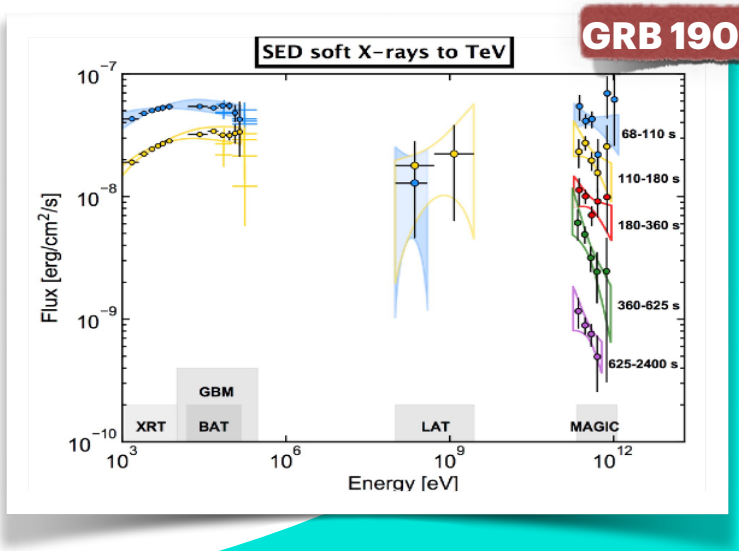


H.E.S.S. coll., 2020 ApJL, 894



AS, Salafia O. S., et al. 2021a, PoS, 944

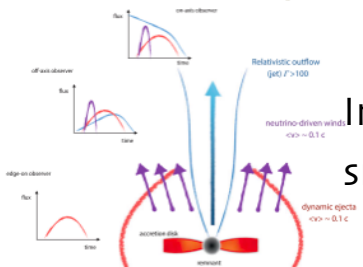
GRB 190114C



MAGIC Coll. et al., Nature,575,459-463(2019)

But, GRBs have been detected at TeV energies since 2019

GRB190114C, GRB190825A, GRB201216C, GRB180720B, GRB221009A

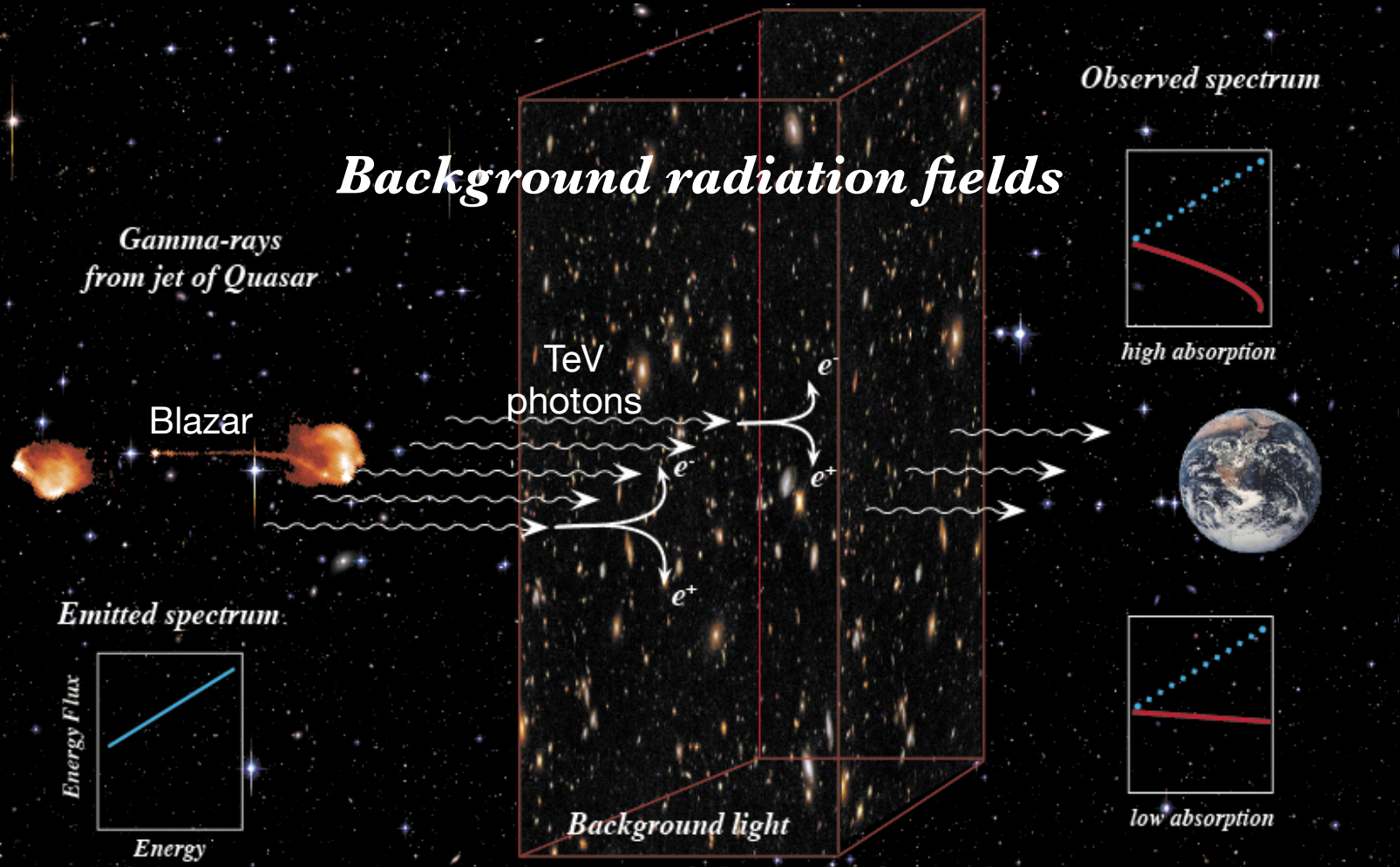


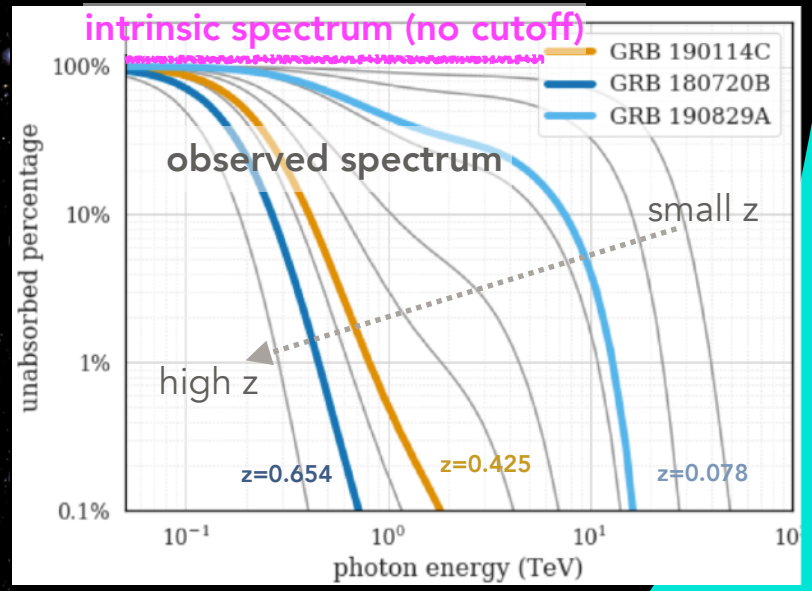
In GW-counterparts, the jet is seen preferentially **off-axis:**

small Lorentz factor -> weaker intensity and delayed peak in light-curve

EBL absorption of TeV photons

EBL: extragalactic Background Light



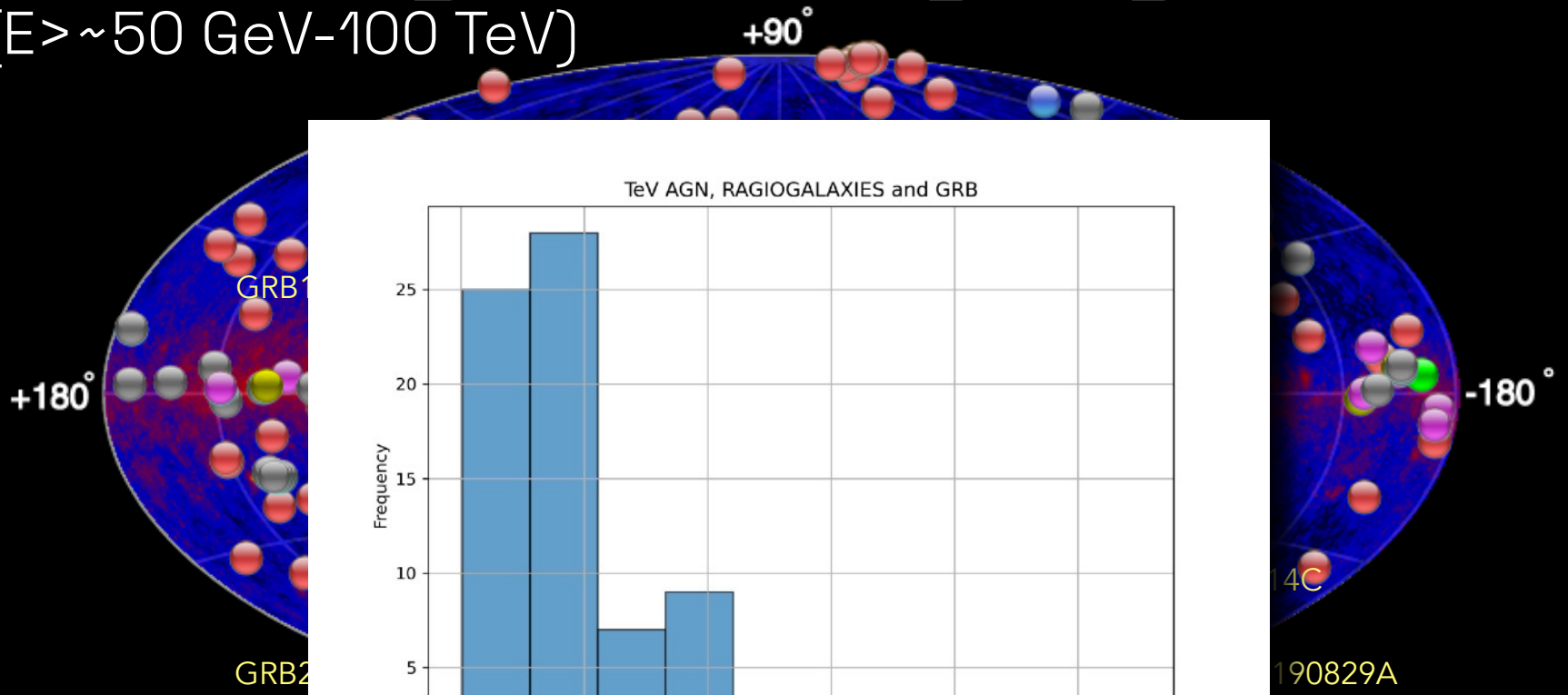


Adapted from E. Pueschel, ICRC2017

$$\Phi_\gamma^{obs}(E) = \Phi_\gamma^{source}(E) \times e^{-\tau(E_\gamma, z)}$$

opacity gamma-ray horizon (z<~1 E>100 GeV)

The TeV gamma-ray sky
(E>~50 GeV-100 TeV)



Source Types

- TeV Halo PWN/TeV Halo PWN
- Binary XRB PSR Gamma BIN
- HBL IBL GRB FRI FSRQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

Most of these TeV sources are variable (minutes-to-months)

308 sources in total

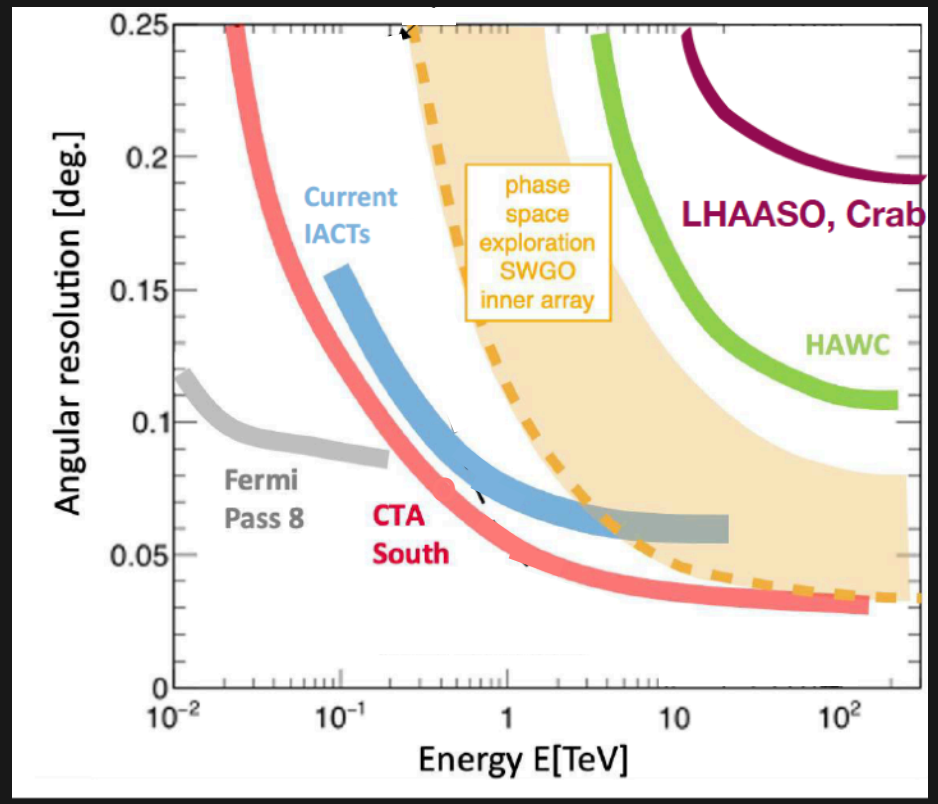
93 are AGN-blazars/radiogalaxies

5 Gamma-RAY Burst GRB

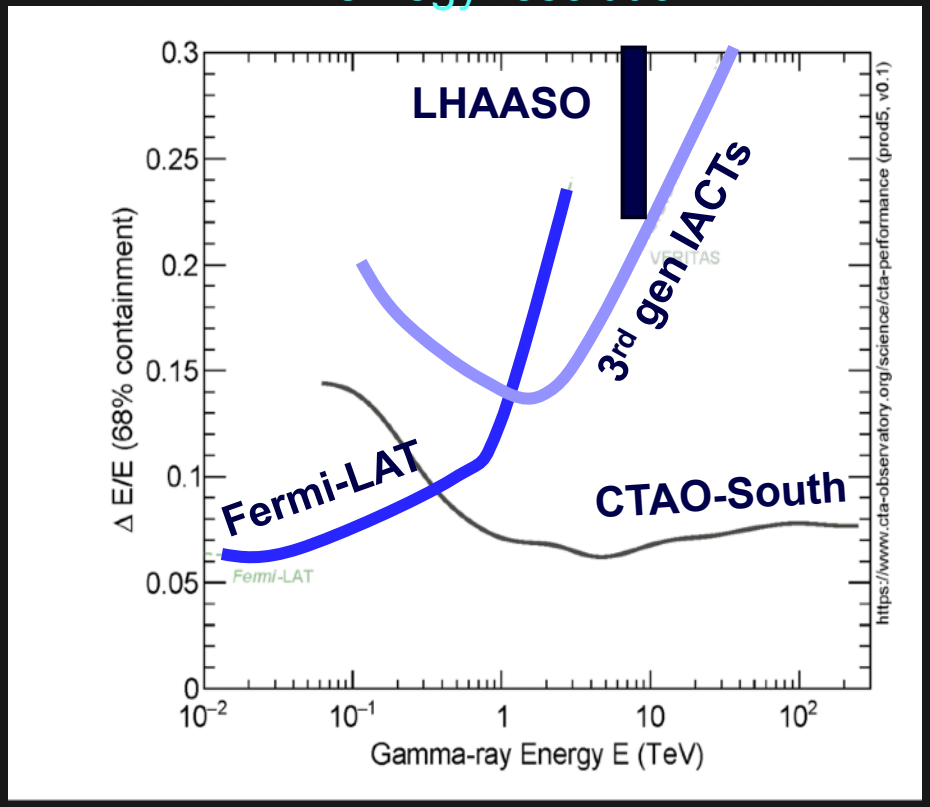
http://tevcat.uchicago.edu

Angular & energy resolution

angular resolution

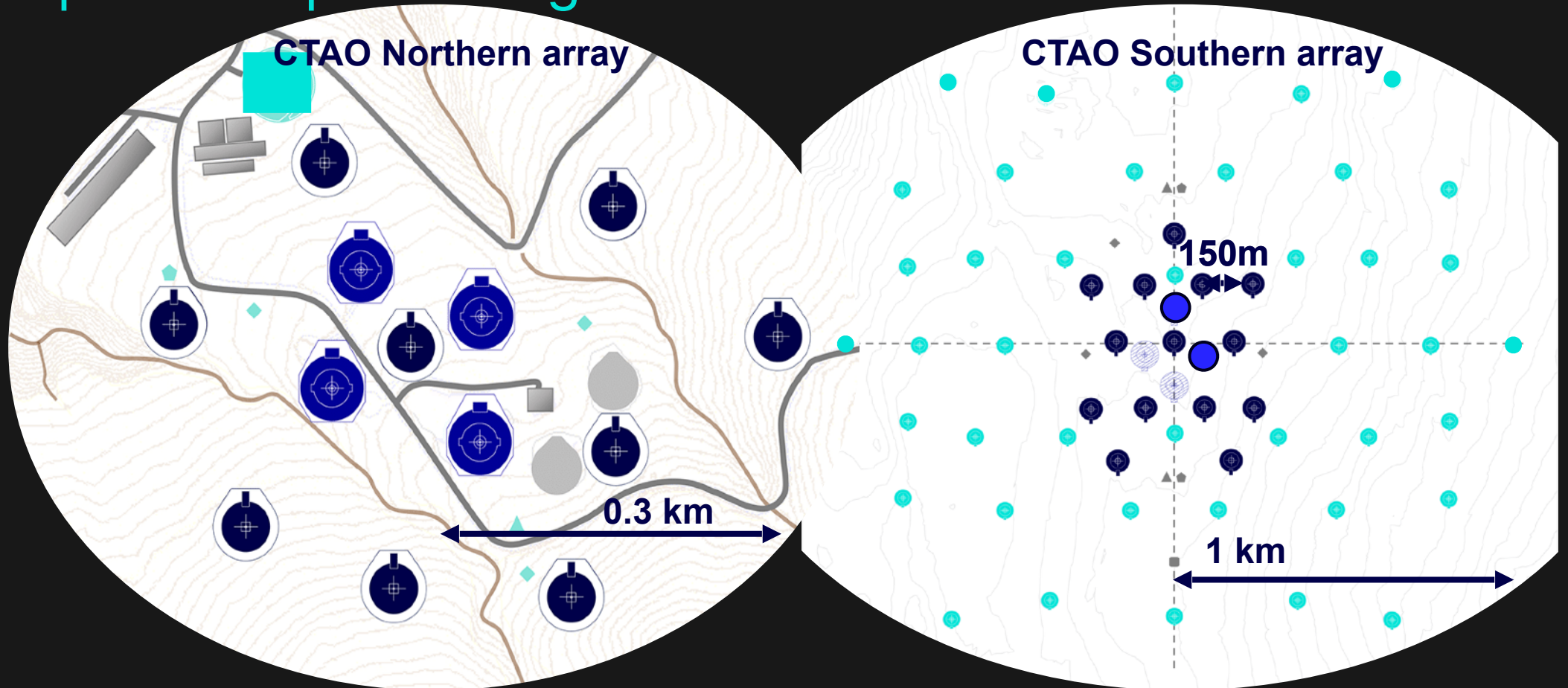


enregy resolution

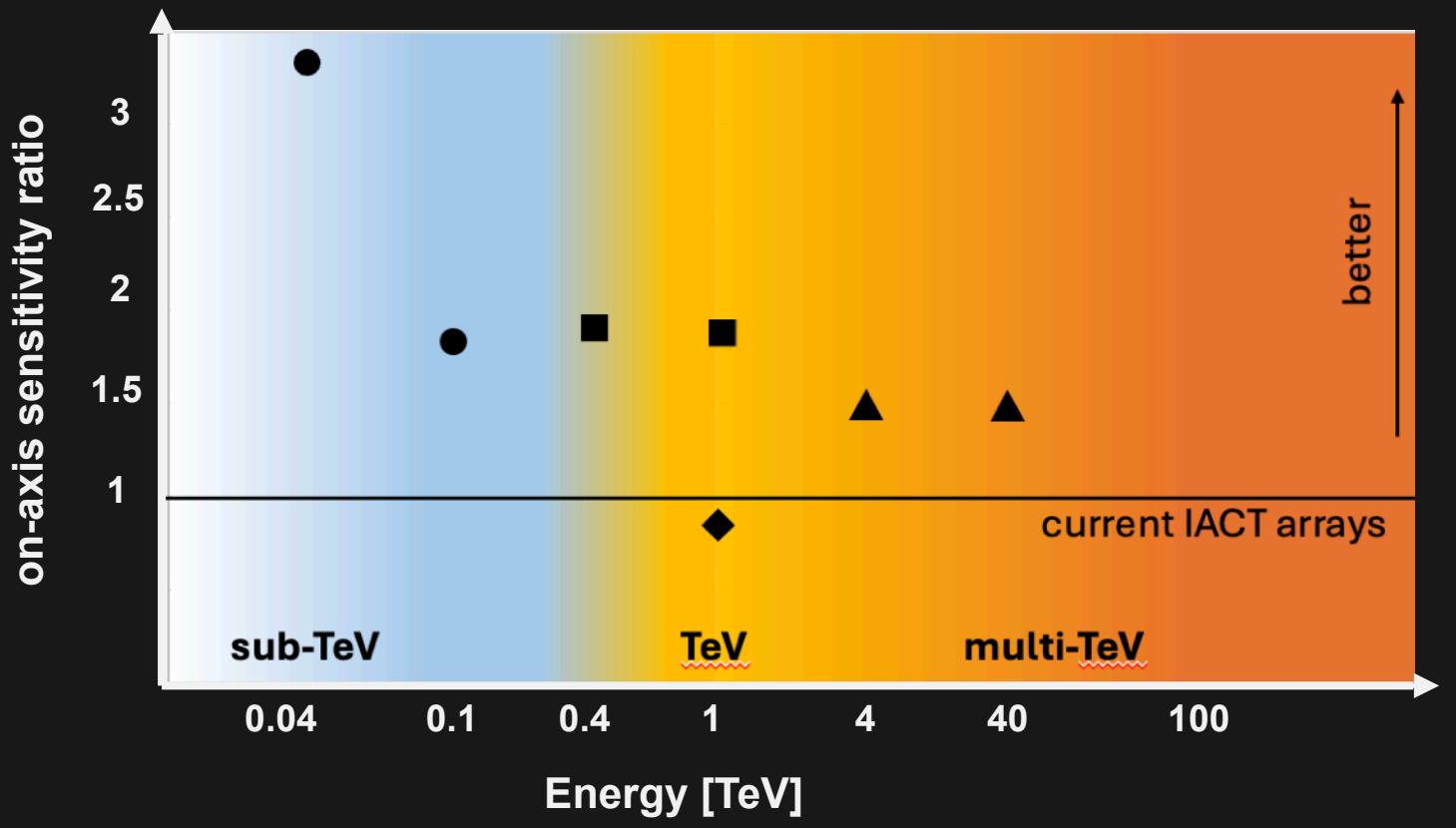


Two observation stations, one unique observatory

Improved Alpha configuration



When will the scientific impact begin?



Intermediate arrays

- 2 LST
- 2 LST + 1 MST
- 1 MST + 5 SST
- 5 SST

Angular resolution up to 40% improvement with respect to current IACT arrays

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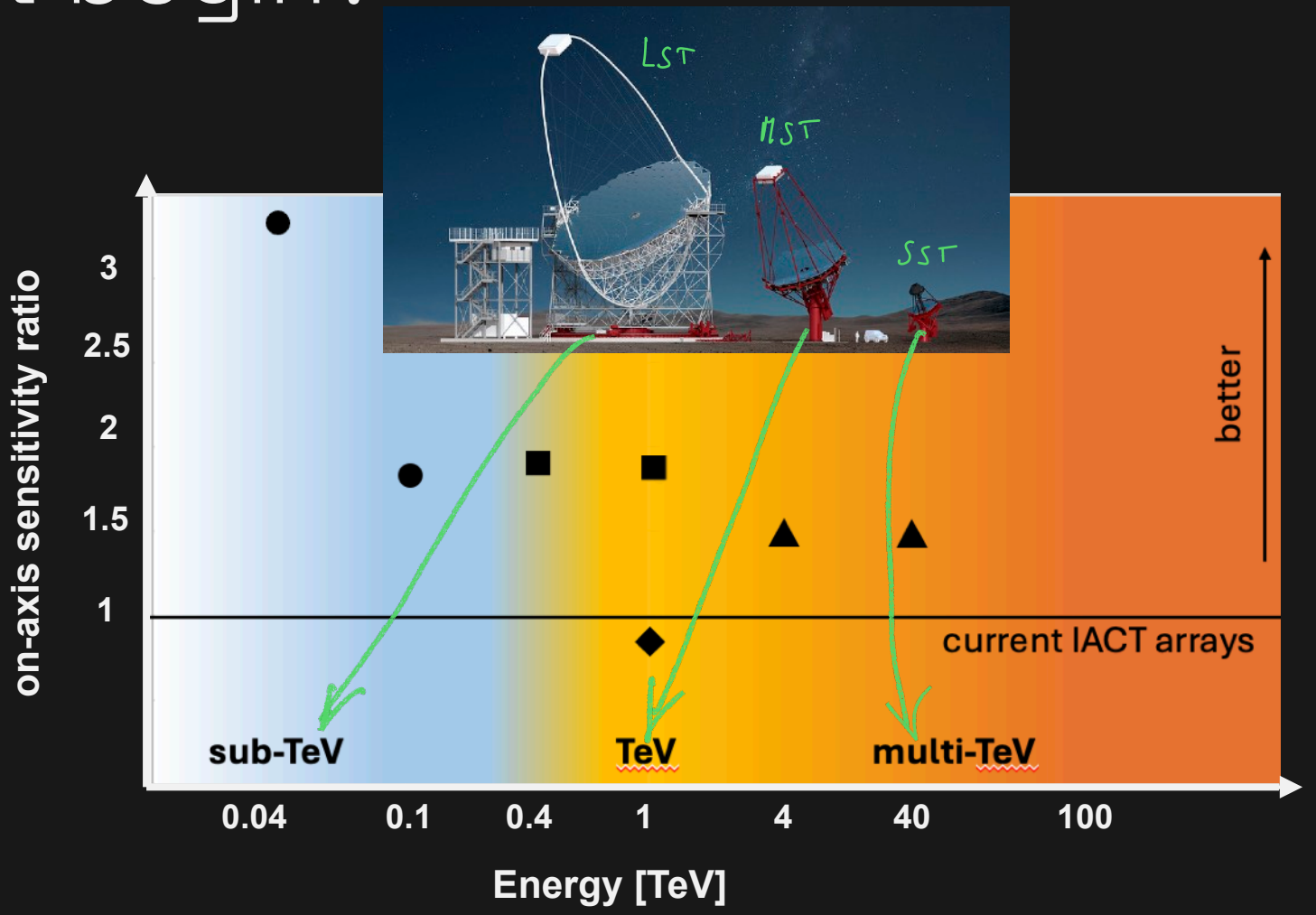

Intermediate arrays

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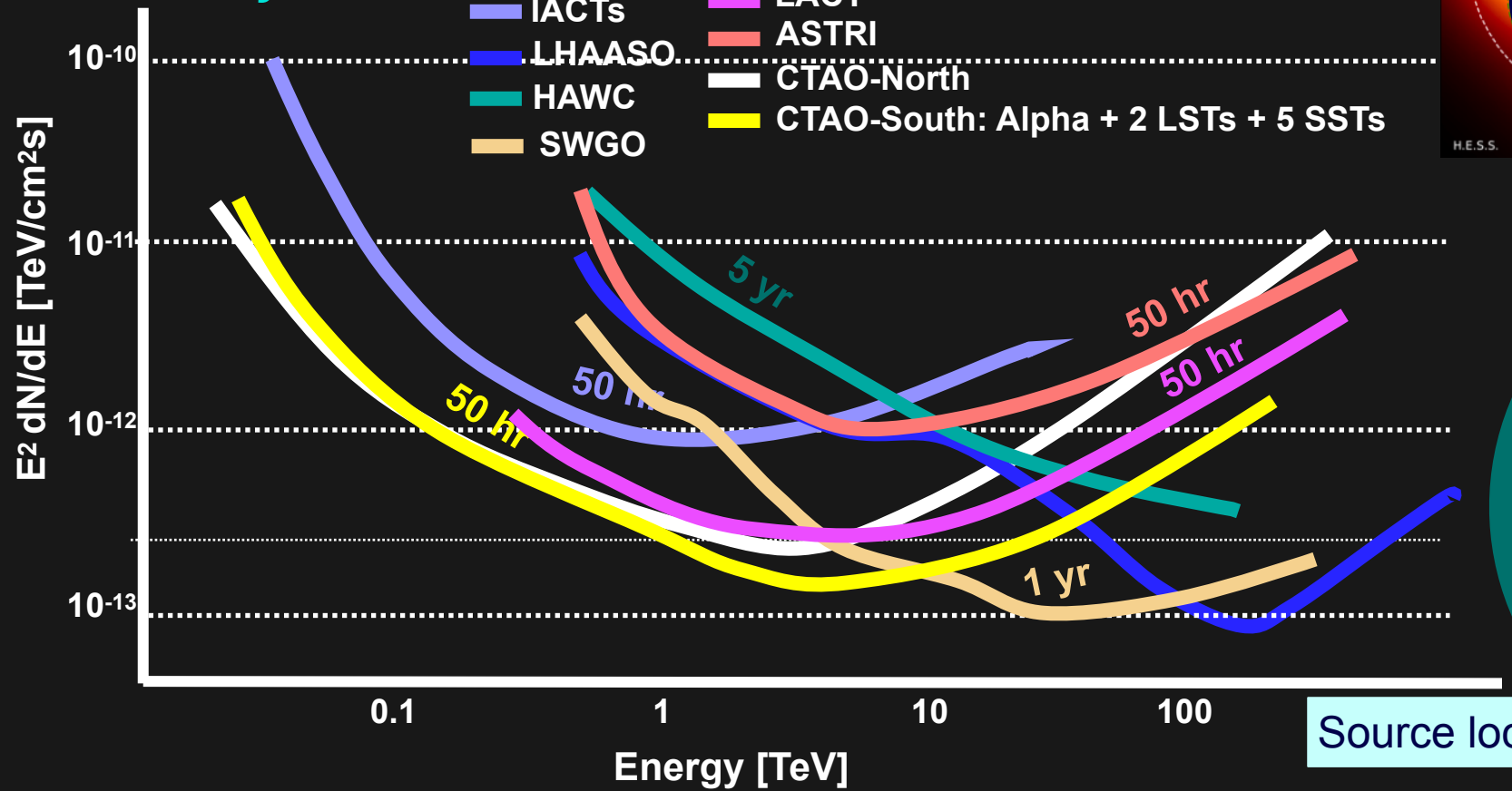
- 1 MST + 5 SST
- 5 SST

Angular resolution up to 40% improvement with respect to current IACT arrays

CTAO Performance

Full sky

Sensitivity



Angular resolution

Source localization of the order of 15-30 arcsec!