CTAO
Cherenkov Telescope Array Observatory

The upcoming observatory for gamma-ray astronomy

Status and involvement of the INAF community in CTAO science and implementation

With contributions by *(in ordine di apparizione)*:
Paolo Da Vela, Patrizia Romano, Stefano Vercellone, Alessandra Lamastra, Carlotta Pittori, Gabriele Ponti, Giorgio Galanti, Michela Rigoselli, Domitilla De Martino Fabio Pintore,Fabrizio Bocchino, Giancarlo Ghirlanda, Lara Nava, Francesco Gabriele Saturni, Andrea Bulgarelli, Biswajit Banerjee, Giovanni Morlino,Enrico Peretti, Barbara Olmi, Sarah Recchia, Niccolò Bucciantini, Barbara Olmi, Giada Peron, Elena Amato, Giovanni Pareschi, Francesco Dazzi, Giampiero Tagliaferri, Maura Pilia, Marta Burgay, ...

From the
RSN4 dedicated Survey documents

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INAF
ISTITUTO NAZIONALE DI ASTROFISICA

The (astro-)physical processes of the TeV Sky

What can we learn with TeV observations

Particle acceleration

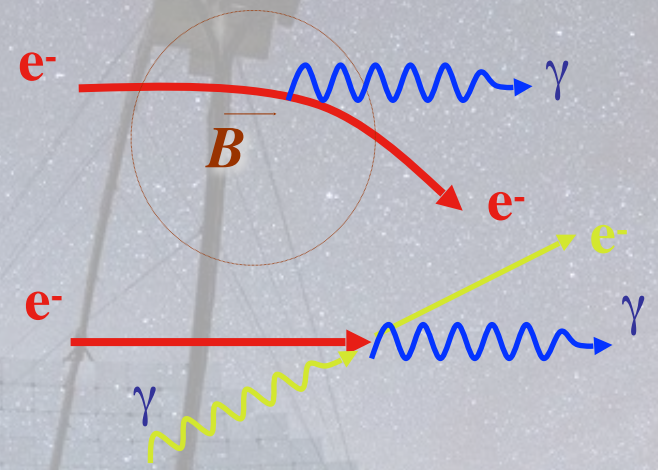
Particle energy distribution
Particle identification
CR-connection

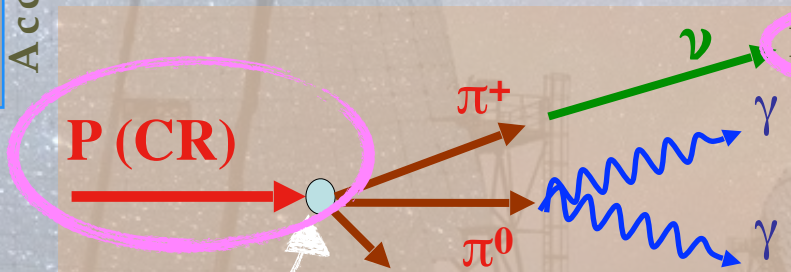
Gamma-ray emission

- B-field
- Density
- Location
- Size

Interaction with the ambient

Accelerated particles





Matter (CO clouds, winds, ISM,...)
Radiation field (high density)

Multifrequency and multi messenger

Synchrotron radiation

Radio to gamma-rays

Inverse Compton

gamma-rays GeV-TeV

Neutrinos TeV-PeV

Particle collisions-cascades

gamma-rays GeV-TeV-PeV

APOD 24 Jul 2020

The (astro-)physical processes of the TeV Sky

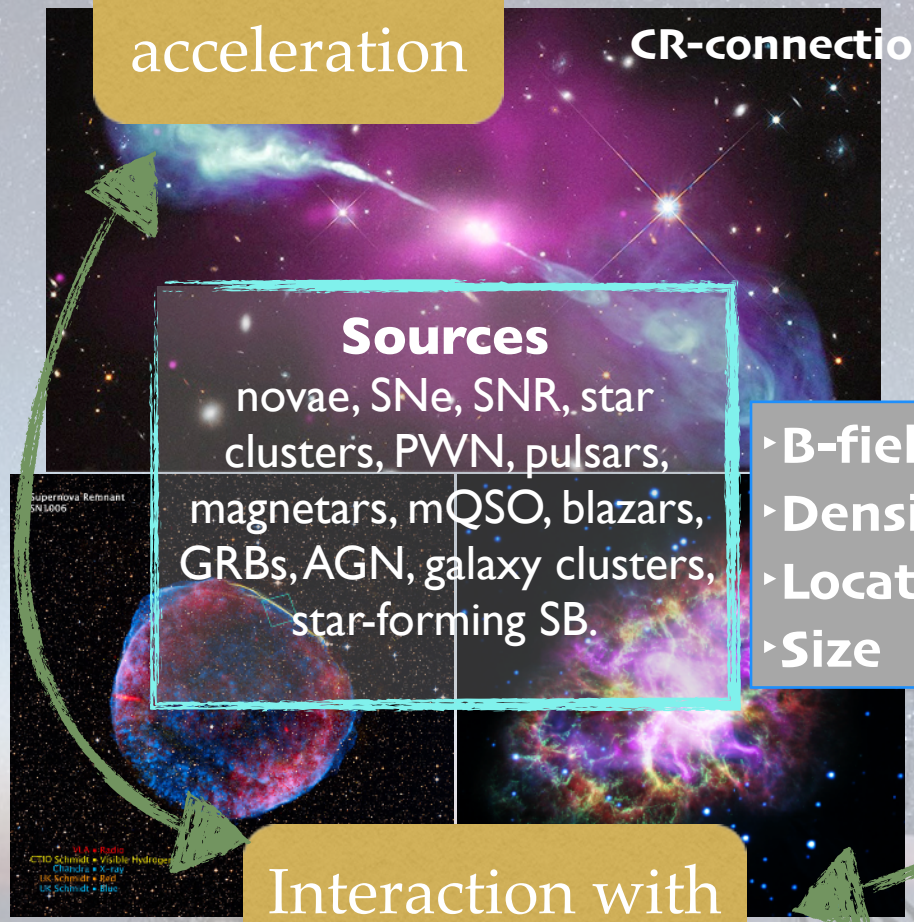
What can we learn with TeV observations

Particle acceleration

Particle energy distribution
Particle identification
CR-connection

Gamma-ray emission

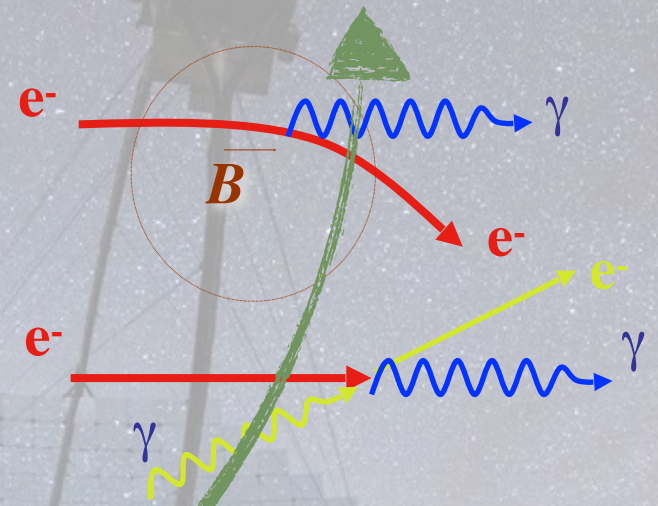
Diagnostics
multi-band observations and correlations, SEDs, variability, light curves, morphology



Sources
novae, SNe, SNR, star clusters, PWN, pulsars, magnetars, mQSO, blazars, GRBs, AGN, galaxy clusters, star-forming SB.

- B-field
- Density
- Location
- Size

Accelerated particles

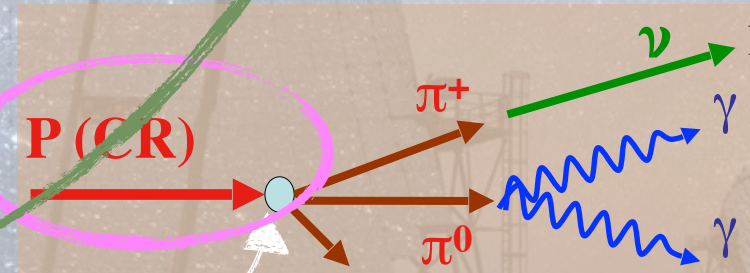


Synchrotron radiation

Radio to gamma-rays

Inverse Compton

gamma-rays GeV-TeV



Neutrinos TeV-PeV

Particle collisions-cascades

gamma-rays GeV-TeV-PeV

Interaction with the ambient

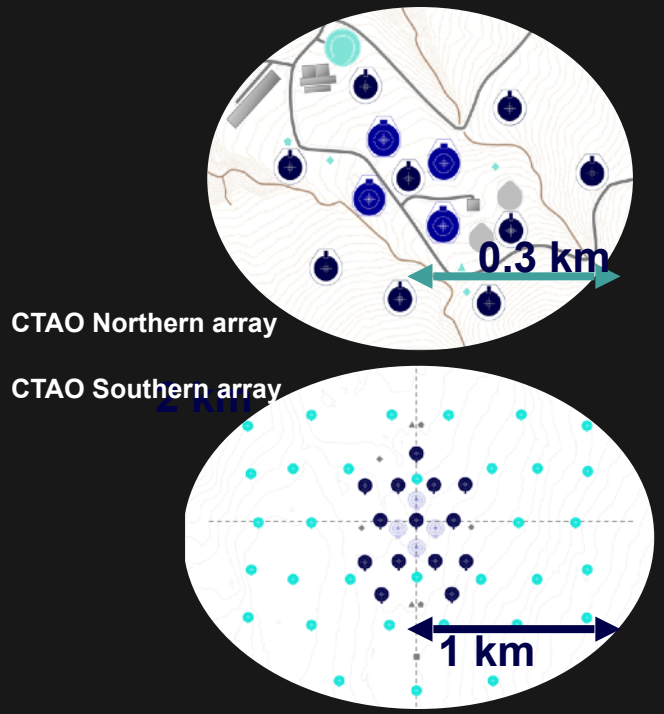
Matter (CO clouds, winds, ISM,...)
Radiation field (high density)

APOD 24 Jul 2020

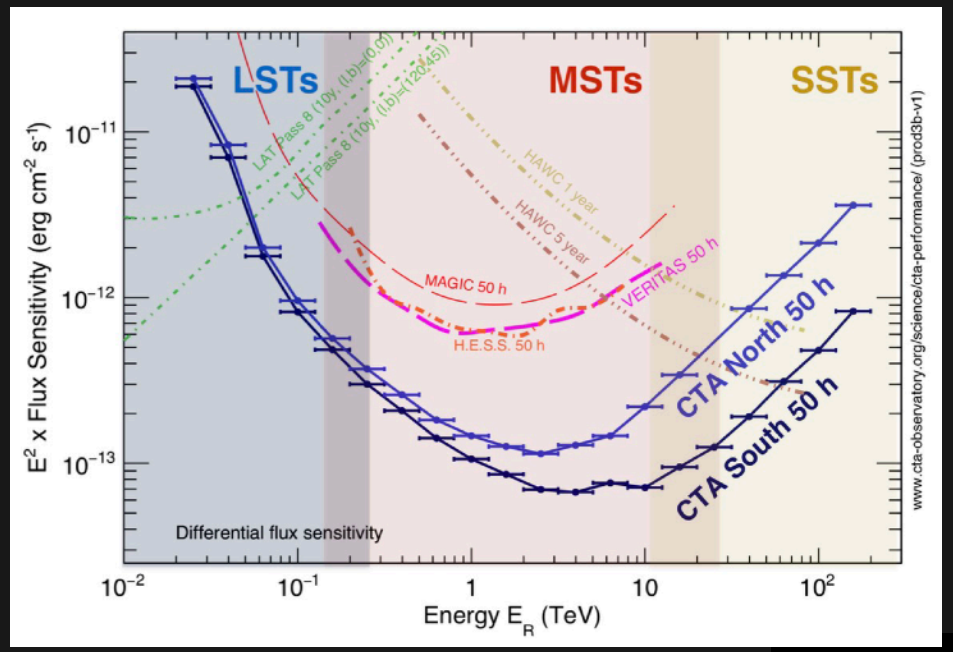
CTAO: a diverse array

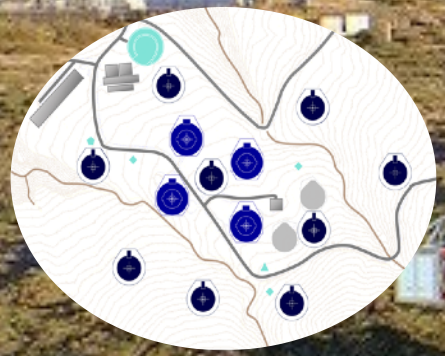
- Extended energy range (20 GeV-300 TeV) with telescopes of 3 sizes.
- Improved sensitivity, up to 5-10 times than current IACTs.
- Improved angular resolution (3′) and energy resolution (7% @1 TeV).

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



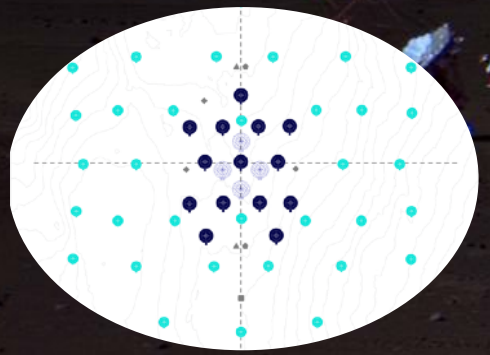
Alpha configuration



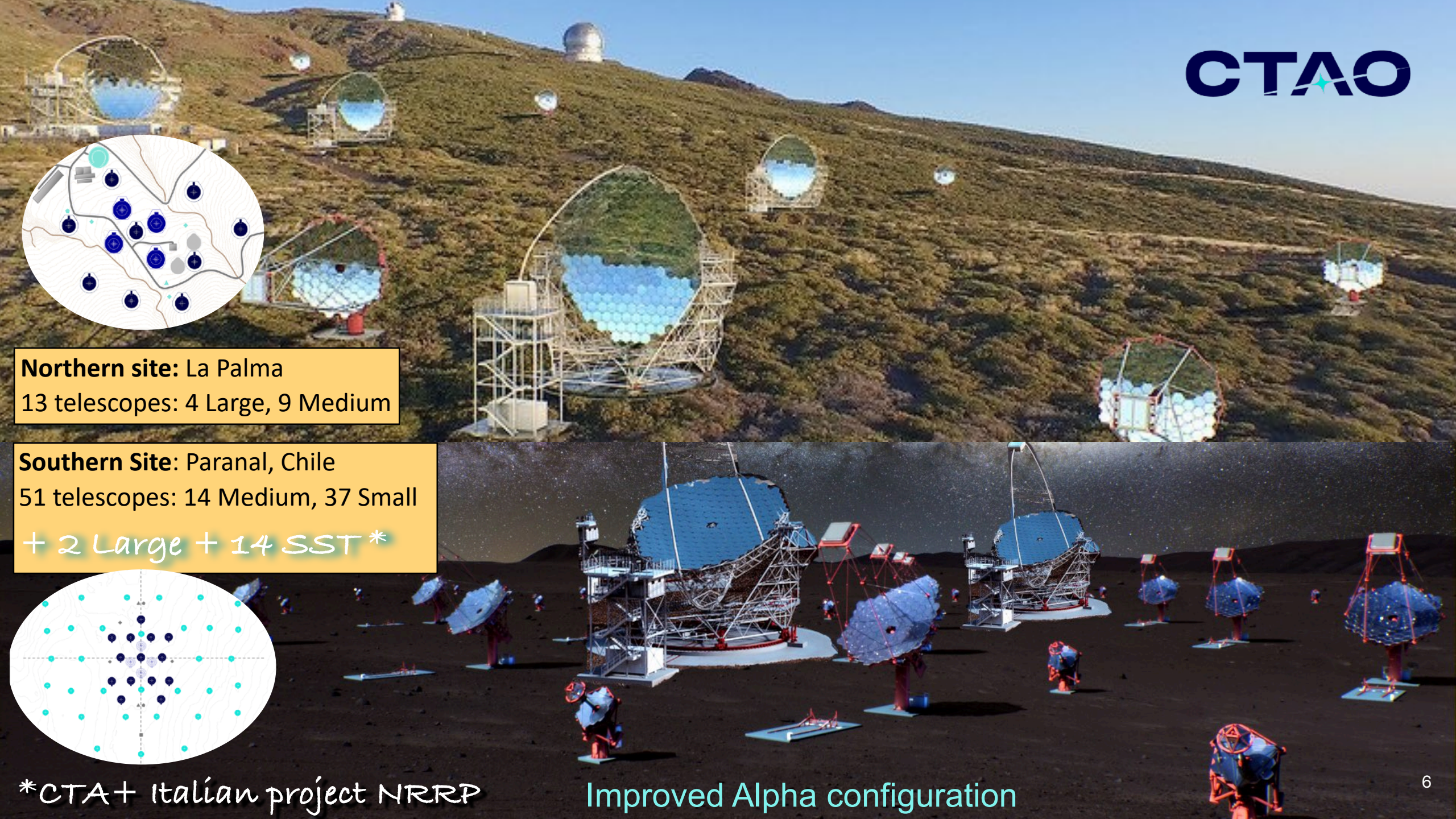


Northern site: La Palma
13 telescopes: 4 Large, 9 Medium

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



Alpha configuration



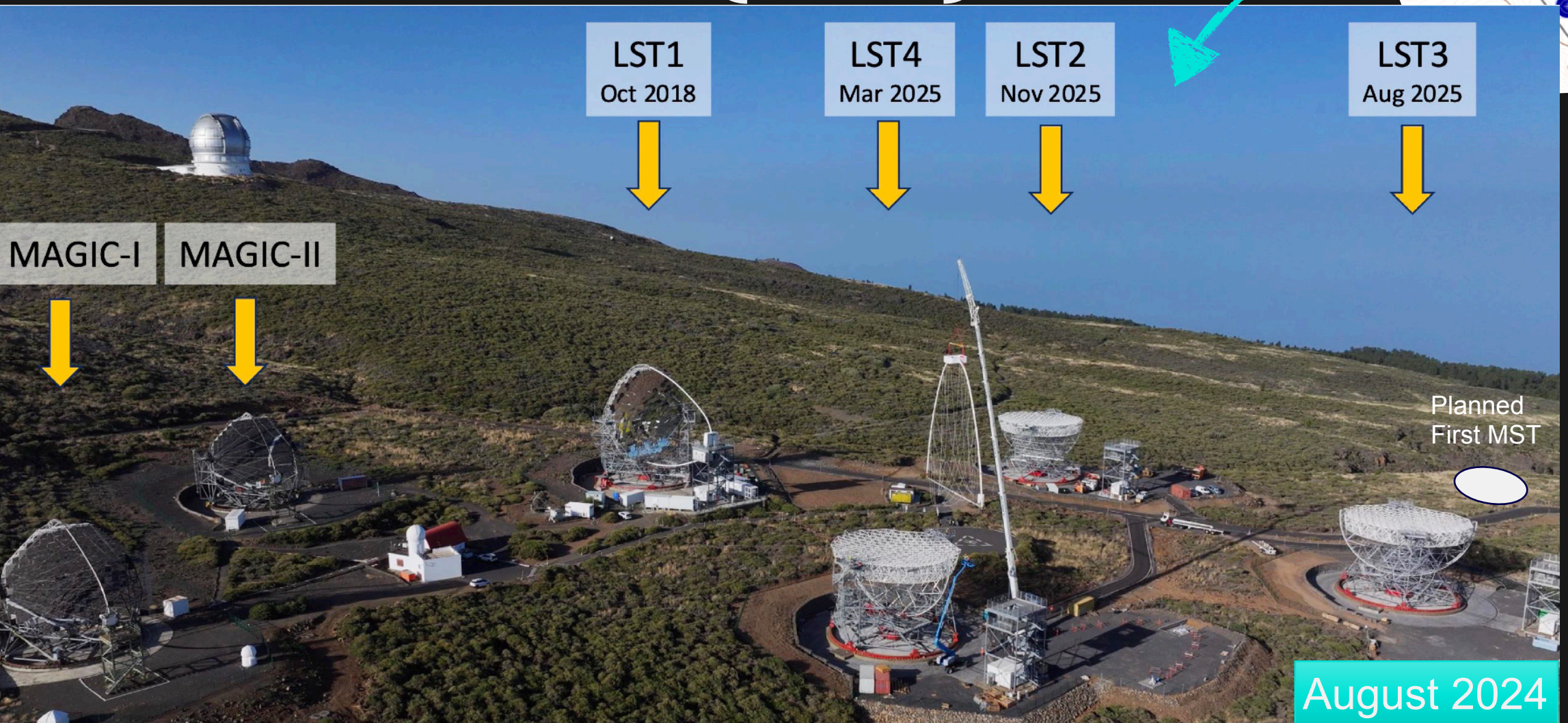
Northern site: La Palma
13 telescopes: 4 Large, 9 Medium

Southern Site: Paranal, Chile
51 telescopes: 14 Medium, 37 Small
+ 2 Large + 14 SST*

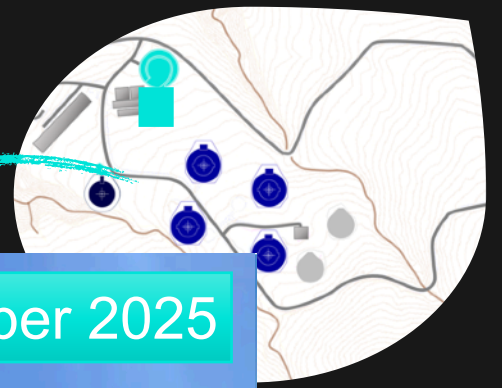
*CTA+ Italian project NRRP

Improved Alpha configuration

CTAO North (LST)



CTAO North (LST)



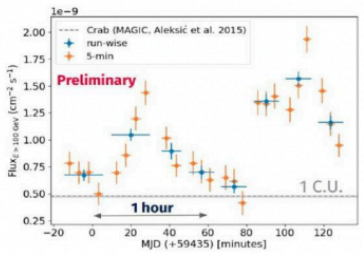
September 2025

Starting the commissioning phase
2027-2028 early science

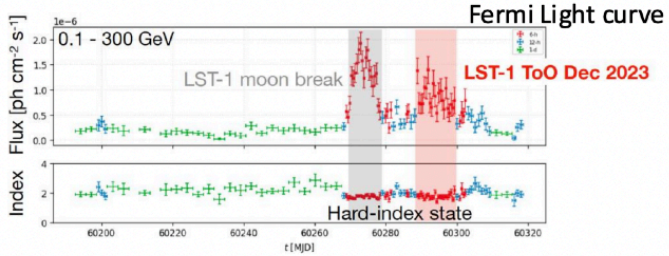
The CTAO prototype LST-1 is already producing science

ICRC 2024 – LST1 performance paper

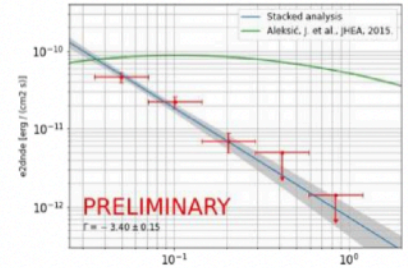
BL Lac intranight fast variability (a few min)



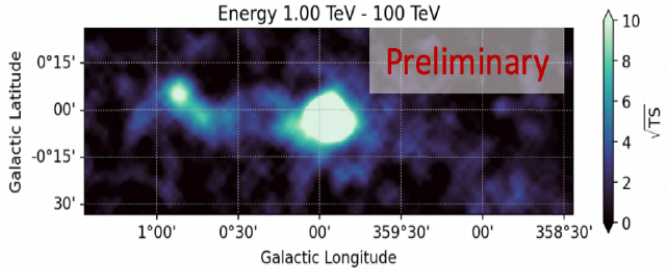
OP313: discovery of the most distant VHE AGN



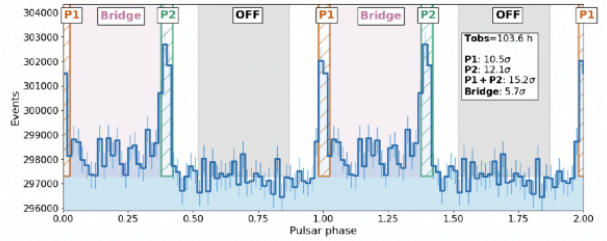
Symbiotic Nova RS Ophiuchi



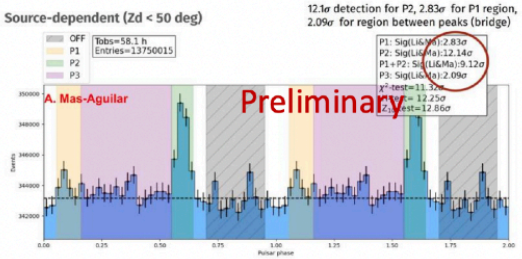
Galactic Center 39hrs (Sgr A*, diffuse)



Crab pulsar above 20GeV

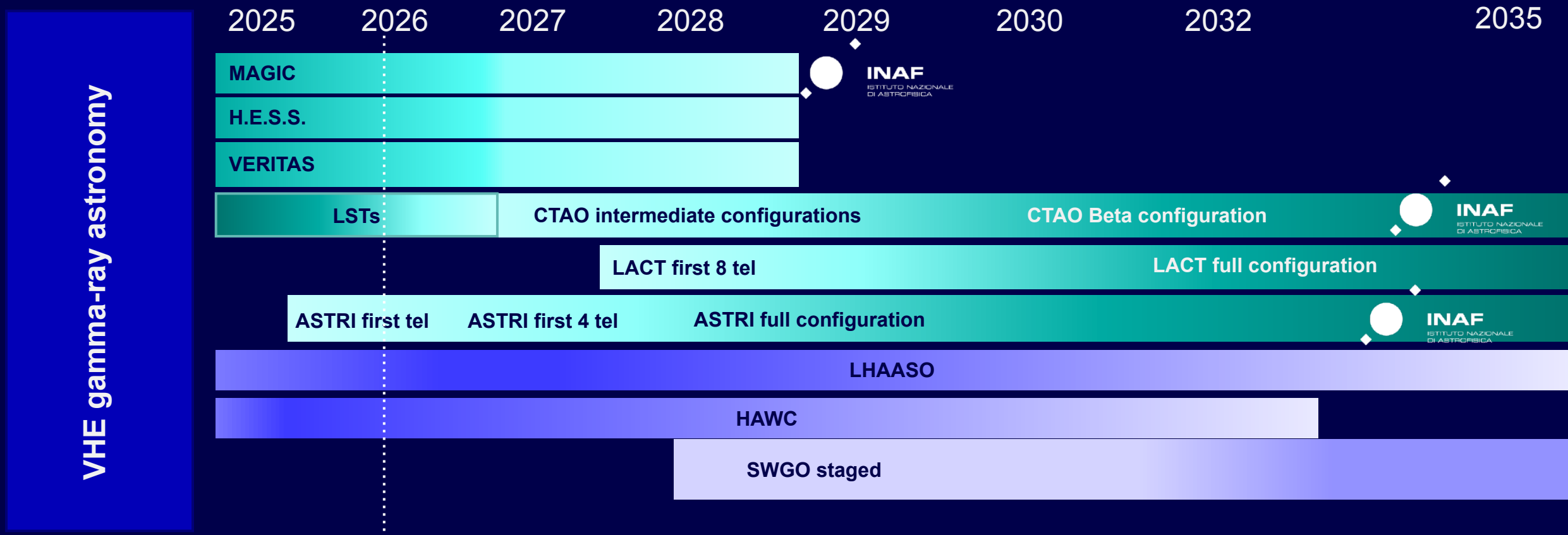


Geminga pulsar above 15GeV



Credits to M. Teshima & the LST collaboration

CTAO in the TeV landscape



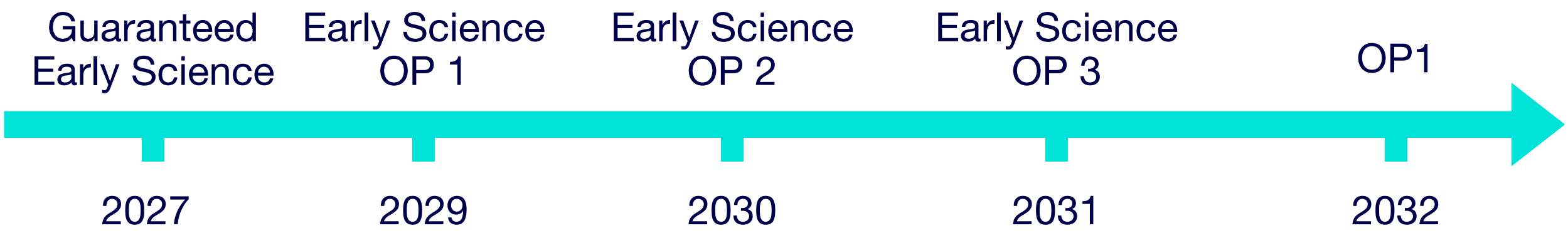
The end dates of the facilities are just indicative: the fate of these instruments is currently under discussion

La timeline della scienza di CTAO

Internamente a INAF bisogna sostenere la consapevolezza su queste attività, che stanno iniziano ORA!

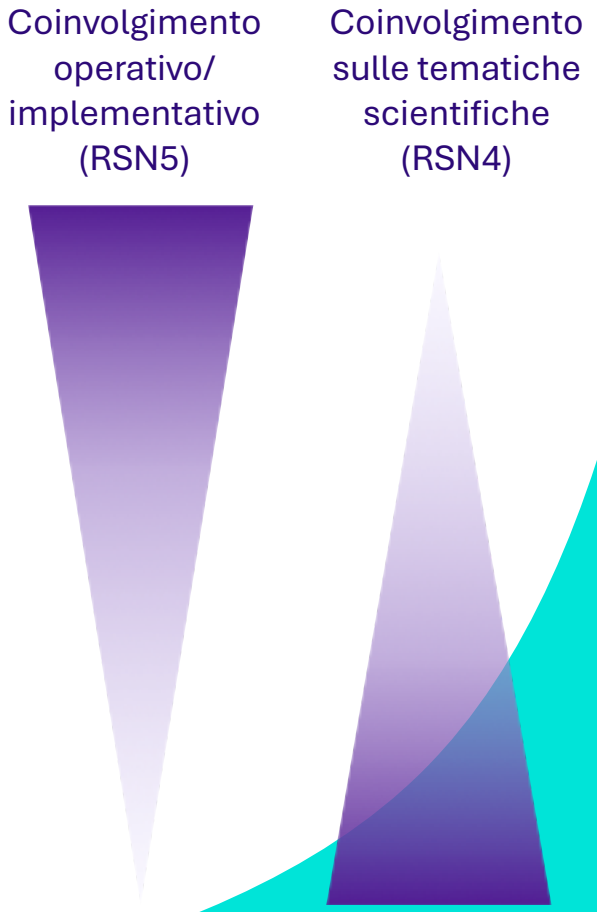
- Step 0: il Science Data Challenge (SDC) -> fine 2026
- Step 0-1: guaranteed early science, LST north, SST south: —> 2027.
- Step 1: Open Early science con gli LST e MST sito nord: —> 2029 (AO call)
    - Early science al sito sud MST-SST: —> 2029 (LST to be approved first)
- Step 2: inizio KSP -> 2032

La preparazione della early science e, soprattutto dei KSP (che hanno un indirizzo legato alla money matrix/IKC) richiede una preparazione scientifica e strategica da parte di INAF e Italia



INAF contributions to CTAO

- **INAF** is responsible for and leads the construction, deployment, and commissioning of the **Small-Size Telescopes (SSTs, CTAO-South)** and of **two LSTs-South** (CTA+, PNRR) within the CTAO requirements.
- **INAF** is involved in CTAO activities through **in-kind contributions** to different subsystems.
- **INAF** is the second-largest contributor within the **CTAO Consortium** in terms of scientific support, carrying out studies on specific science use cases that define and advance the scientific perspectives of CTAO, and coordination (SAPO, PWG coordinators).
- **INAF** is part of the **CTAO-LST collaboration**, contributing through observational shifts, data analysis and interpretation, proposal preparation, and scientific publications.
- **INAF** includes a **broad and distributed community** of groups and researchers with expertise in CTAO science cases and a strong interest in using forthcoming CTAO data.



The CTA+ Program *(PI: M.Cappi)*:

Main contribution is to enhance CTAO-S, opening/strengthening transient science in CTAO South i.e.:

a) CTAO-S baseline + 2 LSTs (major effort) *(PI: Antonelli)*

b) CTAO-S baseline + ~~5~~ 14 SSTs *(PI: Tagliaferri)*

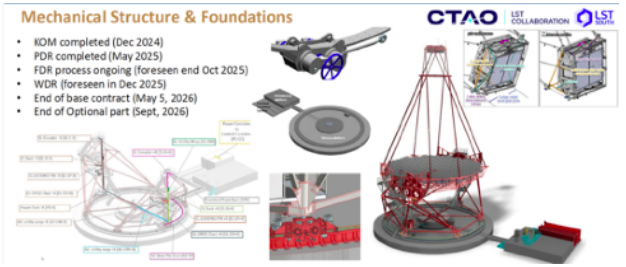
c) + Multi-ν follow-up enhancements:

   i. VST polarimeter *(PI: Schipani)*
   ii. TNG fast photometer *(eSIFAP, PI: Ambrosino)*
   iii. Fast vlbi radio *(PI: Giroletti)*
   iv. Stellar Intensity Interferometry *(for ASTRI; PI: Zampieri)*

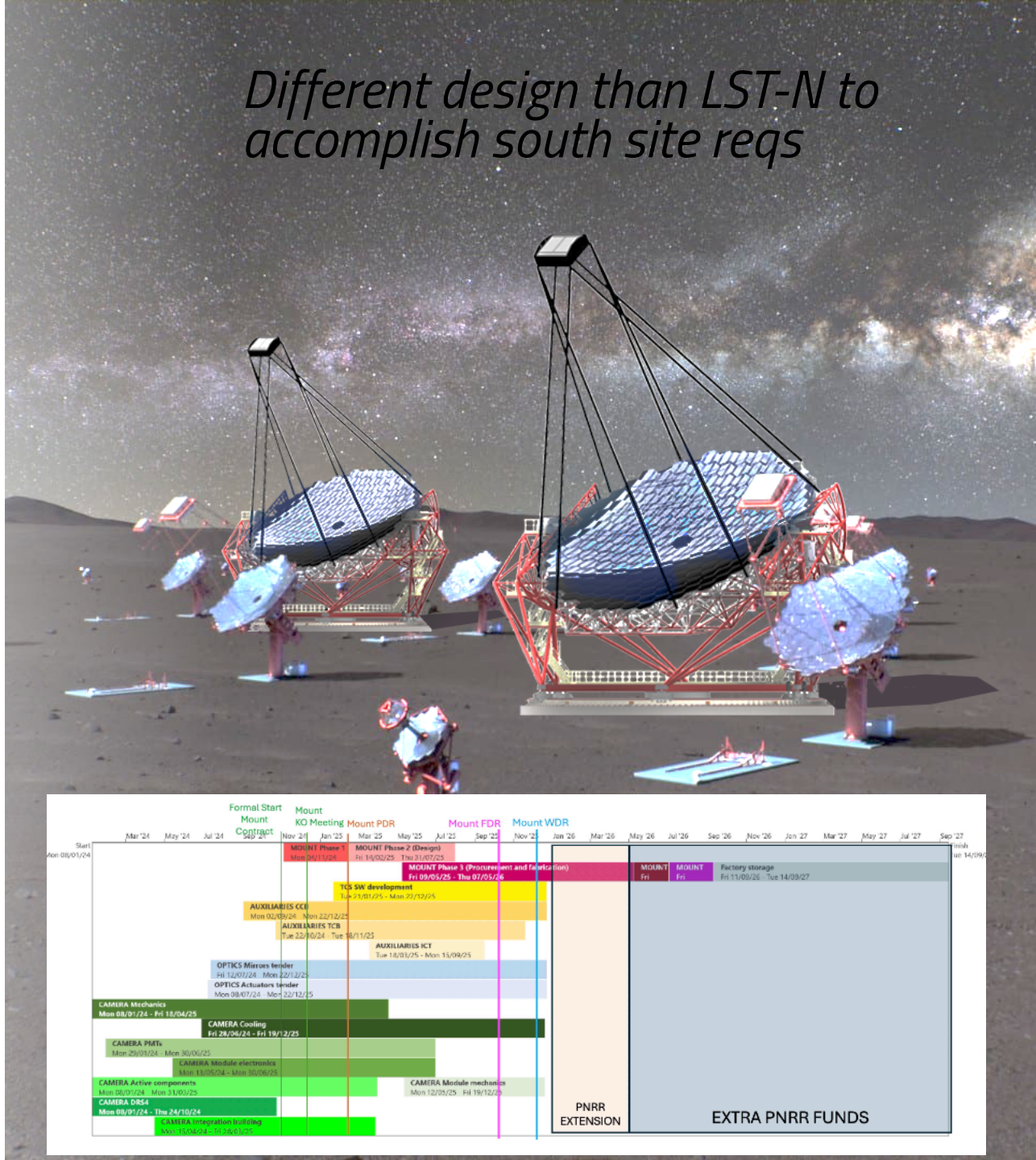
d) + R&D new detectors for Cherenkov tel. or complementary (e.g. SWGO)

e) + science & outreach in Italy and HQs (Resp.: Zanin)

COMPLETED (completed or by end of Jan. 2026)

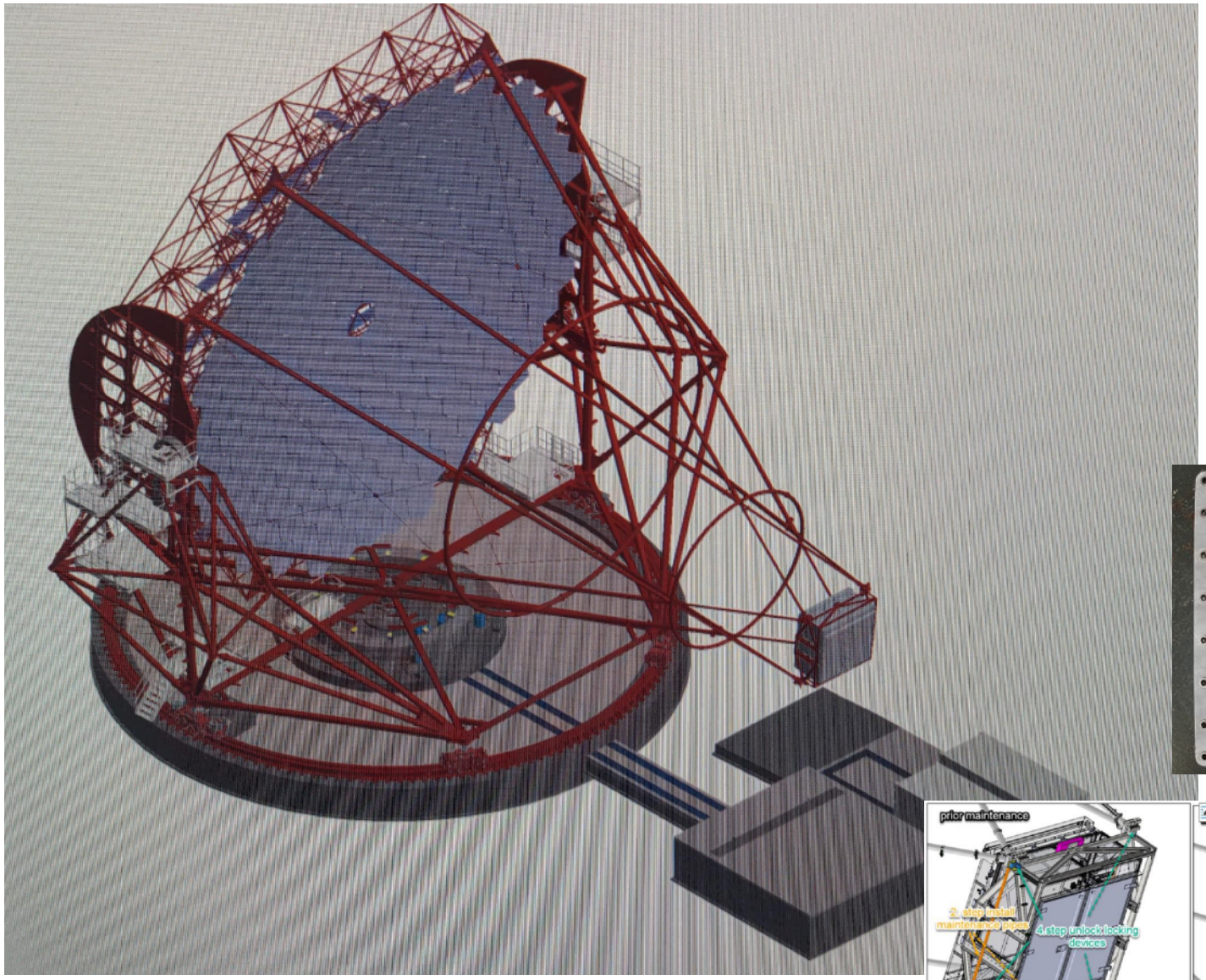


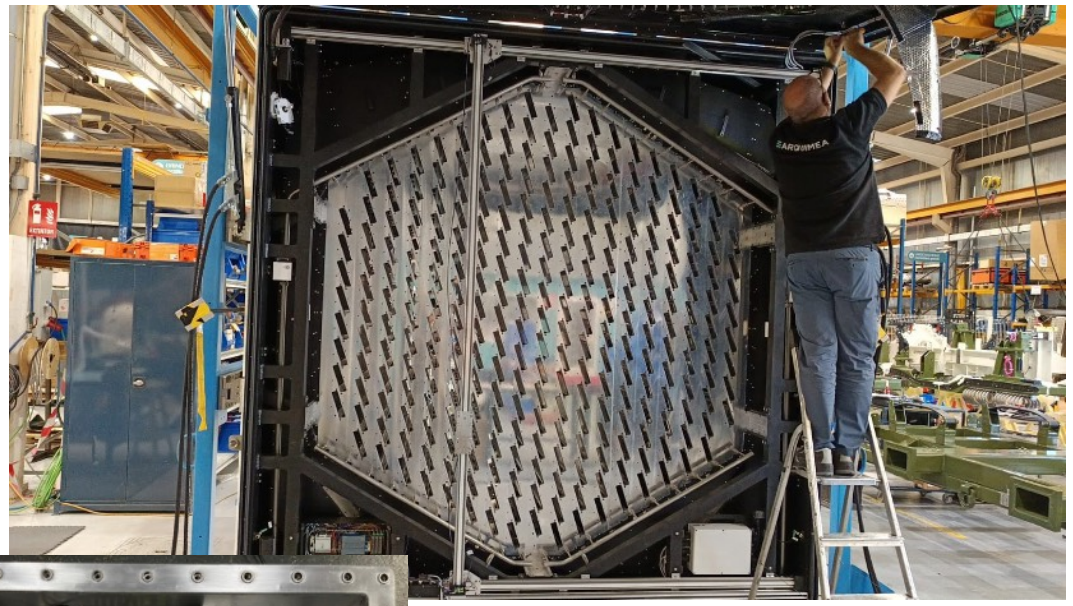
- LST South is a project of the INAF/INFN CTA+ Program and is part of the LST Consortium.
  - In-kind contribution from Japan, Swiss, Germany, France
- **More than 50 INAF people** directly involved in construction, science & operations (37 authors in LST-collaboration papers).
- **Telescopes will be finally delivered to CTAO south site. Shipping in 2027 and on-site integration + commissioning from 2027 to 2029/30**

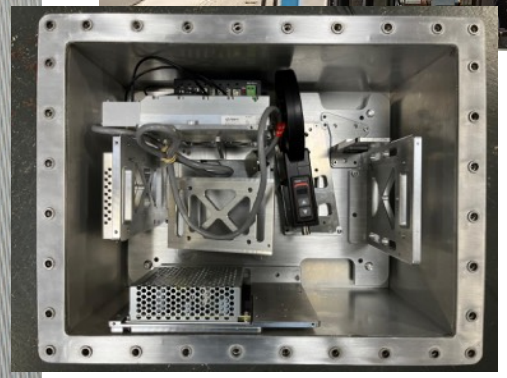


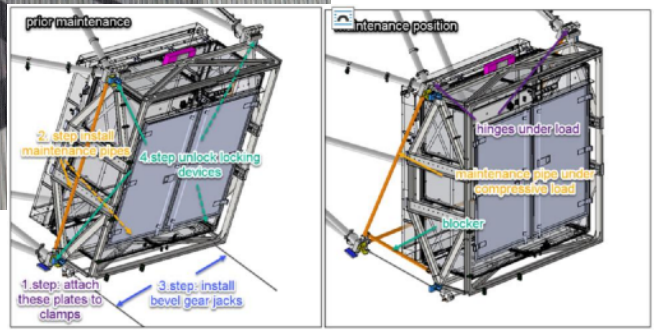
RSN5 for RSN4

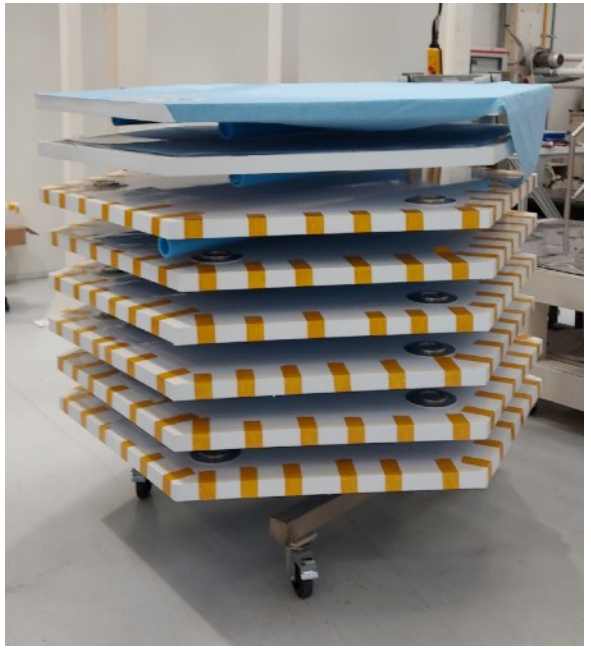
LST South Project











First telescope fully integrated at the factory

CTAO | SST COLLABORATION

SST-MEC #1 (INAF Tender):

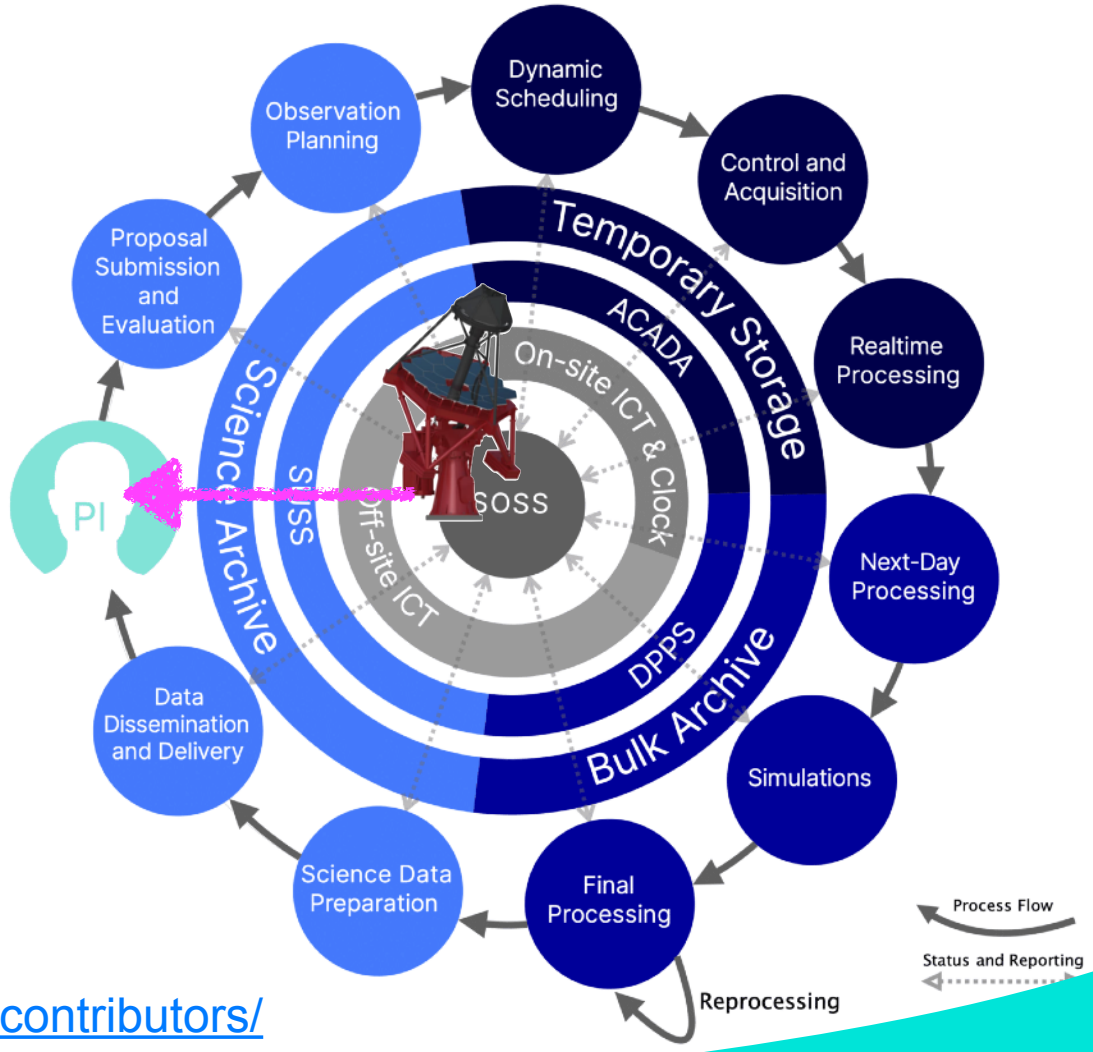
- **first telescope fully integrated with the mirrors, TCS and camera to perform the tests on factory**
- **The other 13 structures will be partially integrated and tested before shipment**
- **we are now doing the on-factory AIT/ AIV activities to be concluded in February**
- **shipping to Chile in March, integration on site expected in June**

The integration of the first SST Telescope in Chile is expected to start by June 2026


DALBEN
Leading vision

INAF In-kind contributions to CTAO subsystems

From the telescope systems to the observer



https://www.ctao.org/partners/in-kind-contributors/

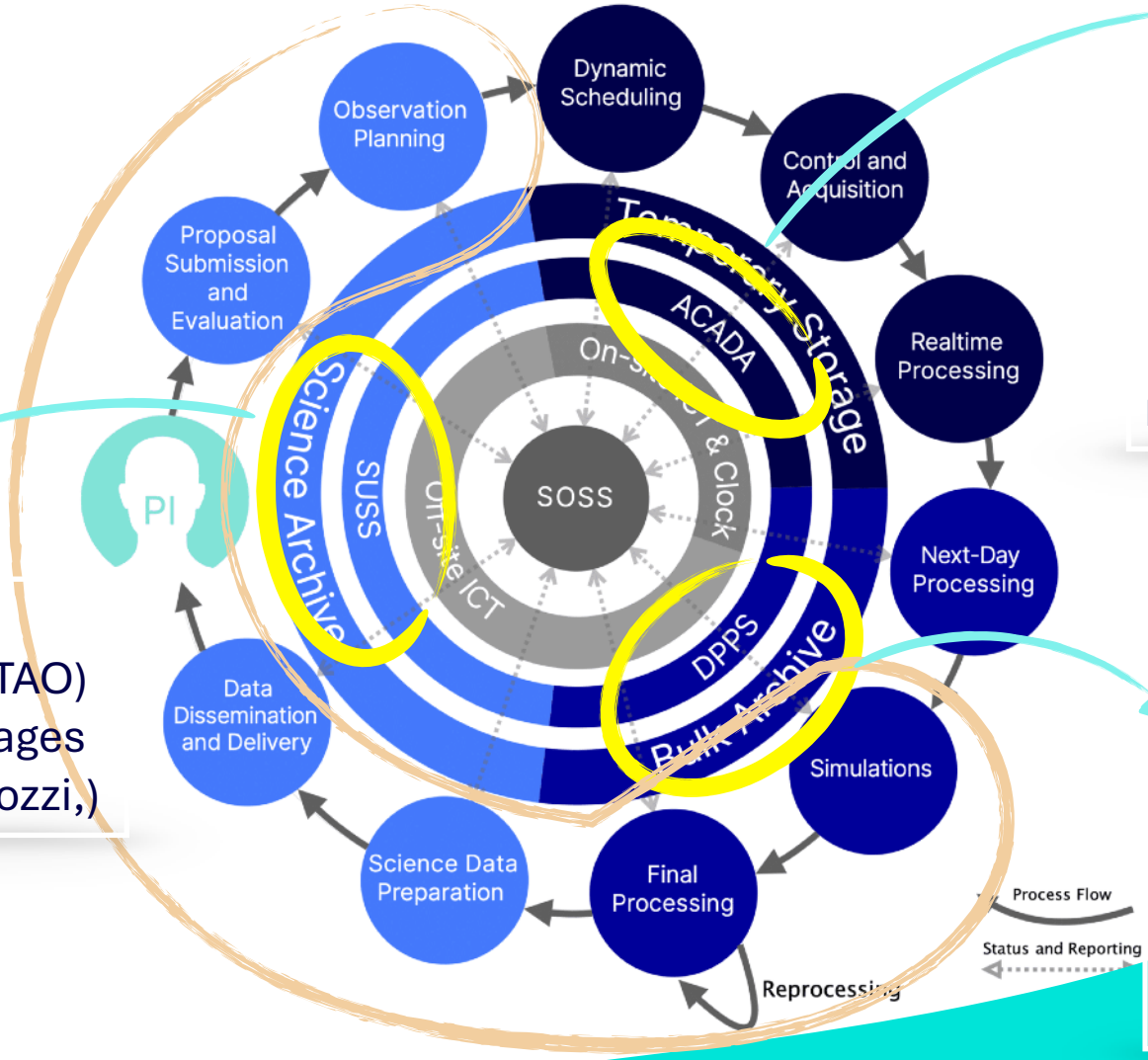
INAF In-kind contributions to CTAO subsystems

ACADA
Array Control and Data Acquisition System

SAG (Science Alert Generation) system
Resp. INAF-OAS
(A. Bulgarelli, N. Parmiggiani, G. Panebianco, G. De Cesare, V. Fioretti, L. Castaldini, A. Di Piano)

SUSS
Science User Support System

Co-Coordination
C. Pittori (INAF-OAR, seconded CTAO)
INAF Involvement in several packages
(Lucarelli, Lombardi Zacharis,Gallozzi,)



DPPS
Data Processing and Preservation System

BDMS (Bulk Data Management System),
Resp.: INAF-OAR
(S.Gallozzi, F. Lucarelli, et al.)
Contributions in Calibration, WMS, et al.

INAF In-kind contributions to CTAO subsystems

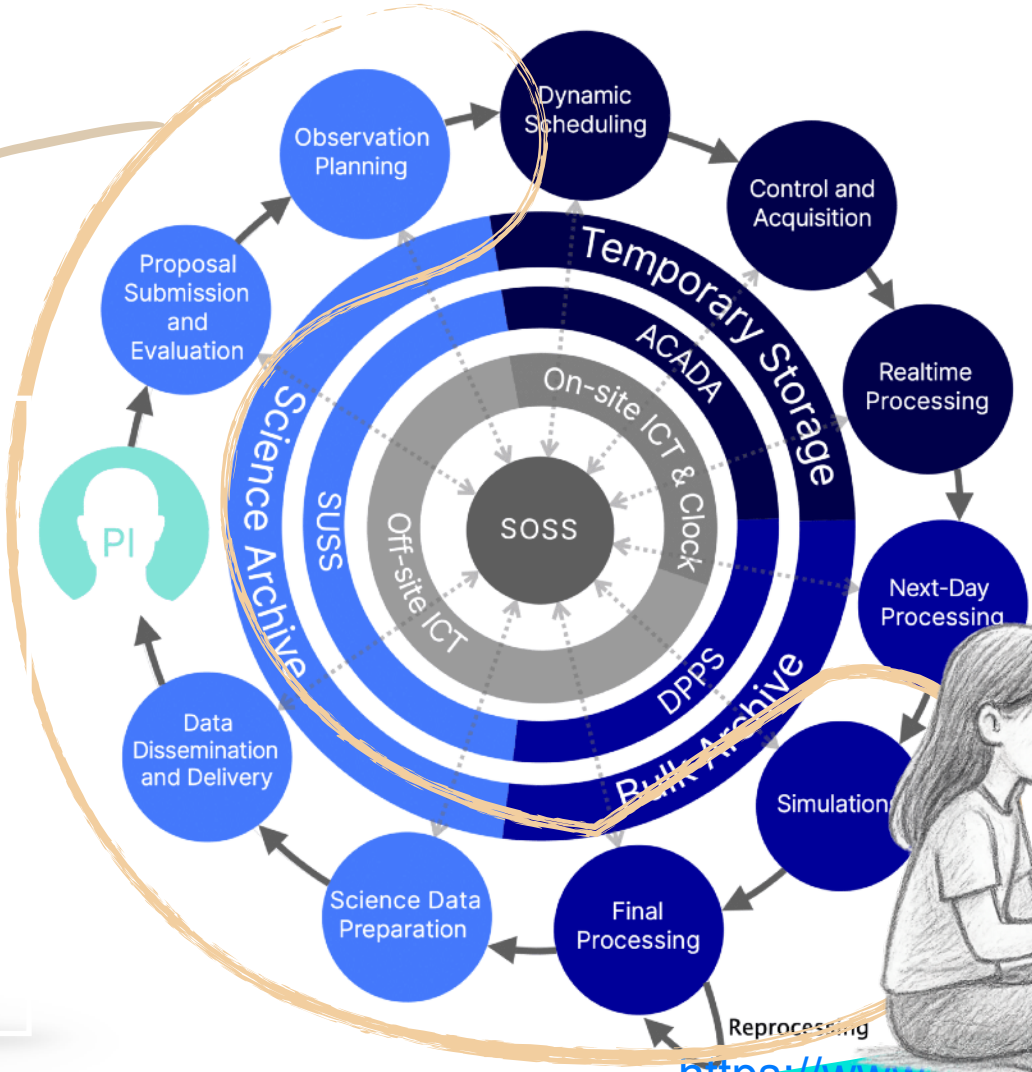
Open-SDC
1st open Science Data Challenge

Open Science Data Challenge

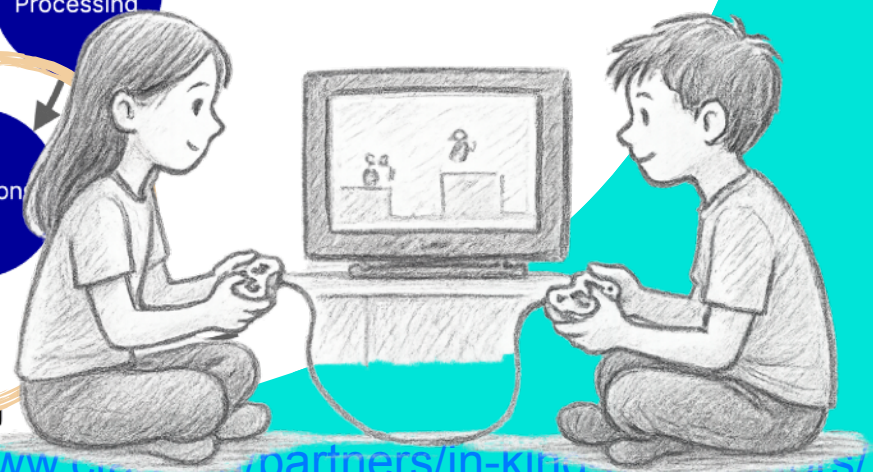
Expected by end-2026

Crucial contribution by INAF through secondee-CTAO

Co-Coordination
A. Stamerra (INAF-OAR)
Technical Team coordination:
P. Da Vela, S. Marchesi (INAF-OAS)
Simulations: F. Pintore (INAF-Pa),
Scheduling: C. Bigongiari (INAF-OAR)



From the telescope systems to the observer



https://www.ctao.org/partners/in-kind-contributors/

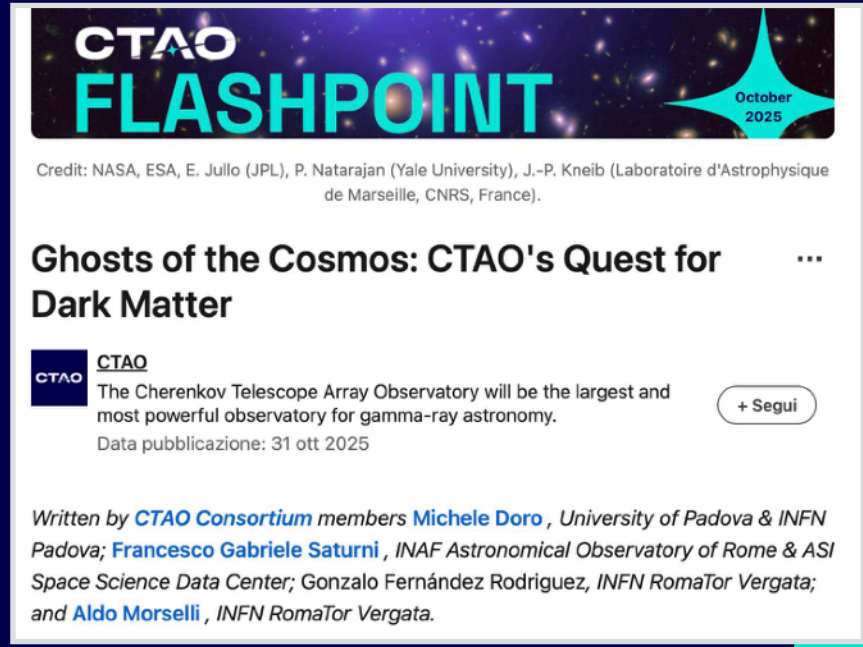
Science with CTAO
CTAO-Consortium

- The international scientific community currently shaping CTAO's scientific goals and exploitation
- Organised in scientific working groups and publication / conference committee
- In agreement with CTAO, it influences decisions on instrument performance, performs simulations, data analysis planning, and multi-wavelength studies

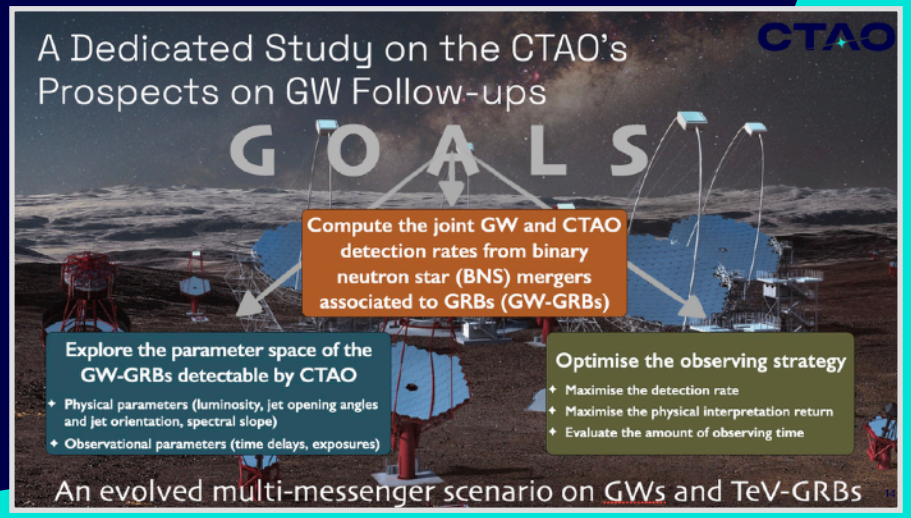
Science with CTAO
CTAO-Consortium

- Several roles of coordination (e.g. Giacomo Bonnoli just ended Science coordinator role)
- INAF Consortium members contribute to science working groups by providing modeling, predictions, and related publications.

CTAO-Consortium paper *on CTAO perspectives for constraining DM from WIMPs annihilation*
Led by Michele Doro (assoc. INAF) and Francesco Saturni (INAF-OAR)



CTAO-Consortium paper *on perspective on GW-followups being submitted soon!*
CTAO-C GW-team led by A. Stamerra, INAF contributions by Lara Nava and Barbara Patricelli (assoc.INAF)



*Recent **CTAO non-consortium papers (2025)***

Science with CTAO
CTAO-Consortiu

- Several roles of coordination (e.g. Giacomo Bonnoli just ended Science coordinator role)
- INAF Consortium memb
  contribute to science wo
  groups by providing mo


/ SAPO / Consortium Publications / Galactic transient sources with the Cherenkov Telescope Array

Galactic transient sources with the Cherenkov Telescope Array

Last modified by Alicia Lopez Oramas on 2024/03/25 08:19

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Galactic transient sources with the Cherenkov Telescope Array

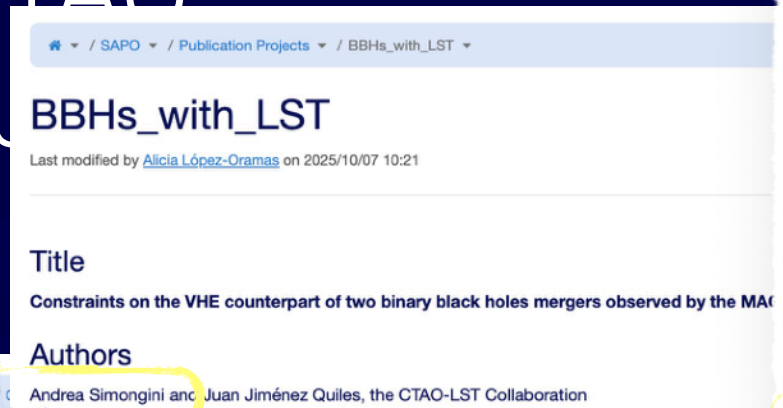
A wide variety of Galactic sources show transient emission at soft and hard X-ray energies: low-mass and high-m
X-ray binaries containing compact objects (e.g., novae, microquasars, transitional millisecond pulsars, supergian
X-ray transients), isolated neutron stars exhibiting extreme variability as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

Corresponding authors

Alphabetical order: Alicia López Oramas

Contributors

Alphabetical order: Alison Mitchell, Arnau Aguasca-Cabot, Ashley Ruiter, Dimitris Kerkizis, Bonnima de Maria G, Emma de Ona Wilhelmi, Enrique Mestre, Giovanni Piano, Iftach Sadeh, Lara Sidoli, Luca Zampieri, Masha Chernyakova, Olga Sergijenko, Patrizia Romano, Pedro Enrique-Escamilla, Samuel McKeague, Sandro Mereghetti


/ SAPO / Publication Projects / BBHs_with_LST

BBHs_with_LST

Last modified by Alicia López-Oramas on 2025/10/07 10:21

Title

Constraints on the VHE counterpart of two binary black holes mergers observed by the MA

Authors

Andrea Simongini and Juan Jiménez Quiles, the CTAO-LST Collaboration


/ SAPO

GW Follow-ups with CTAO

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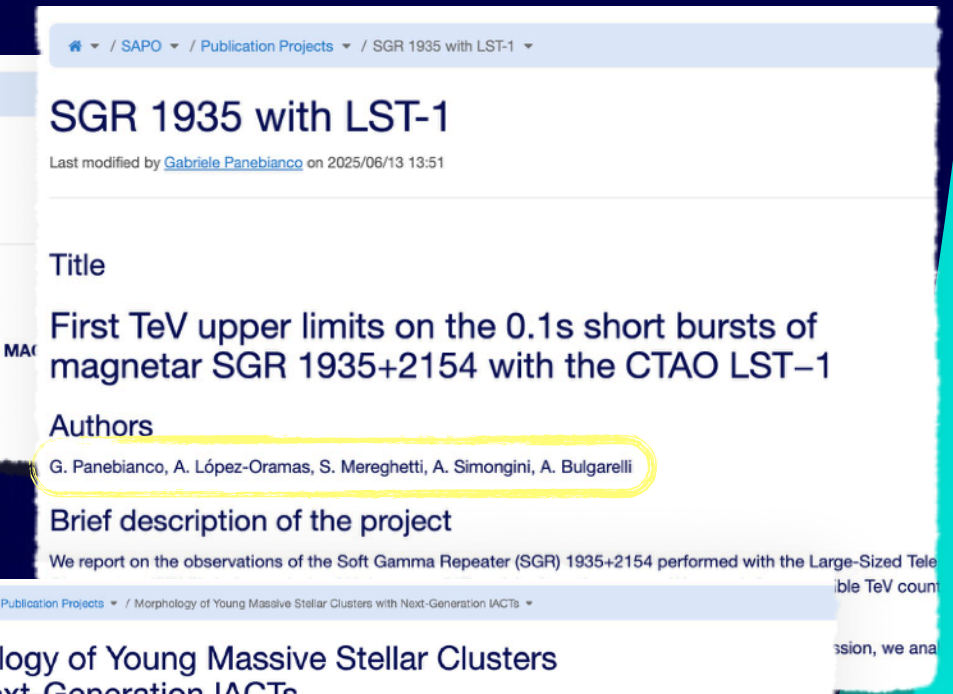
Follow-ups of Gravitational Wave alerts with the Cherenkov Telescope Array Observatory

This study focuses on optimizing the detection of TeV (very high-energy) gamma-ray emissions from binary n
star (BNS) mergers using the upcoming Cherenkov Telescope Array Observatory (CTAO). Motivated by the la
joint detection of gravitational waves and electromagnetic signals from GW170817/GRB 170817A, and by th
detection of TeV emission from GRBs, the work aims to enhance strategies for identifying such multimesseng
events in the future. Using simulated data of BNS systems and gravitational wave localizations, we model po
GeV–TeV emissions—assuming these mergers produce short gamma-ray bursts (GRBs), including off-axis, s
jets. Then, we have simulated CTAO's observational response under varying conditions, evaluating different s
and follow-up strategies to maximize the chances of detecting these transient sources.
Results show that approximately 3% of simulated GW-associated short gamma-ray bursts produce detectat
TeV radiation for CTAO, with detectability sharply declining after 1–4 hours. Rapid follow-up and considerati
and viewing angles are key to improving detection success.

Corresponding authors

Alphabetical order: Jarred Green, Lara Nava, Barbara Patricelli, Fabian Schuessler, Monica Seglar-Arroyo, Ar
Stamerra


/ SAPO / Publication Projects / SGR 1935 with LST-1

SGR 1935 with LST-1

Last modified by Gabriele Panebianco on 2025/06/13 13:51

Title

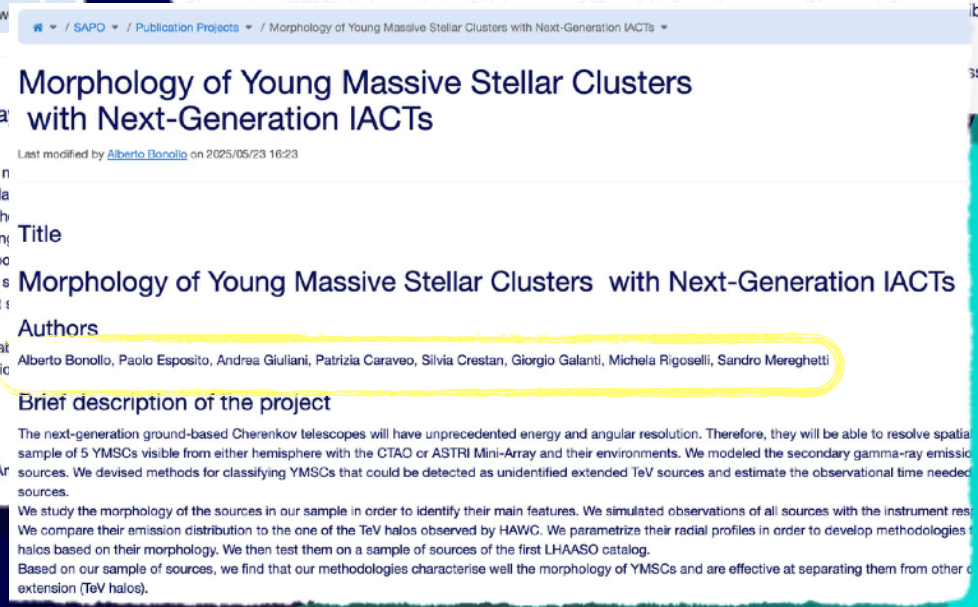
First TeV upper limits on the 0.1s short bursts of magnetar SGR 1935+2154 with the CTAO LST–1

Authors

G. Panebianco, A. López-Oramas, S. Mereghetti, A. Simongini, A. Bulgarelli

Brief description of the project

We report on the observations of the Soft Gamma Repeater (SGR) 1935+2154 performed with the Large-Sized Tele
ible TeV count


/ SAPO / Publication Projects / Morphology of Young Massive Stellar Clusters with Next-Generation IACTs

Morphology of Young Massive Stellar Clusters with Next-Generation IACTs

Last modified by Alberto Bonollo on 2025/05/23 16:23

Title

Morphology of Young Massive Stellar Clusters with Next-Generation IACTs

Authors

Alberto Bonollo, Paolo Esposito, Andrea Giuliani, Patrizia Caraveo, Silvia Crestan, Giorgio Galanti, Michela Rigoselli, Sandro Mereghetti

Brief description of the project

The next-generation ground-based Cherenkov telescopes will have unprecedented energy and angular resolution. Therefore, they will be able to resolve spatia
sample of 5 YMSCs visible from either hemisphere with the CTAO or ASTRI Mini-Array and their environments. We modeled the secondary gamma-ray emissio
sources. We devised methods for classifying YMSCs that could be detected as unidentified extended TeV sources and estimate the observational time needed
sources.
We study the morphology of the sources in our sample in order to identify their main features. We simulated observations of all sources with the instrument res
We compare their emission distribution to the one of the TeV halos observed by HAWC. We parametrize their radial profiles in order to develop methodologies
halos based on their morphology. We then test them on a sample of sources of the first LHAASO catalog.
Based on our sample of sources, we find that our methodologies characterise well the morphology of YMSCs and are effective at separating them from other
extension (TeV halos).

The INAF Community for CTAO Exploitation

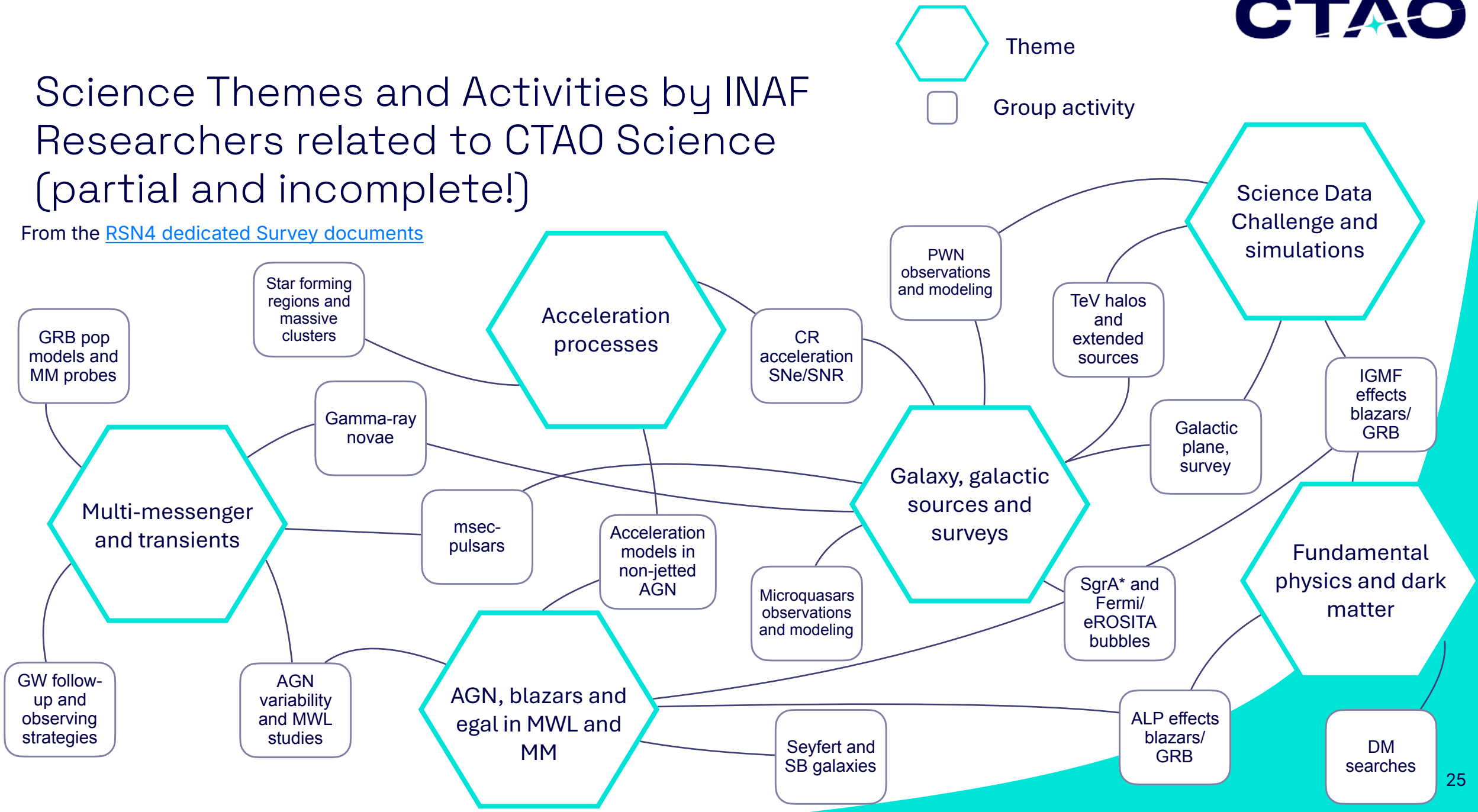
- RSN4 dedicated Survey documents
- From the survey, several INAF researchers and groups conduct studies that can benefit from the observatory's data and capabilities, also with intermediate array configurations. *I believe several more are interested as well, but they are scattered and lack an effective exchange of information and expertise.*
- The (limited...) survey already highlights themes of interest and ongoing activities that could exploit the CTAO's early science phase.

Persona di contatto / contact person	Collaboratori/ gruppo INAF Collaborators/ research group	Istituto/ Institute	Main activity or relevance of current work to CTAO Science or implementation (or construction - bridge with RSN5)	Notes / links
Antonio Stamerra	L. Nava (INAF), B. Patricelli (UniPi)	INAF-OAR	follow-up of GW alerts, prospects and obs. strategies	Lead GW-team
Antonio Stamerra	INAF SDC Team	INAF-OAR	Contribution to the Public CTAO Science Data Challenge (deliver: 2026)	SDC co-coordinator (CTAO seconded)
Antonio Stamerra/Paolo Da Vela	Lead by Paolo Da Vela (INAF-OAS)	INAF-OAR INAF-OAS	Interest and perspectives for IGMF studies on blazars and GRBs observed with CTAO	
Patrizia Romano	Stefano Vercellone	INAF-Brera	Observations of gamma-ray narrow-line Seyfert I with CTAO	Paper-1 Paper-2 Paper-3
Stefano Vercellone	Patrizia Romano	INAF-Brera	Multi-wavelength contribution to the Consortium Paper "Variability Studies of Active Galactic Nuclei with CTAO"	Consortium Paper in preparation
Alessandra Lamastra	S. Manon, E. Peretti, S. Celli	INAF-OAR	Prospects for observing Seyfert and starburst galaxies with CTAO	
Carlotta Pittori		INAF-OAR	Contribution to implement SUSS (Science User support system) in CTAP	Seconded CTAO, deputy SUSS coordinator
Gabriele Ponti	H. Zhang, Pareschi, Tagliaferri, Tresoldi	INAF-Brera	X-ray tracers for the physics of the Galactic center (Sgr A* and the central molecular zone), the Galactic outflow (Fermi and eROSITA bubbles) and the micro quasars (e.g., super-PeVatrons)	
Giorgio Galanti	F. Tavecchio, M. Landoni, L. Nava	INAF-IASF Milano	Capability of CTAO and ASTRI Mini-Array to observe the effects of axion-like particles (ALPs) on blazars/GRBs	
Michela Rigoselli	S. Recchia, S. Crestan, G. Peron	INAF-Brera	Unveiling TeV halos among unidentified extended TeV sources, and test the capability of CTAO and ASTRI Mini-Array to observe them	
Domitilla De Ma...	Papitto, Zampieri	INAF-OANa	Gamma-ray novae, msec pulsar binaries	
Fabio Pintore	INAF SDC Team	INAF/IASF Palermo	Contribution to the data simulation and sky-model preparation for the Public CTAO Science Data Challenge (deliver: 2026)	CTAO seconded: coordinator of the SDC data simulation;

https://docs.google.com/document/d/1PWxU8mr9JFXVTLh-WaFsE2OkyMK4RpIN09myT8KJZQY/

Science Themes and Activities by INAF Researchers related to CTAO Science (partial and incomplete!)

From the RSN4 dedicated Survey documents



CTAO e INAF: una sfida strategica per il prossimo decennio

è già iniziata!

- **CTAO** osservatorio di riferimento mondiale per la **scienza gamma** (~10 GeV – centinaia di TeV) **dal 2026–2035 e oltre**
- **Contributo INAF sostanziale nella costruzione e nell'implementazione (LST-N/S, CTA+, SST)**
- **Accesso privilegiato INAF** alle osservazioni fin dal **2027** (Guaranteed Time), seguito da **Open Early Science (2029)** e piena operatività
- Ruolo chiave dei **Key Science Projects**, definiti dalle nazioni coinvolte nella costruzione
- I prossimi anni sono **cruciali** per:
  - costruire una **comunità INAF solida e coordinata**
  - sviluppare competenze **multi-messaggero e multi-frequenza** dedicate ai casi scientifici CTAO
  - **formare giovani ricercatrici e ricercatori** alla scienza basata sui dati CTAO
- La raccolta di **competenze, interessi e potenzialità** è essenziale per:
  - supportare i gruppi di ricerca INAF interessati alle osservazioni di CTAO e alla scienza collegata
  - **massimizzare il ritorno scientifico di CTAO**

CTAO

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CTAO: a distributed facility

CTAO Headquarters in Bologna, Italy (Site)

Science Data Management Centre (site)

Computing Center at DESY (Germany)

CTAO-North (site)
(or CTAO-North Station)
- CTAO-North Array (site)
- CTAO-North Low Elevation Office (site)

CTAO-South (site)
(or CTAO-South Station)
- CTAO-South Array (site)
- CTAO-South Operations Building (site)

Function: When talking about what they do

Geographical: When talking about location

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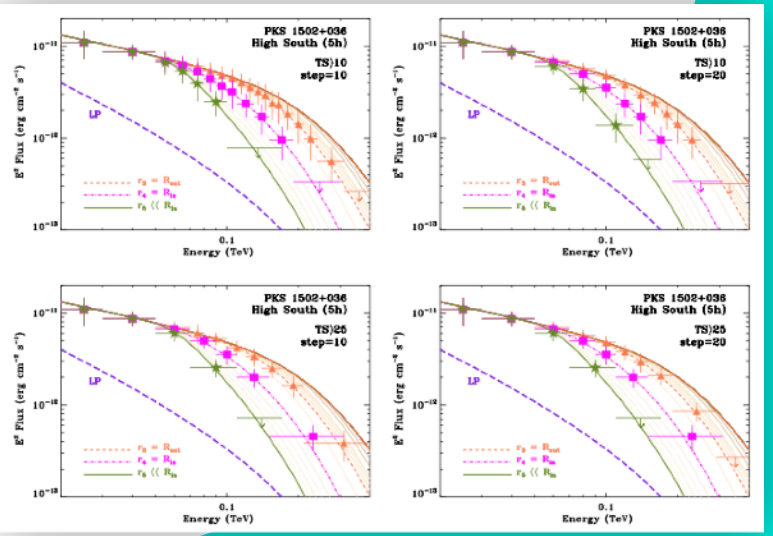
- From the survey, several INAF researchers and groups conduct studies that can benefit from the observatory's data and capabilities, also with intermediate array configurations. *I believe several more are interested as well, but they are scattered and lack an effective exchange of information and expertise.*
- The (limited…) survey already highlights themes of interest and ongoing activities that could exploit the CTAO's early science phase.

Just an example

Establish narrow-line Seyfert galaxies as a new class of TeV emitters. Excellent targets for the **CTAO guaranteed time** and early science (low risk ToOs, high gain)
(P. Romano, S. Vercellone)

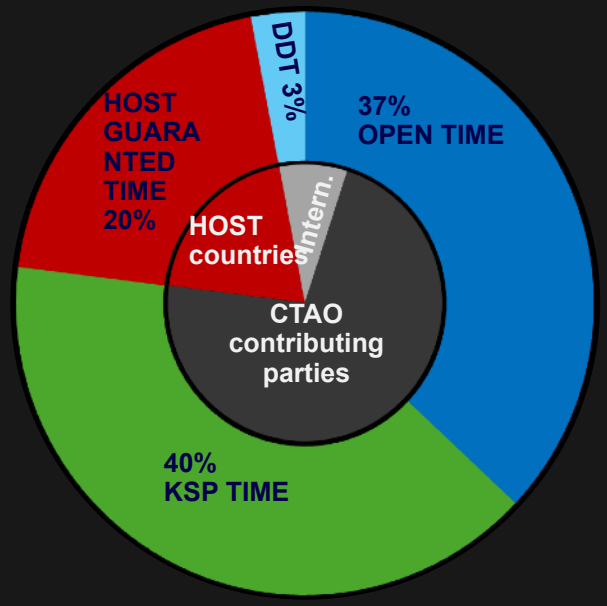


https://docs.google.com/document/d/1PWxU8mr9JFXVTLh-WaFsE2OkyMK4RpIN09myT8KJZQY/

An astronomical observatory

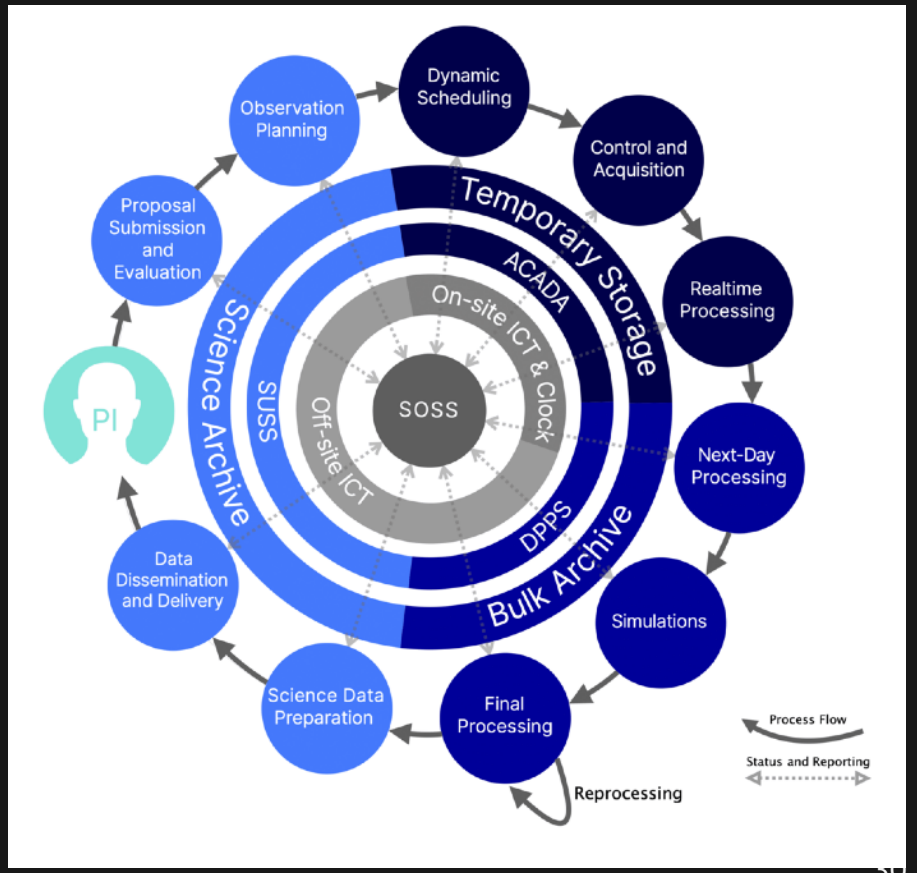
An open proposal-driven observatory

- 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

From telescope systems to the observer



GRB 221009A: the most extreme GRB

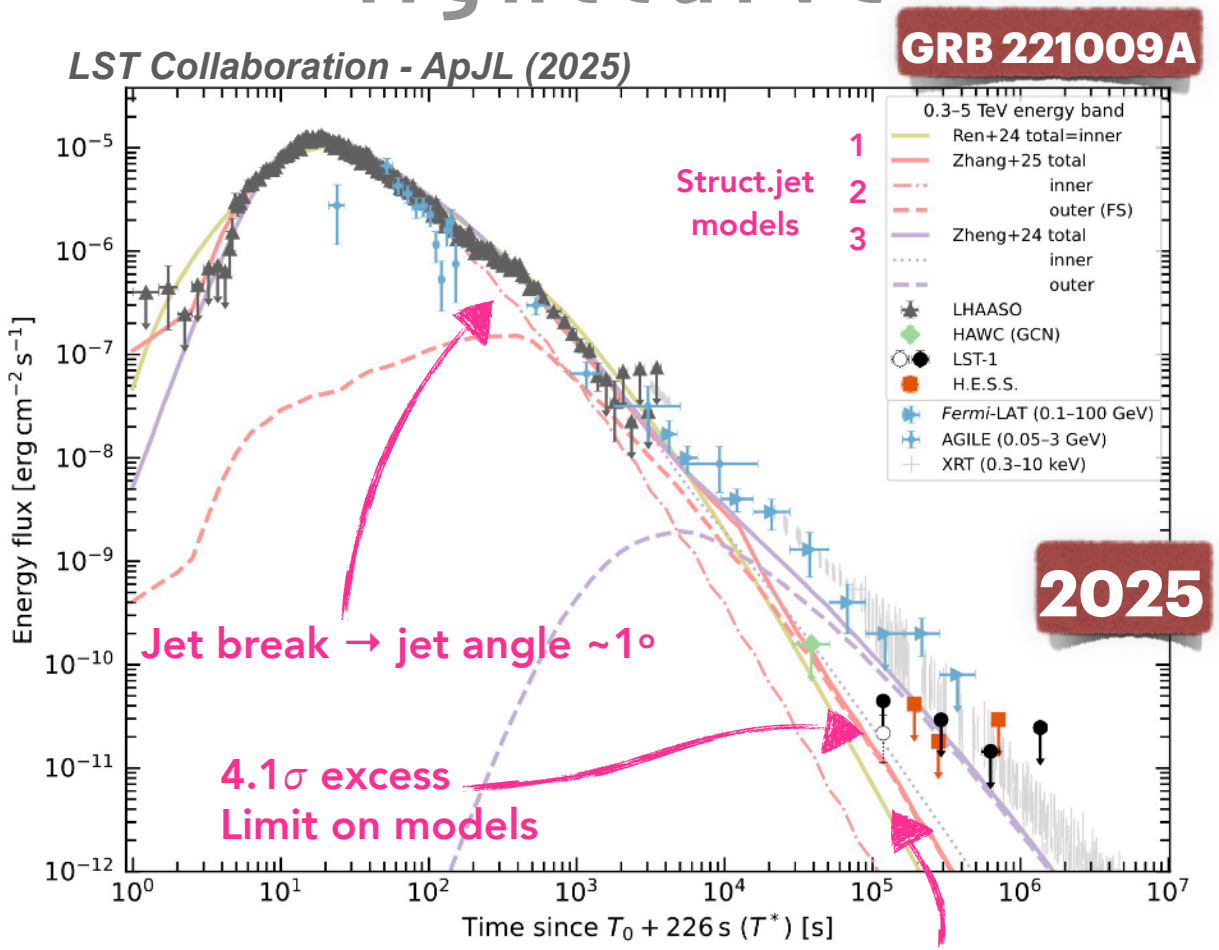
★ TeV (afterglow) emission: key findings

- ✓ GRB engine accelerates photons up to TeV
- ✓ Evidence of a second energetic component
- ✓ Energy budget and time evolution similar to the optical-X-ray component
- ✓ TeV flux follows closely the X-ray flux
- ✓ Constraints on the surrounding medium
- ✓ TeV emission can last days
- ✓ Gamma-rays up to **12 TeV** from the GRB 221009A!
- ✓ Indication on jet structure

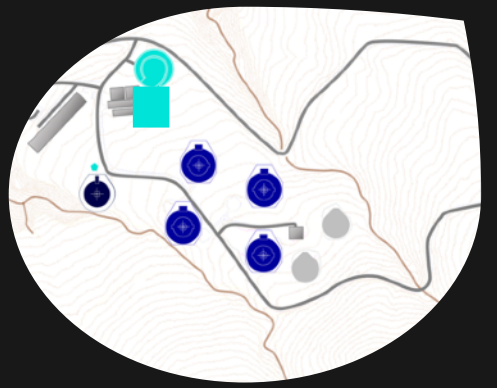
Results on GRB 221009A with LST-1 first CTAO telescope in operation!

CTAO | LST COLLABORATION

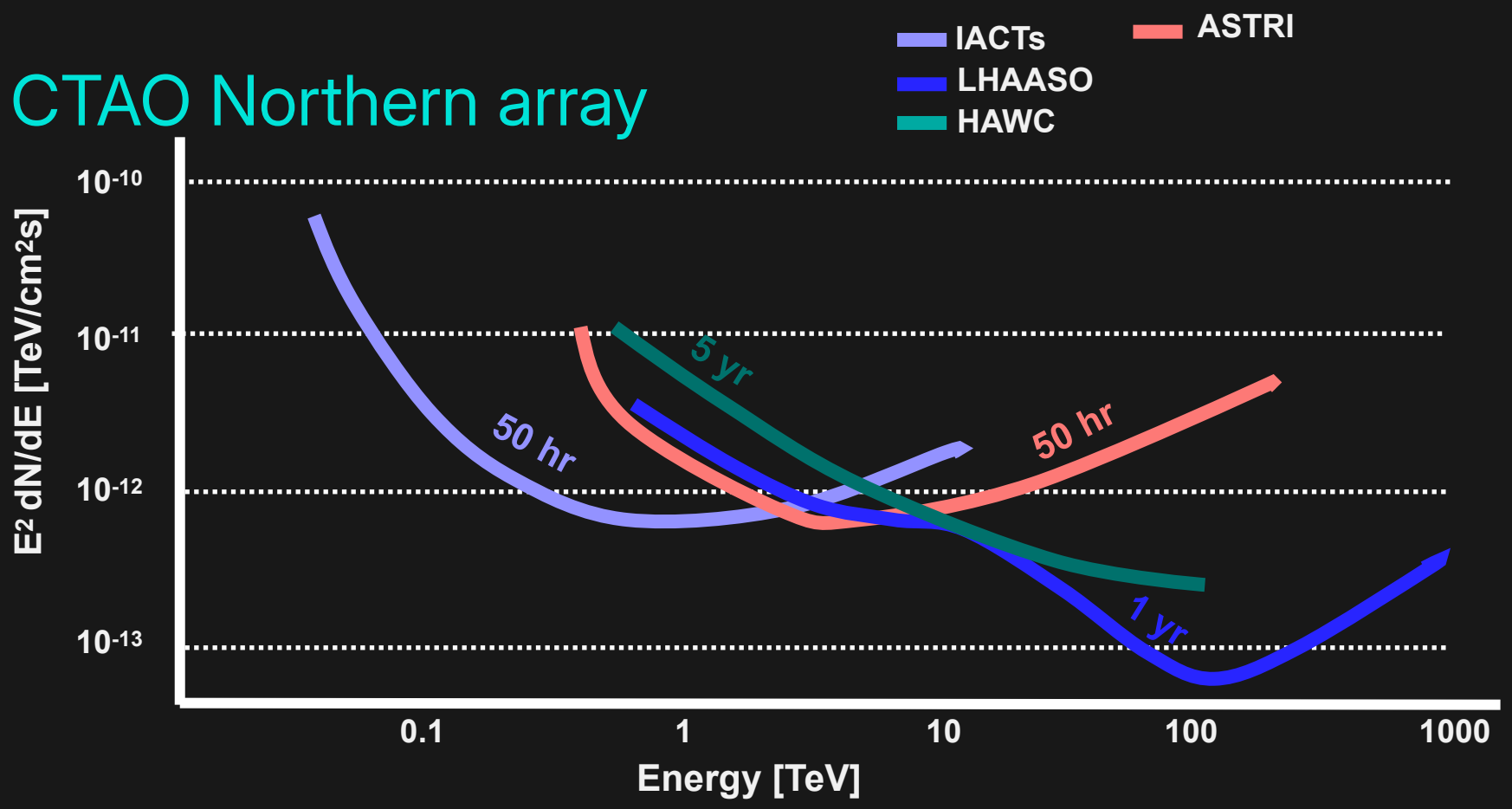
lightcurve



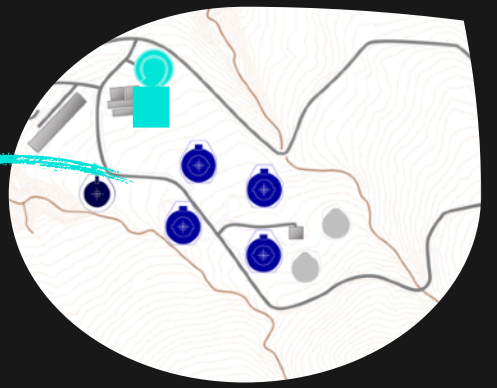
In 3 years from now



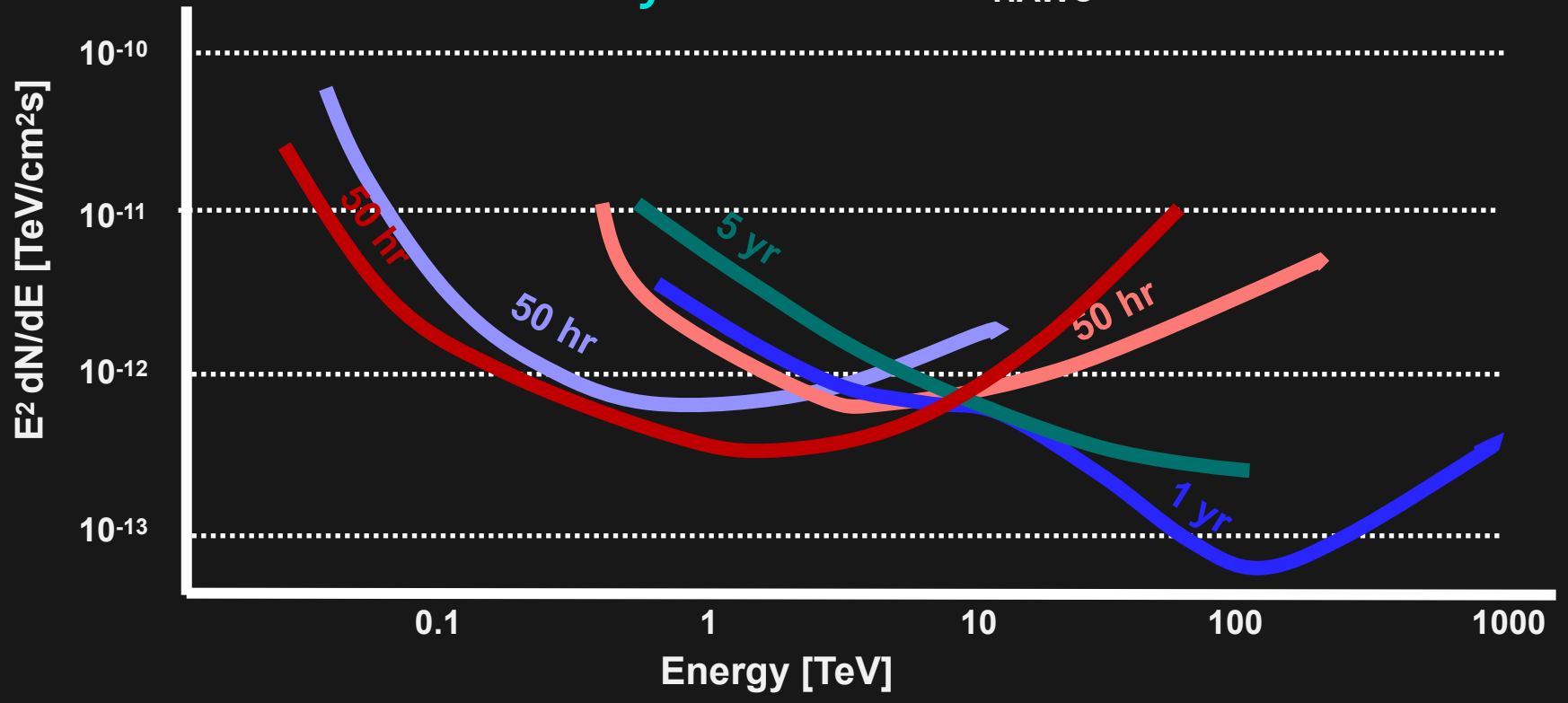
CTAO Northern array



In 3 years from now



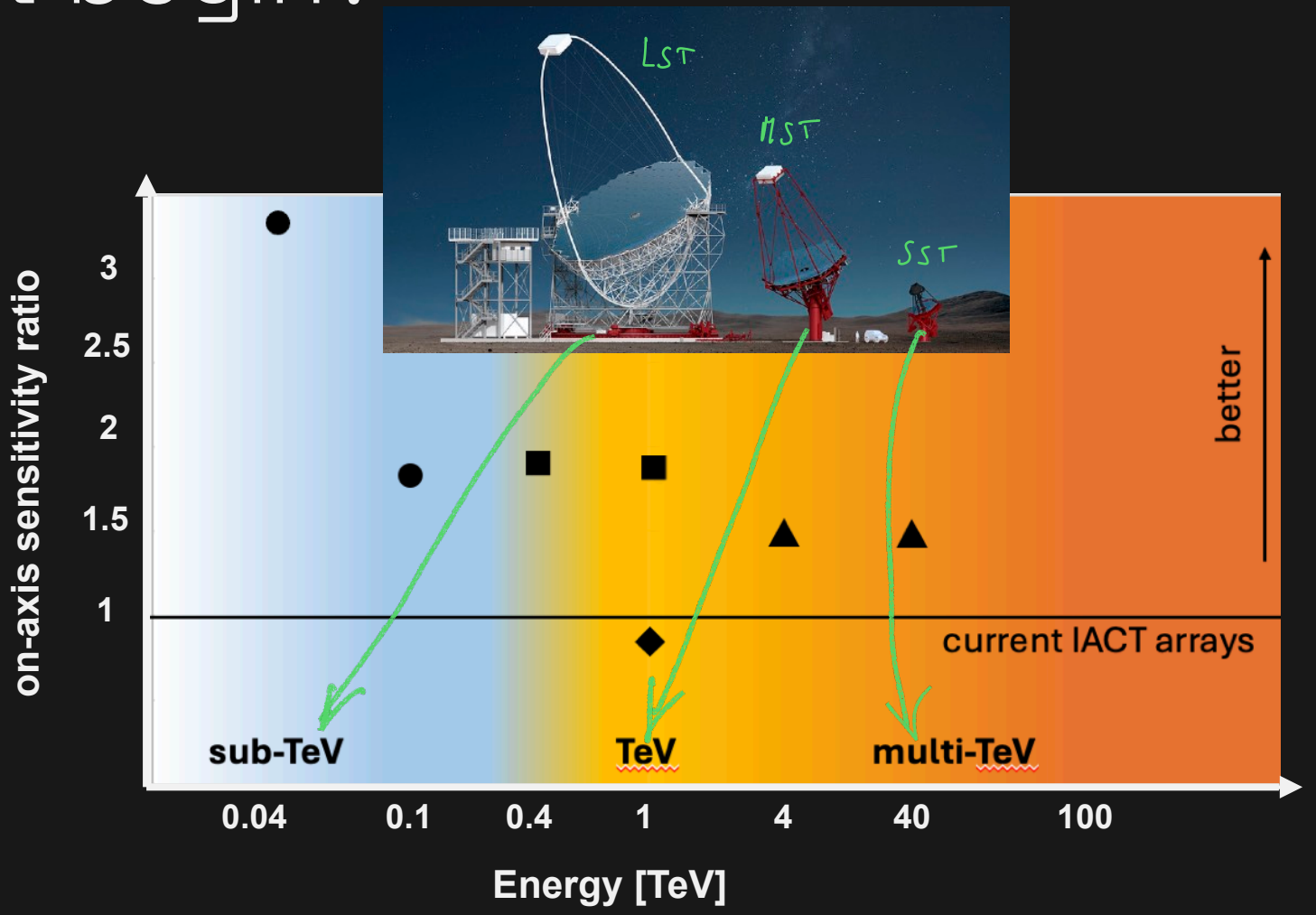
CTAO Northern array



With respect to current IACT arrays:

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

When will the scientific impact begin?



Intermediate arrays

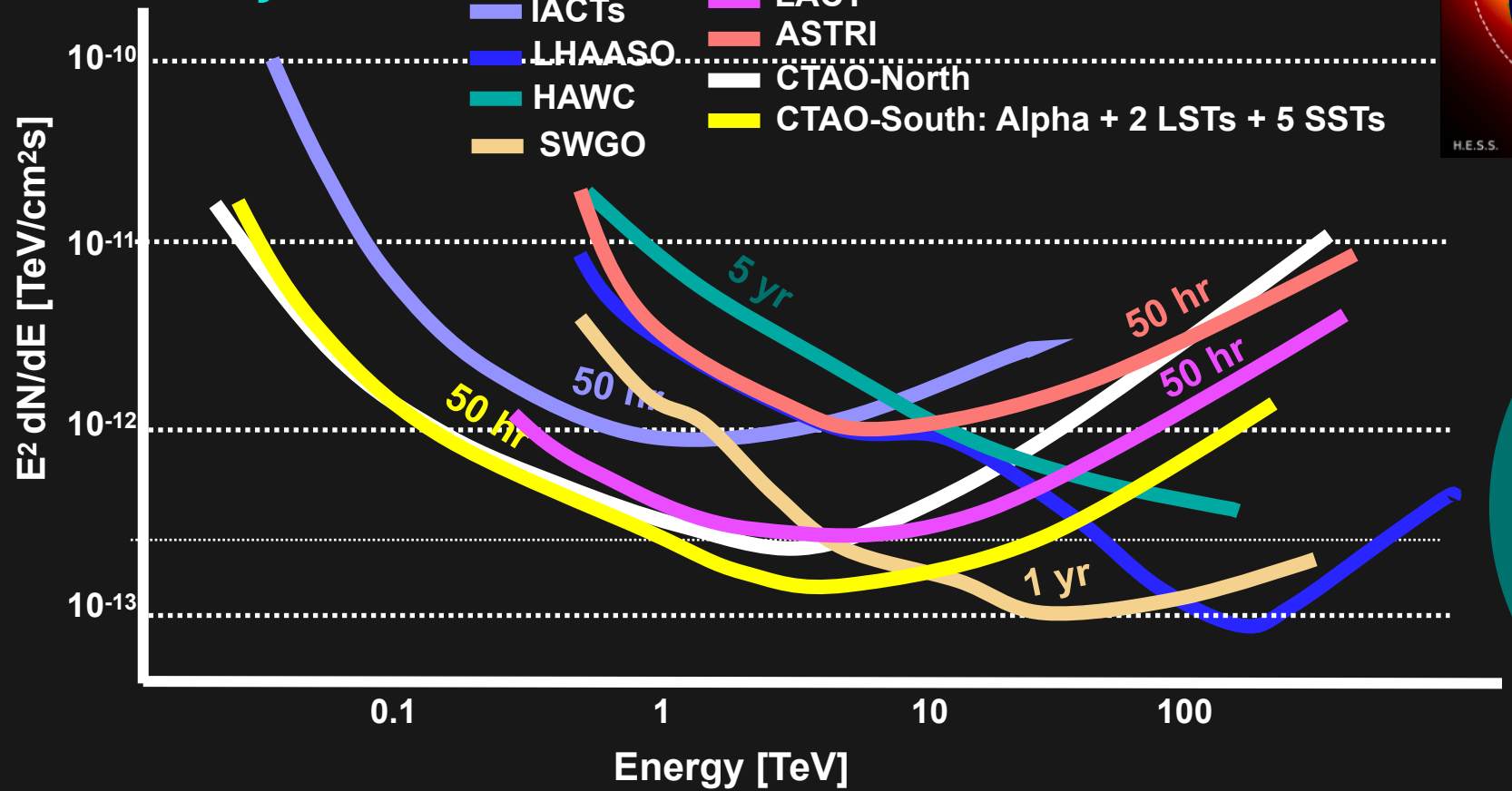
- 2 LST
- 2 LST + 1 MST
- 1 MST + 5 SST
- 5 SST

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

CTAO Performance

Full sky

Sensitivity



Angular resolution

The TeV gamma-ray sky

(E>~50 GeV-100 TeV)

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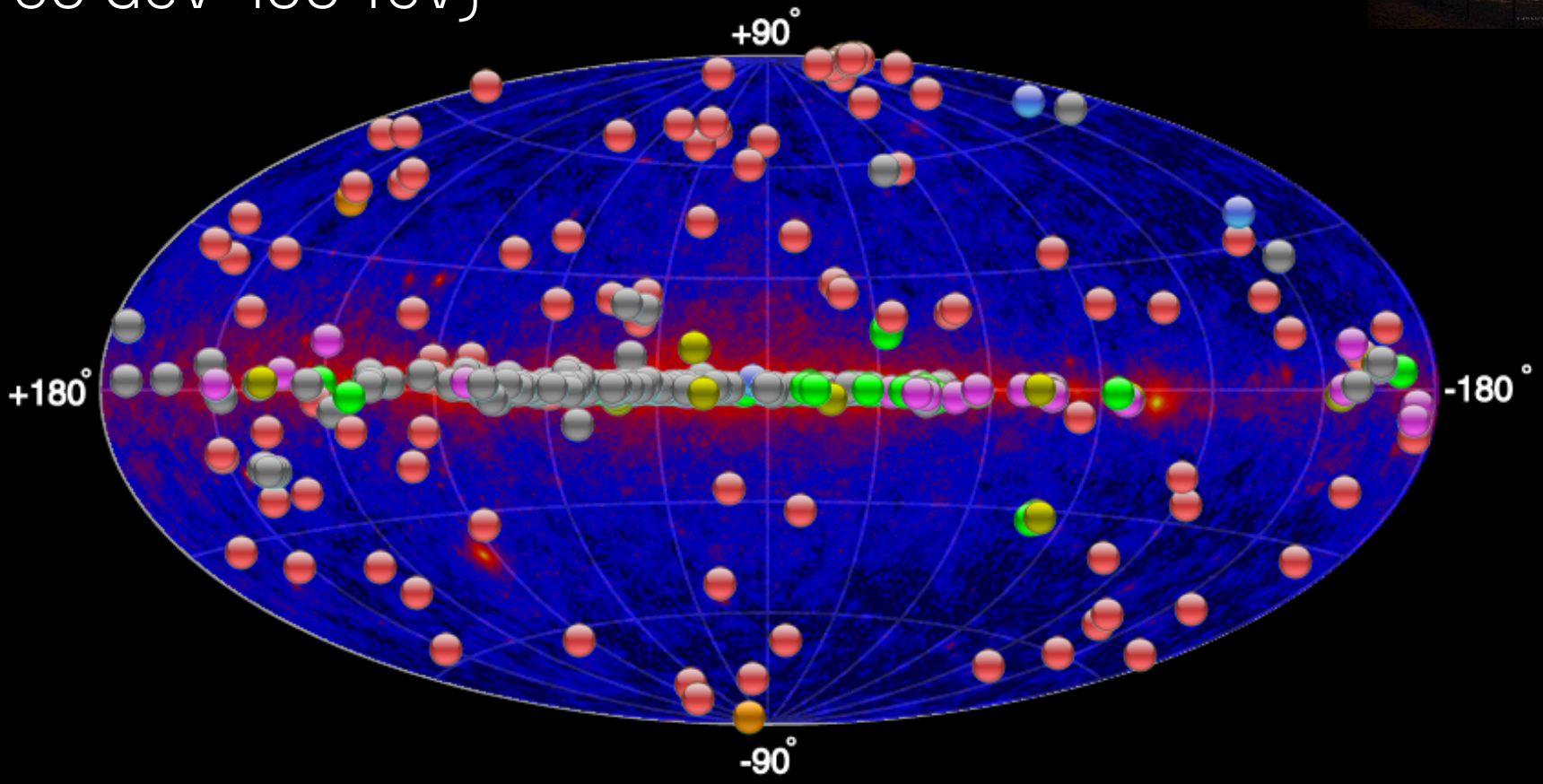


Source Types

- 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

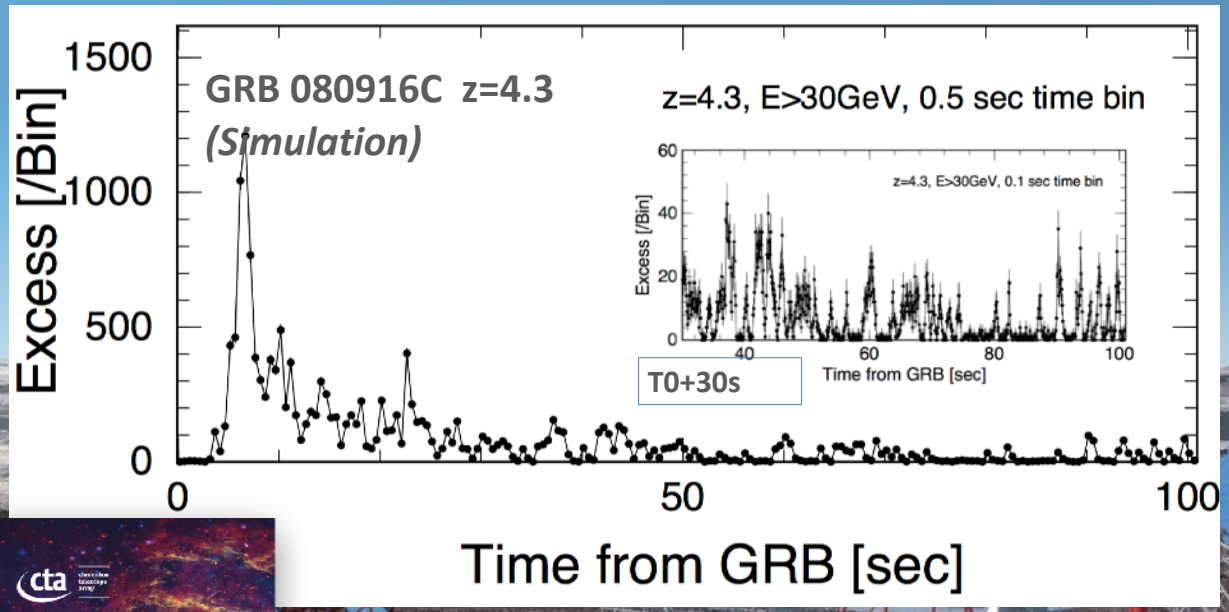
93 are AGN-blazars/radiogalaxies

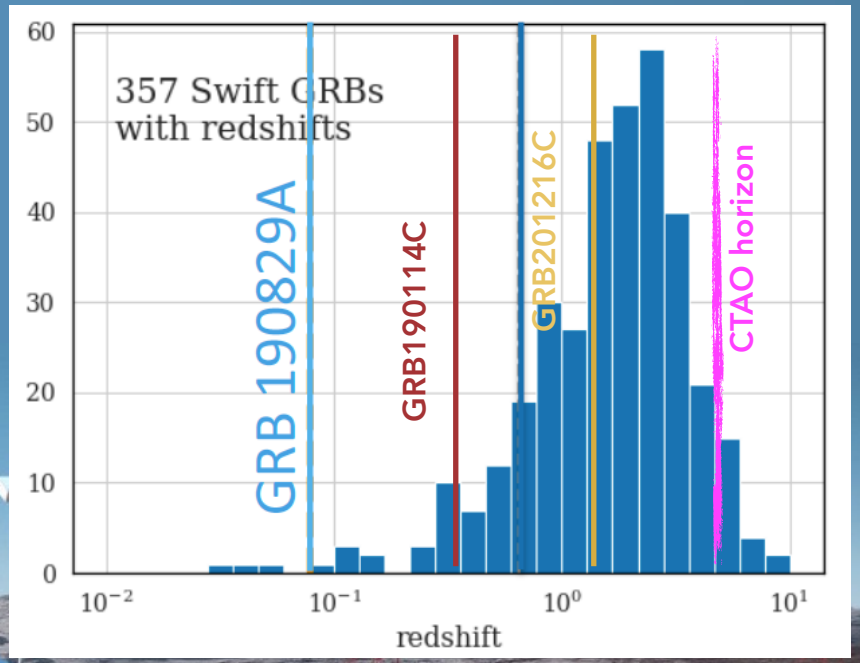
5 Gamma-RAY Burst GRB

http://tevcat.uchicago.edu

Prospects on GRBs with CTAO

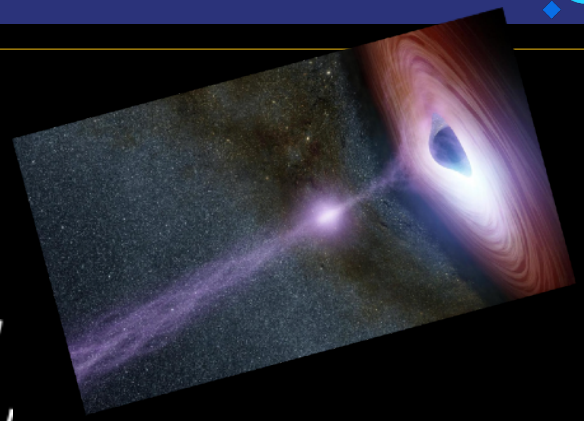
- Lower energy threshold → larger distances/volume
- Up to ten times better sensitivity → precision measurements
- Fast slewing → TeV prompt emission?





www.worldscientific.com/worldscibooks/10.1142/10986

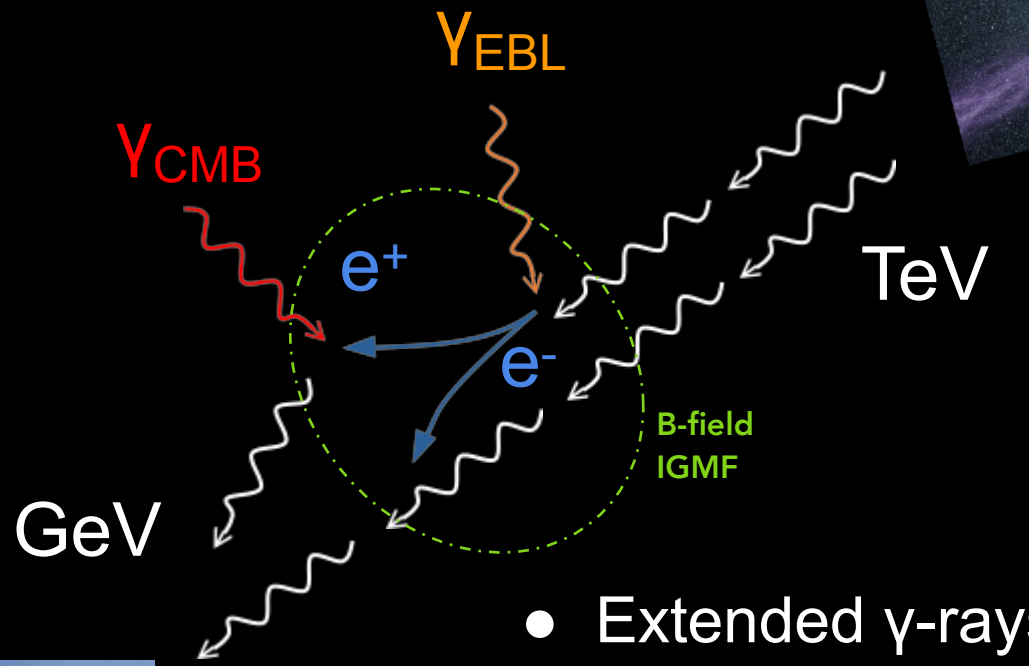
Imprint of IGMF on the GeV-TeV gamma rays



Excess at lower energies

$$E \simeq 70 \left[\frac{E_0}{10\ TeV}\right]^2 \ GeV$$

Neronov et al. 2009



Indirect detection of the IGMF

- Extended γ-rays halos
- Spectral features (cascade spectrum)
- Time delayed γ-ray emission

Credit: Paolo Da Vela - INAF Bologna