Transients at the highest energies and multi-messenger observations with CTAO.

Antonio Stamerra - INAF (Osservatorio Astronomico di Roma)
And the CTAO-GW team

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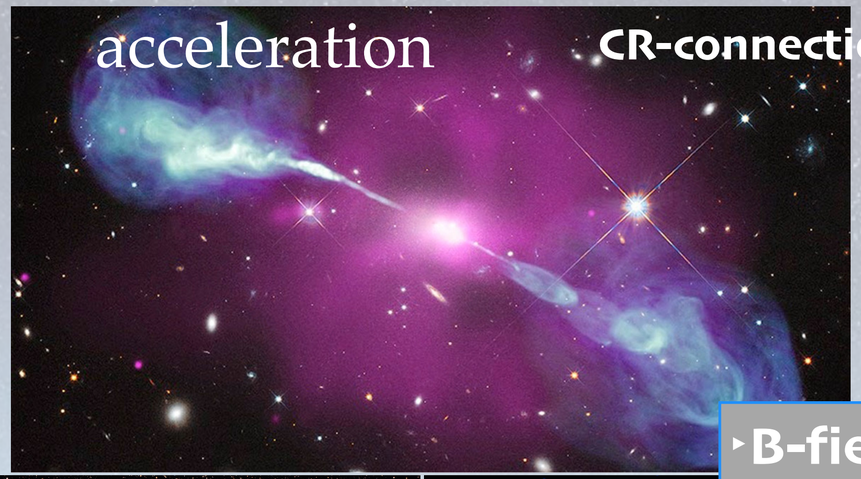
The (astro-)physical processes of the TeV Sky

What can we learn with TeV observations

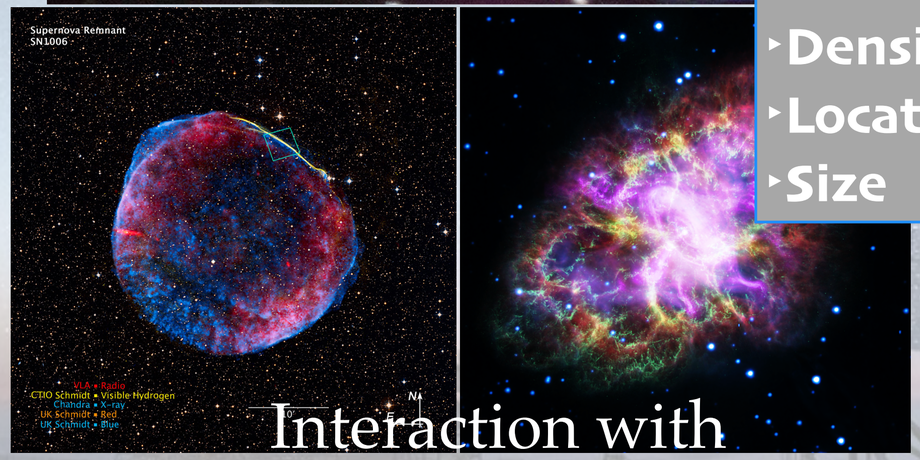
Particle acceleration

Particle energy distribution
Particle identification
CR-connection

Gamma-ray emission

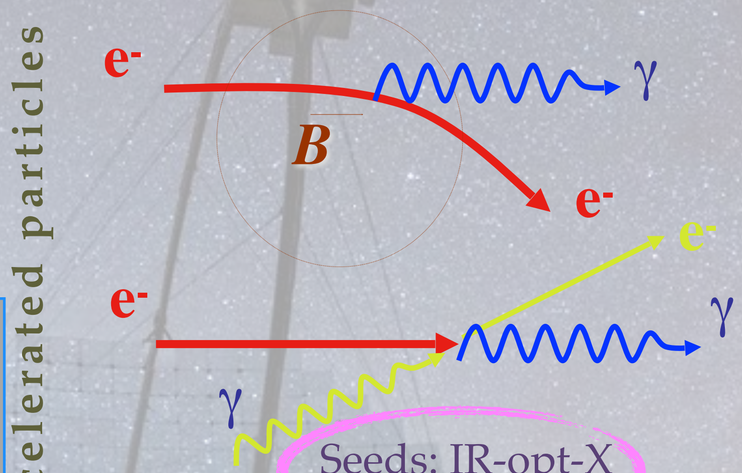


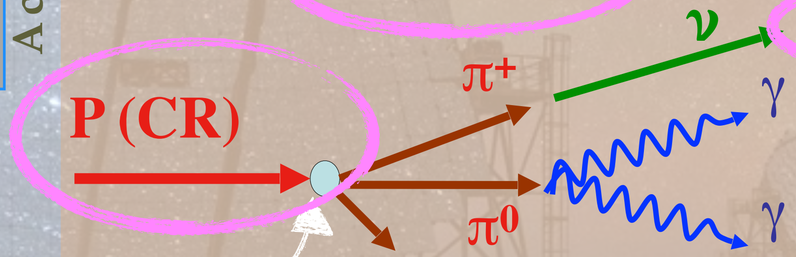
- **B-field**
- **Density**
- **Location**
- **Size**



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

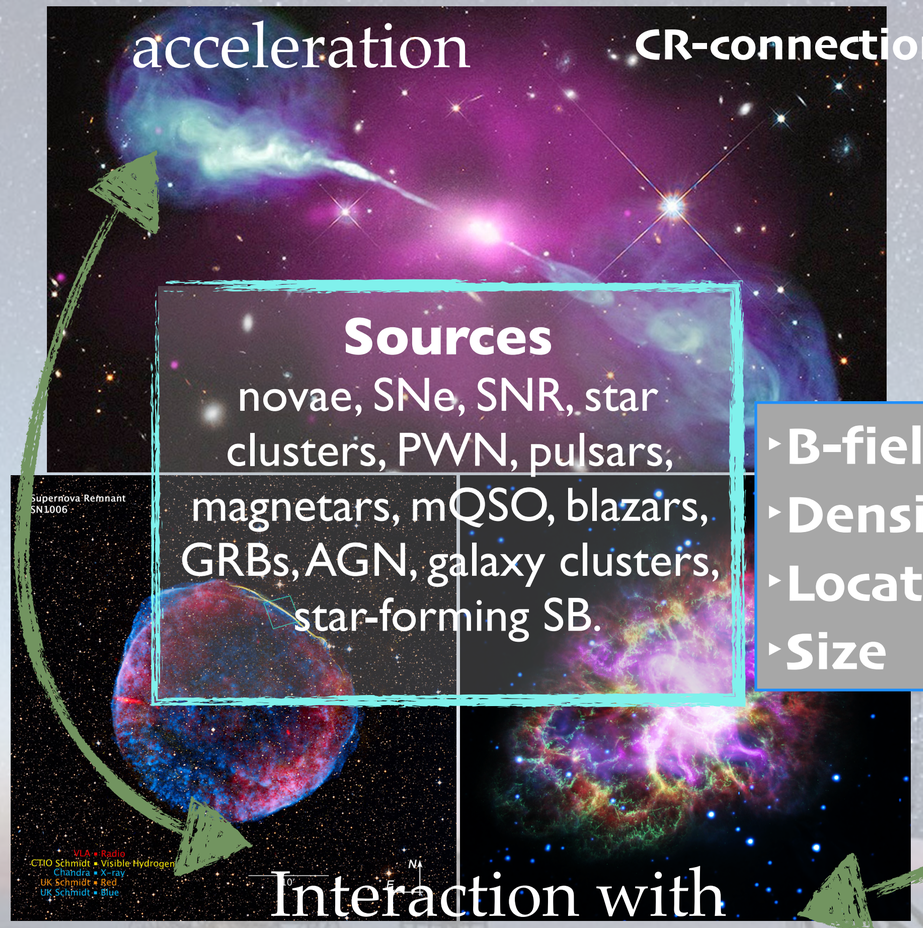
What can we learn with TeV observations

Particle acceleration

Particle energy distribution
Particle identification
CR-connection

Gamma-ray emission

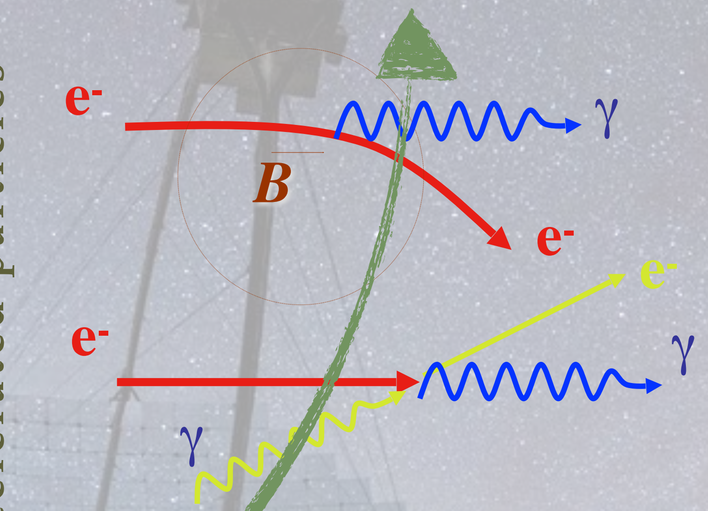
Diagnostics
multi-band observations and correlations, SEDs, variability, light curves, morphology



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

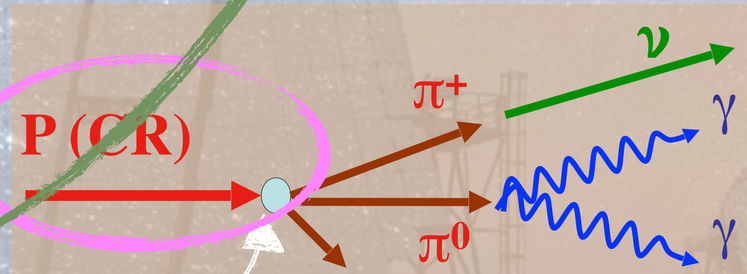


Synchrotron radiation

Radio to gamma-rays

Inverse Compton

gamma-rays GeV-TeV



Neutrinos TeV-PeV

Particle collisions-cascades

gamma-rays GeV-TeV-PeV

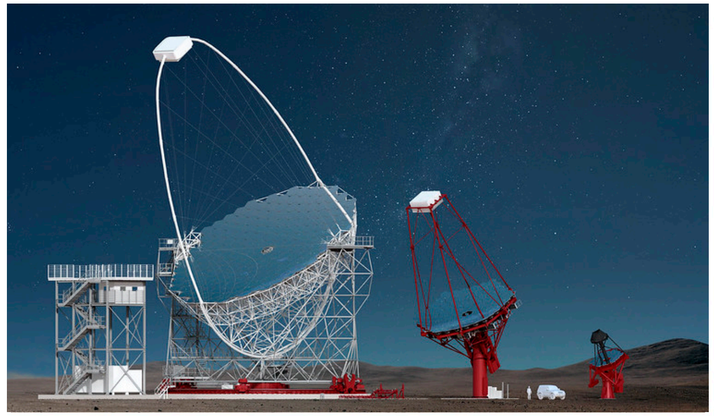
Interaction with the ambient

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

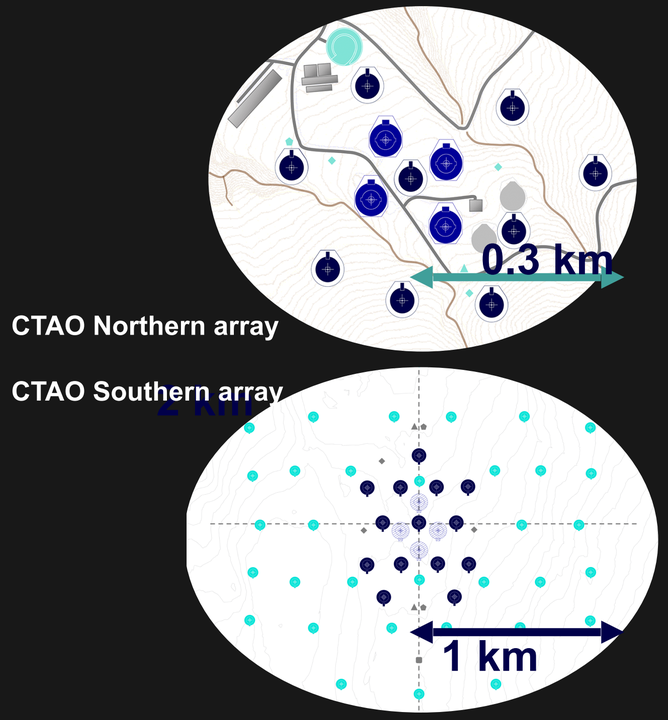
APOD 24 Jul 2009

CTAO: a diverse array

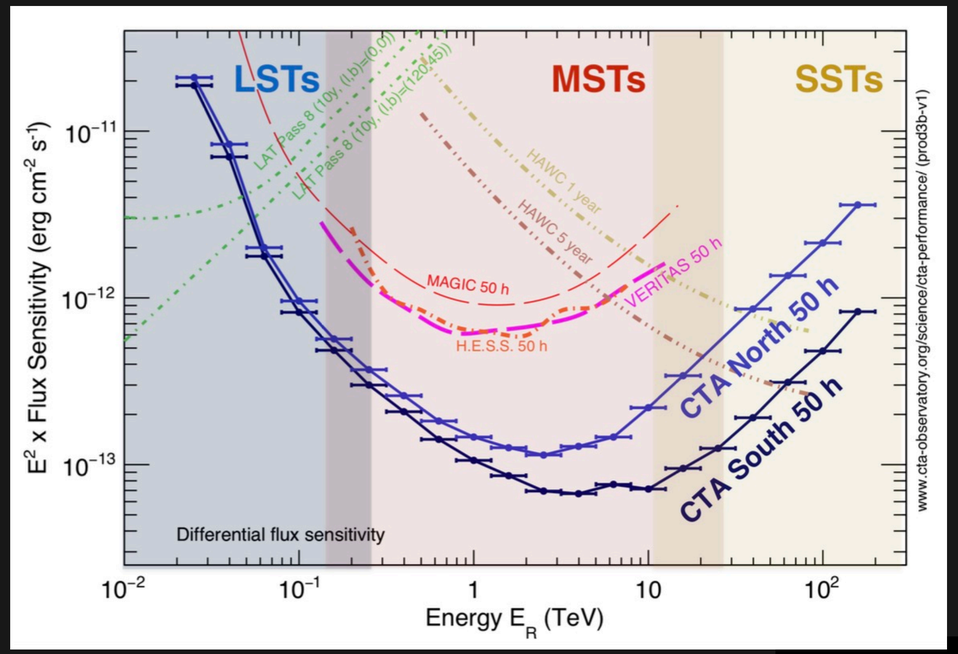
- Extended energy range (20 GeV-300 TeV) with telescopes of 3 sizes.
- Improved sensitivity, up to 5-10 times than current IACTs.
- Improved angular resolution (3’) and energy resolution (7% @1 TeV).



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



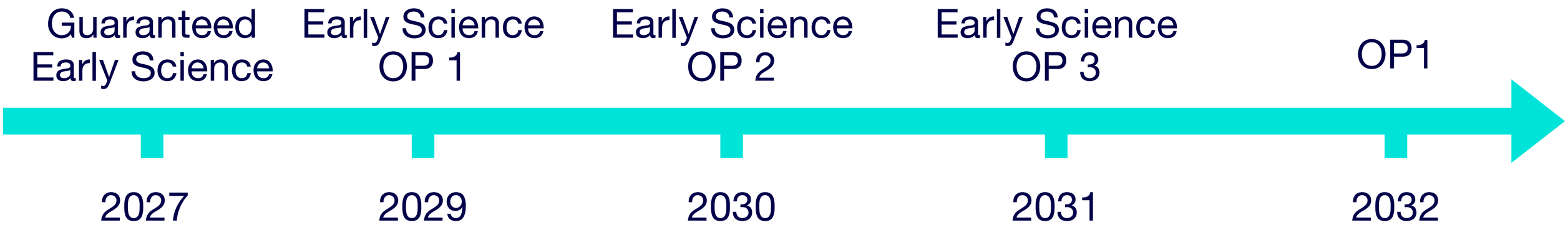
Alpha configuration



La timeline della scienza di CTAO

- 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



GRB 221009A: the most extreme GRB

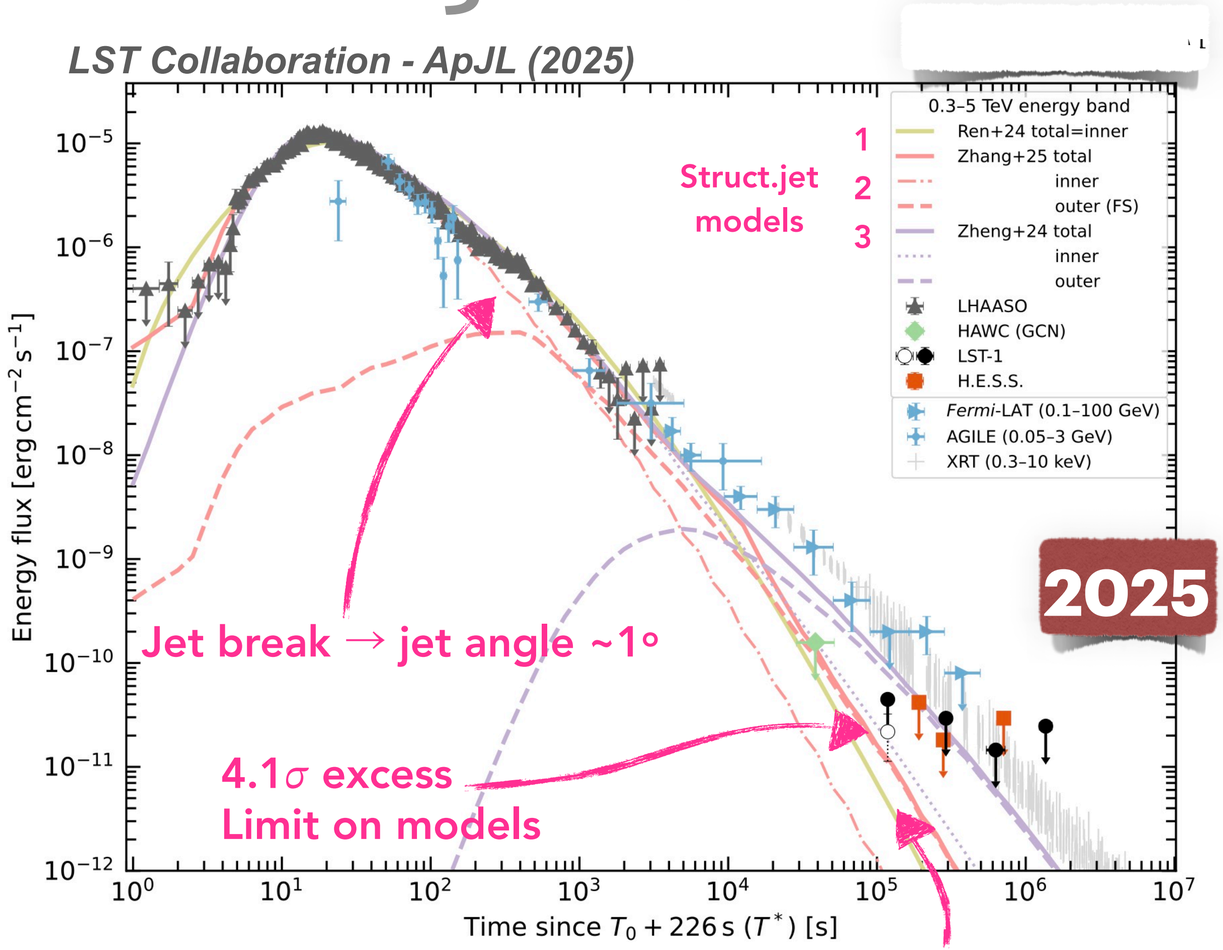
★ TeV (afterglow) emission: key findings

- ✓ 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



Constraints on models!

And possibly on the location of the emission region

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Astronomy & Astrophysics manuscript no. output
February 2, 2026
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Constraints on the VHE counterpart of two binary black hole mergers observed by the MAGIC and CTAO LST-1 telescopes

MAGIC and LST Collaboration *

(Affiliations can be found after the references)

Received ???; accepted ???

ABSTRACT

We present very-high-energy gamma-ray observations of two binary black hole merger candidates, S240615dg and S241125n, performed with the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes and the first Large-Sized Telescope of the Cherenkov Telescope Array Observatory's (CTAO LST-1). S240615dg was the best localized event of the fourth observing run of the LIGO-Virgo-KAGRA gravitational waves interferometers. S241125n was temporally and spatially coincident with a subthreshold short-duration burst detected with the *Swift*-Burst Alert Telescope (BAT), the *Swift*-X-Ray Telescope (XRT) and the *Einstein Probe* Follow-up X-ray Telescope (FXT). We observed the two events in stereoscopic mode, taking advantage of the improved sensitivity of joint MAGIC+LST-1 observations. No detection was achieved in the GeV-TeV gamma-ray band for any of the two sources. The unfavourable observing conditions of both events posed a challenge for a standard analysis and therefore a non standard analysis was necessary for both objects. Owing to the small localization area and the association with a GRB-like burst respectively, these events represented an unprecedented opportunity to study in details the electromagnetic emission from binary black holes merger events and, in particular, we discussed two theoretical models that predict a detectable gamma-ray emission and the possible future applications.

Key words. gamma rays: general – gravitational waves: individual S240615dg – gravitational waves: individual S241125n

1. Introduction

The first detection of a gravitational wave (GW) from a binary black hole (BBH) system merger was a historical breakthrough, marking the beginning of multimessenger astronomy as we know it today (Abbott et al. 2016). This led to a technolo… vanc… (LIC… 2014… tor (… KAGRA (LVK) Collaboration(s). Improvements in broadband sensitivity led to growth in the number of candidate GW events detected throughout the first four observing runs, achieving a total of 219 confirmed events so far[1]. Among them, 11 were observed during the first two observing runs (O1 and O2; Abbott et al. 2019b), 79 during the first and second half of the third run (O3a and O3b; Abbott et al. 2021a, 2023, 2024), and 129 during the first part of the fourth run (O4; Abac et al. 2024; The LIGO Scientific Collaboration et al. 2025)[2], although numerous candidate events were made public via public alert systems. The vast majority of confirmed detections originate from BBH systems, with total masses in the range $14 - 238 M_\odot$, corresponding to chirp masses of $7.4-225 M_\odot$ and distances up to 8.4 Gpc. Among the four observing runs, only two events were classified as binary neutron star (BNS; Abbott et al. 2017b, 2020a) and three neutron-star–black-hole binaries (NSBHs; Abbott et al. 2021b; Abac et al. 2024).

Detecting electromagnetic (EM) counterparts of GW events is one of the main challenges of current astrophysics and many facilities around the world and in space are dedicating their efforts to make this detection possible. The historical detection of GW170817 from a BNS merger by LIGO and Virgo (Abbott … multi-… magnetic … the GW … ma-ray … gamma-… Ray Burst Monitor (GBM; Goldstein et al. 2017) and the INTErnational Gamma-Ray Astrophysics Laboratory (*INTEGRAL*; Savchenko et al. 2017) space satellites, providing strong evidence of the association between BNS mergers and sGRBs (Abbott et al. 2017a). Soon after the initial trigger, an extensive follow-up campaign was launched across the entire EM spectrum leading to the detection of the optical/NIR counterpart AT 2017gfo, followed by X-rays and radio detection of the GRB afterglow (Abbott et al. 2017 and references therein). The afterglow was extensively followed in the gamma-ray band, spanning over 10 orders of magnitude in energy by space and ground-based telescopes. However, no significant detection was achieved in any gamma-ray band (Goldstein et al. 2017; Kocevski et al. 2017; Martinez-Castellanos et al. 2017; Nakahira et al. 2017; Savchenko et al. 2017; Svinkin et al. 2017; Verrecchia et al. 2017; Li et al. 2018). The High Energy Stereoscopic System (H.E.S.S.) array of imaging atmospheric Cherenkov telescopes (IACTs) conducted deep observations in the very-high-energy (VHE; $E > 50$ GeV) gamma-ray regime, achieving upper limits (U.L.s) in the range of 0.13 – 23.7 TeV (Abdalla et al. 2017). Observations were performed with two different cadences: rapid observations from 0.22 to 5.2 days post-merger, and late-time observations 200 days post-merger (Abdalla et al.

* Corresponding authors (alphabetical order): J. Jiménez Quiles, M. Pecimotika, M. Seglar Arroyo, A. Simongini

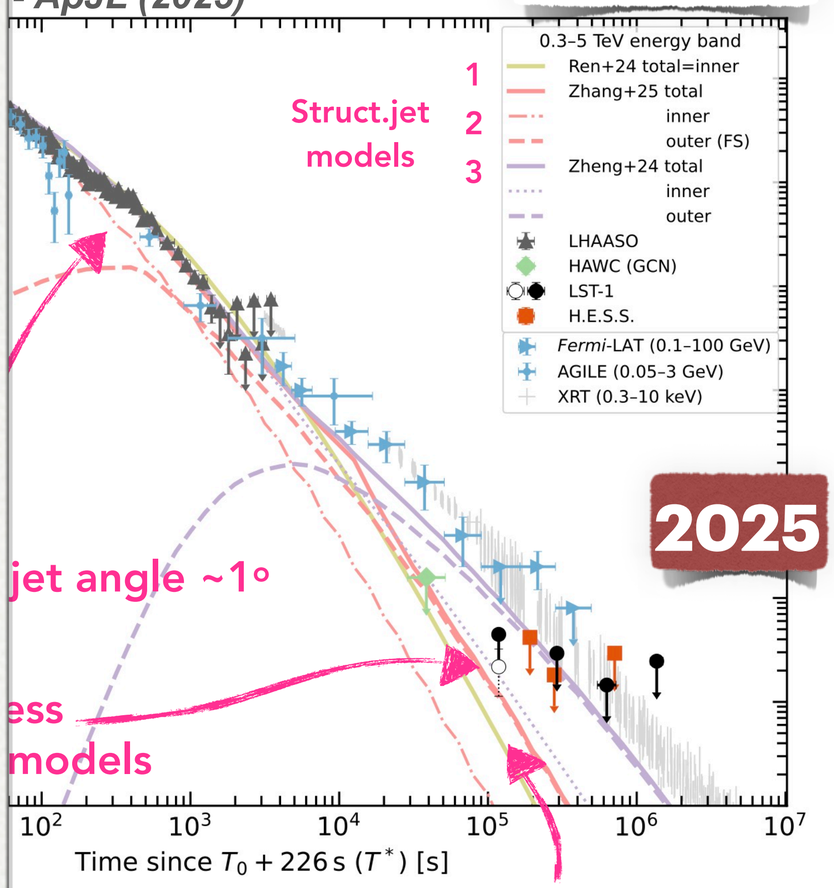
[1] https://gwosc.org/eventapi/html/GWTC/

[2] The number of confirmed events is expected to increase substantially with the upcoming release of the LVK source catalogues from the rest of O4.

to be submitted soon

ightcurve

- ApJL (2025)



Constraints on models!

And possibly on the location of the emission region

TeV Transients with IACTs

Haunting for transients: IACTs have the required performances

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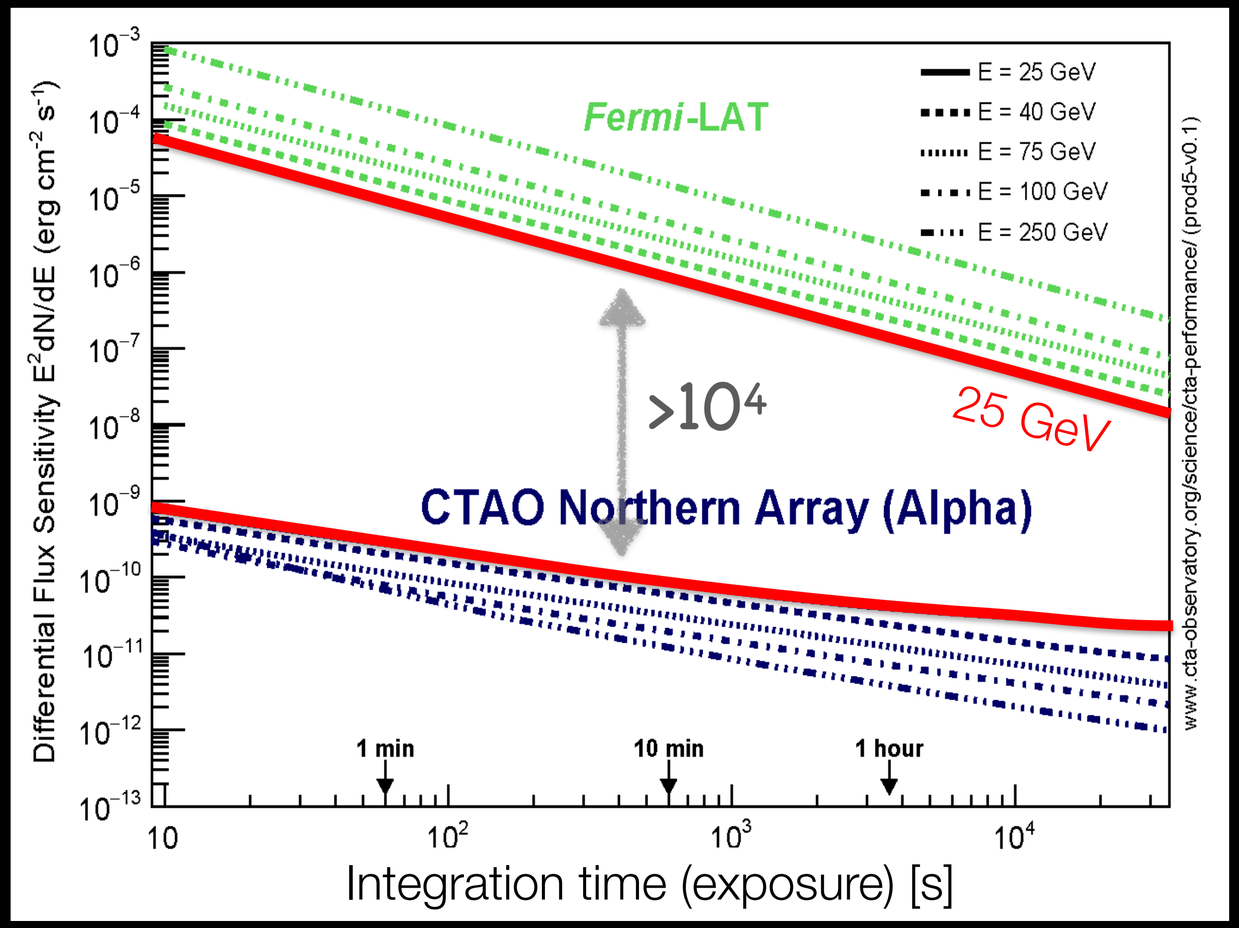
Extended "spectral arm leverage"
High statistics (=precision) on flares

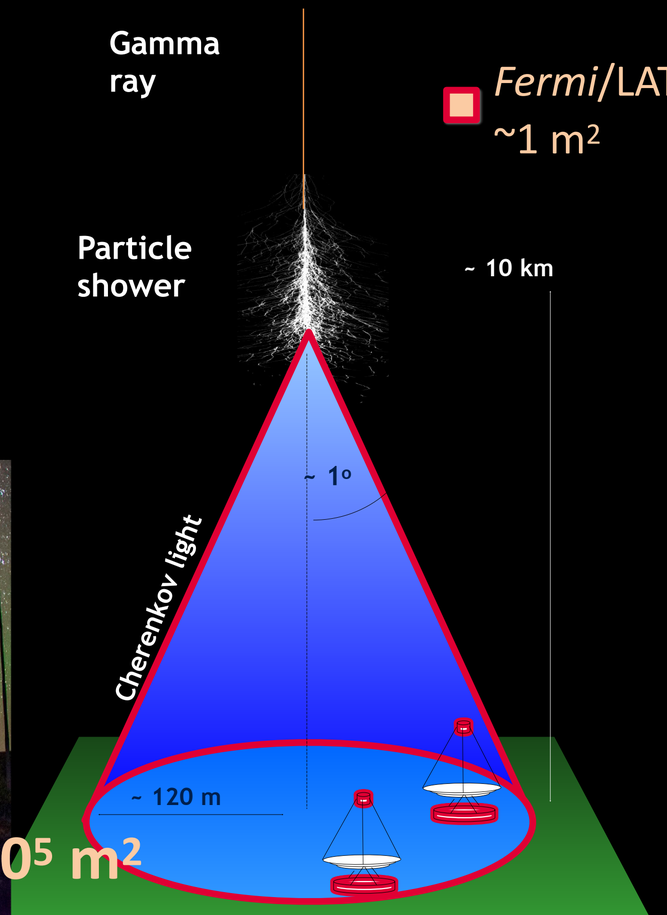


✓ **Big effective area** ➠ photon statistics

✓ **Low energy** threshold (~50 GeV)

✓ **Repositioning speed** ~7 deg/s; *automatic* repointing

✓ Observations in **moon-time**



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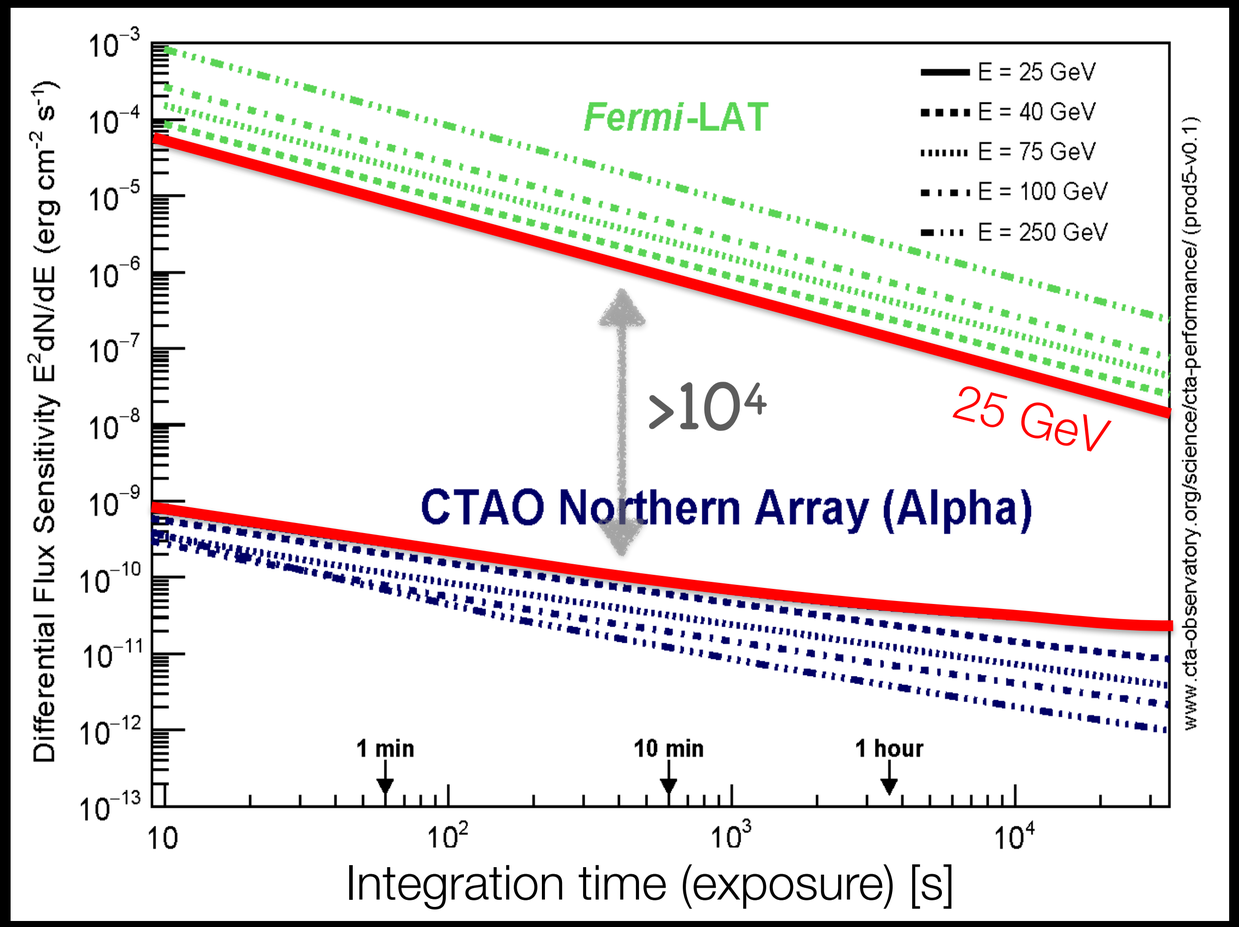

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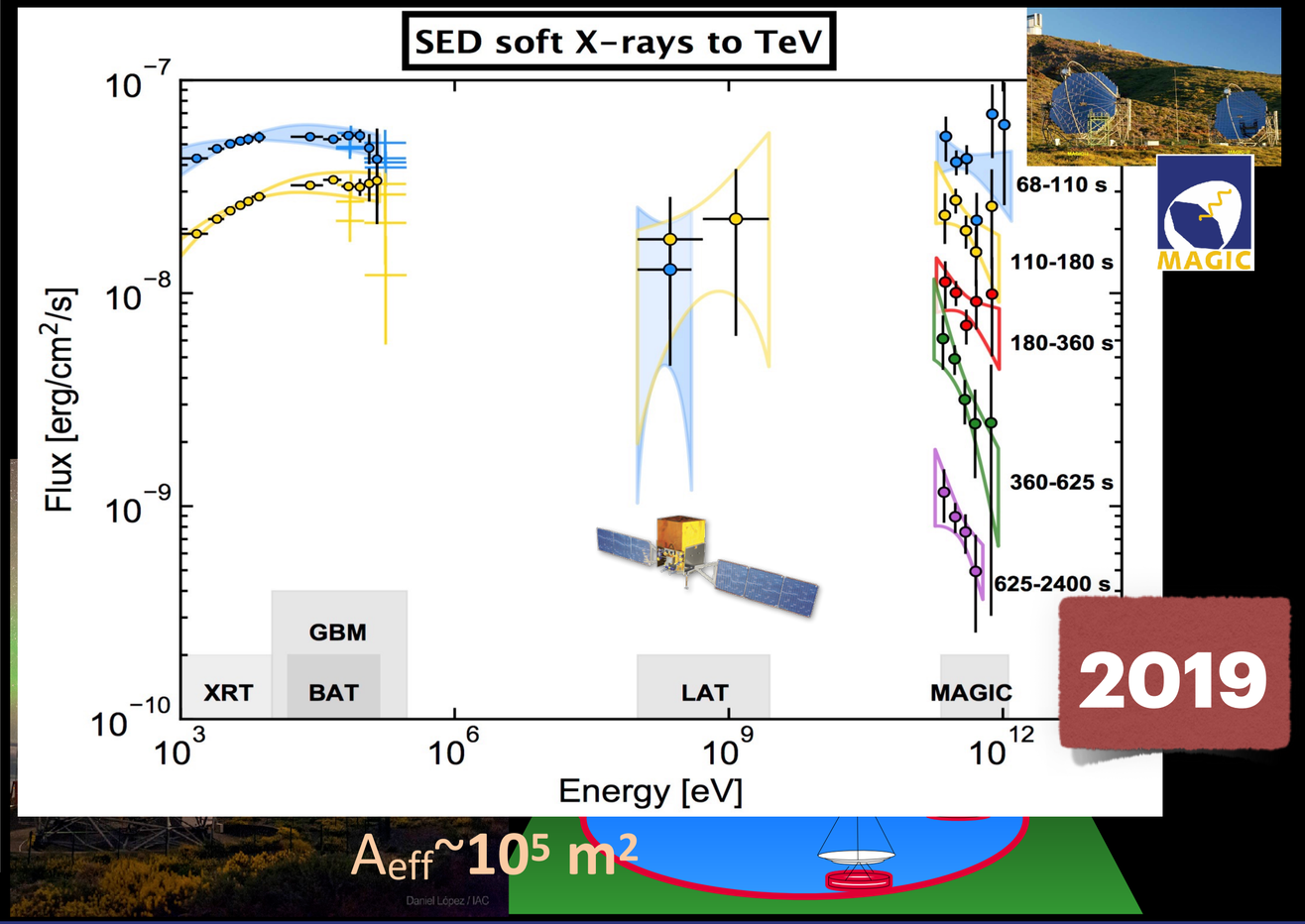


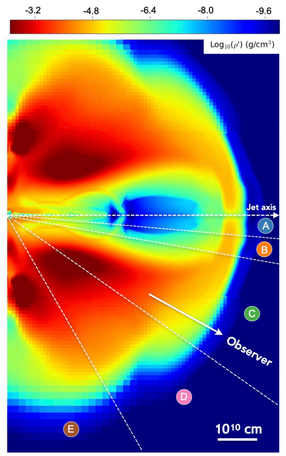
The Role of Off-axis Observations and structured Jet

GeV-TeV emission is expected from the relativistic outflow (structured jets)

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

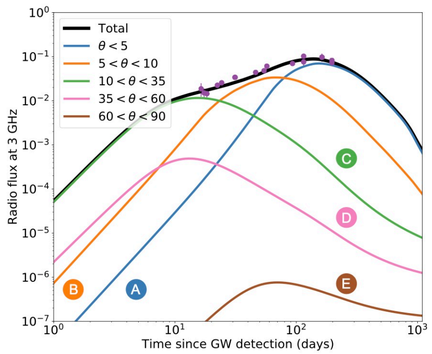
- intensity <u>weaker</u> 10^{-4} to 10^{-6} times than on-axis emission
- light curve <u>delayed</u> (hours/days/months, depending on θ_{view} and jet structure)

Jet profile

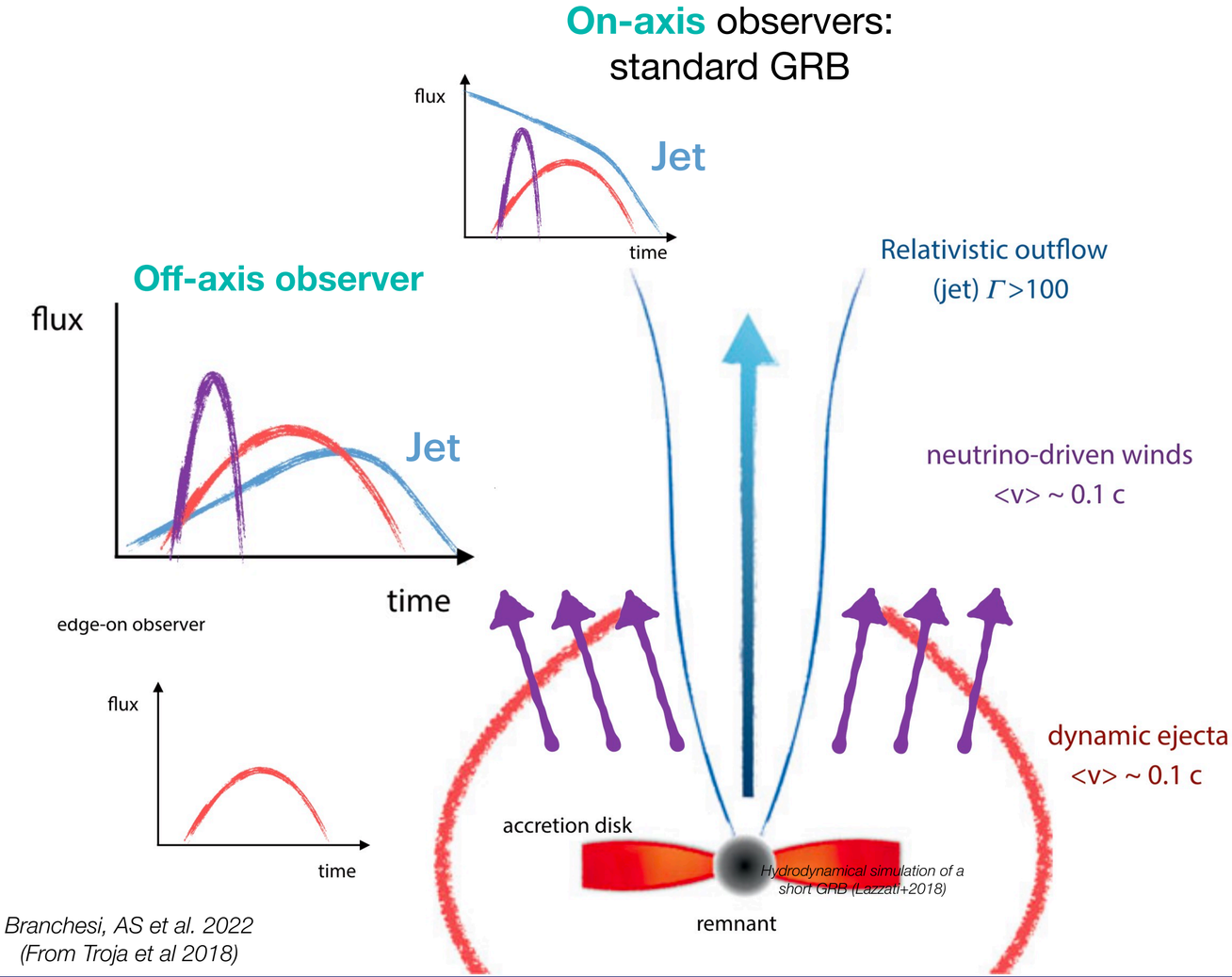


Hydrodynamical simulation of a short GRB (Lazzati+2018)

Off-axis observer and STRUCTURED JET



What do we expect in the TeV band?



Branchesi, AS et al. 2022
(From Troja et al 2018)

CTAO

GOALS

Compute the joint GW and CTAO detection rates from binary neutron star (BNS) mergers associated to GRBs (GW-GRBs)

Optimise the observing strategy

- Maximise the detection rate
- Maximise the physical interpretation return
- Evaluate the amount of observing time

Explore the parameter space of the GW-GRBs detectable by CTAO

- Physical parameters (luminosity, jet opening angles and jet orientation, spectral slope)
- Observational parameters (time delays, exposures)

A Dedicated Study on the CTAO's Prospects on GW follow-ups in an evolved multi-messenger scenario on GWs and TeV-GRBs.

Chasing Gamma-Ray Signals from Binary Neutron Star Coalescenses with the Cherenkov Telescope Array: Prospects and Observing Strategies

Being submitted!

Abstract

The detection of gravitational waves (GWs) from a binary neutron st… and the identification of its electromagnetic counterparts, heralded the b… wave and electromagnetic detections. The intensive follow-up campaign contrib… of the progenitor and its environment. The joint detection of the short GRB 170817A observed by Fermi-GBM and INTEGRAL, together with the VLBI observation of the successful jet, provided the first direct evidence that at least a fraction of BNSs are progenitors of short GRBs. Short GRBs are also expected to emit TeV photons and upper limits have been set with observations performed by ground-based gamma-ray detectors and during the intense electromagnetic follow-up campaign associated with GW170817/GRB 170817A. In the next years, the searches for TeV counterparts will become more effective thanks to the Cherenkov Telescope Array Observatory (CTAO): this instrument will be fundamental for the follow-up of transient GW events at VHE, owing to its unprecedented sensitivity, rapid response and capability to monitor large sky areas via survey-mode operation. The aims of this work are the optimisation of the follow-up strategy with CTAO and a reliable assessment of CTAO capabilities in detecting the TeV emission from GW counterparts in different observing conditions, as well as the evaluation of the expected rate of joint GW-GRB detections with CTAO during Observing run O5. The study presented uses a public, simulated sample of BNS systems, together with the corresponding GW detection during the last inspiraling cycles and merger phase and the 3D sky localisation. The sky position, distance and orientation of the sample of GW-detectable BNSs are used in the subsequent stages. Assuming the correspondence between the BNS merger and the emergence of a short GRB, the gamma-ray emission is simulated using a set of phenomenological prescriptions based on the observed population of short GRBs. The possibility of observing the emission from an off-axis jet is introduced with basic prescriptions on the jet morphology and structure. The response of CTAO to the derived set of spectral and temporal templates is then simulated. The observation with the CTAO is considered with different observing conditions and parameters. The initial uncertainty on the location of the electromagnetic counterpart requires a scan of the GW skymap and hence the definition of a selection strategy of the fields to be observed. Different strategies based on the optimization of a sequence of snapshots with variable and constant integration time are investigated. Among the key results we find that about 3% of simulated GW-associated short gamma-ray bursts produce GeV–TeV radiation detectable by CTAO. Real-time analysis and rapid follow-up are crucial, as the likelihood of detection drops sharply beyond 1–4 hours after the GW event. A 5-minute exposure time per sky tile offers an effective balance between coverage and detection probability. Detectability is strongly influenced by the jet opening angle and viewing angle, suggesting that even rough estimates of the viewing angle in GW alerts could enhance targeting. The simulation framework presented in this work serves as a basis for future studies of scientific scenarios involving GW and gamma-ray signals, including neutron star-black hole mergers, advanced strategies incorporating galaxy distributions, and future detectors such as Einstein Telescope.

Keywords: keyword 1, keyword 2, keyword 3, keyword 4

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METHODS

Simulation of BNS mergers and GW signal in local universe

Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Simulation of CTAO response (set of IRFs)

Observation optimisation and scheduler
CTAO observing strategy

A long journey and a complex construction of a full chain of simulations, from the GW event up to the CTAO response and scheduling.

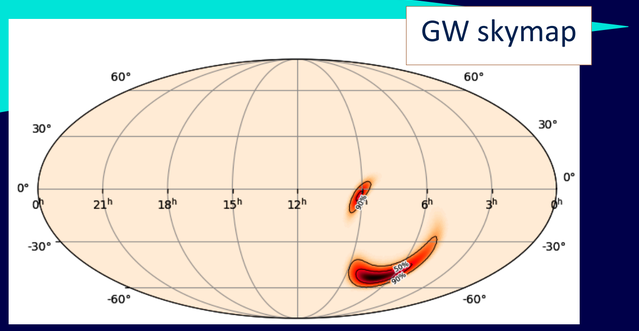
Simulation chain

Simulation of BNS mergers and GW signal in local universe

Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Simulation of CTAO response (set of IRFs)

Observation optimisation and scheduler
CTAO observing strategy



Gravitational wave catalogue of simulated binary neutron star (BNS) mergers from *Petrov et al. 2022 for O5*

Simulation chain

Simulation of BNS mergers and GW signal in local universe

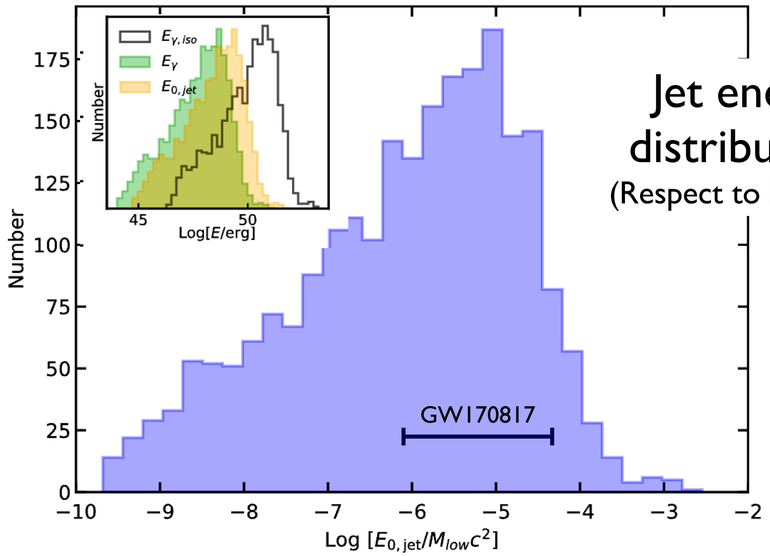
Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

Phenomenological simulation of afterglow emission from short GRBs.

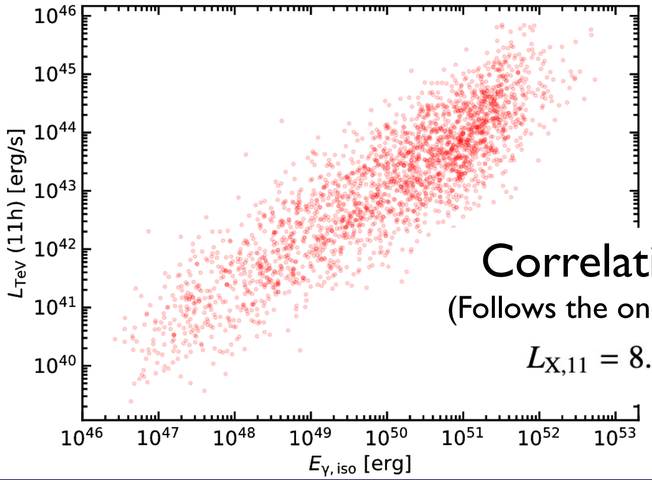
- **Jet opening angle** inferred from short-GRBs seen on-axis, average:~14deg
- **Viewing angle** from the inclination of the BNS
- **Lightcurve**: follows deceleration phase + similar temporal decay as in X-rays
- **Spectrum**: Photon index ~-2; Density of the external medium ~0.1 cm^{-3}
- **Jet structure:** Gaussian distribution for both energy and Lorentz factor

CTAO observing strategy

Consistency checks



Jet energy distributions
(Respect to NS mass)

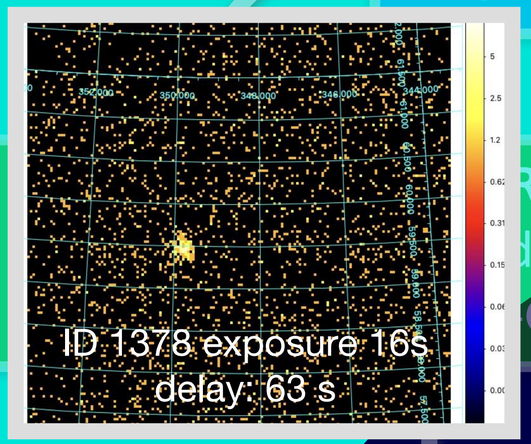


Correlation L_{TeV}-E_{ISO}
(Follows the one observed in X-ray)

$$L_{X,11} = 8.5 \times 10^{43} E_{iso,51}^{0.83}\ erg\ s^{-1}$$

Simulation chain

Simulation of BNS mergers and GW signal in local universe



Credit: Fabio Pintore, gammapy

- Computation of CTAO sensitivity tailored on the GW-GRB models, including EBL absorption
- CTAO Alpha configuration

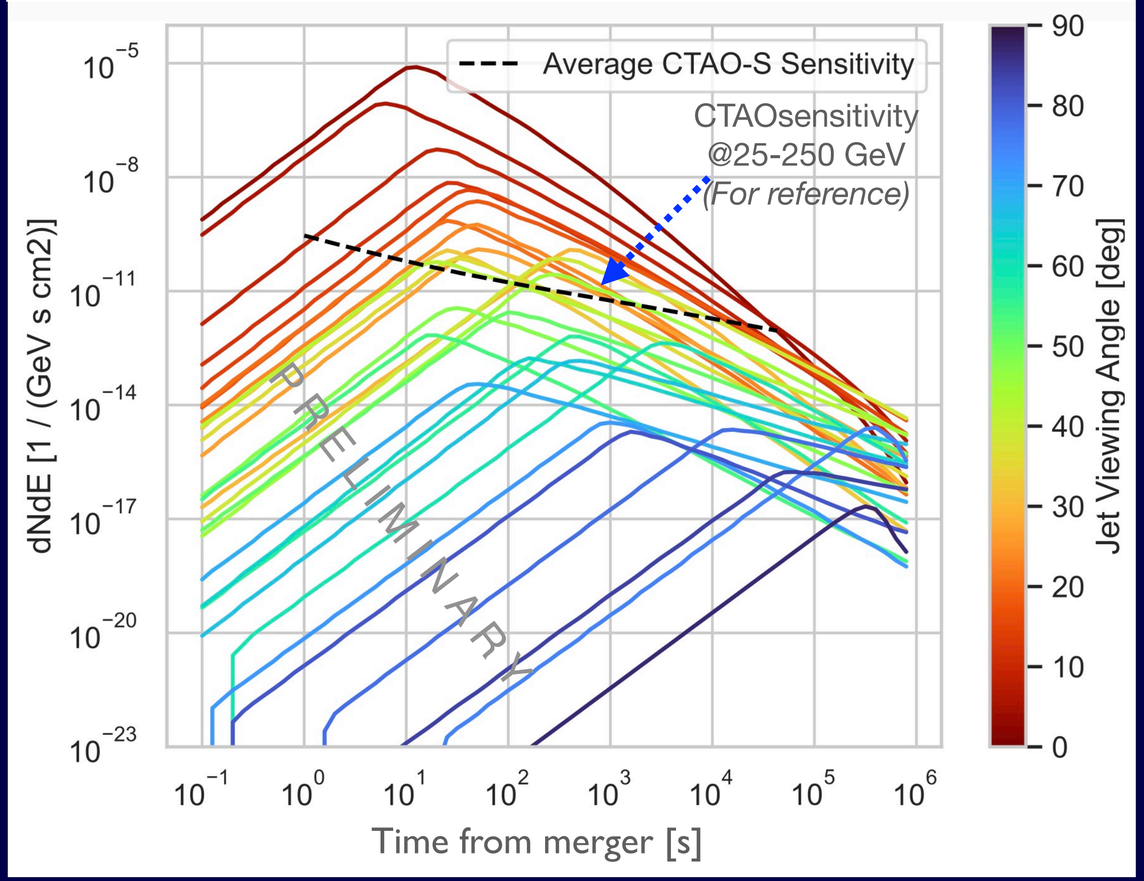
Simulation of CTAO response (set of IRFs*)

* **IRF: Instrument Response Function**

Observation o… and sche… CTAO observi…

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

Afterglow light curves as seen from various viewing angles



Simulation chain

Simulation of BNS mergers and GW signal in local universe

Synthetic GW-GRBs
Phenomenological model of VHE emission of short-GRB

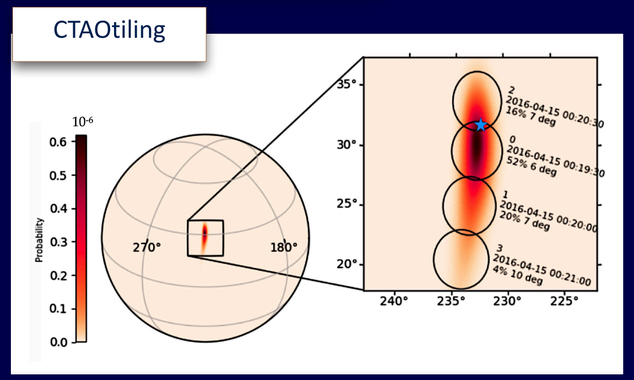
Simulation of CTAO response (set of IRFs)

Observation optimisation and scheduler
CTAO observing strategy

- Realistic observing conditions for CTAO are considered (*Seglar-Arroyo et al. 2019*)
- Based on Tilepy code (*M. Seglar-Arroyo et al. - APJS - 2024*)

Observing strategy:

- *Optimal*: Scheduler iterates on the best visible positions, with increasing, sensitivity-dependent, exposures. If the true source position is covered, by construction, it is detected.
- *Fixed:* Tiling with fixed exposures (1, 5, 20 min)

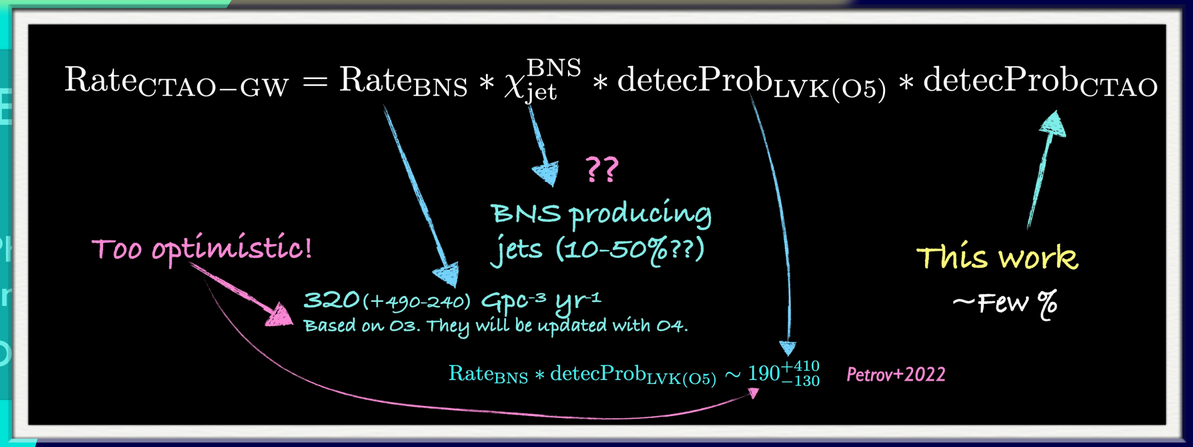


Results

Compute the joint GW and CTAO detection rates from binary neutron star (BNS) mergers associated to GRBs (GW-GRBs)

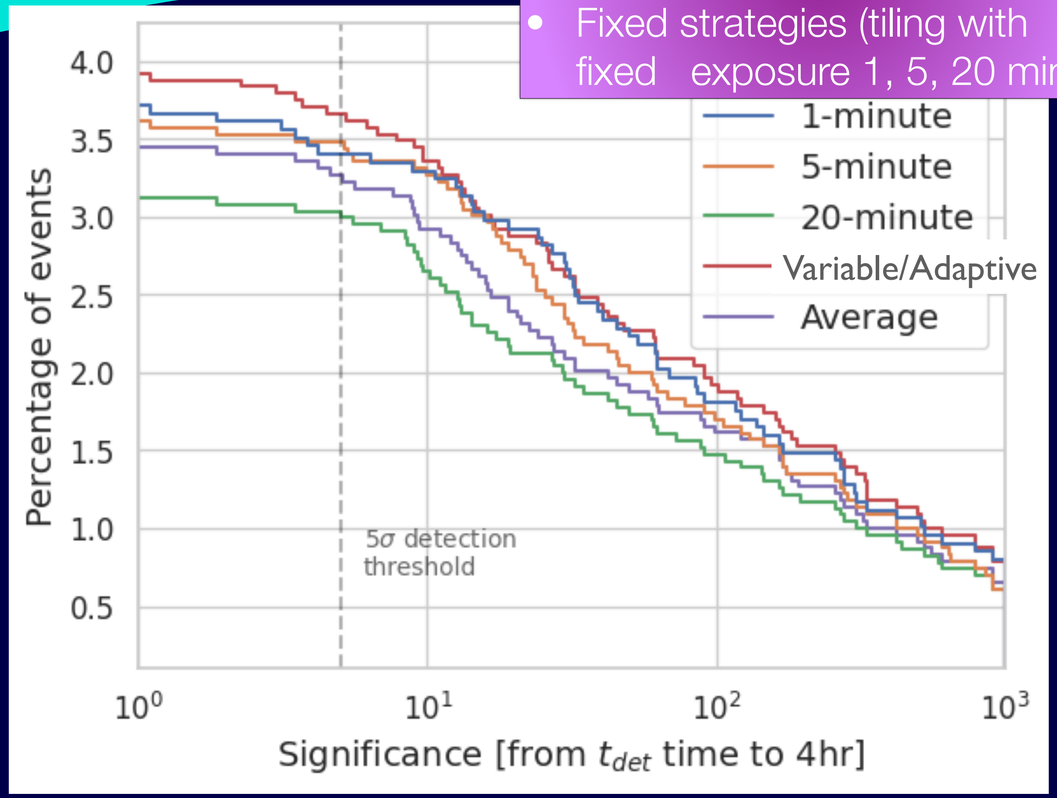
Optimise the observing strategy

- Maximise the detection rate
- Maximise the physical interpretation return
- Evaluate the amount of observing time



Observing strategies:

- ✓ Optimal (adaptive) exposure
- • Fixed strategies (tiling with fixed exposure 1, 5, 20 min)



~3-4% of the sampled BNS mergers are detectable.
Expected yearly rate depends greatly on the **BNS rate** (*largely uncertain!*)

Results

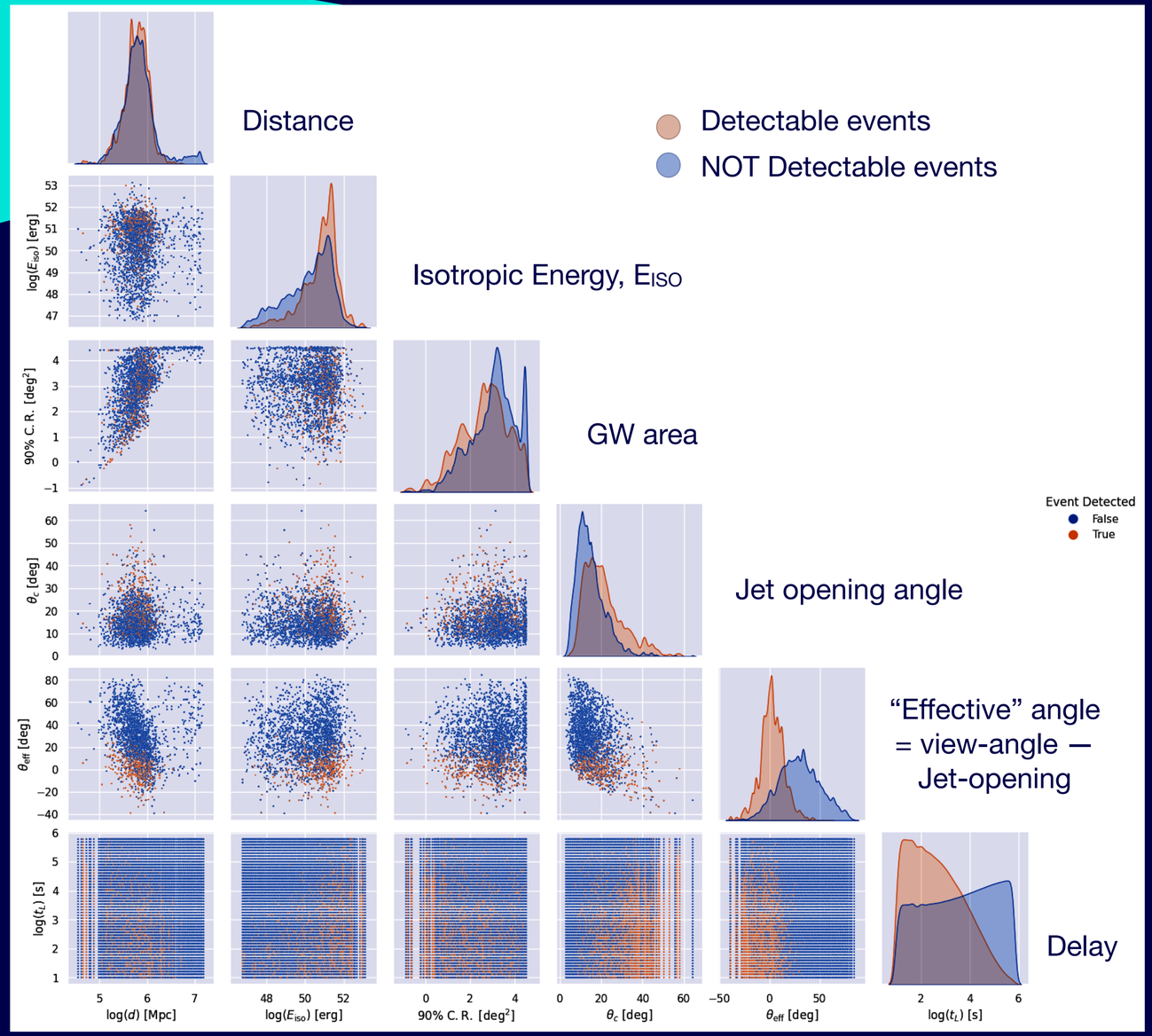
Compute the joint GW and CTAO detection rates from binary neutron star (BNS) mergers associated to GRBs (GW-GRBs)

Optimise the observing strategy

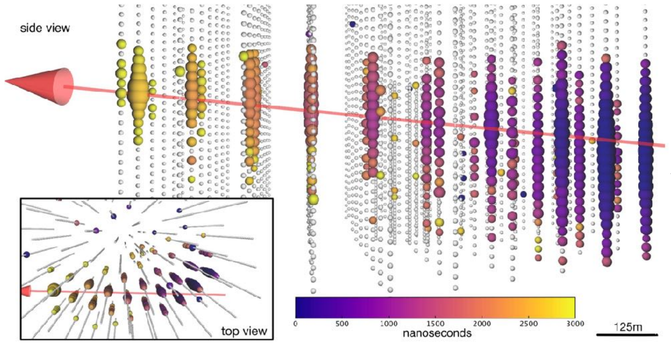
- Maximise the detection rate
- Maximise the physical interpretation return
- Evaluate the amount of observing time

Explore the parameter space of the GW-GRBs detectable by CTAO

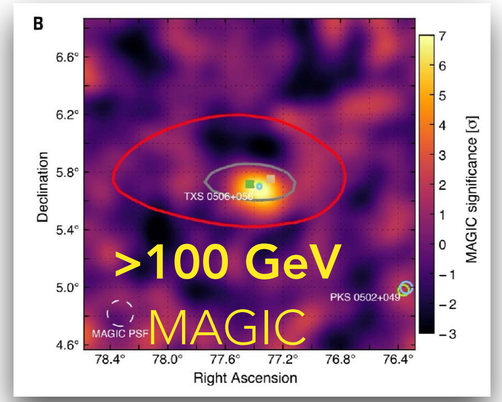
- Physical parameters (luminosity, jet opening angles and jet orientation) and other (GW area, distance)
- Observational parameters (time delays, exposures)



Constraining the neutrino sources with Cherenkov telescopes

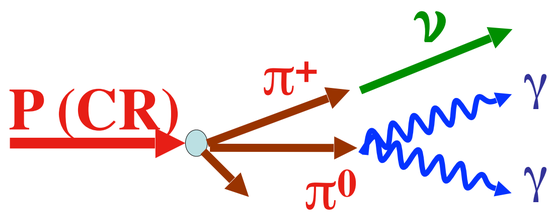


TXS0506+056 associated to IC170922A At 3σ level

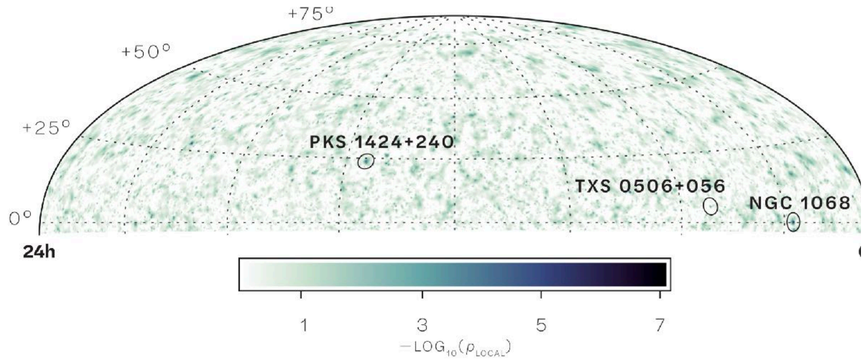


Science 361, eaat1378 (2018)

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

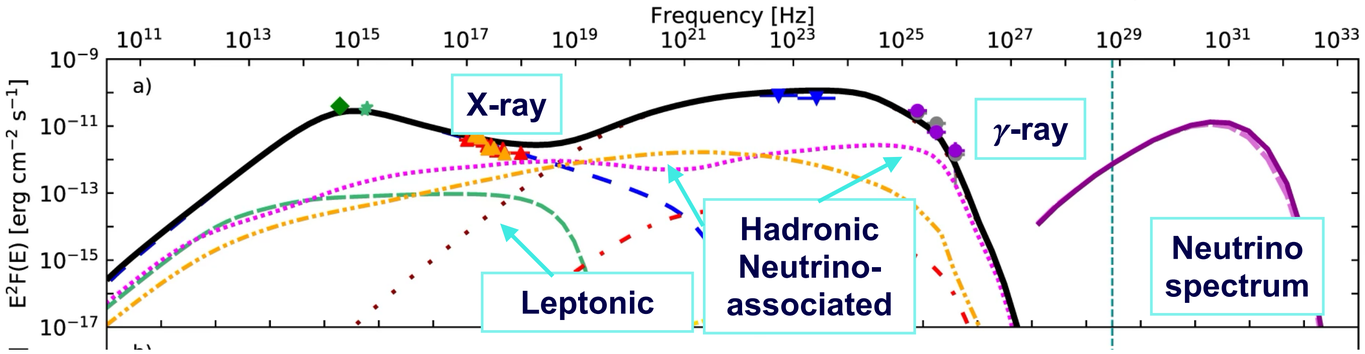


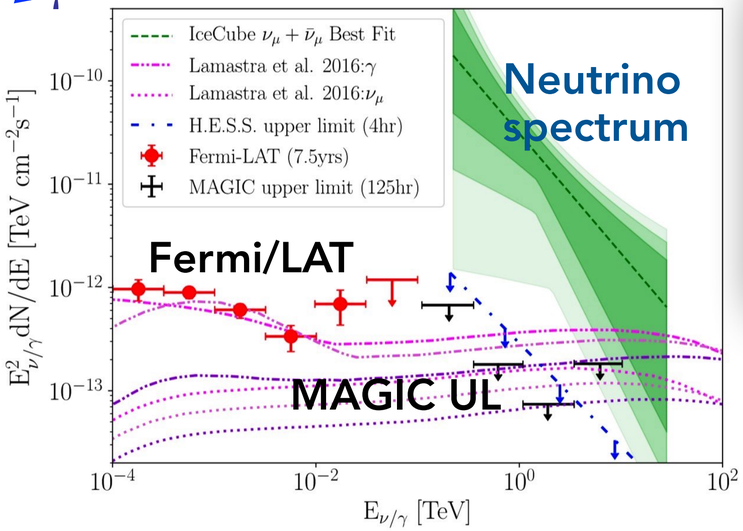
NGC1068 first evidence of neutrino emission from a AGN

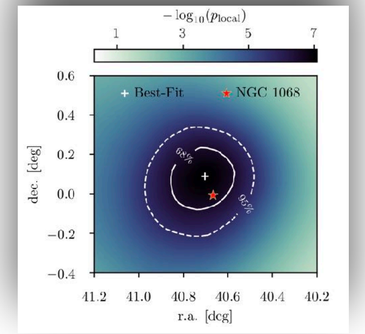


Icecube coll., 2022 Science 378

MAGIC Coll., ApJL, 863 (2018) L10



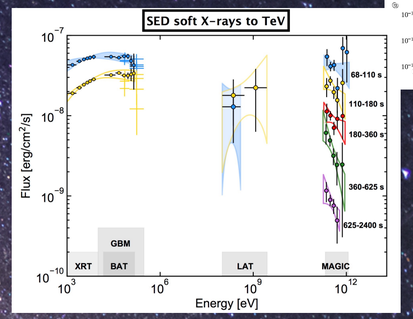


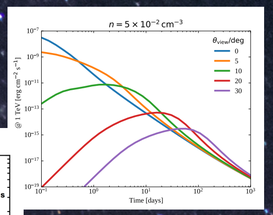


*V. A. Acciari et al 2019 ApJ **883** 135*

Open questions in the MM field at TeV energies - **GRB/GW**

- **Do all GRB exhibits a second high-energy component (Gev-TeV)?** 🥰
- **Is this component significant or even dominant, as observed in GRB 190114C and GRB221009A? Under what conditions?**
- **What is the connection between this emission and the GRB progenitor or its environment?**
- **Is SSC the dominant emission mechanism? What roles do external Compton, pure synchrotron, or hadronic processes play?**
- **Next observational breakthrough: unambigous TeV detection from short-GRB! GW (BNS)! NS-BH and BBH still uncharted territory…** *(see upcoming LST-Magic paper on followup of 2 BBH events)*
- **Which observational strategies in the TeV band are best suited for detecting GW counterparts?**



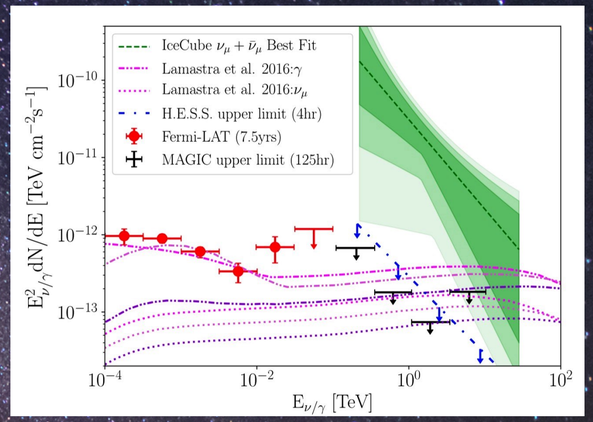


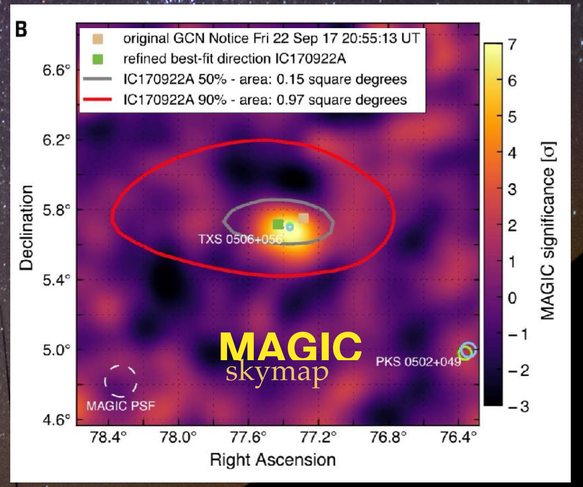
TeV observations can:

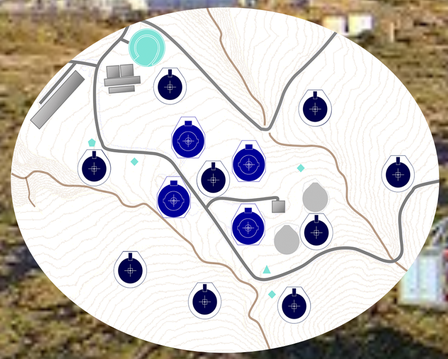
- ✓ **Clarify the structure of the environment (density, winds)**
- ✓ **Better constrain SED modeling and parameters**
- ✓ **Identify/discard dominant emission processes in afterglow**
- ✓ **Identify and shed light on the prompt emission physics.**

Open questions in the MM field at TeV energies - **neutrinos**

- **Which classes of neutrino sources? Seyfert, blazars (BL-Lac? FSRQ?)?**
- **Which emission region? Corona emission? Base of jet / standing shocks? Outflow winds?**
- **Confirm the physical connection between neutrino and gamma-ray emission and the interplay with the environment.**
- **Identify TeV hadronic-driven emission processes in the observed SED**
- **Which models? How to better constraint their parameters? Needs precision and MWL measurements.**

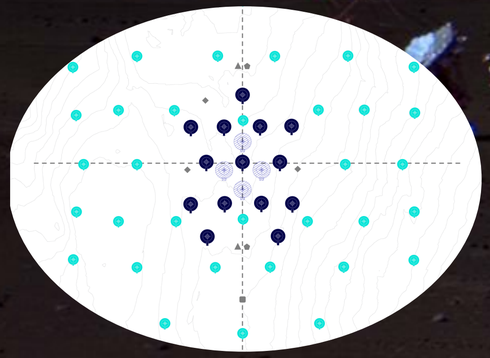




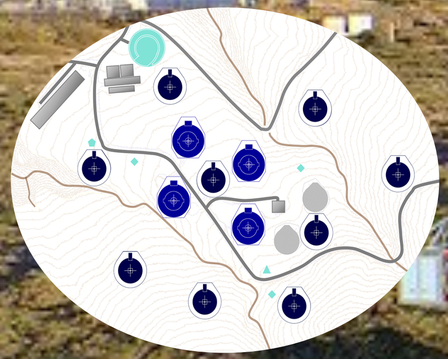


Northern site: La Palma
13 telescopes: 4 Large, 9 Medium

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



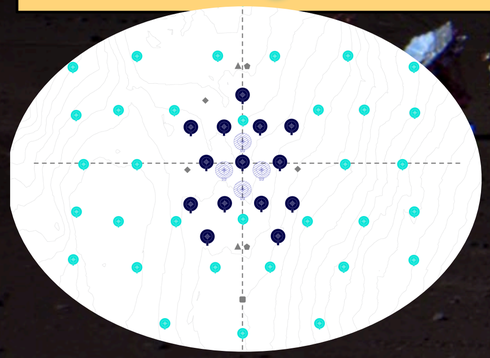
Alpha configuration



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

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

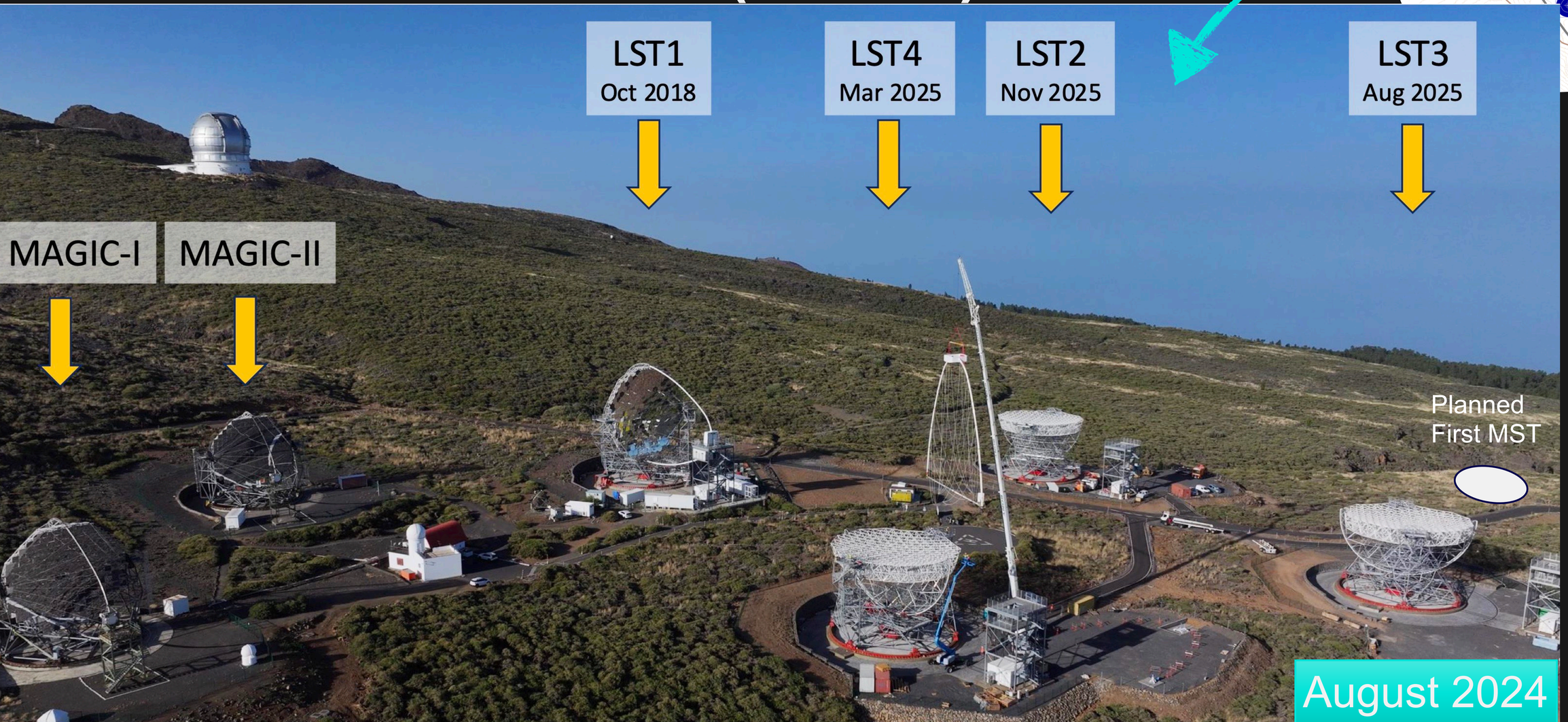
+ 2 Large + 5 SST*



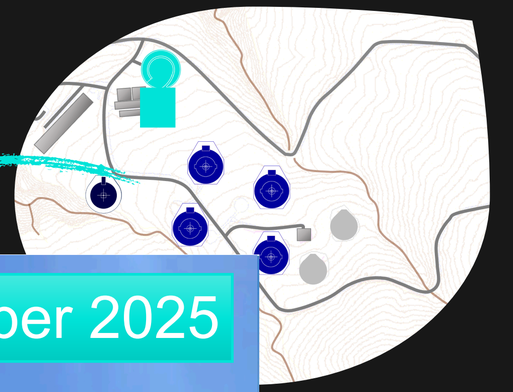
*CTA+ Italian project NRRP

Improved Alpha configuration

CTAO North (LST)



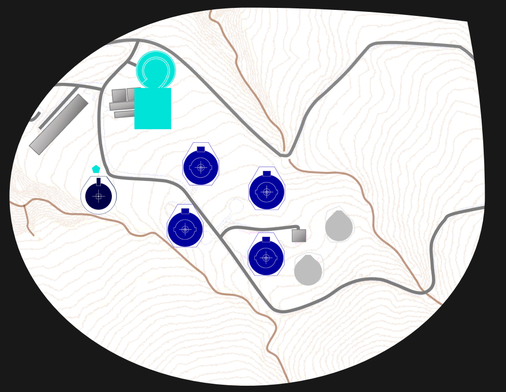
CTAO North (LST)



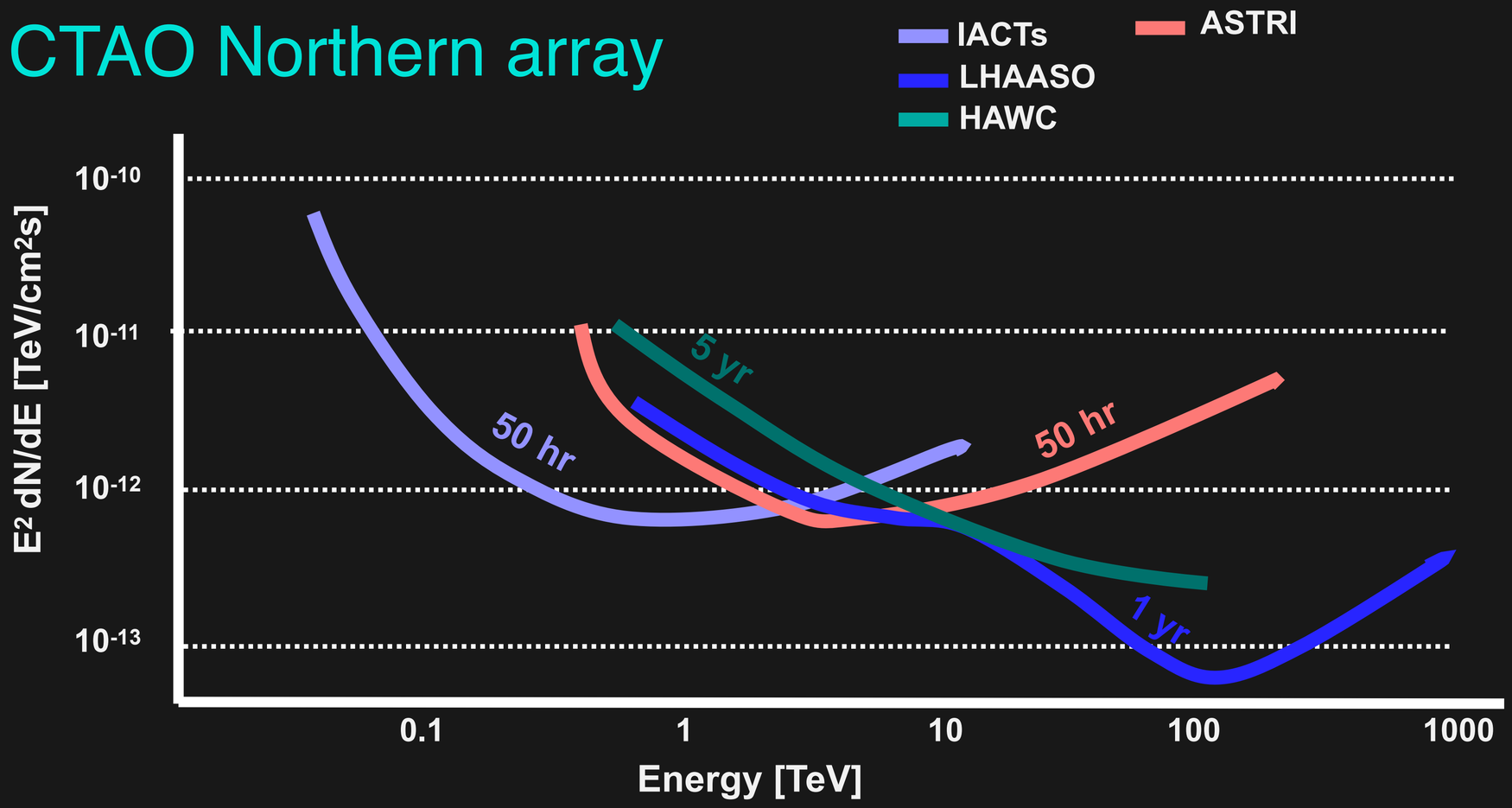
September 2025

Starting the commissioning phase
2027-2028 early science

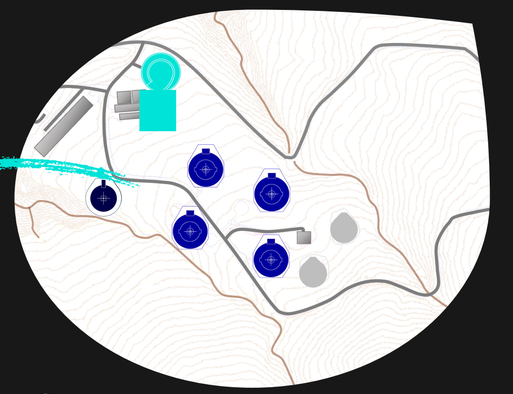
The current landscape



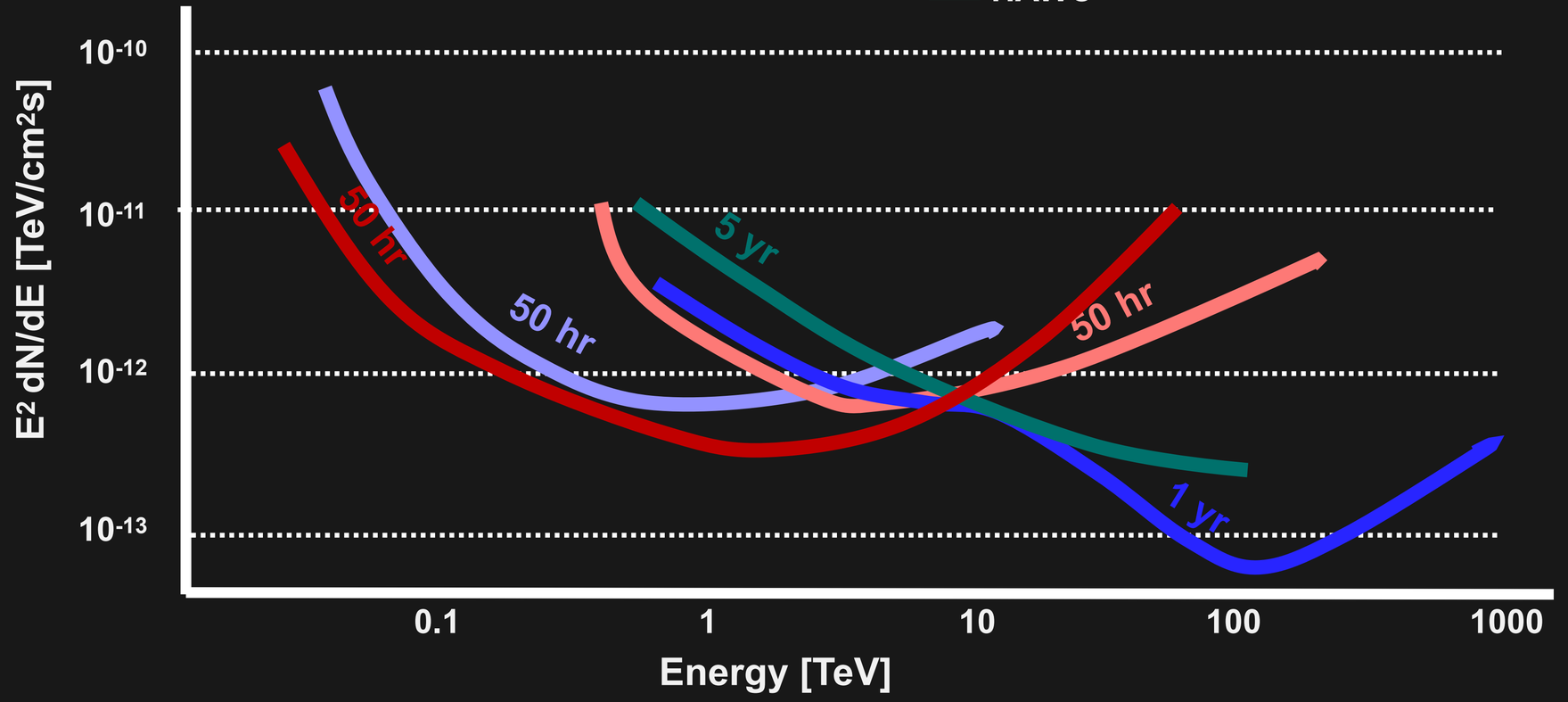
CTAO Northern array



In 3 years from now



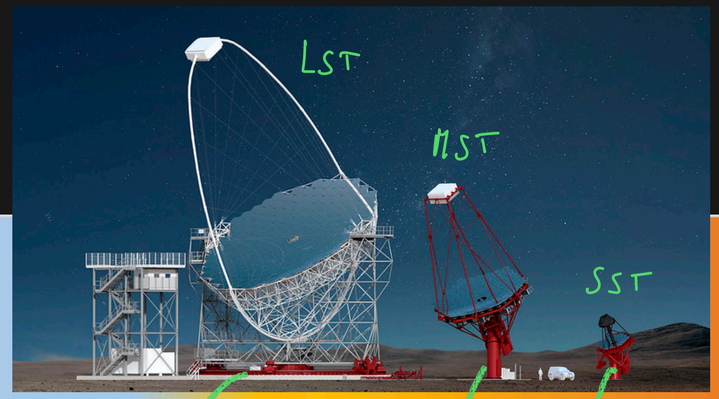
CTAO Northern array

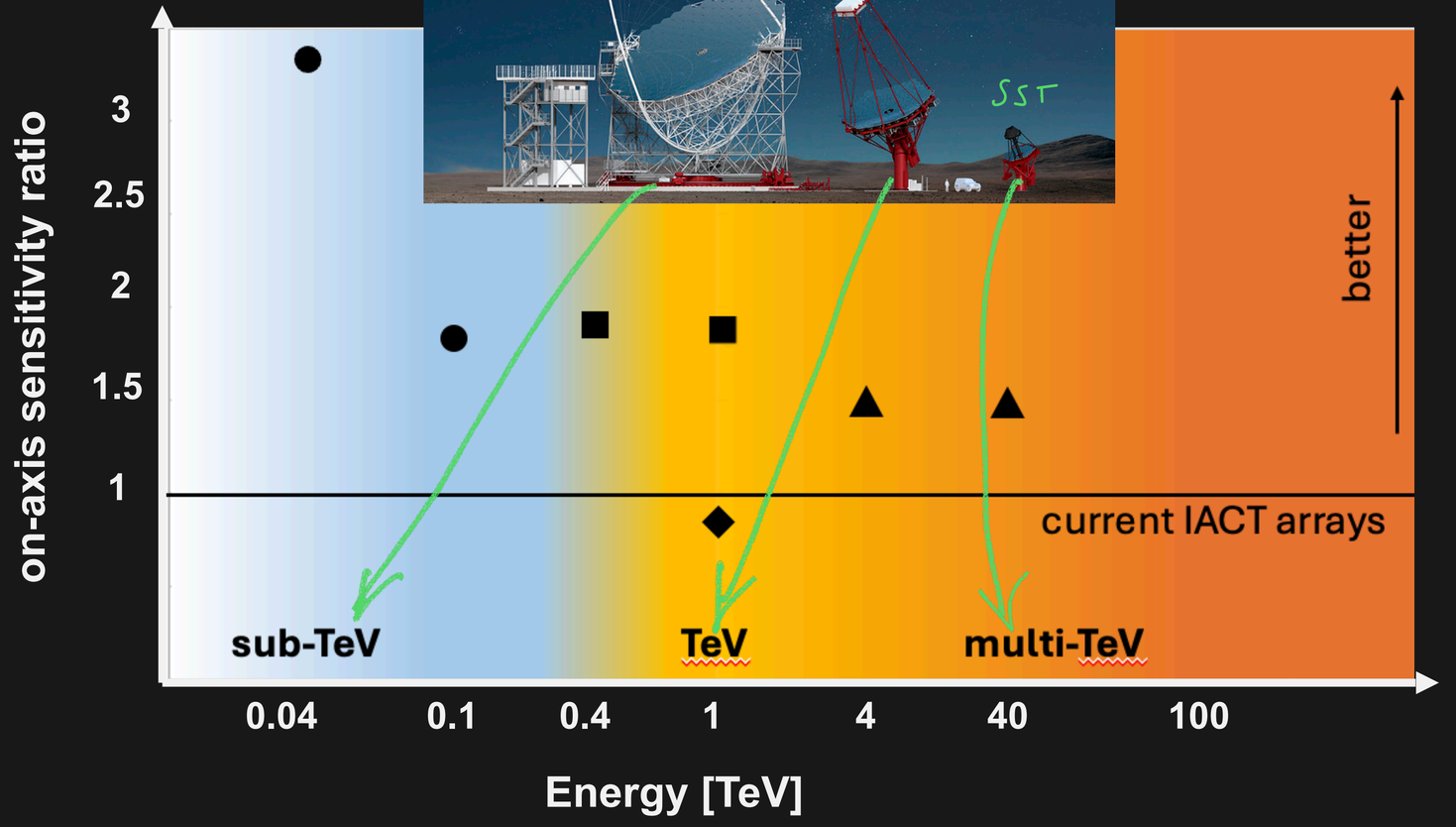


With respect to current IACT arrays:

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

When will the scientific impact begin?





Intermediate arrays

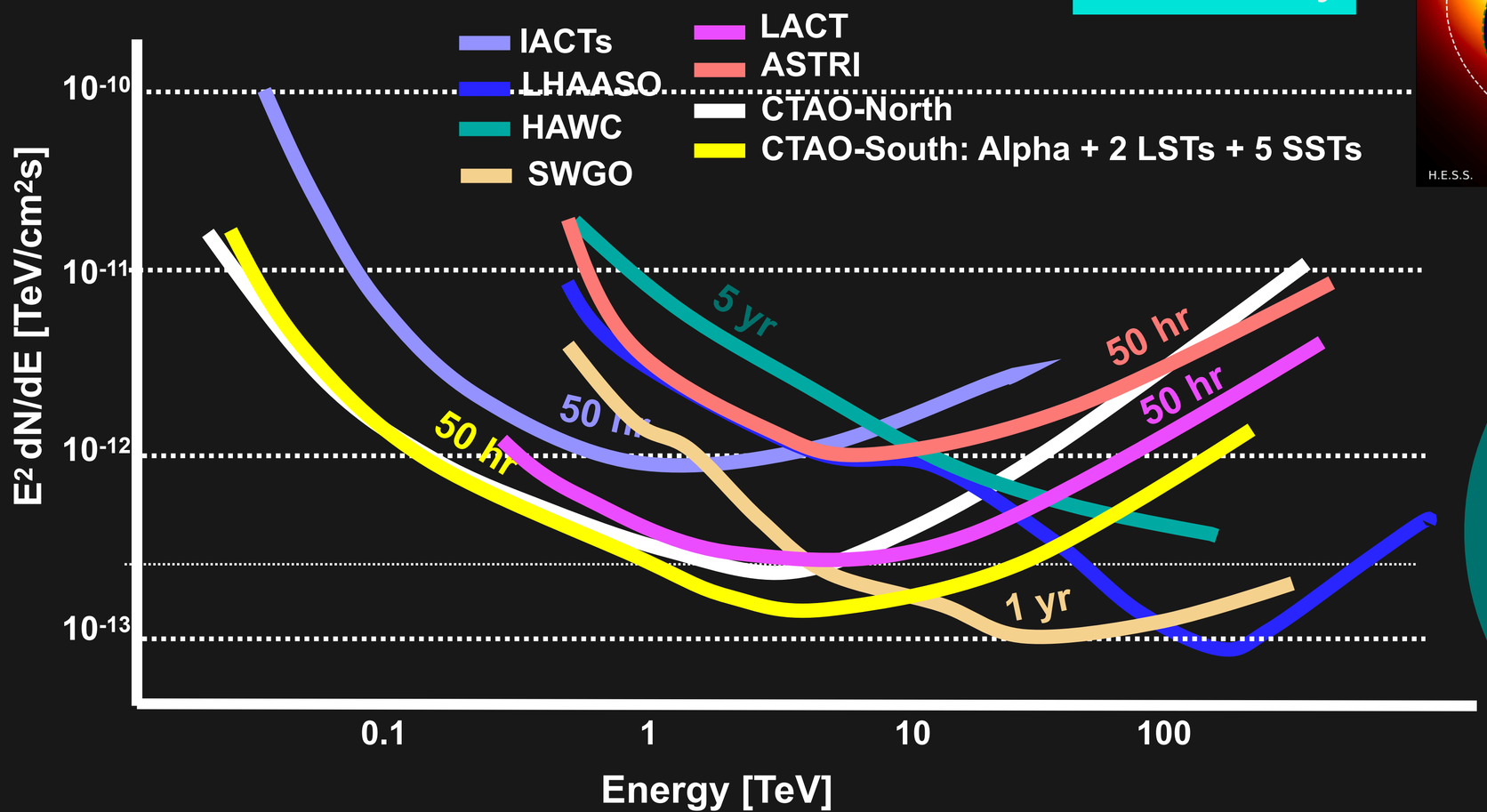
- 2 LST
- 2 LST + 1 MST
- 1 MST + 5 SST
- 5 SST

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

The full CTAO array
improved alpha configuration

Full sky

Sensitivity



Angular resolution

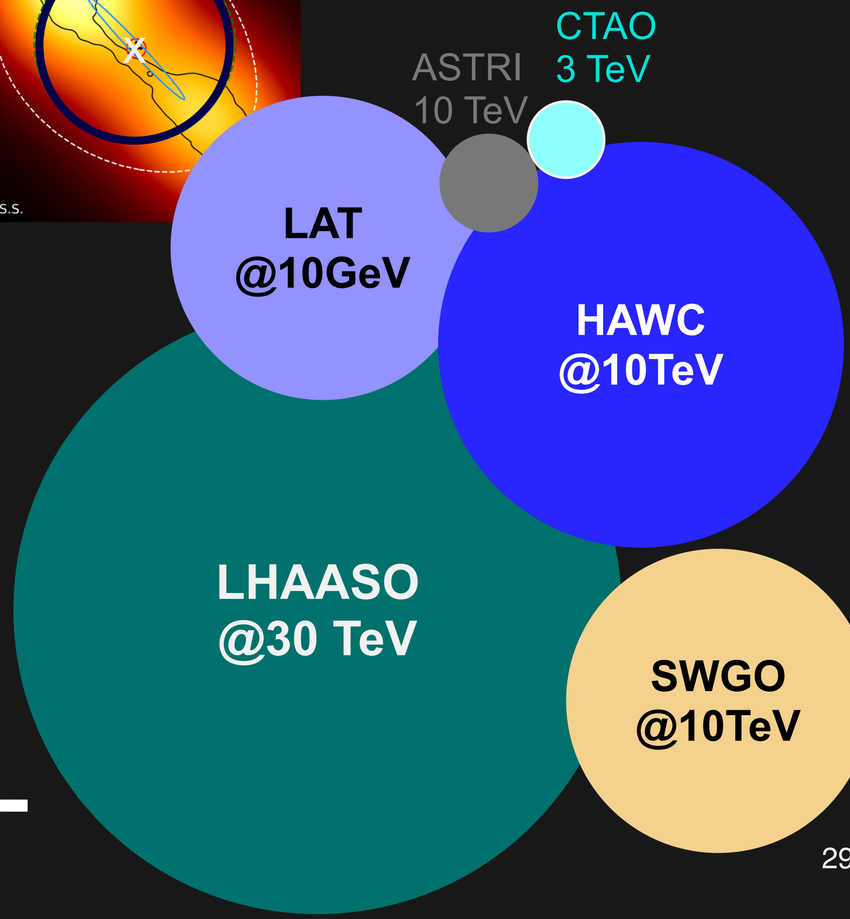
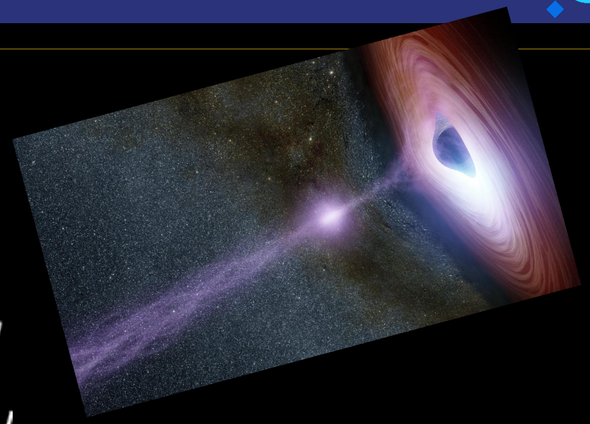


Image Cherenkov telescopes (IACT) as ideal transient detectors

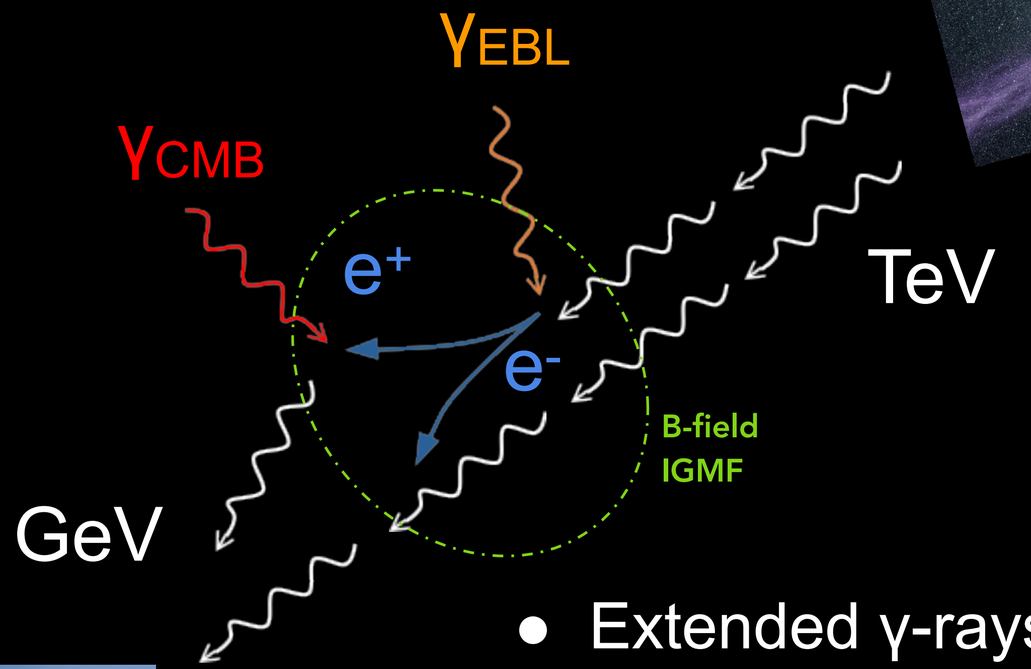
Imprint of IGMF on the GeV-TeV gamma rays



Excess at lower energies

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

Neronov et al. 2009

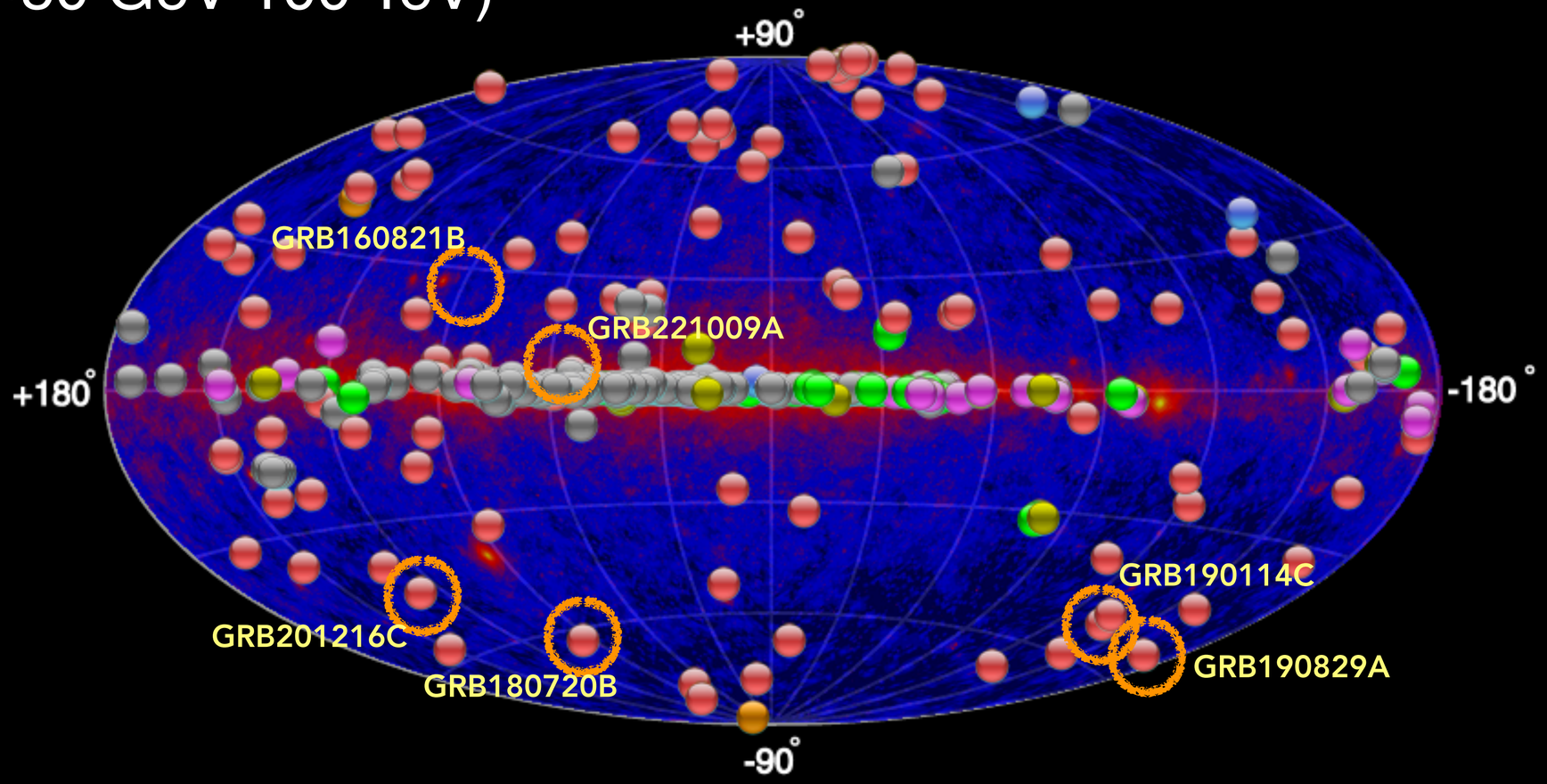


Indirect detection of the IGMF

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

Credit: Paolo Da Vela - INAF Bologna

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 FR FSRQ Blaza 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

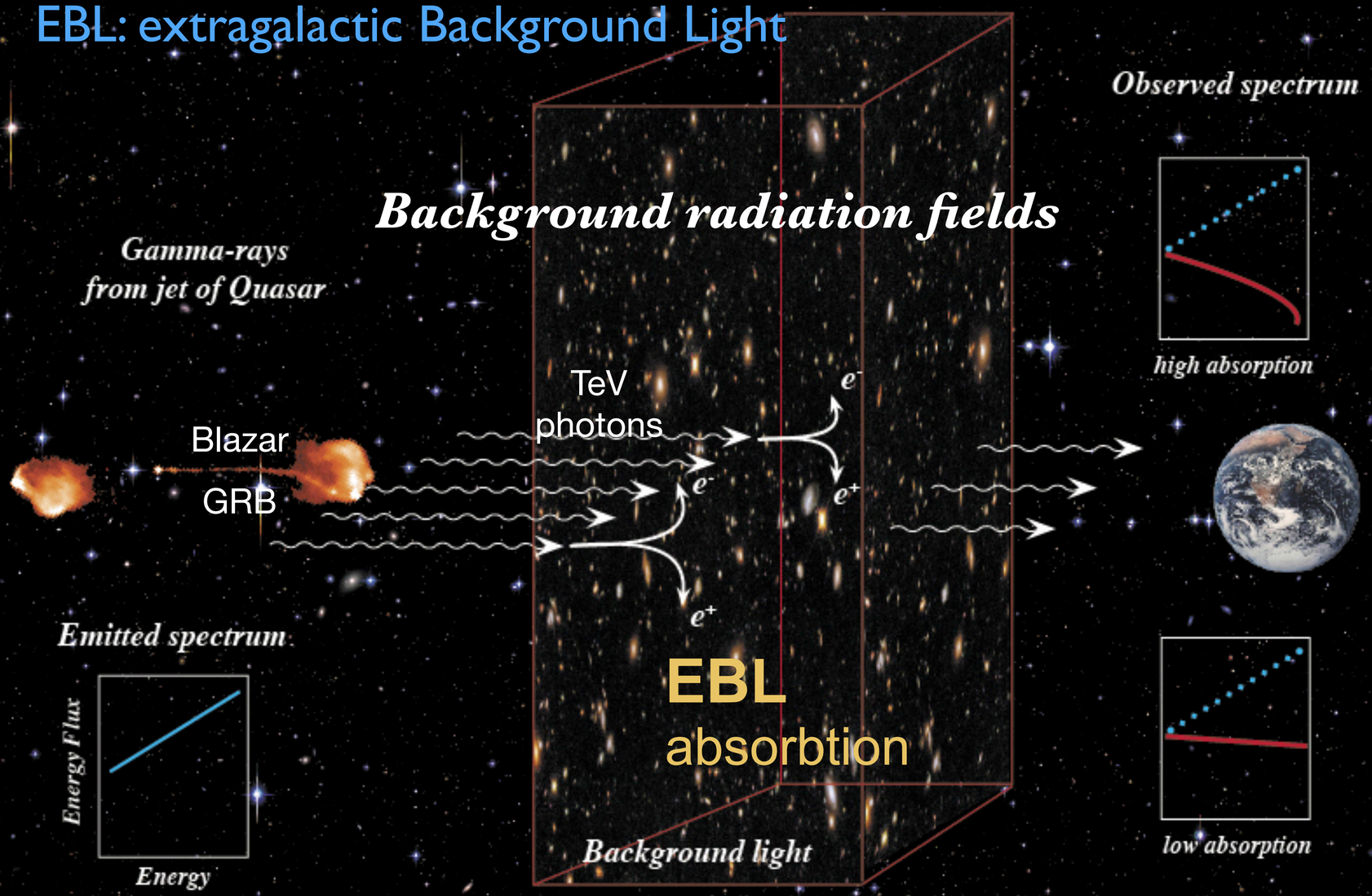
93 are AGN-blazars/radiogalaxies

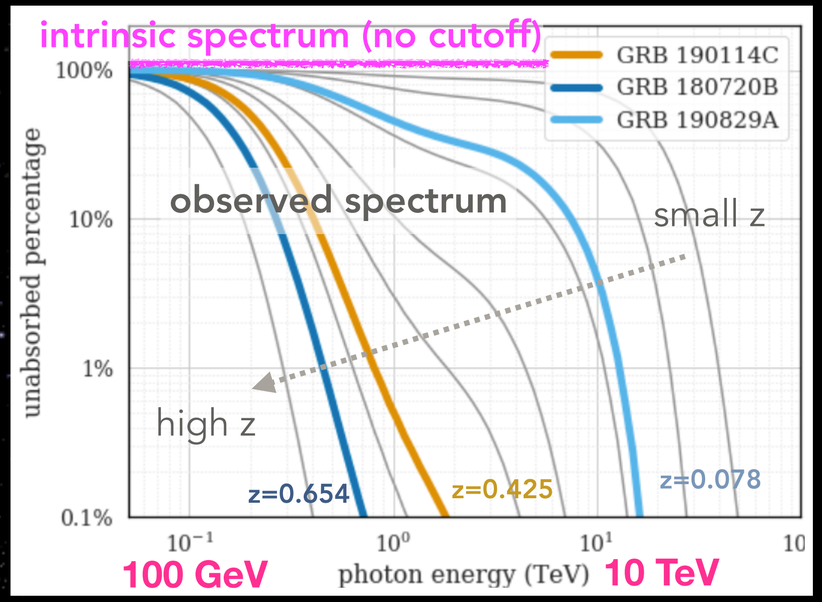
5 Gamma-RAY Burst GRB

http://tevcat.uchicago.edu

EBL absorption of TeV photons

EBL: extragalactic Background Light





Adapted from E. Pueschel, ICRC2017

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

opacity

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