Chasing Gravitational Waves with the Cherenkov Telescope Array

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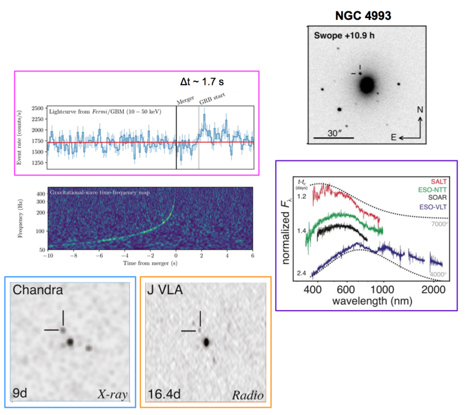
August 17, 2017: the beginning of multi-messenger astronomy with GWs

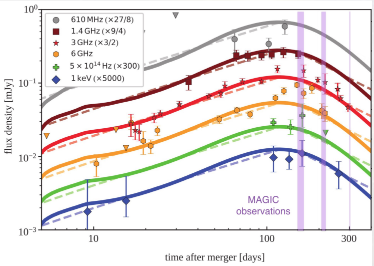


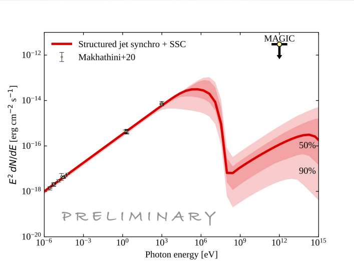
- Coincident short GRBs detected in gamma rays ⇒ first direct evidence that at least some **BNS mergers are progenitors of short GRBs**
- An optical/infrared/UV counterpart has been detected ⇒ first spectroscopic **identification of a kilonova**
- An X-ray and a radio counterparts have been identified ⇒ off-axis afterglow from a **structured jet**
- No significant emission has been found at HE ($E > 100$ MeV) and VHE ($E > 100$ GeV)

Abbott et al., ApJ Letters, 848, 2 (2017) and refs. therein

HE and VHE EM follow-up of GW170817

- *Fermi*-LAT was entering the SAA at the time of the GW trigger; no significant HE EM counterpart was detected at later times (Ajello et al. 2018, ApJ, 861, 85)
- H.E.S.S. performed prompt and long term EM follow-up; no significant VHE emission has been found (Abdalla et al. 2017, ApJL, 850, 22; Abdalla et al 2020 ApJL 894 L16)
- MAGIC follow-up observations were performed for a total amount of $\sim$ 9.5 hrs in 10 different nights from January to June 2018; no significant VHE emission has been found (Stamerra, Patricelli et al. 2021, PoS(ICRC2021)944)





Do GRBs have VHE emission?

The first observations of GRBs at VHE with IACTs have been reported starting from 2019:

- GRB 190114C, GRB 160821B, GRB 201216C and GRB 201015A (MAGIC - Acciari et al. 2019, 2021; Abe et al. 2024, Blanch et al. 2020)
- GRB 180720B and GRB 190829A (H.E.S.S. - Abdalla et al. 2019, 2021)
- GRB 221009A (LHAASO - Cao et al. 2023; see also Aharonian et al. 2023 for H.E.S.S.)

Several open questions:

- Which conditions are required to produce the VHE GRB emission? How common are they?
- Do BNS and NS-BH mergers have a VHE EM counterparts?
- Is the VHE emission dependent on the progenitor system (binary mergers or core collapsing massive stars)?
- How does the VHE emission depend on the environment of the source?

Why joint GW and VHE gamma-ray observations?

- The search for GRBs at VHE can take great advantage of the GW alerts:

  Current GW detectors are all-sky observatories for low redshift events $\Rightarrow$ the associated VHE radiation is not expected to be severely attenuated by EBL

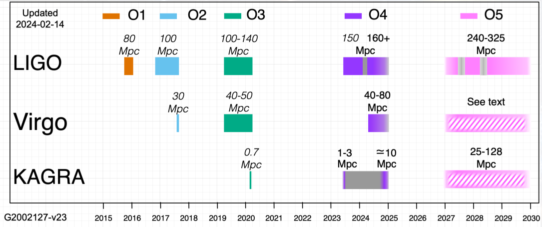
- At the same time, the search for EM counterparts to GWs can take advantage of VHE detectors:

  The γ-ray sky is less "crowded" $\Rightarrow$ clearer association of an EM transient to the GW event

Joint GW and VHE detection could:

- Probe that BNS and NS-BH (and possibly BBH) mergers have VHE EM counterparts
- Allow us to better investigate the dependence of the VHE emission from the progenitor system and its environment

LIGO-Virgo-KAGRA observing plans

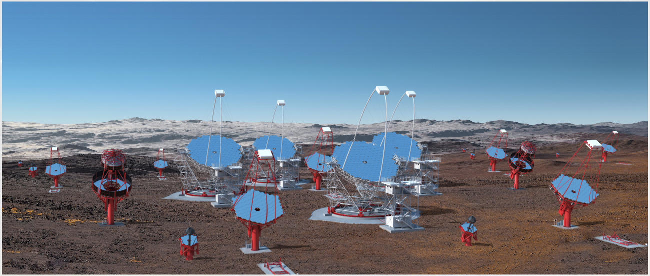


https://observing.docs.ligo.org/plan/

- O4b will run until February 2025
- A fifth observing run (O5) is planned to start in a few years
- O5 matches the timeline of the Cherenkov Telescope Array Observatory

The Cherenkov Telescope Array Observatory (CTAO)

A ground-based observatory for gamma-ray astronomy at very-high energies



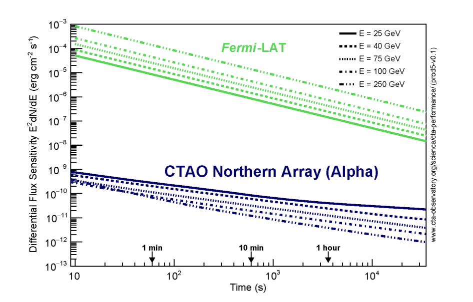
Southern Hemisphere Site Rendering; image credit: Gabriel Prez Diaz, IAC / Marc-Andr Besel, CTAO

- Two arrays: one in the Northern hemisphere (La Palma), one in the Southern hemisphere (Chile) ⇒ **full-sky coverage**
- CTAO Alpha Configuration of the array in the North (South):
  - 4 (0) Large Size Telescopes (LSTs); 20 GeV - 150 GeV
  - 9 (14) Medium Size Telescopes (MSTs); 150 GeV - 5 TeV
  - 0 (37) Small Size Telescopes (SSTs); 5 TeV - 300 TeV

⇒ **wide energy coverage**

Why CTAO?

- Coincident observational schedule with 2nd generation GW detectors at their highest sensitivity
- Large field of view (LST: 4.3 deg)
- Survey mode
- **Rapid response ($\leq$ 30 s) of LST**
- **Very high sensitivity**

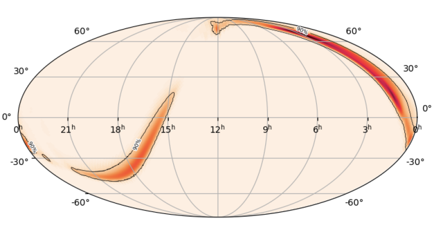


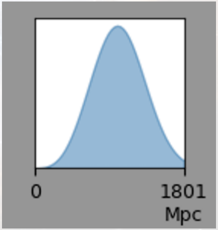
We investigate the capability of CTAO to detect VHE EM counterparts to GWs using detailed simulations of BNS mergers accompanied by short GRBs.

GW simulations

GW catalogs of simulated BNS mergers from Petrov et al. 2022, ApJ, 924, 54

- Homogeneous and isotropic distribution on the binaries in space
- GW detectors at the sensitivity expected for the next observing run (O5), 2 configurations:
  - LIGO-Hanford, LIGO-Livingston, Virgo and KAGRA (O5)
  - LIGO-Hanford, LIGO-Livingston, LIGO-India, Virgo and KAGRA (O6)
- 3D GW sky localization with BAYESTAR (Singer et al. 2016)





Data available in zenodo: O5 and O6

GRB simulations

We assume that all BNS mergers are associated to a short GRB with VHE emission, simulated with a phenomenological approach

- Structured (gaussian) jet

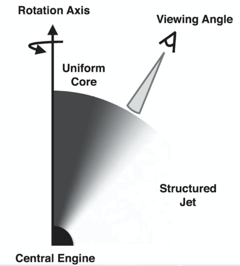


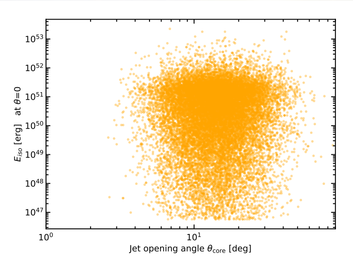
Image from: Abbott et al., ApJ, 848, 13 (2017)

- θ_{core}: distribution inferred from short GRB observations (Fong et al. 2015)
- θ_{view}: given by the orbital inclination of the BNS systems
- Emission received by an observer at θ_{view} estimated following Lamb & Kobayashi 2017, Salmonson 2003

Patricelli et al. 2022, PoS (ICRC2021) 998
Green, Patricelli et al. 2024, PoS (ICRC2023) 1534

GRB simulations

- $E_{\rm iso}$: distribution inferred from short GRB observations (Ghirlanda et al. 2016)



- Light curve: modeled taking into account that temporal decay and luminosity at VHE is similar to that in soft X-ray band
- Spectrum: power-law; photon index: gaussian distribution with μ =-2.2 (consistent with GRB 190114C)

Patricelli et al. 2022, PoS (ICRC2021) 998
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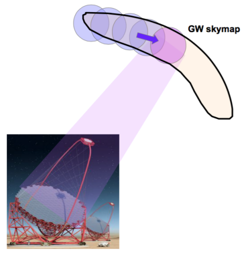
Step 1: GRB detectability

The starting time of the EM follow-up observations typically doesn't coincide with the onset of the GRB emission due to:

- Latency needed to send the GW alert to astronomers ($\sim$ few minutes)
- Telescope slewing time ($\sim$ 30 s for the LSTs)
- Uncertainty in the sky localization of the GW event



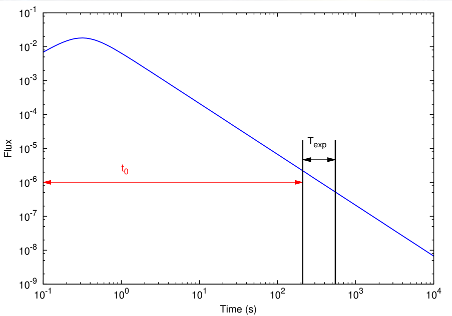
$\Rightarrow$ The exposure time needed to eventually detect the source could vary, depending on the GRB luminosity and the shape of its light curve

We estimate the percentage of GRBs that can be detected by CTAO considering different possible delay times (t_0) and different exposure times ($T_{\rm exp}$)

Step 1: GRB detectability

For each GRB we considered a set of possible values for t_0, then we estimate $T_{\rm exp}$ as the time required to make a 5 σ detection:

$$\int_{t_0}^{t_0+T_{\rm exp}} \mathrm{Flux(t)dt} \geq \mathrm{F}^{\mathrm{s}}_{5\sigma}(\mathrm{T_{exp}}) \qquad (1)$$



- $F^s_{5\sigma}(t)$: minimum detectable fluence at 5σ for an exposure time t
- Instrument response functions (Alpha configuration):

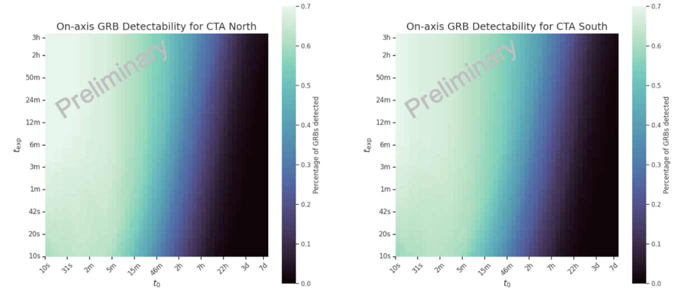
  "North_0.5h" and "South_0.5h", zenith angle=20-60°, Prod. 5 v01 (zenodo)

Patricelli et al. 2018, JCAP, 05, 056

GRB detectability - Results (O5)

$$\theta_{\mathrm{view}} < \theta_{\mathrm{core}}$$

CTAO North CTAO South



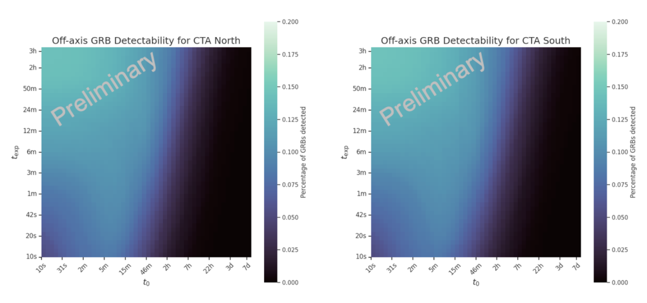
For both CTAO sites:

- For $t_0 \sim 30$ s, $\sim$ 65 % of the GRBs can be detected with $T_{\mathrm{exp}} \sim 1$ minute
- For $t_0 \sim 10$ min, $\sim$ 61 % of the GRBs can be detected with $T_{\mathrm{exp}} \sim 10$ minutes

GRB detectability - Results (O5)

$$\theta_{\text{view}} > \theta_{\text{core}}$$

CTAO North CTAO South



For both CTAO sites:

- For $t_0 \sim 30$ s, ~ 8 % of the GRBs can be detected with $T_{\text{exp}} \sim 1$ minute
- For $t_0 \sim 10$ min, $\sim$11 % of the GRBs can be detected with $T_{\text{exp}} \sim 10$ minutes

Step 2: The CTAO observational strategy

EM follow-up observation scheduler*: it determines the visibility window and computes the most favorable sky coordinates for the observation.

The optimization of observations are currently based on the following steps:

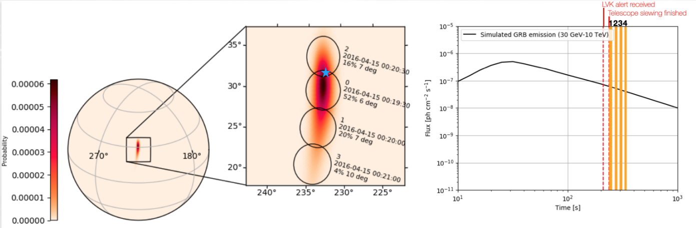
- Sequential order of the observations takes into account the contained GW source sky-position probability, from the highest to the lowest
- Low zenith angle conditions are favored, to achieve lower energy thresholds during observations
- For each CTAO observation, T_{exp} is computed with Eq. 1
- The zenith angle evolution of the source is taken into account in the computation of T_{exp}
- The visibility conditions (e.g., darkness and moonlight) are taken into account

*It is based on tilepy (Ashkar et al. 2020)
see also Seglar-Arroyo, Patricelli et al. 2019, PoS (ICRC2019) 790

A test case: example of a full simulate EM follow-up with CTAO

We selected one BNS system whose associated GRB is on-axis ($E_{iso} \sim 4 \times 10^{50}$ erg)

- t_0: 210 s (3 minutes for the GW alert + 30 s for the first slewing)
- Inter-slewing time: 20 s
- Scheduled observations: 4, covering ∼90 % of the uncertainty region in the GW sky localization (∼ 40 deg^2) in just 2 minutes after t_0



Thanks to the proposed observational strategy, the GRB is covered and detected twice (5 σ), in the first and third observation*

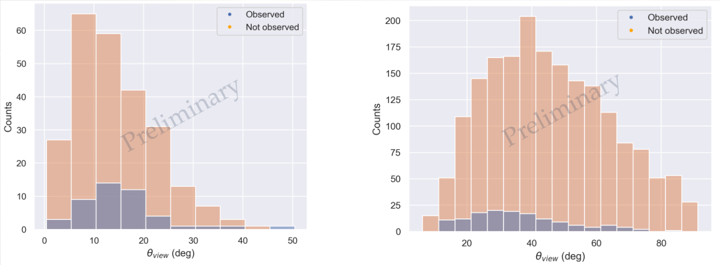
Patricelli et al. 2022, PoS (ICRC2021) 998

* Please note that, in real EM follow-ups, there will be an interplay between the scheduler and the Real Time Analysis

VHE EM follow-up of GWs: preliminary results (O5)

- Followed up GW-GRB events: 8% of the total population
  → 4.5% covering the true location of the source
- Focusing on the viewing angle:
  - On-axis events: 18% are followed up and 10% covered the true location of the source
  - Off-axis events: 7% are followed up and 4% covered the true location of the source

On axis ($\theta_{\rm view} \leq \theta_{\rm core}$) Off axis ($\theta_{\rm view} > \theta_{\rm core}$)



Green, Patricelli et al. 2024, PoS (ICRC2023) 1534

First Conclusions and future developments

- We presented a study on the capability of CTAO to detect VHE EM counterparts to GWs
- We shown that CTAO is sensitive enough to detect both on-axis and off-axis GRBs
- We presented a possible observational strategy to follow-up GW transient events

CTAO represents a promising instrument to identify the VHE emission from GRBs associated with GW transient events

Future developments

- Detailed estimate of the joint GW and VHE EM detection rates
- Investigation of other observational strategies (e.g.: fixed exposure time)
- Extension of the work to third generation GW interferometers, such as the Einstein Telescope