Searching for very-high-energy electromagnetic counterparts to gravitational-wave events with CTA

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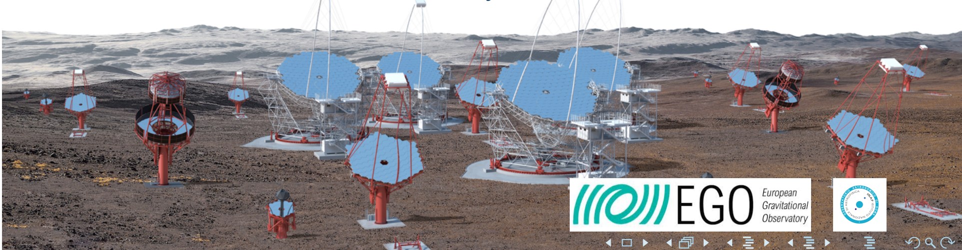
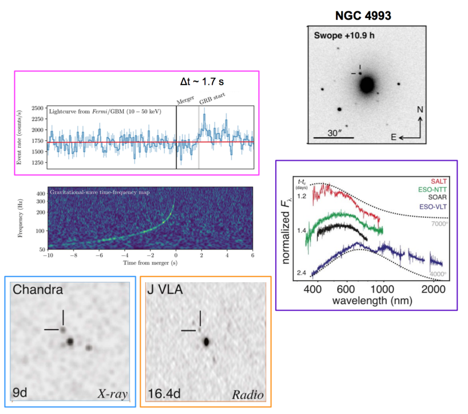


The era of multi-messenger astronomy with GWs has begun!



- 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

Next challenge:

detection of HE and VHE gamma rays associated with GW signals

Do GRBs have GeV-TeV emission?

Before *Fermi*:

limited knowledge about GRB emission above 100 MeV

- A 18 GeV photon was detected by EGRET from the long GRB 940217 (Hurley et al. 1994)
- A hint of $\sim$ TeV emission was detected by Milagrito (500 GeV-20 TeV) from the long GRB 970417A (Atkins et al. 2000)

With *Fermi*:

- tens of GRBs with high energy emission ($>$ 100 MeV)
- highest energy photon: 95 GeV from the long GRB 130427A (Ackermann et al. 2014)
- a few short GRBs with emission above 1 GeV

From 2019:

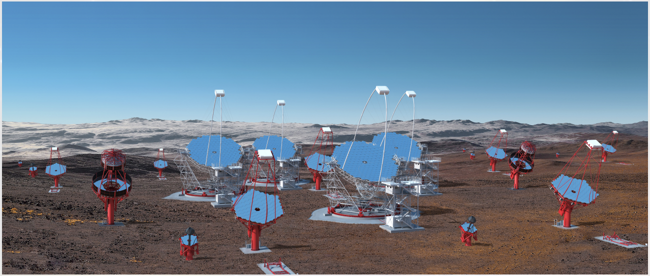
First observations of GRBs at VHE with IACTs have been reported

- GRB 190114C, GRB 160821B and GRB 201216C
(MAGIC - Acciari et al. 2019, 2021; Blanch et al. 2020)
- GRB 180720B and GRB 190829A (H.E.S.S. - Abdalla et al. 2019, 2021)

How can we do better? $\Rightarrow$ **Higher sensitivity is needed!**

The Cherenkov Telescope Array (CTA)

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



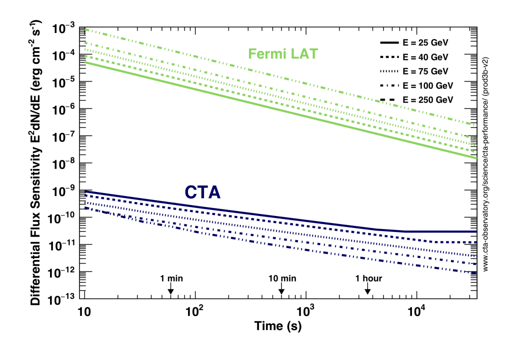
Southern Hemisphere Site Rendering; image credit: Gabriel Pz Diaz, IAC / Marc-Andrsel, CTAO

- two arrays: one in the Northern hemisphere (La Palma), one in the Southern hemisphere (Chile) $\Rightarrow$ **full-sky coverage**
- CTA 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

$\Rightarrow$ **wide energy coverage**

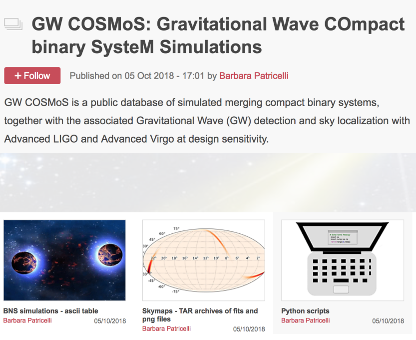
Why CTA?

- 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 CTA to detect VHE EM counterparts to GWs using detailed simulations of BNS mergers accompanied by short GRBs.

GW simulations



https://doi.org/10.6084/m9.figshare.c.4243595

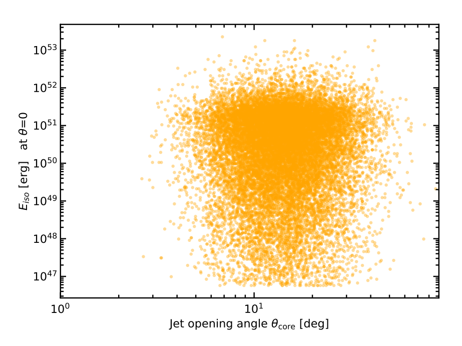
- catalog of BNS merging systems based on population synthesis models (Dominik et al. 2012)
- homogeneous and isotropic distribution on the binaries in space, up to 500 Mpc
- GW emission with TaylorT4 waveforms (Buonanno et al. 2009)
- GW detection with matched filtering technique;
- GW detectors at the sensitivity expected for the next observing run (O4)
- 2D GW sky localization with BAYESTAR (Singer et al. 2014)

Patricelli et al. 2016, JCAP 11, 056;
Patricelli et al. 2018, JCAP 5, 056

GRB simulations

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

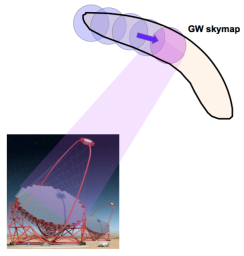
- E_{iso}: distribution inferred from short GRB observations (Ghirlanda et al. 2016)
- Structured (gaussian) jet
- θ_{core}: distribution inferred from short GRB observations (Fong et al. 2015)
- θ_{view}: it is given by the inclination of the BNS systems
- Light curve modeled taking into account the X-ray afterglows of short GRBs and the recent GRB detections at VHE
- Spectrum: power-law with photon index ~-2.2 (consistent with GRB 190114C)



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 in O3)
- telescope slewing time ($\sim$ 30 s for the LSTs)
- uncertainty in the sky localization of the GW event



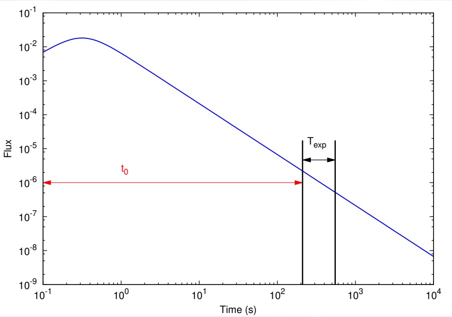
$\Rightarrow$ The exposure time needed to eventually detect the source could vary, depending on the GRB luminosity and the shape of its light curve

We estimate the percentage of GRBs that can be detected by CTA 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_{exp} as the time required to make a 5 σ detection:

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



$F^{s}_{5\sigma}(t)$: minimum detectable fluence at 5σ for an exposure time t

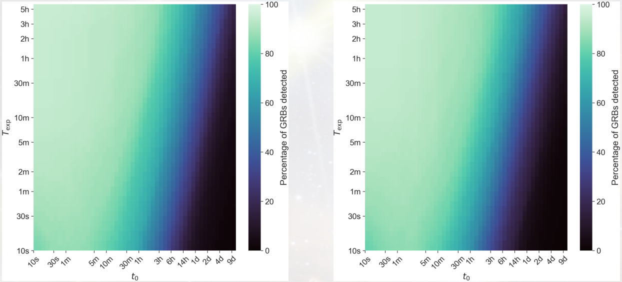
- estimated with the function *cssens* of `ctools`[a]
- instrument response functions: "North_0.5h" and "South_0.5h", zenith angle=20°, Prod. 3 (Acharyya, A., et al., 2019)

[a] http://cta.irap.omp.eu/ctools/, version 1.6.3.

GRB detectability - Results

$$\theta_{\mathrm{view}} < 10^\circ$$

CTA South CTA North



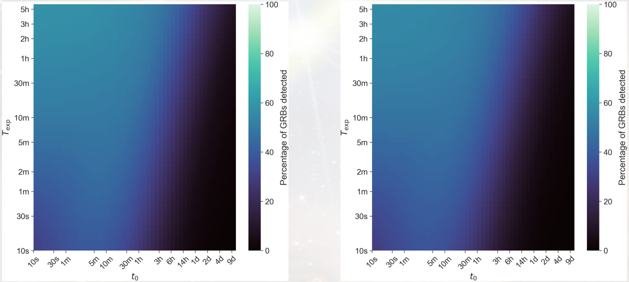
For both CTA sites:

- for $t_0 \sim 30$ s, $\sim$ 94 % of the GRBs can be detected with $T_{\mathrm{exp}} \leq$ 30 minutes
- for $t_0 \sim 10$ min, $\sim$ 92 % of the GRBs can be detected with $T_{\mathrm{exp}} \sim$ few hours

GRB detectability - Results

$$\boxed{\theta_{\rm view} < 45^\circ}$$

CTA South CTA North



For both CTA sites:

- for $t_0 \sim 30$ s, $\sim$ 52 % of the GRBs can be detected with $T_{\rm exp} \leq 30$ minutes
- for $t_0 \sim$ 10 min, ~54 % of the GRBs can be detected with $T_{\rm exp} \sim$ few hours

Step 2: The CTA observational strategy

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

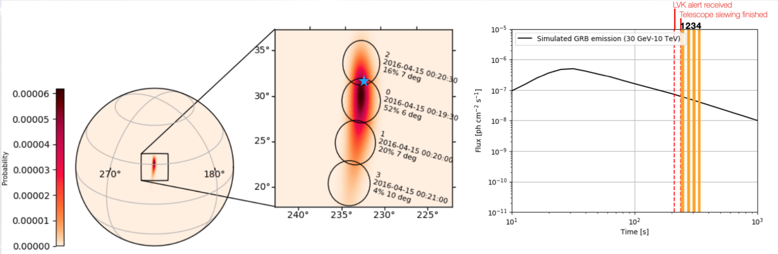
The scheduler optimizes the observations in the following way:

- 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 CTA observation, $T_{\rm exp}$ is computed with Eq. 1, under the assumption that the spectral and temporal evolution of the GRB are known at priori
- The zenith angle evolution of the source is taken into account in the computation of $T_{\rm exp}$
- The visibility conditions (e.g., darkness and moonlight) are taken into account

A test case

We selected one BNS system from the GWCOSMoS database 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

Conclusions

- We presented a study on the capability of CTA to detect VHE EM counterparts to GWs
- We shown that CTA is sensitive enough to detect both on-axis and off-axis GRBs with time delay up to $\sim$ 10 minutes
- We presented a possible observational strategy to follow-up GW transient events

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

Future developments

- Investigation of galaxy targeted searches with 3D GW skymaps
- Generalization of the observational strategy to the case in which GRB properties are unknown
- Detailed estimate of the joint GW and VHE EM detection rates