Very high energy GRB emission in the Multi-Messenger Era

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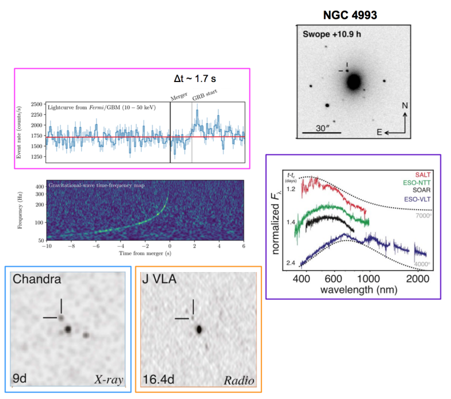
Second Gravi-Gamma Workshop

June 23-25, 2021

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)

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)
- HE emission (up to 200 MeV) was detected by EGRET from the long GRB 941017 (González et al. 2003)
- 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*:

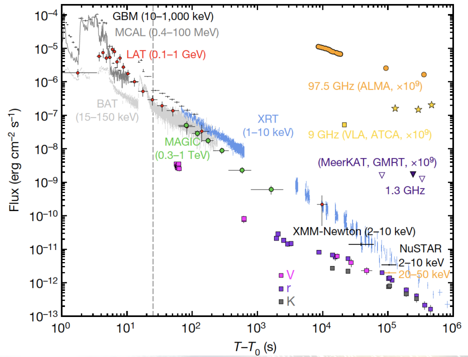
- tens of GRBs with high energy emission ($>$ 100 MeV)
- highest energy photon: 95 GeV from the long GRB 130427A (Ackermann et al. 2014)
- a few short GRBs with emission above 1 GeV

with Imaging Atmospheric Cherenkov Telescopes:

No clear detection of GRBs at VHE has been reported before 2019

MAGIC detections of long GRBs

- **GRB 190114C**
- z = 0.42
- E_{iso}=2.5 × 10^{53} ergs
- MAGIC detection: 1-40 min after the prompt
- VHE emission in the energy range 0.3 - 1 TeV
- Spectrum well described by Synchrotron Self Compton (SSC)

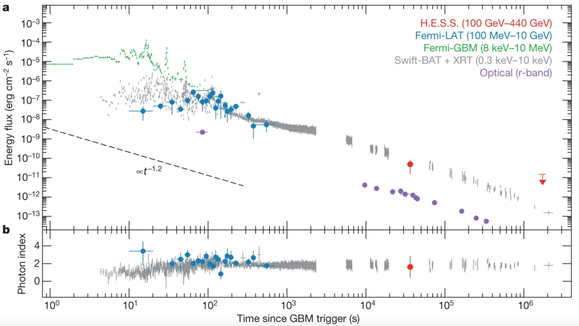


MAGIC Collaboration et al. 2019, Nature, 575, 459

- **GRB 201216C** (ATel #14275)

H.E.S.S detections of long GRBs

- **GRB 180720B**
- z=0.65
- $E_{\mathrm{iso}} = 6 \times 10^{53}$ ergs
- H.E.S.S. detection: $\sim$ 10 hours after prompt
- VHE emission in the energy range 0.1 - 0.44 TeV
- SSC is the most plausible mechanism

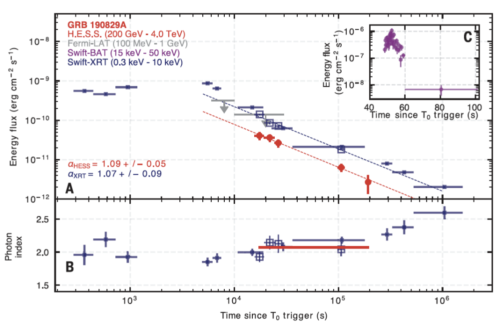


H.E.S.S. collaboration 2019, Nature, 575, 464

H.E.S.S detections of long GRBs

- **GRB 190829A**
- z=0.078
- $E_{iso} \sim 2 \times 10^{50}$ ergs
- H.E.S.S. detection:
  4-56 hr after the trigger
- VHE emission in the energy range 0.2 - 4 TeV
- Spectrum is challenging to explain by SSC

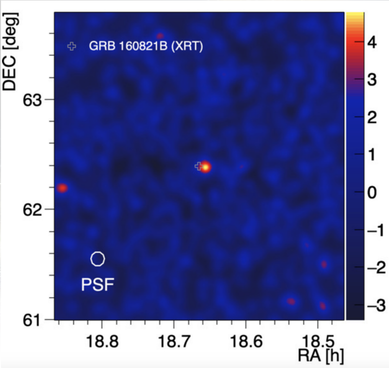
  (see, however, Salafia et al. 2021, arXiv:2106.07169)



H.E.S.S. collaboration 2021, Science, 372, 1081

MAGIC observation of short GRBs

- **GRB 160821B**
- z=0.162
- $E_{iso} \sim 1.2$ x $\times 10^{49}$ ergs
- MAGIC observation: 24 s- 4 hrs after the trigger
- VHE emission above 0.5 TeV (excess significance at the GRB position: 3.1 σ)
- one-zone SSC or hadronic models do not work



MAGIC collaboration 2021, ApJ, 908, 90

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?

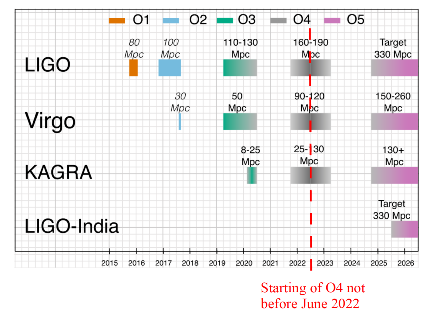
The search for GRBs at VHE can take great advantage of the GW alerts:

- GW detectors are all-sky observatories for low redshift events (associated VHE radiation is not expected to be severely attenuated by EBL)

Joint GW and VHE detection could:

- probe that BNS and NS-BH mergers have VHE EM counterparts
- allow to better investigate the dependence of the VHE emission from the progenitor system

GW detectors and VHE telescopes: timeline



In O4 we expect, for BNS systems:

- higher GW detection rates

  $R^*_{\rm BNS}=10^{+52}_{-10}$ yr^{-1}
- improved accuracy in the sky localization

  median 90% C.R.: 33^{+5}_{-5} deg^2

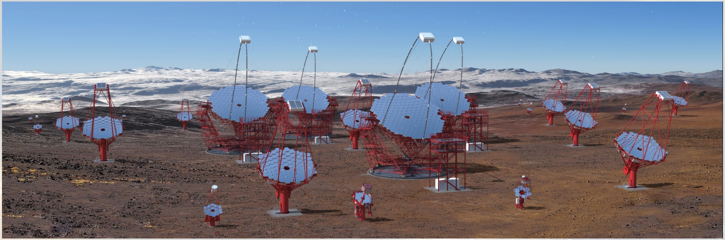
Abbott et al. 2020, LLR, 23, 3

2nd generation GW detectors will operate in synergy with current VHE detectors (such as MAGIC, H.E.S.S., VERITAS) and with next generation VHE instruments (such as the **Cherenkov Telescope Array**)

*rate estimated assuming $\mathcal{R}_{\rm BNS}$=110-3840 Gpc^{-3} yr^{-1} (Abbott et al. 2019, PRX, 9, 031040)

The Cherenkov Telescope Array (CTA)

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



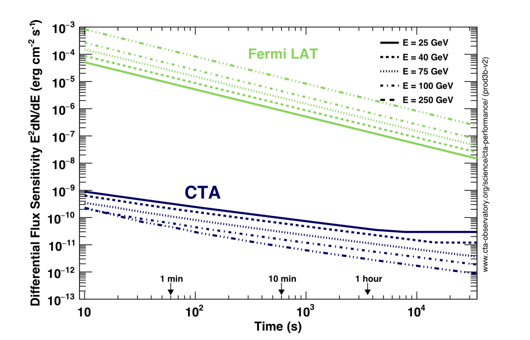
Southern Hemisphere Site Rendering; image credit: G. Perez, SMM, IAC

- two arrays: one in the Northern hemisphere (La Palma), one in the Southern hemisphere (Chile) ⇒ **full-sky coverage**
- CTA Omega Configuration of the array in the North (South):
  - 4 (4) Large Size Telescopes (LSTs); 20 GeV - 150 GeV
  - 15 (25) Medium Size Telescopes (MSTs); 150 GeV - 5 TeV
  - 0 (70) Small Size Telescopes (SSTs); 5 TeV - 300 TeV

⇒ **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**



Several studies have been done to investigate the capability of CTA to perform the EM follow-up of GWs

Bartos et al. 2014,2018,2019; **Patricelli et al. 2018, Seglar-Arroyo et al. 2019**

Simulation of BNSs and their GW emission and detection

BNS mergers

- ρ_{galaxies}=0.0116 Mpc^{-3} (Kopparapu et al. 2008)
- homogeneous and isotropic distribution of galaxies in space, up to 500 Mpc
- Merging systems: Synthetic Universe[1] (Dominik et al. 2012)
- Merger rate density: 830 Gpc^{-3} yr^{-1} (within the range in Abbott et al. 2017,2019)
- Random inclination of the BNS orbital plane with respect to the line of sight

GW emission and detection

- TaylorT4 waveforms (Buonanno et al. 2009)
- Matched filtering technique (Wainstein 1962)
- aLIGO and AdV at design sensitivity, with 80 % independent duty cycle (Abbott et al. 2016)
- Trigger: at least 2 detectors; combined SNR threshold: 12
- 2D GW sky localization with BAYESTAR (Singer et al. 2014)

Patricelli et al. 2016, JCAP 11, 056
Patricelli, B. et al. 2018, JCAP, 05, 056

[1] www.syntheticuniverse.org

GRB simulations

- All BNS mergers are associated to a short GRB;
- Only on-axis GRBs are considered; θ_j=10° (Fong et al. 2014);

- **GRB 090510** as a prototype:

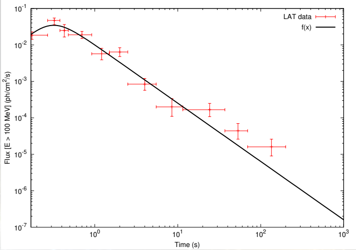
  Light curve:

$$F(\mathrm{t}) = \mathrm{A}\frac{(\mathrm{t}/\mathrm{t}_{\mathrm{peak}})^{\alpha}}{1+(\mathrm{t}/\mathrm{t}_{\mathrm{peak}})^{\alpha+\omega}}$$

  Spectrum:

$$N(E) \propto E^{\beta}, \qquad \beta = -2.1$$

  (De Pasquale et al. 2010)

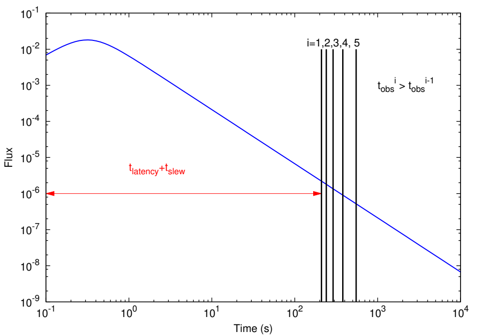


- We corrected $F(\mathrm{t})$ to take into account:
  - the different distance of the sources;
  - a possible range of isotropic energy: 10^{49} ergs $\leq E_{\gamma} \leq 3.5\times10^{52}$ ergs (Ghirlanda et al. 2010, Fong et al. 2015)
- We extrapolate the flux to higher energies assuming a power-law with exponential cut-off spectrum: E_c=30 GeV, 100 GeV

Proposed strategy

Step 1:

We estimate the observing time t^i_{obs} needed for the simulated GRBs to have a fluence equal to the CTA sensitivity, considering a set of consecutive pointings



$$t^i_{start} = (t_{slew} + t_{latency}) + t^{i-1}_{obs}$$
$$t^i_{stop} = t^i_{start} + t^i_{obs}$$
$$i = 1, \ldots, n_p$$

⇒ This will tell us the maximum number of observations n_p that we can do and the observing time of each observation

Proposed strategy

Step 2

We constructed a 2D grid of CTA pointings:

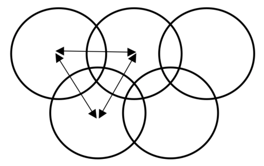


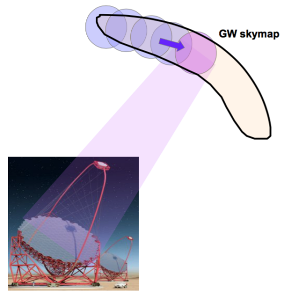
Image credit: Dubus et al. 2013

- multiple evenly-spaced rows of pointings
- Angular step: 2°

  (maximum step that provides nearly uniform sensitivity coverage, see Dubus et al. 2013)

Step 3

Intersection between the GW skymap and the 2D grid of pointings, taking into account n_p



⇒ percentage of the GW skymap that can be covered with n_p observations

GRB simulations at VHE

Observation time:

- We considered a latency to send the GW alert t_l=3 minutes
- We considered a slewing time t_{slew}=30 s (LSTs)

Sensitivity:

- We estimated the sensitivity with the function *cssens* of `ctools`[2] (Knödlseder et al. 2016)
- We used the Instrument Response Functions (IRFs)[3] "North_0.5h" and "South_0.5h" (zenith angle=20 deg)
- We considered a 5 σ (post-trials) detection threshold

CTA Duty cycle:

- We assumed a conservative duty cycle of $\sim$ 10 %

[2] http://cta.irap.omp.eu/ctools/; in this work we used the ctools version 1.4.0
[3] `https://www.cta-observatory.org/science/cta-performance/`

Results: joint GW and EM detection rates

E_{iso} (ergs)	cut-off (GeV)	EM and GW (yr^{-1})
10^{49}	30	$< 10^{-3}$
	100	< 0.001
10^{50}	30	0.01
	100	0.03
10^{51}	30	0.06
	100	0.07
3.5×10^{52}	30	0.08
	100	0.08

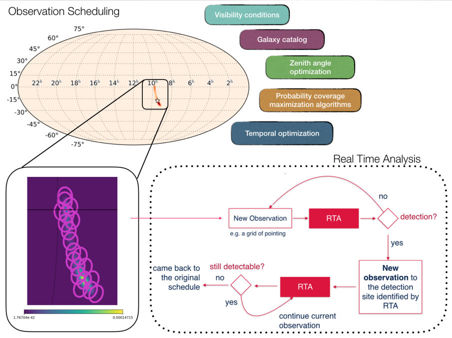
- Increase in the joint GW and EM detection rates with respect to "standard" strategies
- Rates are expected to further increase if:
  - Higher CTA duty cycle is considered (e.g., observations during moonlight)
  - Higher θ_j is assumed
  - Off-axis GRBs are included

Patricelli et al. 2018, JCAP, 05, 056

Extension of the work

A CTA consortium paper on the prospects for CTA observations of GRBs associated with GWs is in preparation:

- Additional BNS-GW catalog with 3D GW skymaps to investigate galaxy targeted searches
- New GRB modeling
  - it takes into account the recent observations by MAGIC and H.E.S.S.
  - it includes off-axis emission
- Visibility conditions and zenith angle evolution are taken into account



Seglar-Arroyo, M. al. 2019, PoS (ICRC2019) 790
Patricelli et al., in preparation, PoS (ICRC2021)
CTA consortium, in preparation

Conclusions

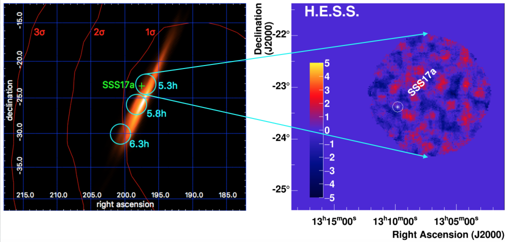
- The joint detection of GW170817 and GRB170817A represents the first direct probe that BNS mergers are short GRB progenitors
- After decades of non-detections, recently several GRBs have been observed at VHE by MAGIC and H.E.S.S.
- One of the challenge for the next years is the detection of VHE counterpart to GWs
- CTA represents a promising instrument to identify the VHE emission from GRBs associated with BNS mergers

Future joint GW and VHE EM detections will be key to better understand the GRB physics ... stay tuned!

Backup slides

HE and VHE EM follow-up of GW170817

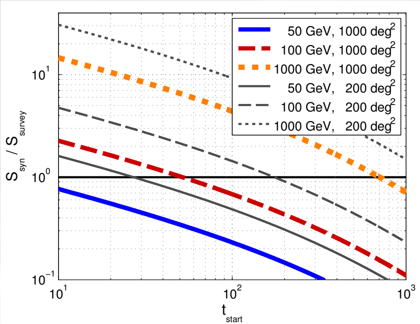
- *Fermi*-LAT was entering the SAA at the time of the GW trigger; no significant HE EM counterpart was detected at later times (Ajello et al. 2018, ApJ, 861, 85)
- H.E.S.S. started the observations 5.3h after the GW trigger; no significant VHE emission has been found (Abdalla et al. 2017, ApJL, 850, 22)



VHE follow-up has been performed also for other GW events, but no EM counterpart has been found (see, e.g., Miceli et al. 2019, Ashkar et al 2021)

CTA is well suited to follow up GWs

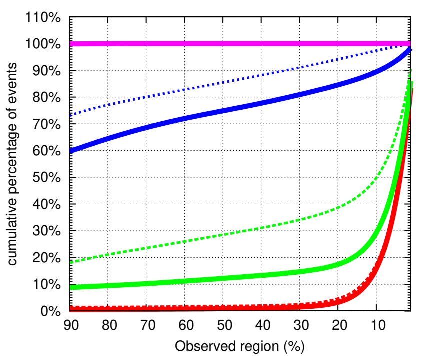
- GRB 090510-like source
  - D_L=300 Mpc
  - Spectrum: power law with exponential cut-off
- 90% C.R.:
  200 deg^2 and 1000 deg^2
- CTA operating in survey mode, for a total observing time of 1000 s
- Same observing time for each consecutive CTA pointing



Short GRBs with HE emission extending up to $\sim$ 100 GeV can be detectable via CTA with a delay of tens of seconds, even if CTA needs to survey a sky area of $\sim$1000 deg^2.

Bartos et al. 2014, MNRAS, 443, 738

Results: GW skymap coverage with CTA pointings



E_{iso} (ergs)		cut-off (GeV)	% of events Obs. region =90 %	% of events Obs. region $\geq$ 50 %
10^{49}	—	30	< 1	< 1
	- -	100	1.5	1.9
10^{50}	—	30	8.8	12.2
	- -	100	18.0	28.8
10^{51}	—	30	59.7	74.5
	- -	100	73.0	85.1
3.5×10^{52}	—	30	99.9	100
	- -	100	99.9	100

Patricelli et al. 2018, JCAP, 05, 056