Multi-messenger astronomy: synergies between gravitational wave and very high energy gamma-ray observations

Barbara Patricelli[1,2,3]

[1] Physics Department, University of Pisa

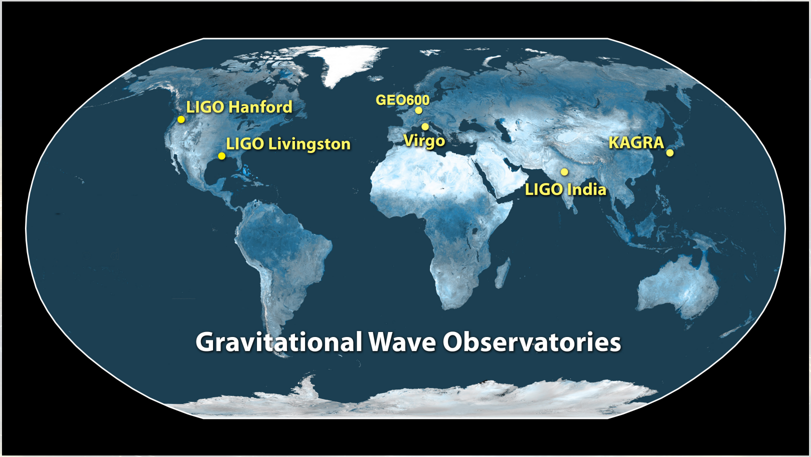
[2] INFN - Sezione di Pisa

[3] INAF - Osservatorio astronomico di Roma

OAS VERY-HIGH ENERGY MEETING

June 8-9, 2022

The 2nd generation GW detector network



Where do we stand?

Three observing runs so far

Credit: LIGO-Virgo

- *O1: September 2015 - January 2016*

  Only the two LIGO detectors were operating

- *O2: November 2016 - August 2017*

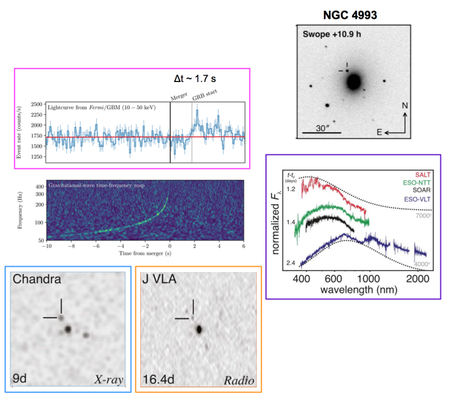
  Virgo joined the network on August 1

- *O3a: April 2019 - September 2019*

  O3b: November 2019 - March 2020

  Virgo and the two LIGO detectors were operating

August 17, 2017 (O2): the birth of multi-messenger astronomy with GWs

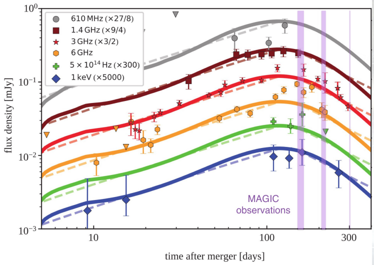


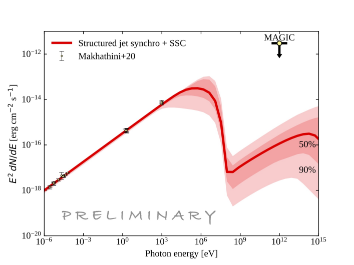
- coincident short GRBs detected in gamma rays ⇒ first direct evidence that at least some **BNS mergers are progenitors of short GRBs**
- an optical/infrared/UV counterpart has been detected ⇒ first spectroscopic **identification of a kilonova**
- An X-ray and a radio counterparts have been identified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

Abbott + BP et al., ApJ Letters, 848, 2 (2017)

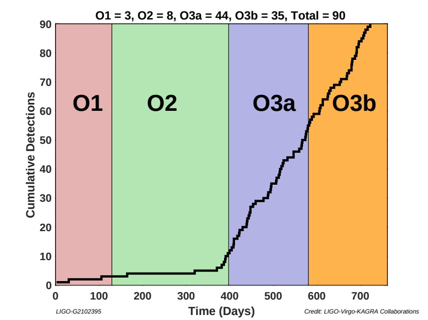
HE and VHE EM follow-up of GW170817

- *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)
- 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 +BP et al. 2021, PoS(ICRC2021)944)





Other GW observations and EM follow-up campaigns



- Total number of candidates: 90
- Most are binary black holes (BBHs)
- Some are neutron star - black hole (NSBH) binaries
- Two are binary neutron stars (BNSs)

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

Do GRBs have VHE emission?

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

- 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)

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?

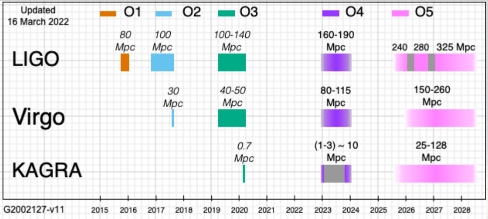
The search for GRBs at VHE can take great advantage of the GW alerts:

- Current GW detectors are all-sky observatories for low redshift events (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 us to better investigate the dependence of the VHE emission from the progenitor system and its environment

The next GW observing runs



- O4 is expected to start on Dec 15, 2022; 1 year of data taking
- Alerts may be released during the engineering run that precedes O4
- O4 may be extended if scheduling O5-upgrades makes that viable

In the next years 2$^{\text{nd}}$ generation GW detectors will operate in synergy with current VHE detectors (such as MAGIC) and with next generation VHE instruments (such as the **Cherenkov Telescope Array**)

Prospects for joint detections of BNS mergers and GRBs in O4

GWs + GRBs, conservative approach

model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	31	1	0.0006 (0.0023)	0.014-0.020	0.003 (0.013)	0.070-0.11	0.0001 (0.0004)	0.0024-0.0035	0.0005 (0.0019)	0.013-0.017
A3	258	5	0.003 (0.01)	0.07-0.10	0.017 (0.068)	0.35-0.54	0.0005 (0.002)	0.01-0.02	0.002 (0.01)	0.06-0.08
A7	765	13	0.008 (0.031)	0.18-0.26	0.045 (0.18)	0.91-1.42	0.001 (0.005)	0.031-0.046	0.006 (0.025)	0.17-0.22

GWs + GRBs, optimistic approach

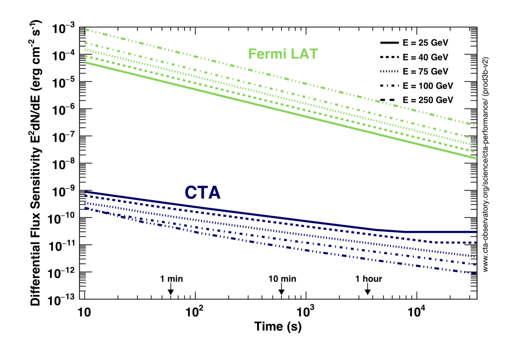
model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	31	5	0.002 (0.01)	0.05-0.08	0.014 (0.06)	0.27-0.46	0.0005 (0.002)	0.009-0.014	0.002 (0.008)	0.05-0.07
A3	258	22	0.01 (0.04)	0.24-0.37	0.06 (0.26)	1.17-2.00	0.002 (0.008)	0.04-0.06	0.009 (0.04)	0.22-0.32
A7	765	61	0.03 (0.12)	0.67-1.05	0.18 (0.74)	3.28-5.65	0.006 (0.02)	0.11-0.18	0.02 (0.10)	0.63-0.90

- There is a **realistic probability to observe at least another multi-messenger event during O4** ⇒ We need to be ready to perform VHE EM follow-ups!
- Accepted observational proposal with MAGIC, cycle 17
  (February 18, 2022 - February 02, 2023)

Patricelli et al. 2022, MNRAS, 513, 4159 (arXiv:2204.12504)

Towards the future: the Cherenkov Telescope Array

- coincident observational schedule with 2$^{\text{nd}}$ generation GW detectors at their highest sensitivity
- large field of view
  CTA's Large-Sized Telescope (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 (see Patricelli et al. 2018, 2022; Seglar-Arroyo +BP et al. 2019, Bartos et al. 2014,2018,2019)

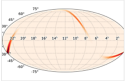
GW simulations


GW COSMoS: Gravitational Wave COmpact binary SysteM Simulations

+ Follow Published on 05 Oct 2018 - 17:01 by Barbara Patricelli

GW COSMoS is a public database of simulated merging compact binary systems, together with the associated Gravitational Wave (GW) detection and sky localization with Advanced LIGO and Advanced Virgo at design sensitivity.


BNS simulations - ascii table
Barbara Patricelli 05/10/2018


Skymaps - TAR archives of fits and png files
Barbara Patricelli 05/10/2018


Python scripts
Barbara Patricelli 05/10/2018

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

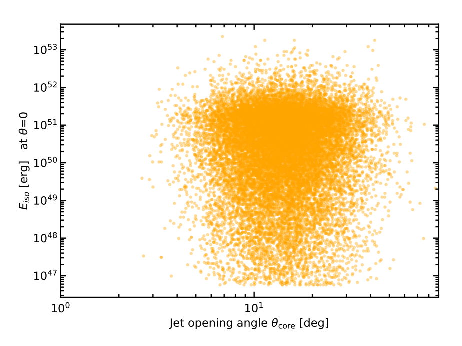
- catalog of BNS merging systems based on population synthesis models (Dominik et al. 2012)
- homogeneous and isotropic distribution on the binaries in space, up to 500 Mpc
- GW emission with TaylorT4 waveforms (Buonanno et al. 2009)
- GW detectors at the sensitivity expected for the next observing run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

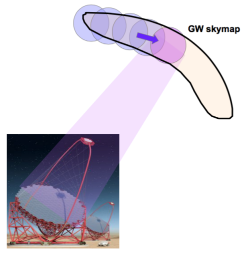
- $E_{\rm iso}$: distribution inferred from short GRB observations (Ghirlanda et al. 2016)
- Structured (gaussian) jet
- $\theta_{\rm core}$: distribution inferred from short GRB observations (Fong et al. 2015)
- $\theta_{\rm view}$: it is given by the inclination of the BNS systems
- Light curve modeled 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



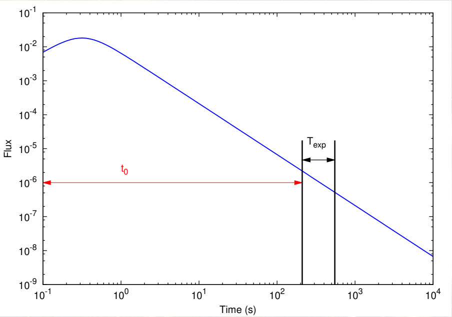
$\Rightarrow$ The exposure time needed to eventually detect the source could vary, depending on the GRB luminosity and the shape of its light curve

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:

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



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

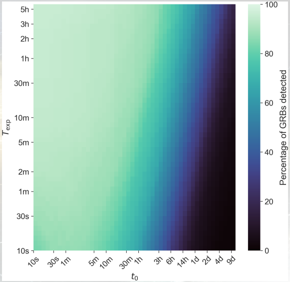
- estimated with the function *cssens* of `ctools`[a]
- instrument response functions: "North_0.5h" and "South_0.5h", zenith angle=20°, Prod. 3 (Acharyya, A., et al., 2019)

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

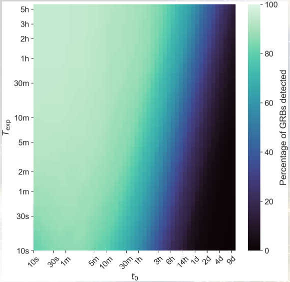
GRB detectability - Results

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

CTA South



CTA North



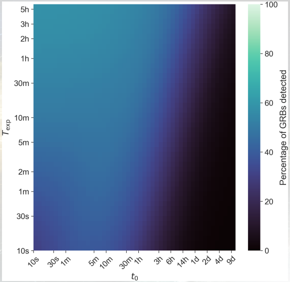
For both CTA sites:

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

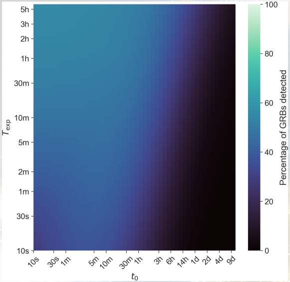
GRB detectability - Results

$$\theta_{\text{view}} < 45^\circ$$

CTA South



CTA North



For both CTA sites:

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

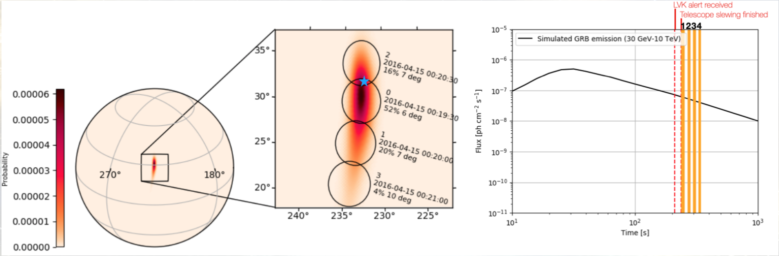
The scheduler optimizes the observations in the following way:

- 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 ($\sim 40\ deg^2$) 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

Next steps

- New catalogs of BNS merging systems for **O5** have recently been released (Petrov et al. 2022)

  `https://zenodo.org/record/4765752#.YULnGh1S9p8`

  `https://zenodo.org/record/4765754#.YUM0AB1S9p8`

  $\rightarrow$ **timeline more consistent with the one of CTA**

- Associated GRB catalog already produced

  $\Rightarrow$ The new BNS+GRB catalog will be used to further investigate the CTA observational strategy and to estimate the expected joint GW + VHE EM detection rates

- Integration of the CTA SAG/Real-Time Analysis (see A. Bulgarelli's talk)

Conclusions

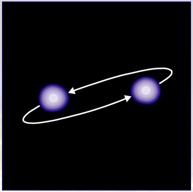
- The joint detection of GW170817 and GRB170817A represents the first direct probe that BNS mergers are short GRB progenitors
- After decades of non-detections, recently several GRBs have been observed at VHE by MAGIC and H.E.S.S.
- One of the challenge for the next years is the detection of VHE EM counterpart 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

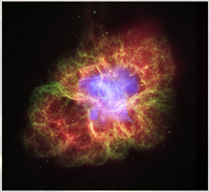
High frequency (10-1000 Hz) GW transient sources

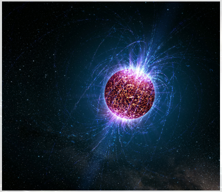
Coalescence of binary systems of NSs and/or BHs



- GW signals accurately modeled by post-Newtonian approximation and numerical simulations $\rightarrow$ **Matched filter modeled searches**

Core collapse of massive stars and Isolated neutron stars





- The modeling of the GW signal is complicated $\rightarrow$ **Unmodeled searches**

Why multi-messenger astronomy with GWs?

GWs and photons provide complementary information about the physics of the source and its environment

GW

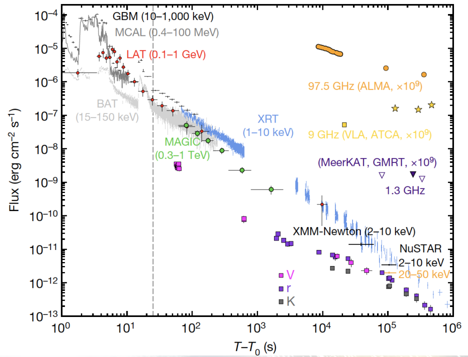
- *mass*
- *spin*
- *eccentricity*
- *system orientation*
- *luminosity distance*
- *compact object binary rate*

EM

- *precise (arcsec) sky localization*
- *host galaxy*
- *redshift*
- *local environment*
- *emission processes*
- *acceleration mechanisms*

MAGIC detections of long GRBs

- **GRB 190114C**
- z = 0.42
- E_{iso}=2.5 $\times$ 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)

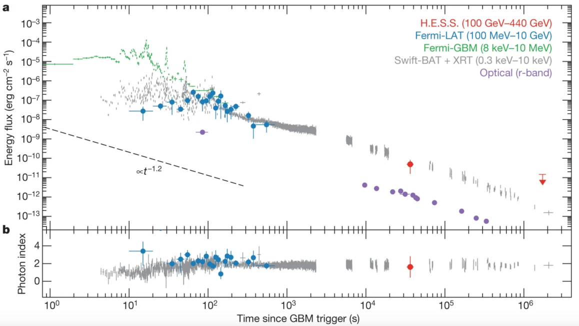


MAGIC Collaboration et al. 2019, Nature, 575, 459

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

H.E.S.S detections of long GRBs

- **GRB 180720B**
- z=0.65
- $E_{iso}=6 \times 10^{53}$ 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

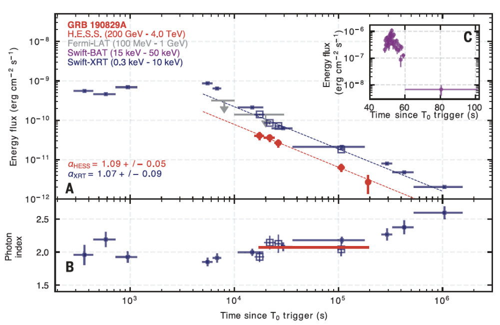


H.E.S.S. collaboration 2019, Nature, 575, 464

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

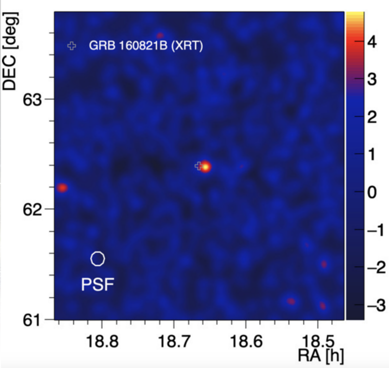
  (see, however, Salafia et al. 2021, arXiv:2106.07169)



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

MAGIC observation of short GRBs

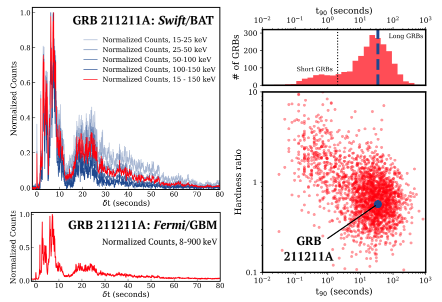
- **GRB 160821B**
- z=0.162
- $E_{iso} \sim 1.2$ x $\times 10^{49}$ ergs
- MAGIC observation: 24 s- 4 hrs after the trigger
- VHE emission above 0.5 TeV (excess significance at the GRB position: 3.1 σ)
- one-zone SSC or hadronic models do not work

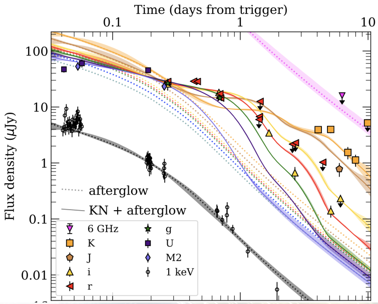


MAGIC collaboration 2021, ApJ, 908, 90

A long GRB from a BNS merger?

Recently a kilonova has been discovered in association with a nearby (350 Mpc) minute-duration GRB $\Rightarrow$ is the progenitor a compact object merger?





Searches for GW signals coincident with long GRBs are a promising route for future multi-messenger astronomy

Rastinejad et al. 2022, arXiv: 2204.10864