Prospects for joint GW and gamma-ray EM observations of binary neutron star mergers

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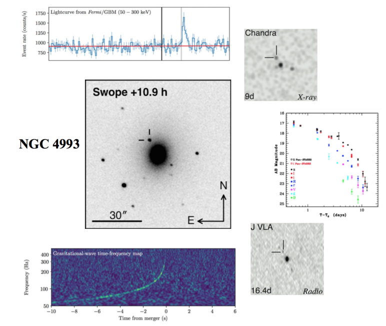
Outline

The era of multi-messenger astronomy has begun!



GW170817:

- coincident short GRBs detected in gamma rays
- an optical/infrared/UV counterpart (the kilonova) has been detected
- X-ray and radio counterparts have been identified
- HE ($E > 100$ MeV) and VHE ($E > 20$ GeV): no significant emission has been found

(Abbott et al. 2017 and refs. therein)

Next challenge:

detection of HE and VHE gamma rays associated with GW signals

Prospects for joint GW and EM detections: Advaced LIGO, Advanced Virgo and *Fermi*

The Fermi mission

Two instruments:

- **GBM**
  - Energy range: 8 keV to 40 MeV
  - FOV: $\sim$ 9.5 sr
  - Sky localization: overall median error for short GRBs of 8°
- **LAT**
  - Energy range: 20 MeV to 300 GeV
  - FOV: $\sim$ 2.4 sr
  - Sky localization: $r_{68} \sim 0.1^\circ$ at 10 GeV on-axis

if GBM detects a GRB above a fixed threshold*, *Fermi* automatically slews to move the GRB into the LAT FOV

* The on-board trigger threshold is $\sim$ 0.7 photons cm^{-2} s^{-1}

Step 1: simulation of the NS-NS mergers

NS-NS mergers

- NS-NS merger rate is dominated by the contribution from Milky-Way-like galaxies (see e.g. O'Shaughnessy et al. 2010)
- Maximum distance set at 500 Mpc
- $\rho_{galaxies}$=0.0116 Mpc^{-3} (Kopparapu et al. 2008)
- Simulated galaxies are uniformly distributed
- Merging systems: Synthetic Universe[1] (Dominik et al. 2012)
- Bimodal distribution in metallicity: half at $Z=Z_\odot$ and half at $Z=0.1 \cdot Z_\odot$ (Panter et al. 2008)
- Merger rates: (Dominik et al. 2012)

$$\begin{cases} \text{“Optimistic” models: V12A } (Z=Z_\odot) \text{ and V2A } (Z=0.1 \cdot Z_\odot) \\ \text{“Pessimistic” models: V12B } (Z=Z_\odot) \text{ and V1B } (Z=0.1 \cdot Z_\odot) \end{cases}$$

[1] www.syntheticuniverse.org

Step 2: GW detections and sky localizations

GW signals

- We assume non-spinning systems
- Random inclination of the orbital plane with respect to the line of sight (θ)
- TaylorT4 waveforms (Buonanno et al. 2009)

GW detections

- Detector configurations (aLIGO and AdV):
  2016-2017 ("O2") and 2019+ (design), see Abbott+Patricelli et al. 2016
- Independent duty cycle of each interferometer: 80 % (Abbott+Patricelli et al. 2016)
- Matched filtering technique (Wainstein 1962)
- Trigger: at least 2 detectors
- Combined detector SNR threshold: 12
- GW localization with BAYESTAR (Singer et al. 2014)

Step 3: GRB simulations - prompt emission

Assumptions:

- All the NS-NS mergers are associated with a short GRB
- Only on-axis GRBs are considered ($\theta < \theta_j$)
- GRB jet opening angles: $0.3^\circ \leq \theta_j \leq 30^\circ$
  (Panaitescu et al. 2011, Rezzolla et al. 2011, Coward et al. 2012)
- "fiducial" θ_j: 10°
  (Fong et al. 2014, Duffell et al. 2015)

Detection of the prompt emission with Fermi/GBM:

- GBM FOV: 9.5 sr
- GBM duty cycle: 50 %
- Is GBM sensitive enough to detect the simulated GRBs? $\Rightarrow$ GBM sensitivity vs GRB brightness

Step 3: GRB simulations - prompt emission detection with GBM

Brightness

It is the 64-ms peak photon flux P_{64} from the prompt emission in the 50-300 keV energy band

$$L[1\mathrm{keV}-10\mathrm{MeV}] = 4\pi \mathrm{D_L^2} \frac{\int_{1\mathrm{keV}}^{10\mathrm{MeV}} \mathrm{EN(E)dE}}{\int_{50\mathrm{keV}(1+z)}^{300\mathrm{keV}(1+z)} \mathrm{N(E)dE}} \mathrm{P_{64}}$$

Lowest brightness measured by Fermi-GBM

- $P_{64,Min}^{meas}$=0.75±0.25 ph/cm2/s (VizieR Online Data Catalog)

Lowest expected brighness for the simulated short GRBs

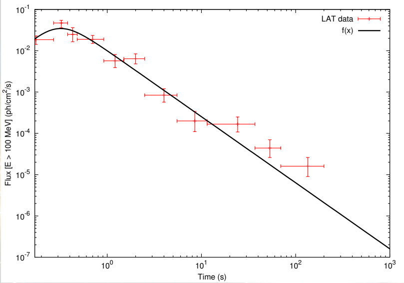
- Minimum L: 2 10^{50} erg/s
  (lowest value for short GRBs with known redshift, see Waderman & Piran 2015)
- Maximum distance: 500 Mpc (z∼0.12)
- $N(E)$: Band function with the typical parameters of Fermi-GBM short GRBs (see Nava et al. 2011, Waderman & Piran 2015)

$$\Rightarrow \mathrm{P_{64,Min}} \sim 5 \text{ ph cm}^{-2}\text{ s}^{-1} > \mathrm{P_{64,Min}^{meas}}$$

⇒ **GBM is sensitive enough to detect all the on-axis GRBs in our sample**

Step 3: GRB simulations - afterglow emission

GRB 090510 as a prototype: unique short GRB to show an extended emission (up to 200 s) at high energies (up to 4 GeV), as detected by Fermi-LAT (Ackermann et al. 2010, De Pasquale et al. 2010)



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:

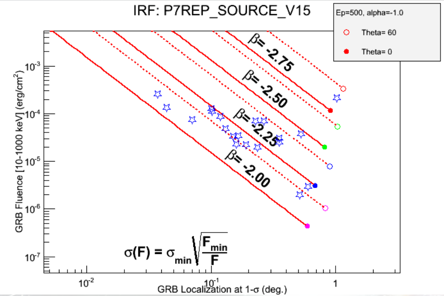
$$N(E) \propto E^{\beta}, \qquad \beta = -2.1$$

(De Pasquale et al. 2010)

- We assumed θ_j=10°;
- We corrected the light curve to take into account the distance of the sources with respect to GRB 090510;
- We re-scaled the light curve considering the following range of isotropic energy: 10^{49} ergs $\leq E_\gamma \leq 3.5\times10^{52}$ ergs (Ghirlanda et al. 2010, Fong et al. 2015)

Step 3: GRB simulations - afterglow emission detection with LAT

We estimated the integration time t_f needed for the simulated GRBs to have a fluence equal to the Fermi-LAT sensitivity:



- We extrapolated this sensitivity to the energy range 0.1-300 GeV
- We choose the value of sensitivity corresponding to a GRB localization of 1 deg, for β=-2 and Theta=0.

http://www.slac.stanford.edu/exp/glast/groups/canda/archive/p7rep_v15/lat_Performance.htm

We considered two cases:

- no latency (the source is already in the FOV of the LAT)
- 10 minute latency

Results: GW detections - I

Configurations	Work	Number of BNS detections (yr^{-1})	% of BNS with Loc. $\leq$ 5 deg^2	% of BNS with Loc. $\leq$ 20 deg^2	% of BNS with Loc. $\leq$ 100 deg^2	% of BNS with Loc. $\leq$ 1000 deg^2
2016-2017 (O2)	This work*	0.001 - $\boxed{0.9}$	3	9	16	70
	Singer et al. 2014[2]	1.5	2	8	15	-
	Abbott+Patricelli et al. 2016	0.006-20	2	14	-	-
2019+ (design)	This work	1 (0.04 - 15)	5	21	50	90
	Abbott+Patricelli et al. 2016	0.2-200	> 3-8	> 8-30	-	-

Patricelli et al. 2016. JCAP, 11, 56

*Rates from Patricelli et al. 2016 have been rescaled to take into account the 8 months duration of O2

[2] These estimates refer to the 2016 scenario.

Results: GW detections - II

"Optimistic" merger rate (Dominik et al. 2012): 830 Gpc^{-3} yr^{-1}

After the detection of GW170817: (320 - 4740) Gpc^{-3} yr^{-1} (Abbott+Patricelli et al. 2017)

$\Downarrow$

Configurations	Work	Number of BNS detections (yr^{-1})	% of BNS with Loc. $\leq$ 5 deg^2	% of BNS with Loc. $\leq$ 20 deg^2	% of BNS with Loc. $\leq$ 100 deg^2	% of BNS with Loc. $\leq$ 1000 deg^2
2016-2017 (O2)	This work*	$\boxed{0.9\ (0.3 - 5)}$	3	9	16	70
	Singer et al. 2014	1.5	2	8	15	-
	Abbott+Patricelli et al. 2016	0.006-20	2	14	-	-
2019+ (design)	This work*	15 (7 - 86)	5	21	50	90
	Abbott+Patricelli et al. 2016	0.2-200	> 3-8	> 8-30	-	-

Patricelli et al. 2016. JCAP, 11, 56

Results: joint HE EM and GW detections - prompt emission with GBM

θ_j deg	EM and GW **2016-2017** yr^{-1}	EM and GW **design** yr^{-1}
0.3	$< 10^{-3}$	$< 10^{-3}$
10	0.03 (0.01 - 0.2)	0.5 (0.2 - 2.9)
30	0.1 (0.04 - 0.6)	2.6 (1 - 15)

Patricelli et al. 2016, JCAP, 11, 56

Evidence that GRB170817A was an atypical GRB?

*Rates from Patricelli et al. 2016 have been rescaled to take into account the 8 months duration of O2 and the estimate of BNS merger rate after GW170817

Results: joint HE EM and GW detections - afterglow emission with LAT

no latency

E_γ (ergs)	EM and GW 2016-2017 (yr^{-1})	EM and GW design (yr^{-1})
3.5×10^{52}	0.05 (0.01 - 0.3)	0.9 (0.3 - 5)
1×10^{49}	0.05 (0.01 - 0.3)	0.6 (0.2 - 3.4)

10 min latency

Integration Time (s)	E_γ (ergs)	EM and GW 2016-2017 (yr^{-1})	EM and GW design (yr^{-1})
10	3.5×10^{52}	0.03 (0.01 - 0.2)	0.1 (0.04 - 0.6)
	1×10^{49}	$< 10^{-3}$	$< 10^{-3}$
10^2	3.5×10^{52}	0.05 (0.02 - 0.3)	0.9 (0.3 - 5)
	1×10^{49}	$< 10^{-3}$	$< 10^{-3}$

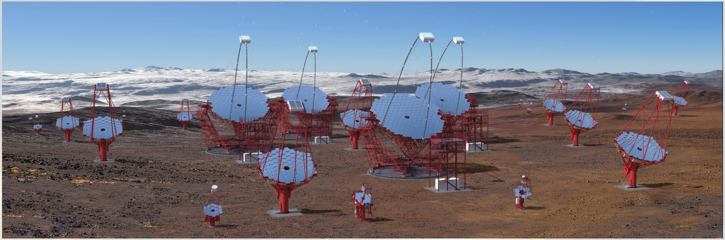
Rates consistent with independent estimates by *Fermi*-LAT collaboration, arXiv:1710.05450

*Rates from Patricelli et al. 2016 have been rescaled to take into account the 8 months duration of O2 and the estimate of BNS merger rate after GW170817

Extension to very-high-energies: Prospects for CTA

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

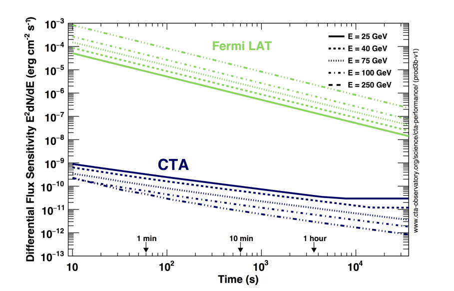
- two arrays: one in the Northern hemisphere, one in the Southern hemisphere

  $\Rightarrow$ **full-sky coverage**
- CTA baseline array in the North (South):
  - 4 (4) Large Size Telescopes (LSTs); $\sim$ 20 GeV - $\sim$ 200 GeV
  - 15 (25) Medium Size Telescopes (MSTs); $\sim$ 100 GeV - $\sim$ 10 TeV
  - 0 (70) Small Size Telescopes (SSTs); $\sim$ 5 TeV - $\sim$ 300 TeV

$\Rightarrow$ **large energy coverage**

Why CTA?

- coincident observational schedule with GW detectors at design sensitivity (CTA completion expected by 2024)
- large FoV (LST: 4.5 deg)
- survey key science programs
- **Rapid response ($\leq$ 30 s) of LST**
- **Very high sensitivity**



https://www.cta-observatory.org/science/cta-performance/

The simulations

- Sample of NS-NS mergers and associated GW signal and detection from Patricelli et al. 2016 (associated with the "optimistic model")
- Only on-axis GRBs are considered; $\theta_j = 10^\circ$;
- GRB 090510 as a prototype, with focus on the afterglow emission;
- EM flux extrapolated to higher energies, assuming a power-law with exponential cut-off spectrum: Ec=30 GeV, 100 GeV.

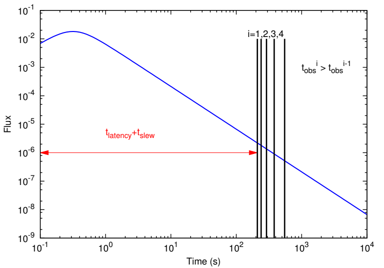
Several CTA pointings will be needed to cover the GW skymap...

which is the best observational strategy?

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



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

$\Rightarrow$ 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:

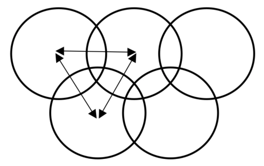


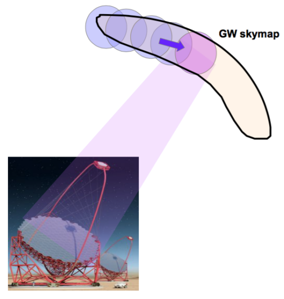
Image credit: Dubus et al. 2013

- 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



$\Rightarrow$ 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[3] (Knödlseder et al. 2016)
- We used the instrument response functions (IRFs)[4] "North_0.5h" and "South_0.5h" (zenith angle=20 deg)
- We considered a 5 σ (post-trials) detection threshold

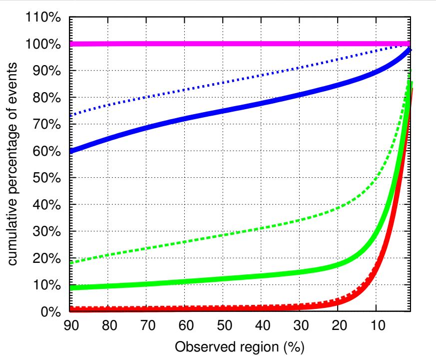
CTA Duty cycle:

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

[3] http://cta.irap.omp.eu/ctools/; in this work we used the ctools version 1.4.0

[4] https://www.cta-observatory.org/science/cta-performance/

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, 5, 56

Results: joint GW and EM detection rates

$E_{\rm iso}$ (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

Rates are expected to increase if:

- Higher CTA duty cycle is considered (e.g., observations during moonlight)
- Higher BNS merger rates are considered (see Abbott+Patricelli et al. 2017)

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For most energetic events up to
1 event per year!

- Higher θ_j is assumed
- Off-axis GRBs are included

Patricelli et al. 2018, JCAP, 5, 56

Conclusions

We presented a comprehensive study of the prospects for joint GW and EM detection of BNS mergers with gamma-ray space and ground-based instruments

- *Fermi* represents a promising instrument to identify the EM counterpart of GW events
- The observational strategy proposed for EM follow-up at VHE is highly efficient and CTA will be potentially able to detect the VHE emission of GRBs associated with GW events.
- The observational strategy proposed for CTA can be generalized to other telescopes and/or other EM emission models

More joint GW and gamma-ray EM observations in the future will shed light on the physics of compact objects and on their association with GRBs.

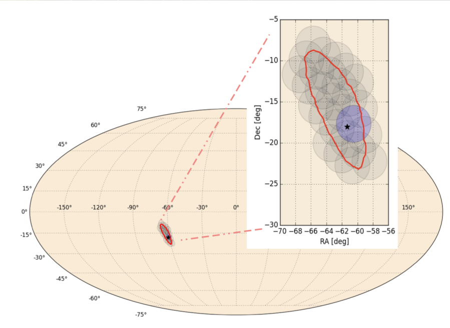
Backup slides

Backup slides

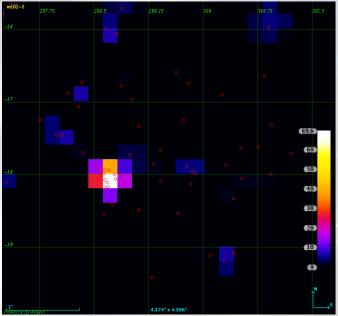
Test case

- SNR=18; 90 % credible region $\sim$ 56 deg^2
- $E_{ISO} = 10^{51}$ ergs; $E_{cut-off}$=100 GeV

GW skymap and CTA tilings



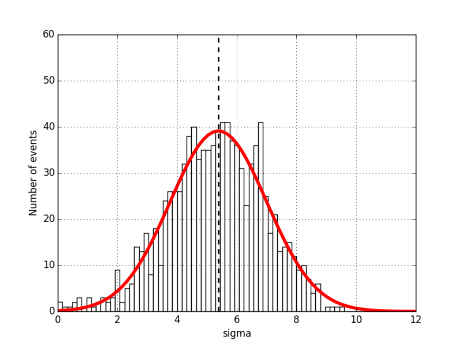
Event and Significance (TS) Map



Patricelli et al. 2018, arXiv:1801.05167

Post-trial significance distribution

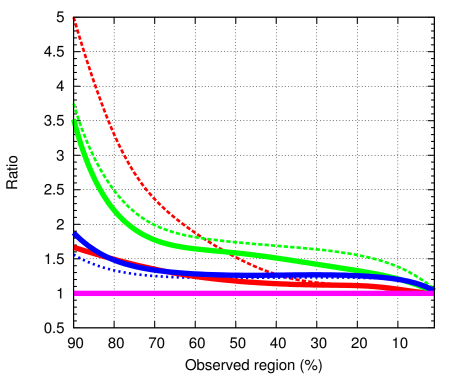
- Different observations of a source with a given intrinsic spectrum could yield different statistical significances, due to fluctuations in the number of detected photons.
- We evaluated these fluctuations repeating the simulation 1000 times



$\Rightarrow$ As expected, the distribution is well described by a Gaussian with mean (post-trials) $\mu \sim 5$!

Patricelli et al. 2018, arXiv:1801.05167

Improvement with respect to "standard" strategies (constant obs time)



Improvement in the GW sky coverage

$\Downarrow$

increase in the joint GW and EM detection rates!

example:

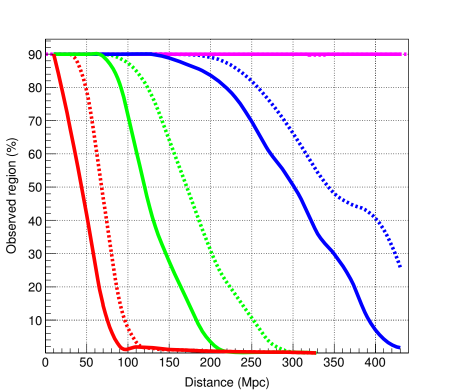
- - $E_{iso} = 10^{50}$ ergs, cut-off=100 GeV

the rate increase by a factor ~ 2

Patricelli et al. 2018, arXiv:1801.05167

CTA coverage vs Distance

The distance of the source possibly provided in the GW alert can be used to further optimize the observational strategy



Patricelli et al. 2018, arXiv:1801.05167