PROSPECTS FOR JOINT GW AND HIGH-ENERGY EM OBSERVATIONS OF NS-NS MERGERS

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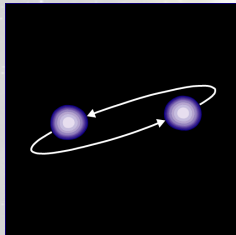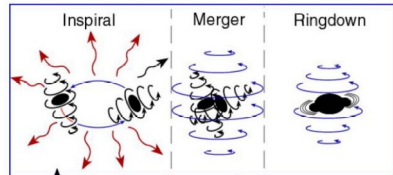in collaboration with:
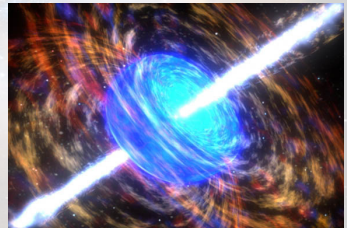M. Razzano, G. Cella, F. Fidecaro, E. Pian,
M. Branchesi, A. Stamerra

Patricelli et al., arXiv:1606.06124

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GW150914 and GW151226: the era of GW astronomy has begun!

Other promising sources for the next GW detections by Advanced LIGO and Advanced Virgo are **mergers of binary systems formed by two neutron stars (NS-NS) or a neutron star and a black hole (NS-BH)**


NS-NS and NS-BH mergers are expected to be associated with **short GRBs**

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joint GW and EM detections

Two possible scenarios:

- **EM follow-up**: a GW event is detected and an alert is sent to EM telescopes, that start looking for an EM counterpart

GW alert ⟶ Sky localization ⟶ EM follow-up
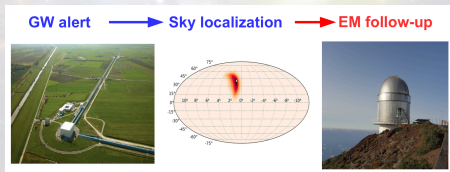
- **Externally-triggered GW search**: an EM transient event is detected and GW data are analyzed to look for possible associated GW events.

We focus on:

- **Large FOV telescopes**:
  - monitoring of a large portion of the sky → higher probability of detecting a transient source
  - good coverage of the large GW error boxes (tens to hundreds of square degrees)

- **γ-ray telescopes**:
  - γ-ray sky less "crowded" ⇒ clearer association of an EM transient to the GW event

Examples: INTEGRAL, AGILE, **Fermi**

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The Fermi mission

Two instruments:

- **GBM**
  - Energy range: 8 keV to 40 MeV
  - FOV: ~ 9.5 sr
  - Sky localization: overall median error for short GRBs of $8°$

- **LAT**
  - Energy range: 20 MeV to 300 GeV
  - FOV: ~ 2.4 sr
  - Sky localization: $r_{68} \sim 0.1°$ 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 ~ 0.7 photons cm^{-2} s^{-1}

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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 considered: 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·Z$_\odot$ (Panter et al. 2008)

- Merger rates: (Dominik et al. 2012)
  - Reference model: Standard Model B
    (it employs the best estimates of the key parameters of the physics of binary systems)
  - $\begin{cases} \text{"Optimistic" models: V12A (Z=Z}_\odot\text{) and V2A (Z=0.1 · Z}_\odot\text{)} \\ \text{"Pessimistic" models: V12B (Z=Z}_\odot\text{) and V1B (Z=0.1 · Z}_\odot\text{)} \end{cases}$

    (they differ in the treatment of the common envelope phase)

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[1]www.syntheticuniverse.org

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Step 2: GW detections and sky localizations

GW signals

- We assume non-spinning systems
  (PSR J0737-3039A has a period of ~ 23 ms $\Rightarrow \chi \sim 0.05$, see Burgay et al. 2003)
- Random inclination of the orbital plane with respect to the line of sight (θ)
- TaylorT4 waveforms (Buonanno et al. 2009)
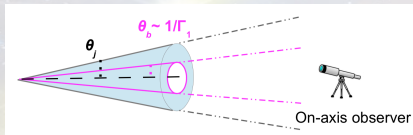
GW detections

- Detector configurations (aLIGO and AdV): 2016-2017 and 2019+ (design) (Abbott et al. 2016)
- Independent duty cycle of each interferometer: 80 % (Abbott 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)

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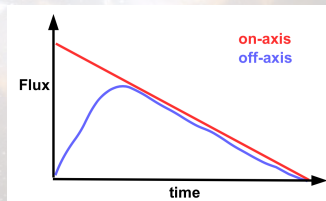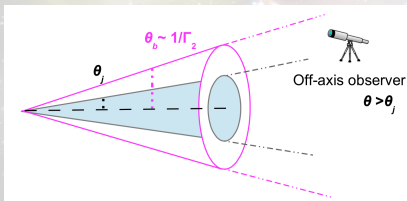GRB simulations

Step 3: GRB simulations

Assumption: All the BNS mergers are associated to a short GRB

Different approach for the *prompt* emission and *afterglow* emission:

- The prompt emission can be observed only if the GRB is on-axis

- The afterglow emission can be potentially observed also if the GRB is off-axis

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Step 3: GRB simulations - the prompt emission

Assumptions:

- The GRB prompt emission is constant within the jet angle θ_j, zero outside

- GRB jet opening angles: $0.3° \leq \theta_j \leq 30°$
  (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 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

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Step 3: GRB simulations - the prompt emission

Brightness

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

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

Lowest brightness measured by Fermi/GBM

- $P_{64,\text{Min}}^{\text{meas}}$=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)

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

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

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Step 3: GRB simulations - the 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)
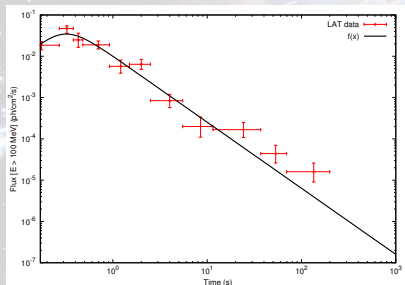
Light curve:

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

Spectrum:

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

(De Pasquale et al. 2010)

Jet opening angle:

$$\theta_j = 0.3° \text{ (Panaitescu et al. 2011)}$$

- We re-scaled this light curve to take into account the distance of the sources with respect to GRB 090510;
- For off-axis sources we further correct the light curve for the beaming angle, considering a continuous evolution of Γ.

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We estimated the integration time t_f needed for the simulated GRBs to have a fluence equal to the Fermi-LAT sensitivity:
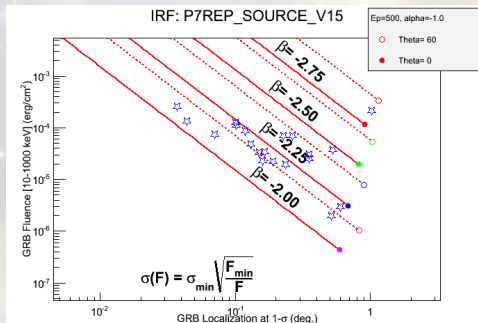
http://www.slac.stanford.edu/exp/glast/groups/canda/archive/p7rep_v15/lat_Performance.htm[2]

- 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.

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[2]Sensitivity estimated with the "Pass 7" reprocessed instrument response function. Recently, the Fermi-LAT collaboration has developed the "Pass 8" event-level analysis that provides a better modeling of the instrument response function; however, the LAT sensitivity to GRBs with this new function is not publicly available yet.

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Results: GW detections

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. $\leq 1000 \ deg^2$
	This work	0.1 (0.002 - 1.5)	3	9	16	70
2016-2017	Singer et al. 2014 [3]	1.5	2	8	15	-
	Abbott et al. 2016	0.006-20	2	14	-	-
2019+ (design)	This work	2.1 (0.08 - 30)	5	21	50	90
	Abbott et al. 2016	0.2-200	> 3-8	> 8-30	-	-

[3] These estimates refer to the 2016 scenario.

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Results: joint HE EM and GW detections - prompt emission

θ_j	EM	EM and GW 2016-2017	EM and GW design
deg	yr^{-1}	yr^{-1}	yr^{-1}
0.3	0.04	$< 10^{-3}$	0.008
	$< 10^{-3}$ - 0.5	$< 10^{-3}$ - 0.003	$< 10^{-3}$ - 0.07
10	1.3	0.01	0.2
	0.1 - 48	$< 10^{-3}$ - 0.1	0.001 - 3
30	4	0.02	0.5
	0.05 - 55	$< 10^{-3}$ - 0.3	0.008 - 7

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Results: joint HE EM and GW detections - afterglow emission

		No latency		
Integration Time (s)	EM (yr^{-1})	EM and GW 2016-2017 (yr^{-1})		EM and GW design (yr^{-1})
10	0.1 (0.003 - 1)	0.001 ($< 10^{-3}$ - 0.01)		0.02 (0.001 - 0.2)
10^2	0.2 (0.004 - 2)	0.002 ($< 10^{-3}$ - 0.02)		0.04 (0.001 - 0.4)
10^3	0.3 (0.009 - 4)	0.003 ($< 10^{-3}$ - 0.05)		0.07 (0.002 - 0.8)
10^4	0.5 (0.02 - 7)	0.007 ($< 10^{-3}$ - 0.09)		0.1 (0.004 - 1)

		10 minute latency		
Integration Time (s)	EM (yr^{-1})	EM and GW 2016-2017 (yr^{-1})		EM and GW design (yr^{-1})
10	0.002 ($< 10^{-3}$ - 0.05)	$< 10^{-3}$ ($< 10^{-3}$ - 0.01)		$< 10^{-3}$ ($< 10^{-3}$ - 0.04)
10^2	0.09 (0.003 - 1)	0.002 ($< 10^{-3}$ - 0.02)		0.03 (0.001 - 0.4)
10^3	0.3 (0.009 - 4)	0.003 ($< 10^{-3}$ - 0.05)		0.07 (0.002 - 0.8)
10^4	0.5 (0.02 - 6)	0.007 ($< 10^{-3}$ - 0.09)		0.1 (0.004 -1)

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Conclusions

- We have estimated the GW detection rates and sky localizations for NS-NS mergers

- We have estimated the joint HE EM and GW detection rates with *Fermi*

  - Prompt emission: as the interferometers approach their final sensitivity, there could be up to 3 joint detections in 1 year

  - Afterglow emission: long exposure times are needed to increase the chance for a coincident EM and GW detection

- *Fermi* represents a promising instrument to identify the EM counterpart of GW events
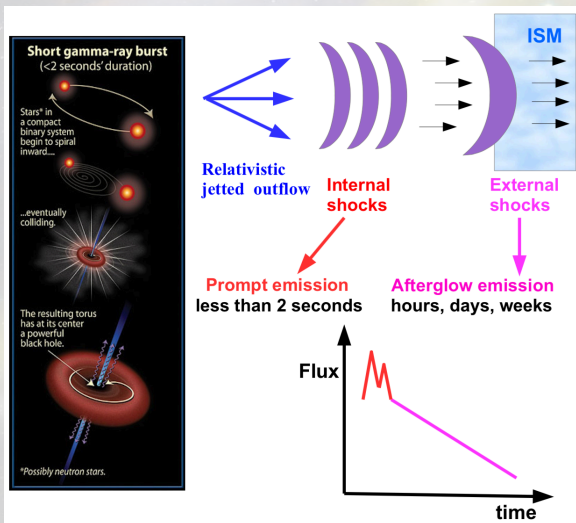
Patricelli et al., arXiv:1606.06124

Next steps

- Extension to other EM observatories (CTA, INTEGRAL etc)
- Extension to NS-BH systems

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Backup slides

Backup slides

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Short GRBs

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GRB afterglow emission - Lorentz factor

Evolution of the Lorentz factor Γ of the shell using an approximate sharp transition from the coasting phase, when

$$\Gamma \sim \Gamma_0$$

to the deceleration phase, when

$$\Gamma(t_{\mathrm{obs}}) = \Gamma_0 (t_{\mathrm{obs}}/t_{\mathrm{dec}})^{-3/8};$$

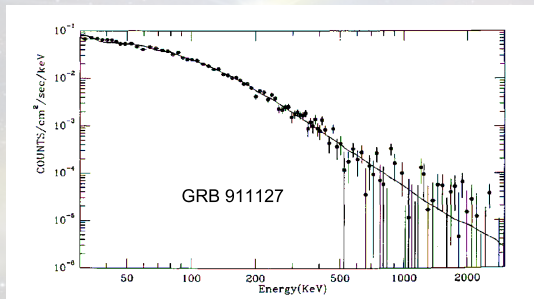furthermore, after the jet break we further evolve the Lorentz factor as

$$\Gamma(t_{\mathrm{obs}}) \propto (t_{\mathrm{obs}}/t_{\mathrm{j}})^{-1/2}$$

(see Sari et al. 1998, Rhoads et al. 1999).

- $\Gamma_0 = 2000$ (Ghirlanda et al. 2010, Ghisellini et al. 2010)
- $t_{\mathrm{dec}} \sim 0.3$ s, corresponding to t_{peak} (see also De Pasquale et al. 2010, Corsi et al. 2010)
- $t_{\mathrm{j}} \sim 2 \ 10^3$ s (Panaitescu et al. 2010)

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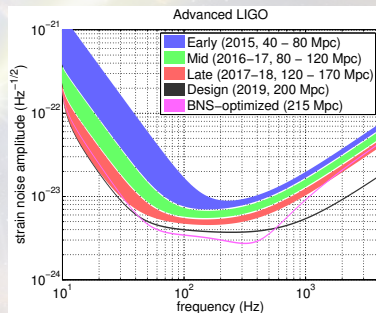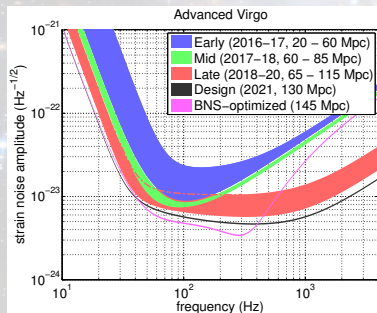## The Band function

$$N_E(E) = \begin{cases} A \left(\frac{E}{100keV} \right)^{\alpha} \exp \left(-\frac{E}{E_0} \right) & (\alpha - \beta)E_0 \geq E \\ A \left[\frac{(\alpha-\beta)E_0}{100keV} \right]^{(\alpha-\beta)} \exp(\beta-\alpha) \left(\frac{E}{100keV} \right)^{\beta} & (\alpha - \beta)E_0 \leq E \end{cases}$$

Band et al. (1993)

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The Advanced Virgo and Advanced LIGO sensitivities

Abbott et al. (2016)

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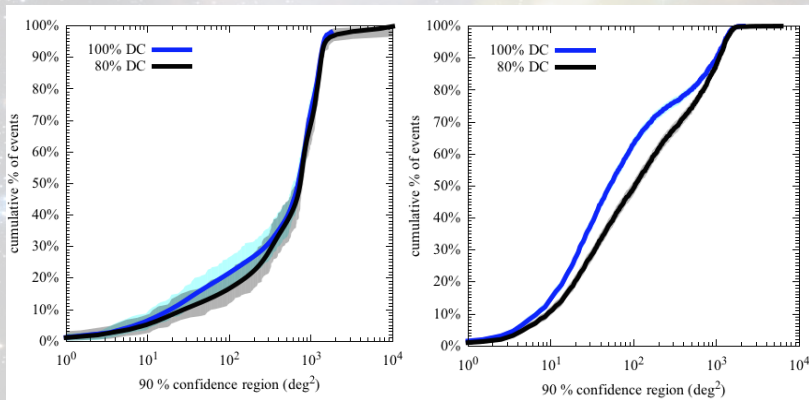
Results: GW detections - I

Figure: Cumulative histograms of sky localization areas of the 90 % confidence region in the 2016-2017 (left) and in the design (right) scenarios, for a 100 % (blue) and an 80 % (black) DC. The Standard model B has been considered.

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GW offline searches triggered by EM detections

Advantages

- Decrease in the time window ($t_{\rm obs}$)
- Decrease in the sky area (Ω)

$\Rightarrow$ Lower SNR threshold required to achieve the same false alarm rate:

$$\rho_c^{trig} \sim \sqrt{2 \times \log\left[\exp\left(\frac{\rho_c^2}{2}\right) \frac{t_{\rm obs} \times \Omega}{t_{\rm obs}^0 \times \Omega_0}\right]} \qquad \text{(Bartos \& Màrka 2015)}$$

Blind GW searches:

- ρ_c=12, $t_{\rm obs}^0$=1 year, Ω_0=4 π

Triggered GW searches:

- $t_{\rm obs}$=Δt $\times$ N$_{\rm GRB}$ (for 1 year of data taking)

  Δt= 6 s ([-5,1] s time window around the GRB trigger, see Abadie et al. 2012)

  N$_{\rm GRB}$ $\sim$ 1 (Standard Model B, θ_j=10$°$)

- Ω=100 deg^2 (spatial resolution of GW detectors)

$$\Rightarrow \rho_c^{trig} \sim \mathbf{10}$$

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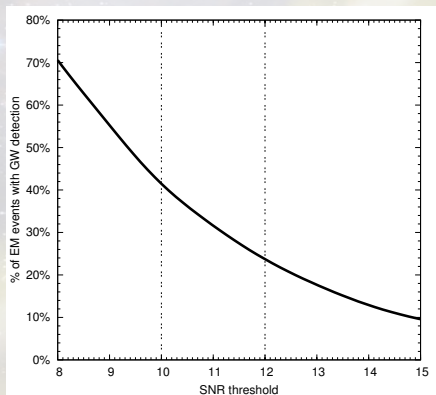## Results: Externally triggered GW searches

Figure: Percentage of short GRB detectable by *Fermi*-GBM that also have an associated GW detection, for different SNR threshold. The Standard model B, $\theta_j = 10°$ and the design configuration of Advanced Virgo and Advanced LIGO have been considered.