Prospects for joint GW and high-energy EM observations of BNS mergers

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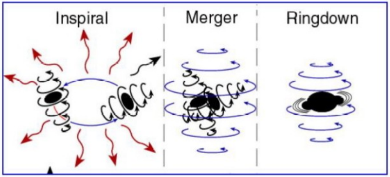
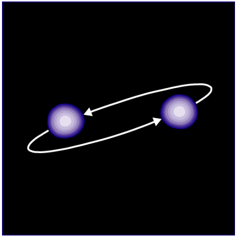
Summary

1. Introduction
2. The method
   - NS-NS mergers
   - GW detections and sky localizations
   - GRB simulations
3. Results
   - GW detections
   - Joint HE EM and GW detections
4. Conclusions and future developments

GW150914: first direct observation of Gravitational Waves from a binary BH merger!

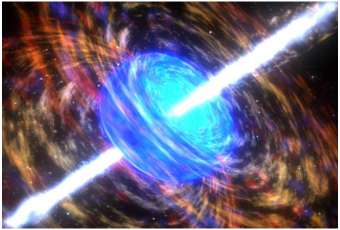
Other promising sources for the next GW detections by Advanced LIGO and Advanced Virgo are **mergers of NS-NS and NS-BH systems**



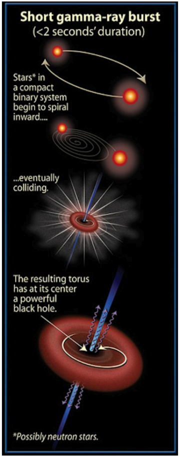


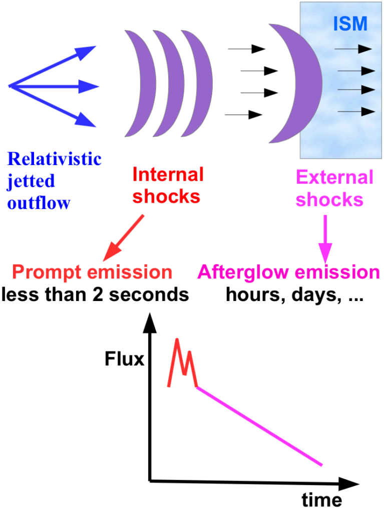
NS-NS and NS-BH mergers are expected to be associated with **short GRBs**

$\Rightarrow$



Short GRBs


Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.


ISM
Relativistic jetted outflow
Internal shocks
External shocks
Prompt emission
less than 2 seconds
Afterglow emission
hours, days, ...
Flux
time

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
- **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:
  - higher probability of detecting a transient source in the monitored portion of sky
  - good coverage of the large GW error boxes (tens to hundreds of square degrees)
- γ-ray telescopes:
  - γ-ray sky less "crowded" $\Rightarrow$ clearer association of an EM transient to the GW event

Among the various γ-ray observatories, **Fermi** is one of those that better combines huge sky and energy coverage.

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: $r_{68} \sim 0.8^\circ$ 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 rates are 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 in volume
- Merging systems: Synthetic Universe (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
  - "Optimistic" models: V12A (Z=Z$_\odot$) and V2A (Z=0.1·Z$_\odot$)
  - "Pessimistic" models: V12B (Z=Z$_\odot$) and V1B (Z=0.1·Z$_\odot$)
- 1000 realizations, each one for a 1 year observing period

Step 2: GW detections and sky localizations

GW signals

- We assume non-spinning systems
- Random inclination of the orbital plane θ with respect to the line of sight
- 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)

Step 3: GRB simulations - the prompt emission

Assumptions:

- All the BNS mergers are associated to a short GRB;
- The prompt emission can be observed only if the GRB is on-axis ($\theta \leq \theta_j$);

  (The GRB prompt emission is constant within the jet angle θ_j, zero outside)
- 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° (see Duffell et al. 2015)

Detection with *Fermi*/GBM

- *Fermi*/GBM FOV: 9.5 sr
- GBM duty cycle: 50 %
- *Fermi*/GBM sensitivity vs GRB brightness?

Step 3: GRB simulations - the prompt emission

Brightness: 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

- $P_{64,\mathrm{Min}}^{\mathrm{meas}}$=0.75±0.25 ph/cm2/s

Lowest expected brighness for the simulated short GRBs

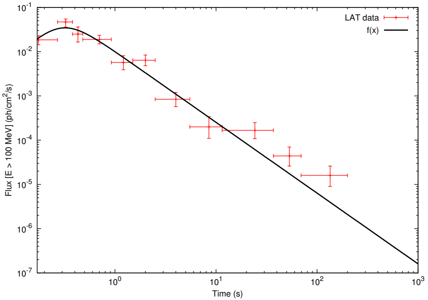
- Minimum L: 2 10^{50} erg/s (lowest luminosity of short GRBs with known redshift)
- Maximum distance: 500 Mpc (z∼0.12)
- $N(E)$: Band function (with the typical parameters of Fermi/GBM short GRBs)

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

⇒ GBM is sensitive enough to detect all the GRBs in our sample

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)



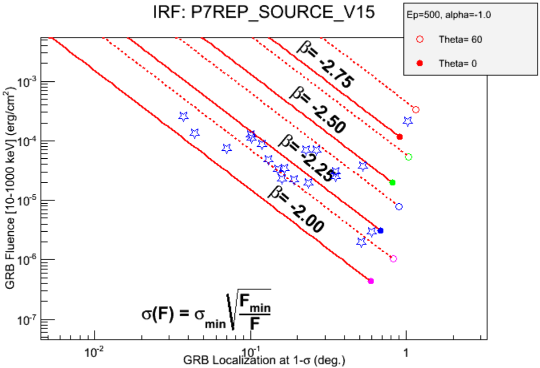
$$F(\mathrm{t}) = \mathrm{A}\frac{(\mathrm{t}/\mathrm{t_{peak}})^{\alpha}}{1+(\mathrm{t}/\mathrm{t_{peak}})^{\alpha+\omega}}$$

Fixing $\alpha = 2$ as required by the standard afterglow theory (Sari et al. 1999), we found

- A=0.07±0.01 ph cm^{-2} s^{-1}
- ω =1.60±0.15
- $\mathrm{t_{peak}}$=0.301±0.04 s
  (see also Ghirlanda et al. 2010)

We simulate the GeV afterglows by re-scaling 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.

Step 3: GRB simulations - the afterglow emission



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

- We extrapolated this sensitivity to the energy range 0.1-300 GeV
- We estimated the integration time t_f needed for the simulated GRBs to have a fluence equal to the Fermi-LAT sensitivity; we choose the value of sensitivity corresponding to a GRB localization of 1 deg, for β=-2.

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
2016-2017	This work	0.1 (0.002 - 1.5)	3	9	16	70
	Singer et al. 2014 [1]	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	-	-

[1] These estimates refer to the 2016 scenario.

Results: joint HE EM and GW detections - prompt emission

θ_j	EM	EM and GW	EM and GW
		2016-2017	**design**
deg	yr^{-1}	yr^{-1}	yr^{-1}
0.3	0.045	$< 10^{-3}$	0.008
	$< 10^{-3}$ - 0.525	$< 10^{-3}$ - 0.003	$< 10^{-3}$ - 0.068
10	1.256	0.010	0.2130
	0.021 - 18.201	$< 10^{-3}$ - 0.130	0.001 - 2.692
30	3.736	0.022	0.549
	0.052 - 54.560	$< 10^{-3}$ - 0.348	0.008 - 7.249

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	0.12 (0.003 - 1.53)	0.001 ($< 10^{-3}$ - 0.01)	0.02 (0.001 - 0.25)
100	0.20 (0.004 - 2.44)	0.002 ($< 10^{-3}$ - 0.02)	0.04 (0.001 - 0.45)
10^3	0.32 (0.009 - 4.15)	0.003 ($< 10^{-3}$ - 0.05)	0.07 (0.002 - 0.81)
10^4	0.52 (0.02 - 6.64)	0.007 ($< 10^{-3}$ - 0.09)	0.12 (0.004 - 1.36)

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)
100	0.09 (0.003 - 1.17)	0.002 ($< 10^{-3}$ - 0.02)	0.03 (0.001 - 0.37)
10^3	0.30 (0.009 - 3.83)	0.003 ($< 10^{-3}$ - 0.05)	0.07 (0.002 - 0.80)
10^4	0.51 (0.02 - 6.47)	0.007 ($< 10^{-3}$ - 0.09)	0.12 (0.004 -1.34)

Conclusions

Conclusions

- We have estimated the GW detection rates and sky localizations for NS-NS mergers, finding values consistent with the ones reported in literature
- We have presented estimates of the joint HE EM and GW detection rates with *Fermi*

Next steps

- Extension to NS-BH systems
- Extension of the work to other observatories (X-ray, optical...)
- Use of galaxy catalogs in the simulations
- Public database?

Use of galaxy catalogs

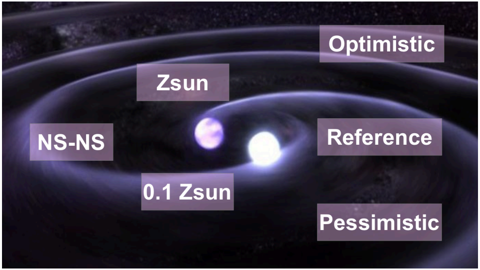
Which galaxy catalogs?

- Good level of completeness
- Good redshift coverage (at least up to $\sim$ 1 Gpc)

- **GLADE** (Dalya et al.)
  - http://aquarius.elte.hu/glade/index.html
  - Constructed from four existing galaxy catalogs: GWGC, 2MPZ, 2MASS XSC and HyperLEDA
  - Complete up to $\sim$ 70 Mpc (50 % of completness at $\sim$ 300 Mpc)
- **GWENS** (Nissanke et al.)
  - https://astro.ru.nl/catalogs/sdss_gwgalcat/index.html
  - Obtained using SDSS photometric and spectroscopic data
  - Problems within 100 - 200 Mpc, but...
  - ...it extends up to $\sim$1 Gpc

Public database?

- Which data?
  - Ascii tables with all simulated NS-NS systems (masses, sky position, distance...) $\sim$ 130 Mb
  - Ascii tables with GW detections (SNR, sky localization area...) $\sim$ 80 Mb
  - Skymaps (fits files) $\sim$ 50 Gb
- VO tools?



Computing resources

Simulations:

- 1000 1-year runs
- 2 metallicities (Z)
- 3 theoretical models for each Z
- 2 GW detector configurations

$\Rightarrow$ 12000 realizations

Example

- 1 job
  (1 run, Standard Model B, "2016-2017" configuration)
- CPU time: $\sim$2200 s
- elapse time: $\sim$ 1 hour
- Memory usage: $\sim$ 1.5 Gb

Backup slides

Backup slides

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

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

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

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

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

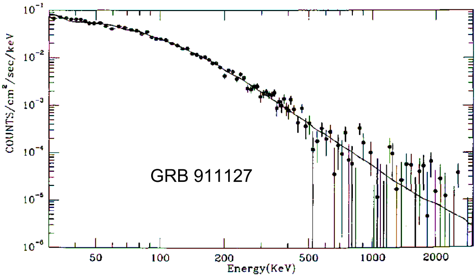
- Γ_0= 2000 (Ghirlanda et al. 2010, Ghisellini et al. 2010)
- $\mathrm{t_{dec}}$ ~0.3 s, corresponding to $\mathrm{t_{peak}}$ (see also De Pasquale et al. 2010, Corsi et al. 2010)

  $\rightarrow \mathrm{t_{dec}^{sim}}=\mathrm{t_{dec}} \times \frac{1+z}{1+z_0}$
- $\mathrm{t_j} \sim 2\ 10^3$ s (Panaitescu et al. 2010)

  $\rightarrow \mathrm{t_j^{sim}}=\mathrm{t_j} \times \frac{(1+z)(\theta+\theta_j)^{8/3}}{(1+z_0)\theta_j^{8/3}}$

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)