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

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SciNeGHE 2016
October 18-21, 2016
Pisa

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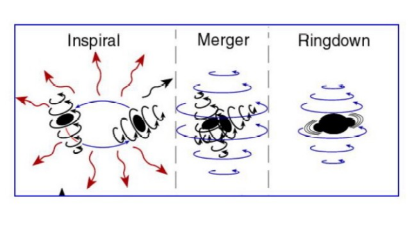
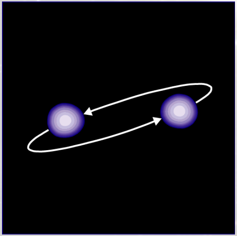
Patricelli et al., arXiv:1606.06124

Summary

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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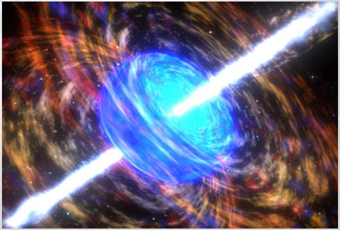
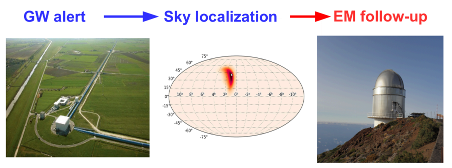


joint GW and EM detections

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



- **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 $\rightarrow$ 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" $\Rightarrow$ clearer association of an EM transient to the GW event

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

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

[1] www.syntheticuniverse.org

Step 2: GW detections and sky localizations

GW signals

- We assume non-spinning systems
  (PSR J0737-3039A has a period of $\sim$ 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)

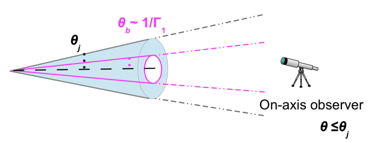
GW detections

- Detector configurations (aLIGO and AdV):
  2016-2017 ("O2") and 2019+ (design), see 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)

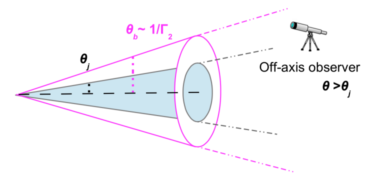
Step 3: GRB simulations

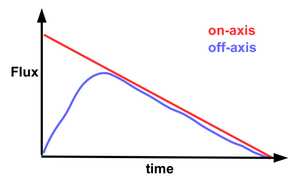
Assumption: All the BNS mergers are associated to a short GRB

- 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...





...but off-axis emission is expected to arise at later times

$\Rightarrow$ **We only focus on on-axis sources** $(\theta \leq \theta_j)$

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: $0.3^\circ \leq \theta_j \leq 30^\circ$
  (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 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 - 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

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

Lowest brightness measured by Fermi/GBM

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

Lowest expected brighness for the simulated short GRBs

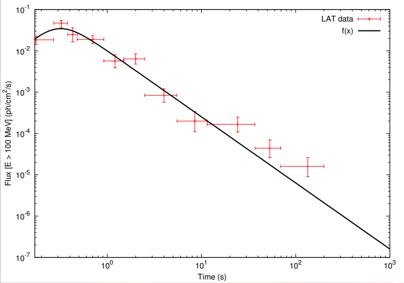
- Minimum L: 2 10^{50} erg/s
  (lowest value for short GRBs with known redshift, see Waderman & Piran 2015)
- Maximum distance: 500 Mpc (z∼0.12)
- $N(E)$: Band function with the typical parameters of Fermi/GBM short GRBs (see Nava et al. 2011, Waderman & Piran 2015)

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

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

Step 3: GRB simulations - 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:

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

Spectrum:

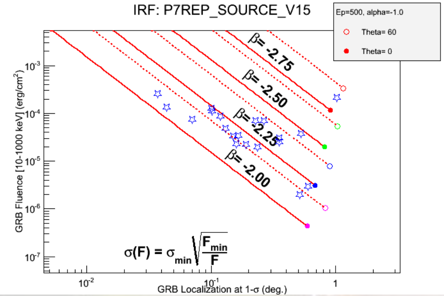
$$N(E) \propto E^{\beta}, \qquad \beta = -2.1$$

(De Pasquale et al. 2010)

- We corrected 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 - the afterglow emission

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[2]

We considered two cases:

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

[2] Sensitivity estimated with the "Pass 7" reprocessed instrument response function. 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.

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:

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

Blind GW searches:

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

Triggered GW searches:

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

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

  $\rm N_{GRB}$ $\sim$ 1
- Ω=100 deg^2 (approximate sky area for GW detections with 2 interferometers)

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

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	0.05 (0.001 - 0.7)	3	9	16	70
	Singer et al. 2014[3]	1.5	2	8	15	-
	Abbott et al. 2016	0.006-20	2	14	-	-
2019+ (design)	This work	1 (0.04 - 15)	5	21	50	90
	Abbott et al. 2016	0.2-200	$>$ 3-8	$>$ 8-30	-	-

[3] These estimates refer to the 2016 scenario.

Results: joint HE EM and GW detections - prompt emission

θ_j deg	EM yr^{-1}	EM and GW **2016-2017** yr^{-1}	EM and GW **design** yr^{-1}
0.3	$< 10^{-3}$ ($< 10^{-3}$) $< 10^{-3}$ - 0.006 ($< 10^{-3}$ - 0.002)	$< 10^{-3}$ ($< 10^{-3}$) ($< 10^{-3}$ - $< 10^{-3}$)	$< 10^{-3}$ ($< 10^{-3}$) ($< 10^{-3}$ - $< 10^{-3}$)
10	0.5 (0.2) 0.02 - 6.6 (0.003 - 2.4)	0.002 (0.001) $< 10^{-3}$ - 0.04 ($< 10^{-3}$ - 0.02)	0.06 (0.03) 0.002 - 0.9 ($< 10^{-3}$ - 0.5)
30	4 (1.5) 0.1 - 59 (0.02 - 22)	0.02 (0.007) $< 10^{-3}$ - 0.4 ($< 10^{-3}$ - 0.1)	0.6 (0.2) 0.02 - 7.6 (0.003 - 2.6)

Results: Externally triggered GW searches

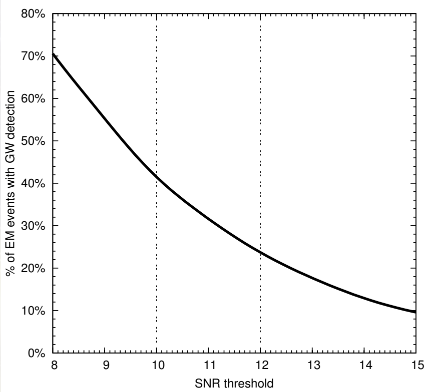


Figure: Percentage of short GRB detectable by *Fermi*-GBM that also have an associated GW detection, for different SNR threshold. The Standard model B and the design configuration of Advanced Virgo and Advanced LIGO have been considered.

Results: joint HE EM and GW detections - afterglow emission

no latency

Integration Time (s)	E_γ (ergs)	EM (yr^{-1})	EM and GW 2016-2017 (yr^{-1})	EM and GW design (yr^{-1})
10	3.5×10^{52}	0.5 (0.02 - 6.6)	0.002 ($< 10^{-3}$ - 0.04)	0.06 (0002 - 0.9)
	1×10^{49}	0.08 (0.002 - 1.1)	0.002 ($< 10^{-3}$ - 0.04)	0.05 ($< 10^{-3}$ - 0.6)
10^2	3.5×10^{52}	0.5 (0.02 - 6.6)	0.002 ($< 10^{-3}$ - 0.04)	0.06 (0002 - 0.9)
	1×10^{49}	0.09 (0.002 - 1.2)	0.002 ($< 10^{-3}$ - 0.04)	0.05 ($< 10^{-3}$ - 0.6)
10^3	3.5×10^{52}	0.5 (0.02 - 6.6)	0.002 ($< 10^{-3}$ - 0.04)	0.06 (0002 - 0.9)
	1×10^{49}	0.1 (0.002 - 1.2)	0.002 ($< 10^{-3}$ - 0.04)	0.05 ($< 10^{-3}$ - 0.6)

10 min latency

Integration Time (s)	E_γ (ergs)	EM (yr^{-1})	EM and GW 2016-2017 (yr^{-1})	EM and GW design (yr^{-1})
10	3.5×10^{52}	0.01 ($< 10^{-3}$ - 0.2)	0.001 ($< 10^{-3}$ - 0.02)	0.007 ($< 10^{-3}$ - 0.1)
	1×10^{49}	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)
10^2	3.5×10^{52}	0.3 (0.01 - 4.1)	0.002 ($< 10^{-3}$ - 0.04)	0.06 (0.002 - 0.9)
	1×10^{49}	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)
10^3	3.5×10^{52}	0.5 (0.02 - 6.6)	0.002 ($< 10^{-3}$ - 0.04)	0.06 (0.002 - 0.9)
	1×10^{49}	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)	$< 10^{-3}$ ($< 10^{-3}$ - $< 10^{-3}$)

Conclusions

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 $\sim$3 joint detections in 1 year
  - Afterglow emission: there is some chance for a coincident EM and GW detection also with a latency of 10 min for the most energetic GRBs
- *Fermi* represents a promising instrument to identify the EM counterpart of GW events

Patricelli et al., submitted to JCAP (arXiv:1606.06124)

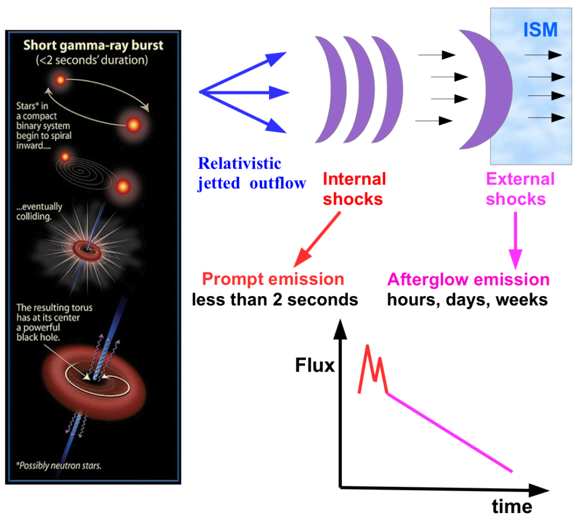
Next steps

- Extension to other GW detectors (KAGRA and LIGO-India, see Wang's poster) and other EM observatories (CTA, INTEGRAL etc)
- Extension to NS-BH systems (see Wang's poster)

Backup slides

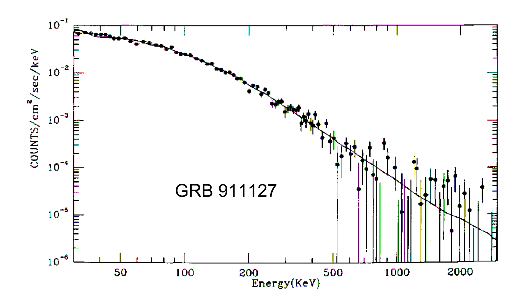
Backup slides

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, weeks
Flux
time

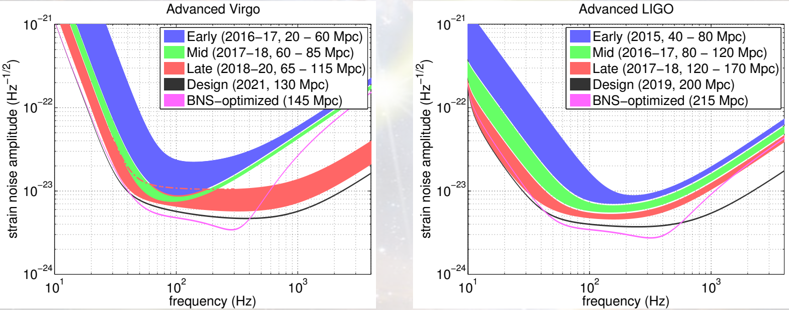
The Band function

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



Band et al. (1993)

The Advanced Virgo and Advanced LIGO sensitivities



Abbott et al. (2016)

Results: GW detections - I

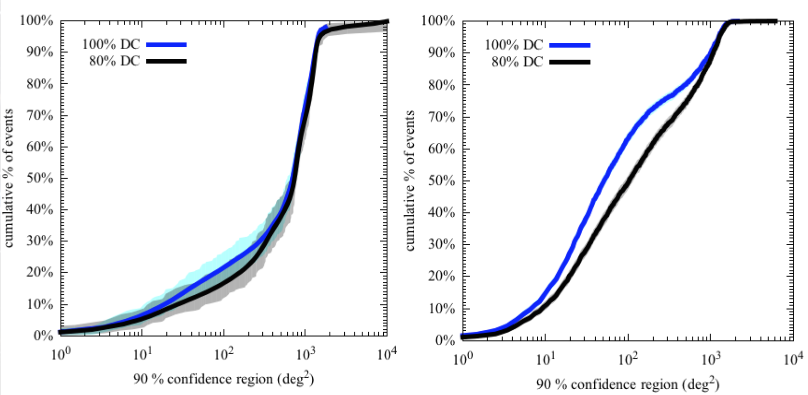


Figure: Cumulative histograms of sky localization areas of the 90 % confidence region in the 2016-2017 (left) and in the design (right) scenarios, for a 100 % (blue) and an 80 % (black) DC. The Standard model B has been considered.

Alternative approach: from the local short GRB rate to the BNS rate

Assumption: All the short GRBs have a BNS progenitor

$$\mathrm{R_{BNS}} = \frac{\rho_{\mathrm{sGRB}}}{f_b} \times \frac{4\pi D^3}{3}$$

- ρ_{sGRB} is the local short GRB rate;
- $f_b = 1 - cos(\theta_j)$ is the beaming factor (fraction of GRBs that are on-axis)
- D is the maximum distance considered (500 Mpc)

Other assumptions:

- ρ_{sGRB}: $\begin{cases} 1\ \mathrm{Gpc^{-3}\ yr^{-1}}\ \text{(Wanderman \& Piran 2015);} \\ 0.2\ \mathrm{Gpc^{-3}\ yr^{-1}}\ \text{(Ghirlanda et al. 2016, model ``a'')} \\ 0.8\ \mathrm{Gpc^{-3}\ yr^{-1}}\ \text{(Ghirlanda et al. 2016, model ``c'')} \end{cases}$
- $0.3^\circ \leq \theta_j \leq 30^\circ$

GW and EM detections:

Same procedure applied in the previous approach

Results based on the local short GRB rate

θ_j deg	Model	BNS yr^{-1}	EM yr^{-1}	GW **2016-2017** yr^{-1}	GW **design** yr^{-1}
	Wanderman & Piran 2015	38200^{+16810}_{-13000}	$0.2^{+0.09}_{-0.07}$	67^{+29}_{-23}	1340^{+590}_{-450}
0.3	Ghirlanda et al. 2016, "a"	7640^{+1530}_{-2670}	$0.04^{+0.008}_{-0.01}$	13^{+3}_{-5}	267^{+53}_{-94}
	Ghirlanda et al. 2016, "c"	30560^{+11460}_{-5730}	$0.16^{+0.06}_{-0.03}$	53^{+20}_{-10}	1079^{+401}_{-200}
	Wanderman & Piran 2015	35^{+15}_{-12}	$0.2^{+0.09}_{-0.07}$	$0.06^{+0.03}_{-0.02}$	$1.2^{+0.5}_{-0.4}$
10	Ghirlanda et al. 2016, "a"	$6.9^{+1.4}_{-2.4}$	$0.04^{+0.008}_{-0.01}$	$0.01^{+0.002}_{-0.004}$	$0.2^{+0.05}_{-0.08}$
	Ghirlanda et al. 2016, "c"	28^{+10}_{-5}	$0.16^{+0.06}_{-0.03}$	$0.05^{+0.02}_{-0.01}$	$1.0^{+0.4}_{-0.2}$
	Wanderman & Piran 2015	$4^{+1.7}_{-1.3}$	$0.2^{+0.09}_{-0.07}$	$0.005^{+0.003}_{-0.002}$	$0.14^{+0.06}_{-0.05}$
30	Ghirlanda et al. 2016, "a"	$0.8^{+0.2}_{-0.3}$	$0.04^{+0.008}_{-0.01}$	$0.001^{+0.0003}_{-0.0005}$	$0.03^{+0.005}_{-0.01}$
	Ghirlanda et al. 2016, "c"	$3^{+1}_{-0.6}$	$0.16^{+0.06}_{-0.03}$	$0.005^{+0.002}_{-0.001}$	$0.1^{+0.04}_{-0.02}$

Results based on the local short GRB rate