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

Barbara Patricelli\textsuperscript{1,2}

\textsuperscript{1}Università di Pisa
\textsuperscript{2}INFN - Sezione di Pisa

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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
Introduction

The method: simulating NS-NS and their multimessenger detection

Results

Conclusions and future developments

Summary

1 Introduction

2 The method: simulating NS-NS and their multimessenger detection
   - NS-NS mergers
   - GW detections and sky localizations
   - GRB simulations
   - Externally-triggered GW search

3 Results
   - GW detections
   - Joint HE EM and GW detections

4 Conclusions and future developments
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
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 → 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
The Fermi mission

Two instruments:

- **GBM**
  - Energy range: 8 keV to 40 MeV
  - FOV: \( \sim 9.5 \text{ sr} \)
  - Sky localization: overall median error for short GRBs of \( 8^\circ \)

- **LAT**
  - Energy range: 20 MeV to 300 GeV
  - FOV: \( \sim 2.4 \text{ sr} \)
  - 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 \( \sim 0.7 \text{ photons cm}^{-2} \text{ s}^{-1} \)
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
- \( \rho_{\text{galaxies}} = 0.0116 \, \text{Mpc}^{-3} \) (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)
  - \{“Optimistic” models: V12A \((Z=Z_\odot)\) and V2A \((Z=0.1 \cdot Z_\odot)\)
    “Pessimistic” models: V12B \((Z=Z_\odot)\) and V1B \((Z=0.1 \cdot Z_\odot)\)
  \}
  
  (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 ($\theta$)
- TaylorT4 waveforms (Buonanno et al. 2009)

GW detections
- 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

⇒ **We only focus on on-axis sources** ($\theta \leq \theta_j$)
**Assumptions:**

- The GRB prompt emission is constant within the jet angle $\theta_j$, 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” $\theta_j$: $10^\circ$  
  (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:

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

Lowest brightness measured by Fermi/GBM

- $P_{64,\text{Min}} = 0.75 \pm 0.25 \text{ ph/cm}^2/\text{s}$ (VizieR Online Data Catalog)

Lowest expected brightness for the simulated short GRBs

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

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

$$\Rightarrow \text{GBM is sensitive enough to detect all the on-axis GRBs in our sample}$$
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)

![Graph showing light curve and spectrum of GRB 090510](image)

Light curve:

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

Spectrum:

\[ N(E) \propto E^\beta, \quad \beta = -2.1 \]

(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: \(10^{49} \text{ ergs} \leq E_\gamma \leq 3.5 \times 10^{52} \text{ ergs}\) (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:

$$\sigma(F) = \sigma_{\min} \sqrt{\frac{F_{\min}}{F}}$$

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 $\beta=-2$ 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 (EM follow-up)

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$^2$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 ($t_{\text{obs}}$)
- Decrease in the sky area ($\Omega$)

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

$$
\rho_c^{\text{trig}} \sim \sqrt{2 \times \log \left[ \exp \left( \frac{\rho_c^2}{2} \right) \frac{t_{\text{obs}} \times \Omega}{t_0^{\text{obs}} \times \Omega_0} \right]} \quad \text{(Bartos & M`ärka 2015)}
$$

**Blind GW searches:**

- $\rho_c=12$, $t_0^{\text{obs}}=1$ year, $\Omega_0=4 \pi$

**Triggered GW searches:**

- $t_{\text{obs}}=\Delta t \times N_{\text{GRB}}$ (for 1 year of data taking)
  
  $\Delta t=6$ s ($[-5,1]$ s time window around the GRB trigger, see Abadie et al. 2012)

  $N_{\text{GRB}} \sim 1$

- $\Omega=100$ deg$^2$ (approximate sky area for GW detections with 2 interferometers)

  $\Rightarrow \rho_c^{\text{trig}} \sim 10$
### Results: GW detections

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Work</th>
<th>Number of BNS detections (yr(^{-1}))</th>
<th>% of BNS with Loc. (\leq 5) deg(^2)</th>
<th>% of BNS with Loc. (\leq 20) deg(^2)</th>
<th>% of BNS with Loc. (\leq 100) deg(^2)</th>
<th>% of BNS with Loc. (\leq 1000) deg(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016-2017</td>
<td>This work</td>
<td>0.05 (0.001 - 0.7)</td>
<td>3</td>
<td>9</td>
<td>16</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Singer et al. 2014</td>
<td>1.5</td>
<td>2</td>
<td>8</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Abbott et al. 2016</td>
<td>0.006-20</td>
<td>2</td>
<td>14</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2019+ (design)</td>
<td>This work</td>
<td>1 (0.04 - 15)</td>
<td>5</td>
<td>21</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Abbott et al. 2016</td>
<td>0.2-200</td>
<td>&gt; 3-8</td>
<td>&gt; 8-30</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^3\)These estimates refer to the 2016 scenario.
## Results: joint HE EM and GW detections - prompt emission

<table>
<thead>
<tr>
<th>$\theta_j$</th>
<th>EM</th>
<th>EM and GW 2016-2017</th>
<th>EM and GW design</th>
</tr>
</thead>
<tbody>
<tr>
<td>deg yr$^{-1}$</td>
<td></td>
<td>yr$^{-1}$</td>
<td>yr$^{-1}$</td>
</tr>
<tr>
<td>0.3</td>
<td>$&lt; 10^{-3}$ ($&lt; 10^{-3}$)</td>
<td>$&lt; 10^{-3}$ ($&lt; 10^{-3}$)</td>
<td>$&lt; 10^{-3}$ ($&lt; 10^{-3}$)</td>
</tr>
<tr>
<td></td>
<td>$&lt; 10^{-3} - 0.006$ ($&lt; 10^{-3} - 0.002$)</td>
<td>($&lt; 10^{-3} - &lt; 10^{-3}$)</td>
<td>($&lt; 10^{-3} - &lt; 10^{-3}$)</td>
</tr>
<tr>
<td>10</td>
<td>0.5 (0.2)</td>
<td>0.002 (0.001)</td>
<td>0.06 (0.03)</td>
</tr>
<tr>
<td></td>
<td>0.02 - 6.6 (0.003 - 2.4)</td>
<td>$&lt; 10^{-3} - 0.04$ ($&lt; 10^{-3} - 0.02$)</td>
<td>0.002 - 0.9 ($&lt; 10^{-3} - 0.5$)</td>
</tr>
<tr>
<td>30</td>
<td>4 (1.5)</td>
<td>0.02 (0.007)</td>
<td>0.6 (0.2)</td>
</tr>
<tr>
<td></td>
<td>0.1 - 59 (0.02 - 22)</td>
<td>$&lt; 10^{-3} - 0.4$ ($&lt; 10^{-3} - 0.1$)</td>
<td>0.02 - 7.6 (0.003 - 2.6)</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Integration Time (s)</th>
<th>$E_\gamma$ (ergs)</th>
<th>EM (yr$^{-1}$)</th>
<th>EM and GW 2016-2017 (yr$^{-1}$)</th>
<th>EM and GW design (yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$3.5 \times 10^{52}$</td>
<td>0.5 (0.02 - 6.6)</td>
<td>0.002 (&lt; 10$^{-3}$ - 0.04)</td>
<td>0.06 (0002 - 0.9)</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{49}$</td>
<td>0.08 (0.002 - 1.1)</td>
<td>0.002 (&lt; 10$^{-3}$ - 0.04)</td>
<td>0.05 (&lt; 10$^{-3}$ - 0.6)</td>
</tr>
<tr>
<td>$10^2$</td>
<td>$3.5 \times 10^{52}$</td>
<td>0.5 (0.02 - 6.6)</td>
<td>0.002 (&lt; 10$^{-3}$ - 0.04)</td>
<td>0.06 (0002 - 0.9)</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{49}$</td>
<td>0.09 (0.002 - 1.2)</td>
<td>0.002 (&lt; 10$^{-3}$ - 0.04)</td>
<td>0.05 (&lt; 10$^{-3}$ - 0.6)</td>
</tr>
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<td>$10^3$</td>
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</tr>
<tr>
<td></td>
<td>$1 \times 10^{49}$</td>
<td>0.1 (0.002 - 1.2)</td>
<td>0.002 (&lt; 10$^{-3}$ - 0.04)</td>
<td>0.05 (&lt; 10$^{-3}$ - 0.6)</td>
</tr>
</tbody>
</table>

#### 10 min latency

<table>
<thead>
<tr>
<th>Integration Time (s)</th>
<th>$E_\gamma$ (ergs)</th>
<th>EM (yr$^{-1}$)</th>
<th>EM and GW 2016-2017 (yr$^{-1}$)</th>
<th>EM and GW design (yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>$3.5 \times 10^{52}$</td>
<td>0.01 (&lt; 10$^{-3}$ - 0.2)</td>
<td>0.001 (&lt; 10$^{-3}$ - 0.02)</td>
<td>0.007 (&lt; 10$^{-3}$ - 0.1)</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{49}$</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
</tr>
<tr>
<td>$10^2$</td>
<td>$3.5 \times 10^{52}$</td>
<td>0.3 (0.01 - 4.1)</td>
<td>0.002 (&lt; 10$^{-3}$ - 0.04)</td>
<td>0.06 (0002 - 0.9)</td>
</tr>
<tr>
<td></td>
<td>$1 \times 10^{49}$</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
</tr>
<tr>
<td>$10^3$</td>
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<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
<td>&lt; 10$^{-3}$ (&lt; 10$^{-3}$ - &lt; 10$^{-3}$)</td>
</tr>
</tbody>
</table>
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 \textit{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

- \textit{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)
Short GRBs

**Introduction**

The method: simulating NS-NS and their multimessenger detection

**Results**

Conclusions and future developments

**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.

**Relativistic jetted outflow**

**Internal shocks**

**Prompt emission**

less than 2 seconds

**External shocks**

**Afterglow emission**

hours, days, weeks

**Flux**

**time**

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

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

Band et al. (1993)

GRB 911127

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Prospects for joint GW and high-energy EM observations of BNS mergers
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The Advanced Virgo and Advanced LIGO sensitivities

Abbott et al. (2016)

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

\[ R_{\text{BNS}} = \frac{\rho_{\text{sGRB}}}{f_b} \times \frac{4\pi D^3}{3} \]

- \( \rho_{\text{sGRB}} \) 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:

\[ \begin{cases} 
1 \text{ Gpc}^{-3} \text{ yr}^{-1} & \text{(Wanderman & Piran 2015)}; \smallskip \\
0.2 \text{ Gpc}^{-3} \text{ yr}^{-1} & \text{(Ghirlanda et al. 2016, model “a”)} \smallskip \\
0.8 \text{ Gpc}^{-3} \text{ yr}^{-1} & \text{(Ghirlanda et al. 2016, model “c”)} \end{cases} \]

- \( 0.3^\circ \leq \theta_j \leq 30^\circ \)

GW and EM detections:

Same procedure applied in the previous approach
## Results based on the local short GRB rate

<table>
<thead>
<tr>
<th>$\theta_j$</th>
<th>Model</th>
<th>BNS $\text{yr}^{-1}$</th>
<th>EM $\text{yr}^{-1}$</th>
<th>GW $2016-2017 \text{yr}^{-1}$</th>
<th>GW design $\text{yr}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>deg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>Wanderman &amp; Piran 2015</td>
<td>$38200^{+16810}_{-13000}$</td>
<td>$0.2^{+0.09}_{-0.07}$</td>
<td>$67^{+29}_{-23}$</td>
<td>$1340^{+590}_{-450}$</td>
</tr>
<tr>
<td></td>
<td>Ghirlanda et al. 2016, “a”</td>
<td>$7640^{+1530}_{-2670}$</td>
<td>$0.04^{+0.008}_{-0.01}$</td>
<td>$13^{+3}_{-5}$</td>
<td>$267^{+53}_{-94}$</td>
</tr>
<tr>
<td></td>
<td>Ghirlanda et al. 2016, “c”</td>
<td>$30560^{+11460}_{-5730}$</td>
<td>$0.16^{+0.06}_{-0.03}$</td>
<td>$53^{+20}_{-10}$</td>
<td>$1079^{+401}_{-200}$</td>
</tr>
<tr>
<td>10</td>
<td>Wanderman &amp; Piran 2015</td>
<td>$35^{+15}_{-12}$</td>
<td>$0.2^{+0.09}_{-0.07}$</td>
<td>$0.06^{+0.03}_{-0.02}$</td>
<td>$1.2^{+0.5}_{-0.4}$</td>
</tr>
<tr>
<td></td>
<td>Ghirlanda et al. 2016, “a”</td>
<td>$6.9^{+1.4}_{-2.4}$</td>
<td>$0.04^{+0.008}_{-0.01}$</td>
<td>$0.01^{+0.002}_{-0.004}$</td>
<td>$0.2^{+0.05}_{-0.08}$</td>
</tr>
<tr>
<td></td>
<td>Ghirlanda et al. 2016, “c”</td>
<td>$28^{+10}_{-5}$</td>
<td>$0.16^{+0.06}_{-0.03}$</td>
<td>$0.05^{+0.02}_{-0.01}$</td>
<td>$1.0^{+0.4}_{-0.2}$</td>
</tr>
<tr>
<td>30</td>
<td>Wanderman &amp; Piran 2015</td>
<td>$4^{+1.7}_{-1.3}$</td>
<td>$0.2^{+0.09}_{-0.07}$</td>
<td>$0.005^{+0.003}_{-0.002}$</td>
<td>$0.14^{+0.06}_{-0.05}$</td>
</tr>
<tr>
<td></td>
<td>Ghirlanda et al. 2016, “a”</td>
<td>$0.8^{+0.2}_{-0.3}$</td>
<td>$0.04^{+0.008}_{-0.01}$</td>
<td>$0.001^{+0.0003}_{-0.0005}$</td>
<td>$0.03^{+0.005}_{-0.01}$</td>
</tr>
<tr>
<td></td>
<td>Ghirlanda et al. 2016, “c”</td>
<td>$3^{+1}_{-0.6}$</td>
<td>$0.16^{+0.06}_{-0.03}$</td>
<td>$0.005^{+0.002}_{-0.001}$</td>
<td>$0.1^{+0.04}_{-0.02}$</td>
</tr>
</tbody>
</table>
Results based on the local short GRB rate

![Graph showing the relationship between \( R_{GW/REM} \) and \( \theta_j \) (deg).]