High-energy electromagnetic follow-up of gravitational wave transient events

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in collaboration with:
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Mergers of compact objects (NSs and/or BHs) are the most promising sources for the first GW detection by Advanced LIGO and Advanced Virgo.

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

EM follow-up of GW events is a key tool to better understand the physics of compact objects and to unveil the nature of short GRB progenitors.
The Fermi Large Area Telescope

- Energy range: 0.02-300 GeV
- Large field of view ($\sim 2.4 \text{ sr}$)
  \(\Rightarrow\) this allows to cover the large error boxes in the sky position of GW candidates
- Accurate localization ($r_{68} \sim 0.8^\circ$ at 10 GeV on-axis)
  \(\Rightarrow\) refinement of the localization of the GW event and alerts to other observatories

Credit: http://fermi.gsfc.nasa.gov/
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)
- \( \rho_{galaxies} = 0.0116 \text{ Mpc}^{-3} \) (Kopparapu et al. 2008)
- Simulated galaxies are uniformly distributed in volume
- Merging systems: www.syntheticuniverse.org (Dominik et al. 2012)
  - NS-NS, \( Z=Z_{\odot} \) and \( Z=0.1 \cdot Z_{\odot} \)
  - Standard model
- Merger rates: 23.5 Myr\(^{-1} \) (\( Z=Z_{\odot} \)) and 8.1 Myr\(^{-1} \) (\( Z=0.1 \cdot Z_{\odot} \)) (Dominik et al. 2012)
- 1000 realizations, each one for a 1 year observing period
Step 2: GW detections and sky localizations

GW signals

- Each NS-NS merging system has the same sky position of the host galaxy
- We assume non-spinning systems
- TaylorT4 waveforms (Buonanno et al. 2009)

GW detections

- Detector configurations (aLIGO and AdV): 2016-2017 and 2019+ (design) (Aasi et al. 2013)
- Matched filtering technique (Wainstein 1962)
- trigger: at least 2 detectors
- Combined detector SNR threshold: 12
- GW localization with BAYESTAR (Singer et al. 2014)
- Independent duty cycle of each interferometer: 100 % and 80 %
Step 3: GRB simulations

**GRB 090510** as a prototype: it is the only 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 well fitted by a power law with a decay index $\alpha_t=1.38$
- spectrum fitted by a power law with photon index $\alpha=-2.1$
Assumptions

- All the merging NS-NS systems are progenitors of short GRBs.
- The total EM energy emitted in $\gamma$ rays is: $10^{49}$ erg $\leq E_\gamma \leq 10^{53}$ erg.
- The extended emission of these GRBs has the same power law decay in time and the same spectral shape observed for GRB 090510.
- GRB 090510 is an on-axis GRB ($\theta=0$).
- The simulated GRBs have random values of $\theta \Rightarrow$ we consider a simplified model of a point source moving along the jet axis at angle $\theta$ relative to the observer (Granot et al. 2002), with a constant Lorentz factor $\Gamma=100^a$.

\footnote{this is a realistic for the early afterglow emission}

- We re-scaled the HE flux of GRB 090510 above 100 MeV to take into account the different distances, total energies, and inclination angles of the progenitors.
- We estimated the integration time $t_f$ needed for the simulated GRBs to have a fluence equal to the Fermi-LAT sensitivity.
Figure: Cumulative histograms of sky localization areas for NS-NS systems at solar metallicity for the 2016-2017 (left) and the design (right) configuration of the interferometers.
### Preliminary results: GW detections - II

<table>
<thead>
<tr>
<th></th>
<th>Number of NS-NS detections</th>
<th>% of NS-NS Localized within 5 deg$^2$</th>
<th>% of NS-NS Localized within 20 deg$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aasi et al. 2013</td>
<td>0.006-20</td>
<td>2</td>
<td>5-12</td>
</tr>
<tr>
<td>Singer et al. 2014$^a$</td>
<td>1.5</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Sim., Z=Zsun, 80 % duty cycle</td>
<td>0.53 (0.006–1.7)$^\dagger$</td>
<td>$2.3^{+1.2}_{-0.8}$</td>
<td>$7.9^{+1.9}_{-1.5}$</td>
</tr>
</tbody>
</table>

Table: Expected GW detection rate and source localization for the 2016-2017 configuration, with an independent **80% duty cycle** of each interferometer.

$^a$ These estimates refer to the 2016 scenario.

$^\dagger$ The range of GW detection rates reported in parenthesis has been estimated considering the highest range of NS-NS merger rates reported by Dominik et al. 2012, corresponding to model V12, sub-models A and B (Dominik et al. 2012).
## Preliminary results: GW detections - III

<table>
<thead>
<tr>
<th></th>
<th>Number of NS-NS detections</th>
<th>% of NS-NS Localized within 5 deg$^2$</th>
<th>% of NS-NS Localized within 20 deg$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aasi et al. 2013</td>
<td>0.2-200</td>
<td>3-8</td>
<td>8-28</td>
</tr>
<tr>
<td>Sim., Z=Zsun, 80% duty cycle</td>
<td>7.5 (0.05–12.4)$^\dagger$</td>
<td>7.6$^{+0.7}_{-0.6}$</td>
<td>27.6$^{+1.1}_{-1.1}$</td>
</tr>
</tbody>
</table>

**Table:** Expected GW detection rate and source localization for the design configuration, with an independent **80% duty cycle** of each interferometer.

$^\dagger$ The range of GW detection rates reported in parenthesis has been estimated considering the highest range of NS-NS merger rates reported by Dominik et al. 2012, corresponding to model V12, sub-models A and B (Dominik et al. 2012).
Preliminary results: Percentage of joint HE EM and GW detections

Figure: Left: cumulative histogram of the integration time needed for the simulated GRBs (in red), for the simulated GRBs with associated GW detection (in black) and with a sky localization ≤20 deg² (in blue) to be detected by the LAT. We assume $E_\gamma = 10^{49}$ erg and, for the GW detections, we consider the design scenario and a 100% duty cycle of each interferometer. NS-NS systems at solar metallicity (standard model) are considered. Right: same as left, but we assume $E_\gamma = 10^{53}$ erg.
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*-LAT.

Next steps

- Investigation of the optimal HE EM follow-up strategies.

- Extension of the work considering the other models by Dominik et al. 2012.

- Extension to NS-BH merging systems.

- Extension to other observatories (for example, ACT, *Swift* etc).
Short GRBs

**Introduction**

- The method
- Preliminary results
- Conclusions

**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**

**External shocks**

**Prompt emission** less than 2 seconds

**Afterglow emission** hours, days, ...

**Flux**

**time**

**ISM**

B. Patricelli

High-energy electromagnetic follow-up of GW transient events
EM follow-up of mergers is a key tool to better understand the physics of compact objects and to unveil the nature of short GRB progenitors.

- Latency to generate GW alerts with sky localization: \( \sim \) minutes
  \( \Rightarrow \) EM observations mainly of the afterglow emission

- Localization uncertainties within tens to hundreds of square degrees
  \( \Rightarrow \) **Wide field of view EM detectors are needed!**
The Advanced Virgo and Advanced LIGO sensitivities

Aasi et al. (2013)
Fermi-LAT sensitivity to GRBs

- 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 Theta=0.

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

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

GRB 911127

Band et al. (1993)
**GW detections**

*Figure:* Cumulative histograms of sky localization areas for NS-NS systems at solar metallicity for the design configuration of the interferometers and with a 100% duty cycle.
### Preliminary results: Percentage of joint HE EM and GW detections

<table>
<thead>
<tr>
<th>Integration Time (s)</th>
<th>% of GRBs with HE EM detection</th>
<th>% of GRBs with HE EM and GW detections, GW loc ( \leq 20 \text{ deg}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.4 (0.1)</td>
<td>2.1 (0.1)</td>
</tr>
<tr>
<td>200</td>
<td>3.5 (0.9)</td>
<td>3.0 (0.8)</td>
</tr>
<tr>
<td>1000</td>
<td>4.3 (1.2)</td>
<td>3.6 (1.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.8 (0.5)</td>
</tr>
</tbody>
</table>

**Table:** Expected percentages of EM and GW detections for the 2019+ (design) configuration, considering a 100 % duty cycle of the interferometers and assuming \( E_\gamma = \text{10}^{53} \) erg (\( \text{10}^{49} \) erg). NS-NS systems at solar metallicity (standard model) are considered.
Figure: Flux time evolution of GRB 090510 (in red) and of two randomly extracted simulated GRBs (in blue and magenta) off axis (solid lines) and on axis (dashed lines); we assumed $E_{EM}^\gamma = 10^{53}$ erg.

Table: Inclination angle $\theta$, redshift $z$, GW localization and integration time $t_f$ of the two simulated GRBs shown in the Figure.