Electromagnetic follow-up of gravitational wave candidates

Silvia Piranomonte
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Osservatorio Astronomico di Roma)
on behalf of a larger collaboration
**Ground-based Gravitational Wave Detectors**

LIGO and Virgo detectors are currently being upgraded and will observe the sky (10-1000 Hz) as a single network aiming at the first direct detection of GWs.

LIGO-Hanford (4 km)

LIGO-Livingston (4 km)

Virgo (3 km)

GEO (600 m)

Courtesy of Branchesi
Expected “transient” GW sources detectable by LIGO/Virgo

“Transient GW signal: signal with duration in the detector sensitive band significantly shorter than the observation time and that cannot be re-observed

Coalescence of Compact Objects

Neutron-Stars and/or Black-Holes

Binary containing a NS:
- **Inspiral** dominant phase
- **GW emission** enters sensitive band (> 50 Hz) < 20 s before merger
- Energy emitted in GW: ~10^{-2}M_\odot c^2

Initial LIGO/Virgo
Binary containing a NS detectable to ~50 Mpc likely rate 0.02 yr^{-1}

Core-collapse of Massive Stars

Energy emitted in GW uncertain: 10^{-8} - 10^{-4} M_\odot c^2


Initial LIGO/Virgo
Detectable within a fraction of the Milky Way (10 kpc)

Ott, C. 2009, CQG, 26

Courtesy of Branchesi
Energetic astrophysical events which are expected to emit EM radiation

Long Soft
Gamma-ray burst

Supernovae

Short Hard
Gamma-Ray Bursts

Optical Kilonovae
Radio Remnant

Gammaray burst

Ejection of r-process material from a NS merger (0.01-0.1 Mo)
Advanced GW detector era observing scenario

Position uncertainties with areas of **tens to hundreds of sq. degrees**

- 90% confidence localization areas
- Signal not confidently detected

Summary of plausible observing scenario

<table>
<thead>
<tr>
<th>LSC &amp; Virgo collaboration</th>
<th>arXiv:1304.0670</th>
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</table>

**aLIGO/Virgo Range**

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Estimated Run Duration</th>
<th>Burst Range (Mpc)</th>
<th>BNS Range (Mpc)</th>
<th>Number of BNS Detections</th>
<th>% BNS Localized within 5 deg²</th>
<th>% BNS Localized within 20 deg²</th>
</tr>
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<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2015</td>
<td>3 months</td>
<td>40 – 60</td>
<td>40 – 80</td>
<td>0.0004 – 3</td>
<td>–</td>
<td>–</td>
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<tr>
<td>2016–17</td>
<td>6 months</td>
<td>60 – 75</td>
<td>80 – 120</td>
<td>0.006 – 20</td>
<td>2</td>
<td>5 – 12</td>
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<tr>
<td>2017–18</td>
<td>9 months</td>
<td>75 – 90</td>
<td>120 – 170</td>
<td>0.04 – 100</td>
<td>1 – 2</td>
<td>10 – 12</td>
</tr>
<tr>
<td>2019+</td>
<td>9 months (per year)</td>
<td>105</td>
<td>200</td>
<td>0.2 – 200</td>
<td>3 – 8</td>
<td>8 – 28</td>
</tr>
<tr>
<td>2022+</td>
<td>9 months (per year)</td>
<td>105</td>
<td>200</td>
<td>0.4 – 400</td>
<td>17</td>
<td>48</td>
</tr>
</tbody>
</table>

\[ E_{GW} = 10^{-2} \times M_{\odot} c^2 \]

BNS system at 80 Mpc

BNS system at 160 Mpc

Courtesy of Branchesi
Advanced GW detector observing scenario

GW triggers

LIGO-H  LIGO-L

Virgo

Sky Pointing Position

Event validation

EM facilities

EM FOLLOW-UP TEAMS

“Search Algorithms” to identify the GW-triggers

“Software” to identify GW-trigger for the EM follow-up:
  • select statistically significant triggers wrt background
  • determine telescope pointing

10 min.  30 min.

ADE latency expected to be improved!


Courtesy of Branchesi
Electro-magnetic (EM) follow-up PROBLEMATICS:

- several 10-100 deg^2 sky areas to cover
- large number of false positive events (background SNe, stellar flares, AGN flares, etc.)
- unknown EM counterparts in many cases (e.g. off-axis GRB, kilonova)
- unknown timing (e.g. light curve morphology of transients)
- EM follow-up will face the well known problem of conciliate large sky coverages with sufficient depth
...but just some of the many ADVANTAGES:

- Assess the astrophysical nature of a GW event
- Localize the GW source down to arcsecond level and individuate its host galaxy from which we can measure the distance
- GW source can be identified and characterized through EM spectra and light curve
- Strong feedback with GW data analysis
- First GW+EM studies of astrophysical sources (mass, spin, distance, system orientation,...)
The EM Counterpart Challenge

Time Domain Astronomy is the gateway to EM counterparts of GWs

Therefore it will be important
1) to have optical survey to study the astrophysical transients in the space-time search region but not directly associated with a GW event
2) to have algorithms for a rapid discovery and classification of transients over a wide sky area
3) to select a small number of counterpart candidates that can be promptly followed-up spectroscopically
4) uniquely identify the optical counterpart of the GW trigger

NS-NS/BH Mergers:
- Large FOV ~several sq.deg
- rapid decay ≤ day
- sensitivity to sources
~ 30 x fainter than SNe

optical imaging surveys: PTF, LSST, ...

Kulkarni 2012
“The case of GRB 130702A demonstrates for the first time that optical transients can be recovered from localization areas of \( \sim 100 \) deg2, reaching a crucial milestone on the road to Advanced LIGO.”

Singer et al. 2013: “We report the discovery of the optical afterglow of the \( \gamma \)-ray burst (GRB) 130702A, identified upon searching 71 deg2 surrounding the Fermi Gamma-ray Burst Monitor (GBM) localization.”
INAF (Istituto Nazionale di Astrofisica) signed the MOU with LVC and decided to participate in the EM follow-up program as an Institution.

LIGO-Virgo Event Follow-Up Program

This form will be attached to the Memorandum of Understanding.

Full name of the partner project: Project of Istituto Nazionale di Astrofisica

Abbreviated name: INAF-project

Project web site (if available): http://www.inaf.it/en

Name, institution, email and title of the leader(s) (who will sign the MOU):

Professor Gianpaolo Vettolani,
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I – 00136 Roma
dir.scienti@infn.it

Scientific Director of INAF

Name, institution, email, and phone numbers of the liaison with LVC:

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Luigi Stella, INAF-Osservatorio Astronomico di Roma, luigi.stella@oa-roma.inaf.it, +39 06 94286436

List of associated members [name, institution and email]:

INAF is an institution and will sign the MoU on behalf of its members who will be involved in the EM project. The members will be required to sign a “disclaimer” to respect all the rules of the actual MoU.
**INAF GW Electromagnetic follow-up collaboration**


**INAF OA Napoli**: A. Grado, F. Getman

**INAF IASF Bologna**: L. Nicastro, E. Palazzi, L. Amati, L. Masetti, D. Vergani, A. Bulgarelli, G. De Cesare, A. Rossi, P.G. Sprimont

**INAF OA Milano**: S. Campana, S. Covino, G. Tagliaferri, P. D’Avanzo, A. Melandri, M.G. Bernardini

**INAF OA Padova**: E. Cappellaro, L. Tomasella

**Univ. Urbino**: M. Branchesi, G. Stratta, G. Greco

**SNS Pisa**: E. Pian, A. Stamerra, F. Longo, M. Razzano, G. Pivato, B. Patricelli, G. Cella

**Human resources**: ~ 160 FTE/year

**Know-how**: Time Domain Astronomy, Observational Strategy, Image analysis, Accurate Photometry in crowded fields, GRB astronomy, Data Interpretation, Theoretical models

**Multi-wavelength Observing Facilities**:

**Visible**: VST, LBT, TNG, NOT + ESO + small telescopes [REM, 1.82m (Asiago, IT), 1.52m (Loiano, IT), 0.9m C. Imperatore, IT)]

**Near-mid IR**: 1.1m AZT–24 (C. Imperatore, IT), IRAIT (Antarctica)

**Radio**: 64m SRT (Cagliari, IT), 2x 32m (Medicina and Noto, IT)

**High energy**: space (Swift, Fermi..) + ground (ASTRI, CTA)

**Near future**: SOXS@NTT + NTE@NOT key tools for GW follow-up
### Work package | Involved Research Units | Goals
--- | --- | ---
WP2 | Naples | **Observations:** VST observational operations following GW alerts. Pre-reduction of VST images.
WP3 | Rome, Bologna, Padua | **Search** of counterpart candidates in wide field images (VST and other Wide Field telescopes) and find their positions in the LVC error box. Software pipeline. Archiving activity.
WP4 | Padua, Bologna, Milan, Pisa, Rome | **Characterization** of the candidate counterparts found in WP3 to identify a few possible astrophysical objects most likely emitting the GW signal. Spectroscopic and multi-wavelength observations and their data analysis.
WP5 | Bologna, Milan, Padua, Pisa, Urbino, Rome | **Follow-up** of the counterpart(s) found in WP3/WP4 to study their physical properties. Spectroscopy, light curves, multi-wavelength observations at ground (ESO-VLT, LBT etc) and space facilities. Relationship with EU partners.
Alert from LVC: starting a EM-follow up

**STEP 1**
*Search & Detect*
Transients in the error box provided by LVC have to be discovered and measured *as soon as possible*

**STEP 2**
*Observe & Characterize*
The detected transients have to be observed to infer their nature

**STEP 3**
*Follow & Study*
Follow-up at all observable λ for an adequate time to study the physical properties of the EM counterparts of GW

Telescopes to find transients in the LVC error box Distributed at different latitudes/longitudes

Computing Facilities “Fast” and “Smart” software to select a handful of transients

Telescopes to obtain spectral features of transients

VST

VLT

LBT
To determine the telescope pointing position: The probability skymap of each GW trigger was ‘weighted’ taken into account luminosity and distance of nearby galaxies and globular clusters.

Function to call every time a GCN is received
- automatic download from GraceDB
- healpix sky map reprojected (3° x 3°)
- observability calculation at VST site
- Target of Opportunity request form

Event ID 4532 – Bayestar, Singer et al. 2014; Berry et al. 2015

*The pipeline is based on the python codes provided by the TechInfo page
https://gw-astronomy.org/wiki/LV_EM/TechInfo
WIDE-FOV telescopes to cover the GW error box

VST - 2.6m VLT Survey ESO telescope

- corrected FOV 1 deg x 1 deg, pixel scale of 0.21″/pixel
  1 hour to cover a sky area of 40 sq. deg.
  reaching $r \sim 23$ mag
- ToO available after agreement with ESO
- in 2016 the INAF-Guaranteed Time Observation
  20% of the total observing VST time
- Public Surveys: a sample of Reference Images available

The most promising astrophysical sources of kHz gravitational waves are the inspiral and merger of binary NS/BH systems.

The plot shows the EM emission in the R band expected from a NS-NS and NS-BH merger at the distance of 80 Mpc.

Kilonova models predictions (varying ejecta mass, ejecta velocity, opacity)

On-axis sGRB observed afterglows (brightest and faintest)

Off axis low energy GRB (ISM)

Courtesy of Branchesi
INAF GW Electromagnetic follow-up collaboration

**INAF: VST ToO mini-survey for GW triggers**

- 100 deg$^2$ to be repeated at three epochs: $t_0$, $t_0+(5-10d)$, $t_0+(20-40d)$
- 2 filters ($g$, $r$)
- 2 dithered exposures per pointing, 40" each (limiting mag 22.5 - 23)

Fine tuning of the observing strategy according to trigger characteristics, observing constraint, synergy with others groups

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**Experience with VST:**

**Alert Sept 14.24**

- Data acquisition: service observing @ VST (Chile)
- Data delivery: via ESO archive (<1–2 h)
- Calibration: VSTtube (Naples)
- Search: SUDARE pipeline (Padua)
- Validation: visual inspection
- Classification: Spectroscopic Classification **Sept 15.27**

**SN2012fa**

**Details:**

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Proposal approved</th>
<th>Proposal Submitted PI</th>
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<tbody>
<tr>
<td>VST</td>
<td>ToO 30h</td>
<td>Cappellaro Grado</td>
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<tr>
<td>LBT</td>
<td>ToO 7h</td>
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<td>Palazzi</td>
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<tr>
<td>NOT</td>
<td>ToO 8h</td>
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HST, VISTA, Swift - proposals submitted with INAF Cols
Processing steps (~ 24 hours)

- Observations (VST)
- Data delivery (>2h)
- Calibration
- Search of transient
- Validation

Characterization (VLT)

How to identify uniquely the EM counterpart?

- Comparison with template spectra
- Light curves

11050 transients in 1 sq degree

9 SN detections

Image Analysis is performed by running specific pipelines.
The human intervention is not yet negligible.
Efforts are needed to improve and automatize these procedures and speed up the process.

STEP 1+2: VST transient search SUDARE (Supernovae)
INAF: Characterization of the EM counterparts candidates

North America

- Large Binocular Telescope (Arizona) excellent for characterization,
  INAF GTO+ToO (25 % INAF)
  
  - two 8.4 meter primary mirrors
  - collecting area equivalent to an 11.8-meter circular aperture
  - Optical/IR spectrographs
  - Large Binocular Camera, FOV 23'x23', sampling of 0.23”/pixel

South America

- Very Large Telescope (VLT, ESO)
  
  - four unit telescopes with main mirrors of 8.2m diameter
  - very useful X-shooter spectrograph covering a very wide range of wavelengths [UV to near infrared] simultaneously

INAF intends to coordinate collaborative ToO proposal involving other European groups working in the field
INAF: Characterization of the EM counterparts candidates

Canarie

- **TNG (Telescopio Nazionale Galileo)**
  - 3.58m optical/infrared telescope
  - currently optimally equipped for “exoplanet search”
  - its position could be crucial for the EM–follow up,
    (few) possibility to set up instruments for this program

- **NOT (Nordic Optical Telescope 2.5 m)**
  - good candidate for GW follow–up, thanks to its good optics and versatile instruments: e.g.
    ALFOSC (Andalucia Faint Object Spectrograph and Camera)
  - GTO (fraction) + proposal for ToO
INAF: Radio facilities

→ INAF radio antennas:
  → Medicina (30 m parabolic antenna)
  → Noto (32 m parabolic antenna)
  → Sardinia Radio Telescope (64 m)

SMALL FOV → characterization

INAF: Space high-energy facilities

→ From space
  → INAF can guarantee access – through submission of regular or DDT proposal starting from coordinated initiatives of the INAF scientists to Swift, XMM, Chandra, Fermi, INTEGRAL.

INAF: Archival search

→ LBT + VST image archives
   ASDC Archive of space missions + ESO data archive
INAF- project: Gravitational Astrophysics

- Large FoV (1x1 d) + mag limits (< 23 m) + High resol. (0.2 p/”)
- Characterization: up to 8m class telescopes
- Site: southern and northern hemisphere
- Wide wavelength coverage: ground based facilities from optical to radio + high-energy space facilities

- Know-how: Time Domain Astronomy, Observational Strategy, Image analysis, Accurate Photometry in crowded fields, GRB astronomy, Data Interpretation, Theoretical models

◆ Collaboration with LIGO-Virgo teams is crucial
Why searching for the EM counterpart signal of a GW event?

Some, not exhaustive, hints:

- To maximizing the science return of GW observations
- To unveil the nature and structure of compact objects
- To investigate the most energetic emission mechanisms
- To give a precise (arcsecond) localization, identify host galaxy, determination of the distance and energy scales
- A coincident detection of a short GRB and a GW signal would provide the final proof of models which predict the merging of two compact objects as origin of short GRBs.
- To start the multi-messenger (GW and photon) astronomy
- GW + γ + ν → Messengers to open a new window in astrophysics
- To reveal the unknown...exotic sources, new physics

......Thank you and good luck to all of us!!! :)

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BACKUP SLIDES