Optical follow-up observations

Enzo Brocato
&
Grawita collaboration

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Osservatorio Astronomico di Roma
**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 $\lambda$ for an adequate time to study the physical properties of the EM counterparts of GW.

*Telescopes* with large FoV distributed at different latitudes/longitudes.

*Computing Facilities* with fast and smart software to select a handful of transients.

*Telescopes* for prompt spectroscopy of selected candidates at different latitudes/longitudes.

*Telescopes* with large collecting area to obtain light curves and spectral features of the EM counterparts of GW.

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**GRAWITA: GRAvitational Wave Inaf TeAm**
Multi-wavelength Observing Facilities:

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

**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 (coll.):** space (coll. Swift, Chandra) + ground (coll. MAGIC, future ASTRI, CTA)

Collaboration: SWIFT, Magic, VISTA (contacts started), INTEGRAL (contacts started)

Positive interaction during O1: Pan-Starrs, iPTF, VISTA, J-GEM

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<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>
<td>Palazzi</td>
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<td>TNG</td>
<td>ToO 12h</td>
<td>Piranomonte</td>
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<td>NOT</td>
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Note: HST, VISTA, Swift - proposals accepted with GRAWITA Cols.
GRAWITA: GRAWita tiona l Wave INaf TeAm

GRAWITA Goals:
The present research group is committed to taking part in the search and the study of electromagnetic counterparts of the GW events by using different observational facilities.

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

Project milestones

05-12-2013...Monte Mario meeting INAF – LVC
2014..............MoU INAF-LVC signed / early Team submitted PRIN INAF
2014..............VST as ToO facility
2015..............Early activities Proposals / fund raising (Unsolicited / Premiale)
07-07-2015...Unsolicited project “Gravitational Wave Astronomy …” approved
15-09-2015... First operational meeting
17-09-2015... VST observations of GW150914
28-12-2015... ESO-VST observations of GW151226
30/12/2015-04/03/2016... TNG and LBT characterization of transients
01-2016........ PRIN MIUR 2015 (INAF-RU) submitted
03-2016........ Joint paper with LVC on GW150914

Who we are

INAF OA Roma: E.Brocato (P.I.), L. Pulone, V. Testa, G. Iannicola, L. Stella, M. Lisi, S. Piranomonte, S. Ascenzi, G. Israel, P. Casella
INAF OA Napoli: A. Grado, F. Getman, L. Limatola, M. della Valle, M. Botticella, M. Capaccioli, P. Schipani
INAF IASF Bologna: L. Nicastro, E. Palazzi, L. Amati, L. Masetti, A. Bulgarelli, G. De Cesare, A. Rossi
INAF OA Milano: S. Campana, S. Covino, G. Tagliaferri, P. D’Avanzo, A. Melandri, G. Ghisellini, G. Ghirlanda, R. Salvaterra
INAF OA Padova: E. Cappellaro, L. Tomasella, S. Yang
University of Urbino: M. Branchesi, G. Stratta, G. Greco
SNS Pisa: E. Pian, A. Stamerra, F. Longo, M. Razzano, G. Pivato, B. Patricelli, G. Cella
ASI Science Data Center: L.A. Antonelli, G. Giuffrida, S. Marinoni, P. Marrese, V. D’Elia
Search GW150914

Telescopes: VST
OBs: 3deg x 3deg (mosaic)

VST campaign on GW150914
- 90 deg\(^2\) to be repeated at six epochs:
  \(t_0\), \(t_0 + 1\)d, \(t_0 + 5\)d, \(t_0 + 8\)d, \(t_0 + 15\)d, \(t_0 + 60\)d \([t_{\text{REF}}]\)
- Filters: r
- 2 dithered exposure per pointing, 40 s each, limiting mag \(r \sim 22.4\)

Area (90%)
- cWB \(\sim 310\) deg\(^2\)
- LIB \(\sim 750\) deg\(^2\)
- BSTR \(\sim 400\) deg\(^2\)
- LALInf \(\sim 620\) deg\(^2\)
GW150914

**Observed Area (deg²)**

- DECam: 4m
- iPTF: 1.2m
- MASTER: 1m
- Pan-STARRS1: 1.8m
- La Silla-QUEST: 1m
- SKYMapper: 1.3m
- TAROT: 0.25m
- TOROS: 0.4m
- VST: 2.6m
- VISTA: 4.1m

**Alert from LVC**

- Contained probability (%)
- Time (days)

**Magnitude limit**

- VST
- Pan-STARRS1
- iPTF
- DECam
- TAROT
- KWFC
- SkyMapper
- La Silla-QUEST
- TOROS

GW150914

VST field P50 epoch 1

- **Number of images**: ≥ 200 images
  (~18000×18000 px to map 1 deg²)
- **Image size**: ~ 1.3 GB / image
- **Calibration time**: ~ 6.5 hrs for a set of ~ 200 images (Grado & WG2: VST center)
Two complementary approaches have been developed:

- Transient identification by photometric analysis of sources identified in the fields (SRPGW)
- Transient identification by image analysis (SUDARE)

Typically, in a VST frame we have from ~10k to 500k sources.

In total, a few million sources analyzed to derive thousands of highly variable objects.

Credits to S. Covino and WG3
GW150914

- No credible counterpart of the GW event (BH+BH merger)
- Many interesting transients, SNae, variables, AGN, minor planets...
- Possibly a hypernova associated to a low redshift GRB.
- Soon a paper will be delivered!
Search GW151226

covered area: \(\sim 72 \text{ deg}^2\)

(Grado et al. GCN 18734)

\(\sim 54 \text{ deg}^2\)

**ESO-VST** Telescope OBs: 3x3 deg\(^2\) (mosaic)

**South**

\(\sim 18 \text{ deg}^2\)

**ESO-VST** Telescope OBs: 3x3 deg\(^2\) (mosaic)

**South**

Display tools: credit to G. Greco
Pan-Starrs: transient PS15-dpn identified (Smith et al GCN 18786)

GRAWITA: photometric data with VST@ESO

Gemini: unusual spectra not characterized z~0.175 (Chambers et al GCN 18811)

GRAWITA: LBT observations imaging + spectra PS15-dpn classified as SN Ibn similar SN2006jc, redshift confirmed (GCN 19145)

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Fig. 2. Left Panel: r-sloan image of Pan-STARRS1 candidate taken with LBC-Blue, the transient and its host galaxy are very well detected.

Right Panel: MODS1-Red spectrum extracted at the transient position. Narrow Hα, NII and OII emission lines from the host galaxy are clearly detected at a redshift of 0.1749. Based on a preliminary calibration, the spectrum shows that the transient is a peculiar supernova of type Ibn similar to SN 2006jc (red spectrum) a few weeks after maximum (Pastorello et al. 2008).
Cooperation between iPTF/GRAWITA/LSQ/Pan-STARRS/SWIFT.

Transient $iPTF15dld$ discovered by iPTF (GCN18497), identified as a Supernova Type Ic by GRAWITA (GCN18563)

Information on the environment can be obtained by Swift/UVOT.

Asiago 1.82m

Preliminary results

Credits to L. Tomasella, E. Pian, G. Raimondo
O2: “Searching for the first optical counterpart of GW detection by LV”

Localization: > ~ 100 deg²  LVC alerts ≥ 5-10 .. (?)

Observing strategy ->

• localization + prompt alerts + info about GW source:

  distance + progenitors + mass  very important !!

• O1 experience pipeline are ready
  fast data analysis of VST images
  (photometry+image subtraction)

• agreements with other groups

WF search -> VST
  30h/semester => 1-2 trigger/semester

Characterization ->
  4m tel. more ToO time: 30 – 60 h needed
Some open issues

- Several ~100 deg² sky areas to cover
- EM follow-up is facing the well known problem of balancing large sky coverage with sufficient depth
- Large number of false positive events (background SNe, stellar flares, AGN flares, etc.)
- Unknown EM counterpart in many cases (e.g. off-axis GRB, kilonova, BBH)
- Unknown timing (e.g. light curve morphology of transients)
- Spectroscopy provides key information
O3: “Multi-messenger era or still struggling around false candidates?”

WF search ->
+ VST still competitive => deep images \((r > 22 \text{ mag})\) + >2 filters

Characterization ->
+ more triggers => more candidates
+ NTE@NOT

SOXS ⇒ Single-object spectrograph
\[ R \approx 4,500 \text{ from U to H (350-17500 nm)} \] @ ESO/NTT
1 hr - SNR~10 - R~20-20.5
150 nights/year for 5-6 years
~3000 – 4000 spectra/year
(P.I. S. Campana)
Long term: 5 – 10 yr
“Full multi-messenger era. Time to explore the EM/GW sources”
Localization: ~ few deg$^2$

WF search ->
+ Large telescopes
  4-8m tel. can be competitive
  => very deep images (r > 25 mag) + >2 filters
+ LSST (2023?): 8.4m, 9.6 deg$^2$, r ~ 24.5, Chile,
  6 bands (0.3 - 1.1µm, ugrizy), 1000 visits over 10 years,
  same RA, DEC every 3 nights (filters?)

ToO: time fraction yet to be finalized but possible
depth sky, galaxy catalog, identification false candidates

Characterization / Follow-up ->
+ E-ELT(2024?): ~40m, Adaptive Optics,
  corrected FoV 10 arcmin,
  e.g. MICADO (Image+spectr. 0.8-2.4 µm, R~8000,
  FoV ~20-50 arcsec)
**Top:** Kilonova light curves from BNS coalescing into a BH (left) or NS (right) remnant at **200 Mpc** (adapted from Kasen et al. 2015).

**Bottom:** SN1998bw associated with GRB 980425 (left) and the simulated off-axis afterglow of the short GRB 130603B (right), as the GRBs were at **200 Mpc**.

The dashed purple line is the **60 s exposure LSST 5-sigma sensitivity** for point sources.

LSST enables to build large sample of sources of gravitational and electromagnetic radiation thus allowing deep insights on source nature, formation history, demographic census, observational cosmology, etc. (Izevic arXiv:0805.2366v).
Landscape in the multi-messenger era 2015-25

LBT - 2008

VLT - 1998-2000

EELT - 2024

LSST - 2023

EUCLID - 2020

ALMA - 2013

CTA - 2024

JWST - 2018

... thank you!