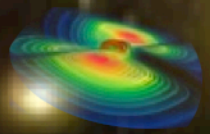
# Optical follow-up observations



**Enzo Brocato**
&
***Grawita collaboration***

Istituto Nazionale di AstroFisica
Osservatorio Astronomico di Roma

# GRAWITA: GRAvitational Wave Inaf TeAm

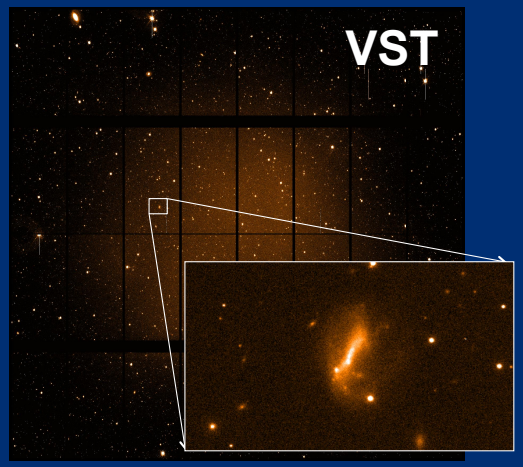
**STEP 1**

*Search & Detect*

Transients in the error box provided by LVC have to be discovered and measured *as soon as possible*

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

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




**STEP 2**

*Observe & Characterize*

The detected transients have to be observed to infer their nature

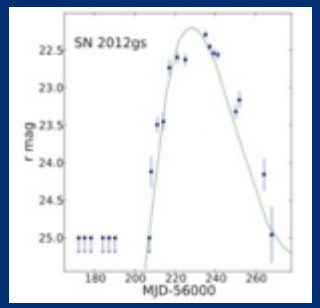
**Telescopes** for prompt spectroscopy of selected candidates at different latitudes/longitudes

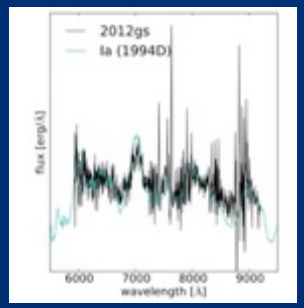

**STEP 3**

*Follow & Study*

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

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




time

λ

# 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)*


| Telescope | Proposal approved | Proposal Submitted PI |
|---|---|---|
| **VST** | ToO 30h | Cappellaro \Grado |
| **LBT** | ToO 7h | Palazzi |
| **TNG** | ToO 12h | Piranomonte |
| **NOT** | ToO 8h | Pian |
| **VLT** | ToO 20h | Pian |
| **SRT** | ToO | Possenti |
| **REM** | ToO | Campana |
| **It Antartic Tel** | yes | Col Brocato |

**Note**: *HST, VISTA, Swift - proposals accepted with GRAWITA Cols.*

***Collaboration***: *SWIFT, Magic, VISTA (contacts started), INTEGRAL (contacts started)*
*Positive interaction during O1: Pan-Starrs, iPTF, VISTA, J-GEM*

# GRAWITA: GRAvitational 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***

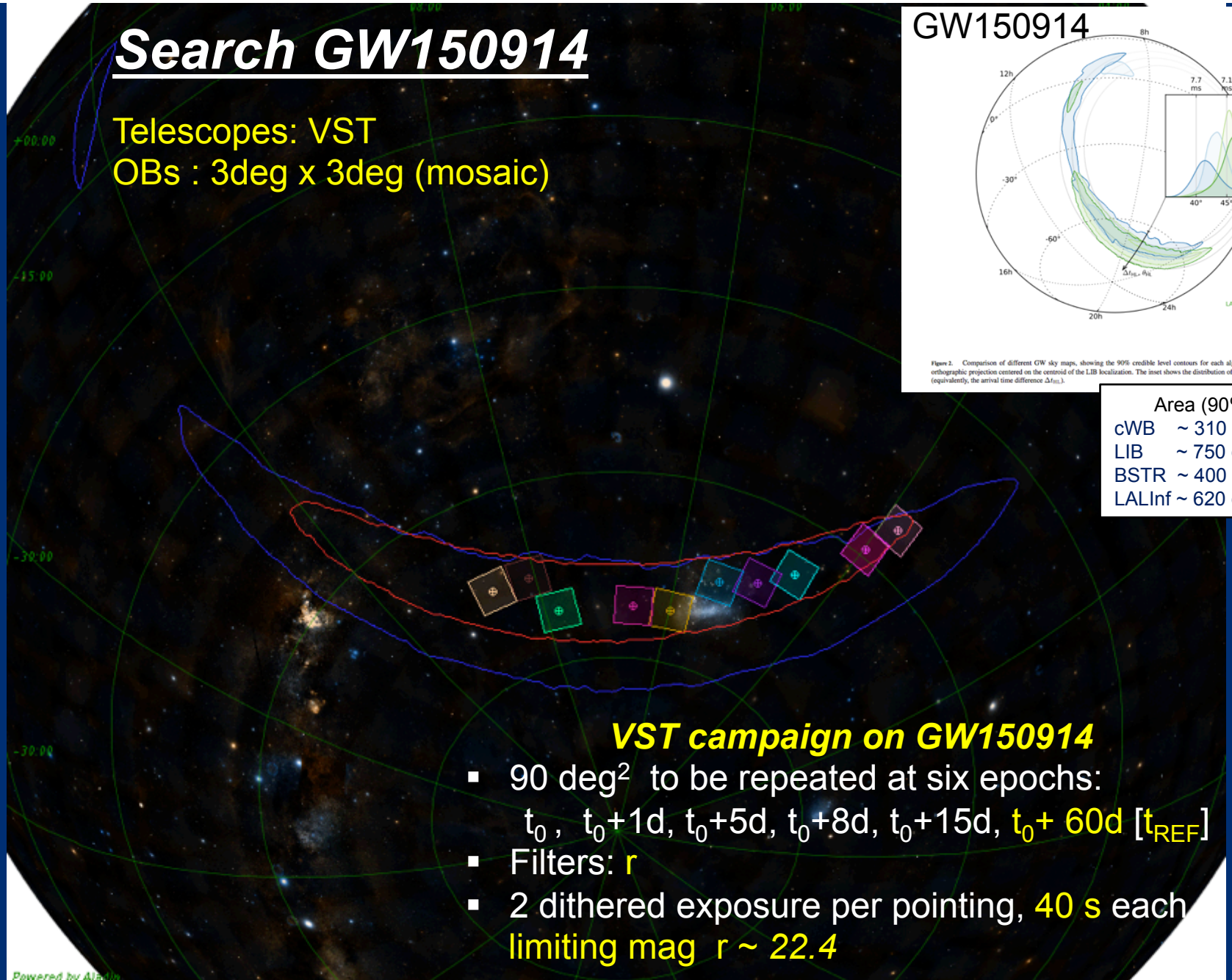
## Who we are

***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

# GRAWITA: GRAvitational Wave Inaf TeAm

## *Search GW150914*

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



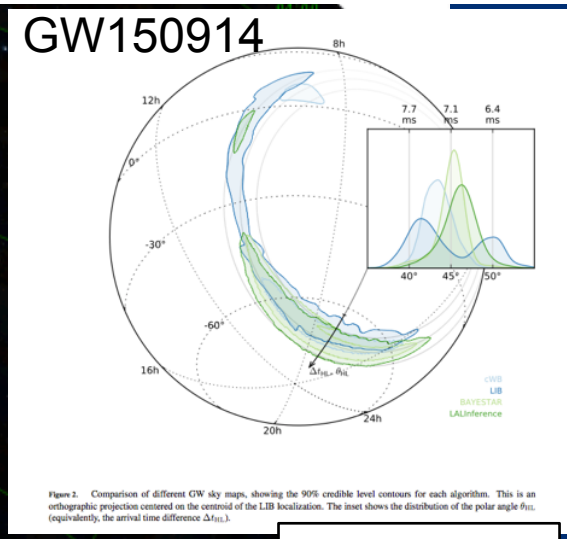




Figure 2. Comparison of different GW sky maps, showing the 90% credible level contours for each algorithm. This is an orthographic projection centered on the centroid of the LIB localization. The inset shows the distribution of the polar angle $\theta_{HL}$ (equivalently, the arrival time difference $\Delta t_{HL}$).

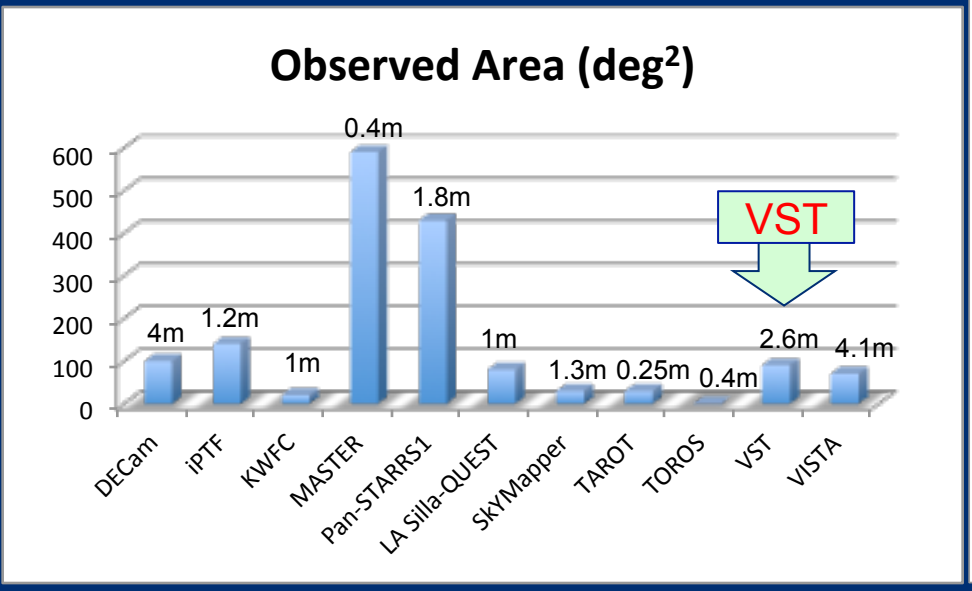
| Area (90%) | |
|---|---|
| cWB | ~ 310 deg$^2$ |
| LIB | ~ 750 deg$^2$ |
| BSTR | ~ 400 deg$^2$ |
| LALInf | ~ 620 deg$^2$ |

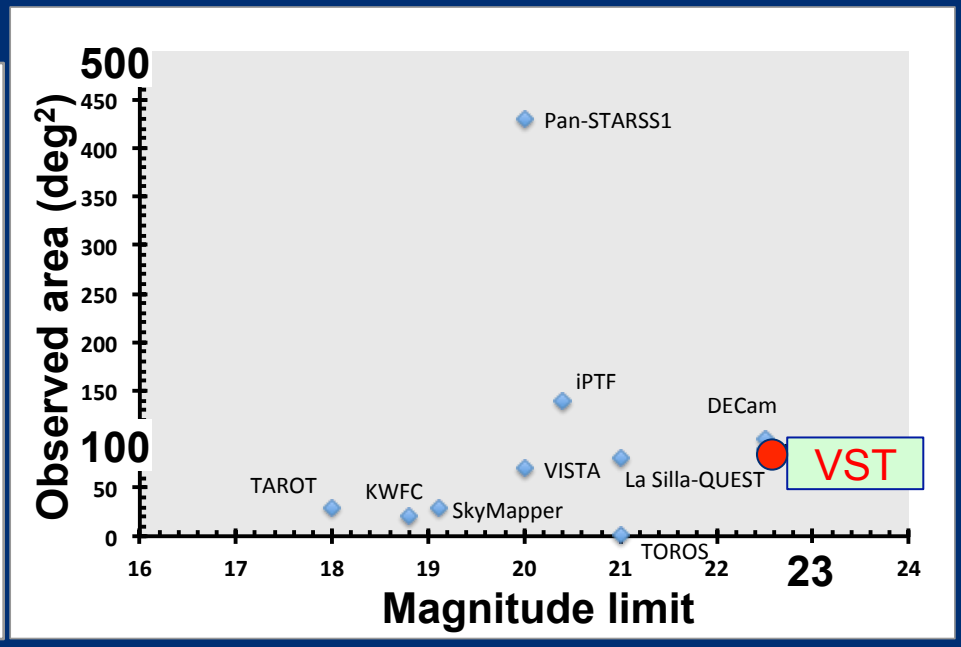
***VST campaign on GW150914***

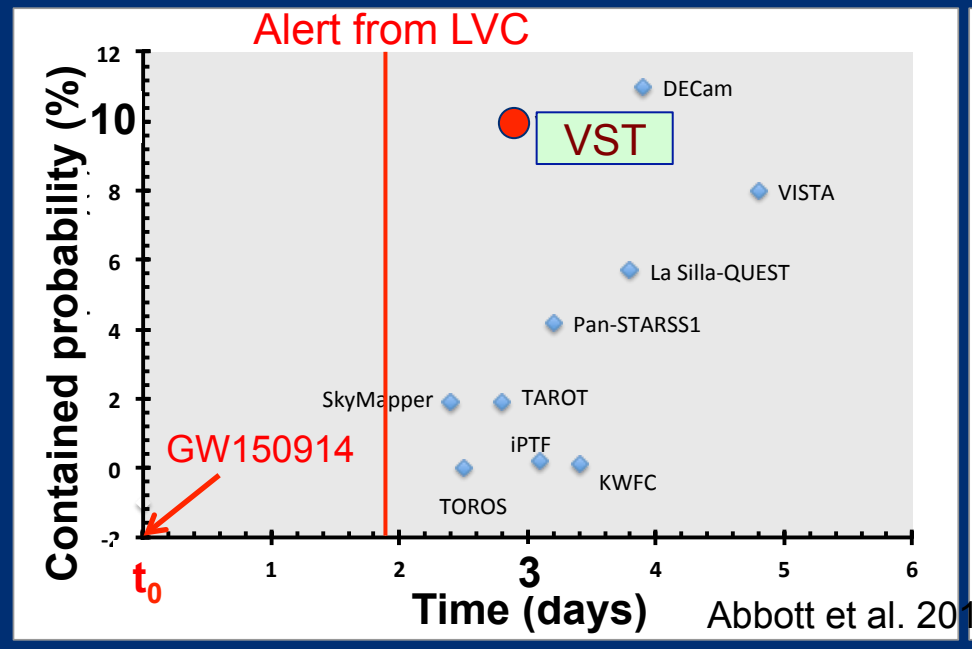
- 90 deg$^2$ to be repeated at six epochs:
  $t_0$ , $t_0$+1d, $t_0$+5d, $t_0$+8d, $t_0$+15d, $t_0$+ 60d [$t_{REF}$]
- Filters: r
- 2 dithered exposure per pointing, 40 s each
  limiting mag r ~ *22.4*

# GRAWITA: GRAvitational Wave Inaf TeAm

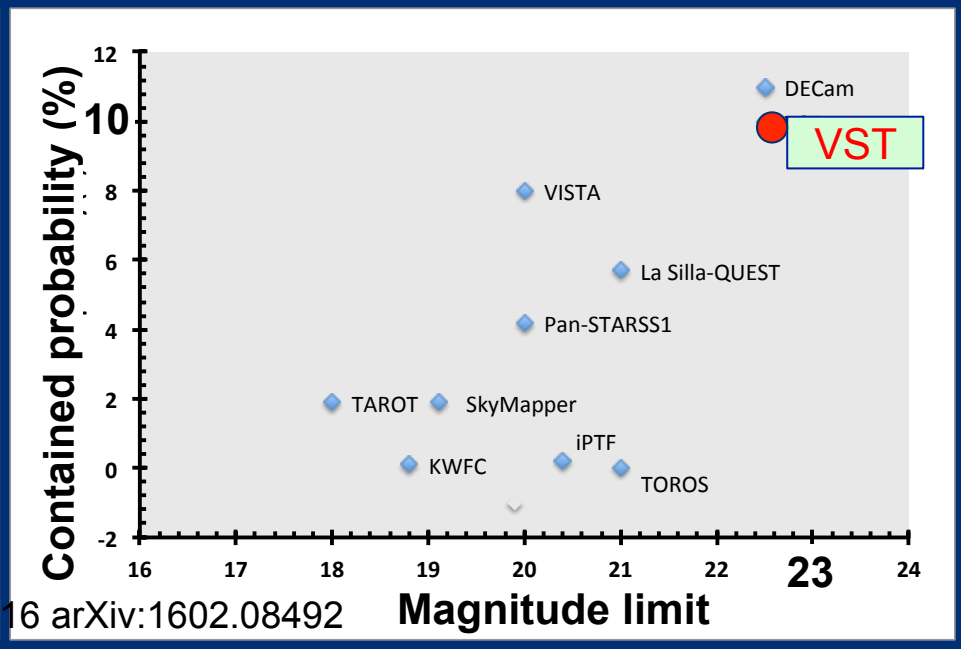
## GW150914



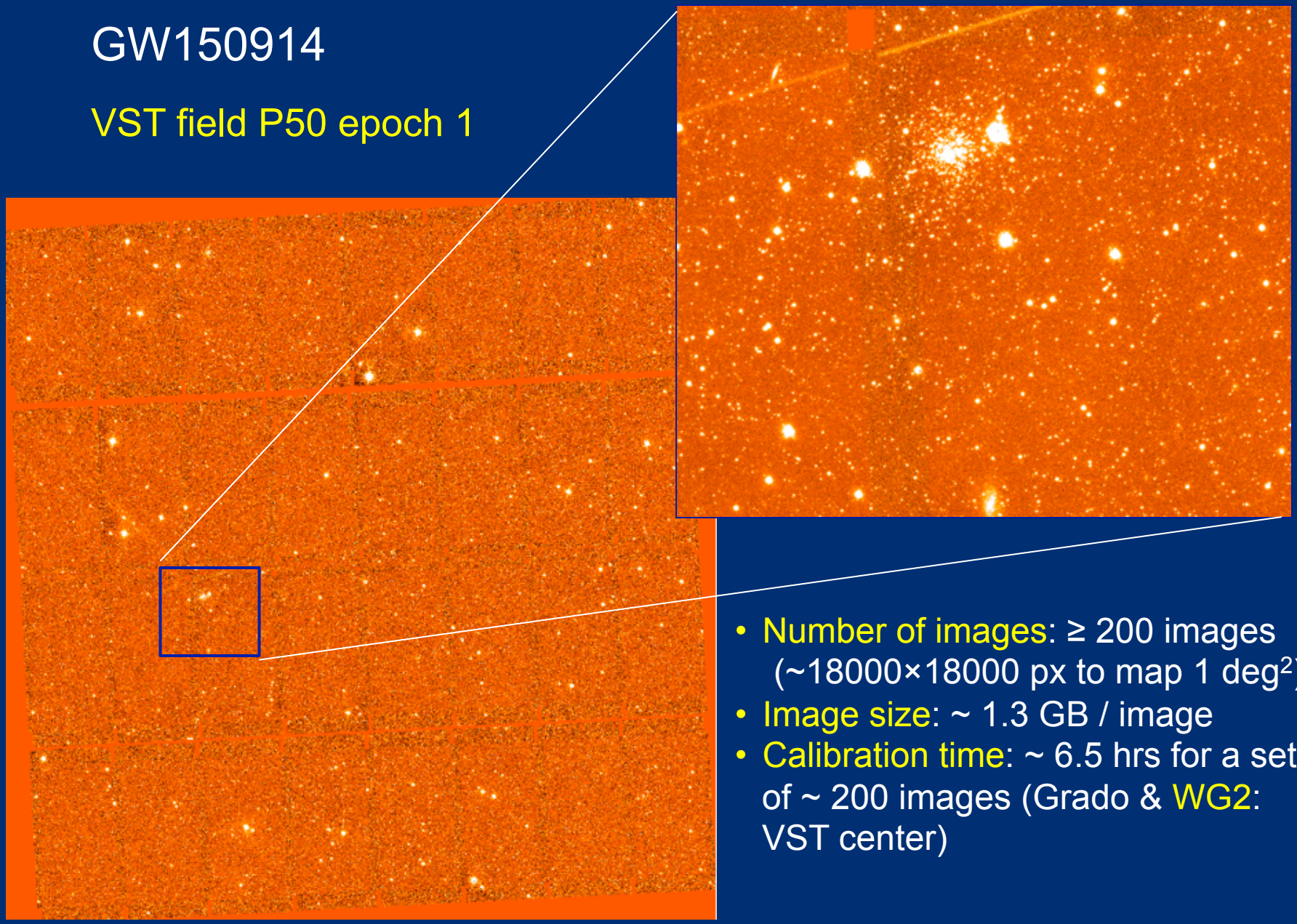

Abbott et al. 2016 arXiv:1602.08492



# GRAWITA: GRAvitational Wave Inaf TeAm

## GW150914

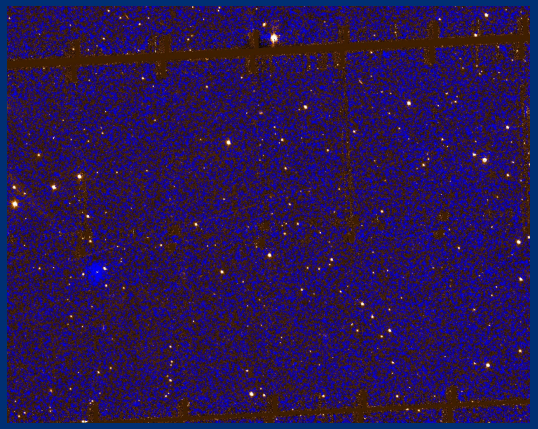
VST field P50 epoch 1



- Number of images: ≥ 200 images (~18000×18000 px to map 1 deg$^2$)
- Image size: ~ 1.3 GB / image
- Calibration time: ~ 6.5 hrs for a set of ~ 200 images (Grado & WG2: VST center)

# • Pipeline for Transient Identification

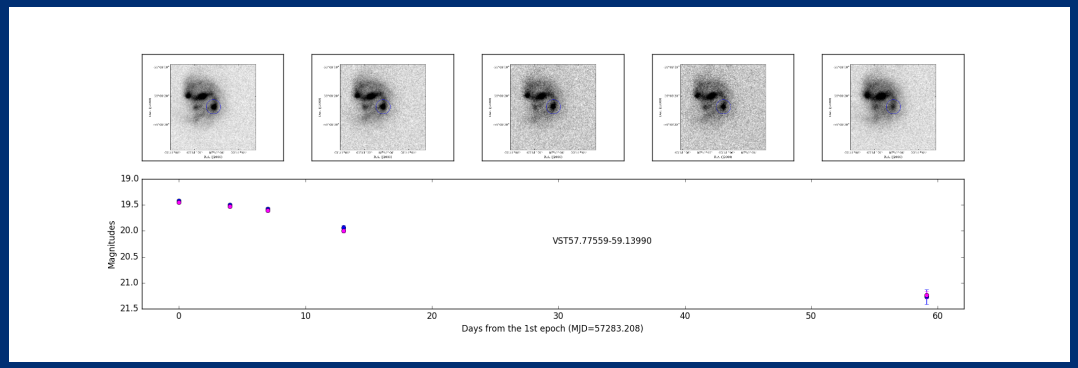
- Two complementary approaches have been developed:
  - Transient identification by photometric analysis of sources identified in the fields (SRPGW)
  - Transient identification by image analysis (SUDARE)

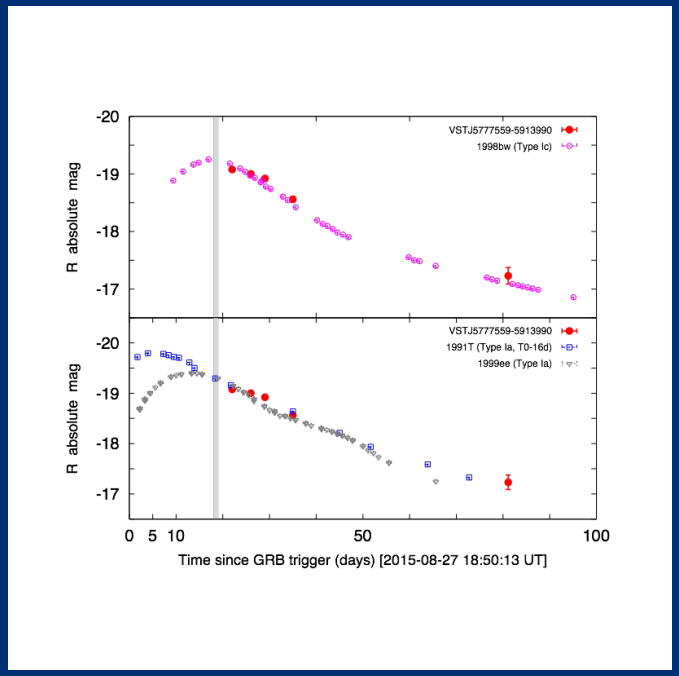


- Typically, in a VST frame we have from ~10k to 500k sources.
- In total, a few million sources analyzed to derive thousands of highly variable objects.

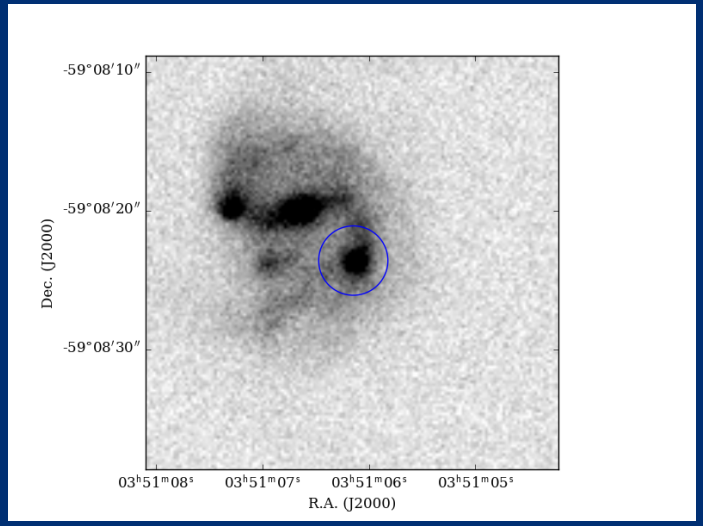
Credits to S. Covino and WG3

# GW150914



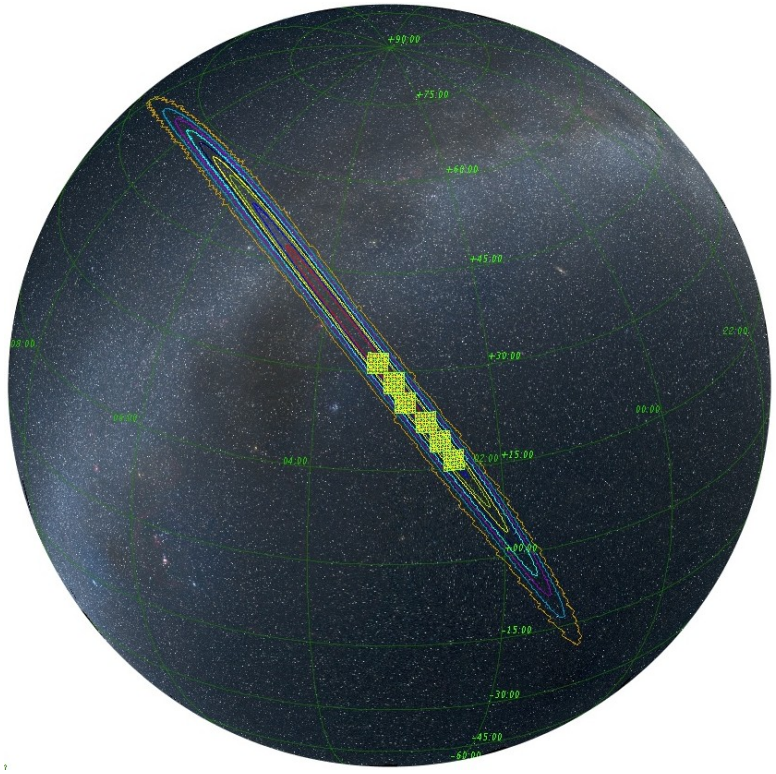




- No credible counterpart of the GW event (BH+BH merger)
- Many interesting transients, SNae, variables, AGN, minor planets...
- Possibly a hypernova associated to a low redshift GRB.
- Soon a paper will be delivered!

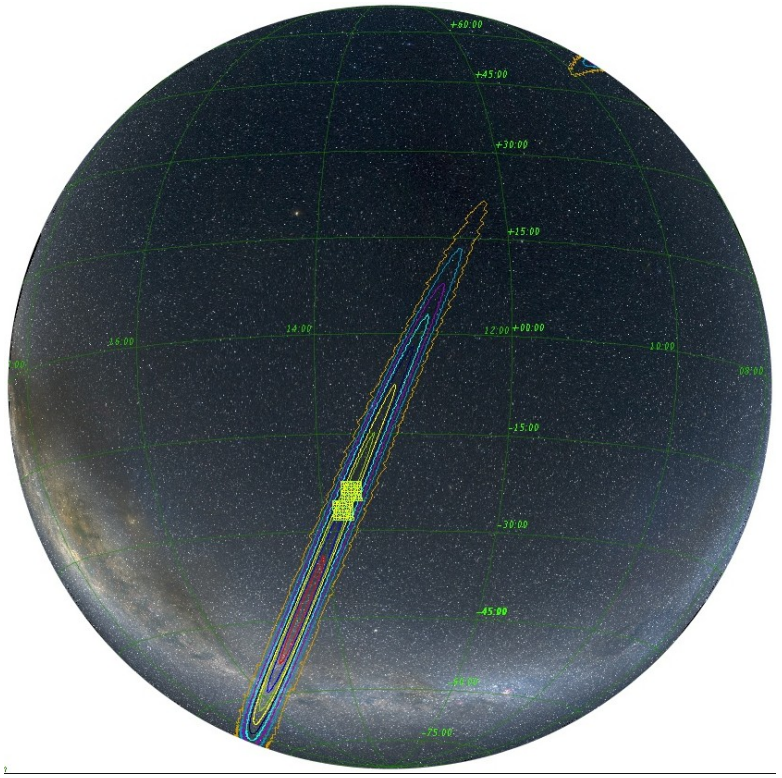


# Search GW151226

**covered area : ~72 deg$^2$**
**(Grado et al.GCN 18734)**



**~54 deg$^2$**
**ESO-VST** Telescope OBs: 3x3 deg$^2$ (mosaic)
**South**



**~18 deg$^2$**
**ESO-VST** Telescope OBs: 3x3 deg$^2$ (mosaic)
**South**

Display tools: credit to G. Greco

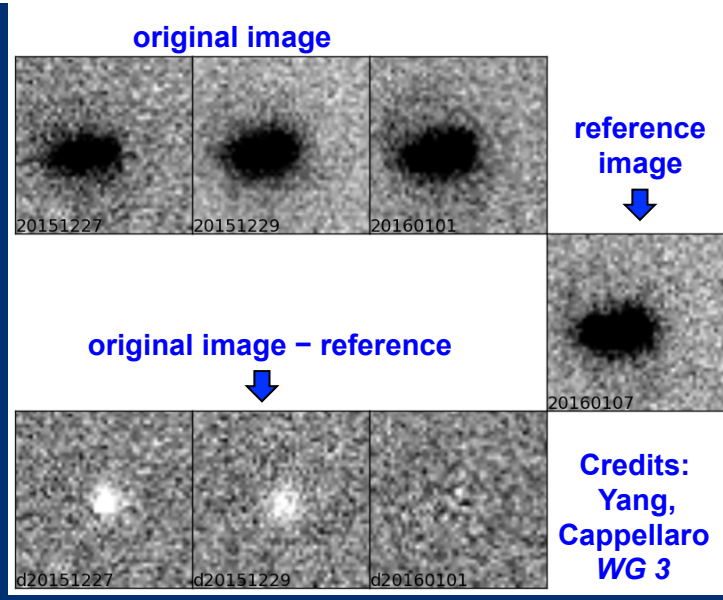
# GRAWITA: GRAvitational Wave Inaf TeAm

Pan-Starrs: transient PS15-dpn identified (Smith et al GCN 18786)

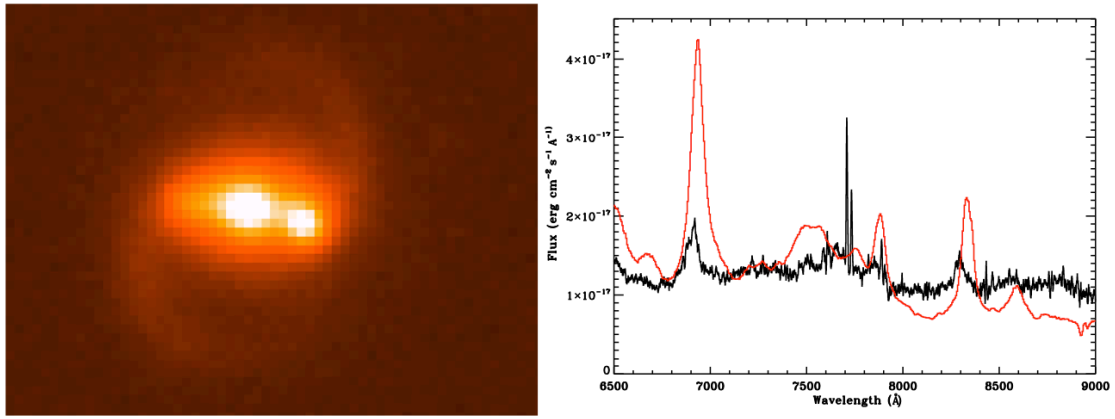
GRAWITA: photometric data with VST@ESO

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)




LBT
8mTelescope
(LBC-Blue)

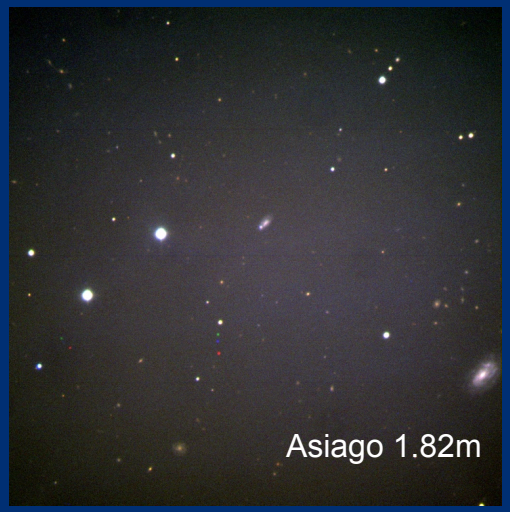


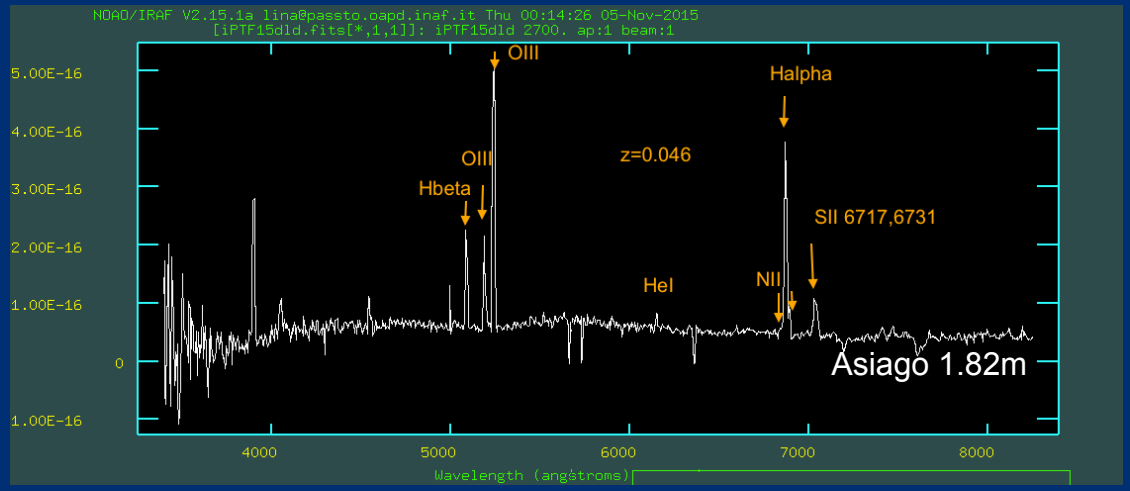

LBT
8m Telescope
(MODS1-Red)

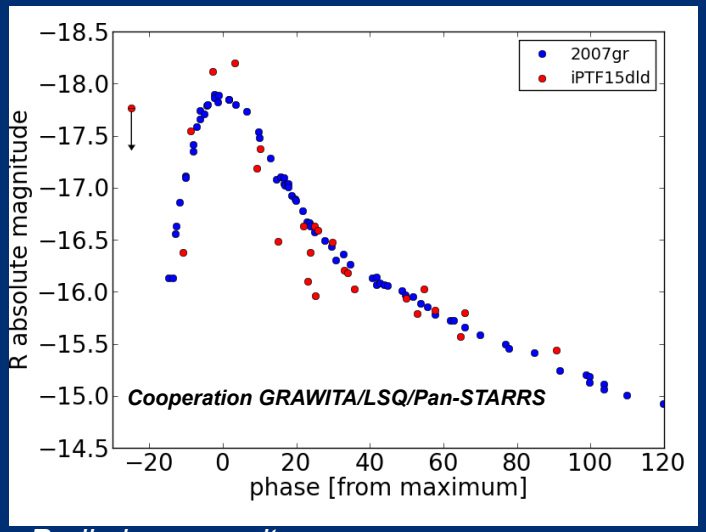
**Fig. 2. Left Panel:** r-sloan image of Pan-STARRS1 candidate taken with LBC-Blue, the transient and its host galaxy are very well detected.
**Right panel:** MODS1-Red spectrum extracted at the transient position . Narrow H$\alpha$, NII and OII emission lines from the host galaxy are cleary detected at a redshift of 0.1749. Based on a preliminary calibration, the spectrun show 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).

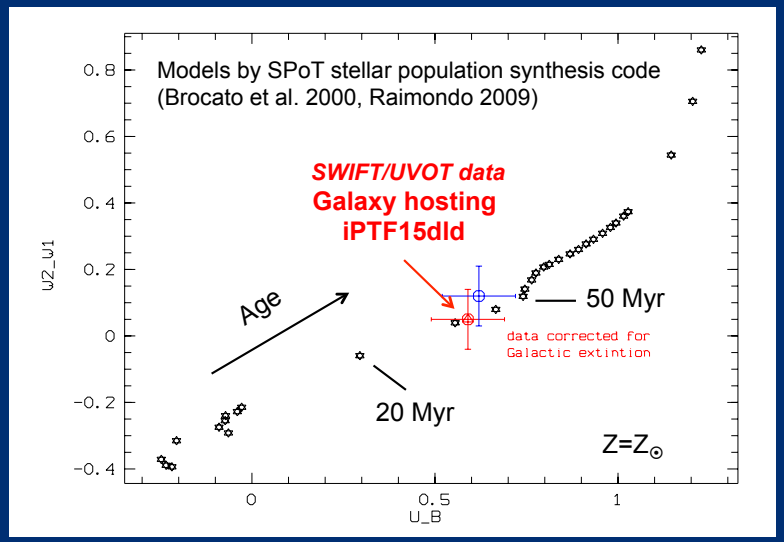
# GRAWITA: GRAvitational Wave Inaf TeAm

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*




*Preliminary results*

Credits to L. Tomasella, E. Pian, G. Raimondo

# GRAWITA: GRAvitational Wave Inaf TeAm

**O2:** "Searching for the first optical counterpart of GW detection by LV"

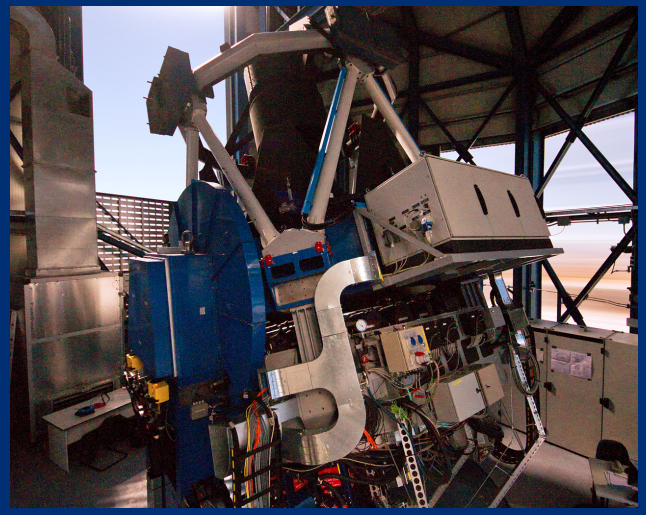
Localization : > ~ 100 $deg^2$ LVC alerts ≥ 5-10 .. (?)

**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

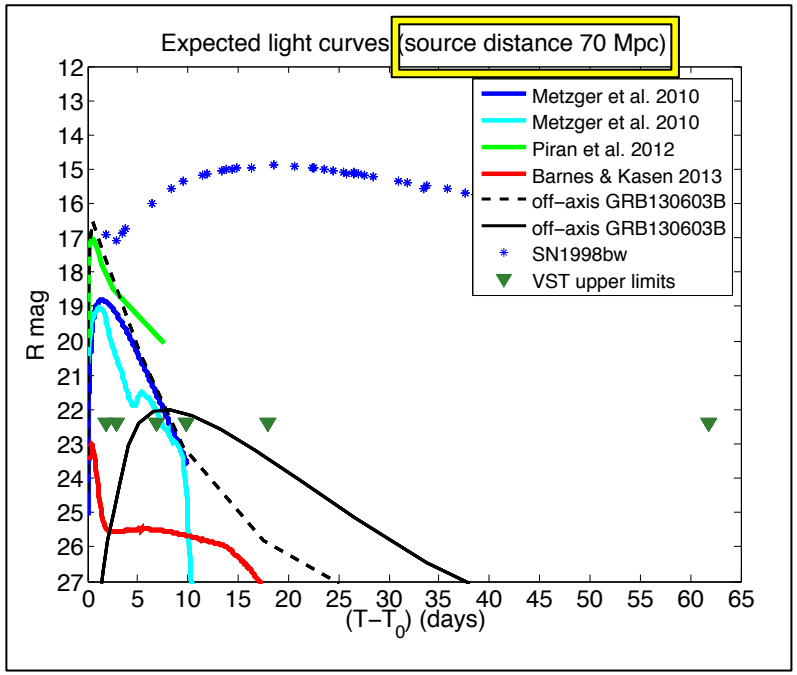
**Characterization ->**

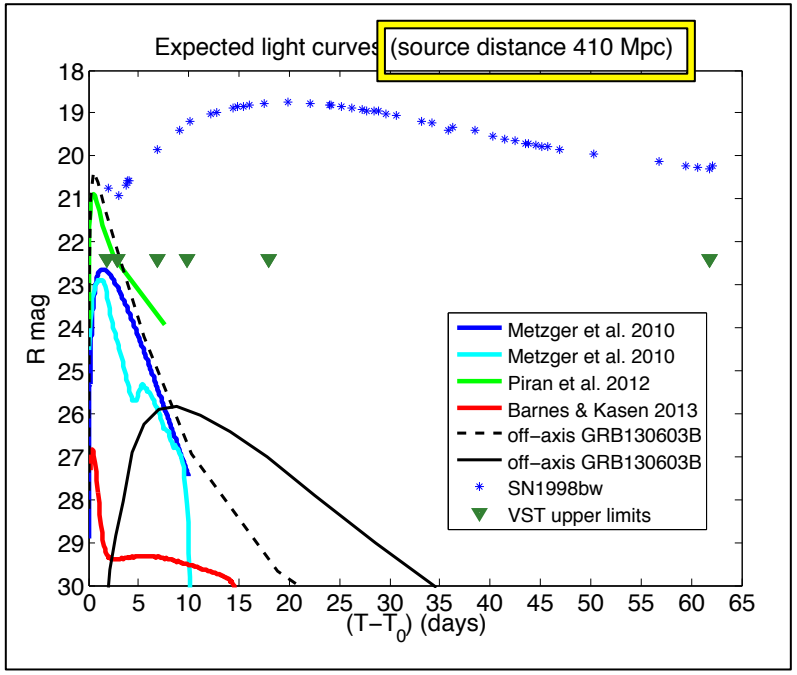
- 4m tel. more ToO time: 30 – 60 h needed

# GRAWITA: GRAvitational Wave Inaf TeAm

Some open issues

- Several ~100 deg$^2$ 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




Courtesy of G. Stratta

# GRAWITA: GRAvitational Wave Inaf TeAm

**O3:** "Multi-messenger era or still struggling around false candidates?"

**WF search ->**

+ VST still competitive => deep images (r > 22 mag) + >2 filters

**Characterization ->**

+ more triggers => more candidates
+ NTE@NOT

SOXS ⇒ **Single-object spectrograph**
**R~4,500 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"

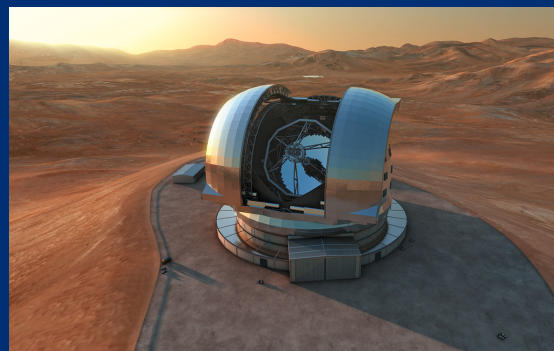
Localization: ~ few $deg^2$

**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
  deep 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)

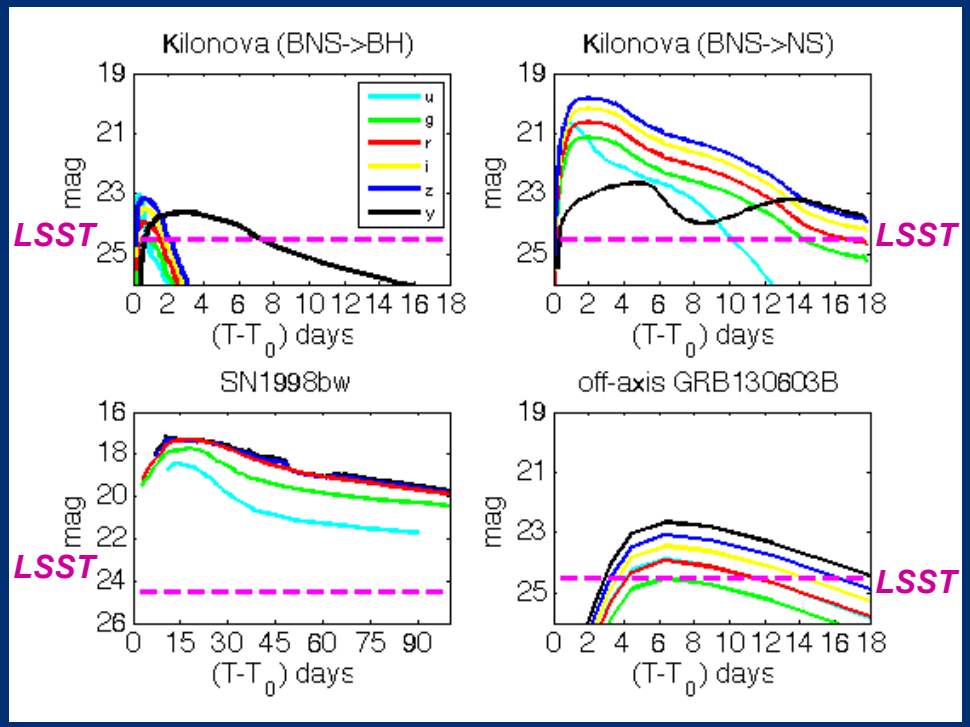
# LSST : observing possible E.M. counterparts of GW sources

**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

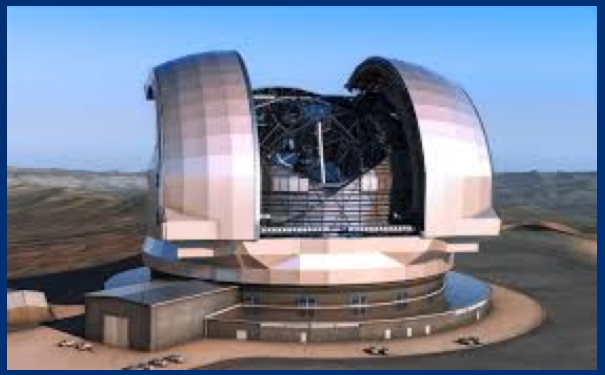
LSST enables to build large sample of sources of gravitational and electromagnetic radiation thus allowing deep insights on source nature, formation history, demographic census, observational cosmology, etc. (Izevic arXiv:0805.2366v).



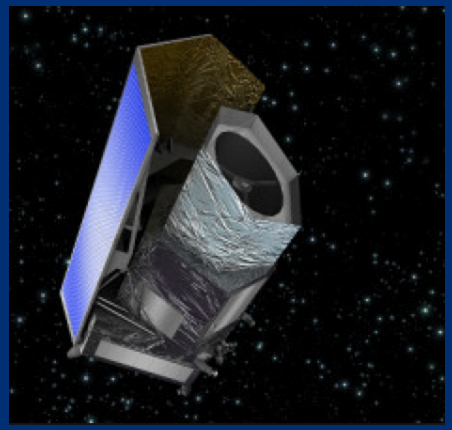

Credits : G. Stratta

# *Landscape* in the multi-messenger era 2015-25

LBT - 2008

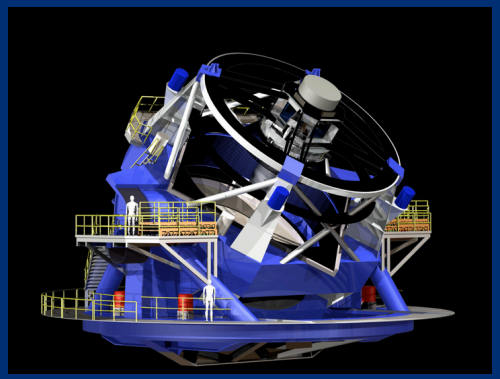


EELT - 2024



EUCLID - 2020

VLT - 1998-2000



LSST - 2023

JWST - 2018

CTA - 2024

ALMA - 2013

… thank you !