EM follow-up of gravitational waves emitters

GRAWITA.INAF.IT

Eliana Palazzi
palazzi@iasfbo.inaf.it

July 2013

INAF expressed the intent to participate in the LIGO/VirgoEM follow-up program with a LoI

February 2014

INAF signed the MoU with the LIGO/VIRGO collaboration **to participate in the EM follow-up program as an Institution** by providing Italian observational resources and the expertise in time domain astronomy

Birth of the **GRA**vitational **W**aves **I**naf **T**e**A**m

GRAWITA: GRAvitational Wave Inaf TeAm

Who we are:

P.I. of the GRAWITA project: Enzo Brocato (OA Roma)

Involved INAF Institutes:
OA Roma, OA Napoli, IASF Bologna, OA Milano, OA Padova, Urbino University, SNS Pisa, ASI Science Data Center

Know-how

- GRB studies and follow-ups
- Multiwavelenght observational strategies on transients sources
- Multiwavelenght data analysis
- Theoretical model development

> 1800 referred papers in 2010−2015

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), ATCA

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	CoI Brocato

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

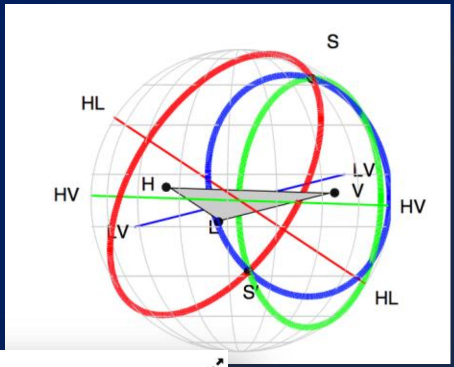
Collaboration: VISTA, MAGIC, SWIFT, INTEGRAL, AGILE
Positive interaction during O1: Pan-Starrs, iPTF, J-GEM

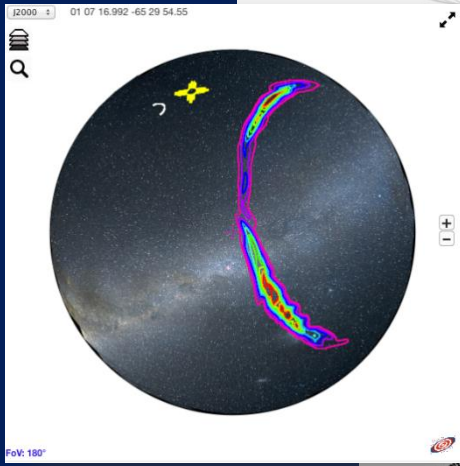
~~(RA, Dec)~~ → GW Skymaps

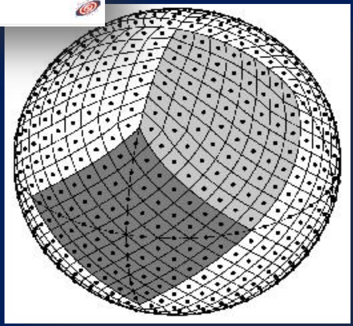
- GW source sky localizations are roughly provided by a network of interferometers via **triangulation**

- Large sky areas are identified depending on the number of GW detectors
  - E.g. with 2 detectors: 100-1000 deg2, with 5 detectors (>2022) ~10 deg2 or less

- Rather than a pair of sky coordinates+uncertainties, GW sources are localized with **sky probability maps**
  - The whole sky is divided in equal area pixels of 0.4 deg2 and to each pixel the probability of finding the GW source is assigned





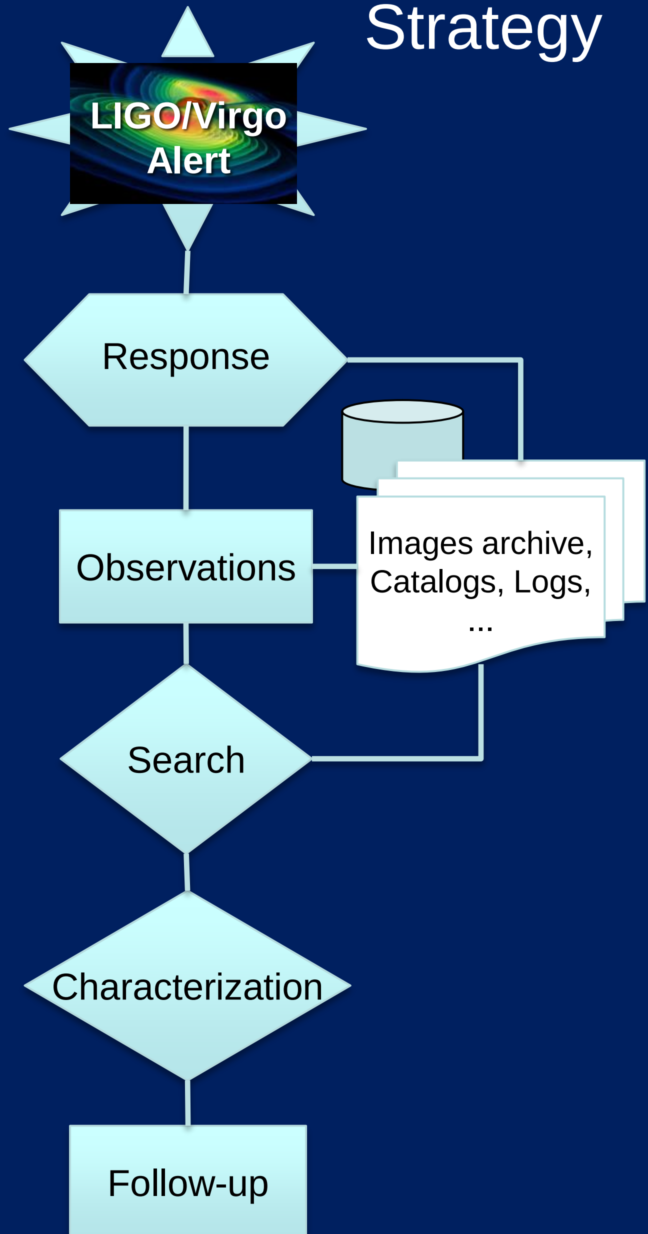


Skymaps are currently computed by different algorithms with different computational costs

Credit: G. Stratta

GRAWITA: GRAvitational Wave Inaf TeAm

Strategy



Telescopes with
large FoV
distributed at different latitudes/longitudes

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

Telescopes with
large collecting area
to obtain light curves and spectral features of transients

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

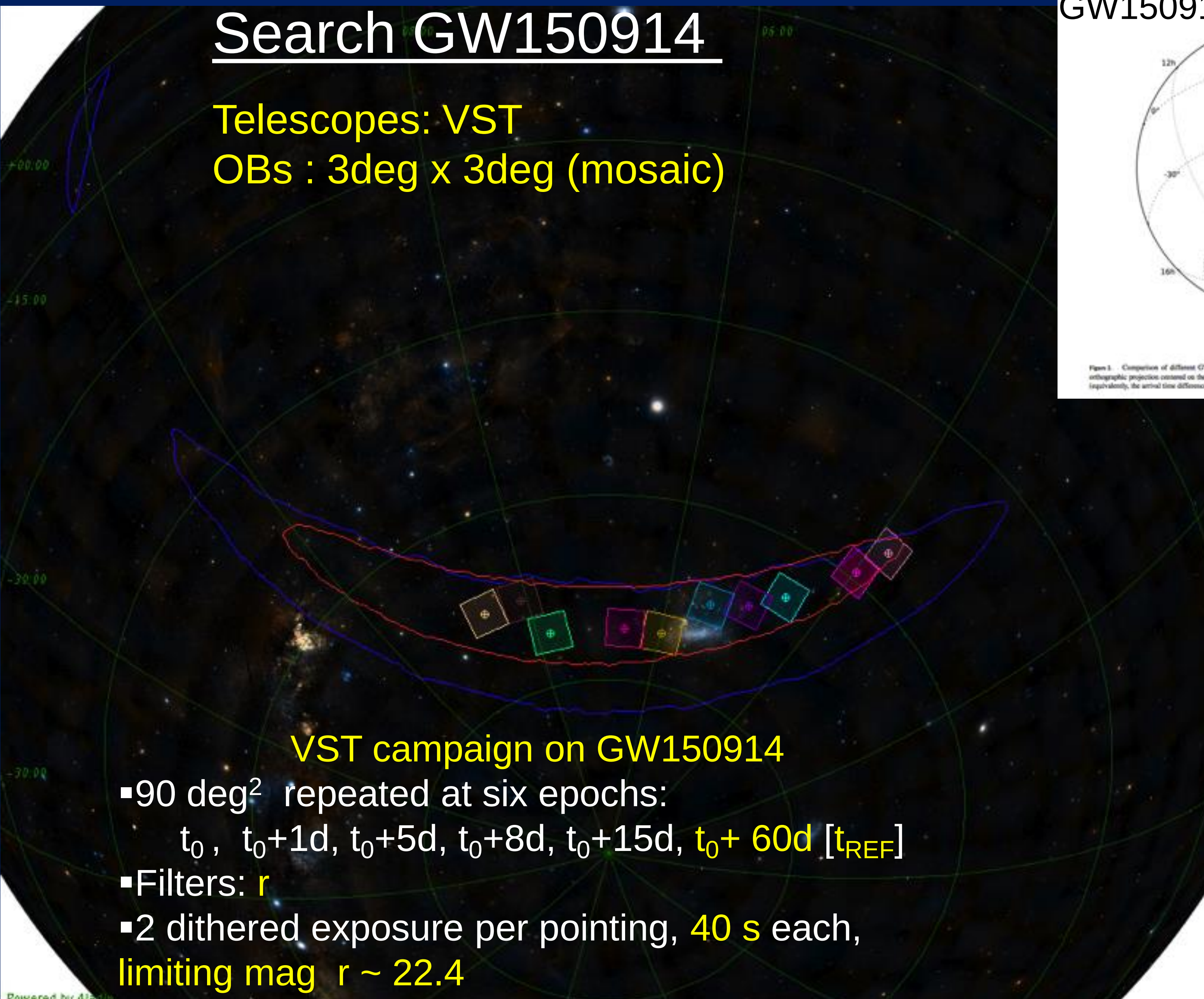
The detected transients have to be observed to infer their nature

STEP 3
Follow & Study

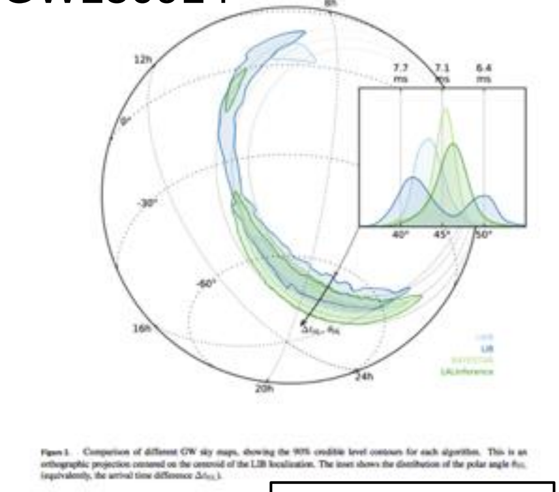
Follow-up at all observable λ for an adequate time to study the physical properties of the **EM counterparts of GW**

Search GW150914

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



GW150914



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

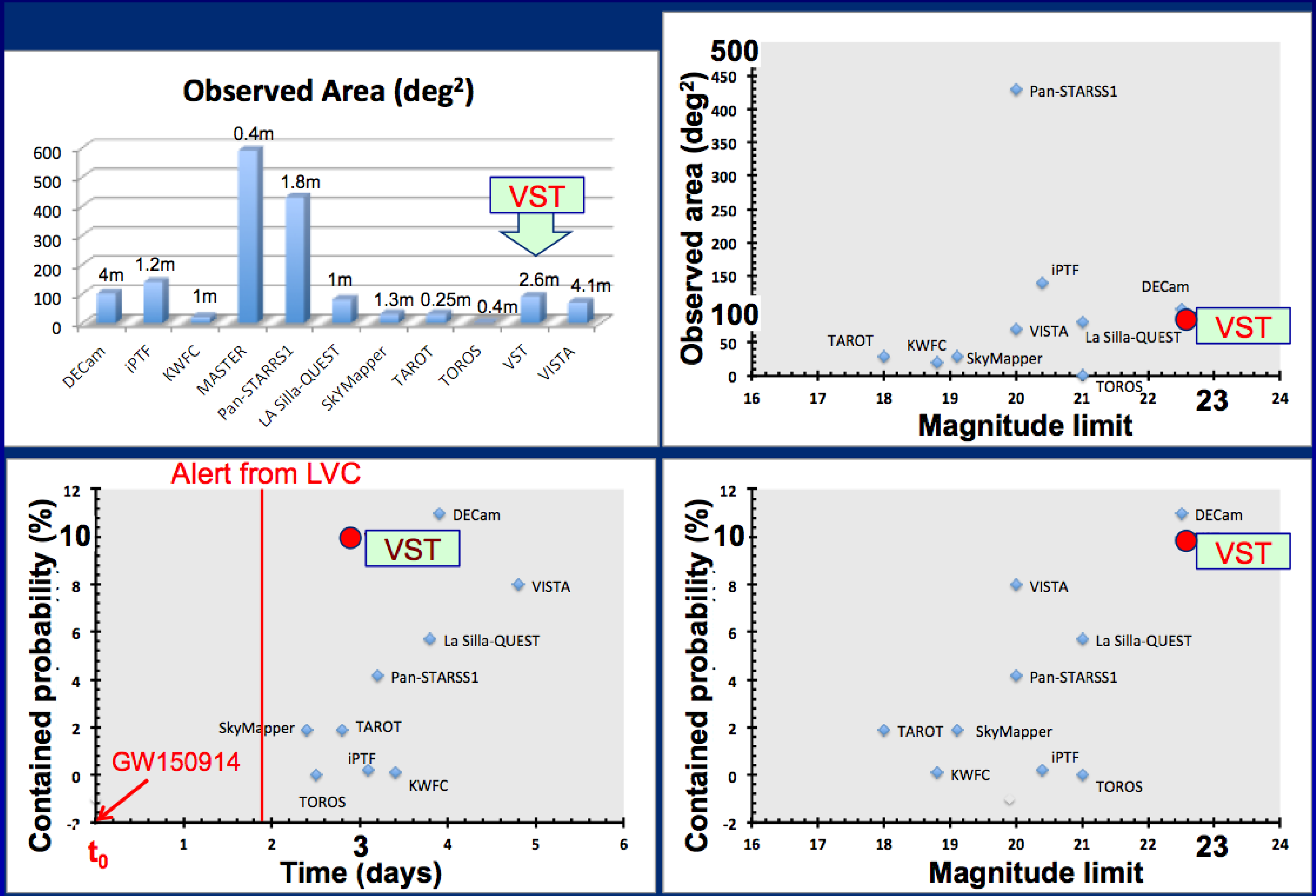
(Abbott+2016 ApJL 826,13)

VST campaign on GW150914

- 90 deg^2 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

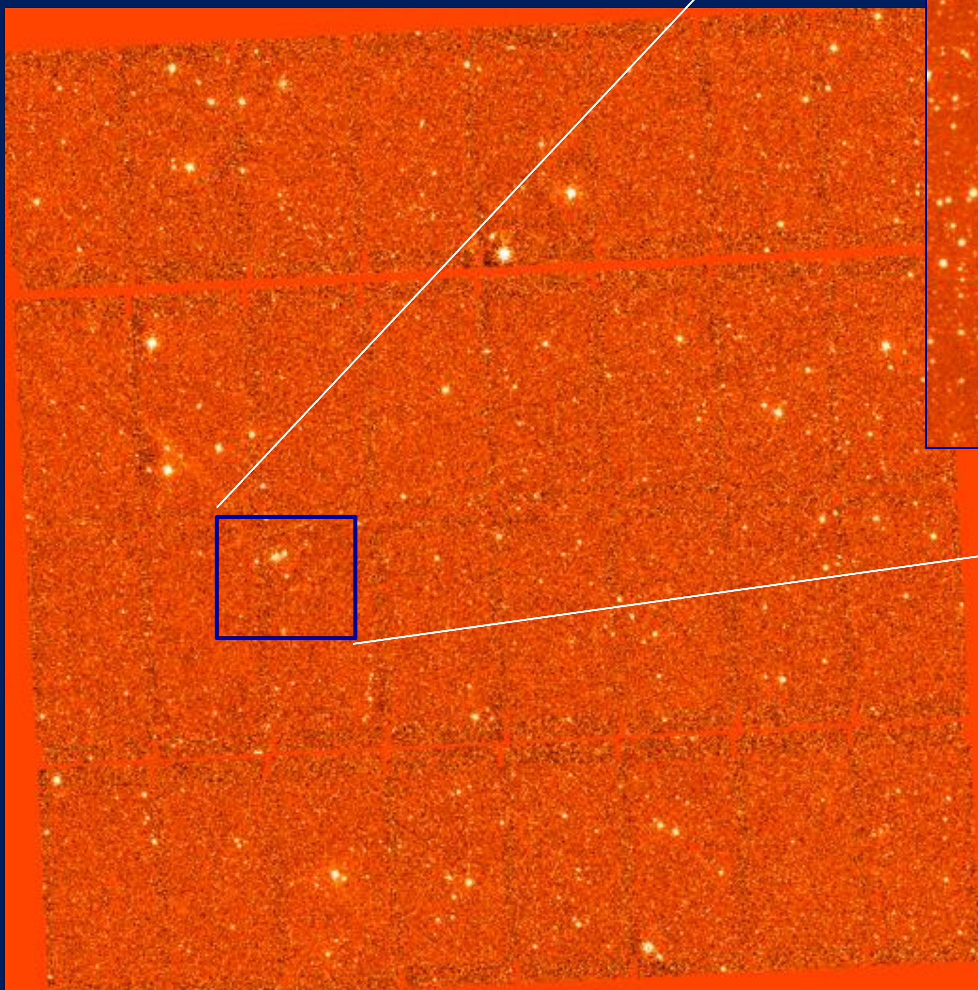
GW150914 (VST one of the best protagonists of the event follow-up)

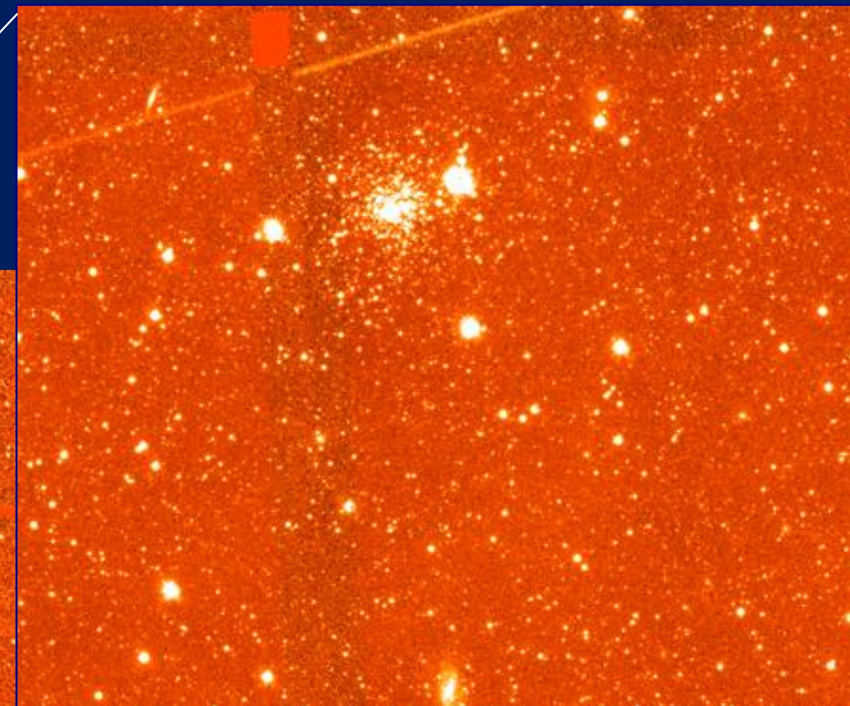


(Brocato & GRAWITA, 2016, in preparation)

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

(VST center OA Napoli; A. Grado – WG2)

GRAWITA: GRAvitational Wave Inaf TeAm

Gravitown server
(OA-Roma)

CPU: 24 core @ 2.4 GHz
RAM: 256 GB
HDD: 16 + 4 TB (raid 0 + 1)
16 disks bay – LSI card 12GB

analysis tools

MariaDB

Reference catalogues
- IGSL v3 (custom, 1.22 G_{obj})
- GSC-2.3, TMASS, UCAC4, ...

Objects catalogues

Tools
- query, X-match, export, ...

Images archive
Ref. catalogues
Extracted cats
Products

Website
(wordpress)
Public info
Images & Products
Blog
References

computational resources

Cloud
(owncloud)
Products
Previews
Biblio
Misce

Google
Drive (proposals)
Group emails - blog
Forms
Misce

Main computing tasks:

- VST-tube (Napoli)
  - Astromatic tools (Scamp, SWarp, SExtractor, ...): *clean images, extracted objects catalogs*
  - 6.5 hr, 10 TB

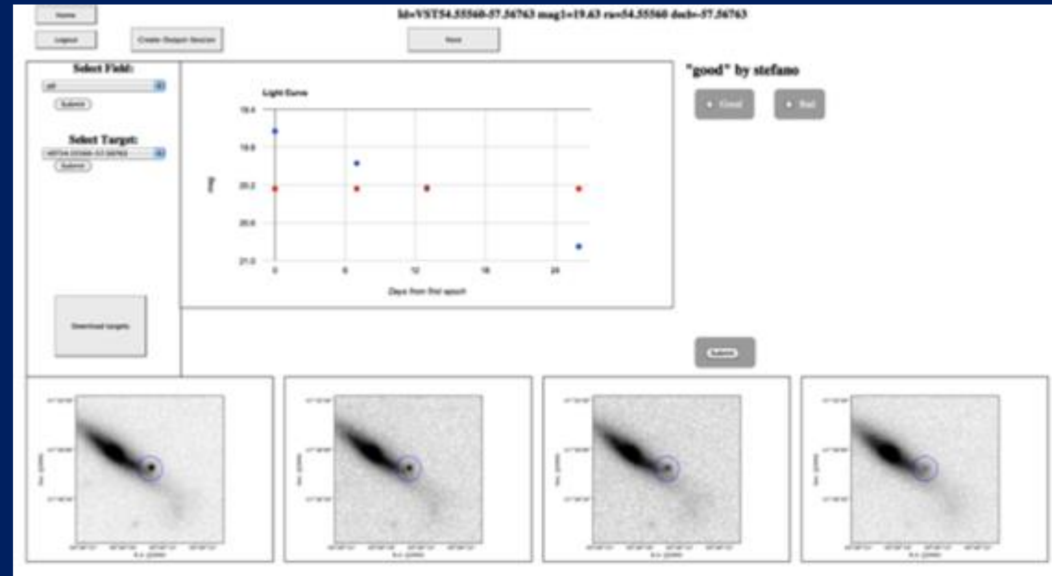
- Catalogs pipeline (Bologna)
  - Filtering, Xmatch, ...
  - 5 min, ~ 1 GB
- Custom image reprocessing pipeline (Merate)
  - Filtering, PSF photometry, Xmatch, LC
  - ~45 hr, 300 GB
- Hotpants, SUDARE@VST (Padova)
  - Images subtraction, LC
  - ~50 hr, 2 TB

Gravitown @ OA-Roma

Totals: ~100 hr, 14 TB, Key point: data throughput

GRAWITA: GRAvitational Wave Inaf TeAm

Transient identification



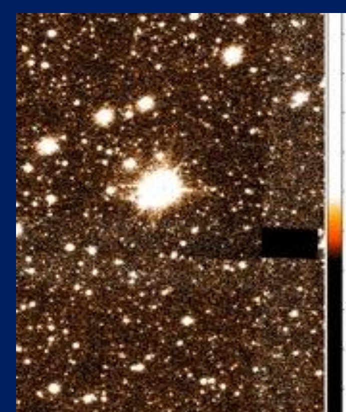
Covino, Giuffrida, Nicastro & WG3

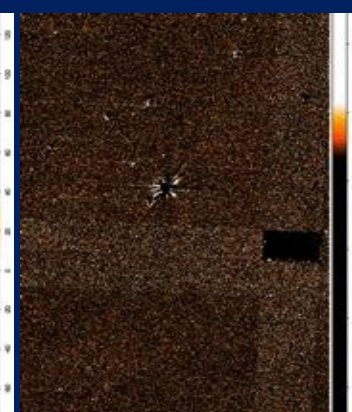
I. Photometry of sources

- Sextractor -> object ident.
- mag_{diff} @ each epoch (7σ)
- check with available catalogs (Initial GAIA Cat.. Simbad, Min. Planet..)
- PSF fitting single object
- Check by eye (LC +images)

II. Image subtractions

SUDARE@VST (Cappellaro et al. 2013)

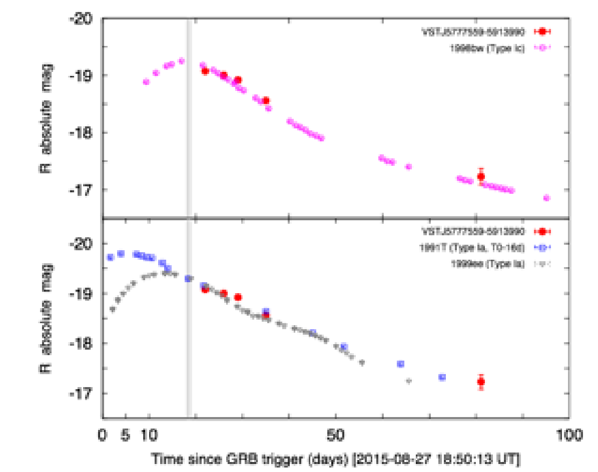


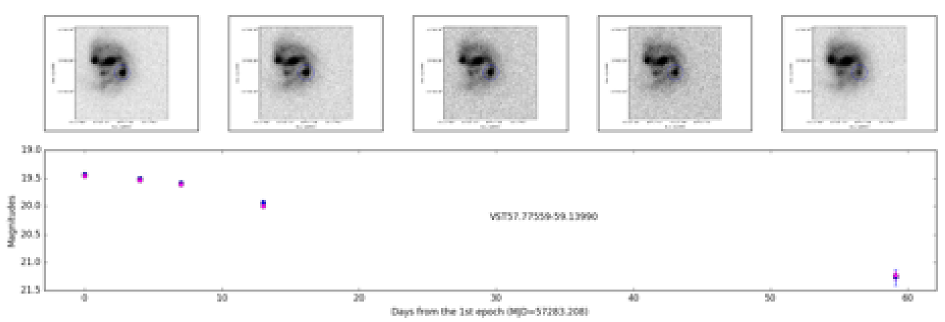


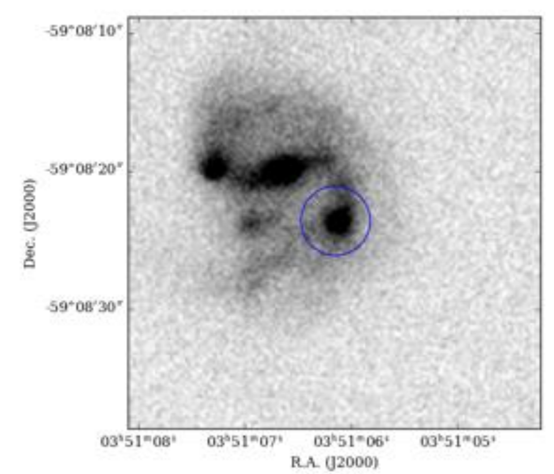
Typically, in a VST frame we have from ~10k to 500k sources. In total, a few million sources analyzed to derive thousands of highly variable objects.

GW150914: VST follow-up results

- A few millions objects considered,
- A few thousands showed large variability
- Many interesting transients, SNae, variables, AGN, minor planets...
- Possibly a hypernova associated to a low redshift GRB
- **No credible counterpart of the GW event** (BH+BH merger)



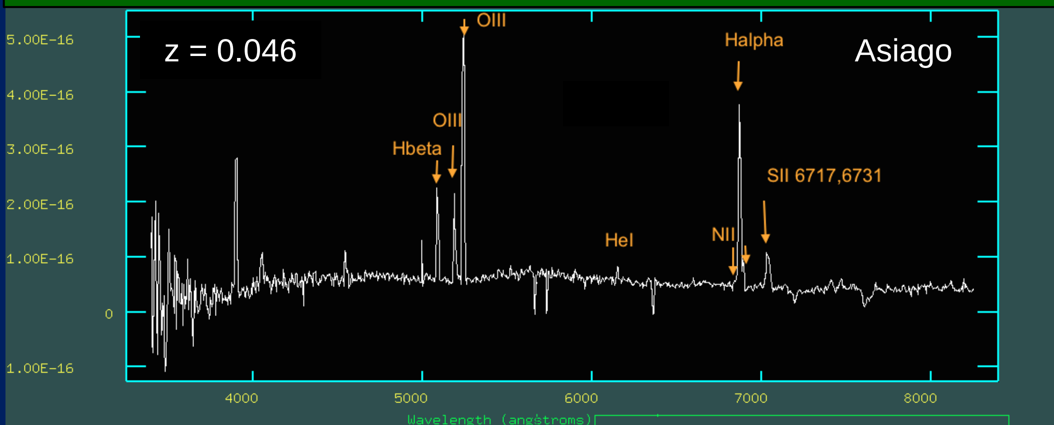


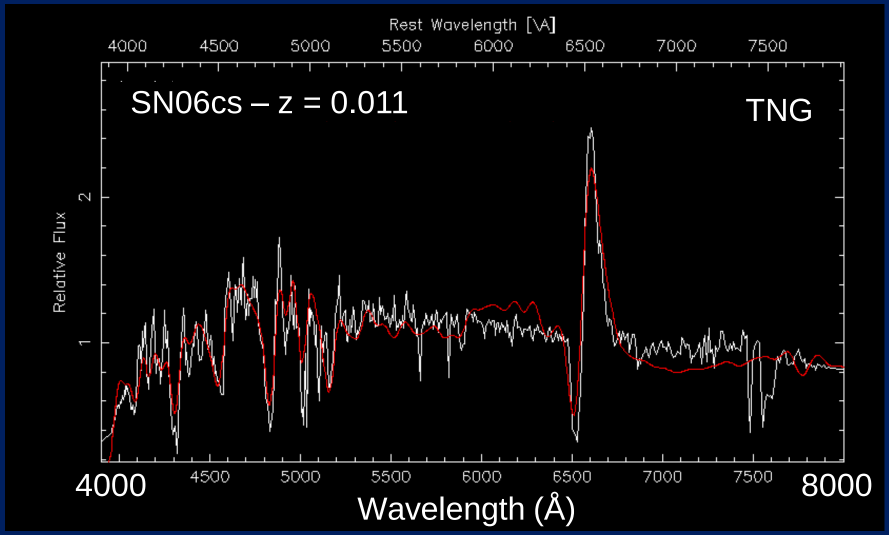


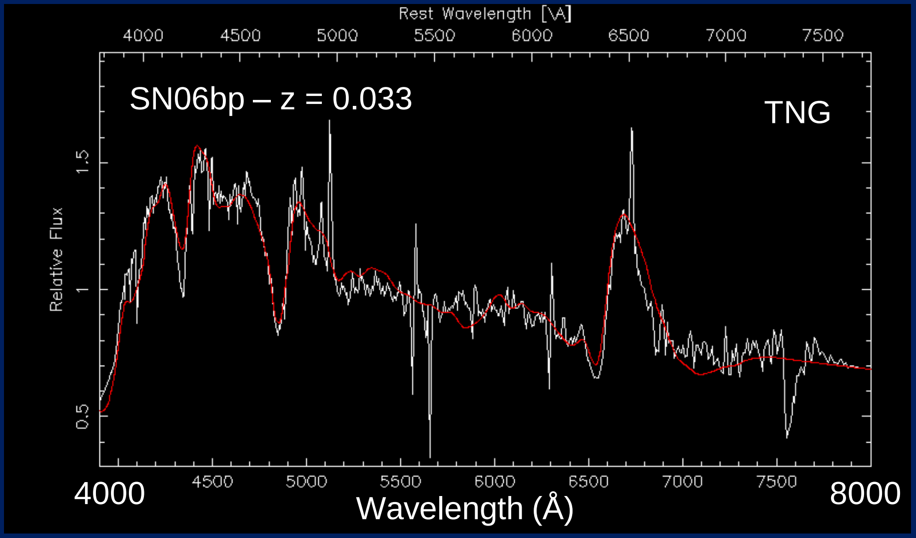
(Brocato & GRAWITA, 2016, in preparation)

GRAWITA: GRAvitational Wave Inaf TeAm

LVT151012: trigger retracted, low S/N
Characterization putative counterparts
Telescopes: LBT / NTT / TNG / NOT / Asiago
Collaborations: IPTF and PanSTARSS/PESSTO



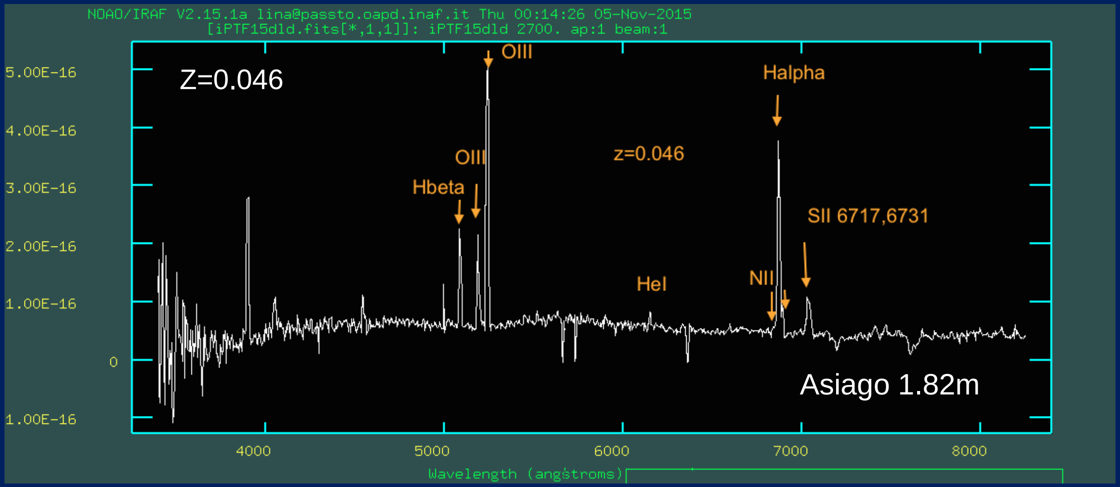


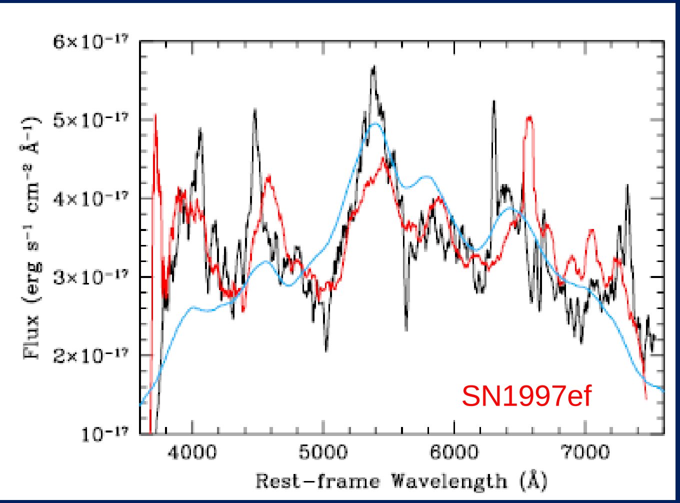


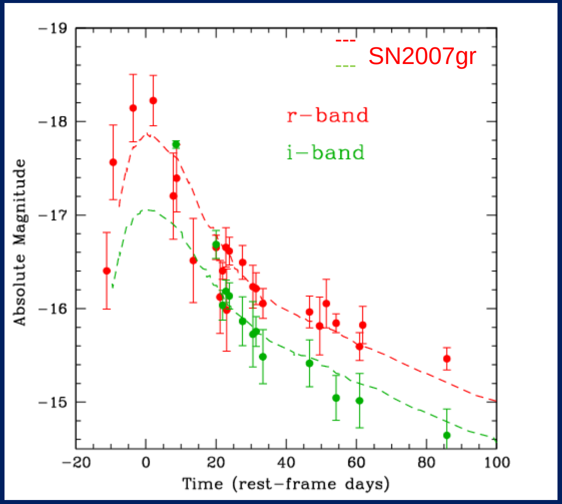
(Piranomonte & GRAWITA, 2016, in preparation)

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



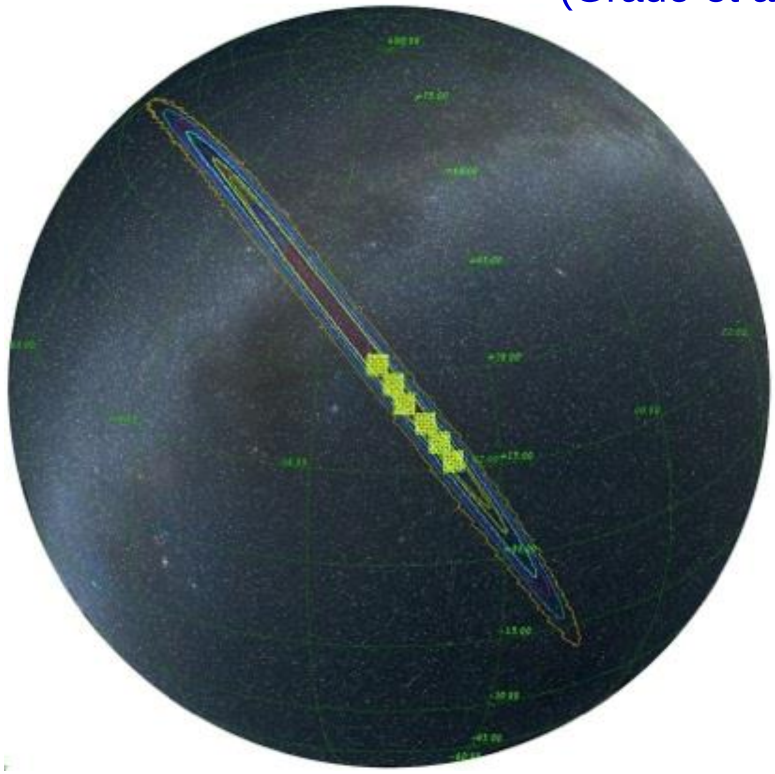




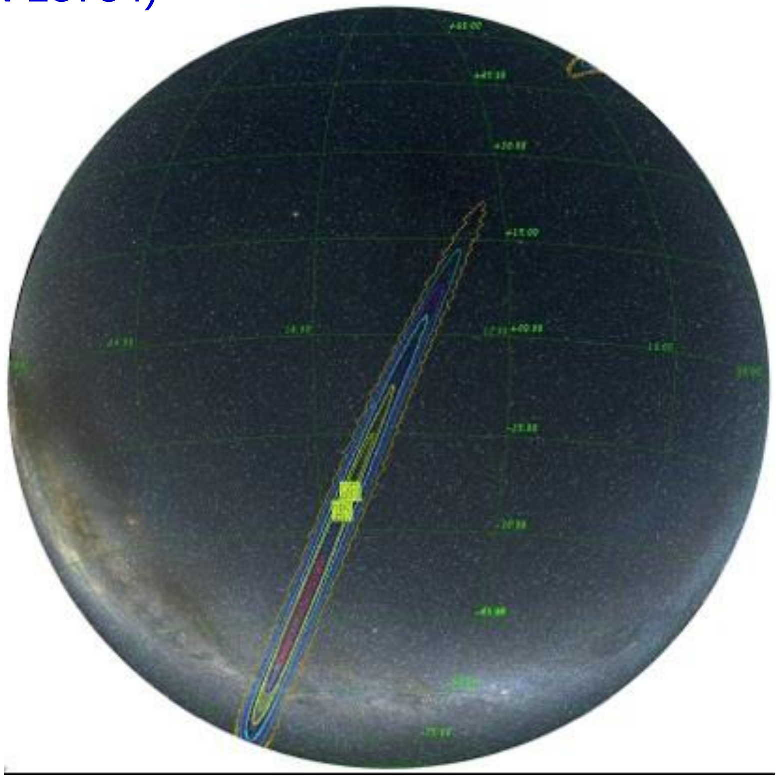
Pian et al , A&A submitted

Search GW151226

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



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



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

Display tools: credit to G. Greco, WG1

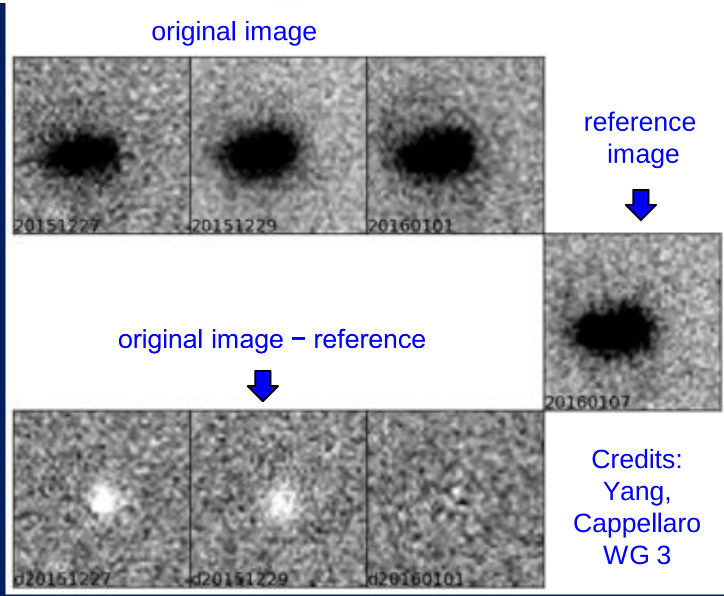
GRAWITA: GRAvitational Wave Inaf TeAm

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

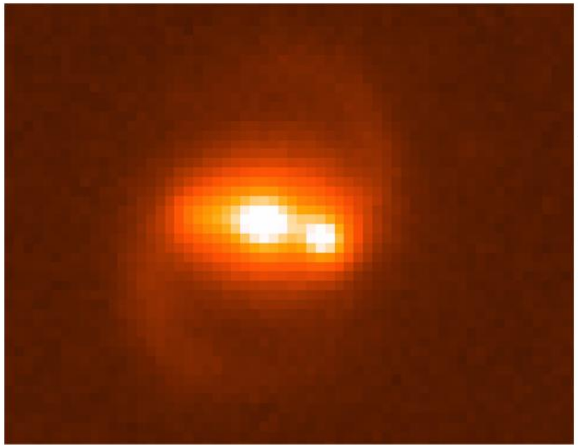
GRAWITA: photometric data with VST@ESO

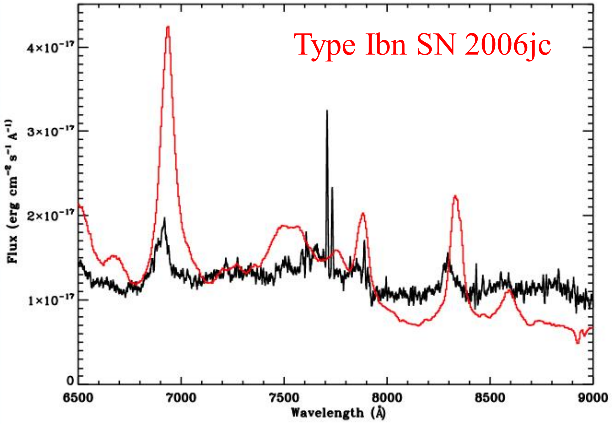
Gemini: unusual spectra not characterized z~0.175
(Chambers et al GCN 18811)

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



(Piranomonte & GRAWITA, 2016, in preparation)





LBT
8mTelescope
(LBC-Blue)

LBT
8m Telescope
(MODS1-Red)

Summary (I)

GRAWITA provided an observational response to the search of optical counterpart of the first detections of gravitational events.
None of the transients localized by our team can be related to the GW150914 and GW151226 gravitational events.

Nevertheless, we could test the reliability and the effectiveness of our plans:

- **prompt response**: within 23 hours from the alert for GW150914 within 9 hours for GW151226
- **observational strategy:** the contained probability of the area covered by the VST is one of the largest region observed by optical ground based telescopes reacting to the GW150914 alert. The magnitude limit of the order of R ~22.4 mag is reached in most of the observed epochs.

Summary (II)

- **data analysis**: on the basis of previous experiences in optical bands in searching for GRB and Supernovae, two independent procedures have been developed. One related to source extraction and algorithms of magnitude comparison between different epochs and the second one to identify transients using difference image techniques. These procedures are now reliable and tested for the next run, O2, by LIGO/VIRGO experiments.
- **by product science**: discovery of interesting objects in the realm of the Time Domain Astronomy. In fact, along the follow-up activity we were able to identify a large number of NEO and asteroids as far as a couple of peculiar supernovae for which individual publications have been prepared.
- **collaborations with other team:** the enormous number of detected transients induced a profitable collaboration among different group involved in this research.

Some open issues for the O2 LVC science run

- several 10−100 deg^2 sky areas to cover
- EM follow-up is facing the well known problem of balancing large sky coverage with sufficient depth
- Info on Distances + Progenitor will greatly help in adopting efficient observational strategies for optical follow-up
- 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)

GRAWITA and the O2 LVC run

- Prepare to Virgo impact on Spring 2017
- Faster alerts from LVC
- Rapid ToO activation
- Faster data analysis of VST image (photometry pipeline + image subtraction)
- Fast follow-up observations of detected transient for characterization
- Agreements with other groups to optimize the observational strategy

GRAWITA: GRAvitational Wave Inaf TeAm