Grawita searches for optical counterparts to Gravitational Waves

Enzo Brocato

&

Grawita collaboration

Istituto Nazionale di AstroFisica
Osservatorio Astronomico di Roma

15° AGILE Science Workshop

May 23-24, 2017, ASI, Rome

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...first meeting INAF – LVC
2014………...MoU INAF-LVC signed / early Team submitted PRIN INAF
2014………...VST as ToO facility
2015..............Early activities Proposals / fund raising
07-07-2015…Unsolicited project "Gravitational Wave Astronomy …" approved
15-09-2015... First operational meeting
17-09-2015... ESO-VST observations of GW150914
28-12-2015... ESO-VST observations of GW151226
30/12/2015-04/03/2016... TNG and LBT characterization of transients
03-2016........ Joint paper with LVC on *GW150914*
2016-2017….. Optical follow-up of LVC O2 run

GRAWITA PAPERS

Abbott et al. 2016: Localization and broadband follow-up of the gravitational-wave transient GW150914
Abbott et al. 2016: Supplement: Localization and broadband follow-up of the gravitational-wave transient GW150914
Pian et al. 2016: Optical photometry and spectroscopy of the low-luminosity, broad-lined Ic supernova iPTF15dld
Brocato et al. 2017: VLT Survey Telescope Observations of the gravitational wave source GW150914 - in prep
GRAWITA PAPER II 2017: EM Follow-up and Characterization of GW151226 event - in prep

Who we are

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

see also www.grawita.inaf.it

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VLT Survey Telescope (VST) follow-up of GW150914 and GW151226

GW150914

Response time
after alert : 23 h
after event : 2.9 d

GW151226

Response time
after alert : 7.6 h
after event : 1.9 d

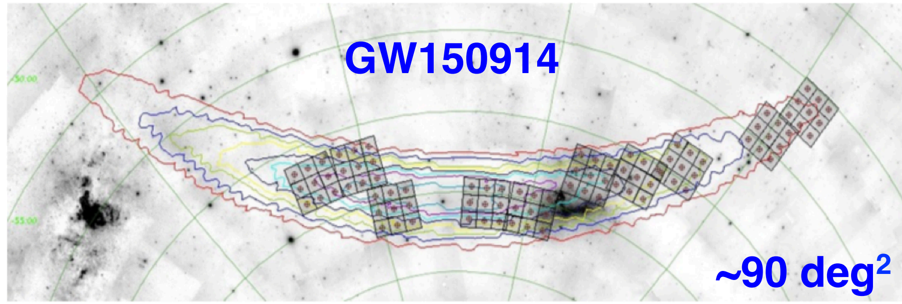


Figure 1. Footprints of the VST r band observations over the contours of the initially distributed cWB localization map of GW150914. Each square represents the VST Observing Block of 3×3 deg^2. The lines represent the enclosed probabilities from a 90% confidence level to a 10% confidence level in steps of 10%. The probability region localized in the northern hemisphere is not shown. The ten tiles enclose a localization probability of ∼ 29%. DSS–red image is shown in the background. An interactive skymap can be found in https://www.grawita.inaf.it/highlights/.

GW150914			
Epoch	Date (UT)	Area deg^2	FWHM arcsec
1	2015-09-17	54	0.9
2	2015-09-18	90	0.9
3	2015-09-21	90	0.9
4	2015-09-25	90	1.1
5	2015-10-01	72	1.0
5	2015-10-03	18	1.0
6	2015-10-14	45	1.5
6	2015-11-16	9	1.2
6	2015-11-17	18	1.1
6	2015-11-18	18	1.5

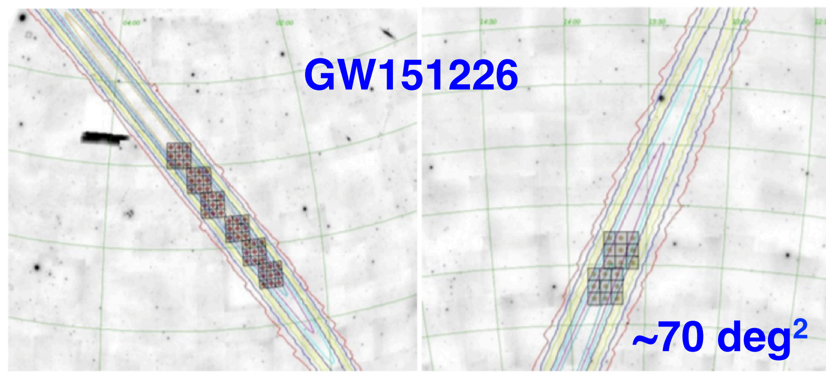
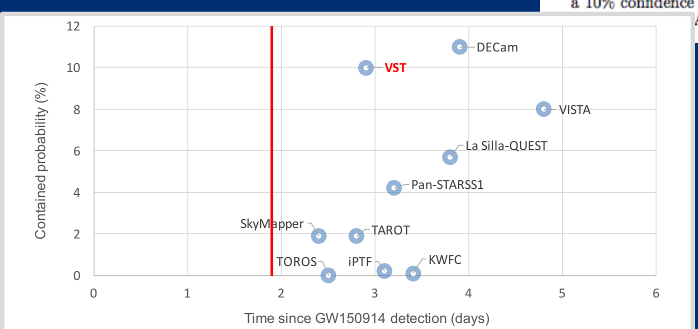


Figure 2. Footprints of the VST r band observations over the contours of the initially distributed BAYESTAR localization map of GW151226. From left to right, the VST coverage in the northern and southern hemispheres is shown. Each square represents the VST Observing Block of 3×3 deg^2. The lines represent the enclosed probabilities from a 90% confidence level to a 10% confidence level in steps of 10%. The eight tiles enclose a localization probability of ∼ 9%. DSS–red image is shown in the background. An interactive skymap can be found in https://www.grawita.inaf.it/highlights/.

GW151226			
Epoch	Date (UT)	Area deg^2	FWHM arcsec
1	2015-12-27	72	1.0
2	2015-12-29	72	1.6
3	2015-12-30	9	1.3
3	2016-01-01	45	0.9
3	2016-01-02	9	0.9
4	2016-01-05	18	1.2
4	2016-01-06	18	1.1
4	2016-01-07	27	0.8
5	2016-01-13	45	1.5
5	2016-01-14	27	1.1
6	from 2016-01-28 to 2016-02-10	63	1.1

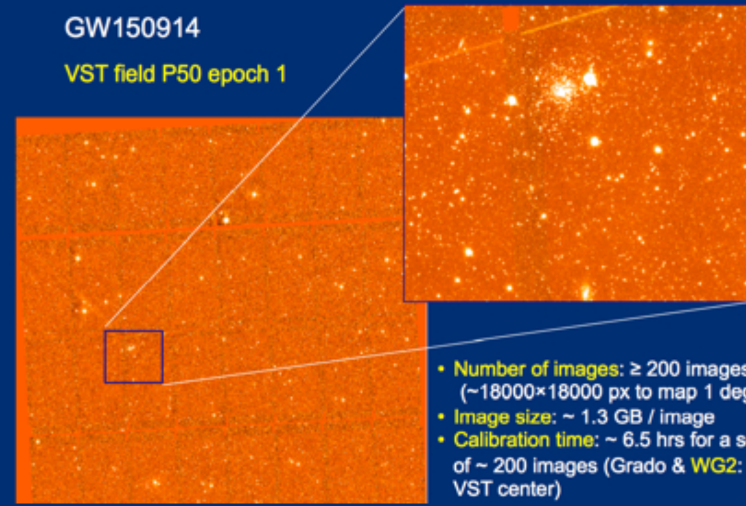


interactive tool ➔ http://www.grawita.inaf.it/highlights

Search for transients in VLT surveys (O1)

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)

Two independent pipelines are now ready to process wide field images and identify transient candidates

✧ 10^4 – 10^6 sources in each VST field (LMC)

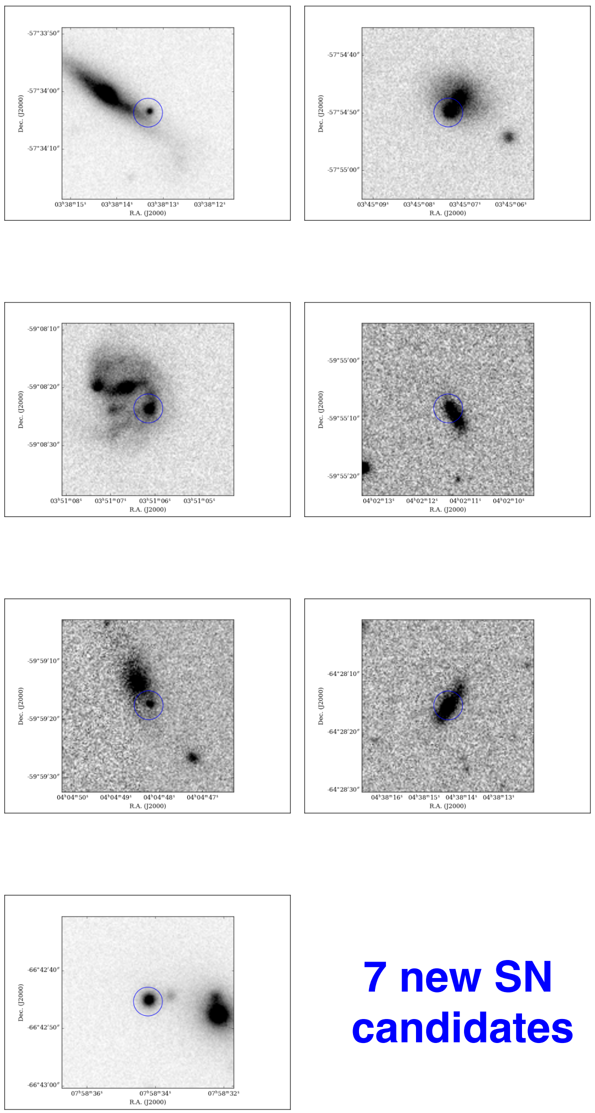
✧ ~ 10^4 transient candidates in the full area (90 deg^2)

✧ ~ 10^2 to be visually examined after selection of known objects (variables, asteroids etc)

✓ Reliability verification of the pipelines on the VST observed fields of GW150914 follow-up:
Example: Variables known by OGLE survey = 6722
same variables recognized by GRAWITA = 6302
i.e. **a percentage of ~ 94%** of recognized objects.

Transients Identification: few examples of SN candidates (blu circle)

GW150914



7 new SN candidates

Comparison with other searches

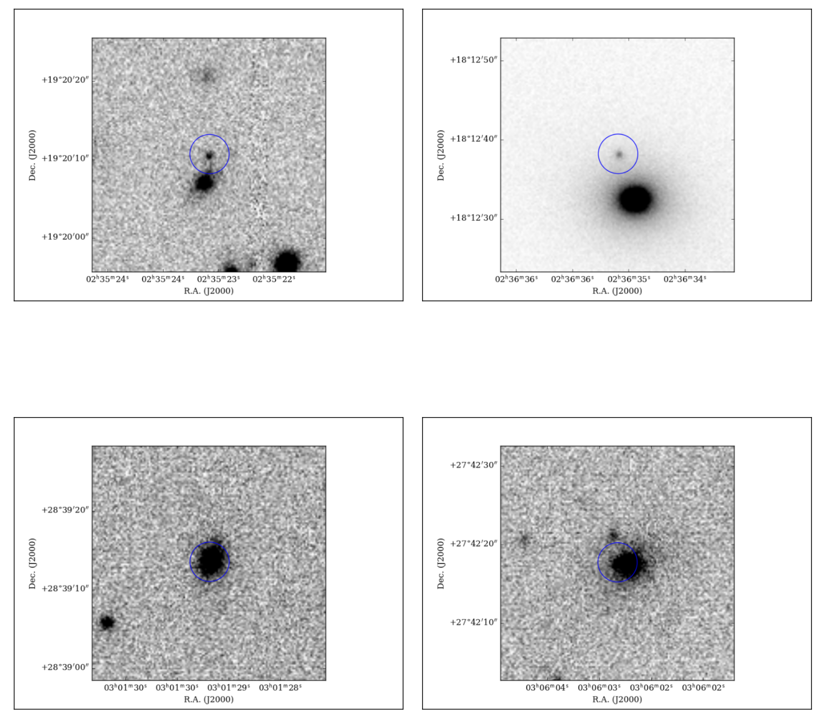
Example:

by taking into account the area covered for GW151226, Grawita finds:

10 SNe already discovered by other surveys

+ 4 new SN candidates

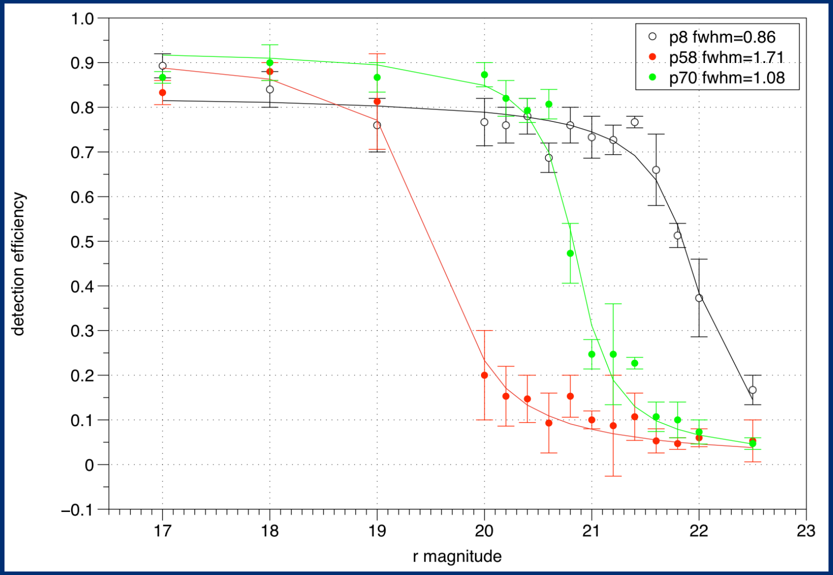
GW151226



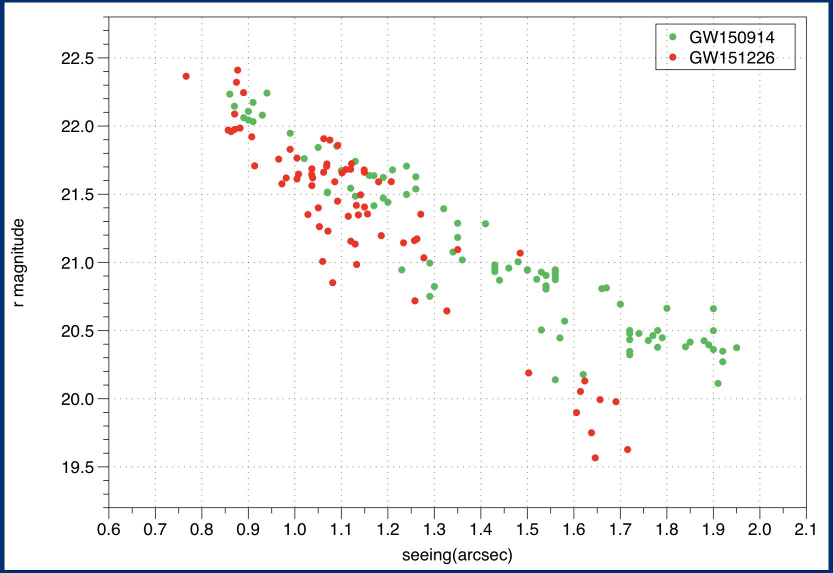
4 new SN candidates

VST survey: magnitude limits and efficiency

We add a number of *artificial stars of different magnitudes in random positions*.
Then, we run the image difference pipeline and count the number of artificial stars that are recovered with a score above the adopted threshold.
The ratio of recovered over injected stars gives the **detection efficiency** as a function of magnitude.



The **limiting magnitude (*r*) for transient detection as function of seeing** for the pointings of GW150914 and GW151226.
The scatter is due to the fact that other factors are affecting the DE, first of all sky transparency and crowdness and contamination by bright stars.



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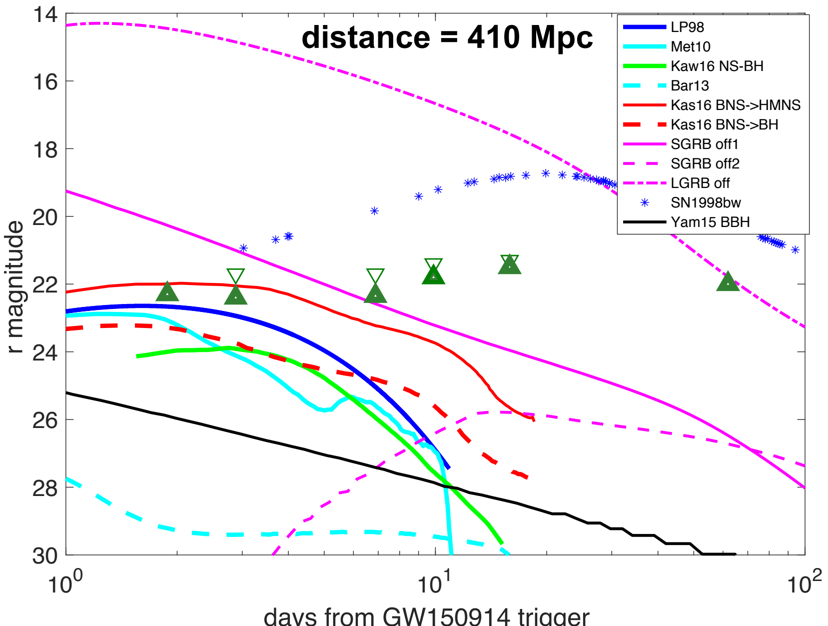
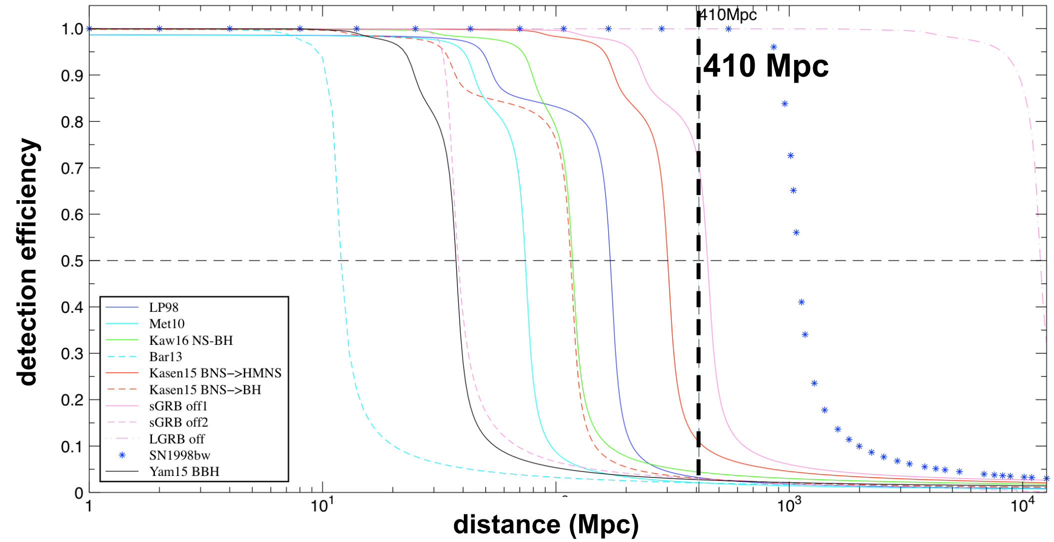
VST magnitude limit vs models



VST detection efficiency vs distances (same models) .



The expected fluxes (r band magnitudes) versus observed time from GW150914 trigger, assuming several possible electromagnetic GW source emission models, plotted against the 6 epochs VST observation 5σ limiting magnitude (*dark green triangles*) and the detection upper limits computed from artificial stars in frame P31 (*light green triangles*). *Blue and cyan solid lines*: kilonova models from Metzger et al. (2010), assuming a radioactively-powered emission for an ejecta mass 10^{-2} $M_\odot$, outflow speed $v = 0.1c$, iron-like opacities, and thermalization efficiency of 1 (cyan line) and a blackbody emission(blue line, Li & Paczyński (1998)) with the same values of the mass and velocity. *Cyan dashed line:* kilonova model from (Barnes & Kasen 2013) assuming an ejected mass of 10^{-3} $M_\odot$ and velocity of 0.1 c and lanthanides opacity. *Green solid line*: kilonova model from (Kawaguchi et al. 2016) for a BH-NS merger with a BH/NS mass ratio of 3, ejected mass of 0.0256 $M_\odot$ and velocity $v = 0.237c$, hard equation of state for the NS, and BH spin of 0.75. *Red lines*: kilonova disk-outflow models from (Kasen et al. 2015), assuming accretion disc mass of 0.03 $M_\odot$ and a remnant hyper-massive NS (solid) or a remnant NS collapsing into a BH within 100 ms (dashed). *Purple lines*: simulated off-axis afterglow light curve (van Eerten & MacFadyen 2011), assuming a short GRB with ejecta energy of $E_{jet} = 10^{50}$ erg, interstellar matter density of $n \sim 10^{-3}$ cm^{-3}, jet half-opening angle of $\theta_{jet} \sim 0.2$ rad and an observed viewing angle of $\theta_{obs} \sim 0.2$ rad (solid) and $\theta_{obs} \sim 0.4$ rad (dashed) and a long GRB with ejecta energy of 2×10^{51} erg, $\theta_{jet} \sim 0.2$ rad and an observed viewing angle of $\theta_{obs} \sim 0.3$ rad. *Blue asterisks*: SN 1998bw associated with GRB 980425 (Clocchiatti et al. 2011). *Black solid line*: R-band emission from a BBH merging according to the model by (Yamazaki et al. 2016).

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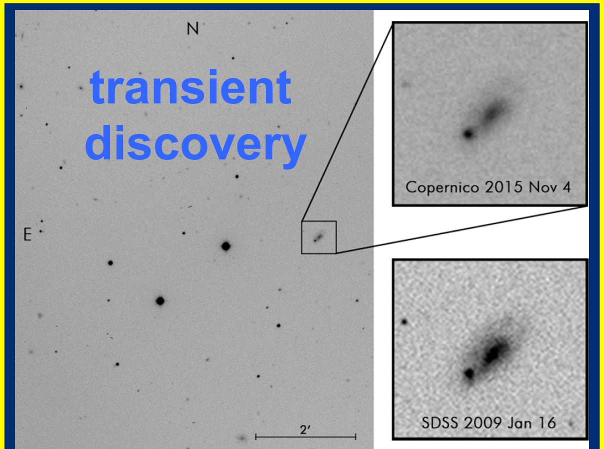
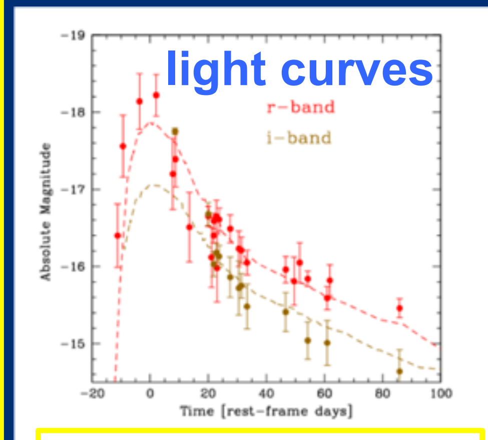
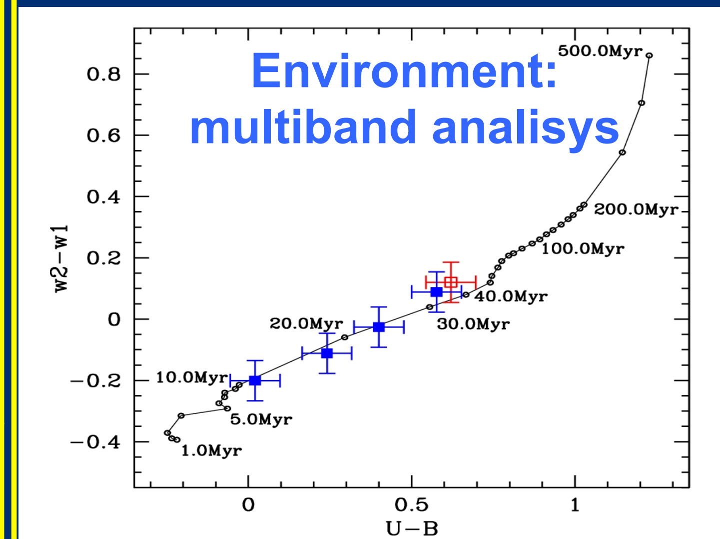
Cooperation between ***iPTF / GRAWITA / LSQ / Pan-STARRS / SWIFT***
Transient iPTF15dld discovered by iPTF (GCN18497),
identified as a Supernova Type Ic by GRAWITA (GCN18563)
Information on the environment can be obtained by Swift/UVOT





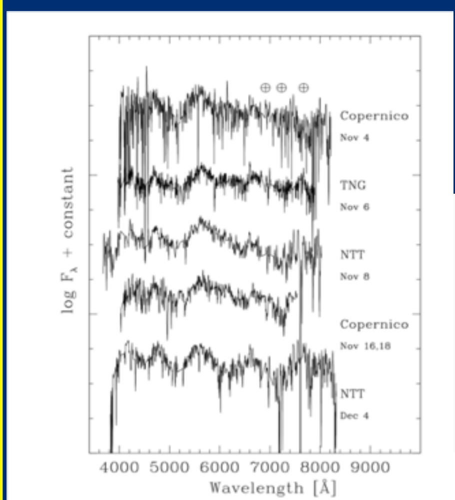
Classification

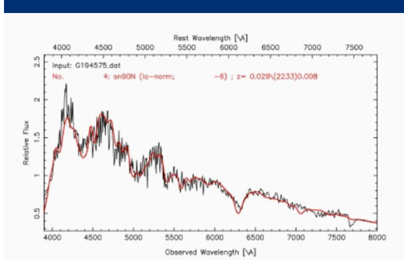
Pian et al. 2016



Stellar population synthesis for the starburst region underlying iPTF15dld. Ages of the stellar populations are indicated. The squares represent the observed (open red) and de-reddened (filled blue) colours of the starburst, for different amounts of internal absorption [$E(B-V)$ = 0.027, 0.137, 0.237, 0.377]

spectral analysis



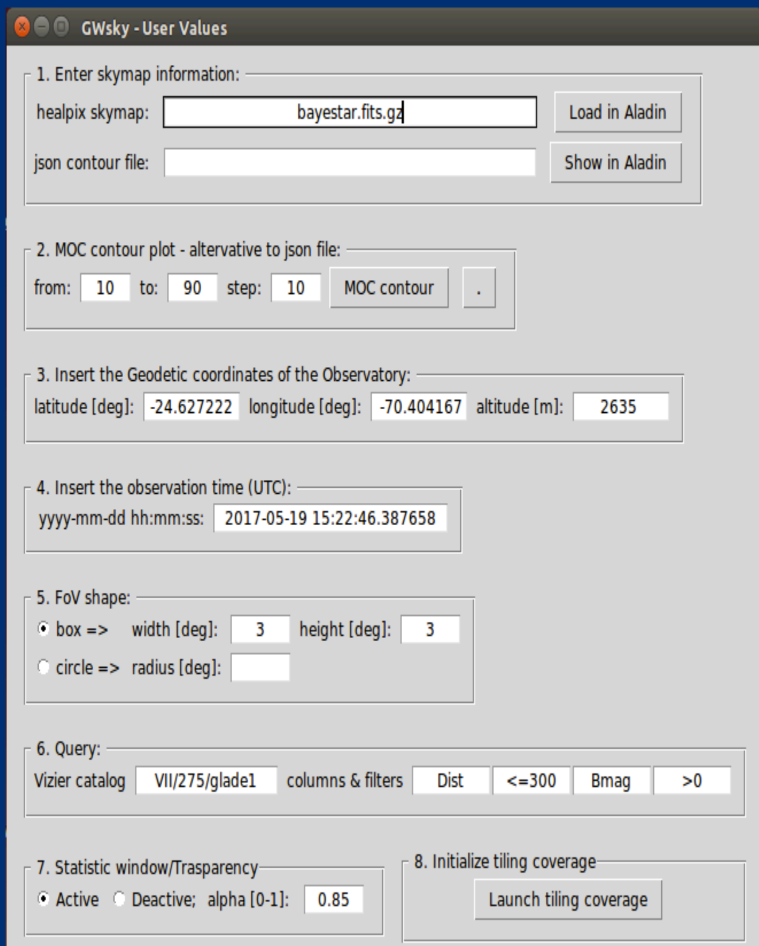


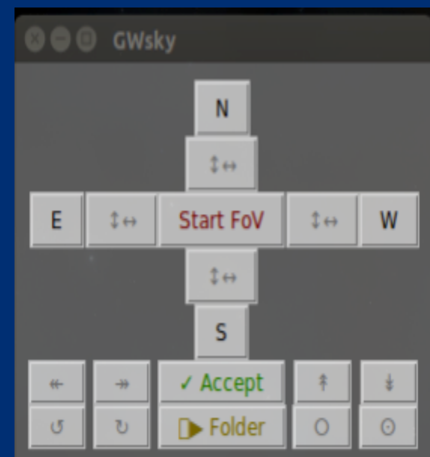
data analysis : L. Tomasella

“GW” distance vs redshift of the EM counterpart

GWsky: *initialization and coverage*

The Graphical User Interface (GUI) is optimized for fast and interactive pointing operations. The GUI consists of two main modules: *UserValues* and *Coverage.*





Input for the UserValues modulus :

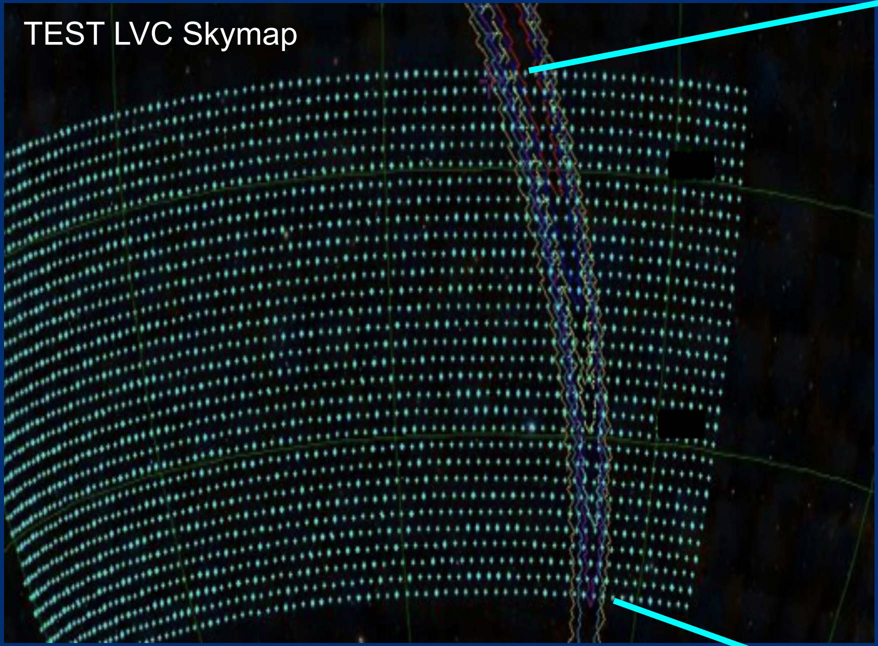
- **LVC skymap**
- **Coordinates of the Telescope**
- **Observation time (UT)**
- **Field of View**
- **Galaxy catalogues and selection (Distance and Bmag)**

Output → **tiling coverage of the LVC skymap**

Gwsky is developed by G. Greco

GWsky: tiling and intersection with VST surveys

Gwsky optimizes the probability coverage and takes into account the availability of reference images from previous surveys and shows the results using _Aladin_ framework.



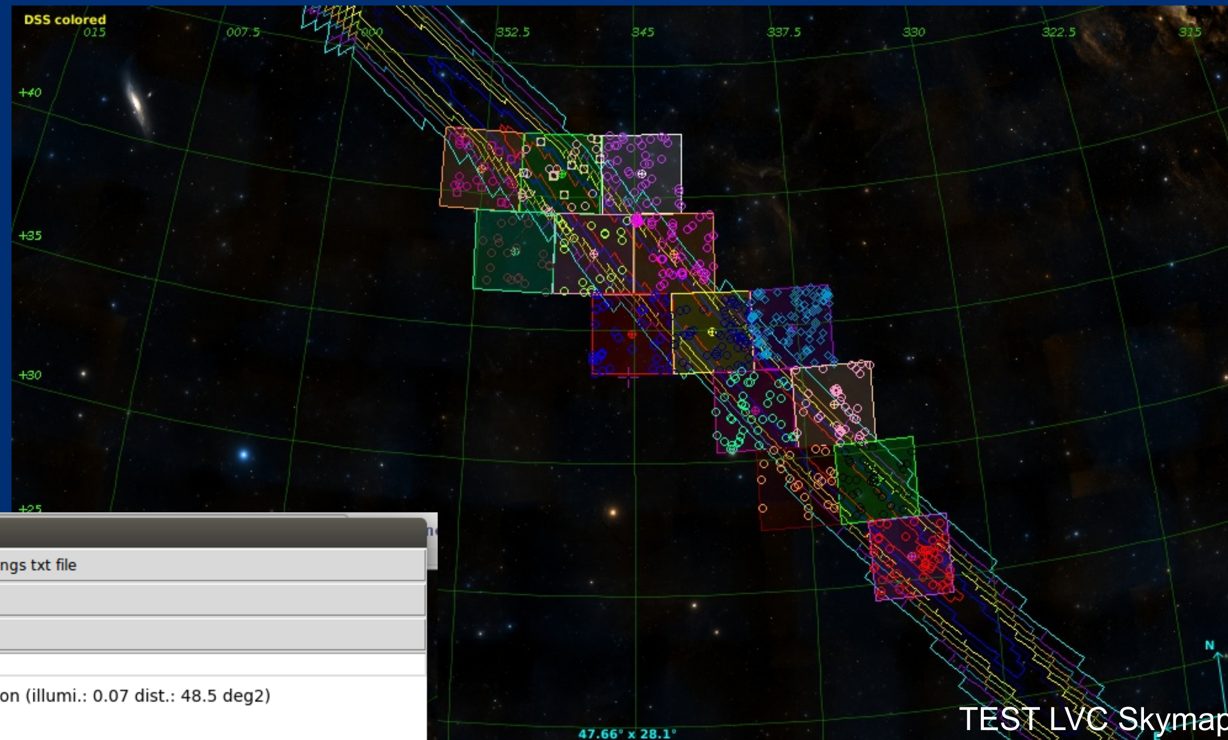
GWsky shows the footprints of the archival VST data over the LVC probability skymap.

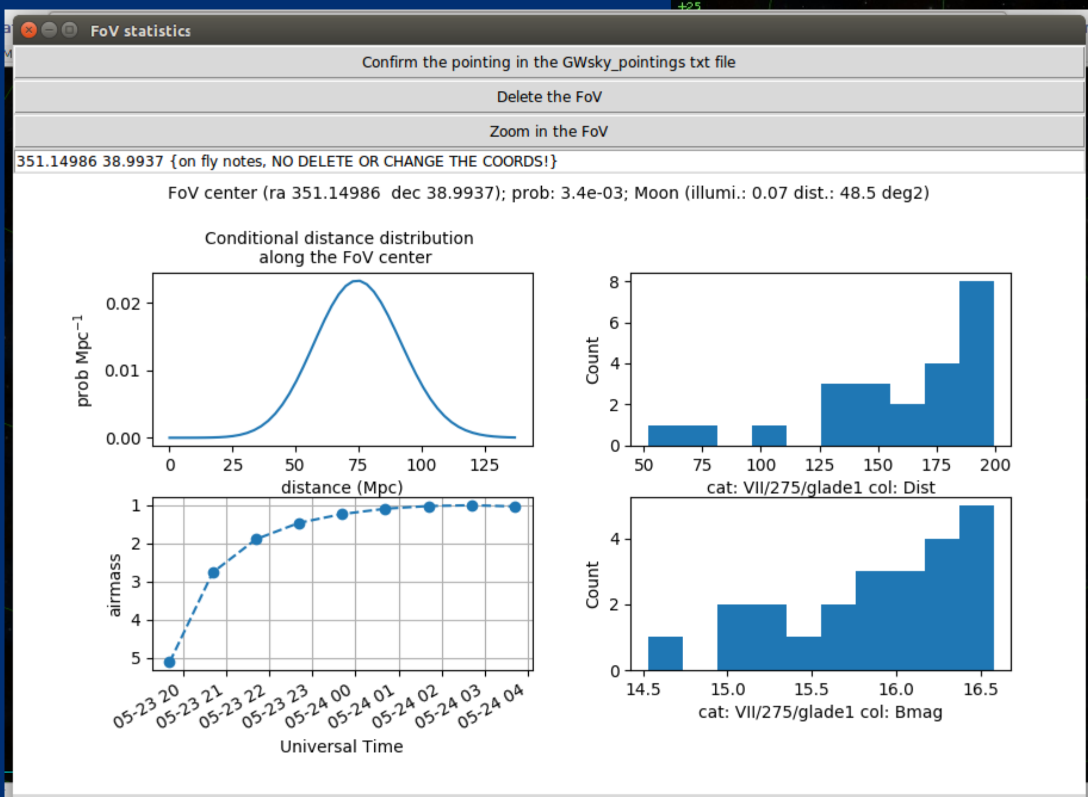
Gwsky computes the grid of pointing for the VST telescope.

Credits : G. Greco

GRAWITA: GRAvitational Wave Inaf TeAm

GWsky: *tiling*





Each Field of View is accompanied by descriptive statistics to manage the sequence of pointings.

Credits : G. Greco

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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 CoIs.*

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Observatory of Campo Imperatore
The Schmidt Telescope (65/91/183 cm)

FoV = 1.15 x 1.15 °

Pixel scale = 1.0 arcsec/pixel

Filters : Sloan (u', g', r', i', z')

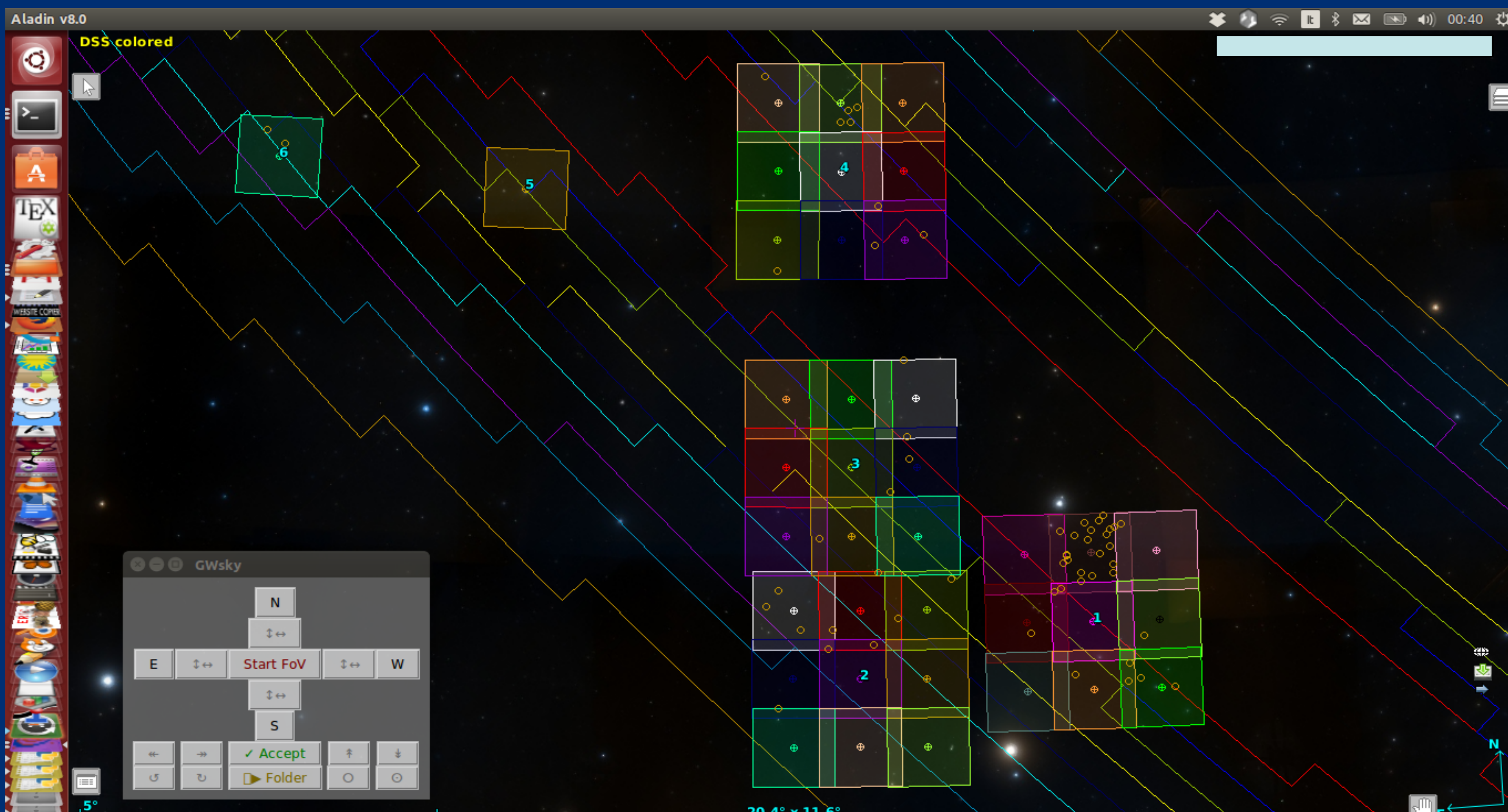
Involved researchers: A. Di Paola, A. Giunta & collaborators

GRAWITA: GRAvitational Wave Inaf TeAm

LVC - O2

Observatory of Campo Imperatore
The Schmidt Telescope (65/91/183 cm)
FoV = 1.15 x 1.15 °
Pixel scale = 1.0 arcsec/px
Filters : Sloan (u', g', r', i', z')

- ✓ **survey ~50 deg^2**
- ✓ **5 epochs : T0+1, +2, +5, +14, +28 days**
- ✓ ***lim. mag for this survey r'=20.5-21.0***



GRAWITA: GRAvitational Wave Inaf TeAm

LVC - O2

Observatory of Campo Imperatore
The Schmidt Telescope (65/91/183 cm)

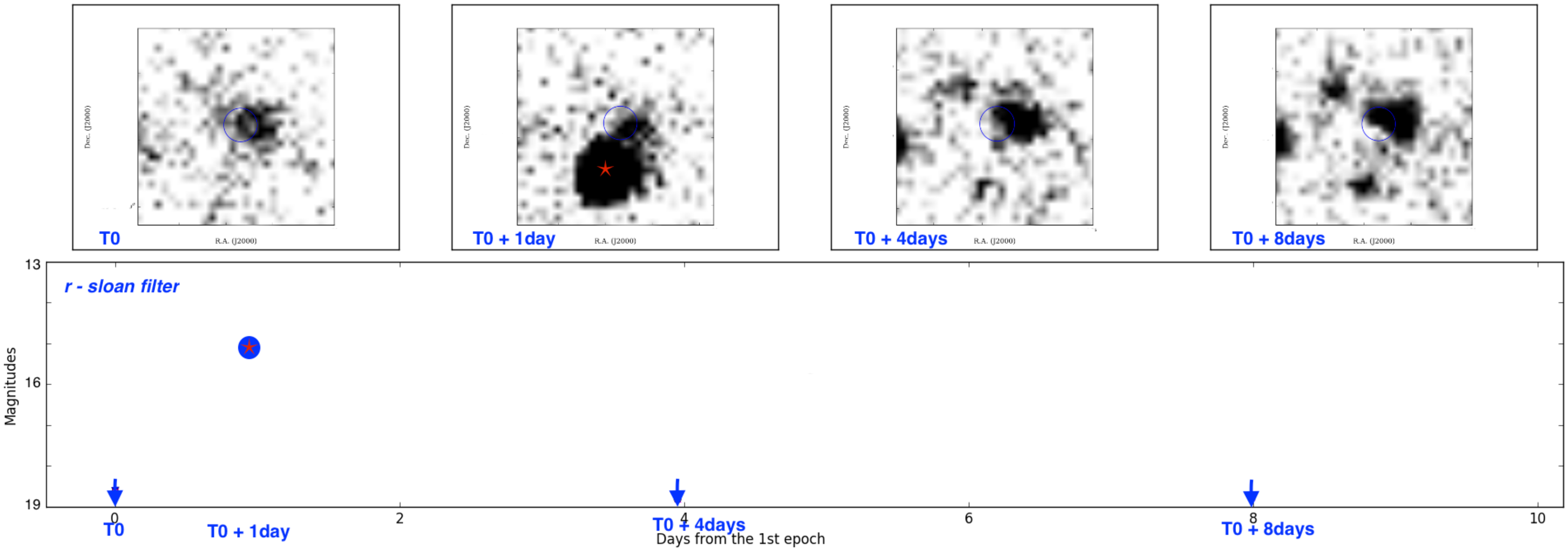
FoV = 1.15 x 1.15 °

Pixel scale = 1.0 arcsec/px

Filters : Sloan (u', g', r', i', z')

lim. mag for this survey r'=20.5-21.0

- *One of the transient candidates found by GRAWITA during follow-up activities after a Gravitational Wave detection in LVC run O2 in Campo Imperatore*



GRAWITA: GRAvitational Wave Inaf TeAm

LVC - O2

Observatory of Campo Imperatore
The Schmidt Telescope (65/91/183 cm)

✓ **coverage of the error box after an AGILE detection**

(zoom: the contours of the LVC probability skymap are removed)

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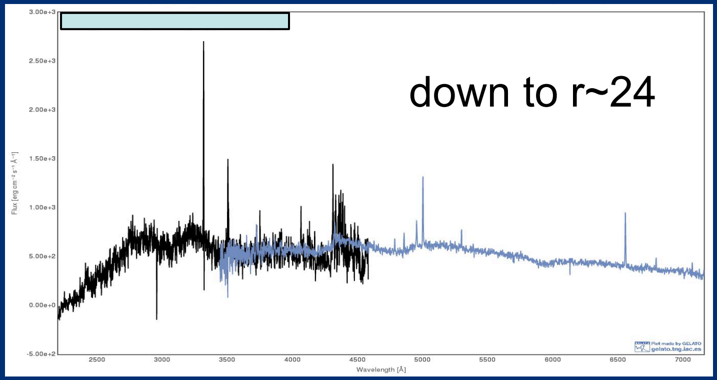
GRAWITA Activity during O2

GCN ---------: **Asiago** observations of xxxxxx
GCN ---------: **TNG** observations of xxxxx
GCN ---------: **TNG** observations of xxxx
GCN ---------: **Campo Imperatore** Observations (5 pointings)
GCN ---------: **Asiago** Observations of xxx
GCN ---------: **Asiago** Observations of xxxxxx
GCN ---------: **REM** optical/NIR observations
GCN ---------: **NOT** Observations of xxxx
GCN ---------: **Asiago** observations (galaxies < 20mpc) 35 pointings
GCN ---------: **TNG** host galaxy detection of xxxxxx
GCN ---------: **Campo Imperatore** Observations (7 pointings)
GCN ---------: **NOT** Observation of xxxxxx
GCN ---------: **Asiago** observations of xxxx

LVS - O2: As of April 23, **6 triggers** have been identified by the online analysis, using a loose false-alarm-rate threshold of one per month.
http://ligo.org/news.php#sthash.0G0gQplD.dpuf

Active follow-up @ **LBT**, **TNG**, **Campo Imperatore, Asiago, GTC**



GRAWITA: GRAvitational Wave Inaf TeAm

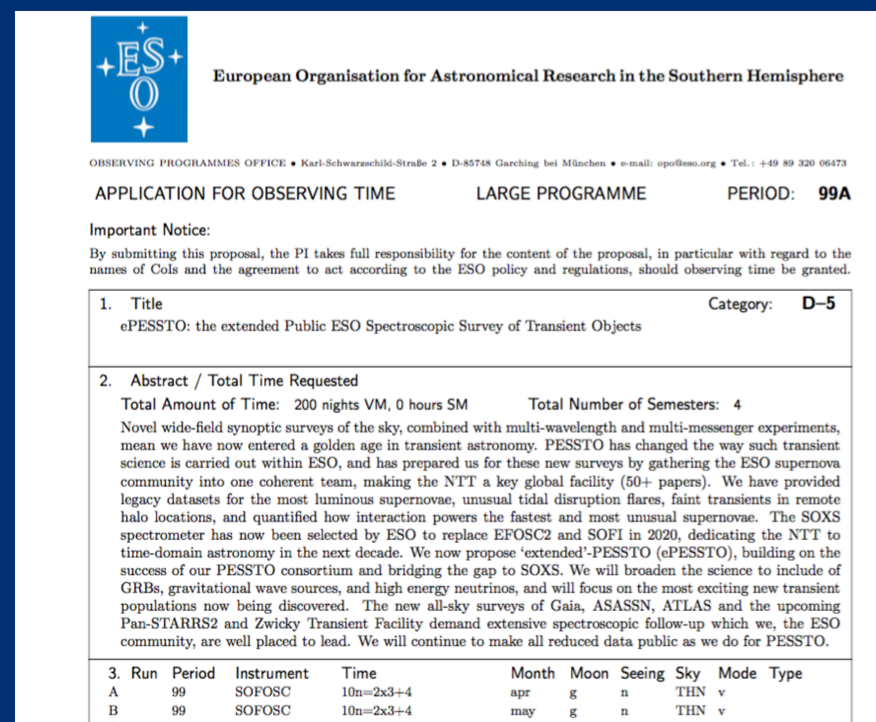
GRAWITA joined ePESSTO :

the extended Public ESO Spectroscopic Survey of Transient Objects

Spectroscopy and photometry SOFOSC@NTT over the period 2017-19
P.I.: S. Smartt (UK)

Scientific targets:

- Nuclear Transients
- Superluminous supernovae and the most massive stars
- Unexplained transients in remote locations
- Gamma-ray bursts
- Gravitational wave and neutrino sources



European Organisation for Astronomical Research in the Southern Hemisphere

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49 89 320 06473

APPLICATION FOR OBSERVING TIME LARGE PROGRAMME PERIOD: **99A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title Category: **D–5**
ePESSTO: the extended Public ESO Spectroscopic Survey of Transient Objects

2. Abstract / Total Time Requested
Total Amount of Time: 200 nights VM, 0 hours SM Total Number of Semesters: 4

Novel wide-field synoptic surveys of the sky, combined with multi-wavelength and multi-messenger experiments, mean we have now entered a golden age in transient astronomy. PESSTO has changed the way such transient science is carried out within ESO, and has prepared us for these new surveys by gathering the ESO supernova community into one coherent team, making the NTT a key global facility (50+ papers). We have provided legacy datasets for the most luminous supernovae, unusual tidal disruption flares, faint transients in remote halo locations, and quantified how interaction powers the fastest and most unusual supernovae. The SOXS spectrometer has now been selected by ESO to replace EFOSC2 and SOFI in 2020, dedicating the NTT to time-domain astronomy in the next decade. We now propose 'extended'-PESSTO (ePESSTO), building on the success of our PESSTO consortium and bridging the gap to SOXS. We will broaden the science to include of GRBs, gravitational wave sources, and high energy neutrinos, and will focus on the most exciting new transient populations now being discovered. The new all-sky surveys of Gaia, ASASSN, ATLAS and the upcoming Pan-STARRS2 and Zwicky Transient Facility demand extensive spectroscopic follow-up which we, the ESO community, are well placed to lead. We will continue to make all reduced data public as we do for PESSTO.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	99	SOFOSC	10n=2x3+4	apr	g	n	THN	v	
B	99	SOFOSC	10n=2x3+4	may	g	n	THN	v	

The astrophysical sources of gravitational waves and the variable X and Gamma-Ray sky

LSST
TVS Science Collaboration

INAF supports 15 LSST projects:

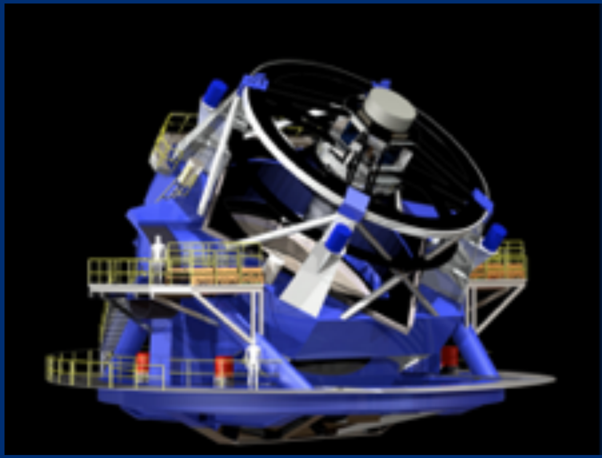
Title: The astrophysical sources of gravitational waves and the variable X and Gamma-Ray

PARTICIPANTS
PIs: ***E.Brocato*** *(INAF–OAR)* ***/ M. Tavani / M. Feroci*** *(INAF–IAPS)*

Junior Researchers: ***G. Stratta*** (INAF-IASF Bo), ***S. Piranomonte*** (INAF –OAR), ***I. Donnarumma*** (ASI), ***G. Piano*** (INAF-IAPS)

SCIENTIFIC / TECHNICAL INTEREST
GW sources; gamma-ray transients and binaries; blazars; Tidal Disruption Events

LSST SCIENCE COLLABORATION(S) OF INTEREST
Transients/Variable Stars; Active Galactic Nuclei



The astrophysical sources of gravitational waves and the variable X and Gamma-Ray sky

TVS Science Collaboration

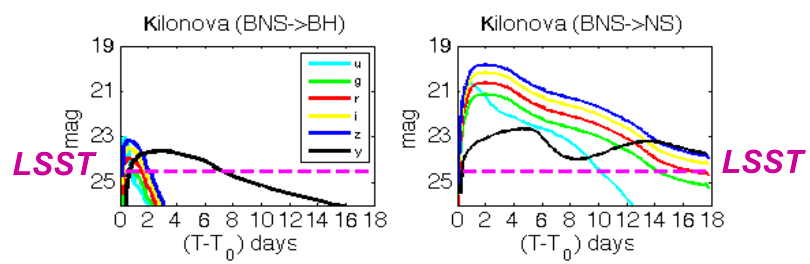
Goal: Identification and study of EM counterparts of GW signals
LSST will match the multi-messenger era (sky localization ≈ a few tens of deg^2). Time to explore the EM/GW sources

LIGO/Virgo KAGRA LIGO India eLISA

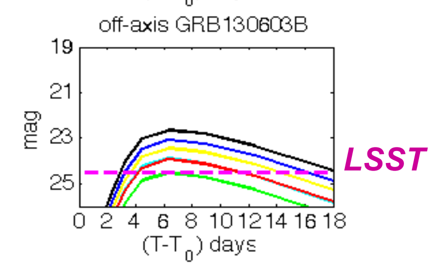
2020 2025

SOXS LSST E-ELT

LSST enables to build large sample of sources of gravitational and electromagnetic radiation thus allowing deep insights on source nature, host galaxy properties, formation history, tests of GR, strong gravity labs, stellar evolution, etc.



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



Examples of expected optical counterparts at 200 Mpc

Credits : G. Stratta


Thank you