GRAWITA and VST: a fruitful partnership

Enzo Brocato
INAF – Osservatorio Astronomico di Roma

2013 LIGO/Virgo : call for MoU for searching EM counterparts of GW events

- ***High quality science:***
  - possibility of opening a new field in astrophysics
  - possibility of breakthrough discoveries
- ***High risk :***
  - measure of GW (high level of skepticism),
  - uncertainties on the direction of GW in sky (skymaps of hundreds/thousand deg^2),
  - a lot of false candidate (tens/hundreds),
  - short time in reaction (hours/days)…
- ***A lot of work to be done 'before' LVC alerts:***
  - Proposals at selected telescopes
  - Procedures to optimize observations (epochs, pointings, exp. times, filters…)
  - Procedures for fast data reductions
  - Procedures for searching transients in observed fields
  - Procedures for spectral analysis of candidates
  - Set up the opt-nir follow-up of the counterparts
  - etc

Our Group

GRAvitational Waves Inaf TeAm

www.grawita.inaf.it

INAF OA Roma: **E. Brocato** (**P.I.**), **S. Piranomonte**, S. Ascenzi, L. Stella, A. Stamerra, P. Casella, G. Israel, L. Pulone, A. Giunta, A. Di Paola

INAF OA Napoli: **A. Grado, F. Getman, L. Limatola, M.T. Botticella**, M. della Valle, M. Capaccioli, P. Schipani

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

INAF OA Brera / IASF Milano: **S. Campana, S. Covino**, **P. D'Avanzo**, **A. Melandri**, G. Ghisellini, G.Ghirlanda, R. Salvaterra

INAF OA Padova: **E. Cappellaro, L. Tomasella**, **S. Benetti, M. Turatto, S. Yang,** M. Mapelli, R. Ciolfi

INAF OA Cagliari: **A. Possenti,** M. Burgay

GSSI: **M. Branchesi**

University of Urbino: **G. Stratta, G. Greco**

SNS Pisa: M. Razzano, B. Patricelli,

Space Science Data Center: L.A. Antonelli, **V. D'Elia,** S. Marinoni, P. Marrese,

INAF OA Abruzzo: **G. Raimondo, M. Cantiello**

University of Calabria: **S. Savaglio**

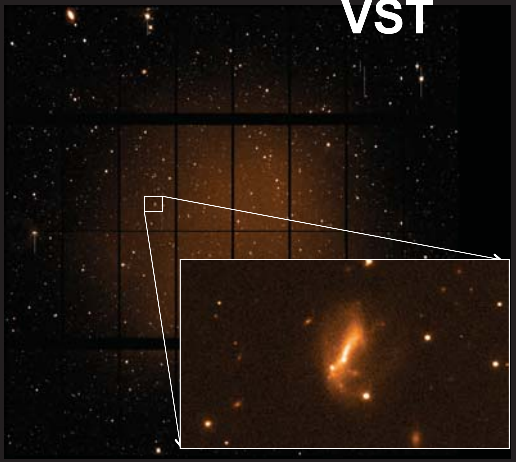
University of Bologna: **A. Cimatti, M. Moresco,** M. Brusa, G. Lanzuisi, M. Talia

The route for the EM counterpart

STEP 1
Search & Detect
Transients in the ***skymap*** 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

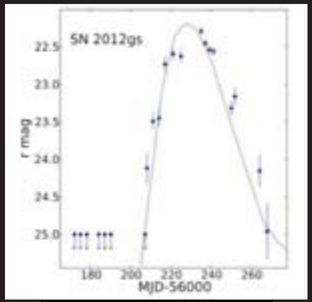


STEP 2
Observe & Characterize
The detected transients have to be observed to infer their nature

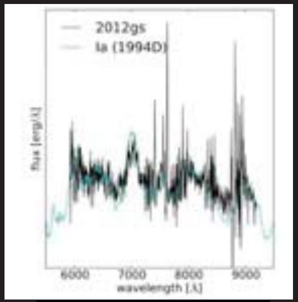
Telescopes for prompt spectroscopy of selected candidates at different latitudes/longitudes

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

The route for the EM counterpart

STEP 1

Search & Detect

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

I

Gamma emission
and precise localization by satellite
(< few arcmin)

→ immediate follow-up of the source

II

'Small' error boxes (< ~40 deg^2) and known distances

Galaxy targeting

Aasi et al. 2014, ApJS, 211

III

Mosaic of tiles

Wide field Opt-Nir search

+

GRAvitational Wave Inaf TeAm

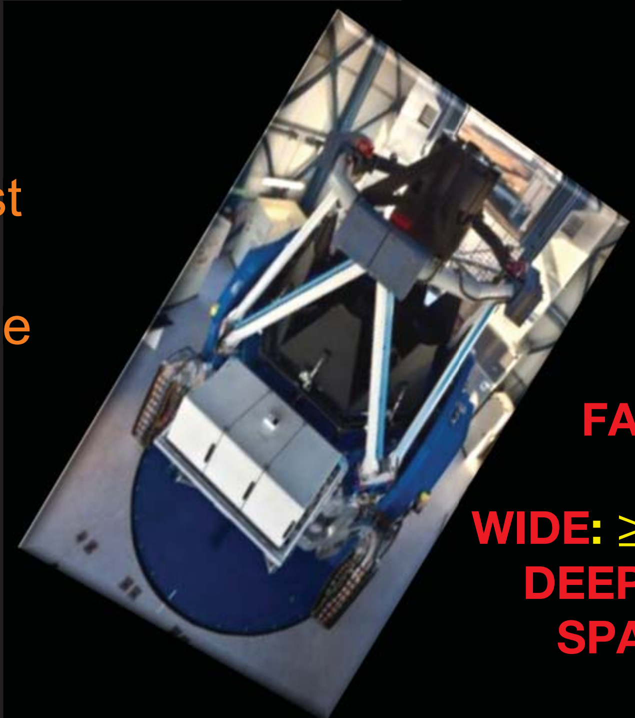
Search of transient objects in the LVC skymap

Initial LVC skymaps cover a very large region of the sky:

GW150914 ~ 600 deg^2
LVT151012 ~ 1600 deg^2
GW151226 ~ 1000 deg^2
GW170104 ~ 1200 deg^2
GW170608 ~ 520 deg^2
(90% credible areas)

Credit: LIGO/Virgo/NASA/Leo Singer

VST is one of the best facilities to identify transient objects in the LVC skymap



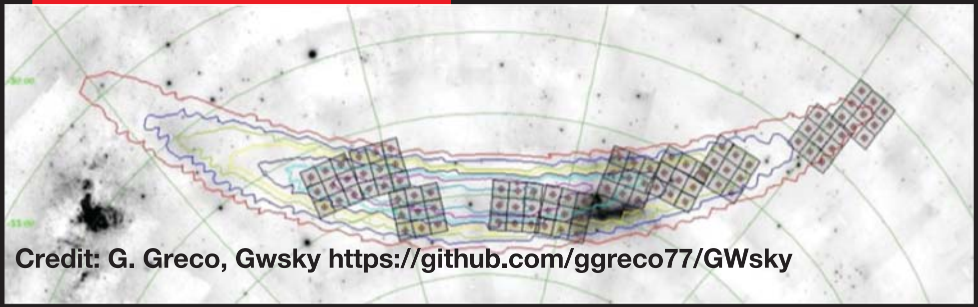
FAST: hours after LVC alert
FoV: 1°x1° FoV
WIDE: ≥90 deg^2 contained probability
DEEP: r_lim ~ 22.5 mag (80s exp)
SPAT. RES.: 0.21 arcsec/pixel

Search for counterparts: wide field

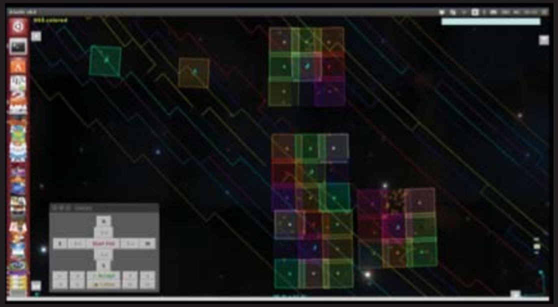
ESO–VST
2.6m FoV = 1 deg^2
(PI Cappellaro/Grado)

Campo Imperatore Schmidt Tel.
0.61/0.91m FoV=1.3 deg^2
(PI: Di Paola, Giunta)

Asiago Schmidt Telescope
0.67/0.92m FoV=1 deg^2
(PI: Tomasella)



Credit: G. Greco, Gwsky https://github.com/ggreco77/GWsky

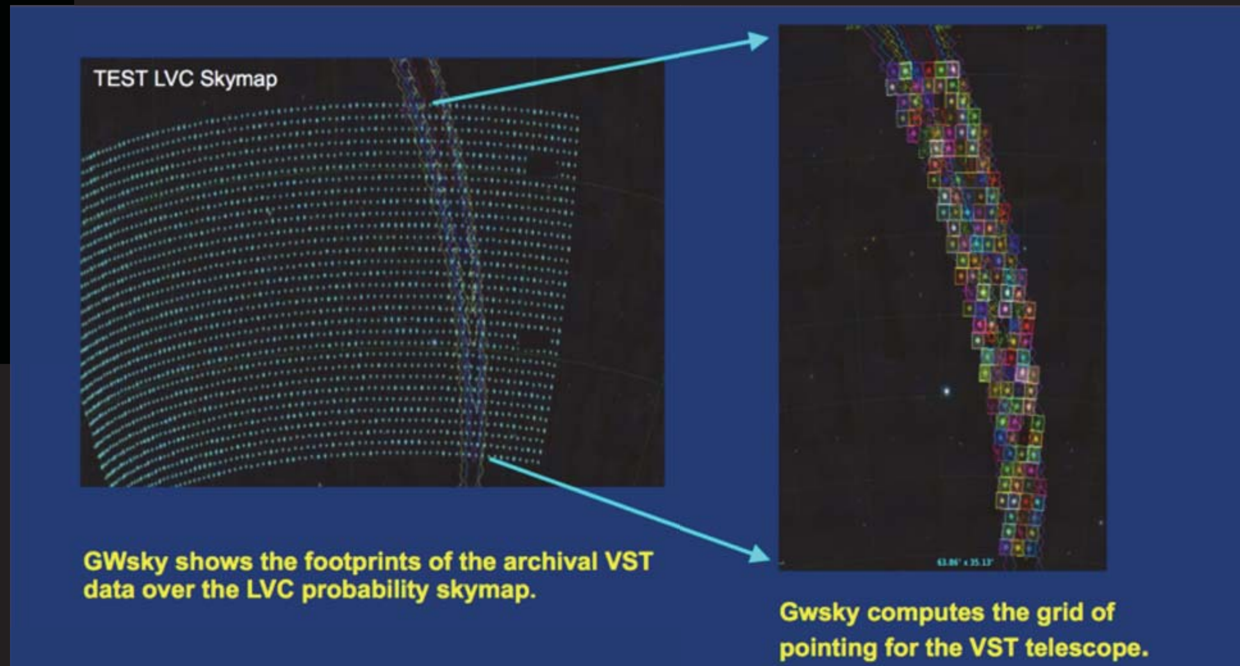


VST & CI successfully operated in O1 & O2, Asiago ready for O3

Brocato et al. 2018

GRAvitational Wave Inaf TeAm

Transient objects in the LVC skymap



G. Greco, ***Gwsky*** https: //github.com/ggreco77/GWsky

To cover a very large region of the LVC skymap one observing strategy is to build up a mosaic of single pointing (tile):

GW150914 ~ 600 deg^2
LVT151012 ~ 1600 deg^2
GW151226 ~ 1000 deg^2
GW170104 ~ 1200 deg^2
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(90% credible areas)

GRAvitational Wave Inaf TeAm

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GW170104 ~ 1200 deg^2
GW170608 ~ 520 deg^2

(90% credible areas)

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*
- Each *tile* is 3x3 pointings and cover ~10deg^2

Sept 2015 – Jan 2016: LVC O1 science run
2 high-significance (FAR < 1/century) GW events during O1 (GW 150914, GW 151226) + 1 possible, low-significance event (LVT 151210). All BBH. (Abbott et al. 2016a,b)

Nov 2016 – Aug 2017: LVC O2 science run
Other BBH detected (GW 170104, GW 170608, GW 170814). Improved strategies for EM follow-up at all wavelengths.

VST optical follow-up of gravitational waves

Two companion programs on GTO time:

- On ***VST-GTO***: PI A. Grado
- On ***OmegaCam-GTO***: E. Cappellaro

After a negotiation with ESO, we obtained the possibility of using VST in Target of Opportunity (ToO) mode.

Since P95 (1 April-30 Sept 2015) we obtained obseeving time for ToO and follow-up programs.

Up to now, 240h have been allocated to these programs

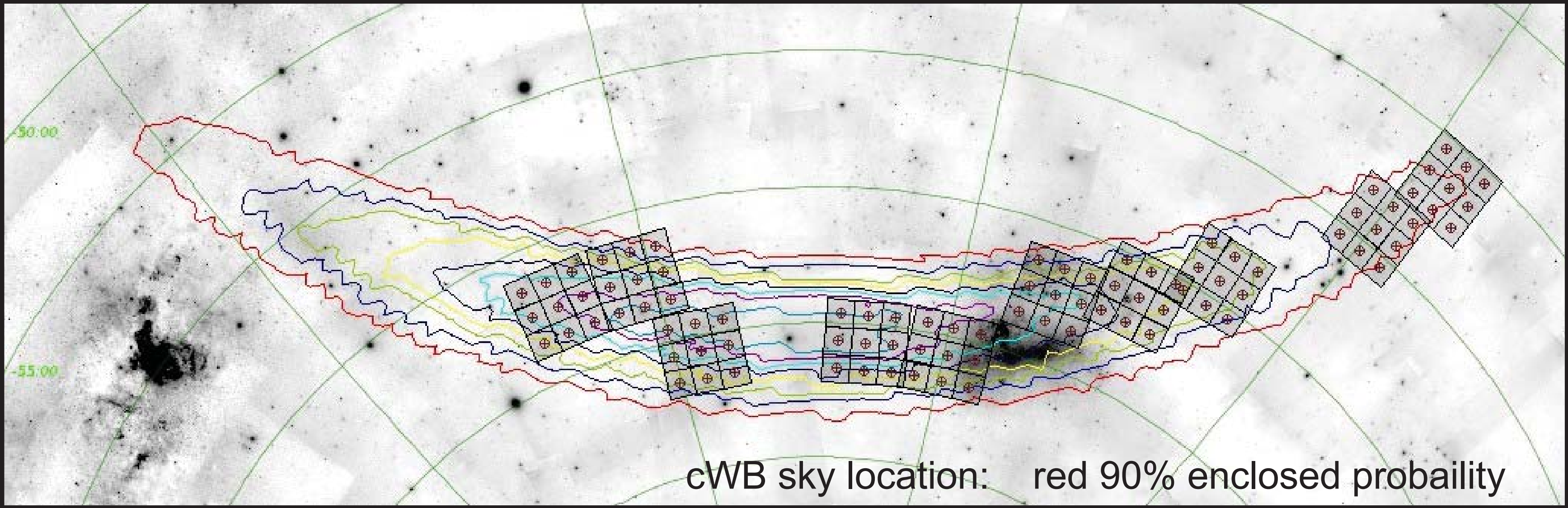
Courtesy of L. Grado

GW follow-up Data Flow

- The pipeline is checking every 10 minutes if new data with a specified PROG-ID appears on the ESO archive
  - From Paranal to Garching archive:
    - Time after which 75% of the file are received: 6.3 min
    - Time after which 90% of the file are received: 8.3 min
- If available the data are downloaded
- When a pointing is completed and available on local storage the pipeline starts the processing
- If the pointing has been already processed (in a previous epoch) the final mosaic will be pixel registered on the previous one (for image subtraction)
- ~ 10 min to get a fully calibrated coadded image ready for analysis (from when we have the data locally).

Courtesy of L. Grado

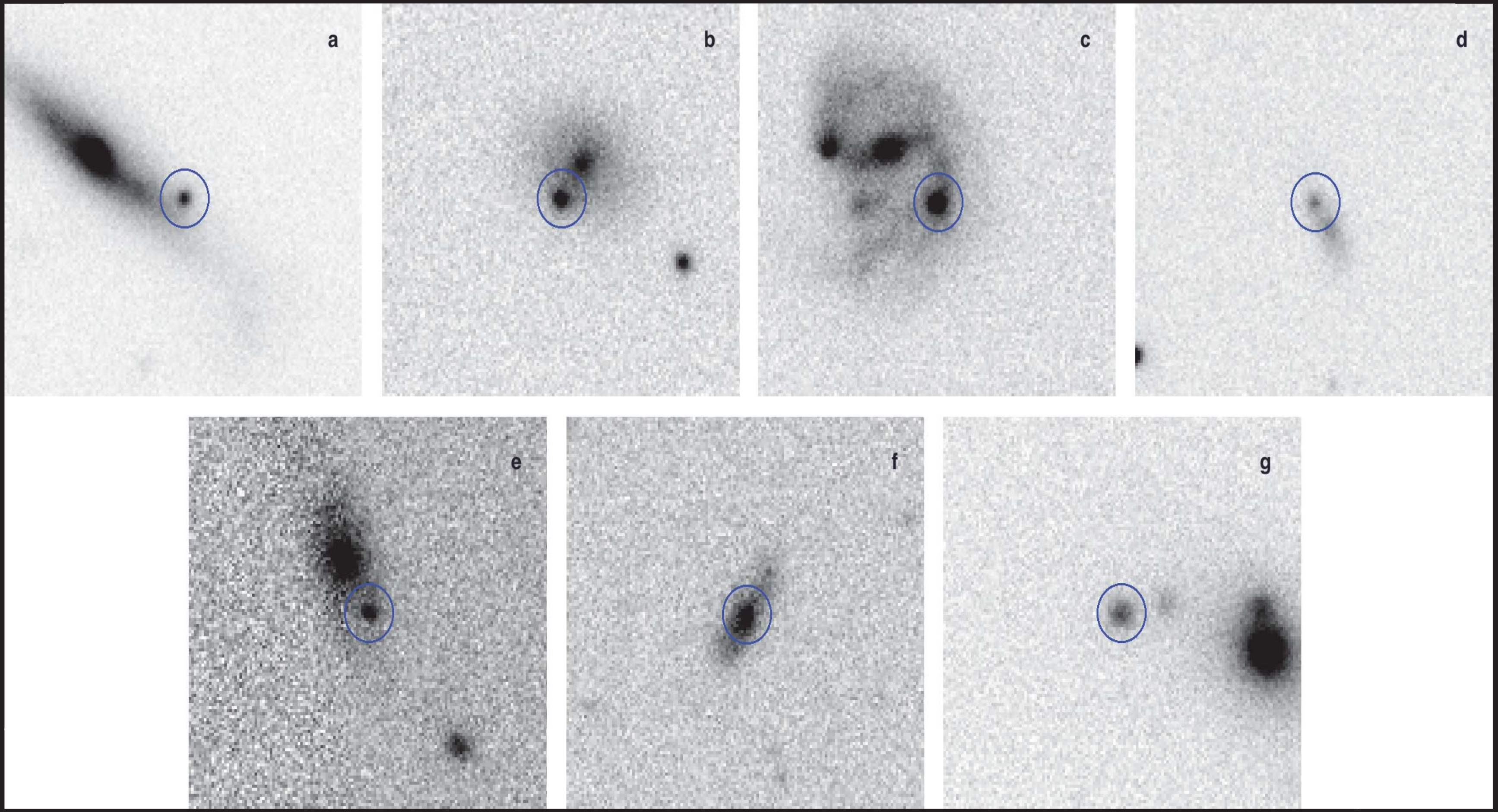
First event GW150914



Blocks of 3x3 deg^2
2x40 s dithered images (to fill ccds mosaic gaps)
90 deg^2 in 6 epochs (over 2 months, no reference images)
29% of the localization probability for cWB sky map enclosed
10% considering the LALinference sky map (shared with observers on 2016 January 13)

Pointings obtained with GWsky (Greco et al. in preparation)

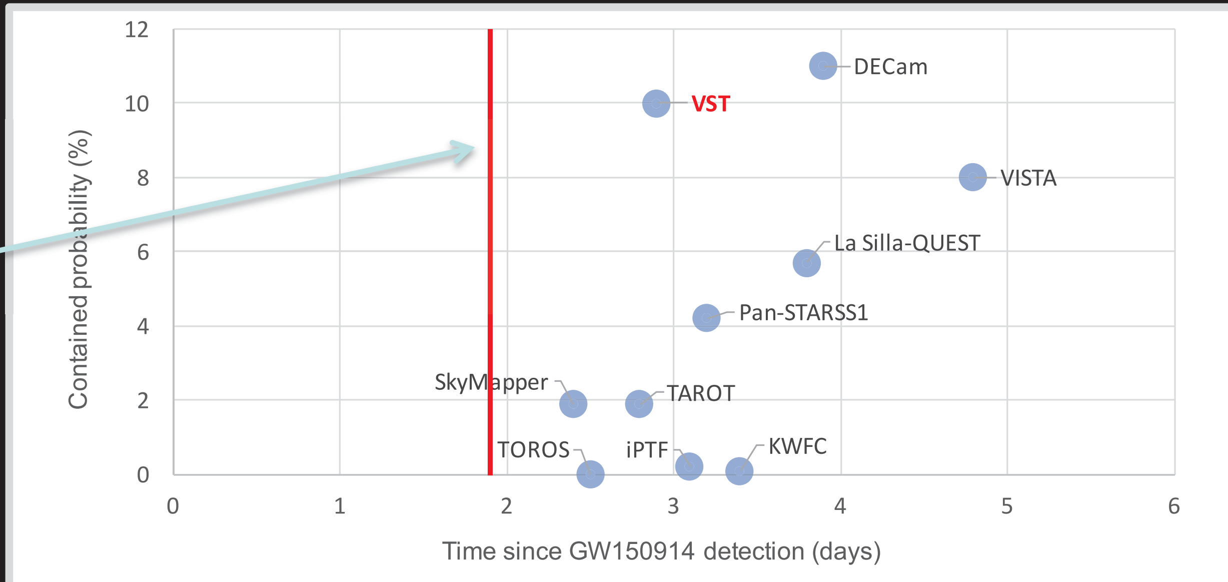
GW150914 :
Example of SN candidates found by VST



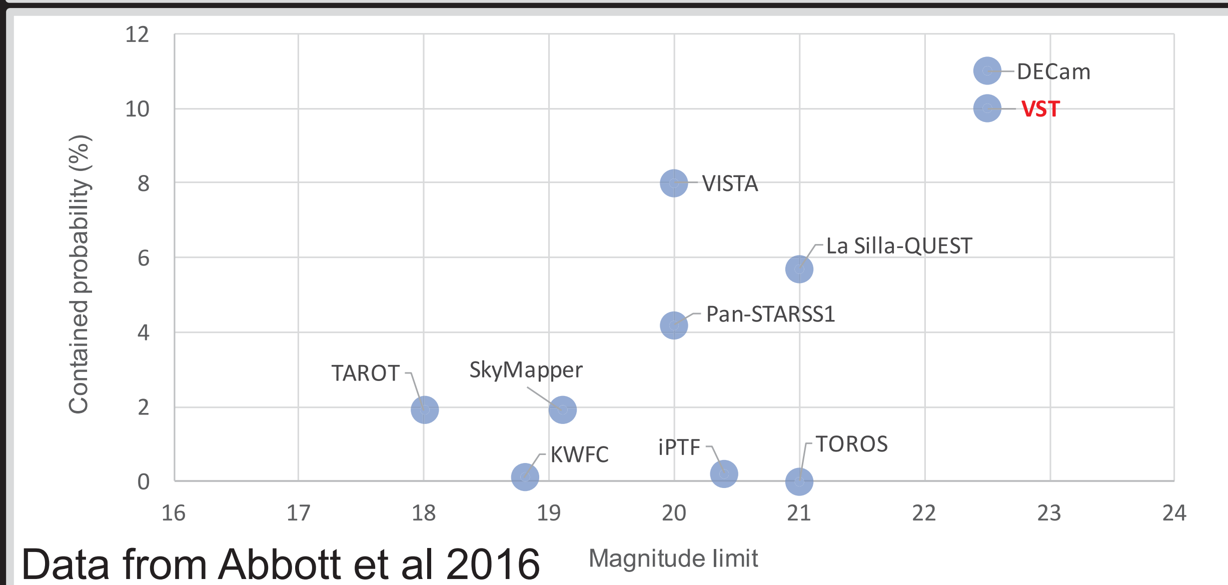
VST survey performance

LVC alert

Contained probability vs Time response

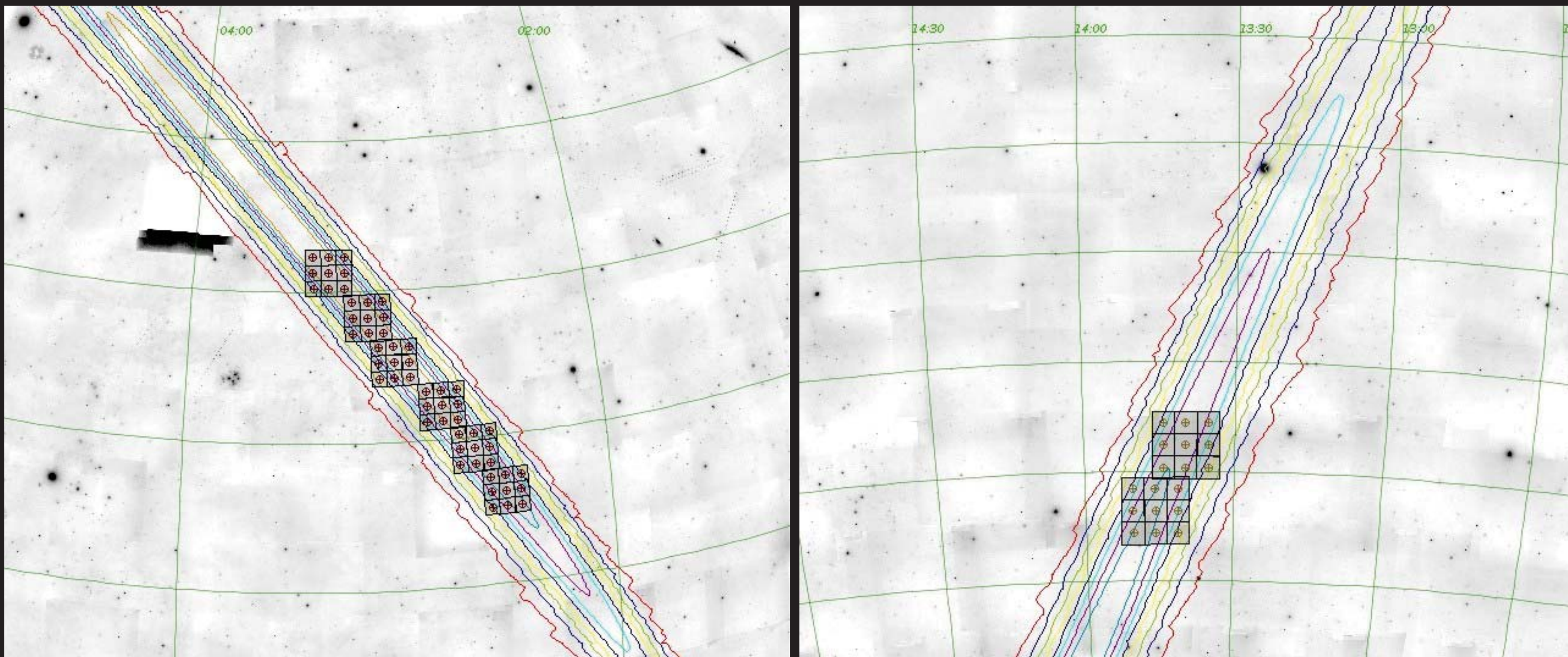


Contained probability vs limiting magnitude



Data from Abbott et al 2016

Second event GW151226



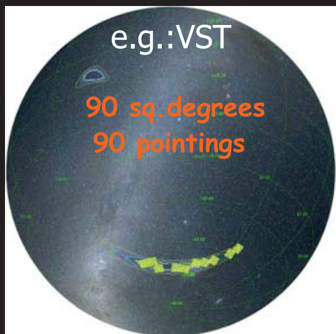
72 deg² in 6 epochs

First obs 7.6 hours after the alert and 1.9 days after the merger event (GCN Grado et al. 2015).

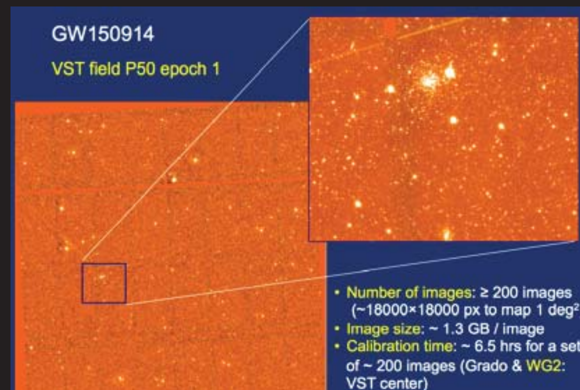
9% of the initial BAYESTAR sky map and 7% of the LALinference sky map

Example of GRAWITA response

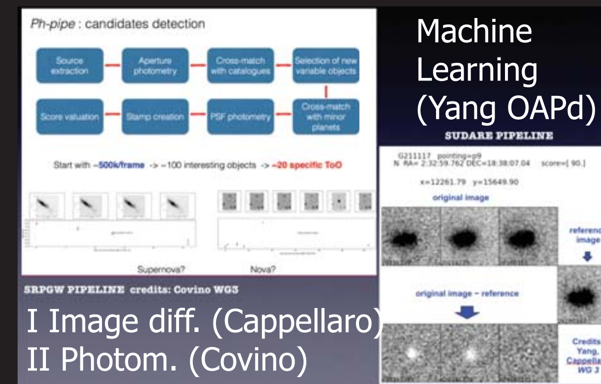
1. Tiling



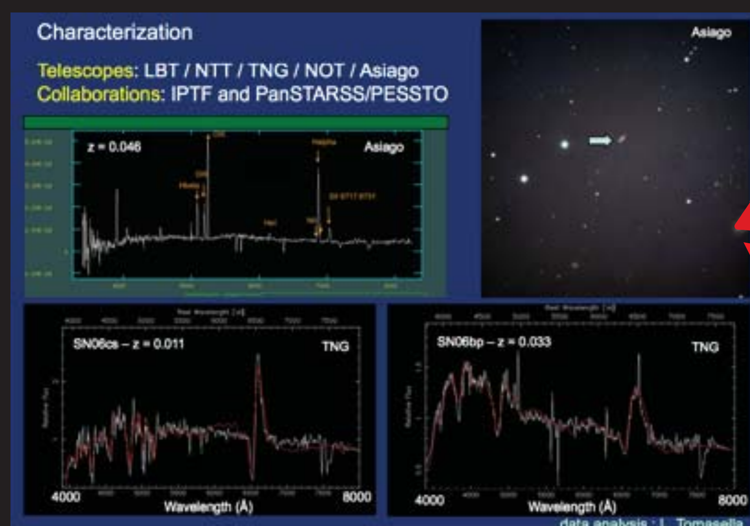
2. Observations



3. Search



4. Characterization and follow-up

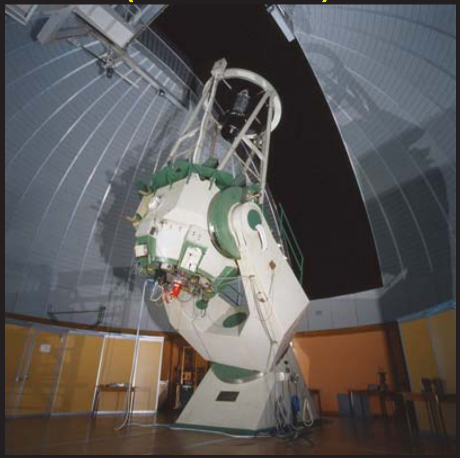


3+. Candidates from other teams or from GCN

Brocato et al. 2018

Candidate classification / follow-up

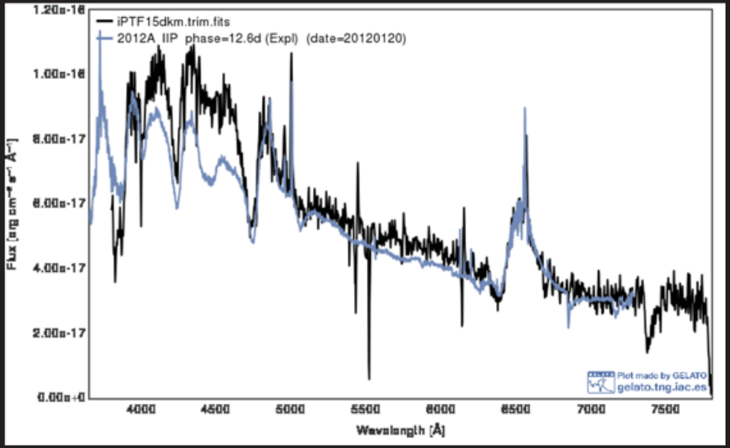
Copernico 1.8 m telescope (Asiago)
optical imaging & spectroscopy
(PI: Tomasella)



TNG 3.6 m
optical/NIR imaging & spectroscopy
(PI: Piranomonte)

LBT (2x)8.2 m
optical/NIR imaging & spectroscopy
(PI: Palazzi)

ESO-NTT 3.6 m
optical/NIR imaging & spectroscopy
(PI: Botticella within ePESSTO)



ESO-VLT 8.5 m
optical/NIR imaging & spectroscopy
(PI: P. D'Avanzo)

All successfully operated in O1 & O2

Piranomonte et al. in prep.

Multi-wavelength search and follow-up

Swift

- BAT: 15-150 keV, 2 sr FoV
- XRT: 0.2-10 keV, 0.15 deg^2 FoV
- UVOT: UV/opt imaging; 0.08 deg^2 FoV
- ToO program (GRAWITA co-Is)
- Tiling
- Targeted search
- Follow-up

Evans et al. 2016, 2017

Sardinia Radio Telescope (SRT)

64 m antenna

- 300 MHz – 100 GHz
- ToO program (PI: Possenti)
- Targeted search
- Follow-up

also Medicina & Noto radio telescopes (2x32m)

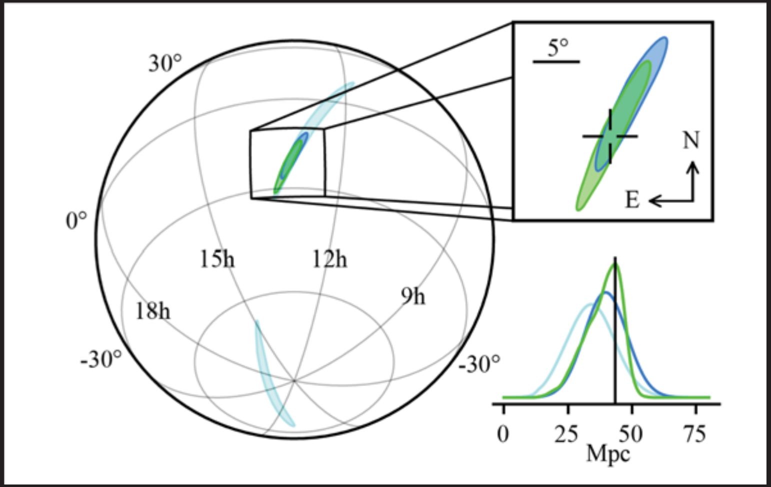
Aresu et al. GCN 21914

Both successfully operated in O1 & O2

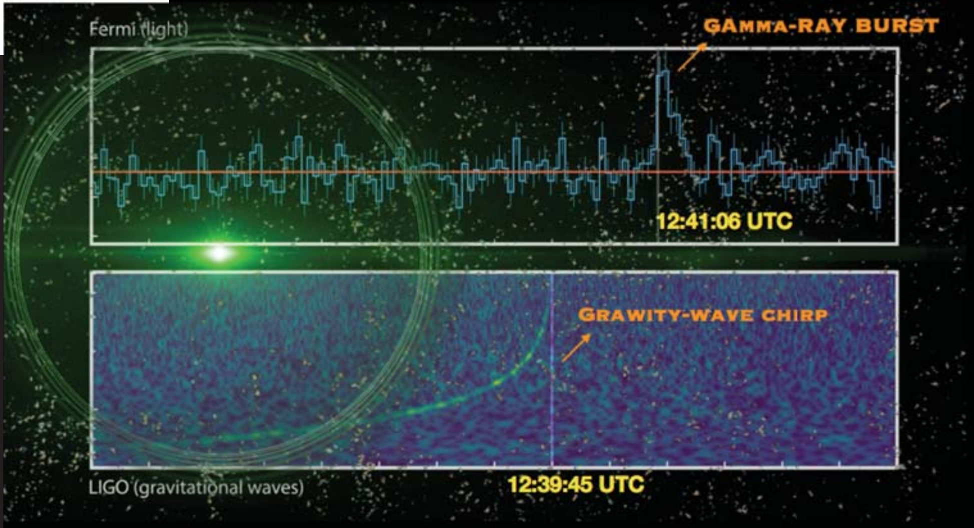
2017/08/17 UT: 12:41:04.445710

From: Bacodine <vxw@capella2.gsfc.nasa.gov>
Date: 17 agosto 2017 15:08:18 CEST
Subject: GCN/LVC_INITIAL_SKYMAP

TITLE: GCN/LVC NOTICE
NOTICE_DATE: Thu 17 Aug 17 13:08:17 UT
NOTICE_TYPE: LVC Initial Skymap
TRIGGER_NUM: G298048
TRIGGER_DATE: 17982 TJD; 229 DOY; 2017/08/17 (yyyy/mm/dd)
TRIGGER_TIME: 45664.445710 SOD {12:41:04.445710} UT
SEQUENCE_NUM: 1
GROUP_TYPE: 1 = CBC
SEARCH_TYPE: 0 = undefined
PIPELINE_TYPE: 4 = GSTLAL
FAR: [illegible].478e-12 [Hz] (one per [illegible]022.5 days)
PROB_NS: 1.00 [range is 0.0-1.0]
PROB_REMNANT: 1.00 [range is [illegible]-1.0]
TRIGGER_ID: 0x8
MISC: 0x1100001
SKYMAP_URL: https://gracedb.ligo.org/api/events/G298048/files/bayestar.fits.gz
SKYMAP_BASIC_URL: https://gracedb.ligo.org/apibasic/events/G298048/files/bayestar.fits.gz
EVENT_URL: https://gracedb.ligo.org/events/G298048
COMMENTS: LVC Initial Skymap -- a location probability map.
COMMENTS: This event has been vetted by a human.
COMMENTS: LIGO-Hanford Observatory contributed to this candidate event.



False-alarm rate < 1 per ~8 × 10^4 years



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GROUP_TYPE: 1 = CBC
SEARCH_TYPE: 0 = undefined
PIPELINE_TYPE: 4 = GSTLAL
FAR: [illegible].478e-12 [Hz] (one per [illegible]022.5 days)
PROB_NS: 1.00 [range is 0.0-1.0]
PROB_REMNANT: 1.00 [range is 0.0-1.0]
TRIGGER_ID: 0x8
MISC: 0x1100001
SKYMAP_URL: https://gracedb.ligo.org/api/events/G298048/files/bayestar.fits.gz
SKYMAP_BASIC_URL: https://gracedb.ligo.org/apibasic/events/G298048/files/bayestar.fits.gz
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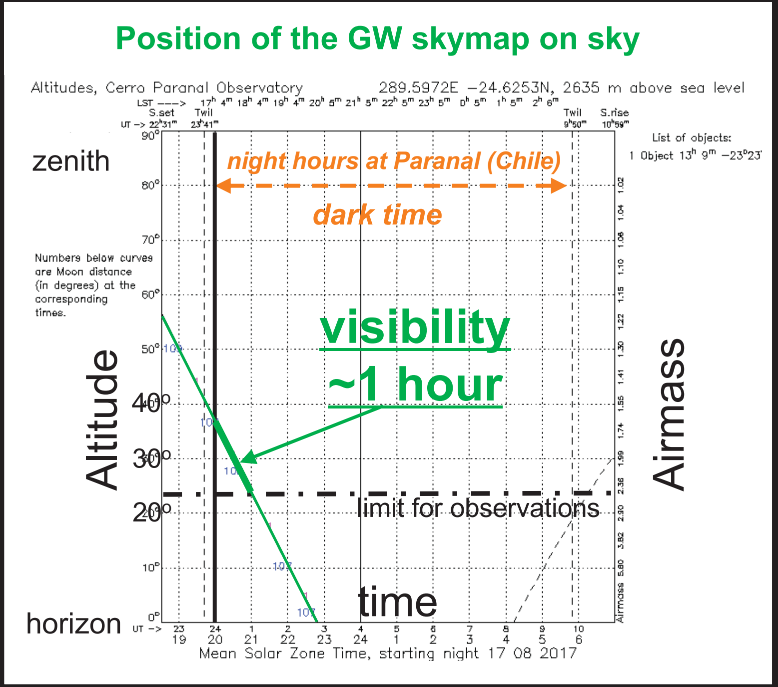
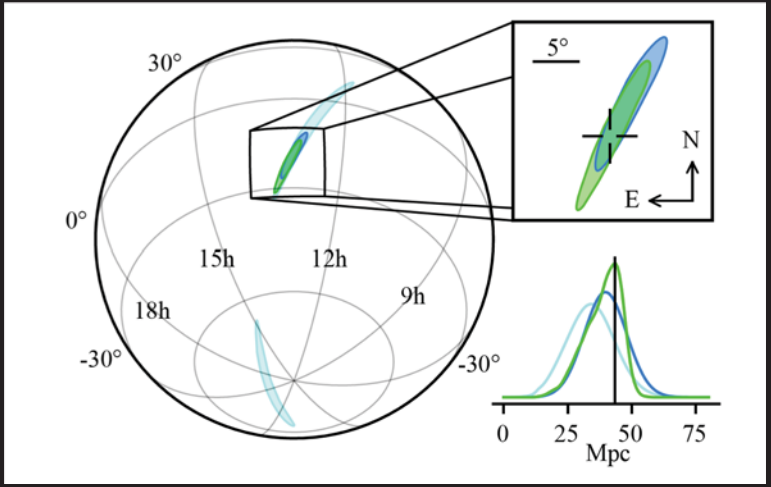
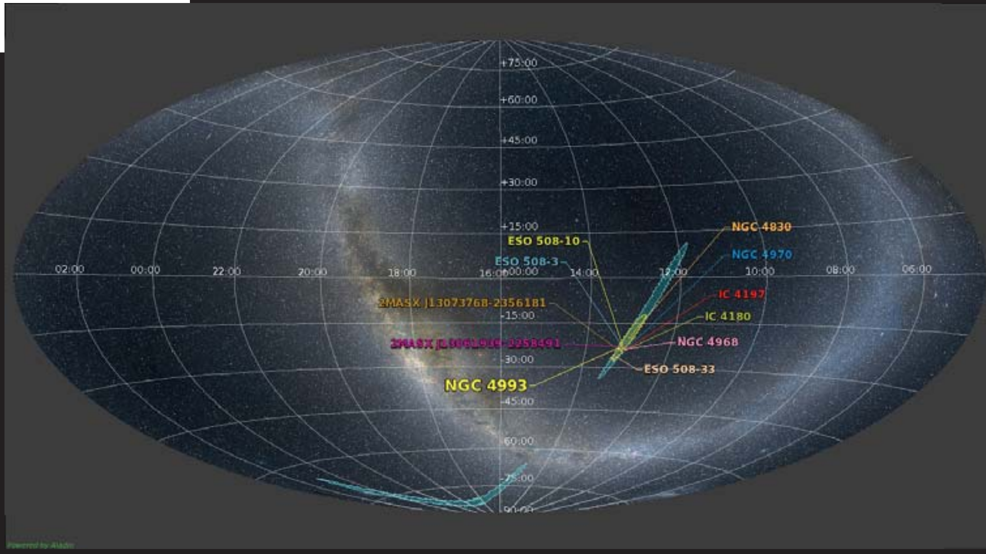
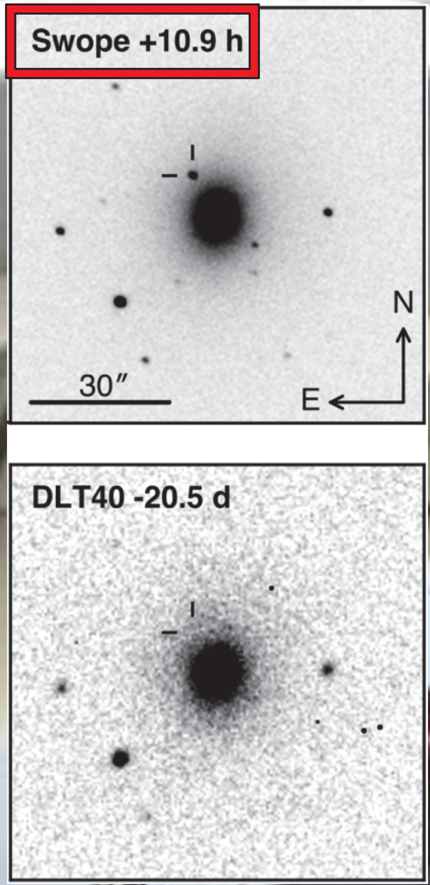






GW 170817: optical counterpart in NGC 4993



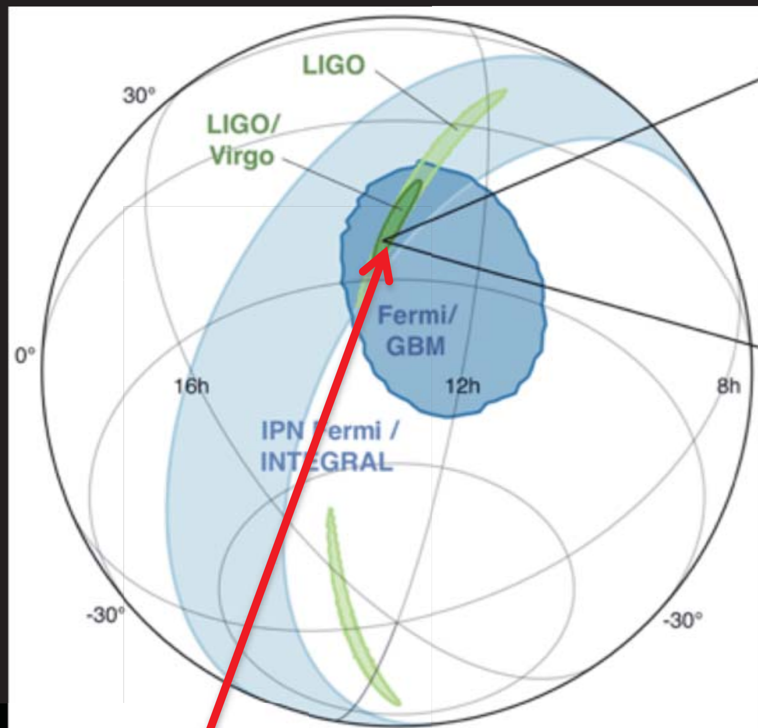
LVC + "partner astronomy groups" (2017)

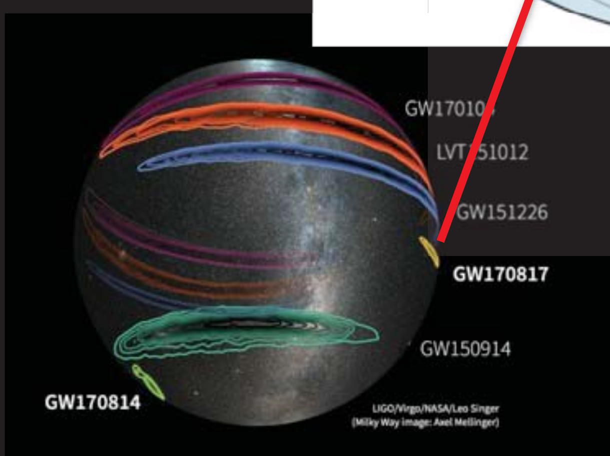
Five other teams took images of the transient within an hour of the 1M2H image (and before the SSS17a announcement) using different observational strategies to search the LIGO-Virgo sky localization region. They reported their discovery of the same optical transient in a sequence of GCNs: the Dark Energy Camera (01:15 UTC; Allam et al. 2017), the Distance Less Than 40 Mpc survey (01:41 UTC; Yang et al. 2017a), Las Cumbres Observatory (04:07 UTC; Arcavi et al. 2017a), the Visible and Infrared Survey Telescope for Astronomy (05:04 UTC; Tanvir et al. 2017a), and MASTER (05:38 UTC; Lipunov et al. 2017a). Independent searches were also carried out by the Rapid Eye Mount (REM-GRAWITA, optical, 02:00 UTC; Melandri et al. 2017a), Swift UVOT/XRT (utraviolet, 07:24 UTC;

Credits: A. Melandri (INAF-OAB)

2017-08-17 12:41:04 UTC

NGC4993@ VST





GW event: 12:41:04 UTC

First skymap: 17:54:51 UTC

31 deg^2 (90% credibility)

centered on $12h57^m$ $-17^o51'$

VST observations of GW170817:

covering 9 deg^2 23:18:42 UTC

Swope OT observation: 23:33 UTC

(targeted survey) GCN21529

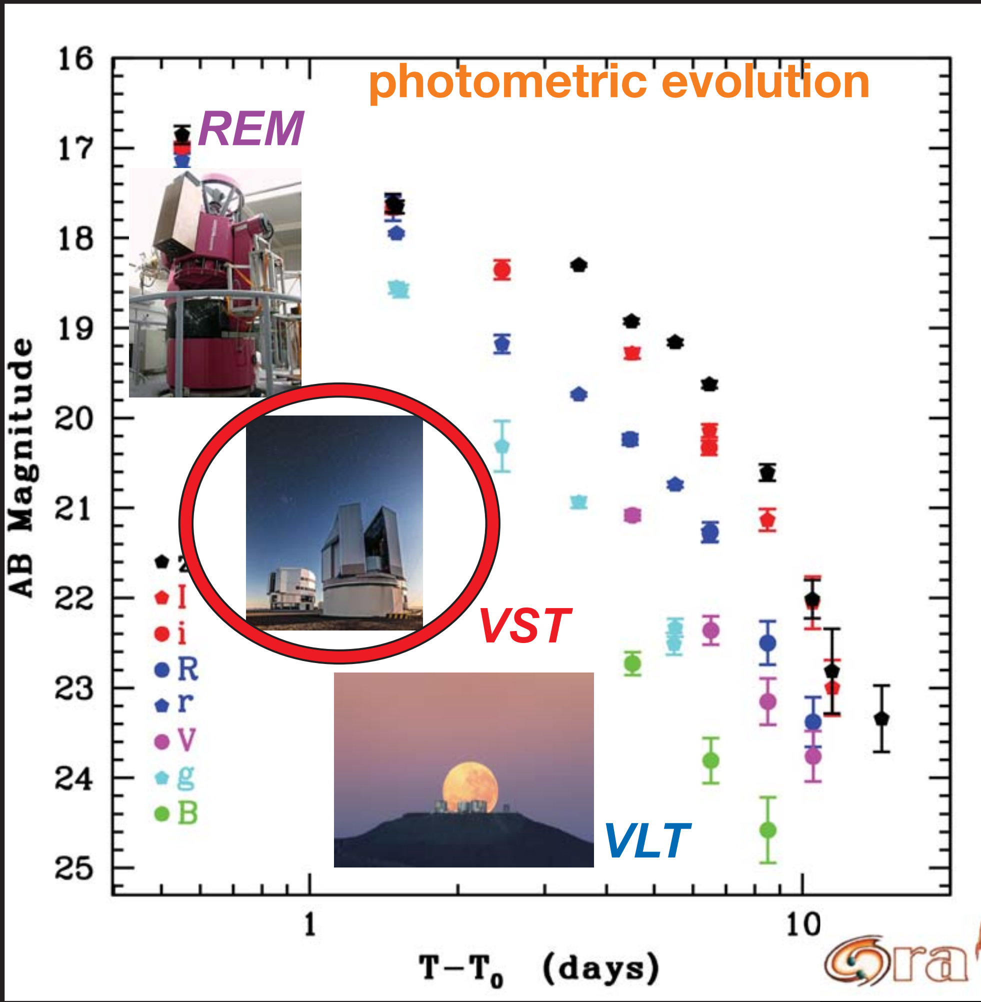
Updated skymap: 23:54:40 UTC

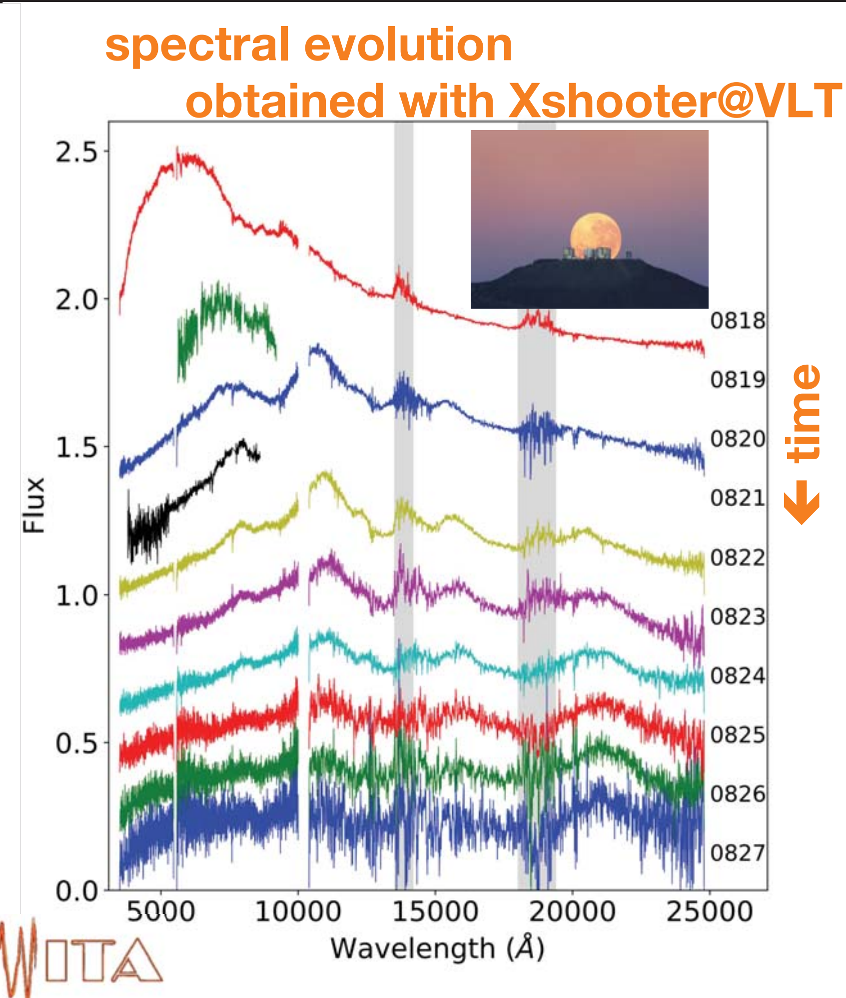
34 deg^2 (90% credibility)

centered on $13h09^m$ $-25^o37'$

Courtesy of L. Grado

GW 170817: imaging and spectroscopic follow-up



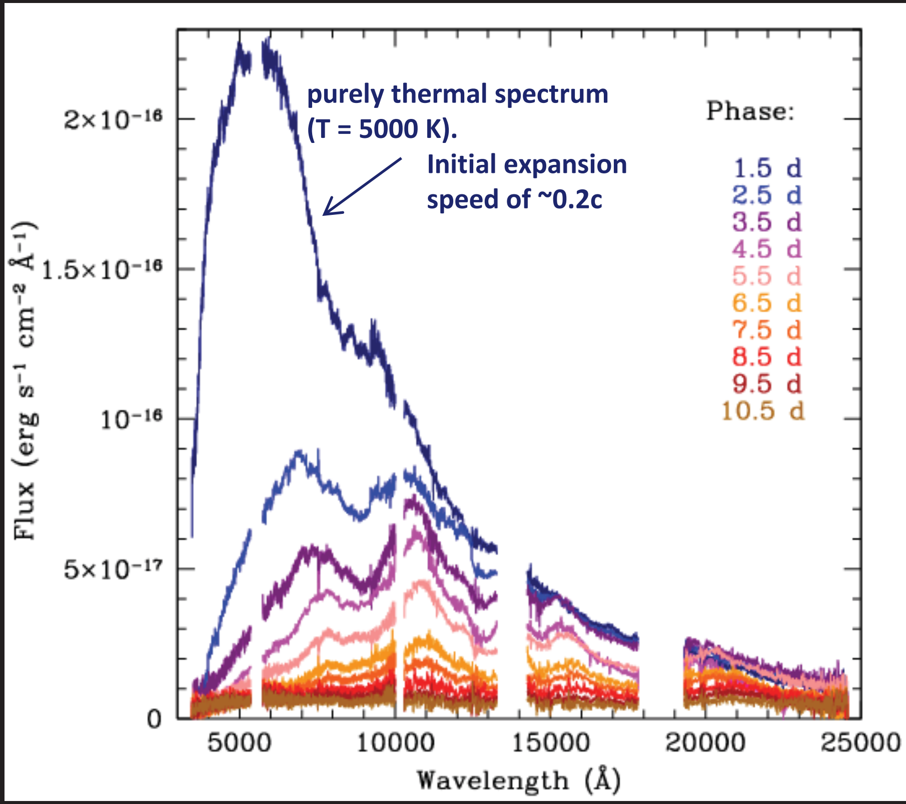


Pian, D’Avanzo et al. 2017, Nature

The Optical/nIR evolution of the kilonova

ESO VLT X-Shooter spectral sequence of GW170817

These data revealed signatures of the ***radioactive decay of r-process nucleosynthesis*** providing the ***first spectral identification of the kilonova emission*** due to coalescence of two neutron stars



Pian et al. 2017; Smartt et al. 2017

The **best fit** of these spectroscopic data requires **three components**

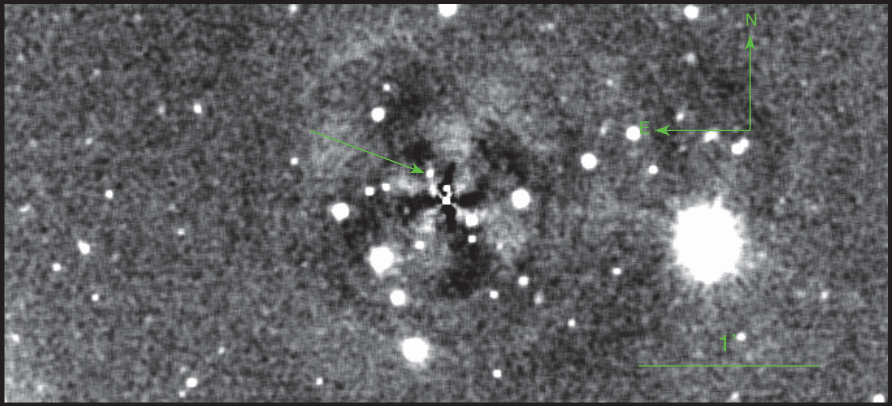
ejected mass ~ 0.03 – 0.05 $M_\odot$

Tanaka et al 2017

European Southern Observatory Very Large Telescope (VLT)
4 Units Telescopes with Primary Mirrors 8.2 m in diameter
Cerro Paranal (Chile)

Photometric evolution of GW170817

- At +6.4 days: **VST** 200 s in g,r,i,z filters 23.3, 22.4, 21.3, no visible in z **(GCN 21703 A. Grado et al.)**
- At +14.4 days: **VST** 1200 s in i filter **No detection** (22.53 mag 50% complet. for pointlike surces) **(GCN 21833 A. Grado et al.)**
- At +108 days: **VST** 4320s in g,i filters **No detection** (25.0 and 24.5 50% complet. For pointlike sources) **(GCN 22368 A. Grado et al.)**



NGC 4993 r filter (galaxy subtracted)

- **And …….**

Courtesy of L. Grado

GRAWITA recent results with LBT

- ……
- At **+160 days**: **LBT** 8000s in r-sloan filter **detection** (**26.2+-0.4 mag** for point-like source) **(GCN 22763 A. Rossi et al. 2018).**

```
TITLE:   GCN CIRCULAR
NUMBER:  22763
SUBJECT: GW170817/GRB170817A: LBT optical detection
DATE:    18/06/05 14:03:37 GMT
FROM:    Andrea Rossi at INAF  <a.rossi@iasfbo.inaf.it>

A. Rossi (INAF-OAS),  M. Cantiello (INAF-OA Abruzzo) V. Testa, D. Paris
(INAF-OAR), A. Melandri, S. Covino,  O. S. Salafia, P. D'Avanzo, S.
Campana (INAF-OAB), L. Nicastro, E. Palazzi, F. Cusano (INAF-OAS), G.
Stratta (Urbino University/INFN Firenze), R. Carini, S. Piranomonte, E.
Brocato (INAF-OAR), V. D'Elia (ASDC), and M. Branchesi (GSSI) report on
behalf of the GRAWITA collaboration and its partners:

We observed the optical counterpart of GRB 170817A (Kienlin et al., GCN
21520) associated to GW 170817 (LVC GCN Circ. 21509, 21513) with the LBC
imager mounted on the Large Binocular Telescope (Mt Graham, AZ, USA).
Observations were performed in the r-sloan filter on 2018-01-23, i.e.,
~160 days after the GW/GRB trigger.

At the location of the optical transient (e.g., Coulter et al., GCN
21529; Adams et al., 21816) we detect the optical afterglow of GRB
170817A with magnitude r-sloan=26.2+-0.4, calibrated against Pan-STARRS
field stars. Image analysis was performed after preliminary removal of
an elliptical model of the underlying host galaxy from each single
frame. However, some residual emission is left which contributes for
~0.2 mags to the uncertainty of the photometry.

Our detection is the first one from a ground-based optical telescope. It
is in agreement with a turnover/flattening in the optical light curve of
GW 170817/GRB 170817A as inferred by Alexander at al. 2018
(arXiv:1805.02870) and with the overall flattening/declining temporal
evolution observed in the X-ray and radio bands (D'Avanzo et al. 2018,
A&A, 613 L1; Hajela et al. GCN Circ. 22692; Troja et al. GCN Circ.
22693; Dobie et al. arXiv:1803.06853; Alexander at al. 2018;
arXiv:1805.02870).

We acknowledge the excellent support from the LBT staff in obtaining
these observations.
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This late observations (X-ray, Radio and Optical) are playing a key role in understanding the origin of the afterglow of GW170817.

- Structured Jet (GRB theory)
- re-energized cocoon (new object)

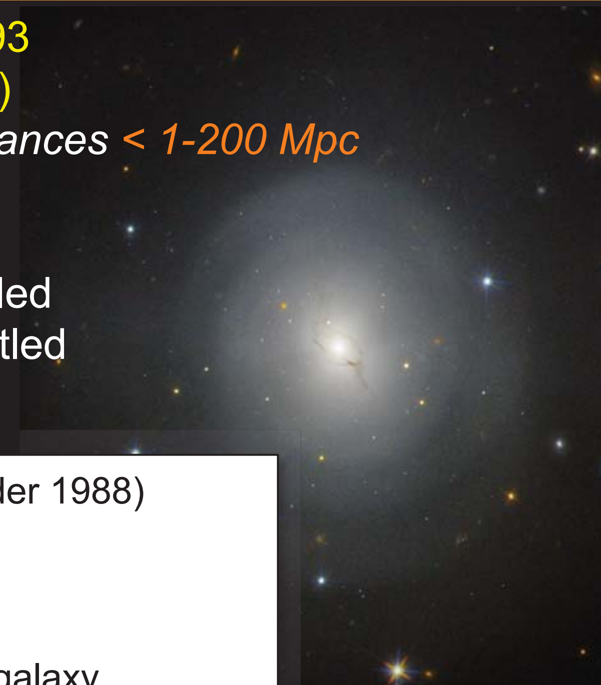
(see e.g. Alexander et al. 2018, Troja et al 2018 etc)

BNS Merger: further work on GW170817

New distance evaluation of NGC 4993
Surface Brightness Fluctuation (SBF)
typical uncertainties are ~5% for distances < 1-200 Mpc

The basic idea is:

… closer ⇔ more grainy, more mottled
… farther ⇔ less grainy, less mottled



$f_{SBF} \equiv \sum_i n_i f_i^2 / \sum_i n_i f_i$ (Tonry & Schneider 1988)

n_i = number of stars in pixel i

f_i = flux measured in pixel I

the sum is extended to all the pixel of the galaxy

i.e.

SBF = Ratio of the 2nd to the 1st moment of the stellar luminosity function (LF)

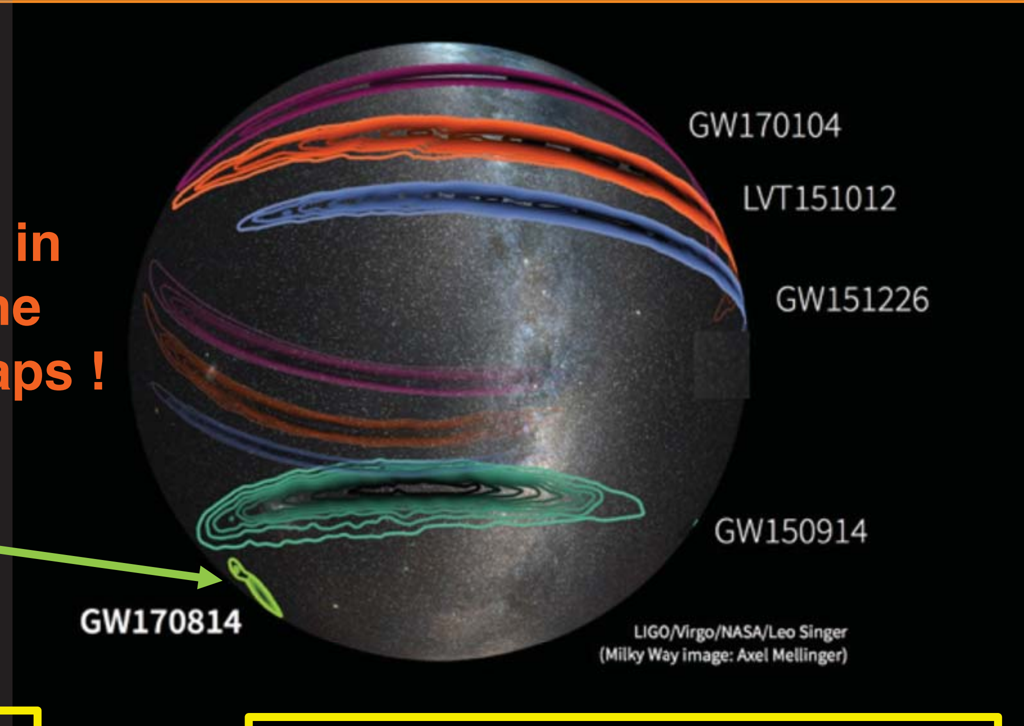
Results:

- ✓ By using the SBF method on HST images we derive the most precise distance to NGC4993 **d = 40.7 ± 1.4 ± 1.9$_{syst}$ Mpc** available to date
- ✓ Combining our distance measurement with the corrected recession velocity of NGC 4993 implies a Hubble constant $H_0 = 71.9 \pm 6.3$ km s^{-1} Mpc^{-1}
- ✓ Useful for the distance-inclination issue

Cantiello et al. 2018

VST vs LVC run O3

Virgo made a fundamental improvement in decreasing the size of skymaps !

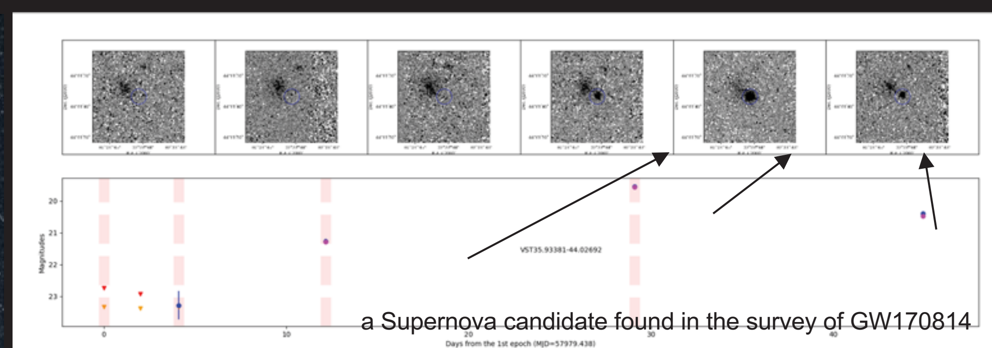


GW170814 ~ 62 deg²

(90% credible areas)

VST observed ~ 80% of the sky map

***VST* is a *KEY* instrument for *RUN O3* of LVC**



a Supernova candidate found in the survey of GW170814

ENGRAVE

Electromagnetic counterparts of gravitational waves at the Very Large Telescope

An European collaboration of 196 ESO scientists

Governing Council : M. Branchesi, E. Brocato, P. D'Avanzo, J. Hjorth, P. Jonker, E. Pian, S. Smartt, J. Sollerman, D. Steeghs, N. Tanvir

ENGRAVE

VLT ToO Large Programme *(submitted)*

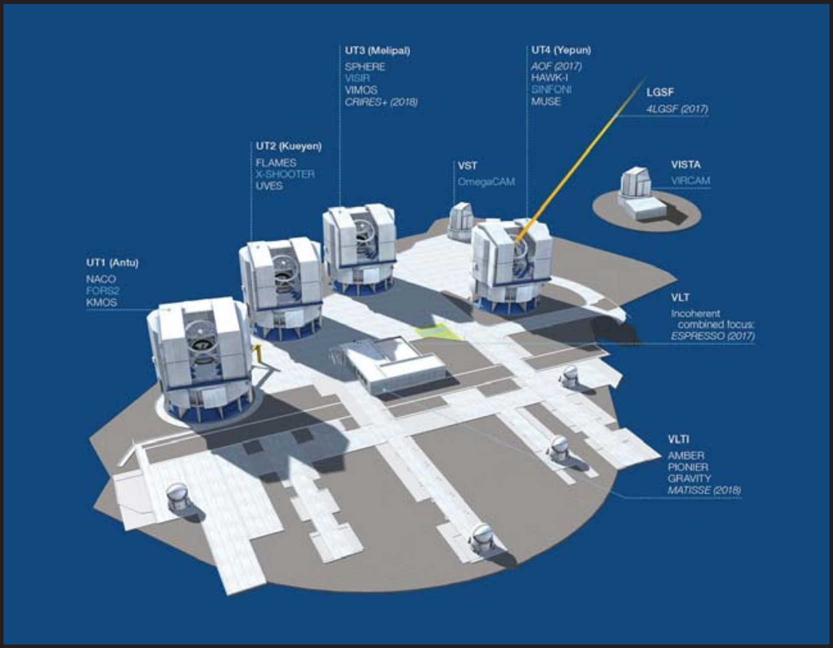
3 Periods P102 - P104 Oct 2018 - Mar 2020

Fully Covering O3

Requesting 180hrs of VLT

4 triggers @ 45hrs per event

All usable VLT instruments (depending on mag and SED of source)



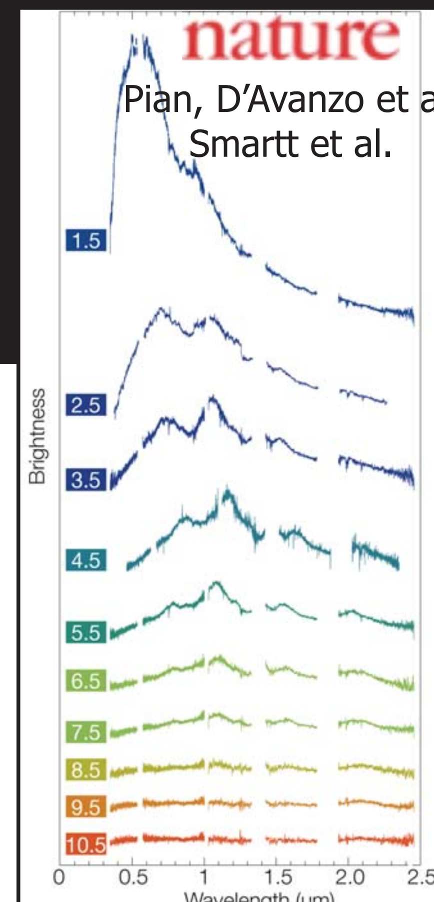
+ PESSTO, GRAWITA, VIN ROUGE

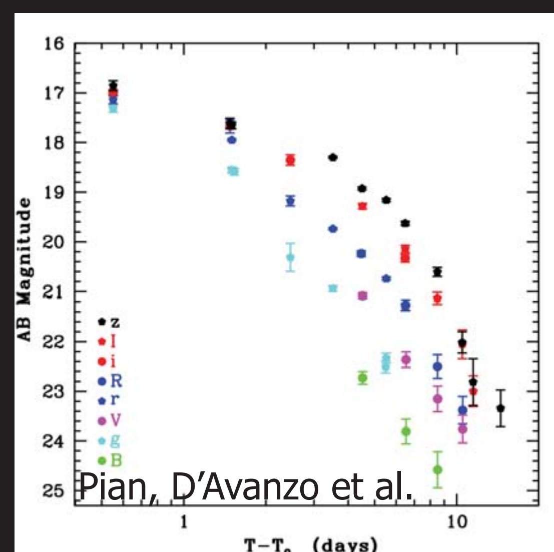
Proposal writing team : S. Covino, A. Levan, K. Maguire, D. Malesani, S. Vergani

ENGRAVE

Simple goal
every useful ESO instrument, every night

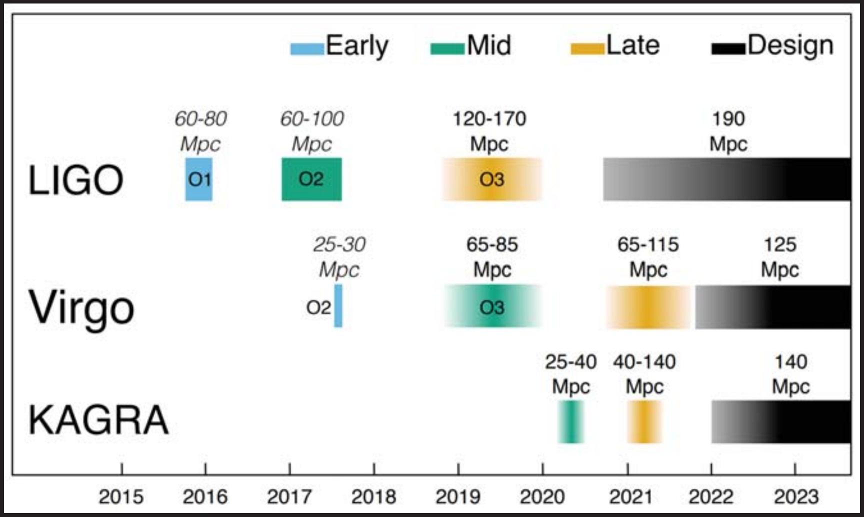
- 0.3 - 2.5 micron **spectra** (xshooter + FORS + EFOSC2/SOFI if bright enough)
- 0.3 - 3.5 micron **lightcurve** (VST, NTT, VISTA, FORS, HAWKI, NACO, REM)
- 1-3 mm afterglow emission (ALMA)

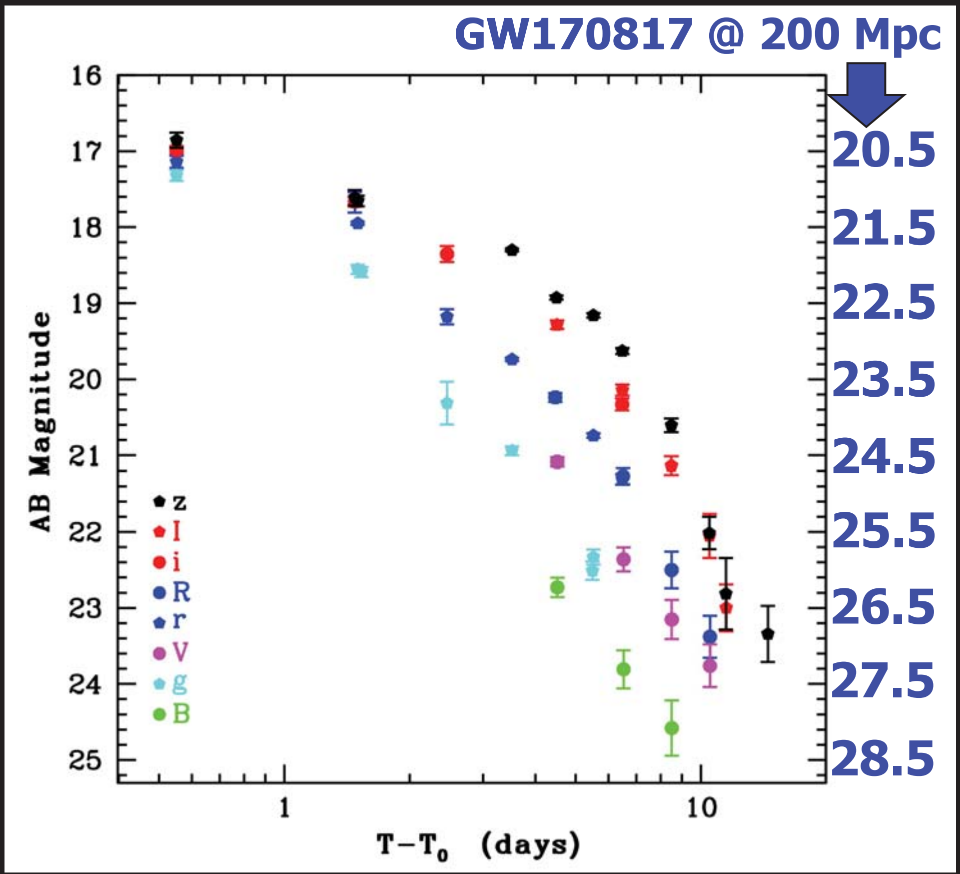




GRAWITA vs O3 and beyond

Increasing the sensibility of GW detectors move the horizon toward more distant objects, i.e. fainters sources





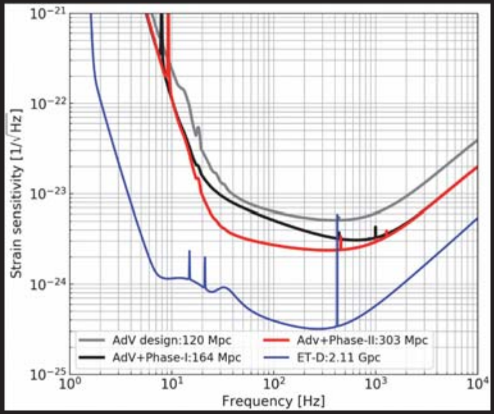
Expected multi-messenger event rates

BBH: at least a few per month

BNS: 1-10, possibly 1 per month

NSBH: uncertain, one or more in O3

TownHall Amsterdam 12-13 April 2018



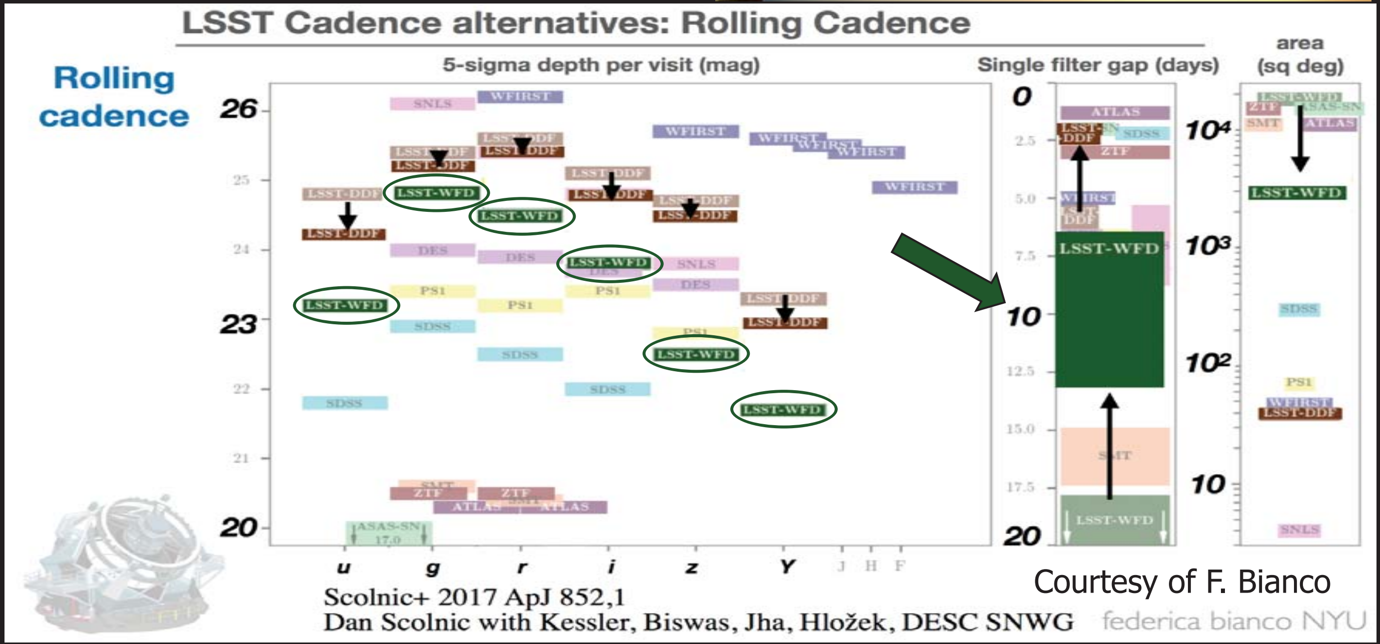
LSST - Large Synoptic Survey Telescope

WF search

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

- deep sky
- galaxy catalogs
- identification false candidates



Courtesy of F. Bianco

LSST

- LSST has a LARGE Field of View (9.6 deg^2)
- LSST horizon increased ==> fainter sources (> 24.5)
- The strategy of targeting galaxies is unlikely to often succeed

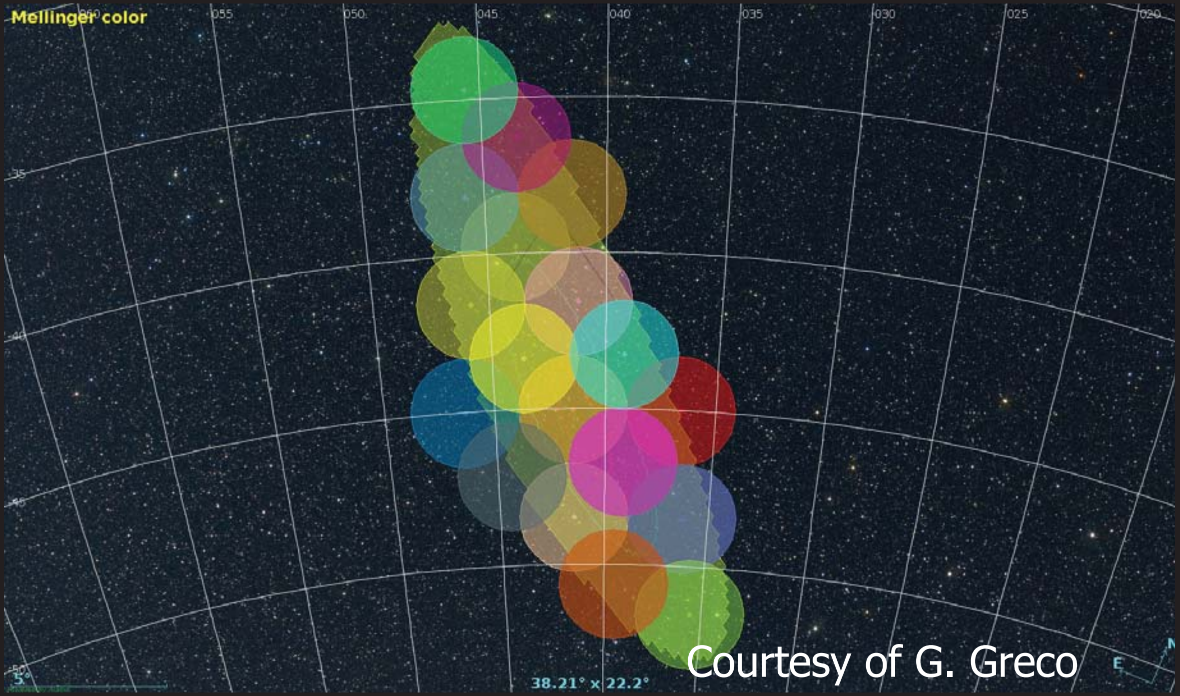
Target of Opportunity mode !

To completely cover the skymap of GW170817 provided by LIGO/Virgo Collaboration,

LSST needs less than 20 tiles/pointing

(not optimized)

to reach r~24.5



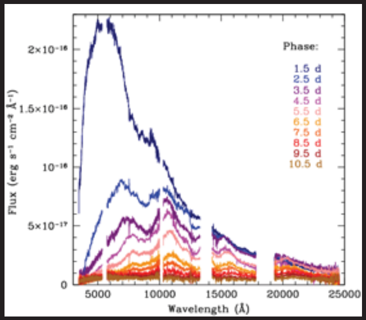
Action:

- **Make the case of ToO@LSST**
- **Design best ToO strategy for GWs**
- **Evaluate Observing time needed (< 1%)**

SOXS@NTT
MOONS@VLT

GRAvitational **W**ave **I**naf **T**e**A**m

2018 LIGO/Virgo : RUN O3 expected to start early 2019



- ***High quality science:***
  - ✓ ~~possibility of opening a~~ **new field in astrophysics**
  - ✓ ~~possibility of~~ **breakthrough discoveries**
- ***~~High risk~~ very promising research:***
  - ✓ **measure of GW** ~~(high level of skepticism)~~,
  - ✓ uncertainties on the direction of GW in sky (skymaps of ~~hundreds/thousand~~ **tens/hundreds squaredegree**),
  - ✓ ~~a lot of~~ **few false candidate** ~~(tens/hundreds)~~,
  - ✓ short time in reaction (~~hours/days~~) **minutes/hours**…
- ***Still….A lot of work to be done <u>'before and after'</u> LVC alerts:***
  - Proposals at selected telescopes
  - optimize observations (epochs, pointings, exp. times, filters…)
  - fast data reductions
  - search transients in observed fields
  - spectral analysis of candidates
  - Multi-wavelength follow-up of the counterparts
  - Data interpretation, comparison with models
  - etc