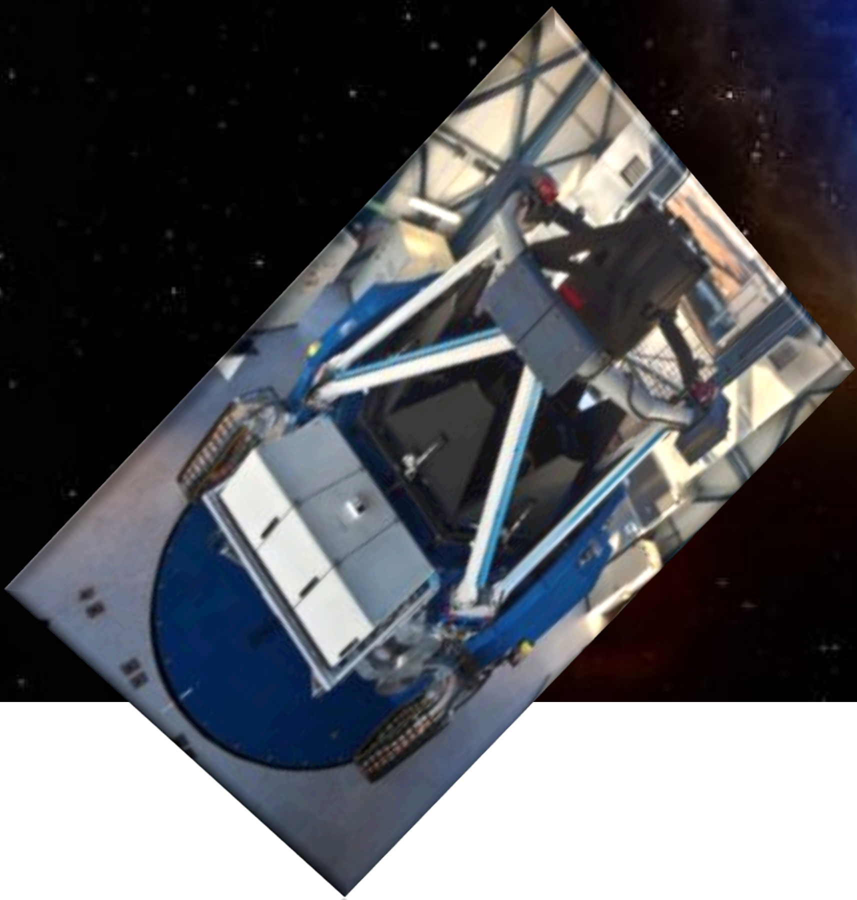
GW optical counterpart search in the Multi-Messenger Astronomy Era



Aniello Grado
INAF-Napoli
INFN –Napoli
&
GRAWITA team

Credit: NASA's Goddard Space Flight Center/CI Lab

The GRAWITA team

GRAvitational Waves Inaf TeAm

www.grawita.inaf.it

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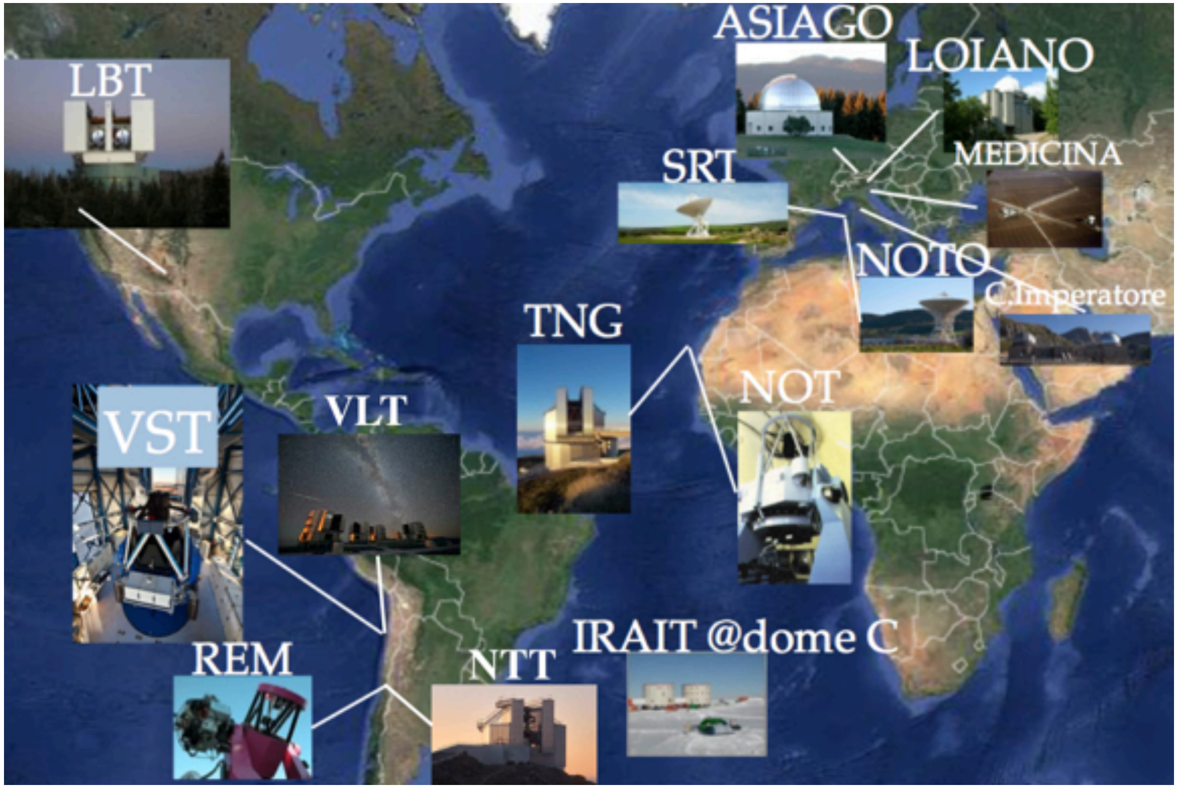
Multi-wavelengths Facilities Network

Visible: *VST, LBT, TNG, NOT (coll.), 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(Swift, Chandra, XMM) + ground (coll. MAGIC, future ASTRI, CTA)*



Collaborations: ***ePESSTO,*** *INTEGRAL, AGILE*
Positive interactions during O1+O2: *Pan-Starrs, iPTF, VISTA, HST …..*

GWs from compact objects

What? How far? How many? Where?

Source type	Detectors sensitivity O3 (Mpc)	Estimated # of detections in O3 (in 12 months)	localization
NS-NS	120-170 (LIGO) 65-85 (Virgo)	0.04-120[1]	1-4 % in 5 deg^2 12-21 % in 20 deg^2
NS-BH	190-270 (LIGO) 100-140 (Virgo)	0.04-4.4[3,4]	~ BNS
BBH	1110-1490 (LIGO) 610-1030 (Virgo)	6 - 130[2]	Tens to hundreds deg^2

Abbott et al 2017 arXiv:1304.0670

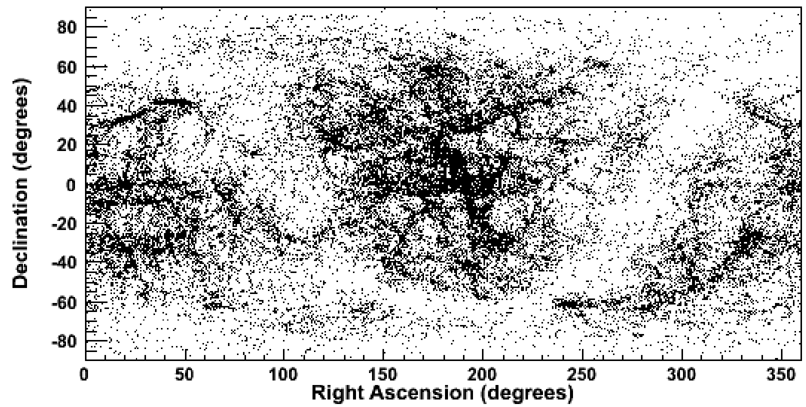
[1]Assuming a rate of 10^{-8} - 10^{-5} Mpc^{-3} yr^{-1} (Abbott et al. 2017, PRL, 119, 161101)
[2]Rodriguez et al. 2016, PRD, 93,8, 084029 (rate 2-20 $Gpc^{-3} yr^{-1}$)
[3]Assuming an upper limit rate of 3.6×10^{-6} Mpc^{-3} yr^{-1}
[4]Pannarale et al. 2014 ApJ, 791, 5

Optical counterpart search problem statement

- Sky error area (3 detectors): 30-100 deg^2
- For BNS absolute magnitude ~ -16 mag
- Alert within tens of minutes (with human vetting)
- We want to find OC candidates as soon as possible for further spectroscopic follow-up

Two approaches:

- Targeted search
- blind search



White et al. 2011

Efficient search requires:

- Reference catalogs/images
- Elimination of fore- and back-ground events (multi-epochs full sky surveys)

Observational strategy

Wide error area
+
nearby source → Targeted search

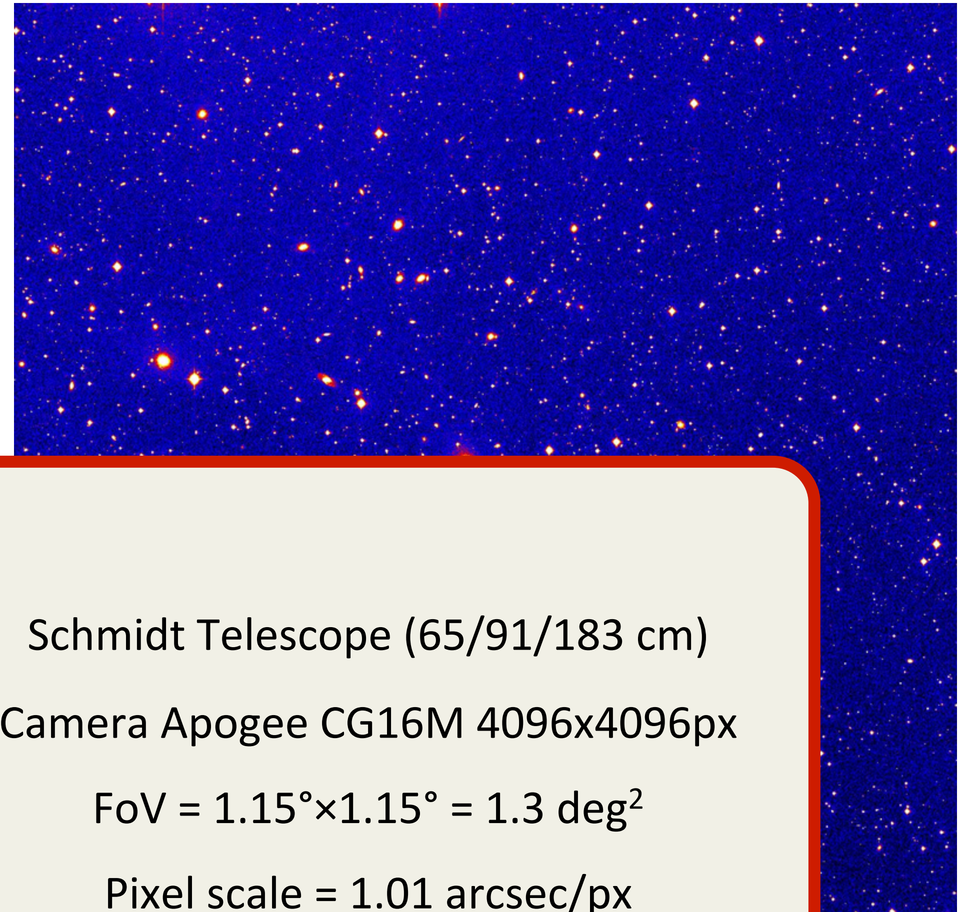
We need a complete galaxies catalog

GWGC (white 2011) complete up to 40 Mpc for M_B=-15 mag

Small to moderate
Error area
+
far source → Blind search

20 deg^2 error area ~200 Mpc define a volume with ~ 500 galaxies L > 0.1 x L_* (L_* ~ luminosity of Milky Way)

Schmidt telescope Campo Imperatore



Schmidt Telescope (65/91/183 cm)

Camera Apogee CG16M 4096x4096px

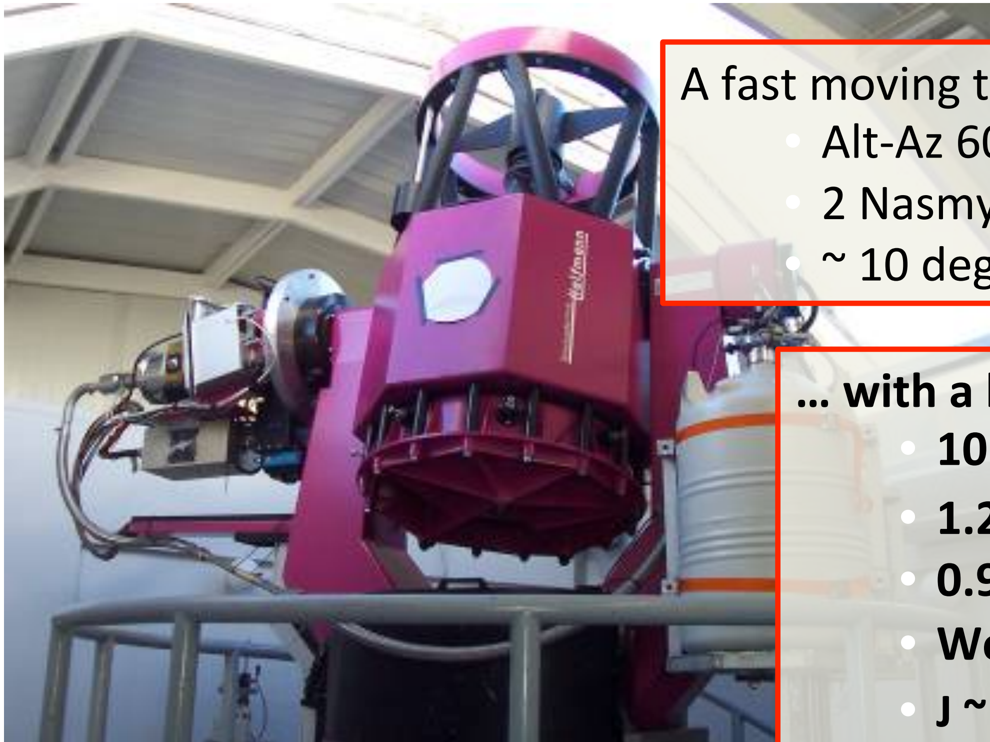
FoV = 1.15°×1.15° = 1.3 deg^2

Pixel scale = 1.01 arcsec/px

Filtri : Sloan u', g', r', i', z'

Mag limite r'=21.5 in 5x90s (SNR=3)

REM (Rapid Eye Mount) telescope



A fast moving telescope …
- Alt-Az 60 cm, f/8 focal ratio, mirror silver-coated
- 2 Nasmyth foci (one idle)
- ~ 10 deg/s – to any position in the sky in ~ 60 s

… with a high throughput NIR Camera: REMIR…
- **10' × 10' FoV**
- **1.2" pixel scale**
- **0.9 – 2.3 µm (z ', J, H, K_s)**
- **Wobbling plate for dithering**
- **J ~ 15.5 in 10 s, SNR ~ 10**

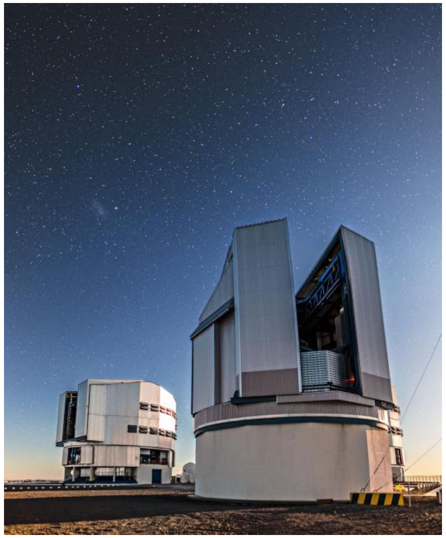
… and an Optical Camera: ROS2
- **0.58" pixel scale**
- **~ 10' × 10' FoV**
- **4000 – 9500 Å (*g* ', *r* ', *i* ', *z* ')**
- **4 channels simultaneously observed**
- ***r* ~ 19 in 10 s, SNR ~ 10**

Simultaneous observations
g ', r, ' i ', z ' + 1 NIR band

VST optical follow-up of gravitational waves

Two companion programs on GTO time (in reward of telescope and camera construction):

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

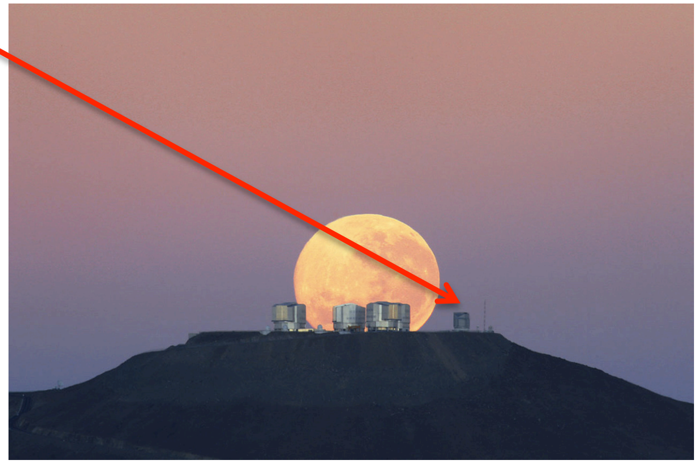


We start with a negotiation with ESO to have the VST in Target of Opportunity (ToO) mode.

Since P95 (1 April-30 Sept 2015) ToO and follow-up programs.

Up to now allocated 240h on these surveys

VST in a nutshell

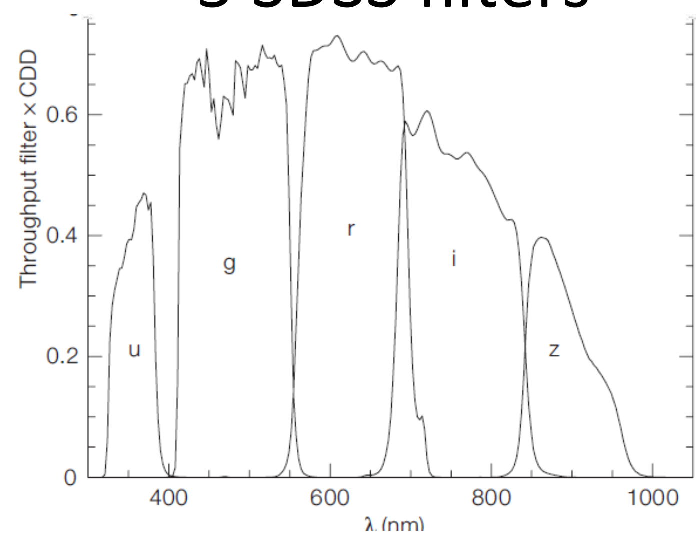


Located on Paranal Chile

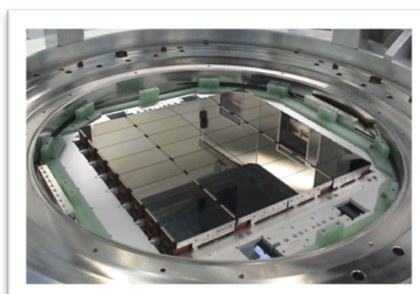
In operation since October 2011

- Primary mirror: 2.6m
- 1.46 deg corrected FoV (∅)
- 80% EE in 0.4″

5 SDSS filters



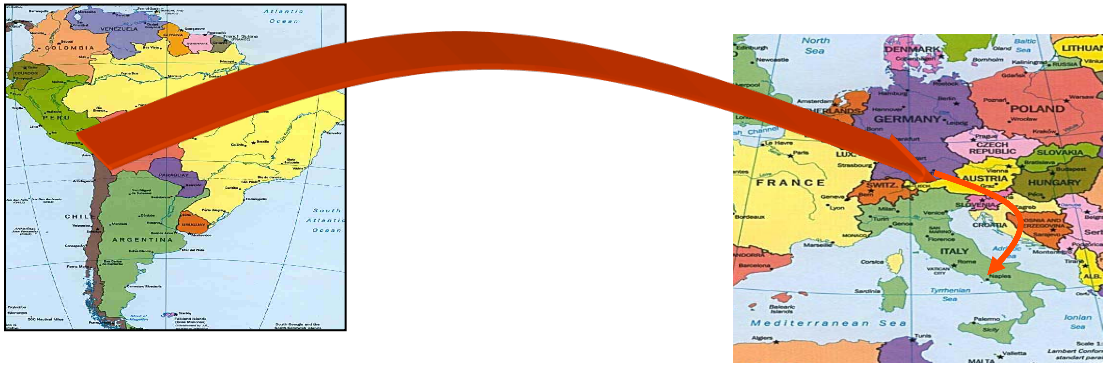
Camera OmegaCam



- 268 Mpixel 1°x1° FoV
- 0.21 arcsec/pixel
- 32 scientific CCDs + 4 outer CCDs

Founds, design and construction @Osservatorio di Capodimonte

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).

GW150914 EM sky coverage

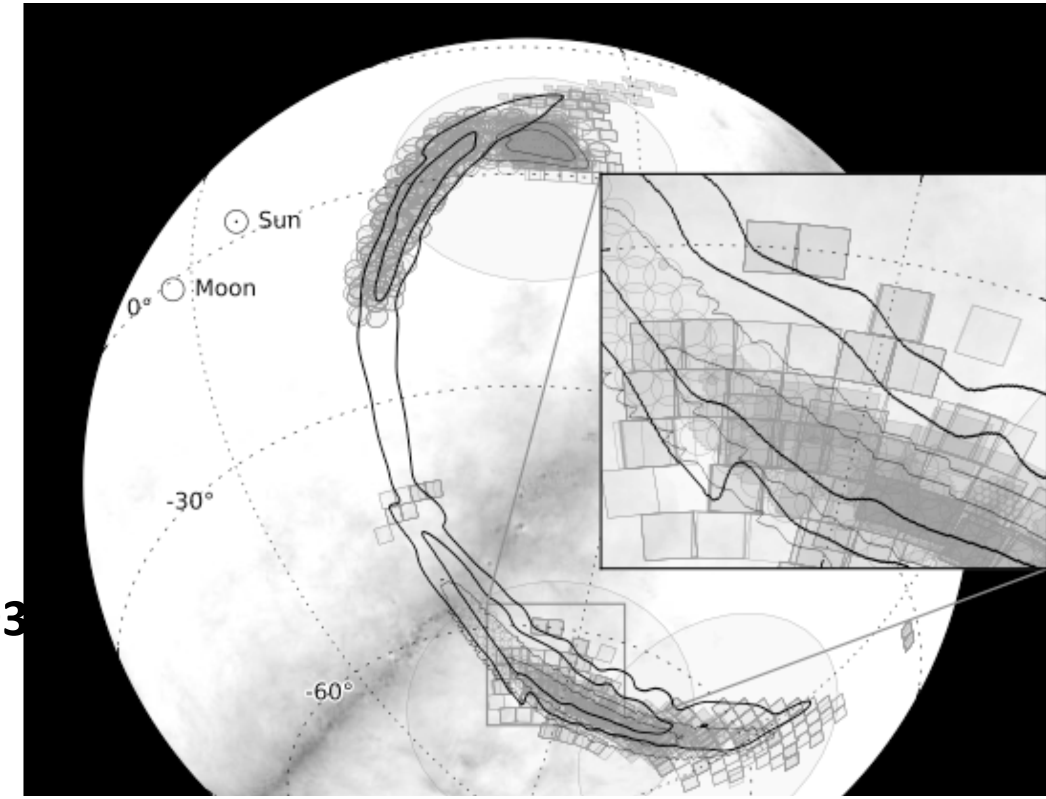
24 observatories involved !!

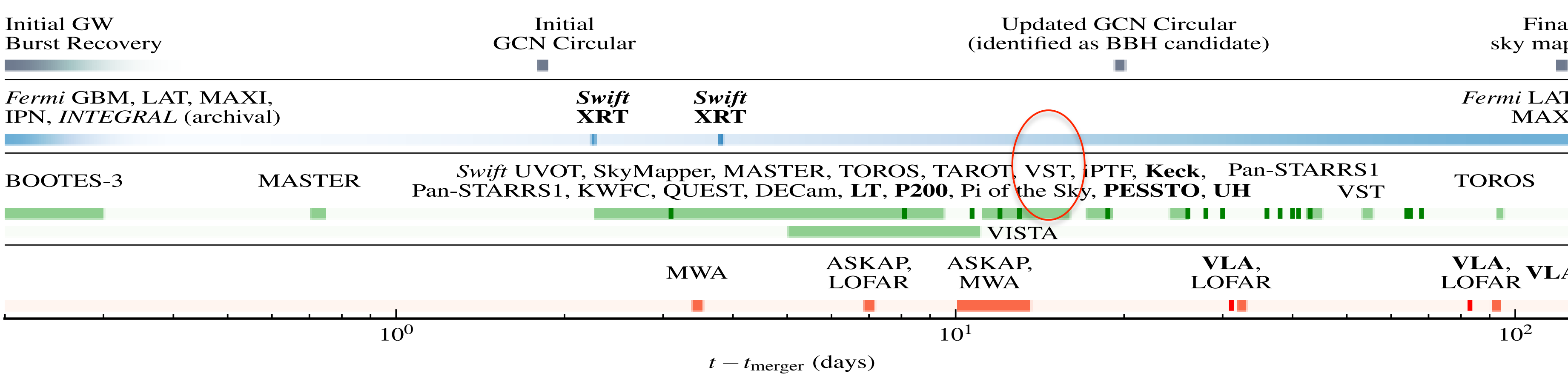
19 orders of magnitude in frequency space

+ neutrino search IceCube/ Antares (+/- 500s)

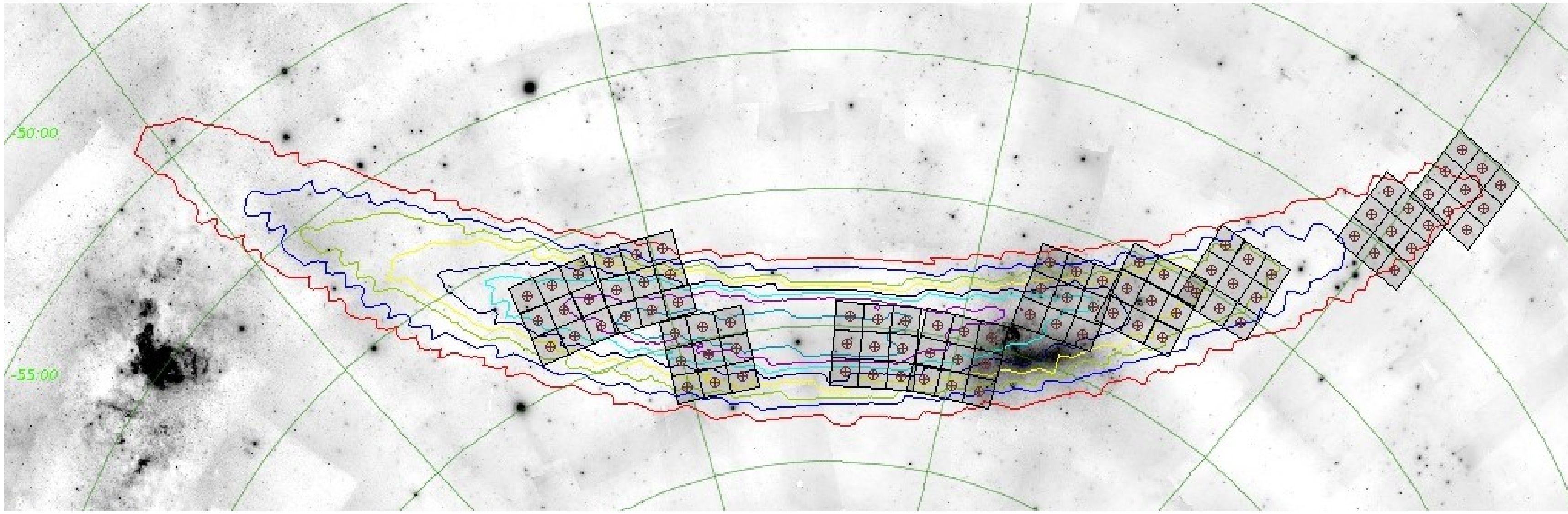
LVC-EM, APJL,826,1 L13,2016

Antares,IceCube, LVC, Phys. Rev. D**93** 122010,2016





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)

29% of the localization probability for cWB sky map enclosed

10% considering the LALinference sky map (shared with observers on 2016 January 13)

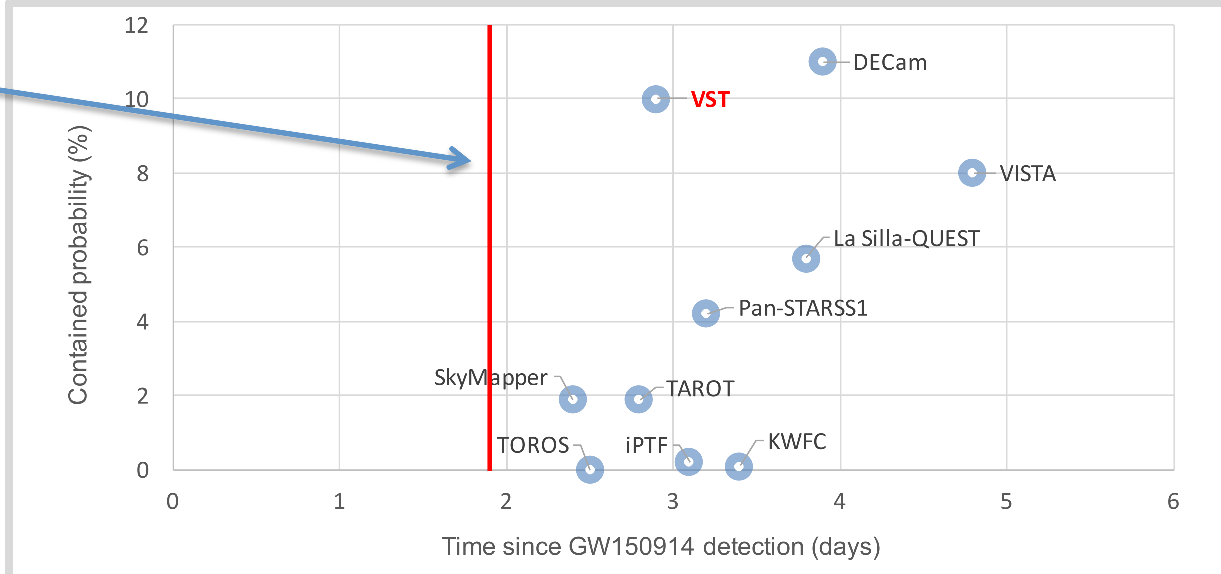
cWB sky location: red 90% enclosed probaility

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

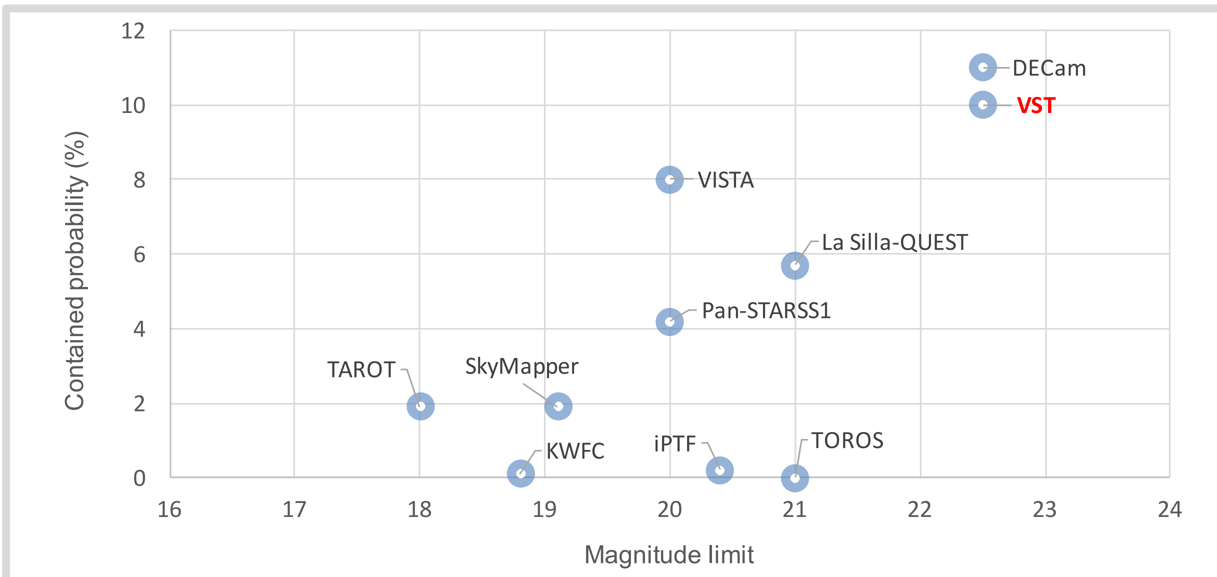
VST survey performance

LVC alert

Contained probability vs Time response

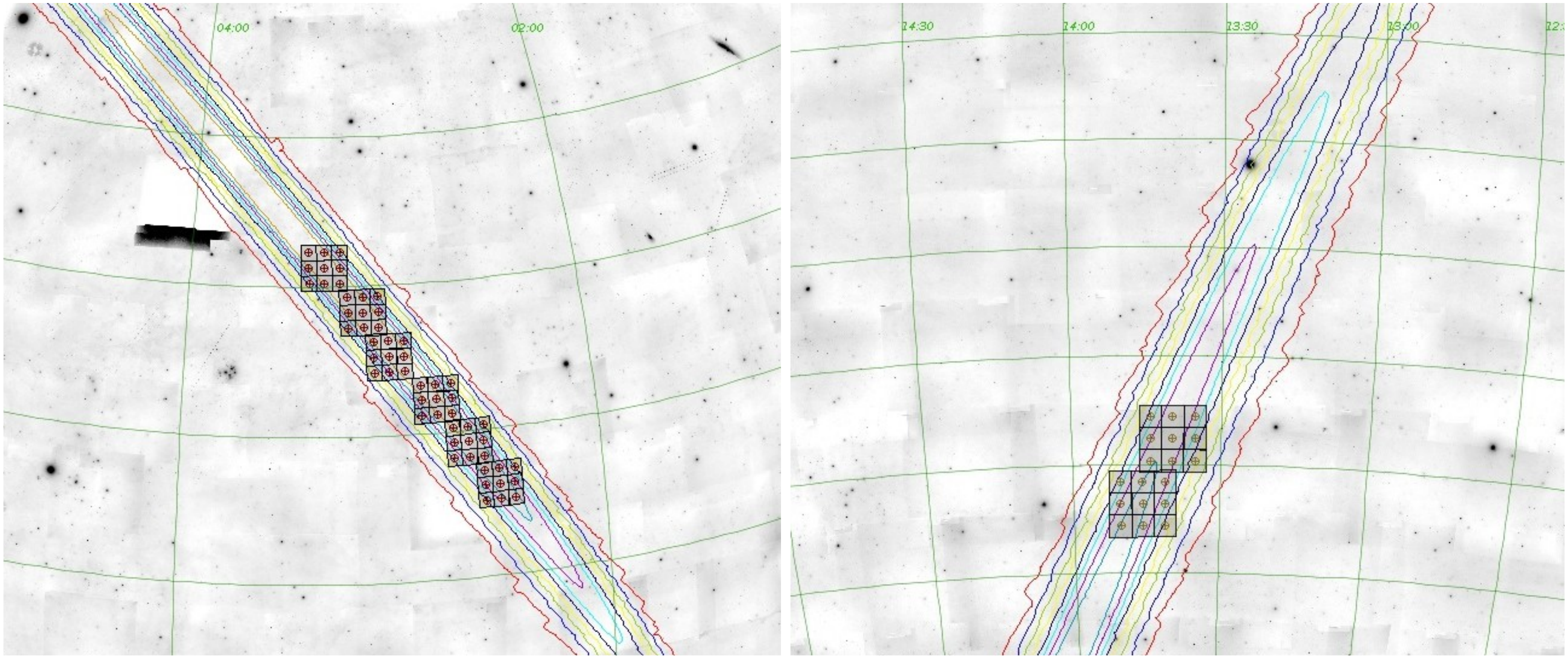


Contained probability vs limiting magnitude



Data from Abbott et al 2016

Second event GW151226



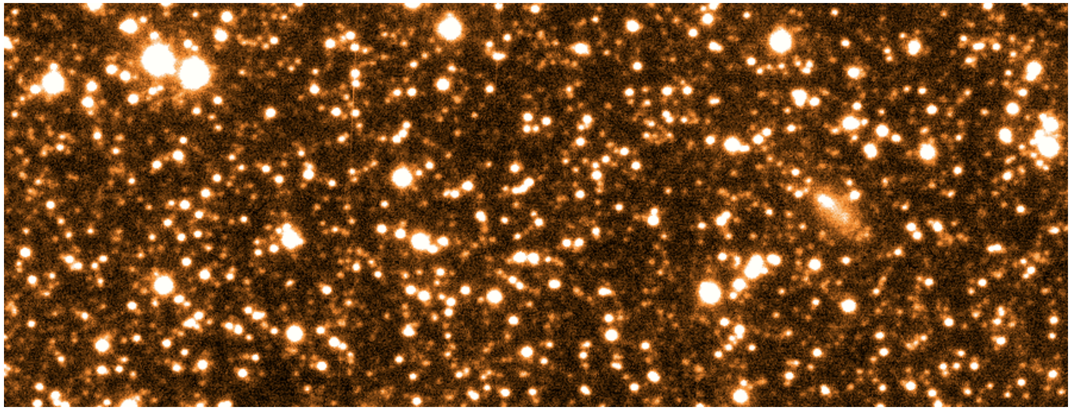
72 deg^2 in 6 epochs

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

EM counterpart search: a very tough task

Find ONE transient in the GW error area. For the first two events 90% enclosed prob. ~ 200-1000 deg^2



In 1 deg^2 ~ 300k sources !!

- 10-50 SN
- > 100 AGN
- Thousand of variable stars
- Thousand of asteroids

Transients search in Grawita

Two complementary pipeline for transients search

- ***diff-pipe*** images subtraction (Cappellaro et al. 2015)

  PRO: deeper (with good seeing, transients detected up to r=22 mag AB), for crowded fields, source embedded in extended objects;

  CON: slow, more sensible to images defects

- ***phot-pipe*** (S. Covino) comparison among epochs in catalog space

  PRO: fast;

  CON: shallower, missing transients in extended sources…

Results for GW150914 event

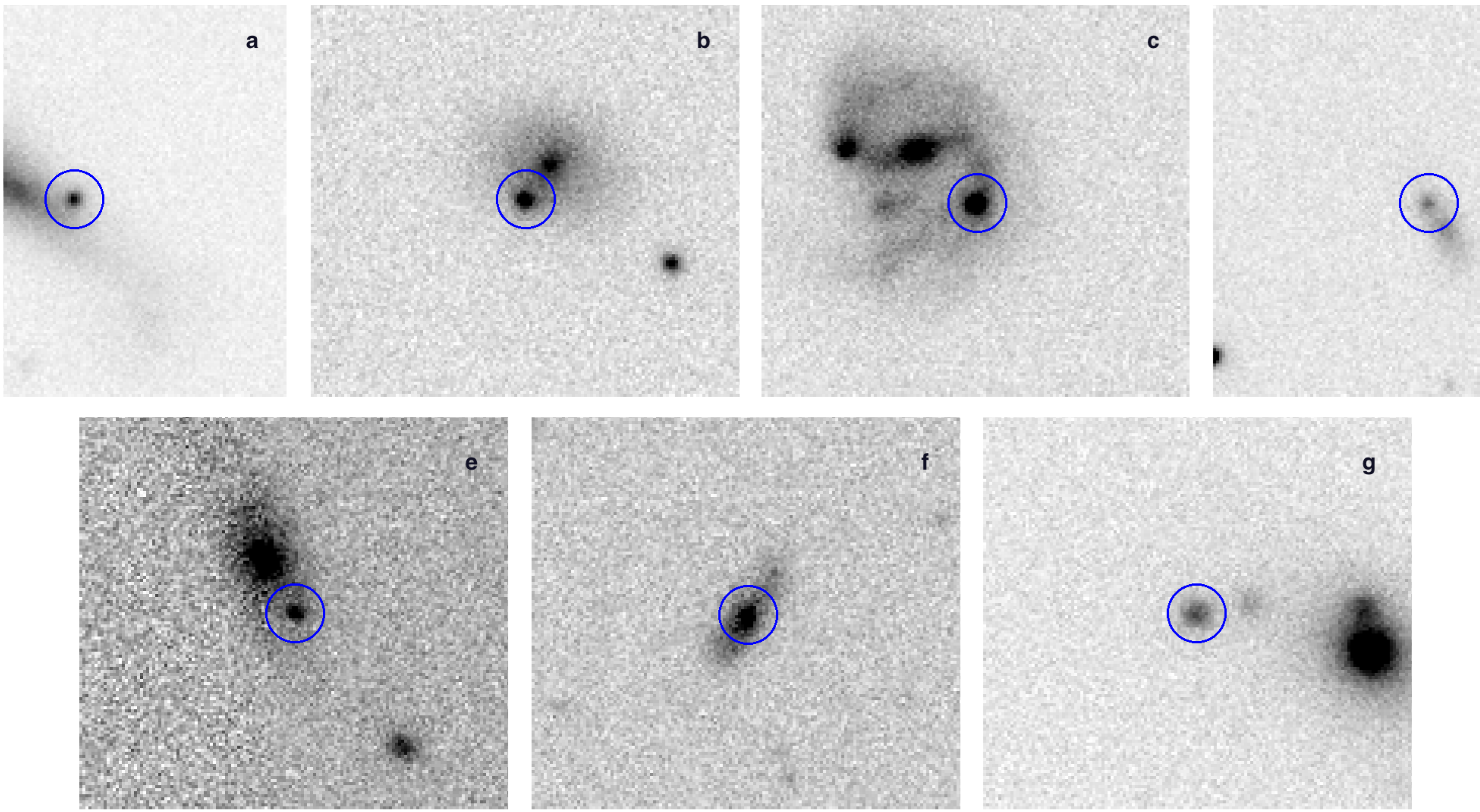
	Diff-pipe	Phot-pipe
Initial number of sources in all epochs	9,000,000	9,000,000
Initial # of candidates	170,000	54,239
Total # of transients	8,000	939
# known variables	6722	
# of known SN in the field/detected	4/4	
# new SN candidates	7	

Brocato et al. 2018 MNRAS, 474, 411

Evident spurious and known variables already removed

VSTJ57.77559-59.13990 SN Ib/c candidate possibly associated with Fermi-GBM GRB 150827A

SN candidates in the GW150914 VST follow-up



Results for GW151226 event

	Diff-pipe	Phot-pipe
Initial number of sources in all epochs	~ 900,000	~ 900,000
initial # of candidates	6,310	4500
total # of transients	3,127	305
# known variables	54	
# minor planets (within 10")	3670	
# of known SN in the field/detected	54/17	
# new SN candidates	4	

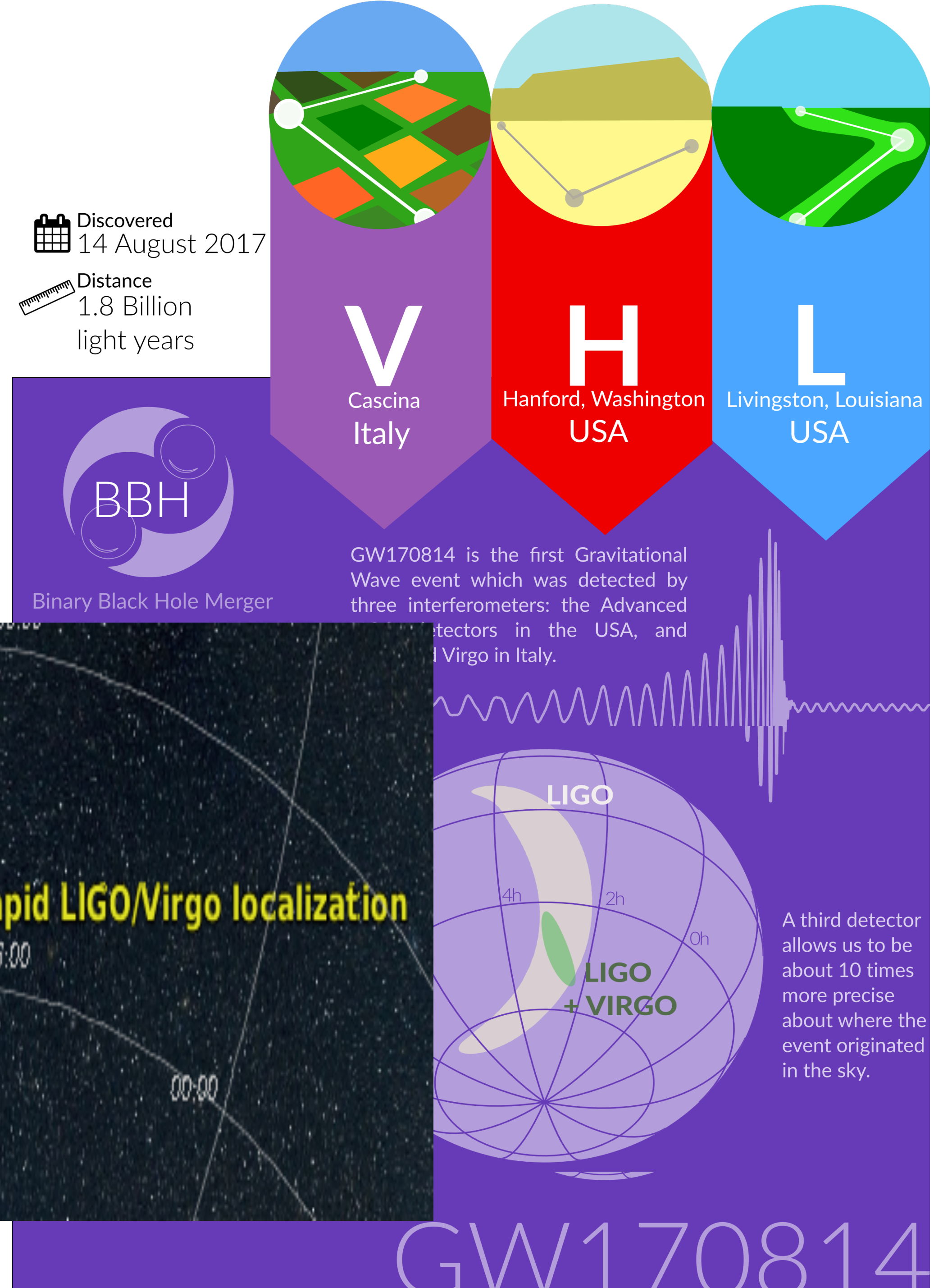
Brocato et al. 2018 MNRAS, 474, 411

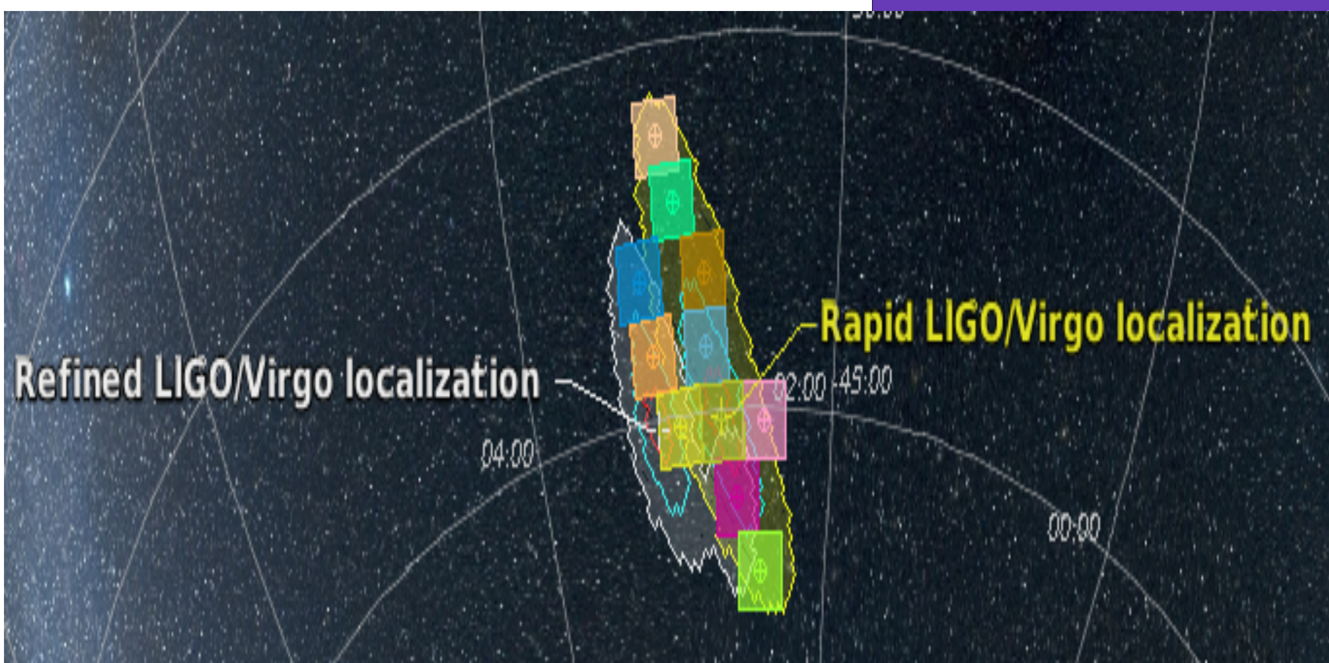
Spurious and known variables already removed

GW170814 the promise of Multi-messenger Astronomy

Abbott et al 2017.

VST was there !!





~ 80% of the initial bayestar map

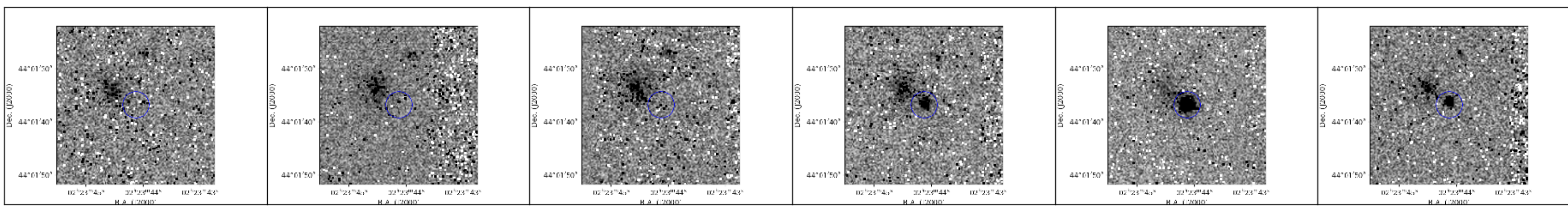
GW170814

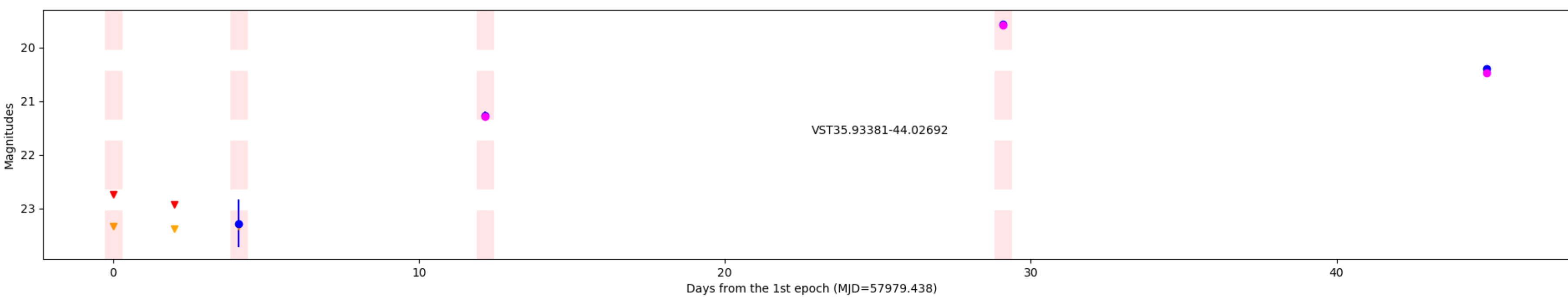
Diff-pipe found 495 optical transients

Phot-pipe found 230 optical transients

A. Grado et al. in preparation

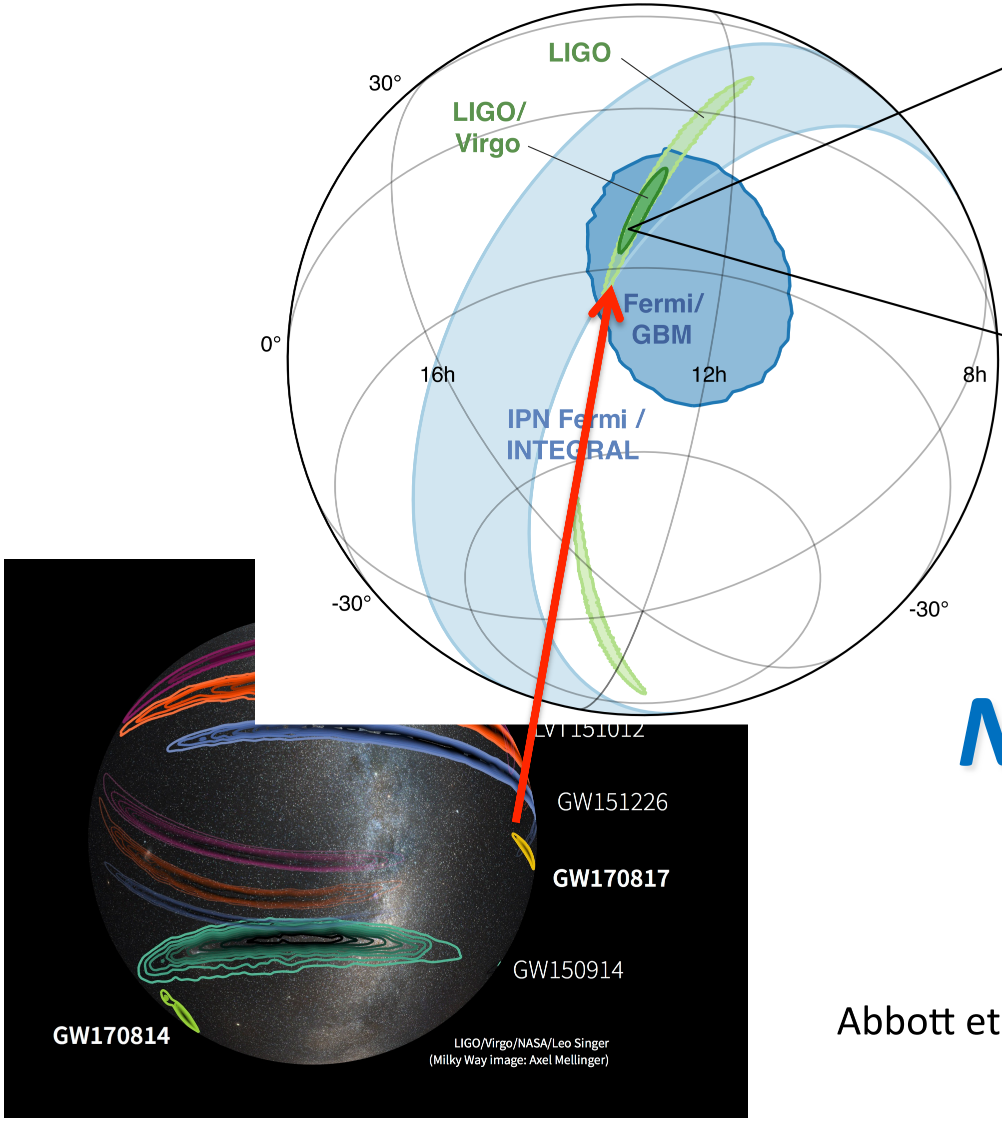
SN candidate from the VST search in GW170814

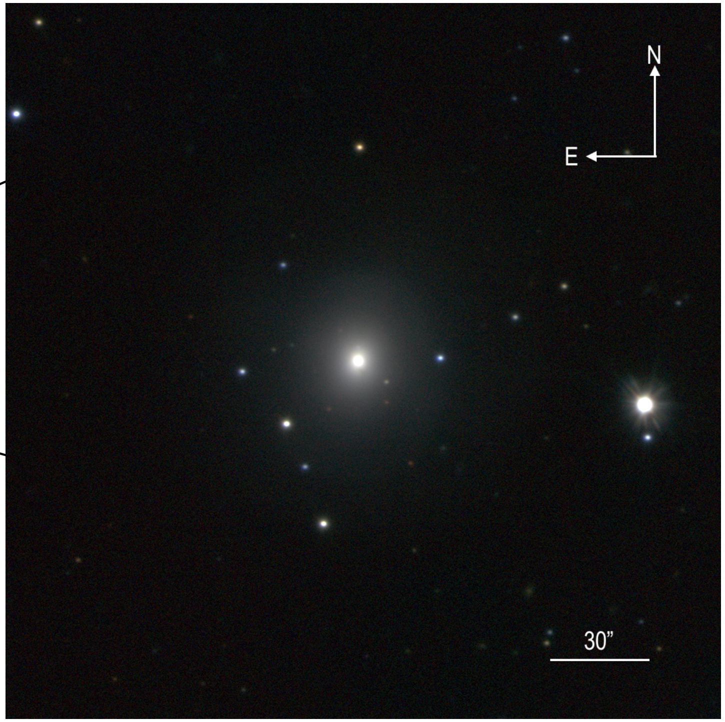




The watershed

2017-08-17 12:41:04 UTC





NGC4993@ VST

Abbott et al. 2017, PRL, 119, 1101

GW170817 timeline

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: 23:18:42 UTC

covering 9 deg^2

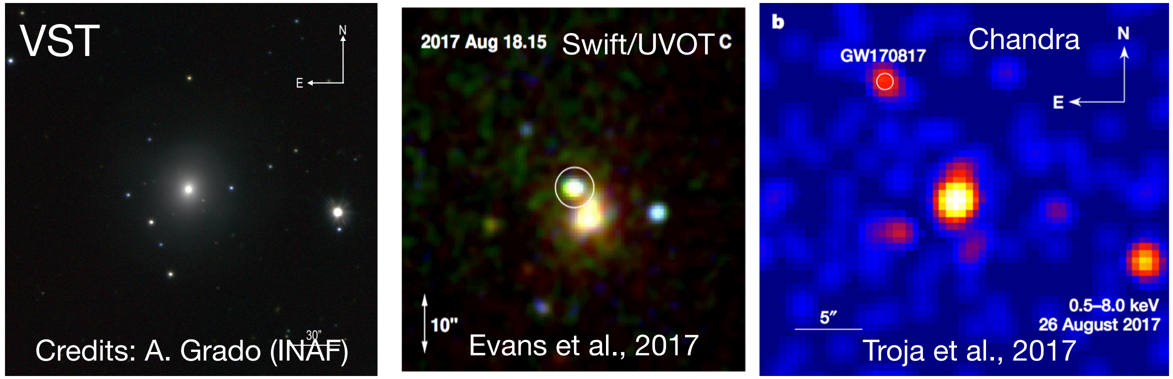
Swope OT observation: 23:33 UTC

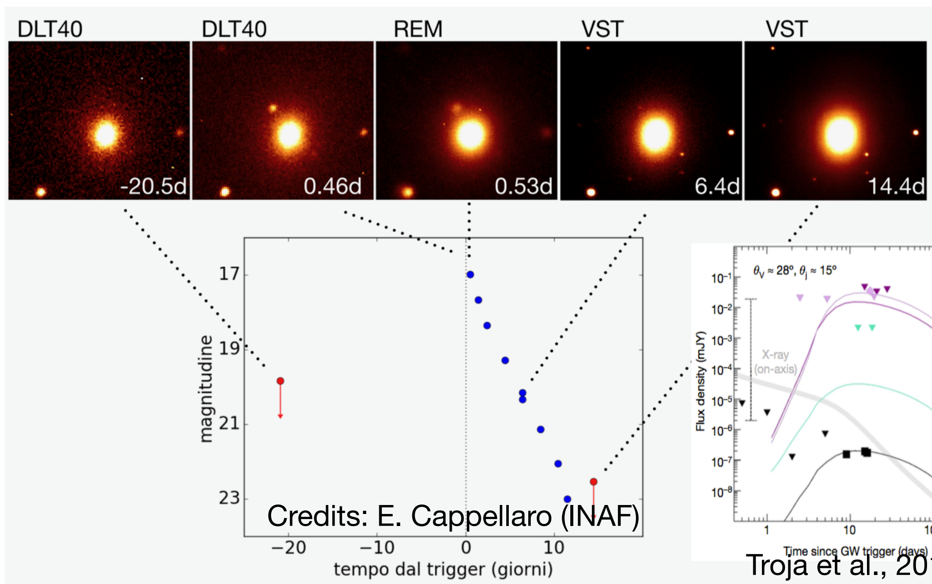
(targeted survey) GCN21529

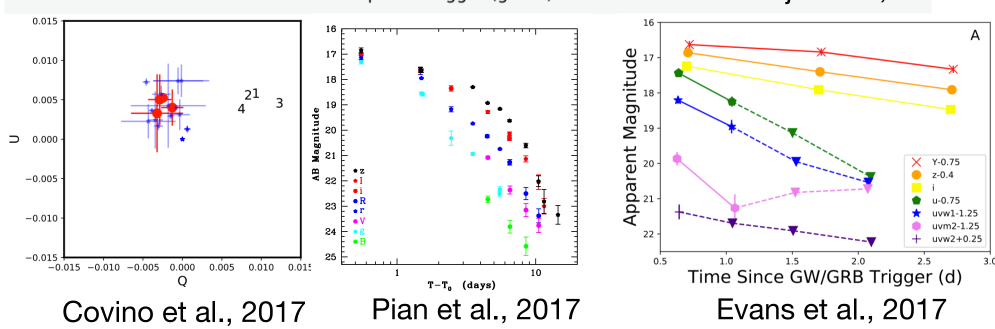
Updated skymap: 23:54:40 UTC

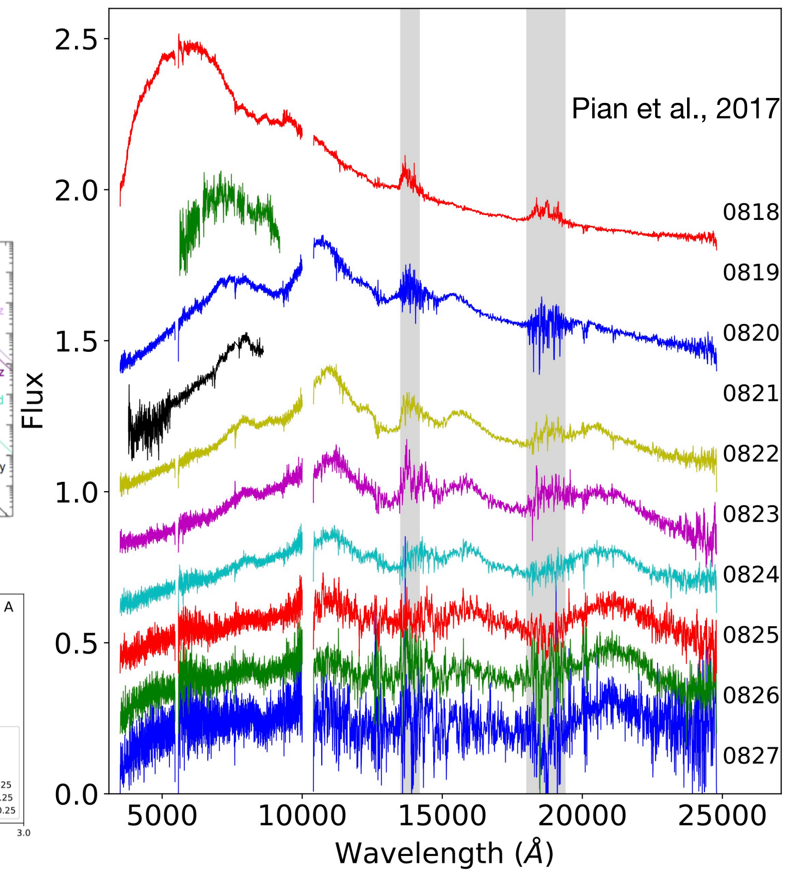
34 deg^2 (90% credibility)

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



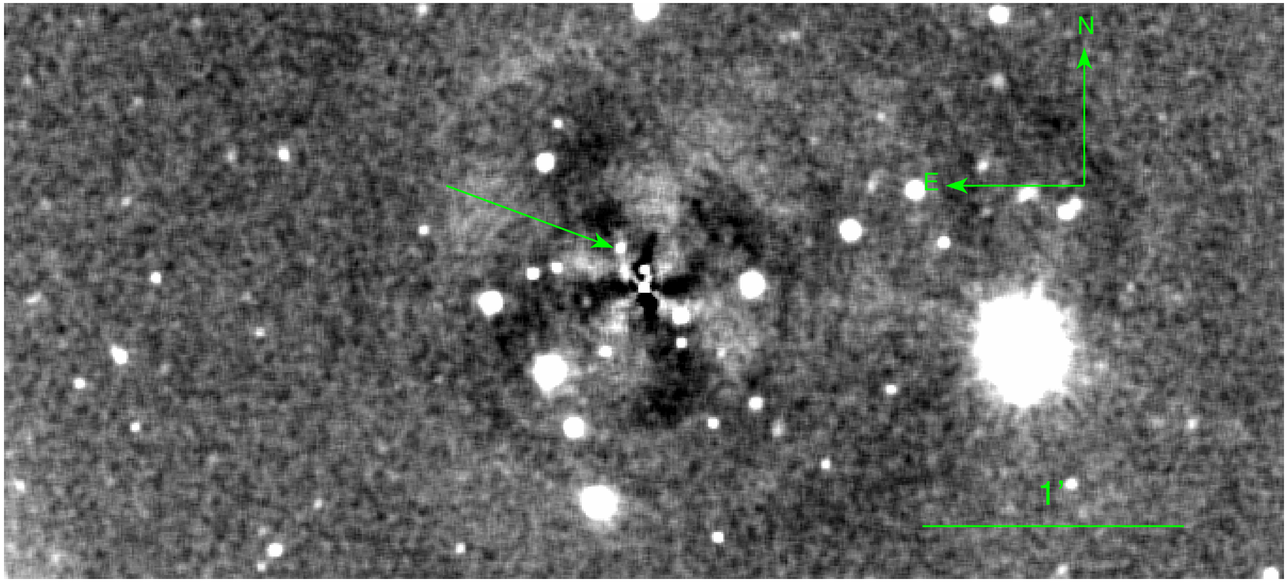






Credit. E. Cappellaro

Smoothed residuals of isophotal elliptical fit



NGC 4993
r filter

At +6.4 days: 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: 1200 s in i filter **No detection** (22.53 mag 50% complet. for pointlike surces) **(GCN 21833 A. Grado et al.)**

At +108 days: 4320 s in g,i filters **No detection** (25.0 and 24.5 50% complet. For pointlike sources) **(GCN 22368 A. Grado et al.)**

O3 and beyond

- We foresee to allocate time at VST up to P107 (sept 2021)
  - **50** hours/semester on VST-GTO
  - **~30** hours/semester on OmegaCam-GTO

In ~4 hours we cover 90 deg^2 2x40s dithered exposures.

BLIND SEARCH

Assuming 6 epochs we can observe from ~2.5 (90 deg^2) to ~8 events (30deg^2)/semester

We will focalize on GW from BNS and nearby (~100 -200 Mpc) BBH and NS-BH if any

Conclusion

- The multi-messenger Astronomy is started
- GW optical follow-up has an important role
  - *Lesson learned: very important to have as soon as possible a refined map*
- GRAWITA has expertise and facilities to face the search of optical counterparts
- We can do both wide area and blind search
- With VST we plan to follow (six epochs distributed over 2 months) ~ 2.5 to 8 events/semester


Thanks
NGC4993@VST +6.4days