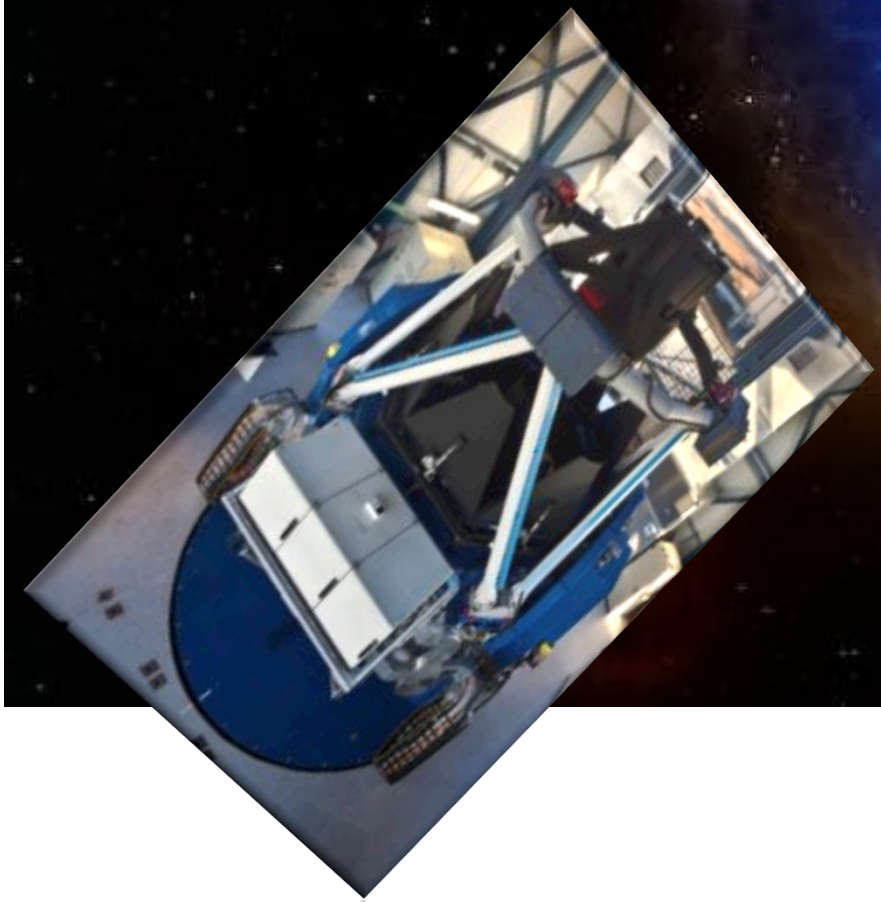
Search of GW optical counterpart with the VST



Aniello Grado

INAF-Napoli

Enrico Cappellaro

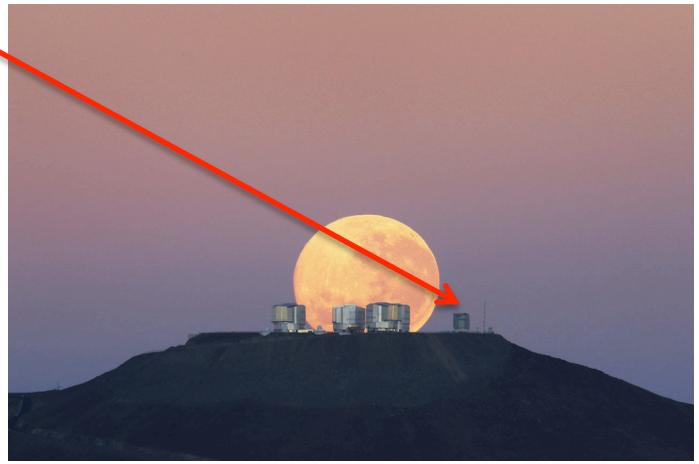
INAF-Padova

&

the GraWITA team

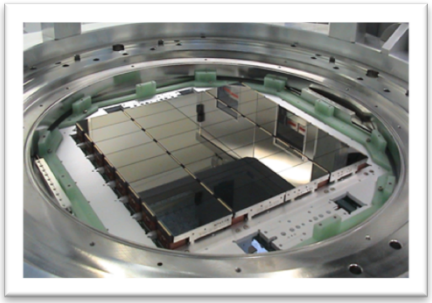
Credit: NASA's Goddard Space Flight Center/CI Lab

VST in a nutshell



Located on Paranal Chile
In operation since October 2011

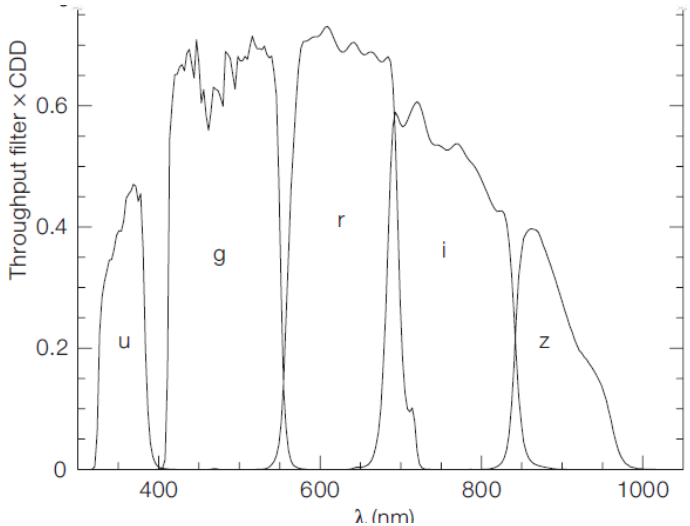
- Primary mirror: 2.6m
- 1.46 deg corrected FoV (∅)
- 80% EE in 0.4″



Camera OmegaCam

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

5 SDSS filters



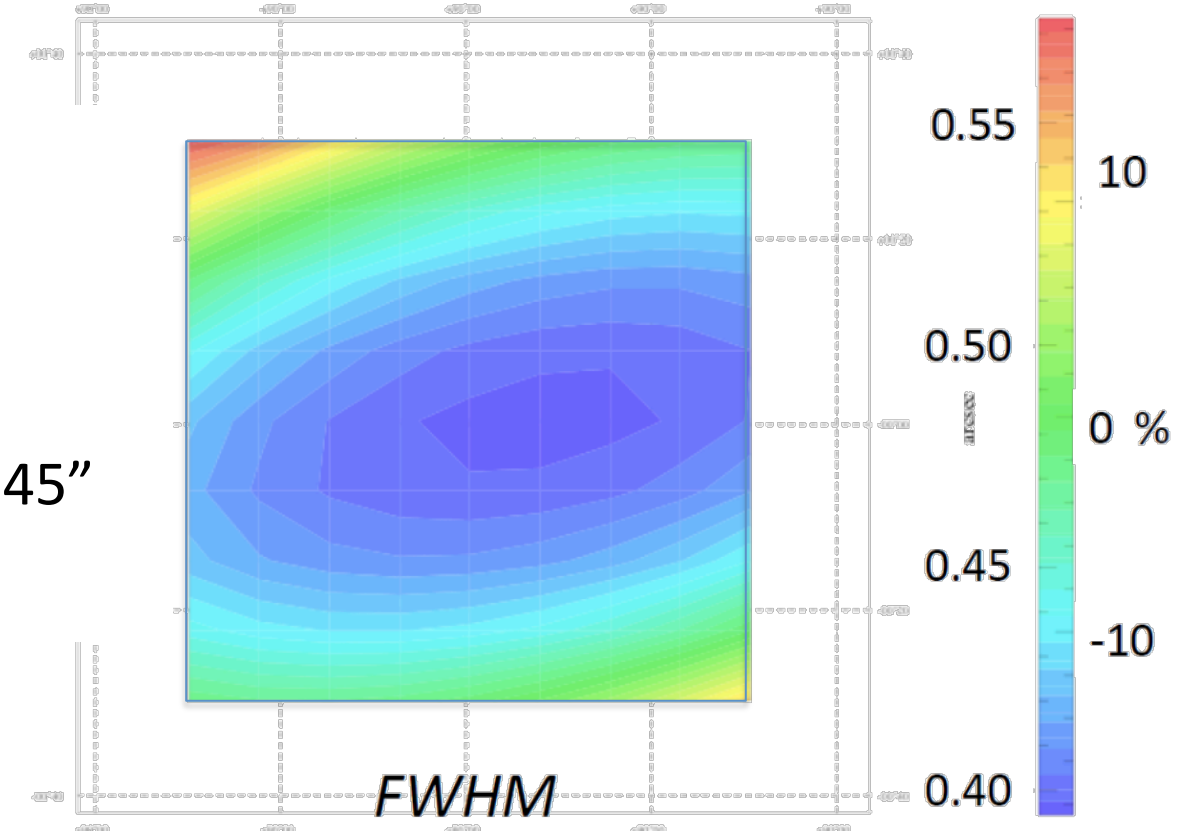
Founds, design and construction @Osservatorio di Capodimonte

VST performances: FWHM

VST regularly delivers images down to 0.5’’ FWHM uniformly over the whole field, with small ellipticities

i-band

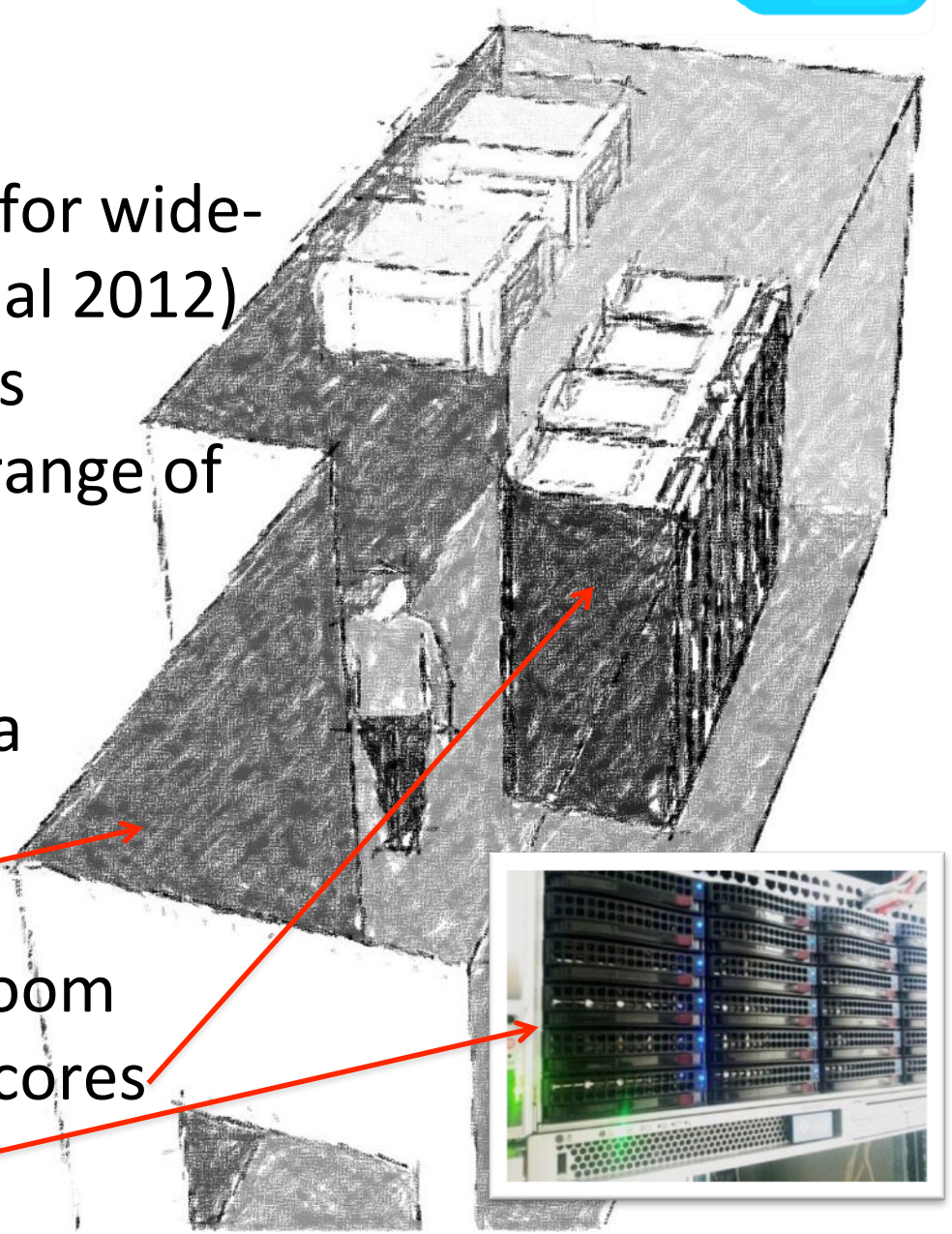
Median FWHM =0.45”



VST Data Center @OACN

- ***SW***
  - VST-Tube
    in house dev. pipeline for wide-field images (Grado et al 2012)
  - Support 18 VST surveys
  - tailored on very wide range of science goals
  - > 50 papers based on VST-Tube reduced data

- ***HW***
  - Dedicated computer room
  - beowulf cluster ~ 300 cores
  - ~ 1 PB data storage



VST optical follow-up of gravitational waves
In the framework of GraWita

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

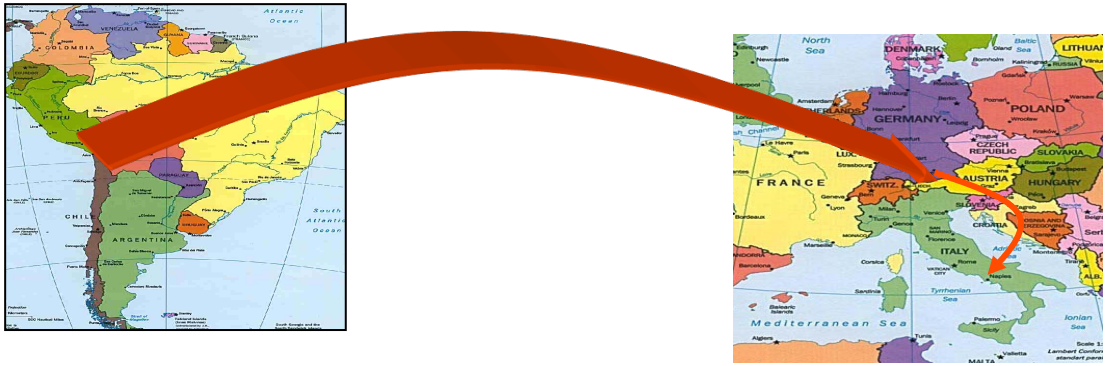
- On ***VST-GTO***: PI A. Grado
- On ***OmegaCam-GTO***: E. Cappellaro

We start with a negotiation with ESO to have the VST in ToO mode.

Since P95 ToO and follow-up programs.

Up to now allocated 240h on these surveys

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

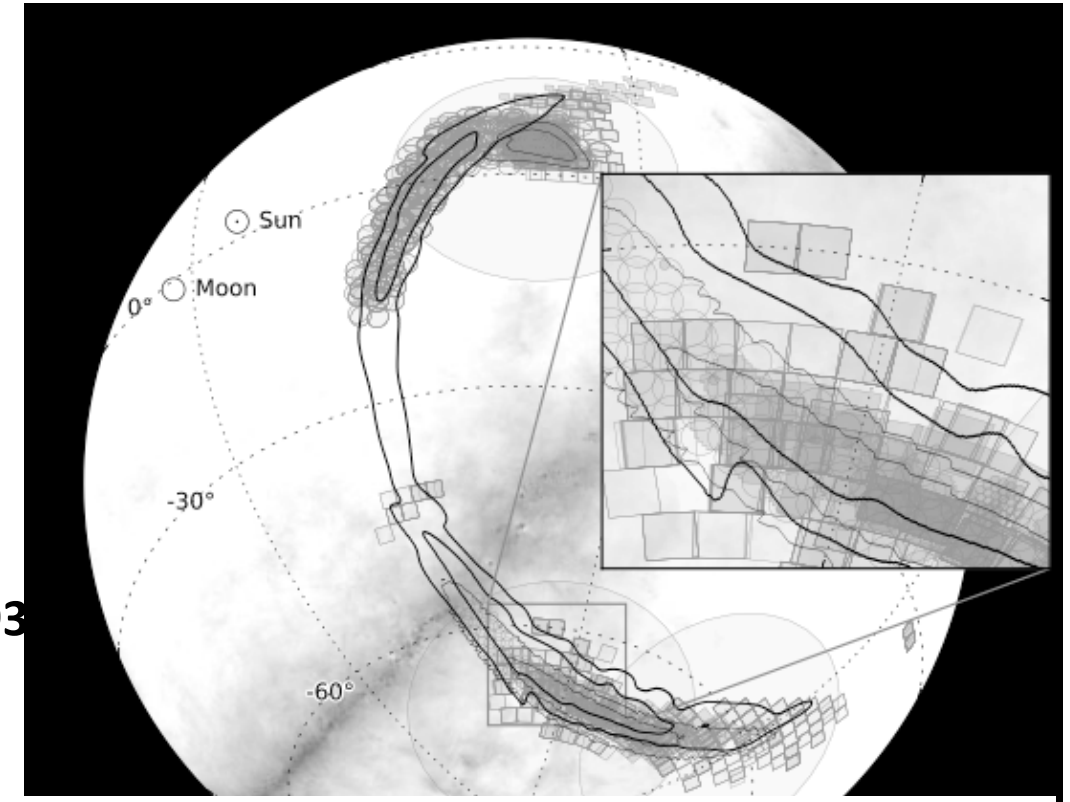
24 observatories involved !!

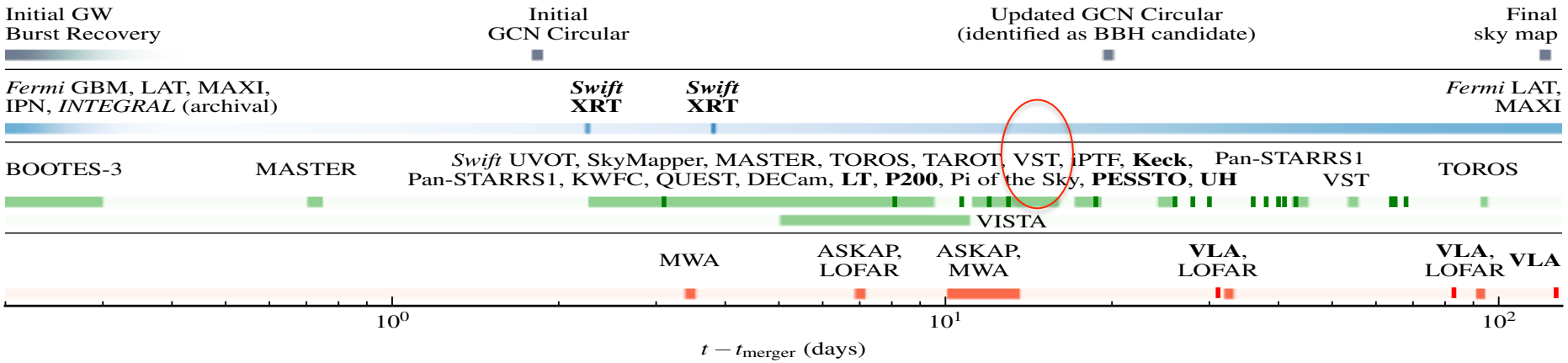
19 orders of magnitude in frequency space

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

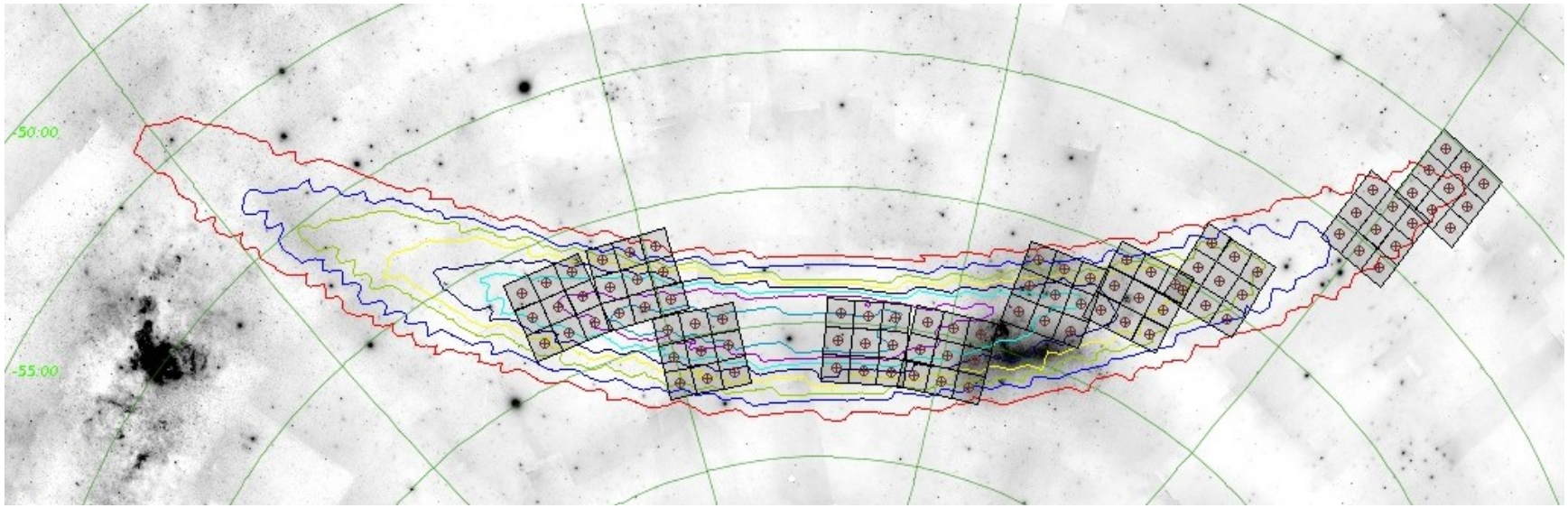
LVC-EM, APJL,826,1 L13,2016

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





First event GW150914



cWB sky location: red 90% enclosed probaility

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

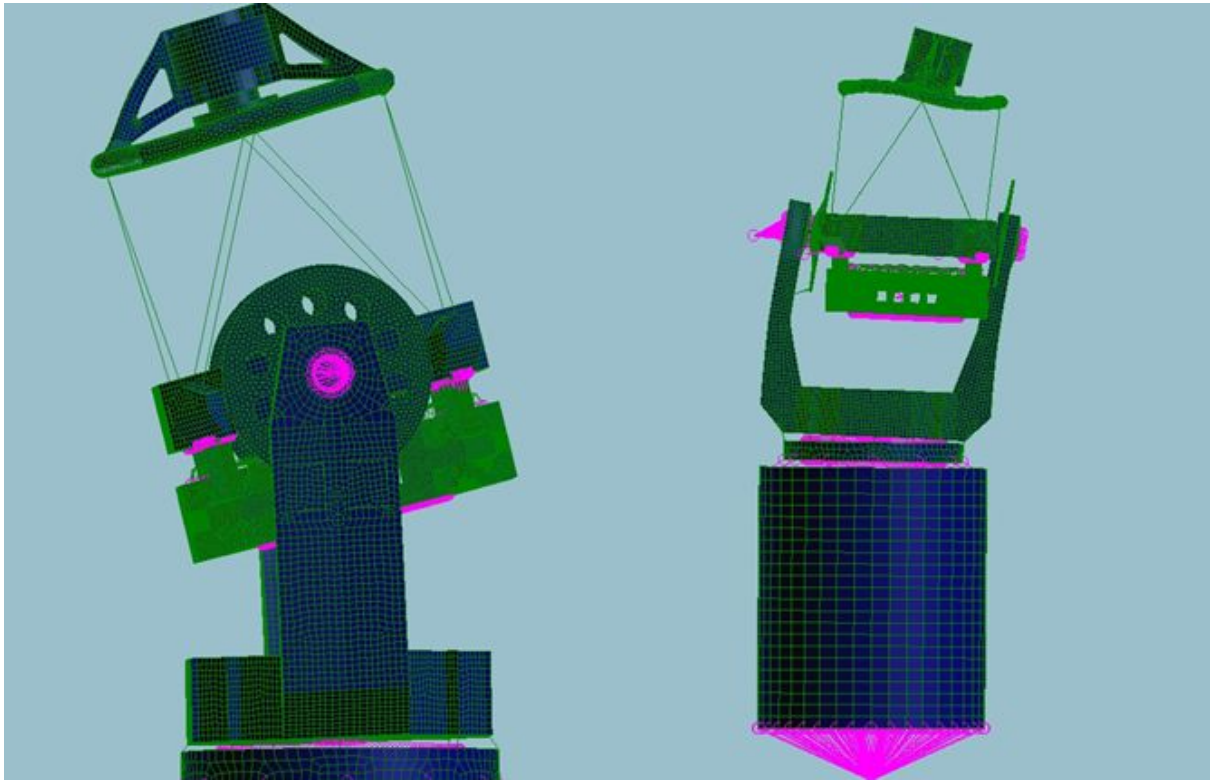
10% considering the LALinference sky map (shared with observers on 2016 January 13)

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

GW150914

First observations: 23h after the alert (GCN 18336 Brocato et al.) (the first “big” high resolution telescope to cover the area)

Illapel (200Km from Paranal) earthquake in Chile September 16 at 19:54 Chilean Time Mw=8.3! (observations started 7 h later)

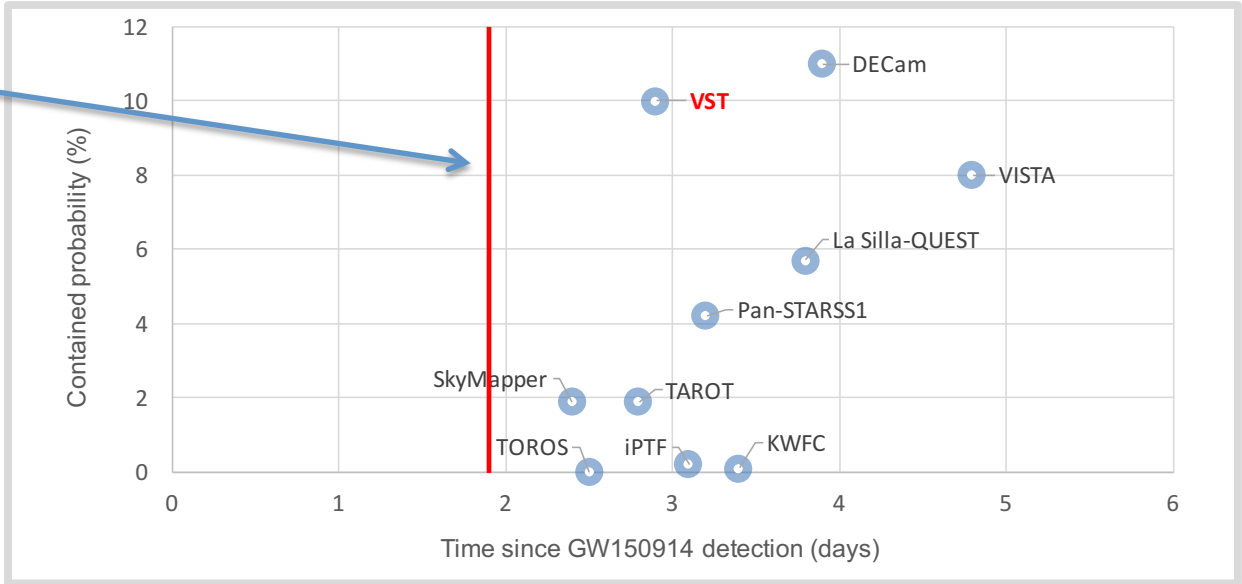


Courtesy: Francesco Perrotta

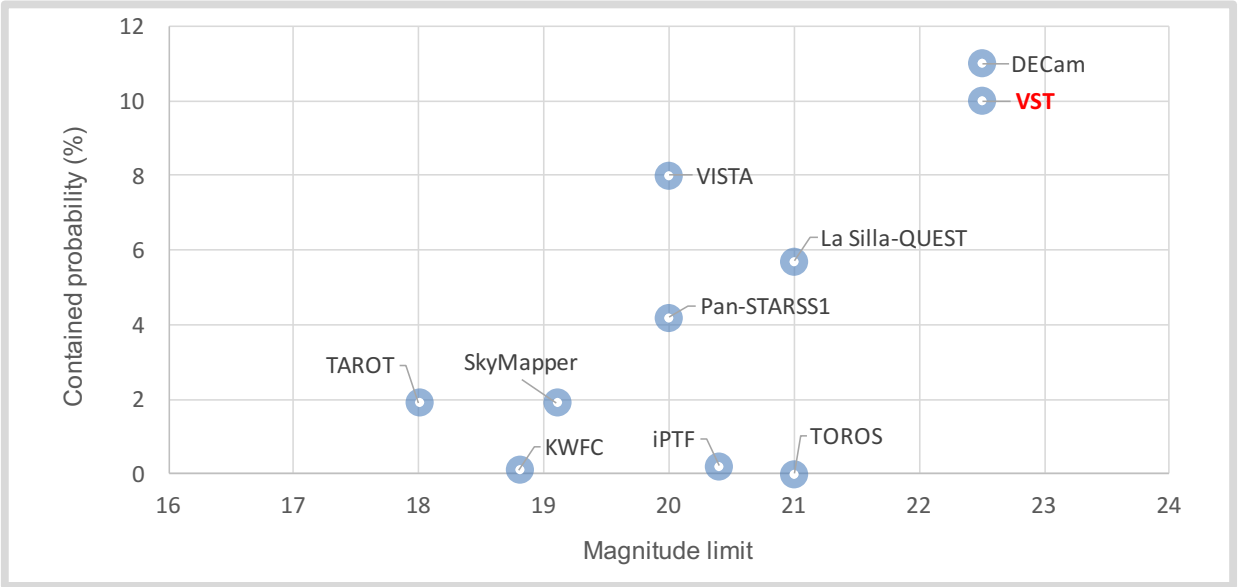
VST survey performance

LVC alert

Contained probability vs Time response

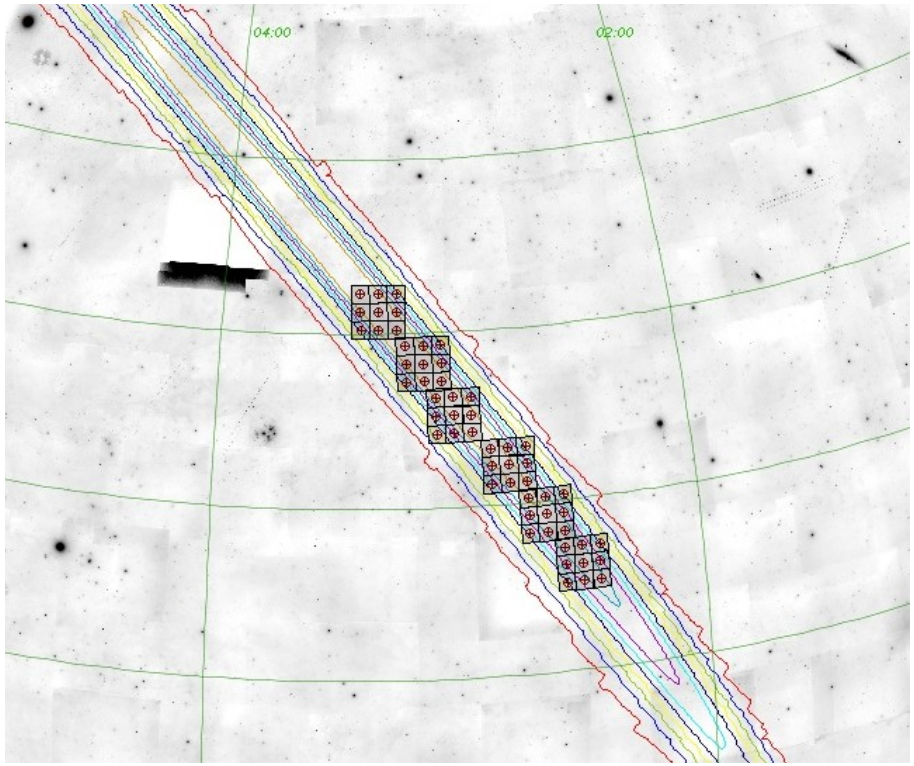


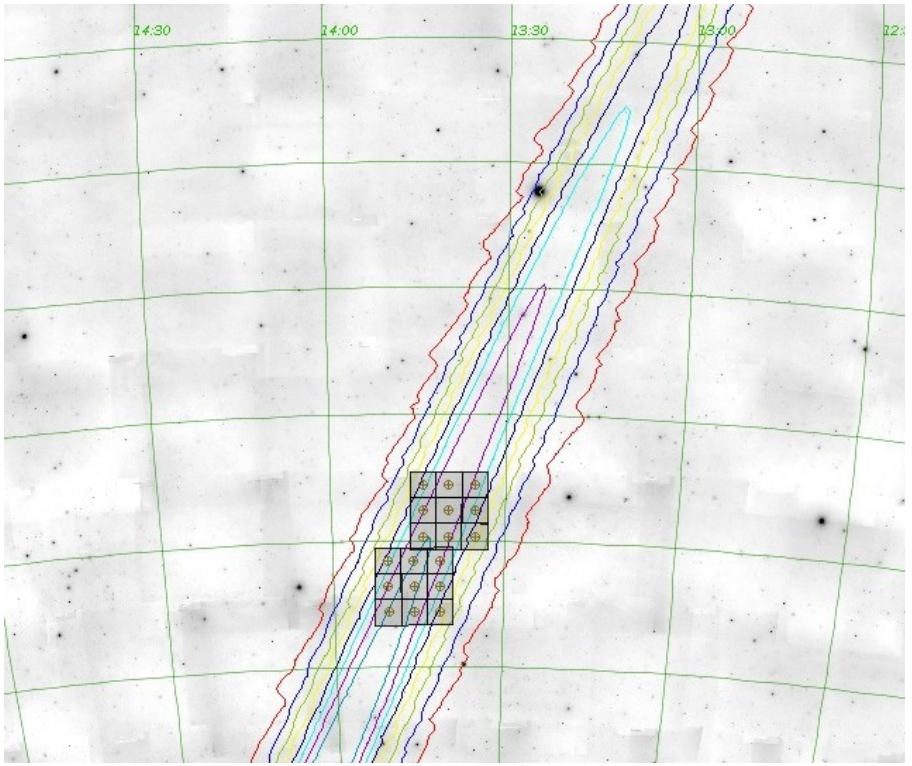
Contained probability vs limiting magnitude



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

EM counterpart search: a very tough task

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

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

Transient search

Two complementary pipeline for transients search

- ***diff-pipe*** images differences (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

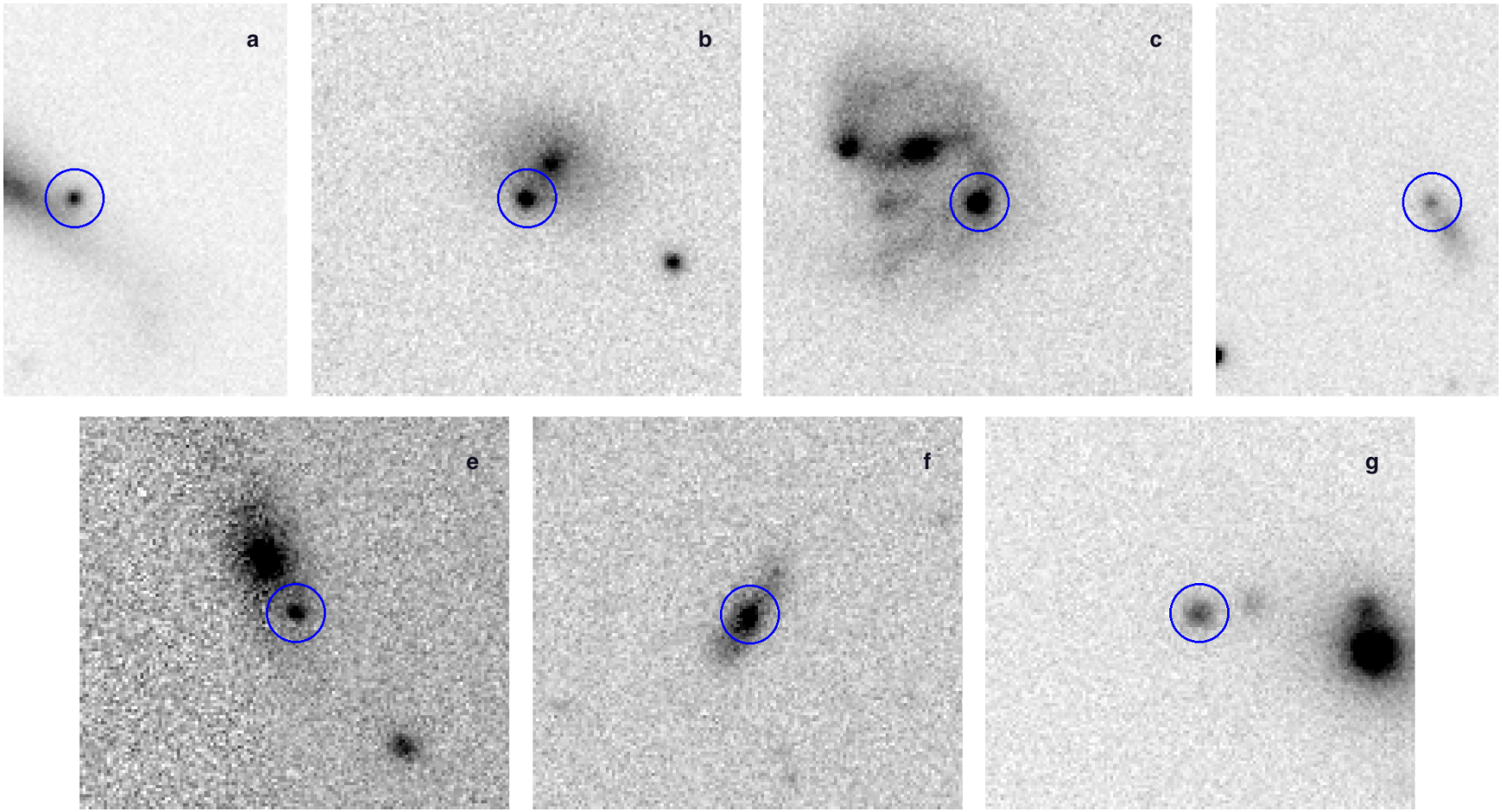
	Diff-pipe	Phot-pipe
Initial number of sources in all epochs	9,000,000	9,000,000
Initial # of candidates	170,000	54,239
Total # of transients	8,000	939
# known variables	6722	
# of known SN in the field/detected	4/4	
# new SN candidates	7	

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	

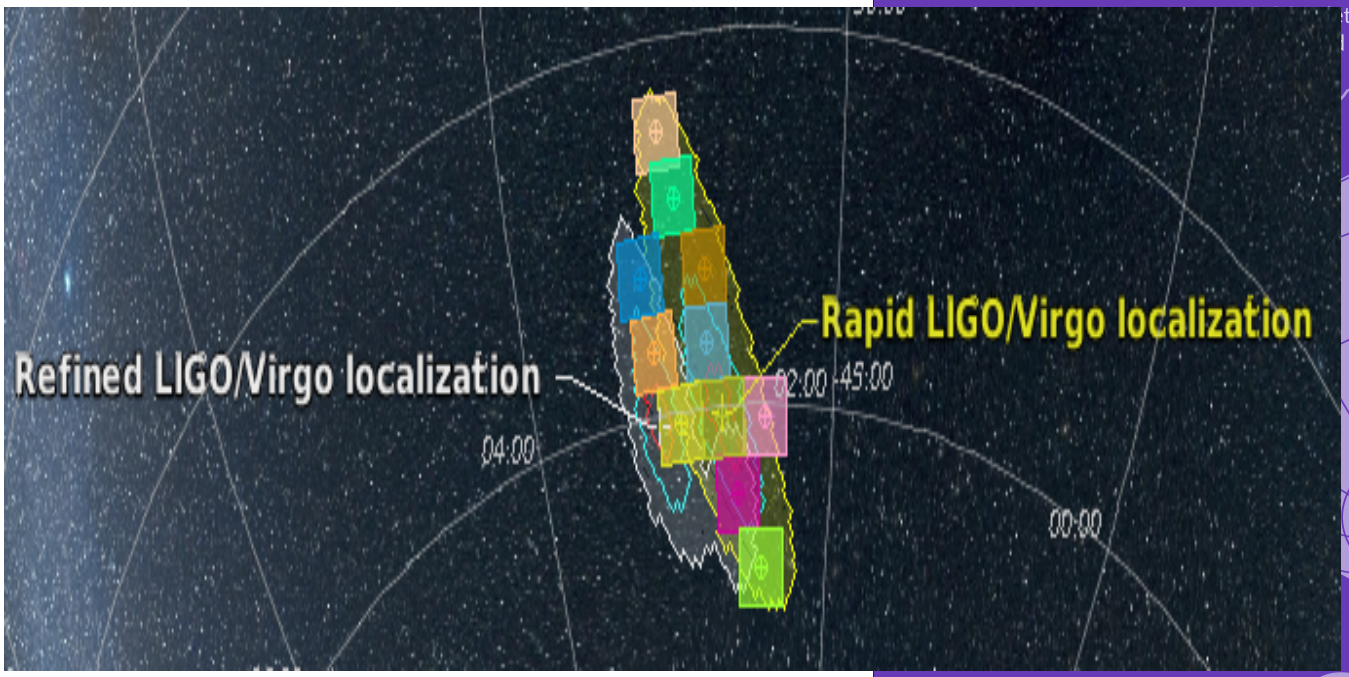
Brocato et al. 2018 MNRAS, 474, 411

Spurious and known variables already removed

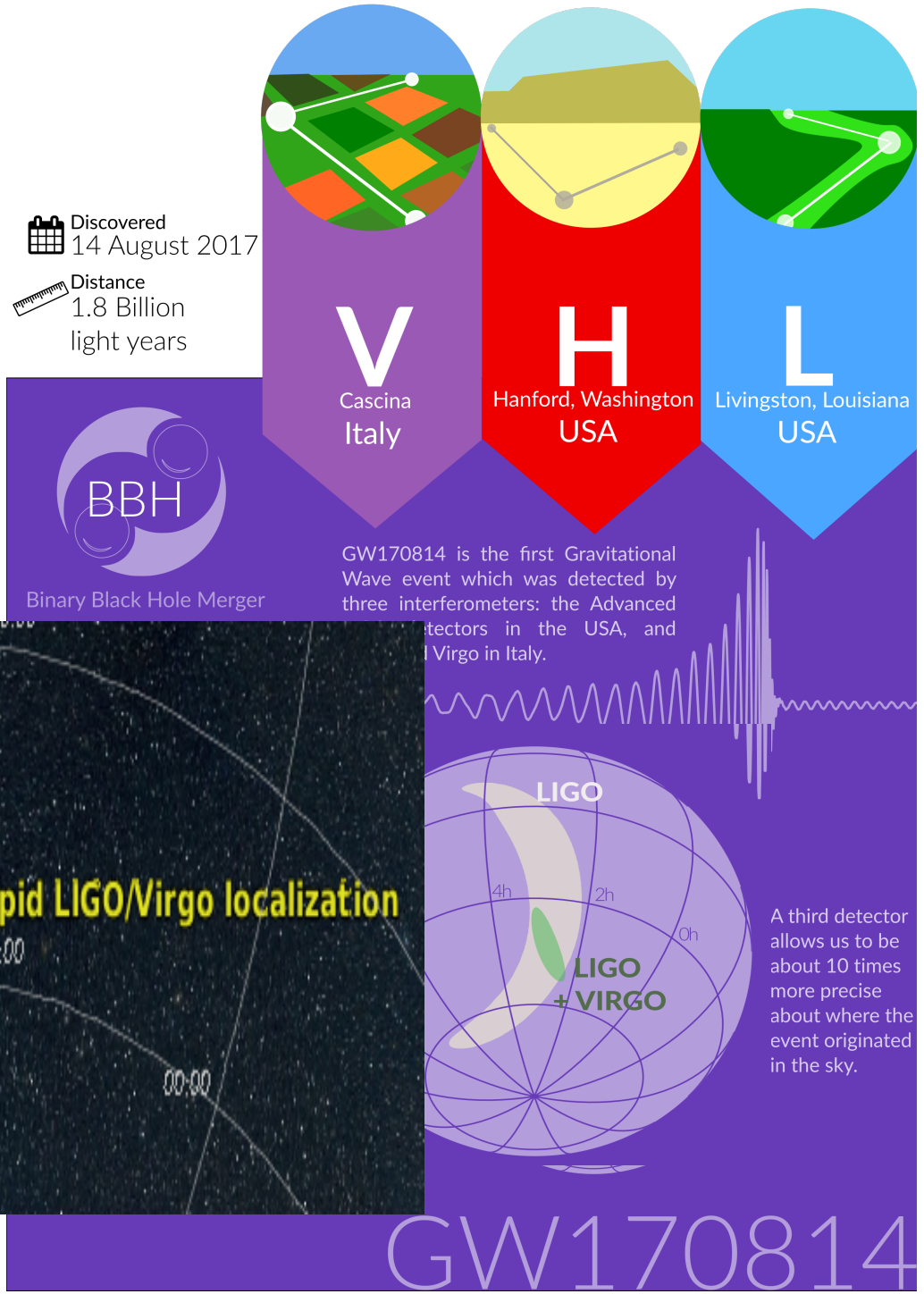
GW170814 the promise of Multi-messenger Astronomy

Abbott et al 2017.

VST was there !!



~ 80% of the initial bayestar map

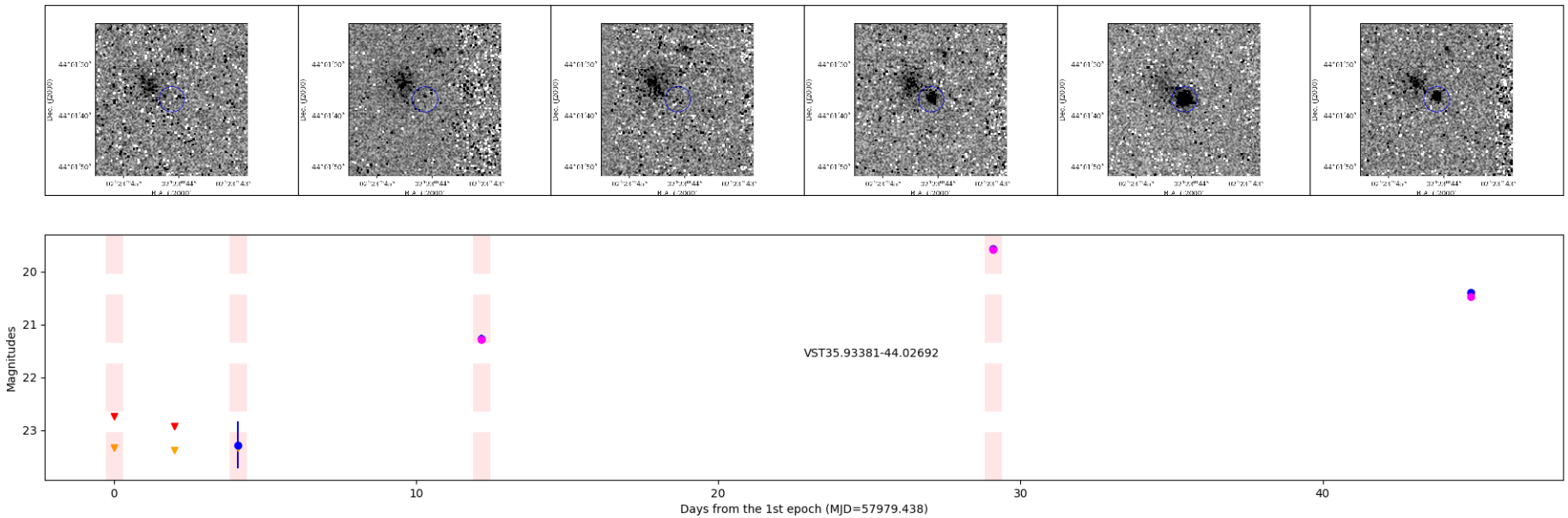


GW170814

Diff-pipe found 495 optical transients
Phot-pipe found 230 optical transients

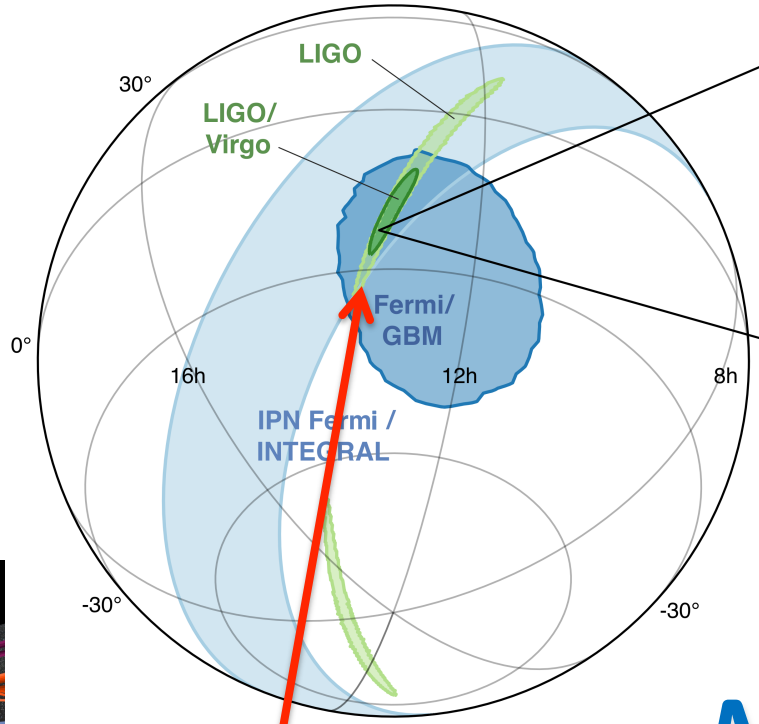
A. Grado et al. in preparation

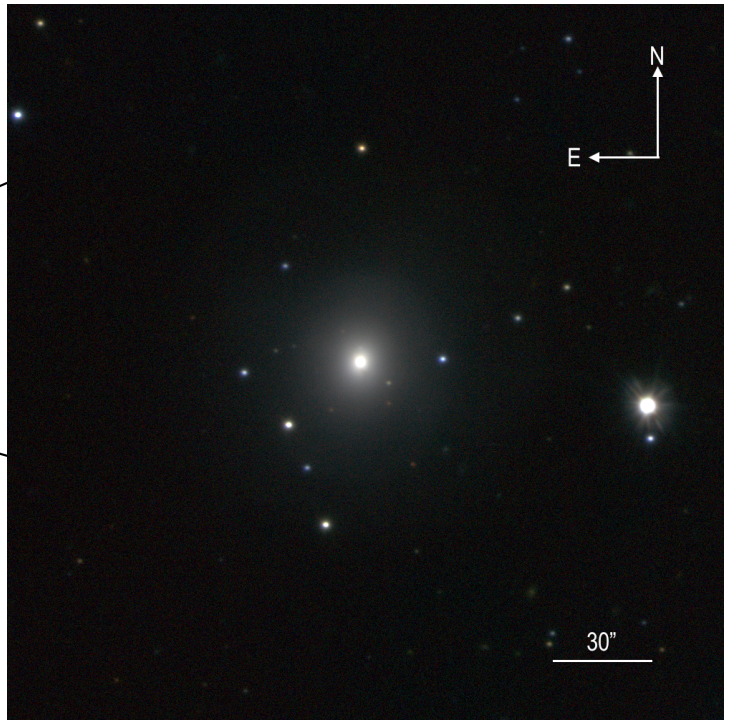
SN candidate from the VST search in GW170814

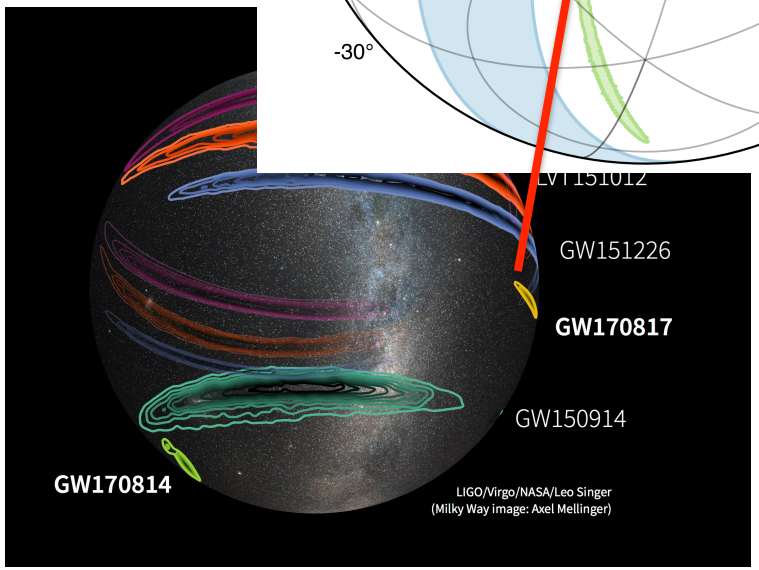


The watershed

2017-08-17 12:41:04 UTC







NGC4993@ VST

GW170817 @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: 23:18:42 UTC

covering 9 deg^2

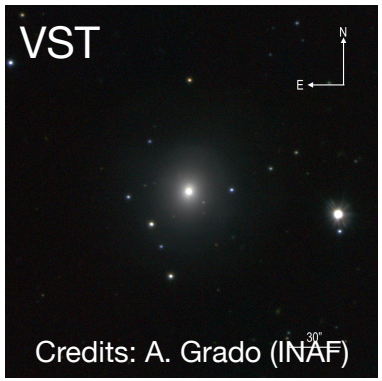
Swope OT observation: 23:33 UTC

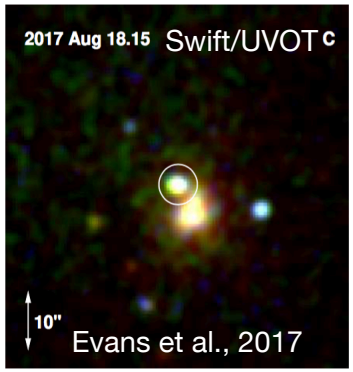
(targeted survey) GCN21529

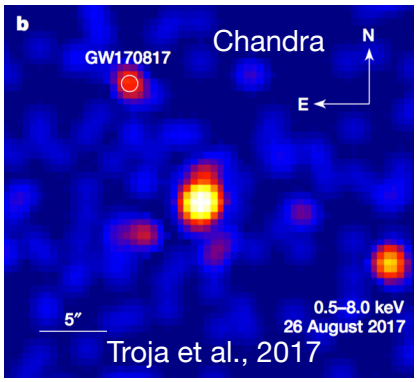
Updated skymap: 23:54:40 UTC

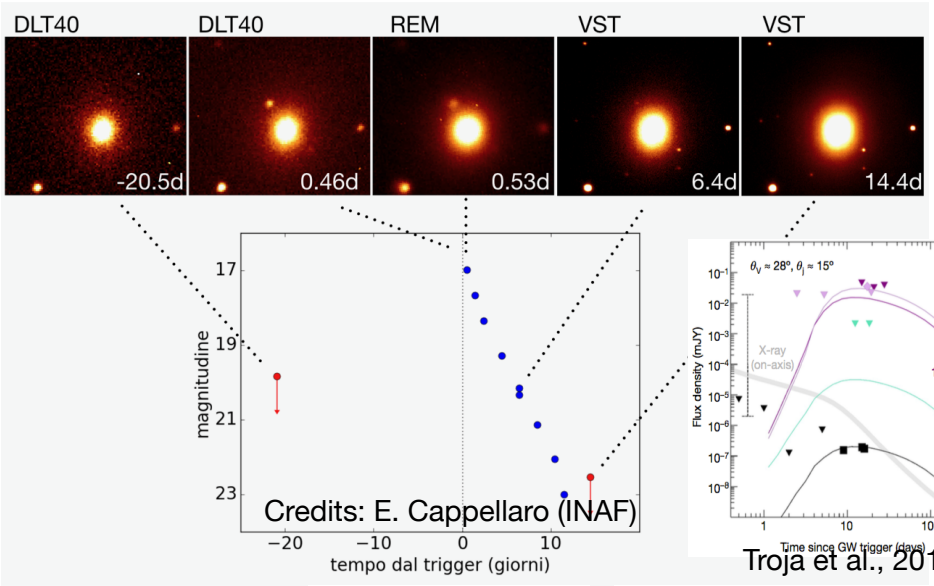
34 deg^2 (90% credibility)

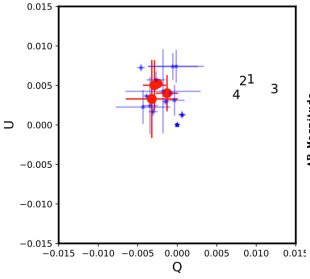
centered on $13h09^m$ $-25^o37'$

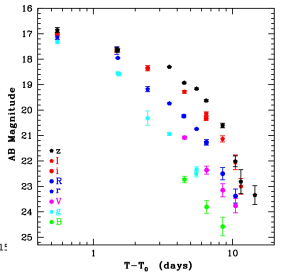


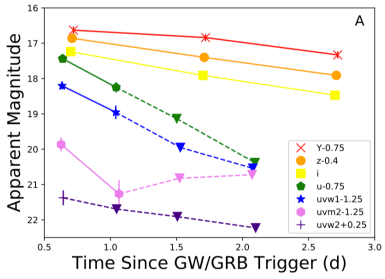


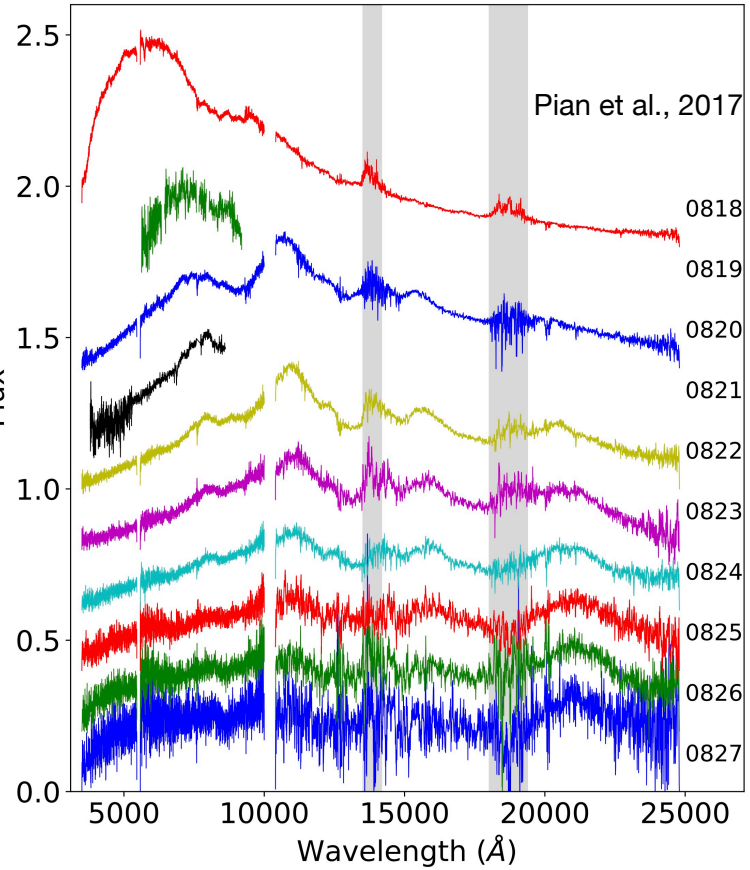






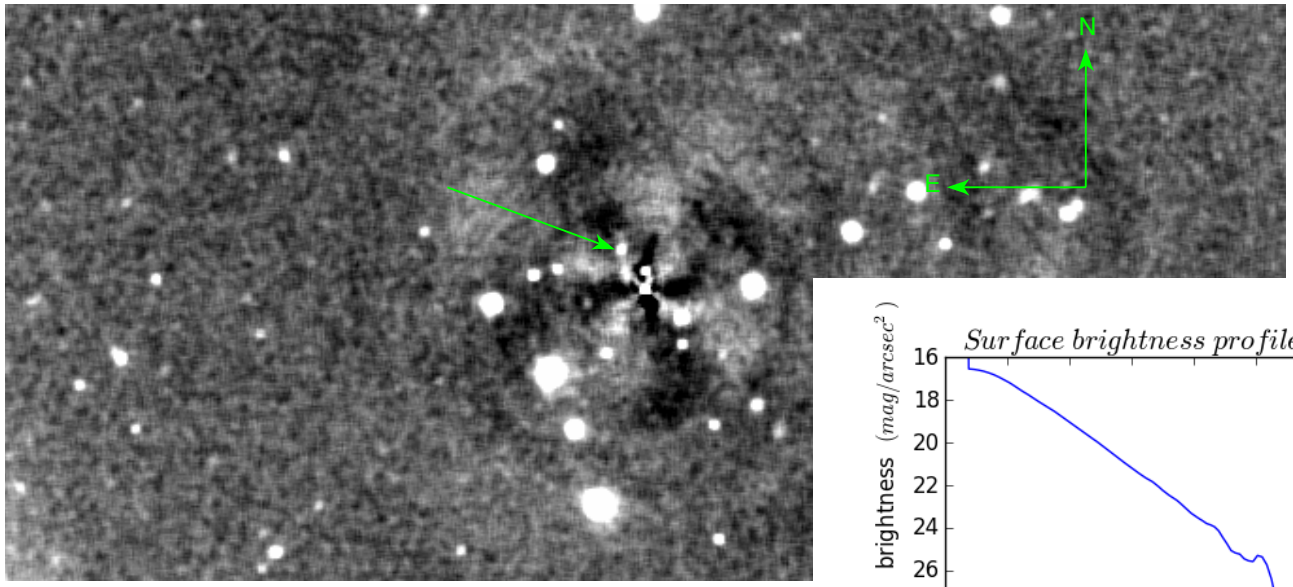




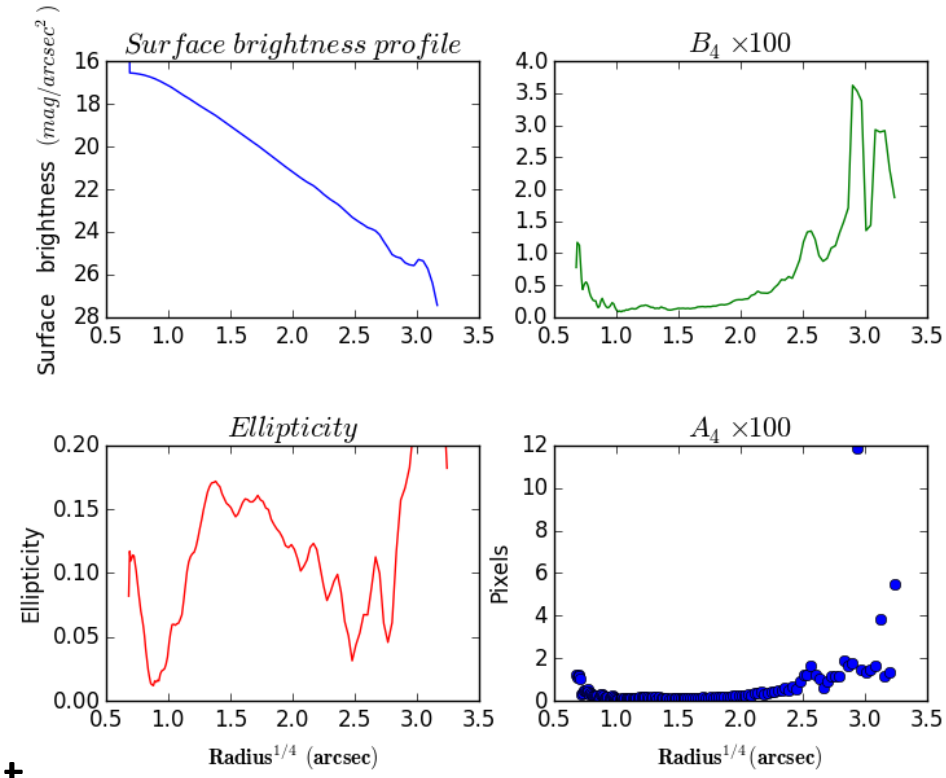


Credit. E. Cappellaro

Smoothed residuals of isophotal elliptical fit



NGC 4993
r filter



At +6.4 days 200 s in g,r,i,z filter
GCN 21703 A. Grado et al.
23.3, 22.4, 21.3, no visible in z

At +14.4 days 1200 s in i filter
GCN 21833 A. Grado et al.
No detection (22.53 50% complet.
for pointlike surces)

O3 and beyond

- O3 expected rate for BNS: 1- few dozens events in 12 months

  Alert issued in few minutes without human wetting

- We foresee to allocate up to P107
  - **50** hours/semester on VST-GTO
  - **~30** hours/semester on OmegaCam-GTO

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

NON TARGETTED SEARCH

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

Conclusion

- The multi-messenger Astronomy is started
- GW optical follow-up has an important role
- Among the optical observation facilities VST is an important player in particular with VIRGO in action
- We plan to follow ~ 2.5 to 8 events/semester

Open points/Future actions

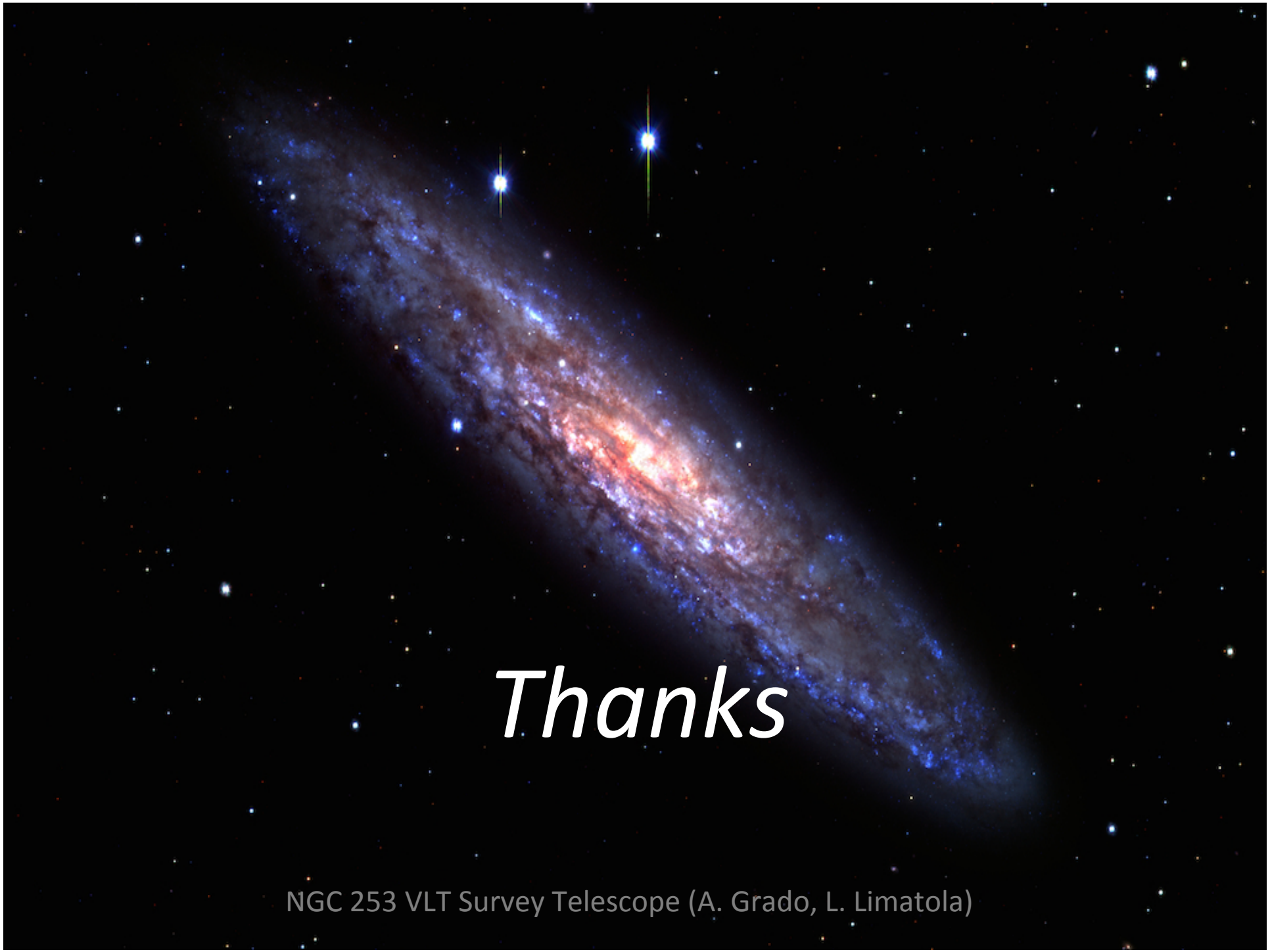
- How we can secure observations in the follow-up?
- Can we interrupt/modify OB “on the fly” to meet refined map?
- Can we reduce access time to ESO archive data?
- We plan to increase the VST data processing speed
  - In both HW and SW sides
- For faint transients (detectable with ~ deep surveys) still work needed to shorter the candidates list for further spectroscopic follow-up

A HUGE thanks to the

ESO User Support

and

Paranal staff



NGC 253 VLT Survey Telescope (A. Grado, L. Limatola)

Area covered for each epoch

GW150914

Epoch	Night	Area (deg^2)	Total (deg^2)
1	2015-09-16	54*	54
2	2015-09-17	90	90
3	2015-09-21	90	81
4	2015-09-24	90	90
5	2015-09-30	72	
	2015-10-02	18	90
6	2015-10-13	45	
	2015-11-15	9	
	2015-11-16	18	
	2015-11-17	18	90

Epoch	Night	Area (deg^2)	Total (deg^2)
1	2015-12-27	72	72
2	2015-12-29	72	72
3	2015-12-30	9	
	2016-01-01	45	
	2016-01-02	9	63
4	2016-01-05	18	
	2016-01-06	18	
	2016-01-07	27	63
5	2016-01-13	45	
	2016-01-14	27	72
6	2016-01-28	9	
	2016-01-30	9	
	2016-01-31	18	
	2016-02-01	9	
	2016-02-02	9	
	2016-02-10	9	63

GW151226