GRAWITA: The Electromagnetic Follow-up of GW170817 and beyond

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Our Group

GRAvitational Waves Inaf TeAm

www.grawita.inaf.it

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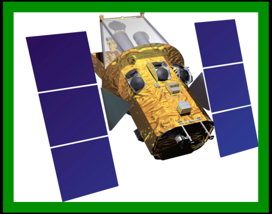
The route for the EM counterpart

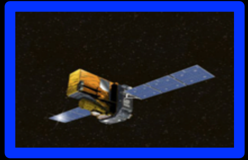
STEP 1

Search & Detect

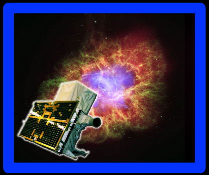
Transients in the ***skymap*** provided by LVC have to be discovered and measured *as soon as possible*

I





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



➡ immediate follow-up of the source

II

Large error boxes (< ~40 deg^2)
a specific observational strategy

Galaxy targeting

Aasi et al. 2014, ApJS, 211

III

Very large error boxes (> ~40 deg^2)
Wide field Opt-Nir search

+

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*

STEP 2
Observe & Characterize

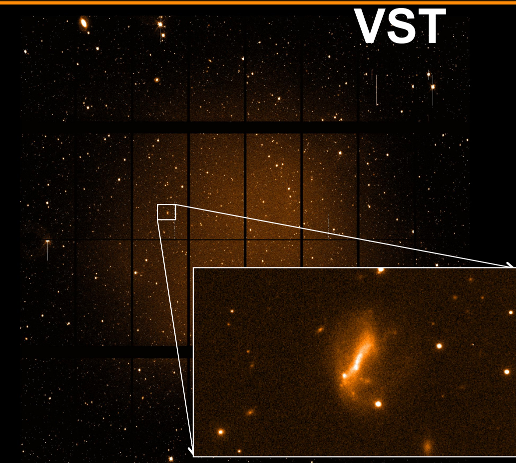
The detected transients have to be observed to infer their nature

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**

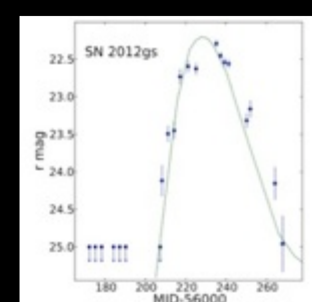
Telescopes with large FoV distributed at different latitudes/longitudes

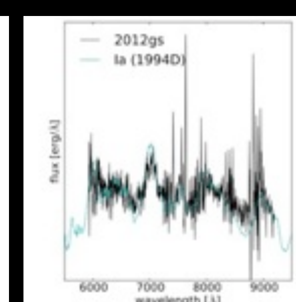
Computing Facilities with fast and smart software to select a handful of transients



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

Telescopes with large collecting area to obtain light curves and spectral features of the EM counterparts of GW





time

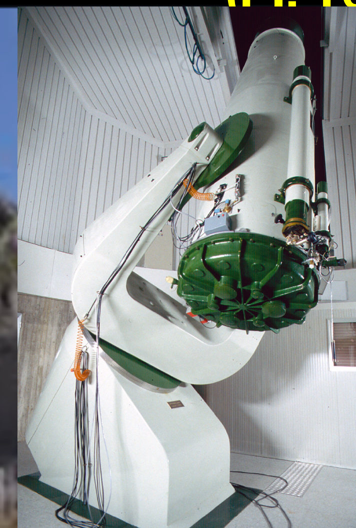
λ

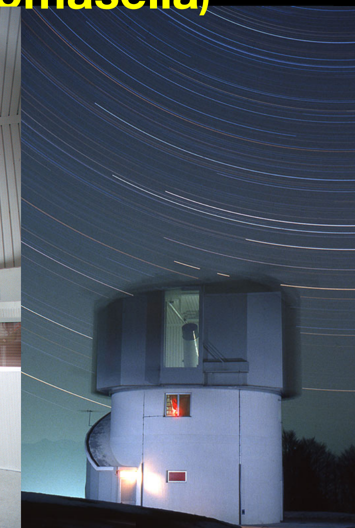
Search for counterparts: wide field

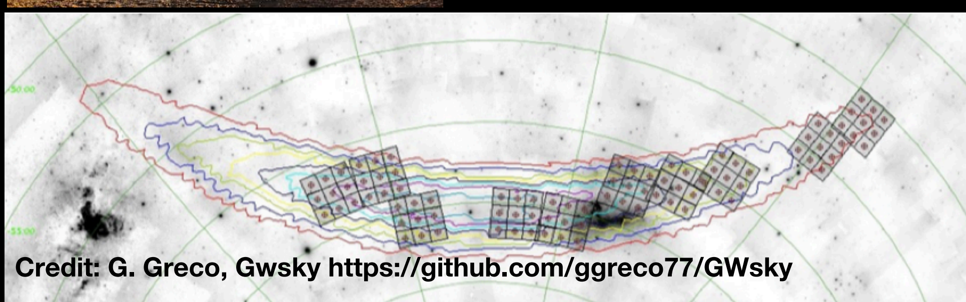
ESO–VST
2.6m FoV = 1 deg^2
(PI Cappellaro/Grado)

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

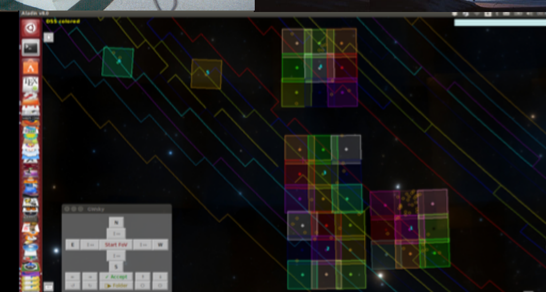
Asiago Schmidt Telescope
0.67/0.92m FoV=1 deg^2
(PI: Tomasella)







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

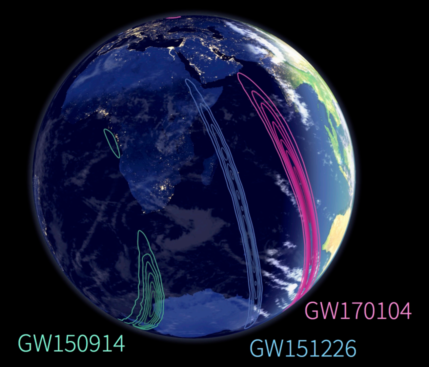


FAST: hours after LVC alert
WIDE: 50 - 90 deg^2 large contained probability
DEEP: r_lim ~ 21 (CI & Asiago) - 22.5 (VST) mag

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

Brocato et al. 2017

Transient objects in the LVC skymap

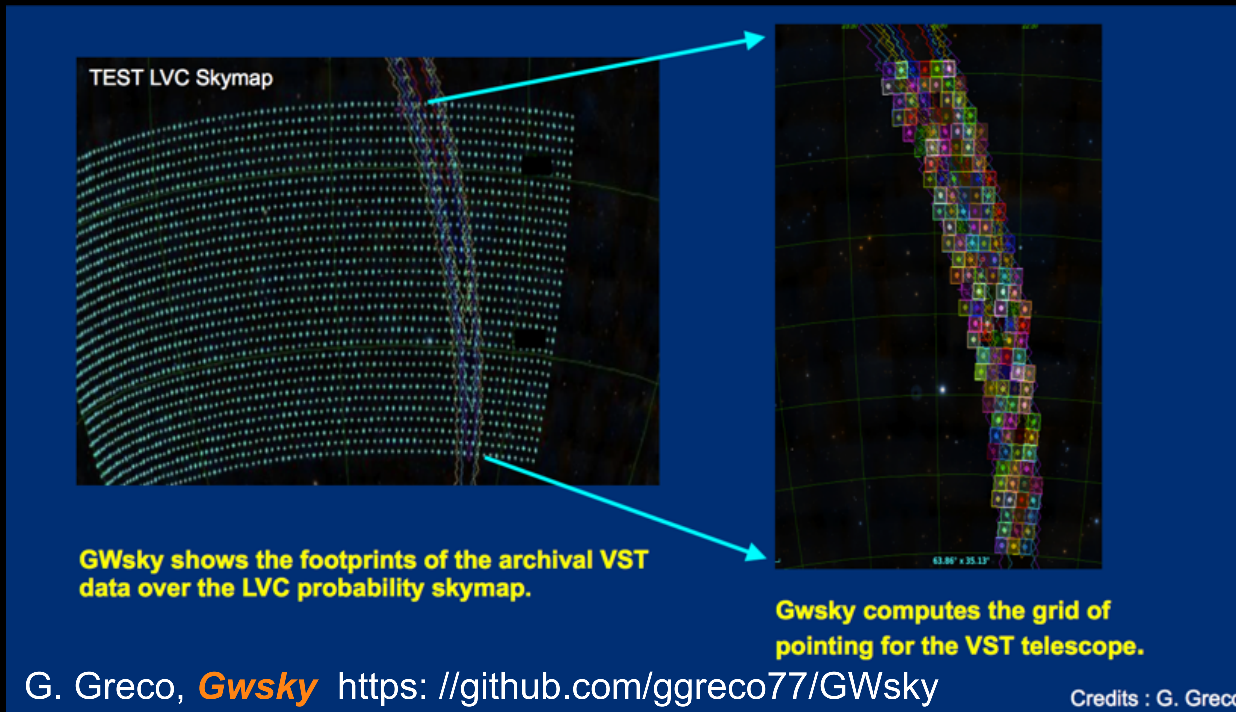


Credit: LIGO/Virgo/NASA/Leo Singer

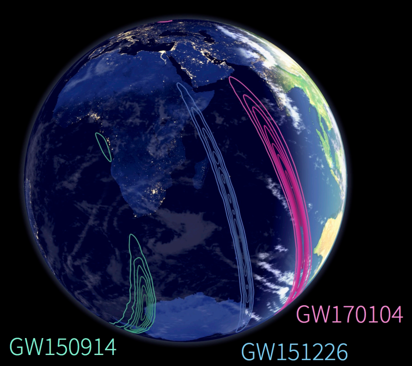
To cover a very large region of the LVC skymap one observing strategy is to build up a mosaic of single pointing (tile):

GW150914 ~ 600 deg^2
LVT151012 ~ 1600 deg^2
GW151226 ~ 1000 deg^2
GW170104 ~ 1200 deg^2
GW170608 ~ 520 deg^2
GW170814 ~ 62 deg^2

(90% credible areas)



***GRA**vitational **W**ave **I**naf **T**e**A**m*



Credit: LIGO/Virgo/NASA/Leo Singer

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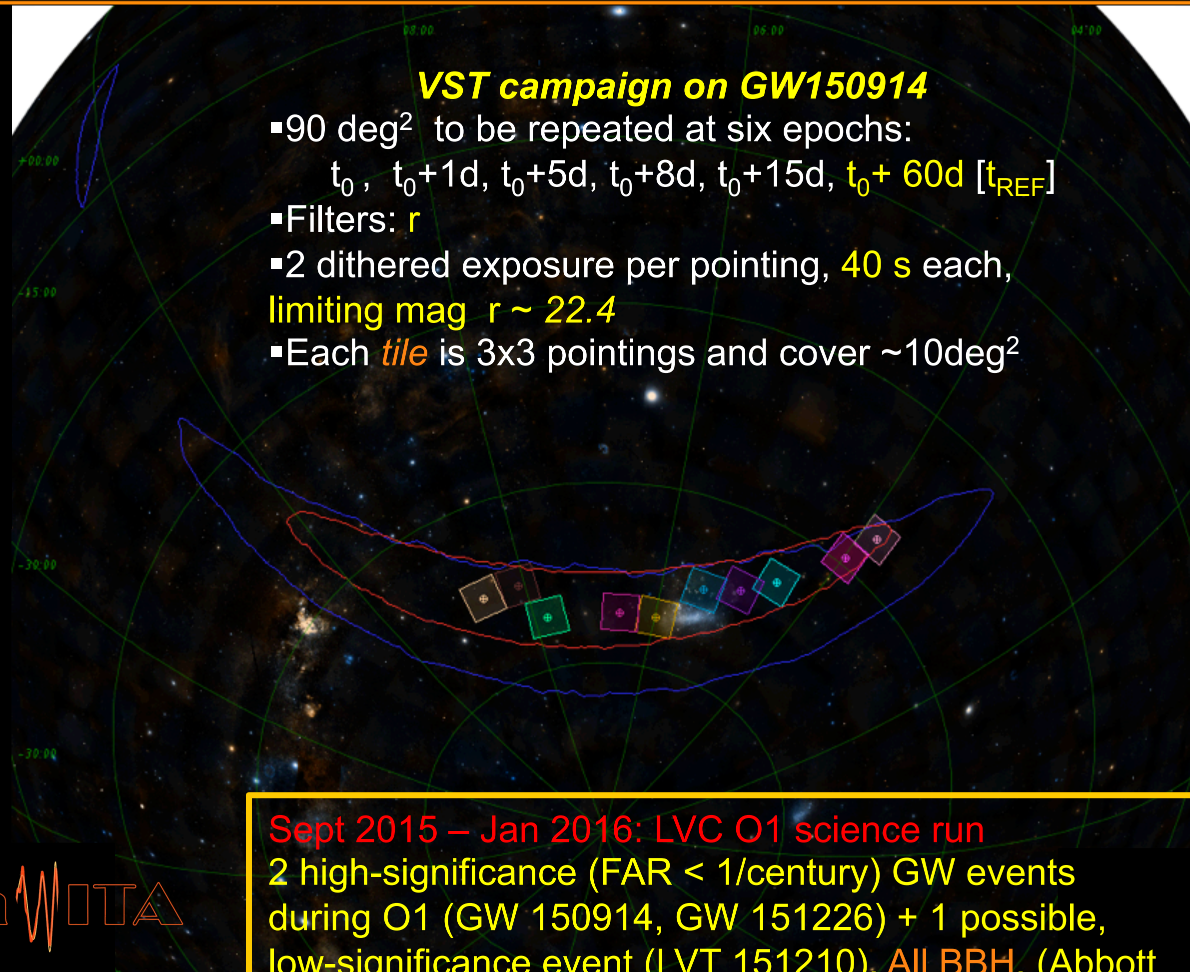


VST campaign on GW150914

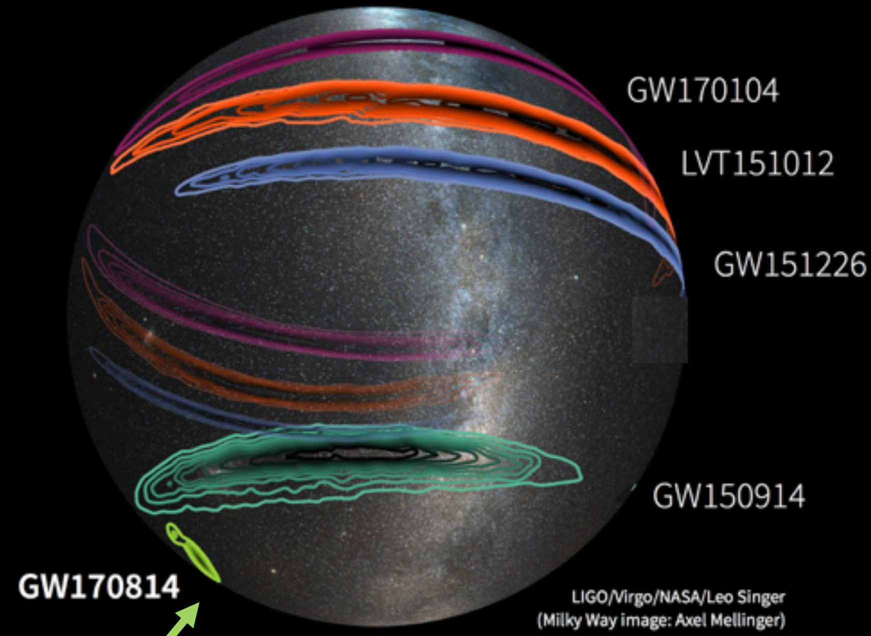
- 90 deg^2 to be repeated at six epochs:
  t_0, t_0+1d, t_0+5d, t_0+8d, t_0+15d, t_0+ 60d [t_{REF}]
- Filters: r
- 2 dithered exposure per pointing, 40 s each, *limiting mag r ~ 22.4*
- Each *tile* is 3x3 pointings and cover ~10deg^2

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.

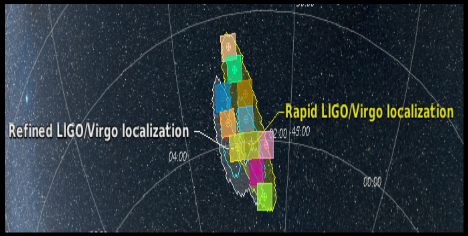
Example of GRAWITA response

Virgo made a key improvement on sky maps

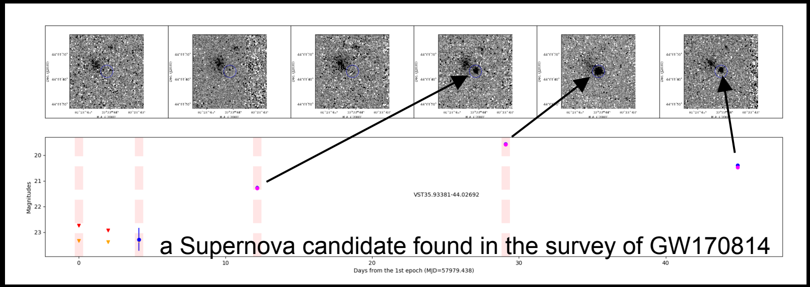


GW170814 ~ 62 deg^2

(90% credible areas)

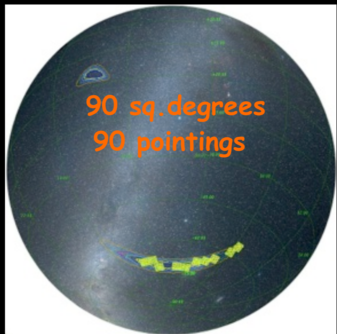


VST observed
~ 80% of the sky map

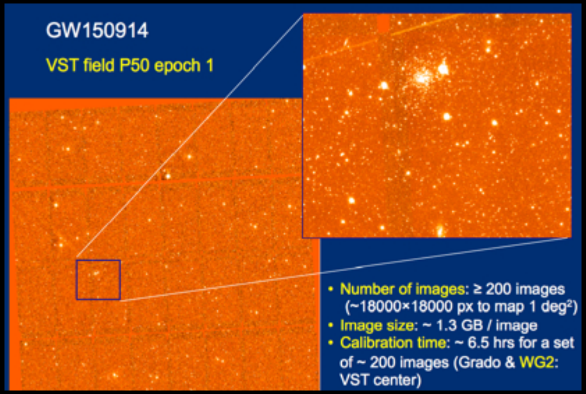


EXAMPLE OF GRAWITA RESPONSE

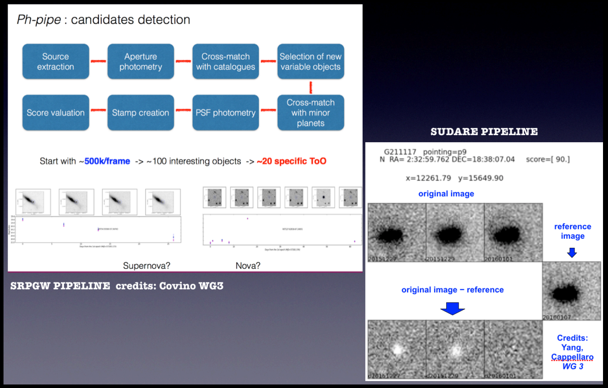
1. Tiling



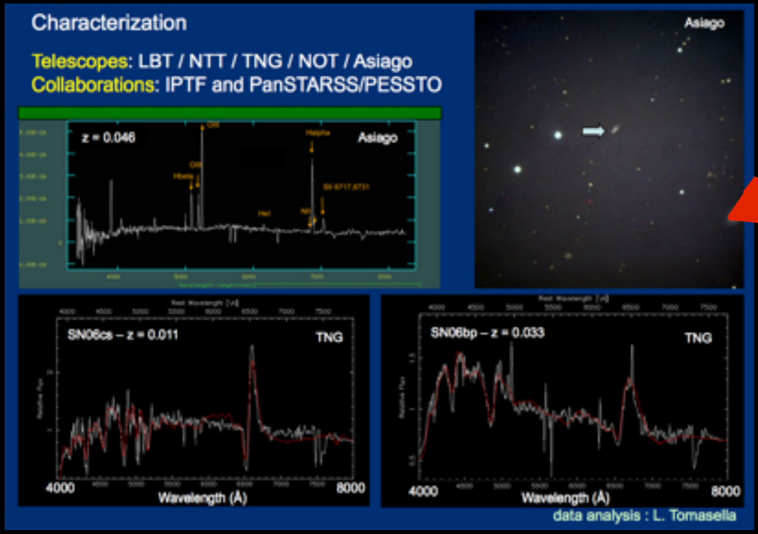
2. Observations



3. Search



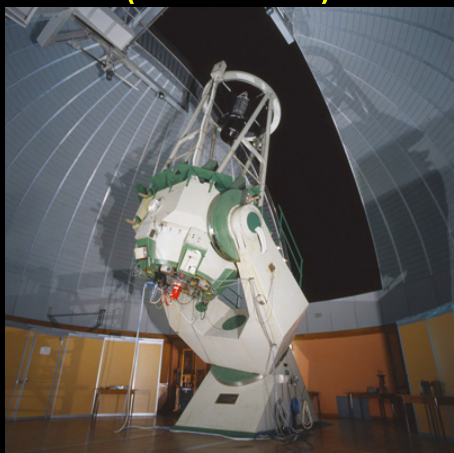
4. Characterization and follow-up



Brocato et al. 2017

Candidate classification / follow-up

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

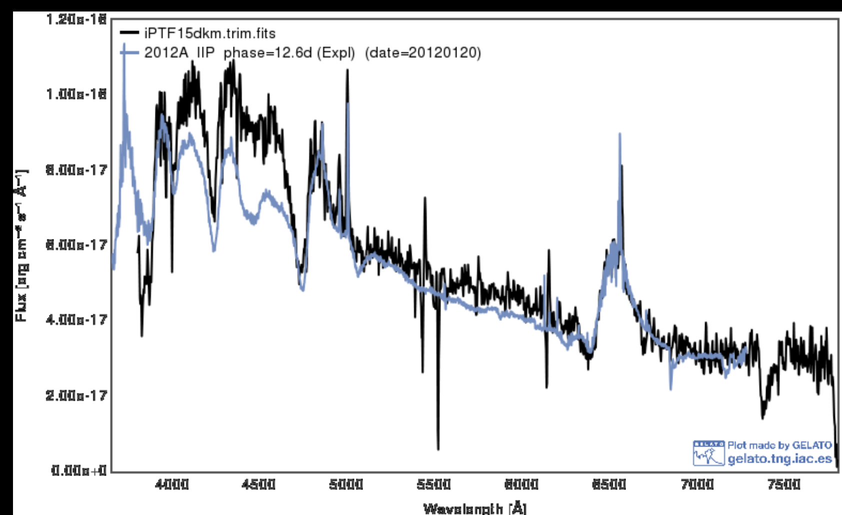


TNG 3.6 m
optical/NIR imaging & spectroscopy
(PI: Piranomonte)

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

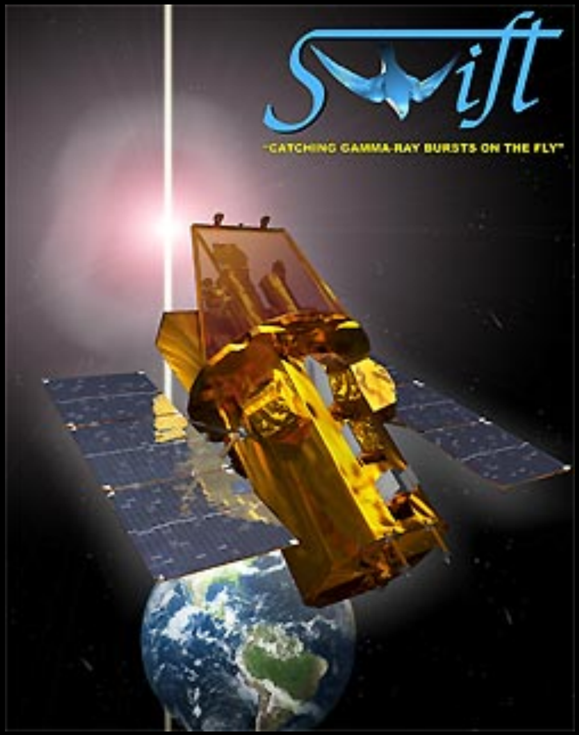
ESO-NTT 3.6 m
optical/NIR imaging & spectroscopy
(PI: Botticella within ePESSTO)

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

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)

Both successfully operated in O1 & O2

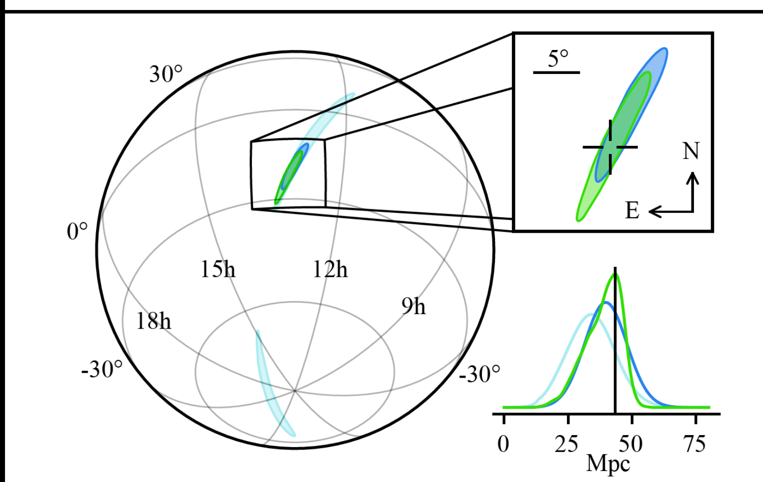
Evans et al. 2016, 2017
Aresu et al. GCN 21914

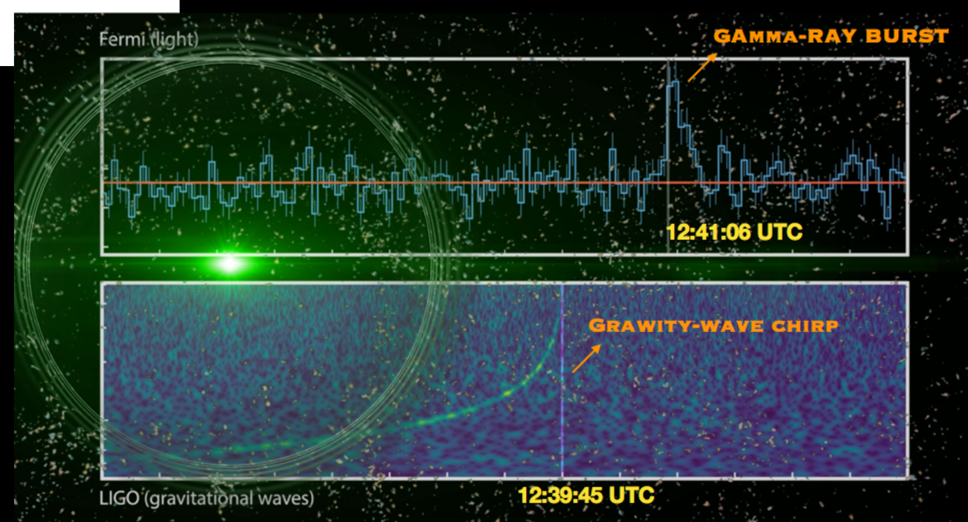
2017/08/17 UT: 12:41:04.445710

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: 3.478e-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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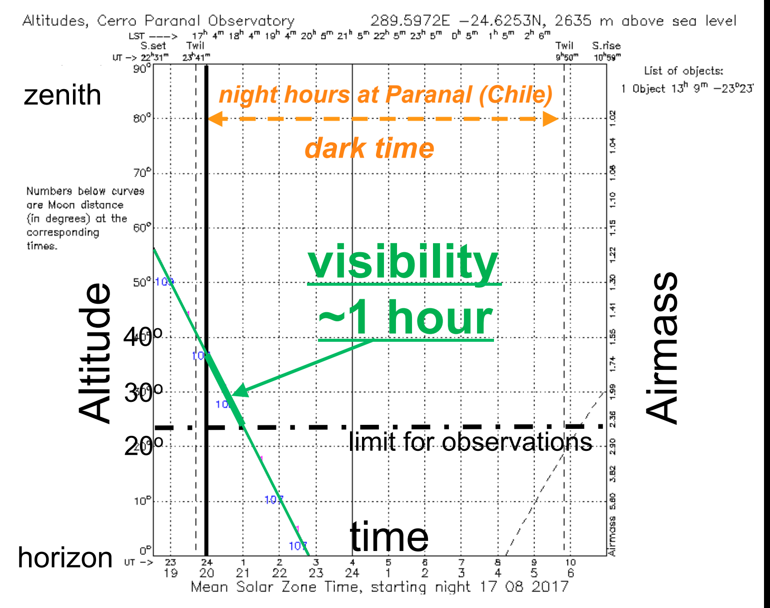
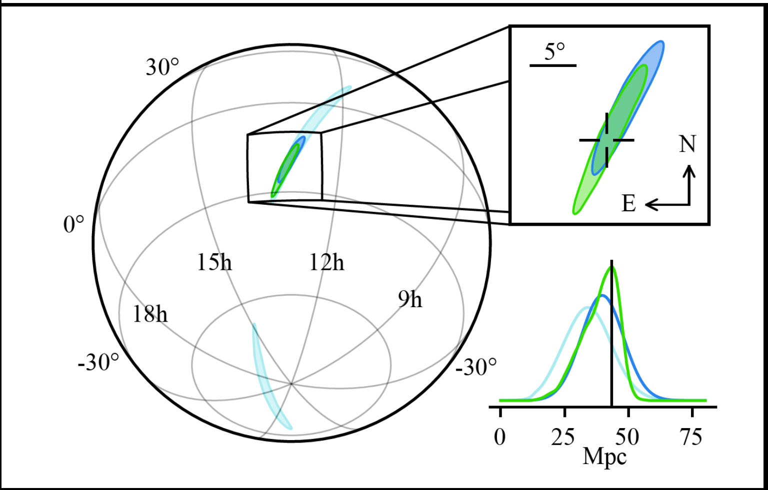
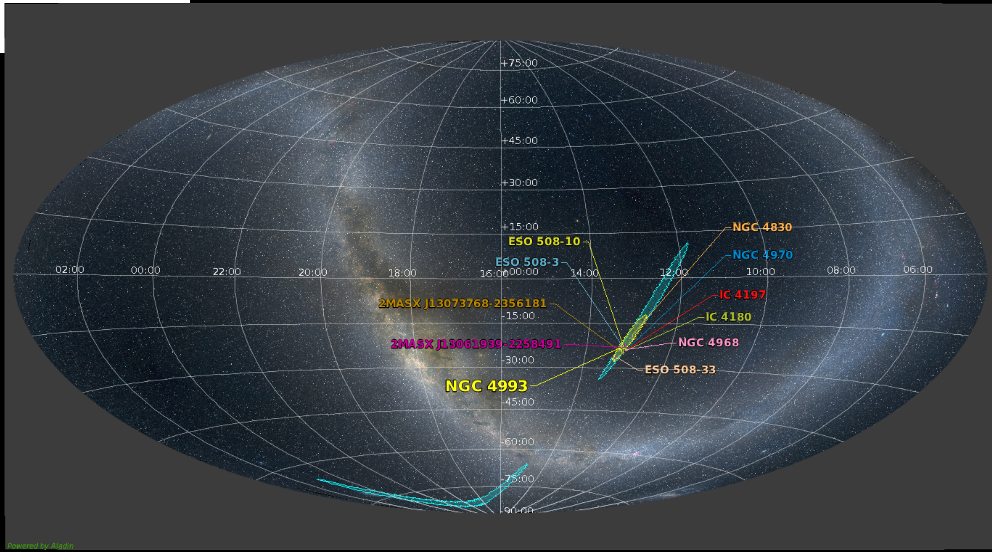
COMMENTS: LIGO-Hanford Observatory contributed to this candidate event.

Position of the GW skymap on sky





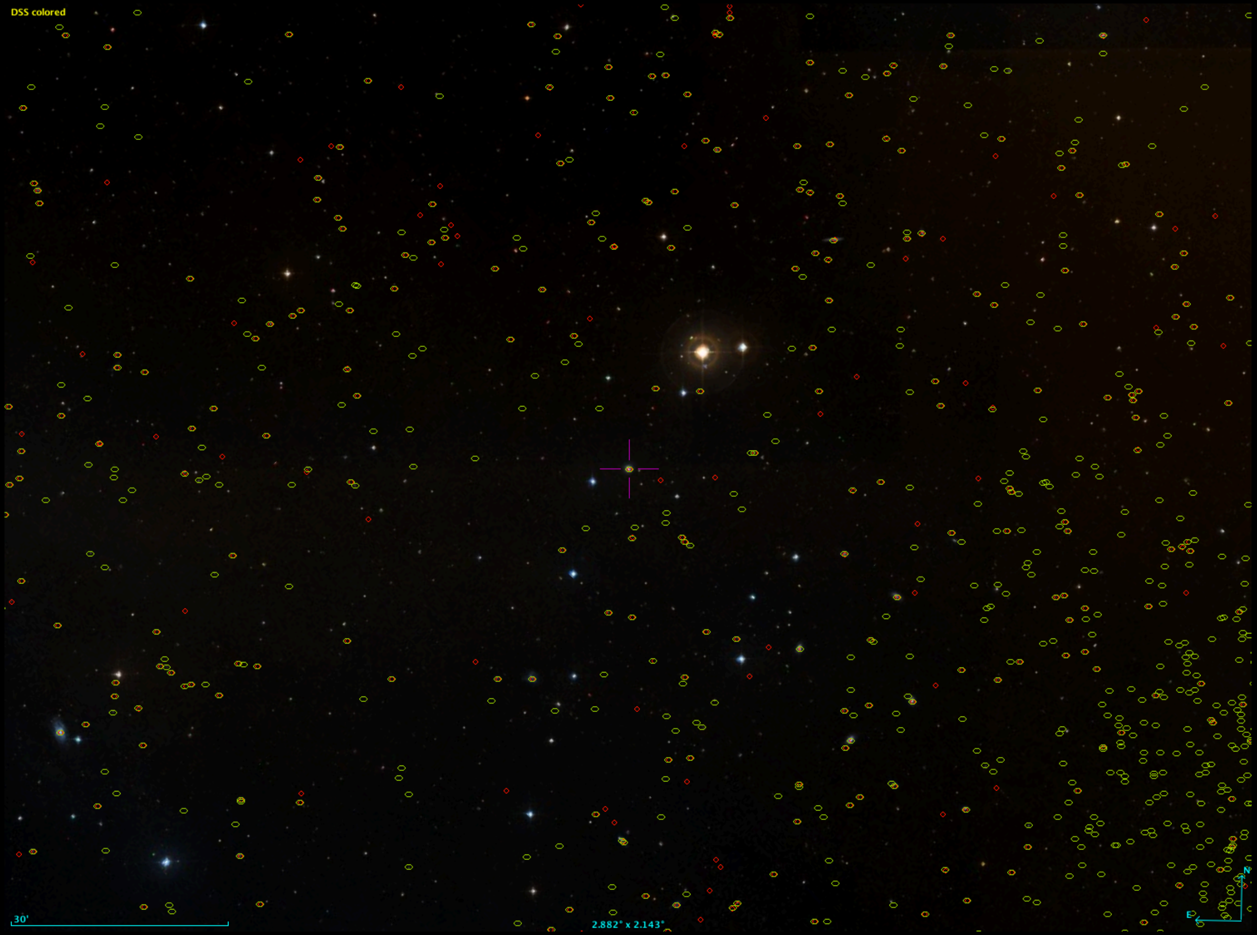


Observational strategies

The sky around GW170817 (~3 deg x ~2 deg)

The ***distance*** is a *critical quantity* for searching the EM counterparts

The sky around GW170817 (~3 deg x ~2 deg)



The ***distance*** is a *critical quantity* for searching the EM counterparts

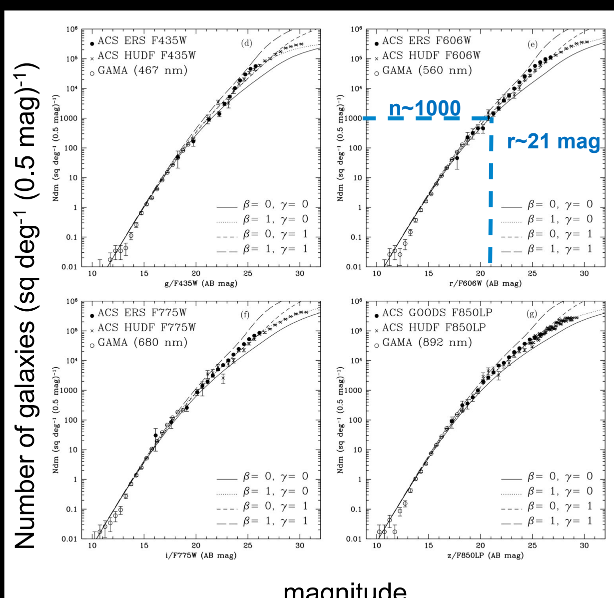
Observational strategies

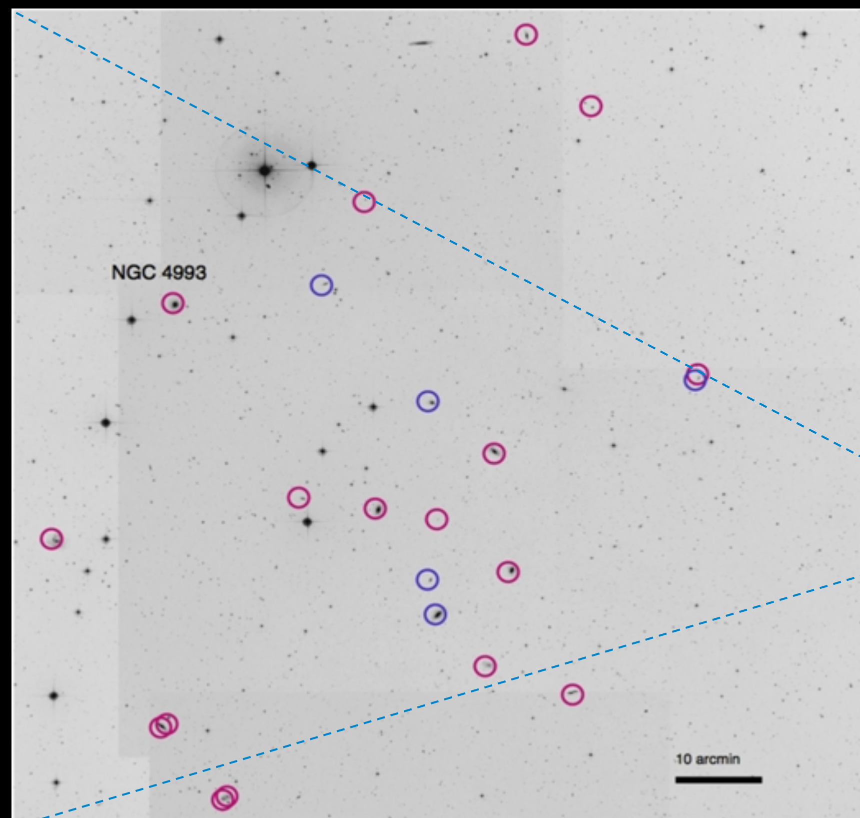
When the distance (including uncertainties) is available, (no mosaics) the best observing strategy is

Galaxy targeting strategy :

•Select a sample of galaxies using catalogs of galaxies with known distances. Constrains: position (LVC skymap) + distance (in the range given by LVC)
•Start observations (telescopes with small FoV are OK!) giving priority to high mass (luminosity) galaxies

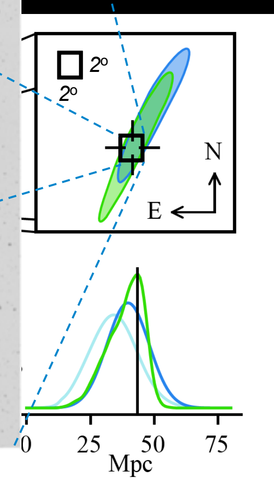
The number of galaxies increases rapidly in a given region of the sky





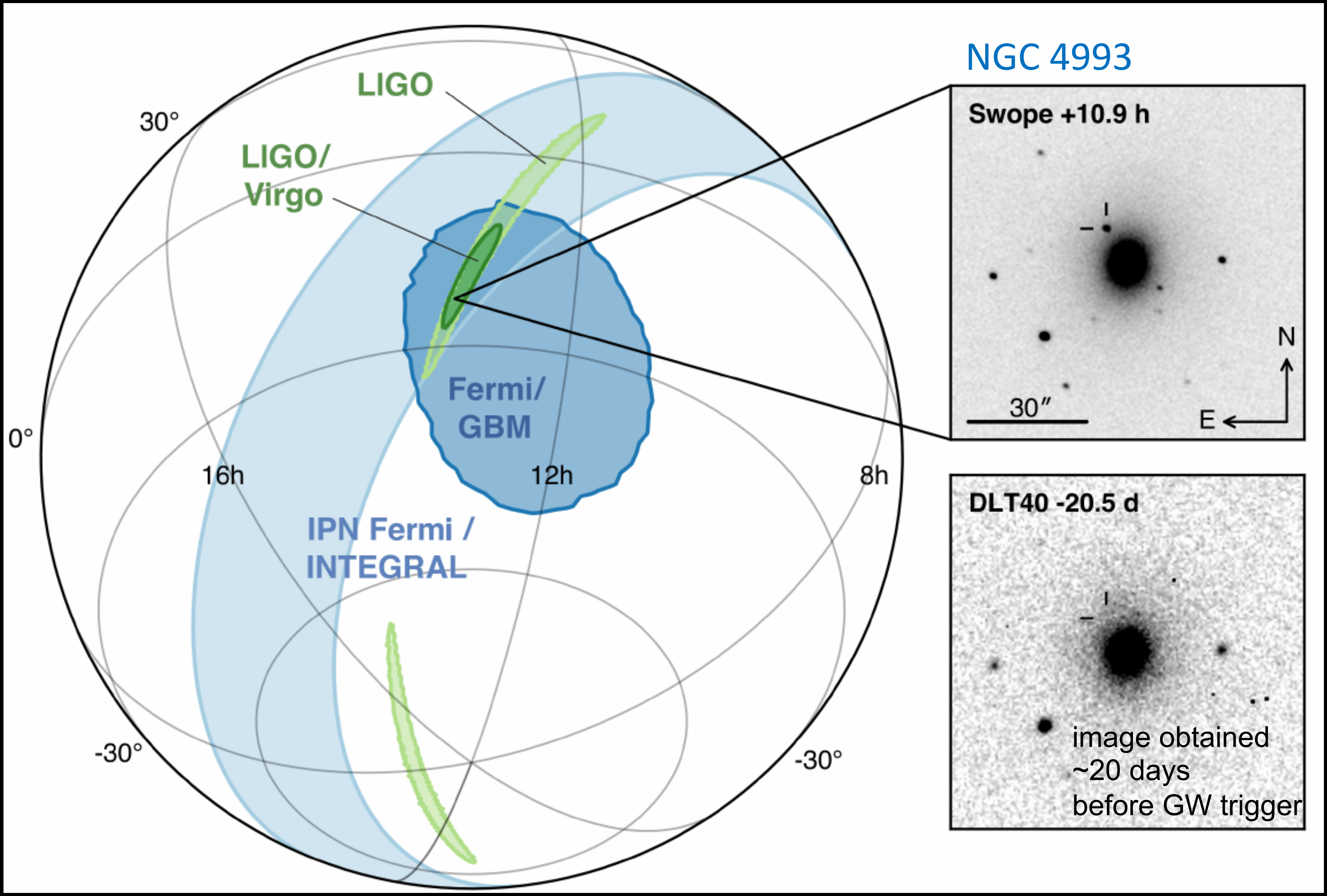
Hjorth et al. 2017

Inside the entire LVC skymap of GW170817 can be found **~50 galaxies** in the range **25 < d(Mpc) < 50**

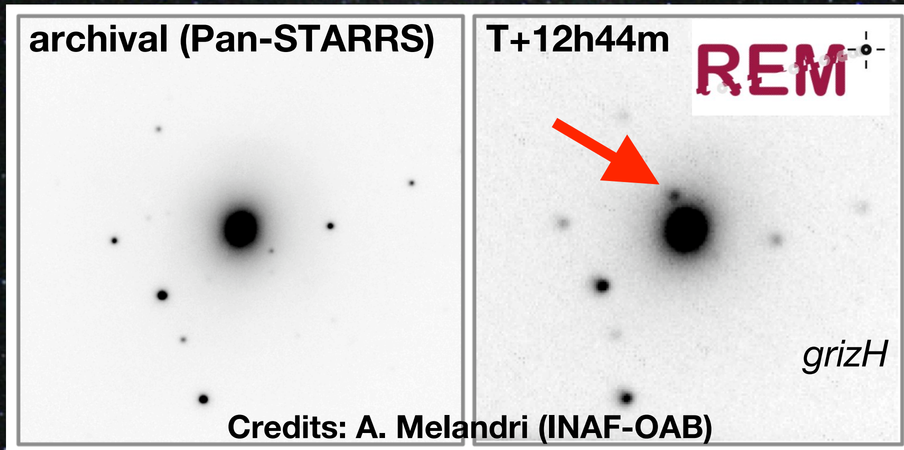


Discovery of an Optical/nIR Transient

OPTICAL counterpart detection ~ 11 hours after GW trigger

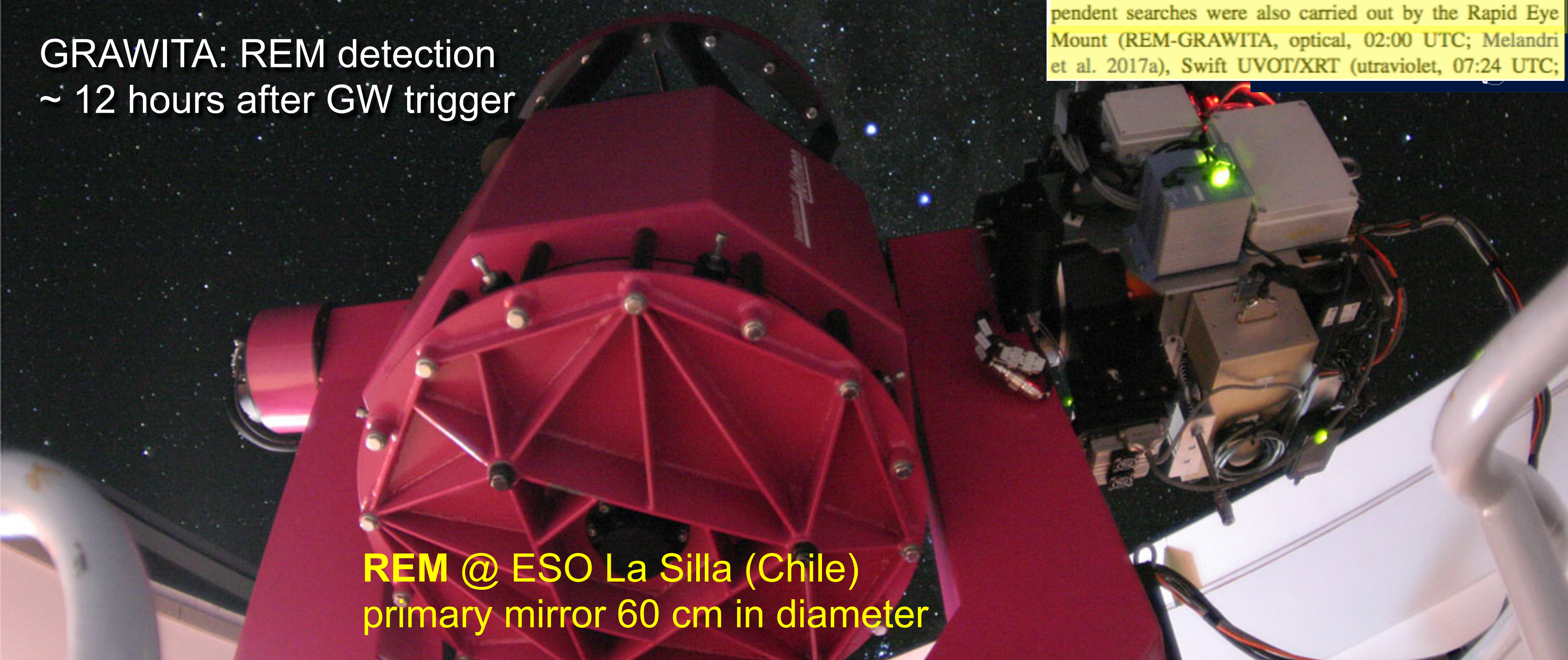


GW 170817: optical counterpart in NGC 4993



LVC + "partner astronomy groups" (2017)

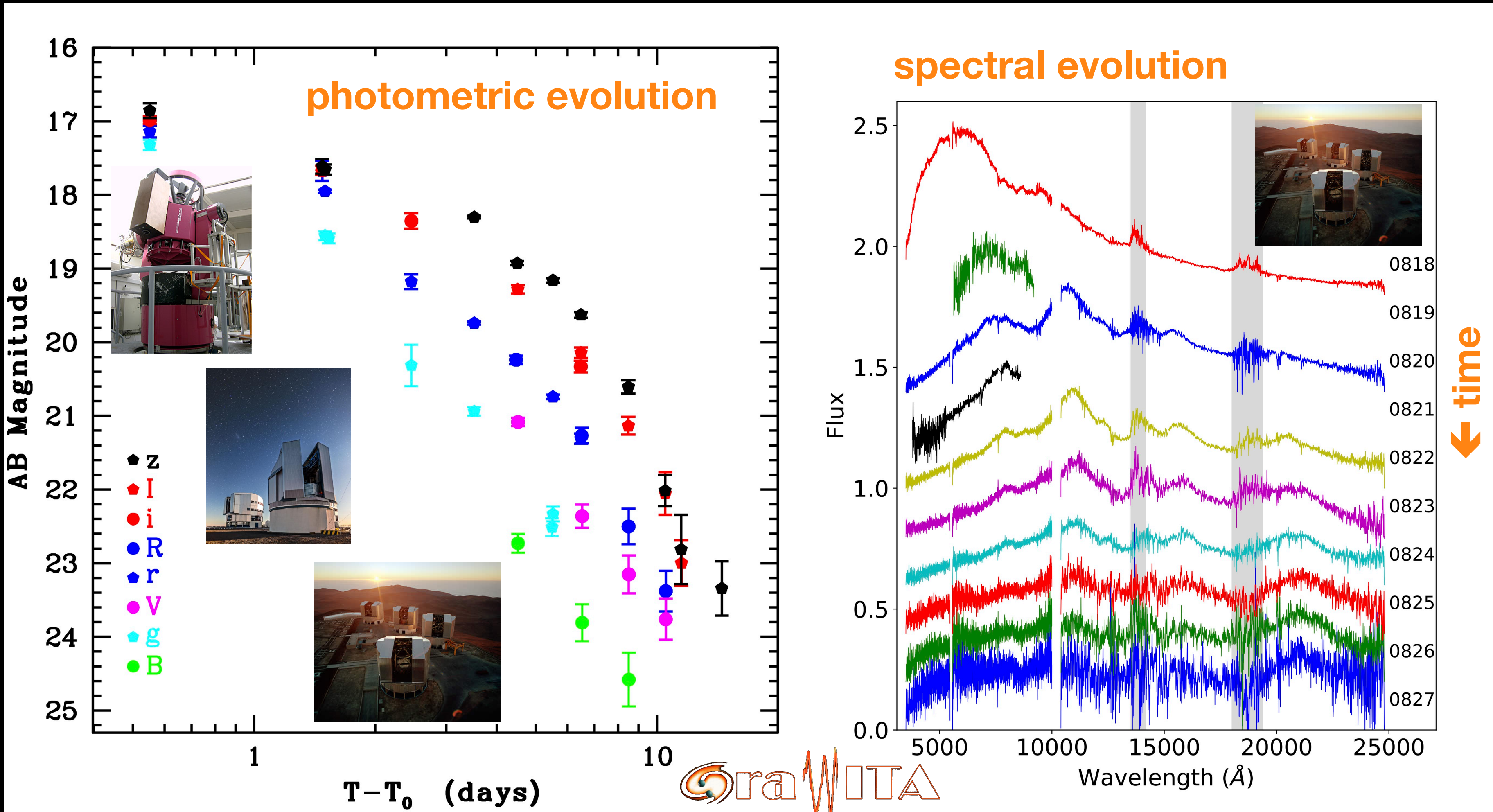
Five other teams took images of the transient within an hour of the 1M2H image (and before the SSS17a announcement) using different observational strategies to search the LIGO-Virgo sky localization region. They reported their discovery of the same optical transient in a sequence of GCNs: the Dark Energy 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;



GRAWITA: REM detection
~ 12 hours after GW trigger

REM @ ESO La Silla (Chile)
primary mirror 60 cm in diameter

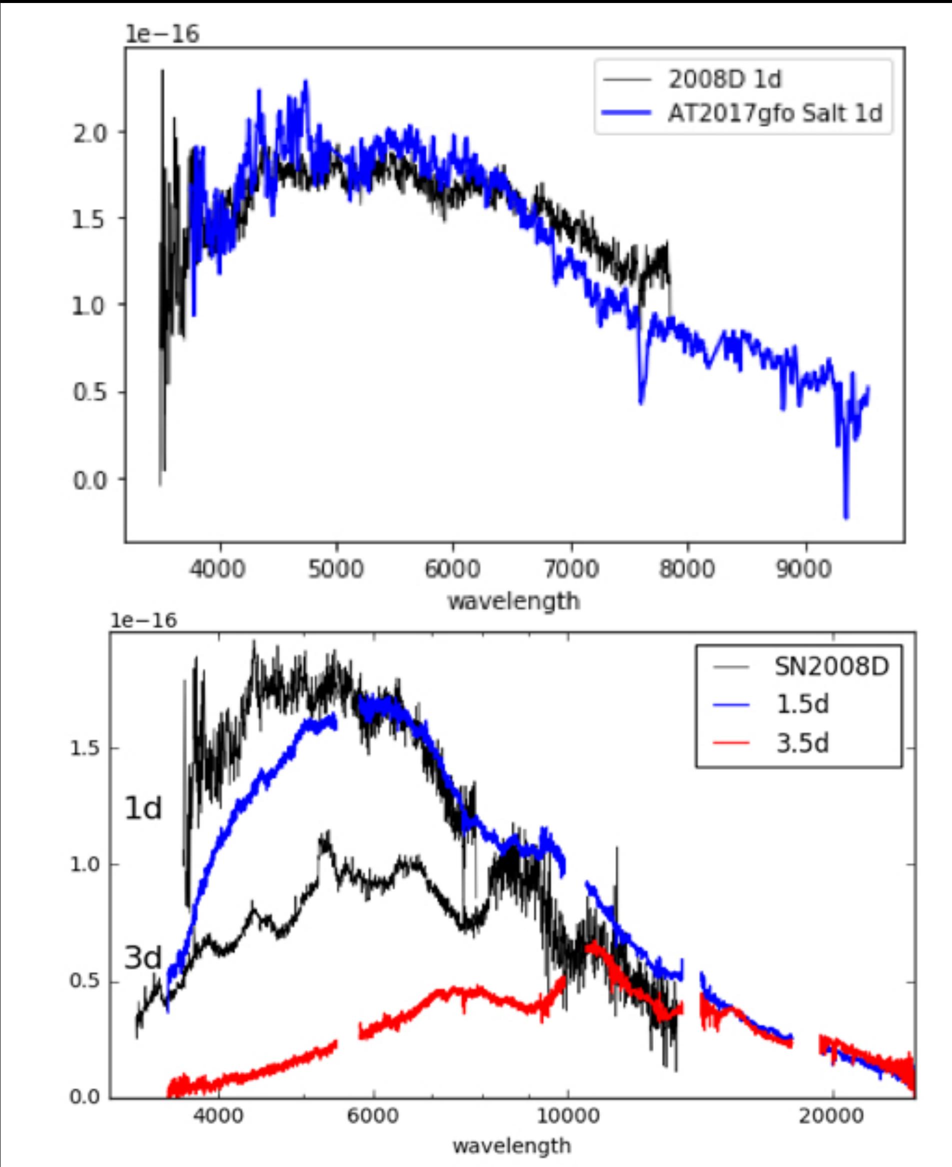
GW 170817: imaging and spectroscopic follow-up



Pian, D’Avanzo et al. 2017, Nature

The Optical/nIR Transient

Why temporal and spectral sampling (+ good S/N) are important

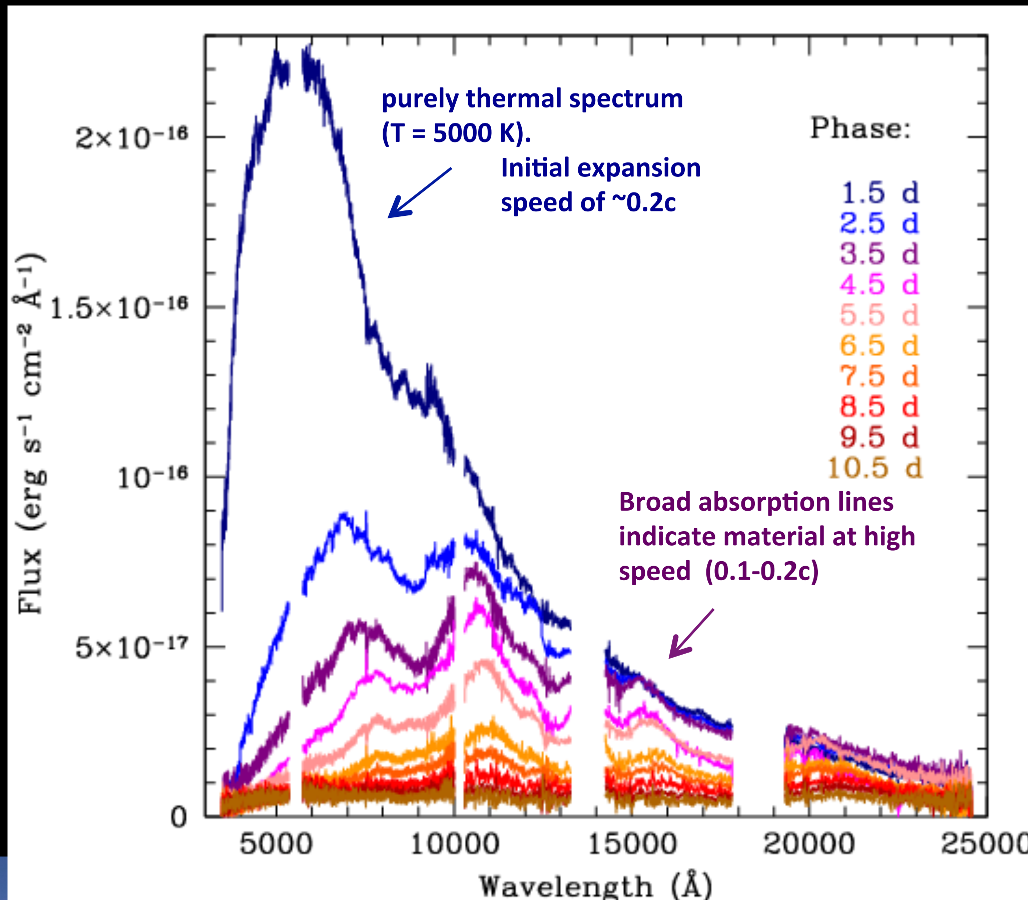


The low S/N spectrum ***at 1 day*** matches very well that of the supernova ***SN2008D / XRF080109 (type Ibc)*** at a similar phase.

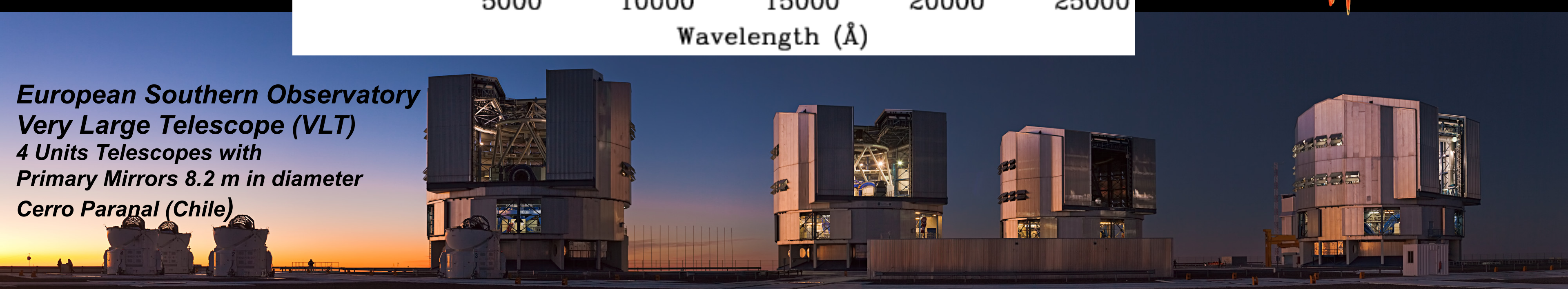
In a couple of day the peak of the Spectral Energy Distribution shifts to the near-infrared. Broad spectral features appear that are completely different from that of all known SN types.

The Optical/nIR Transient

ESO VLT X-Shooter spectral sequence of AT2017gfo

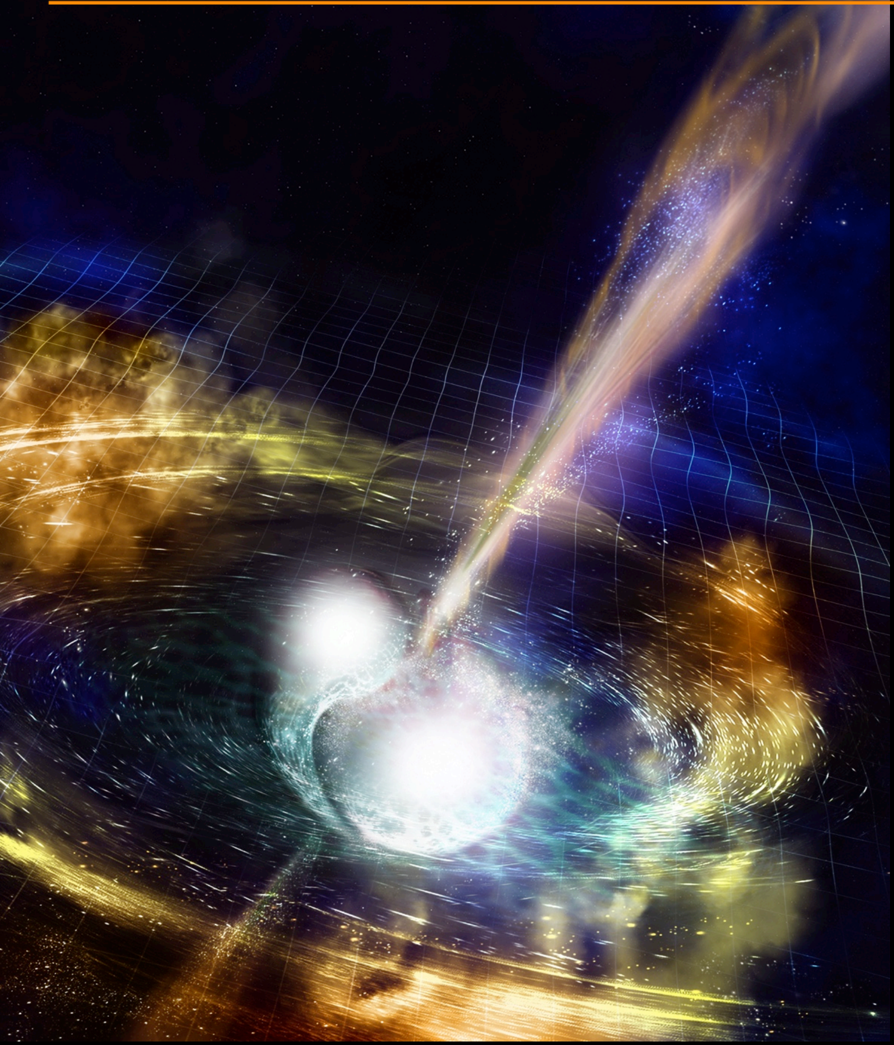


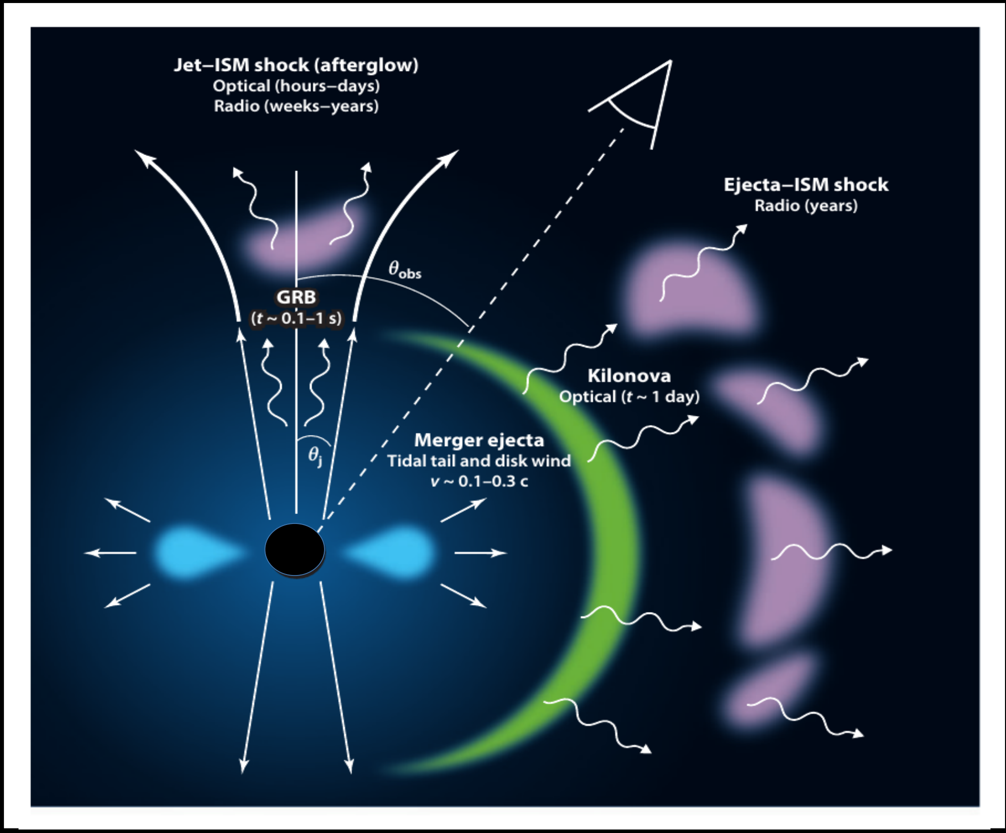
Pian et al. 2017;
Smartt et al. 2017



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

BNS Merger: What we expected



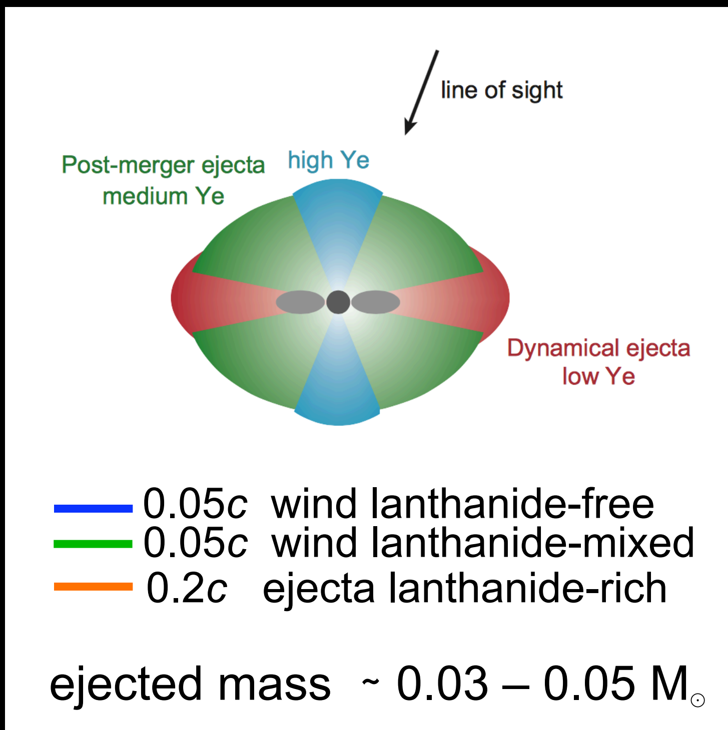


Metzger & Berger et al 2011

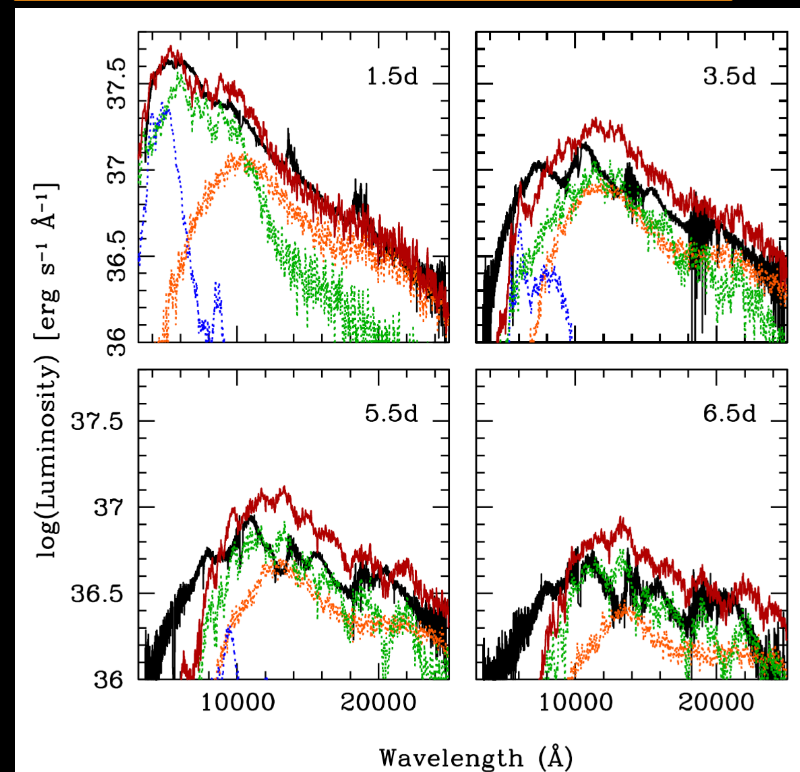
BNS Merger: Kilonova models

Pure r-process composition cannot explain the blue component in the spectra which is attributed to a lanthanide-free wind region *(Pian et al. 2017, Nature,551, 57)*.

Models: Tanaka et al 2017
Observations: Pian et al. 2017



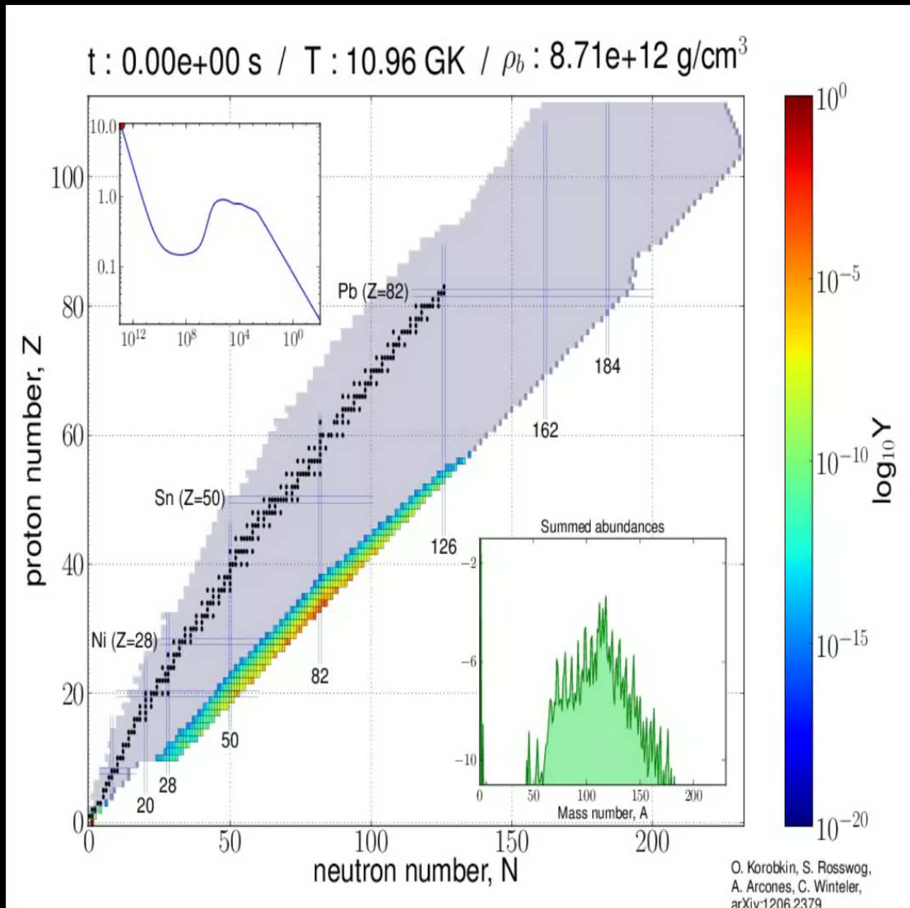
Best fit requires three components



At present models reproduce the general trend.
Nevertheless, models are not able to reproduce consistently **all** the observed spectral features

BNS Merger: Kilonova

BNS and NS-BH mergers as factories of heavy elements

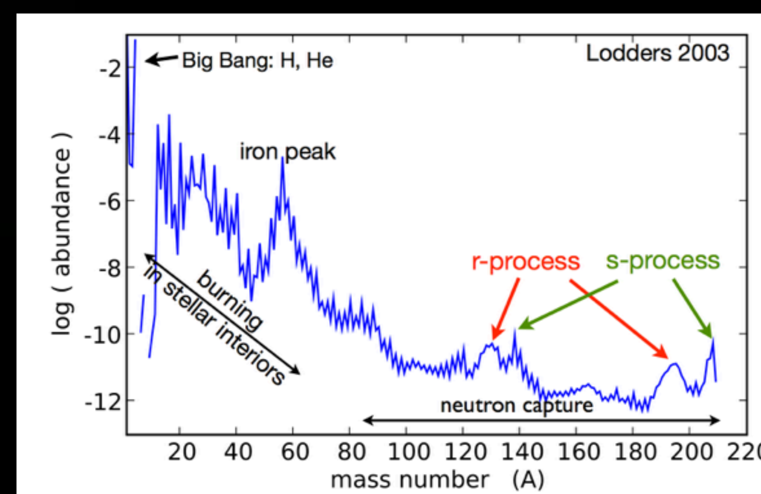


video by Rosswog: *r*-process nucleosynthesis in a kilonova environment

r-process elements:

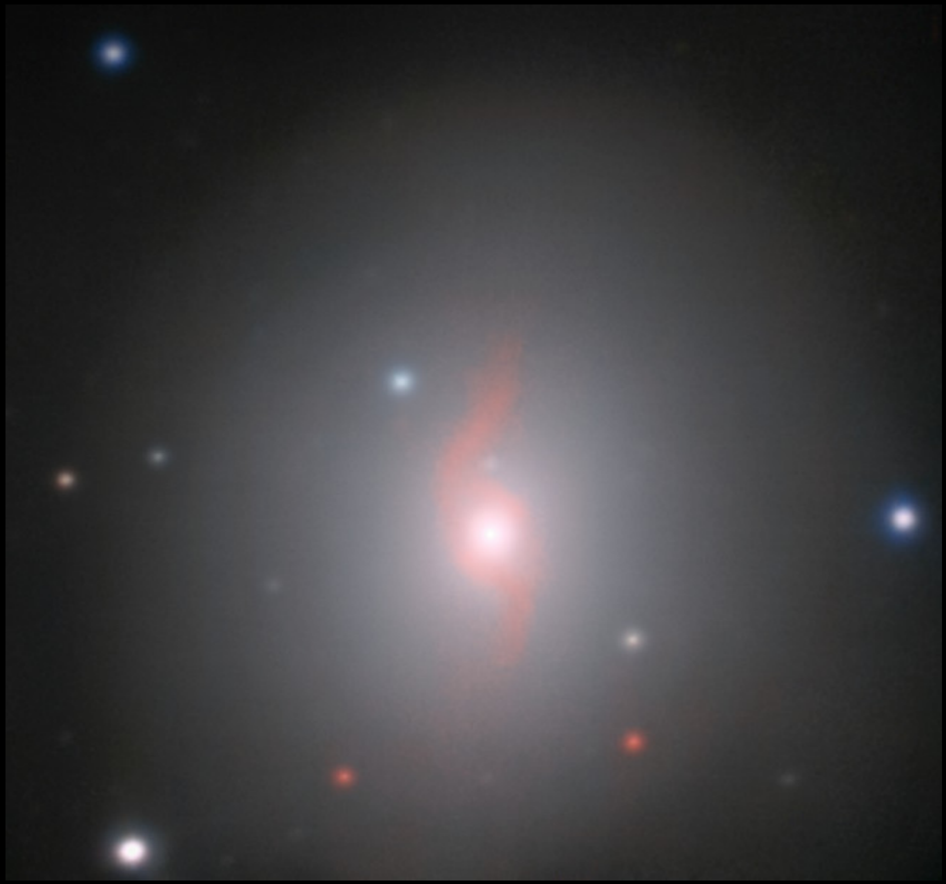
- Iridium (Z=77,A=192)
- Platinum (Z=78,A=19)
- Gold (Z=79, A=197)

Solar system abundances



The host galaxy NGC 4993

MUSE instrument operating on ESO VLT



Credit: ESO/J.D. Lyman, A.J. Levan, N.R. Tanvir

The host galaxy:

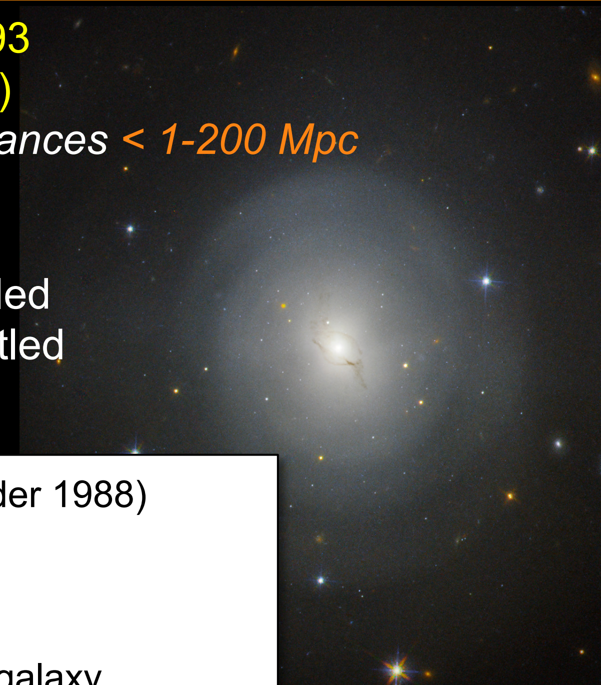
- ✓ lenticular galaxy (S0 galaxy type)
- ✓ redshift z_{helio} = 0.00978 +/- 0.00002
- ✓ Evidence of emission from gas (red in the image) revealing a surprising spiral structure
- ✓ relatively recent (~1 Gyr) episode of merger with another galaxy
- ✓ no globular cluster or young stellar cluster (with Mass > few 10^3 Mo) at the position of GW170817

BNS Merger: lastminute news 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 2^{nd} to the 1^{st} moment of the stellar luminosity function (LF)

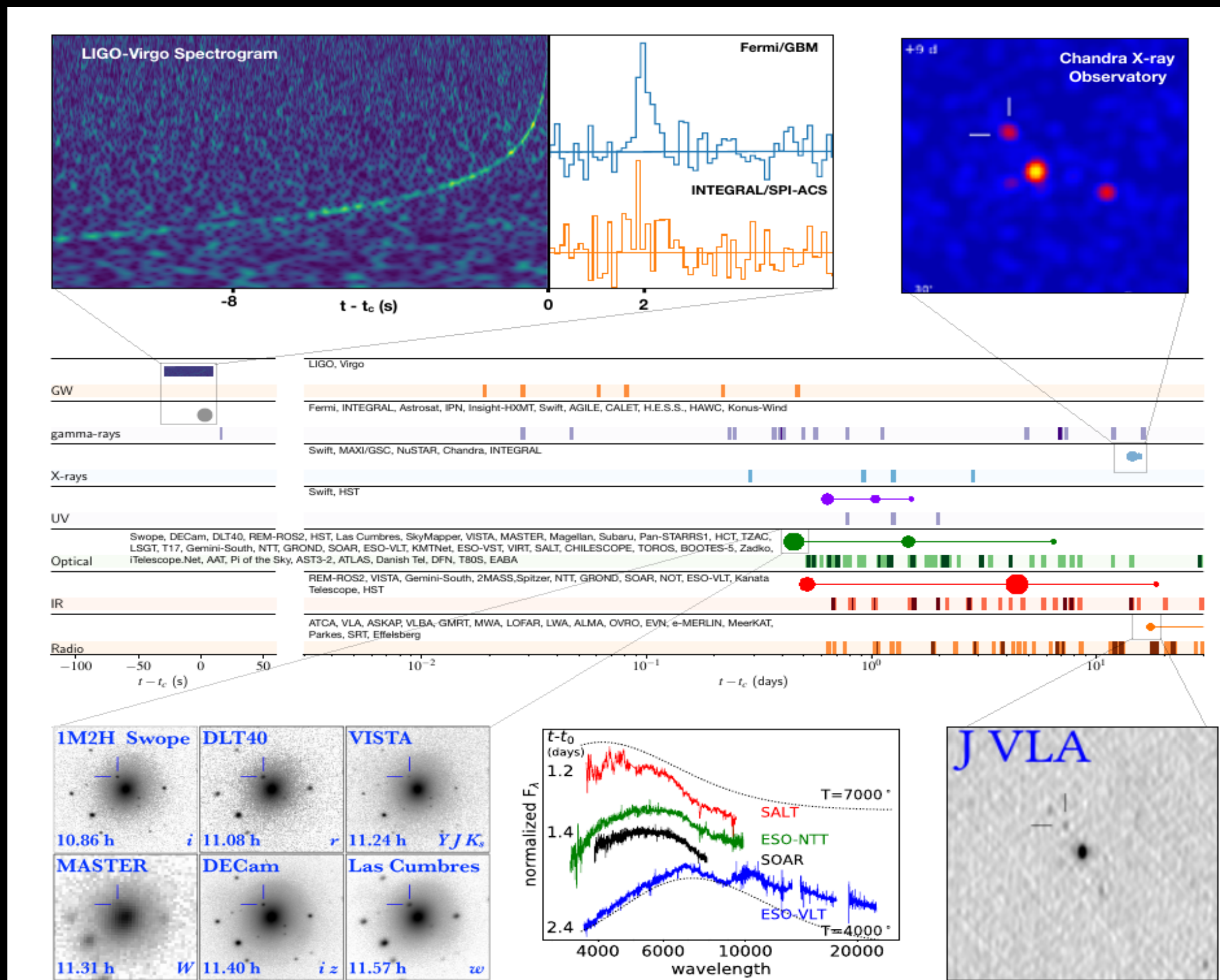
Preliminary results:

- ✓ By using the SBF method on HST images we derive the most precise distance to NGC4993 **$d = 40.7 \pm 1.4 \pm 1.9_{syst}$ 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}

Cantiello et al. 2018

Multi-messenger Observations Summary

More than 70 groups observed the field of GW170817

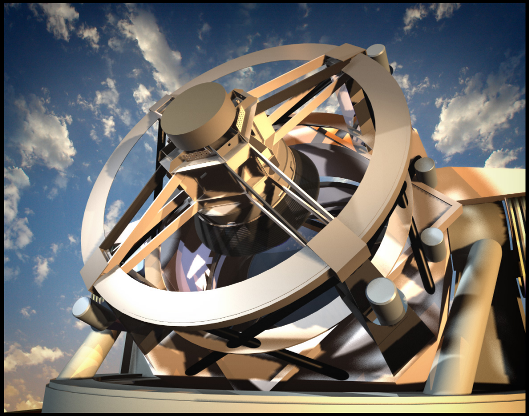


Abbott et al. 2017

See initial publications web archive: https://lco.global/~iarcavi/kilonovae.html

GraWITA

The Multi-messenger Era: next future



WF search ->

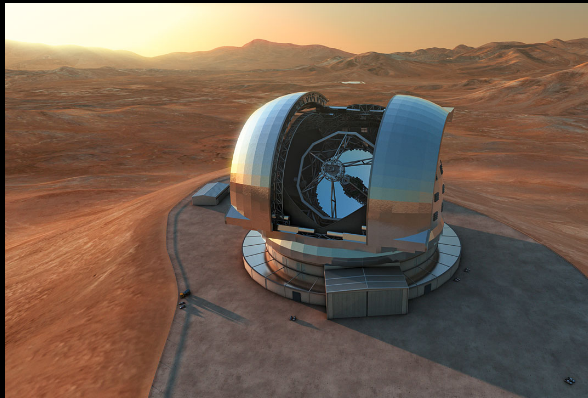
- Large telescopes (VLT etc)
  4-8m tel. can be competitive
  => very deep images (r > 25 mag) + >2 filters

- **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 (filters?)

  ToO: time fraction yet to be finalized but possible
  deep sky, galaxy catalog, identification false candidates
  LSST has a EM/GW group (16+ members). Part of LSST transients collaboration.

Characterization / Follow-up ->

- **E-ELT**(2024?): ~40m,Adaptive Optics,
  corrected FoV 10 arcmin,
  e.g. MICADO (Image+spectr. 0.8-2.4 µm, R~8000,
  FoV ~20-50 arcsec)



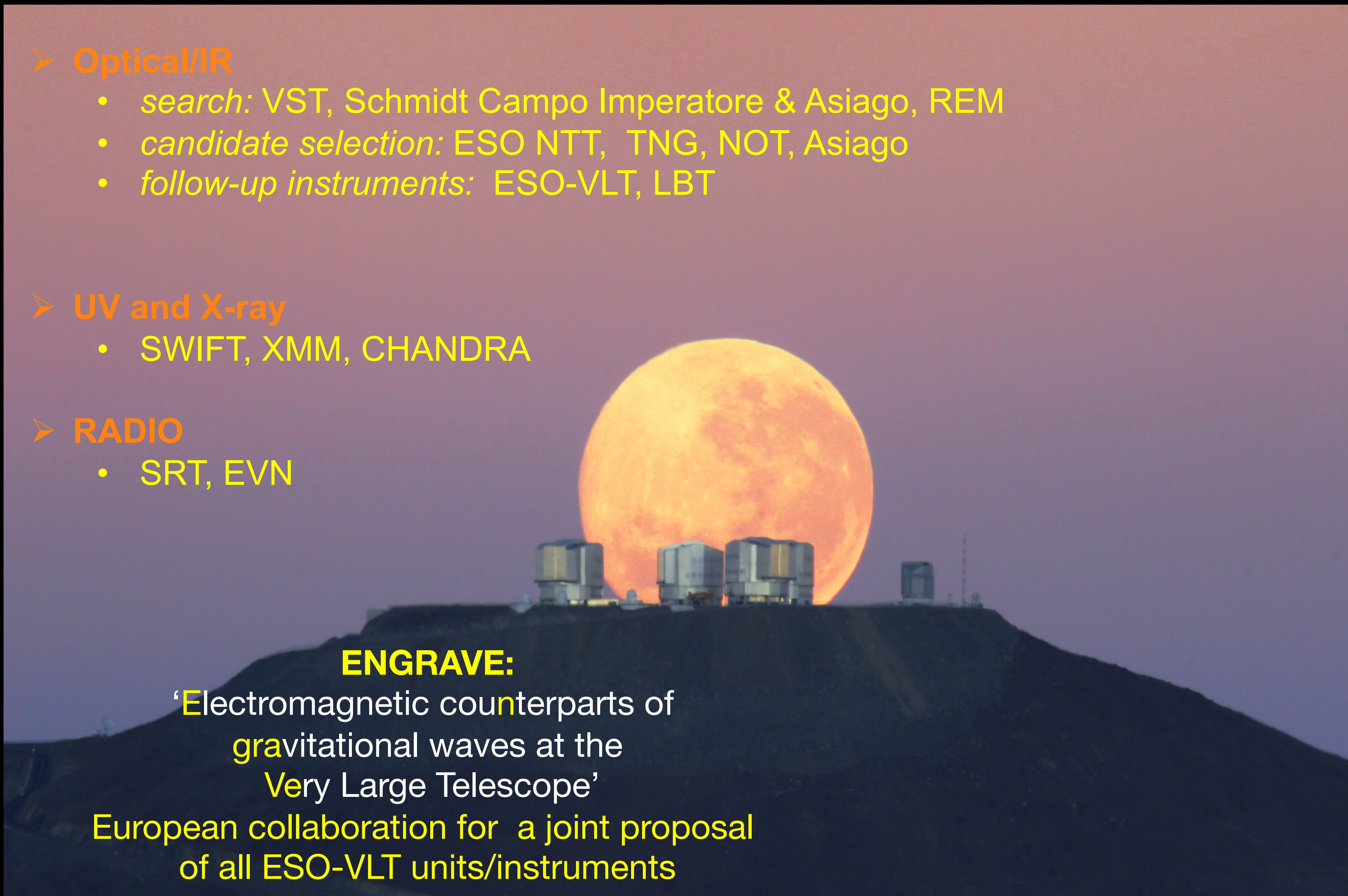
INAF

GRAWITA vs LVC run O3 (September 2018)

- **Optical/IR**
  - *search:* VST, Schmidt Campo Imperatore & Asiago, REM
  - *candidate selection:* ESO NTT, TNG, NOT, Asiago
  - *follow-up instruments:* ESO-VLT, LBT

- **UV and X-ray**
  - SWIFT, XMM, CHANDRA

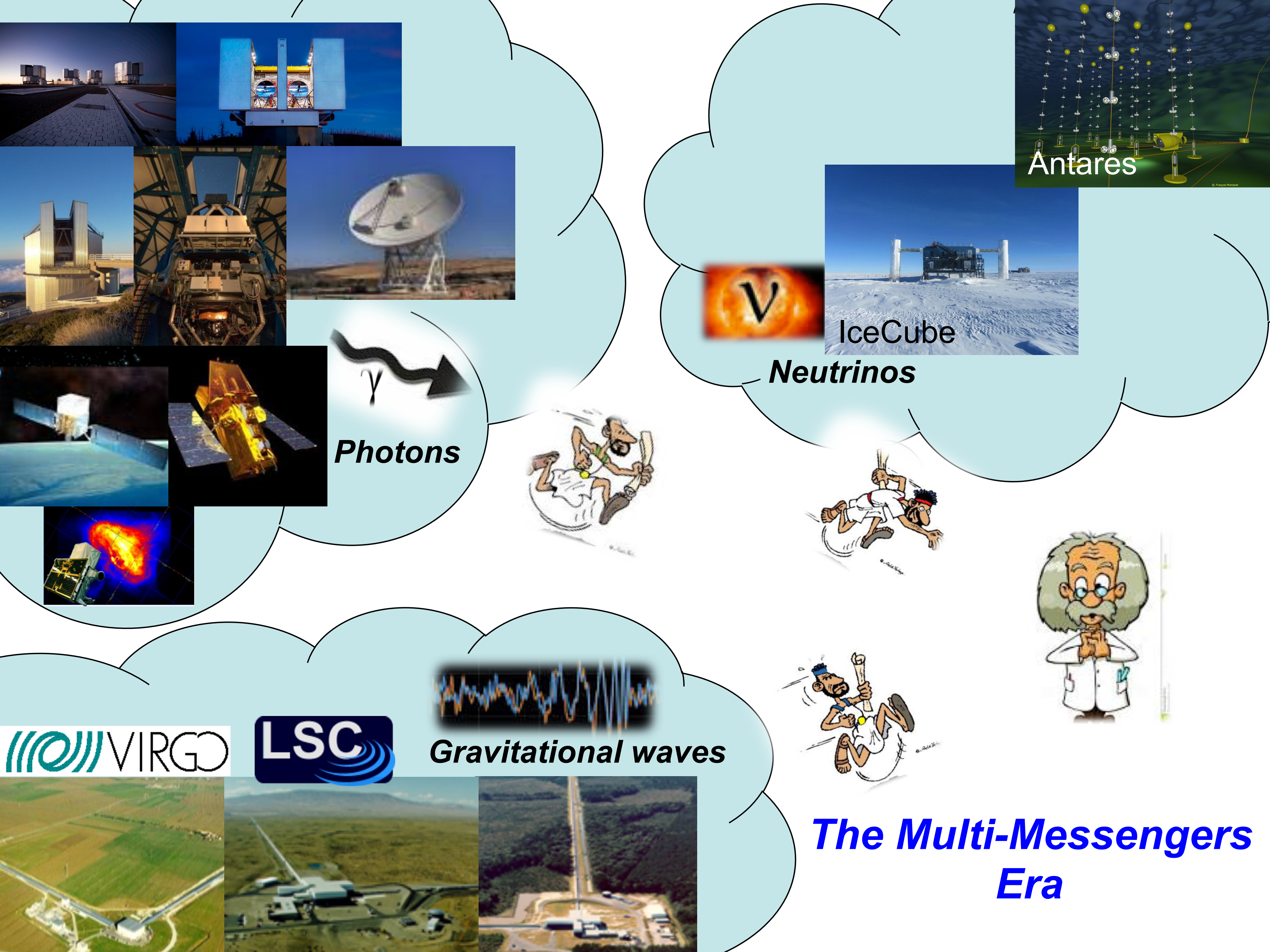
- **RADIO**
  - SRT, EVN



ENGRAVE:

'Electromagnetic counterparts of gravitational waves at the Very Large Telescope'

European collaboration for a joint proposal of all ESO-VLT units/instruments


Antares
IceCube
Neutrinos
Photons
Gravitational waves
VIRGO
LSC
The Multi-Messengers Era