Kilonova Observations by GRAWITA

Enzo Brocato
INAF – Osservatorio Astronomico di Roma

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

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SEQUENCE_NUM: 1
GROUP_TYPE: 1 = CBC
SEARCH_TYPE: 0 = undefined
PIPELINE_TYPE: 4 = GSTLAL
FAR: 3.478e-12 [Hz] (one per 3328022.5 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
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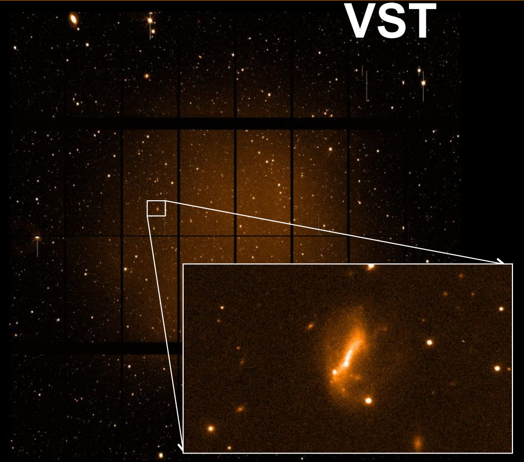
The route for the EM counterpart

STEP 1
Search & Detect

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

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

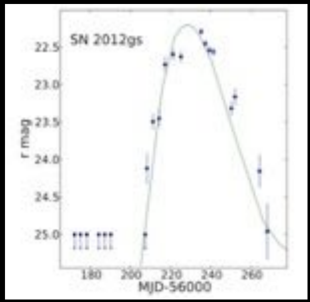
The detected transients have to be observed to infer their nature

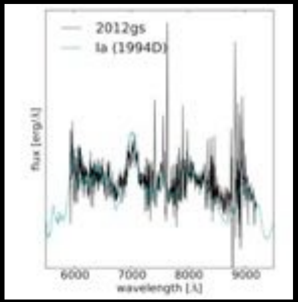
Telescopes for prompt spectroscopy of selected candidates at different latitudes/longitudes

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

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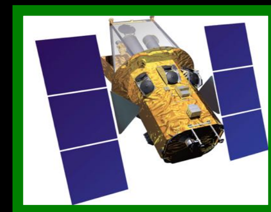
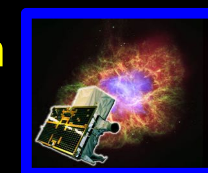
I



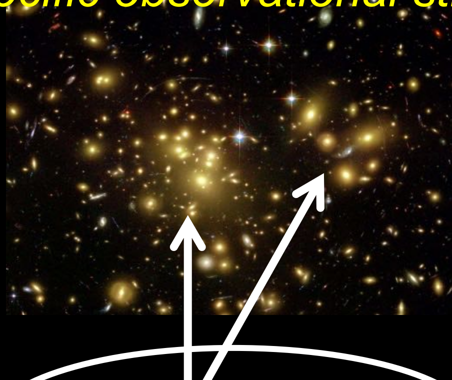


Gamma emission
and precise localization
by satellite
(< few arcmin)

➡ 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

+

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

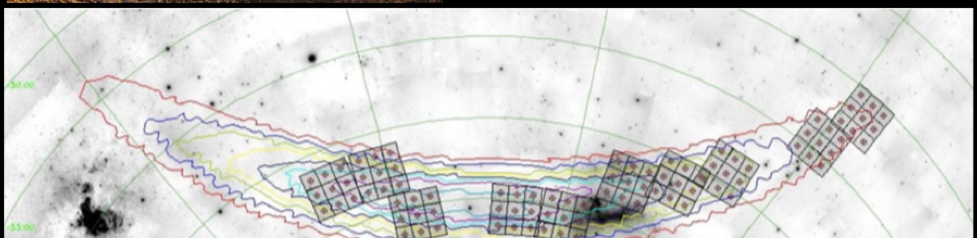
University of Bologna: A. Cimatti, M. Moresco, M. Brusa, G. Lanzuisi, M. Talia

Search for counterparts: wide field

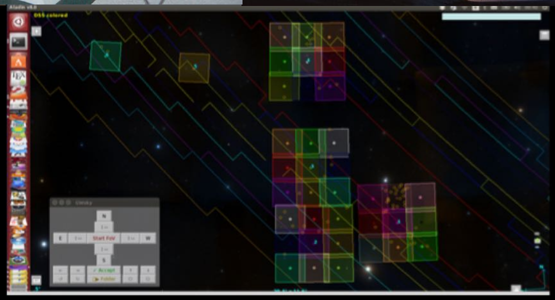
ESO–VST
2.6m FoV = 1 deg^2
(PI Cappellaro/Grado)

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

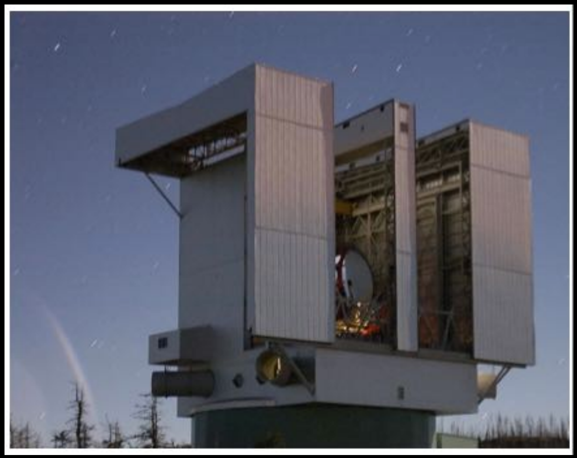
Brocato et al. 2017

Candidate classification / follow-up

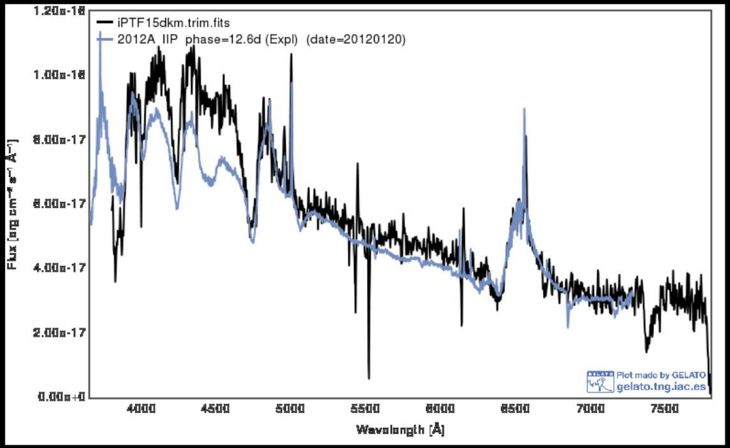
Copernico 1.8 m telescope (Asiago)
optical imaging & spectroscopy
(PI: Tomasella)

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)

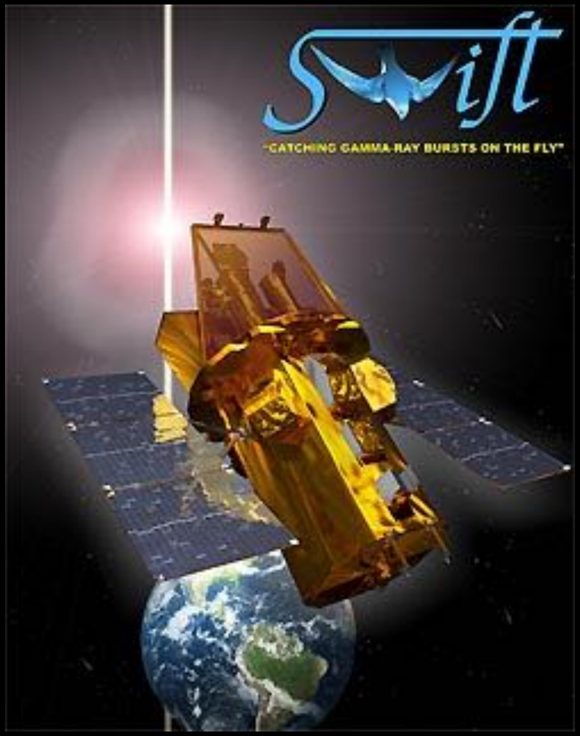


ESO-VLT 8.5 m
optical/NIR imaging & spectroscopy
(PI: P. D'Avanzo)

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

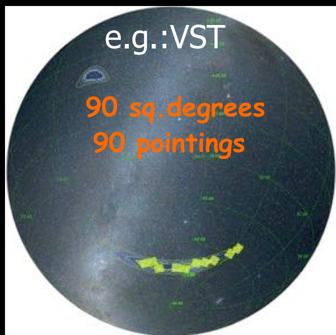
also Medicina & Noto radio telescopes (2x32m)

Aresu et al. GCN 21914

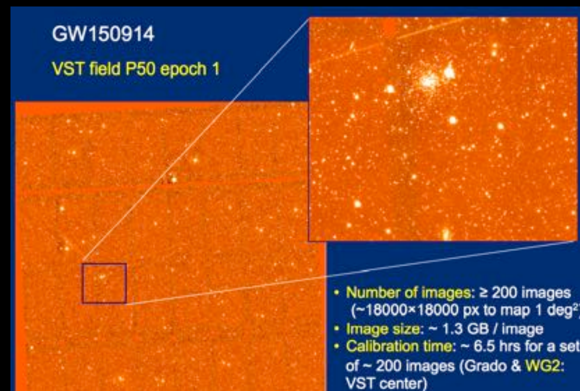
Both successfully operated in O1 & O2

Example of GRAWITA response

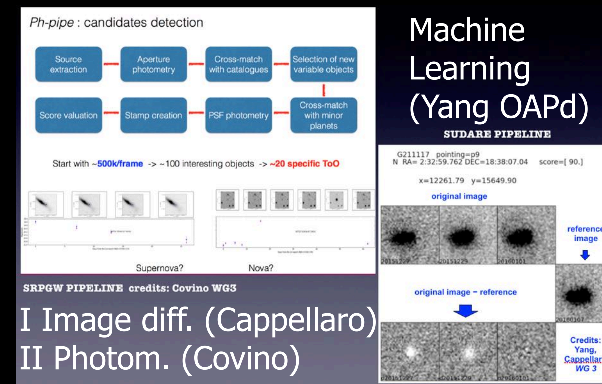
1. Tiling



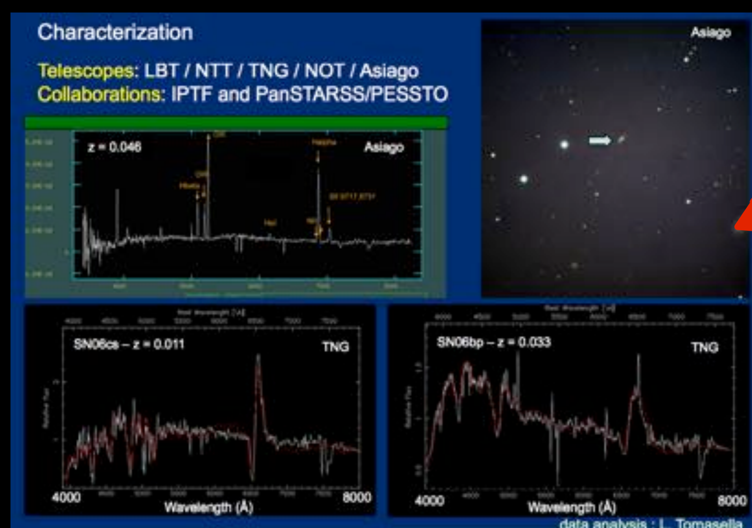
2. Observations



3. Search



4. Characterization and follow-up



Brocato et al. 2017

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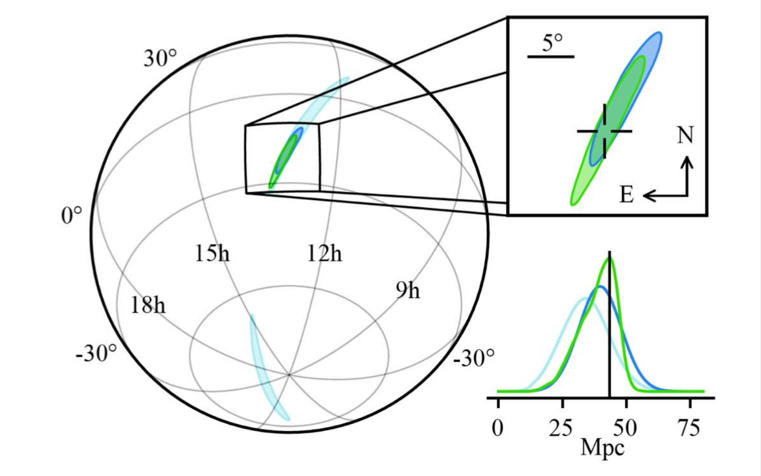
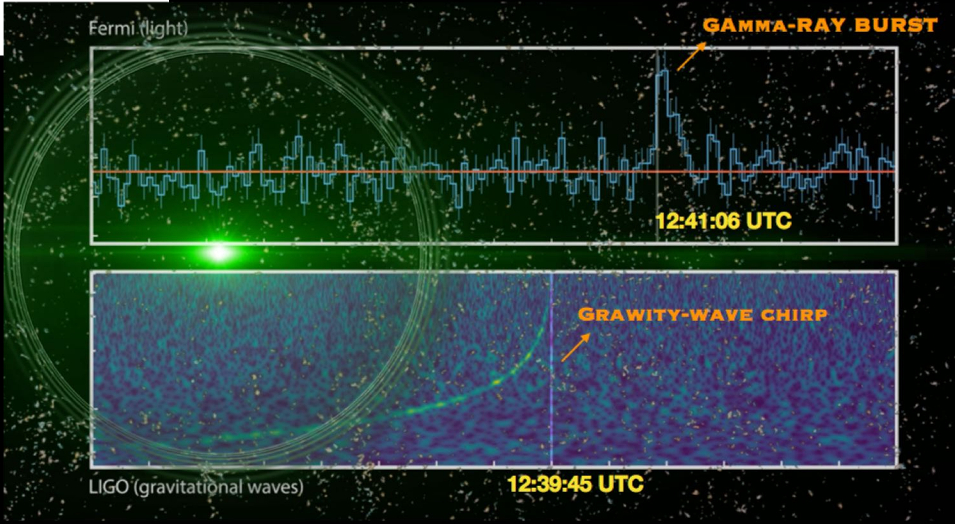
False-alarm rate < 1 per ~8 × 10^4 years





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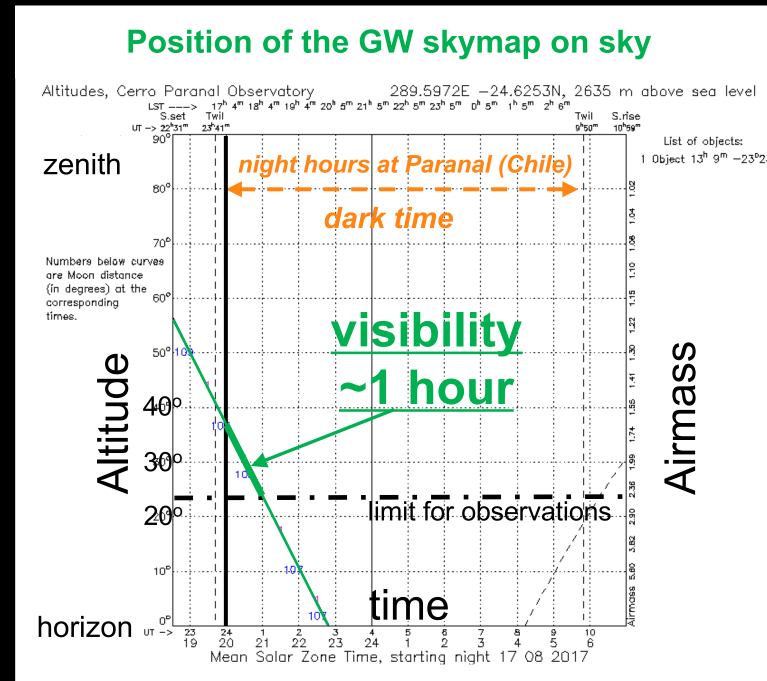
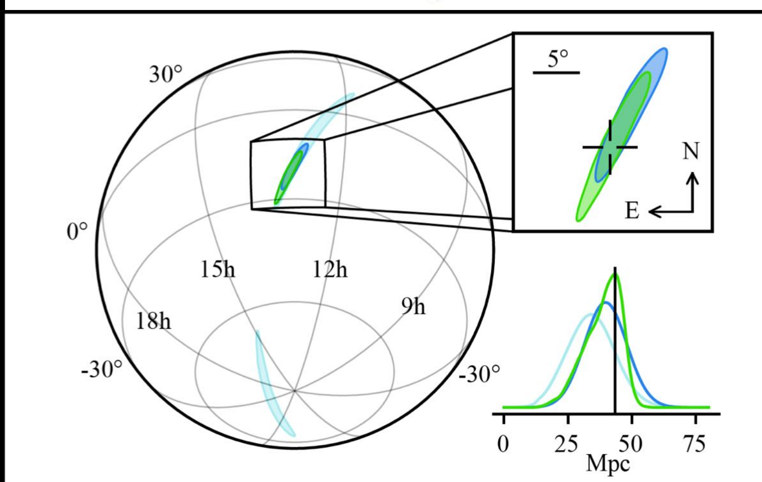
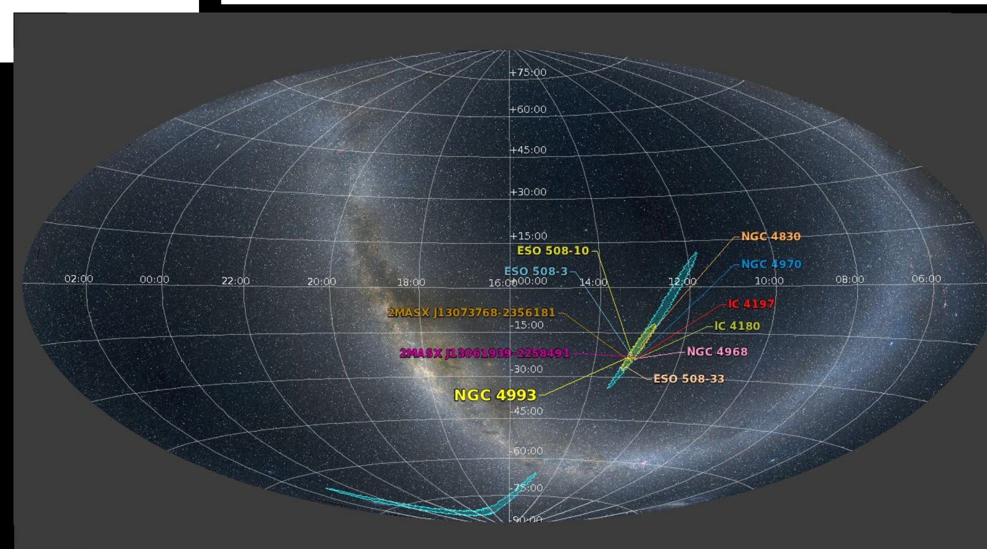






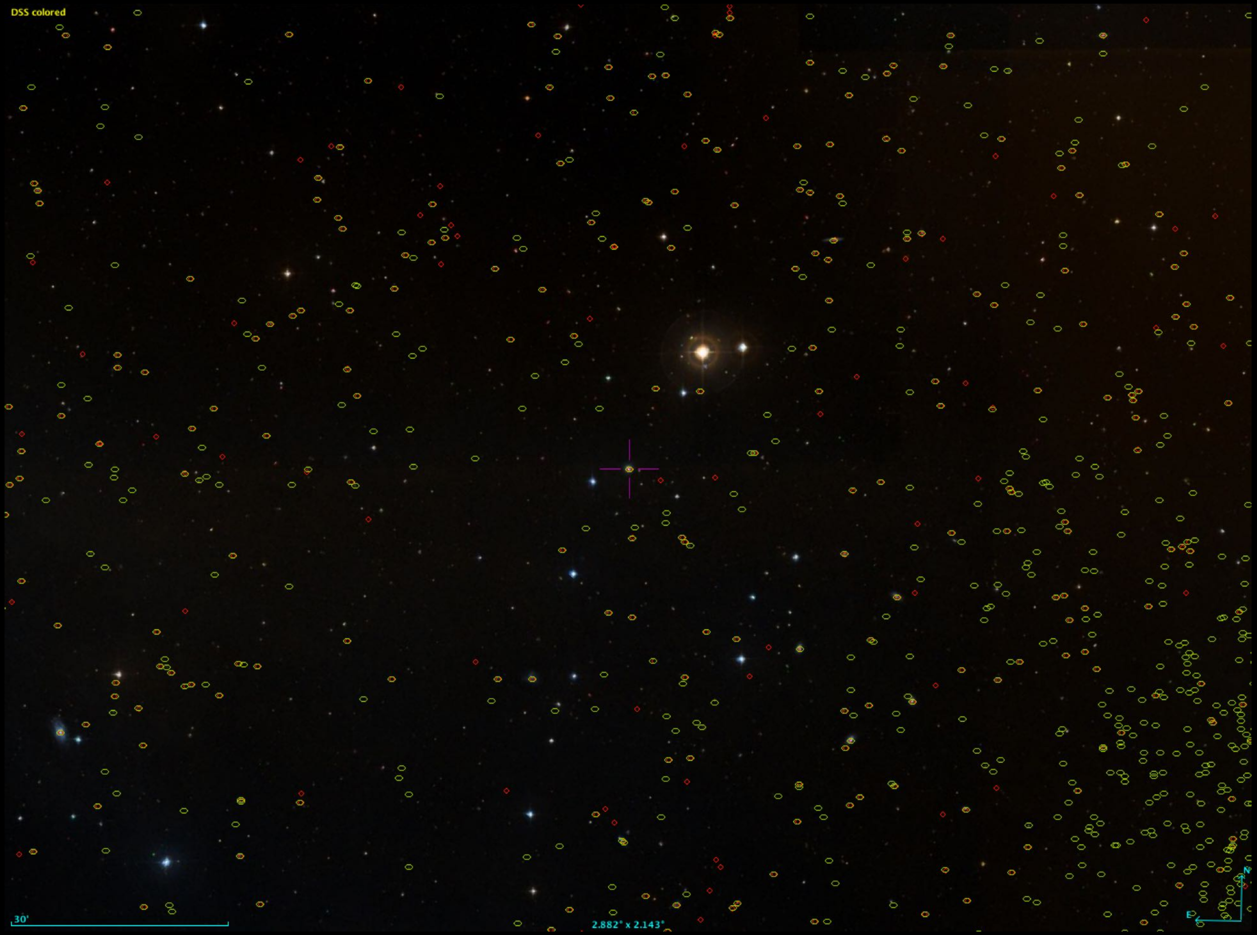
Observational strategies

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

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

Observational strategies

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



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

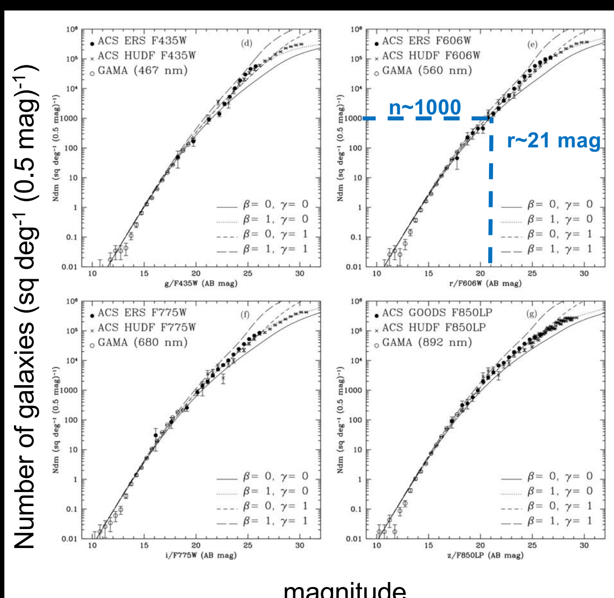
Observational strategies

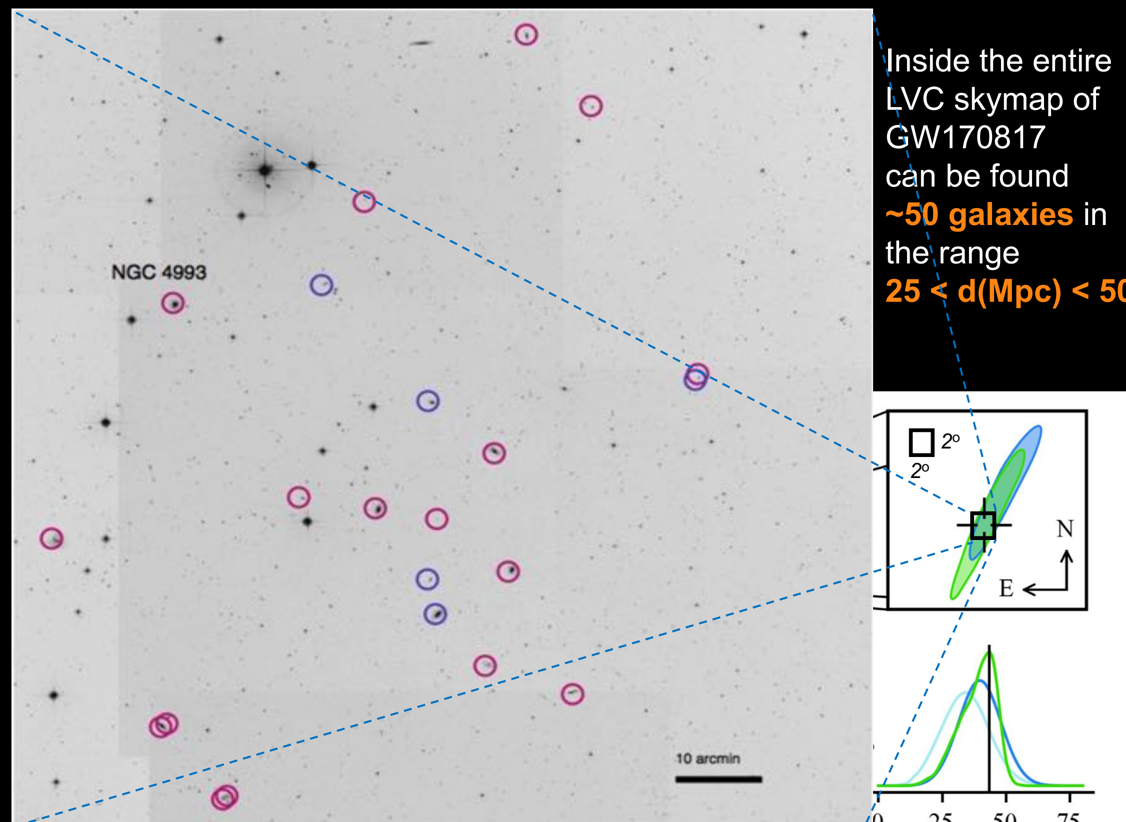
When the distance (including uncertainties) is available, (no mosaics) the best observing strategy is

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



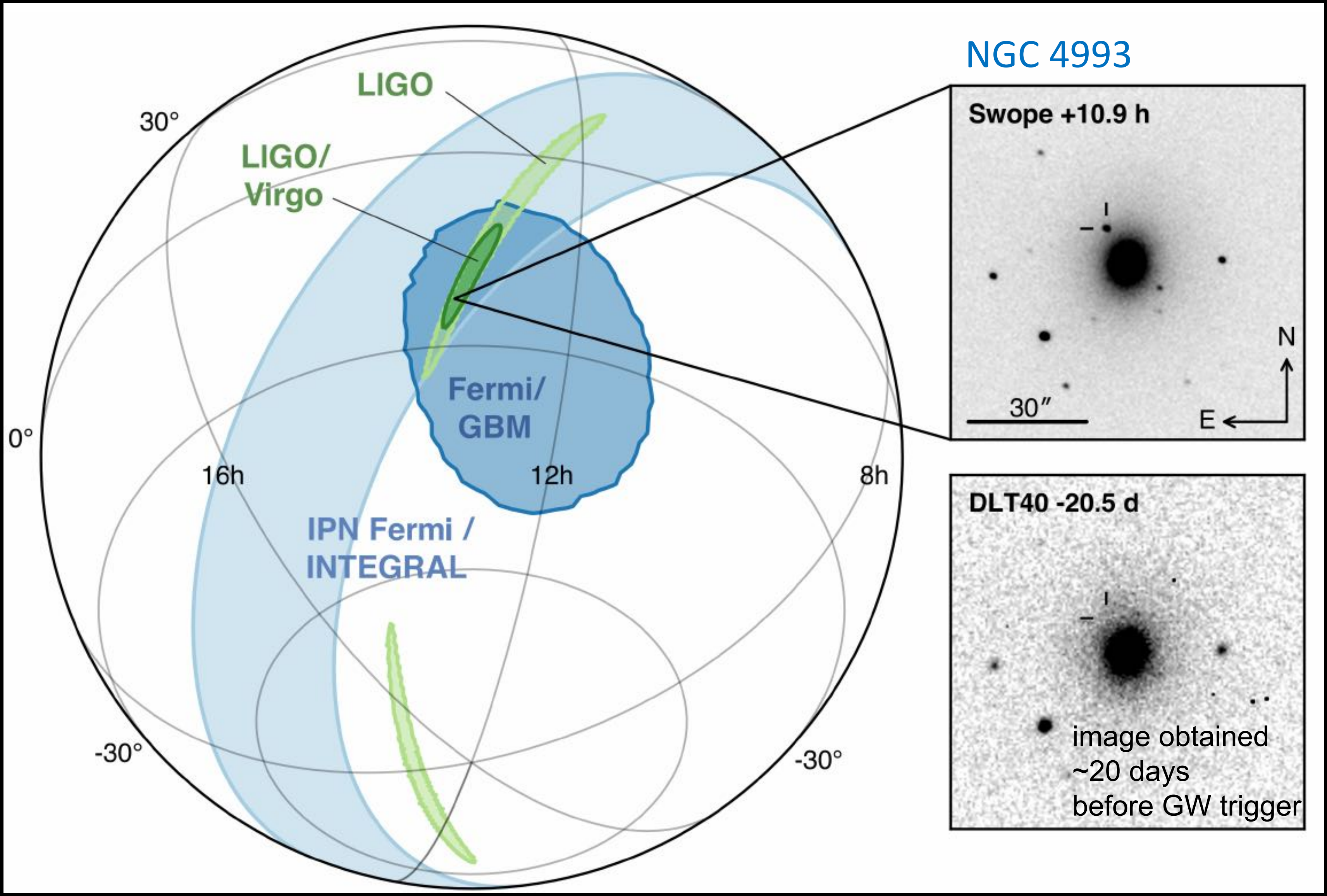


Hjorth et al. 2017

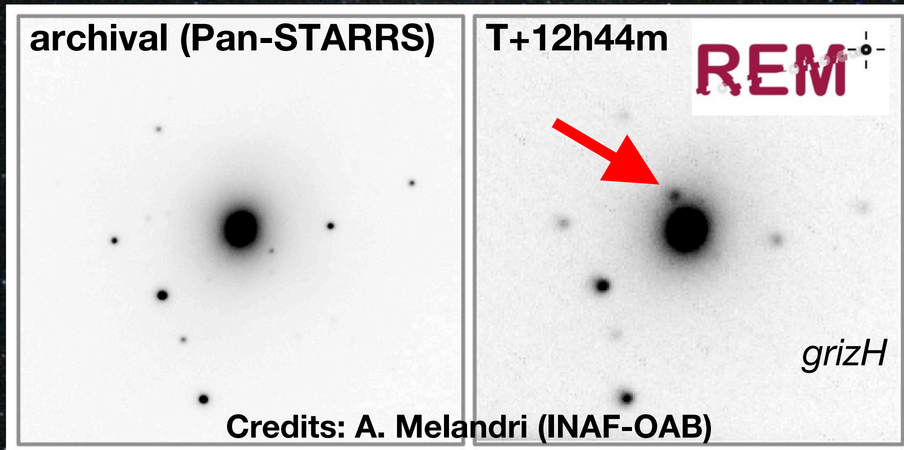
Inside the entire LVC skymap of GW170817 can be found **~50 galaxies** in the range **25 < d(Mpc) < 50**

Discovery of an Optical/nIR Transient

OPTICAL counterpart detection ~ 11 hours after GW trigger



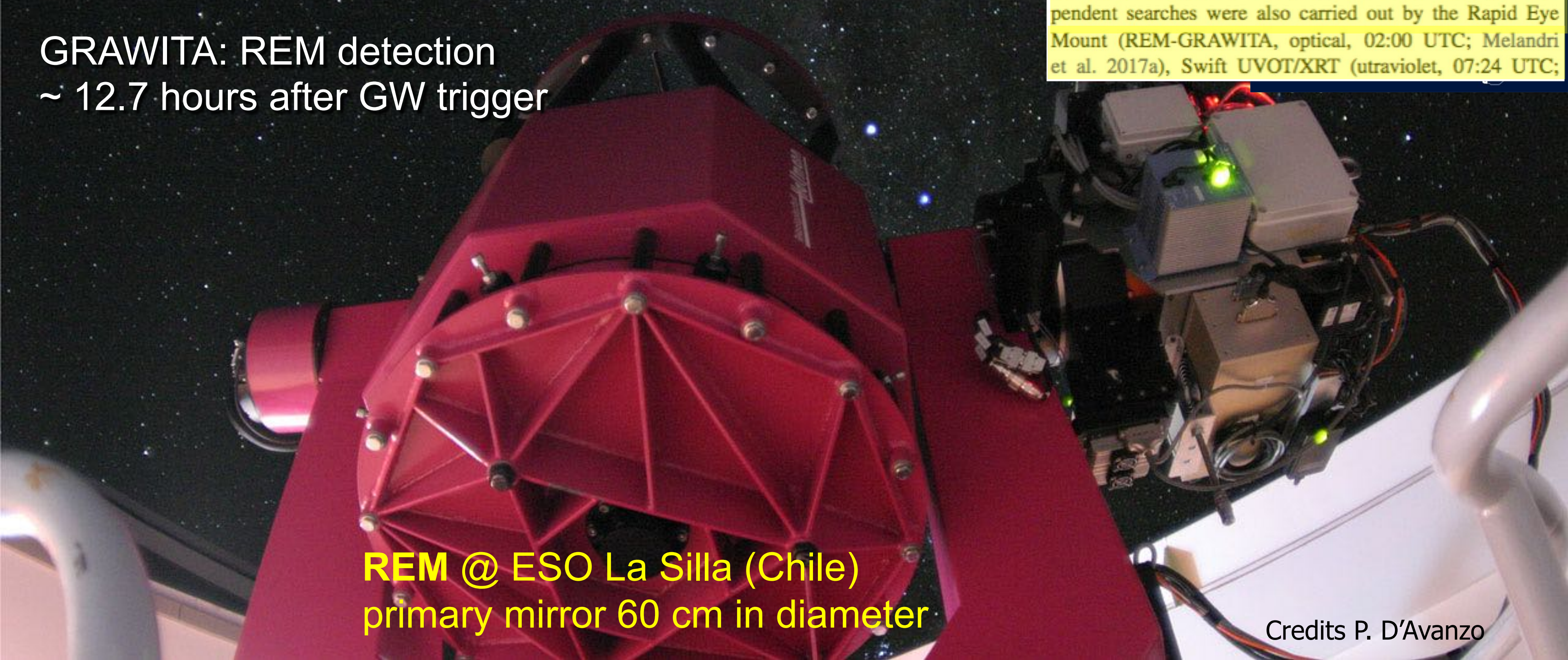
GW 170817: optical counterpart in NGC 4993



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;

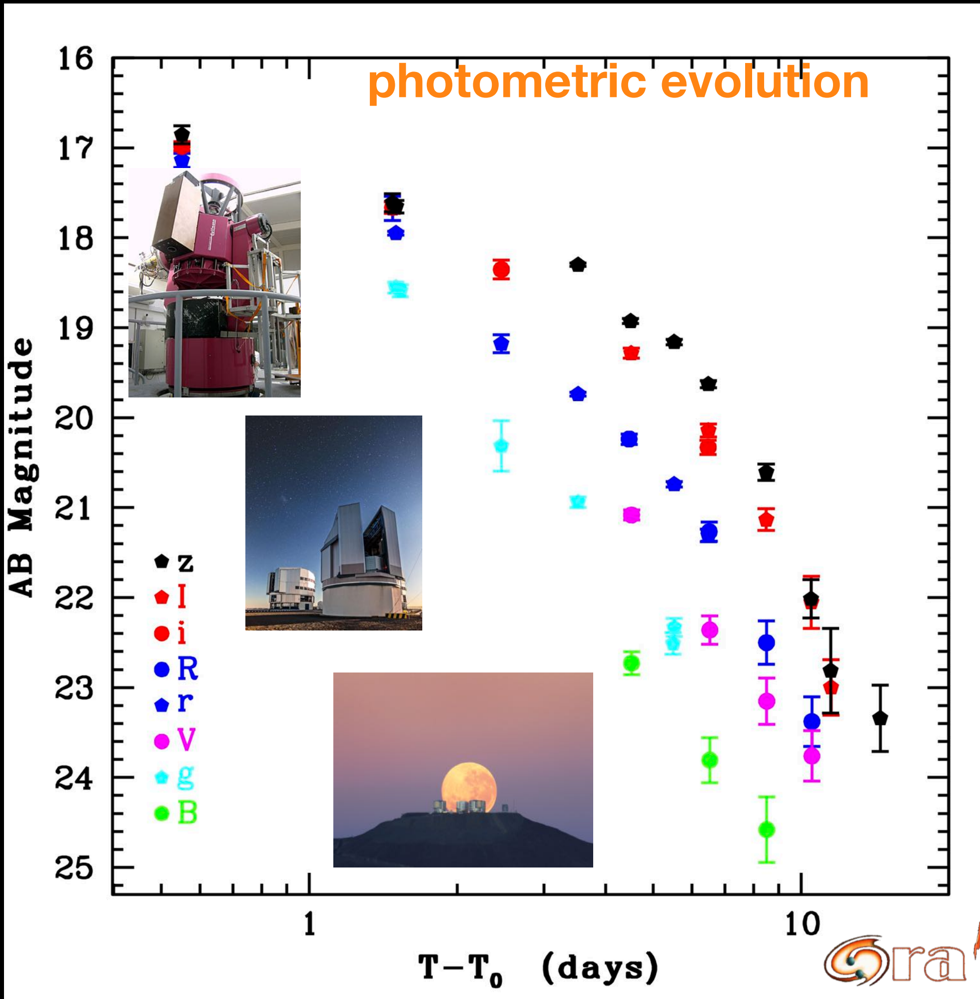
GRAWITA: REM detection
~ 12.7 hours after GW trigger

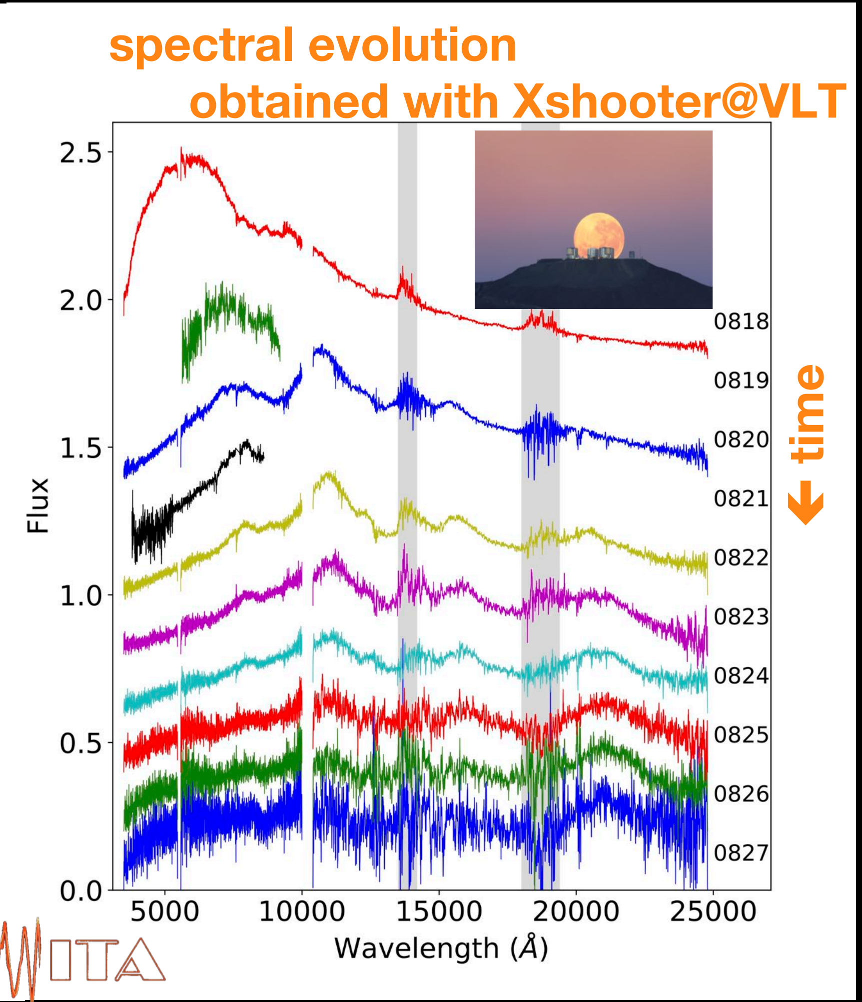


REM @ ESO La Silla (Chile)
primary mirror 60 cm in diameter

Credits P. D’Avanzo

GW 170817: imaging and spectroscopic follow-up

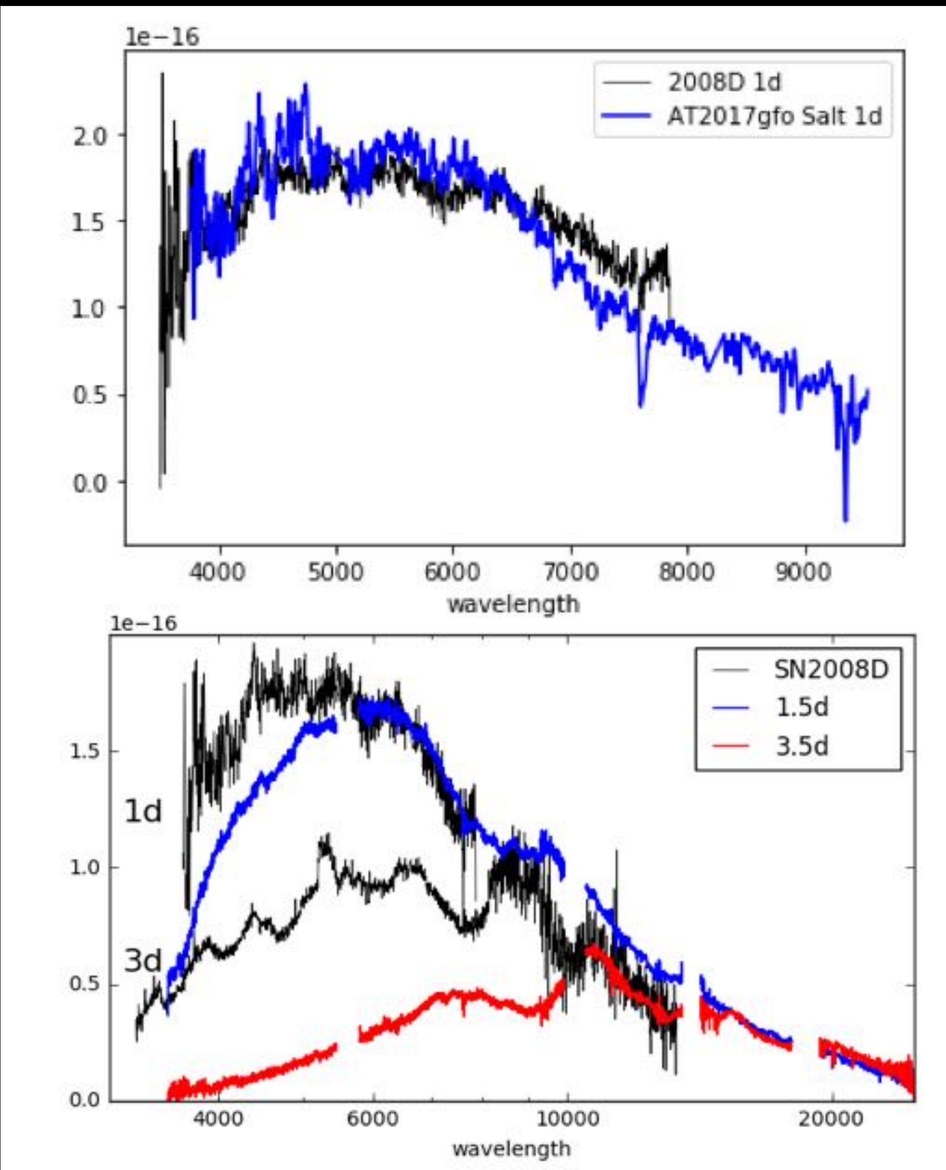




Pian, D'Avanzo et al. 2017, Nature

The Optical/nIR Transient

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

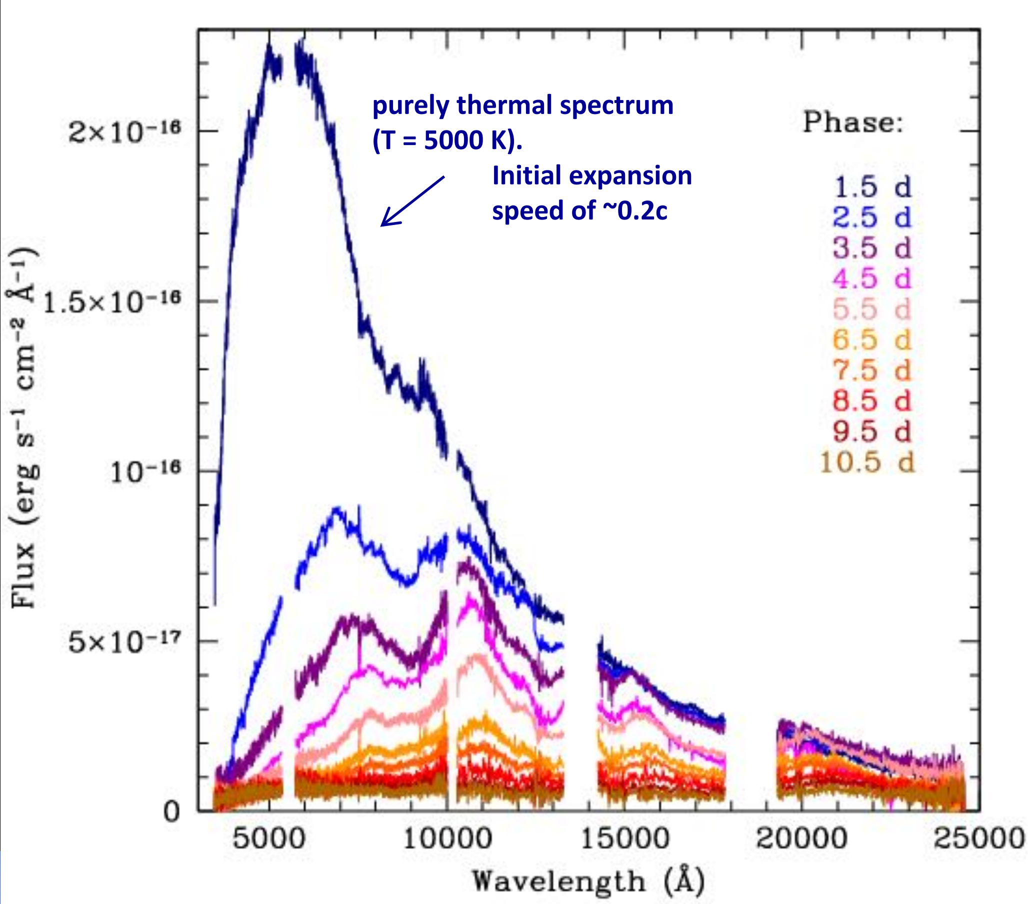


The low S/N spectrum ***at 1 day*** matches very well that of the supernova ***SN2008D / XRF080109 (type Ibc)*** at a similar phase.

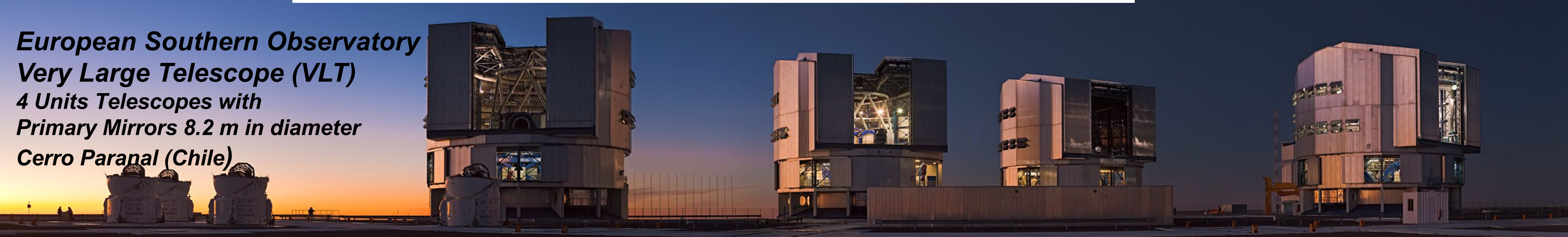
In a couple of day the peak of the Spectral Energy Distribution shifts to the near-infrared. Broad spectral features appear that are completely different from that of all known SN types.

The Optical/nIR evolution of the kilonova

ESO VLT X-Shooter spectral sequence of GW170817

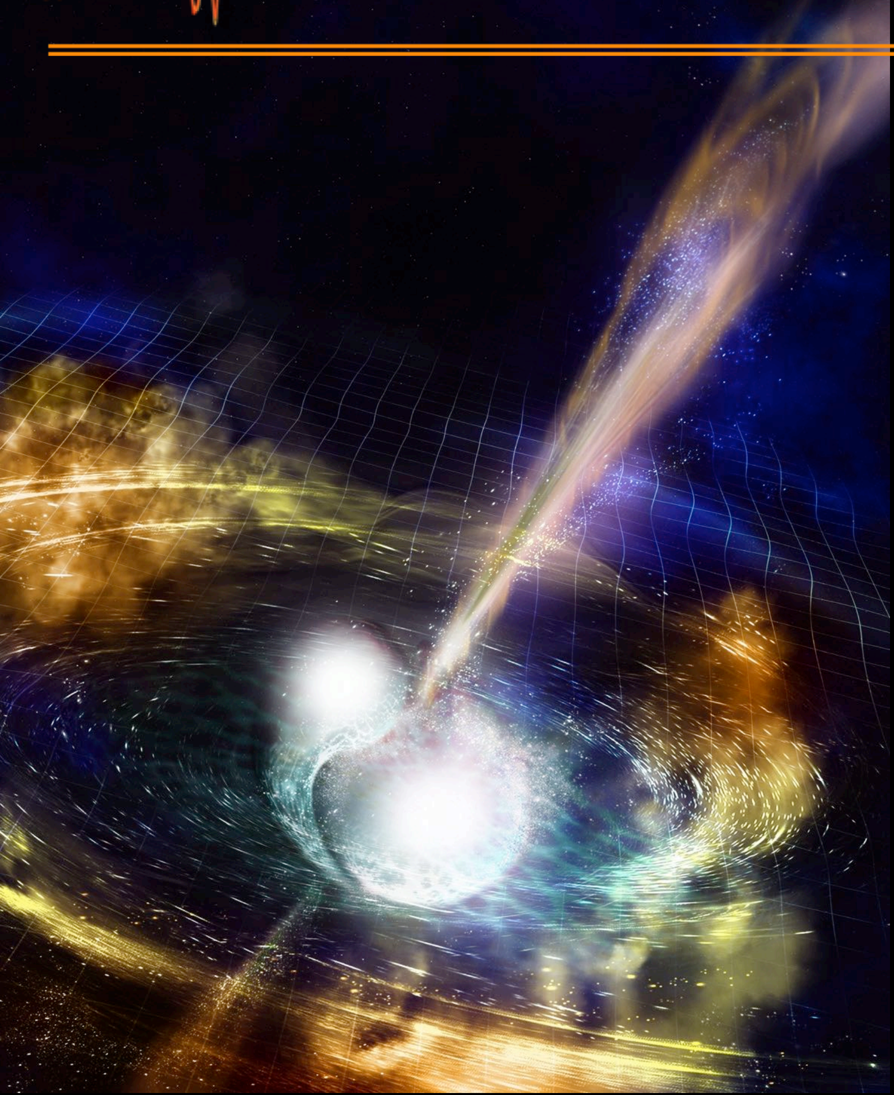


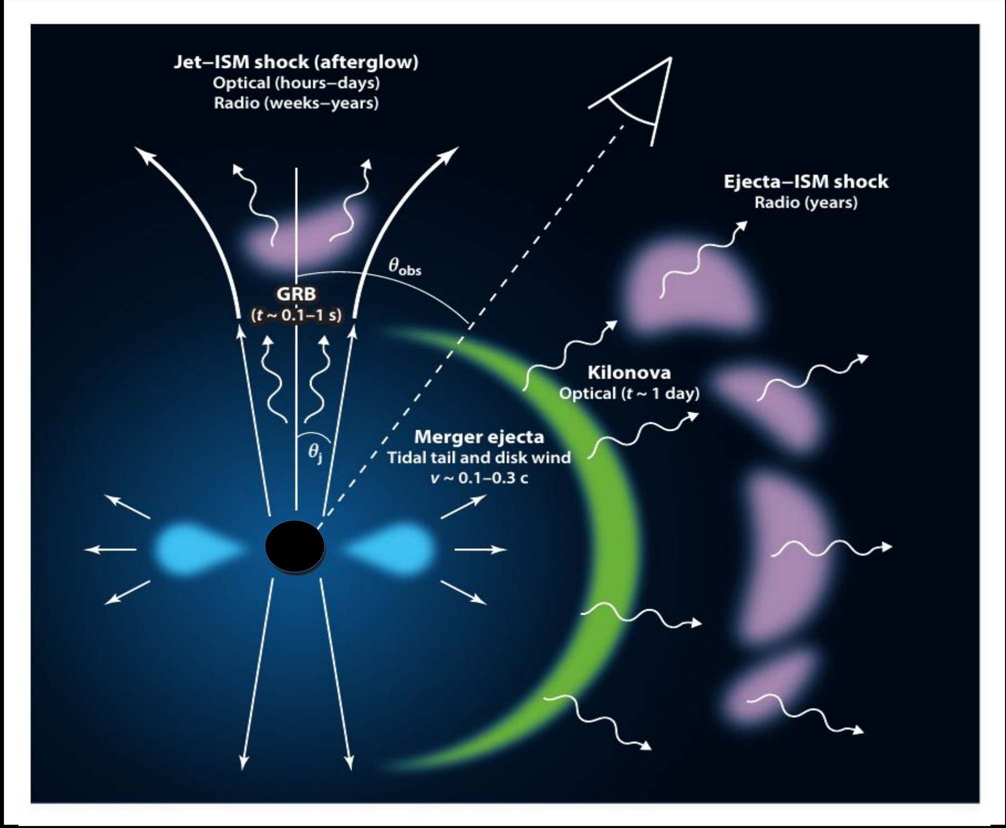
Pian et al. 2017;
Smartt et al. 2017



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

BNS Merger

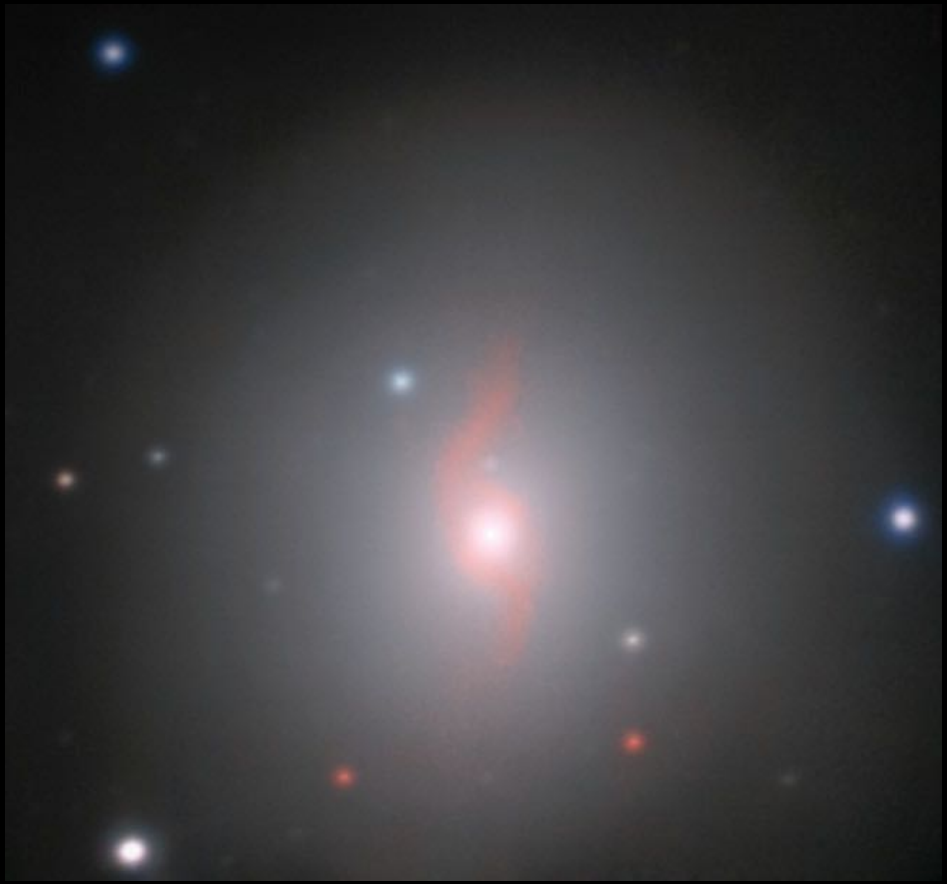




Metzger & Berger et al 2011

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: further work on GW170817

New distance evaluation of NGC 4993

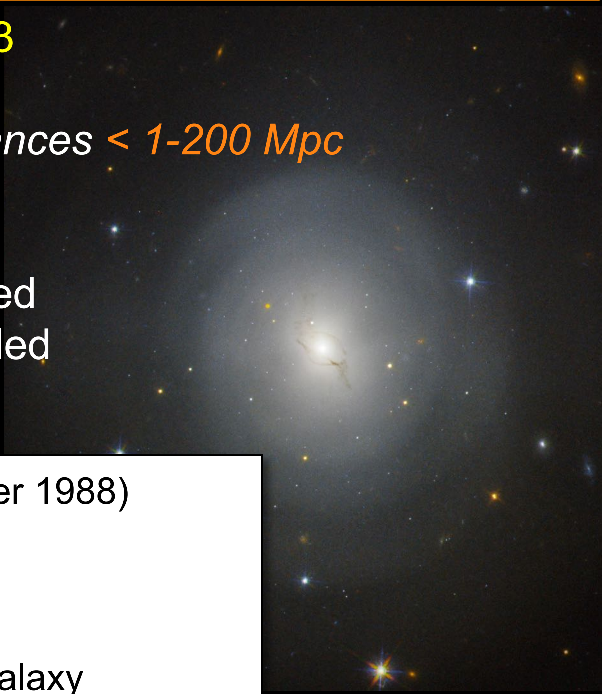
Surface Brightness Fluctuation (SBF)

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

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)*

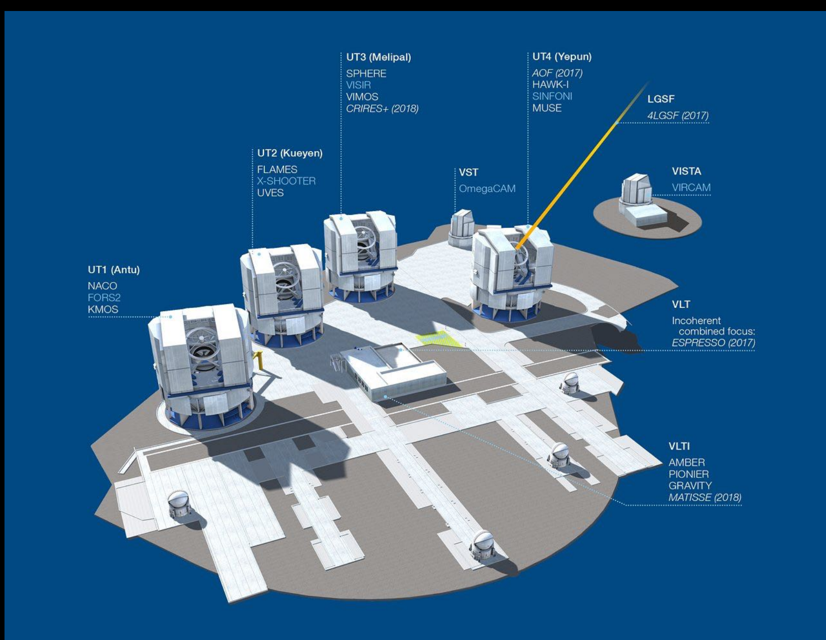
3 Periods P102 - P104 Oct 2018 - Mar 2020

Fully Covering O3

Requesting 180hrs of VLT

4 triggers @ 45hrs per event

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



+

VIN ROUGE

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

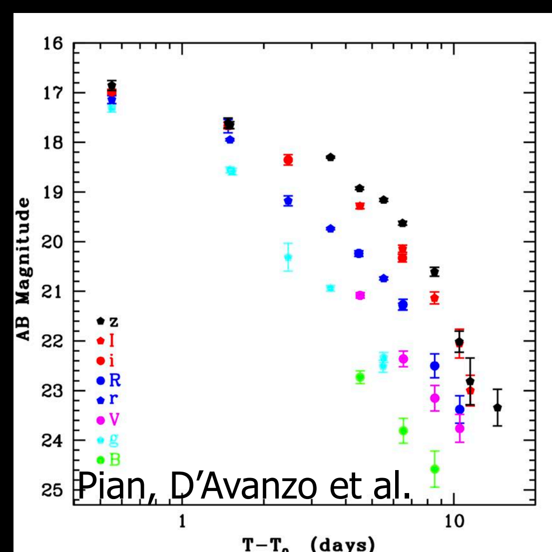
ENGRAVE

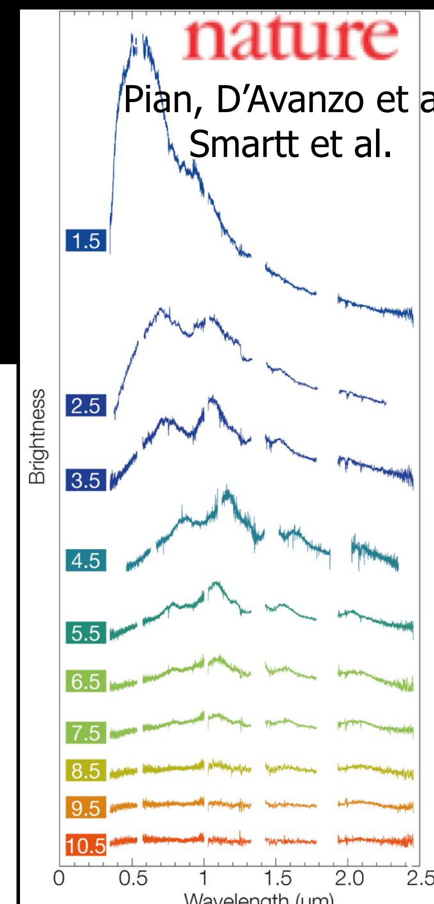
Simple goal

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)

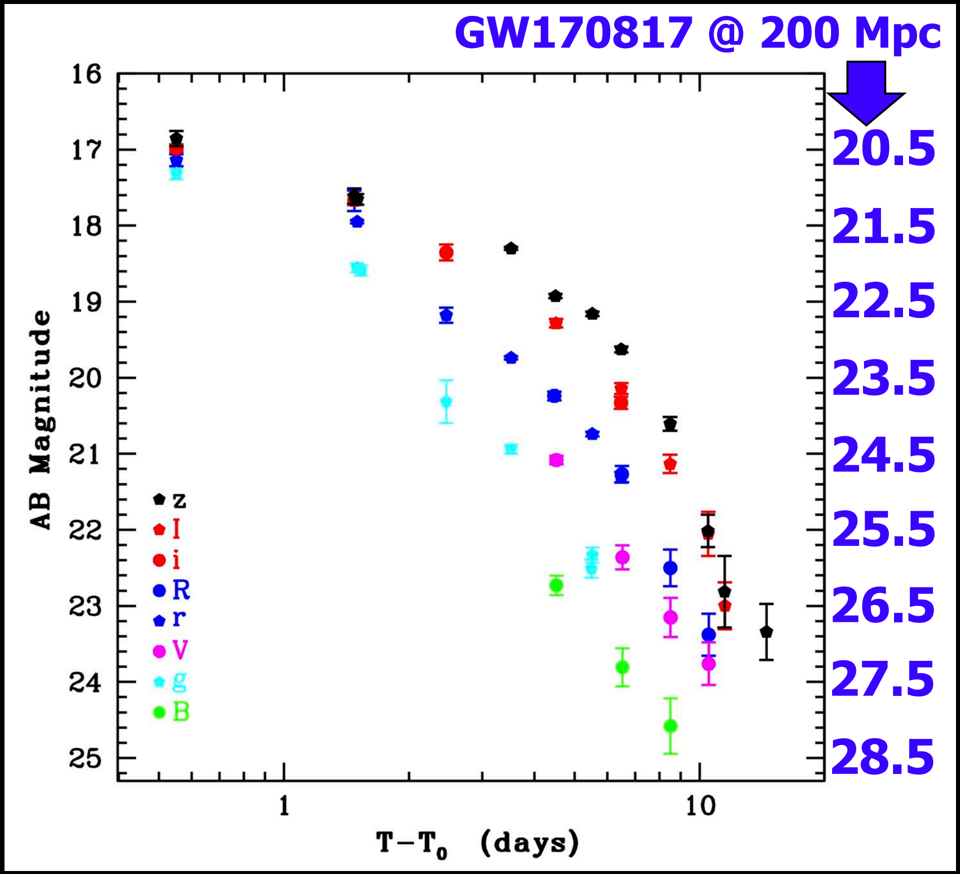
VLT + MUSE IFU

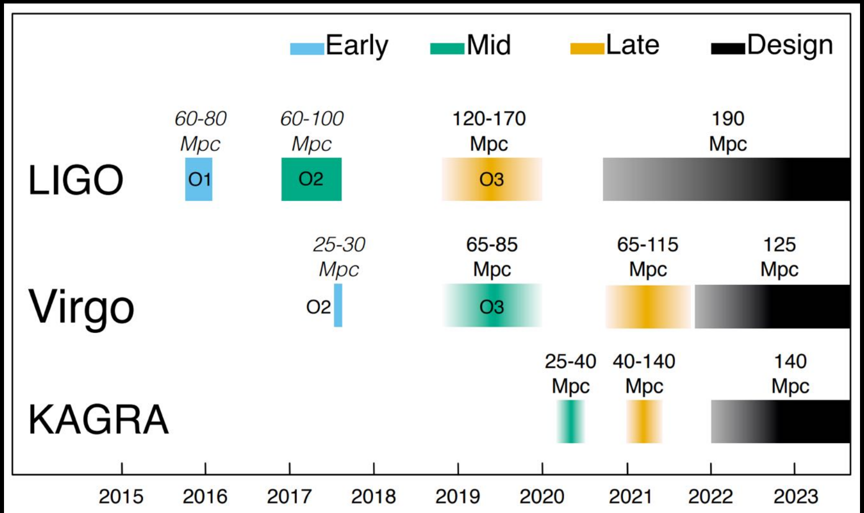




GRAWITA vs O3 and beyond

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





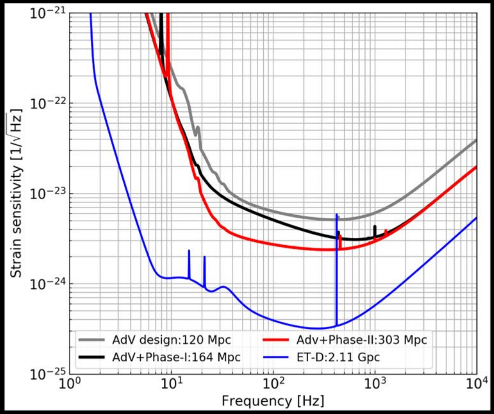
Expected multi-messenger event rates

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

WF search

LSST (2022?):

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

LSST has a EM/GW group (< GW LSST-Inaf team).
Part of LSST transients collaboration.

LSST

Large Synoptic Survey Telescope Corporation

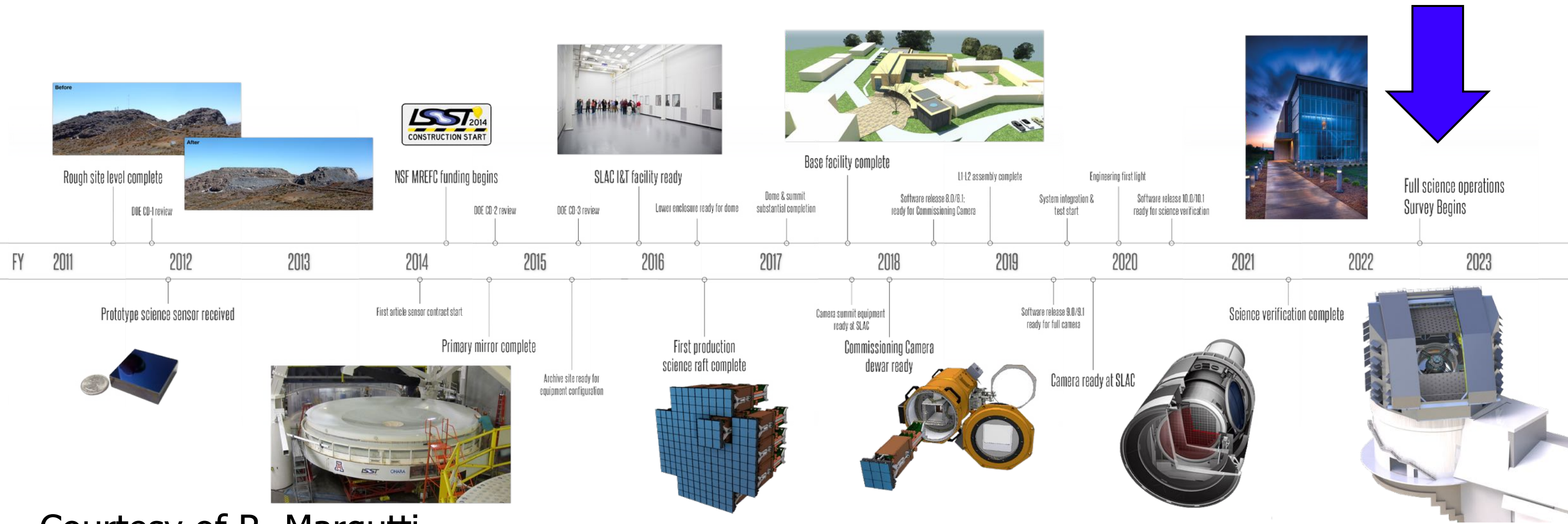
Transients and Variable Stars workshop

Naples April 9-11, 2018

INAF – Osservatorio Astronomico di Capodimonte

LSST Time line:

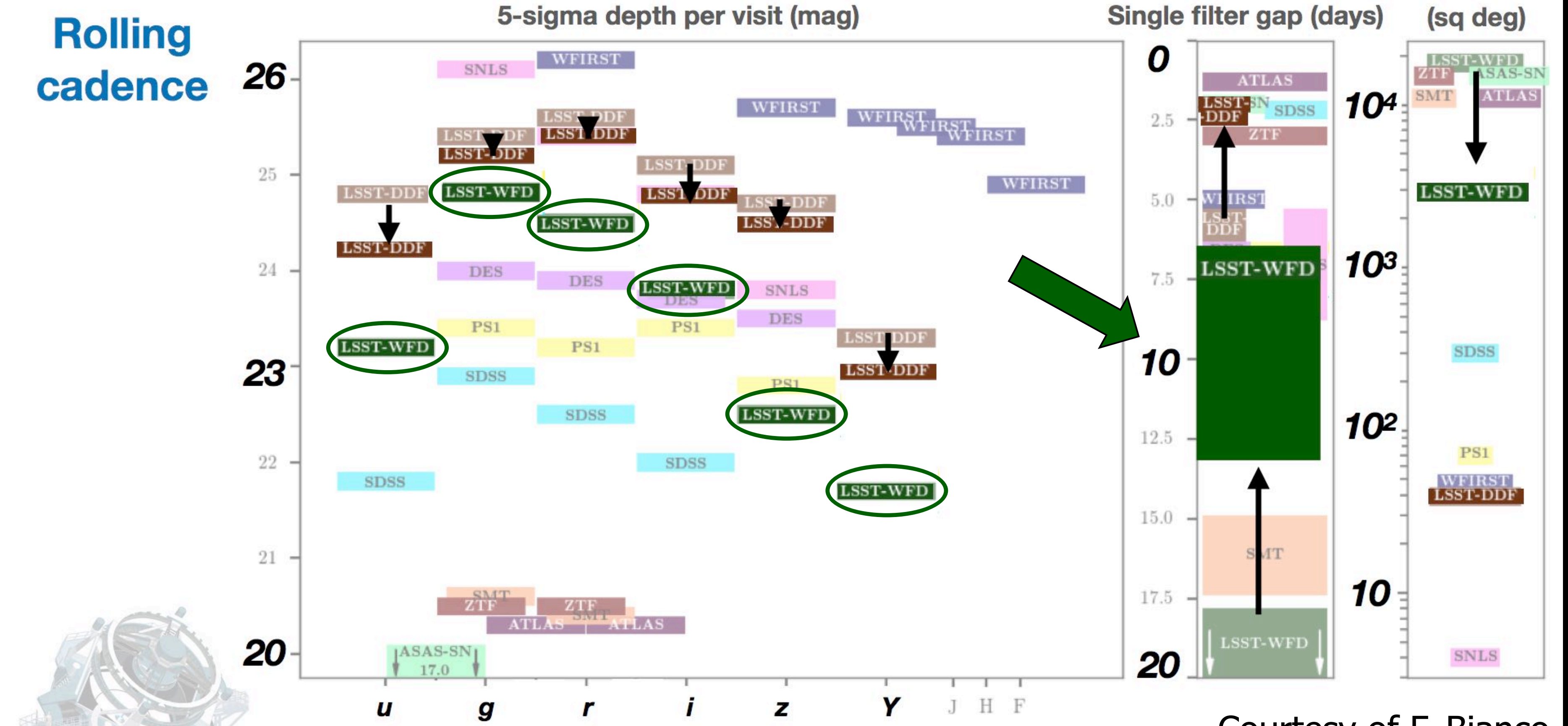
2023
Full Science
Operations



Courtesy of R. Margutti

LSST

LSST Cadence alternatives: Rolling Cadence



Scolnic+ 2017 ApJ 852,1
Dan Scolnic with Kessler, Biswas, Jha, Hložek, DESC SNWG

Courtesy of F. Bianco

federica bianco NYU

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

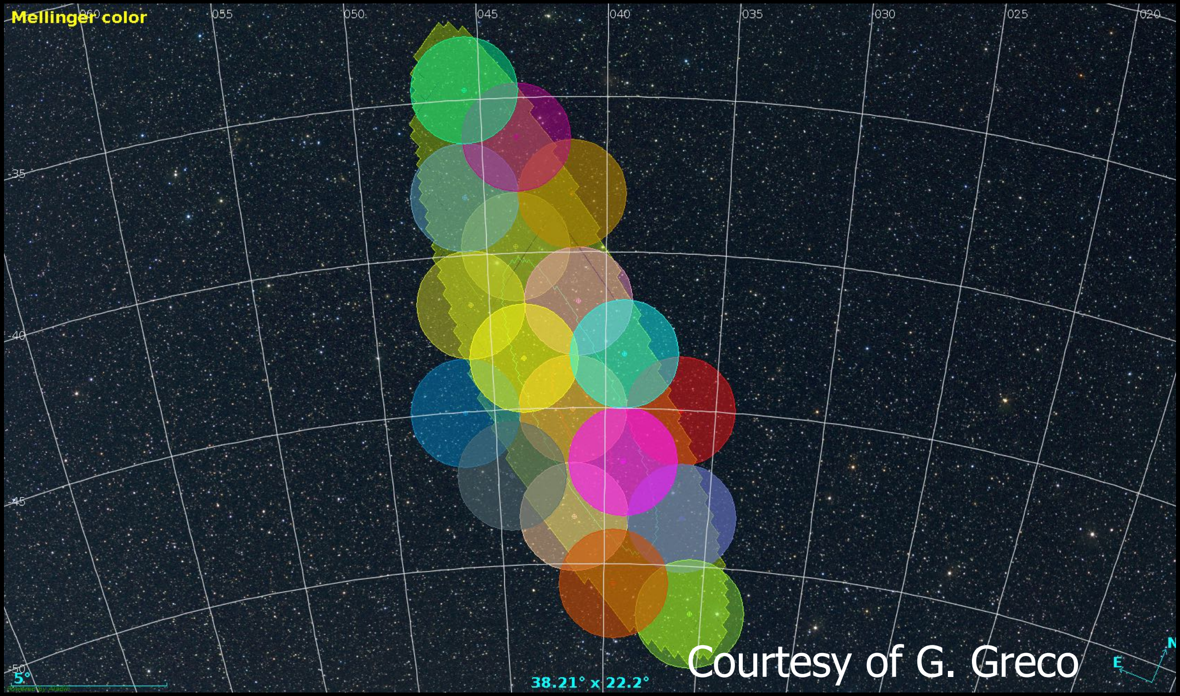
Target of Opportunity mode !

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%)**

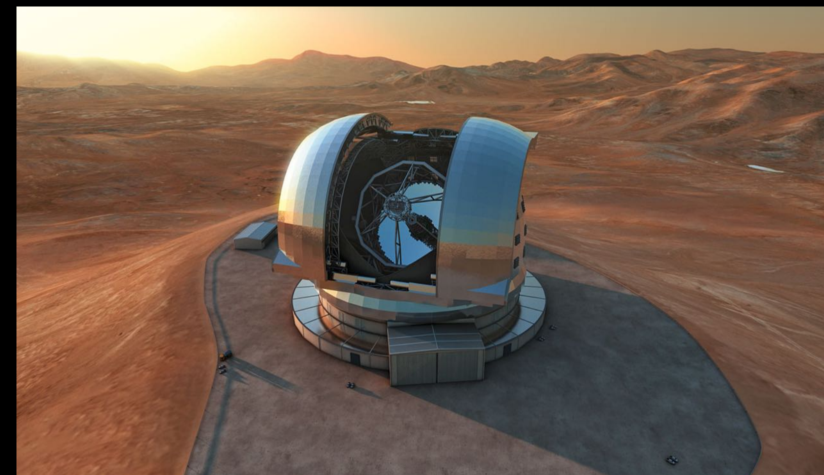
SOXS@NTT
MOONS@VLT

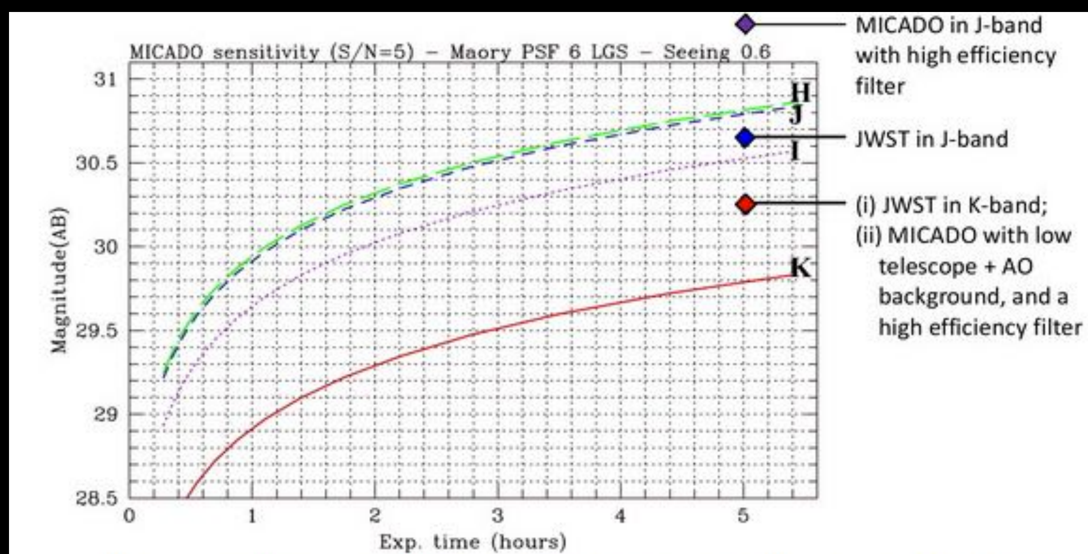
E-ELT

Follow-up

E-ELT (2024?):

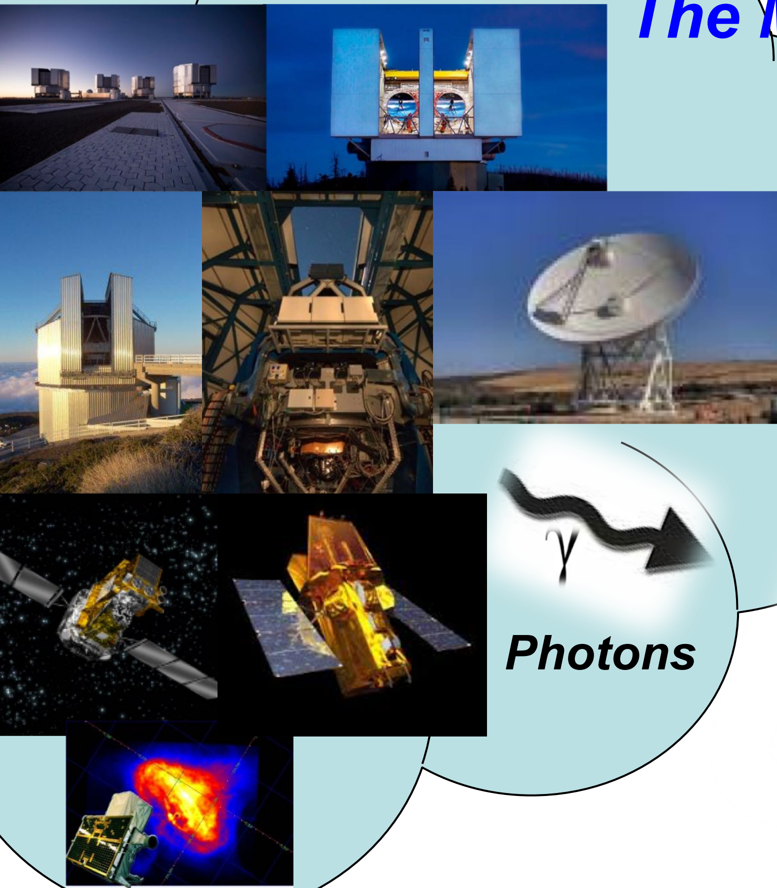
~40m, Adaptive Optics
corrected FoV 10 arcmin
e.g. MICADO
Image+spectr. 0.8-2.4 µm, R~8000
FoV ~20-50 arcsec



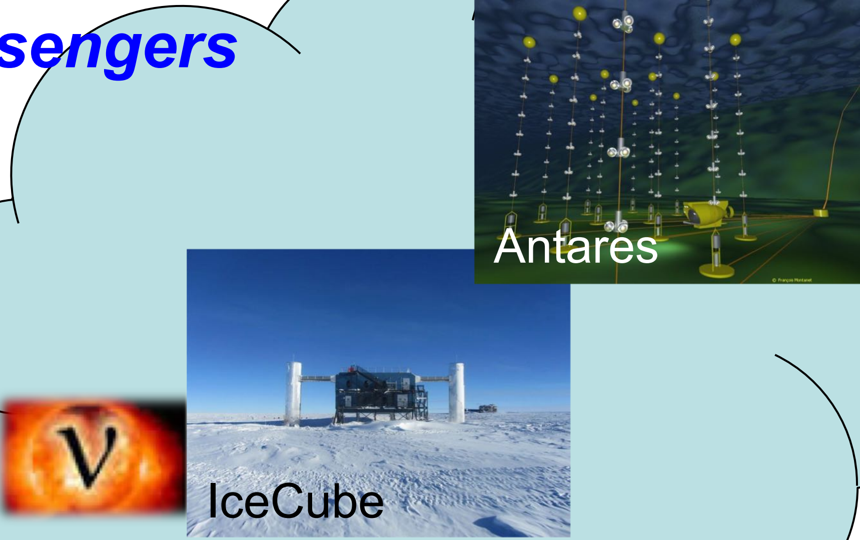


Broadband imaging sensitivity of MICADO as a function of integration time

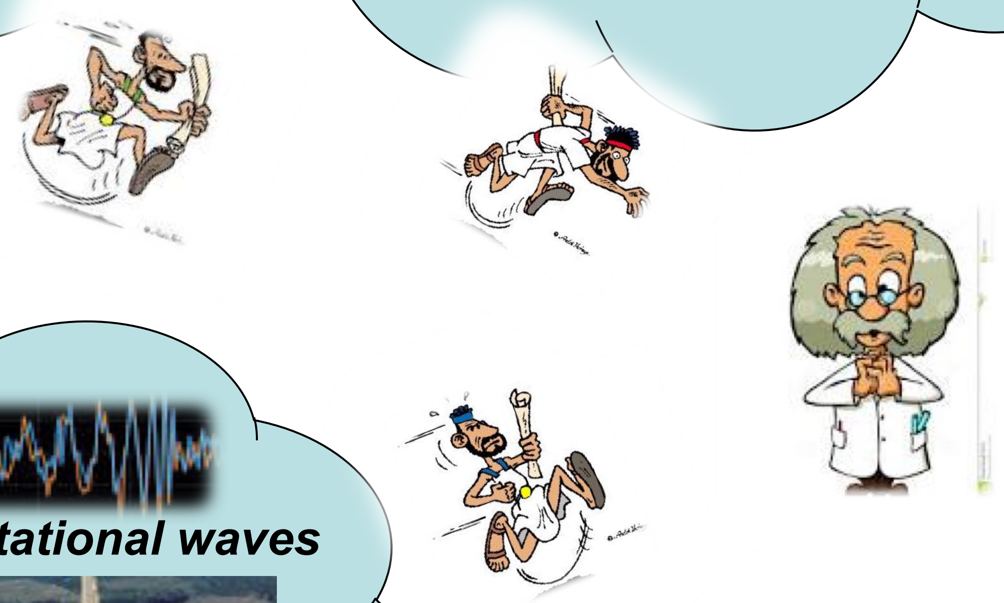
The Multi-Messengers Era



Photons



Neutrinos



Gravitational waves

Thank you