The Electromagnetic Follow-up of GW170817

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Why EM counterparts are interesting?

- Precise (arcsec) sky localization – e.g. link to EM event
- Energetics – e.g. EM emission (beamed and isotropic)
- Host galaxy – e.g. Redshift, Environment (stellar populations, dynamics..) where the EM counterparts are generated and evolve
- Nucleosynthesis of elements
- Cosmology
- Fundamental physics – e.g. speed of photons and gravitational waves (GW)
- Constraint models of GW+EM emitters

Our Group

GRAvitational Waves Inaf TeAm

www.grawita.inaf.it

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GSSI: M. Branchesi

University of Urbino: G. Stratta, G. Greco

SNS Pisa: M. Razzano, B. Patricelli,

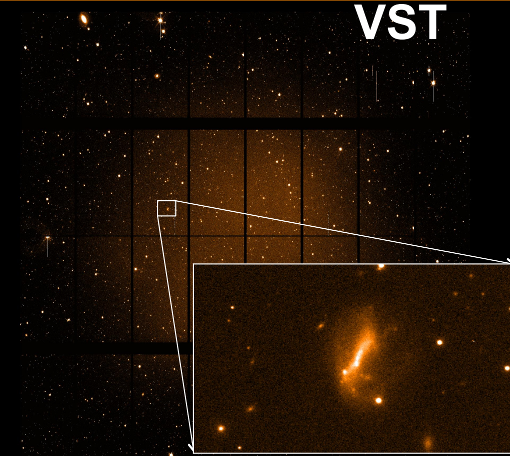
Space Science Data Center: L.A. Antonelli, **V. D'Elia**, S. Marinoni, P. Marrese,

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

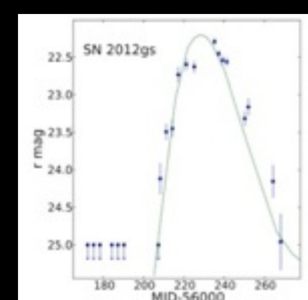


STEP 2
Observe & Characterize
The detected transients have to be observed to infer their nature

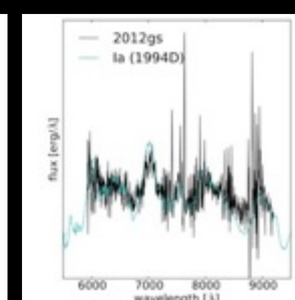
Telescopes for prompt spectroscopy of selected candidates at different latitudes/longitudes

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



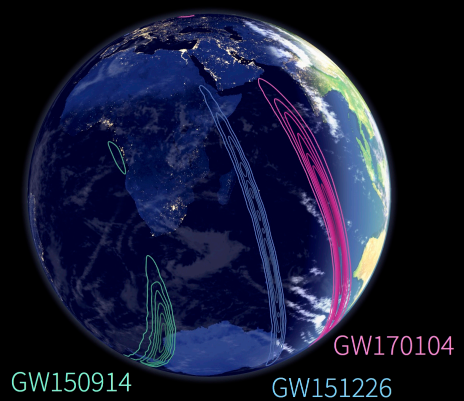
λ

Multi-wavelength Observing Facilities:

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

***Collaboration**: **ePESSTO** SWIFT, Magic, INTEGRAL , AGILE*
Positive interaction during O1+O2: Pan-Starrs, iPTF, VISTA, J-GEM

Transient objects in the LVC skymap

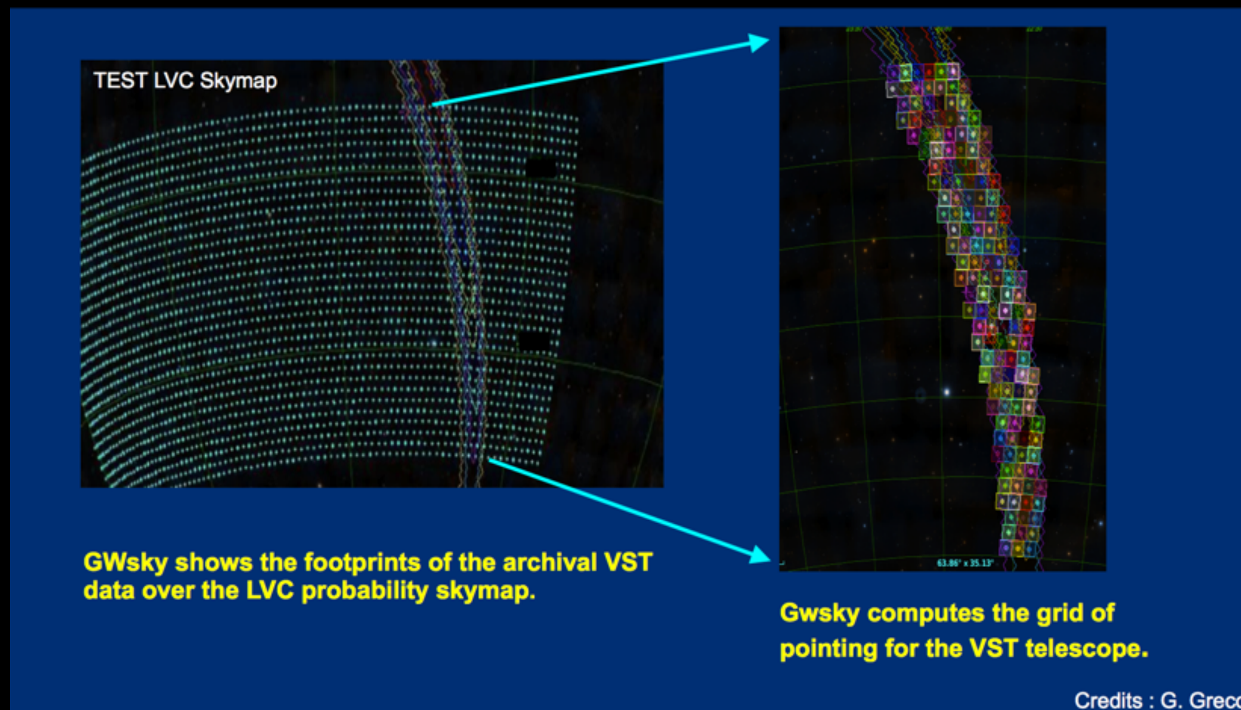


Credit: LIGO/Virgo/NASA/Leo Singer

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

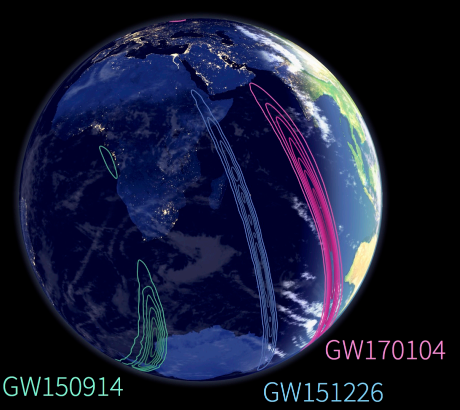
GW150914 ~ 600 deg^2
LVT151012 ~ 1600 deg^2
GW151226 ~ 1000 deg^2
GW170104 ~ 1200 deg^2

(90% credible areas)



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

GRAvitational Wave Inaf TeAm



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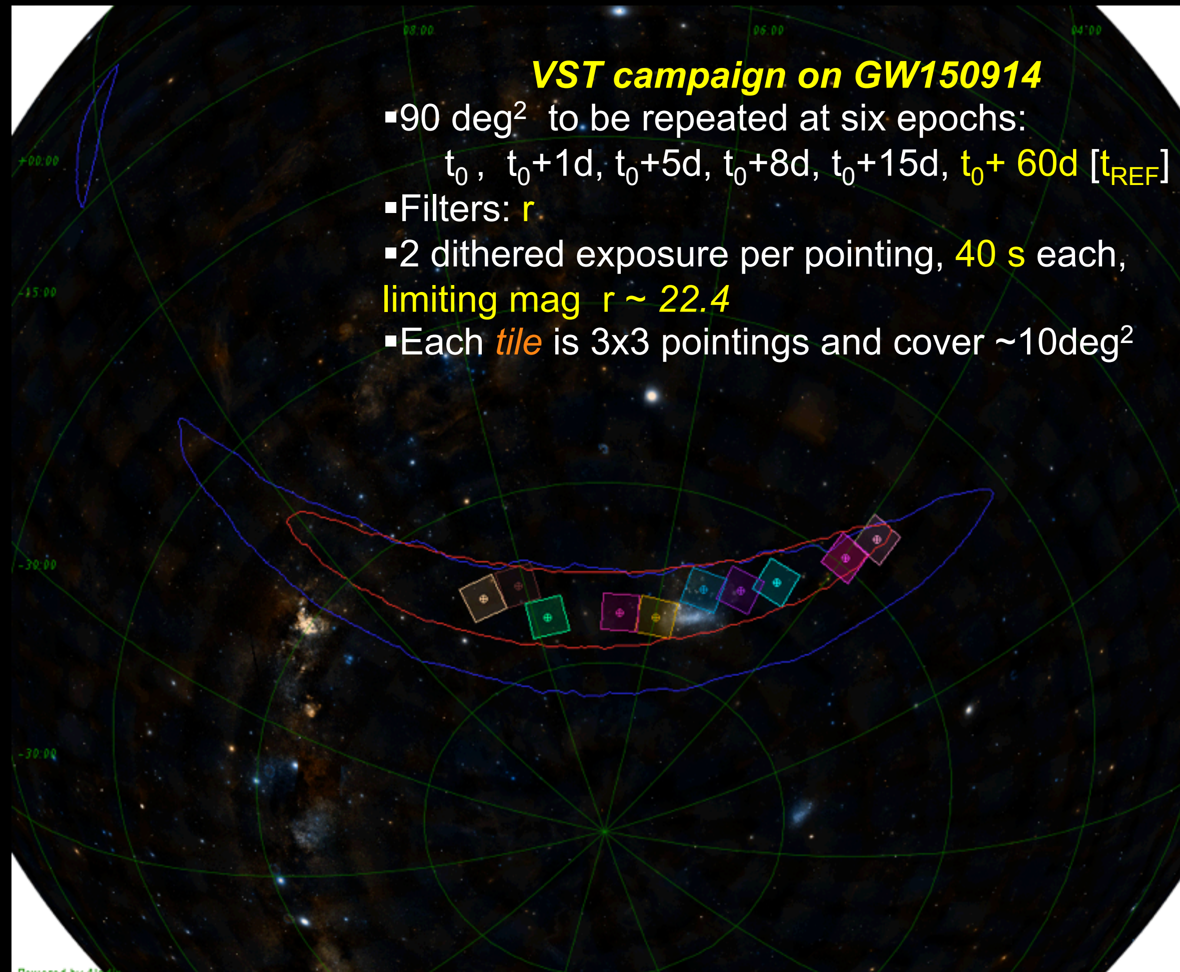
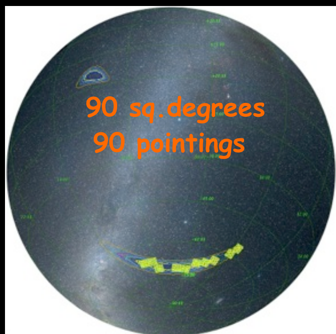
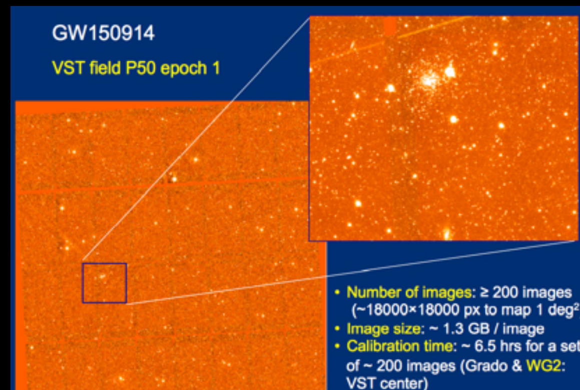


EXAMPLE OF GRAWITA RESPONSE

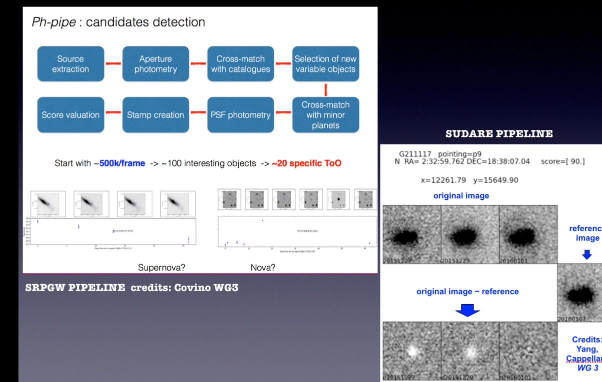
1. Tiling



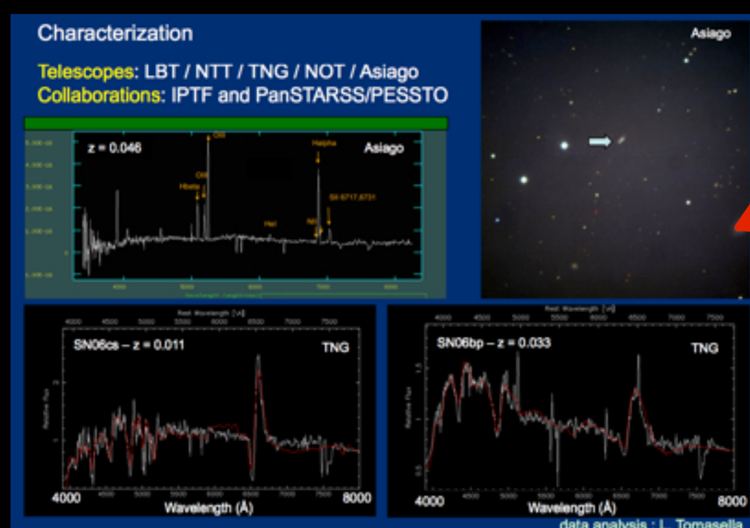
2. Observations



3. Search

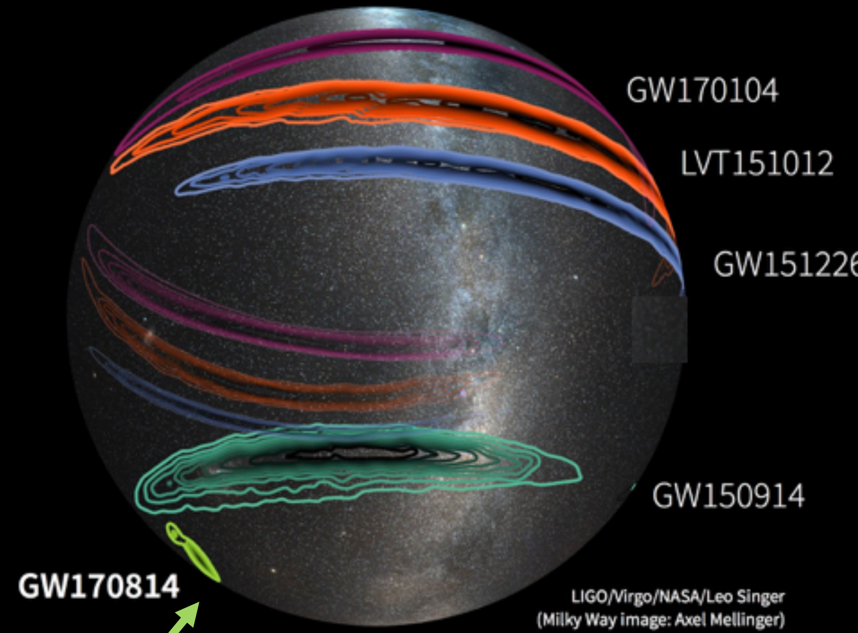


4. Characterization and follow-up



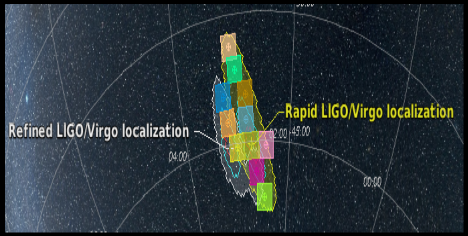
Example of GRAWITA response

Virgo made a key improvement on sky maps

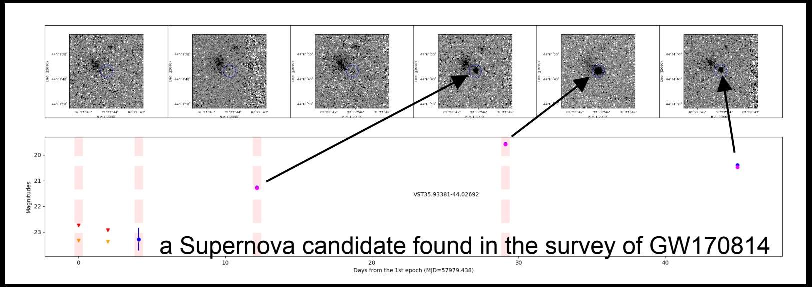


GW170814 ~ 60 deg^2

(90% credible areas)



VST observed
~ 80% of the sky map



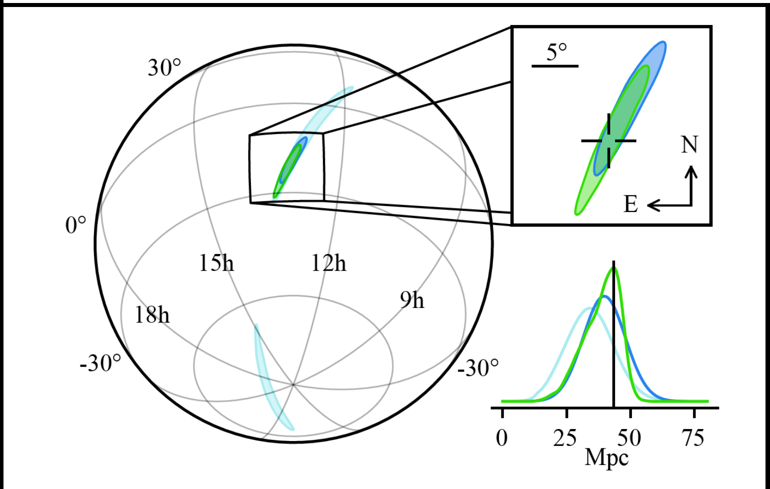
a Supernova candidate found in the survey of GW170814

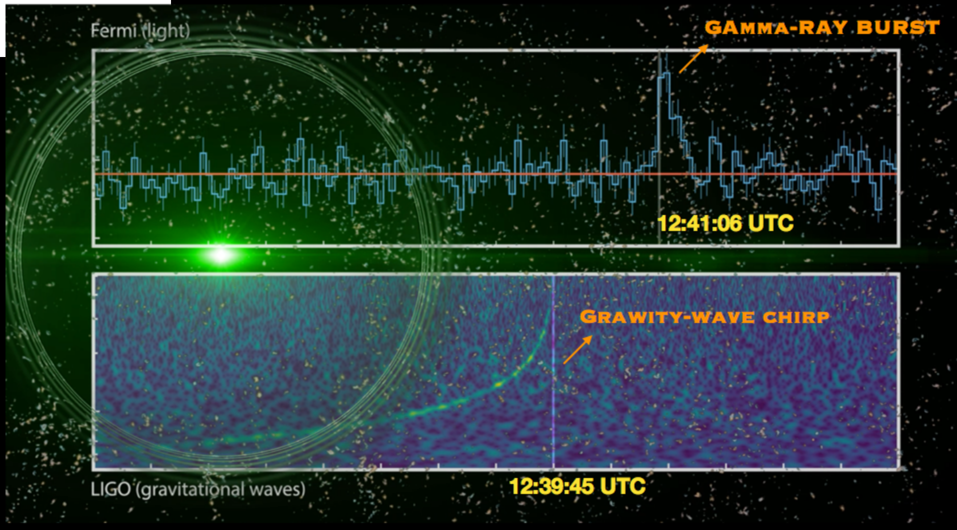
2017/08/17 UT: 12:41:04.445710

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 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
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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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: 6.4786e-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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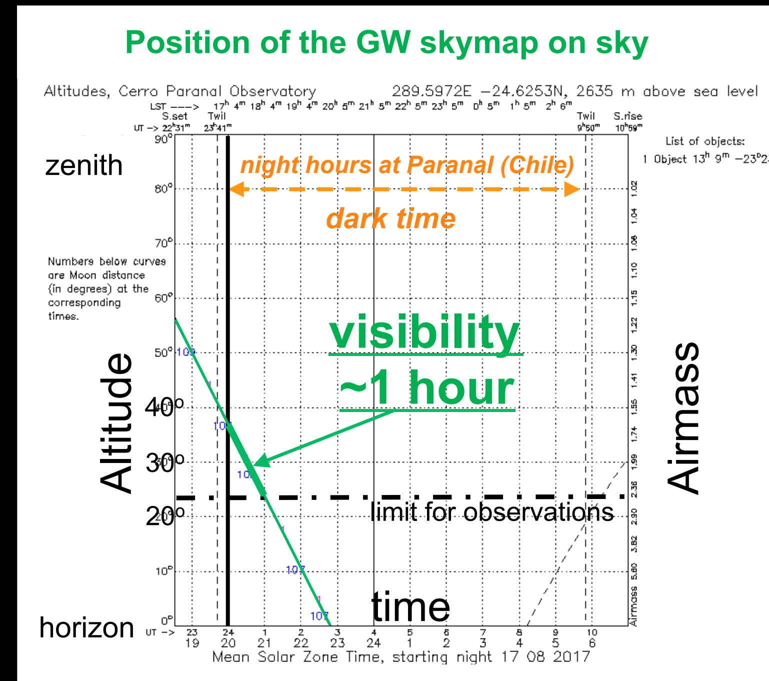
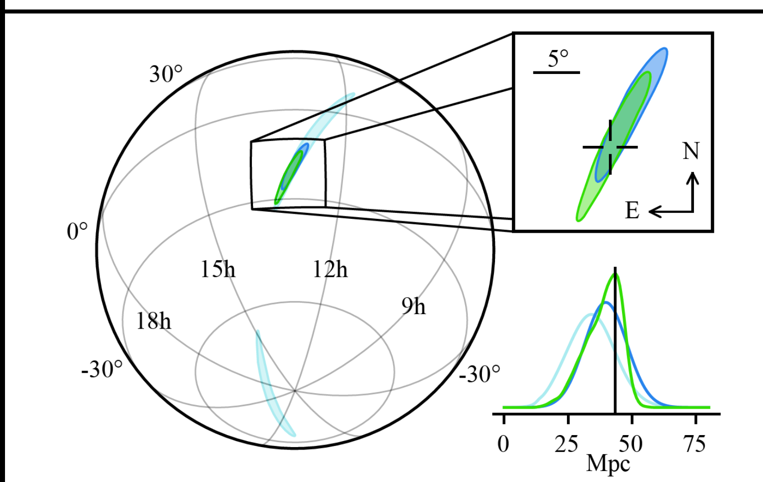
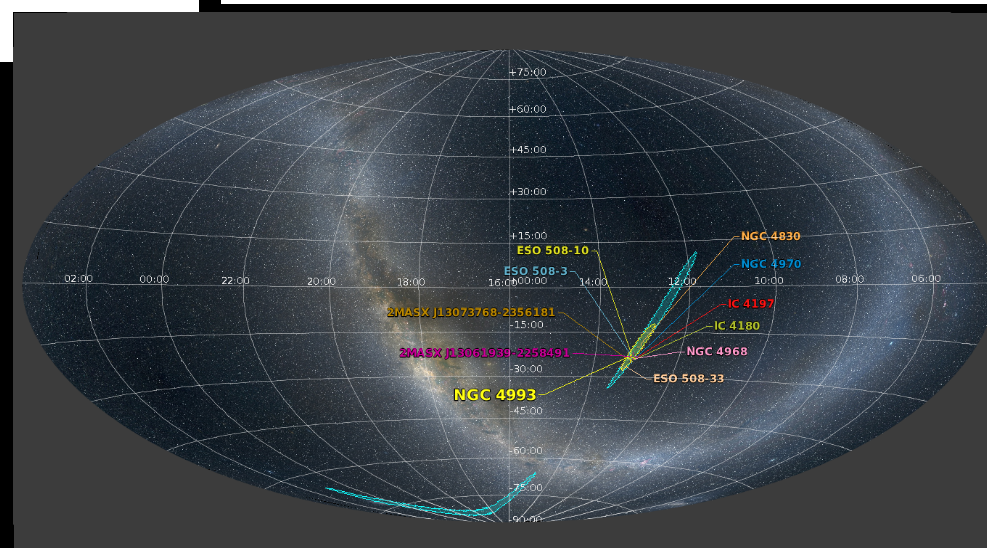
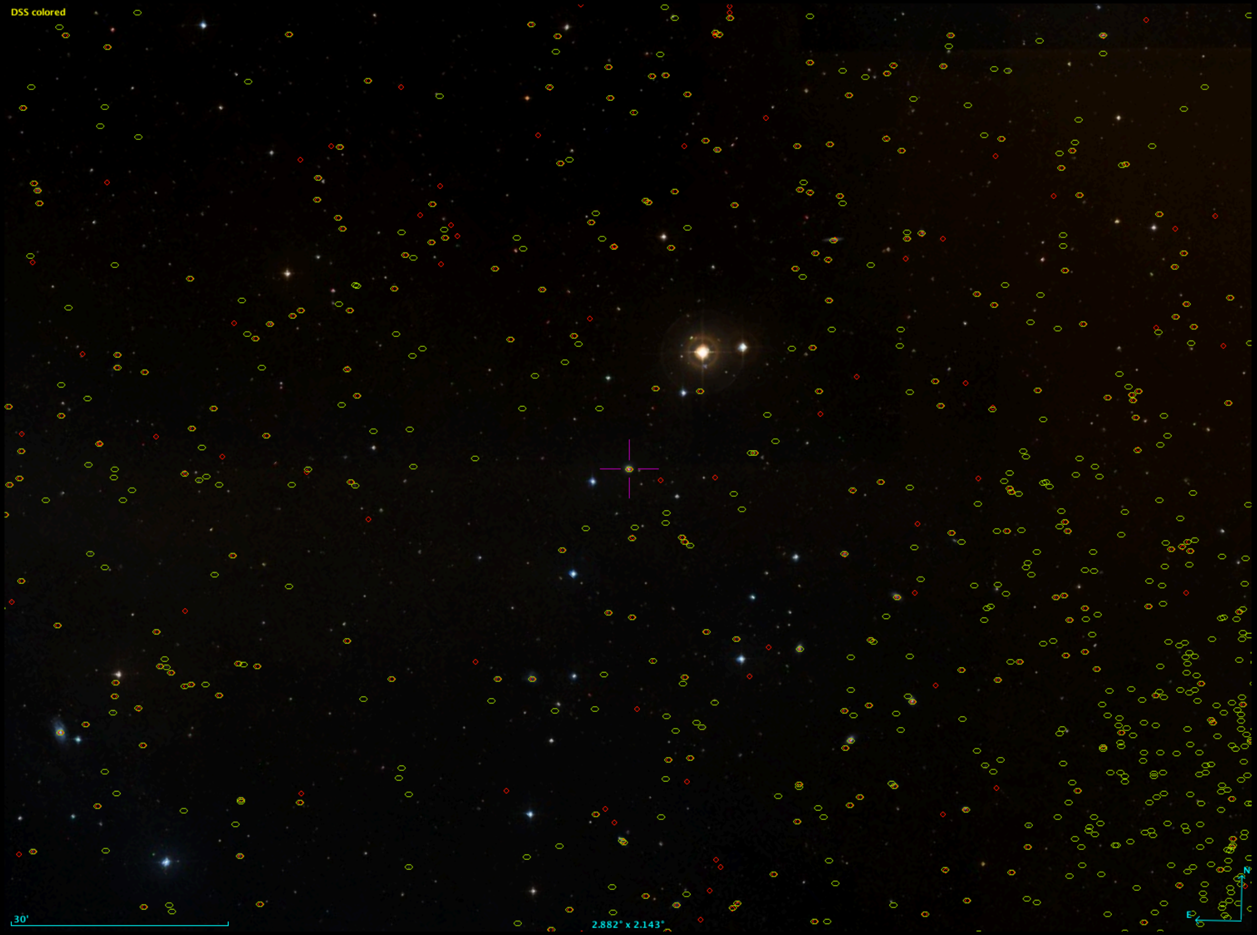






Observational strategies

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



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

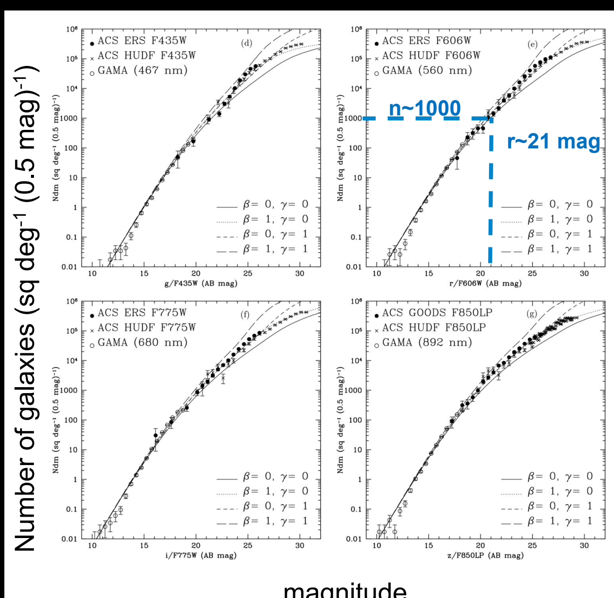
Observational strategies

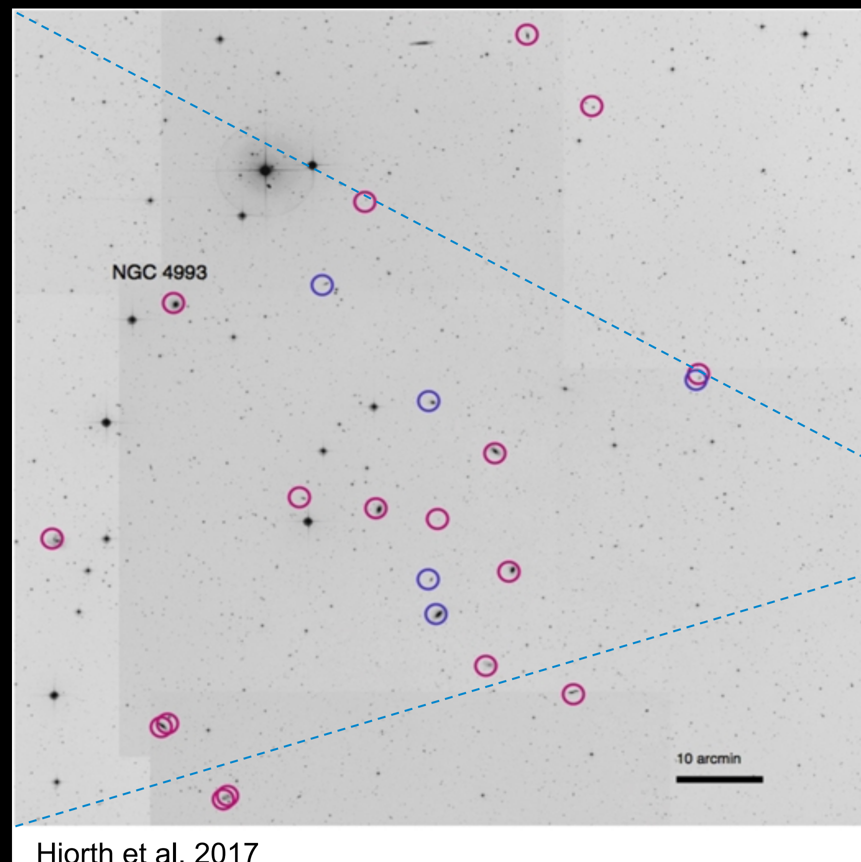
When the distance (including uncertainties) is available, (no mosaics) the best observing strategy is

Galaxy targeting strategy :

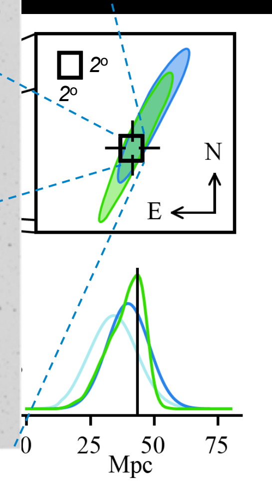
•Select a sample of galaxies using catalogs of galaxies with known distances. Constrains: position (LVC skymap) + distance (in the range given by LVC)
•Start observations (telescopes with small FoV are OK!) giving priority to high mass (luminosity) galaxies

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



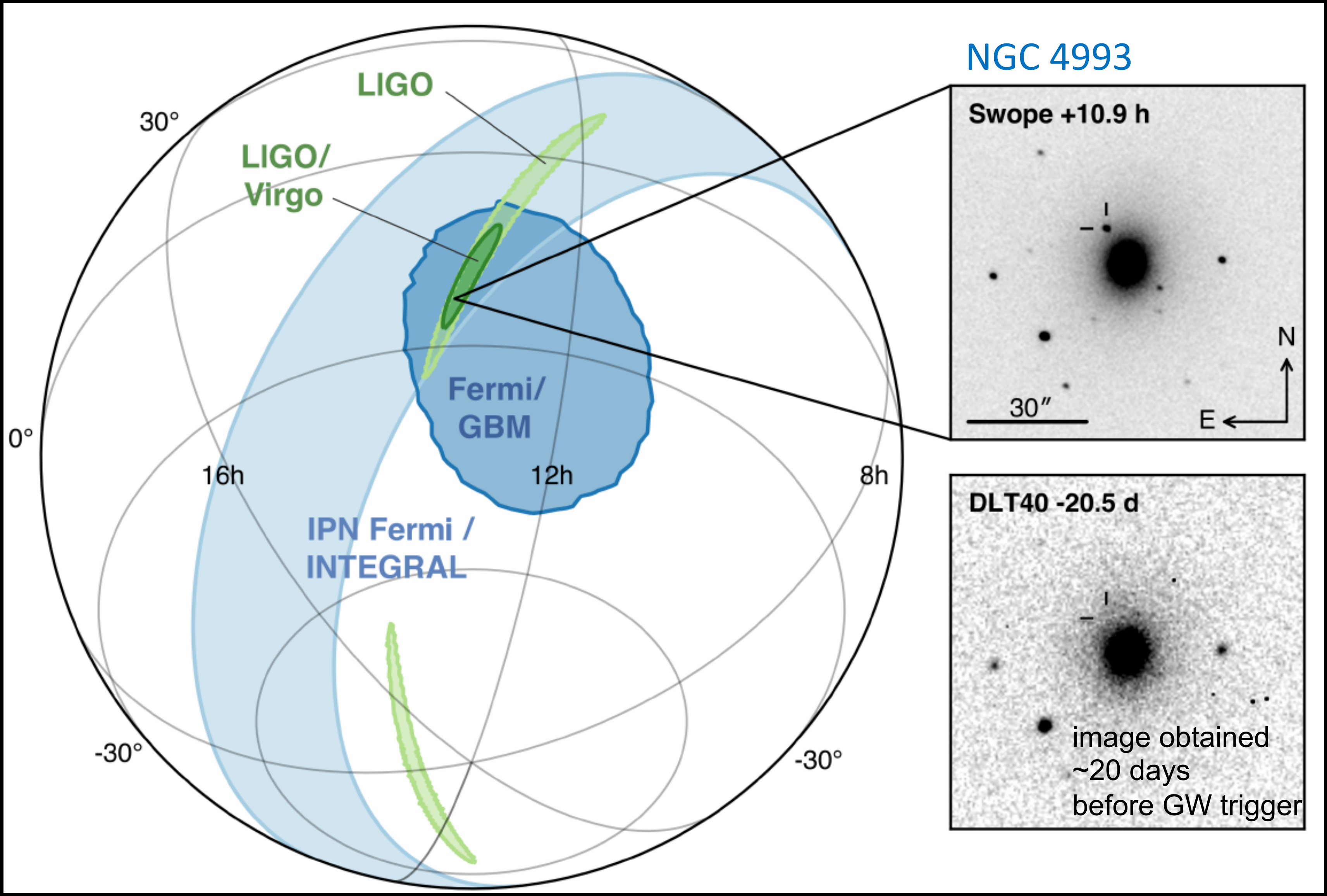


Inside the entire LVC skymap of GW170817 can be found **~50 galaxies** in the range **25 < d(Mpc) < 50**

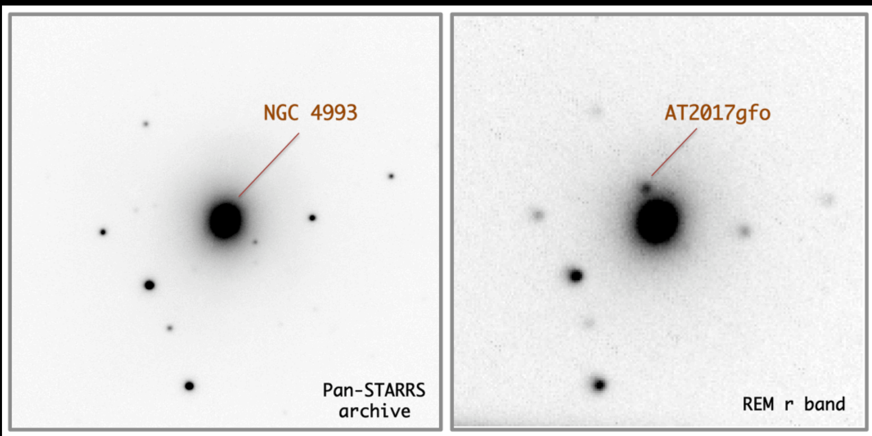


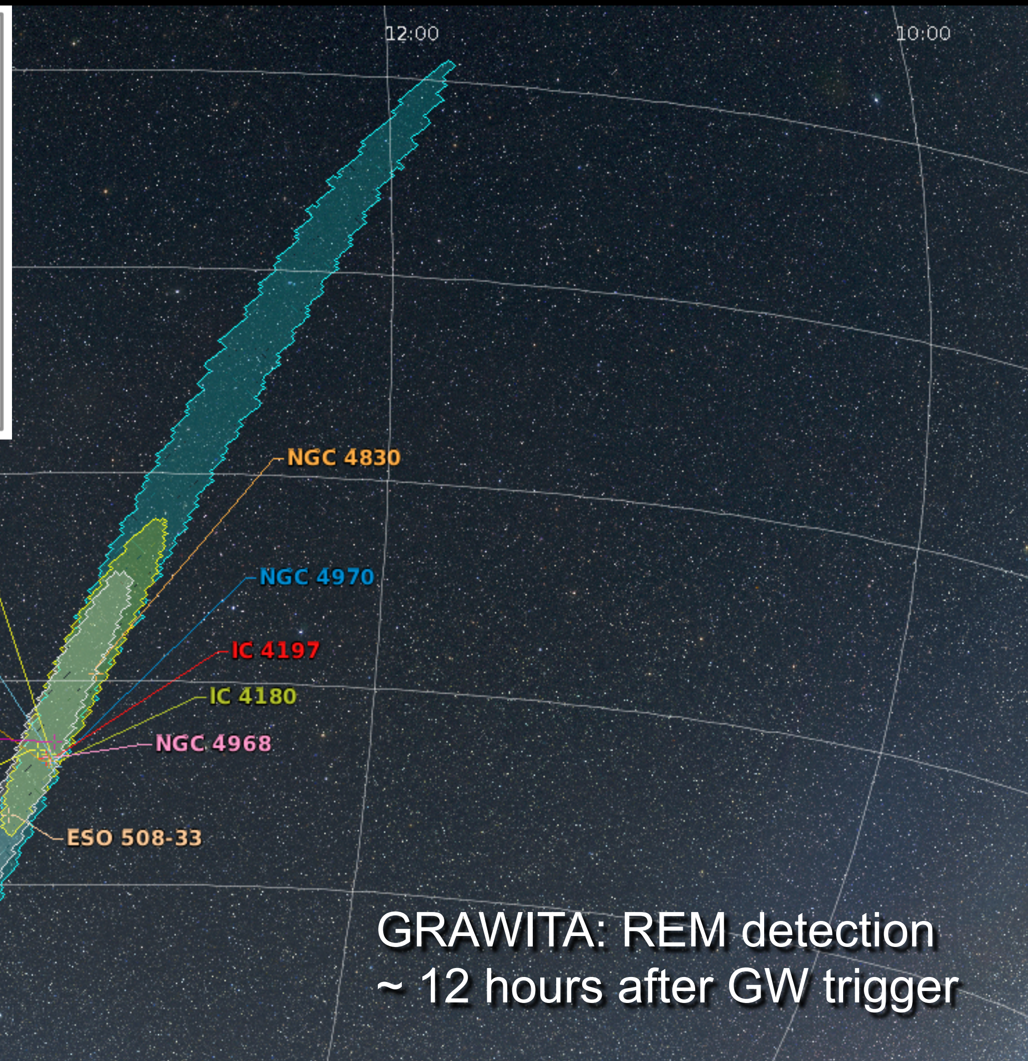
Discovery of an Optical/nIR Transient

OPTICAL counterpart detection ~ 11 hours after GW trigger



The Optical/nIR Transient





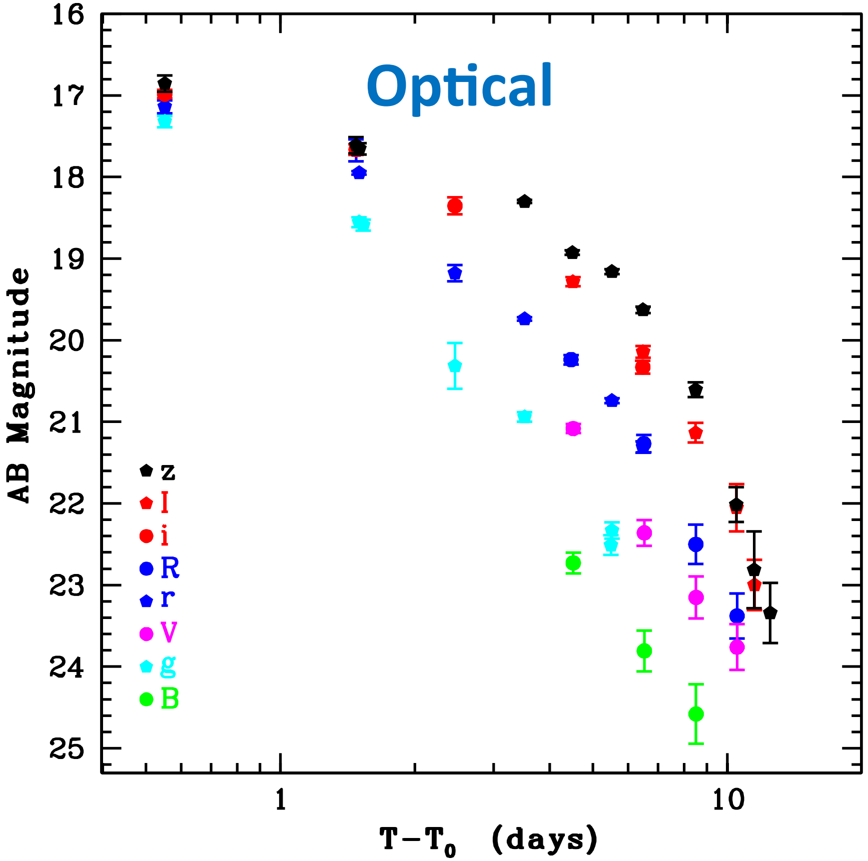
GRAWITA: REM detection
~ 12 hours after GW trigger

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

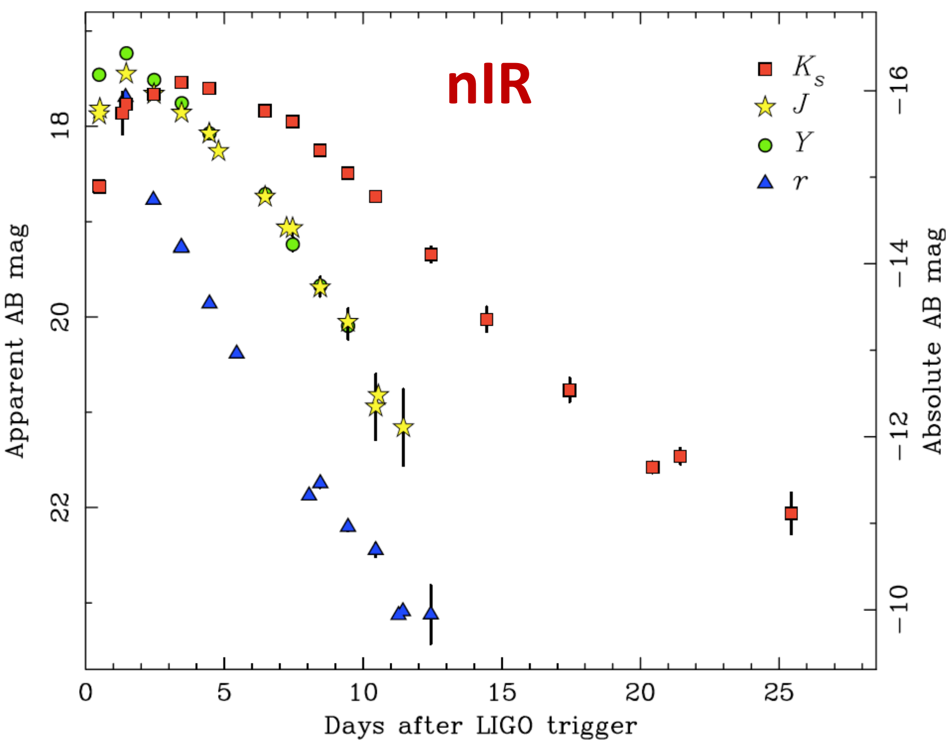
The Optical/nIR Transient

Optical and near-infrared light curves of AT2017gfo

Pian et al. 2017

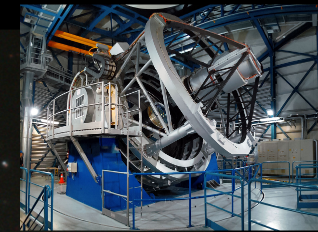


Tanvir et al. 2017

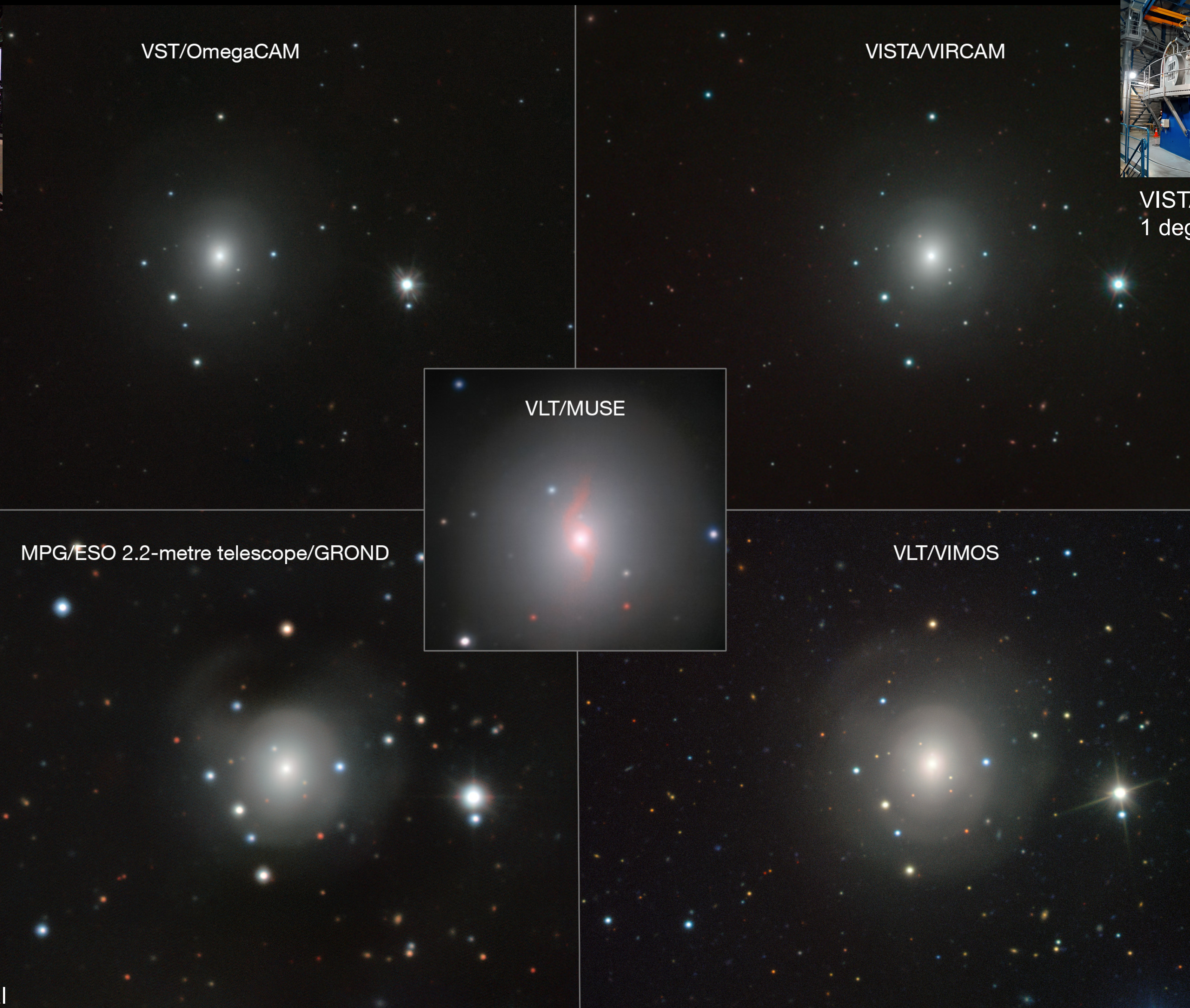


The Optical/nIR Transient

VST 2.6m Optical
1 deg FoV



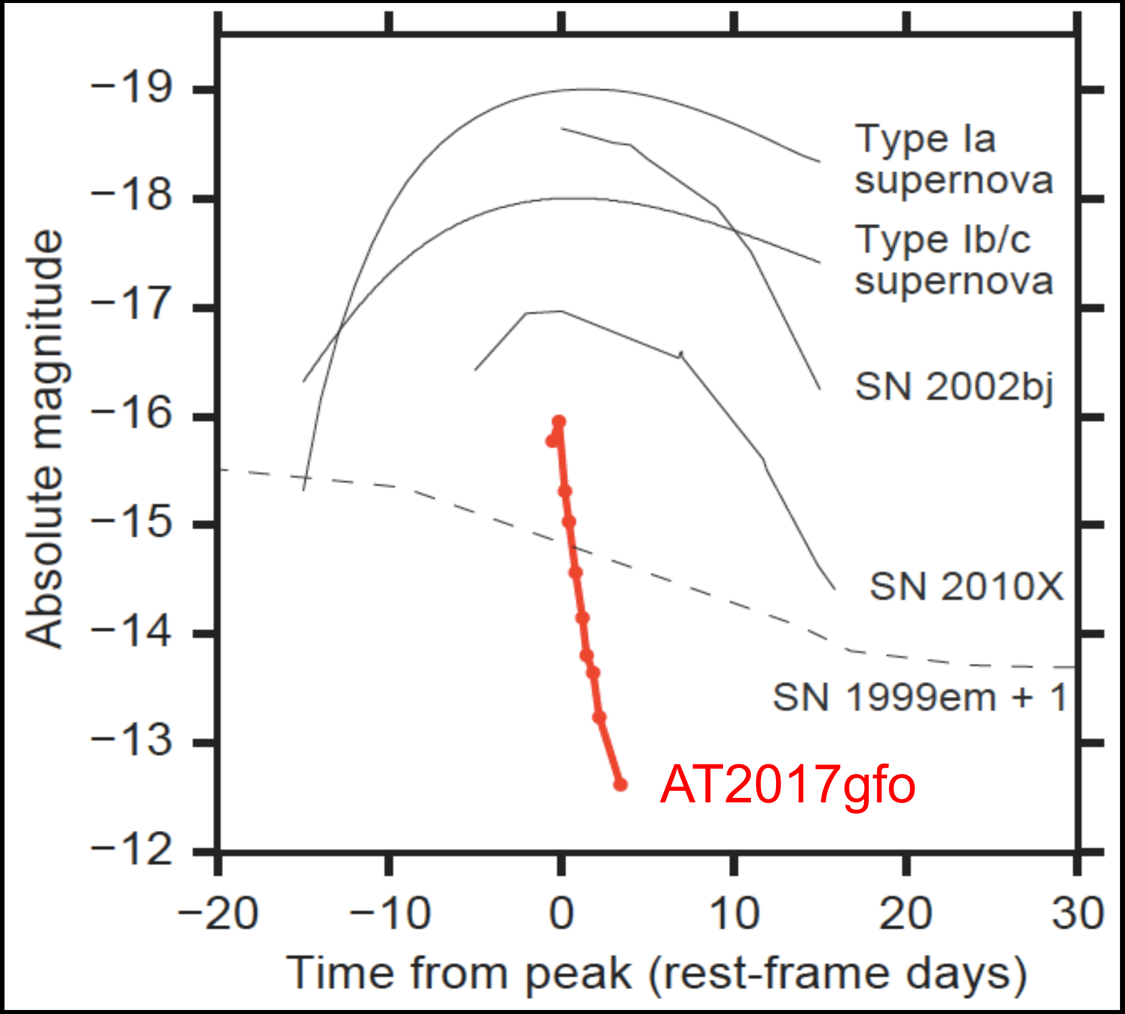
VISTA 2.6m nIR
1 deg FoV



MPG/ESO 2.2m Optical

VLT Unit 1
8.2m nIR

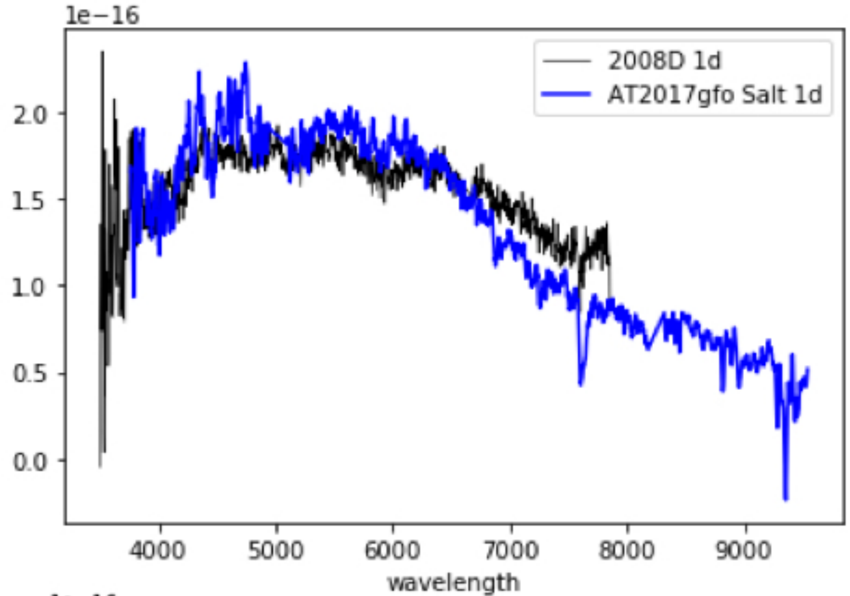
AT2017gfo evolves much more rapidly than any supernova

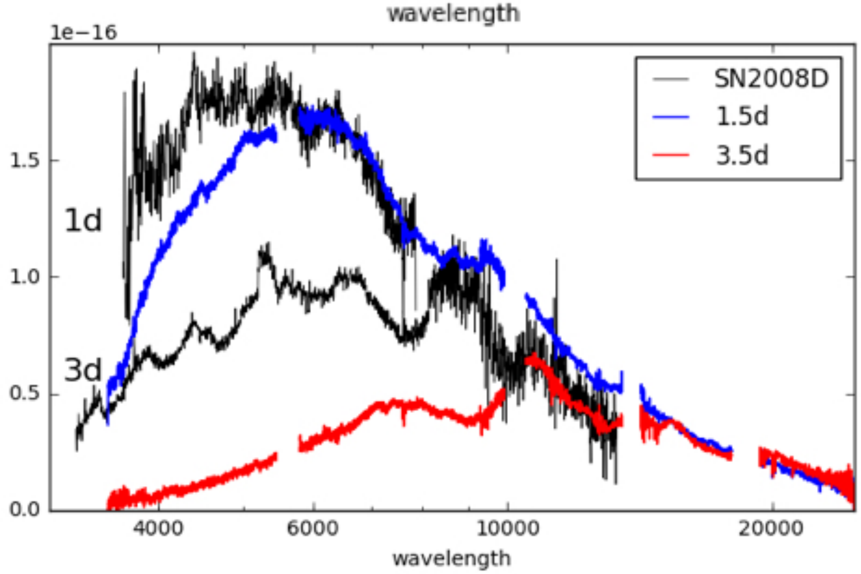


Arcavi et al. 2017

The Optical/nIR Transient

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



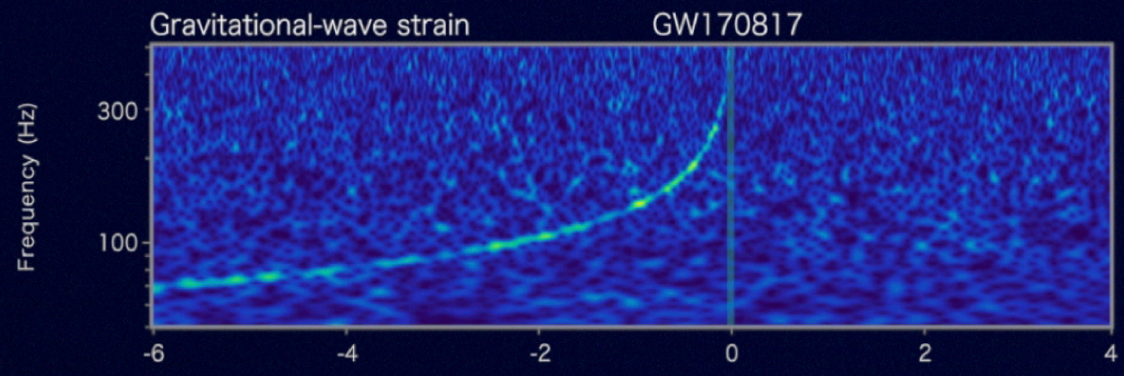


The low S/N spectrum ***at 1 day*** matches very well that of the supernova ***SN2008D / XRF080109 (type Ibc)*** at a similar phase.

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.

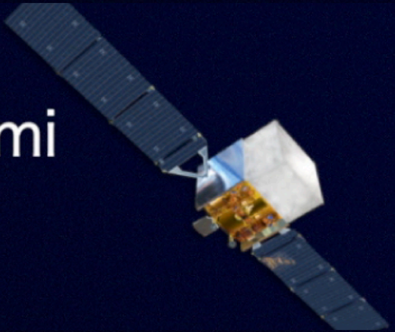
GW signal and sGRB detection

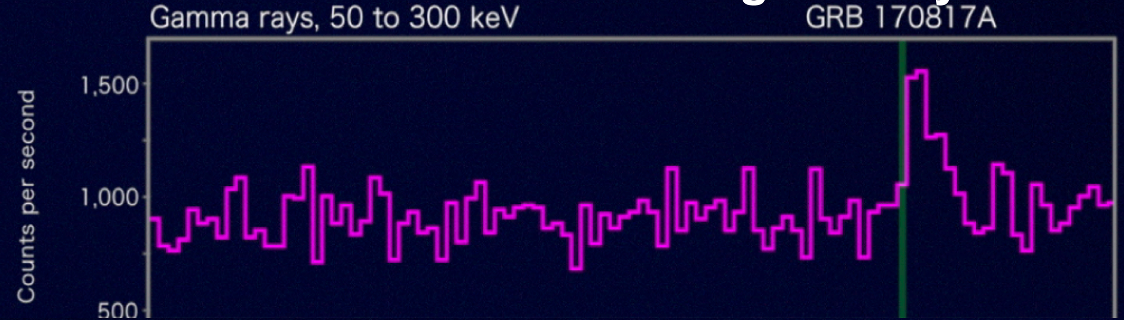
LIGO-Virgo



sGRB lags GW by 1.7 s

Fermi





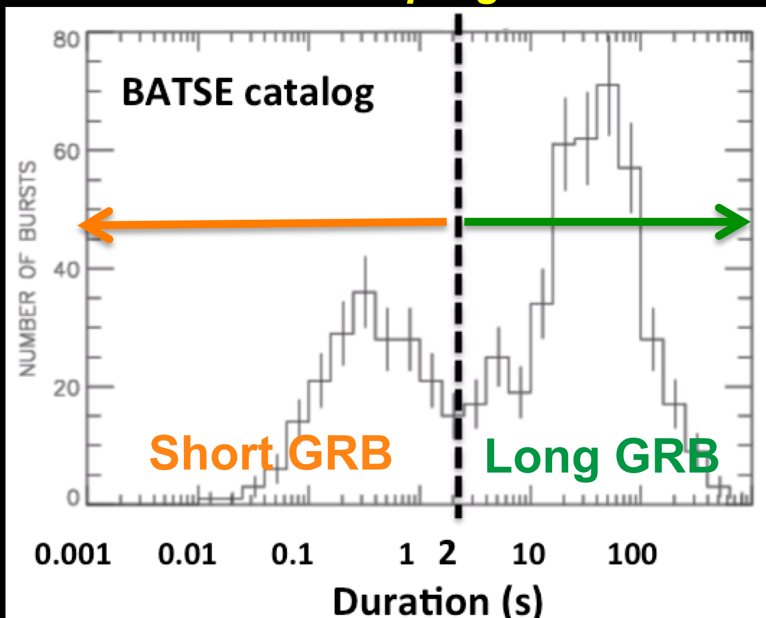
INTEGRAL

***First direct evidence** that NS mergers are progenitor of short GRB*

BNS Merger: What we expected

Gamma Ray bursts were discovered in the late 1960s

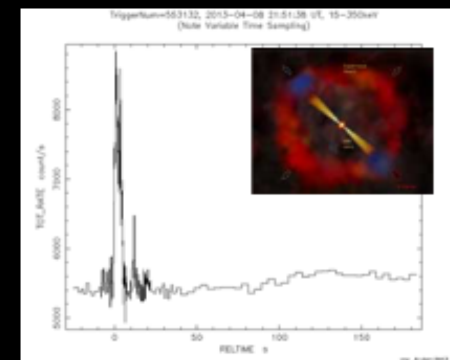
Bimodal duration distribution
and *different progenitors*



Kouveliotou et al. 1993

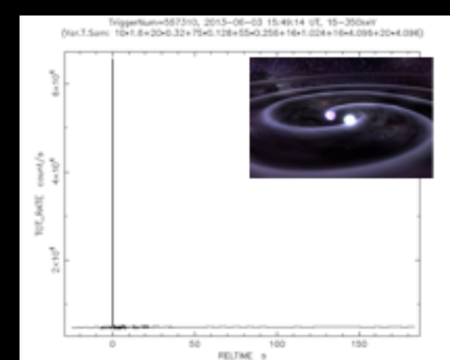
Core-collapse of massive stars

Long Gamma Ray Burst (lGRB)
•observed Type Ic SN spectrum
•accretion disk is fed by fallback of SN material onto disk, timescale t ~ 10-100s



Short Gamma Ray Burst (sGRB)
•lack of observed SN
•association with older stellar population
•larger distance from the host galaxy center (~5-10 kpc)
•accretion timescale of disk in binary merger model is short (t~1s)

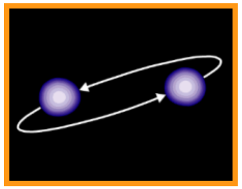
NS – NS
NS – BH
mergers

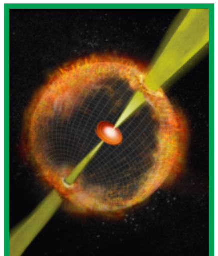


BNS Merger: What we expected

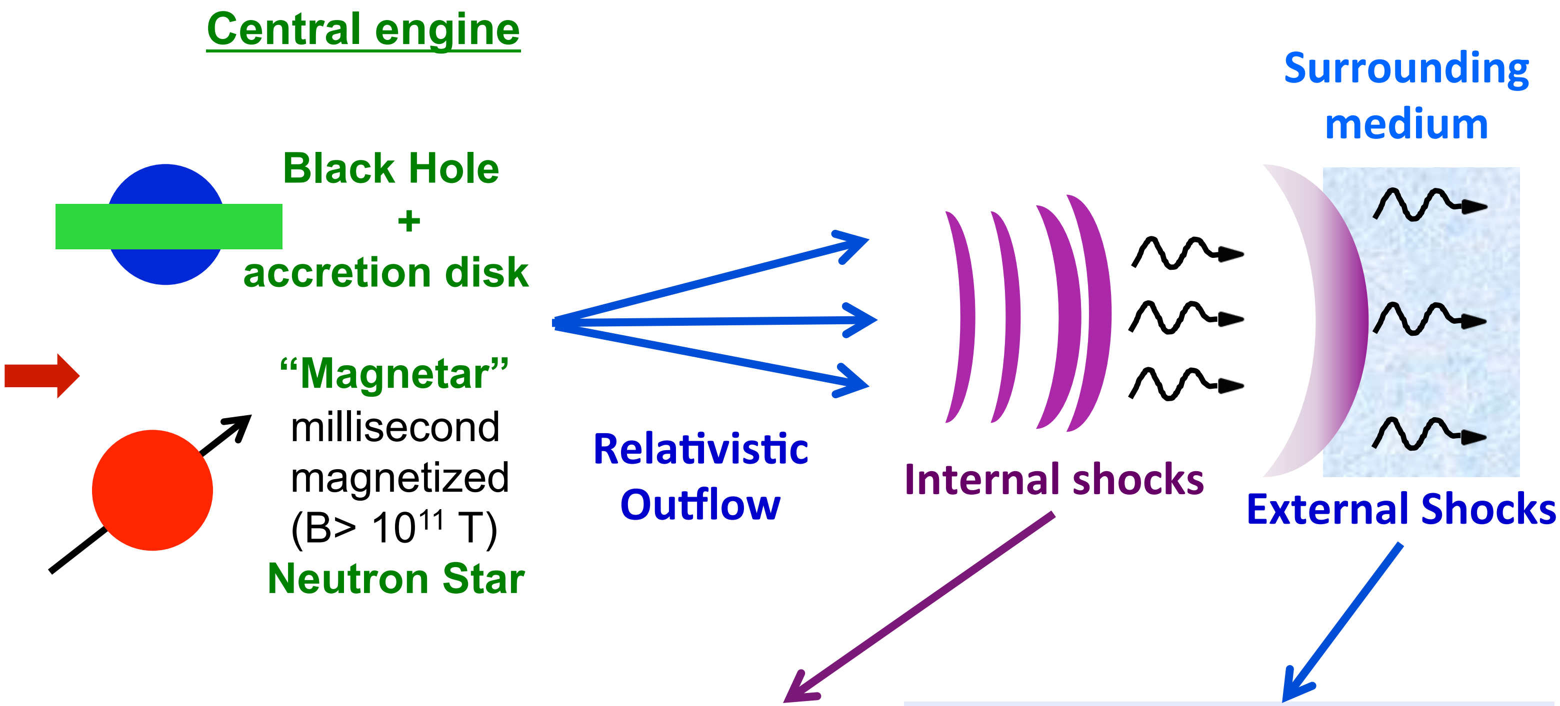
GRB emission – Fireball Model

NS – NS
NS – BH
mergers





Core-collapse of massive stars



Prompt emission

ϒ-ray - within seconds

Afterglow emission

Optical, X-ray, radio -
hours, days, months

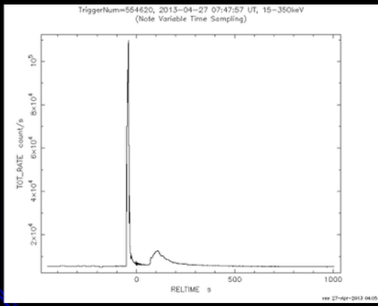
Kinetic energy of the relativistic jet converted into radiation
Mjet = 10^{-7}-10^{-5} Mo, $\Gamma \geq 100$, E=10^{48}-10^{51} erg

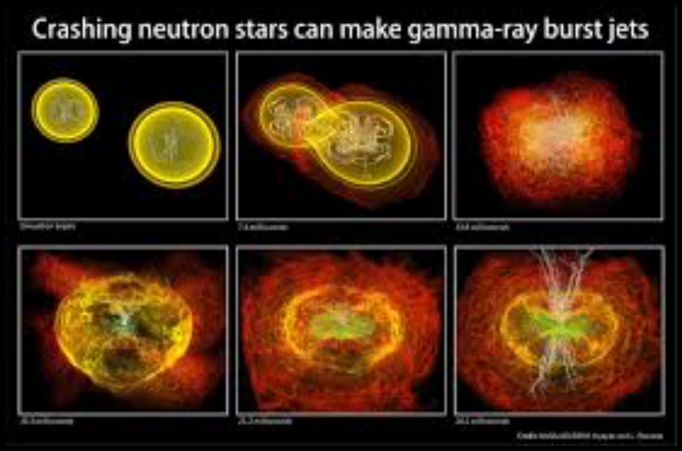
Credit : M. Branchesi

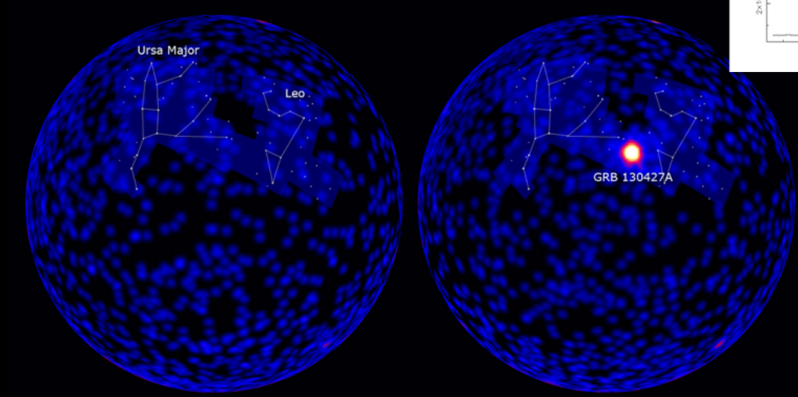
BNS Merger: What we expected

NS-NS and NS-BH mergers are expected to produce a
Collimated EM emission: Gamma Ray Burst (Short GRBs)

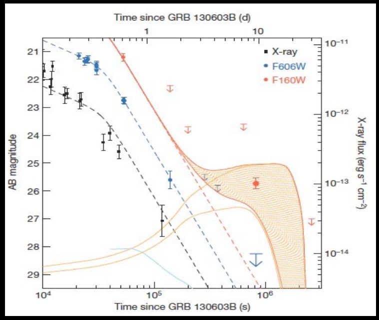
Associated to Short GRBs are also observed
X-ray/UV/optical/IR/radio counterpart (afterglow)







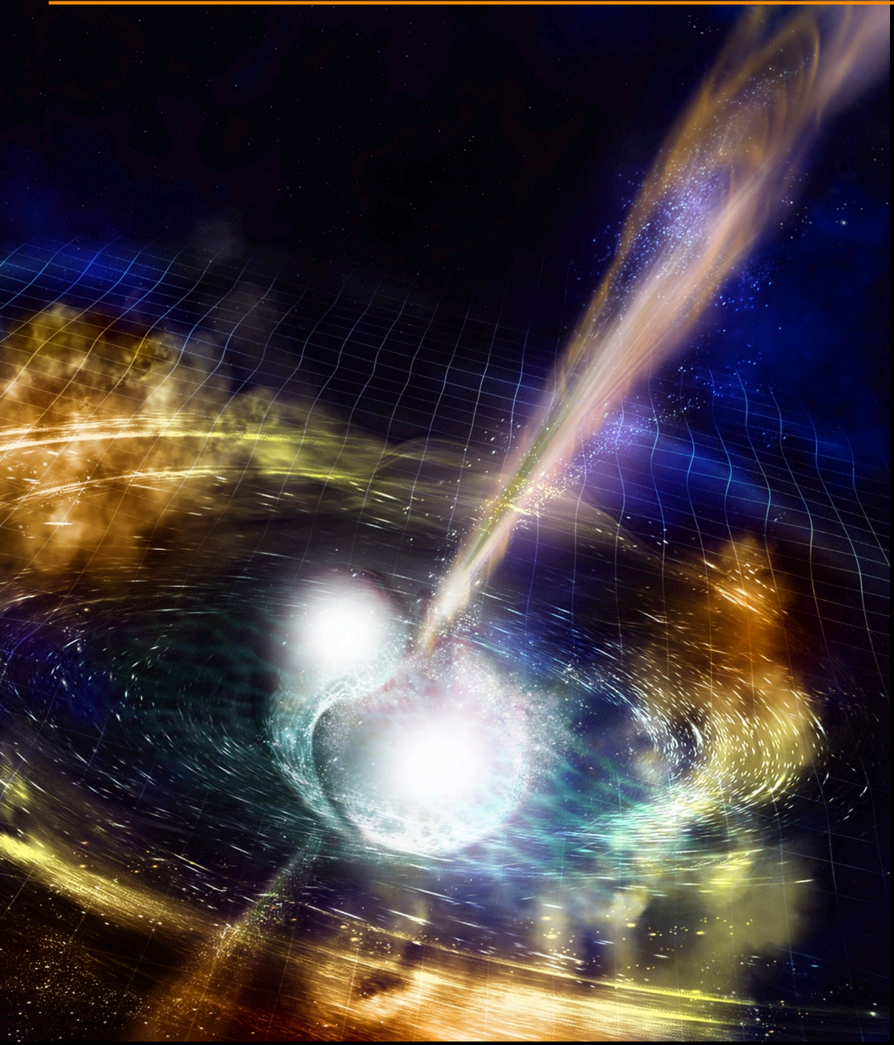
The Gamma-ray sky: Before and after Fermi LAT views of a sGRB

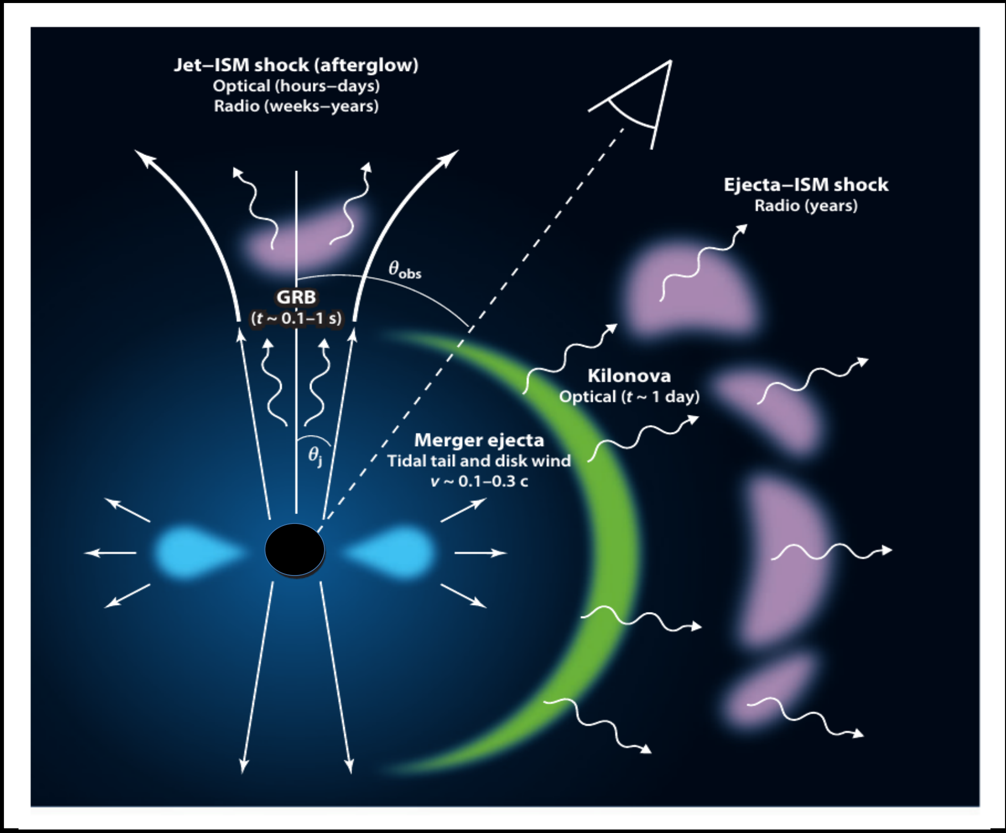


NS-NS and NS-BH mergers may also produce a
Optical/nIR isotropic emission: Kilonova/Macronova

Berger et al 2013, Tanvir et al 2013

BNS Merger: What we expected





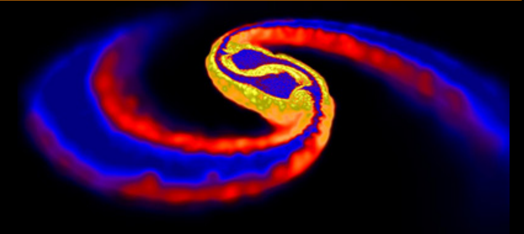
Metzger & Berger et al 2011

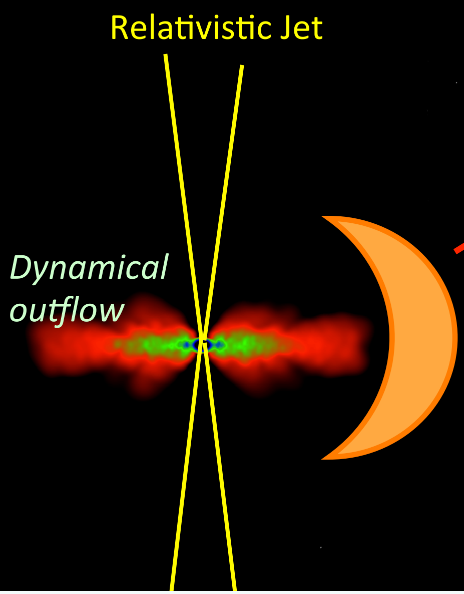
The Optical/nIR Transient (video)

Photometric and Spectroscopic evolution of AT2017gfo

BNS Merger: Kilonova models

Significant **mass (0.01-0.1 M_o)** is **dynamically ejected**
during **NS-NS NS-BH mergers**
at **sub-relativistic velocity (0.1-0.3 c)**





Rosswog et al. 2013

r-process

Neutron capture rate much faster than decay, special conditions:
T > 10^9 K, high neutron density 10^{22} cm^{-3}

nucleosynthesis of heavy nuclei

↓

radioactive decay of heavy elements

↓

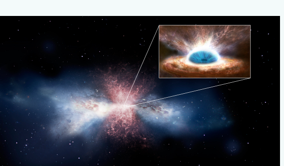
Power MACRONOVA
short lived IR-UV signal (days)

Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507 Metzger et al. 2010, MNRAS, 406; Tanaka et al. 2014 ApJ, 780; Barnes & Kasen 2013, ApJ, 775.

Accretion disc wind outflow

→winds unbind a fraction of the disk

→neutrino irradiation raises the electron fraction → No nucleosynthesis heavier element/high-opacity
→ brief (~ 2 day)
blue optical transient

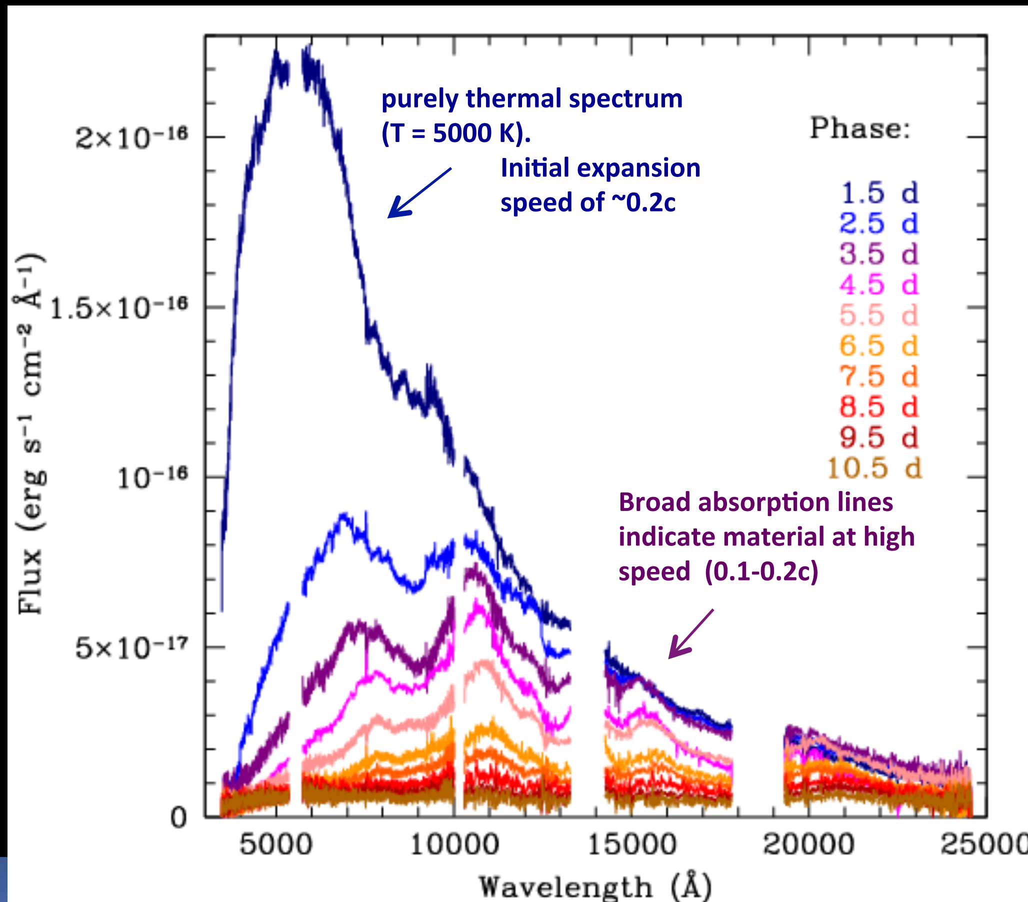


Kasen et al. 2015, Perego et al. 2014

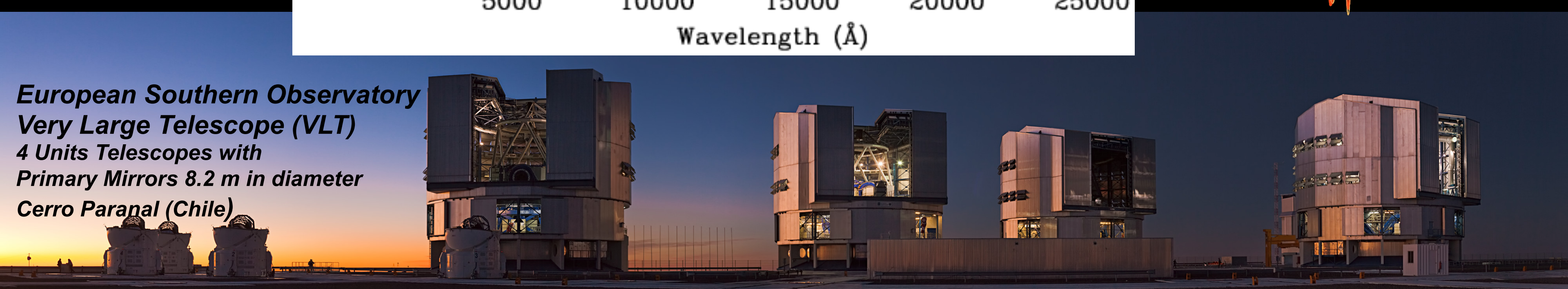
Credit : M. Branchesi

The Optical/nIR Transient

ESO VLT X-Shooter spectral sequence of AT2017gfo

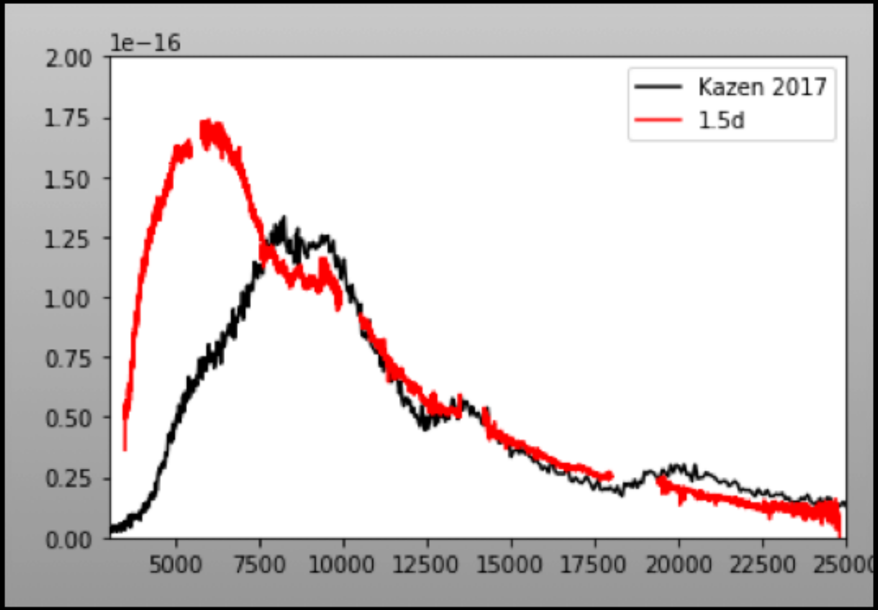


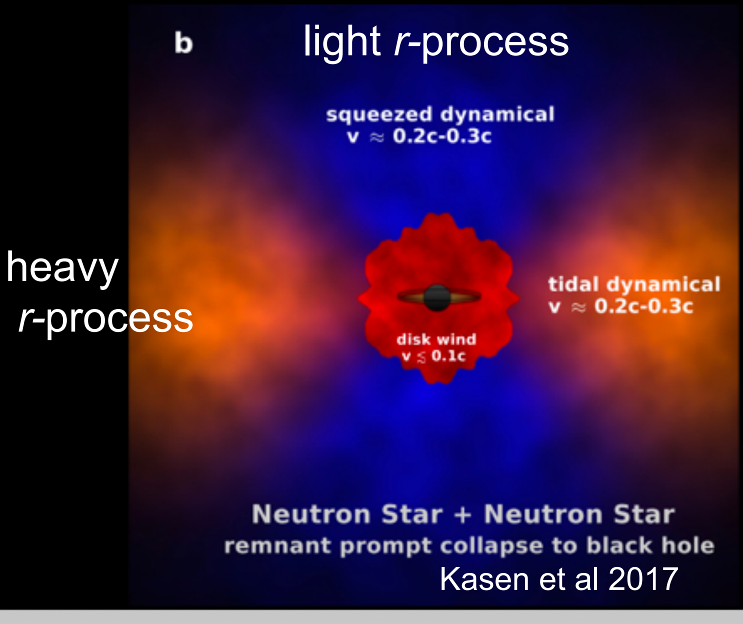
Pian et al. 2017;
Smartt et al. 2017



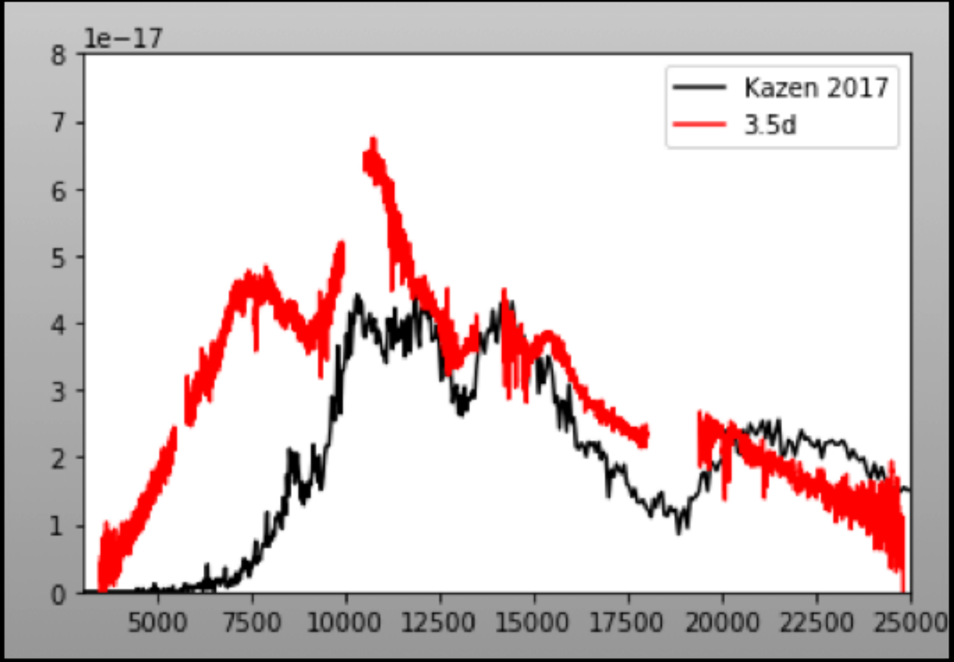
European Southern Observatory
Very Large Telescope (VLT)
4 Units Telescopes with
Primary Mirrors 8.2 m in diameter
Cerro Paranal (Chile)

BNS Merger: Kilonova models



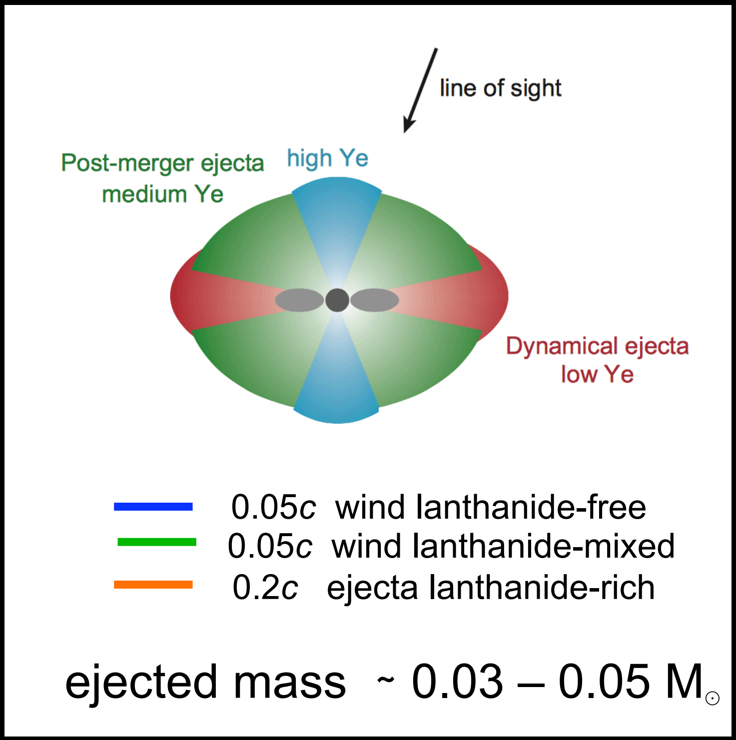


Models: Kasen et al 2017
Observations: Pian et al. 2017



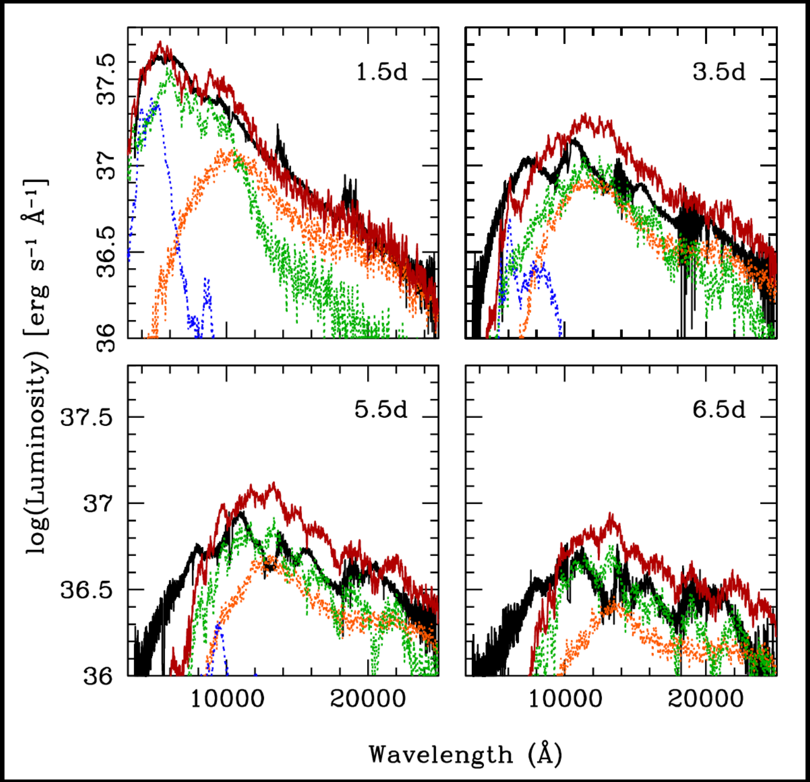
BNS Merger: Kilonova models

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)*.



Best fit requires three components

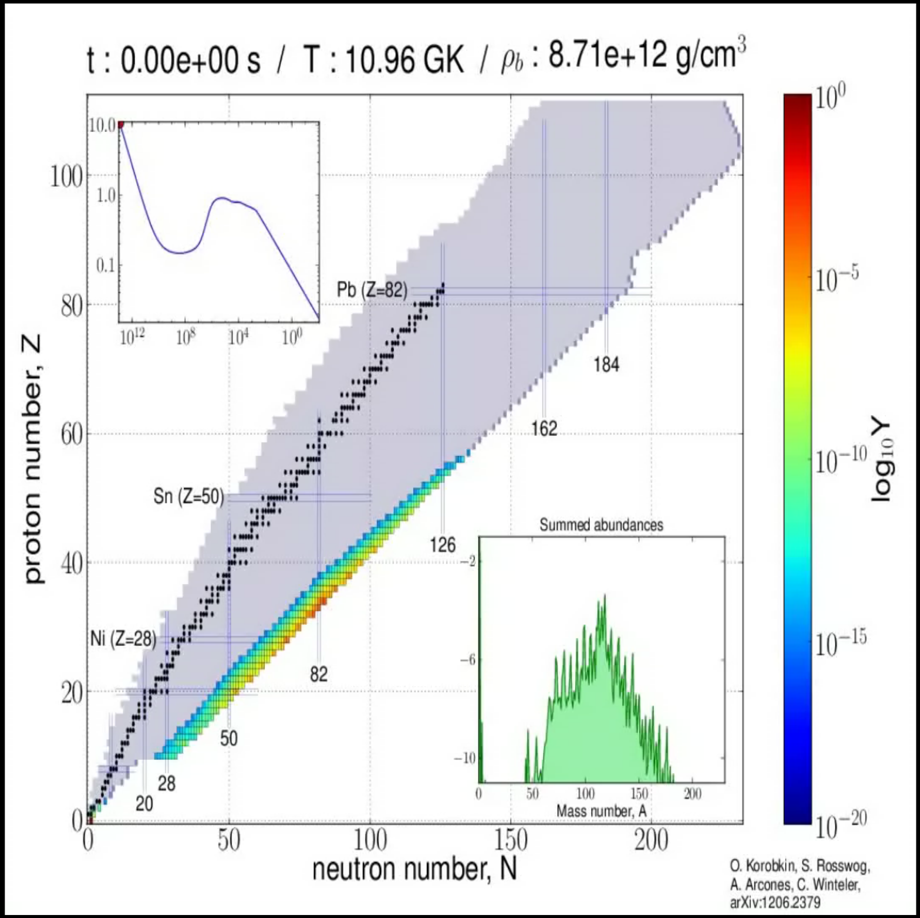
Models: Tanaka et al 2017
Observations: Pian et al. 2017



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

BNS Merger: Kilonova

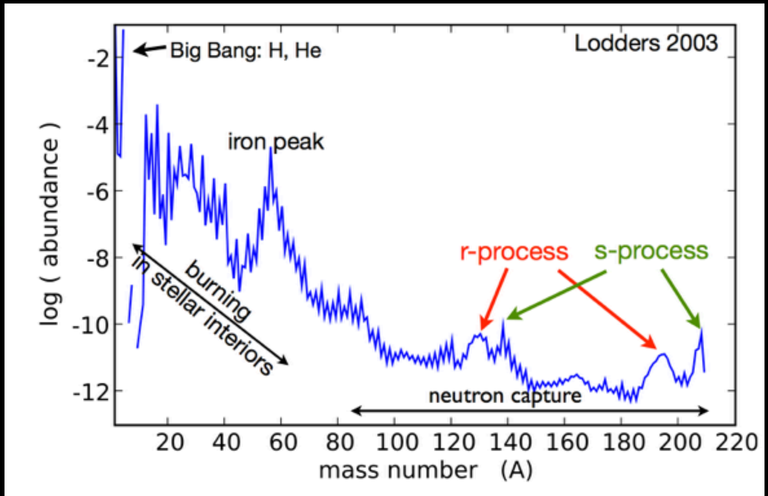
BNS and NS-BH mergers as factories of heavy elements



r-process elements:

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

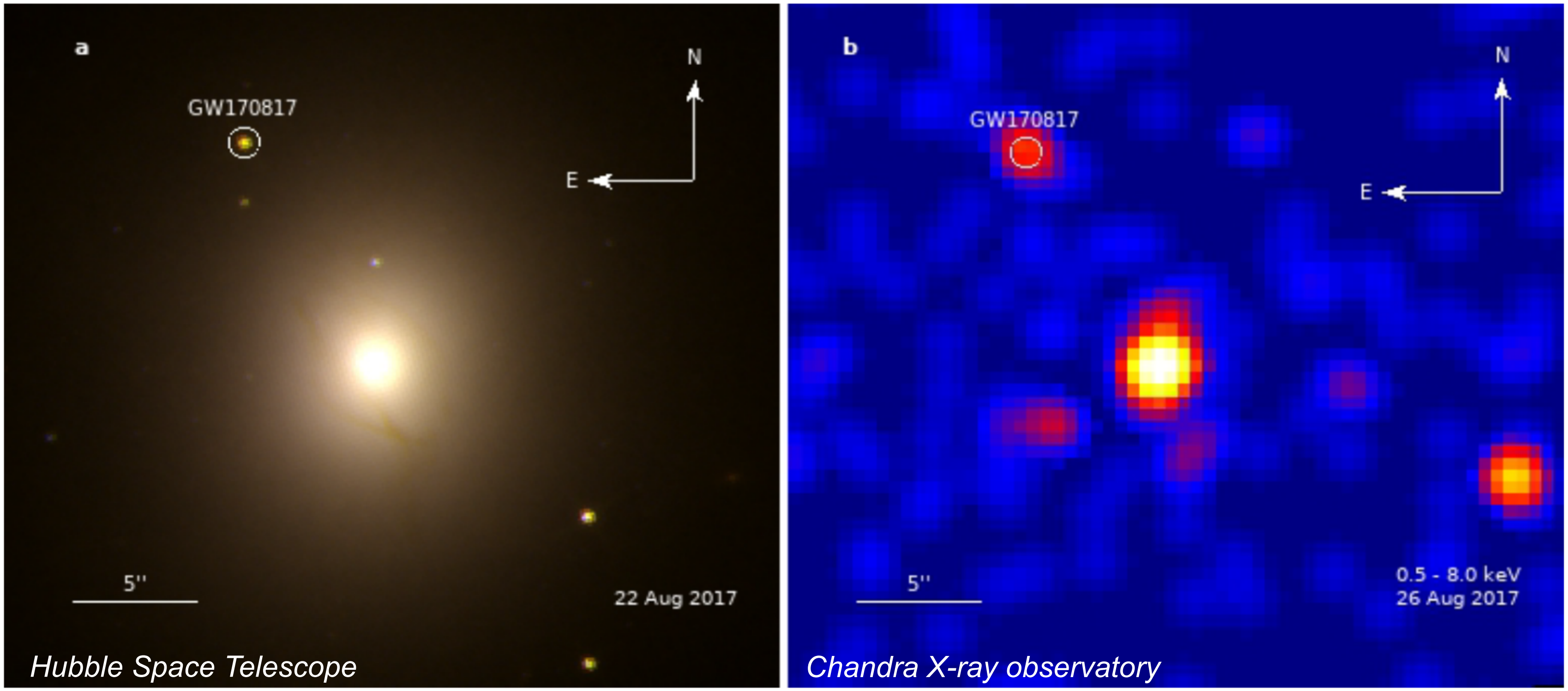
Solar system abundances



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

X-ray and Radio afterglow

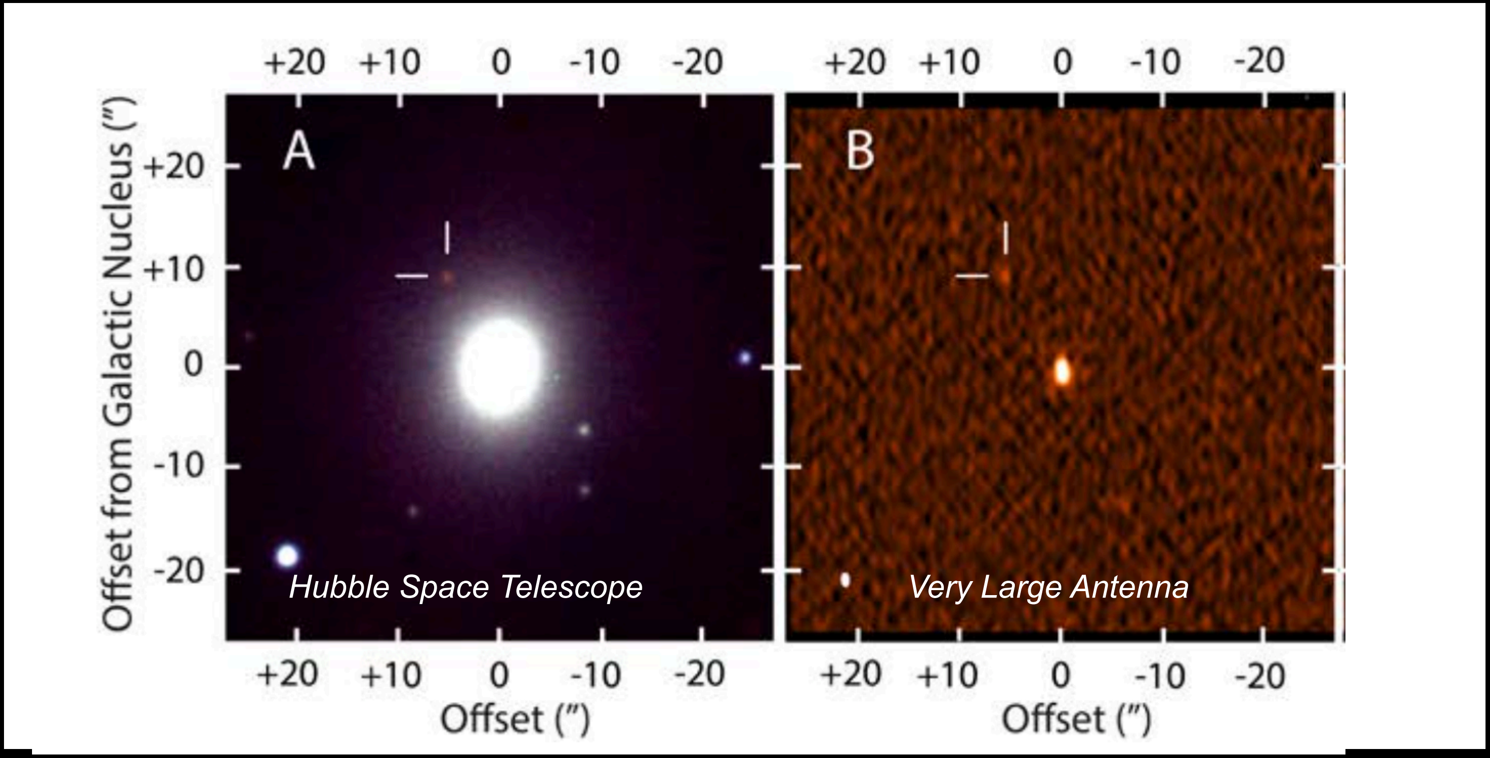
The 26 August 2017 the X-ray emission at the position of GW170817 was detected. At a similar epoch the onset of radio emission was also detected.



credits: NASA/ESA/E.Troja et al. 2017

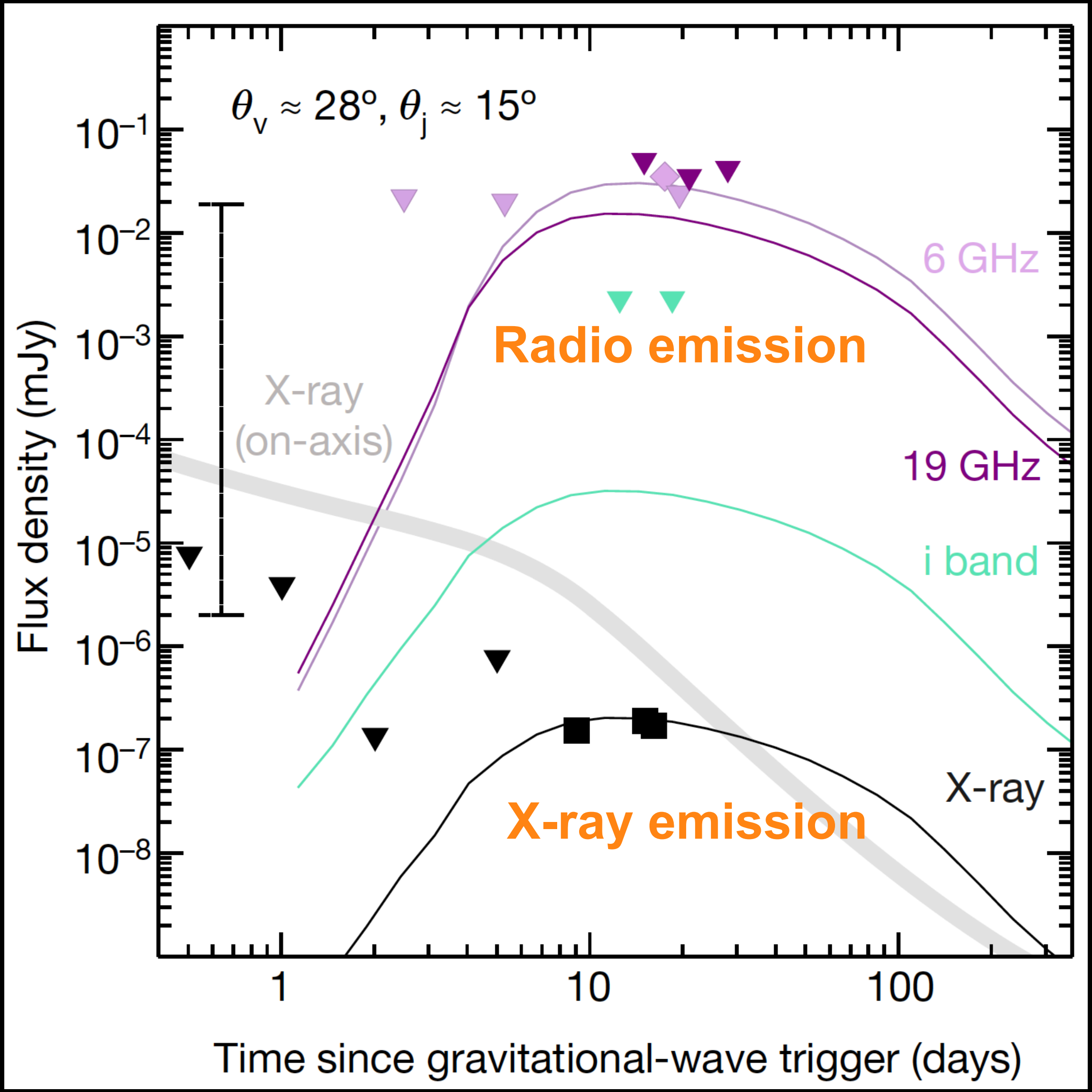
X-ray and Radio afterglow

Nearly at the same time of X-ray detection, the onset of Radio emission was also detected.



Hallinan et al., 2017

X-ray and Radio afterglow



"..Our observations are instead consistent with the onset of an off axis afterglow from the GRB jet. This would explain the low luminosity of the observed gamma-ray emission, and the lack of early afterglow detections."

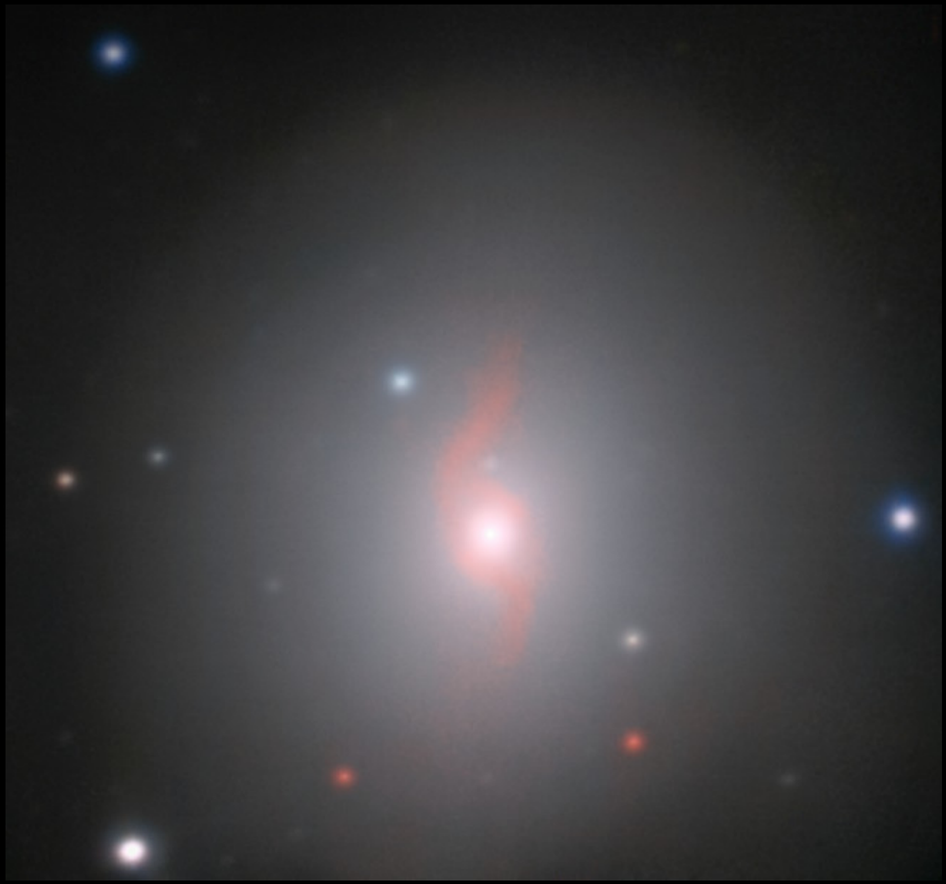
First GRB observed off-axis !

Short GRB seen off axis (θ_v~28°)

Troja et al. 2017

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

Margutti et al. 2018 astroph-180103531

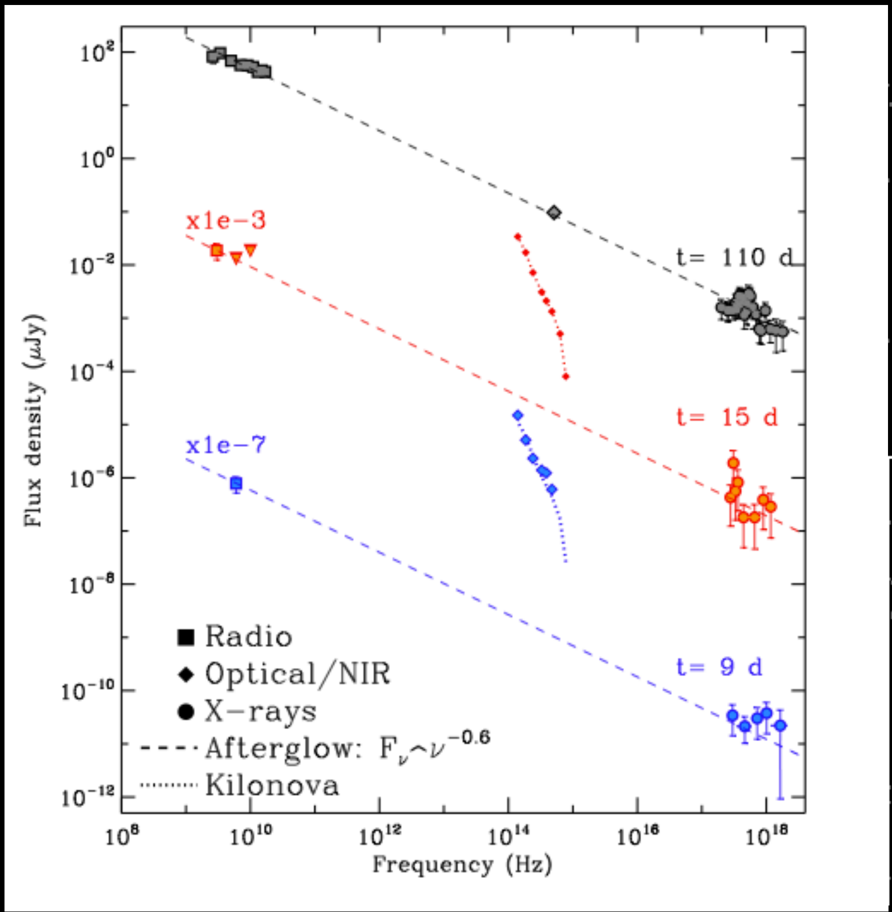
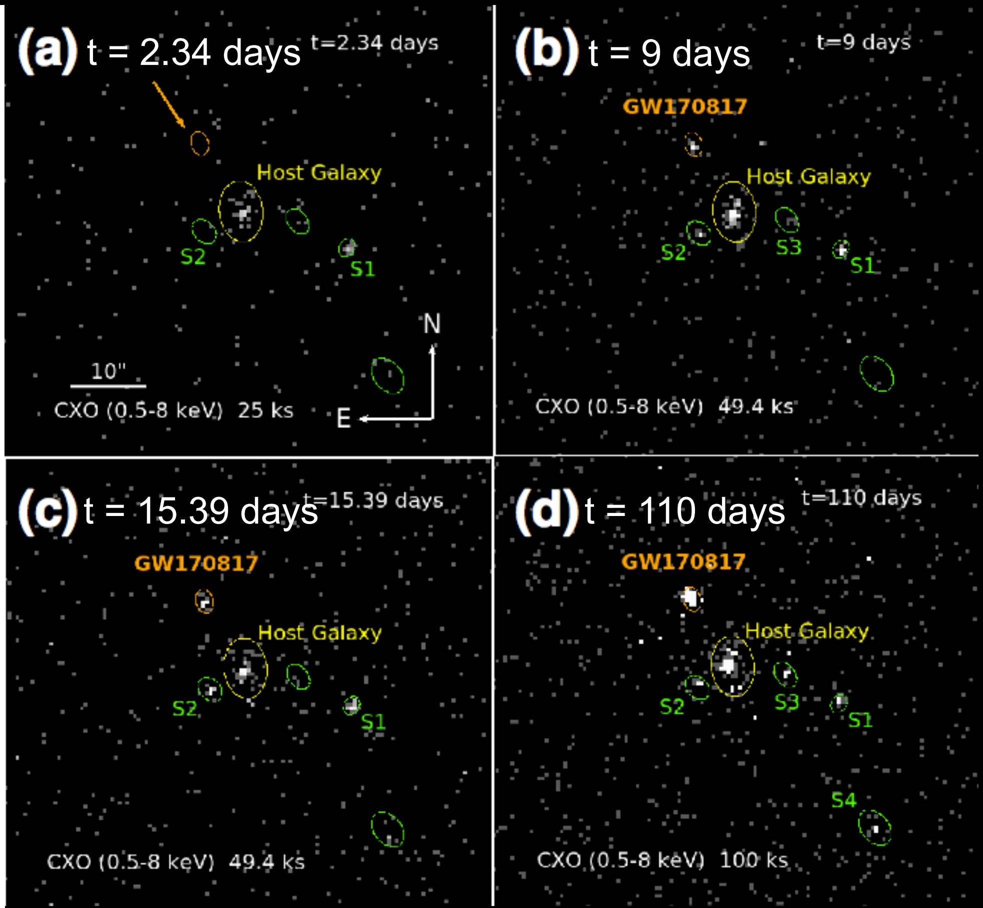


FIG. 1.— Evolution of the broad-band radio-to-X-ray SED of GW170817 from 9 d until 110 d since merger. The radio and X-ray data are dominated by non-thermal synchrotron emission from the GW170817 afterglow at all times

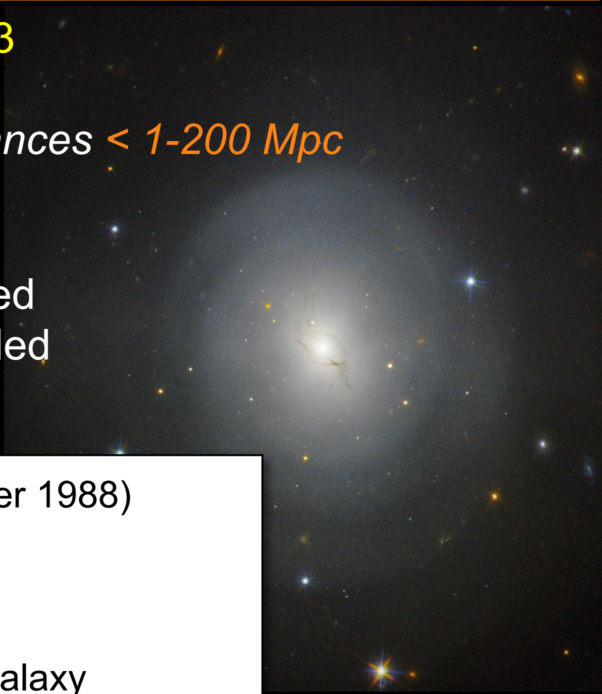
Evolution of X-ray emission



Chandra X-ray Observatory

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

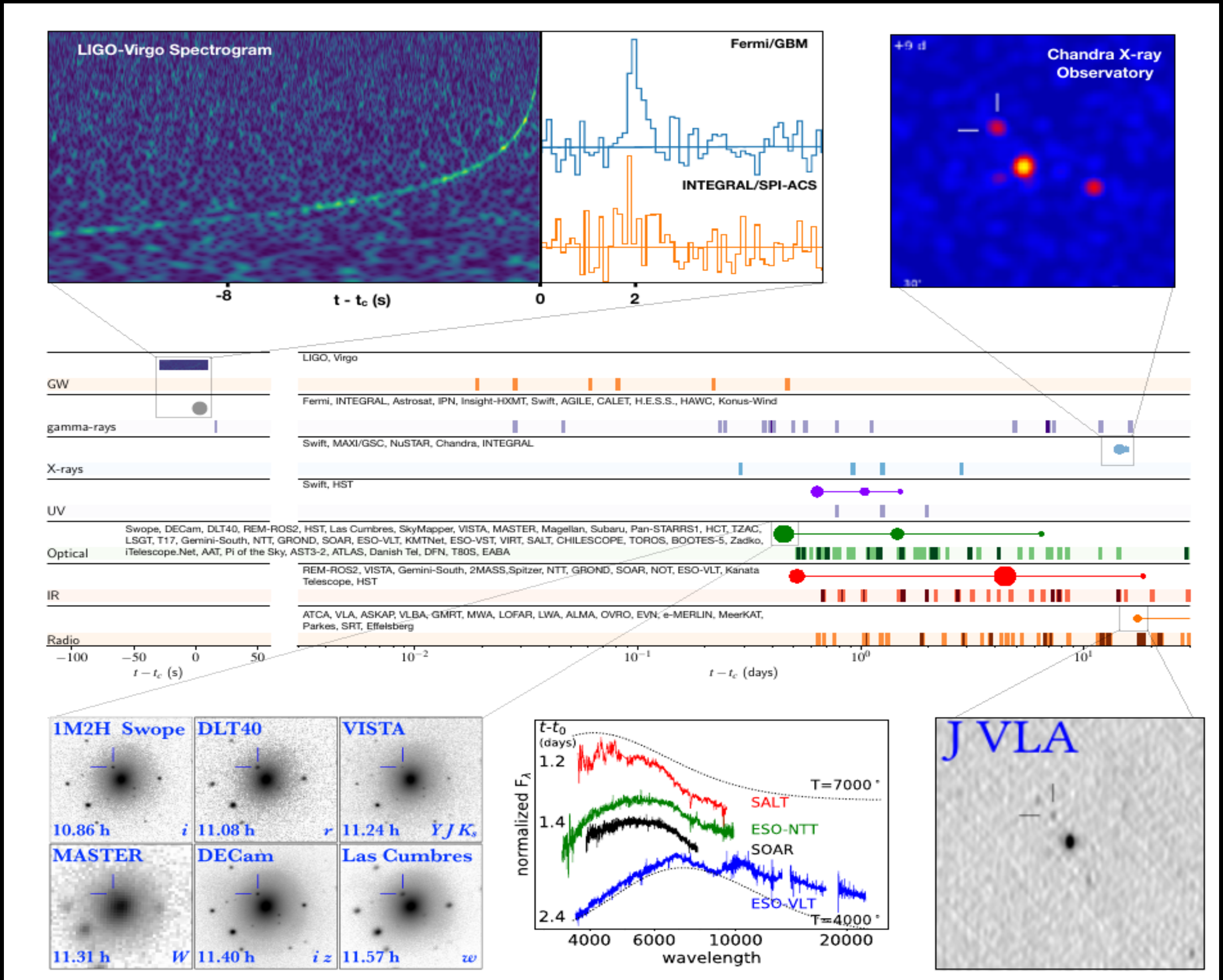
Preliminary results:

- ✓ 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 submitted

Multi-messenger Observations Summary

More than 70 groups observed the field of GW170817

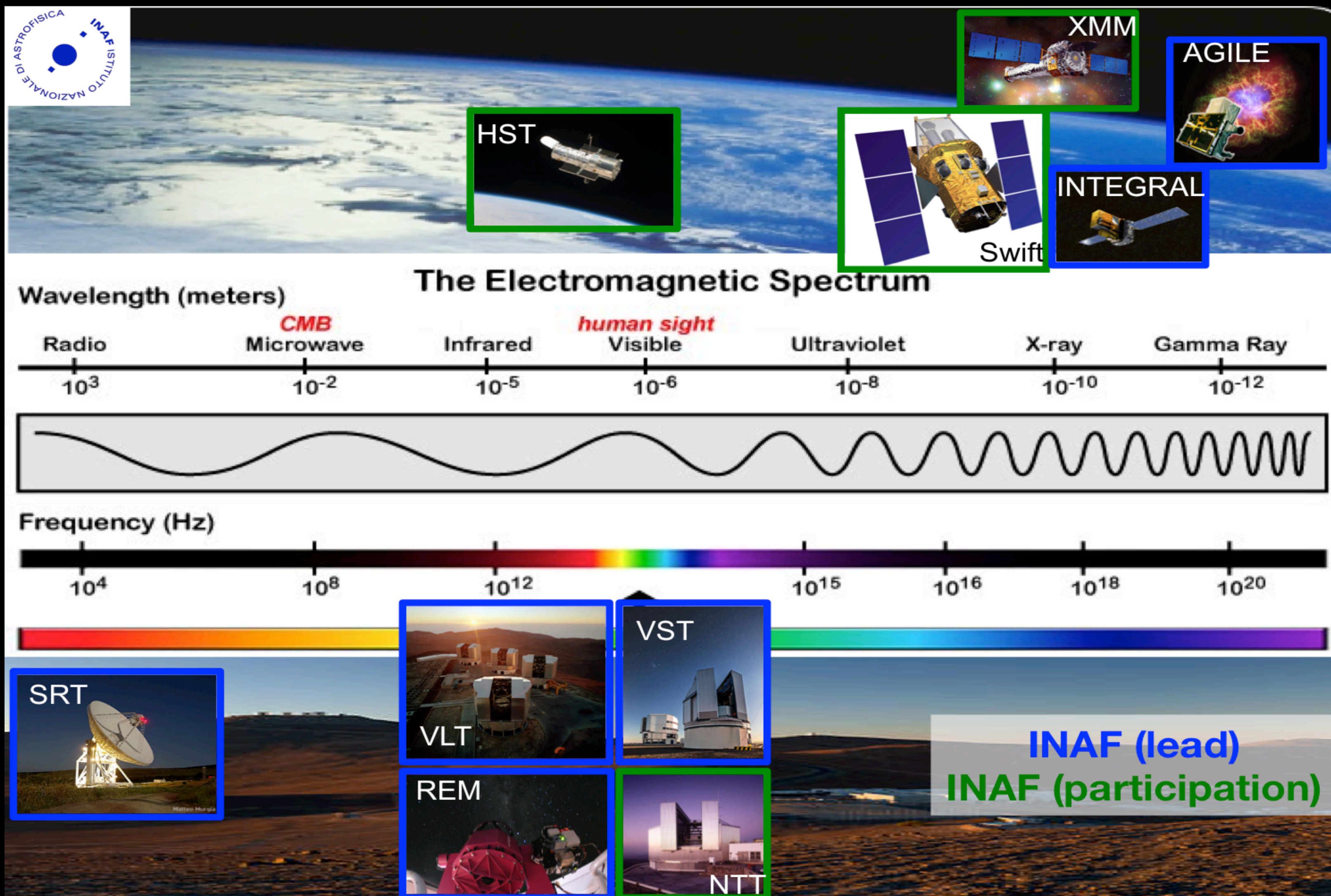


Abbott et al. 2017

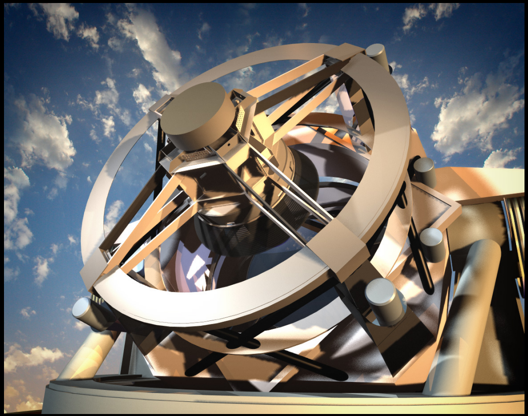
See initial publications web archive: https://lco.global/~iarcavi/kilonovae.html

Multi-messenger Observations Summary

INAF *vs* GW170817



The Multi-messenger Era: next future



WF search ->

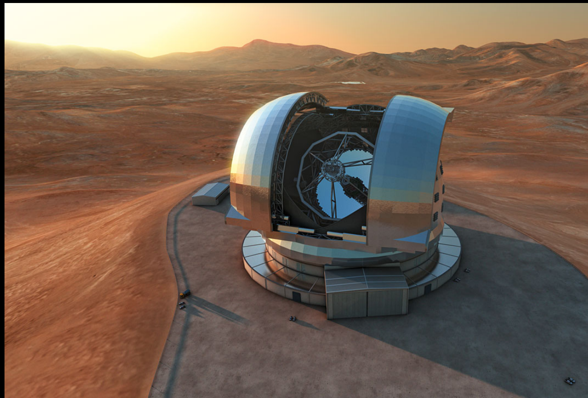
- Large telescopes (VLT etc)
  4-8m tel. can be competitive
  => very deep images (r > 25 mag) + >2 filters

- **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)



Conclusions

- The detection of GWs from a double neutron star merger and of its transient counterparts across the EM spectrum has initiated the era of **multi-messenger astronomy.**

- The simultaneous GW – sGRB detections have been finally confirmed the **BNS merger as progenitor of the sGRBs**.

- The detection of a **kilonova** is the signature of r-process nucleosynthesis which likely **produce the heaviest elements** in the Universe.

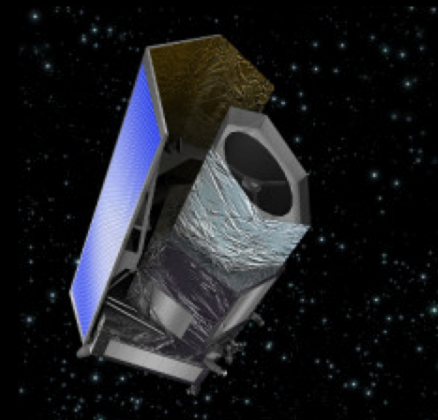
- The preliminary models require more than one component, with different proportions of species (lanthanide-rich vs lanthanide-free). The ejecta are about **0.03 – 0.05 solar masses** with velocities **0.1 – 0.3 c.**

- However we need more realistic atomic models and opacities to use with our radiative transport codes. Future work must focus on identifying accurately the atomic species and measuring their abundances. **We will thus trace heavy elements formation and evolution in the Universe.**

GraWITA *Landscape* in the multi-messenger era 2018-25

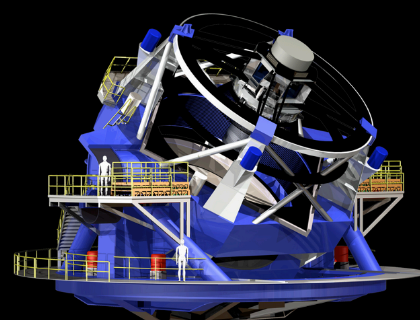
LBT - 2008

EELT - 2024



EUCLID - 2021

VLT - 1998-2000



LSST - 2023

JWST - 2018

CTA - 2024

ALMA - 2013

… thank you !