The electromagnetic counterpart of the gravitational wave event GW170817

Aniello Grado

INAF-Napoli

INFN –Napoli

&

GRAWITA team

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

GRAWITA project

GRAWITA goals

The present research group is committed to taking part in the search and the study of electromagnetic counterparts of the GW events by using observational facilities.

Know how

Time Domain Astronomy, Observational Strategy, Wide field images, Image analysis, Accurate Photometry in crowded fields, GRB astronomy, Supernovae, Data Interpretation, Theoretical models

Who we are ~ 80 people

INAF OA Roma: **E. Brocato (P.I.)**, L.A. Antonelli, S. Ascenzi, P. Casella, G. Israel, G. Iannicola, M. Lisi, S. Piranomonte, L. Pulone, L. Stella, A. Stamerra, V.Testa, R. Carini, A. Di Paola, A. Giunta

INAF OA Napoli: **A. Grado**, M Botticella, M. Capaccioli, M. della Valle, F. Getman, L. Limatola, P. Schipani

INAF OAS Bologna: **L. Nicastro**, L. Amati, A. Bulgarelli, M. Dadina, G. De Cesare, N. Masetti, E. Palazzi, A. Rossi, D. Vergani, D. Romano, E. Maiorano,

INAF OA Brera: **S. Campana**, S. Covino, P. D'Avanzo, A. Melandri, G. Tagliaferri, G. Ghirlanda, G. Ghisellini, M. Bernardini

INAF OA Padova: **E. Cappellaro**, S. Benetti, L. Tomasella, M. Turatto, S. Yang, R. Ciolfi, M. Mapelli, M. Spera

GSSI: **M. Branchesi**

Uni Urbino: **G. Greco**, G. Stratta

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

INAF IASF Milano: R. Salvaterra

Uni. Pisa: B. Patricelli, M. Razzano

ASI Science Data Center: **V. D'Elia**, G. Giuffrida, S. Marinoni, P. Marrese

INAF Cagliari: A. Possenti, M. Burgay, E. Molinari

INAF OA Abruzzo: **M. Cantiello**, G. Raimondo

UNI Calabria: S. Savaglio

INFN Trieste: F. Longo

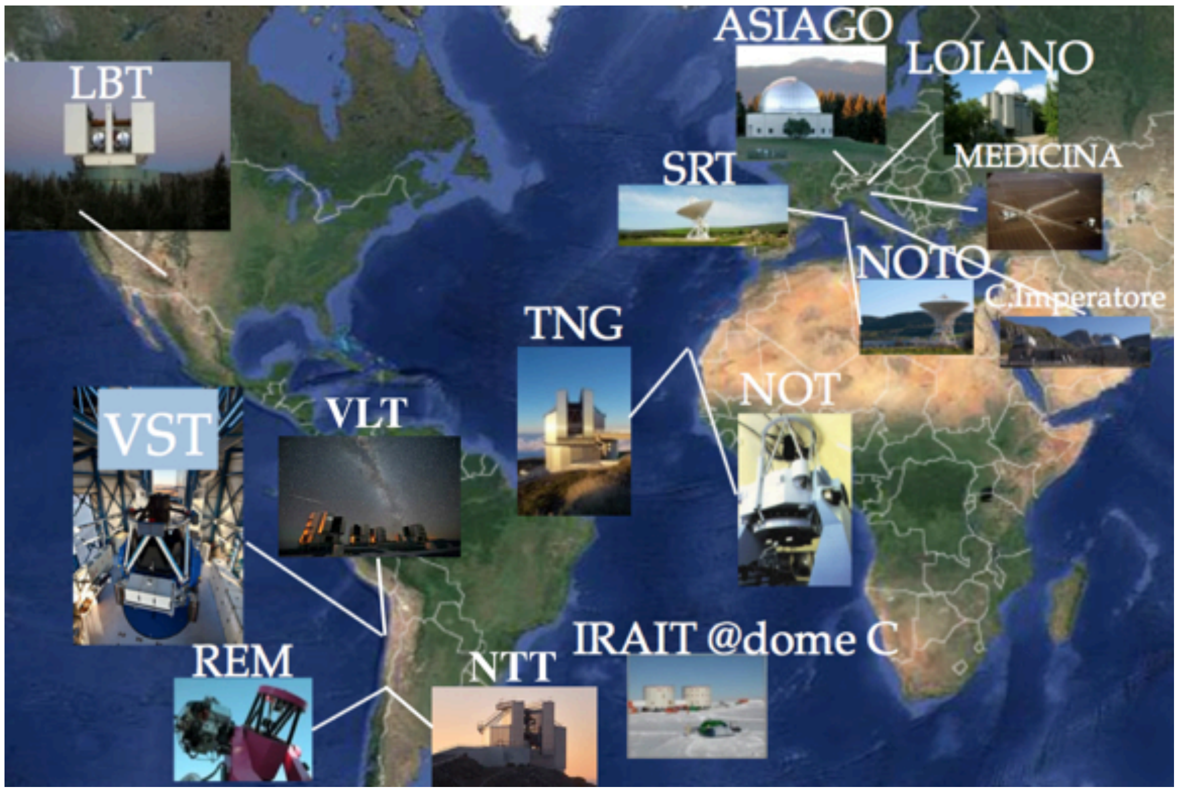
Uni. Trieste: F. Matteucci,

Uni Milano: A. Perego, O. Salafia

INAF OA Trieste: R. Cescutti

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)*



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

Why search for EM counterpart

GW

- Mass
- Spins
- Eccentricity
- NS compactness
- System orientation
- Luminosity distance

- Identify host galaxy
- Constraints on progenitors
- H_0
- GW speed
- GR tests
- Formation scenario
- Massive stars evolution

EM

- Energetics and beaming
- Sky localization (arcsec)
- Host galaxy
- environment
- Redshift
- Nuclear astrophysics

Multi-messenger astronomy

We focus on:

GW:

compact binary coalescence (CBC)

EM:

photons in optical near infrared band

GWs from compact objects

Source type? How far? How many? Localization?

Source type	Detectors sensitivity O3 (Mpc)	Estimated # of detections in O3 (in 12 months)	localization
NS-NS	120-170 (LIGO) 65-85 (Virgo)	1-50[1]	20-26 % in 5 deg^2 42-50 % in 20 deg^2
NS-BH	190-270 (LIGO) 100-140 (Virgo)	1-2[3,4]	~ BNS
BBH	1110-1490 (LIGO) 610-1030 (Virgo)	6 - 130[2]	Tens to hundreds deg^2

Abbott et al 2018 Liv. Rev. Relat. 21;3

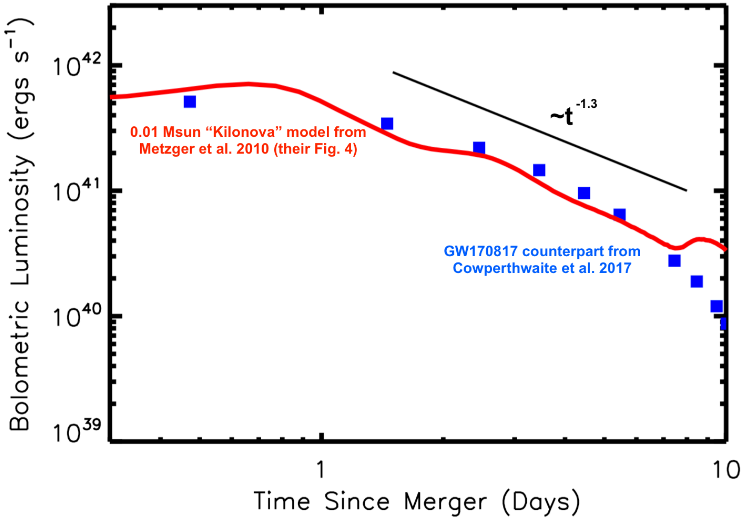
[1]Assuming a rate of 10^{-8} - 10^{-5} Mpc^{-3} yr^{-1} (Abbott et al. 2017, PRL, 119, 161101)
[2]Rodriguez et al. 2016, PRD, 93,8, 084029 (rate 2-20 $Gpc^{-3} yr^{-1}$)
[3]Assuming an upper limit rate of 3.6×10^{-6} Mpc^{-3} yr^{-1}
[4]Pannarale et al. 2014 ApJ, 791, 5

EM emission from CBC

For binaries with at least one NS

Lattimer & Schramm 1974 (r-process)
Li & Paczynski 1998, Metzger 2010
(UV-Optical emission prediction),

For BNS we expect M_{AB} ~ -16 mag



Metzger 2017 arXiv:1710.0593

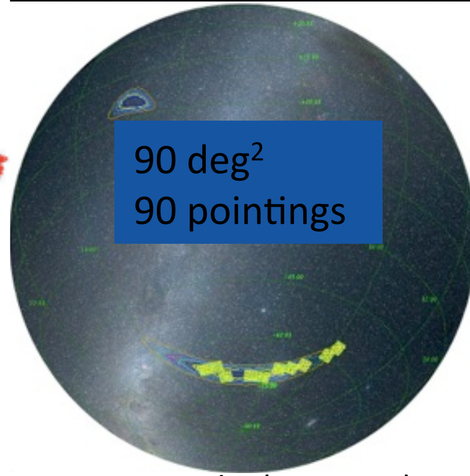
Rosswog et al. 1999, Perego et al. 2017 (material ejection mechanism) (see Albino talk)

For binary black holes

EM signal if a low mass circumbinary disk survives until the coalescence.
(de Mink et al. 2017) (Yamazaki et al. 2016)

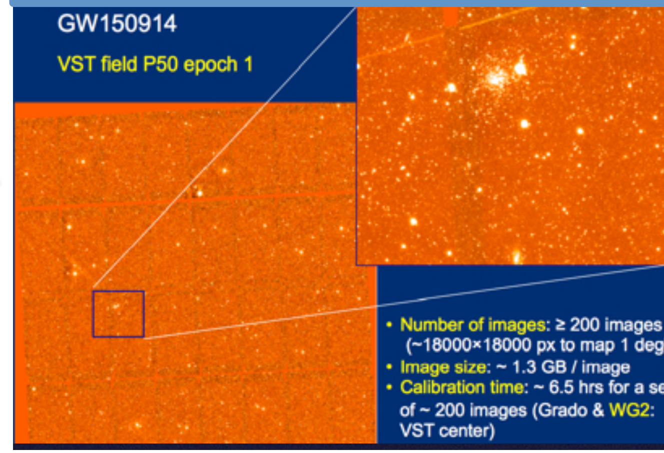
Alert

Observations preparation

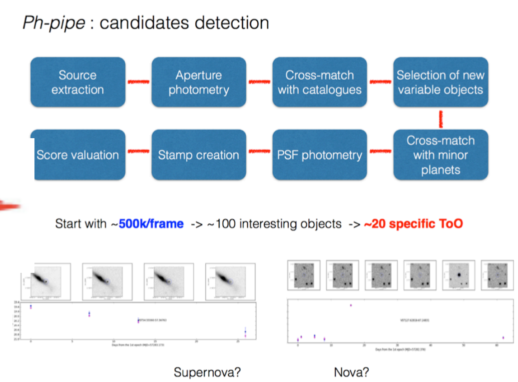


GWSky (G. Greco)

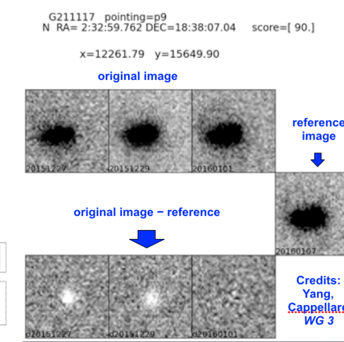
Observations+image reduction



Search

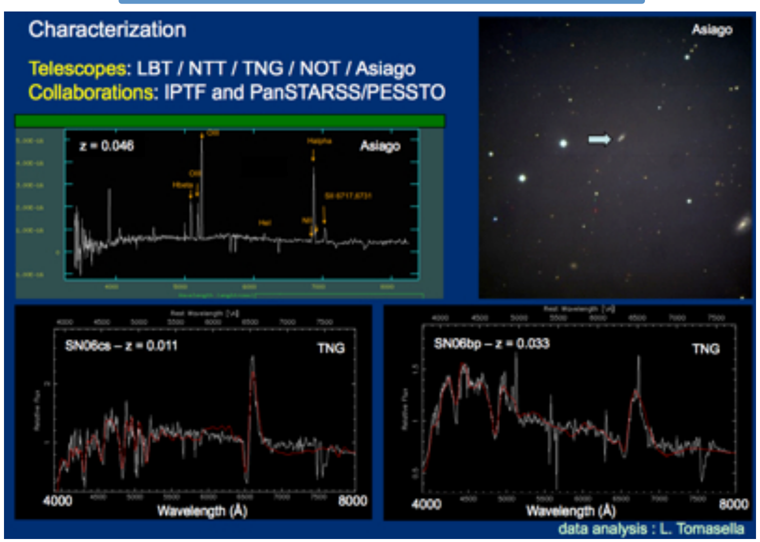


Credit: S. Covino



Credit: E. Cappellaro, S. Yang

Characterization



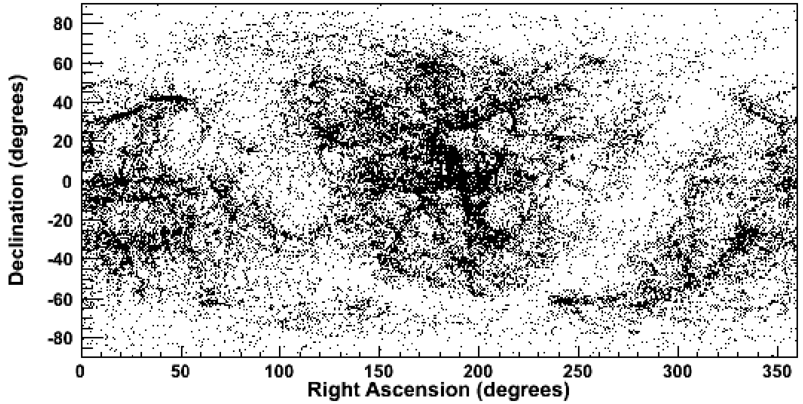
Pian et al. 2017

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 (Pan-Starrs, Slymapper, SDSS)
- 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)

Blind search @VST

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

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

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

Founds, design and construction @Osservatorio di Capodimonte

Processing astronomical images

Go from raw to instrumental signatures cleaned full calibrated images

CCD offset

Geometrical distortion correction

Illumination correction

$$I^{stacked}_{science-ready} = \sum_i \wp\{\,\Gamma\{\frac{I^i_{raw} - Bias}{FF \times Harmgain} \times IC\}\} + Zp$$

Absolute photometric calibration

Tangential projection

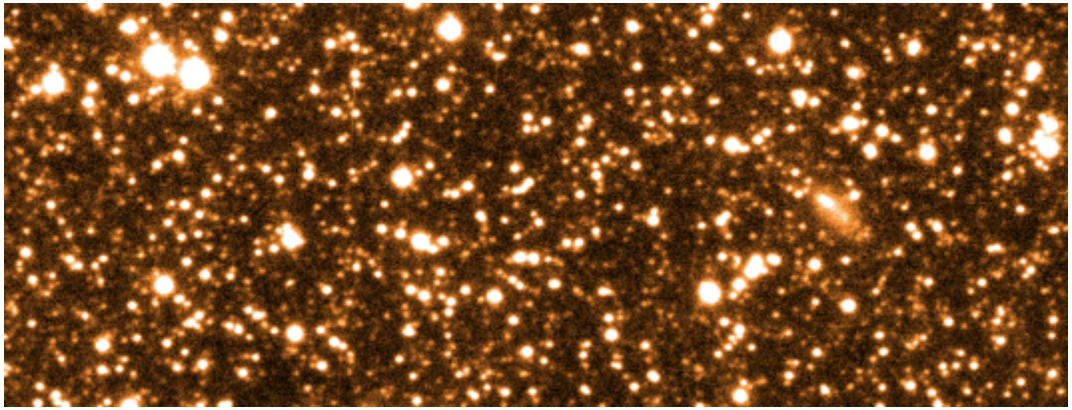
CCD gain harmonization

Low and high spatial frequency pixels gain variation

VST images processed with VST-Tube pipeline (100.000 lines Python, C in house dev. code A. Grado et al. 2012 MSAIS, 19, 362)

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	

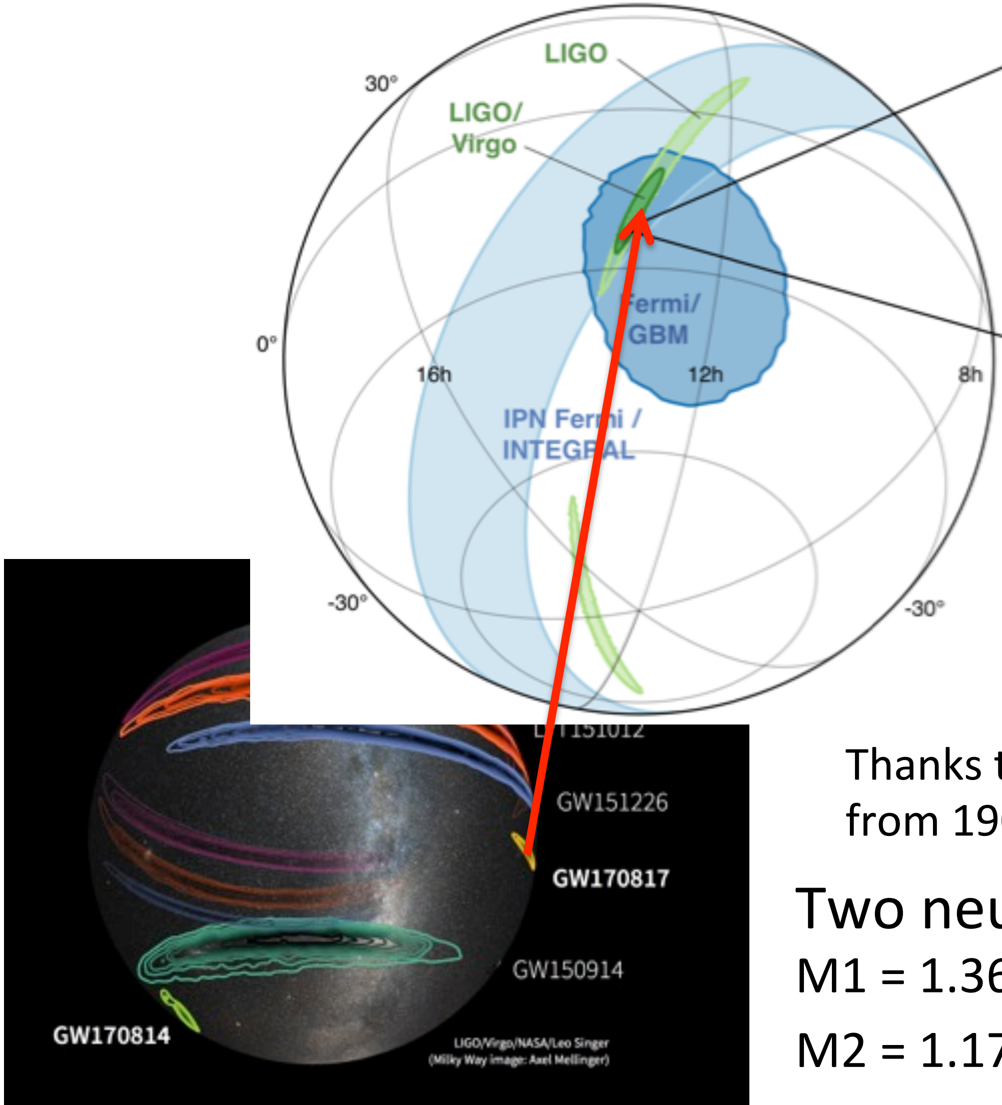
Brocato et al. 2018 MNRAS, 474, 411

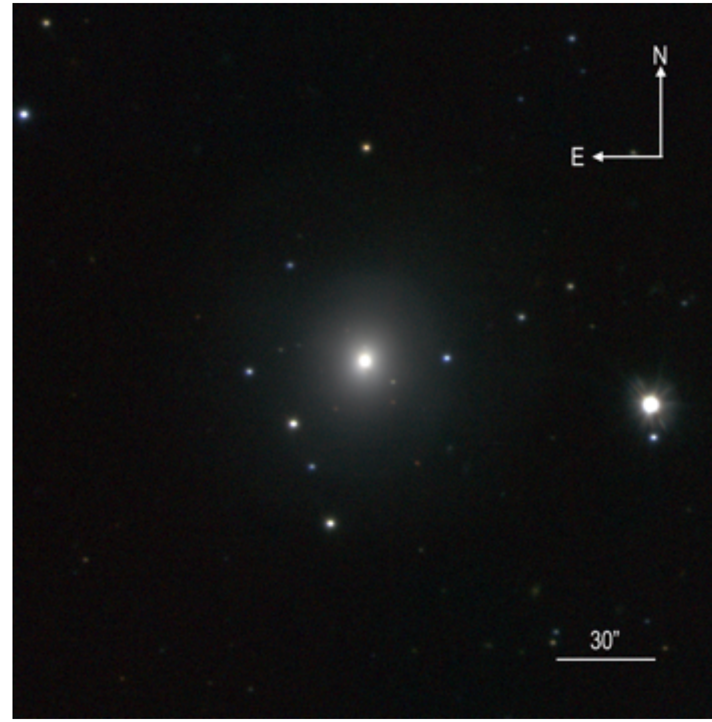
Evident spurious and known variables already removed

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

GW170817 the watershed

2017-08-17 12:41:04 UTC





NGC4993@ VST

Thanks to Virgo error area reduced
from 190 deg^2 to 28 deg^2

Two neutron stars

M1 = 1.36 – 1.6 $M_\odot$

M2 = 1.17 -1.36 $M_\odot$ Abbott et al. 2017, PRL, 119, 1101

The largest multi-messenger campaign ever done

62 telescopes for optical/infrared photometric and spectroscopic follow-up

For X/radio follow-up see Melandri's talk

Abbott et al. ApJL, 2017, 848, L12,59

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger*

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

3667 autors !!

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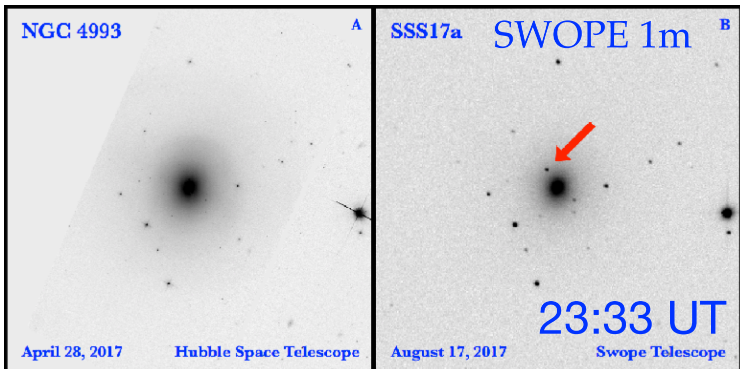
Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of $\sim$1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky

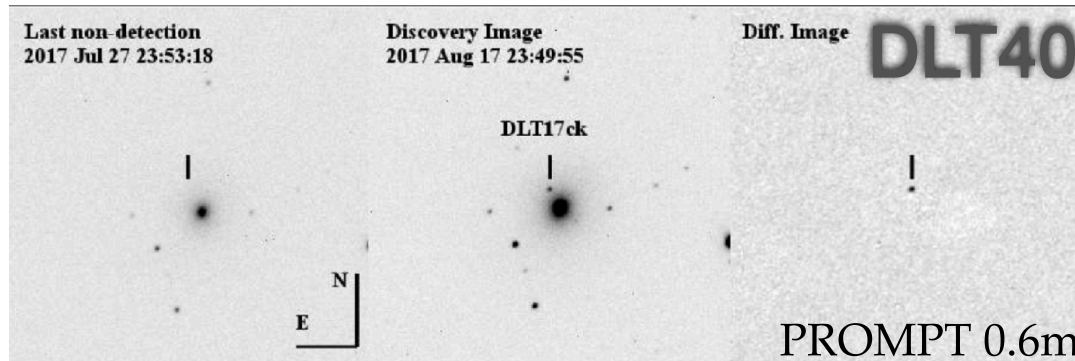
Discovery of the kilonova

targeted search: sss17a=DLT17ck=AT2017gfo

Coulter et al. 2017

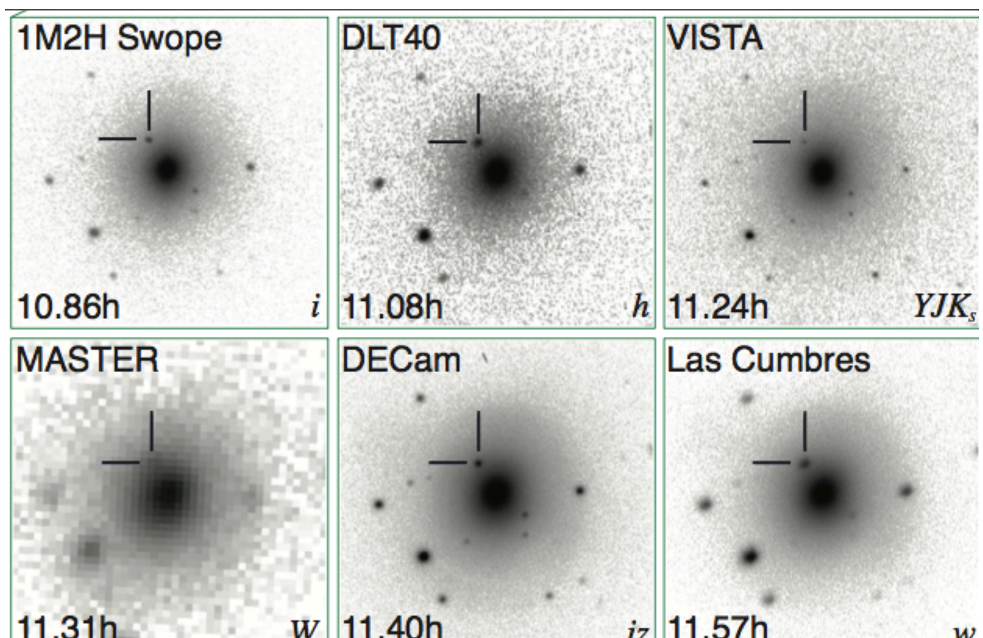


Valenti et al. 2017, Yang et al. 2017

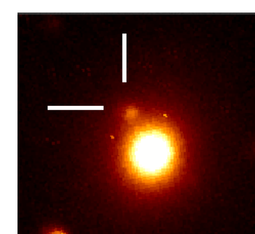


GW at

12:41:04 UT

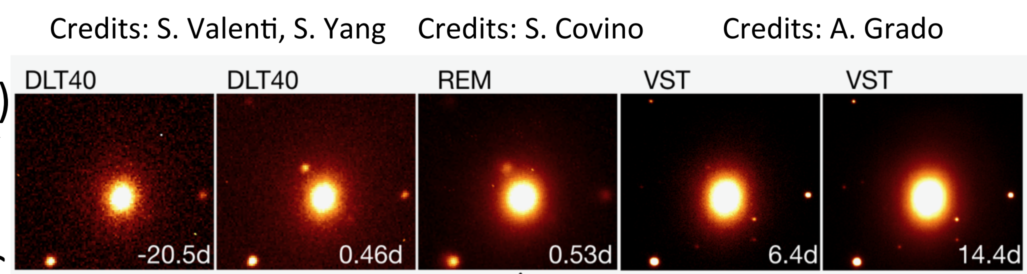


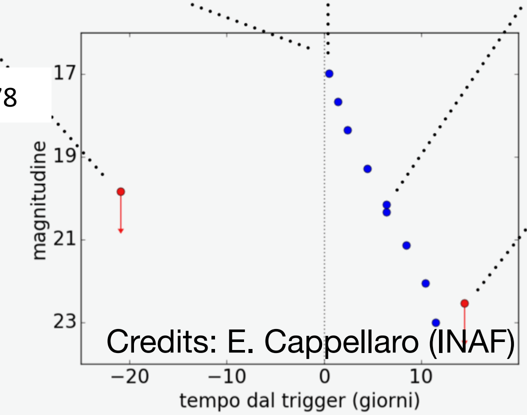
REM + 12.40

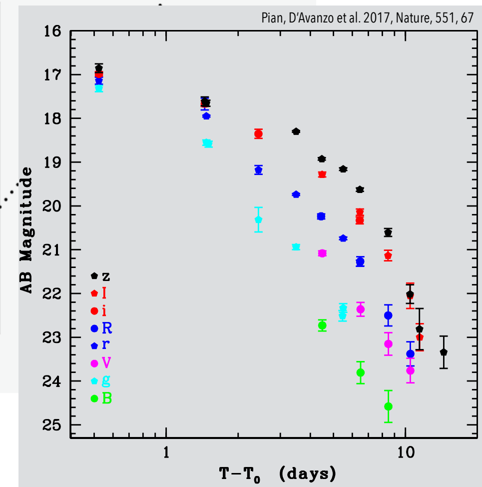


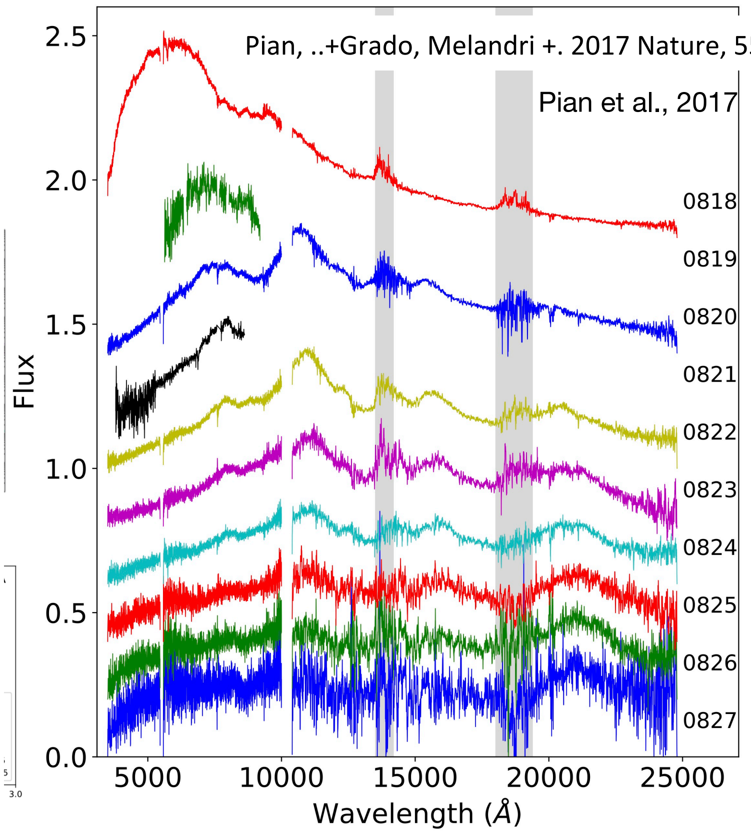
Grawita's follow up of AT2017gfo

- From 12.8 h to 144 d
- BgVRrIiz (~ 9 h on source)
- Spectroscopy (~15 h on source)
- REM, VST, VLT/X-shooter, VLT/ Fors2
- Not visible from TNG, Asiago, C.

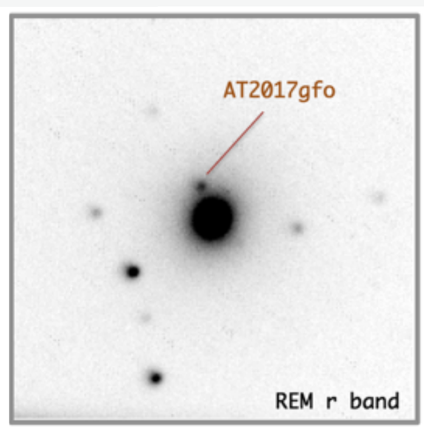








Pian, ..+Grado, Melandri +. 2017 Nature, 551, 7678



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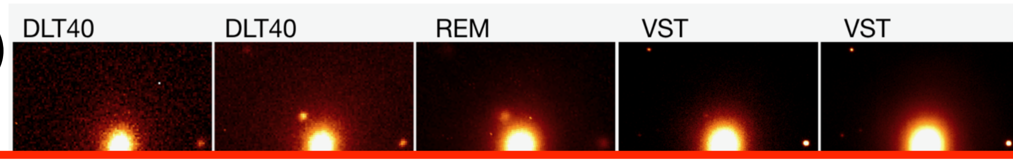


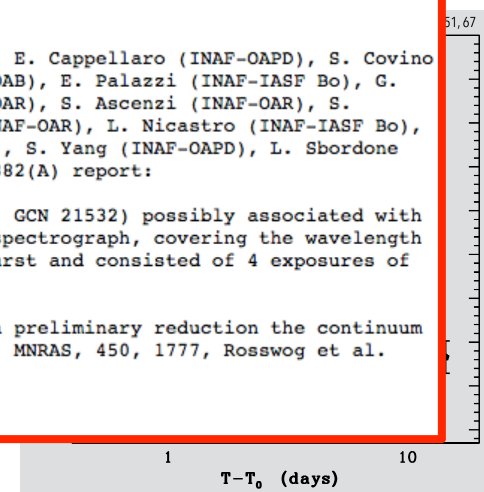
TITLE: GCN CIRCULAR
NUMBER: 21592
SUBJECT: LIGO/Virgo G298048: GRAWITA VLT/X-shooter observations
DATE: 17/08/19 12:16:37 GMT
FROM: Andrea Melandri at INAF-OAB <andy.melandri@gmail.com>

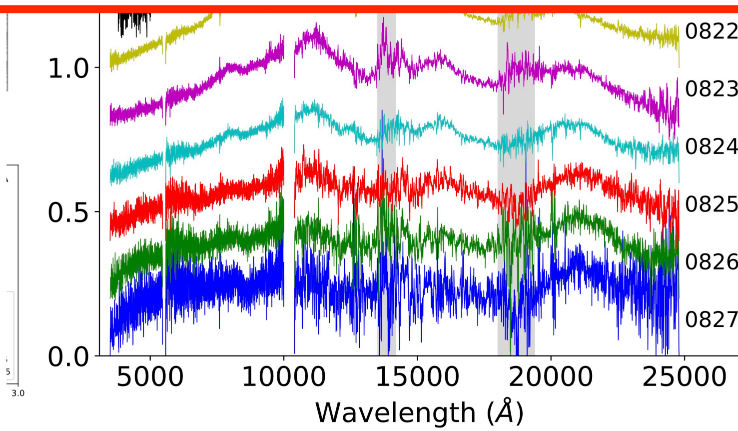
E. Pian (INAF-IASF Bo), V. D'Elia (INAF-ASDC), S. Piranomonte (INAF-OAR), M. Branchesi (GSSI), S. Campana (INAF-OAB), E. Cappellaro (INAF-OAPD), S. Covino (INAF-OAB), P. D'Avanzo (INAF-OAB), A. Grado (INAF-OAC), G. Greco (Urbino University/INFN Firenze), A. Melandri (INAF-OAB), E. Palazzi (INAF-IASF Bo), G. Stratta (Urbino University/INFN Firenze), L . Tomasella (INAF-OAPD), L. Amati (INAF-IASF Bo), L. A. Antonelli, (INAF-OAR), S. Ascenzi (INAF-OAR), S. Benetti (INAF-OAPD), M.T. Botticella (INAF-OAC), D. Fugazza, F. Getman (INAF-OAC), L. Limatola (INAF-OAC), M. Lisi (INAF-OAR), L. Nicastro (INAF-IASF Bo), L. Pulone (INAF-OAR), A. Rossi (INAF-IASF Bo), P. Schipani (INAF-OAC), G. Tagliaferri (INAF-OAB), V. Testa (INAF-OAR), S. Yang (INAF-OAPD), L. Sbordone (ESO) and E. Brocato (INAF-OAR) on behalf of GRavitational Wave Inaf TeAm and the team of the ESO VLT program 099.D-0382(A) report:

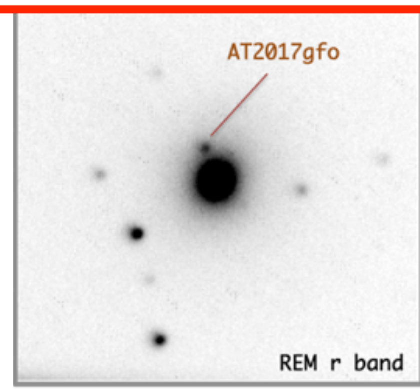
We observed object SSS17a (Coulter et al., GCN 21529; Allam et al., GCN 21530; Yang et al., GCN 21531, Melandri et al., GCN 21532) possibly associated with the LIGO/Virgo event G298048 (GCN 21509), with the ESO Very Large Telescope UT 2 (Kueyen) equipped with the X-shooter spectrograph, covering the wavelength range 3000-25000 AA. Observations started at 23:16 UT on 2017-08-18, during the twilight, roughly 1.5 days after the burst and consisted of 4 exposures of 600 s each.

The transient is bright, well detected in the acquisition image, and clearly visible in all the spectral range. After a preliminary reduction the continuum appears to be similar to that predicted by kilonova models (Tanaka & Hotokezaka 2013, ApJ, 775, 113; Kasen et al. 2015, MNRAS, 450, 1777, Rosswog et al. 2016, arxiv1611.09822). We do not detect any obvious emission lines throughout the spectrum.

Further X-shooter observations are planned.



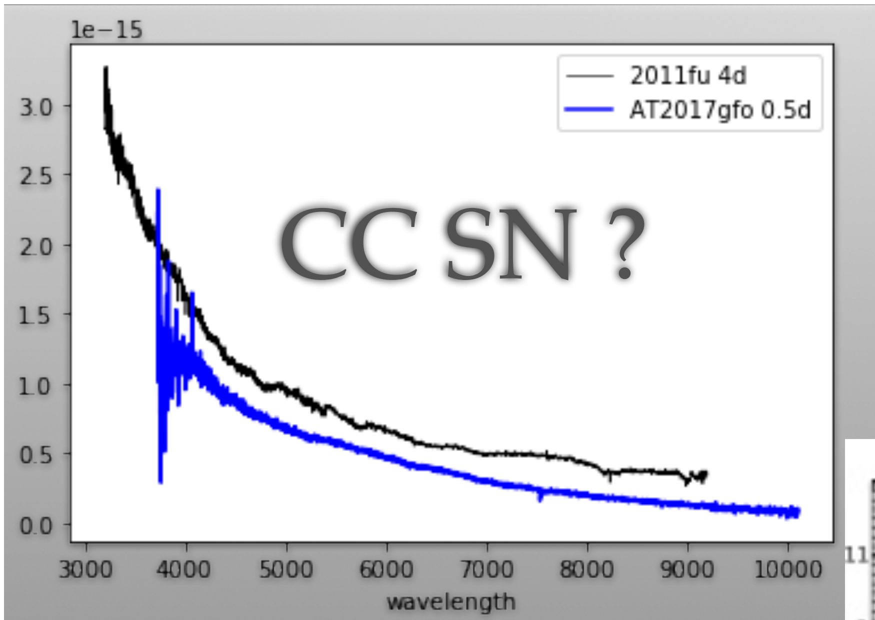




Discovey of the Kilonova

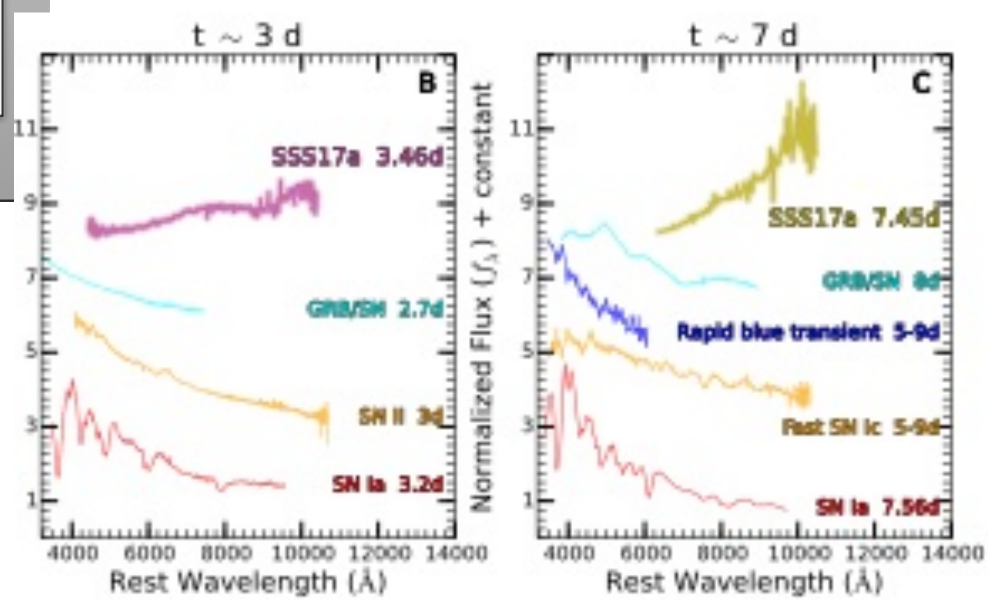
never seen spectrum

Shappee et al. 2017



Credit: E. Cappellaro

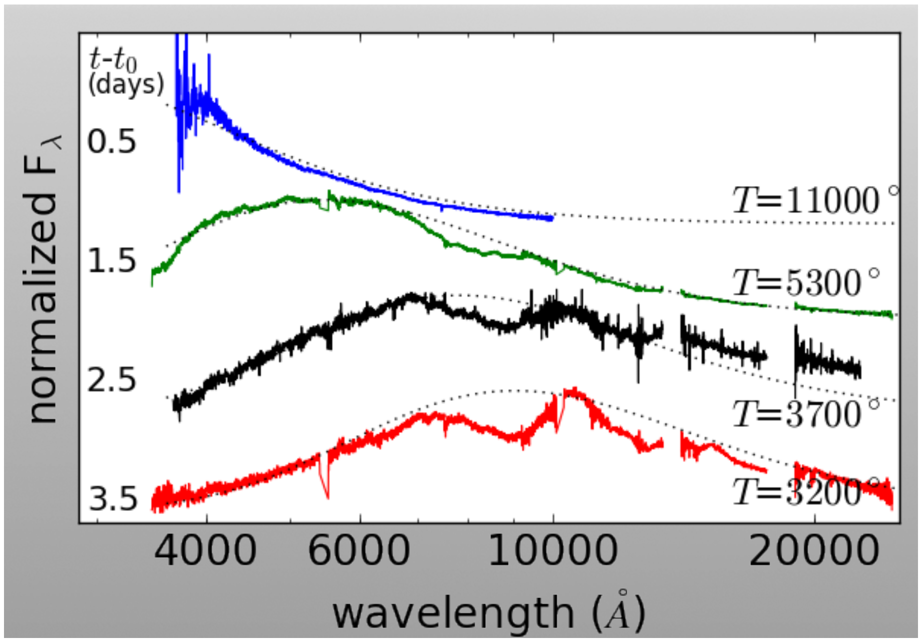
After 3 days the spectrum of AT2017gfo are different from ANY other known transient



What we learned?

very fast expansions

Credit: E. Cappellaro



From $L \propto R^2 T^4$

First spectrum at t=0.49d

T ~ $11,000^{+3400}_{-900}$ K

R ~ $3.3^{+0.3}_{-0.8} \times 10^{14}$ cm

Expansion velocity:

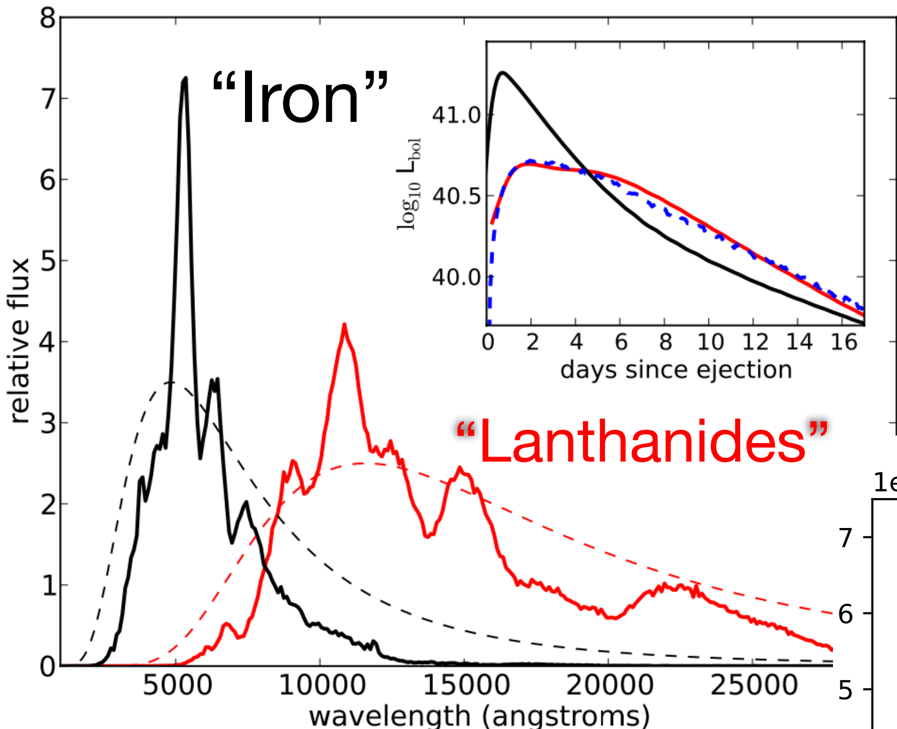
$$77,000^{+7000}_{-20,000}\ \mathrm{km\,s^{-1}}$$

~ 0.3 c

Shappee et al 2017

Kilonova as heavy elements factory

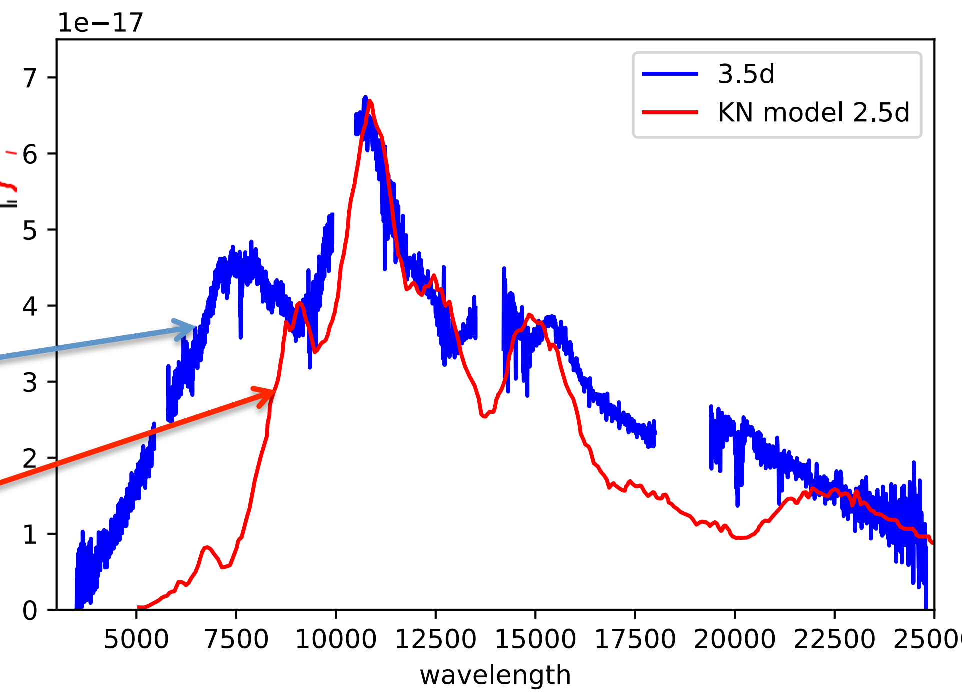
Kasen et al. 2013



Synthetic spectra at 2.5 days for r-process.

BE CAREFULL

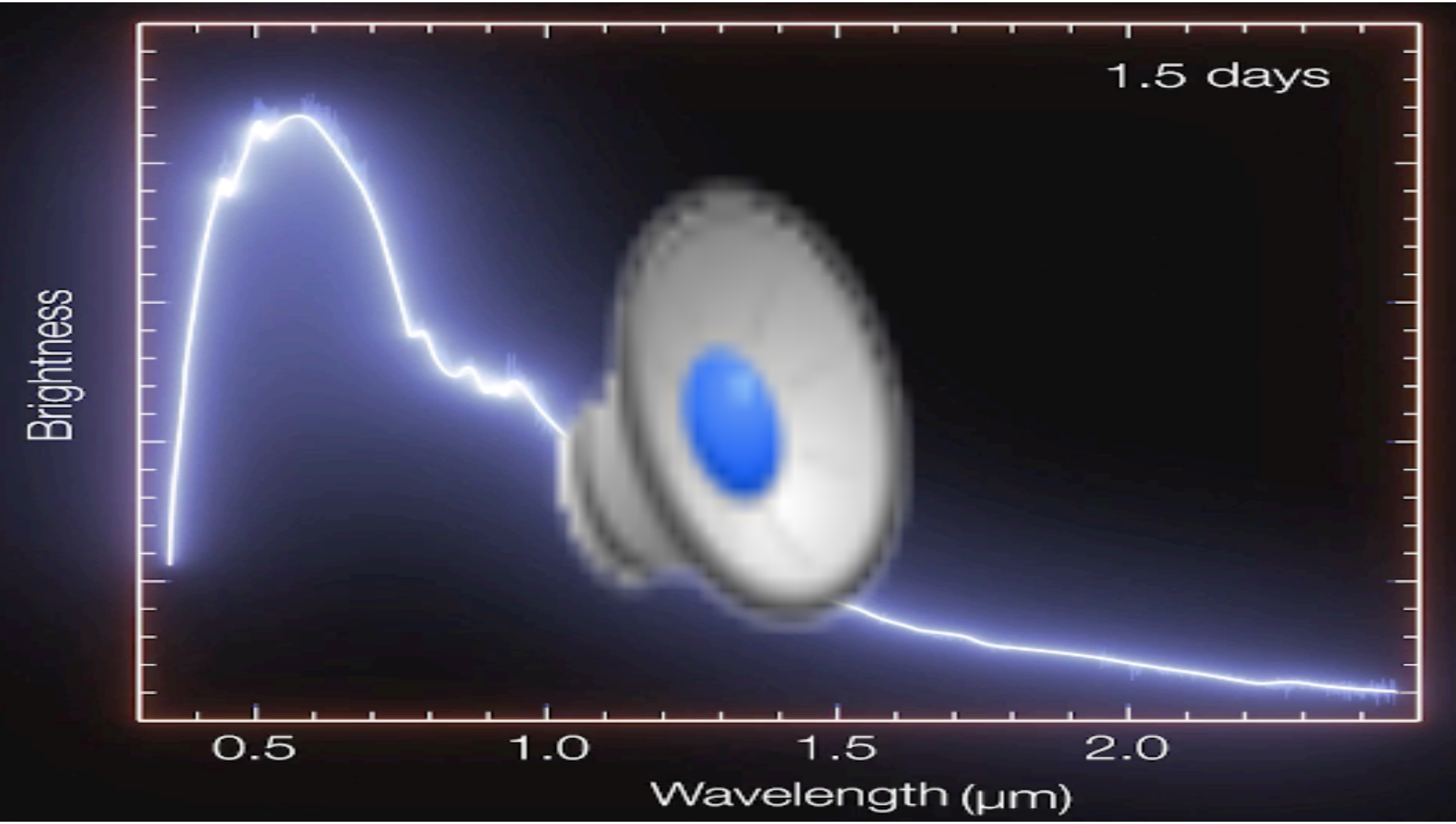
NO individual lines



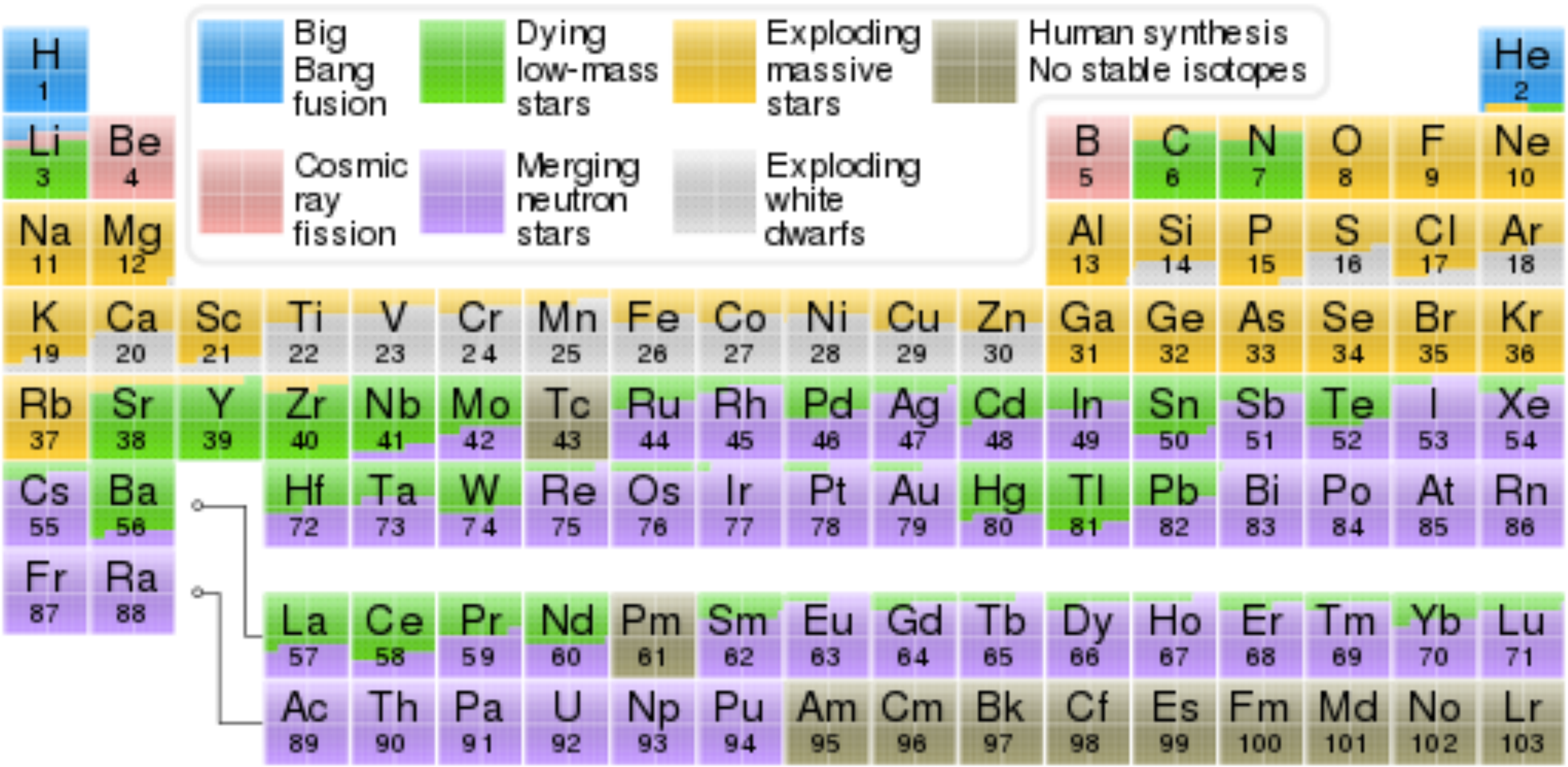
observations

Kilonova model with lanthanides

X-Shooter follow up of AT2017gfo

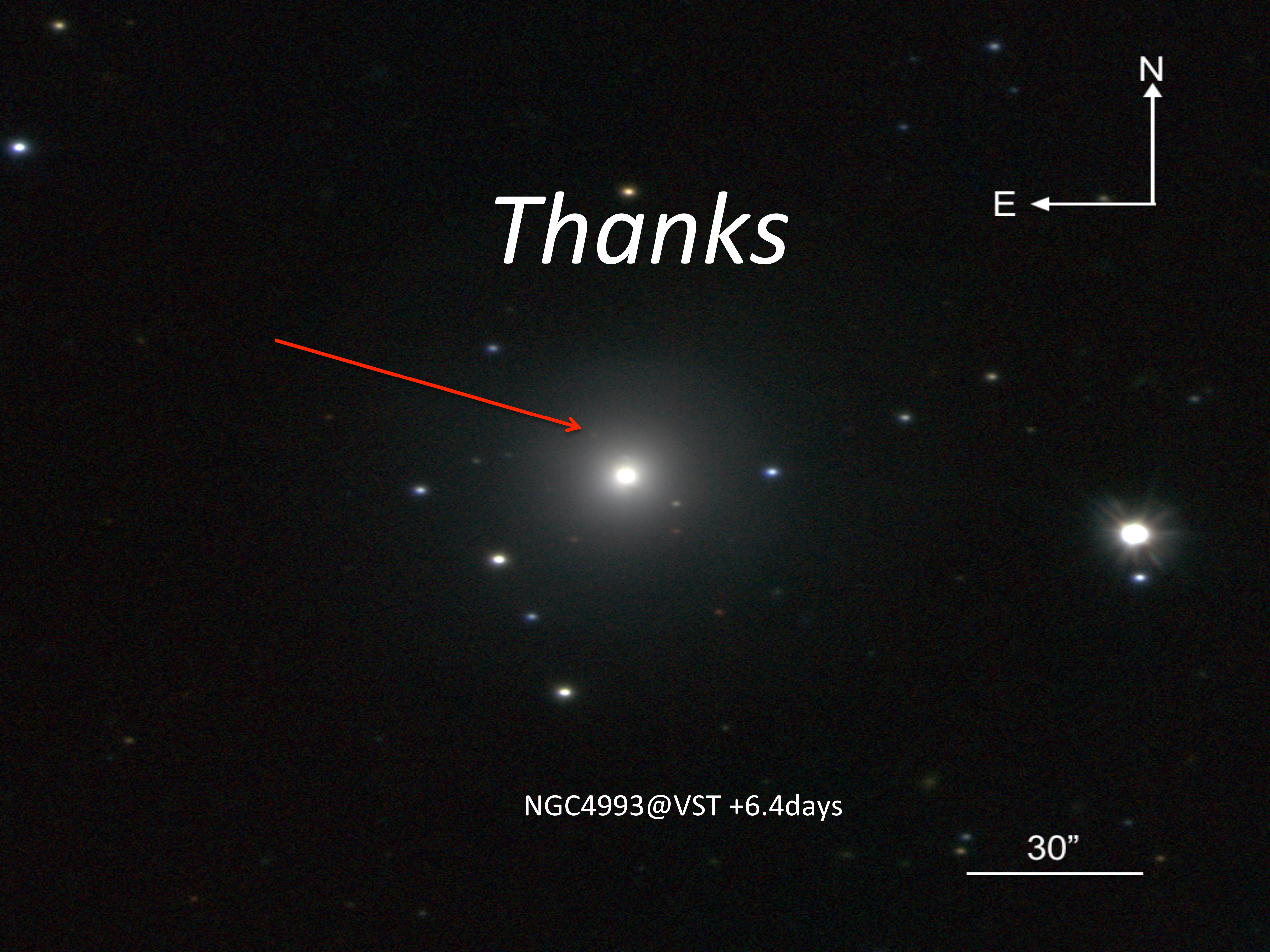


Kilonova as heavy elements factory



Conclusion

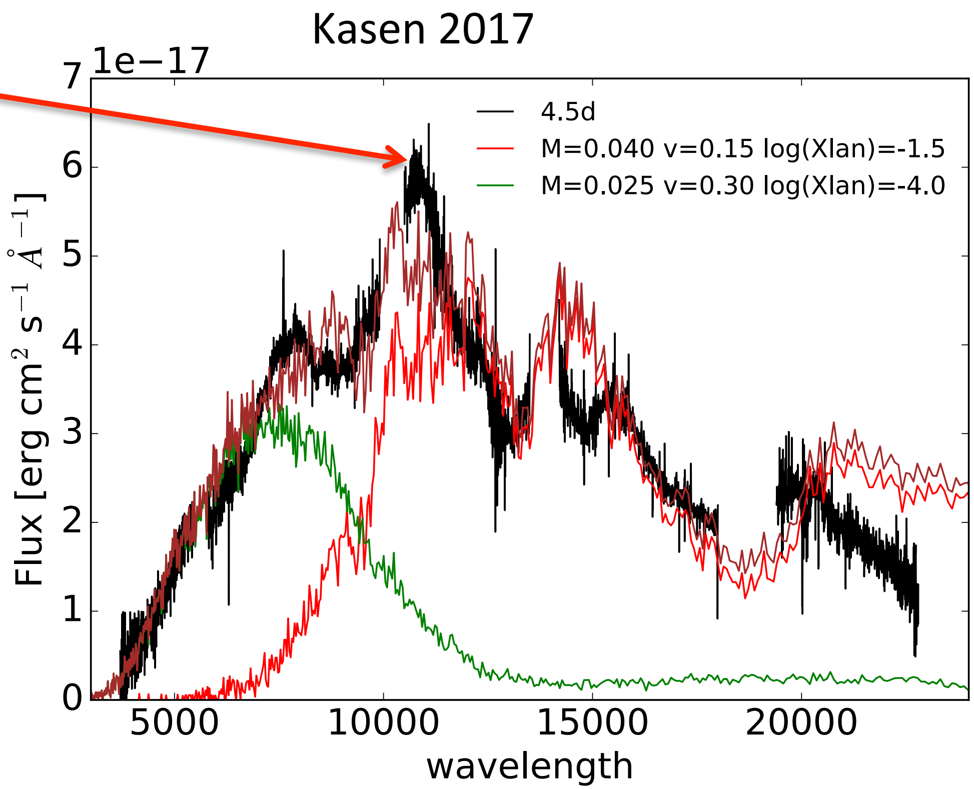
- The multi-messenger era involving GW is started
- An extraordinary worldwide effort has been made to find and follow-up the GW counterpart
- The EM counterparts complement the amazing GW signal giving insight in several physical aspects
  - H_0 Independent method
  - GWs propagates at light speed (from sGRB)
  - First kilonova with evidence of heavy elements r-process nucleosynthesis
- Open questions:
  - GW170817 produced by NS-BH or BNS?
  - Remnant, NS or BH ?
  - Better understanding of kilonova process
- A large European group (ENGRAVE 230 people) will make spectroscopic follow-up of GW using ESO facilities
- We look forward for the O3 ALIGO/AVirgo run to detect more kilonovae events and gain deeper knowledge on Universe


Thanks
N
E
NGC4993@VST +6.4days
30”

Kilonova AT2017gfo

observations

Two components model match
Better the observations



Grawita's Proposals

- Proposal VST (P102 80 h up to 8 events 30deg^2)
- Proposal LBT 2018B 65h
- Proposal TNG (10/2018-4/2019 90h)
- Asiago, Campo Imperatore
- Proposal ENGRAVE 200 Co-I (P102-P104, 200 h X-shooter, Fors2)
- Proposal ENGRAVE (P102, 10 h MUSE)
- Proposal NOT (P57 14 h)
- REM (AOT37 40 h)