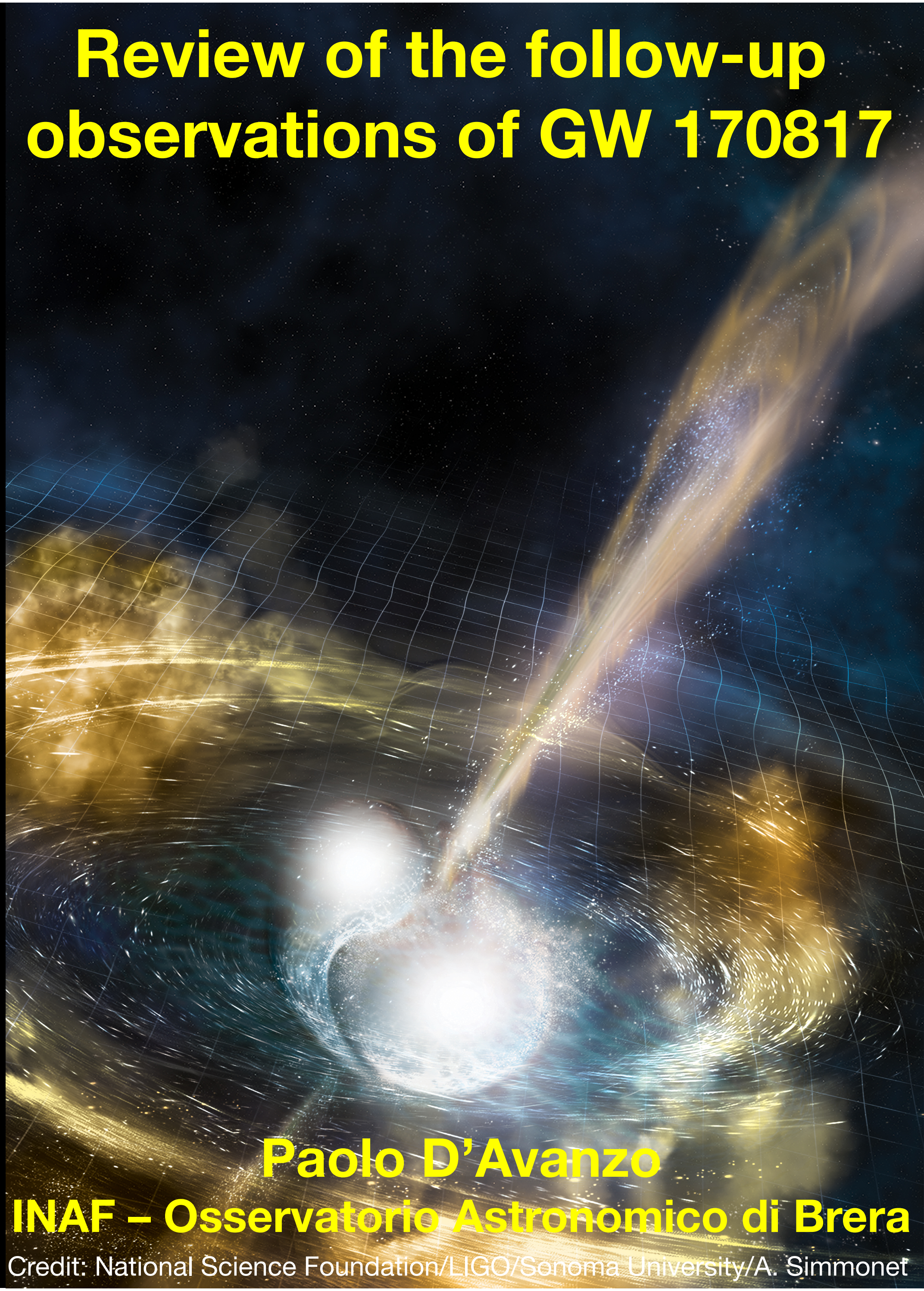
Review of the follow-up observations of GW 170817

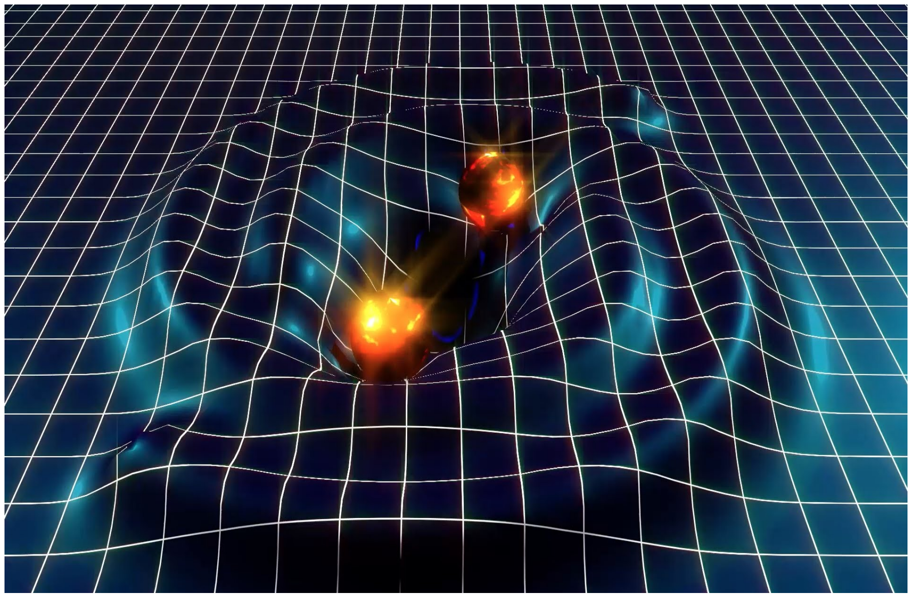


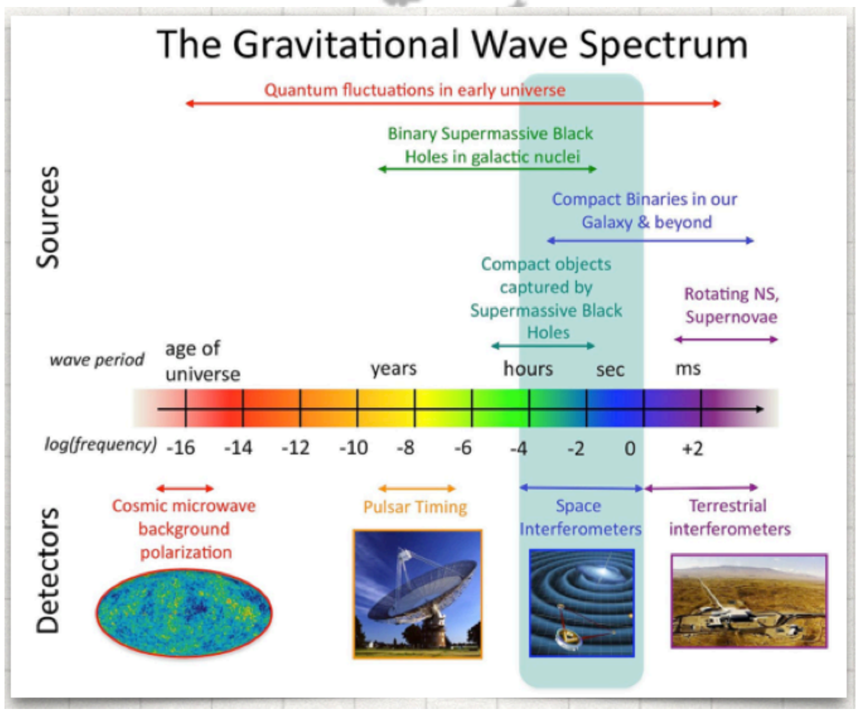
Paolo D’Avanzo
INAF – Osservatorio Astronomico di Brera

Credit: National Science Foundation/LIGO/Sonoma University/A. Simmonet

The GW era

LIGO Hanford
GEO 600
Virgo
KAGRA
LIGO Livingston
LIGO-India





The Gravitational Wave Spectrum
Quantum fluctuations in early universe
Binary Supermassive Black Holes in galactic nuclei
Compact Binaries in our Galaxy & beyond
Compact objects captured by Supermassive Black Holes
Rotating NS, Supernovae
Sources
wave period
age of universe
years
hours
sec
ms
log(frequency)
-16
-14
-12
-10
-8
-6
-4
-2
0
+2
Detectors
Cosmic microwave background polarization
Pulsar Timing
Space Interferometers
Terrestrial interferometers

The GW era: GW 150914

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

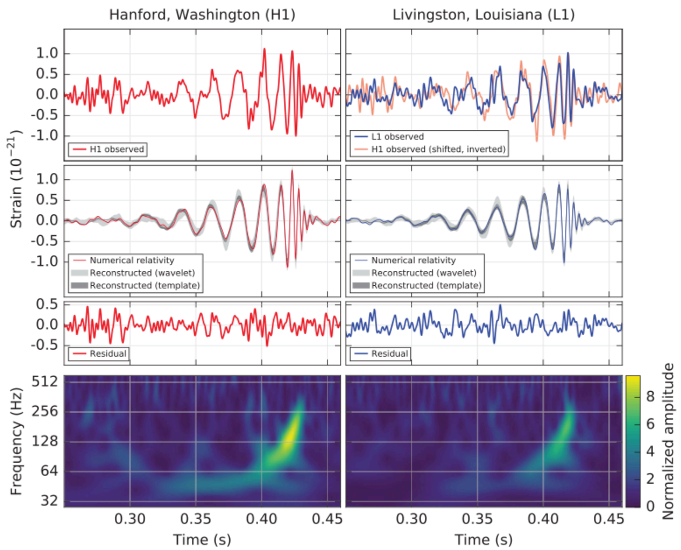
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

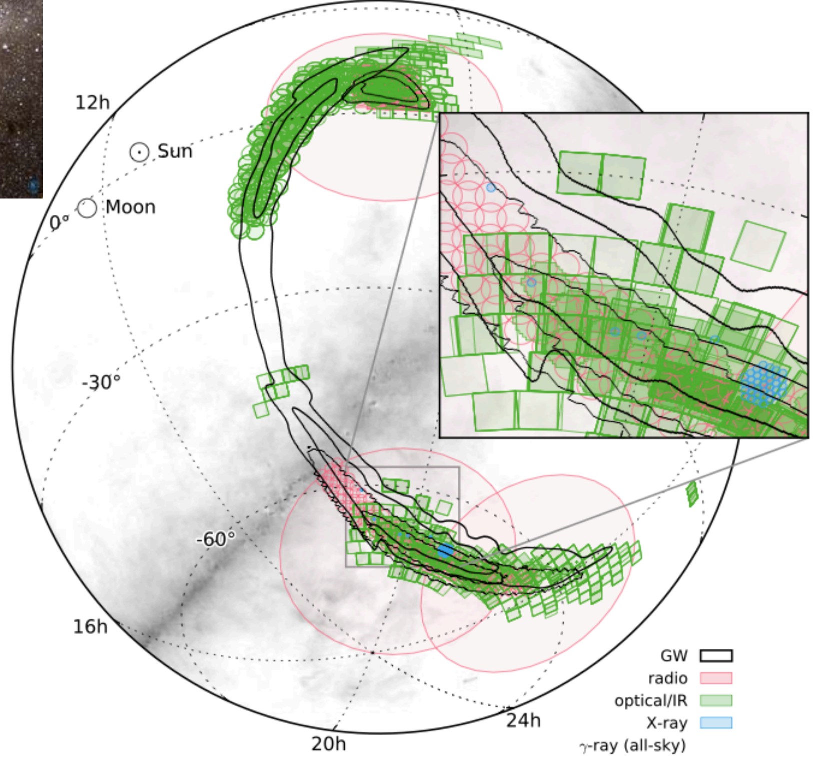
DOI: 10.1103/PhysRevLett.116.061102

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



The GW era: GW 150914 – EM search

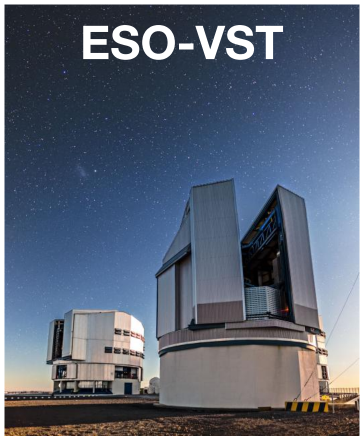
Abbott et al. 2016

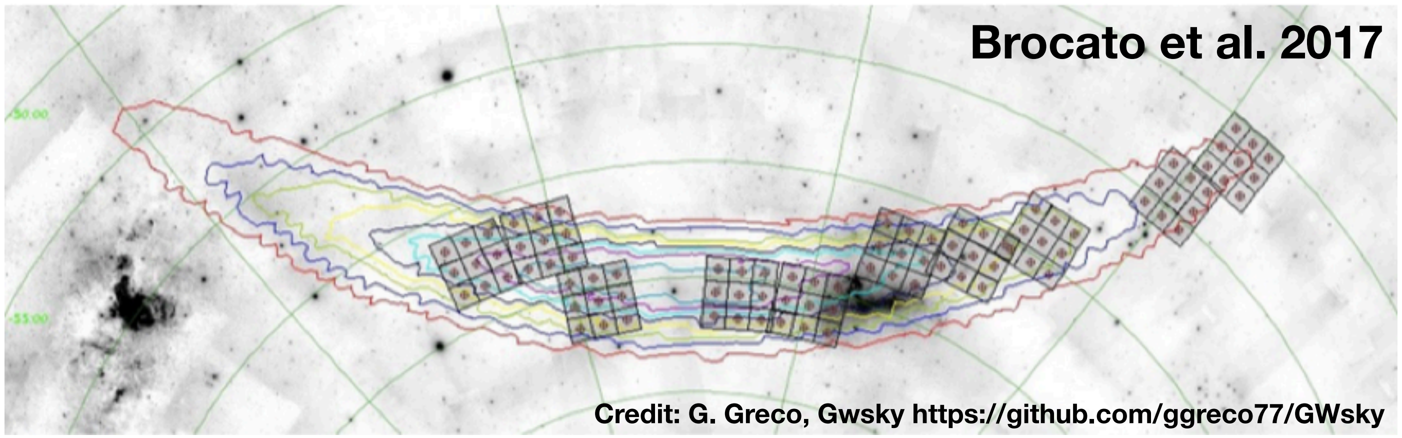


600 deg^2 skymap from LIGO/Virgo
Huge observational effort, mainly with wide-field facilities

No EM counterpart found

No EM counterpart expected from BHBH merger
Expected EM counterparts for NSNS/NSBH merger:
-Short GRBs (beamed emission)
-Kilonovae (isotropic emission)





The GW era – O1 & O2

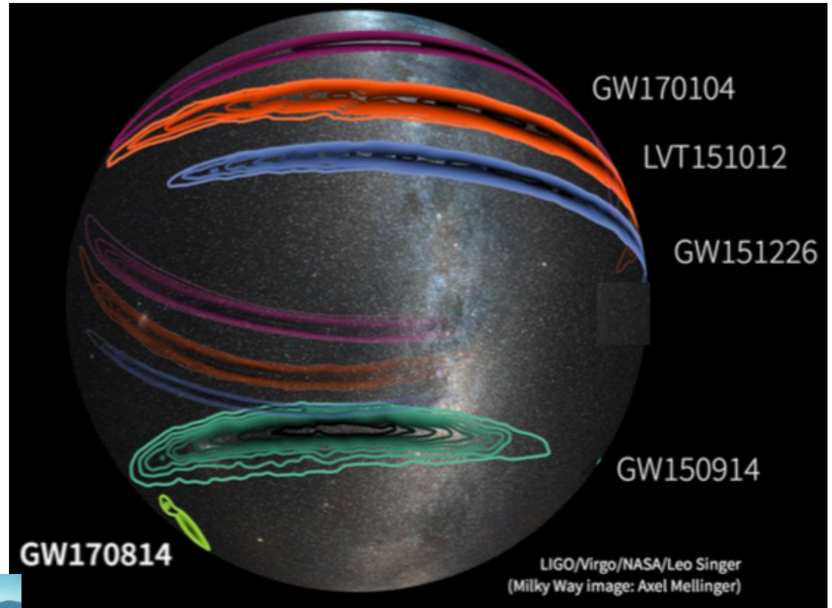
Sept 2015 – Jan 2016: LVC O1 science run

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) and one NSNS (GW 170817)
Improved strategies for EM follow-up at all wavelengths.

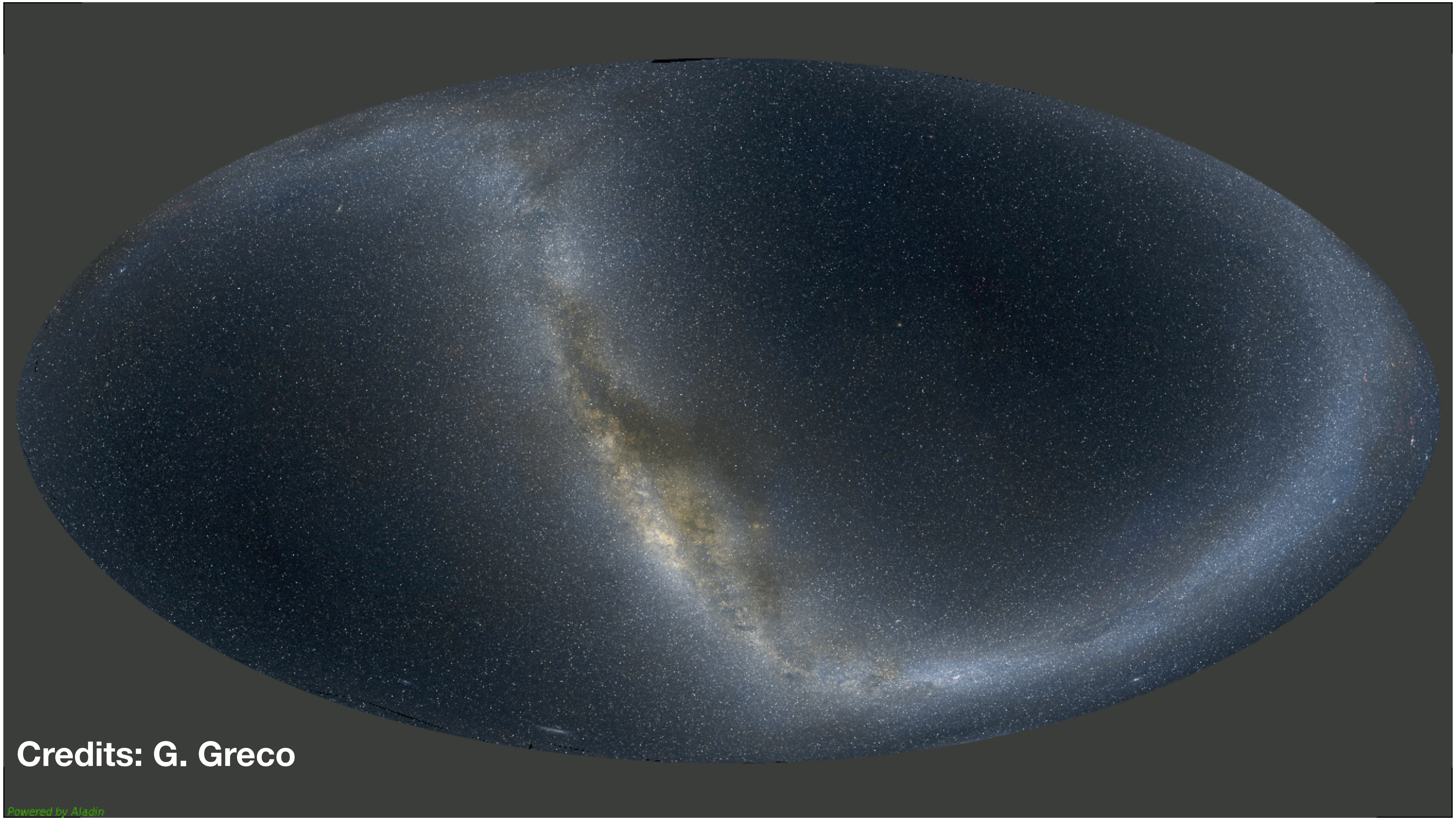
Sky localizations (90% credible area)
600 deg^2 GW 150914
1600 deg^2 LVT 151012
850 deg^2 GW 151226
2000 deg^2 GW 170104
520 deg^2 GW 170608
62 deg^2 GW 170814
28 deg^2 GW 170817



No EM counterpart found for BBH (despite huge observational effort)

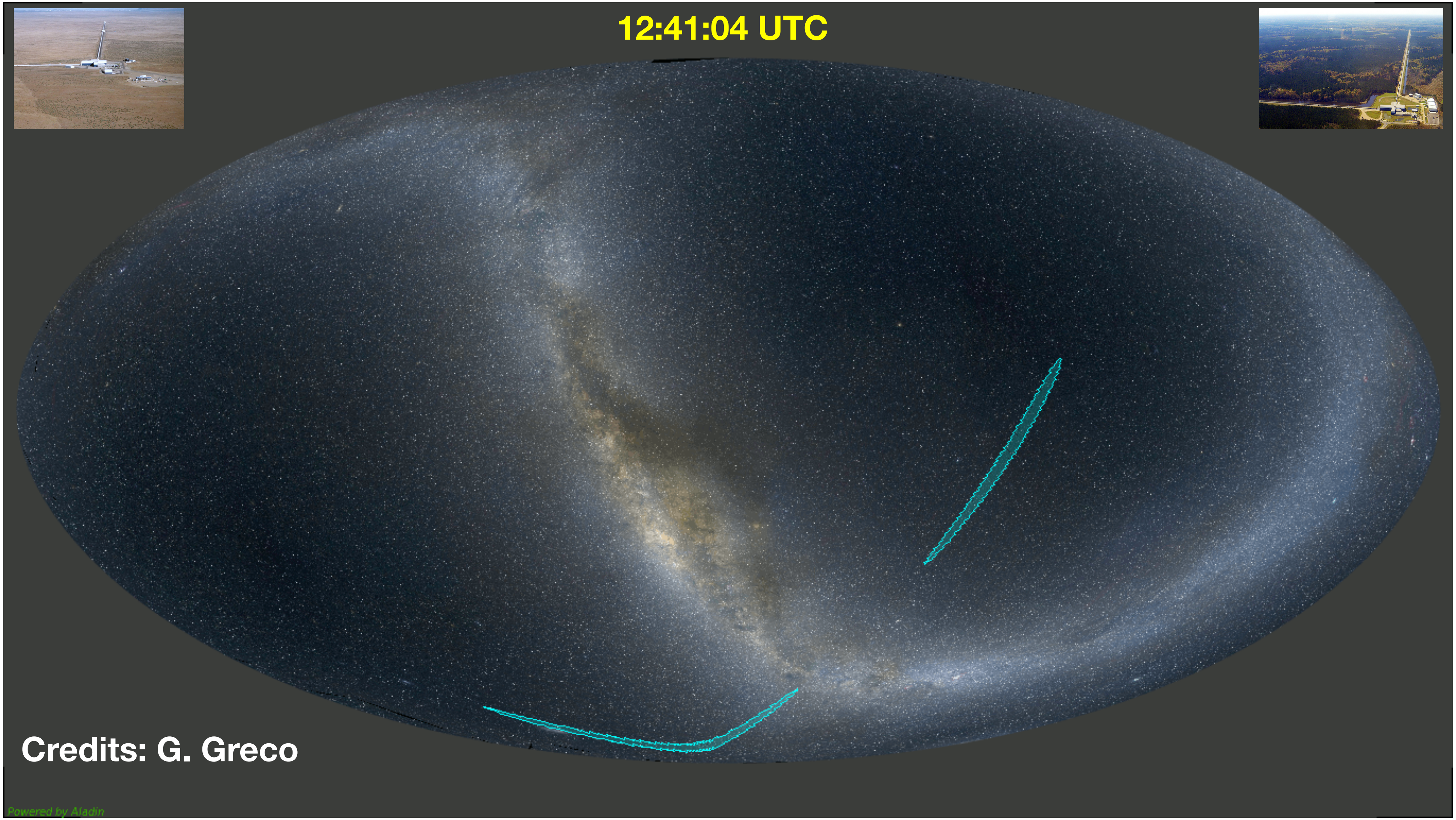
!!! EM counterpart found for NSNS !!!

17 August

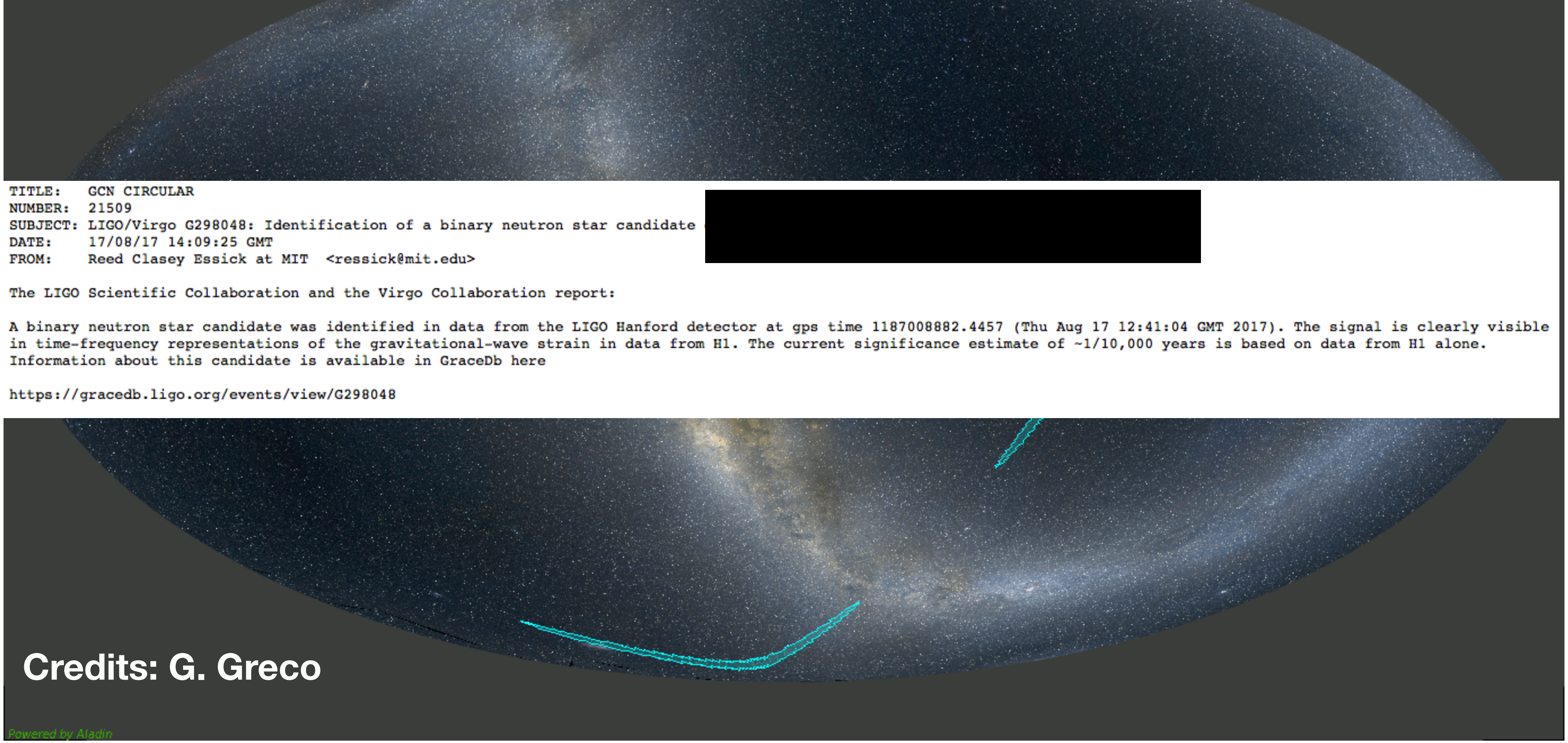


Credits: G. Greco

17 August



12:41:04 UTC



TITLE: GCN CIRCULAR
NUMBER: 21509
SUBJECT: LIGO/Virgo G298048: Identification of a binary neutron star candidate [redacted]
DATE: 17/08/17 14:09:25 GMT
FROM: Reed Clasey Essick at MIT <ressick@mit.edu>

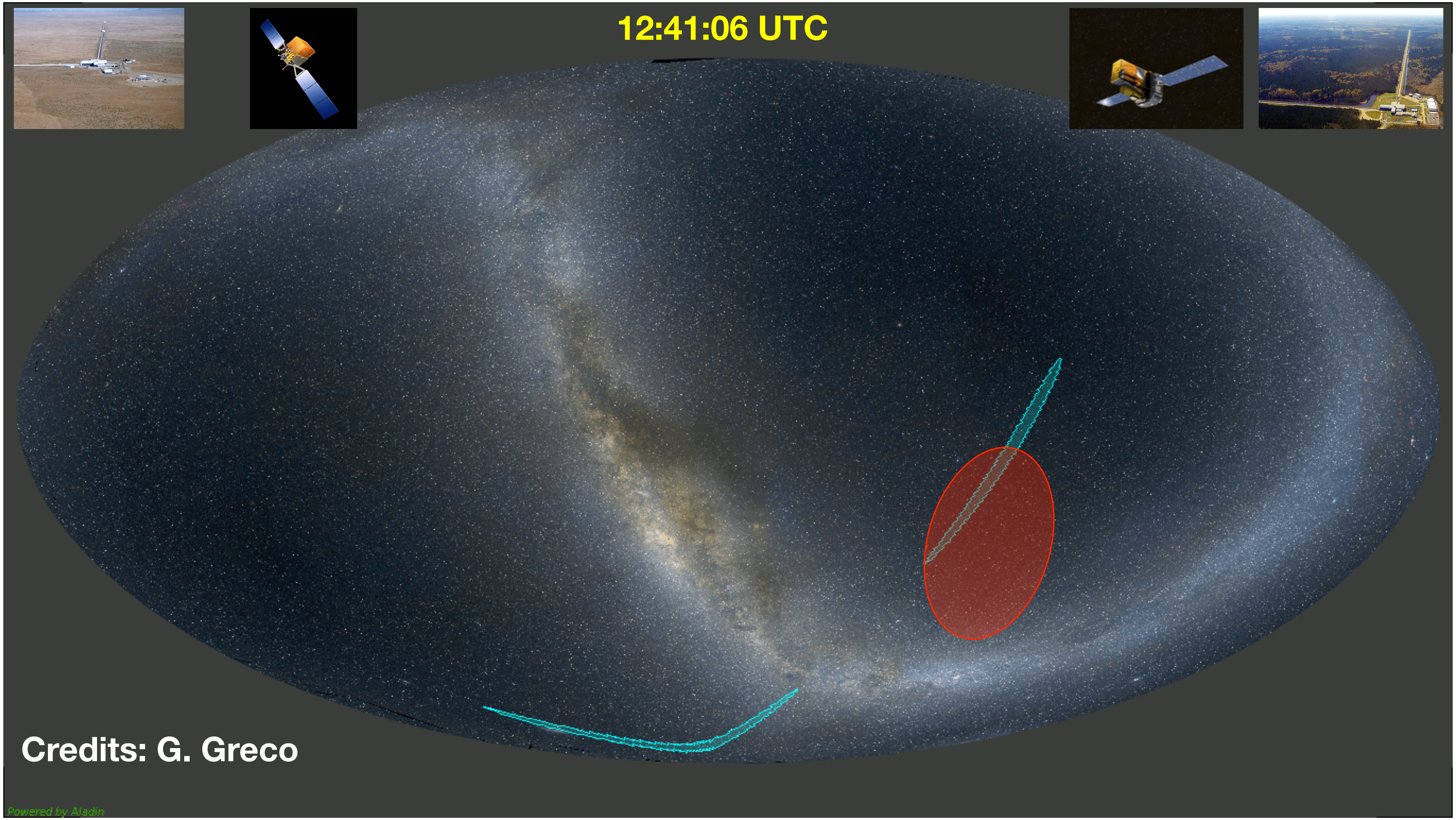
The LIGO Scientific Collaboration and the Virgo Collaboration report:

A binary neutron star candidate was identified in data from the LIGO Hanford detector at gps time 1187008882.4457 (Thu Aug 17 12:41:04 GMT 2017). The signal is clearly visible in time-frequency representations of the gravitational-wave strain in data from H1. The current significance estimate of ~1/10,000 years is based on data from H1 alone. Information about this candidate is available in GraceDb here

https://gracedb.ligo.org/events/view/G298048

Credits: G. Greco


17
August


12:41:06 UTC
Credits: G. Greco
Powered by Aladin

17 August

12:41:06 UTC

TITLE: GCN CIRCULAR
NUMBER: 21509
SUBJECT: LIGO/Virgo G298048: Identification of a binary neutron star candidate coincident with Fermi GBM trigger 524666471/170817529
DATE: 17/08/17 14:09:25 GMT
FROM: Reed Clasey Essick at MIT <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

A binary neutron star candidate was identified in data from the LIGO Hanford detector at gps time 1187008882.4457 (Thu Aug 17 12:41:04 GMT 2017). The signal is clearly visible in time-frequency representations of the gravitational-wave strain in data from H1. The current significance estimate of ~1/10,000 years is based on data from H1 alone. Information about this candidate is available in GraceDb here

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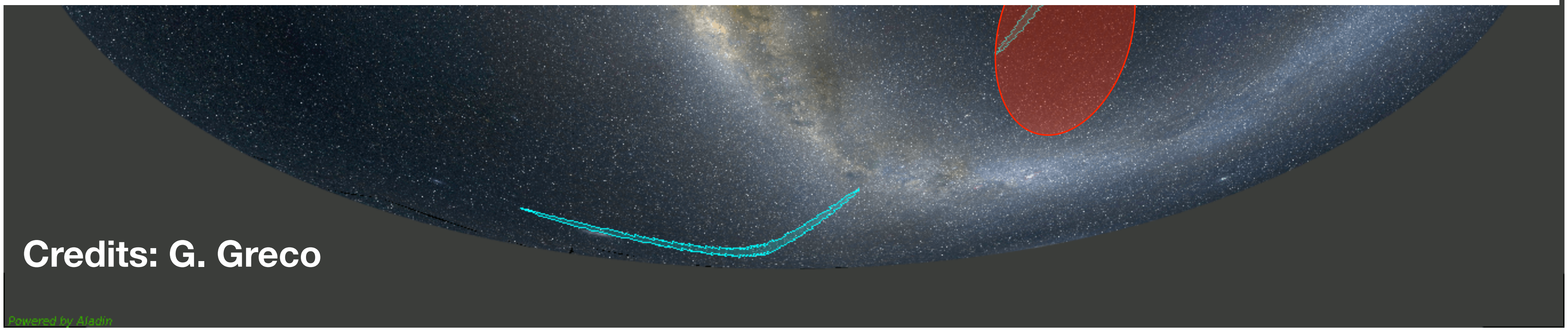
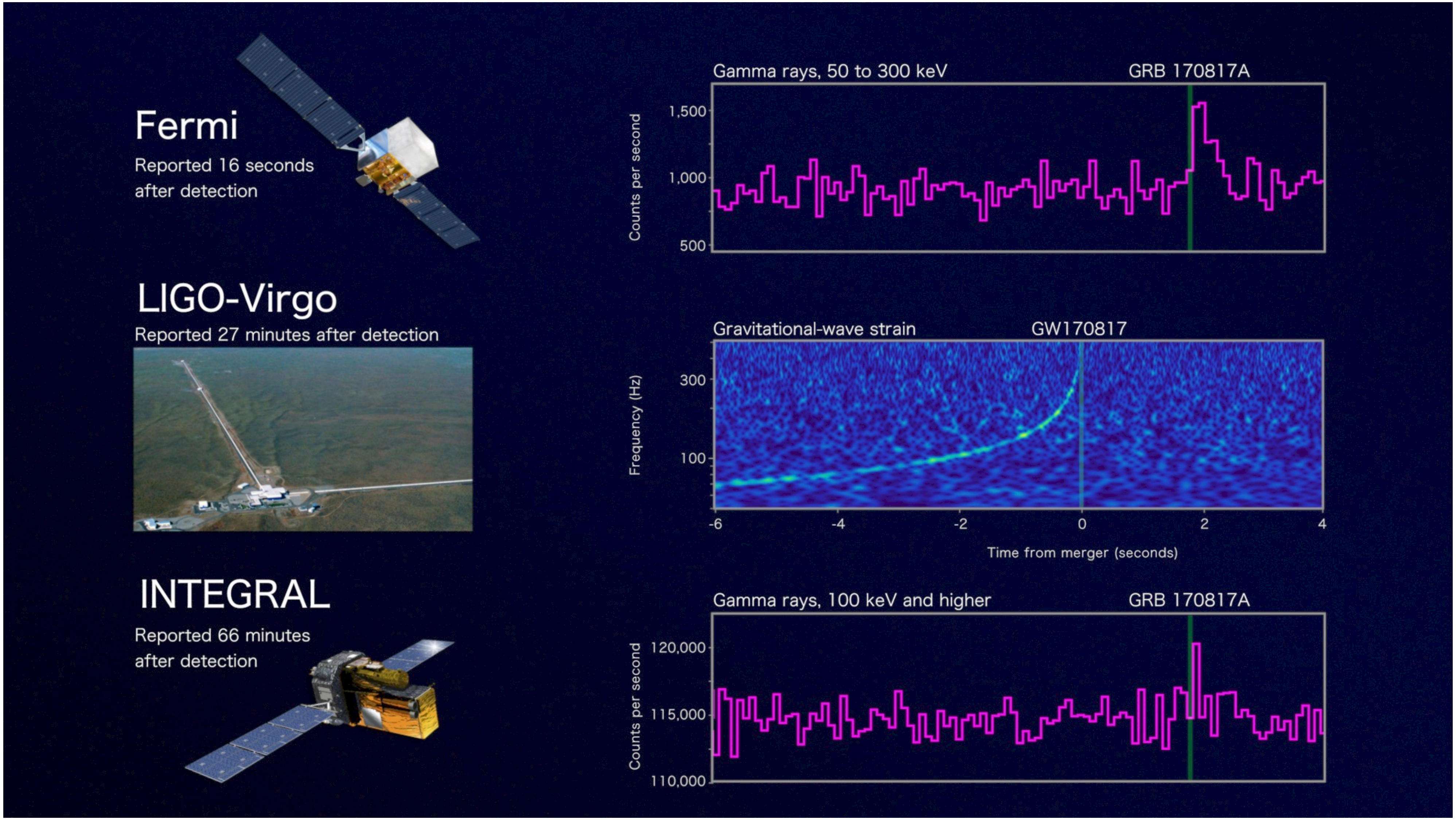


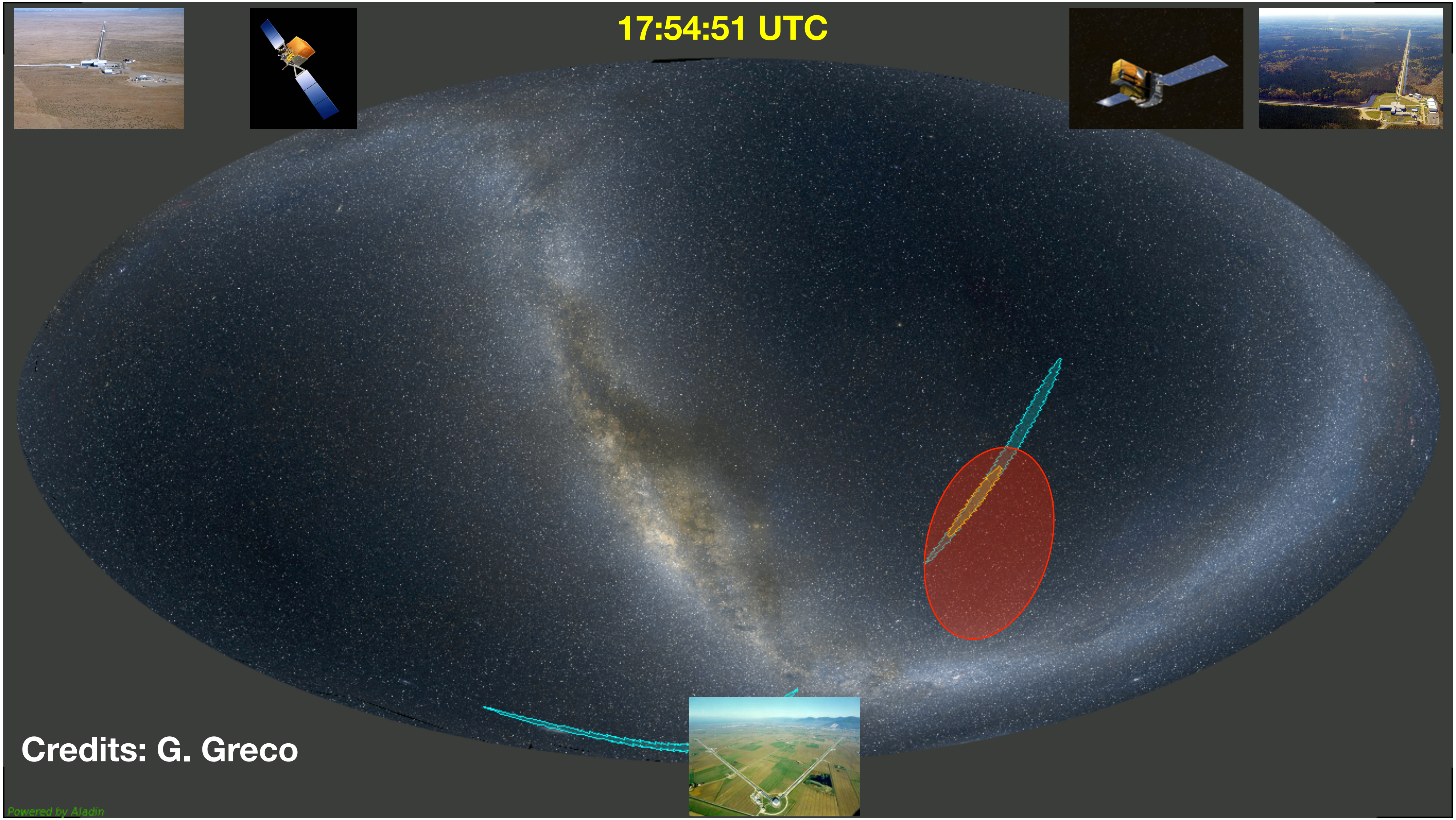
Credits: G. Greco

GW 170817 & GRB 170817A



Goldstein et al. (2017); LVC + "partner astronomy groups" (2017); Savchenko et al. (2017)


17
August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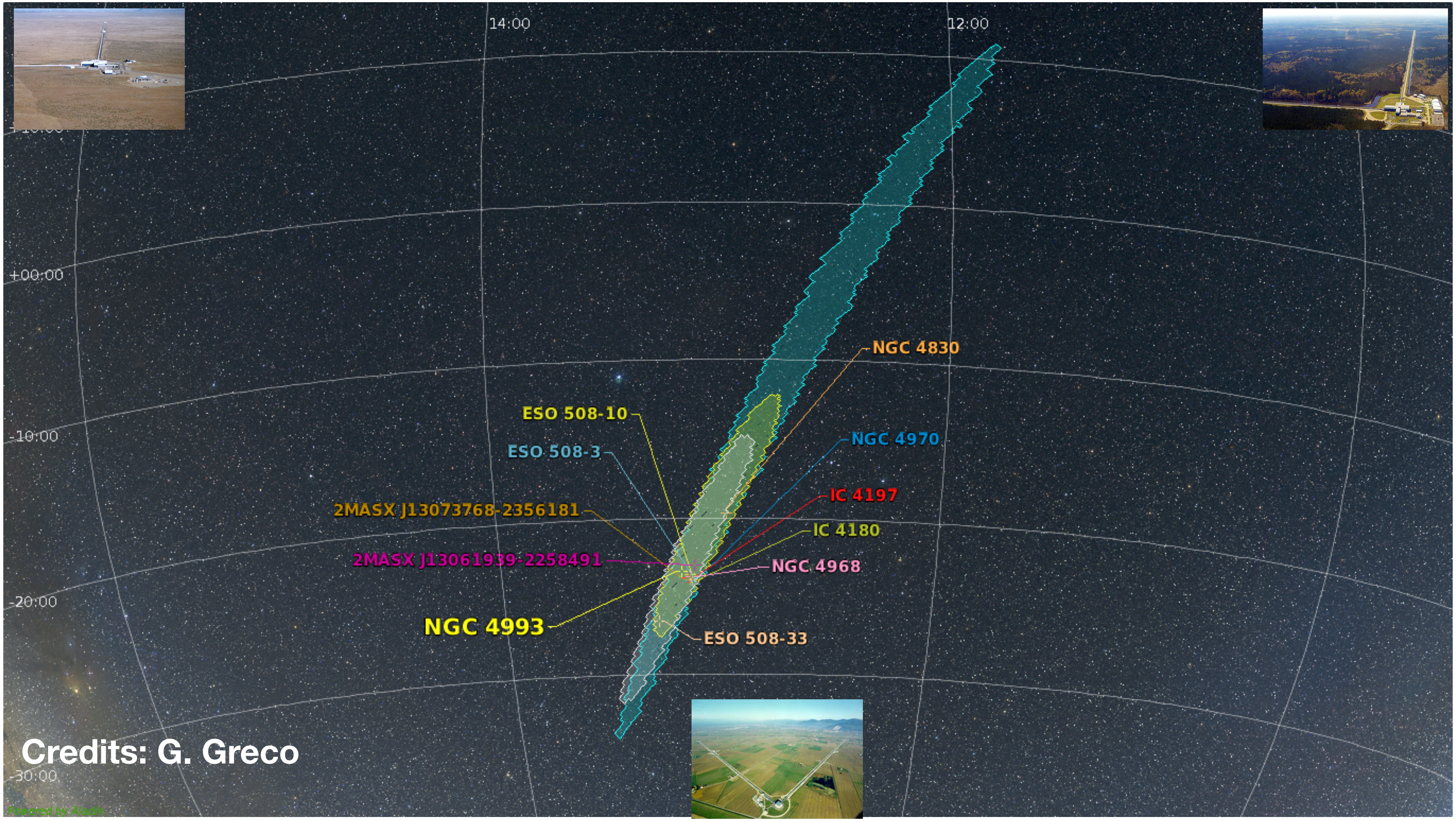
Powered by Aladin

17
August



14:00
12:00
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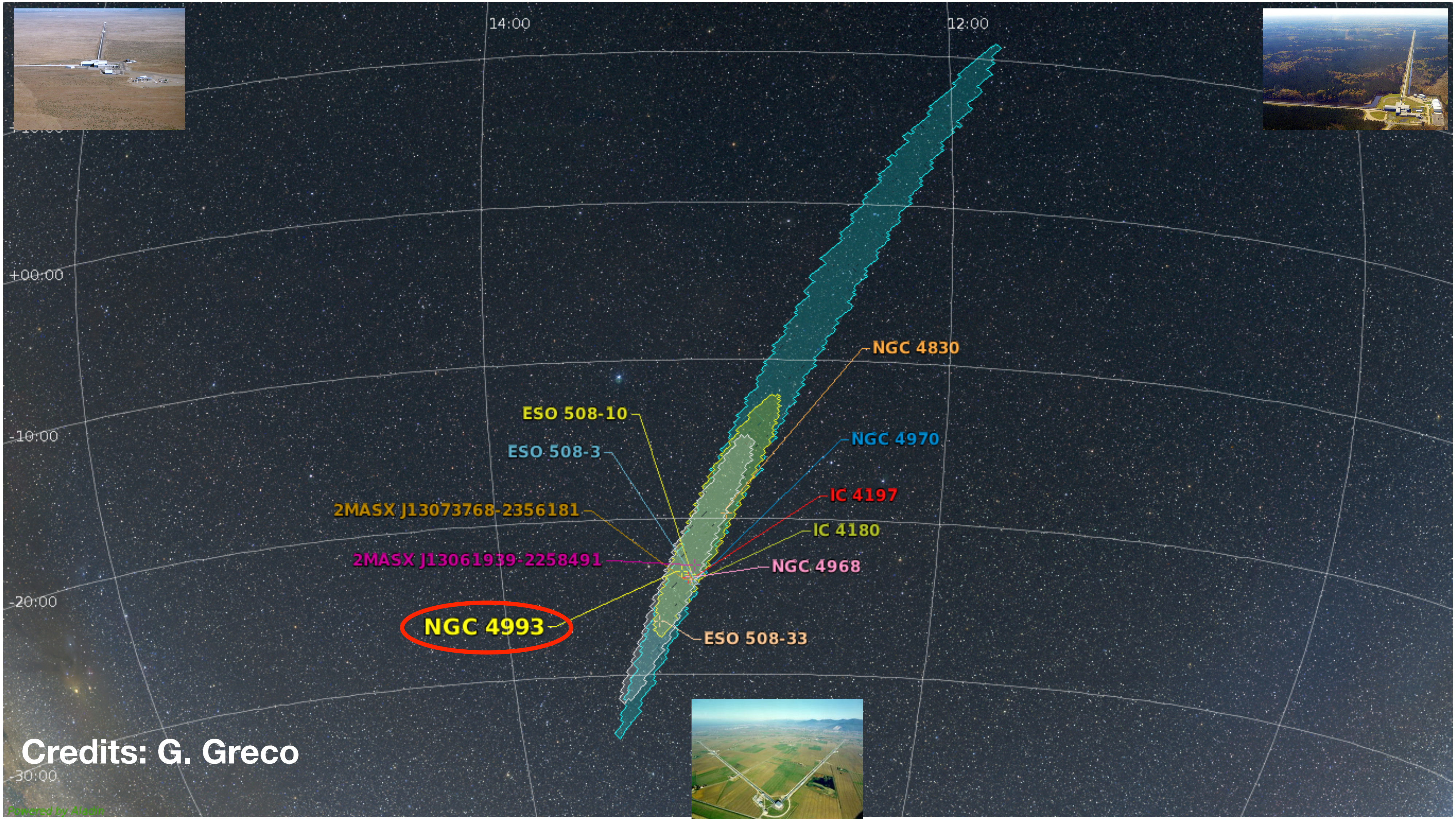
-10:00
-20:00
-30:00
NGC 4830
ESO 508-10
ESO 508-3
NGC 4970
IC 4197
2MASX J13073768-2356181
IC 4180
2MASX J13061939-2258491
NGC 4968
NGC 4993
ESO 508-33
Credits: G. Greco


17
August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NGC 4830
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ESO 508-3
NGC 4970
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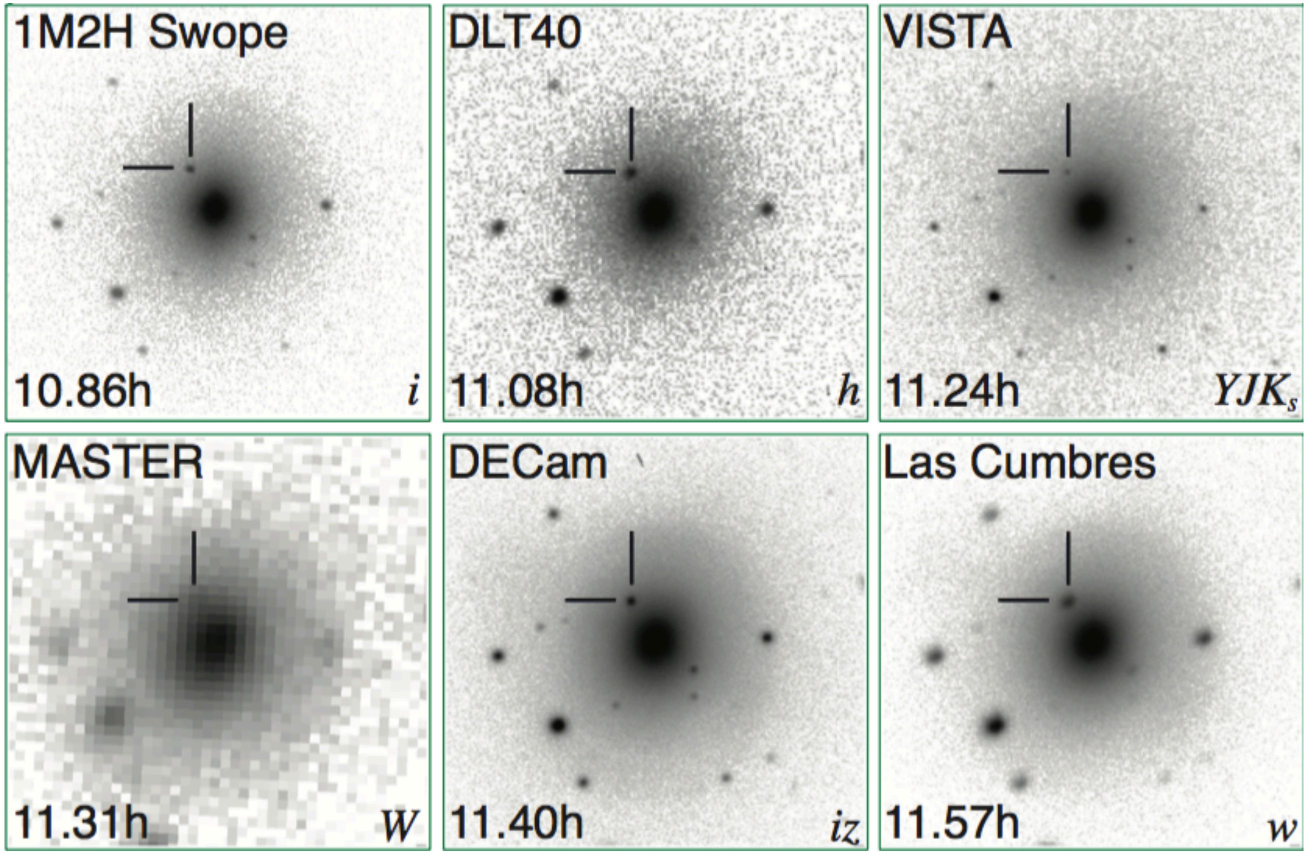
IC 4197
IC 4180
2MASX J13061939-2258491
NGC 4968
NGC 4993
ESO 508-33
Credits: G. Greco

Optical counterpart in NGC 4993

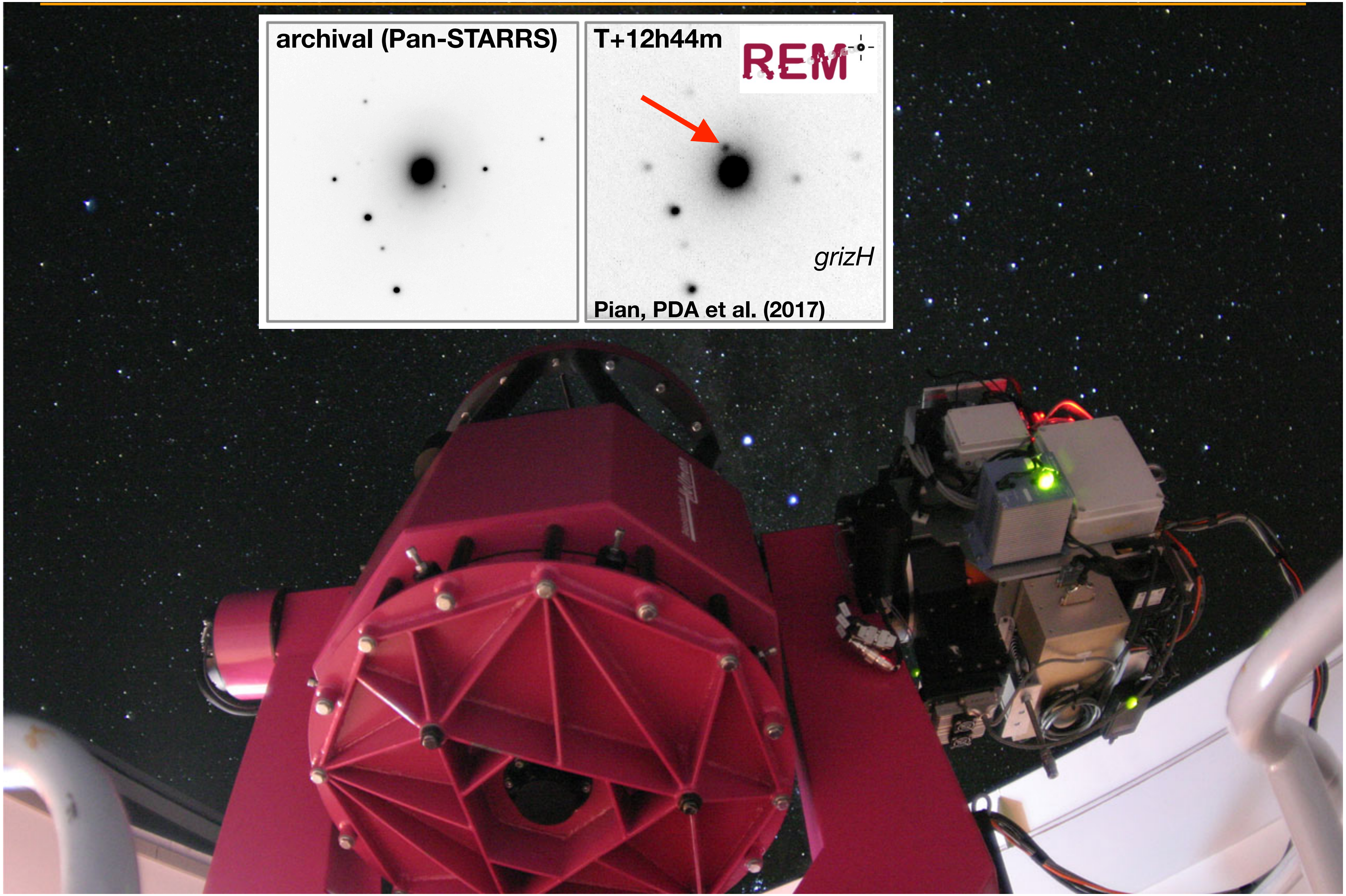
Coulter et al. (2017) Valenti et al. (2017) Tanvir et al. (2017)



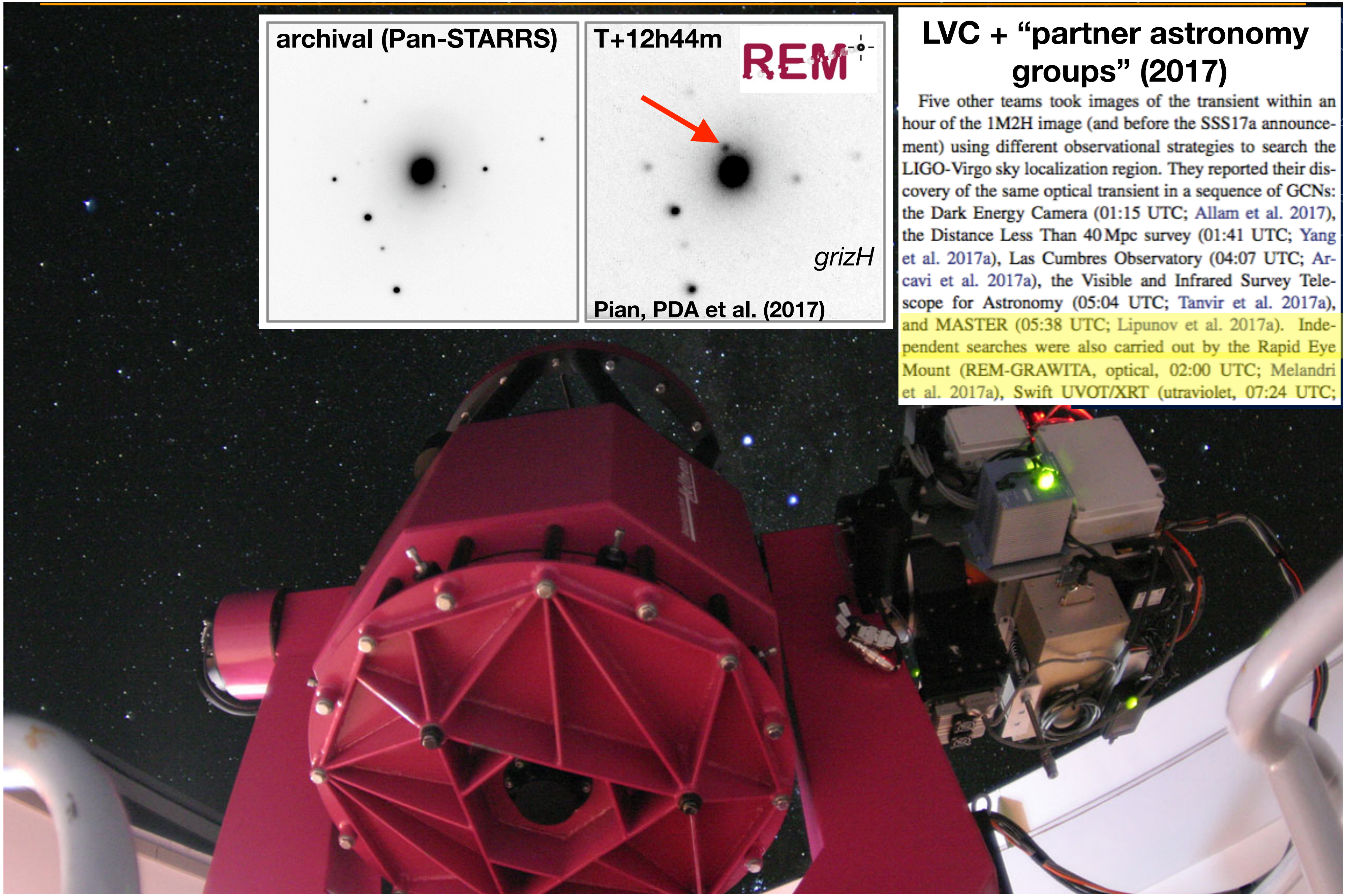
Lipunov et al. (2017) Allam et al. (2017) Arcavi et al. (2017)

NGC 4993, S0 galaxy @ D ~ 41 Mpc, z = 0.00968 (Hjorth et al. 2017; Cantiello et al. 2018)

Optical counterpart in NGC 4993



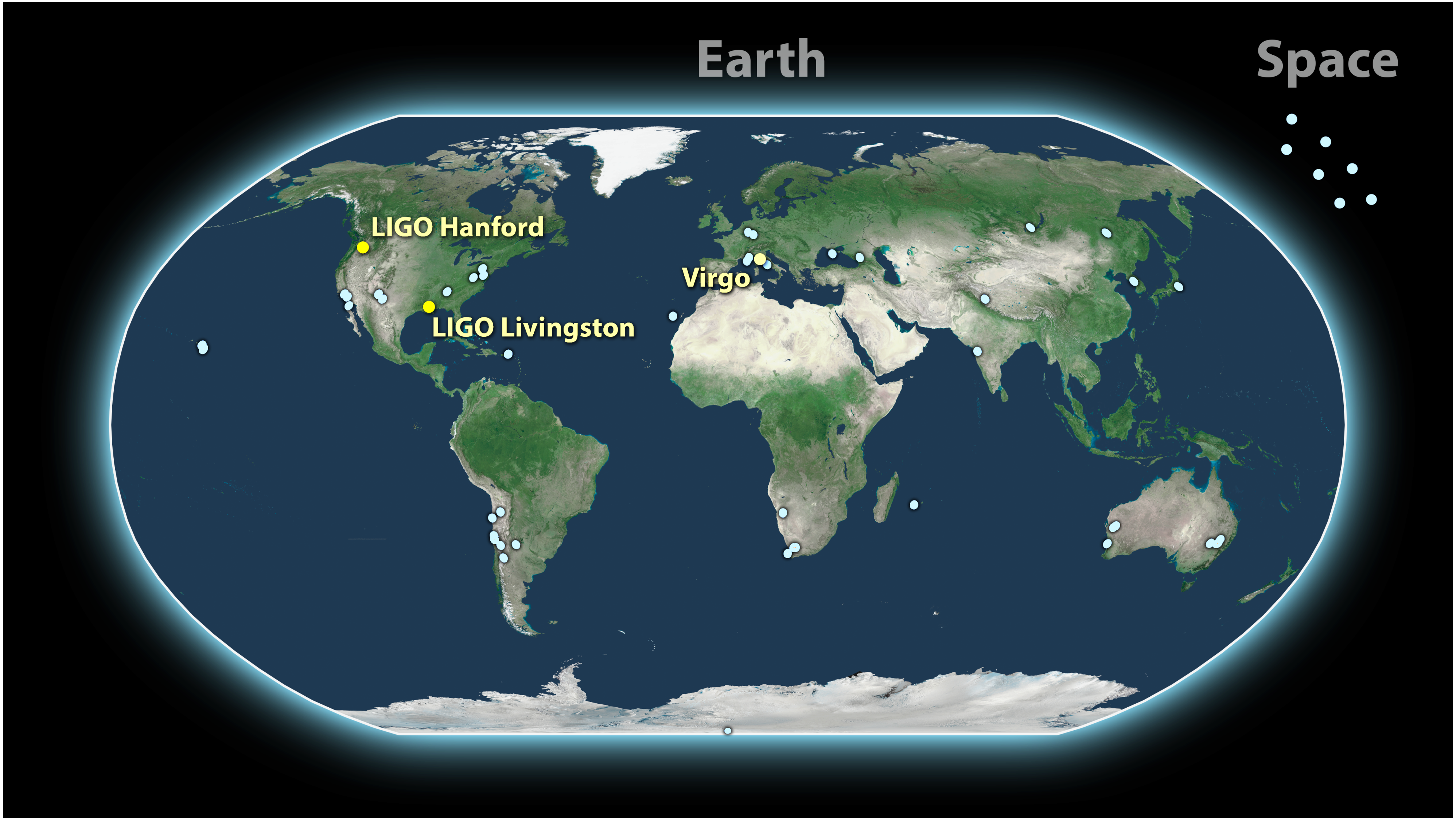
Optical counterpart in NGC 4993



LVC + "partner astronomy groups" (2017)

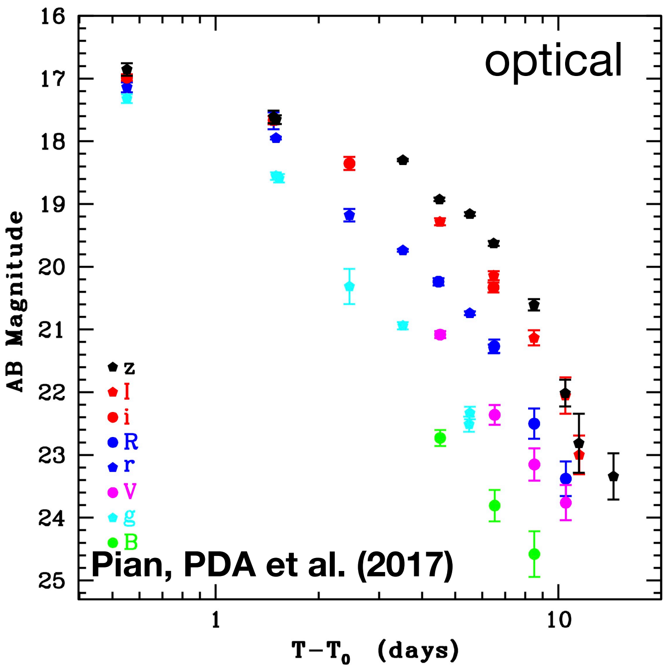
Five other teams took images of the transient within an hour of the 1M2H image (and before the SSS17a announcement) using different observational strategies to search the LIGO-Virgo sky localization region. They reported their discovery of the same optical transient in a sequence of GCNs: the Dark Energy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

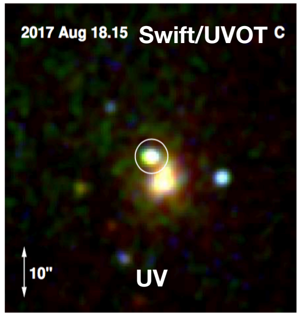
An impressive observational campaign

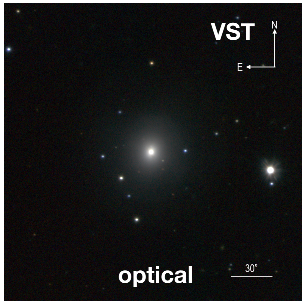


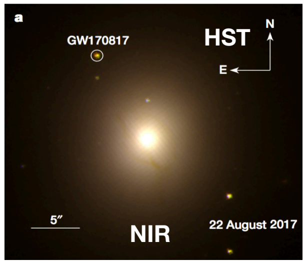
LVC + “partner astronomy groups” (2017)

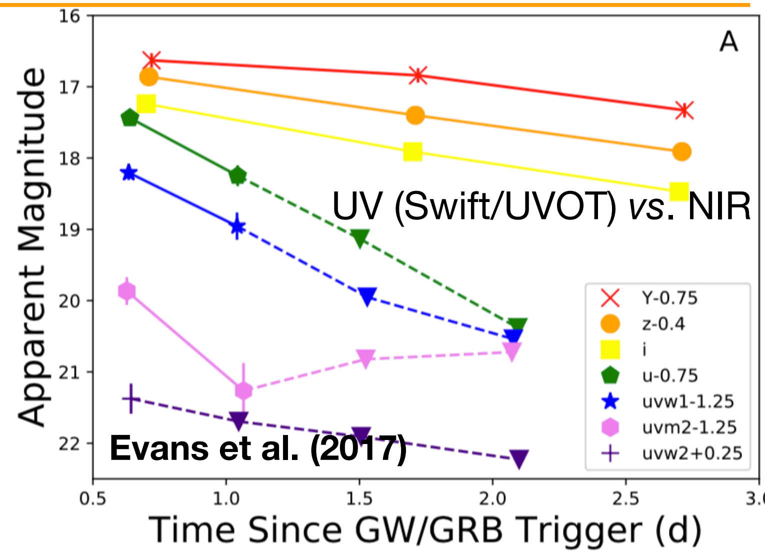
Light curves

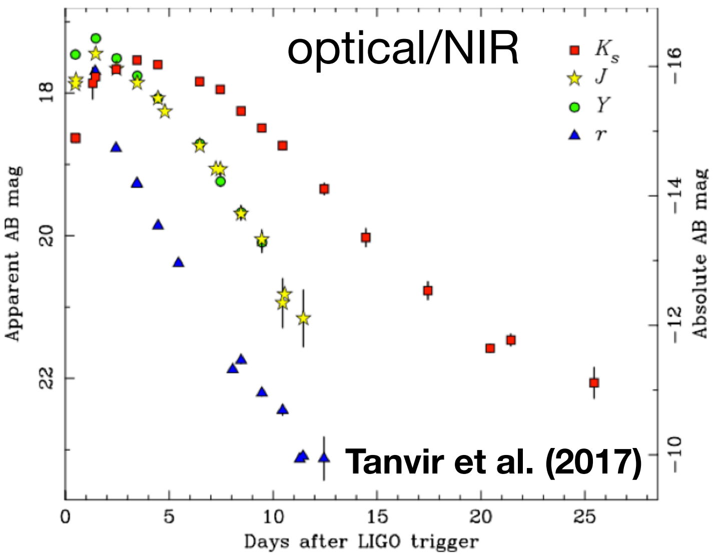


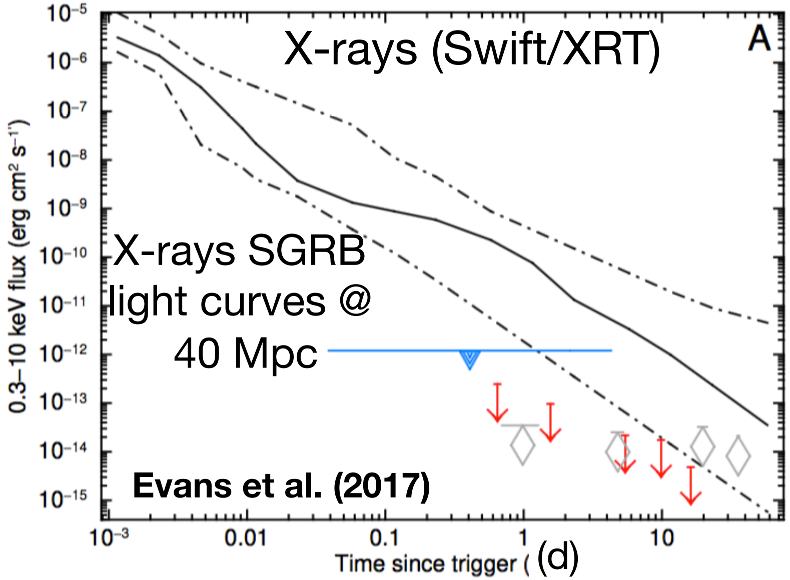








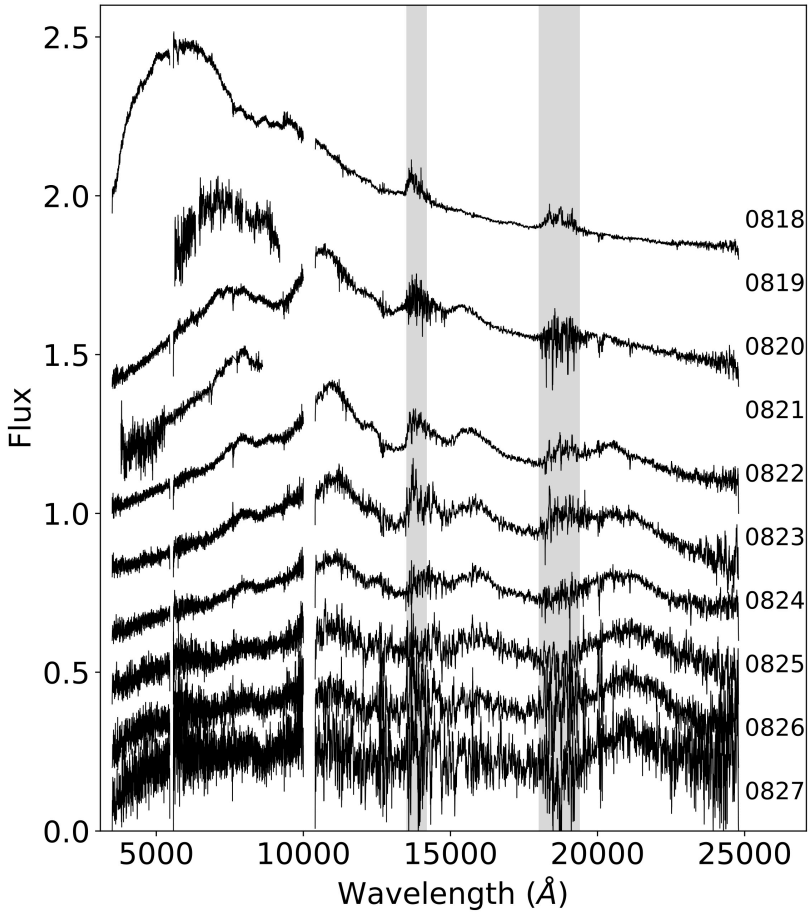




Bright UV/Opt/NIR source, slower fading in the NIR
No early-time X-ray (and no radio) emission: inconsistent with on-axis GRB

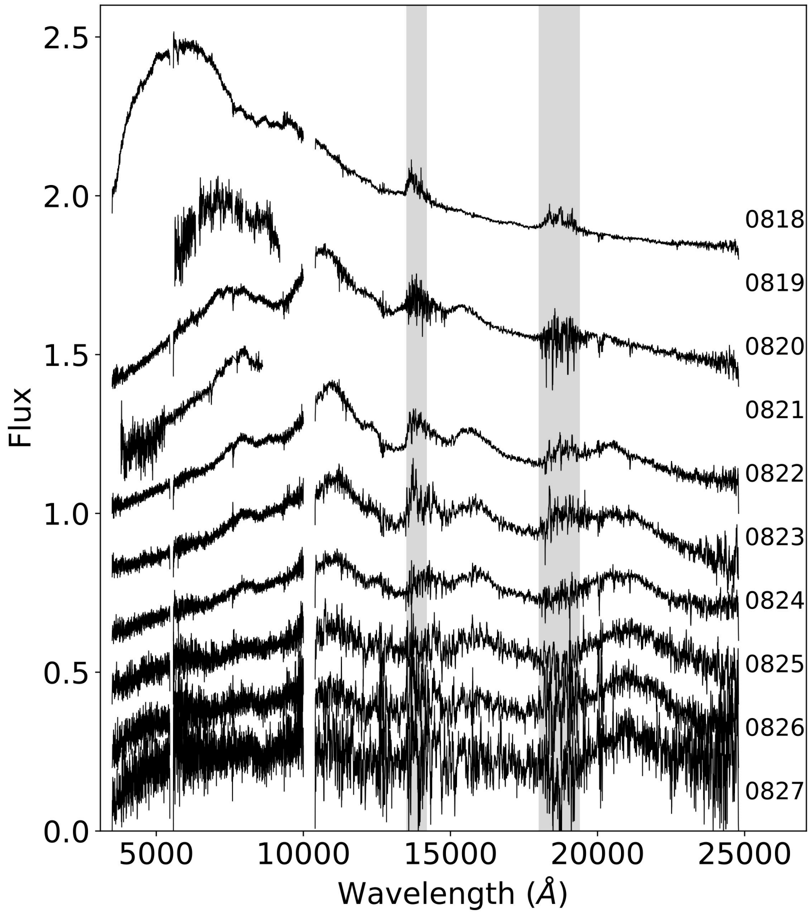
Optical/NIR Spectra

Pian, PDA et al. (2017)

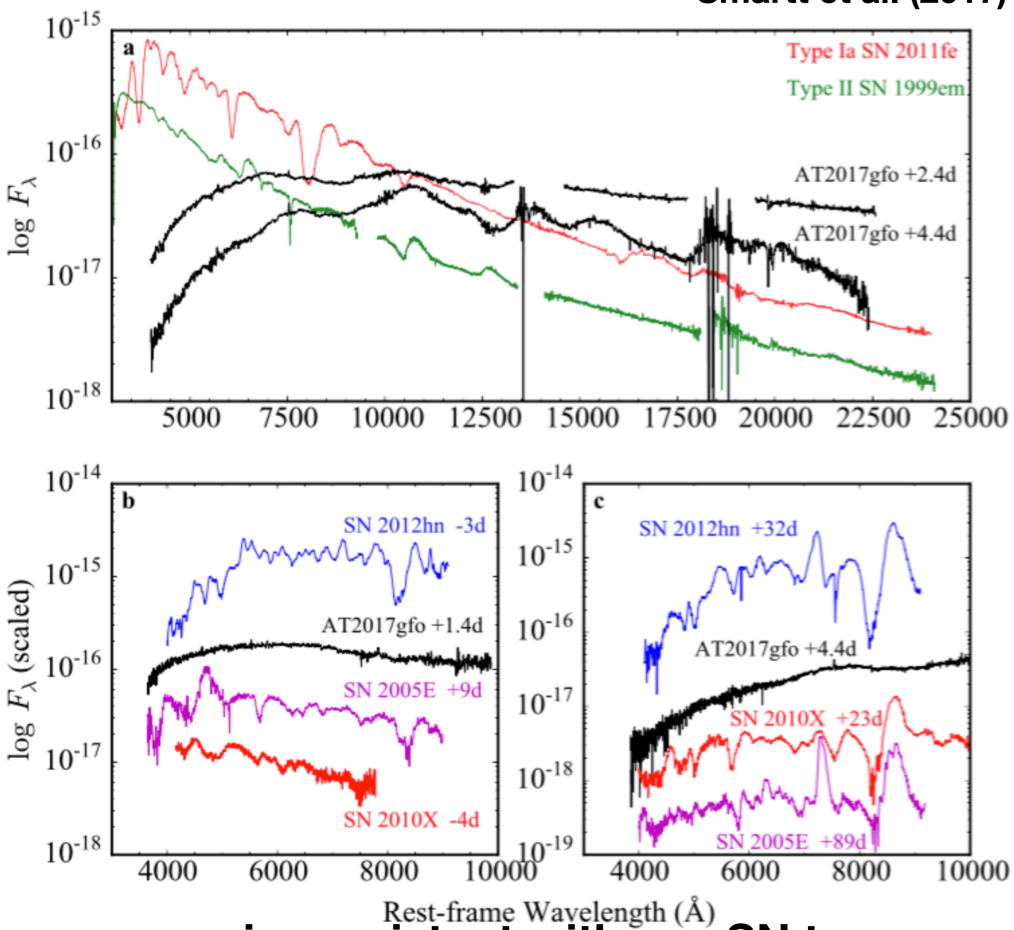


Optical/NIR Spectra

Pian, PDA et al. (2017)



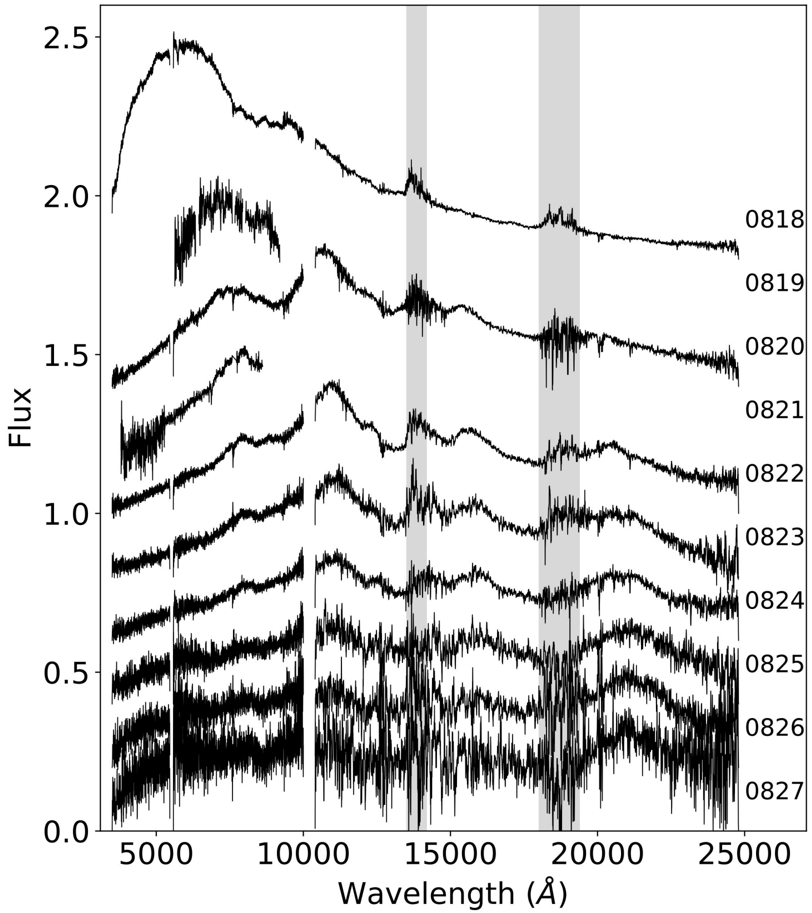
Smartt et al. (2017)



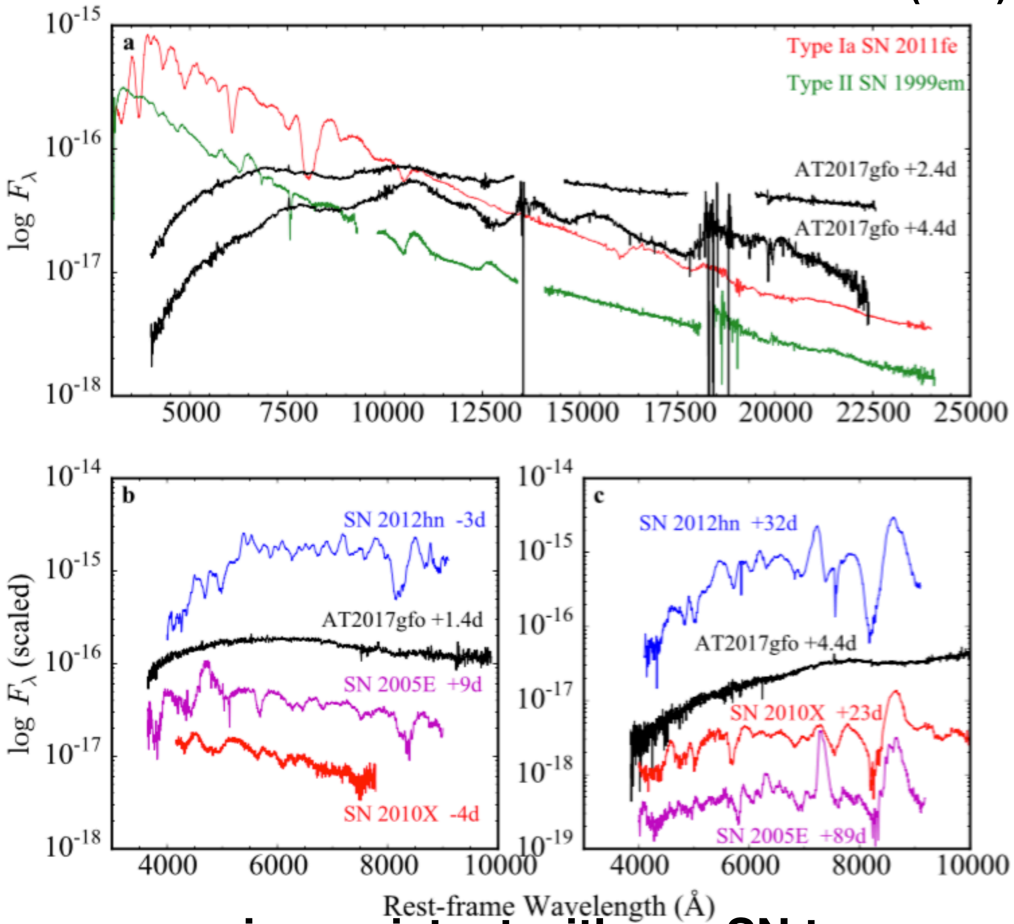
inconsistent with any SN type

Optical/NIR Spectra

Pian, PDA et al. (2017)



Smartt et al. (2017)



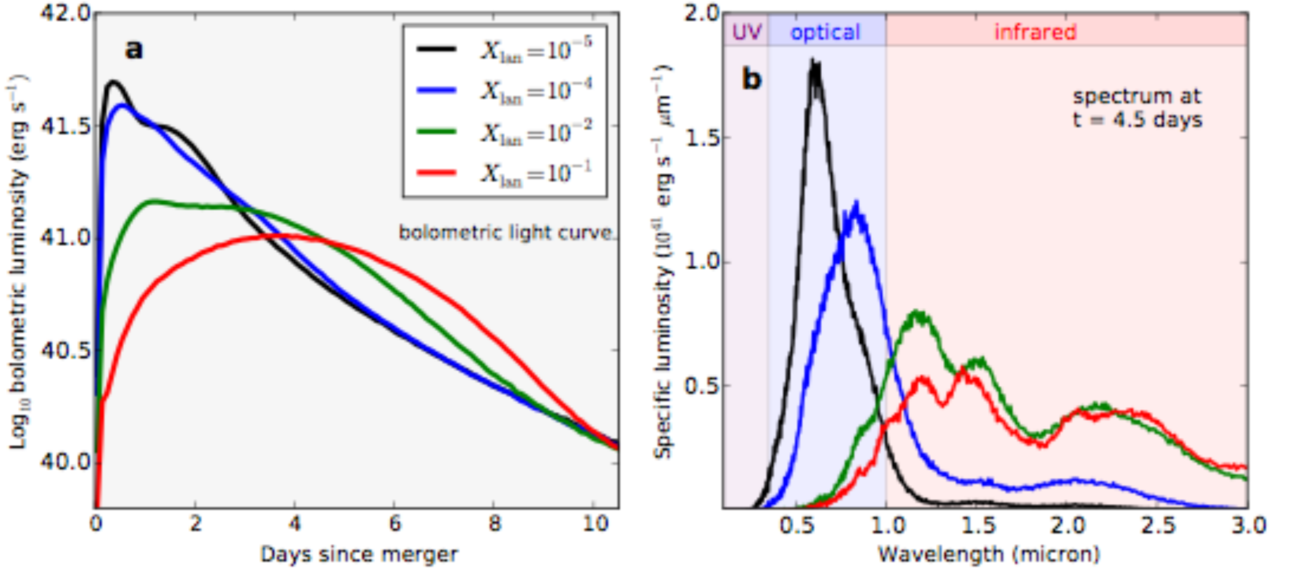
inconsistent with any SN type

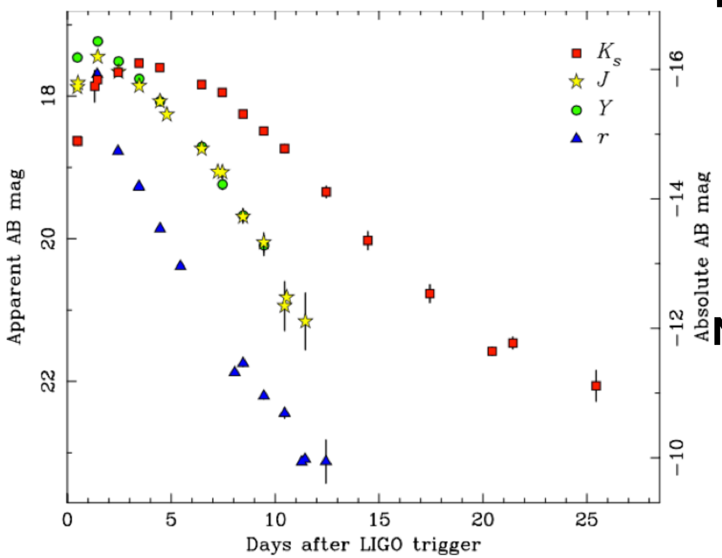
A key signature of an NS–NS/NS–BH binary merger is the production of a so-called "kilonova" (aka "macronova") due to the decay of heavy radioactive species (e.g. lanthanides) produced by the *r*-process and ejected during the merger that is expected to provide a source of heating and radiation (Li and Paczynski 1998; Rosswog, 2005; Metzger et al., 2010).

Kilonova signatures

r-process:
- rapid (faster than decay) neutron capture.
- requires high T (>10^9 K) and high neutron density (> 10^{22} cm^{-3})
-> nucleosynthesis of heavy elements
-> unstable, radioactive decay on > days timescale
-> UV/optical/NIR emission

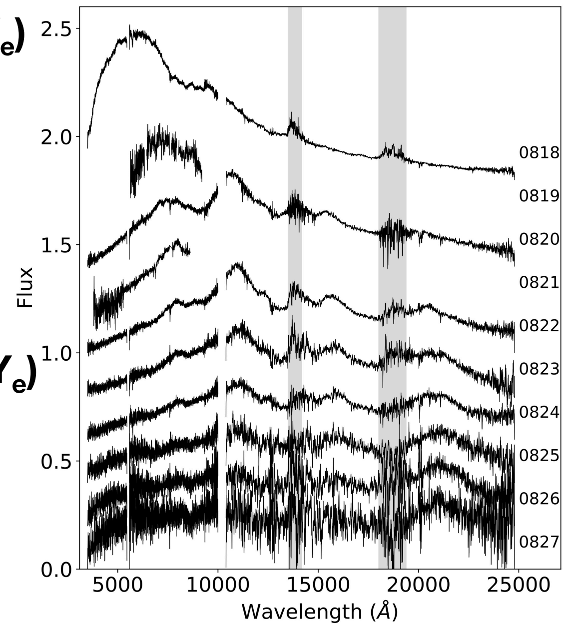
Kasen+17





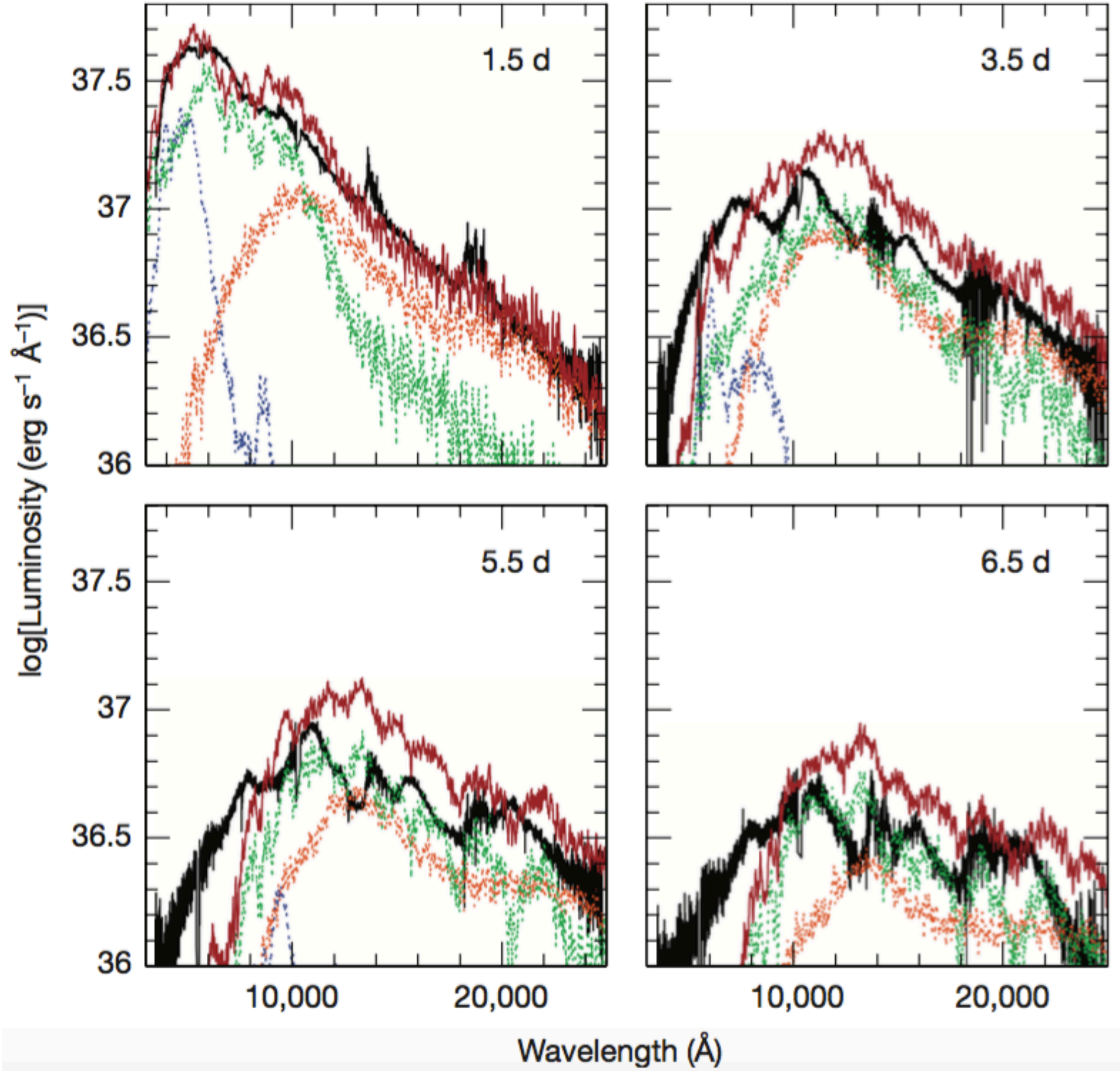
Neutron-rich ejecta (low e^- fraction Y_e)
Strong r-process
Very heavy elements (A>140)
Lanthanide rich
Higher opacity
Red KN, peak time~ 1 week

Neutron-rich ejecta (high e^- fraction Y_e)
Strong r-process
heavy elements (A<140)
Lanthanide poor
Lower opacity
Blue KN, peak time~ 1 day

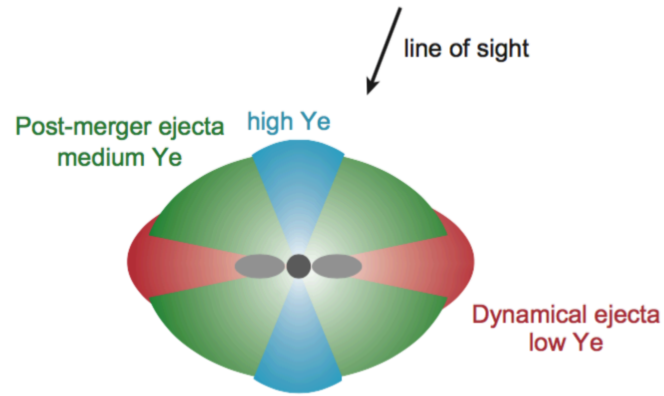


Optical/NIR spectra: evidences for KN

Pian, PDA et al. (2017)



Tanaka et al. (2017)

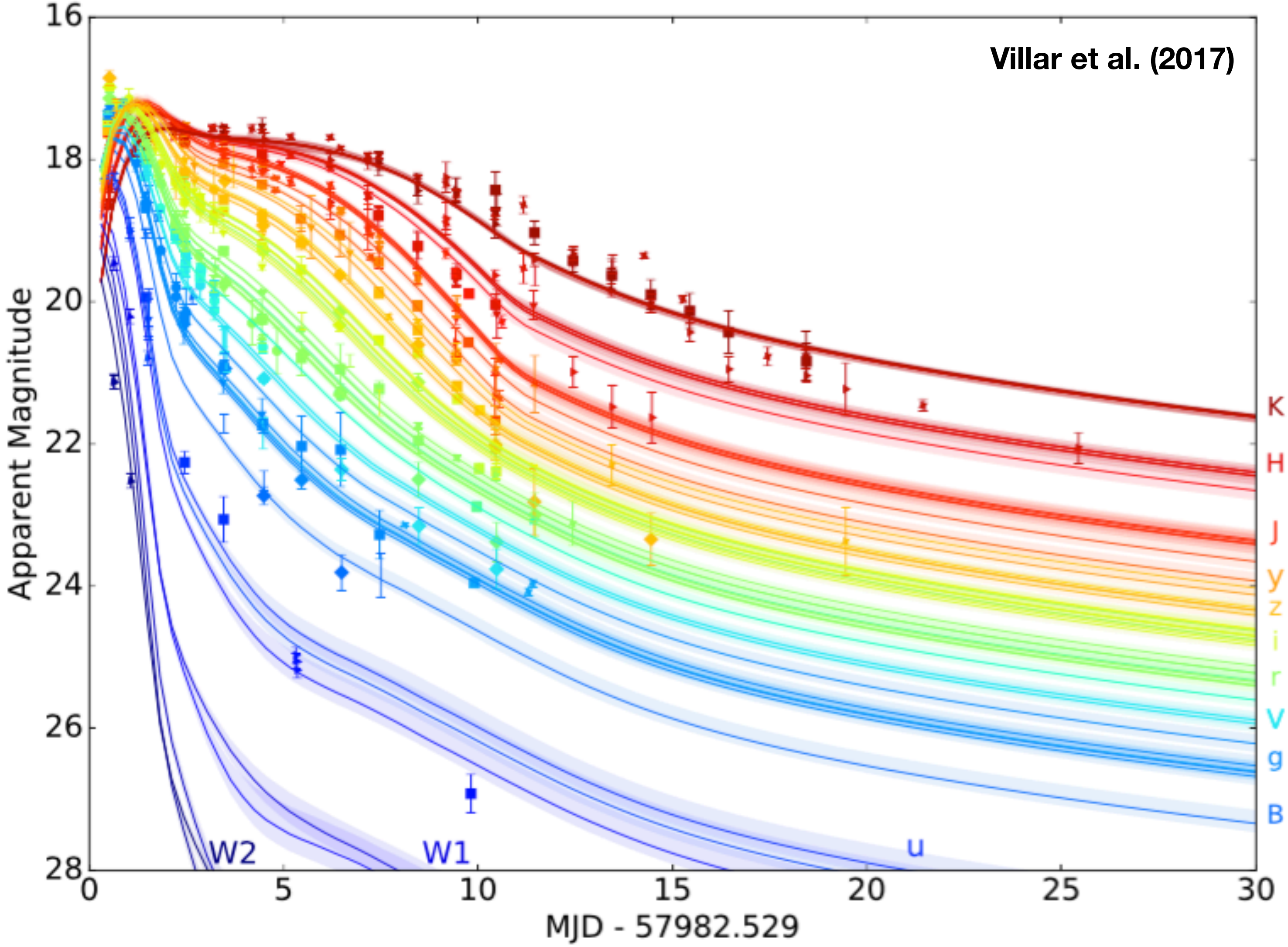


Three components Kilonova model with different velocity, composition and electron (proton) fraction (low Ye: lanthanide-rich; high Ye: lanthanide-poor)

Their sum and rescaling (red) can reproduce the observed spectra (black)

0.03-0.05 M_{Sun} ejected mass
Fast moving dynamical ejecta (blue, 0.2c) + slower wind (red/green, 0.05c)

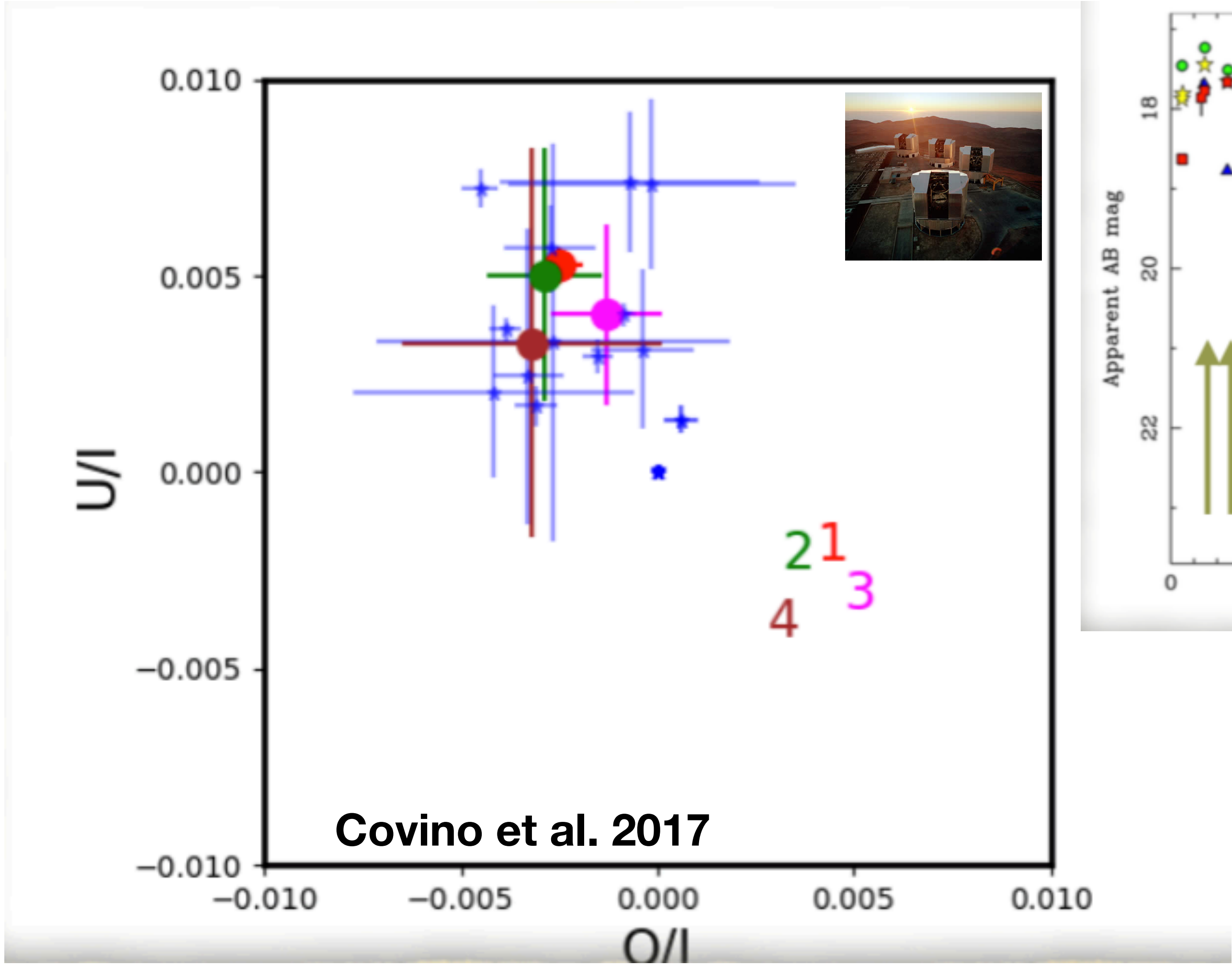
UV/Optical/NIR LCs: evidences for KN

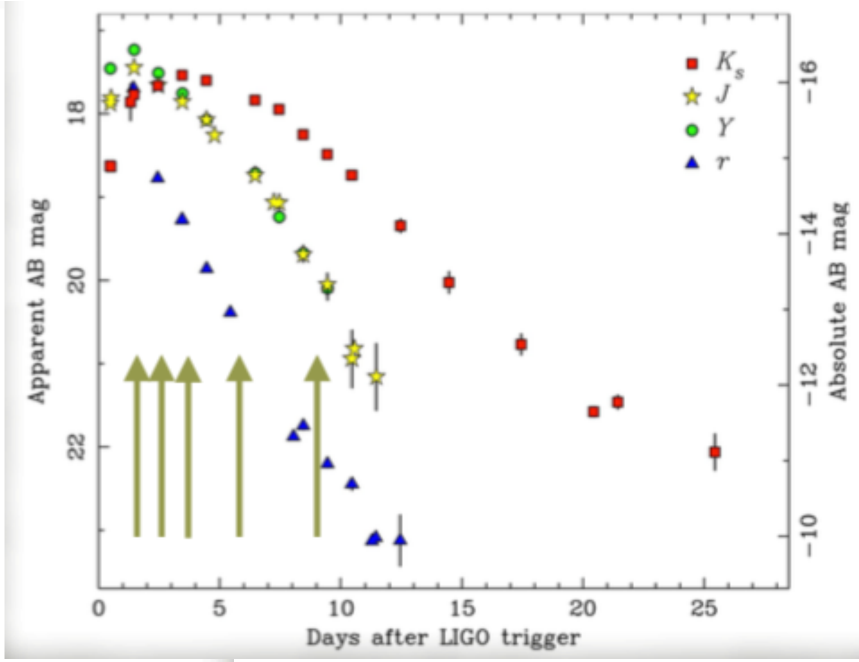


Multi-wavelength light curves best fitted with 3-component KN model

(possbile component such as long lived NS? Li et al. 2018)

Optical/NIR Polarimetry

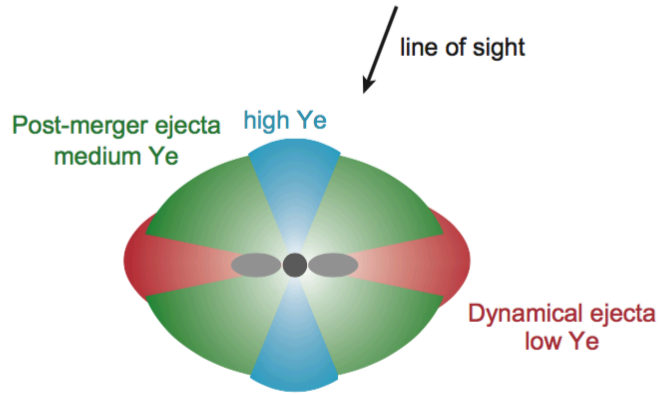




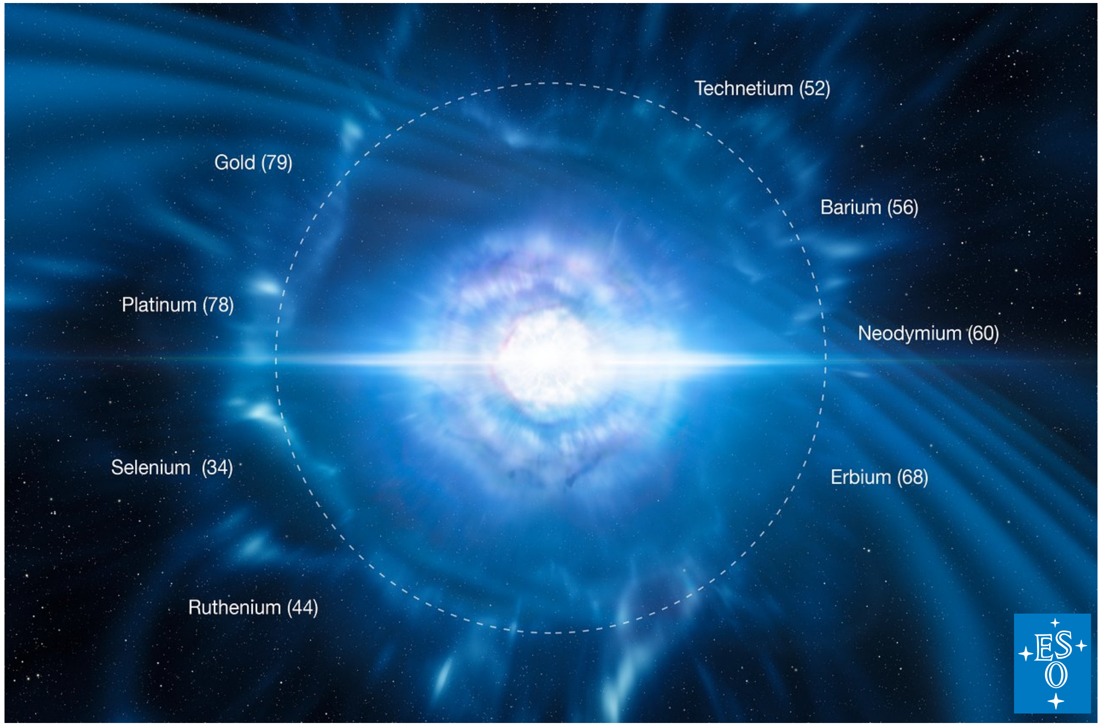
P < 0.5% - 0.9% --> No polarisation

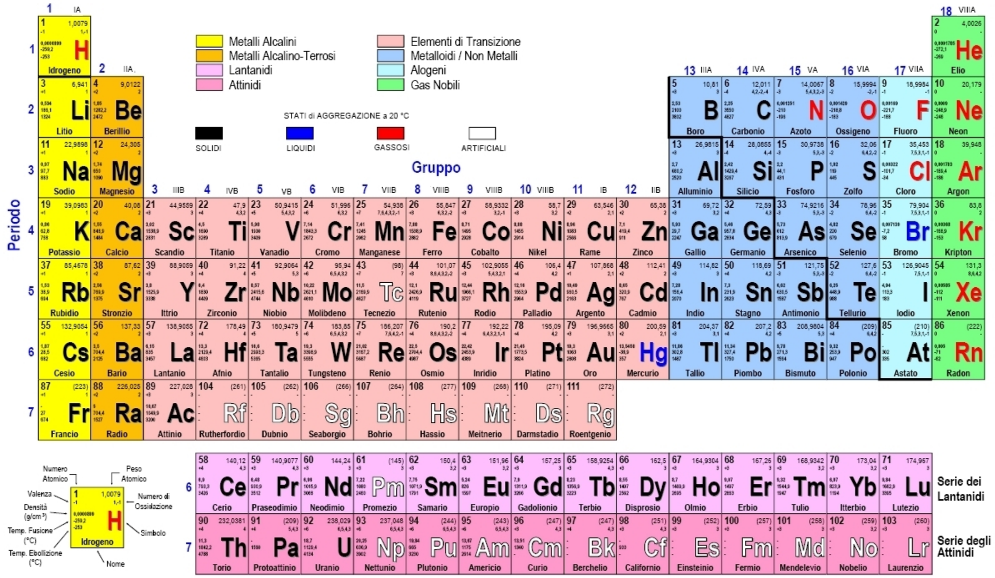
-Early time: rather symmetric emitting region (high latitude viewing angle)

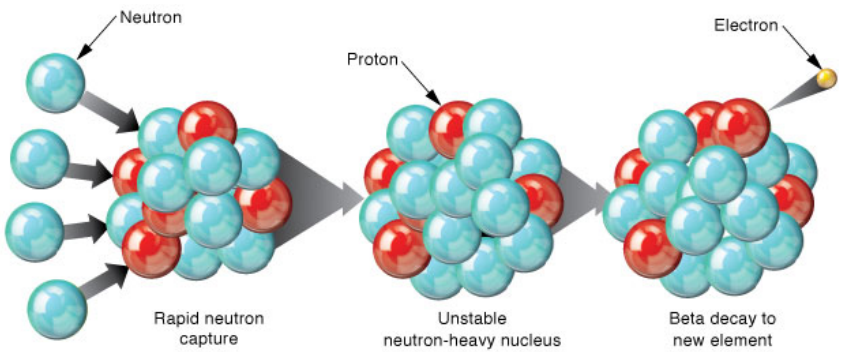
- late time: emission from Lanthanide-rich ejecta



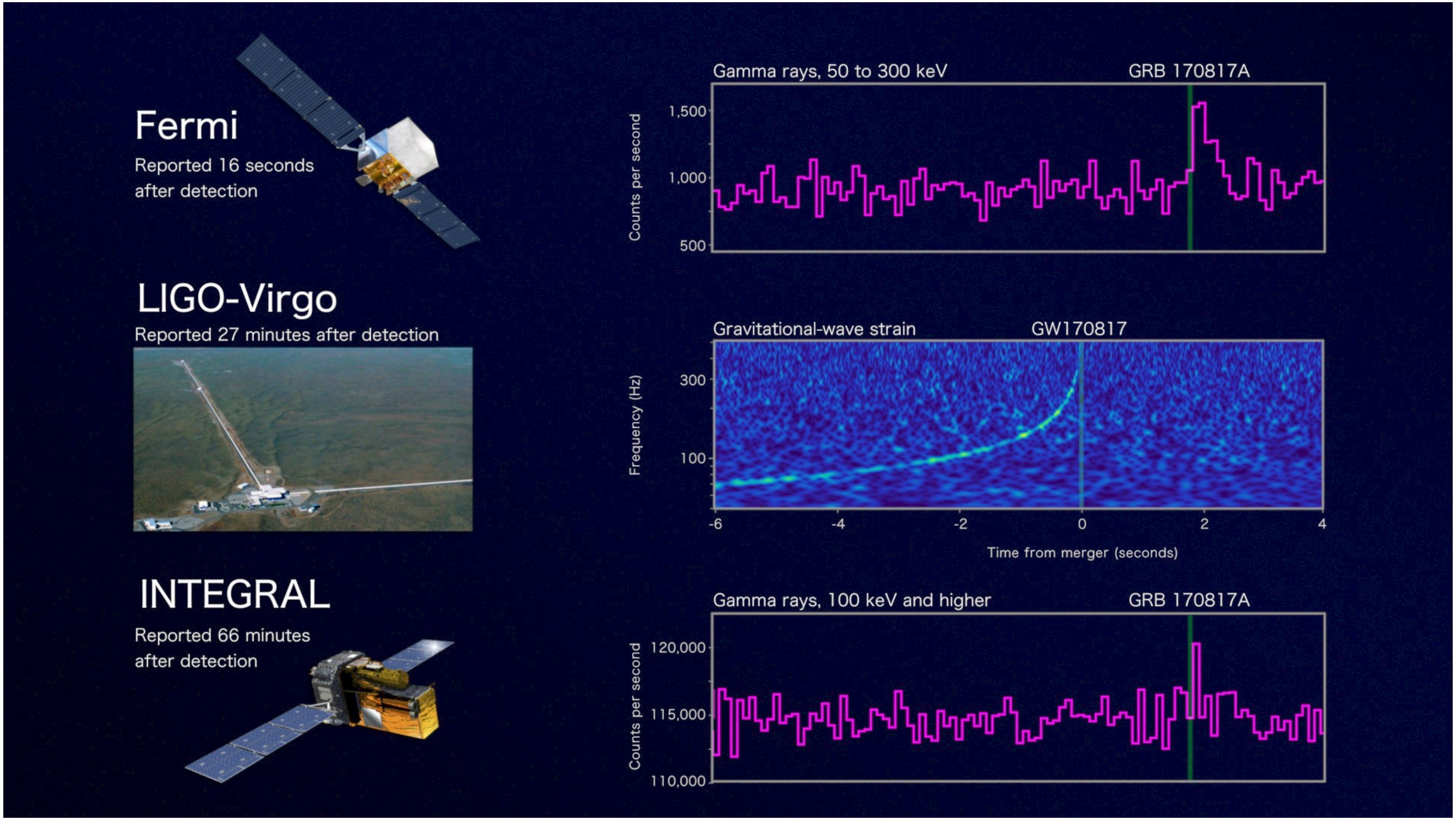
Kilonova: a heavy elements factory





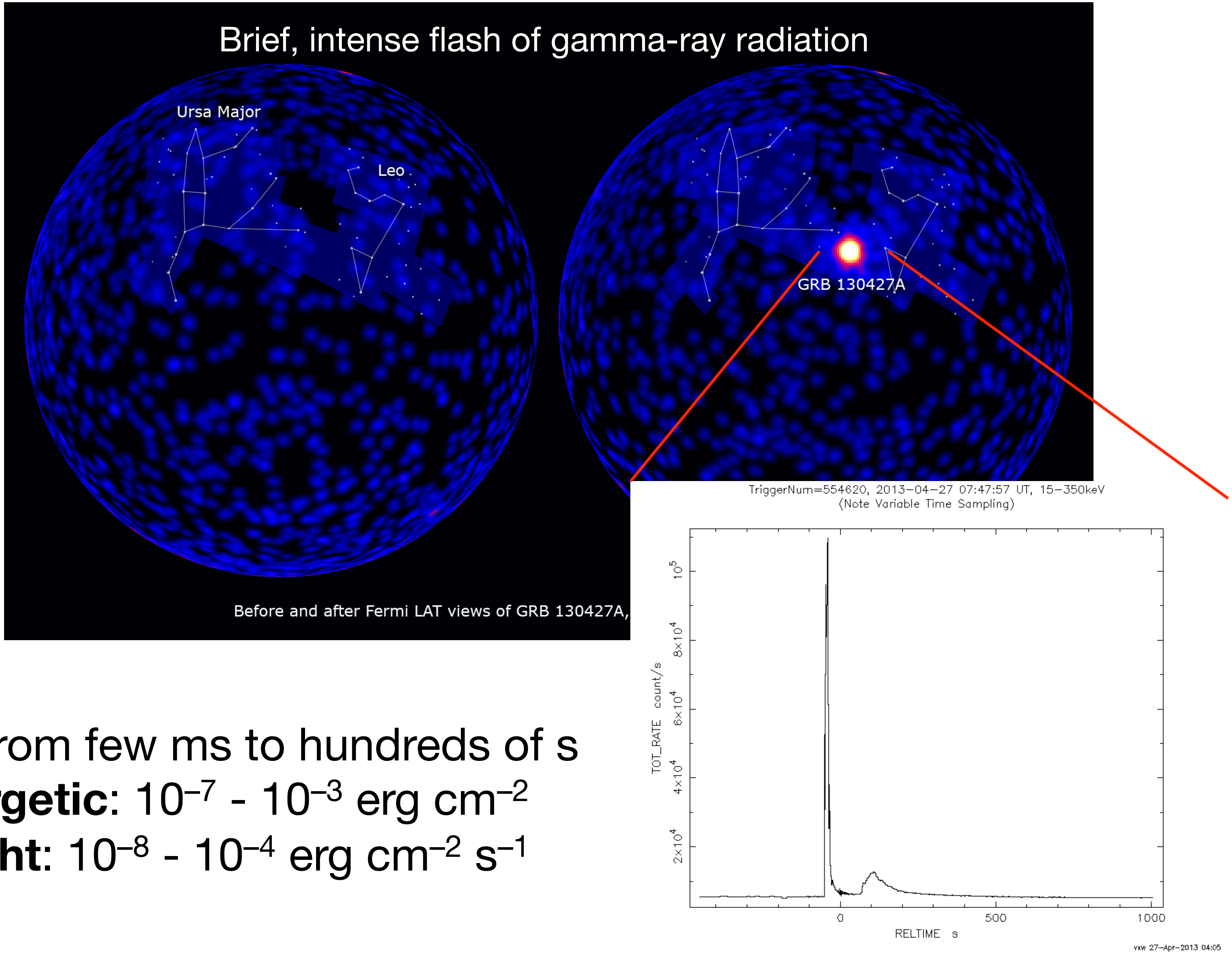


What about the GRB?



Goldstein et al. (2017); LVC + "partner astronomy groups" (2017); Savchenko et al. (2017)

Gamma-ray bursts (GRBs)

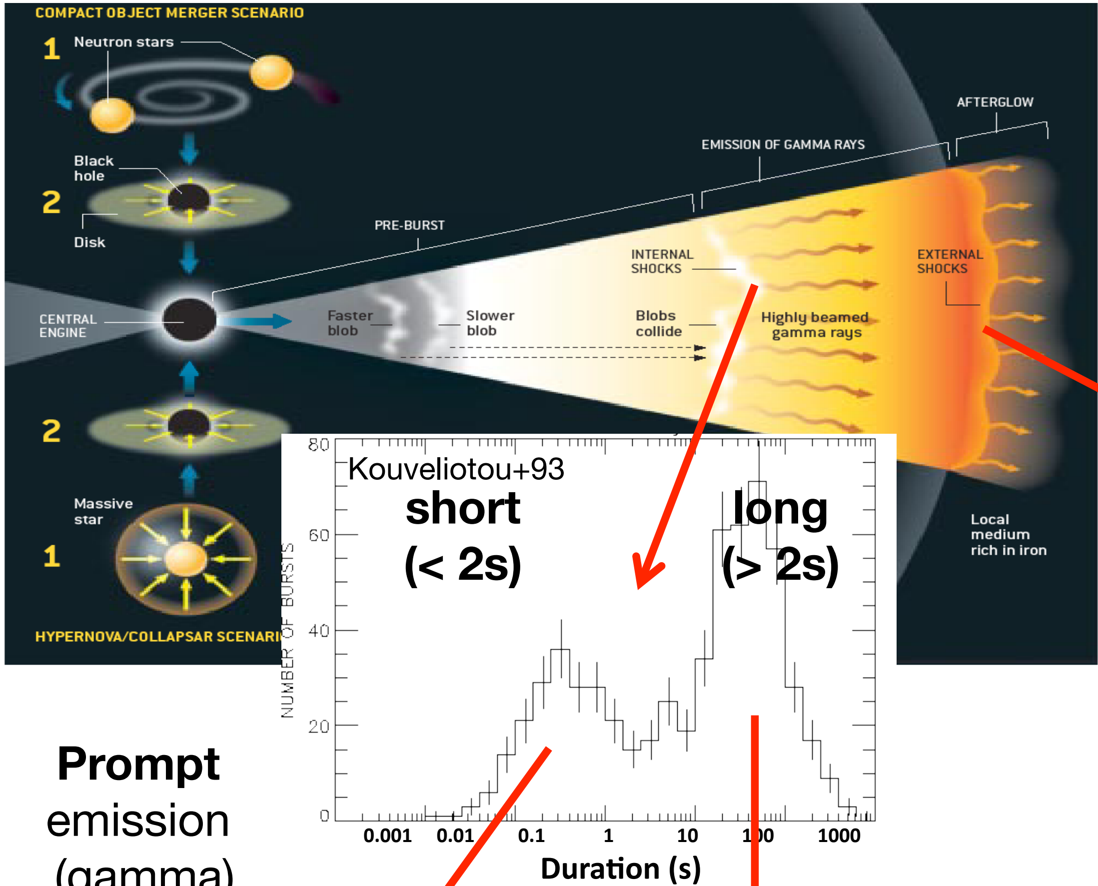


Fast: from few ms to hundreds of s

Energetic: 10^{-7} - 10^{-3} erg cm^{-2}

Bright: 10^{-8} - 10^{-4} erg cm^{-2} s^{-1}

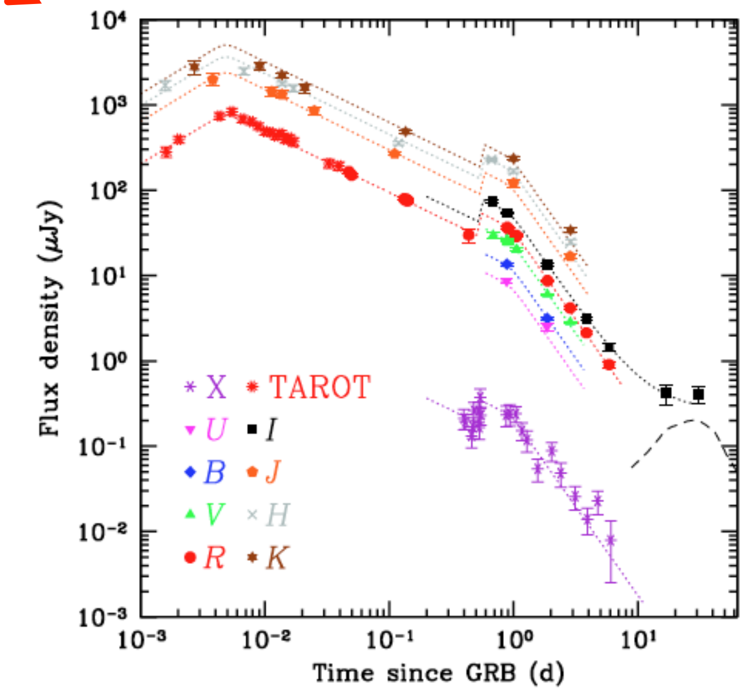
Gamma-ray bursts (GRBs)



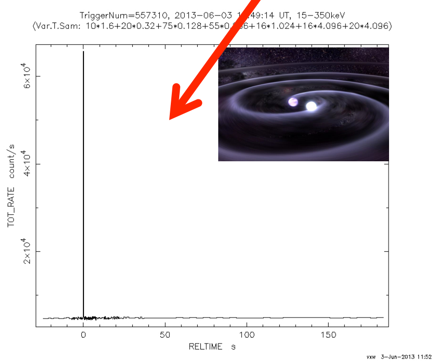
GRBs are cosmological: <z> = 2.1

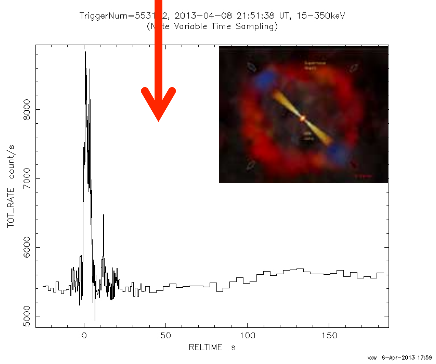
This implies they are powerful: E ~ 10^{52} erg

Long lasting, multiwavelength (X, opt, radio) emission: **afterglow**

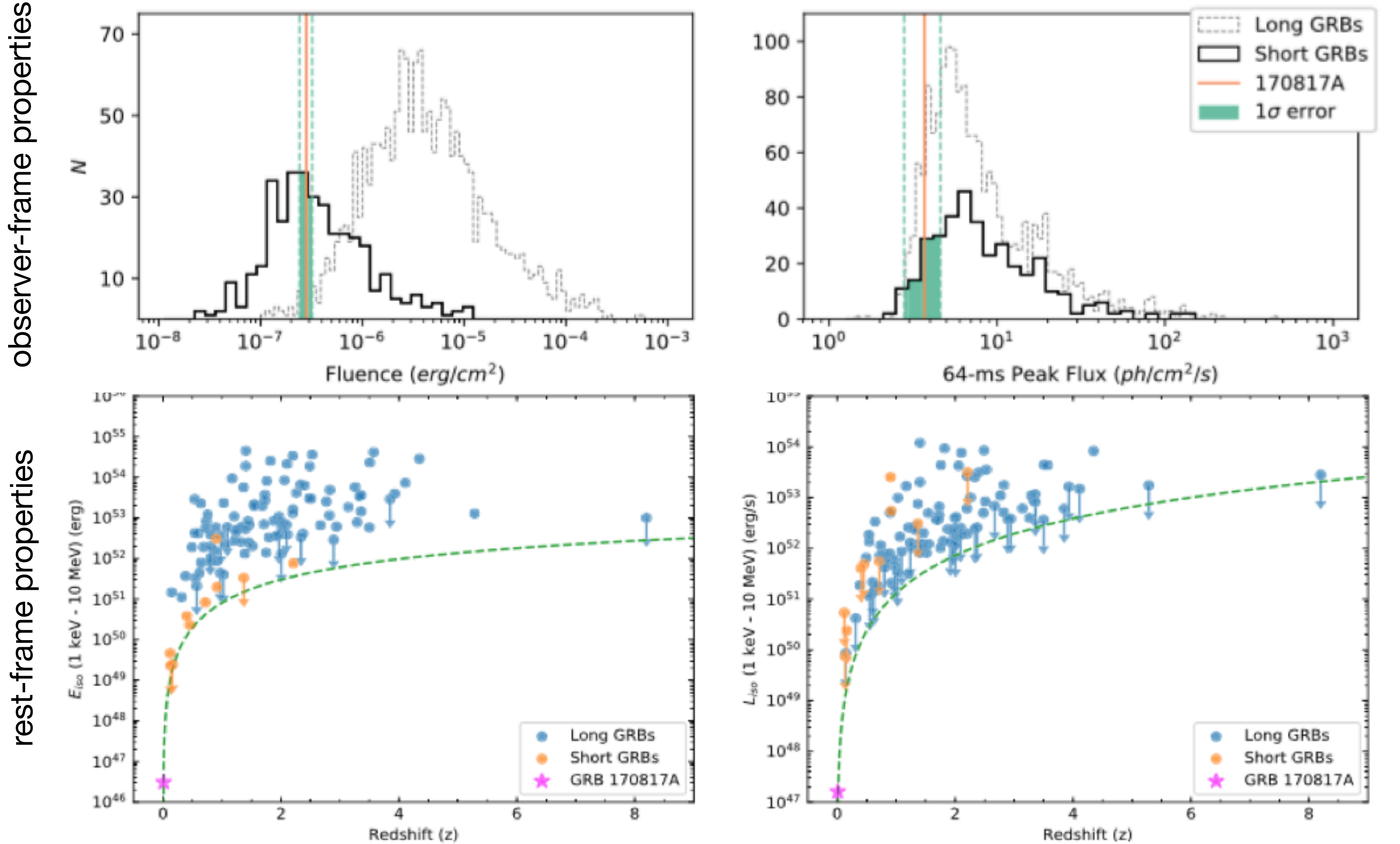


Prompt emission (gamma)





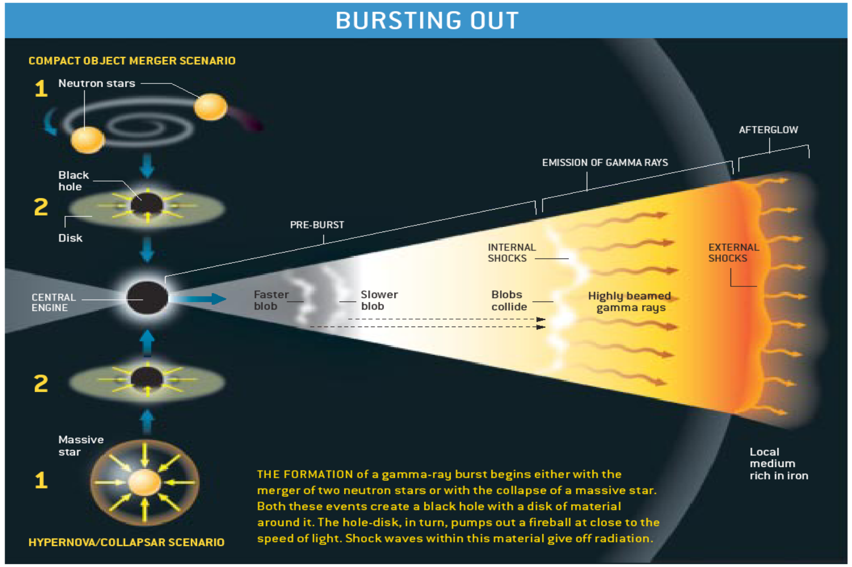
A faint short GRB?

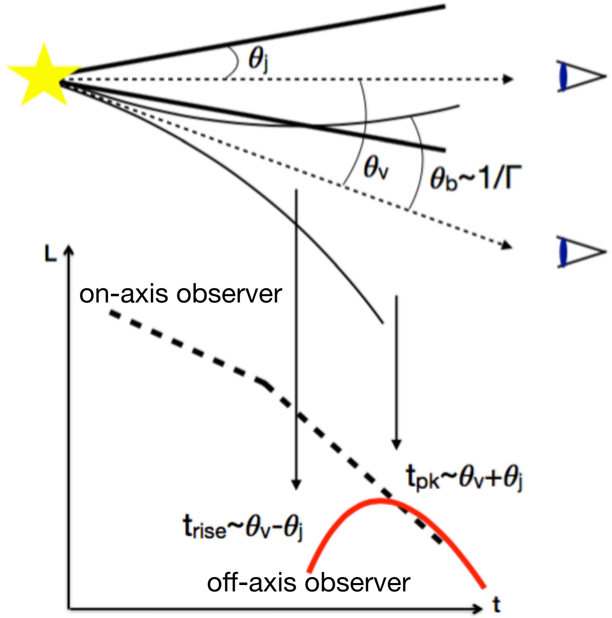


ordinary fluence and peak flux but E_{iso} = 3 x 10^{46} erg --> 3-6 orders of mag less than other SGRBs

Goldstein et al. 2017; LVC, Fermi & INTEGRAL joint paper (2017)

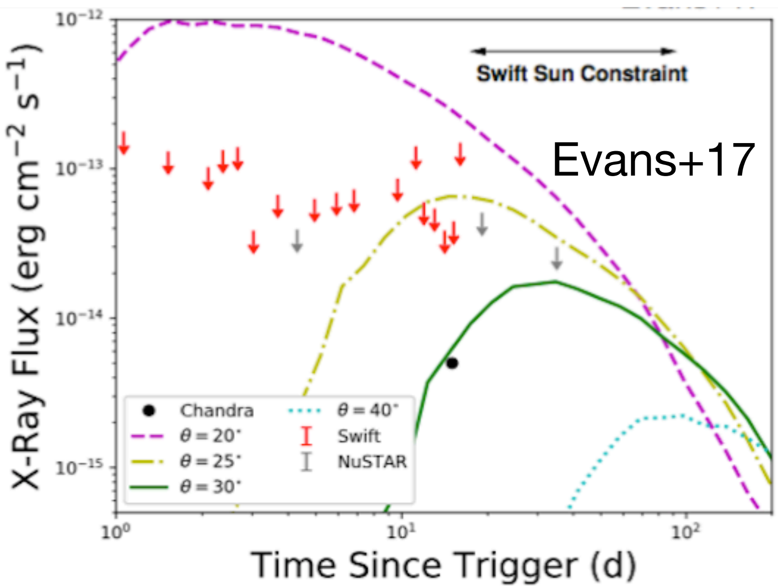
GRB 170817A: an off-beam short GRB?



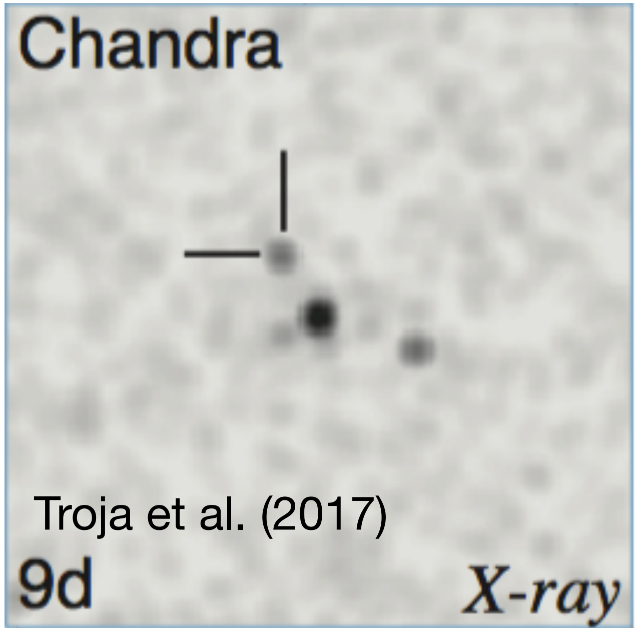


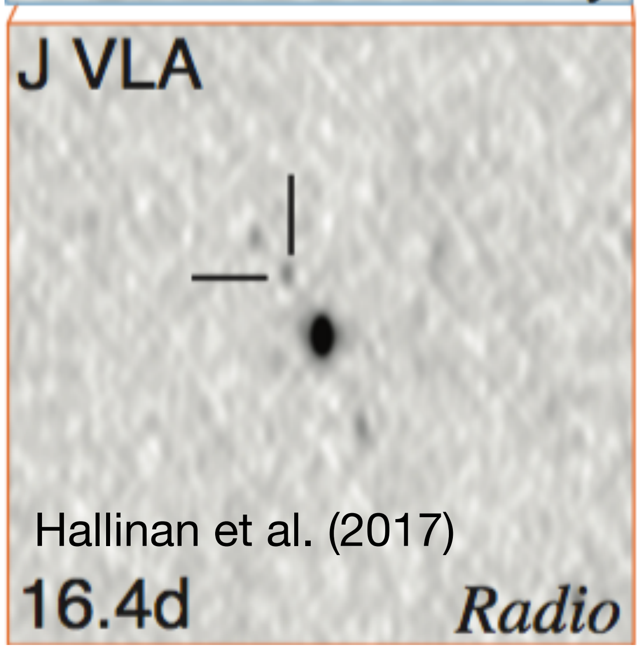
Upper limits with Swift/XRT and NuSTAR:

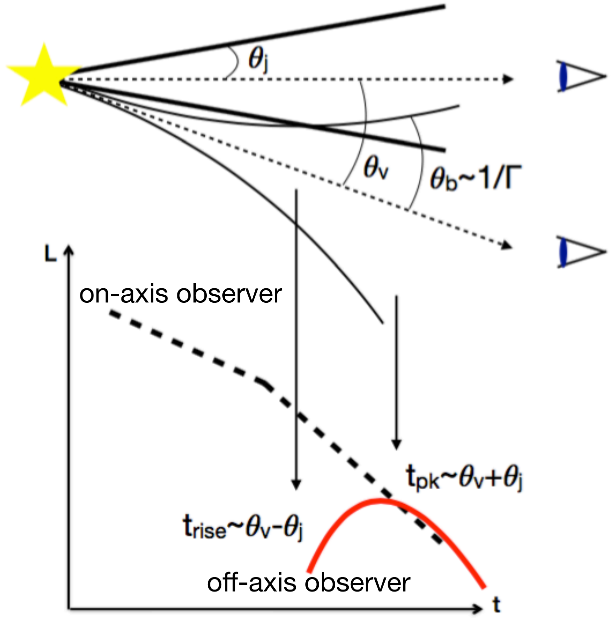
- **X-ray aftergglow of GRB 170817A dimmer than for typical SGRBs (D'Avanzo+14)**
- **possibly consistent with the orphan afterglow scenario**
- **supported by Chandra observations**



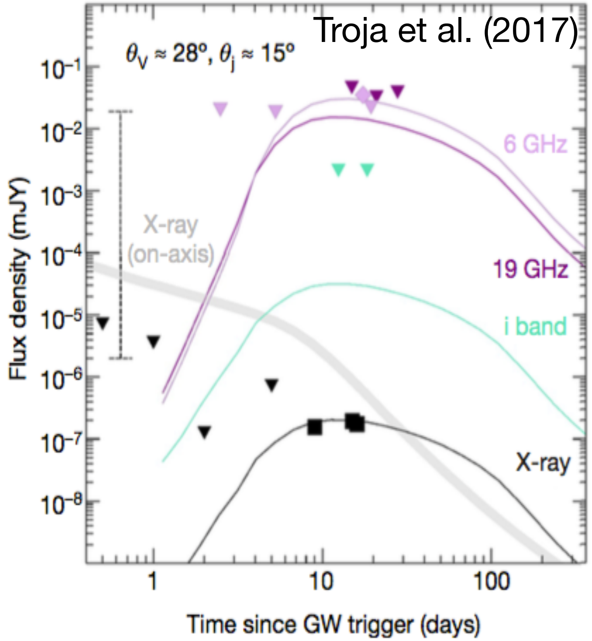
GRB 170817A: an off-beam short GRB?





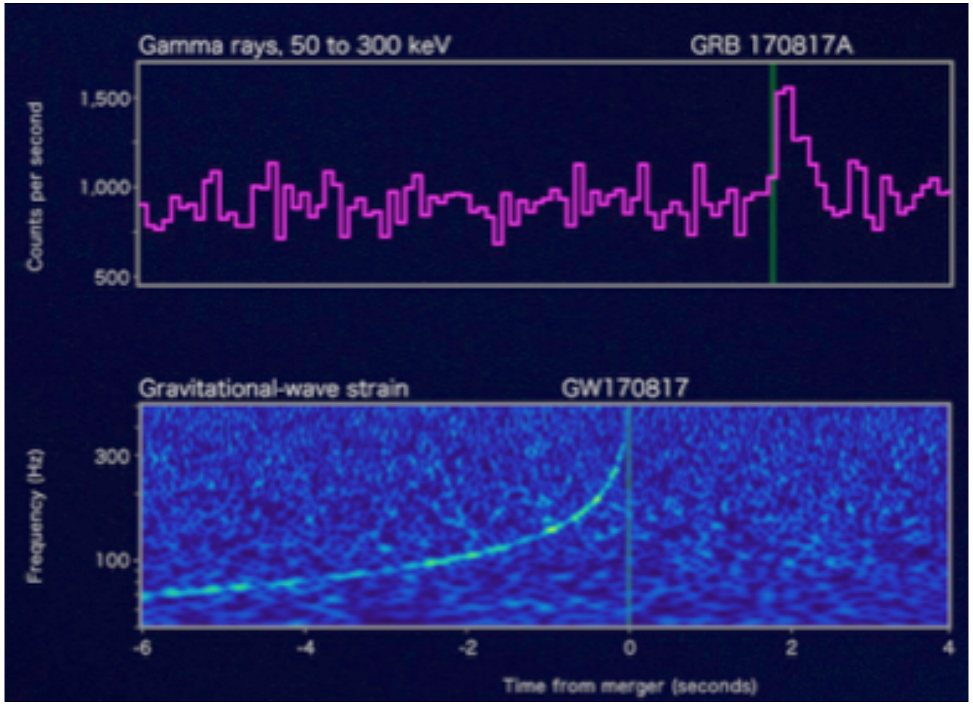


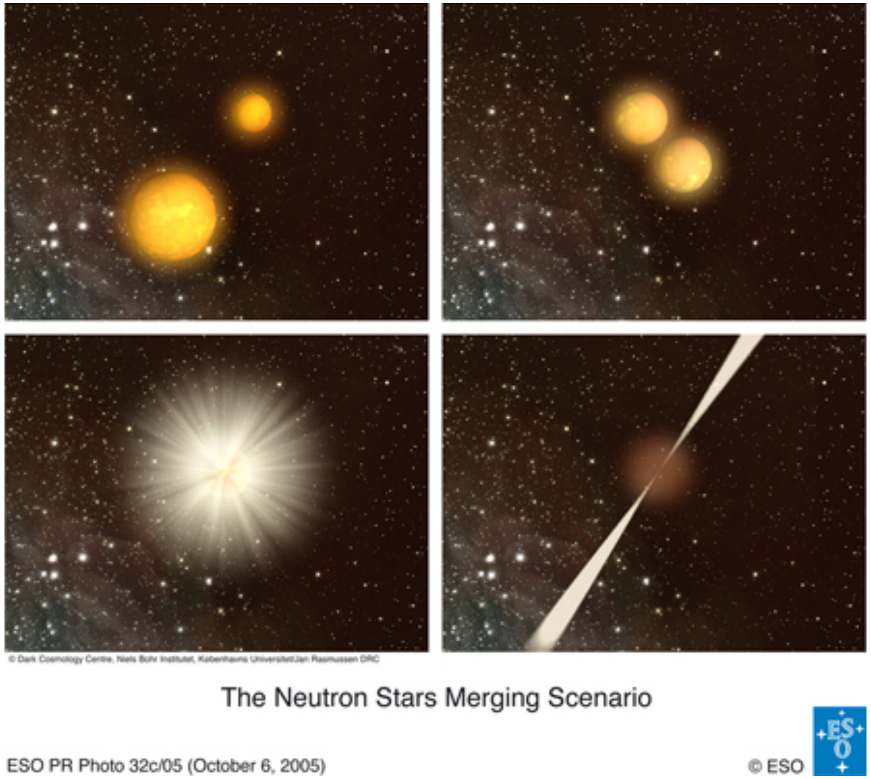
Late-time X-ray and radio detection:
- possibly consistent with the orphan afterglow scenario
- supported by Chandra and VLA observations



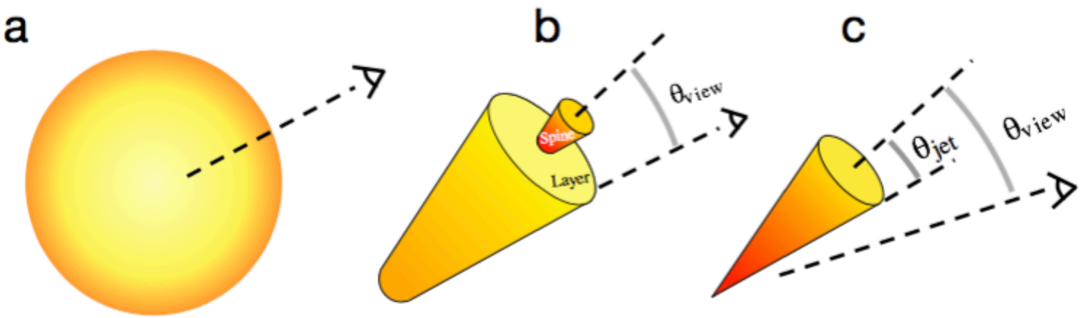
Short GRBs progenitors

The long sought ‘smoking gun’





GRB 170817A: an off-beam short GRB?



Salafia+17

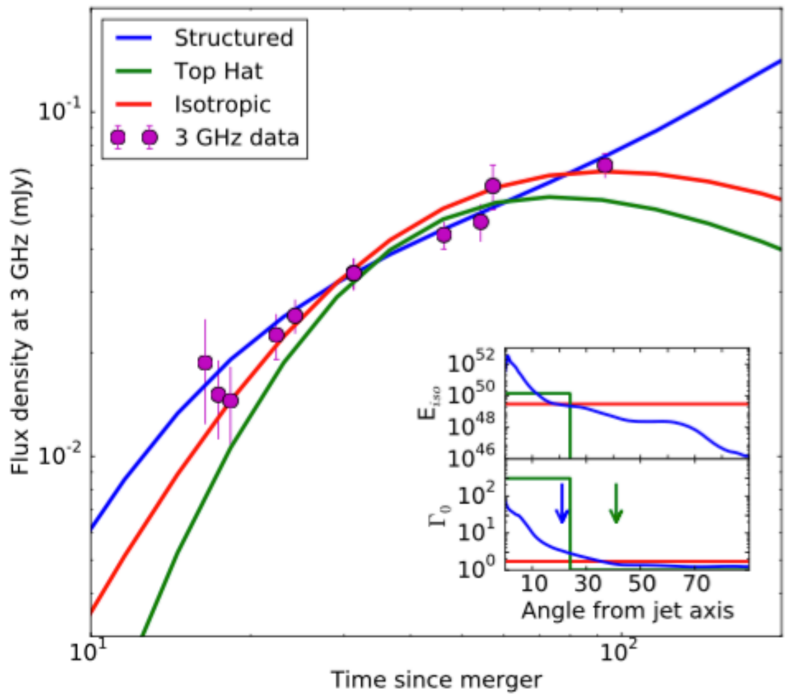
Different scenarios:

a) **Isotropic fireball or hot cocoon from a failed jet**
b) **Structured jet: standard jet+less energetic cocoon/layer**
c) **Uniform (top hat) jet with unusually low Lorentz factor**

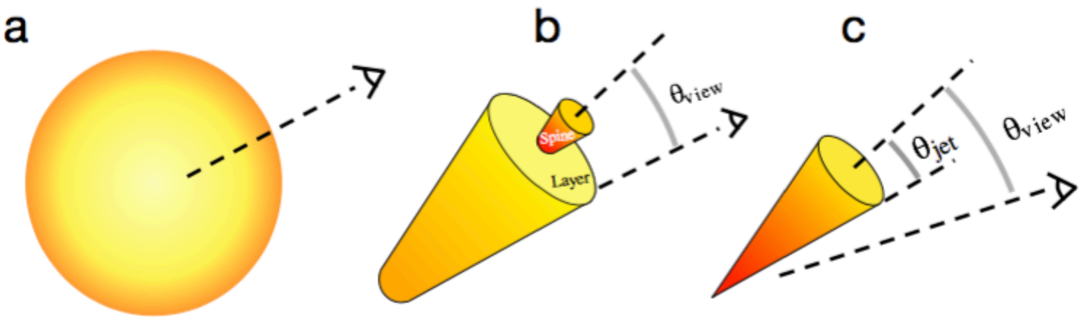
Radio observations up to t~107 d
(Mooley et al. 2017)

-> the emission is still rising

Lazzati+17



GRB 170817A: an off-beam short GRB?



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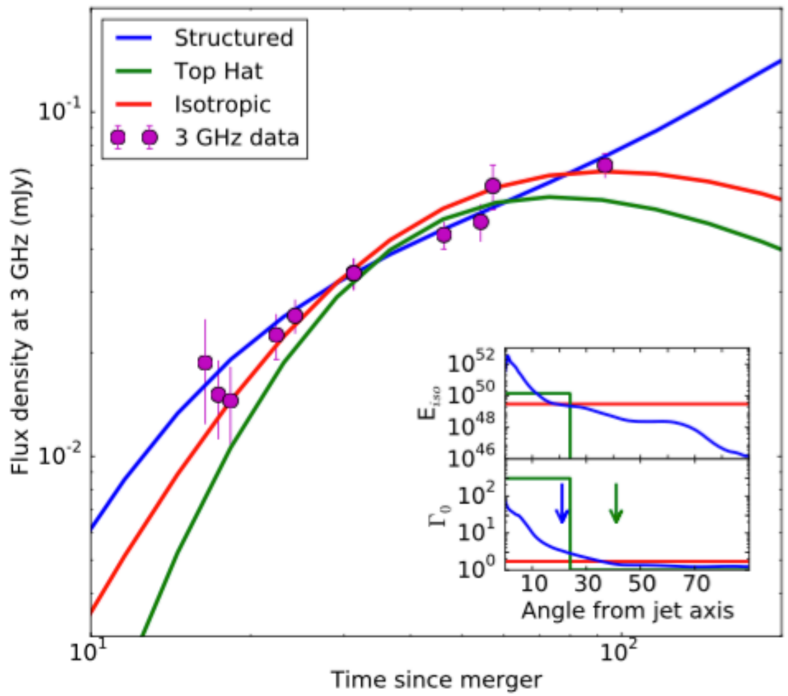
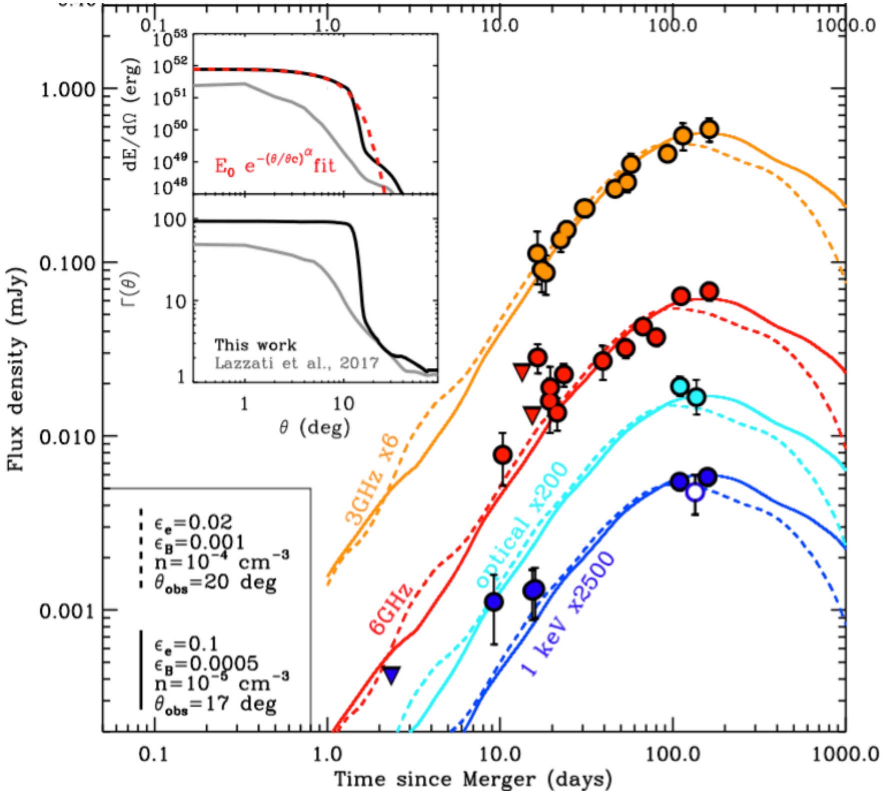
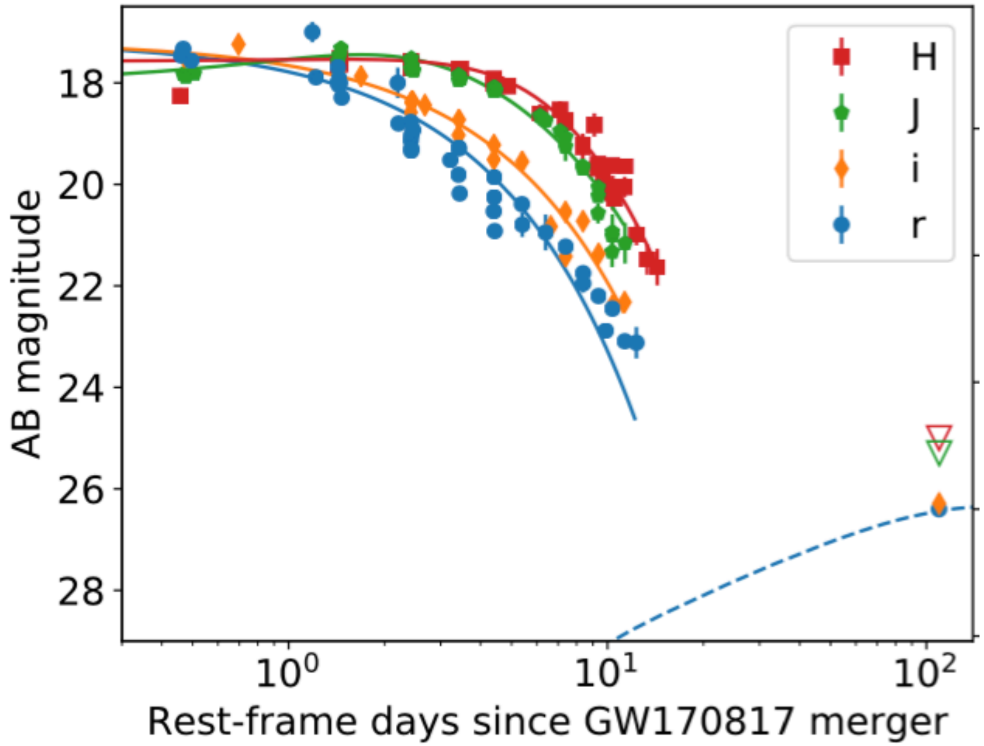


GRB 170817A: an off-beam short GRB?

Margutti+18



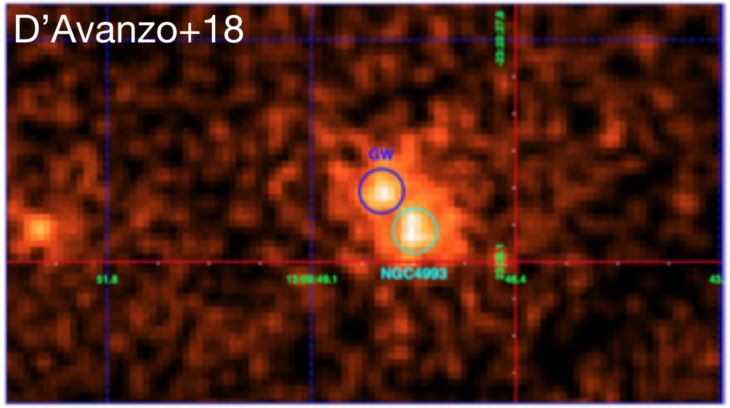
Lyman+18

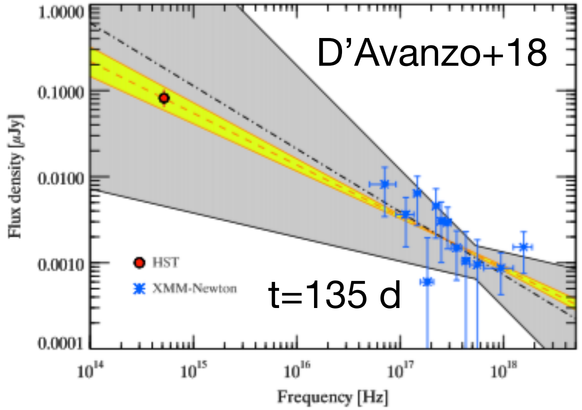


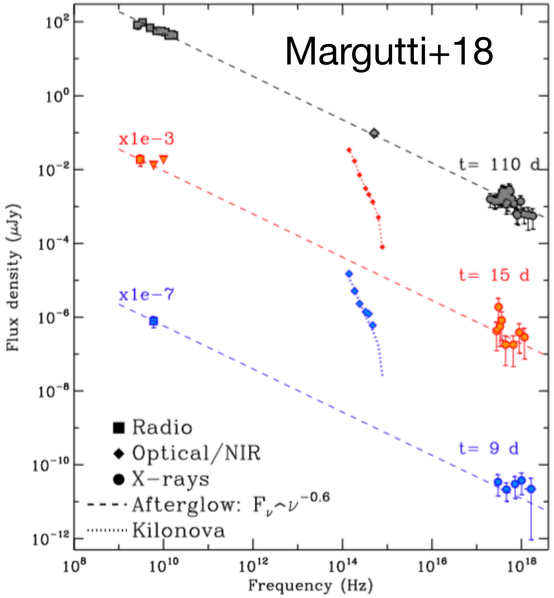
- **Further observations with Chandra (post-Sun constraint) @ t = 107-109 d (Margutti+18; Ruan+18; Troja+18) -> the X-ray emission is rising (as observed in the radio)**
- **Optical emission at t=110 (Lyman+18) -> unrelated to the kilonova, likely associated to GRB 170817A**

-> constraints on the nature of the emission process (synchrotron)
-> no contraints on the nature of the relativistic ejecta (struct. jet / isotropic both valid)

GRB 170817A: evidence for a turnover in the light curve



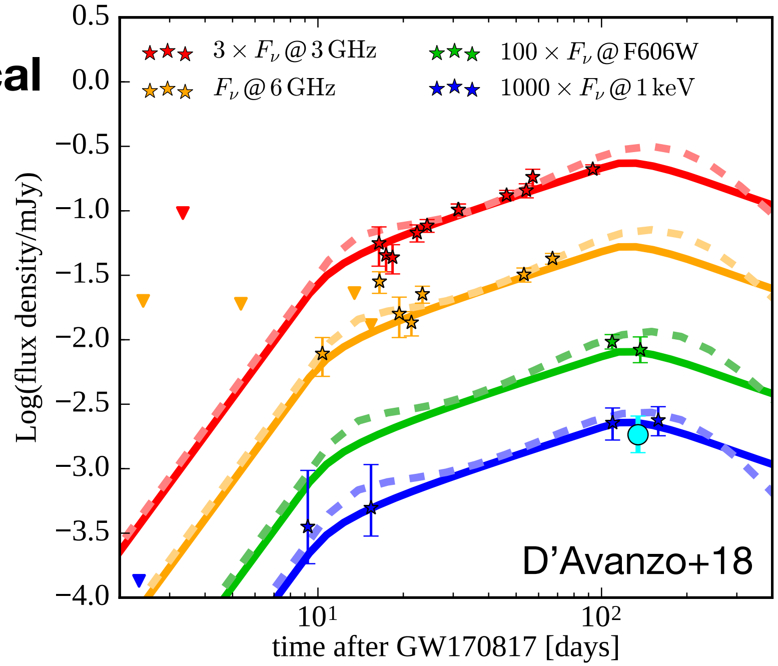


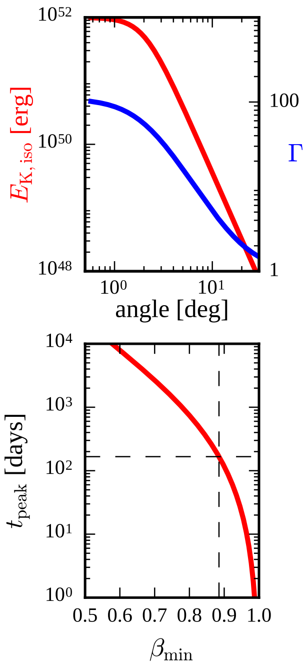


XMM detection at t=135 d (D'Avanzo+18)
-opt/X-ray spectral slope unchanged w.r.t. previous epochs: no passage of the cooling frequency
- evidence for a change in the light curve slope (flattening): likely geometrical effect

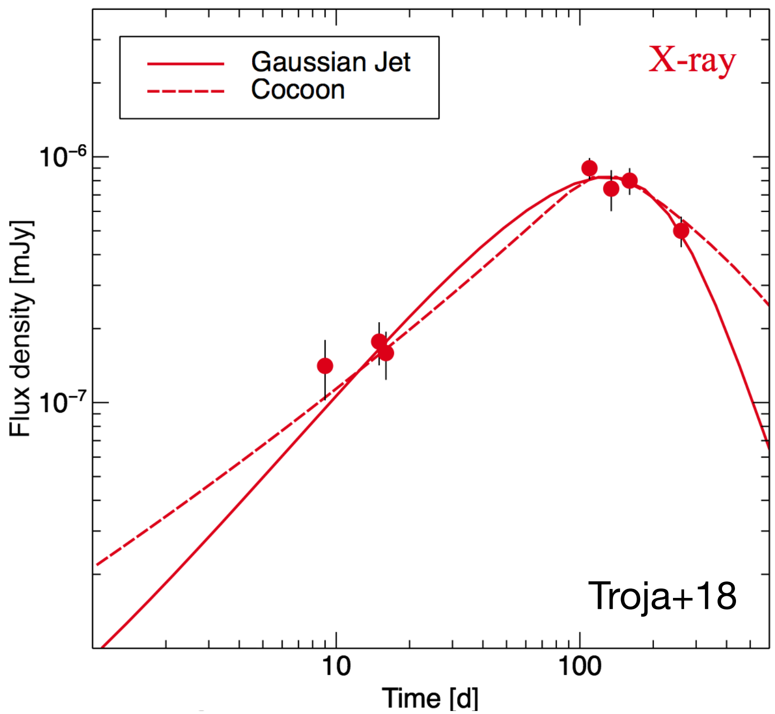
Chandra detection at t=153-164 d (Haggard+18; Troja+18): still consistent with light curve flattening

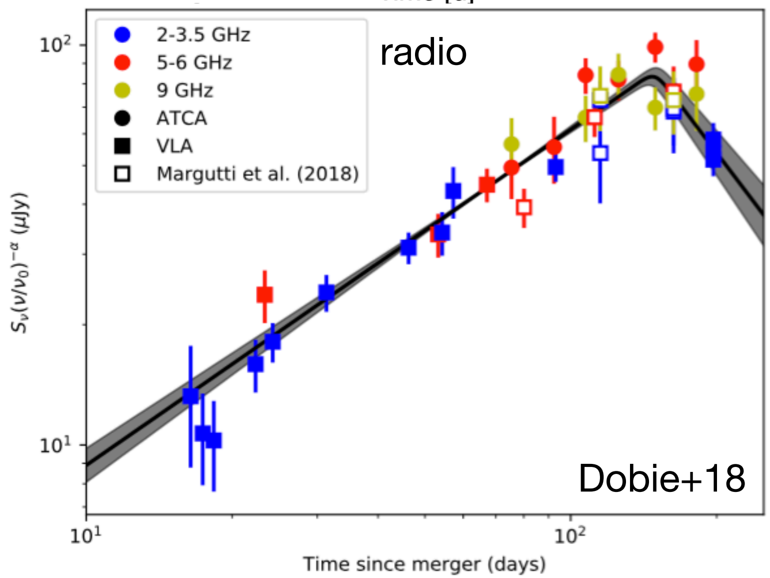
Structured jet and isotropic emission both still valid.

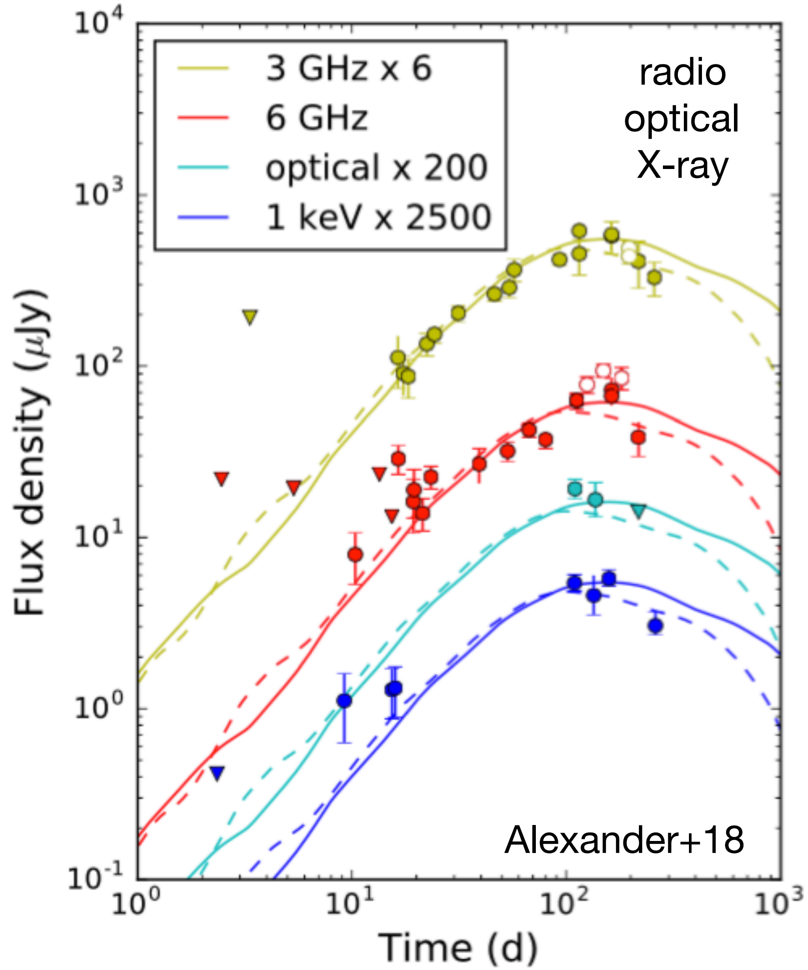




GRB 170817A: evidence for a fading afterglow







X-ray, optical and radio observations at t = 200-264 d confirm the turnover in the light curve and show evidence for decay. Both scenarios (struct. jet vs. isotropic still valid)

Conclusions

- **EM follow-up campaigns for O1 and O2 very successful**

- **GW 170717 / GRB 170817A results:**
    - **Definition and consolidation of successful follow-up strategies**
    - **First EM counterpart (at all wavelengths)**
    - **First unambiguous observational evidence for a kilonova**
    - **Evidence for kilonovae as a heavy elements factory**
    - **`Smoking gun' for short GRB progenitors (but is GRB 170717A a 'classical' short GRB?)**
    - **Clues on short GRB outflow geometry and properties (first observation of an off-beam afterglow? First evidence for a structured jet? First evidence for isotropic prompt emission?)**

- **the dawn of multi-messenger astronomy era**

- **waiting for O3 LVC run**
    - **how many NS-NS?**
    - **NS-BH?**
    - **how many KN flavours?**
    - **how many short GRB flavours?**