Observations of kilonovae

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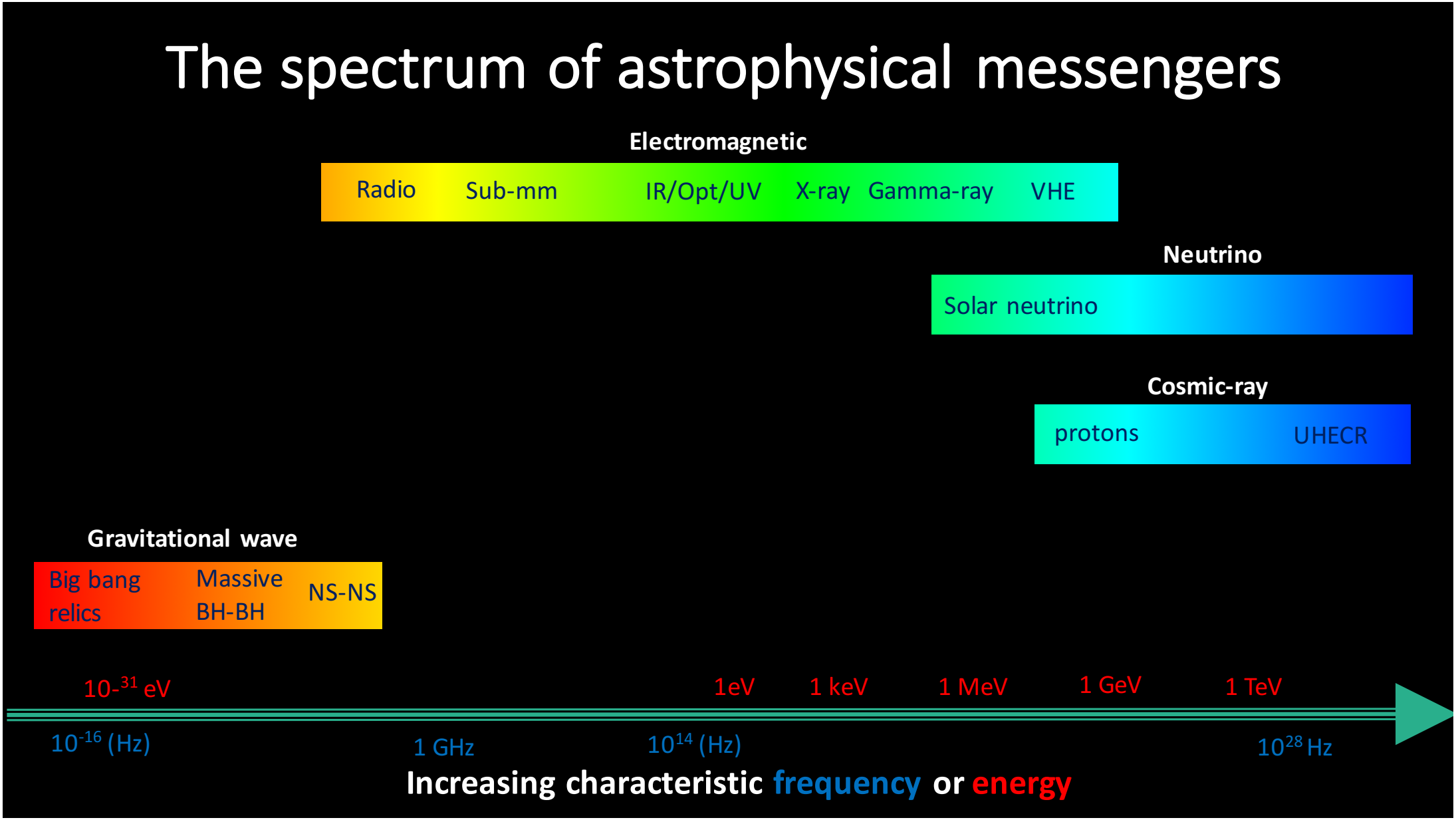
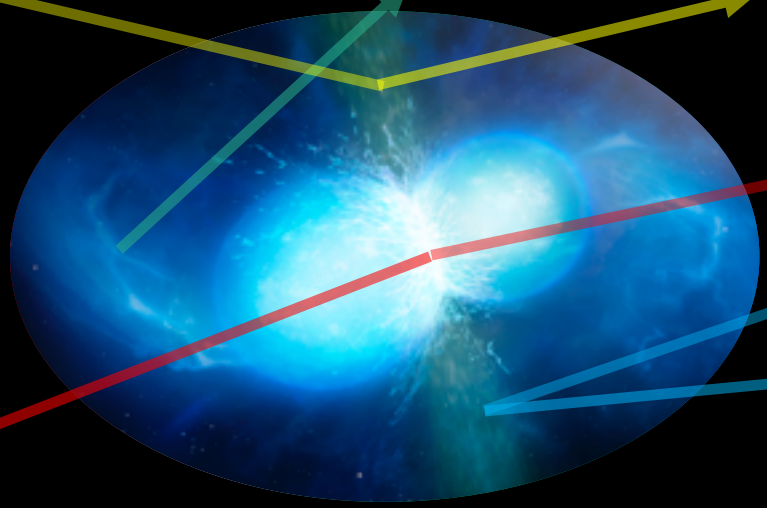
GSI, Darmstadt, 4 June 2018

The spectrum of astrophysical messengers



The spectrum of astrophysical messengers



Electromagnetic

Radio | Sub-mm | IR/Opt/UV | X-ray | Gamma-ray | VHE

Neutrino

Cosmic-ray

protons | UHECR

- **Non-Thermal**
- **Thermal**
- **Particle acceleration**
- **Physical mechanisms**

Gravitational wave

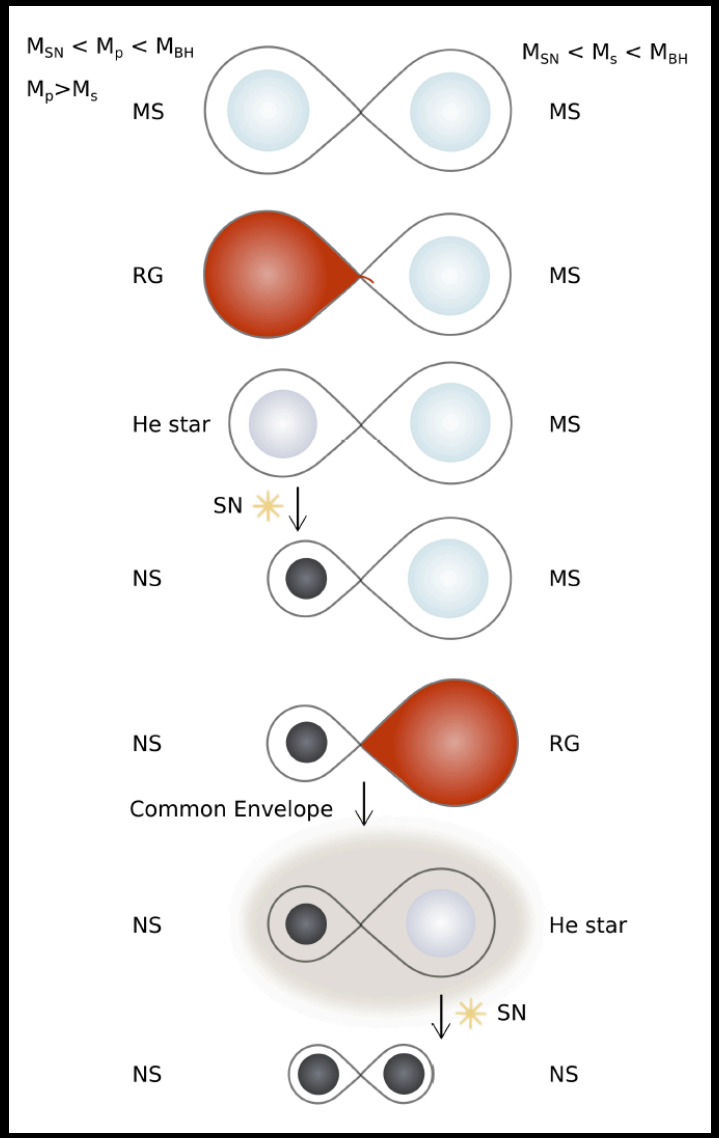
Big bang relics | Massive BH-BH | NS-NS

10^{-31} eV — 1eV — 1 keV — 1 MeV — 1 GeV — 1 TeV

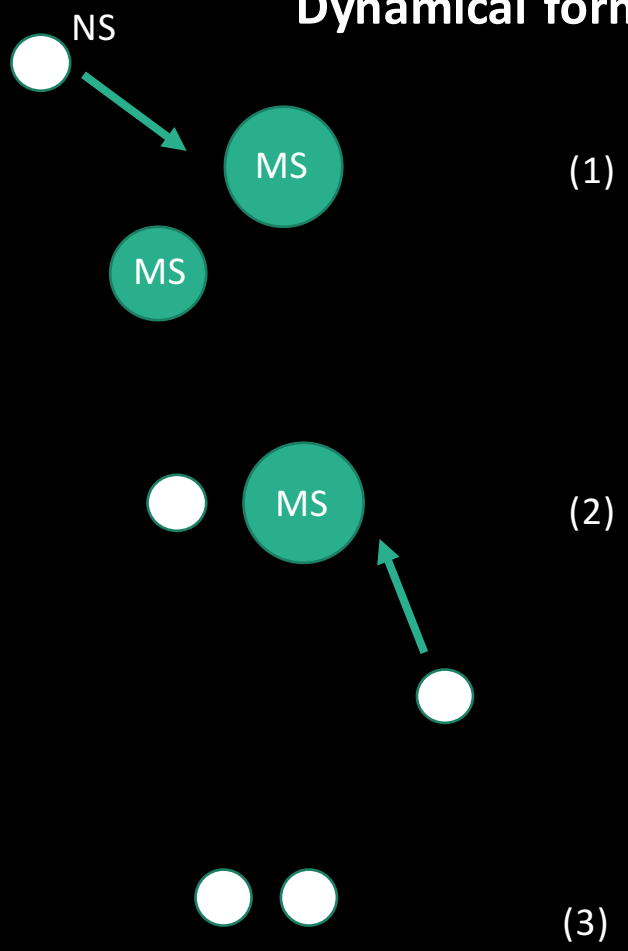
10^{-16} (Hz) — 1 GHz — 10^{14} (Hz) — 10^{28} Hz

Increasing characteristic frequency or energy

Formation in the field



Dynamical formation



Formation in the field

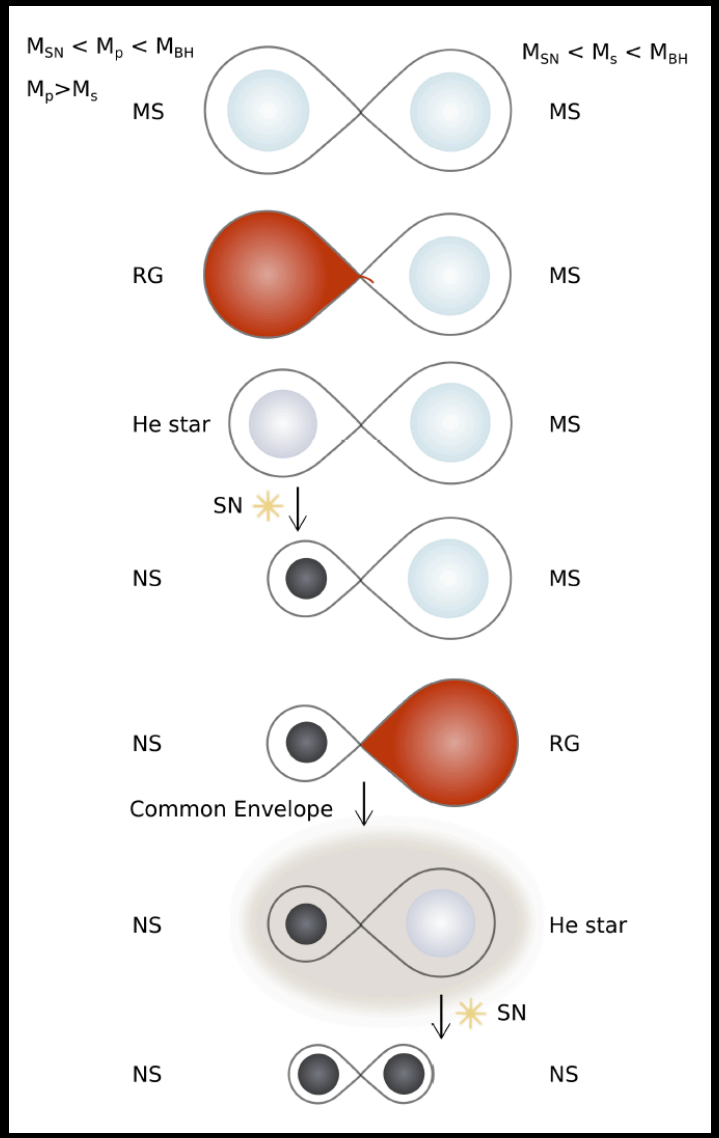
Relative fractions of field versus dynamical

SN and NS kicks

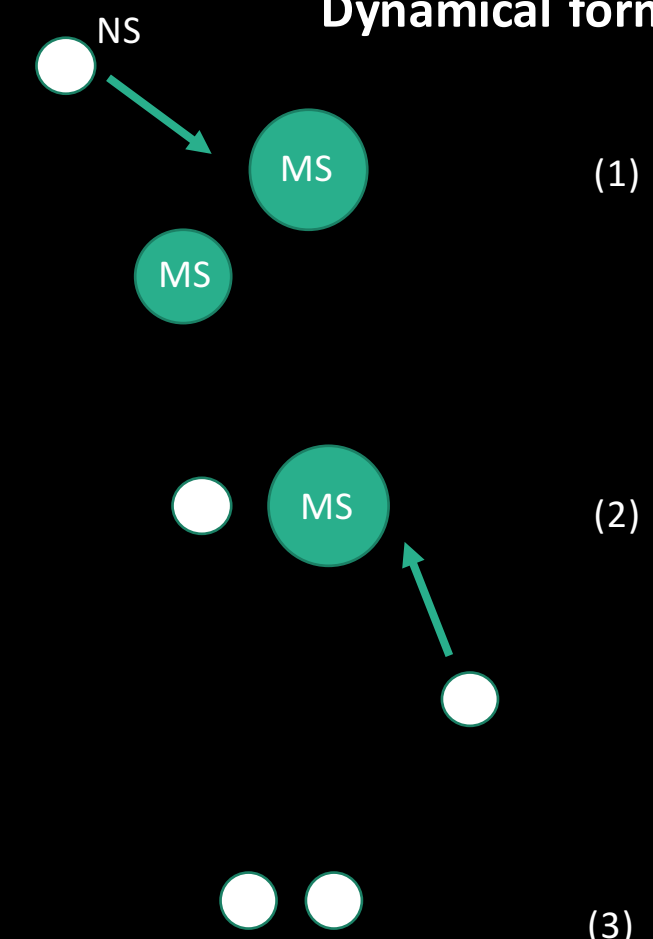
Common envelope efficiency

Delay time distributions

Rates



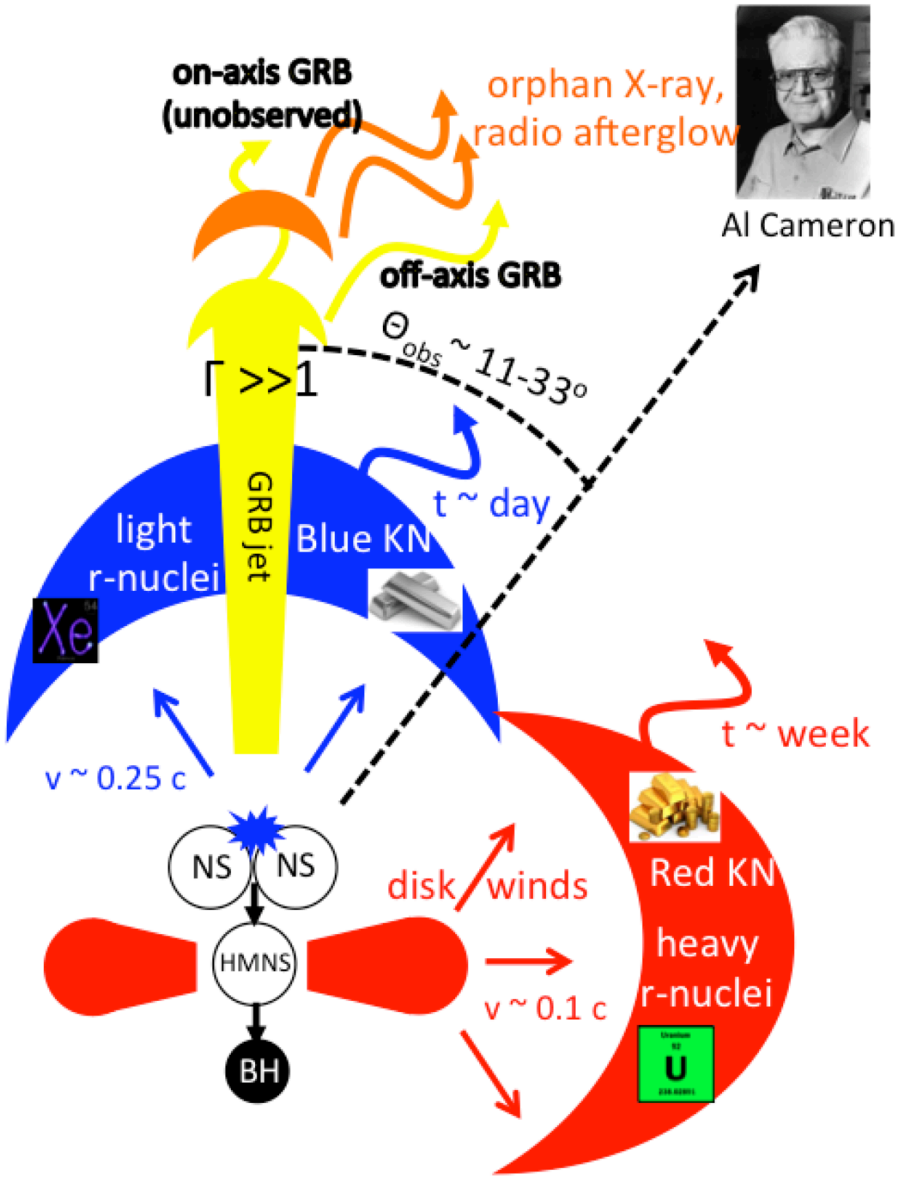
Dynamical formation



$$t_{merge} \approx 10^8 \left(\frac{a}{R_\odot}\right)^4 \left(\frac{M_\odot}{M_1 M_2 (M_1 + M_2)}\right) \text{ years}$$

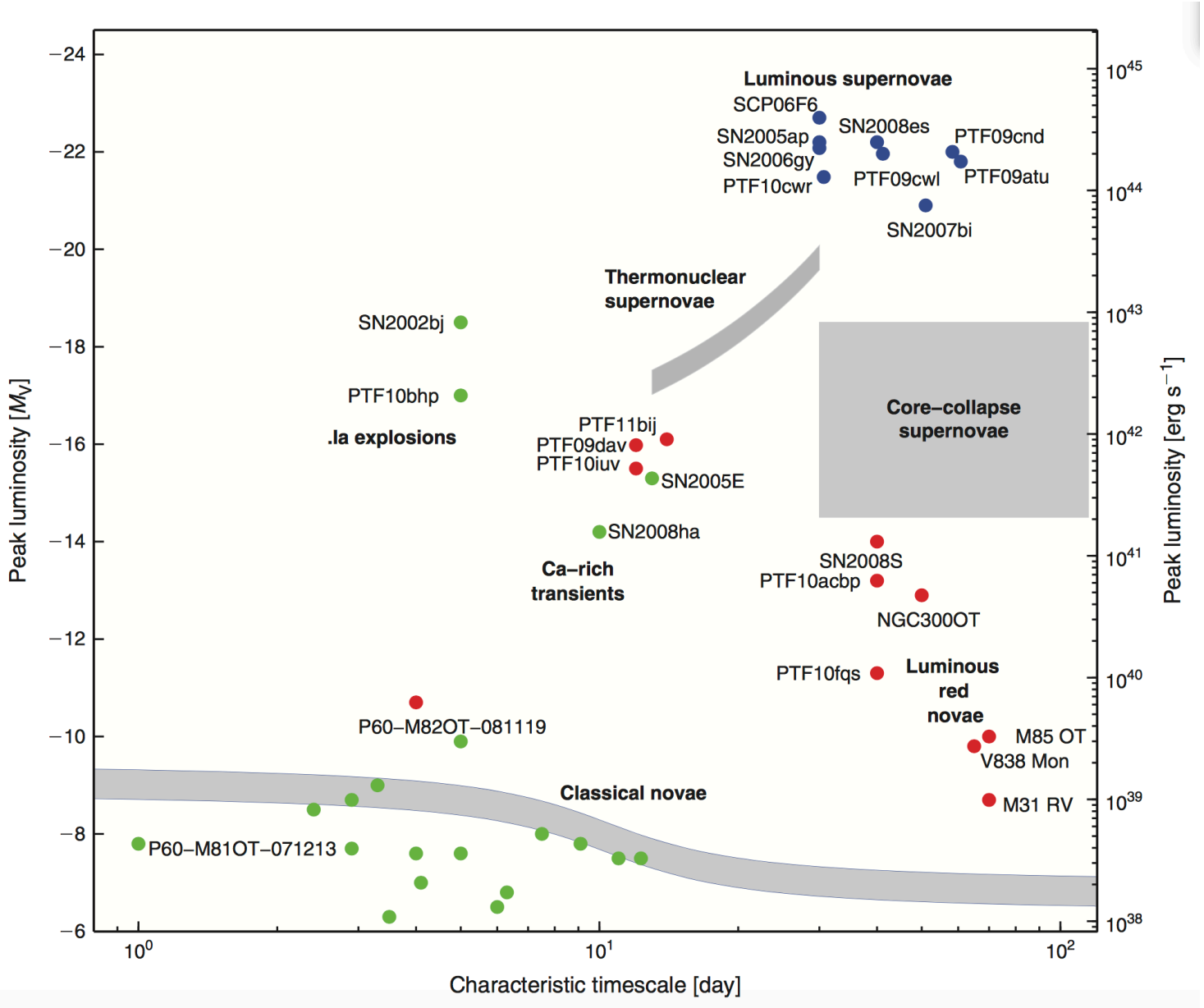
What are kilonovae?

Scientific potential:
Pin down the progenitors of short gamma-ray bursts
Enable multi-messenger (GW-EM-v) detections
r-process nucleosynthesis



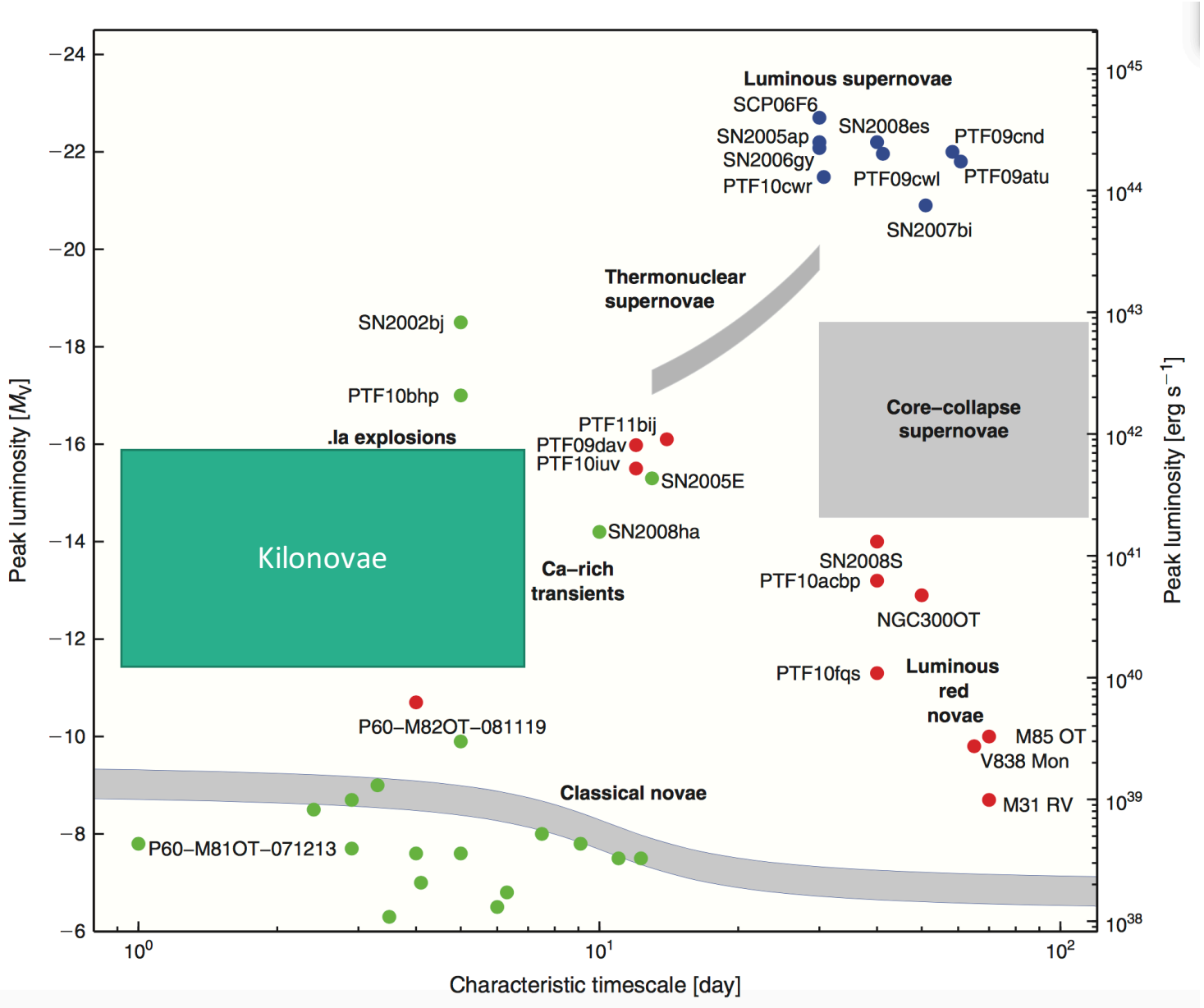
Li & Paczynski 1998 507 59
Metzger 2017 arXiv:1719.05931

The transient sky



Kasliwal 2012

The transient sky

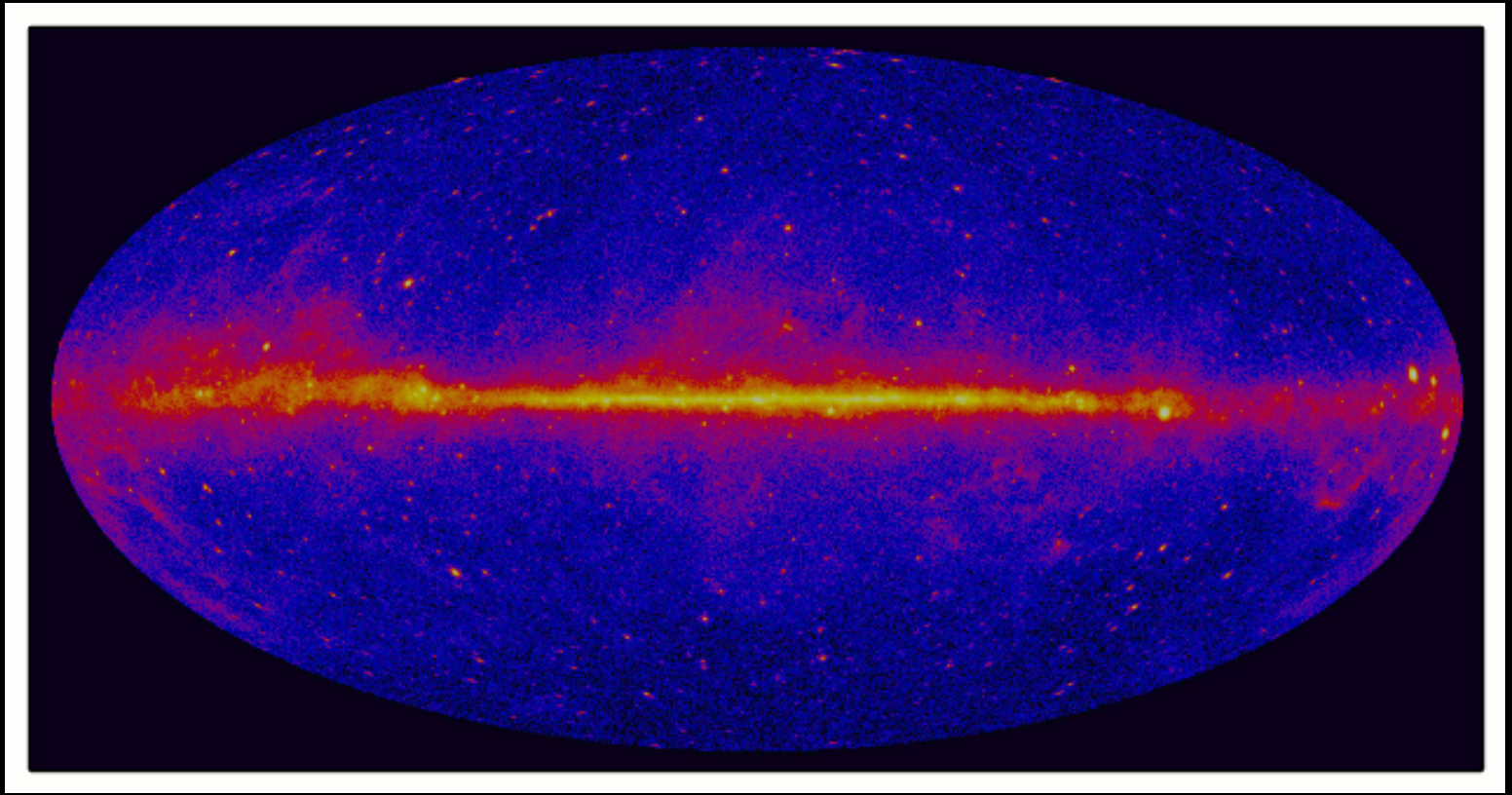


Kasliwal 2012

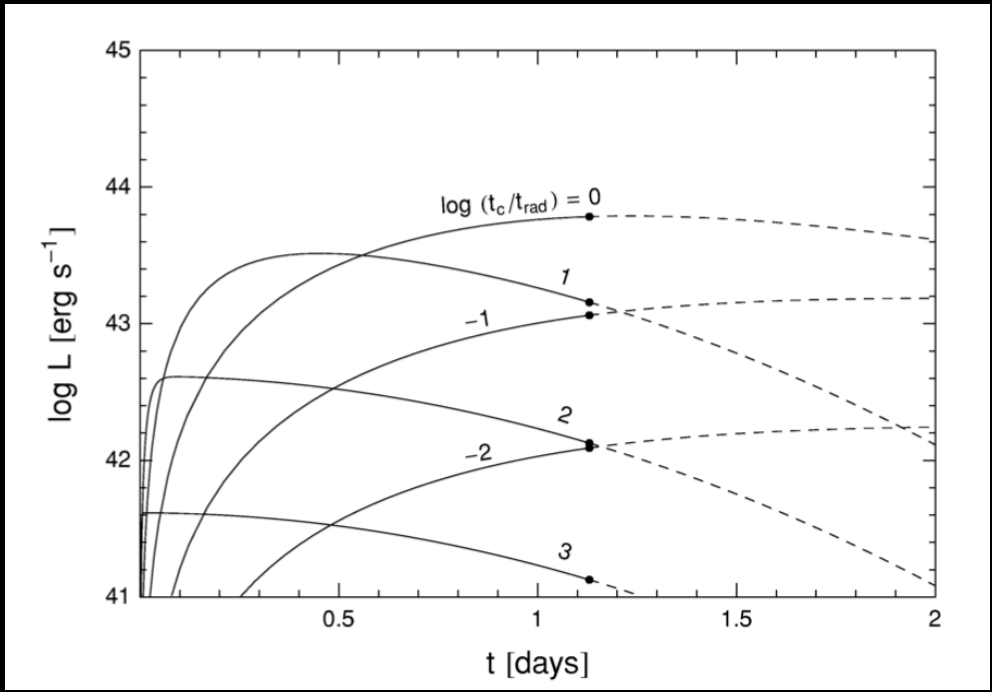
Rates

Object	Rate (Gpc^{-3})	Peak brightness (erg/s)	Timescale (days)	FOM (log(Rate x peak x time), erg Gpc^{-3})
Type Ia SN	25000	10^{43}	20	53.6
Type II SN	100000	10^{42}	20	52.2
Long GRB (low L)	250	10^{47} (optical)	0.01	52.3
Long GRB (high L)	2500	10^{45} (optical)	0.1	52.3
SLSNe	30	10^{44}	100	52.4
NS-NS (kilonova)	1000	10^{41}	1	48.9
NS-BH	2	?	?	
BH-BH	5	?	?	

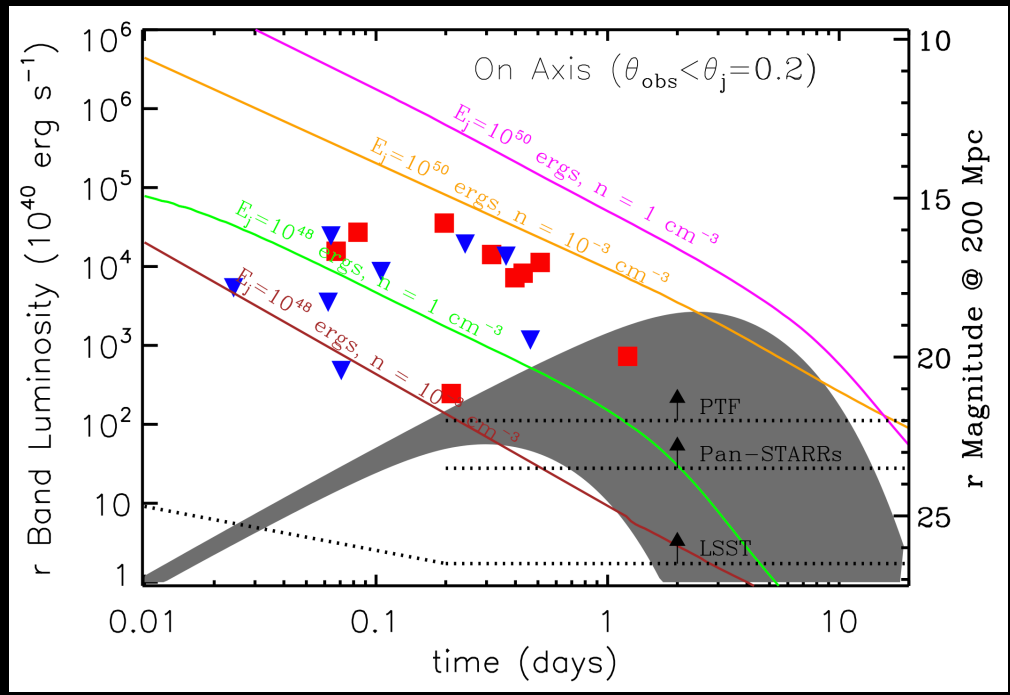
Short GRBs



Kilonovae

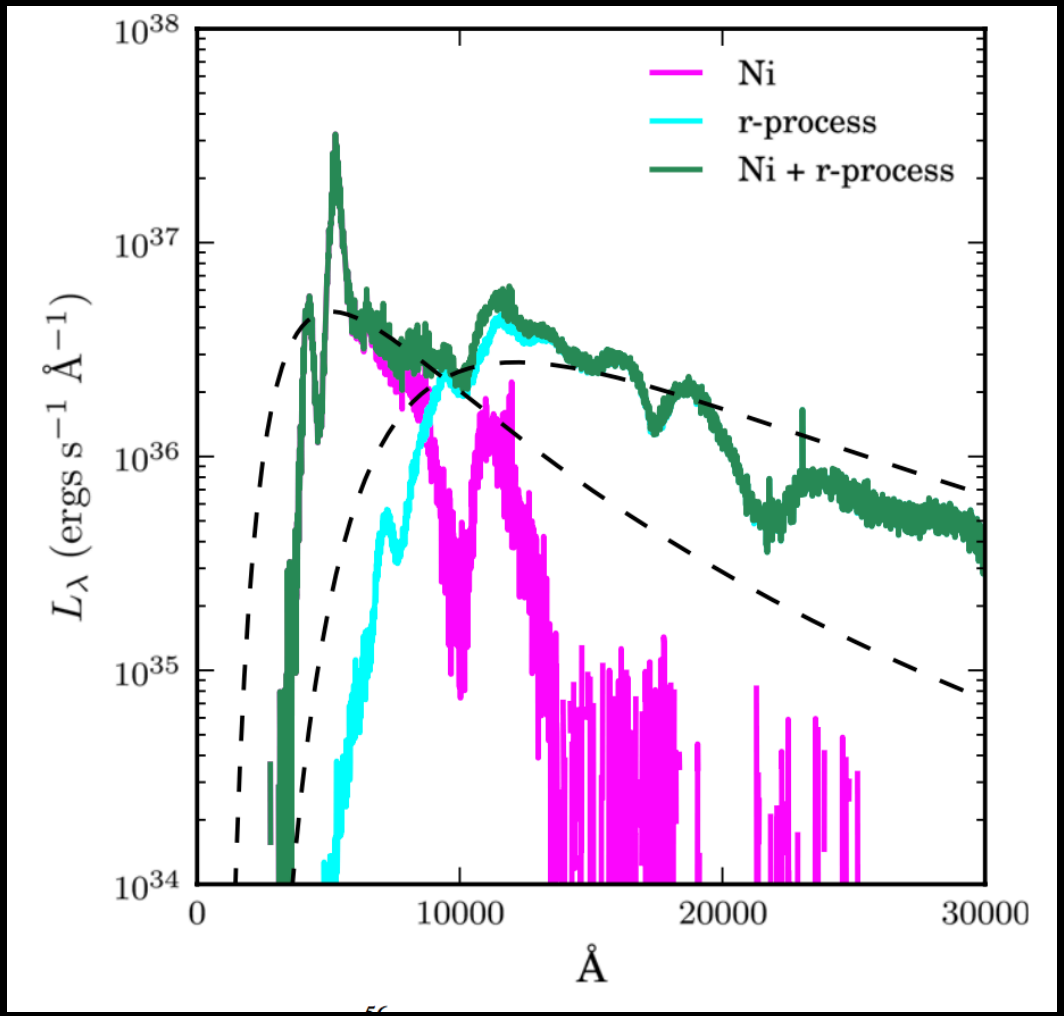


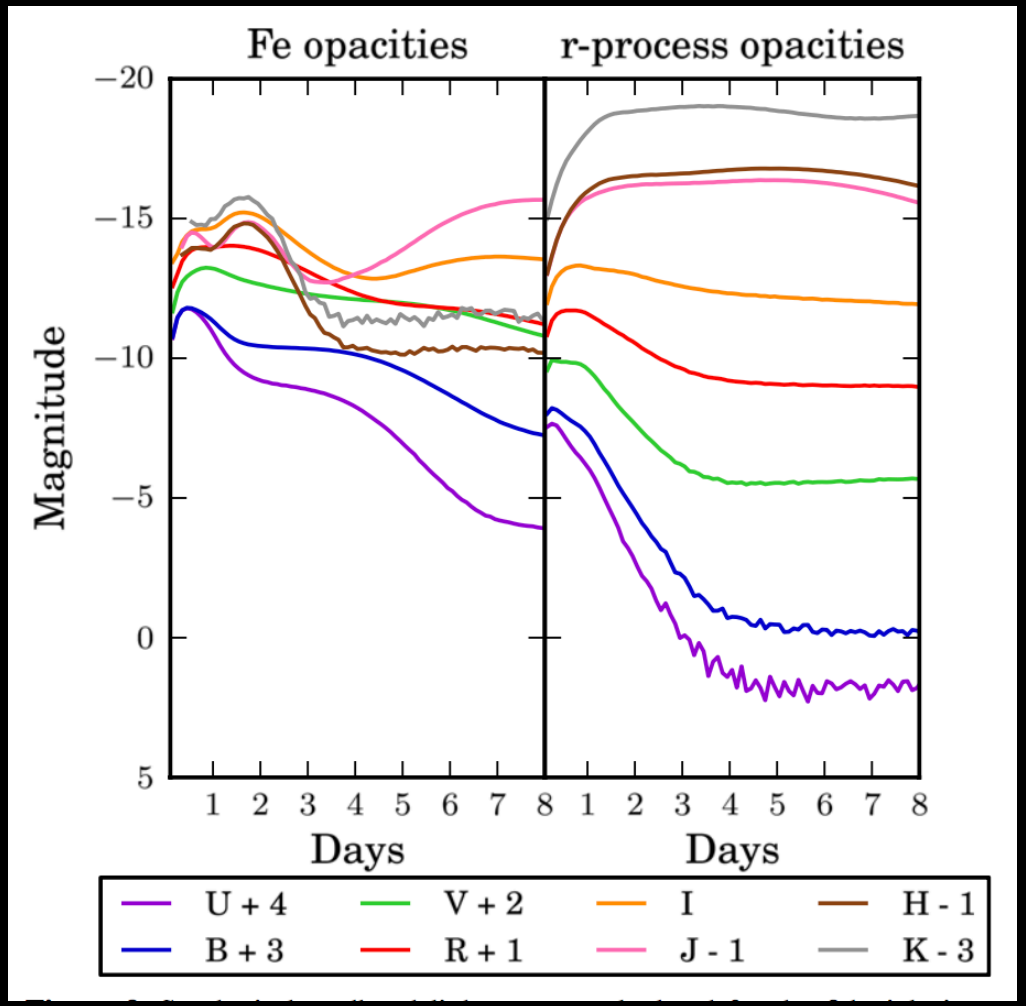
Li & Paczynski 1998 507 59



Metzger & Berger 2012 ApJ 746 48

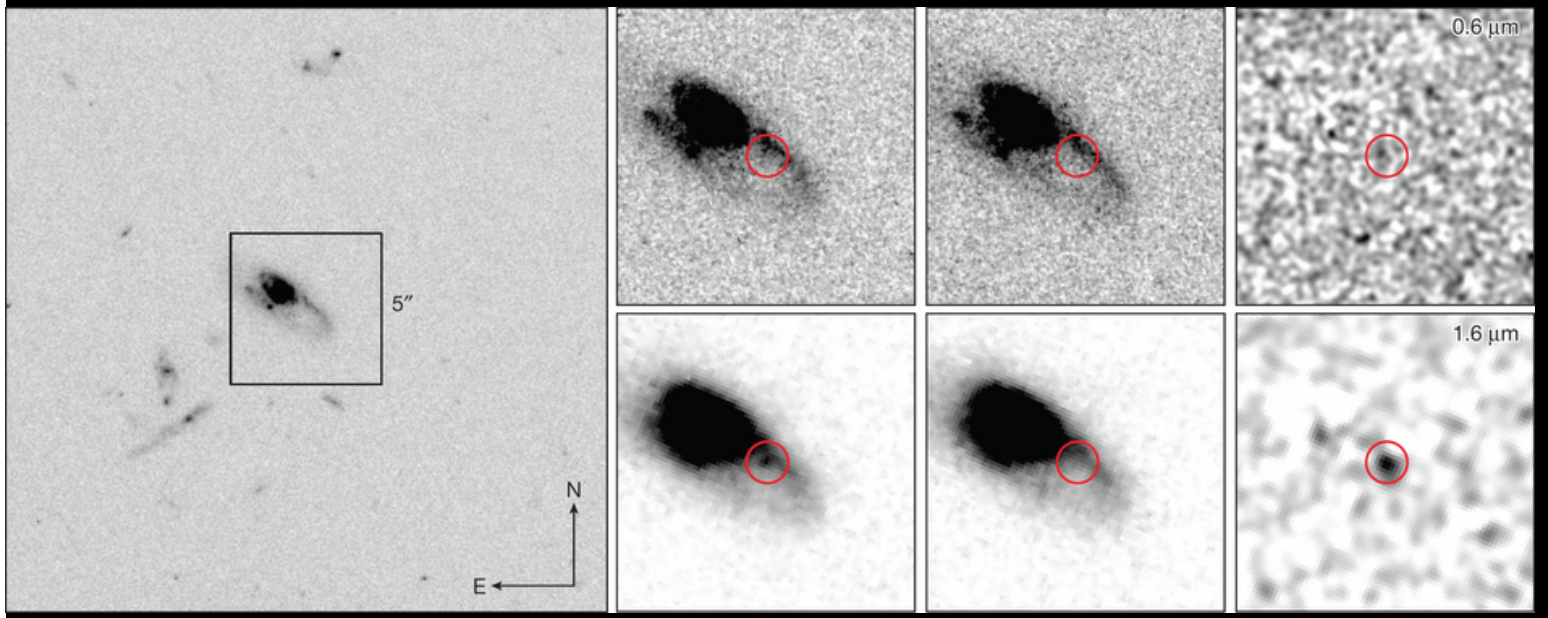
Go to the infrared

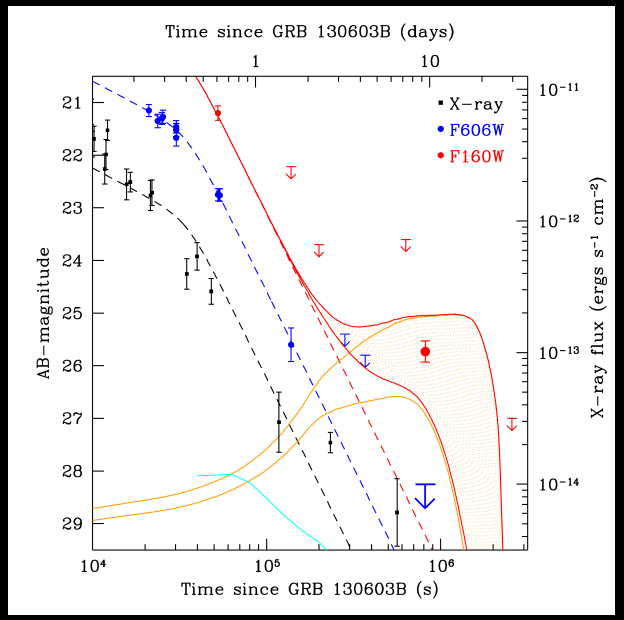




Barnes & Kasen 2013 ApJ 775 13

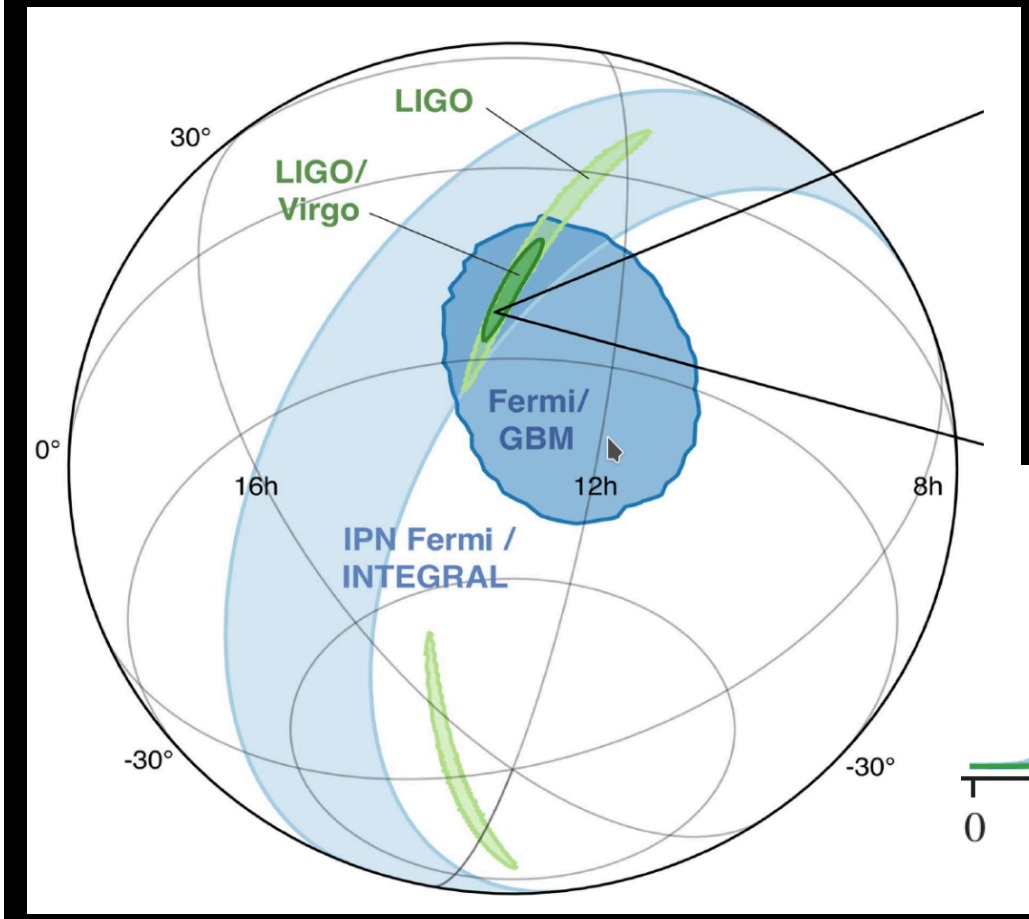
Short gamma-ray bursts and kilonova

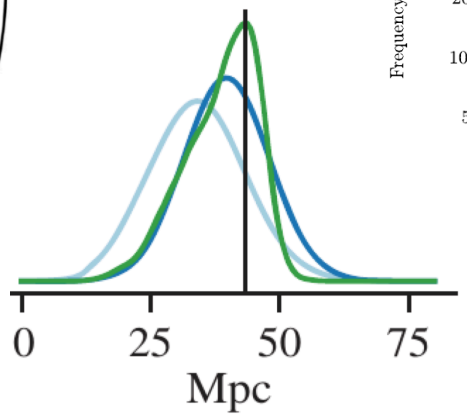


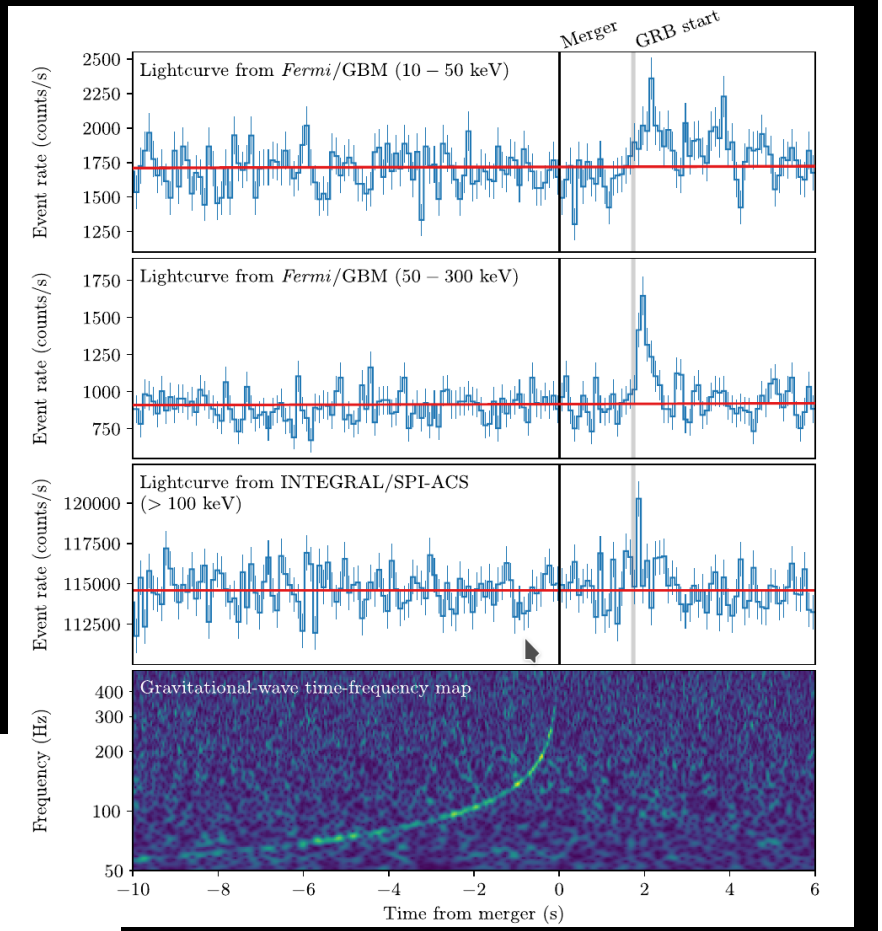


Tanvir, Levan et al. 2013 Nature 500 547, Berger, Fong & Chornock 2013 ApJ 774 23

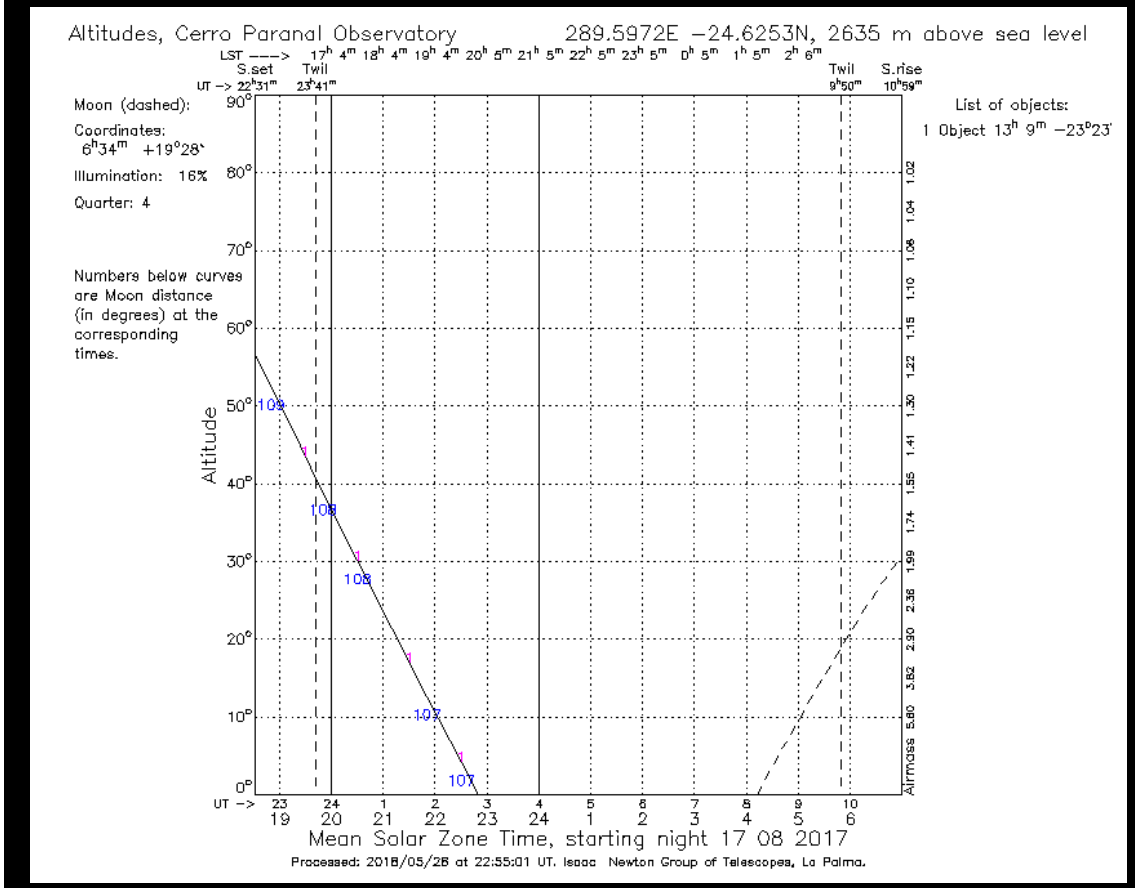
GW170817 / GRB 170817A

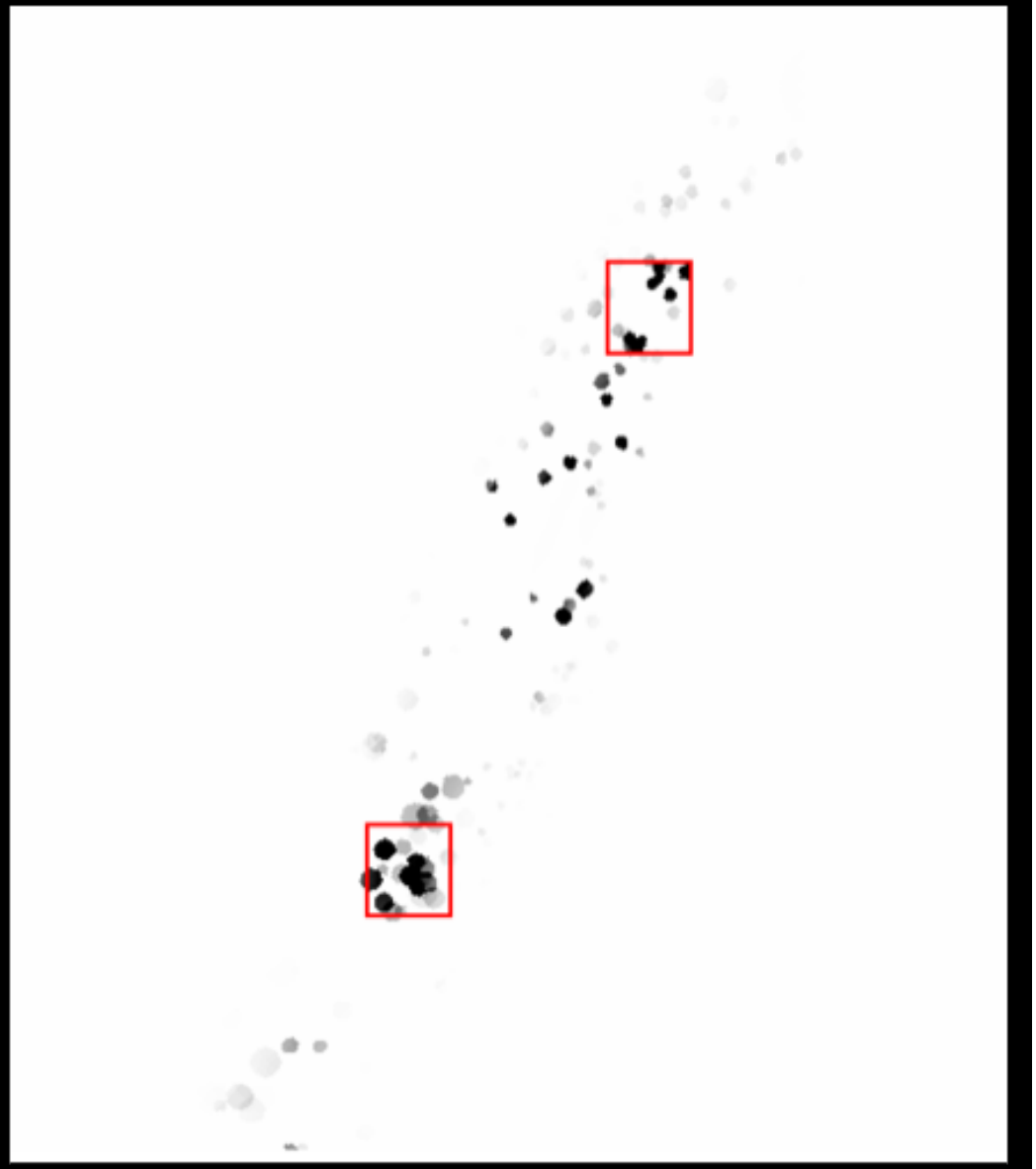


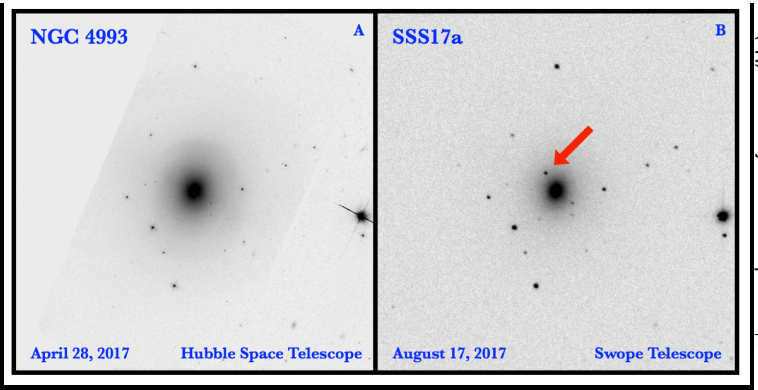




LVC 2017


Altitudes, Cerro Paranal Observatory
289.5972E −24.6253N, 2635 m above sea level
LST ---> 17h 4m 18h 4m 19h 4m 20h 5m 21h 5m 22h 5m 23h 5m 0h 5m 1h 5m 2h 6m
S.set Twil Twil S.rise
UT -> 22h31m 23h41m 9h50m 10h59m
Moon (dashed):
Coordinates:
6h34m +19°28'
Illumination: 16%
Quarter: 4
Numbers below curves are Moon distance (in degrees) at the corresponding times.
List of objects:
1 Object 13h 9m −23°23'
Altitude
Airmass
UT ->
Mean Solar Zone Time, starting night 17 08 2017
Processed: 2018/05/28 at 22:55:01 UT. Isaac Newton Group of Telescopes, La Palma.



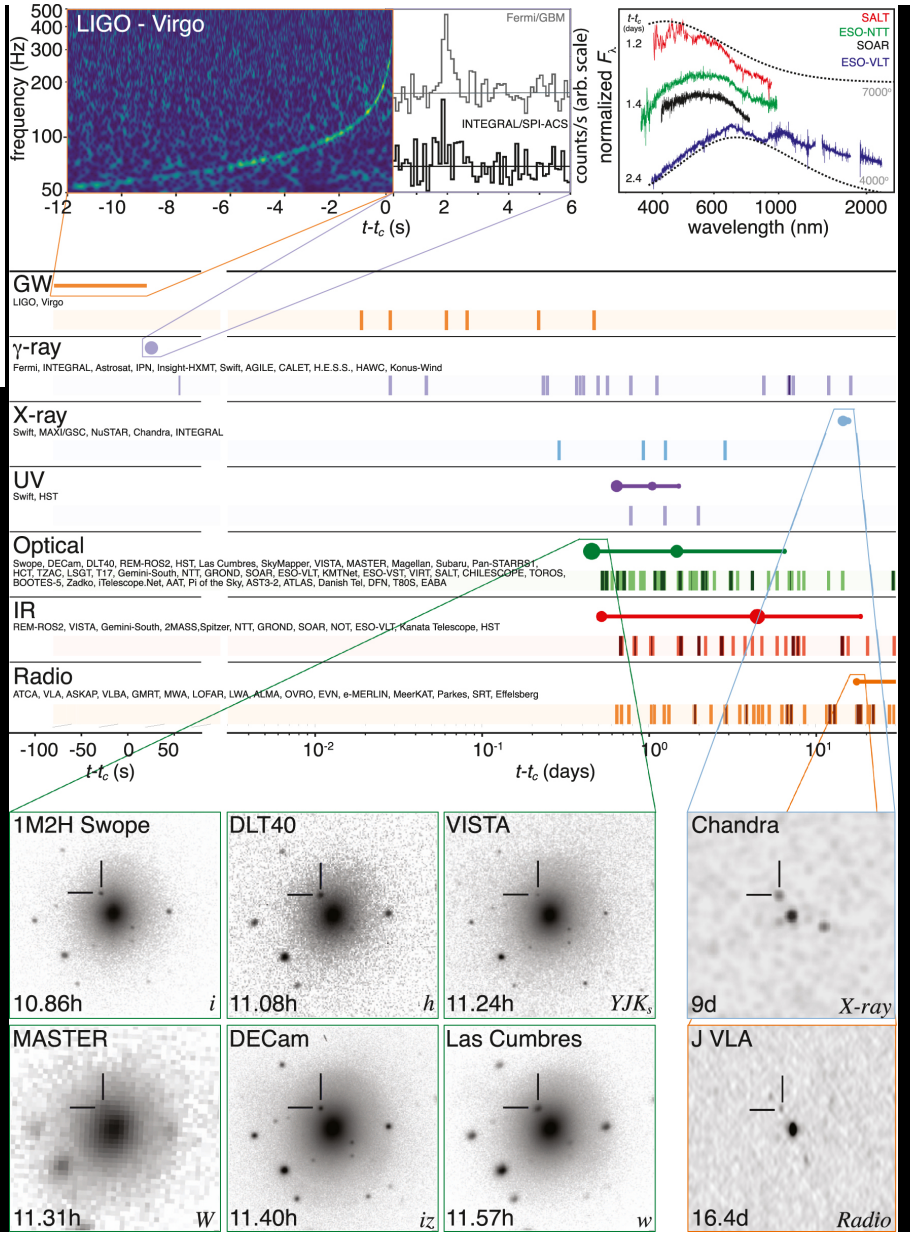


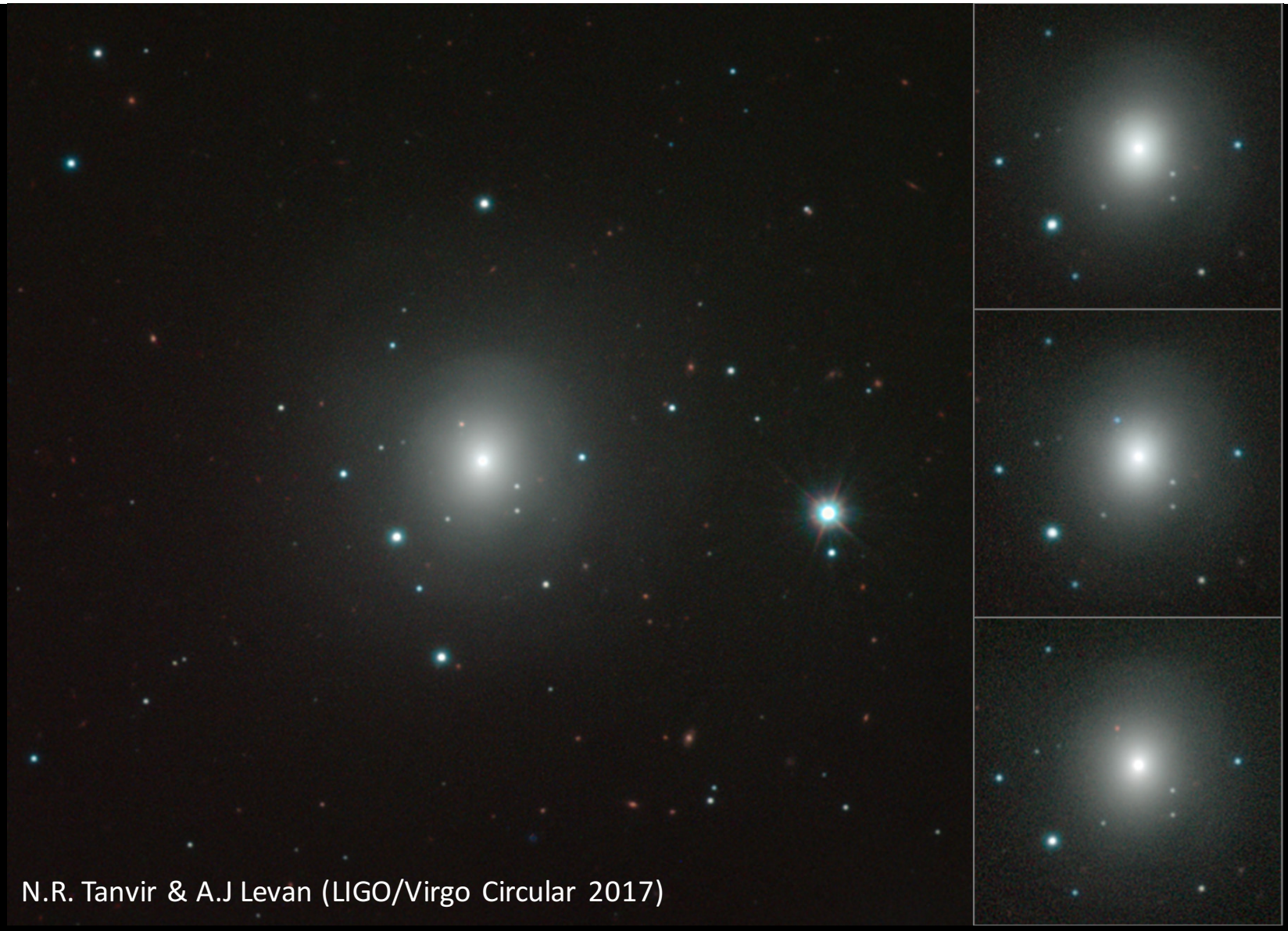
Coulter et al. 2017 Science in press

LVC et al. 2017 ApJL

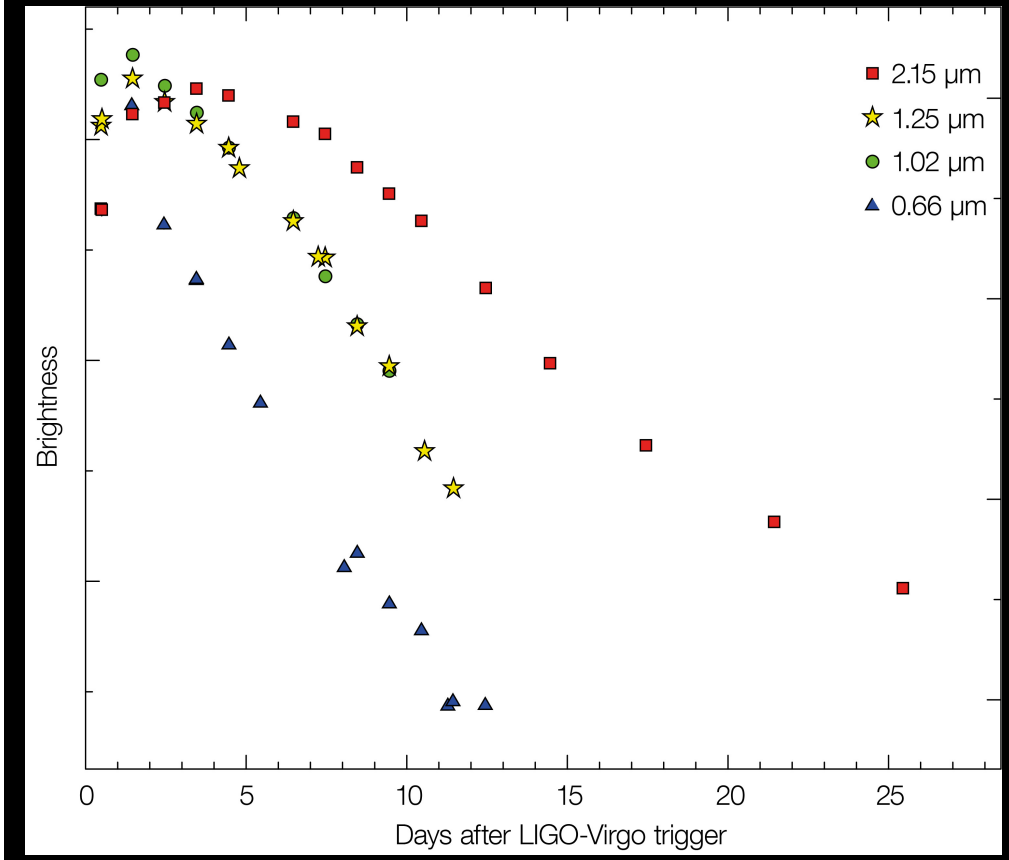
See also:

Arcavi et al. 2017, Cowperthwaite et al. 2017, Chornock et al. 2017, Drout et al. 2017 Nicholl et al. 2017, Haggard et al. 2017, Hallinan et al. 2017, Kasliwal et al. 2017, Lipunov et al. 2017, Margutti et al. 2017, Smartt et al. 2017, Soares-Santos et al. 2017, Tanvir et al. 2017, Troja et al. 2017, Valenti et al. 2017

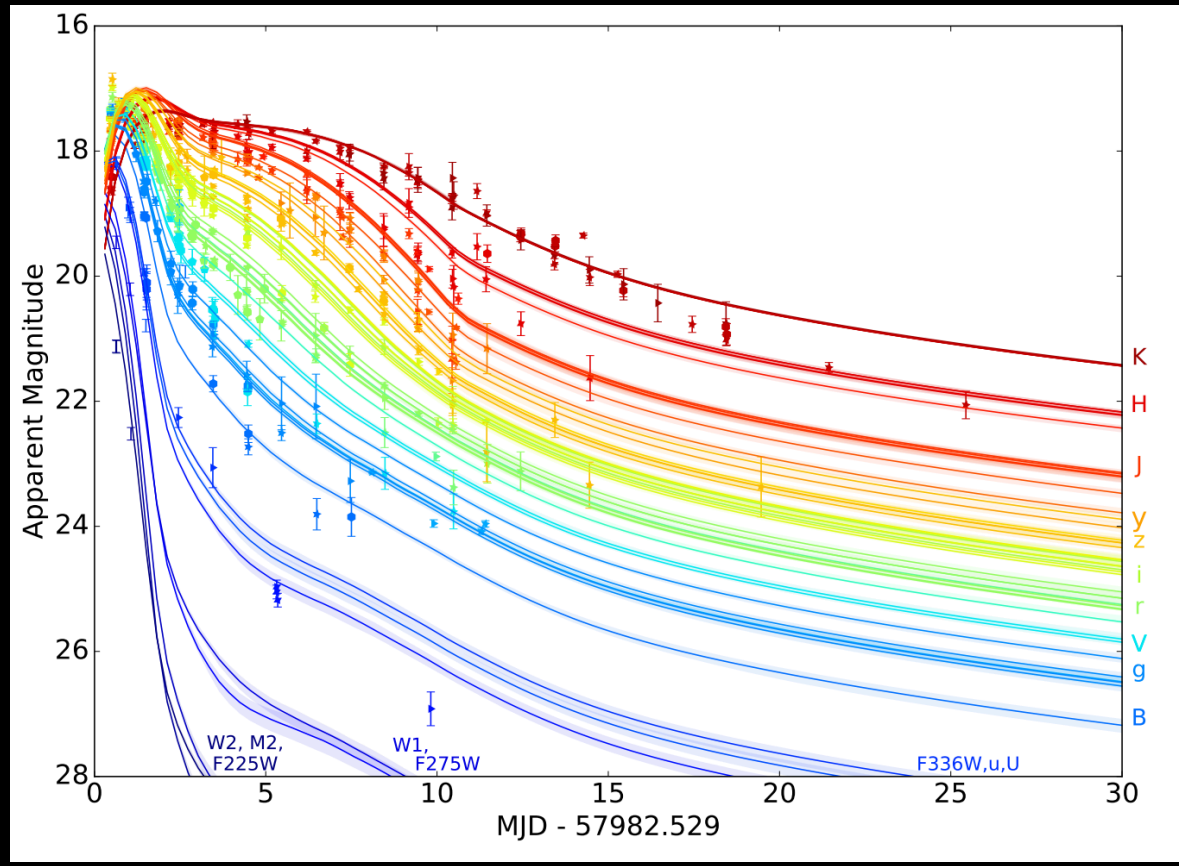



N.R. Tanvir & A.J Levan (LIGO/Virgo Circular 2017)

Lightcurve

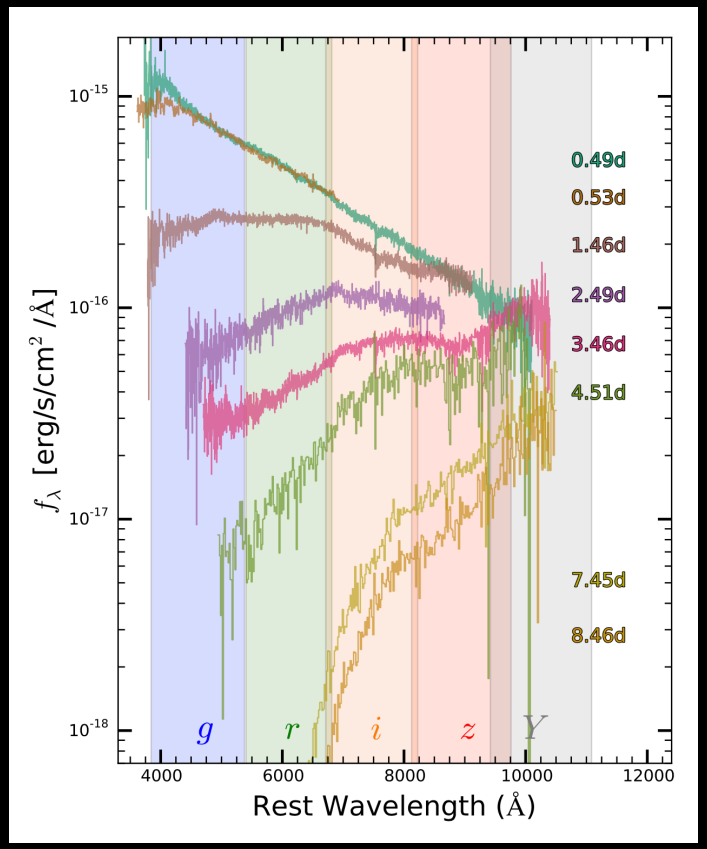


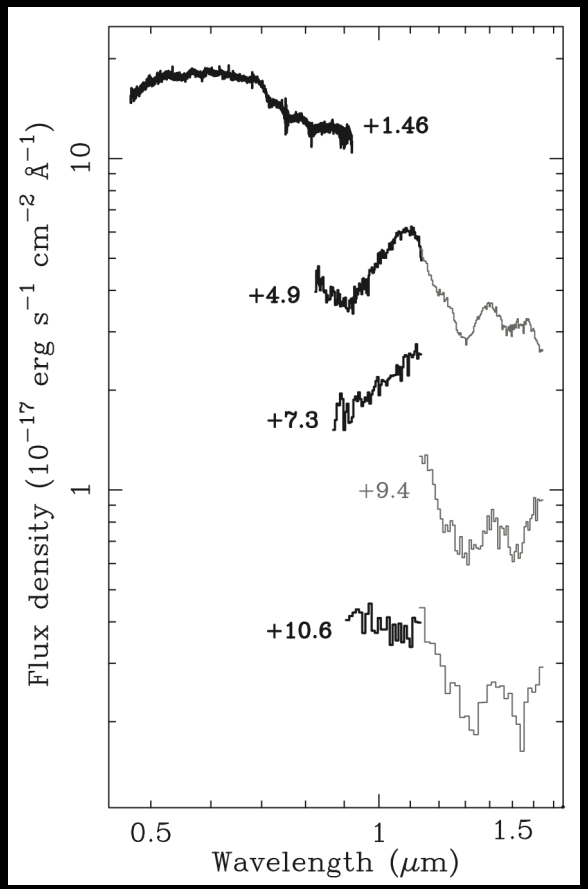
Tanvir et al. 2017 ApJ 848 27

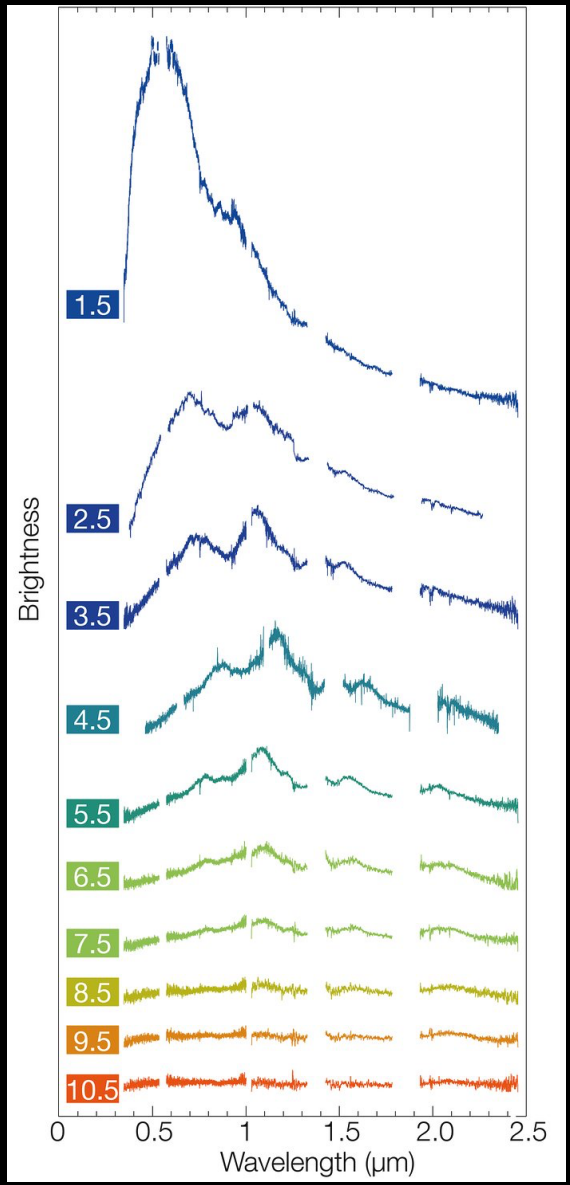


Villar et al. 2017; data from Arcavi et al. 2017, Cowperthwaite et al. 2017, Chornock et al. 2017, Drout et al. 2017 Nicholl et al. 2017, Haggard et al. 2017, Hallinan et al. 2017, Kasliwal et al. 2017, Lipunov et al. 2017, Margutti et al. 2017, Smartt et al. 2017, Soares-Santos et al. 2017, Tanvir et al. 2017, Troja et al. 2017, Valenti et al. 2017

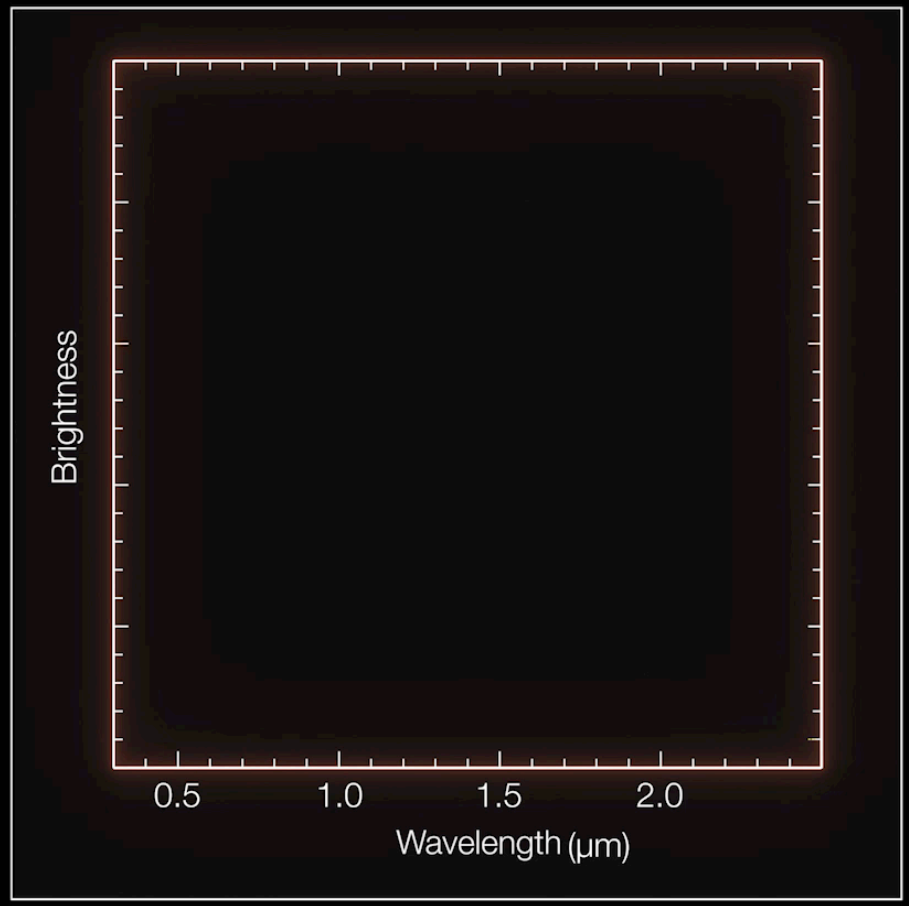
Spectral sequence







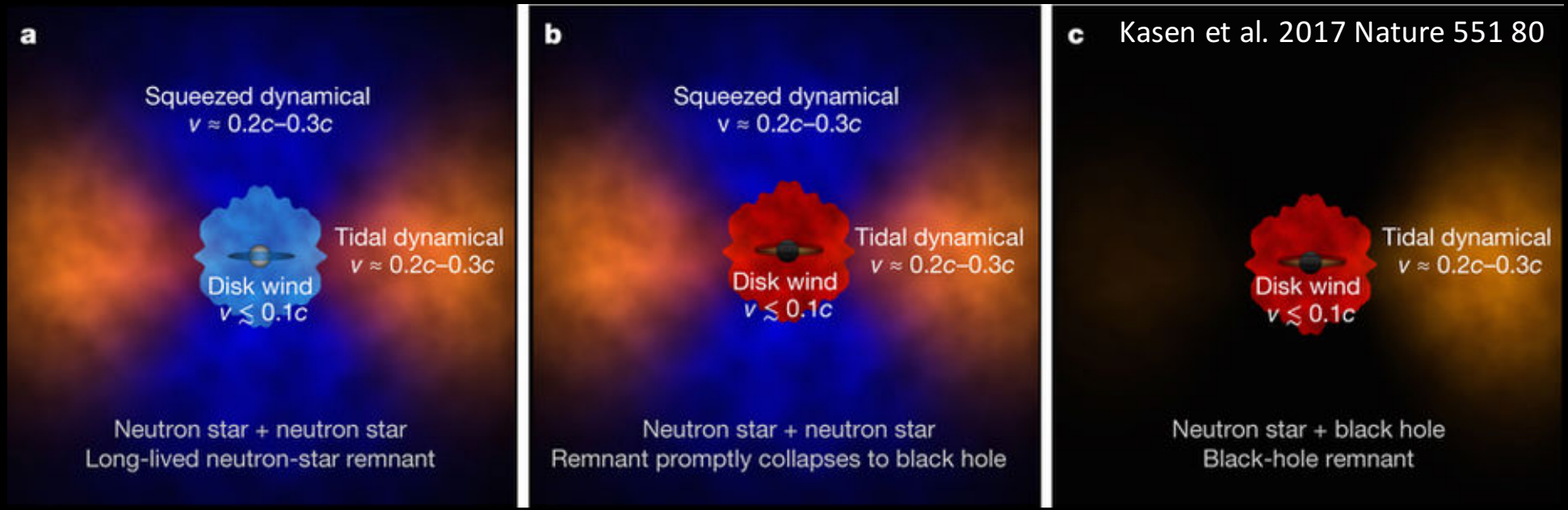
Shappe et al. 2017, Tanvir et al. 2017, Pian et al. 2017 Nature 551 67,
Smartt et al. 2017 Nature 551 75



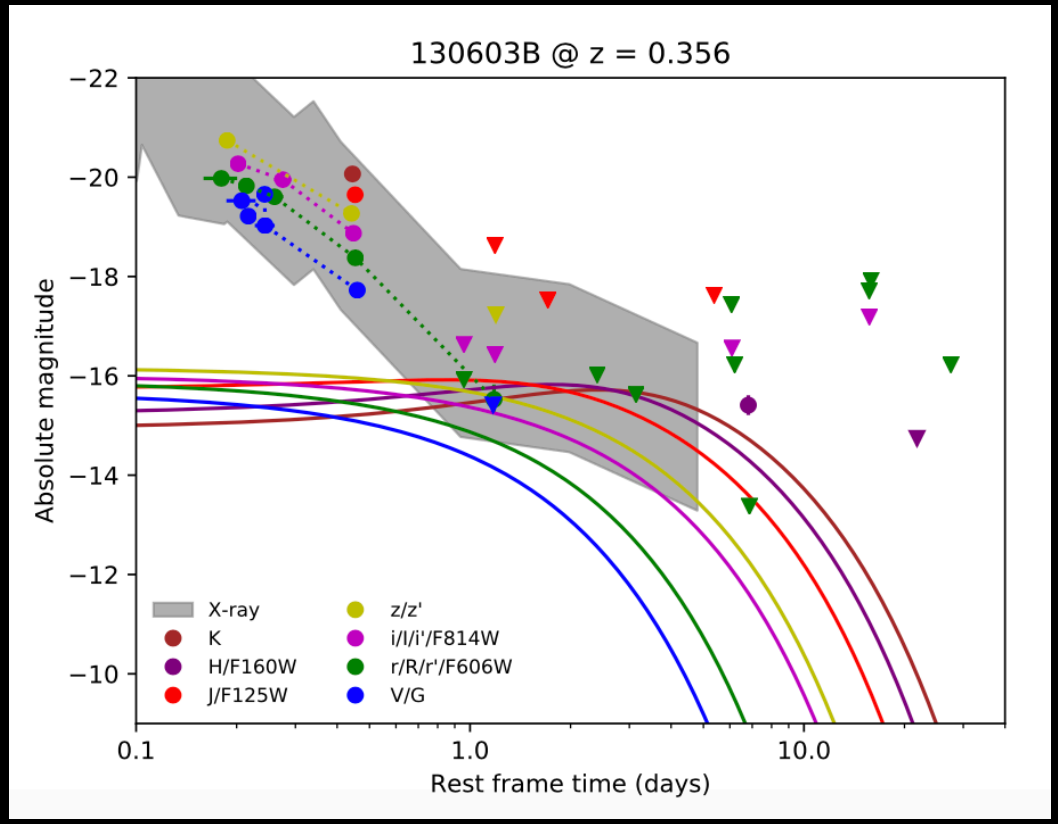
Time: -1225 days

Kilonova properties

- Strongly evolving blue to red. Peaking early (~1 day) in the optical and later (~5 days) in the IR. Strong source of opacities.
- Emergence of broad features in IR. Lanthanides?
- Two/three components
- Total ejecta mass up to 0.1 solar masses (composition matters)

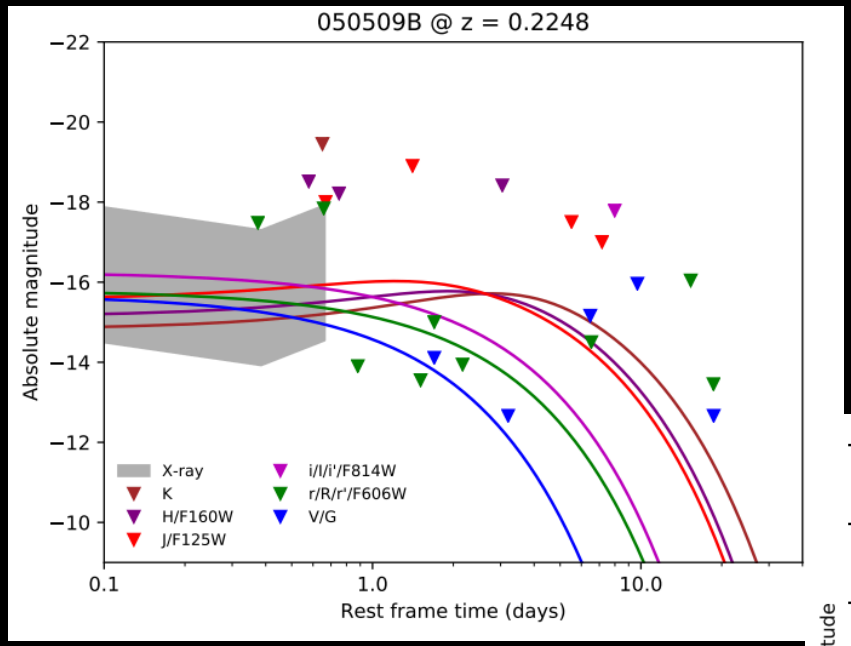


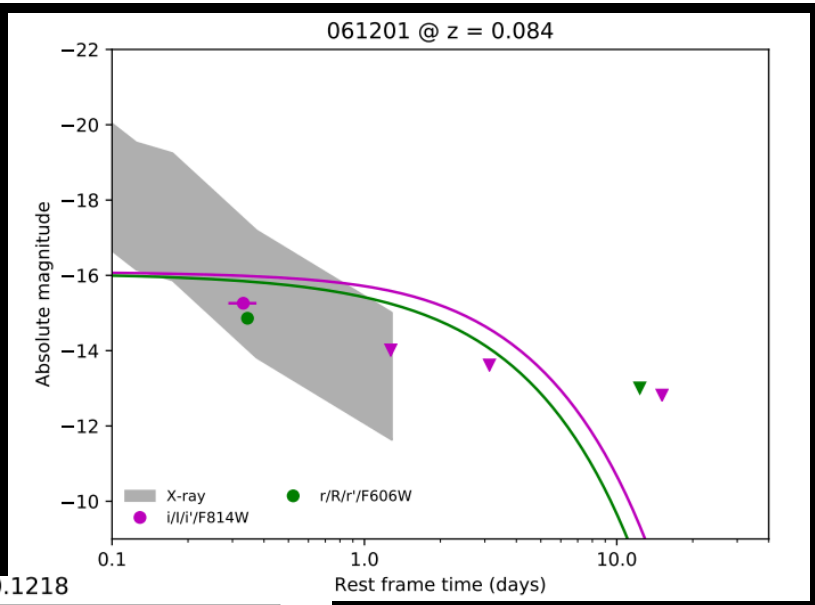
Comparison with short GRBs

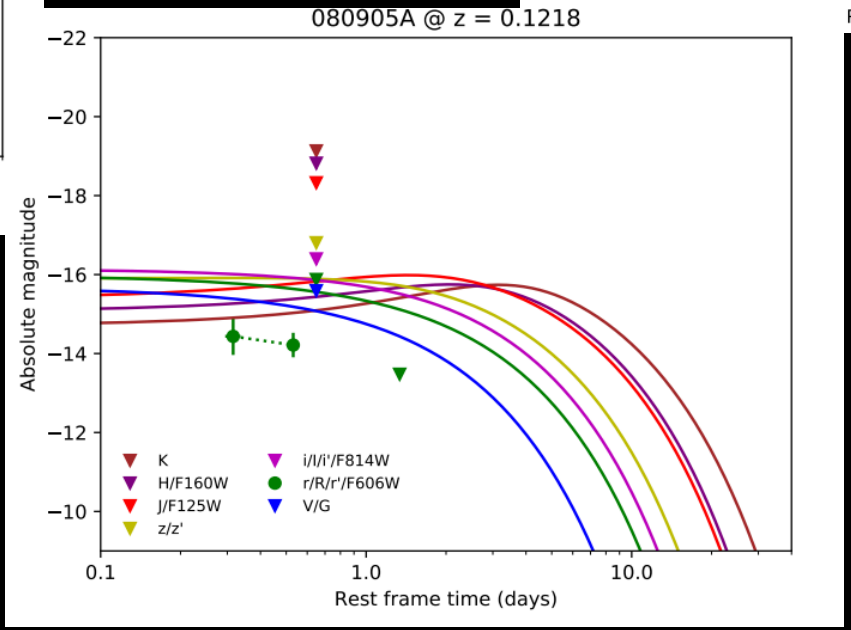


Gompertz et al. 2018

Comparison with short GRBs

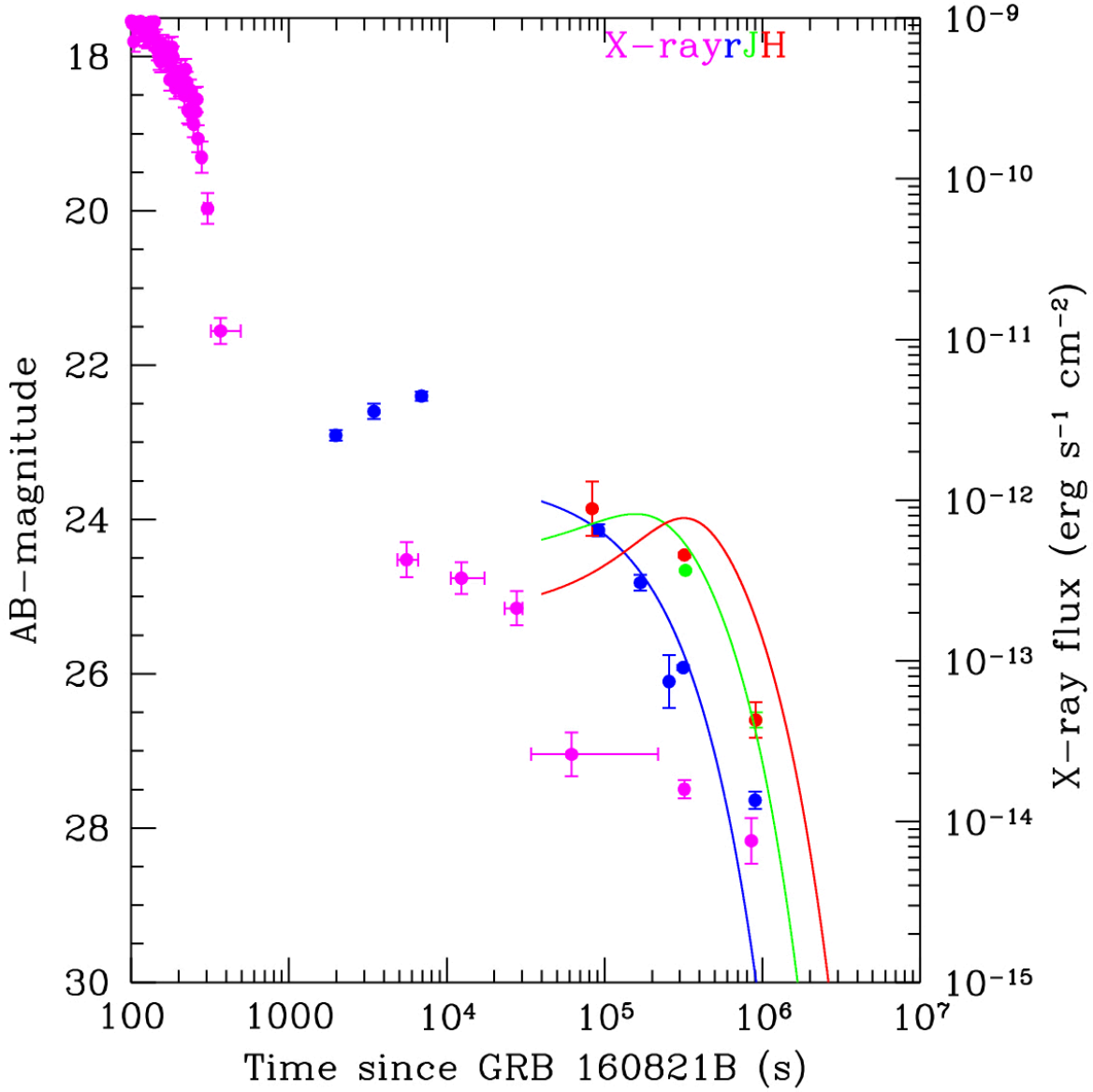






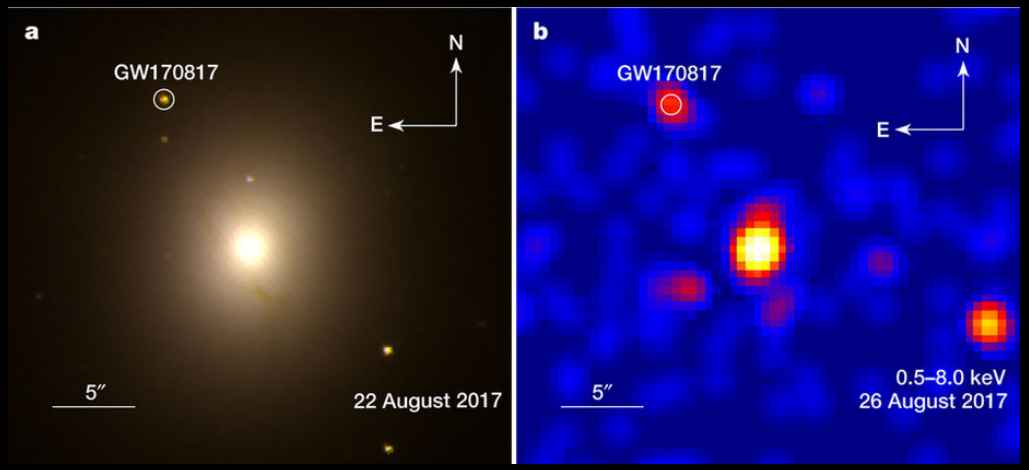
Gompertz et al. 2018

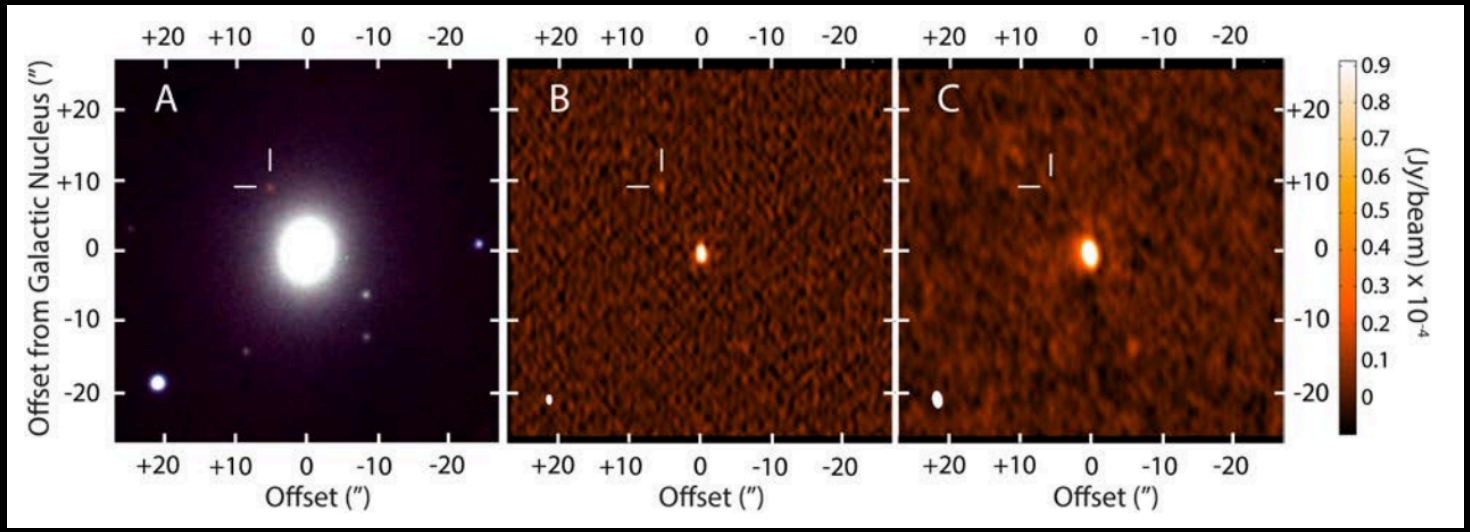
GRB160821B



Tanvir, Levan et al. in prep

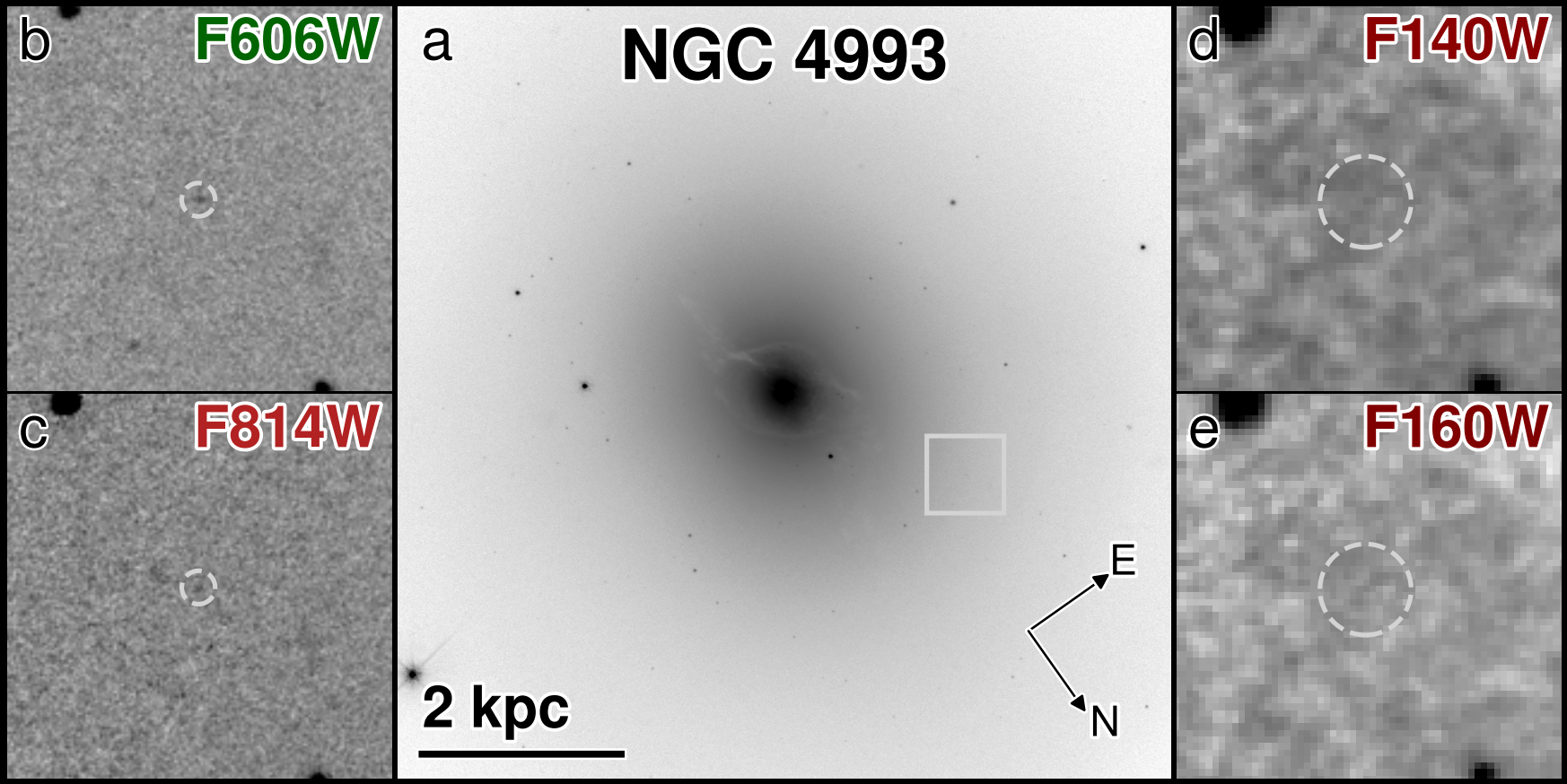
Afterglow





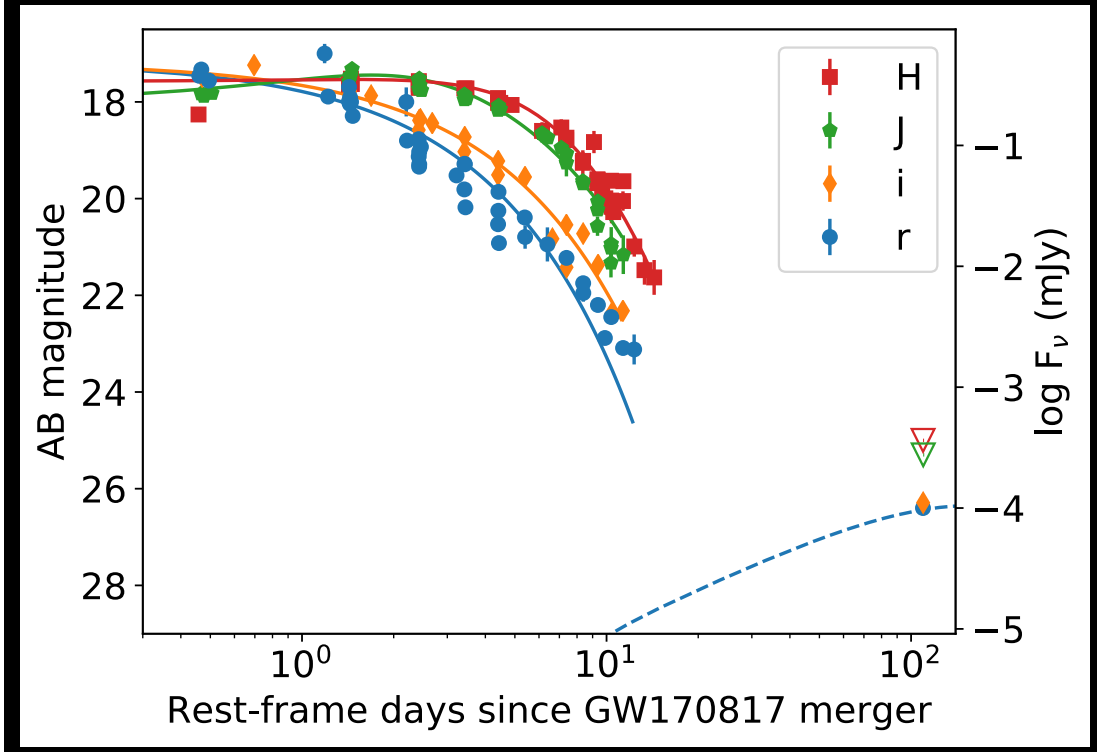
Hallinan et al. 2017 Science, in press, Troja et al. 2017 Nature 551 71

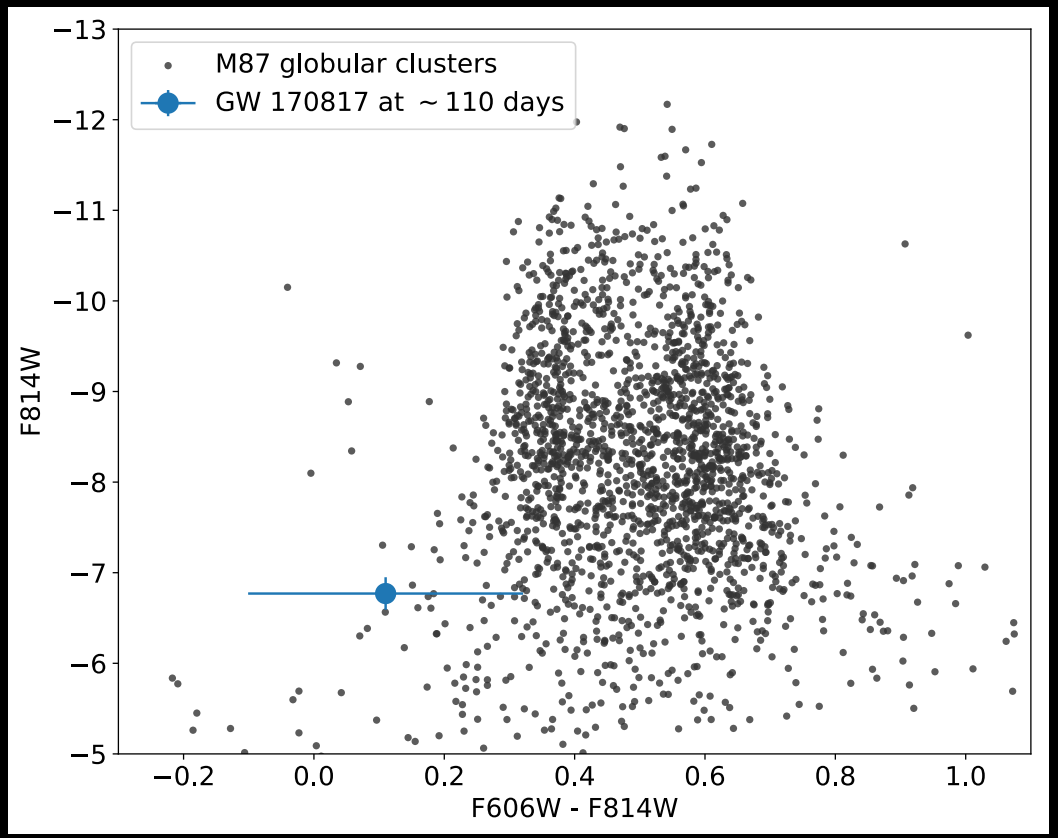
At late times



Lyman et al. 2018

At late times

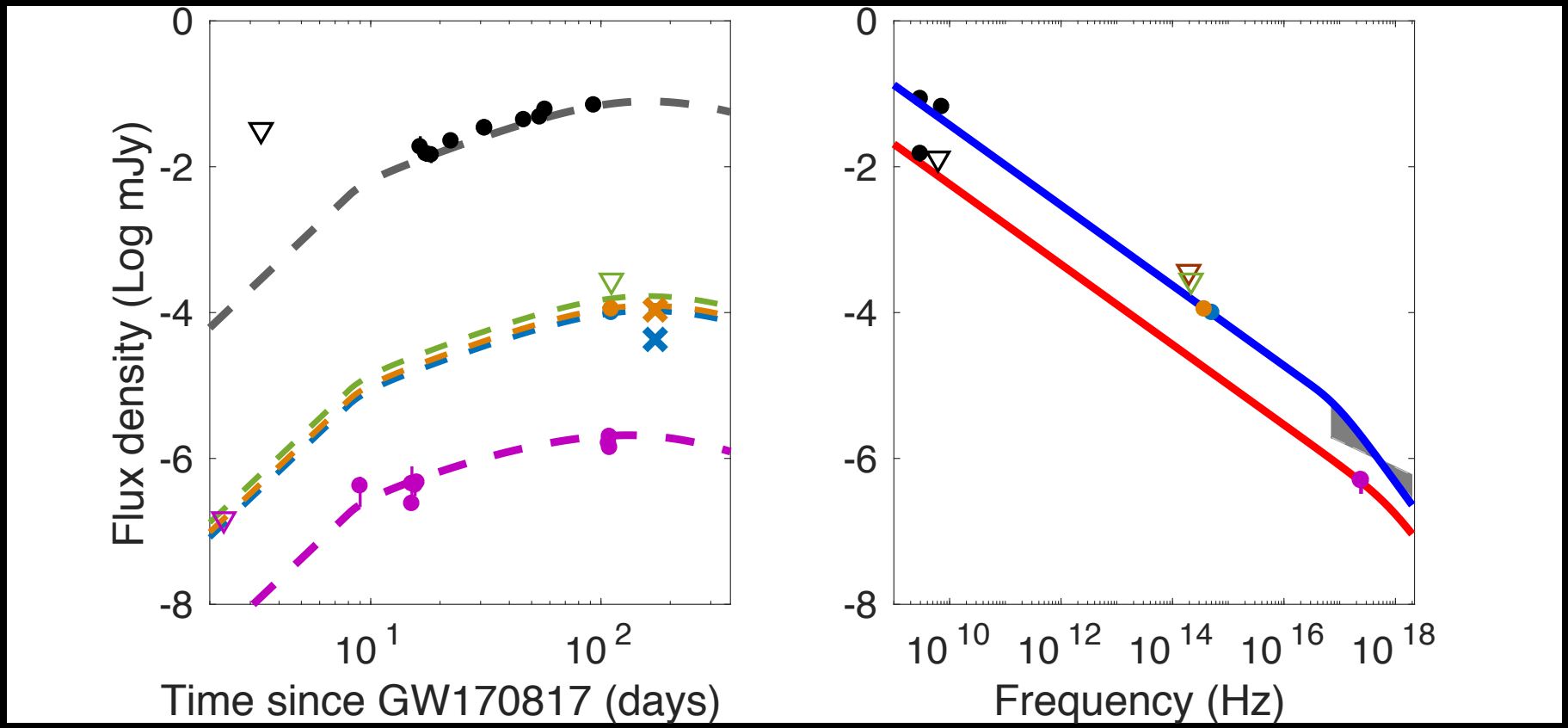




Lyman et al. 2018

At late times

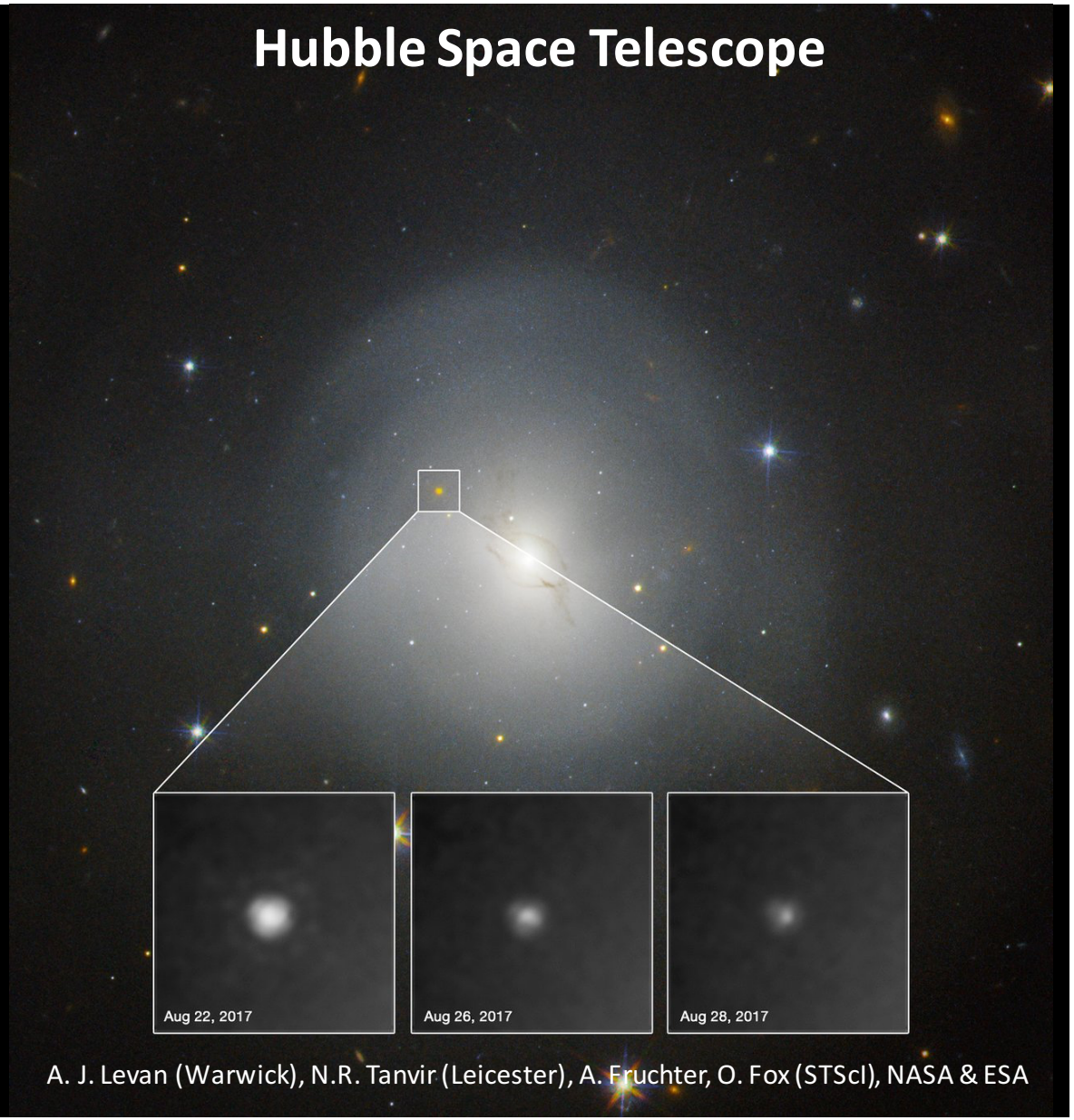
Off-axis GRB or mildly relativistic cocoon?



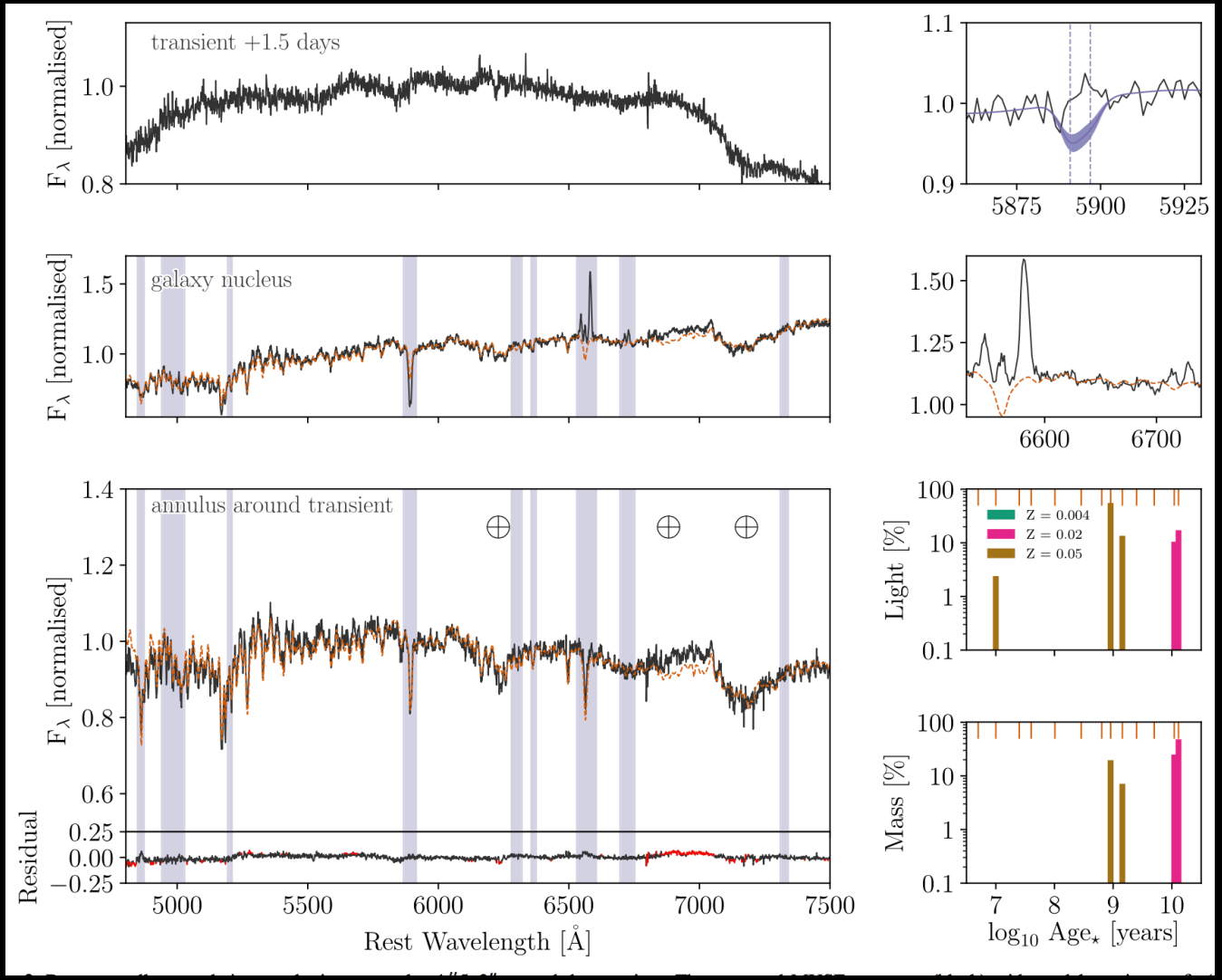
Lyman et al. 2018

See also: Troja et al. 2017, Hallinan et al. 2017, Mooley et al. 2017, Margutti et al. 2018, D'Avanzo et al. 2018, Troja et al. 2018

The host galaxy NGC 4993

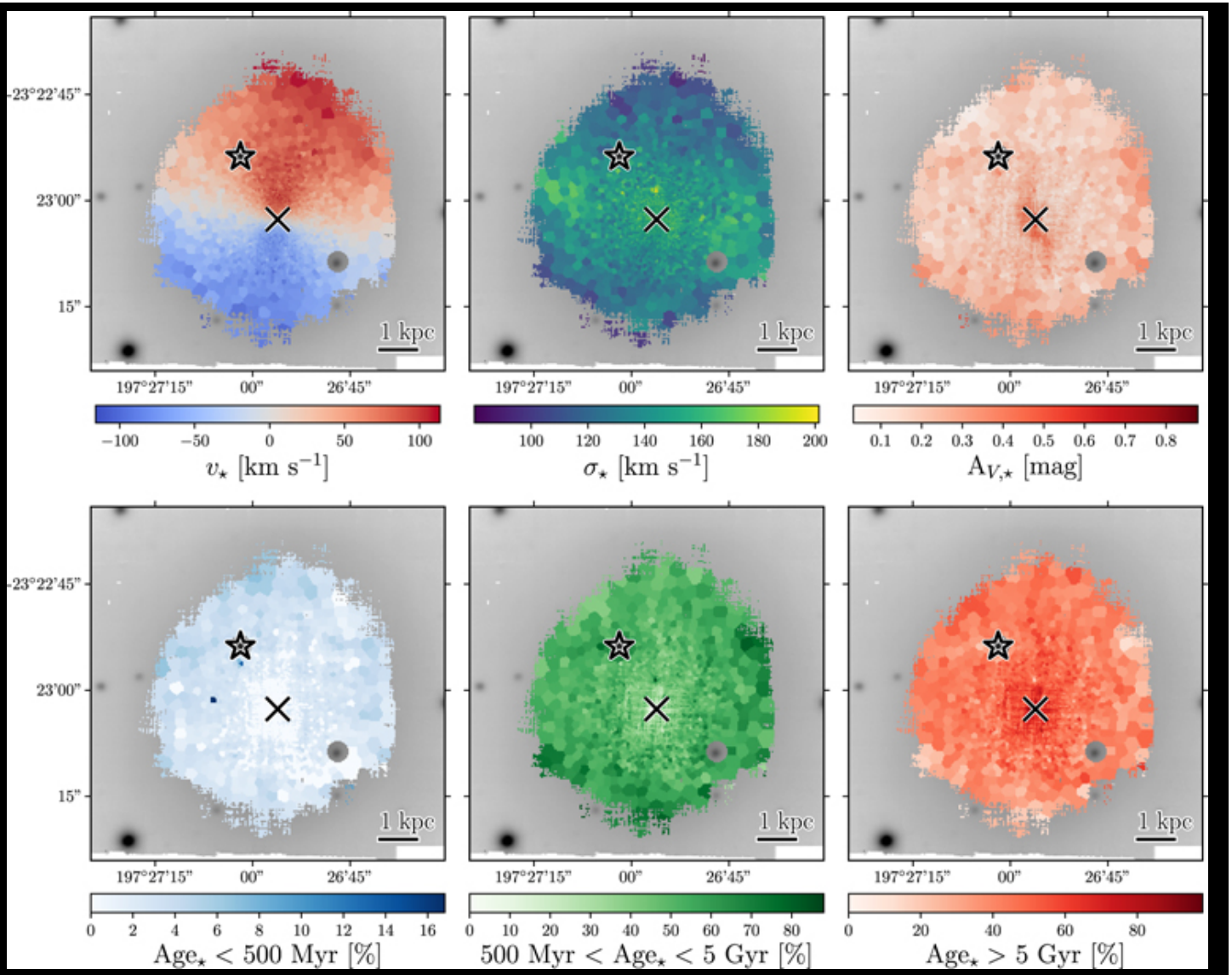


The host galaxy NGC 4993



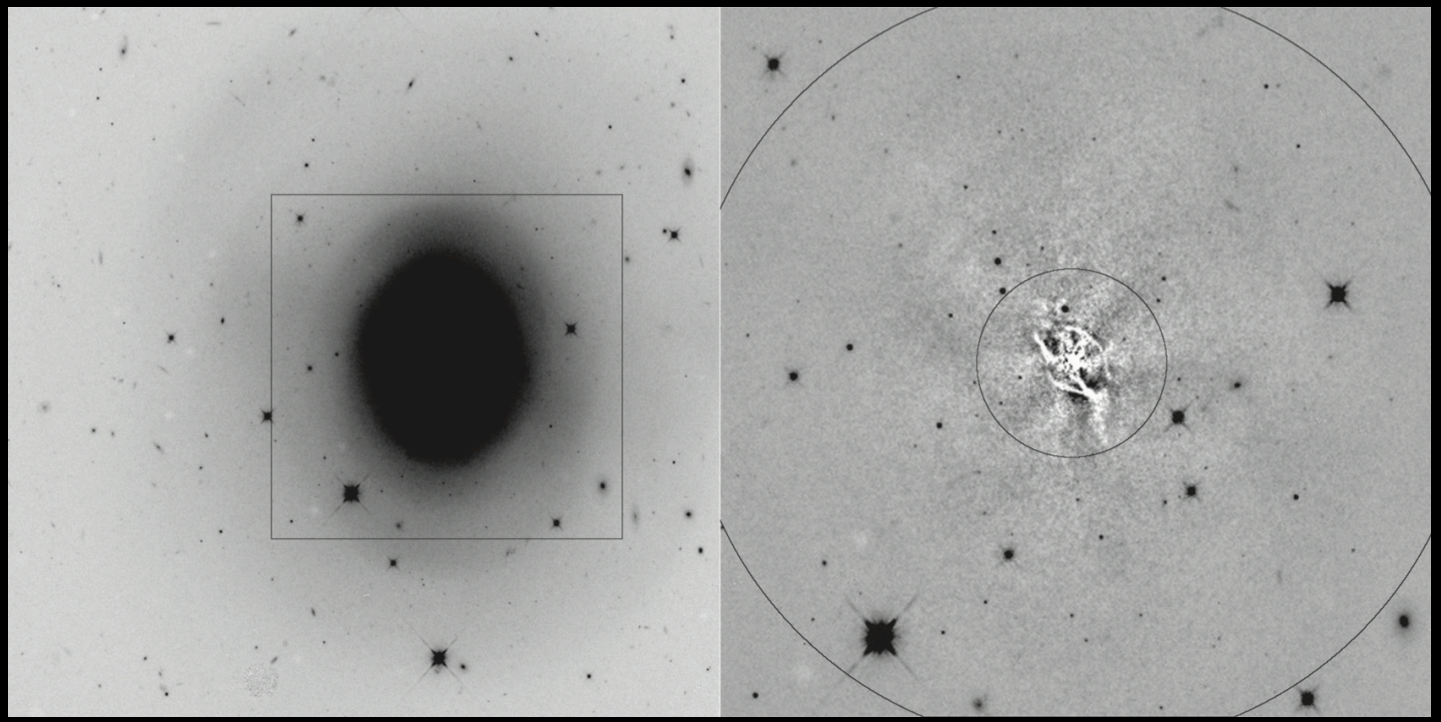
Levan et al. 2017 ApJ 848 28

The host galaxy NGC 4993



Levan et al. 2017 ApJ 848 28

The host galaxy NGC 4993 Distance



D_{FP} = 41.0 +/- 3.1

D_{SB} = 40.7 +/- 1.4 +/-1.9 (random + systematic)

$D_{GW}=43.8^{+2.9}_{-6.9}$

Peculiar velocities

Degenerate nature of D_{GW} and inclination angle

Hjorth et al. 2017 ApJ 848 31, Cantiello et al. 2018

Are short GRBs compact object mergers?

Yes, both NS-NS and NS-BH	24%
Yes, but not all mergers make SGRBs	76%

Have we seen a kilonova?

Yes	59%
No	41%

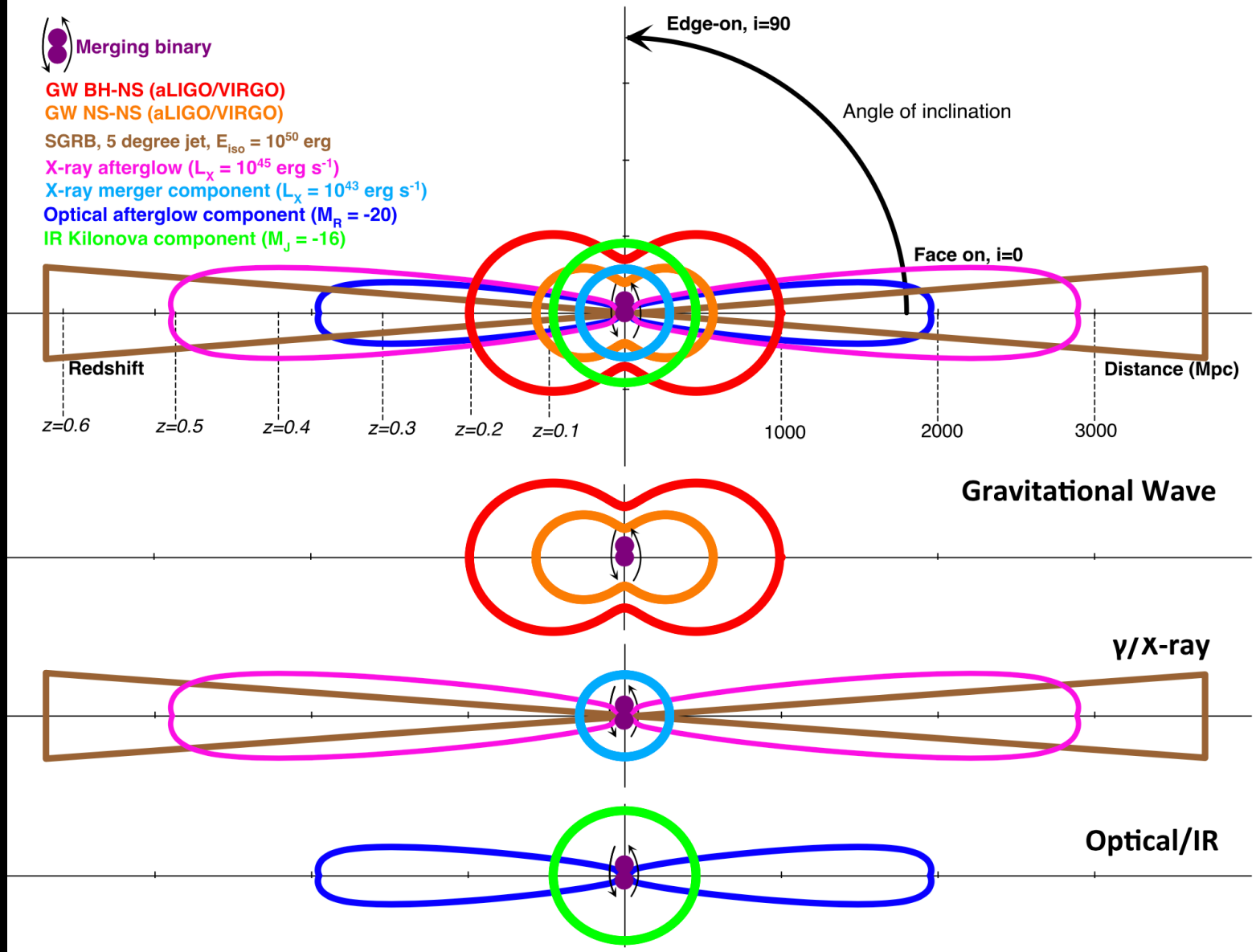
What will be the first EM counterpart to a GW source?

Short GRB prompt emission	24%
Off-axis afterglow	6%
Kilonova	24%
Radio flare	24%
Something else	6%
We won't find any EM-counterparts	18%

Will the source be a

NS-NS	44%
NS-BH	39%
BH-BH	0%
I said we won't find any	17%

Future prospects

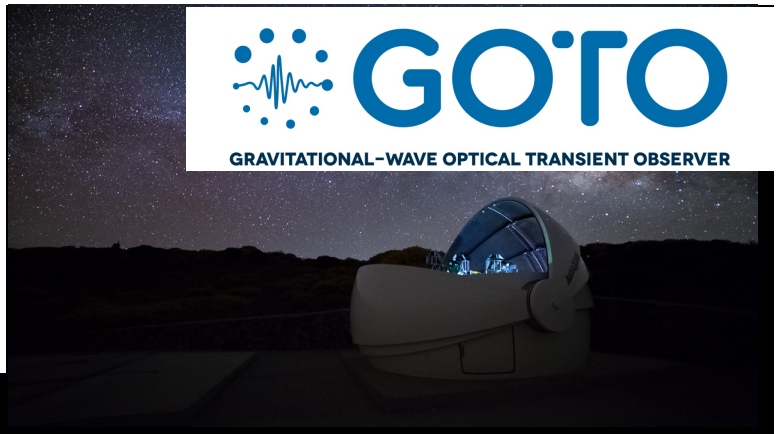


Levan et al. 2016

ZTF

BlackGEM

GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER



Ready for O3

Expect “a handful” of NS-NS or NS-BH mergers

ENGRAVE

Electromag**n**etic Counterparts of **Gra**vitational Wave source at the **Ve**ry Large Telescope

196 ESO scientists

Things we have learned?

Merging neutron star binaries create detectable optical counterparts (plus GRBs of course)

The counterpart evolution matches the expectations of pre-existing kilonova models

Ejecta mass for this event is probably 0.1 solar masses, on the high side of model predictions

The progenitor was probably old, with a Gyr or more decay time

It was probably formed in the field, not in a globular cluster

A slowing rising optical afterglow is present, consistent with an off-axis jet.

Things we need to know

What is the ejected mass? What is the diversity? How does it depend on viewing angle?

What is the mass spectrum of ejected elements?

What is the merger rate? (1540^{+3200}_{-1220} Gpc^{-3} yr^{-1})

Do all NS-NS mergers create a GRB for a suitably aligned observer?

Can we see signatures of NS-BH mergers?

Can we find GW bursts as well as inspiral events?