SVOM Scientific Workshop

Kilonova, what's the link with GRBs?

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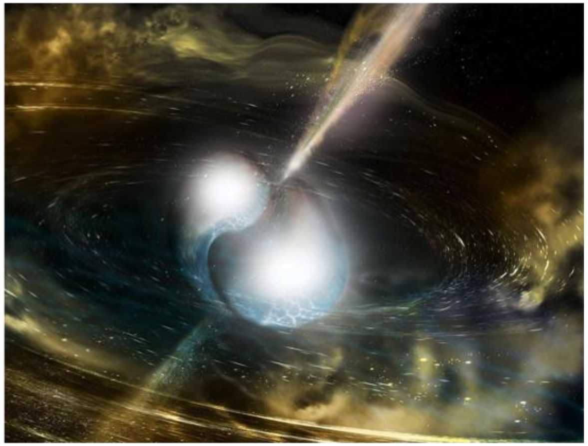
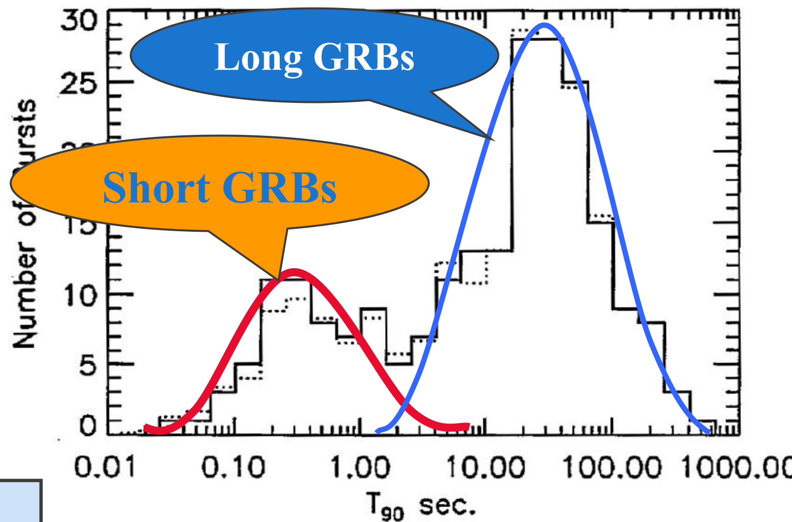
Outline

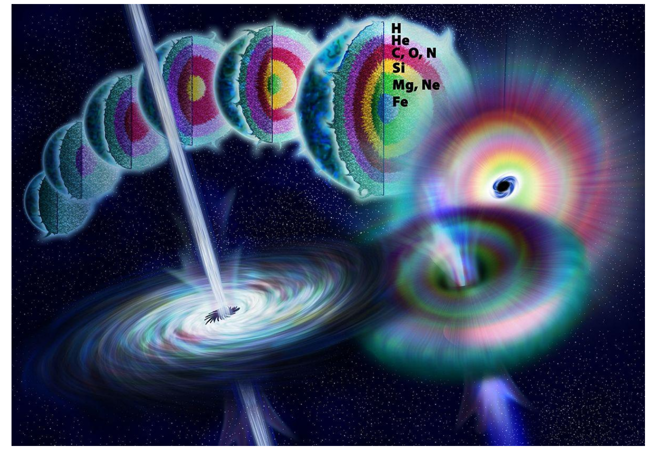
- Background
- Kilonovae linked to GRBs
- Implications
- Prospects

Gamma-ray bursts: short vs long

Gamma-ray burst: the most violent and energetic event in our universe after the big bang.







BNS or NS-BH merger (~10 km) / Kilonova

Eichler et al. 1989

Kouveliotou C. et al. 1993

Massive star collapse (~1E6 km) / Supernova

Colgate 1968

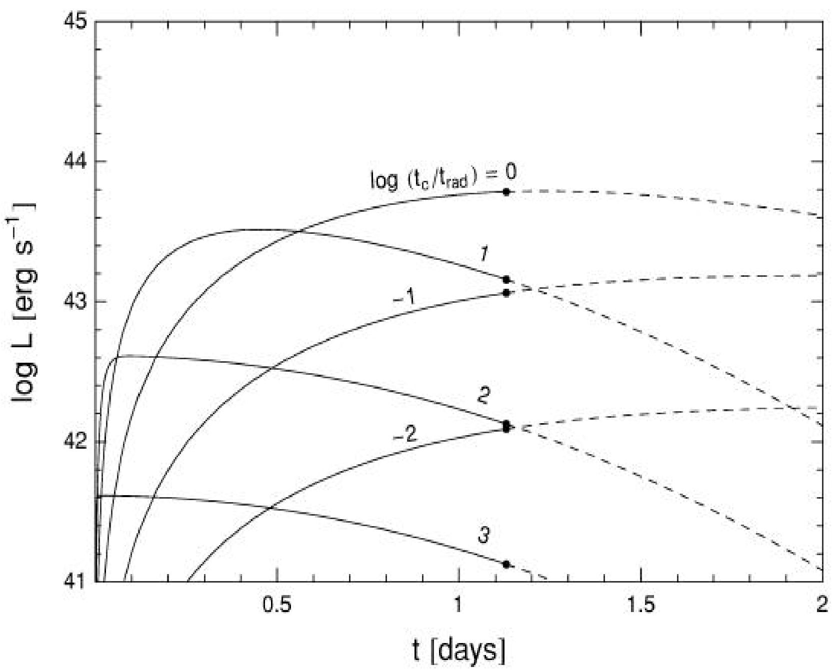
Kilonova: transient from neutron star merger

A supernova like transient powered by the radioactive decay of r-process material synthesized in the outflow (Lattimer & Schramm 1974) from neutron star (BNS or NS-BH) merger (Li & Paczynski 1998), electromagnetic counterparts to gravitational wave events

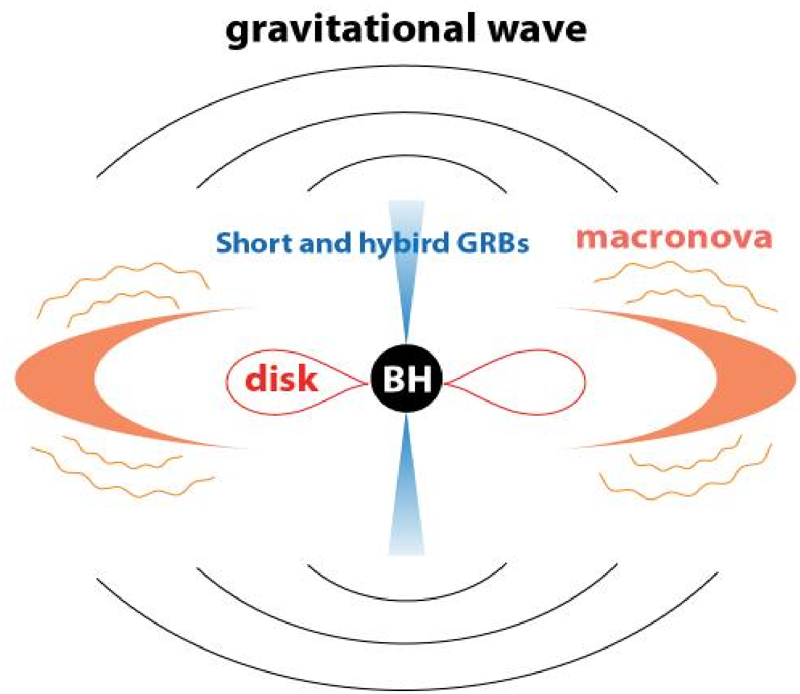
Macronova (Kulkarni 2005, including flux enhancement by a living magnetar)

Kilonova luminosity about 1000 times of nova (Metzger et al. 2010)

Merger-nova magnetar-boosted kilonova (Yu et al. 2013, Gao et al. 2015, 2017)

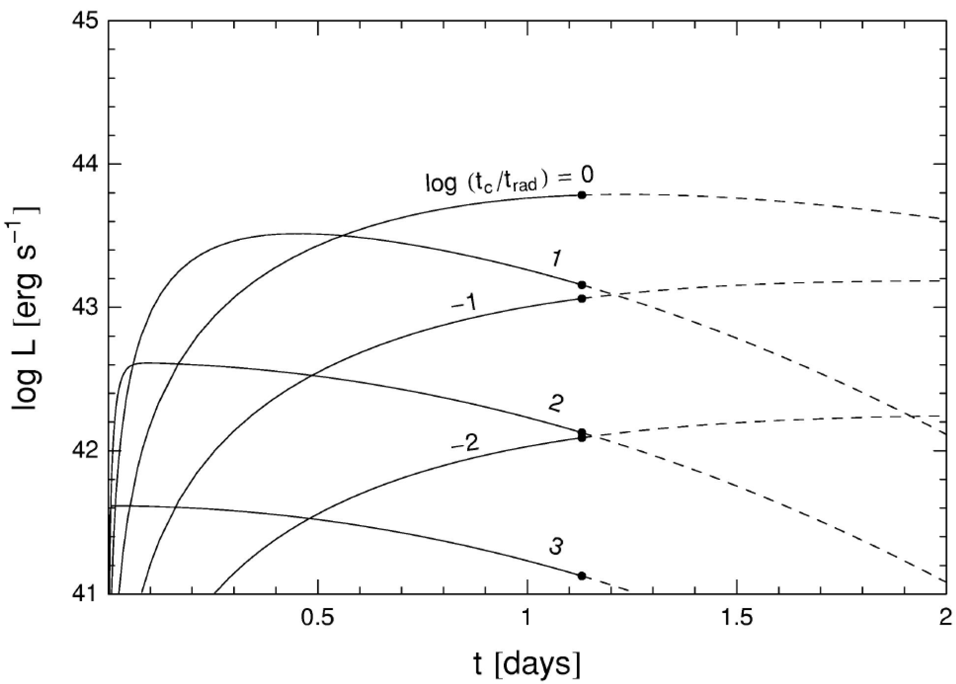


Li & Paczynski 1998 ApJL



Kilonova: transient from neutron star merger

The peak luminosity, time and temperature at peak luminosity.



$$t_m \approx 1.5\beta^{1/2} t_c$$

$$= 0.98 \text{ days} \left(\frac{M}{0.01\ M_\odot}\right)^{1/2} \left(\frac{3V}{c}\right)^{-1/2} \left(\frac{\kappa}{\kappa_e}\right)^{1/2} . \quad (12)$$

$$L_m \approx 0.88\beta^{1/2} L_0 = 2.1 \times 10^{44} \text{ ergs s}^{-1}$$

$$\times \left(\frac{f}{0.001}\right)\left(\frac{M}{0.01\ M_\odot}\right)^{1/2} \left(\frac{3V}{c}\right)^{1/2} \left(\frac{\kappa}{\kappa_e}\right)^{-1/2} . \quad (13)$$

$$T_{\text{eff},m} \approx 0.79\beta^{-1/8} T_1 = 2.5 \times 10^4 \text{ K}$$

$$\times \left(\frac{f}{0.001}\right)^{1/4} \left(\frac{M}{0.01\ M_\odot}\right)^{-1/8} \left(\frac{3V}{c}\right)^{-1/8} \left(\frac{\kappa}{\kappa_e}\right)^{-3/8} , \quad (14)$$

fission heating rate **opacity**

Li & Paczynski 1998

The pioneers in the search for kilonovae

Soon after the discovery of the SGRB afterglow, people started to search for KN.

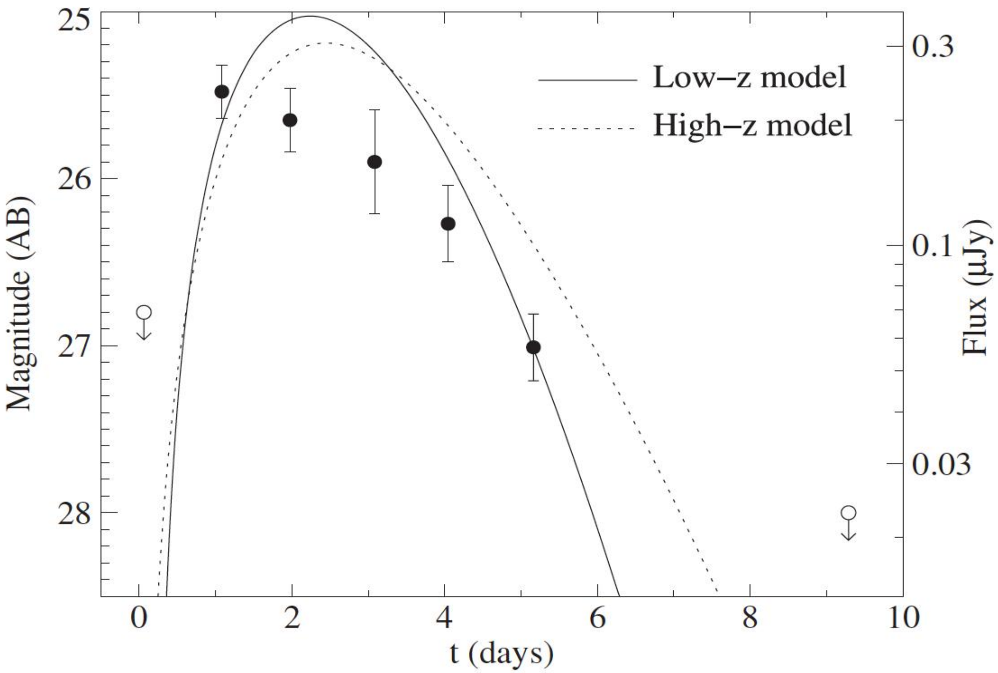
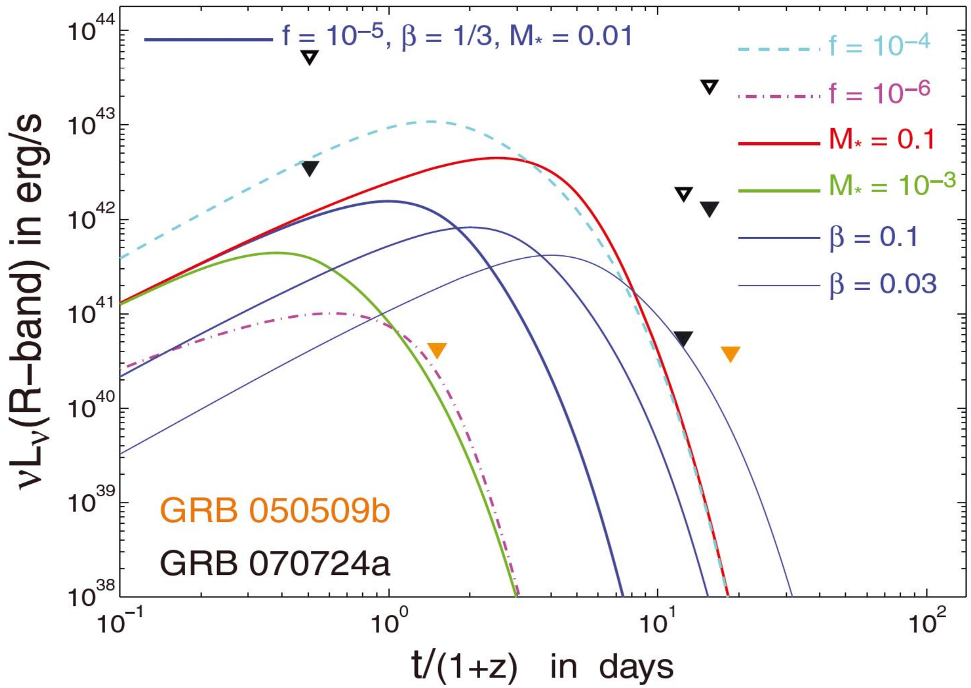


Figure 11. Two AB magnitude (Oke 1974) light-curve models for a Ni-powered "mini-SN" from GRB 080503, based on the model of Li & Paczyński (1998); Kulkarni (2005), and Metzger et al. (2008b). The solid line indicates a model at $z = 0.03$ with a ^{56}Ni mass $\approx 2 \times 10^{-3}$ $M_{\odot}$, total ejecta mass ≈ 0.4 $M_{\odot}$, and outflow velocity $\approx 0.1c$. The dotted line is for a pure Ni explosion at $z = 0.5$ with mass ≈ 0.3 $M_{\odot}$ and velocity $\approx 0.2c$. Also shown are our r-band and F606W detections and upper limits from Gemini and *HST*.

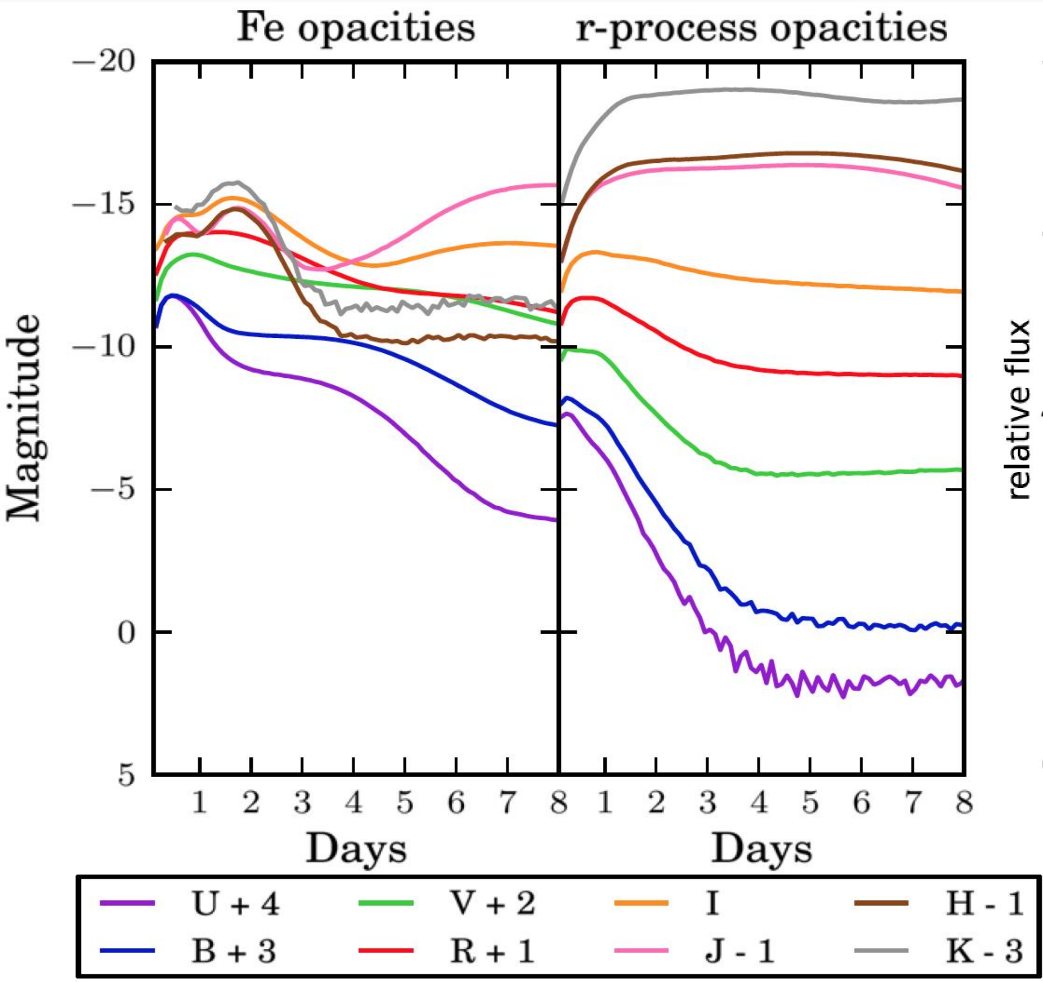
Perley et al. 2009 ApJ

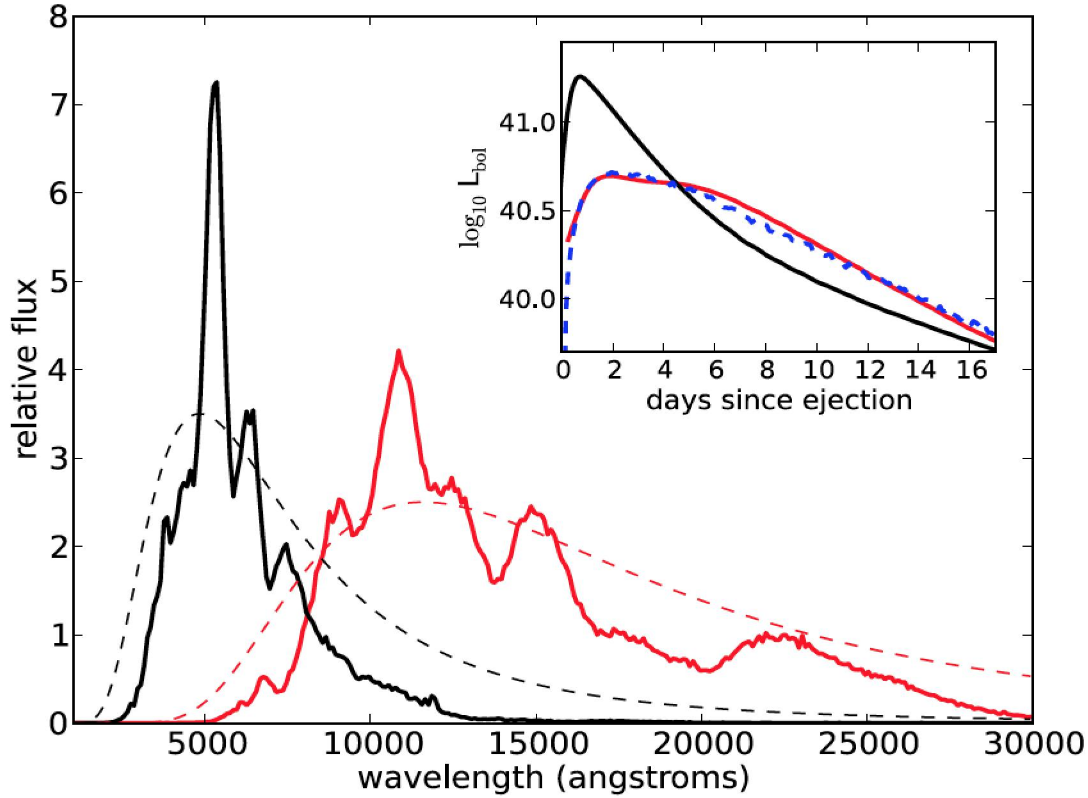


Kocevski et al. 2010 MNRAS

The opacity plays a significant role

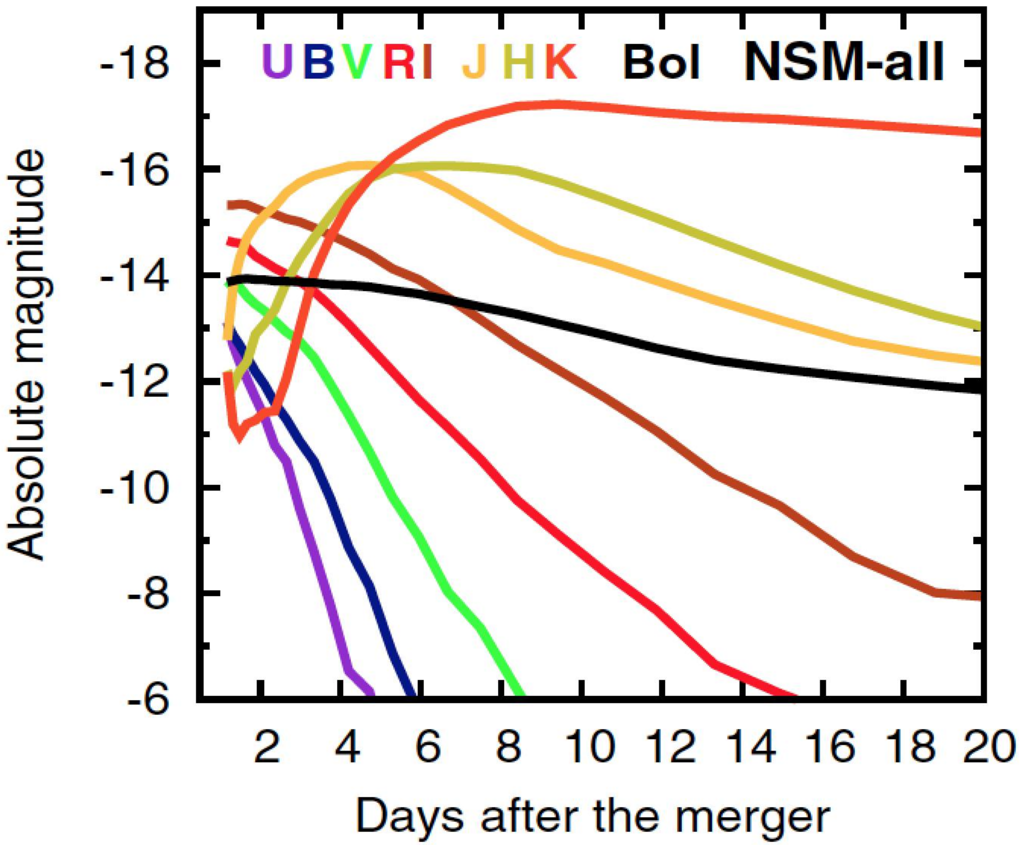
The kilonova ejecta are rich in r-process material, resulting in an opacity that is about a hundred times higher than ejecta dominated by iron group elements.

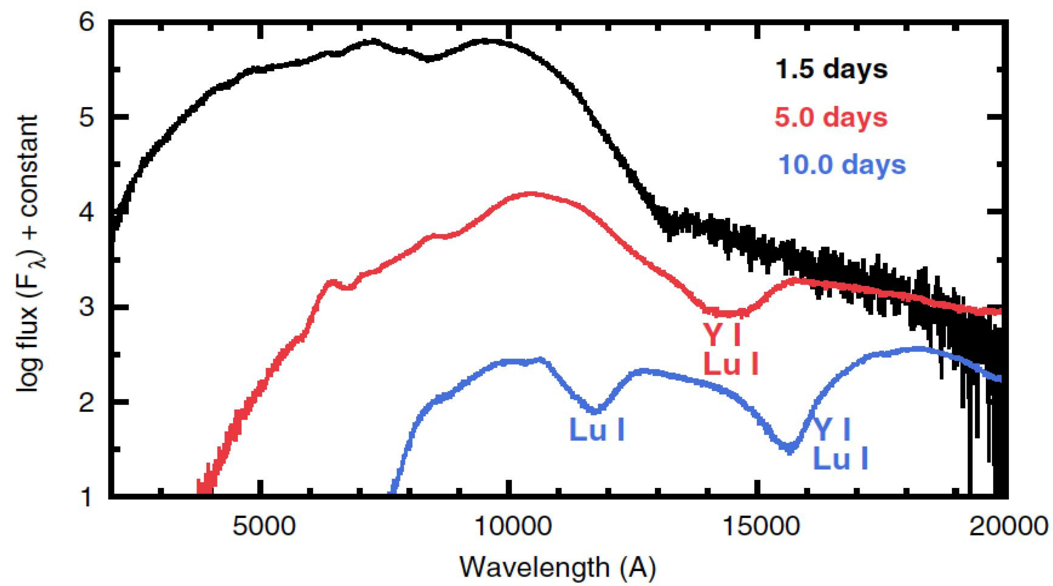




Barnes & Kasen 2013 ApJ (arXiv.1303.5787v1)

The opacity plays a significant role





Tanaka & Hotokezaka 2013 ApJ (arXiv:1306.3742)

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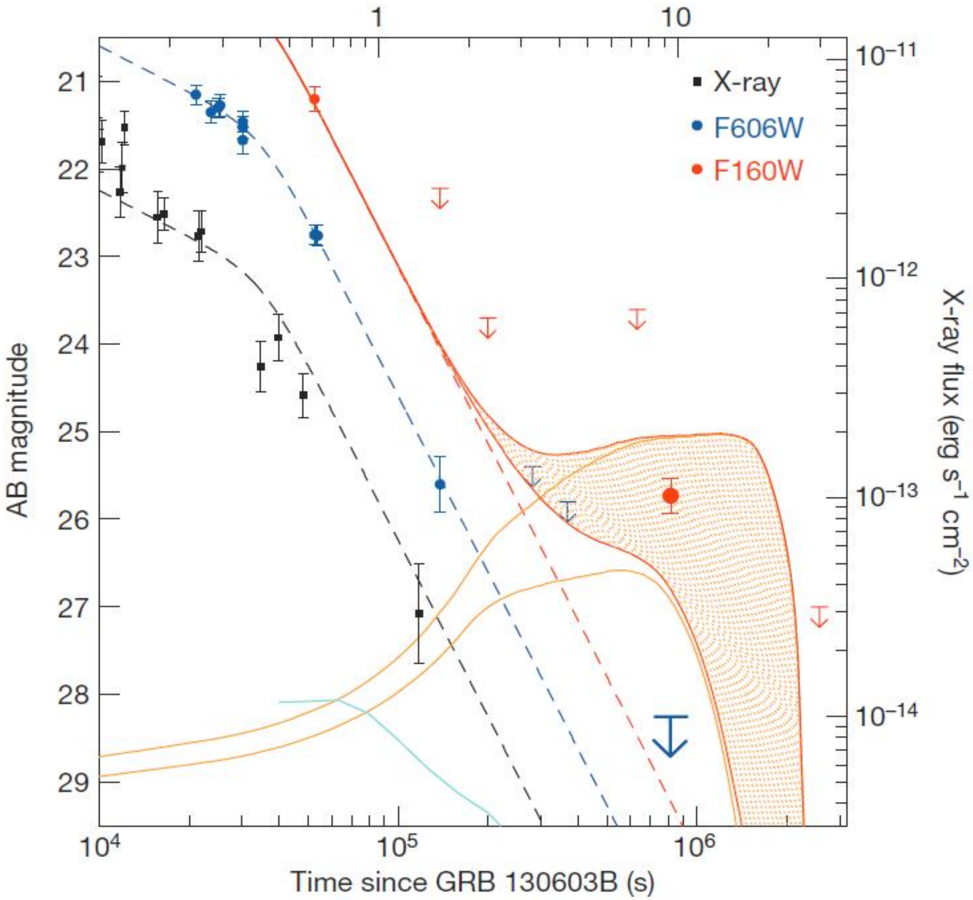
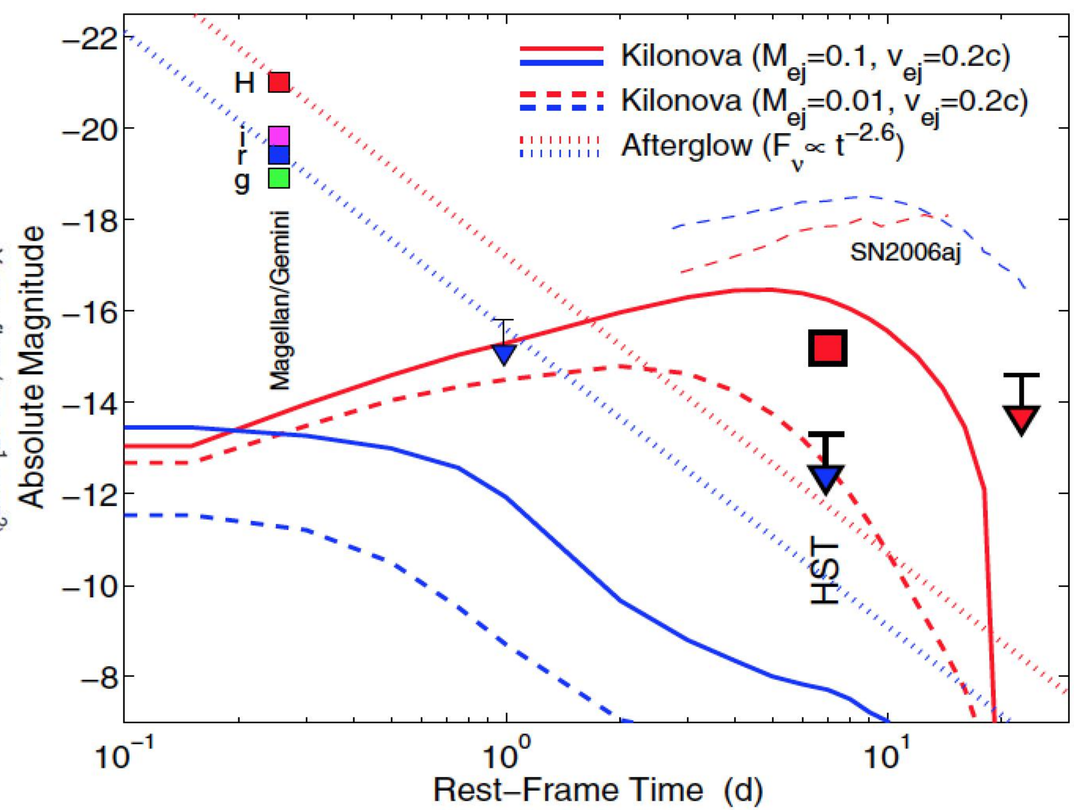
GRB 130603B: first kilonova signal

One H-band excess and 1 simultaneous r-band upper limit

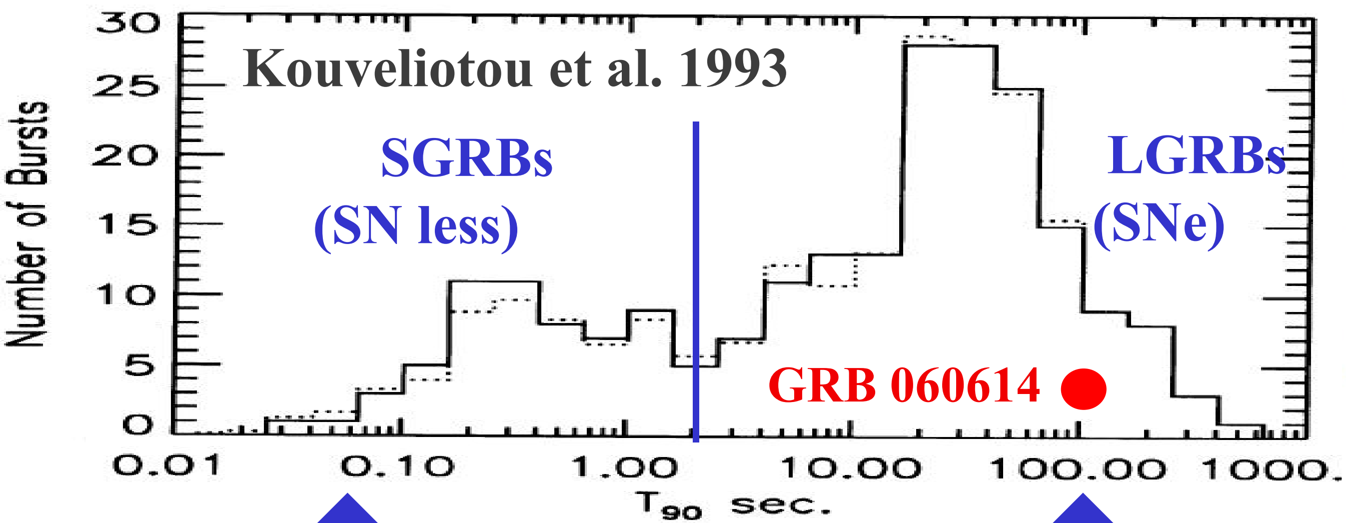


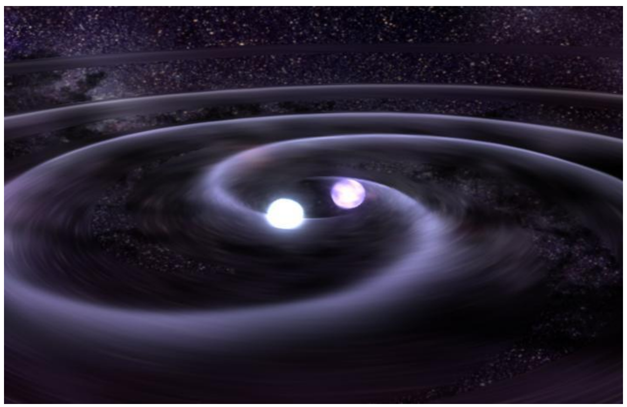
Tanvir et al. 2013, Nature

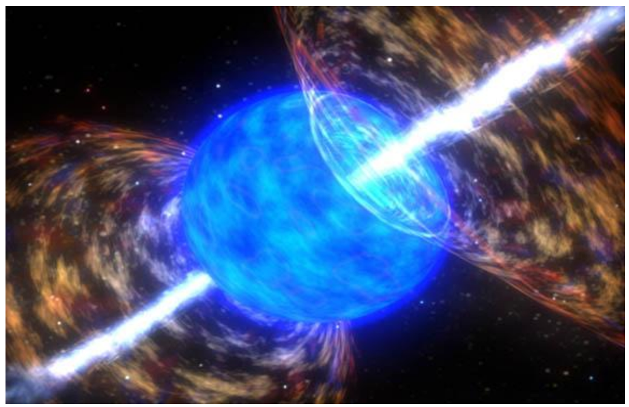


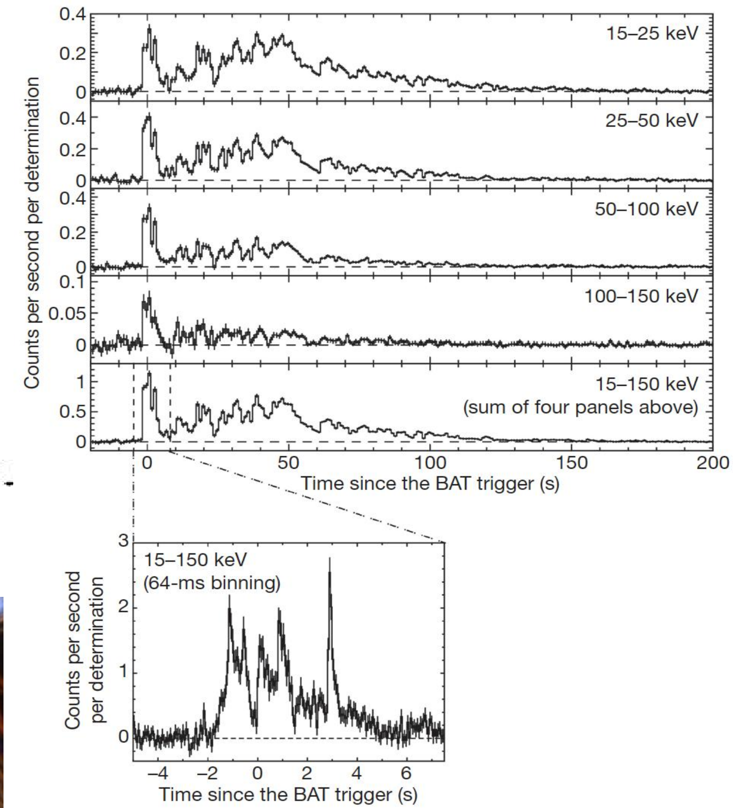
Berger et al. 2013, ApJL

GRB 060614: a long gamma ray burst







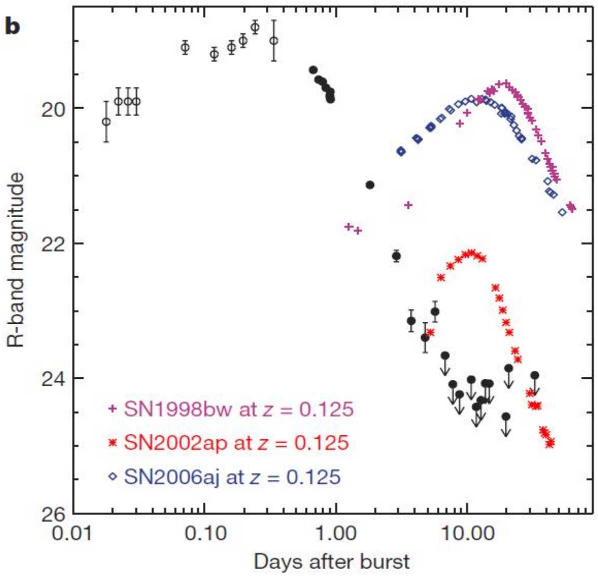


Gehrels et al. 2006 Nature

There is a second component which is weak and soft (extended emission). But the first hard spike is still longer than 5 seconds.

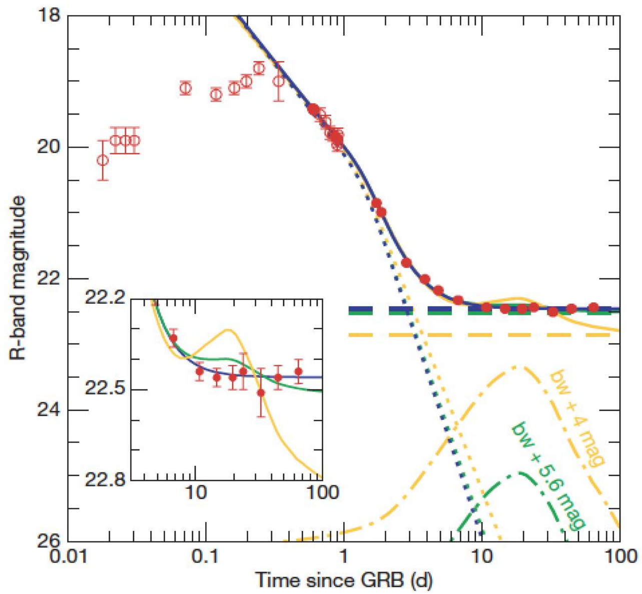
GRB 060614: no SN at all!

1.5m Danish Telescope



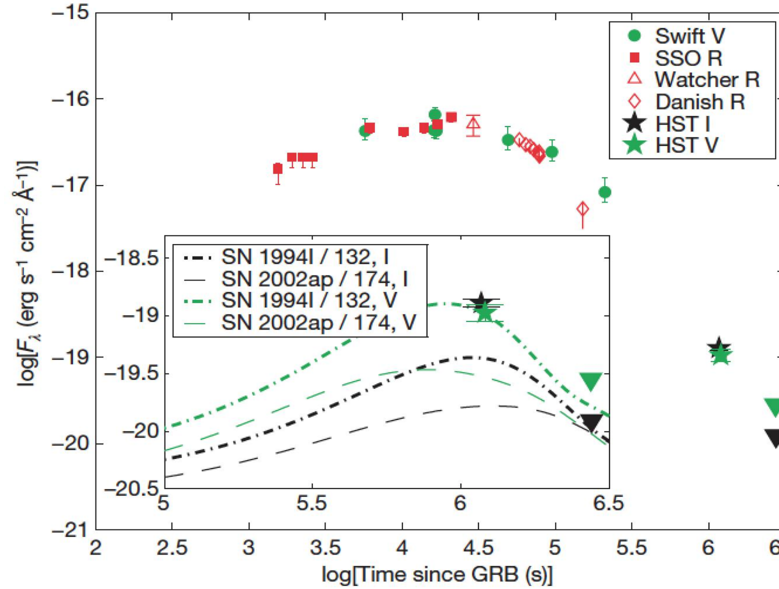
Fynbo et al. 2006 Nature

ESO VLT (8.2m 6 hours)



Della Valle et al. 2006 Nature

HST (10 hours)

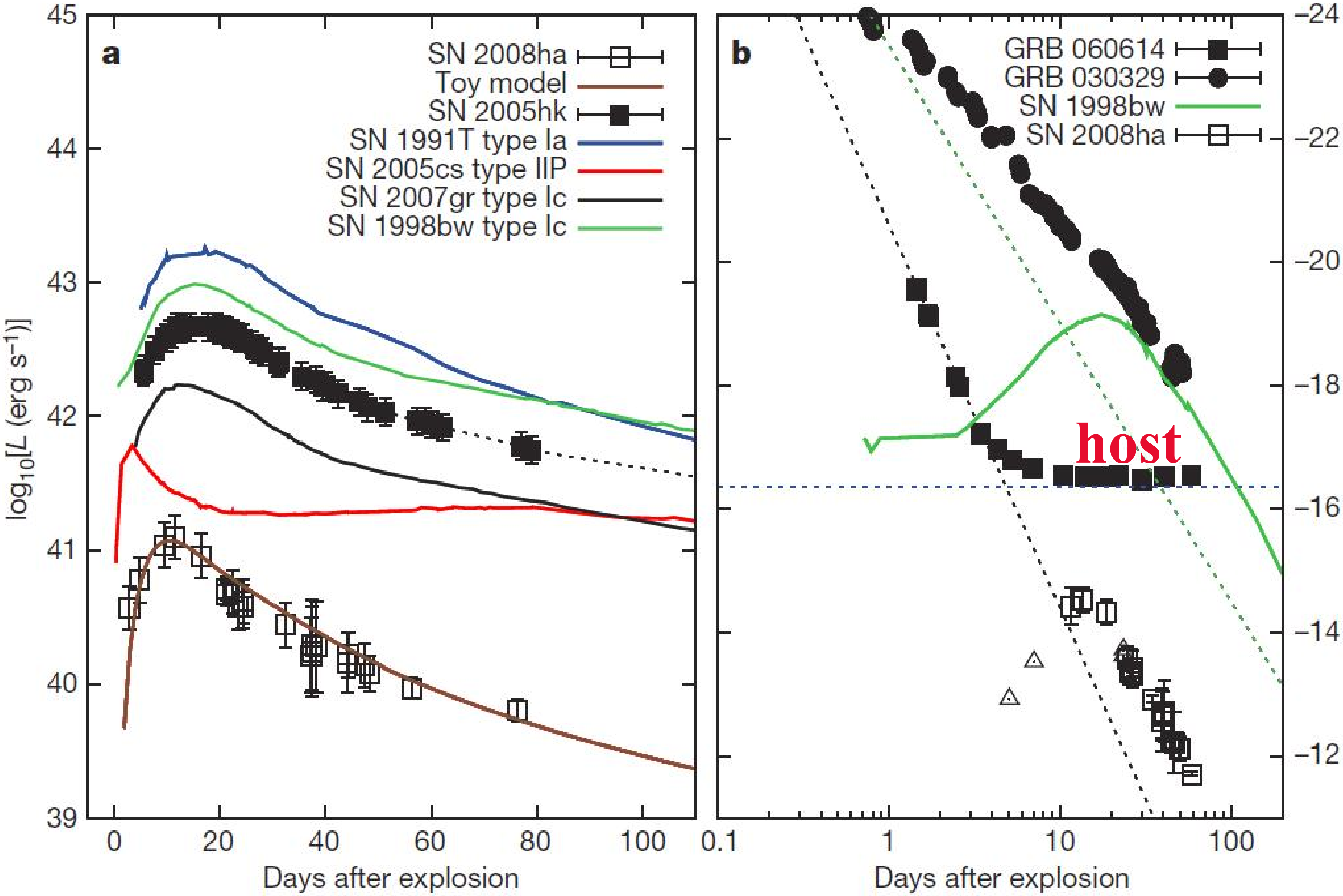


Gal-Yam et al. 2006 Nature

Long duration (102 seconds), redshift z=0.125;
But no associated bright SN. Its origin had been long debated!

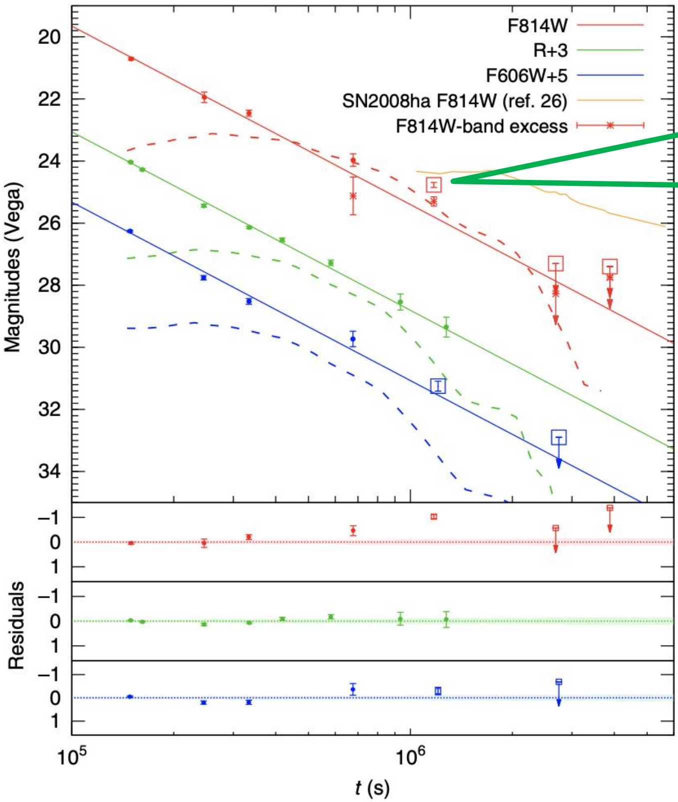
GRB 060614: is the collapsar model favored?

SN 2008ha: a low-energy core-collapse supernova



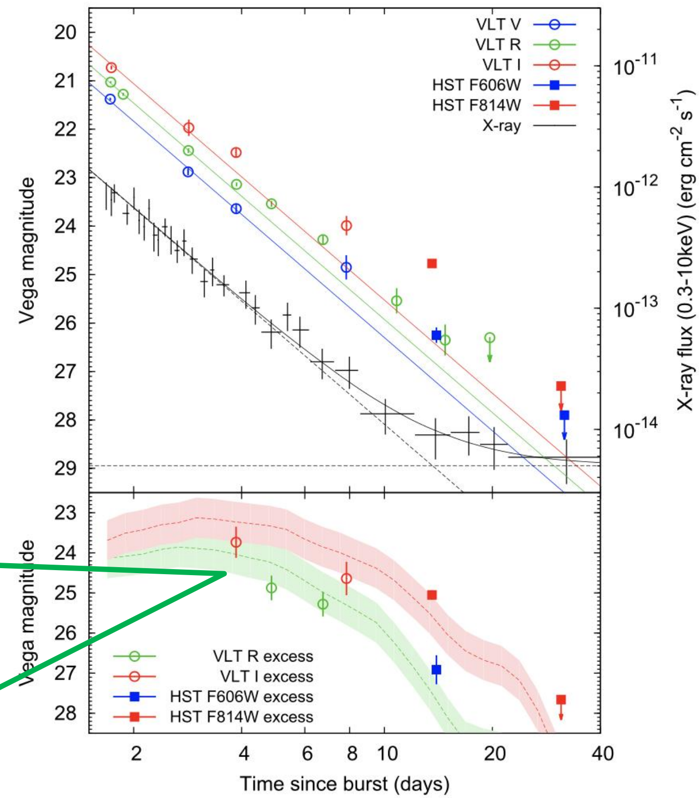
Valenti et al. 2009

GRB 060614: first kilonova in a long GRB



There is a new emission component in excess of the afterglow with a confidence level over 5 sigma.

If only the first seven data points are fitted as afterglow, R and I band lightcurve is obtained for the new component, which is consistent with a kilonova produced by the merger of NS-BH, requiring an ejecta with ~0.1 solar mass, rich in elements heavier than iron.

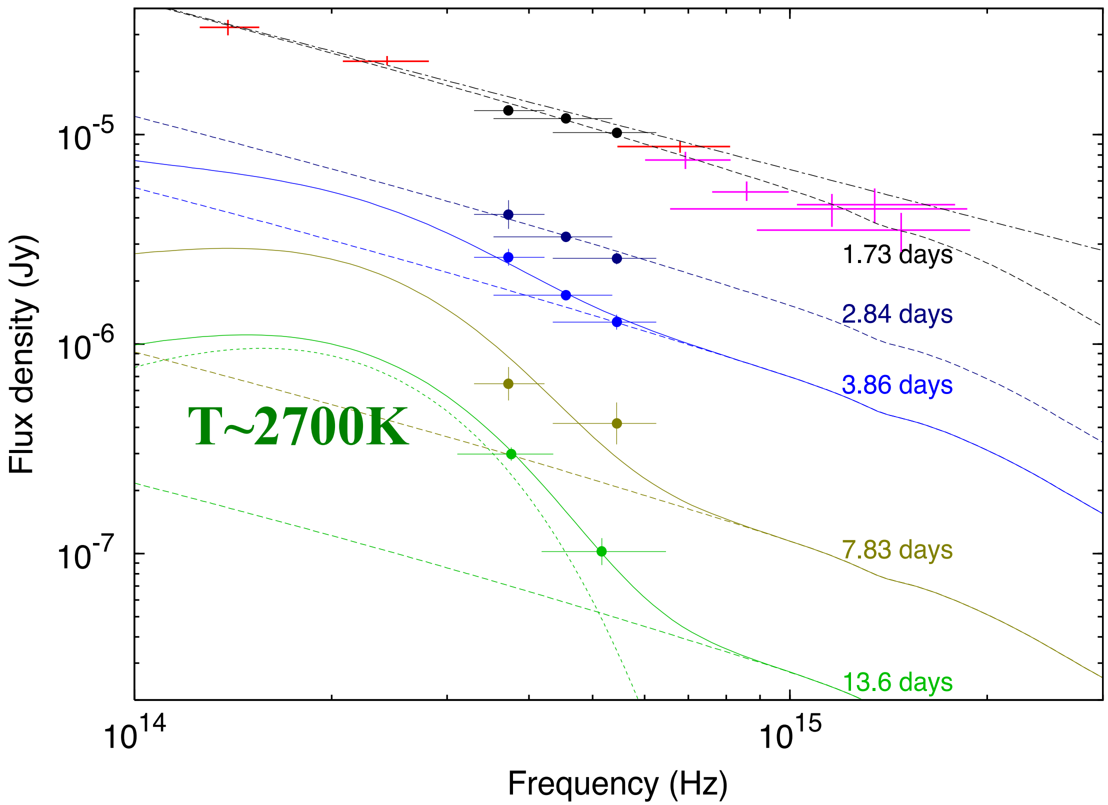


Yang, Jin* et al. 2015 NatCo

Jin et al. 2015 ApJL

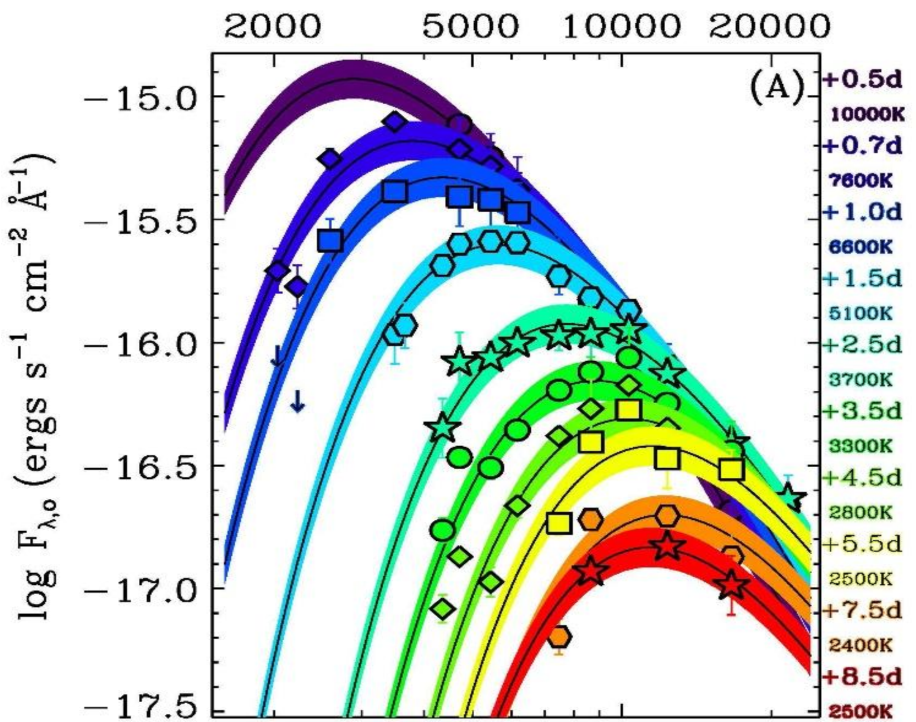
GRB060614: first estimate of kilonova temperature

GRB 060614
temperature ~2700K@13.6days



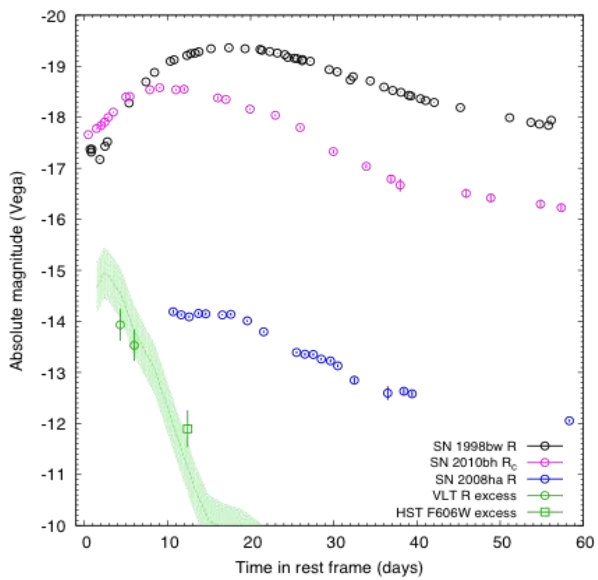
Jin et al. 2015 ApJL

AT2017gfo
late temperature ~2500K

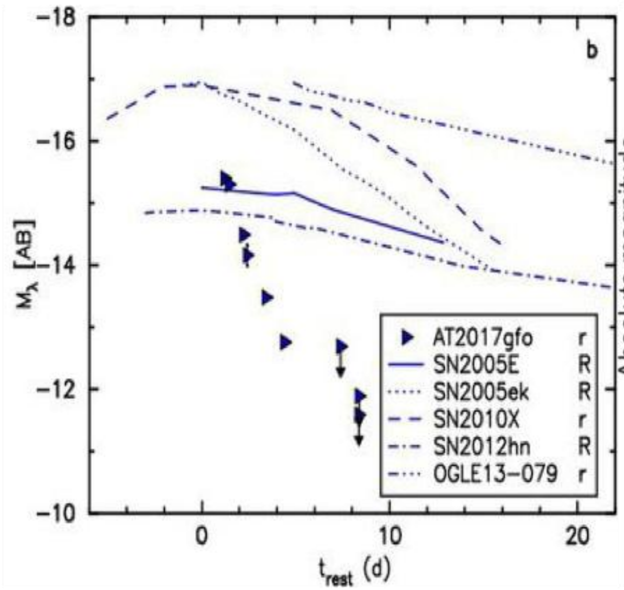


Drout et al. 2017 Science

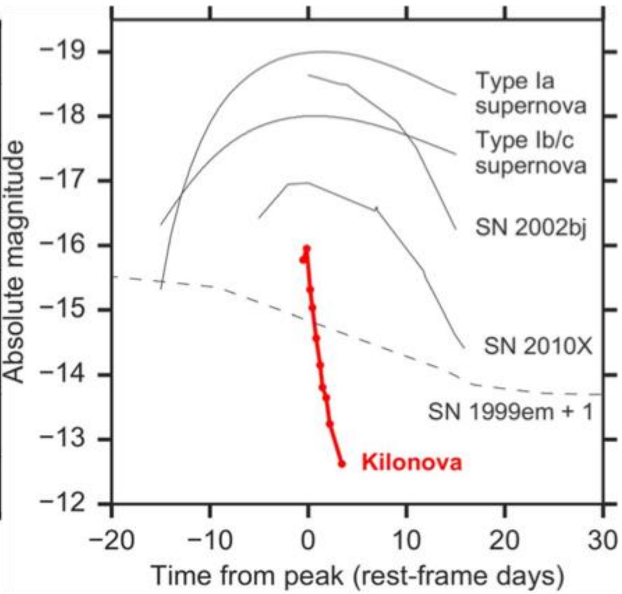
GRB 060614 vs GW170817



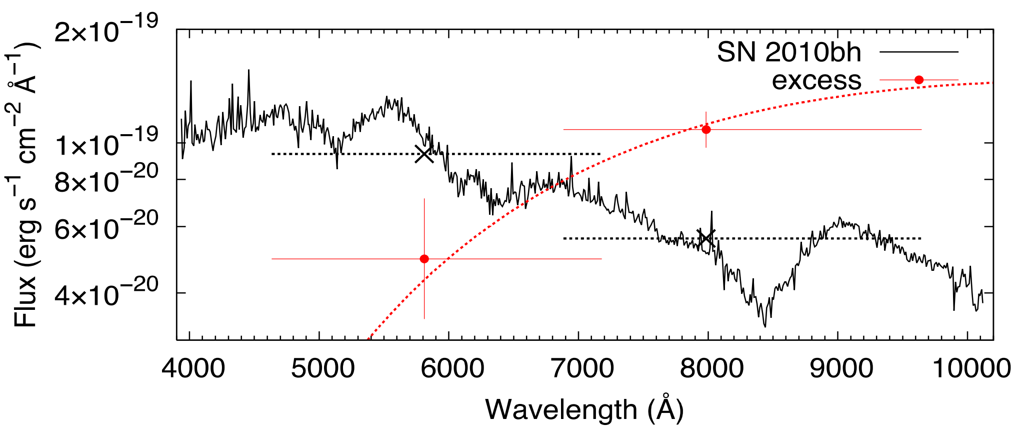
Jin et al. 2016 EPJWC



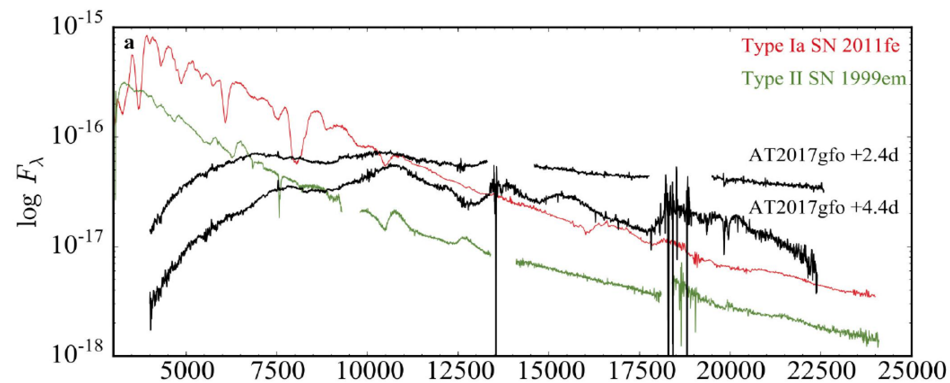
Smartt et al. 2017 Nature



Arcavi et al. 2017 Nature



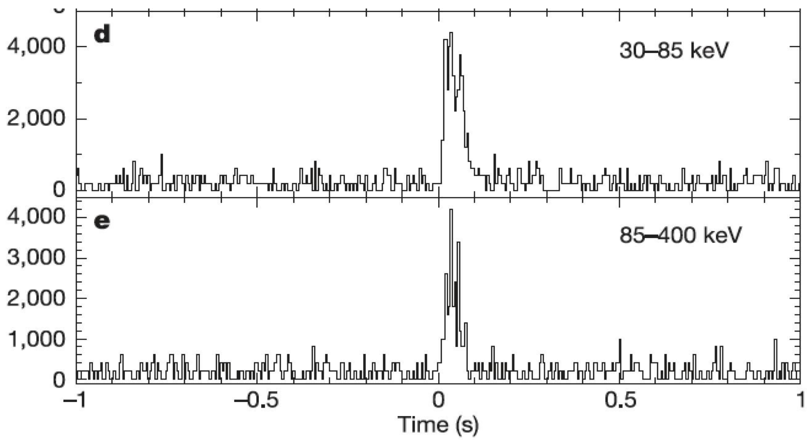
Jin et al. 2016 EPJWC (OMEG 2015)



Smartt et al. 2017 Nature

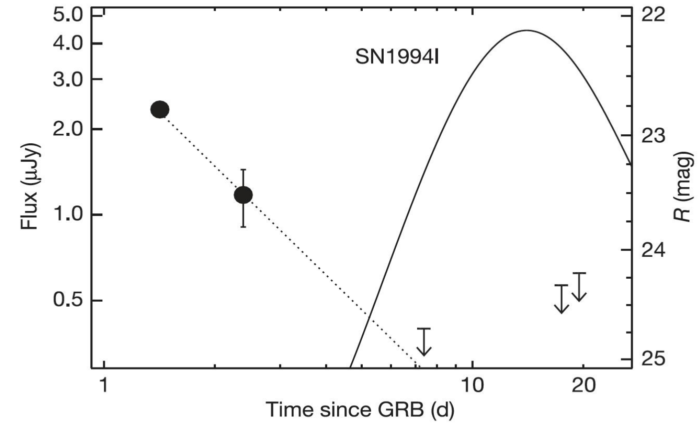
GRB 050709： first sGRB with optical afterglow

HETE 2



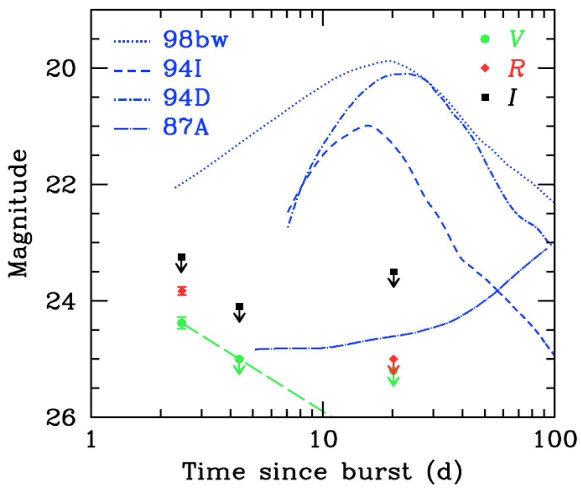
Villasenor et al. 2005

Danish 1.5m



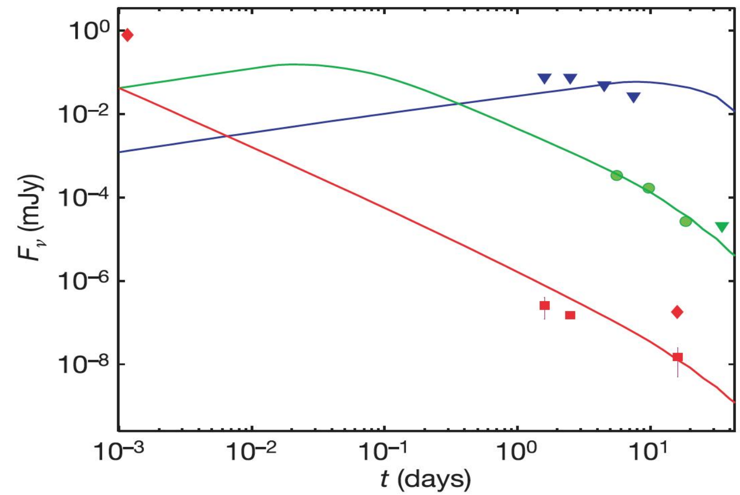
Hjorth et al. 2005

VLT



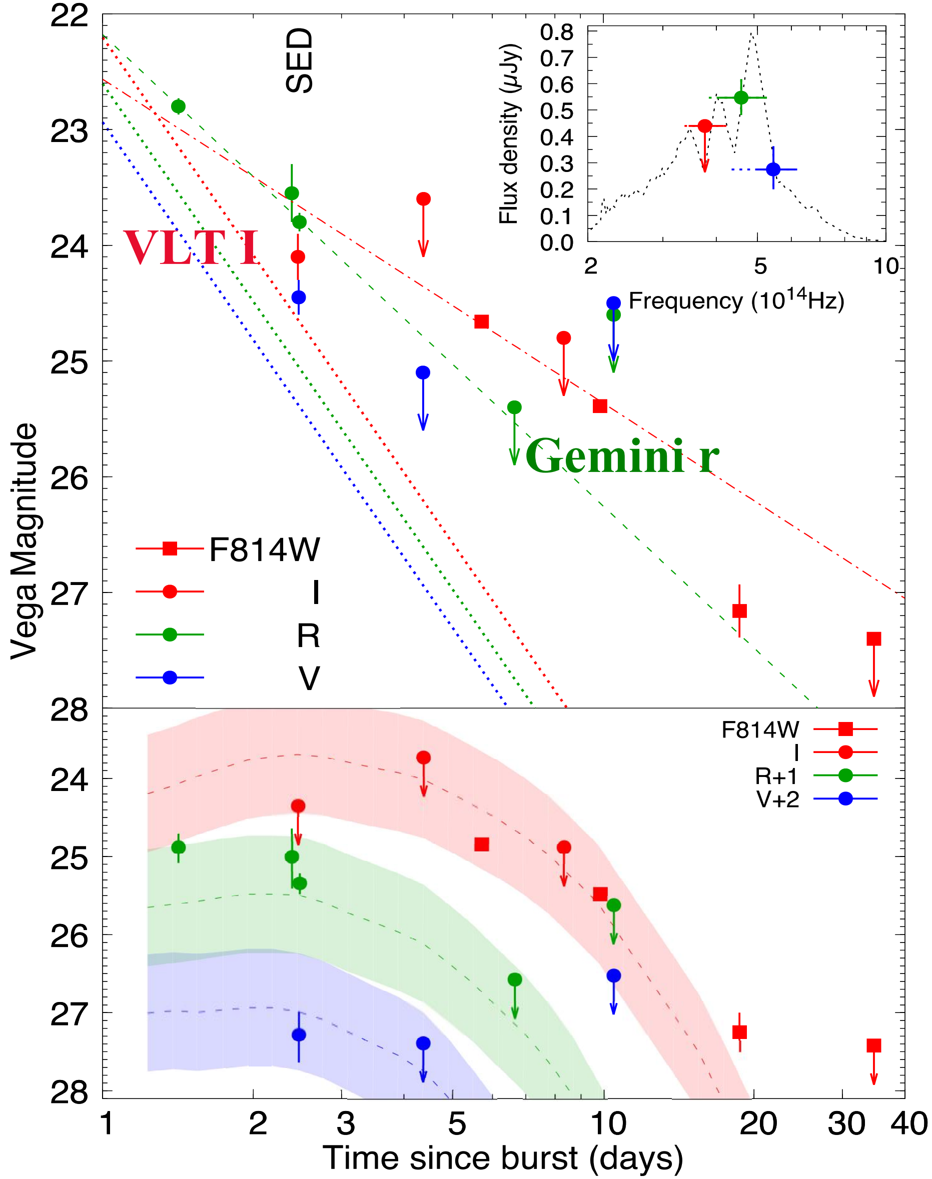
Covino et al 2005

HST

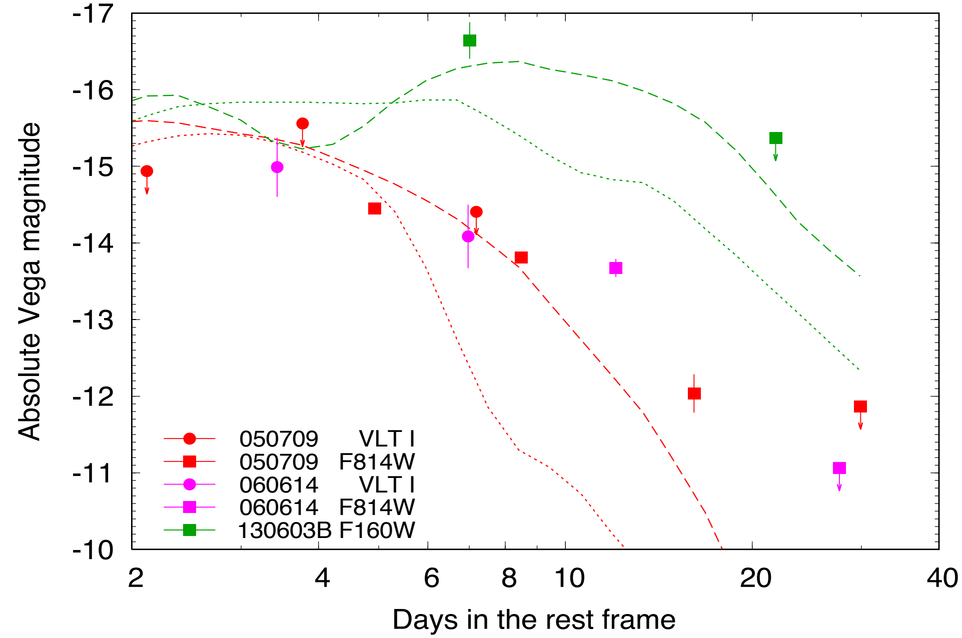


Fox et al. 2005

GRB050709: afterglow is dominated by a KN



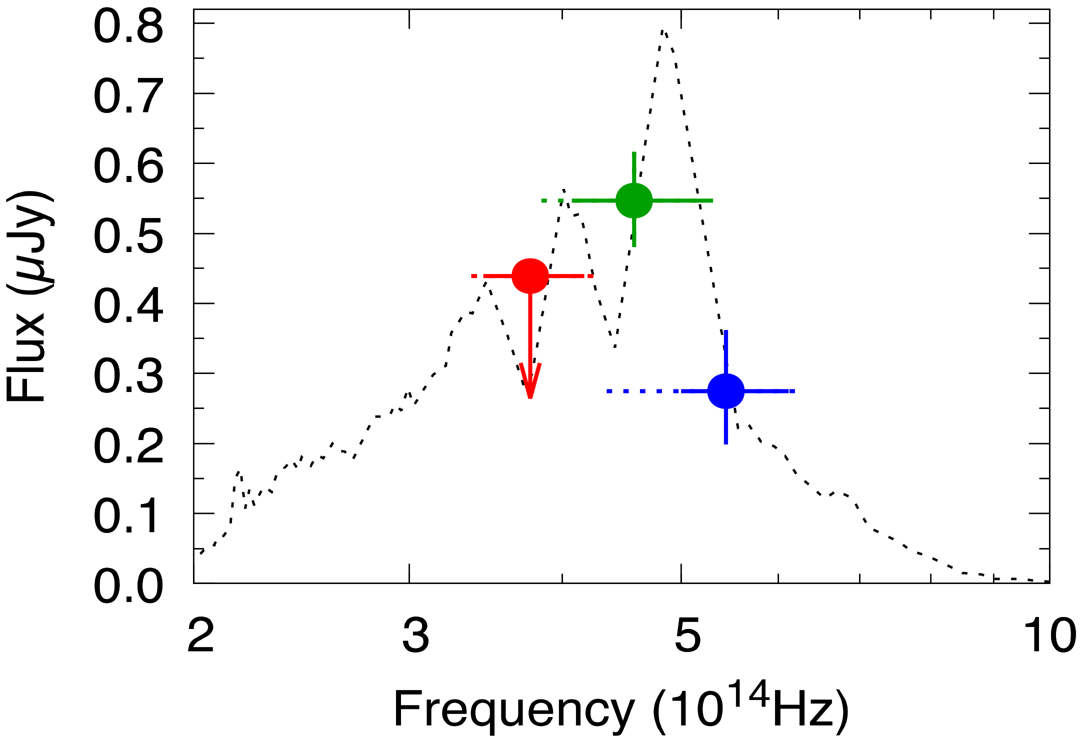
Jin et al. 2016 NatCo

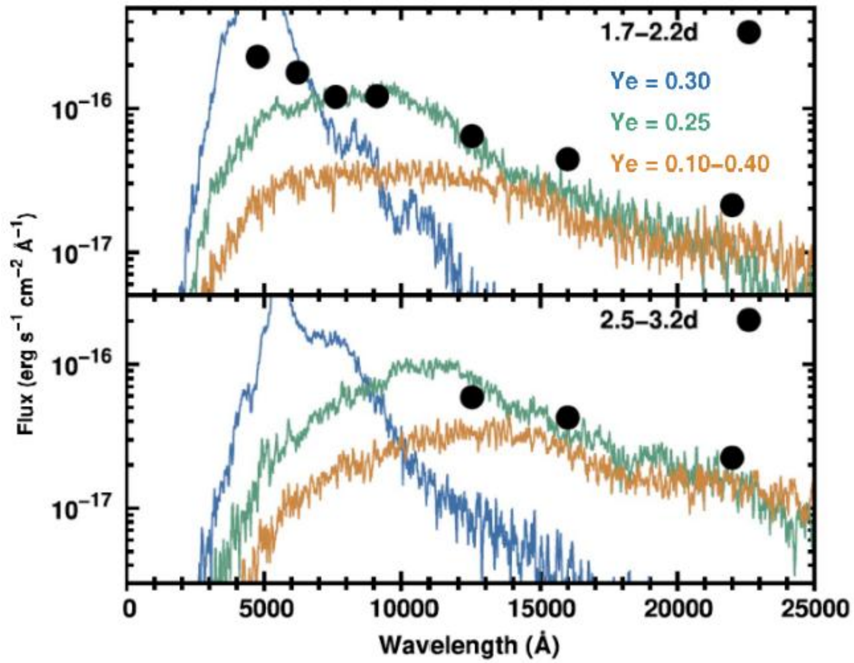


Left: The decline behaviors of I/F814W and R are significantly different! Right: GRB 050709 I/F814W band lightcurve is similar to the kilonova in GRB 060614.

A kilonova signal displays in the first sGRB with detected optical counterpart!

First line like signal in kilonova SED





VLT 2.5 SED around 2.5 days after burst, compared with the kilonova spectrum dominate lanthanide group elements.

Broad-line-like spectral structures appear in kilonova numerical simulation.

Jin et al. 2016 NatCo

Tanaka et al. 2017

sGRBs - kilonovae connection is ubiquitous

ARTICLE

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OPEN

The Macronova in GRB 050709 and the GRB-macronova connection

Zhi-Ping Jin[1], Kenta Hotokezaka[2], Xiang Li[1,3], Masaomi Tanaka[4], Paolo D'Avanzo[5], Yi-Zhong Fan[1,6], Stefano Covino[5], Da-Ming Wei[1] & Tsvi Piran[2]

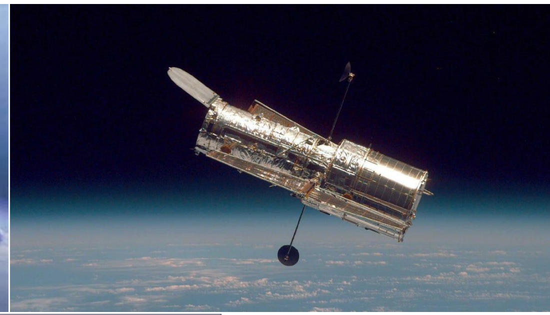
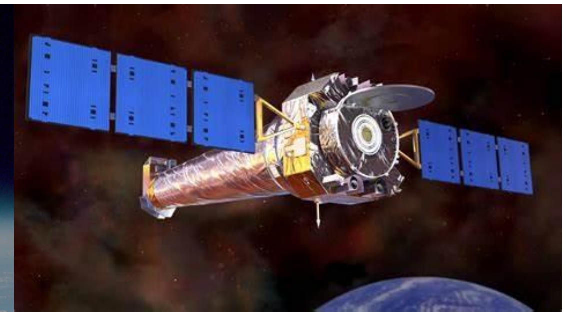
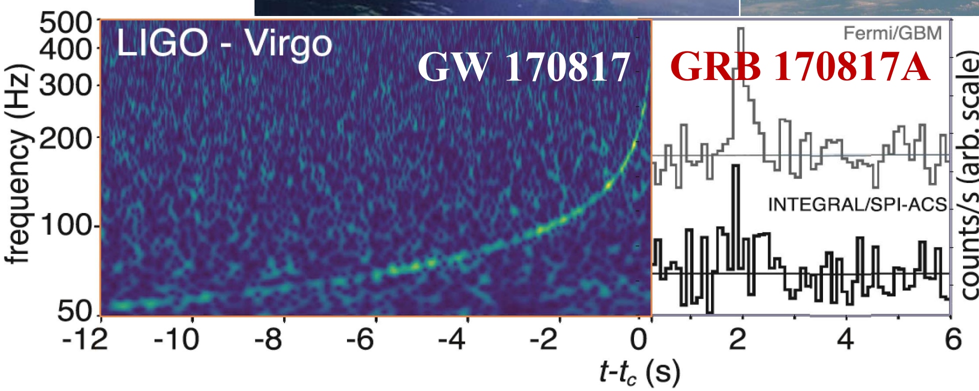
GRB 050709 was the first short Gamma-ray Burst (sGRB) with an identified optical counterpart. Here we report a reanalysis of the publicly available data of this event and the discovery of a Li-Paczynski macronova/kilonova that dominates the optical/infrared signal at $t > 2.5$ days. Such a signal would arise from 0.05 $M_{\odot}$ r-process material launched by a compact binary merger. The implied mass ejection supports the suggestion that compact binary mergers are significant and possibly main sites of heavy r-process nucleosynthesis. Furthermore, we have reanalysed all afterglow data from nearby short and hybrid GRBs (shGRBs). A statistical study of shGRB/macronova connection reveals that macronova may have taken place in all these GRBs, although the fraction as low as 0.18 cannot be ruled out. The identification of two of the three macronova candidates in the *I*-band implies a more promising detection prospect for ground-based surveys.

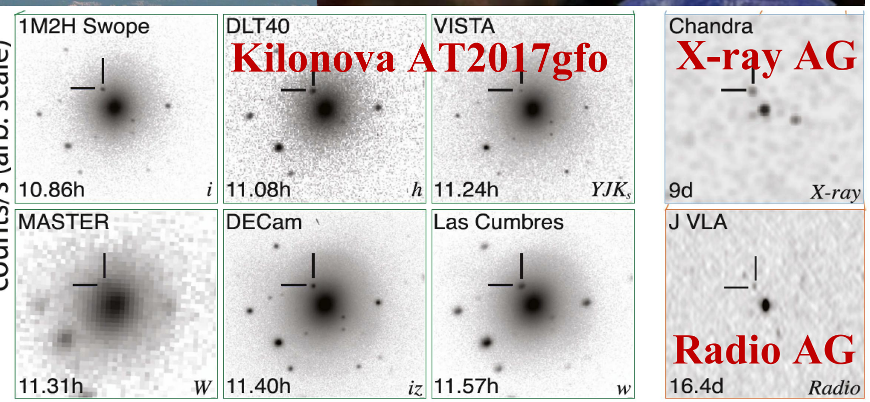
A statistical study of the sGRB/kilonova connection suggests that the kilonovae should be ubiquitous in sGRBs.

The non-identification of the signal in other events is likely due to the lack of enough data.

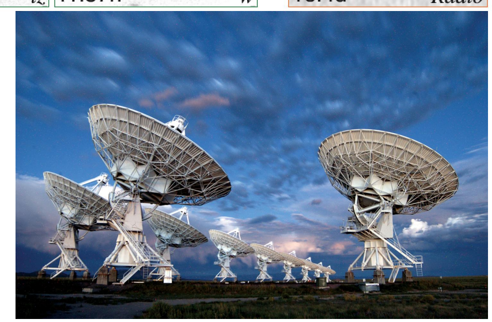
The first GW event from the merger of a BNS

2017.8.17, LIGO successfully detected a gravitational wave event from a binary neutron star merger for the first time, and within the following one to two weeks, many astronomical facilities around the world aimed their telescopes at the same target.

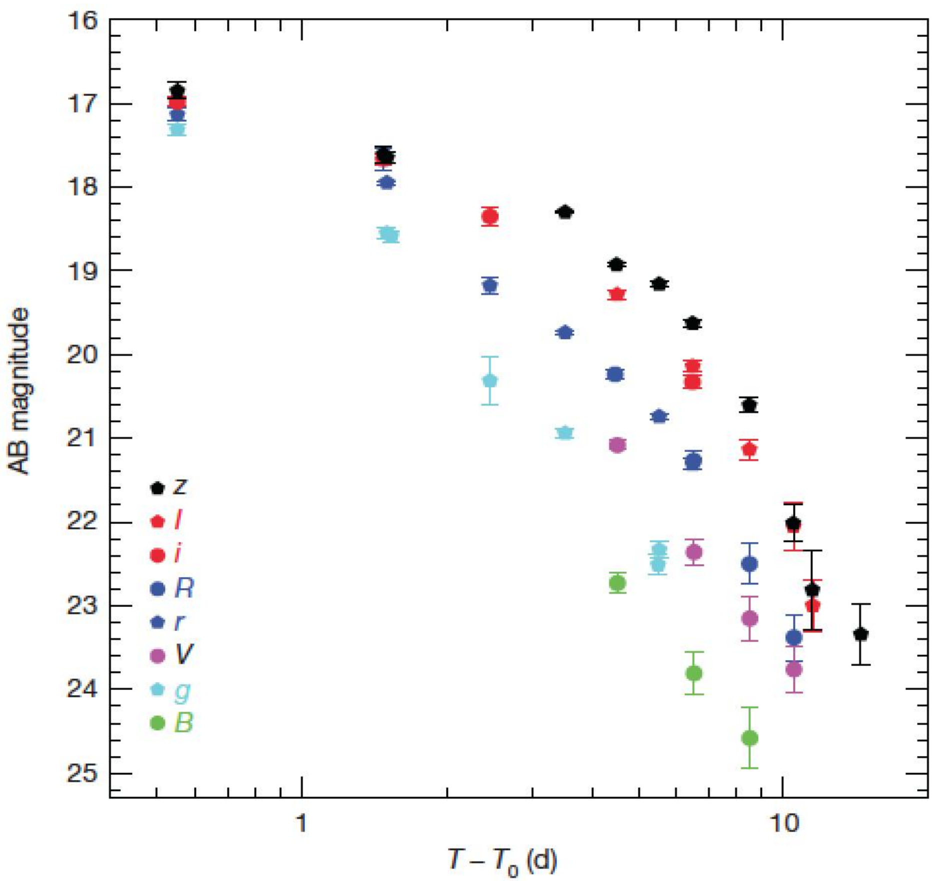


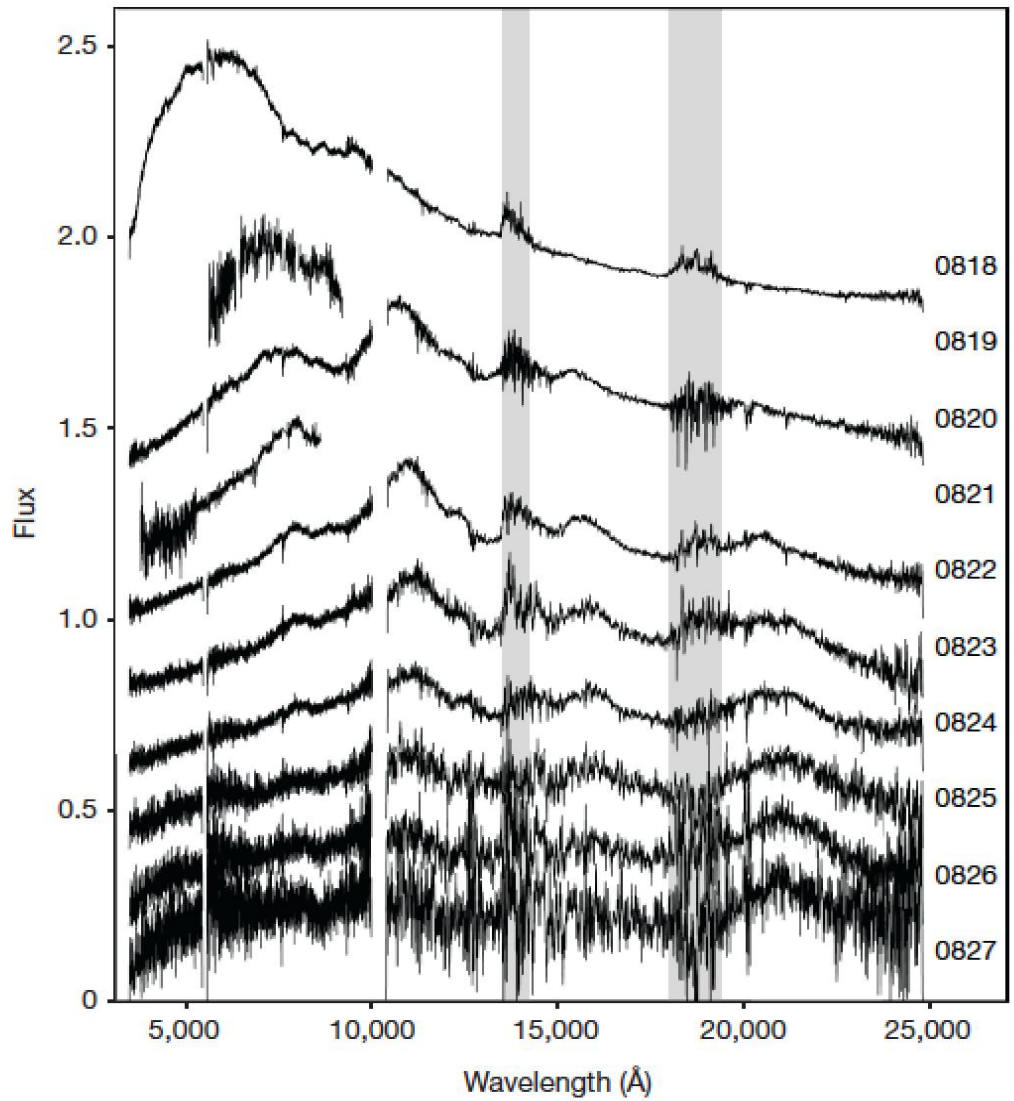




Kilonova linked to GW 170817/GRB 170817A

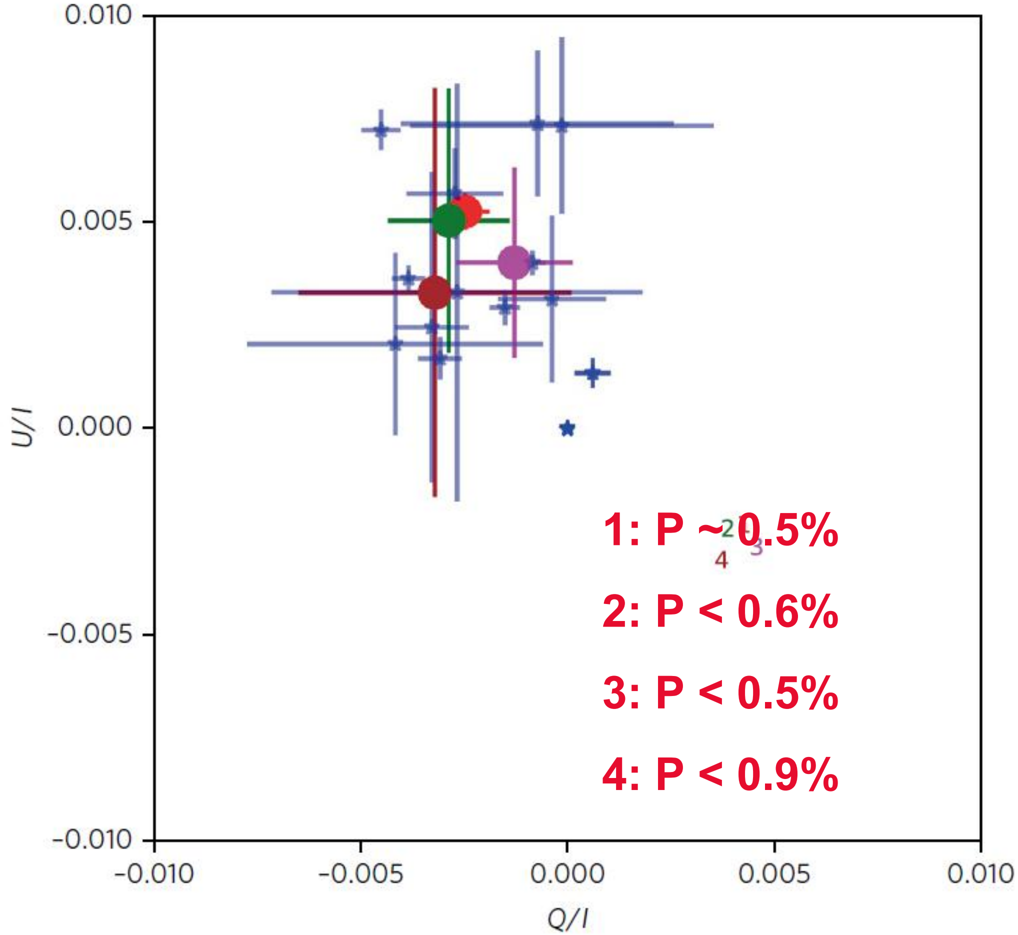
Dozens of remarkable observation papers!



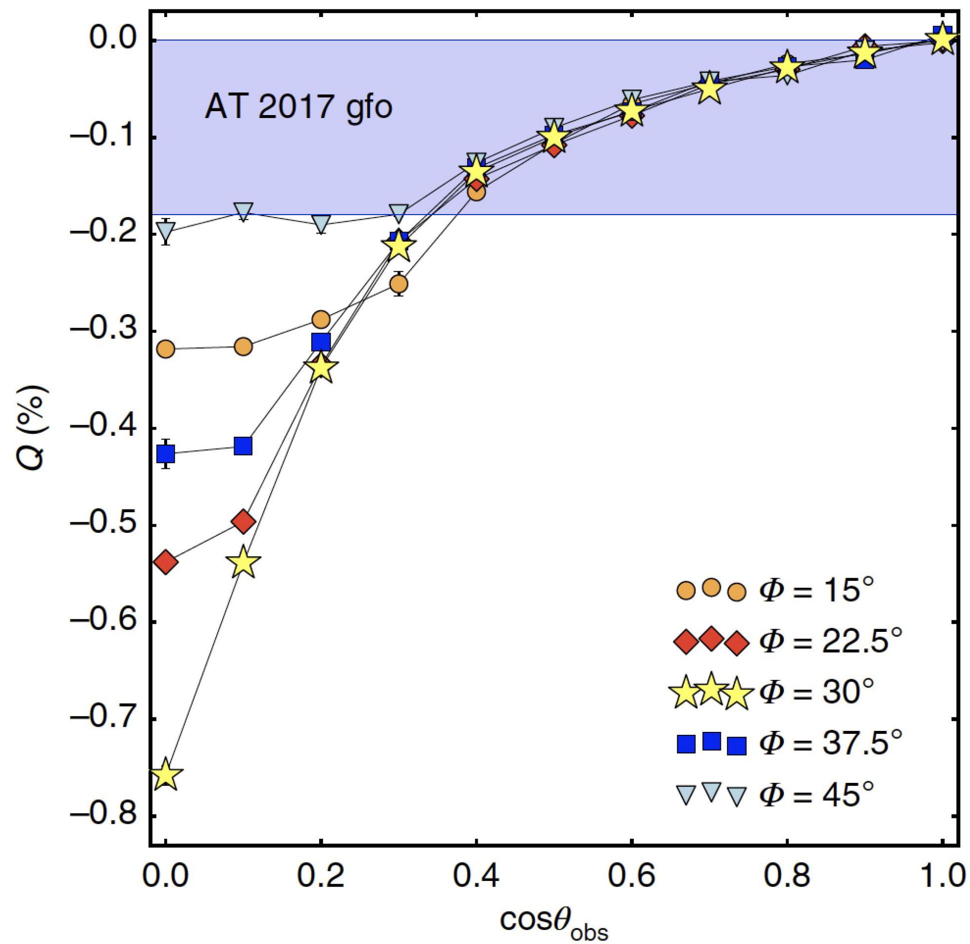


Pian, D'Avanzo et al. 2017 Nature

The first polarization measurement for kilonova



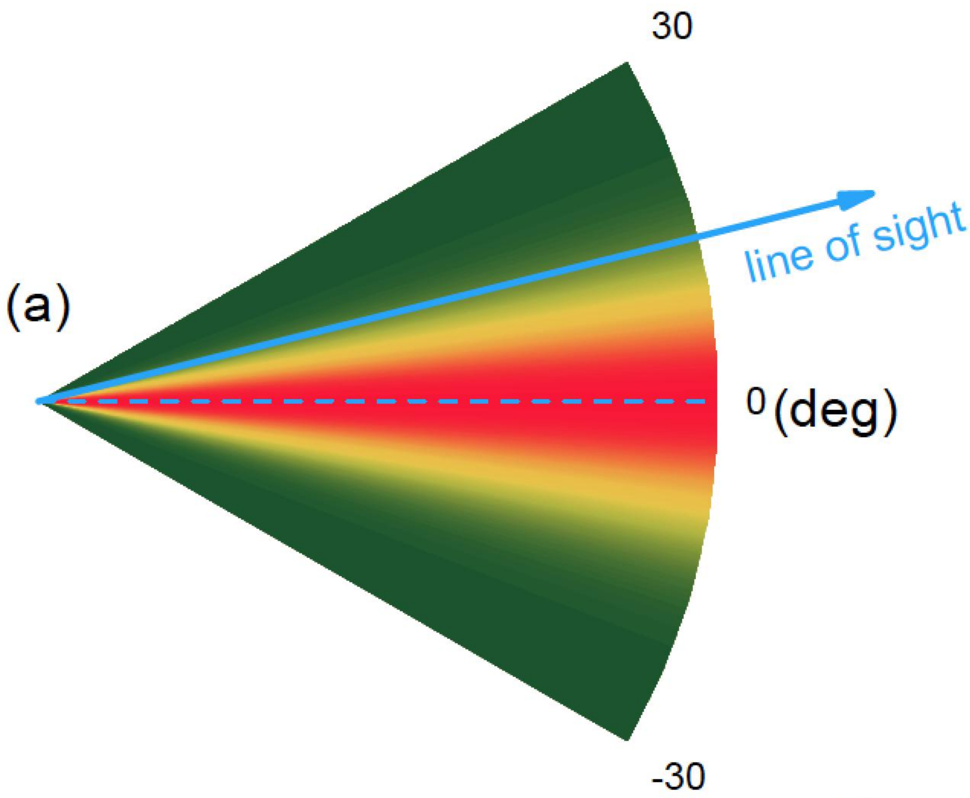
Covino et al. 2017 Nat. Astron.

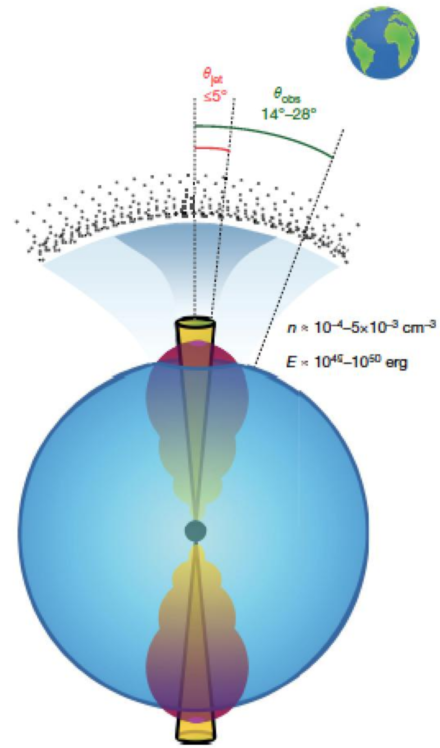


Bulla et al. 2019 Nat. Astron.

The polarization of AT2017gfo (circles) is essentially indistinguishable from that shown by field stars (blue stars).

GRB 170817A: structured jet

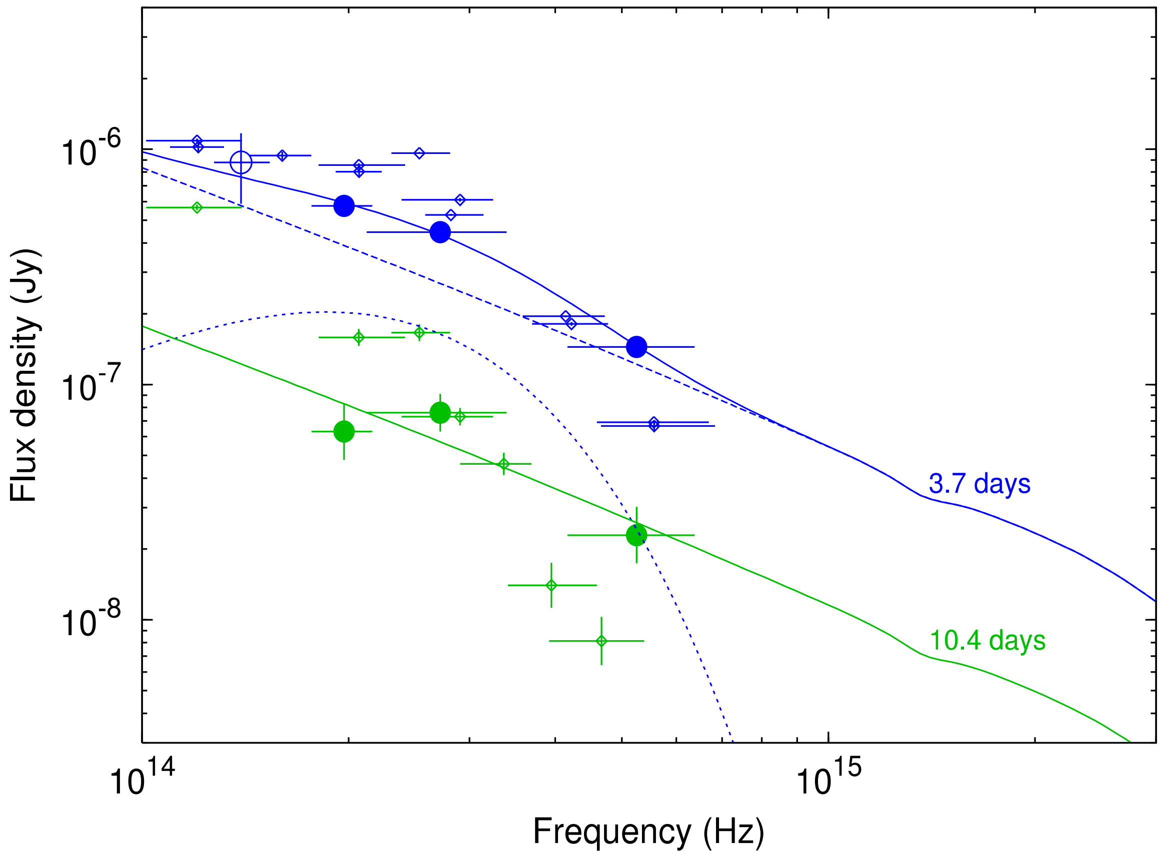




Jin et al. 2018 (arXiv:1708.07008 2017.08.23) Mooley et al. 2018 Nature

We were the first to point out that structured jet flow can significantly increase the correlation rate of short bursts and gravitational wave events from 1% to 10%.

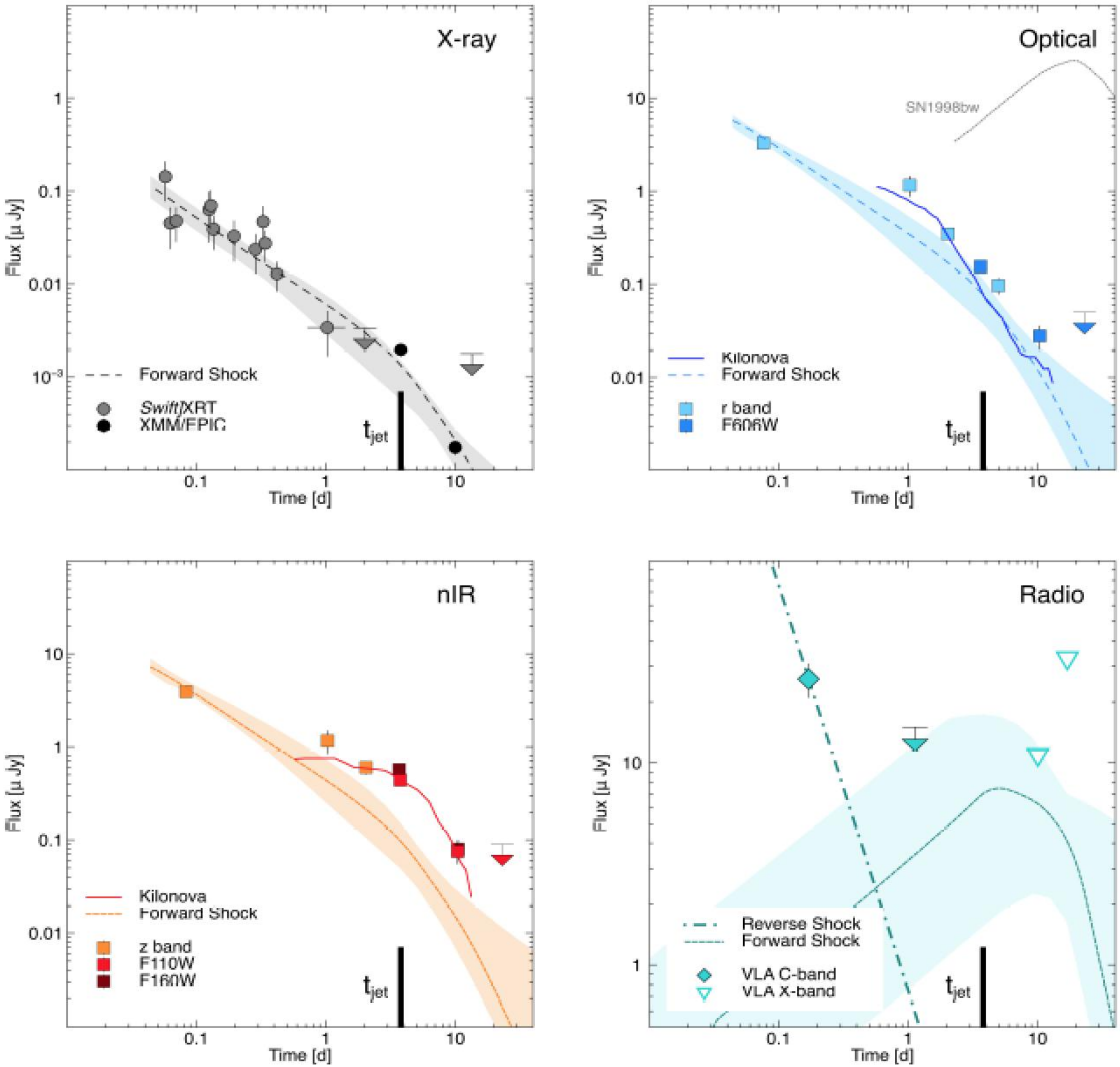
GRB 160821B



Jin et al 2018 ApJ (arXiv:1708.07008)

The HST measured data at t ~3.7 days after the trigger can be interpreted as the superposition of a power-law afterglow component and a thermal-like component at a temperature of~ 3000 K.

GRB 160821B

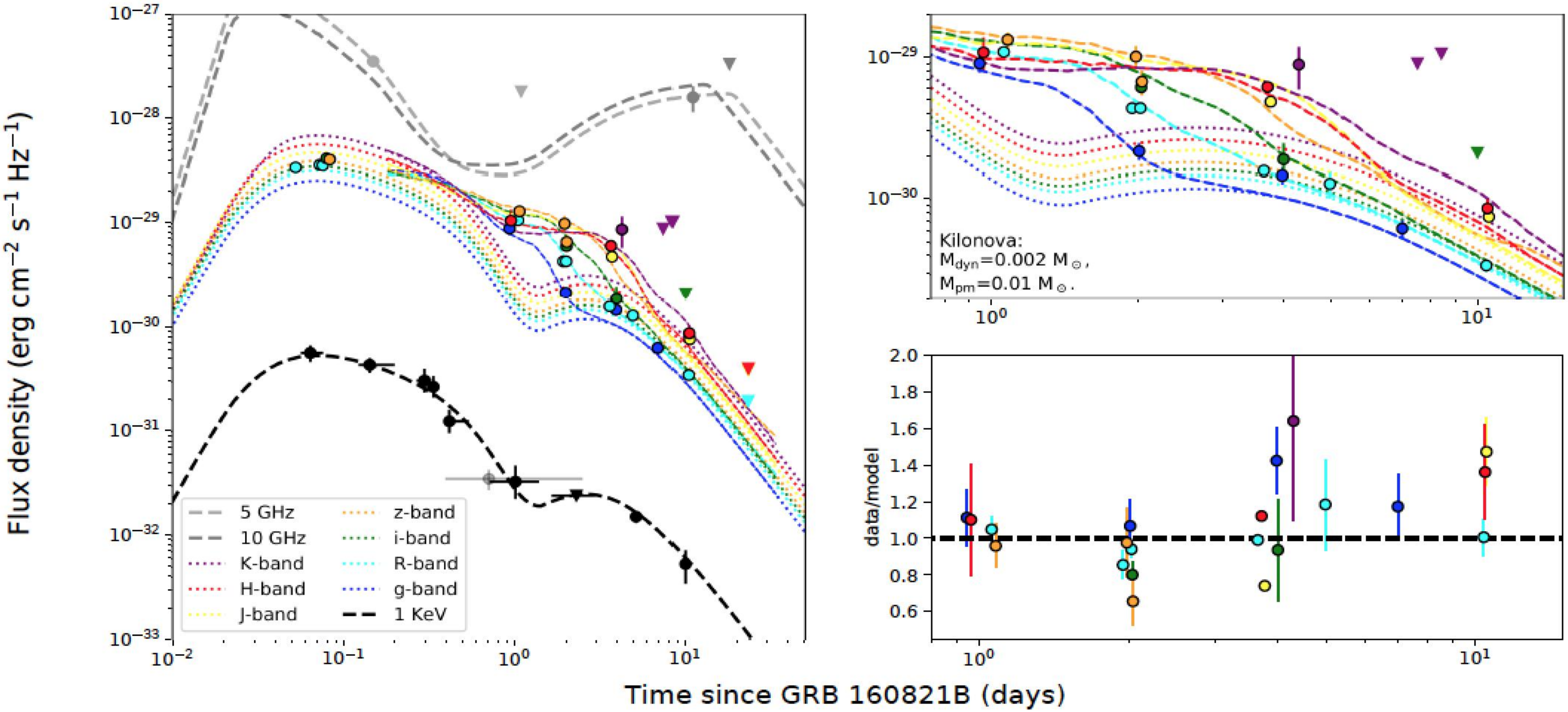


More X-ray data from XMM-Newton.

Optical NIR in excess compared with afterglow model.

Troja et al. 2019

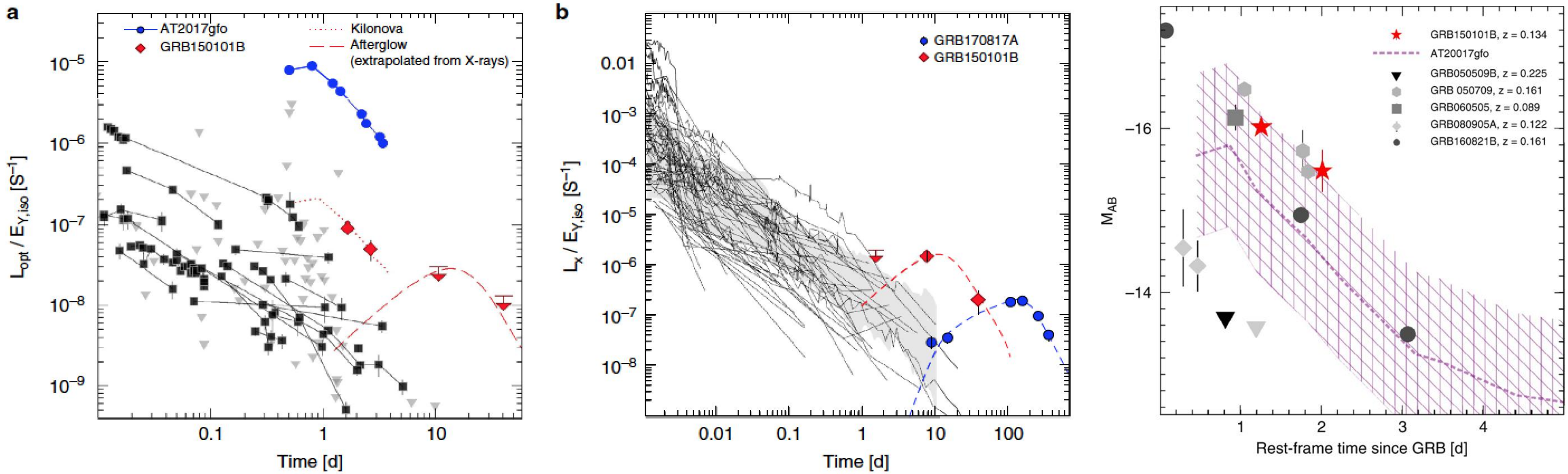
GRB 160821B



Lamb et al. 2019

Similar as Troja et al, but more complex afterglow model.

GRB 150101B



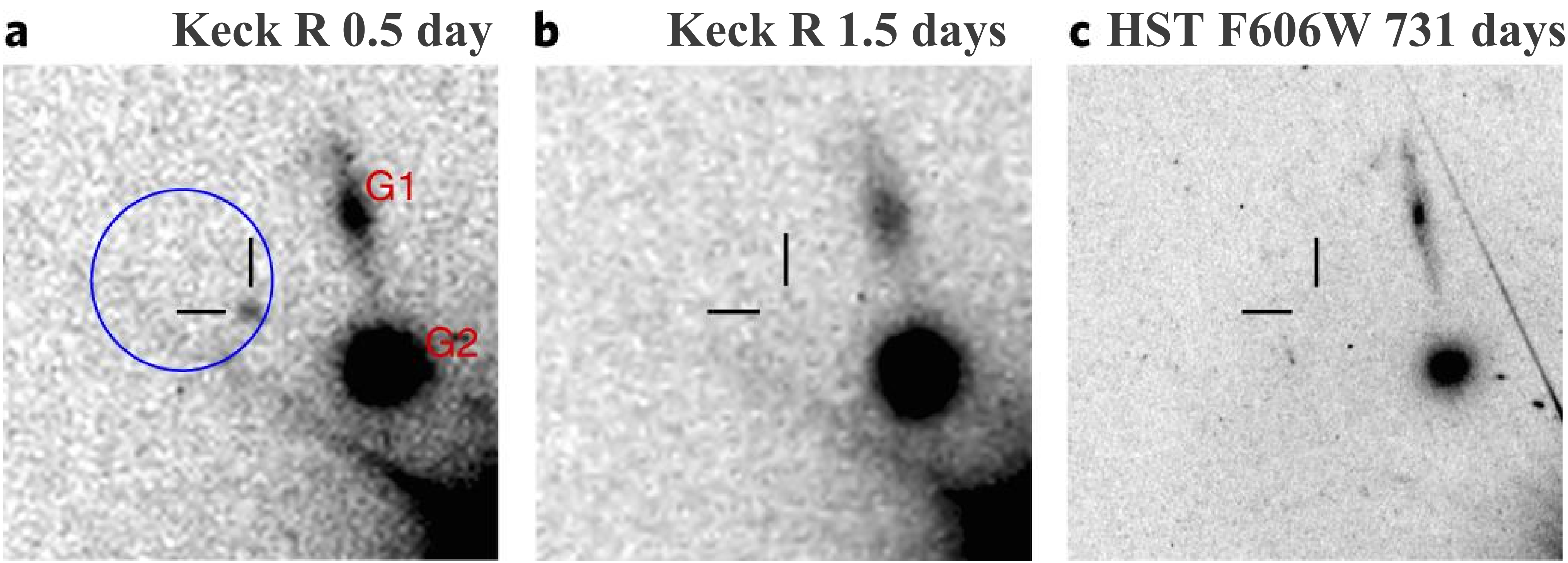
bright kilonova. Interestingly, its brightness and decay rate closely resemble the candidate kilonova from GRB050709[40]. By assum-

Troja et al. 2018

X-ray: a rising afterglow from either an off-axis jet or a cocoon.

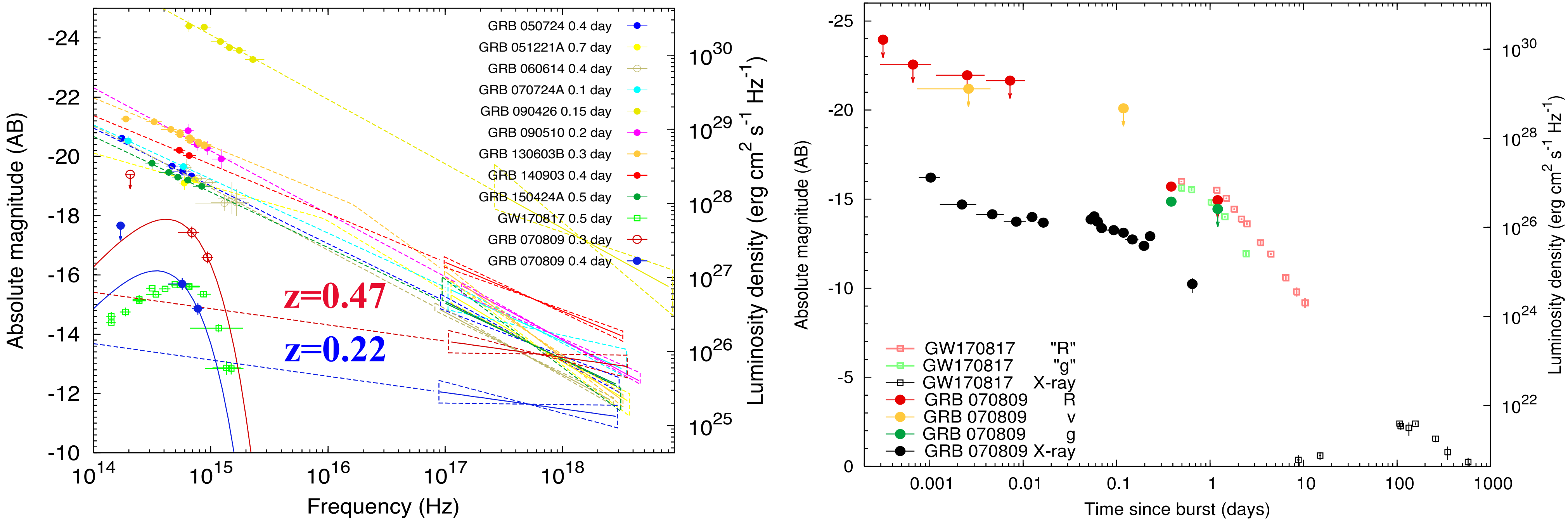
Optical: in excess above afterglow.

GRB 070809: far away from its host galaxy



G1 z=0.218 offset 5.9 seconds, chance of coincidence 0.1(Perley 2008)
G2 z=0.473 offset 6.0 seconds, chance of coincidence 0.02 (Berger 2010)
GRB site m(F606W)>28.0 AB mag

GRB 070809: unusual SED

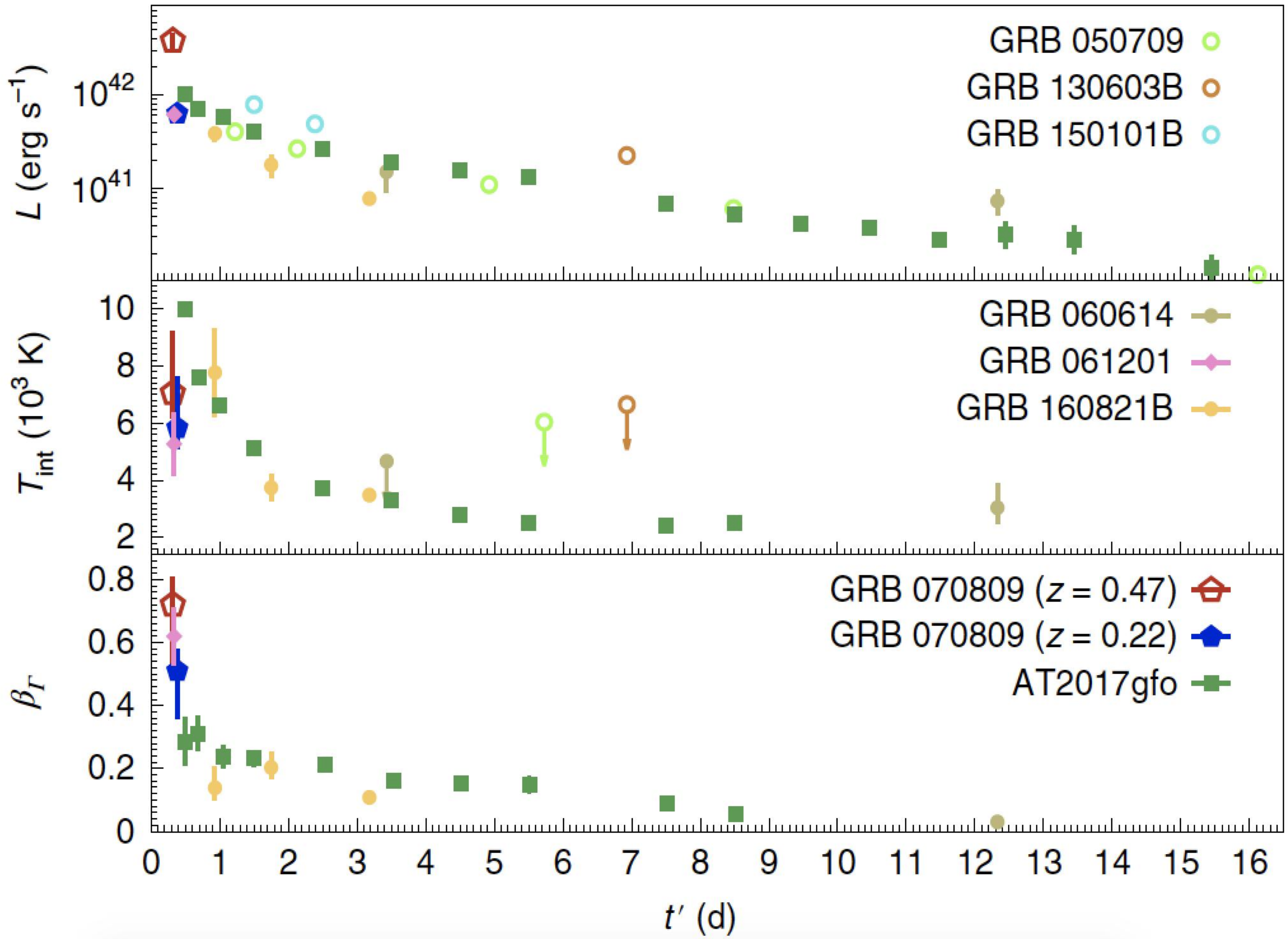


Jin et al. 2020 Nat. Astro.

GRB 070809 is distinguished by it's very hard X-ray spectrum and unusually soft optical spectrum, its flux is close to AT2017gfo (if z=0.22), but lower temperature (5800K vs 10000K). It can be naturally interpreted as a kilonova.

GRB 070809 is the first kilonova candidate far away from its host (GRB 230307A is also far away form its host, Levan et al 2024).

GRB 070809: kilonova with lowest temperature



Jin et al. 2020

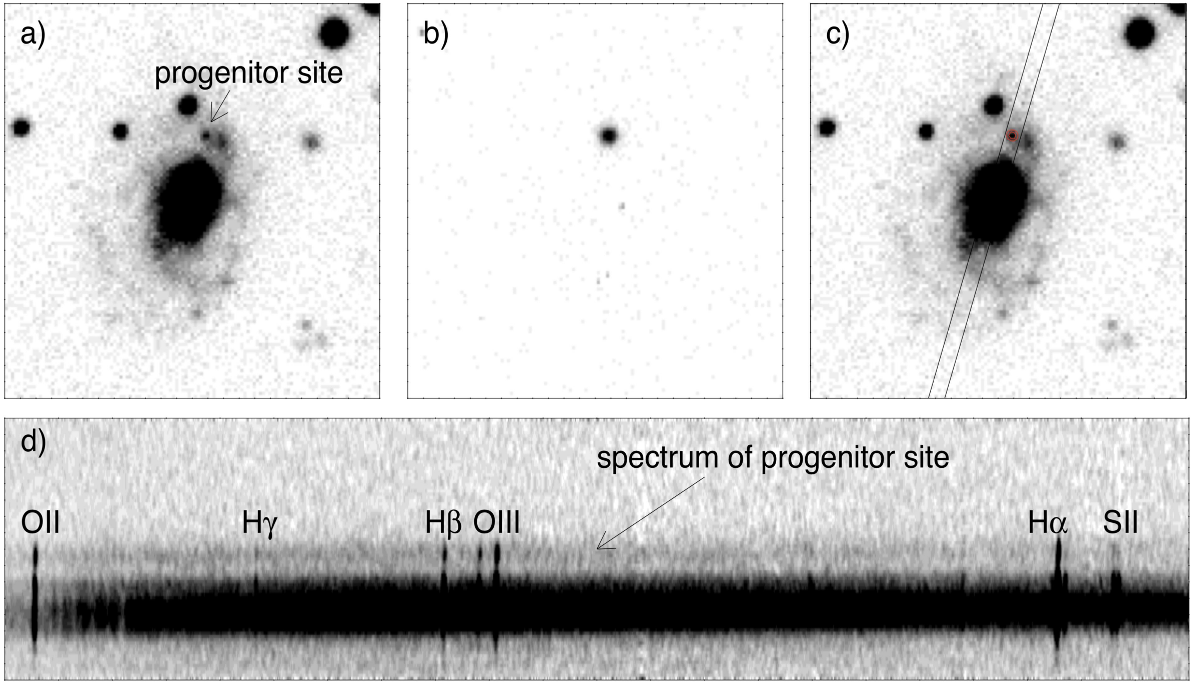
Similar (z=0.22) or higher (z=0.47) luminosity.

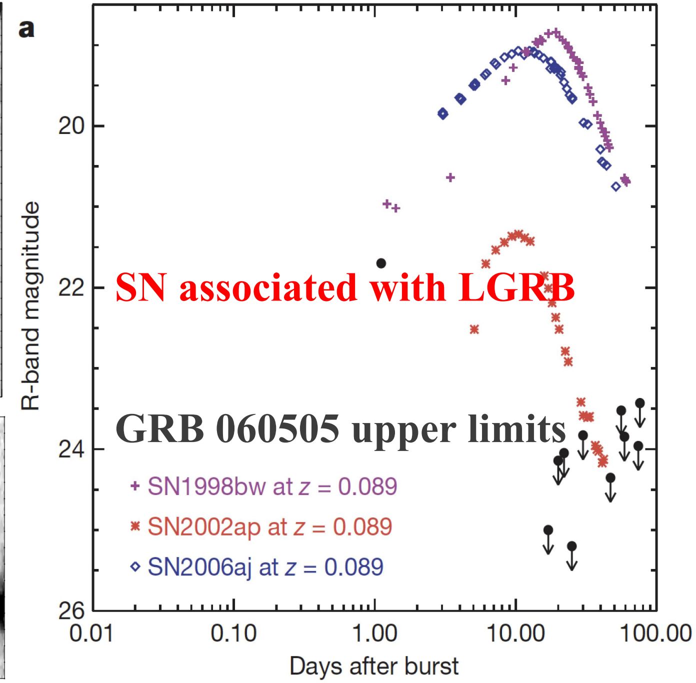
Lower temperature.

Higher velocity.

Suggesting that kilonova may have sub classes.

GRB 060505: first long-short GRB

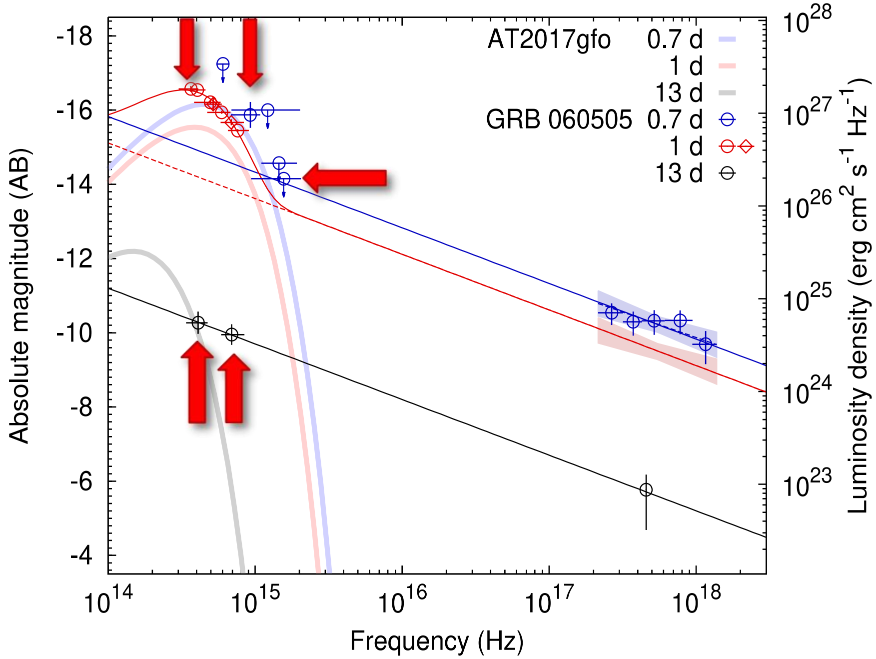


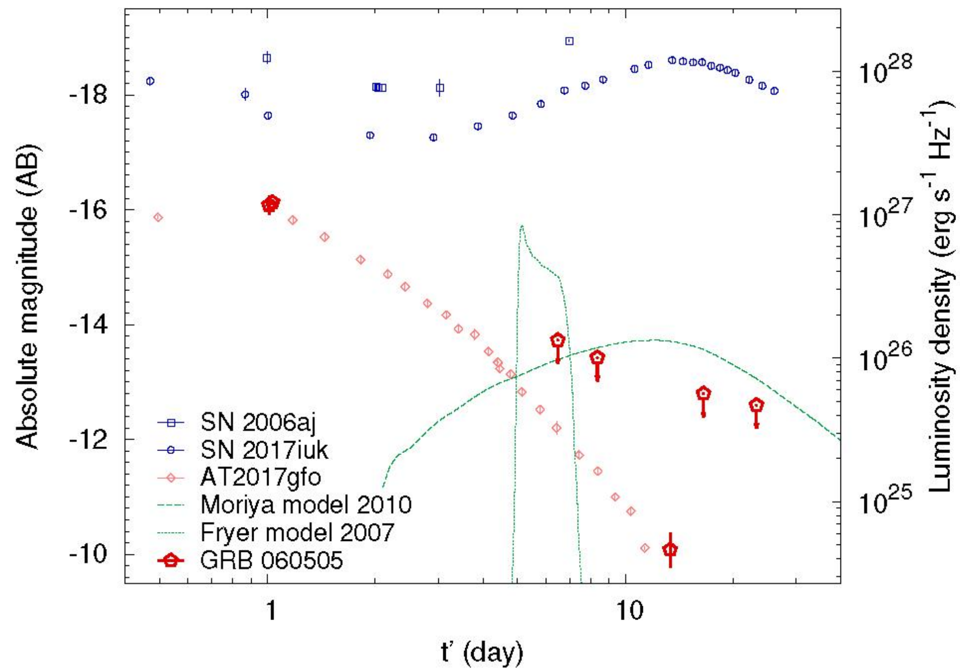


Fynbo et al. 2006 Nature

The first long-short burst GRB 060505 is occuring in a young star-forming region (HI emission line <10Myr, population age 6-10Myr).

GRB 060505: AT2017gfo-like thermal component





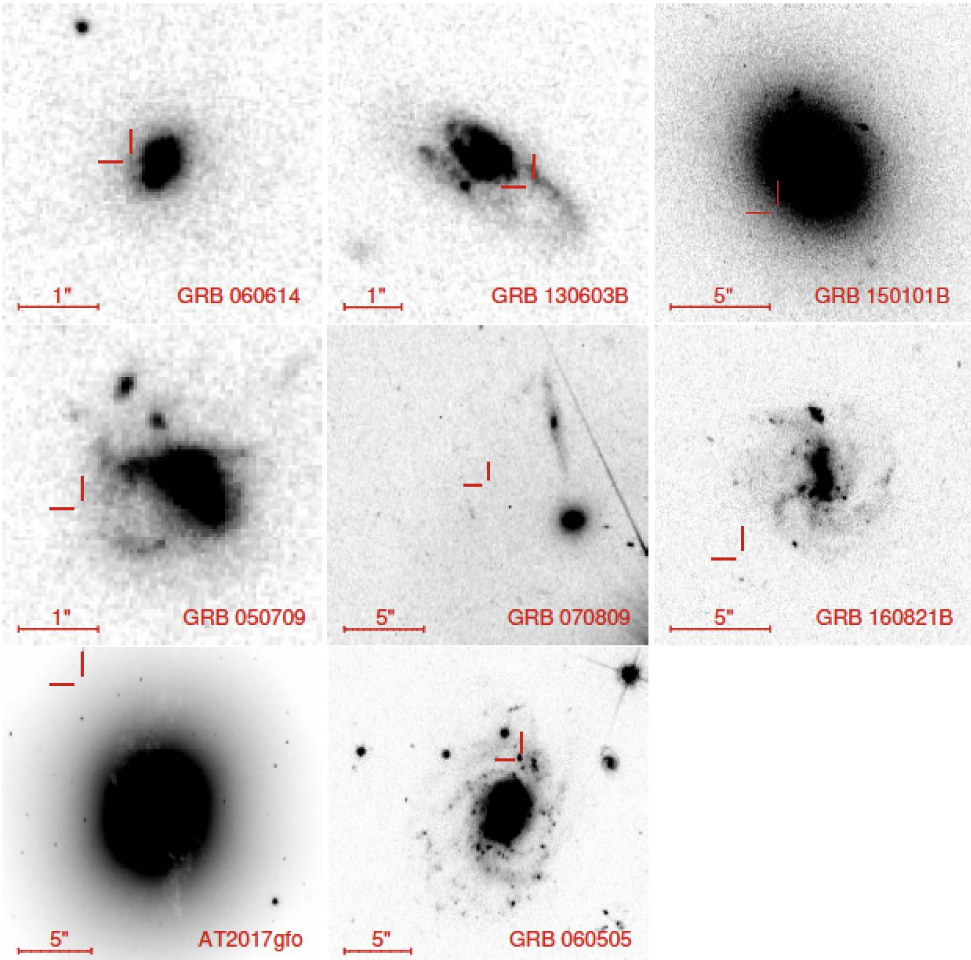
Jin et al. 2021 arXiv:2109.07694

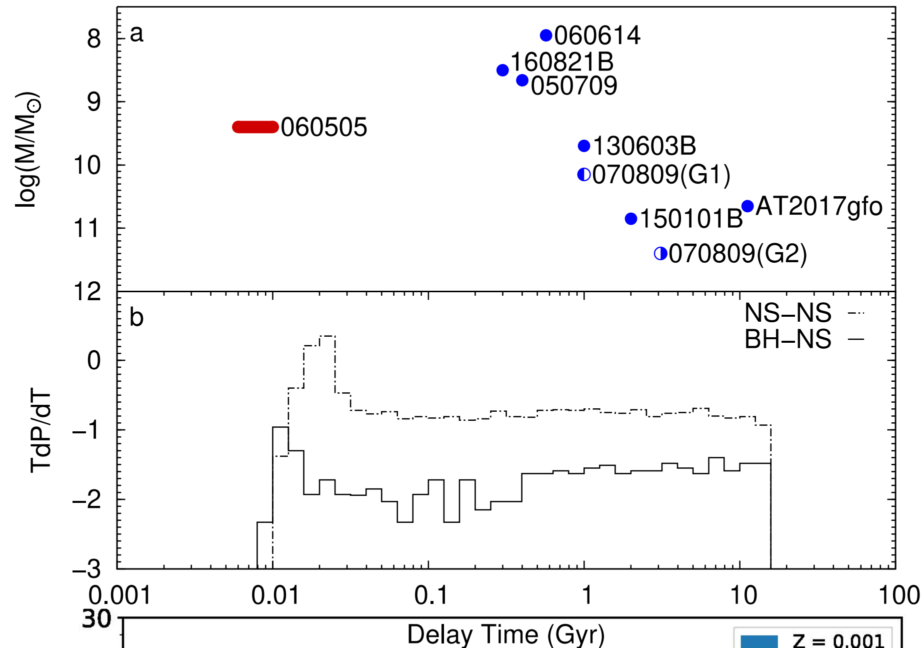
1. Improvement of image subtraction technology: former HST F814W, F475W, Swift UVOT U-band upper limit point changed to detection point;

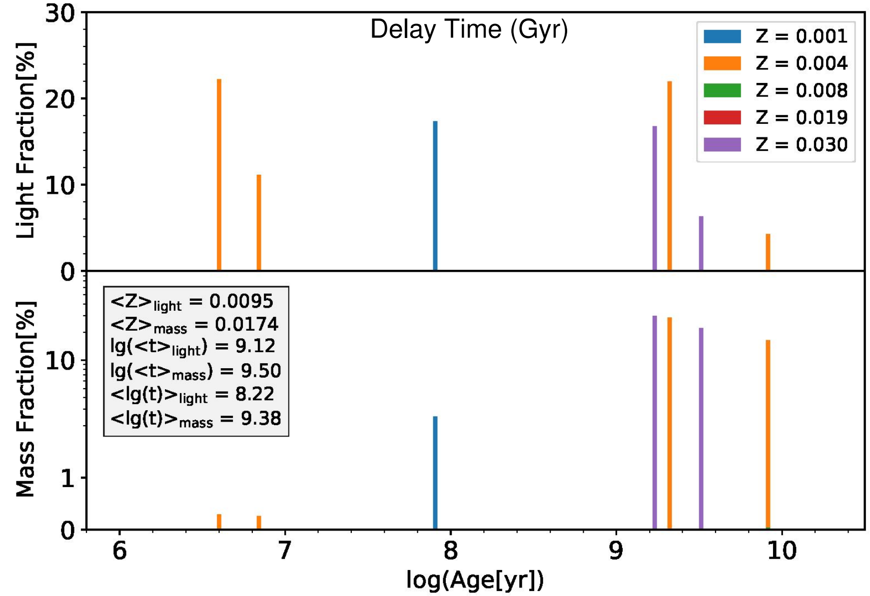
2. Make use of more archive data: the VLT z-band was not processed before, and we did photometry after fringing was removed;

3. AT2017gfo provided a good comparison object.

A kilonova from an ultra-quick merger?





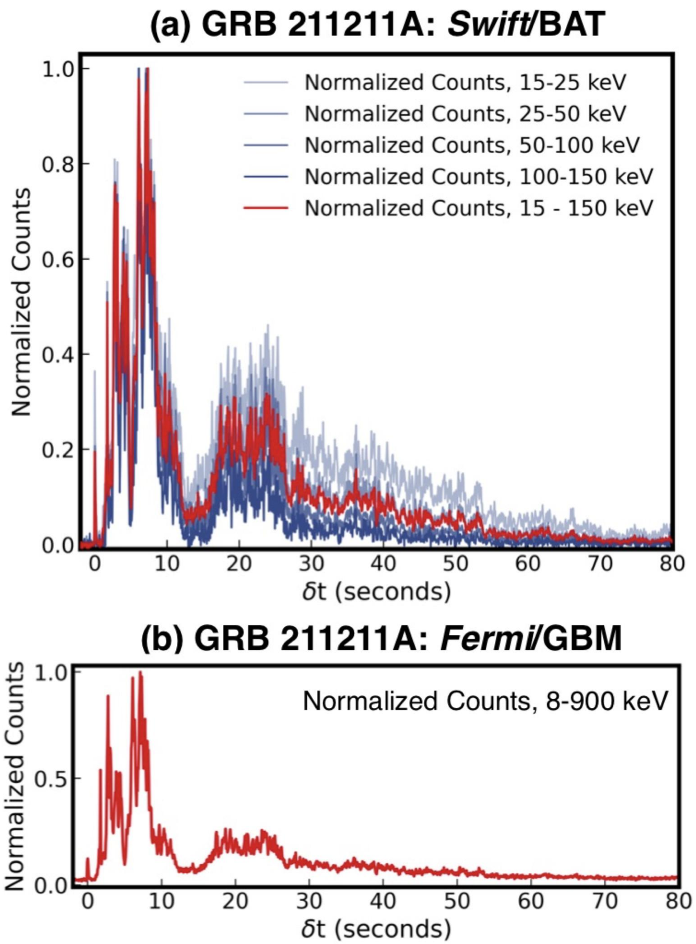


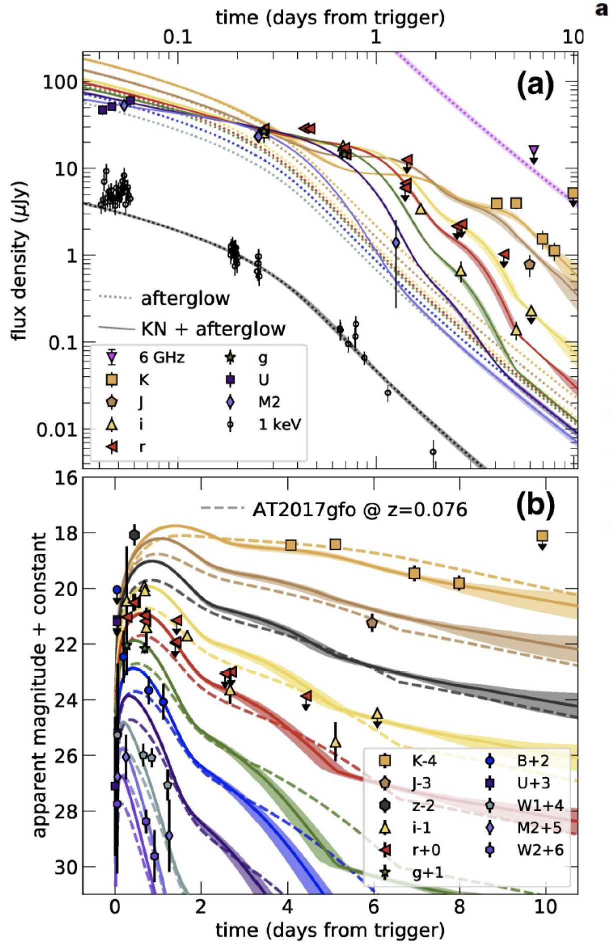
Merger delay time:

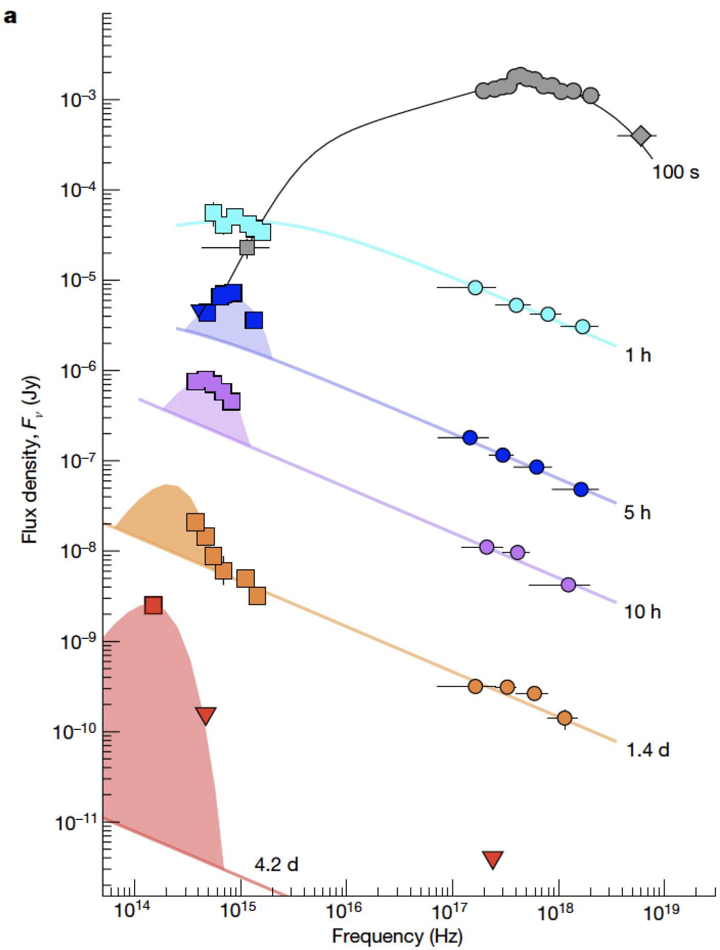
1. Stellar population age (upper limit);
2. Offset to the host galaxy (lower limit).

Jin et al. 2021

New KN were discovered in long GRB 211211A







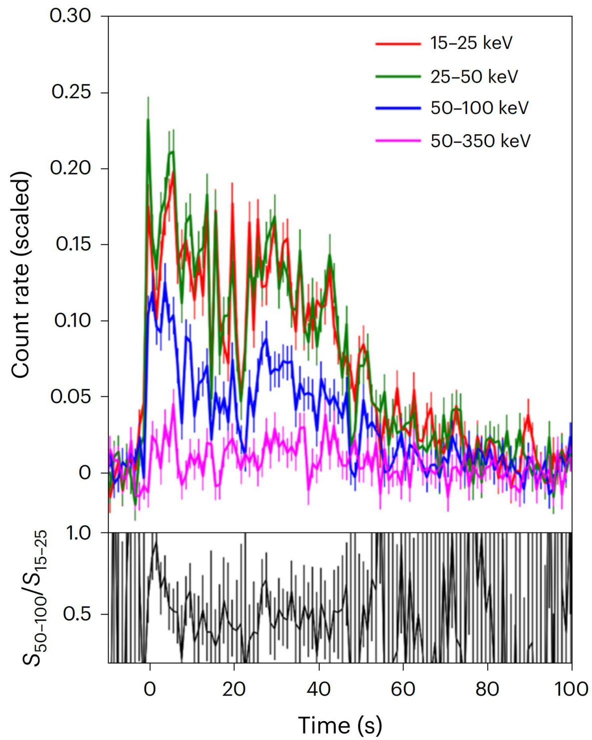
Rastinejad et al. 2022 Nature

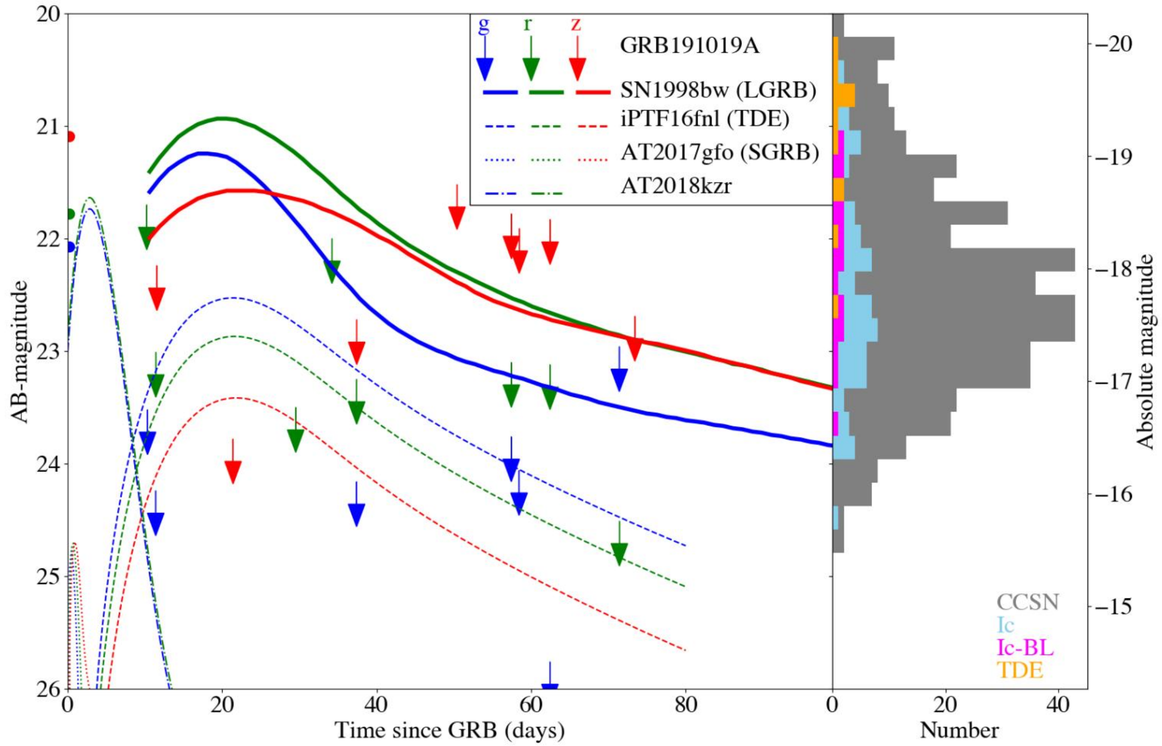
Troja et al. 2022 Nature

See also Yang et al. 2022 Nature, Mei et al. 2022 Nature

Long GRB 191019A of merger origin

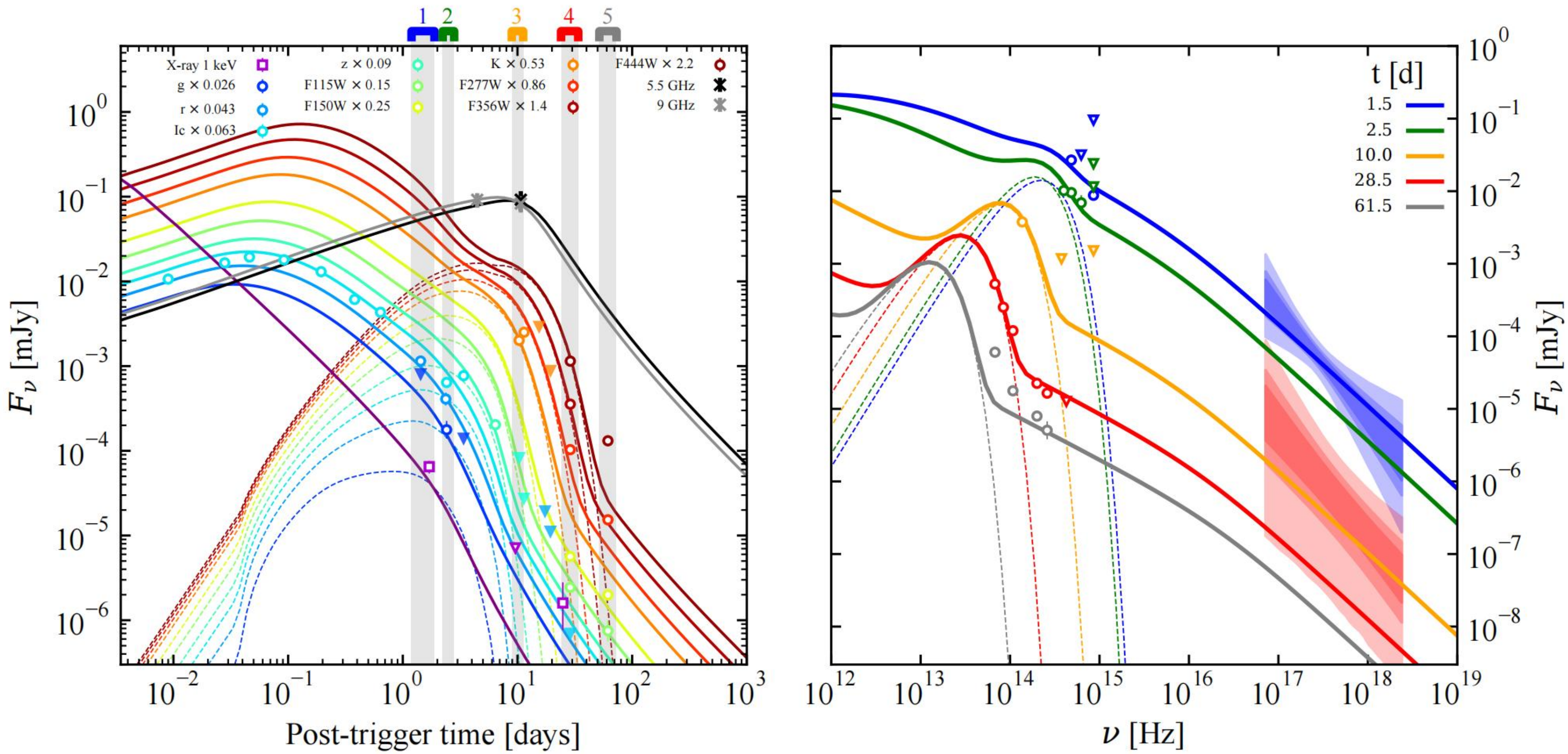
Lack of evidence for star formation and deep limits on any supernova emission make a massive star origin difficult to reconcile with observations.





Levan et al. 2023 Nat. As.

New KN were discovered in long GRB 230307A

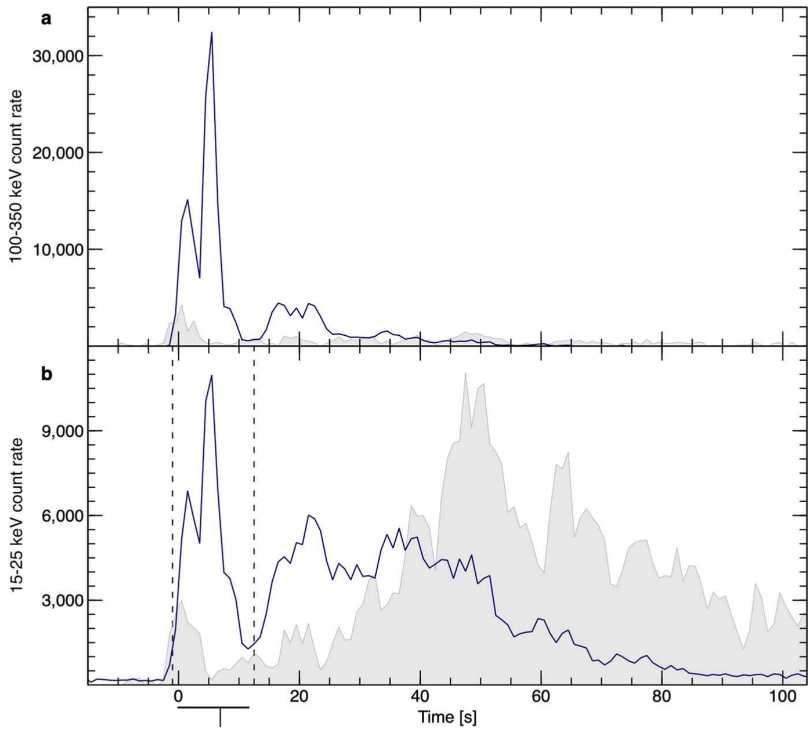


Levan et al. 2024 Nature, See also Yang et al. 2024 Nature

be compatible with our observations. Therefore, we conclude that GRB 230307A is a long-duration GRB formed from a compact object merger. This falls into a class that includes GRB 211211A [17–19, 32], GRB 060614 [33], GRB 111005A [34] and GRB 191019A [35], among others.

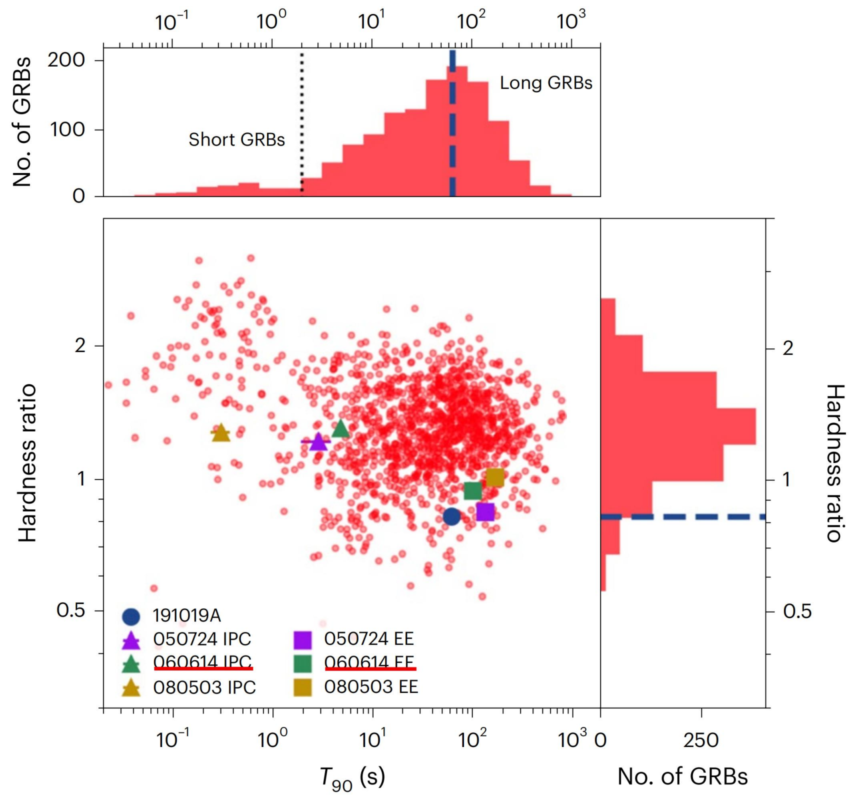
Similarities between long GRBs linked to kilonovae

All events exhibit a short and hard main burst, accompanied by a longer and softer extended emission.



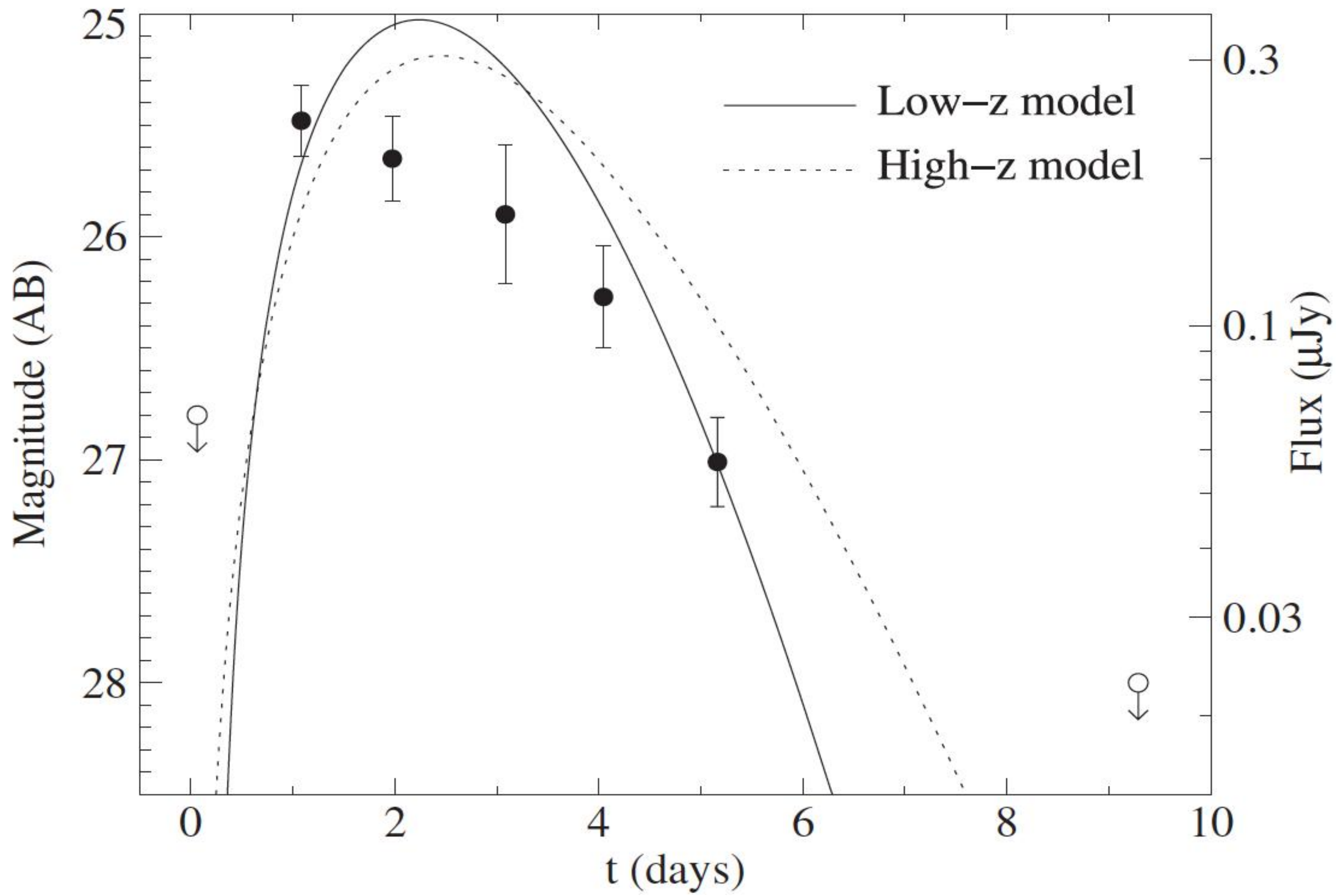
Extended Data Fig. 1 | Prompt gamma-ray phase of GRB 211211A. a,b, The Swift background subtracted light curves of GRB 211211A are shown in two energy bands and compared with the time history of GRB 060614 (grey shaded area) rescaled at a distance of 346 Mpc. The time bin is 1 s. Error bars are 1σ. Both bursts display a first episode with hard spectrum (dominant in GRB 211211A), followed by a long-lasting tail with soft spectrum (dominant in GRB 060614). **c**, The inset magnifies the first 12 s, showing a weak precursor at T_0 preceding the main prompt event. The time bin is 16 ms.

Troja et al. 2022 Nature



Levan et al. 2023 Nat. As.

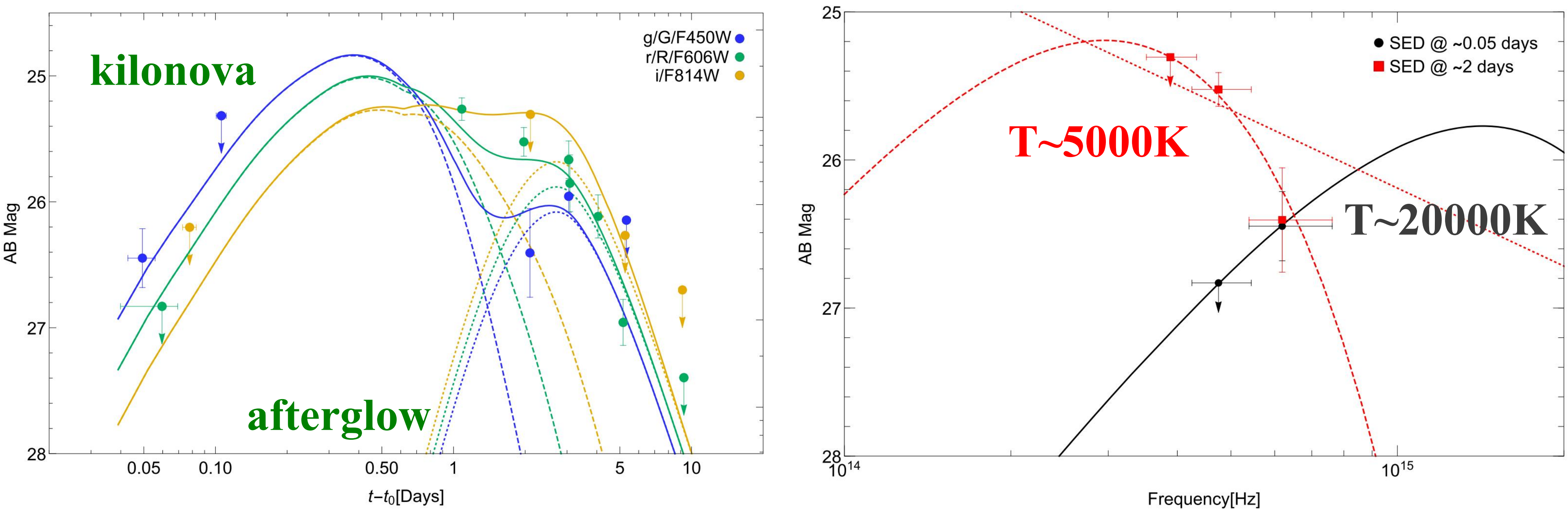
GRB 080503: optical kilonova candidate?



Perley et al. 2009 ApJ

2009 Perley et al.: optical kilonova candidate following GRB 080503 (Metzger 2019)

GRB 080503: very early kilonova component



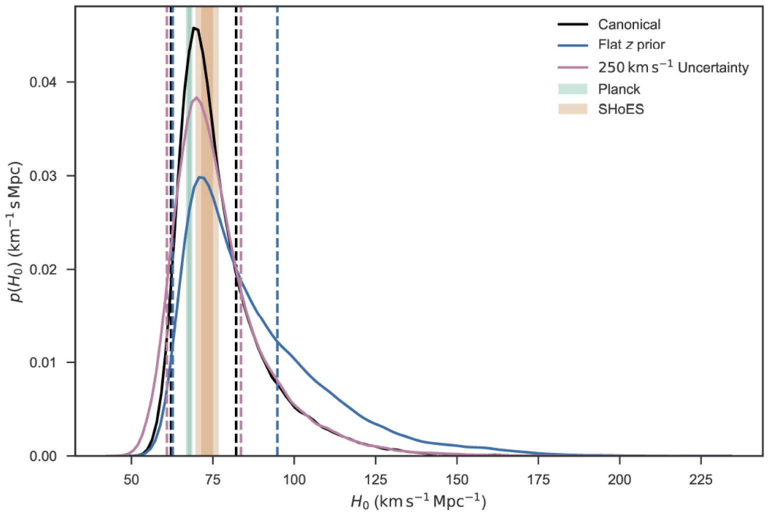
Zhou et al. 2023 ApJ

The kilonova of GRB 080503 resembles AT 2017gfo if happened at a redshift of ~0.3. If correct, this would be the earliest detection of the kilonova with the highest temperature up to date.

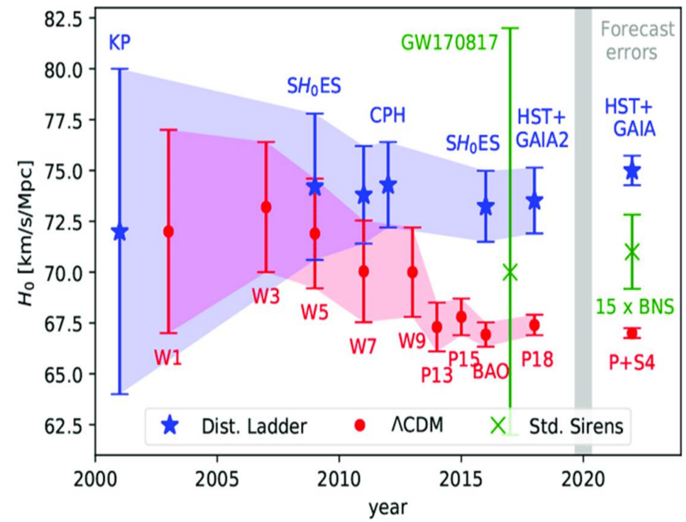
Outline

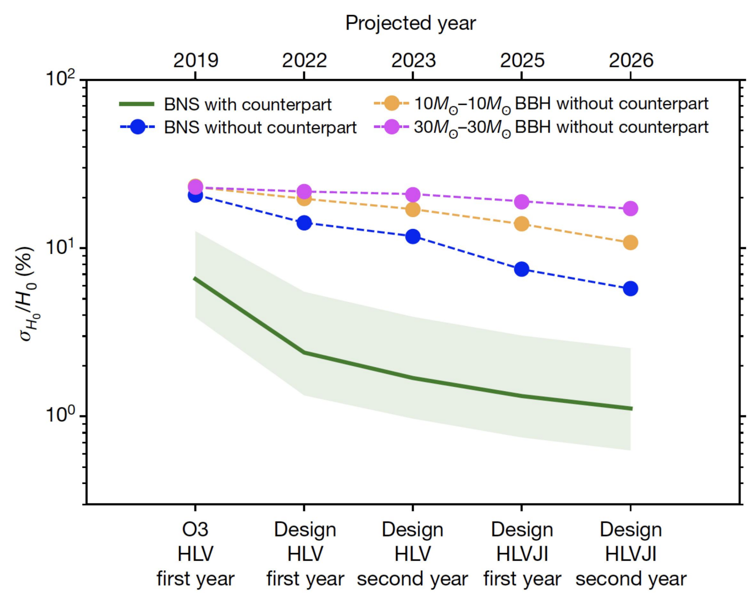
- ◆ Background
- ◆ Kilonovae linked to GRBs
- ◆ Implications
- ◆ Prospects

Implication 1: Hubble constant



LVC 2017 Nature

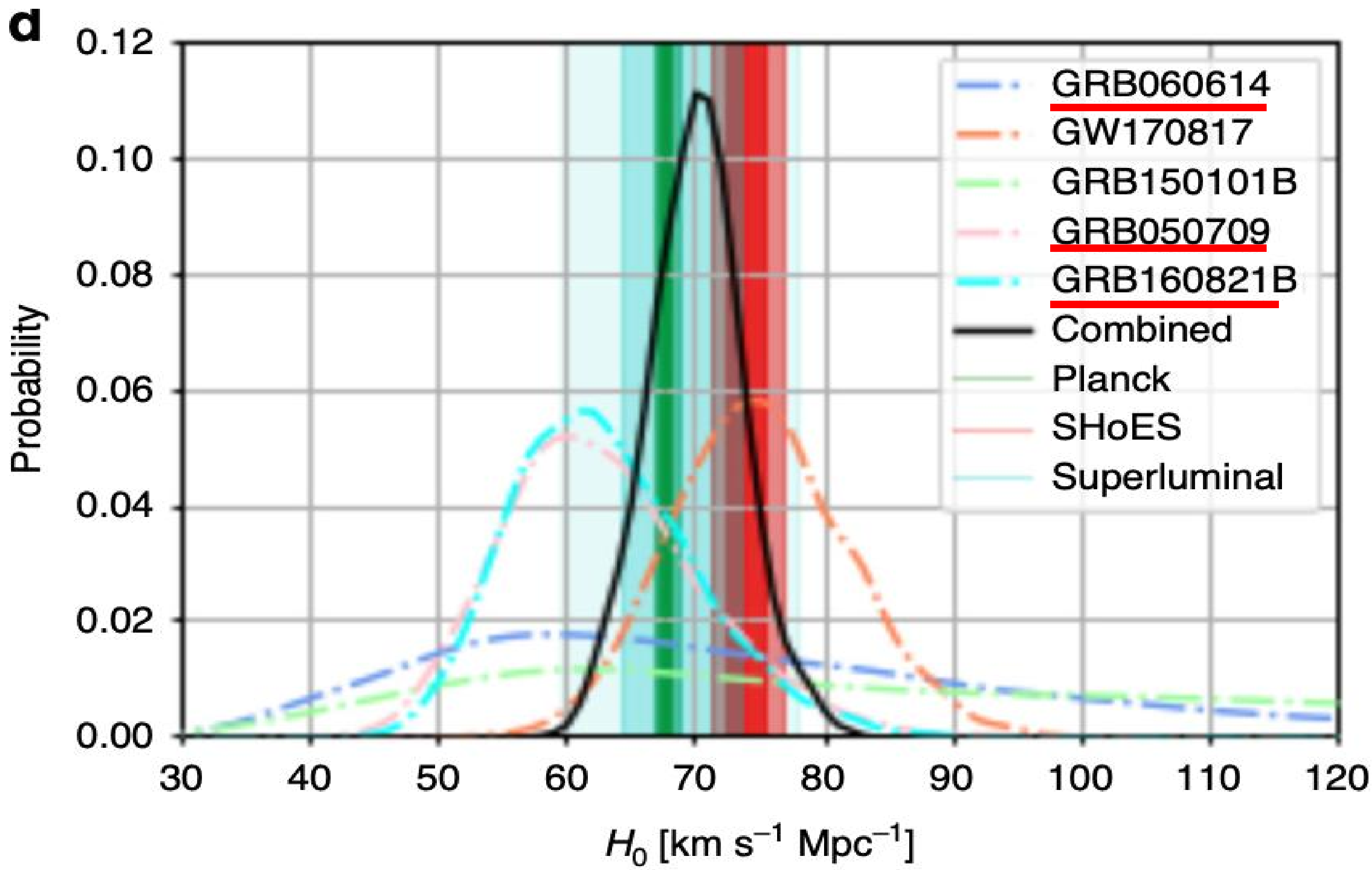




The measurement error is inversely proportional to $\sqrt{N}$, and the accuracy can be improved to 1-2% for 100 BNS event measurements

Chen et al. 2018 Nature

Implication 1: Hubble constant

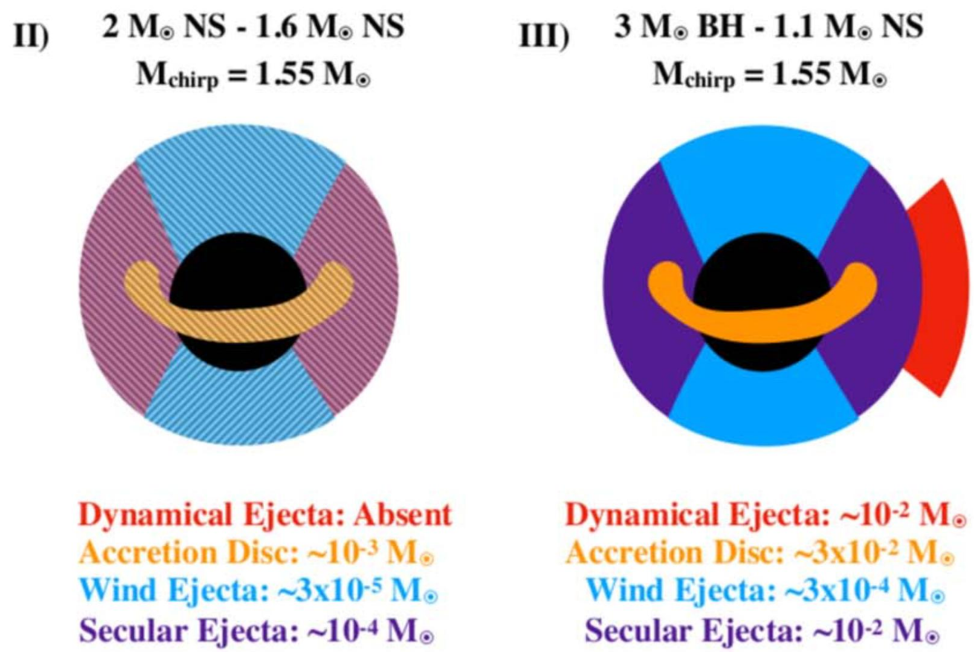


Coughlin et al. 2020 NatCo

If the kilonova can be used as a standard candle,
it will provide a new method to measure the Hubble constant.

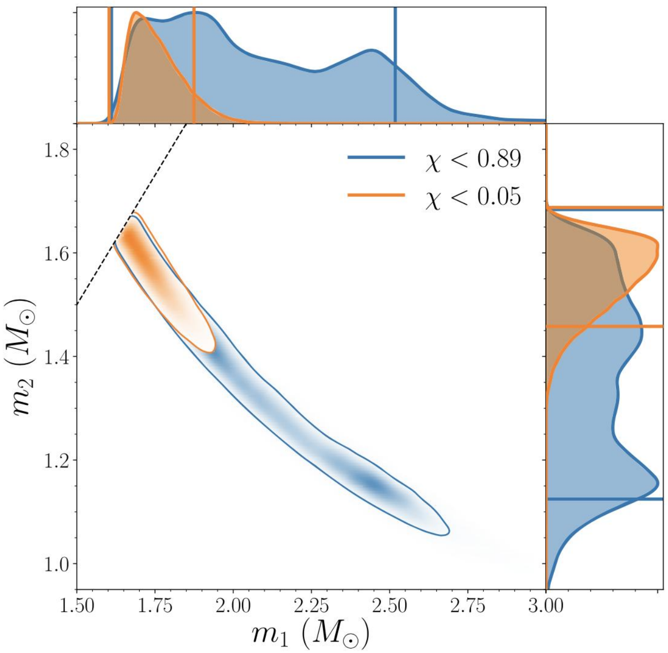
Implication 2: Type of progenitor

When a NS or BH near the mass boundary merges with a lighter NS,
it is difficult to distinguish the types by gravitational wave data.

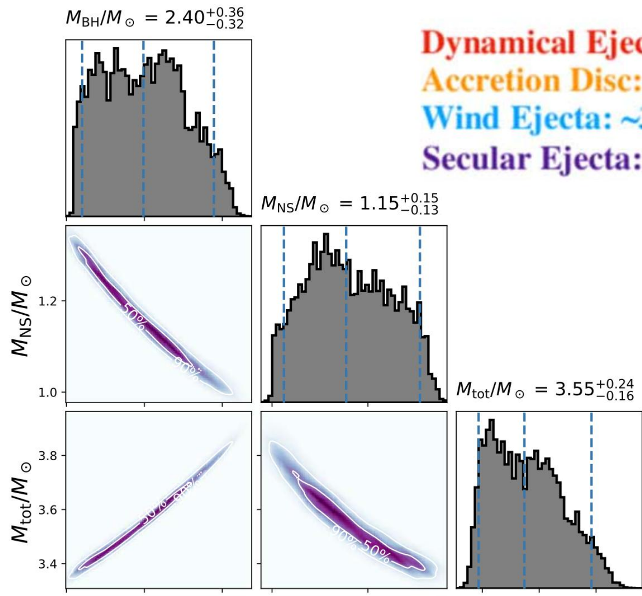


Barbieri et al. 2019 ApJL

GW 190425 BNS or NS-BH?



Abbott et al. 2020 ApJL

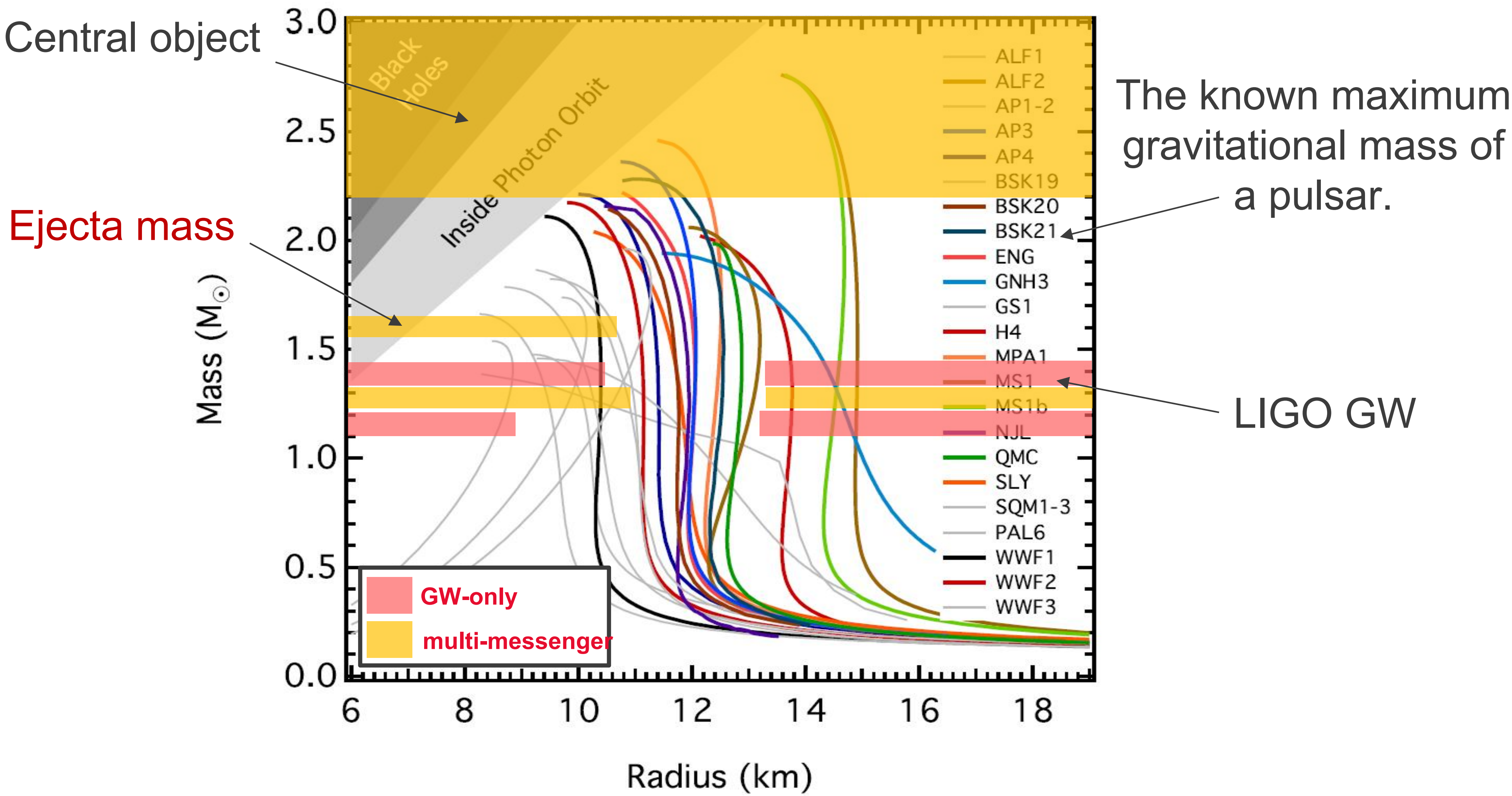


Han et al. 2020 ApJL

Nature of the progenitor (BNS or NS-BH) can be inferred from the properties of the kilonova.

Implication 3: Constraints on the EOS of NSs

The ejecta mass in kilonovas is correlated with the equation of state of neutron stars.



Ozel & Freire 2016

Implication 3: Neutron star merger rate

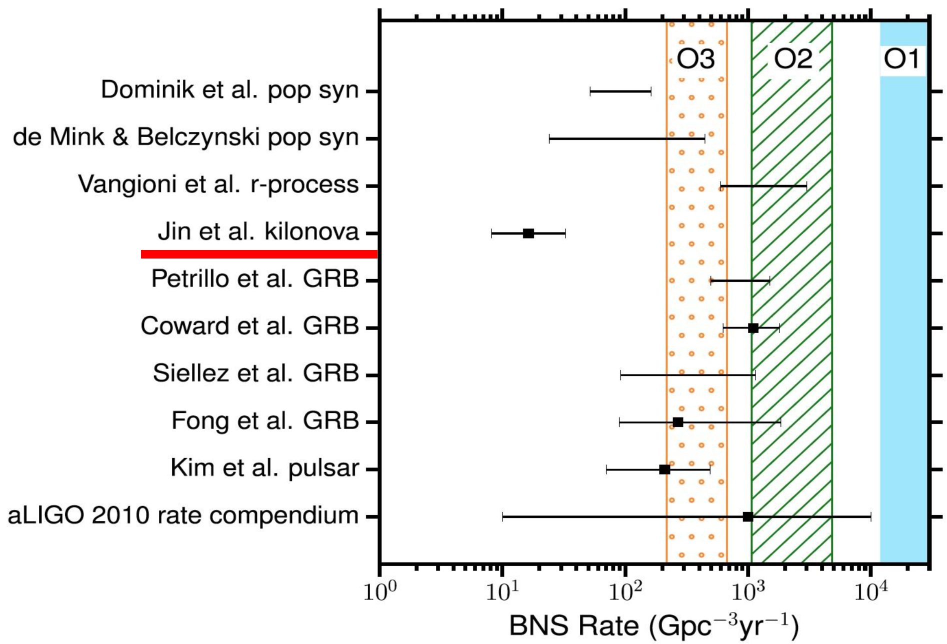
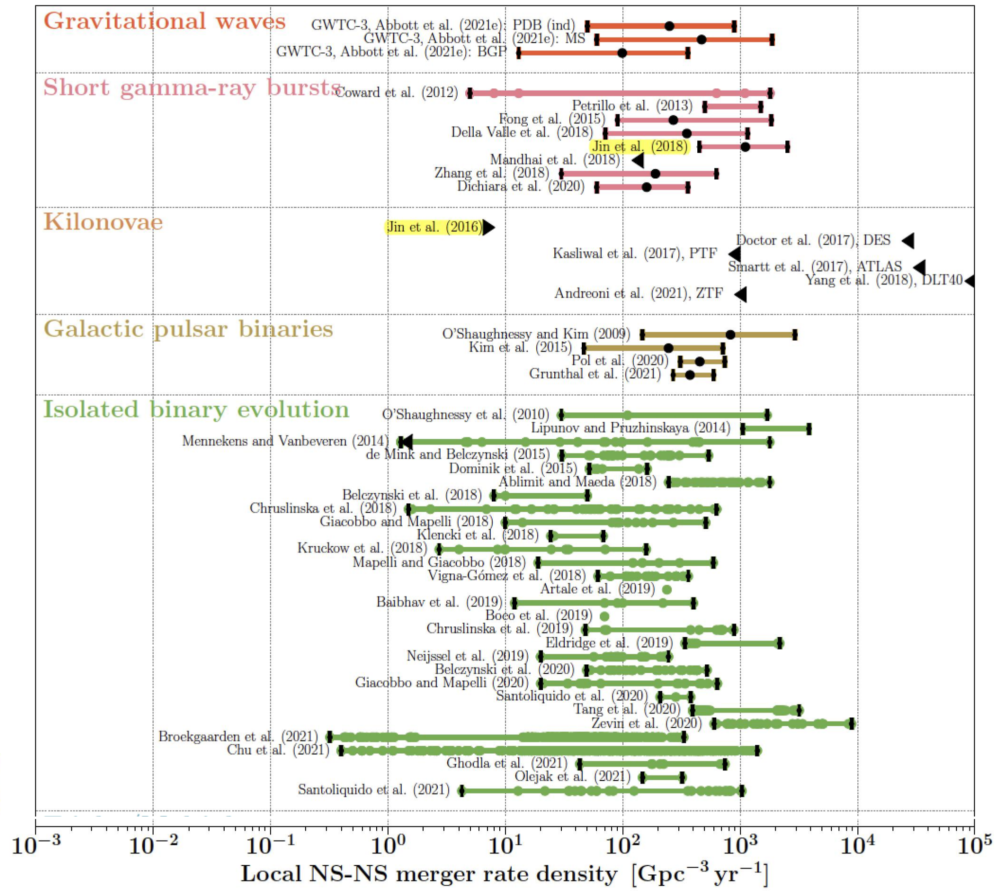


Figure 6. Comparison of the O1 90% upper limit on the BNS merger rate to

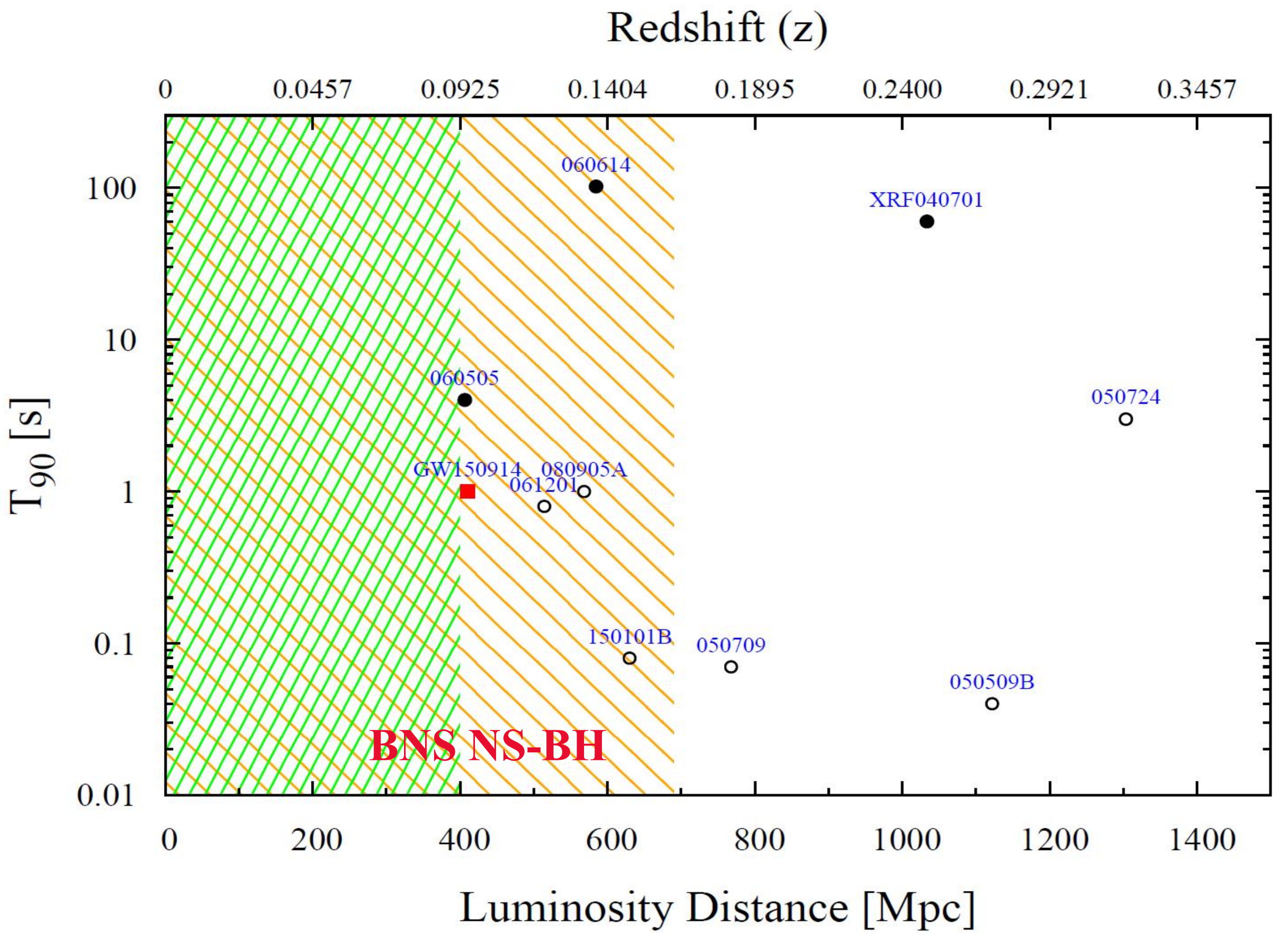
and an estimated kilonova rate gives an additional lower bound on compact binary mergers (Jin et al. 2015).



LIGO VIRGO Collaboration 2016

Mandel & Broekgaarden 2022

Implication 3: Neutron star merger rate



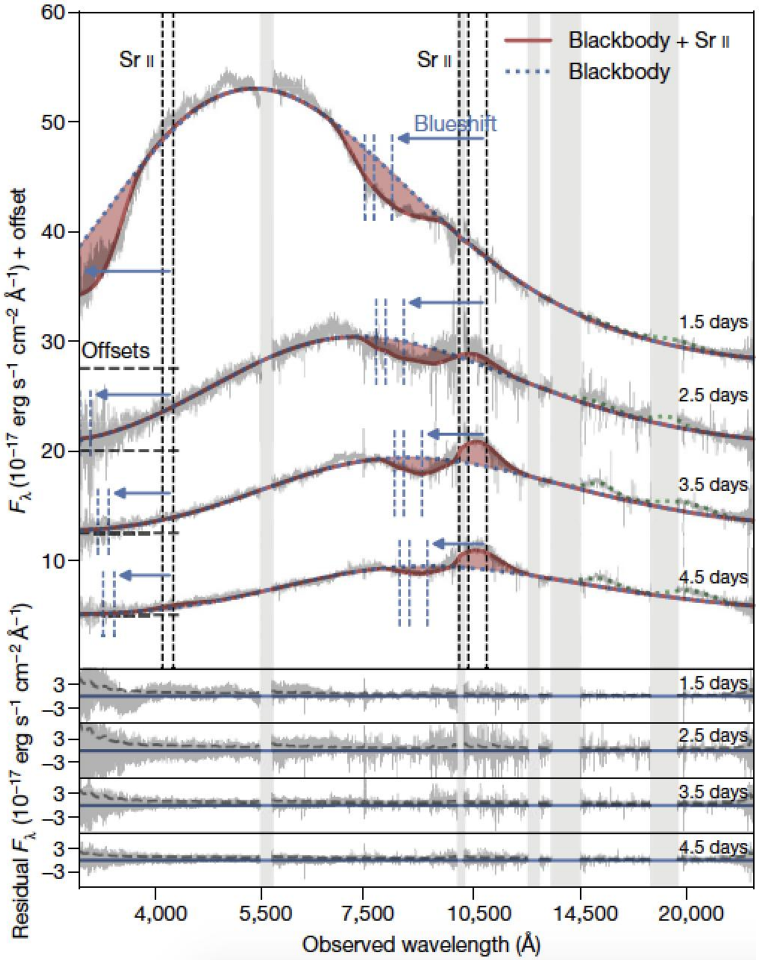
Li et al. 2016

Advanced LIGO/Virgo can only detect neutron star merger at z<0.15.

Kilonova can be detected at z~0.4 (HST, ground base 8m-class telescopes)!

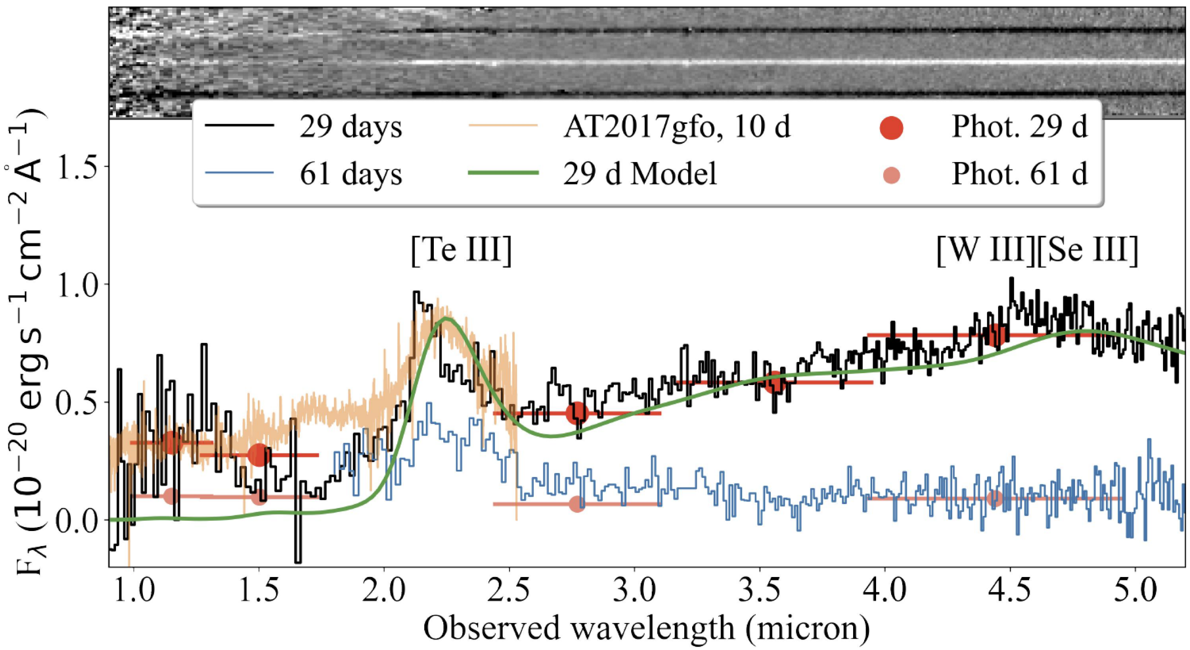
Implication 4: Origin of heavy elements

AT2017gfo（^{38}Sr）



Watson et al. 2019 Nature

GRB 230307A （^{52}Te、^{74}W、^{34}Se）



Levan et al. 2024 Nature

Implication 4: Origin of heavy elements

Table 1 | Physical properties of GRBs/macronovae/afterglows with known redshifts.

Jin et al 2016

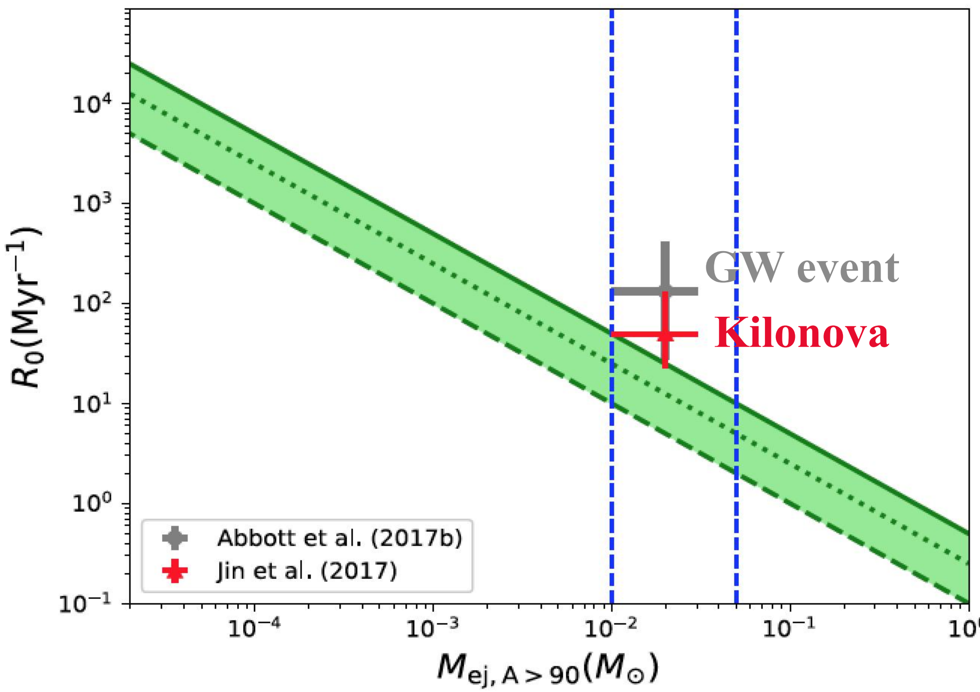
	GRB 050709*	GRB 060614†	GRB 130603B‡
$E_{\gamma,iso}$ (10^{51} erg)	0.069	2.5	2.1
z	0.16	0.125	0.356
Duration[§] (s)	0.5 (+130)	5 (+97)	0.18
Classification	sGRB + extended X-rays	hGRB	sGRB
Identifying macronova	in *I*/F814W	in *I*/F814W	in F160W
Macronova peak luminosity	$\sim 10^{41}$ erg s^{-1} (*I*)	$\sim 10^{41}$ erg s^{-1} (*I*)	$\sim 10^{41}$ erg s^{-1} (F160W)
M_{ej}[‖]	$\sim 0.05 M_\odot$	$\sim 0.1 M_\odot$	$\sim 0.03 M_\odot$
$R_{MN/X}$[¶]	~ 1	~ 0.1	~ 0.4

half A>90

Table 3
Short/lsGRBs with a Jet Break (or Upper Limit)

GRB	z	E_{iso} (10^{51} erg)	t_{jet} (days)	θ_j (rad)	References
050709	0.16	0.07	<1.4	<0.14	(1)
051221A	0.546	2.4	5	0.09	(2), (3)
060614	0.125	2.5	1.4	0.08–0.09	(4), (5)
061201	0.111	0.14	0.03	0.02–0.03	(6)
090426A	2.609	4.2	0.4	0.08–0.12	(7)
111020A	···	0.21/1.9[a]	2	0.05–0.14	(8)
130603B	0.356	2.1	0.47	0.07–0.14	(9), (10)
140903A	0.351	0.06	1.2	0.05–0.1	(11), (12)
150424A	0.30	4.3	3.7	0.12	this work
160821B	0.16	0.21	0.7	0.10	this work, (13)

Jin et al. 2018: local NS merger rate



Wang et al. 2017

Outline

- Background
- Kilonovae linked to GRBs
- Implications
- Prospects

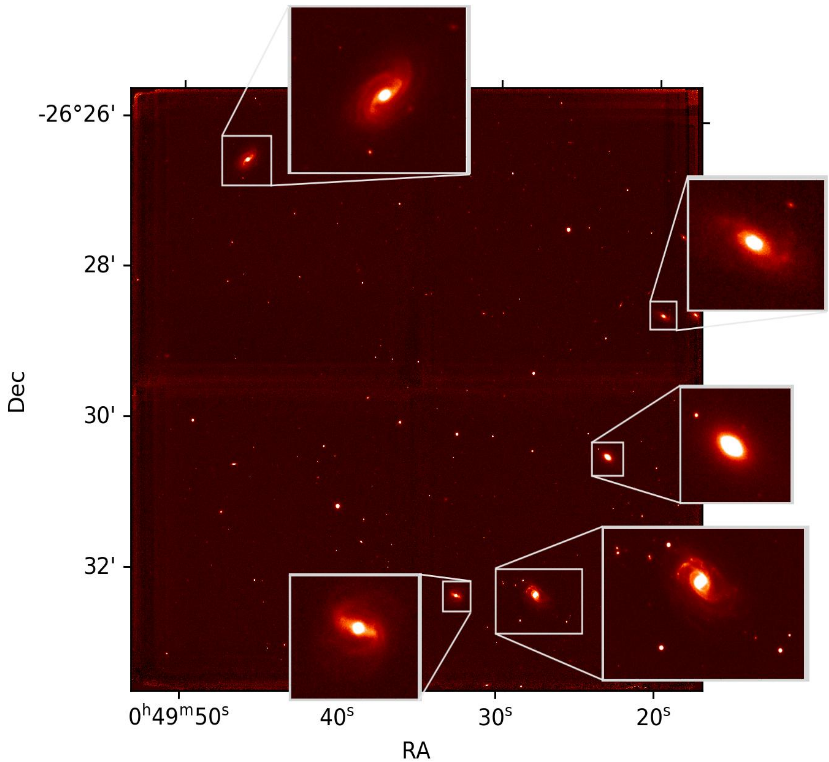
Prospect 1: NS-BH merger

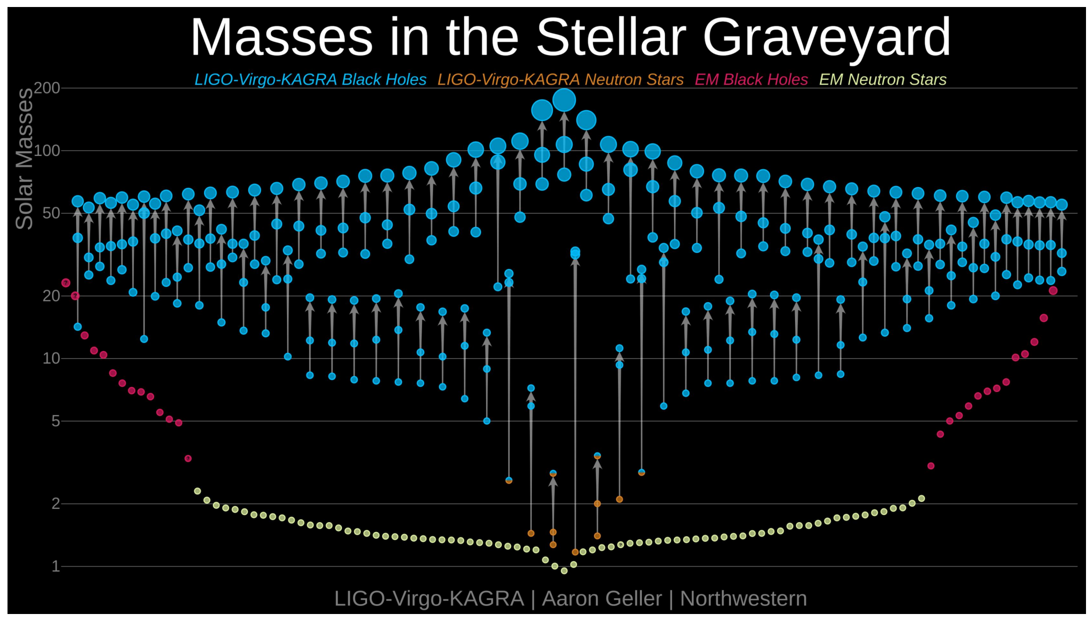
The gravitational wave event of NS-BH merger may have been detected, but no electromagnetic counterpart has been found.

First light of ENGRAVE and a potential NS-BH merger

20 August 2019

engrave · webpages





Prospect 2: Blind Search

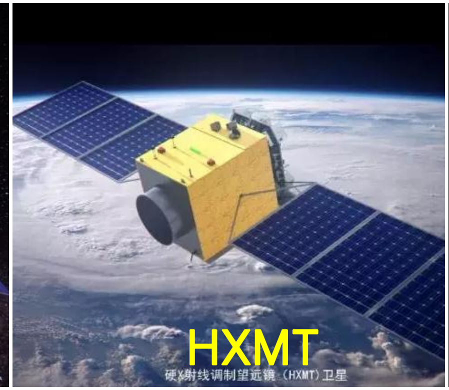
Expected Number of KNe Found in Each Sample

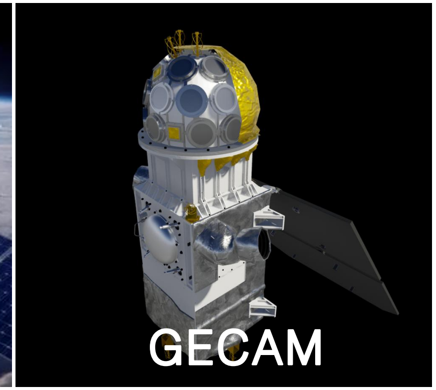
Survey	# KNe[a]	Survey Years	KN Redshift Range
SDSS	0.13	2	0.02–0.05
SNLS	0.11	4	0.05–0.20
PS1	0.22	4	0.03–0.11
DES	0.26	5	0.05–0.20
ASAS-SN	<0.001	3	...
SMT	0.001	5	0.01–0.01
ATLAS	8.3	5	0.01–0.03
ZTF	10.6	5	0.01–0.04
LSST WFD	69	10	0.02–0.25
LSST DDF	5.5	10	0.05–0.25
WFIRST	16.0	2	0.1–0.8

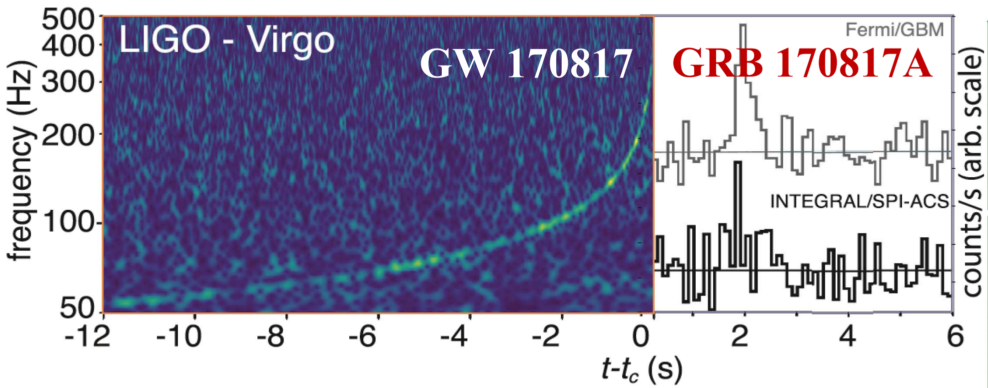
Scolnic et al. 2018

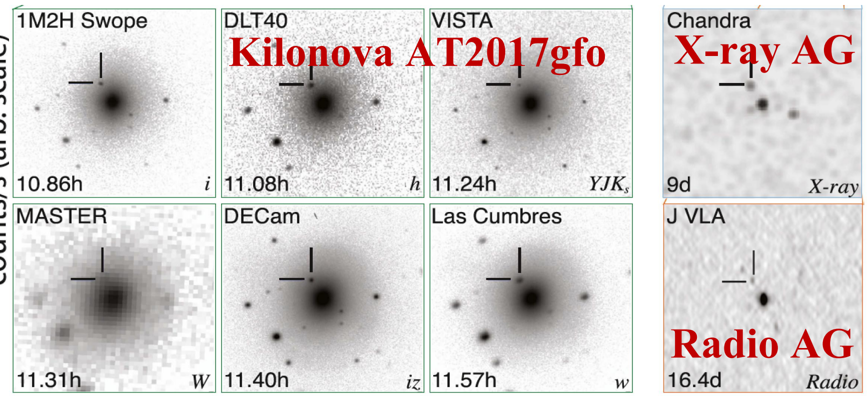
Main difficulties: There are too many transient sources, and redshift and spectral confirmation consume too many resources.

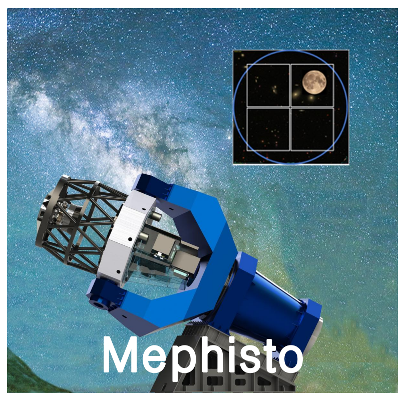
Prospect 3: Chinese observation network

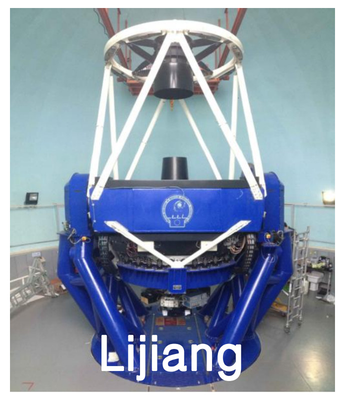












Summary

- Kilonovae and candidates:
  - GRB 130603B （Tanvir et al. 2013, Berger et al. 2013）
  - GRB 060614 （long GRB） （Yang et al. 2015, Jin et al. 2015）
  - GRB 050709 （Jin et al. 2016）
  - AT2017gfo (…Pian et al. 2017, Covino et al. 2017, Abbott et al. 2017…)
  - GRB 150101B (Troja et al. 2018)
  - GRB 160821B (Jin et al. 2018, Gompertz et al. 2018, Troja et al. 2019, Lamb et al. 2019)
  - GRB 070809 (Jin et al. 2019)
  - GRB 060505 (Jin et al. 2021)
  - GRB 211211A (Rastinejad et al. 2022, Troja et al. 2022, Yang et al. 2022, Mei et al. 2022)
  - GRB 191019A (Levan et al. 2023)
  - GRB 080503 (Perley et al. 2009, Zhou et al. 2023)
  - GRB 070707 (Zhu et al. 2023)
  - GRB 230307A (Levan et al. 2024, Yang et al. 2024)

- Implications:
  - Cosmology and the Hubble constant.
  - Equation of state of neutron stars.
  - Neutron star merger rate.
  - Origin of elements heavier than iron.

Thank you! Jin Zhiping (jin@pmo.ac.cn)

Thank you!

Jin Zhiping (jin@pmo.ac.cn)