Compact Object Mergers as Probes of the Origins of Heavy Elements

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Gamma-ray Bursts

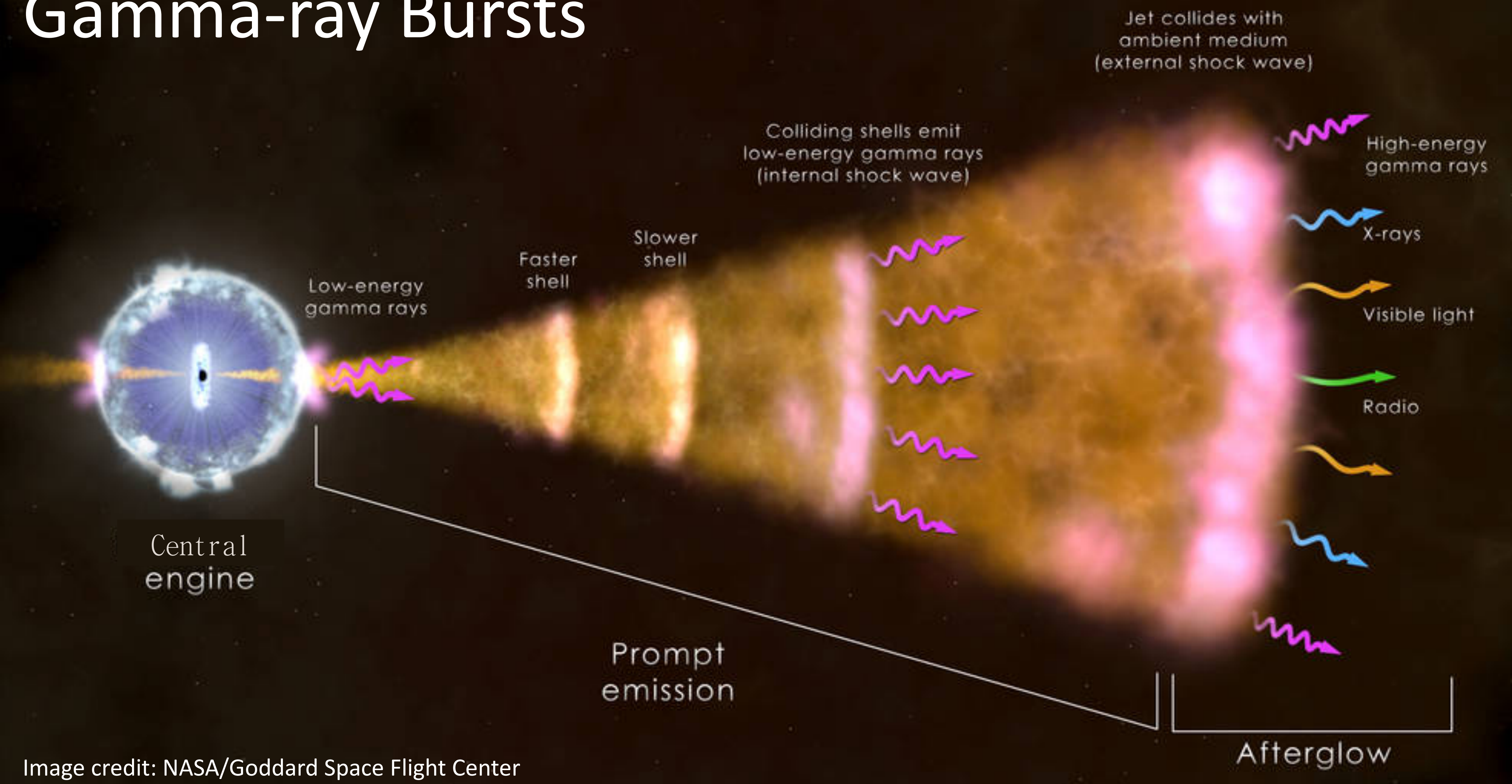


Image credit: NASA/Goddard Space Flight Center

Gamma-ray Bursts

Kouveliotou et al. (1993)

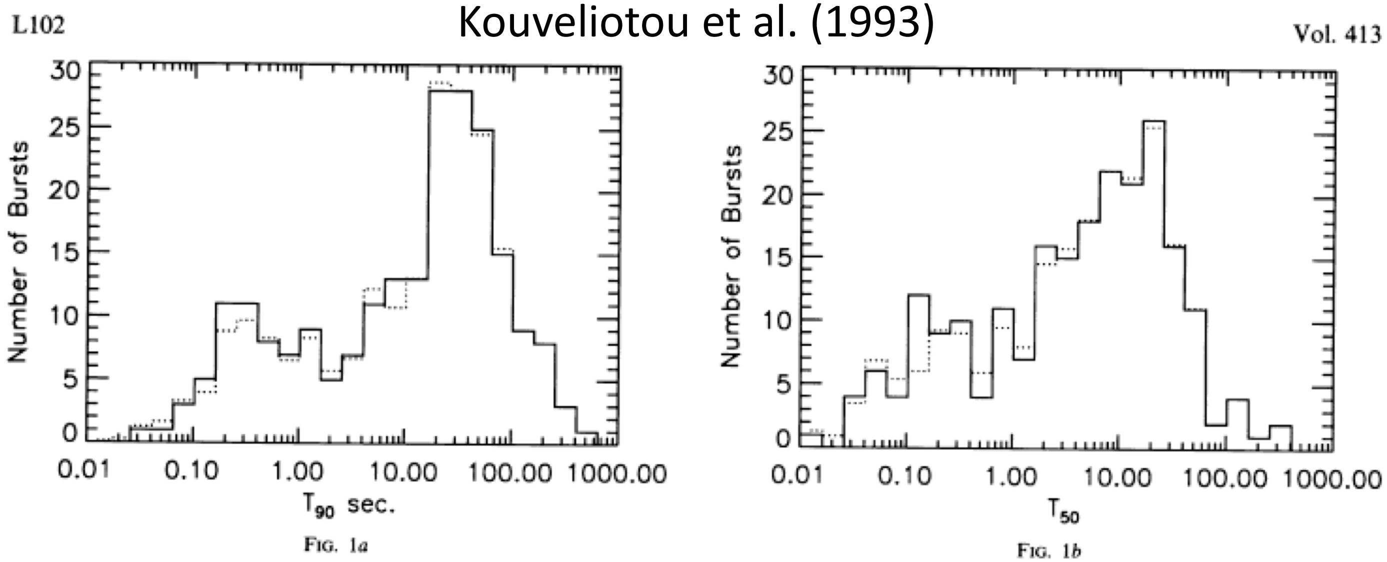
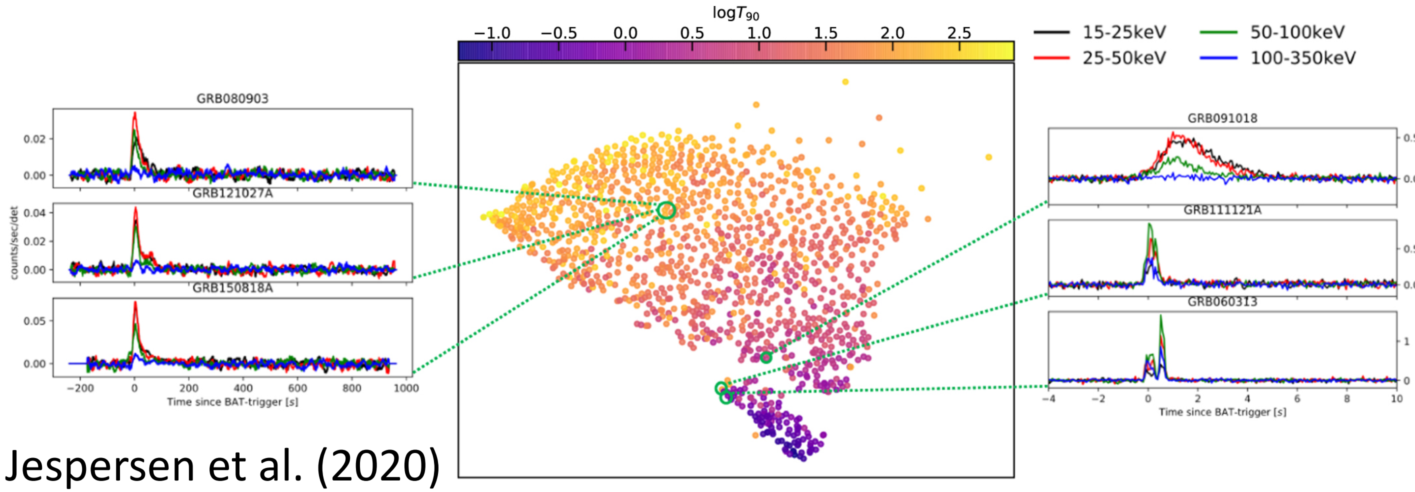


FIG. 1.—(a) Distribution of T_{90} for the 222 GRBs of the first BATSE catalog. (b) Distribution of T_{50} for the same GRB set. Solid lines are the histograms of the raw data; dotted lines are the error-convolved histograms as explained in the text.



Jespersen et al. (2020)

Two types of GRB (at least)

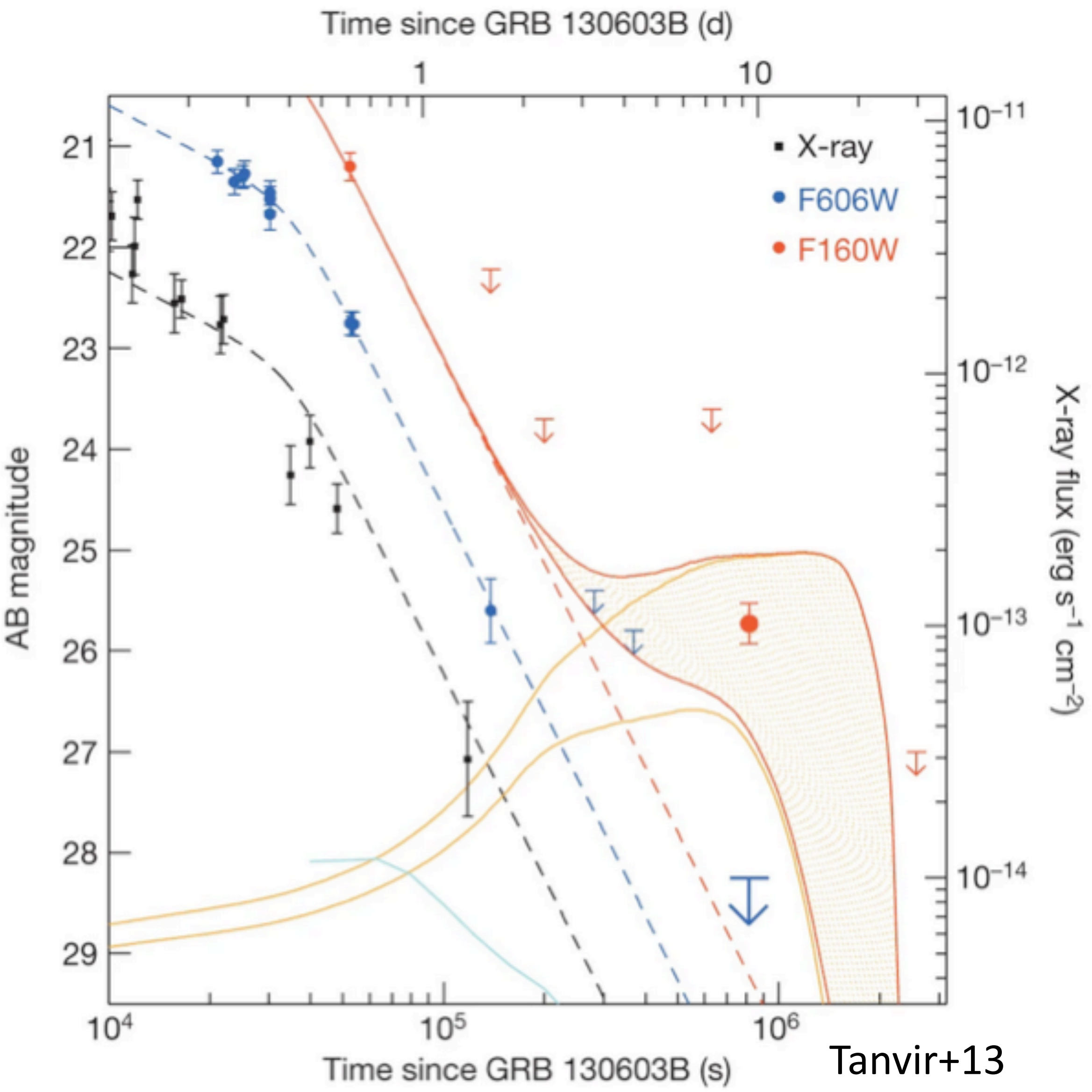
Long GRBs:
- Sit on star-forming regions
- Have supernovae

= Core-collapse of massive stars

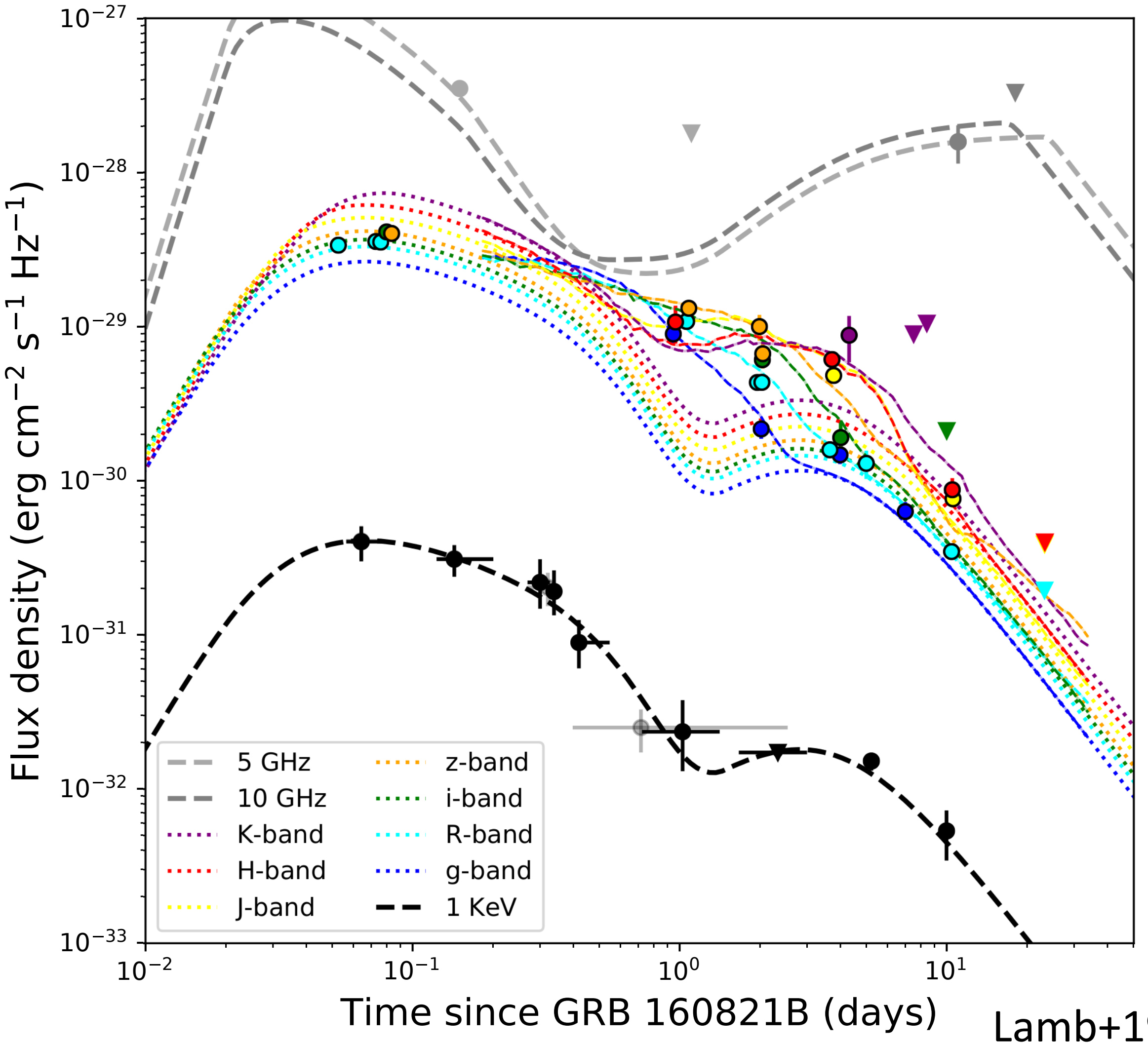
Short GRBs:
- Don’t care about star formation
- No supernovae
- Sometimes seen a long way from galaxies

= Mergers of neutron stars (+ black holes?)

Kilonova Candidates



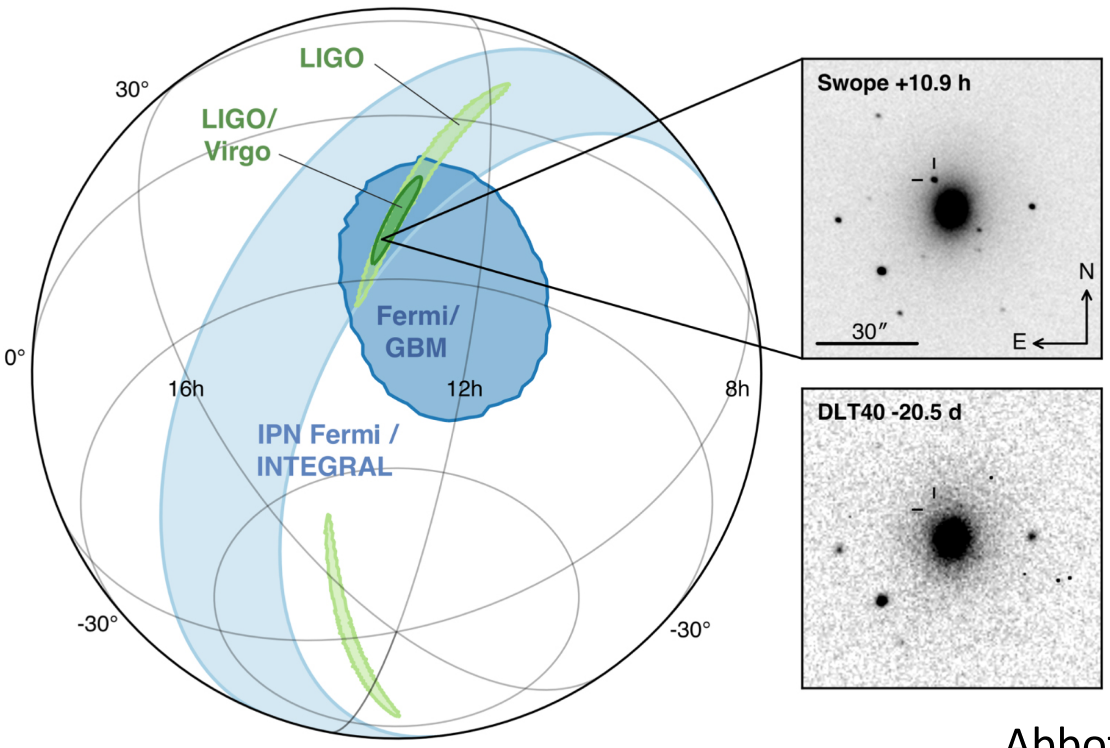
Tanvir+13

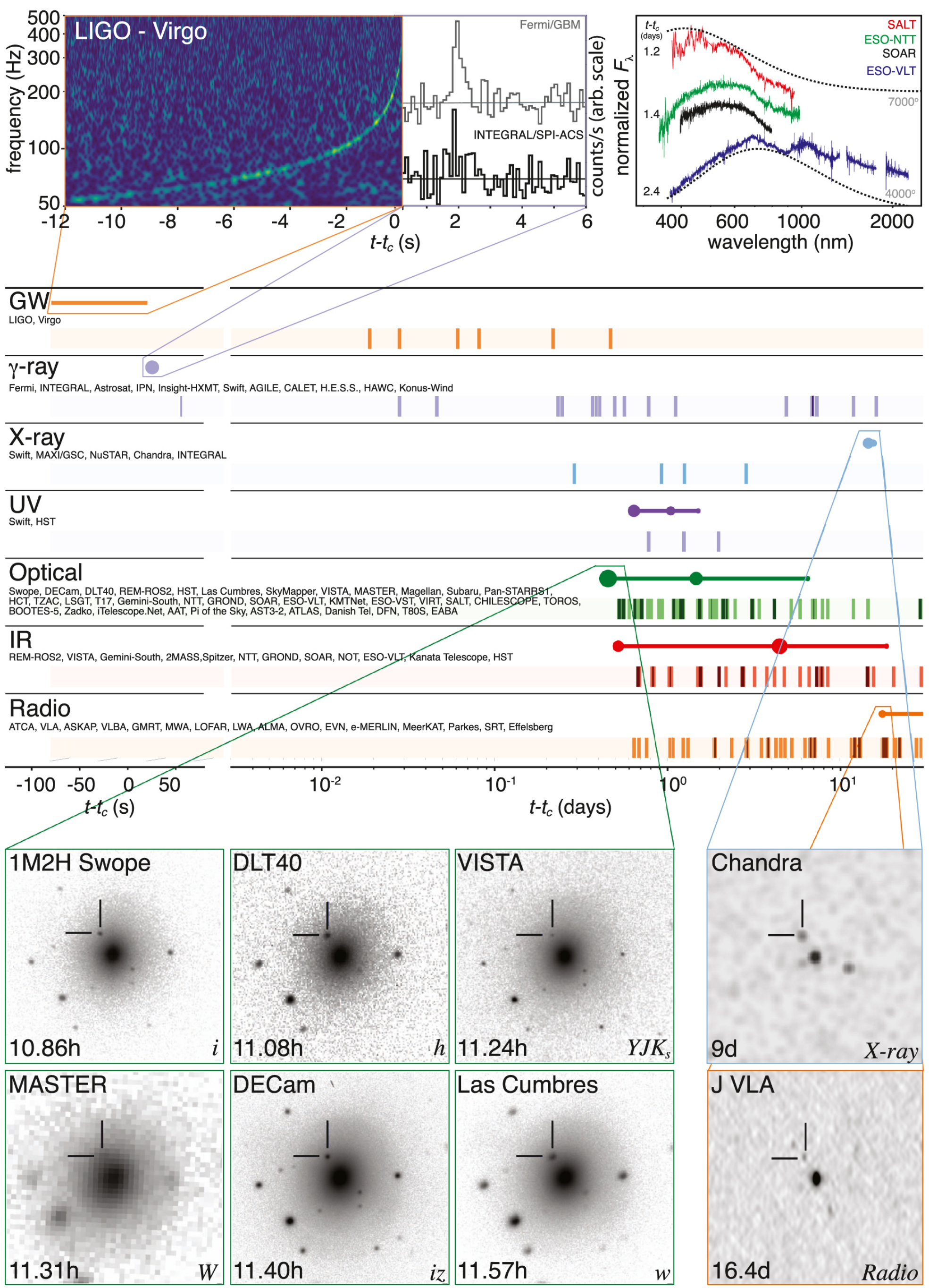


Lamb+19

GW170817 Changed Everything!

- LIGO/Virgo detected a binary neutron star merger.
- INTEGRAL & Fermi detected a (weak) short GRB.
- An optical/nIR transient was discovered in NGC 4993.
- A rising afterglow was later detected.



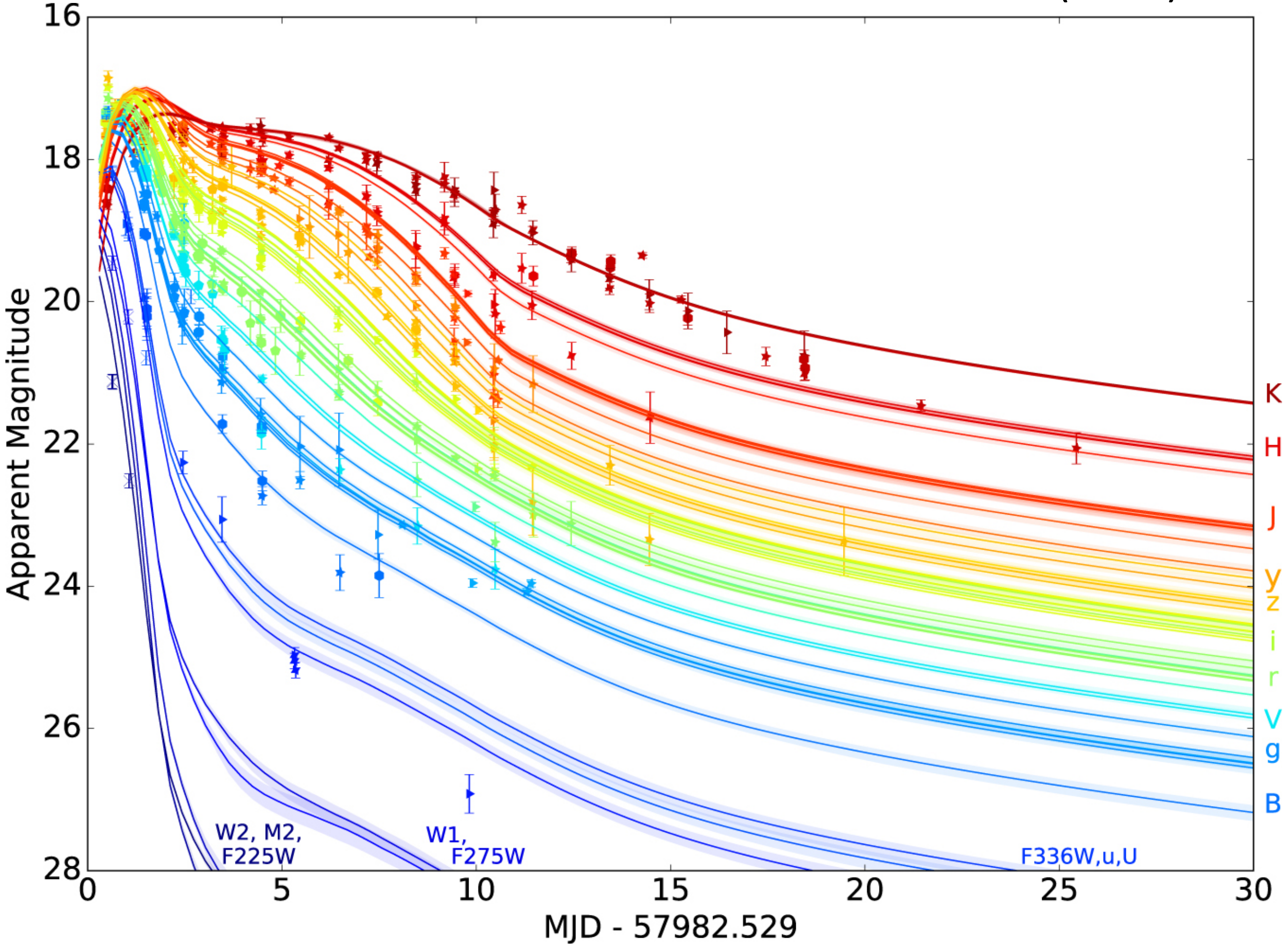


Abbot+17

A Unique Dataset

Figure 1. from The Combined Ultraviolet, Optical, and Near-infrared Light Curves of the Kilonova Associated with the Binary Neutron Star Merger GW170817: Unified Data Set, Analytic Models, and Physical Implications
null 2017 APJL 851 L21 doi:10.3847/2041-8213/aa9c84
http://dx.doi.org/10.3847/2041-8213/aa9c84

Villar+ (2017)



Best fit with a multiple-component kilonova model:

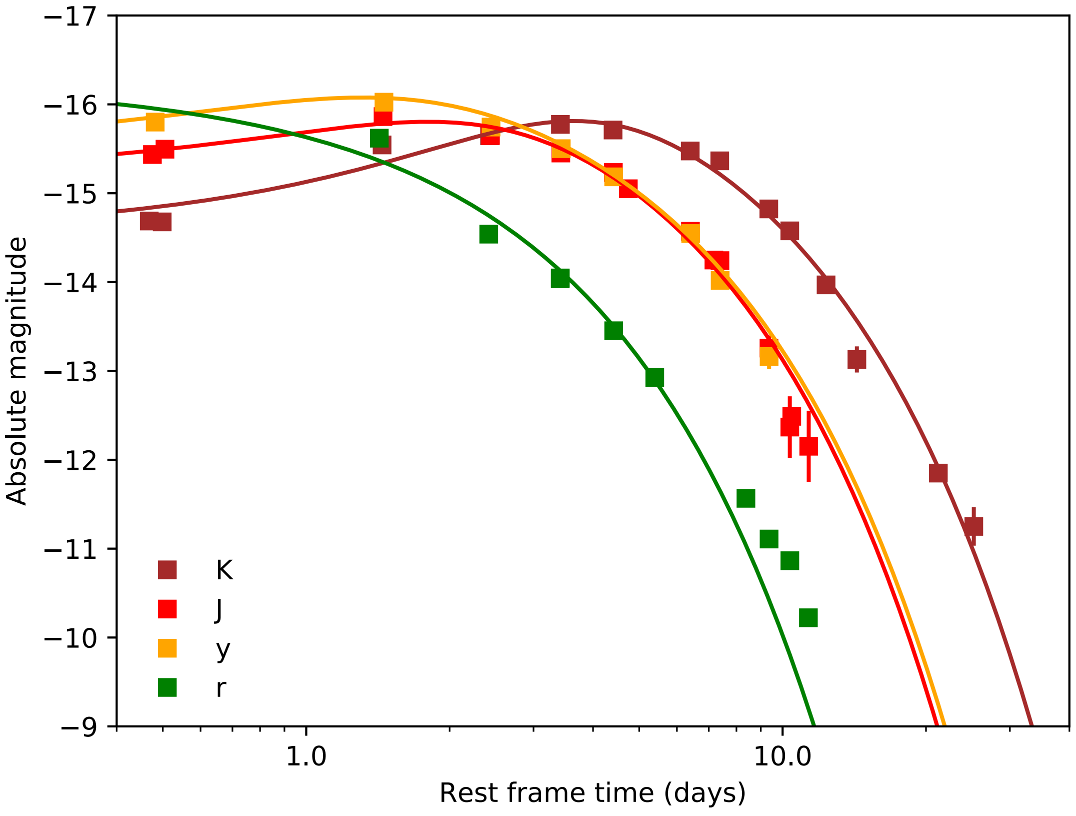
- ‘Blue’ lanthanide-poor dynamical ejecta from the poles (~ 0.02 Msol).
- ‘Red’ lanthanide-rich component from a disk wind (~ 0.01 Msol).
- A third ‘purple’ component (~ 0.05 Msol).
- Velocities between 0.1 – 0.3c, depending on the component.
- Other groups found a total ejecta mass of between 0.02 – 0.06 Msol (e.g. Kasliwal17+; Kilpatrick17+; Tanaka 17+).

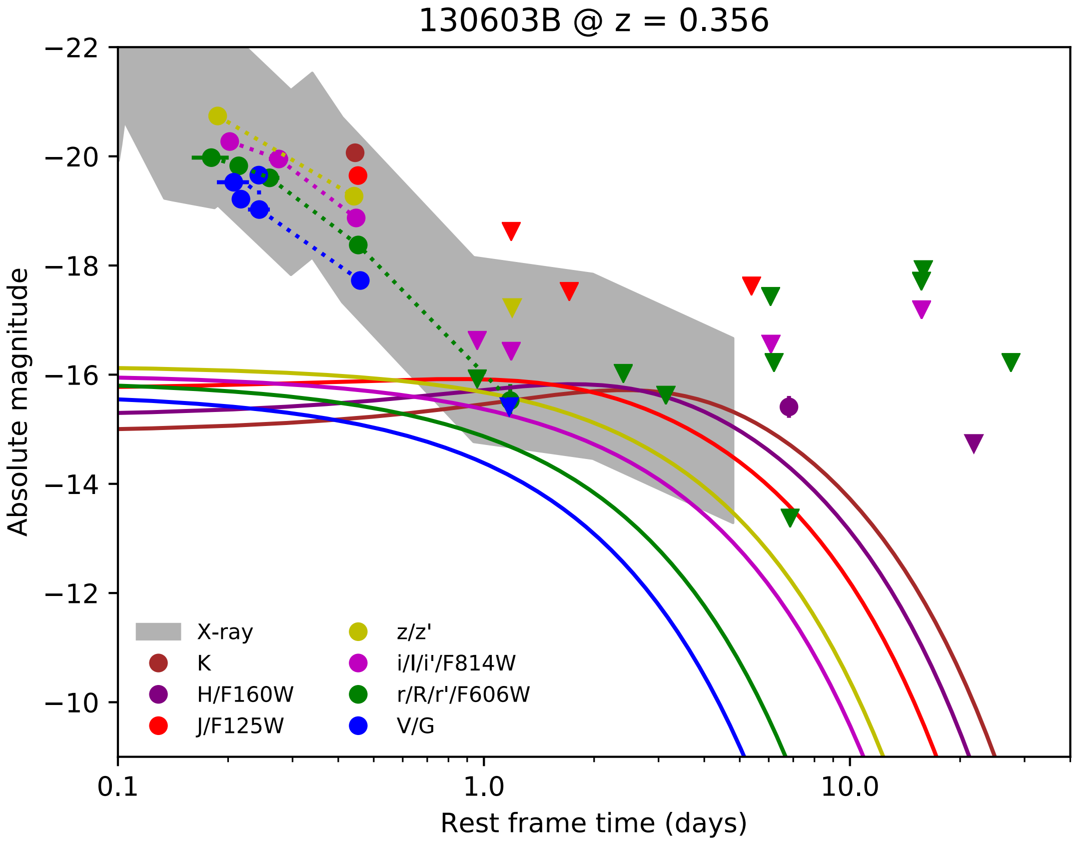
A Template for Short GRBs

We took simple Bazin fits of the VISTA observations (Tanvir+17), supplemented by UVOT detections (Evans+17).

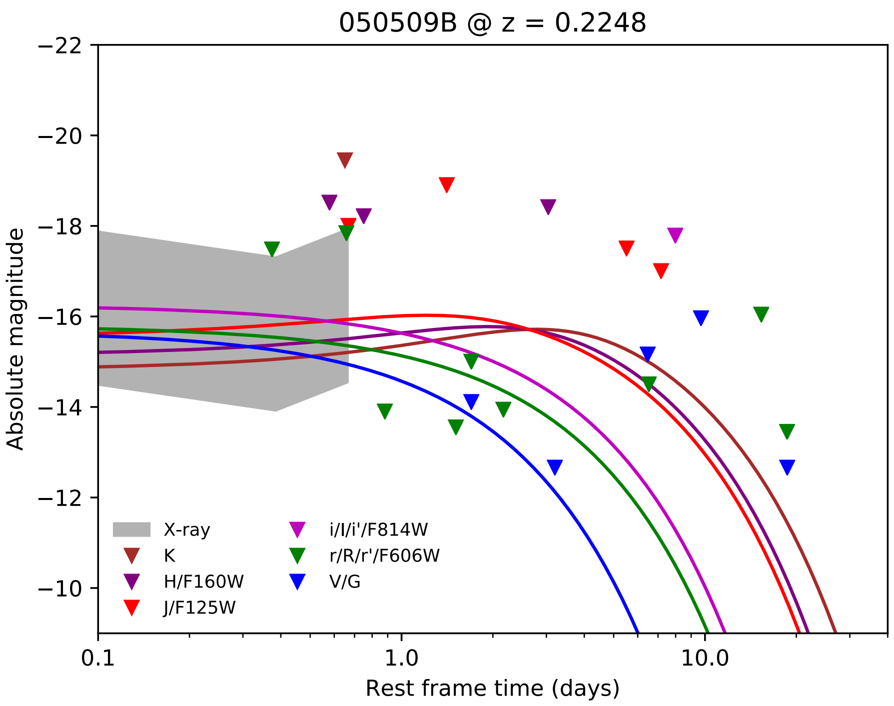
This template can be compared to short GRBs with known redshift.

Extra complication of the GRB afterglow to contend with.



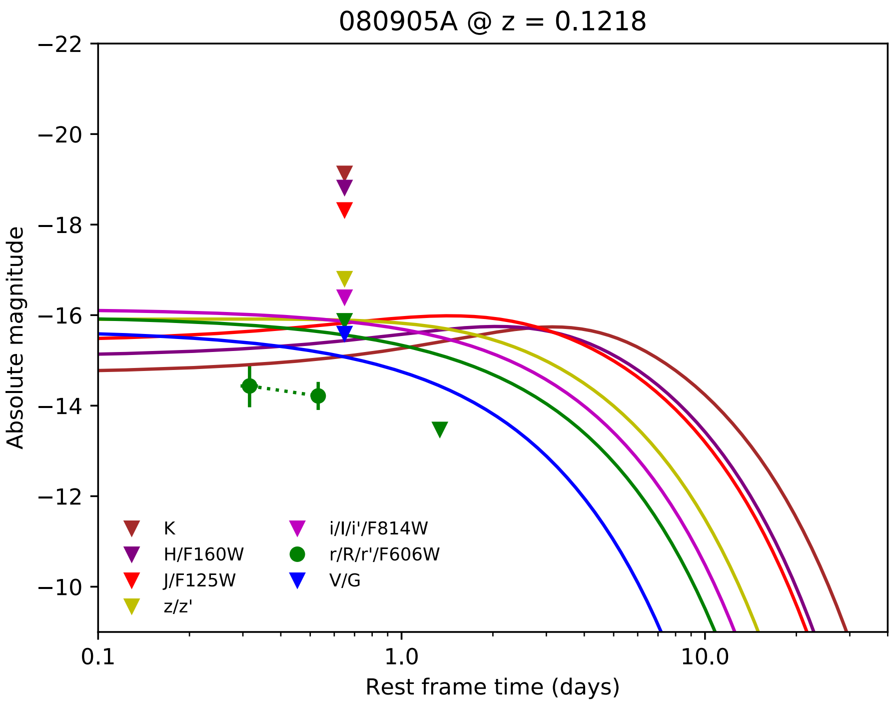


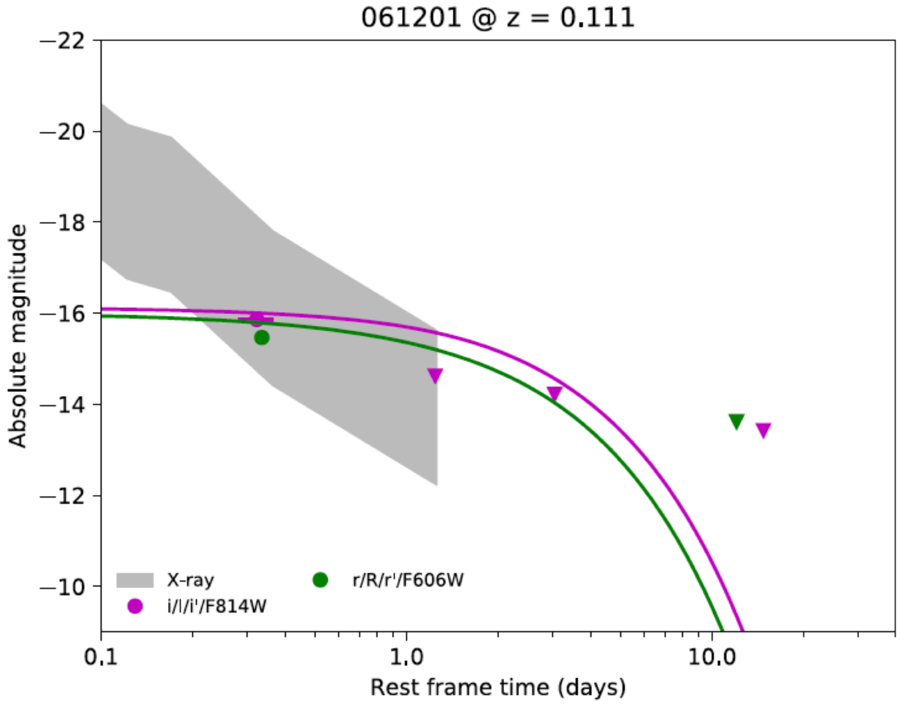
Missing Kilonovae?



NB:

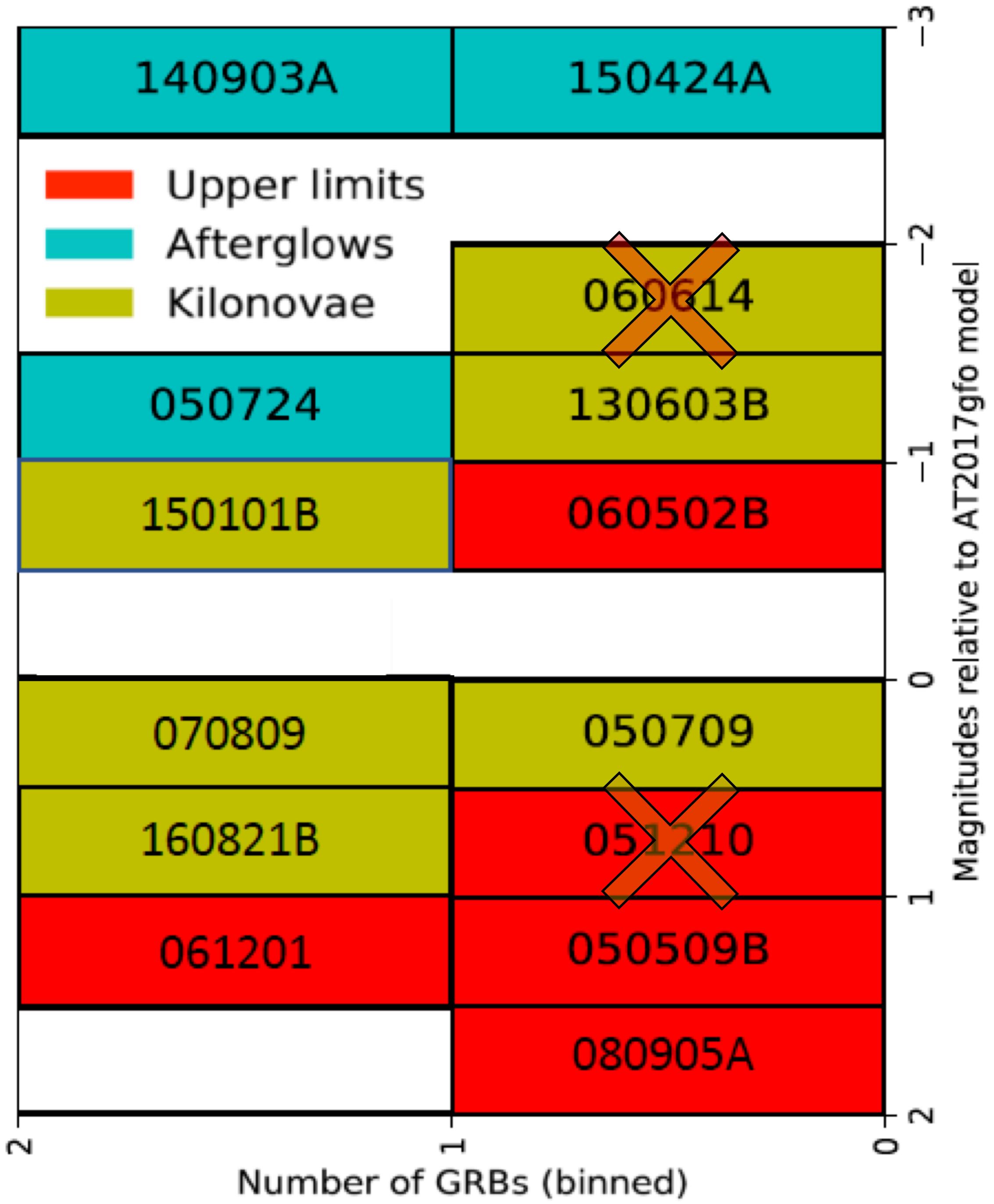
- Host galaxy absorption is not accounted for (not enough data for an SED).
- Redshifts are obtained by associating the afterglow with a galaxy in the field; misidentification of the host is possible.



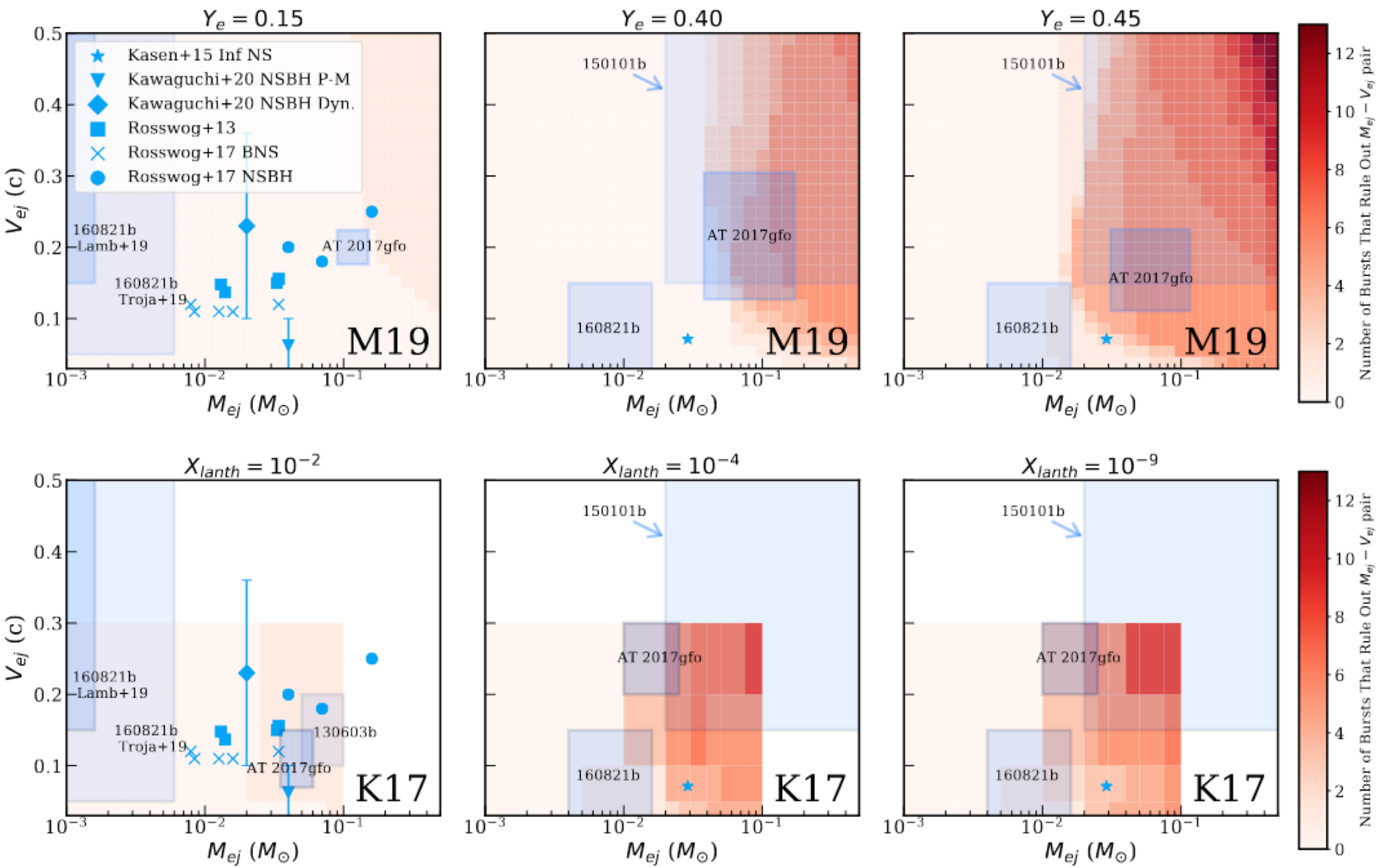


Diversity in SGRB Kilonovae

- The difference is unlikely to be the viewing angle (GRBs are pole-on).
- May be dictated by the binary parameters:
    - Mass ratio is influential
    - Higher ejecta mass → Brighter transient
    - Higher velocity/lower mass → Faster evolution
    - Higher opacity → Slower evolution
    - See Nicholl+2021
- Possibility of extra emission components?
- Some SGRBs with KNe (e.g. 130603B; 160821B) also have late X-ray excesses. Could reprocessed X-ray emission play a role? (e.g. Kisaka+2016).
- Is there another type of binary merger in play..?
- See also Ascenzi+19 for KN luminosity distribution



Recent Update



- Rastinejad+21 proposed a further 7 SGRBs with limits probing luminosities deeper than AT2017gfo.
- These limits are compared to two KN model grids here to assess constraints.

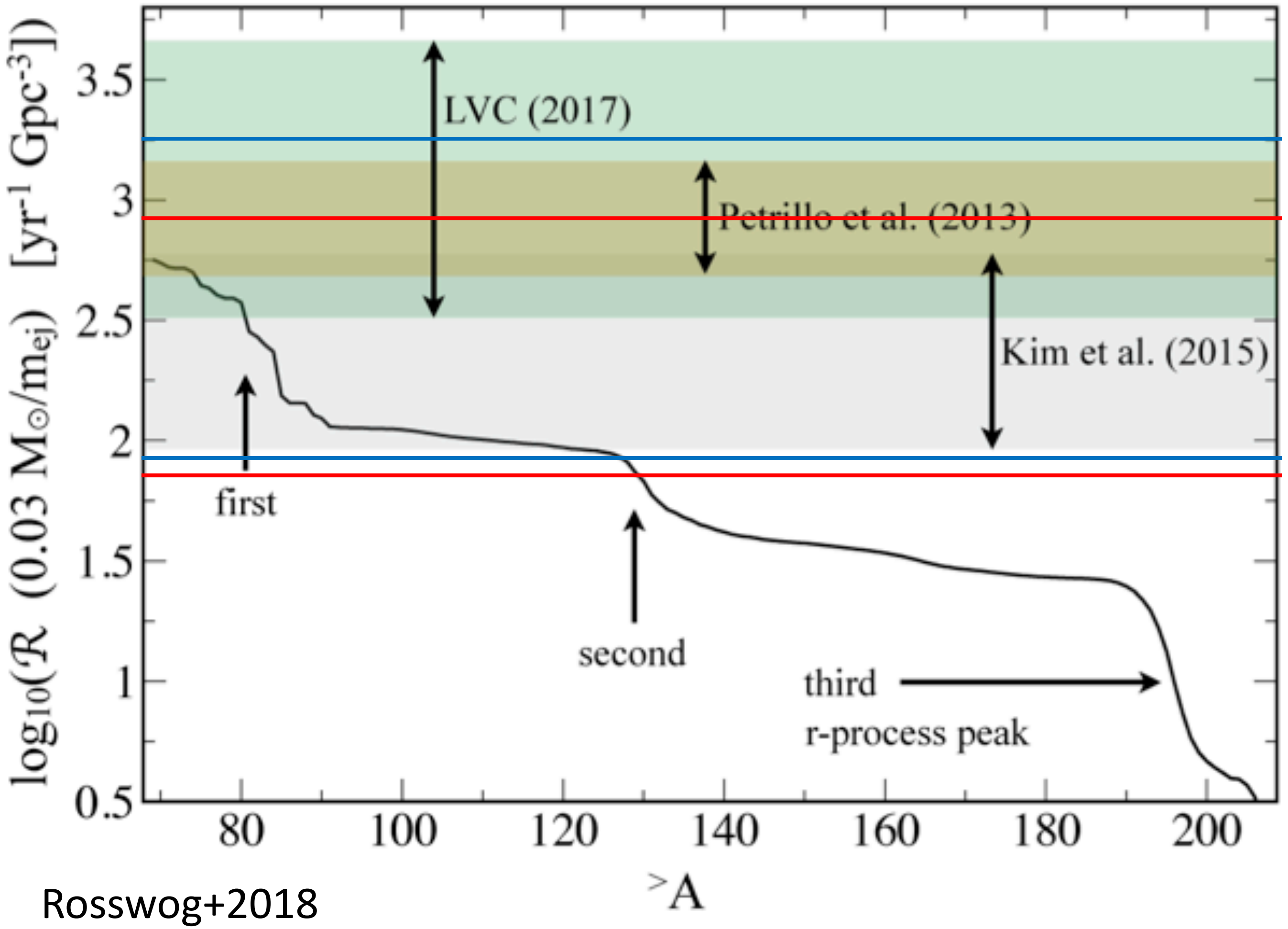
r-process Contribution

- The O3a rate density for BNS mergers was $320^{+490}_{-240}\ Gpc^{-3}yr^{-1}$ (Abbott+20)
- This is consistent with the beaming-corrected SGRB rate of $270^{+1580}_{-180}Gpc^{-3}yr^{-1}$ (Fong+15)

The derived rates are sufficient to produce all r-process (in solar proportions) assuming 0.03 solar masses of ejecta per merger (Rosswog+18).

However, converting a light curve into a yield is more complicated than just ejected mass!

There are lots of uncertainties in the modelling – particularly regarding GRBs.



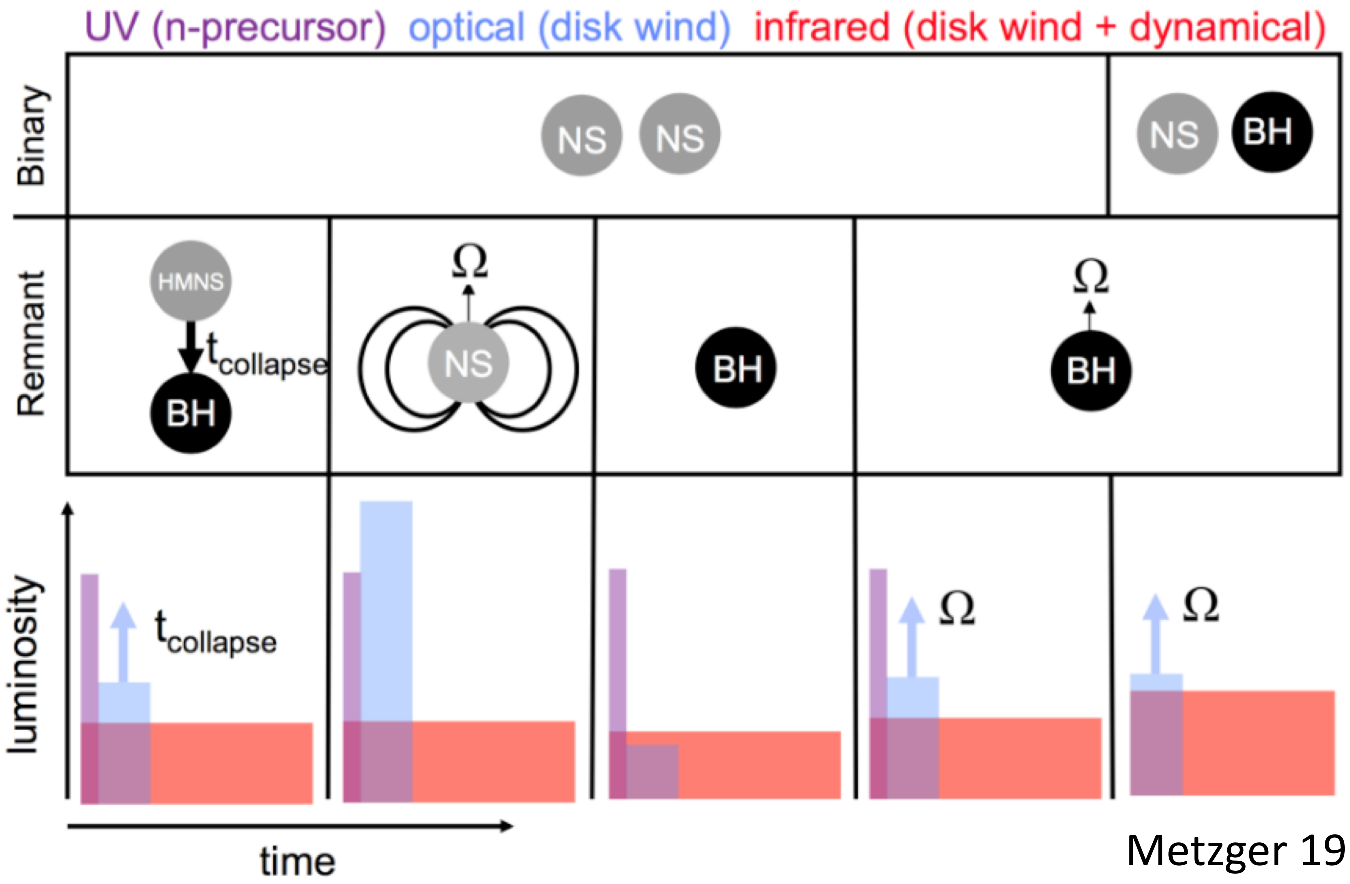
Rosswog+2018

Could NS-BH Mergers Contribute?

In theory, an NS-BH merger could launch a GRB jet if the NS is disrupted during inspiral.

We may expect a number of differences in the appearance of such a GRB:

- Longer durations? NS may be disrupted over several passages (e.g. Hotokezaka+13).
- Greater energy budget?
- Brighter, redder kilonovae? (see right).
- Differing locations on their hosts? The populations may have differing merger times and/or kick velocity distributions.



Metzger 19

A Search for NS-BH Mergers

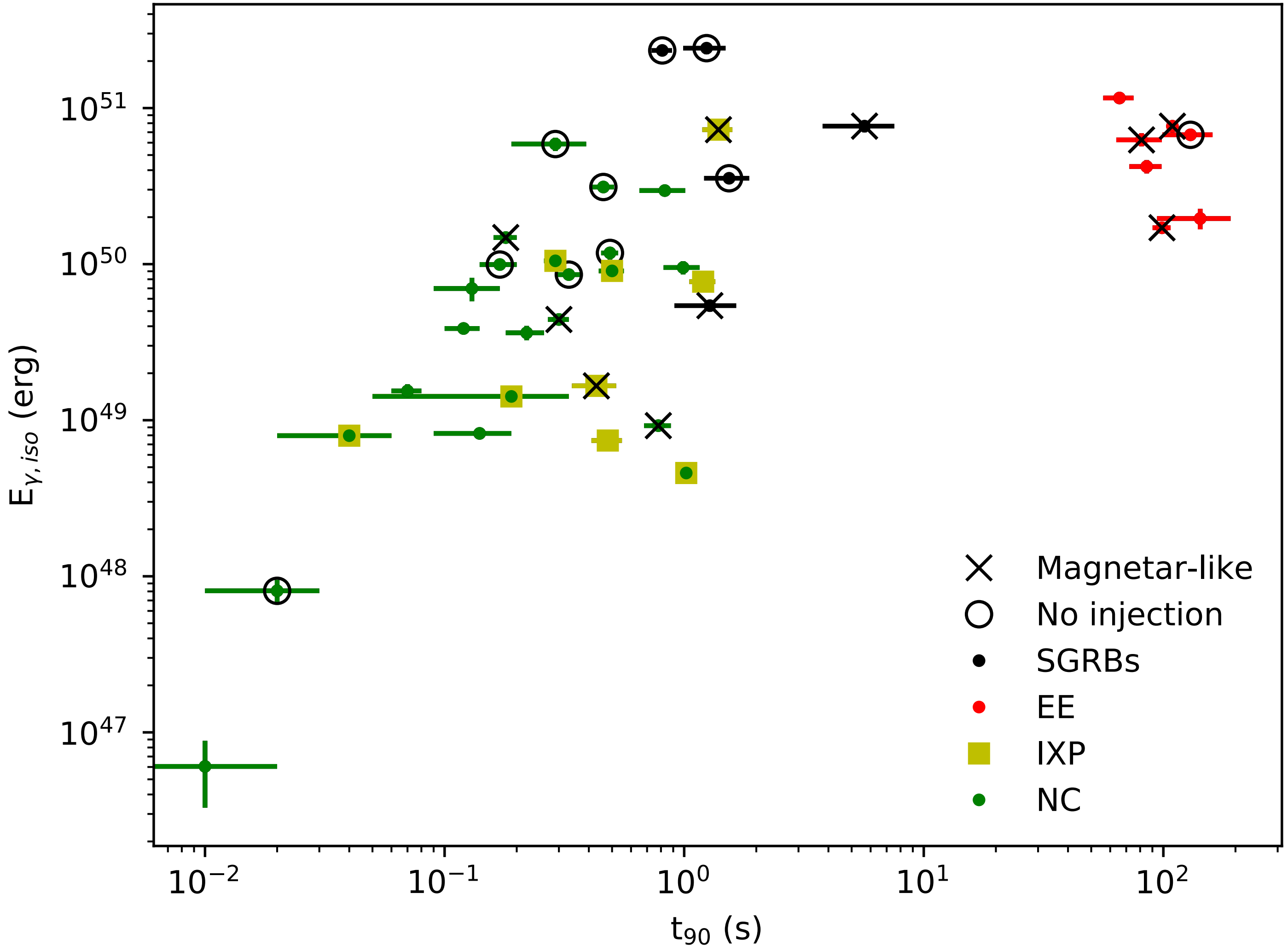
`Magnetar-like' – the afterglow is consistent with energy injection from dipole spin-down.

`No injection' – the afterglow follows standard synchrotron evolution.

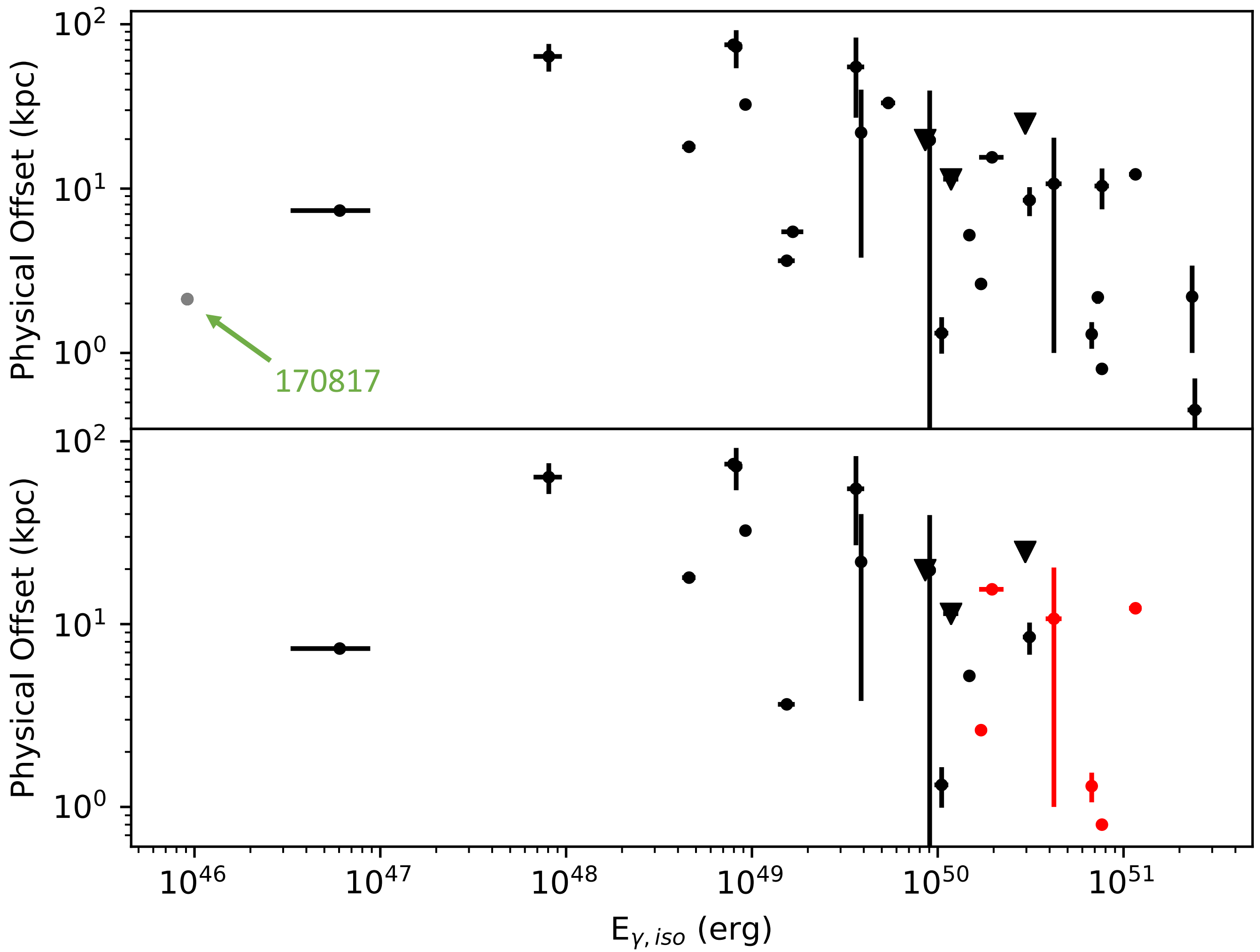
`EE' – Extended Emission. The prompt emission has a long, soft tail after the initial SGRB spike (Norris+ 2001, 2006, 2010).

`IXP' – Internal X-ray Plateau. The X-ray emission declines too steeply to be related to the afterglow forward shock. EE analogues.

`NC' – Non-collapsar. These bursts pass the `purity' criteria of Bromberg+13, designed to remove interloping LGRBs.



A Search for NS-BH Mergers



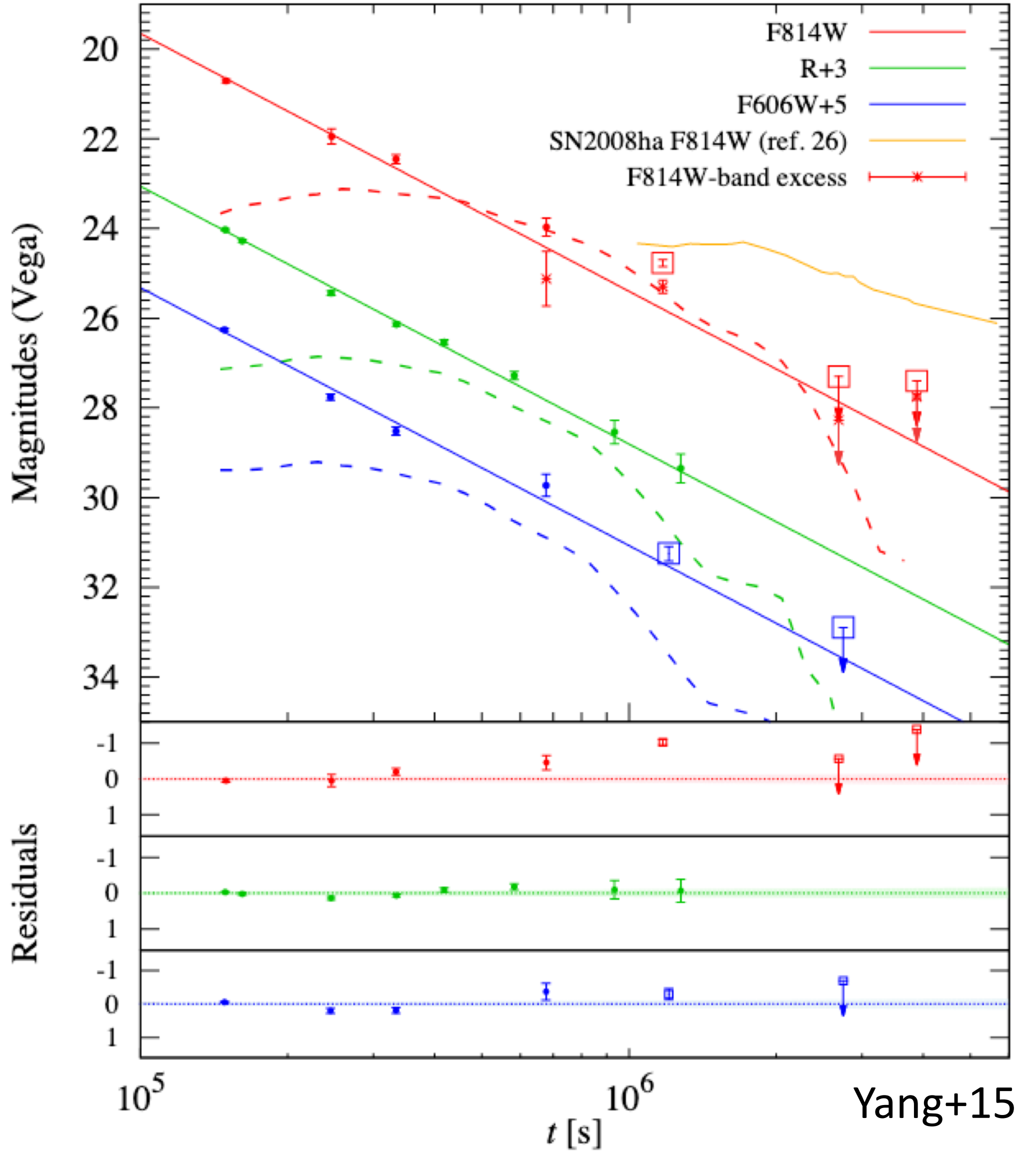
EE GRBs (red) show longer durations (by definition), and these durations are also sensitive to the measured band (unlike SGRBs and LGRBs).

In addition, they appear systematically closer to the cores of their host galaxies than do SGRBs.

However, the separation is only marginal in host-normalized units.

We also observe a strong anti-correlation between the prompt emission energy of a GRB and its offset from its host…

Clues from the KNe?



Yang+15

Of the EE sample, only 060614 has a KN candidate (Yang+15).

… and it may not even be a short GRB after all (Jespersen+20).

Two non-EE GRB KNe were reasonably fitted with NS-BH models: 050709 and 130603B

So not really!

- We need to establish the nature of the `IXP' – a possible intermediate class between EE and normal SGRBs.
- The host association of high offset GRBs also needs more investigation.
- We need more KN candidates!

Conclusions

- The r-process yield from individual BNS mergers may vary by a lot.

- The measured yields and rates are sufficient to account for all r-process (but there are a lot of uncertainties in both factors).

- We have tentative evidence for NS-BH mergers in the SGRB population.

- NS-BH contributions to the r-process add further uncertainty (rates, yields, etc).

- The locations of GRBs with respect to their galaxies matters a lot in the context of r-process enrichment. The scatter in their yields is also important.