GW170817/GRB170817A/AT2017gfo/afterglow: What did the first NS-NS merger event tell us?

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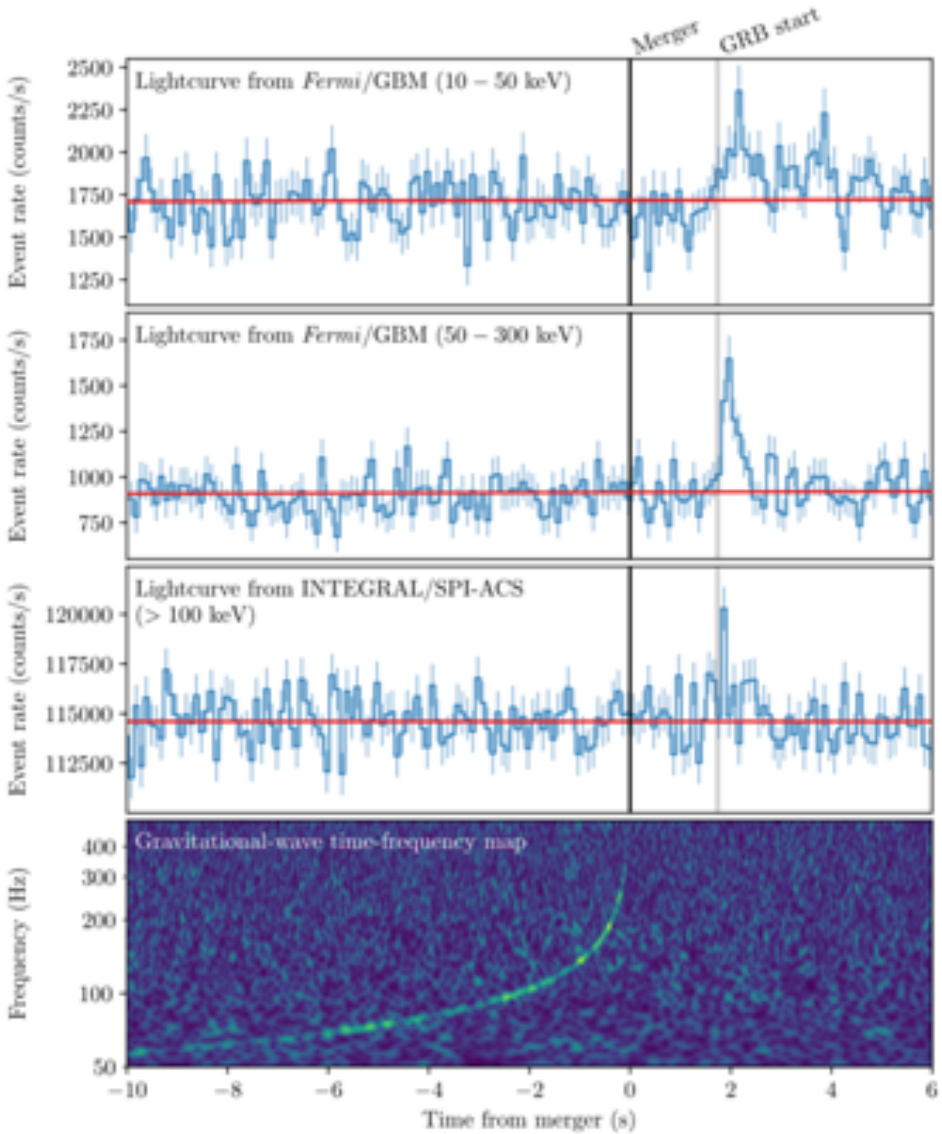
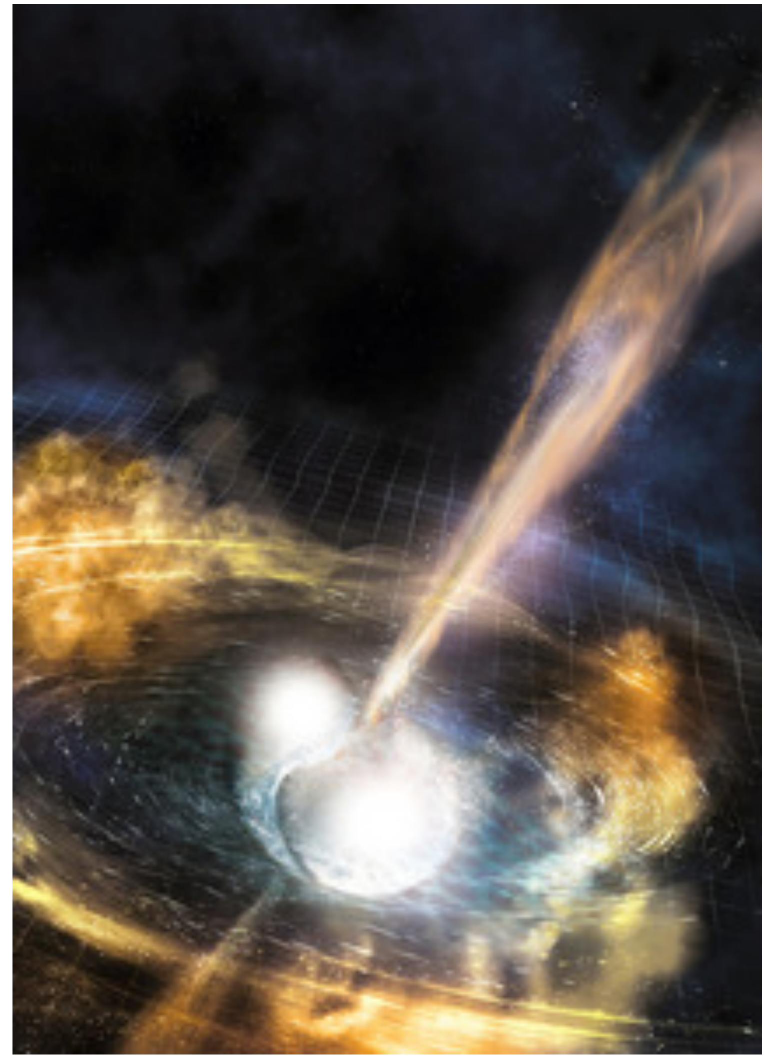
May 15, 2018

Third SVOM Workshop:
Disentangling the merging universe with SVOM

13-18 May 2018, Les Houches, France

Most beautiful figure in astrophysics: GW170817/GRB 170817A





Early theoretical models

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GAMMA-RAY BURSTERS AT COSMOLOGICAL DISTANCES

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Received 1986 May 12; accepted 1986 June 23

ABSTRACT

We propose that some, perhaps most, gamma-ray bursters are at cosmological distances, like quasars, with a redshift $z \approx 1$ or $z \approx 2$. This proposition requires a release of supernova-like energy of about 10^{51} ergs within less than 1 s, making gamma-ray bursters the brightest objects known in the universe, many orders of magnitude brighter than any quasars. This power must drive a highly relativistic outflow of electron-positron plasma and radiation from the source. The emerging spectrum should be roughly a black body with no annihilation line, and a temperature $T \approx (E/4\pi r_0^2 \sigma)^{1/4}$. As an example the spectrum would peak at about 8 MeV for the energy injection rate of $\dot{E} = 10^{51}$ ergs s^{-1} and for the injection radius $r_0 = 10$ km.

We propose that three gamma-ray bursts, all with identical spectra, detected from B1900+14 by Mazets, Golenetskii, and Gur'yan and reported in 1979, were all due to a single event multiply imaged by a gravitational lens. The time intervals between the successive bursts, 10 hr to 3 days, were due to differences in the light travel time for different images. The required mass of the lens is 10^{10} $M_{\odot}$, just right for a galaxy.

Subject headings: cosmology — gamma rays: bursts — gravitation

On various occasions very energetic phenomena that involved bare neutron stars were suggested for a variety of reasons. Haensel and Schaeffer (1982) calculated models of neutron stars with a phase transition in their structure leading to a release of 10^{48} ergs in a small fraction of a second and noticed a possibility of even more powerful events. Ostriker (1979) considered the fate of the inner cores of globular clusters where the dominant constituents may be neutron stars. From time to time neutron stars will collide, releasing up to 10^{53} ergs per event. The binary radio pulsar PSR 1913+16 will coalesce with its neutron star companion within about 10^8 yr as a result of gravitational radiation losses (Taylor and Weisberg 1982). The final stage is likely to be very violent, and again of the order of 10^{52} or 10^{53} ergs will be released. In all of these cases the details of a violent energy release are not known, and it is not clear at all that a significant fraction of energy will be radiated in the gamma-ray region. But it is not unreasonable to expect that some of these, or perhaps some other rare phenomena may generate enough gamma-ray energy. The frequency of events required by the available observations is very low: perhaps 1000 bursts per year per 10^{11} galaxies.

LETTERS TO NATURE

Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

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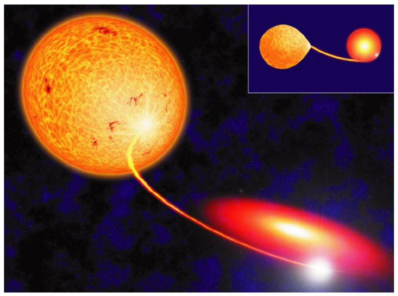
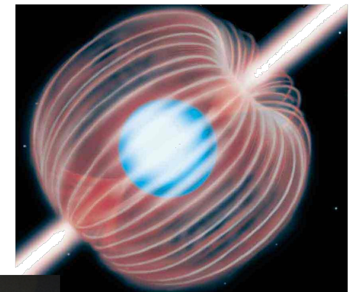
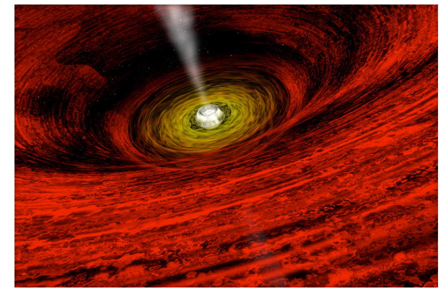
NEUTRON-STAR collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

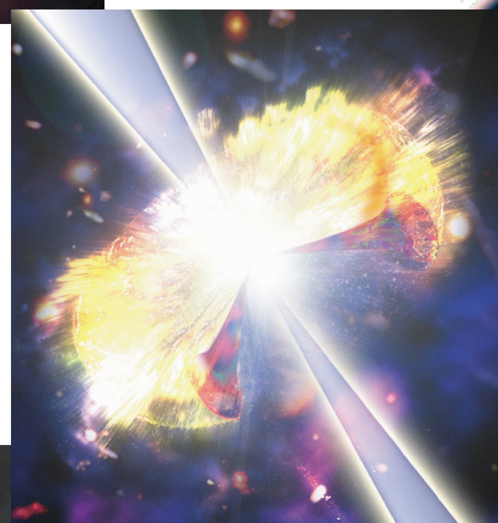
Astrophysical powers of Electromagnetic Radiation

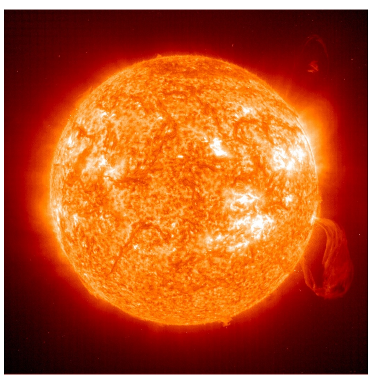
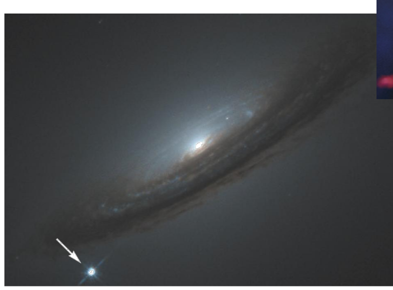



Gravitational

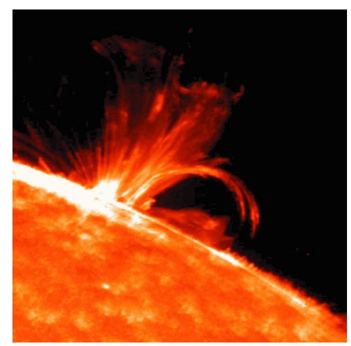
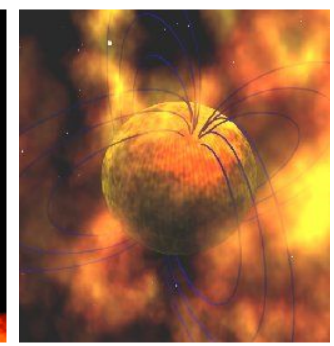



Rotational



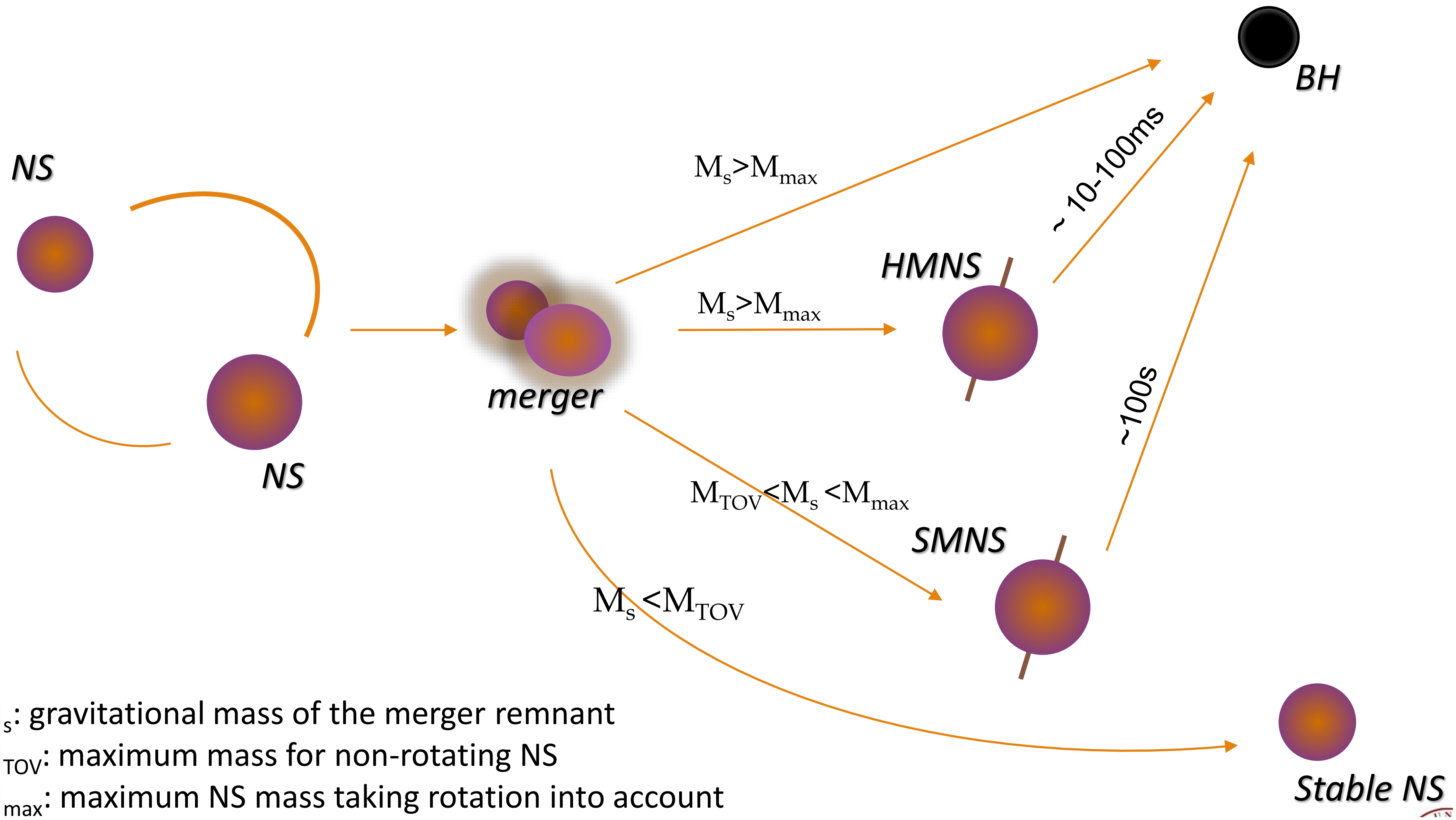



Nuclear

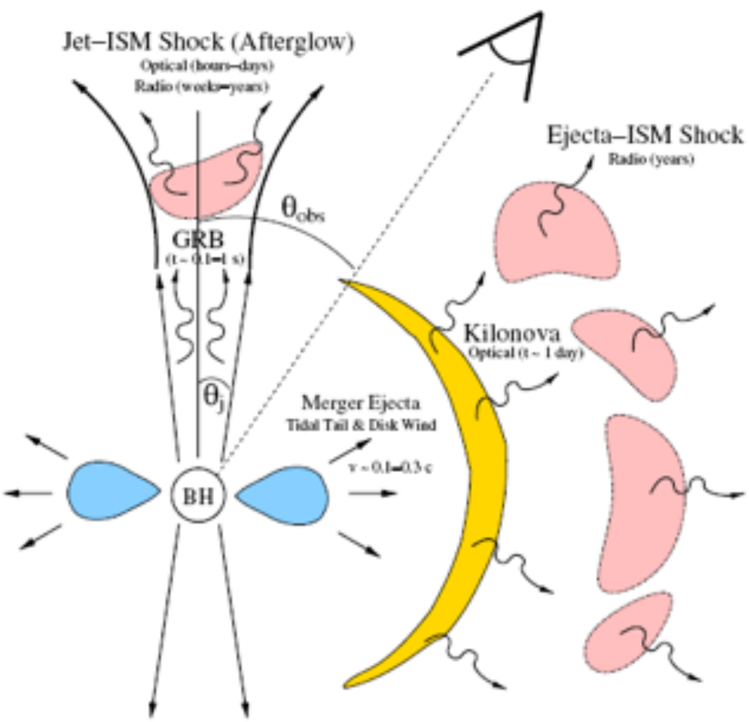
Magnetic

NS-NS mergers

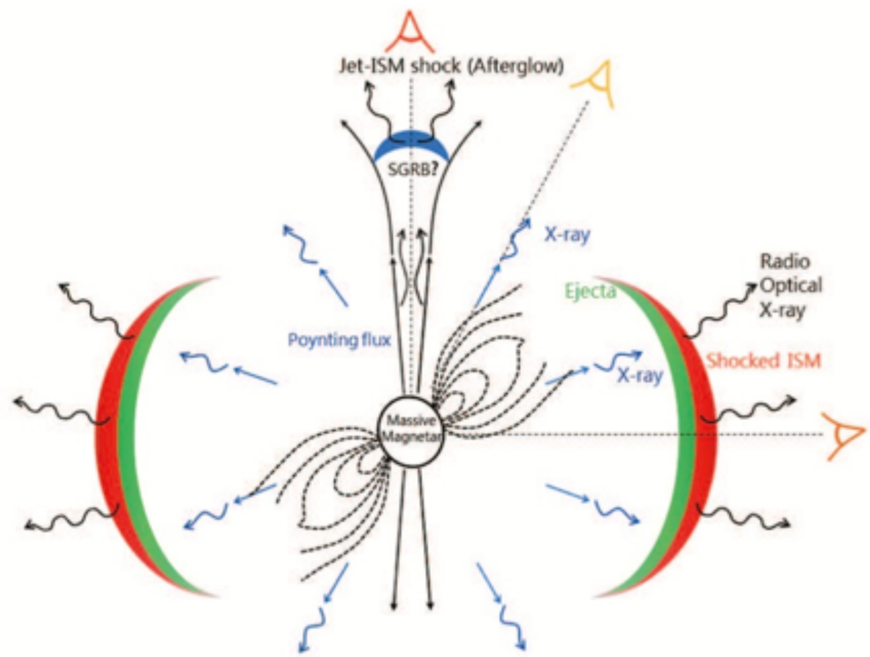


M_s: gravitational mass of the merger remnant
M_{TOV}: maximum mass for non-rotating NS
M_{max}: maximum NS mass taking rotation into account

NS-NS merger
EM counterparts

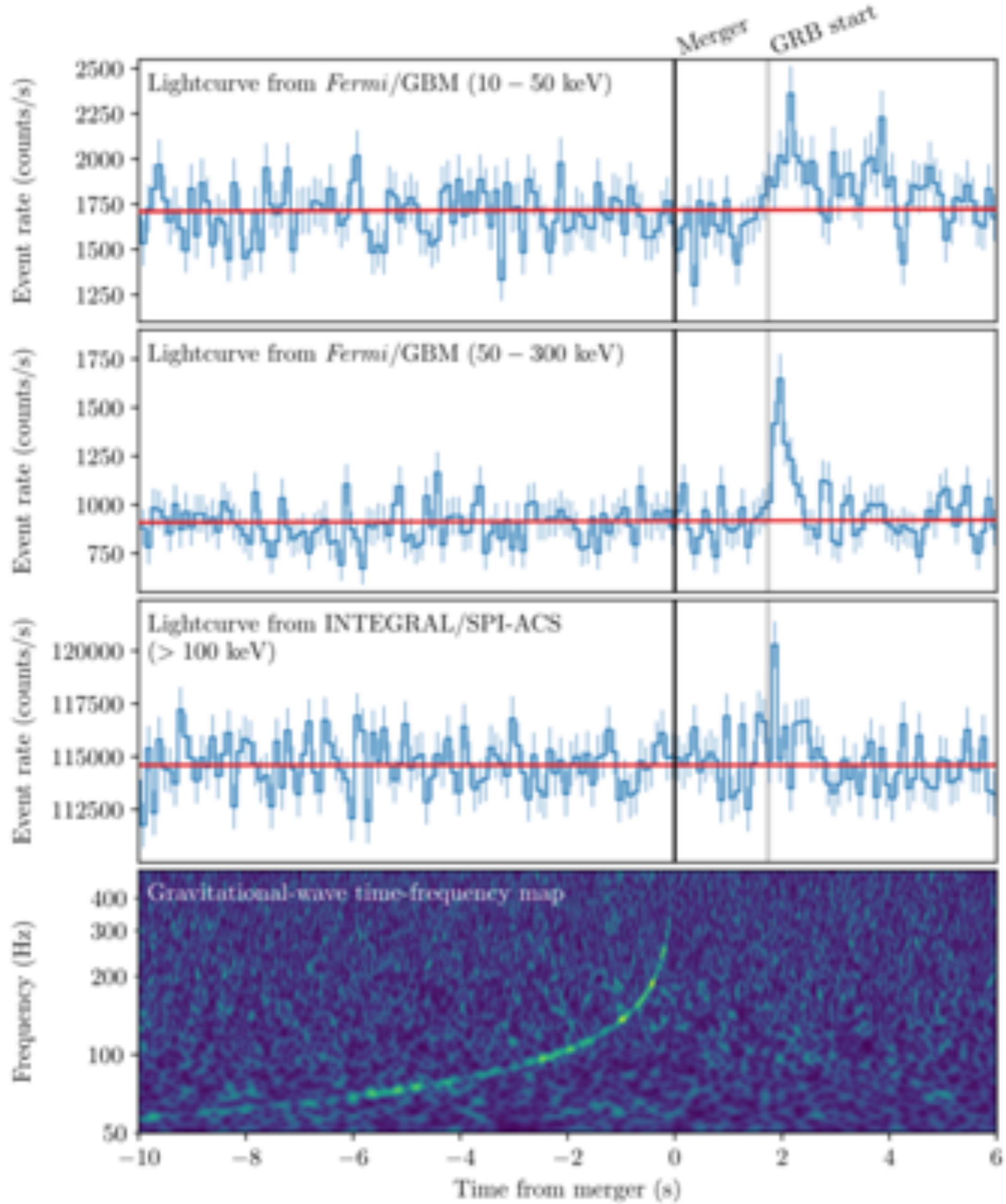


Metzger & Berger (2012)

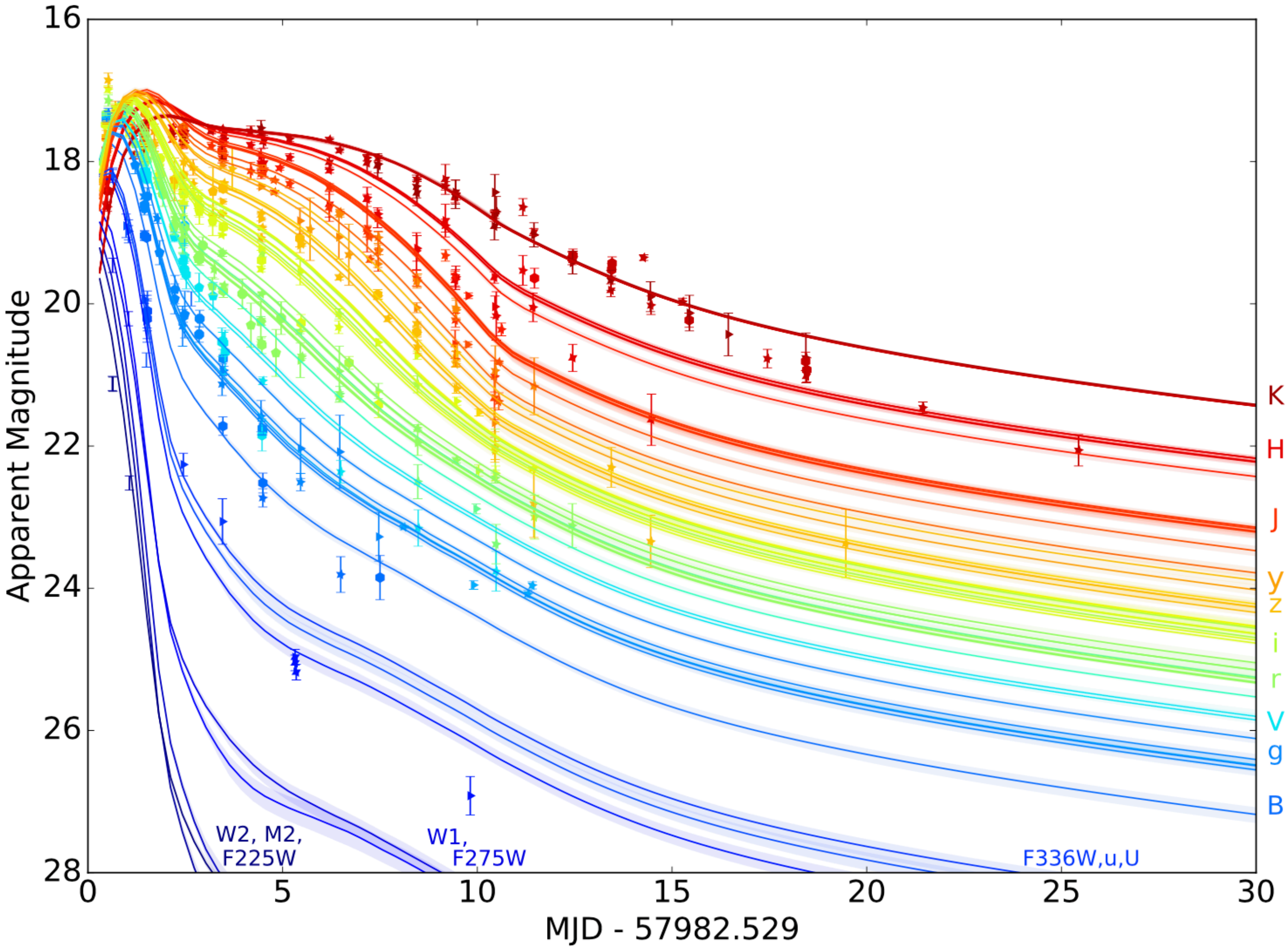


Gao et al. (2013)

GW170817/GRB 170817A

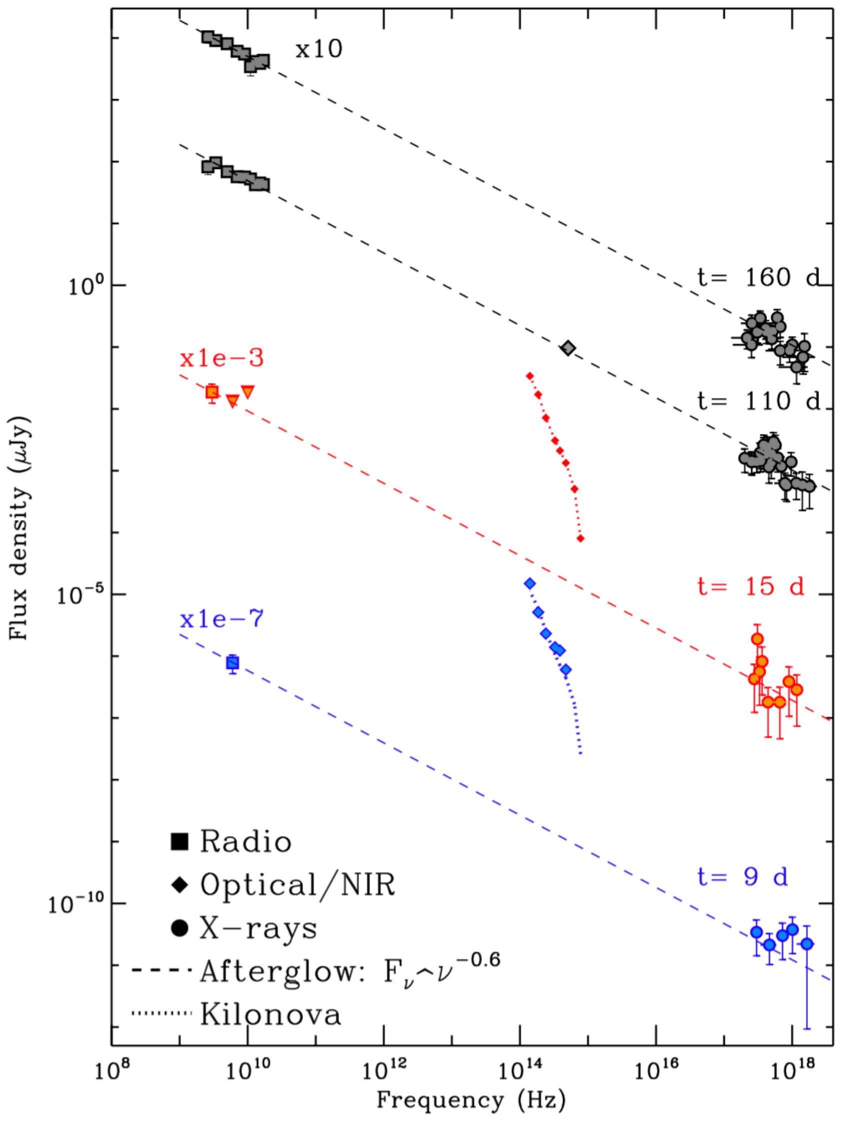


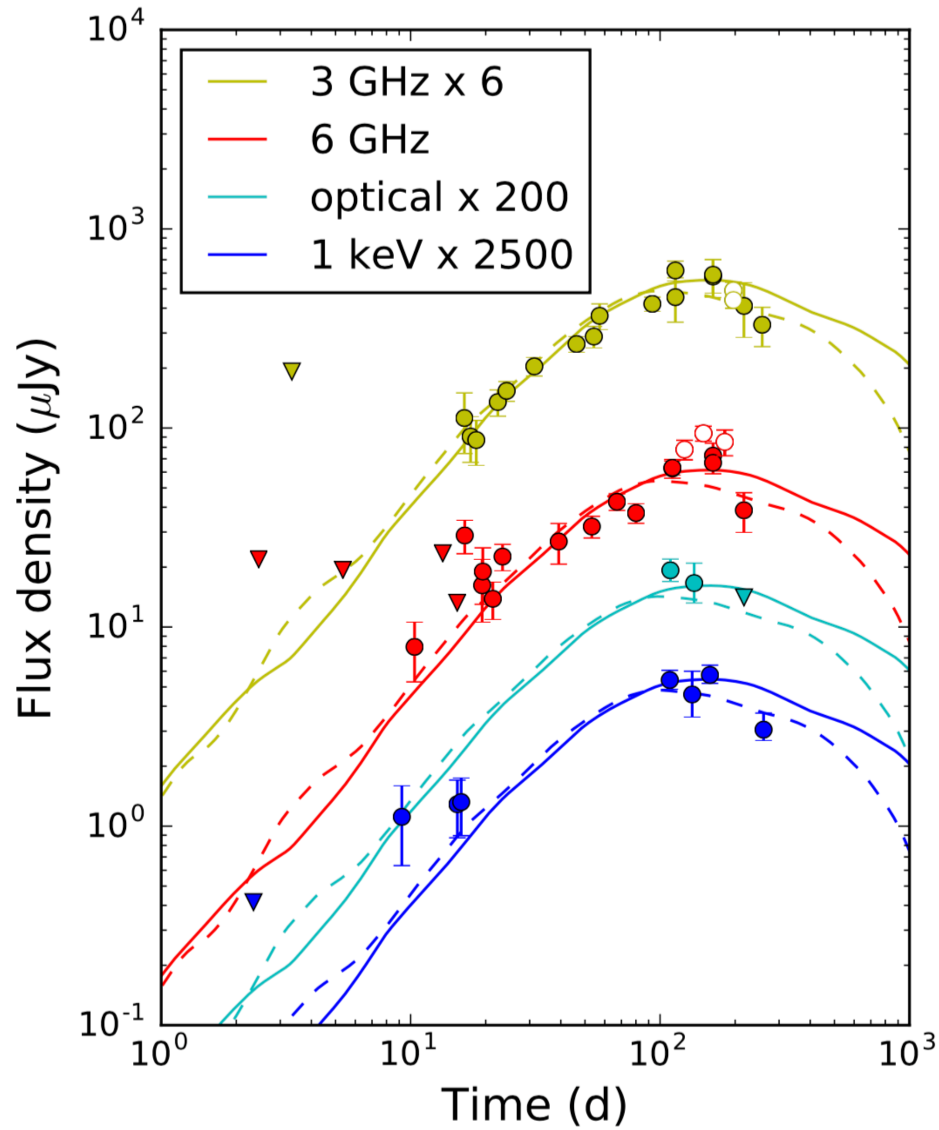
AT2017gfo



Villar et al. (2017): a collection of observations of many teams
Coutler et al.; Pian et al; Tanvir et al. …

Broad-band afterglow





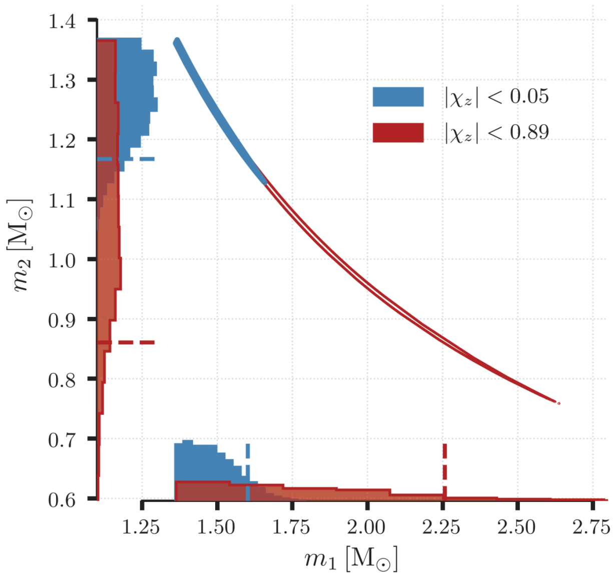
Margutti et al. (2018); Alexander et al. (2018): great power law in sky up to 160 days

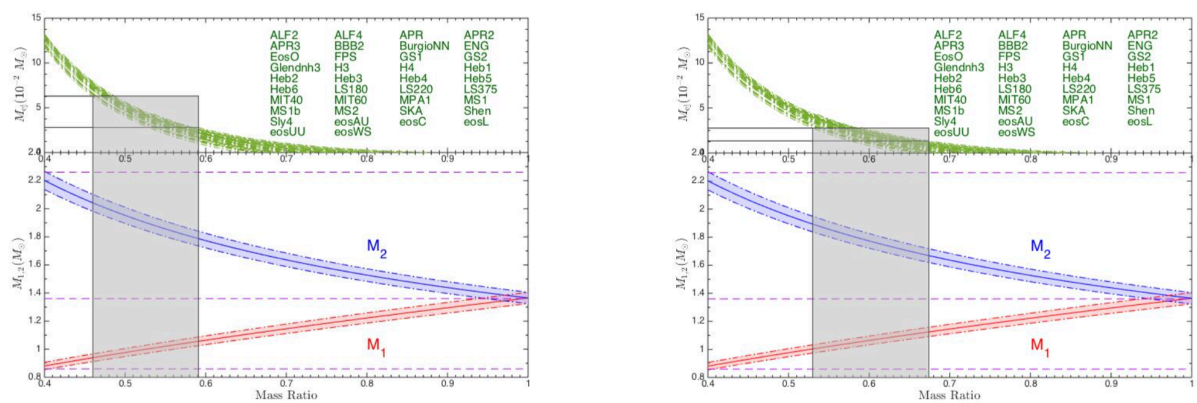
What did we learn from GW170817/GRB170817A/ AT2017gfo/afterglow?

GW170817

Abbott et al. 2017, PRL, 119, 161101; Chassande-Mottin's talk

	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400





Narrower mass ranges when ejecta mass constraint considered; Gao et al. (2017, ApJL, 851, L45)

Neutron star / quark star equation of state

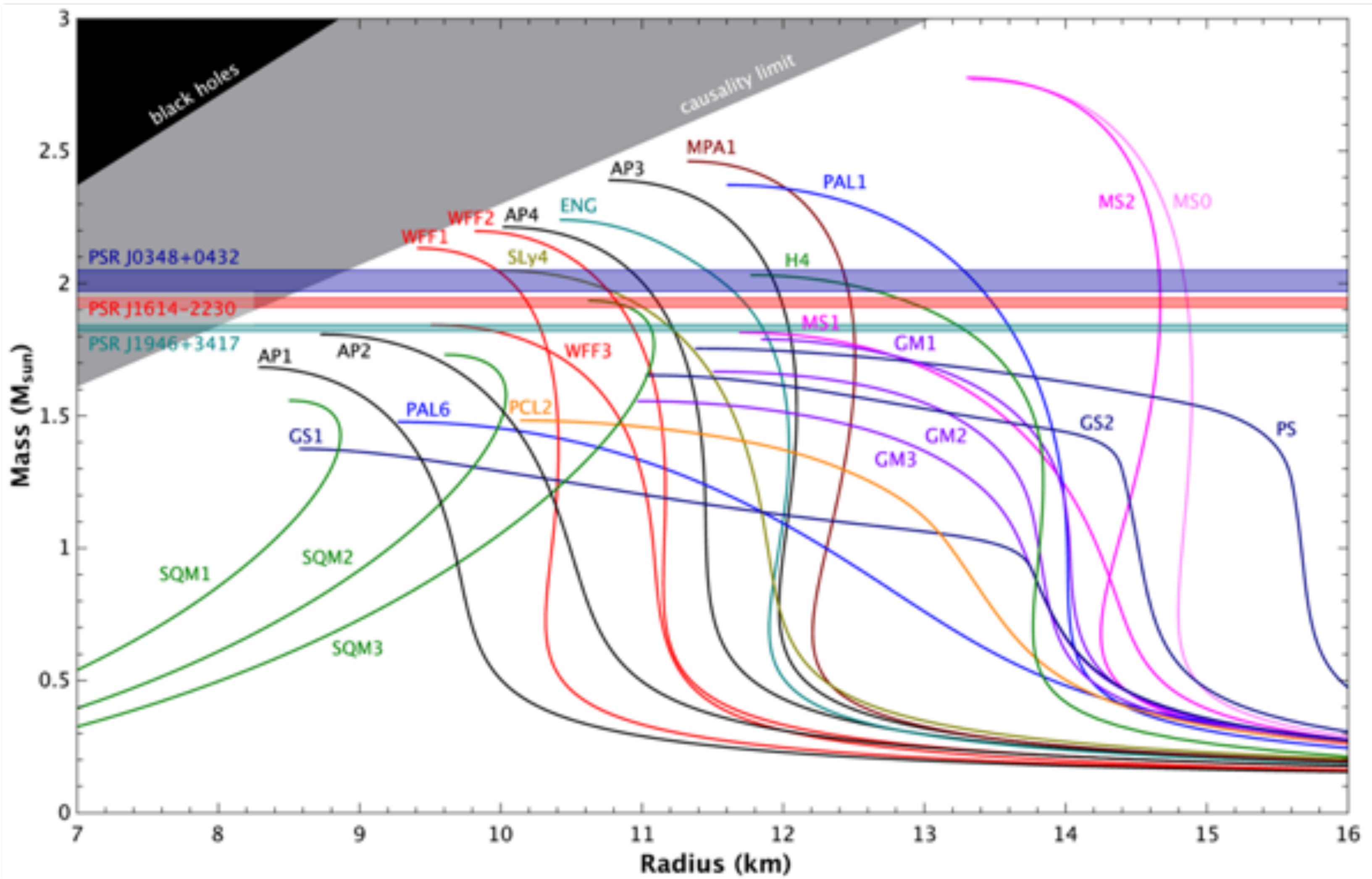
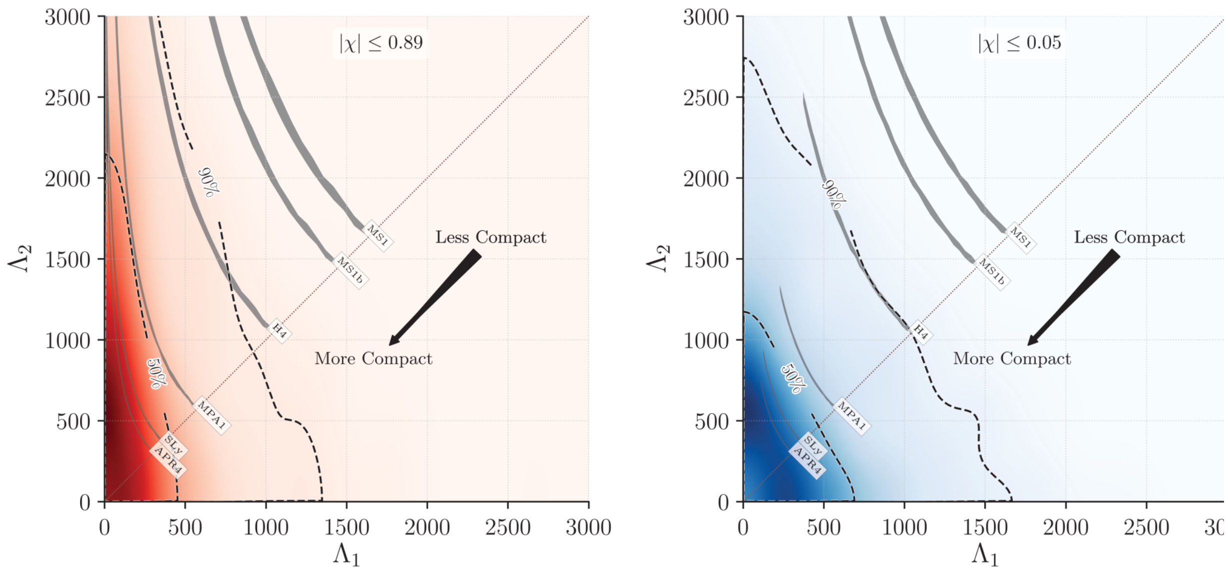


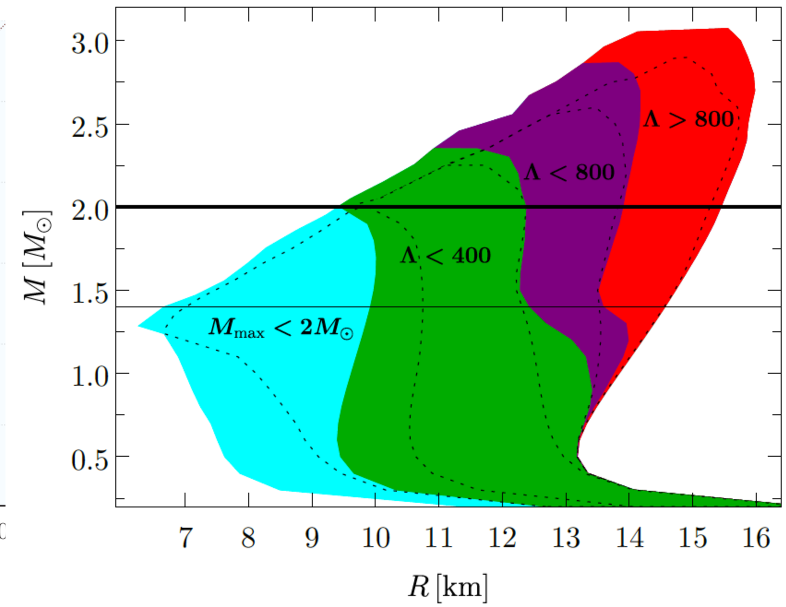
Figure by Norbert Wex. See http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

GW170817

Abbott et al. 2017, PRL, 119, 161101



Chassande-Mottin's talk



Annala et al. (2017)

$$\Lambda = \lambda / M^5 = \frac{2}{3} k_2 (R/M)^5$$

(tidal deformability)

$$\lambda = -Q_{ij}/\mathcal{E}_{ij} \quad k_2 = \frac{3}{2} G \lambda R^{-5}$$

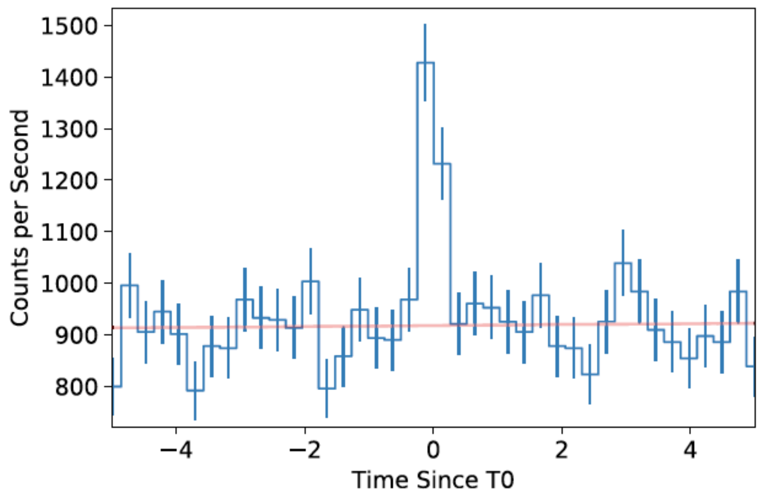
$\mathcal{E}_{ij}$: External quadruple tidal field

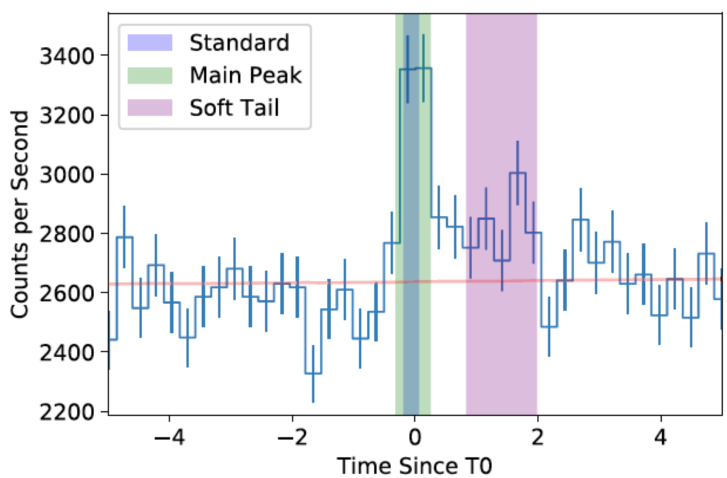
Q_{ij} : induced quadruple moment

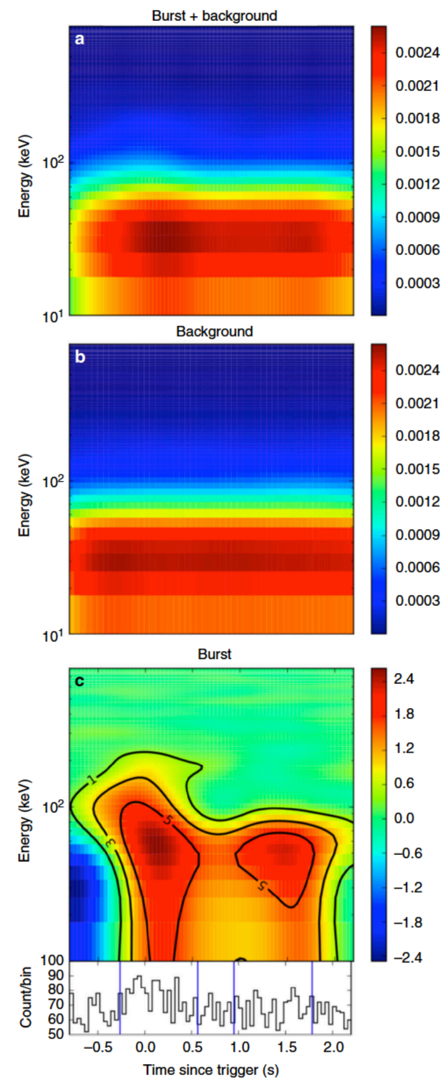
GRB 170817A:

lightcurves

Abbott et al. 2017, ApJL, 848, L13; Goldstein et al. 2017, ApJL, 848, L14
B.-B. Zhang et al. 2018, Nature Communications, 9, 447







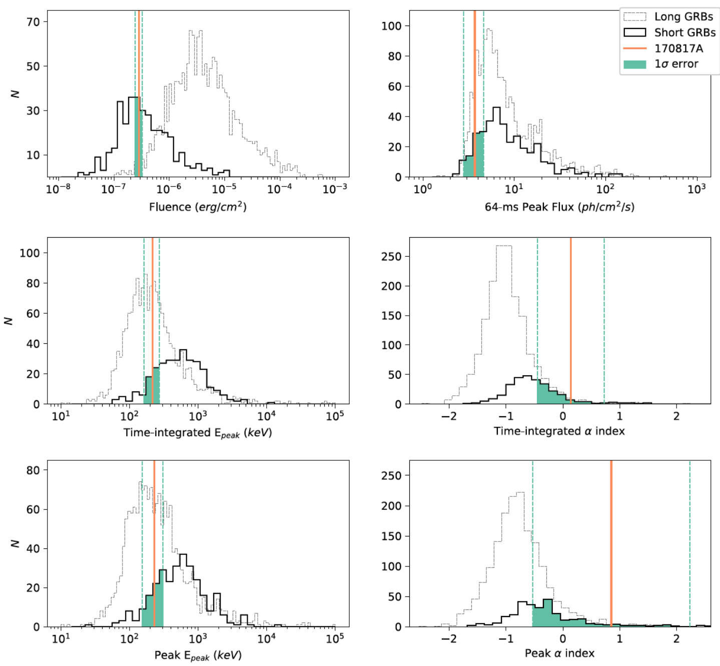
Piron's talk

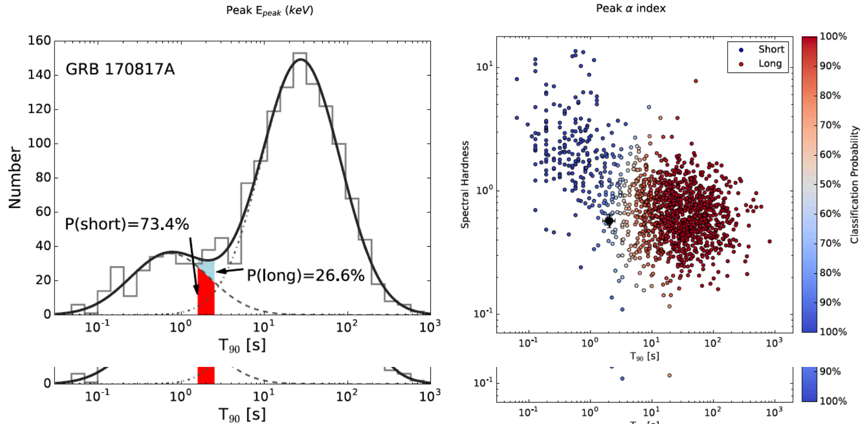
GRB 170817A:

“normal” observed properties

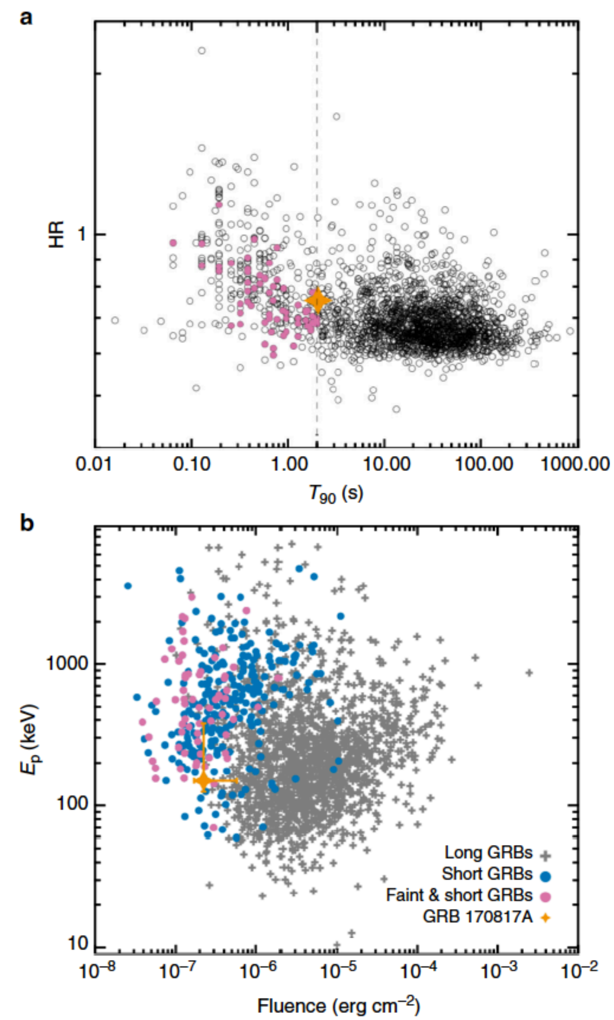
Goldstein et al. 2017, ApJL, 848, L14

B.-B. Zhang et al. 2018, Nature Communications, 9, 447





Piron’s talk

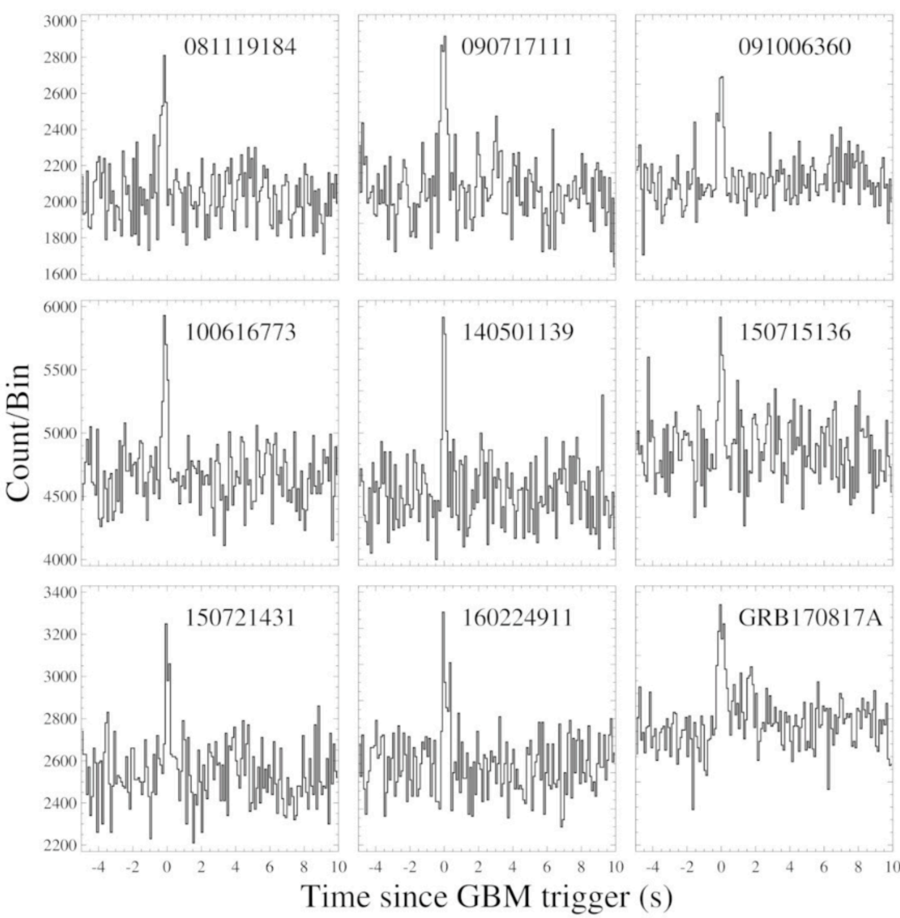


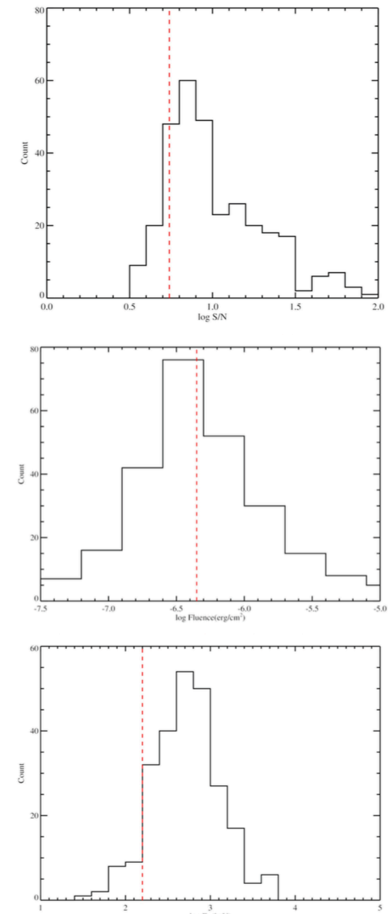
GRB 170817A:

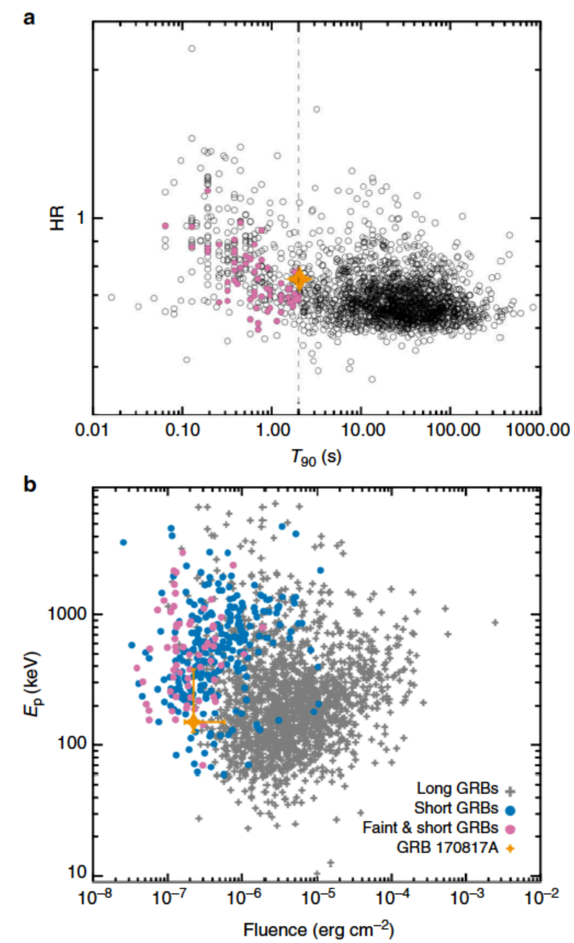
Similar events from GBM archives?

B.-B. Zhang et al. 2018, Nature Communications, 9, 447

Examples: GRB 170817A-like GRBs in GBM archives



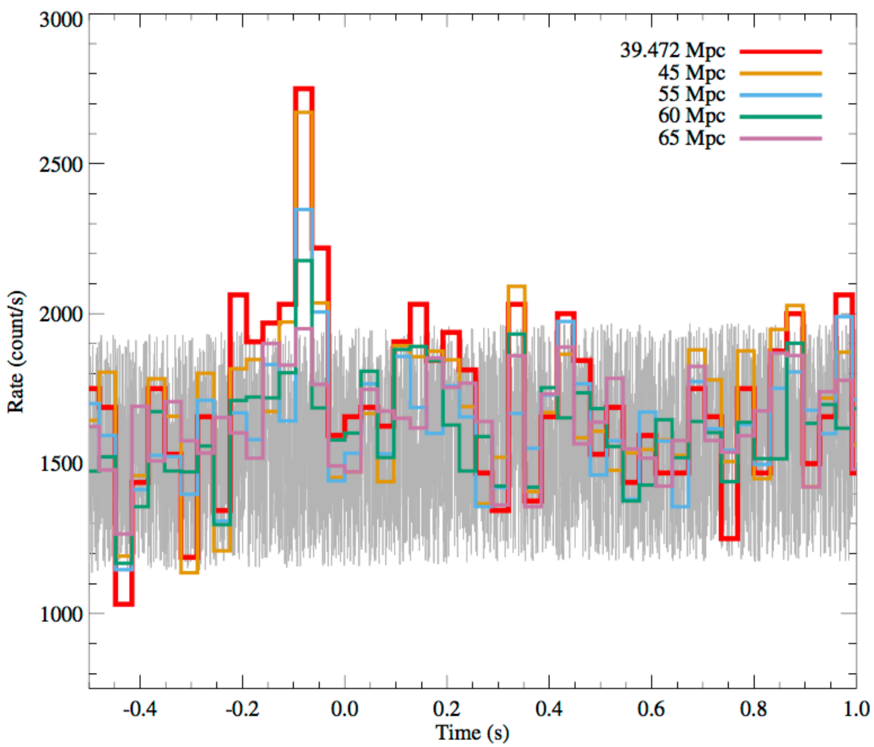


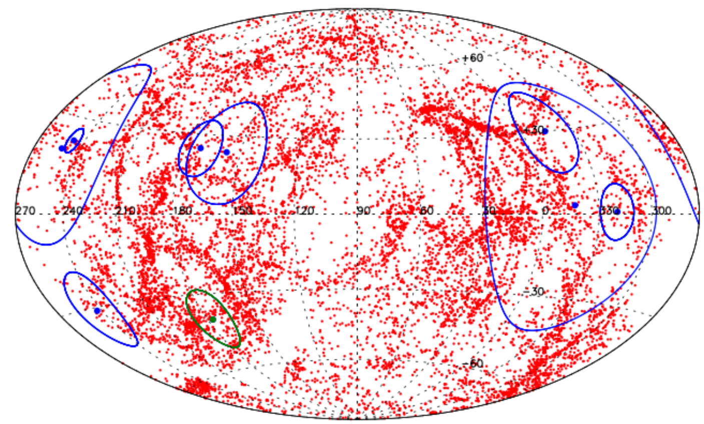


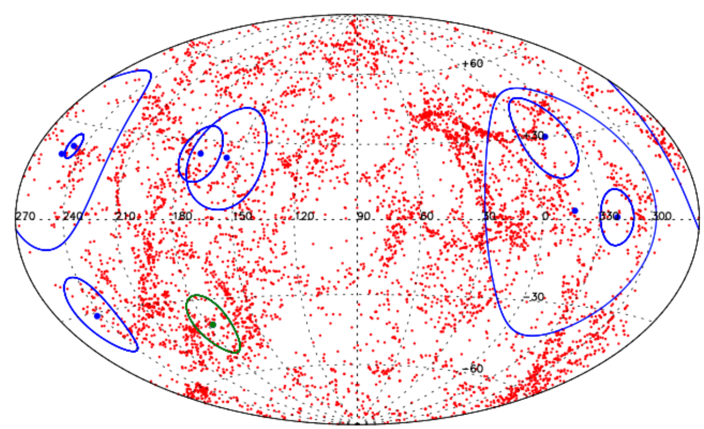
GRB 170817A:

Similar events from GBM archives? Can we identify them?

B.-B. Zhang et al. 2018, Nature Communications, 9, 447





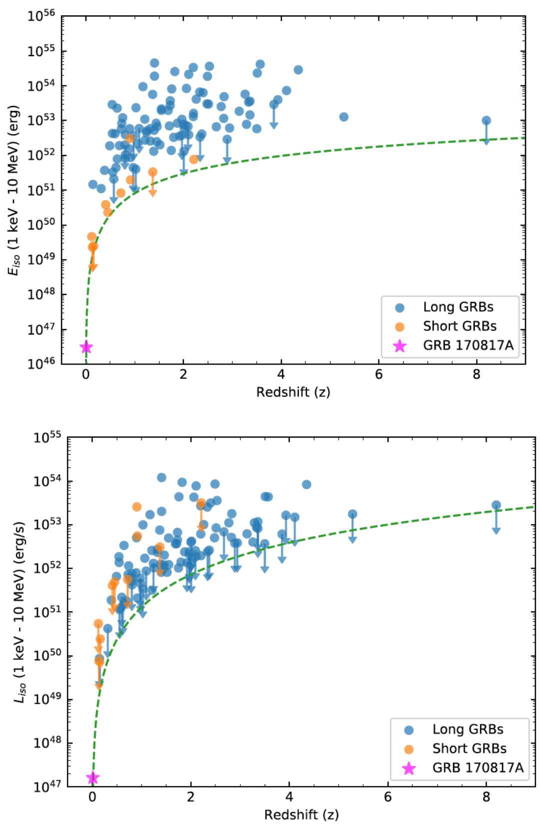


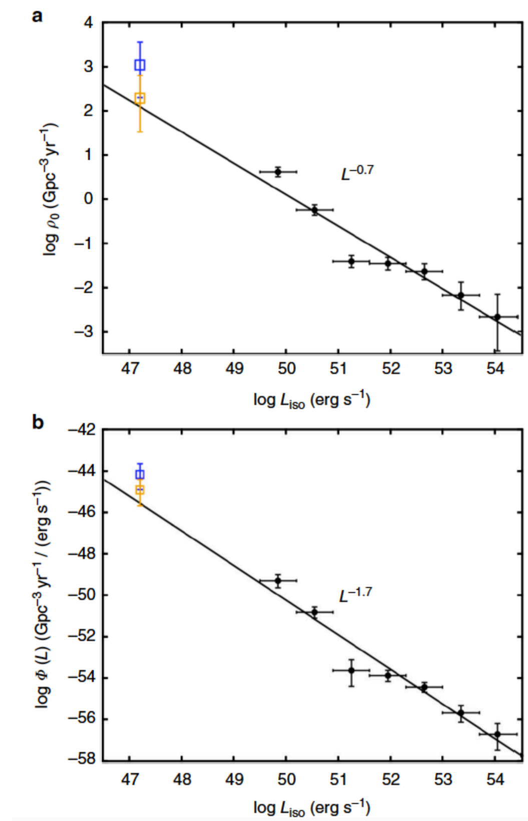
GRB 170817A:

“abnormal” luminosity & luminosity function

Abbott et al. 2017, ApJL, 848, L13

B.-B. Zhang et al. 2018, Nature Communications, 9, 447





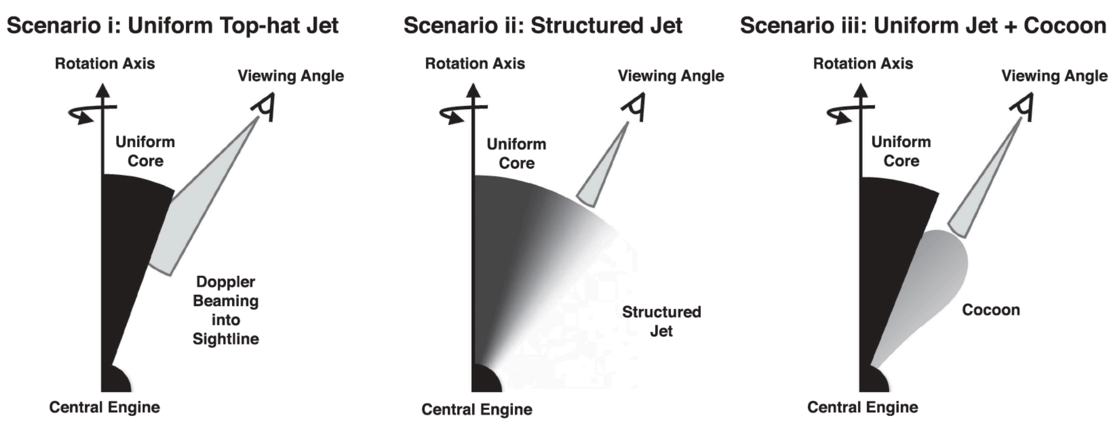
$$N_{\rm sGRB} = \frac{\Omega_{\rm GBM} T_{\rm GBM}}{4\pi} \rho_{0,\rm sGRB} V_{\rm max} = 1.$$

$$N_{\rm DNS} = \frac{\Omega_{\rm LVC}}{4\pi} \rho_{0,\rm DNS} (V_{\rm max,O1} T_{\rm O1} + V_{\rm max,O2} T_{\rm O2}) = 1.$$

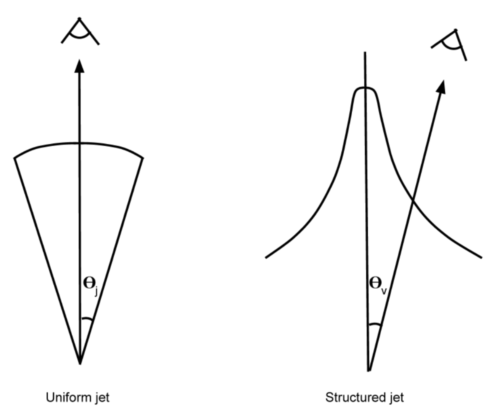
GRB 170817A:

physical origin?

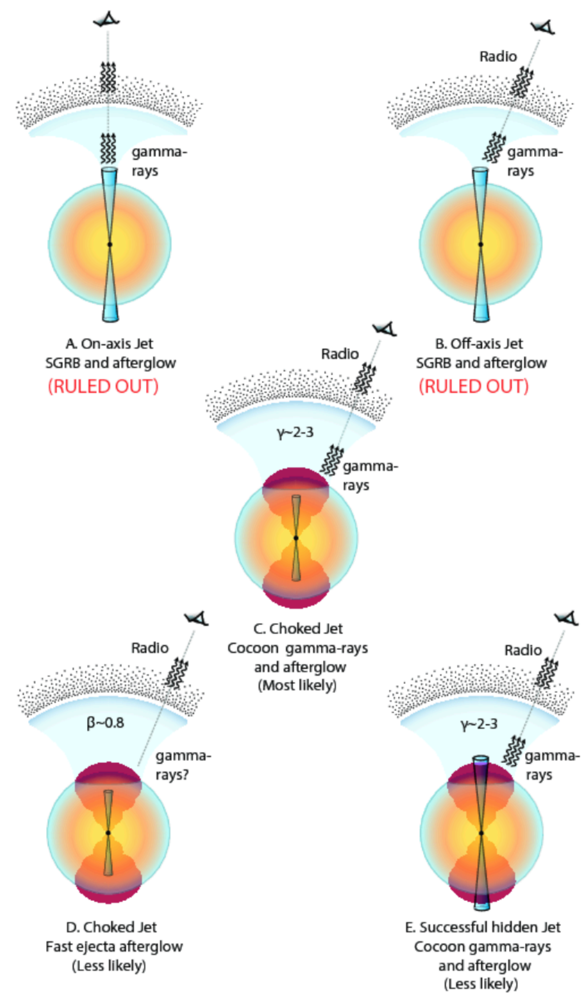
Abbott et al. 2017, ApJL, 848, L13; Mooley et al. 2018, Nature, 554, 207; B.-B. Zhang et al. 2018, Nature Communications, 9, 447



Favored



Structured jet: Zhang & Meszaros (2002)

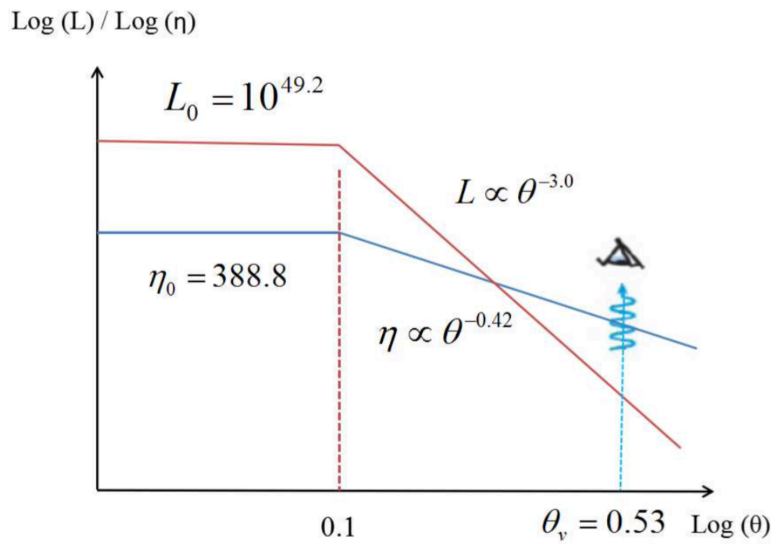


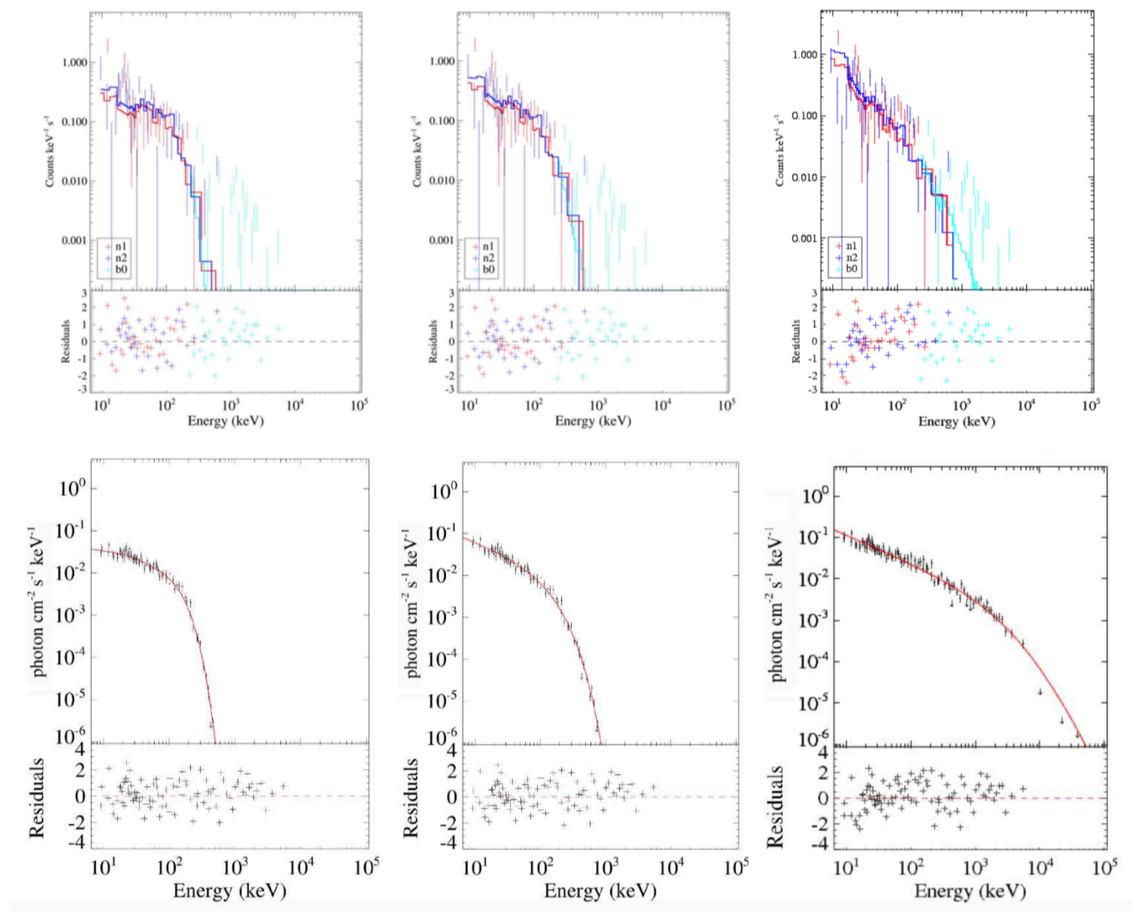
“Oversold” cocoon model

GRB 170817A:

prompt emission mechanism?

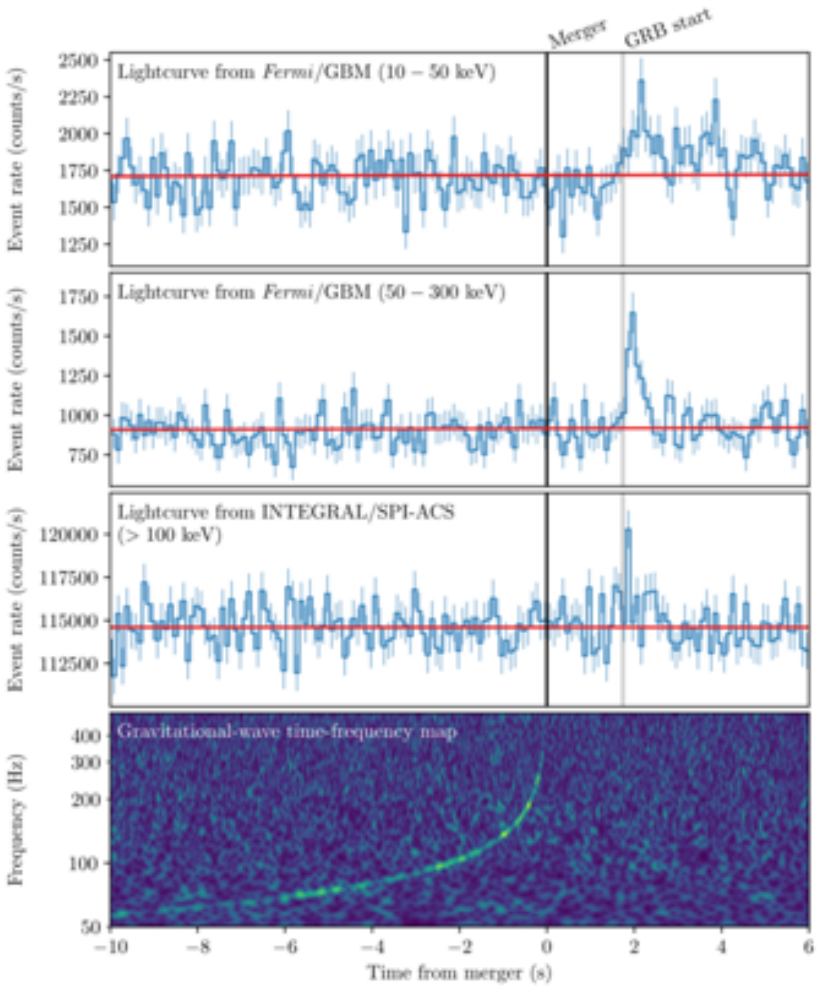
Meng et al. 2018, ApJ, arXiv:1801.01410





photosphere (delay needed)   cutoff PL   synchrotron

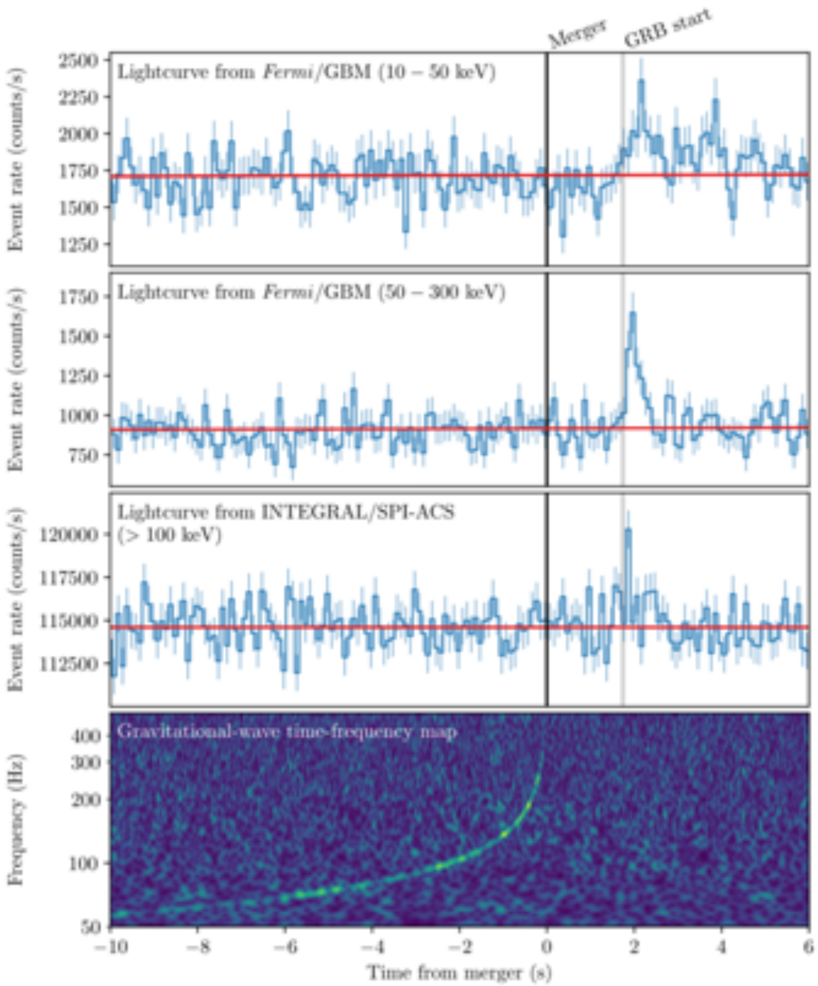
Origin of the 1.7 s delay?



- Delayed launch of the jet?
- Delayed formation of a BH?
- Delayed dissipation (magnetic field amplification)?
- No intrinsic delay at all!

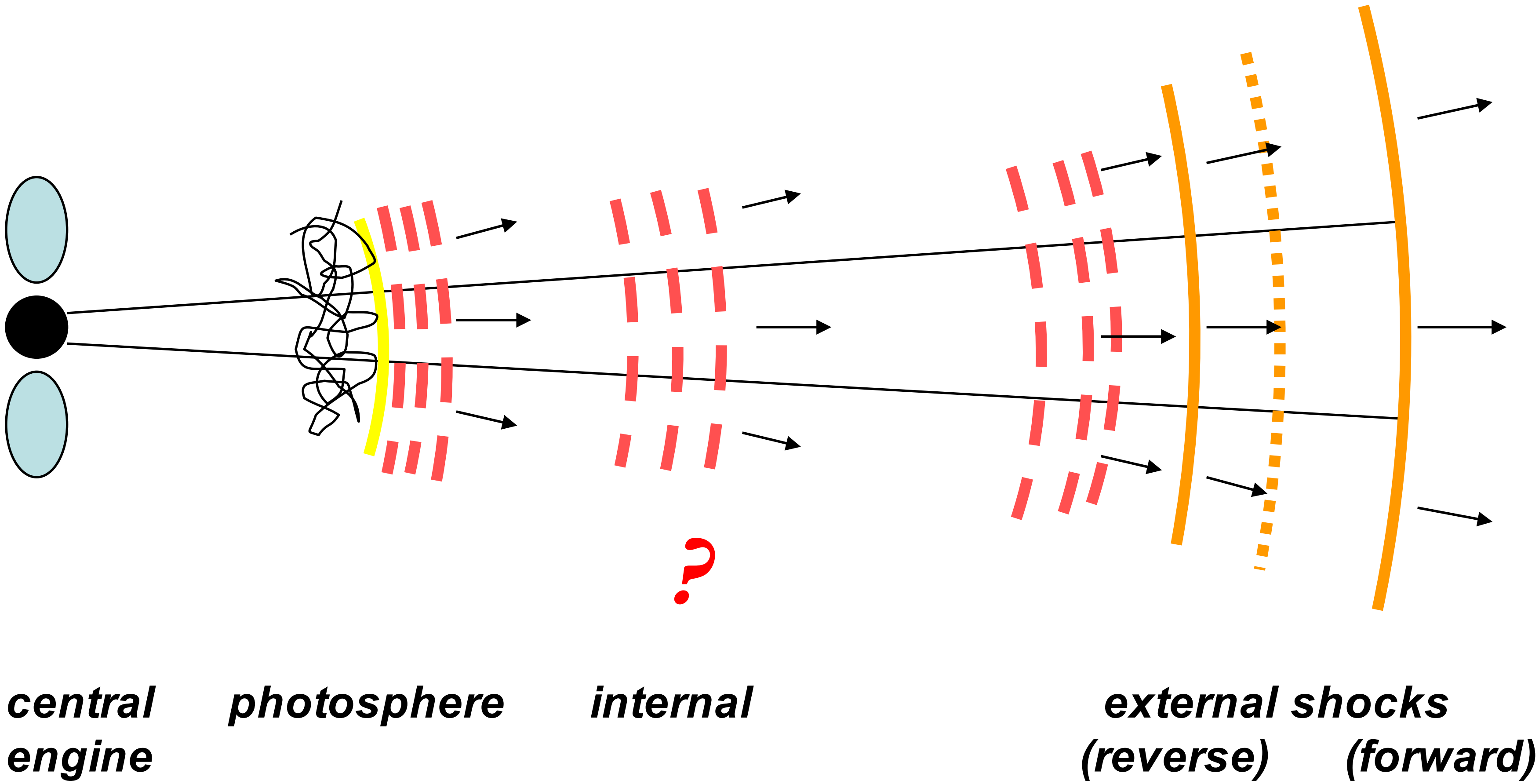
See also Daigne's, Mochkovitch's talk

Origin of the 1.7 s delay?



- Delayed launch of the jet?
  - What did the system do in 1.7 s (very long time)?
- Delayed formation of a BH?
  - Why jet not launched during the hypermassive phase?
  - BH not needed to produce short GRBs!
- Delayed dissipation (magnetic field amplification)?
  - Allowed but not needed
- No intrinsic delay at all (propagation)!
  - Duration ~ 2 s
  - Delay ~ 1.7 s
  - Both time scales ~ $R/\Gamma^2 c$
  - Traditional GRB mechanism
  - Large emission radius
  - Poynting-flux dissipation

GRB Emission Models



Uncertainties in GRB Prompt Emission:

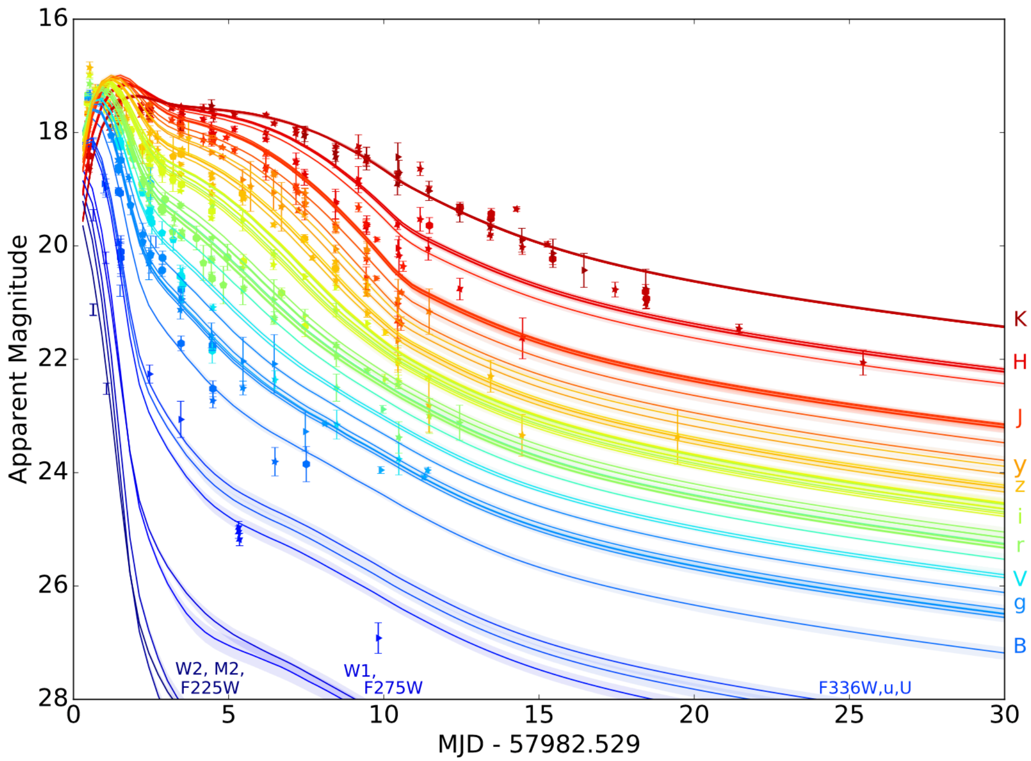
What *is the jet composition (baryonic vs. Poynting flux)?*

Where *is (are) the dissipation radius (radii)? – three possible locations*

How *is the radiation generated (synchrotron, Compton scattering, thermal)?*

See also Daigne's talk; Mochkovitch's talk

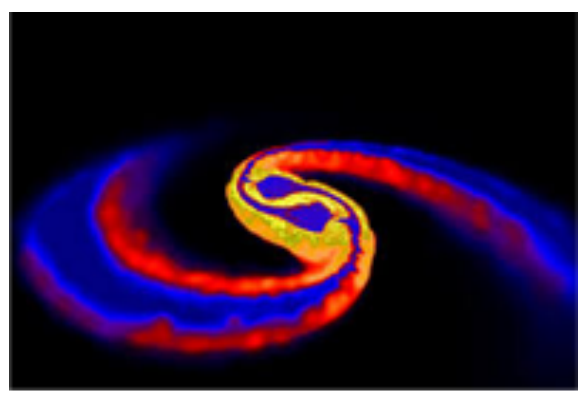
AT2017gfo



Villar et al. (2017)

Li & Paczynski (1998)
Metzger et al. (2010)

“macronova/kilonova/mergernova”



Naming issue:

Li-Paczynski nova / macronova / kilonova / mergernova

Living Rev Relativ (2017) 20:3
DOI 10.1007/s41114-017-0006-z
CrossMark
REVIEW ARTICLE

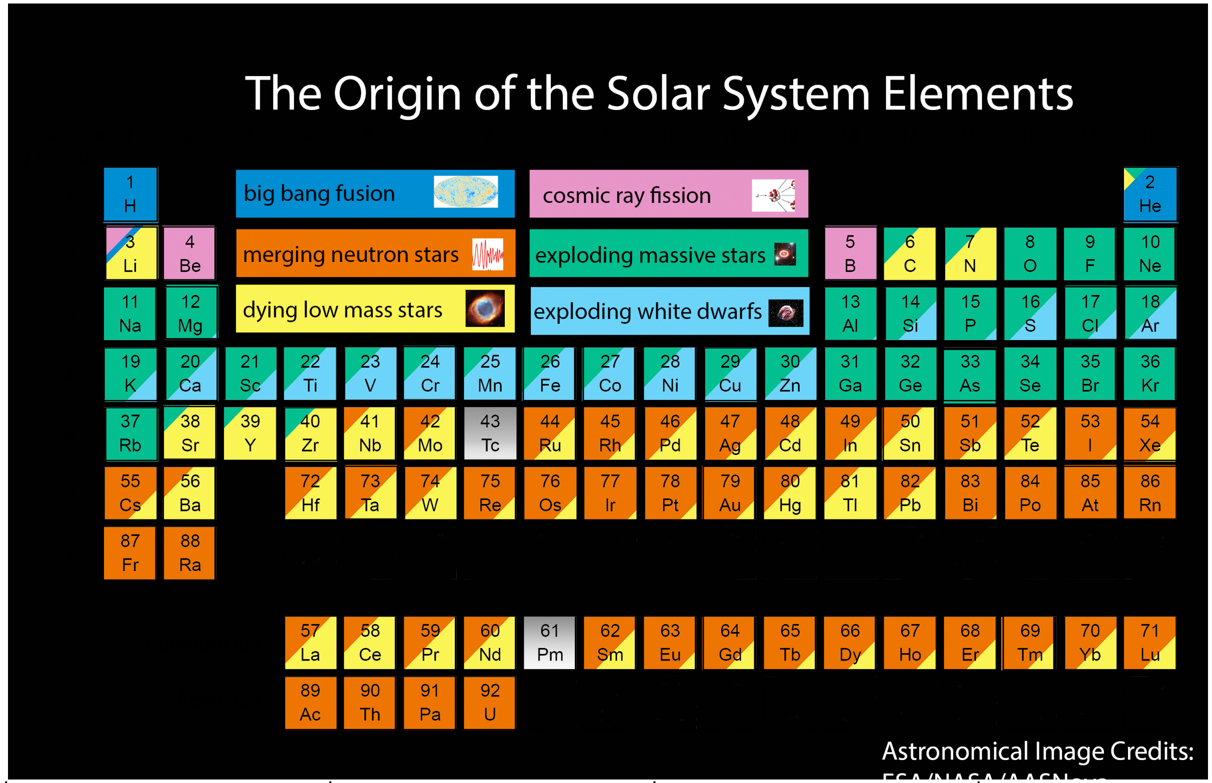
Kilonovae

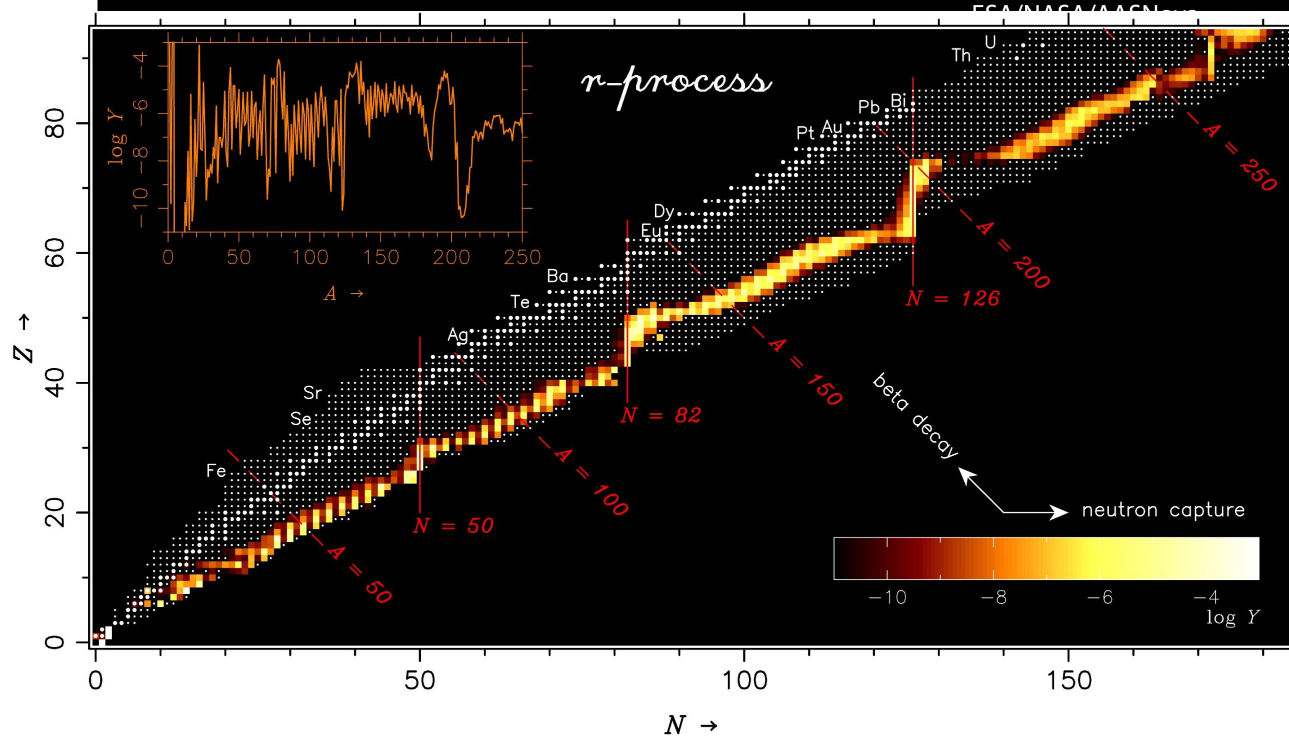
Brian D. Metzger[1]

Table 1 Timeline of major developments in kilonova research

1974	Lattimer and Schramm: r-process from BH–NS mergers
1975	Hulse and Taylor: discovery of binary pulsar system PSR 1913 + 16
1982	Symbalisty and Schramm: r-process from NS–NS mergers
1989	Eichler et al.: GRBs from NS–NS mergers
1994	Davies et al.: first numerical simulation of mass ejection from NS–NS mergers
1998	Li and Paczyński: first kilonova model, with parameterized heating
1999	Freiburghaus et al.: NS–NS dynamical ejecta ⇒ r-process abundances
2005	Kulkarni: kilonova powered by free neutron-decay ("macronova"), central engine
2009	Perley et al.: optical kilonova candidate following GRB 080503 (Fig. 9)
2010	Metzger et al., Roberts et al., Goriely et al.: kilonova powered by r-process heating
2013	Barnes and Kasen, Tanaka and Hotokezaka: La/Ac opacities ⇒ NIR spectral peak
2013	Tanvir et al., Berger et al.: NIR kilonova candidate following GRB 130603B
2013	Yu, Zhang, Gao: magnetar-boosted kilonova ("merger-nova")
2014	Metzger and Fernandez, Kasen et al.: blue kilonova from post-merger remnant disk winds

r-process


The Origin of the Solar System Elements
big bang fusion
cosmic ray fission
merging neutron stars
exploding massive stars
dying low mass stars
exploding white dwarfs
1 H
2 He
3 Li 4 Be 5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg 13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
89 Ac 90 Th 91 Pa 92 U
Astronomical Image Credits:


r-process
log Y
A →
0 50 100 150 200 250
Th U Pb Bi Pt Au Dy Eu Ba Te Ag Sr Se Fe
N = 50
N = 82
N = 126
A = 50
A = 100
A = 150
A = 200
A = 250
beta decay
neutron capture
−10 −8 −6 −4
Z →
0 20 40 60 80
N →
0 50 100 150

Kilonova basics

$$t_{\rm p} = \left(\frac{3M\kappa}{4\pi\beta v c}\right)^{1/2}$$
$$\approx 1.6\,{\rm d}\left(\frac{M}{0.01M_{\odot}}\right)^{1/2}\left(\frac{v}{0.1\,c}\right)^{-1/2}\left(\frac{\kappa}{1\,{\rm cm^2\,g^{-1}}}\right)^{1/2} \quad (3)$$

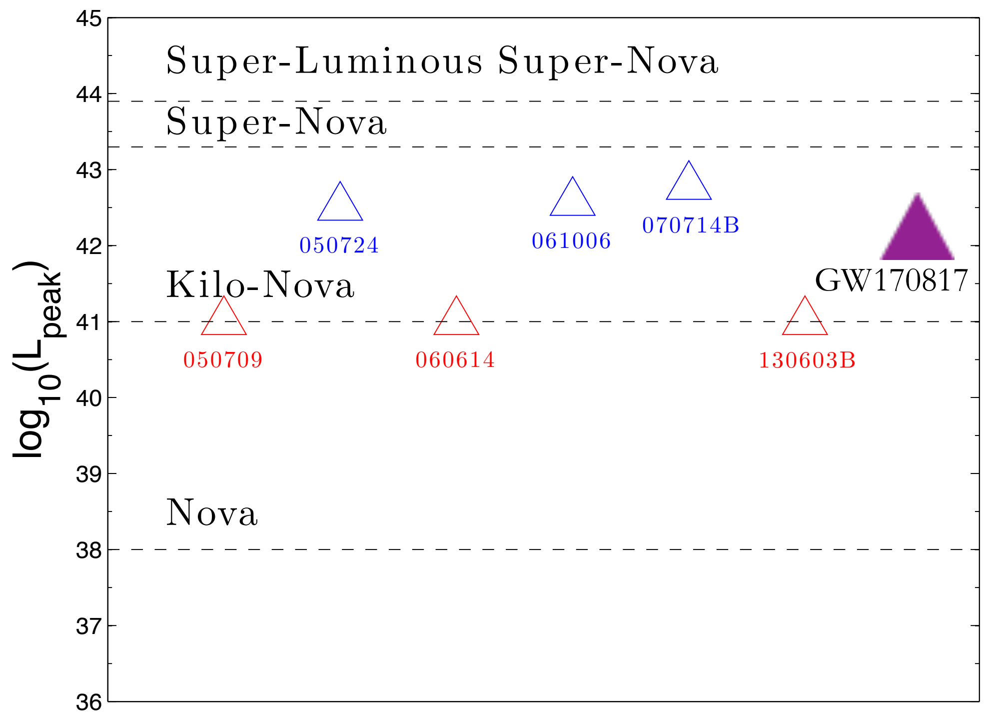
$$L_{\rm p} = 1.2\times10^{41}{\rm erg\,s^{-1}}$$
$$\left(\frac{M}{0.01M_{\odot}}\right)^{1-\alpha/2}\left(\frac{v}{0.1\,c}\right)^{\alpha/2}\left(\frac{\kappa}{1\,{\rm cm^2\,g^{-1}}}\right)^{-\alpha/2} \quad (4)$$

$$L_{\rm p} = \eta_{\rm th} M \varepsilon(t_{\rm p}),$$

$$\varepsilon(t) \approx 2\times10^{10}{\rm erg\,g^{-1}s^{-1}}\left(\frac{t}{1\,{\rm day}}\right)^{-\alpha},$$

$$\alpha \;=\; 1.3$$

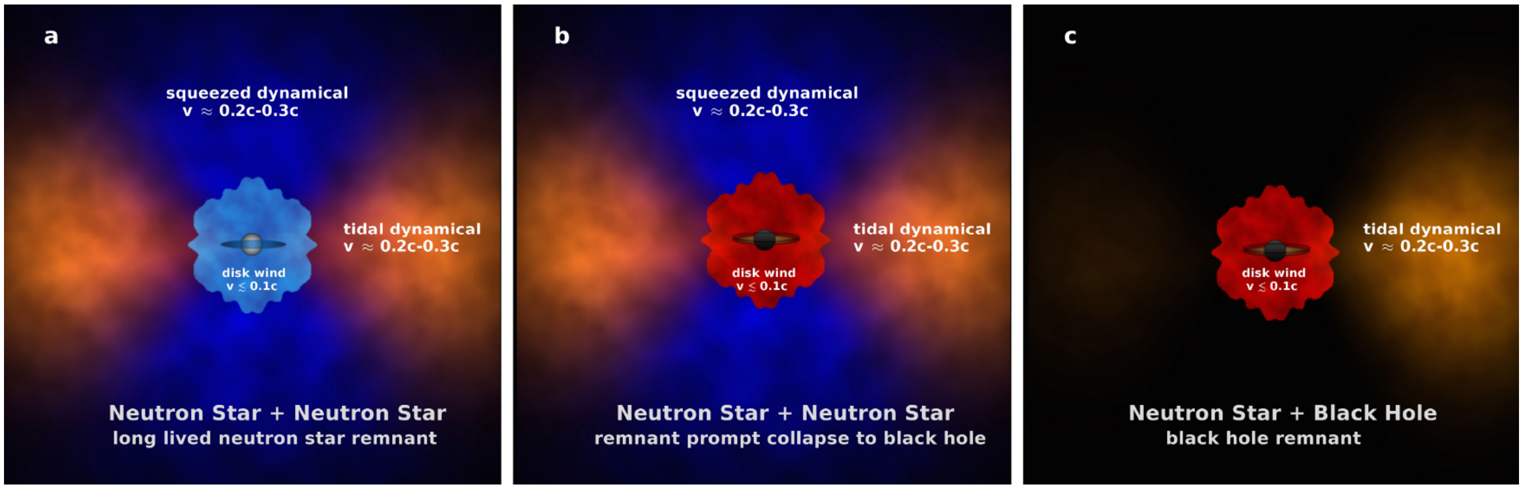
Metzger (2017)



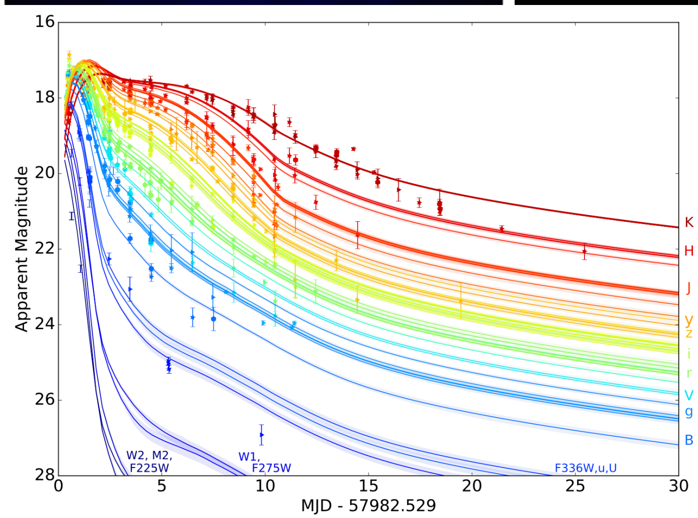
Gao et al. 2017, ApJ, 837, 50

AT2017gfo:

Blue and red (and purple?)



Kasen et al. 2017



D’Avanzo’s talk

Villar et al. 2017

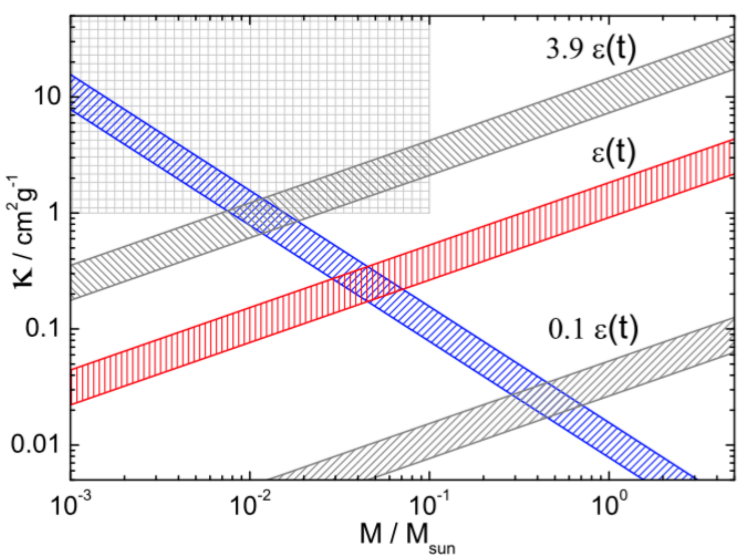
Table 2
Kilonova Model Fits

Model	M_{ej}^{blue}	v_{ej}^{blue}	κ_{ej}^{blue}	T^{blue}	M_{ej}^{purple}	v_{ej}^{purple}	κ_{ej}^{purple}	T^{purple}	M_{ej}^{red}	v_{ej}^{red}	κ_{ej}^{red}	T^{red}	σ	θ	WAIC
2-Comp	$0.023^{0.005}_{0.001}$	$0.256^{0.005}_{0.002}$	(0.5)	3983^{66}_{70}	⋯	⋯	⋯	⋯	$0.050^{0.001}_{0.001}$	$0.149^{0.001}_{0.002}$	$3.65^{0.09}_{0.28}$	1151^{45}_{72}	$0.256^{0.006}_{0.004}$	⋯	−1030
3-Comp	$0.020^{0.001}_{0.001}$	$0.266^{0.008}_{0.008}$	(0.5)	674^{486}_{417}	$0.047^{0.001}_{0.002}$	$0.152^{0.005}_{0.005}$	(3)	1308^{42}_{34}	$0.011^{0.002}_{0.001}$	$0.137^{0.025}_{0.021}$	(10)	3745^{75}_{75}	$0.242^{0.008}_{0.008}$	⋯	−1064
Asym. 3-Comp	$0.009^{0.001}_{0.001}$	$0.256^{0.009}_{0.004}$	(0.5)	3259^{302}_{306}	$0.007^{0.001}_{0.001}$	$0.103^{0.007}_{0.004}$	(3)	3728^{94}_{178}	$0.026^{0.004}_{0.002}$	$0.175^{0.011}_{0.008}$	(10)	1091^{29}_{45}	$0.226^{0.006}_{0.006}$	66^{1}_{3}	−1116

AT2017gfo

$$t_{\rm p} = \left(\frac{3M\kappa}{4\pi\beta v c}\right)^{1/2}$$
$$\approx 1.6\,{\rm d}\left(\frac{M}{0.01M_\odot}\right)^{1/2}\left(\frac{v}{0.1\,c}\right)^{-1/2}\left(\frac{\kappa}{1\,{\rm cm^2\,g^{-1}}}\right)^{1/2} \quad (3)$$

$$L_{\rm p} = 1.2\times10^{41}{\rm erg\,s^{-1}}$$
$$\left(\frac{M}{0.01M_\odot}\right)^{1-\alpha/2}\left(\frac{v}{0.1\,c}\right)^{\alpha/2}\left(\frac{\kappa}{1\,{\rm cm^2\,g^{-1}}}\right)^{-\alpha/2} \quad (4)$$



Li et al. 2018, arXiv:1804.06597

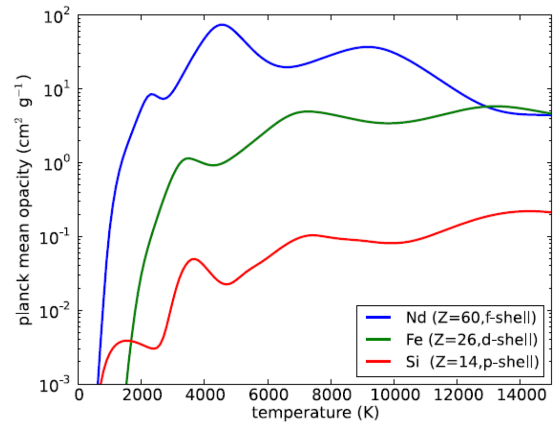


Figure 6. Planck mean expansion opacities for three different elements, showing the expected dependence on atomic complexity. The Nd opacities (blue line, $Z = 60$, open f-shell) were derived from `Autostructure` models, while the silicon (red line, $Z = 14$, open p-shell) and iron (green line, $Z = 26$, open d-shell) opacities used Kurucz line data. The calculations assume a density $\rho = 10^{-13}$ g cm^{-3} and a time since ejection $t_{\rm ej} = 1$ days.

(A color version of this figure is available in the online journal.)

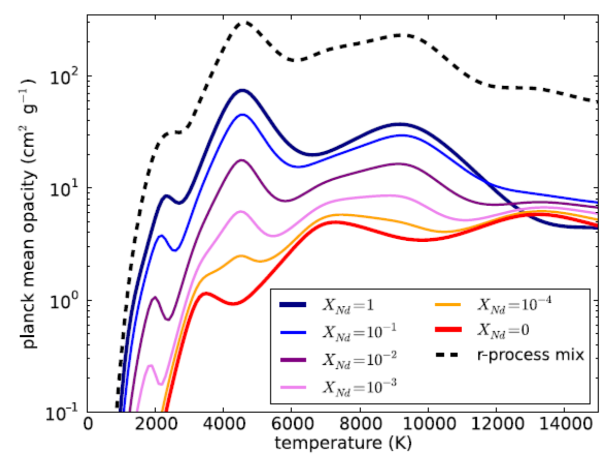
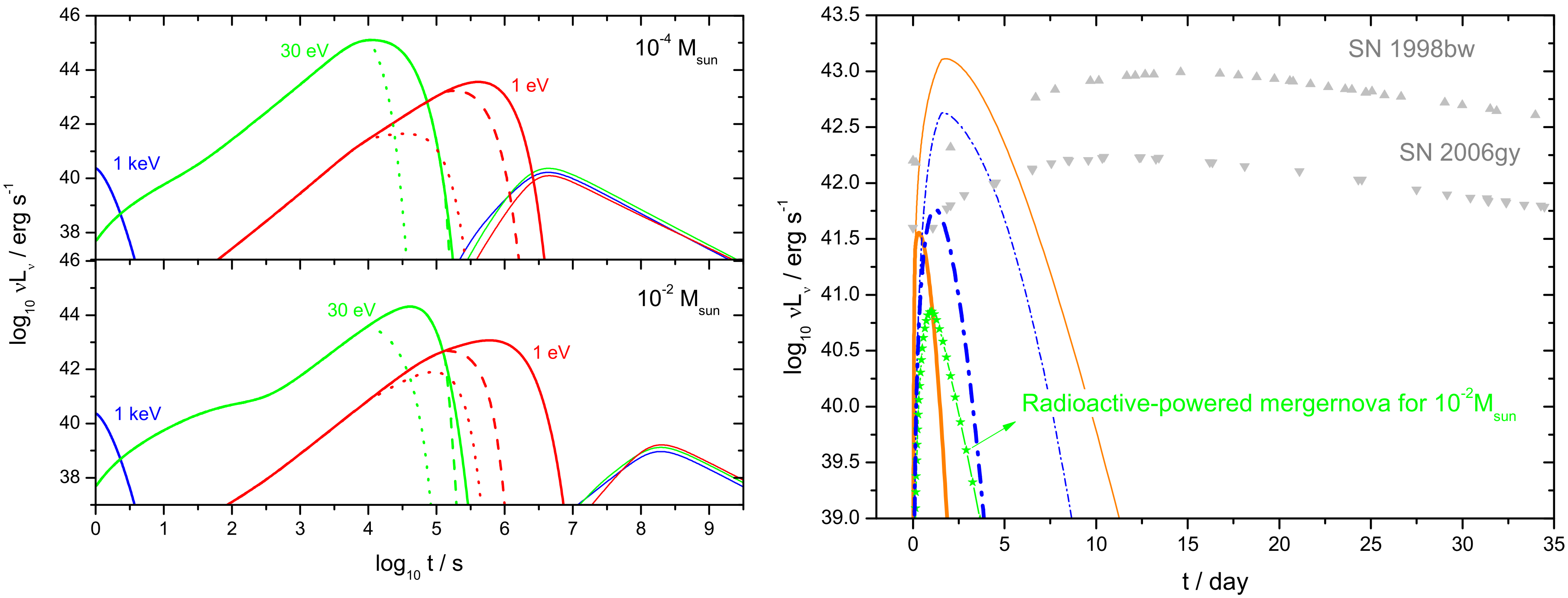


Figure 10. Dependence of the mean expansion opacity on the abundance of lanthanides. The solid lines show the Planck mean opacity for various mass fractions of neodymium in a mixture with iron. The dashed line shows the opacity of the approximate r-process mixture (with all 14 lanthanides) discussed in Section 6.

Kasen et al. 2013

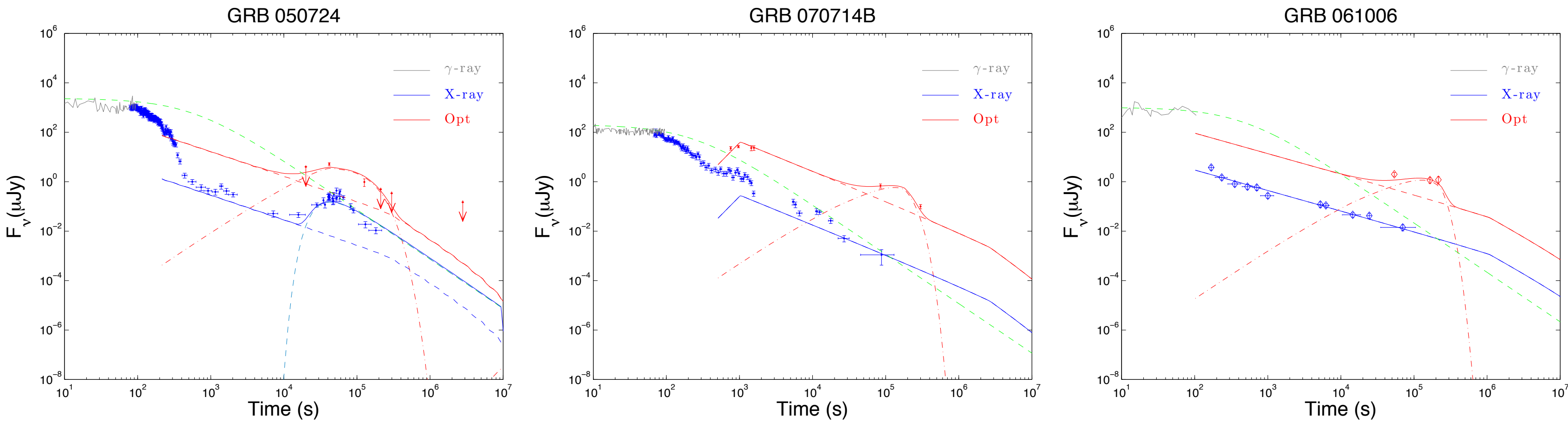
Engine-driven mergernova

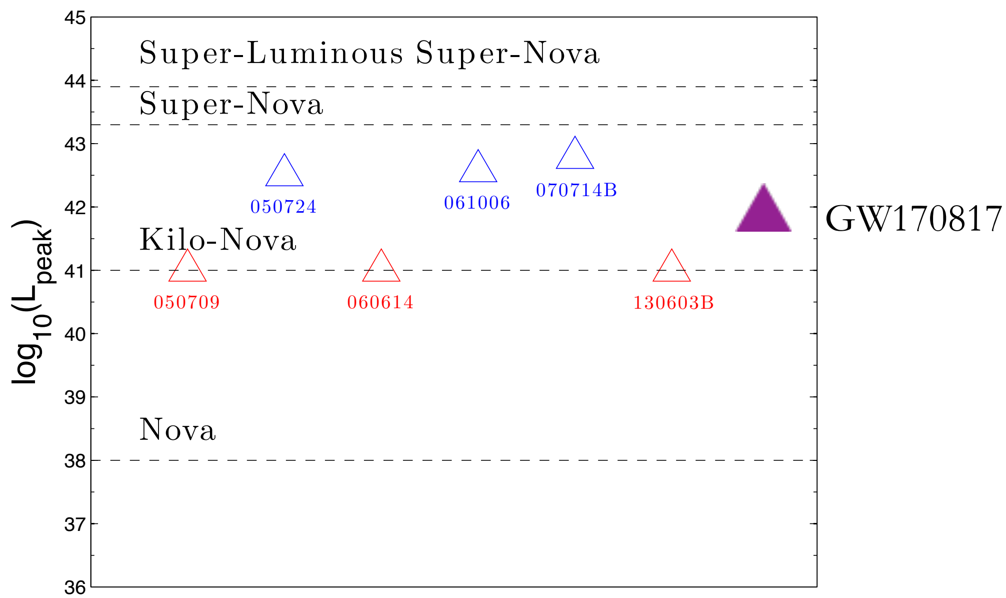
Yu, Zhang & Gao, 2013, ApJ, 763, L22



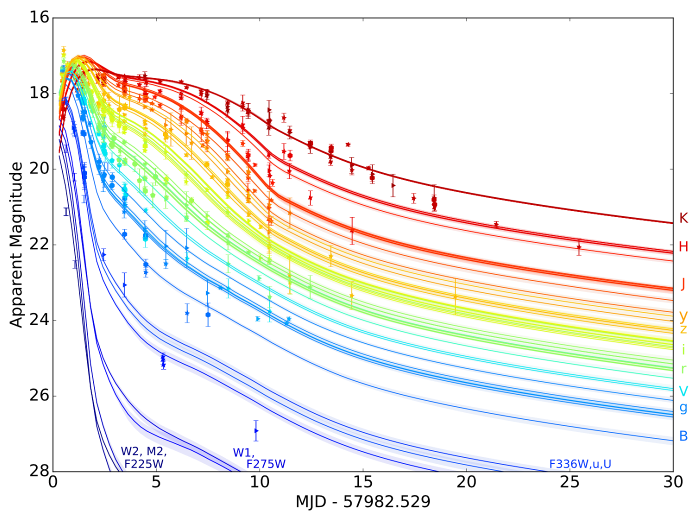
Previous cases

Gao et al., 2017, ApJ, 837, 50

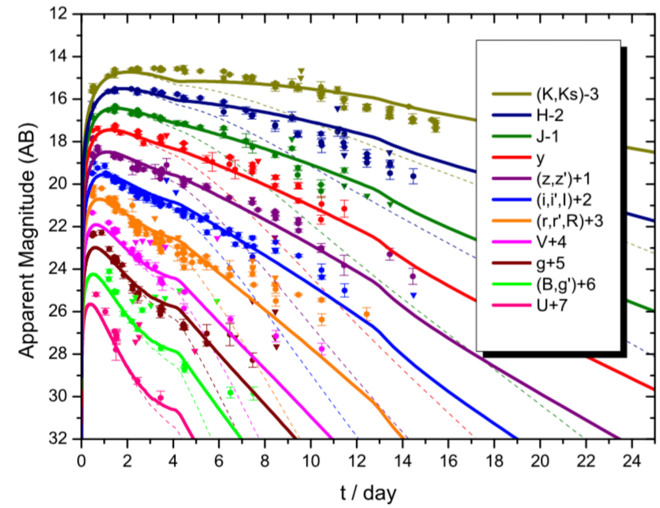




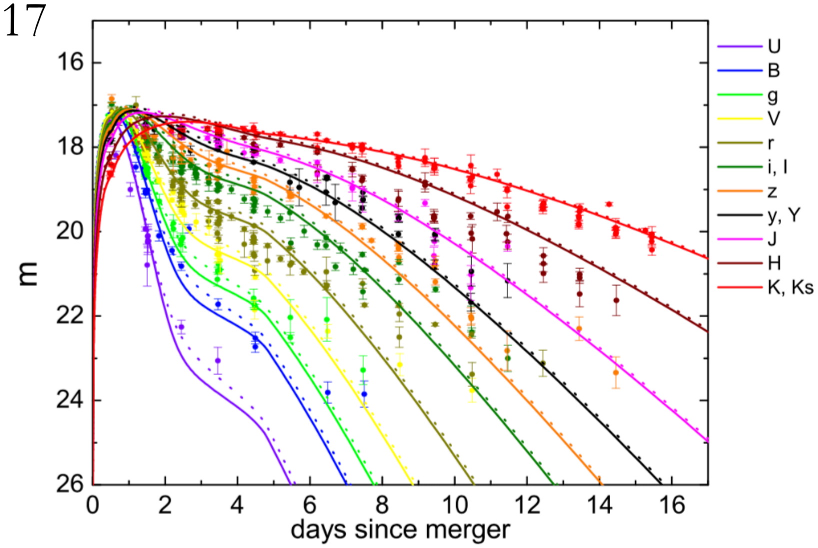
AT2017gfo: long-lived-NS-driven?



Villar et al. 2017



Yu & Dai, arXiv:1711.01898

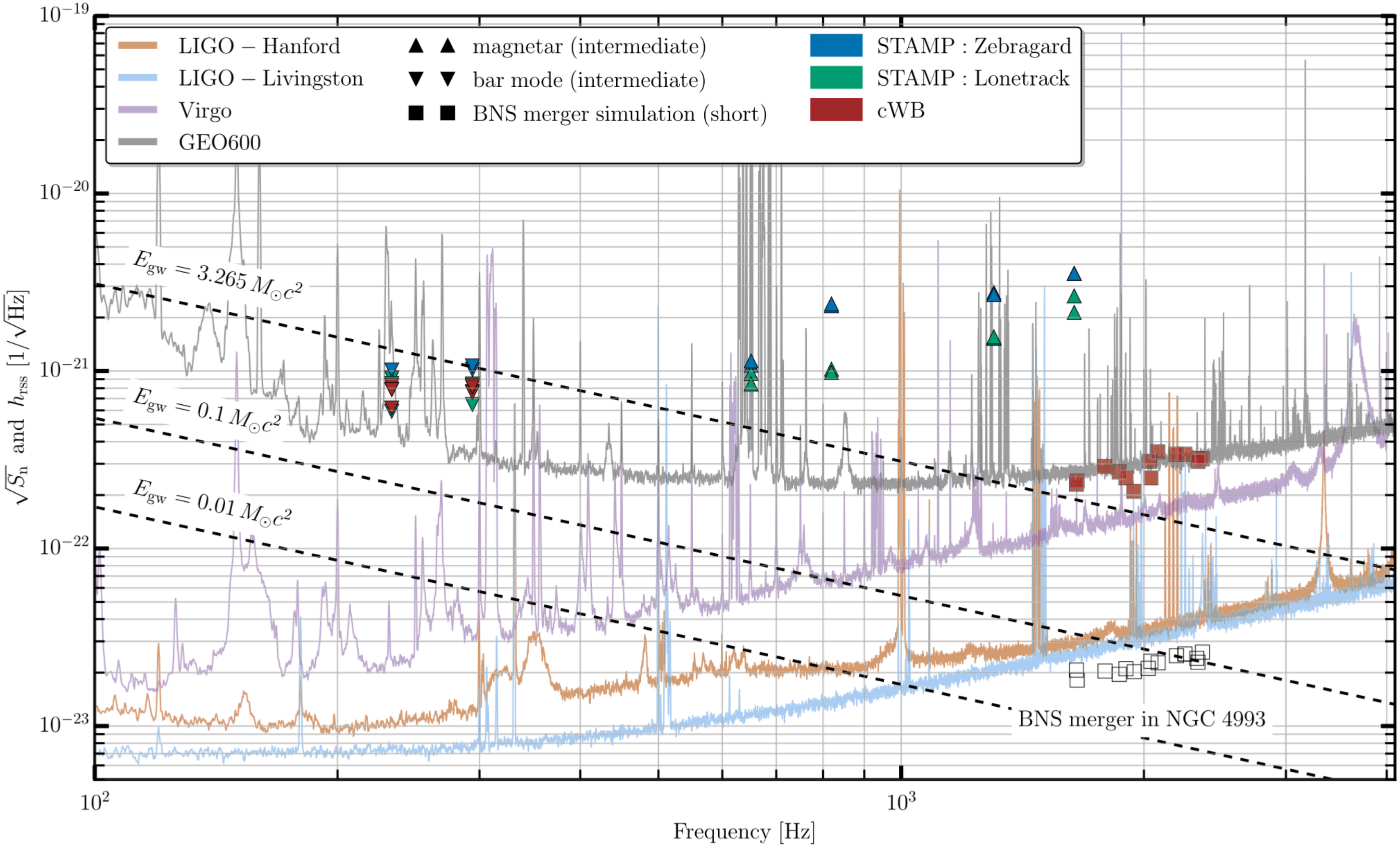


Li et al. arXiv:1804.06597

	$M_{fb,i}/M_\odot s^{-1}$	$L_{md,i}/erg\,s^{-1}$	$t_{sd,gw}/s$	B/G	ϵ	ejecta	$M_{ej}/M_\odot$	κ/cm^2g^{-1}	$v_{ej,i}/c$	Ω	δ	ζ	A
NS	-	3.4×10^{44}	500	3.4×10^{12}	0.0035	polar	1×10^{-3}	1	0.35	2π	-1	10	6
						equatorial	5×10^{-3}	5	0.2	2π	-1	10	6

GW170817:

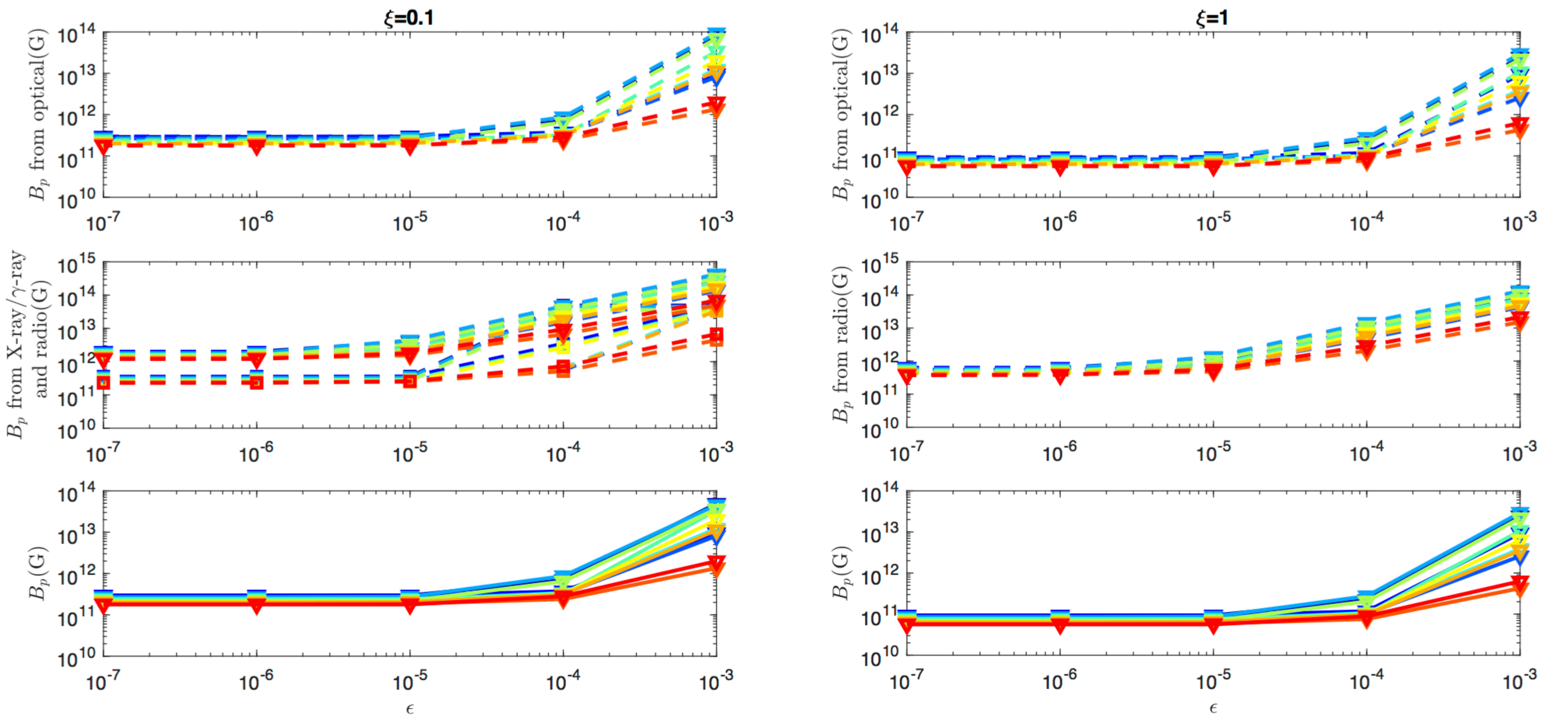
Is a long-lived NS allowed?



GW constraints: upper limit at least one order above prediction

Abbott et al. 2017, ApJL, 851, L16 Chassande-Mottin's talk

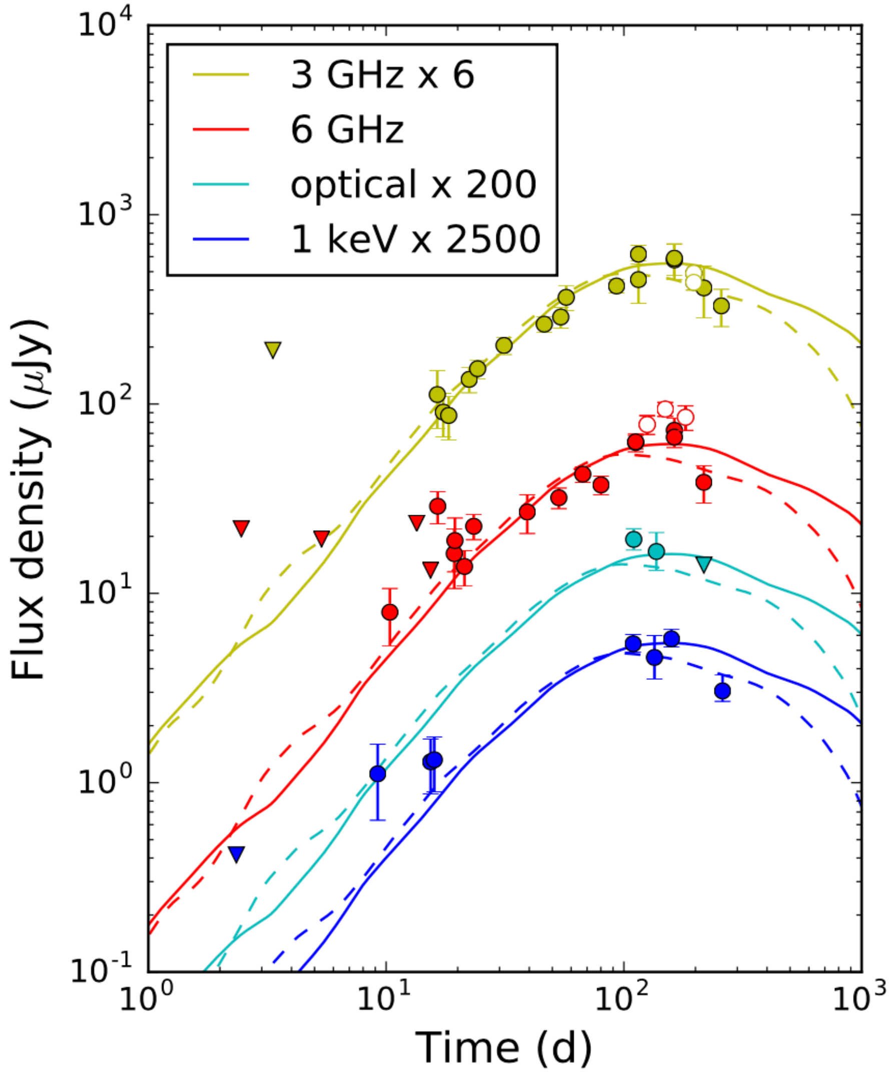
GW170817:
Is a long-lived NS allowed?



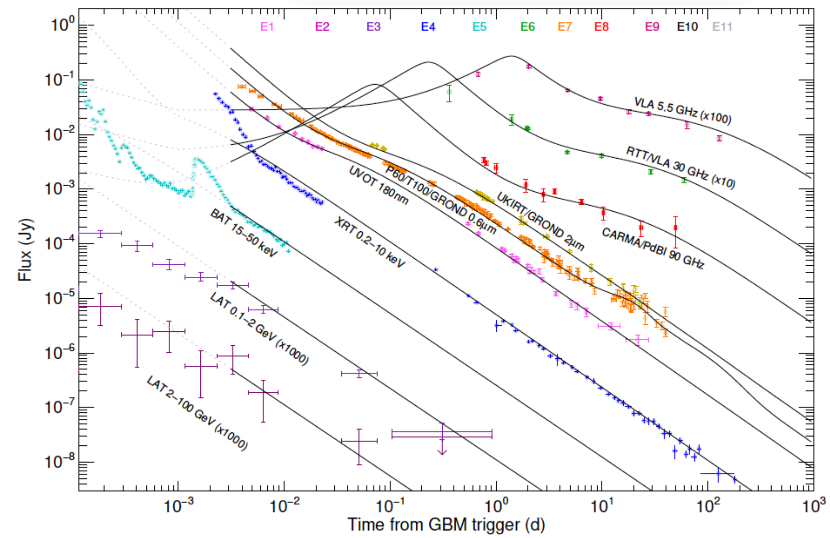
EM constraints: As long as Bp is low – constraints from UV/optical/IR (upper), gamma/X/radio (middle) and multi-band (lower)

Ai et al. 2018, ApJ, in press (arXiv:1802.00571) Gao's talk

Broadband afterglow



Alexander et al. (2018)



GRB 130427A (for comparison)

Energy injection!!!

- Ejecta Lorentz factor stratification (radial injection)
- Structured jet (lateral injection)
- Central engine

Energy injection in GW170817

$$L(t) = L_0 (t/t_b)^{-q}.$$

$$M(>\gamma) \propto \gamma^{-s}.$$

$$s = \frac{10-7q}{2+q}, \quad q = \frac{10-2s}{7+s}, \quad \text{ISM}$$

$$s = \frac{4-3q}{q}, \quad q = \frac{4}{3+s}, \quad \text{wind}$$

TABLE 2

Temporal Index α and Spectral Index β in Various Afterglow Models

		No Injection		Injection	
GRB Models	β	α	$\alpha(\beta)$	α	$\alpha(\beta)$
ISM, Slow Cooling					
$\nu < \nu_m$	$-\frac{1}{3}$	$-\frac{1}{2}$	$\alpha = \frac{3\beta}{2}$	$\frac{5q-8}{6}$ (−0.9)	$\alpha = (q-1) + \frac{(2+q)\beta}{2}$
$\nu_m < \nu < \nu_c$	$\frac{p-1}{2}$ (0.65)	$\frac{3(p-1)}{4}$ (1.0)	$\alpha = \frac{3\beta}{2}$	$\frac{(2p-6)+(p+3)q}{4}$ (0.3)	$\alpha = (q-1) + \frac{(2+q)\beta}{2}$
$\nu > \nu_c$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$
ISM, Fast Cooling					
$\nu < \nu_c$	$-\frac{1}{3}$	$-\frac{1}{6}$	$\alpha = \frac{\beta}{2}$	$\frac{7q-8}{6}$ (−0.8)	$\alpha = (q-1) + \frac{(2-q)\beta}{2}$
$\nu_c < \nu < \nu_m$	$\frac{1}{2}$	$\frac{1}{4}$	$\alpha = \frac{\beta}{2}$	$\frac{3q-2}{4}$ (−0.1)	$\alpha = (q-1) + \frac{(2-q)\beta}{2}$
$\nu > \nu_m$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$
Wind, Slow Cooling					
$\nu < \nu_m$	$-\frac{1}{3}$	0	$\alpha = \frac{3\beta+1}{2}$	$\frac{q-1}{3}$ (−0.2)	$\alpha = \frac{q}{2} + \frac{(2+q)\beta}{2}$
$\nu_m < \nu < \nu_c$	$\frac{p-1}{2}$ (0.65)	$\frac{3p-1}{4}$ (1.5)	$\alpha = \frac{3\beta+1}{2}$	$\frac{(2p-2)+(p+1)q}{4}$ (1.1)	$\alpha = \frac{q}{2} + \frac{(2+q)\beta}{2}$
$\nu > \nu_c$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$
Wind, Fast Cooling					
$\nu < \nu_c$	$-\frac{1}{3}$	$\frac{2}{3}$	$\alpha = \frac{1-\beta}{2}$	$\frac{(1+q)}{3}$ (0.5)	$\alpha = \frac{q}{2} - \frac{(2-q)\beta}{2}$
$\nu_c < \nu < \nu_m$	$\frac{1}{2}$	$\frac{1}{4}$	$\alpha = \frac{1-\beta}{2}$	$\frac{3q-2}{4}$ (−0.1)	$\alpha = \frac{q}{2} - \frac{(2-q)\beta}{2}$
$\nu > \nu_m$	$\frac{p}{2}$ (1.15)	$\frac{3p-2}{4}$ (1.2)	$\alpha = \frac{3\beta-1}{2}$	$\frac{(2p-4)+(p+2)q}{4}$ (0.7)	$\alpha = \frac{q-2}{2} + \frac{(2+q)\beta}{2}$

Zhang et al., 2006, ApJ, 642, 354

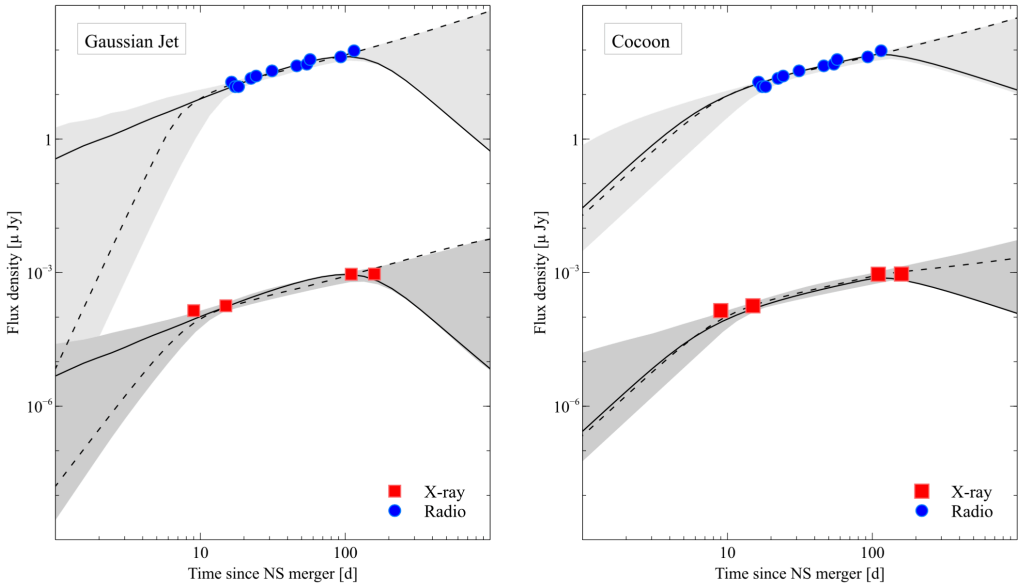
$$F_\nu \propto t^{0.8} \Longrightarrow q \sim -0.29$$

Pulsar: q=0 or q=1

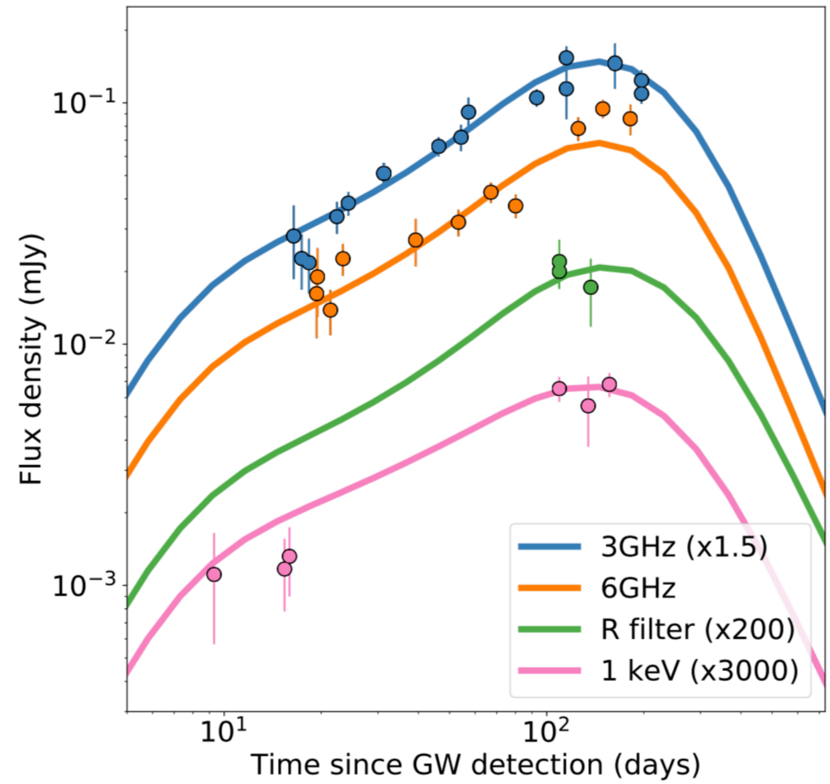
Not enough but allowed!

Extra injection lateral/radial injection needed

Energy injection in GW170817



Troja et al., 2018, MNRAS



Lazzati et al., 2017, arXiv:1712.03237

What is the merger product?

Argument in favor of a BH

- There was a short GRB
  - Accretion-powered short GRB? Not necessarily true
  - If so, NS/QS maximum mass $2.16 - 2.28\ M_\odot$
- Low luminosity prompt emission and afterglow
  - Cannot be a magnetar, low-B pulsar allowed but not required
- Lack of smoking gun signature of a long-lived NS/QS

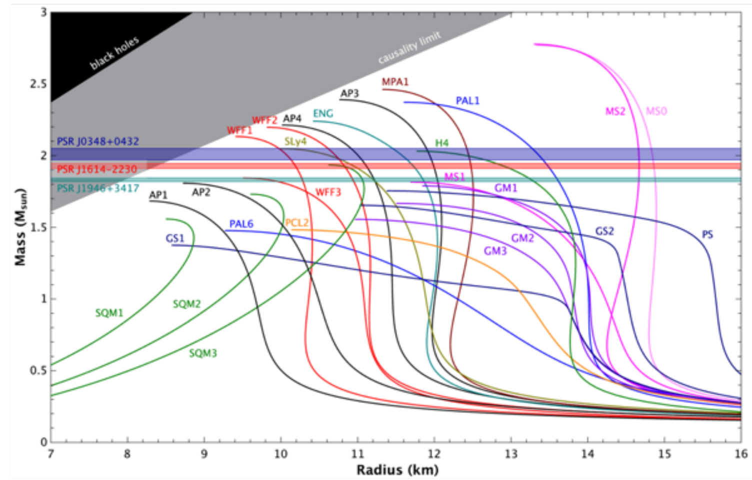
Surprise! Surprise!

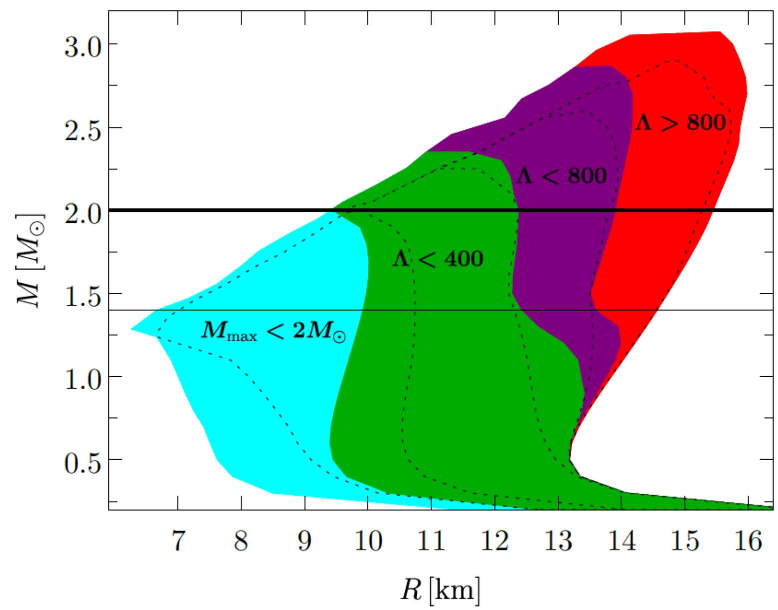
A self-consistent picture

- GW170817 left behind a long-lived NS/QS
- Low poloidal B but high toroidal B
- An early Poynting-flux-dominated flow emerges from the ejecta, naturally structured
- Magnetic dissipation at a large distance powers prompt emission
- Energy injection from the pulsar powers kilonova with regular mass; large velocity due to Poynting-flux acceleration
- Late-time activity powers the X-ray flare

Implications

- M_{TOV} is large! Rule out many soft EoSs
- Small tidal deformability rules out many stiff EoSs
- "Goldilocks" EoSs
- Consistent with conclusions drawn from short GRB observations and modeling (Gao et al. 2016).





Summary

- GW170817 / GRB 170817A / AT2017gfo / afterglow presented rich data for human to study the very first NS-NS merger system
- Some interesting constraints reached; many questions remain; observations of more systems desired.
- Excitements yet to come!