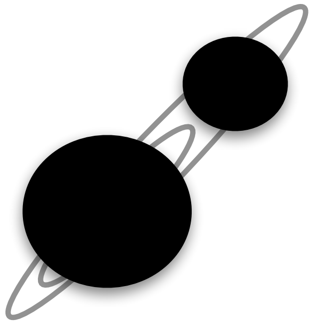
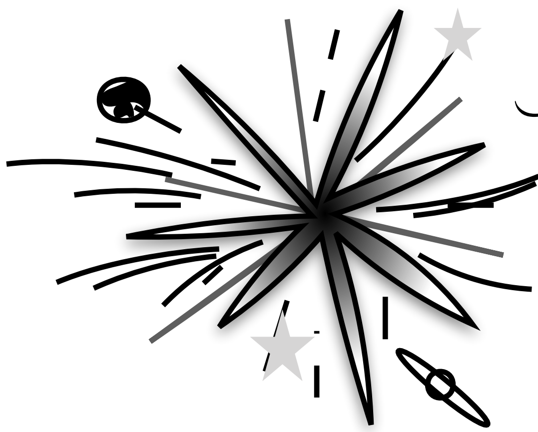
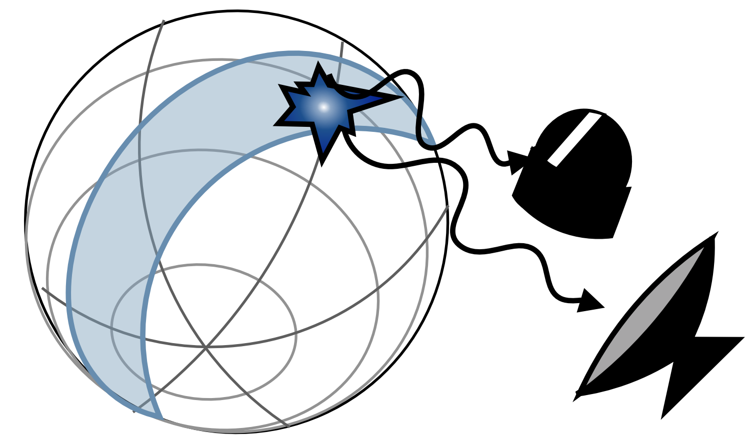


Astrophysics of LIGO/Virgo sources in O3 era





ELECTROMAGNETIC COUNTERPARTS OF GRAVITATIONAL WAVES

MONASH University

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)

KAVLI IPMU

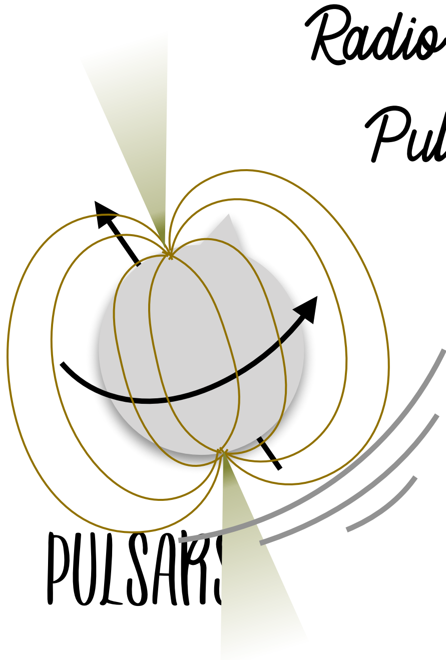
Credit some topics/slides to Marica Branchesi and Kendall Ackley

Serena Vinciguerra

POSSIBILITIES FOR MULTI MESSENGER ASTRONOMY

Radio / gamma-ray

Pulsar glitches



PULSARS

UNKNOWN

Fast Radio Bursts

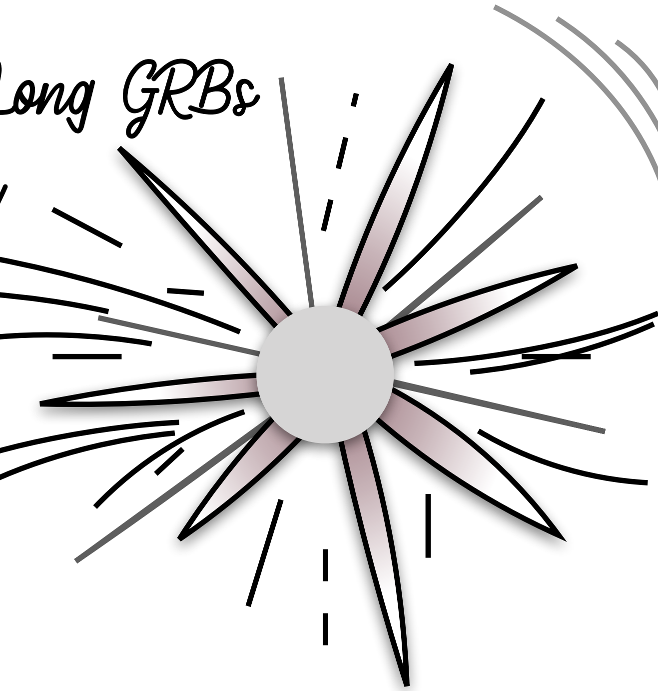
Sometimes Long GRBs

X-ray, UV

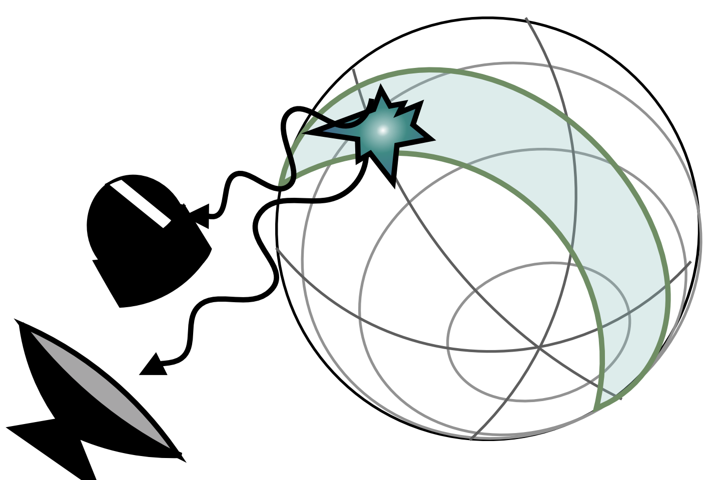
Optical

Radio

Neutrinos



SUPERNOVAE

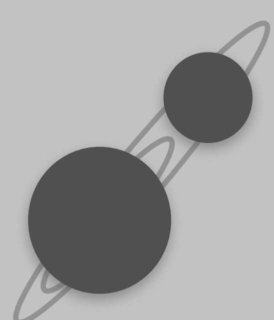


. . . ESTEND BEYOND MERGERS OF COMPACT BINARIES

POSSIBILITIES FOR MULTI MESSENGER ASTRONOMY

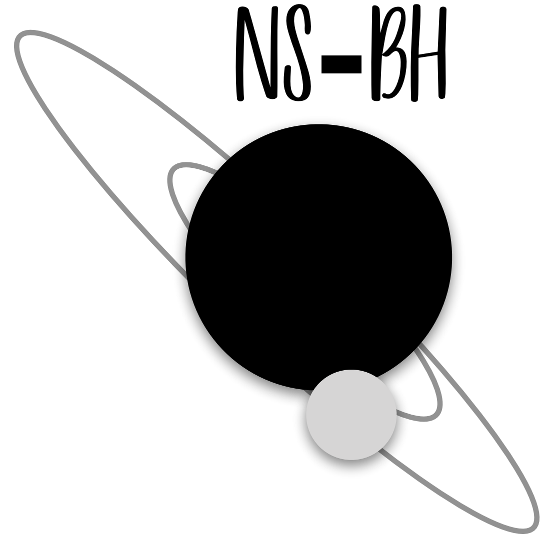
COMPACT BINARY COALESCENCES

BH-BH

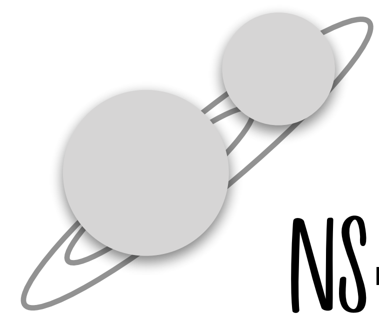


BLACK HOLE-
BLACK HOLE ✓

NS-BH



BLACK HOLE-
NEUTRON STAR

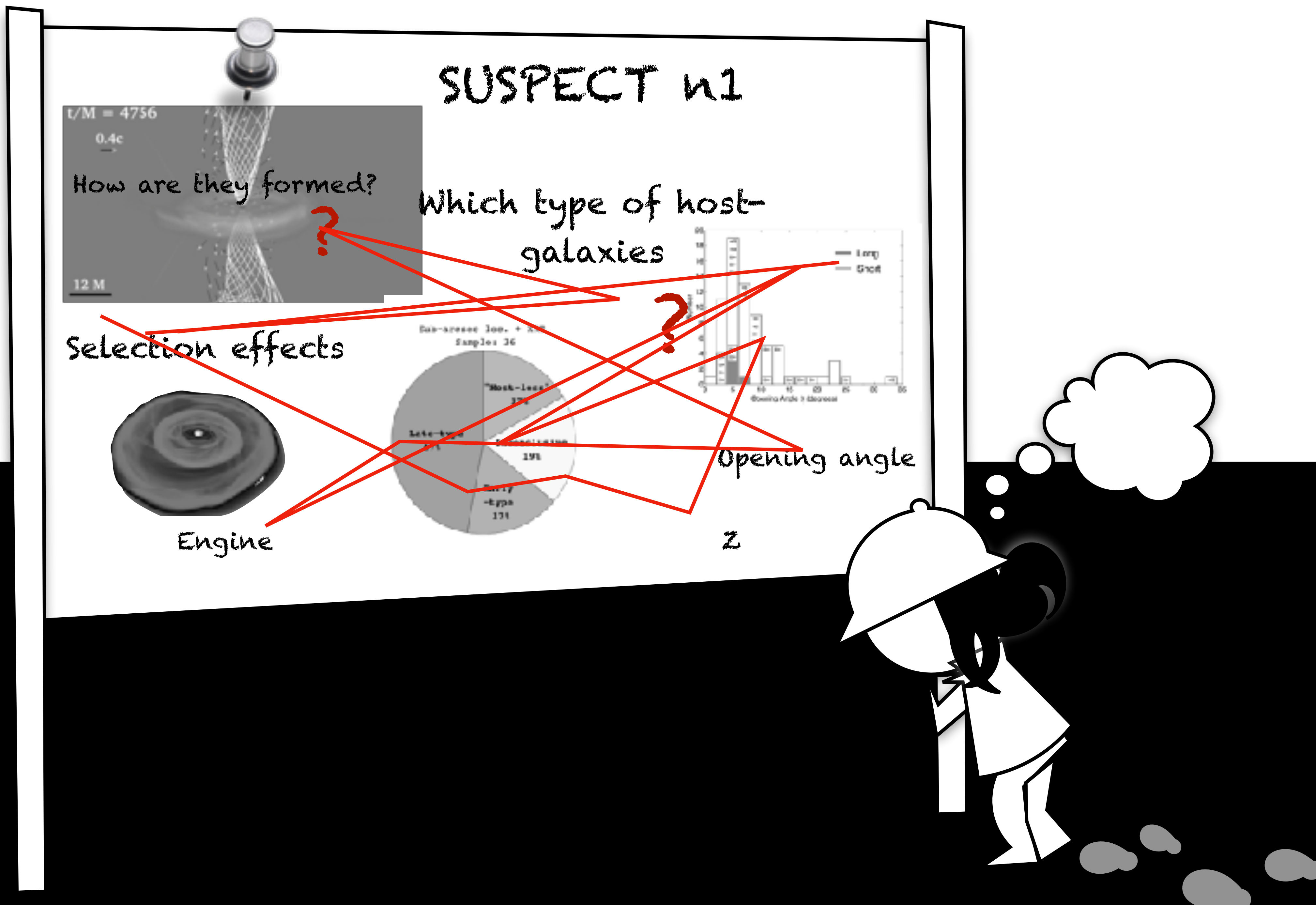


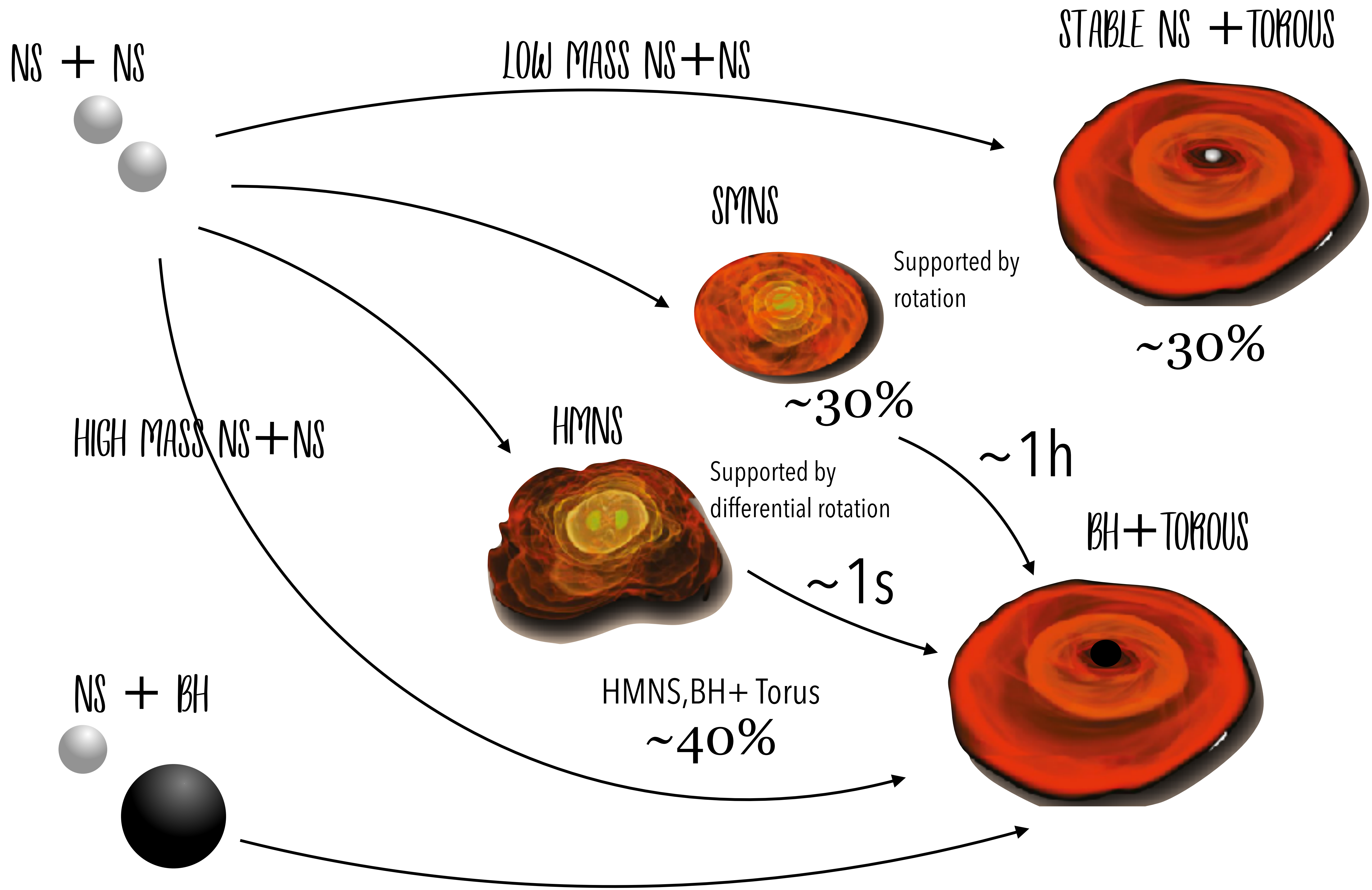
NS-NS

NEUTRON STAR-
NEUTRON STAR ✓

SHORT GRBs

BNS & NS-BH MERGERS

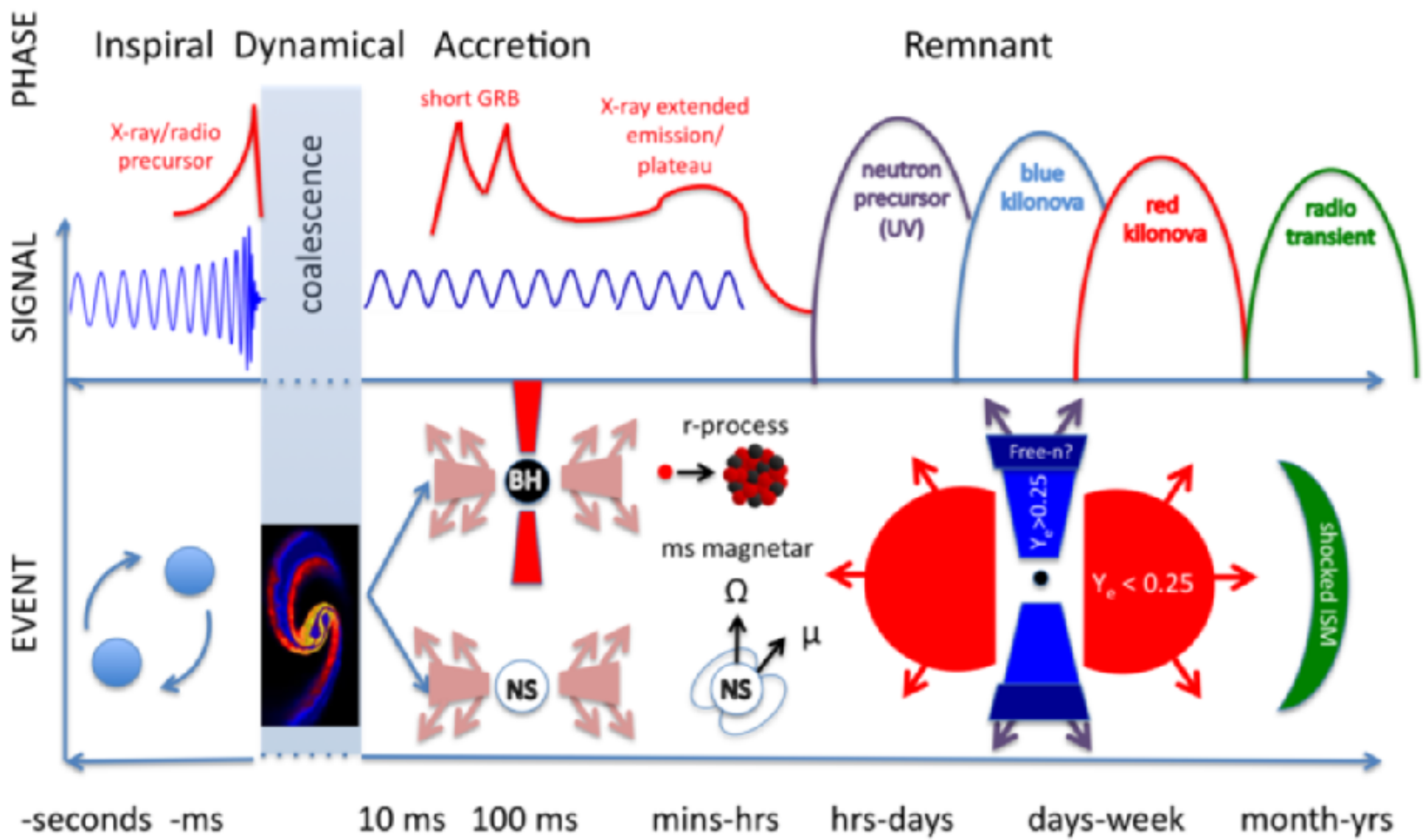




Gao et al.
ArXiv 1511.00753v2

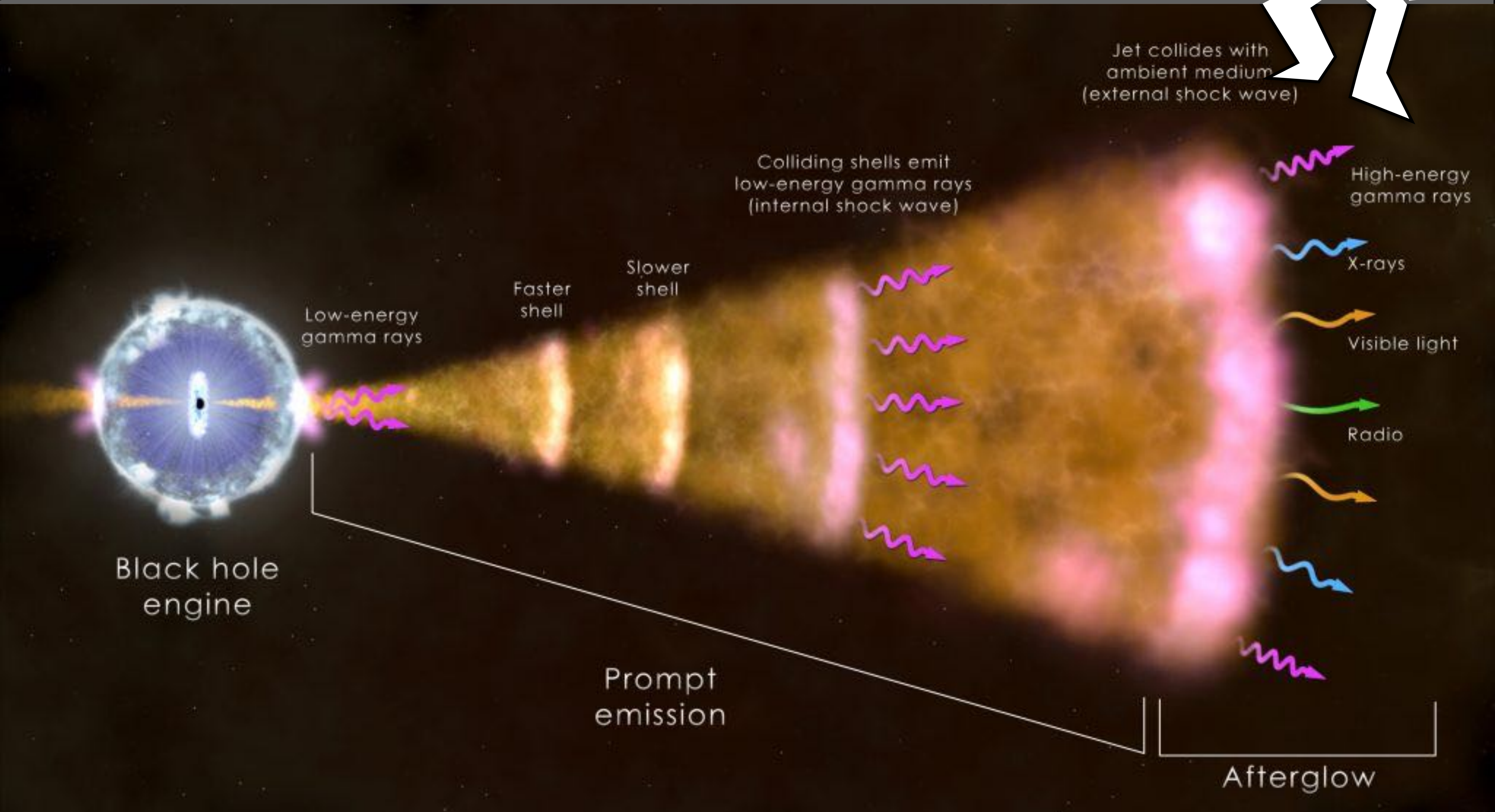
Image Credit - L. Rezzolla

ELECTROMAGNETIC EMISSION ASSOCIATED TO BNS MERGERS



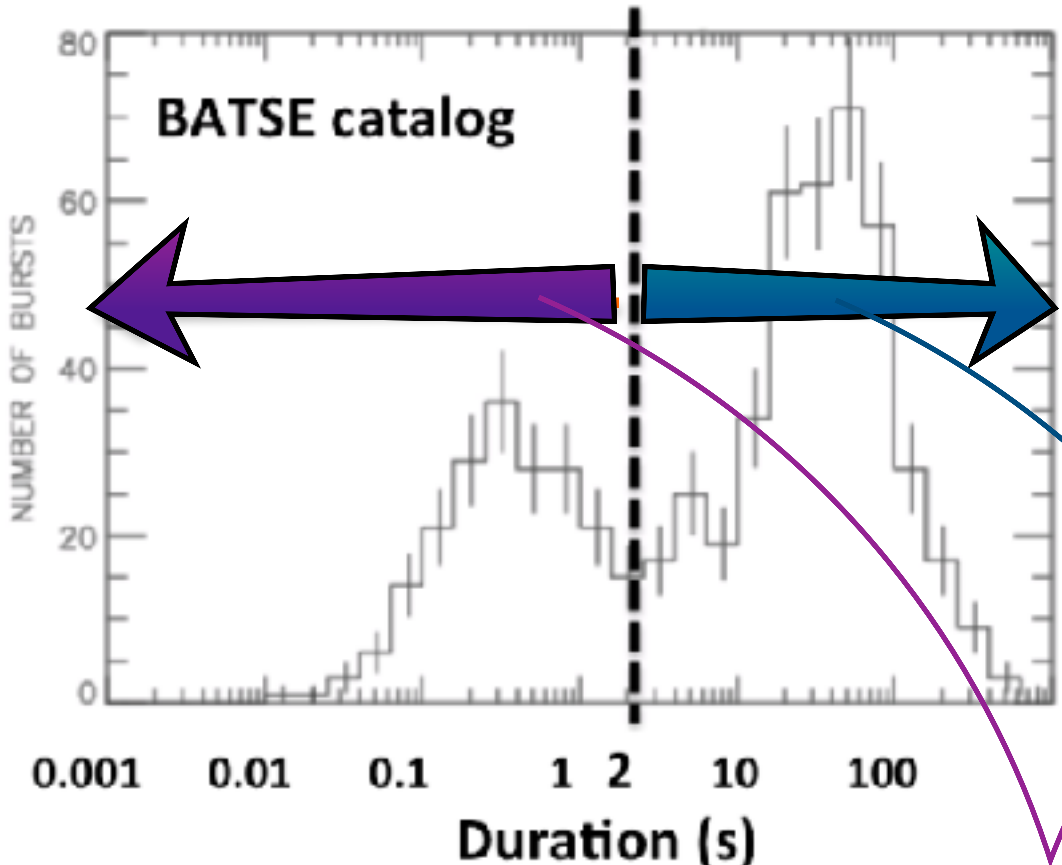
Rodrigo Fernández and Brian D. Metzger Ann. Rev. Nuc. Part. Sci. 2016. 66:1–24

THE FIREBALL MODEL

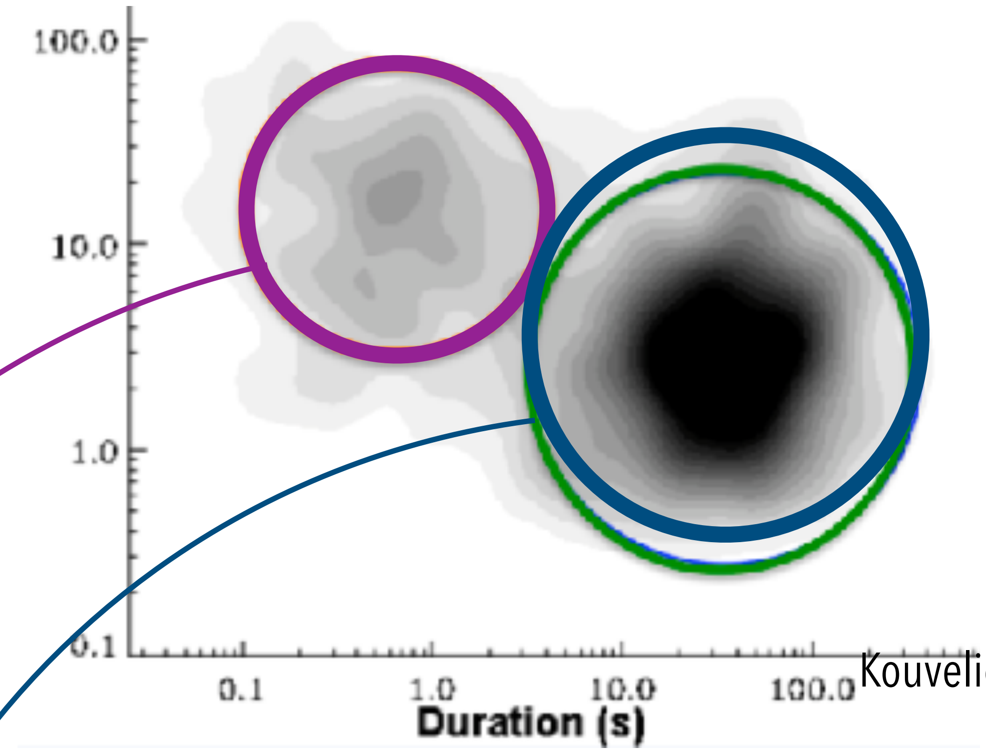


GRBs

Bimodal duration distribution



Hardness ratio



Kouveliotou et al. 1993

DIFFERENT PROGENITORS

Short Hard GRB

- lack of observed SN
- association with older stellar population
- larger distance from the host galaxy center (~ 5-10 kpc)
- accretion timescale of disk in binary merger model is short (t ~ 1s)

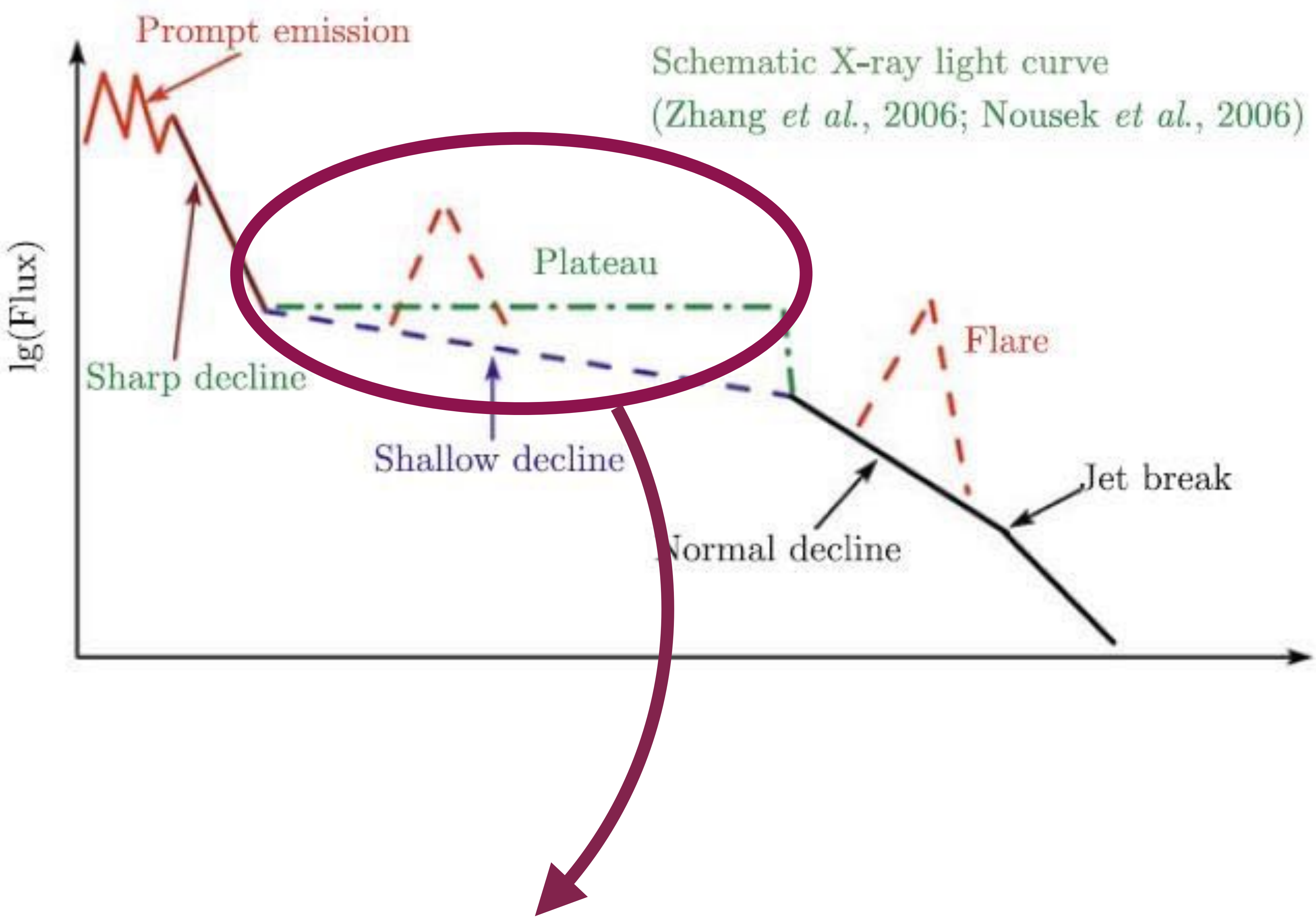
NS-NS NS-BH mergers

Long Soft GRB

- observed Type Ic SN spectrum
- accretion disk is fed by fallback of SN material onto disk, timescale t ~ 10-100s

Core-collapse of massive stars

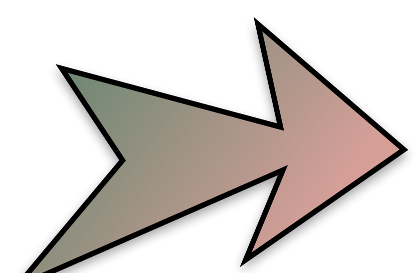
SHORT GRB



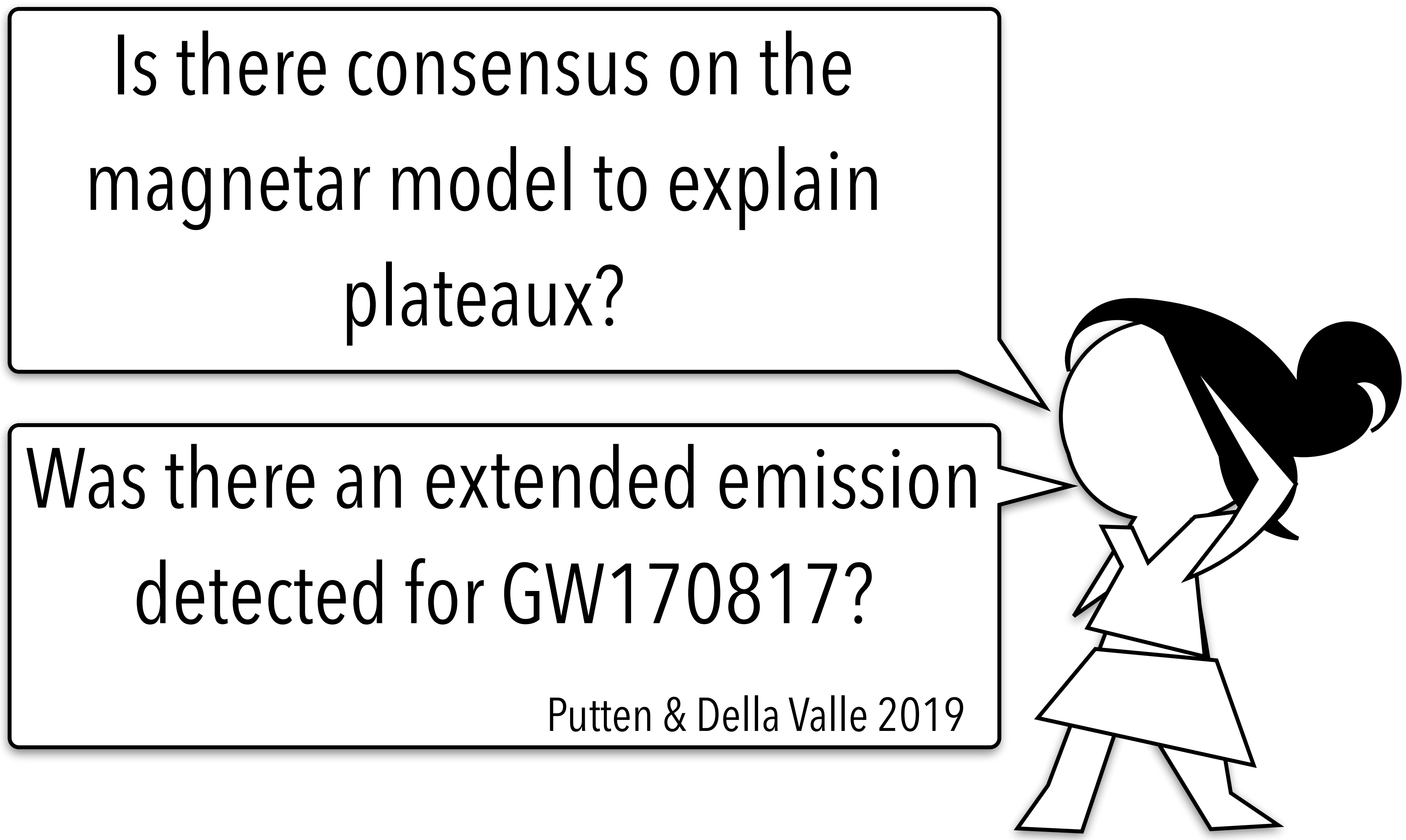
Rowlinson et al. MNRAS
Vol. 430, 2, 1061-1087

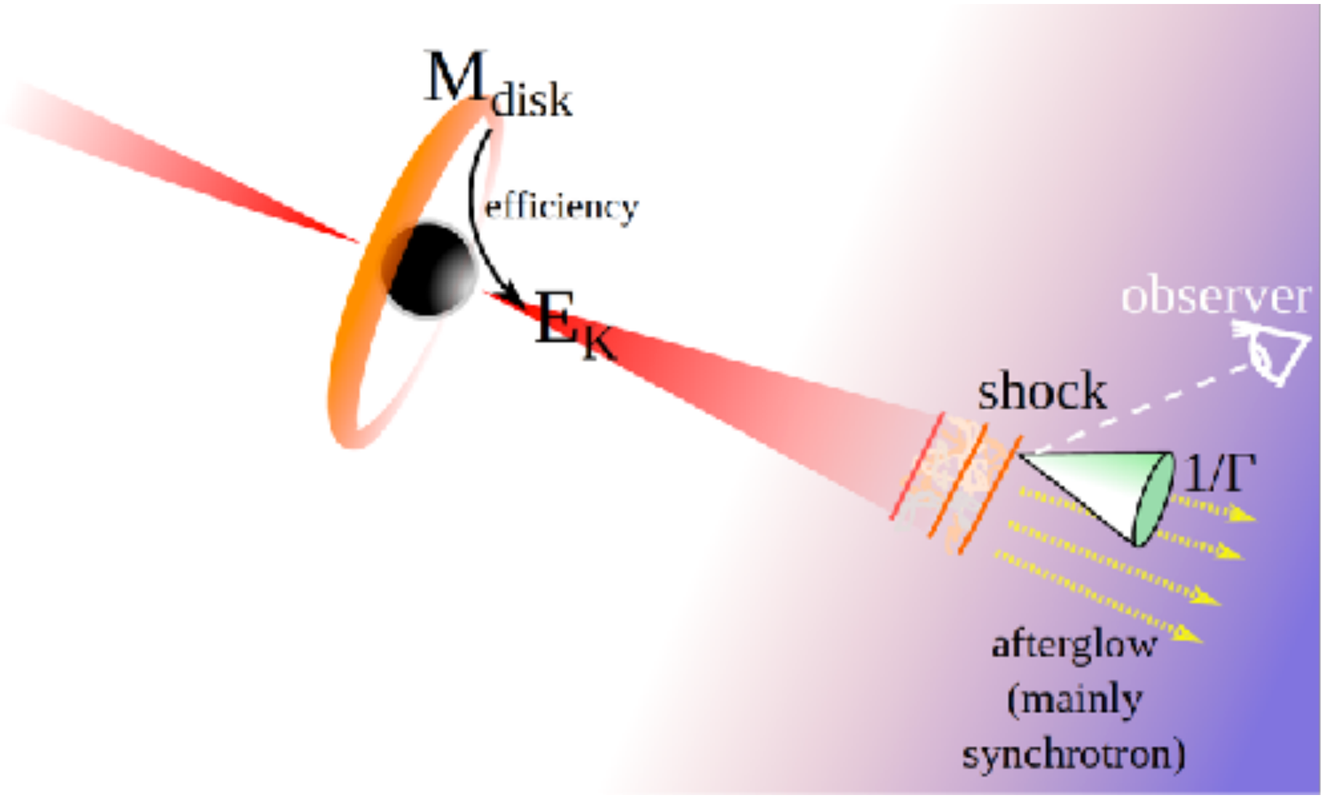
~50%
SGRBs have a
plateaux phase

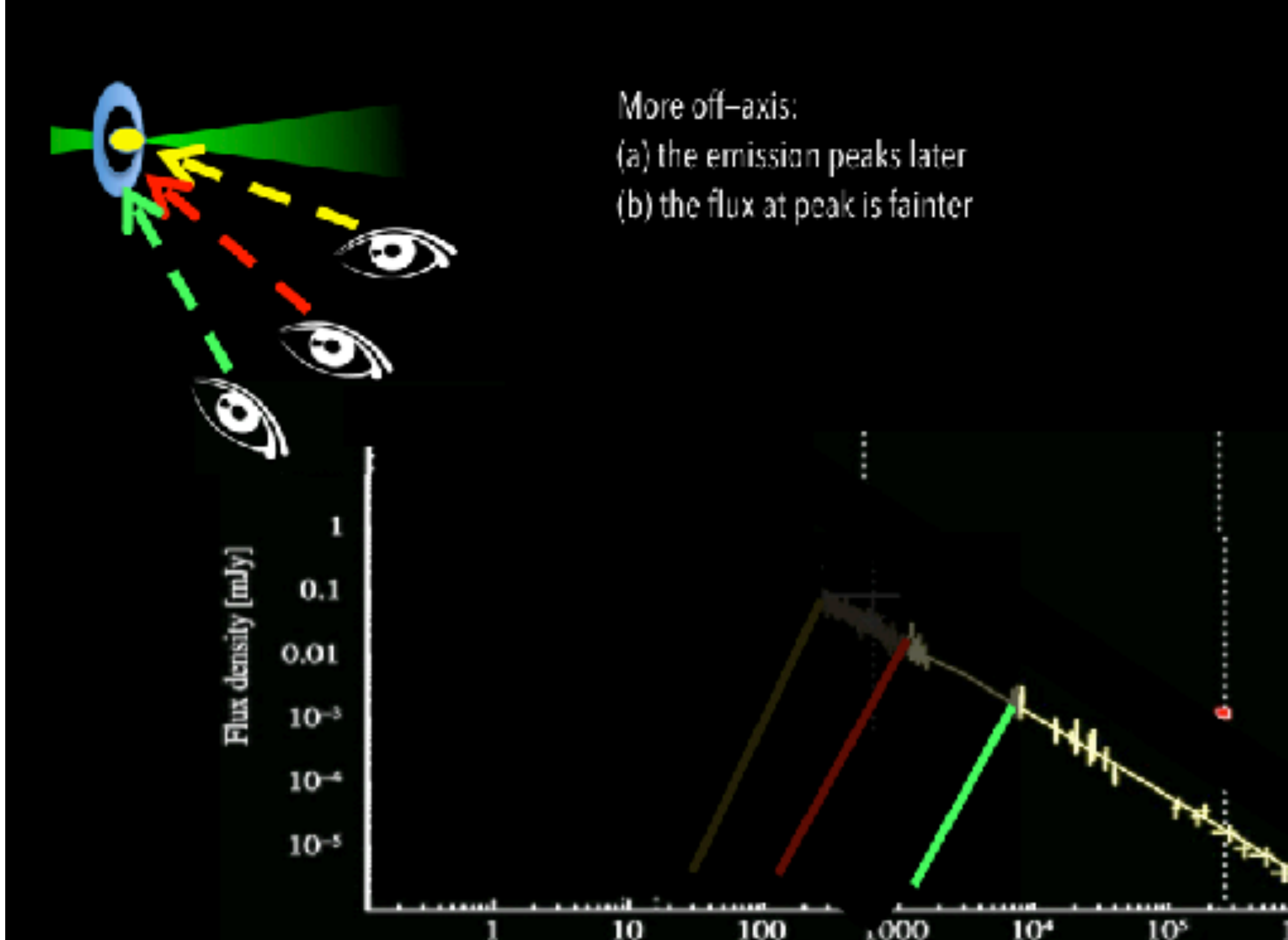
THE FIREBALL MODEL can not explain this emission



MAGNETAR MODEL

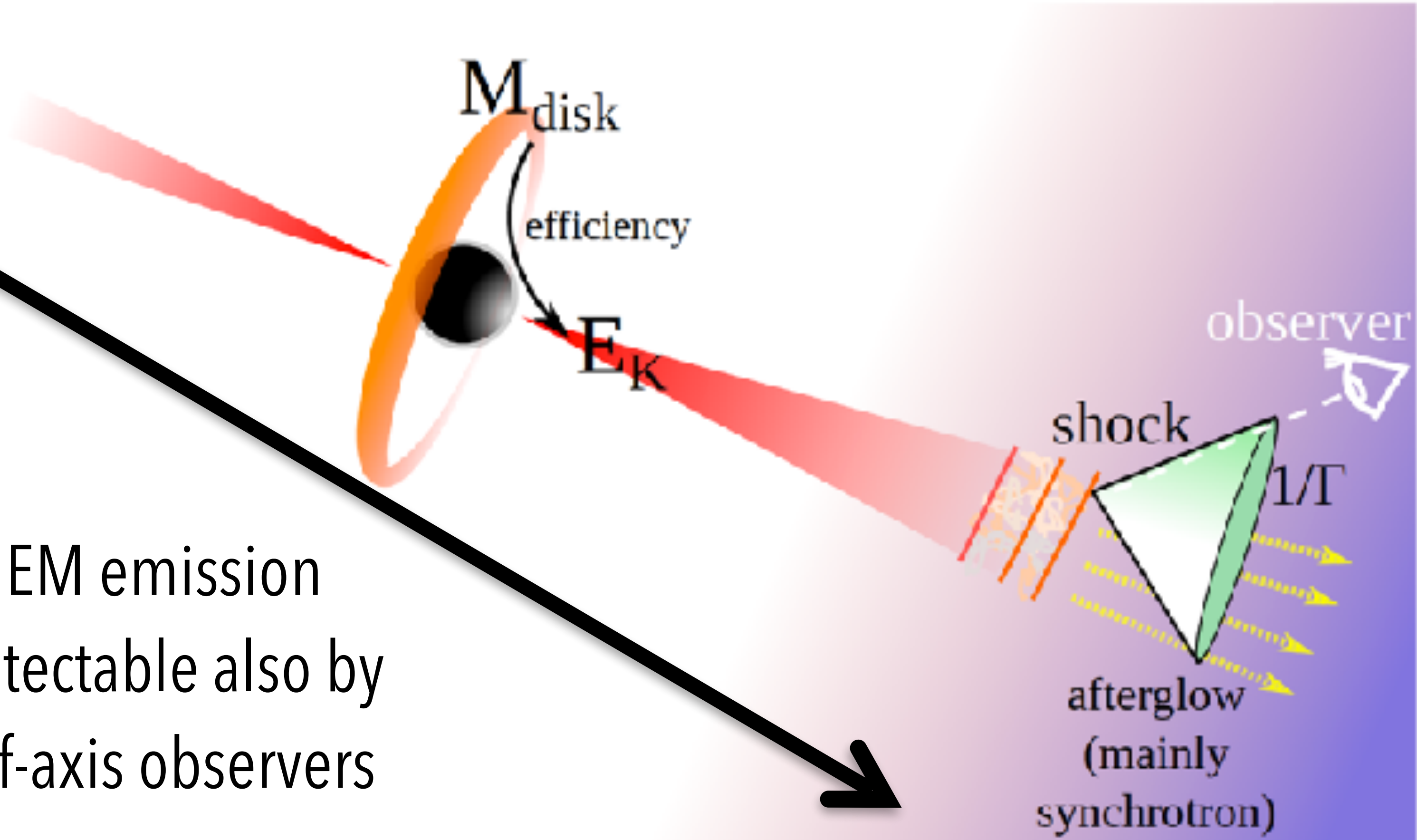

Is there consensus on the magnetar model to explain plateaux?
Was there an extended emission detected for GW170817?
Putten & Della Valle 2019





Credit: Ghirlanda

Early EM emission detectable only by on-axis observers



EM emission detectable also by off-axis observers

Credit: Salafia

SHORT GRB HOSTs

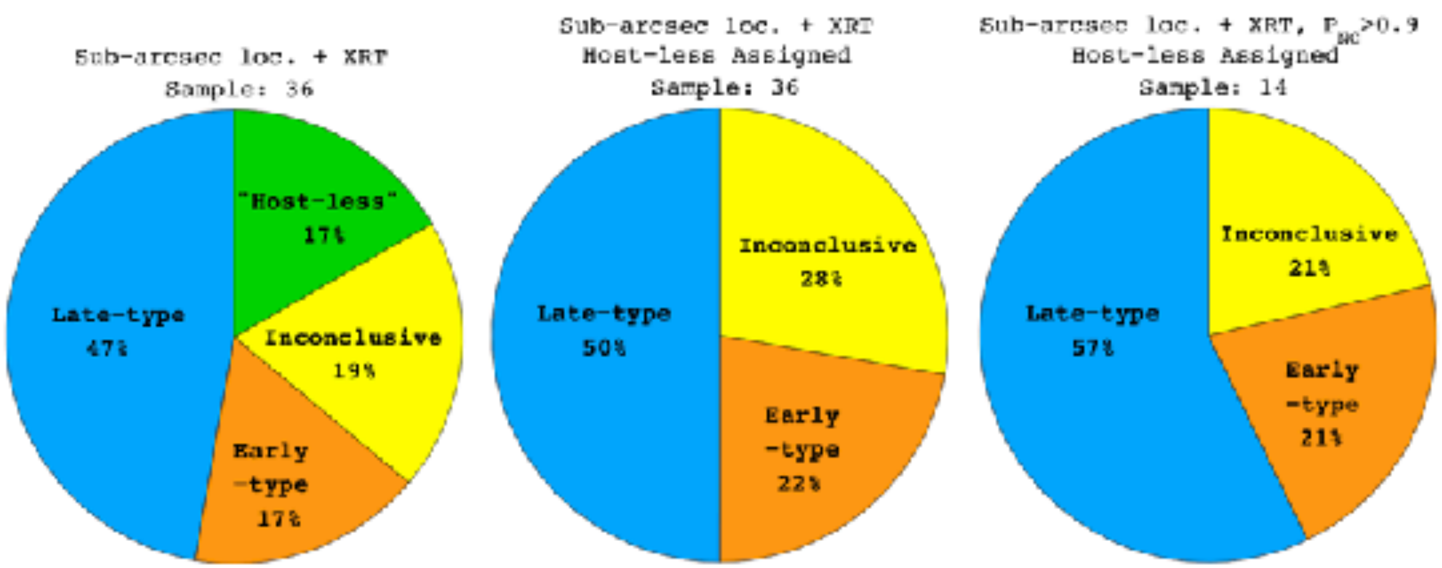
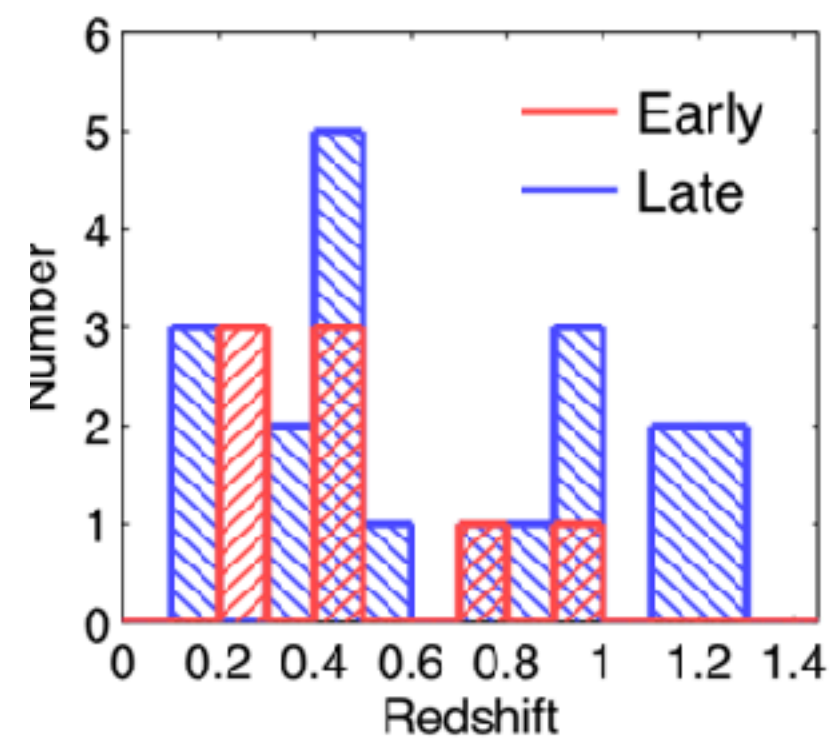


Figure 5:

Demographics of the galaxies hosting short GRBs. *Left:* A breakdown into late-type (blue), early-type (orange), host-less (green), and inconclusive (yellow) for all identified hosts based on sub-arcsecond positions and *Swift*/XRT positions (Table 2). *Middle:* Same as the left panel, but with the host-less events assigned to the other categories based on the galaxies with the lowest probability of chance coincidence in each case (Berger 2010, Fong & Berger 2013). *Right:* Same as the middle panel, but for short GRBs with a probability of a non-collapsar origin of $P_{NC} \gtrsim 0.9$ based on the analysis of Bromberg et al. (2013). Regardless of the sample selection, late-type galaxies dominate the host sample. This indicates that star formation activity plays a role in the short GRB rate. Adapted from Fong et al. (2013).



Short GRBs
($\langle z \rangle \approx 0.5$)

Berger 2013

Short GRB Hosts

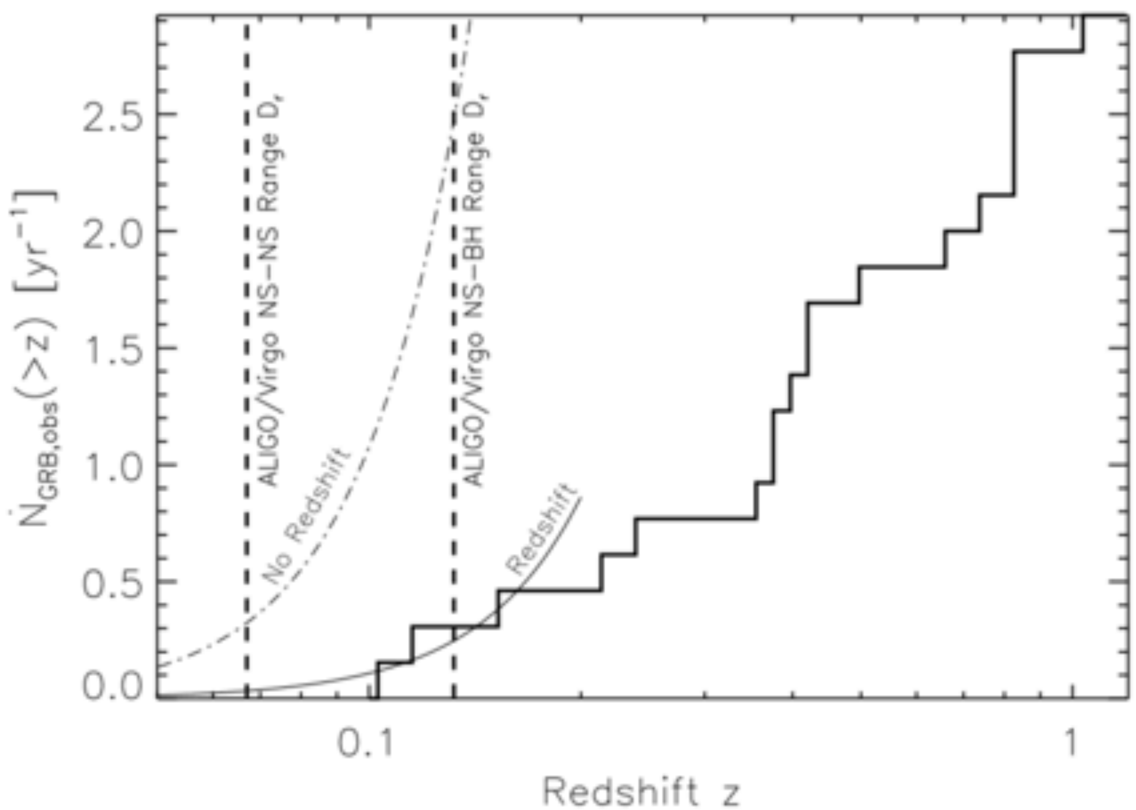


FIG. 2.— Cumulative detection rate of SGRBs with measured redshifts $> z$ (*thick solid line*), calculated using 19 (mostly *Swift*) SGRBs (e.g., Berger 2011b). Dashed vertical lines mark the estimated sensitivity range of ALIGO/Virgo to NS-NS and NS-BH mergers, respectively, including a boost due to the face-on binary orientation. The thin solid line shows an approximate fit to $\dot{N}_{\rm GRB,obs}(> z)$ at low redshift. The dot-dashed line shows an estimate of the *total* SGRB detection rate (with or without redshift information) by an all-sky γ-ray telescope with a sensitivity similar to *Fermi*/GBM.

B. D. Metzger and E. Berger 2011

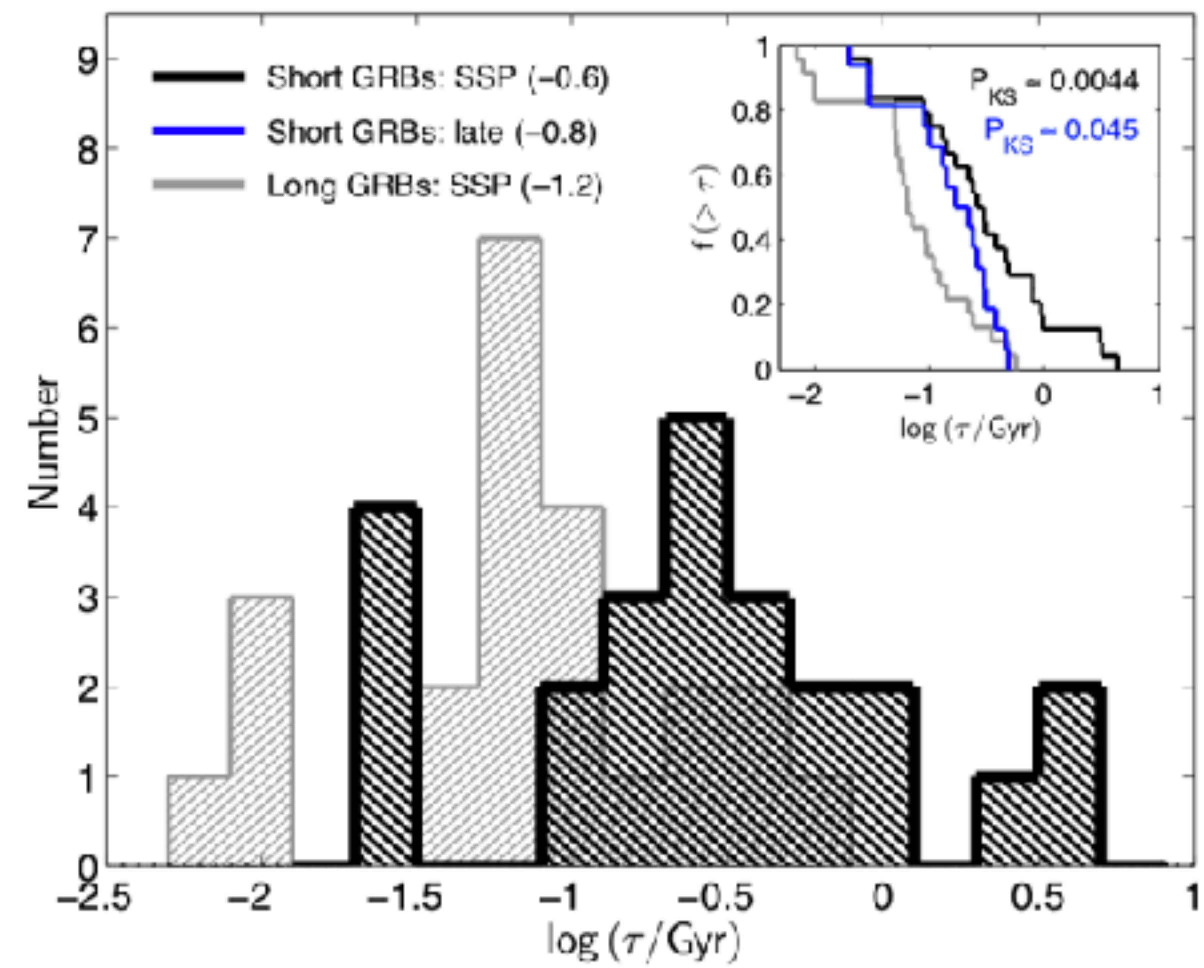


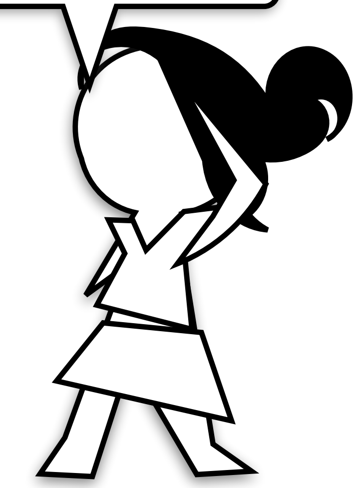
Figure 7:

Histogram of host galaxy stellar population ages for short GRBs (black) and long GRBs (gray). Median values for each population (and separately for short GRB late-type hosts) are quoted in parentheses. The inset shows the cumulative distributions along with K-S probabilities that the short and long GRB hosts are drawn from the same parent population. The results indicate that short GRB hosts, even the late-type galaxies, have systematically older stellar population than long GRB hosts. Adapted from Leibler & Berger (2010).

Berger 2013

SHORT GRB LOCAL RATES

What is the role of BH-NS mergers? Do people believe they significantly contribute?



"estimates of local SGRB rates range from **0.1-0.6 Gpc^{-3} yr^{-1}** *(e.g. Guetta & Piran 2005; 2006) to* **1-10 Gpc^{-3} yr^{-1}** *(Guetta & Piran 2006; Guetta & Stella 2009; Coward et al. 2012; Siellez et al. 2014, WP15) to even larger values like* **40-240 Gpc^{-3} yr^{-1}** *(Nakar et al. 2006; Guetta & Piran 2006)"*

Ghirlanda 2016

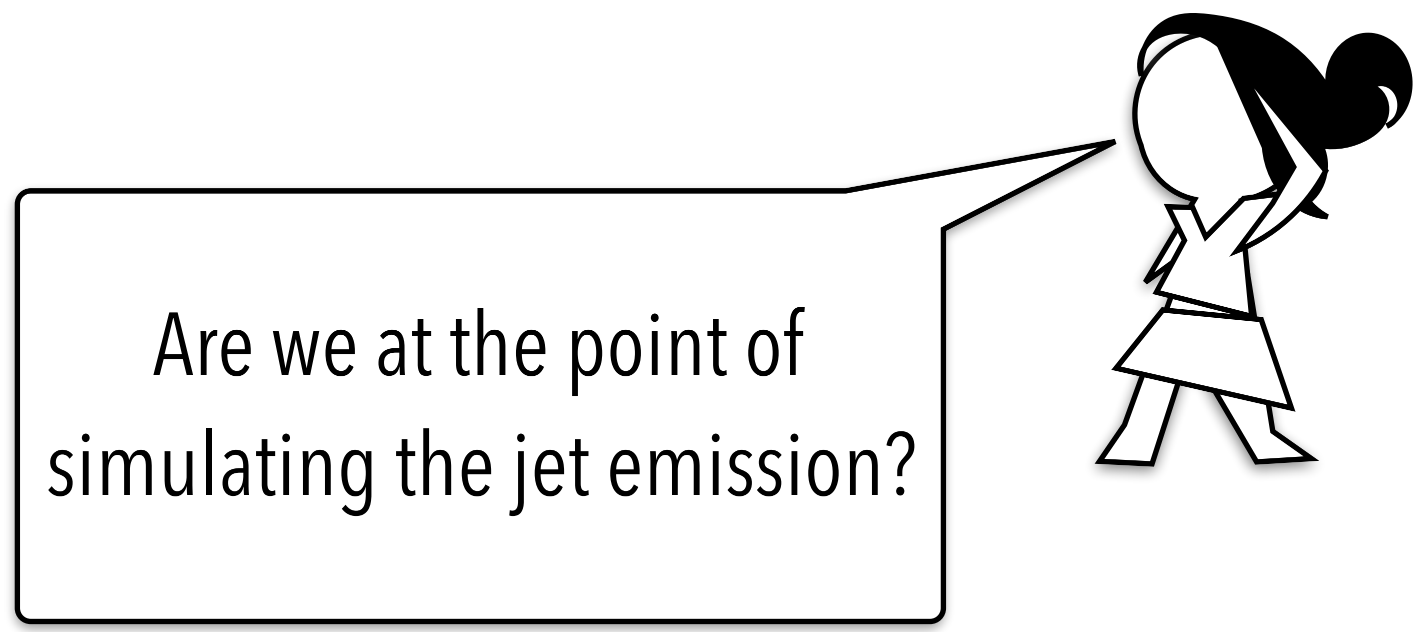
<4y^{-1} at d<200 Mpc*, corresponding to <5 % of sGRBs.*

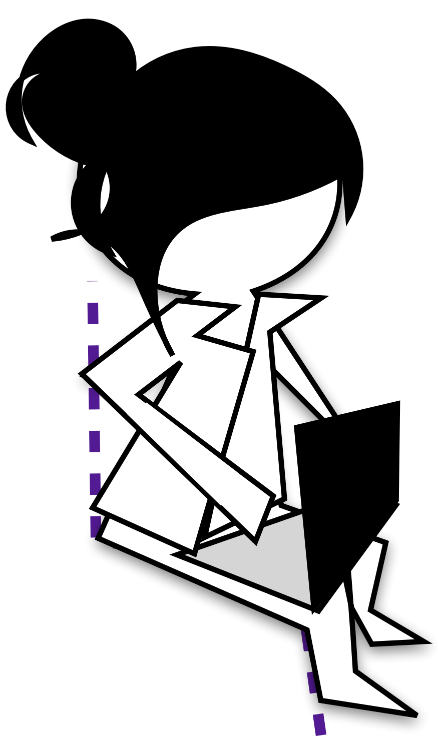
-Mandhai et al 2018

The local formation rate of sGRBs is ***7.53 events Gpc^{-3} yr^{-1}****. Considering the beaming effect, the local formation rate of sGRBs including off-axis sGRBs is* ***$203.31^{+1152.09}_{-135.54}$ events Gpc^{-3} yr^{-1}****.*

- Zhang Wang 2017

SHORT GRB JET LAUNCHED?



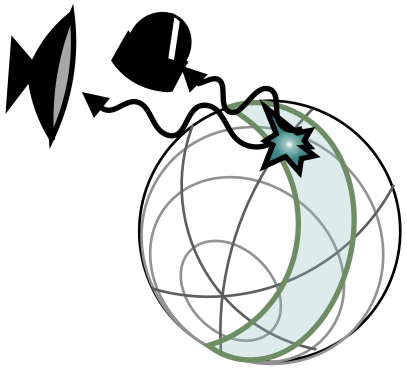


e.g.

JJ Geng - 2019

Kawamura et. al 2016

Ruiz et al. 2016



O1-O2

11 confident detection

8 sent in low-latency

Event	Low-latency analysis d_L(Mpc)	Low-latency analysis $\Delta\Omega$ (deg^2)	Low-latency analysis IFOs	Refined analysis d_L(Mpc)	Refined analysis $\Delta\Omega$ (deg^2)	Refined analysis IFOs
GW150914	—	307	HL	440^{+150}_{-170}	182	HL
GW151012	—	—	—	1080^{+550}_{-490}	1523	HL
GW151226	—	1337	HL	490^{+180}_{-190}	1033	HL
GW170104	730^{+340}_{-320}	1632	HL	990^{+440}_{-430}	921	HL
GW170608	310^{+200}_{-120}	864	HL	320^{+120}_{-110}	392	HL
GW170729	—	—	—	2840^{+1400}_{-1360}	1041	HLV
GW170809	1080^{+520}_{-470}	1155	HL	1030^{+320}_{-390}	308	HLV
GW170814	480^{+190}_{-170}	97	HLV	600^{+150}_{-220}	87	HLV
GW170817	40^{+10}_{-10}	31	HLV	40^{+7}_{-15}	16	HLV
GW170818	—	—	—	1060^{+420}_{-380}	39	HLV
GW170823	1380^{+700}_{-670}	2145	HL	1940^{+970}_{-900}	1666	HL

GW170817

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

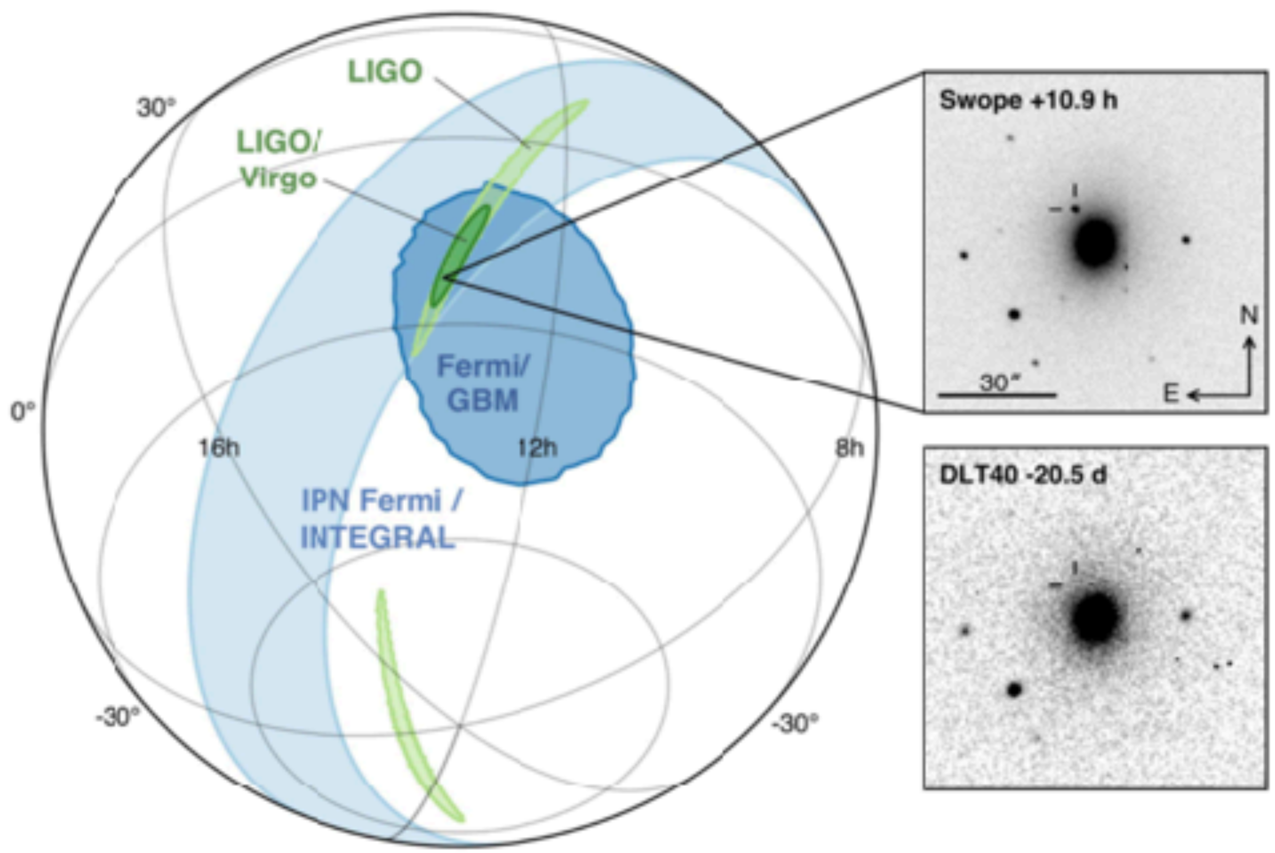
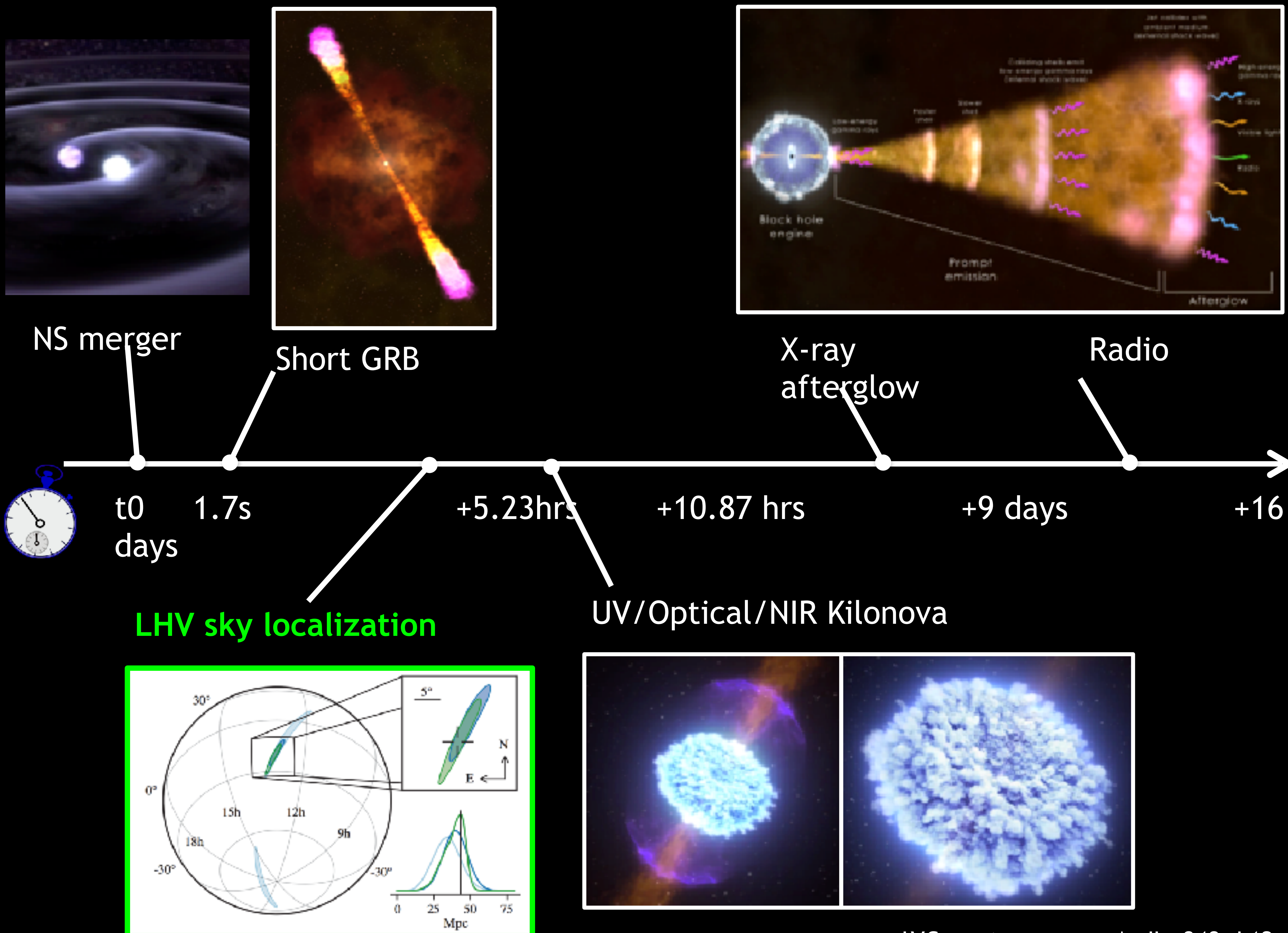


Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2; light green), the initial LIGO-Virgo localization (31 deg^2; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

No neutrinos directionally coincident with the source were detected within ±500 s around the merger time

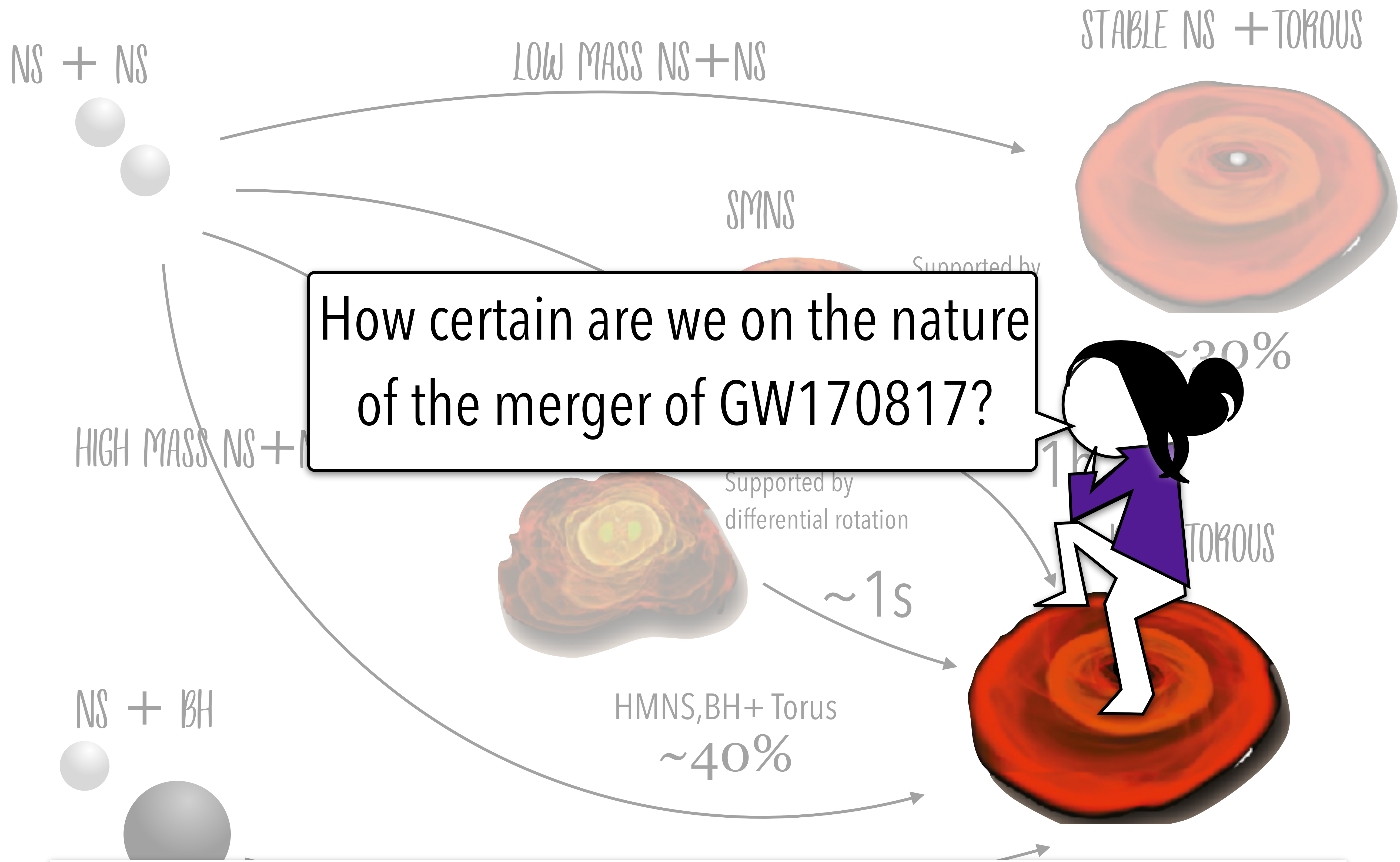
Abbott et al 2017 GW170817

Abbott et al 2017 Multi messenger astronomy



LVC + astronomers, ApJL, 848, L12

Credit Marica Branchesi



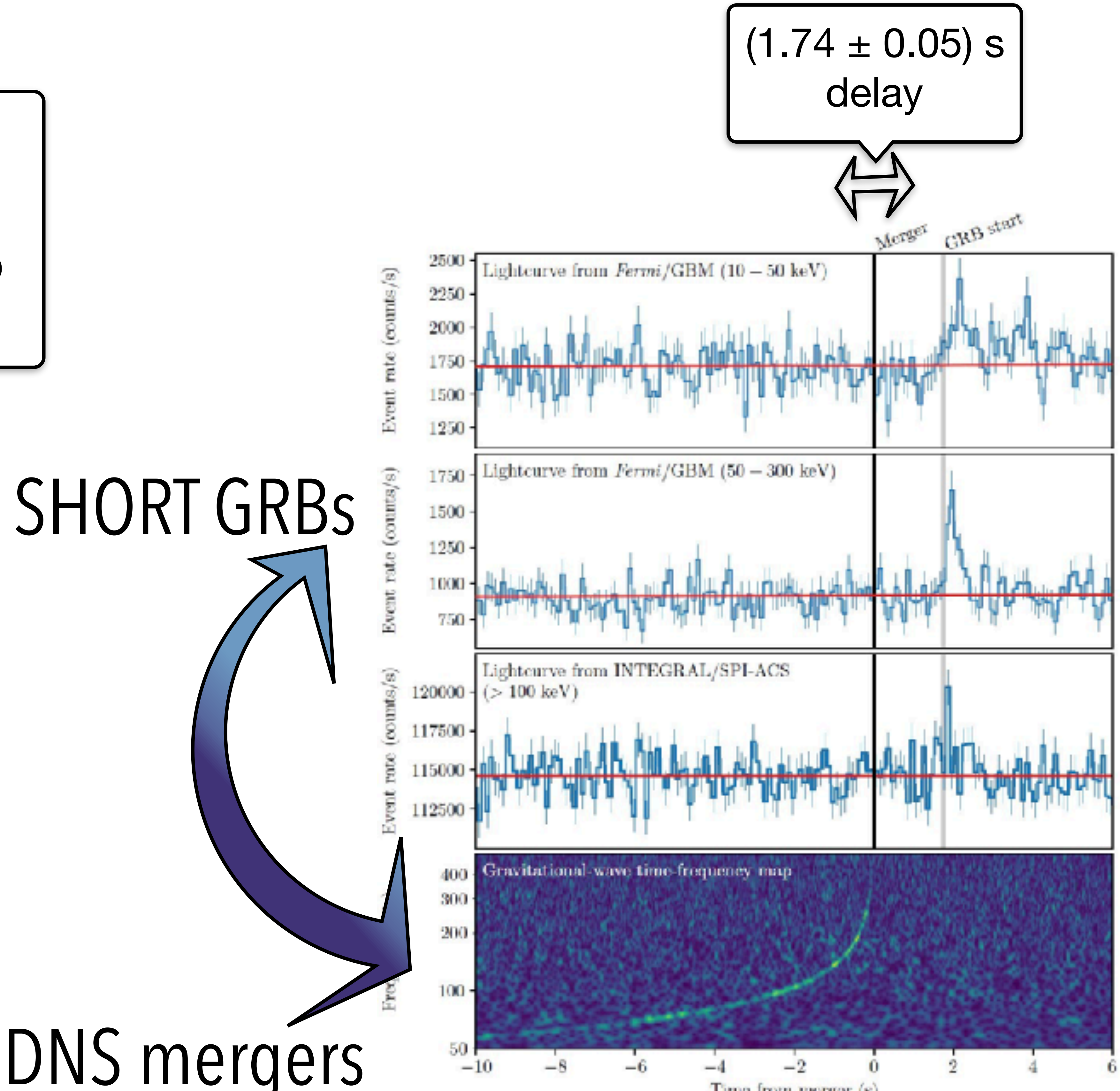
The short duration of the burst is consistent with a prompt black hole or a hyper-massive neutron star that survived for a short (e.g. ~ 100 ms) period of time before collapsing to a black hole (Zhang et al 2018).

ArXiv 1511.00753v2

Image Credit - L. Rezzolla

GRB170817A

DO ALL DNS MERGERS PRODUCE SHORT GRBs?



(1.74 ± 0.05) s delay
Merger
GRB start
SHORT GRBs
DNS mergers
Lightcurve from Fermi/GBM (10 – 50 keV)
Lightcurve from Fermi/GBM (50 – 300 keV)
Lightcurve from INTEGRAL/SPI-ACS (> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Time from merger (s)

GRB170817A

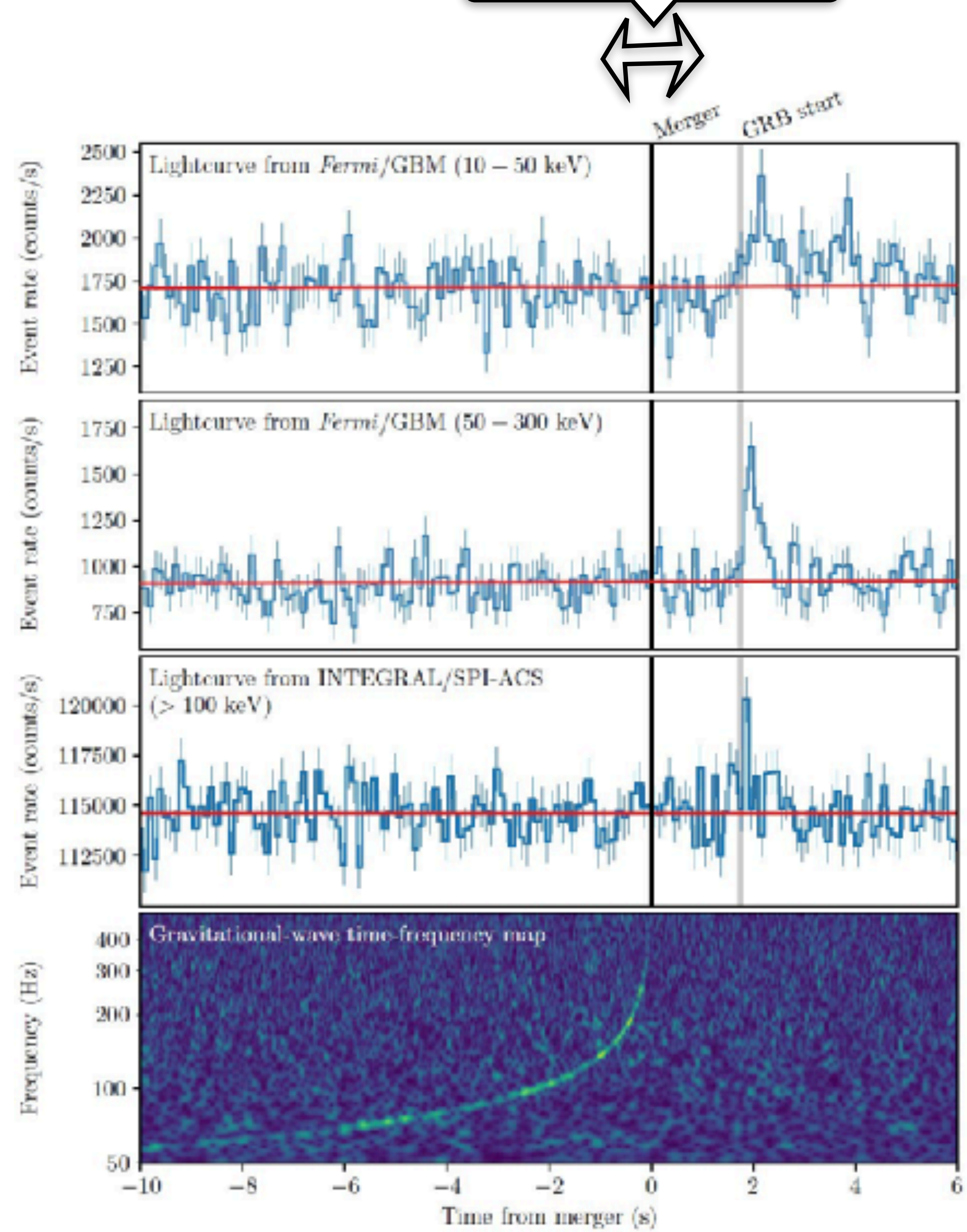
Very under luminous GRB ($L_p \sim 10^{47}$ erg/s 4/5 order of magnitude less than previously detected)

Outlier of E_p - L_{iso} correlation

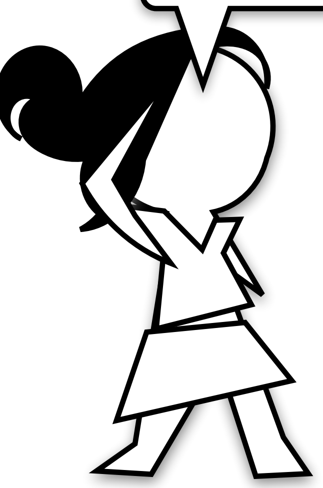
0-0.7s Non thermal spectrum

Possibly followed by thermal tail

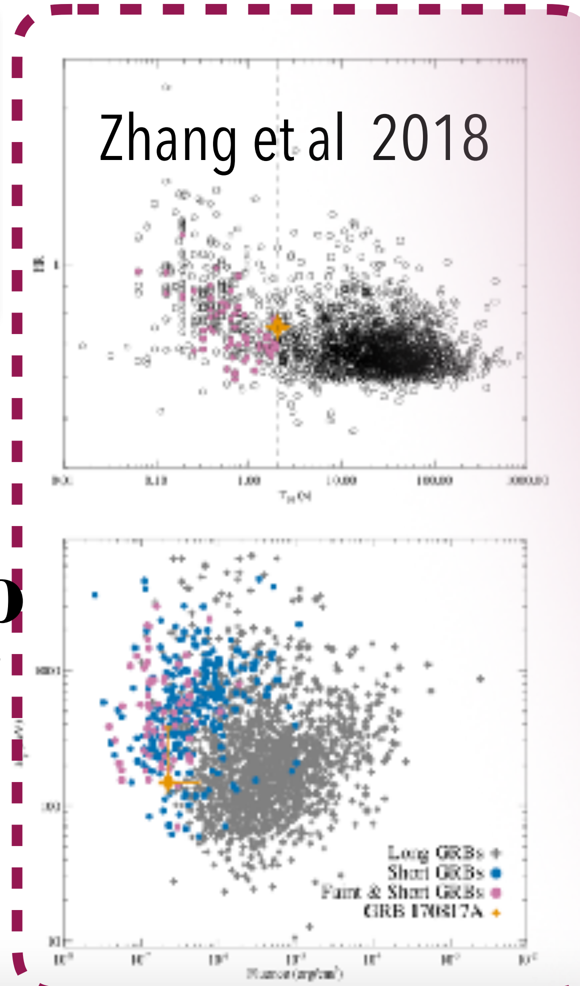
(1.74 ± 0.05) s delay



Was GRB 170817A special?



DO ALL DNS MERGERS PRODUCE SHORT GRBs?



GRB170817A

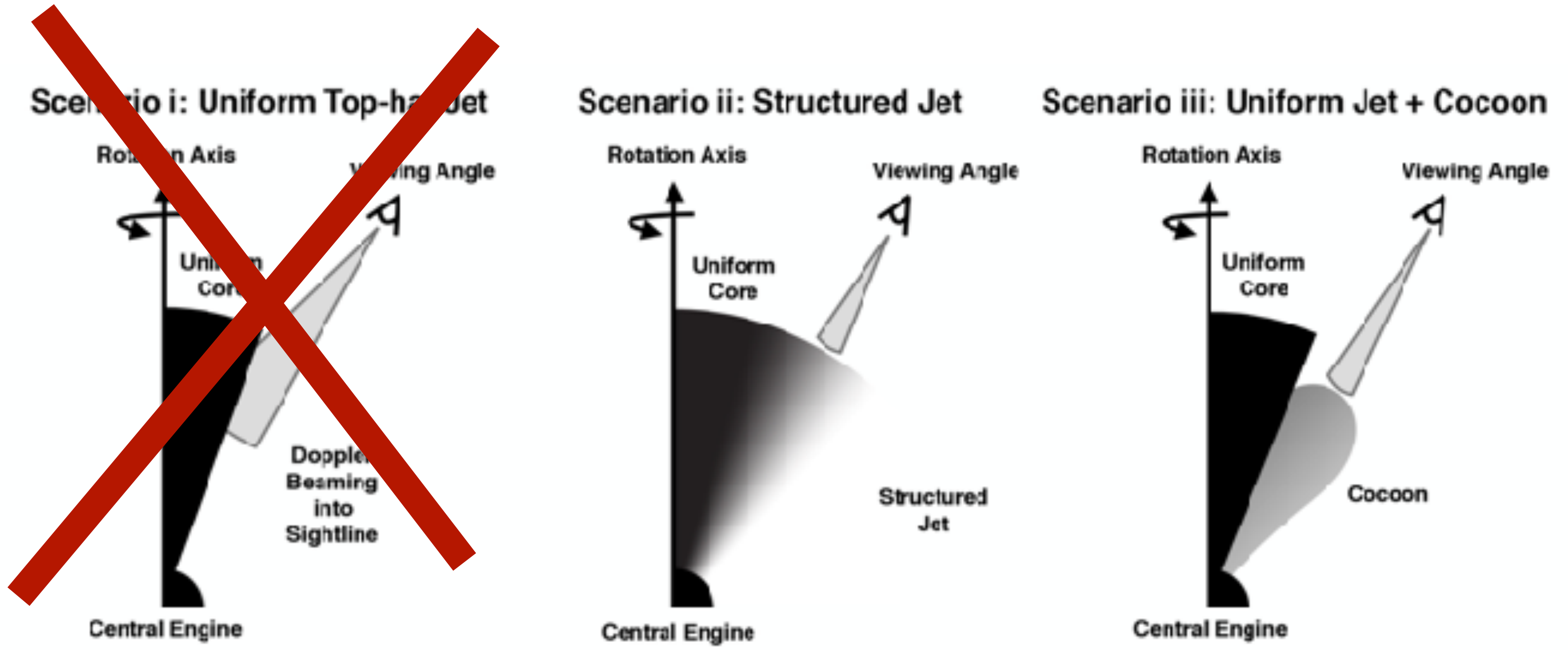
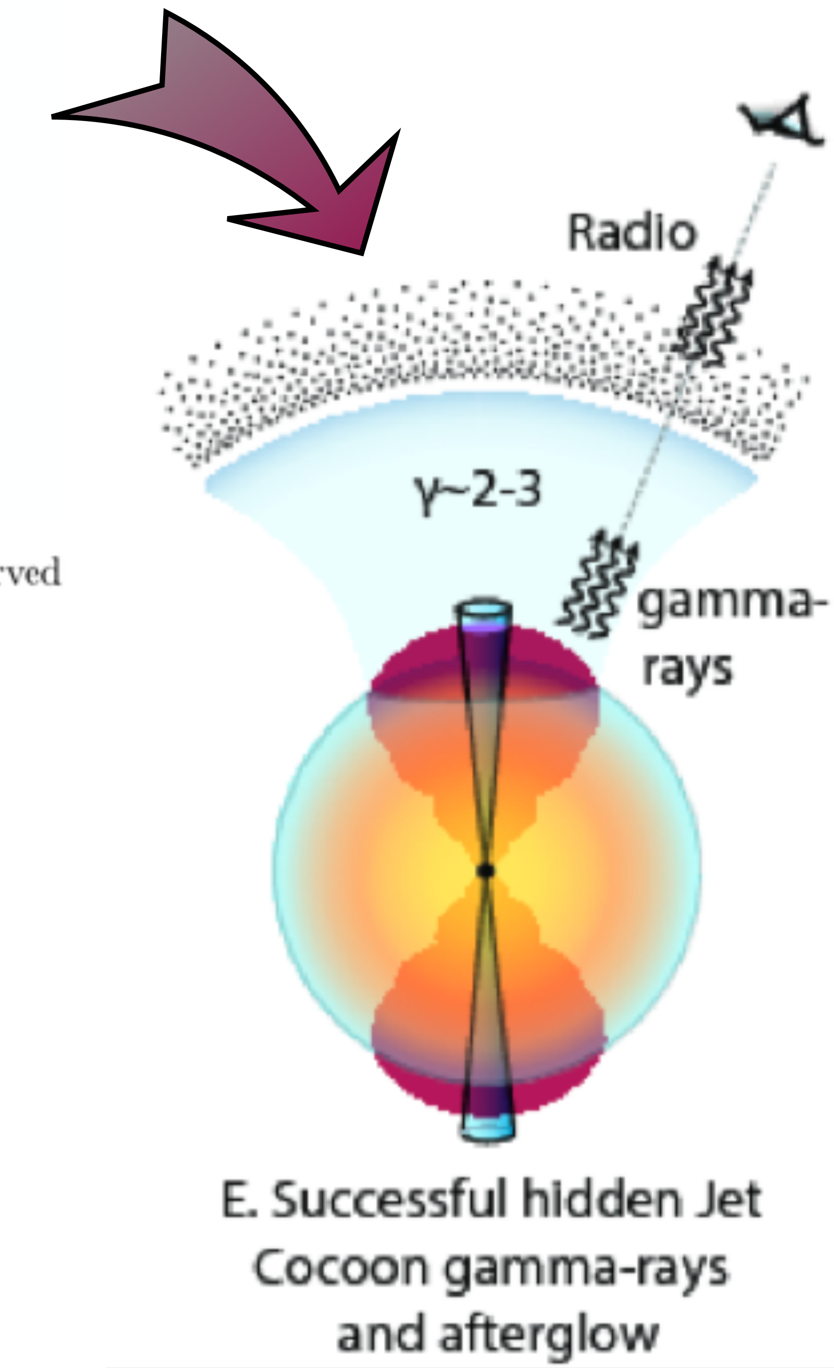
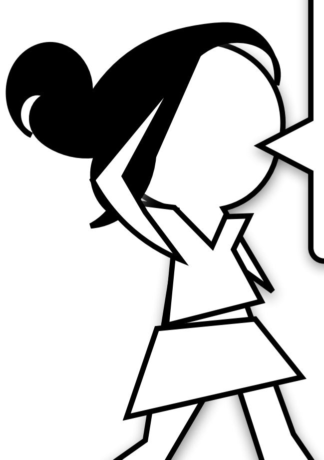


Figure 5. The three potential jet viewing geometries and jet profiles that could explain the observed properties of GRB 170817A, as described by scenarios (i)–(iii) in Section 6.2.





Is the scenario of structured jet and small cocoon the most commonly accepted?

Mooley et al 2018

NGC 4993

~44.1 Mpc distance

(0.3-1.2) 10^{11}solar masses

a mean stellar age greater than ~3 Gyr

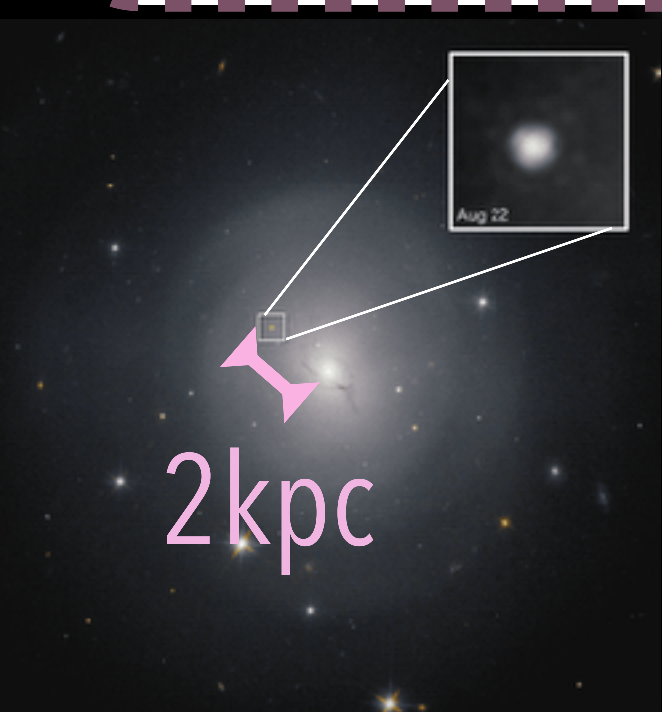
metallicity of about 20%–100% of solar abundance

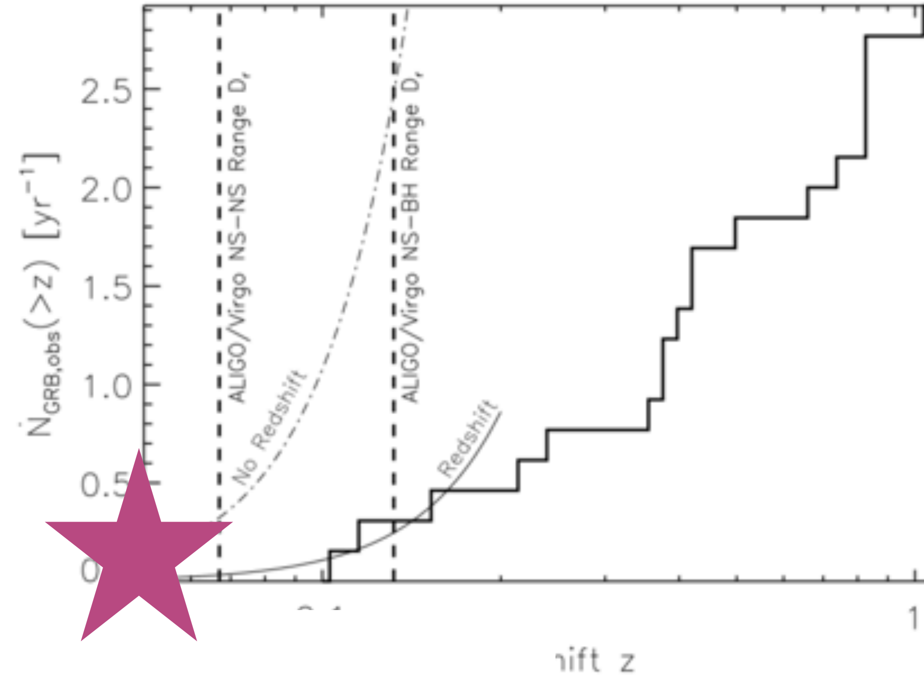
250 GLOBULAR CLUSTERS

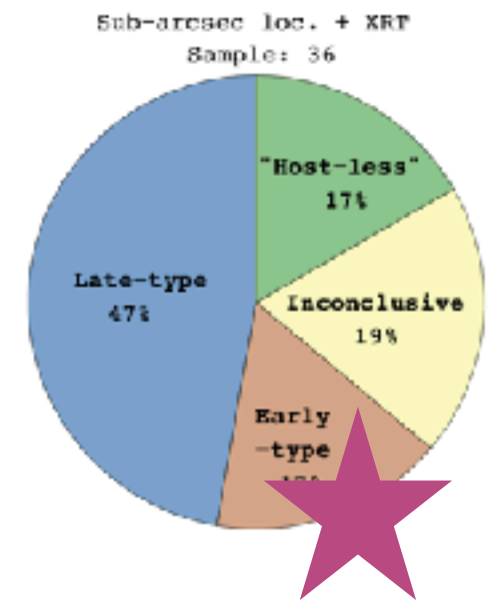
SUPERMASSIVE BH 80 - 100 MILLION SOLAR MASSES

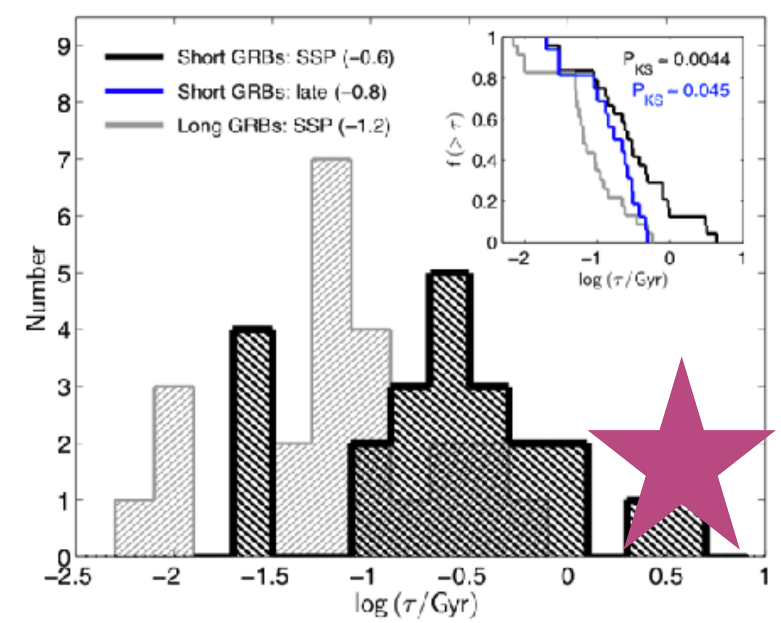
RECENT MERGER WITH ANOTHER GALAXY

Im1 et al 2017









OTHER KILONOVAE - SHORT GRBS ASSOCIATIONS

GRB 070809

2 possible host: 1 early type no star forming and 1 star forming galaxy

Nature 2019

GRB 160821

face-on spiral

E. Troja et al. 2019

GRB 150101B

massive elliptical galaxy with stellar population of ~**5.7 Gyr**

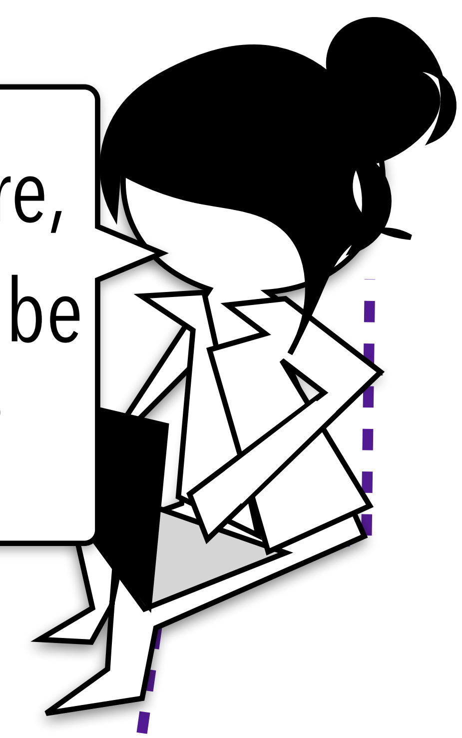
Xie et al 2016

GRB 130603B

The GRB was located at the edge of a disrupted arm of a **moderately star forming galaxy** with **near-solar metallicity**.

A. de Ugarte Postigo et al 2013

I probably missed some more, but do people think it would be a good direction to go for?



AFTERGLOWS

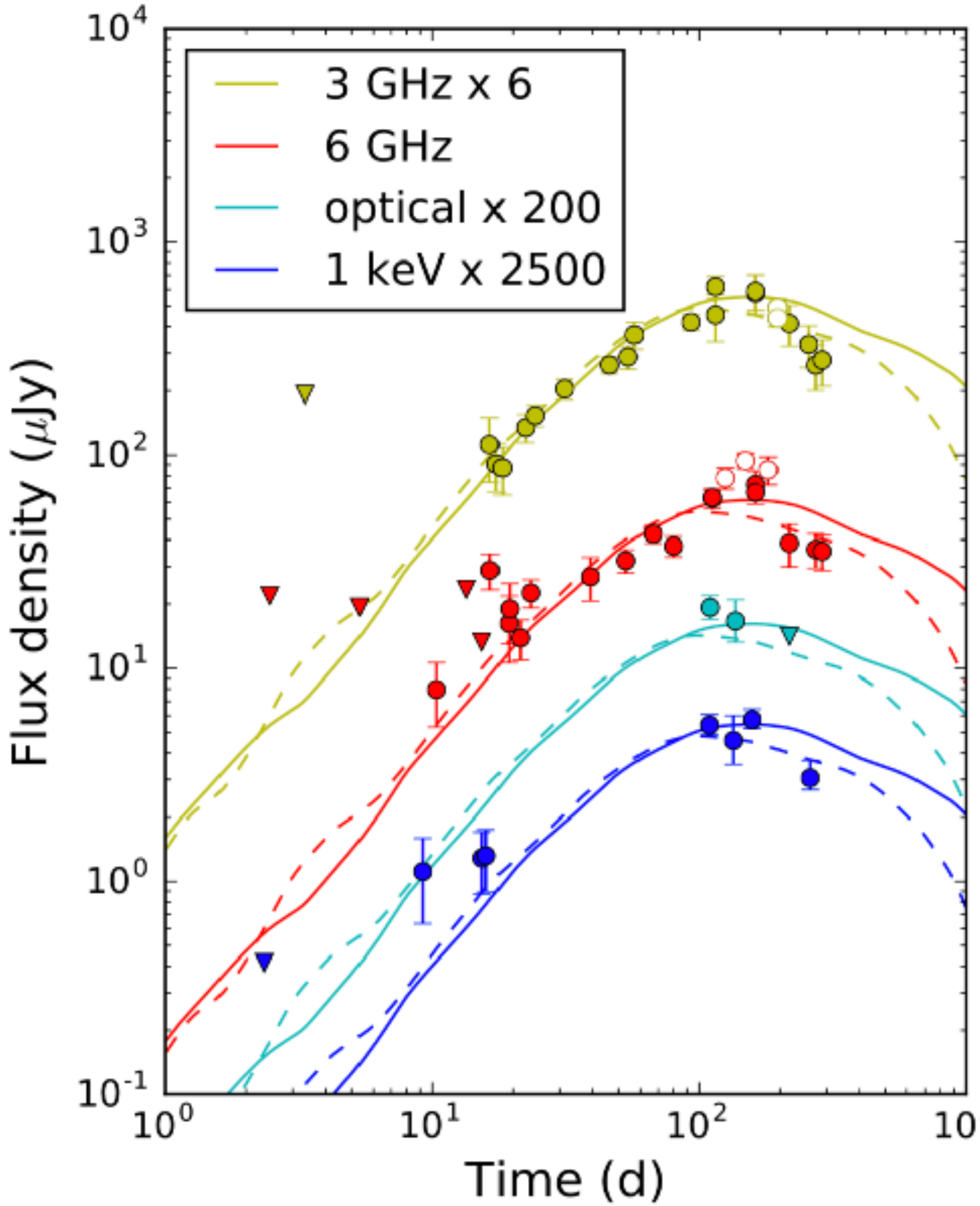
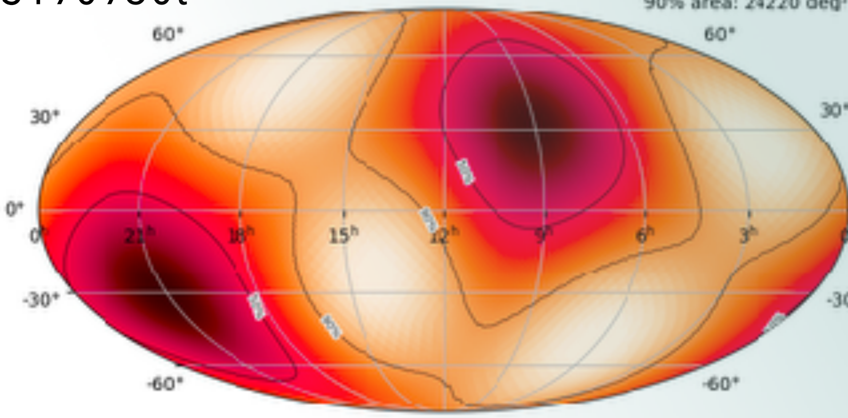


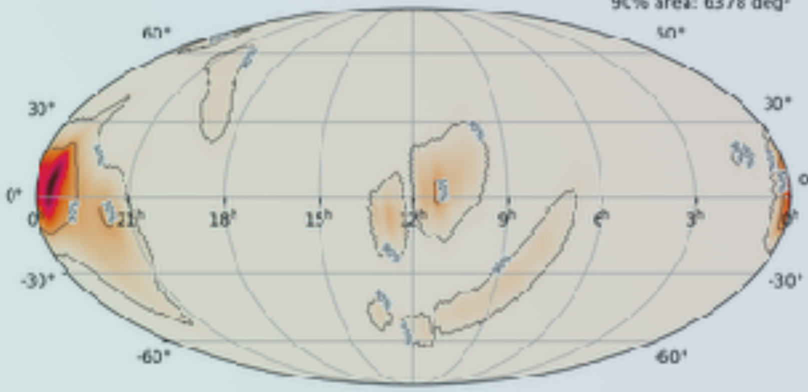
Figure 1. Up-to-date X-ray, optical, and radio light curves of GW170817 (solid circles; open circles are the new data presented in Dobie et al. 2018). The data are clearly indicative of a decline at $\gtrsim$200 days. Also shown are our structured jet models from Margutti et al. (2018); see Xie et al. (2018) for full details of the simulations. Both jets have an ultra-relativistic core with $E_{\rm K,iso} = 6 \times 10^{52}$ erg within an opening angle $\theta_{\rm jet} = 9°$. The solid lines are for a model with $n = 10^{-5}\ {\rm cm}^{-3}$, $\theta_{\rm obs} = 17°$, $\epsilon_e = 0.1$, and $\epsilon_B = 0.0005$, while the dashed lines are for $n = 10^{-4}\ {\rm cm}^{-3}$, $\theta_{\rm obs} = 20°$, $\epsilon_e = 0.02$, and $\epsilon_B = 0.001$. Our new radio, optical, and X-ray observations continue to support these models.

03 CANDIDATES

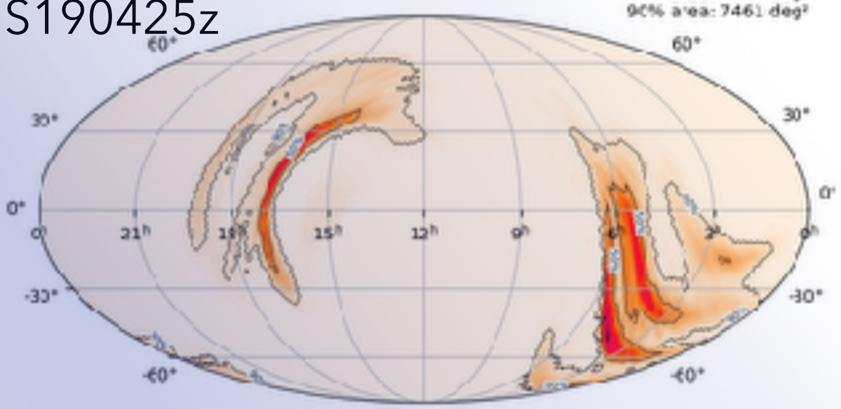
S190930t



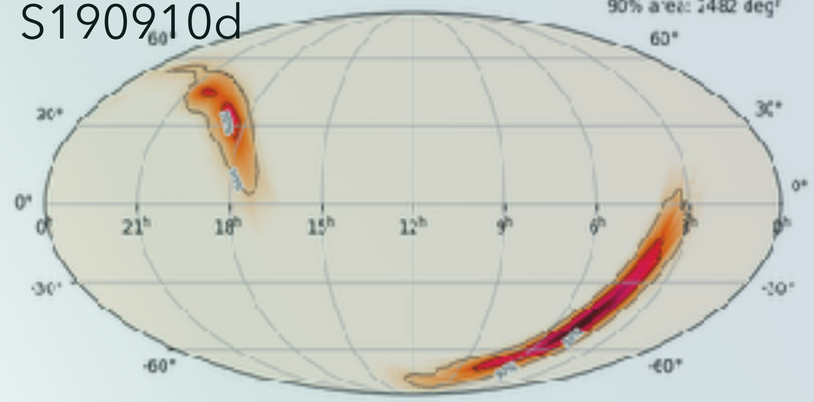
S191205ah



S190425z

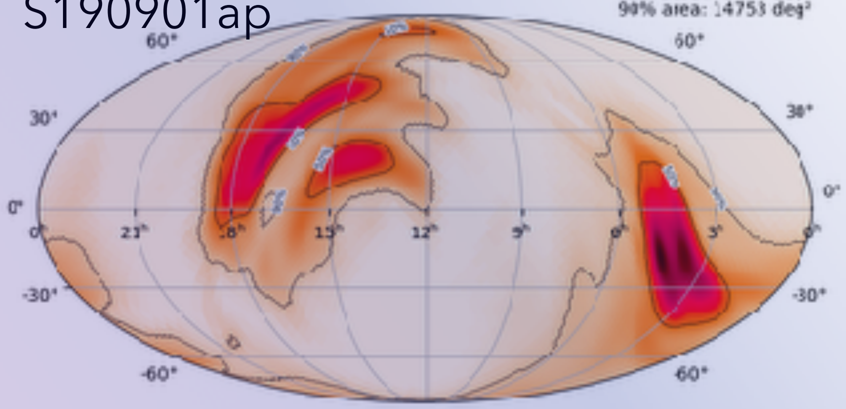


S190910d

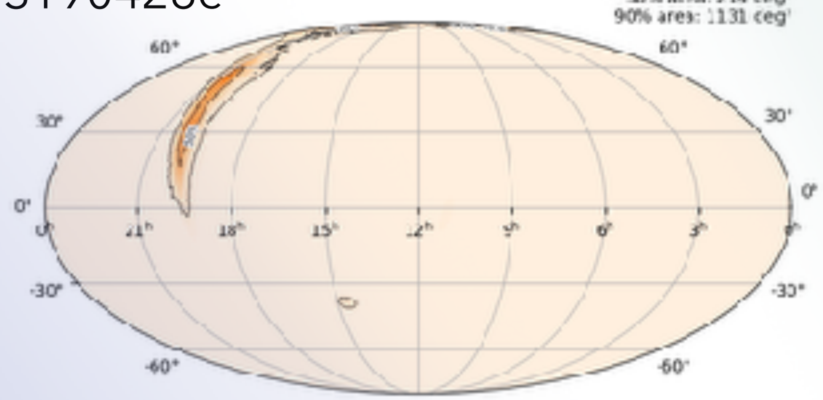


BNS : ~5 **NSBH**: 5

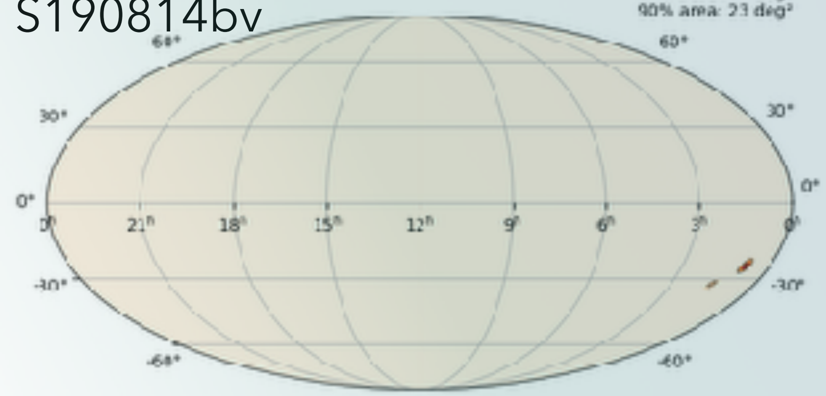
S190901ap



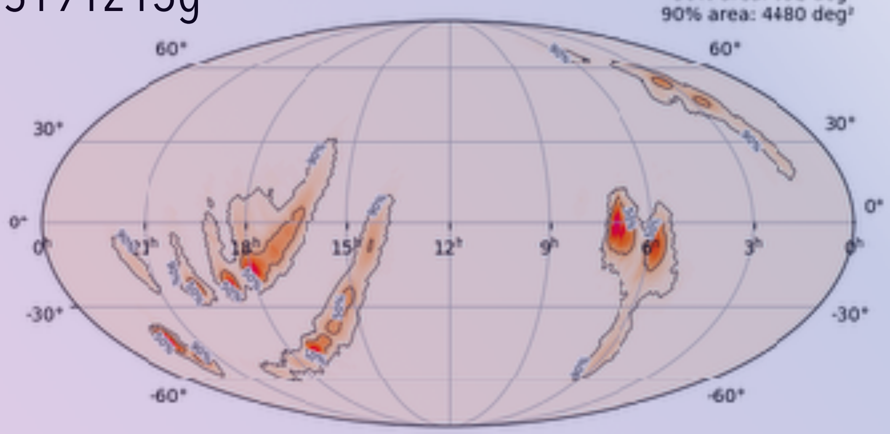
S190426c



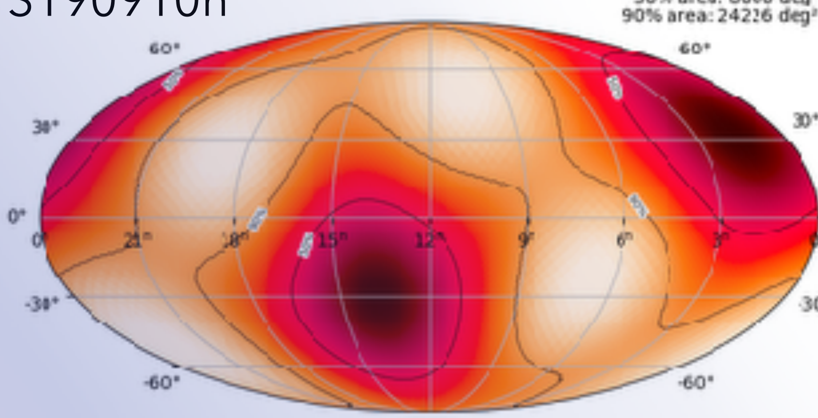
S190814bv



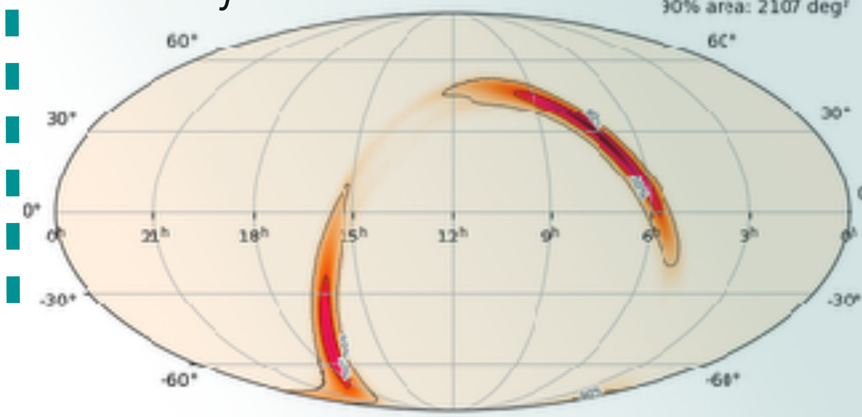
S191213g



S190910h



S190923y



Epoch			2015–2016	2016–2017	2018–2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40–60	60–75	75–90	105	105
		Virgo	–	20–40	40–50	40–70	80
		KAGRA	–	–	–	–	100
Expected BNS range/Mpc		LIGO	40–80	80–120	120–170	190	190
		Virgo	–	20–65	65–85	65–115	125
		KAGRA	–	–	–	–	140
Achieved BNS range/Mpc		LIGO	60–80	60–100	–	–	–
		Virgo	–	25–30	–	–	–
		KAGRA	–	–	–	–	–
Estimated BNS detections			0.05–1	0.2–4.5	1–50	4–80	11–180
Actual BNS detections			0	1	–	–	–
90% CR	% within	5 deg^2	< 1	1–5	1–4	3–7	23–30
		20 deg^2	< 1	7–14	12–21	14–22	65–73
	Median/deg^2		460–530	230–320	120–180	110–180	9–12
Searched area	% within	5 deg^2	4–6	15–21	20–26	23–29	62–67
		20 deg^2	14–17	33–41	42–50	44–52	87–90

LIGO Virgo collaborations 2018 (Prospects)