Electromagnetic Counterparts of Gravitational Waves

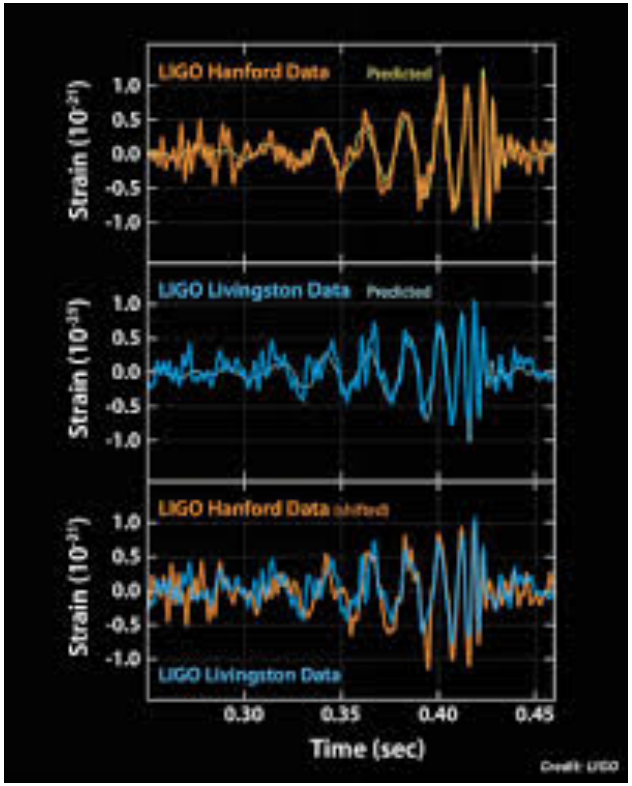
Bing Zhang

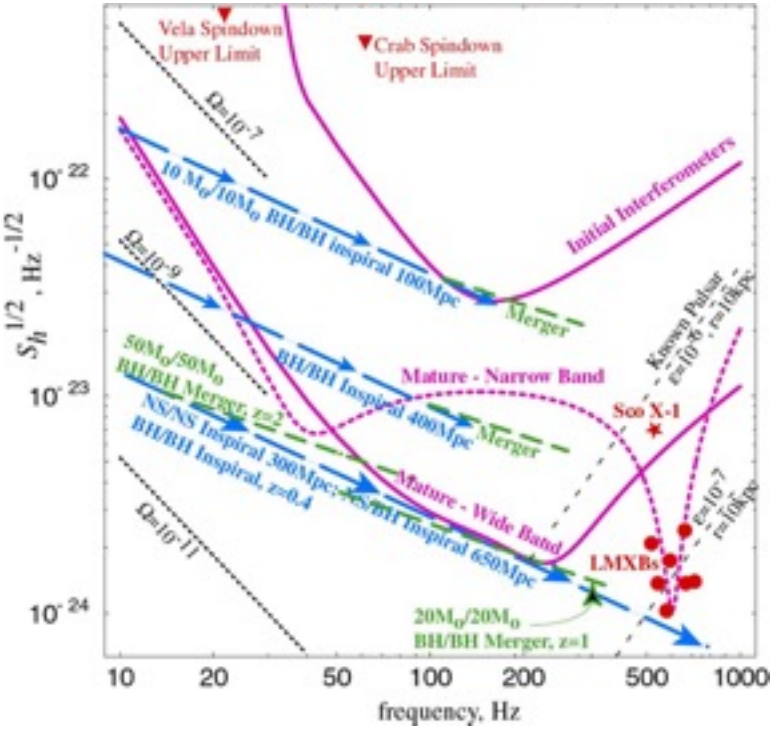
University of Nevada, Las Vegas

Nov. 3, 2016

Compact Stars and Gravitational Waves,
YITP, Kyoto, Nov. 2016

Gravitational waves detected!





GW 150914, GW 151226, LVT 151012

NS-NS, NS-BH mergers?

BH-BH mergers (Abbott et al. 2016a,b)

Nuttall's talk

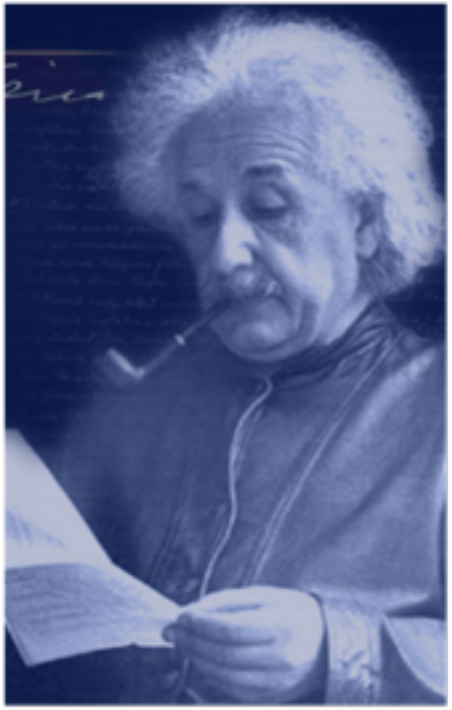
Gravitational waves

- Quadrupole rather than dipole

$$-\dot{E} = \frac{G}{5c^3}\left\langle \dddot{I}_{ij}\dddot{I}^{ij}\right\rangle$$

Quadrupole moment tensor:

$$I_{ij} = \int \rho(x_i x_j - r^2\delta_{ij}/3)d^3x$$



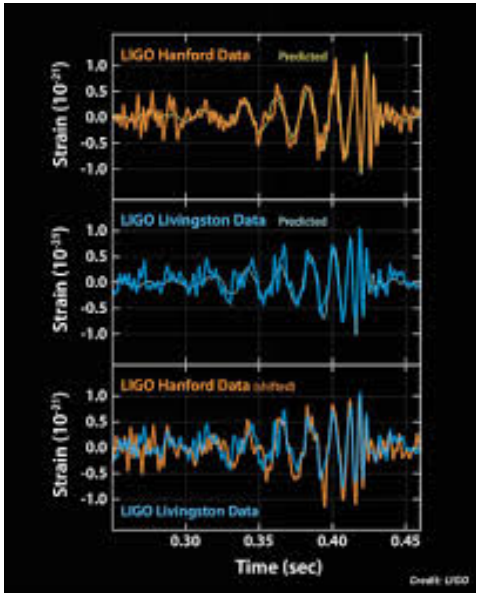
- Speed of light
- Luminosity

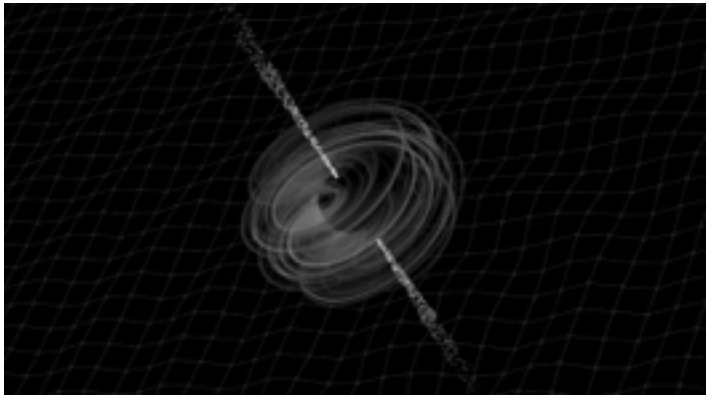
$$L_{\mathrm{GW}} \sim \frac{c^5}{G}\left(\frac{GM}{c^2L}\right)^5 \sim \frac{c^5}{G}\left(\frac{r_g}{L}\right)^5 \qquad \frac{c^5}{G} \simeq 3.6\times 10^{59}\ \mathrm{erg\ s^{-1}}$$

- Top candidates: NS-NS, BH-NS, BH-BH mergers
- Amplitude proportional to r $^{-1}$
- Final frequency

$$\Omega \sim \frac{c^3}{GM} \simeq 2.0\times 10^5\ \mathrm{Hz}\ \left(\frac{M}{M_\odot}\right)^{-1}$$

EM signals associated with GWs: Not firmly detected yet





- Confirm the astrophysical origin of the GW signals
- Study the astrophysical physical origin of the GW sources (e.g. host galaxy, environment, etc)
- Study the detailed physics involved in GW events (e.g. equation of state of nuclear matter, black hole electrodynamics)

- Need matter or EM field

Plan of the Talk

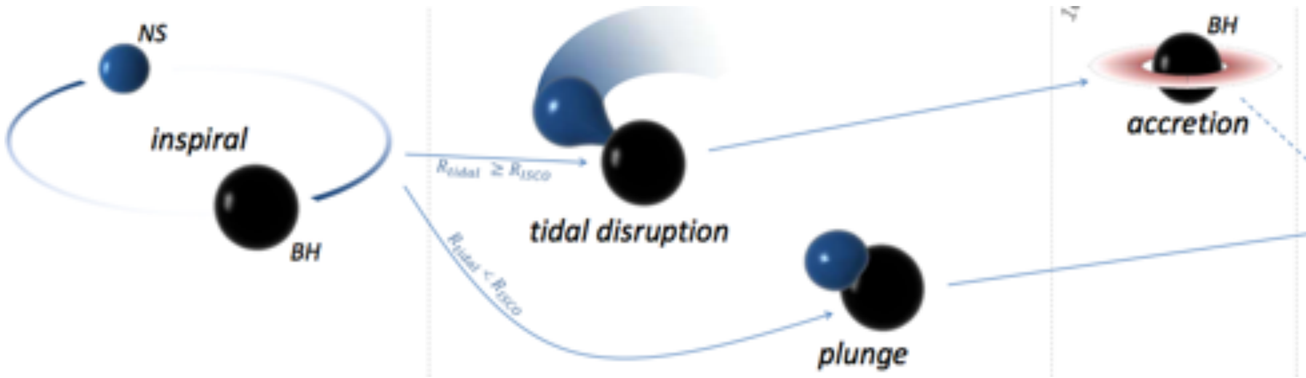
Discuss 3 types of merger systems:

- BH - NS mergers
- NS - NS mergers
  - BH remnant
  - millisecond magnetar remnant
- BH - BH mergers

Discuss 5 types of EM counterparts:

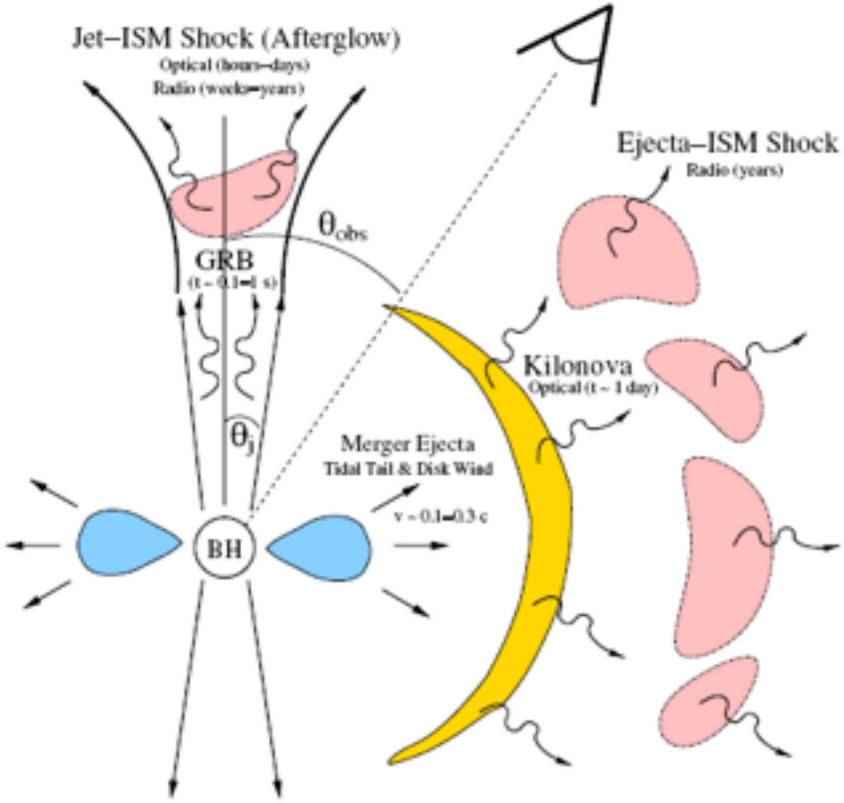
- short GRBs and afterglows
- kilonova / macronova / mergernova
- kilonova afterglow
- X-ray emission from magnetar
- fast radio bursts

BH-NS mergers



Bartos, I., Brady, P., Marka, S. 2013, CQGrav., 30, 123001

BH-NS mergers (small mass ratio)

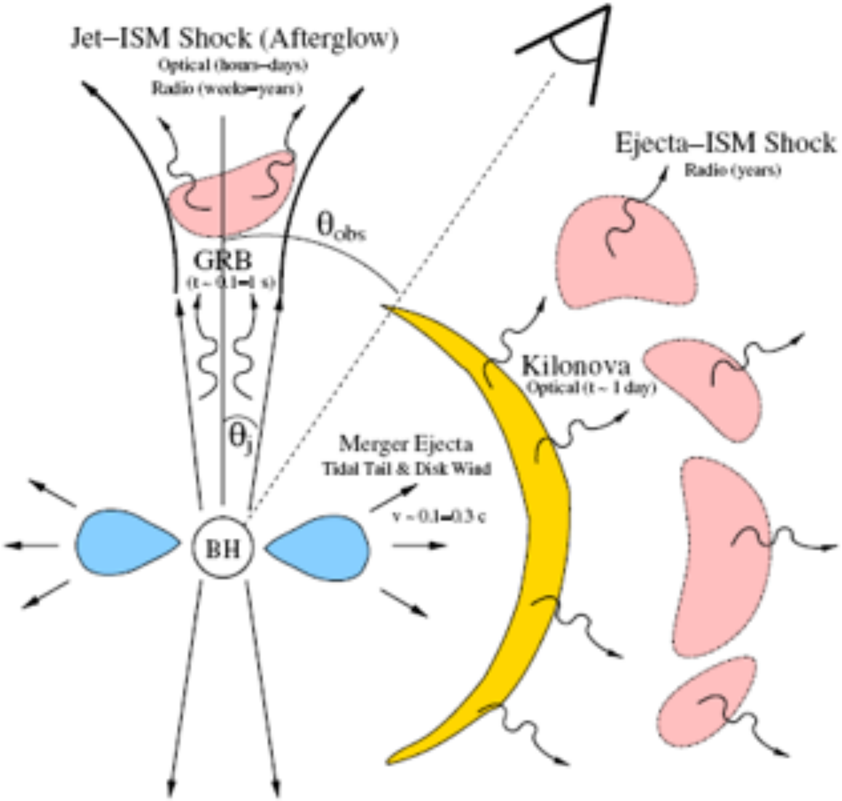


Metzger & Berger (2012)

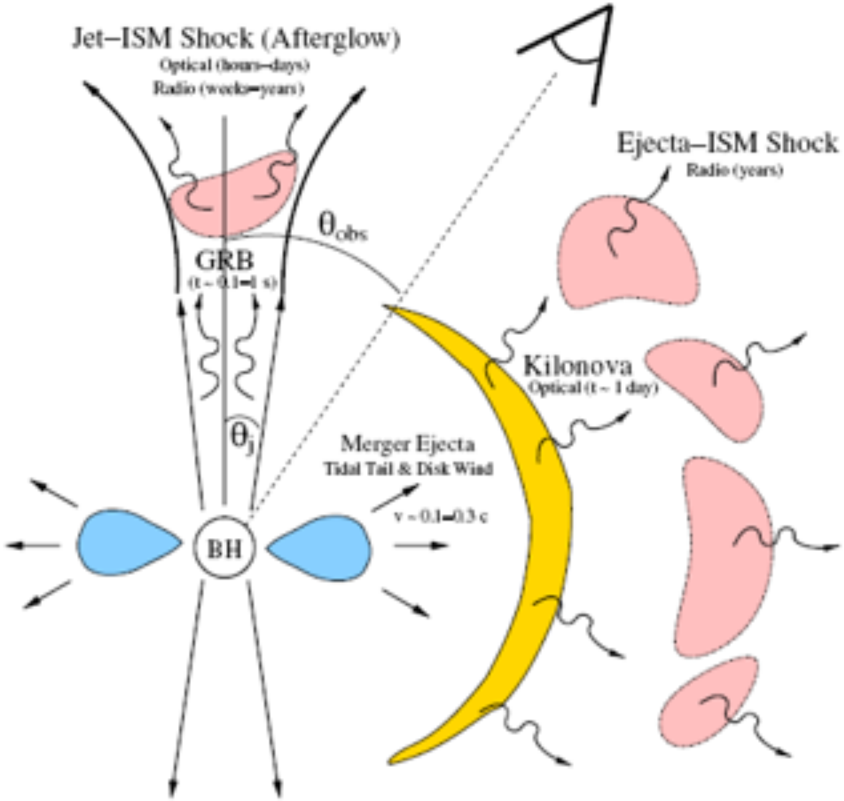
- Jetted component (likely, but low probability):
  - Short GRB (sGRB)
  - sGRB afterglow (X-ray, UV/ optical/IR, radio)
- Quasi-Isotropic component (likely, but faint):
  - Macronova/kilonova/ mergernova (optical/IR) - detected with sGRBs
  - kilonova afterglow (radio flare)

Talks by Nissanke, Tanaka, Janka, Piran

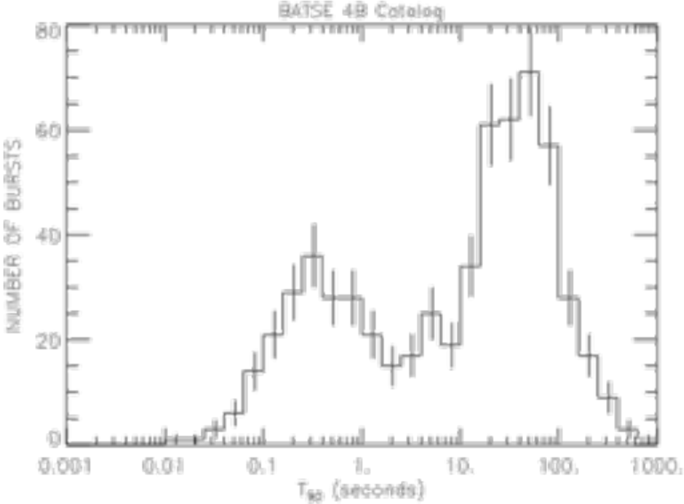
Halloween Pumpkin



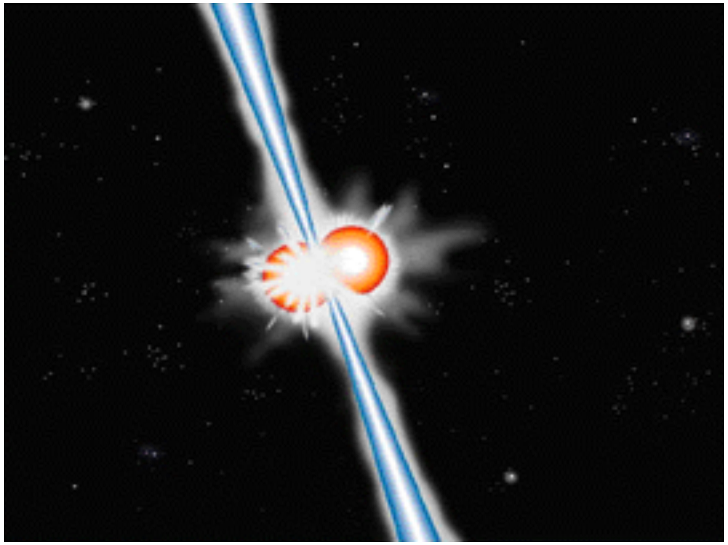
Halloween Pumpkin

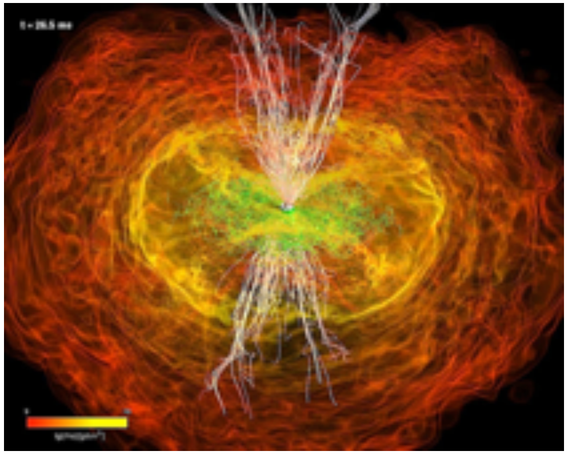


EM counterpart 1 (likely): Short GRBs/afterglows



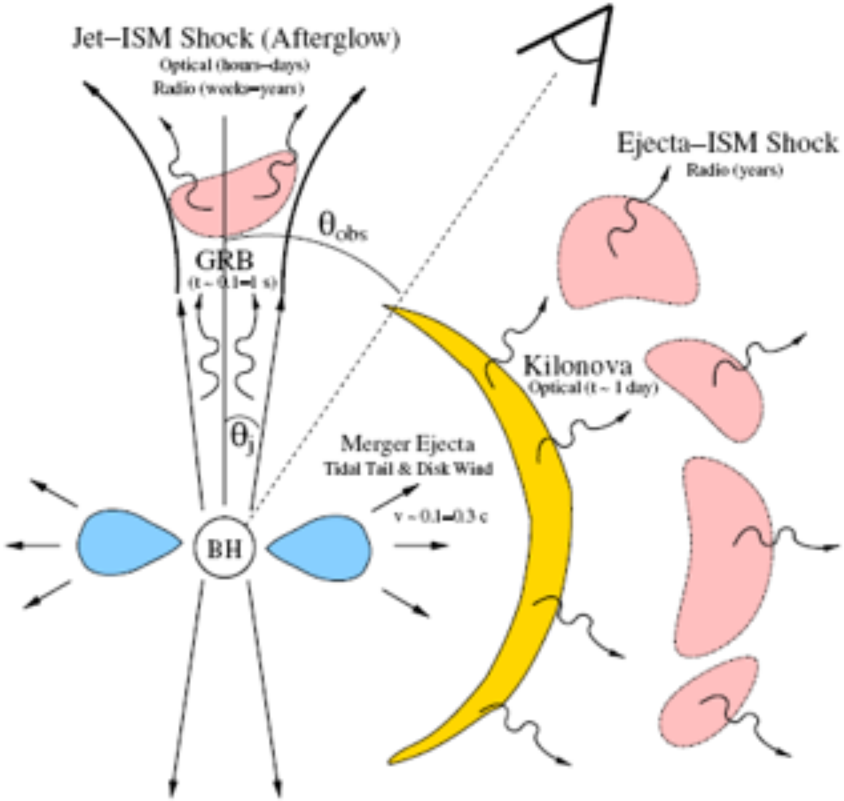
- In different types of host galaxies, including a few in elliptical/early-type galaxies, but most in star-forming galaxies
- Large offsets, in regions of low star formation rate in the host galaxy. Some are outside the galaxy.
- Relatively faint afterglows
- Leading model: NS-NS or NS-BH mergers





Rezzolla et al. 2011

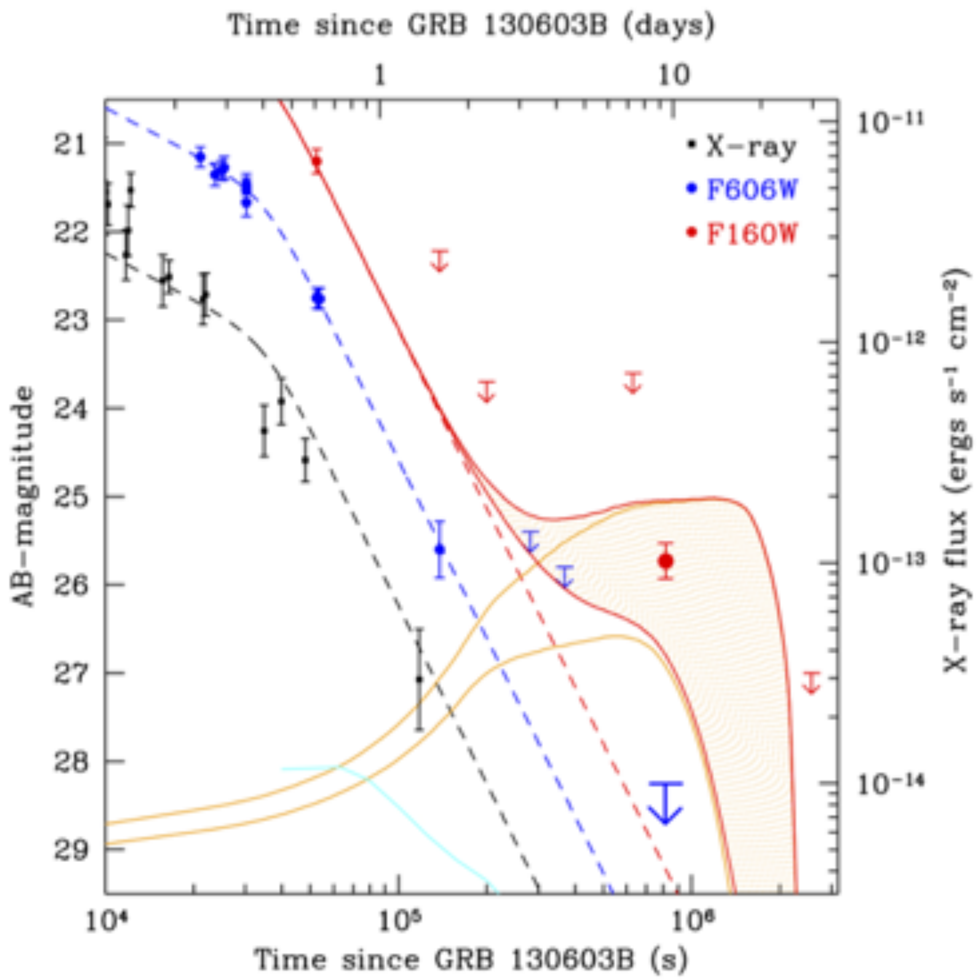
Short GRBs as GW EM counterpart: Caveats



- Not all SGRBs are related to mergers – some may be related to massive stars (similar to LGRBs) (Zhang et al. 2009; Virgili et al. 2012; Bromberg et al. 2013)

- SGRBs are collimated - only a small fraction of GW events will be associated with SGRBs.

EM counterpart 2 (likely): Kilonova, macronova, mergernova

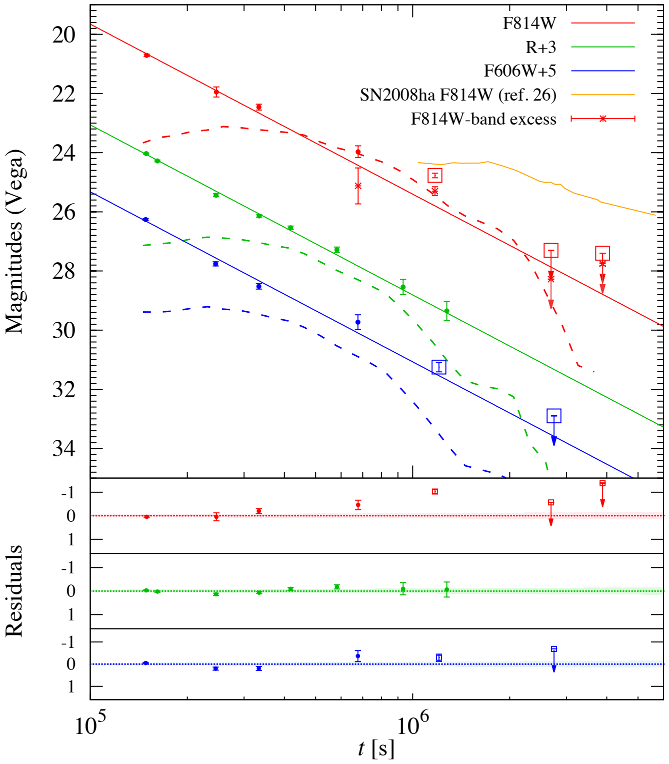


Tanvir et al. (2013, Nature), Berger et al. (2013, ApJL)

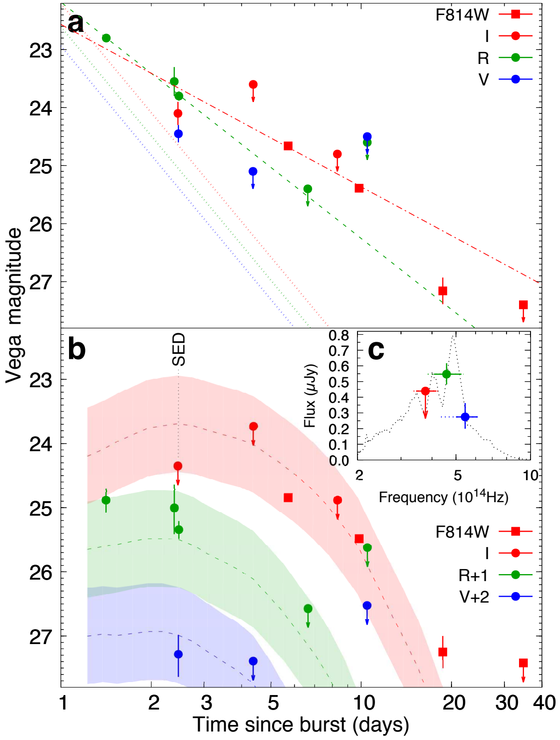
- Kilonova (macronova, Li-Paczynski nova, r-process nova, mergernova): SN-like transients powered by nuclear radioactivity (and possible a magnetar) in the ejecta of compact star mergers
- 1-day V-band luminosity: 3×10^{41} erg/s (Metzger et al. 2010): 3-5 orders of magnitude fainter than GRB afterglow
- High opacity from heavier elements (e.g. lanthanides) – peak in IR (Barnes & Kasen 2013)

- Detections in GRB 130603B and several others

Kilonova, macronova, mergernova



GRB 060614
Yang et al. (2015)



GRB 050709
Jin et al. (2016)

The Kilonova Handbook

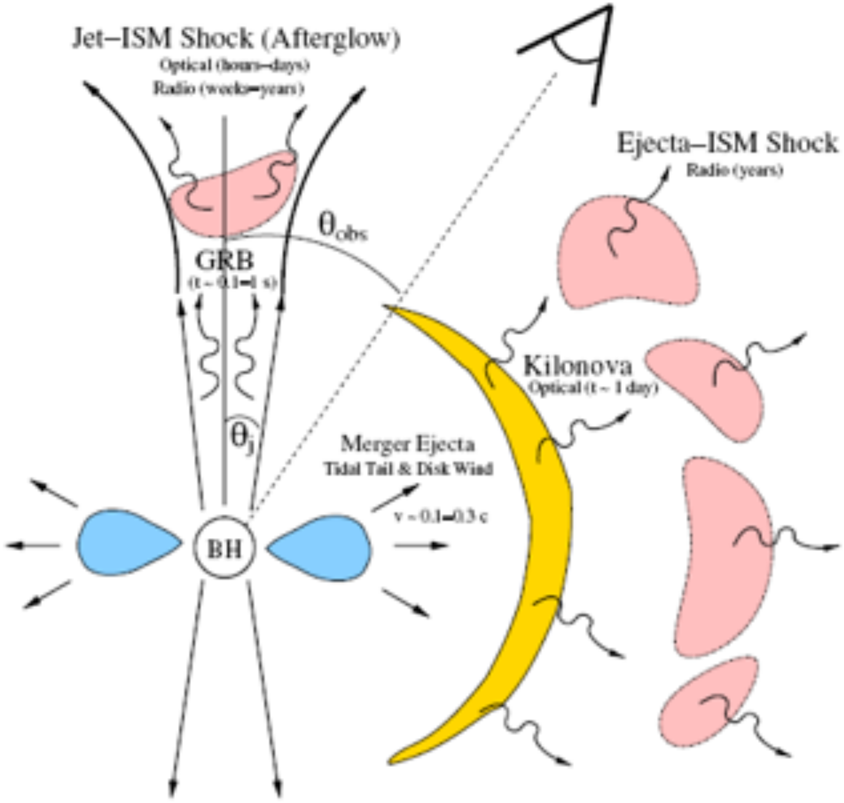
Brian D. Metzger*

November 1, 2016

1974	Lattimer & Schramm: r-process from BH-NS mergers
1975	Hulse & Taylor: discovery of binary pulsar system PSR 1913+16
1989	Eichler et al.: GRBs, r-process from NS-NS mergers
1998	Li & Paczynski: first kilonova model, with parametrized heating
1999	Freiburghaus et al.: NS-NS dynamical ejecta $\Rightarrow$ r-process abundances
2005	Kulkarni: kilonova powered by free neutron-decay ("macronova")
2009	Perley et al.: optical kilonova candidate following GRB 080503 (Fig. 10)
2010	Metzger et al., Roberts et al.: kilonova powered by r-process heating
2013	Barnes & Kasen, Tanaka & Hotokezaka: La/Ac opacities $\Rightarrow$ 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 & Fernandez, Kasen et al.: blue kilonova from the disk winds

Figure 1: Timeline of major developments in kilonova research

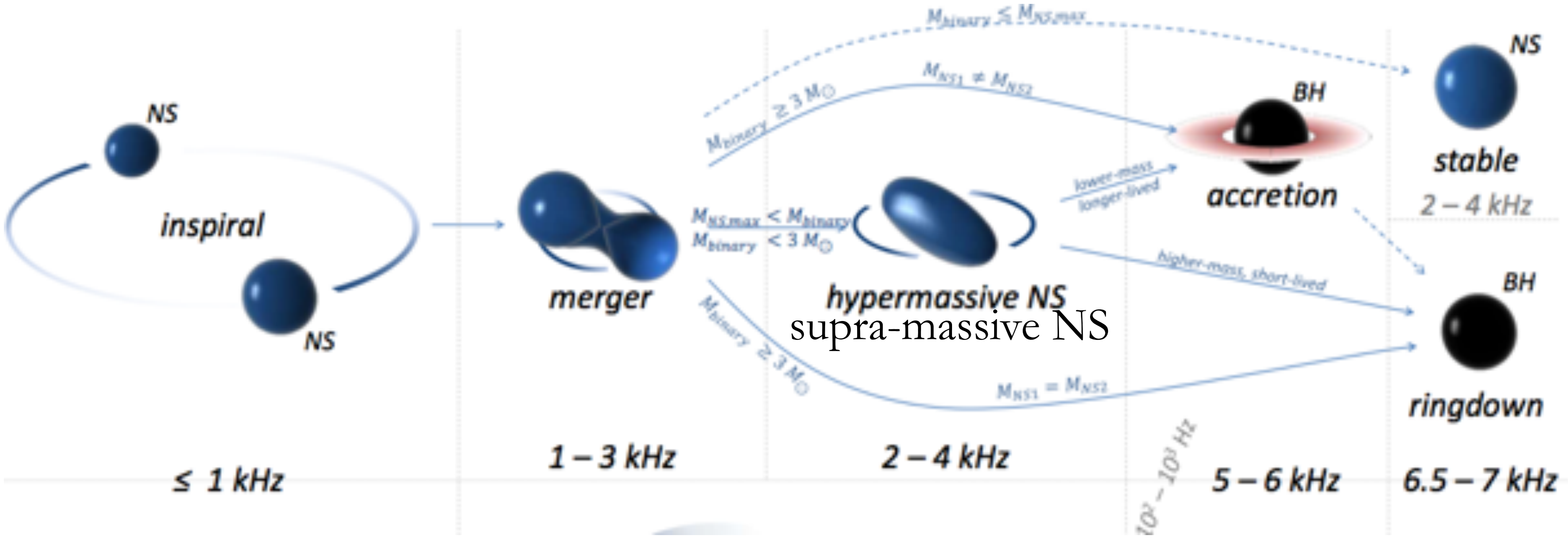
EM counterpart 3 (likely):
Radio afterglow of kilonova (radio flare)



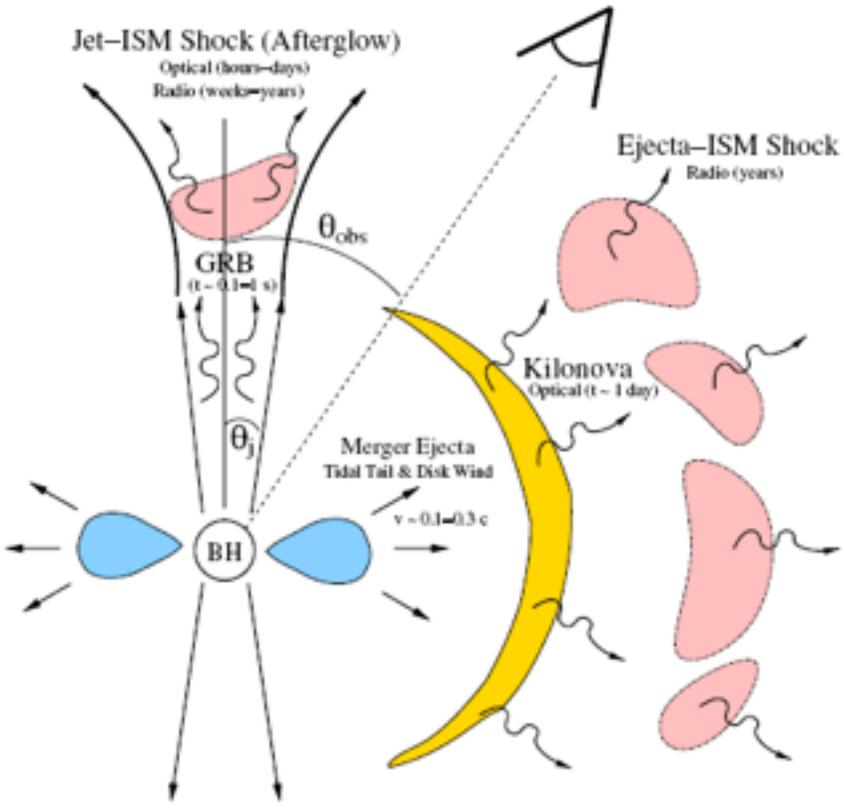
- Radio afterglow: synchrotron emission from shock when the kilonova ejecta is decelerated (Nakar & Piran, 2011; Piran et al. 2013; Hotokezaka & Piran 2015)

- No candidate yet
- Issue:
  - Long delay
  - Density n is likely small (kick)

NS-NS mergers:
Three types of merger products



EM counterparts of NS-NS mergers
the case of a BH engine: similar to BH-NS mergers



Metzger & Berger (2012)

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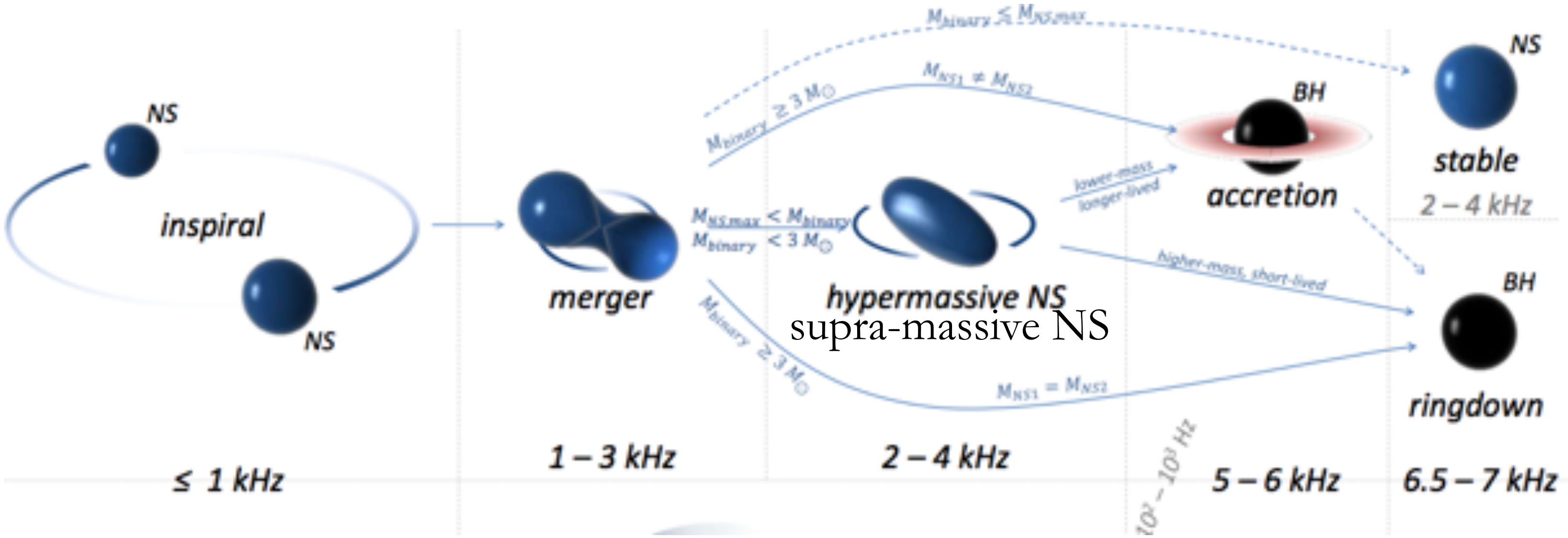
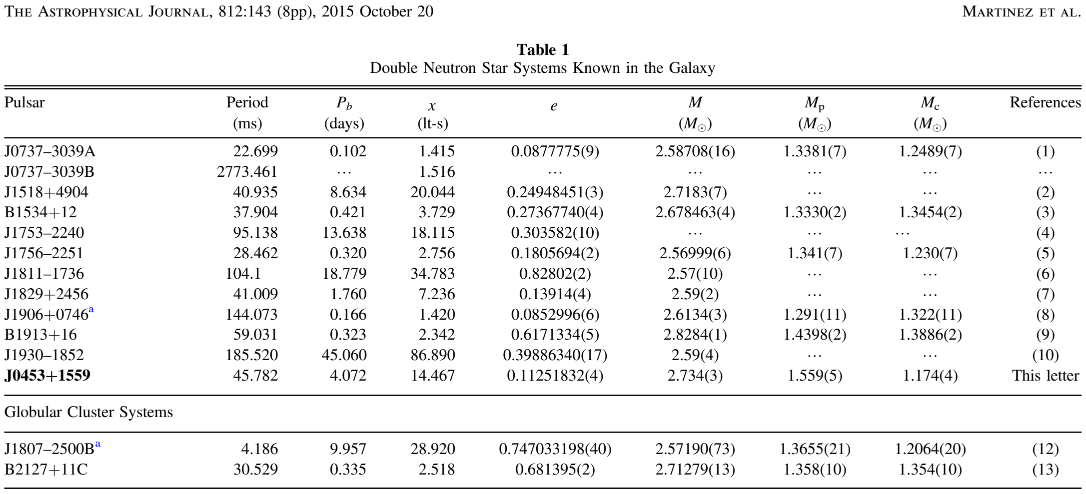
Supra-massive and stable NSs



supra-massive NS

Observational hints of a possible supra-massive / stable NS as the merger product (I)

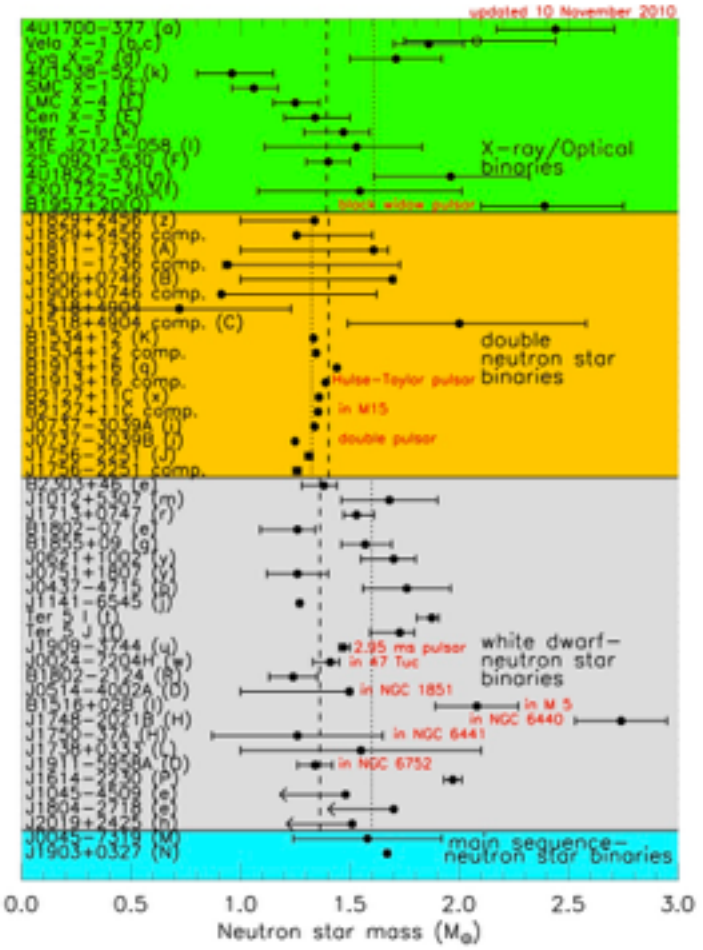


The Astrophysical Journal, 812:143 (8pp), 2015 October 20 — Martinez et al.

Table 1
Double Neutron Star Systems Known in the Galaxy

Pulsar	Period (ms)	P_b (days)	x (lt-s)	e	M ($M_\odot$)	M_p ($M_\odot$)	M_c ($M_\odot$)	References
J0737–3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	(1)
J0737–3039B	2773.461	⋯	1.516	⋯	⋯	⋯	⋯	⋯
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	⋯	⋯	(2)
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	(3)
J1753–2240	95.138	13.638	18.115	0.303582(10)	⋯	⋯	⋯	(4)
J1756–2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	(5)
J1811–1736	104.1	18.779	34.783	0.82802(2)	2.57(10)	⋯	⋯	(6)
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)	⋯	⋯	(7)
J1906+0746[a]	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	(8)
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	(9)
J1930–1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)	⋯	⋯	(10)
J0453+1559	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This letter
Globular Cluster Systems								
J1807–2500B[a]	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	(12)
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	(13)

- NS with mass > 2 M$_\odot$ has been discovered
- NS-NS systems: total mass ~ 2.5-2.6 M$_\odot$



Lattimer & Prakash (2010)

Talks by Lattimer, Baldo, Freire …

Observational hints of a possible supra-massive / stable NS as the merger product (I)

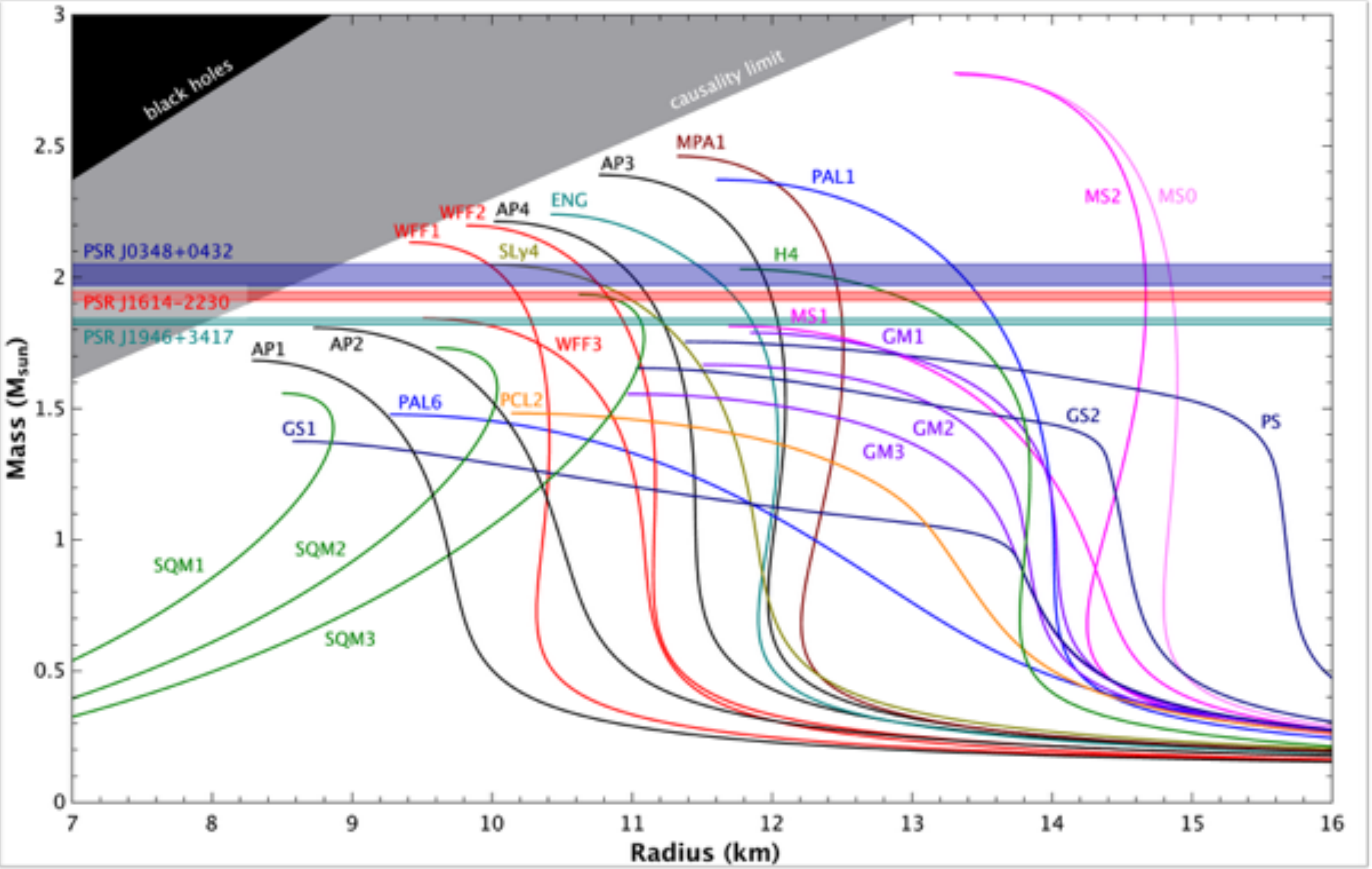
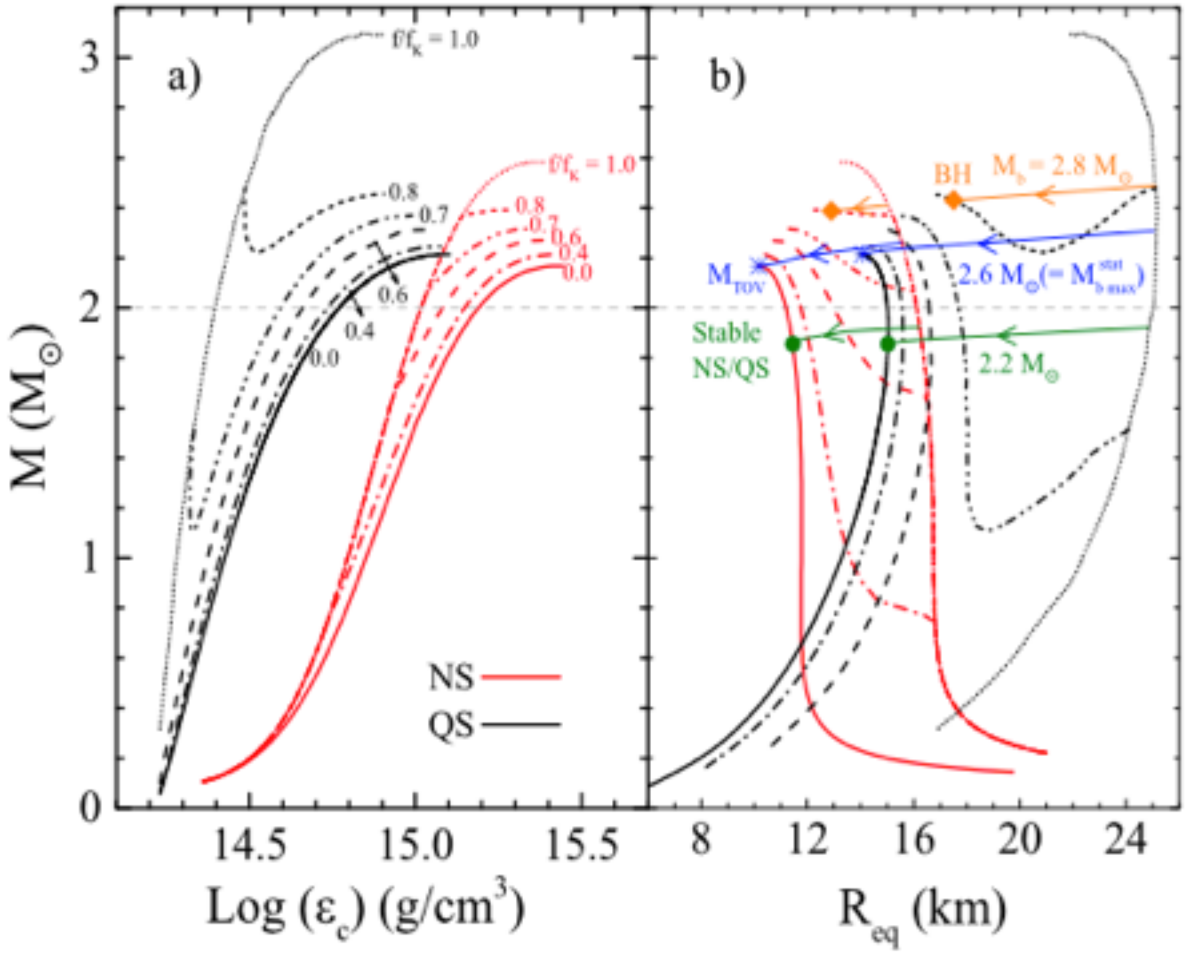


Figure by Norbert Wex. See http://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html

Freire's talk

Supra-massive and stable NSs/QSs

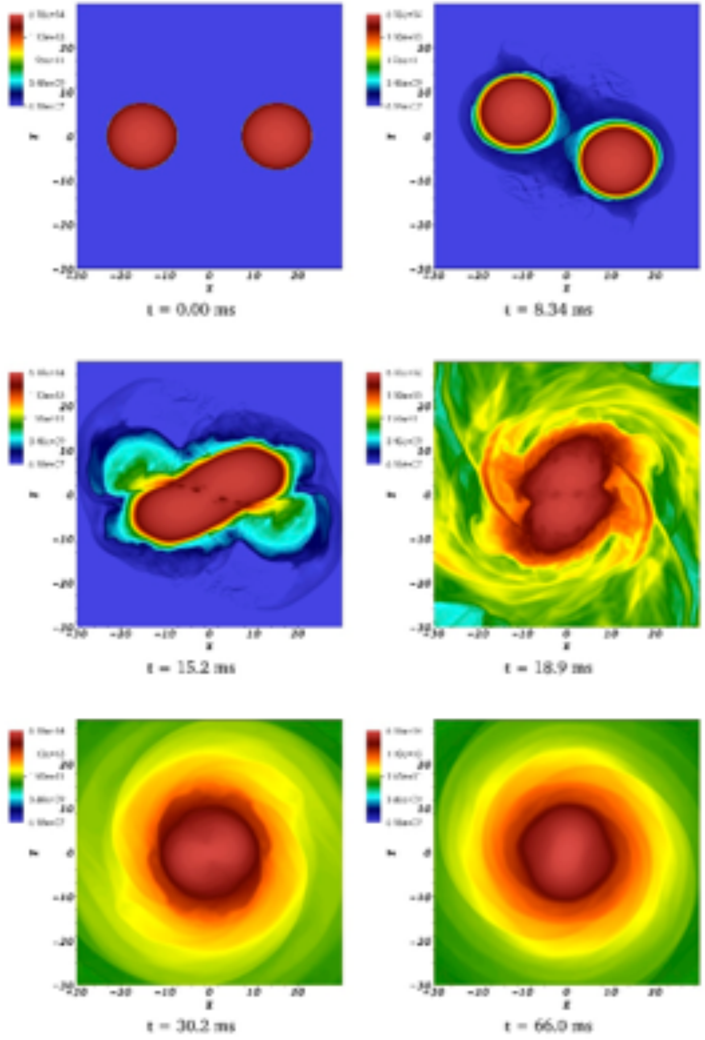


Example EoSs:

NS: BSK20
QS: CDDM1

A. Li et al. (2016, PRD, 94, 083010, arXiv:1606.02934)

Forming a supra-massive / stable neutron star via a NS-NS merger

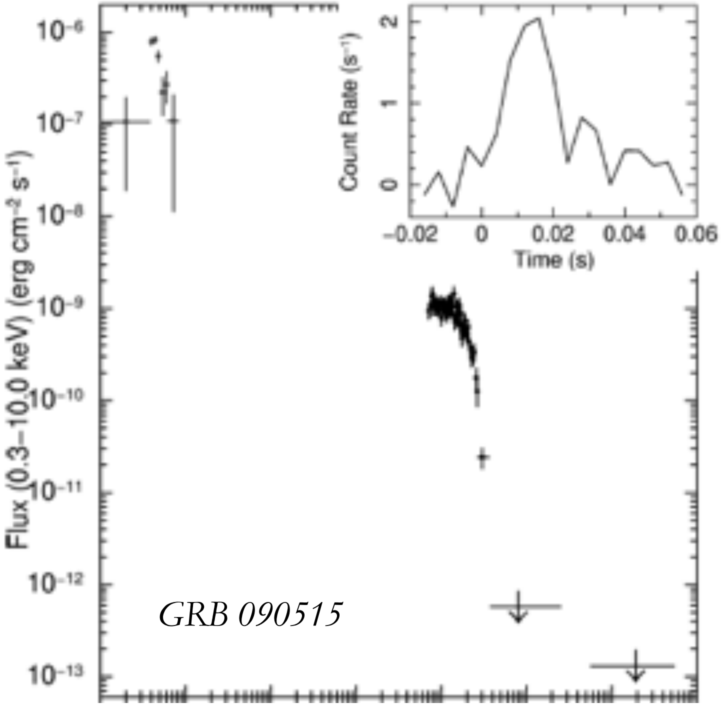


For small enough NS masses and a reasonable NS equation of state, a stable magnetar can survive a NS-NS merger.

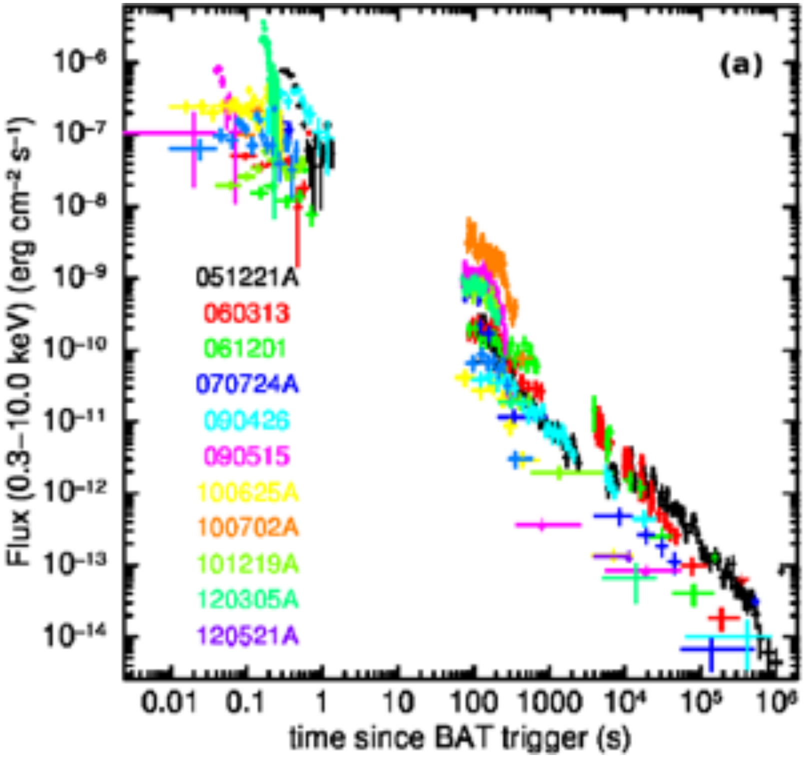
Giacomazzo & Perna (2013)

Observational hints of a possible supra-massive / stable NS as the merger product (II)

- Internal X-ray plateaus in some short GRB afterglows

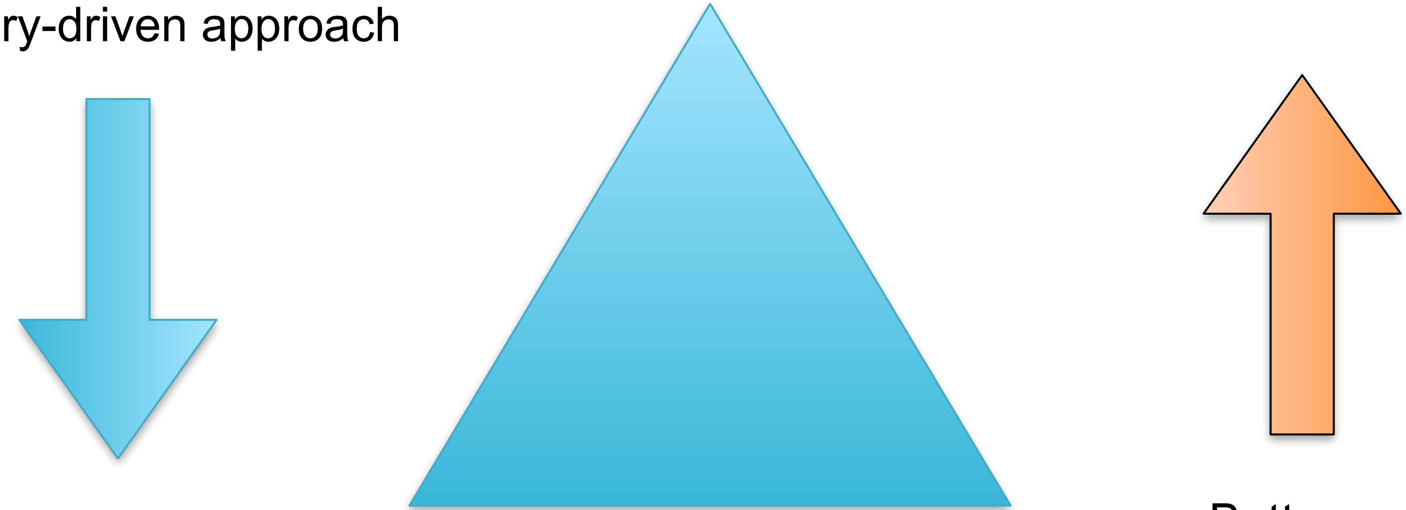


Rowlinson et al. (2010)



Rowlinson et al. (2013)

Theory

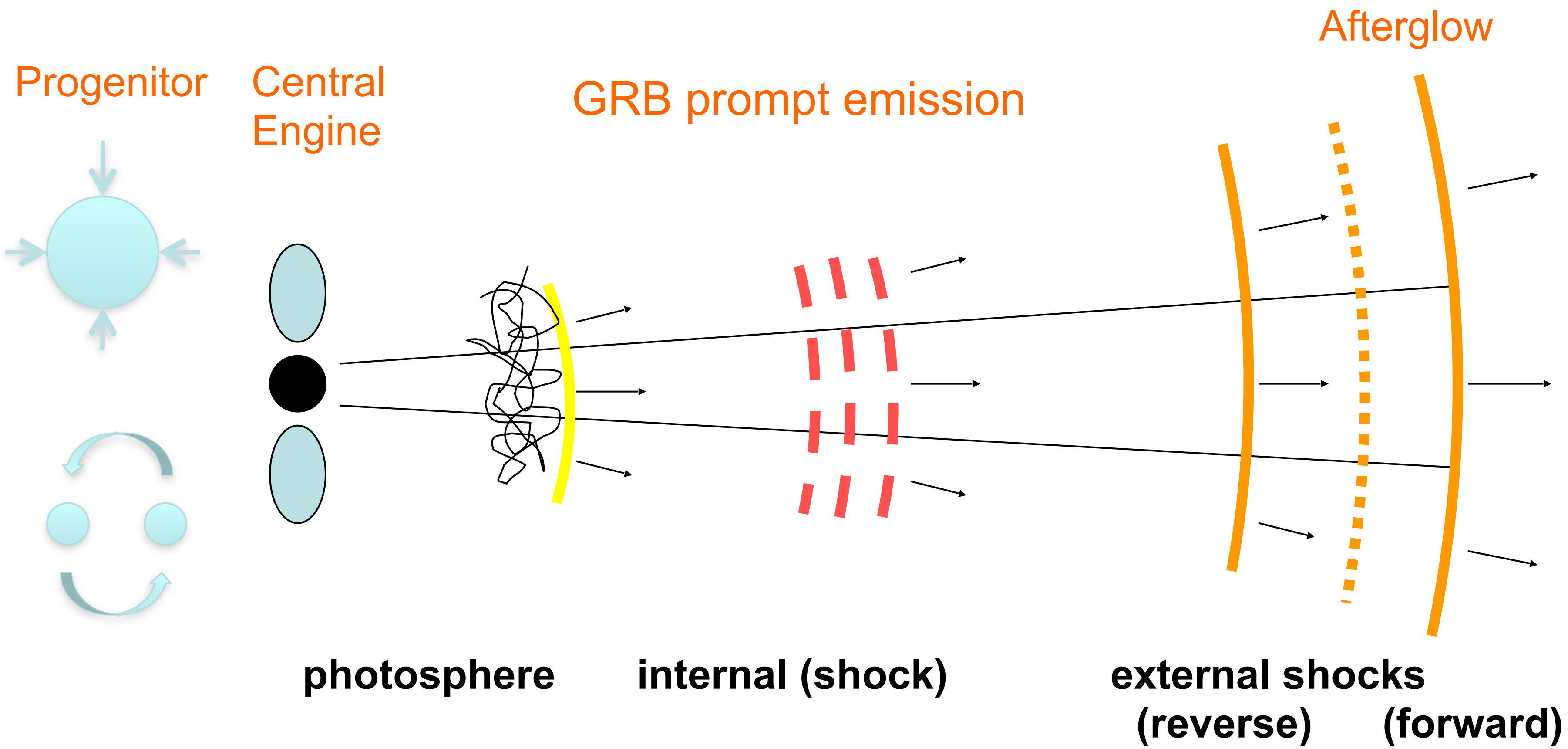


Top-down:
Theory-driven approach

Bottom-up:
Data-driven approach

Data

GRB model: internal vs. external



Progenitor

Central Engine

GRB prompt emission

Afterglow

photosphere

internal (shock)

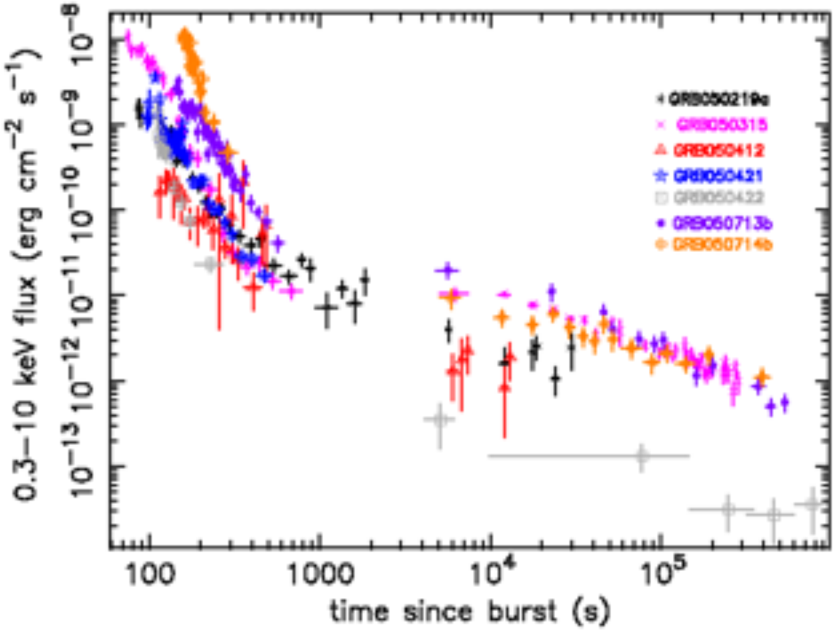
external shocks

(reverse)

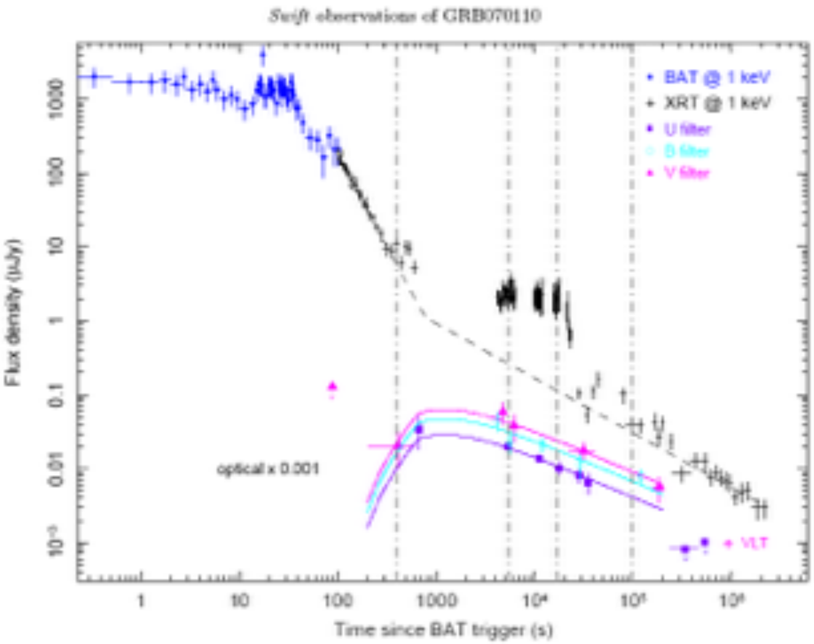
(forward)

External vs. internal plateaus

- Plateaus in GRB X-ray afterglows
- Internal: steep decay, chromatic, “internal” origin



Nousek et al. (2006)

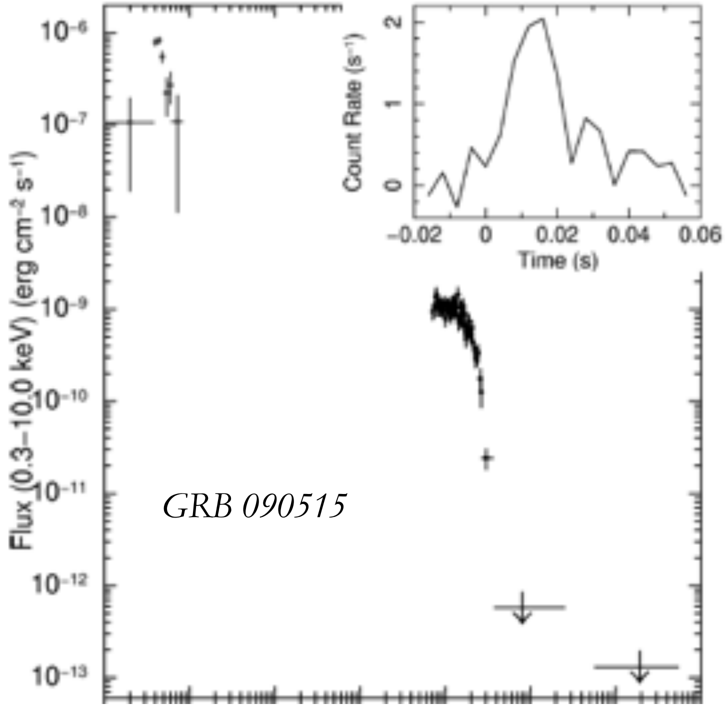


Troja et al. (2007)

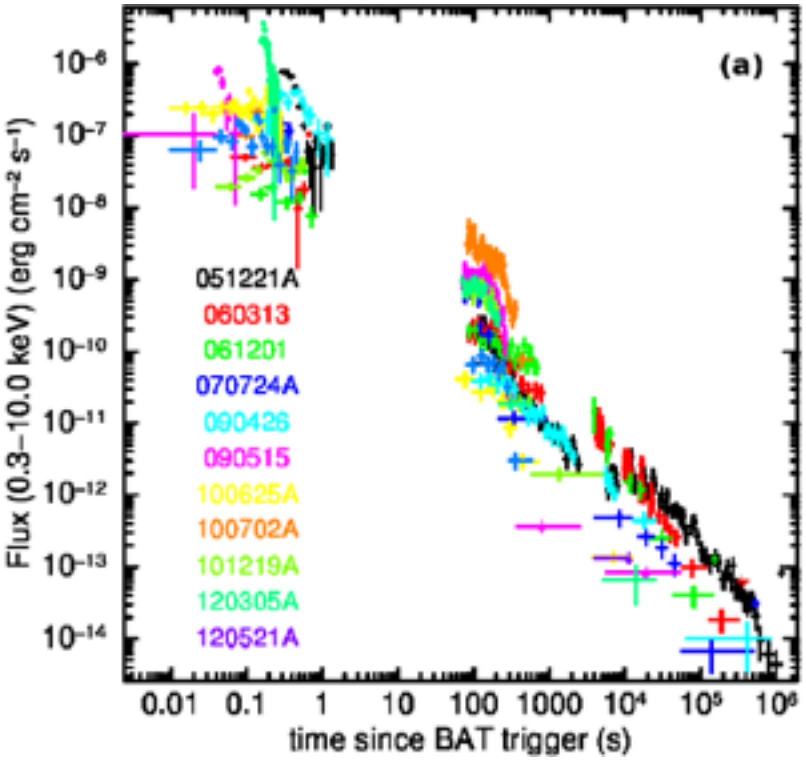
Internal Plateau in short GRBs

- Require engine lasts for 100’s of seconds, then disappears
- A supra-massive magnetar collapses into a BH at the end of plateau

(alternative view: Rezzolla & Kumar 2015; Ciolfi & Siegel 2015)



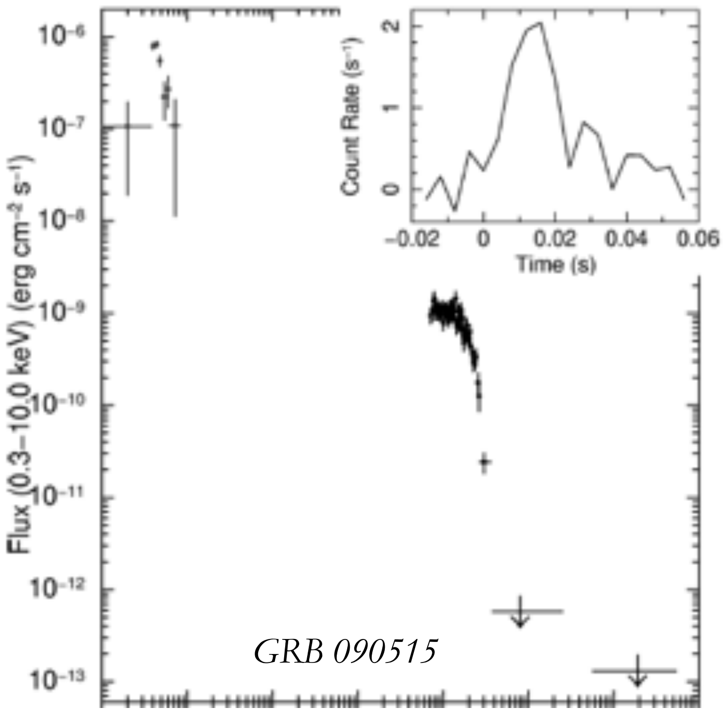
Rowlinson et al. (2010)



Rowlinson et al. (2013)

A multi-messenger approach to constrain NS/QS equation-of-state

- GW signal: NS-NS system parameters (mass of the merger product)
- EM signal: brightness of the X-ray emission, collapse time – infer initial period, magnetic field, ellipticity, etc.
- Putting everything together: constrain NS/QS EoS!



Rowlinson et al. (2010)

Without GW signal, one can already make some constraints

$$M_{\max} = M_{\mathrm{TOV}}(1 + \alpha P^{\beta}),$$

$$P_c = \left(\frac{M_s - M_{\mathrm{TOV}}}{\alpha M_{\mathrm{TOV}}}\right)^{1/\beta}.$$

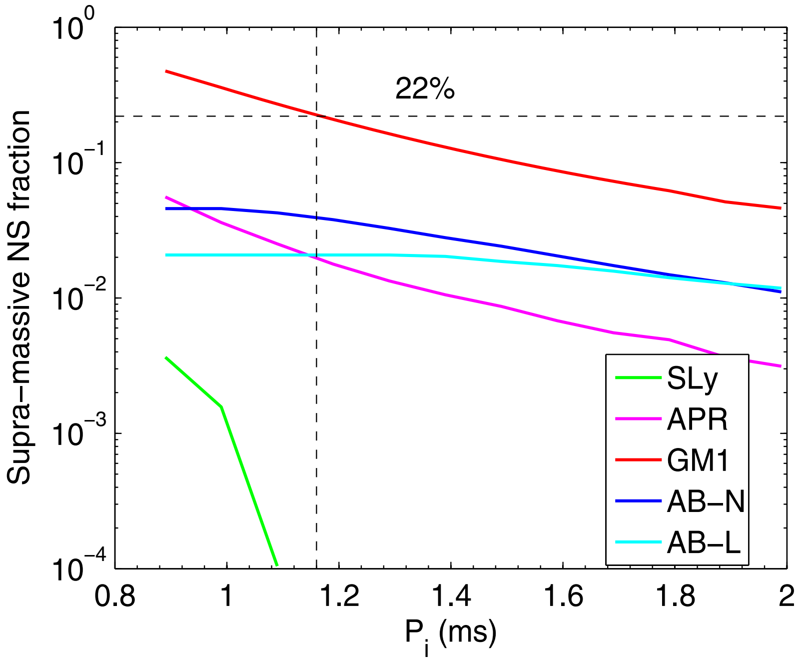
$$\dot{E} = I\Omega\dot{\Omega} = -\frac{32GI^2\epsilon^2\Omega^6}{5c^5} - \frac{B_p^2R^6\Omega^4}{6c^3},$$

$$L_b = \frac{\eta B_p^2 R^6 \Omega_{\mathrm{col}}^4}{6c^3},$$

PHYSICAL REVIEW D **93,** 044065 (2016)

Constraints on binary neutron star merger product from short GRB observations

He Gao,[1,*] Bing Zhang,[2,3,4] and Hou-Jun Lü[5,6]

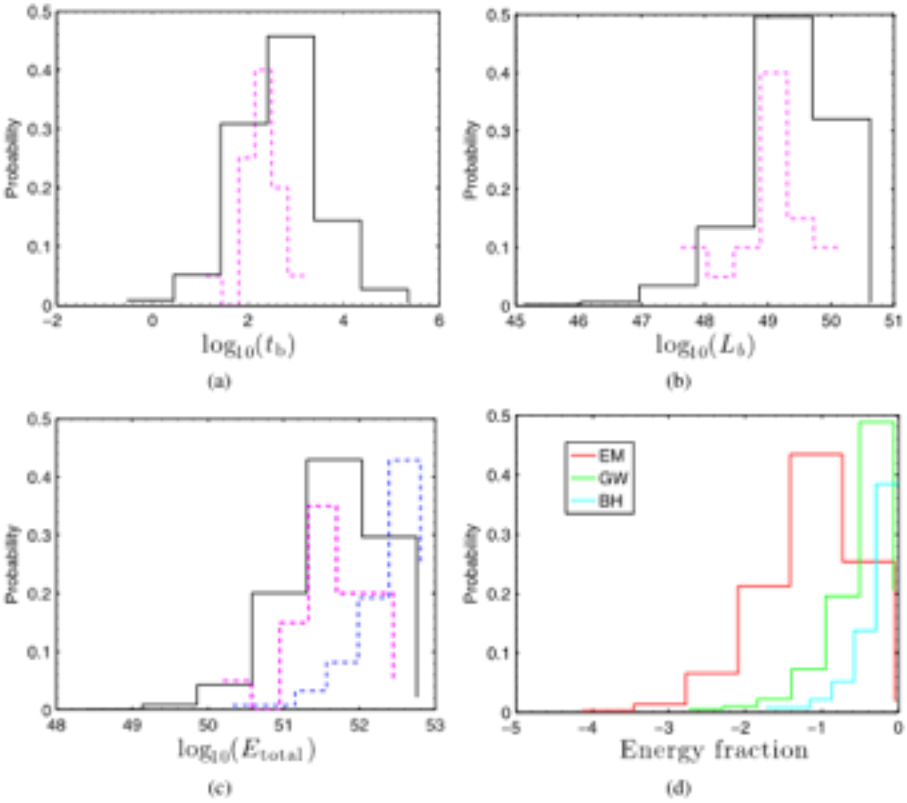


Use a sample of sGRBs

Look at the collapse fraction, collapse time distribution, plateau luminosity distribution

Constraints on NS-NS merger products from known short GRBs

- For one EoS (GM1)
- Maximum mass: ~ 2.37 $M_\odot$
- Initial spin: ~ 1 ms
- BH:SMNS:SNS ~ 4:3:3
- Surface B field: ~10^{15} G
- ellipticity: 0.004-0.007
- Energy output in the EM channel: 10^{49} – 10^{52} erg
- Other energy channels:
  - GW emission
  - Fall into BH



(a) (b) (c) (d)

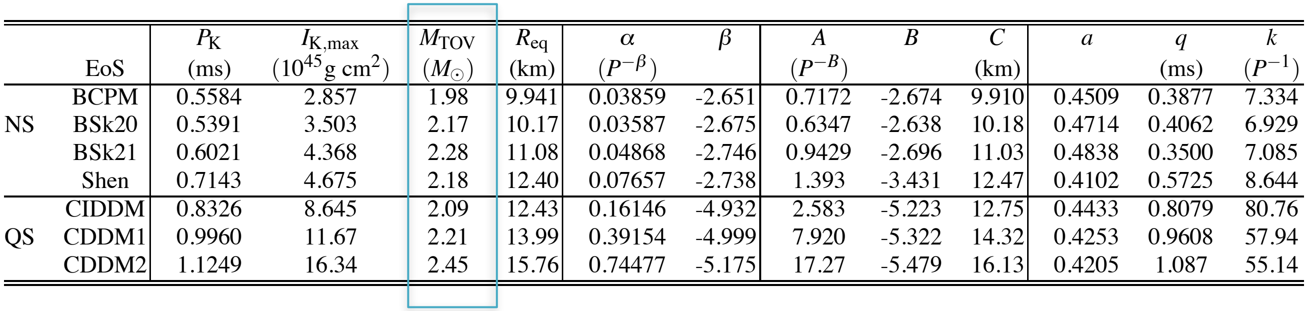
Gao, Zhang & Lu, 2016, PRD, 93, 044065

More Equations of State

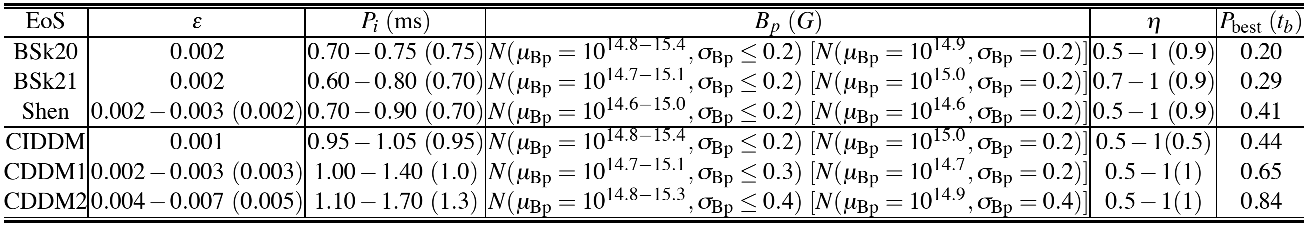
Internal X-ray plateau in short GRBs: Signature of supramassive fast-rotating quark stars?

Ang Li[1,2*], Bing Zhang[2,3,4†], Nai-Bo Zhang[5], He Gao[6], Bin Qi[5], Tong Liu[1,2]

2016, PRD, 94, 083010, arXiv:1606.02934)



	EoS	P_K (ms)	$I_{K,max}$ (10^{45}g cm^2)	M_{TOV} ($M_\odot$)	R_{eq} (km)	α ($P^{-\beta}$)	β	A (P^{-B})	B	C (km)	a	q (ms)	k (P^{-1})
NS	BCPM	0.5584	2.857	1.98	9.941	0.03859	-2.651	0.7172	-2.674	9.910	0.4509	0.3877	7.334
	BSk20	0.5391	3.503	2.17	10.17	0.03587	-2.675	0.6347	-2.638	10.18	0.4714	0.4062	6.929
	BSk21	0.6021	4.368	2.28	11.08	0.04868	-2.746	0.9429	-2.696	11.03	0.4838	0.3500	7.085
	Shen	0.7143	4.675	2.18	12.40	0.07657	-2.738	1.393	-3.431	12.47	0.4102	0.5725	8.644
QS	CIDDM	0.8326	8.645	2.09	12.43	0.16146	-4.932	2.583	-5.223	12.75	0.4433	0.8079	80.76
	CDDM1	0.9960	11.67	2.21	13.99	0.39154	-4.999	7.920	-5.322	14.32	0.4253	0.9608	57.94
	CDDM2	1.1249	16.34	2.45	15.76	0.74477	-5.175	17.27	-5.479	16.13	0.4205	1.087	55.14

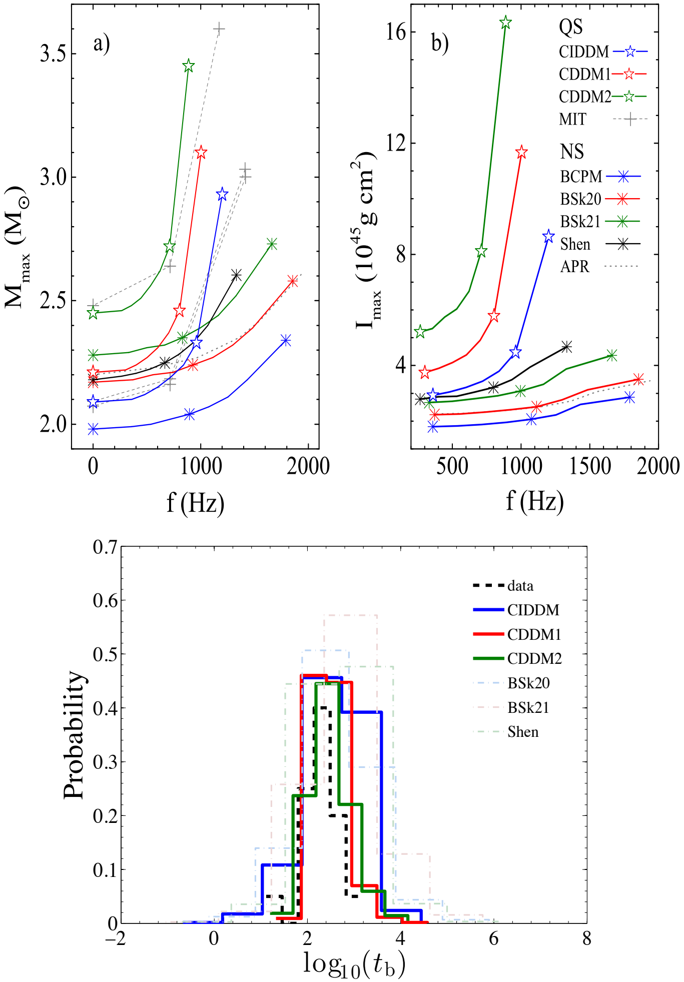


EoS	ε	P_i (ms)	B_p (G)	η	P_{best} (t_b)
BSk20	0.002	0.70 – 0.75 (0.75)	$N(\mu_{Bp} = 10^{14.8-15.4}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{14.9}, \sigma_{Bp} = 0.2)]$	0.5 – 1 (0.9)	0.20
BSk21	0.002	0.60 – 0.80 (0.70)	$N(\mu_{Bp} = 10^{14.7-15.1}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{15.0}, \sigma_{Bp} = 0.2)]$	0.7 – 1 (0.9)	0.29
Shen	0.002 – 0.003 (0.002)	0.70 – 0.90 (0.70)	$N(\mu_{Bp} = 10^{14.6-15.0}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{14.6}, \sigma_{Bp} = 0.2)]$	0.5 – 1 (0.9)	0.41
CIDDM	0.001	0.95 – 1.05 (0.95)	$N(\mu_{Bp} = 10^{14.8-15.4}, \sigma_{Bp} \leq 0.2)$ $[N(\mu_{Bp} = 10^{15.0}, \sigma_{Bp} = 0.2)]$	0.5 – 1(0.5)	0.44
CDDM1	0.002 – 0.003 (0.003)	1.00 – 1.40 (1.0)	$N(\mu_{Bp} = 10^{14.7-15.1}, \sigma_{Bp} \leq 0.3)$ $[N(\mu_{Bp} = 10^{14.7}, \sigma_{Bp} = 0.2)]$	0.5 – 1(1)	0.65
CDDM2	0.004 – 0.007 (0.005)	1.10 – 1.70 (1.3)	$N(\mu_{Bp} = 10^{14.8-15.3}, \sigma_{Bp} \leq 0.4)$ $[N(\mu_{Bp} = 10^{14.9}, \sigma_{Bp} = 0.4)]$	0.5 – 1(1)	0.84

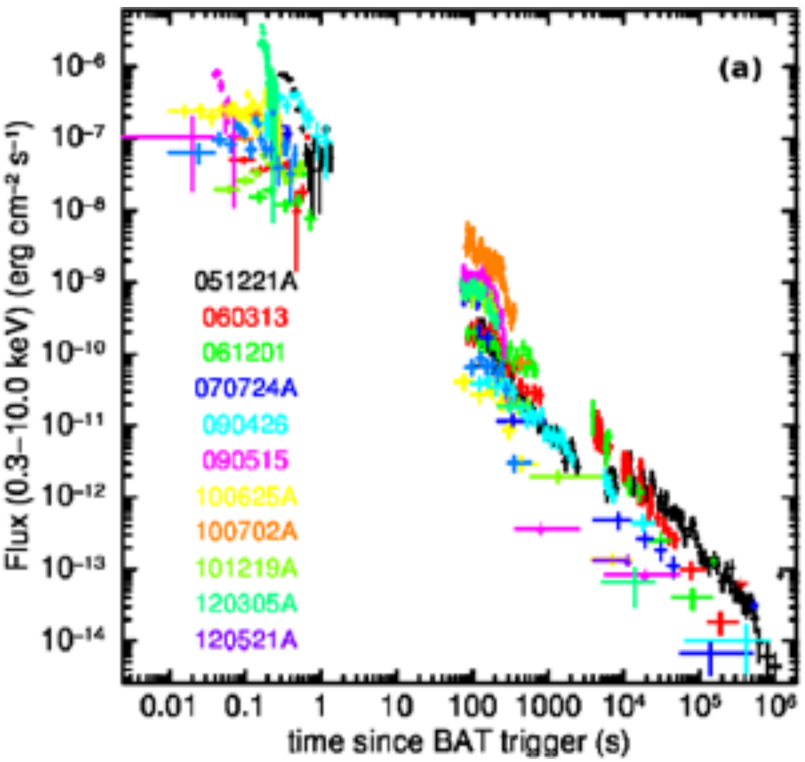
Degeneracy with EM data only, with GW, can greatly narrow down

Collapse time: QSs favored
Quark de-confinement during the merger?

Also Drago et al. 2016, PRD



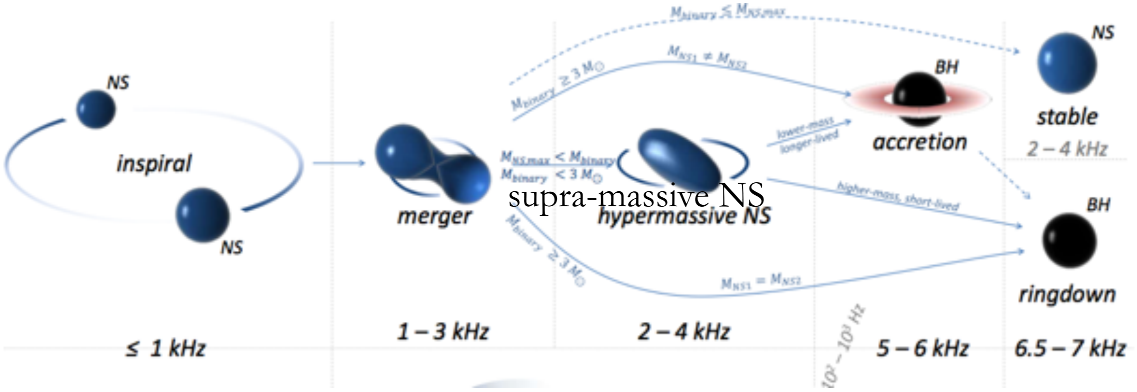
Li et al. (2016)

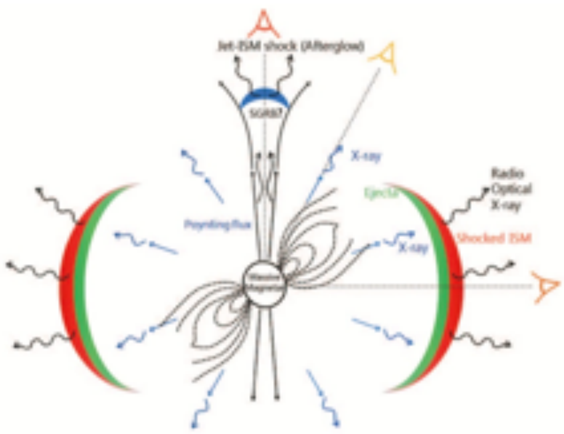


Rowlinson et al. (2013)

EM counterparts of NS-NS mergers

(forming a stable or supra-massive NS)



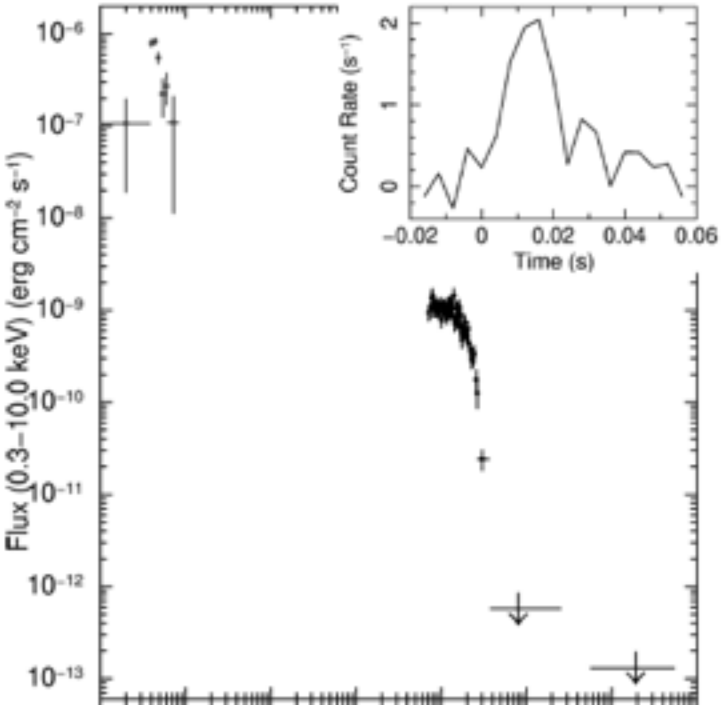


Gao et al. (2013)

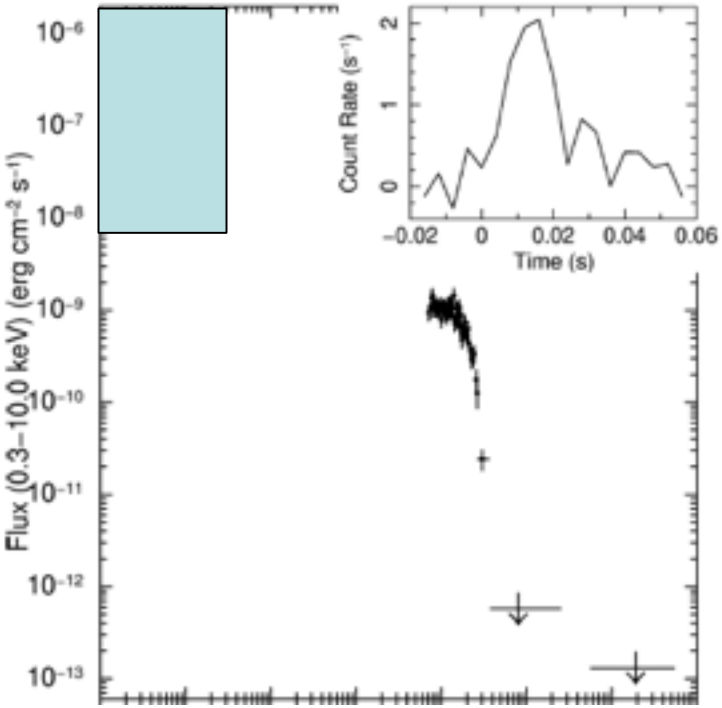
- Jetted component (likely, still low probability):
  - Short GRB (sGRB)
  - sGRB afterglow (X-ray, UV/optical/IR, radio)
- Quasi-Isotropic component:
  - Macronova/kilonova/mergernova (optical/IR): enhanced
  - mergernova afterglow: enhanced
  - sGRB-less X-ray transients (plausible)
  - Fast radio bursts (speculative)

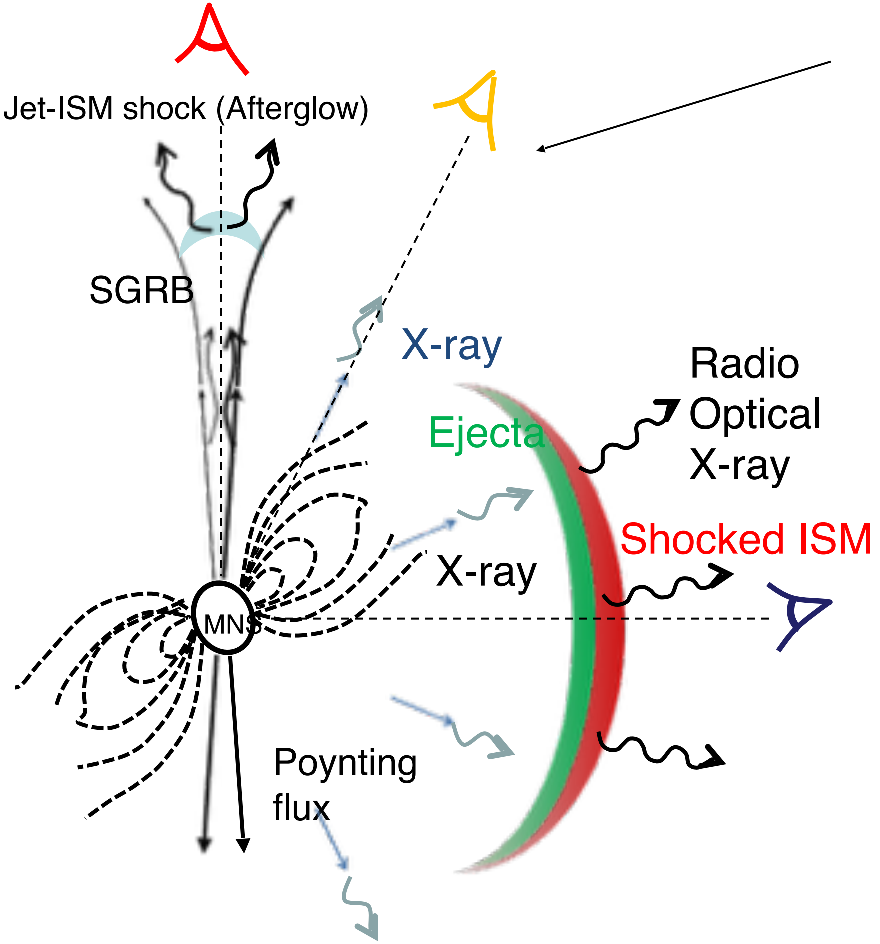
EM counterpart 4 (plausible): sGRB-less X-ray counterpart

(orphan internal plateau)



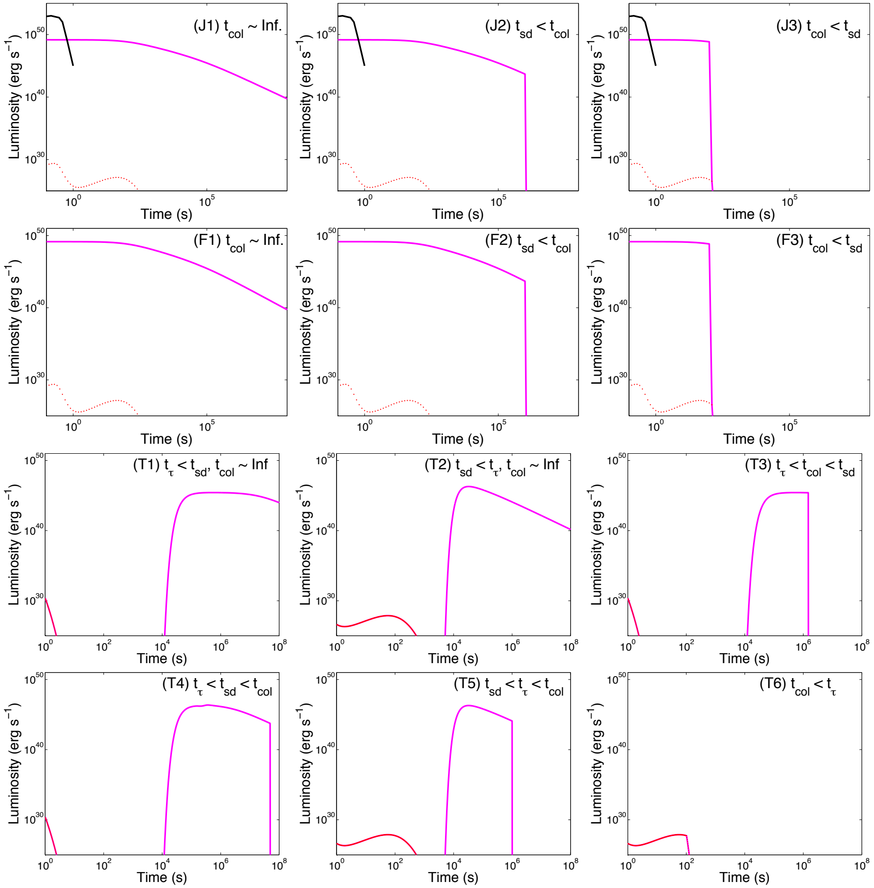
EM counterpart 4 (plausible): sGRB-less X-ray counterpart
(orphan internal plateau)

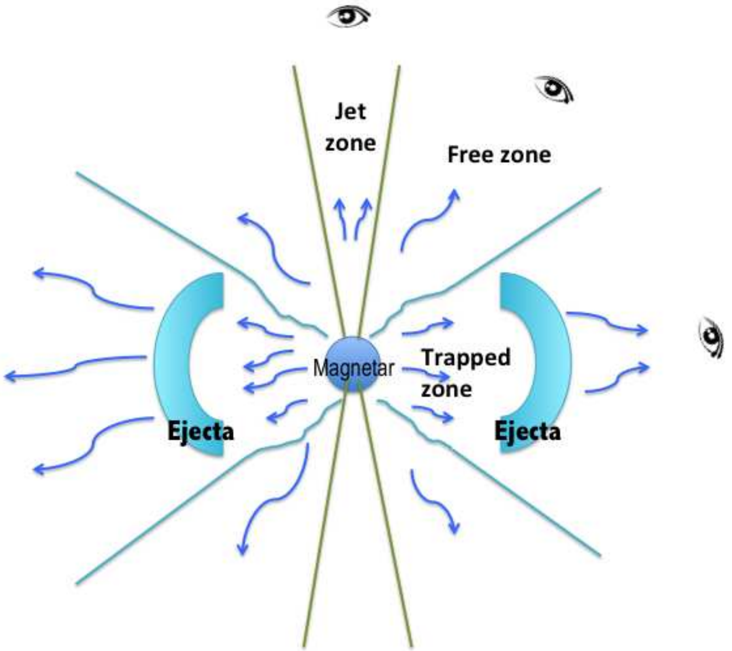




Zhang (2013)

sGRB-less X-ray counterpart:
light curve gallery

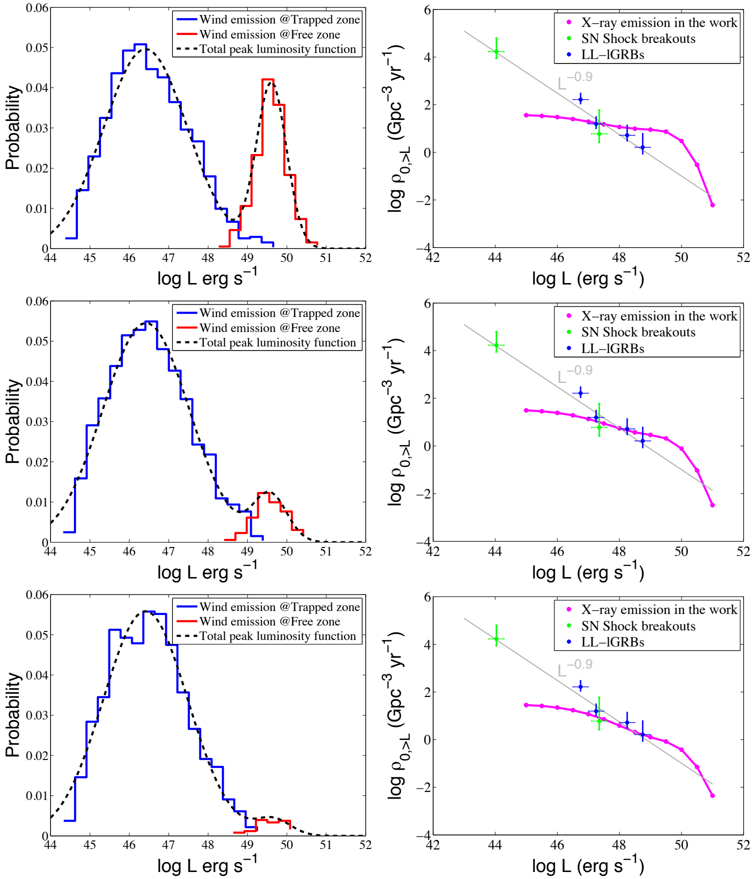


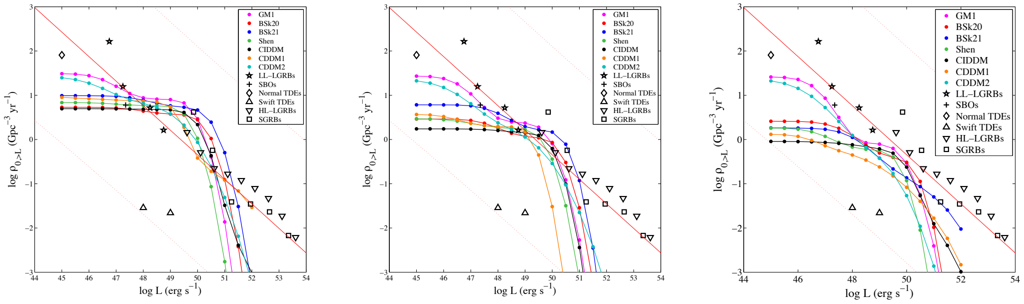


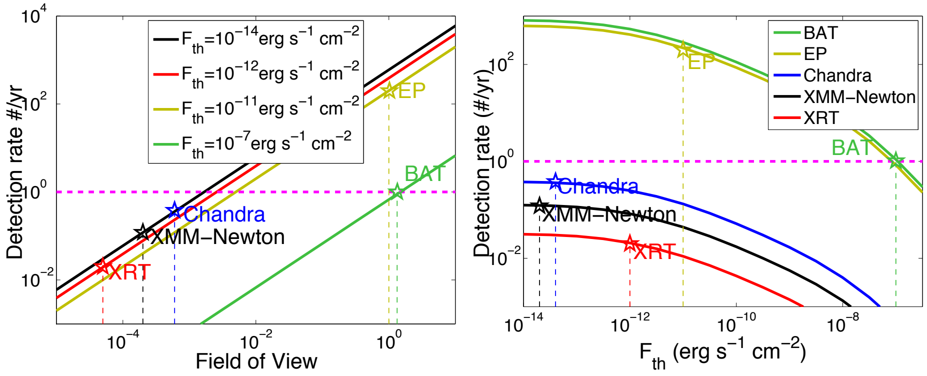
Sun, Zhang & Gao, arXiv:1610.03860

Alternative idea: X-ray scattering (Kisaka, Ioka & Nakamura 2015)

sGRB-less X-ray counterpart:
luminosity function & event rate density







Sun, Zhang & Gao, arXiv:1610.03860

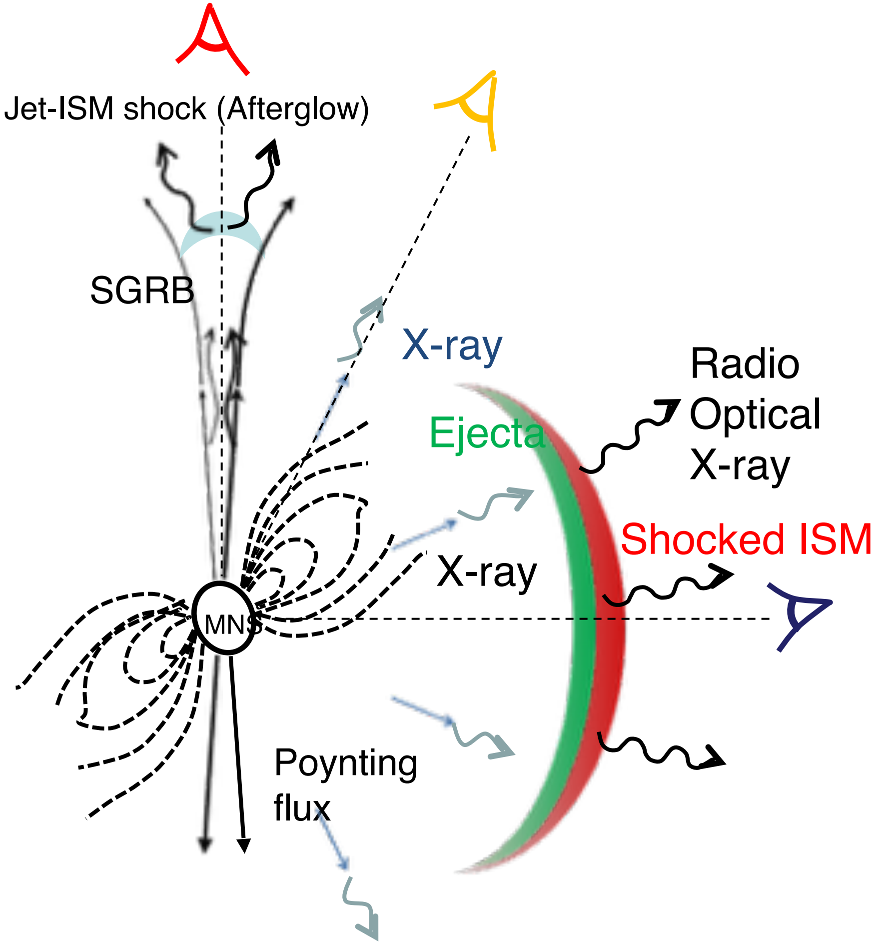
Candidate(s) found - stay tuned

Enhanced (Magnetar powered) Merger Novae

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

$$\frac{d\Gamma}{dt} = \frac{L_{\rm sd} + L_{\rm ra} - L_e - \Gamma\mathcal{D}(dE'_{\rm int}/dt')}{M_{\rm ej}c^2 + E'_{\rm int}}.$$

$$\frac{dE'_{\rm int}}{dt'} = \xi L'_{\rm sd} + L'_{\rm ra} - L'_e - P'\frac{dV'}{dt'}$$



Enhanced (Magnetar powered) Merger Novae

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

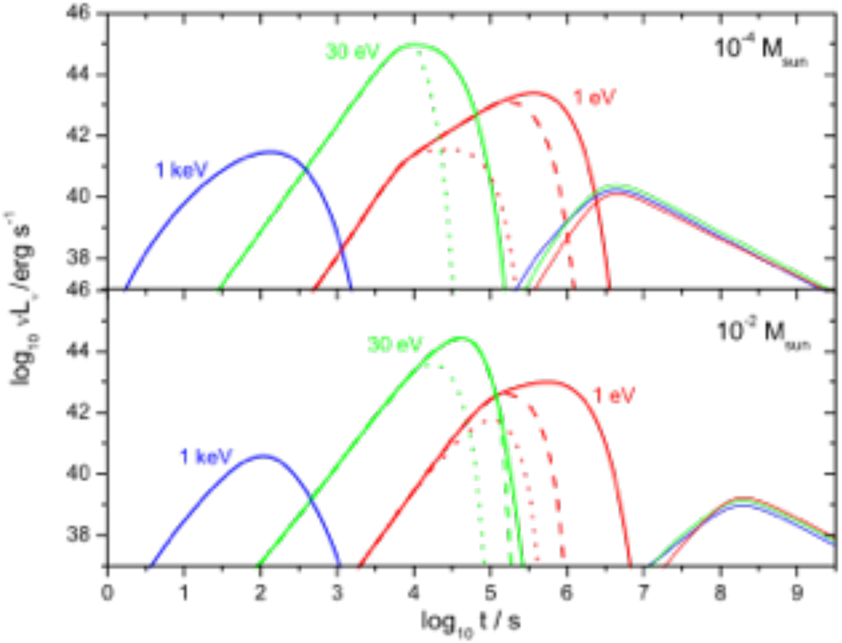


Figure 2. Light curves of the merger-nova (thick) and afterglow (thin) emissions at different observational frequencies as labeled. The dashed and dotted lines are obtained for an optionally taken magnetar collapsing time as $t_{\rm col} = 2t_{\rm md}$ and $t_{\rm col} = 10^4$ s, respectively. The ambient density is taken as 0.1 cm^{-3}, and other model parameters are the same as Figure 1.

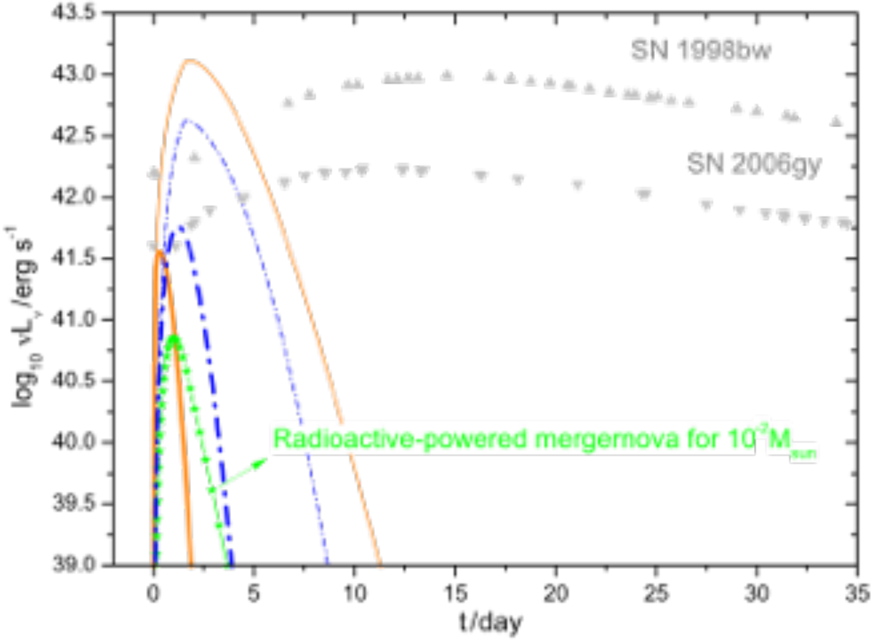
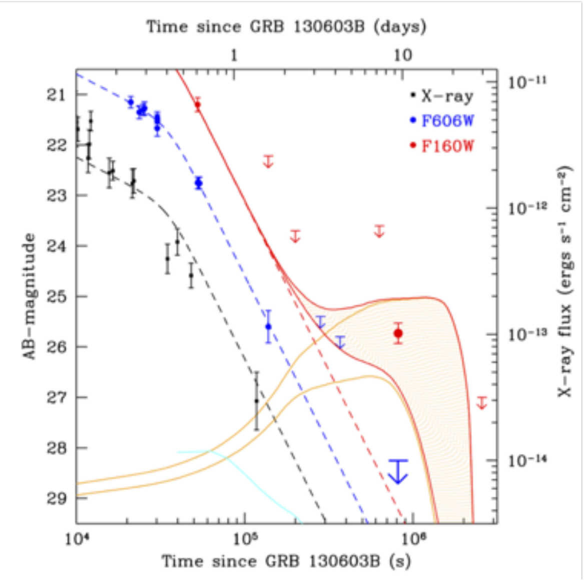
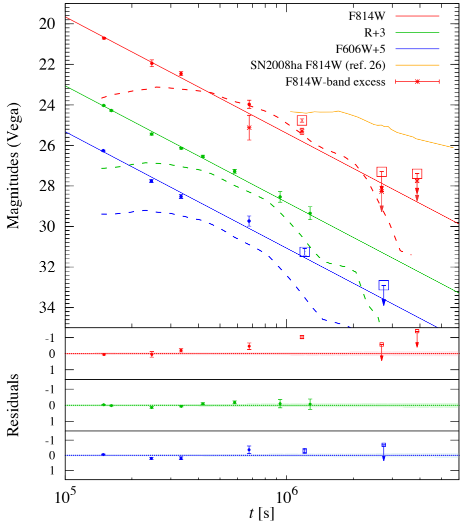


Figure 3. Optical (∼1 eV) light curves of the millisecond-magnetar-powered merger-nova, in comparison with the light curves of two supernovae (bolometric) and one radioactive-powered merger-nova (as labeled). The dash-dotted (blue) and solid (orange) lines represent $M_{\rm ej} = 10^{-2}\,M_\odot$ and $10^{-4}\,M_\odot$, respectively. The thick and thin lines correspond to a magnetar collapsing time as $t_{\rm col} = 10^4\ {\rm s} \ll t_{\rm md}$ and $t_{\rm col} = 2t_{\rm md}$, respectively. The zero-times of the supernovae are set at the first available data.

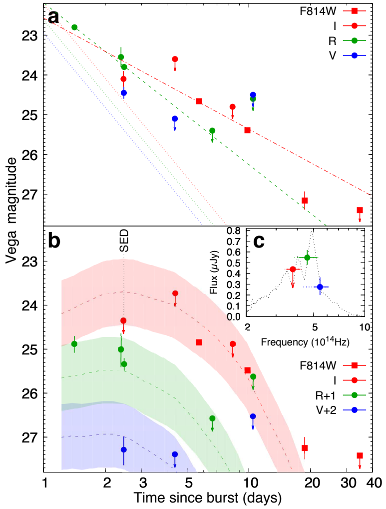
Kilonova, macronova, mergernova



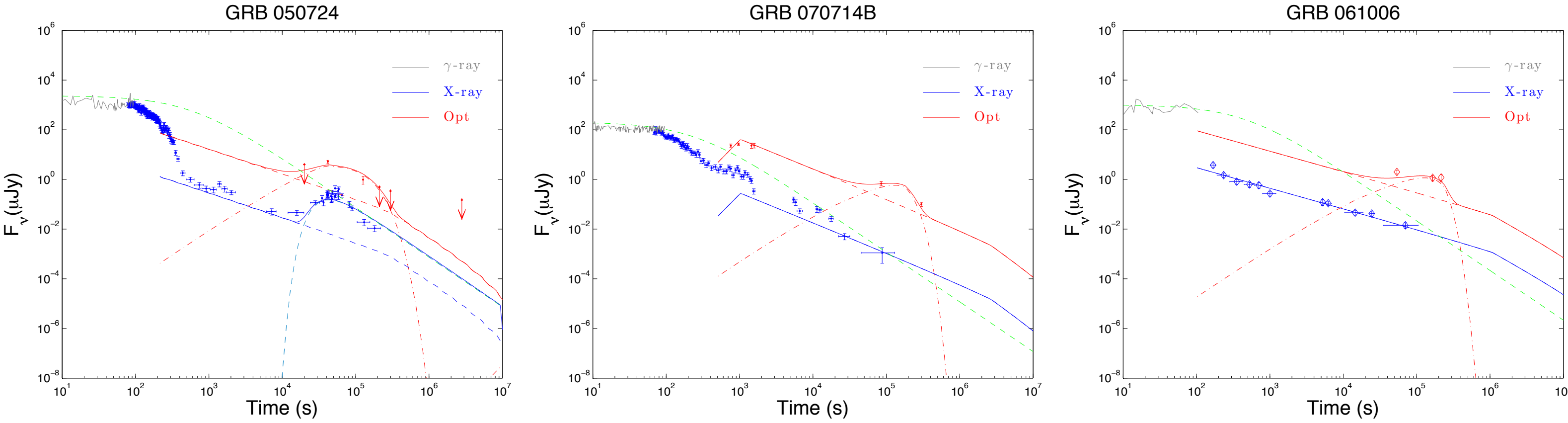
GRB 130603B, Tanvir et al. (2015); Berger et al. (2015)



GRB 060614, Yang et al. (2015)

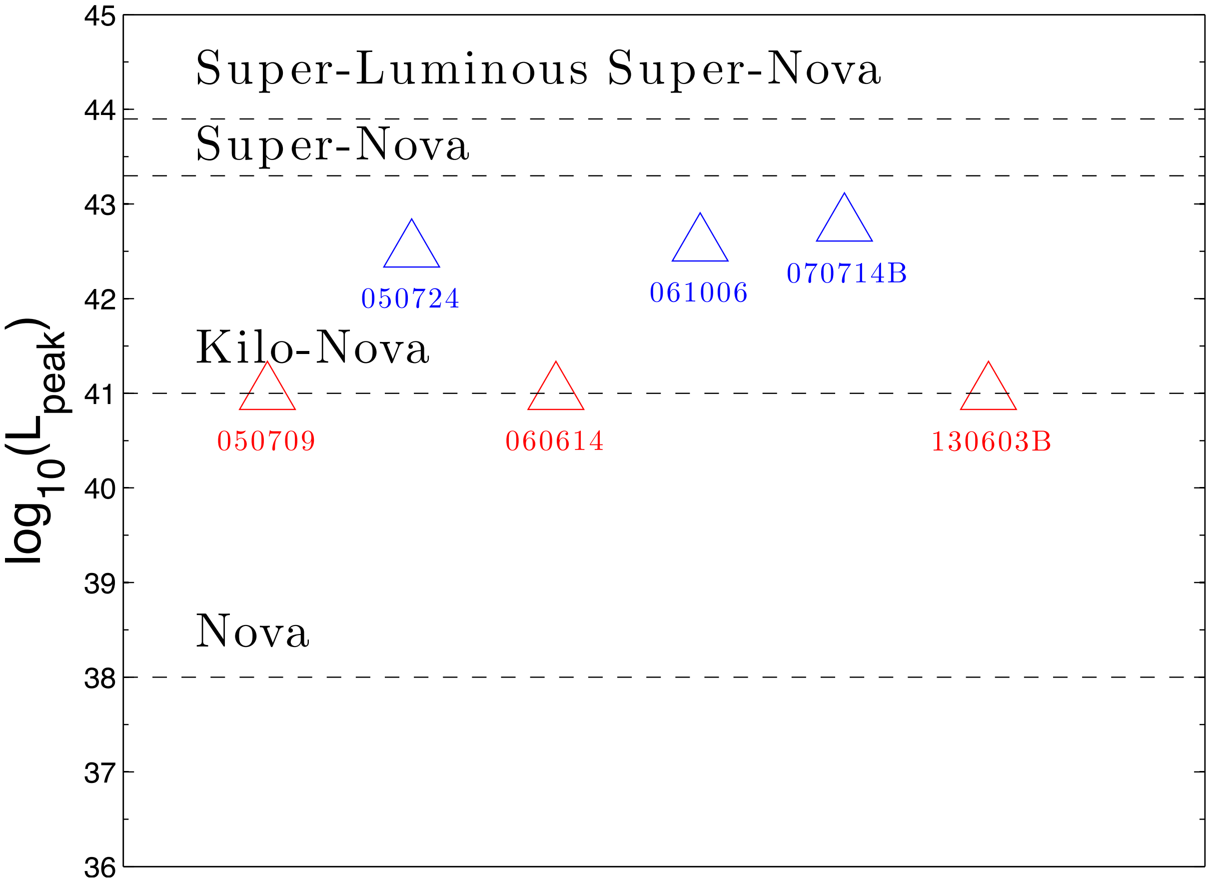


GRB 050709, Jin et al. (2016)



Gao et al. (2016, arXiv:1608.03375)

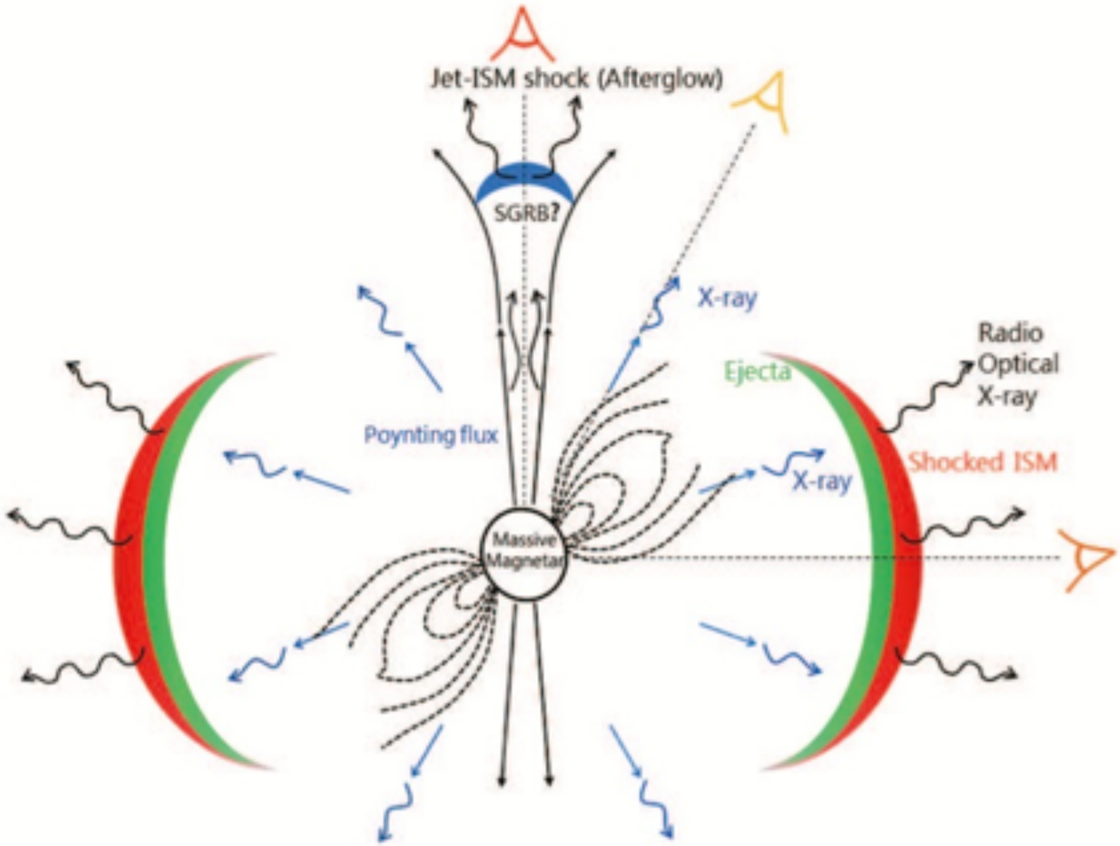
Kilonova, macronova, mergernova



Some could be super-kilo
Some could be hecto

Gao et al. (2016, arXiv:1608.03375)

Enhanced magnetar-powered afterglow



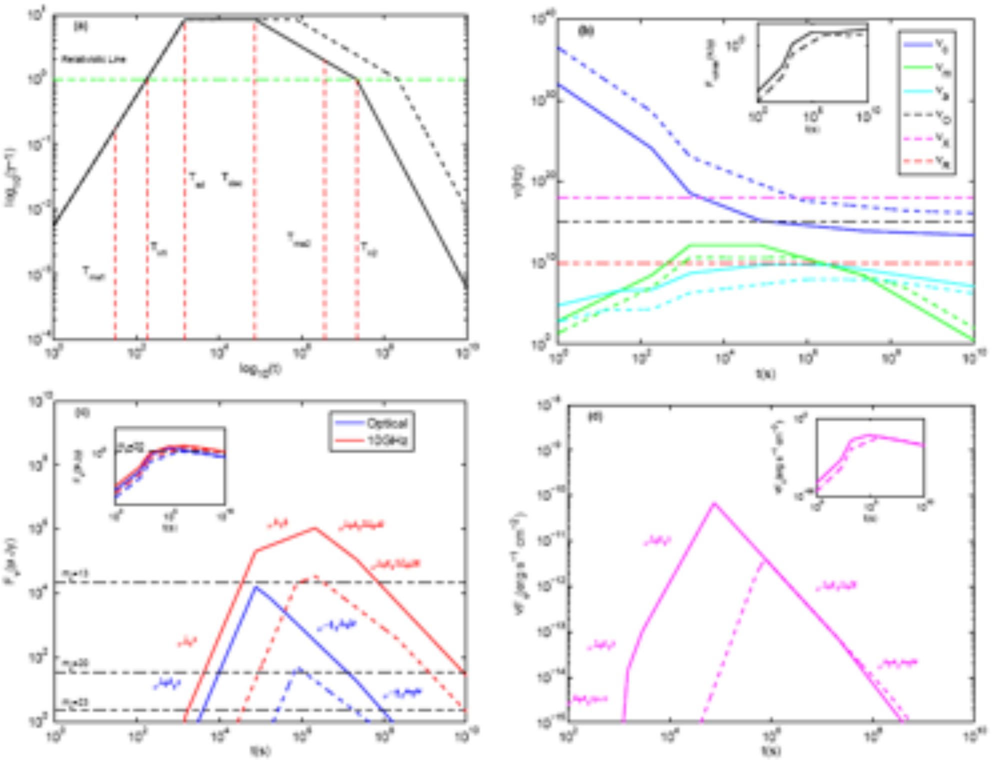
Gao et al, 2013, ApJ, 771, 86

Ejecta-ISM shock with Energy Injection

Gao et al. 2013, ApJ, 771, 86

$$B_{\perp} \sim 10^{15}\, G, \quad M_{ej} \sim 10^{-3}\, M_{\odot}$$

$$T_{sd} < T_{dec}$$



X-ray: $T_{peak} \sim T_{sd} \sim 10^{3}\, s$

$F_{peak} \sim 10^{-10}\, erg\, cm^{-2} s^{-1}$

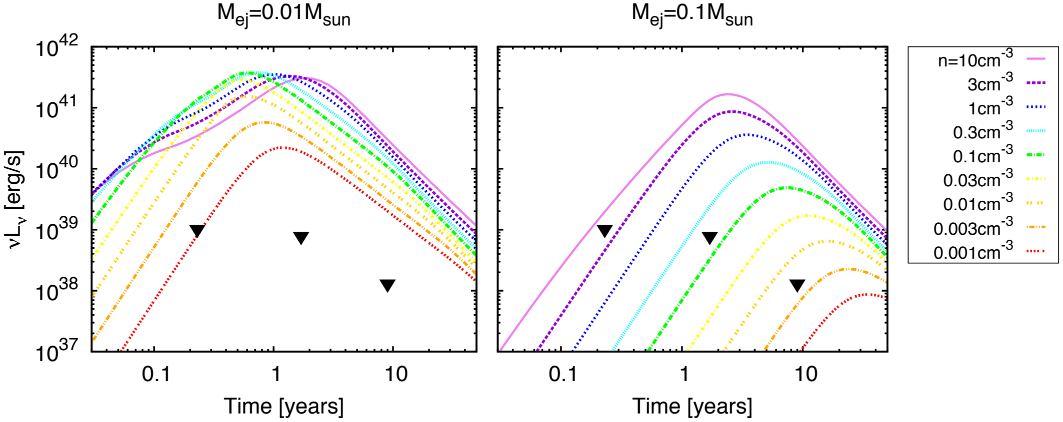
Opt: $T_{peak} \sim T_{sd} \sim 10^{3}\, s$

$F_{peak} \sim 10 mJy$

Radio: $T_{peak} \sim 10^{7}\, s$

$F_{peak} \sim 1 Jy$

Constraints on magnetar parameters



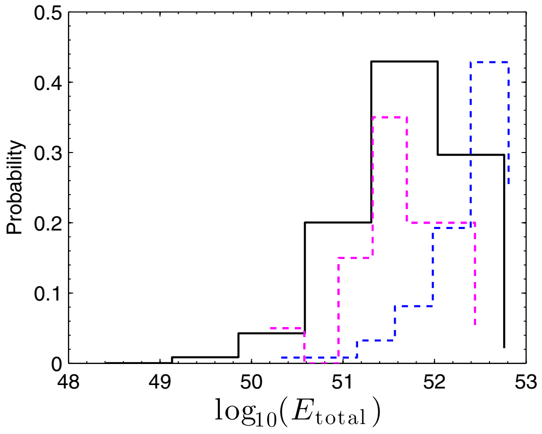
Horesh, Hotokezaka, Piran et al. (2016)

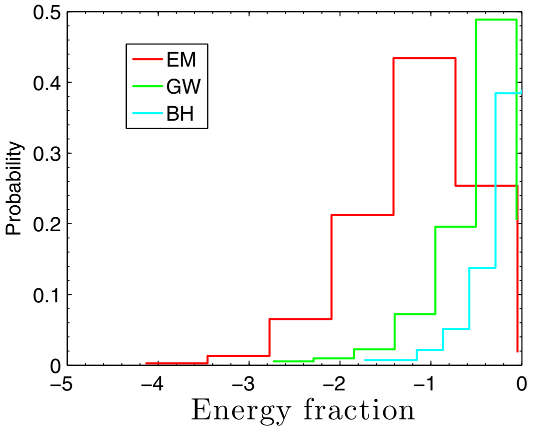
However,

$$E_k = 3 \times 10^{52}\ \mathrm{erg}.$$
$$\epsilon_{\mathrm{e}} = 0.1$$
$$\epsilon_{\mathrm{B}} = 0.1$$

has been assumed

Piran's talk

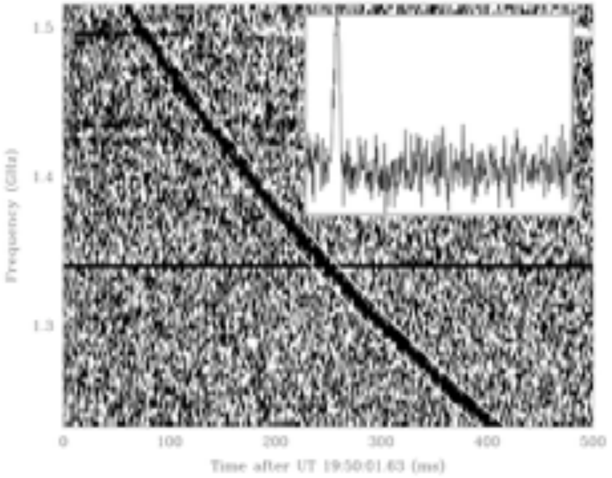




The magnetar energy in sGRB remnants is much smaller, due to GW emission and falling into the BH

Gao et al. (2016)

EM Counterpart 5: Speculative
A possible connection with FRBs



Lorimer's talk

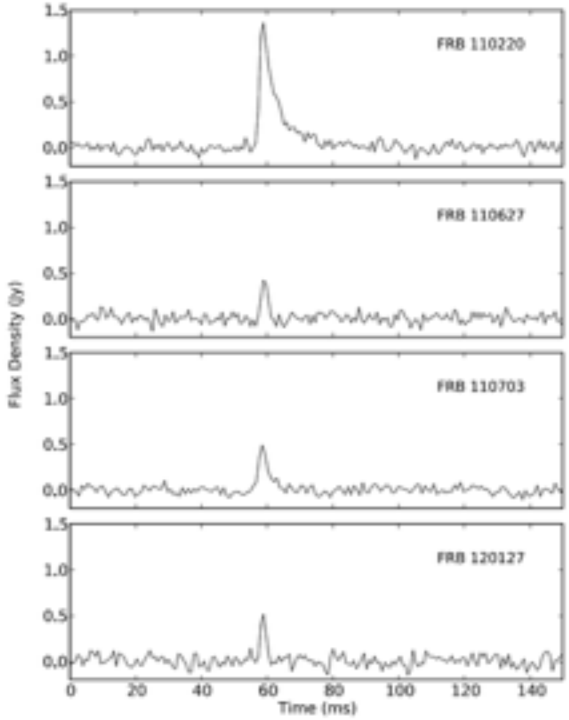


Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).

FRBs vs. GRBs

- Physically related???
- Culturally/socially related!

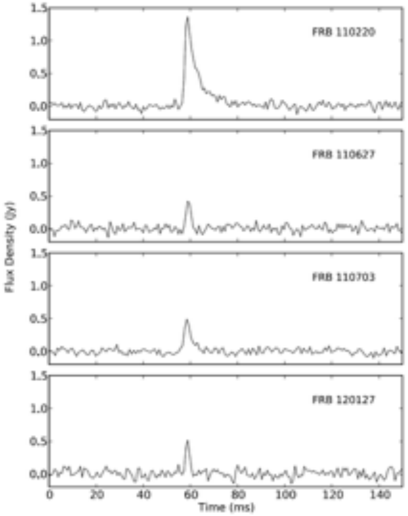
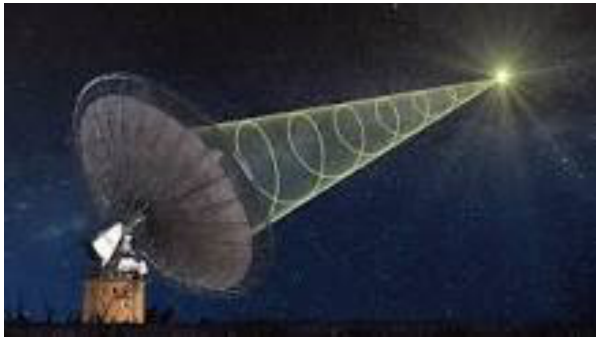
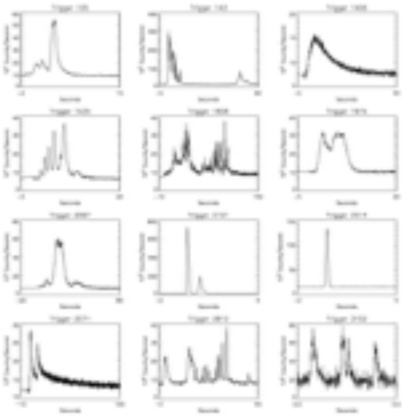


Fig. 1. The frequency-integrated flux densities for the four FRBs. The time resolutions match the level of dispersive smearing in the central frequency channel (0.8, 0.6, 0.9, and 0.5 milliseconds, respectively).

Thornton et al. (2013)





FRBs vs. GRBs

	GRBs	**FRBs**
Step one: Are they astrophysical?	1967 – 1973	2007 – 2015
Step two: Where are they (distance)?	1973 – 1997 – 2004	2016??
Step three: What make them?	1998 – ???	???

Observationally driven
Healthy dialog between observers and theorists

FRBs: Where are they?

- Cosmological
- Extragalactic but not cosmological
- Galactic

What may make them?

(An incomplete list)

- Collapses of supra-massive neutron stars to black holes (thousands to million years later after birth, or in a small fraction hundreds/thousands of seconds after birth), ejecting "magnetic hair" (Falcke & Rezzolla 2013; Zhang 2014)
- BH-BH mergers (charged) (Zhang 2016; Liu et al. 2016)
- Magnetospheric activity after NS-NS mergers (Totani 2013)
- Unipolar inductor in NS-NS mergers (Piro 2012; Wang et al. 2016)
- Mergers of binary white dwarfs (Kashiyama et al. 2013)
- Supergiant radio pulses (Cordes & Wasserman 2015; Connor et al. 2015; Pen & Connor 2015) – good for the repeating FRB
- Magnetar giant flare radio bursts (Popov et al. 2007, 2013; Kulkarni et al. 2014; Katz 2015)
- Cosmic sparks from superconducting strings (Vachaspati 2008; Yu et al. 2014)
- Evaporation of primordial black holes (Rees 1977; Keane et al. 2012)
- White holes (Barrau et al. 2014; Haggard)
- Flaring stars (Loeb et al. 2013; Maoz et al. 2015)
- Axion miniclusters, axion stars (Tkachev 2015; Iwazaki 2015)
- NS-Asteroid collisions (Geng & Huang 2015; Dai et al. (repeaters))
- Quark Nova (Shand et al. 2015)
- Dark matter-induced collapse of NSs (Fuller & Ott 2015)
- Higgs portals to pulsar collapse (Bramante & Elahi 2015)

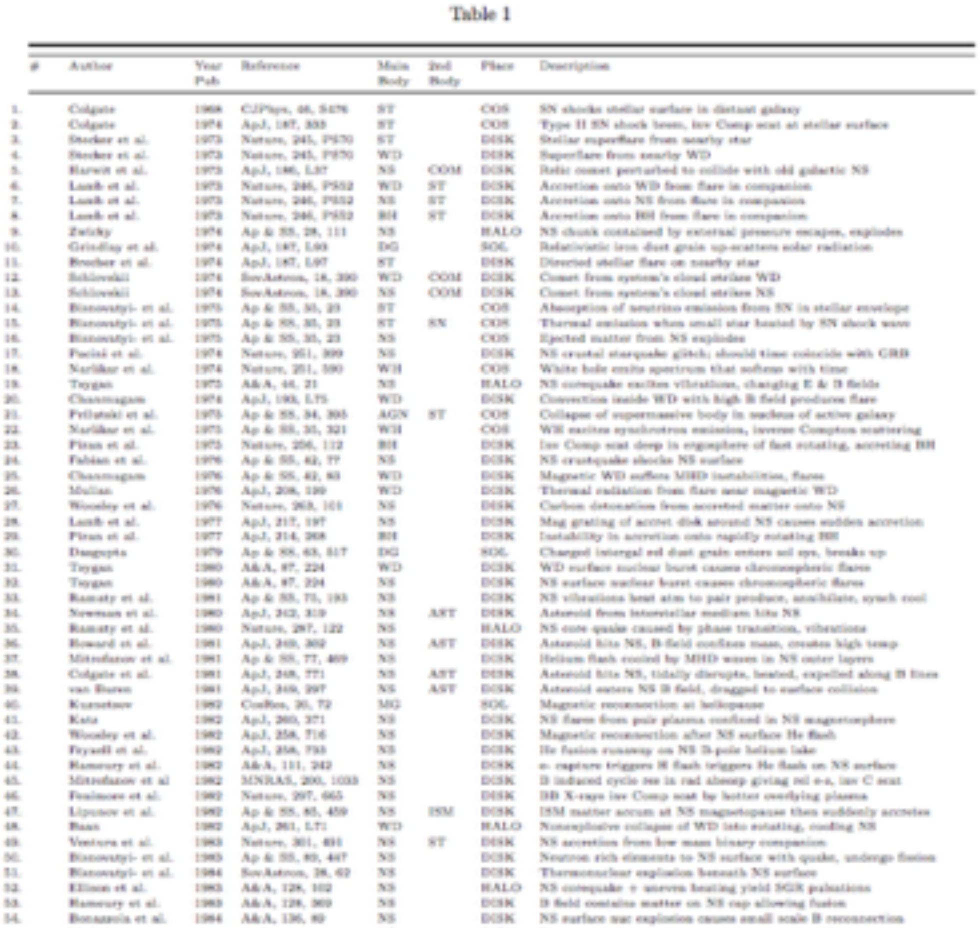
……

Lessons from GRBs

- Discovered in late 1960s
- Didn't know where they come from
- More than 100 models

- "The only feature that all but one (and perhaps all) of the very many proposed models have in common is that they will not be the explanation of gamma-ray bursts"
  - Malvin Ruderman (1975)

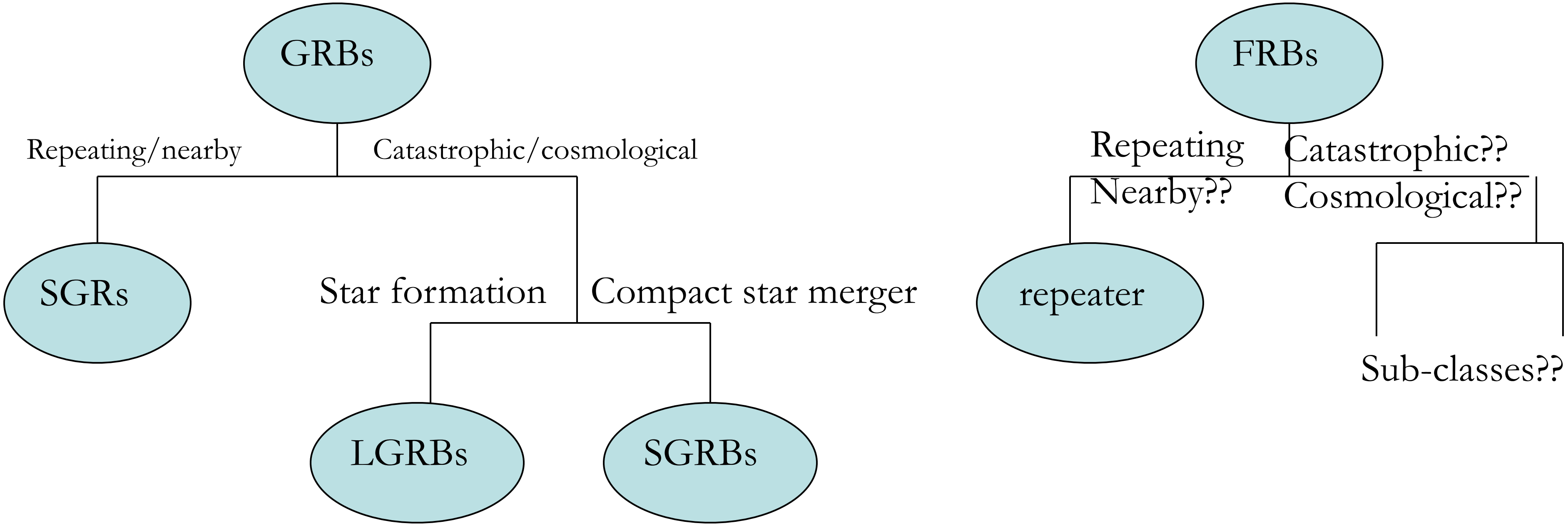
- The same may be stated for FRB models



Nemiroff, 1994, Comments on Astrophysics, 17, 189

128 models

Multiple progenitor systems?



GRBs

Repeating/nearby

Catastrophic/cosmological

SGRs

Star formation

Compact star merger

LGRBs

SGRBs

FRBs

Repeating

Nearby??

Catastrophic??

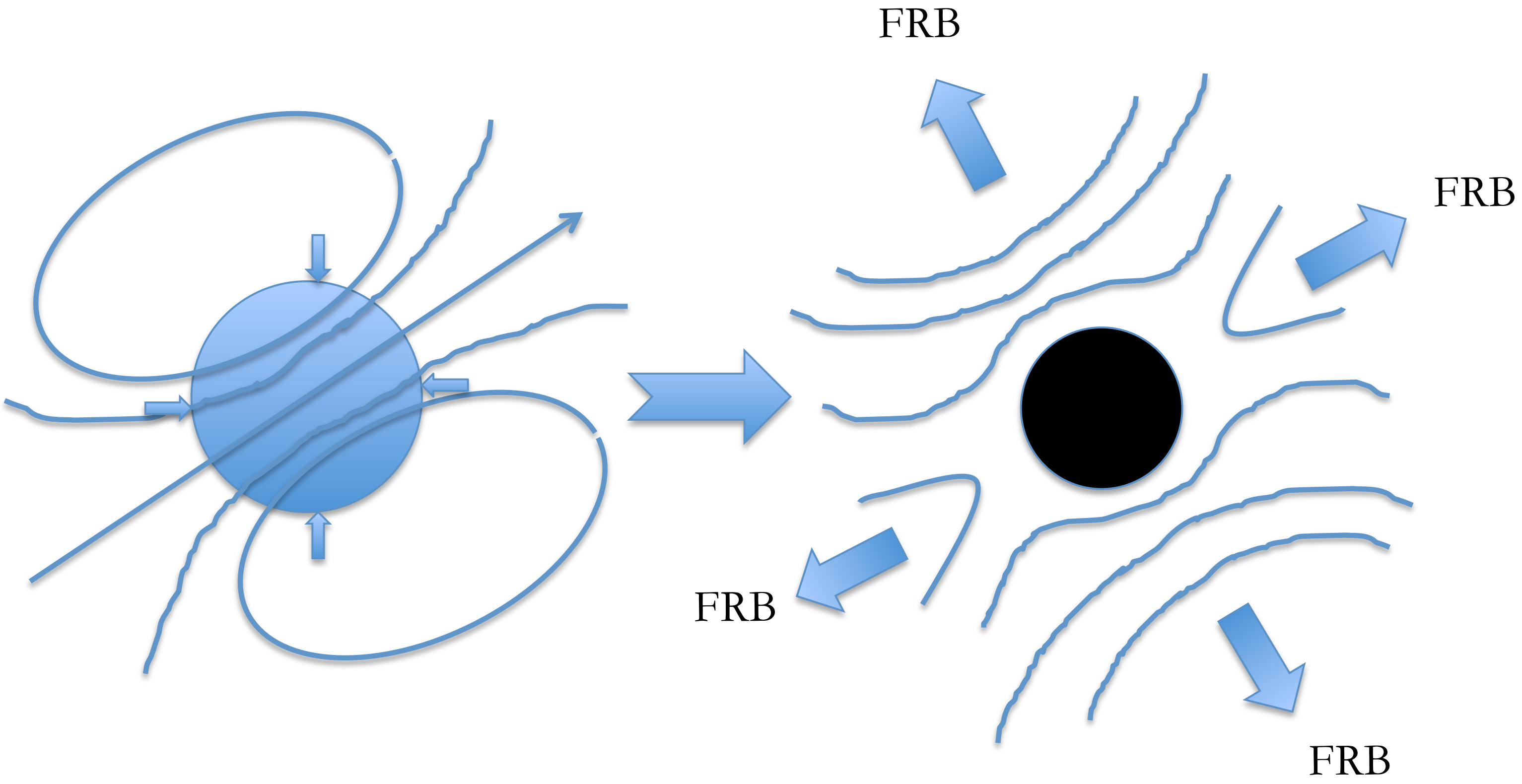
Cosmological??

repeater

Sub-classes??

High event rate: Easy to make! More than one way to make!

Blitzar: Magnetic hair ejection of neutron star implosion

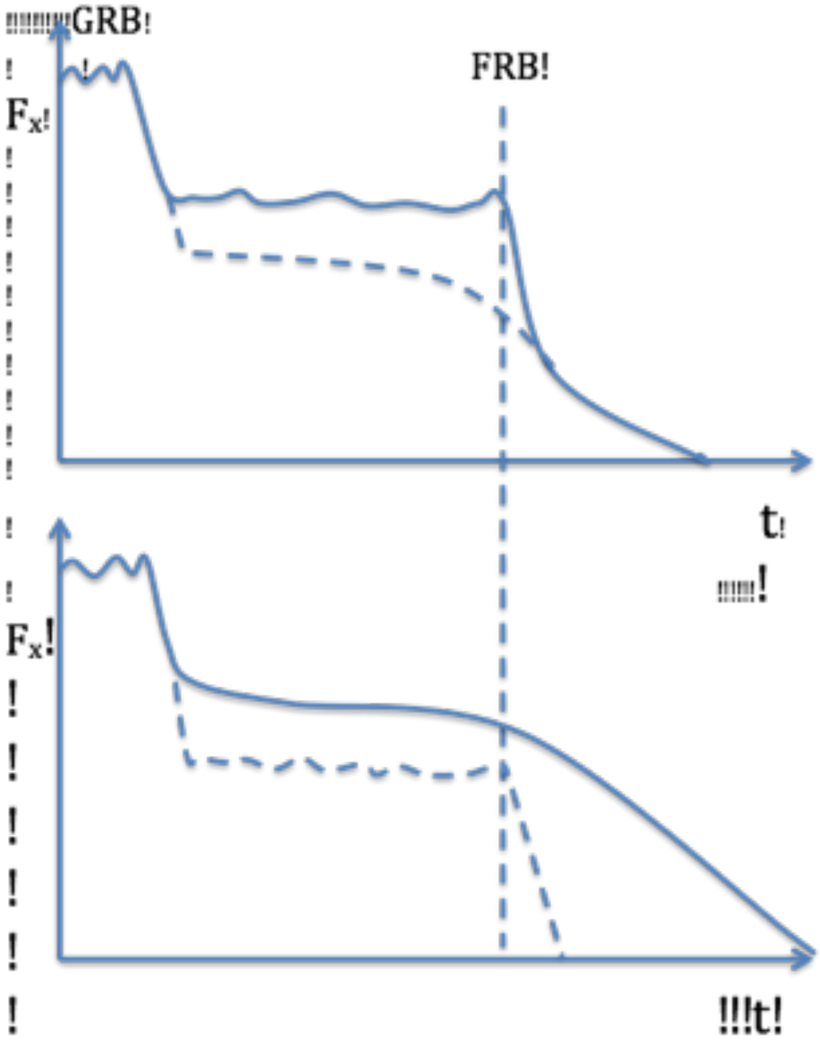


Falcke & Rezzolla (2014): happen thousands to millions of years after the birth of SMNSs
Zhang (2014): a small fraction can happen minutes to days after the birth of SMNSs

Rezzolla's talk

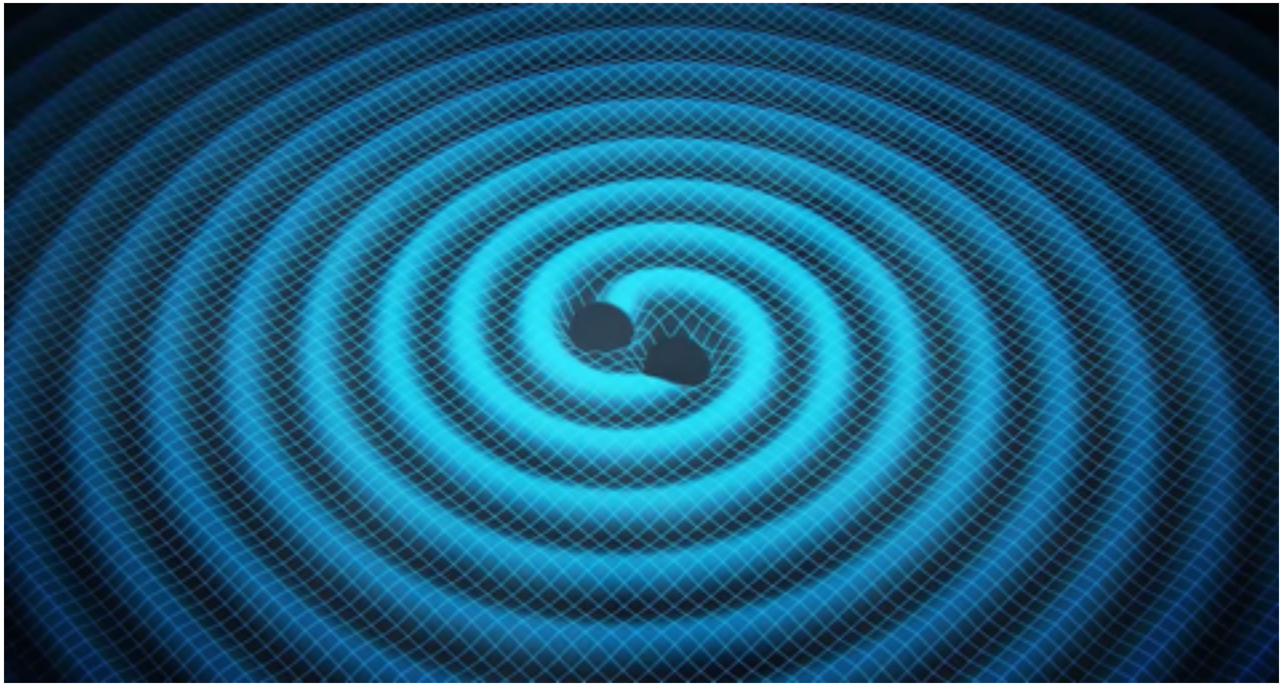
FRBs in GRBs

- Internal plateaus cannot be interpreted within the framework of the external shock models
- The rapid drop at the end of plateau may mark collapse of a millisecond magnetar to a black hole
- So the end of plateau may be the epoch when an FRB is emitted
- Rapid radio follow-up (within 100 s) of GRBs may lead to discovery of an associated FRB, may be brighter than normal FRBs.



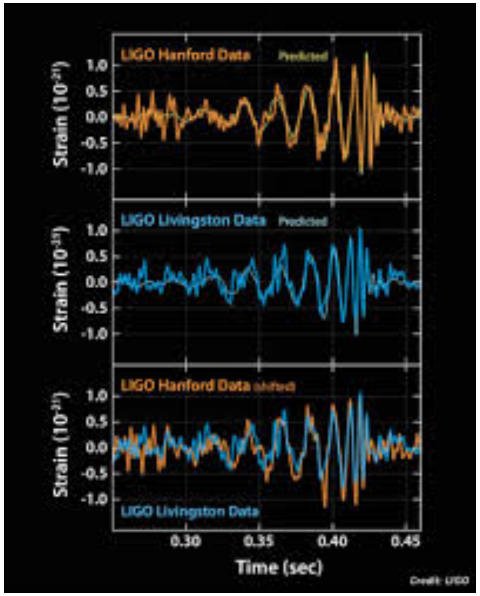
Zhang, 2014, ApJ, 780, L21

BH-BH mergers

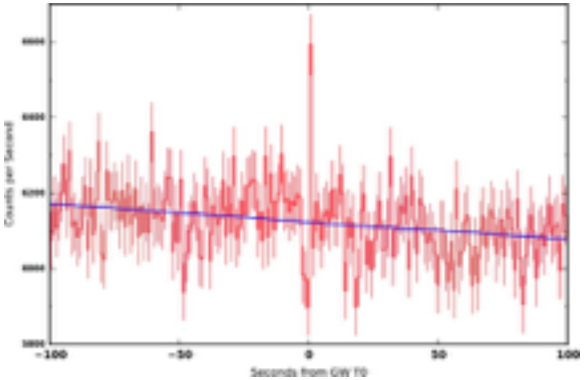


- Two naked BHs: No EM counterpart expected!
- EM counterparts can be generated if at least one BH can retain matter or EM fields

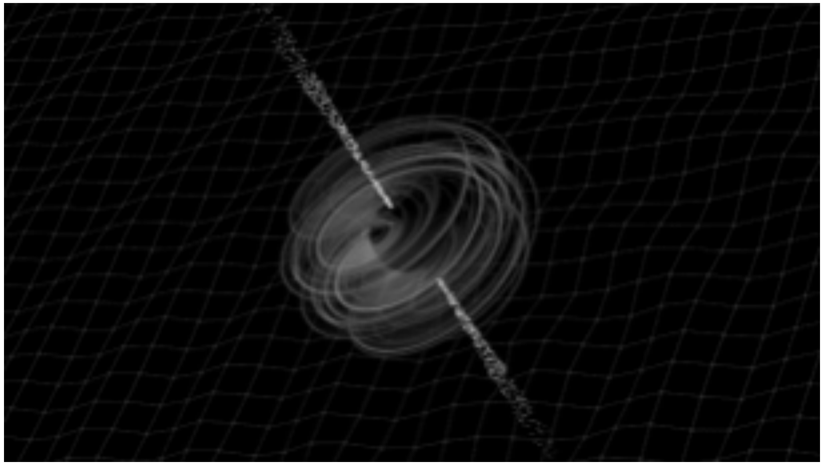
GRB following GW 150914? (GW150914-GBM)



Abbott et al. 2016)



Connaughton et al. (2016)



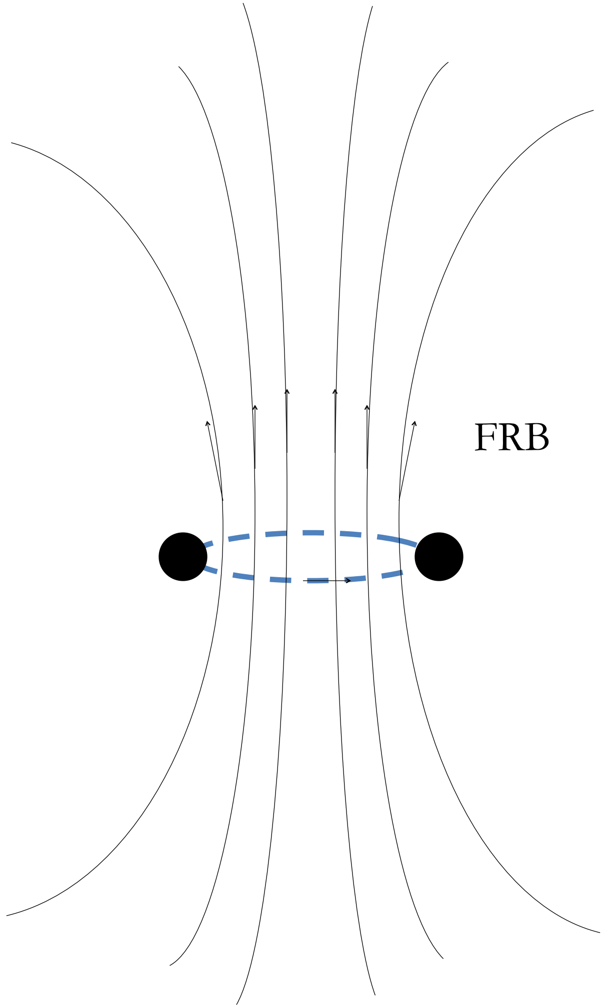
- Weak burst above 50 keV
- Onset time: 0.4 s after GW 150914
- Duration 1s
- Direction broadly consistent
- False alarm probability 0.0022 (2.9 σ)
- L ~ $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s^{-1}

but see Greiner et al. (2016); Xiong (2016)

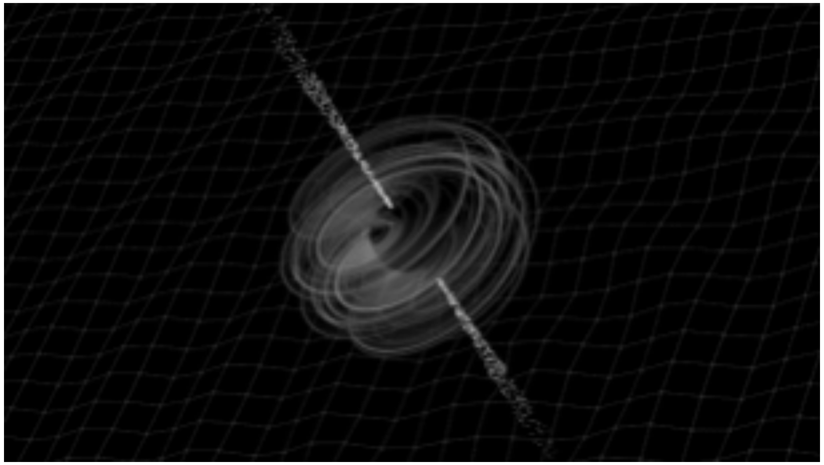
Unconventional Ideas for EM counterparts of BH-BH mergers

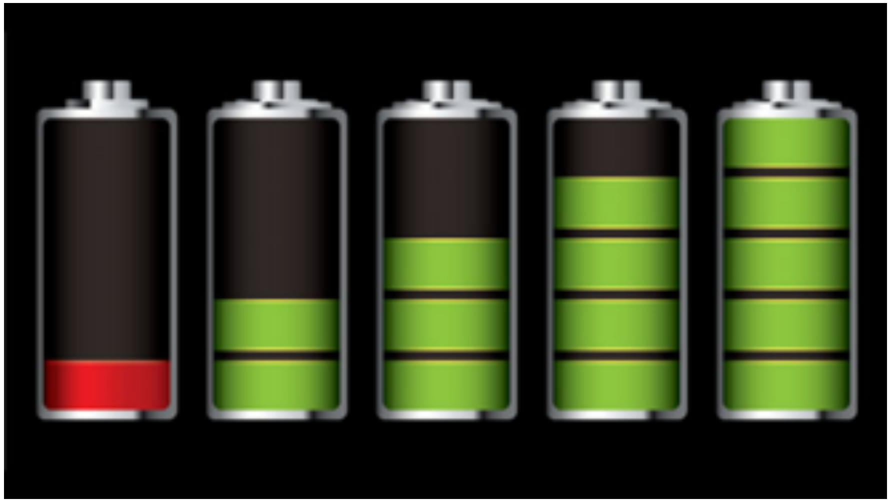
- Models with matter
  - Twin BHs inside one star (Loeb 2016, but see Woosley 2016)
  - Reactivated accretion disk (Perna et al. 2016, but see Kimura et al. 2016)
  - Multi-body interactions …

- Models with EM fields
  - Charged BH-BH mergers (Zhang 2016, Liu et al. 2016; Fraschetti 2016; Liebling & Palenzuela 2016)



Charged

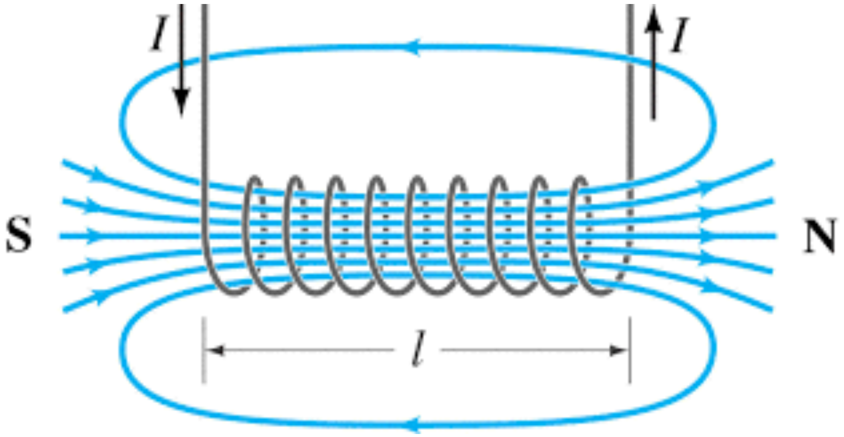


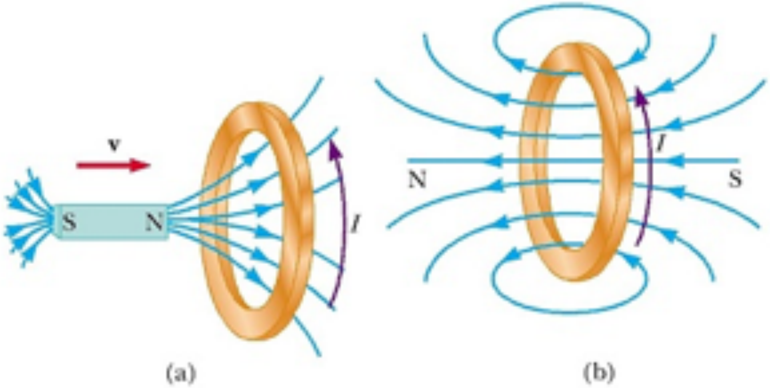


Charged BH merger model

(Zhang, ApJ, 827, L31)

Part 1: Consequence of charges





1. $\nabla \cdot \mathbf{D} = \rho_V$
2. $\nabla \cdot \mathbf{B} = 0$
3. $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
4. $\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$

High school E&M

Charged BH merger model

(Zhang, ApJ, 827, L31)

Part 1: Consequence of charges

$$\mu = \frac{\pi I (a/2)^2}{c} = \frac{\sqrt{2GMa}Q}{4c} = \frac{\sqrt{2}G^{3/2}M^2}{c^2}\hat{q}\hat{a}^{1/2}$$
$$= (1.1\times 10^{33}\ \mathrm{G\ cm^3})\left(\frac{M}{10M_\odot}\right)^2 \hat{q}_{-4}\hat{a}^{1/2},$$

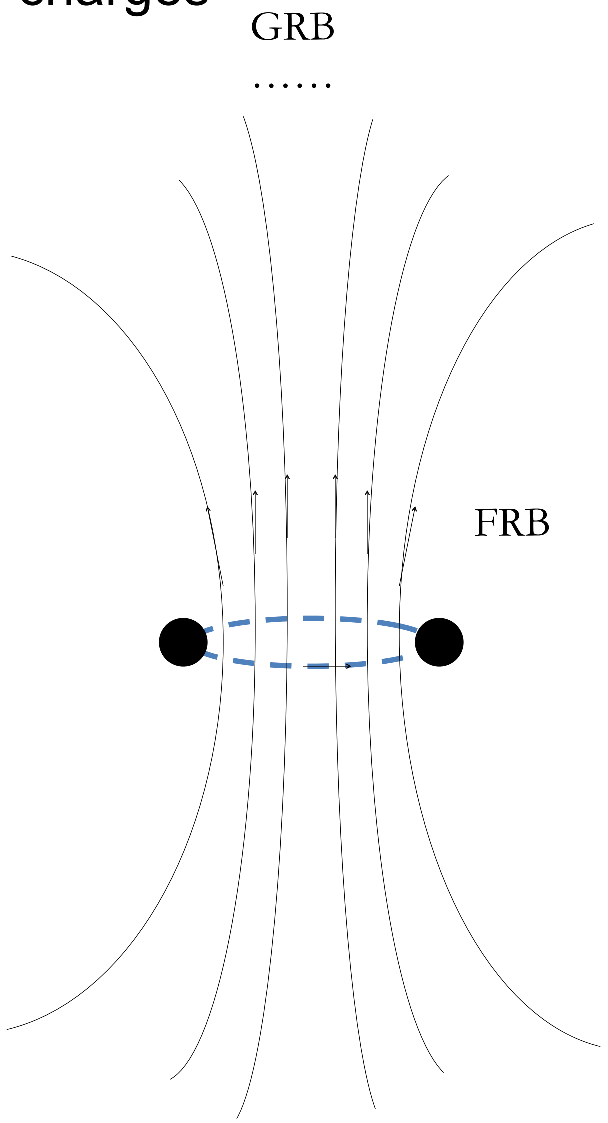
$$L_w \simeq \frac{2\ddot{\mu}^2}{3c^3} \simeq \frac{49}{120000}\frac{c^5}{G}\hat{q}^2\hat{a}^{-15}$$
$$\simeq (1.5\times 10^{48}\ \mathrm{erg\ s^{-1}})\hat{q}_{-4}^2\hat{a}^{-15},$$

$$L_w \sim 0.4\hat{q}^2 L_{\rm GW}\hat{a}^{-10}.$$

$$Q = \hat{q}Q_c,$$

$$\frac{da}{dt} = -\frac{2}{5}\frac{c}{\hat{a}^3}$$

$$Q_c \equiv 2\sqrt{G}M = (1.0\times 10^{31}\ \mathrm{e.s.u.})\left(\frac{M}{10M_\odot}\right)$$



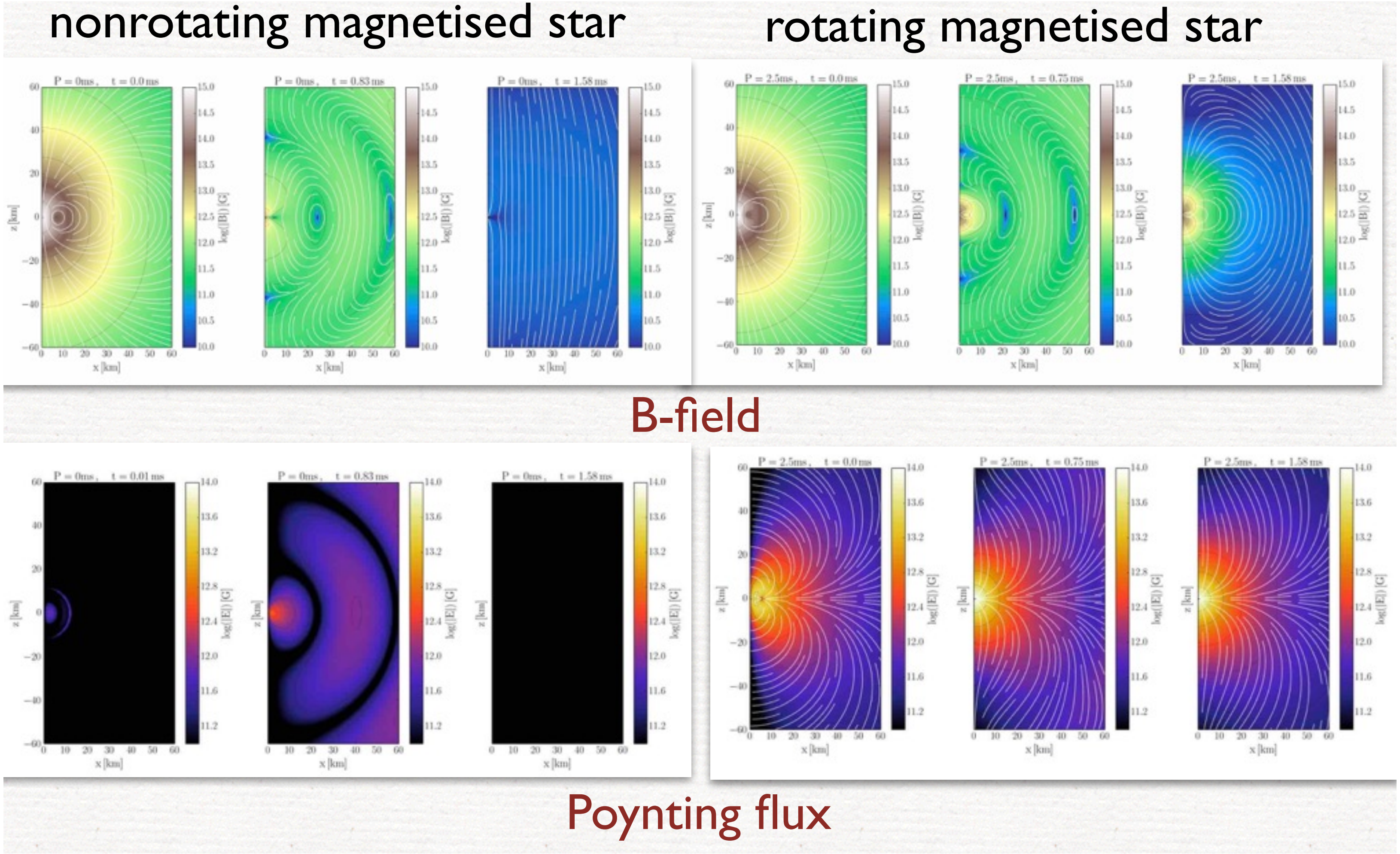
Can produce Fast radio bursts (FRBs) and short GRBs

$\hat{q} \sim (10^{-9}$–$10^{-8})$ $\hat{q} \sim (10^{-5}$–$10^{-4})$

Charged BH merger model

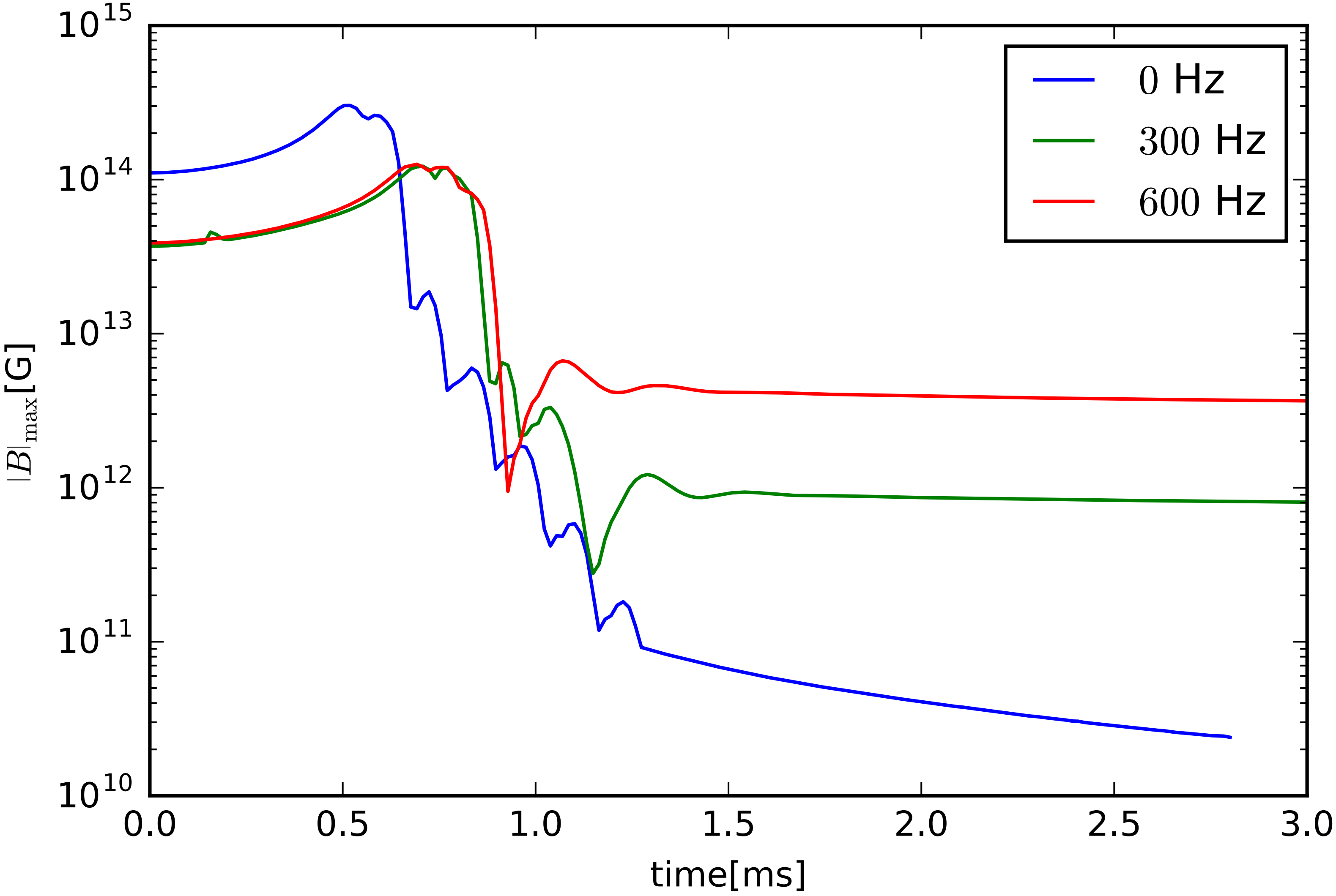
(Zhang, ApJ, 827, L31)

Part 2: How to make and maintain charged BHs?



Mosta, Nathanail & Rezzolla (2016)

Rezzolla's talk



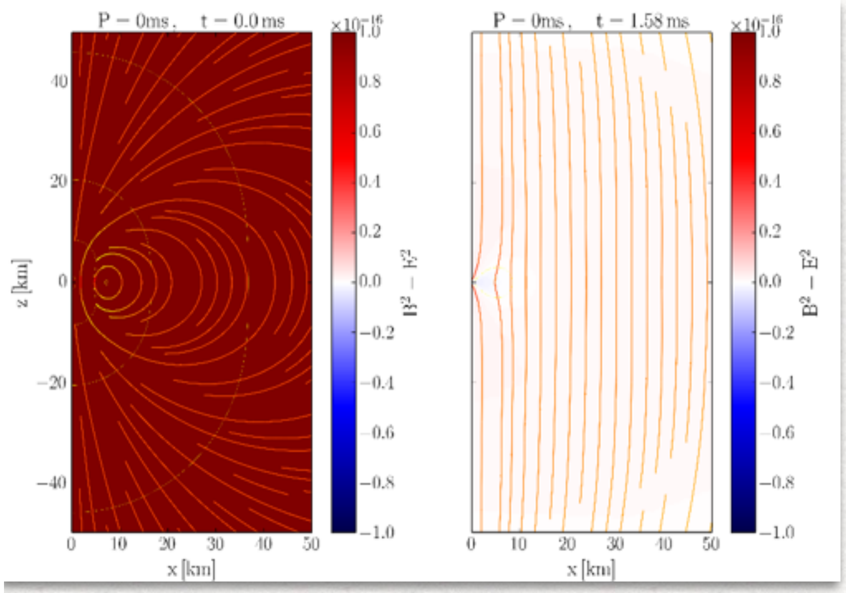
Mosta, Nathanail & Rezzolla (2016)

Rezzolla's talk

Collapse to what?

Nathanail, Most, LR 2016

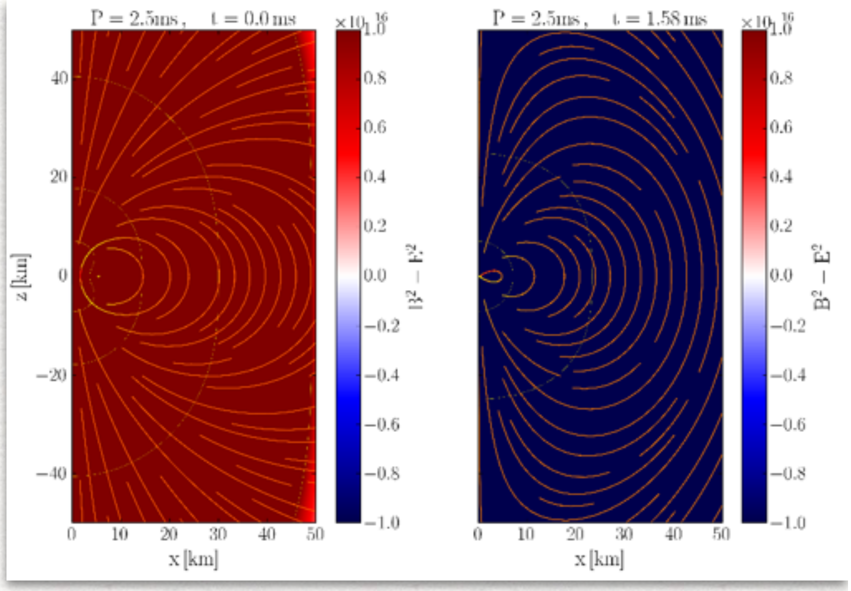
nonrotating magnetised star



$$\frac{1}{2}F^{\mu\nu}F_{\mu\nu} = \boldsymbol{B}^2 - \boldsymbol{E}^2 = 0$$

collapse to **Schwarzschild BH**

rotating magnetised star



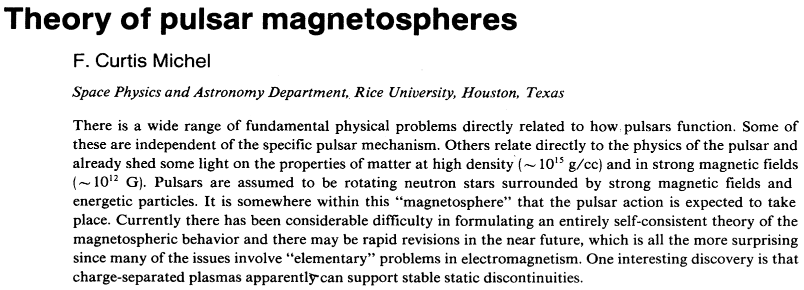
$$\frac{1}{2}F^{\mu\nu}F_{\mu\nu} = \boldsymbol{B}^2 - \boldsymbol{E}^2 < 0$$

collapse to **Kerr-Newman BH**

Rezzolla's talk

Bottom line

- A rotating magnet is charged and remain charged - a pulsar is charged

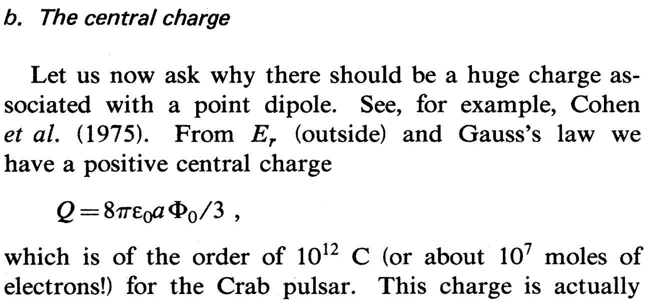


Theory of pulsar magnetospheres

F. Curtis Michel

Space Physics and Astronomy Department, Rice University, Houston, Texas

There is a wide range of fundamental physical problems directly related to how pulsars function. Some of these are independent of the specific pulsar mechanism. Others relate directly to the physics of the pulsar and already shed some light on the properties of matter at high density ($\sim 10^{15}$ g/cc) and in strong magnetic fields ($\sim 10^{12}$ G). Pulsars are assumed to be rotating neutron stars surrounded by strong magnetic fields and energetic particles. It is somewhere within this "magnetosphere" that the pulsar action is expected to take place. Currently there has been considerable difficulty in formulating an entirely self-consistent theory of the magnetospheric behavior and there may be rapid revisions in the near future, which is all the more surprising since many of the issues involve "elementary" problems in electromagnetism. One interesting discovery is that charge-separated plasmas apparently can support stable static discontinuities.



b. The central charge

Let us now ask why there should be a huge charge associated with a point dipole. See, for example, Cohen *et al.* (1975). From E_r (outside) and Gauss's law we have a positive central charge

$$Q = 8\pi\varepsilon_0 a \Phi_0/3 \ ,$$

which is of the order of 10^{12} C (or about 10^7 moles of electrons!) for the Crab pulsar. This charge is actually

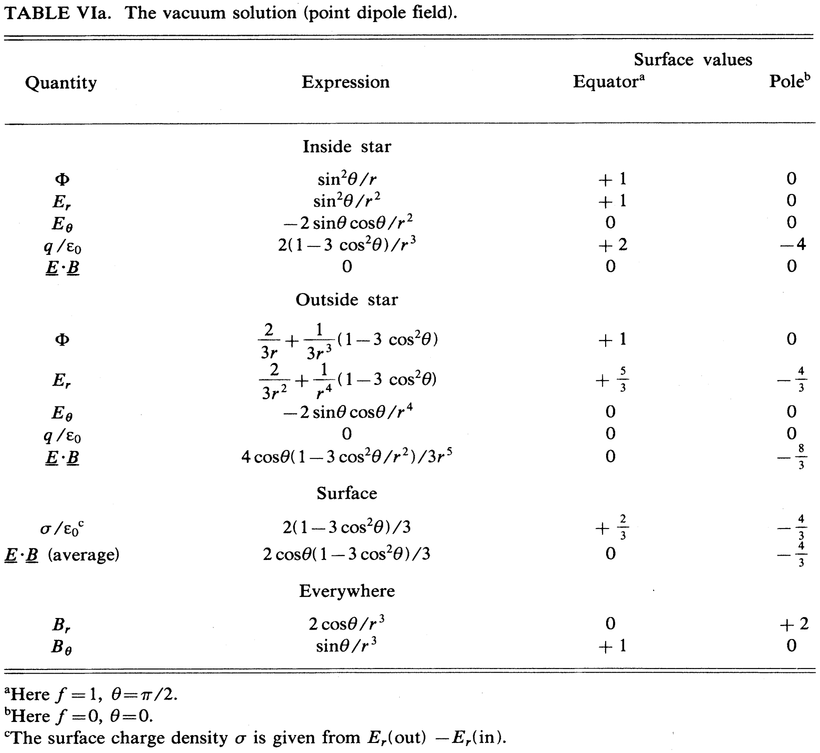


TABLE VIa. The vacuum solution (point dipole field).

Quantity	Expression	Surface values Equator[a]	Pole[b]
	Inside star		
Φ	$\sin^2\theta/r$	$+1$	0
E_r	$\sin^2\theta/r^2$	$+1$	0
E_θ	$-2\sin\theta\cos\theta/r^2$	0	0
q/ε_0	$2(1-3\cos^2\theta)/r^3$	$+2$	-4
$\underline{E}\cdot\underline{B}$	0	0	0
	Outside star		
Φ	$\frac{2}{3r}+\frac{1}{3r^3}(1-3\cos^2\theta)$	$+1$	0
E_r	$\frac{2}{3r^2}+\frac{1}{r^4}(1-3\cos^2\theta)$	$+\frac{5}{3}$	$-\frac{4}{3}$
E_θ	$-2\sin\theta\cos\theta/r^4$	0	0
q/ε_0	0	0	0
$\underline{E}\cdot\underline{B}$	$4\cos\theta(1-3\cos^2\theta/r^2)/3r^5$	0	$-\frac{8}{3}$
	Surface		
σ/ε_0[c]	$2(1-3\cos^2\theta)/3$	$+\frac{2}{3}$	$-\frac{4}{3}$
$\underline{E}\cdot\underline{B}$ (average)	$2\cos\theta(1-3\cos^2\theta)/3$	0	$-\frac{4}{3}$
	Everywhere		
B_r	$2\cos\theta/r^3$	0	$+2$
B_θ	$\sin\theta/r^3$	$+1$	0

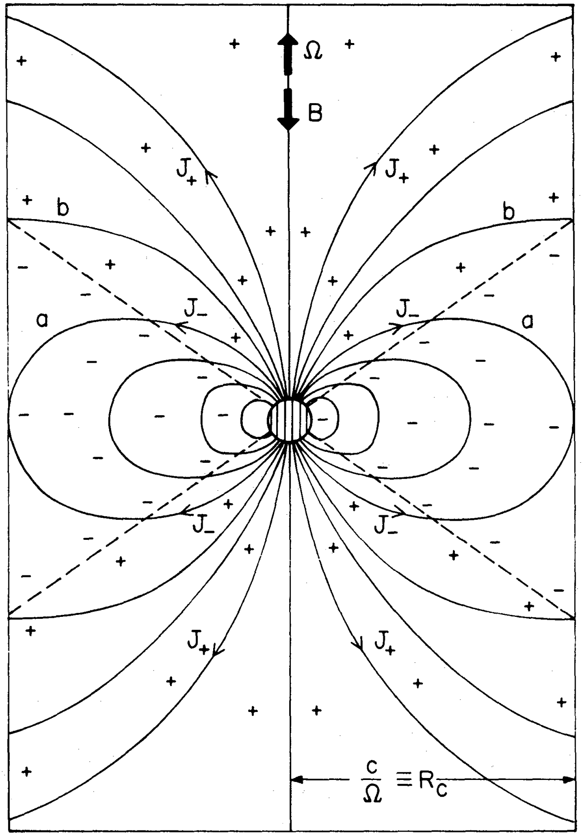
[a] Here $f=1$, $\theta=\pi/2$.
[b] Here $f=0$, $\theta=0$.
[c] The surface charge density σ is given from $E_r(\text{out}) - E_r(\text{in})$.

Charged pulsars

THE ASTROPHYSICAL JOURNAL, **196**:51–72, 1975 February 15

THEORY OF PULSARS: POLAR GAPS, SPARKS, AND COHERENT MICROWAVE RADIATION

M. A. RUDERMAN*
AND
P. G. SUTHERLAND†



Goldreich and Julian (1969) elucidated the characteristics of the corotating magnetosphere surrounding an axisymmetric neutron star with aligned magnetic moment and rotation axes. They assumed that (*a*) the neutron star can supply the necessary negative charges (electrons) and positive charges (ions and positrons) required to fill and maintain the magnetosphere with $\boldsymbol{E}\cdot\boldsymbol{B} \sim 0$, and (*b*) the currents in the magnetosphere are negligible. They showed that the magnetosphere would then corotate with a local charge density

$$\rho_e = -\frac{\boldsymbol{\Omega}\cdot\boldsymbol{B}}{2\pi c}\frac{1}{1 - \Omega^2 r_\perp{}^2/c^2} \qquad (1)$$

The magnetic fields inside/outside a NS is co-rotating with the NS, so charged

When a NS collapses to a BH, the BH is a spinning, charged BH - Kerr Newman

How long does a Kerr-Newman BH sustain?

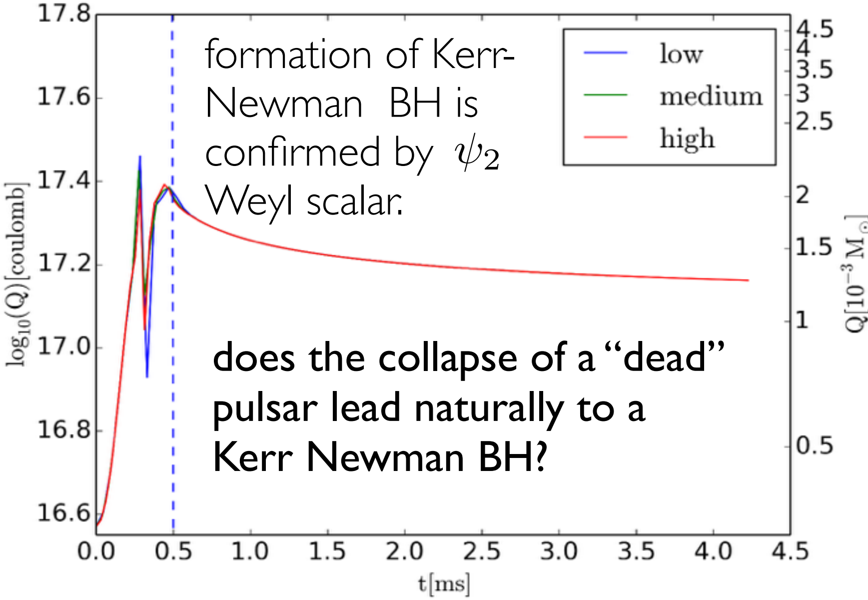
I don’t know. More work is needed.

But not easy to neutralize because of the pulsar-like magnetosphere activities.

If the BHs merge before discharged, then an FRB or even a GRB will be produced

$$Q \sim \frac{\Omega_* \mu_*}{3c},$$

$$\mu_* \Omega_* \sim (9 \times 10^{36}\,\mathrm{G\,cm^3\,s^{-1}}) \left(\frac{M}{10\,M_\odot}\right) \hat{q}_{-5}.$$



formation of Kerr-Newman BH is confirmed by ψ_2 Weyl scalar.

does the collapse of a “dead” pulsar lead naturally to a Kerr Newman BH?

Rezzolla’s talk

FRB

(Zhang, ApJL, 827, L31)

Frequency:

$$\nu = \frac{3}{4\pi}\frac{c}{\rho}\gamma_e^3 \simeq (0.9\times10^9\ \mathrm{Hz})\ \hat{a}^{-1}\left(\frac{M}{10M_\odot}\right)^{-1}\gamma_{e,2}^3,$$

Duration:

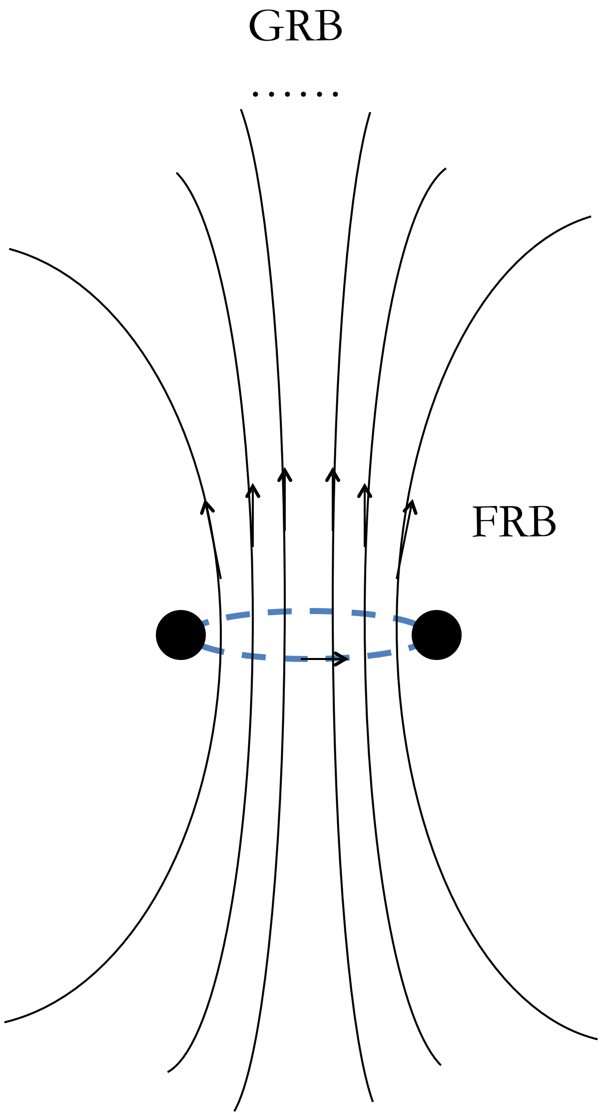
$$\tau_{1.5} \lesssim \frac{P}{|\dot{P}|} = \frac{20}{3}\frac{GM}{c^3}\hat{a}^4 \simeq (1.7\ \mathrm{ms})\left(\frac{M}{10M_\odot}\right)\left(\frac{\hat{a}}{1.5}\right)^4,$$

$$L_w \simeq \frac{2\ddot{\mu}^2}{3c^3} \simeq \frac{49}{120000}\frac{c^5}{G}\hat{q}^2\hat{a}^{-15} \simeq (1.5\times10^{48}\ \mathrm{erg\ s^{-1}})\hat{q}_{-4}^2\hat{a}^{-15},$$

To produce an FRB with L ~ 10^{41} erg/s, one needs:

$$\hat{q} > 3\times10^{-8}\ \text{ for }\ \hat{a} = 1$$

$$\hat{q} > 2\times10^{-10}\ \text{ for }\ \hat{a} = 0.5$$



GRB

(Zhang, ApJL, 827, L31)

$$t_1 = \frac{R_1}{2\Gamma_1^2 c}, \quad t_2 = \frac{R_2}{2\Gamma_2^2 c}.$$

- The delay time between the onset of the GRB and the final GW chirp signal is

$$\Delta t_{\rm GRB} \sim (t_1 - \tau_{1.5})(1+z). \tag{19}$$

- The rising time scale of the GRB is defined by

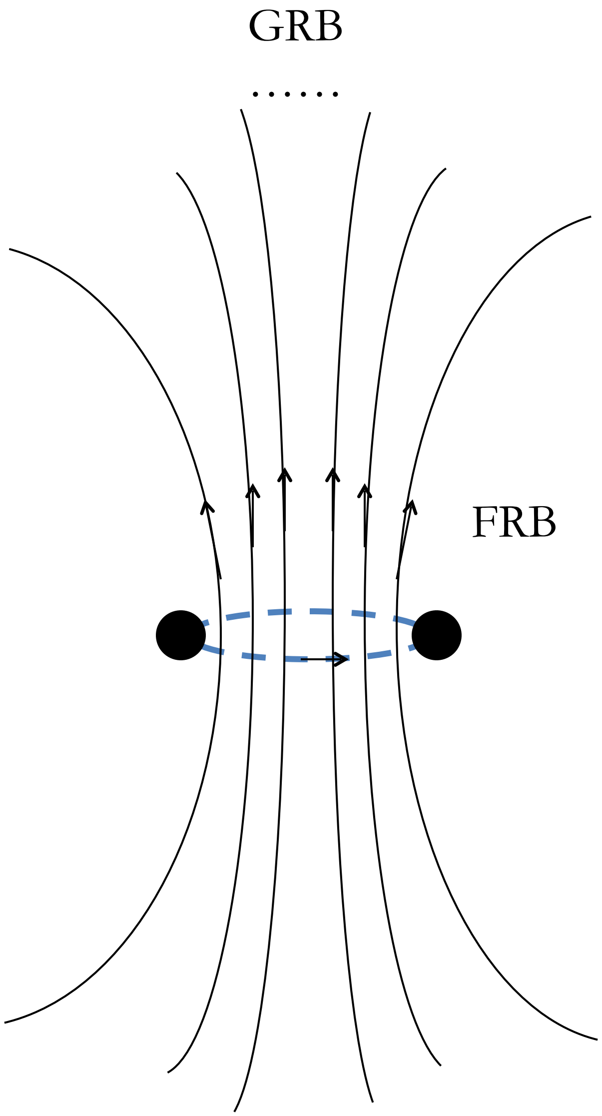
$$t_r \sim \max(\tau_{1.5}, t_2 - t_1)(1+z). \tag{20}$$

- The decay time scale of the GRB is defined by

$$t_d \sim t_2(1+z). \tag{21}$$

- The total duration of the GRB is

$$\tau = t_r + t_d. \tag{22}$$



Model parameters:

$$\hat{q}_{-4} \simeq 3.5 \hat{a}^{15/2} \eta_\gamma^{-1/2} \simeq 0.02 \left(\frac{\hat{a}}{0.5}\right)^{15/2} \eta_\gamma^{-1/2},$$

$$R_1 \sim 2\Gamma_1^2 c t_{\rm GRB} = (2.4 \times 10^{14}\ {\rm cm}) \left(\frac{\Gamma_1}{100}\right)^2 \left(\frac{\Delta t_{\rm GRB}}{0.4\ {\rm s}}\right)$$

$$R_2 \sim 2\Gamma_2^2 c t_2 \sim 2\Gamma_2^2 c\tau = (6.0 \times 10^{14}\ {\rm cm}) \left(\frac{\Gamma_2}{100}\right)^2 \left(\frac{\tau}{1\ {\rm s}}\right)$$

BH-BH merger & FRB rate

- BH-BH merger event rate density (Abbott et al. 2016)

$$(9 - 240)\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

- FRB event rate density

$$\dot{\rho}_{\mathrm{FRB}} = \frac{365\dot{N}_{\mathrm{FRB}}}{(4\pi/3)D_z^3} \simeq (5.7 \times 10^3\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}) \times \left(\frac{D_z}{3.4\ \mathrm{Gpc}}\right)^{-3} \left(\frac{\dot{N}_{\mathrm{FRB}}}{2500}\right),$$

Charged compact star mergers

- Since NSs do carry a magnetosphere, they should be “charged” also
- The theory applies to NS-NS and NS-BH mergers as well – a precursor of NS-NS and NS-BH mergers; FRBs could be associated with all compact star mergers!

Summary:
Possible EM counterparts of GW events

- **Short GRBs** (gamma-rays) **and afterglows** (multi-wavelength)
  - NS-NS mergers, BH-NS mergers
  - BH-BH mergers?
- **Kilonova/Macronova/Mergernova** (optical/IR) and **afterglows** (multi-wavelength, strongest in radio)
  - BH-NS mergers, NS-NS mergers
  - Enhanced in some NS-NS mergers with a supra-massive/ stable NS
- **Early X-ray emission** (X-rays)
  - NS-NS mergers with a supra-massive/stable NS
- **Fast radio bursts** (radio)
  - NS-NS mergers with a supra-massive NS
  - Mergers of charged BH-BH systems (also NS-NS, BH-NS?)