北京师范大学天文系
Astronomy Department, Beijing Normal University

Constraints on Double Neutron Star Merger Product

He Gao（高鹤）

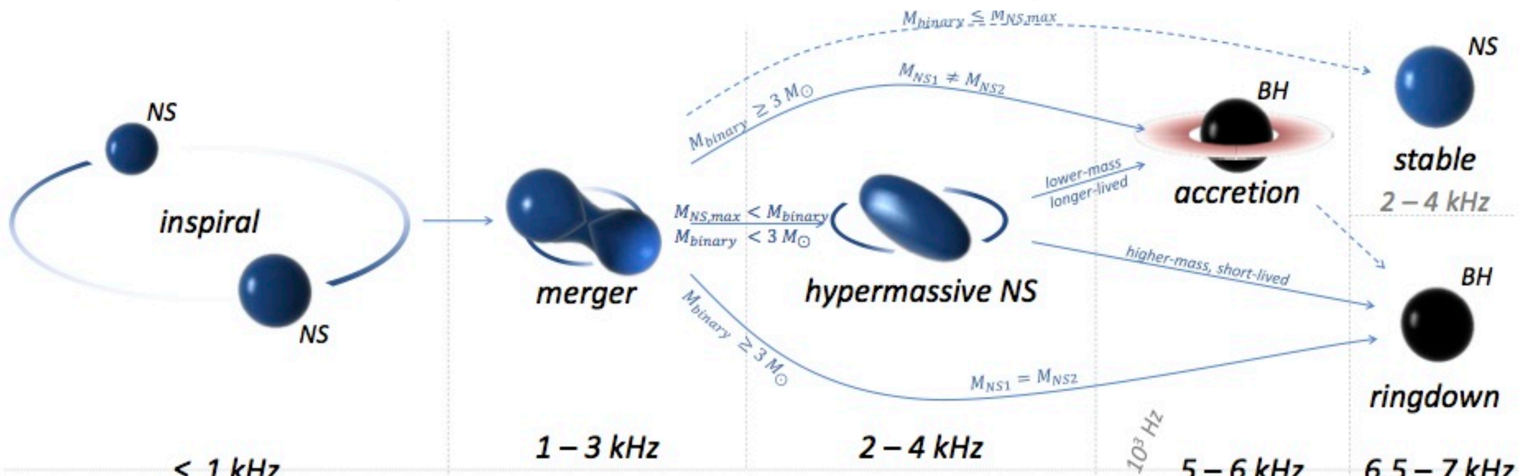
Department of Astronomy, Beijing Normal University
北京师范大学一天文系

Collaborators: **Bing Zhang, Zi-Gao Dai, Xue-Feng Wu, Yun-Wei Yu, Wei-Hua Lei, Hou-Jun Lv, Ang Li, Zhou-Jian Cao, Shunke Ai…**

2018-05-15 **@ Les Houches**

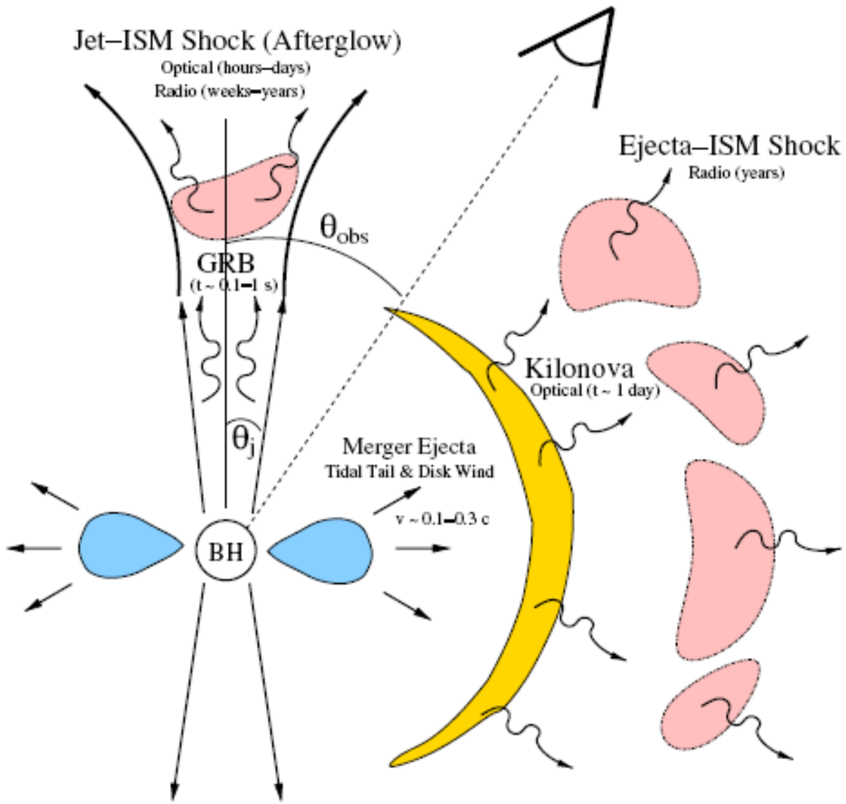
Central product from NS-NS mergers

- Immediate collapse into a black hole (BH);
- A temporal hyper-massive NS (supported by differential rotation) which survives 10–100 ms before collapsing into a BH;
- A supra-massive NS temporarily supported by rigid rotation, which collapses to a BH at a later time after the NS spins down;
- A stable NS (or strange quark star?).



Bartos+. 2013 CQGra.

EM signals for a BH as merger product



Metzger & Berger (2012)

Short GRB

Multi-wavelength afterglow

~hours, days

Li-Paczyński Nova (Macronova, Kilonova)

Li & Paczyński, 1998

Optical flare

~ days, weeks

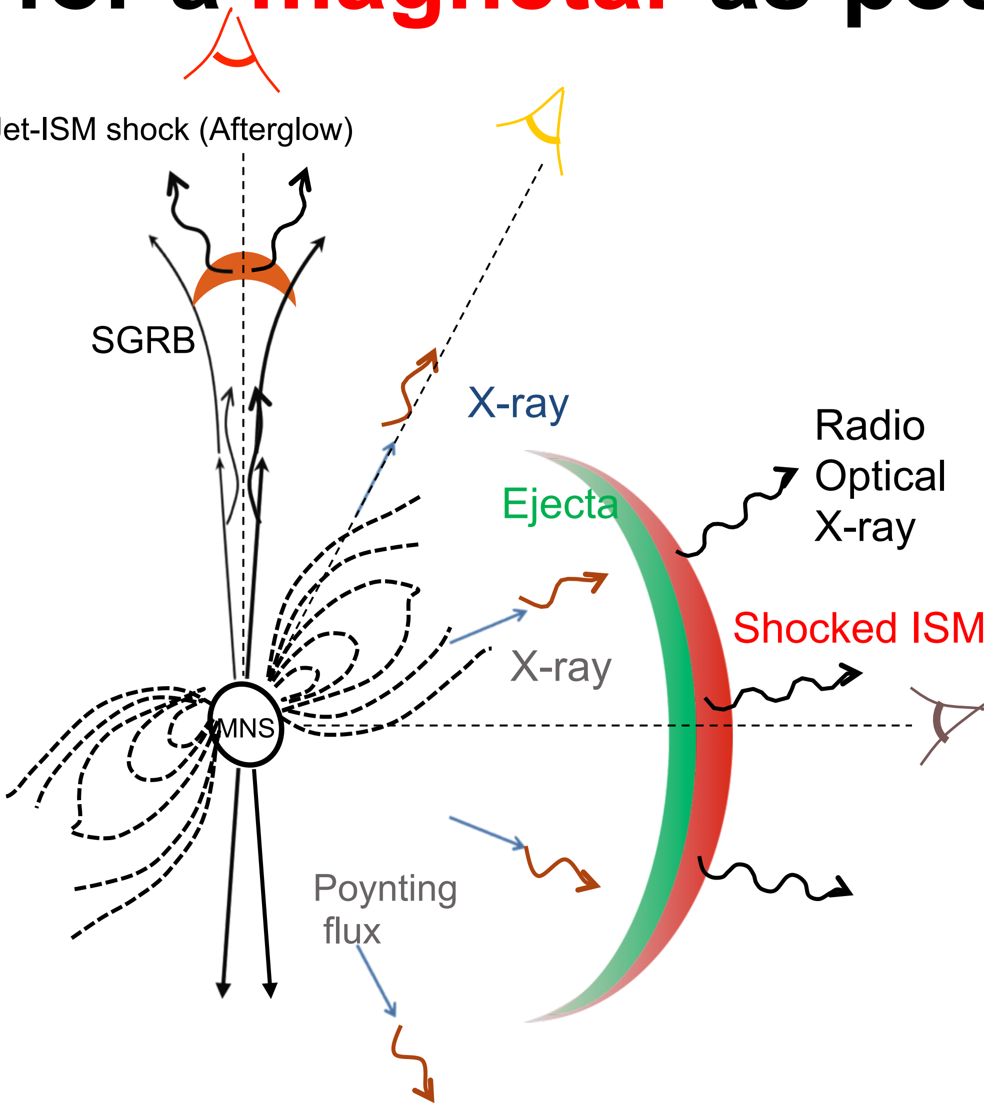
Ejecta-ISM interaction shock

Nakar & Piran, 2011

Radio

~years

EM signals for a magnetar as post-merger product



Gao+ 2013 ApJ

SGRB?

Late central engine activity

~Plateau & X-ray flare

Magnetic Dissipation

X-ray Afterglow

$\sim 10^{-8} \, erg \, s^{-1} \, cm^{-2}$

1000 ~10000 s

Zhang, 2013 ApJL

Shock breakout X-ray flash

$10^{-11} - 10^{-9} \, erg \, s^{-1} \, cm^{-2}$

1000 ~10000 s

Li & Yu, 2015 ApJ

Li-Paczyński Nova ➡

Merger-Nova

Yu+ 2013 ApJL

Ejecta-ISM shock with Energy Injection (EI)

Multi-band transient

~hours to even years

Gao+ 2013 ApJ, Wang & Dai 2013 ApJL

Central product from NS-NS mergers

? % {
- Immediate collapse into a black hole (BH);
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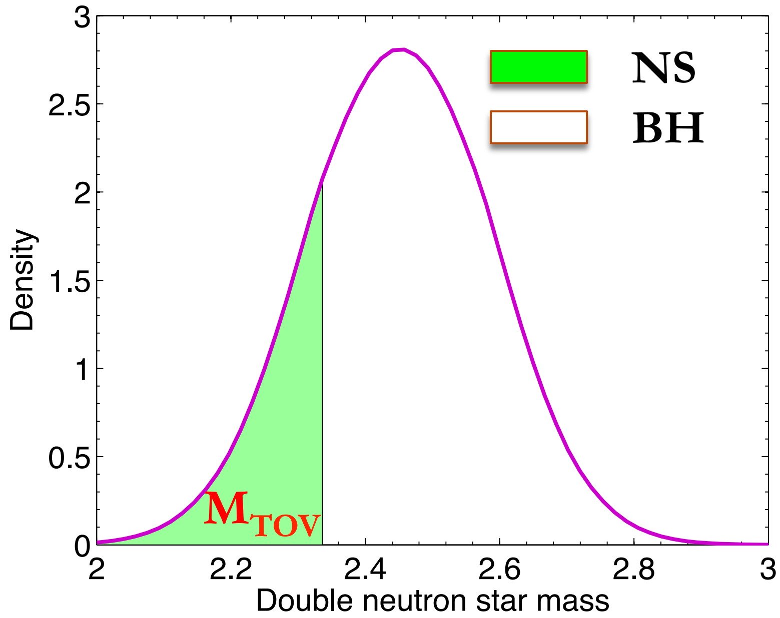
? % {
- A supra-massive NS temporarily supported by rigid rotation, which collapses to a BH at a later time after the NS spins down;
- A stable NS.



M_{TOV}: maximum gravitational mass for a nonrotating NS

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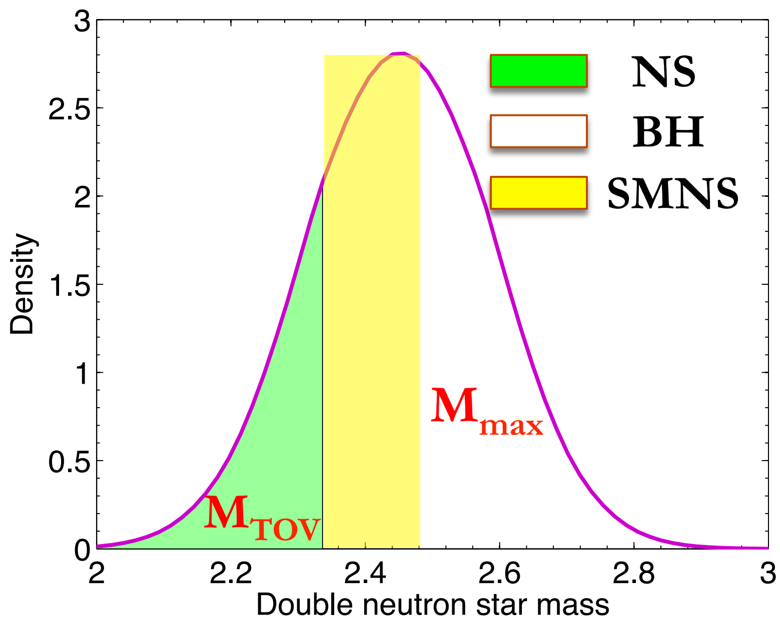

M_{TOV}: maximum gravitational mass for a nonrotating NS

M_{max}: maximum gravitational mass

$M_{max} \sim 1.2\ M_{TOV}$

Central product from NS-NS mergers

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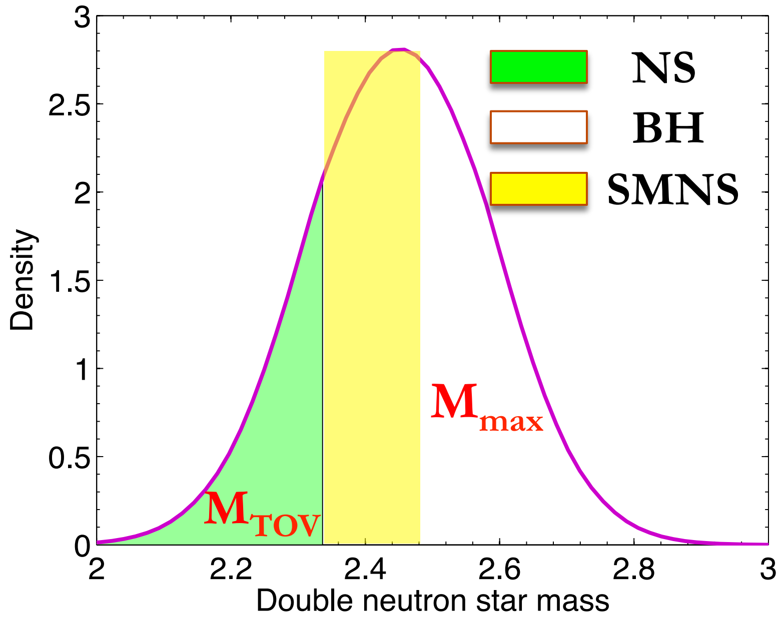


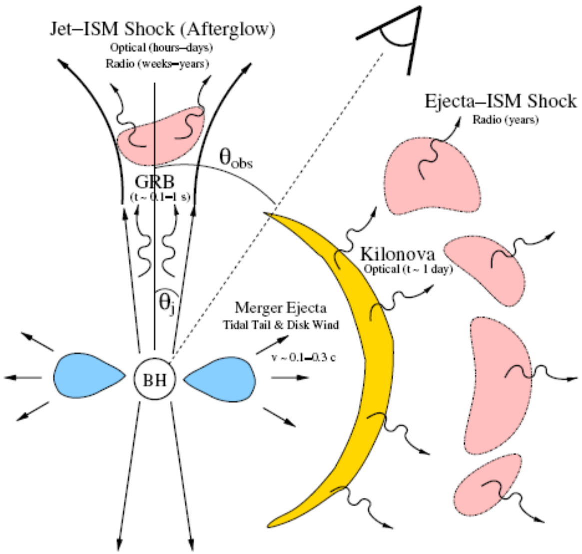
NS-NS total mass distribution?

NS equation of state?

NS or BH or SMNS fraction?

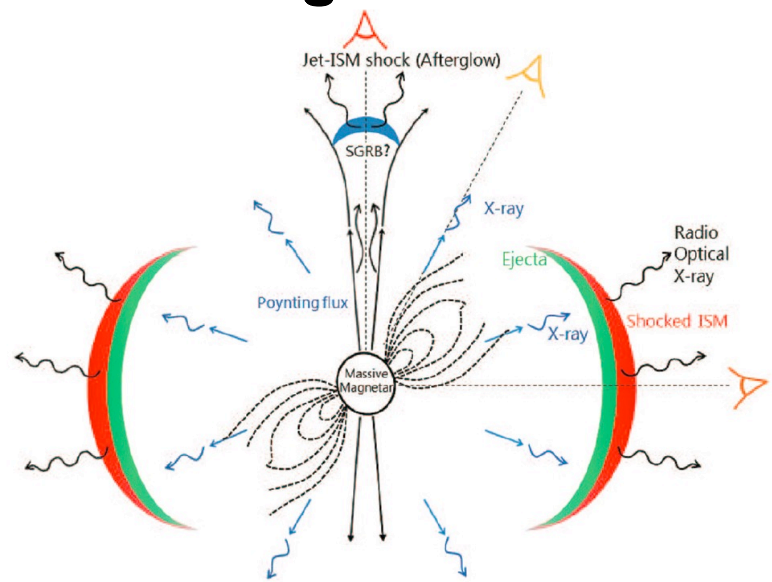
NS-NS EMC: BH vs Magnetar

BH



Metzger & Berger, 2012

Magnetar



Gao et al., 2013

Short GRB

Li-Paczyński Nova
(Kilonova, Macronova)

Long-lasting Radio Emission

Increased

Magnetic Dissipation X-ray Afterglow

Shock breakout X-ray flash

Enhanced

Short GRB + Internal Plateau

Kilonova → Merger-Nova

Radio→ Broad Band

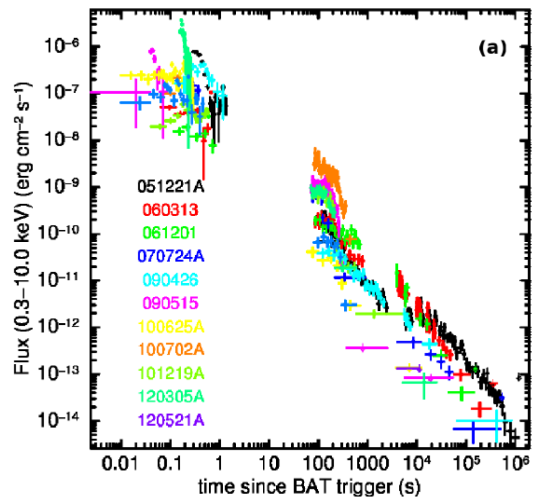
Constraints on NS-NS merger product from SGRB observations

- SGRBs are from NS-NS/BH mergers;
- Cosmological NS-NS systems have the same mass distribution as the observed Galactic system;
- Internal plateau marks the collapse of a magnetar to a BH.

Neutron Star – Neutron Star Binaries (mean = 1.325 $M_\odot$, weighted mean = 1.403 $M_\odot$)

J1829+2456	$1.338^{+0.002}_{-0.338}$	z (20)	J1829+2456 (c)	$1.256^{+0.346}_{-0.003}$	z (20)
J1811-1736	$1.608^{+0.066}_{-0.608}$	A (21)	J1811-1736 (c)	$0.941^{+0.787}_{-0.021}$	A (21)
J1906+07	$1.694^{+0.012}_{-0.694}$	B (22)	J1906+07 (c)	$0.912^{+0.710}_{-0.004}$	B (22)
J1518+4904	$0.72^{+0.51}_{-0.58}$	C (23)	J1518+4904 (c)	$2.00^{+0.58}_{-0.51}$	C (23)
1534+12	$1.3332^{+0.0010}_{-0.0010}$	K (24)	1534+12 (c)	$1.3452^{+0.0010}_{-0.0010}$	K (24)
1913+16	$1.4398^{+0.0002}_{-0.0002}$	q (25)	1913+16 (c)	$1.3886^{+0.0002}_{-0.0002}$	q (25)
2127+11C	$1.358^{+0.010}_{-0.010}$	x (26)	2127+11C (c)	$1.354^{+0.010}_{-0.010}$	x (26)
J0737-3039A	$1.3381^{+0.0007}_{-0.0007}$	i (27)	J0737-3039B	$1.2489^{+0.0007}_{-0.0007}$	i (27)
J1756-2251	$1.312^{+0.017}_{-0.017}$	J (28)	J1756-2251 (c)	$1.258^{+0.017}_{-0.017}$	J (28)

Lattimer & Prakash (2010)



Rowlinson et al. (2013)

Equation of State

EoS Parameterization

Lv et al., 2015

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

$M_{\max}$: maximum gravitational mass

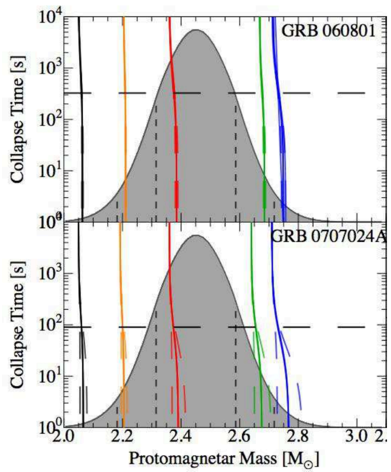
M_{TOV} : maximum gravitational mass for a nonrotating NS

P : spin period

Parameters of Various NS EOS Models

Parameters	SLy	APR	GM1	AB-N	AB-L
$M_{\rm TOV}\,(M_\odot)$	2.05	2.20	2.37	2.67	2.71
R (km)	9.99	10.0	12.05	12.9	13.7
$I\,(10^{45}$ g cm$^2)$	1.91	2.13	3.33	4.30	4.70
$\hat{\alpha}\,(10^{-10}\,s^{-\hat{\beta}})$	1.60	0.303	1.58	0.112	2.92
$\hat{\beta}$	−2.75	−2.95	−2.84	−3.22	−2.82

From the general-relativistic NS equilibrium code RNS



Lasky et al., 2014

Equations of State

Model	Interactions	Many-Body Theory
A.	Reid soft core—adapted to nuclear matter	Variational principle applied to correlation function
B.	Same as A; arbitrary reduction for hyperon-hyperon attraction	Same as A
C.	Modified Reid soft core; noninteger n in equation (3.1)	Constrained variational principle
D.	Same as C; more nearly realistic adaptation to hyperon matter	Same
E.	Reid soft core; modified hyperon interactions based on quark theory	Reaction matrix
F.	Thomas Fermi model	Brueckner G-matrix
G.	Modified Reid soft core. Localization via nonrelativistic harmonic oscillators.	T-matrix; includes spin dependence
H.	None	Fermi statistics
I.	Levinger-Simmons velocity-dependent V_α	Hartree-Fock approximation with two-body potential
L.	Nuclear attraction due to scalar exchange	Mean field approximation for scalar; variational method
M.	Nuclear attraction due to pion exchange tensor interactions	Constrained variational method
N.	Relativistic mean field scalar plus vector exchange fitted to nuclear matter	Mean field approximation (relativistic)
O.	Nonperturbative, phenomenological approximation to relativistic meson exchange	Relativistic finite density Green's functions

Arnett & Bowers, 1977

SGRB sample

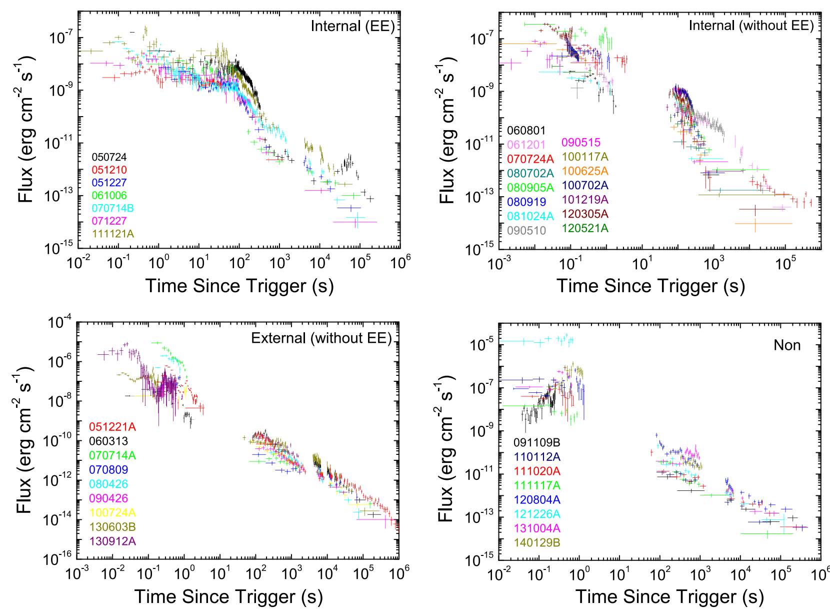
2005/01-2015/10

- 10 years Swift: 96 SGRBs
- 21 (22%) with "internal plateaus",

  9 (10%) with "external plateaus"

Lv+ 2015, ApJ

We extrapolate the BAT (15—150KeV) data to the XRT band (0.3 — 10 KeV) by assuming a single power-law spectrum, and then perform a temporal fit to the combined light curve with a smooth broken power law in the rest frame to identify a possible plateau (defined as a temporal segment with decay slope smaller than 0.5). A plateau followed by a decay index steeper than 3 as our "internal plateau" sample, otherwise it is "external plateau".



Constraints on NS-NS merger product from SGRB observations

Gao+ 2016, PRD

1） Mass distribution of Galactic NS-NS systems
2） 5 EOS with a range of the maximum masses
3） SGRB fraction with "internal plateau"

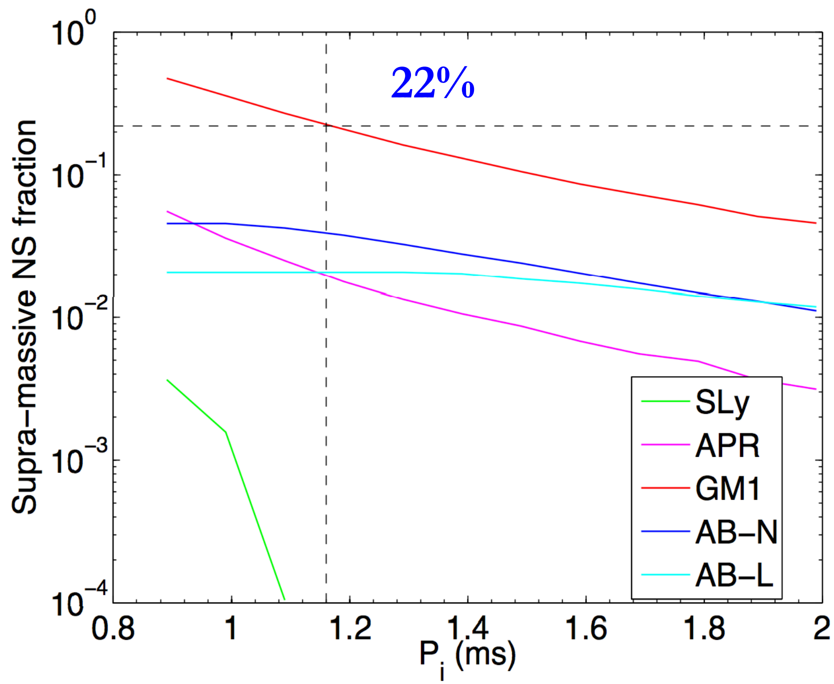
Critical period

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

M_s: gravitational mass of the merger remnant

$M_s < M_{TOV}$ Stable NS 30%

$M_s > M_{TOV}$
- $P_i > P_c$ BH 40%
- $P_i < P_c$ NS->BH 30%



$$P_i \leq 1.2ms$$

$$GM1: M_{max} = 2.37 M_{\odot}(1 + 1.58 \times 10^{-10} P^{-2.84})$$

Constraints on the Magnetar Properties

Gao et al., 2016 PRD, 93, 044065

- Initial Spin？
- How strong of the Magnetic field？
- Spin down mechanism?
  - GW dominate or EM dominate?

Constraints on Magnetic field and Ellipticity

Theoretical results

Dipole radiation luminosity

$$L_c = \frac{B_p^2 R^6 \Omega_c^4}{6c^3}$$

X-ray luminosity

$$L_b = \eta L_c$$

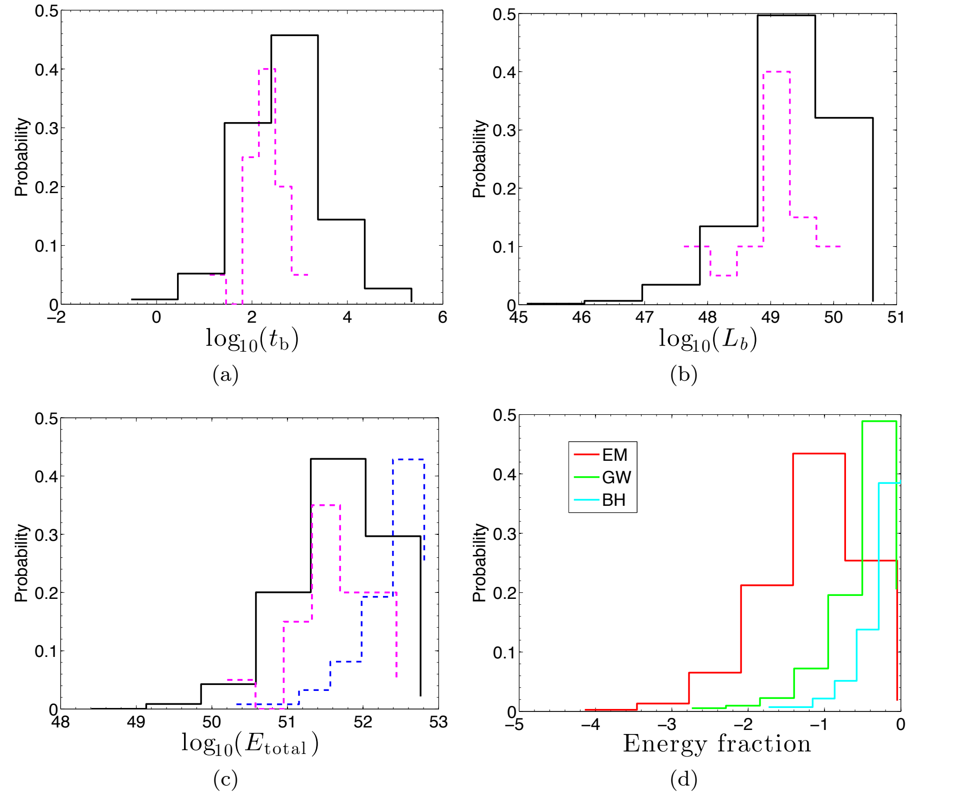
η: X-ray radiation efficiency

EM/GW radiation ratio

$$\frac{\dot{E}_{EM}}{\dot{E}_{GW}} = \frac{\int_{\Omega_i}^{\Omega_c} b\Omega^4 / (a\Omega^6)\, d\Omega}{\int_{\Omega_i}^{\Omega_c} d\Omega} = \frac{b}{a\Omega_i\Omega_c}$$

EM channel total energy

$$E_{EM} \simeq \frac{Ib(\Omega_i^2 - \Omega_c^2)}{2(a\Omega_i\Omega_c + b)}$$



Observations

"Internal plateau sample", plateau ending time(a) as the collapsing time, plateau lumniosity(b) as the X-ray luminosity, Isotropic energy(c) as the EM channel total energy。

Summary of the results

Gao+, 2016 PRD

Basic Assumption

- Part of (or all) SGRBs are from NS-NS mergers
- Cosmological NS-NS systems have the same mass distribution as the observed Galactic system
- Internal plateau marks the collapse of a magnetar to a BH.

Conclusion

- Equation of State $M_{\max} = 2.37\,M_{\odot}(1 + 1.58\times10^{-10}P^{-2.84})$
- NS-NS merger product:40% BH，30% stable NS，30% NS->BH
- Initial spin period of the magnetar is around 1ms；
- High magnetic field：10^{15} G
- High X-ray radiation efficiency，>40%
- Large ellipticity, GW radiation dominates spin-down

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Magnetic-distortion-induced Ellipticity

Bonazzola & Gourgoulhon 1996b; Haskell et al. 2008; Mastrano et al. 2011 …

- Magnetic pressure could distort the star, where the induced ellipticity depends on the strength and the configuration of the magnetic fields (including the inclination angle and the toroidal-to-poloidal ratio)

Magnetic-distortion-induced Ellipticity is proportional to B^2

$$\epsilon = \beta \bar{B}^2$$

Average B

$$\bar{B}^2 = \frac{1}{V}\int \mathbf{B}^2 dV$$

Contains the information of the Magnetic field configurations.

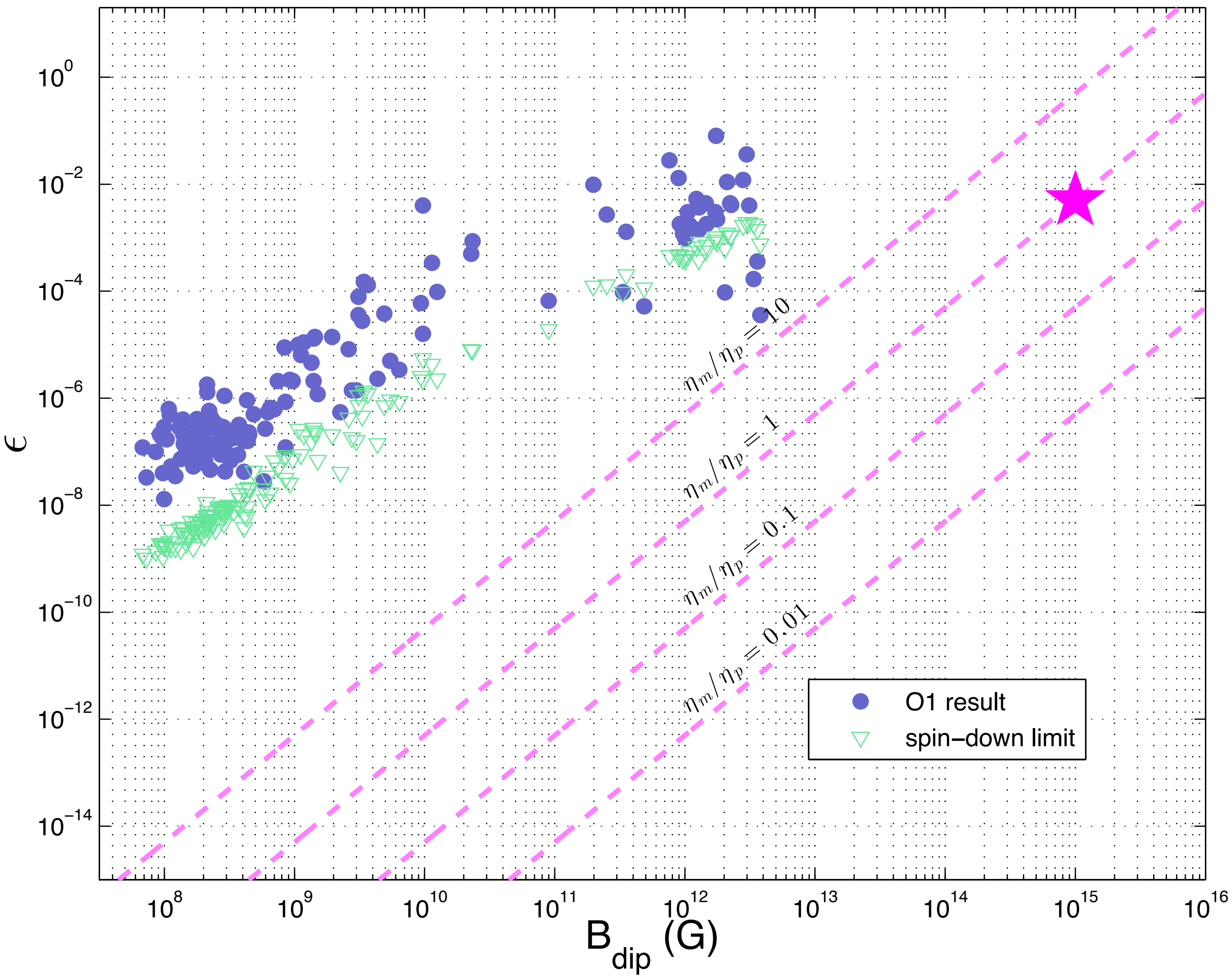
Haskell et al. 2008

Observation

$$B_{\rm dip} = \eta \bar{B}$$

η=0, Purely Toroidal
η=1, Purely Poloidal

Comparing Magnetar Ellipticity with LIGO Results



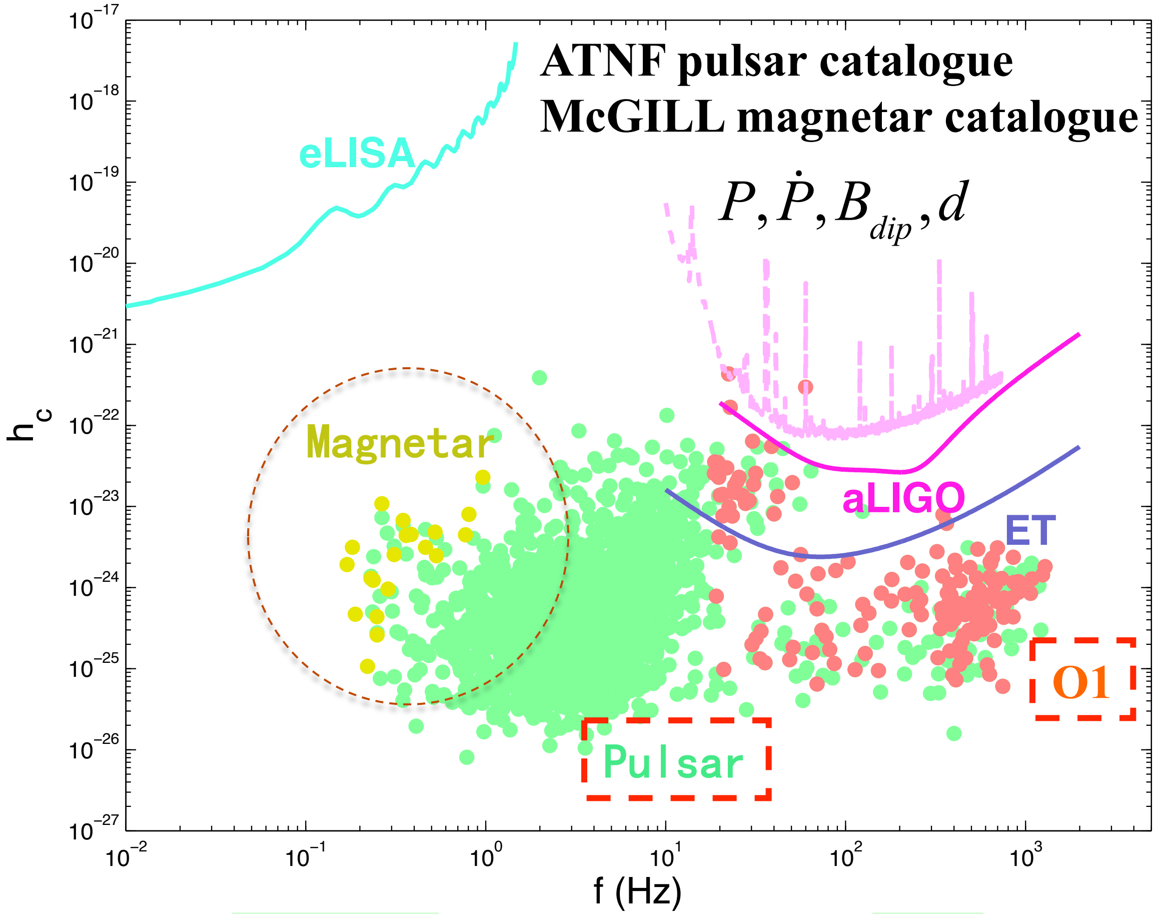
$$\epsilon_p = 5 \times 10^{-9} \frac{\epsilon_m}{0.005} \left(\frac{\eta_m}{\eta_p}\right)^2 \left(\frac{B_{\rm dip,p,12}}{B_{\rm dip,m,15}}\right)^2$$

Using the ellipticity of SGRB magnetars as calibration to estimate the ellipticity and GW strain of Galactic pulsars and magnetars

The results are consistent with the null detection results of Galactic pulsars and magnetars with the aLIGO O1

Gao, Cao , & Zhang, 2017, ApJ

Detectability of Known Pulsars and Magnetars



All **known pulsars** and **magnetars**;

The **GW signals** from pulsars and magnetars are **not detectable** for the aLIGO and the eLISA.

aLIGO

$$S_n(f) = S_0\left[x^{-4.14} - 5x^{-2} + \frac{111(1-x^2+x^4/2)}{1+x^2/2}\right]$$

ET

$$S_n(f) = S_0\left[2.39\times10^{-27}x^{-15.67} + 0.349x^{-2.145} + 1.76x^{-0.12} + 0.409x^{1.1}\right]^2$$

Gao, Cao , & Zhang, 2017, ApJ

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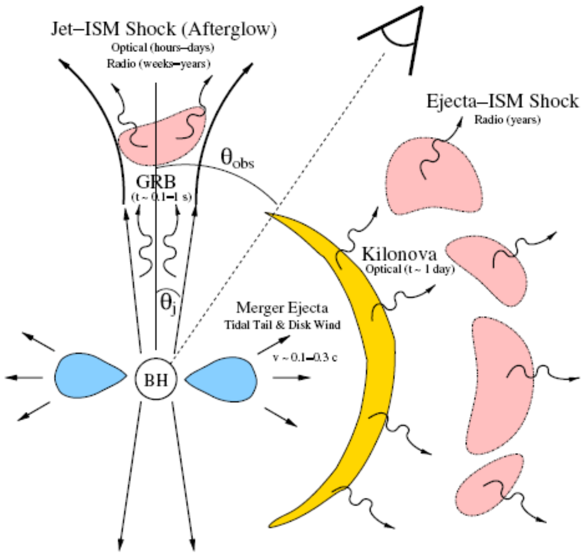
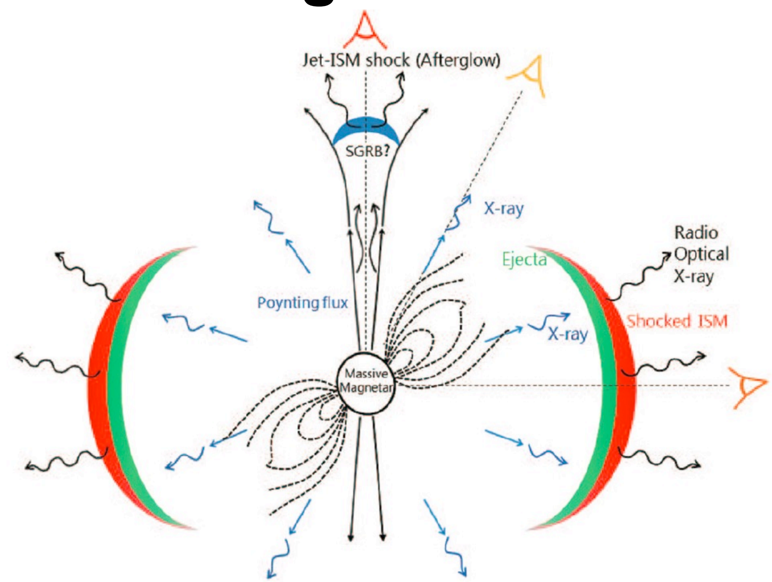
NS-NS EMC: BH vs Magnetar

BH



Metzger & Berger, 2012

Magnetar



Gao et al., 2013

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Shock breakout X-ray flash

Enhanced

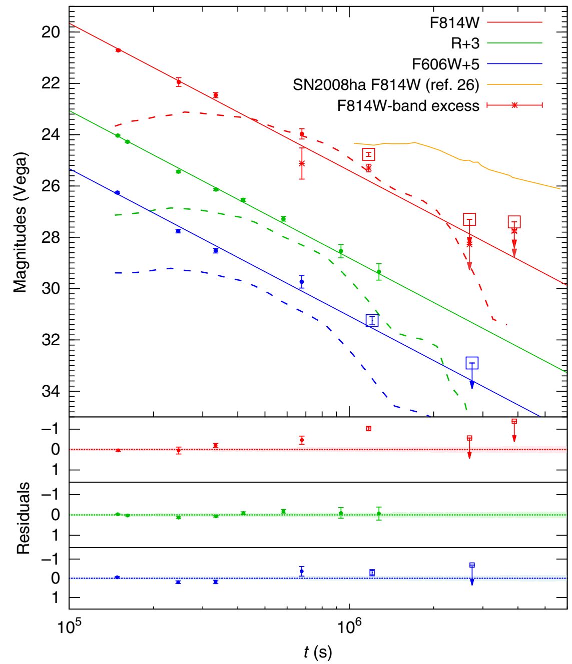
Short GRB + Internal Plateau

Kilonova → Merger-Nova

Radio→ Broad Band

r-process Merger-nova Candidate

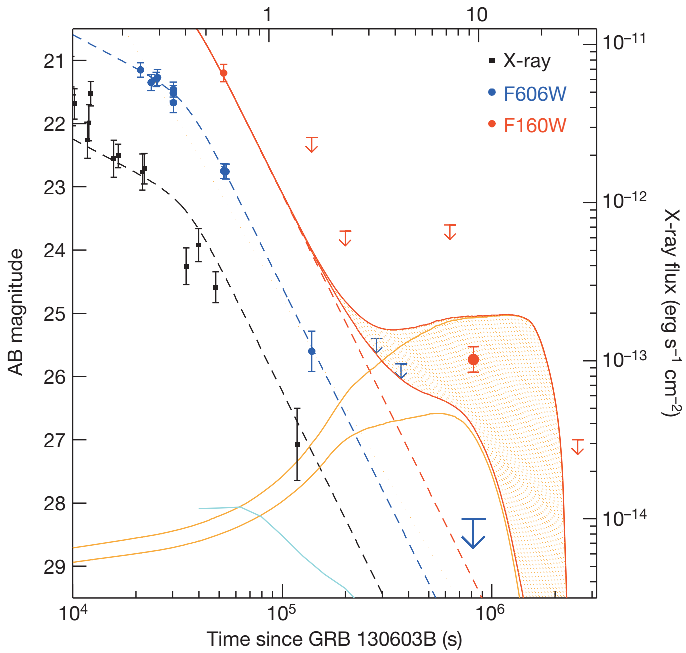
GRB060614



Tanvir et al. Nature 2013

Yang et al. 2015, NatCo

Jin et al. 2016, NatCo



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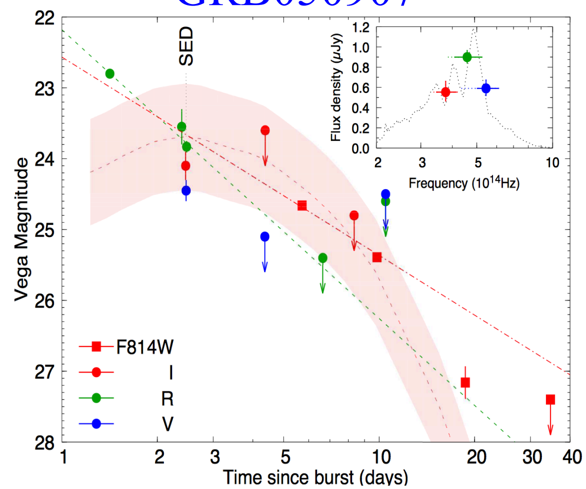
GRB050907



Criteria

All nearby short GRBs have been explored.

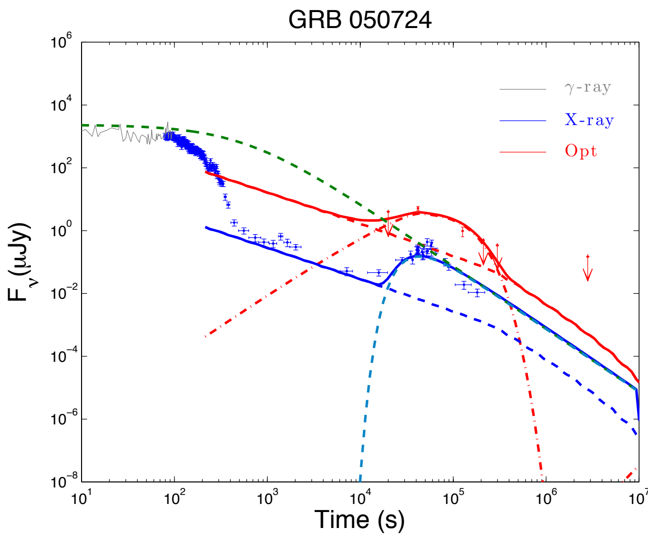
With late time optical/IR observation.

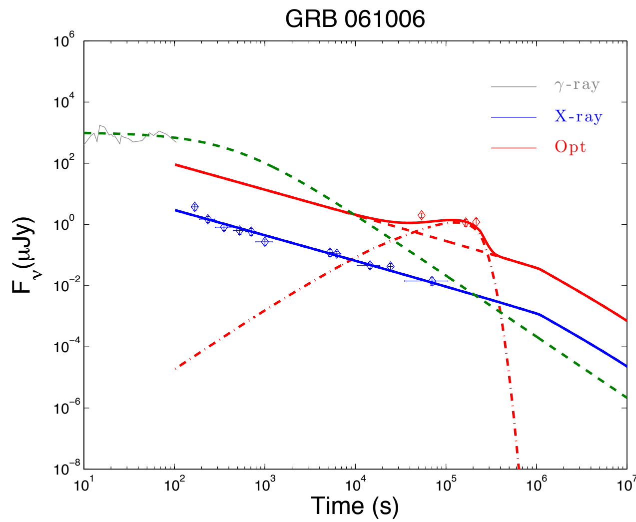
Deviation from afterglow model.

Magnetar Merger-nova Candidate

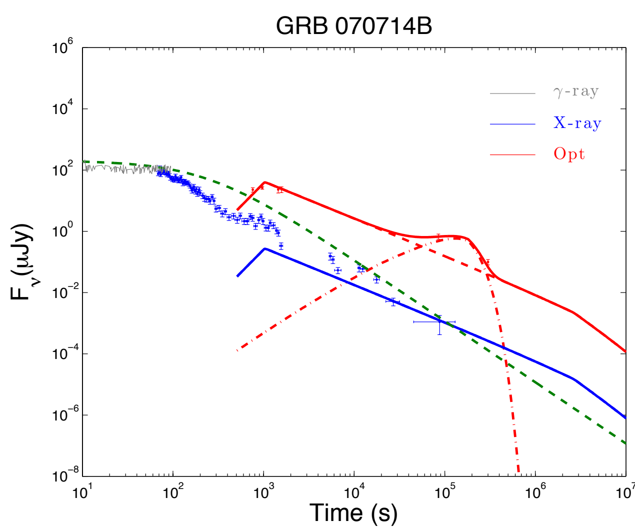
Gao et al. , 2015, ApJ, 807, 163

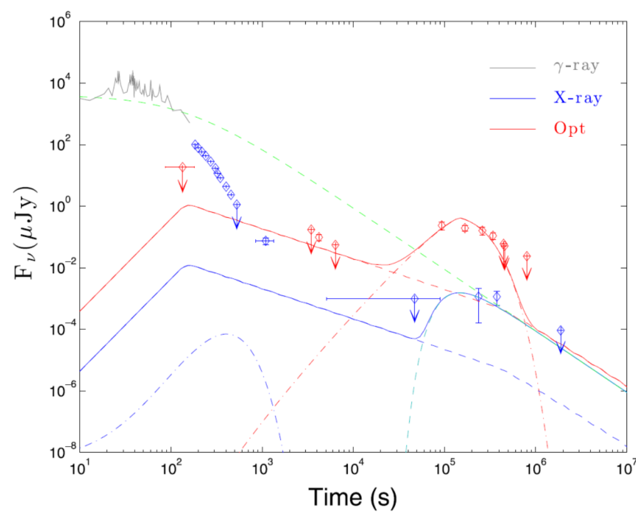
Gao et al. , 2017, ApJ, 837,50





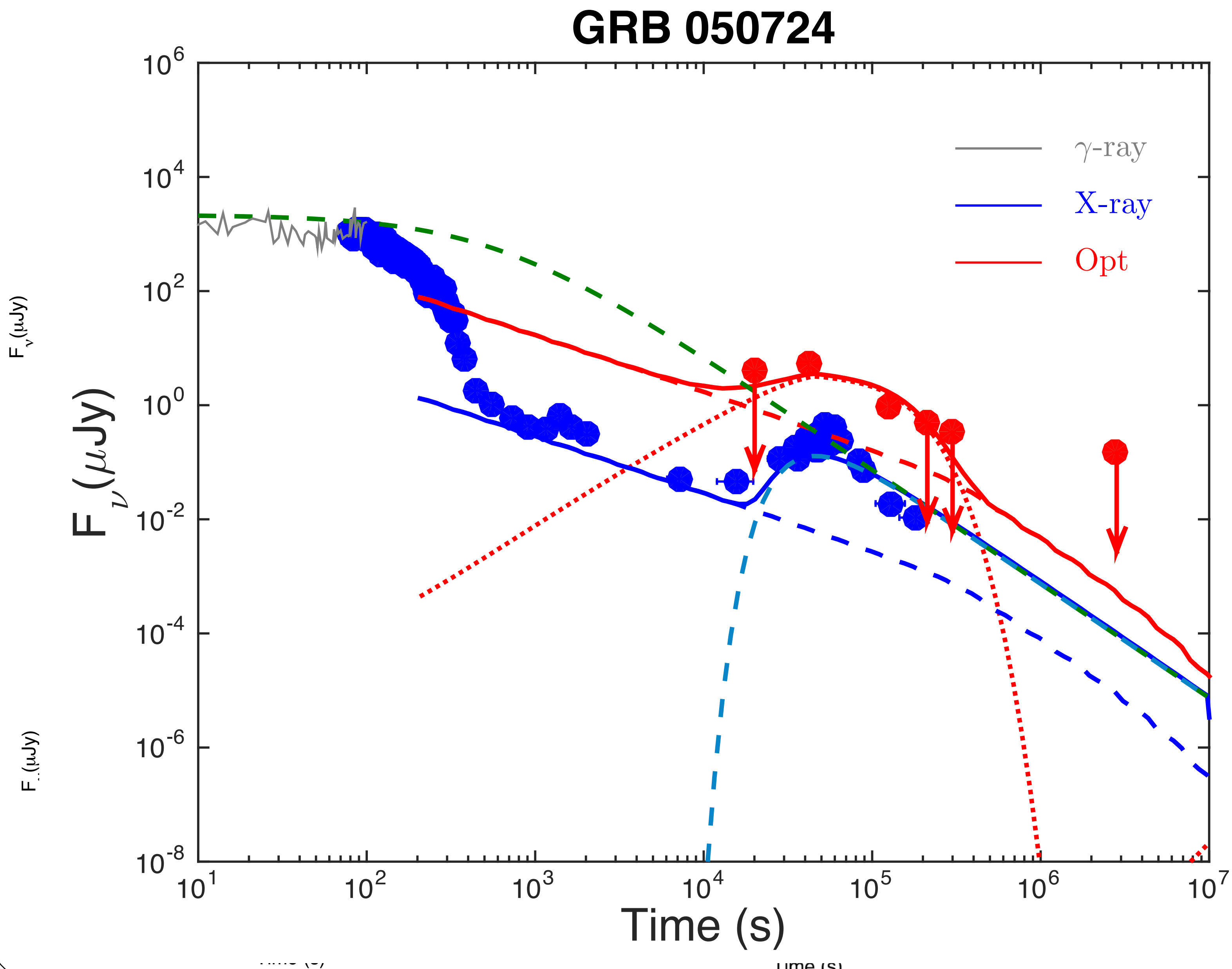
SGRBs with extended emission or internal plateau, which may signify the presence of magnetars as the central engine.





With standard parameter values, the magnetar remnant scenario could well interpret the multi-band data of three bursts, including the extended emission and their late chromatic features in the optical and X-ray data.

Magnetar Merger-nova Candidate



ApJ, 807, 163

ApJ, 837,50

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Merger-nova：r—process or Magnetar

Gao et al. , 2017 ApJ, 837, 50

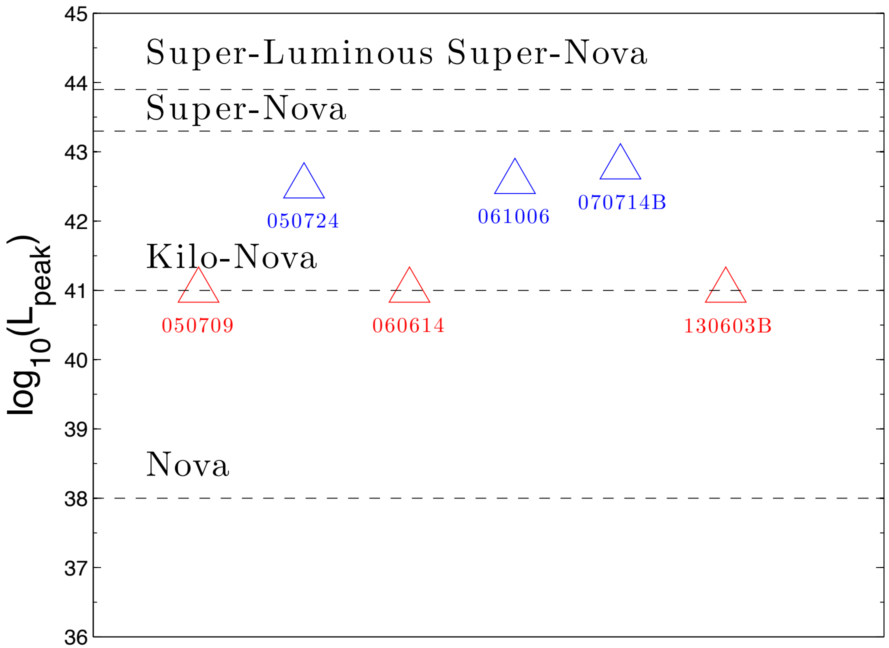


FIG. 2.— Peak luminosity for all claimed "kilo-novae" and magnetar-powered merger-novae.

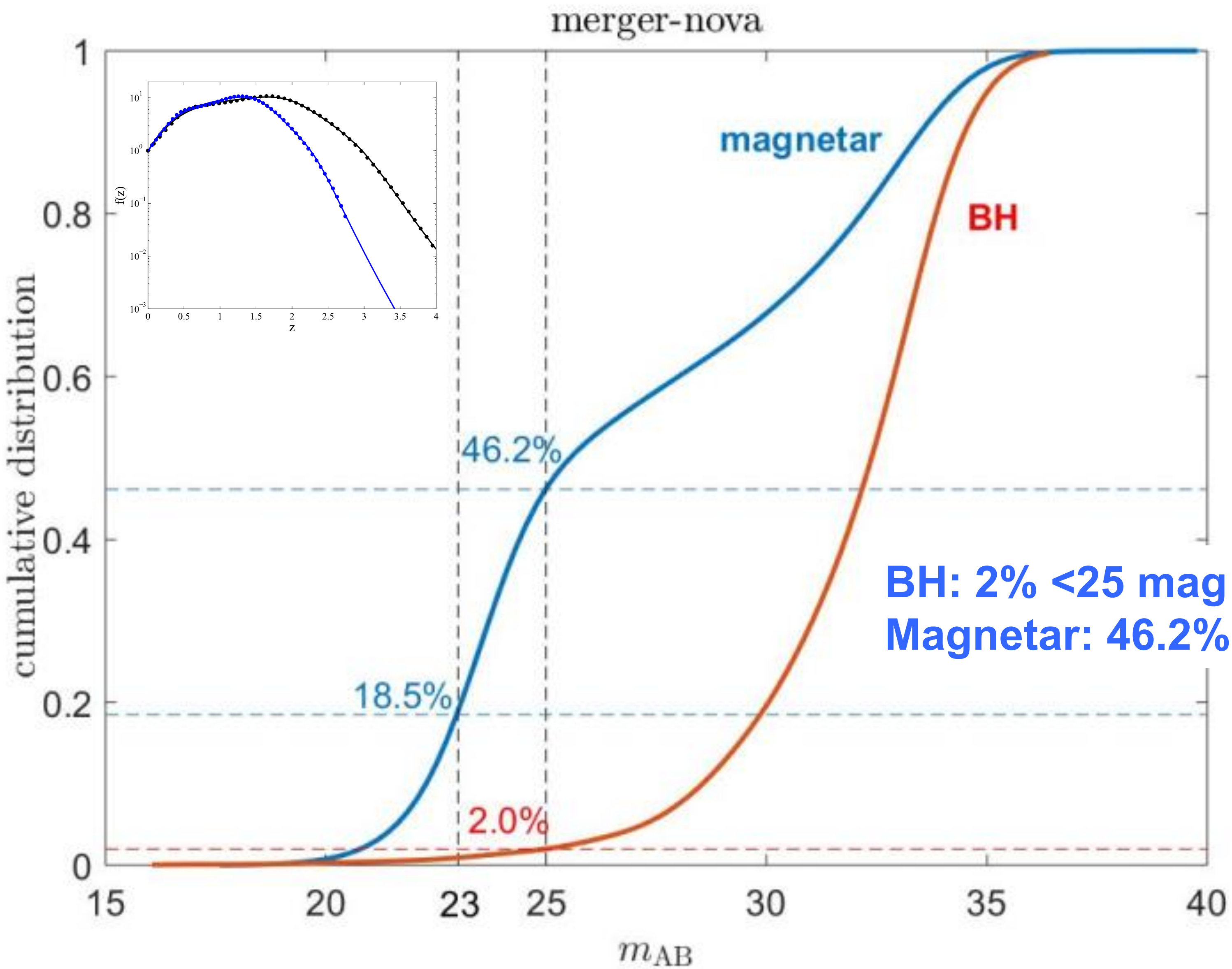
Taking into account GRB 080503, we now have 4 candidates of magnetar-powered merger-nova.

GRB 080503 and GRB 050724 indicating a stable NS; GRB 070714B and GRB 061006, indicating a supra-massive NS.

3 candidates of r-process powered merger-nova have been claimed. The ratio of BH, stable NS and supra-massive NS is roughly 1:1:1, which is consistent with previous results.

Magnetar-powered merger-novae are systematically brighter.
We propose to call r-process powered merger-nova.

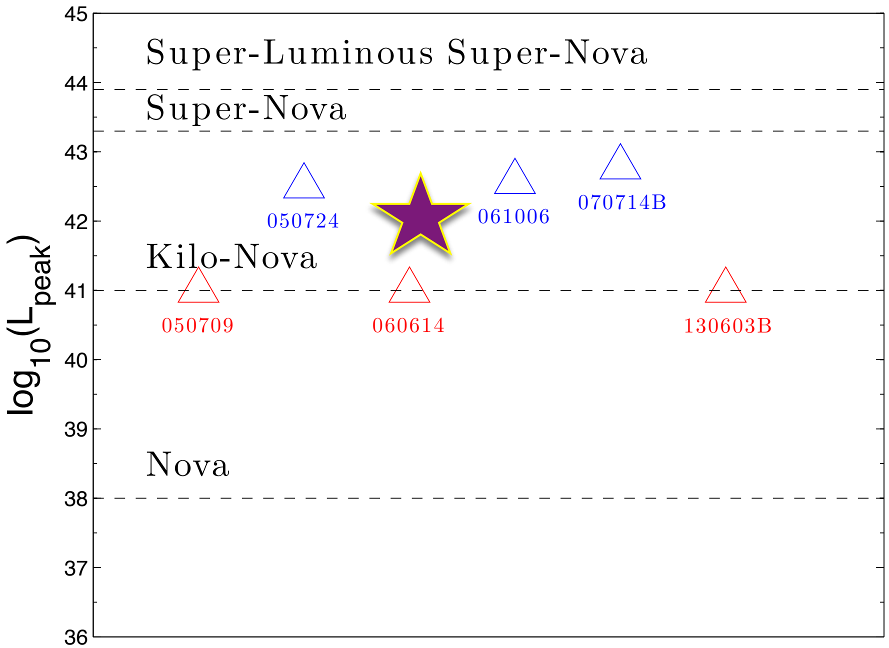
Merger-nova：r—process or Magnetar



BH: 2% <25 mag
Magnetar: 46.2% <25mag

Merger-nova：r—process or Magnetar

Gao et al. , 2017 ApJ, 837, 50



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GW Analysis

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

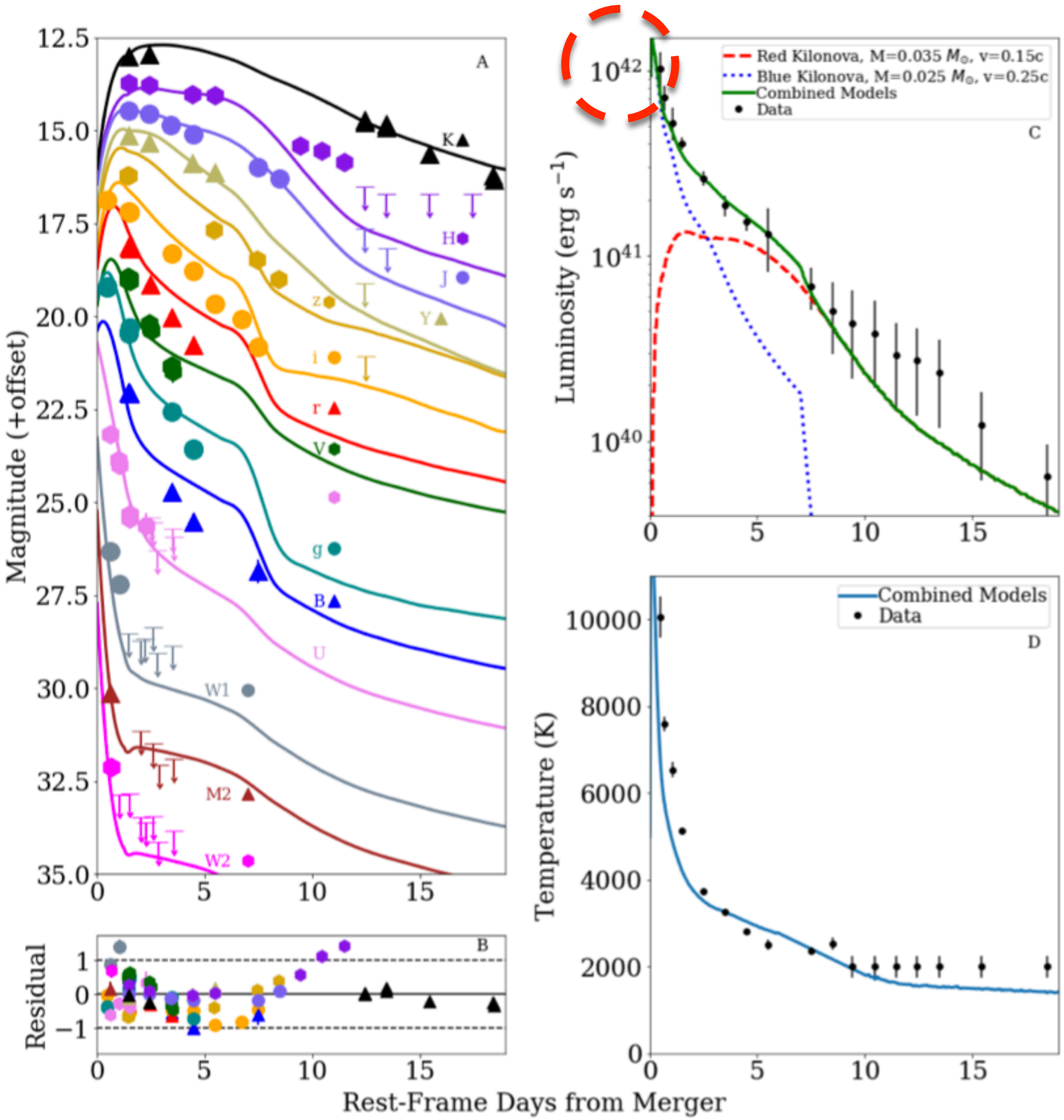
On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-n … mate of less than one per 8.0×10^4 years. We infer th … een 0.86 and 2.26 $M_\odot$, in agreement with masses of kn … ins to the range inferred in binary neutron stars, we find th … component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the

Total mass $2.74M_\odot$

astrophysical origin. However, upper limits placed on the strength of gravitational-wave emission cannot definitively rule out the existence of a short- or long-lived postmerger neutron star. The implications of various postmerger scenarios are explored in [45,193].

Allowed parameter space for NS ?

Kilo-novae : Red and Blue



Kilpatrick et al. 2017, Nature

Red

$$M_{\rm ej} = 0.035\,{\rm M}_\odot$$

$$v_{\rm k} = 0.15\,c$$

$$\log(X_{\rm lan}) = -2.0$$

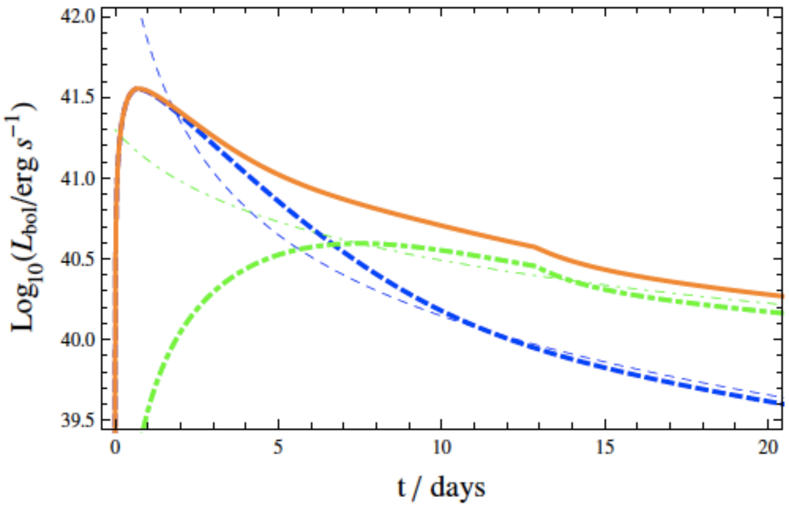
Blue

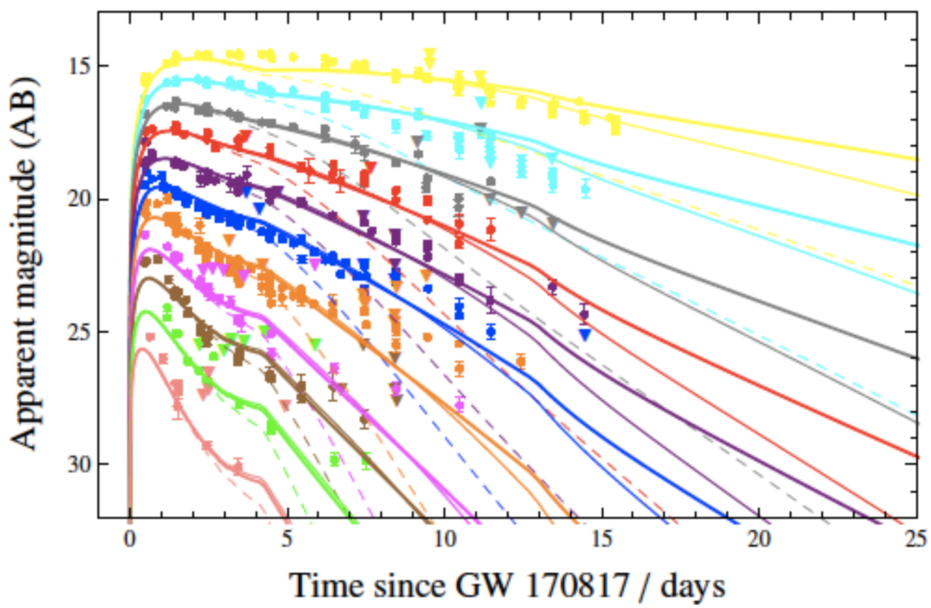
$$M_{\rm ej} = 0.025\,{\rm M}_\odot$$

$$v_{\rm k} = 0.25\,c$$

$$\log(X_{\rm lan}) = -4$$

GW170817: Magnetar as Merger Product





Yu & Dai , 2017

Blue：r-process

$$M_{\rm ej} = 0.035 M_\odot$$

$$v_{\rm min} = 0.12c,\ v_{\rm max} = 0.35c,$$

$$\kappa = 1.0\,{\rm cm^2 g^{-1}}$$

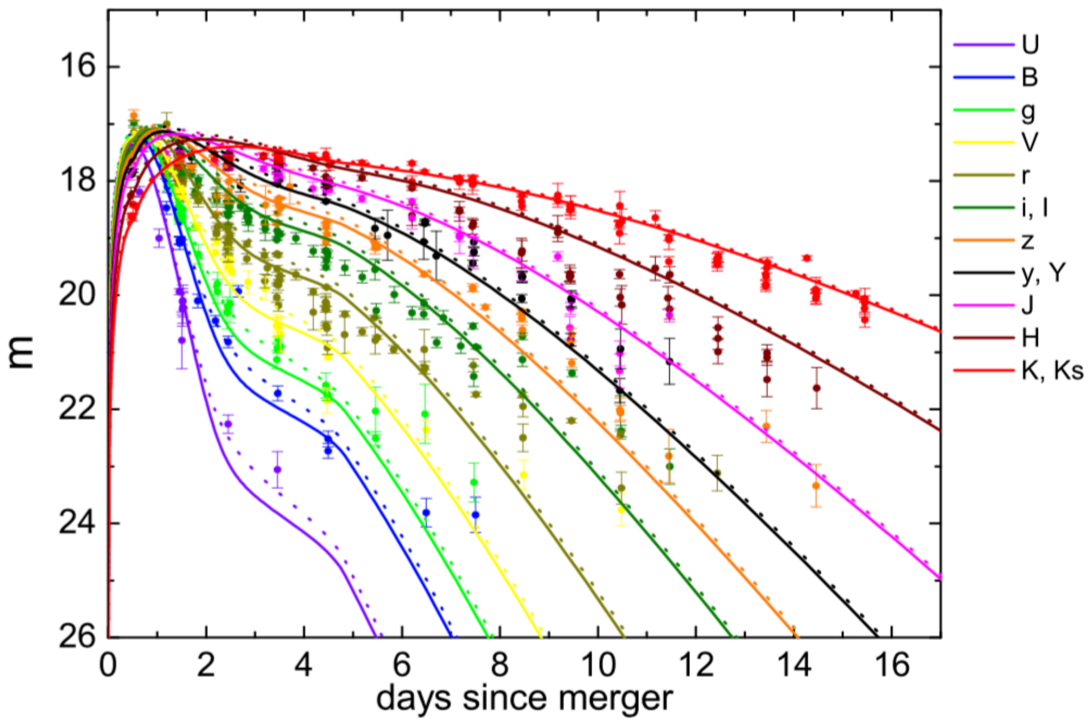
Red：Magnetar powered

$$B_{\rm p} = 1.4\times10^{11}\xi^{-1/2}R_6^{-3}P_{{\rm i},-3}^2{\rm G},$$

$$t_{\rm sd,gw} = \frac{5P_{\rm i}^4c^5}{2048\pi^4GI\epsilon^2} = 9.1\times10^5\epsilon_{-4}^{-2}I_{45}^{-1}P_{{\rm i},-3}^4{\rm s}$$

GW170817: Magnetar as Merger Product

Li et al. arXiv:1804.06597



Blue and Red

Magnetar powered

	$M_{fb,i}/M_{\odot}s^{-1}$	$L_{md,i}/erg\,s^{-1}$	$t_{sd,gw}/s$	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: Allowed Parameter Space of NS

Ai, Gao, Dai et al. 2018, ApJ

Total mass → Spin Period

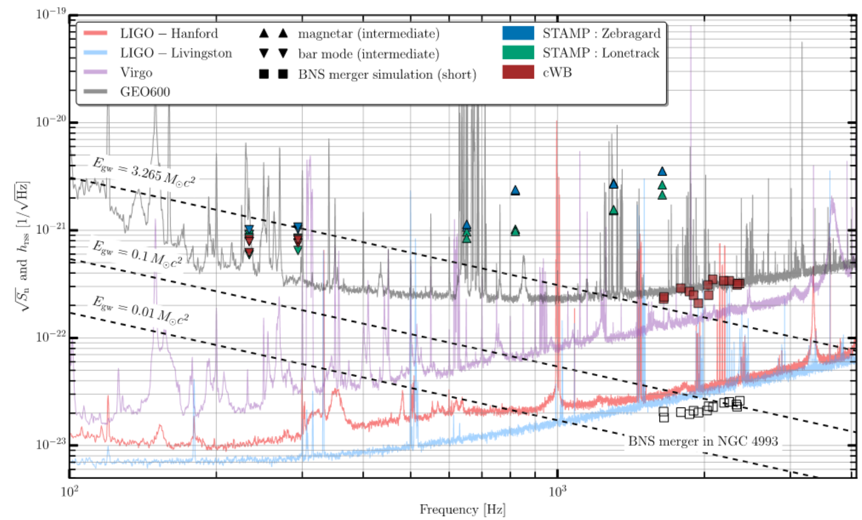
$$M_{\max} = M_{TOV}(1+\alpha P^{\beta})$$

TABLE 1
THE BASIC PARAMETERS OF THE EOS AND THE COLLAPSE PERIOD ($P_{\rm col}$) WHEN CONSIDER THE MASS OF REMNANT IS $2.59 M_{\odot}$

	$M_{\rm TOV}$ ($M_{\odot}$)	R_s (km)	I (10^{45}g cm^2)	α ($s^{-\beta}$)	β	P_K (ms)	$P_{\rm col}$ (ms)
CIDDM	2.09	12.43	8.645	2.58×10^{-16}	-4.93	0.83	0.921
CDDM1	2.21	13.99	11.67	3.93×10^{-16}	-5.00	1.00	1.118
CDDM2	2.45	15.76	16.37	2.22×10^{-16}	-5.18	1.12	1.652
MIT2	2.08	11.48	7.881	1.67×10^{-15}	-4.58	0.71	0.807
MIT3	2.48	13.71	13.43	3.35×10^{-15}	-4.60	0.85	1.404
GM1	2.37	12.05	3.33	1.58×10^{-10}	-2.84	0.72	0.817
BSk21	2.28	11.08	4.37	2.81×10^{-10}	-2.75	0.60	0.945
NS1	2.42	11.89	5.43	1.370×10^{-10}	-2.88	0.65	0.946
NS2	2.48	12.09	5.85	1.966×10^{-10}	-2.84	0.66	1.100
AB-N	2.67	12.9	4.3	0.112×10^{-10}	-3.22	1.00	∞
AB-L	2.71	13.7	4.7	2.92×10^{-10}	-2.82	1.00	∞

NS should be with millisecond spin

Post-merger GW signal → NS Ellipticity



$$h(t) = \frac{4G\Omega^2}{c^4 d} I\epsilon, \quad \dot{E} = I\Omega\dot{\Omega} = -\frac{32GI^2\epsilon^2\Omega^6}{5c^5}$$

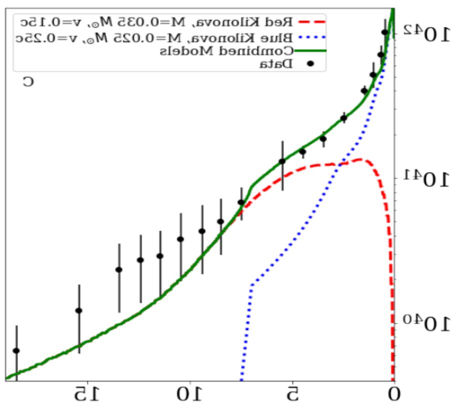
$$h_{\rm rss} = \sqrt{2\int_{f_{\rm min}}^{f_{\rm max}} \left(|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2\right) {\rm d}f}$$

No Constraint on NS Ellipticity

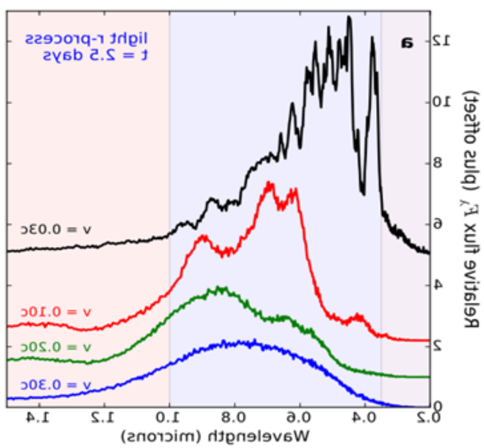
GW170817: Allowed Parameter Space of NS

Ai, Gao, Dai et al. 2018, ApJ

Optical data

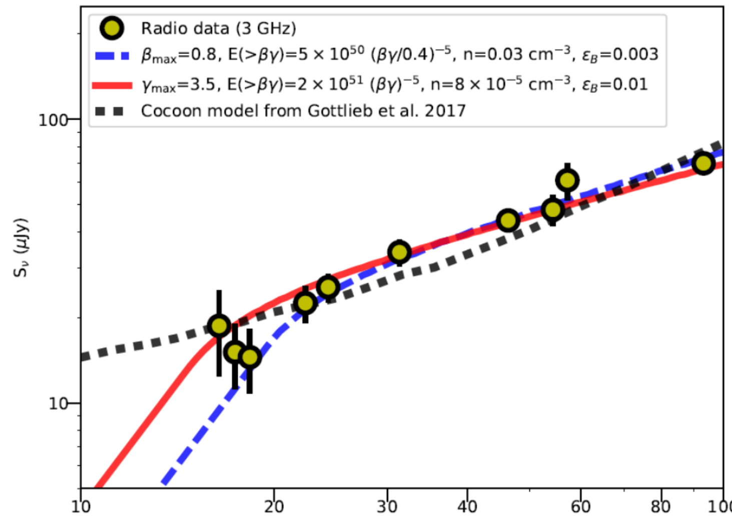


Merger-Nova Luminosity

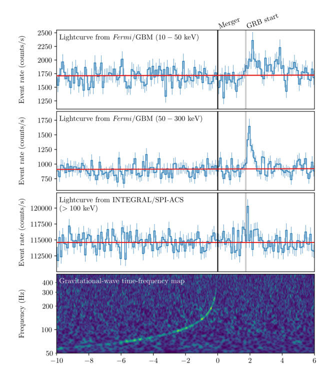


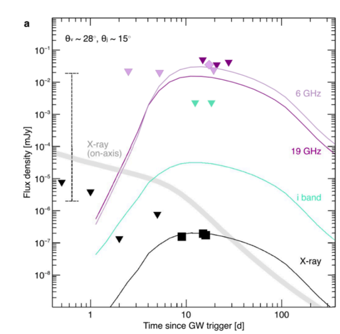
Ejecta Velocity

Radio data



Gamma/X-ray data





NS should be with small B field

Summary of the results

Gao+, 2016 PRD

Basic Assumption

- Part of (or all) SGRBs are from NS-NS mergers
- Cosmological NS-NS systems have the same mass distribution as the observed Galactic system
- Internal plateau marks the collapse of a magnetar to a BH.

Conclusion

- Equation of State $M_{max} = 2.37 M_{\odot}(1 + 1.58 \times 10^{-10} P^{-2.84})$
- NS-NS merger product:40% BH, 30% stable NS, 30% NS->BH
- Initial spin period of the magnetar is around 1ms;
- High magnetic field: 10^{15} G
- High X-ray radiation efficiency, >40%
- Large ellipticity, GW radiation dominates spin-down

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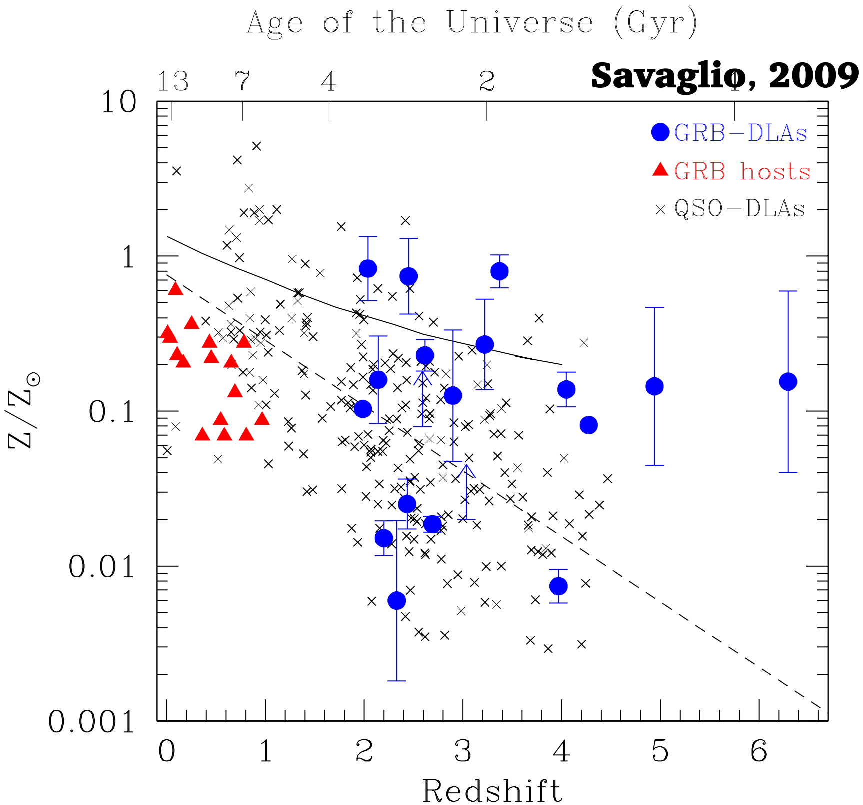
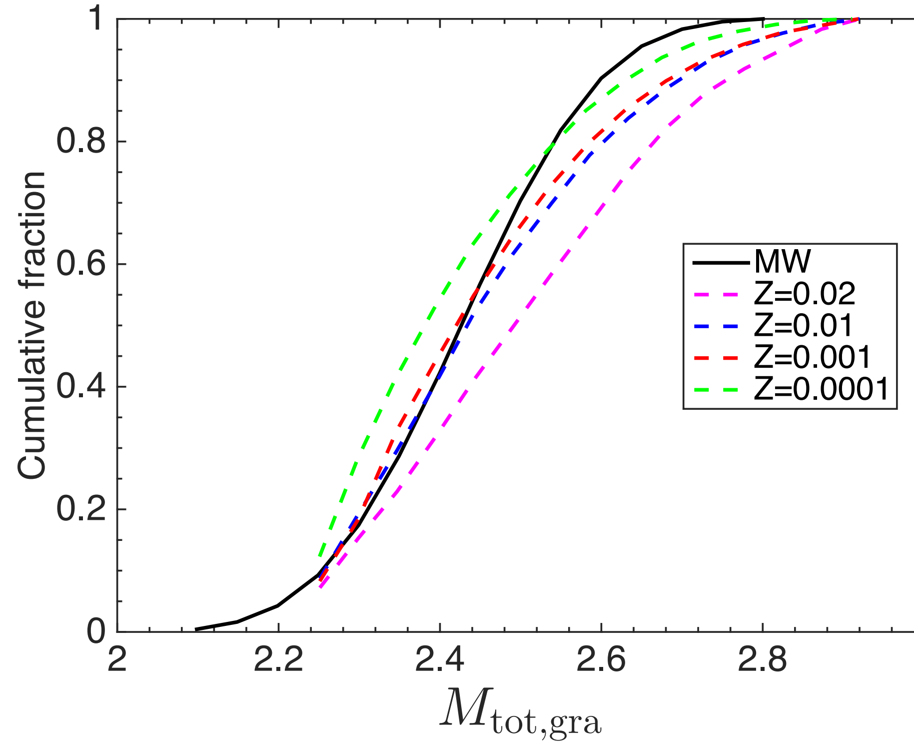
Total mass distribution of NS-NS systems





	Black Hole	Supra-Massive NS	Stable NS
Z=0.02	0.54	0.24	0.22
Z=0.01	0.43	0.28	0.29
Z=0.001	0.39	0.28	0.33
Z=0.0001	0.32	0.27	0.41
MW	0.40	0.30	0.30

Gao H., Zhang, X.-F. et al. 2018, in prep.

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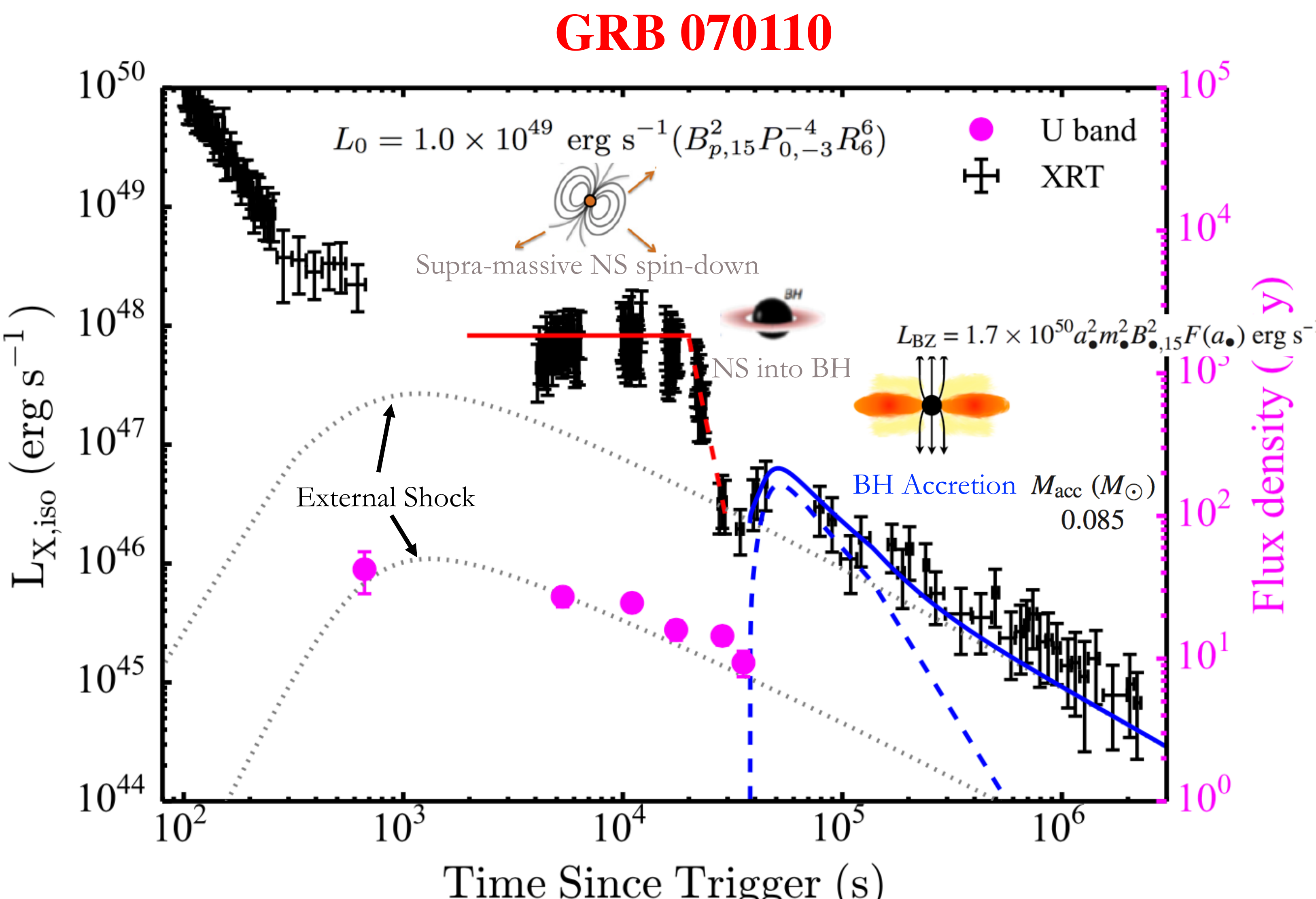
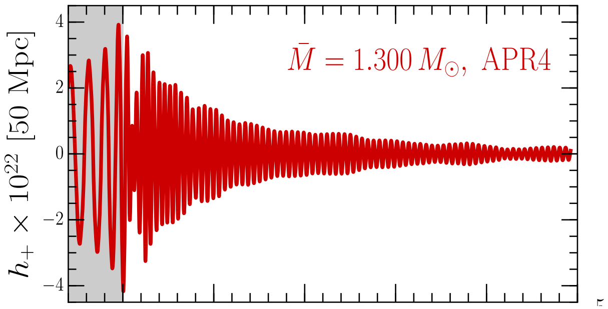
EM Signature: Fall-back accretion

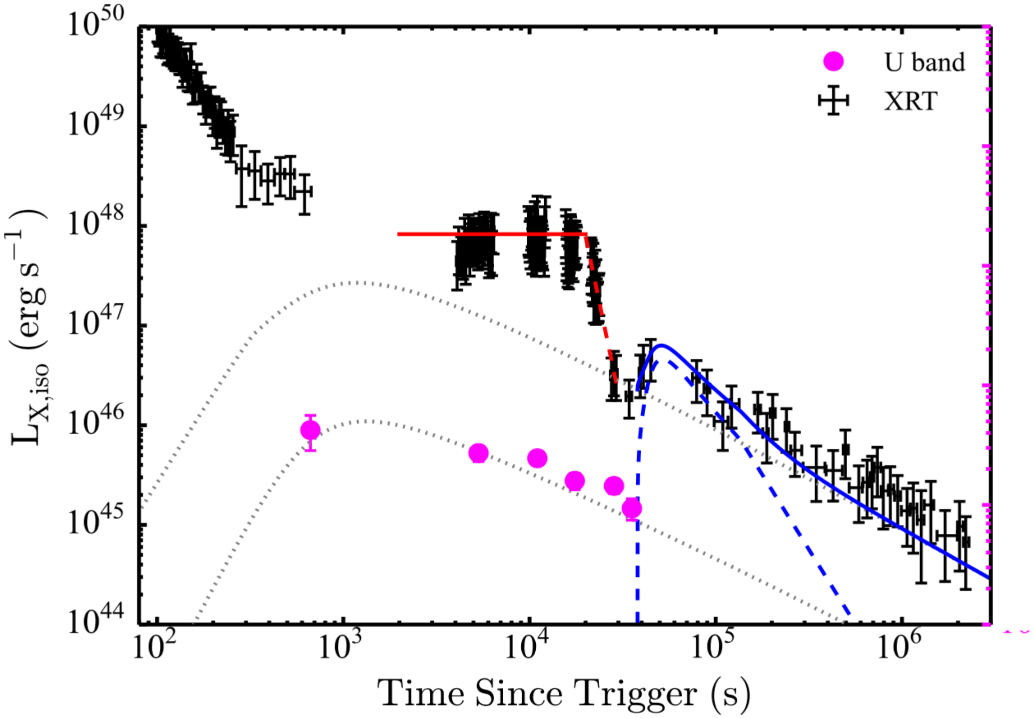
Chen, Xie, Lei et al. 2017 ApJ



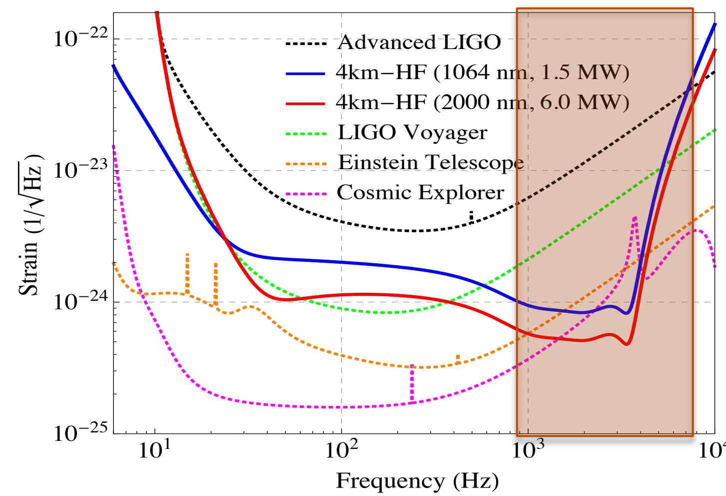
GW Signature: Ring-down Phase

Rezzolla & Takami, 2016





Miao et al. , 2017



Simultaneous observation:
Steep decay phase in EM
Ring-down phase in GW

Ai et al. 2018 in prep.

Summary

- Era of GW Astronomy has been Opened
- NS-NS merger product determines EM signals
- Short GRB data could constrain NS-NS merger product fraction
  - NS-NS merger product:40% BH，30% stable NS，30% NS->BH
  - Initial spin period of the magnetar is around 1ms；
  - High magnetic field：10^{15} G
  - Large ellipticity, GW radiation dominates spin-down
- More GW170817-like multi-messenger evens to test the post merger product fraction.

Thanks for the attention！