What’s the central object after GW170817?

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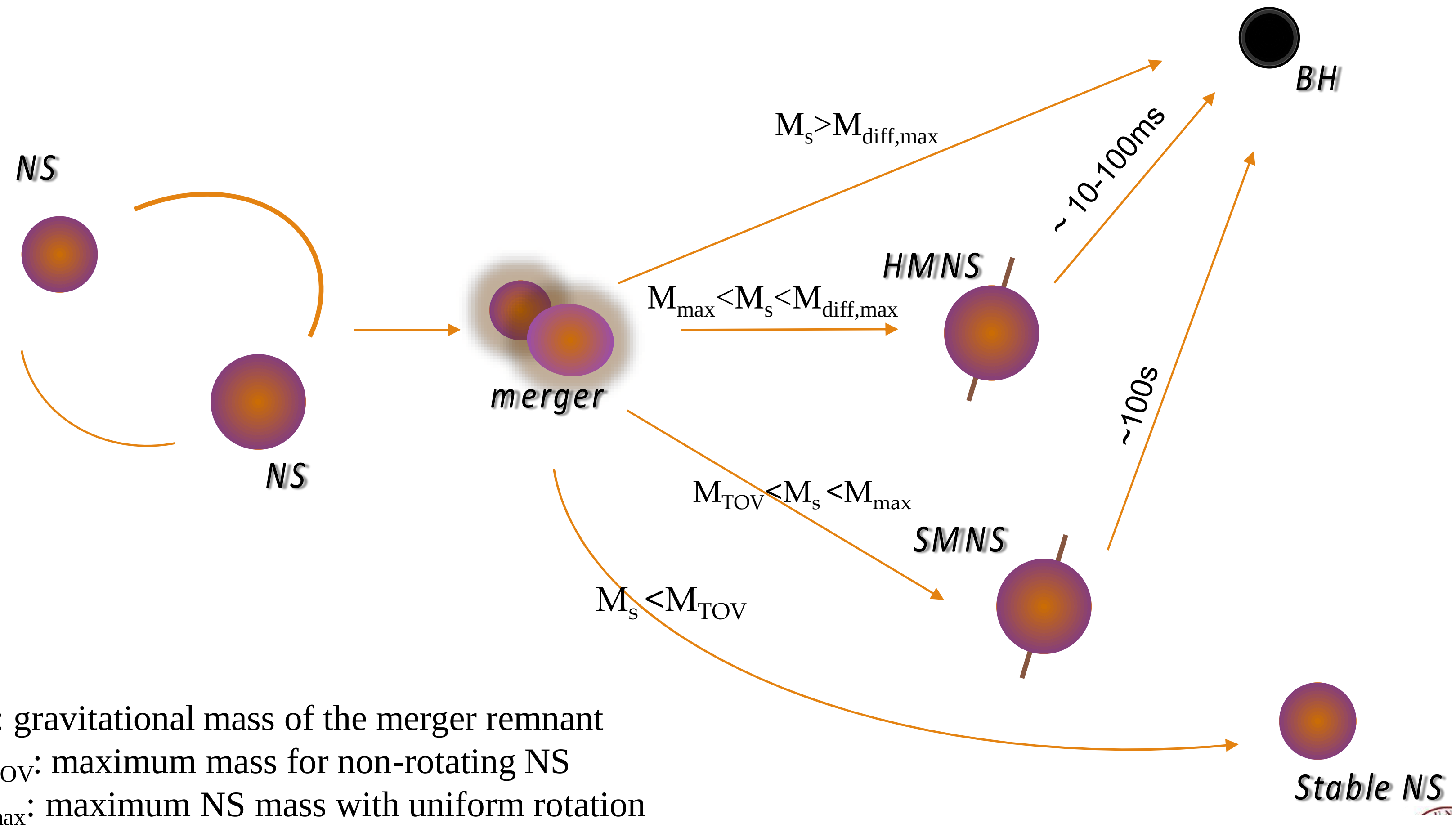
Central objects post NS-NS mergers



NS

NS

merger

$M_s>M_{diff,max}$

BH

~ 10-100ms

HMNS

$M_{max}<M_s<M_{diff,max}$

$M_{TOV}<M_s<M_{max}$

SMNS

~100s

$M_s<M_{TOV}$

Stable NS

M_s: gravitational mass of the merger remnant
M_{TOV}: maximum mass for non-rotating NS
M_{max}: maximum NS mass with uniform rotation
$M_{diff,max}$: maximum NS mass with differential rotation

(I) Black holes + disks

- Forming an accretion disk in a NS-NS merger: 0.03-0.3$M_\odot$ (Rosswog et al. 1999, 2000, 2001)
- Forming an accretion disk in a NS-BH merger: 0.1-0.3$M_\odot$, depending on $q=M_{\rm NS}/M_{\rm BH}$ (Janka et al. 1999; Davies et al. 2005)
- Neutrino-dominated accretion rate and disk's lifetime (Narayan et al. 2001; Liu et al. 2015a):

$$\dot{M}_{\rm acc} = 0.6\left(\frac{\alpha}{0.1}\right)\left(\frac{M_{\rm BH}}{3\,M_\odot}\right)^{-13/7}\left(\frac{M_{\rm d}}{0.1\,M_\odot}\right)^{9/7}\left(\frac{R_{\rm d}}{10R_{\rm s}}\right)^{-3/2} M_\odot\ {\rm s}^{-1}$$

$$t_{\rm acc} = 0.2\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{M_{\rm BH}}{3\,M_\odot}\right)^{13/7}\left(\frac{M_{\rm d}}{0.1\,M_\odot}\right)^{-2/7}\left(\frac{R_{\rm d}}{10R_{\rm s}}\right)^{3/2} {\rm s}$$

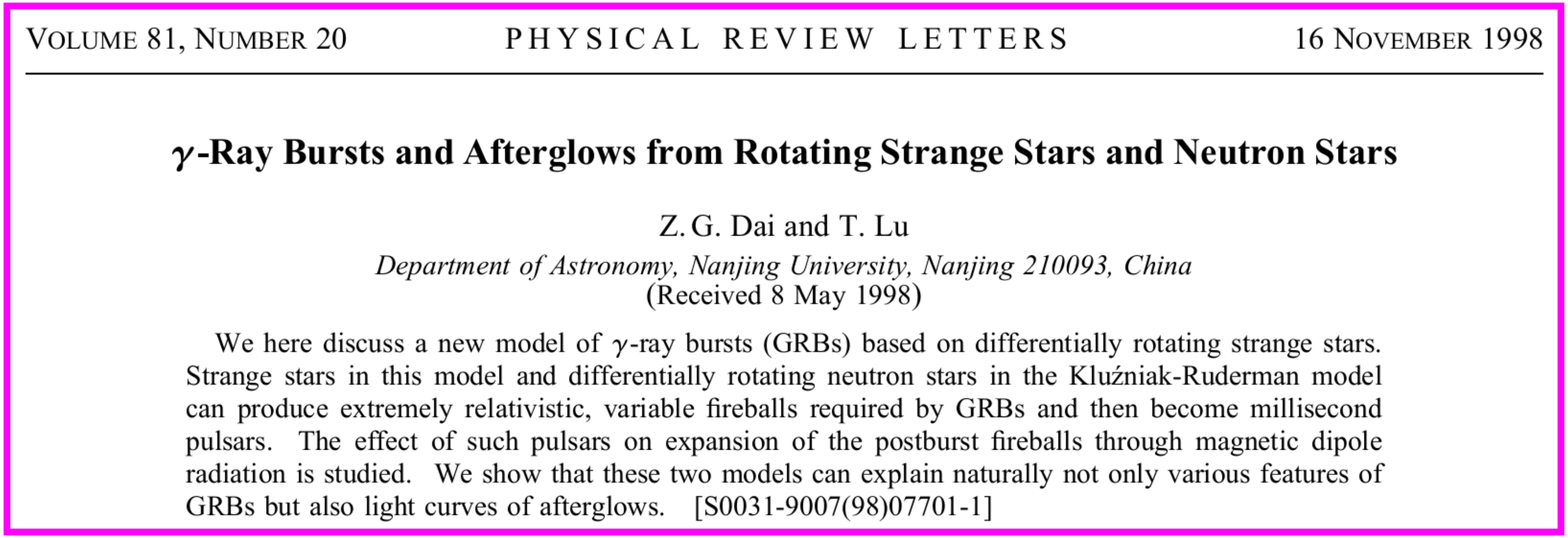
➢Launching a jet

① Neutrino-driven jet (Goodman et al. 1987; Eichler et al. 1989; Narayan et al. 2001; Di Matteo et al. 2002; Liu et al. 2015b): neutrino annihilation efficiency ~0.01-0.001, $E \sim 10^{49}(M_{\rm disk}/0.1M_{\odot})$ erg.

② Magnetically-driven (BZ) jet (Narayan et al. 1992; Meszaros & Rees 1997): $E \sim 10^{51}(M_{\rm disk}/0.1M_{\odot})$ erg.

(II) Millisecond pulsars

- A transient hypermassive or supramassive NS (Kluzniak & Lee 1998; Baumgarte et al. 2000; Shapiro 2000; Rosswog & Davies 2002; Rosswog & Ramirez-Ruiz 2002; Rosswog et al. 2003; Shibata et al. 2006; Duez et al. 2006)
- A post-merger stable massive NS or a strange quark star (Dai & Lu 1998a, 1998b; Dai et al. 2006; Fan & Xu 2006; Gao & Fan 2006; Zhang 2013)
- A short GRB could be due to differential rotation in the interior (Kluzniak & Ruderman 1998; Dai & Lu 1998b) or an accretion disk (Zhang & Dai 2008, 2009, 2010).



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γ-Ray Bursts and Afterglows from Rotating Strange Stars and Neutron Stars

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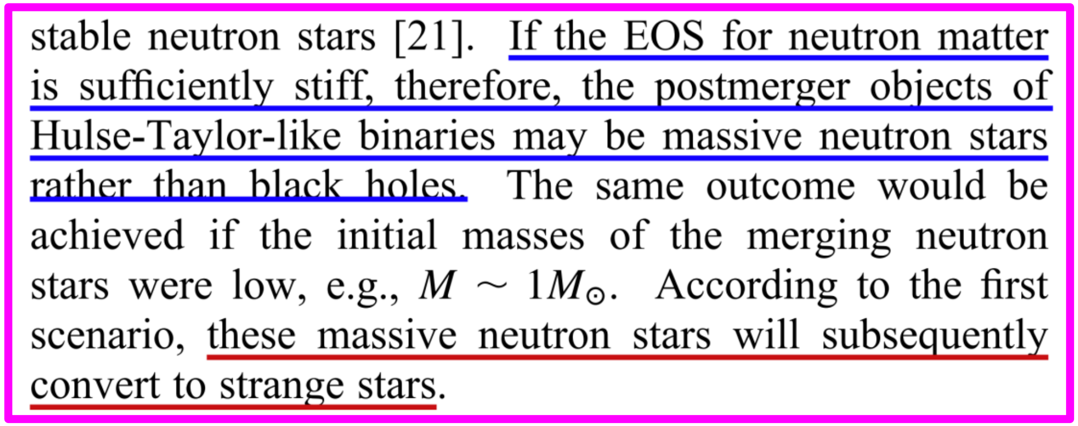
(Received 8 May 1998)

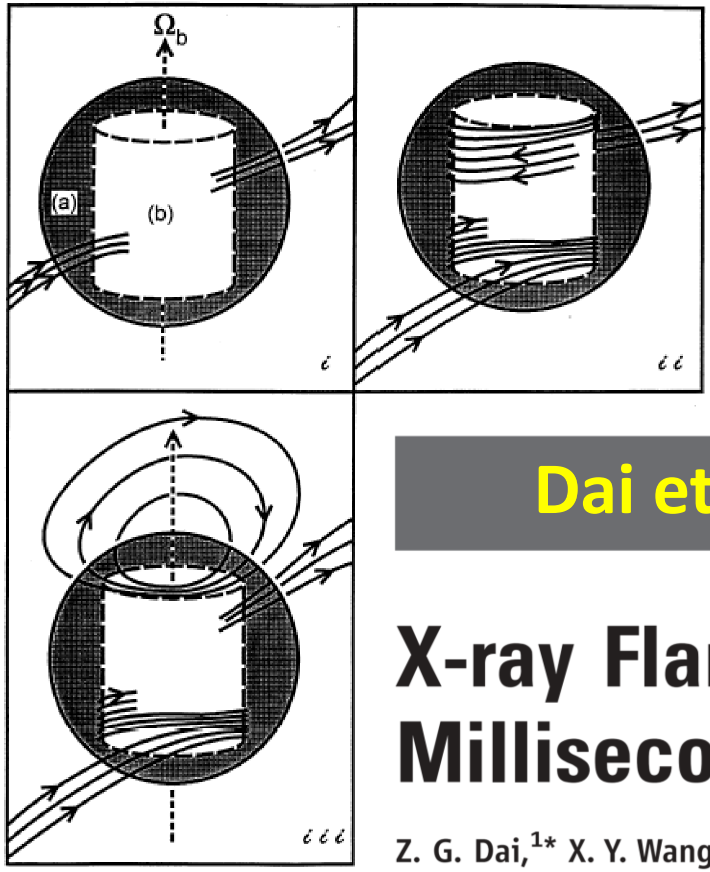
We here discuss a new model of γ-ray bursts (GRBs) based on differentially rotating strange stars. Strange stars in this model and differentially rotating neutron stars in the Kluźniak-Ruderman model can produce extremely relativistic, variable fireballs required by GRBs and then become millisecond pulsars. The effect of such pulsars on expansion of the postburst fireballs through magnetic dipole radiation is studied. We show that these two models can explain naturally not only various features of GRBs but also light curves of afterglows. [S0031-9007(98)07701-1]



stable neutron stars [21]. If the EOS for neutron matter is sufficiently stiff, therefore, the postmerger objects of Hulse-Taylor-like binaries may be massive neutron stars rather than black holes. The same outcome would be achieved if the initial masses of the merging neutron stars were low, e.g., $M \sim 1 M_\odot$. According to the first scenario, these massive neutron stars will subsequently convert to strange stars.

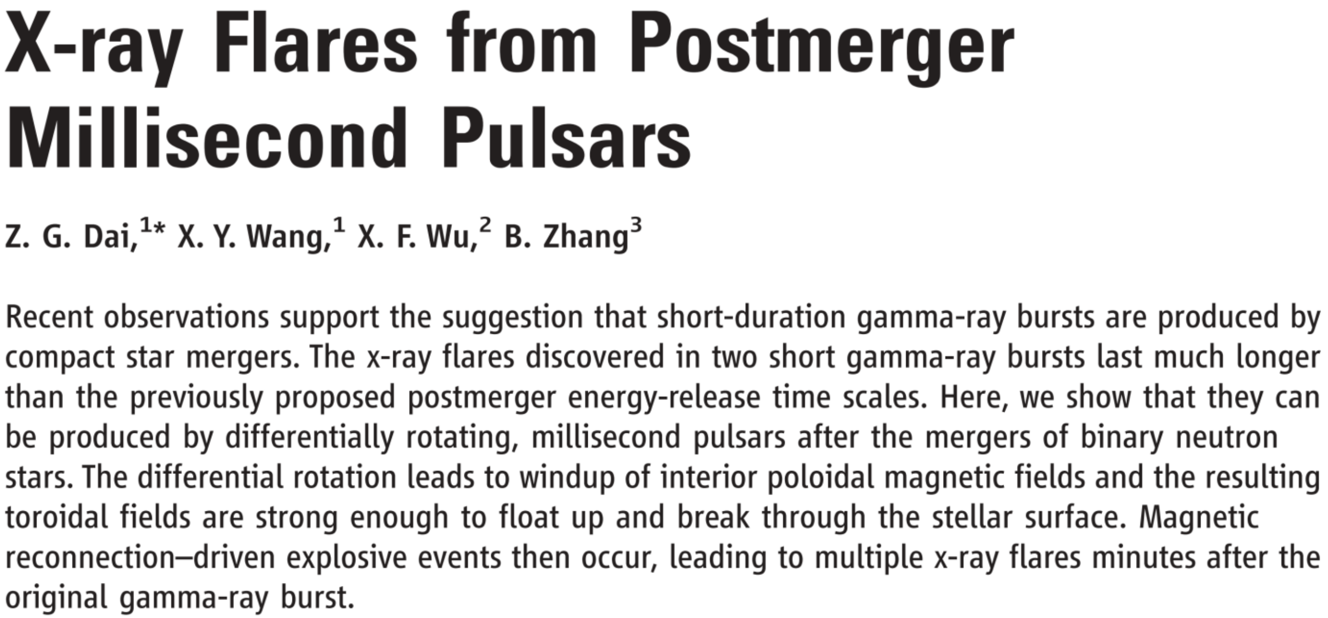
Pulsar's rotational energy injection to post-merger fireballs leads to plateaus in light curves of gamma-ray burst afterglows (Dai & Lu 1998a, A&A, 333, L87).

Kluzniak & Ruderman (1998)



To explain late-time X-ray flares, both a low poloidal magnetic field and an ultrastrong toroidal field are required!

Dai et al. 2006, Science, 311, 1127

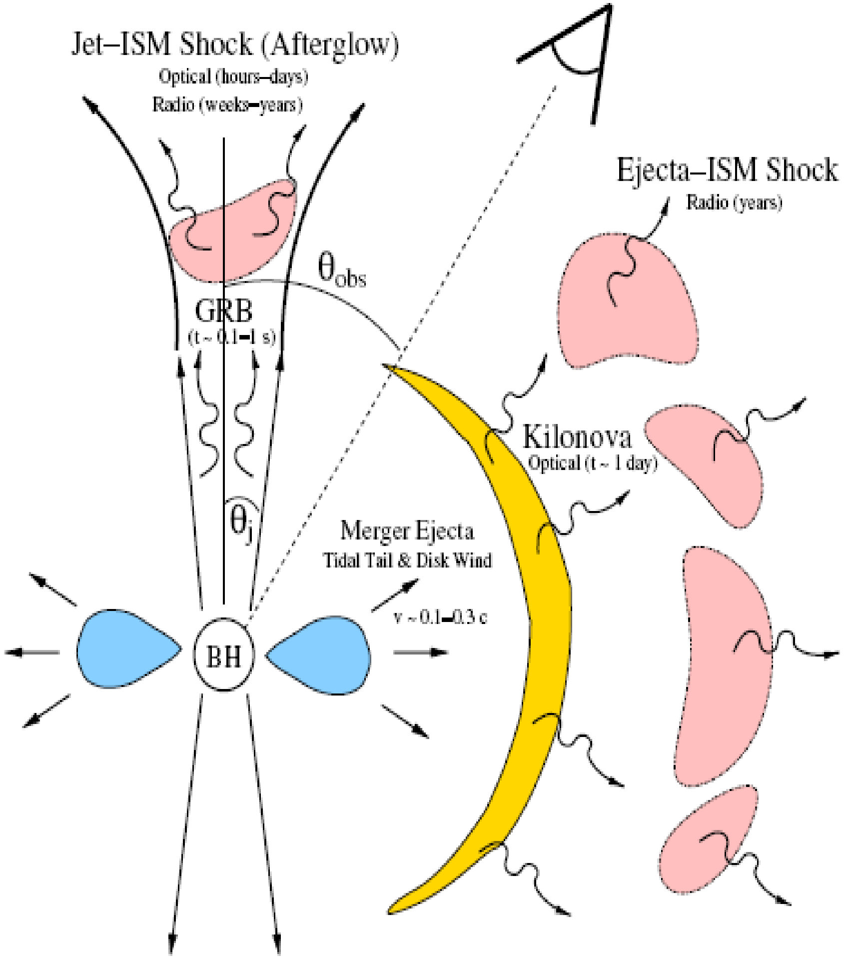


X-ray Flares from Postmerger Millisecond Pulsars

Z. G. Dai,[1]* X. Y. Wang,[1] X. F. Wu,[2] B. Zhang[3]

Recent observations support the suggestion that short-duration gamma-ray bursts are produced by compact star mergers. The x-ray flares discovered in two short gamma-ray bursts last much longer than the previously proposed postmerger energy-release time scales. Here, we show that they can be produced by differentially rotating, millisecond pulsars after the mergers of binary neutron stars. The differential rotation leads to windup of interior poloidal magnetic fields and the resulting toroidal fields are strong enough to float up and break through the stellar surface. Magnetic reconnection–driven explosive events then occur, leading to multiple x-ray flares minutes after the original gamma-ray burst.

EM signals from post-merger BHs



Metzger & Berger 2012

Short GRBs and afterglows

Multiwavelength transients
Durations ~ seconds, days, weeks, years

Radioactively-powered kilonovae

Li & Paczyński 1998

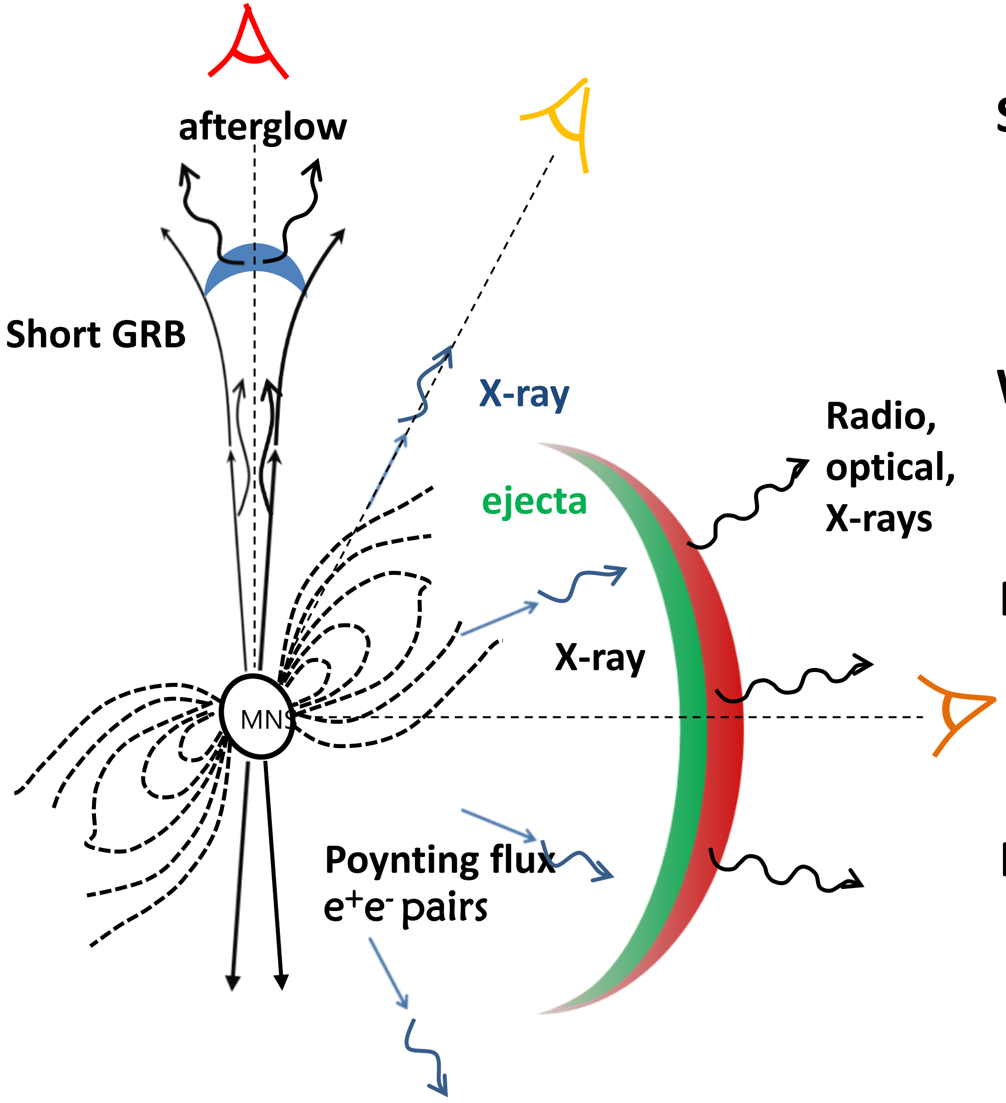
Dark optical transients
Duration ~ a few days

Forward shock emission

Nakar & Piran 2011

Radio afterglows
Duration ~ years

EM signals from post-merger pulsars



From Wu Xuefeng

Short GRBs and afterglows

Long-lasting activity
⇒ plateaus and flares

Dai & Lu 1998;
Dai et al. 2006

Wind dissipation-induced emission

1000 to 10000 s *Dai 2004; Zhang 2013*

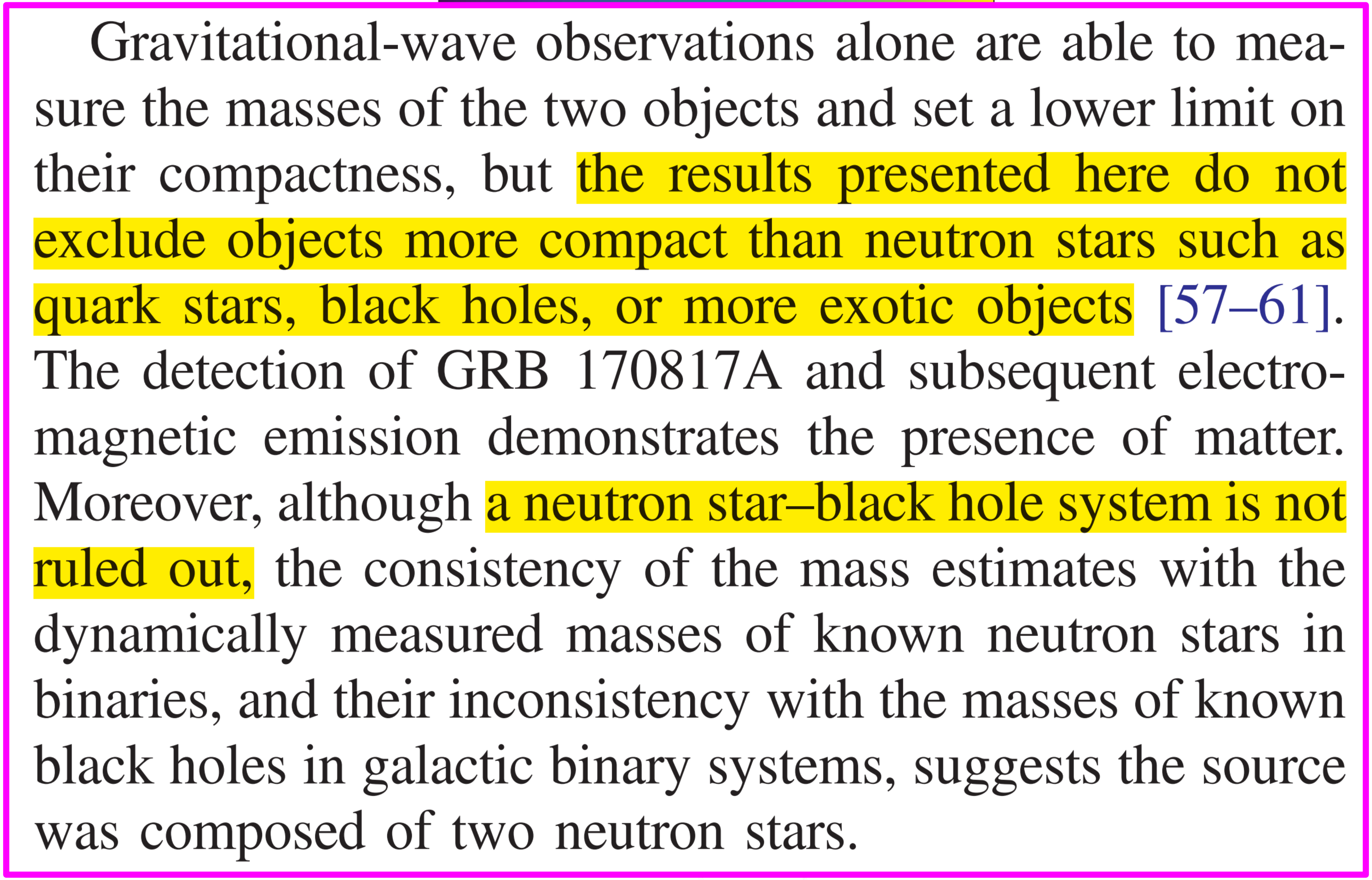
Rotationally-powered mergernovae

Luminous optical transients
Duration ~ days *Yu, Zhang & Gao 2013*

Forward shock emission

Luminous transients
Durations ~ hours, days, months, years

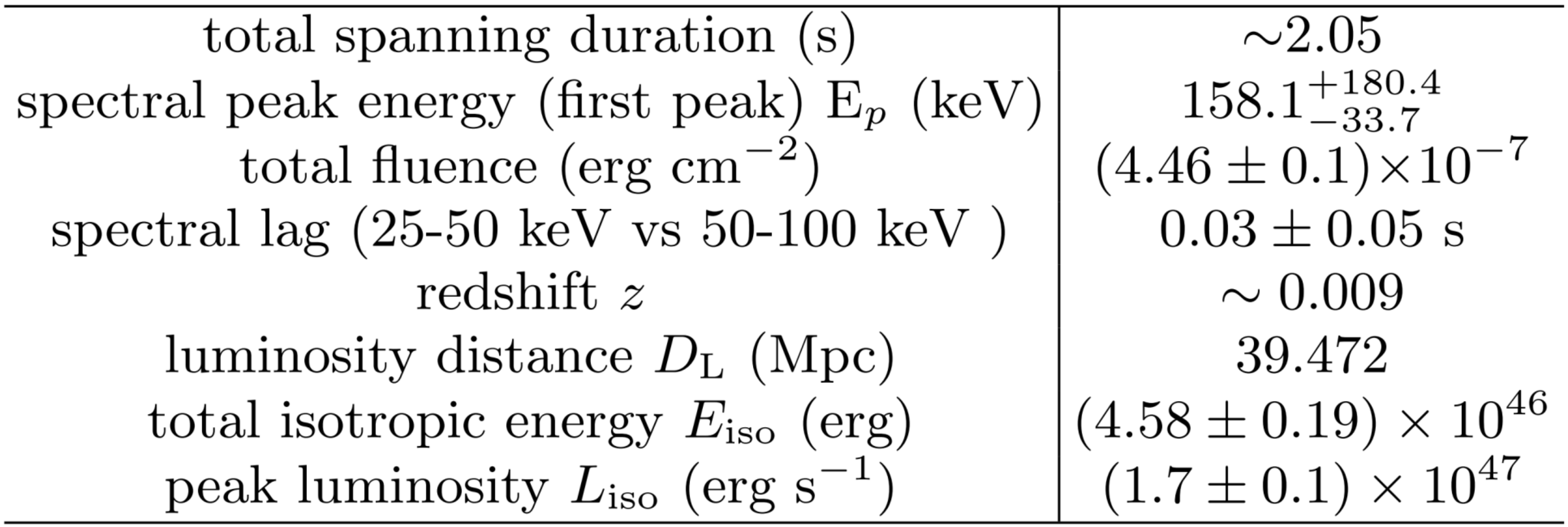
Gao, Ding, Wu, Zhang & Dai 2013
Wang & Dai 2013; Wu et al. 2014


Gravitational-wave observations alone are able to measure the masses of the two objects and set a lower limit on their compactness, but the results presented here do not exclude objects more compact than neutron stars such as quark stars, black holes, or more exotic objects [57–61]. The detection of GRB 170817A and subsequent electromagnetic emission demonstrates the presence of matter. Moreover, although a neutron star–black hole system is not ruled out, the consistency of the mass estimates with the dynamically measured masses of known neutron stars in binaries, and their inconsistency with the masses of known black holes in galactic binary systems, suggests the source was composed of two neutron stars.

Abbott et al. 2017, PRL, 119, 161101

(1) GRB170817A

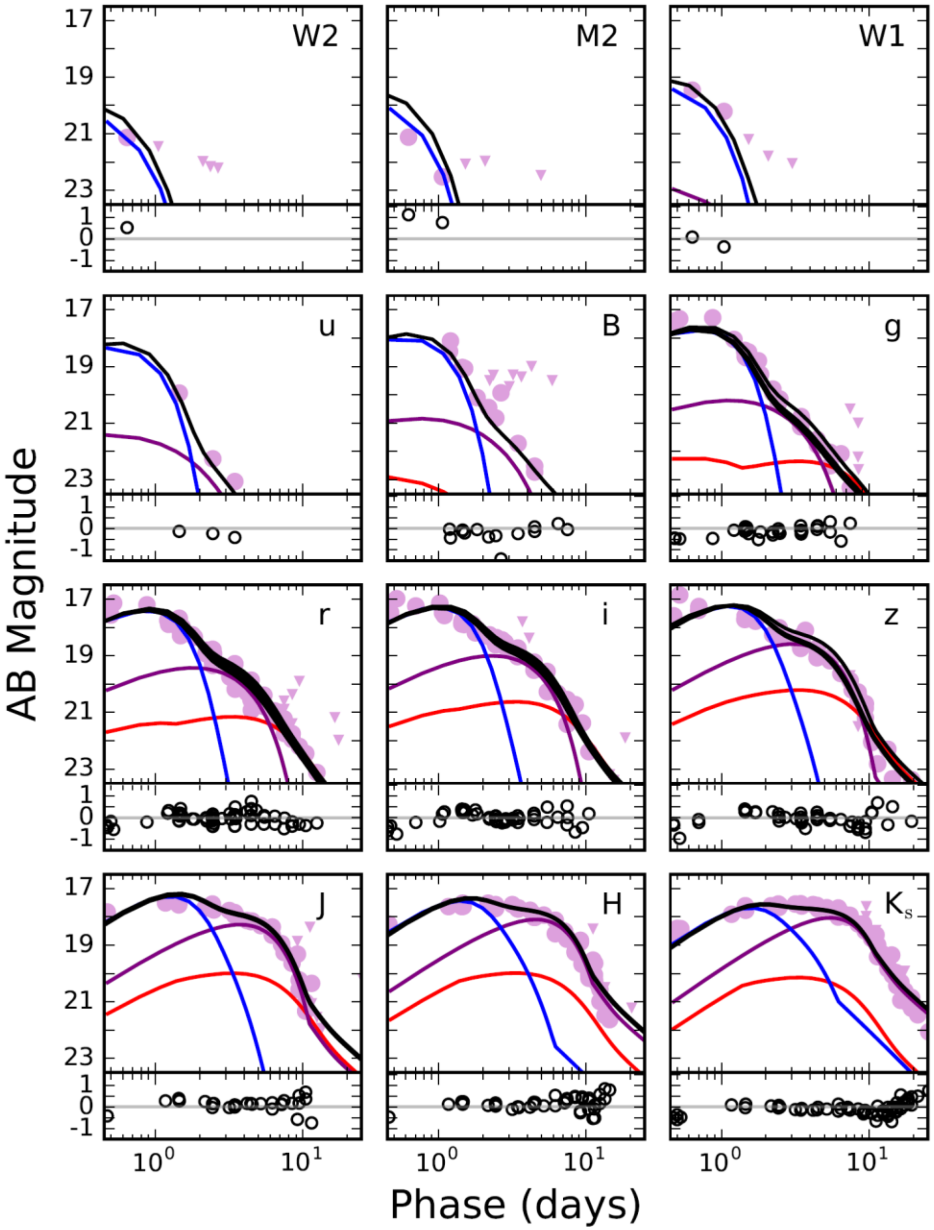
TABLE I: Properties of GRB 170817A.



total spanning duration (s)	$\sim$2.05
spectral peak energy (first peak) E_p (keV)	$158.1^{+180.4}_{-33.7}$
total fluence (erg cm^{-2})	$(4.46 \pm 0.1) \times 10^{-7}$
spectral lag (25-50 keV vs 50-100 keV)	0.03 ± 0.05 s
redshift z	~ 0.009
luminosity distance $D_{\rm L}$ (Mpc)	39.472
total isotropic energy $E_{\rm iso}$ (erg)	$(4.58 \pm 0.19) \times 10^{46}$
peak luminosity $L_{\rm iso}$ (erg s^{-1})	$(1.7 \pm 0.1) \times 10^{47}$

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

(2) Kilonova AT2017gfo



Villar et al. (2017, ApJL, 851, L21) modeled the complete UVOIR dataset for kilonova:

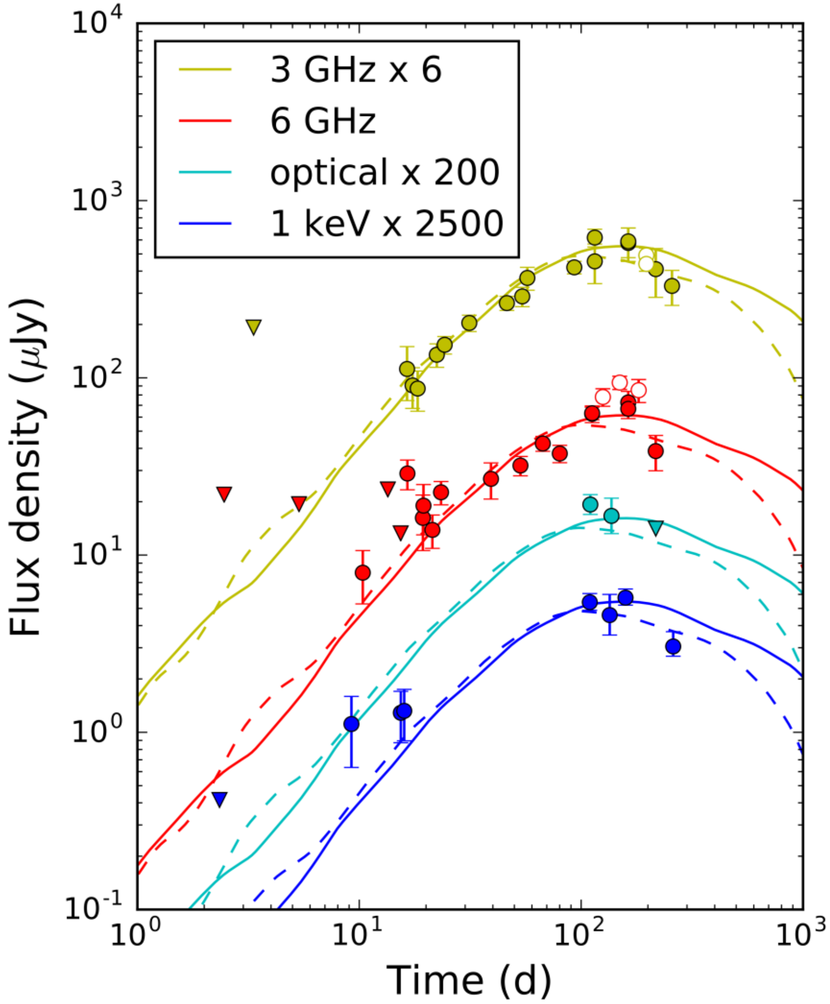
① a **blue** lanthanide-poor component (≈0.5cm^2/g, M_{ej}≈0.016$M_\odot$ &v_{ej}≈0.27c);

② an intermediate opacity **purple** component (≈3cm^2/g, M_{ej}≈0.040$M_\odot$ & v_{ej}≈0.14c);

③ a **red** lanthanide-rich component (≈10cm^2/g, M_{ej}≈0.009$M_\odot$ & v_{ej}≈0.08c).

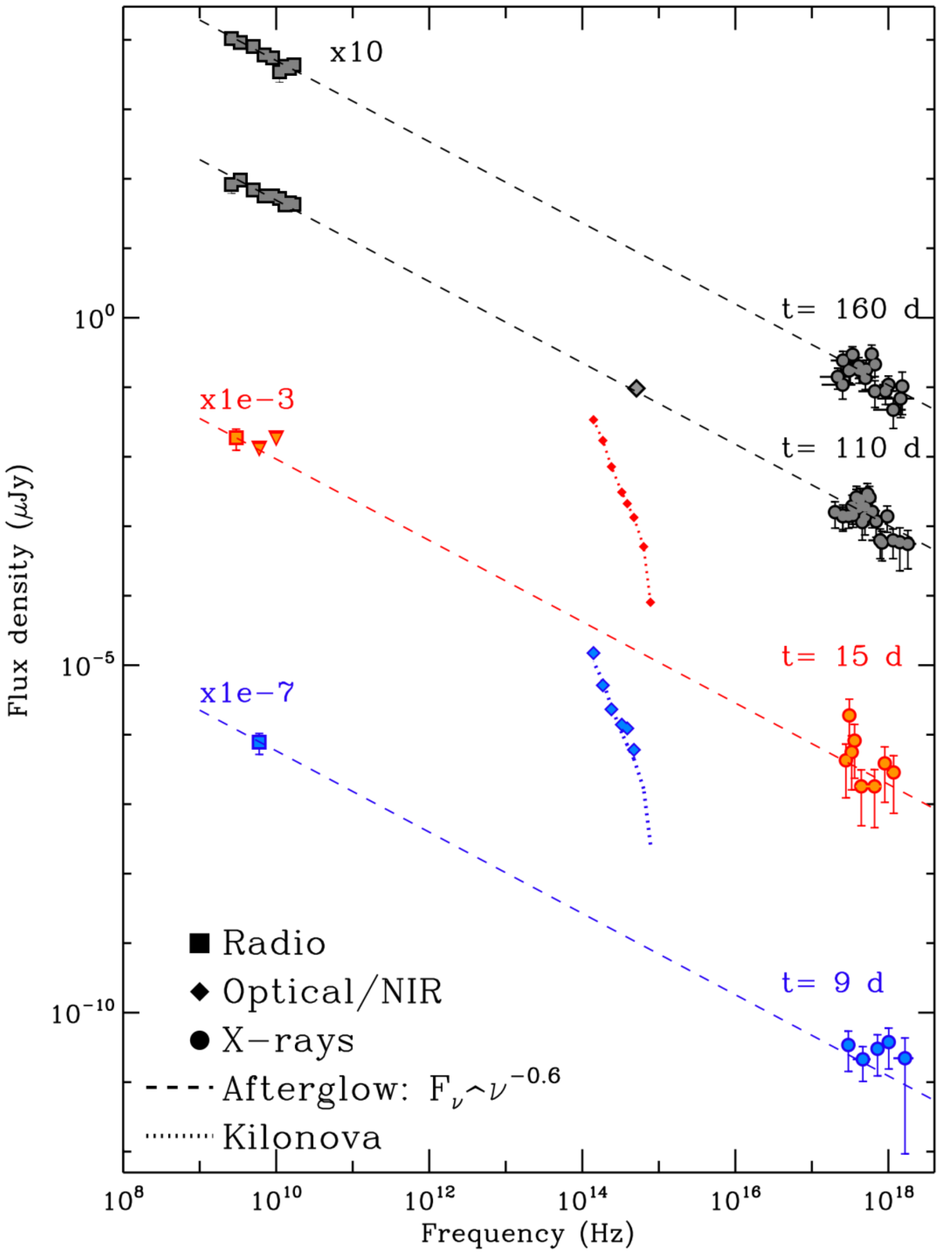
$M_{\mathrm{ej,tot}}$≈0.065$M_\odot$, too large!

(3) Broadband afterglow



Brightening via energy injection: Central, angular, & radial

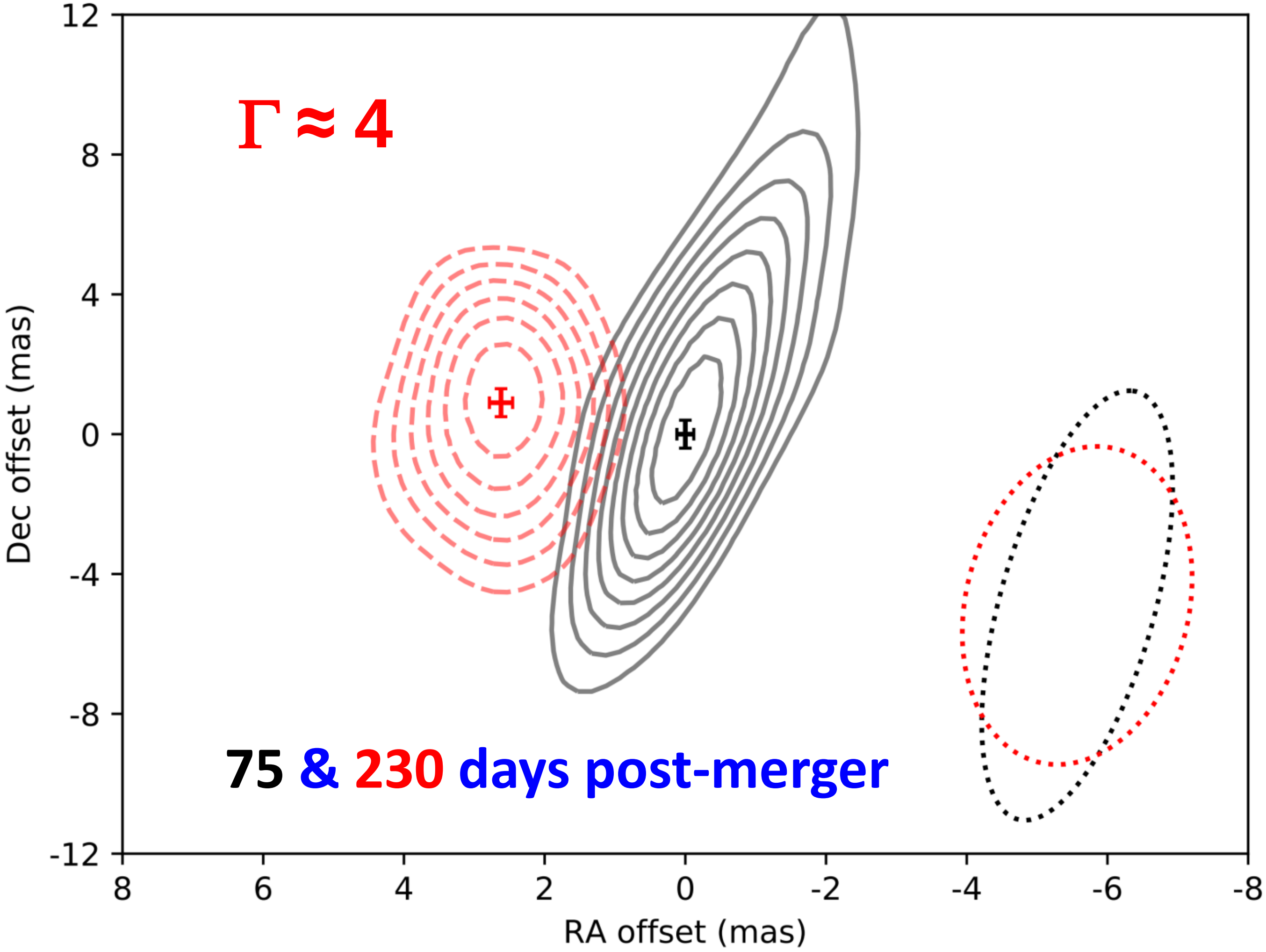
VLA, Chandra & HST: Alexander et al. 2018, arXiv:1805.02870

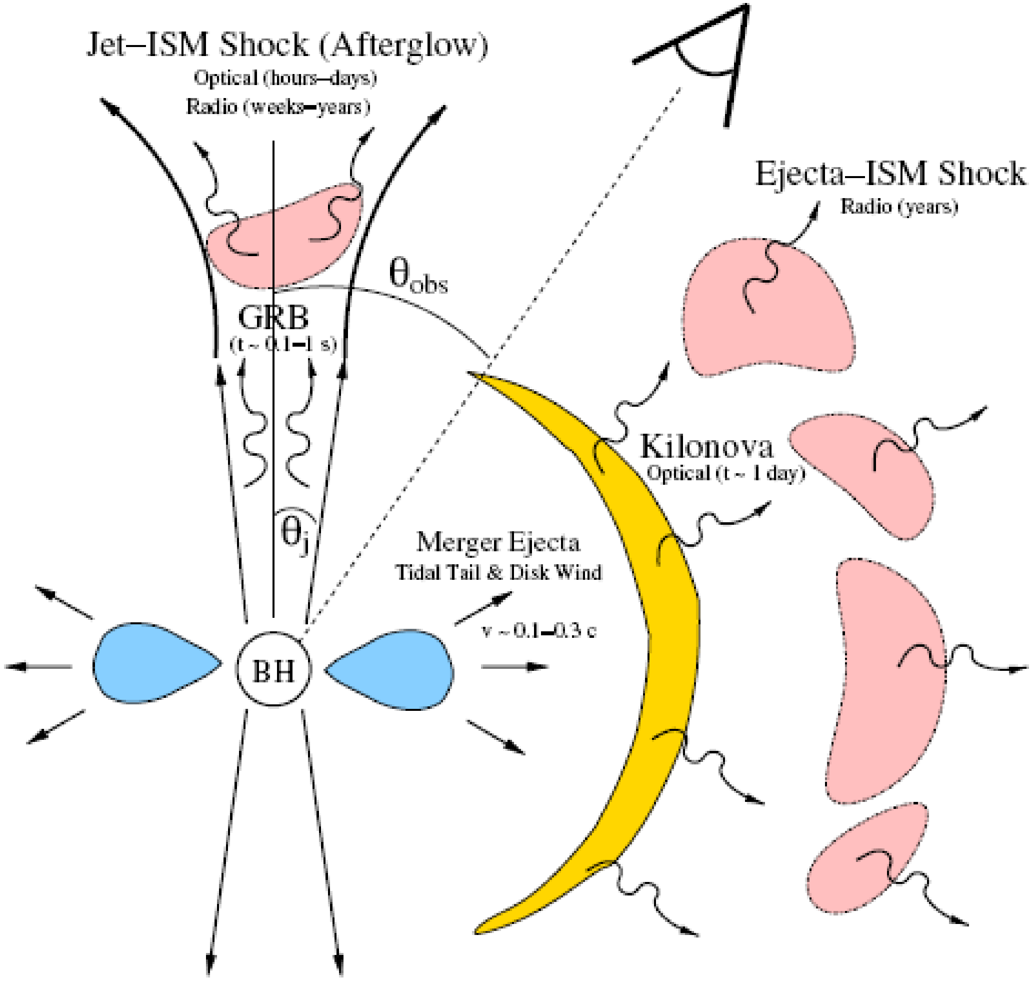


Margutti et al. 2018, ApJL, 856, L18： **Evolution of the broad-band SED** from 9 d to 160 d since merger.

SED: $F_{\nu}\propto\nu^{-0.6}$

Superluminal motion of a relativistic jet in GW170817 by VLBI observations: Mooley et al. 2018, arXiv:1806.09693





Standard picture (Metzger & Berger 2012)

Why off-axis?

- High detection rate
- Low-luminosity GRB
- Faint afterglow
- Superluminal motion
- Dominated kilonova
- **But structured jet or two-component jet**

A NS remnant is possible, but

- To see a **faint afterglow**, the spin-down luminosity is low or its conversion efficiency is low, requiring B_p is not very strong, say, $\mathbf{B_p<10^{12}\,G}$ (Pooley, Kumar et al. 2018; Ai, Gao, Dai et al. 2018, ApJ).

- To see a **brightening afterglow only in 150 days**, most of the rotational energy should be carried off by GWs, requiring a **large ellipticity** (Ai et al. 2018).

A NS remnant is further required

An X-ray flare detected by *Chandra* at ~155 days post-merger requires late activity of the GW170817 remnant, ruling out a BH based on the $t^{-5/3}$ fallback accretion rate (Piro, Troja, Zhang et al. 2018).

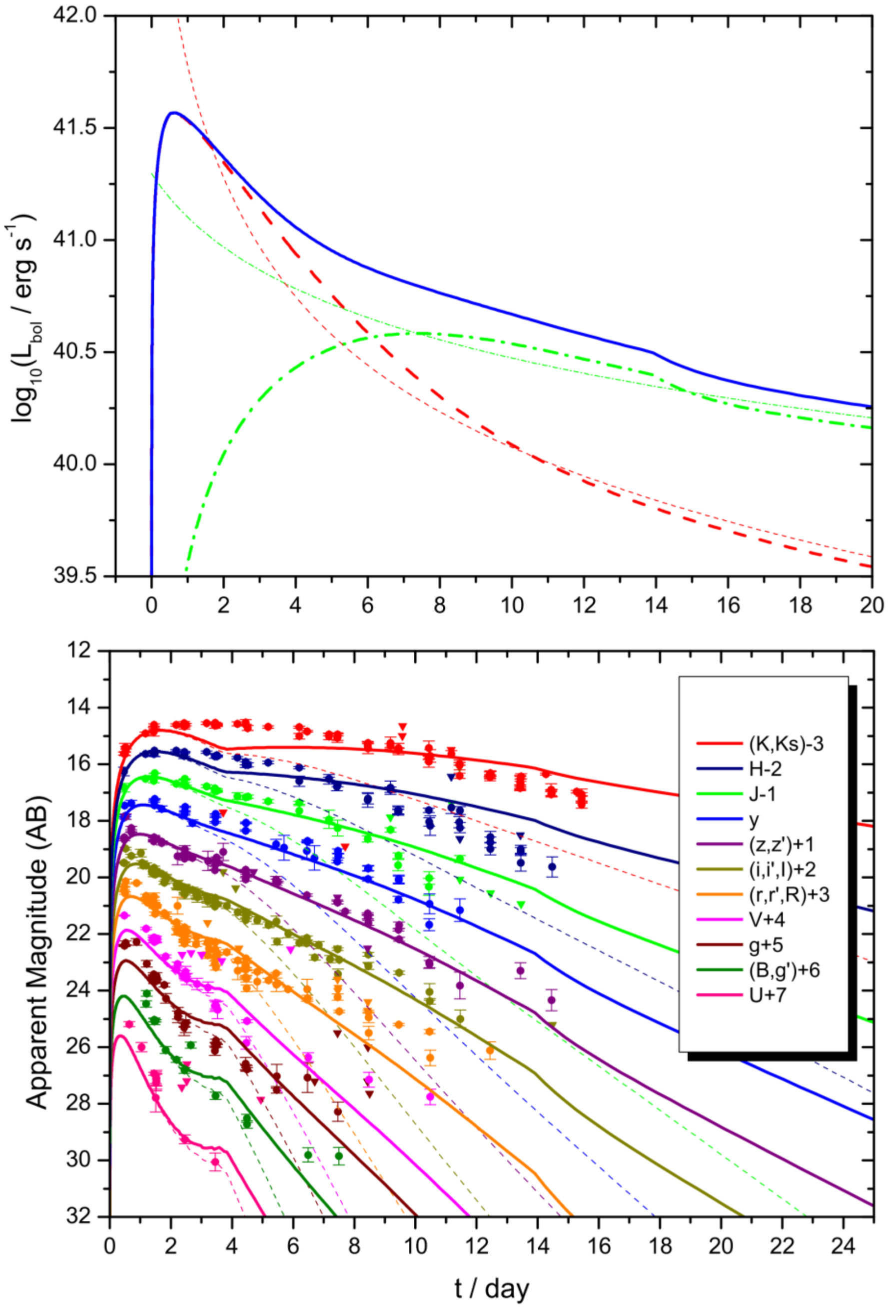
Possible signature for a long-lived NS remnant (Dai et al. 2006, Science, 311, 1127).

Talk by Bing Zhang at the 2nd GW workshop in Xiamen on 23-25 May 2018

Models for kilonova AT2017gfo

- **Radioactively-powered models**, but their inconsistencies: (1) The estimated mass for **red kilonova** (~0.01-0.1$M_\odot$) is more massive than the theoretical prediction (<0.01$M_\odot$) for dynamical ejecta; (2) The ejecta velocity required for **blue kilonova** (>0.1-0.3c) is too high for postmerger ejecta found in numerical simulations (~0.05c) (Shibata et al. 2017).

- **Pulsar-powered models**: a long-lived NS remnant (Yu, Liu & Dai 2018; Ai, Gao, Dai et al. 2018; Li, Liu, Yu & Zhang 2018).



Yu, Liu & Dai 2018, ApJ, in press: **A long-lived neutron star remnant after GW170817, in a hybrid-energy model.**

The ejecta parameters: opacity κ=0.97 cm^2/g, mass **M_{ej}=0.03$M_\odot$**, velocity v_{min}=0.10c, v_{max}=0.40c, & δ=1.46.

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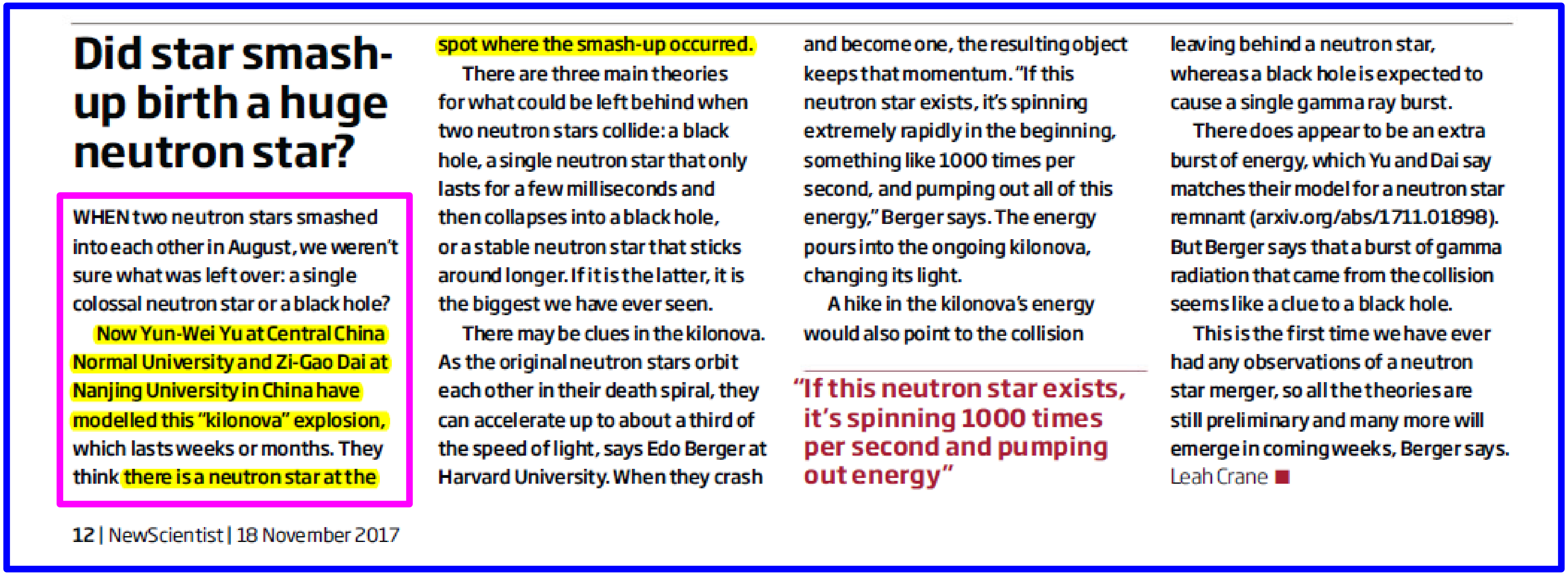


Did star smash-up birth a huge neutron star?

WHEN two neutron stars smashed into each other in August, we weren't sure what was left over: a single colossal neutron star or a black hole?

Now Yun-Wei Yu at Central China Normal University and Zi-Gao Dai at Nanjing University in China have modelled this "kilonova" explosion, which lasts weeks or months. They think there is a neutron star at the spot where the smash-up occurred.

There are three main theories for what could be left behind when two neutron stars collide: a black hole, a single neutron star that only lasts for a few milliseconds and then collapses into a black hole, or a stable neutron star that sticks around longer. If it is the latter, it is the biggest we have ever seen.

There may be clues in the kilonova. As the original neutron stars orbit each other in their death spiral, they can accelerate up to about a third of the speed of light, says Edo Berger at Harvard University. When they crash and become one, the resulting object keeps that momentum. "If this neutron star exists, it's spinning extremely rapidly in the beginning, something like 1000 times per second, and pumping out all of this energy," Berger says. The energy pours into the ongoing kilonova, changing its light.

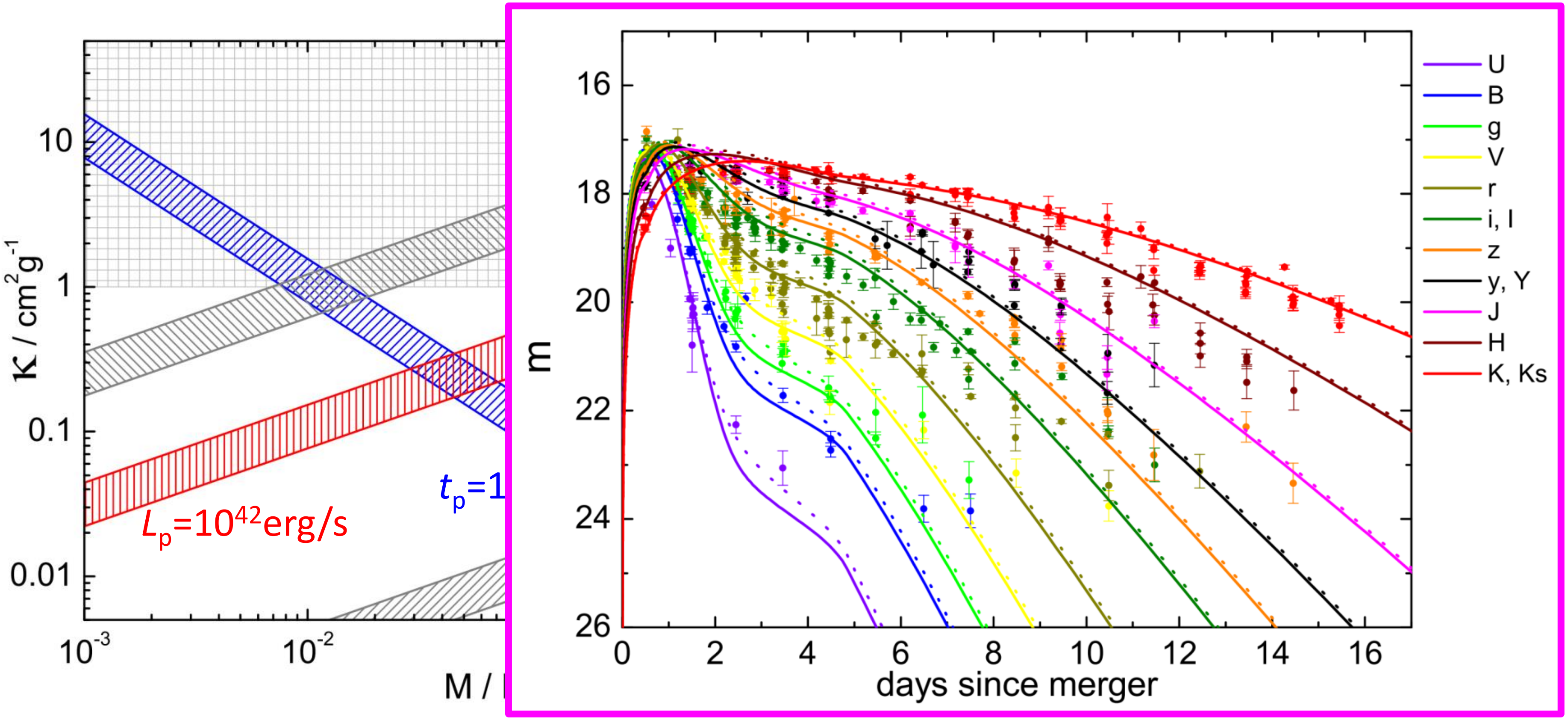
A hike in the kilonova's energy would also point to the collision leaving behind a neutron star, whereas a black hole is expected to cause a single gamma ray burst.

> "If this neutron star exists, it's spinning 1000 times per second and pumping out energy"

There does appear to be an extra burst of energy, which Yu and Dai say matches their model for a neutron star remnant (arxiv.org/abs/1711.01898). But Berger says that a burst of gamma radiation that came from the collision seems like a clue to a black hole.

This is the first time we have ever had any observations of a neutron star merger, so all the theories are still preliminary and many more will emerge in coming weeks, Berger says.
Leah Crane ■

No radioactivity, only pulsar power

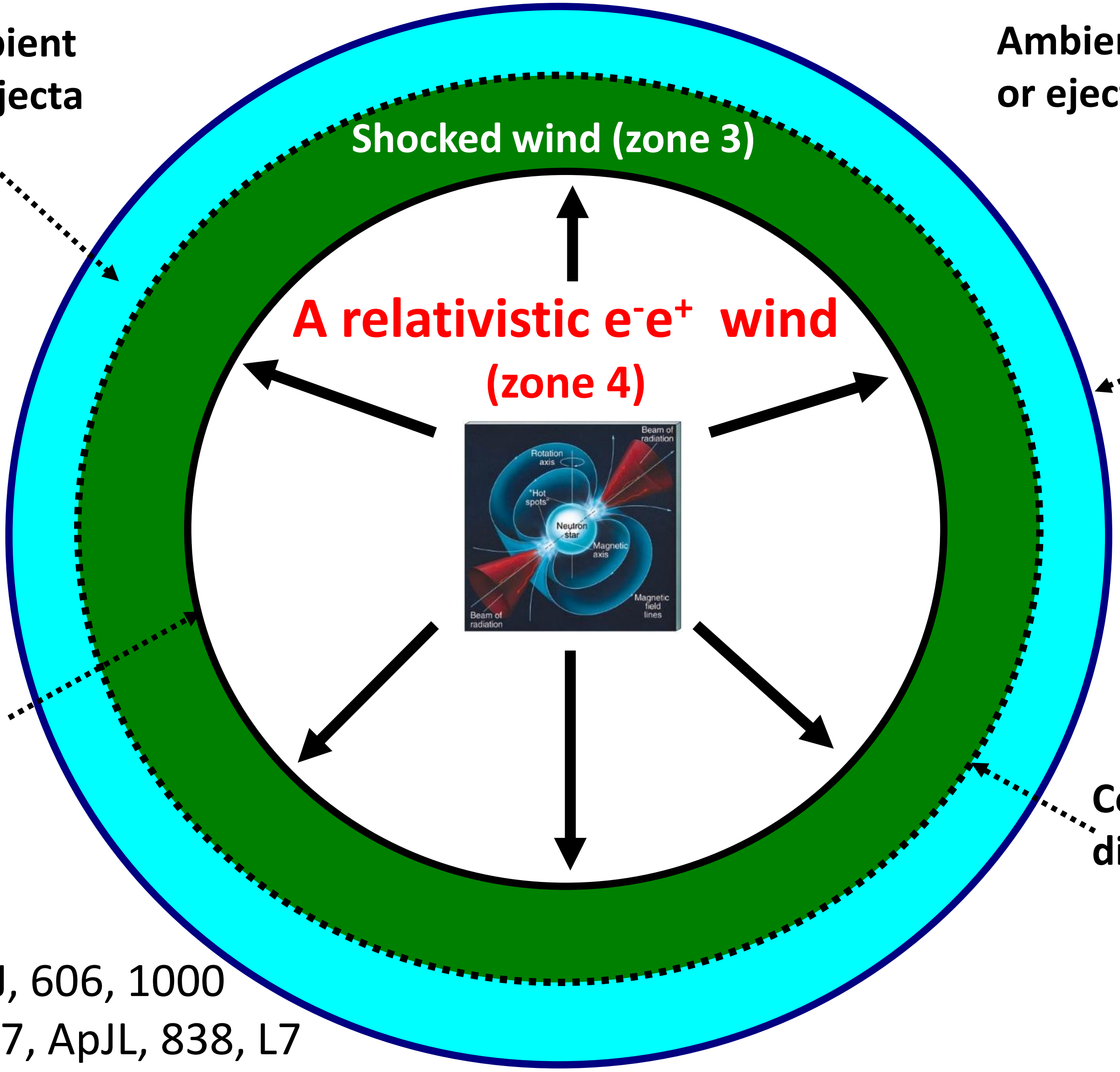


Li, Liu, Yu & Zhang, ApJL, in press: **$M_{ej}\approx 0.006M_{\odot}$**

Models for broadband afterglow

- **Jet with angular distribution** (**Structured jet**; Lazzati et al. 2017; Ruan et al. 2018; Lyman et al. 2018; Troja et al. 2018; Resmi et al. 2018; Gill & Granot 2018; Alexander et al. 2018)
- **Cocoon with radial distribution** (**Mass as a function of $\Gamma\beta$**; Mooley et al. 2018; Nakar & Piran 2018; Troja et al. 2018; Nakar, Gottlieb, Piran et al. 2018; Gill & Granot 2018)
- **Pulsar-powered relativistic jet** (Geng, Dai, Huang et al. 2018)

Relativistic Pulsar Wind Nebula



Shocked ambient medium or ejecta (zone 2)

Ambient medium or ejecta (zone 1)

Shocked wind (zone 3)

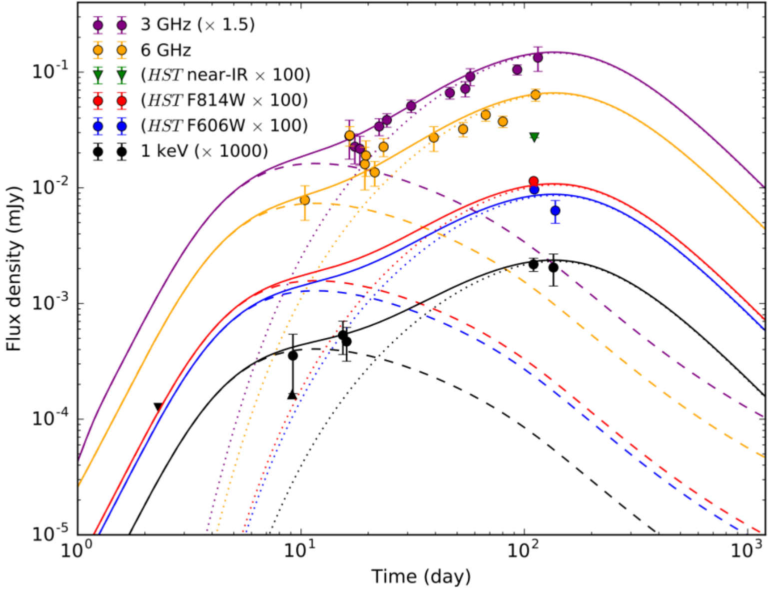
A relativistic $e^{-}e^{+}$ wind (zone 4)

Forward shock

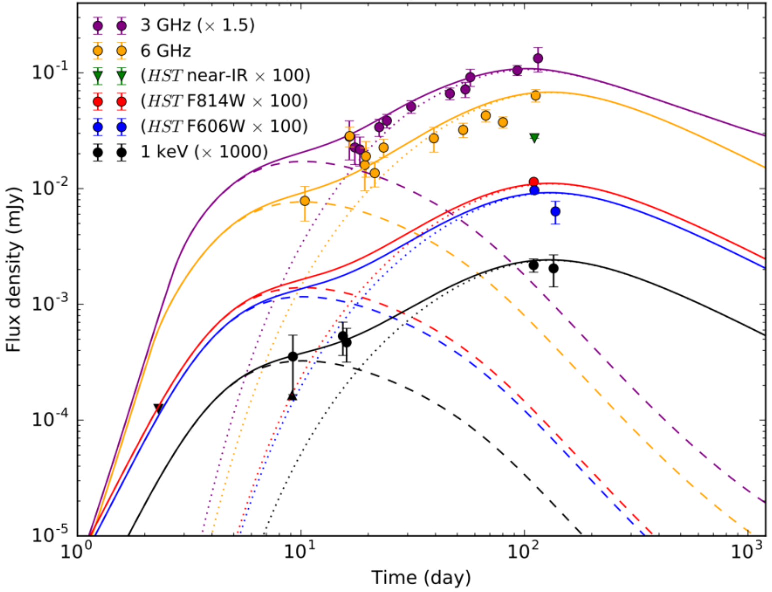
Reverse shock

Contact discontinuity

Dai 2004, ApJ, 606, 1000
Dai et al. 2017, ApJL, 838, L7



Spin-down by MDR



Spin-down by GW radiation

Pulsar-powered relativistic jet

(Geng, Dai, Huang et al. 2018, ApJL, 856, L33)

Parameters	MDR	GW radiation
θ_j	11°	10°
θ_V	20°	20°
$E_{\rm K,iso}{}^{\rm a}(10^{50}\ {\rm erg})$	5	2
$\Gamma_0{}^{\rm b}$	100	100
p_2	2.12	2.15
$\xi_{\rm e,2}$	0.012	0.05
$\xi_{B,2}$	0.003	0.002
$n_1\ ({\rm cm}^{-3})$	8×10^{-4}	8×10^{-4}
$B_{\rm NS}$ (G)	1.3×10^{13}	10^{12}
$\Gamma_4{}^{\rm c}$	10^4	10^4
p_3	2.17	2.17
$\xi_{B,3}$	2×10^{-7}	0.02
$\xi_{\rm e,3}$	$1 - \xi_{B,3}$	$1 - \xi_{B,3}$
σ	2×10^{-7}	0.02
ϵ	0	4.4×10^{-5}

This model is also consistent with position and polarization measurements (Lan et al. 2018)

Summary

- ✓ **GW170817 and its EM counterparts show that NS-NS mergers should be a physical origin of short GRBs.**

- ✓ **A long-lived NS remnant (~2.6$M_\odot$) provides an understanding of all the EM counterparts including an XRF and must rule out many soft equations of state for NS matter.**

- ✓ **GWB/GRB/FRB (and X-ray precursor), kilonova, and afterglow would provide probes of NS-NS merger processes.**