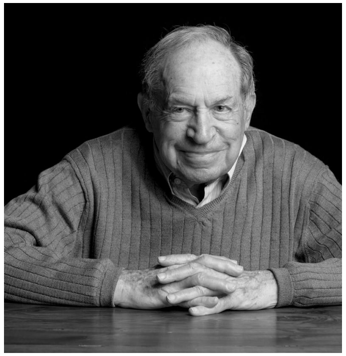
双中子星并合研究

过去、现在和未来

戴子高

中国科学技术大学天文学系

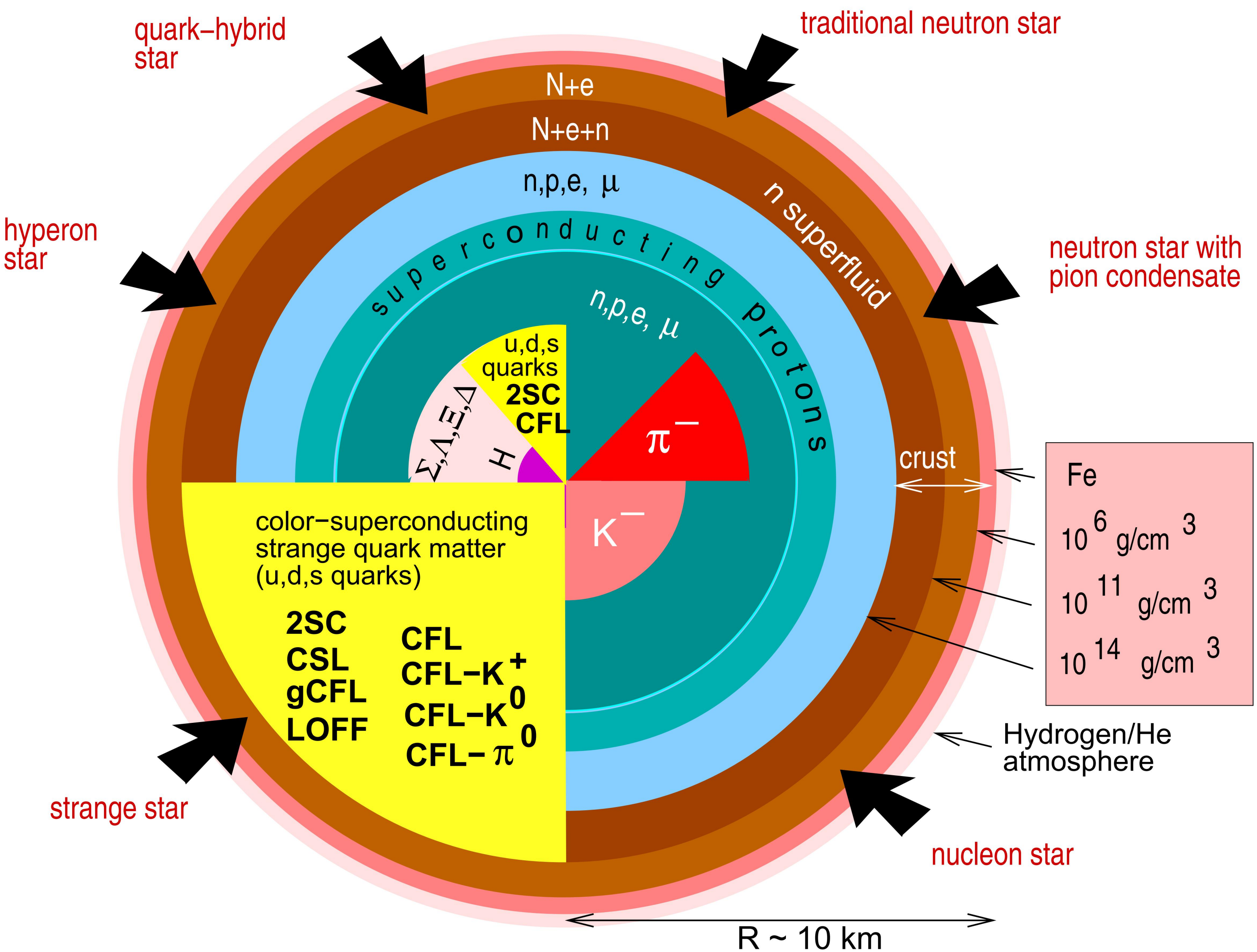
彭桓武高能基础理论研究中心学术报告，2021年9月3日



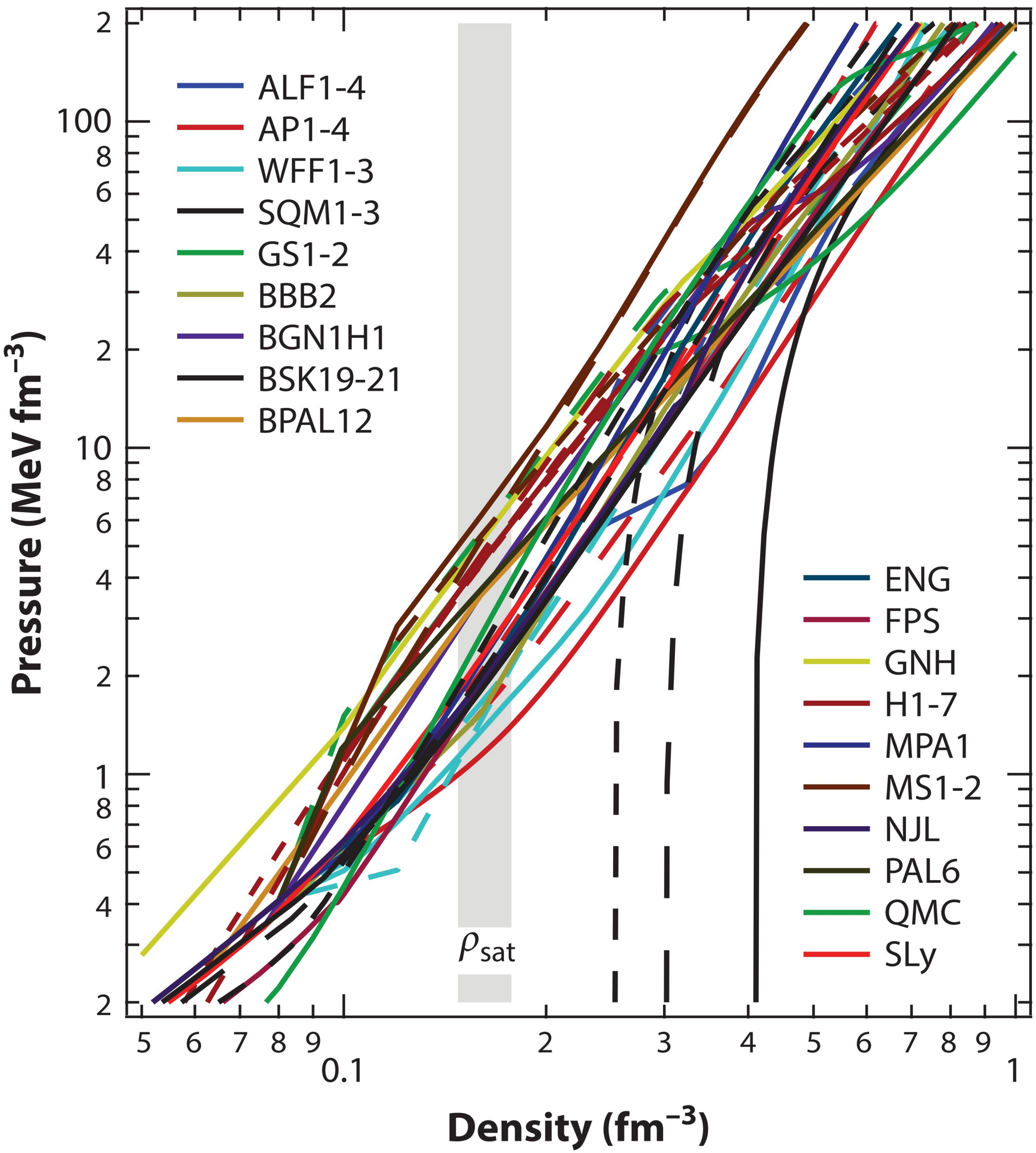
Pines Theorem (David Pines 1990)

Neutron Stars are Superstars.

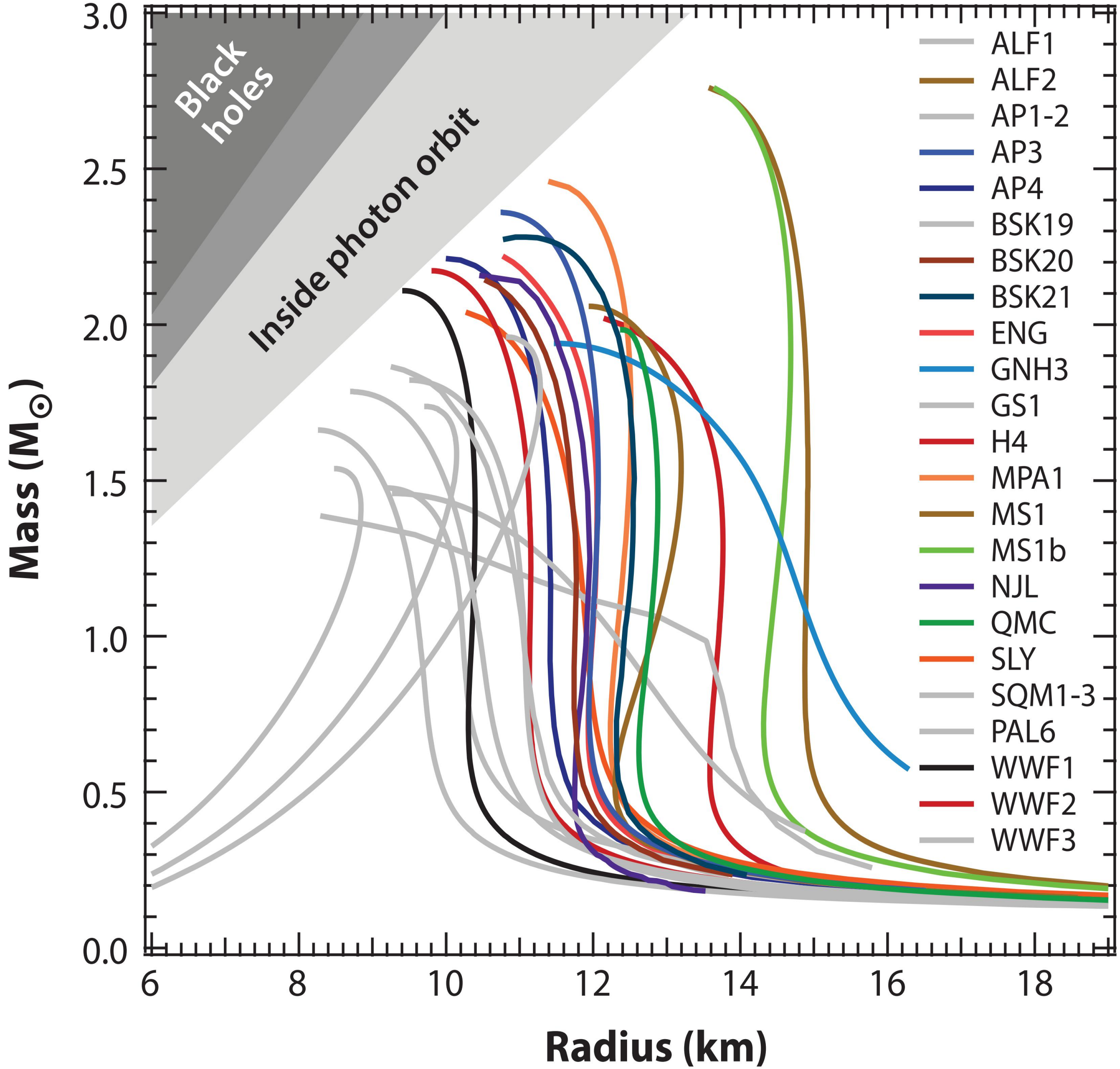
Proof: Neutron stars are ***super*dense** objects, ***super*fast** rotators, ***super*fluid** and ***super*conducting** inside, ***super*accelerators** of high-energy particles, sources of ***super*strong** magnetic fields, ***super*precise** timers, ***super*glitching** objects, and ***super*rich** in the range of physics involved. ✪ Neutron stars are related to ***many branches*** of contemporary physics and astrophysics.



Neutron star structure: Weber 2005, Prog.Part.Nucl.Phys., 54, 193

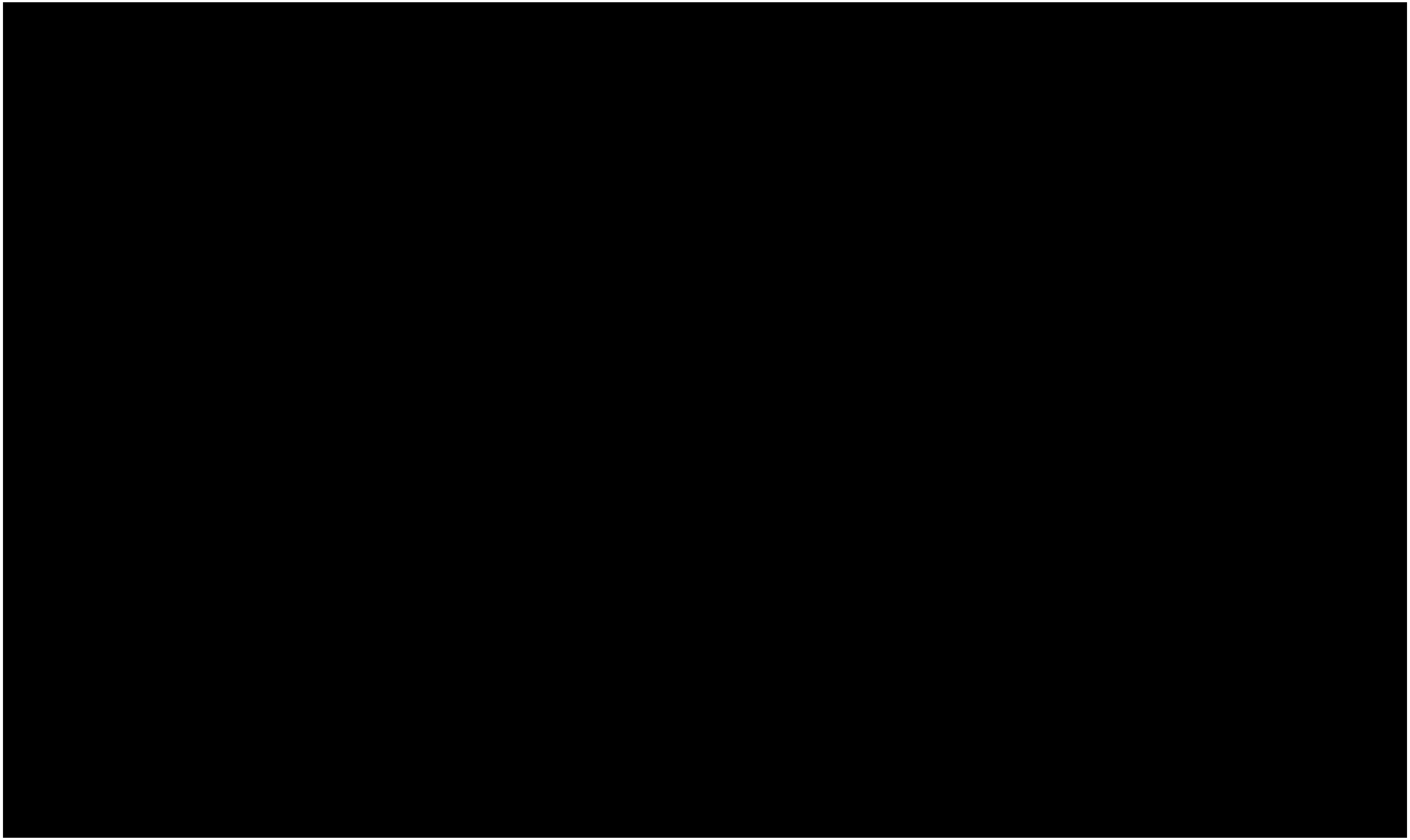


Neutron-star equations of state: Ozel & Freire, 2016, ARA&A, 54, 401



Neutron-star mass-radius relations: Ozel & Freire, 2016, ARA&A, 54, 401

BNS merger process



Outline

1. Short gamma-ray bursts
2. GW170817 from a BNS merger
3. EM signals from a BNS merger (γ-rays, kilonova, afterglow)
4. Models and conclusions
5. Questions and prospects

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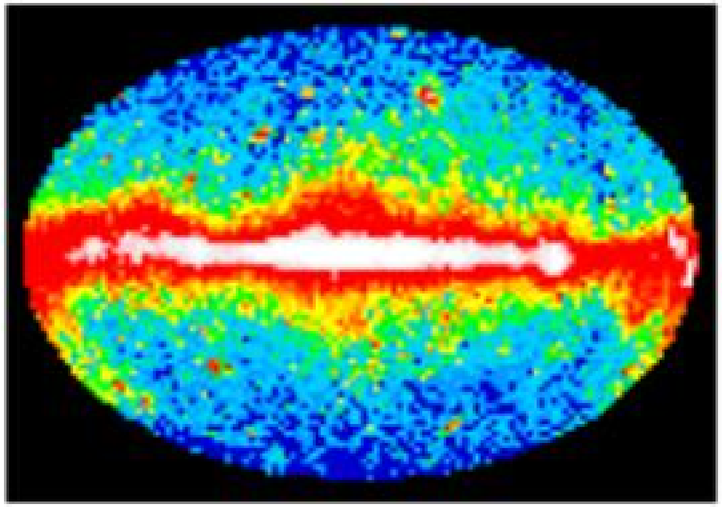
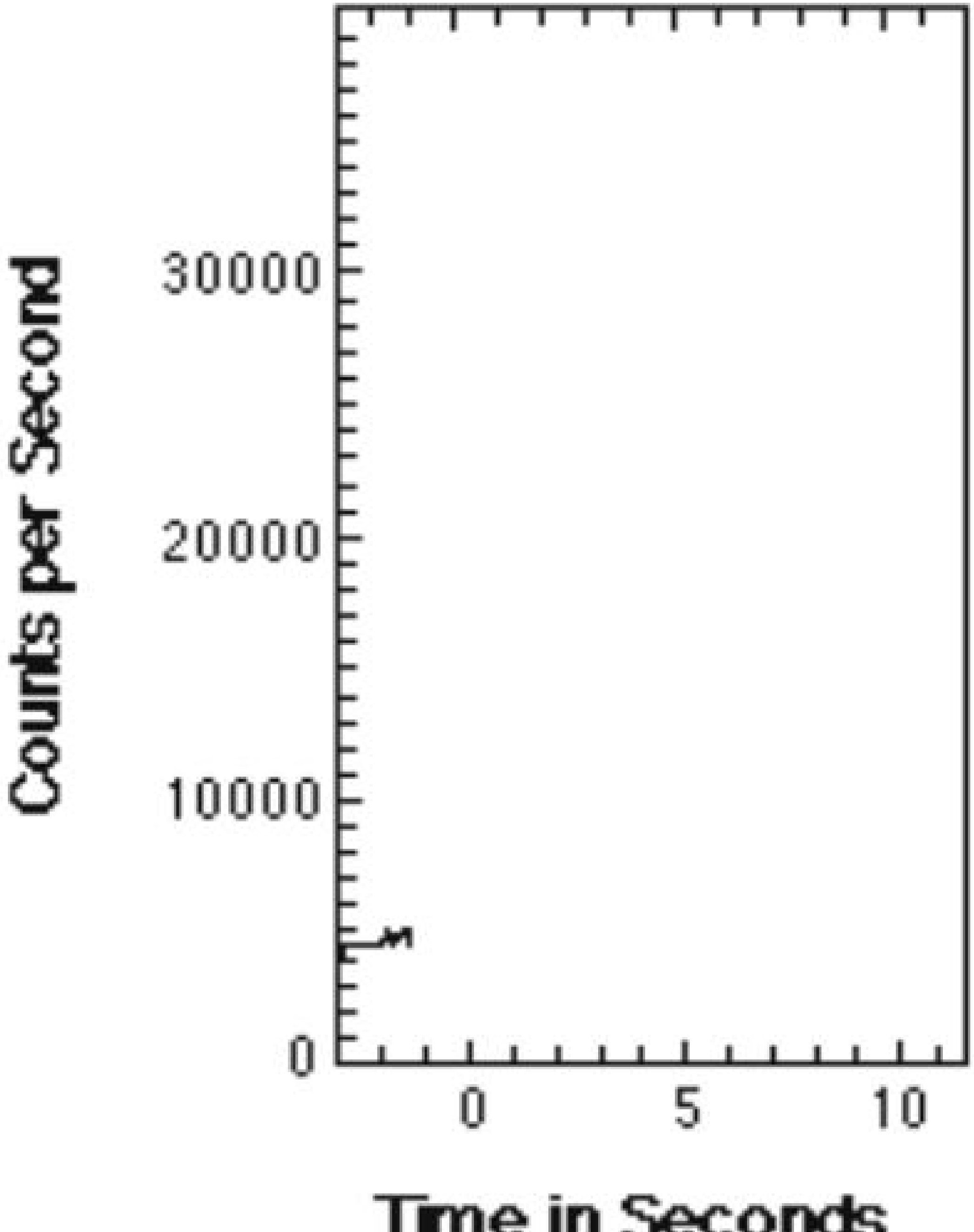




Counts per Second
30000
20000
10000
0
0
5
10
Time in Seconds

nary: PSR1913+16 (Hulse & eisberg 1982)

$$\dot{\omega} = \frac{6\pi G M_2 \sin i}{a_1 \sin i (1 - e^2) P c^2}$$

$$= \frac{3G^{2/3}(M_1 + M_2)^{2/3}}{(1 - e^2)c^2}\left(\frac{2\pi}{P}\right)^{5/3}$$

$$\gamma = \frac{G^{2/3} M_2 (M_1 + 2M_2) e}{(M_1 + M_2)^{4/3} c^2}\left(\frac{P}{2\pi}\right)^{1/3}$$

$$= (0.0007344 \text{ s}) M_2 (2.8278 + M_2)$$

$$\dot{P} = \frac{-192\pi}{5} \frac{G^{5/3} M_1 M_2 f(e)}{c^5 (M_1 + M_2)^{1/3}}\left(\frac{2\pi}{P}\right)^{5/3}$$

$$= -1.202 \times 10^{-12} M_2 (2.8278 - M_2)$$

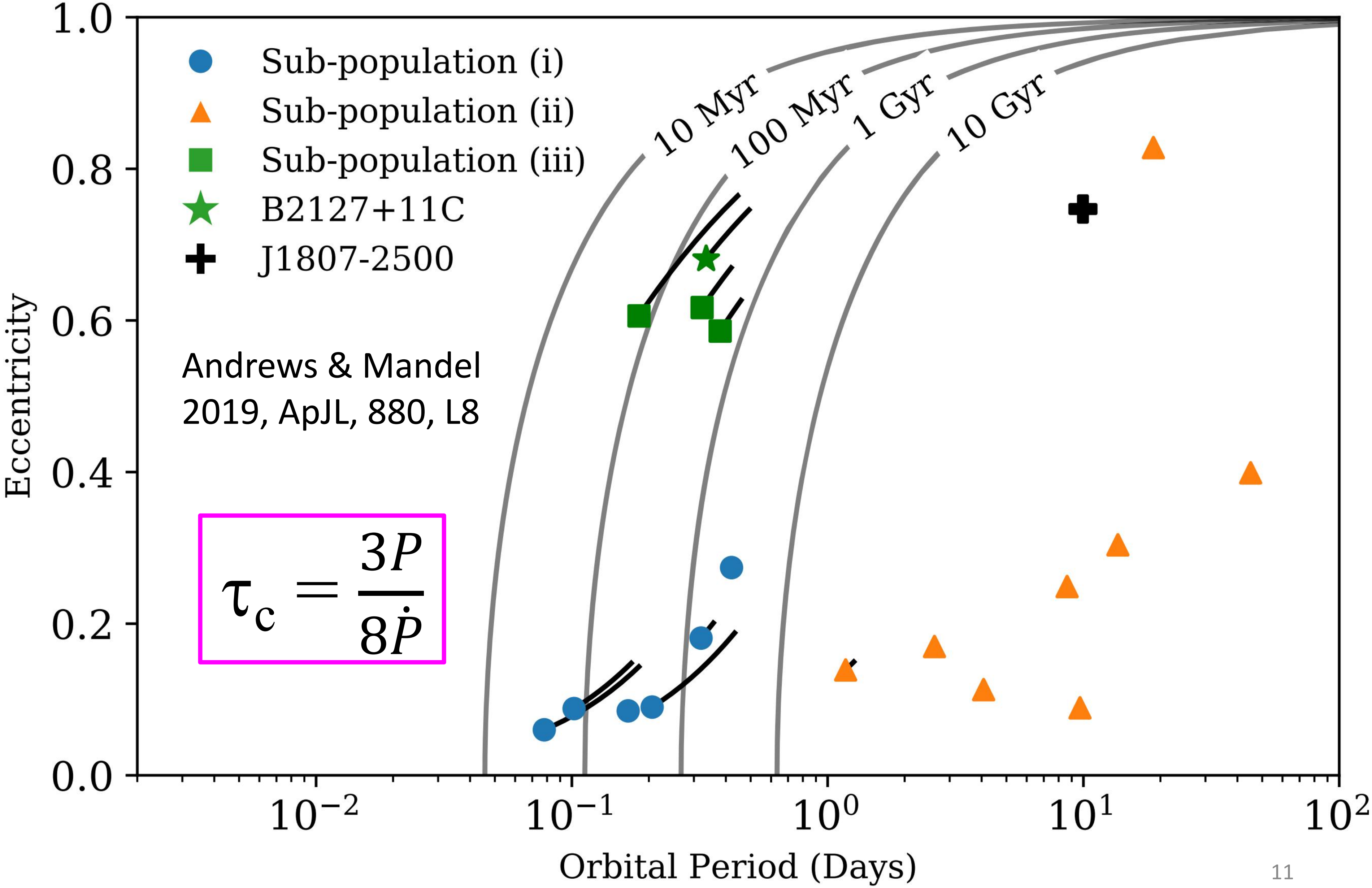
Parameters for the Binary Pulsar[a]

Parameter	Value
P_p (s)	0.0590299952709(20)
$\dot{P}_p$ (10^{-18})	8.628(20)
$\ddot{P}_p$ (10^{-30} s^{-1})	−58(1200)
$(a_1 \sin i)/c$ (s)	2.34186(24)
e **Eccentricity**	0.617139(5)
P (s) **Orbital period**	27906.98161(3)
ω (deg)	178.8656(15)
T_0 (Julian Day No.)	2442321.4332092(15)
$\dot{\omega}$ (deg yr^{-1})	4.2261(7)
γ (s)	0.00438(24)
$\dot{P}$ (10^{-12})	−2.30(22)

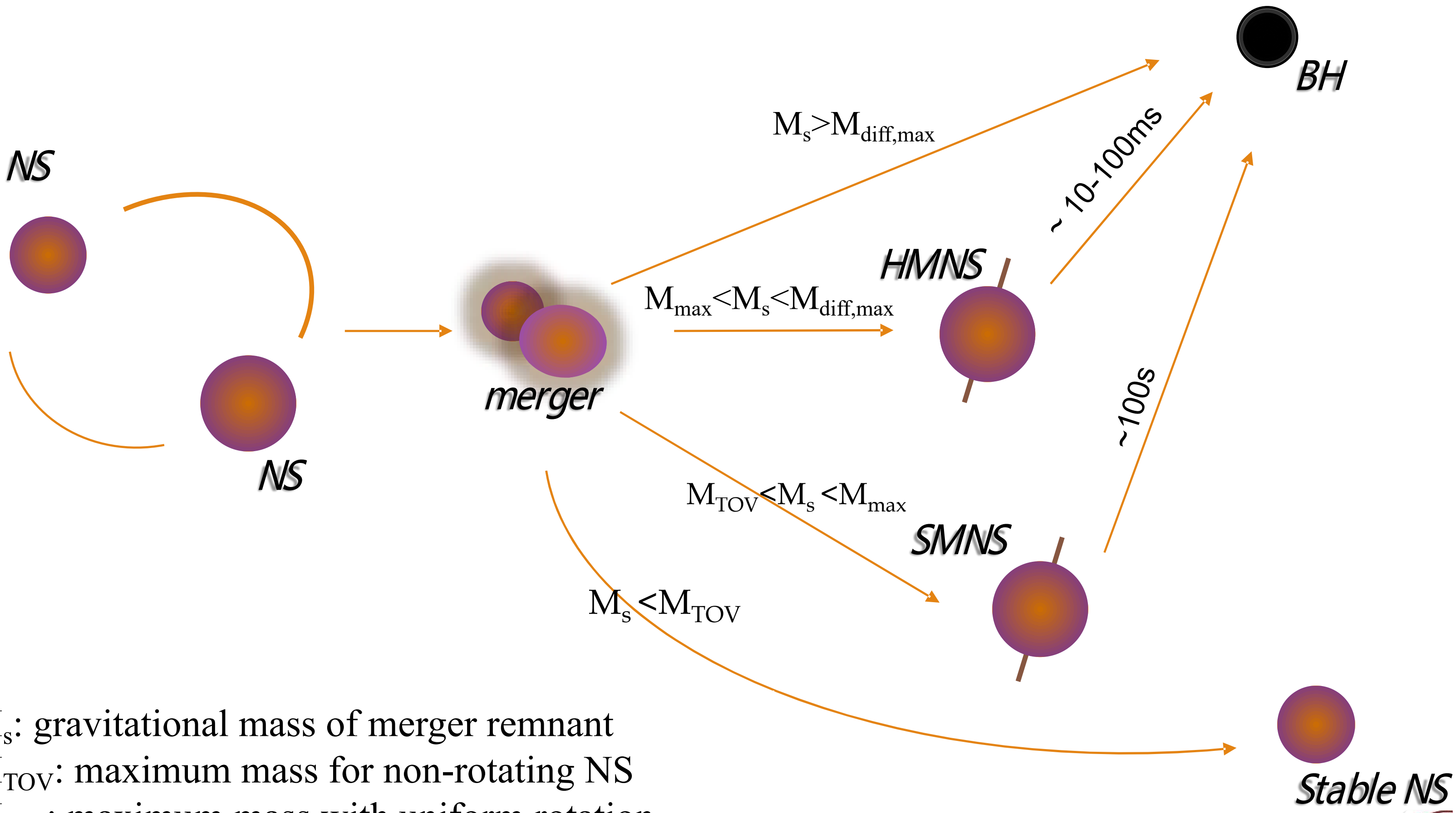
Periastron advance

- GR predicts **-2.40×10^{-12}**, proving gravitational waves. **1993 Nobel Prize** motivates LIGO's detections.

19 BNS Systems in our Galaxy

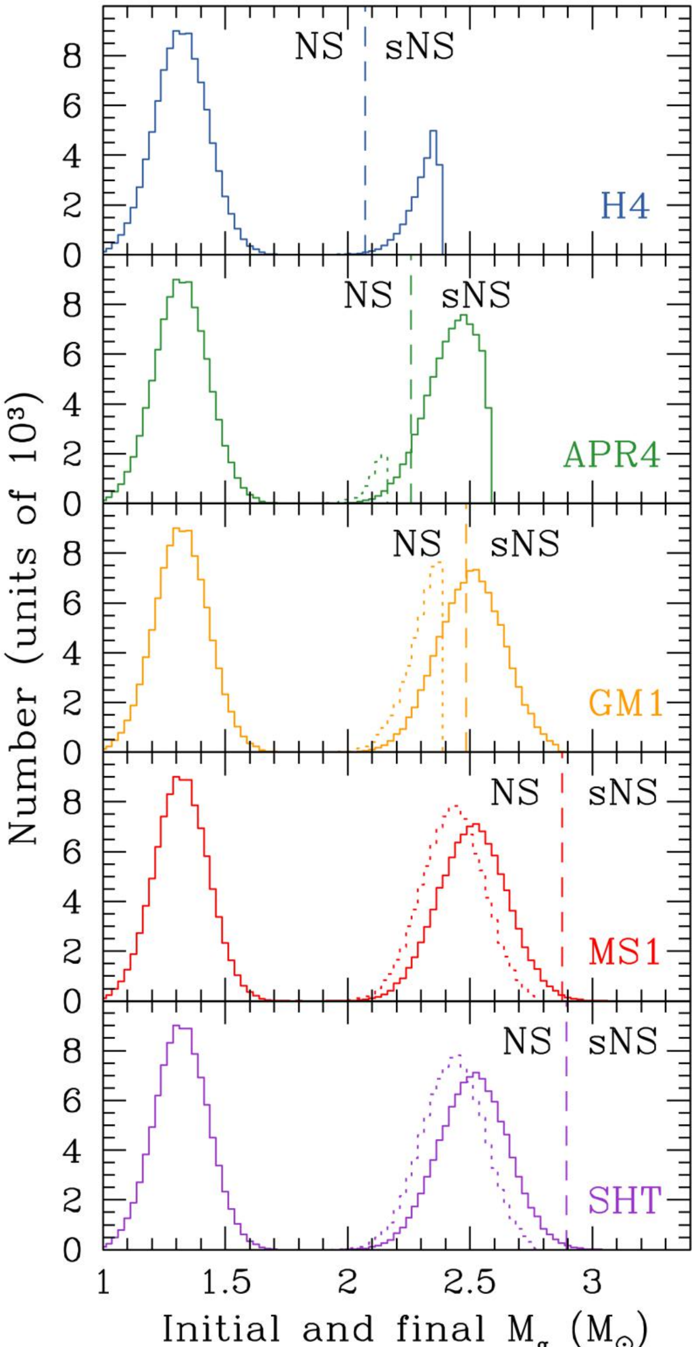


Central engines post BNS mergers



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

From Bing Zhang



Piro, Giacomazzo & Perna 2017, ApJL, 844, L19: "The fate of binary NS mergers" by Monte Carlo techniques

NS – stable NS
sNS – supramassive NS

Right two bumps:
Solid lines – mass shedding
Dotted lines – no spin

- The merger of a NS-NS binary as a potential GRB progenitor was briefly mentioned in Blinnikov et al. (1984), Paczynski (1986), Goodman (1986), and Goodman et al. (1987).
- The association of NS-NS mergers with GRBs was discussed in detail for the first time by Eichler et al. (1989, Nature) and later by Narayan et al. (1992).
- Similar models of a BH-NS binary as a possible progenitor were discussed by Paczynski (1991), Narayan et al. (1992), and Mochkovitch et al. (1993).
- Two post-merger central engines were proposed: (I) BHs + accretion disks, (II) millisecond magnetars.

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

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

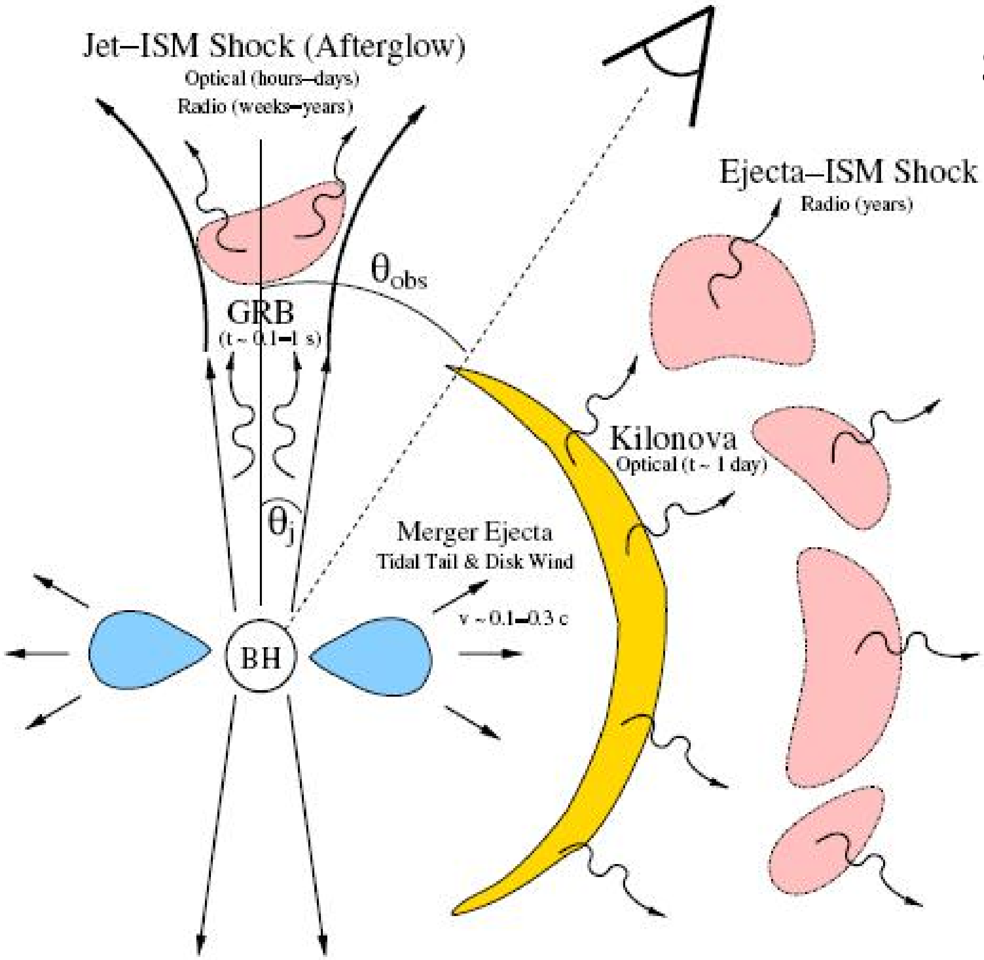
$$t_{acc} = 0.2 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{M_{BH}}{3\,M_\odot}\right)^{13/7} \left(\frac{M_d}{0.1\,M_\odot}\right)^{-2/7} \left(\frac{R_d}{10 R_s}\right)^{3/2} s$$

➢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 $\sim$ 0.01-0.001, $E_{\rm jet} \sim 10^{49}(M_{\rm disk}/0.1M_{\odot})$ erg.

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

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

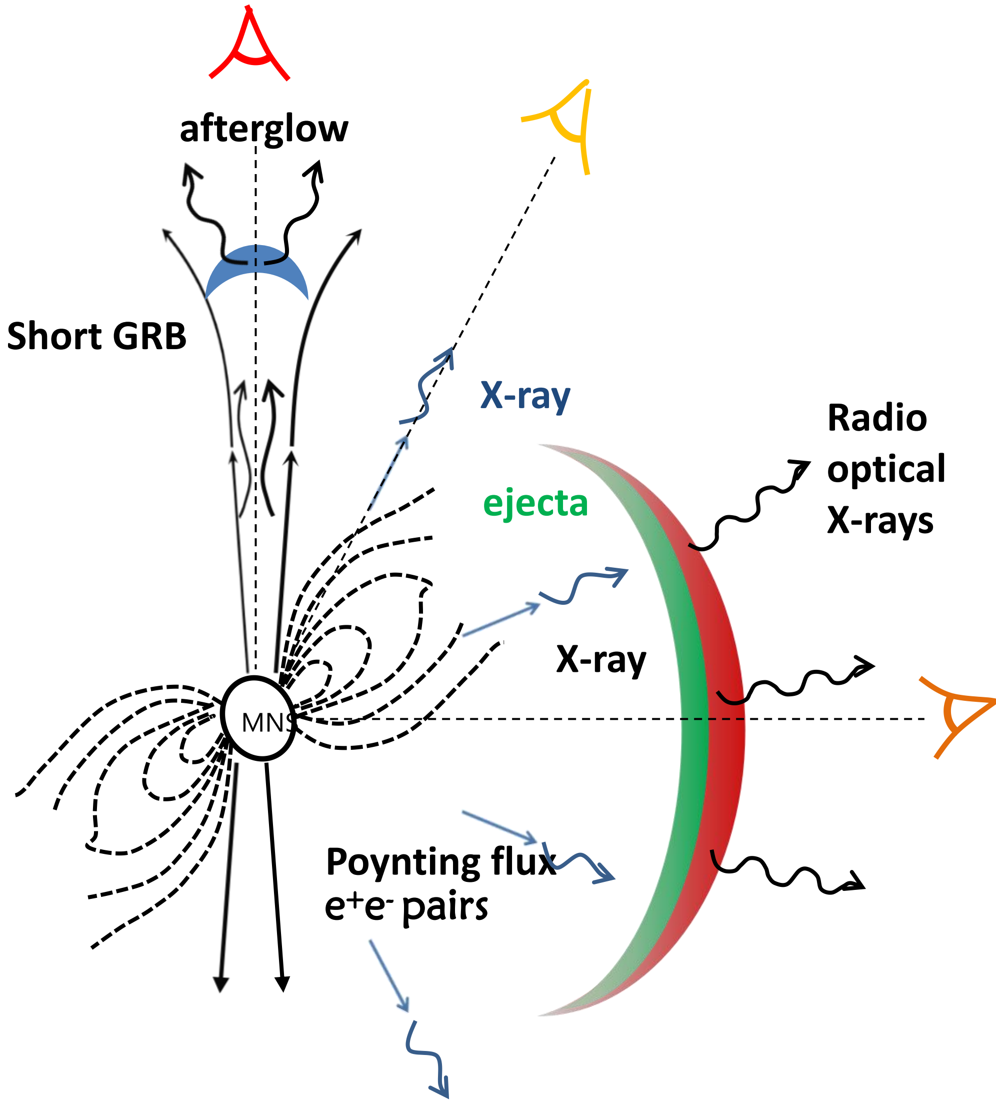
Nakar & Piran 2011

Radio afterglows
Duration ~ years

(II) Millisecond magnetars

- 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, Science, 311, 1127; 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).

EM signals from post-merger magnetars



From Xuefeng Wu

Short GRBs and afterglows

Long-lasting activity

➔ plateaus and flares

Dai & Lu 1998a, 1998b; 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

Why short GRBs/NS-NS or NS-BH mergers?

- **The energy release $E_{iso} \sim 10^{48} - 10^{51}$ erg, and the duration is a fraction of one second;**
- **The medium density $n \sim 10^{-4}$-10^{-2} cm^{-3};**
- **The host galaxies are old and short GRBs are usually in their outskirts (~ 10-100 kpc);**
- **No supernovae are associated with short GRBs.**

➔ Support NS-NS or NS-BH merger models!

Only indirect evidence for these models!

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

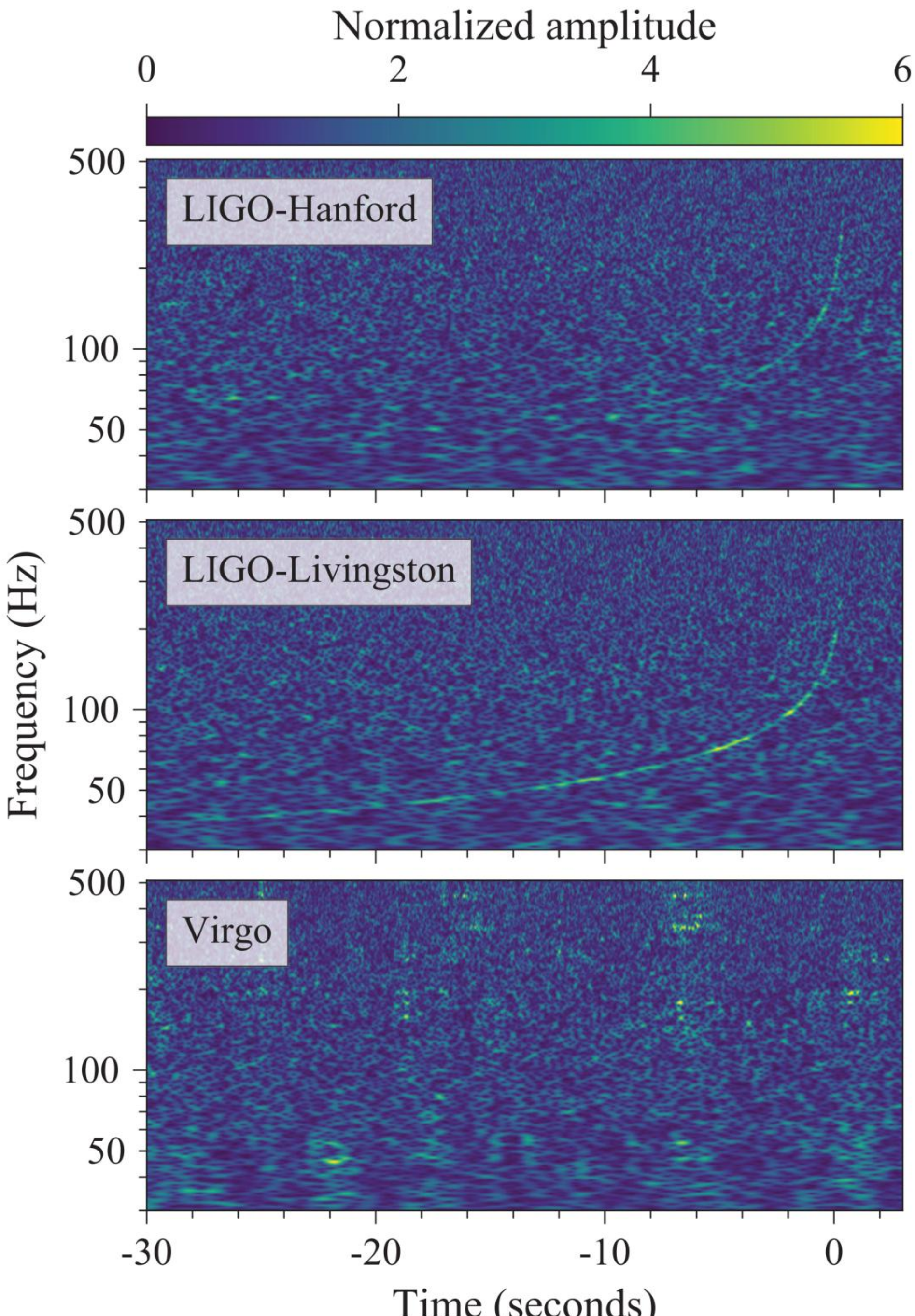
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the 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 coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

GW170817及其电磁波信号的位置



GW170817

At early times, for low orbital and GW frequencies, the chirp-like time evolution of the GW frequency is determined primarily by the **chirp mass** (a specific combination of the component masses m_1 and m_2).

As the orbit shrinks and the GW frequency grows rapidly, the GW phase is increasingly influenced by relativistic effects related to the **mass ratio** $q = m_2/m_1$, where $m_1 \geq m_2$, as well as spin-orbit and spin-spin couplings.

Abbott et al. 2017, PRL, 119, 161101

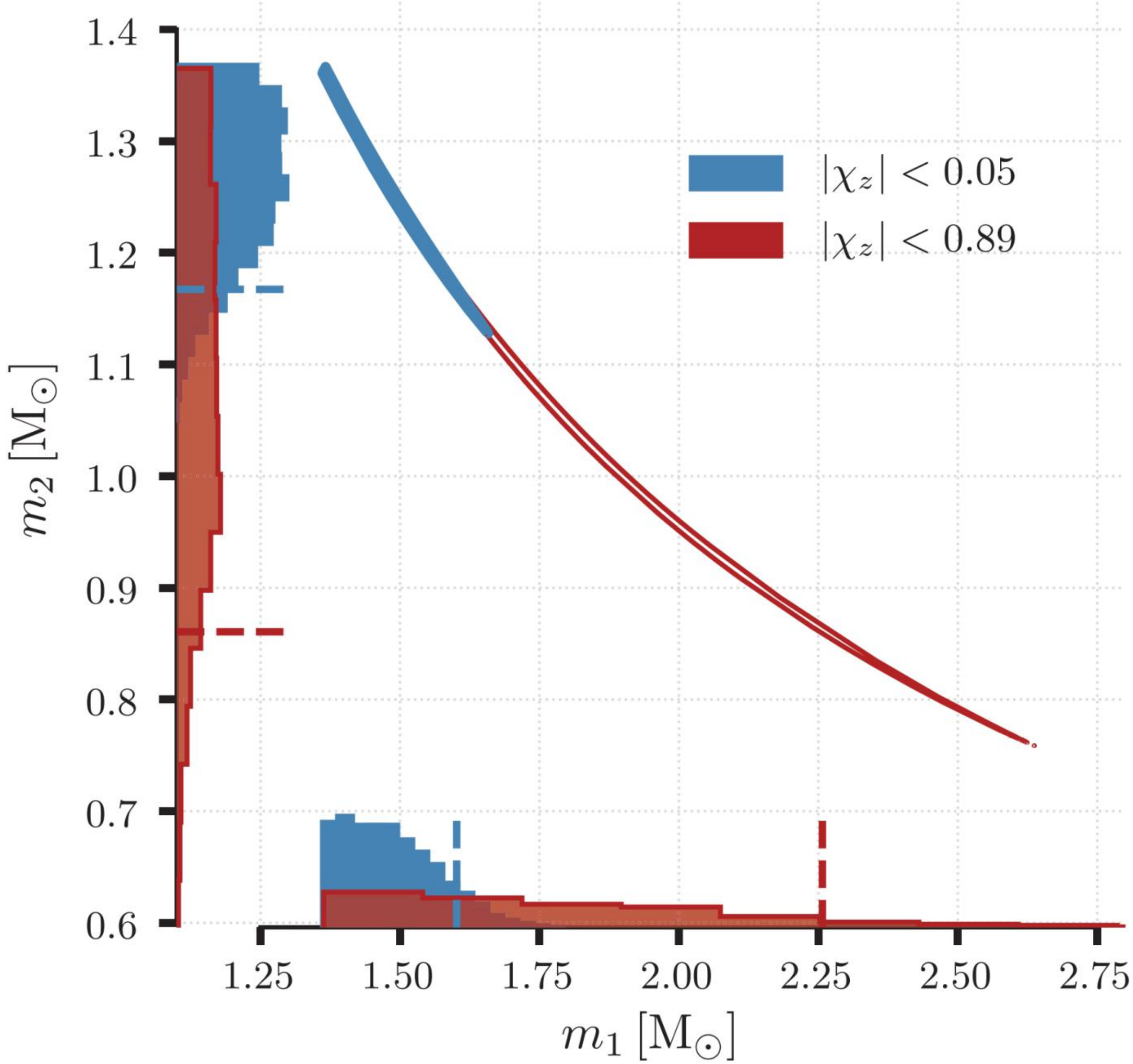
Some key equations

Chirp mass: $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$

Tidal Love number k_2: $Q_{ij} = -k_2 \frac{2R^5}{3G} E_{ij}$ (Love 1909)

Tidal deformability: $\Lambda = (2/3) k_2 \left[(c^2/G)(R/m)\right]^5$

➔ $\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$

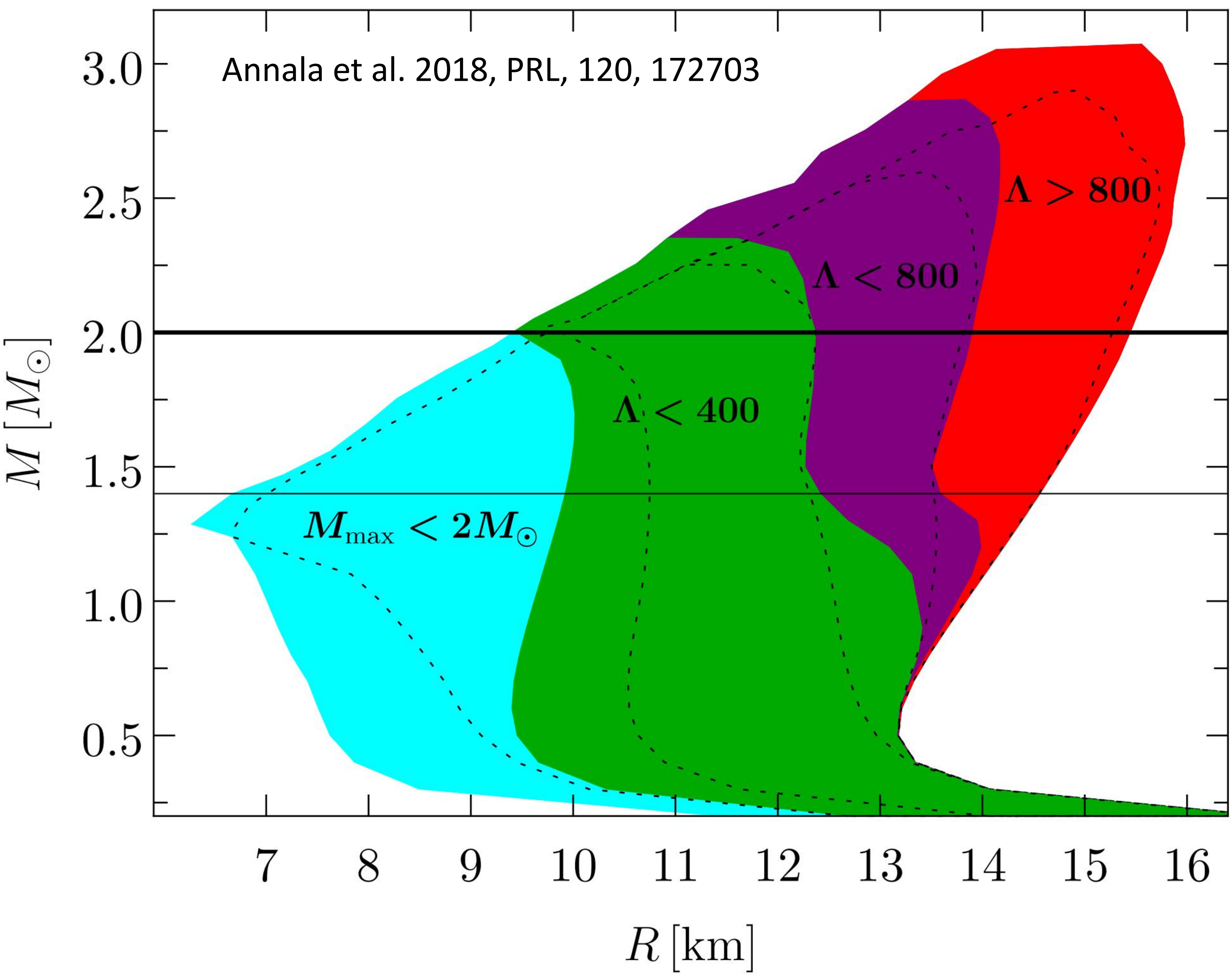


Abbott et al. 2017, PRL, 119, 161101

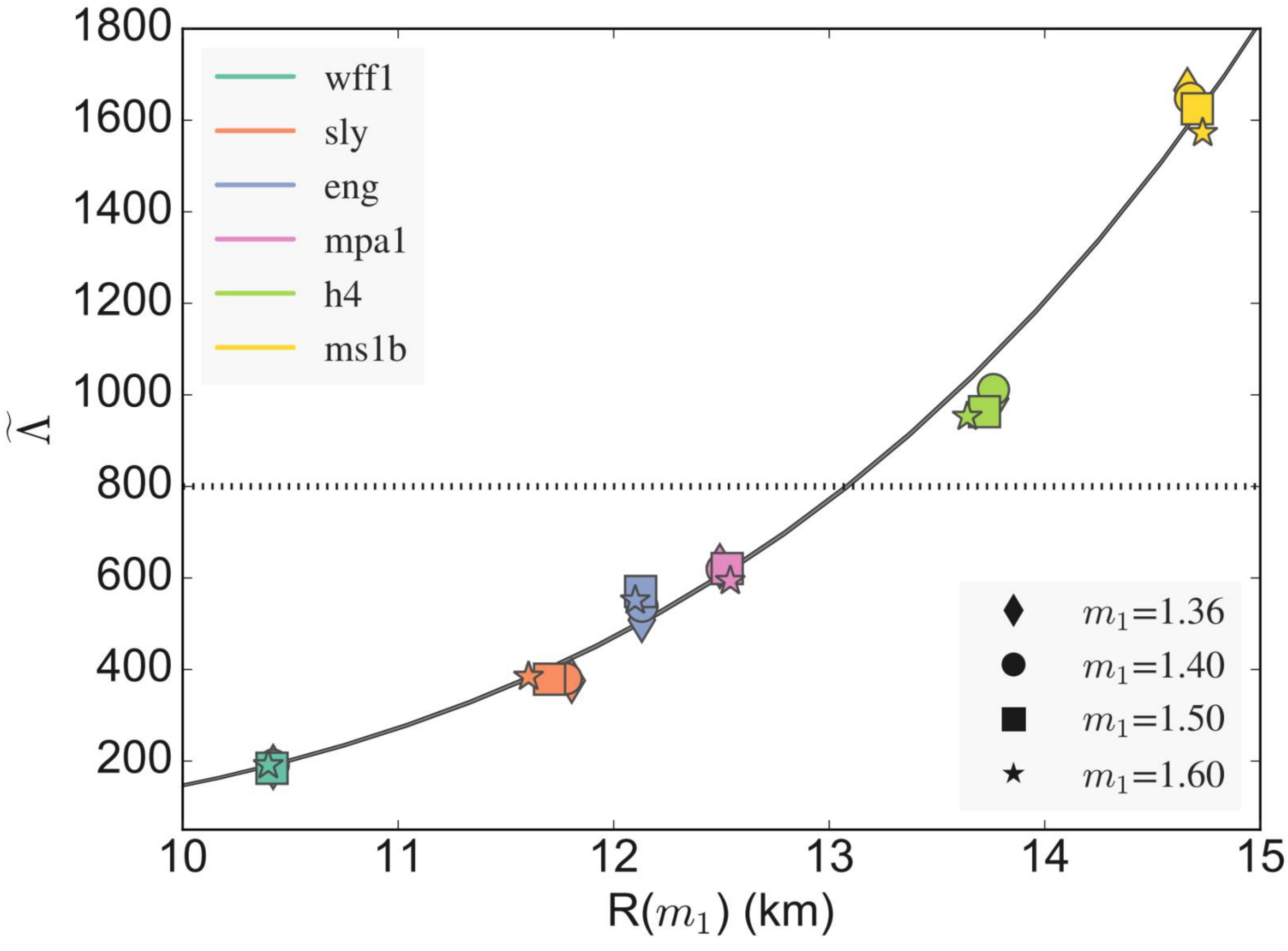
Source properties for GW170817

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

Abbott et al. 2017, PRL, 119, 161101


Annala et al. 2018, PRL, 120, 172703
3.0
2.5
2.0
1.5
1.0
0.5
$M\,[M_\odot]$
7
8
9
10
11
12
13
14
15
16
$R\,[\mathrm{km}]$
$\Lambda > 800$
$\Lambda < 800$
$\Lambda < 400$
$M_{\max} < 2M_\odot$

Constraint on neutron-star radius



Raithel, Ozel & Psaltis 2018, ApJL, 857, L23

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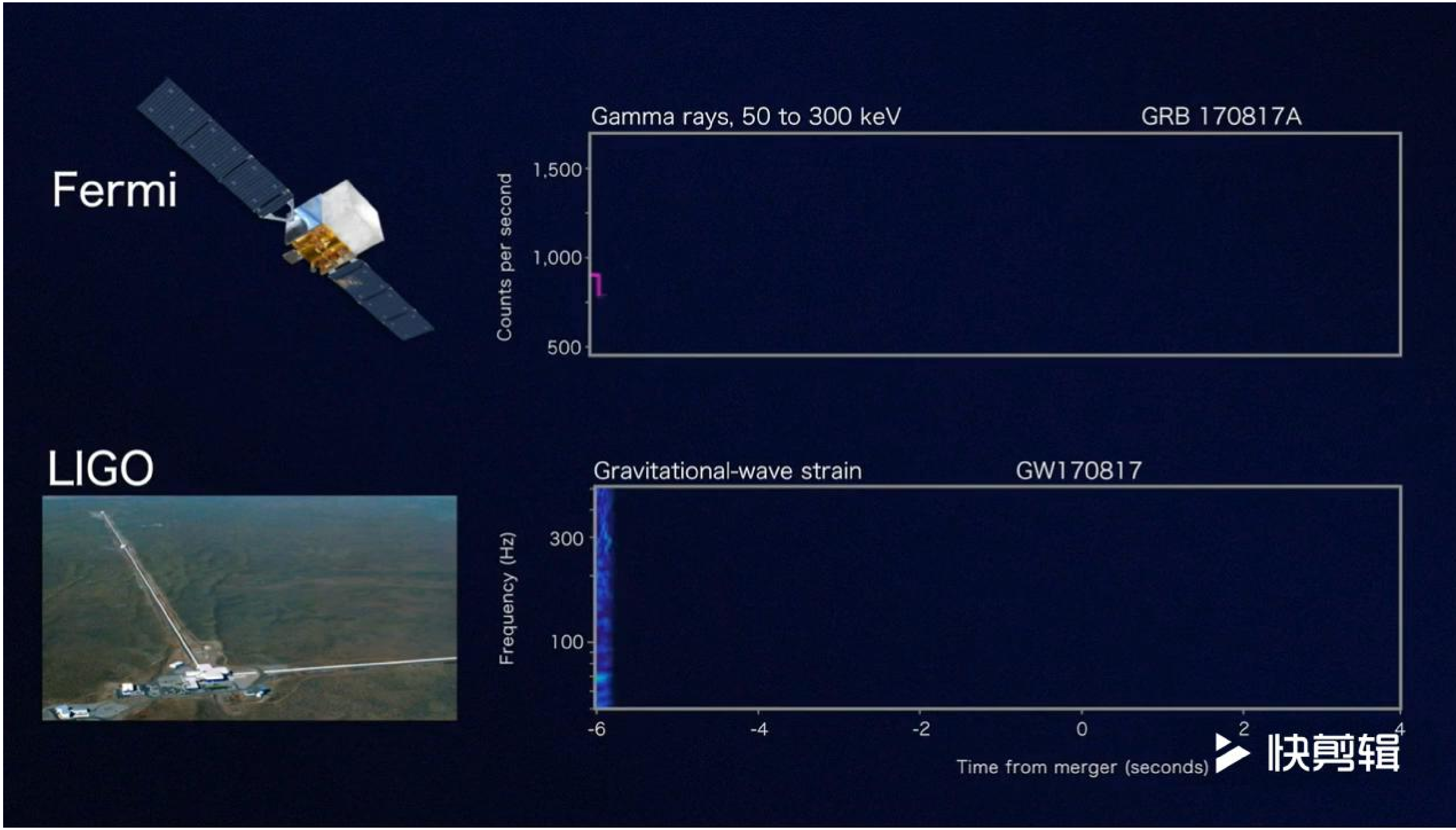
(I) GRB170817A

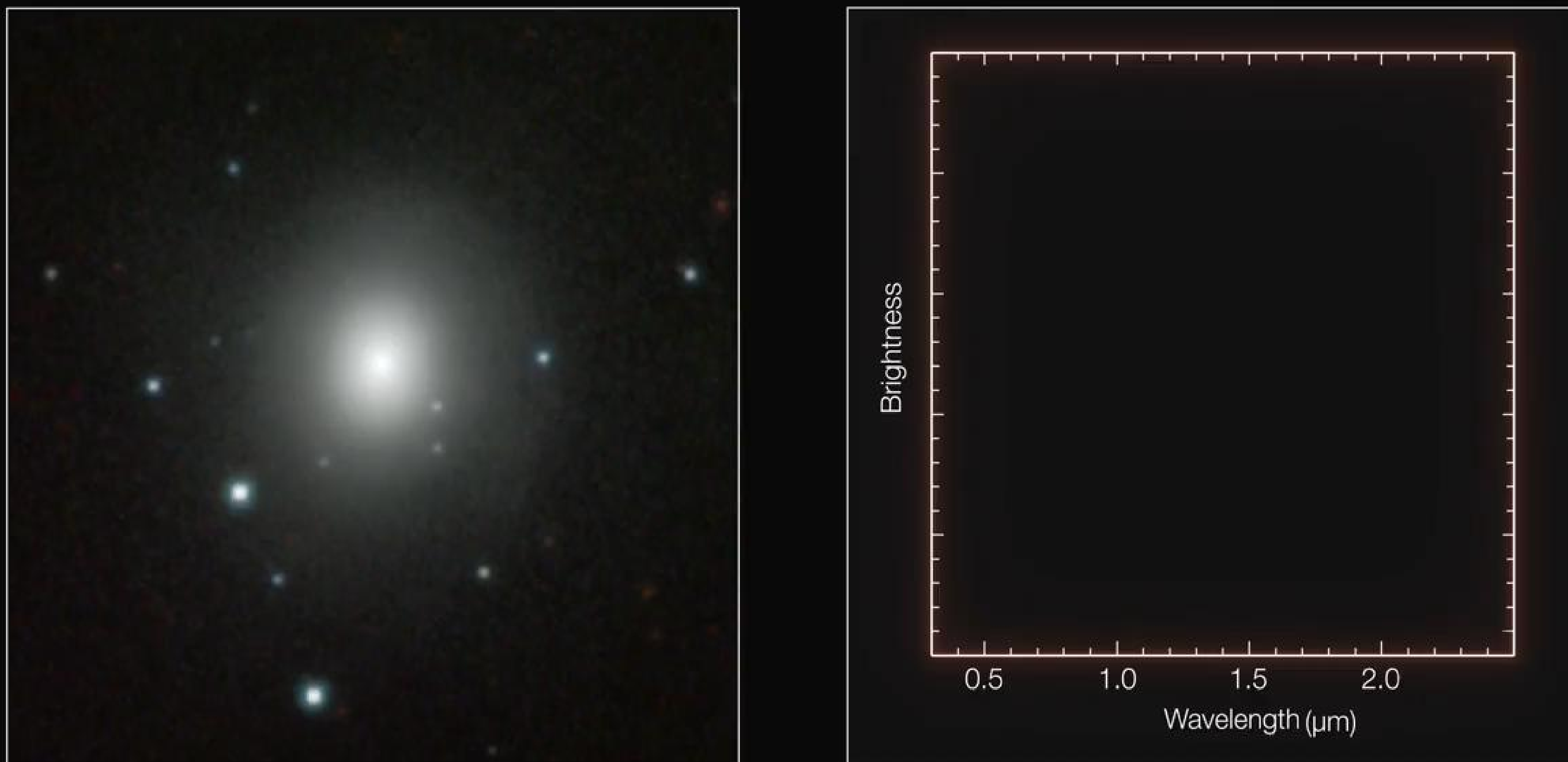


Properties of GRB 170817A

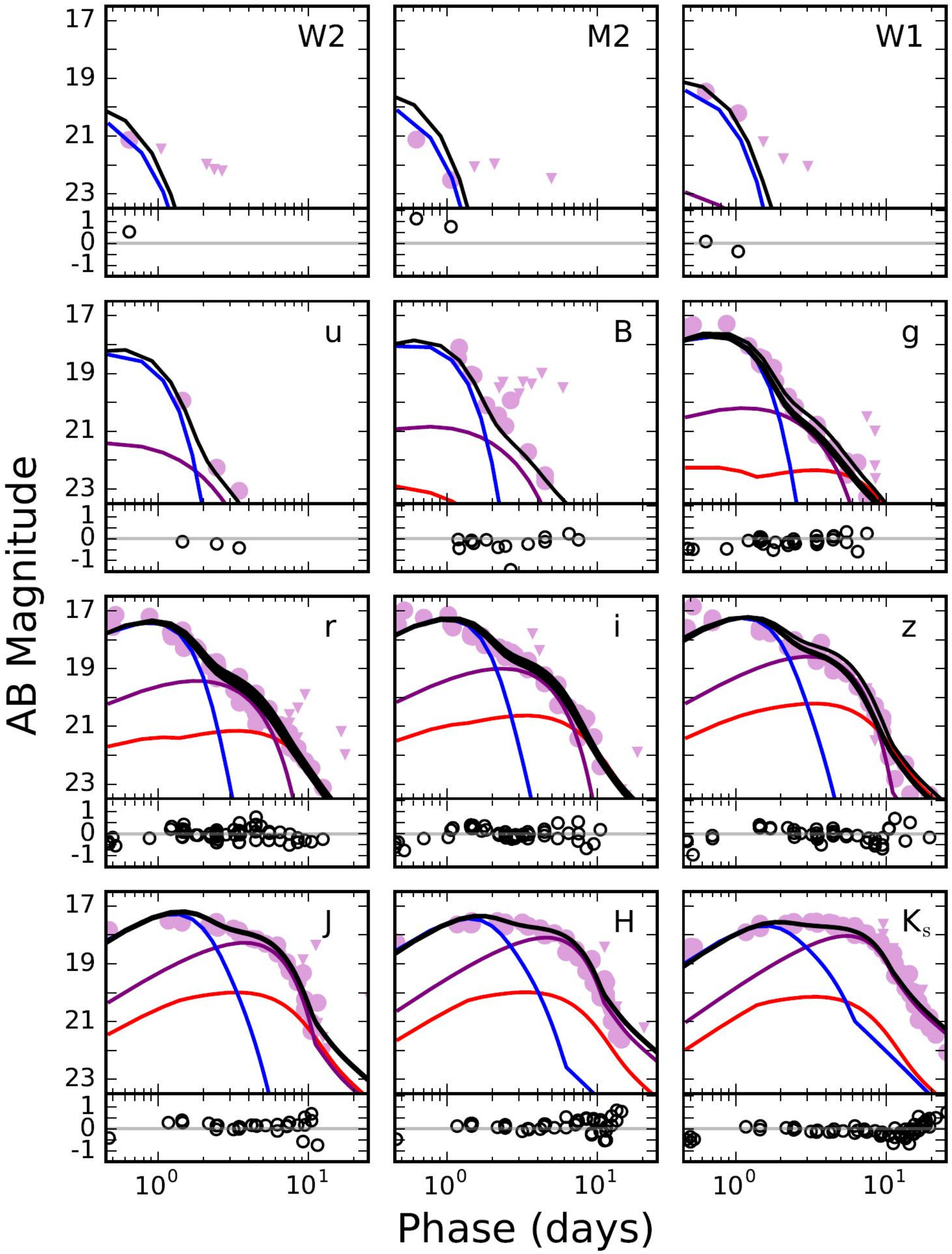
total spanning duration (s)	$\sim$2.05
spectral peak energy (first peak) E_p (keV)	$158.1^{+180.4}_{-33.7}$
total fluence (erg cm^{-2})	$(4.46 \pm 0.1) \times 10^{-7}$
spectral lag (25-50 keV vs 50-100 keV)	0.03 ± 0.05 s
redshift z	~ 0.009
luminosity distance D_{L} (Mpc)	39.472
total isotropic energy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

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

(II) Kilonova: AT2017gfo



Time: -1225 days



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

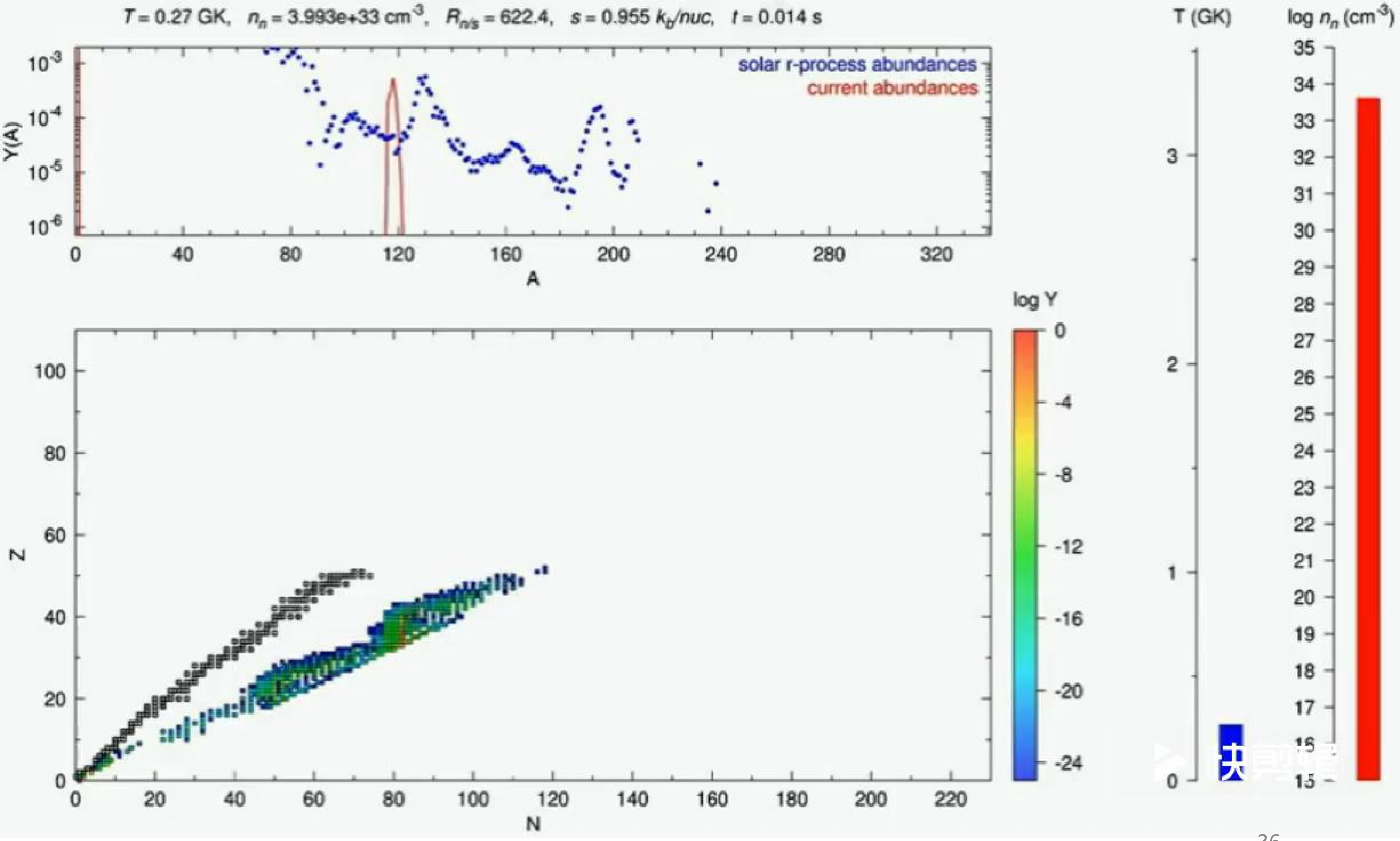
① a **blue** lanthanide-poor component (≈0.5cm²/g, M_{ej}≈0.016$M_\odot$ &v_{ej}≈0.27c);

② an intermediate opacity **purple** component (≈3cm²/g, M_{ej}≈0.040$M_\odot$ & v_{ej}≈0.14c);

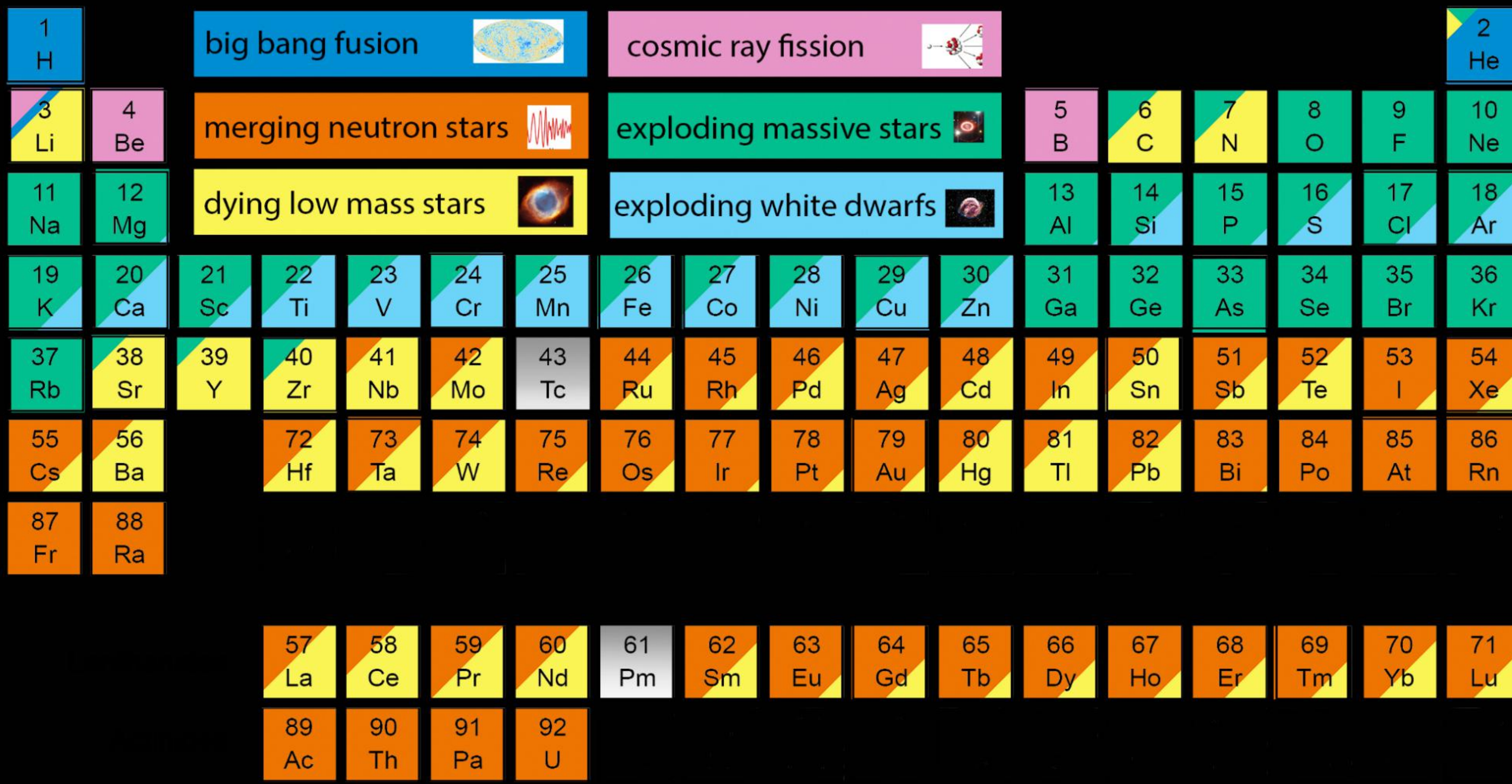
③ a **red** lanthanide-rich component (≈10cm²/g, M_{ej}≈0.009$M_\odot$ & v_{ej}≈0.08c).

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

Nucleosynthesis in BNS Merger Outflow

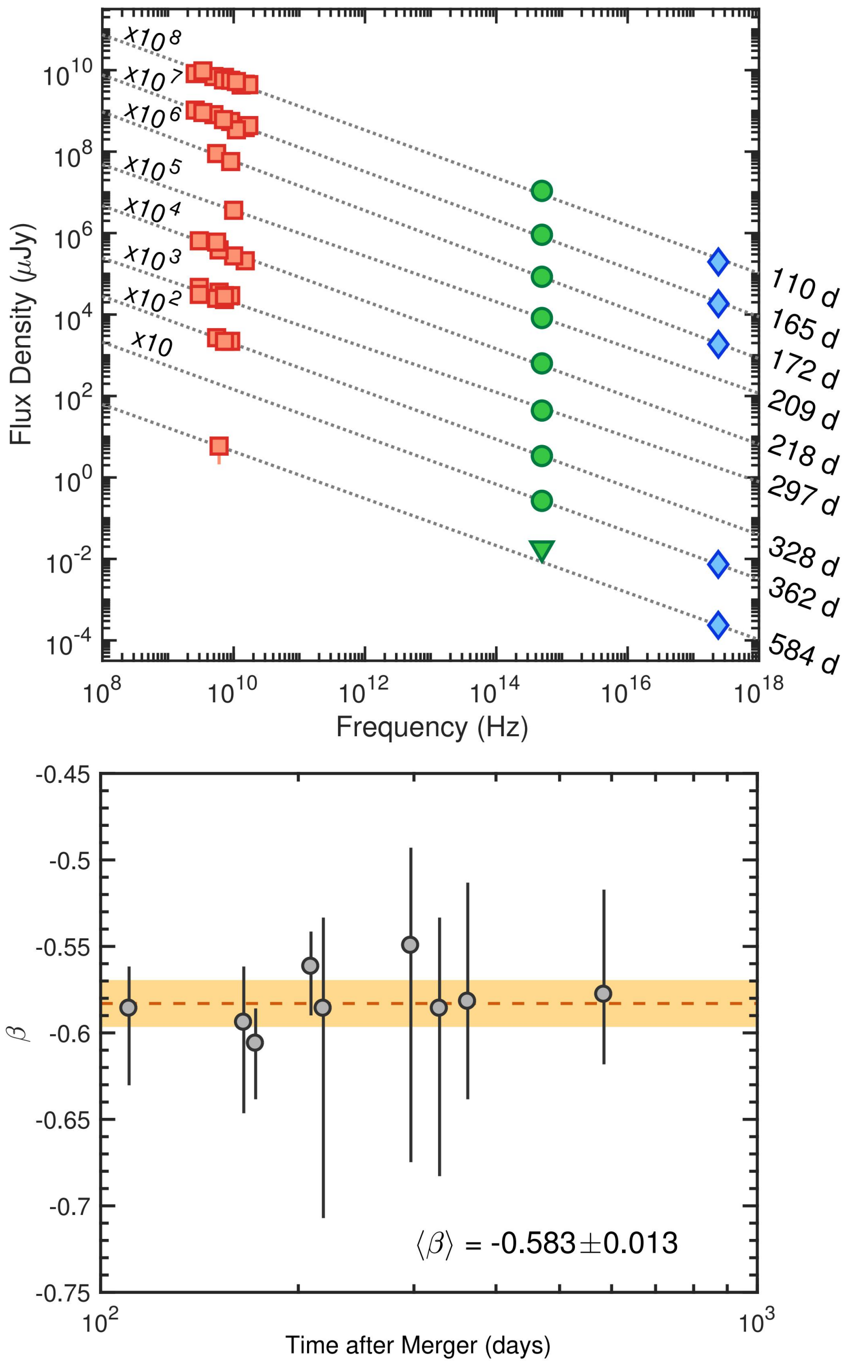


The Origin of the Solar System Elements



Graphic created by Jennifer Johnson

Astronomical Image Credits:
ESA/NASA/AASNova



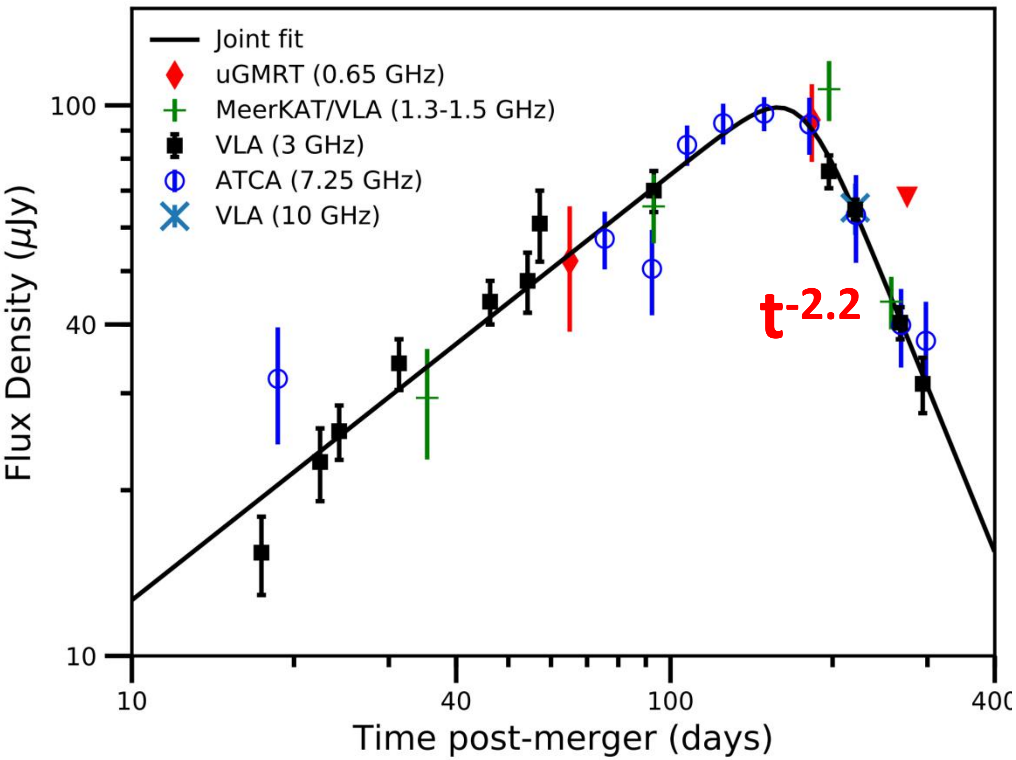
(III) X-ray, optical & radio afterglow

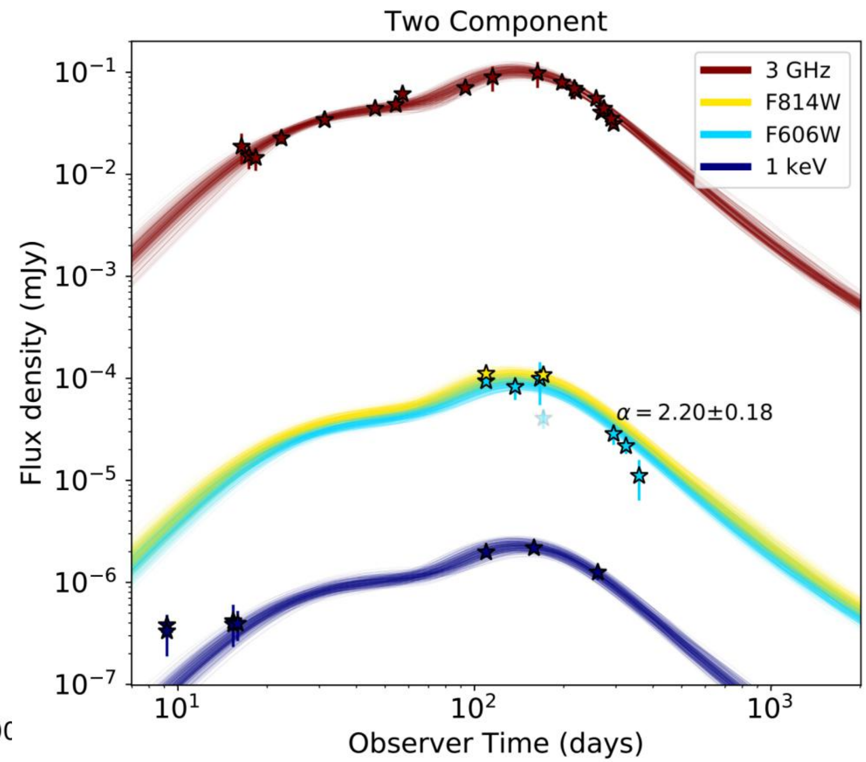
Fong et al. 2019, ApJL, 883, L1： **Evolution of the broad-band SED** from 110 d to 584 d since merger.

SED: $F_\nu \propto \nu^\beta$

A Strong Jet Signature in Late-Time Lightcurves

$F_\nu \propto t^{-p}$ after jet break

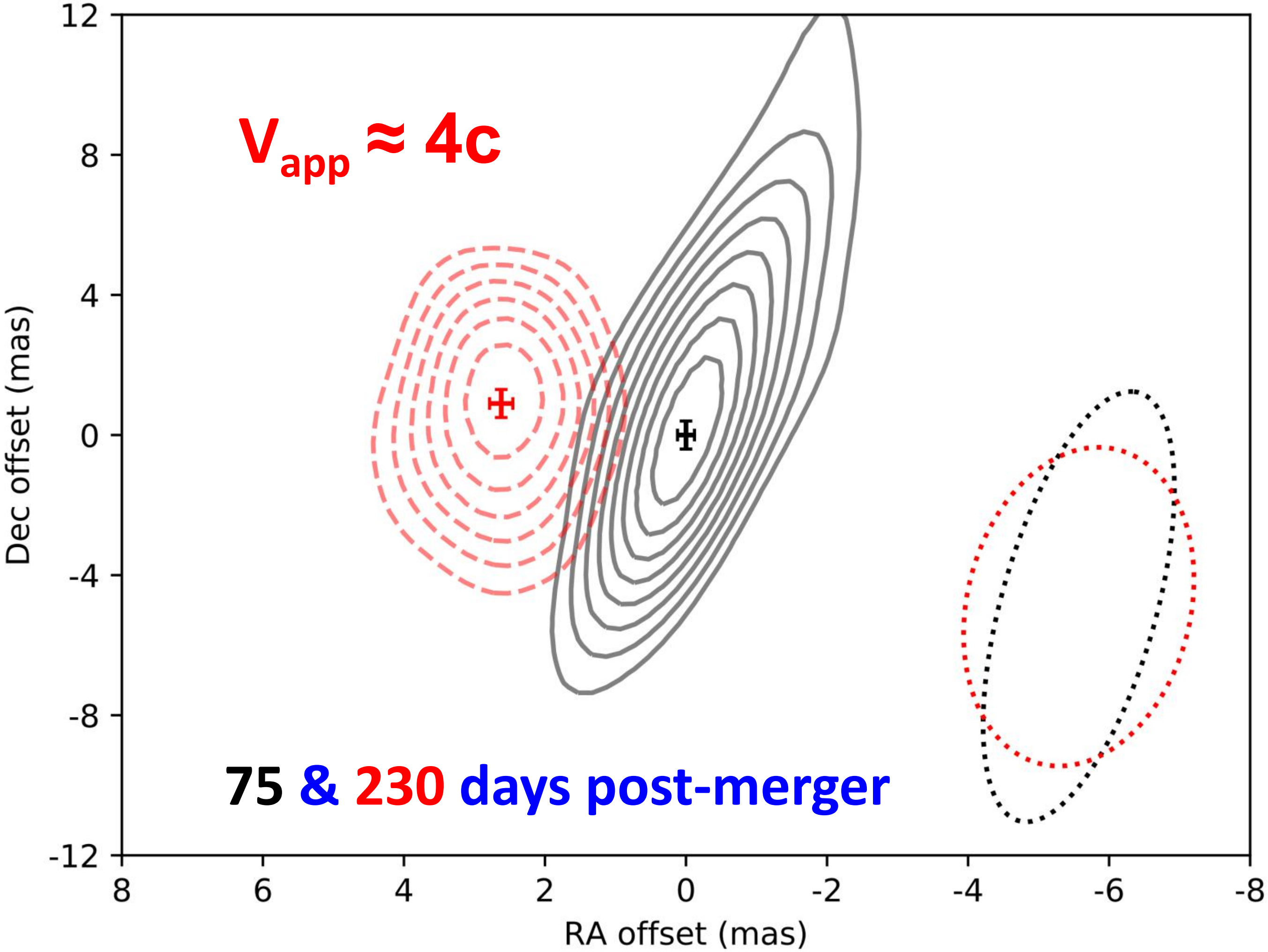




Radio: Mooley et al. 2018, ApJL, 868, L11

Optical: Lamb et al. 2019, ApJL, 870, L15

Superluminal motion of a relativistic jet in GW170817 by VLBI observations: Mooley et al. 2018, Nature, 561, 355



Ghirlanda et al. 2019, Science, 363, 968

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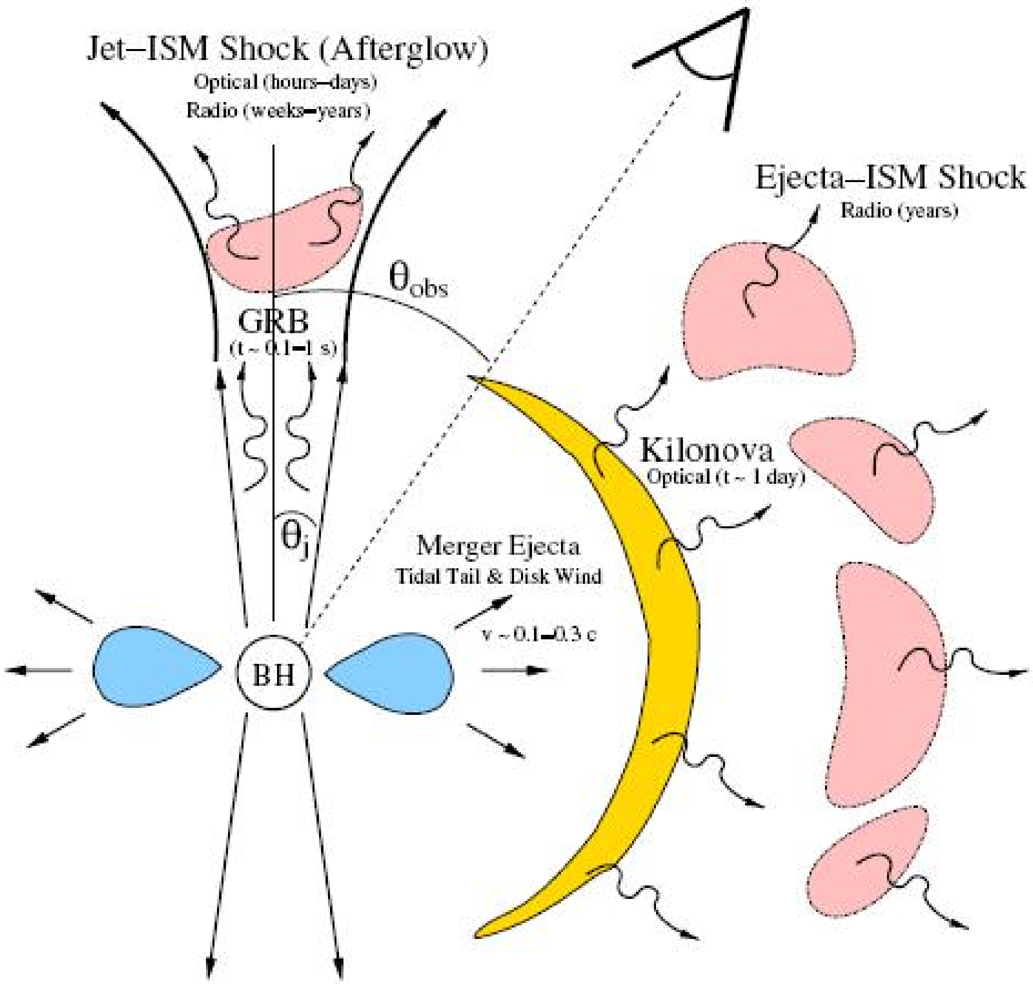
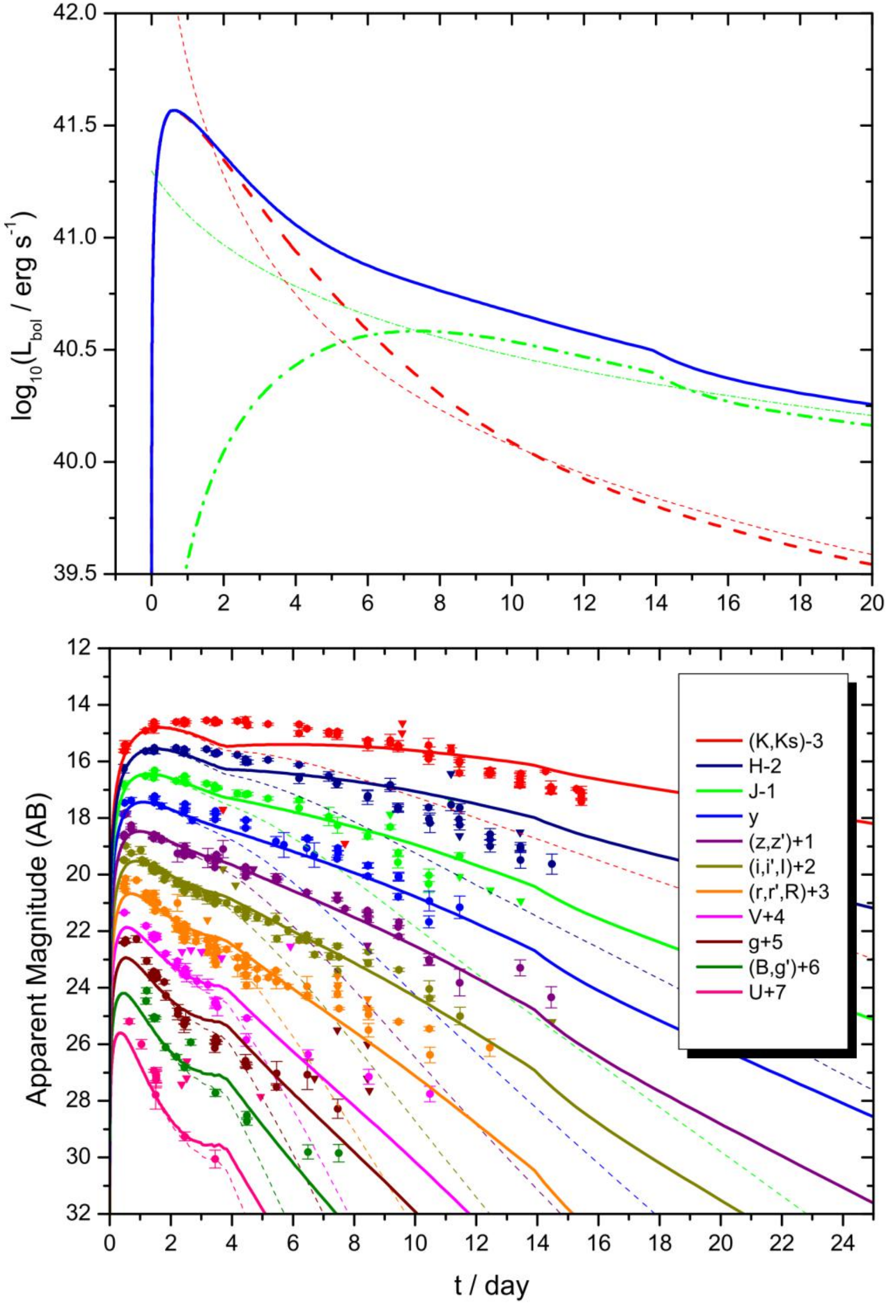
GW170817/GRB 170817A



Why off-axis?

- High detection rate
- Low-luminosity GRB
- Faint afterglow
- Superluminal motion
- Dominated kilonova

Standard picture (Metzger & Berger 2012)



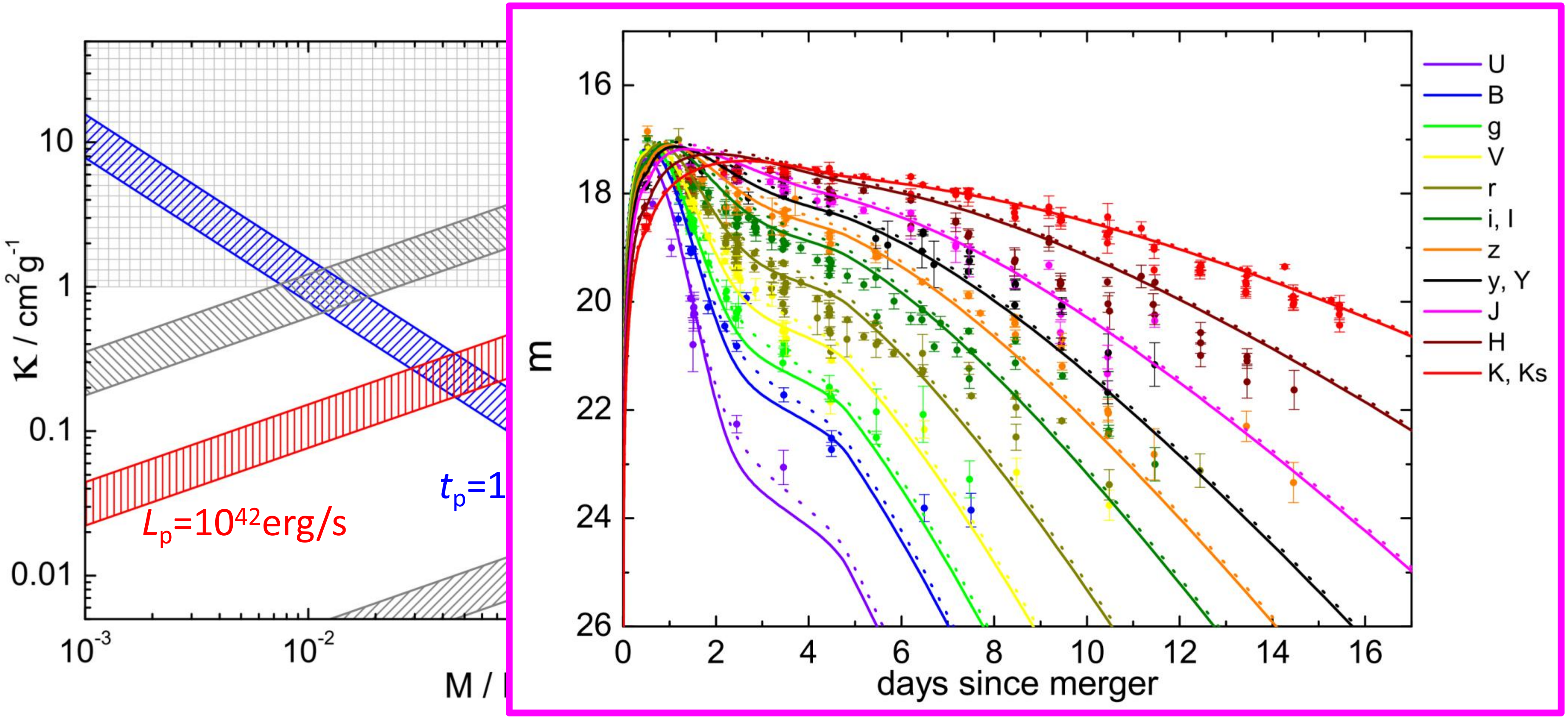
Kilonova

Question of the popular model: **too massive M_{ej}**

Yu, Liu & Dai 2018, ApJ, 861, 114: **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.

No radioactivity, only pulsar power



Li, Liu, Yu & Zhang, ApJL, 861, L12: $M_{ej} \approx 0.006 M_{\odot}$

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GW ... $t^{-5/3}$
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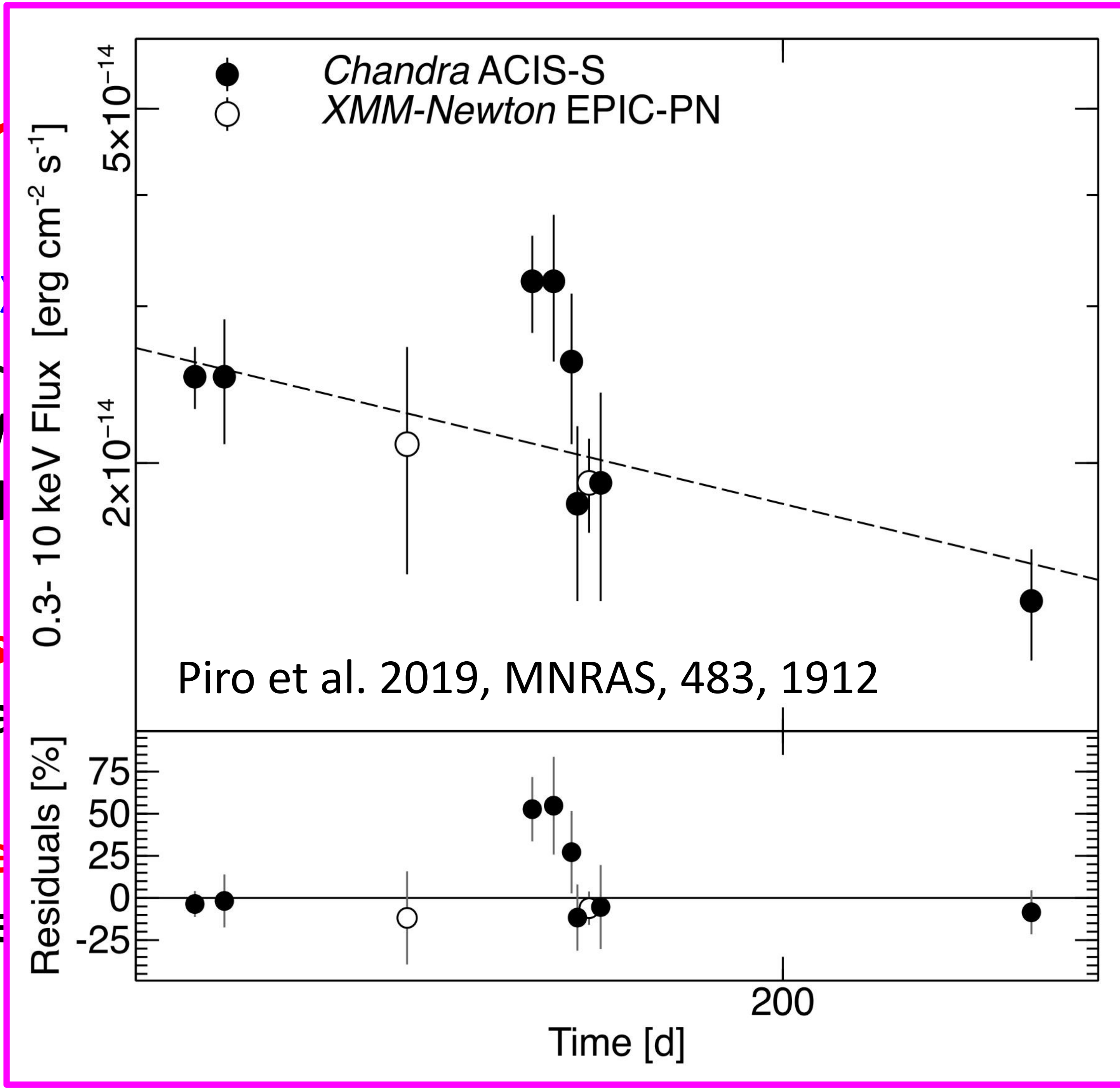
Xue



LETTER

https://doi.org/10.1038/s41586-019-1079-5

A magnetar-powered X-ray transient as the aftermath of a binary neutron-star merger

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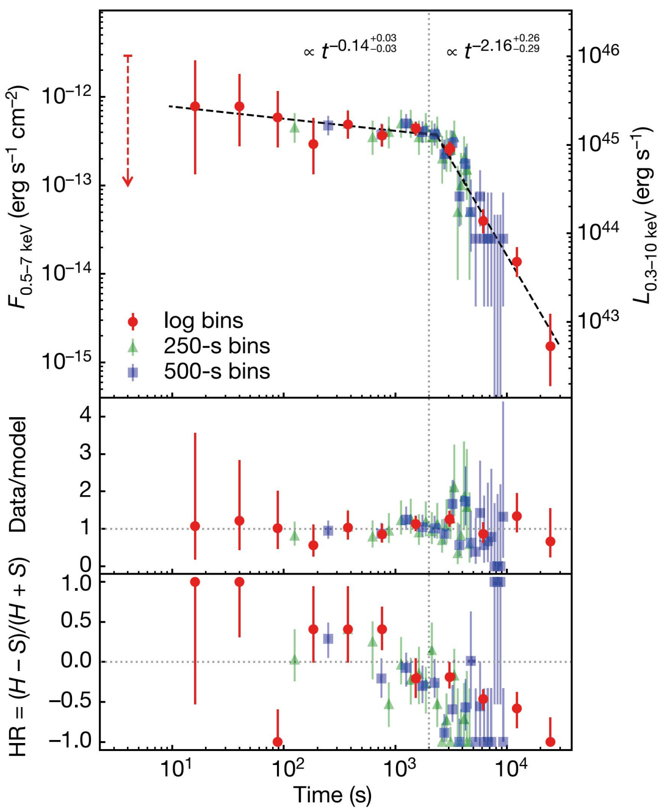
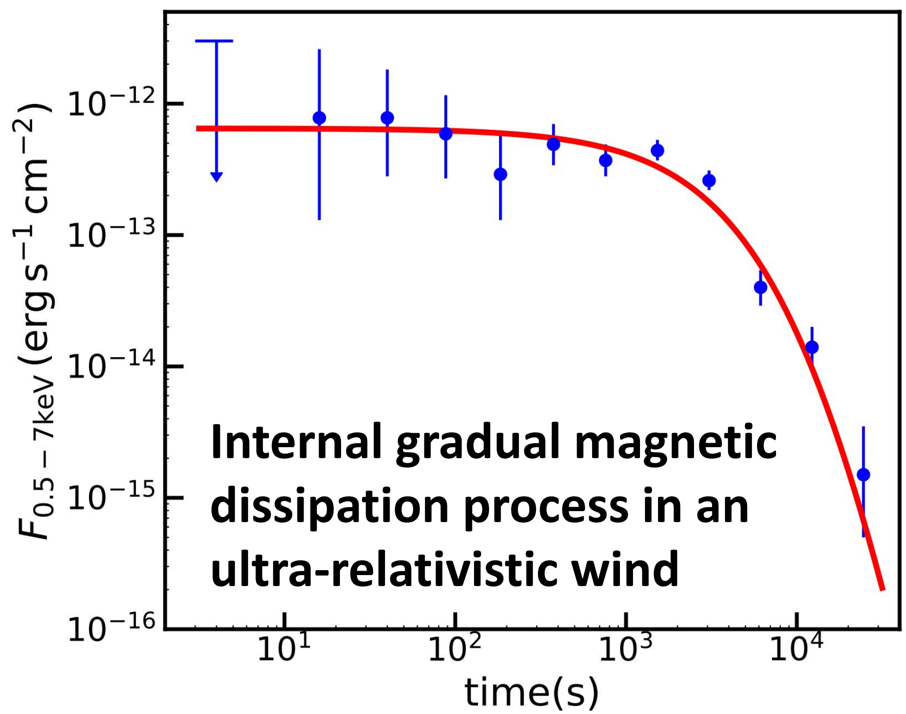
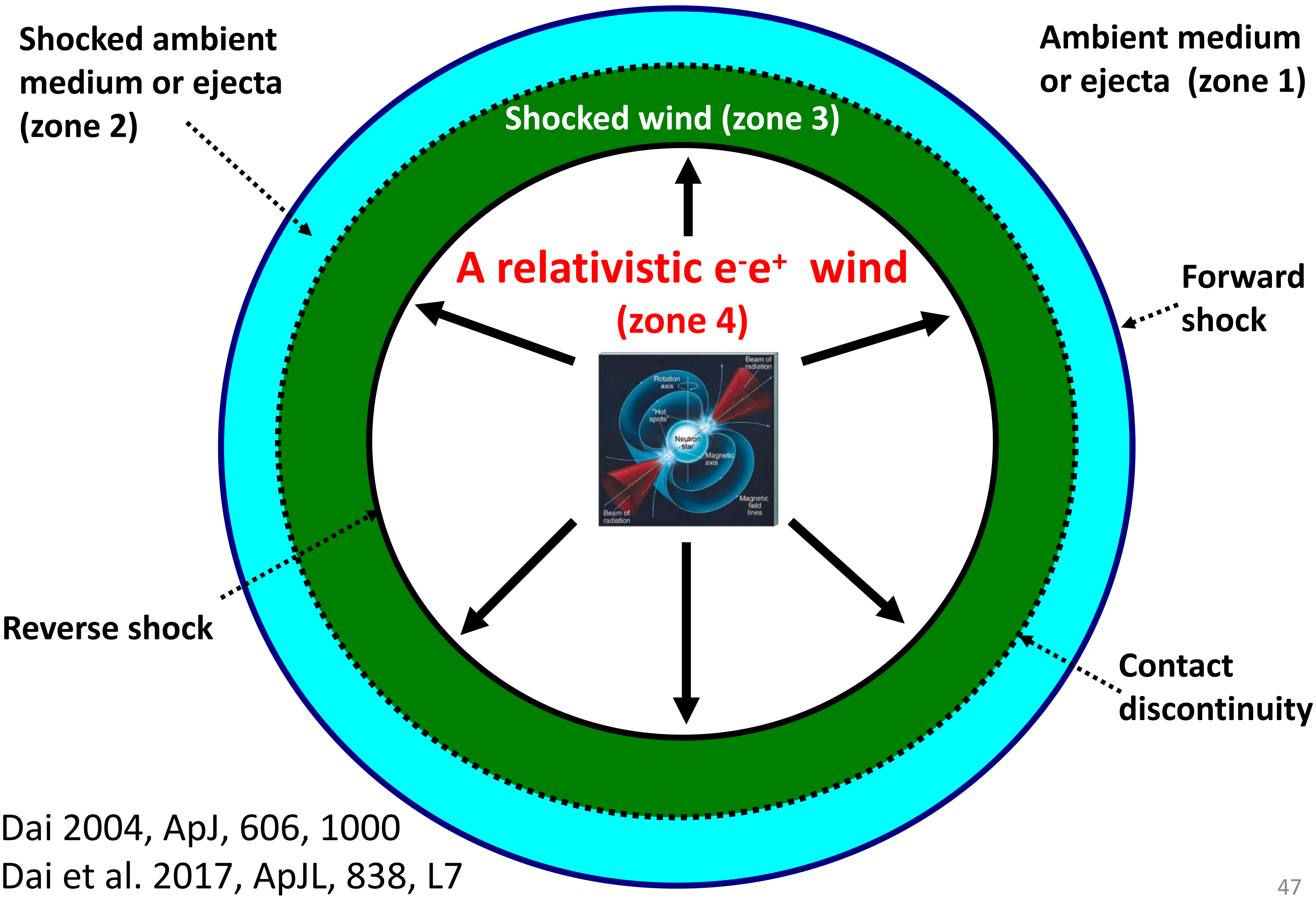




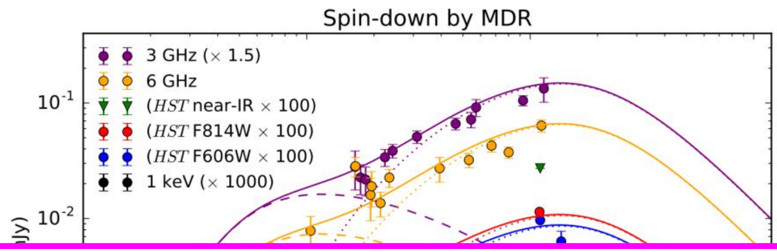
Xiao, Zhang & Dai 2019, ApJL, 879, L7

Relativistic Pulsar Wind Nebula for afterglow



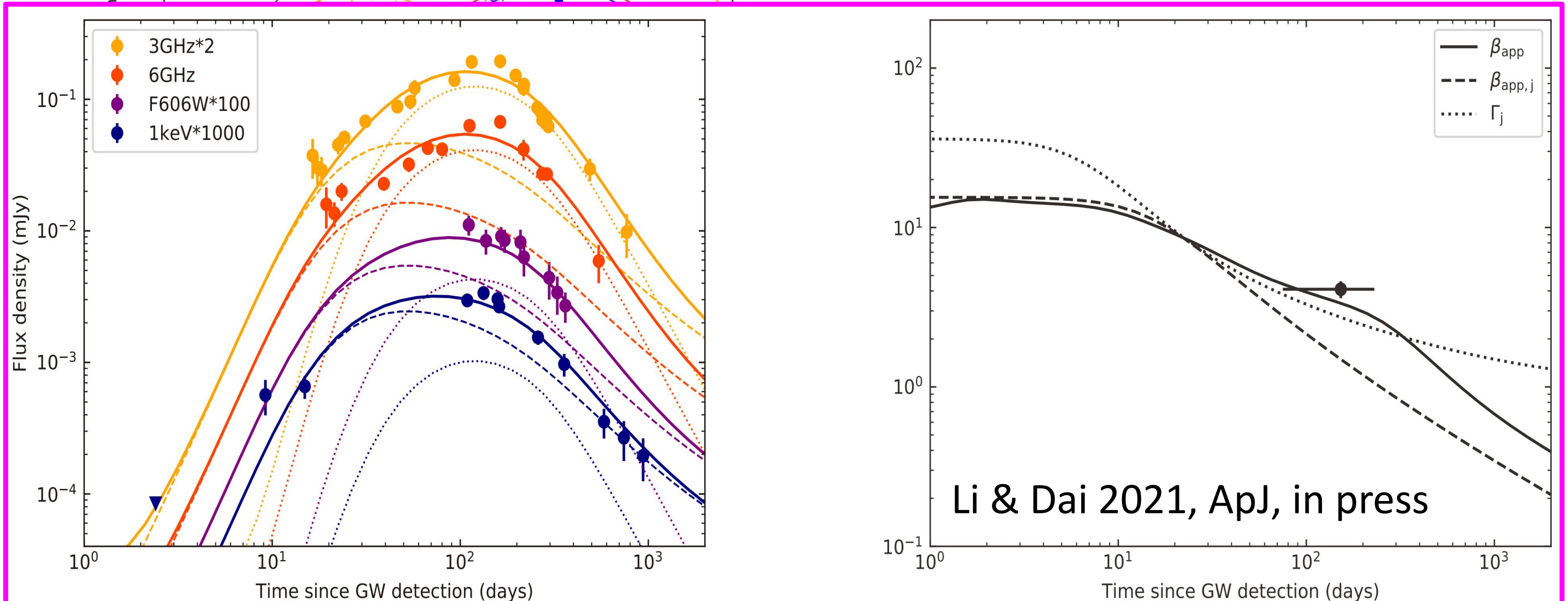
Dai 2004, ApJ, 606, 1000

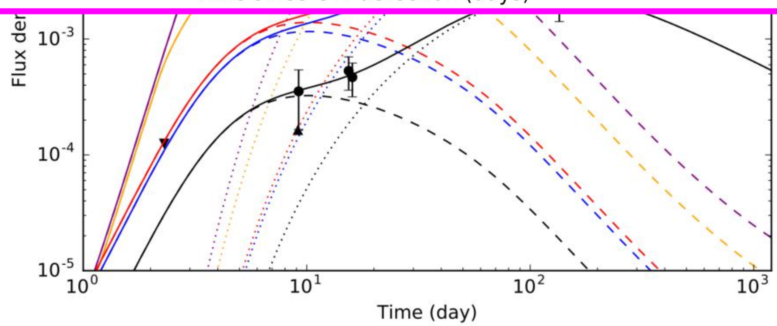
Dai et al. 2017, ApJL, 838, L7



Pulsar-powered relativistic jet

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





This model is also consistent with **position** **and** **polarization** **measurements** (Lan, Geng, Wu & Dai 2019, ApJ, 870, 96)

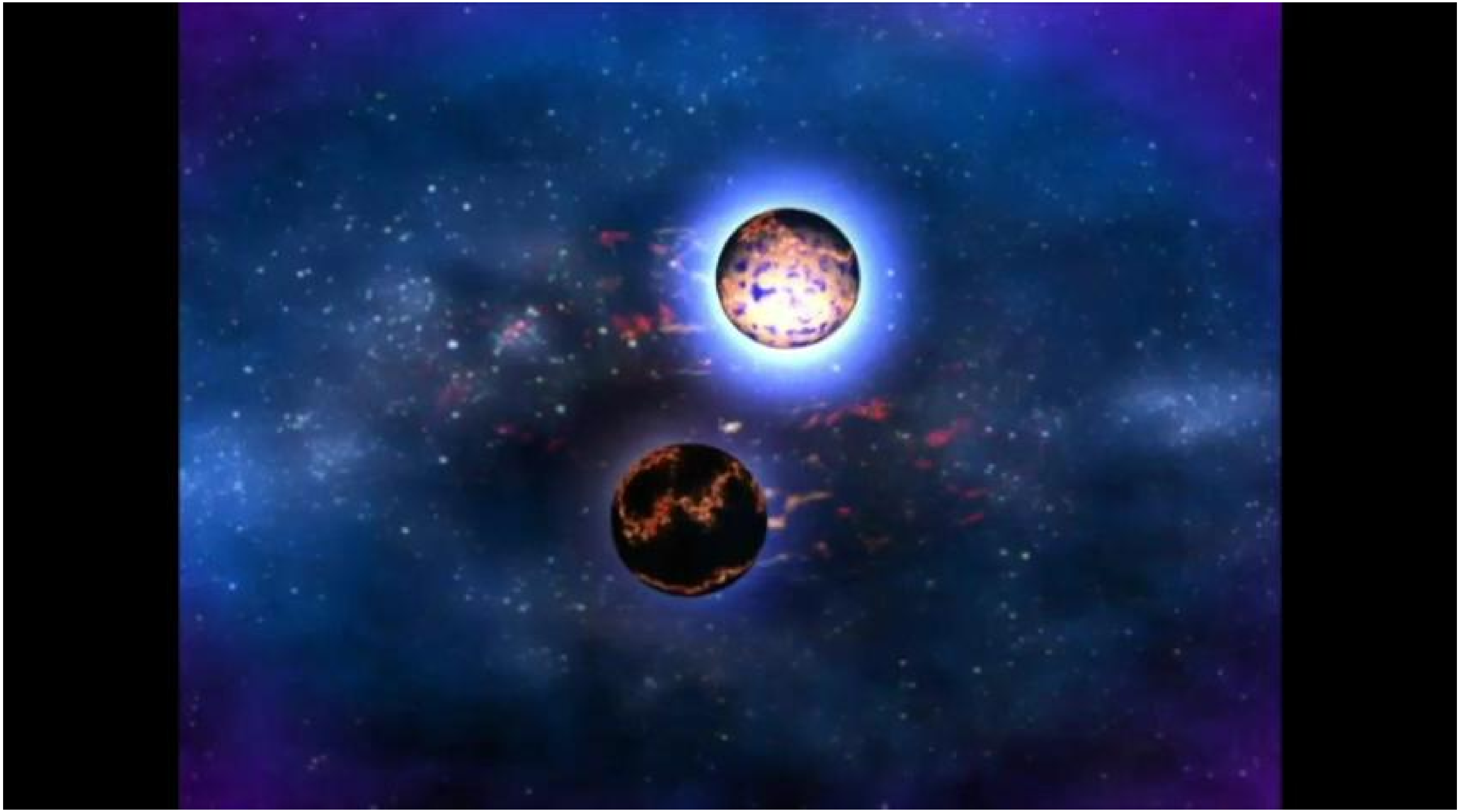
Outline

1. Short gamma-ray bursts
2. GW170817 from a BNS merger
3. EM signals from a BNS merger
   (γ-rays, kilonova, afterglow)
4. Models and conclusions
5. **Questions and prospects**

Questions

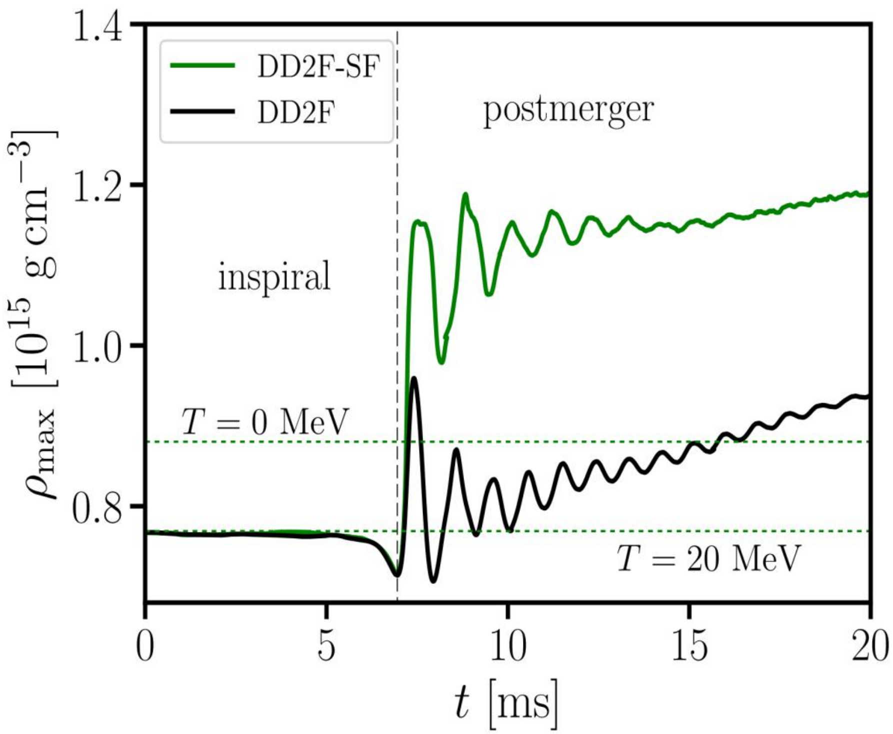
- **More low-*L* short GRBs? Prompt emission mechanisms? Merger rate? Luminosity function up to high-*L* short GRBs?**
- **EOS for NS matter? Post-merger BHs or NSs or quark stars?**
- **Nucleosynthesis during mergers? Distributions of composition, opacity, mass, and velocity in ejecta? Radioactive heating?**
- **Tests of the basic physics such as Lorentz invariance & WEP?**
- **Triplets: GW event/fast radio burst (X-ray precursor)/GRB?**
- **GW and EM signals from black hole-neutron star mergers?**
- **Independent constraints on the cosmological parameters?**

Fast radio burst from inspiral of two NSs



GWs from postmerger radially pulsating NSs

Dai 2019, A&A, 622, A194



Bauswein et al. 2019, PRL, 122, 061102

- Maximum density variation implies a radial pulsation;
- Radial pulsation amplitude $\alpha \sim$ 0.03-0.1;
- Stellar interior temperature kT >10-20 MeV.

Damping mechanisms and implications

Damping mechanisms: GWs, bulk viscosity, and pulsational magnetic radiation. GWs damp radial pulsations efficiently.

$$\omega = \left[\frac{4\pi}{3}(3\gamma - 4)G\rho\right]^{1/2} = 2.6\times 10^4 \eta_\gamma^{1/2}\left(\frac{M}{2.5M_\odot}\right)^{1/2} R_6^{-3/2}\,\mathrm{s}^{-1} \qquad \eta_\gamma \equiv (3\gamma - 4)/2$$

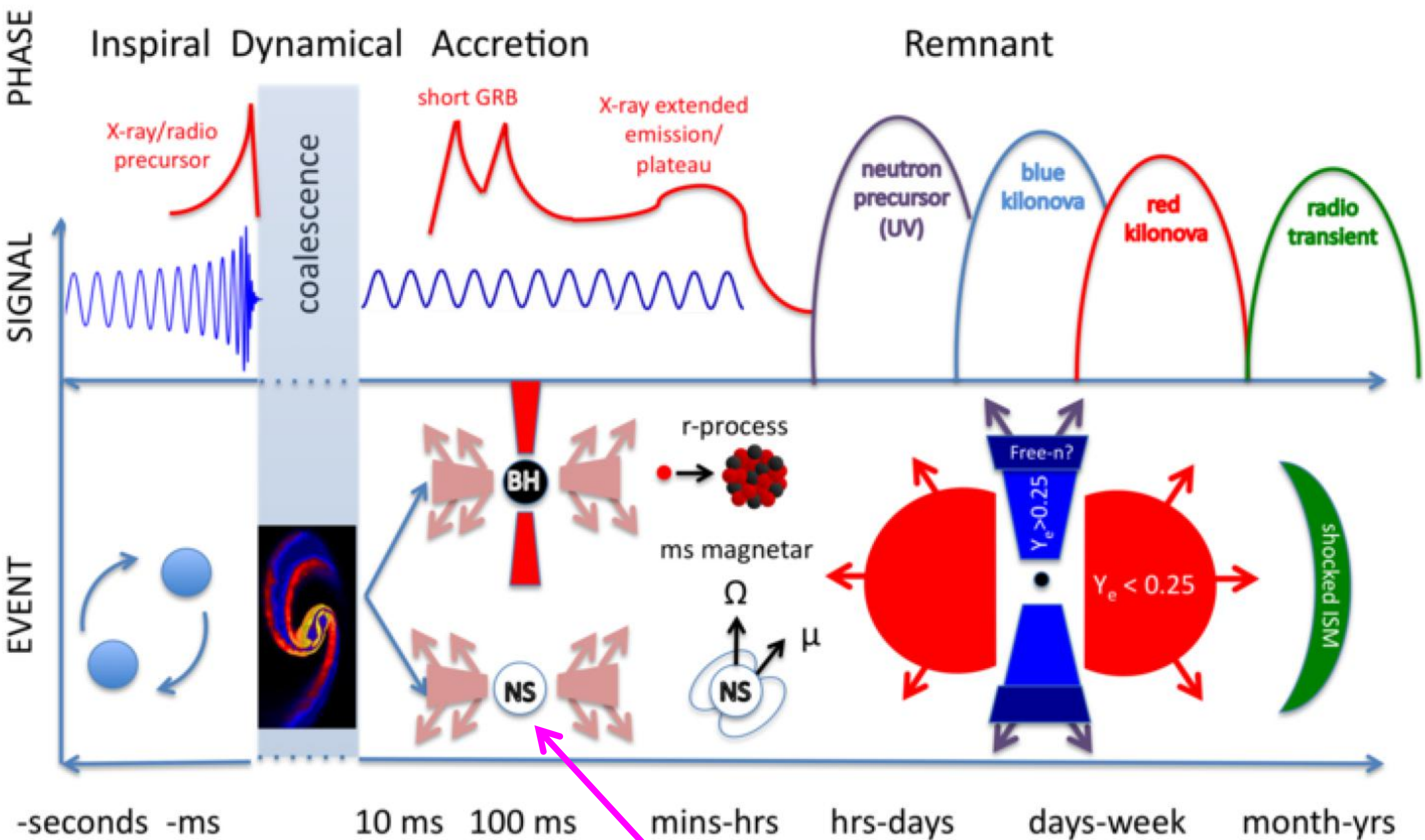
$$t_{\rm GW} \equiv \frac{\mathcal{E}}{\dot{\mathcal{E}}_{\rm GW}} = 6.3\kappa_\gamma^{-2}\left(\frac{M}{2.5M_\odot}\right)^{-1} R_6^{-2} P_{-3}^4\,\mathrm{ms} \qquad \kappa_\gamma \equiv (225\gamma - 36)/414$$

$$h_c \simeq 4.5\times 10^{-22}\eta_\gamma^{1/4}\alpha_{-1} R_6^{1/4}\left(\frac{M}{2.5M_\odot}\right)^{3/4}\left(\frac{d}{100\mathrm{Mpc}}\right)^{-1}$$

- GWs make a leading contribution to the high-frequency spectrum.
- If $\alpha\sim 0.1$, detectable rate ~20/yr for aLIGO and $\sim 7\times 10^4$/yr for ET;
  If $\alpha\sim 0.03$, detectable rate ~0.6/yr for aLIGO and $\sim 2\times 10^3$/yr for ET.
- α, $P_{\rm NS}$, and *M*-*R* relation would be constrained with detected GWs.

Triplets: GWB, FRB, & GRB from a BNS merger

Fernández & Metzger (2016)



Dai & Lu 1998, *Phys. Rev. Lett.*, 81, 4301; Dai et al. 2006, *Science*, 311, 1127

Black Hole-Neutron Star Mergers

GW190814 & others: BH-NS merger candidates

- Gravitational waves stronger than BNS mergers
- EM signals (short GRBs, kilonovae & afterglows)
- Necessary condition: tidally disrupted ejecta
- If $M_{BH}>7M_{\odot}$ & $M_{NS}=1.4M_{\odot}$, then NS as a whole will plunge into BH, leading to no EM signals.
- One model was proposed: initially & constantly charged BH or NS (Zhang 2019, ApJL, 873, L9).
- Question of model: instantaneous discharge from an ionized ISM (Levin et al. 2018).

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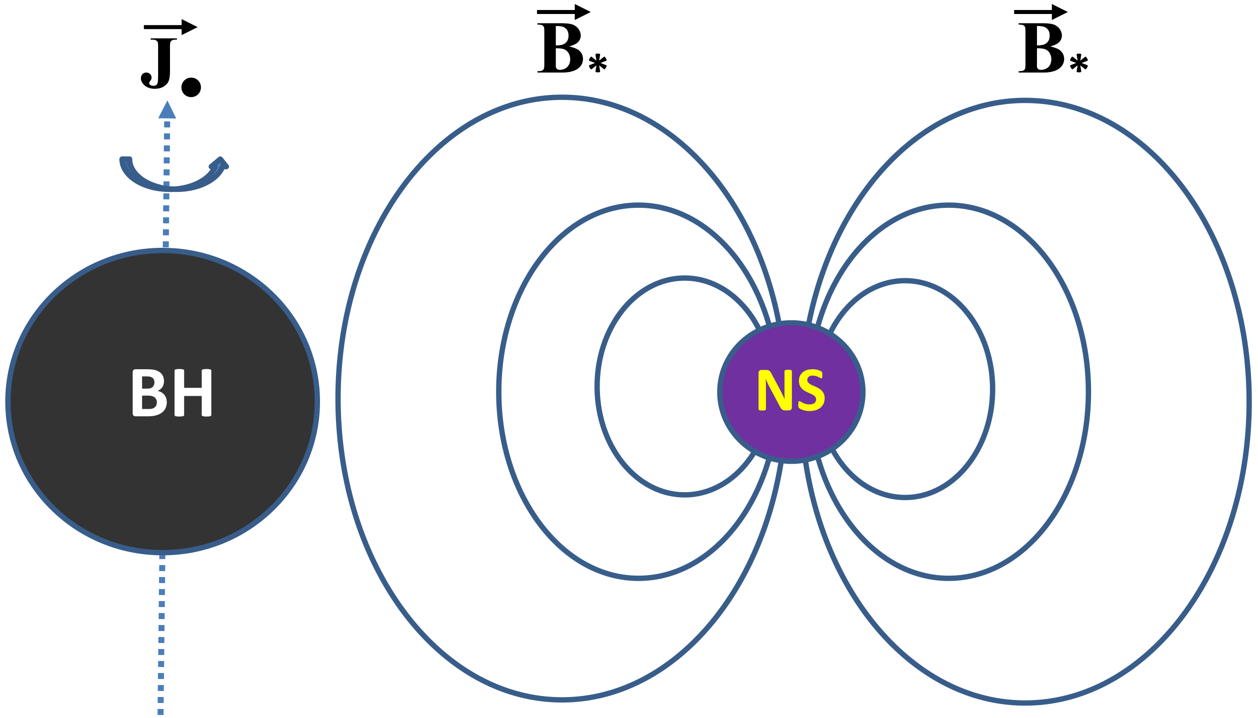
Inspiral of a Spinning Black Hole–Magnetized Neutron Star Binary: Increasing Charge and Electromagnetic Emission

Z. G. Dai[1,2]



Astrophysical origins: (1) high-mass X-ray binaries and (2) **wandering** NSs captured by **isolated** high-spin BHs!

Charging mechanism of Wald (1974)

$$Q_{\rm W} \;=\; \frac{2G}{c^3} J_\bullet B_* = \frac{1}{2} a_\bullet R_{{\rm S},\bullet}^2 B_*$$

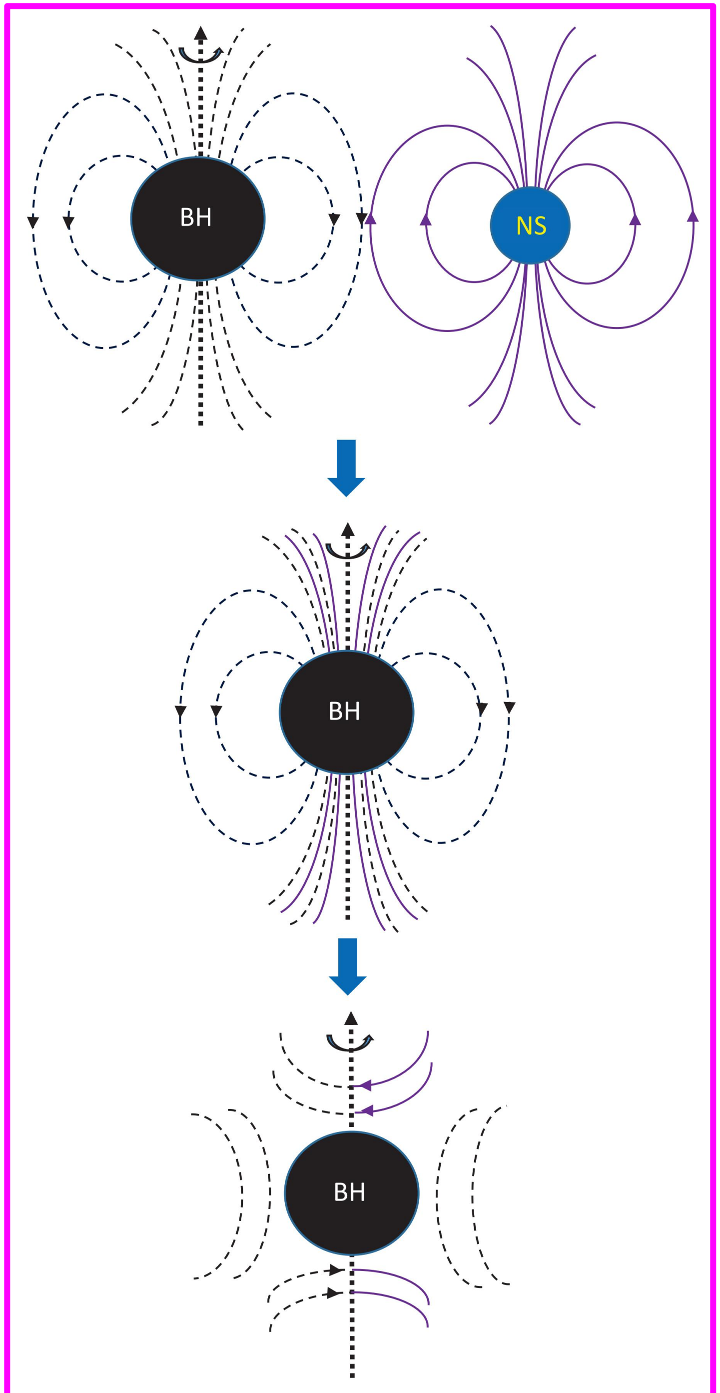
$$|\mathbf{m}_{\bullet,1}| \;=\; \frac{J_\bullet}{M_\bullet c} Q_{\rm W} = \frac{1}{4} a_\bullet^2 R_{{\rm S},\bullet}^3 B_*$$

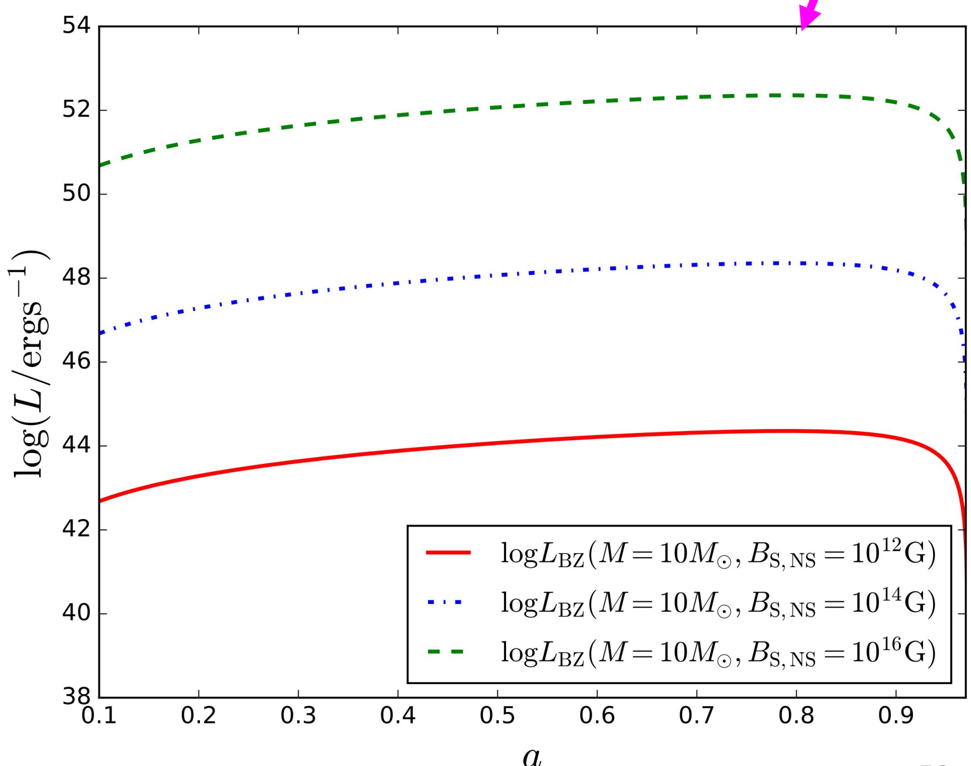
$$|\mathbf{m}_{\bullet,2}| \;=\; \frac{\pi r_\bullet^2}{c} \frac{Q_{\rm W}}{P}$$

Magnetic dipole radiation, electric dipole radiation, & magnetic reconnection generate short EM signals such as X-ray transients and/or fast radio bursts.

Zhong, Dai & Deng 2019, ApJL, 883, L19

Chen & Dai 2021, ApJ, 904, 4: **EM emission during the merger of a spinning BH-magnetized NS binary ------ fast radio bursts & short GRBs**





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

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Department of Astronomy, Nanjing University, Nanjing 210093, China

(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]

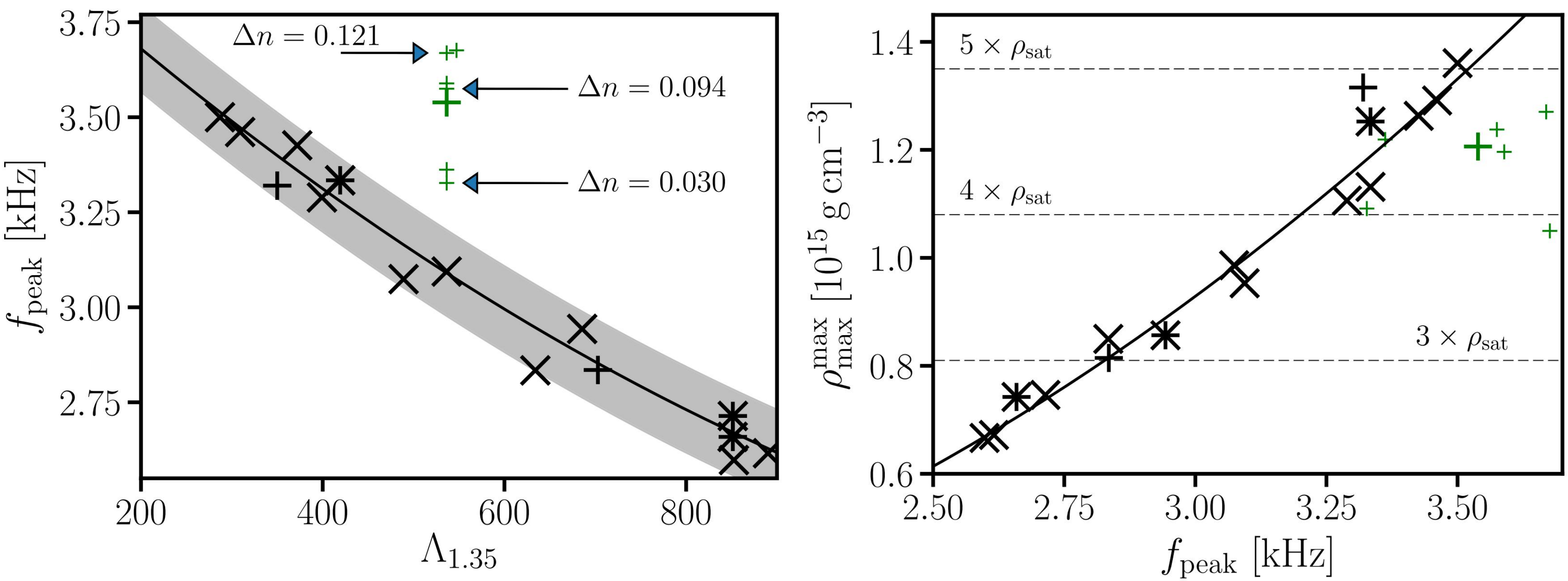
stable neutron stars [21]. If the EOS for neutron matter is sufficiently stiff, therefore, the postmerger objects of Hulse-Taylor-like binaries may be massive neutron stars rather than black holes. The same outcome would be achieved if the initial masses of the merging neutron stars were low, e.g., $M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

PHYSICAL REVIEW LETTERS **122,** 061102 (2019)

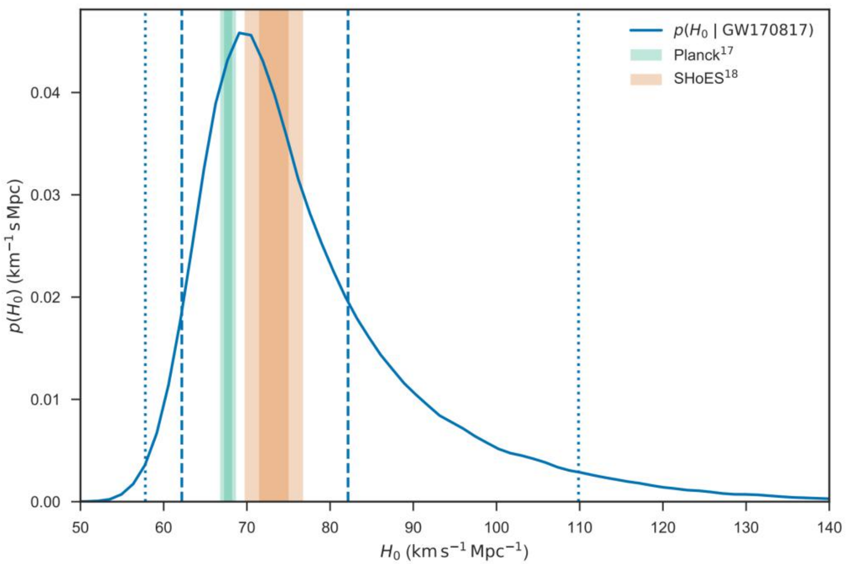
Editors' Suggestion

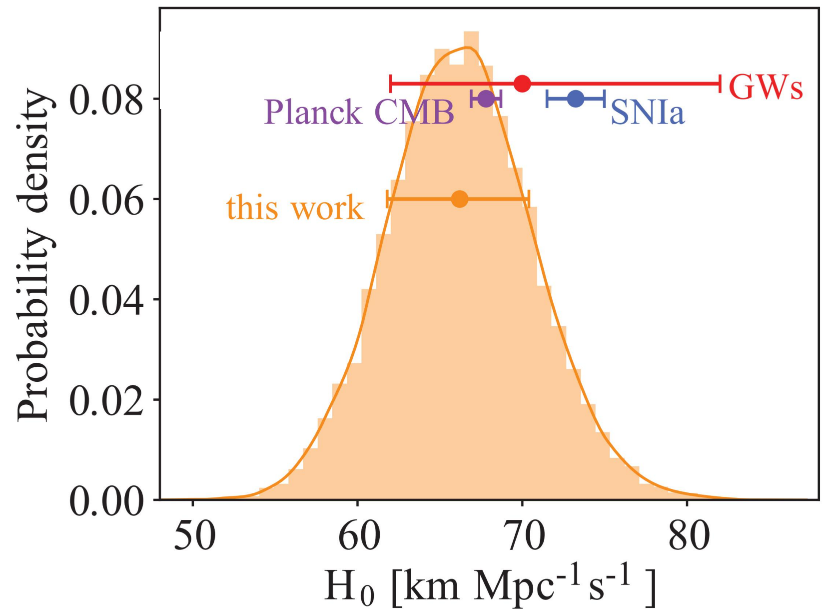
Identifying a First-Order Phase Transition in Neutron-Star Mergers through Gravitational Waves

Andreas Bauswein,[1] Niels-Uwe F. Bastian,[2] David B. Blaschke,[2,3] Katerina Chatziioannou,[4,7] James A. Clark,[5] Tobias Fischer,[2] and Micaela Oertel[6]



Constraint on Hubble constant





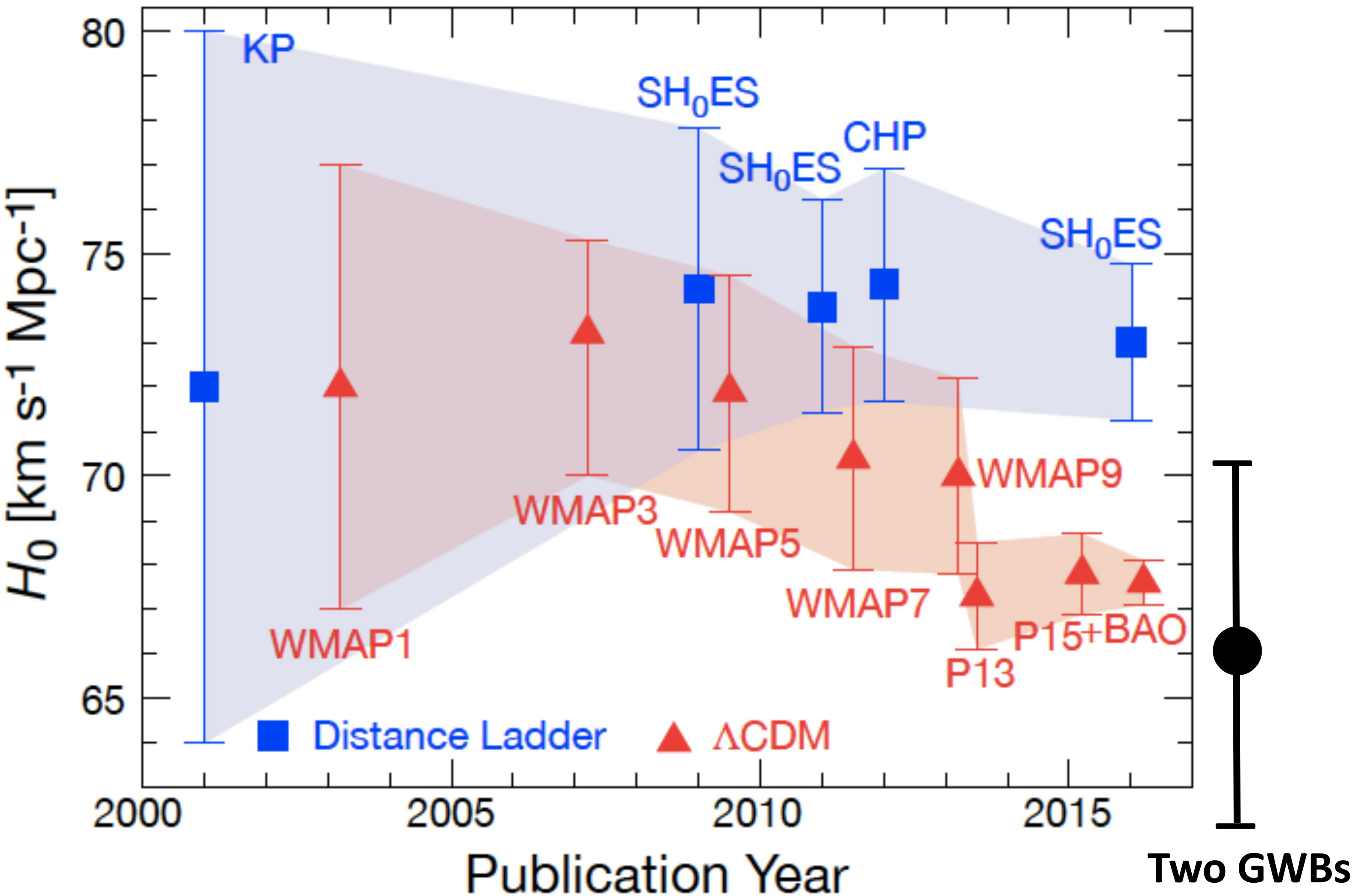
$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

$$H_0 = 66.2^{+4.4}_{-4.2}$$

GW170817 only:
Abbott et al. 2017, Nature, 551, 85

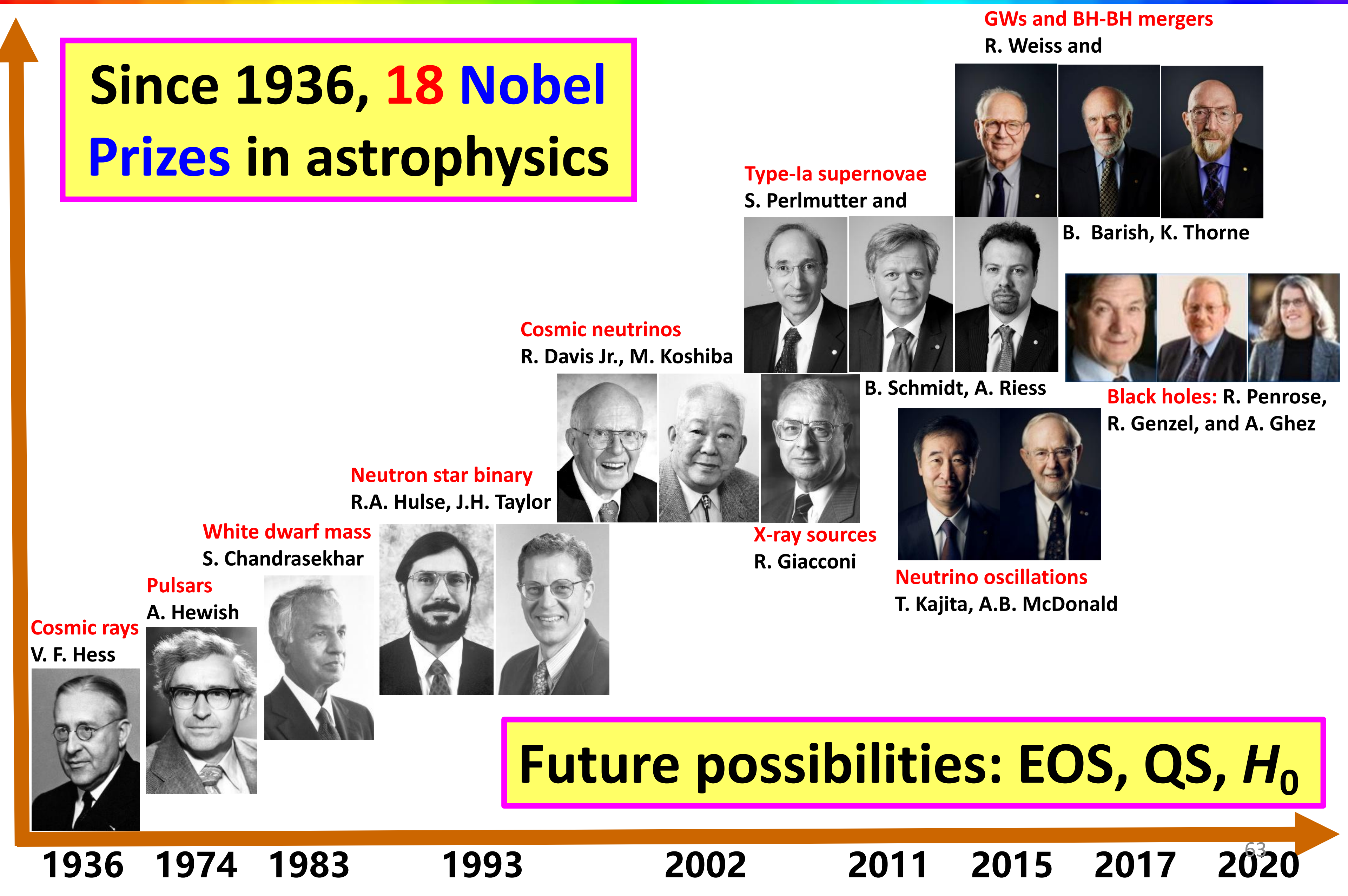
GW170817 and EM waves:
Dietrich et al. 2021, Science, 370, 1450

H_0 tension: crisis in cosmology



Freeman 2017, Nature Astronomy, 1, 0169: **disagreement at >3σ**

10 Nobel Prizes in High-Energy Astrophysics



Prospects

- **Telescopes:** **large field of view, high sensitivity, good seeing, and good luck;**
- **A new, great era:** **GW170817 marks the beginning of multi-messenger, time-domain astronomy;**
- **A new opportunity:** **new ideas and new discoveries.**