The 8th Huada School on QCD in Central China Normal University
May 6 - May 10, 2019

Constraint on NS maximum mass from multi-messenger data of NS-NS mergers

He Gao (高鹤)

Department of Astronomy, Beijing Normal University

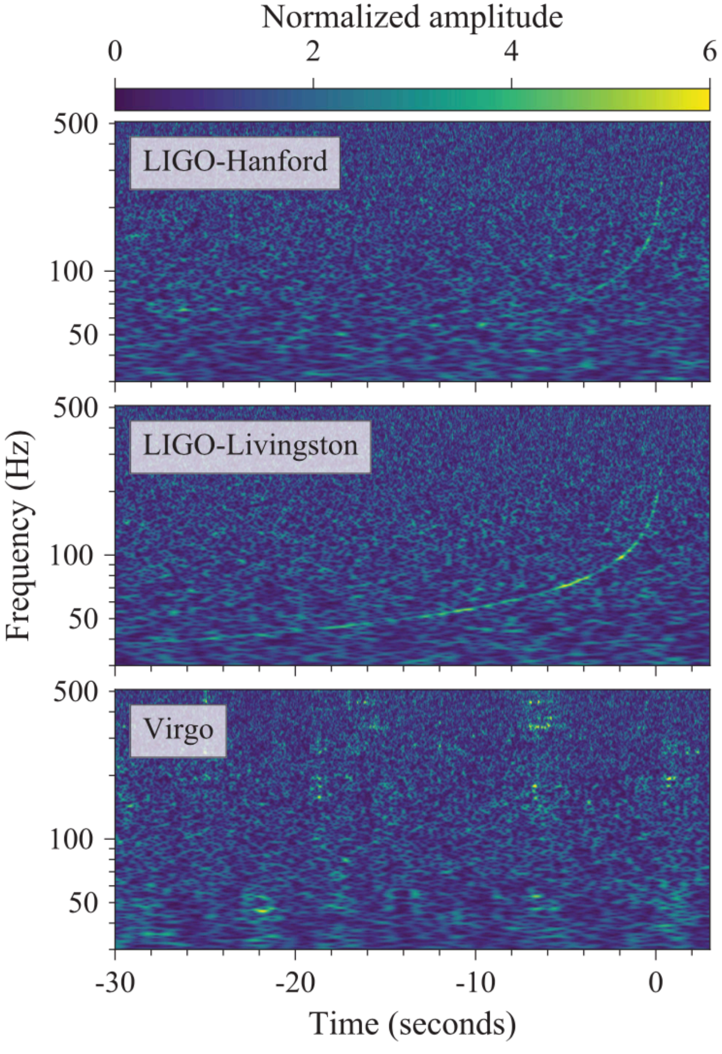
北京师范大学 - 天文系

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

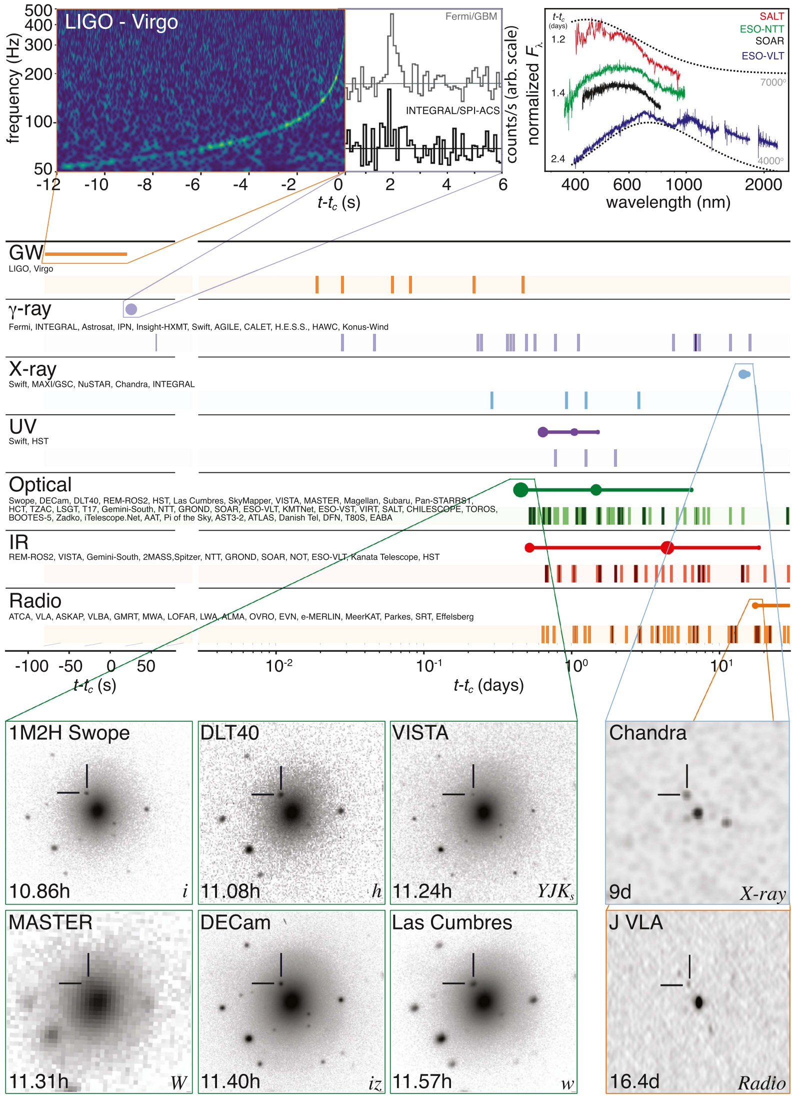
2019-05-10

@CCNU

GW170817: First NS-NS Merger Detection



Abbott et al. 2017， PRL



Multi-Messenger

GW detector triggered；

1.7s later, Fermi / GBM Detect a Short GRB;

10 hours later, an optical IR counterpart detected;

9 days later, Chandra find a X-ray counterpart;

16 days later, VLA detected a radio counterpart.

BNS mergers could be used to …

- **Measure Hubble Constant H_0**

  Abbott et al. 2017 Nature; Chen et al .2018 Nature; Remya et al. 2018 PRD; Valentino et al. 2018 PRD; Fishbach et al 2019 ApJ; Feeney et al. 2019 PRL …

- **Test Gravity Theory**

  Baker et al. 2017 PRL; Langlois et al .2018 PRD; Amendola et al. 2018 PRL; Mendes & Ortiz. 2018 PRL; Burrage 2018 LRR; Arai & Nishizawa 2018 PRD…

- **Constrain NS EoS**

  Abbott et al. 2018 PRL; Annala et al .2018 PRL; Radice et al. 2018 ApJ; Bauswein et al. 2018 ApJ; Tews et al. 2018 PRC; Malik et al. 2018 PRC…

- **Study the Origin of Heavy Elements**

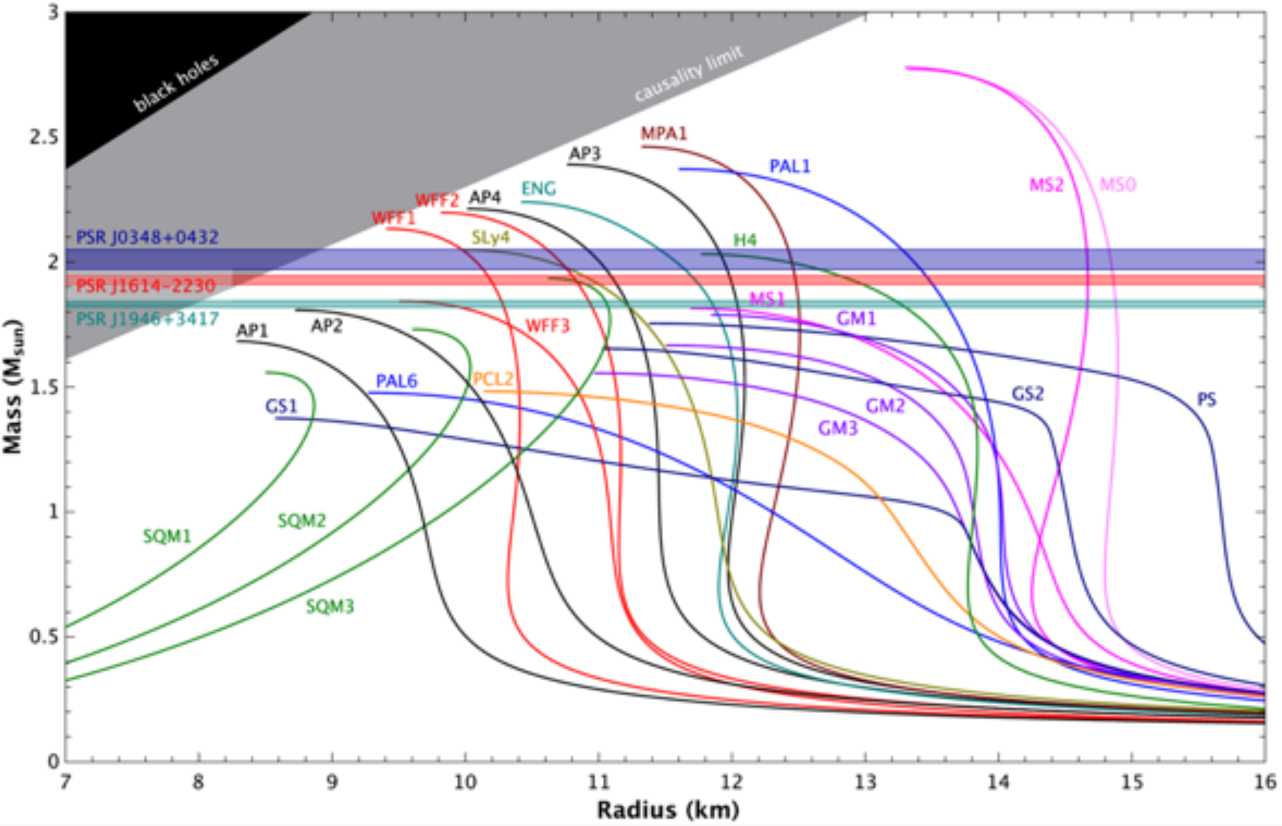
  Kasen et al .2017 Nature; Pian et al. 2017 Nature; Drout et al. 2017 Science; Cote et al. 2018 ApJ; Hotokezaka et ak. 2018 IJMPD; Cote et al. 2019 ApJ…

- **Study the Properties of Short Gamma-ray Bursts**

  Goldstein et al .2017 ApJL; Zhang et al. 2018 NC; Meng et al. 2018 ApJ; Lazzati et al. 2018 RPL; Troja et al. 2018 ApJ; Ghirlanda et al. 2019 Science …

BNS mergers for Constraining EoS

Neutron Star / Quark Star Equation of State



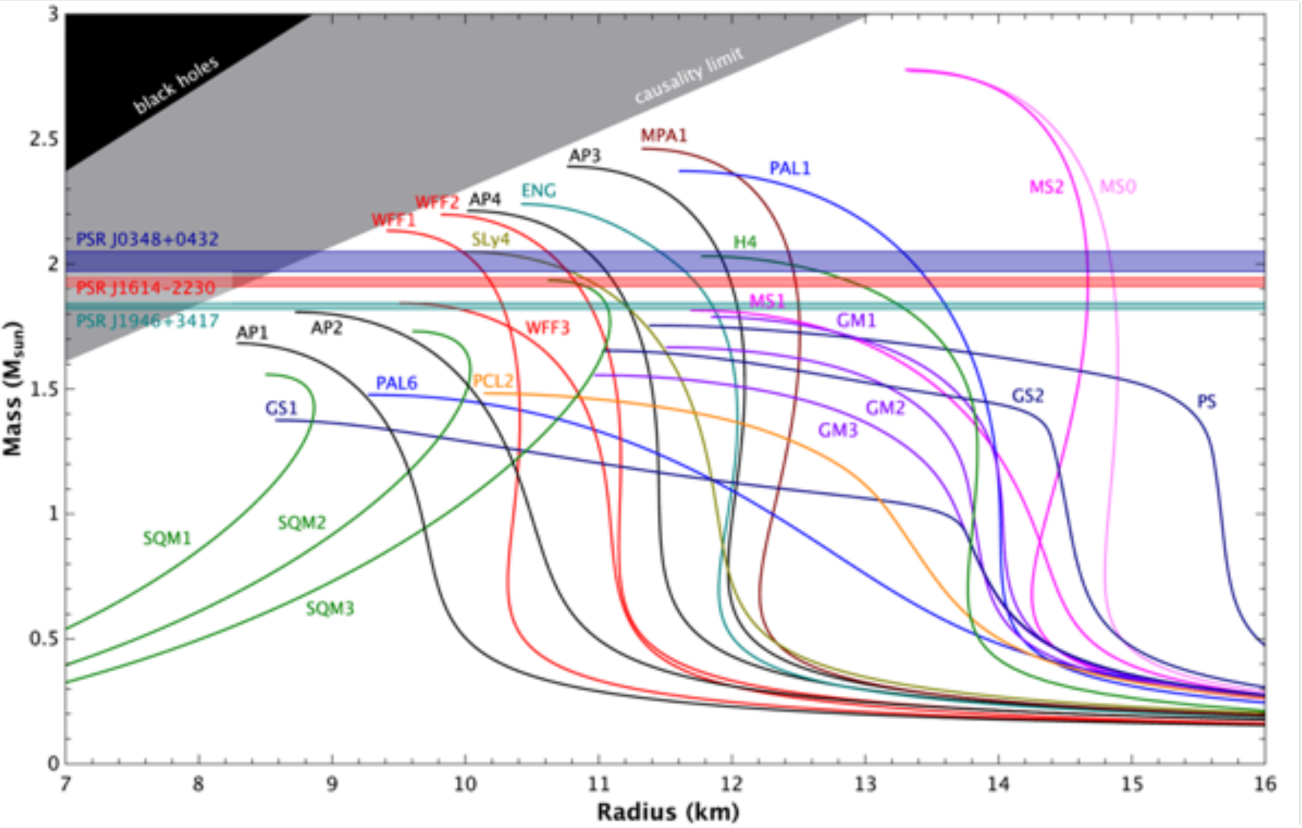
In contrast to mass determinations, there are no high-accuracy radius measurements. Moreover, there are no radius measurements for any neutron star with a precise mass determination. Many astrophysical observations that could lead to the extraction of neutron star radii, or combined mass and radius constraints, have been proposed. These observations include the following.

1. Thermal X-ray and optical fluxes from isolated and quiescent neutron stars (78).
2. Type I X-ray bursts on neutron star surfaces (79).
3. Quasi-periodic oscillations from accreting neutron stars (80).
4. Spin-orbit coupling, observable through pulsar timing in extremely compact binaries, leading to moments of inertia (81).
5. Pulsar glitches, which constrain properties of neutron star crusts (82).
6. Cooling following accretion episodes in quiescent neutron stars that also constrain crusts (83).
7. Neutron star seismology from X-rays observed from flares from soft γ-ray repeaters (84).
8. Pulse profiles in X-ray pulsars, which constrain M/R ratios due to gravitational light bending (85).
9. Gravitational radiation from tidal disruption of merging neutron stars (7).
10. Neutrino signals from proto–neutron stars formed in Galactic supernovae (72).

Lattimer, 2012, ARAA

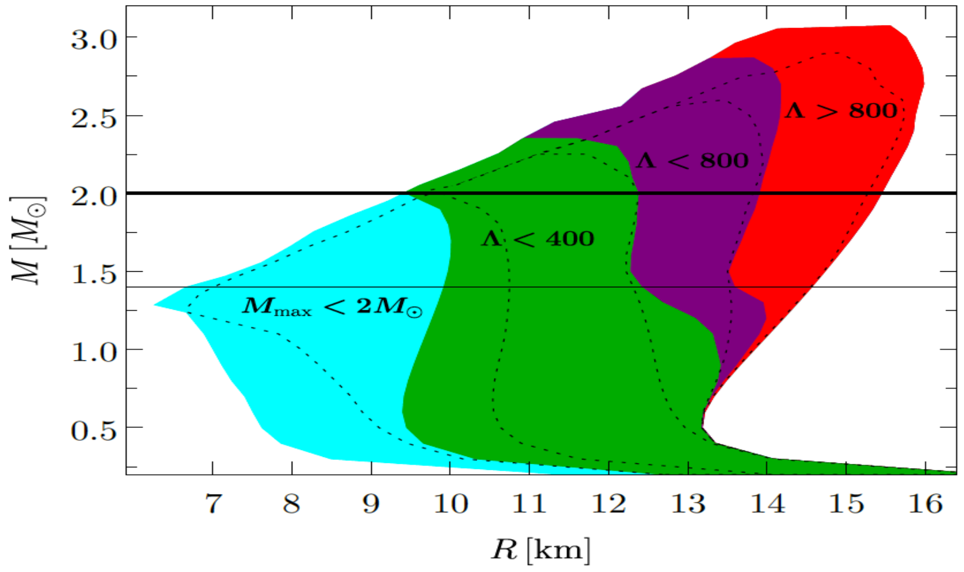
BNS mergers for Constraining EoS

Neutron Star / Quark Star Equation of State



Lattimer, 2012, ARAA

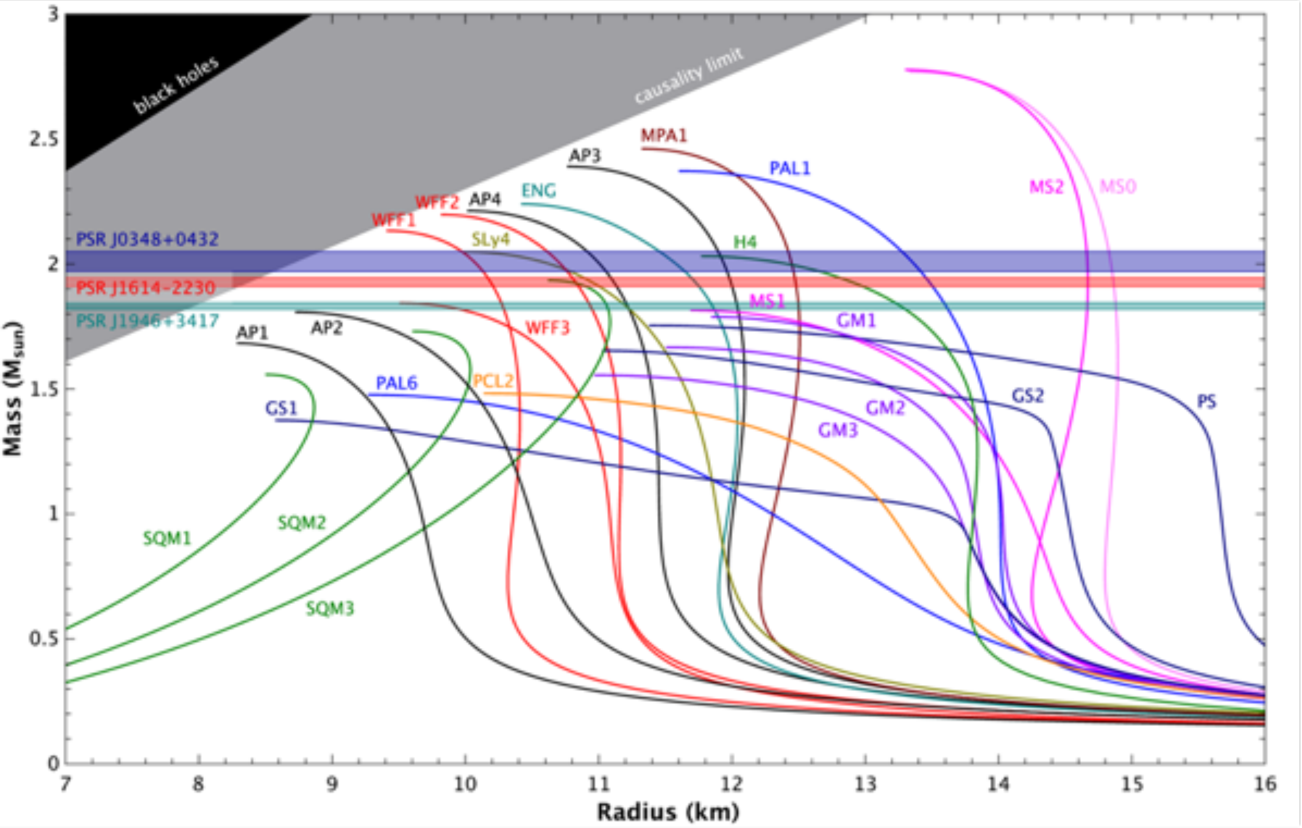
- Gravitational waves provide tidal deformability of NS, which could constain NS radius.



Annala, 2018, PRL

BNS mergers for Constraining EoS

Neutron Star / Quark Star Equation of State

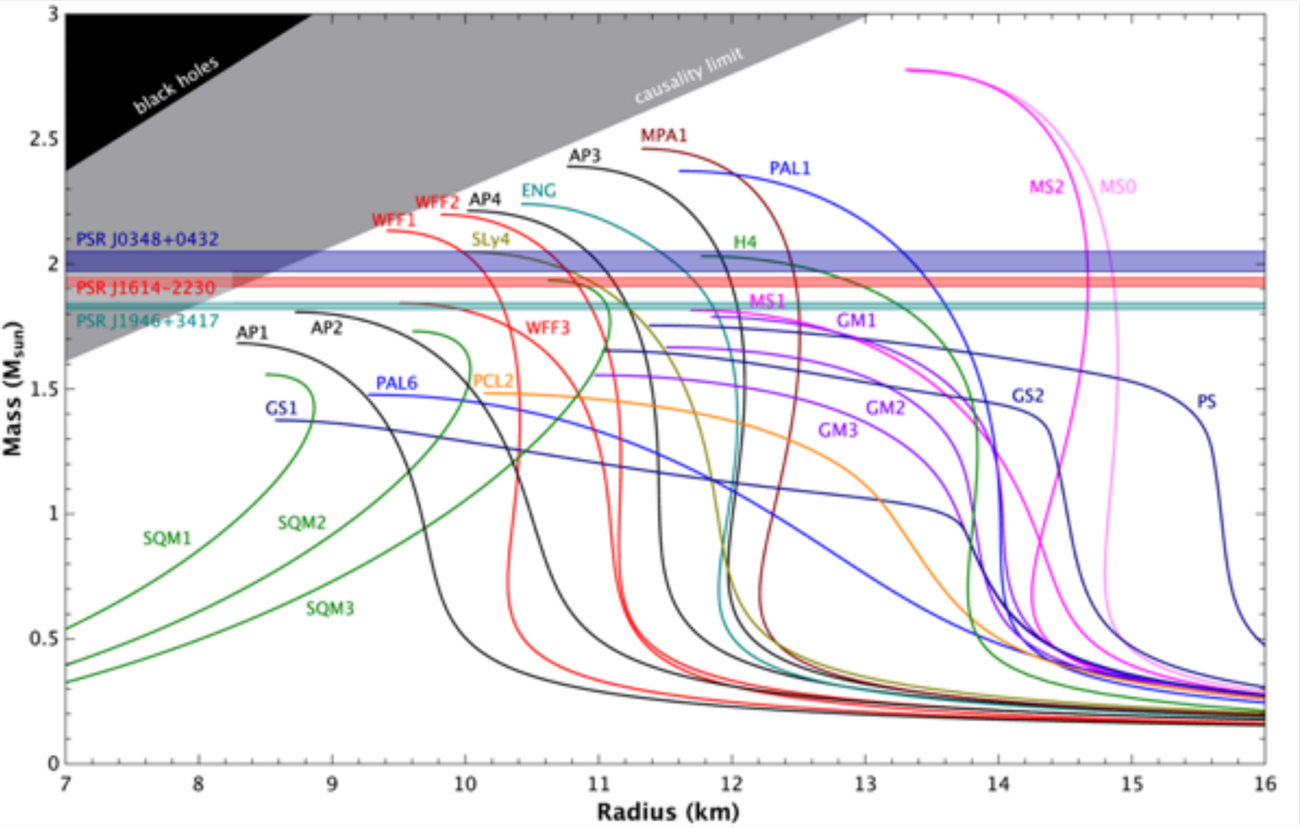


Lattimer, 2012, ARAA

- Sufficiently large observed NS masses could set interesting lower limits to M_{TOV}, which could help ruling out soft EoSs.

BNS mergers for Constraining EoS

Neutron Star / Quark Star Equation of State



Lattimer, 2012, ARAA

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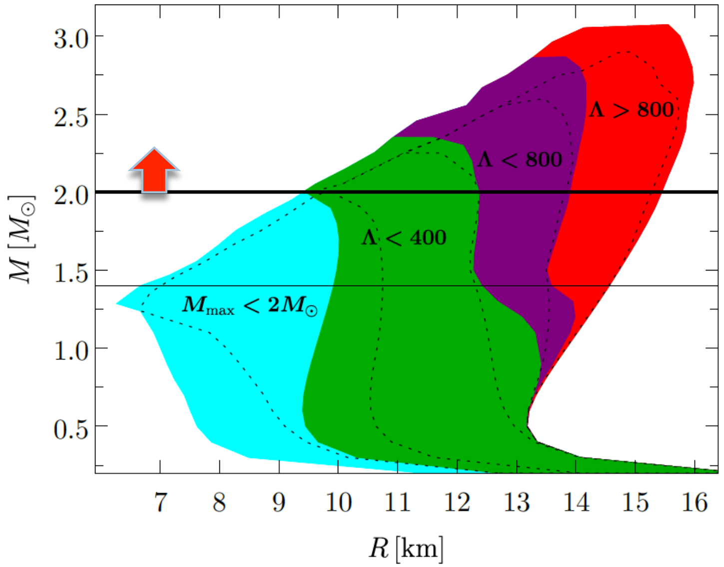
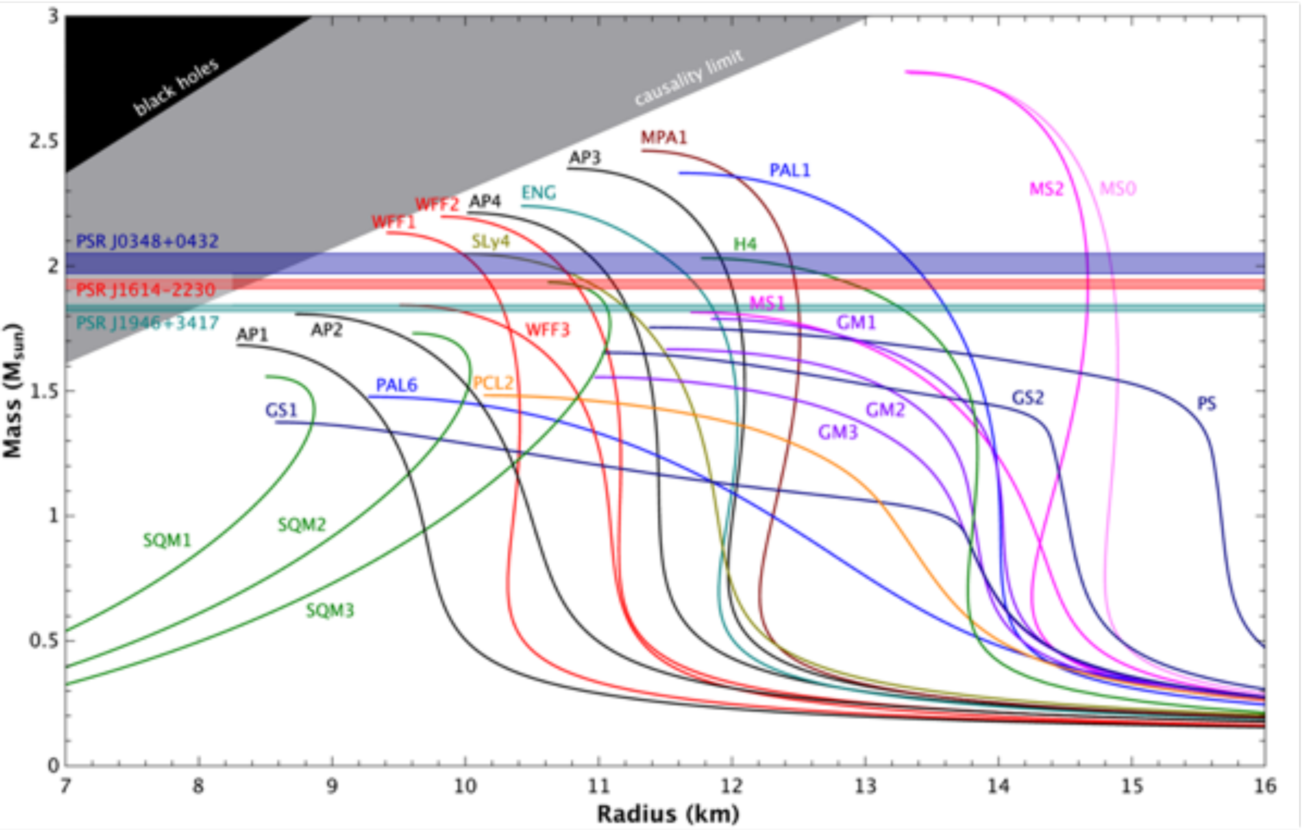
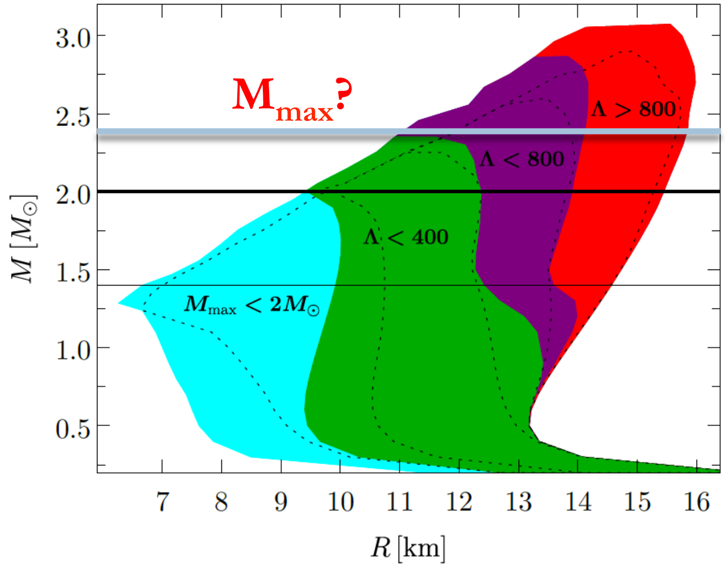


BNS mergers for Constraining EoS

Neutron Star / Quark Star Equation of State

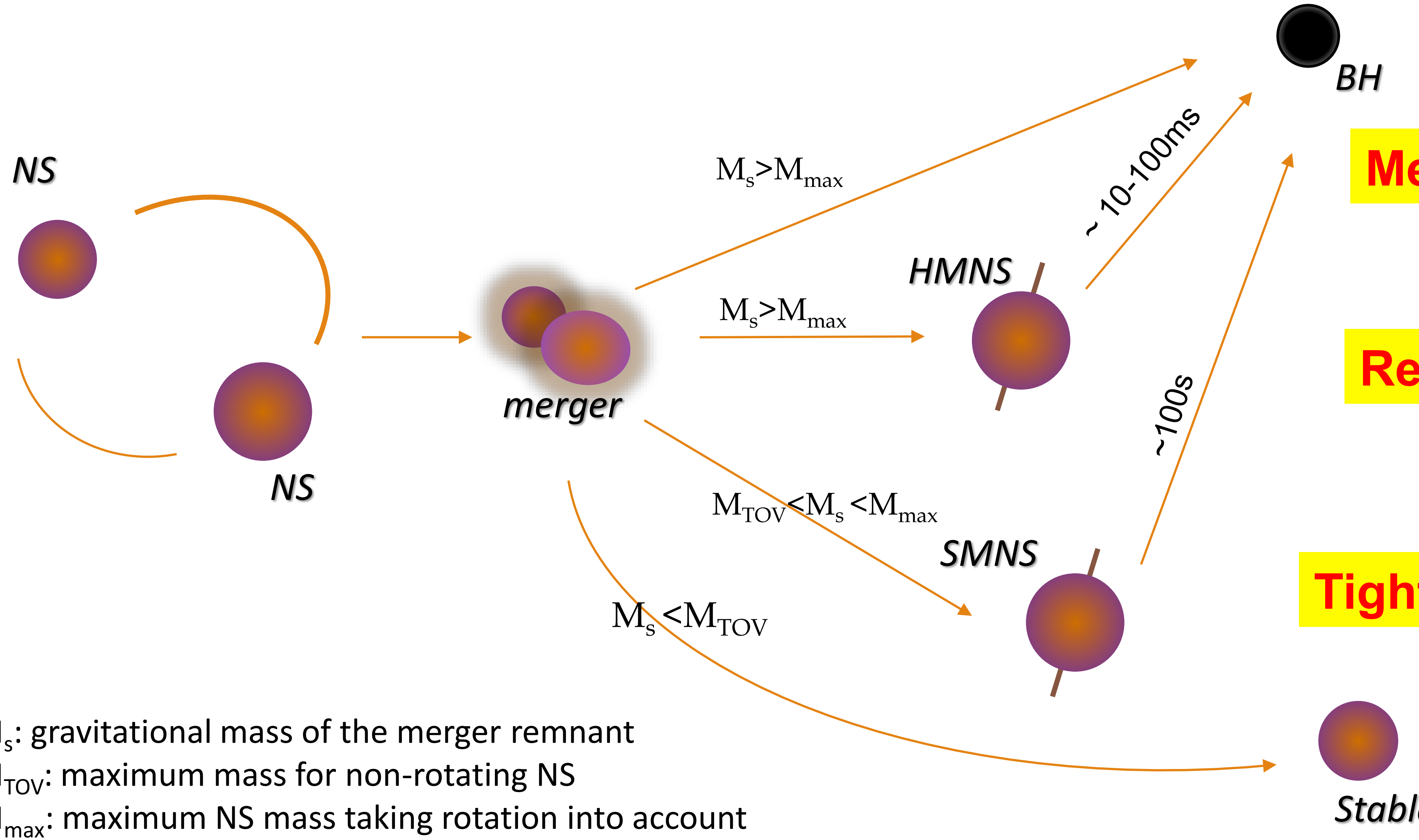


- BNS mergers are proposed to place stringent constraints on NS maximum mass, it could be lower limits or upper limits.



Lattimer, 2012, ARAA

NS M_{TOV} constraint from NS-NS mergers



Merger remnant mass

+

Remnant being BN/NS

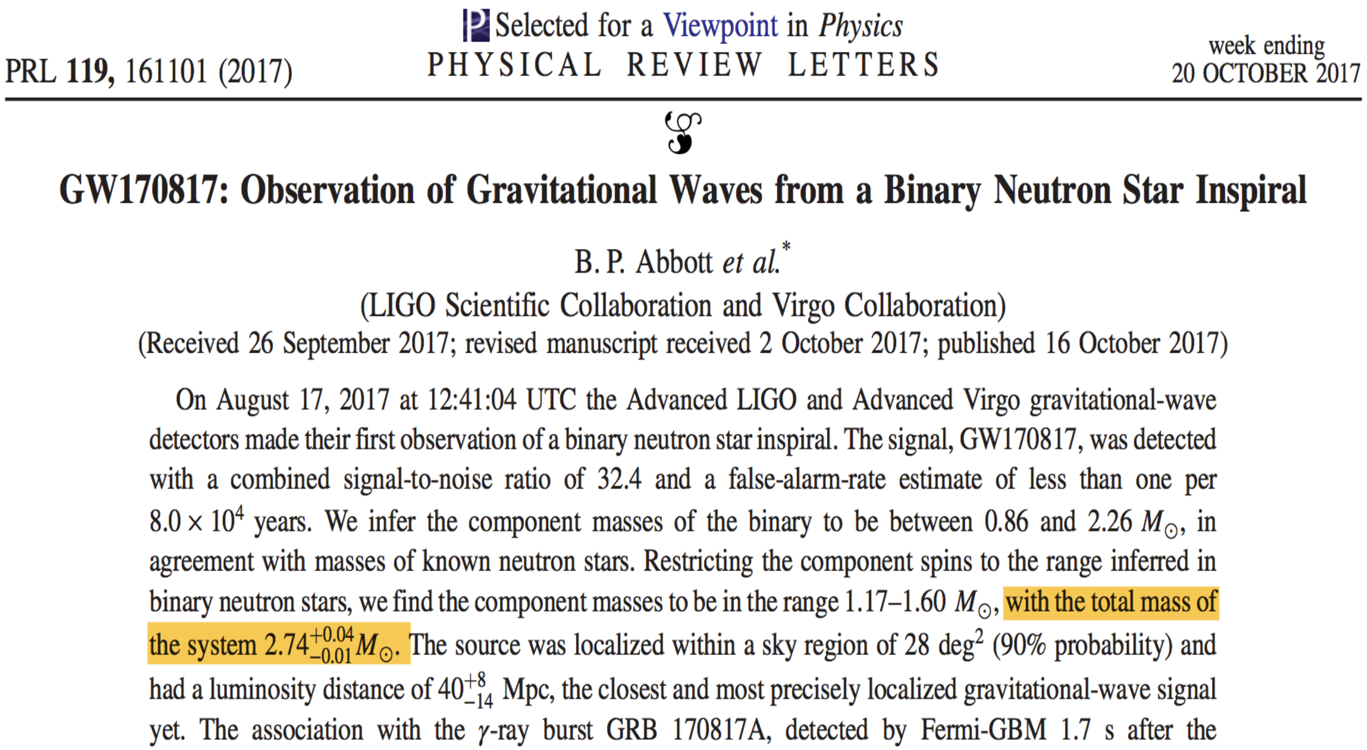
Tight constraints on M_{TOV}

M_s: gravitational mass of the merger remnant

M_{TOV}: maximum mass for non-rotating NS

M_{max}: maximum NS mass taking rotation into account

Merger Remnant Mass M_s



PRL 119, 161101 (2017)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending 20 OCTOBER 2017

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

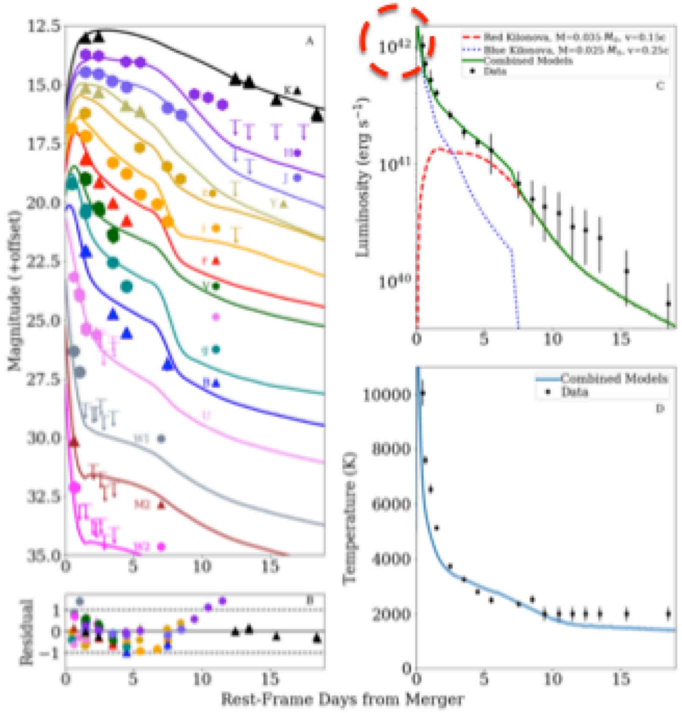
B. P. Abbott *et al.**

(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

GW170817 Optical Observation



Kilpatrick et al. 2017, Nature

Red

$$M_{ej} = 0.035\,M_\odot$$
$$v_k = 0.15\,c$$
$$\log(X_{lan}) = -2.0$$

Blue

$$M_{ej} = 0.025\,M_\odot$$
$$v_k = 0.25\,c$$
$$\log(X_{lan}) = -4$$

GW → M_{tot}

KN → M_{ej}

$$M_s = M_{tot} - M_{ej}$$

Current GW detectors cannot determine remnant being NS/BH

Search for gravitational waves from a long-lived remnant of the binary neutron star merger GW170817

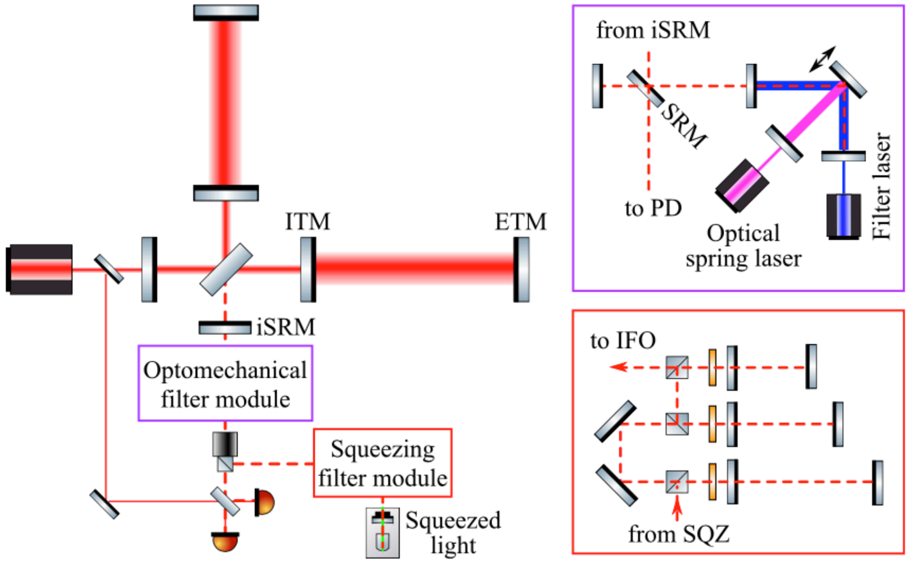
THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION

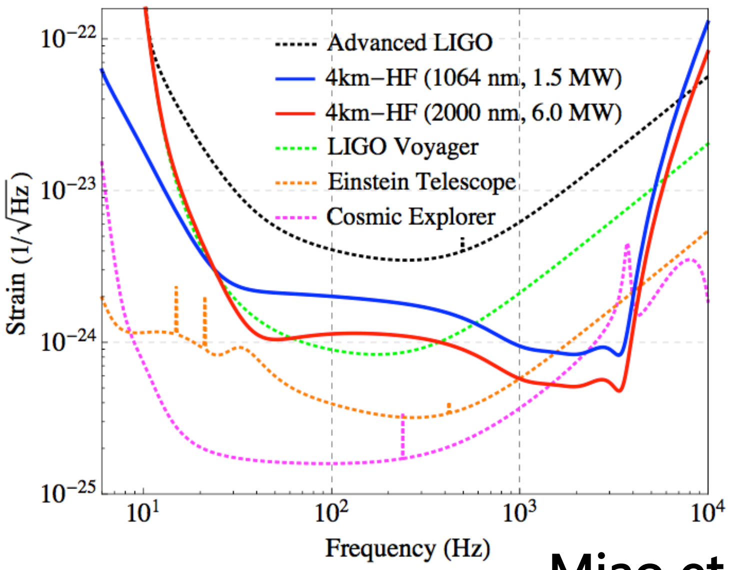
(Dated: 2018-10-05; report no. LIGO-P1800195)

ABSTRACT

One unanswered question about the binary neutron star coalescence GW170817 is the nature of its post-merger remnant. A previous search for post-merger gravitational waves targeted high-frequency signals from a possible neutron star remnant with a maximum signal duration of 500 s. Here we revisit the neutron star remnant scenario with a focus on longer signal durations up until the end of the second Advanced LIGO-Virgo observing run, 8.5 days after the coalescence of GW170817. The main physical scenario for such emission is the power-law spindown of a massive magnetar-like remnant. We use four independent search algorithms with varying degrees of restrictiveness on the signal waveform and different ways of dealing with noise artefacts. In agreement with theoretical estimates, we find no significant signal candidates. Through simulated signals, we quantify that with the current detector sensitivity, nowhere in the studied parameter space are we sensitive to a signal from more than 1 Mpc away, compared to the actual distance of 40 Mpc. This study however serves as a

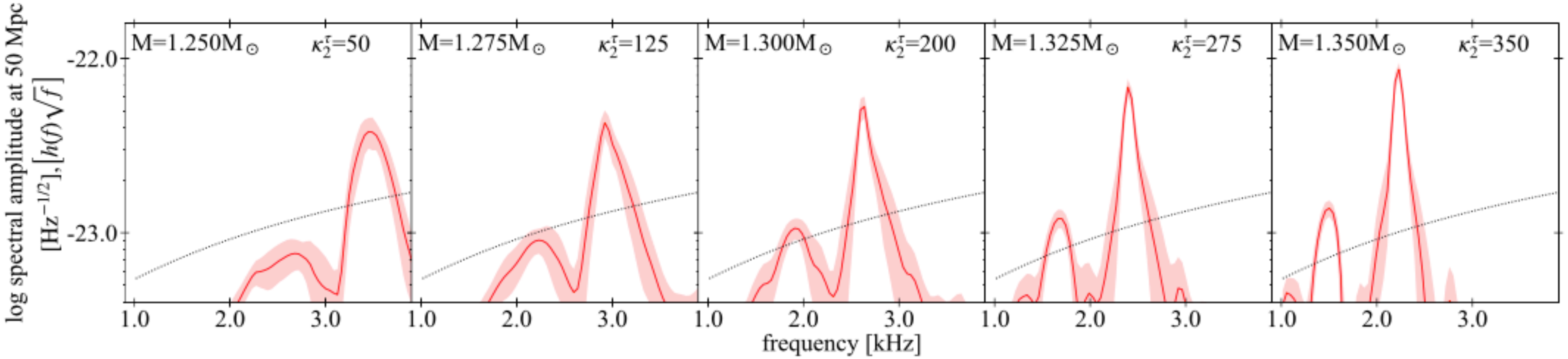
Improving GW detector or post-merger waveforms





- 3^{rd} Generation Detector
- kHz Detector

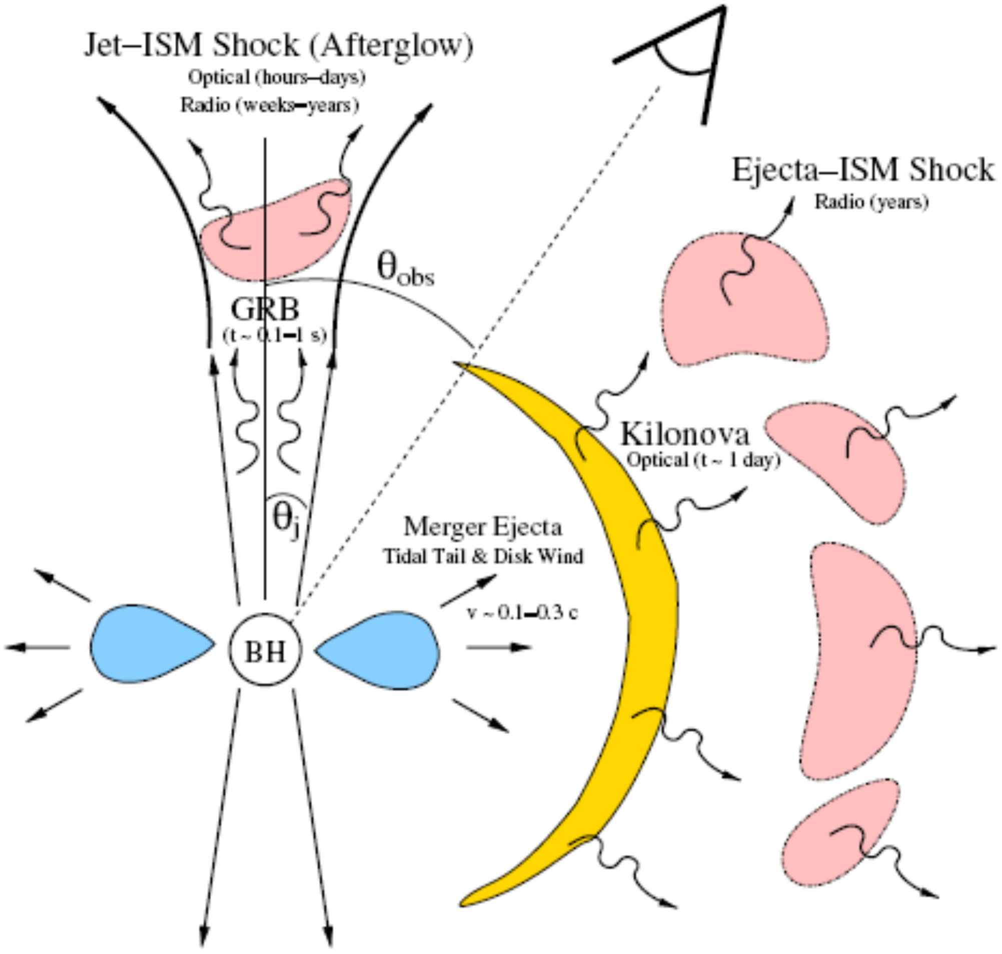
Miao et al. 2018, PRD



Fast and Reliable Waveforms

Easter et al. 2018

EM signature when remnant being BH



Metzger & Berger (2012)

Short GRB

Multi-wavelength afterglow

~hours, days

Li-Paczyński Nova (Macronova, Kilonova)

Optical flare

~ days, weeks

Li & Paczyński, 1998
Metzger et al .2010

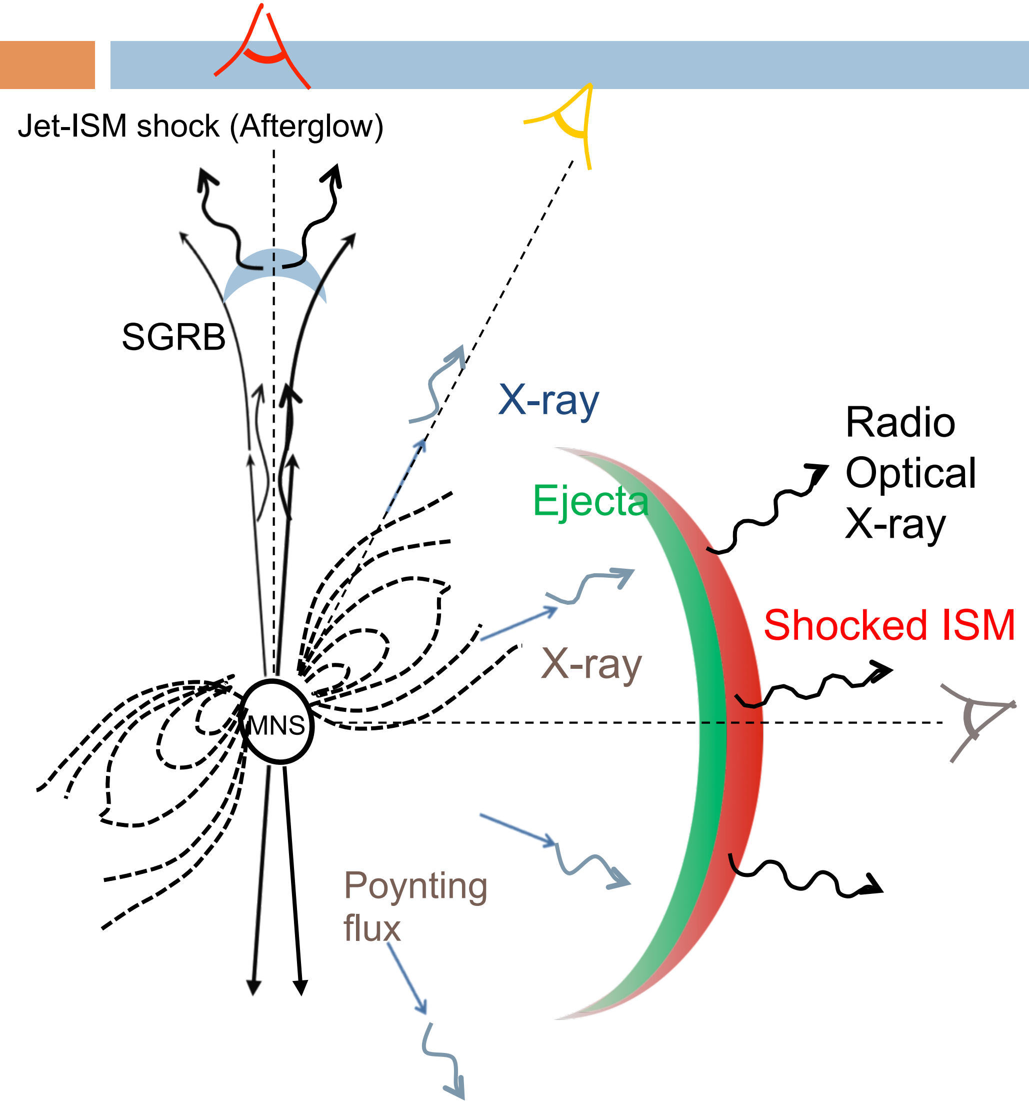
Ejecta-ISM interaction shock

Radio

~years

Nakar & Piran, 2011

EM signature when remnant being NS



Gao+ 2013 ApJ

SGRB?

Late central engine activity

~Plateau & X-ray flare

Orphan X-ray Plateau

1000 ~10000 s

Zhang, 2013 ApJL

Li-Paczyński Nova ⇨ Merger-Nova

Yu, Zhang & Gao 2013 ApJL

Ejecta-ISM shock with Energy Injection

Multi-band transient, ~hours to even years

Gao+ 2013 ApJ, Wang & Dai 2013 ApJL

Agree to disagree

Evidence for BH as remnant:

– There was a GRB

– Kilonova is “kilo” and the kinetic energy inferred from sGRB or ejecta afterglow is small (A supramassive NS would inject a huge mount of energy to the ejected material, and GRB jet ($\sim 10^{52}$ergs)

– No evidence of a magnetar (e.g. no internal plateau in X-ray)

If you believe:

– Long-lived NS never be the central engine for any GRB

– Secular GW radiation would not take away too much energy

Agree to disagree

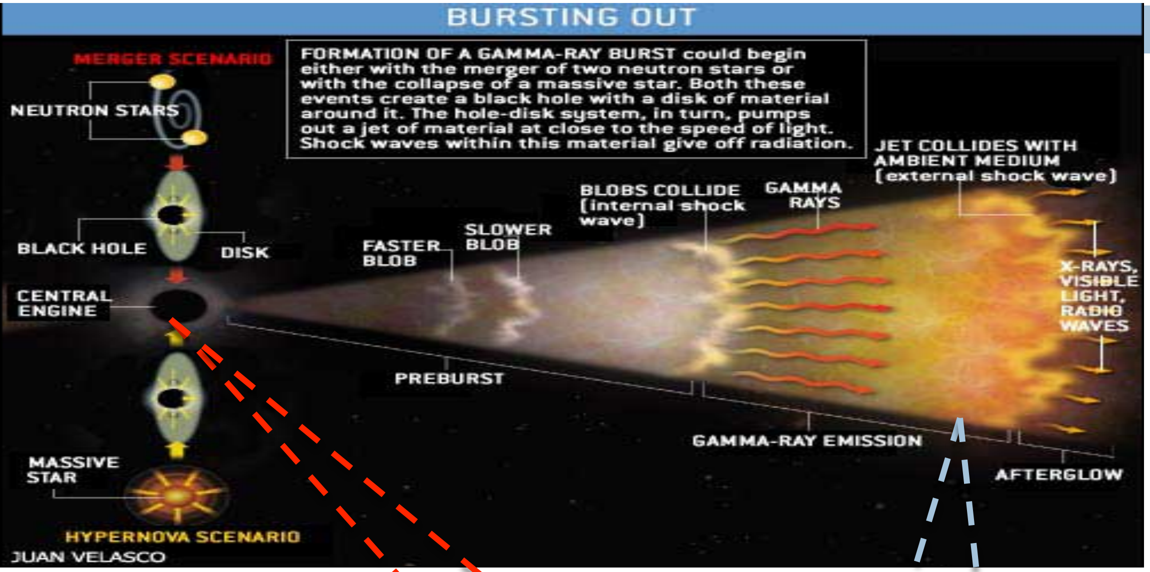
Evidence for NS as remnant:

- X-ray plateau with/without SGRB association
- Kilonova (10^{41}erg/s) becomes 10-100 times brighter ($10^{42\text{-}43}$erg/s) or kinetic energy inferred from sGRB or ejecta afterglow is large (~10^{52}ergs)
- Late central engine activity, such as late X-ray flare

If you believe:

- BH central engine can never give internal plateau signature in X-ray
- There are upper limits for the mass of ejected material, so that there are upper limits for the bright of r-process powered kilonova

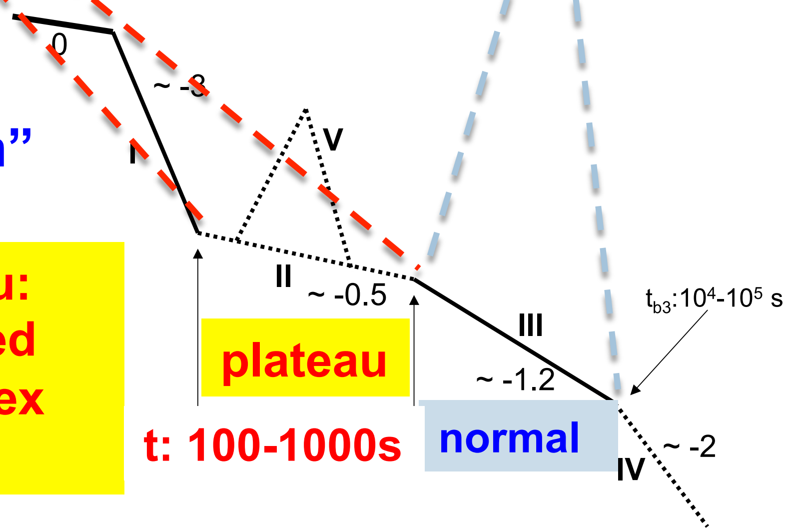
NS vs BH: SGRB with plateau feature in X-ray afterglow



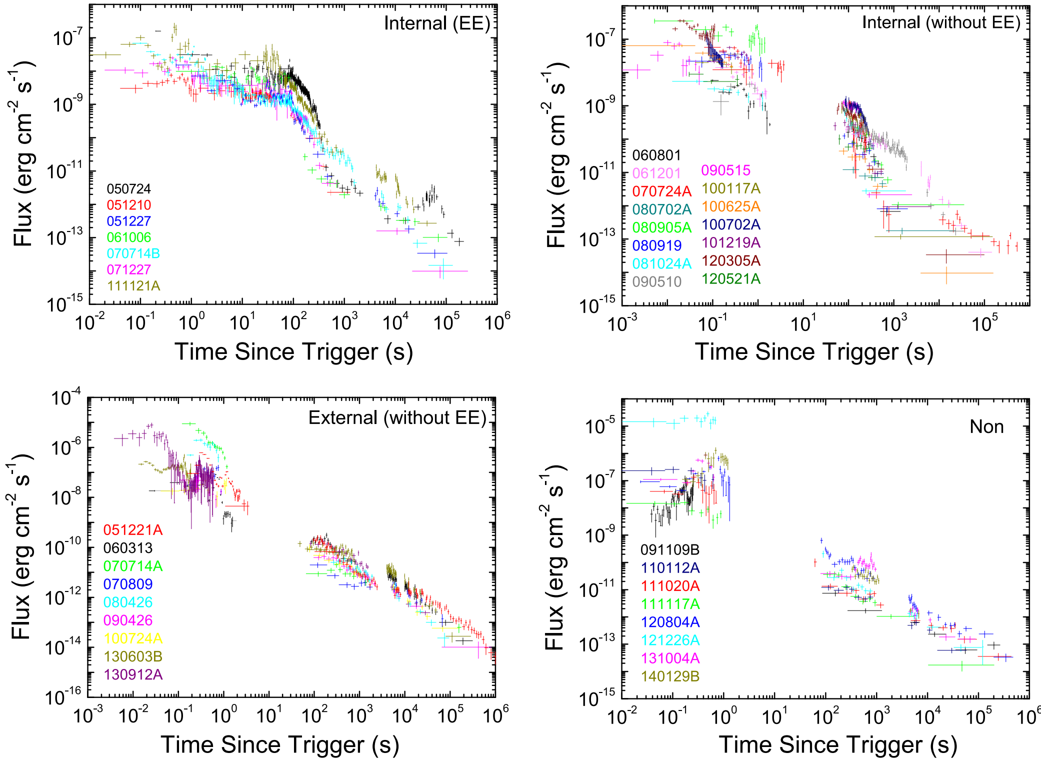
- Swift 10 years: 96 SGRBs
- 30/96 (32%) with plateau,

21/96 (22%) with "internal plateau"

"Smoking gun"

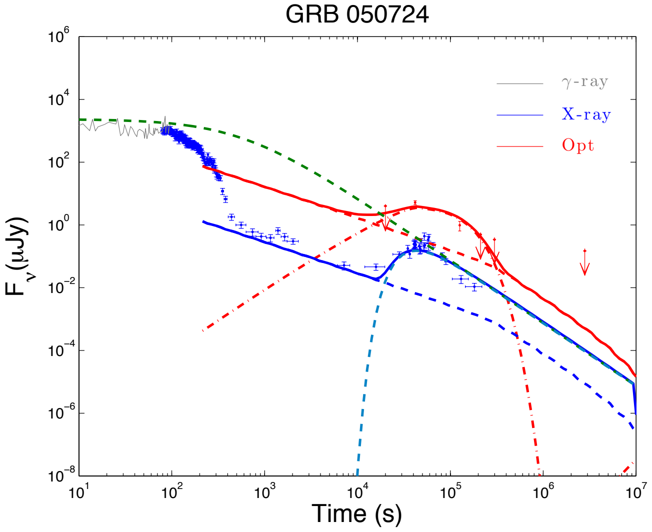


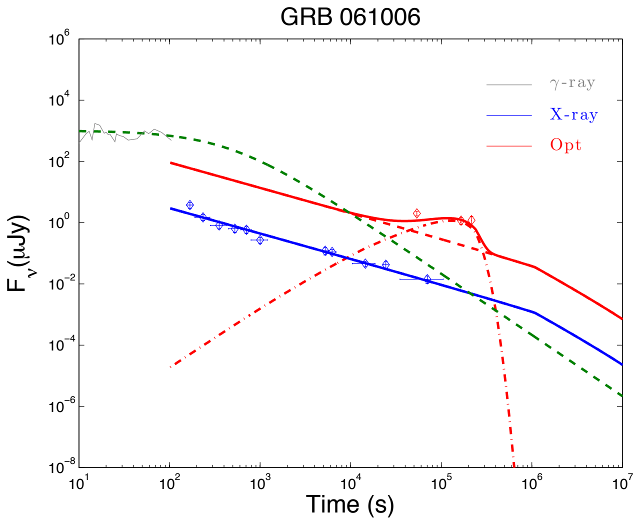
Internal plateau: plateau followed by a decay index steeper than 3.



zhang et al. 2016, ApJ

NS vs BH: Kilonova becomes 10-100 times brighter





21 SGRBs with internal plateau;
3/21 with high quality late data and z measurement;
3/3 show brighter kilonova

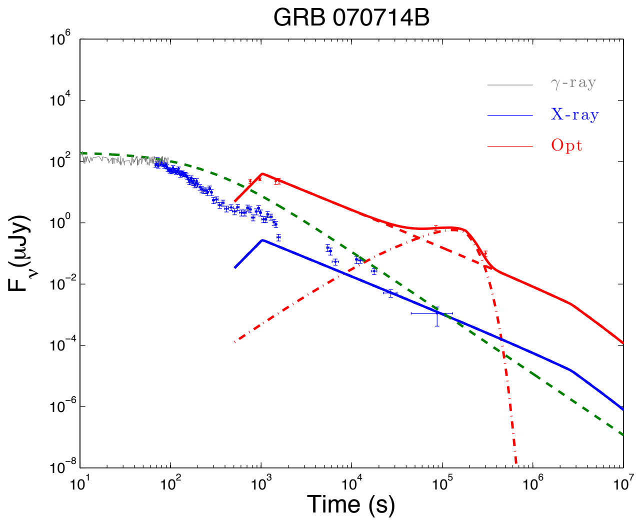
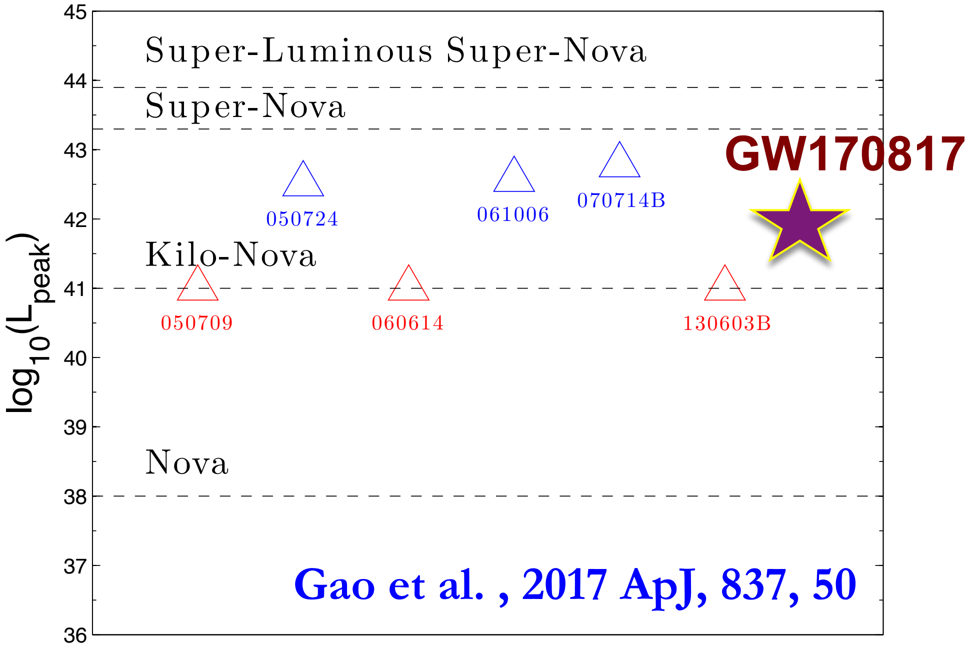
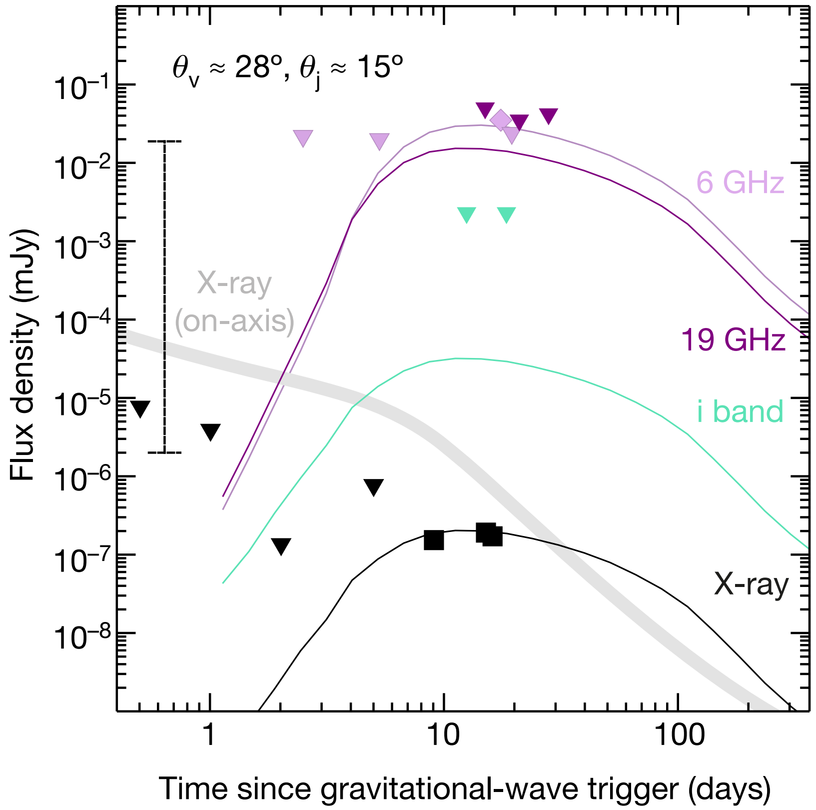


TABLE 1
MODEL PARAMETERS TO INTERPRET THE BROADBAND DATA OF GRB 050724, GRB 070714B AND GRB 061006

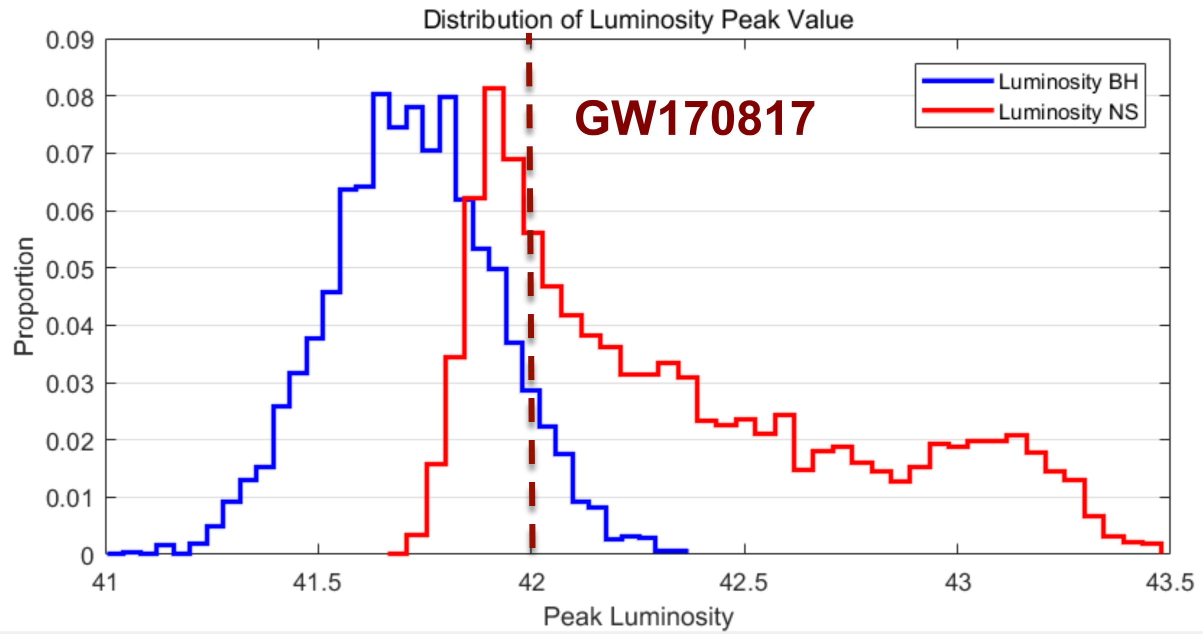
Magnetar and ejecta parameters						
	B (G)	P_i (ms)	R_s (cm)	M_{ej} ($M_\odot$)	v_i/c	κ (cm^2 g^{-1})
GRB 050724	6×10^{15}	5	1.2×10^6	10^{-3}	0.2	1
GRB 070714B	1×10^{16}	2.5	1.0×10^6	10^{-2}	0.2	1
GRB 061006	5×10^{15}	2	1.0×10^6	10^{-2}	0.2	1
Jet and ambient medium parameters						
	E (erg)	Γ_0	n (cm^{-3})	θ (rad)		
GRB 050724	3.9×10^{50}	200	0.1	0.2		
GRB 070714B	10^{52}	95	0.01	0.2		
GRB 061006	1.6×10^{52}	200	0.1	0.2		
Other parameters						
	ϵ_e	ϵ_B	p	ξ		
GRB 050724	0.025	0.001	2.3	0.01		
GRB 070714B	0.06	0.0002	2.6	0.1		
GRB 061006	0.015	0.00003	2.1	0.01		



GW170817: cannot determine BH or NS



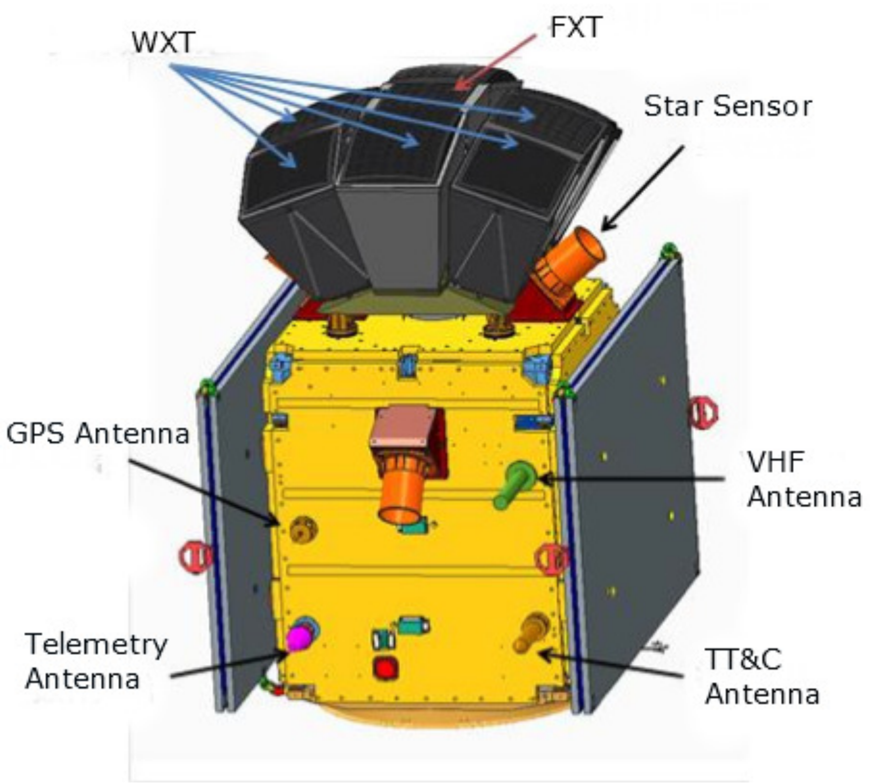
X-ray observation starts too late

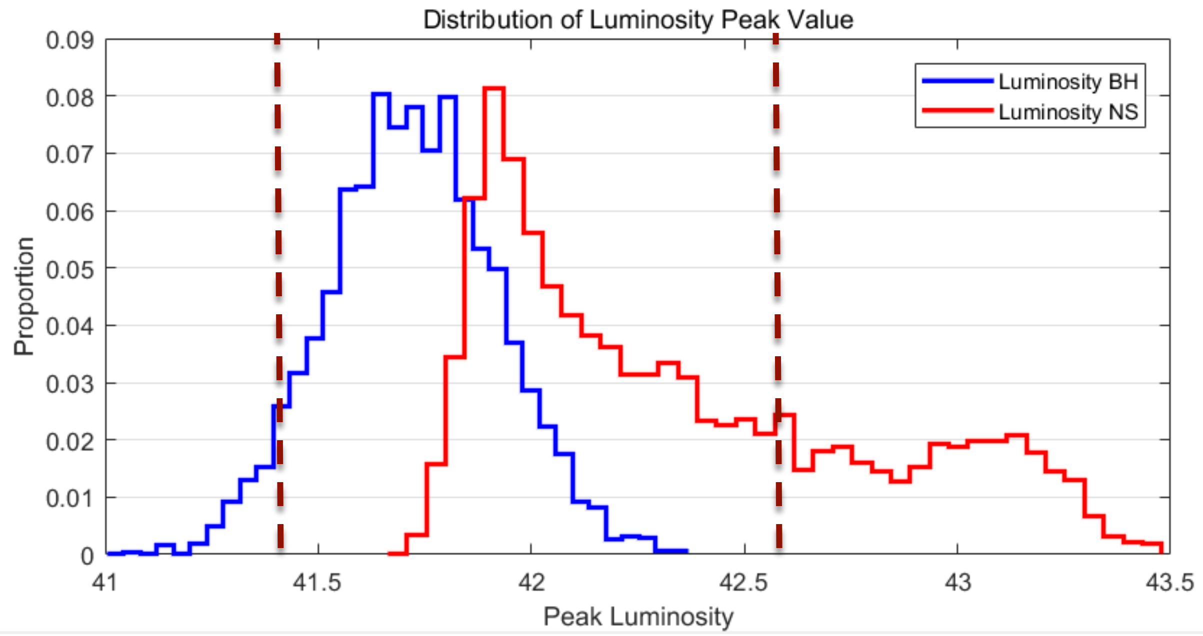


Optical luminosity is just in between BH and NS cases

Future GW Cases

Einstein Probe： large FoV X-ray telescope



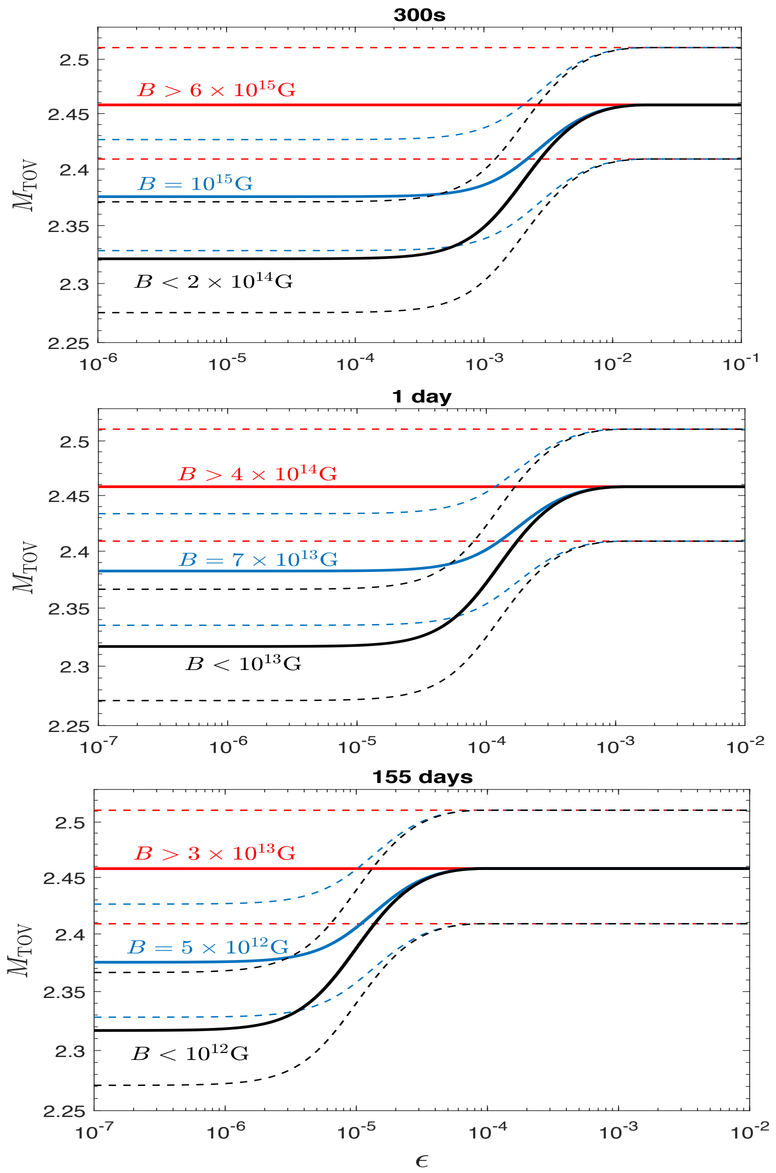


Early X-ray afterglow observation

Optical transient with much lower or higher luminosity

What's M_{TOV} from GW170817 / GRB 170817A?

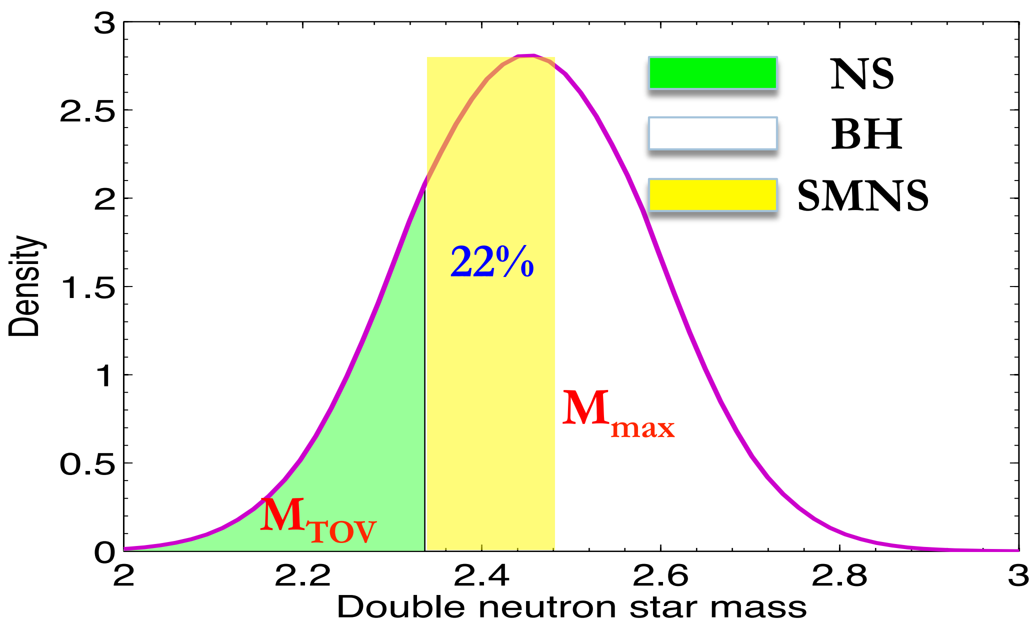
- M_{TOV} <~ 2.5 $M_{\odot}$: if the remnant was a BH or hypermassive NS;
- M_{TOV} ~ (2.3-2.4) $M_{\odot}$: if the remnant was a supramassive magnetar with "typical" parameters surviving ~300 seconds;
- M_{TOV} ~ (2.3-2.5) $M_{\odot}$: if the remnant was still active ~1 day
- M_{TOV} ~ 2.5 $M_{\odot}$: if active at ~155 days, unless the NS parameters are very abnormal (low B, low ϵ)



Ai et al. (2019)

Constraints on M_{TOV} with SGRB Data

- Part of (or all) SGRBs are from NS-NS mergers
- Given mass distribution of NS-NS systems
- Internal plateau indicates supra-massive NS as merger remnant



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

M_{max}: maximum gravitational mass

EoS Parameterization Lasky et al., 2014

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

α and β are functions of M_{TOV}, NS radius (R) and moment of inertia (I)

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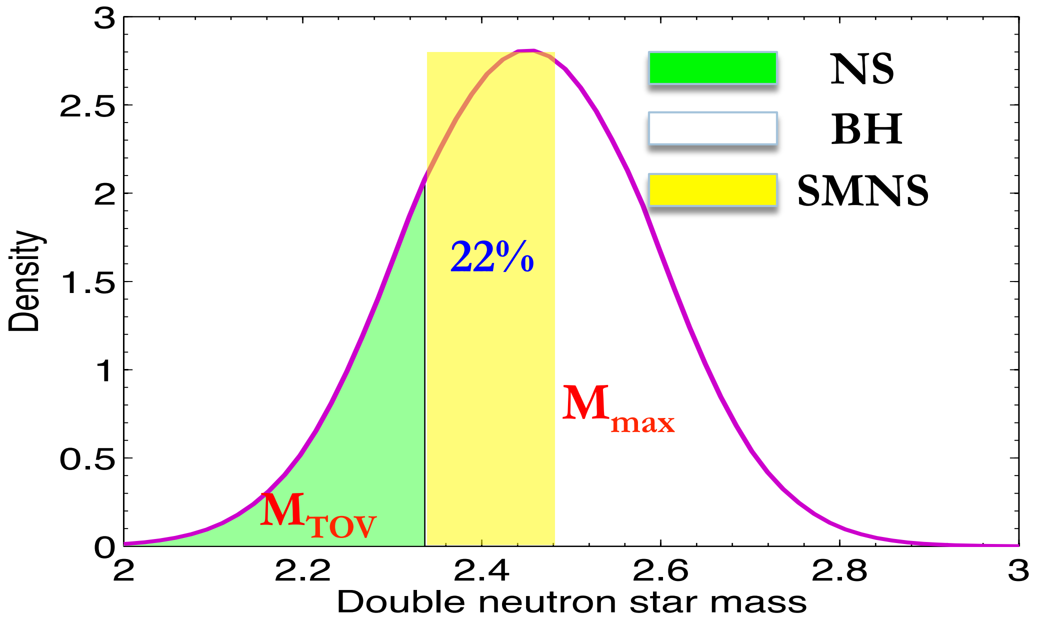

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α and β are functions of M_{TOV}, NS radius (R) and moment of inertia (I)

Mass Distribution of NS-NS Systems

- Cosmological NS-NS systems have the same mass distribution as the observed Galactic system;

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)

Constraints on M_{TOV} with SGRB Data

Gao et al., 2016 PRD, 93, 044065
Li et al., 2016 PRD, 94, 083010

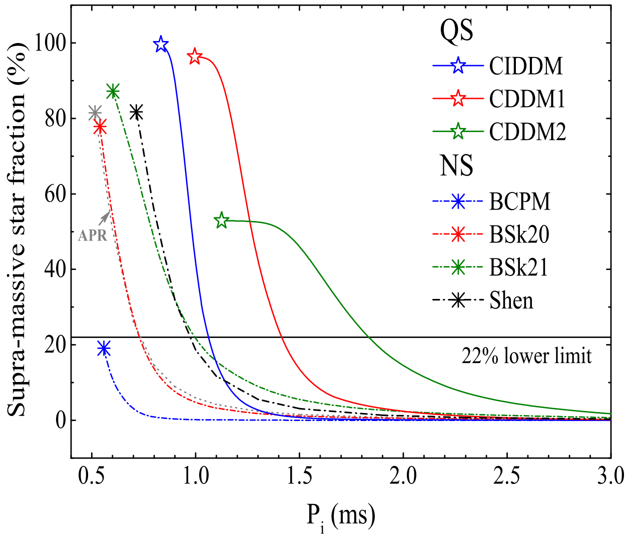
EoS Parameterization

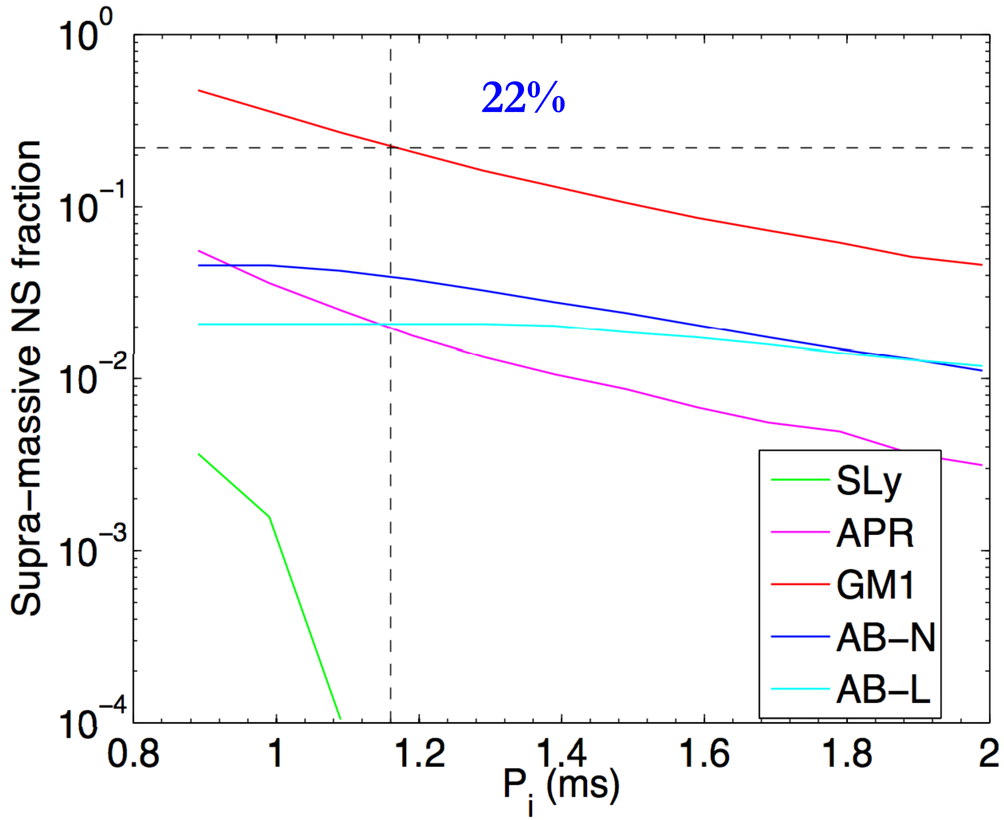
$$M_{max} = M_{TOV}(1+\alpha P^{\beta})$$

M_{max} : maximum gravitational mass

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

P : spin period

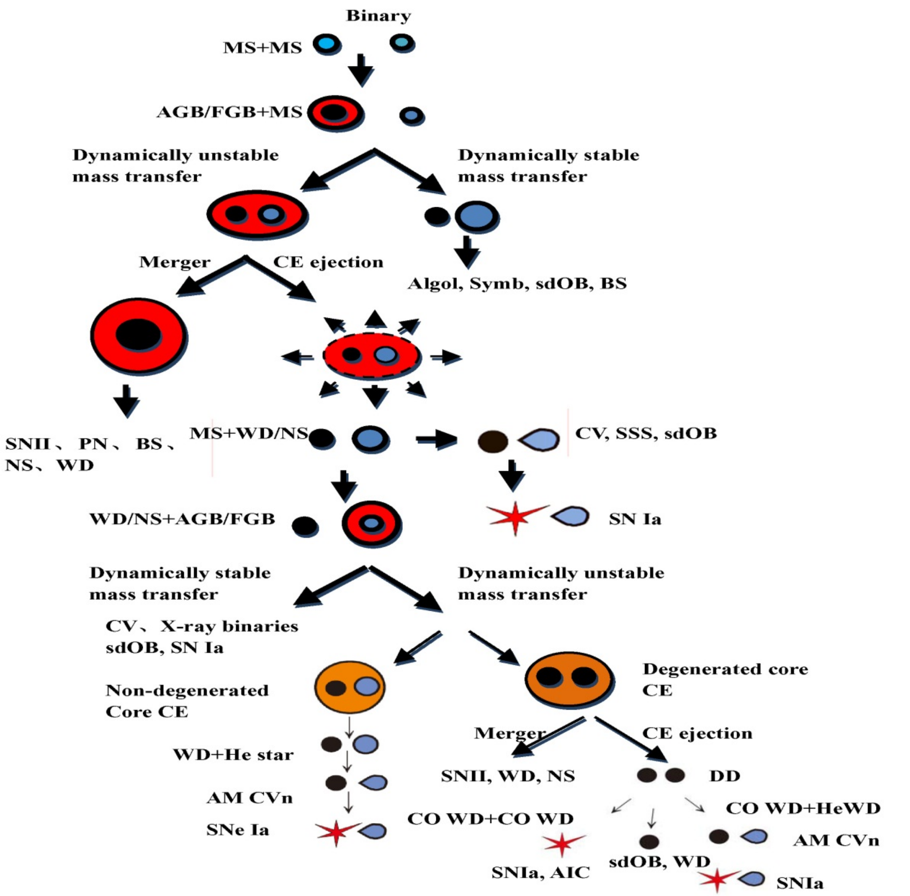


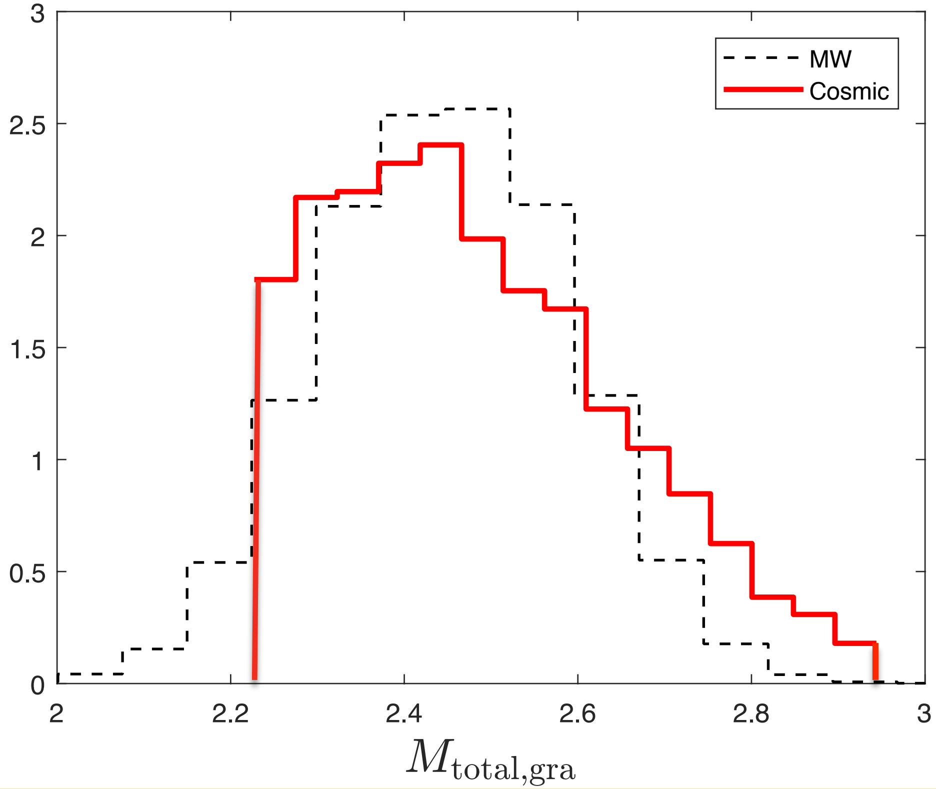


Bottom line: M_{TOV} >~ 2.3 $M_{\odot}$

Mass Distribution of NS-NS Systems

Population Synthesis





Monte Carlo simulation results based on the NS-NS redshift distribution and population synthesis method are consistent with MW.

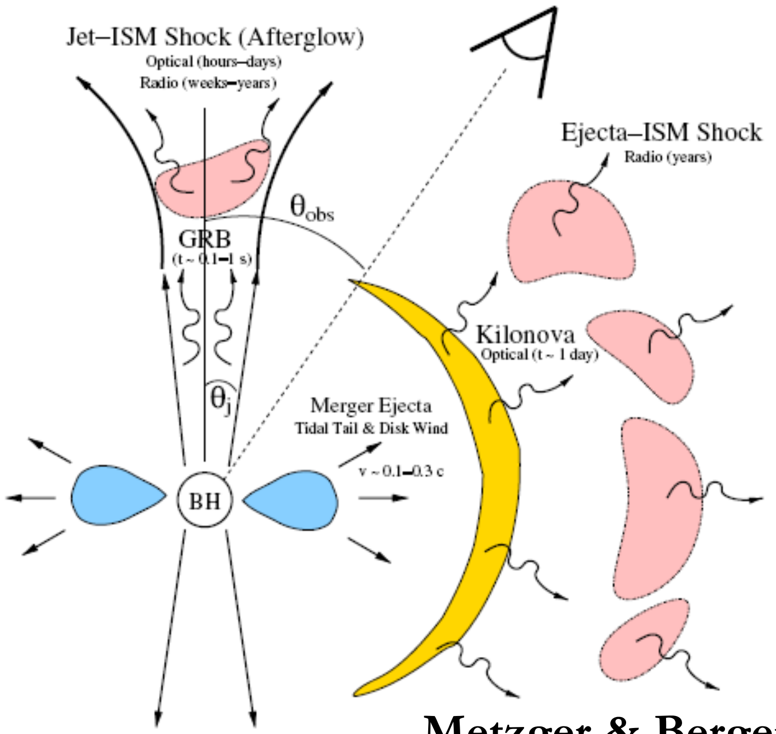
Summary

- Era of GW Astronomy has been Opened
- GW-EM joint detection of NS-NS merger event could make tight constraints on NS maximum mass
  - GW+EM give remnant mass
  - GW/EM determine remnant being BH/NS
- Short GRB data only could also make constraints on NS maximum mass
  - Known NS-NS mass distribution
  - Fraction of SGRBs with Internal plateau
  - Current data favors M_{TOV}~2.3-$2.4M_{\odot}$

Thanks for the attention！

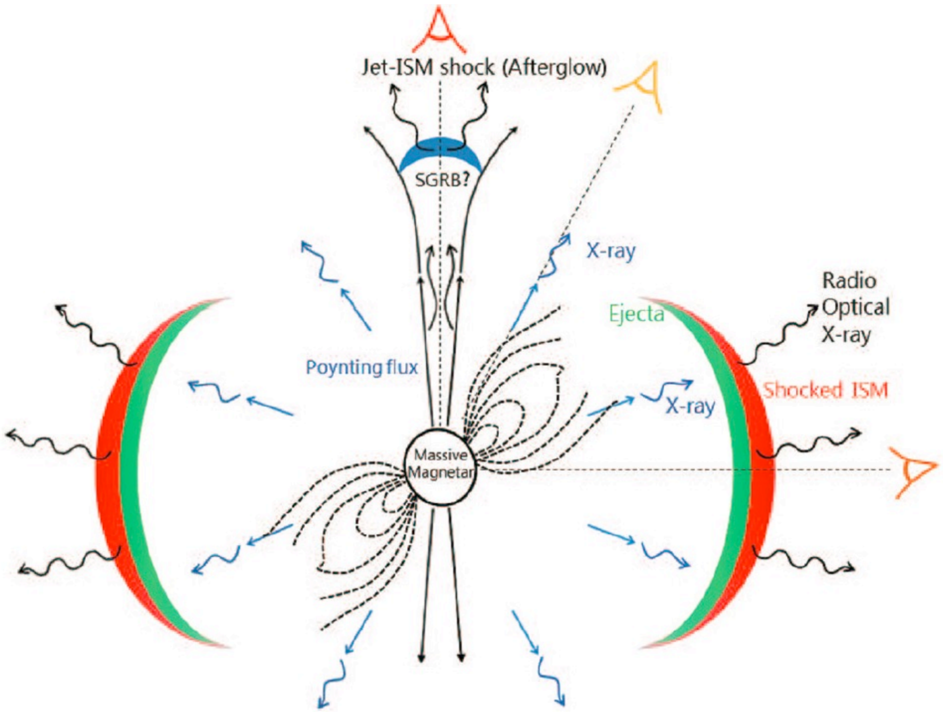
Identifiable EM signature for NS

BH



Metzger & Berger, 2012

NS



Gao et al., 2013

X-ray plateau with/without SGRB association

Kilonova (10^{41}erg/s) becomes 10-100 times brighter (10^{42-43}erg/s)