Binary Neutron Star Mergers and Nuclear Physics

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Plan of the Lectures

- 1. Isolated and Binary Neutron Stars: an Introduction
- 2. Gravitational Wave Emission from Binary Neutron Star Mergers
- 3. Electromagnetic Emission from Binary Neutron Star Mergers
- 4. Observations of Binary Neutron Star Mergers



GW170817

https://www.ligo.org/detections/GW170817.php

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Time from merger (seconds)

Credit: NASA GSFC & Caltech/MIT/LIGO Lab

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

Abbott et al.



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Swift, HST			1.1	1 /	/
Optical				• •	
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Abbott et al.

The event was detected in the full EM spectrum from gamma-ray to radio.

Properties of the BNS Merger GW170817 Abbott et al 2019, PHYSICAL REVIEW X 9, 011001

	Low-spin prior ($\chi \le 0.05$)	High-spin prior ($\chi \le 0.89$)	
Binary inclination θ_{JN}	146^{+25}_{-27} deg	152^{+21}_{-27} deg	
Binary inclination θ_{JN} using EM distance constraint [108]	151_{-11}^{+15} deg	153_{-11}^{+15} deg	
Detector-frame chirp mass \mathcal{M}^{det}	$1.1975^{+0.0001}_{-0.0001}~{ m M}_{\odot}$	$1.1976^{+0.0004}_{-0.0002}~{ m M}_{\odot}$	
Chirp mass \mathcal{M}	$1.186^{+0.001}_{-0.001} M_{\odot}$	$1.186^{+0.001}_{-0.001} M_{\odot}$	
Primary mass m_1	$(1.36, 1.60) M_{\odot}$	$(1.36, 1.89) M_{\odot}$	
Secondary mass m_2	(1.16, 1.36) M _☉	$(1.00, 1.36) M_{\odot}$	
Total mass m	$2.73^{+0.04}_{-0.01}~{ m M}_{\odot}$	$2.77^{+0.22}_{-0.05}~{ m M}_{\odot}$	
Mass ratio q	(0.73, 1.00)	(0.53, 1.00)	
Effective spin $\chi_{\rm eff}$	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$	
Primary dimensionless spin χ_1	(0.00, 0.04)	(0.00, 0.50)	
Secondary dimensionless spin χ_2	(0.00, 0.04)	(0.00, 0.61)	
Tidal deformability $\tilde{\Lambda}$ with flat prior	$300^{+500}_{-190}(\text{symmetric})/300^{+420}_{-230}(\text{HPD})$	(0, 630)	
$\chi_{\text{eff}} = \frac{(m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2) \cdot L_N}{M} \qquad \qquad \mathcal{M} \equiv (1 + z)$	$(m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$ $\mathcal{M} = \frac{c^3}{G}$	$-\left[\frac{5}{96}\frac{1}{\pi^{8/3}}\dot{\nu}_{GW}\nu_{GW}^{-11/3}\right]^{3/5}$	

First estimate of NS radius via gravitational waves. Several stiff EOSs now excluded.

GRB170817A

GRB170817A was 2 orders of magnitude closer and 2 to 6 orders of magnitude less energetic than other GRBs ($E_{iso} \approx 3 \times 10^{46} erg$).

X-rays were detected 9 days later by Chandra.

https://doi.org/10.3847/2041-8213/aa920c

GRB170817A: Theoretical Models Radio Radio Radio emission Radio emission emissior $\beta \approx 0.8$ $\gamma \approx 2-3$ $\gamma \approx 2-3$ 333 γ-rays γ-rays γ-rays? γ-rays Mooley et al 2017 γ-rays (C) Choked jet (D) Choked jet (E) Successful hidden jet (B) Off-axis jet (A) On-axis jet Cocoon y-rays Fast ejecta afterglow SGRB and afterglow Cocoon y-rays SGRB and afterglow and afterglow and afterglow

Observations consistent with successful jet observed off axis (~15^o - 20^o) with $\theta_{jet} \leq 5^{o}$ (Lazzati et al 2018).

1.7 s delay between GW and GRB probably due to time required by the fireball to reach the photospheric radius (Lazzati et al 2020) $_{\rm 10}$

r-process produced an observed kilonova

~200 Earth masses of gold produced

Using GW and GRB to Infer Maximum NS Mass

In order to produce an SGRB it seems necessary to have an HMNS phase followed by BH collapse (see also Ciolfi 2020).

This would constrain the maximum mass to M_{max} ~2.15-2.28 in order to explain GW170817 and GRB 170817A

Ruiz, Shapiro, and Tsokaros 2018, PRD 97, 021501(R)

GW190425

https://www.ligo.org/detections/GW190425.php

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Abbott et al 2020, http://arxiv.org/abs/2001.01761

Detected only by LIGO Livingston. Very poor localization compared to GW170817 (8284 vs 28 square degrees). GW signal lasted for ~128 s (~3900 phase cycles).

No EM counterpart has been identified and this is consistent with being a BNS (see Barbieri et al 2020 and Kyutoku et al 2020 for kilonova models comparing NS-NS with NS-BH). 14

Table 1Source Properties for GW190425

	Low-spin Prior	High-spin Prior
	$(\chi < 0.05)$	$(\chi < 0.89)$
Primary mass m_1	$1.60 - 1.87 \ M_{\odot}$	$1.61-2.52~M_{\odot}$
Secondary mass m_2	$1.46 - 1.69 \ M_{\odot}$	$1.12 extrm{}1.68~M_{\odot}$
Chirp mass \mathcal{M}	$1.44^{+0.02}_{-0.02}M_{\odot}$	$1.44^{+0.02}_{-0.02}M_{\odot}$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}M_{\odot}$	$1.4873^{+0.0008}_{-0.0006}~M_{\odot}$
Mass ratio m_2/m_1	0.8 - 1.0	0.4 - 1.0
Total mass m _{tot}	$3.3^{+0.1}_{-0.1}~{ m M}_{\odot}$	$3.4^{+0.3}_{-0.1} M_{\odot}$
Effective inspiral spin parameter χ_{eff}	$0.012\substack{+0.01\\-0.01}$	$0.058\substack{+0.11\\-0.05}$
Luminosity distance $D_{\rm L}$	$159^{+69}_{-72} \mathrm{~Mpc}$	$159^{+69}_{-71} \mathrm{Mpc}$
Combined dimensionless	≤600	≤1100
tidal deformability $ ilde{\Lambda}$		Abbott et al 2020, http://arxi

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$$\mathcal{M} \equiv (1+z)(m_1m_2)^{3/5}(m_1+m_2)^{-1/5} \quad \chi_{\text{eff}} = \frac{(m_1\vec{\chi_1}+m_2\vec{\chi_2})\cdot\hat{L}_N}{M}$$

Total mass significantly higher than galactic BNS systems. It may have formed in a low metallicity stellar binary (~5-10% solar metallicity, Giacobbo & Mapelli 2018).

GW190425

Numerical relativity simulation of last orbits, merger and black hole formation

Neutron star masses: 1.55 vs 1.75 M_{sun} Mass density in the strong-field region Volume: ~ (100 km)³

https://youtu.be/yYCnp_42mgY

Updated 16 June 2022	— 01	— 02	O 3	— O4	O5
LIGO	80 Mpc	100 Мрс	100-140 Мрс	160-190 Mpc	240-325 Mpc
Virgo		30 Mpc	40-50 Mpc	80-115 Mpc	150-260 Mpc
KAGRA			0.7 Mpc	(1-3) ~ 10 Mpc	25-128 Mpc
G2002127-v12	2015 2016	2017 2018 2	2019 2020 2021	2022 2023 2024 2025 20	26 2027 2028

https://observing.docs.ligo.org/plan/

Other References

Frontiers Research Topic, "Gravitational Waves: A New Window to the Universe" <u>https://www.frontiersin.org/research-</u> topics/11345/gravitational-waves-a-new-window-to-the-universe

It contains 8 short reviews on the status of multimessenger astronomy and compact binary mergers.