Binary Neutron Star Mergers and Nuclear Physics

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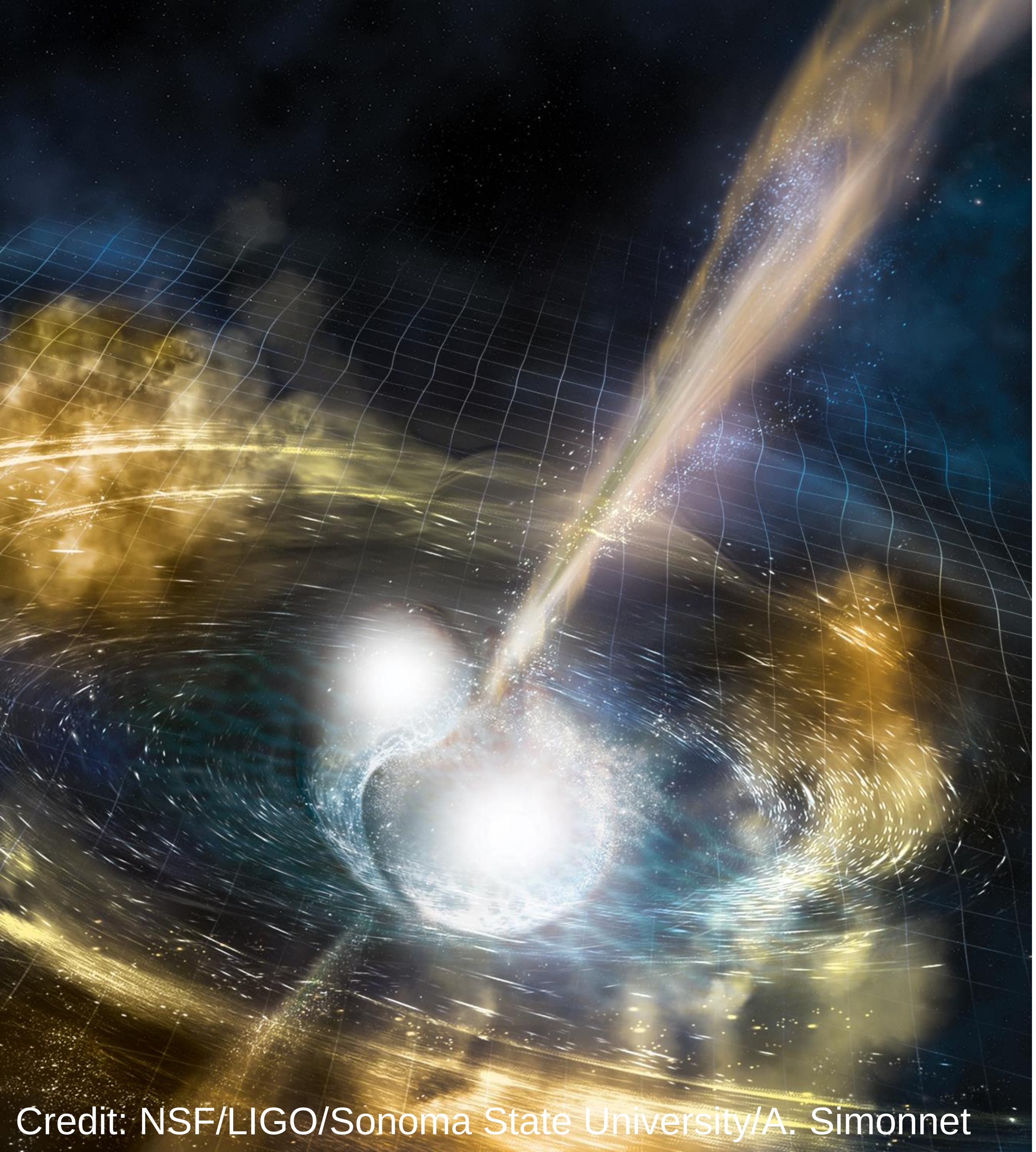
Plan of the Lectures

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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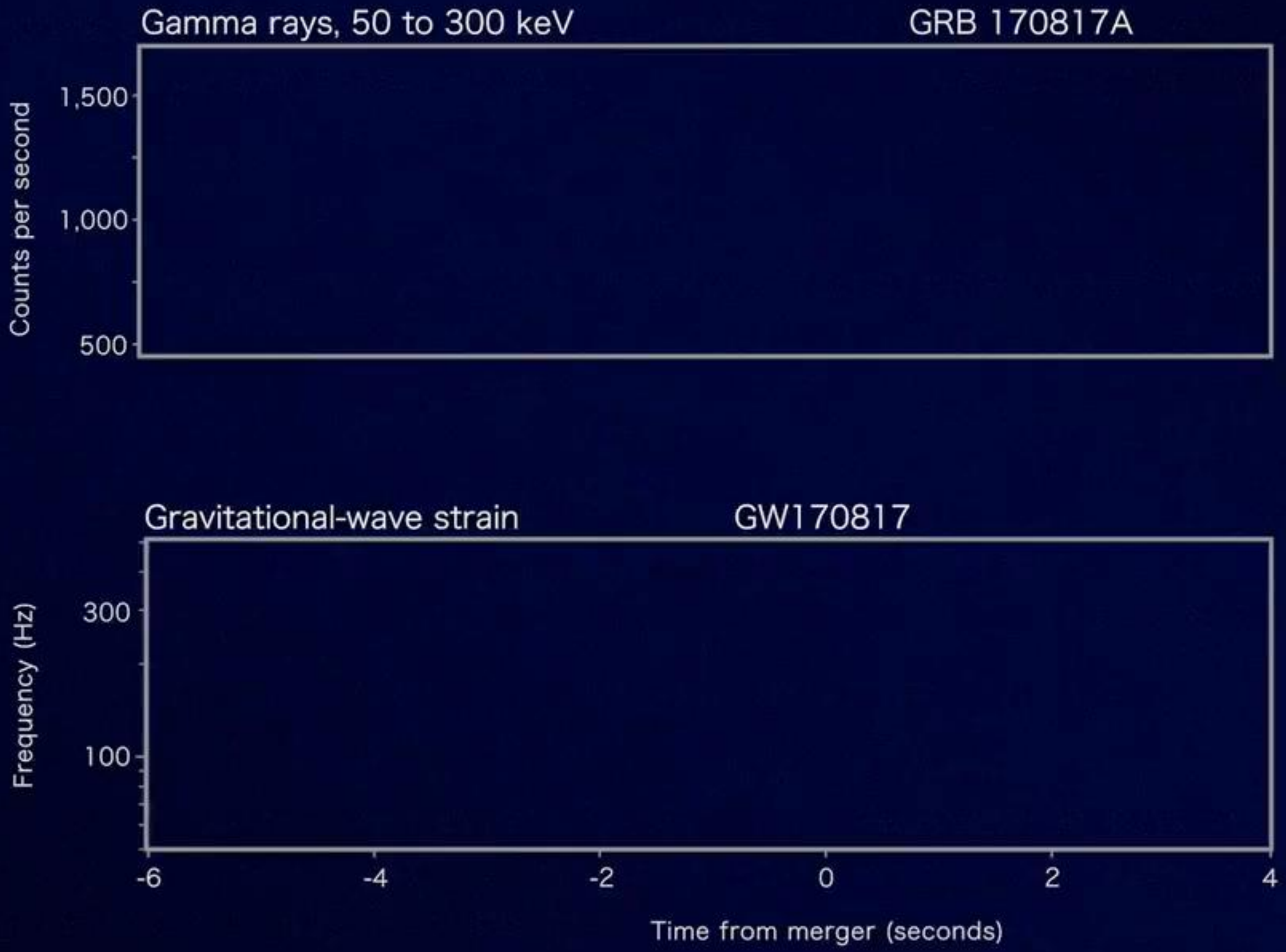
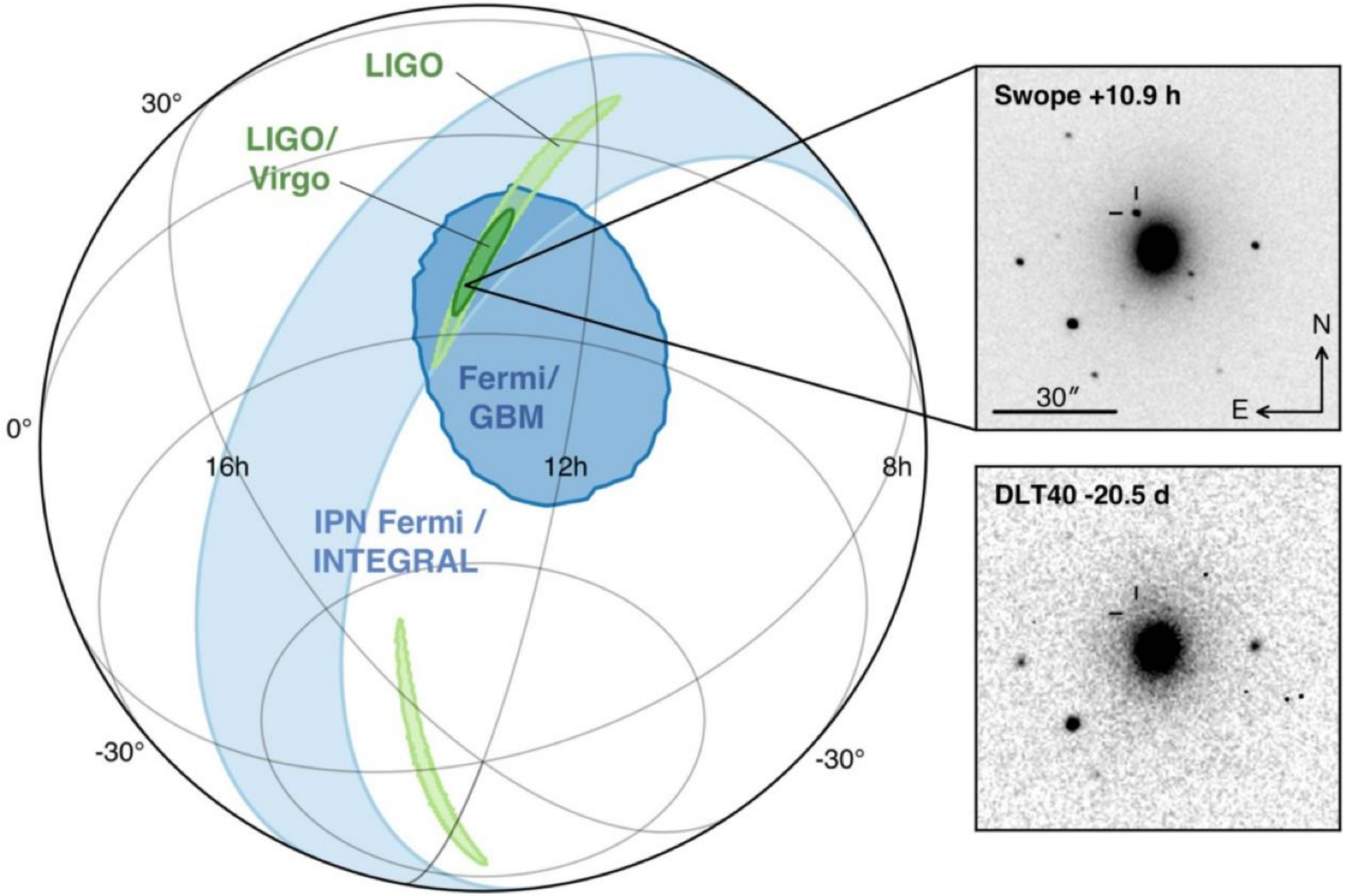
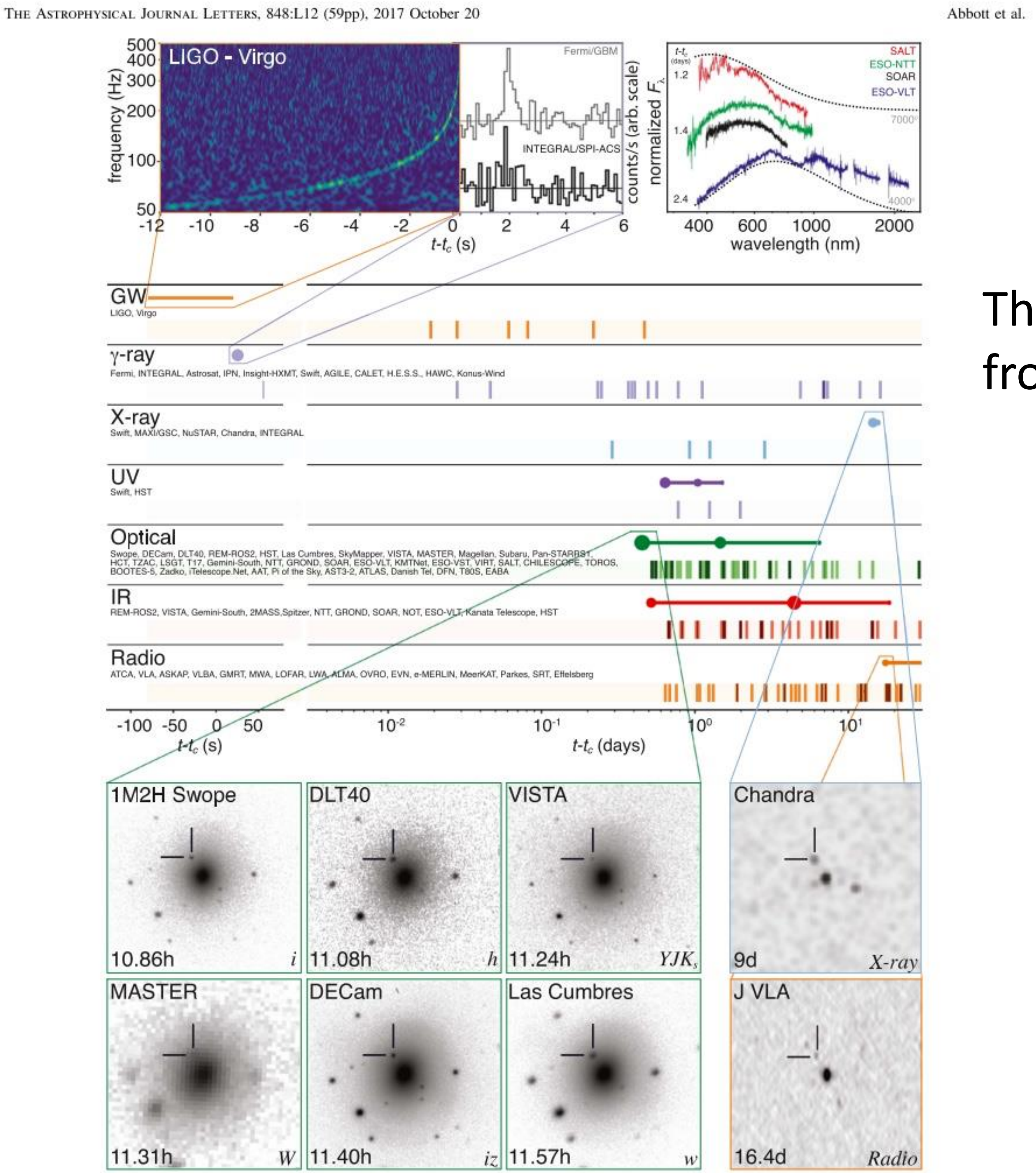
Fermi



LIGO

Credit: NASA GSFC & Caltech/MIT/LIGO Lab


LIGO
LIGO/
Virgo
30°
0°
16h
12h
8h
-30°
-30°
Fermi/
GBM
IPN Fermi /
INTEGRAL
Swope +10.9 h
30″
N
E
DLT40 -20.5 d



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

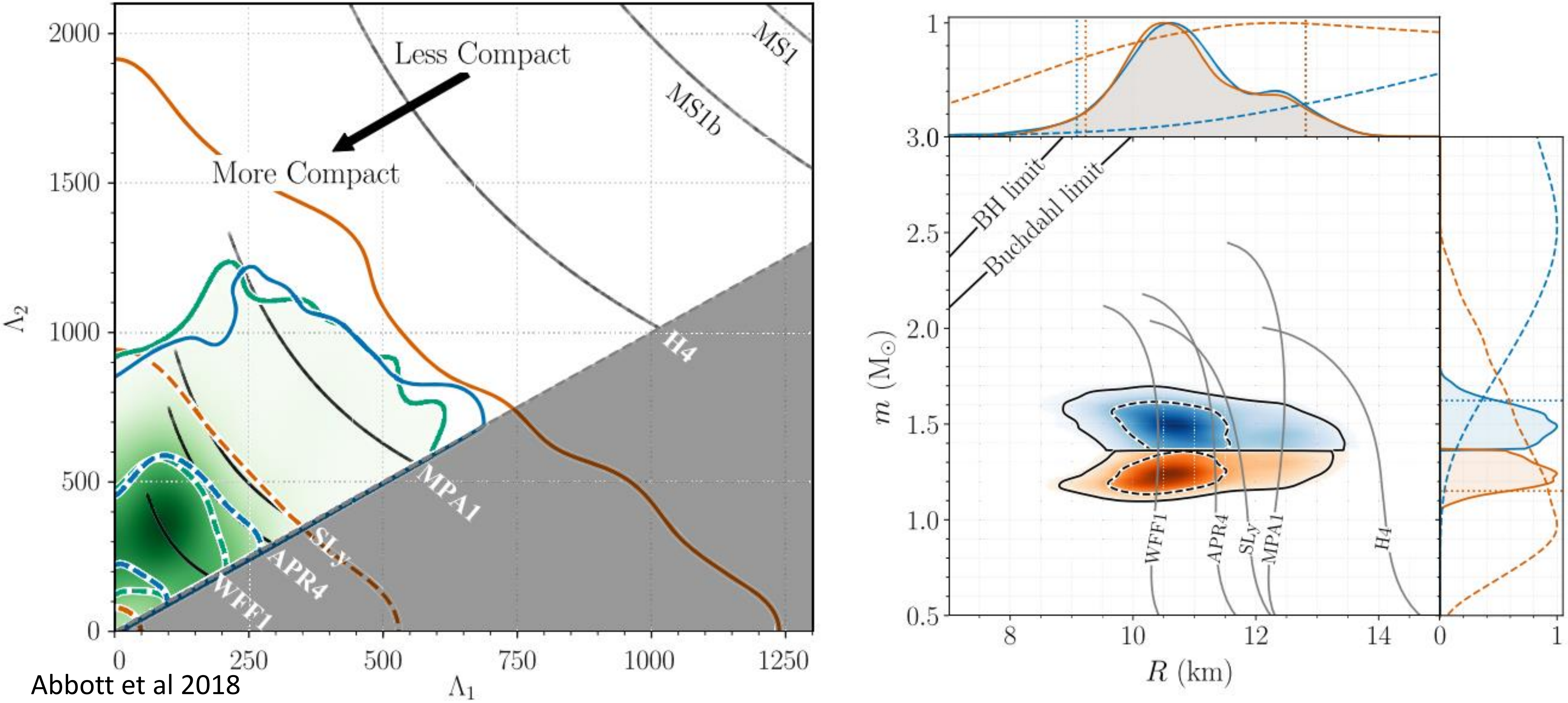
	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [108]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector-frame chirp mass $\mathcal{M}^{\mathrm{det}}$	$1.1975^{+0.0001}_{-0.0001}$ $\mathrm{M}_\odot$	$1.1976^{+0.0004}_{-0.0002}$ $\mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $\mathrm{M}_\odot$	$1.186^{+0.001}_{-0.001}$ $\mathrm{M}_\odot$
Primary mass m_1	$(1.36, 1.60)$ $\mathrm{M}_\odot$	$(1.36, 1.89)$ $\mathrm{M}_\odot$
Secondary mass m_2	$(1.16, 1.36)$ $\mathrm{M}_\odot$	$(1.00, 1.36)$ $\mathrm{M}_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}$ $\mathrm{M}_\odot$	$2.77^{+0.22}_{-0.05}$ $\mathrm{M}_\odot$
Mass ratio q	$(0.73, 1.00)$	$(0.53, 1.00)$
Effective spin χ_{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}(symmetric)/300^{+420}_{-230}(HPD)	$(0, 630)$

$$\chi_{\mathrm{eff}} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot L_N}{M}$$

$$\mathcal{M} \equiv (1+z)(m_1 m_2)^{3/5}(m_1+m_2)^{-1/5}$$

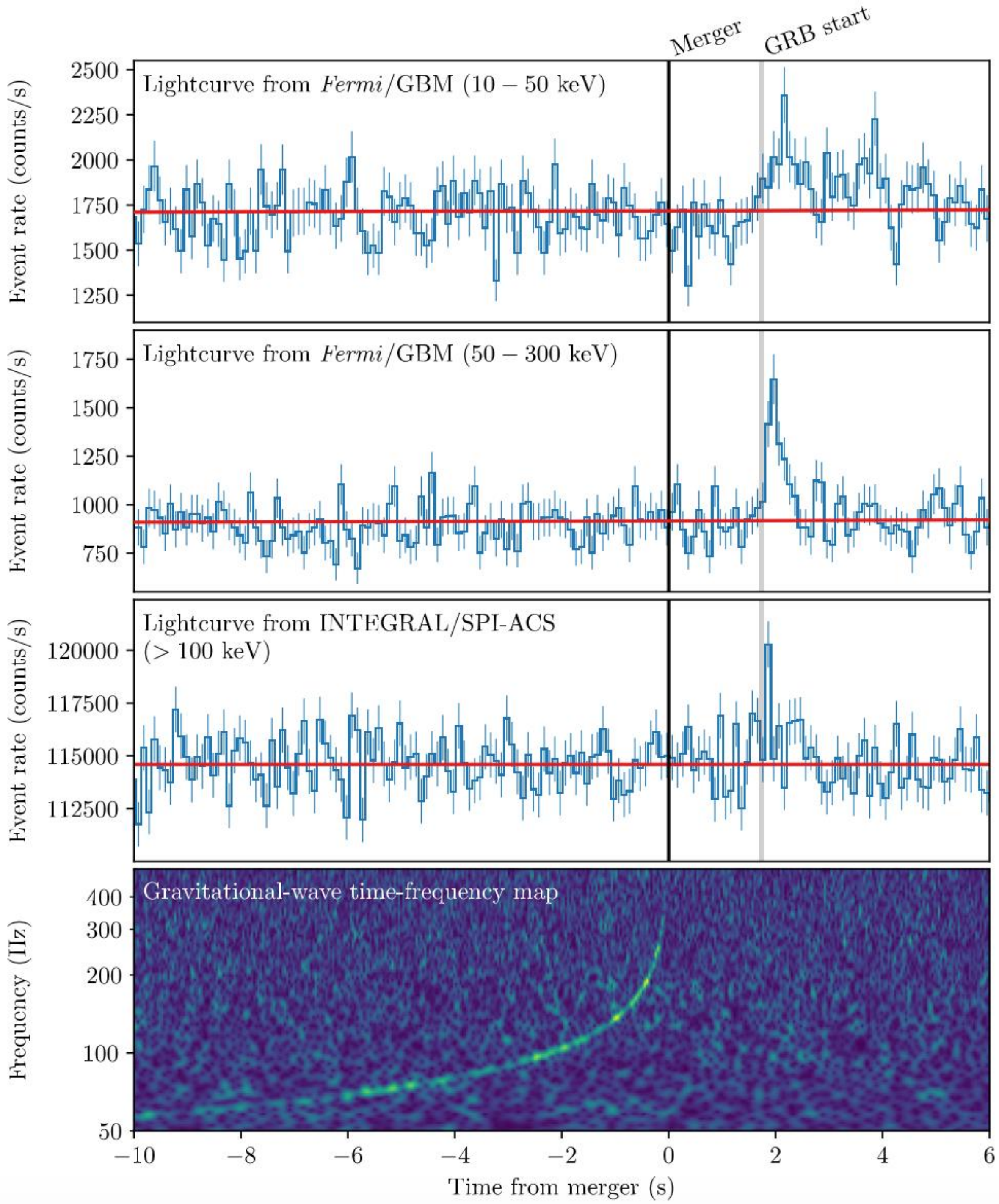
$$\mathcal{M} = \frac{c^3}{G}\left[\frac{5}{96}\frac{1}{\pi^{8/3}}\dot{\nu}_{GW}\nu_{GW}^{-11/3}\right]^{3/5}$$

GW170817: EOS constraints



Abbott et al 2018

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



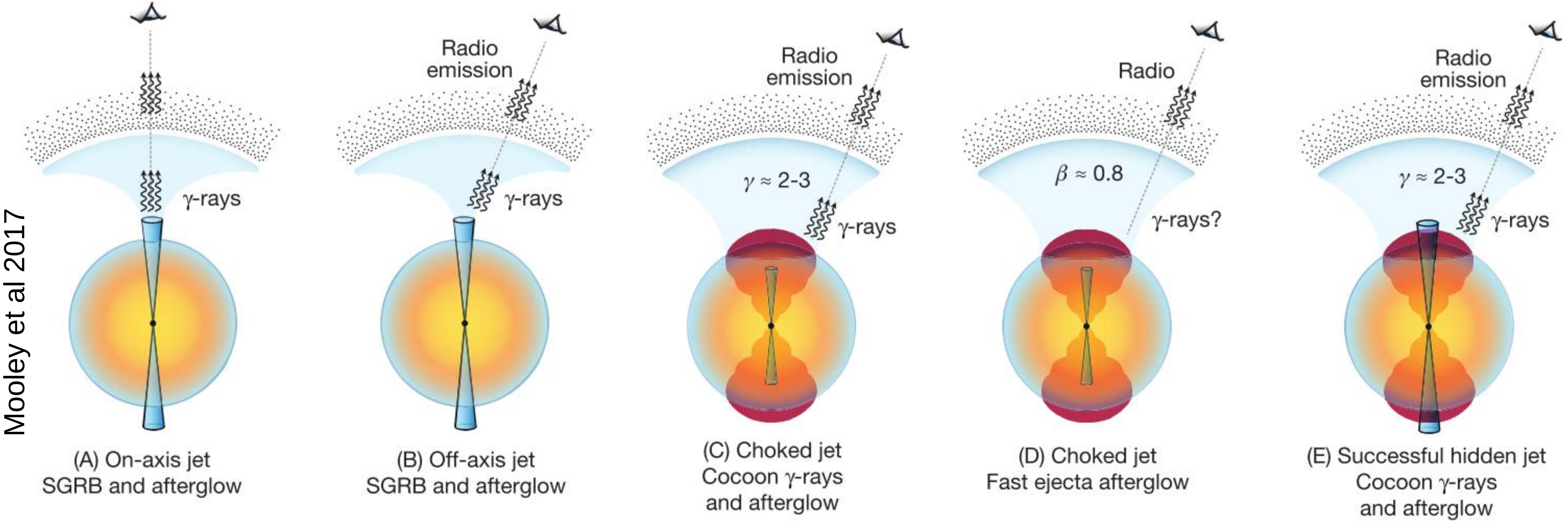
GRB170817A

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

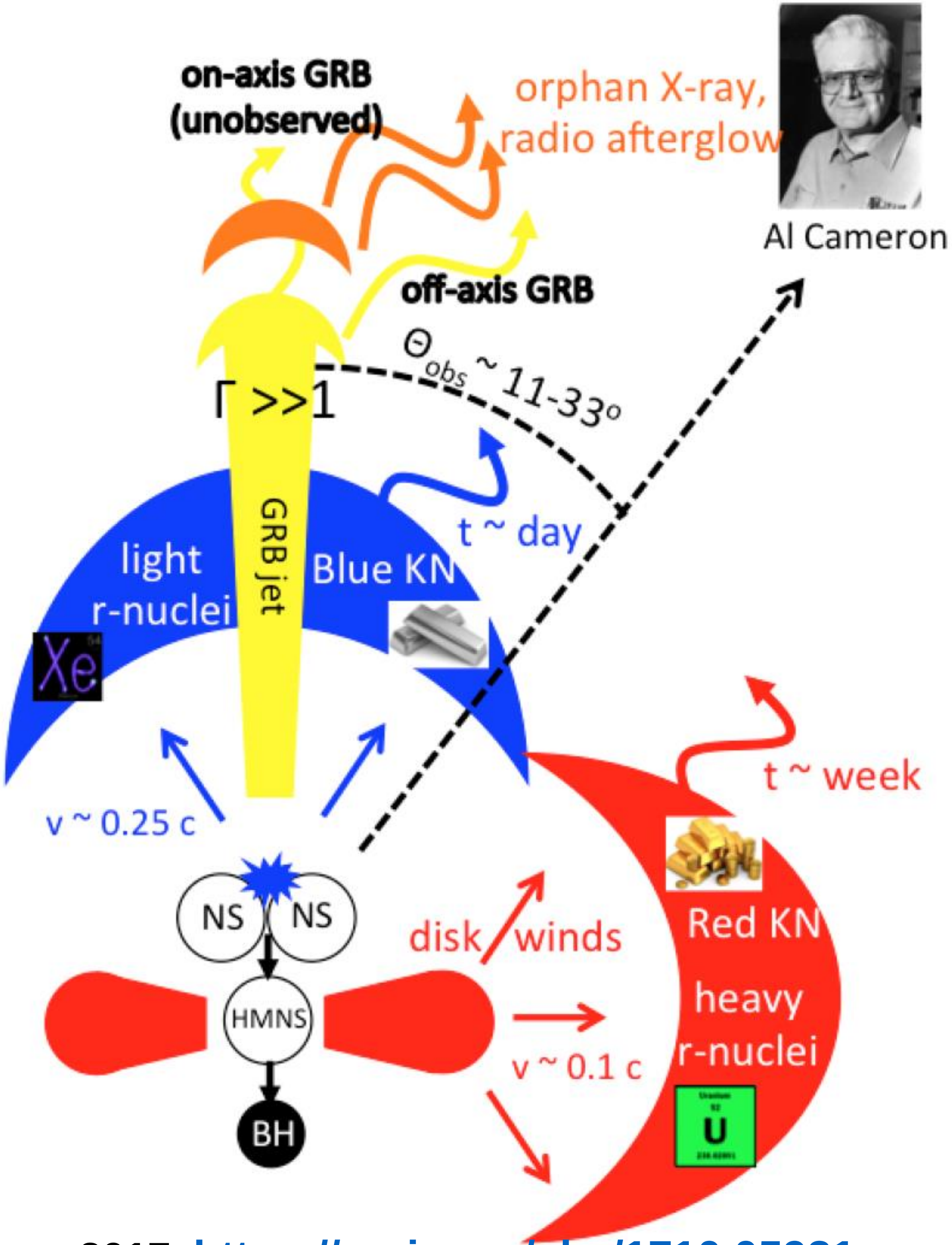
GRB170817A: Theoretical Models



Mooley et al 2017

Observations consistent with successful jet observed off axis ($\sim 15^o - 20^o$) with $\theta_{jet} \lesssim 5^o$ (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)

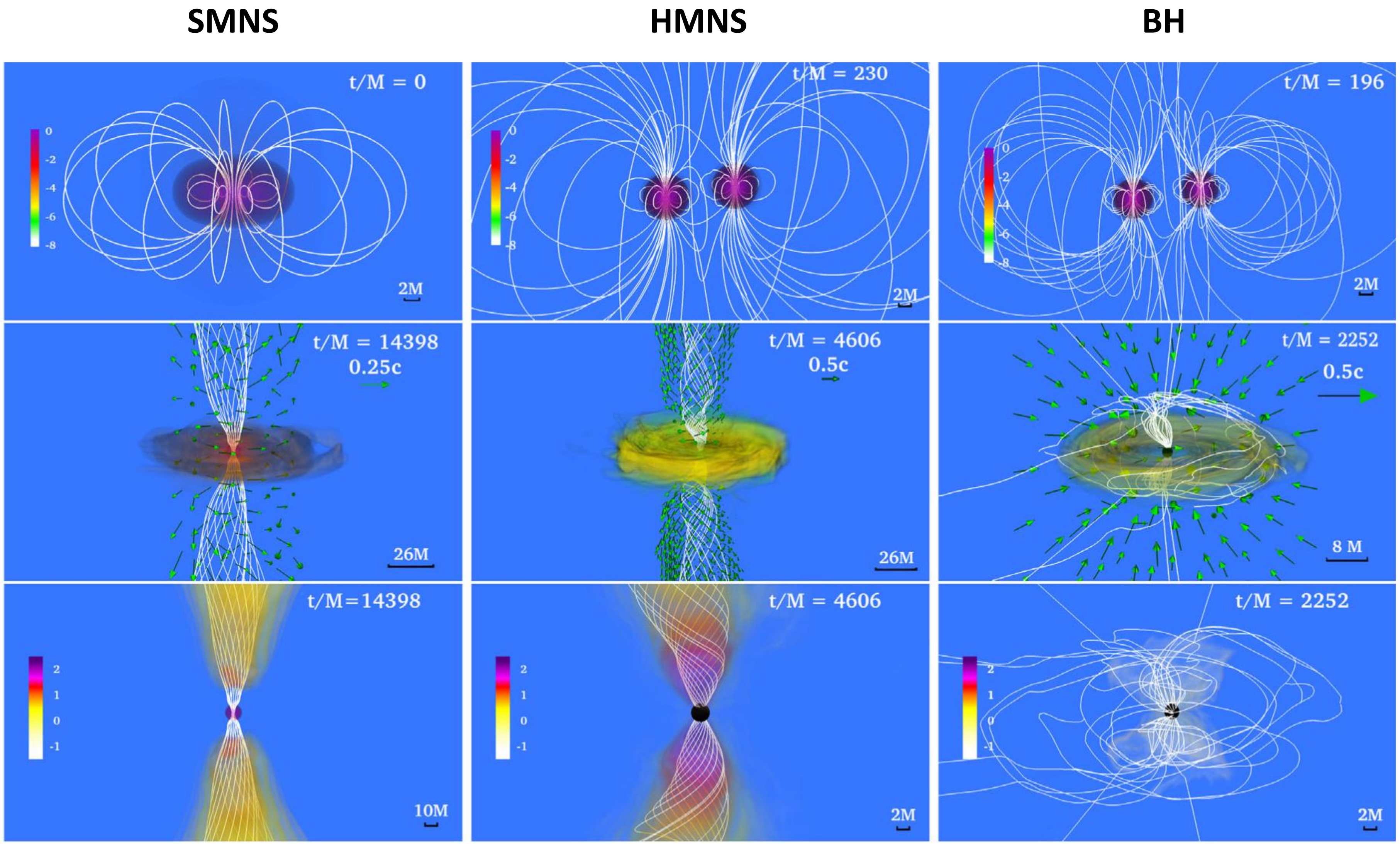


r-process produced an observed kilonova

~200 Earth masses of gold produced

Metzger 2017, https://arxiv.org/abs/1710.05931

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)

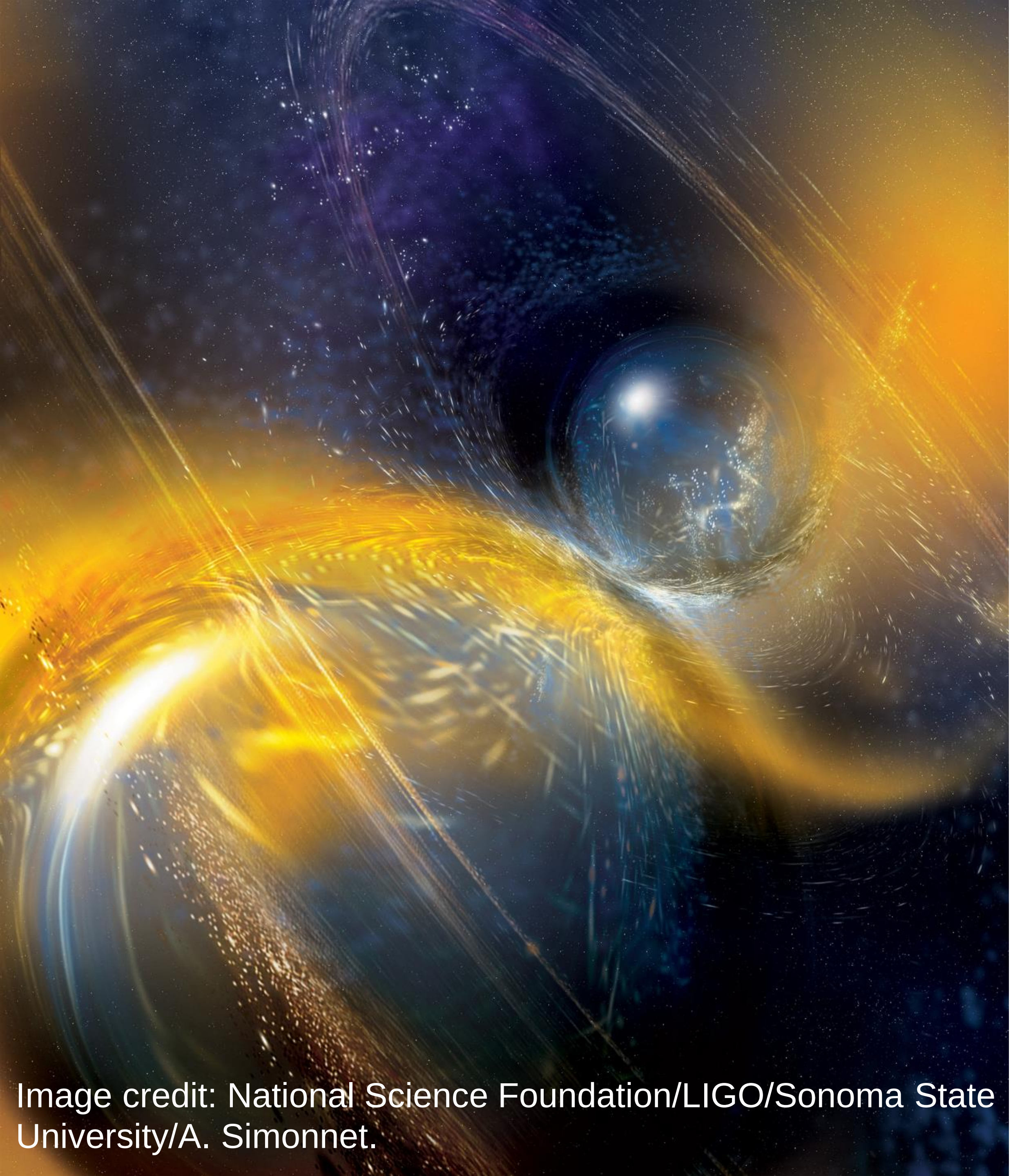


Image credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet.

GW190425

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

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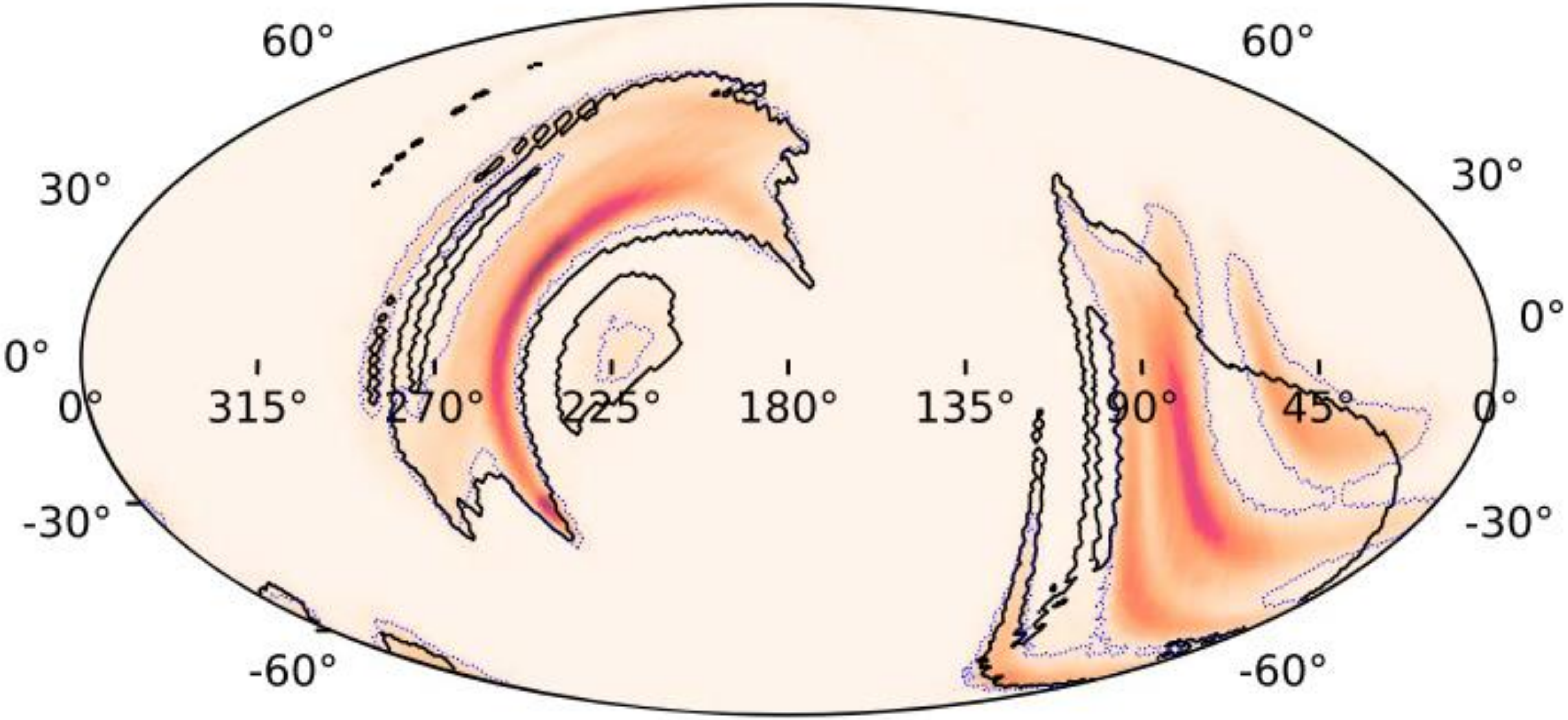


Abbott et al 2020, http://arxiv.org/abs/2001.01761

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).

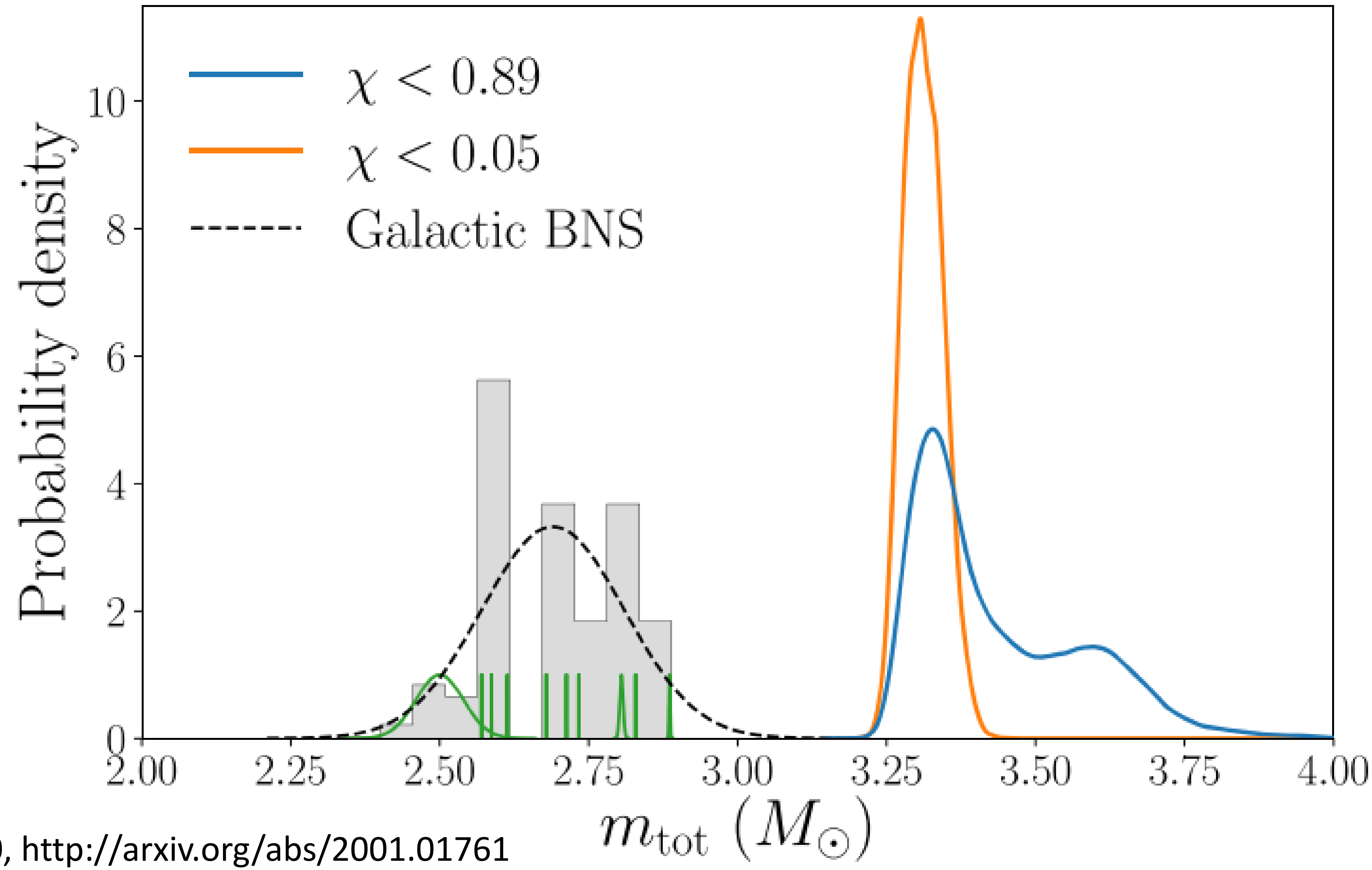
Table 1
Source Properties for GW190425

	Low-spin Prior ($\chi < 0.05$)	High-spin Prior ($\chi < 0.89$)
Primary mass m_1	1.60–1.87 $M_\odot$	1.61–2.52 $M_\odot$
Secondary mass m_2	1.46–1.69 $M_\odot$	1.12–1.68 $M_\odot$
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 $m_{\rm tot}$	$3.3^{+0.1}_{-0.1}$ $M_\odot$	$3.4^{+0.3}_{-0.1} M_\odot$
Effective inspiral spin parameter $\chi_{\rm eff}$	$0.012^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance $D_{\rm L}$	159^{+69}_{-72} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leqslant 600$	$\leqslant 1100$

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

$$\mathcal{M} \equiv (1+z)(m_1 m_2)^{3/5}(m_1+m_2)^{-1/5}$$

$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M}$$



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

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

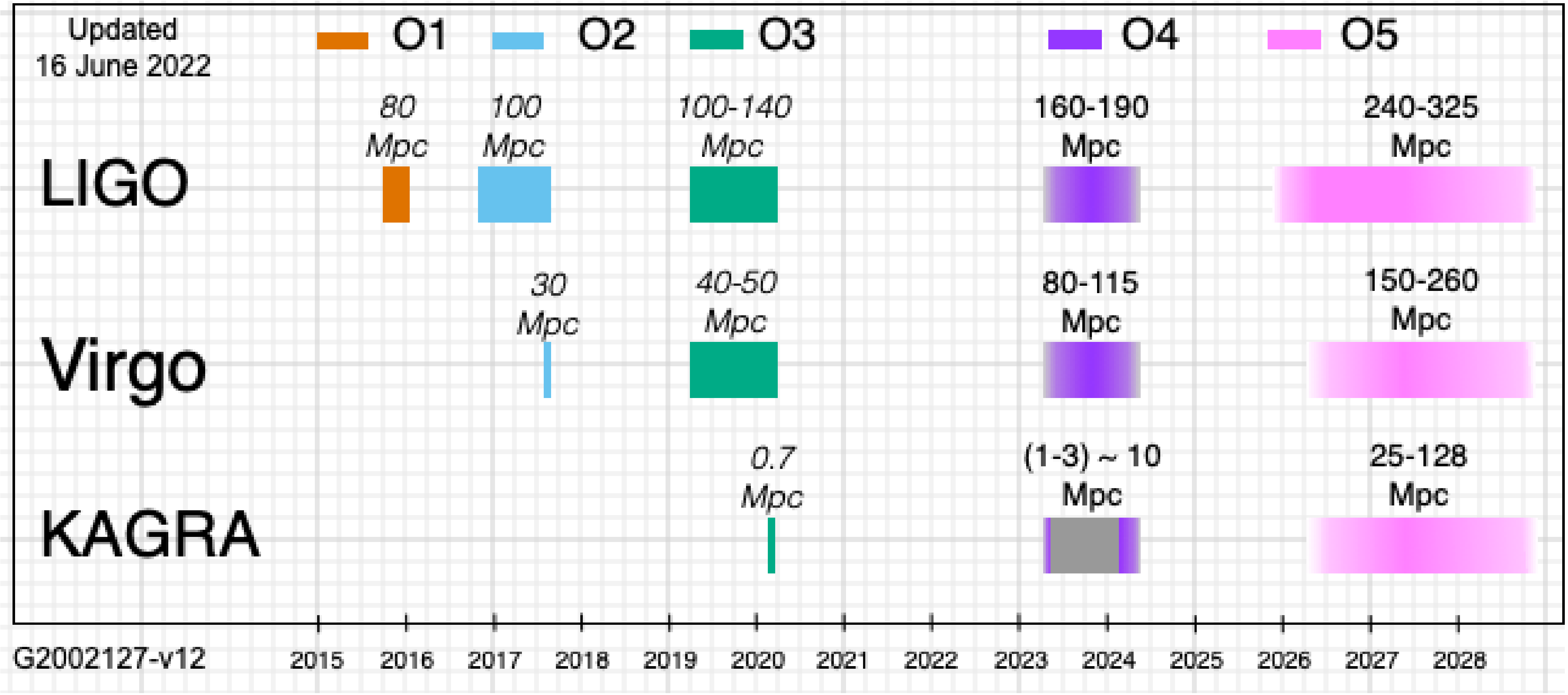
Numerical relativity simulation of
last orbits, merger and black hole formation

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



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

Other References

Frontiers Research Topic, “Gravitational Waves: A New Window to the Universe” https://www.frontiersin.org/research-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.