

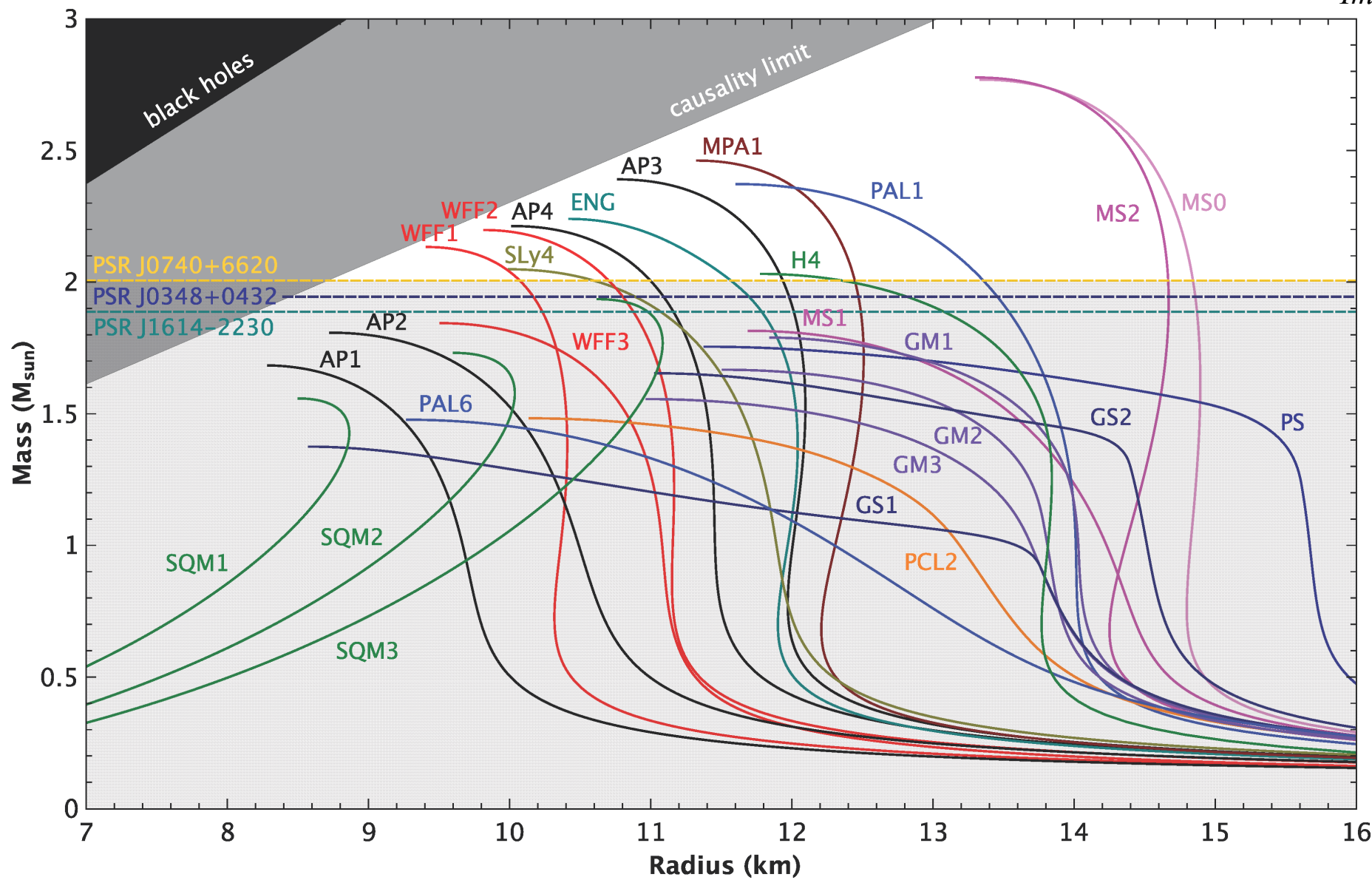
Dense nuclear matter and gravitational waves

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Wed 2nd October 2019



Neutron star radius is not directly measured in pulsars, X-ray binaries or gravitational waves, but is dependent on the matter Equation of State

Editors' Suggestion

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GW170817: Measurements of Neutron Star Radii and Equation of State

B. P. Abbott *et al.* (The LIGO Scientific Collaboration and the Virgo Collaboration)
Phys. Rev. Lett. **121**, 161101 – Published 15 October 2018



Article

References

Citing Articles (61)

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ABSTRACT

On 17 August 2017, the LIGO and Virgo observatories made the first direct detection of gravitational waves from the coalescence of a neutron star binary system. The detection of this gravitational-wave signal, GW170817, offers a novel opportunity to directly probe the properties of matter at the extreme conditions found in the interior of these stars. The initial, minimal-assumption analysis of the LIGO and Virgo data placed constraints on the tidal effects of the coalescing bodies, which were then translated to constraints on neutron star radii. Here, we expand upon previous analyses by working under the hypothesis that both bodies were neutron stars that are described by the same equation of state and have spins within the range observed in Galactic binary neutron stars. Our analysis employs two methods: the use of equation-of-state-insensitive relations between various macroscopic properties of the neutron stars and the use of an efficient parametrization of the defining function $p(\rho)$ of the

Issue

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LIGO-Virgo result for gravitational wave event GW170817

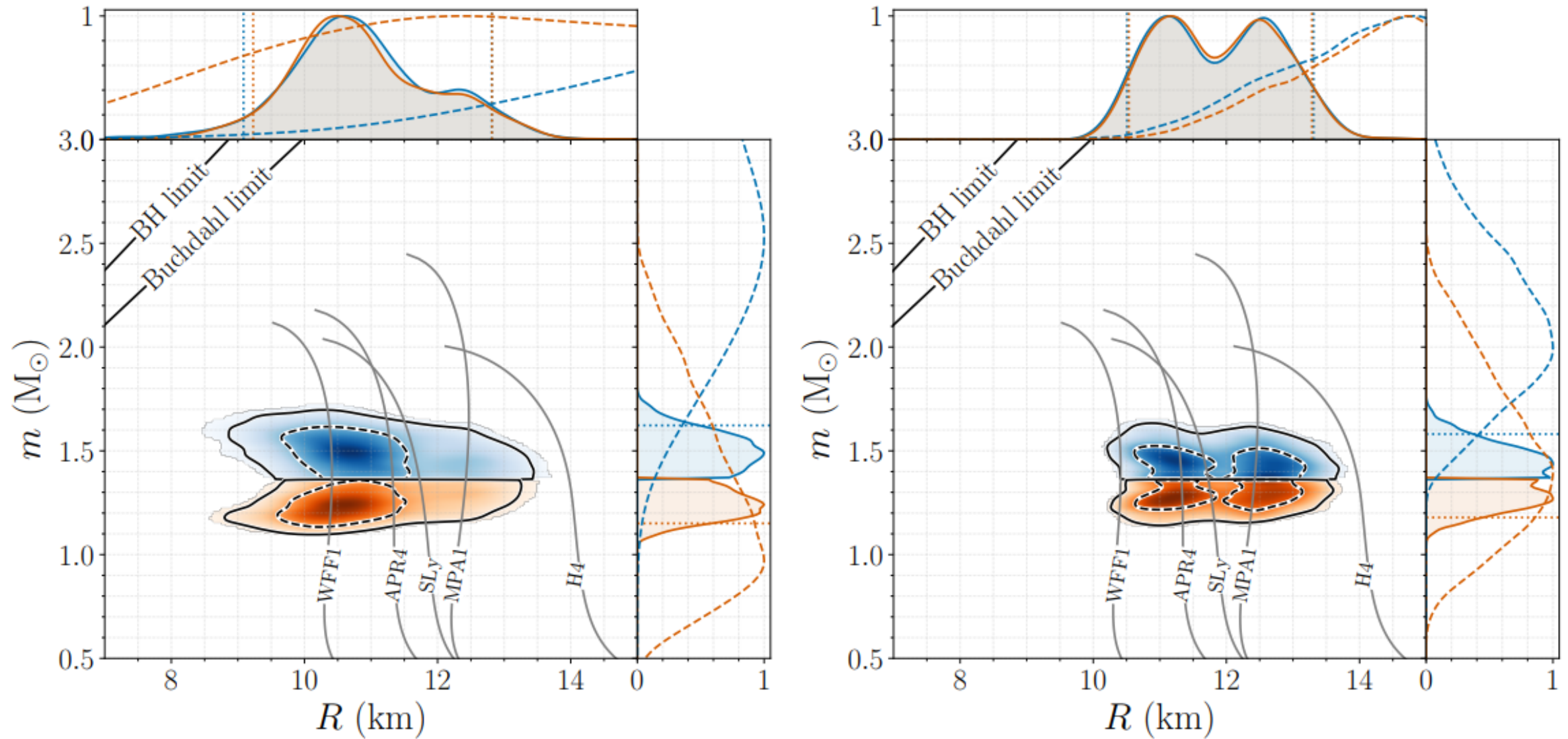


Fig 3, LVC, PRL121, (2018) 161101

Assumptions in fitting tidal parameters

- **Event is an astrophysical gravitational wave event**
- **Event is two neutron stars**
- **Event occurs exactly at the location of optical counterpart**
- **Both spins are low, consistent with observed galactic binaries**
- **Both neutron stars have the same equation of state**
- **GW detector noise is Gaussian, de-glitching of L1 is successful**
- **PhenomPNRT waveform model is accurate in inspiral phase**

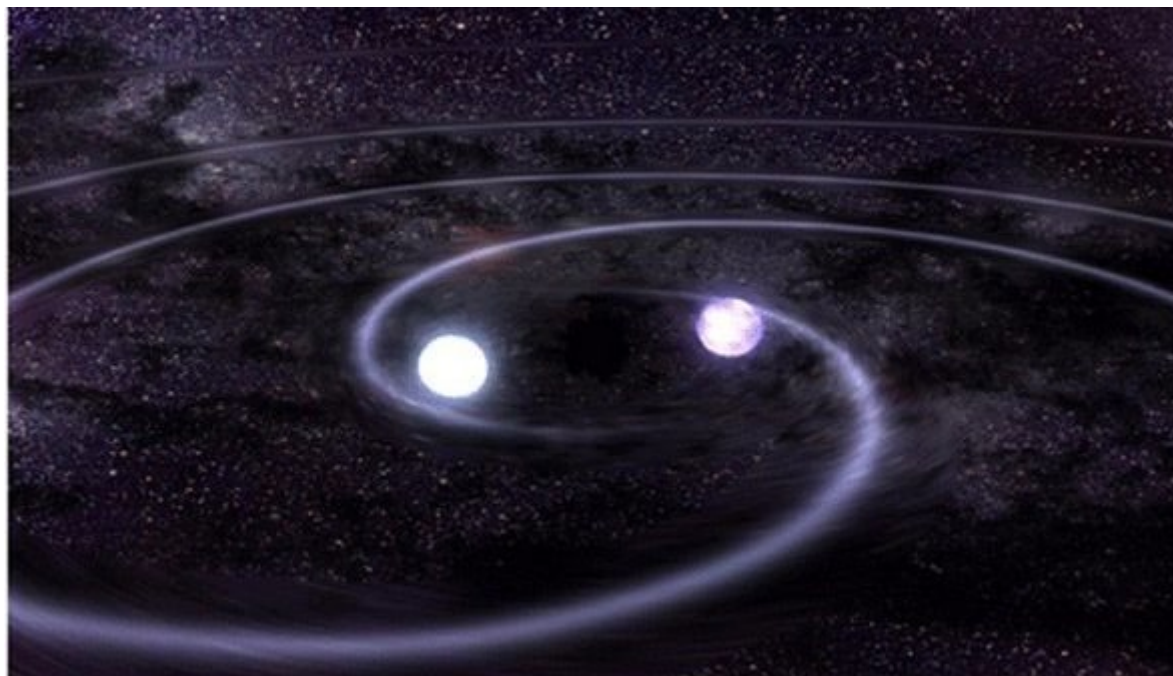
Gravitational wave detectors (this one in Italy)



*Image Credit: The Virgo
Collaboration*

Notable gravitational wave events (so far)

- GW150914 Binary Black Hole (BBH)
- GW170817 Binary Neutron Star (BNS)



*Image Credit:
NASA/Dana Berry*

Multi-messenger astronomy, 3,677 authors...

THE ASTROPHYSICAL JOURNAL LETTERS

OPEN ACCESS

Multi-messenger Observations of a Binary Neutron Star Merger*

B. P. Abbott¹, R. Abbott¹, T. D. Abbott², F. Acernese^{3,4}, K. Ackley^{5,6}, C. Adams⁷, T. Adams⁸, P. Addesso⁹, R. X. Adhikari¹, V. B. Adya¹⁰ [+ Show full author list](#)

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[The Astrophysical Journal Letters, Volume 848, Number 2](#)

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Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and

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GW and EM observations of GW170817 (no neutrinos or cosmic rays seen)

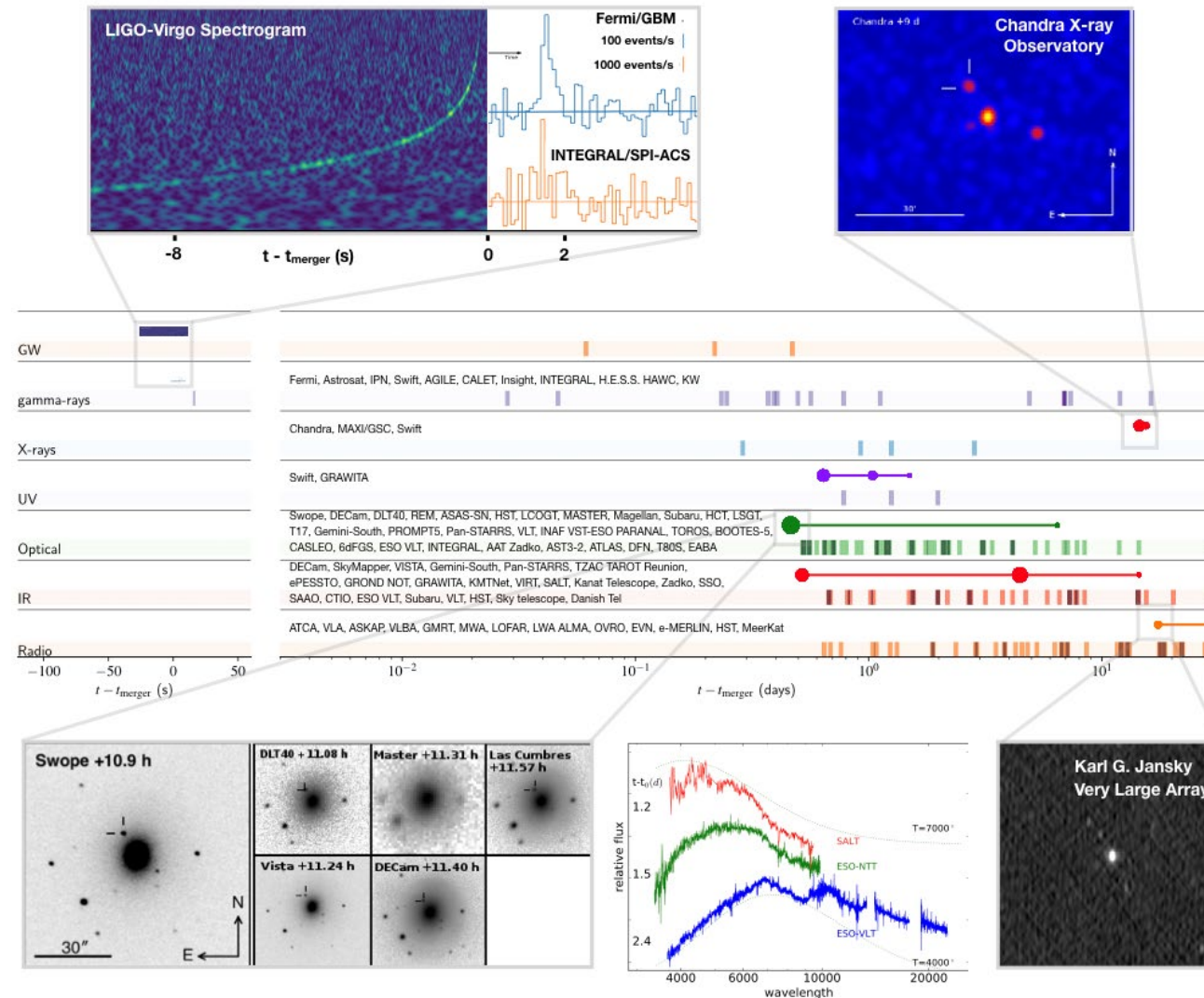


Fig 2, ApJL848, (2017) L12

GW170817 timeline

“But, as critics have pointed out correctly, the LIGO alert for this event came 40 minutes *after* NASA’s gamma-ray alert. For this reason, the event cannot be used as an independent confirmation of LIGO’s detection capacity.”

–Hossenfelder, 4 Sep 2019

- 12:41:04 GstLAL automatic alert of single trigger in H1
- 12:41:06 onboard GRB trigger on GBM
- +~15 mins Rapid Response Team meets
- +~40 mins GCN sent of H1 trigger
- +~90 mins PyCBC live run on HLV with gated glitch
- +~5 hours, GCN with HLV BAYESTAR skymap
- +~12.5 hours, first optical counterpart from Swope Telescope

GW170817 sky location

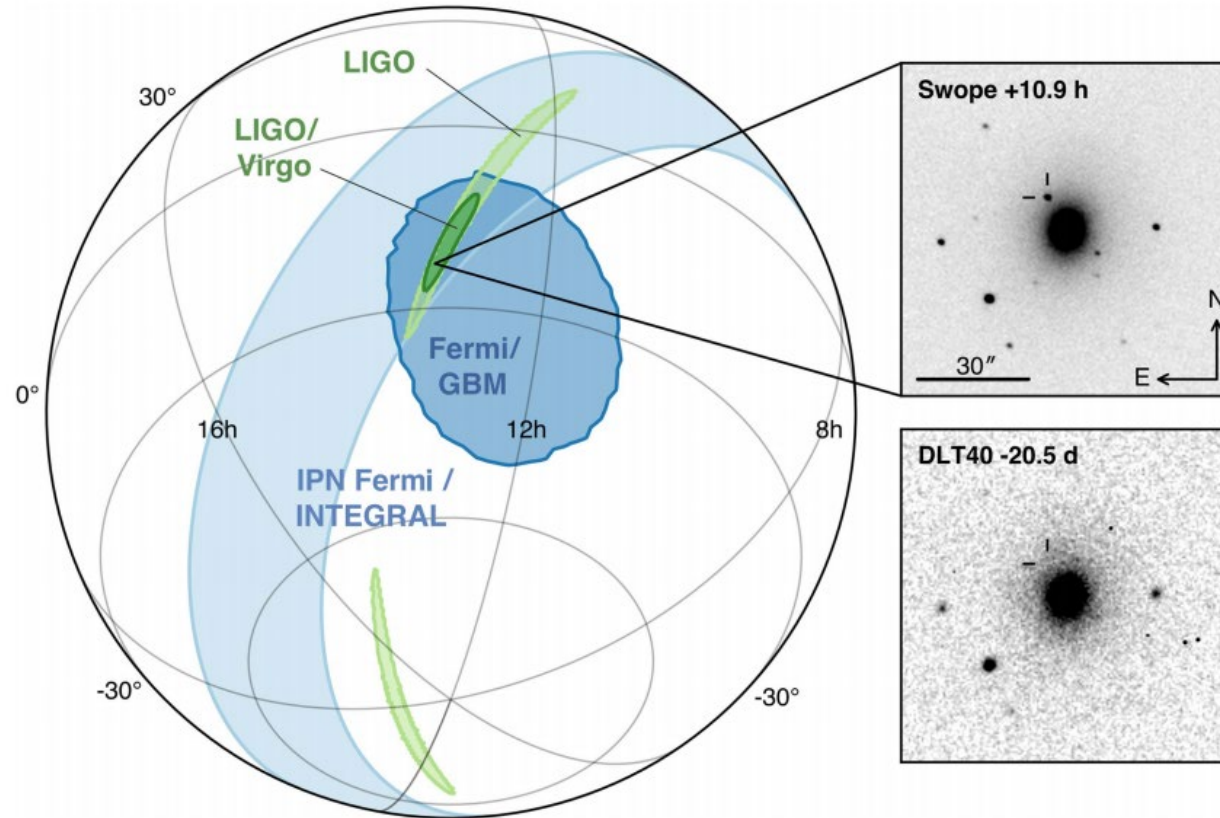
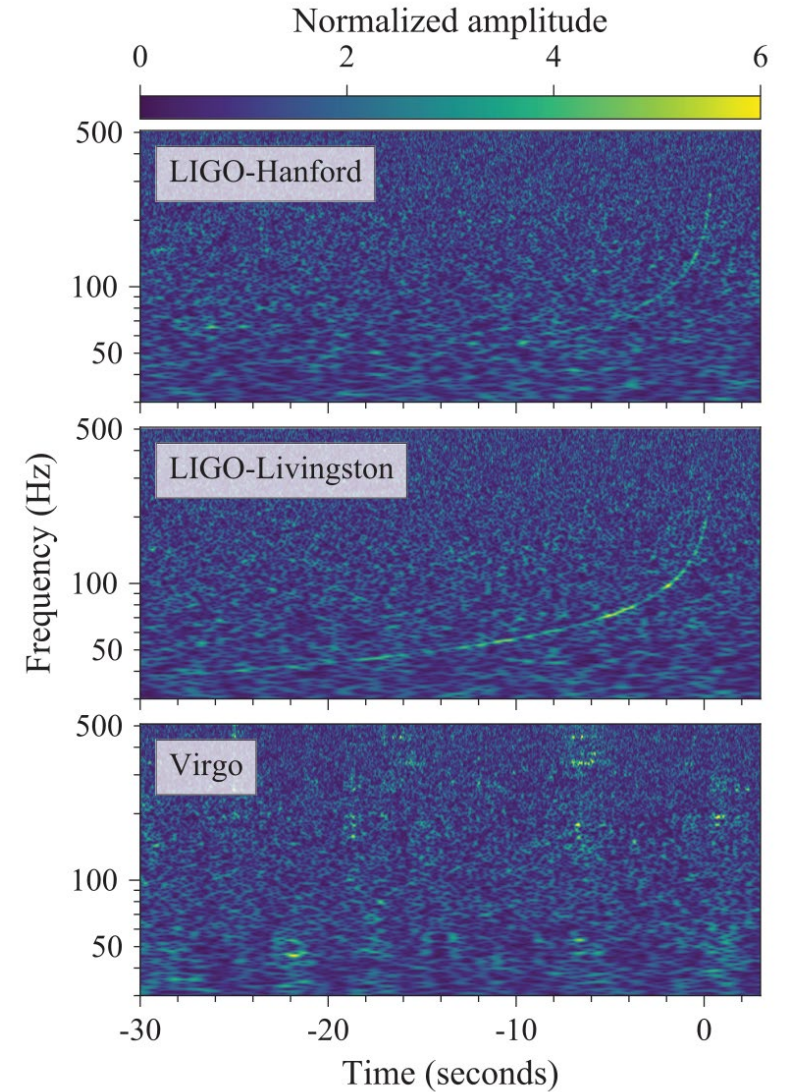
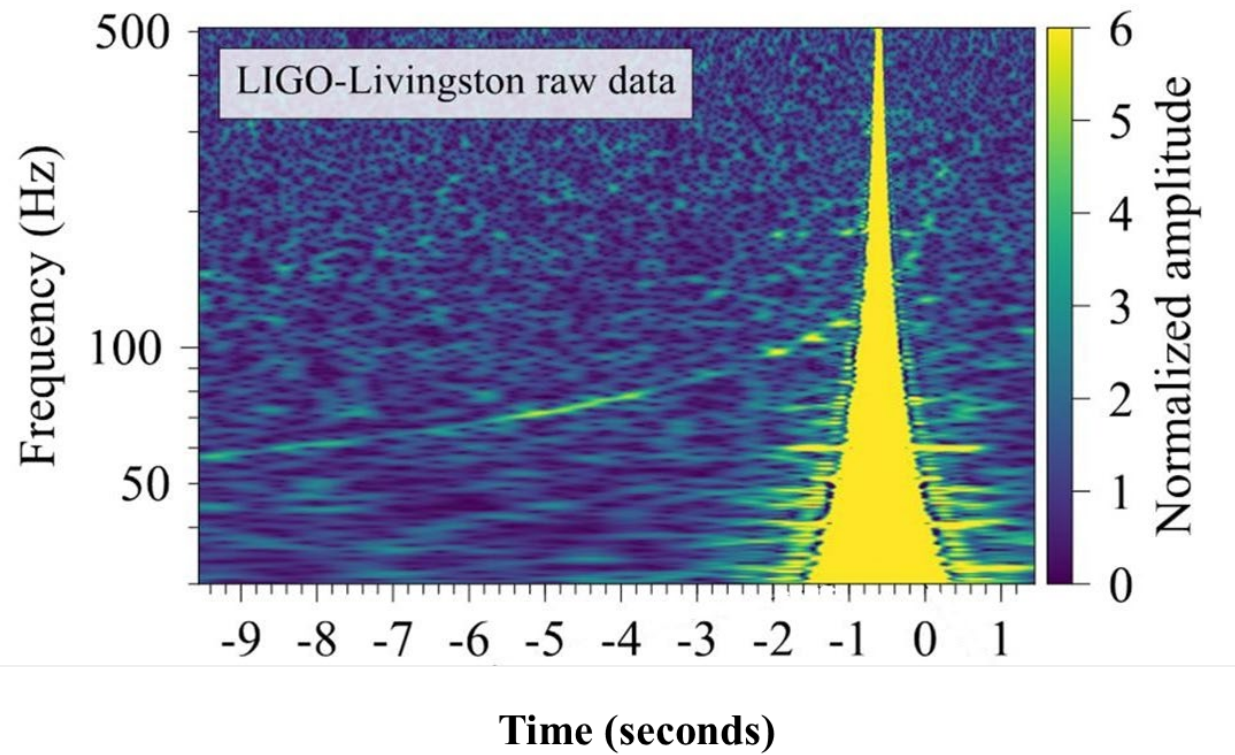


Fig 1, ApJL848, (2017) L12

Data cleaning GW170817



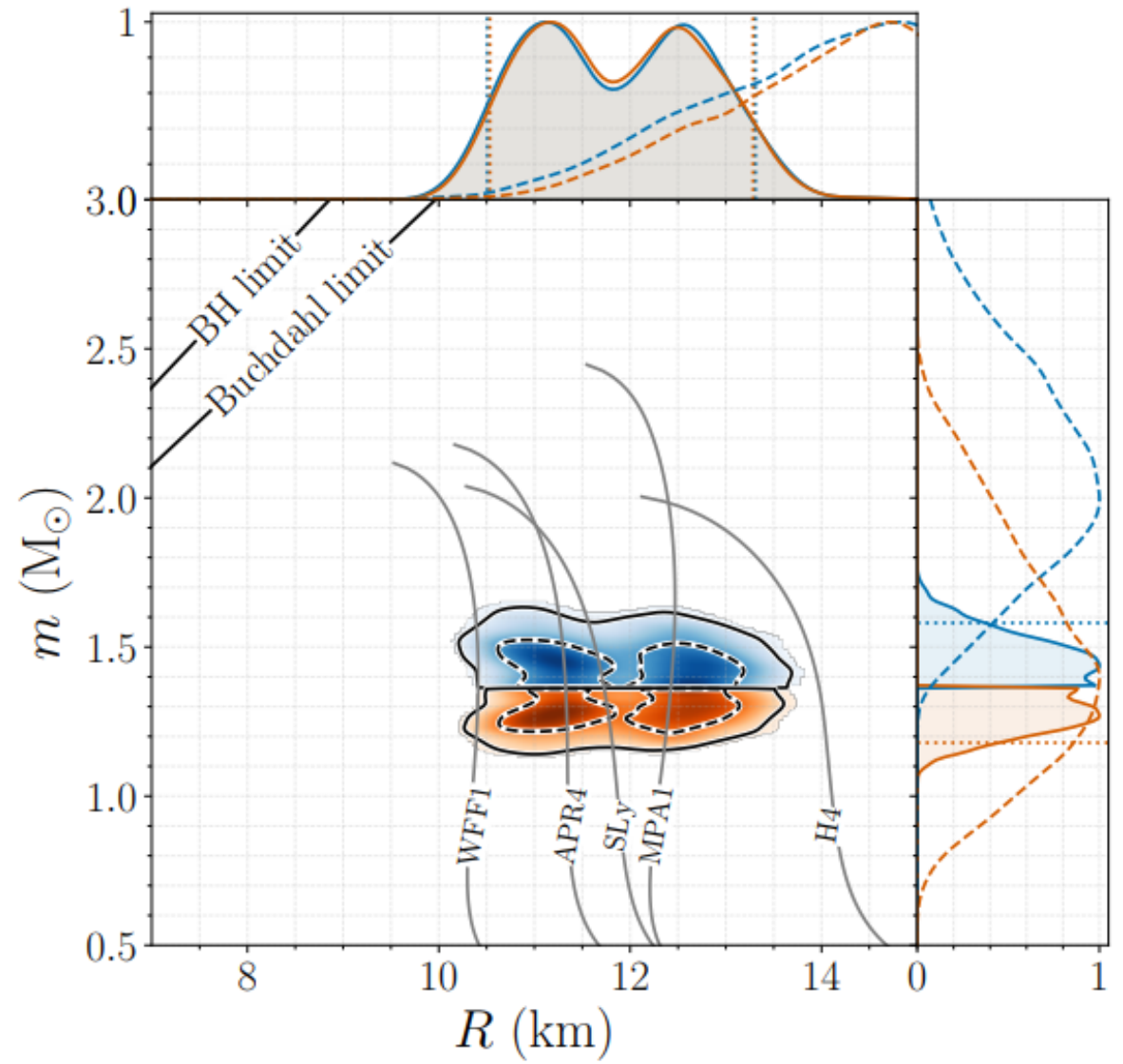
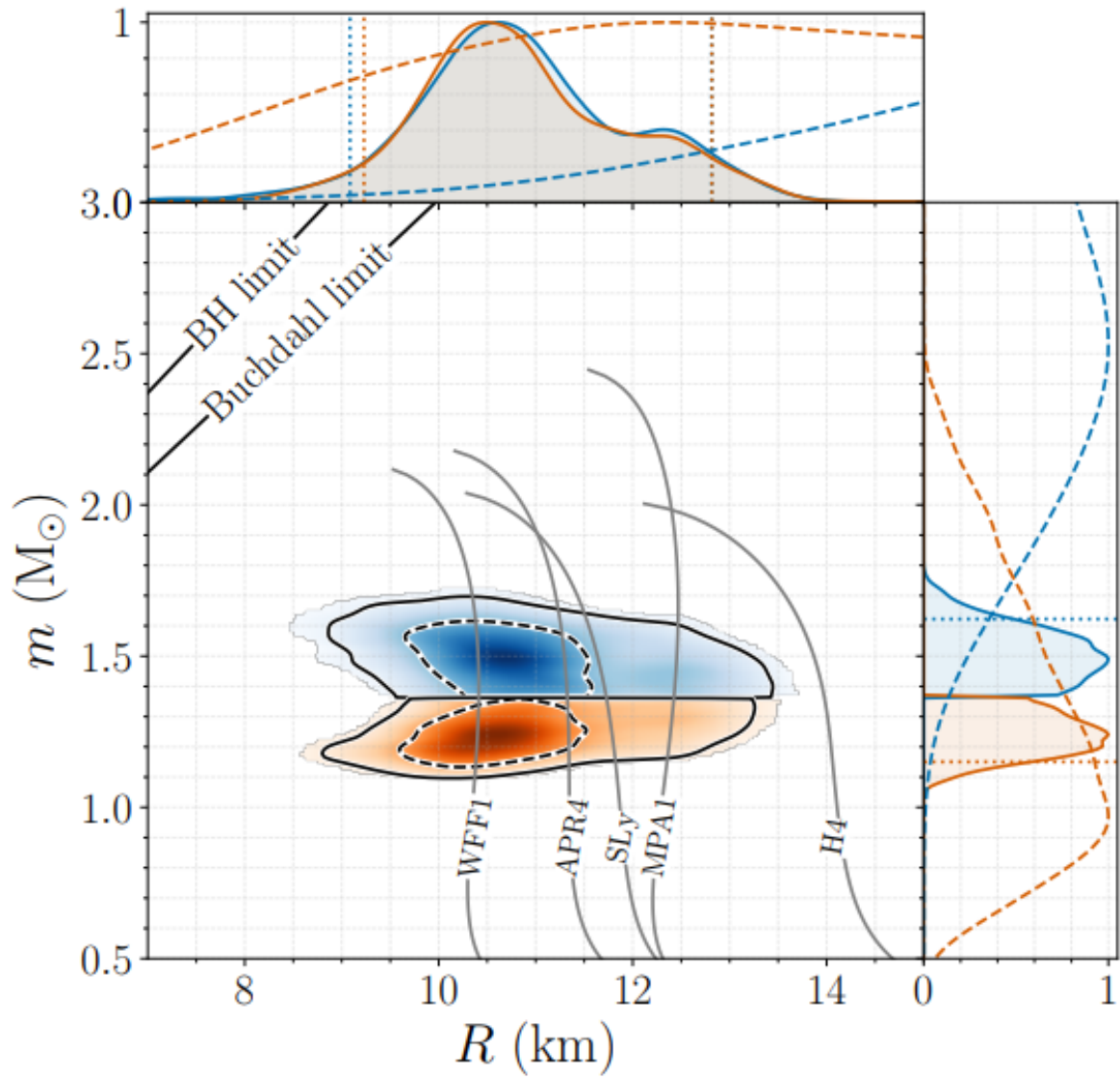


Fig 3, LVC, PRL121, (2018) 161101

- At leading order, orbit is Keplerian $f_{\text{GW}}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5} \left(\frac{G\mathcal{M}}{c^3} \right)^{5/3} (t_c - t),$ $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$
- Expand around Keplerian result in powers of v/c
- At power $(v/c)^{10}$ finite-size terms appear (parameterised by Λ)
- Point particle terms not known at $(v/c)^{10}$
- Account for ignorance by fitting to numerical simulations (PhenomPNRT)
- Not used in detection (only in parameter estimation)

- Two models used in the LVC paper to relate tidal terms to radii and EoS

- 1) **EoS insensitive relations (Yagi+Yunes (2015))**

- employ approximate relation between mass ratio and tidal terms
- tune to large set of EoS models
- marginalise over model errors
- employ fit of tidal terms to NS compactness to obtain radii

- 2) **Parameterisation of EoS (Lindblom+Indik (2012))**

- parameterise EoS adiabatic index as polynomial in pressure
- sample in the coefficients of this parameterisation
- choose prior ranges consistent with range of EoS models
- employ TOV to obtain radii

Tidal deformability parameters (what is actually measured)

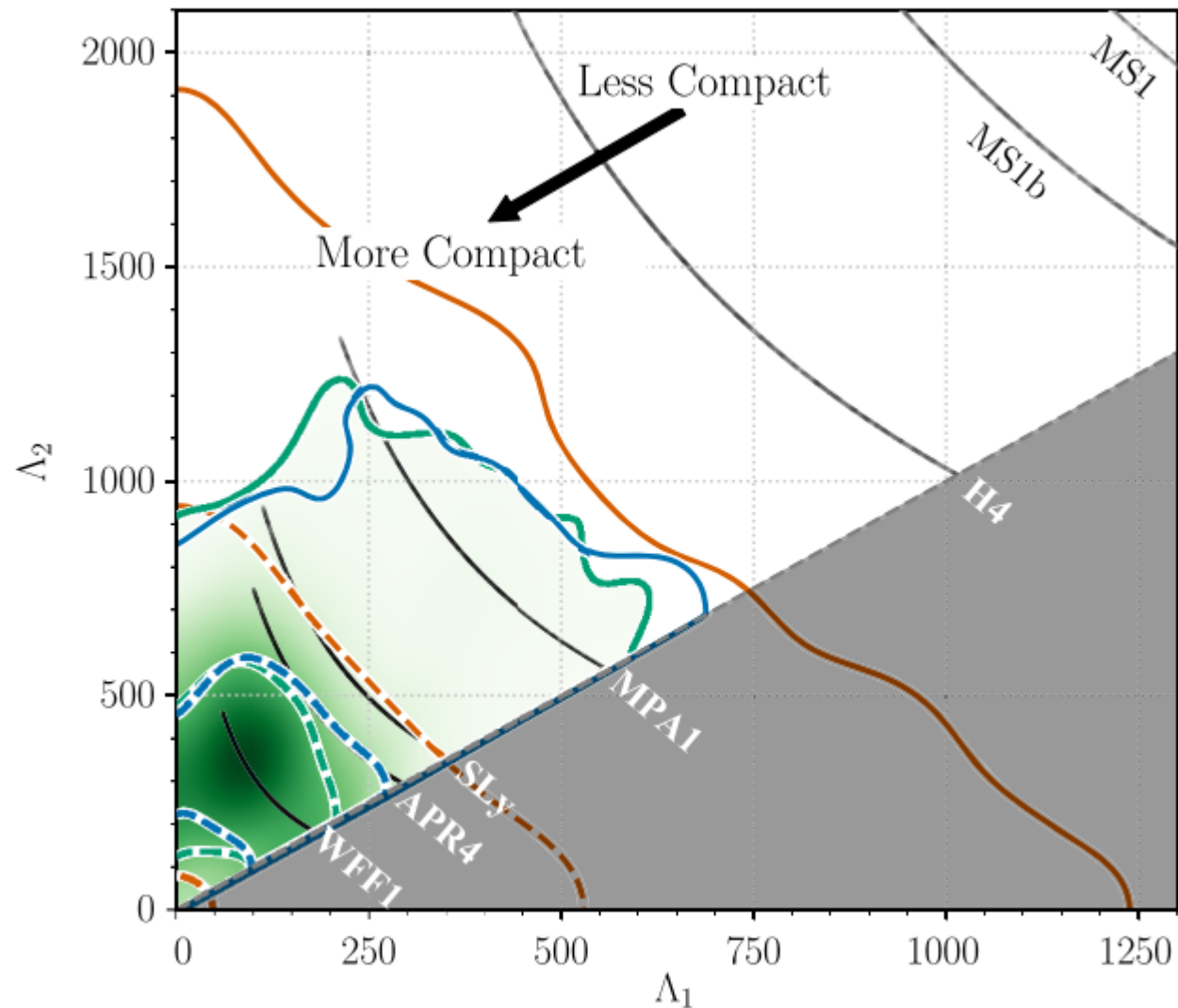


Fig 1, LVC, PRL121, (2018) 161101



GW170817: Stringent constraints on neutron-star radii from multimessenger observations and nuclear theory

Collin D. Capano, Ingo Tews, Stephanie M. Brown, Ben Margalit, Soumi De, Sumit Kumar, Duncan A. Brown, Badri Krishnan, Sanjay Reddy

(Submitted on 27 Aug 2019)

The properties of neutron stars are determined by the nature of the matter that they contain. These properties can be constrained by measurements of the star's size. We obtain the most stringent constraints on neutron-star radii to date by combining multimessenger observations of the binary neutron-star merger GW170817 with nuclear theory that best accounts for density-dependent uncertainties in the equation of state. We construct equations of state constrained by chiral effective field theory and marginalize over these using the gravitational-wave observations. Combining this with the electromagnetic observations of the merger remnant that imply the presence of a short-lived hyper-massive neutron star, we find that the radius of a $1.4M_{\odot}$ neutron star is $R_{1.4M_{\odot}} = 11.0^{+0.9}_{-0.6}$ km (90% credible interval). This constraint has important implications for dense-matter physics and for astrophysics.

Comments: 28 pages, 3 figures

Subjects: **High Energy Astrophysical Phenomena (astro-ph.HE)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)

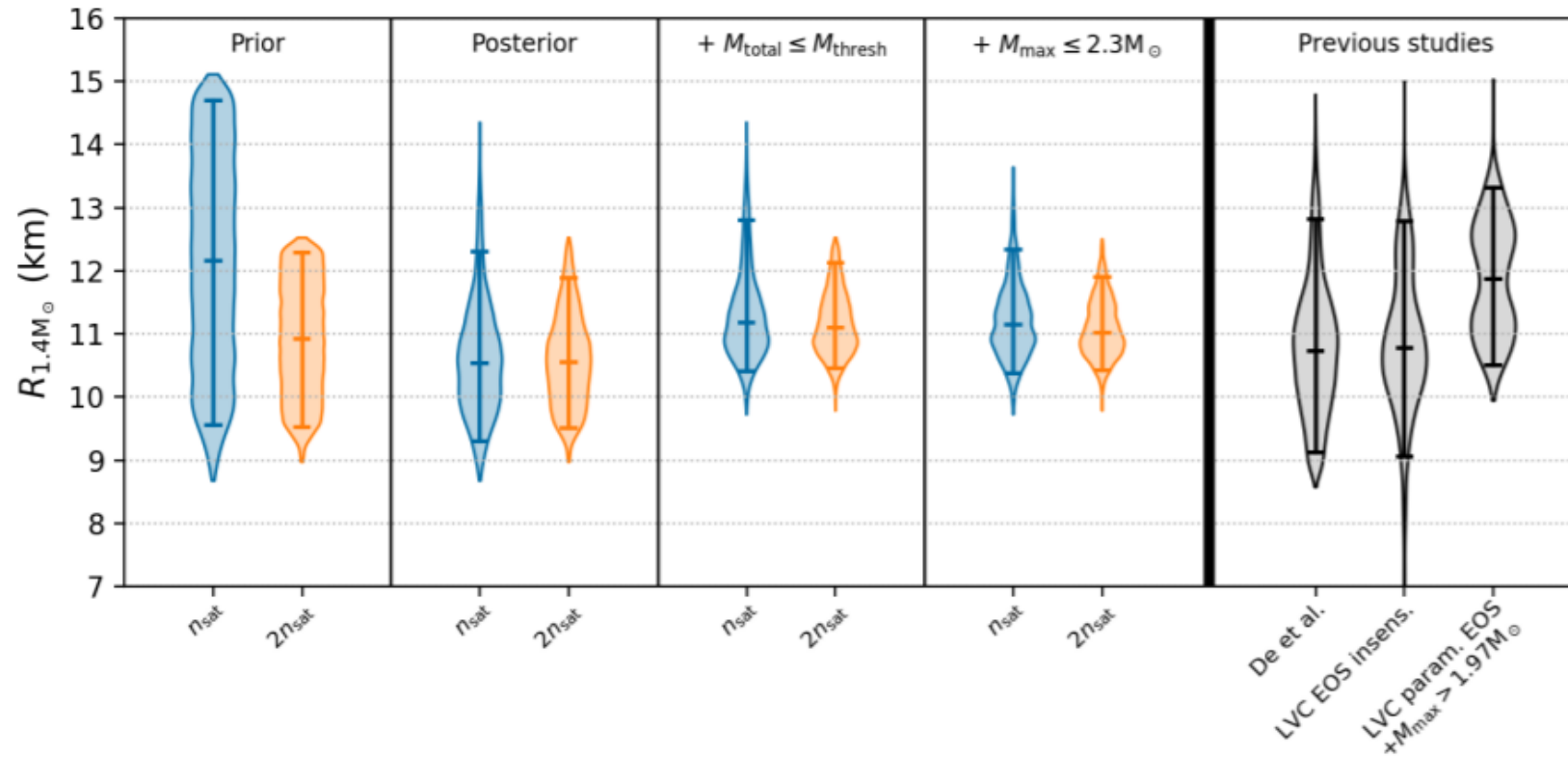


Figure 1: Comparison of the estimated radius of a $1.4 M_\odot$ neutron star, $R_{1.4M_\odot}$, at different stages of our analysis. In all panels, 1D marginal distributions are indicated by the shaded regions, with the median and the plus/minus 95th and 5th percentiles indicated by the lines. The left panel shows the marginalized prior on $R_{1.4M_\odot}$, assuming chiral effective field theory up to n_{sat} (blue) and $2n_{\text{sat}}$ (orange). Subsequent panels show the posterior on $R_{1.4M_\odot}$ from the gravitational-wave analysis alone, the posterior with the constraint that the estimated total mass

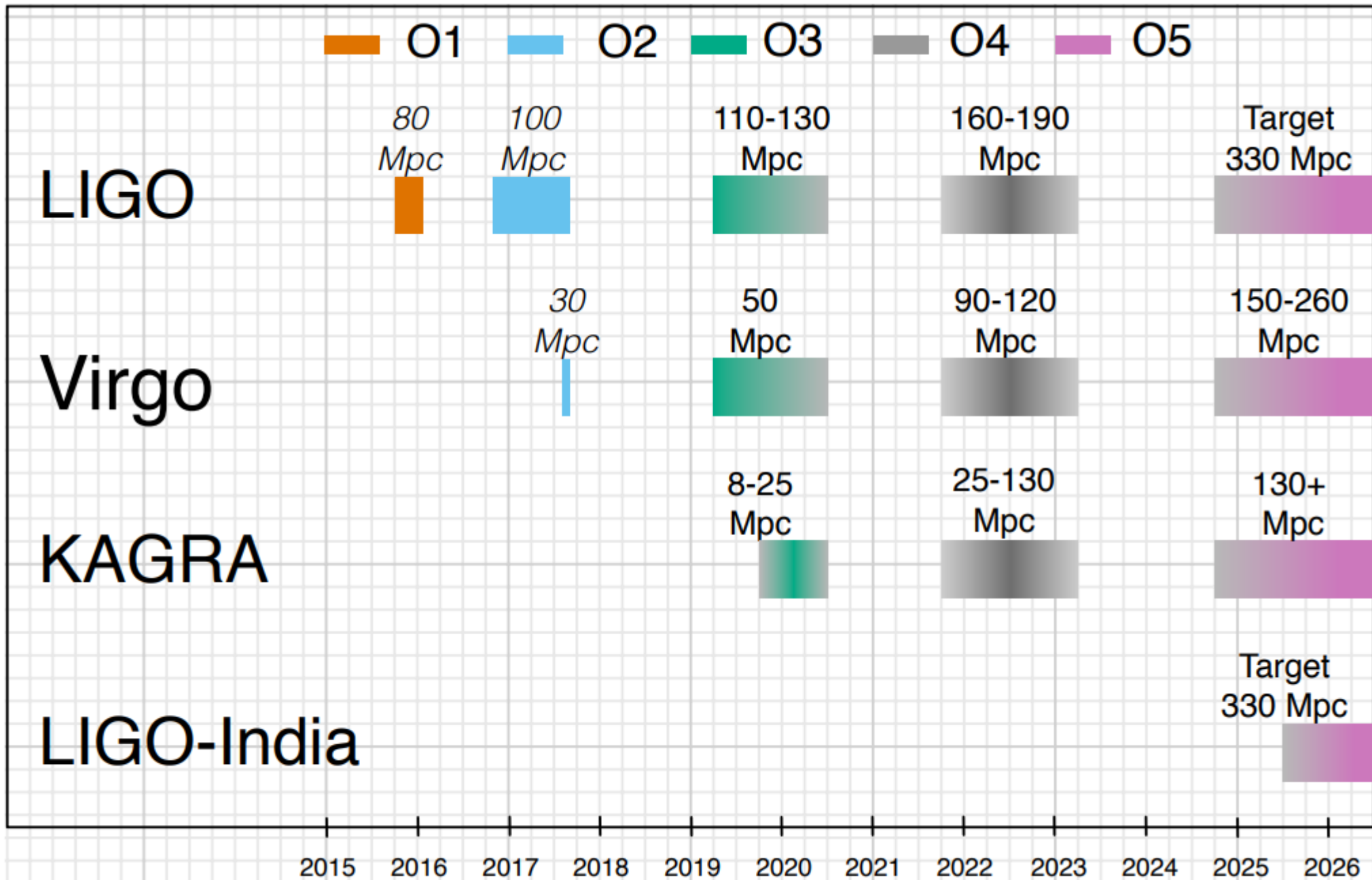







Figure 2, LVC, LRR 21:3 (2018)

The Origin of the Solar System Elements

| | | | | | | | | | | | | | | | | | | | | | | |
|----------|---|---|----------|----------|----------|----------|----------|----------|----------|----------|--|---|----------|----------|----------|----------|----------|----------|---------|---------|----------|----------|
| 1 H | big bang fusion  | | | | | | | | | | cosmic ray fission  | | | | | 2 He | | | | | | |
| 3 Li | 4 Be | merging neutron stars  | | | | | | | | | | exploding massive stars  | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 11 Na | 12 Mg | dying low mass stars  | | | | | | | | | | exploding white dwarfs  | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr | | | | | |
| 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe | | | | | |
| 55 Cs | 56 Ba | | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn | | | | | |
| 87 Fr | 88 Ra | | | | | | | | | | | | | | | | | | | | | |
| | | | 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu | | | | | |
| | | | 89 Ac | 90 Th | 91 Pa | 92 U | | | | | | | | | | | | | | | | |

- Obtaining an EM counterpart depends on beaming angle (for GRB) or sky location and distance (for kilonova)
- R-process nucleosynthesis contributions depend on BNS rates
- GW observation of tidal disruption, merger, oscillations of short-lived hypermassive neutron star (lots of hadronic/QCD physics) currently beyond frequency sensitivity of detectors ($\sim 5\text{kHz}$)
- GW observations of single, spinning deformed NS also possible – reasonable rates unknown – depends possibly on crust stiffness

Thank you