# CONSTRAINING DENSE NUCLEAR MATTER WITH GRAVITATIONAL WAVES

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CENTRE

### gravitational waves: observations

• Since 2015, gravitational-wave instruments have witnessed over 90





# compact-binary coalescences.



### GW170817



#### • On 17 Aug. 2017, gravitational-wave instruments detected the first neutron-star merger.



Primary mass  $m_1$ Secondary mass  $m_2$ Chirp mass  $M$ Mass ratio  $m_2/m_1$ Total mass  $m_{\text{tot}}$ Radiated energy  $E_{rad}$ Luminosity distance  $D_{L}$ Viewing angle  $\Theta$ Using NGC 4993 location Combined dimensionless tidal de Dimensionless tidal deformabilit

[Abbott+ 2017, *Phys. Rev. Lett.* **119**, 161101]









#### LETTER

#### **A gravitational-wave standard siren measurement of the Hubble constant**

The LIGO Scientific Collaboration and The Virgo Collaboration\*, The 1M2H Collaboration\*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration\*, The DLT40 Collaboration\*, The Las Cumbres Observatory Collaboration\*, The VINROUGE Collaboration\* & The MASTER Collaboration\*

**within a region of the sky consistent with the LIGO–Virgo-derived location of the gravitation of the gravitation of the gravitation was a strategies of the strategies of the strat** 

**On 17 August 2017, the Advanced LIGO<sup>1</sup>**

 **and Virgo<sup>2</sup>**

 **detectors** 

**observed the gravitational-wave event GW170817—a strong signal** 

**from the merger of a binary neutron-star system<sup>3</sup>**

**subsequently observed by optical astronomy facilities<sup>7</sup>**

**in the identification8–13 of an optical transient signal within about the galaxy NGCC 4993. The galaxy NGCC 4993. The galaxy NGCC GW170817. INCAS represents the first 'multi-messenger' astronomical observation. Such observations enable GW170817 to be used as a 'standard** 

The Hubble constant *H*0 measures the mean expansion rate of the Universe. At nearby distances (less than about 50 Mpc) it is well approximately in the second se

 $v_{\rm H} = H_0 d$  (1) where  $\mathbf{v}$  is the local velocity of a source and  $\mathbf{v}$  $H$ distances all cosmological distributions are  $H$  $\cup$ i $\cup$ i $\cup$ ivity  $\cup$ 4. Testing general relativity **F** GW170817, the differences between the different distance measures are

much smaller than the overall errors in distance. Our measurement of *H*0 is similarly insensitive to the values of other cosmological parameters, such as the matter density *Ωm* and the dark-energy density *ΩΛ*. To obtain the Hubble flow velocity at the position of GW170817, we tification is based solely on the two-dimensional projected offset and is  $\overline{D}$ iivalizing of potential sky locations. The uncertainty of  $\overline{D}$ PH I SICAL REVIEW LE Editors' Suggestion  $tanh$  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$  factor that depends on the correlation of the correlation of  $\overline{\phantom{a}}$  $\Gamma$ I and the line-of-sight vector from the source to the source the source to the source to the source to the detector of the source to the s (LIGO Scientific Collaboration and Virgo Collaboration)  $\mathbf{r}$  system is orbital clockwise (or, equivalently, equivalently, equivalently,  $\mathbf{r}$ Projected distance of ∠2 kpc away from the galaxy's center. We use this minimal set of facts and the mass of fa posteriors of the two neutron stars to derive the first constraints on the progenitor of GW170817 at the time o  $k = \frac{1}{\sqrt{N}}$  binary neutron star (BNS) birth to the merger time, accounting for pre-SN galactic for  $S_{\rm{N}}$  in though not considerably tight, we find the constraints to be comparable to those for Galactic to those for  $\mathbf{S}_{\rm{N}}$ with pressure at twice nuclear saturation density measured at  $3.5$  $\blacksquare$ LIGO [1] and Advanced Virgo [2] observatories have opened a window on the gravitational-wave (GW) universe [3,4]. A new type of astrophysical source of GWs was detected on 17 August 2017, when the GW signal emitted  $\int$  (Received 20 110)

**determined directly from the gravitational-wave measurements) to measure the Hubble constant of the Hubble constant of the local standard constant of the local**  $\bullet$  **local**  $\bullet$  **local \ expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Here we report a measurement of the Hubble constant that combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the** 

**the luminosity distance out to cosmological scales directly, without** 

#### **the use of intermediate astronomical distance measurements. We determine the Hubble constant to be about 70 kilometres per**

**second per megaparsec. This value is consistent with existing measurements20,21, while being completely independent of them. Additional standard siren measurements from future gravitationalwave sources will enable the Hubble constant to be constrained to** 



 $(1)$  observations. The optical source was associated with the early-type galaxy NGC 4993 at a distance of  $\overline{a}$  $PHYSICAL REVIEW LETTERS 123, 011102 (2019)$ 

#### Tests of General Relativity with GW170817

 $B. P.$  Abbott *et al.*<sup>\*</sup> information about whether the EOS is soft or stiff and what  $\mathcal{R}$ 

use the optical identification of the host galaxy NGC 49937

independent of any assumed value of *H*0. The position and redshift of

## science potential of neutron-star binaries

1. Cosmology

**THE ASTROPHYSICAL JOURNAL LETTERS 850.140 (18pp) 2017 December 1 C** 2017. The American Astronomical Society. **lOPEN ACCESS**  $\degree$  2017. The American Astronomical Society.

2. Nuclear physics

3. Astrophysics

Key words: binaries: general – gravitational waves – stars: kinematics and dynamics – stars: neutron

face-on-on-face-on-on-face-or face-off), and sources are therefore usually characterized usually characterized usually characterized usually characterized usually characterized usually characterized usually characterized

emission, however, remained elusive until now.

Aided by the tight localization constraints of the three-

burst, GRB 170817A [6,7], verifying that the source binary source bi contained matter, which was further corroborated by a series of observations that followed across the electromag-

5. Multi-messenger astronomy and the Astronomy  $\sum_{\text{max}}$   $\sum_{\text{max}}$  **hole coalescence GPEN ACC** Advanced LIGO detectors (Aasi et al. 2015). Discovery of a GW source accompanied by coincident electromagnetic (EM) netic spectrum; see e.g., [8–12]. The measured masses of the bodies and the variety of electromagnetic observations conomi Neutron stars are unique natural laboratories for studying the behavior of cold high-density  $\mathbf{r}$ behavior is governed by the equation of state (EOS), which

2014).

constrain effects due to large extra dimensions. Finally, the polarization content of the gravitation content of the gravitation content of the gravitation content of the gravitational wave of the gravitational wave of the **OPEN ACCESS** 

The recent discovery by Advanced LIGO and Advanced Virgo of a gravitational wave signal from a binary neutron star inspiral has enabled tests of general relativity (GR) with this new type of source. This source, for the first time, permits tests of strong-field dynamics of compact binaries in the presence of matter. In this Letter, we place constraints on the dipole radiation and possible deviations from GR in the post-Newtonian

 $\Omega$  (Received 20 November 2018; revised manuscript received (Received 20 November 2018; revised manuscript received 21 March 2019; published 1 July 2019; corrected 20 August 2019)  $2019$ , gwiezd meanwegint geesived  $21$  Meash  $2010$ , aubliches  $\omega$   $\omega$  for  $\omega$  manuscript received  $\omega$  fractice  $\omega$  states by published

10. Lipunov 2017b; Tanvir & Levan 2017; Tanvir & Levan 2017; Yang et al. 2017; Yang et al. 2017; Yang et al. 20

 $20\text{ m}$  are anticipally  $\text{Iarm}$  is  $\text{Iarm}$   $\theta$  40.1.12  $\text{(6m)}$  2017  $\text{O}$  the  $\text{O}$ THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20<br>
2011 The American Astropomical Society, All rights recented © 2017. The American Astronomical Society. All rights reserved.

equivalence principle by constraining the Shapiro delay



#### **is and consistently localized at other consistently localized at other shows being a late of a late of a late o**<br>Inspiral dynamics in the phase of a late pha  $\frac{1}{2}$ Multi-messenger Observations of a Binary Neutron Star Merger

 $LIOU$  (COV) COV) COV<br>Table and August 17 the Advanced Ligarity 17 the Advanced Ligarity 17 the Advanced Ligarity 17 the Advanced Li rend Advanced Virgo (Acernese et al. 2015) interferometers et al. 2015) inter network recorded a transient consistent and consistent with the consistent with the constant of the constant o  $\frac{1}{2}$ Content and  $\frac{1}{2}$  $\frac{\text{ATay}}{\text{end } C\Lambda\Lambda S}$ and  $C(X)$  $\frac{1}{\text{N}}$  and  $\frac{1}{\text{N}}$ Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Afray, HAWC Collaboration, The Pierre Auge<br>Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team a When in the από το πρόπολη του προσπάθεια, το προσπάθει το προσπ  $L_{\text{C}\text{S}\text{C}\text{I}}$  (Fig. and later improved to ;28 deg<sup>2</sup> with a fully coherent data LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKAP athfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltechand CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-<br>NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic DRAO, TTU-NKAO, and NuSTAK Conaborations, Pan-STAKKS, The MAAT Team, TZAC Consortunit, KU Conaboration, Northern<br>Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of (See the end matter for the full list of authors.) light, allowed new bounds to be placed on local Lorentz  $\sigma$  vLBI feam, Pt of the Sky Collaboration, the Changra feam at  $\sigma$ Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT

 $\frac{1}{\sqrt{5}}$ s in other galaxies, though below the median values, though below the median values of  $\frac{1}{\sqrt{5}}$ Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

distance inferred from the GW signal with the one inferred



<sup>R</sup><sup>2</sup> <sup>¼</sup> <sup>11</sup>.9þ1.<sup>4</sup> <sup>−</sup>1.<sup>4</sup> km at the 90% credible level. Finally, we obtain constraints on <sup>p</sup>ðρ<sup>Þ</sup> at supranuclear densities,

prescribes a relationship between pressure and density. This determines the relation between NS mass and radius, as well as other macroscopic properties such as the stellar such as the stellar such as the stellar such as the s moment of inertia and the tidal deformability (see e.g., [13]). While terrestrial experiments are able to test and constrain the cold EOS at densities below and near the saturation density of nuclei products of nuclei products of nuclei products of nuclei products of nuclei and a e.g., [14–17] for a review), currently they cannot probe the extreme conditions in the deep core of NSs. Astrophysical merging NS binaries differs from that of two merging

Editors' Suggestion

### neutron-star binaries

- holes due to the material response to the tidal field.
- These features enter the waveform phase  $\Psi$  at 5PN.
- $numbers\ k_l$ , which depend on the state of the nuclear matter.

• The signal emitted from inspiralling neutron stars differs to that of black

• The deformability of the stellar material is characterised by the *tidal Love* 









### the static tide

 $m\Psi \ll \omega_{\alpha}$ . .<br>İ  $\Psi \ll \omega_\alpha$ 

• This result generalises to relativity, where the potential  $U$  is promoted to the

![](_page_5_Picture_12.jpeg)

![](_page_5_Picture_13.jpeg)

• We start by assuming that the external field is *static*,

• The tidal Love numbers  $k_l$  are defined at the surface of the neutron star  $r = R$ by

• Therefore, they can be inferred from the behaviour in the exterior,

$$
\delta\Phi(R,\theta,\phi)=\sum_{l,m}\delta\Phi_l(R)\,Y_l^m(\theta,\phi)=\sum_{l,m}\,2k_l\,\chi_l(R)\,Y_l^m(\theta,\phi).
$$

$$
U_l \equiv \delta \Phi_l + \chi_l = \left[ 2k_l \left( \frac{R}{r} \right)^{2l+1} + 1 \right] \left( \frac{r}{R} \right)^l \chi_l(R).
$$

(linearised) metric of the spacetime  $h_{ab}$ .

![](_page_6_Picture_62.jpeg)

# state of play

![](_page_6_Picture_2.jpeg)

![](_page_6_Figure_3.jpeg)

[Abbott+ 2019, *Phys. Rev. X* **9**, 011001]

![](_page_7_Figure_0.jpeg)

![](_page_7_Figure_1.jpeg)

[Raaijmakers+ 2021, *Astrophys. J.* **918**, L29]

![](_page_7_Figure_4.jpeg)

## the dynamical tide

 $m\Psi \sim \omega_{\alpha}$ . .<br>İ  $\Psi \thicksim \omega_{\alpha}$ 

- However, the static tide approximation will inevitably break down.
- As the compact objects inspiral, the tidal frequency increases and eventually becomes comparable to the neutron star's natural modes of oscillation,

• This regime is known as the *dynamical tide* and it has the exciting potential

to probe the oscillation spectrum.

![](_page_8_Figure_3.jpeg)

![](_page_8_Figure_4.jpeg)

![](_page_8_Figure_9.jpeg)

![](_page_8_Picture_10.jpeg)

![](_page_8_Picture_11.jpeg)

![](_page_8_Figure_14.jpeg)

# (some of) the modes

![](_page_9_Picture_10.jpeg)

- *• f*-modes: Fundamental oscillations of the star; scale with the average density,  $\omega_{\alpha}/(2\pi) \sim \sqrt{GM/R^3} \sim 1\,\text{kHz}.$
- *• g*-modes: Restored by buoyancy that arises from composition gradients;  $\omega_{\alpha}/(2\pi) \sim 100 \,\text{Hz}$ .
- *•* inertial modes (including the *r*-mode): Restored by rotation; primarily excited by the gravitomagnetic tide (a relativistic effect) [Flanagan+Racine 2007];  $ω_α$  ~  $Ω$ .
- *• i*-modes: Oscillations that arise due to the core-crust interface; possible association with short gamma-ray bursts [Tsang+ 2012];  $\omega_{\alpha}/(2\pi) \sim 100 \,\text{Hz}$ .
- *•* The natural oscillation modes depend on the nuclearmatter equation of state.

[credit: C. Hanna+B. Owen]

![](_page_9_Picture_13.jpeg)

### the mode-sum

• The normal modes form a complete basis [Chandrasekhar 1964, *Astrophys. J.* **<sup>139</sup>**,

664], such that the tidal response of the star can be decomposed as

 $\xi(t, \mathbf{x}) =$ 

from the orbit. This will change the phase by .<br>İ  $\Psi = \omega_{\alpha}$ 

• Thus, the equation of motion becomes that of a driven harmonic oscillator,

$$
\sum_{\alpha} q_{\alpha}(t) \xi_{\alpha}(\mathbf{x}).
$$

$$
\frac{d^2q_{\alpha}}{dt^2} + \omega_{\alpha}^2 q_{\alpha} = Q_{\alpha} \propto e^{-im\Psi}
$$

.

• At resonance  $m\dot{\Psi} = \omega_{\alpha}$ , the mode will become excited and extract energy

$$
\frac{\Delta \Psi_{\alpha}}{2\pi} \approx -\frac{t_{\rm D}}{t_{\rm orb}} \frac{\Delta E_{\alpha}}{|E_{\rm orb}|} \propto \left(\frac{Q_{\alpha}}{\omega_{\alpha}}\right)^2
$$

.

![](_page_10_Picture_11.jpeg)

![](_page_10_Picture_12.jpeg)

![](_page_10_Picture_17.jpeg)

### the *f*-mode approximation

- There has been some work in representing the dynamical tide using just the *f*-mode.
	- (i) Effective approach: generalising the Newtonian action for the orbital dynamics to relativity [Steinhoff+ 2016, *Phys. Rev. D* **94**, 104028; Schmidt+Hinderer 2019, *Phys. Rev. D* **100**, 021501].
	- (ii) Phenomenological approach [Andersson+Pnigouras 2021, *Mon. Not. R. Astron. Soc.* **503**, 533].
- However, it seems they do not match results from numerical simulations [Gamba+Bernuzzi 2023, *Phys. Rev. D* **107**, 044014].

![](_page_11_Figure_5.jpeg)

![](_page_11_Figure_6.jpeg)

![](_page_12_Picture_126.jpeg)

# state of play

![](_page_12_Picture_2.jpeg)

![](_page_12_Figure_3.jpeg)

## the *g*-modes

![](_page_13_Figure_0.jpeg)

*Mon. Not. R. Astron. Soc.* **270**, 611],

• But some recent work in light of third-generation observatories (Cosmic Explorer and The Einstein Telescope) are more optimistic [Ho+Andersson 2023, *Phys.* 

- *Rev. D* **108**, 043003].
- 

• Even without direct measurements of the *g*-modes, the sensitivity improvements will place constraints on properties of the nuclear matter.

![](_page_13_Picture_9.jpeg)

![](_page_13_Picture_10.jpeg)

![](_page_13_Figure_13.jpeg)

$$
\frac{\Delta \Psi_g}{2\pi} \approx -4.3 \times 10^{-4} \left[ \frac{100 \,\text{Hz}}{\omega_g/(2\pi)} \right]^2 \left( \frac{Q_g}{0.0003} \right)^2
$$

.

• The phase shifts are expected to be very small [Lai 1994,

#### summary

• Gravitational waves carry information about the dense nuclear matter

• We understand the static tide well. However, this approximation *will* break

• The dynamical tide is less well-understood and much of our understanding

- inside neutron stars.
- down during the inspiral.
- still relies on Newtonian gravity.
- opportunity to see these effects.

• Opportunities to detect resonances are quite tantalising and the resonances will hold information about the interior stellar physics. Thirdgeneration detectors will be more sensitive and may give us an

![](_page_14_Picture_9.jpeg)