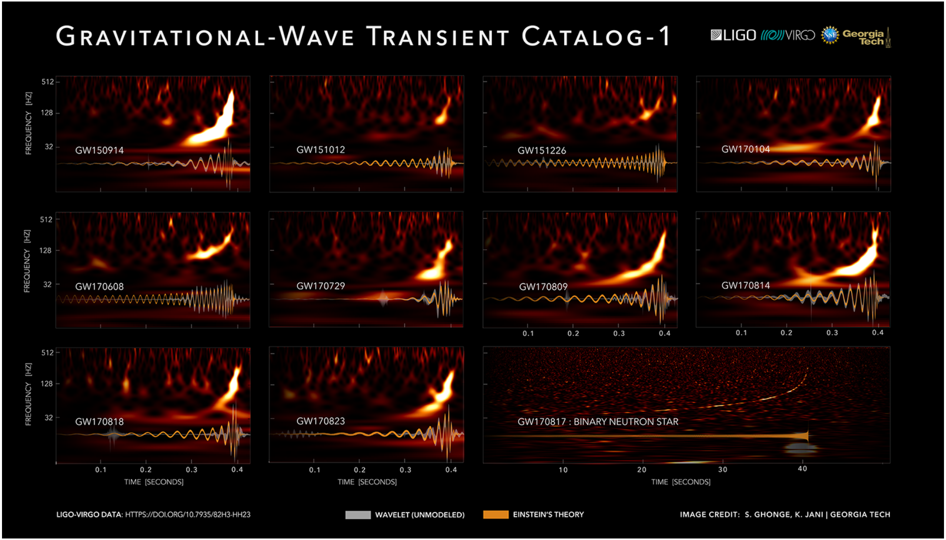
Science from gravitational-wave data

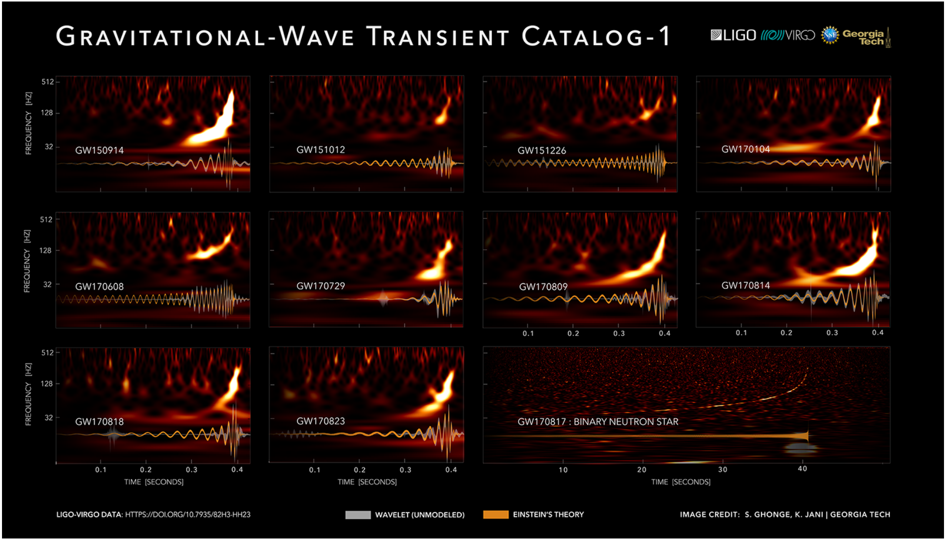
Archisman Ghosh
Nikhef, Amsterdam

7^{th} Nikhef Jamboree

Utrecht, 2018 December 18



GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO VIRGO Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
IMAGE CREDIT: S. GHONGE, K. JANI | GEORGIA TECH



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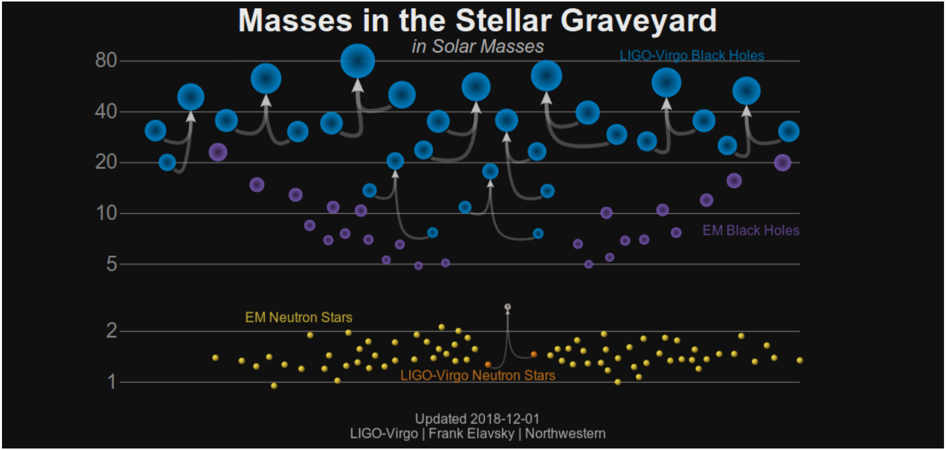

Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
Updated 2018-12-01
LIGO-Virgo | Frank Elavsky | Northwestern

Data analysis efforts at Nikhef

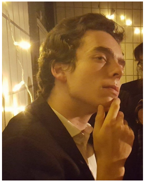
- Searches

- Neutron star matter

- Strong field gravity

- Cosmology

Searches

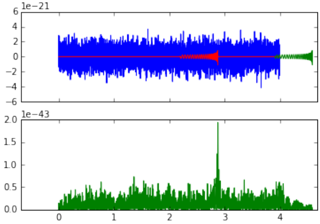


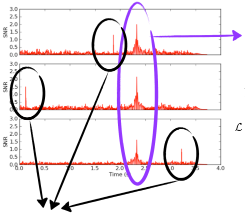
GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs

The LIGO Scientific Collaboration and The Virgo Collaboration
(Compiled: 3 December 2018)

Searches

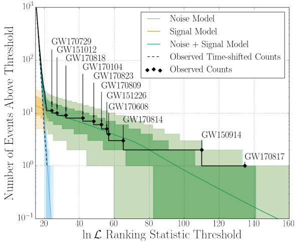
MATCHED FILTERING





BACKGROUND

COINCIDENT TRIGGERS

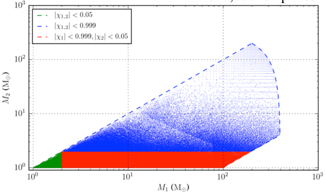


Abbott *et al.* arXiv:1811.12907 [astro-ph.HE]

RANKING & SIGNIFICANCE

Event	Network SNR GstLAL
GW150914	24.4
GW151012	10.0
GW151226	13.1
GW170104	13.0
GW170608	14.9
GW170729	10.8
GW170809	12.4
GW170814	15.9
GW170817	33.0
GW170818	11.3
GW170823	11.5

677,000 templates



gstLAL

O2 TEMPLATE BANK

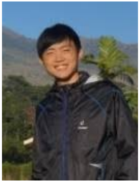
GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs

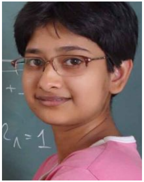
The LIGO Scientific Collaboration and The Virgo Collaboration
(Compiled: 3 December 2018)

Abbott *et al.* arXiv:1811.12907 [astro-ph.HE]

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/(\rm erg\,s^{-1})$	d_L/Mpc	z	$\Delta\Omega/\rm deg^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4} \times 10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	179
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7} \times 10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1555
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7} \times 10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.1^{+5.2}_{-3.9}$	$0.66^{+0.08}_{-0.10}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-0.9} \times 10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	924
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3} \times 10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	396
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$0.36^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5} \times 10^{56}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$	1033
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.16}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9} \times 10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	340
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5} \times 10^{56}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1 \times 10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7} \times 10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$0.08^{+0.20}_{-0.22}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9} \times 10^{56}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1651

Neutron star matter



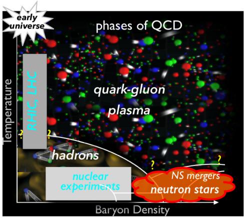


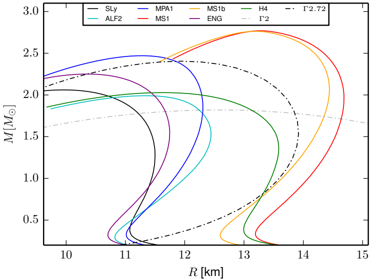
Properties of the binary neutron star merger GW170817

The LIGO Scientific Collaboration and The Virgo Collaboration
(Compiled 30 May 2018)

GW170817: properties of the neutron star

Figure from: Dietrich *et al.* (2015)

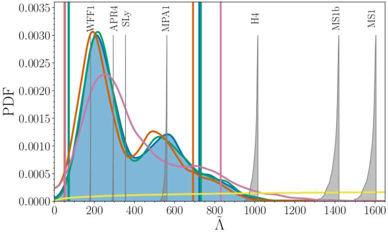




Waveform systematics for binary neutron star gravitational wave signals: effects of the point-particle baseline and tidal descriptions

Anuradha Samajdar[1] and Tim Dietrich[1]
[1] *Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands*

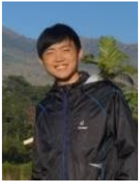
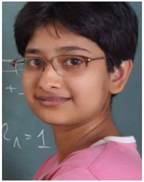
(Dated: October 10, 2018)



Abbott *et al.* arXiv:1805.11579 [gr-qc]

Strong-field gravity



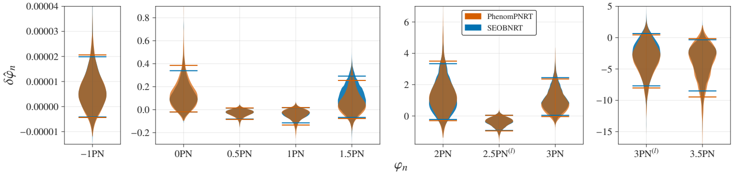
Tests of General Relativity with GW170817

B. P. Abbott,[1] R. Abbott,[1] T. D. Abbott,[2] F. Acernese,[3,4] K. Ackley,[5] C. Adams,[6] T. Adams,[7] P. Addesso,[8]

Tests of general relativity with GW170817

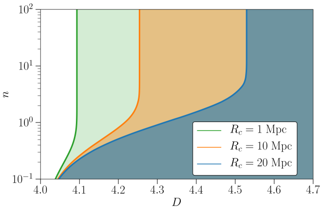
Dipole radiation

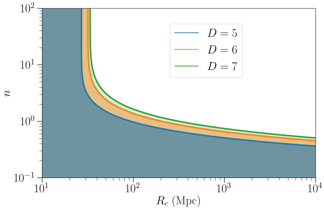
Abbott *et al.* arXiv:1811.00364 [gr-qc]



- Parameterized deviations do not show any departures from GR values.

- "Inverse square law" $\rightarrow$ constraints on extra dimensions.





Probing the nature of compact objects

Are they really black holes, or exotic compact objects mimicking black holes?

Boson stars, dark matter stars, gravastars, shells, wormholes, . . .

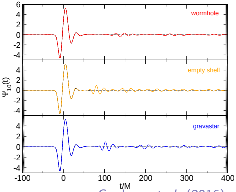
Different **complementary** methods probing different regimes:

PHYSICAL REVIEW D **98,** 104020 (2018)

Empirical tests of the black hole no-hair conjecture using gravitational-wave observations

Gregorio Carullo,[1,2,*] Laura van der Schaaf,[2] Lionel London,[3] Peter T. H. Pang,[4] Ka Wa Tsang,[2] Otto A. Hannuksela,[4] Jeroen Meidam,[2] Michalis Agathos,[5] Anuradha Samajdar,[2] Archisman Ghosh,[2] Tjonnie G. F. Li,[4] Walter Del Pozzo,[1,6] and Chris Van Den Broeck[2,7]

- Finite size effects during inspiral.
- Ringdown quasinormal modes $\rightarrow$ no-hair conjecture.
- Search for post-merger oscillations or "echoes".



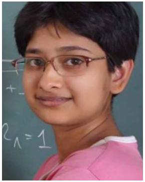
Cardoso *et al.* (2016)

PHYSICAL REVIEW D **98,** 024023 (2018)

A morphology-independent data analysis method for detecting and characterizing gravitational wave echoes

Ka Wa Tsang,[1] Michiel Rollier,[1] Archisman Ghosh,[1] Anuradha Samajdar,[1] Michalis Agathos,[2] Katerina Chatziioannou,[3] Vitor Cardoso,[4] Gaurav Khanna,[5] and Chris Van Den Broeck[1,6]

Cosmology

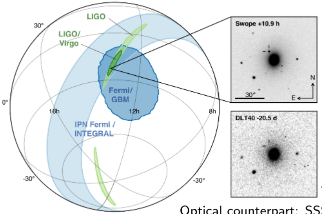


A standard siren measurement of the Hubble constant from GW170817 without the electromagnetic counterpart

M. Fishbach,[1] R. Gray,[2] I. Magaña Hernandez,[3] H. Qi,[3] A. Sur,[4] and
members of the LIGO Scientific Collaboration and the Virgo Collaboration

[1]*Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637, USA*
[2]*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[3]*University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA*
[4]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*

Cosmology: Hubble parameter with GW170817



Standard siren Schutz (1986), Holz & Hughes (2005)

GWs provide a direct measurement of the luminosity distance!

$$v_H = H_0 d_L$$

Recession velocity (or redshift) can come from a transient EM counterpart or an identified host galaxy.

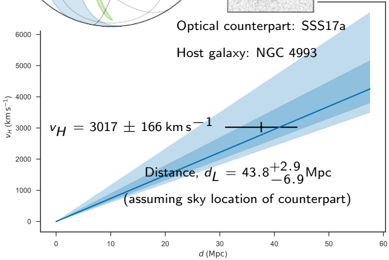
Optical counterpart: SSS17a

Host galaxy: NGC 4993

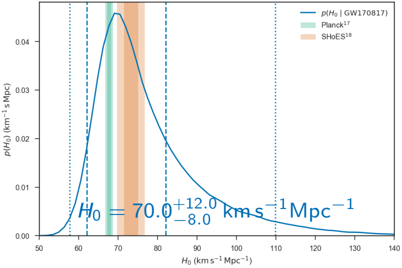
$v_H = 3017 \pm 166\ \mathrm{km\,s^{-1}}$

Distance, $d_L = 43.8^{+2.9}_{-6.9}$ Mpc

(assuming sky location of counterpart)



$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$



Independent of any distance ladder!

Abbott *et al.* Astrophys. J. **848** #2, L12 (2017); LSC-EPO

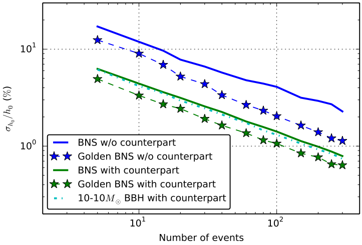
Abbott *et al.* Nature **551** #7678, 85-88 (2017)

H_0: future prospects

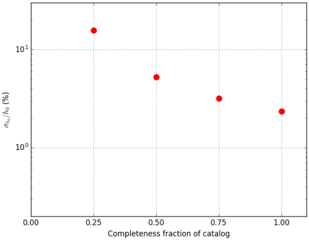
"Statistical" method in absence of uniquely identified host galaxy.

Schutz (1986); Del Pozzo (2012)

Chen *et al.* (2017): counterpart & statistical



Sur (2017, Masters thesis), Gray *et al.* (in prep.)



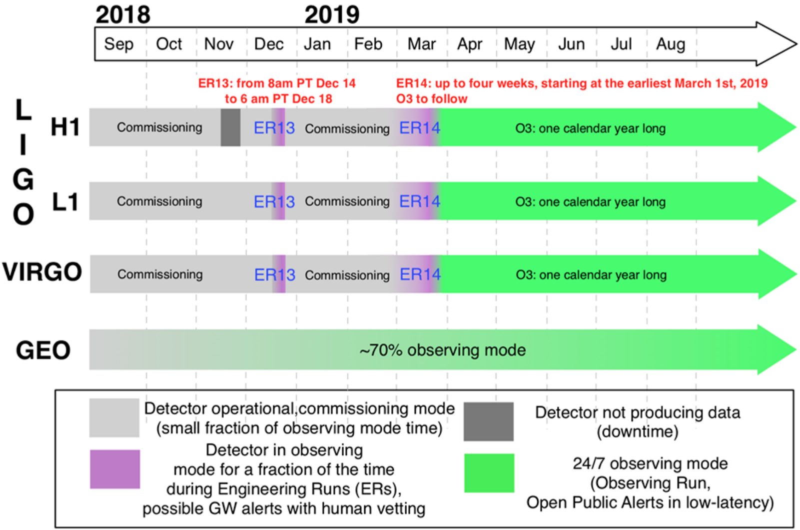
Statistical: incomplete galaxy catalogue


LEGENDS
BERKELEY

LIGO-VIRGO Joint Run Planning Committee

Working schedule for O3

(Public document G1801056-v4, based on G1800889-v7)



Gravitational Wave Detector Network

Operational Snapshot as of Dec 16, 07:09 UTC

Detector	Status	Duration
GEO 600	Observing	2:59
LIGO Hanford	Observing	1:47
LIGO Livingston	Observing	1:40
Virgo	Science	3:07
KAGRA	Future addition	

Detector status summary pages

LVC links