LIGO and Virgo Results from the O2 Observing Run

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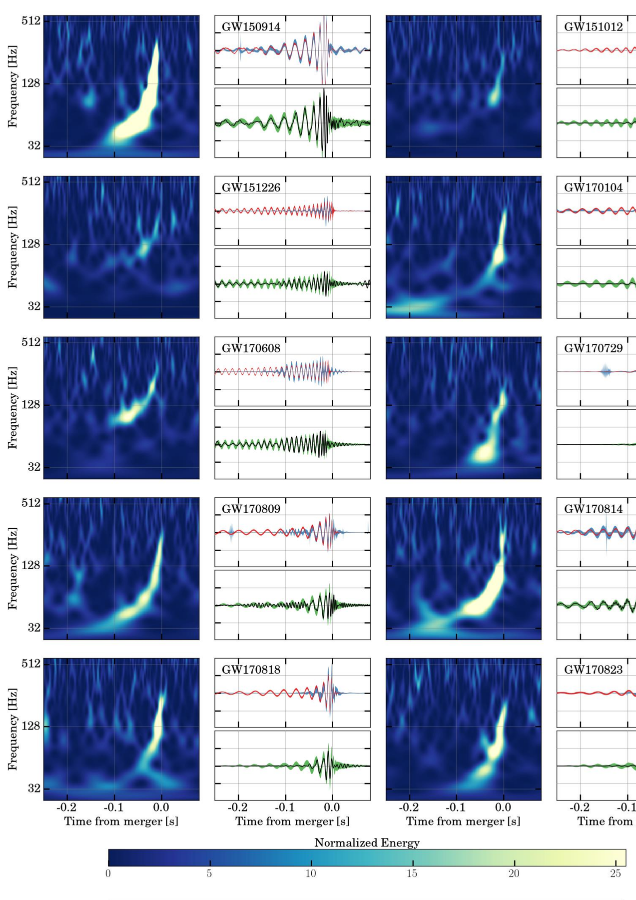
Seven BBH GW Events Confidently Detected in O2 *plus*

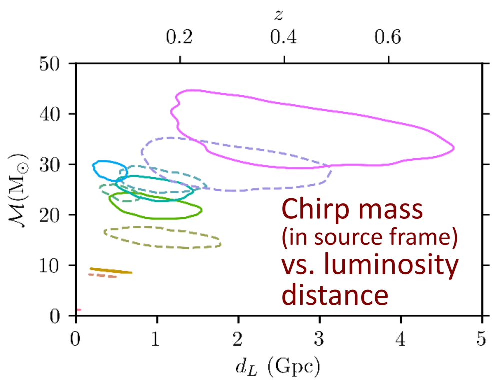
During the O2 observing run (30 Nov 2016 to 25 Aug 2017), NSF's Advanced LIGO observatories and Europe's Advanced Virgo detected 7 binary black hole (BBH) mergers plus one binary neutron star (BNS) merger. Together with the 3 BBH mergers detected during the O1 run, these were published as the **GWTC-1 catalog** *[Abbott+, PRX 9, 031040]*



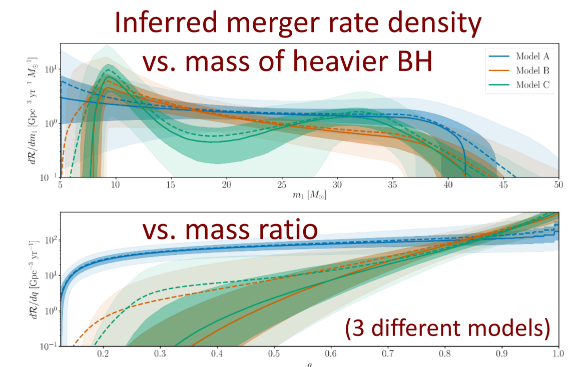
Spectrograms and reconstructed signals (inferred from strain data, whitened) for the 10 BBH mergers

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	$35.7^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
GW151012	$23.3^{+15.0}_{-5.5}$	$13.7^{+4.1}_{-4.8}$	$15.3^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.7^{+10.7}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+550}_{-480}	$0.21^{+0.09}_{-0.09}$	1524
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$31.0^{+7.3}_{-5.6}$	$20.1^{+4.9}_{-4.6}$	$21.5^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$49.1^{+5.2}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0}\times10^{56}$	960^{+440}_{-420}	$0.19^{+0.08}_{-0.08}$	921
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
GW170729	$50.6^{+16.4}_{-10.3}$	$34.3^{+9.0}_{-10.1}$	$35.7^{+6.4}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2760^{+1380}_{-1340}	$0.48^{+0.19}_{-0.21}$	1041
GW170809	$35.1^{+8.3}_{-5.9}$	$24.0^{+5.1}_{-5.2}$	$25.0^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.5^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.8^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.06}_{-0.07}$	312
GW170814	$30.7^{+5.6}_{-3.0}$	$25.3^{+2.8}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	570^{+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	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$	39
GW170823	$39.8^{+11.4}_{-6.7}$	$29.2^{+6.9}_{-7.8}$	$29.4^{+4.7}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.8^{+10.3}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1}\times10^{56}$	1880^{+930}_{-860}	$0.34^{+0.14}_{-0.14}$	1669

[Also PRL 118, 221101 (GW170104)*; ApJL 851, L35* (GW170608)*; PRL 119, 141101* (GW170814)*]*



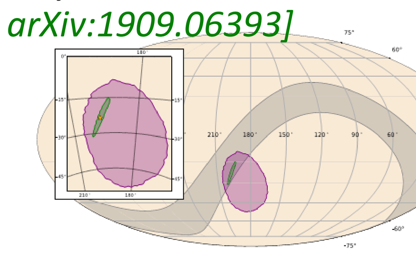
Inferred merger rate density

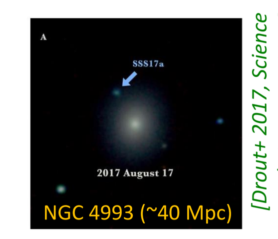


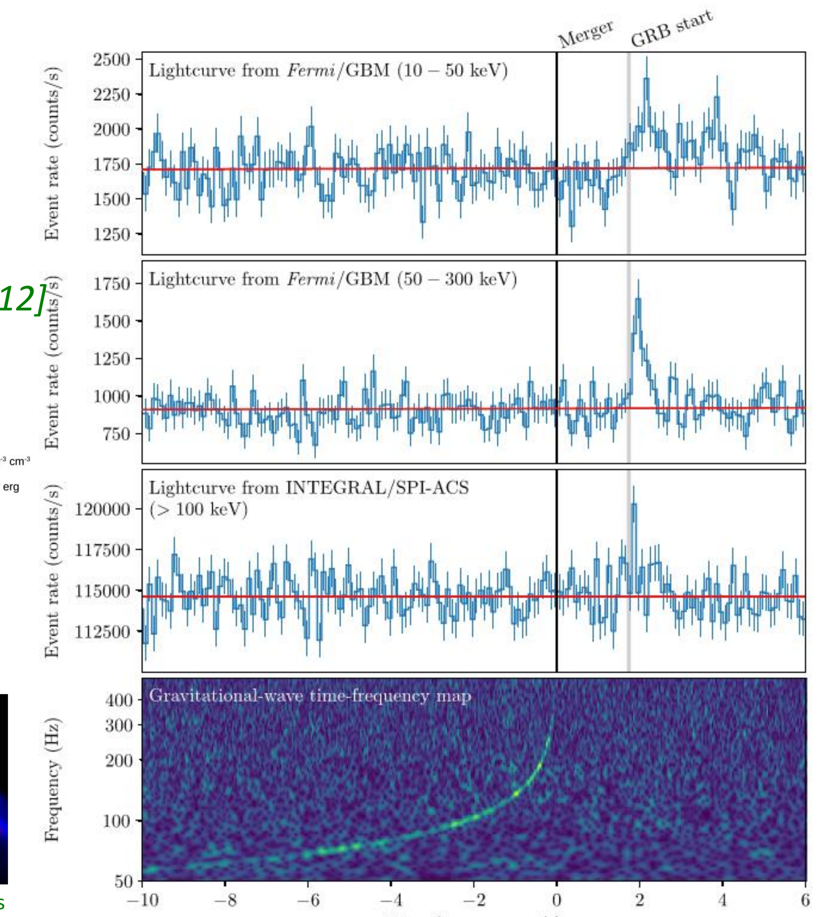
- ➔ Enables inferences about the BBH merger rate and distribution of progenitor system parameters *[Abbott+, ApJL 882, L24]*
- ➔ Additional events/candidates with lower significance have been reported by other groups and in the GWTC-1 catalog paper

GW170817: Multi-Messenger Breakthrough!

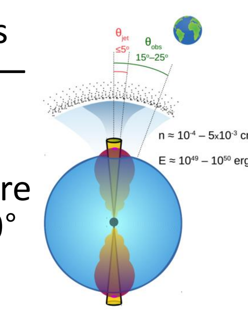
The BNS merger "chirp" was very strong in the gravitational-wave (GW) data and was accompanied by a short GRB detected by *Fermi*/GBM and INTEGRAL/SPI-ACS.
An optical counterpart was found in the galaxy NGC 4993 and studied intensely at all wavelengths, tracing out a kilonova light curve which was visible for weeks *[e.g. see Villar+, ApJL 851, L21]* plus X-ray and radio afterglow emission which peaked after ~100 days and was detectable for over a year. *[e.g. see Troja+, MNRAS 489, 1919 and Hajela+, arXiv:1909.06393]*







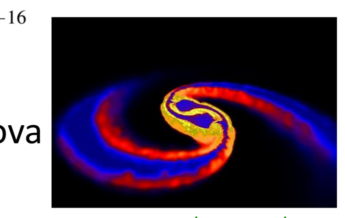
[Abbott+, PRL 119, 161101; ApJ 848, L13; ApJ 848, L12]



- ➔ Confirmed picture of BNS mergers as progenitors of short-hard GRBs—in this case, detected off-axis. VLBI imaging *[Mooley+, Nature 561]* and other observational handles are consistent with viewing angle ~20°
- ➔ Verified to high precision that GWs travel at the speed of light

$$-3\times10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7\times10^{-16}$$

- ➔ Investigated dynamical ejecta contribution to kilonova associated with GW170817 *[Abbott+, ApJL 850, L39; also many other papers]*



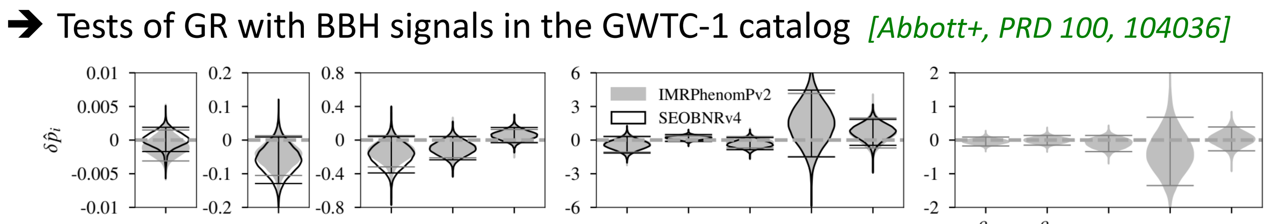
Price/Rosswog/Press

- ➔ Detailed study of binary system properties from the GW waveform *[Abbott+, PRX 9, 01101]*

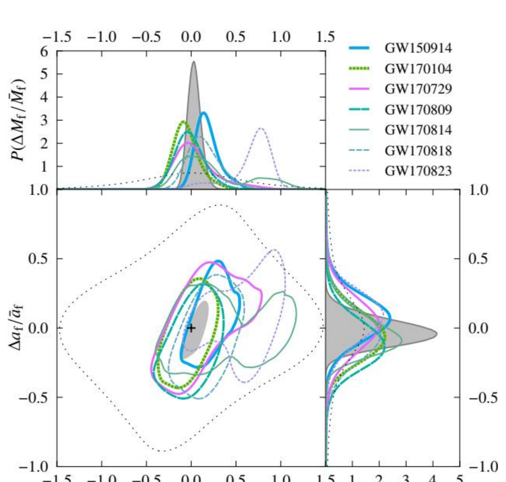
Tests of General Relativity (GR)

Using detailed studies of the waveforms to test general relativity

- ➔ Tests of GR with GW170817 *[Abbott+, PRL 123, 011102]*
- ➔ Tests of GR with BBH signals in the GWTC-1 catalog *[Abbott+, PRD 100, 104036]*



Combined posteriors and limits on parameters describing GR violations

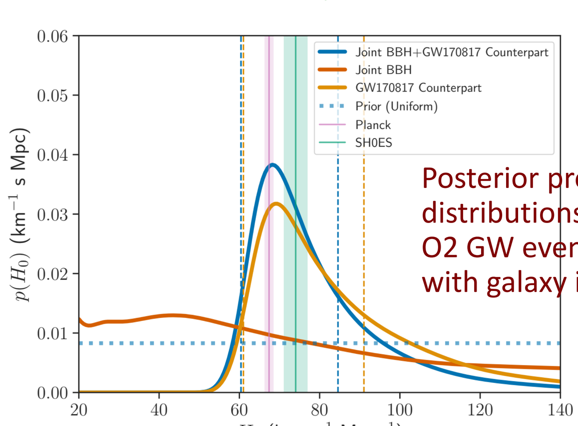


Inspiral-merger-ringdown consistency test

Cosmological Measurements

Binary mergers are "standard sirens", measuring luminosity distance directly – although with statistical uncertainty if the binary orbit inclination angle is unknown

- ➔ Measurement of the Hubble constant from associating GW170817 with the redshift of the cluster including its host galaxy, NGC 4993 *[LIGO, Virgo, 1M2H, DECam GW-EM and DES Collaboration, DLT40, Las Cumbres Observatory, VINROUGE and MASTER, Nature 551, 85]*
- ➔ Implications for the stochastic GW background from BNS mergers like GW170817 *[Abbott+, PRL 120, 091101]*
- ➔ "Dark standard siren" measurement of the Hubble constant by associating the BBH merger GW170814 statistically with galaxies cataloged by the Dark Energy Survey *[Soares-Santos+, ApJL 876, L7]*
- ➔ Combined Hubble constant measurement using statistical analysis of several BBH events together with GW170817 *[Abbott+, arXiv:1908.06060]*



Posterior probability distributions for H_0 from O2 GW events combined with galaxy info

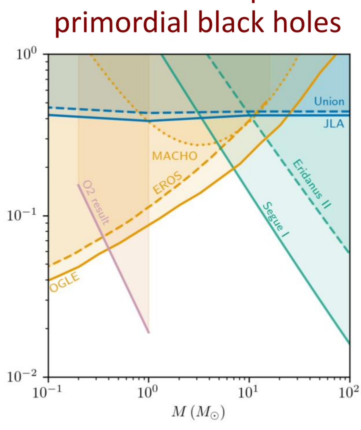
Searches for Other Types of GW Signals

LIGO and Virgo are still exploring the gravitational-wave sky with data analyses optimized for a wide variety of plausible signals

Other classes of compact binary mergers

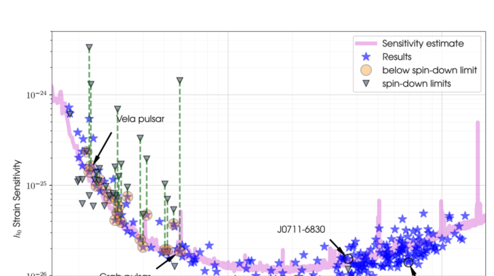
- ➔ Search for sub-solar-mass ultracompact binaries, e.g. of primordial black holes *[Abbott+ and S. Shandera, PRL 123, 161102]*
- ➔ Search for intermediate mass black hole binary (IMBHB) mergers with total masses up to ~800 $M_\odot$; distance reach > 1 Gpc around $100+100\ M_\odot$ *[Abbott+, PRD 100, 064064]*
- ➔ Search for eccentric BBH mergers *[Abbott+, 883, 149]*

Constraints on fraction of dark matter composed of primordial black holes



Continuous-wave (quasiperiodic) GW signals

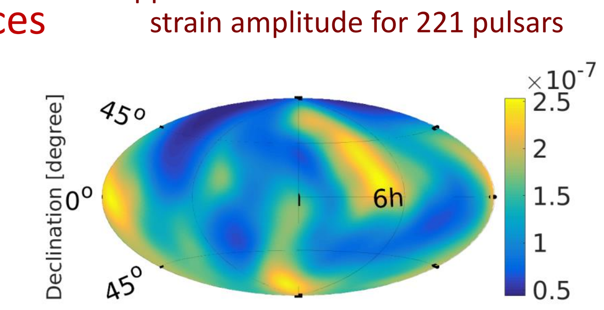
- ➔ Searches for GW signals from known pulsars; for 20 of them, set upper limits below allowable GW fluxes inferred from spin-down *[Abbott+ and radio astronomers, ApJ 879, 10; PRD 99, 122002]*
- ➔ Search for GWs from Scorpius X-1 (the brightest low-mass X-ray binary) over a frequency range 60-650 Hz and allowing for spin wandering *[Abbott+, PRD 100, 122002]*
- ➔ All-sky search for continuous GW signals from isolated neutron stars which are spinning and not axisymmetric, from 20 to >1900 Hz *[Abbott+, PRD 100, 024004]*



Upper limits on continuous-wave GW strain amplitude for 221 pulsars

A stochastic background of GWs, from cosmological and/or astrophysical sources

- ➔ Search for an isotropic stochastic GW background *[Abbott+, PRD 100, 061101]*
- ➔ Directional limits on persistent stochastic GWs *[Abbott+, PRD 100, 062001]*



Directional upper limits on stochastic GW energy flux, assuming flat spectrum

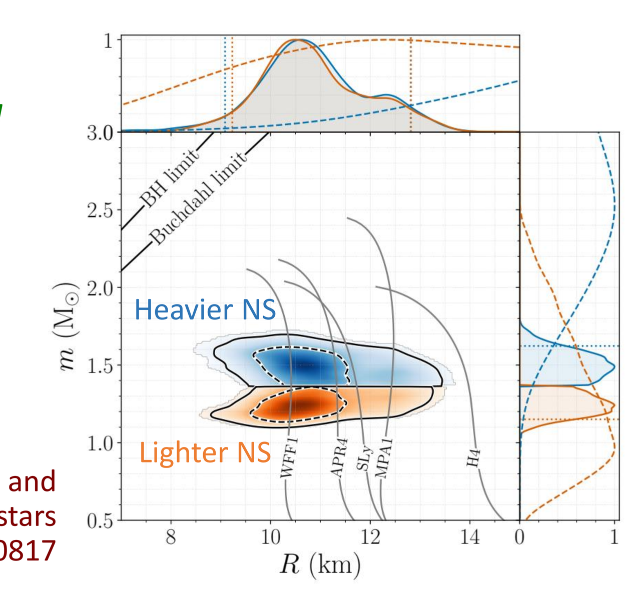
GW "bursts" (generic transient searches)

- ➔ All-sky search for short-duration (up to ~1 sec) GW bursts *[Abbott+, PRD 100, 024017]*
- ➔ All-sky search for long-duration (up to ~500 sec) GW bursts *[Abbott+, PRD 99, 104033]*

Neutron Star Astrophysics Investigations

Inferences from the detection and properties of GW170817

- ➔ Searched for a post-merger GW signal from a metastable remnant, up to ~1 second or up to ~500 seconds long *[Abbott+, ApJL 851, L16]*
- ➔ Searched for GWs from a possible long-lived remnant, up to 8.5 days (when the O2 run ended) *[Abbott+, ApJ 875, 160]*
- ➔ Consideration of where and how the progenitor BNS system formed *[Abbott+, ApJL 850, L40]*
- ➔ Measurements of neutron star equation of state (EOS) and radii, using EOS models, EOS-insensitive relations, or parameterized EOS *[Abbott+, PRX 9, 10010; PRL 121, 161101]*
- ➔ Model comparison from LIGO-Virgo data on GW170817's binary components and consequences for the merger remnant *[Abbott+, arXiv:1908.01012]*
- ➔ Constraining the p-mode – g-mode nonlinear tidal instability *[Abbott+ and N. Weinberg, PRL 122, 061104]*



Marginalized posteriors for mass and areal radius for the neutron stars which merged in GW170817

Additional Multi-Messenger Searches

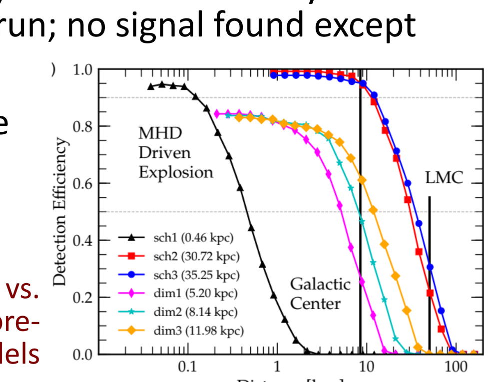
Rapid searches for EM counterparts was enabled by low-latency analysis of the GW data, selection of promising GW event candidates, and communication of their times, types and sky localization to astronomers *[Abbott+, ApJ 875, 161]*

Besides the observed electromagnetic counterpart to GW170817:

- ➔ Search for high-energy neutrinos from the BNS merger GW170817 with ANTARES, IceCube and the Pierre Auger Observatory *[ANTARES, IceCube, Pierre Auger, LIGO and Virgo, ApJL 850, L35]*

And searches for GWs associated with astrophysical phenomena recorded during the O2 run:

- ➔ Search for transient GW signals associated with magnetar bursts *[Abbott+, ApJ 874, 163]*
- ➔ Search for GW signals (binary merger or generic GW burst) associated with any of ~100 gamma-ray bursts which were detected during the O2 run; no signal found except in the case of GW170817 *[LIGO, Virgo and IPN, ApJ 886, 75]*
- ➔ Optically targeted search for GWs emitted by core-collapse supernovae, sensitive out to several kpc, tens of kpc or tens of Mpc for some emission models *[LIGO, Virgo, DLT-40 and ASSASN, arXiv:1908.03584]*



GW detection efficiency vs. distance for one class of core-collapse supernova models

Download LIGO/Virgo Data and Software Tools

from **gw-openscience.org** Gravitational Wave Open Science Center

In addition to online materials, see guides to the data and recommended analysis techniques: *[Abbott+, arXiv:1912.11716; arXiv:1908.11170]*

Also see poster 103.03, "Discovery and Analysis with Public LIGO and Virgo Data" (Jonah Kanner)

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