PX4224: Advanced General Relativity and Gravitational Waves

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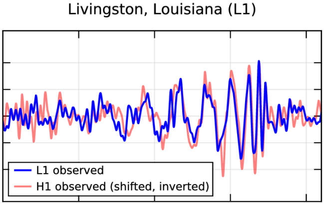
Lecture 18: LIGO Detections

Discovery: GW150914

- Advanced LIGO was just finishing final commissioning, left overnight in observing mode.
- Signal arrived at 09:50:45 UTC on 14 Sept 2015. Louisiana: 05:50, Hanford: 03:50.
- Was it real? No injections, no apparent hacking. Yes, it was real!
- Months of analysis, calibration, and paper-writing followed.
- Announced on 11 February 2016, after discovery paper was accepted by PRL.
- Huge PR event: 70 million tweets, PRL website crashed!

Properties of GW150914



GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^{5} km^{2}
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^{3} Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

How signals are found: data analysis

- Binary coalescence signals can be modelled, so we use *matched filtering*. Assume model signal is $h(t)$.
- Detector output $s(t)$ is correlated with signal arriving at t:

$$o(t) = [s \star h](t) := \int s(t')h(t'-t)dt'.$$

- If detector output is just Gaussian noise $n(t)$ with standard deviation σ, then

$$< o(t) >= 0; \qquad < |o(t)|^2 >= \sigma^2 |h|^2.$$

- But if $o(t) = n(t) + h(t - t_0)$ for some t_0, then

$$< o(t_0) >= |h|^2; \qquad \mathrm{SNR}^2 = |h|^2/\sigma^2.$$

- NB: if $h(t)$ is a wavetrain with N cycles of amplitude a

$$|h|^2 \propto Na^2; \qquad \mathrm{SNR} \propto N^{1/2} a/\sigma.$$

Exercise 18

For GW150914, use the waveform and Factsheet to estimate:

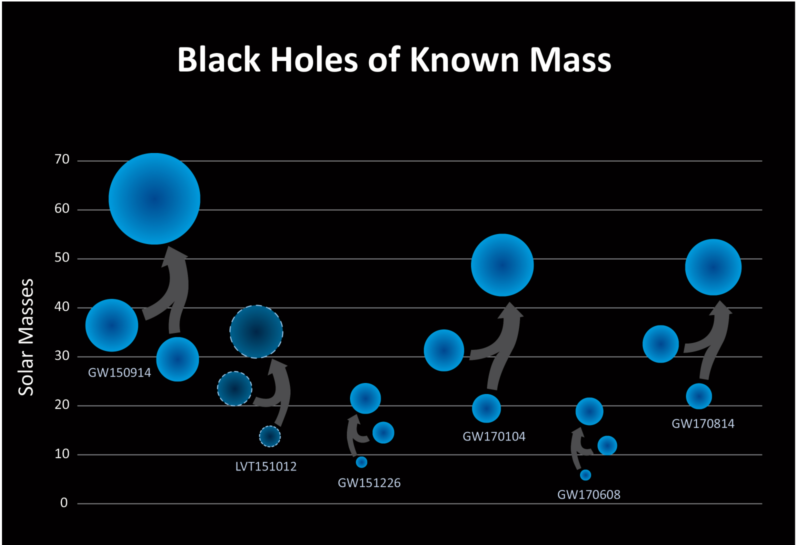
1. the wave's amplitude, frequency, and rate of change of frequency just before merger;
2. the amplitude of the noise;
3. the number of cycles the signal was in band;
4. the expected SNR from matched filtering in one detector;
5. the average mass M of the black holes from

$$\frac{dP}{dt} = -3.4 \times 10^{-12} \left(\frac{M}{M_\odot} \frac{1\mathrm{h}}{P} \right)^{5/3} \qquad (1.1)$$

Waveform families

- $h(t)$ depends on many parameters: masses, spins (intrinsic); sky location and orbit orientation (extrinsic).
- All but last few orbits can be modelled with a very high order post-Newtonian analytic approximation.
- The last orbits need numerical relativity (for BBH), also tidal approximation (for BNS).
- Template families: analytical approximations called EOB and TaylorF2 that fit well over whole parameter space.
- When something is detected, the data are re-analysed with the best approximations.
- Significance: SNR, but also because of glitches we quote a false-alarm rate.

Further BBH detections

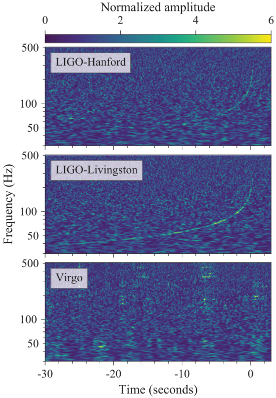


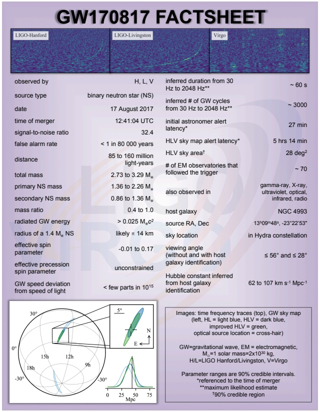
Why so many heavy black holes?

- Most astronomers pre-2015 believed BBHs might not exist: system would not survive common-envelope evolution phase.
- Belczinski and others predicted that low-metallicity stars would survive, and would also have higher masses.
- Another possibility is formation in globular clusters, via hierarchical mergers.
- A recent suggestion by Smoot and colleagues: they are ordinary BHs subject to extreme lensing.

GW170817: the first BNS merger

- Strong GW detection followed within 2 seconds by gamma-ray burst.





GW170817 FACTSHEET

observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≤ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, -23°22'53"
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}

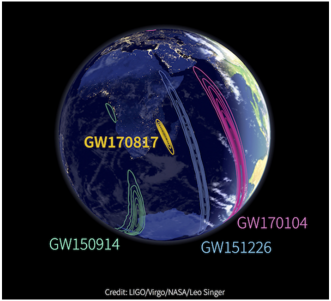
Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=$2\text{x}10^{30}$ kg, H/L=LIGO Hanford/Livingston, V=Virgo

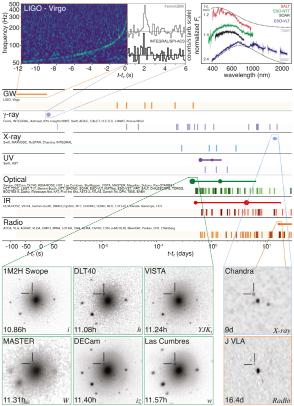
Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region

Multimessenger observations of GW170817

- With 3 detectors, the GW observation pinned down the sky location *and distance*, enabling follow-up.



Credit: LIGO/Virgo/NASA/Leo Singer

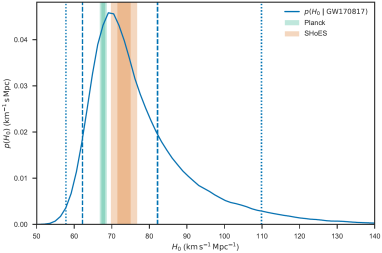


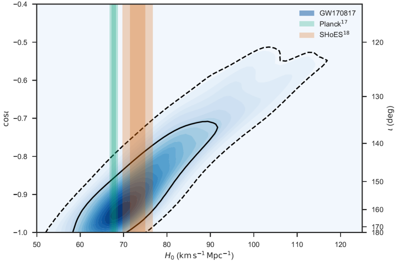
Distance measurement and the Hubble Constant

- How was distance d measured for these events? Binary inspirals are *standard sirens*.
- Chirp rate informs us how fast system is losing energy – intrinsic luminosity L.
- Observed amplitude tells us the apparent brightness B.
- To within angular factors (measured by 3 detectors) $L/B = 4\pi d^2$.
- Distance (40 Mpc) helped identify host galaxy, NGC4993.
- The cosmological recession velocity v of NGC4993 gives local expansion rate of universe (Hubble constant H_0):

$$H_0 := v/d. \tag{1.2}$$

Hubble Constant measurement





Models of the merger

- Although event was very nearby, gamma-ray burst was not exceptionally strong. Why?
- Tidal effects and problems with GW data led to uncertainties on individual masses.
- That, plus inclination uncertainty, make modelling of merger event uncertain.
- Standard model: bright gamma-ray burst broke through expanding cloud, we view from $\sim 30^o$ angle ($\cos\iota = 0.87$).
- Alternative: weak burst almost hidden by cloud, viewed from $\sim 10^o$ angle ($\cos\iota = 0.98$).

Prospects for future observations

- LIGO and Virgo expected to resume late 2018, maybe range ×1.5, event rate ×3, vetoing glitches.
- Clarify origin of BBHs, statistics of BNS, better H_0.
- 2020: Japanese KAGRA (3km, cryo); LIGO, Virgo ×1.5?
- LIGO-India joins 2025(?)
- Improvements to LIGO continue with newer technologies.
- Long-range plans for LIGO (40-km detector) and Virgo (10-km underground triangle called Einstein Telescope).
- ESA's LISA detector launches 2034, opens up rich mHz GW frequency band – confusion-limited!
- Pulsar timing arrays (radio astronomy) could detect nHz GWs from SMBH binaries any time now.
- CMB polarisation telescopes looking for primordial GWs – *fundamental!*