GW150914 Direct Detection by LIGO

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Fermilab JC on LIGO

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LIGO and Virgo, arXiv:1602.03837

Hanford site

Livingston site

Other literature from LIGO

- ALIGO surpassed LIGO in 16 days, arXiv:1602.03838.
- Statistical significance of the two events: $>5.1\sigma, 2.1\sigma$, arXiv:1602.03839.
- Detailed binary system properties, arXiv:1602.03840.
- GR test: consistent, new PN terms, insensitive to polarization information, arXiv:1602.03841.
- Rate estimate: $2-400$ Gpc^{-3} yr^{-1}, arXiv:1602.03842.
- Observing with minimal assumptions, arXiv:1602.03843.
- Transient noise: there was none, arXiv:1602.03844.
- Calibration, arXiv:1602.03845.
- Astrophysical implications: high mass BHs exist and form into binaries, arXiv:1602.03846.
- Stochastic background: higher than previously thought, possibly measurable, arXiv:1602.03847.

($\Delta t_{ij} = 1$s.)

Other literature

- GWs through extra dimensions, arXiv:gr-qc/0103070.
- Mass single NS, arXiv:1511.00358.
- Confirmation of the ergoregion, arXiv:1601.07217, arXiv:1602.02875.
- Test of the EEP, arXiv:1602.01566.
- Predicted BH-BH mass distribution, arXiv:1602.02809.
- Inflation $\rightarrow$ Higgs $\rightarrow$ GWs (undetectable), arXiv:1602.03085.
- Analytic E_{min} circular orbit with Kerr, arXiv:1602.03134.
- Massive gravity on ring down, arXiv:1602.03460.
- Extends the template bank to spins, arXiv:1602.03509.
- BBH rates and their X-ray emission, arXiv:1602.03831.
- GWs from NSs in $f(R)$, arXiv:1602.03880.
- New physics from spectrum of events, arXiv:1602.03883.
- EM follow-up up to 300 Mpc, degeneracy with SN can be broken with broadband, arXiv:1602.03888.

Other literature (cont)

- BBHs in AGN disks, rate prediction (considerable), and EM signature, arXiv:1602.04226.
- MOND and mass screening, arXiv:1602.04337.
- Comparing GW150914 and Fermi event, $|c_{GW} - c_{\gamma}| < 10^{-17}$, arXiv:1602.04460, arXiv:1602.04764.
- This background, arXiv:1602.04476.
- Stellar evolution leading to this BBH system, arXiv:1602.04531.
- GRBs from BBHs with small charge, arXiv:1602.04542.
- Students can analyze GW data for education, arXiv:1602.04666.
- eLISA could measure some comparable BBHs, arXiv:1602.04715.
- EM counterparts not expected, unless BBH formed after core collapse; could explain GBM observation, arXiv:1602.04735.

Other literature (cont cont)

- Due to uncertainties in BH m, a parameters, alternate theories are still allowable, arXiv:1602.04738.
- Shapiro time delay (TeVeS relevant) is consistent with GR to 10^{-9}, arXiv:1602.04779.
- Constraints on Lorentz violating operators are placed, arXiv:1602.04782.

Pipeline to EM detectors

- Two days after the event was detected, the Coherent WaveBurst (cBW) pipeline was activated.
- A false alarm rate of 1.178×10^{-8} Hz was given (1 event per 2.7 yr at this rate).
- A skymap covering 750 deg^2 was released.

EM + ν follow-up searches

- Swift followed up and saw nothing.
  Covered 4.7% of the final region, arXiv:1602.03868.
- DEC followed up and saw nothing.
  Covered 11% of the final region, arXiv:1602.04198.
- DES also looked for direct collapse to a BH from a catalog of red supergiants in the LMC, arXiv:1602.04199.
- Pan-STARRS1 and PESSTO saw nothing significant, arXiv:1602.04156.
- INTEGRAL limits in hard X-ray and gamma rays:
  $E_\gamma/E_{GW} < 10^{-6}$, arXiv:1602.04180.
- IceCube sees nothing,
  dcc.ligo.org/public/0123/P1500271/013/GW150914_neutrino.pdf
- Fermi-LAT sees nothing, arXiv:1602.04488.

The non observation is not surprising given the distance and lack of localization.
(The initial numbers were eventually improved to 1 event per 400 yr, then 230,000 yr; 600 deg^2.)

Fermi GBM follow-up search

arXiv:1602.03920

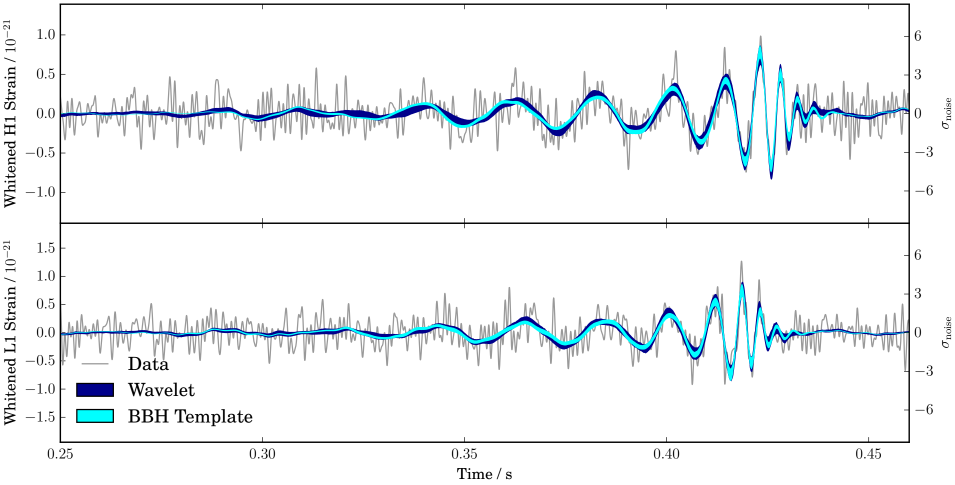
- They saw an event 0.4 s after GW150914 lasting 1 s.
- Characterized as a weak transient above 50 keV.
- Source luminosity: $1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s^{-1}.
- False alarm: $p = 0.0022$.
- Not connected with any known astrophysical, solar, terrestrial, or magnetospheric activity.
- Event is in the worst part of the detector, so localization is hard, but consistent with the LIGO localization.
- The 1-σ localization is 54 deg - $>$ 9000 deg^2 (22% sky).
- Combining their coverages: 601 $\rightarrow$ 199 deg^2.
- The event did not trigger, and is generally quite weak.
- An EM emission for a stellar BH merger isn't understood.
- Saw another at $+11$s, towards the GC, and a softer spectrum.

From the press release

- The Earth jiggles like Jello,
- Southern sky, towards the Magellanic cloud,
- Peak power output is 50 times the power of all the stars in the observable universe,
- Mirrors hang like a pendulum so it rides like a Cadillac, not a truck, and
- The event was before the science run began during an engineering test.

Kip Thorne's tie is a BH-BH merger waveform

Waveforms



Whitened H1 Strain / 10^{-21}
1.0
0.5
0.0
−0.5
−1.0
6
3
0
−3
−6
σ_{noise}
Whitened L1 Strain / 10^{-21}
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Data
Wavelet
BBH Template
0.25
0.30
0.35
0.40
0.45
Time / s

Mass determination (plus ad-hoc source determination)

$$\{f, \dot{f}\} \to \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \approx 30 M_\odot$$

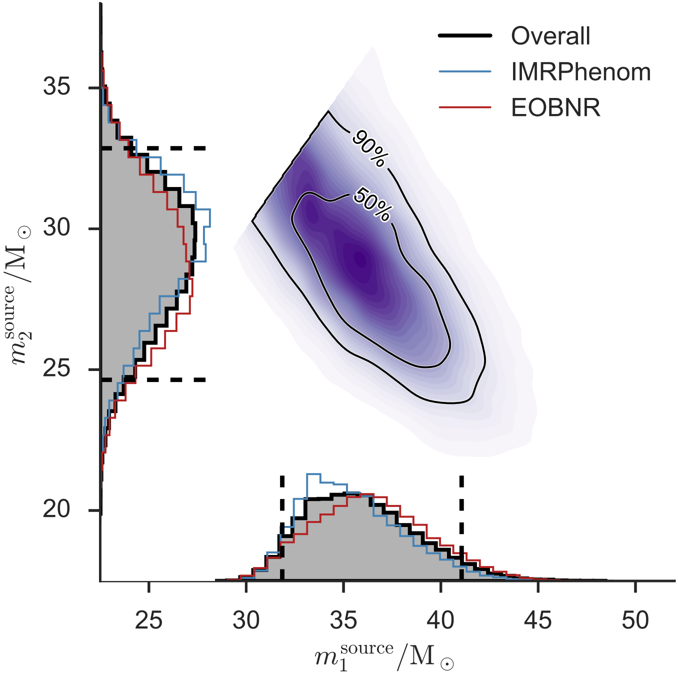
$\Rightarrow m_1 + m_2 \gtrsim 70 M_\odot$,
$\Rightarrow r_1 + r_2 \gtrsim 210$ km.
$f \Rightarrow r_{1-2} \approx 350$ km.
NS-NS is ruled out because they don't have enough mass,
BH-NS is ruled out from f,
So it looks like BH-BH.
Waveform decay is also consistent with BH-BH $\to$ Kerr.

Event overview: GW150914

Date	September 14, 2015
Time	9:50:45 UTC
SNR	24
Direction	600 deg^2 (1.5% sky)
Δt	$6.9^{+0.5}_{-0.4}$ms
Generic	$4.4-4.6\sigma$
Binary	5.1σ
m_1	36^{+5}_{-4}
m_2	29 ± 4
a_1	<0.7
a_2	<0.8
M_f	62 ± 4
a_f	$0.67^{+0.05}_{-0.07}$
D_L	410^{+160}_{-180} Mpc
z	$0.09^{+0.03}_{-0.04}$

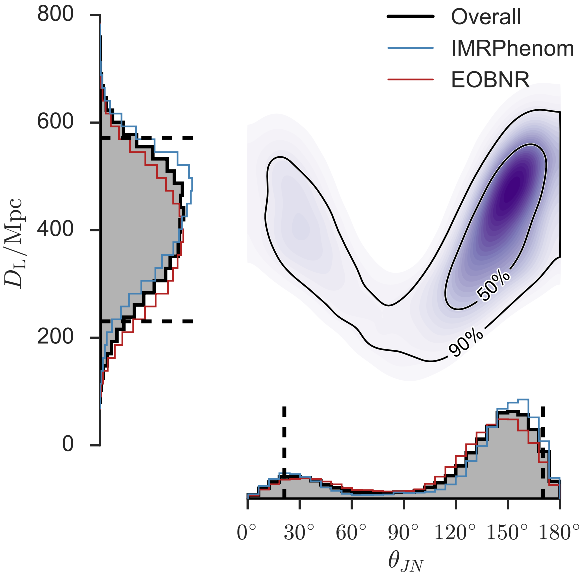
(90% CL)

Masses

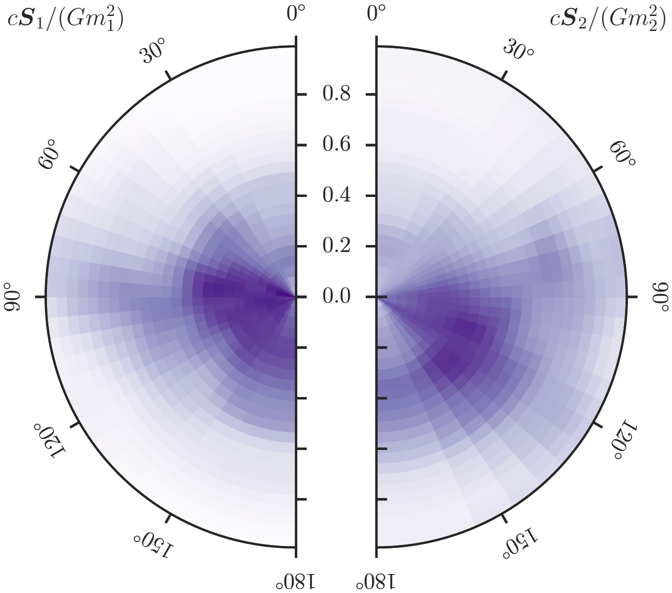


Overall
IMRPhenom
EOBNR
90%
50%
35
30
25
20
$m_2^{\mathrm{source}}/\mathrm{M}_\odot$
25
30
35
40
45
50
$m_1^{\mathrm{source}}/\mathrm{M}_\odot$

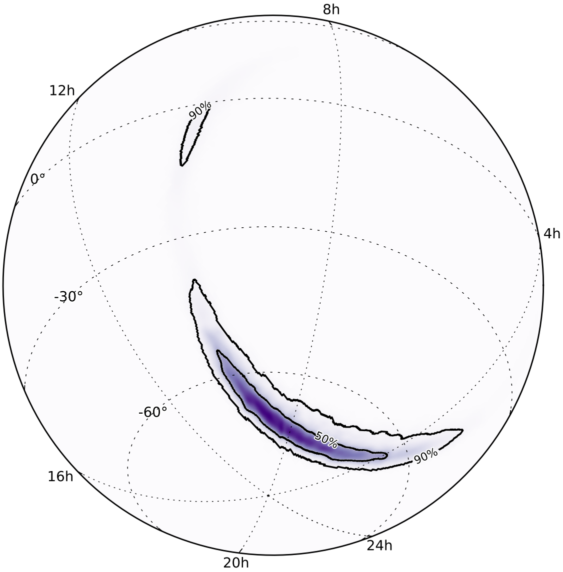
Distance and binary inclination



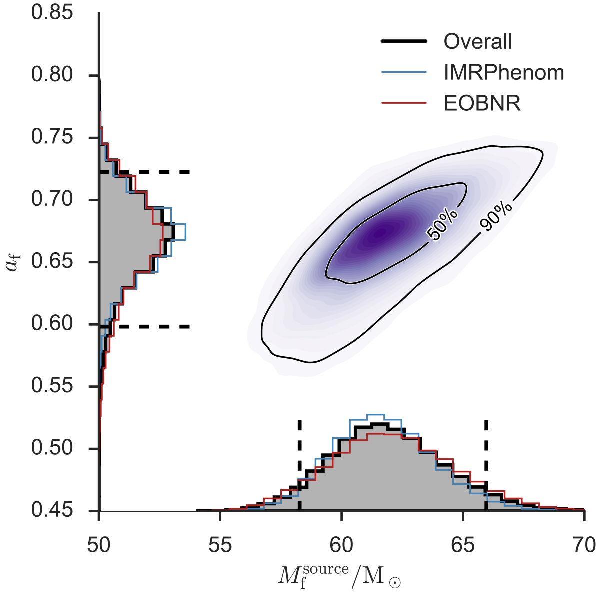
Spins



Source direction



Final Kerr properties



Other event: LVT151012

Name	Ligo-Virgo Trigger
Date	October 12, 2015
Time	9:54:43 UTC
SNR	9.6
p	$0.02 \to 2.1\sigma$
m_1	23^{+18}_{-5}
m_2	13^{+4}_{-5}
D_L	1100$\pm$500 Mpc
Source	BH-BH

(90% CL)

Graviton

From dispersion relations, LIGO places the limit:

$$\lambda_g > 10^{13}\,\mathrm{km}\,,\;\; m_g < 1.2 \times 10^{-22}\,\mathrm{eV}$$

Bounds are model independent and worse than those from model dependent galactic cluster dynamics. Described in C. Will, Phys.Rev. D57 (1998) 2061-2068.
From weak gravitational lensing, $m_g < 6 \times 10^{-32}$ eV (PDG).
Other weaker (but still stronger than LIGO) limits come from Kerr BHs, pulsars, and the solar system (PDG).

For reference, $m_\gamma < 10^{-18}$ eV (PDG).

Present + future experiments

- LIGO: two detectors in WA and LA; 10 ms apart; 4 km arms; nearly identical polarization.
- Virgo: Italian/French collaboration; near Pisa, Italy; 3 km arms; advanced Virgo to come online in late 2016.
- GEO600: near Hanover, Germany; 600 m arms; pathfinder experiment.
- KAGRA: University of Tokyo; 3 km arms; underground; expected to come online in 2018 (after initial estimate of 2009).
- INDIGO's LIGO-India: proposed.
- Einstein Telescope: 3×10 km arms - equilateral triangle; six detectors; proposed.

International Pulsar Timing Array

- Released their first results at the same time as LIGO.
- Combining data from different pulsar measurements.
- Their limits are not yet competitive.

arXiv:1602.03640

New physics probed by GWs

- NS density and EOS from NS-NS or, even better, BH-NS.
  - NS phase transitions to strange matter, free quark matter.
- A test of the PN/NR derived waveforms.
- A test of Kerr BHs ringing down in BH perturbation theory.
- Extreme mass ratios make for an extremely accurate test of BH fundamental properties.
- GWs propagating into the bulk.
- $v_{\mathrm{GWs}} \neq c$.
- Composite gravitons.
- Inflationary perturbations.
- First order phase transitions in the early universe.

arXiv:astro-ph/0110349 (2001 Snowmass)

Speed of GWs

From arXiv:1602.04188,

- From the lack of gravitational Cherenkov radiation of HE CRs,

$$c_{GW} \gtrsim 1 - 10^{-15}\,.$$

- Model dependent bounds imply,

$$c_{GW} \lesssim 1.01\,.$$

- Model independent bound from GW150914 gives the two sigma bound,

$$c_{GW} < 1.7\,.$$

First order phase transitions

arXiv:1602.04203 proposes that a $\mathcal{O}(10^7)$ GeV first order phase transition could be detectable by LIGO + Virgo.

- Two local minima + tunneling or thermal fluctuations $\Rightarrow$ first order phase transition.
- Bubble of the true vacuum accelerates due to the pressure difference, and approaches c.
- Bubble walls collide giving rise to a stochastic GW background.

Note that arXiv:1602.03901 makes a similar proposition as the above with more discussion on the nature of the phase transition as well as domain walls.

First order phase transitions (cont)

Peak f, energy density today, and amplitude:

$$f_* \approx (5.2 \times 10^{-8}\,\mathrm{Hz}) \left(\frac{\beta}{H_*}\right) \left(\frac{T_*}{1\,\mathrm{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$$

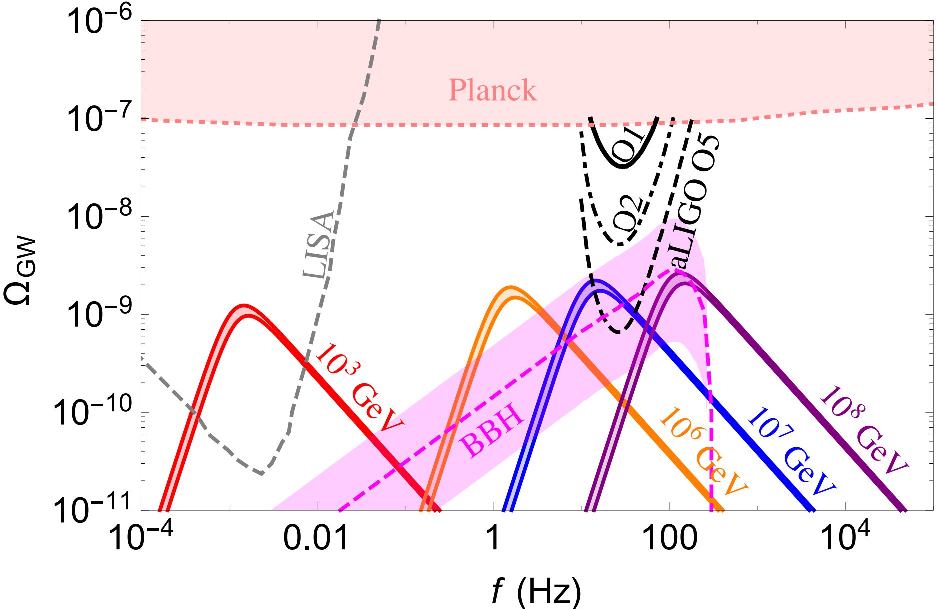
$$\Omega_{GW} h^2 \approx (1.1 \times 10^{-6}) \kappa^2 \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{v^3}{0.24 + v^3}\right) \left(\frac{H_*}{\beta}\right)^2 \left(\frac{100}{g_*}\right)^{1/3}$$

$$h(f) \approx (1.3 \times 10^{-18}) \sqrt{\Omega_{GW}(f) h^2} \left(\frac{1\,\mathrm{Hz}}{f}\right)$$

Note that the primordial GWs contribute

$$\Omega_{GW} = \frac{3}{128} r A_s \Omega_r \lesssim 2 \times 10^{-16}\,.$$

Stochastic GW background from a phase transition



First order phase transitions (BSM)

$$V(\phi,\chi)=\frac{1}{4!}g^2(\phi^2-v_*^2)^2+\frac{1}{2}h\phi^2\chi^2$$

First order phase transition occurs for $h\sim\mathcal{O}(1)$.

$$\sqrt{\frac{2g}{h}}v_*=T_*\sim10^7\,\mathrm{GeV}$$

gives a signal in LIGO's range.

PQ axion:

- $f_a\sim T_*\sim v_*\sim10^7-10^8$ GeV gives an observable signal and isn't ruled out.
- Domain wall problem can be avoided.

First order phase transitions (SUSY inspired)

- High scale SUSY breaking, $\langle S \rangle \sim 10^7 - 10^8$ GeV can still give $\mu \sim 1$ TeV.
- Alternatively split SUSY provides a high scale, that could be in the $10^7 - 10^8$ range.

GWs from walking

gr-qc/9810016

- Kip Thorne, et al (his wife) wrote on GWs from walking, slamming a door, punching a wall, and stopping a car.
- Estimates that one person at 10 m contributes $h \sim 10^{-23}$.
- $h \propto \sqrt{N}$ where N is the number of people walking incoherently.
- Has fun footnotes such as,

  > *Beware: Biokinesiologists (influenced by the Biomechanics literature) use different axis conventions from physicists: y and z are interchanged so their y is vertical and z is medial.*

- Was cited in a 2010 LIGO report on noise in the 10-40 Hz range. 10.1088/0264-9381/27/8/084006

Hulse-Taylor binary: PSR B1913+16 → 1993 Nobel Prize