LIGO First Highlights
Gravitational Waves detected from Binary Black Hole Coalescence

Ofek Birnholtz
for LIGO-VIRGO Scientific Collaboration

February 15, 2016
Israeli National Astronomy Day
at Hebrew University of Jerusalem

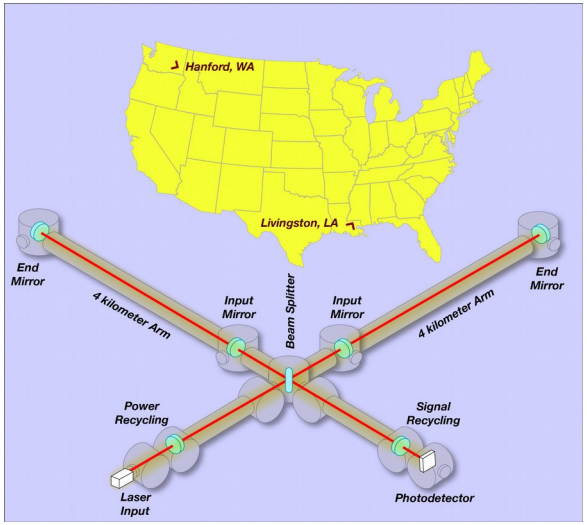
LIGO-G1600167

Who we are

- ~1000 scientists in LVC, >90 institutions
- 2 active Advanced detectors (H1, L1)
- 2 more detectors (VIRGO, GEO600)

Who we are

- ~1000 scientists in LVC, >90 institutions
- 2 active Advanced detectors (H1, L1)
- 2 more detectors (VIRGO, GEO600)

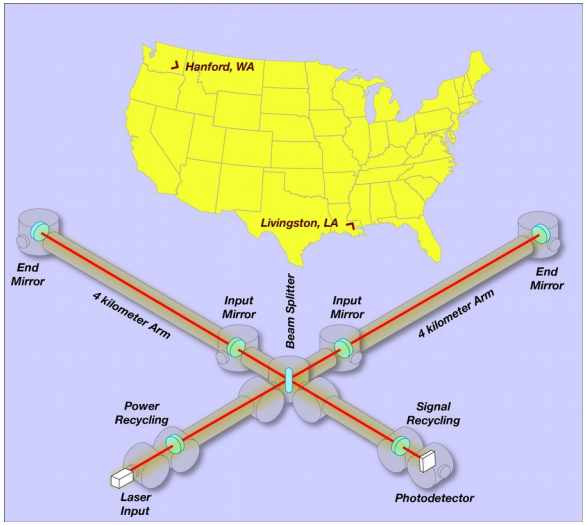


Who we are

- ~1000 scientists in LVC, >90 institutions
- 2 active Advanced detectors (H1, L1)
- 2 more detectors (VIRGO, GEO600)

What we've done

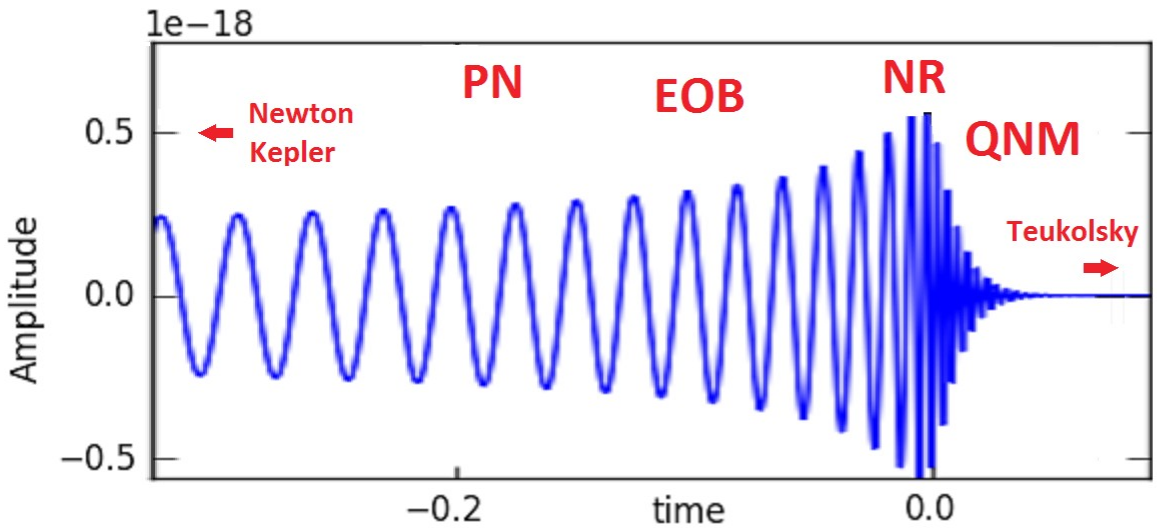
- Observation time analyzed 12.9-20.10
  - of which ~16days net data
- Found 2 significant triggers:
  - GW150914 – 1st BBH Gravitational Wave @5.1 б
  - LVT151012 – LIGO-VIRGO Trigger BBH @2.1 б
- Full O1 until 01/2016; yet to be analyzed
- Issued 3 EM triggers, and 12 papers

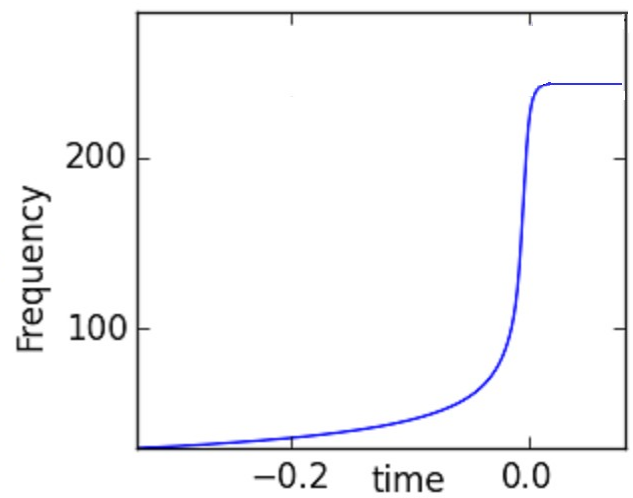


How it's done

- Interferometers & Actuators => Strain h(t)
- Frequency band-passing, noise-whitening
- Matched filtering against templates

What's in a template?





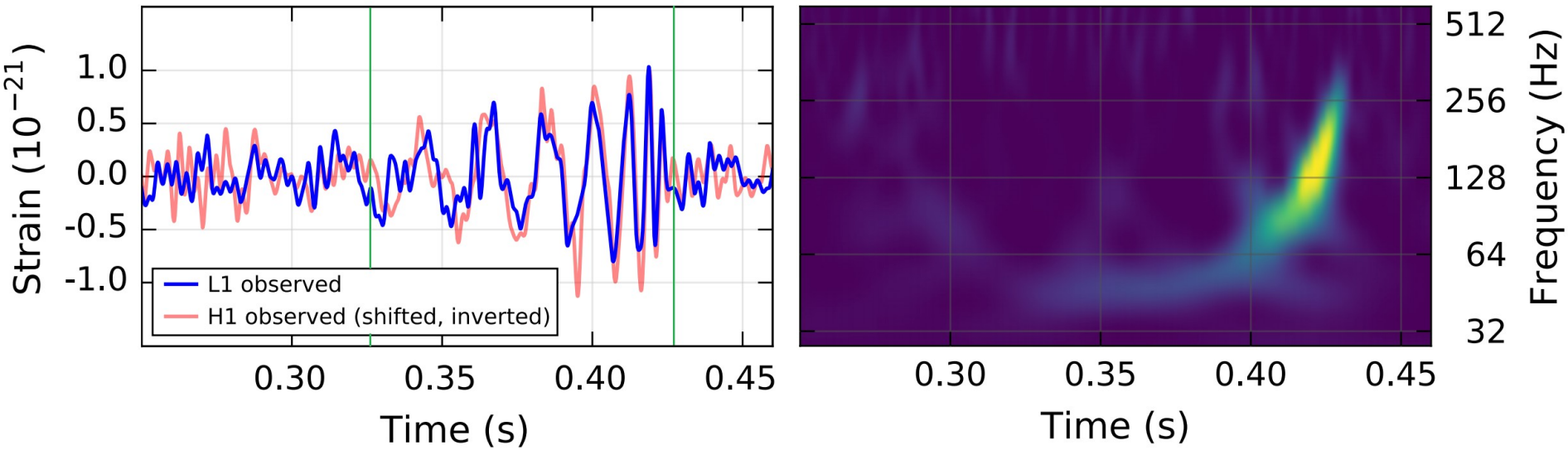
- Not even shown: EMRI, Spins, Phenomenological fits, more...

What can we learn about the event even **without** templates?

We can tell it's two coalescing Black Holes!

What we measured

From Detection Paper (Figure 1):



- Rise of Amplitude => not a single perturbed object dampening down

- Rise of Frequency => inspiral (Kepler's Law)

- End of Rise f(t),h(t) => single remnant, settling down

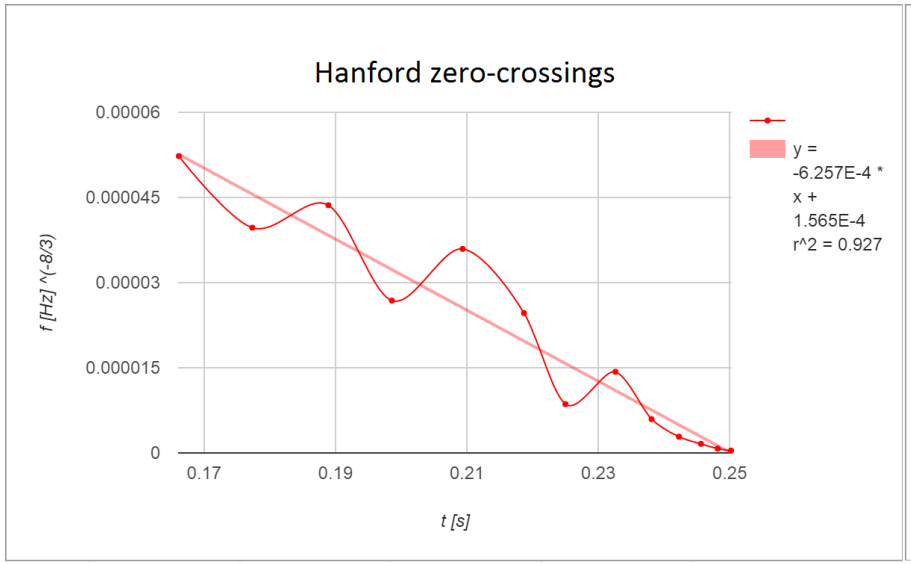
Chirp Mass from zero-crossings

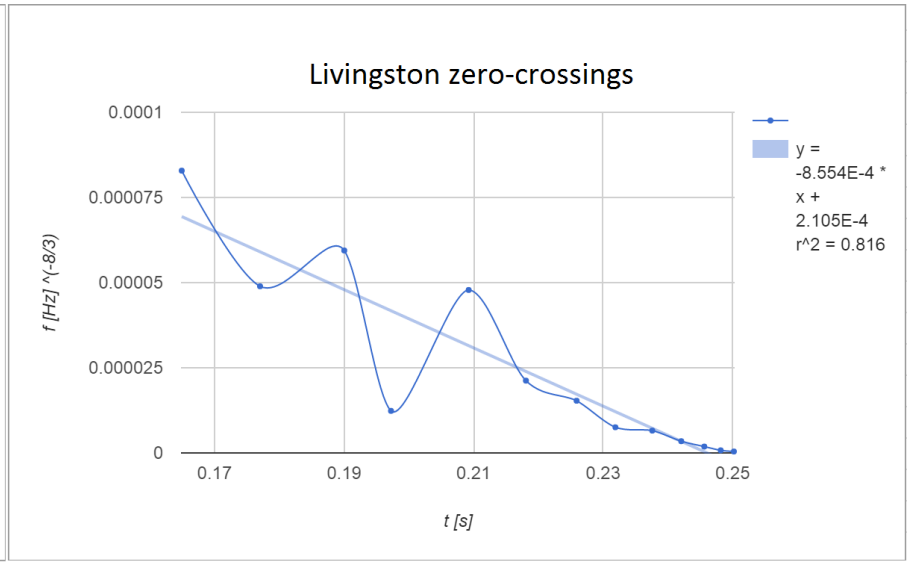
$t-t_0$ [s]	Hanford		$t-t_0$ [s]	Livingston	
0.153	Period	f [Hz]	0.150	Period	f [Hz]
0.166	0.024	40.3	0.164	0.029	33.93
0.177	0.022	44.7	0.177	0.024	41.34
0.188	0.023	43.1	0.190	0.026	38.43
0.198	0.019	51.7	0.197	0.014	69.29
0.209	0.021	46.4	0.209	0.023	41.69
0.218	0.018	53.4	0.218	0.017	56.55
0.225	0.012	79.3	0.225	0.01	63.89
0.232	0.015	65.6	0.231	0.011	83.38
0.238	0.010	91.1	0.237	0.011	87.85
0.242	0.0083	120	0.242	0.0089	111.8
0.245	0.0067	149.0	0.245	0.0071	140.5
0.248	0.0050	196.8	0.248	0.0050	196.8
0.250	0.004	246	0.250	0.004	246

$$M_c = \frac{c^3}{G}\left((5/96)^3 \pi^{-8} f^{-11} \dot{f}^3\right)^{1/5}$$

$$f^{-8/3}(t) = -\frac{(8\pi)^{8/3}}{5}\left(\frac{G\,M_c}{c^3}\right)^{5/3}(t-t_0)$$

$$\Rightarrow \quad M_c \cong 30\,\mathrm{M}_\odot$$





The simplest case

- Equal Mass

$$m_1 = m_2 = 2^{1/5} M_c = 35\,\mathrm{M}_\odot$$

$$M = m_1 + m_2 = 70\,\mathrm{M}_\odot$$

- Circular Orbit (Kepler's Law)

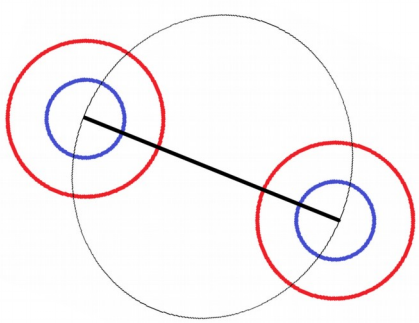
$$\omega_{\mathrm{Kepler-max}} = 2\pi f_{\mathrm{GW-max}}/2 = 2\pi \times 75\ \mathrm{Hz}$$

effective separation

$$R = \left[\frac{GM}{\omega^2_{\mathrm{Kepler-max}}}\right]^{1/3} = 350\ \mathrm{km}$$

- No spin

$$r_{\mathrm{Schwarz}}(M) = \frac{2GM}{c^2} = 200\mathrm{km}$$



$$\text{compactness ratio } \mathcal{R} = 350\mathrm{km}/200\mathrm{km} \sim 1.75$$

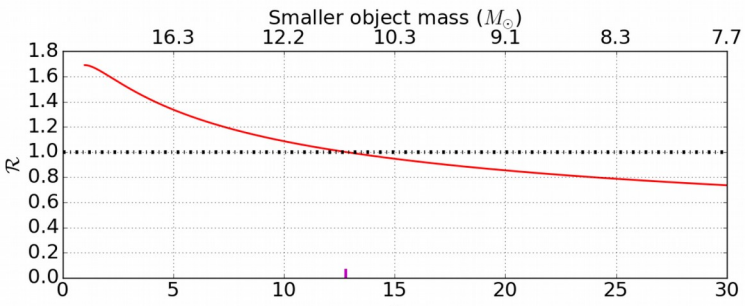
Compact + Heavy => Black Holes

Relaxing the assumptions

- Eccentric orbits: *tighter*: semi-minor axis shrinks,

  semi-major axis independent of e

- Unequal masses: *tighter:*



$$M = m_1 + m_2 = M_c(1+q)^{6/5}q^{-3/5}$$

$$\mathcal{R} = \frac{R}{r_{\mathrm{Schwarz}}(M)} = \frac{c^2}{(2\pi f_{\mathrm{GW-max}} G M_c)^{2/3}}(1+q)^{-4/5}q^{2/5}$$

- Spin: at most, for extremal spin: factor x2
- Kepler's Law?

  Breaks when $v^2/c^2 \sim GM/Rc^2$ large - i.e. a compact orbit!

What if M_c formula itself is wrong?

- This *could* happen if both mass ratio and spin are large
- This is Extreme Mass Ratio (EMR) scenario:
  - GW frequency given by corrected Kepler

$$\omega_{orb} = \frac{\sqrt{GM}}{r^{3/2} + \chi \left(\sqrt{GM}/c\right)^3}$$

  - Highest frequency from around Light Ring (LR)

$$r_{LR} = \frac{2\,G\,M}{c^2}\left(1 + \cos\left(\frac{2}{3}\cos^{-1}(-\chi)\right)\right)$$

=> expected f_{max}~70 Hz, we have f_{max}~250 Hz

=> ruled out

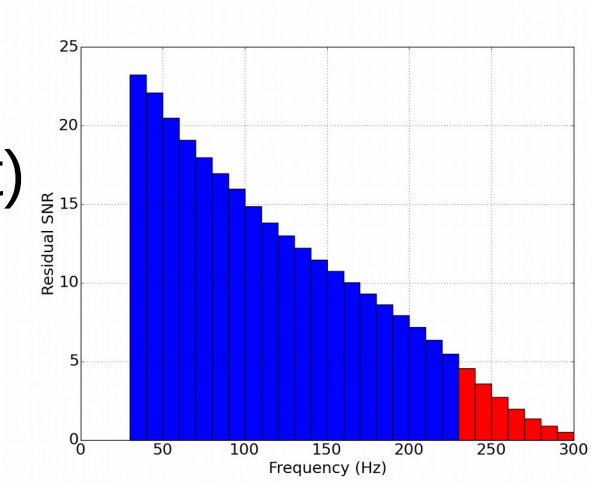
Final remnant – What can it be?

- Compact (~few $R_{Schwarz}$) + heavy (~60 M_{sun})

  => density $\gtrsim 10^{14}$ kg/m^3:
  - 10^5 denser than White Dwarves
  - 10^3 *less* dense than Neutron Stars
- 20 times heavier than any observed or theorized NS

  => Only possible known object – Black Hole

- BH expected to "ringdown" at f~f(LR)
  - For q~1: f~125-500 Hz (spin-dependent)
  - We clearly see final f ~ 250 Hz
  - But we would like more SNR for
    - more modes, longer RD => Kerr!



What lies ahead?

- More data to analyze
- Improvements expected for O2 (summer '16), O3 ('17)
- More detectors
- Coherent searches, more polarizations
- More CBC physics:
  - Still looking for Neutron Stars
  - Precessing systems
  - Ringdown analyses
- Other sources: Continuous Waves, Bursts
- And most importanly: Unknown Unknowns!