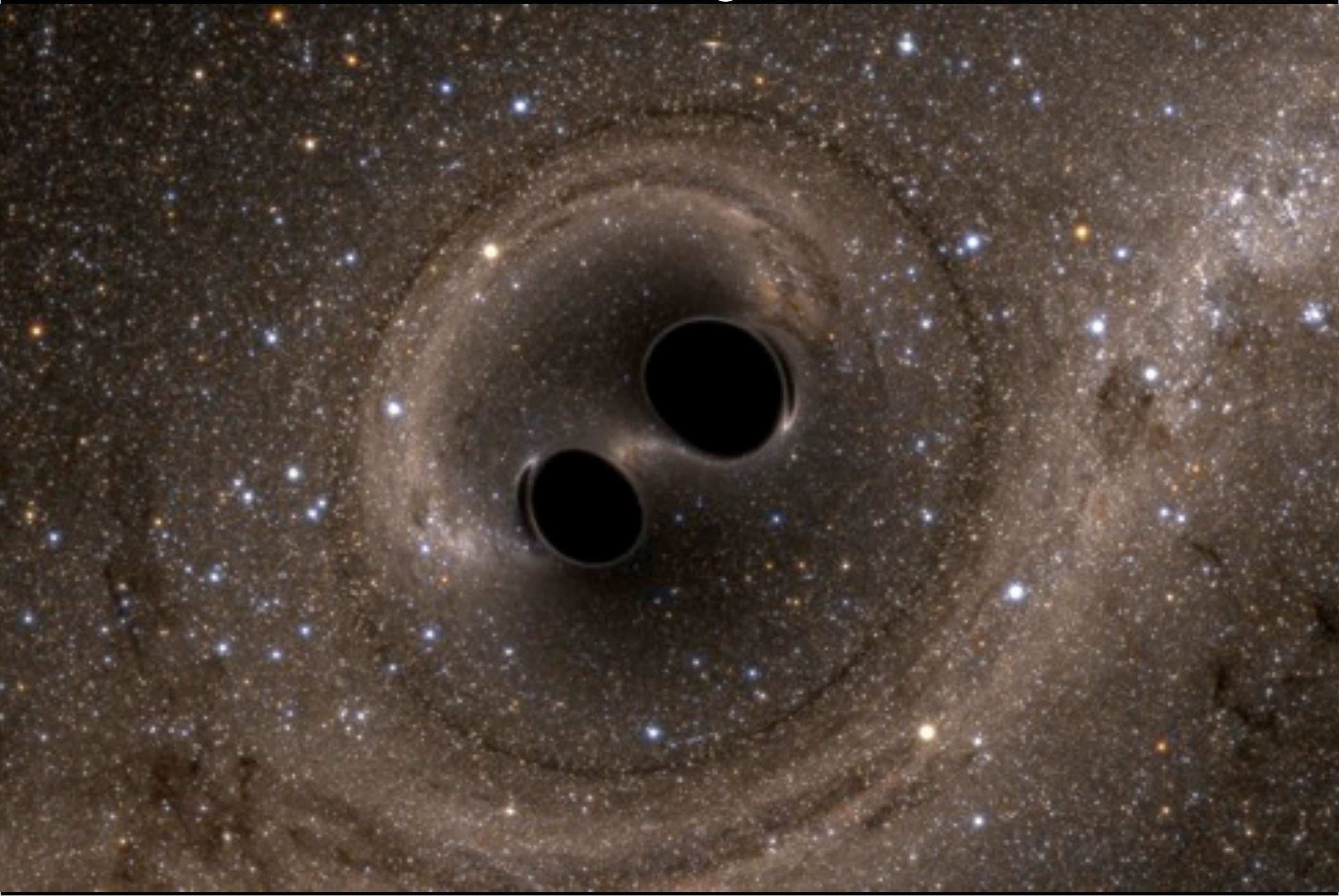
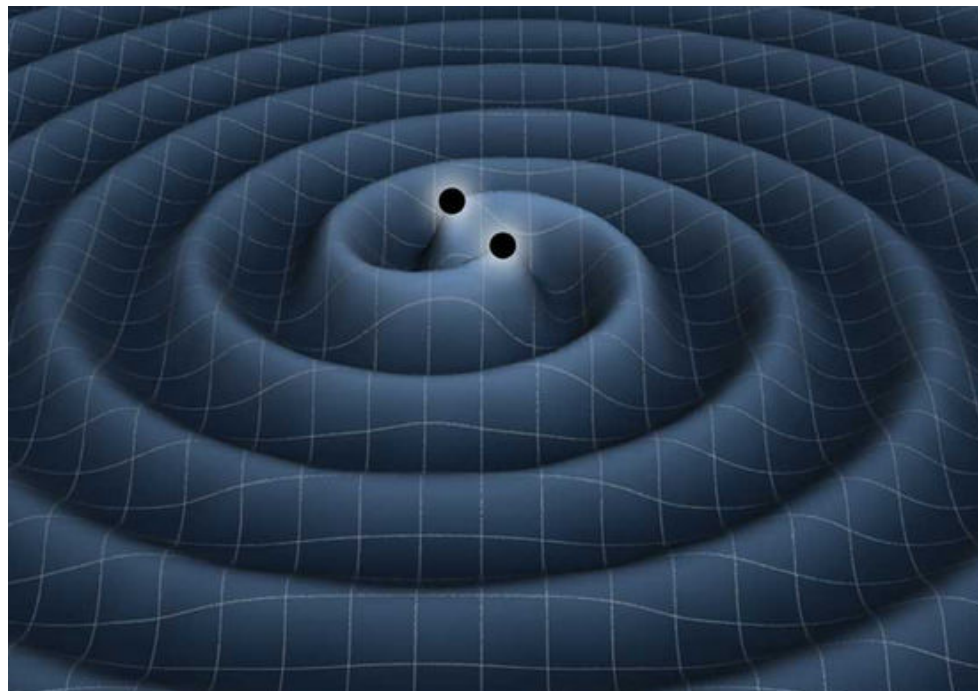
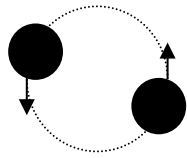


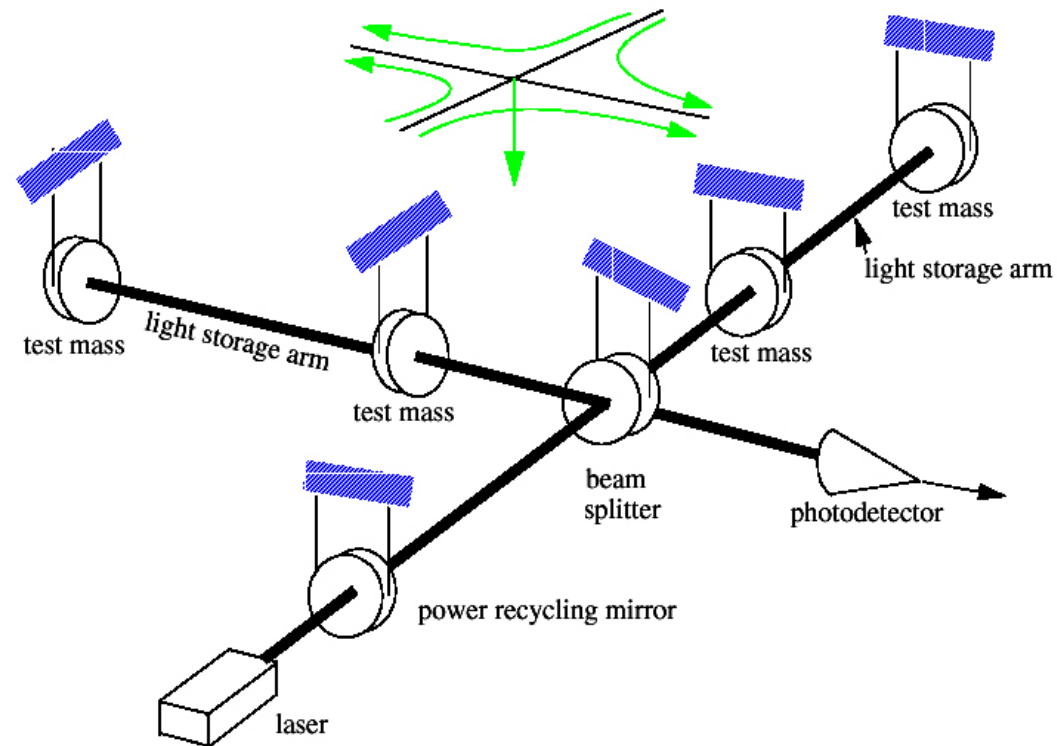
Gravitational Waves from Binary Black Hole Mergers



Binary black hole system



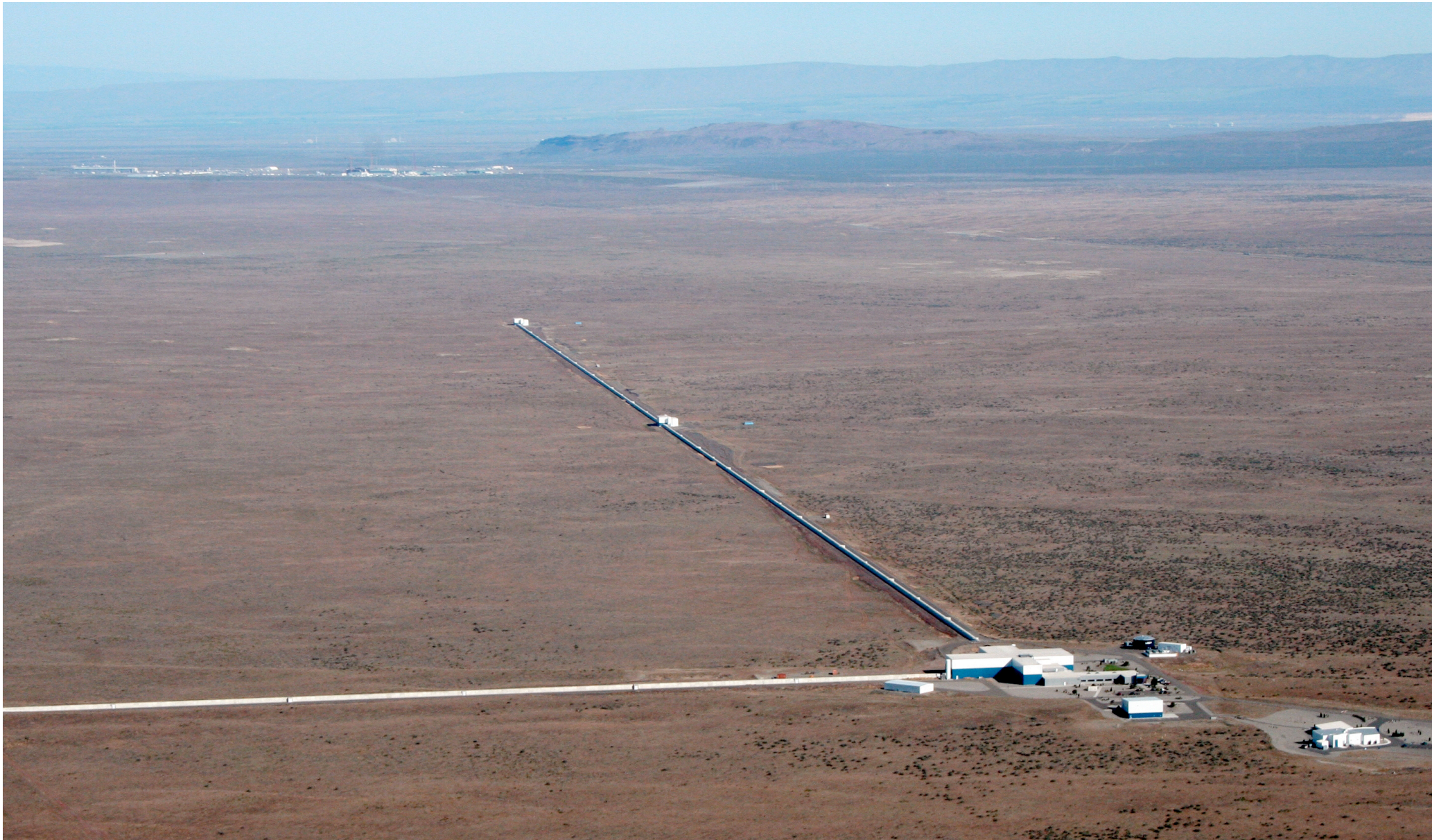
As detected by LIGO:

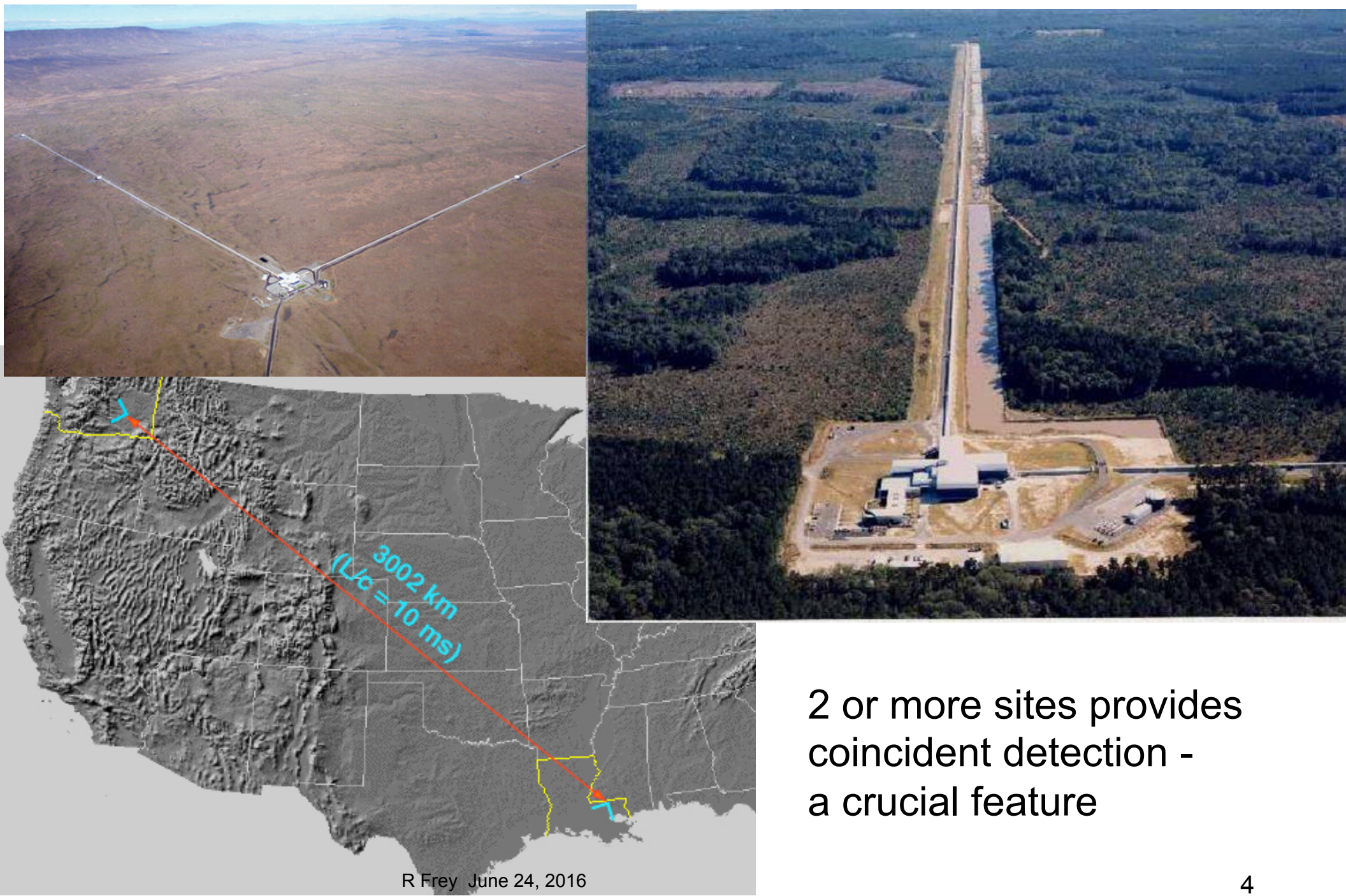


GW ripples are a space strain h ,
where $h = \Delta L / L$

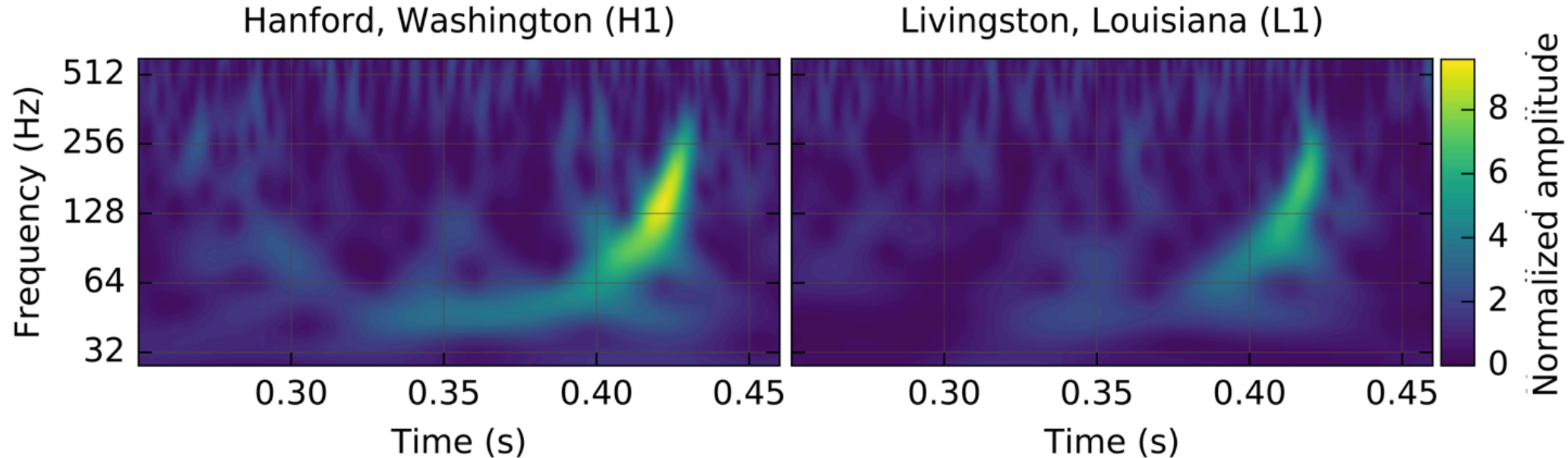
Realistic sources: $h \sim 10^{-23}$

$\Rightarrow \Delta L \sim 10^{-19} \text{ m}$ (Yikes !)

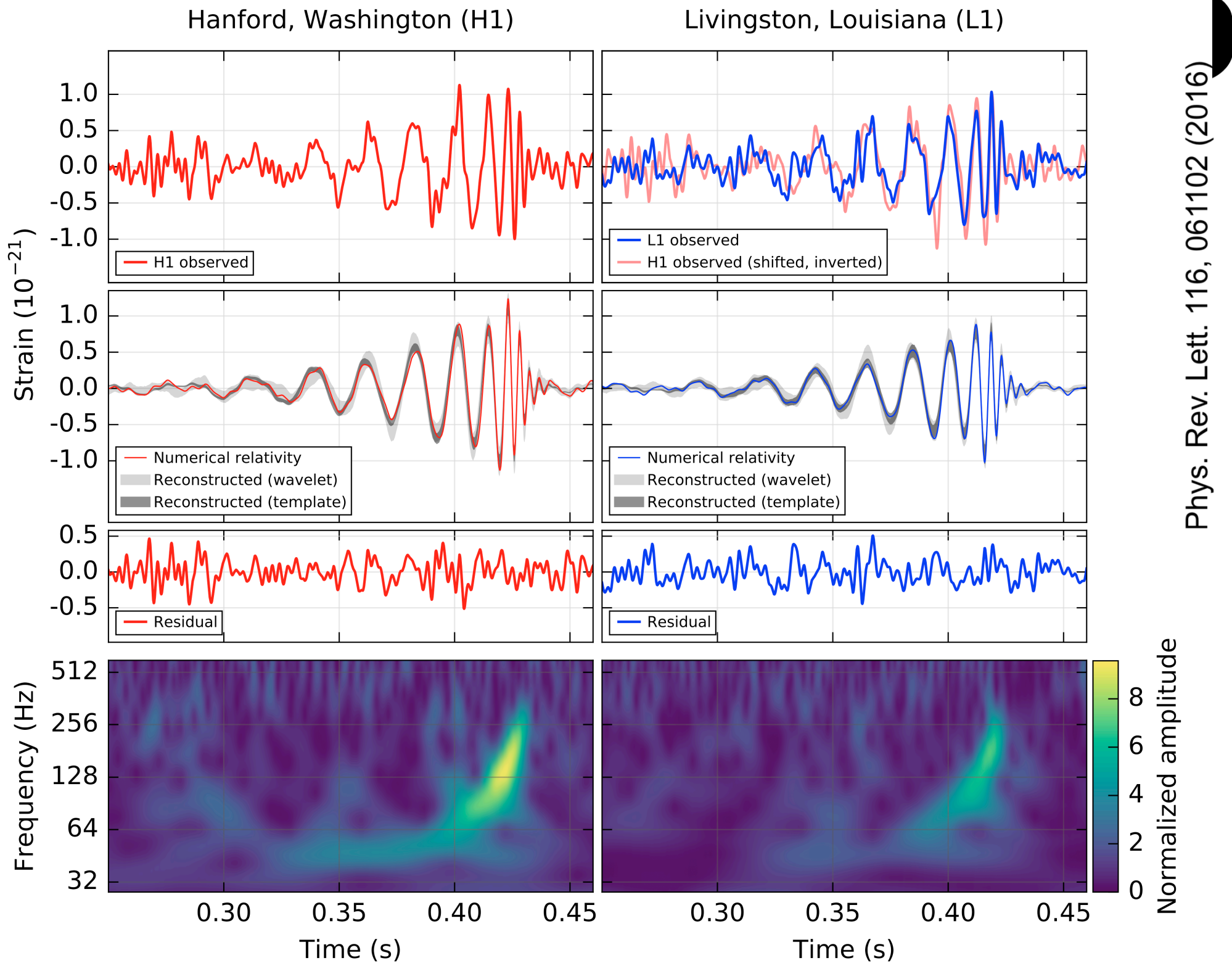


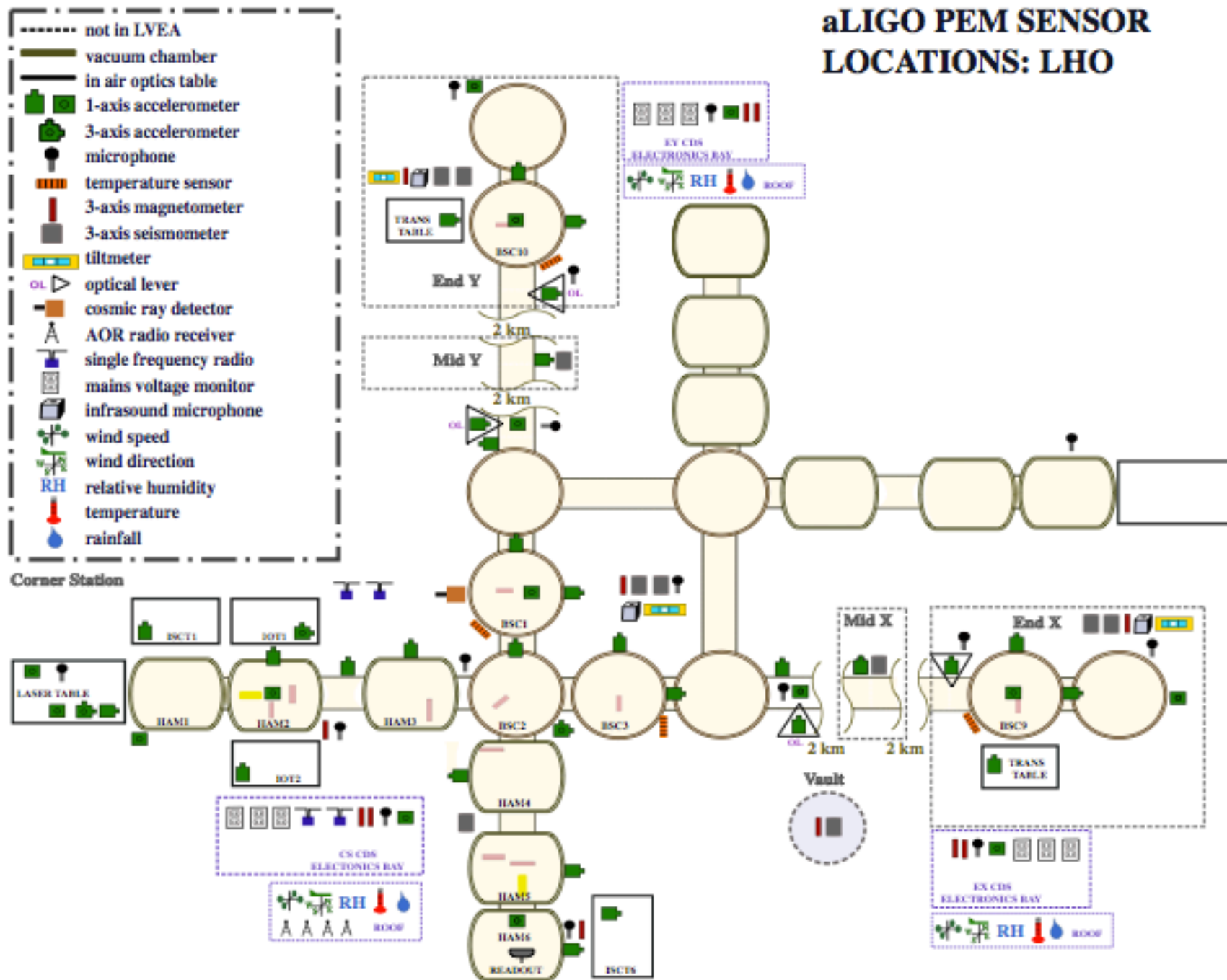


Boom !



Phys. Rev. Lett. 116, 061102 (2016)





Installing sensors

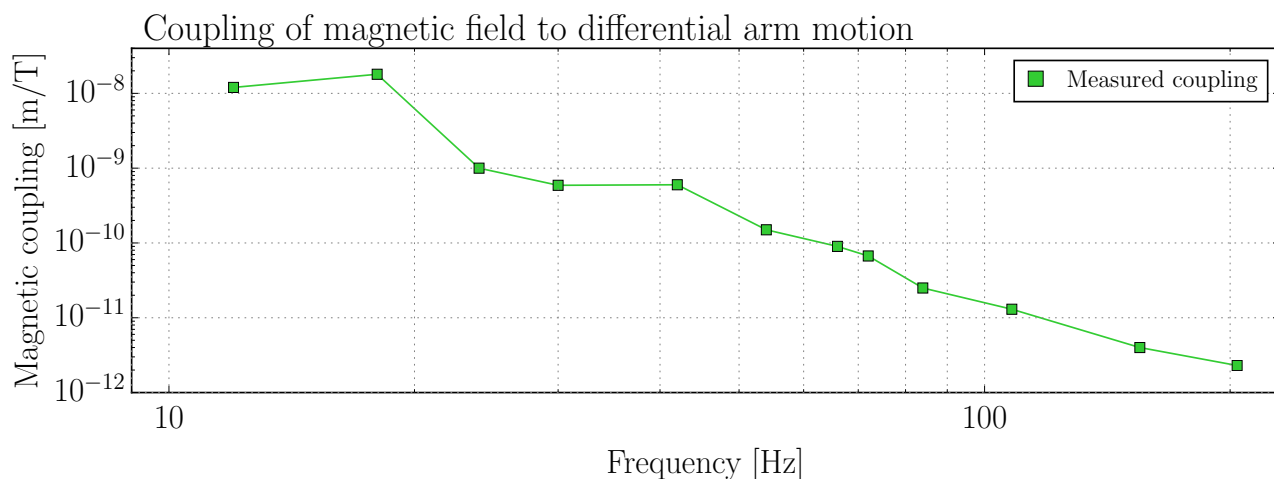
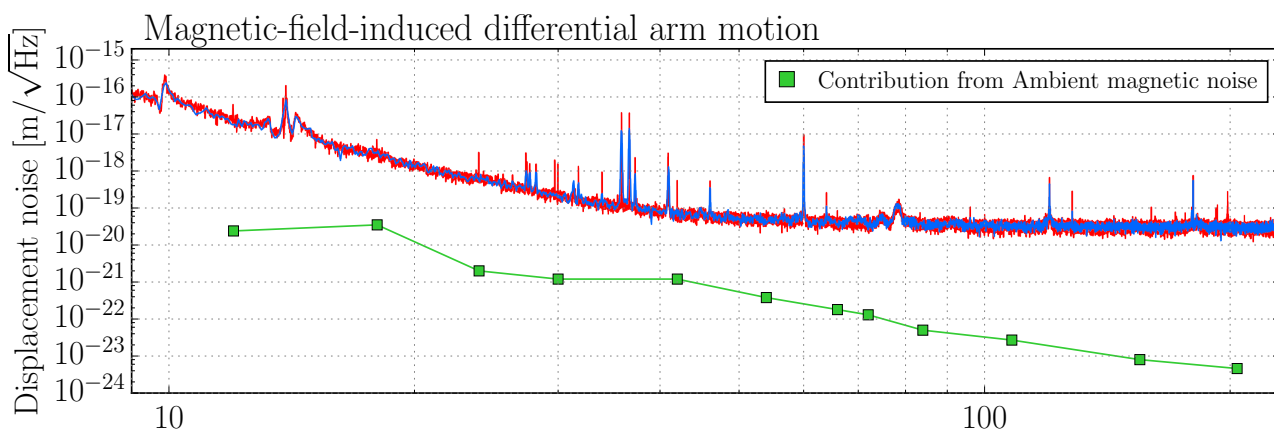
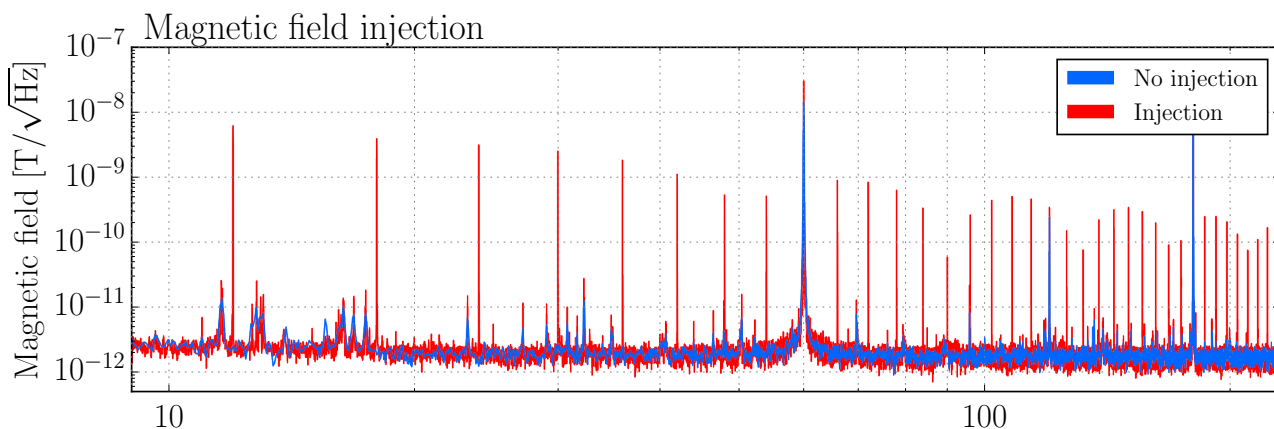


Terra and Vinny install accelerometers on PSL table

Is it really an astrophysical signal?

Coincident environmental noise?

arXiv:1602.03844

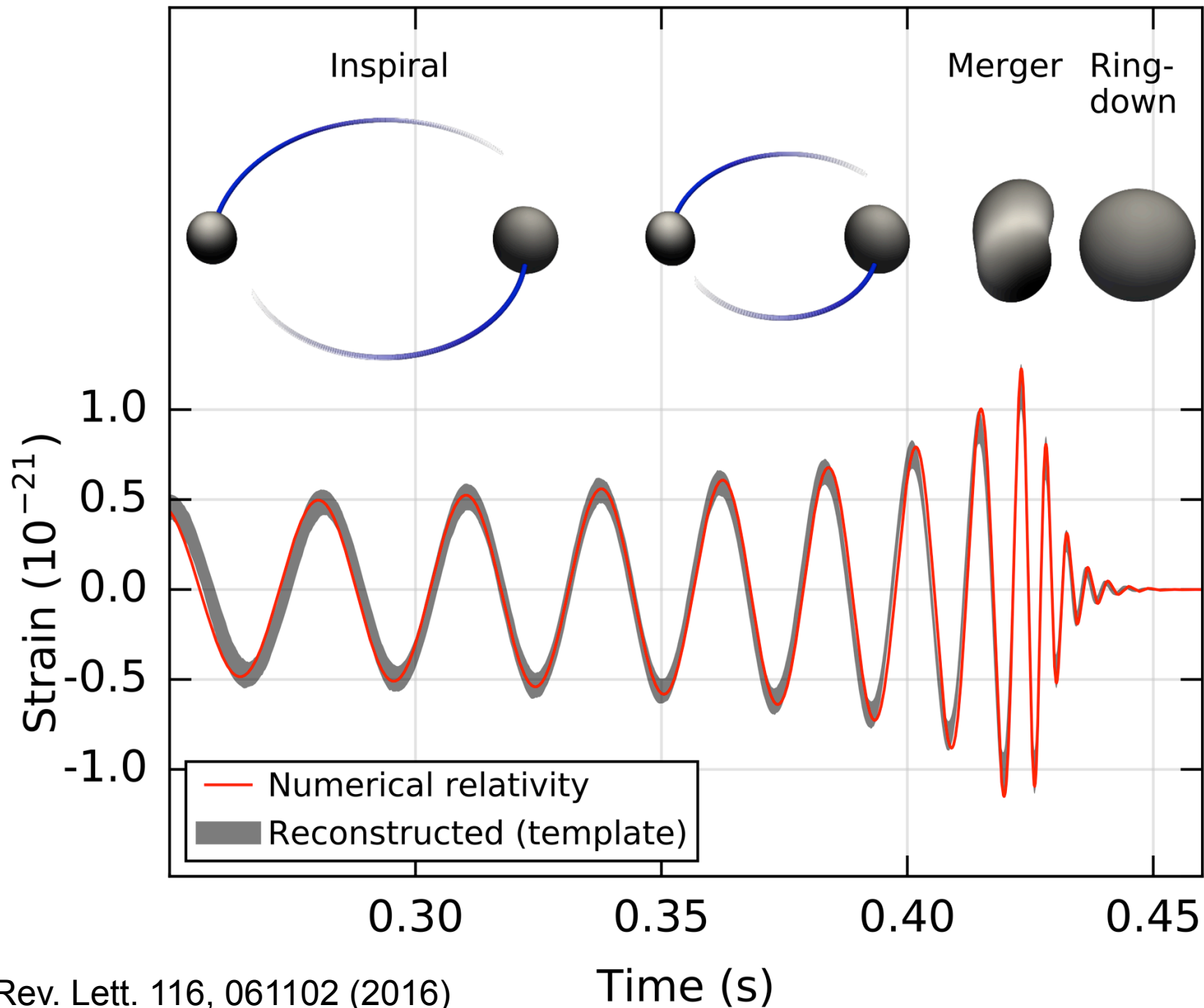


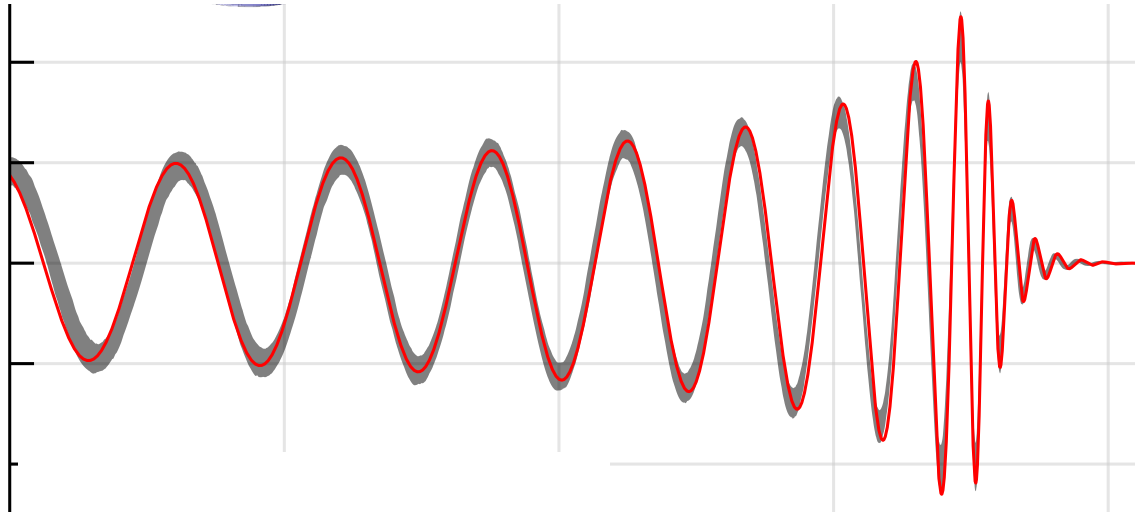
- GW waveform precludes known environmental disturbance.
- Would see a much larger environmental signal on nearby sensors than seen in GW detector.
- Saw nothing.



- **Discovery paper:** Phys. Rev. Lett. 116, 061102 (2016)
- Astrophysical implications: ApJL, 818, L22, 2016
- Tests of General Relativity: arXiv:1602.03841
- Rate of BBH mergers: arXiv:1602.03842
- Parameter estimation: arXiv:1602.03840
- Data characterization: arXiv:1602.03844
- Detector status: arXiv:1602.03838
- Compact binary searches: arXiv:1602.03839
- Searches with minimal assumptions: arXiv:1602.03843
- Calibration: arXiv:1602.03845
- Implication for a stochastic GW background: arXiv:1602.03847
- High-energy neutrinos: arXiv:1602.05411

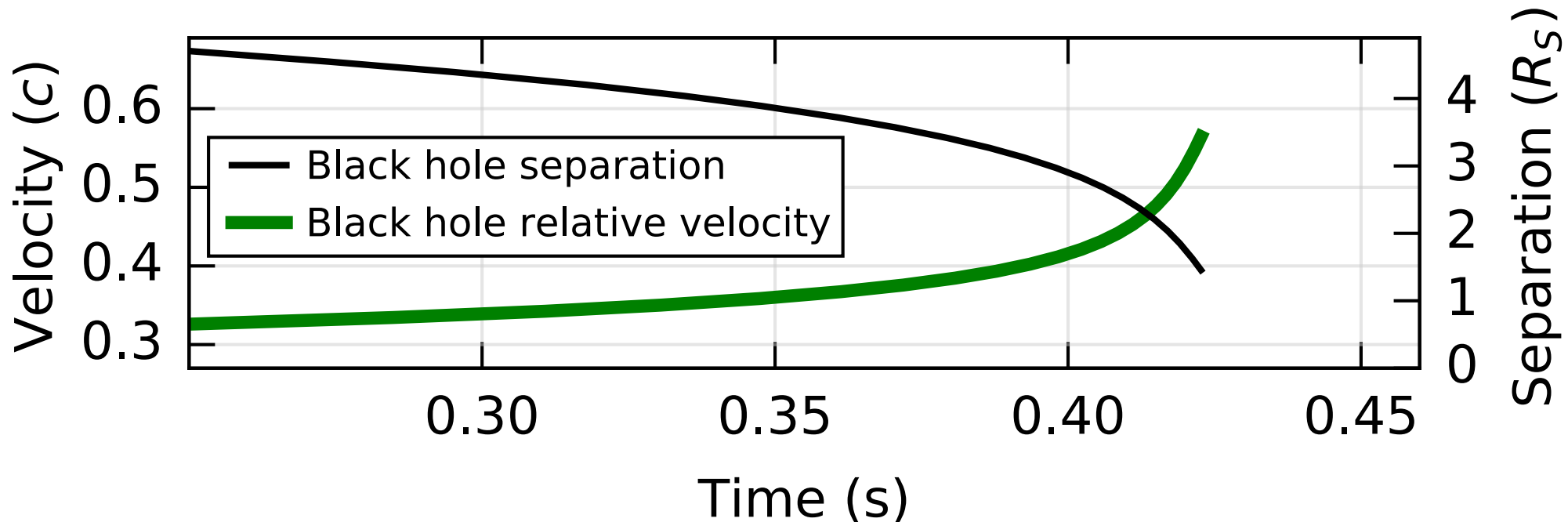
Is it really a merger of black holes ?





- The chirp function tells us we have 2 objects each of mass about 30 solar masses ($30M_{\odot}$)
- At merger, they are orbiting each other 75 times per second and their separation is about 350 km... *And they are still missing each other!*
- They are indeed black holes.

- Predicts gravitational waves... ☒
- Waveforms from GR fit the data beautifully... ☒



A unique and important test of GR

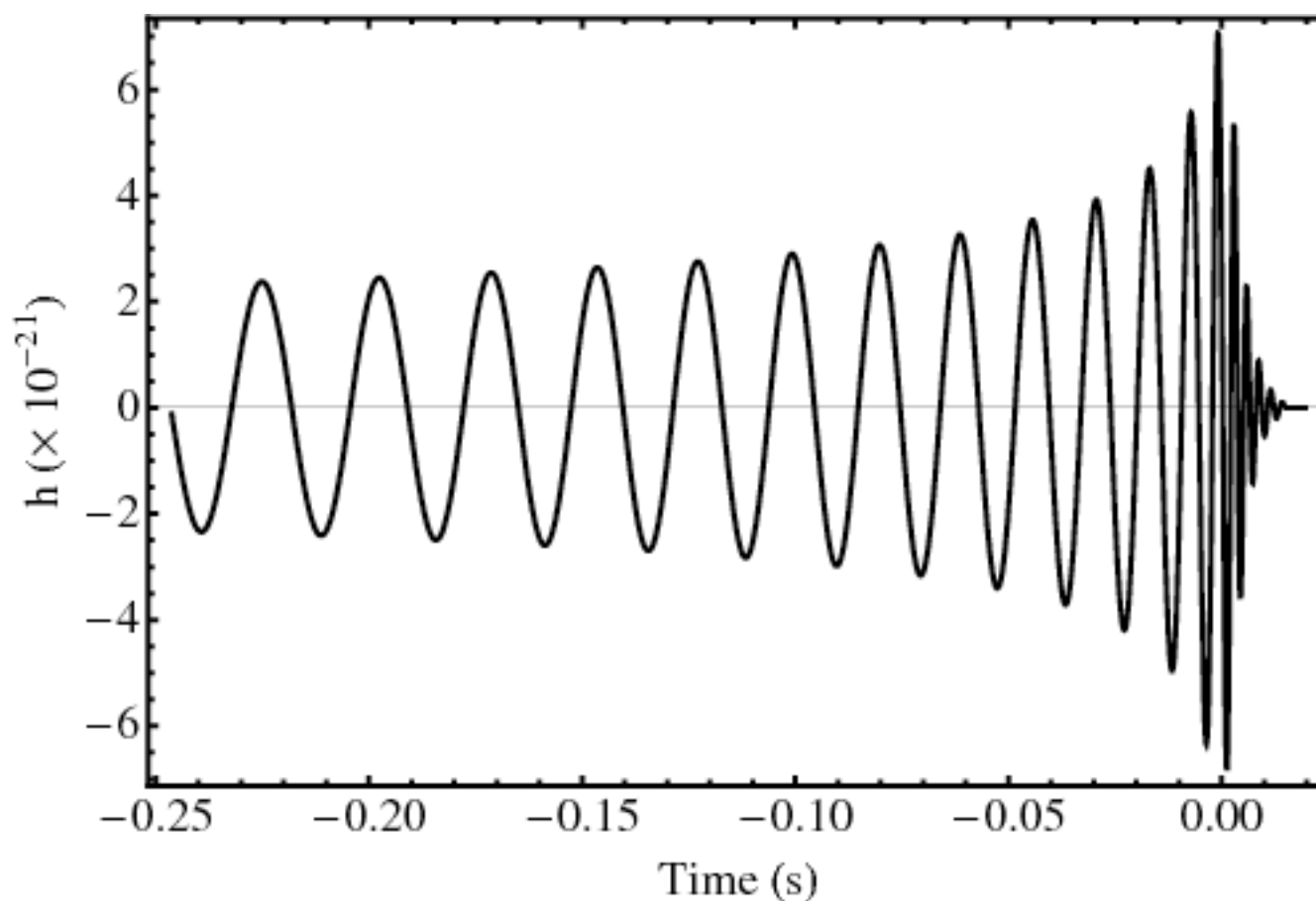
Primary black hole mass	$36^{+5}_{-4} M_{\odot}$
Secondary black hole mass	$29^{+4}_{-4} M_{\odot}$
Final black hole mass	$62^{+4}_{-4} M_{\odot}$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180} \text{ Mpc}$
Source redshift, z	$0.09^{+0.03}_{-0.04}$

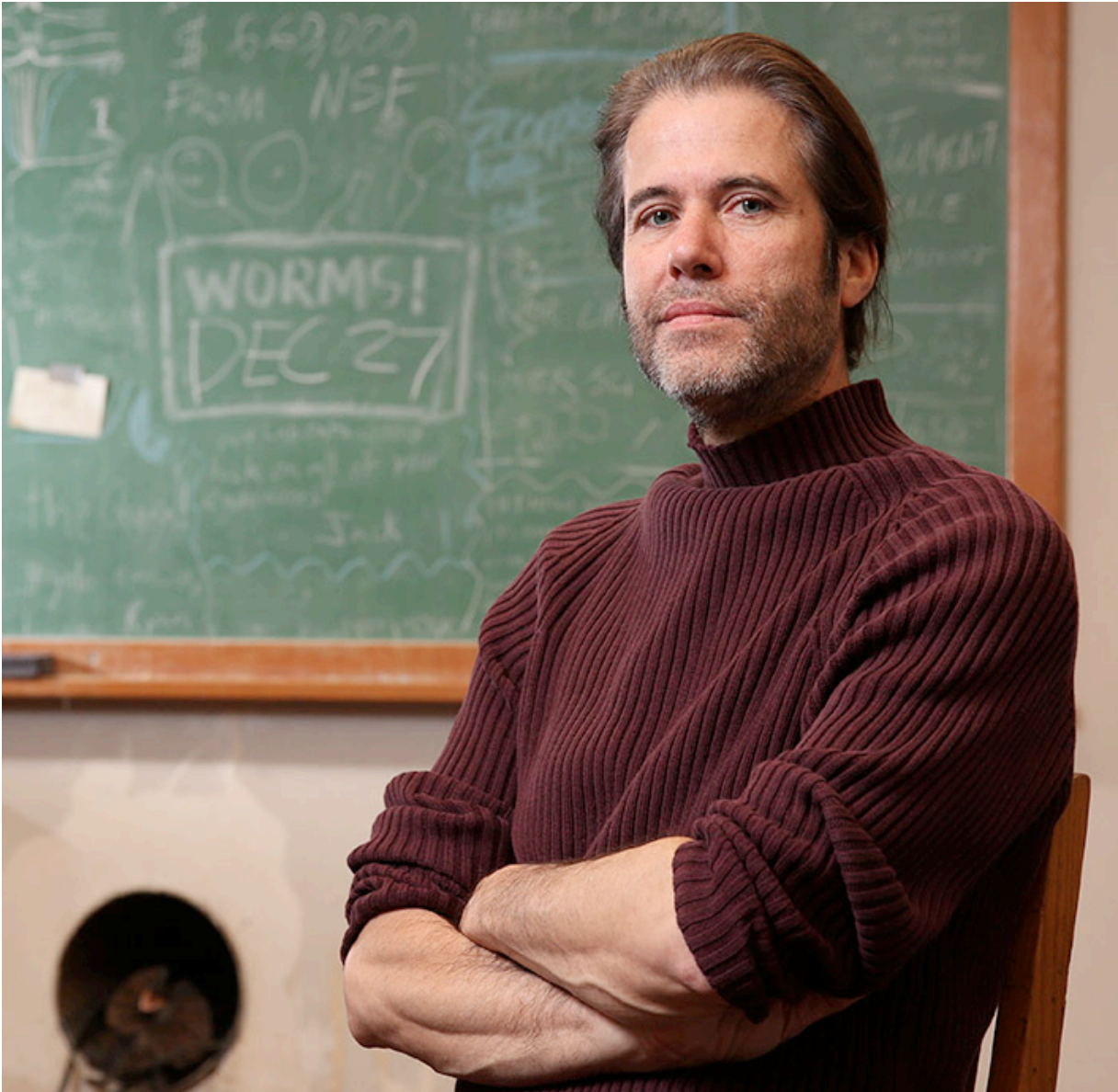
- Energy radiated in GWs: $3.0^{+0.5}_{-0.5} M_{\odot} c^2$
- Peak GW power: $3.6^{+0.5}_{-0.4} \times 10^{56} \text{ erg/s}$

	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/M_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm 0.9}_{-4.5\pm 1.0}$
Detector-frame chirp mass $\mathcal{M}/M_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm 0.4}_{-1.9\pm 0.4}$
Detector-frame primary mass $m_1/M_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm 0.9}_{-4.1\pm 0.3}$
Detector-frame secondary mass $m_2/M_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm 0.1}_{-4.9\pm 0.6}$
Detector-frame final mass $M_f/M_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm 0.8}_{-4.0\pm 0.9}$
Source-frame total mass $M^{\text{source}}/M_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm 1.0}_{-3.9\pm 0.5}$
Source-frame chirp mass $\mathcal{M}^{\text{source}}/M_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm 0.4}_{-1.7\pm 0.2}$
Source-frame primary mass $m_1^{\text{source}}/M_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm 1.1}_{-3.8\pm 0.0}$
Source-frame secondary mass $m_2^{\text{source}}/M_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm 0.2}_{-4.4\pm 0.5}$
Source-frame final mass $M_f^{\text{source}}/M_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm 0.9}_{-3.5\pm 0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm 0.01}_{-0.21\pm 0.03}$
Effective inspiral spin parameter χ_{eff}	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm 0.01}_{-0.18\pm 0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm 0.04}_{-0.28\pm 0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm 0.07}_{-0.42\pm 0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm 0.00}_{-0.07\pm 0.03}$
Luminosity distance D_L/Mpc	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm 20}_{-180\pm 40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm 0.004}_{-0.038\pm 0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_{\text{s/n}}$	288.7 ± 0.2	290.1 ± 0.2	—

- GW150914 was the first observation of gravitational waves
- GW150914 was the first direct observation of a black hole
- Prior to GW150914, the astrophysical consensus was that there should not be $\sim 30 M_{\odot}$ black holes – more on this later

Simulated (ideal) binary black hole system, $D \sim 100$ Mpc ,
 $30 M_{\odot} + 30 M_{\odot}$





Robert Schofield, UO Research Professor

04:32 AM, Sep 14, 2015
LIGO Livingston (Louisiana)

Robert Schofield leaves the site with one last test undone. The test would likely have taken the detector out of operation.

GW150914 arrives 18 minutes later.



GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

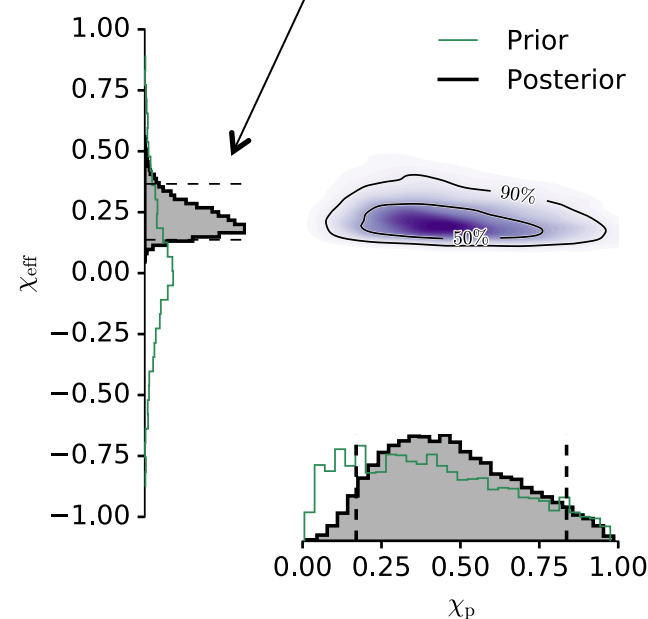
(Received 31 May 2016; published 15 June 2016)

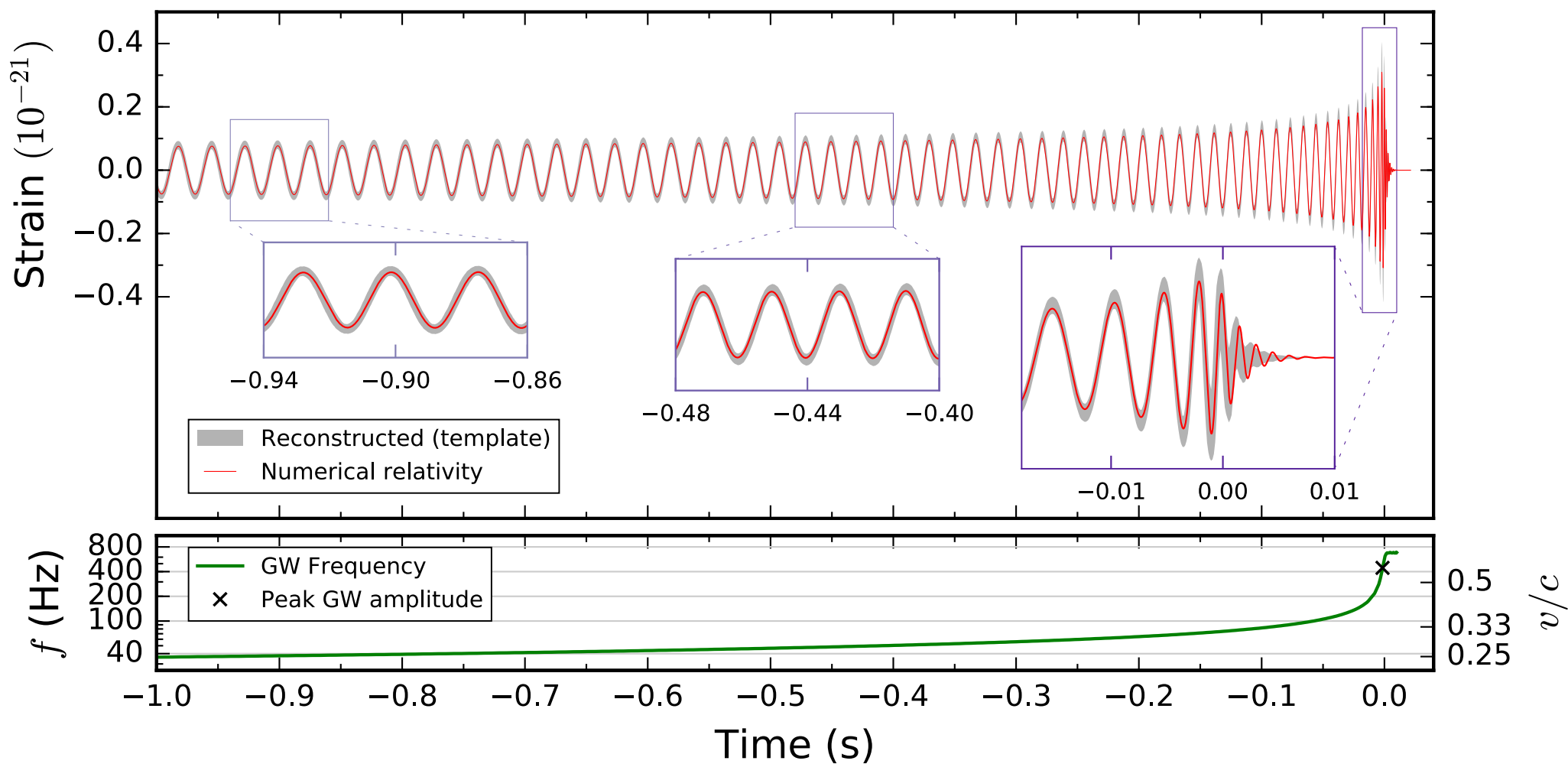
We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ . The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4_{-0.9}^{+0.7} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2_{-3.7}^{+8.3} M_{\odot}$ and $7.5_{-2.3}^{+2.3} M_{\odot}$, and the final black hole mass is $20.8_{-1.7}^{+6.1} M_{\odot}$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440_{-190}^{+180} Mpc corresponding to a redshift of $0.09_{-0.04}^{+0.03}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

Primary black hole mass	$14.2^{+8.3}_{-3.7} M_{\odot}$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_{\odot}$
Chirp mass	$8.9^{+0.3}_{-0.3} M_{\odot}$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_{\odot}$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_{\odot}$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_{\odot} c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56} \text{ erg/s}$
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	$440^{+180}_{-190} \text{ Mpc}$
Source redshift z	$0.09^{+0.03}_{-0.04}$

← Lighter masses

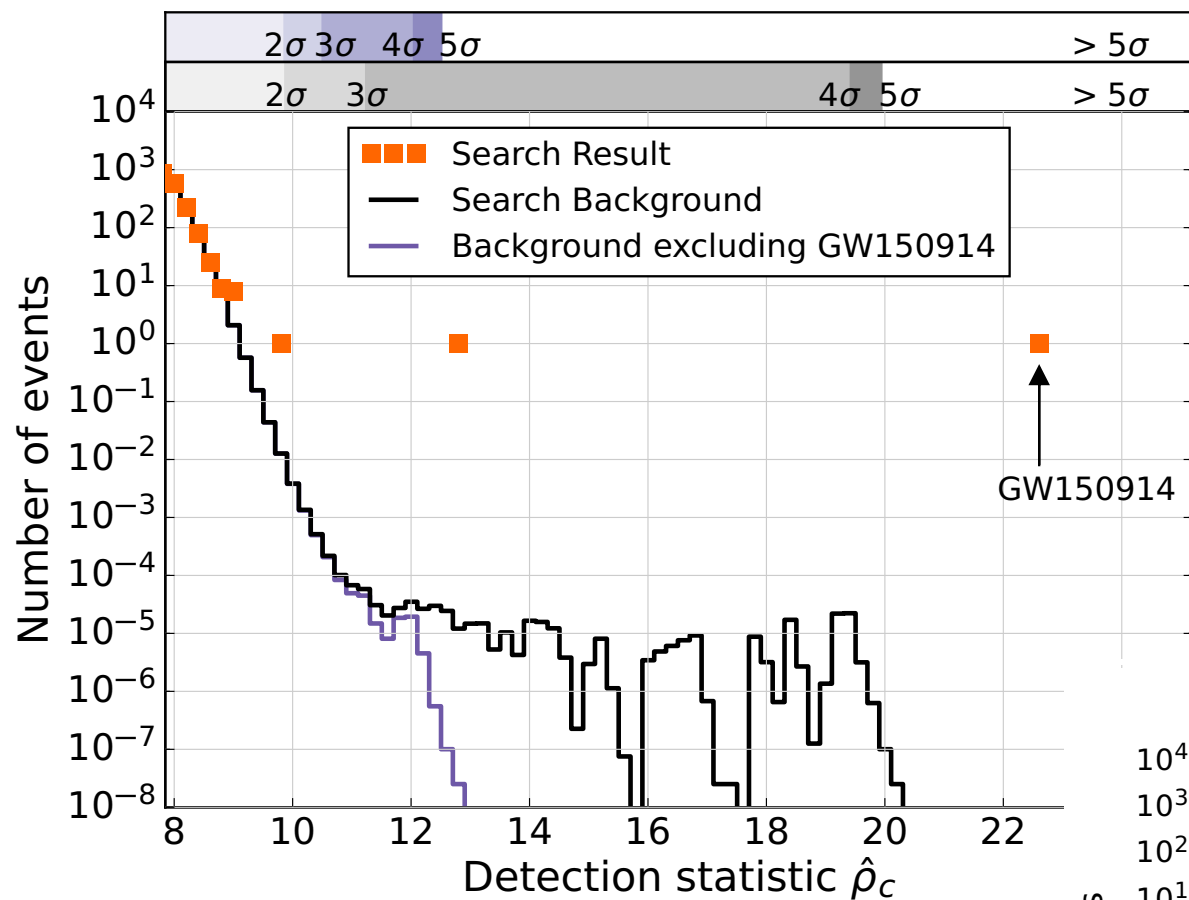
Non-zero
initial BH spin



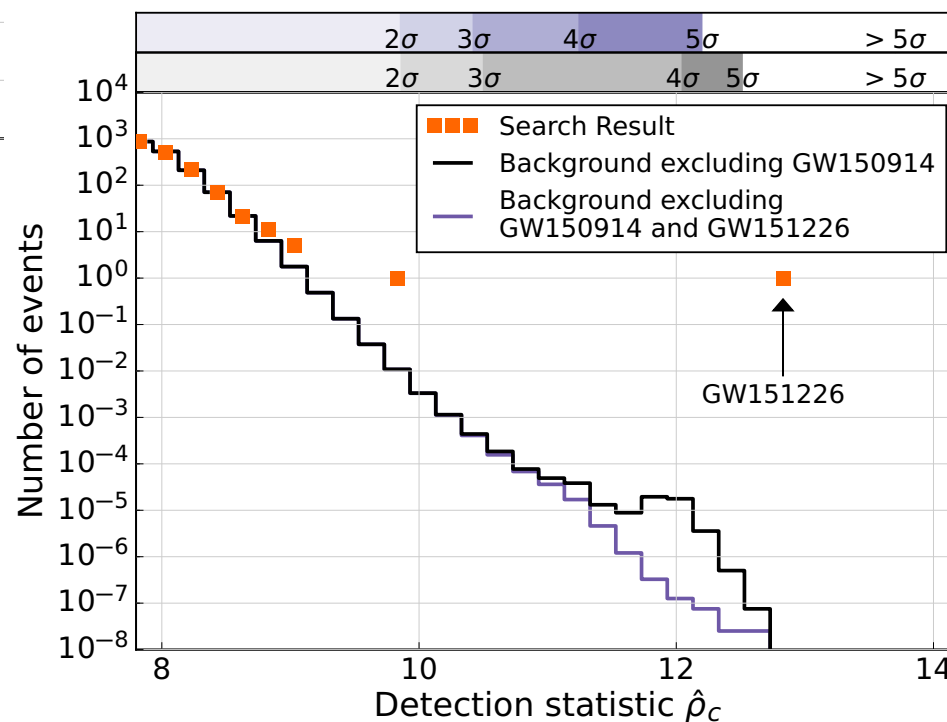


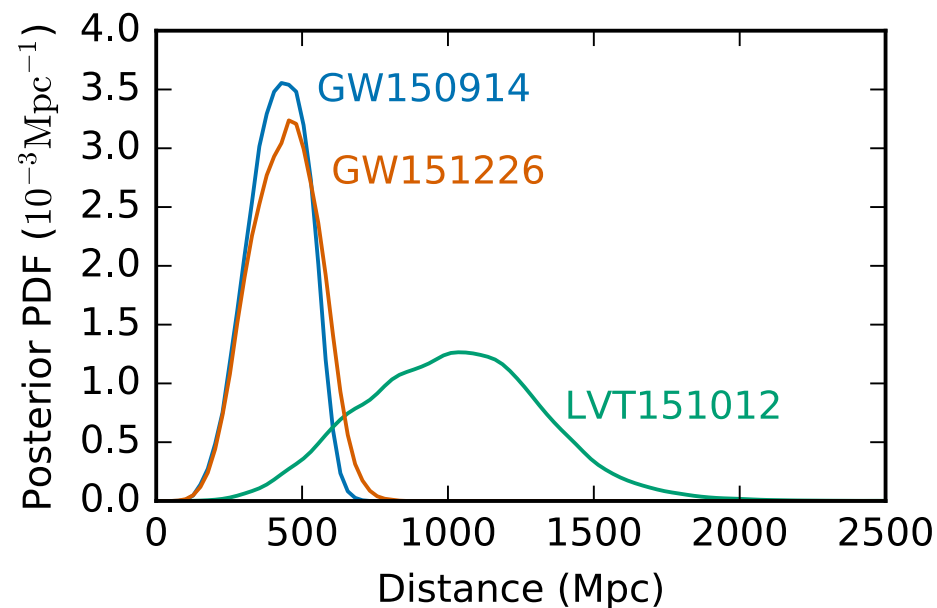
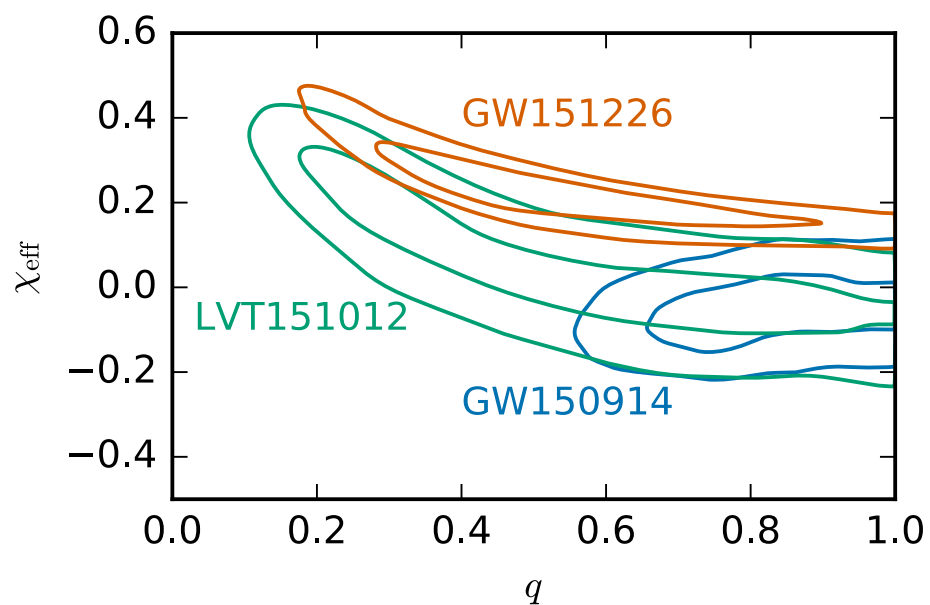
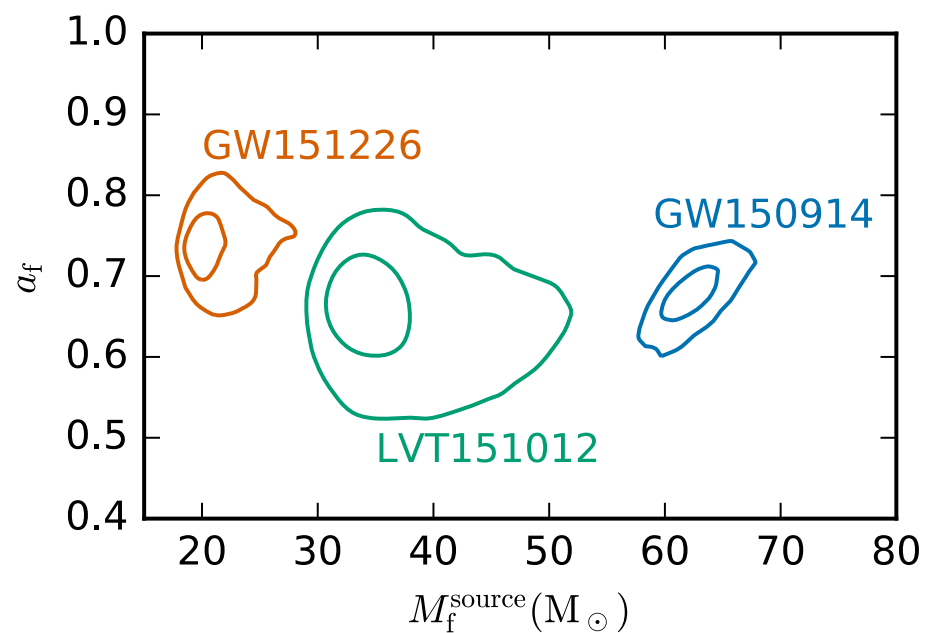
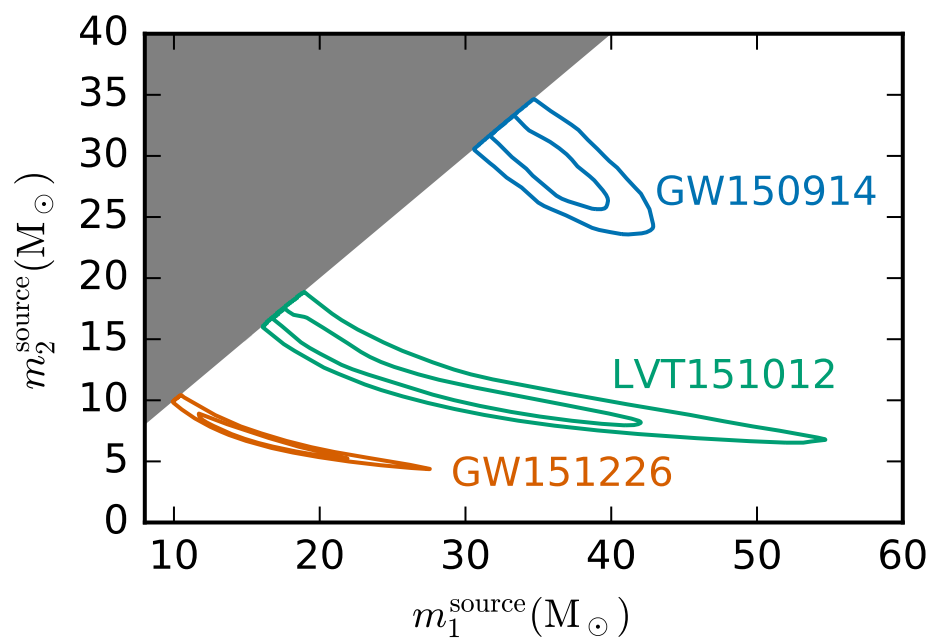
- About 30 cycles of GW waveform observed
- Precision test of General Relativity

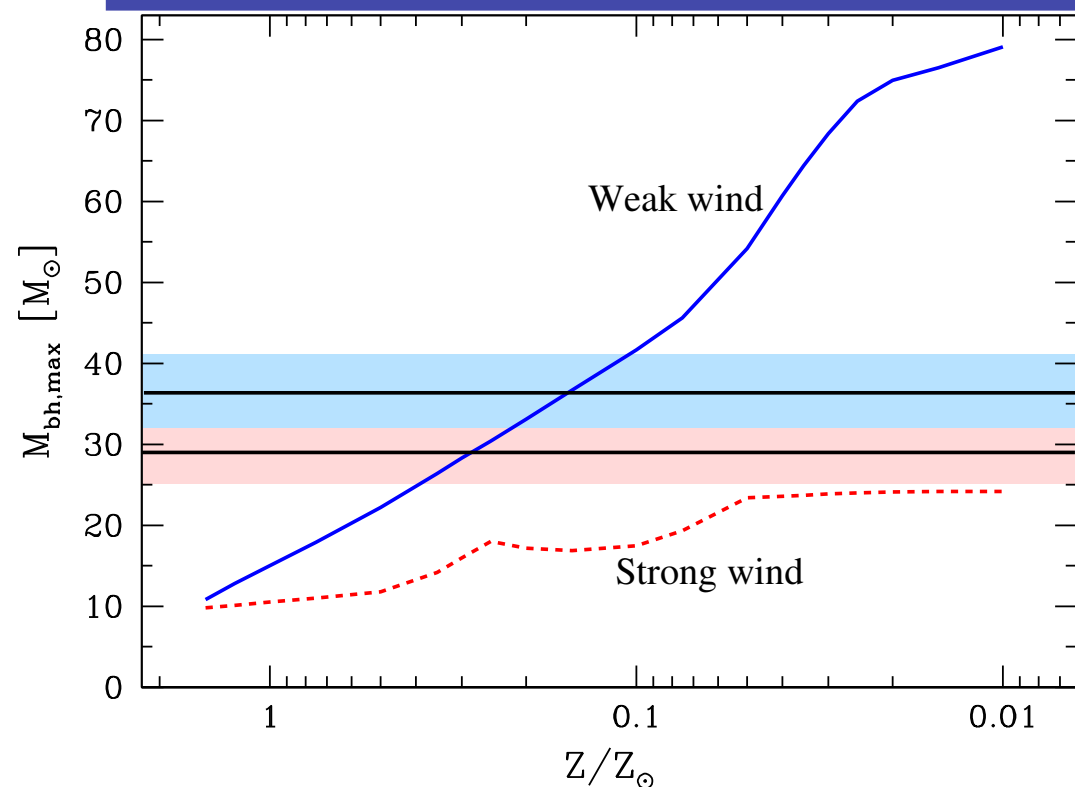
Actually, three BBHs Observed in First Run!



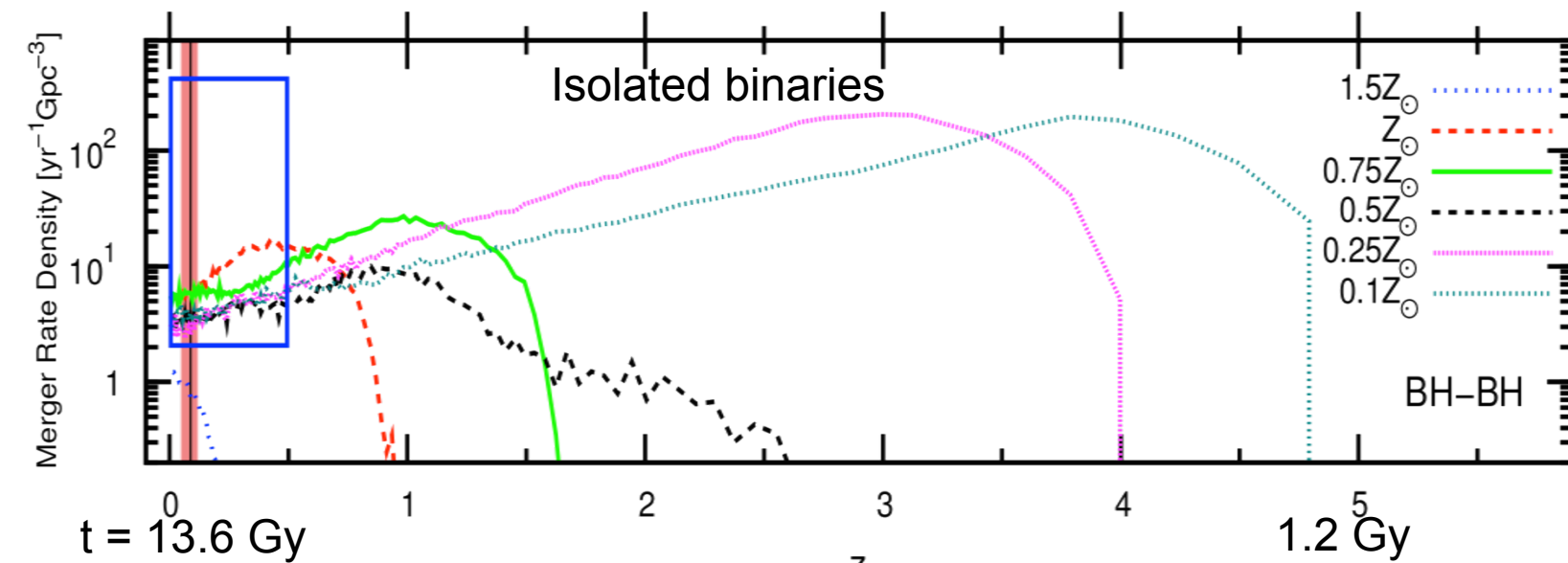
GW150914
LVT151012
GW151226

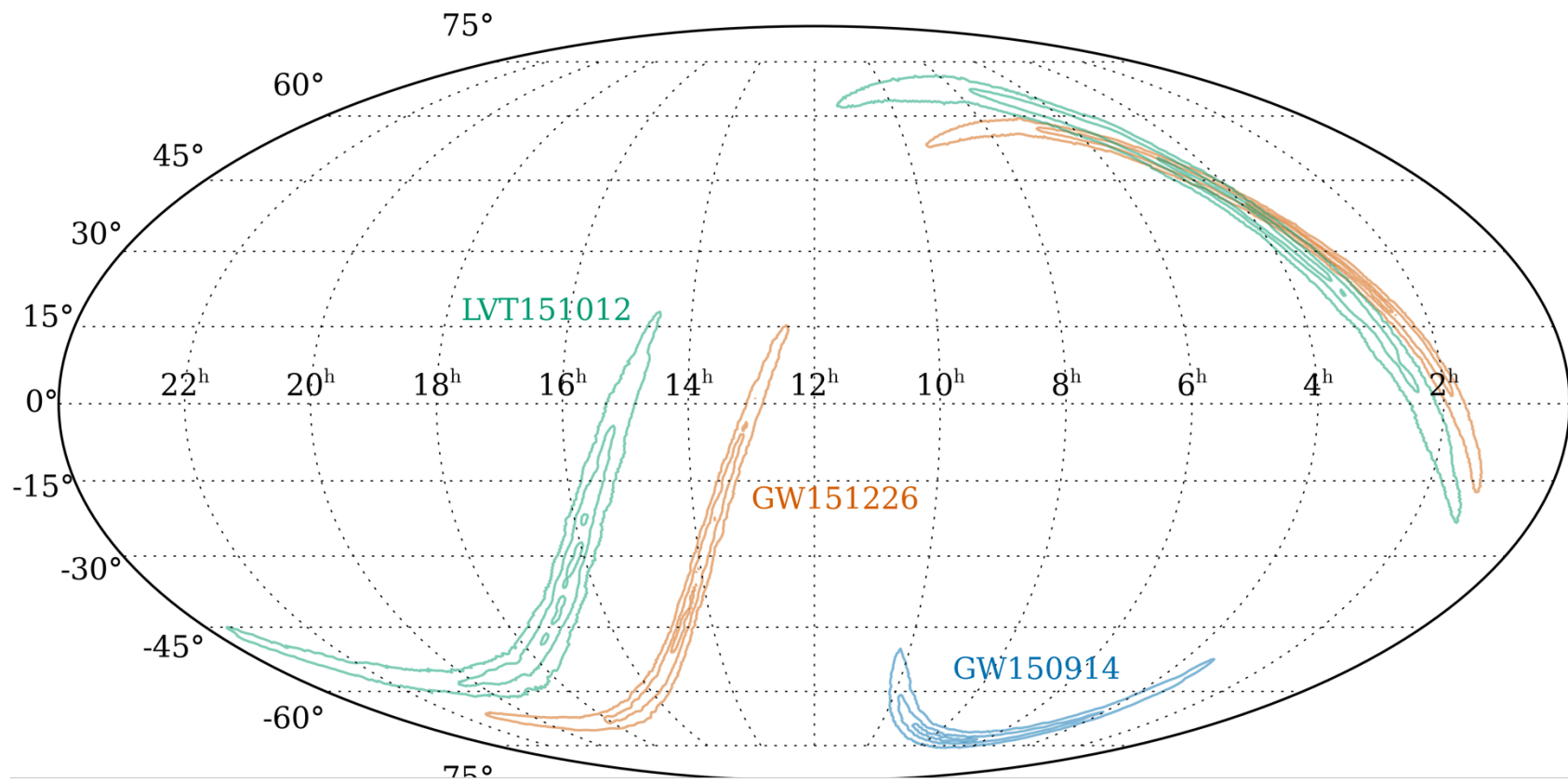


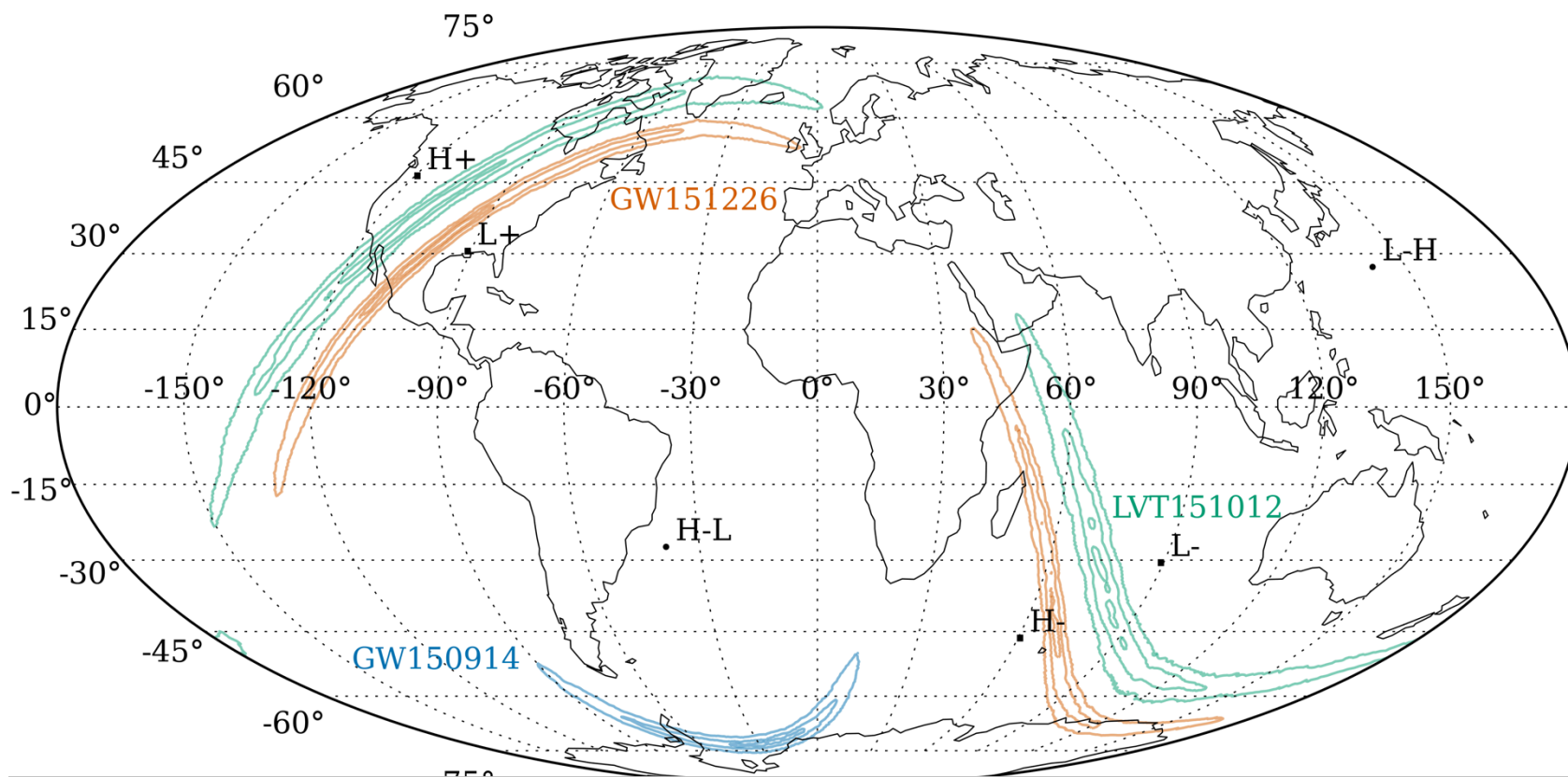




- Implies low metallicity and weak winds; Pop III stars?
- Rate ~consistent with isolated binary formation; may require dynamical formation







Fermi GBM Observations of LIGO Gravitational Wave event GW150914

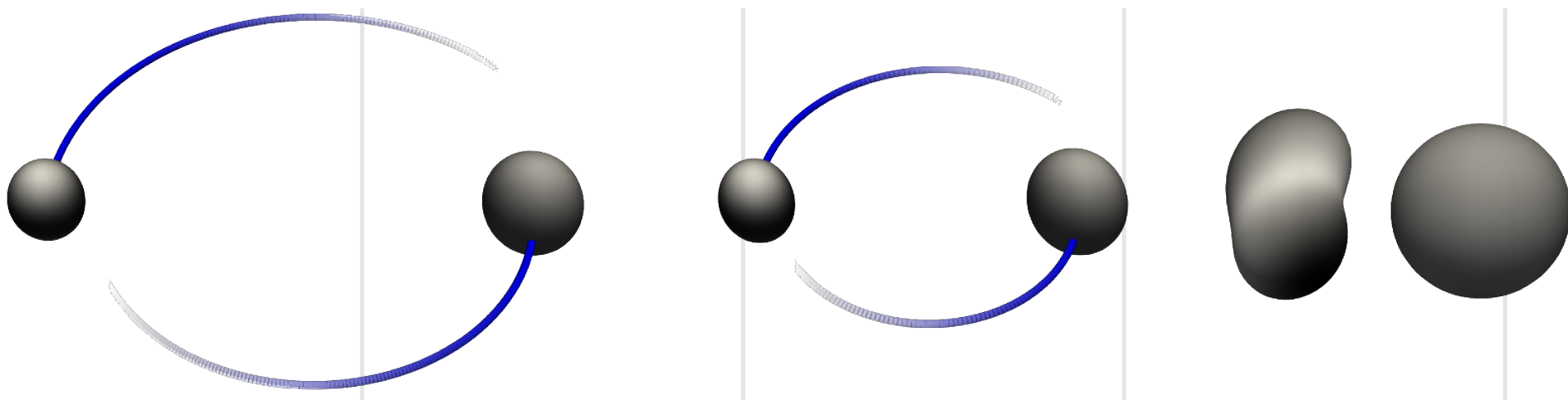
V. Connaughton^{*,1}, E. Burns², A. Goldstein^{+,3}, L. Blackburn⁴, M. S. Briggs⁵, B.-B. Zhang⁶,
C. M. Hui³, P. Jenke⁶, J. Racusin⁷, C. A. Wilson-Hodge³, P. N. Bhat⁶, W. Cleveland¹,
G. Fitzpatrick⁶, M. M. Giles⁸, M. H. Gibby⁸, J. Greiner⁹, A. von Kienlin⁹, R. M. Kippen¹⁰,
S. McBreen¹¹, B. Mailyan⁶, C. A. Meegan⁶, W. S. Paciesas¹, R. D. Preece⁵, O. Roberts¹⁰,
L. Sparke¹², M. Stanbro², K. Toelge⁹, P. Veres⁶, H.-F. Yu^{9,13}

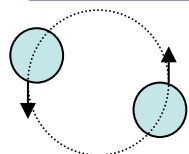
and other authors

ABSTRACT

With an instantaneous view of 70% of the sky, the *Fermi* Gamma-ray Burst Monitor (GBM) is an excellent partner in the search for electromagnetic counterparts to gravitational wave (GW) events. GBM observations at the time of the Laser Interferometer Gravitational-wave Observatory (LIGO) event GW150914 reveal the presence of a weak transient source above 50 keV, 0.4 s after the GW event was detected, with a false alarm probability of 0.0022. This weak transient lasting 1 s does not appear connected with other previously known astrophysical, solar, terrestrial, or magnetospheric activity. Its localization is ill-constrained but consistent with the direction of GW150914. The duration and spectrum of the transient event suggest it is a weak short Gamma-Ray Burst arriving at a large angle to the direction in which *Fermi* was pointing, where the GBM

- Short Answer: “Yes”
- Longer Answer:
 - The ~3 months of run O1 yielded 3 BBH events.
 - For O1, LIGO was at ~30% of its design sensitivity
 - Expect improved sensitivity for O2, O3, ... until 100% reached 2019-ish
 - O2 scheduled to start late summer 2016
 - At design: 1 event/month $\rightarrow$ 1 event/day





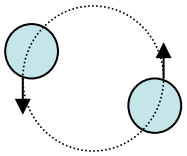
arXiv: 1003.2480 , CQG

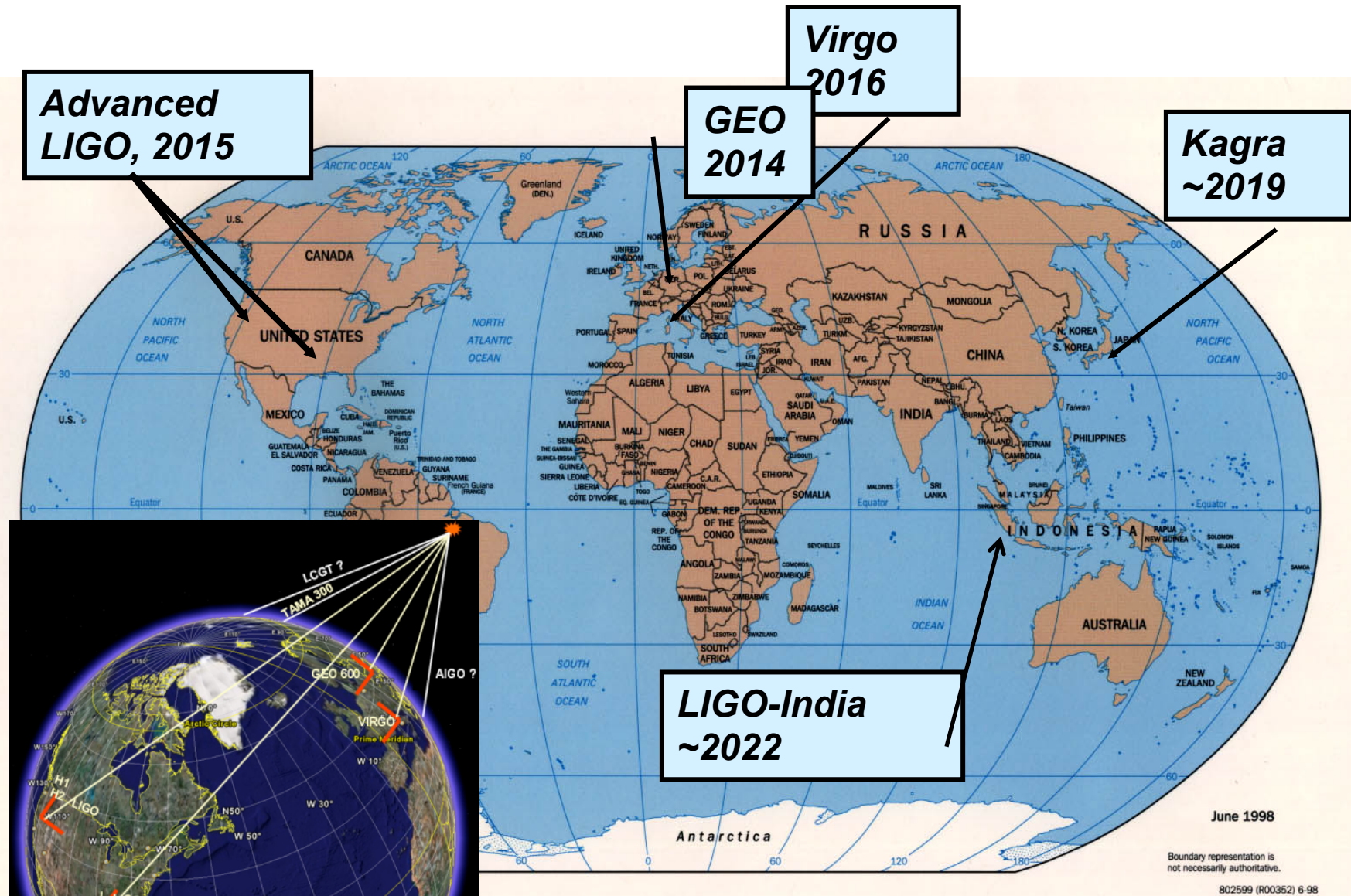
TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source ^a	$\dot{N}_{\text{low}}$ yr^{-1}	$\dot{N}_{\text{re}}$ yr^{-1}	$\dot{N}_{\text{high}}$ yr^{-1}	$\dot{N}_{\text{max}}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^b$	0.01^c
	IMBH-IMBH			10^{-4d}	10^{-3e}
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^b	300^c
	IMBH-IMBH			0.1^d	1^e

For O1, sensitivity 3x lower.
Expectation <1 NS-NS event

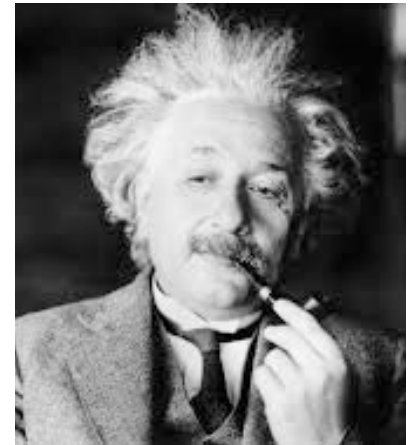
- Advanced LIGO had just turned on with sensitivity about 30% of the eventual (2019-ish) goal.
- Expectation was that we would have about a 10%-ish chance for observing a faint binary neutron-star merger.
- Speculation was rife for other kinds of signals, such as supernovae, black-hole mergers, gamma-ray bursts, ... But all very uncertain.
- Expect other types of astrophysical sources!





3 or more detectors: localization from
~100 square degrees to ~10 sq degrees

- Gravitational Waves discovered.
 - UO rocks!
- General Relativity (still) looks good.
- A lot of science from a few events
- The (really) exciting part:
A new window on the Universe...
The fun is just beginning!



A few extra slides with some math...

In special relativity:

$$ds^2 = (c dt)^2 - (dx^2 + dy^2 + dz^2) = \sum \eta_{\mu\nu} dx_\mu dx_\nu \quad \text{Einstein, 1905}$$

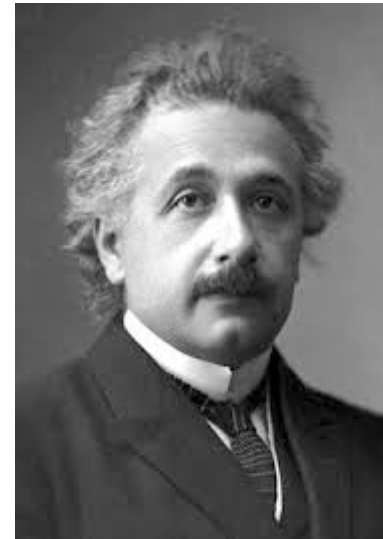
$$\eta_{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

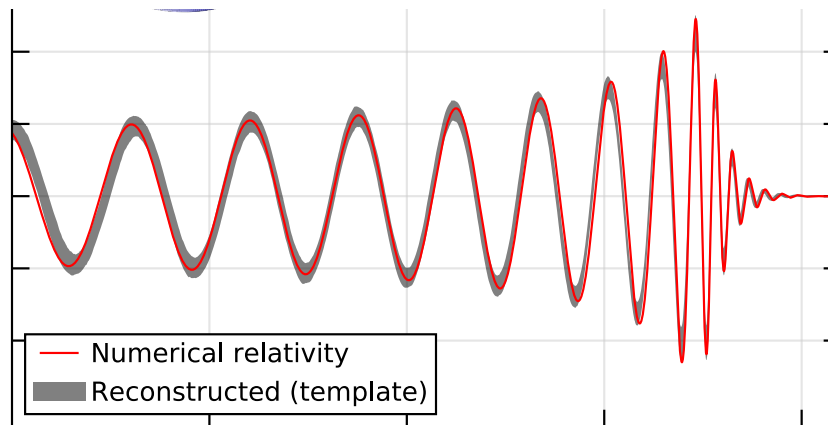
GR:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \quad G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \quad \text{Einstein, 1915}$$

$$\eta_{\mu\nu} \rightarrow g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = -16\pi T_{\mu\nu} \quad \text{Einstein, 1916}$$





$$h_+ = h_o \frac{1 + \cos^2 \iota}{2} \cos 2\Phi(t)$$

$$h_\times = -h_o \cos \iota \sin 2\Phi(t)$$

- The phase evolution implies $\mathcal{M} \approx 30M_\odot$
- $\Rightarrow M_{\text{tot}} \geq 70M_\odot$
- at merger, orbit freq is ~ 75 Hz. Separation is ~ 350 km $\sim 3R_s$
- $R_s = 2GM/c^2$

$$\Phi(t) = \Phi_c - \left[\frac{t_c - t}{5(1+z)\mathcal{M}} \right]^{5/8}$$

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$h_o = \frac{(1+z)\mathcal{M}}{D} [8\pi f(1+z)\mathcal{M}]^{2/3}$$