Direct observation of gravitational waves from the merger and inspiral of two black holes

Bruce Allen

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

Hannover, Germany

Date: Sat, 21 Sep 91 14:37:51 EDT
From: Rainer Weiss <weiss@tristan.mit.edu>
To: ballen@dirac.phys.uwm.edu
Subject: Thank you and some help

Bruce,
I have scanned your paper Gravitational Radiation from Cosmic Strings.
Could you save me some time by giving me the conversion of C_n(omega)
to h(f) at the earth for obvious practical reasons.
RW

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Date: Mon, 14 Oct 91 18:05:48 EDT
From: Rainer Weiss <weiss@tristan.mit.edu>
To: ballen@dirac.phys.uwm.edu
Subject: LIGO sensitivity

Bruce,
The phones don't seem to do it, so here is more e mail.
The LIGO project seems to have made it. The House and Senate reconciliation
left LIGO with $23.5M for FY 1992. So unless Bush vetoes the appropriations
bill LIGO will start this year.

The projected LIGO sensitivity after 10**7 seconds of integration on the
cross-correlation of two interferometers

Initial interferometer 90% confidence limit
Band 50 to 200 Hz  omega(gw) = 3 x 10**-7

Second generation interferometer 90% confidence limit
Band 40 to 100 Hz  omega(gw) = 1 x 10**-10

Later with dual recycling this may go to omega(gw) = 3 x 10**-11

RW
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3 weeks later…

Outline

- 4 days *before* starting its first observational run, Advanced LIGO observed a strong gravitational wave burst
- Source unambiguous:
  merger of a 29 and 36 solar mass BH
- What did we see?
  What is the interpretation?
- How can we be sure it is real?
- What can we learn?
- Prospects for the future

References

https://www.ligo.caltech.edu/page/detection-companion-papers

Discovery Paper

"Observation of Gravitational Waves from a Binary Black Hole Merger"
Published in *PRL* **116**, 061102 (2016).

Related papers

"Observing gravitational-wave transient GW150914 with minimal assumptions"

"GW150914: First results from the search for binary black hole coalescence with Advanced LIGO4"

"Properties of the binary black hole merger GW150914"

"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"

"Astrophysical Implications of the Binary Black-Hole Merger GW150914"

"Tests of general relativity with GW150914"

"GW150914: Implications for the stochastic gravitational-wave background from binary black holes"

"Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914"

"Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914"

"High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES"

"GW150914: The Advanced LIGO Detectors in the Era of First Discoveries"

"Localization and broadband follow-up of the gravitational-wave transient GW150914"

GW150914 Data Release

Data release at LIGO Open Science Center (LOSC) website.

Gravitational Waves 1916

June 1916

Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen.

(It follows that the gravitational field propagates at the speed of light. In connection with these general solutions, we'll investigate gravitational waves and their sources.)

$$L = \frac{G}{5c^5}\left(\frac{d^3}{dt^3}Q_{ab}\right)\left(\frac{d^3}{dt^3}Q_{ab}\right)$$

SBer Preuss. Akad. Wiss. 1916, I

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

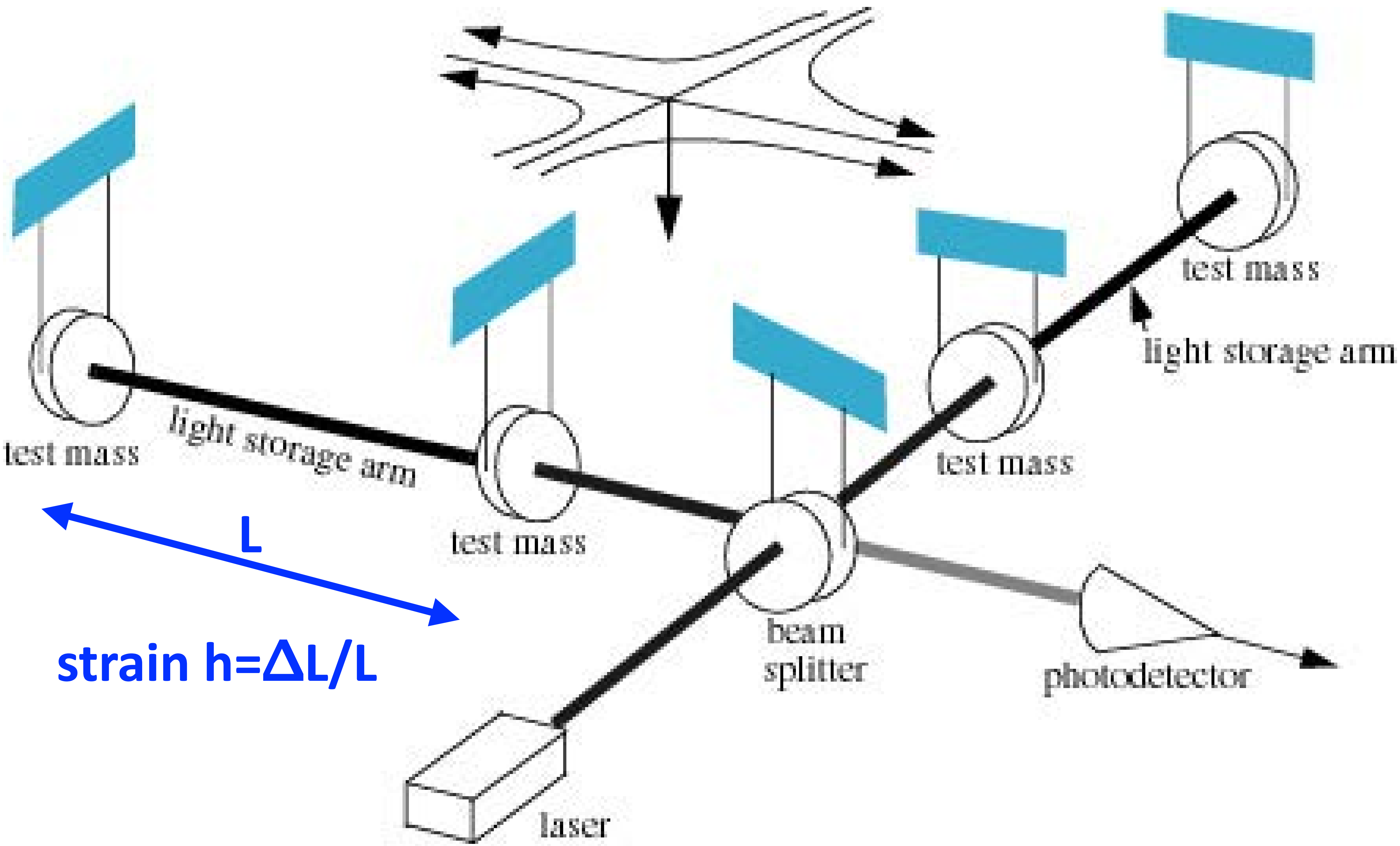
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen de Sitter, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihn früher gegeben hatte[1]. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

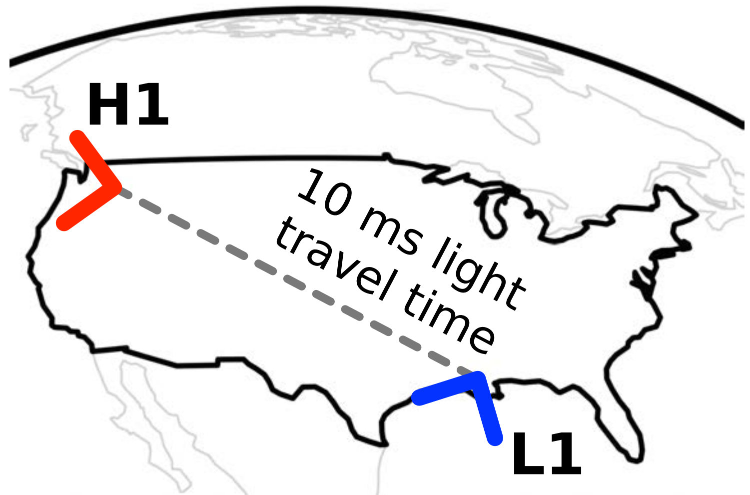
[1] Sitzungsber. XLVII, 1915, S. 833.

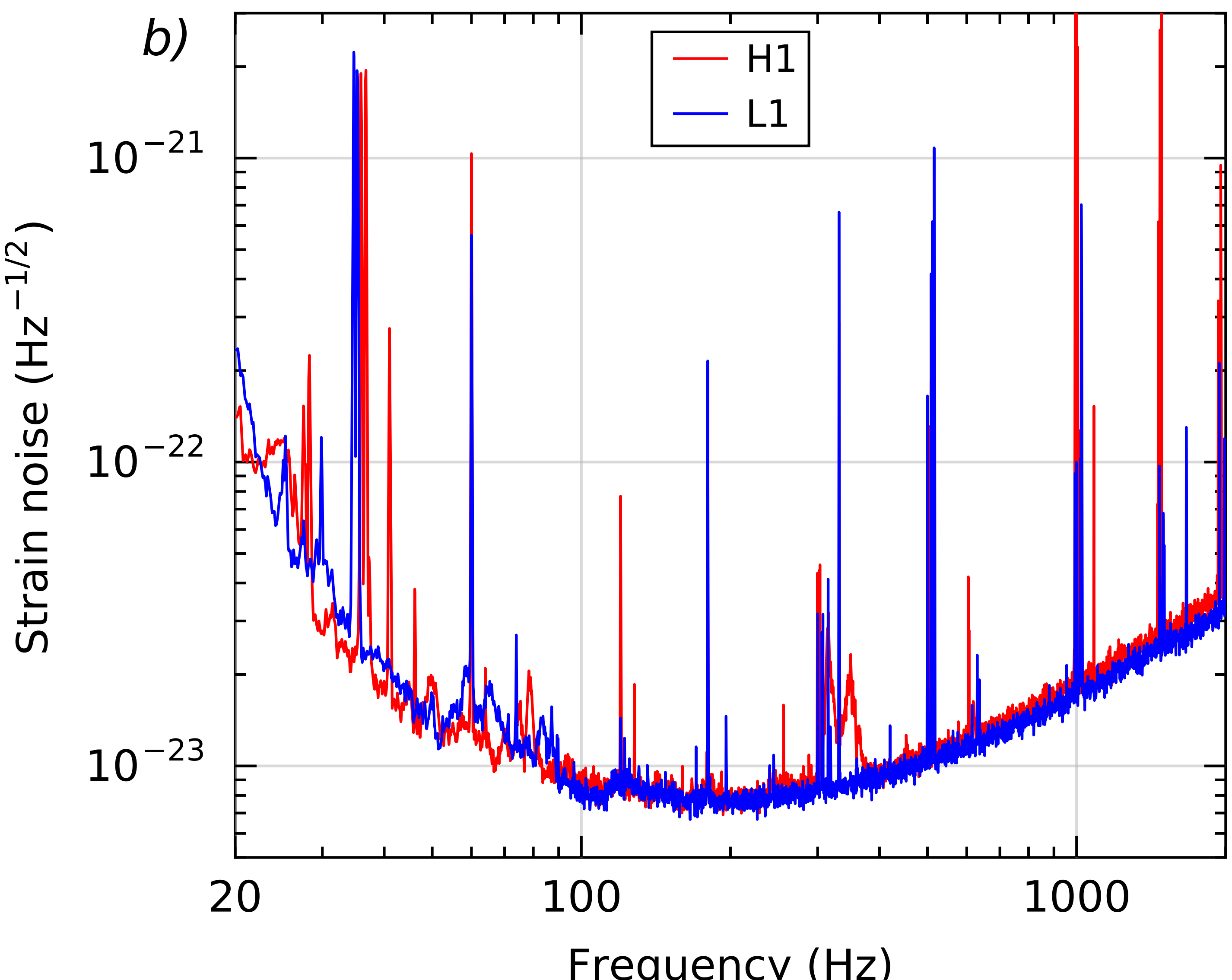
Gravitational Wave Detector



Gravitational Wave Detectors

LIGO Livingston
LIGO Hanford
3000 km apart





Most sensitive in frequency range from 30 HZ to 2000 Hz

Currently: a factor ~3 below the final design sensitivity

September 14, 2015

- 09:50 UTC
  LIGO Hanford, WA local time 02:50
  LIGO Livingston, LA local time 04:50
  AEI, Hannover Germany local time 11:50
- Engineering run had begun 17 August, for calibration, injection, noise and characterisation studies
- VIRGO still in commissioning/construction
  GEO-600 off-the-air (factor of 100 too insensitive)
- Injection tests included some simulated signals, but these did not reproduce the desired waveforms because there was not enough “actuator authority” at high frequencies.
- First observing run O1 (“science operations mode”) scheduled to begin on 18 September
- NB: **Blind injections were only planned for science operations, not for the engineering run**

September 14, 2015

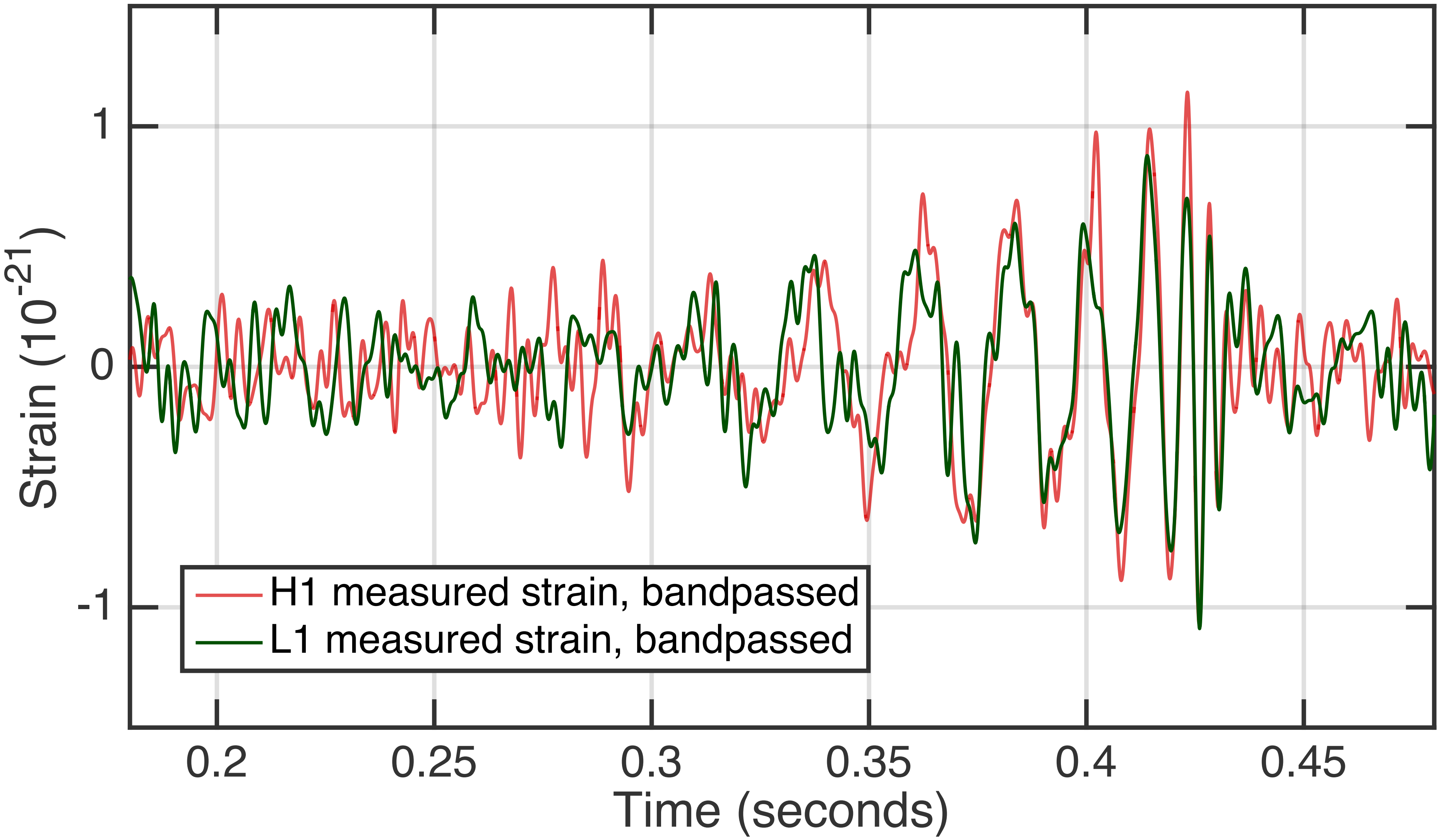
Marco Drago

Andrew Lundgren

- AEI Hannover, 11:50 on Monday morning.
- Coherent Waveburst pipeline running at Caltech
- Event database had ~1000 entries
- Marco and Andy checked injection flags and logbooks, data quality, made Qscans of LHO/LLO data

- Called operators at the two sites: "everyone's gone home"
- At 12:54, Marco sent an email to the collaboration, asking for confirmation that it's not a hardware injection.
- Next hours: flurry of emails, decision to lock down sites, freeze instrument state

The Data



- Bandpass filtered 35-350 Hz, some instrumental and calibration lines removed
- Hanford inverted, shifted 7.1 ms earlier
- Signal visible ~200 ms

Interpretation

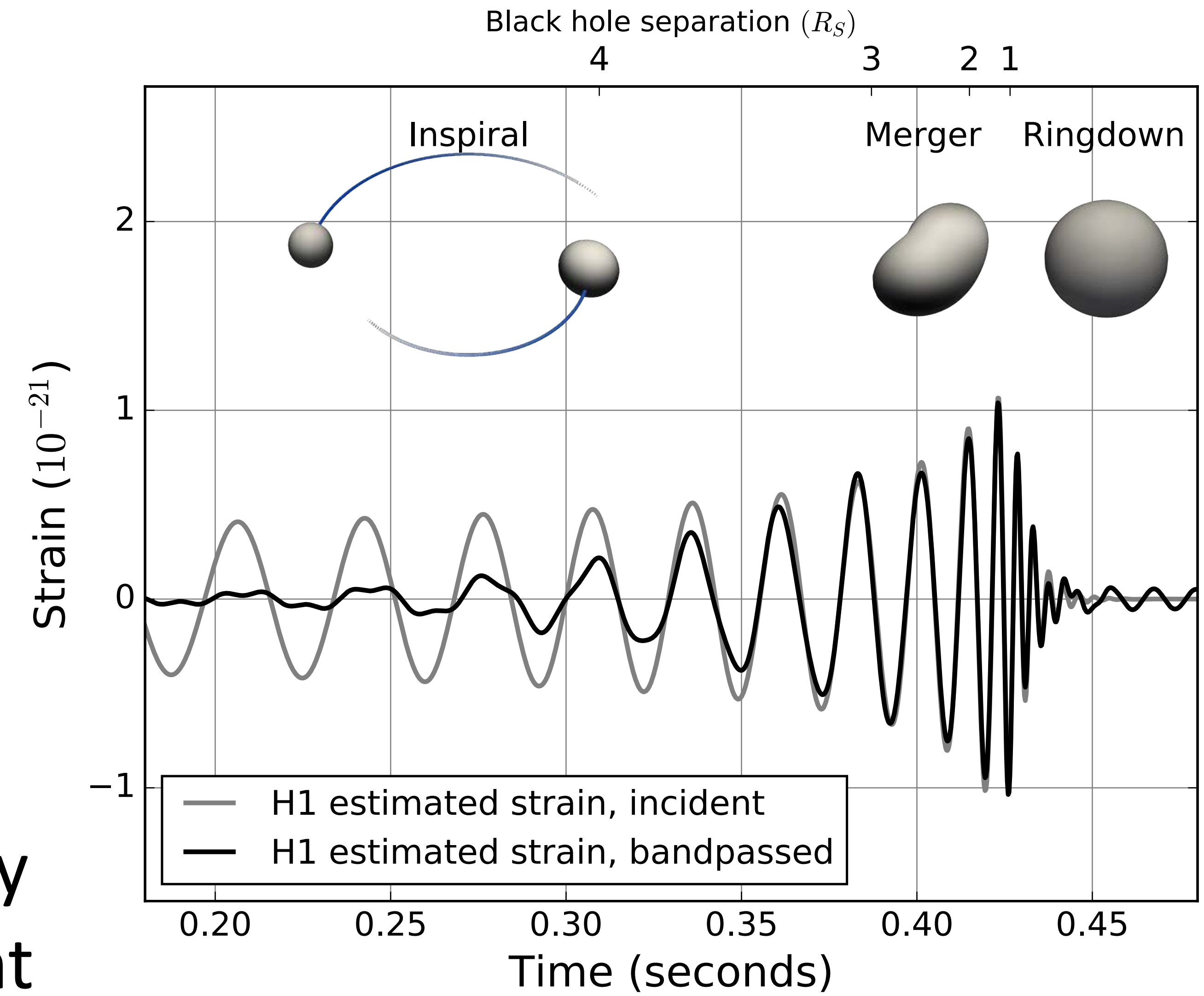
- Oscillations => orbital motion
- Newtonian approximation =>

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

- Chirp mass $\mathcal{M}$ ~ 30 $M_\odot$
- If equal: $m_1 = m_2$ ~ 35 $M_\odot$

  => Schwarzschild radii: 103km
- At peak f_{GW} = 150 Hz, orbital frequency = 75 Hz separation of Newtonian point masses 346km
- Ordinary stars are 10^6 km in size, white dwarfs are 10^4 km.
- Neutron stars not possible:

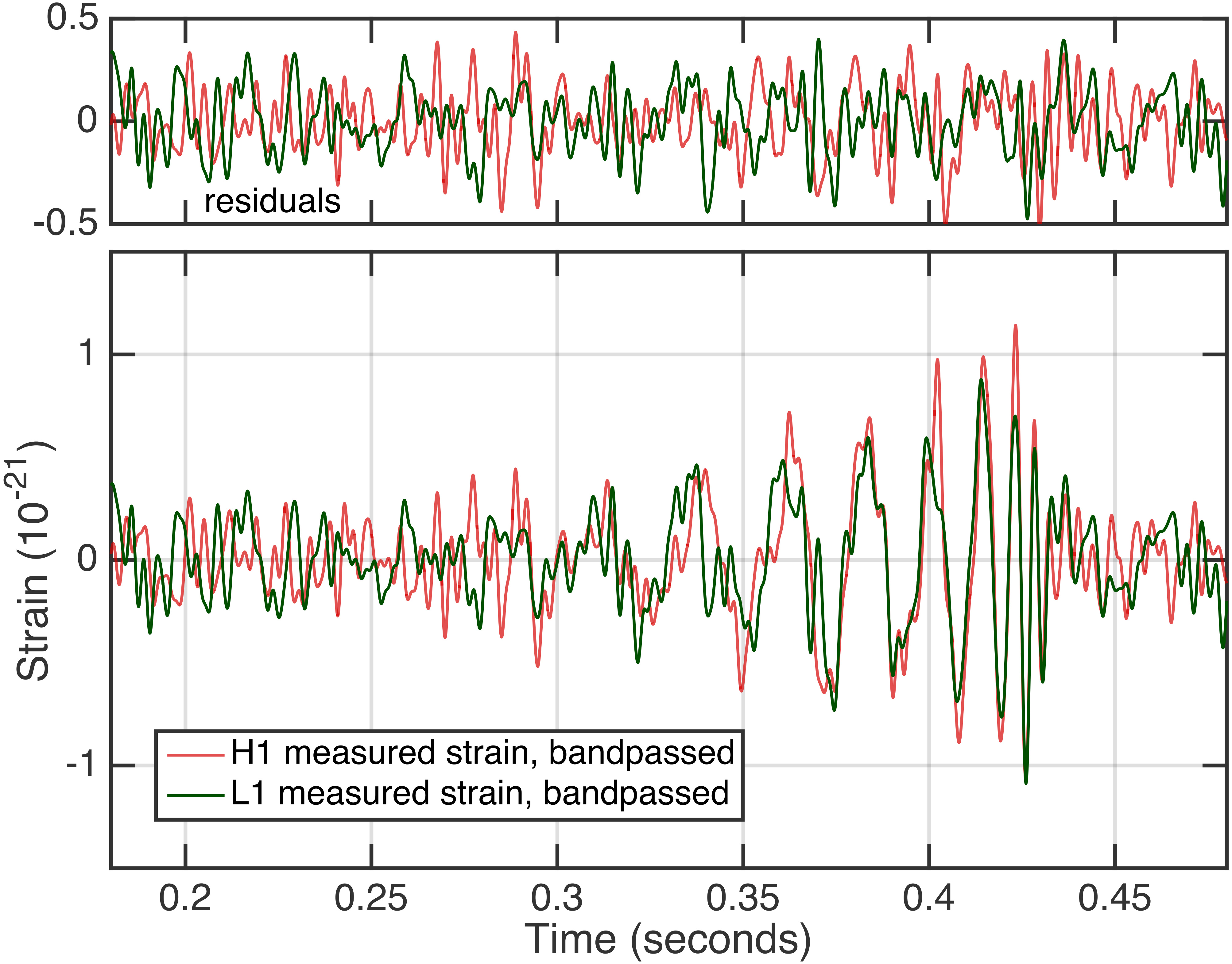
  $m_1 = 4\ M_\odot$ => $m_2 = 600\ M_\odot$



Only black holes are sufficiently massive *and* compact!

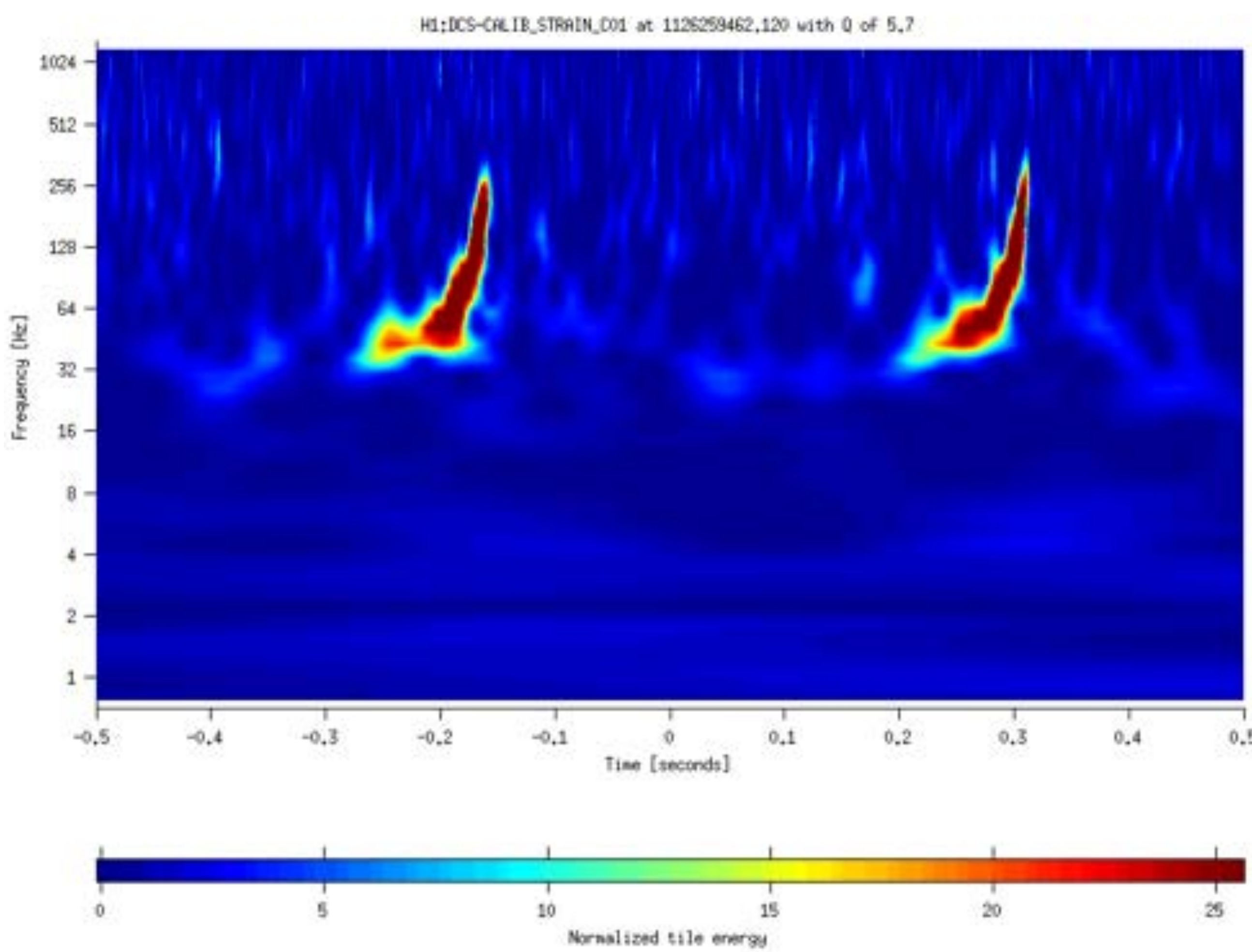
P. C. Peters, Phys. Rev. 136, B1224 (1964);
Blanchet, Damour, Iyer, Will and Wisema, Phys. Rev. Lett. 74, 3515 (1995).

Residuals after subtracting a best-fit waveform

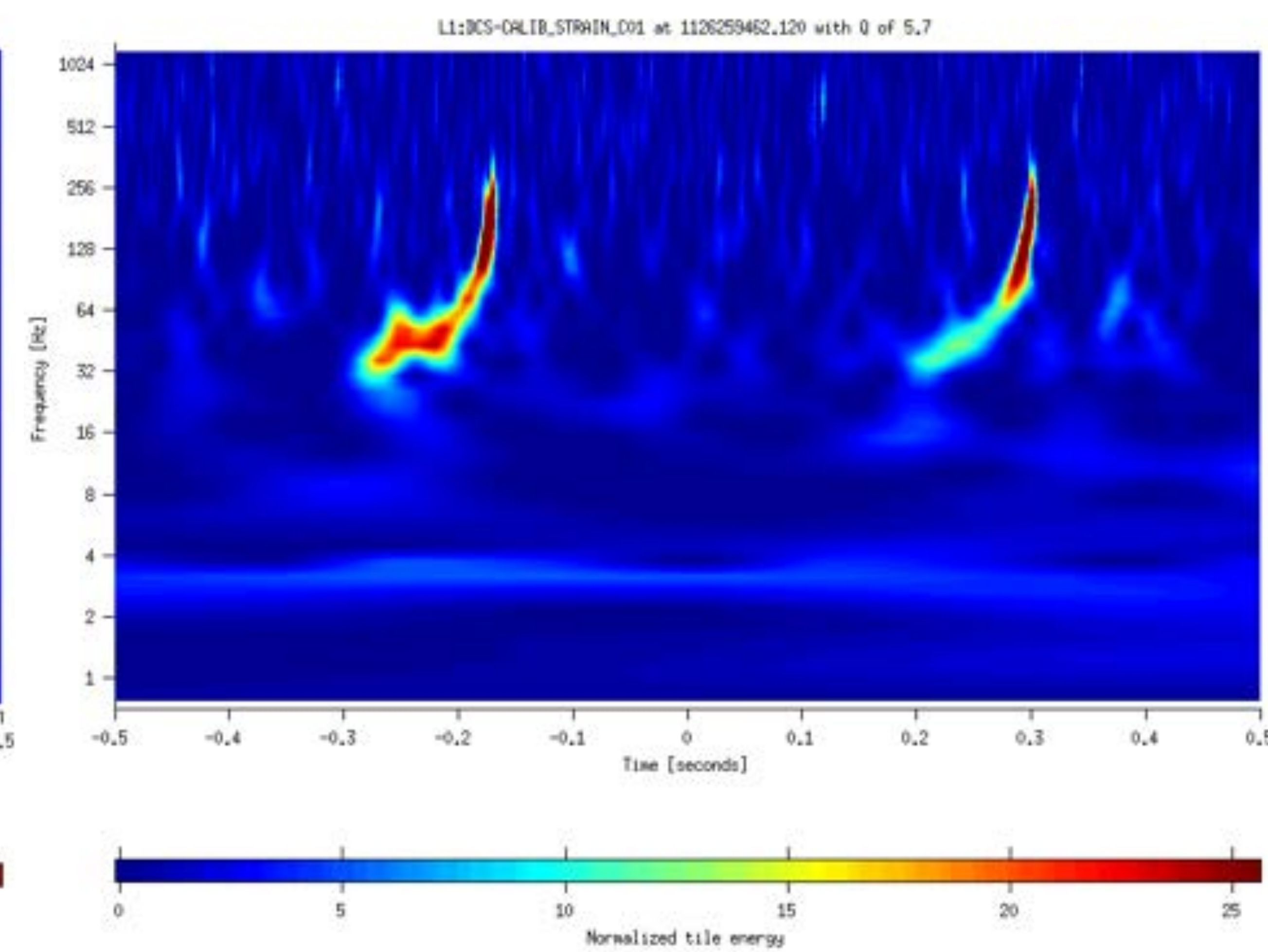


Time/Frequency Plots

Hanford



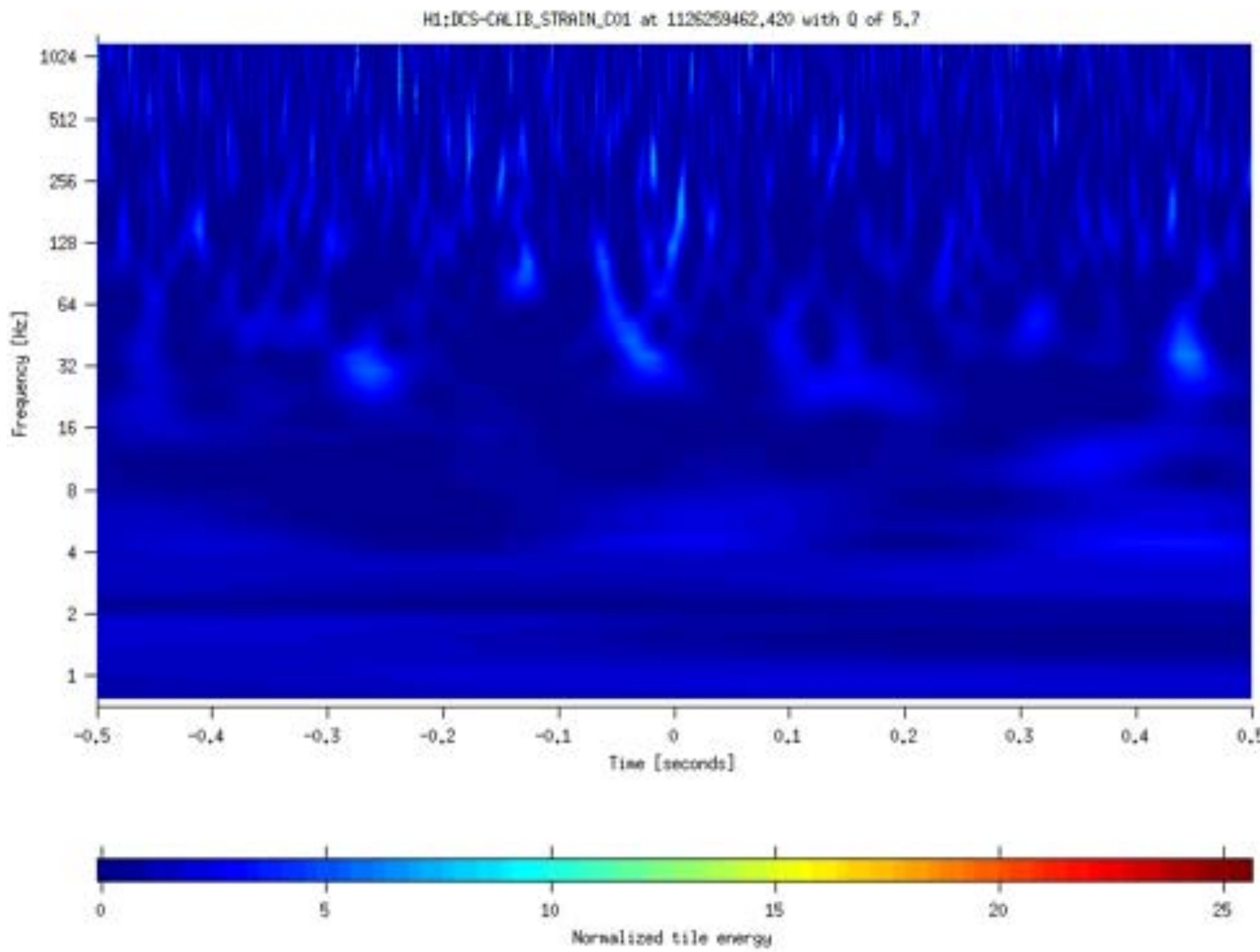
Livingston



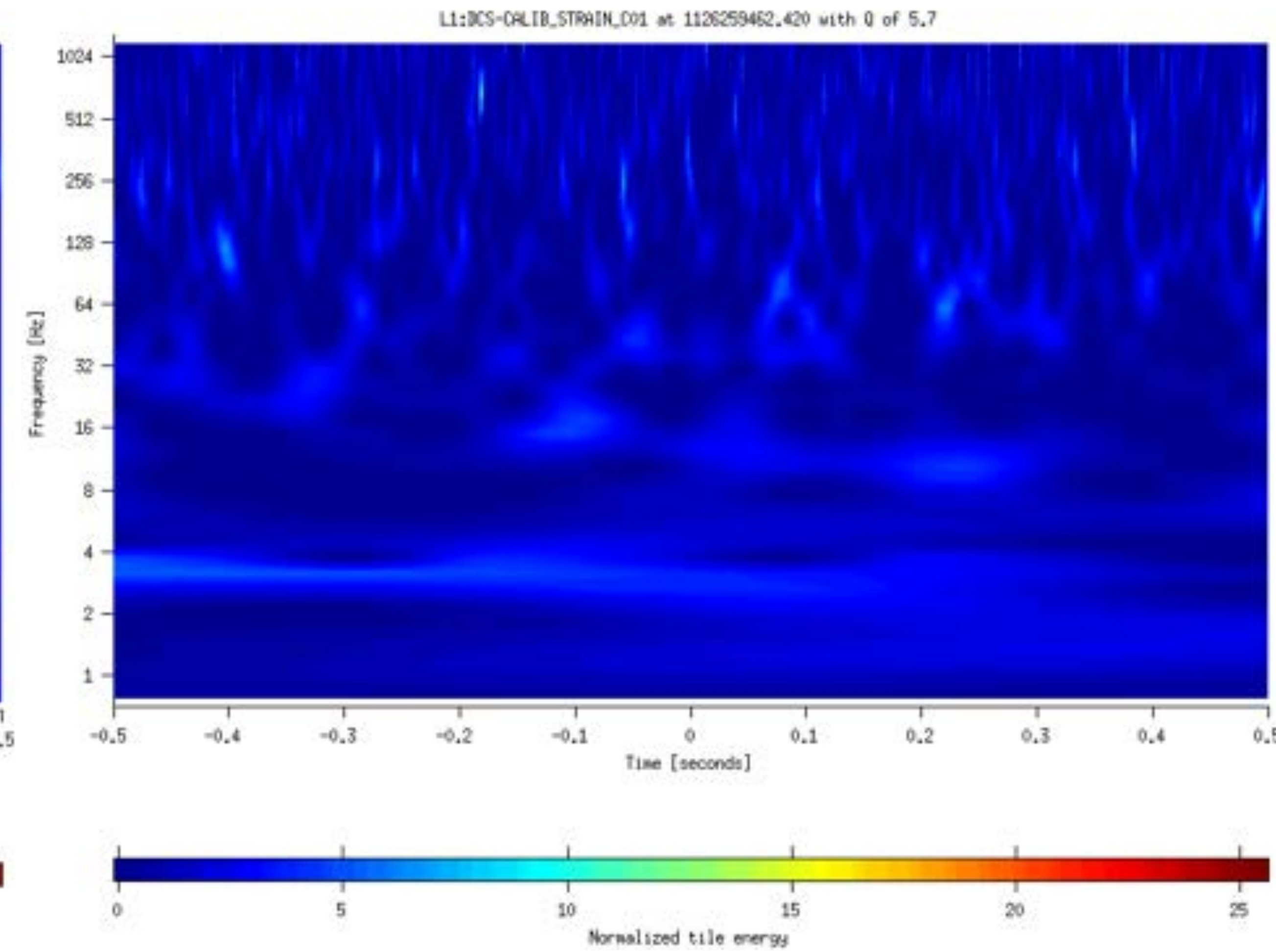
- Right: The Event
- Left: a best-fit waveform model added 0.6 seconds before The Event

Residuals in Time/Frequency

Hanford



Livingston



- Here the best-fit waveform is subtracted from the data streams

Real? Or a detector artifact?

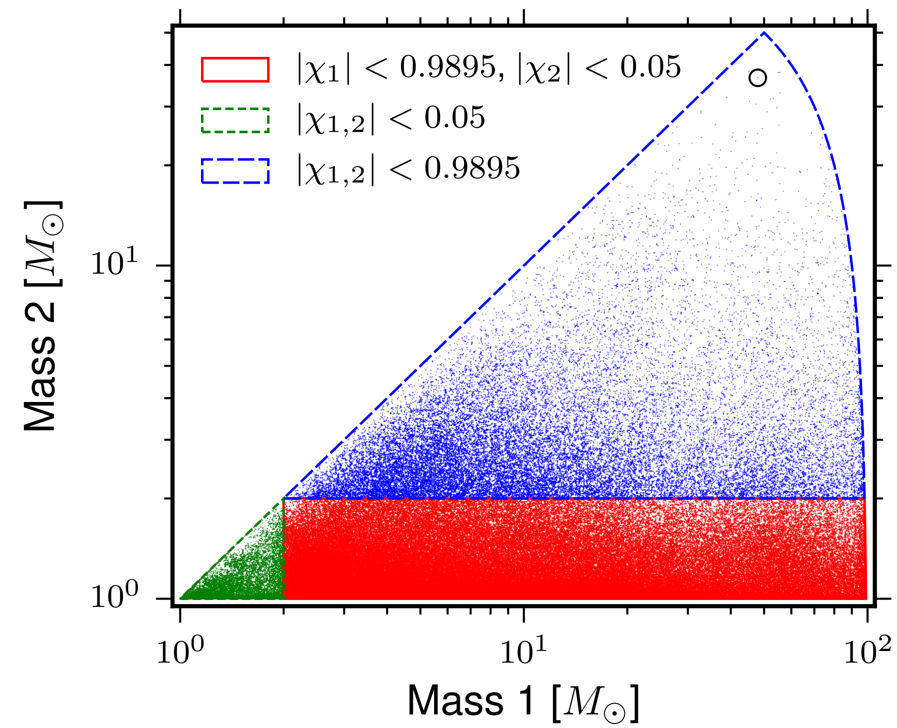
- Instruments were in normal operation and stable since September 12th (apart from deliberate intervention)
- Last scientists left the sites about 2 hours (LHO) and 15 minutes (LLO) before the event. Only operators on duty.
- Waveform does not resemble any known instrumental glitches or artefacts
- Susceptibility to radio, acoustic, magnetic, seismic and other external disturbances measured. These external disturbances are monitored: can not explain more than 6% of the observed GW amplitude
- Was not an accidental or malicious hardware injection: recorded control loop signals permit reconstruction of the actuators: no fake signal was added


Robert Schofield and **Anamaria Effler**, departed the LLO site at 04:35am **15 minutes before the event**


Stefan Ballmer and **Evan Hall**, departed the LHO site soon after midnight, **2 hours before the event**

Optimal Filtering

- Filter data through model waveforms
- Waveforms grouped by mass into 3 classes, relevant one is blue. Grid of template waveforms in parameter space.
- Compute optimal statistic signal-to-noise ratio (SNR) ρ
- Normalised so the expected/average value of ρ^2 is 2.
- Large ρ^2 => strong signal present
- ρ^2 also divided by a χ^2 factor which reduces it if signal does not resemble template.
- Triggers at two sites must be in the same template, within 15 msec
- Final ranking statistic is quadrature sum of SNR at both sites



Fourier Transform $$\tilde{s}(f) = \int_{-\infty}^{\infty} s(t) e^{-2\pi i f t}\, \mathrm{d}t$$

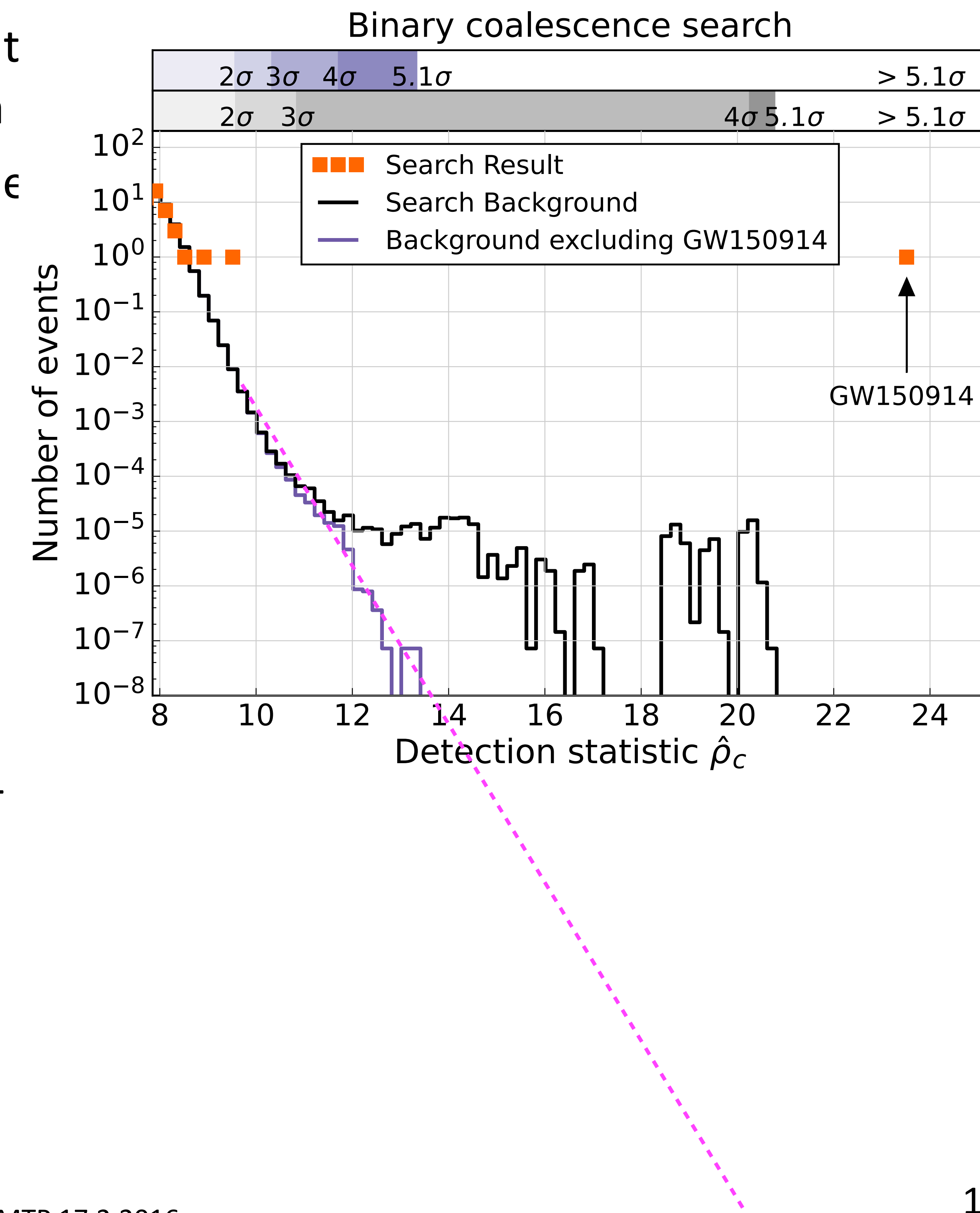
SNR $$\rho^2(t) \equiv \frac{1}{\langle h|h \rangle} \left[\langle s|h_c \rangle^2(t) + \langle s|h_s \rangle^2(t) \right]$$

Inner product $$\langle s|h \rangle(t) = 4 \int_0^{\infty} \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t}\, \mathrm{d}f$$

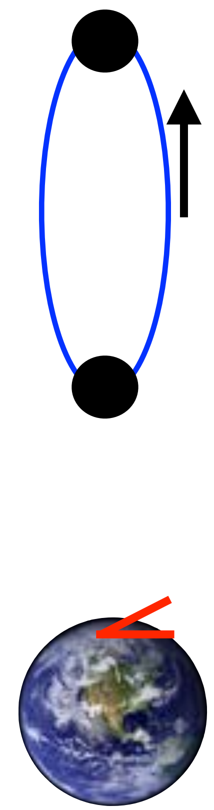
Normalisation $$\langle h|h \rangle = 4 \int_0^{\infty} \frac{\tilde{h}(f)\tilde{h}^*(f)}{S_n(f)}\, \mathrm{d}f$$

False Alarm Probabilty

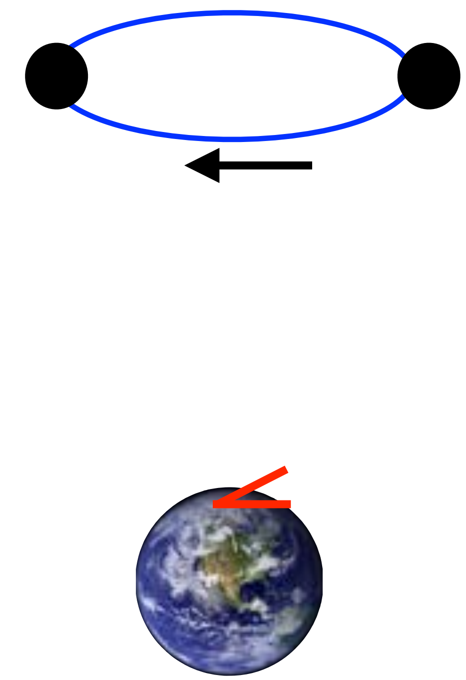
- To avoid statistical bias, tuning carried out before discovery, with pre-discovery data
- Orange squares: highest SNR events in the first 16 days of data collected (12 Sept - 20 Oct)
- Estimate background by shifting instrumental data in time at one site in 0.1 second increments (>> 10 msec light-travel time) approximately 2×10^6 times.
- Generate 608,000 years of "artificial" data, search for events
- Including trials factor, false alarm rate < 1 in 203,000 years
- For a Gaussian process, this is > 5.1σ
- Real false alarm rate much less! We got lucky, could have confidently detected this at ~twice the distance.



What can we infer about system?



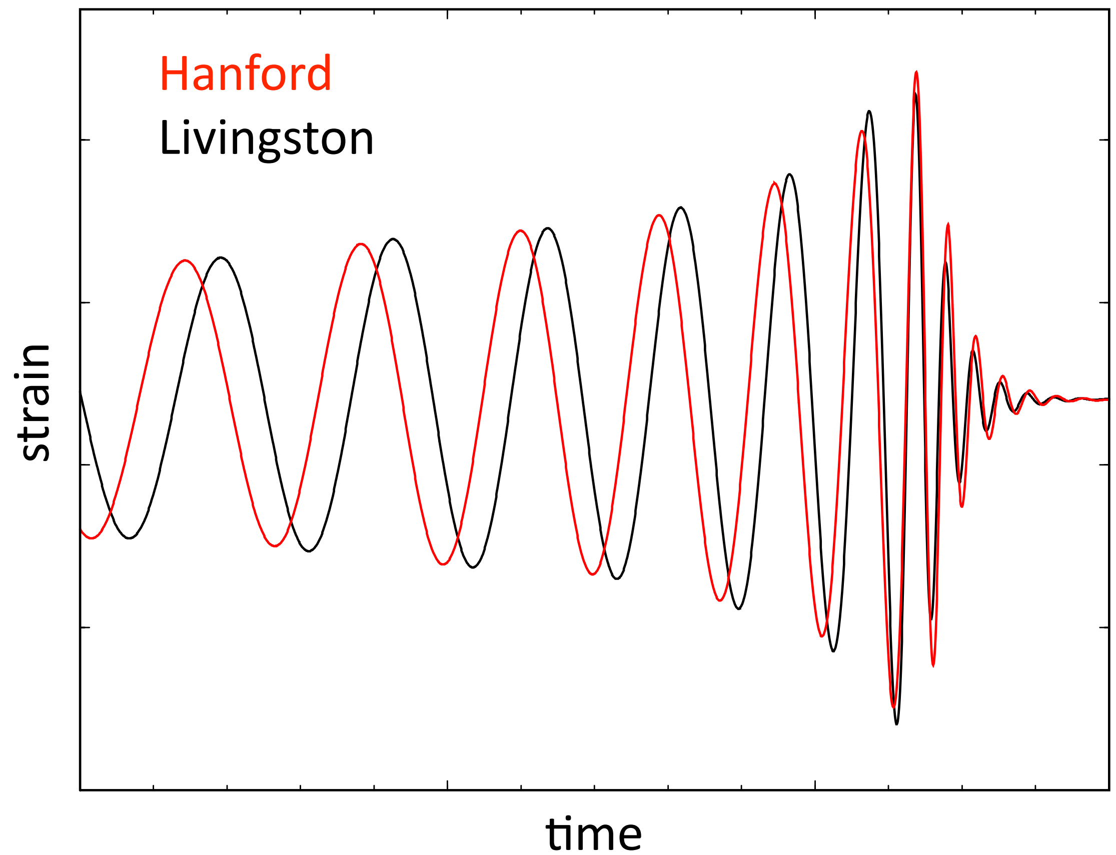
Orbital plane edge-on
(GWs have linear polarisation)



Orbital plane face-on
(GWs have circular polarisation)

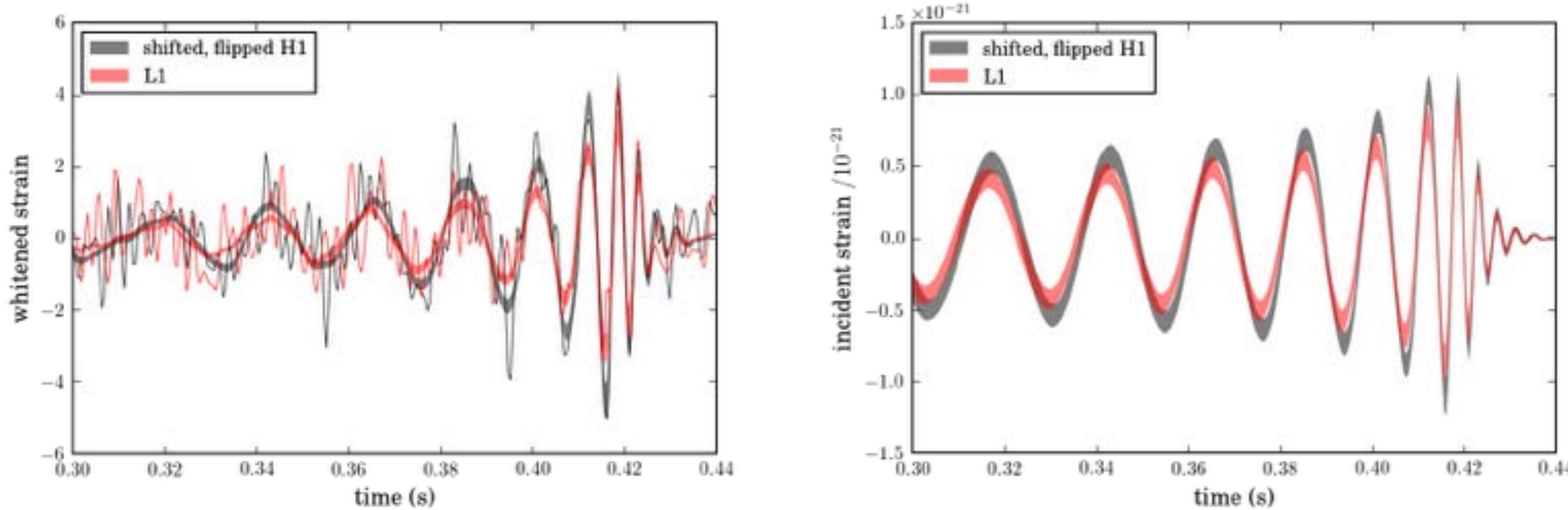
- Edge-on orientation of the orbital plane: only one polarisation, both detectors would see this (with projection cosine, depending upon orientation)
- Face-on/off orientation: two polarisations, detectors see different linear combinations (but same total amplitude)
- Face-on/off orientation is ab initio more likely than edge-on: face-on/off, because it has unit projection onto detector arms => stronger signal. (*NB: this statement is independent of the data!*)

What would polarisation look like?

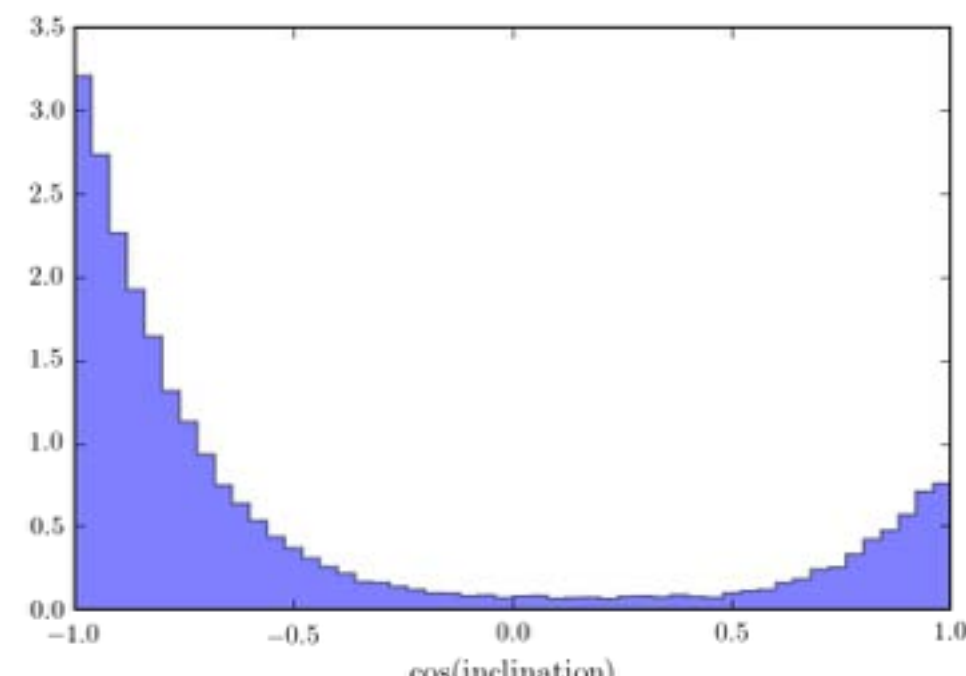


- If detectors are seeing distinct polarisations, one phase leads the other by 90 degrees
- After "lining up" arrival times, would look like above
- Edge-on: one polarisation, signals always in phase
- Face-on: two polarisations, phase shift possible

Weak evidence for face-off



- The slight phase shift suggests face-off is more likely (79%) than face-on (21%)
- Edge-on unlikely because expected signal would be weaker, NOT based on data.



face-off face-on

Other Parameters (in source frame)

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

- Bayes' theorem: multiply a prior probability distribution (uninformed) by likelihood that (data) - (signal model) is consistent with pure detector noise.
- Waveforms are analytic models, tuned to match numerical solutions of GR
- Radiated energy $3M_\odot$ (±0.5)
- Peak luminosity 3.6 x 10^{56} erg/s (± ~15%): 200 solar masses per second!
- Spins s_1 and s_2 only weakly constrained: not extreme. Consistent with merger of two non-spinning black holes.

Hawking's Area Theorem PRL 21, 1344 (1971)

Gravitational Radiation from Colliding Black Holes

S. W. Hawking
Institute of Theoretical Astronomy, University of Cambridge, Cambridge, England
(Received 11 March 1971)

It is shown that there is an upper bound to the energy of the gravitational radiation emitted when one collapsed object captures another. In the case of two objects with equal masses m and zero intrinsic angular momenta, this upper bound is $(2-\sqrt{2})m$.

Weber[1-3] has recently reported coinciding measurements of short bursts of gravitational radiation at a frequency of 1660 Hz. These occur at a rate of about one per day and the bursts appear to be coming from the center of the galaxy. It seems likely[3,4] that the probability of a burst causing a coincidence between Weber's detectors is less than $\frac{1}{10}$. If one allows for this and assumes that the radiation is broadband, one finds that the energy flux in gravitational radiation must be at least 10^{10} erg/cm^2 day.[4] This would imply a mass loss from the center of the galaxy of about $20\,000 M_\odot$/yr. It is therefore possible that the mass of the galaxy might have been considerably higher in the past than it is now.[5] This makes it important to estimate the efficiency with which rest-mass energy can be converted into gravitational radiation. Clearly nuclear reactions are insufficient since they release only about 1% of the rest mass. The efficiency might be higher in either the nonspherical gravitational collapse of a star or the collision and coalescence of two collapsed objects. Up to now no limits on the efficiency of the processes have been known. The object of this Letter is to show that there is a limit for the second process. For the case of two colliding collapsed objects, each of mass m and zero angular momentum, the amount of energy that can be carried away by gravitational or any other form of radiation is less than $(2-\sqrt{2})m$.

I assume the validity of the Carter-Israel conjucture[6,7] that the metric outside a collapsed object settles down to that of one of the Kerr family of solutions[8] with positive mass m and angular momentum a per unit mass less than or equal to m. (I am using units in which $G=c=1$.) Each of these solutions contains a nonsingular *event horizon*, two-dimensional sections of which are topographically spheres with area[9]

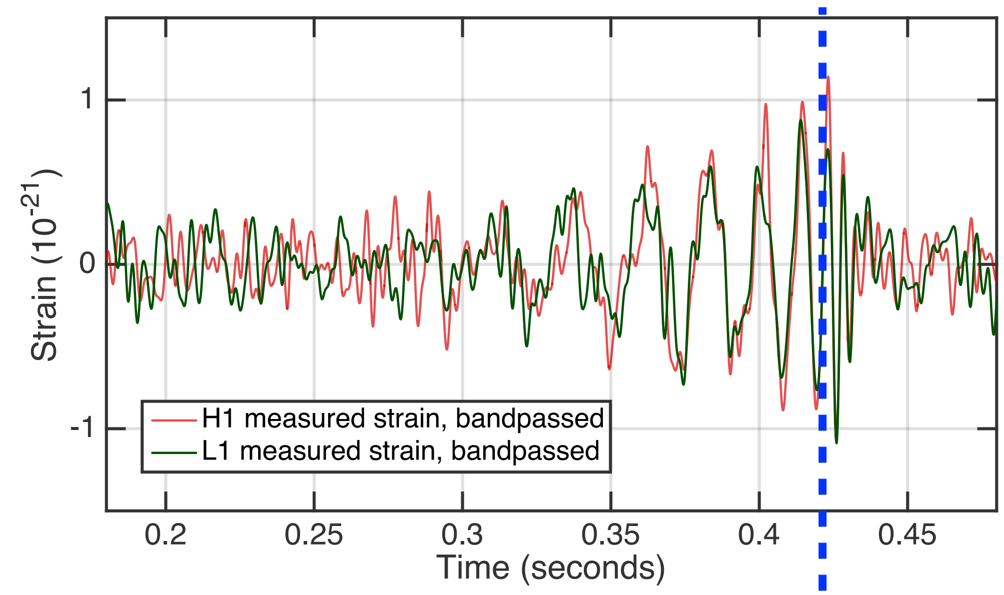
$$8\pi m[m+(m^2-a^2)^{1/2}]. \tag{1}$$

The event horizon is the boundary of the region of space-time from which particles or photons can escape to infinity. I shall consider only

Hawking's Area Theorem PRL 21, 1344 (1971)

- Plug in m_1, m_2, m_f and s_f: it's satisfied!
- Problem: most of the SNR is before the merger, so only values of m_1, m_2 are determined independently. The value of m_f and s_f are determined by numerical relativity (which gives the matching waveforms). GUARANTEED to satisfy the area theorem, because the numerical solution satisfies Einstein's equations.

$$m_f^2\left(1+\sqrt{1-s_f^2}\right) >$$
$$m_1^2\left(1+\sqrt{1-s_1^2}\right)+m_2^2\left(1+\sqrt{1-s_2^2}\right)$$



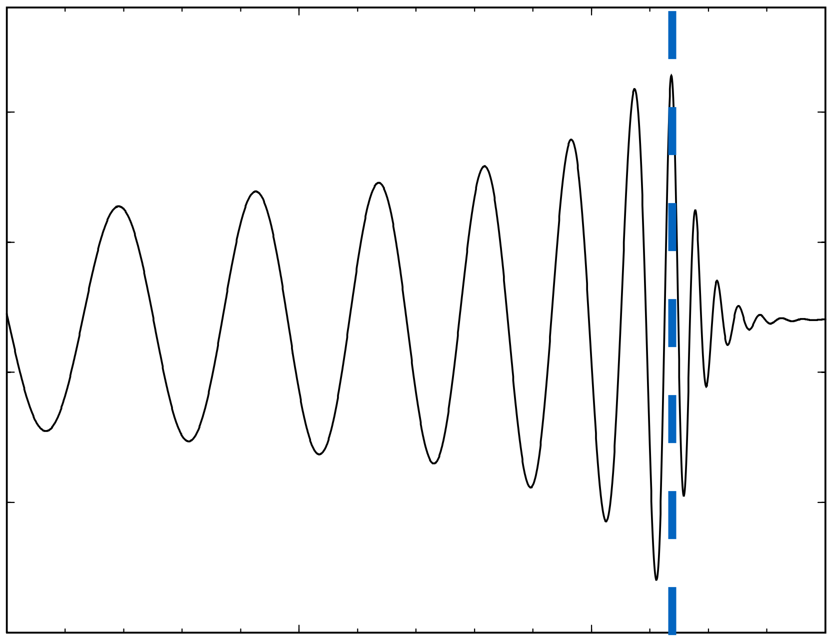
For this event, the area theorem is being tested by the code that's solving Einstein equations, not by Nature.

How to test the Area Theorem

- Starting 10M-20M after the peak/merger, waveform described by sum of quasi-normal modes

$$e^{-t/\tau}\sin(2\pi f t+\phi)$$

- Low spin: dominant mode 220
- For GW150914, 10M = 3.3 msec ~ one cycle after peak
- From frequency f and damping time τ determine mass M and spin s

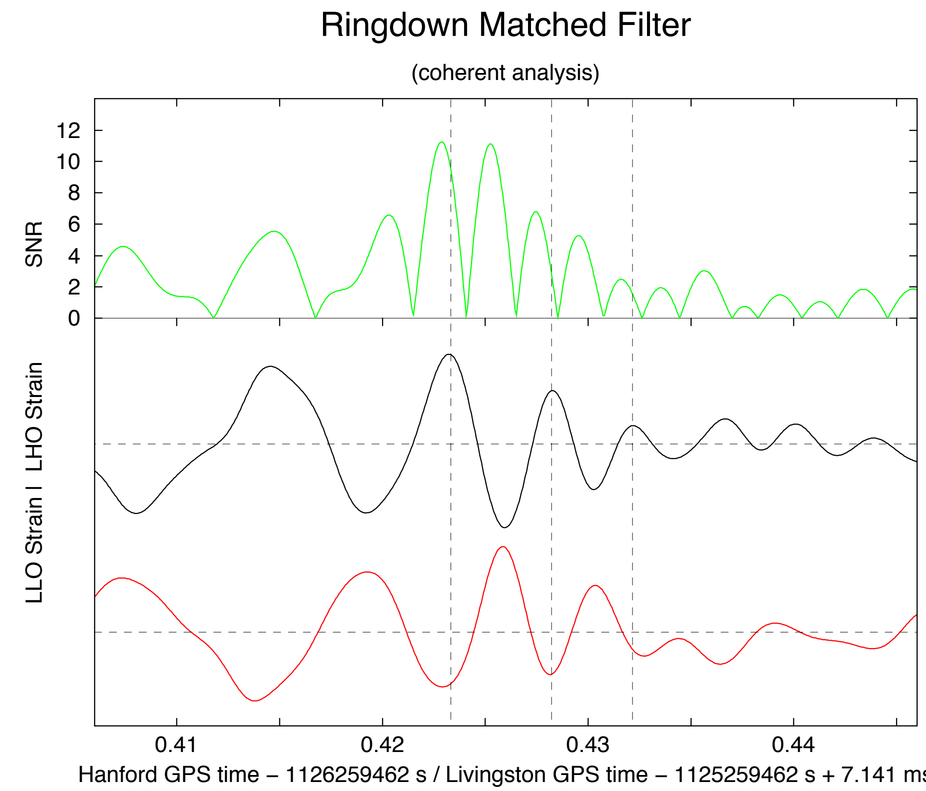


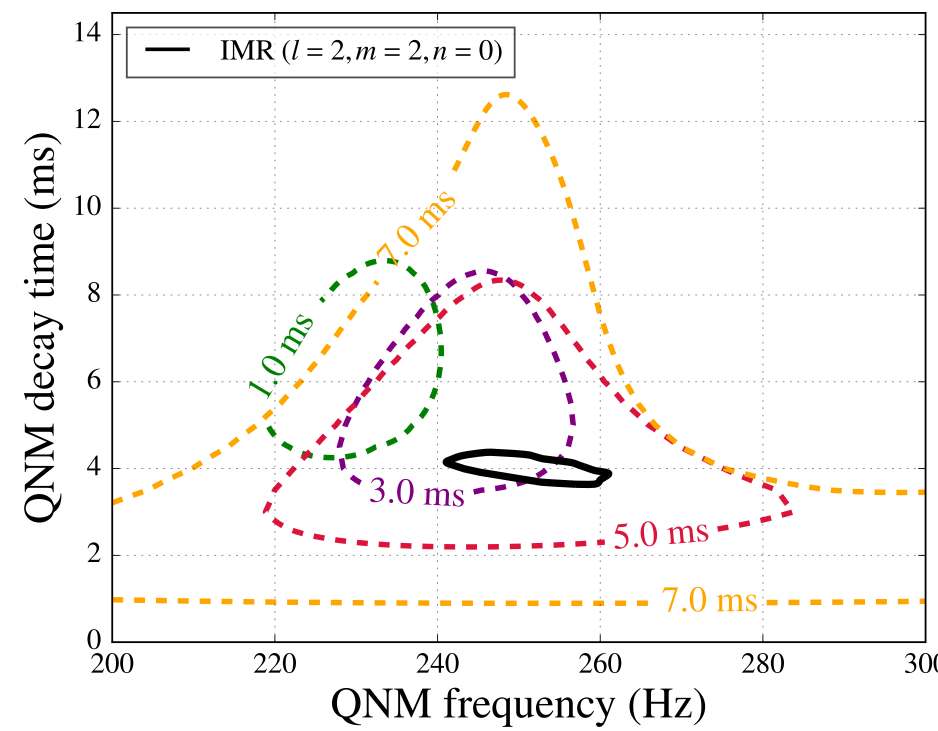
$$\begin{aligned} f &= \left(\frac{70M_\odot}{M}\right)\left(686-520(1-s)^{0.13}\right)\ \mathrm{Hz} \\ \tau &= \left(0.7+1.42(1-s)^{-0.5}\right)/(\pi f) \end{aligned}$$

Berti, Cardoso, and Will, Phys. Rev. D73, 064030 (2006).
Kamaretsos, Hannam, Husa, and Sathyaprakash, PRD85, 024018 (2012)

How to test the Area Theorem

- Dotted lines show 10M (3.3 msec) and 20M (6.6 msec) after the peak for GW150914
- A ringdown matched filter has almost no SNR left
- Can not find m_f and s_f accurately enough to test the area theorem





Things I didn't talk about

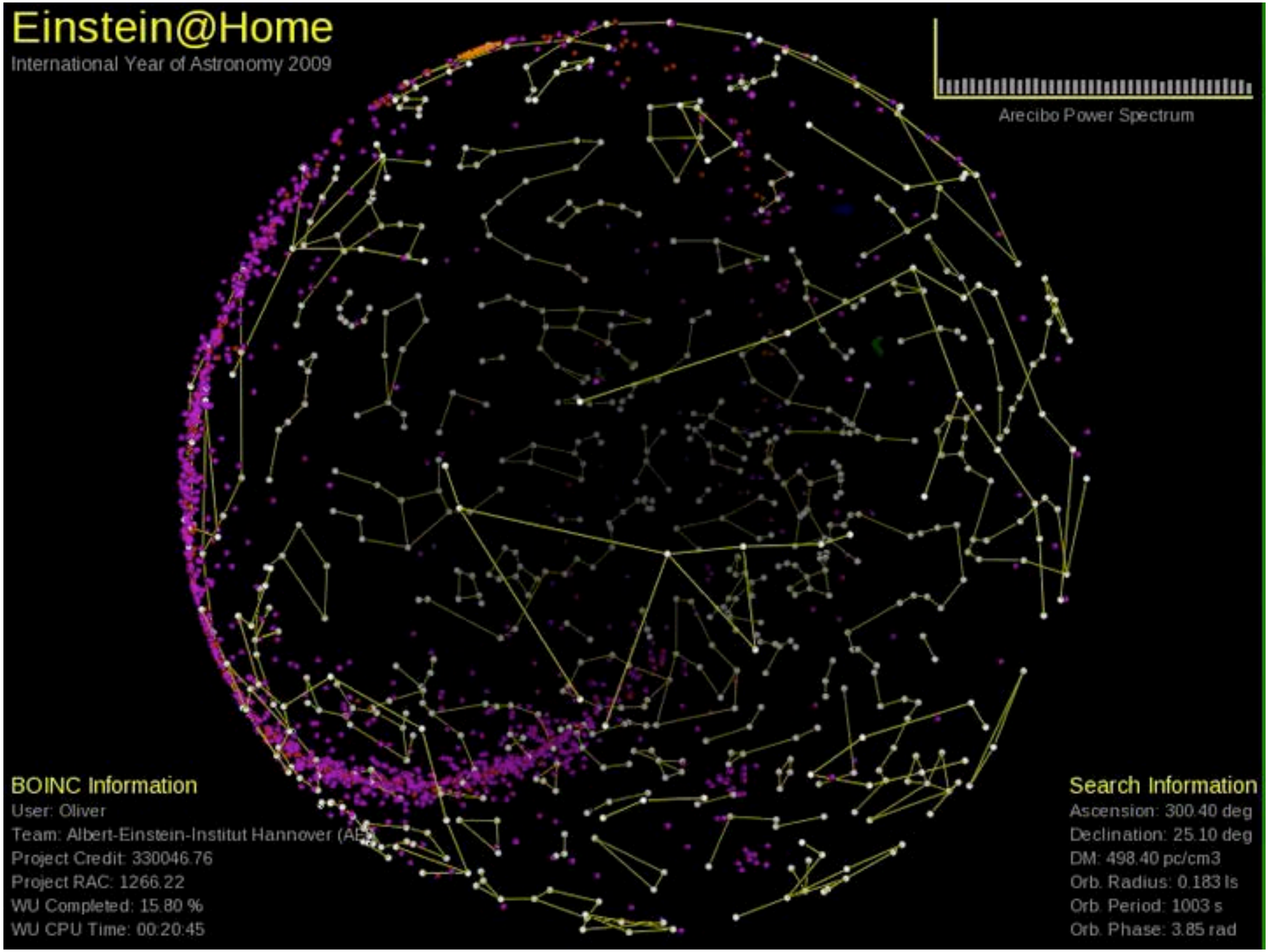
- Testing GR: everything consistent. Nice limits on PN parameters.
- Upper limit on graviton mass (dispersion of the vacuum): Compton wavelength of the gravition > 10^{13} km
- Astrophysical implications: metallicity during star formation that led to these BH could not have been too large
- Limit on the rate per space-time volume
  2 - 400 per cubic Gpc per year
  (broad range, will get better in coming year…)
- Stochastic "background" from more distant weaker sources: potentially detectable when we reach design sensitivity

Prospects

- Published work covers data from 12 Sept - 20 Oct 2015. But the observing run continued to Jan 12! Maybe there are more…
- O2 run will start in September 2016. A 60% sensitivity improvement will increase observable volume by a factor of 4: perhaps one event every four days: 10-20 events. Adding VIRGO to the network would increase pointing sensitivity, provide polarisation information
- O3 run will start in 2017. Additional sensitivity increase: one event per day for a year!
- Over the coming several years we will know the mass and spin distribution of these sources
- Report of a weak gamma-ray burst (GBM onboard Fermi satellite) 0.4 seconds after The Event
- Hope to get at least one event strong enough to directly determine the final mass and spin and test the area theorem

THANK YOU!

To help us to find MORE gravitational waves, please sign up your home and office computers to Einstein@Home



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