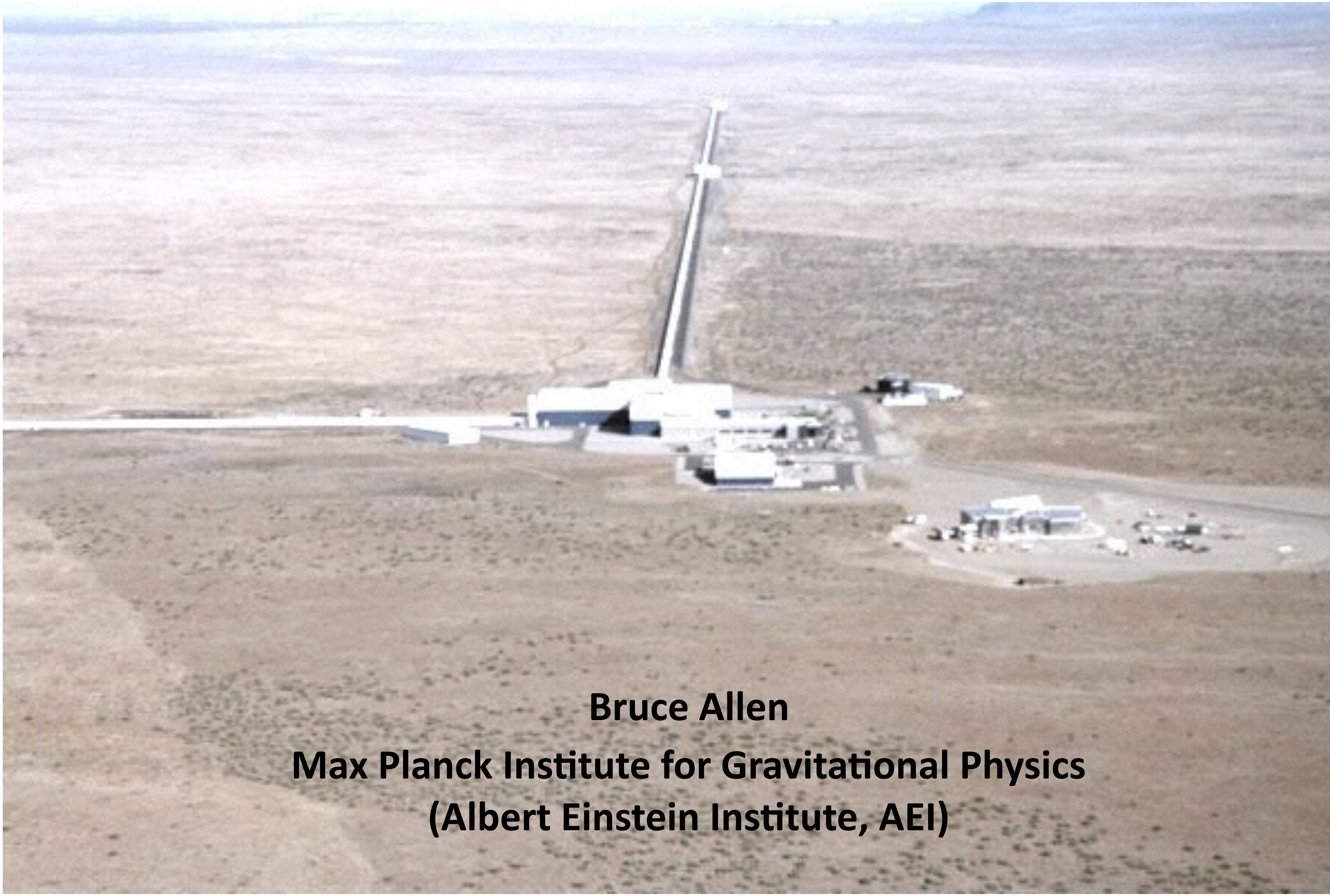
The LIGO Discoveries



Bruce Allen

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute, AEI)


DER SPIEGEL
Nr. 7 / 13.2.2016
Deutschland €4,60
Brummmm!
DIE SPRACHE DER
STERNE
Sensationelle Signale: Das Universum erzählt sein Geheimnis
BRANDHERD SYRIEN
Der Krieg, der unsere Welt verändert

Discovery Paper (+ companion papers and 1h data release)

"The statistic that really struck me was that in the first 24 hours, not only was the page for your PRL abstract hit 380,000 times, but the PDF of the paper was downloaded from that page 230,000 times. This is far more hits than any PRL ever, and the fraction of times that it resulted in a download was unusually high. Hundreds of thousands of people actually wanted to read the whole paper! That is just remarkable."

Robert Garistro, PRL editor

PRL **116,** 061102 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}M_\odot$ and $29^{+4}_{-4}M_\odot$, and the final black hole mass is $62^{+4}_{-4}M_\odot$, with $3.0^{+0.5}_{-0.5}M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that the linearized weak-field equations had wave solutions: transverse waves of spatial strain that travel at the speed of light, generated by time variations of the mass quadrupole moment of the source [1,2]. Einstein understood that gravitational-wave amplitudes would be remarkably small; moreover, until the Chapel Hill conference in 1957 there was significant debate about the physical reality of gravitational waves [3].

Also in 1916, Schwarzschild published a solution for the field equations [4] that was later understood to describe a black hole [5,6], and in 1963 Kerr generalized the solution to rotating black holes [7]. Starting in the 1970s theoretical work led to the understanding of black hole quasinormal modes [8–10], and in the 1990s higher-order post-Newtonian calculations [11] preceded extensive analytical studies of relativistic two-body dynamics [12,13]. These advances, together with numerical relativity breakthroughs in the past decade [14–16], have enabled modeling of binary black hole mergers and accurate predictions of their gravitational waveforms. While numerous black hole candidates have now been identified through electromagnetic observations [17–19], black hole mergers have not previously been observed.

[*]Full author list given at the end of the article.

The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery, along with emerging astrophysical understanding [22], led to the recognition that direct observations of the amplitude and phase of gravitational waves would enable studies of additional relativistic systems and provide new tests of general relativity, especially in the dynamic strong-field regime.

Experiments to detect gravitational waves began with Weber and his resonant mass detectors in the 1960s [23], followed by an international network of cryogenic resonant detectors [24]. Interferometric detectors were first suggested in the early 1960s [25] and the 1970s [26]. A study of the noise and performance of such detectors [27], and further concepts to improve them [28], led to proposals for long-baseline broadband laser interferometers with the potential for significantly increased sensitivity [29–32]. By the early 2000s, a set of initial detectors was completed, including TAMA 300 in Japan, GEO 600 in Germany, the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States, and Virgo in Italy. Combinations of these detectors made joint observations from 2002 through 2011, setting upper limits on a variety of gravitational-wave sources while evolving into a global network. In 2015, Advanced LIGO became the first of a significantly more sensitive network of advanced detectors to begin observations [33–36].

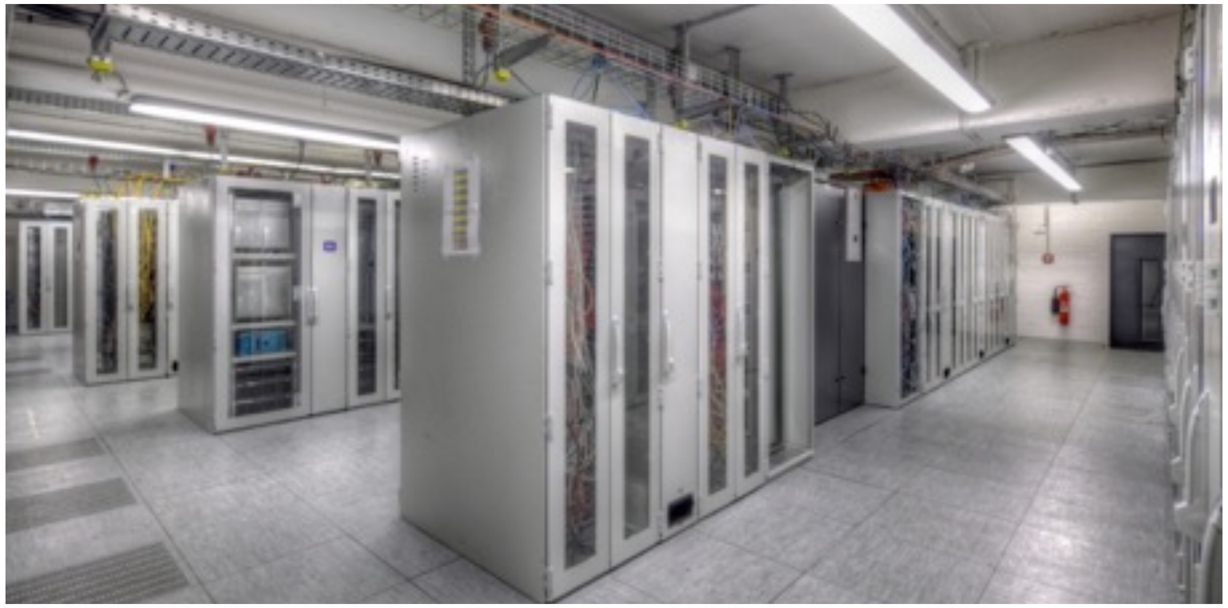
A century after the fundamental predictions of Einstein and Schwarzschild, we report the first direct detection of gravitational waves and the first direct observation of a binary black hole system merging to form a single black hole. Our observations provide unique access to the

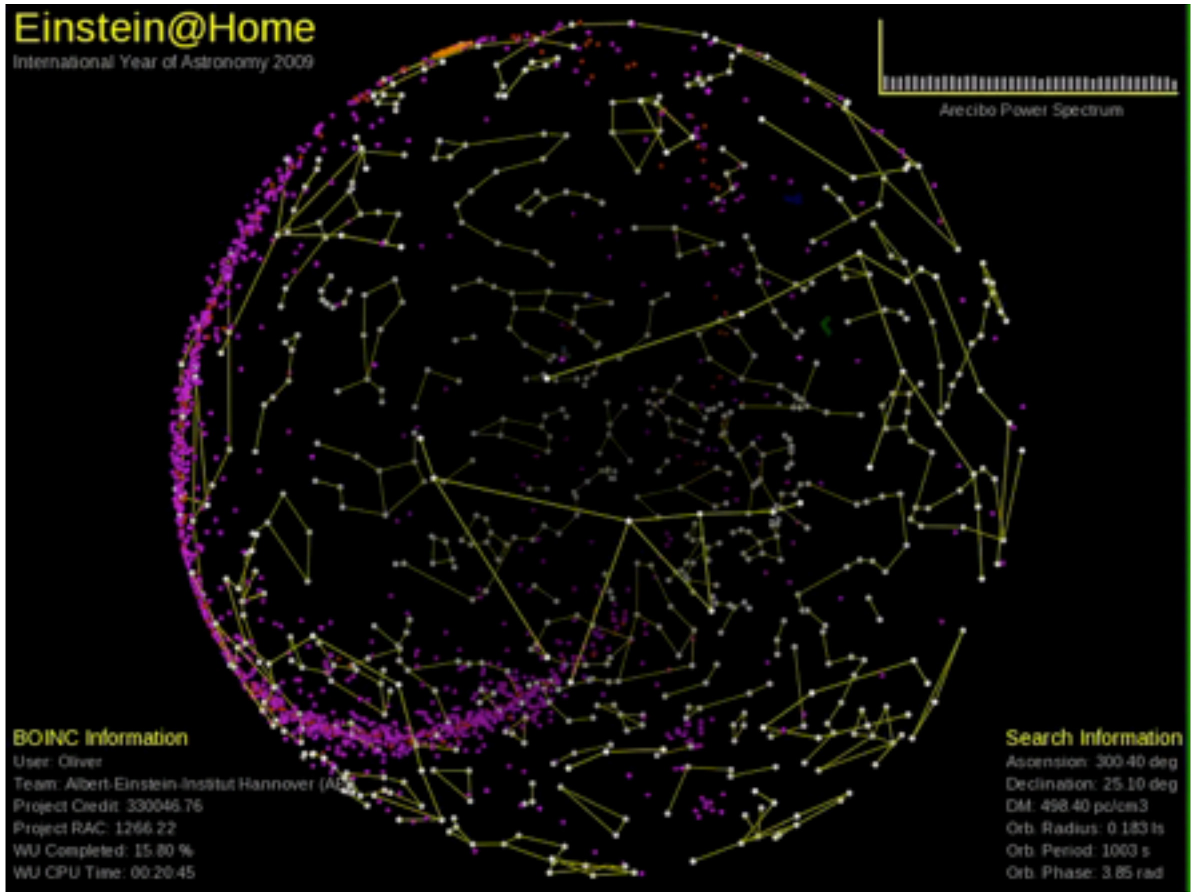
Outline

- On 14 September 2015, 4 days ***before*** starting its first observational run O1, Advanced LIGO recorded a strong gravitational wave burst
- Source unambiguous. In source frame: **merger of a 29 and 36 solar mass BH**
- What did we see?
  How do we know it is two black holes?
  How can we be sure it is real?
  What was going on "behind the scenes"?
  What do we know about the system?
  [Basic physics arguments: arXiv:1608.01940, Annalen der Physik, 10.1002/andp.201600209]
- Further discoveries, prospects for the future

Something about myself

- Worked on LIGO data analysis since mid-1990s
- Group at AEI: 40 people
- Atlas is the largest resource world-wide in the LIGO/VIRGO collaboration: 15,000 CPU cores, 2,500 GPUs, 10 PB, 1 MW
- Direct the Einstein@Home volunteer computing project
- Methods and technology also used for conventional (electromagnetic) astronomy: ~100 radio and gamma-ray pulsars discovered so far.





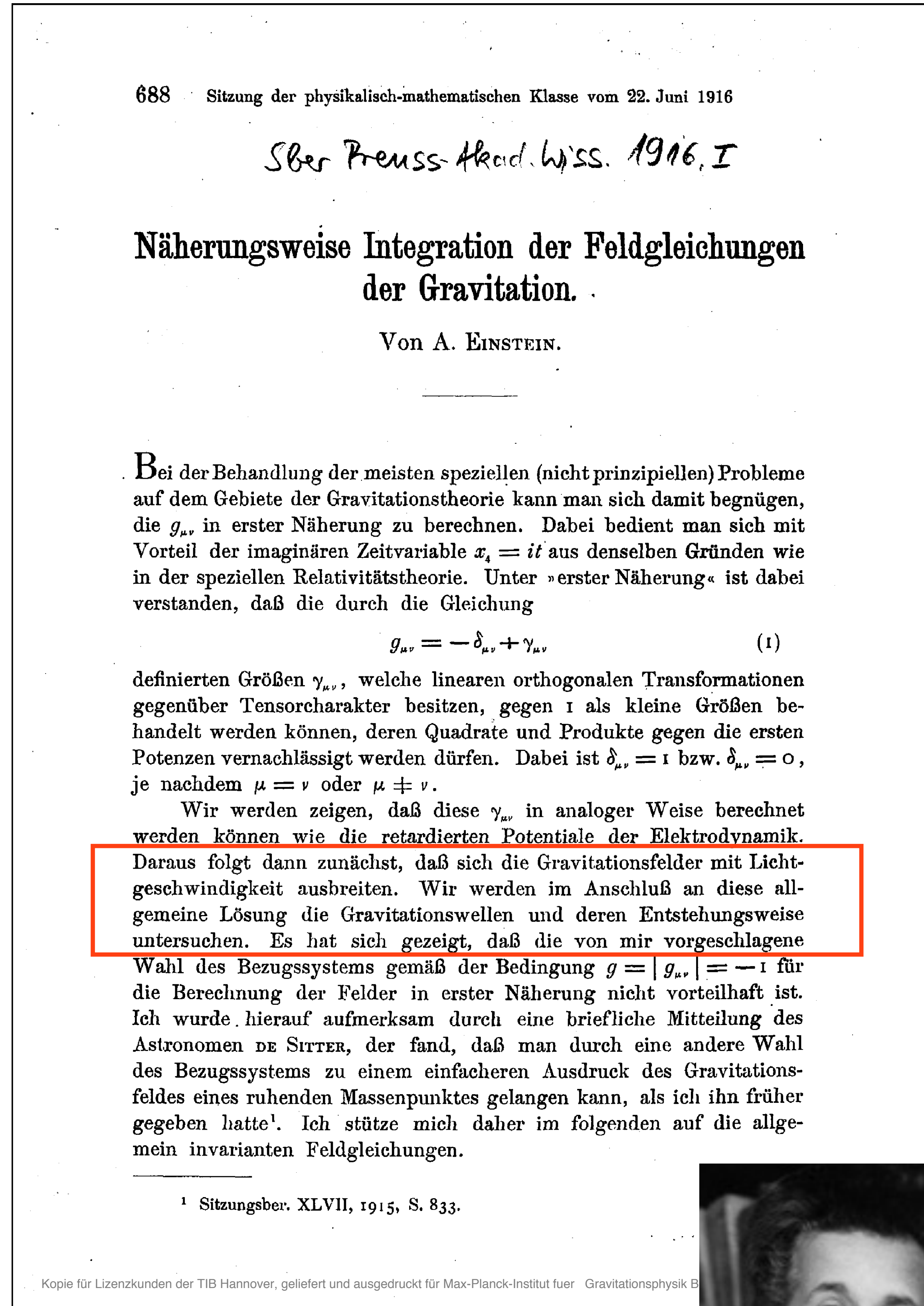
Gravitational Waves

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.)

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



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Sber Preuss. Akad. Wiss. 1916, I

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

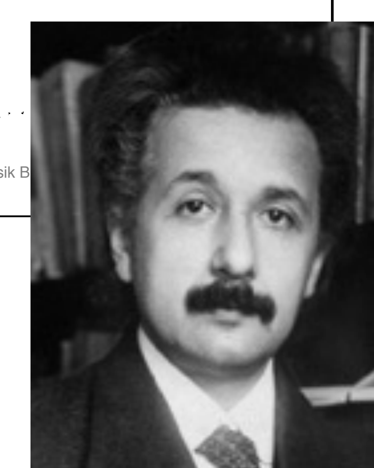
Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen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

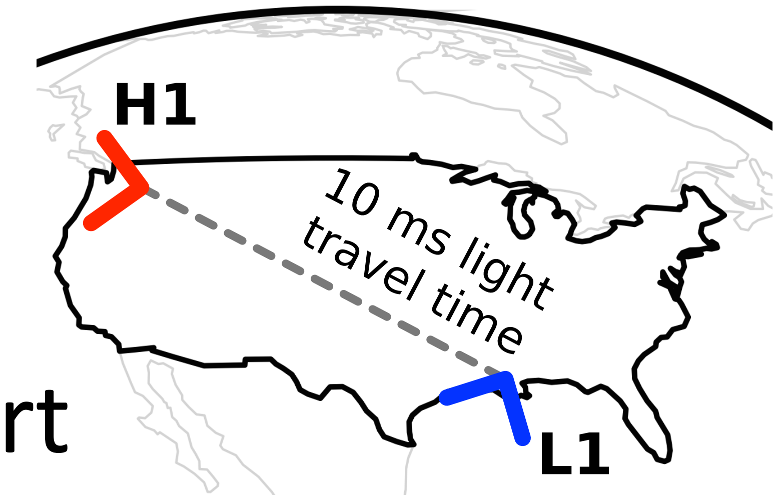
Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen 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.

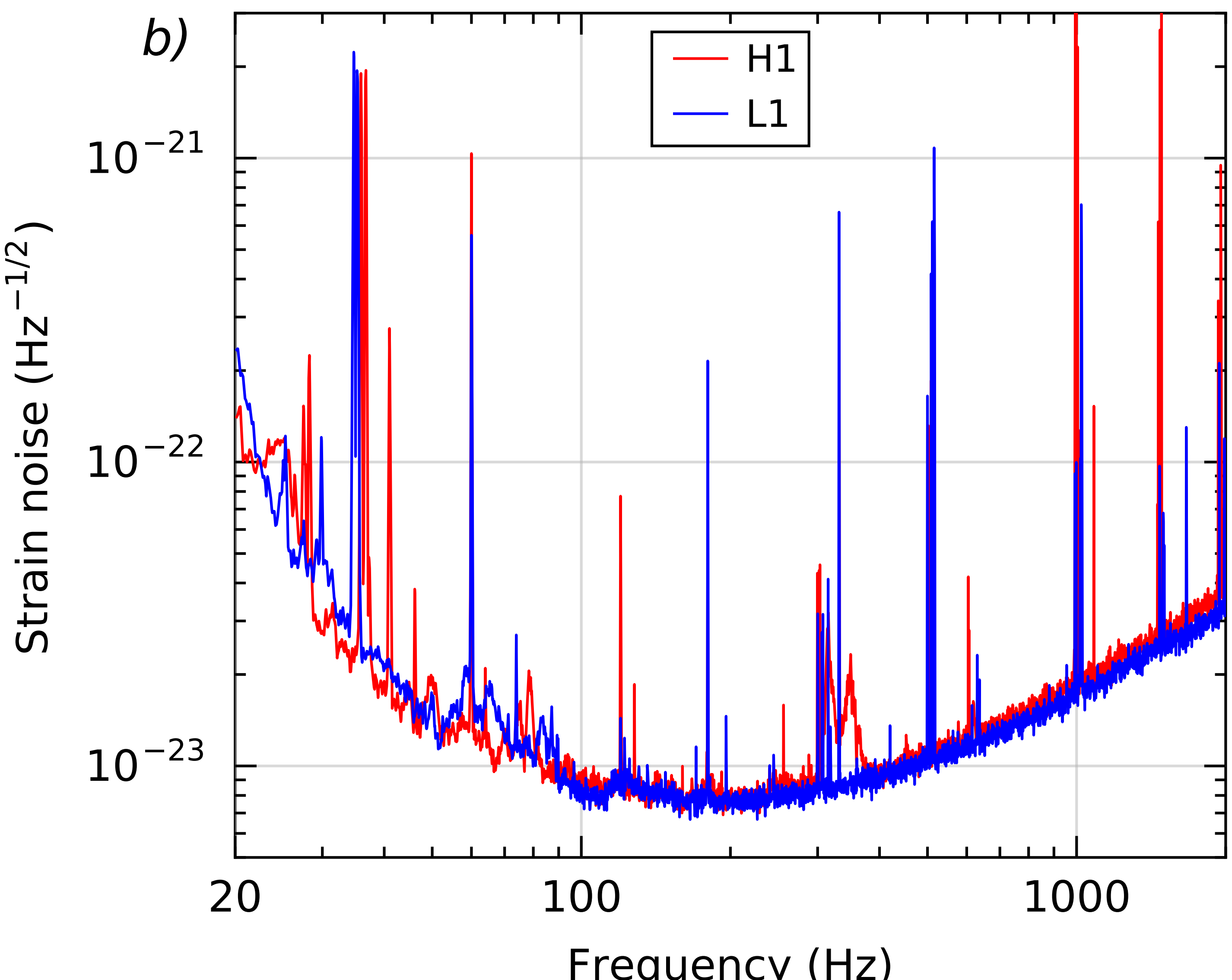
[1] Sitzungsber. XLVII, 1915, S. 833.



Advanced LIGO Detectors

Livingston & Hanford 3000 km apart





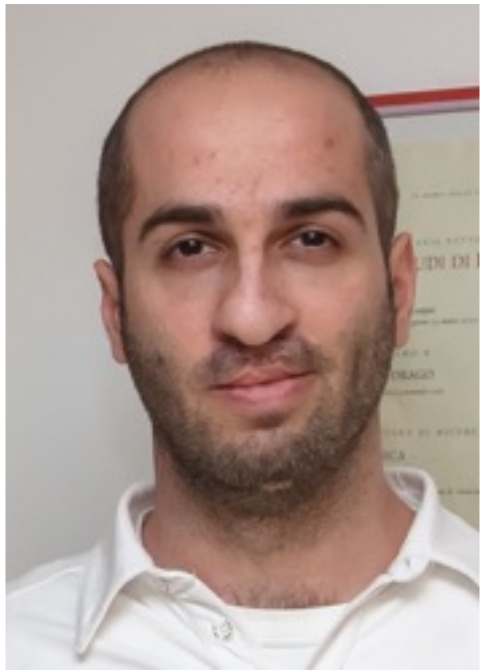
- Sensitive from 30 to 2000 Hz
- Strain $h=\Delta L/L$
- In 100 Hz band at minimum, r.m.s. noise $h\sim10^{-22}$
- O1 noise a factor ~3 above design sensitivity

2016

GW150914

- Engineering run had begun 17 August 2015, for tuning, calibration, injection tests, and noise characterisation studies.
- First observing run O1 ("science operations mode") scheduled to start on **18 September 2015**
- **VIRGO** not operating (under construction)
  GEO-600 lost lock 10 minutes before (AND not sufficiently sensitive at low frequencies)
- **Event before O1 start, at 09:50 UTC on 14 September 2015**
  02:50 at LIGO Hanford, WA
  04:50 at LIGO Livingston, LA
  11:50 in Germany

AEI Hannover, September 14, 2015



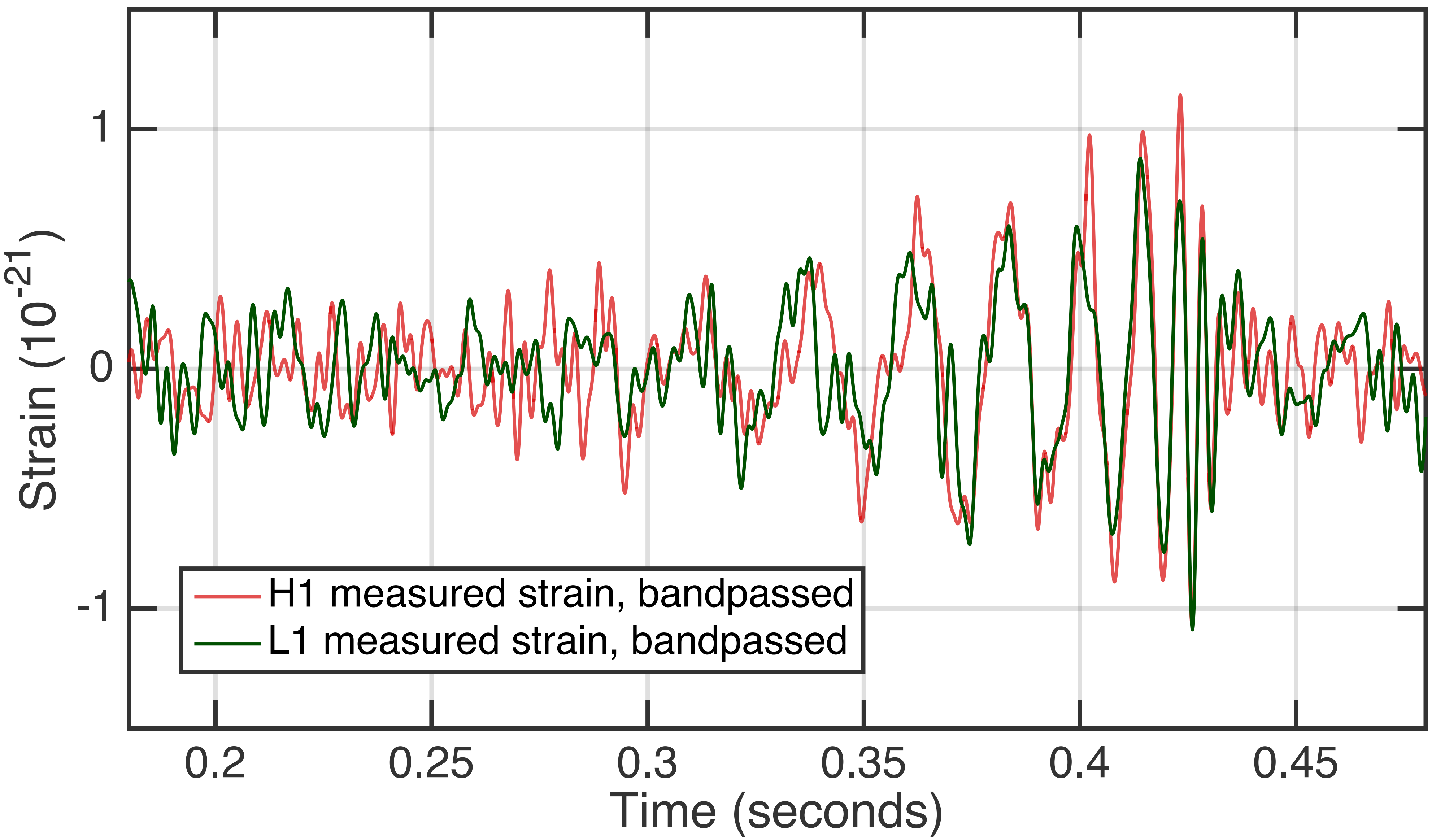
Marco Drago

Andrew Lundgren

- Monday morning 11:50
- 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 LIGO operators: "everyone's gone home"

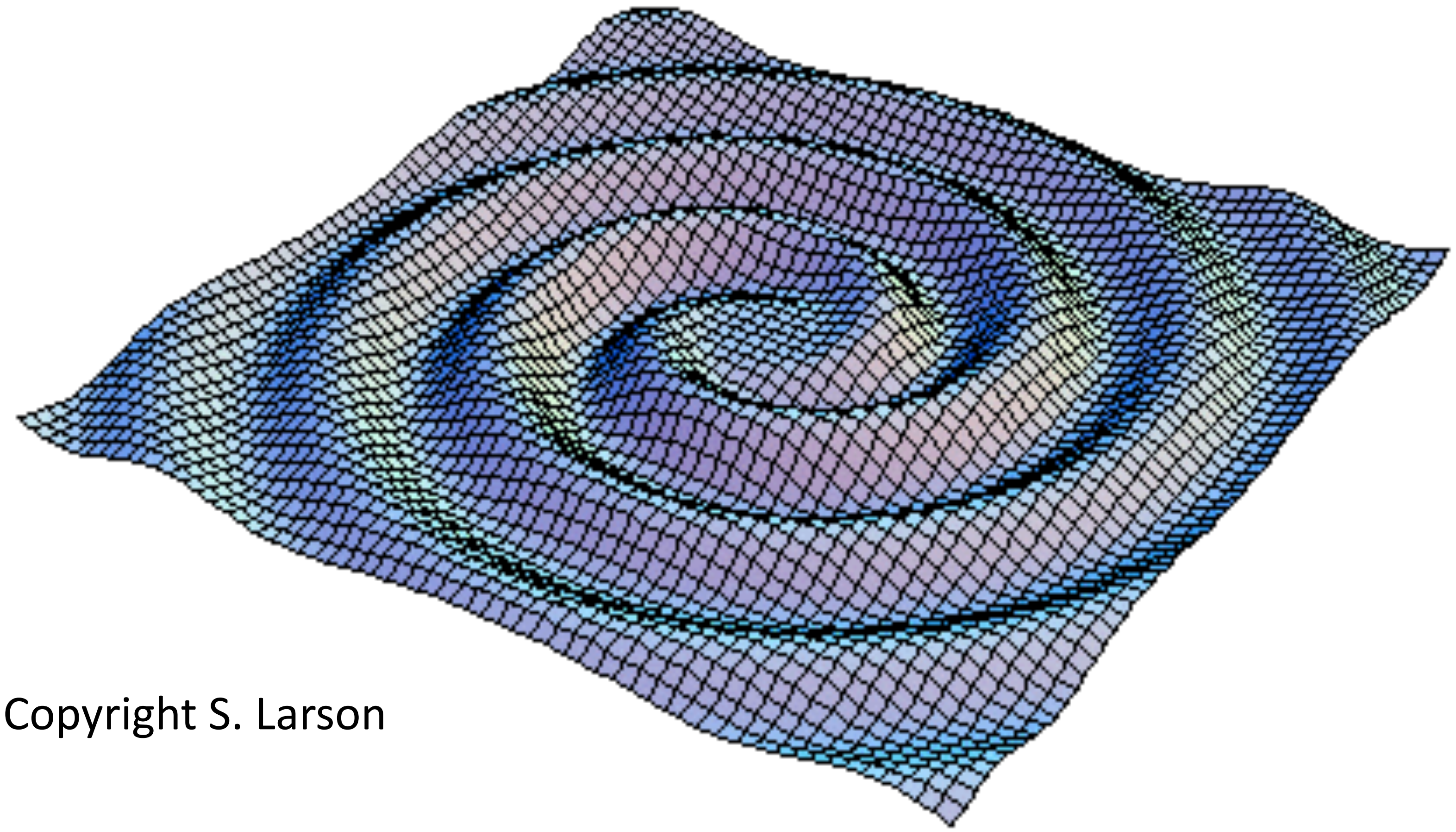
- At 12:54, Marco sent an email to the collaboration, asking for confirmation that it's not a hidden test signal (hardware injection)
- Next hours: flurry of emails, decision to lock down sites, freeze instrument state

The Chirp



- Bandpass filtered 35-350 Hz, some instrumental and calibration lines removed
- Hanford inverted, shifted 7.1 ms earlier
- Signal visible to the naked eye: ~200 ms
- "Instantaneous" SNR ~5, optimal filter SNR ~ 24

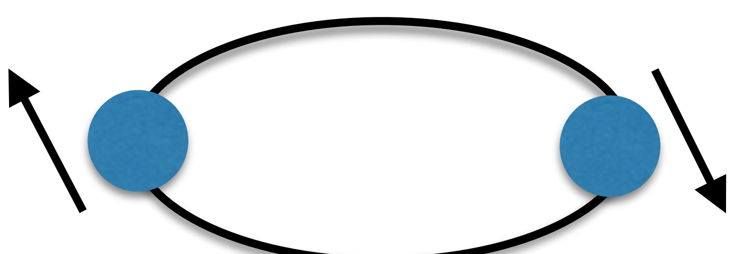
One orbit makes 2 cycles



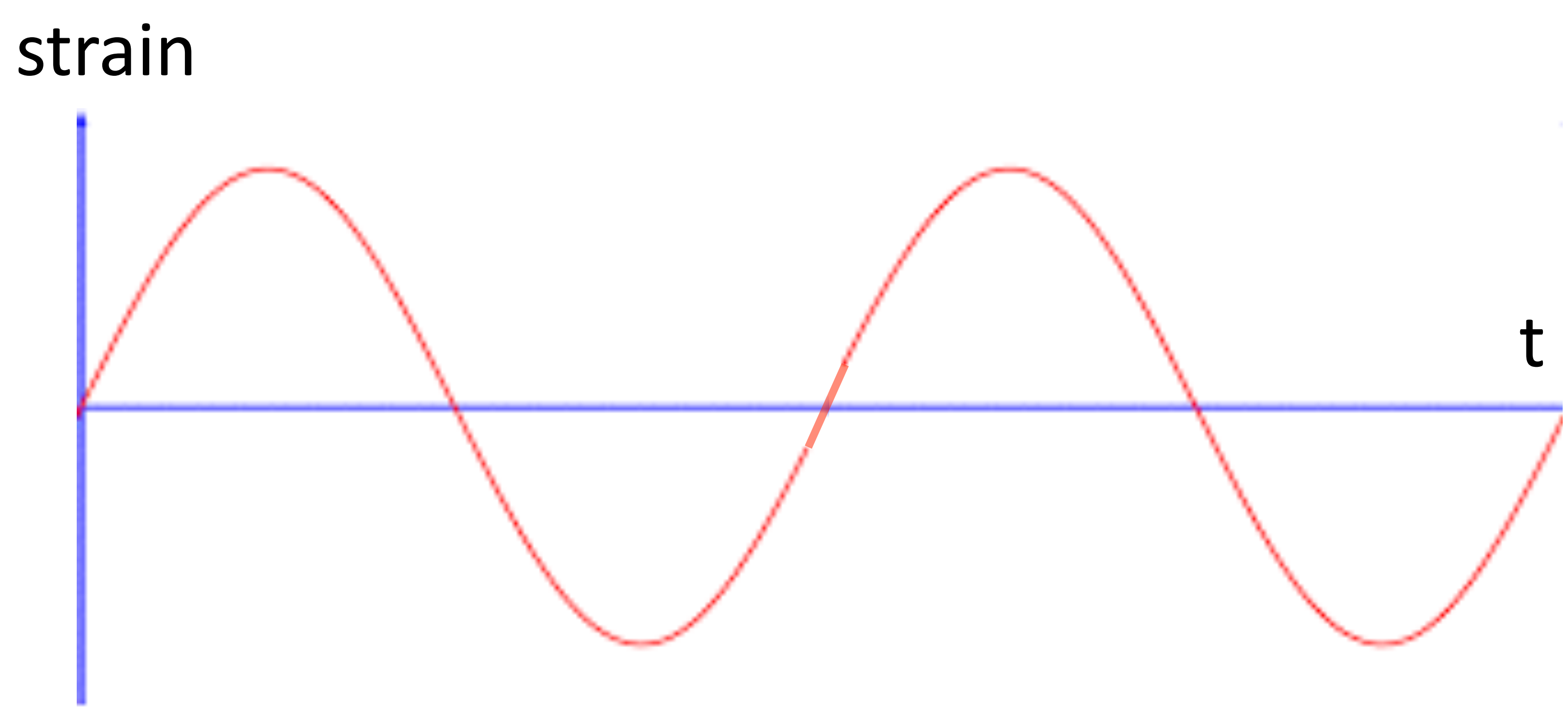
$$d = \Sigma\, m_i\, x_i$$

$$\dot{d} = \Sigma\, m_i\, v_i = p$$

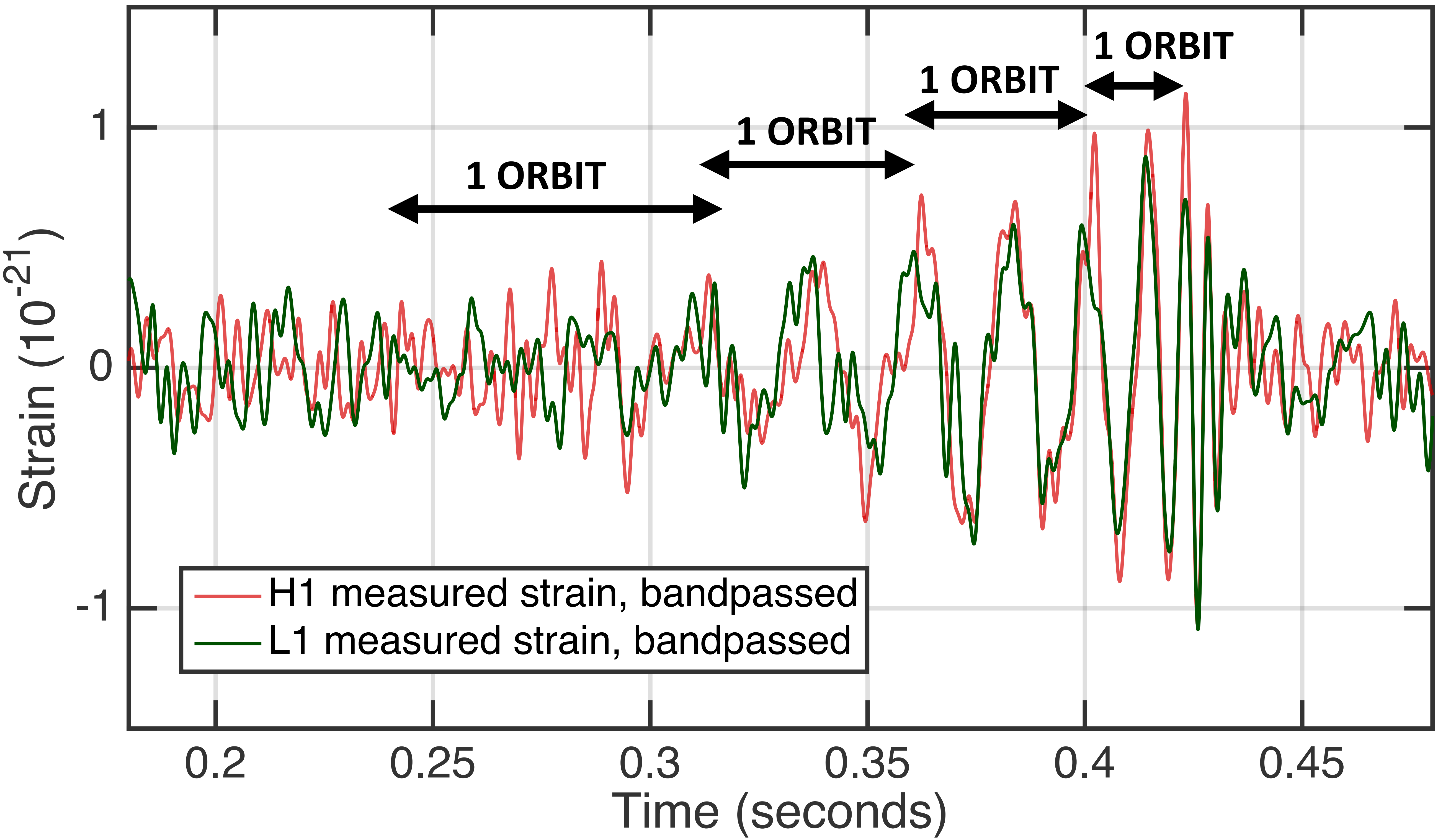
$$\ddot{d} = 0$$



1 orbit

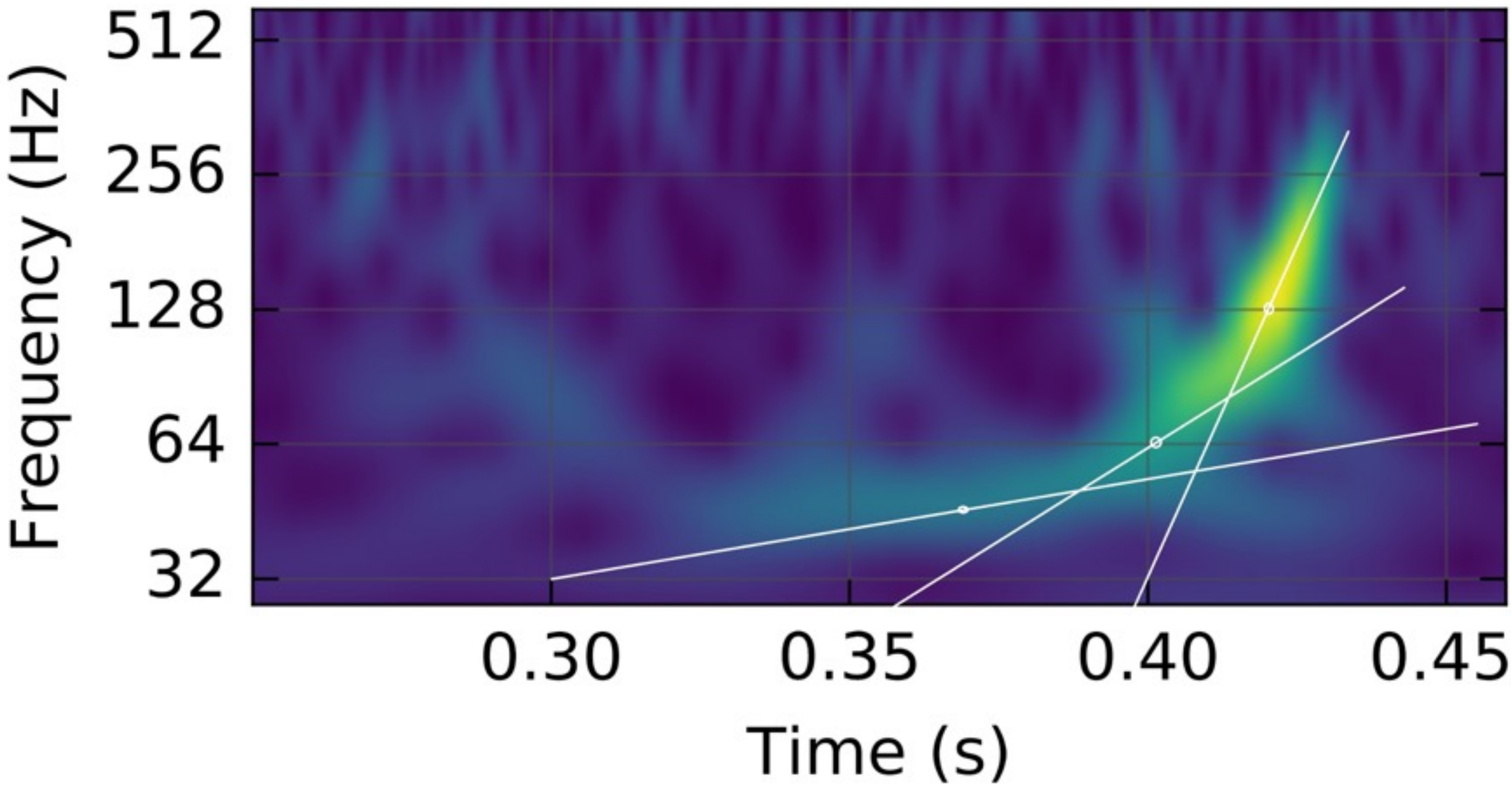


The Chirp



1 ORBIT
1 ORBIT
1 ORBIT
1 ORBIT
1
0
-1
Strain (10^{-21})
0.2
0.25
0.3
0.35
0.4
0.45
Time (seconds)
H1 measured strain, bandpassed
L1 measured strain, bandpassed

Masses of the objects can be read from the rate of frequency increase



Can only be two black holes!

- Newtonian approximation =>

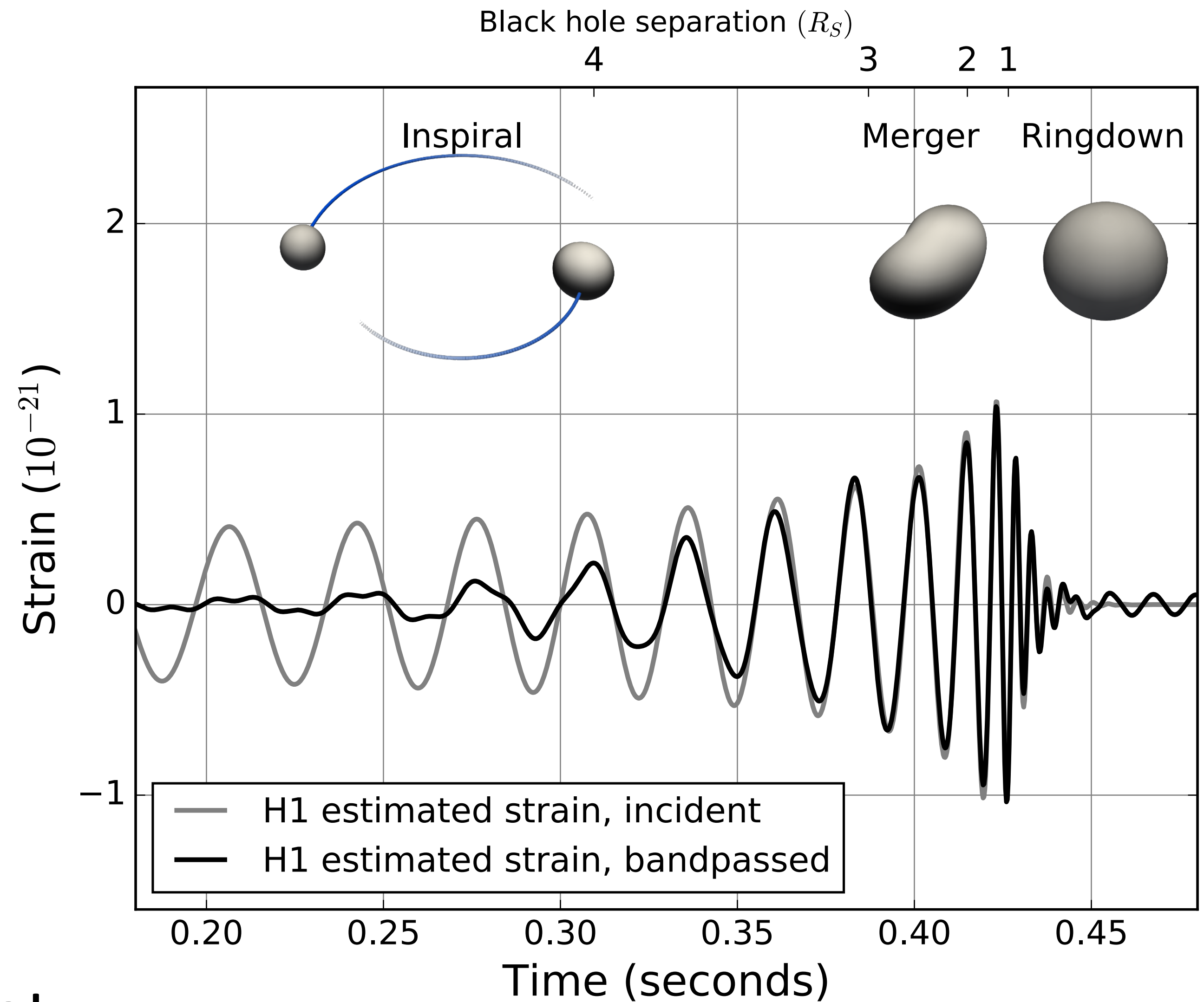
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

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

  => Sum of Schwarzschild radii ≥206km
- At peak f_{GW} = 150 Hz, orbital frequency = 75 Hz. Separation of Newtonian point masses 346km
- **Ordinary stars** are 10^6 km in size (merge at mHz). **White dwarfs** are 10^4 km (merge at 1 Hz). They are too big to explain this!
- **Neutron stars** are also not possible:

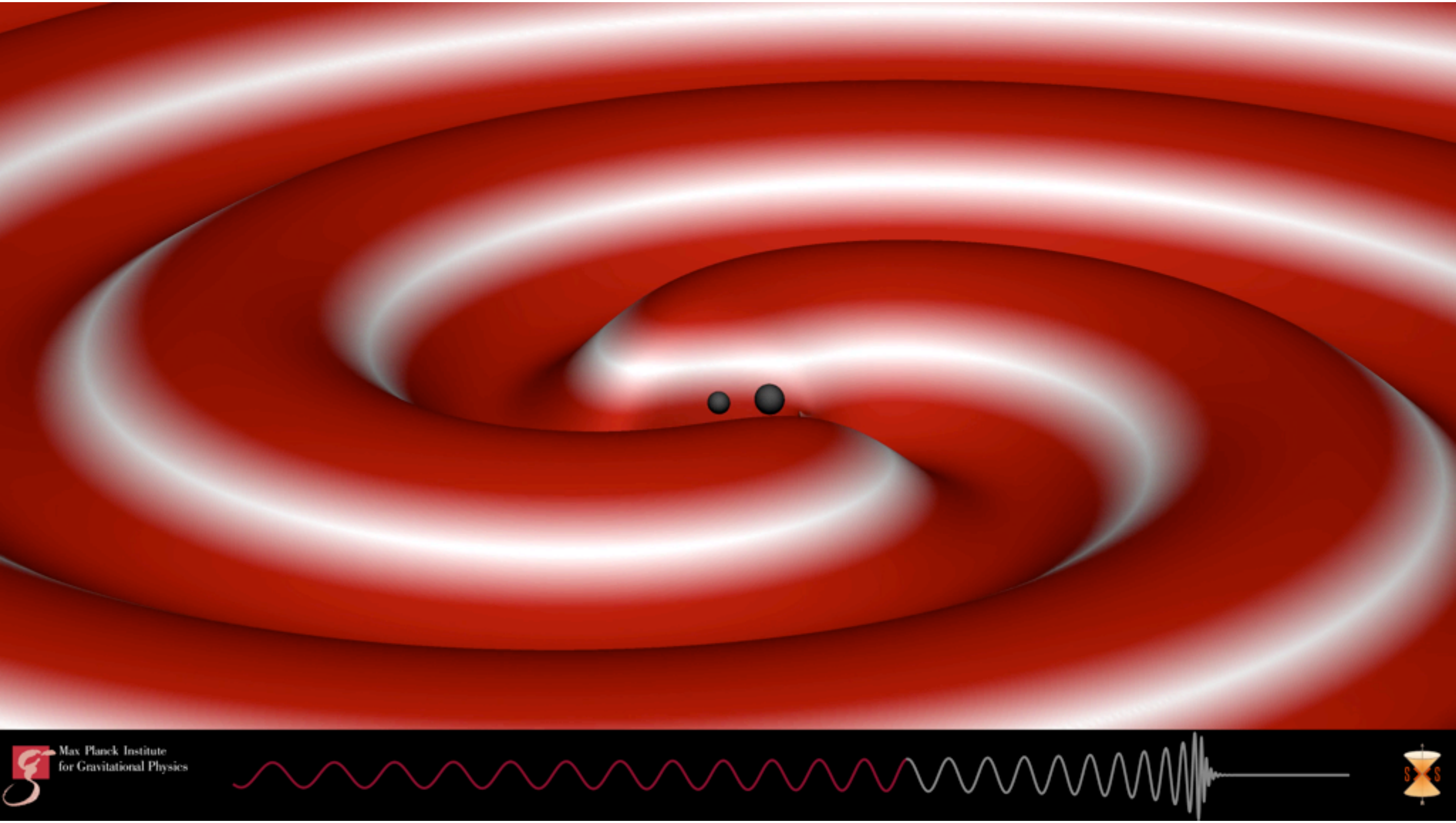
  m_1 = 4 $M_\odot$ => m_2=600 $M_\odot$

  =>Schwarzschild radius 1800km => too big!



Only black holes are sufficiently massive *and* compact!

The Movie



- Alessandra Buonanno and postdocs Sergei Ossokine and Roland Haas, with the SXS Collaboration

Luminosity Distance Estimate

- Schwarzschild radius ~ 200 km
- Metric strain h is order h~0.1 at Schwarzschild radius
- Strain h fall off like inverse of distance d
- At detector, maximum metric perturbation $h \sim 10^{-21}$
- This implies a distance
  $d \sim 10^{20}$ x 200 km
  ~ 2 x 10^{25} m
  ~ 2 x 10^{9} light years (correct to factor of two)

Real? Or a detector artifact?

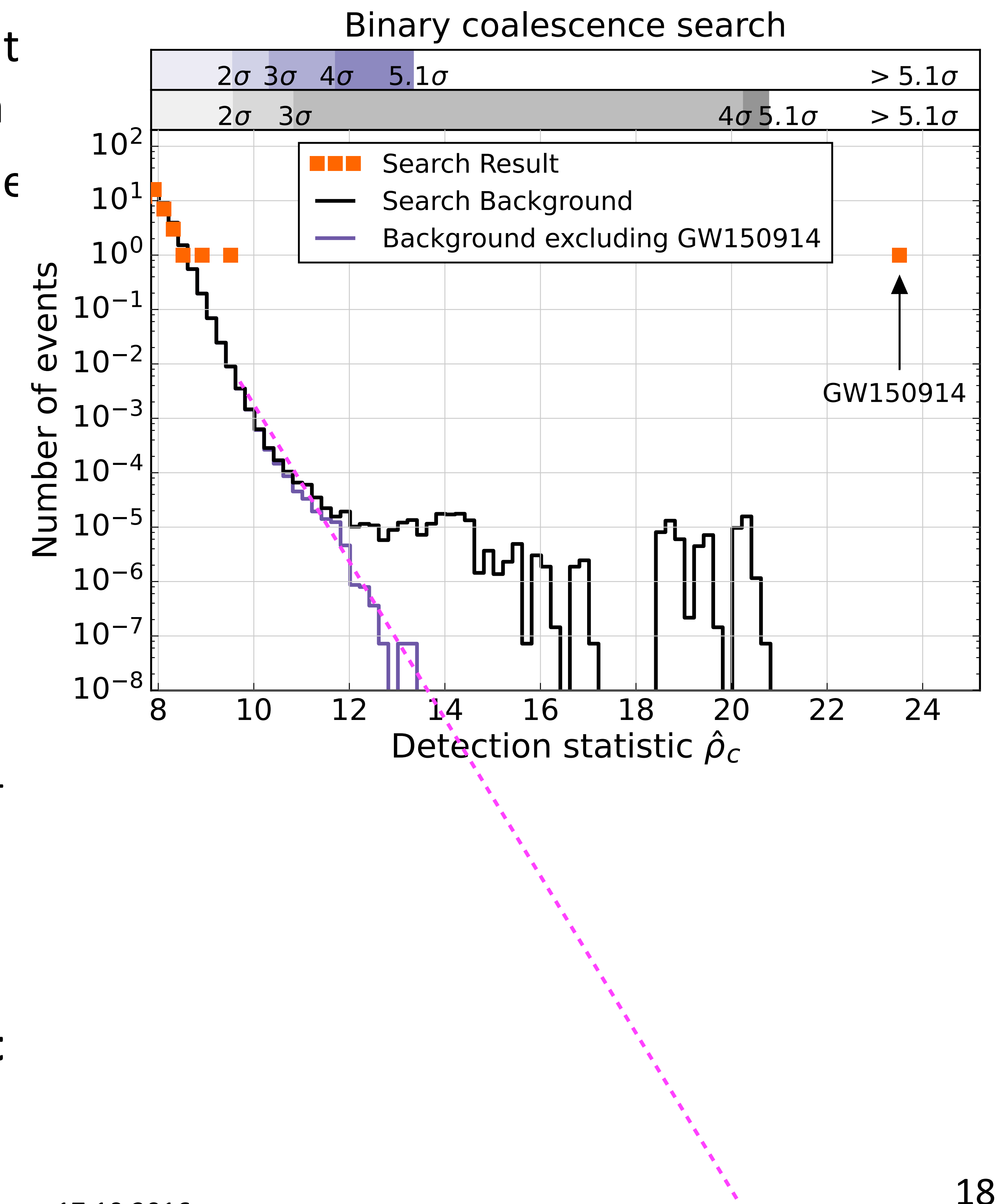
- Instruments in normal operation and stable since September 12th (apart from deliberate intervention)
- This instrument can see such sources at 6 times the distance => 6x6x6 ~ 200 times the rate at initial LIGO instruments
- Last scientists left sites 2 hours (LHO) and 15 minutes (LLO) before the event. Operators only.
- Waveform does not resemble 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


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


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

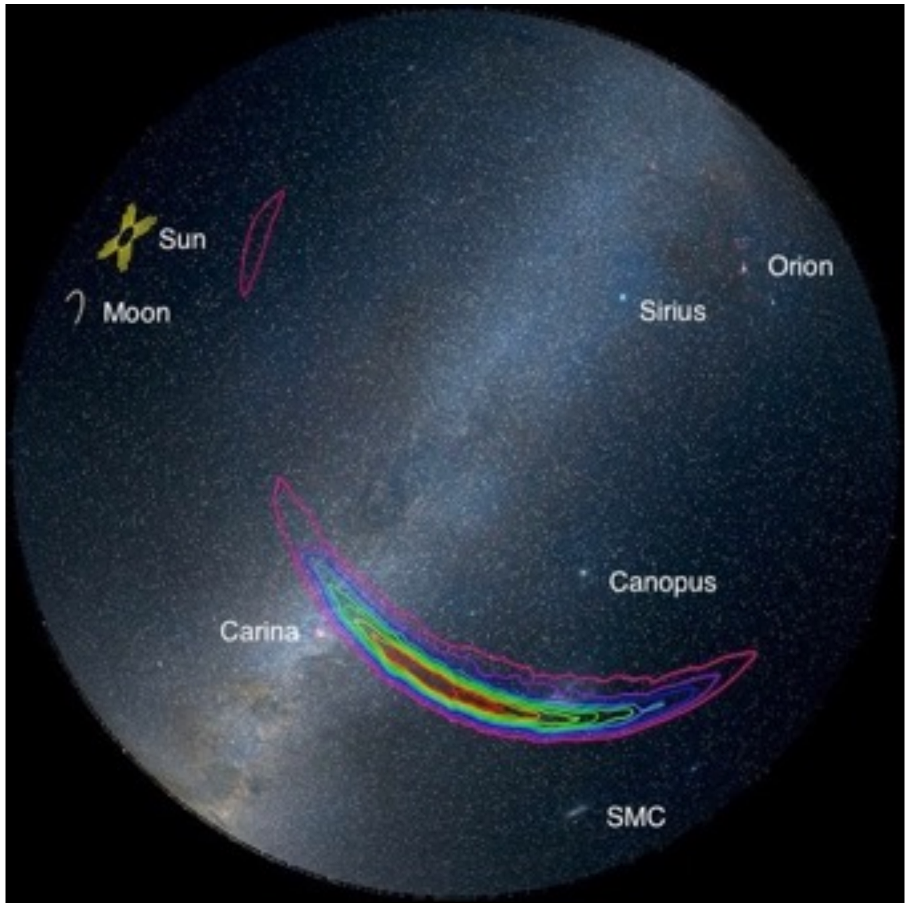
False Alarm Probability

- 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 2x10[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 it 70% farther away.**



Parameters from fitting (in source frame)

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} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

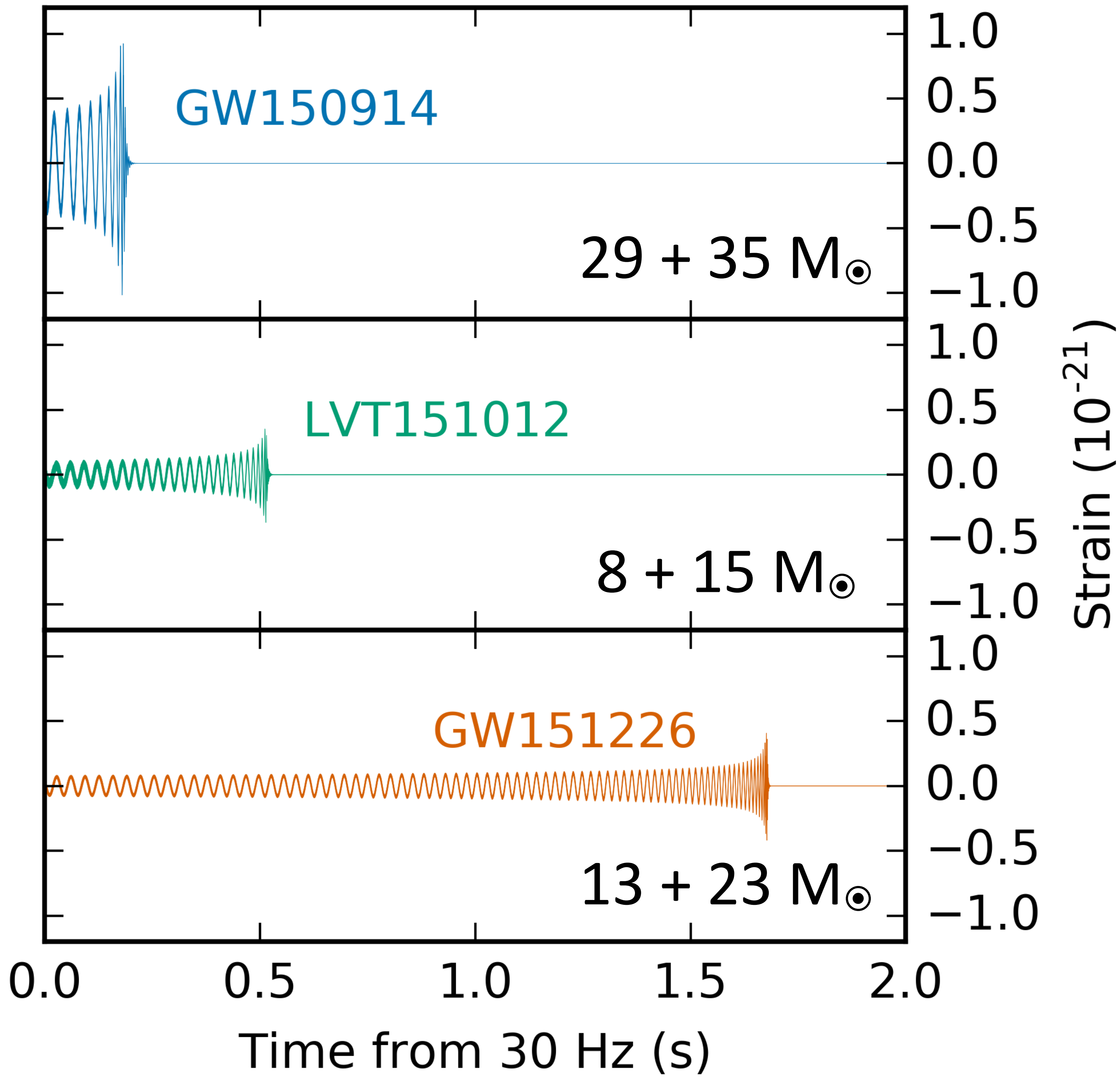


- Radiated energy: $3M_\odot$ (±0.5)
- Peak luminosity: 3.6×10^{56} erg/s (±15%): 200 solar masses per second! (About $1\mu W/cm^2$ at detector, ~10^{12} millicrab!)
- Spins s_1 and s_2 only weakly constrained: not extreme. Consistent with merger of two non-spinning black holes.
- Final spin of 0.67 is about 6000 rpm

Things I didn't talk about

- Testing GR: everything consistent. New ability to test GR in the strong field dynamic regime.
- Second LIGO detection, GW151226
  Astrophysical implications: metallicity during star formation that led to these BH could not have been too large. (Broad) limits on rate per cubic Gpc. **See talk by Ilya Mandel**
- Stochastic "background" from more distant weaker sources: potentially detectable when we reach design sensitivity.
- Report of a weak gamma-ray burst (GBM onboard Fermi satellite) 0.4 seconds after The Event. Other potential LIGO sources of gravitational waves.
- Searches for gravitational waves with other instruments and in other frequency bands (LISA, Pulsar TIming Arrays, …).

Binary Black Holes in O1



20016-18: a “Golden Age” of GW astronomy

- Second observing run O2 starts in November
  30% strain sensitivity improvement, increase observable volume by a factor of 2.4. **~10 events total**
  VIRGO will join at the end, adding better pointing and polarization information
- Advanced LIGO O3 run will start in 2017. Additional sensitivity increase: one event every few days for a year: **~100 events total**
- Within 3 years, we will know the mass and spin distribution of these binary black hole sources
- Expect at least one event strong enough to directly determine the final mass and spin and test the area theorem

LIGO Louisiana status on Friday last week

Conclusions

- We can detect gravitational waves **directly** (tracking amplitude and phase)
- Existence of stellar mass black hole binaries established (not visible any other way!). Will be our dominant source.
- A golden age for GW astronomy is coming. We will go from 2 detections to 10 to 100 in the next few years.
- Other signal sources (NS/NS, NS/BH, CW, or the unexpected. Please sign up for Einstein@Home