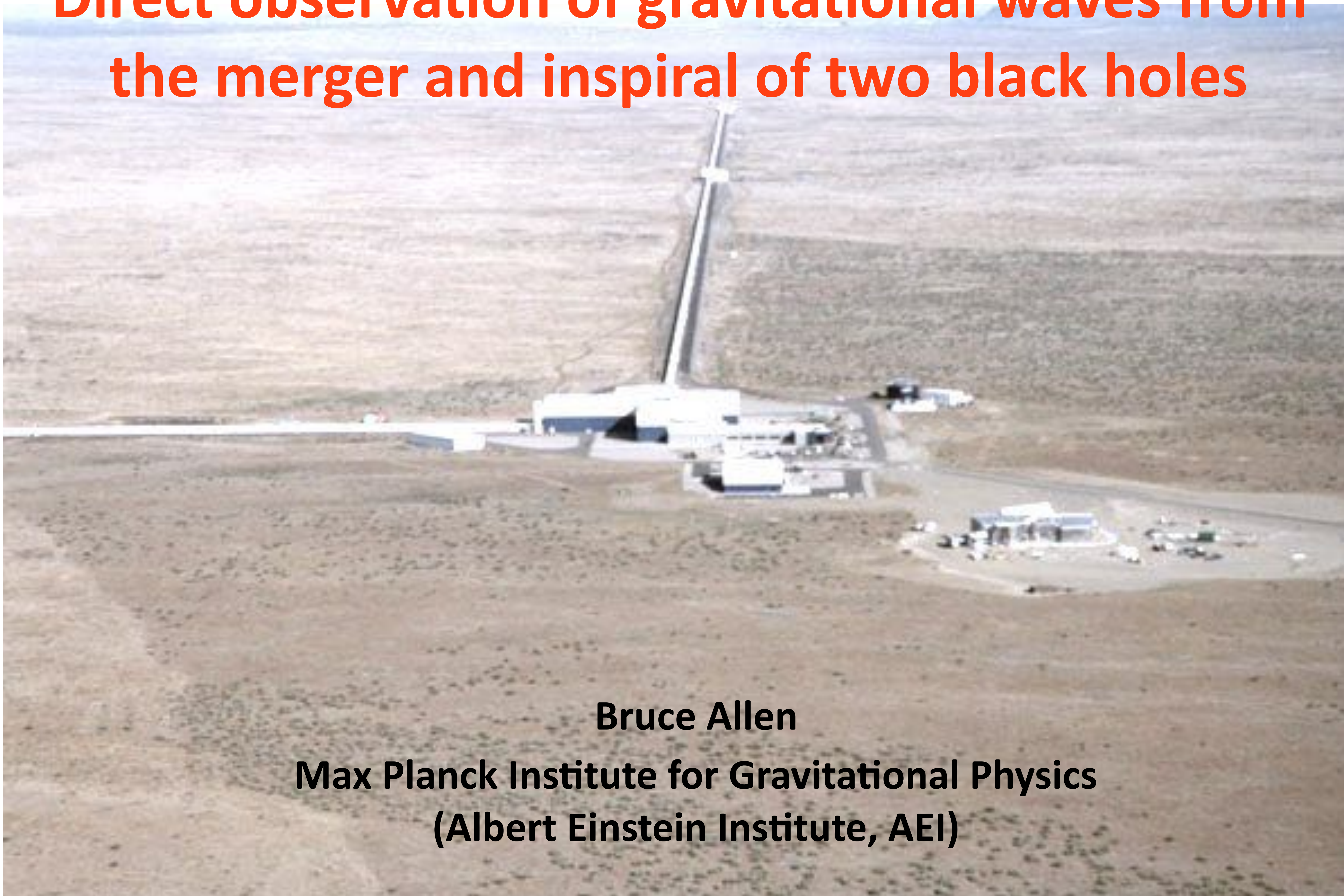
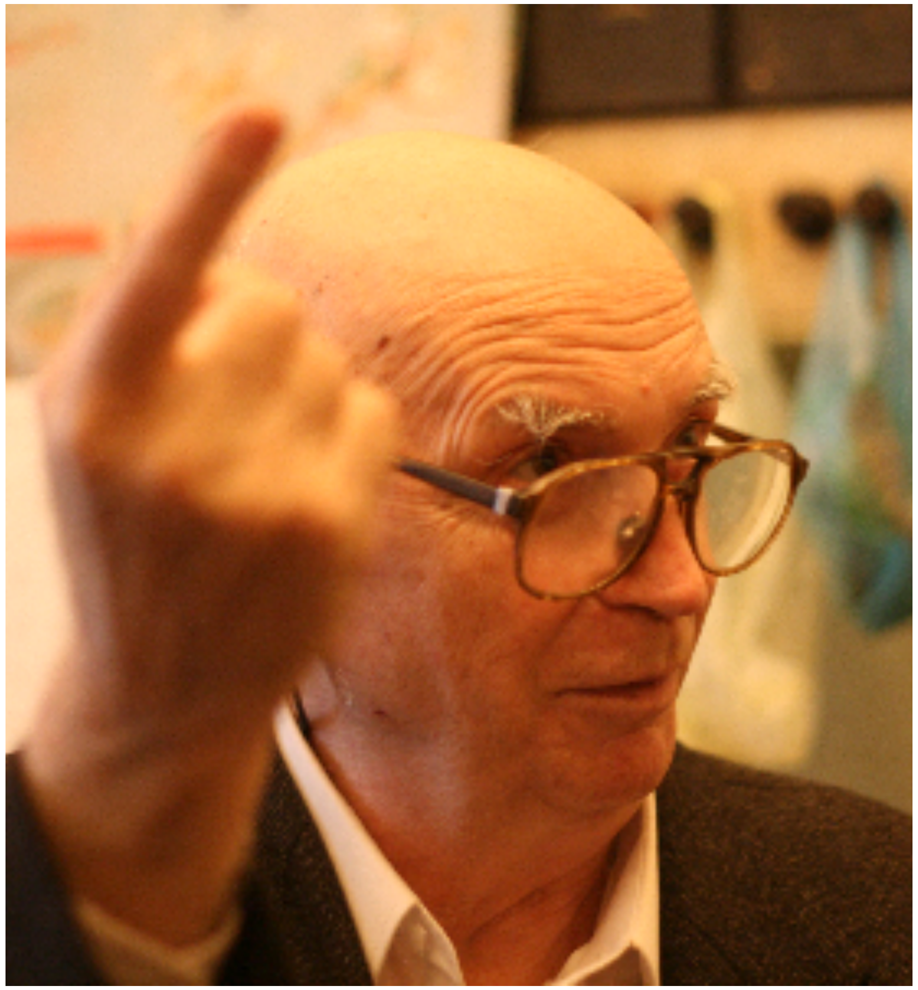
Direct observation of gravitational waves from the merger and inspiral of two black holes



Bruce Allen

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute, AEI)



Vladimir Braginsky

3 August 1931 – 29 March 2016

Leonid Grishchuk

16 August 1941 – 13 September 2012

First Detection

4 September 2015:
Advanced LIGO recorded a strong gravitational wave burst:
merger of a 29 and 36 solar mass BH.

Discovery Paper

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) 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].

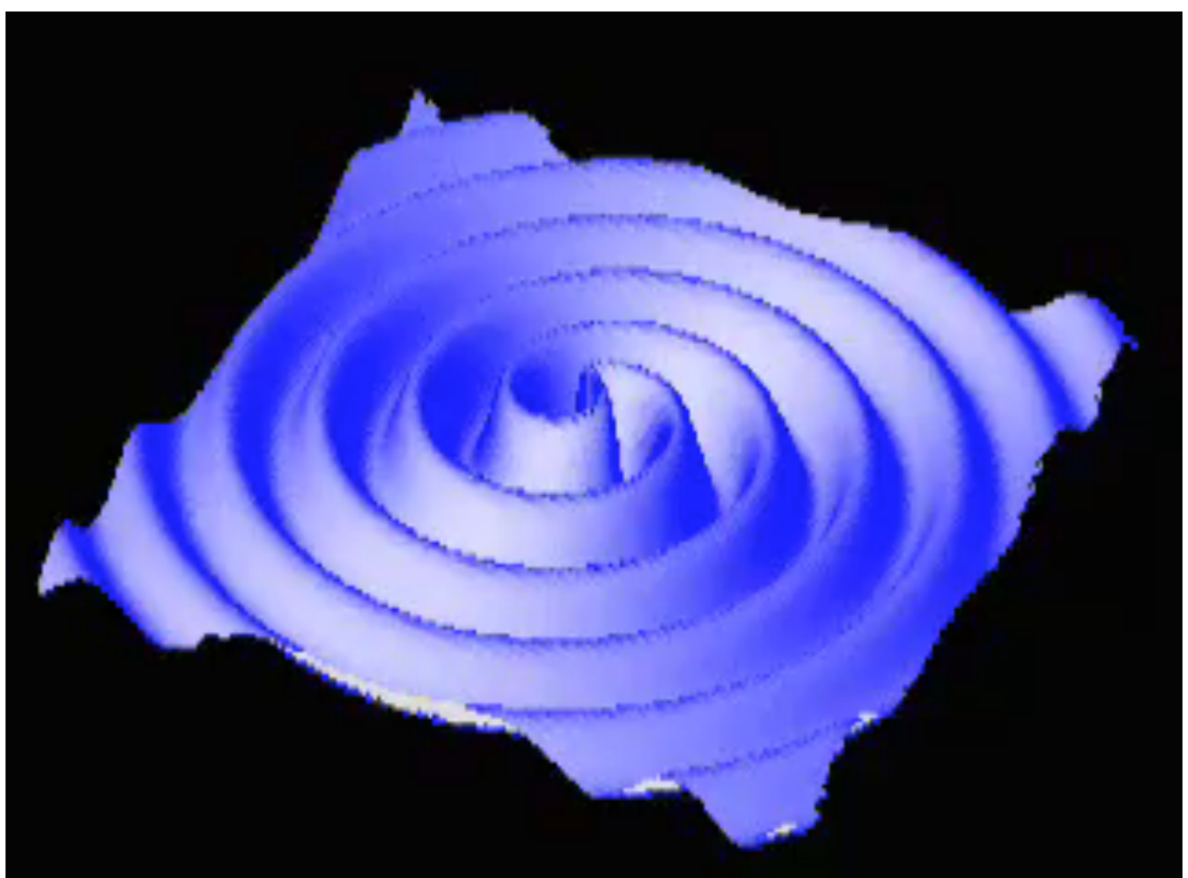
A century after the fundamental predictions of Einstein and Schwarzschild, we report the first direct detection of gravitational waves and the first direct observation of a binary black hole system merging to form a single black hole. Our observations provide unique access to the

Gravitational Waves

June 1916: perturbative solutions

- Massless, propagate at c
- For v<<c, dominant radiation quadrupole (NOT dipole)
- Luminosity given by:

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



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

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

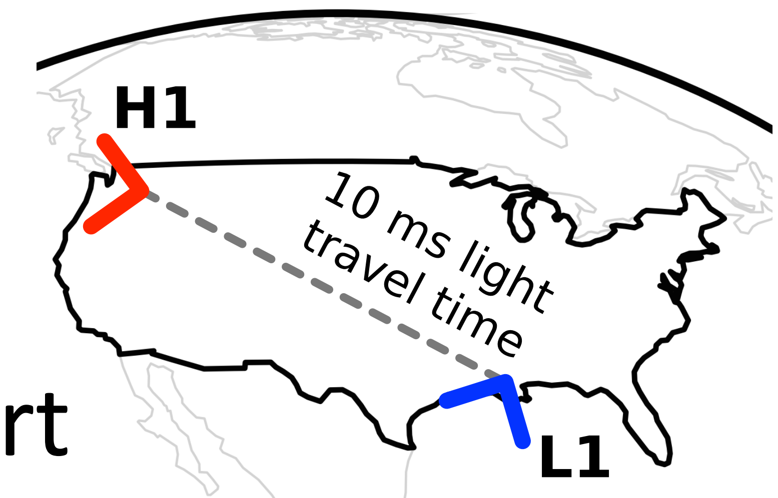
definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu}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

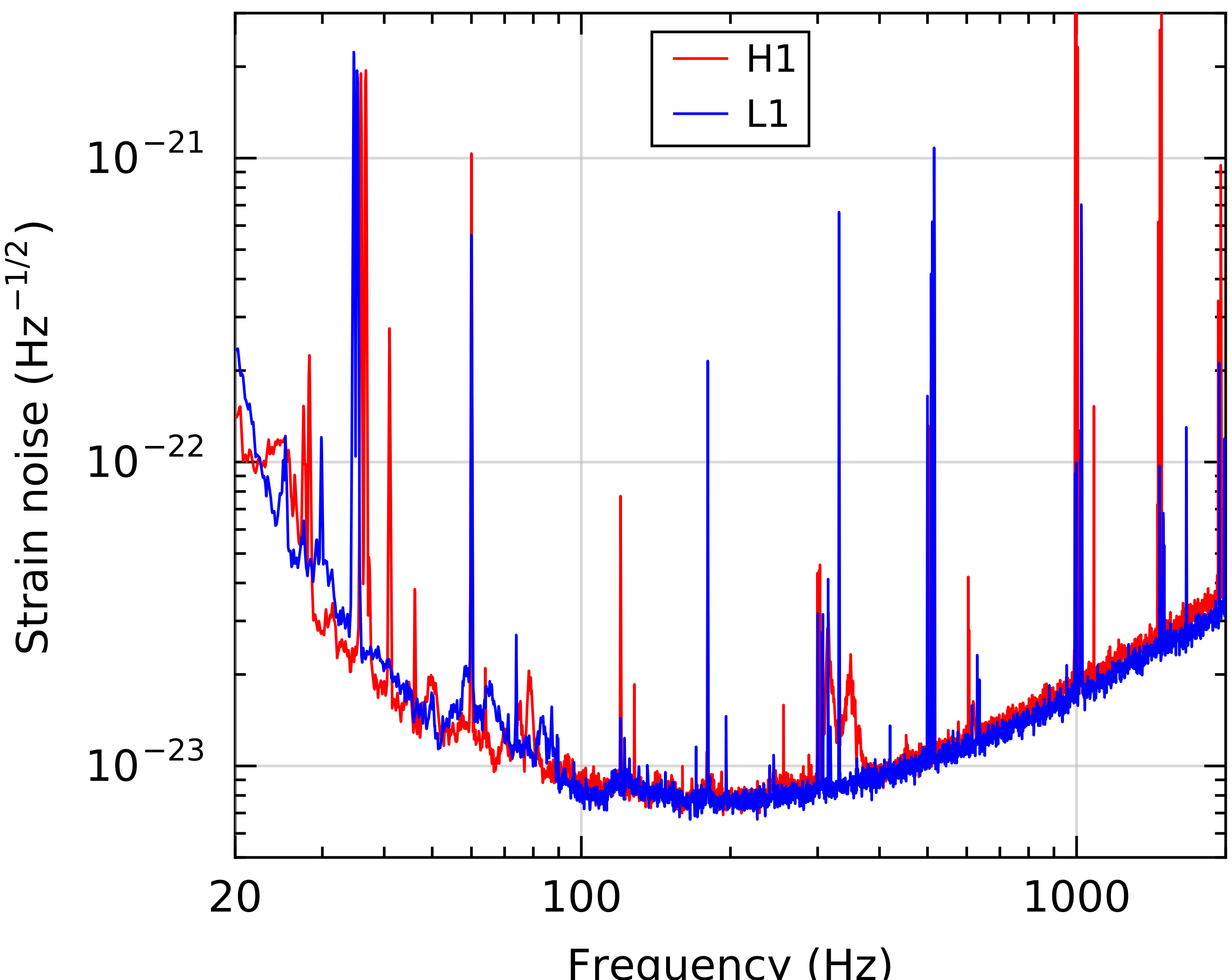
Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen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

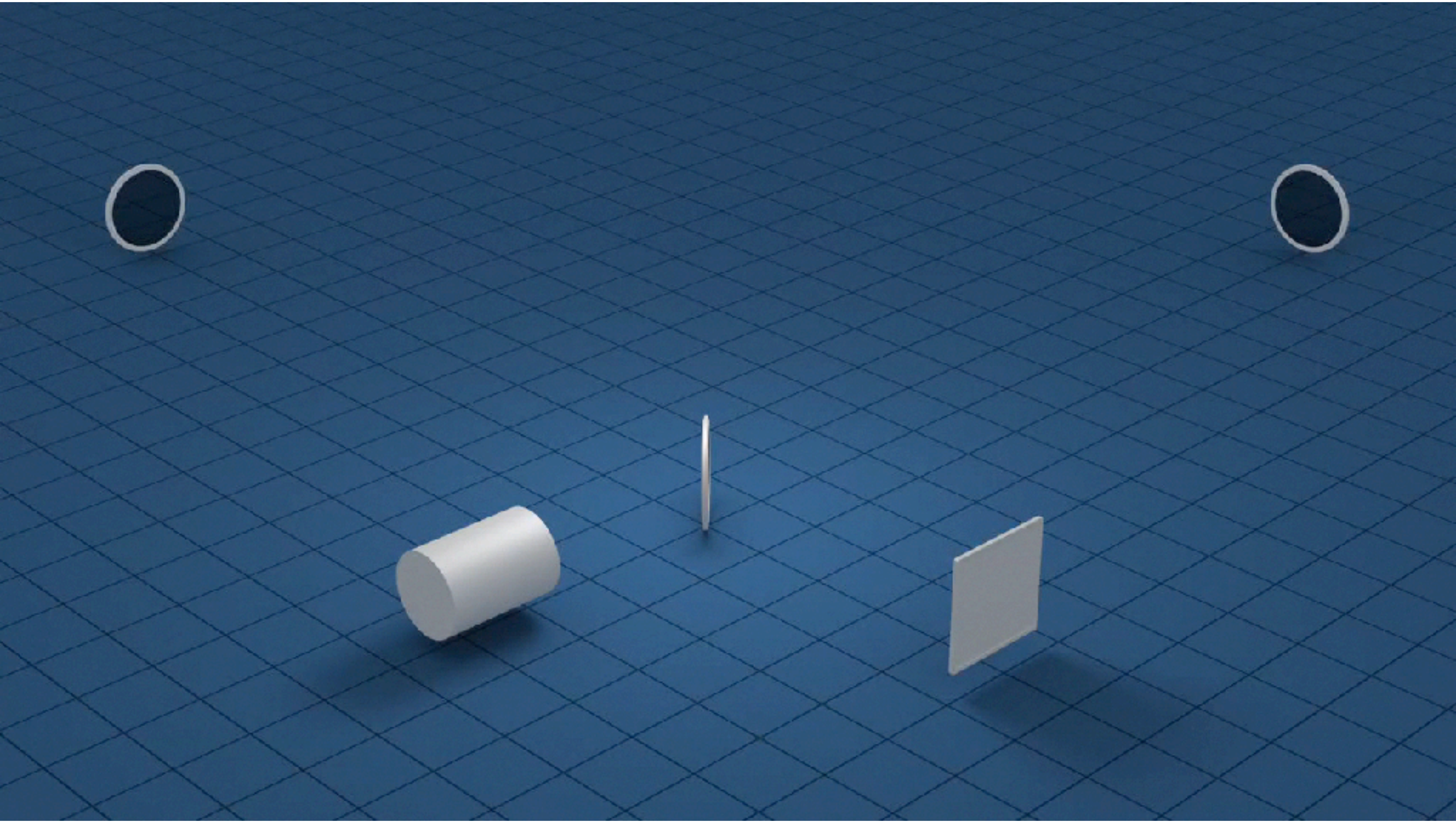
Advanced LIGO Detectors

Livingston & Hanford 3000 km apart





- Sensitive band: 30 to 2000 Hz
- Strain h=ΔL/L
- In 100 Hz band at minimum, r.m.s. noise $h \sim 10^{-22}$



GW150914

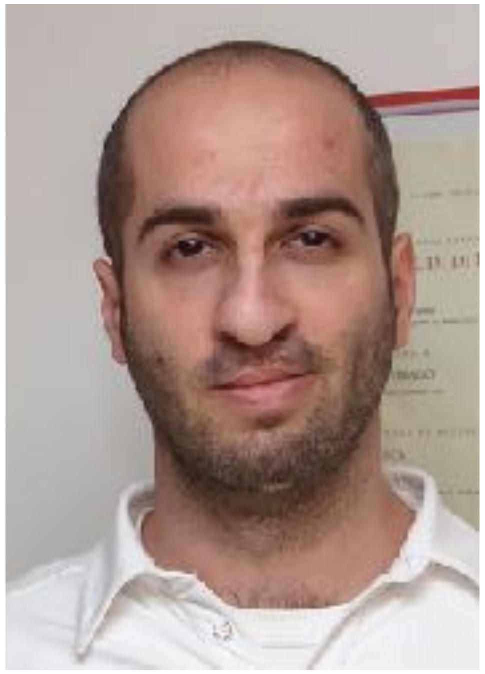
- First observing run (O1, science operations) start planned for **18 September 2015**
- Event on **14 September 2015, four days before O1 start**

  02:50 at LIGO WA

  04:50 at LIGO LA

  11:50 in Germany

AEI Hannover, September 14, 2015



Marco Drago

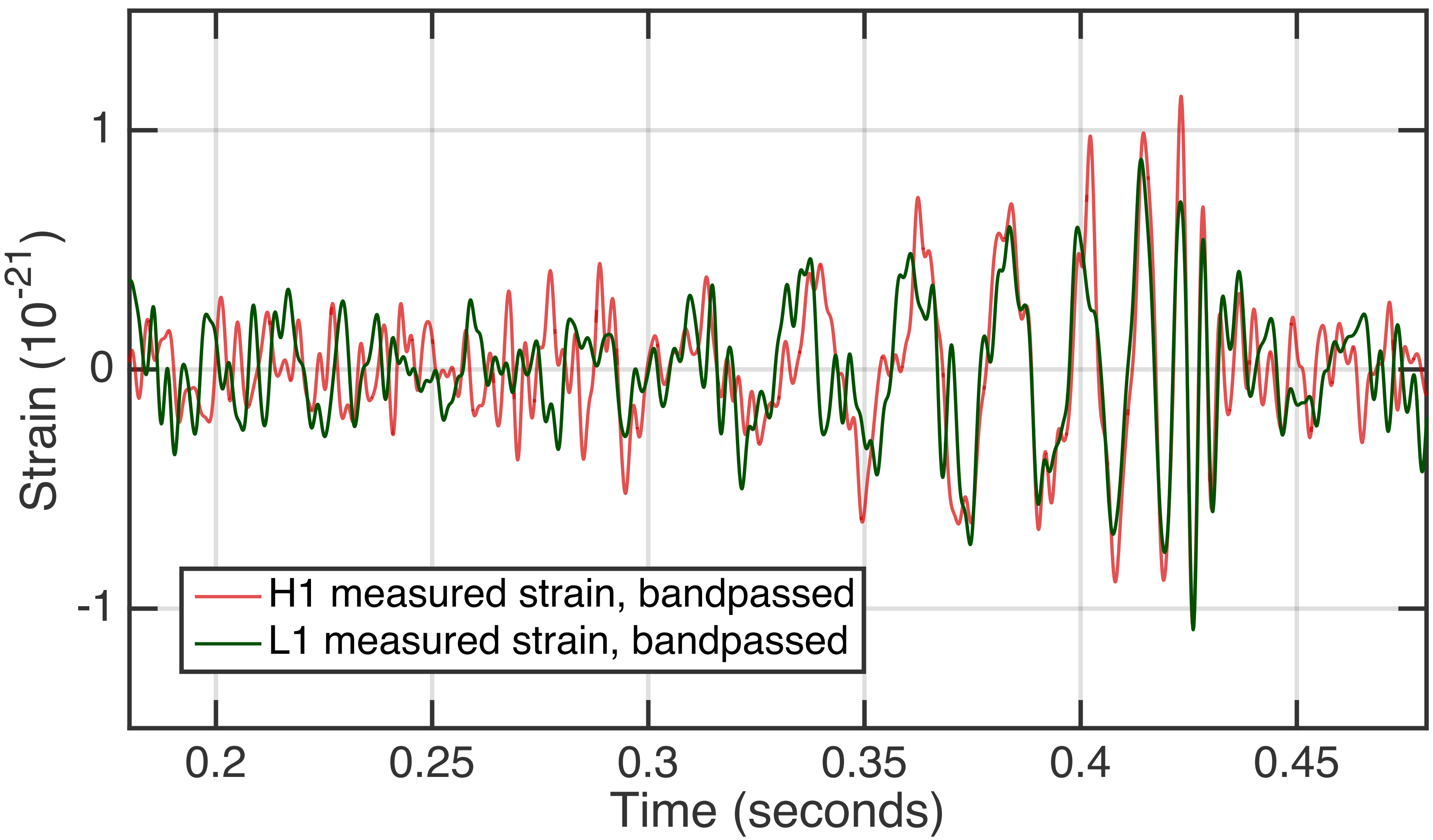
Andrew Lundgren

- Monday morning 11:50
- Coherent waveburst analysis had ~1000 entries in event database
- Marco and Andy checked injection flags and logbooks, data quality, made Qscans of LHO/LLO data.

- Contacted LIGO operators: “everyone’s gone home”
- At 12:54, Marco emailed the collaboration
- Next hours: flurry of emails, decision to lock down sites, freeze instrument state

“Raw Data”: the Chirp

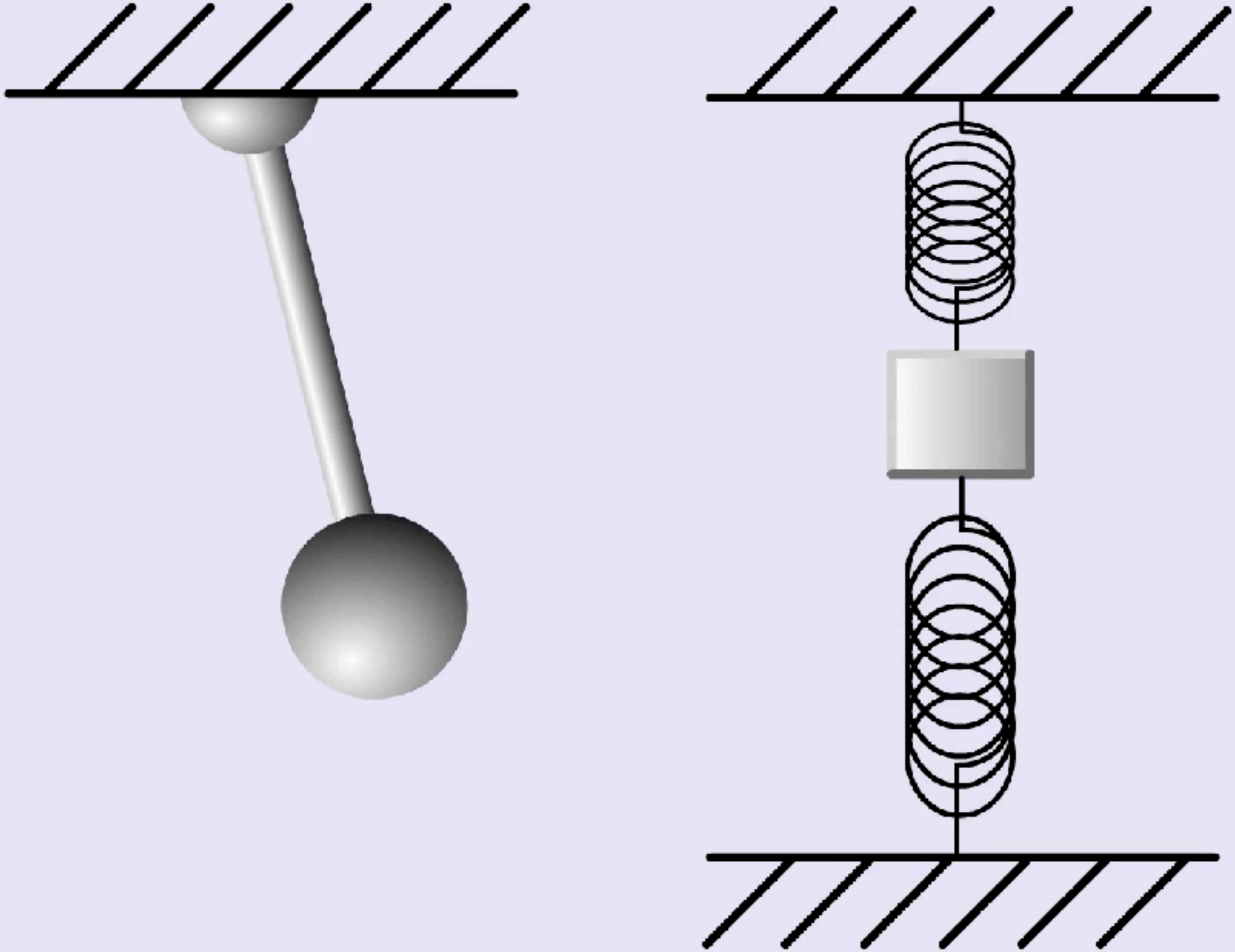
ΔL/L



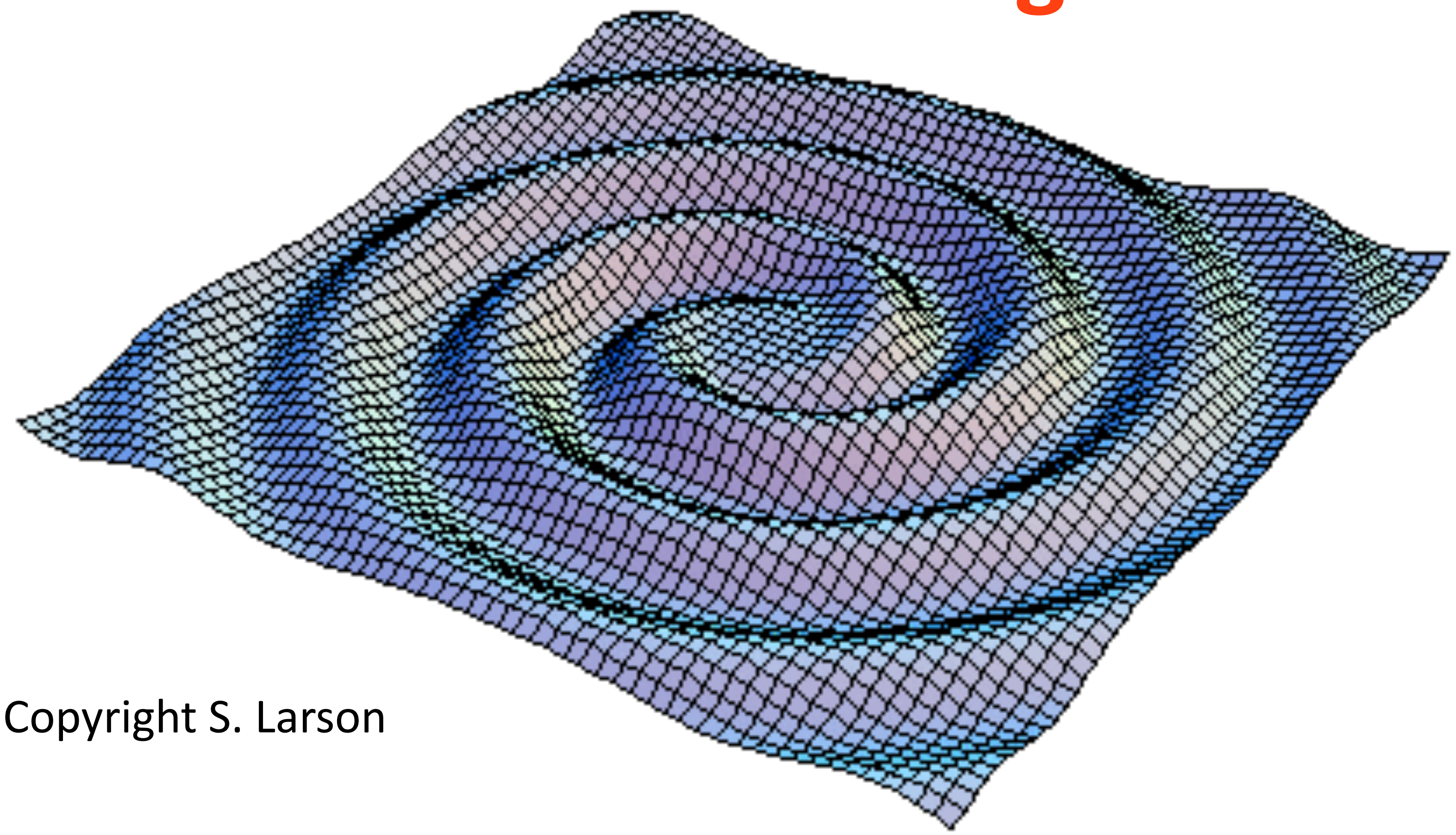
- Bandpass filtered 35-350 Hz, some instrumental and calibration lines removed
- Hanford inverted, shifted 7.1 ms earlier

- Signal visible to the naked eye: ~200 ms
- “Instantaneous” SNR ~5, optimal filter SNR ~ 24

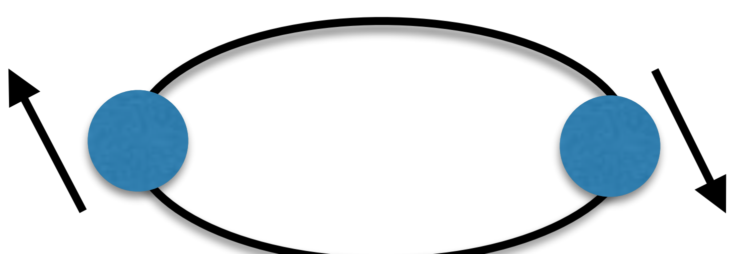
Oscillations



Each orbit makes two gravitational wave cycles

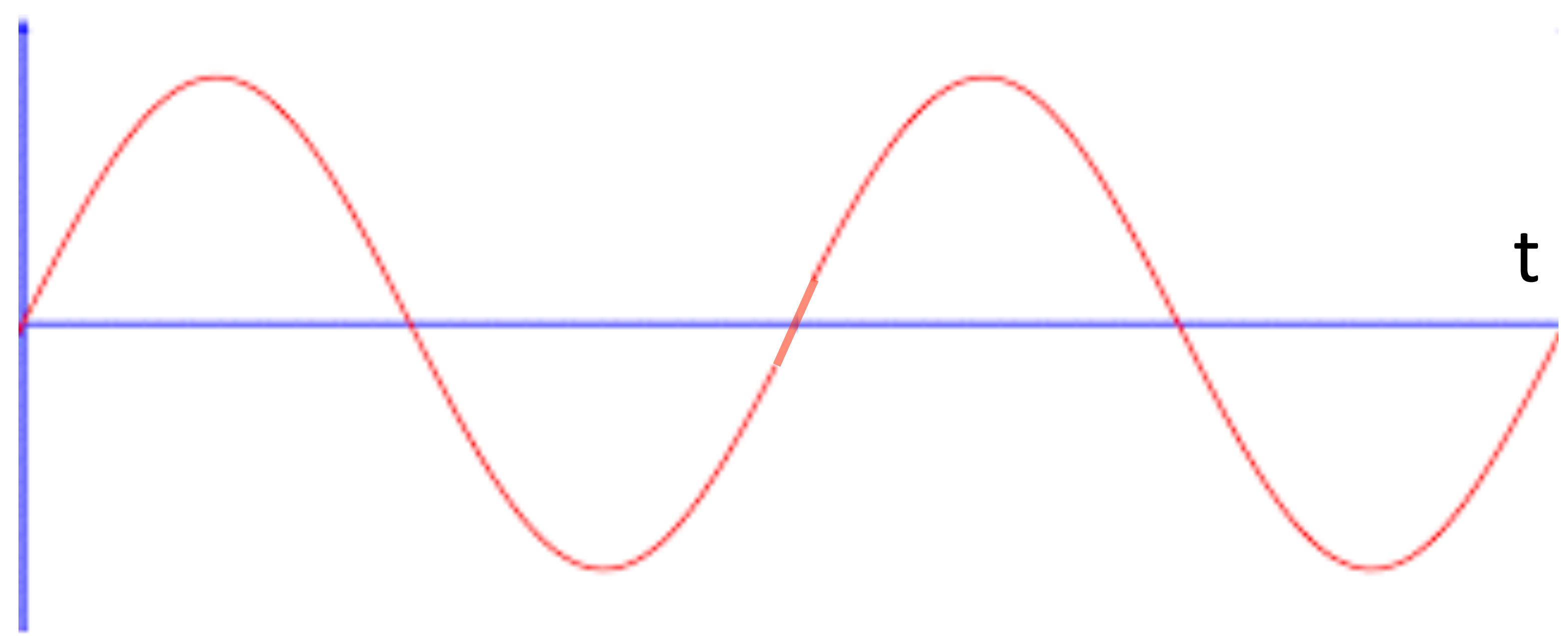


Copyright S. Larson

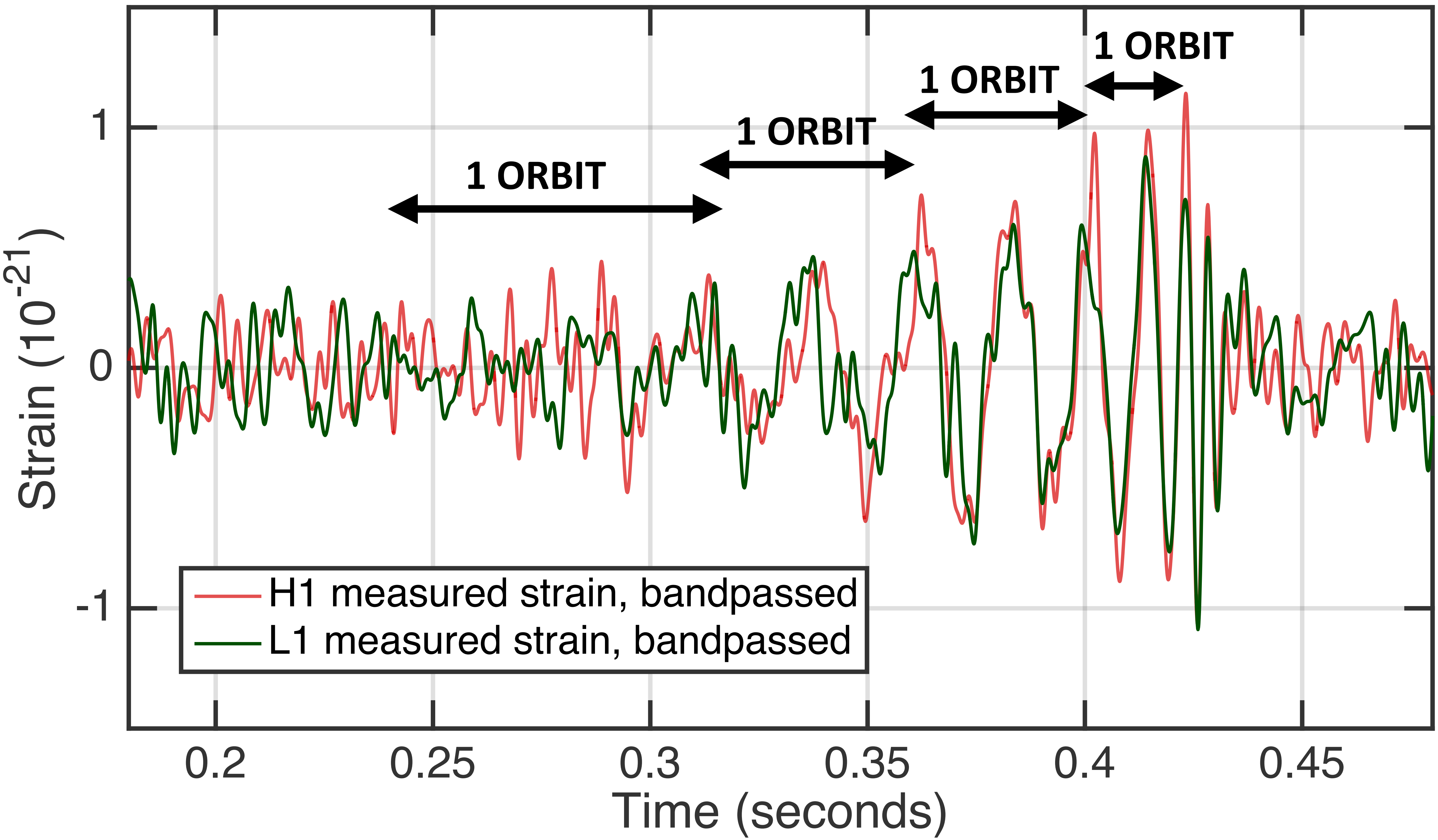


1 orbit

ΔL/L = gravitational wave strain

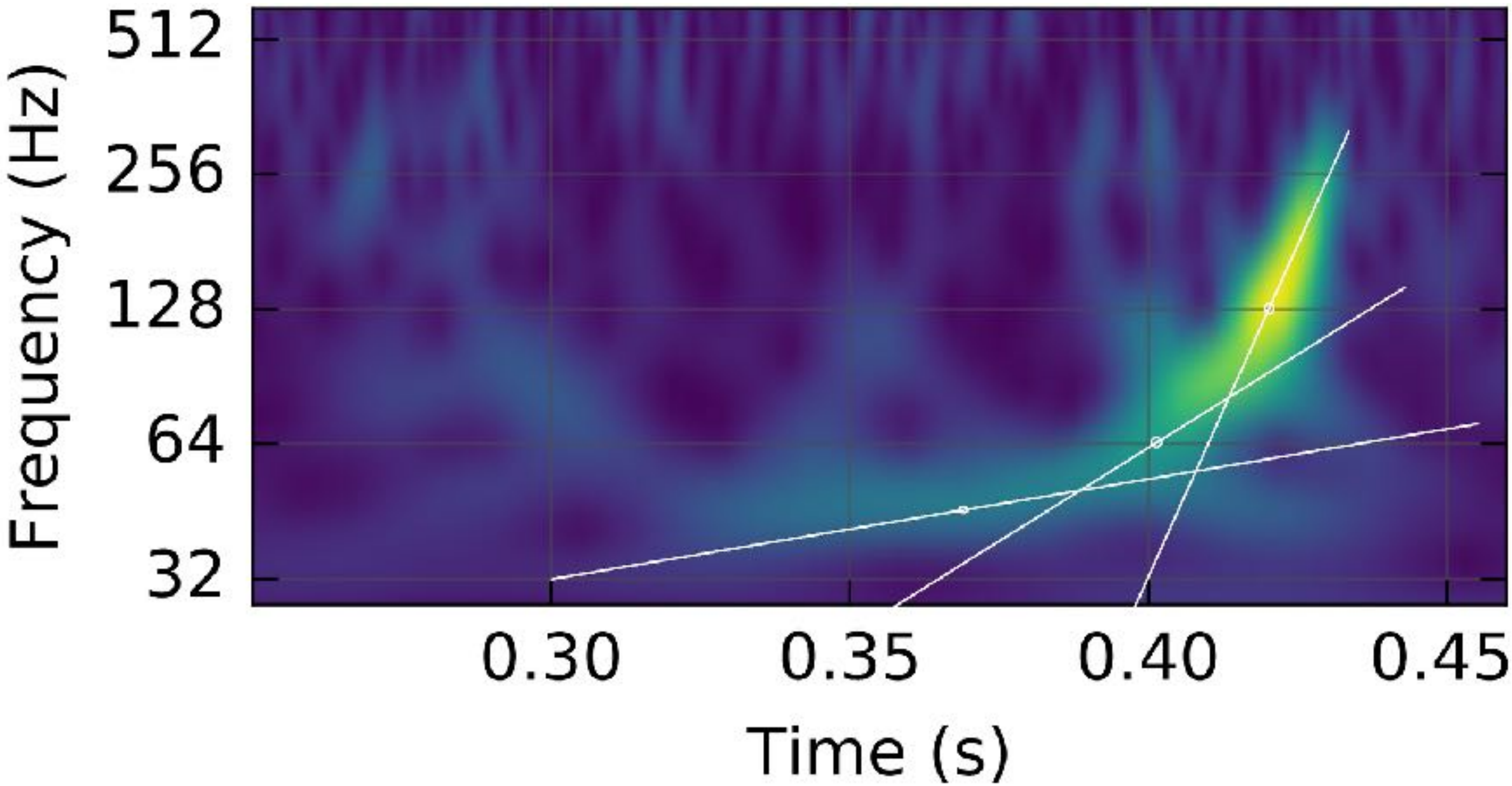


The Chirp


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

Masses from the rate of frequency increase

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5} = 30\ M_\odot$$



Can only be two black holes!

- Chirp mass $\mathcal{M}$ ~ 30 M☉

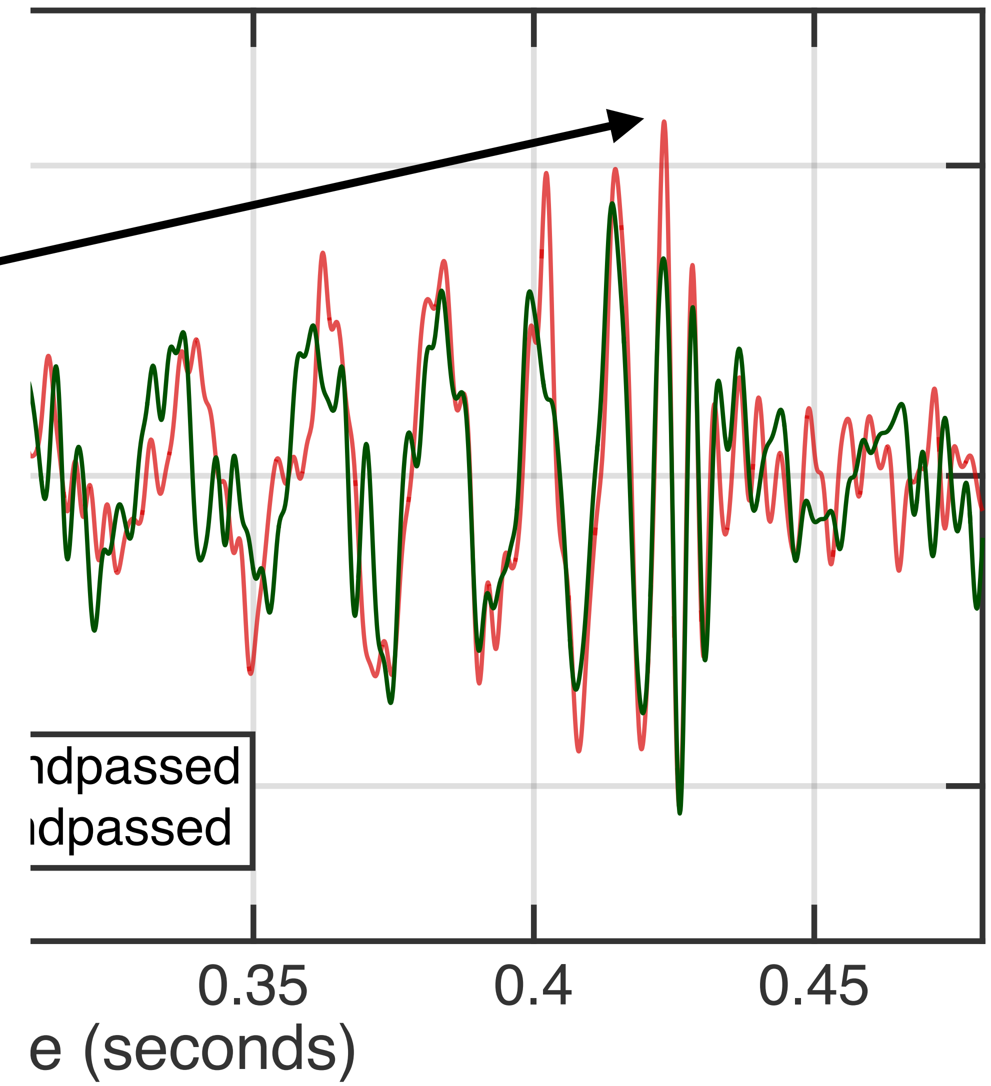
  => $m_{1,} m_2$ ~ 35 M☉ =>

  Sum of Schwarzschild radii ≥206km
- At peak f_{GW} = 150 Hz, orbital frequency = 75 Hz separation of Newtonian point masses 346 km
- **Ordinary stars** are 10^6 km in size (merge at mHz): too big!

  White dwarfs are 10^4 km (merge at 1 Hz): too big!

  Neutron stars not massive enough: m_1 = 4 M☉ => m_2=600 M☉

  =>Schwarzschild radius 1800km => too big!



Only black holes are heavy enough and small enough!

Real? Or a detector artifact?

- Normal stable operation starting September 12th, 2015
- Last scientists left sites 2 hours (LHO) and 15 minutes (LLO) before the event
- Waveform does not resemble instrumental glitches or artefacts
- Susceptibility to radio, acoustic, magnetic, seismic and other external disturbances measured. Can not explain more than 6% of the observed GW amplitude


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

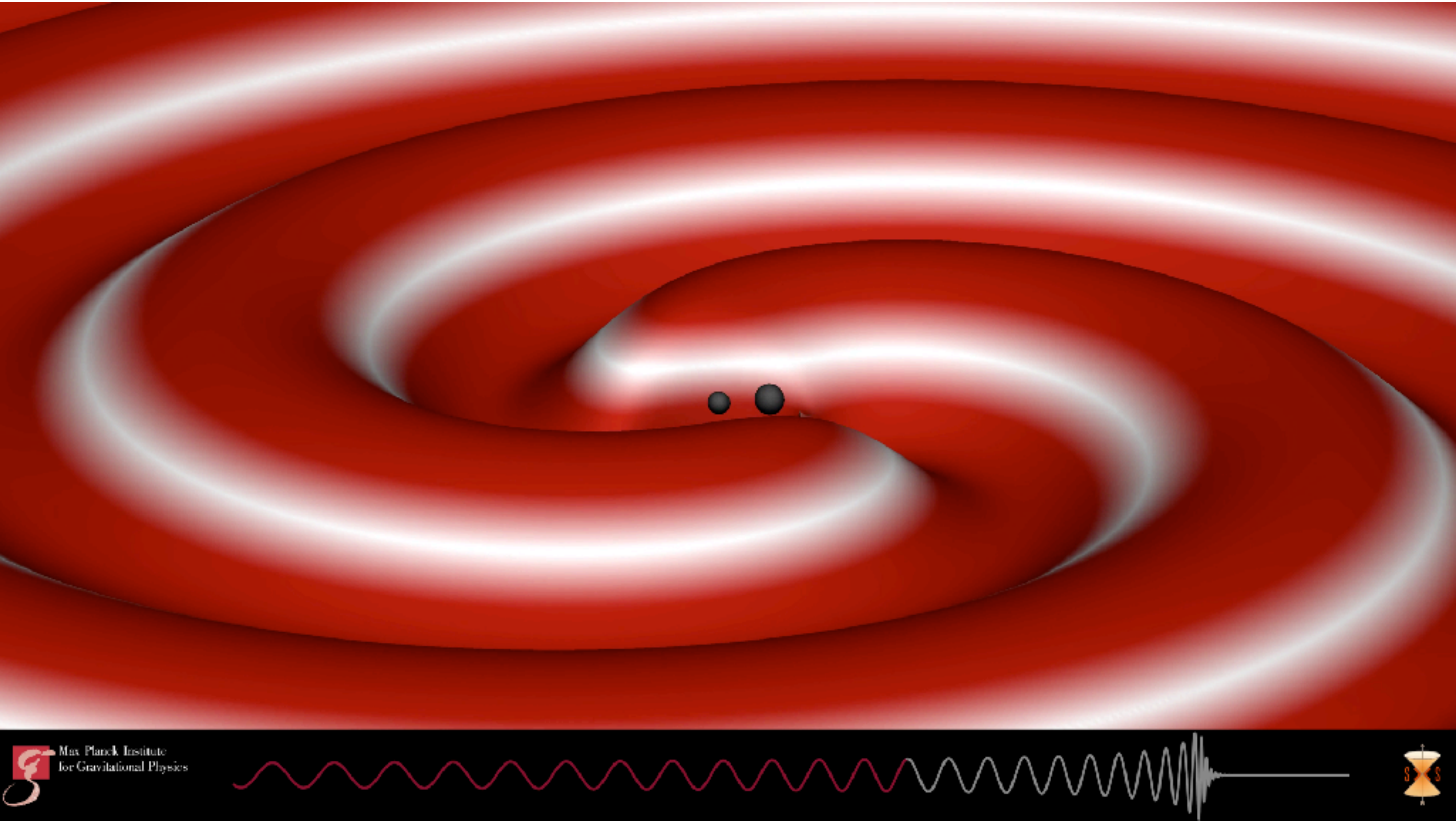

Robert Schofield and **Anamaria Effler**, departed the LLO site at 04:35am
15 minutes before the event

Random Noise?

Bound: more than 200,000 years before noise in the detector would mimic this signal, or signal with different mass values

(How much more? Probably longer than the age of the Universe!)

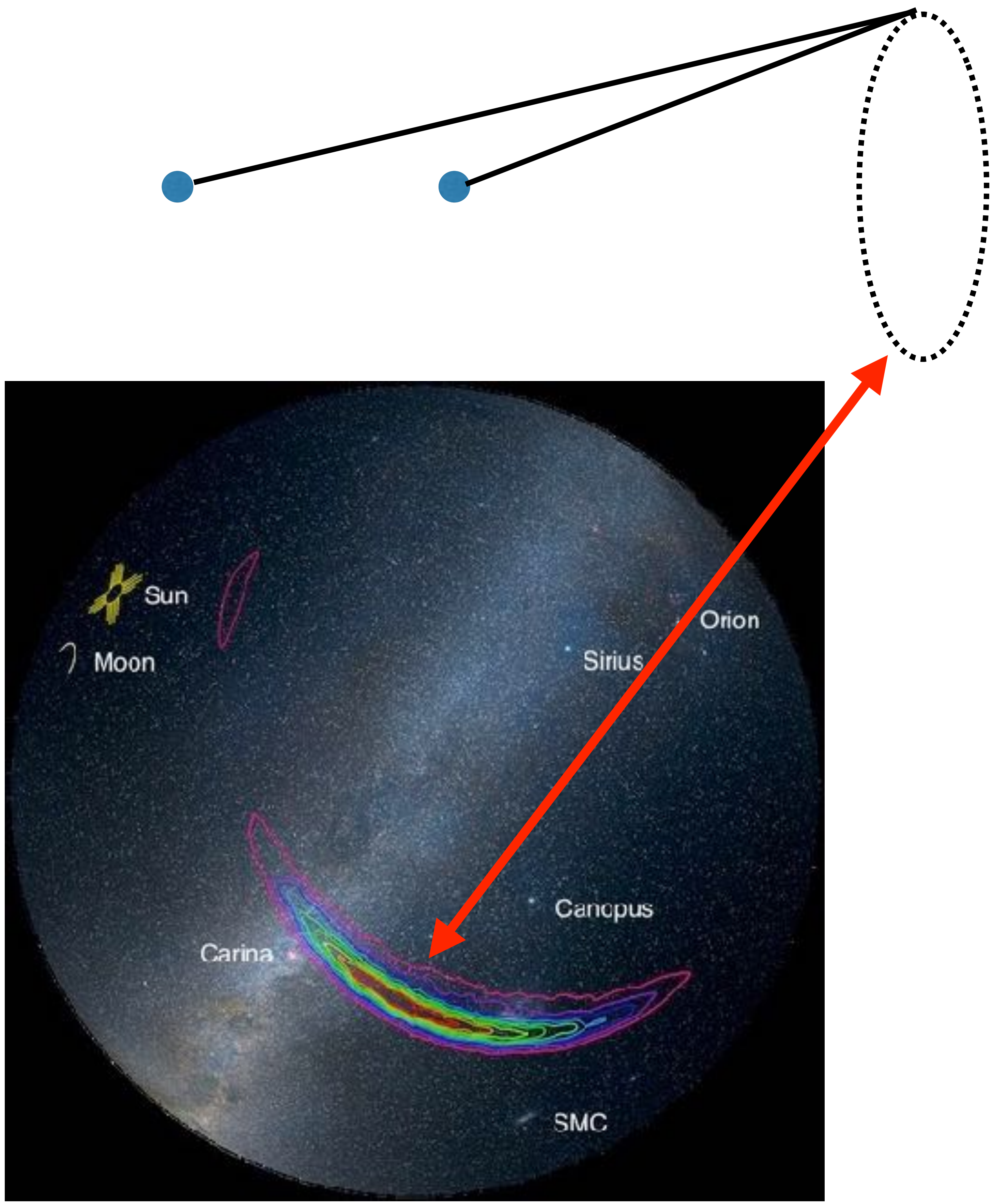
The Movie



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

Sky position

- 7-msec time delay: CIRCLE on the sky
- ARC because most likely source direction directly above/below plane of detector.



Masses and distance

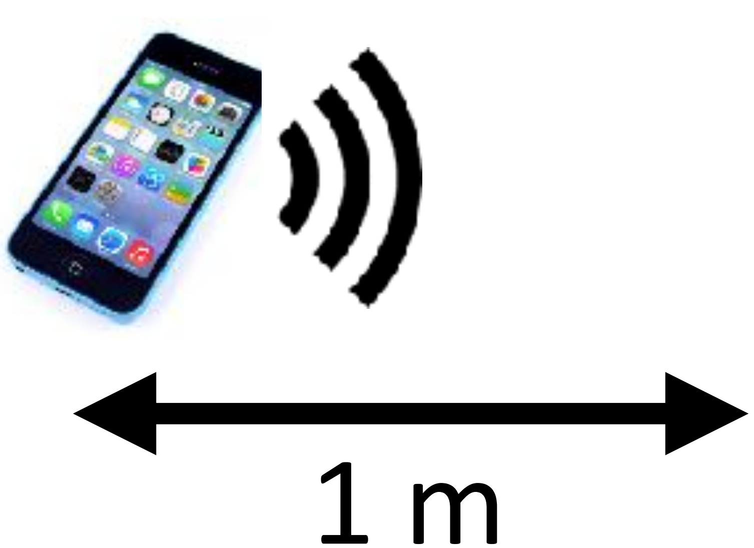
Primary black hole mass	$36^{+5}_{-4}\,M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,M_\odot$
Final black hole mass	$62^{+4}_{-4}\,M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

- Waveform models and Instrument calibration: ± 3% percent errors
- Detector noise: ± 5% errors
- Reasonable: errors in masses and spins at ±10% level
- **But distance uncertainties are ±40% . Because we don't know how orbital plane of binary was oriented.**

Energy lost, power radiated

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	$0.09^{+0.03}_{-0.04}$

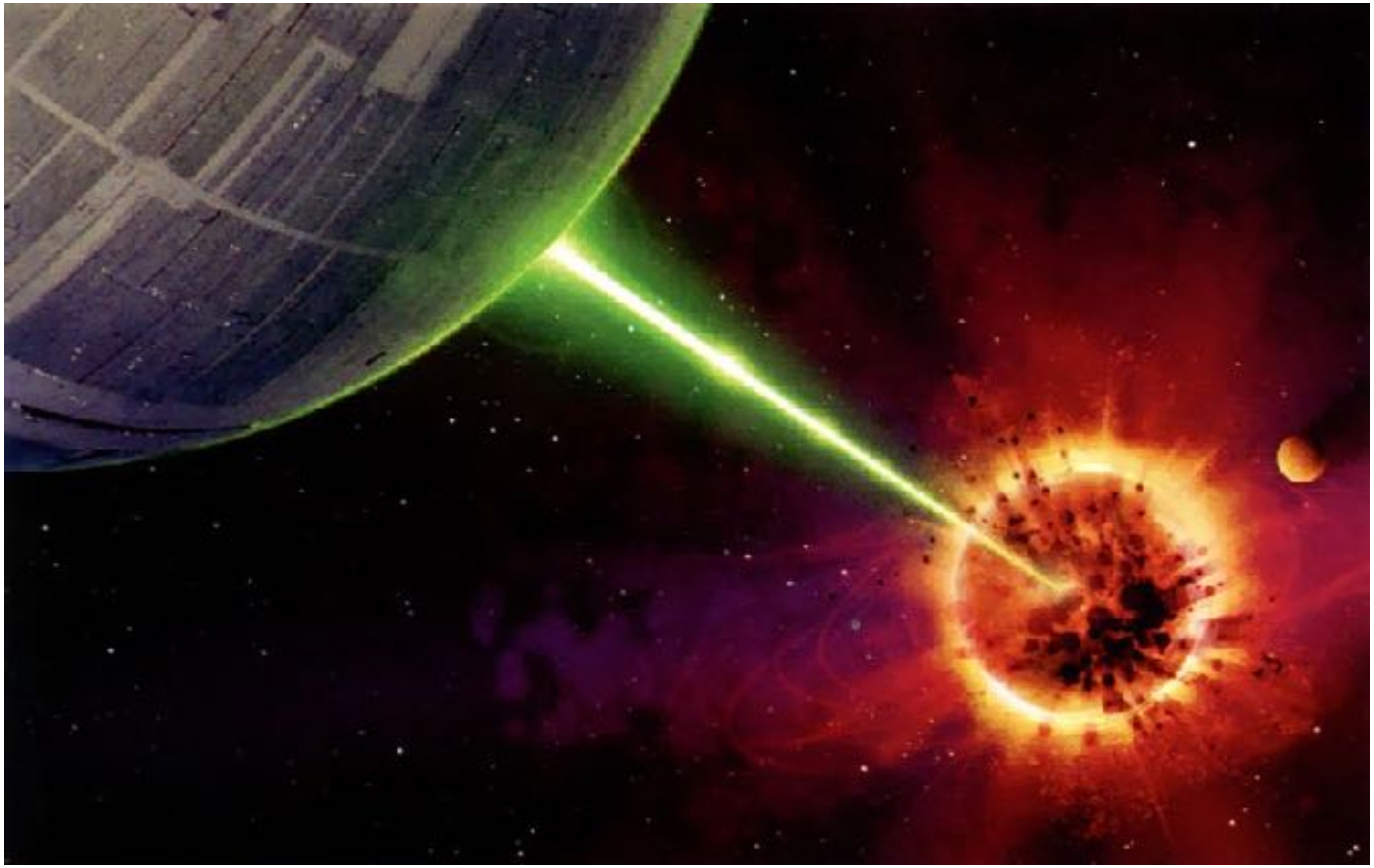
- Radiated energy: $3M_\odot$ (±0.5)
- Peak luminosity: 3.6 x 10^{56} erg/s (±15%) = 200 $M_\odot$/s
- Flux about 1μW/cm^2 at detector, ~10^{12} millicrab
- Cell phone at 1 meter!



Radiated Energy

$$E_{\text{mechanical}} = -\frac{Gm^2}{2r}$$

m = 35 $M_\odot$, r=346 km, get $E_{\text{mechanical}}$ ~ 3 $M_\odot c^2$



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

Non-spinning black hole horizon has area = 4π (2m)²
= 16π m²

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/cm² 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]

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

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

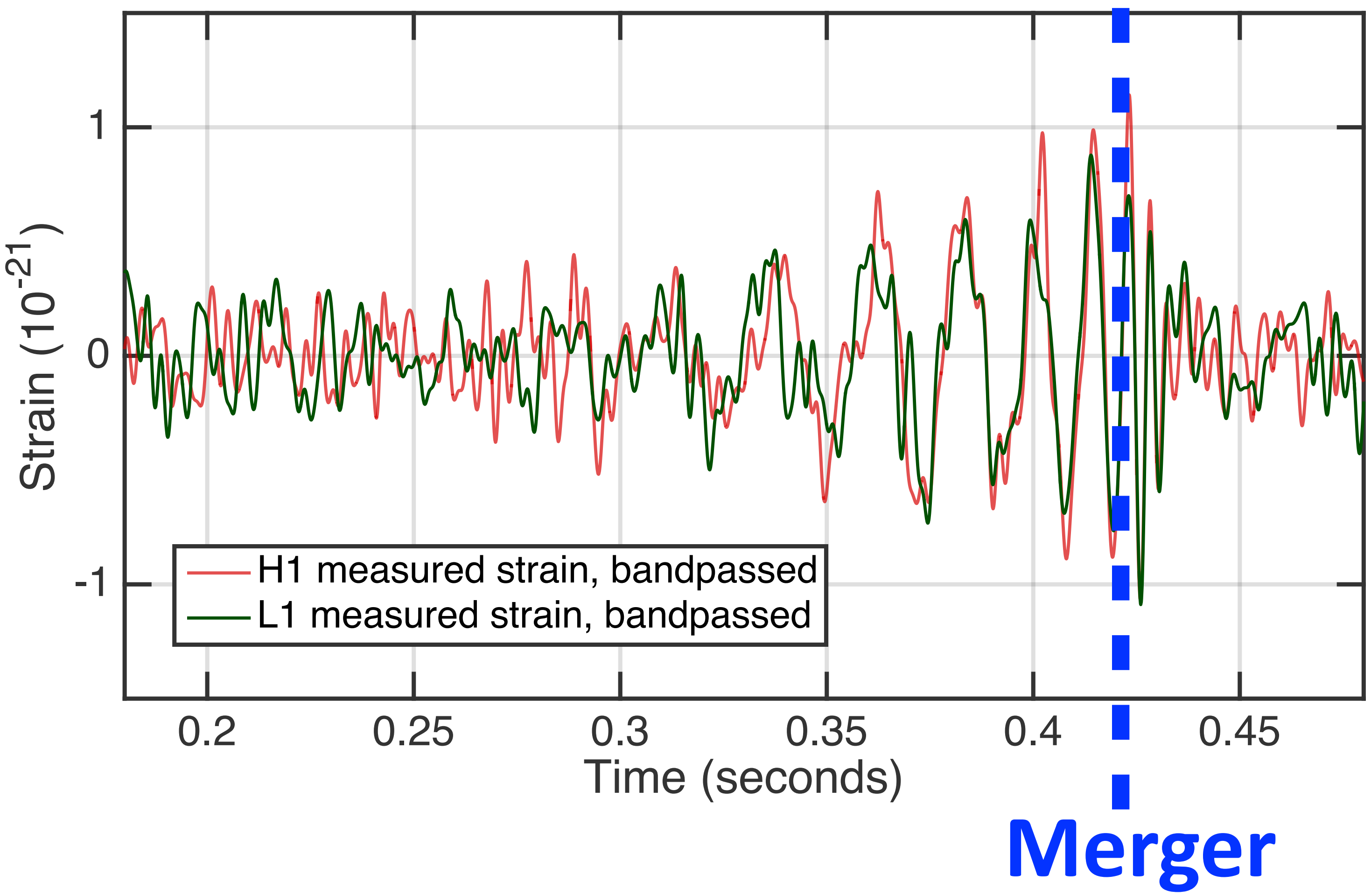
1344

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

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	$0.67^{+0.05}_{-0.07}$

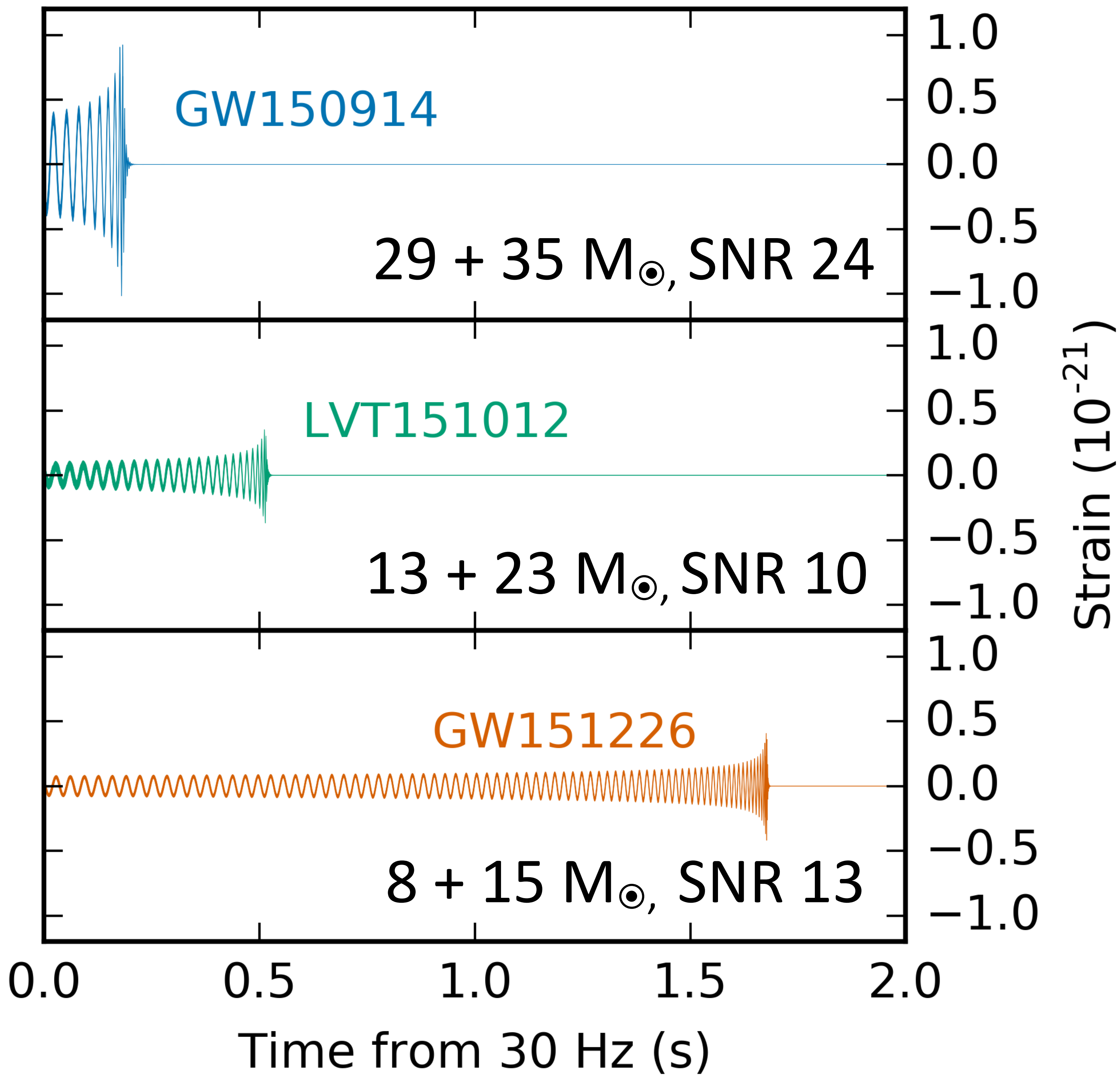
Plug in m_1, m_2, m_f and s_f: it's satisfied! ✓

Does data test Area Theorem? No!



- Large signal-to-noise **before** merger: initial masses and spins are “from data”
- Small signal-to-noise **after** merger: final mass/spin found by numerical relativity
- If area theorem were NOT satisfied, then the numerical relativity code must be faulty

Binary Black Holes in O1



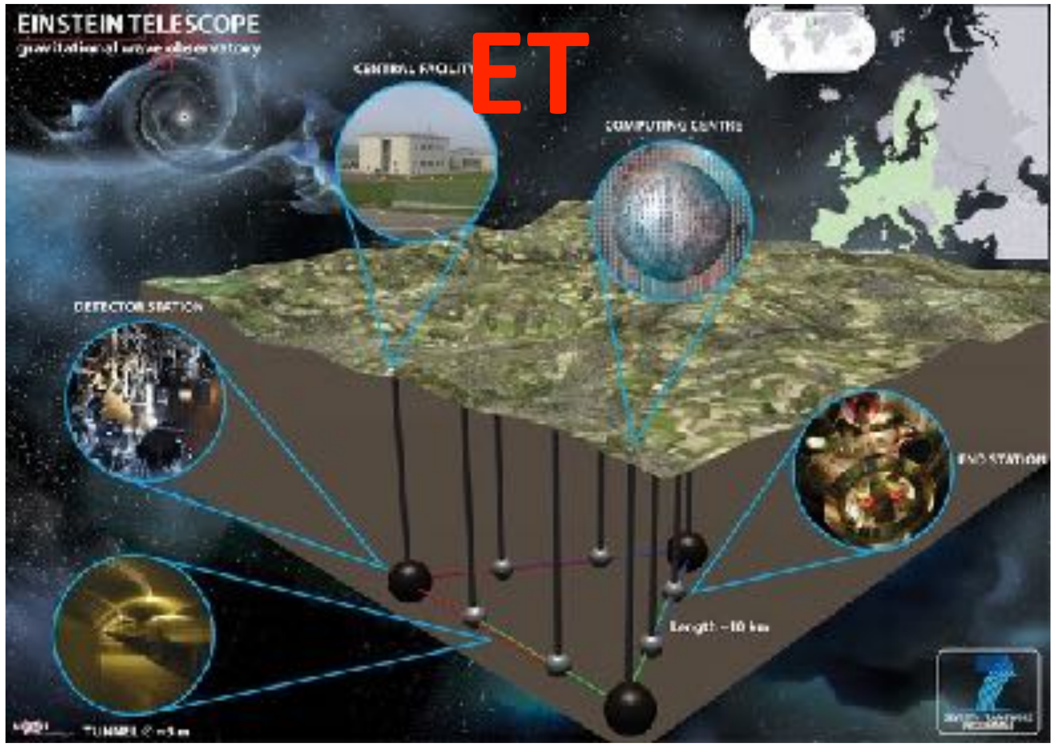
(Edited) LIGO Collaboration statement from May 3rd on status of O2

The second Advanced LIGO run began on November 30, 2016 and is currently in progress. As of April 23 approximately 67 days of Hanford-Livingston coincident science data have been collected.

As of April 23, 6 triggers, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

Things I didn't talk about

- Testing GR: everything consistent. New ability to test GR in the strong field dynamic regime.
- Astrophysical implications: how to form BH pairs? Spin?
- Stochastic "background" from more distant weaker sources: potentially detectable
- Other sources of gravitational waves: neutron stars
- Additional instruments: Virgo,Kagra, LIGO-India; ET and LIGO Voyager
- Detection in other frequency bands: pulsar timing arrays, LISA satellite, CMB



2017-20: a "Golden Age" of GW astronomy

- Hope for O3 run to start in 2018. At design sensitivity (factor of 3 better): one black hole binary every few days for a year: **~100 events total**
- Within a few years, we will know the mass and spin distribution of these binary black hole sources. Perhaps pairs of black holes make up a significant amount of the missing "dark matter" in the Universe
- Expect at least one event close enough to directly determine the final mass and spin and test Hawking's black hole area theorem
- Can we learn more about physics of black holes, for example the information-loss paradox, firewalls, quantum properties, ???

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