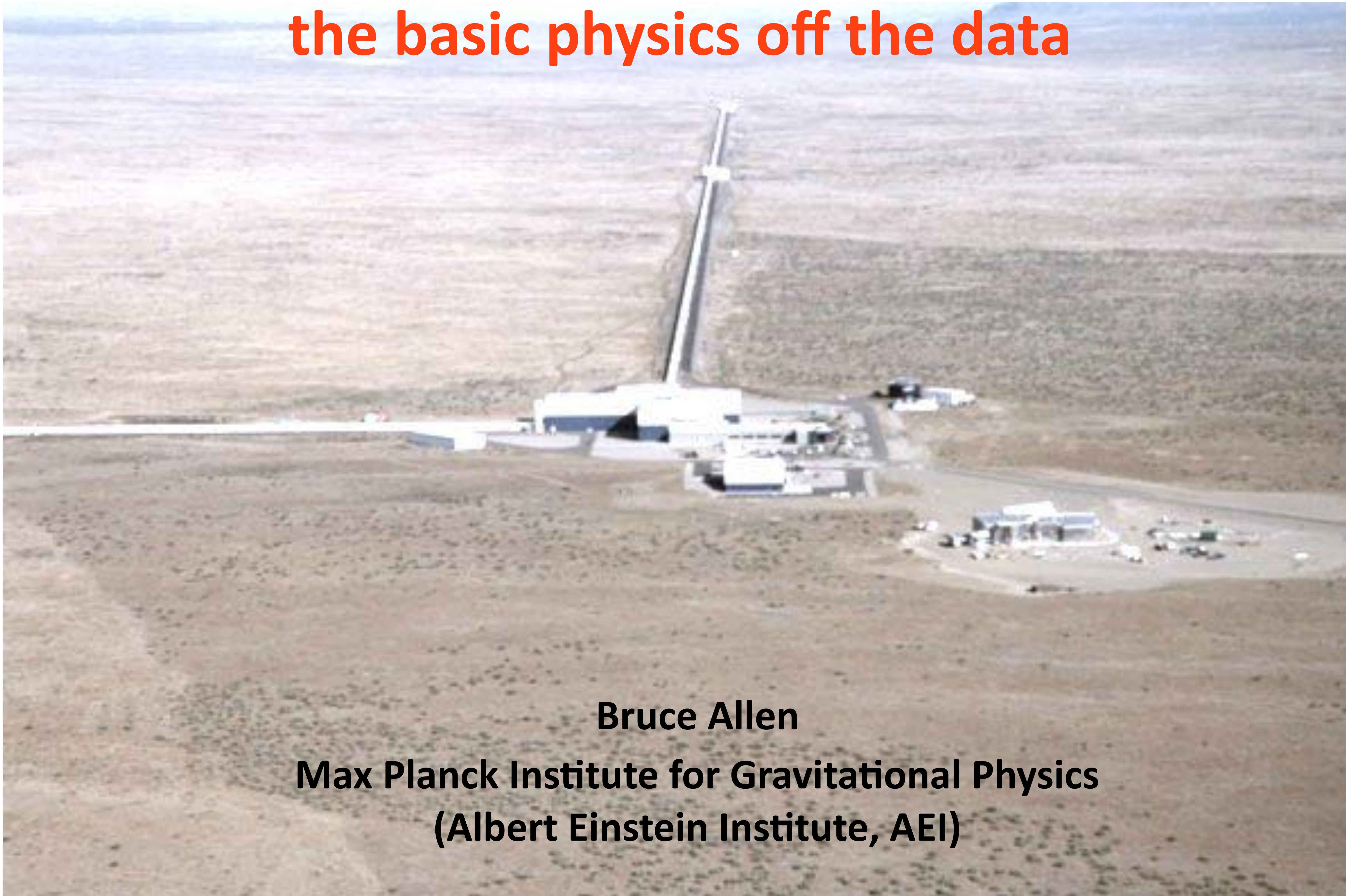
The LIGO discoveries: how to read the basic physics off the data



Bruce Allen

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute, AEI)

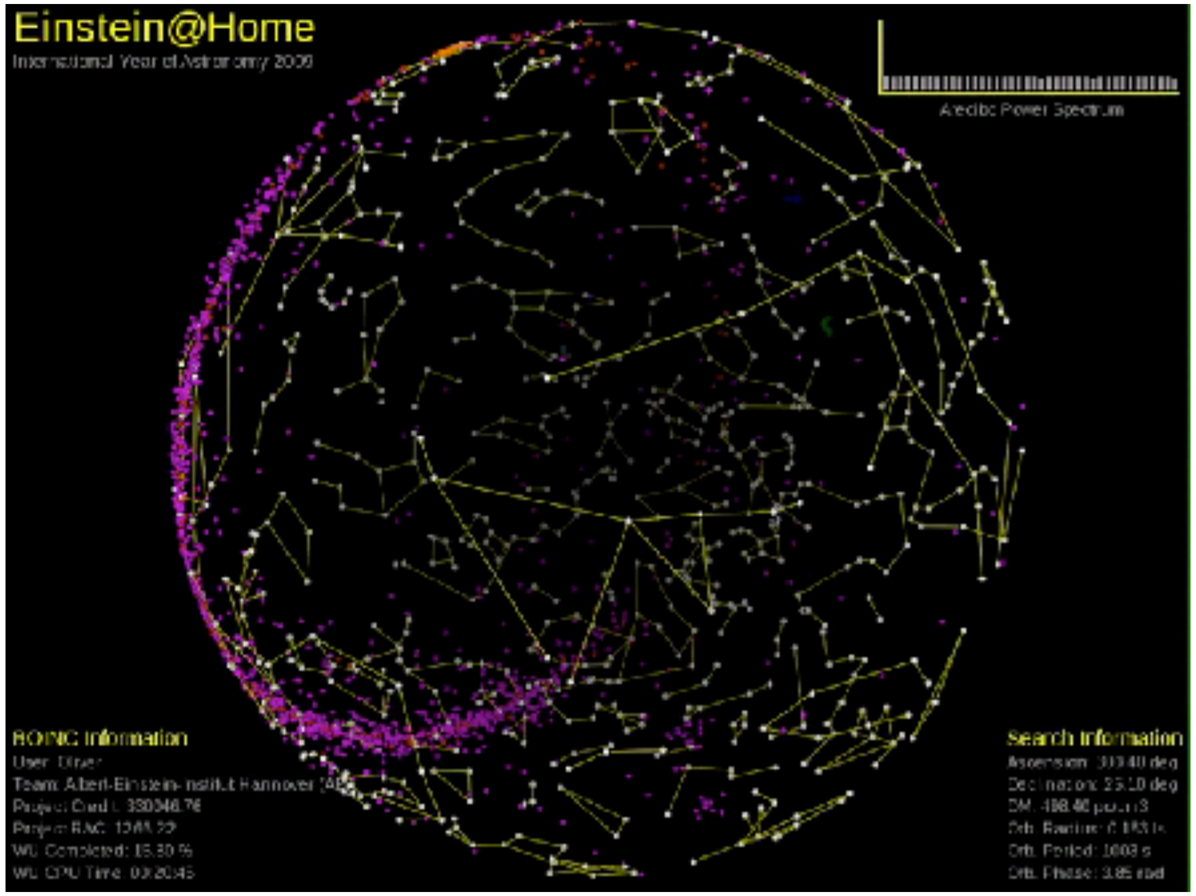
Topics

- Simple physical argument that GW150914 is 2 x BHs
- Why we be sure it was not error/accident/ malicious
- What is the false alarm rate? ("5σ" bound is often misunderstood)
- Why are some parameters (distance) much more poorly determined?
- Why aren't we testing the area theorem?

References: PRL 116, 061102 (2016); PRX 6, 041015 (2016); Ann. Phys. 529, 1600209 (2017); PRL 118, 221101 (2017)

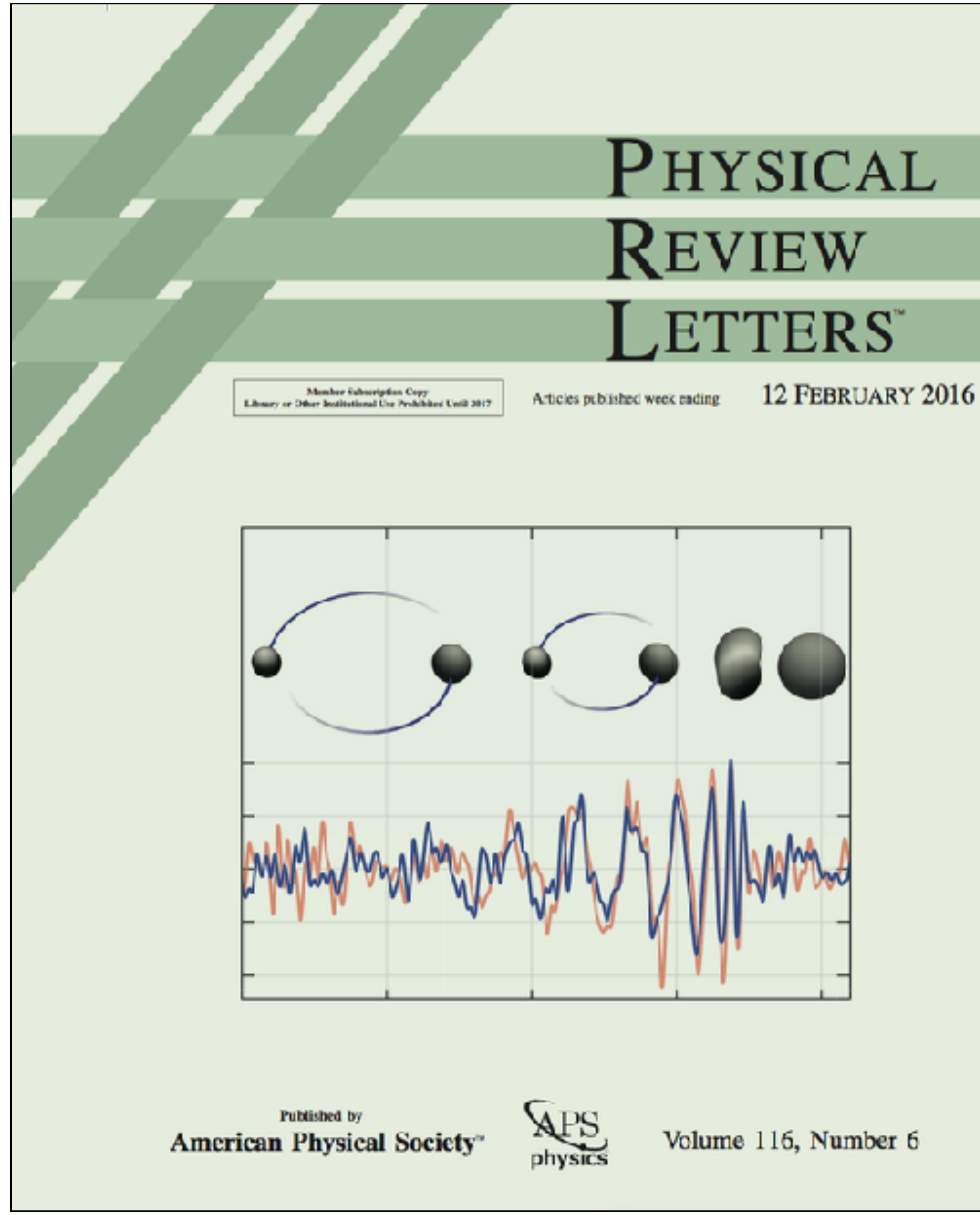
Something about myself

- Worked on gravitational wave data analysis methods and production computing since mid-1990s
- Group of ~30 people at AEI
- Atlas is the largest resource world-wide in the LIGO/VIRGO collaboration: 36,000 CPU cores, 2,500 GPUs, 10 PB, 1 MW
- Direct the Einstein@Home volunteer computing project (few x Atlas)
- Methods and technology also used for conventional (electromagnetic) astronomy: ~100 radio and gamma-ray pulsars discovered so far.



First Detection

14 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.

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

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

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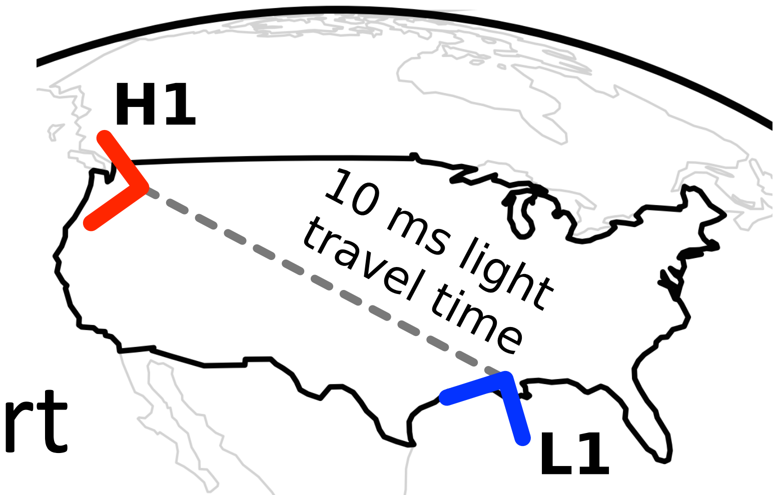
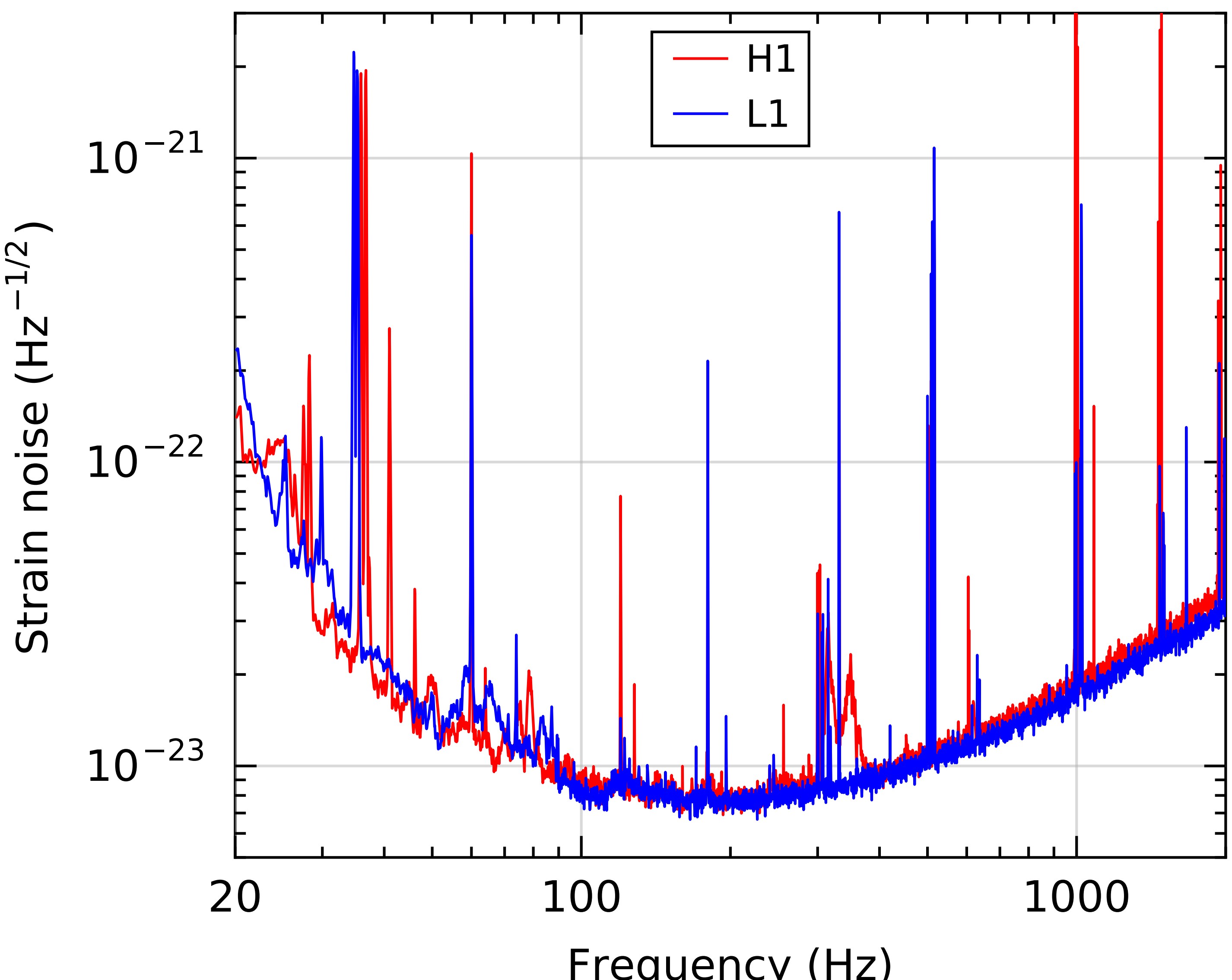
Advanced LIGO Detectors

Livingston & Hanford 3000 km apart





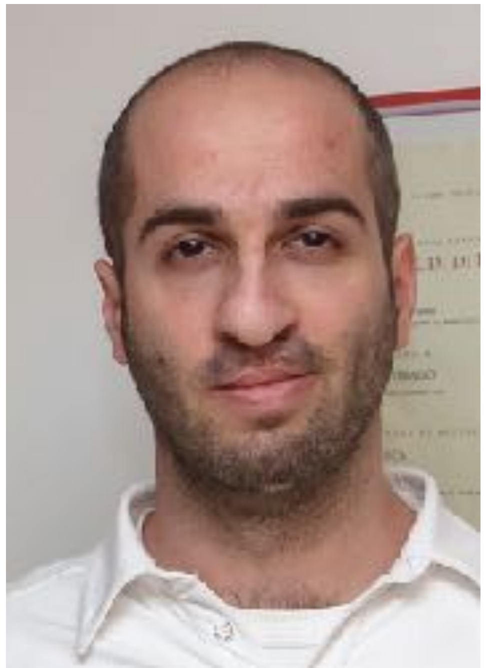
- Sensitive band: 30 to 2000 Hz
- Strain $h=\Delta L/L$
- In 100 Hz band at minimum, r.m.s. noise $h \sim 10^{-22}$

GW150914

- First observing run (O1, science operations) start scheduled **18 September 2015**

- Event at **09:50 UTC on 14 September 2015, four days before O1 start**

AEI Hannover, September 14, 2015



Marco Drago

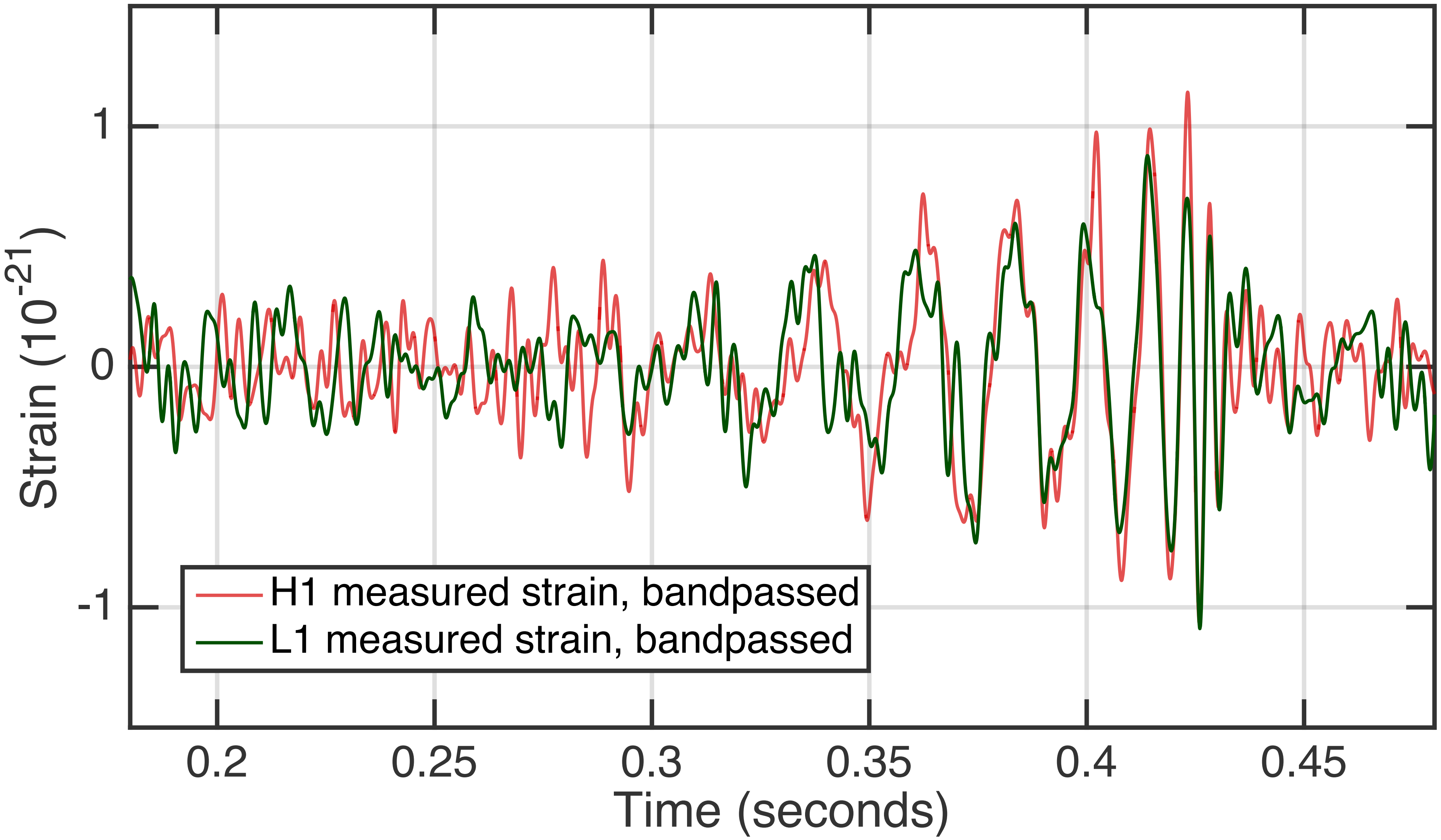
Andrew Lundgren

- Monday morning 11:50 in Germany (02:50 in Hanford, 04:50 in Livingston)
- 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.

- Contacted 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

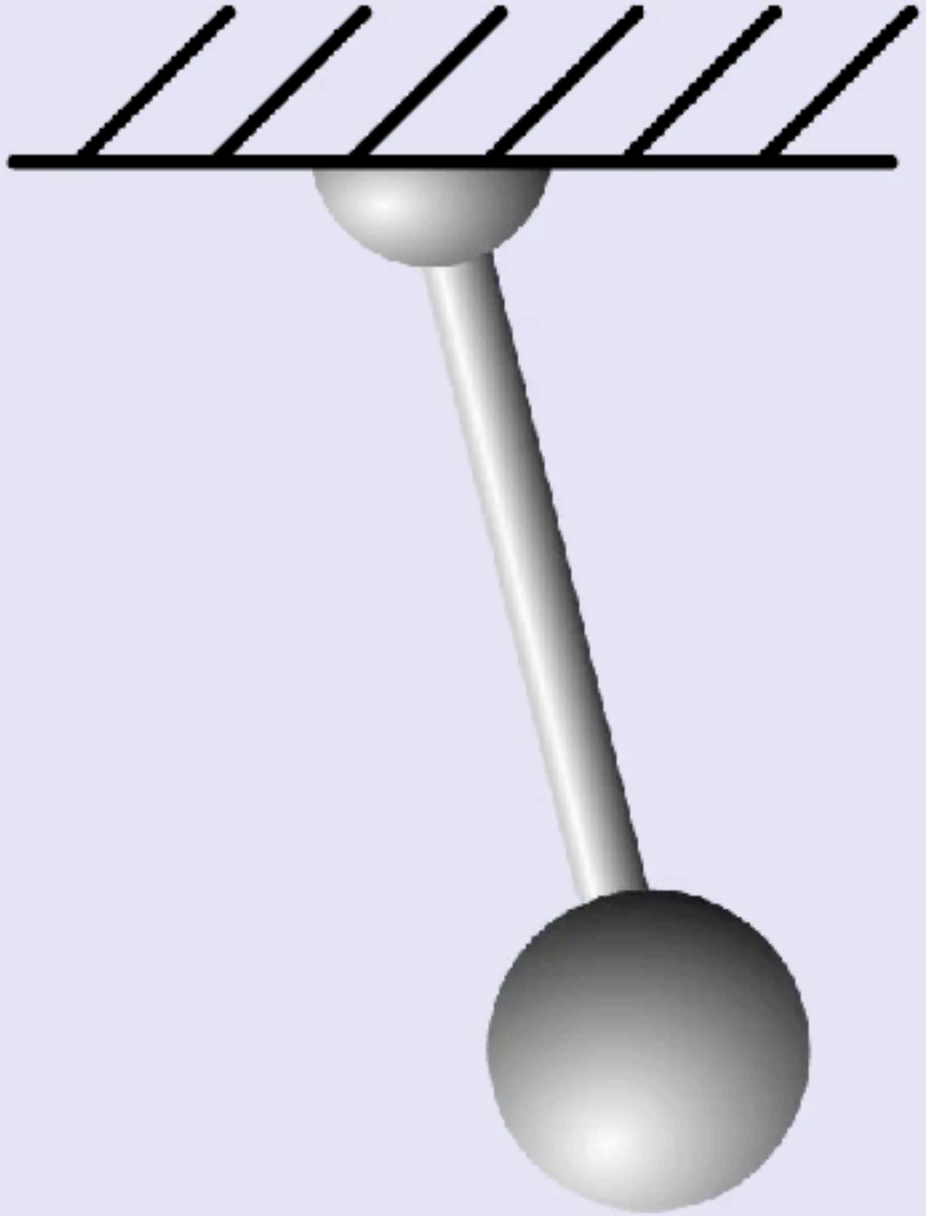
The Chirp

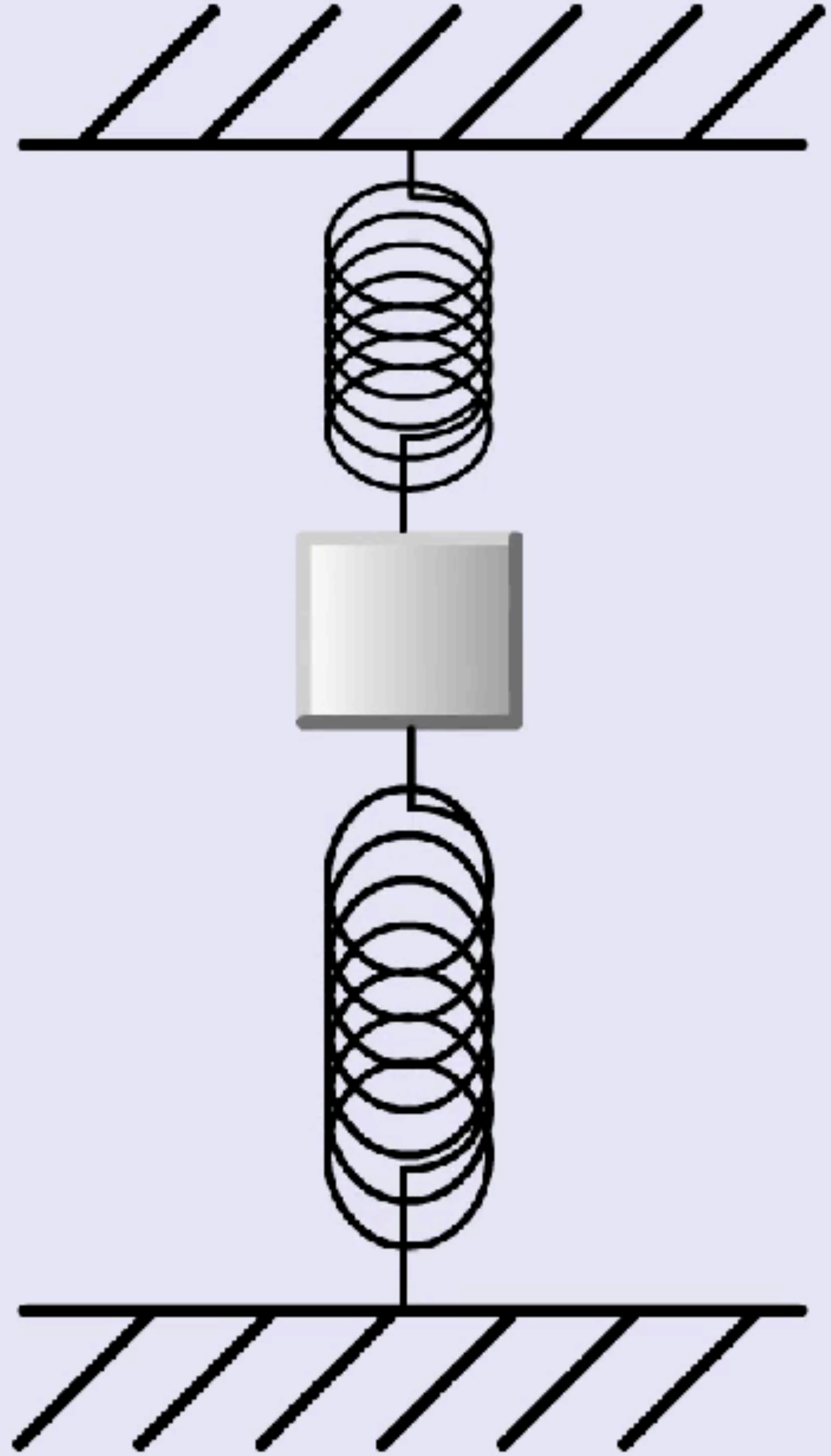
ΔL/L



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

Oscillations





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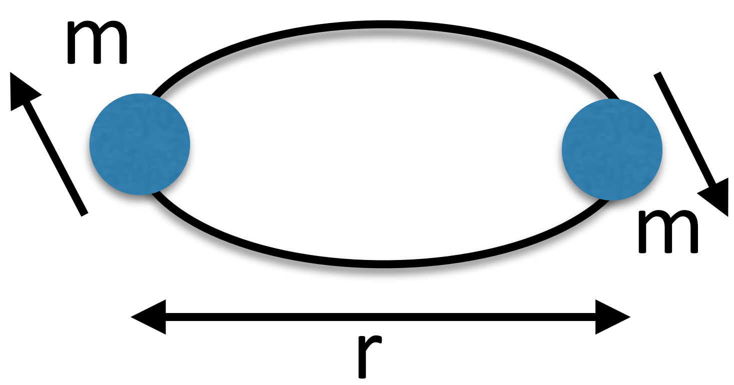
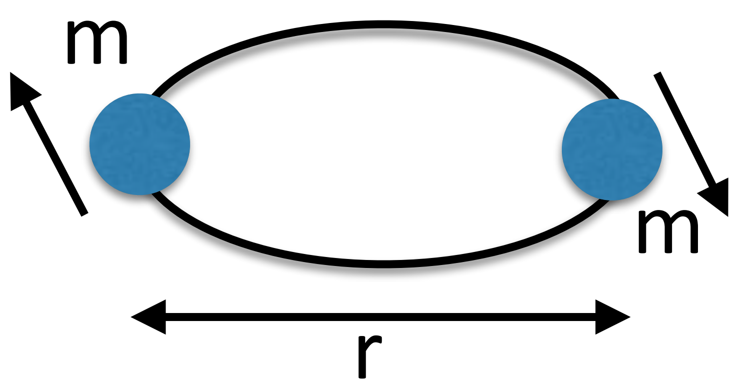
Gravitational waves from orbiting masses



orbital angular frequency ω

$$\mathrm{Newton}: \frac{Gm^2}{r^2} = m\omega^2\left(\frac{r}{2}\right) \Rightarrow r^3 = \frac{2Gm}{\omega^2}$$

Gravitational waves from orbiting masses



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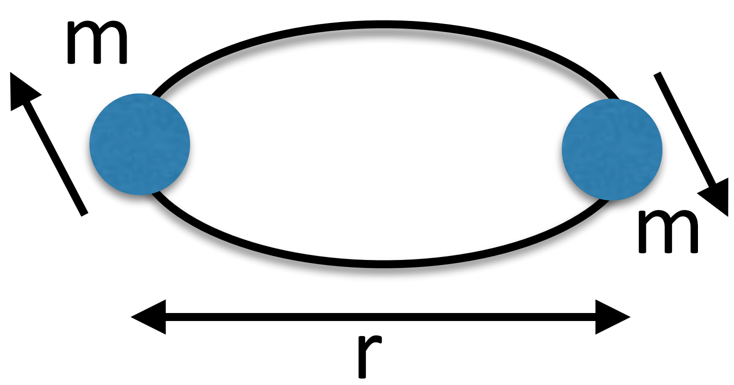
$$\text{Newton}: \frac{Gm^2}{r^2} = m\omega^2 (\frac{r}{2}) \Rightarrow r^3 = \frac{2Gm}{\omega^2}$$

$$\mathrm{E}_{\mathrm{mechanical}} = \frac{1}{2} m (\frac{\omega r}{2})^2 + \frac{1}{2} m (\frac{\omega r}{2})^2 - \frac{Gm^2}{r} = -\frac{Gm^2}{2r} = -\frac{G^{2/3} m^{5/3}}{2^{4/3}} \omega^{2/3}$$

Gravitational waves from orbiting masses



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NO dipole gravitational radiation

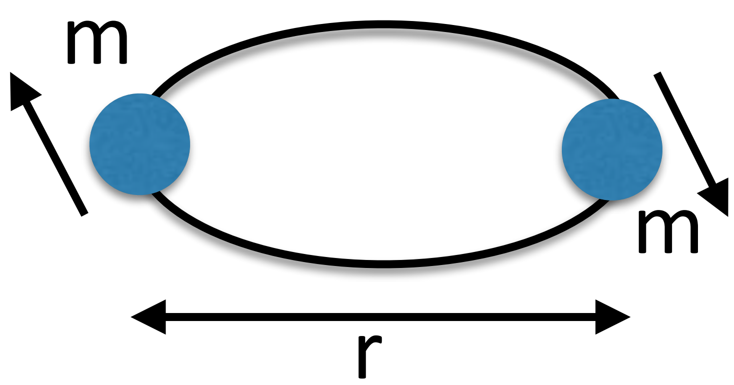
$\mathbf{d} = \Sigma\, m_i\, \mathbf{x}_i$

$\dot{\mathbf{d}} = \Sigma\, m_i\, \mathbf{v}_i = \mathbf{p}$

$\ddot{\mathbf{d}} = 0$

(Note: for equal masses, **d**=0)

Gravitational waves from orbiting masses



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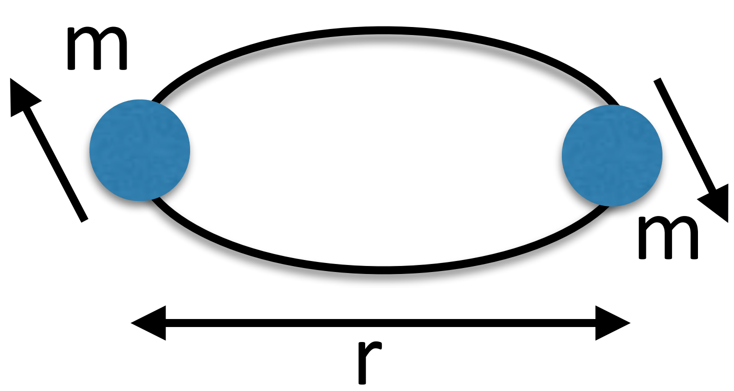
$$\text{GW Luminosity} = \frac{G}{5c^5}\left(\frac{d^3}{dt^3}Q_{ab}\right)\left(\frac{d^3}{dt^3}Q_{ab}\right) = \frac{8G}{5c^5}m^2r^4\omega^6 = \frac{2^{13/3}G^{7/3}m^{10/3}}{5c^5}\omega^{10/3}$$

Gravitational waves from orbiting masses



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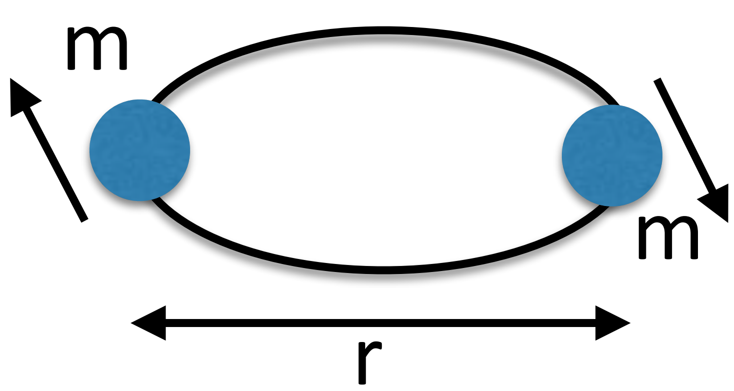
$$\text{GW Luminosity} = -\frac{d}{dt}\mathrm{E}_{\text{mechanical}} = \frac{G^{2/3}m^{5/3}}{3\cdot 2^{1/3}}\omega^{-1/3}\frac{d\omega}{dt}$$

$$\frac{d\omega}{dt} = \frac{3\cdot 2^{14/3}G^{5/3}m^{5/3}}{5c^5}\omega^{11/3}$$

now r and ω change with time!

Gravitational waves from orbiting masses



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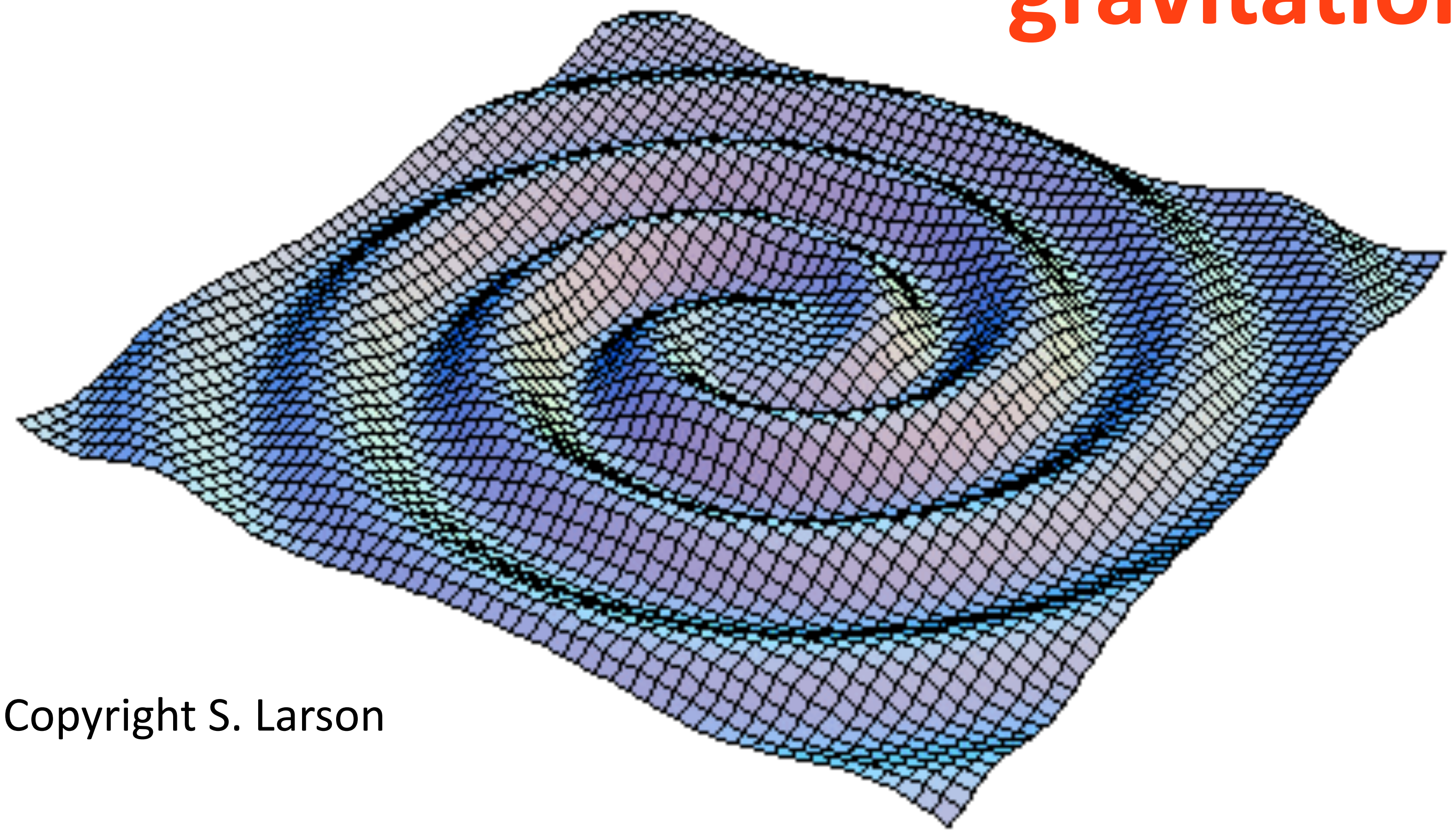
$$\frac{d\omega}{dt} = \frac{3\cdot 2^{14/3}G^{5/3}m^{5/3}}{5c^5}\omega^{11/3}$$

get mass from frequency and its rate of change!

Each orbit makes two gravitational wave cycles



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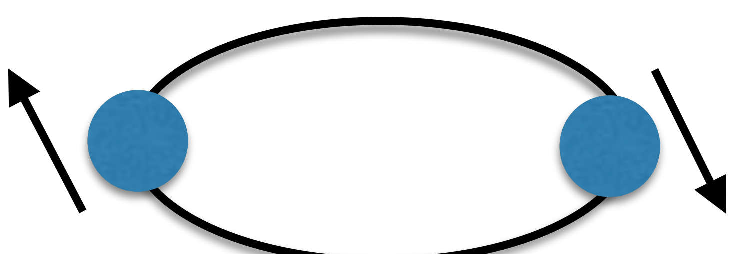
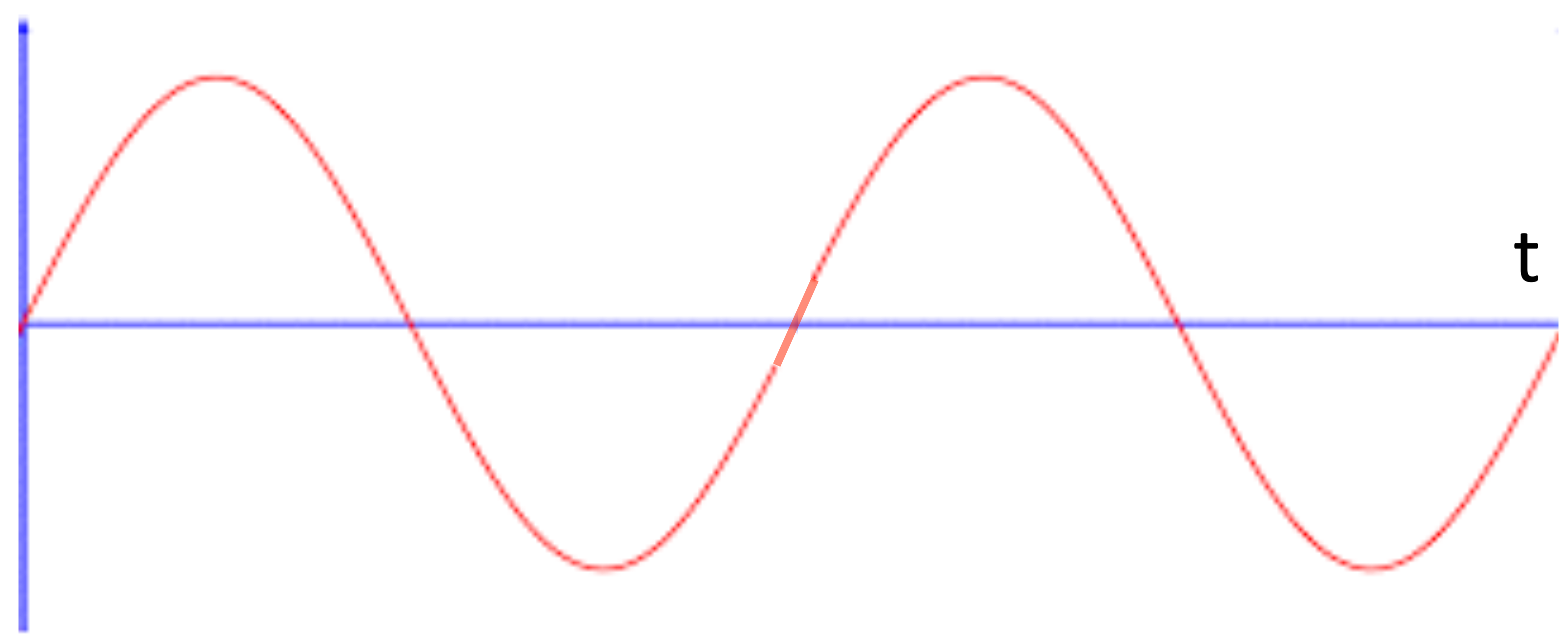


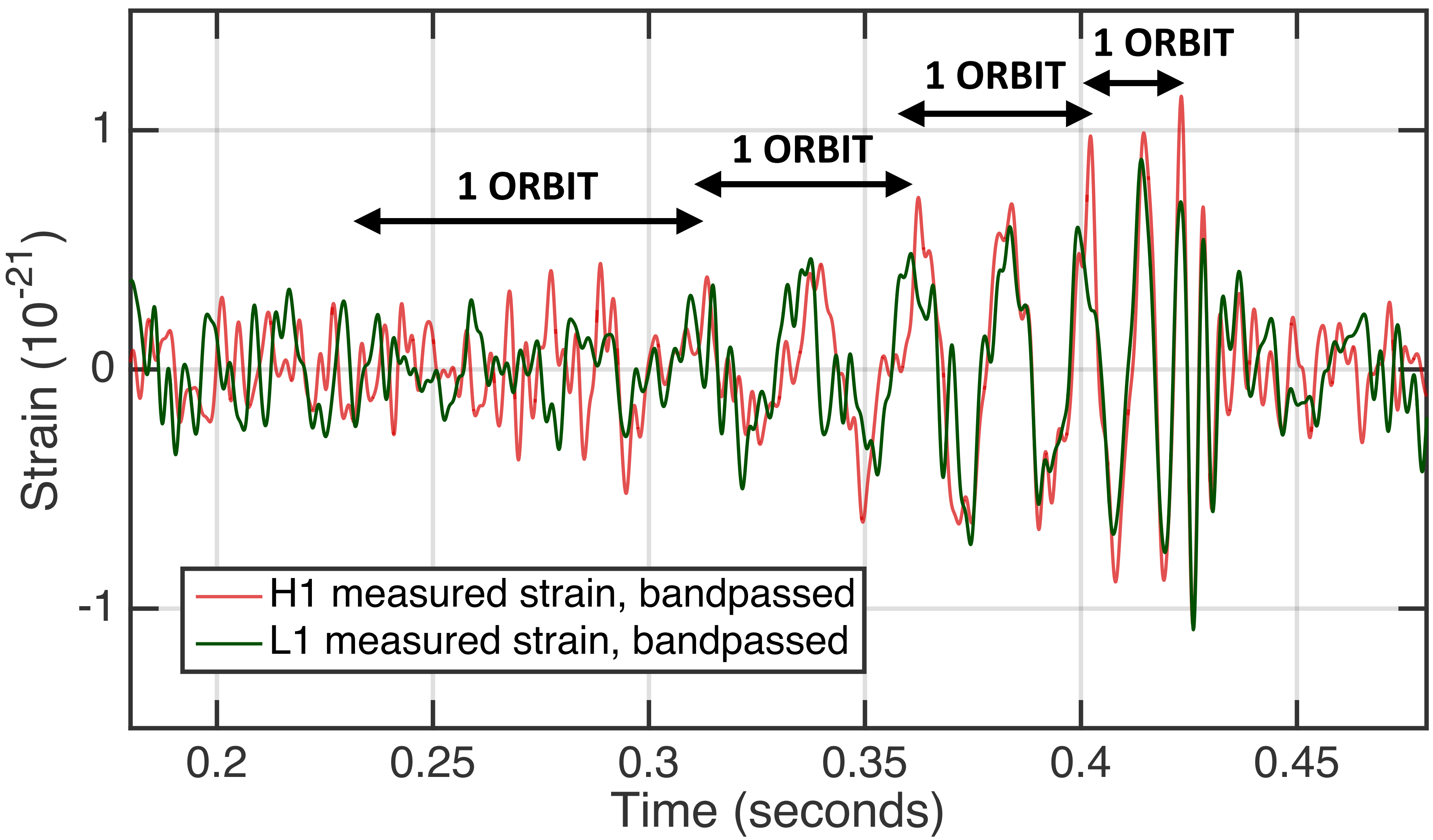
1 orbit

ΔL/L = gravitational wave strain



The Chirp

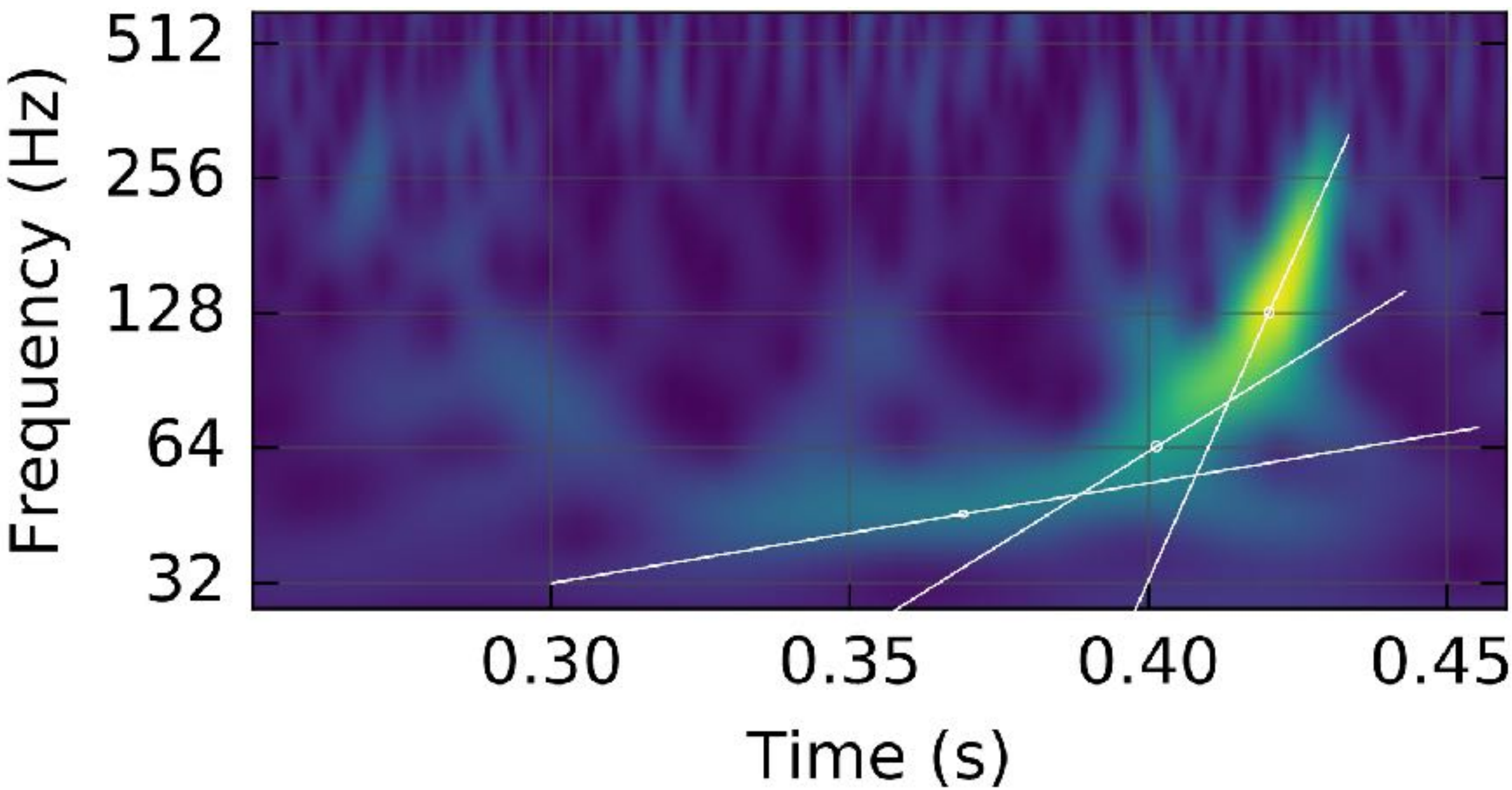
$\Delta L/L$



- Last four binary orbits followed by merger and ringdown
- No sign of eccentricity in raw data

Chirp Mass

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

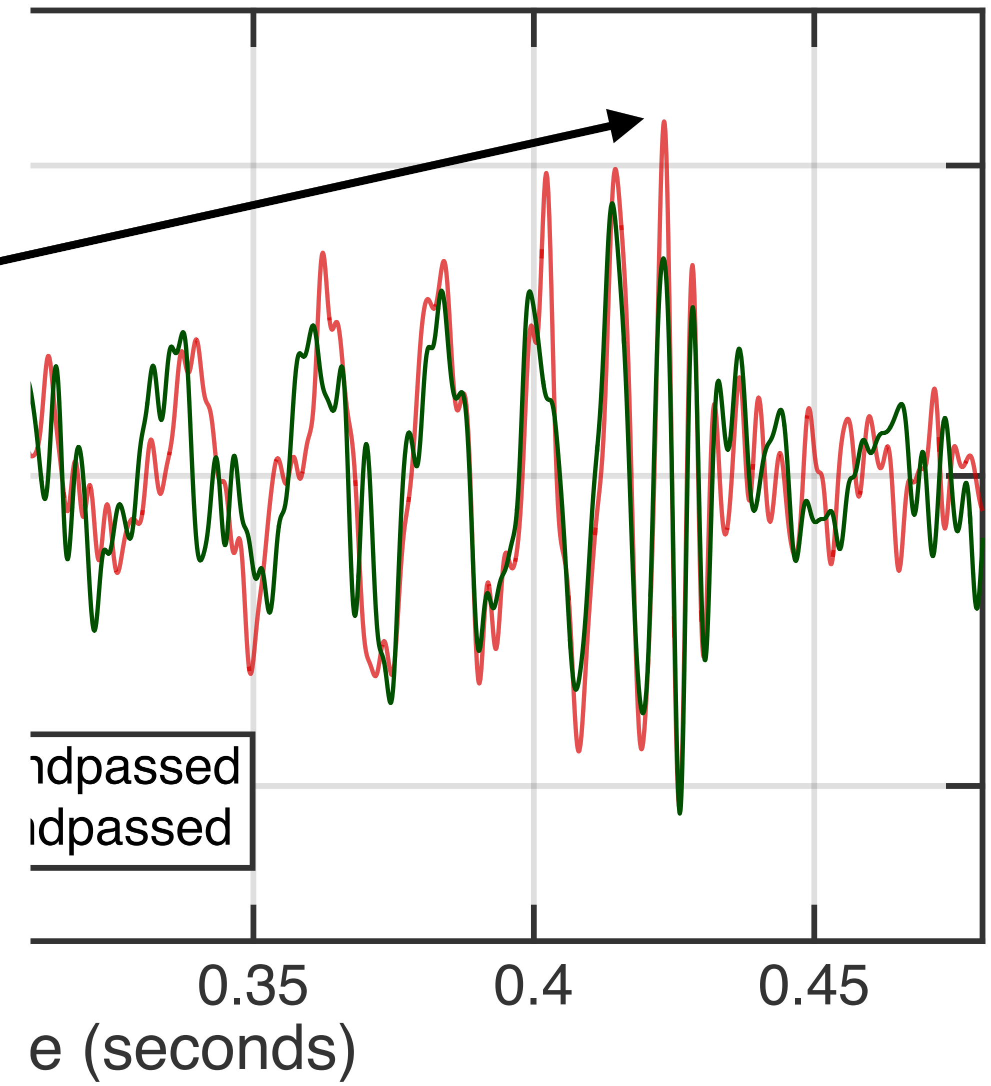


Can only be two black holes!

- Chirp mass $\mathcal{M} \sim 30\ M_\odot$

  => $m_1, m_2 \sim 35\ M_\odot$ =>

  Sum of Schwarzschild radii $\geq$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). **White dwarfs** are 10^4 km (merge at 1 Hz). They are too big to explain data!
- **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 heavy enough and small enough!

Real? Detector artifact? Fraud?

- Instruments stable since September 12th, 2015
- 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 environment (radio, acoustic, magnetic, seismic, …) 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**

23 September 2015

Hi Ajith,

BA | | | | >>>> Busy but exciting time, no?

AP | | | >>> Very! I really hope that this won't turn out to be a blind injection 🙂

BA >> It has been categorically stated (starting on day 1) that this is NOT a blind injection. If it IS a blind injection, then it is malicious: the person responsible went to a lot of trouble to find and use a new method for it, which did not pass through any of the conventional channels, or "hacked" the LIGO hardware and data analysis system very effectively to cover their tracks.

AP > I have seen the (rather surprising) statement that this is not a
> hardware injection.

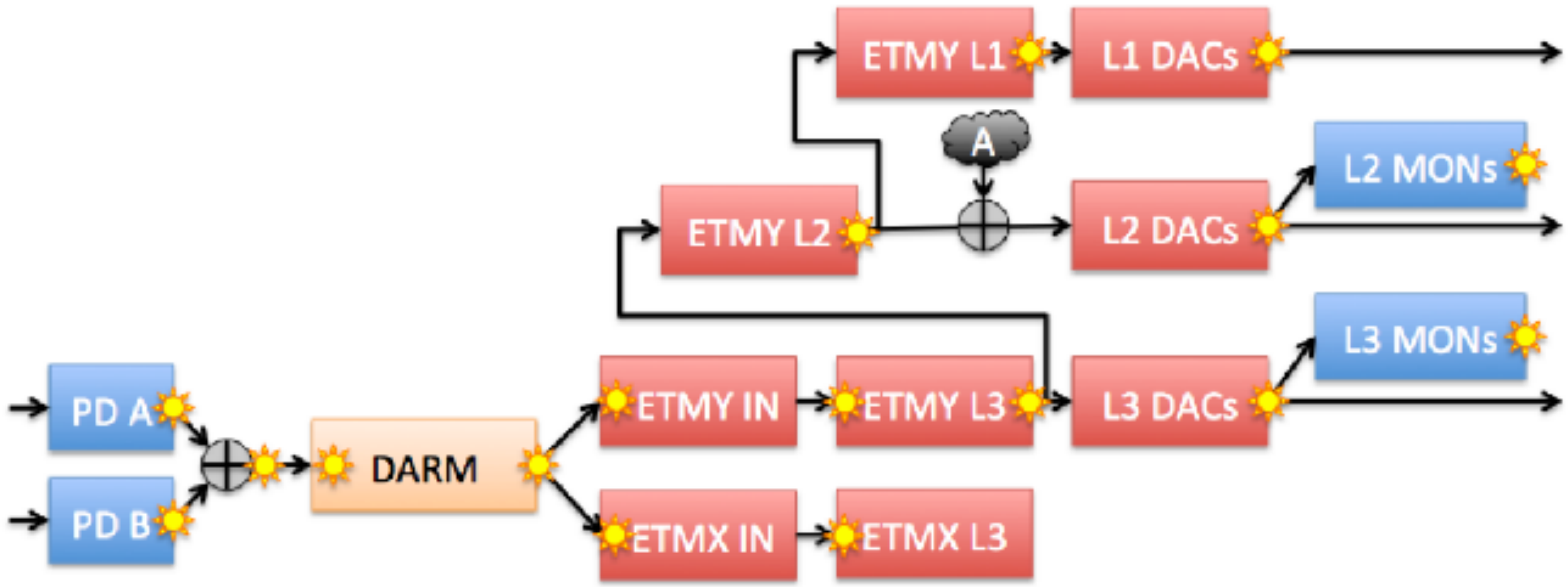
BA This is not a deliberate or an accidental hardware injection. If it is a hardware injection, then it is malicious.

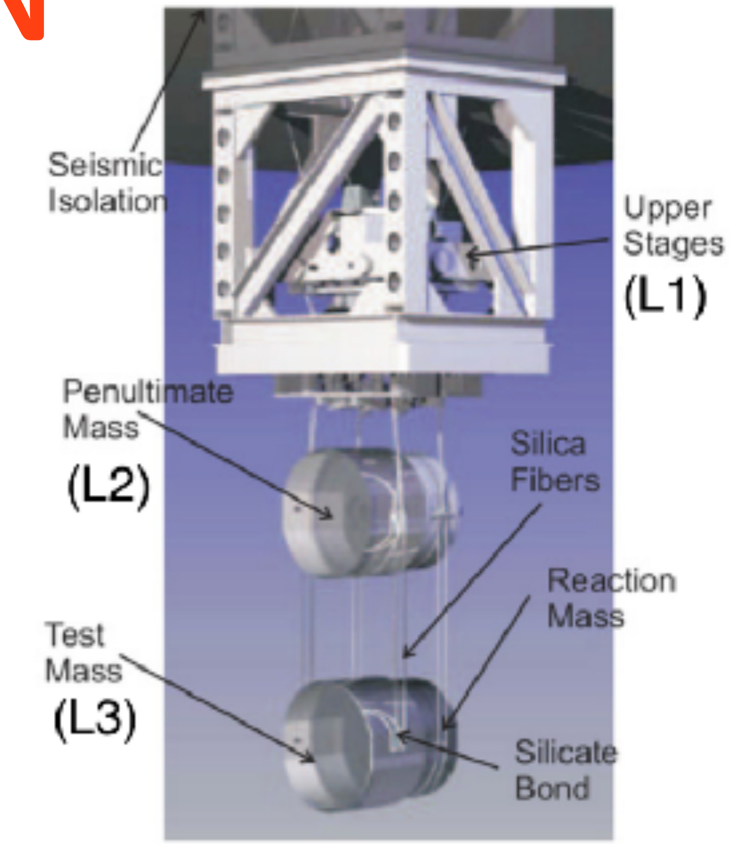
AP > But I wasn't sure if there is a possibility of
> "double blinded" injections. I understand that this is very unlikely.

BA This is NOT a blind or double blind injection. It's the first aLIGO GW detection.

Cheers,
Bruce

CONTROL LOOP RECONSTRUCTION





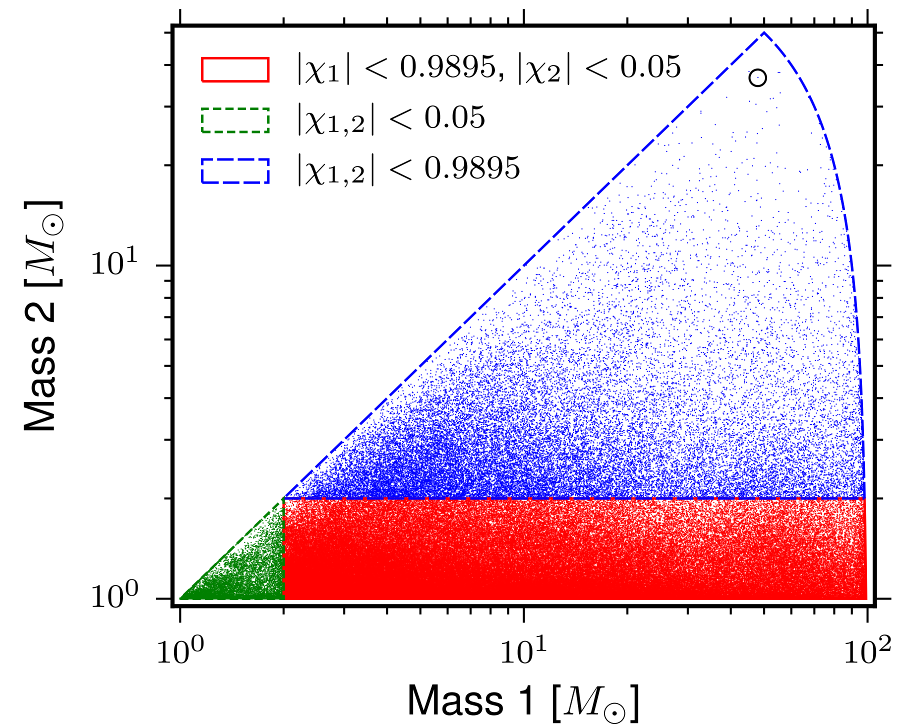
- Photodiode (PD) signals from fringes
- Signals: recorded at yellow stars
- Injections: add into End Test Mass (ETMX) controller
- **So: compare L2/L3 DACs to expectation from DARM input**
- Examination of these recorded values and (consistent) reconstruction of the filter operation proves no injection signal (Evans, LIGO-T1500536-v3)

Random Noise?

Much longer than 200,000 years before noise in the detector would mimic this signal, or a similar signal of the types that we search for.

Optimal Filtering

- Filter data through model SEOB 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 is 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 $$\tilde{s}(f) = \int_{-\infty}^{\infty} s(t) e^{-2\pi i f t}\, \mathrm{d}t$$

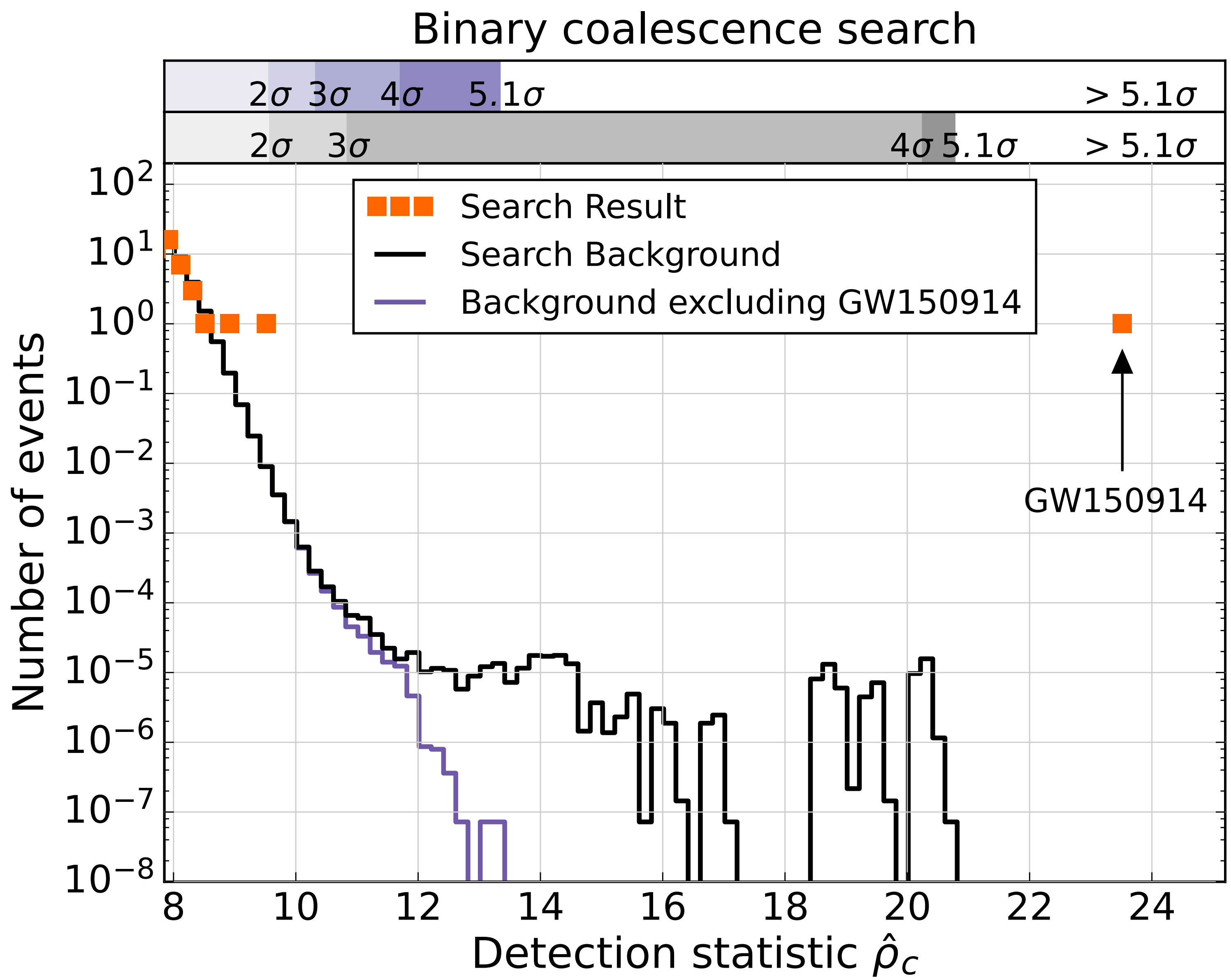
SNR $$\rho^2(t) \equiv \frac{1}{\langle h|h\rangle} \left[\langle s|h_c\rangle^2(t) + \langle s|h_s\rangle^2(t)\right]$$

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

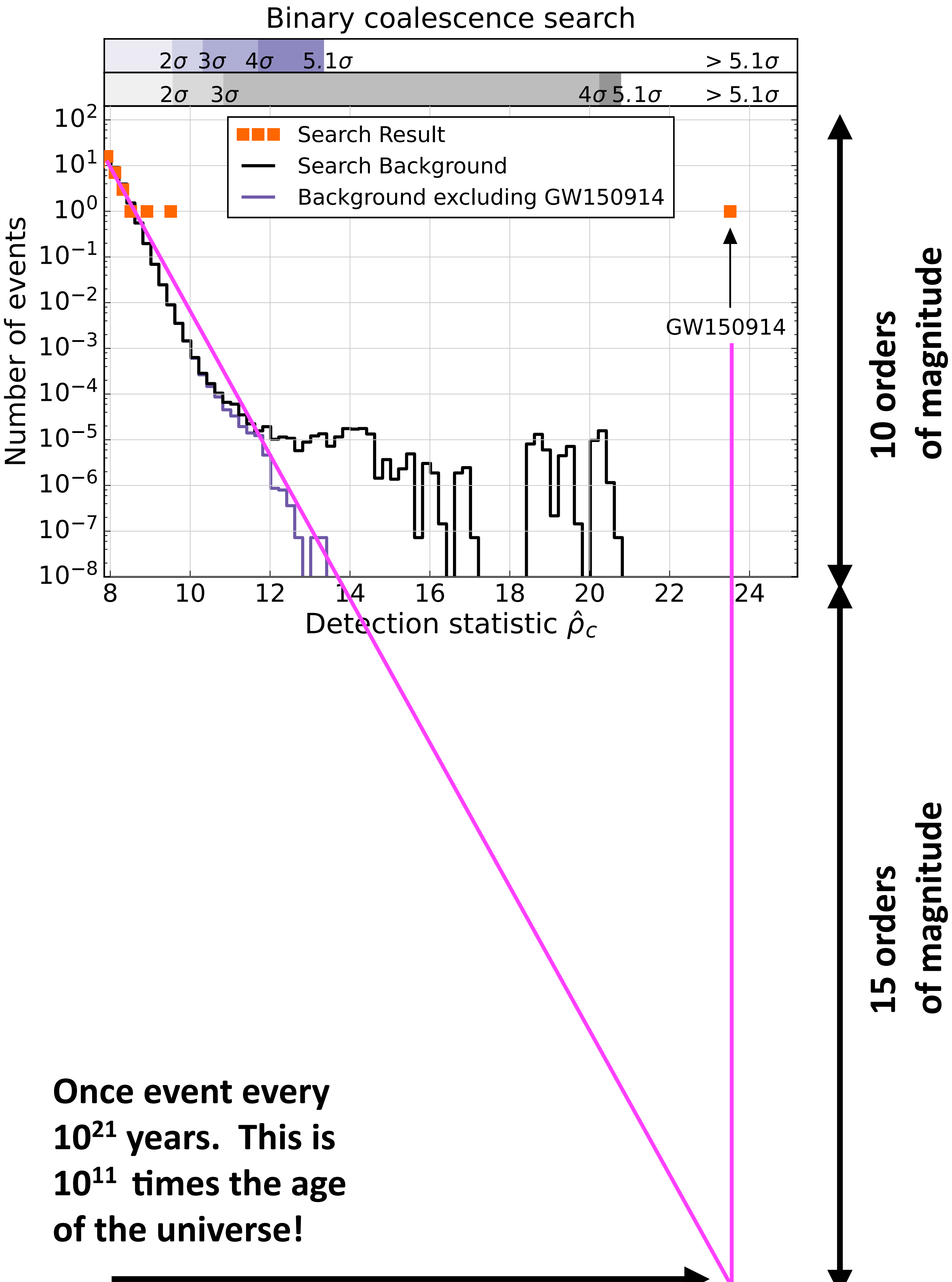
B. Allen et al., Phys. Rev. D 85, 122006 (2012)
B. Allen, Phys. Rev. D 71, 062001 (2005)

What is the false alarm probability?



- 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

What is the false alarm probability?



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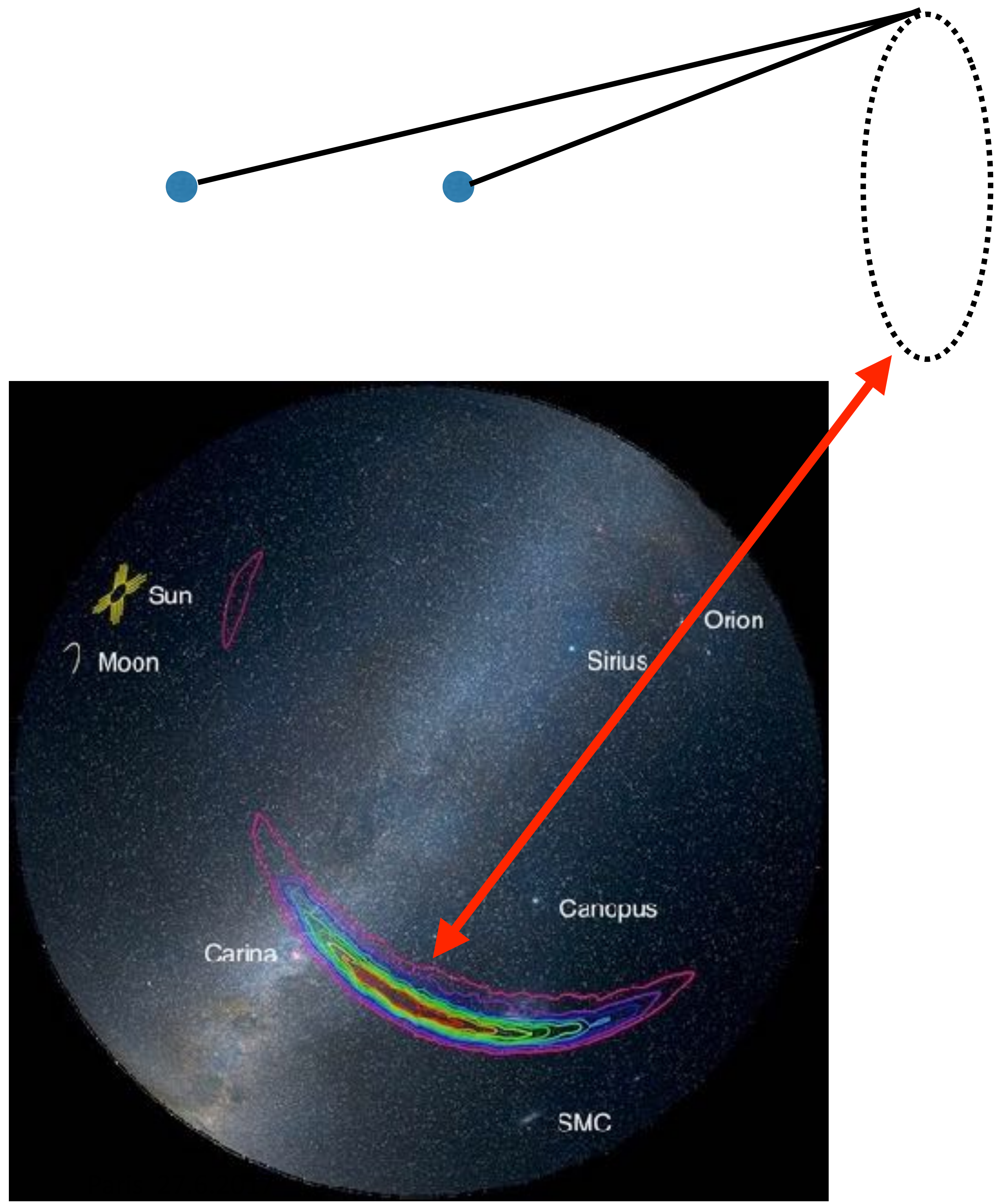
- Generate 608,000 years of “artificial” data, search for events
- Including trials factor, false alarm rate < 1 in 203,000 years
- For a Gaussian process, this is > 5.1σ
- Real false alarm rate much much less! **We got lucky, could have confidently detected it 70% farther away.**

Parameters: sky position

- 7-msec time delay gives a CIRCLE on the sky. Why an arc?
- Bayesian analysis: most likely source direction is directly above or below plane of detector.
- Intersect these, get only a portion of circle



Crudest (Luminosity) Distance Estimate

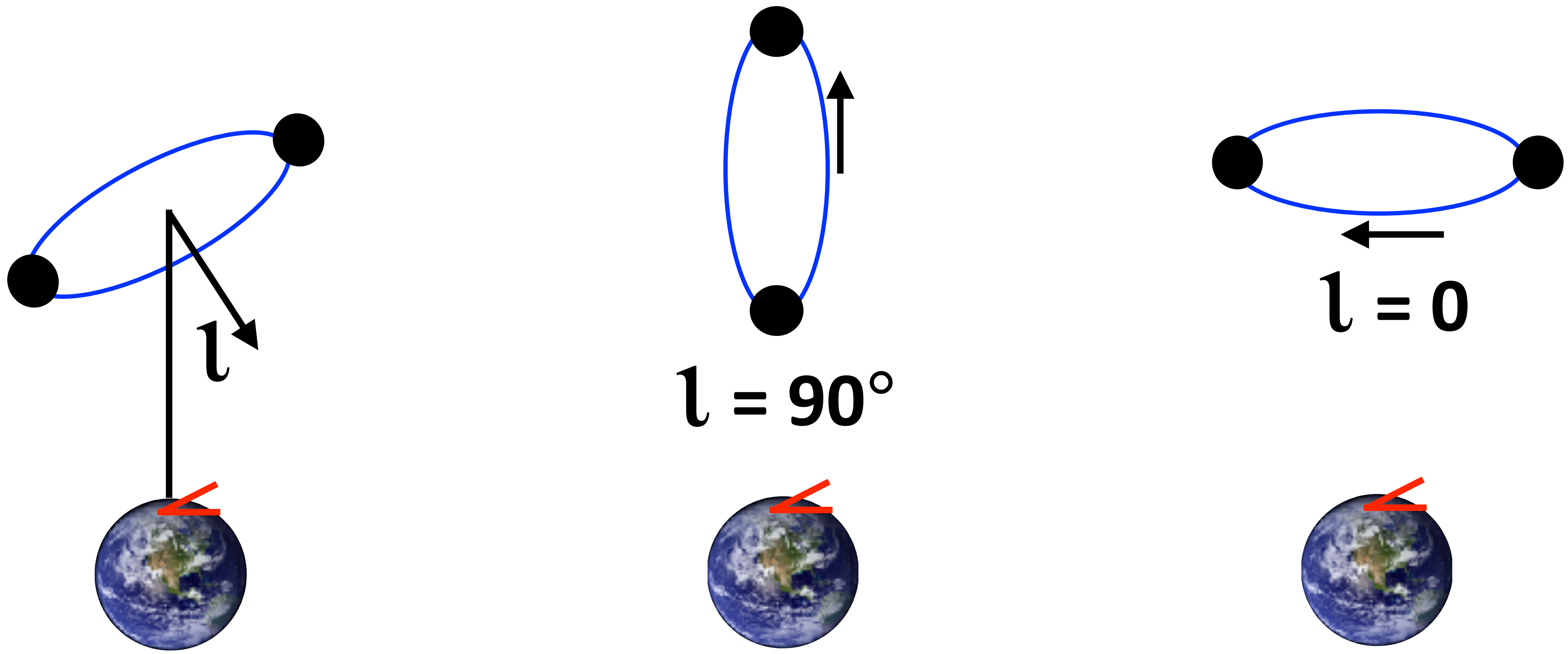
- Schwarzschild radius ~ 200 km
- Metric strain h is order h~0.1 at Schwarzschild radius
- Strain h falls off like inverse of distance d
- At detector, maximum metric perturbation $h \sim 10^{-21}$
- This implies a distance
  $d \sim 10^{20} \times 200$ km
  $\sim 2 \times 10^{25}$ m
  $\sim 2 \times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

Parameters: masses and distance

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	$410^{+160}_{-180}\,\mathrm{Mpc}$
Source redshift, z	$0.09^{+0.03}_{-0.04}$

- Instrument calibration accurate 3% percent.
- Waveform models accurate to 1%
- SNR high enough that noise should give errors of ~5%
- Errors in masses and spins at ±10% level
- Why are distance uncertainties ±40% ?

Why is distance so uncertain?

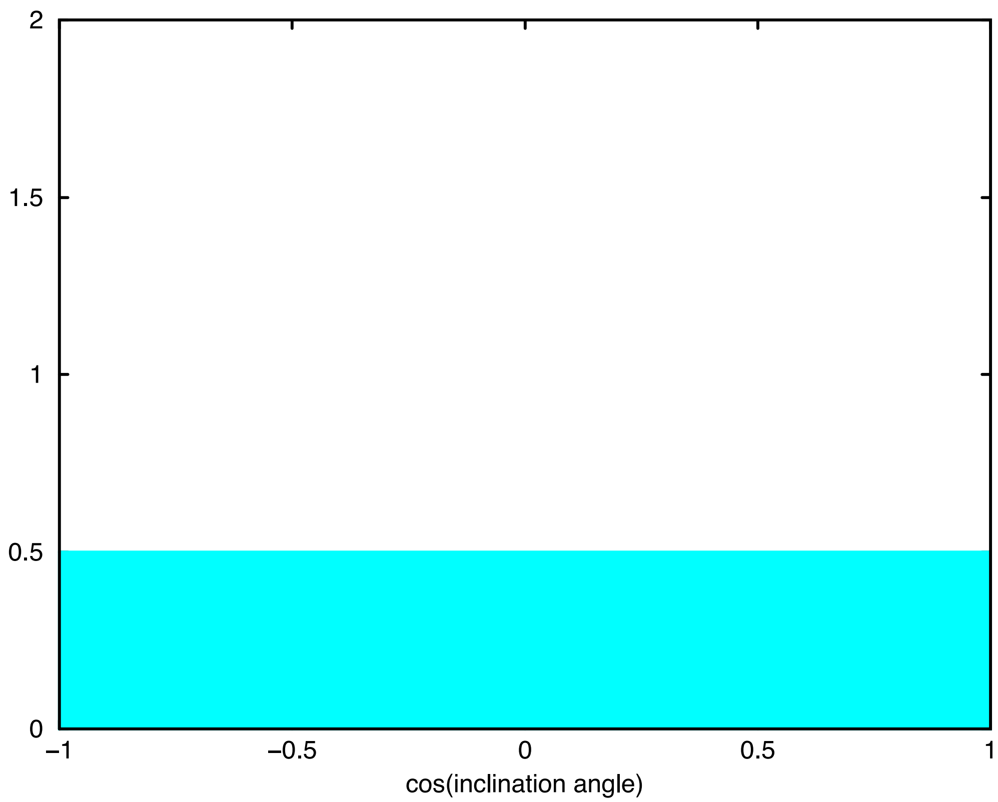


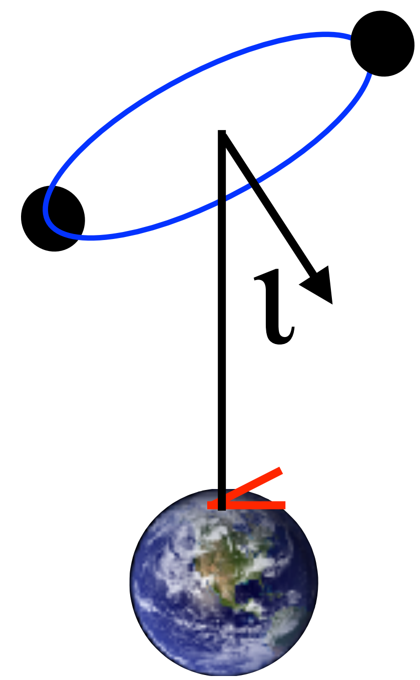
Orbital plane edge-on
GWs have linear polarisation

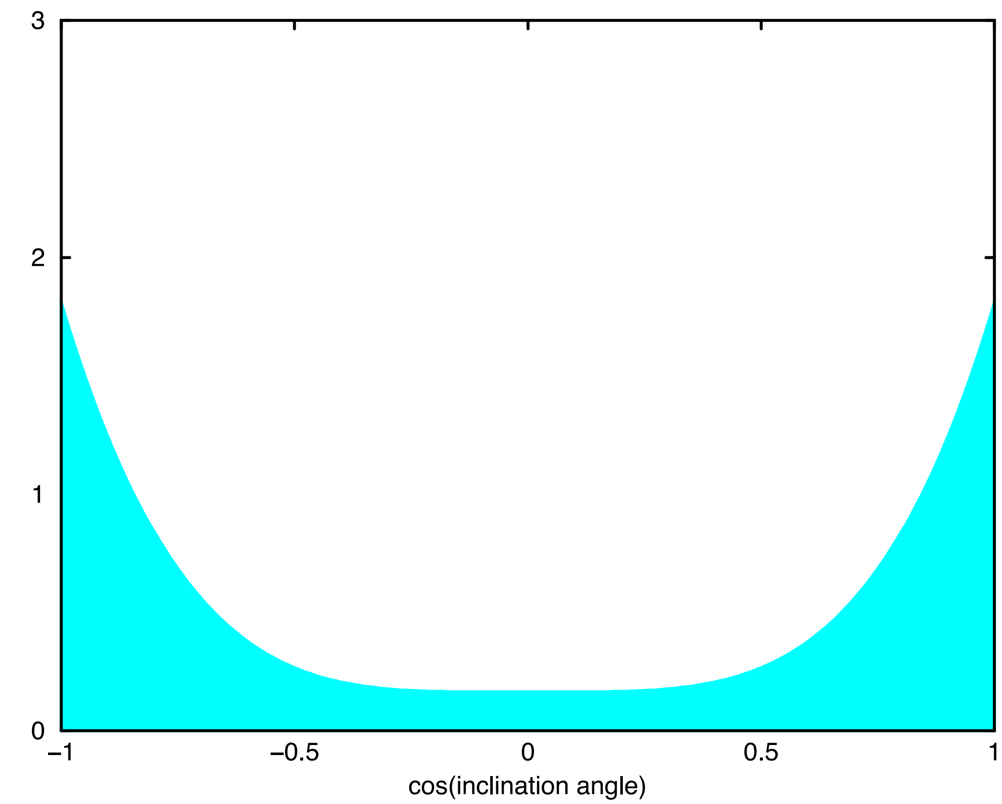
Orbital plane face-on
GWs have circular polarisation

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

Inference about orbital inclination



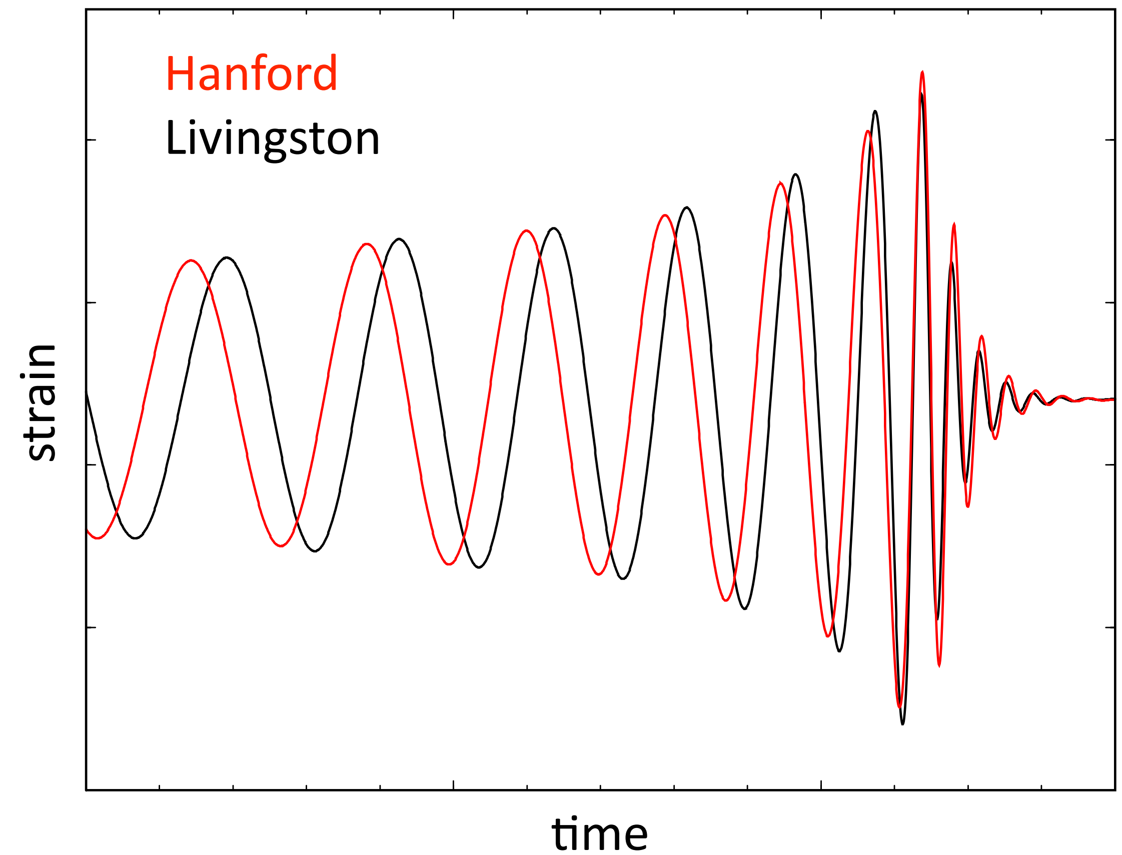




Prior (astrophysical) probability distribution for cos(ι)

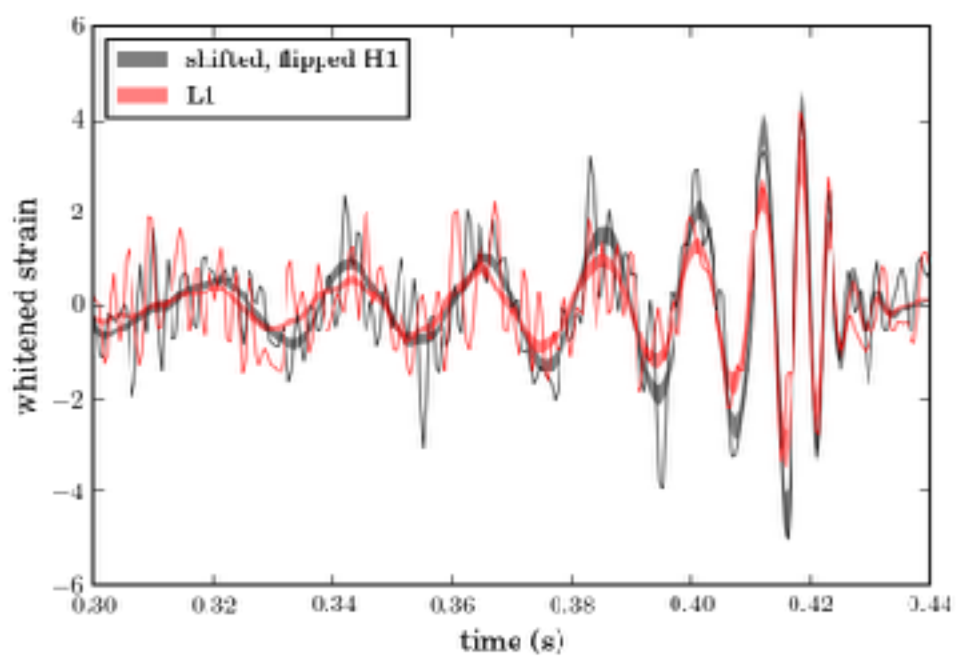
Posterior probability distribution for cos(ι), using **only** the information that we have detected something with SNR=24 (but with no other information from the data)

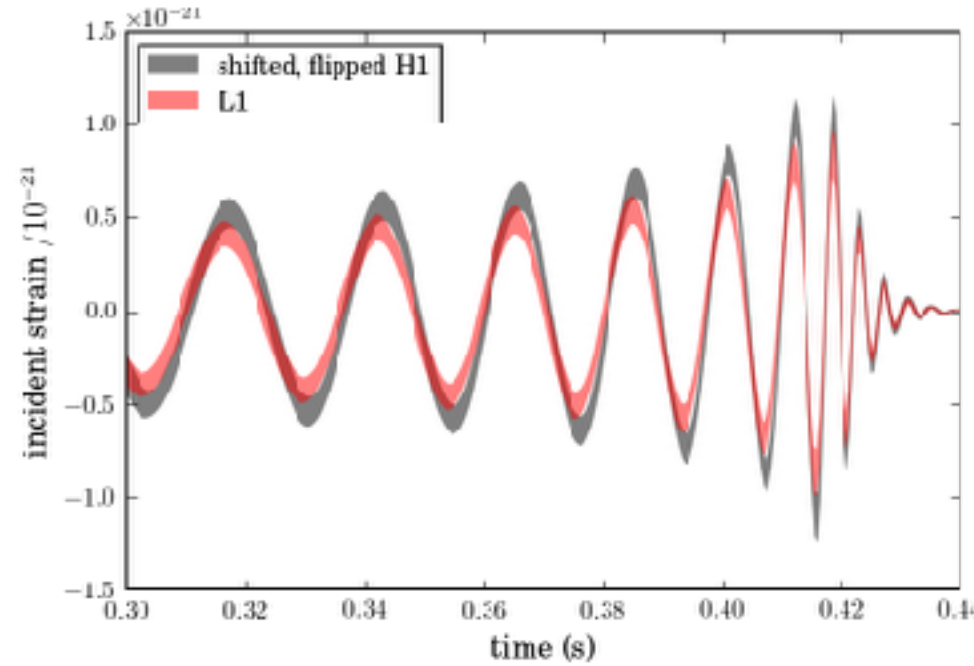
How would circular polarisation look?



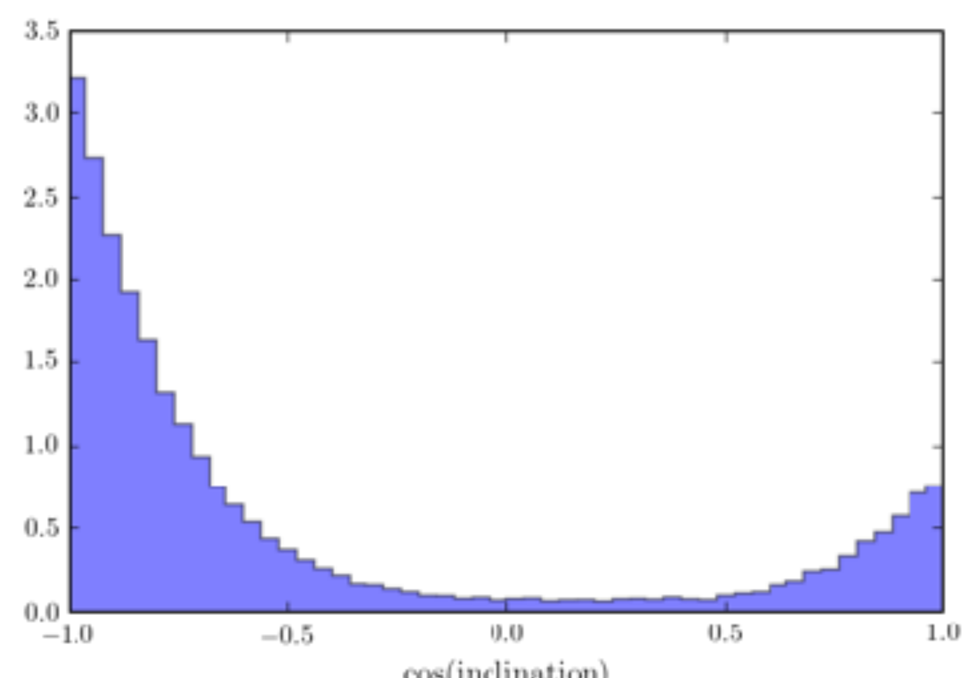
- If detectors are seeing distinct polarisations, phase in one detector leads the other detector by 90 degrees
- After "lining up" arrival times, would look like above
- Edge-on: one polarisation, signals always in phase
- Face-on: two polarisations, phase shift possible

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.



Masses and distance

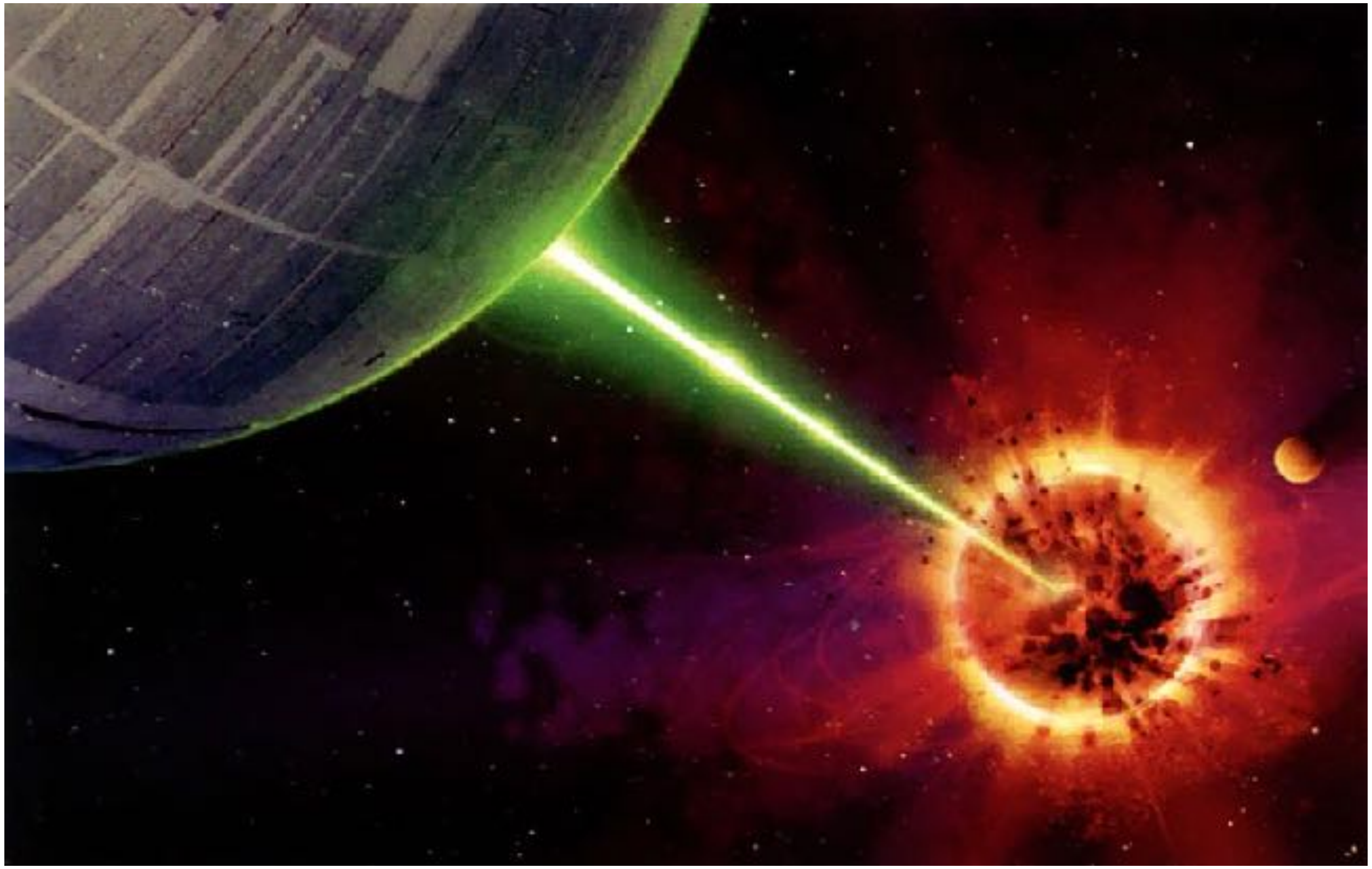
Primary black hole mass	$36^{+5}_{-4}\,\mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	$410^{+160}_{-180}\,\mathrm{Mpc}$
Source redshift, z	$0.09^{+0.03}_{-0.04}$

- 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.**

Radiated Energy

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

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



Energy lost, power radiated

Primary black hole mass	$36^{+5}_{-4}\ \mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\ \mathrm{M}_\odot$
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Final black hole spin	$0.67^{+0.05}_{-0.07}$
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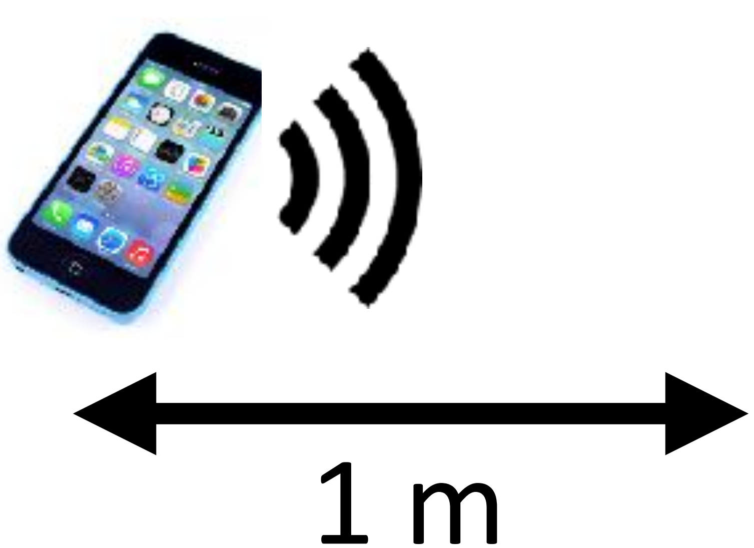
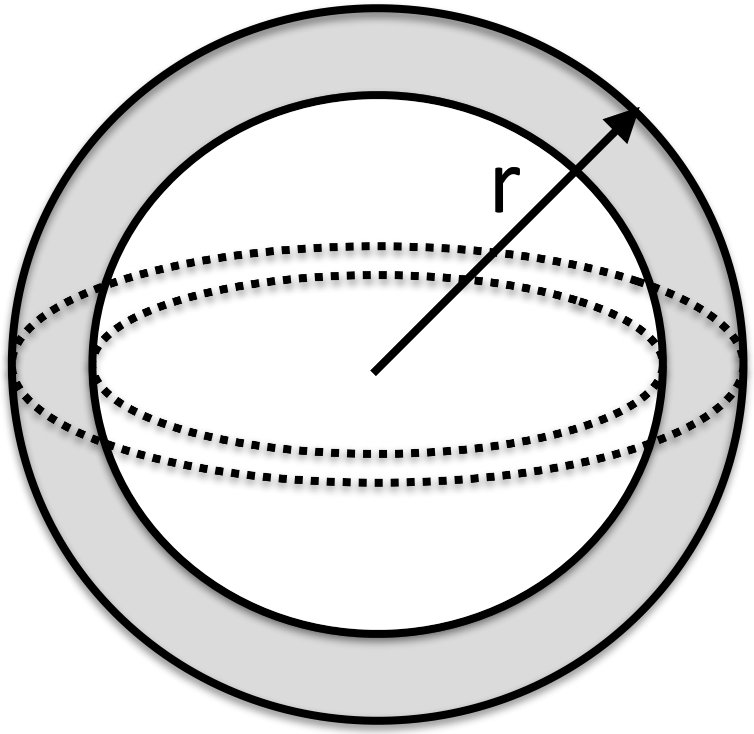


- Radiated energy: $3M_\odot$ (±0.5)
- Peak luminosity: 3.6×10^{56} erg/s ($\pm15\%$) $= 200\ M_\odot/s$
- Flux about $1\mu W/cm^2$ at detector, $\sim10^{12}$ millicrab
- Cell phone at 1 meter!

3 solar masses in gravitational waves

- Most of the energy emitted in ~40 msec
- 10 msec after merger, expanding shell of GW energy 15,000 km in radius. Energy density in GW: ~60kg/cm^3
- 1 sec after merger, shell 300,000km radius, energy density in shell ~ 100 g/cm^3. **You could safely observe from this distance in a space-suit: strain would change your body length by ~1mm**
- 10 s after merger, shell has expanded to 3,000,000 km radius. Energy density in GW: ~1 g/cm^3



$r \sim t$

$\rho \sim r^{-2} \sim t^{-2}$

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]

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

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

Primary black hole mass	$36^{+5}_{-4}\ \mathrm{M}_\odot$
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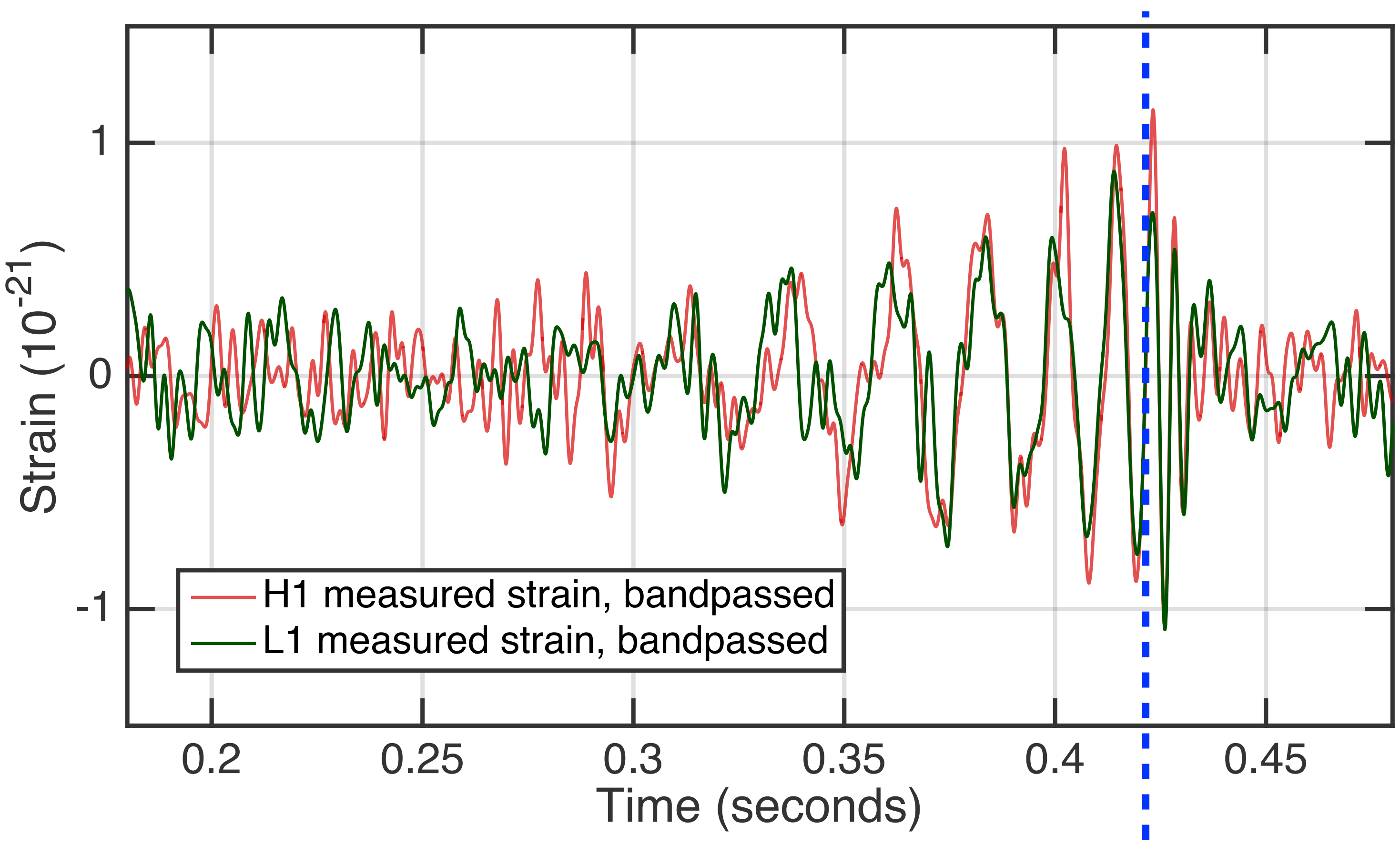
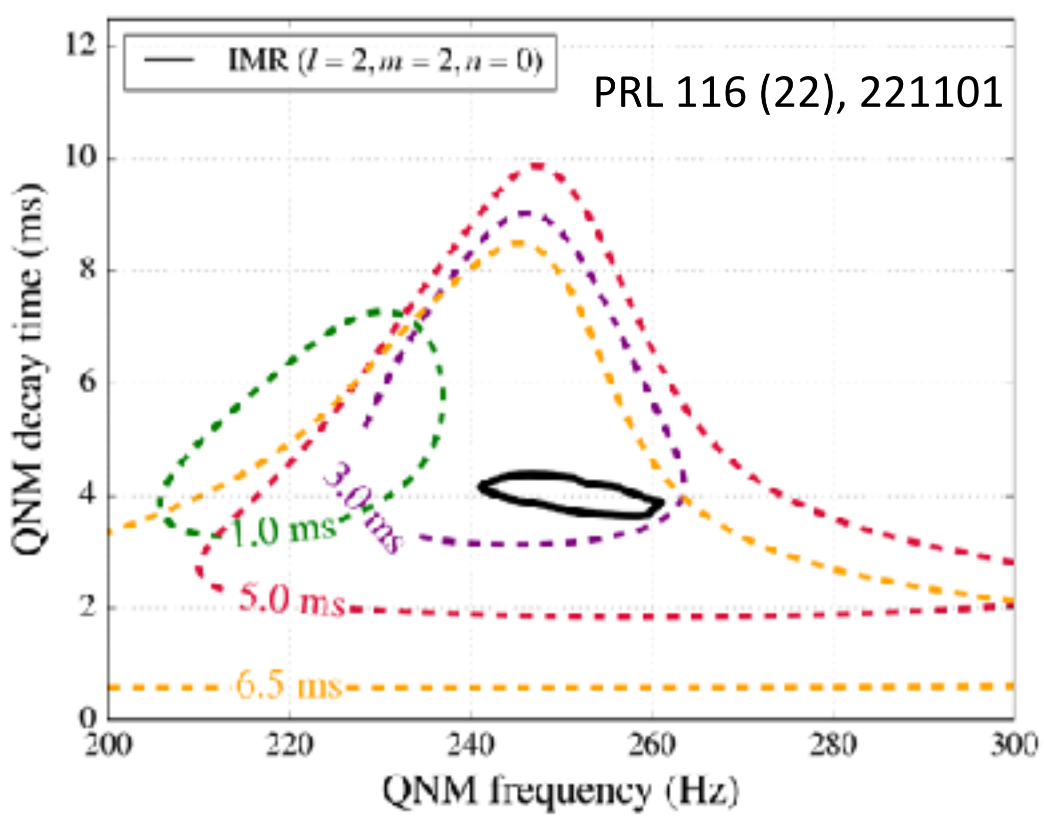
$$m_f^2\left(1+\sqrt{1-s_f^2}\right) > m_1^2\left(1+\sqrt{1-s_1^2}\right)+m_2^2\left(1+\sqrt{1-s_2^2}\right)$$

GW150914 test area theorem? No!



- Most SNR before merger: only values of m_1, m_2 are determined independently.
- m_f and s_f determined by numerical relativity (which gives the matching waveforms)
- If area theorem were NOT satisfied, then the numerical relativity code solving the Einstein equations must be faulty



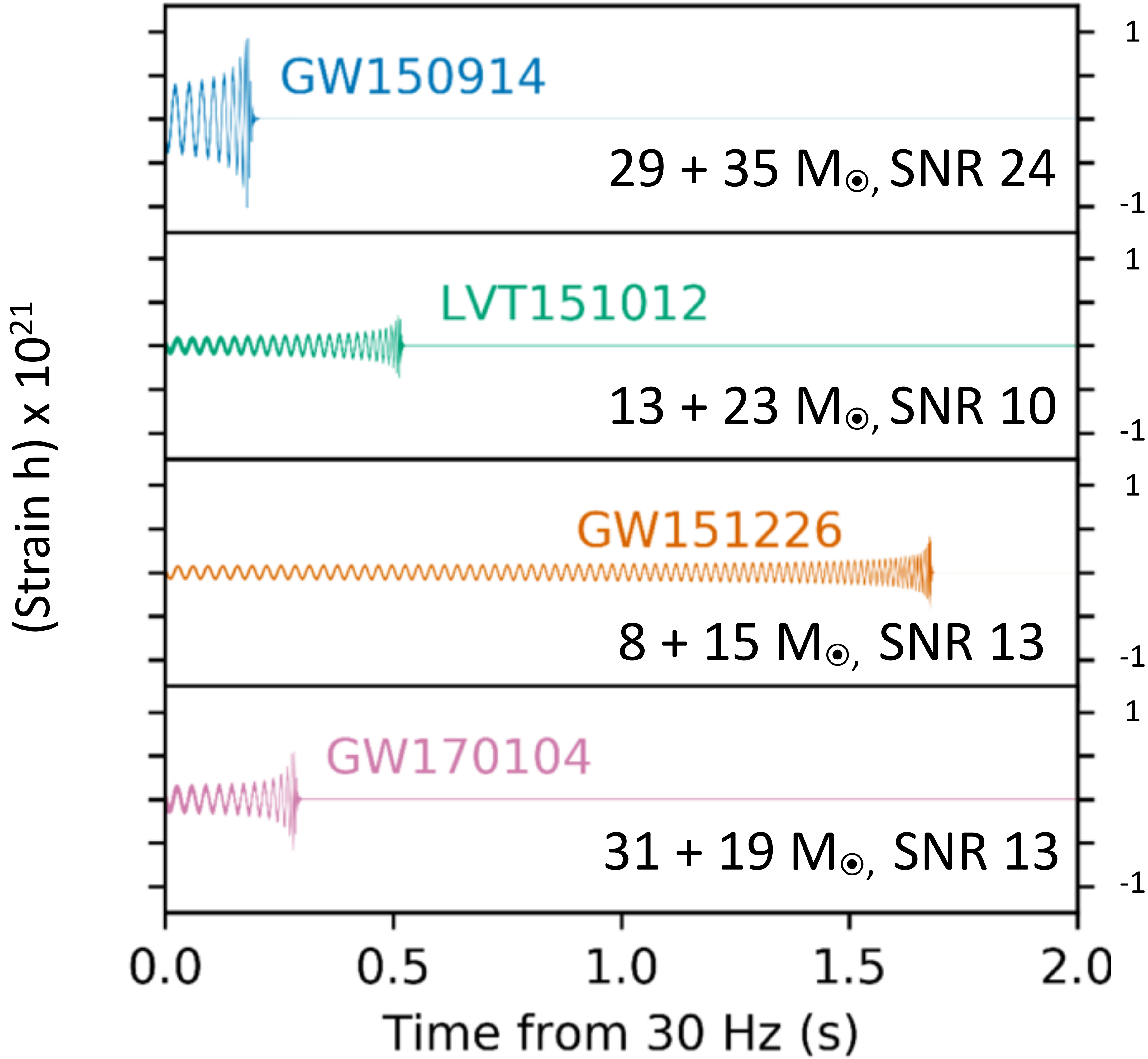
PRL 116 (22), 221101

M = 340 μs (in detector frame)

Numerical simulations: QNM dominates starting ~10M after peak

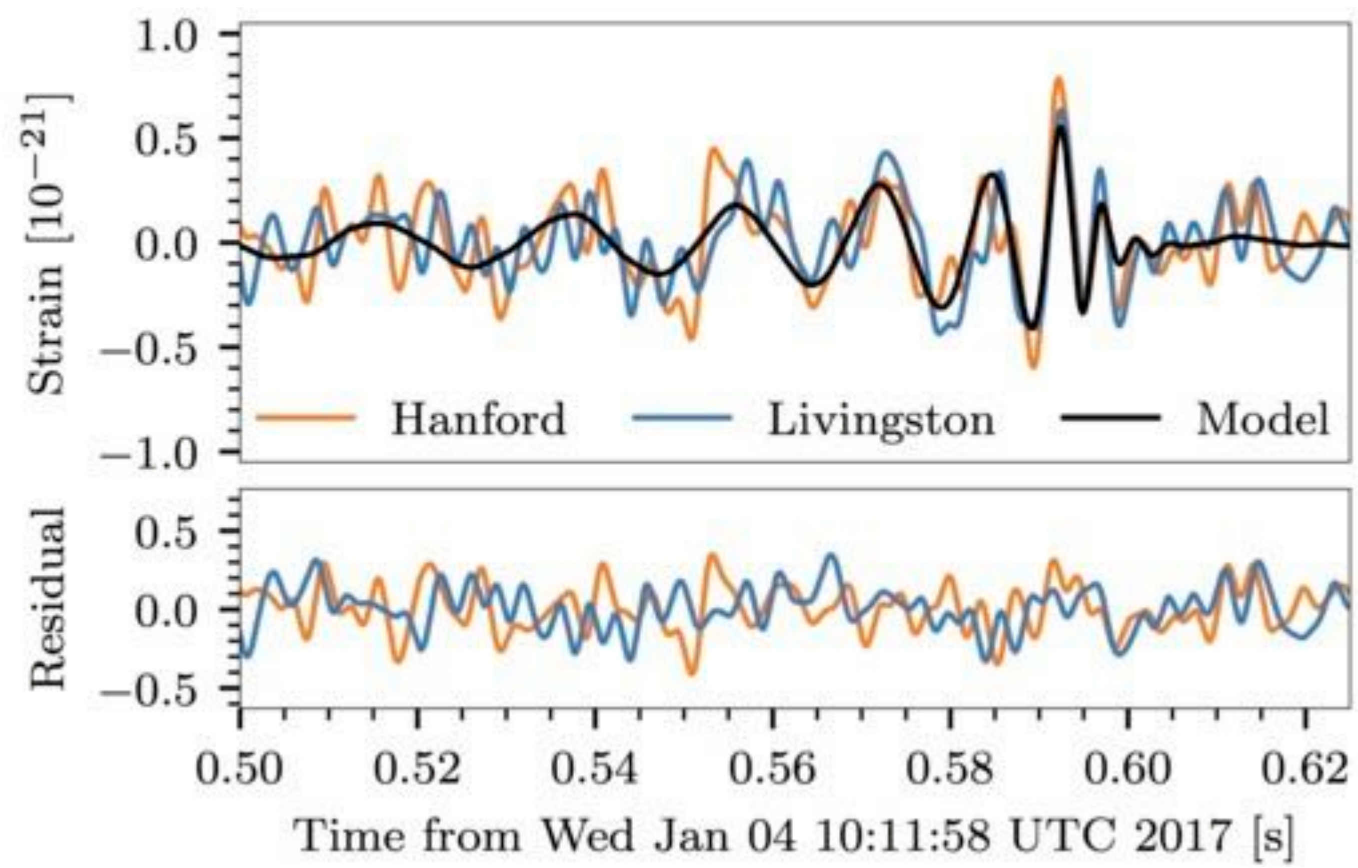
10M = 3.4 ms (in detector frame)

Binary Black Holes in O1/O2



GW170104: first Detection in O2

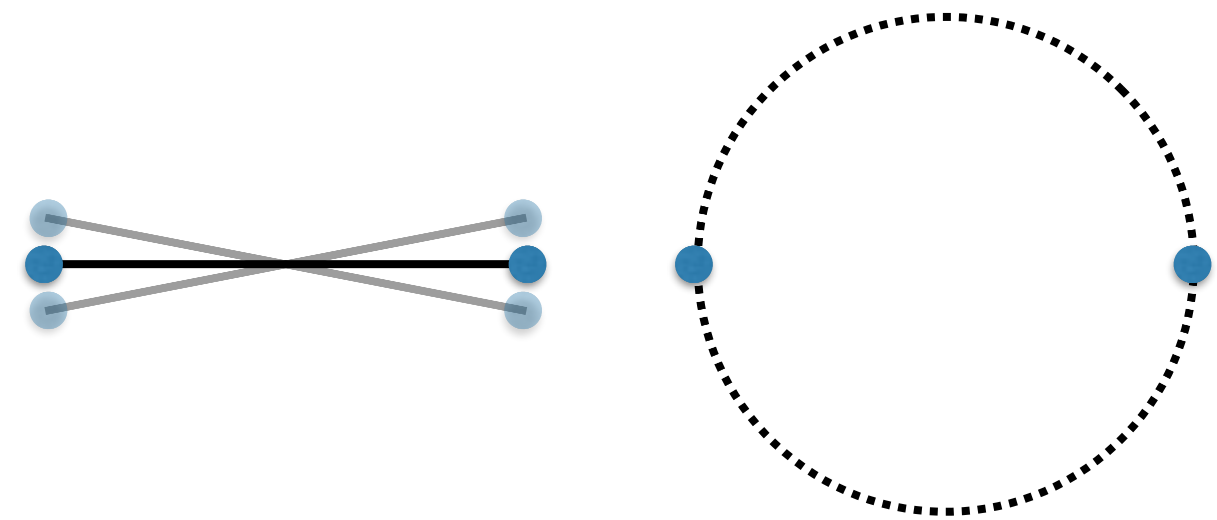
- Merger of 31 and 19 $M_\odot$ black holes
- 2 $M_\odot$ lost in GWs
- Distance: redshift 0.18 corresponding to 880 Mpc
- Like first detection GW150914, only at twice the distance!
- *“GW170104 was first identified by inspection of low latency triggers from Livingston data. An automated notification was not generated as the Hanford detector’s calibration state was temporarily set incorrectly in the low-latency system.”*

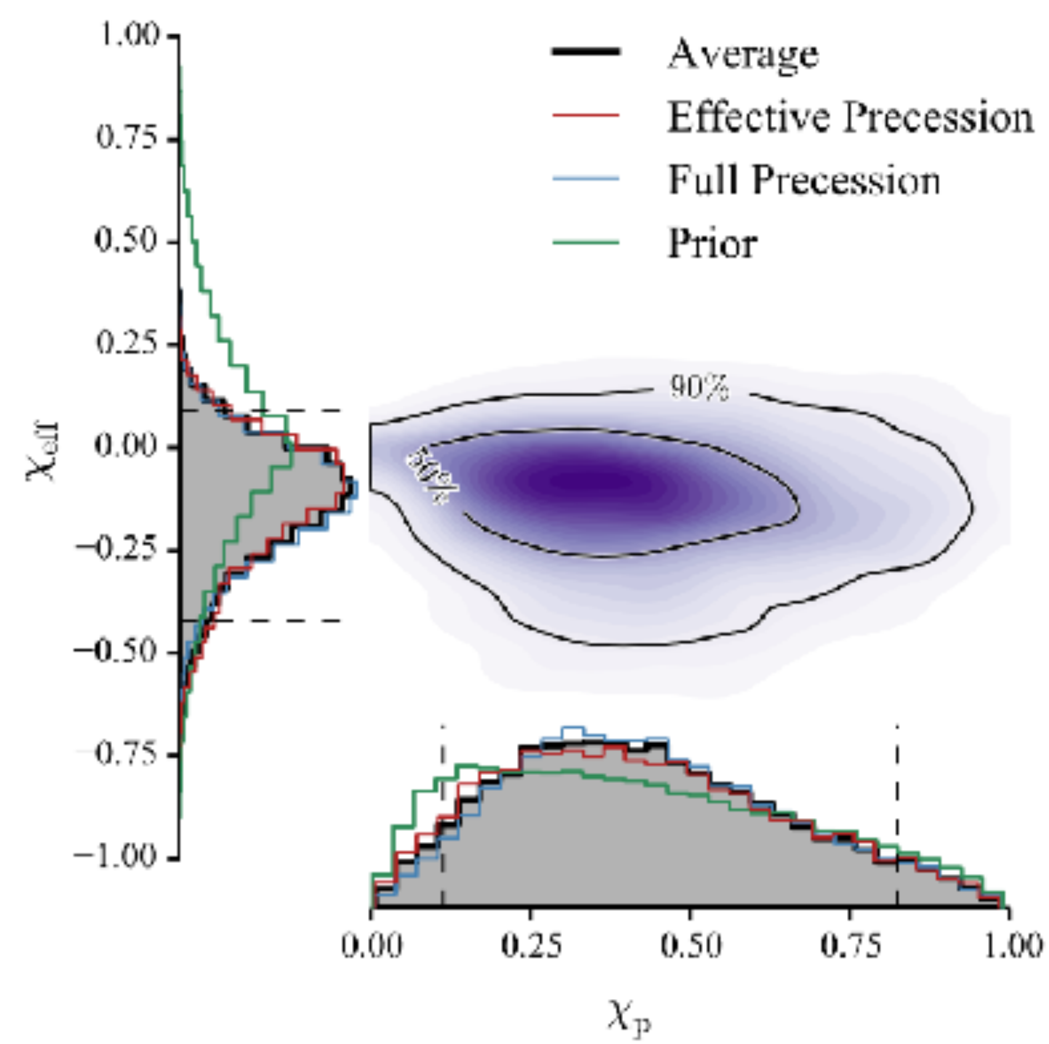


Phys. Rev. Lett. 118, 221101 (2017)

Inference about black hole spins

- Might provide evidence about the origins of the binary black hole systems
- “Smoking gun”: precession of the orbital plane
- Hard to detect: effects on waveform strongest when orbital plane viewed edge-on; hidden when viewed face-on/off.
- A network of detectors with different orientations will make us more likely to detect systems that are not face-on/off
- Compare priors and posteriors





GW170104

Summary

- Inference from the aLIGO data is very direct. But can sometimes be misleading
- Data analysis is very compute intensive, but the human element is still important
- If the false alarm rate/probability is a bound rather than a number, don't misinterpret it
- Solar masses radiated in tens of milliseconds is dramatic, but nevertheless ineffectual
- When looking at posterior probability distributions for parameters, be sure to compare this with priors. What comes from the data itself?

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