Phenomenology 2016 Symposium
University of Pittsburgh

Observation of Gravitational Waves by LIGO

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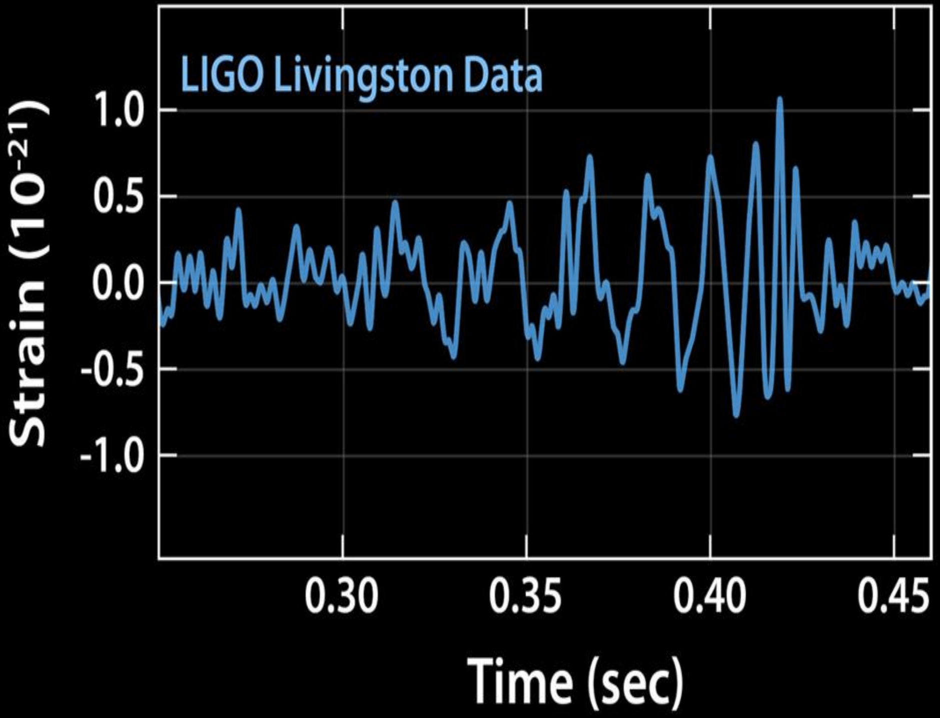
CALTECH

10 May 2016

September 14, 2015



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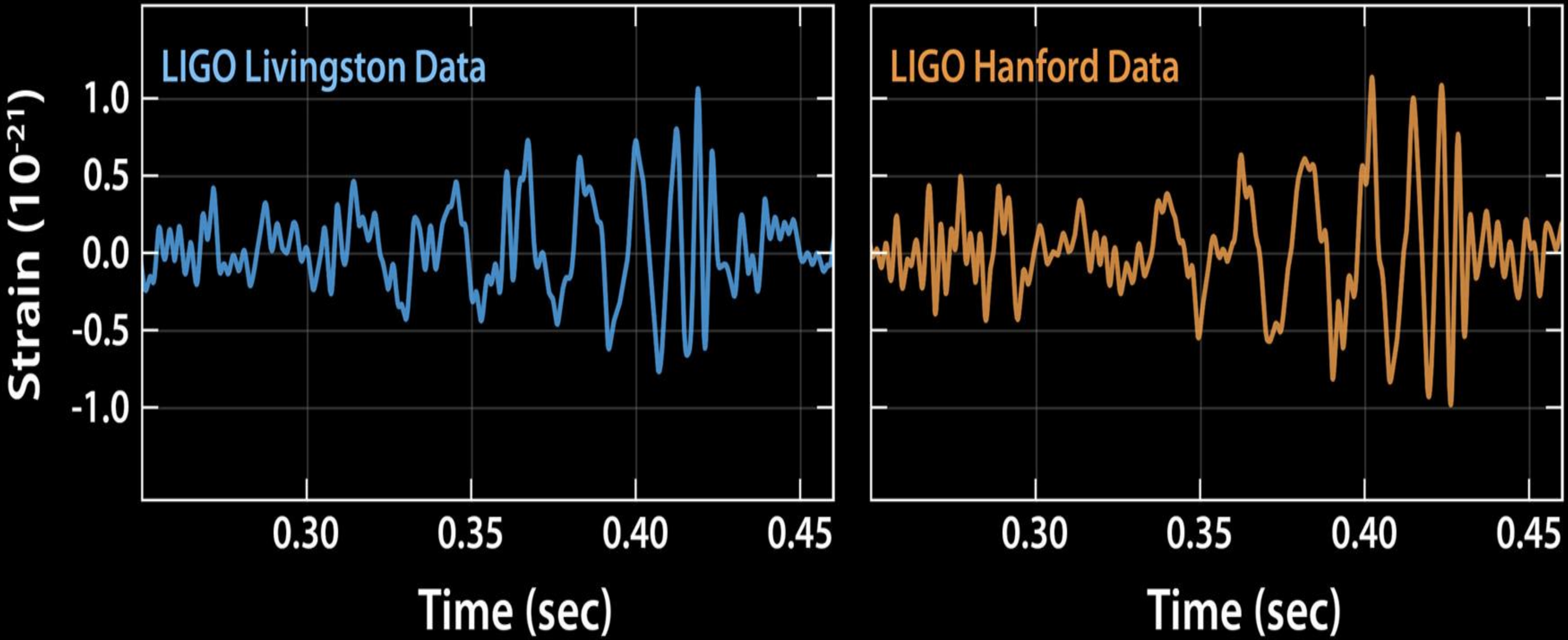

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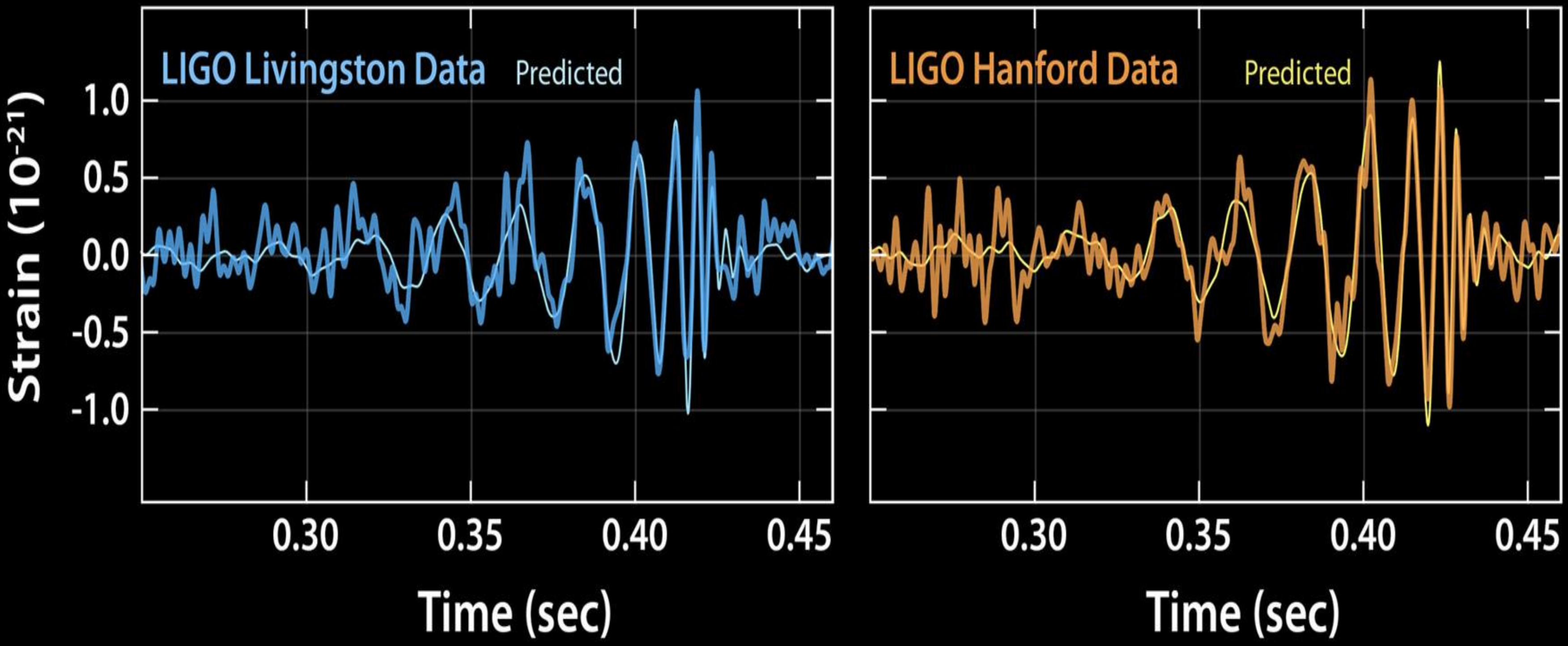
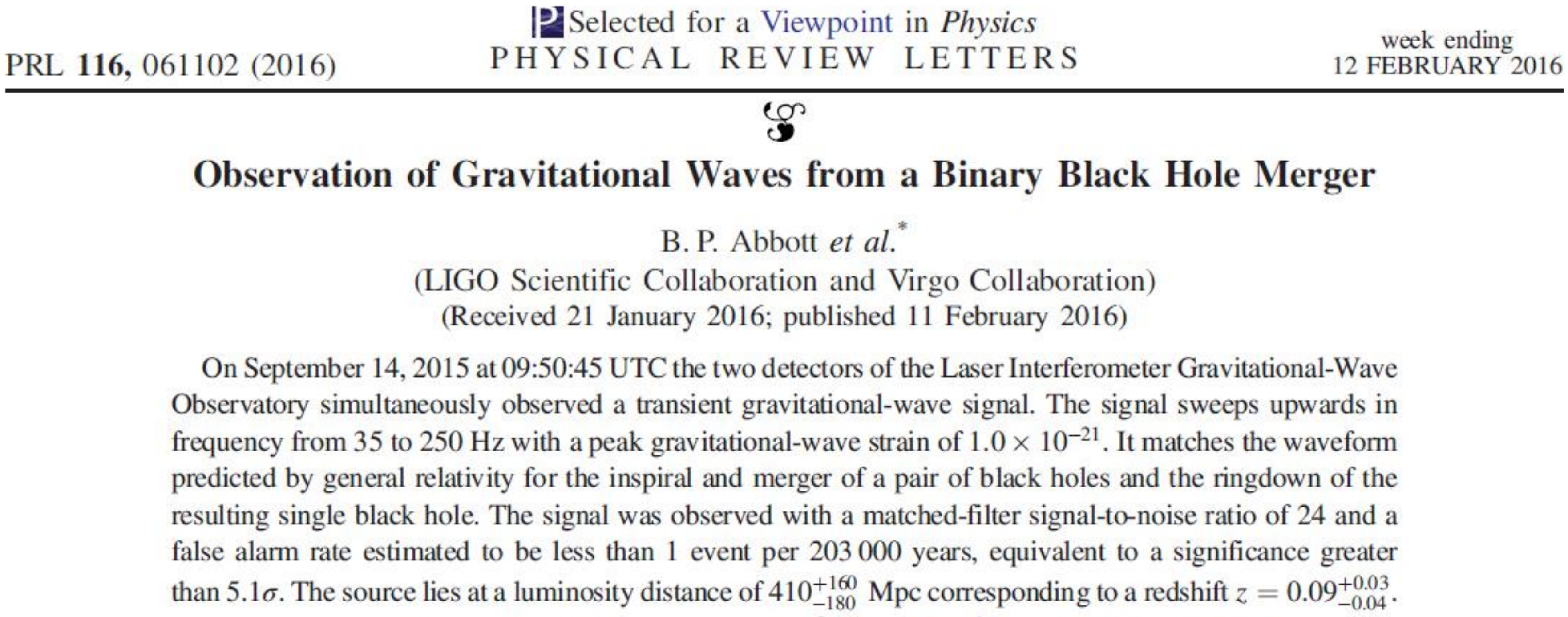


Link to our PRL paper



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

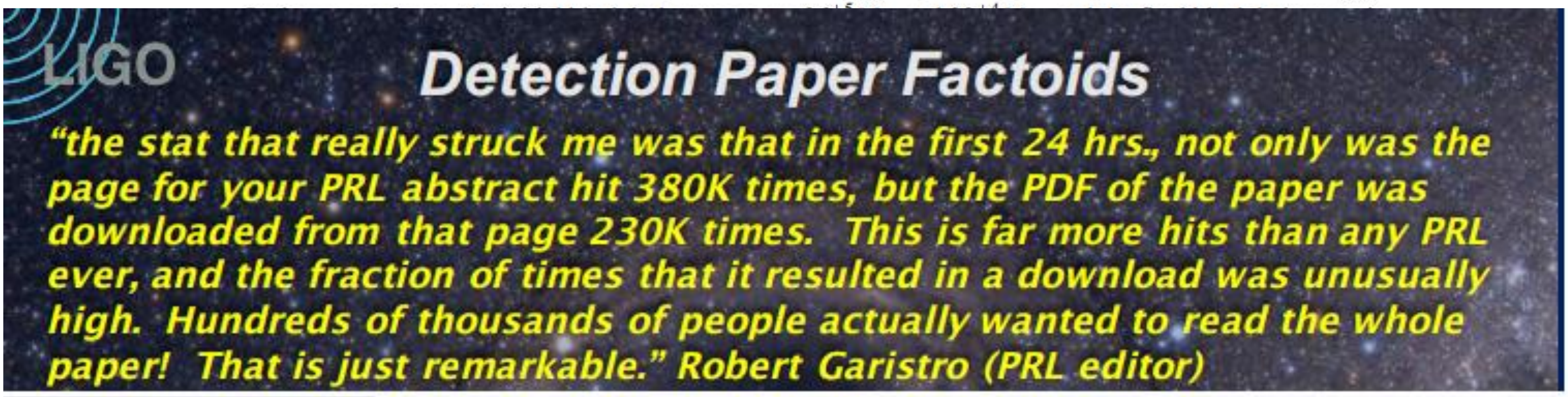
Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

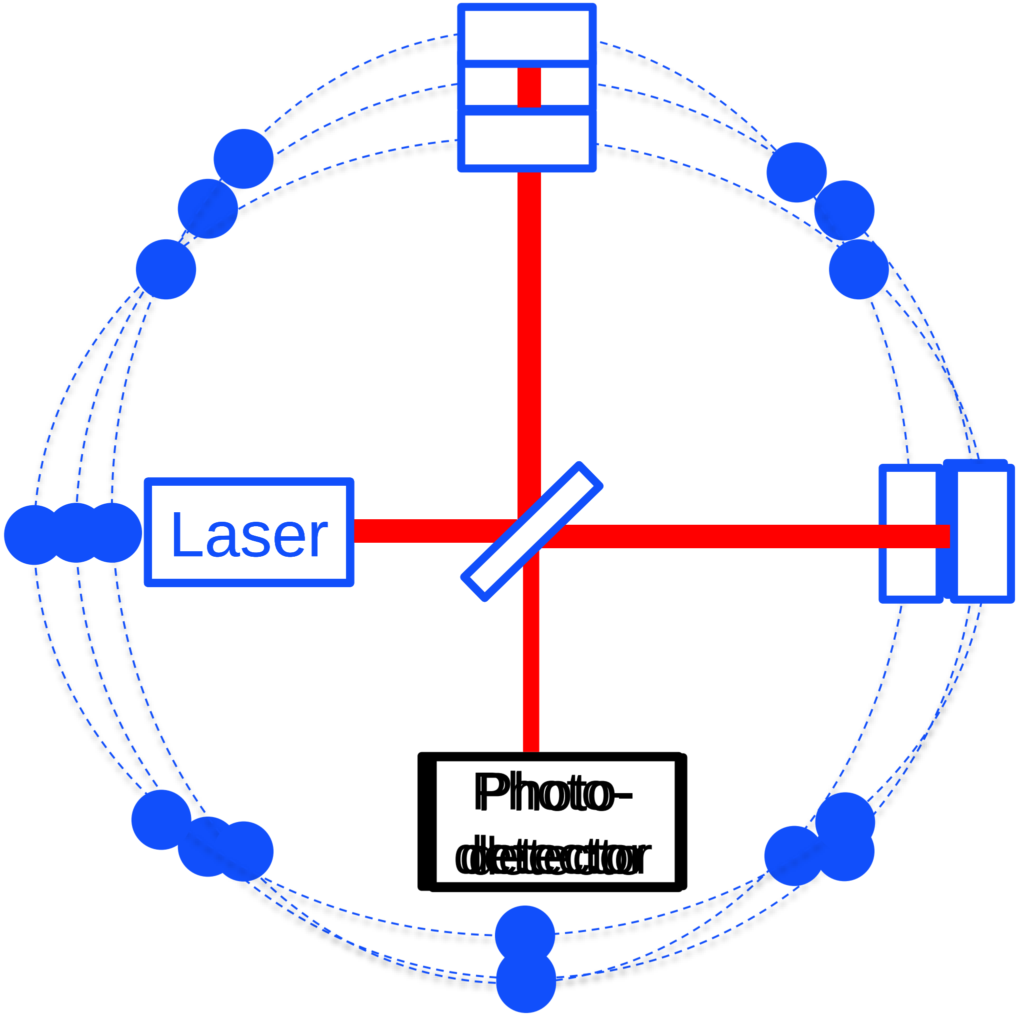
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches 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 $z = 0.09^{+0.03}_{-0.04}$.



Detection Paper Factoids

"the stat that really struck me was that in the first 24 hrs., not only was the page for your PRL abstract hit 380K times, but the PDF of the paper was downloaded from that page 230K 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)

Interferometry - Gravitational Waves



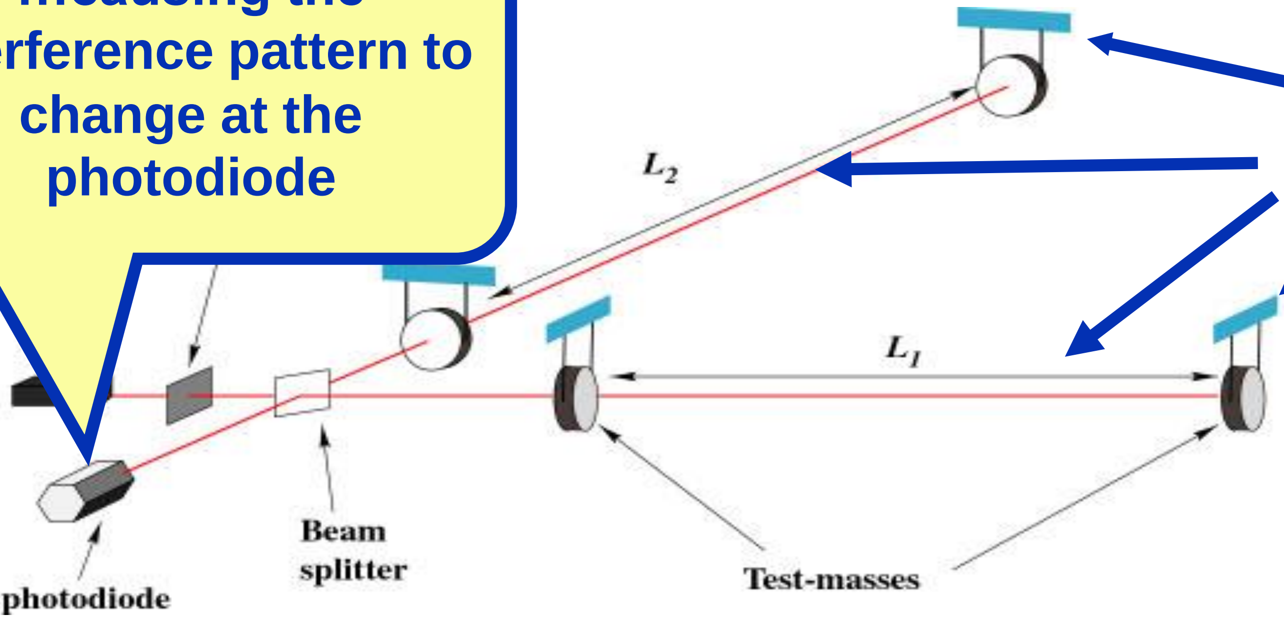
Laser

Photo-detector

LIGO Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms

- Arms in LIGO are 4km
- Measure difference in length to one part in 10^{21} or 10^{-18} meters



…causing the interference pattern to change at the photodiode

Suspended Masses

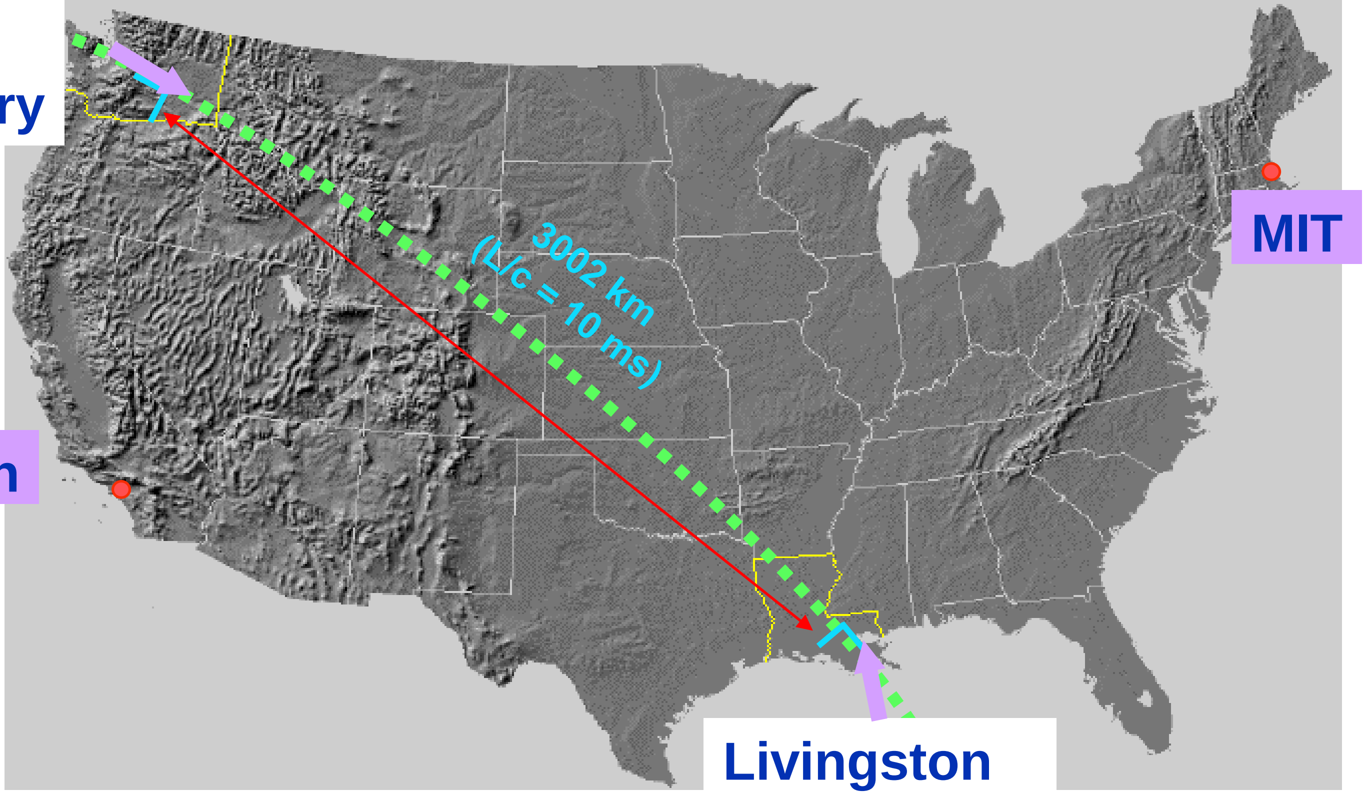
change in different ways….

LIGO Livingston Observatory

LIGO Hanford Observatory

LIGO

Simultaneous Detection



Hanford Observatory

Caltech

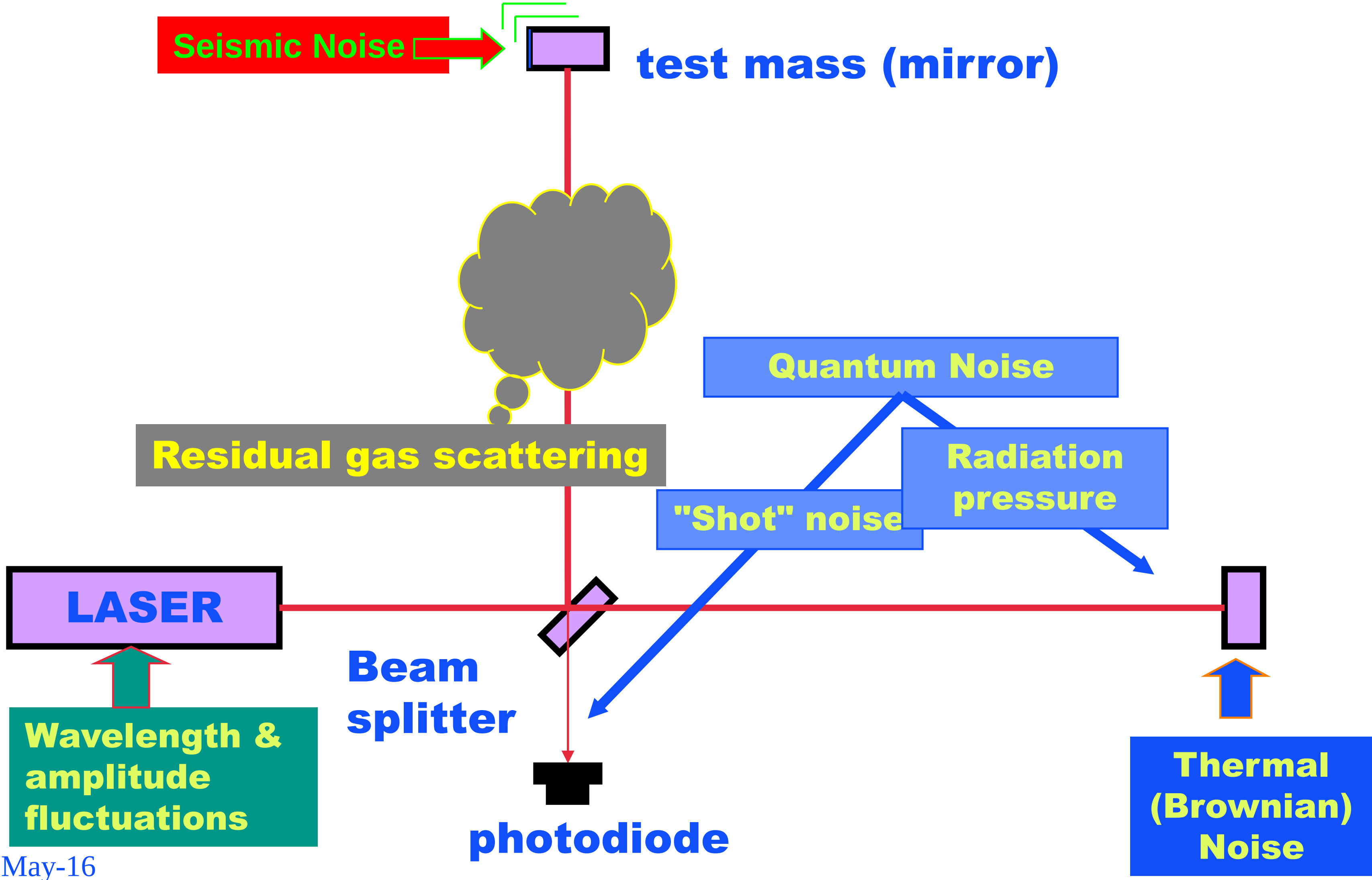
MIT

Livingston Observatory

LIGO
beam tube

LIGO
vacuum equipment

Interferometer Noise Limits



Seismic Noise

test mass (mirror)

Residual gas scattering

Quantum Noise

Radiation pressure

"Shot" noise

LASER

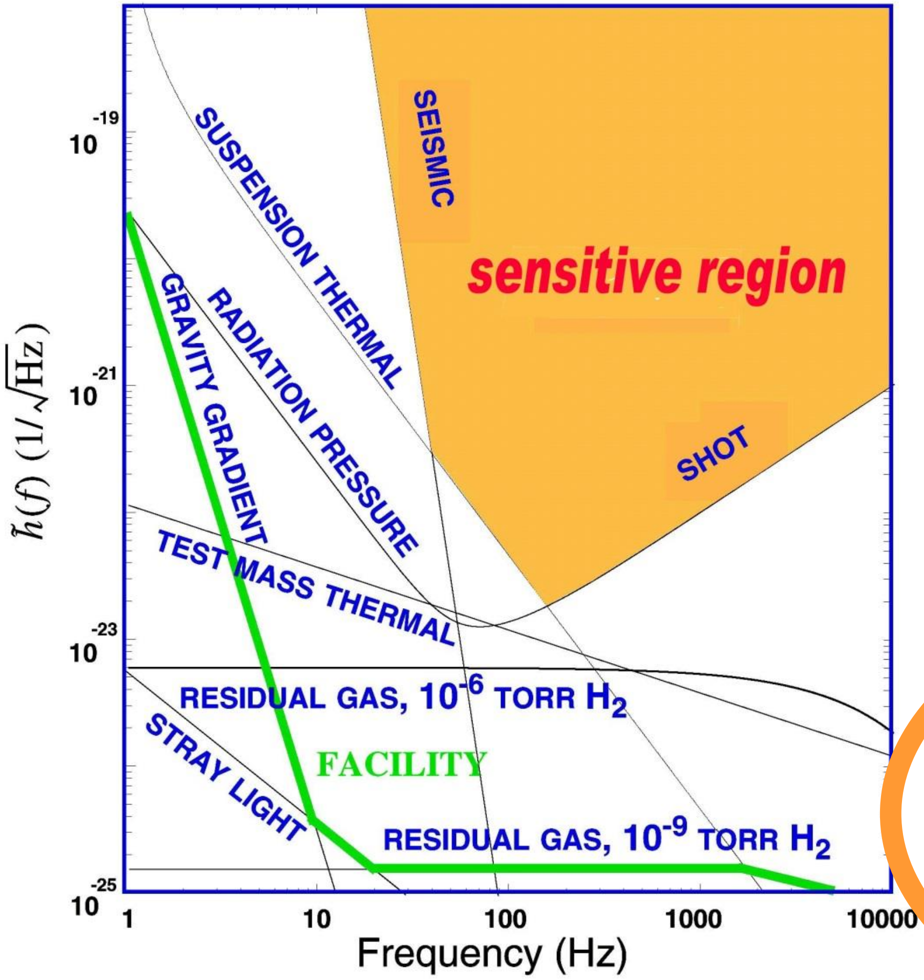
Beam splitter

Wavelength & amplitude fluctuations

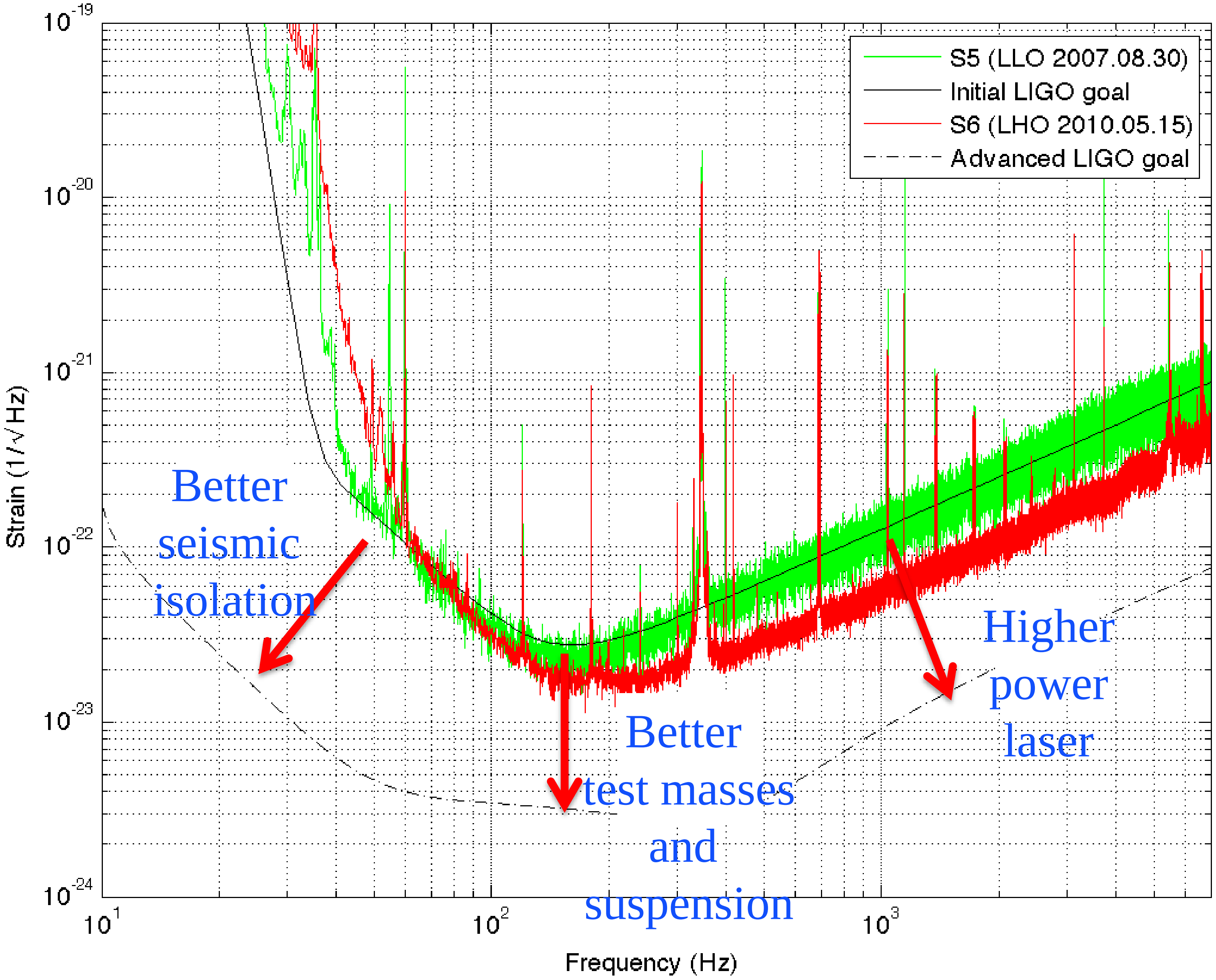
photodiode

Thermal (Brownian) Noise

What Limits LIGO Sensitivity?



- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals



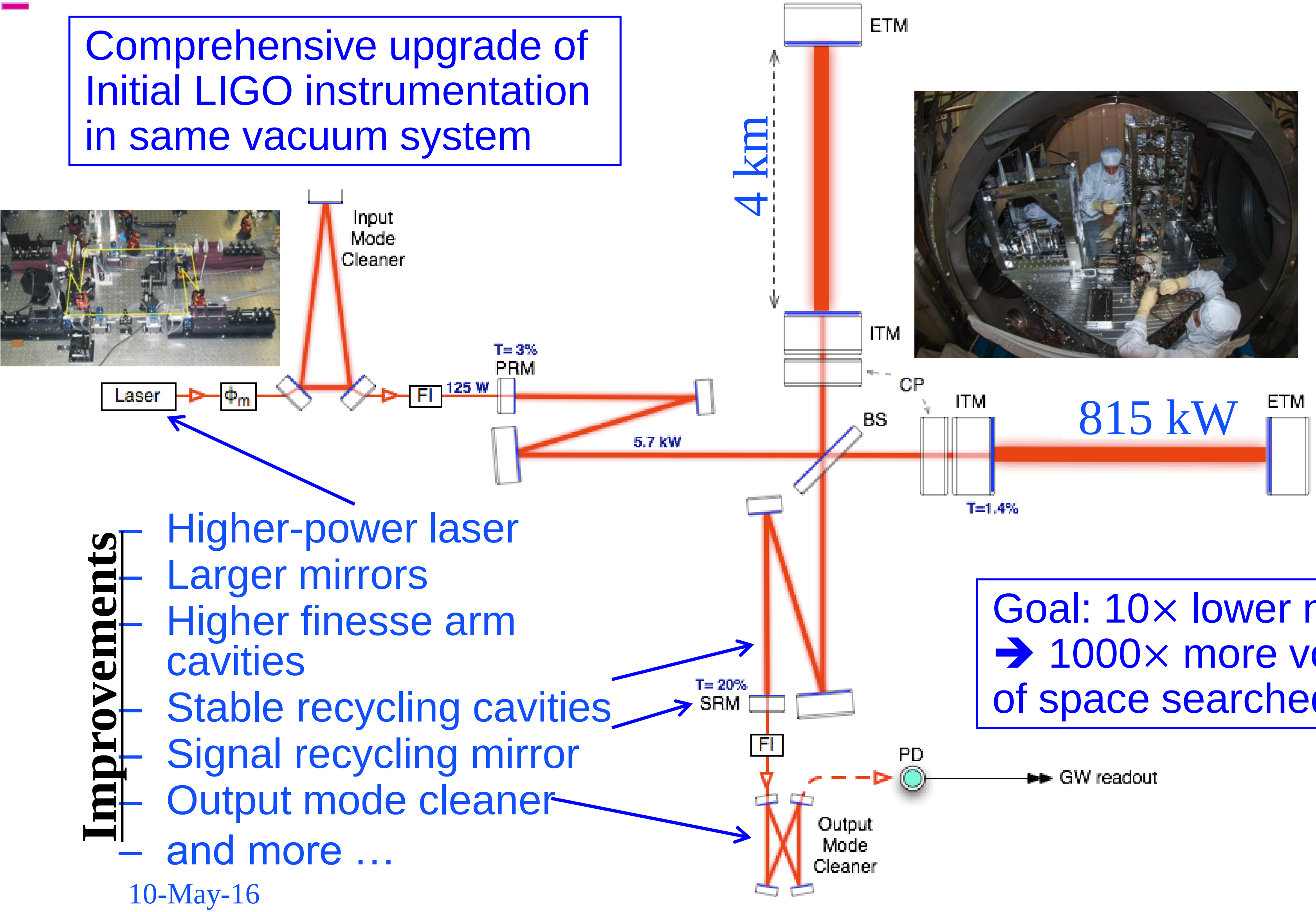
Better seismic isolation

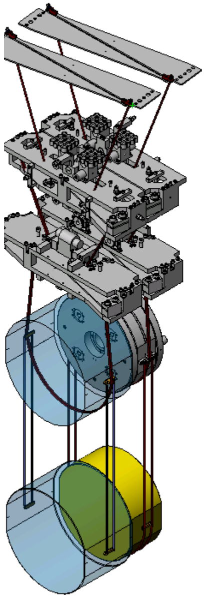
Better test masses and suspension

Higher power laser

Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system



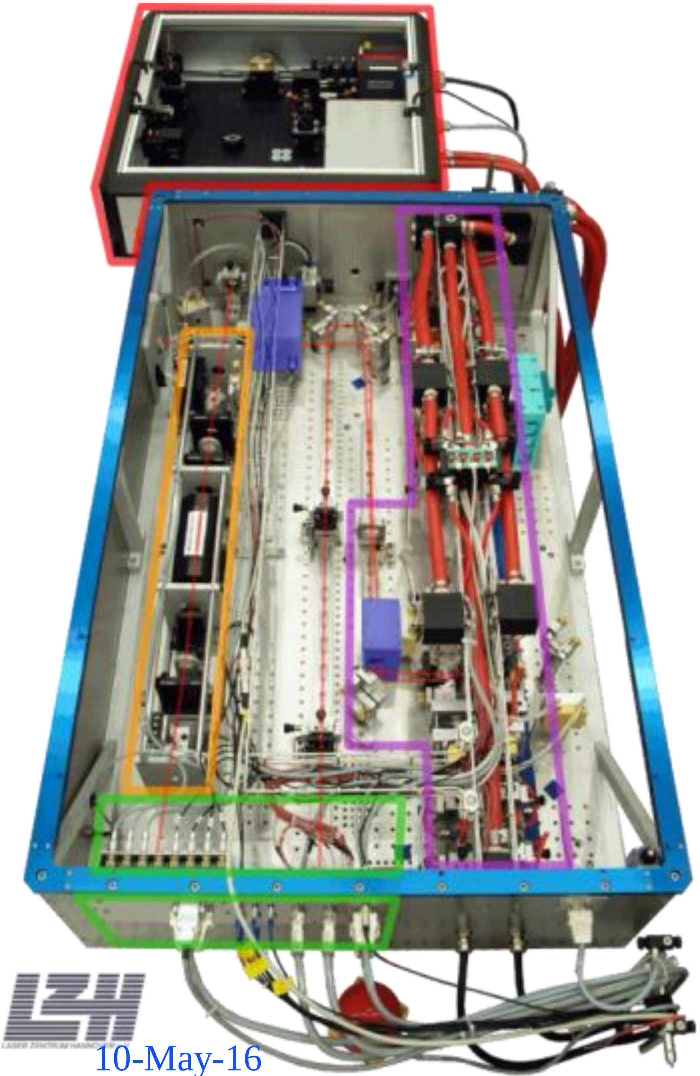


Improvements

- Higher-power laser
- Larger mirrors
- Higher finesse arm cavities
- Stable recycling cavities
- Signal recycling mirror
- Output mode cleaner
- and more …

Goal: 10× lower noise
➔ 1000× more volume of space searched

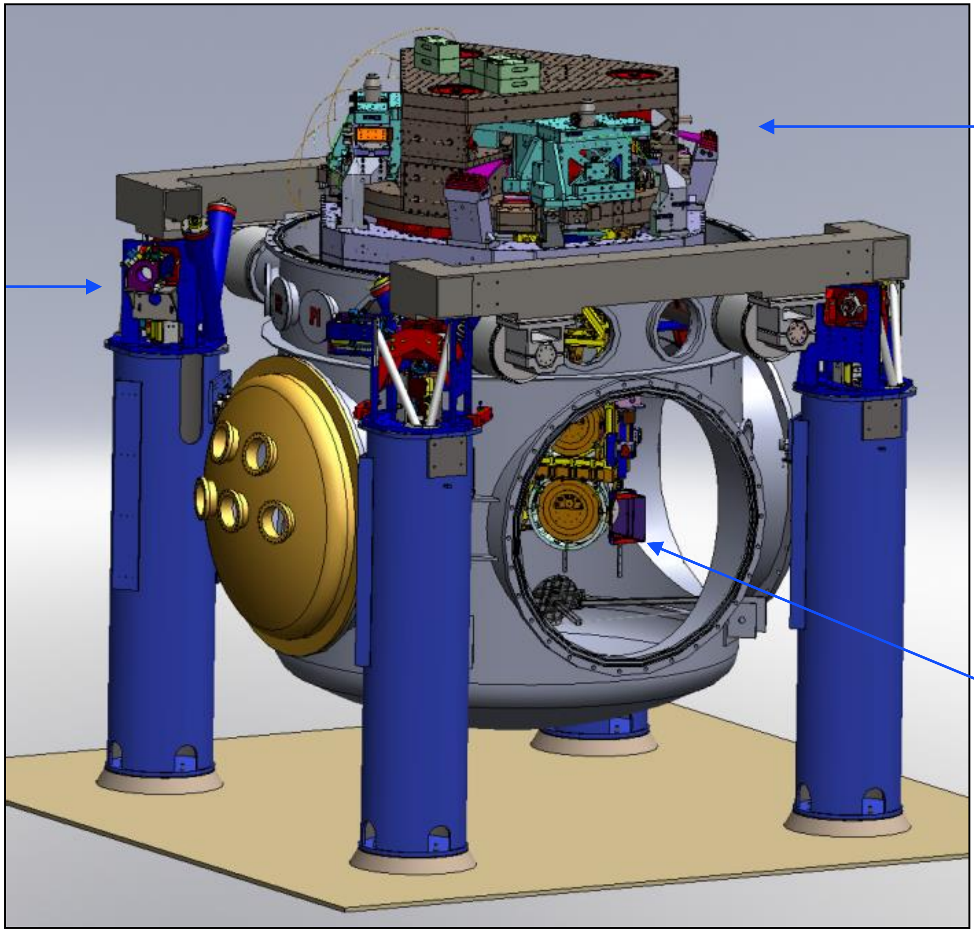
200W Nd:YAG Laser



- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

Suspensions and Seismic Isolation

Advanced LIGO Test Mass Isolation



active isolation platform (2 stages of isolation)

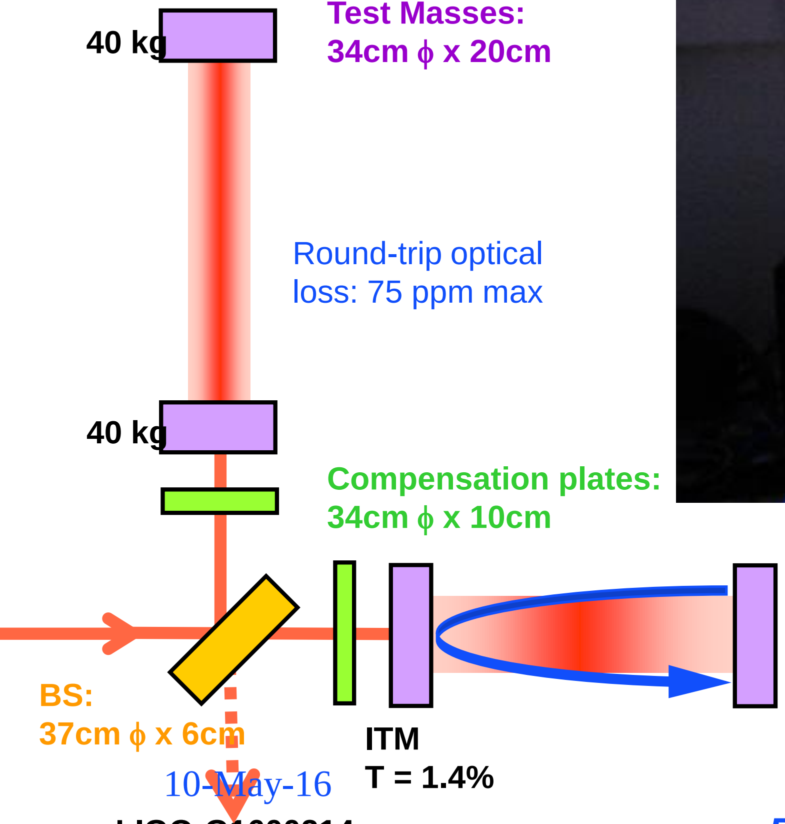
hydraulic external pre-isolator (HEPI) (one stage of isolation)

quadruple pendulum (four stages of isolation) with monolithic silica final stage

Ref: LIGO-G1000469-v1, Kissel PhD

Mirrors

Test Masses



40 kg

Test Masses:
34cm ϕ x 20cm

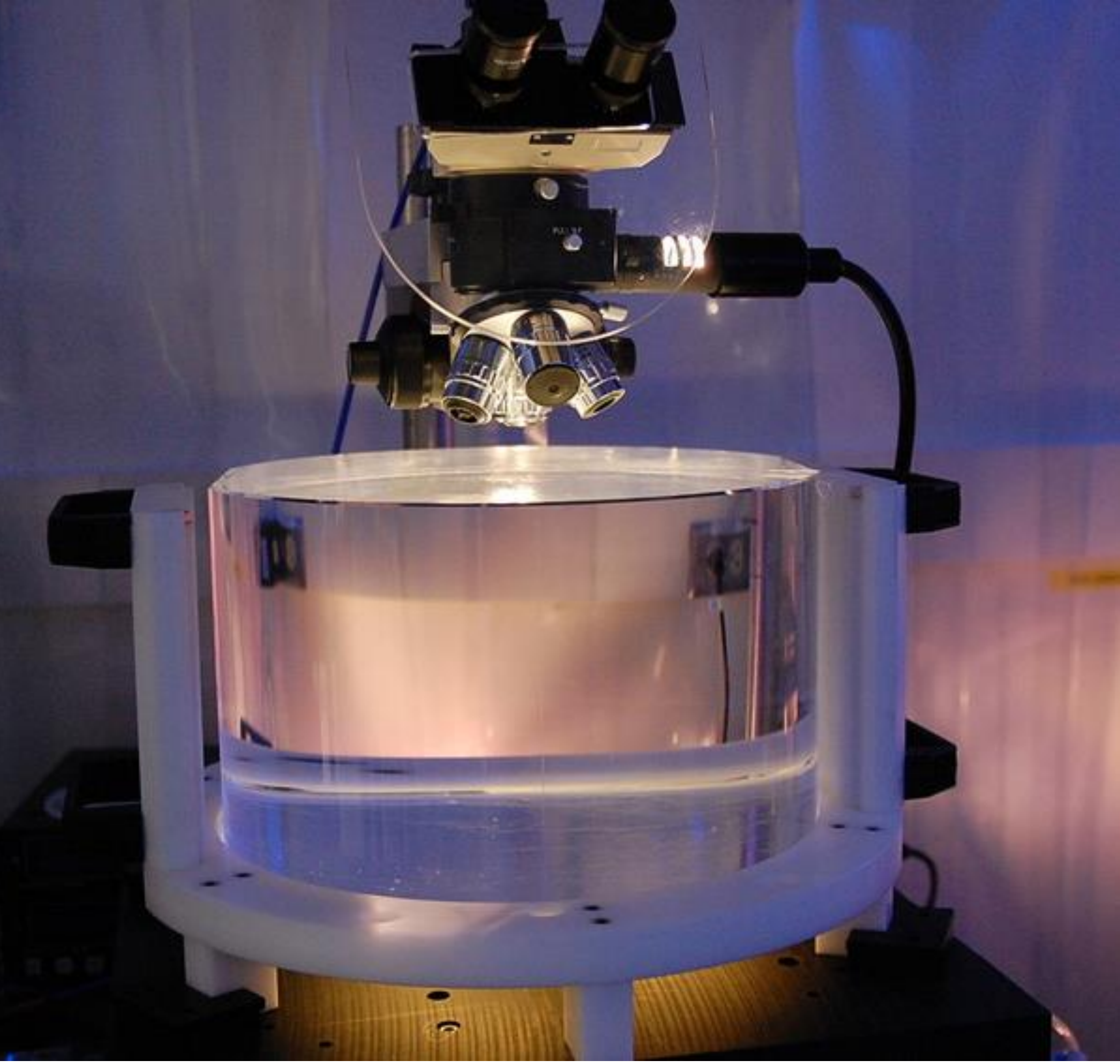
Round-trip optical loss: 75 ppm max

40 kg

Compensation plates:
34cm ϕ x 10cm

BS:
37cm ϕ x 6cm

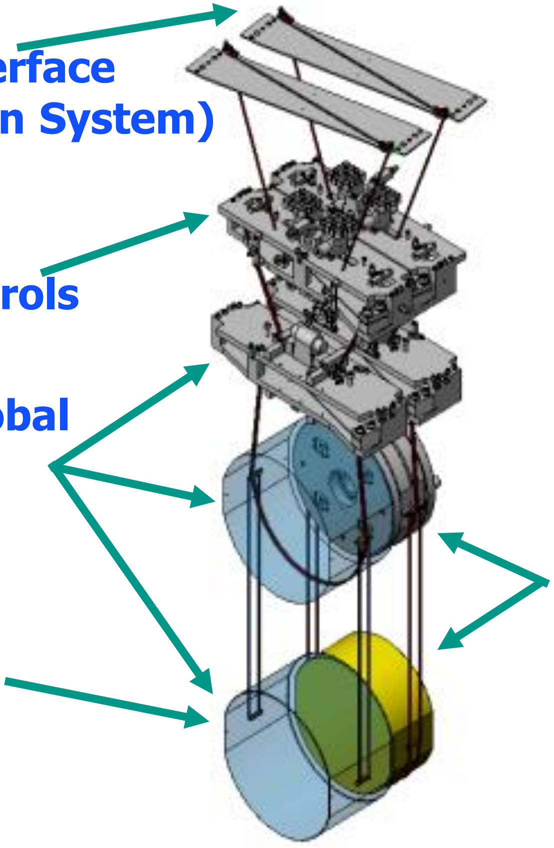
ITM
T = 1.4%



- Requires the state of the art in substrates and polishing
- Pushes the art for coating!
- Sum-nm flatness over 300mm

Test Mass

Quadruple Pendulum suspension



Optics Table Interface (Seismic Isolation System)

Damping Controls

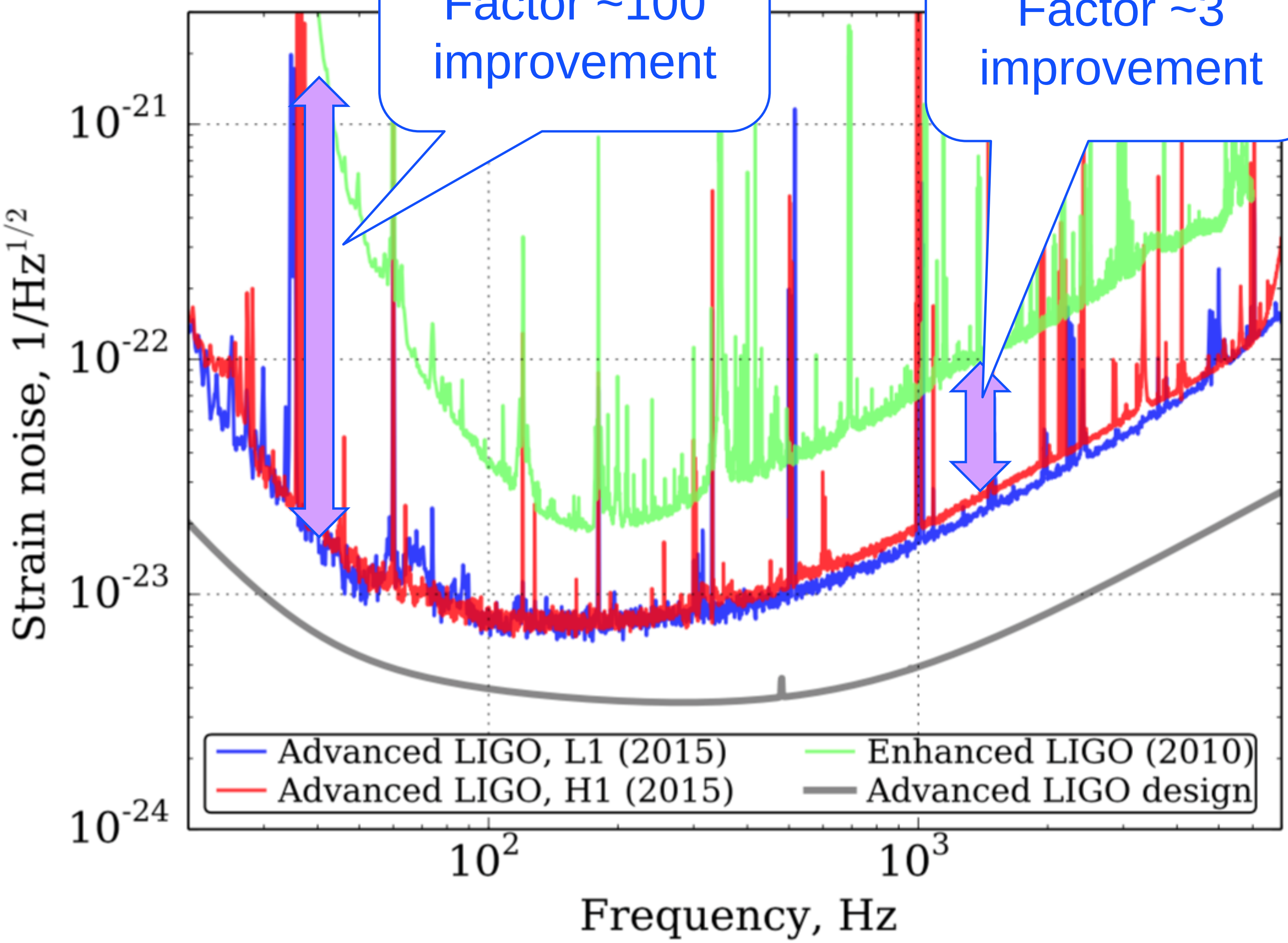
Hierarchical Global Controls

Electrostatic Actuation

Final elements All Fused silica

Sensitivity

First Advanced LIGO Data Run



At ~40 Hz, Factor ~100 improvement

Broadband, Factor ~3 improvement

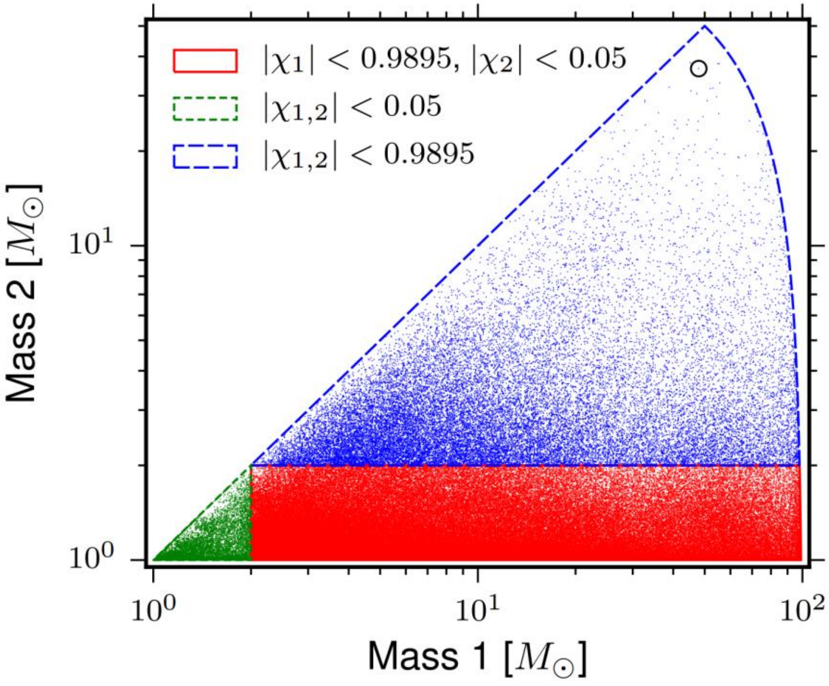
Initial LIGO

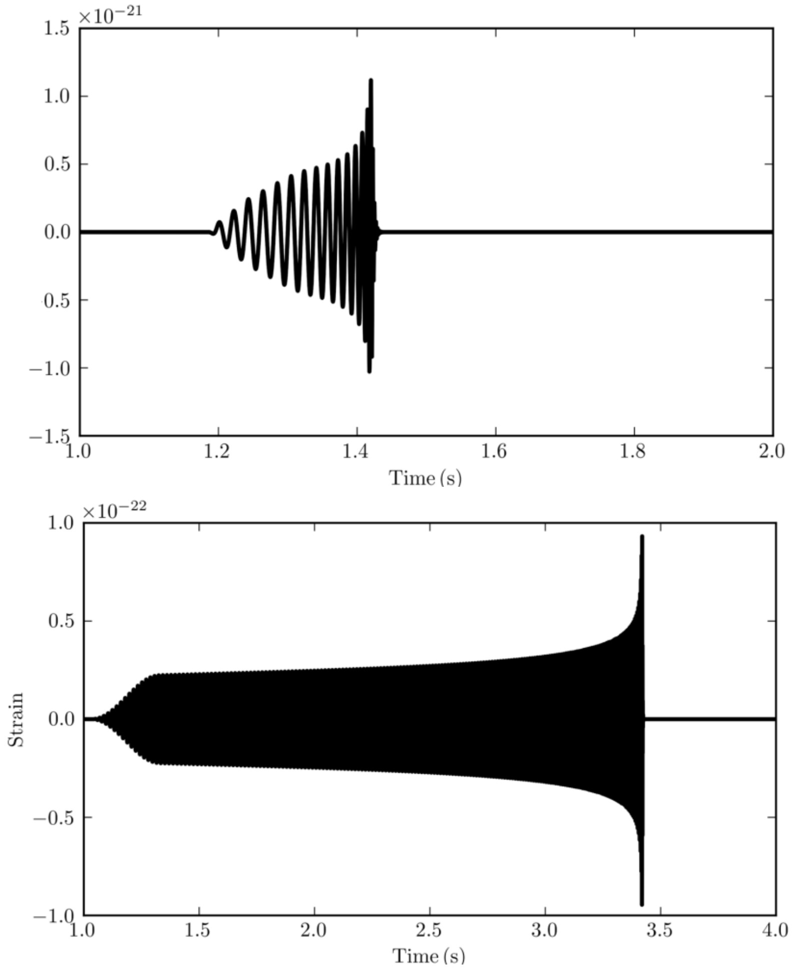
O1 aLIGO

Design aLIGO

Binary Inspiral Waveforms

- Use GR predicted waveforms
- Convolve waveforms with data
- Demand coincidence between detectors
- Reject glitches w/ consistency checks





Gravitational Wave Event

GW150914

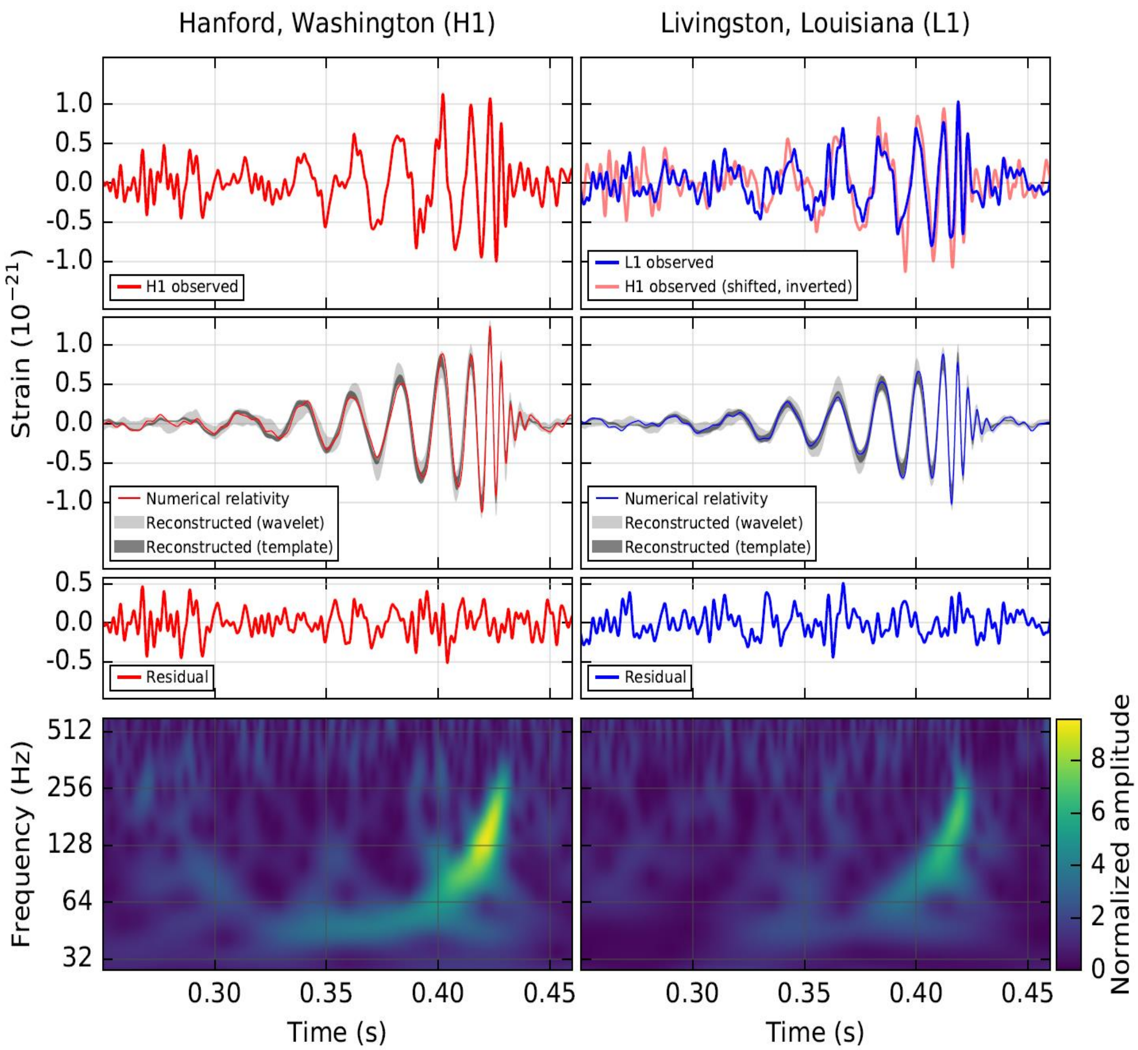
Data bandpass filtered between 35 Hz and 350 Hz

Time difference 6.9 ms with Livingston first

Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)

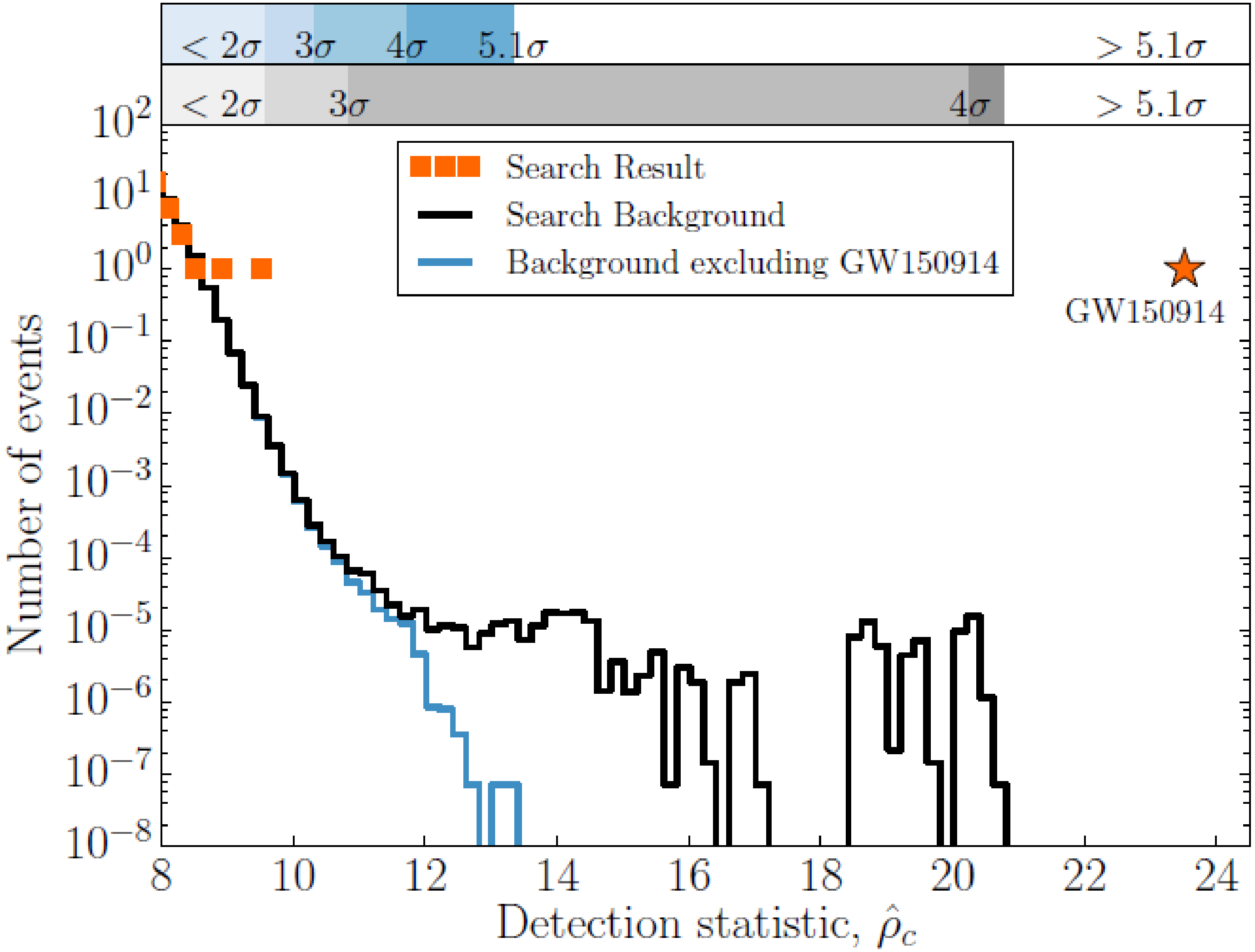
Third Row –residuals

bottom row – time frequency plot showing frequency increases with time (chirp)



Statistical Significance of GW150914

Binary Coalescence Search



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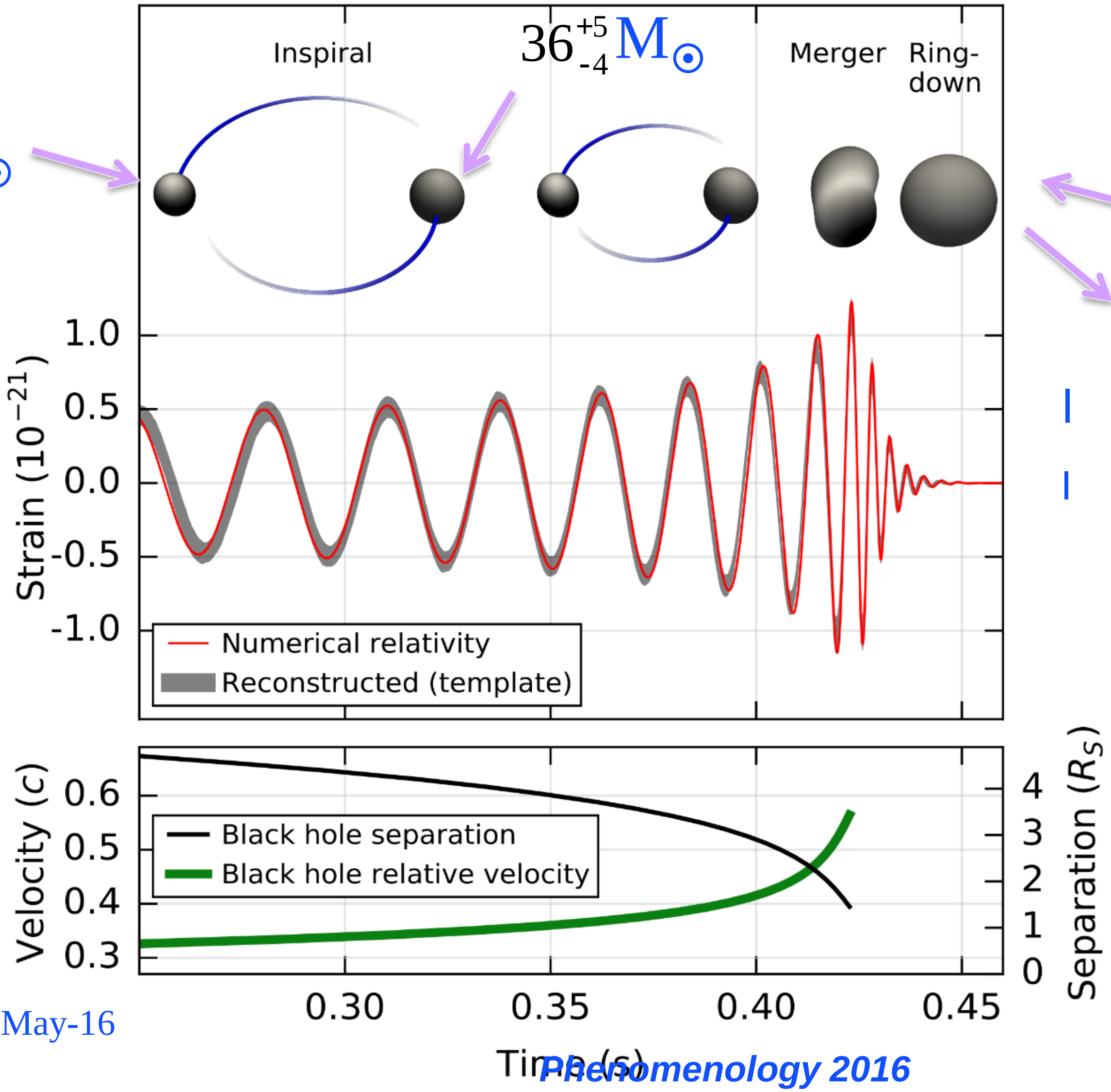
GW150914

$29^{+4}_{-5} M_\odot$

$36^{+5}_{-4} M_\odot$



Source distance

410^{+160}_{-180} Mpc

$62^{+4}_{-4} M_\odot$

$3^{+0.5}_{-0.5} M_\odot$ in GWs!

Effective black hole separation in units of Schwarzschild radius ($R_s=2GM_f / c^2$); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_f \pi f/c^3)^{1/3}$

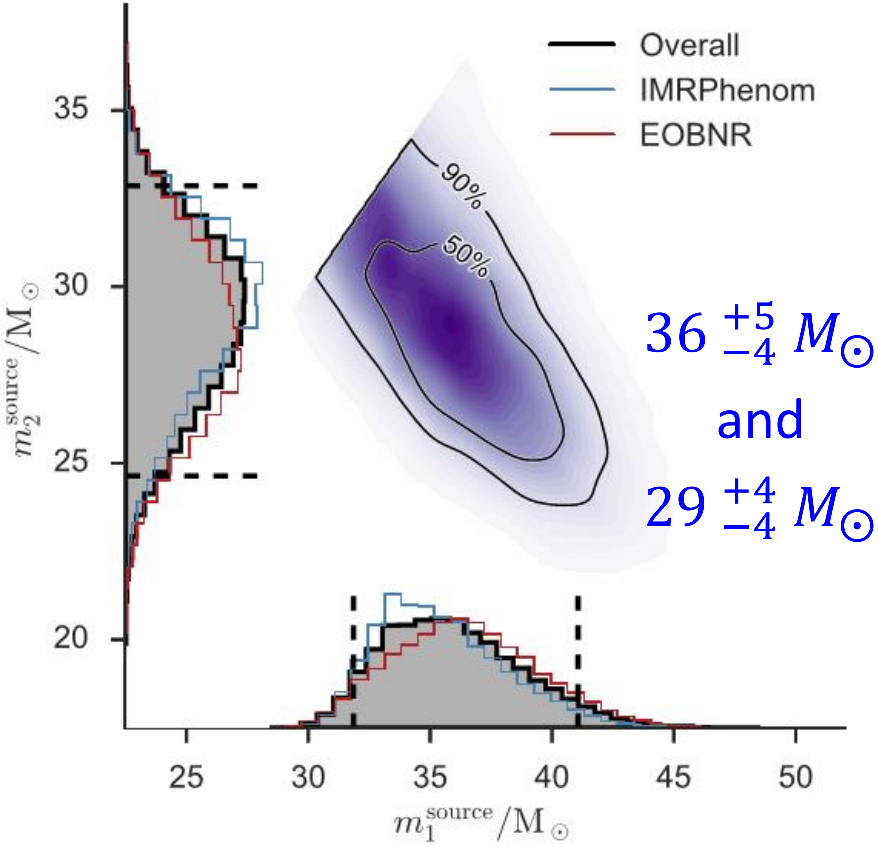
Measuring the parameters

- Orbits decay due to emission of gravitational waves
  - **Leading order** determined by “chirp mass”

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

  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z) m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession.
- Sky location, distance, binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

Properties of GW150914



$36^{+5}_{-4}\,M_\odot$

and

$29^{+4}_{-4}\,M_\odot$

- Use waveform models which include black hole spin, but no orbital precession
- Much more massive than black holes found in X-ray binaries.

Properties of GW150914

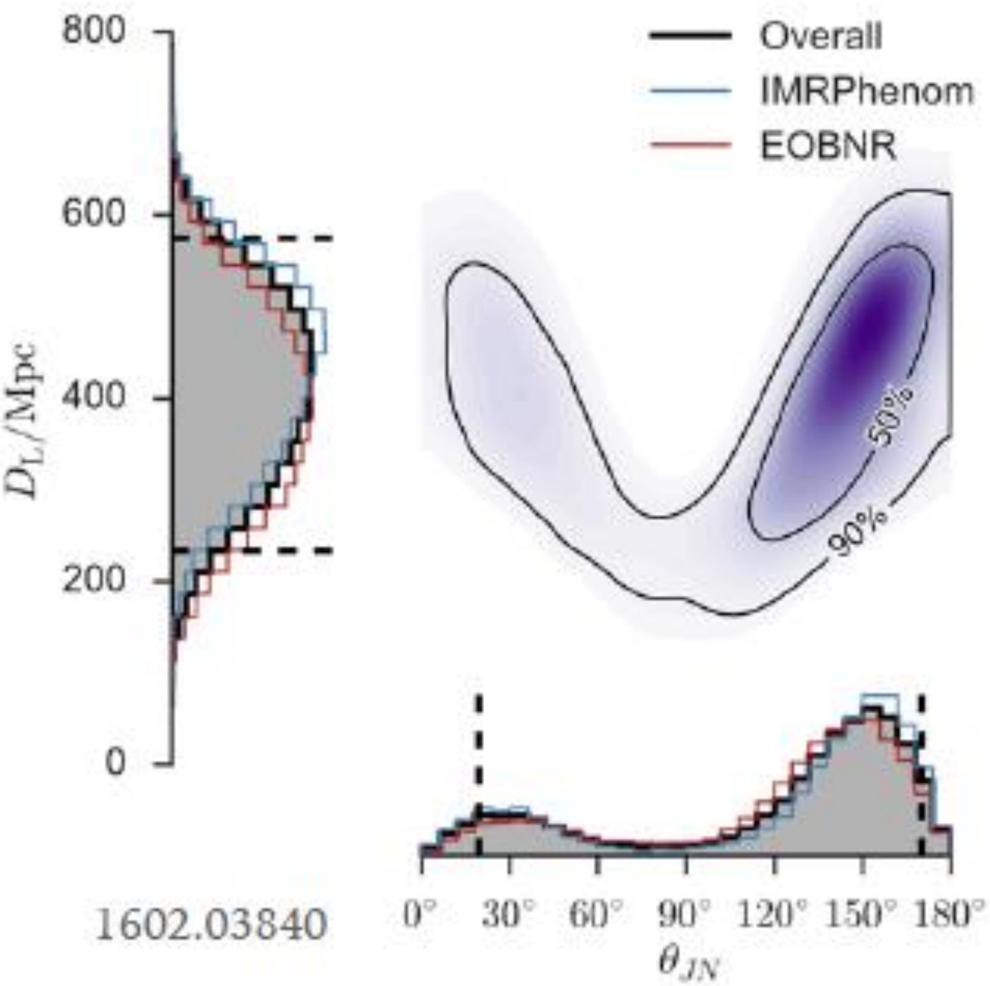
- Distance and Inclination (from amplitude) are typically degenerate in GW signals

- Luminosity distance is 400 Mpc (redshift = 0.09)

- Orbital Inclination nearly face away (total angular momentum points away from earth)

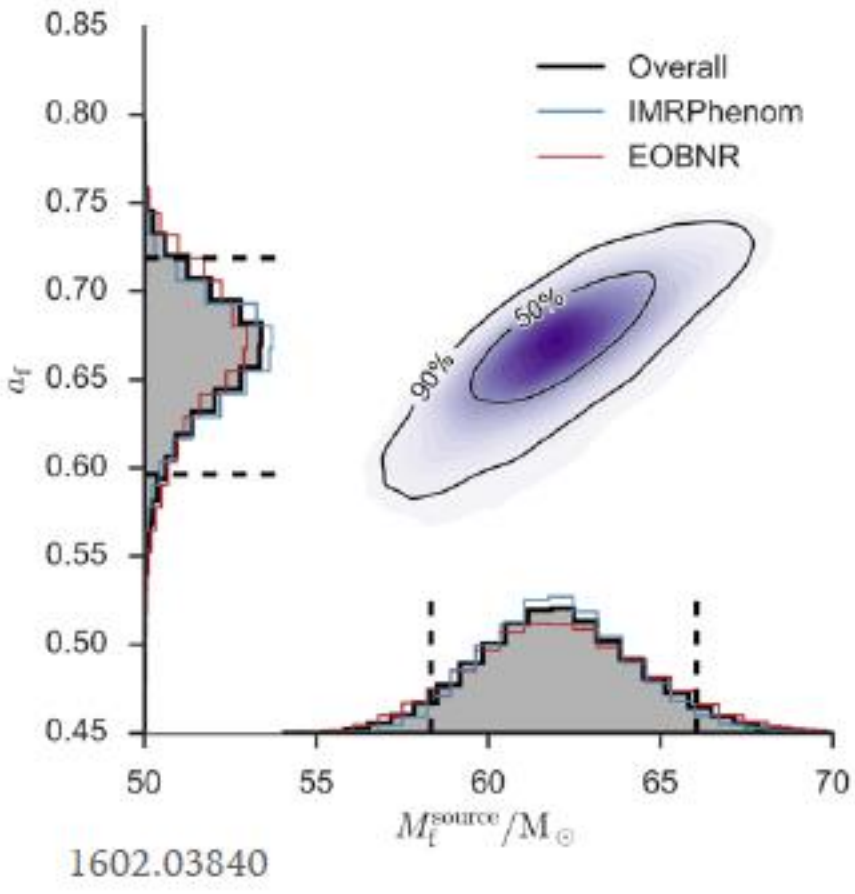
- Difficult to estimate spin precession in this orientation

-



1602.03840

Properties of GW150914

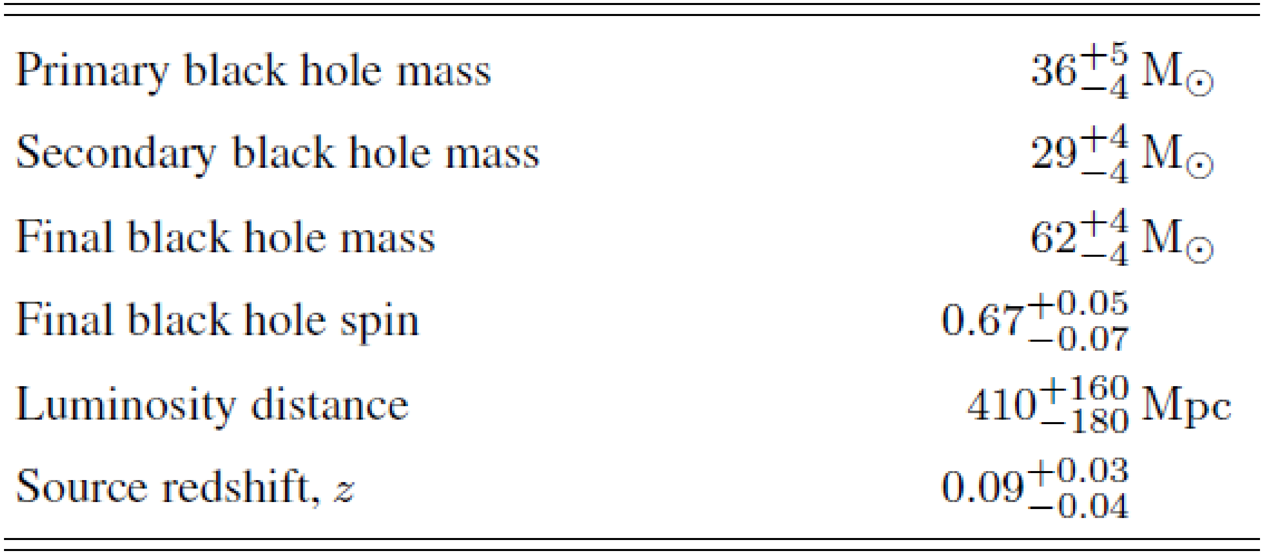


1602.03840

- From *merger amplitude* and *ringdown frequency*
- Final BH mass = 62 solar masses
- Final BH spin = 0.67
- ~ 3 solar masses radiated away in GWs

Source Parameters for GW150914

- Use numerical simulations fits of black hole merger to determine parameters, we determine total energy radiated in gravitational waves is $3.0 \pm 0.5\ M_o c^2$. The system reached a peak ~3.6 x10^{56} ergs, and the spin of the final black hole < 0.7 (not maximal spin)



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

New Astrophysics

- Stellar binary black holes do exist!
  - **Form** and **merge** in time scales accessible to us
  - Predictions previously encompassed [0 – 10^3] / Gpc^3 / yr
  - Now we exclude lowest end: **rate > 1 Gpc^3 / yr**
- Masses ($M > 20\ M_\odot$) are large compared with *known* stellar mass BHs
- Progenitors are
  - Likely **heavy**, $M > 60\ M_\odot$
  - Likely with a **low metallicity**, $Z < 0.25\ Z_\odot$
- Low metallicity models can produce low-*z* mergers at rates consistent with our observation.
- Why low metallicity? Stars at lower metallicity exhibit weaker winds and more likely “stay big” throughout their lives
  - Low content of elements heavier than He → less opacity → easier radiation transport
  - Reduce radiation momentum transfer → less mass loss from the star surface

Testing GR

- Most relativistic binary know today : J0737-3039
  - Orbital velocity $v/c \sim 2 \times 10^{-3}$

- GW150914 : Higly disturbed black holes
  - Non linear dynamics
- Access to the properties of space-time
  - Strong field, high velocity regime testable for the first time

$$\longrightarrow v/c \sim 0.6$$

- Tests :
  - Check of the residuals
  - Waveform internal consistency check
  - Deviation of PN coefficients from General Relativity ?
  - Bound on graviton mass

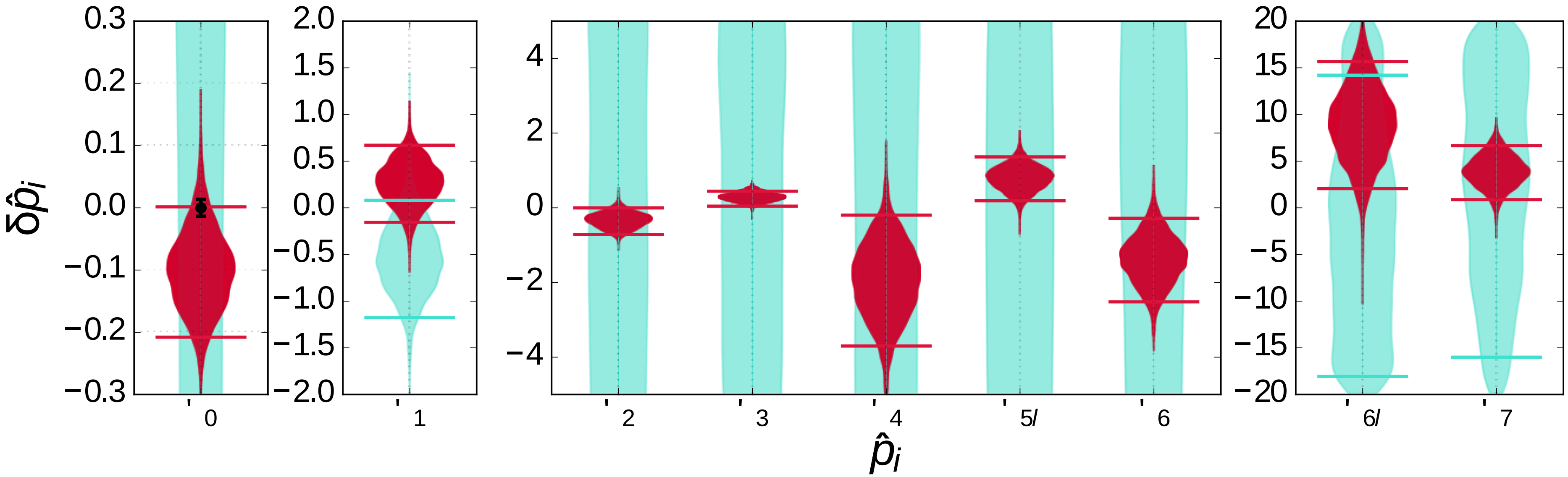
- Confirms predictions of General Relativity

Testing GR parameters

- Nominal value predicted by GR
- Allow variation of the coefficients
  - -> Is the resulting waveform consistent with data ?

Red : vary one parameter at a time

Cyan : allow all parameters to vary

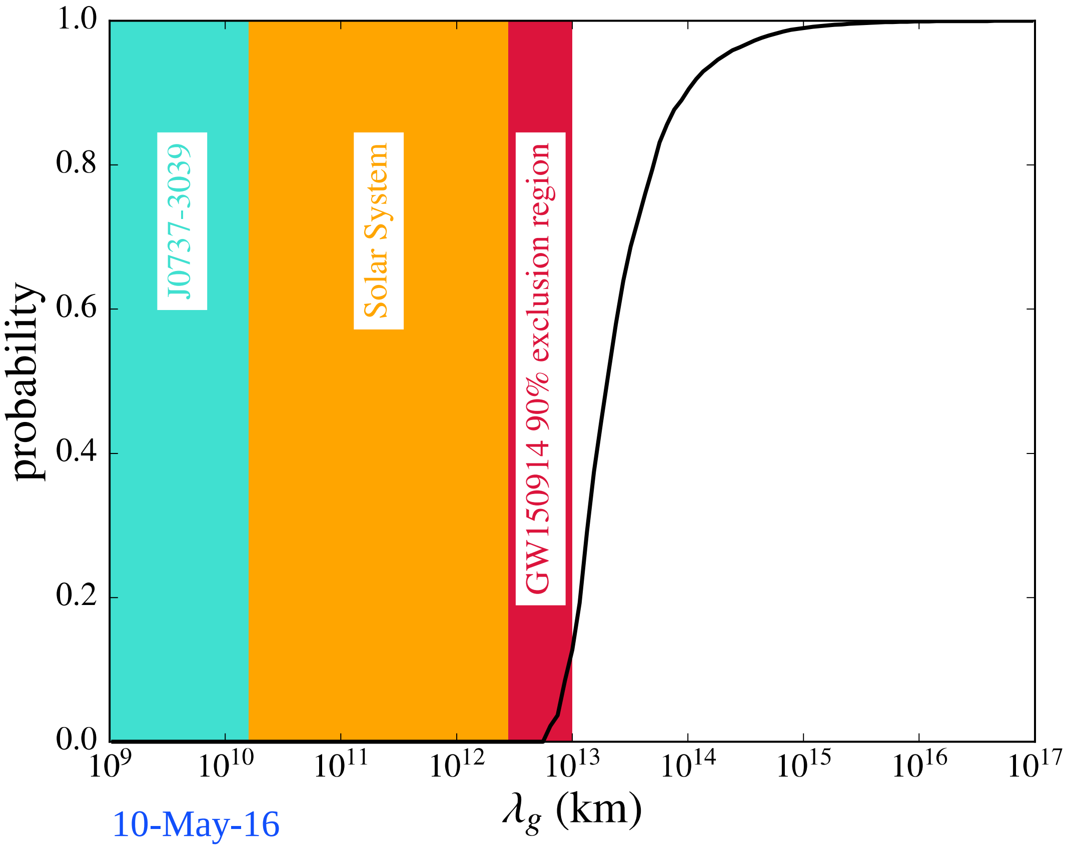


- Find no evidence for violations of GR

Testing General Relativity

graviton mass

- If $v_{GW} < c$, gravitational waves then have a modified dispersion relation. We see no evidence of modified inspiral



LIMIT 90% Confidence

$$\lambda_g > 10^{13}\ \mathrm{km}$$

$$m_g < 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$

Conclusions

- LIGO has observed gravitational waves from the merger of two stellar mass black holes
- The detected waveforms match the prediction of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting black hole.
- This observation is the first direct detection of gravitational waves and the first observation of a binary black hole merger
- **Result from one month of four month O1 run. Complete O1 result soon.**

End