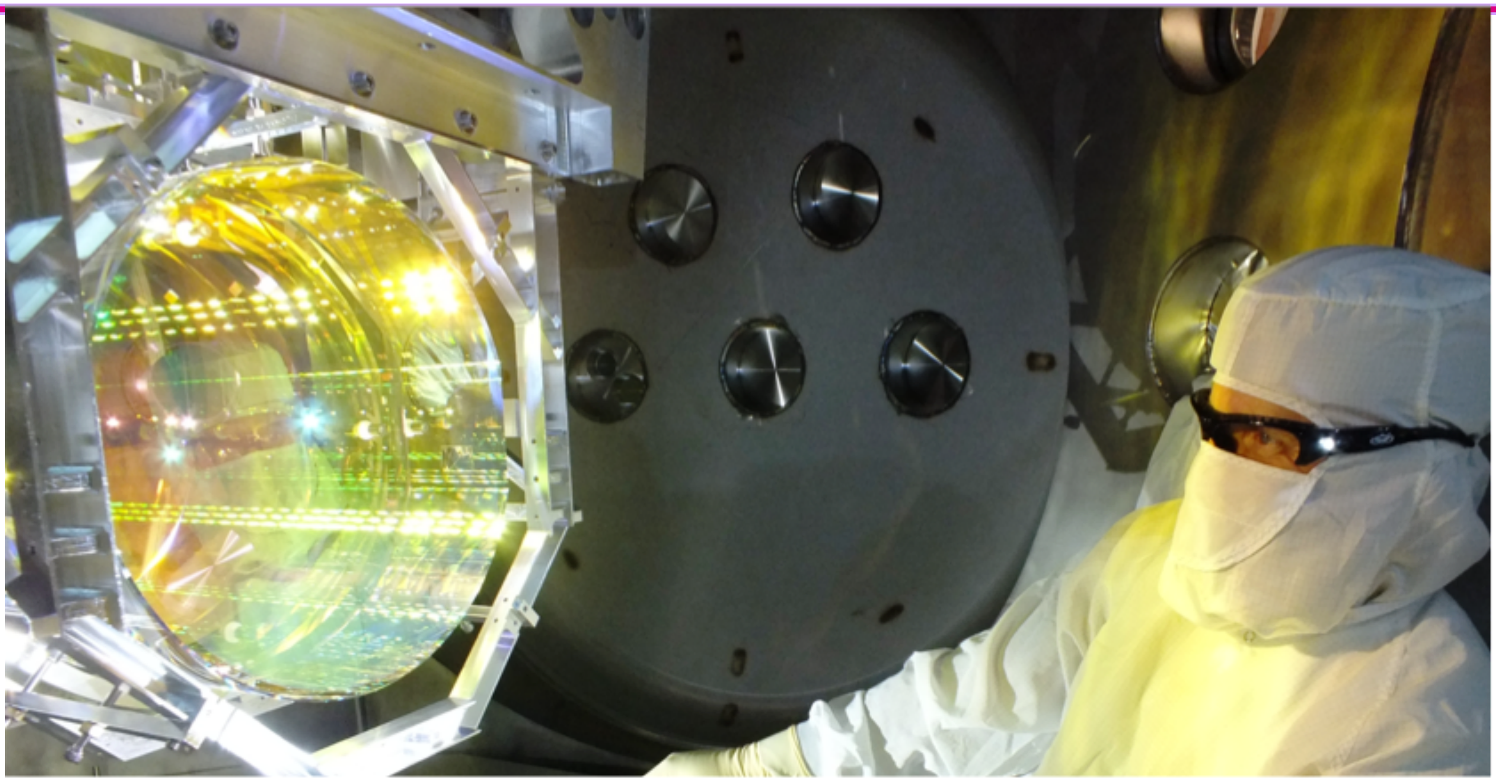
Optical Challenges in LIGO: Past and Future

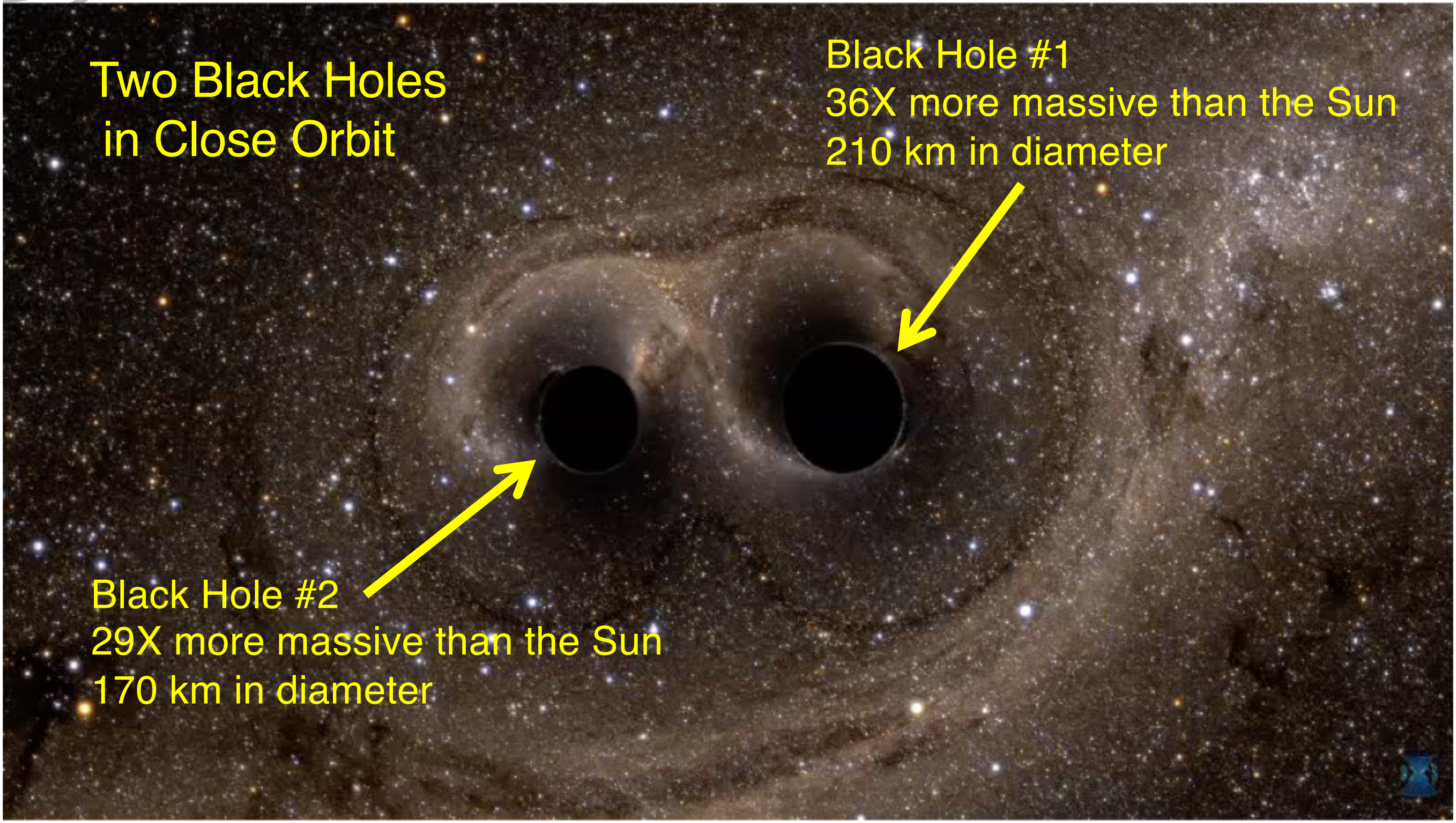


Stan Whitcomb

CREOL IA Symposium

15 March 2019

This story begins 1.3 Billion years ago,
in a distant galaxy…

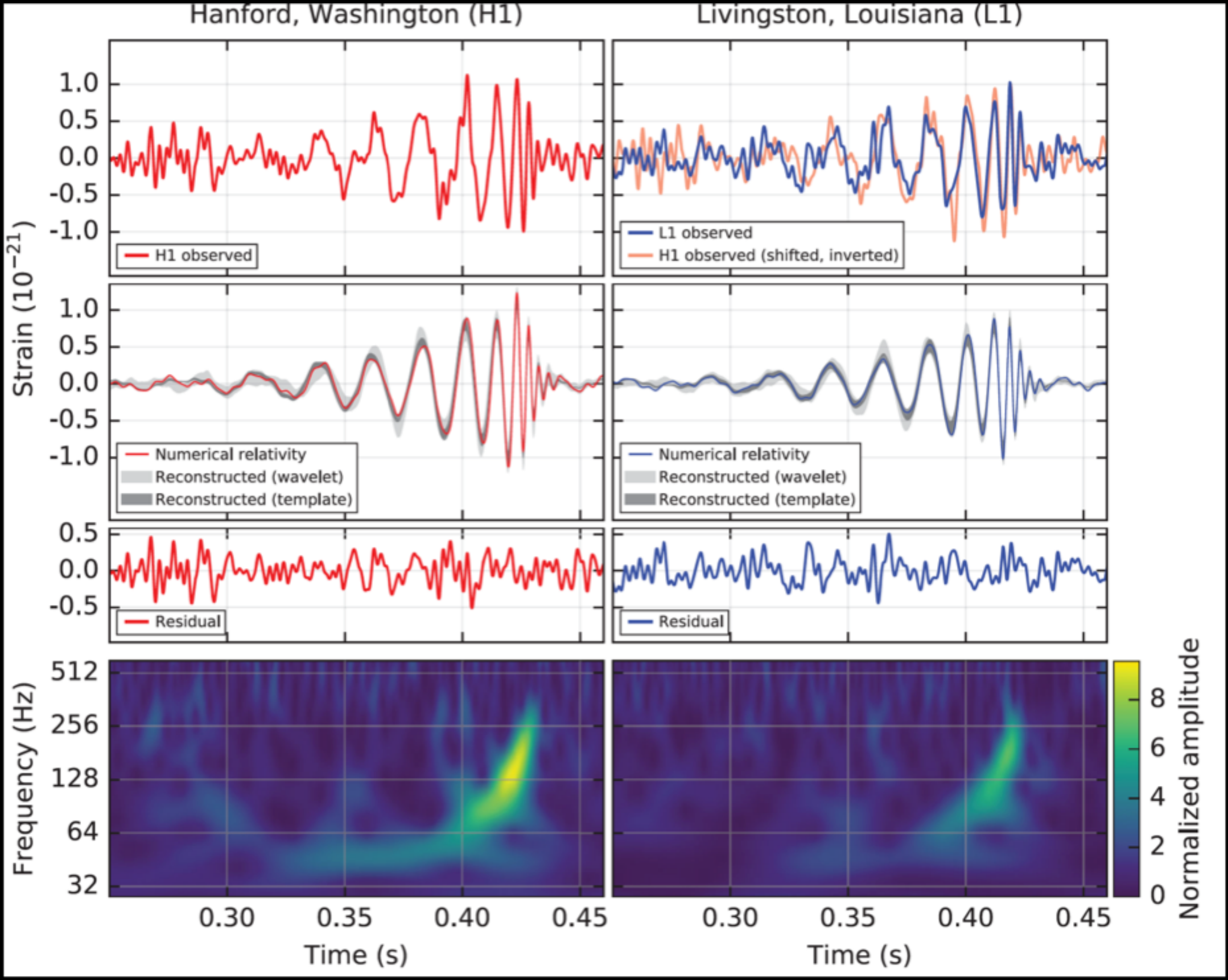


Two Black Holes
in Close Orbit

Black Hole #1
36X more massive than the Sun
210 km in diameter

Black Hole #2
29X more massive than the Sun
170 km in diameter

Then on 14 September 2015, at the LIGO sites…

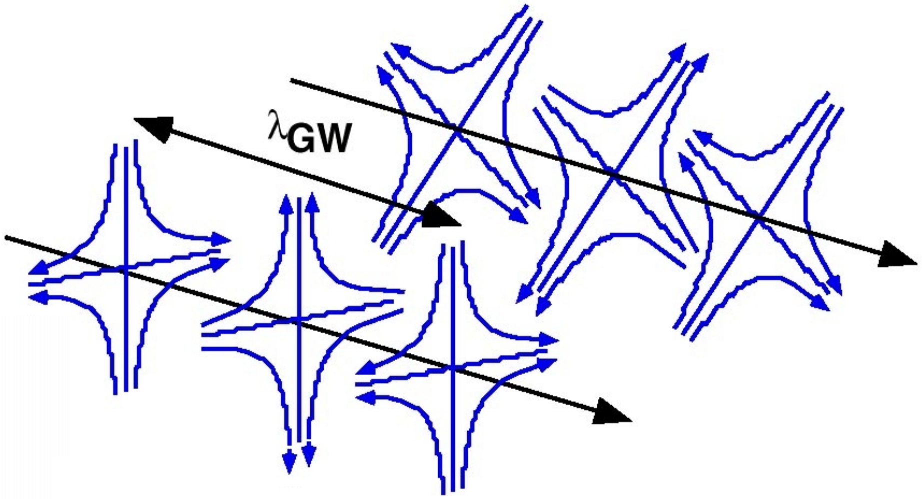


B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. 116, 061102 (2016)


LIGO
September 14, 2015
The Independent
The theory of relativity proved
Heilbronner Stimme
The Guardian
El Espectador
Einstein tenía razón
Correio Braziliense
O senhor do universo
ara
Tenia raó
Il Giornale di Vicenza
Einstein aveva ragione
USA Today Weekend
A whole new window on the universe
Südwest Presse
The Washington Post
The New York Times
Süddeutsche Zeitung
O Estado de S. Paulo
The Daily Star
Scientists detect Einstein's elusive gravity ripples
הארץ
La Nacion
El Mundo
Frankfurter Allgemeine
de Volkskrant
Público
重力波を初観測
聯合晚報
重力波
The Scotsman
University team sheds fresh light on mysteries of universe
Basler Zeitung

Gravitational Wave Basics

- **Einstein (in 1916) recognized gravitational waves in his theory of General Relativity**
  - » **Necessary consequence of Special Relativity with its finite speed for information transfer**
  - » **Most distinctive departure from Newtonian theory**
- **Time-dependent distortions of space-time created by the acceleration of masses**
  - » **Propagate away from the sources at the speed of light**
  - » **Pure transverse waves**
  - » **Two orthogonal polarizations**



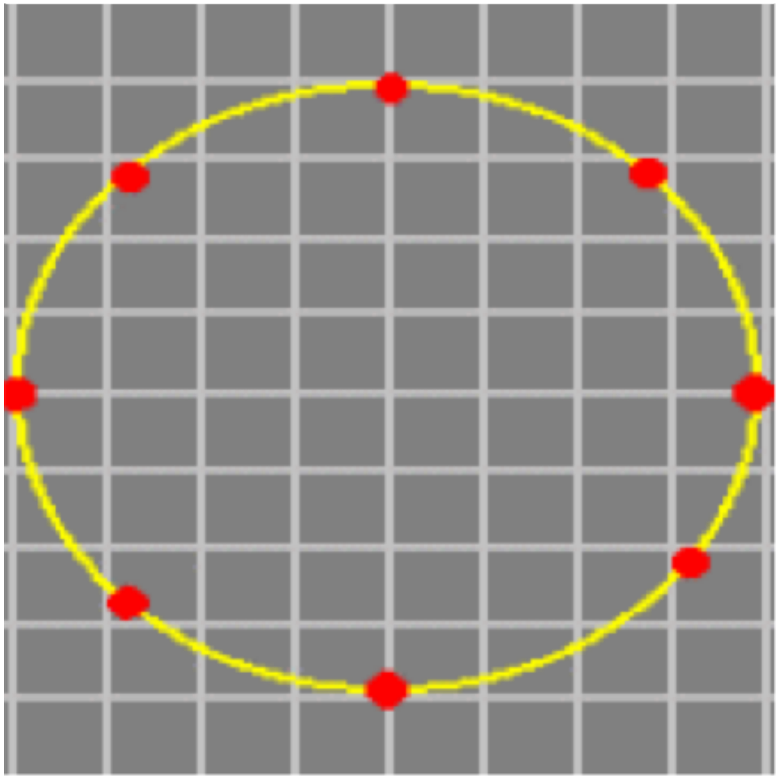
$$h = 2(\Delta L / L)$$

- **Requires huge masses and relativistic accelerations**

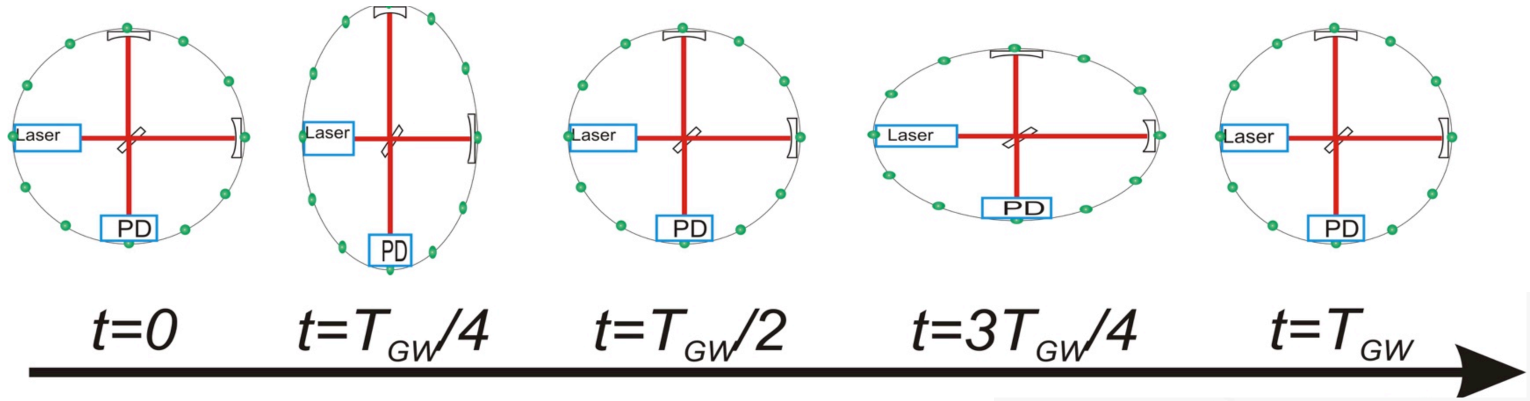
$h \sim 10^{-21}$ for plausible astrophysical sources

Effect of Gravitational Wave

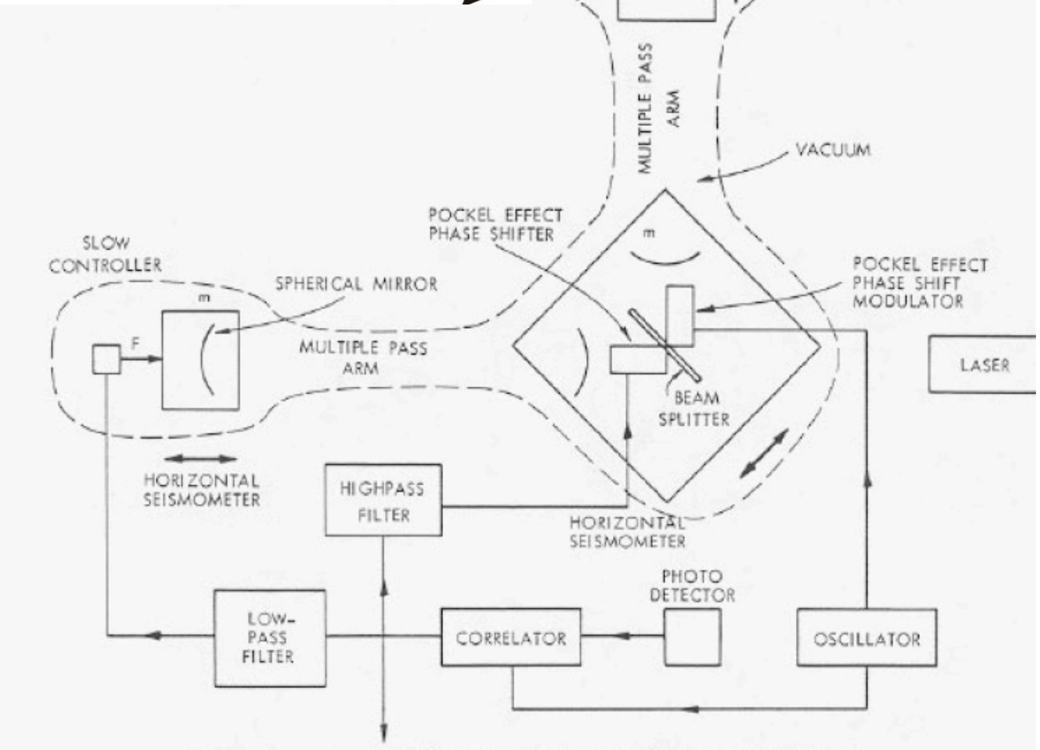
- Gravitational wave travelling INTO the plane of this slide
- Changes the separations of “free masses”



Detecting GWs with Interferometry



Earliest concepts show interferometer mirrors mounted on a "free test mass"

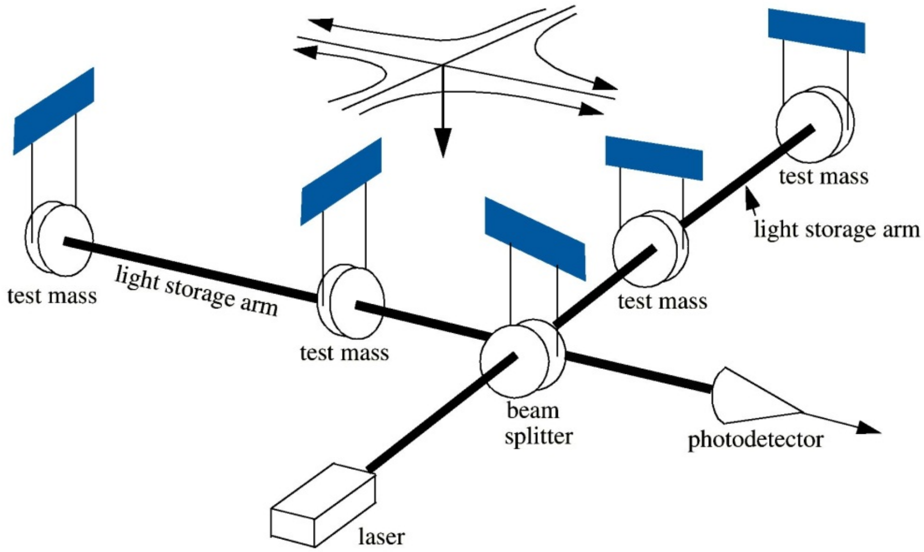


Weiss, 1972

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies $f \gg f_{pend}$

$$\Delta L = hL/2$$



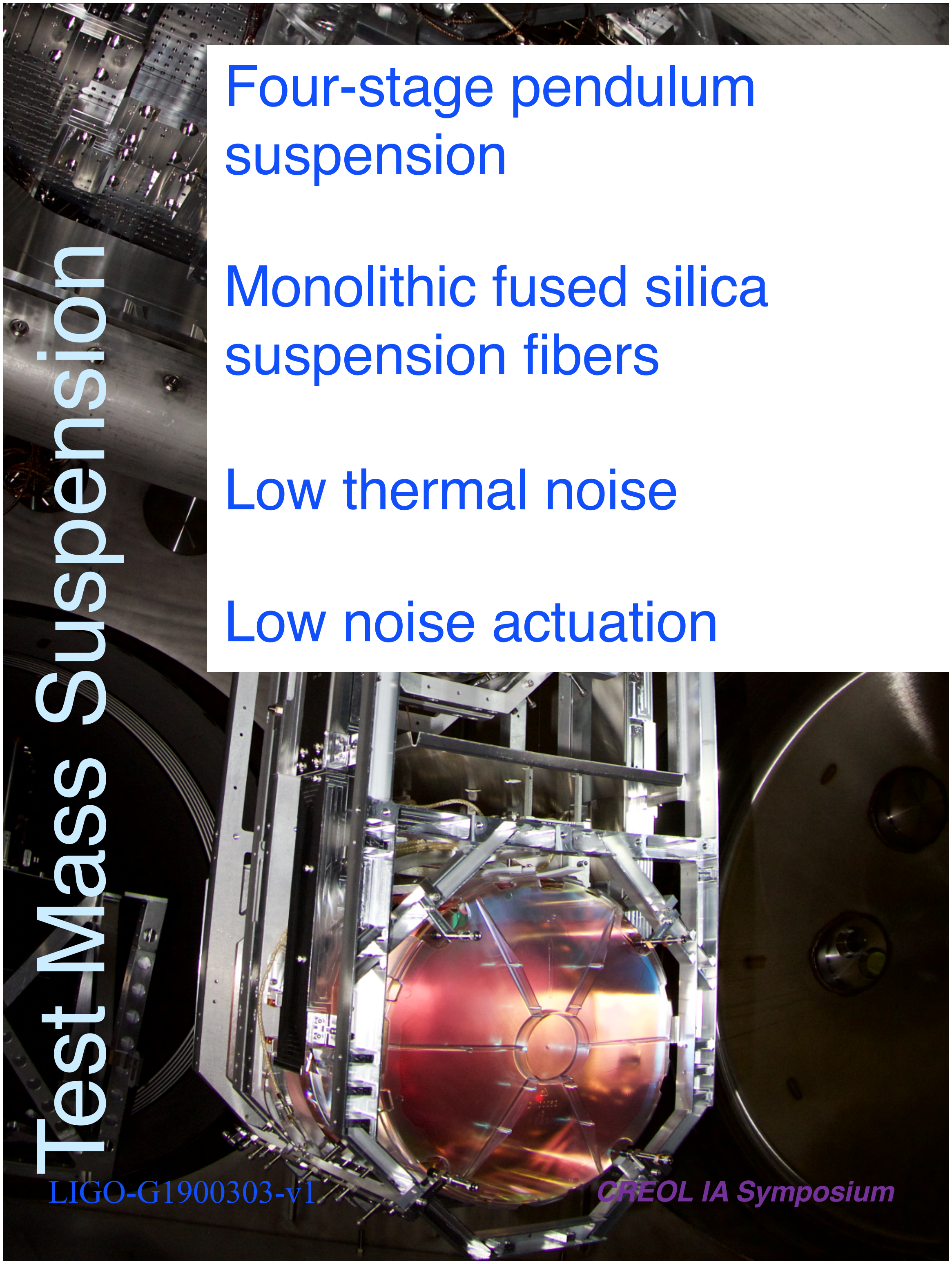
For a LIGO detector,
$L \sim 4$ km, $h \sim 10^{-21}$
$\Delta L \sim 10^{-18}$ m

Test Mass

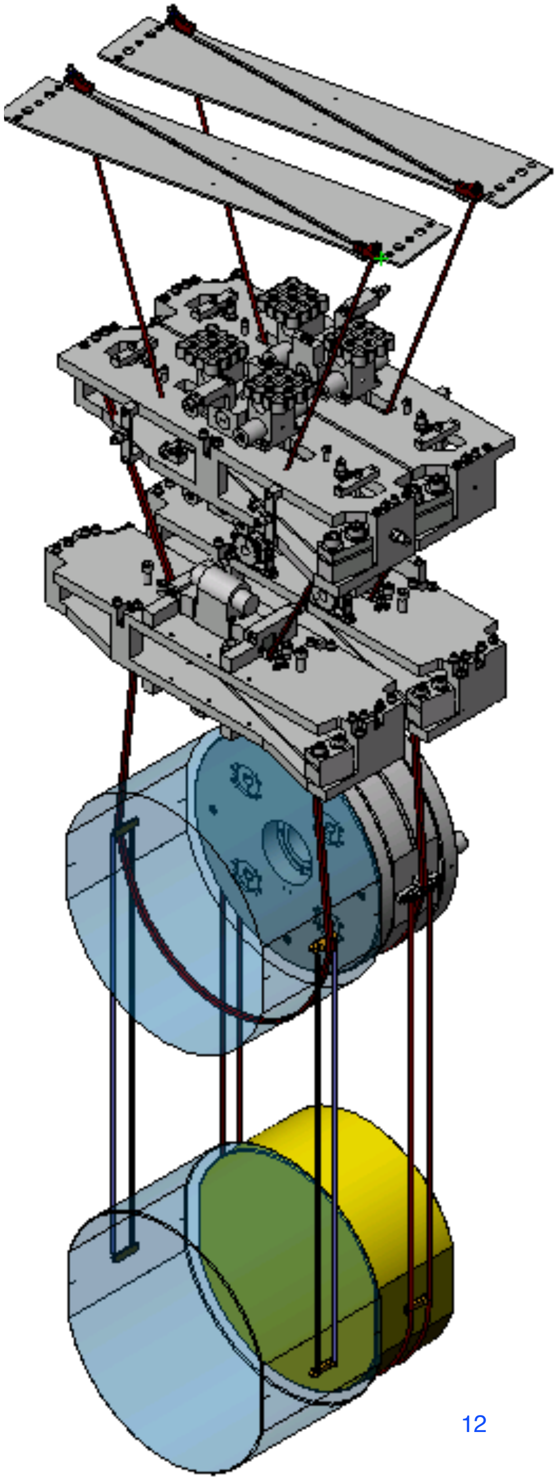
Must act like a free mass in GR

Ultra-high purity fused silica
~35 cm diameter, 40 kg

Test Mass Suspension



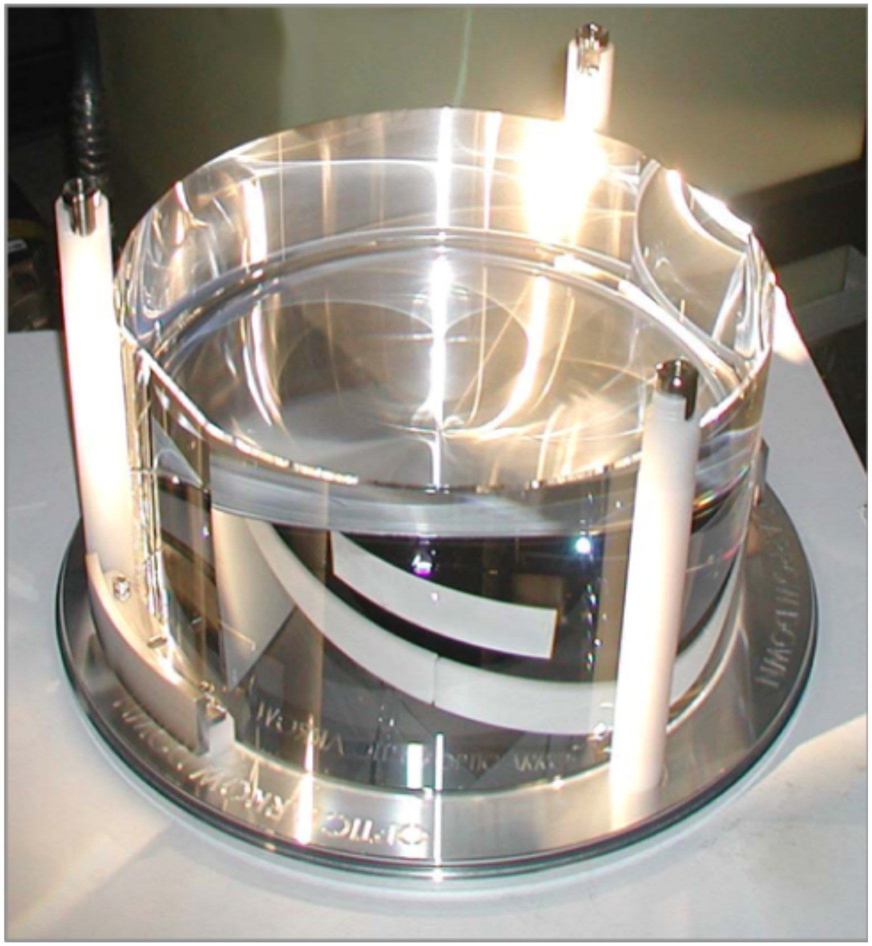
- Four-stage pendulum suspension
- Monolithic fused silica suspension fibers
- Low thermal noise
- Low noise actuation

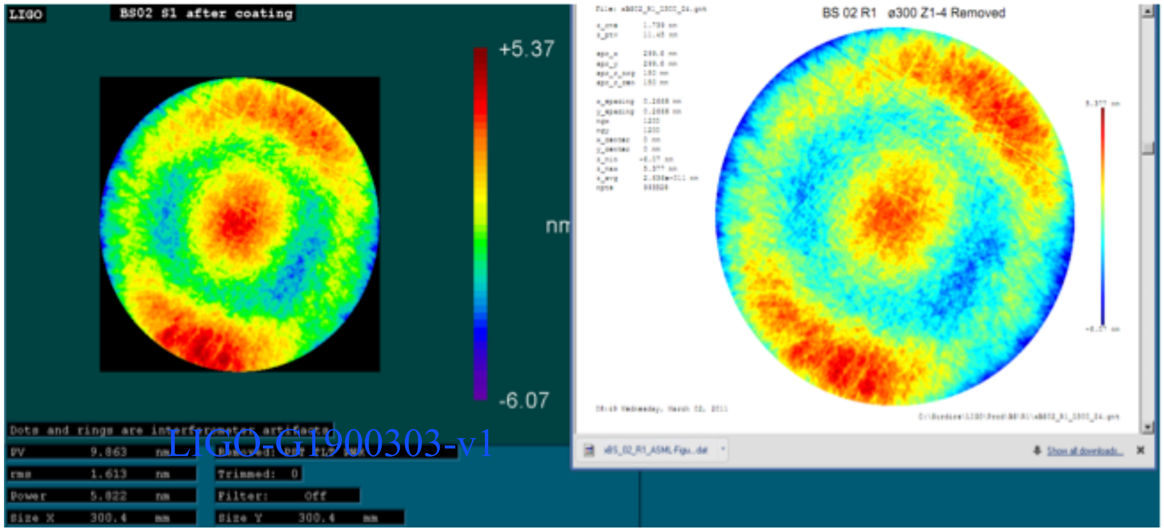


Core Optics Specifications

Challenging optical requirements:

- ROC match to <1%
- $\lambda/1000$ surface figure
- < 0.5 ppm absorption
- ~10 ppm scatter
- 0.1 % coating uniformity





BS02 S1 after coating

Dots and rings are interferometer artifacts

PV 9.863 nm
rms 1.613 nm
Power 5.822 nm
Size X 300.4 mm
Trimmed: 0
Filter: Off
Size Y 300.4 mm

BS 02 R1 ø300 Z1-4 Removed

Precision Interferometry = Controlling Measurement Noises

Displacement Noise

- **Seismic noise**
- **Radiation Pressure**
- **Thermal noise**
  - **Suspensions**
  - **Optics**

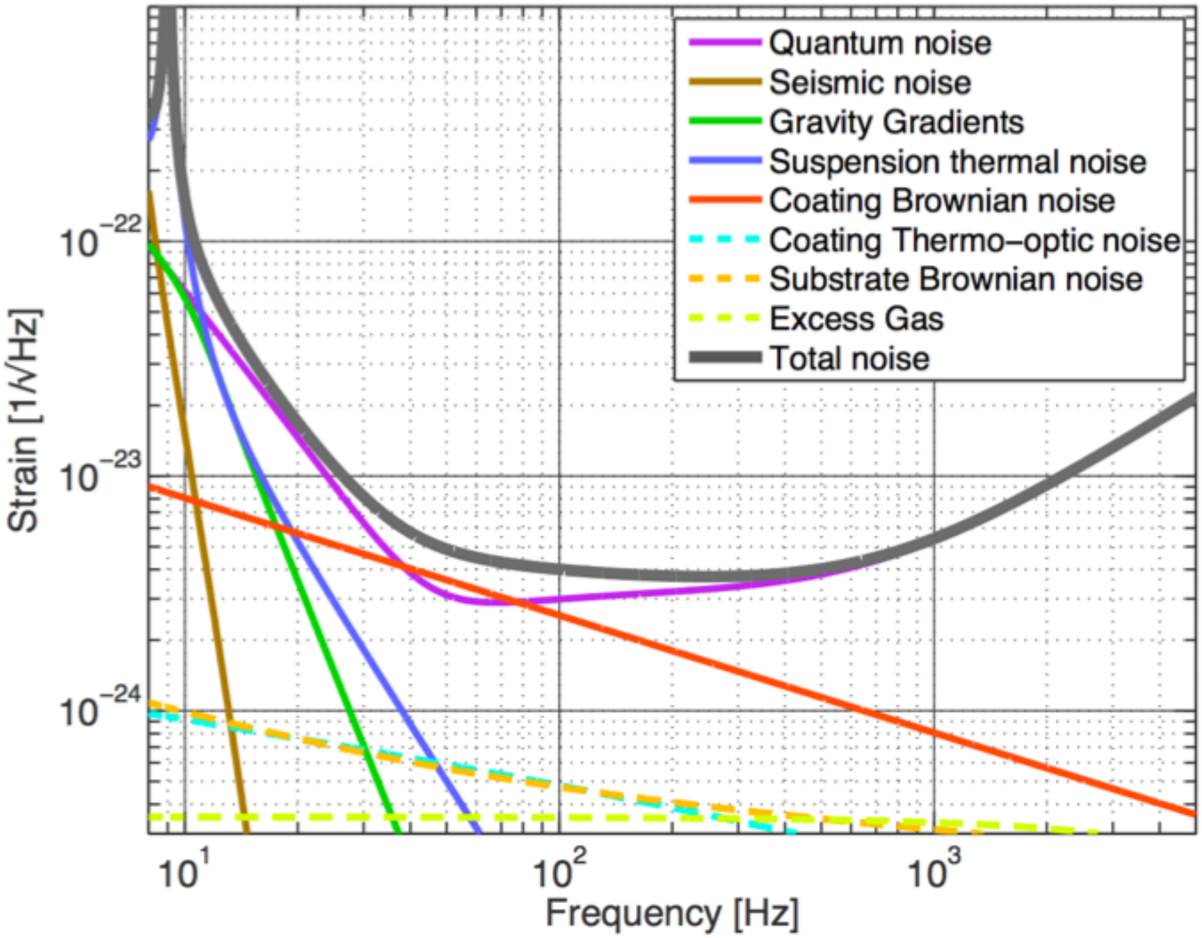
Sensing Noise

- **Shot Noise**
- **Residual Gas**

Technical Noises:

Hundreds of them…

Broadband tuning, full input power (125 W)



Advanced LIGO Detector Sensitivity During O1

Displacement Noise

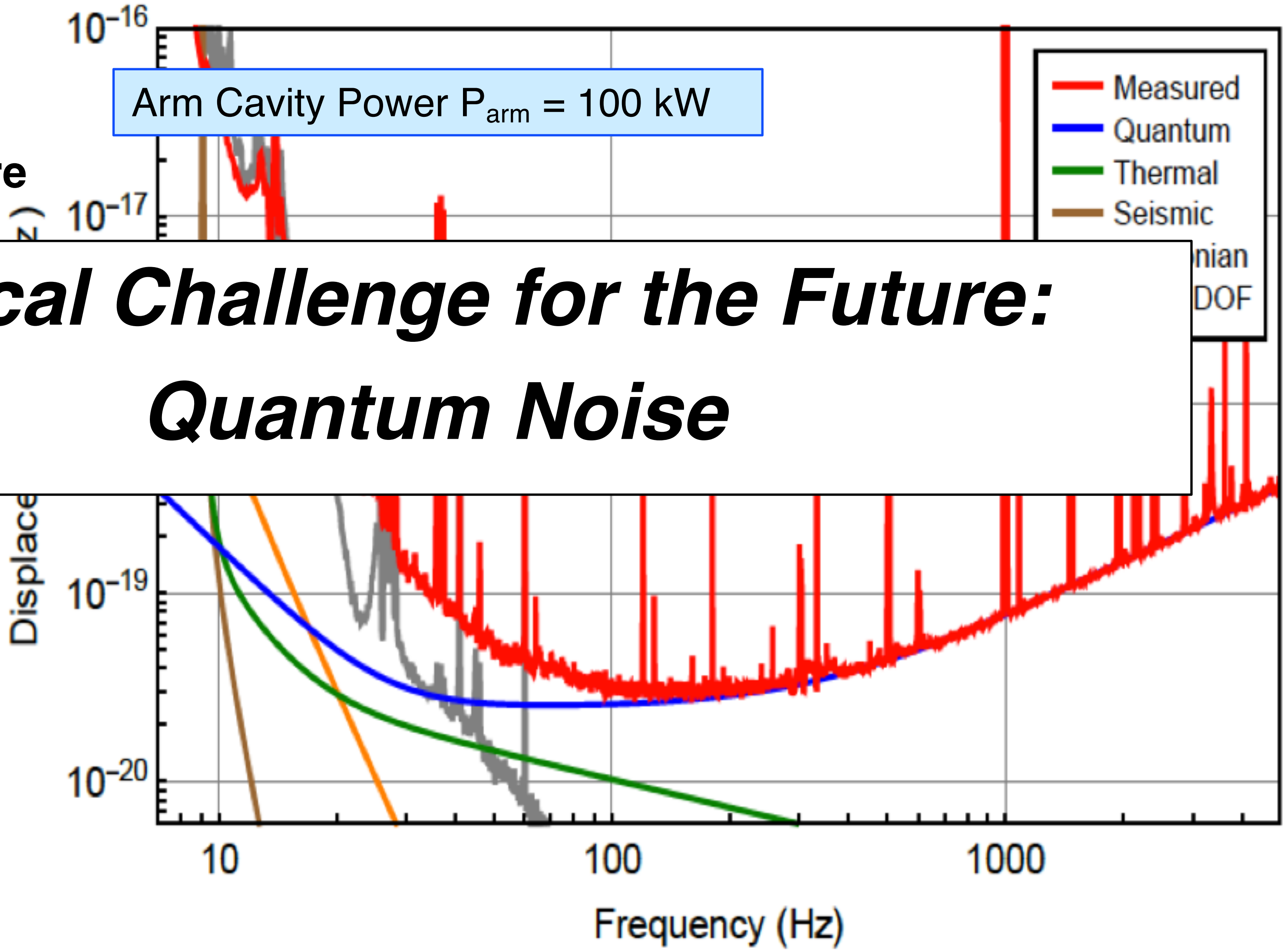
- **Seismic noise**
- **Radiation Pressure**
- **Thermal noise**
  - **S**
  - **C**

Sensi

- **Shot Noise**
- **Residual Gas**

Technical Noises:

Hundreds of them…

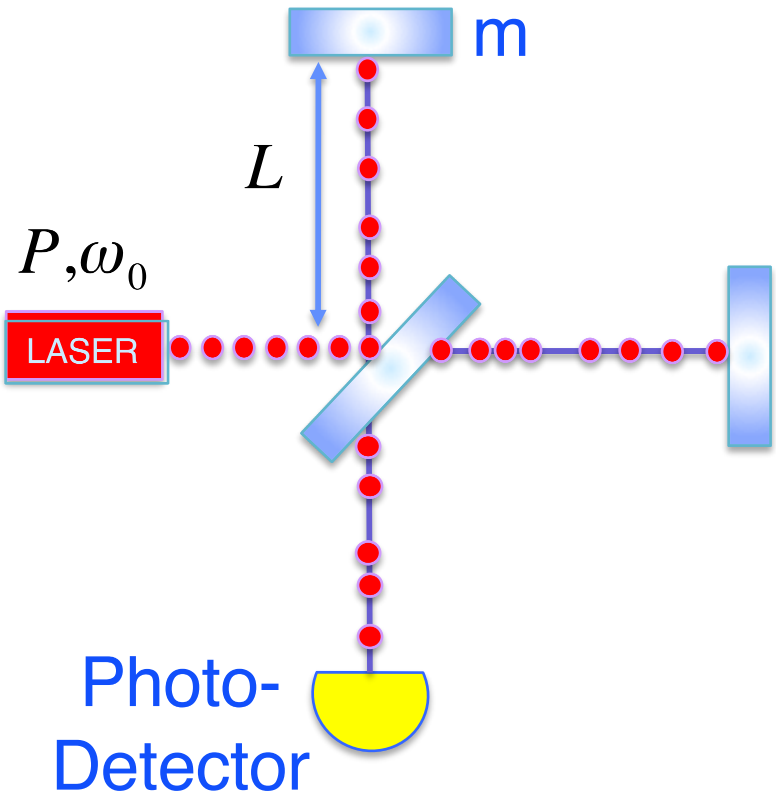


Arm Cavity Power P_{arm} = 100 kW

Optical Challenge for the Future: Quantum Noise

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “GW150914: The Advanced LIGO Detectors in the Era of First Discoveries”, Phys. Rev. Lett. 116, 131103 (2016).

Two Aspects to Quantum Noise



$$h_{quantum} = \sqrt{h_{rad}^2 + h_{shot}^2}$$

SHOT NOISE:

Photon counting noise

$$h_{shot} \propto \frac{1}{L}\sqrt{\frac{1}{P}}$$

RADIATION PRESSURE NOISE:

Noise caused by photon pressure on mirrors

$$h_{rad} \propto \frac{1}{f^2 L}\frac{\sqrt{P}}{\mathrm{m}}$$

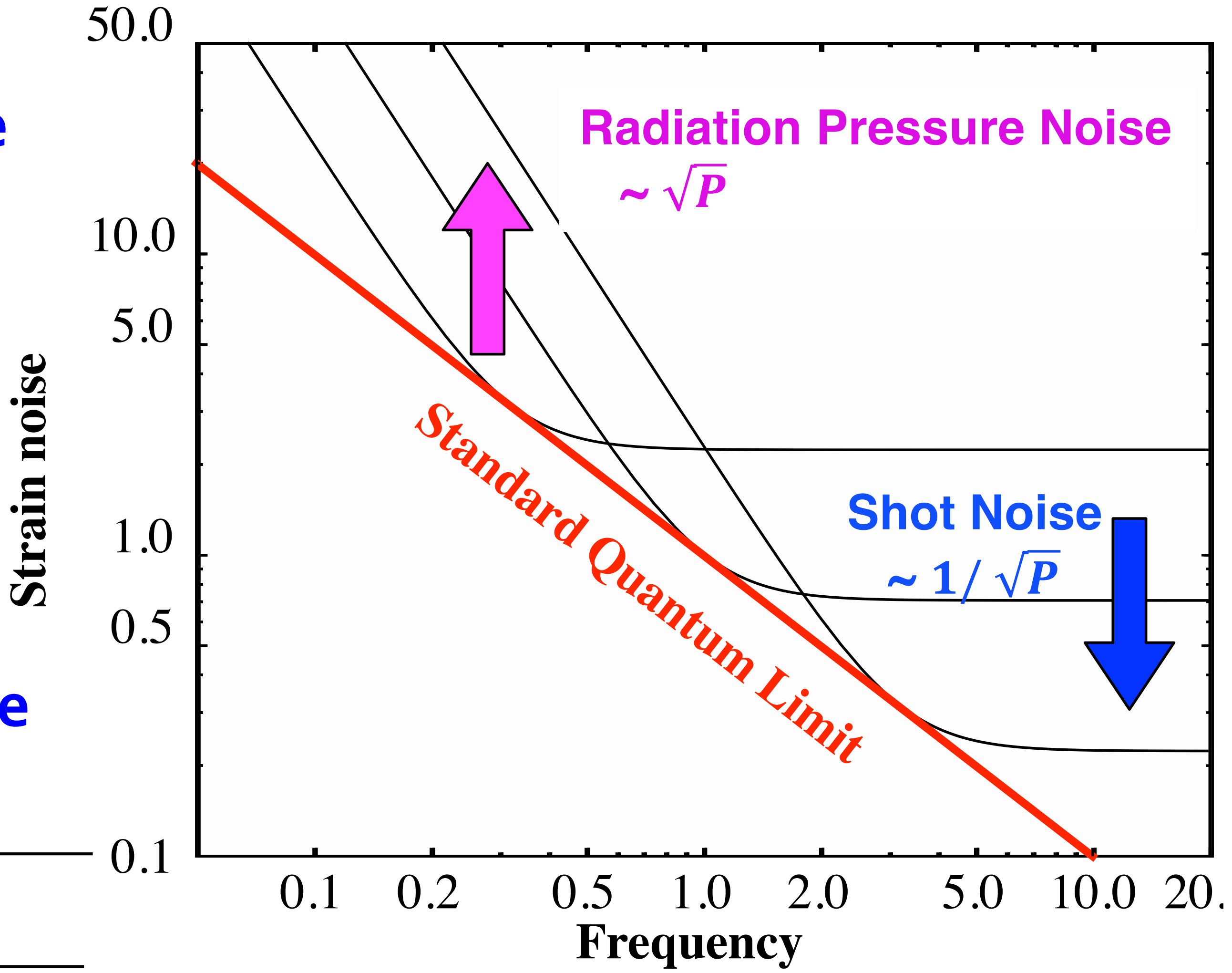
↑

Measurement frequency

Slide courtesy of L. Barsotti

Standard Quantum Limit

- Trade-off in Power Between Shot Noise and Radiation-Pressure Noise
- Standard Quantum Limit (SQL): Uncertainty of test mass position due to Heisenberg Uncertainty Principle



$$\sqrt{S_h^{\mathrm{SQL}}} = \sqrt{\frac{8\hbar}{M(2\pi f)^2 L^2}}$$

Reduce Quantum Noise?

- Quantum noise

$$h_{Quantum} = \sqrt{\frac{4\hbar}{m\Omega^2 L^2}}\sqrt{\frac{1}{2}\left(\overset{\text{RPN}}{\overset{\downarrow}{\mathrm{K}}} + \overset{\text{SN}}{\overset{\swarrow}{\frac{1}{\mathrm{K}}}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

  - » Make the interferometer longer
  - » Heavier test masses & more optical power

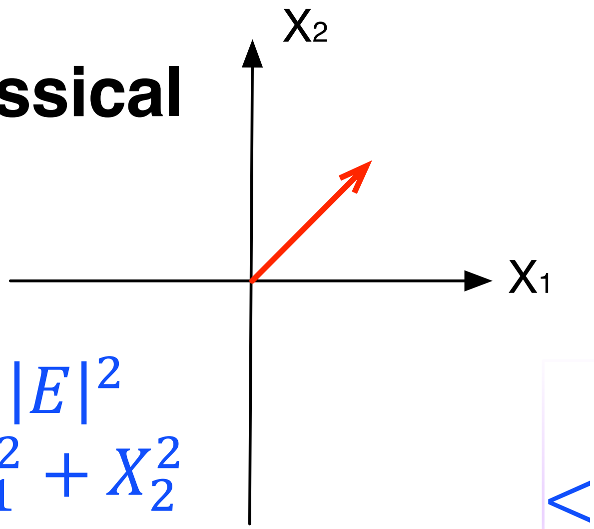
  - » Inject of squeezed states of light

Ball and Stick Picture of Quantum Optical Noise

- **Quantized Electromagnetic Fields Quadrature Field Amplitudes**

$$\hat{E} = \hat{X}_1 \cos \omega t + i \hat{X}_2 \sin \omega t$$

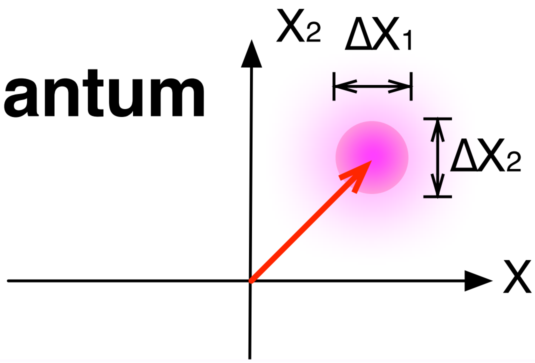
Classical



$$N \sim |E|^2$$

$$N \sim X_1^2 + X_2^2$$

Quantum



Coherent State

$$N \sim (X_1 + \Delta X_1)^2 + (X_2 + \Delta X_2)^2$$

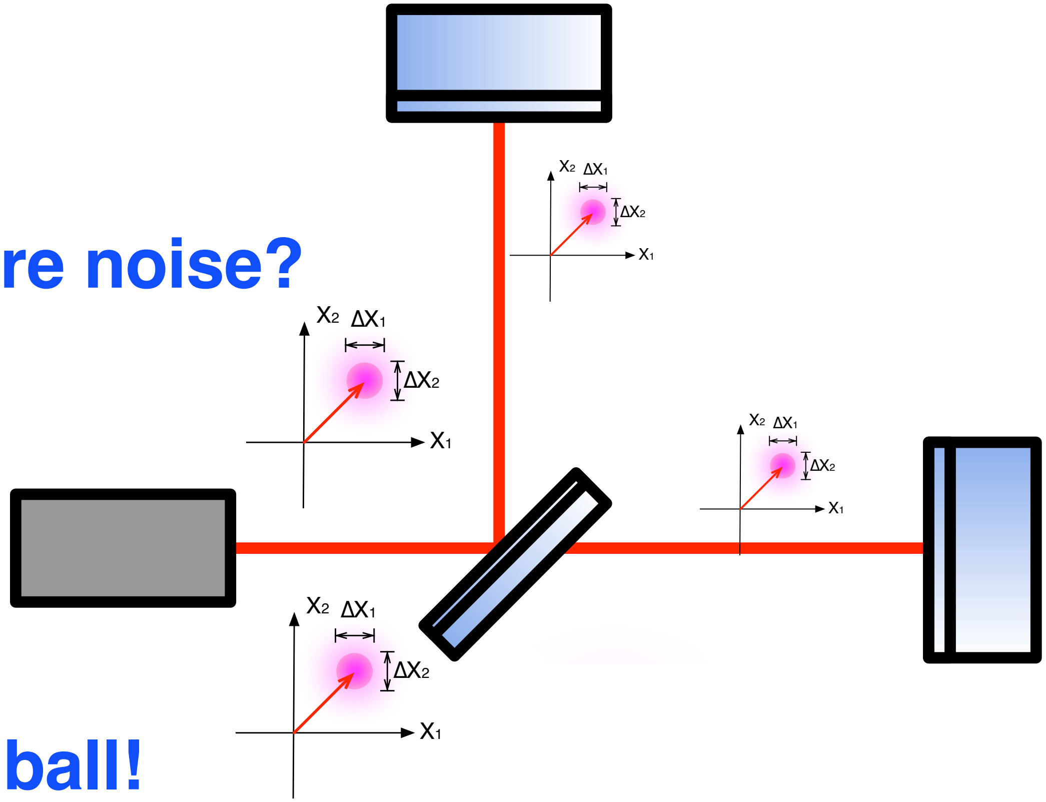
$$< N > \sim X_1^2 + X_2^2 + \Delta X_1^2 + \Delta X_2^2$$

Heisenberg's uncertainty principle $\boldsymbol{\Delta X_1 \Delta X_2 \geq 1}$

Equivalent to ½ photon

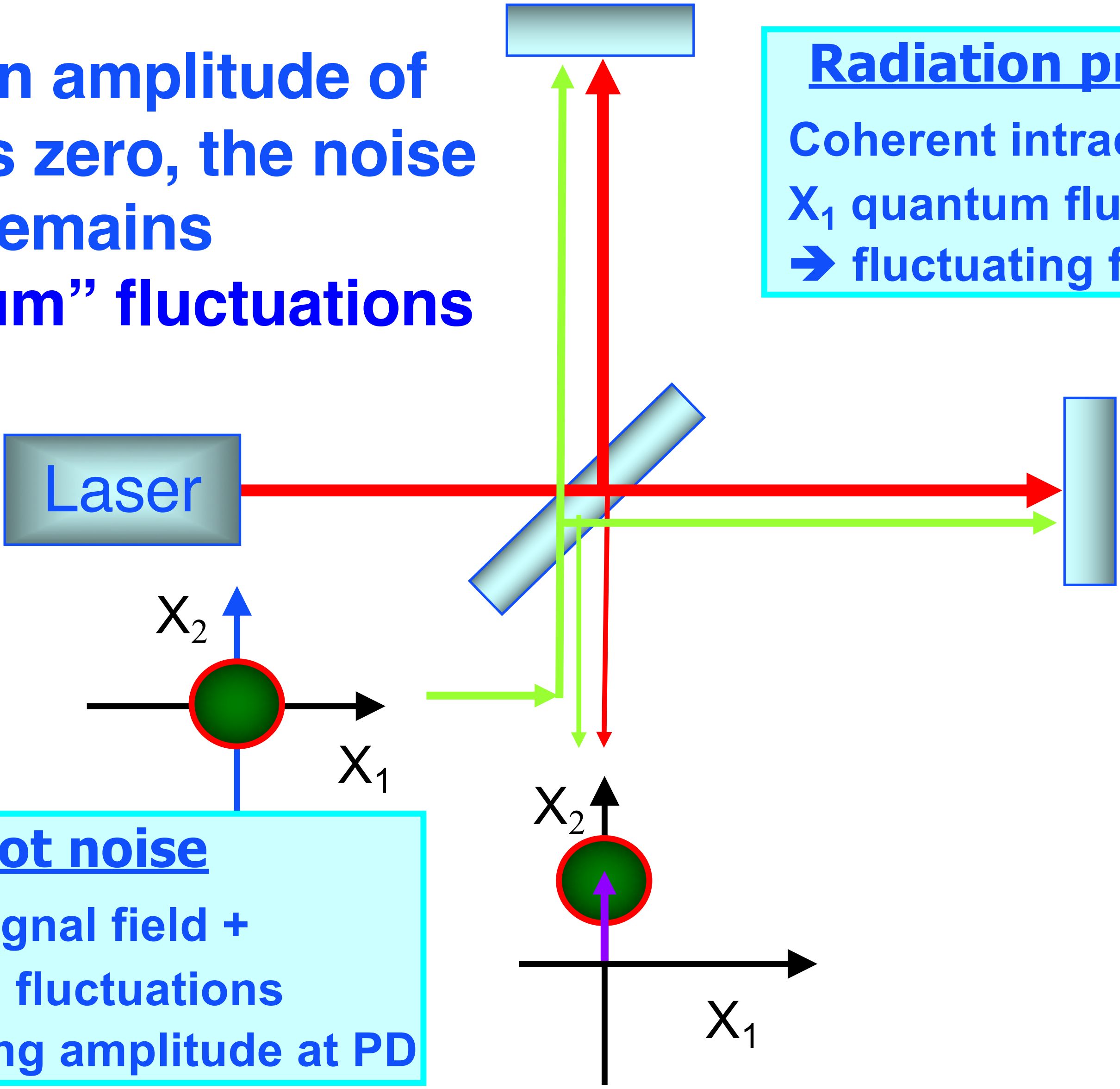
How Does Quantum Noise Enter the Measurement?

- Beamsplitter acts the same on the stick and the ball!
  -> no radiation pressure noise?
- Interferometer arms set to interfere the light back toward laser— both the stick and the ball!
  -> no shot noise either?
- No such thing as Quantum Noise?



LIGO Quantum Noise in an Interferometer

Even when amplitude of the field is zero, the noise fuzz ball remains
=> “vacuum” fluctuations



Radiation pressure noise

Coherent intracavity field +
X_1 quantum fluctuations
➔ fluctuating force on mirrors

Shot noise

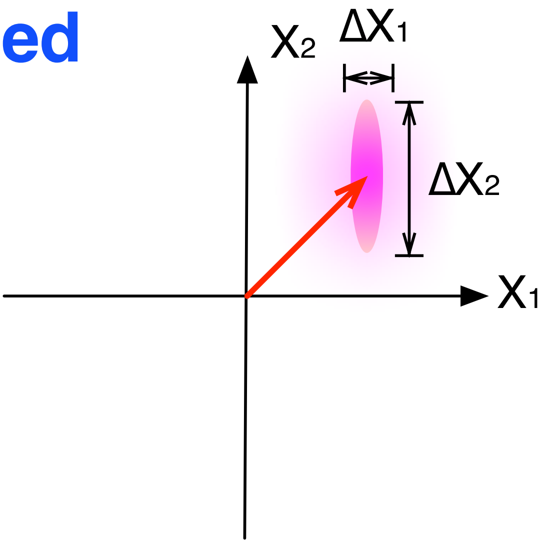
Coherent signal field +
X_2 quantum fluctuations
➔ fluctuating amplitude at PD

Squeezing

- No quantum constraints individually on ΔX_1 *or* ΔX_2 , only their product
- The noise can be redistributed while keeping the minimum uncertainty product

$$\Delta X_1 \, \Delta X_2 \geq 1$$

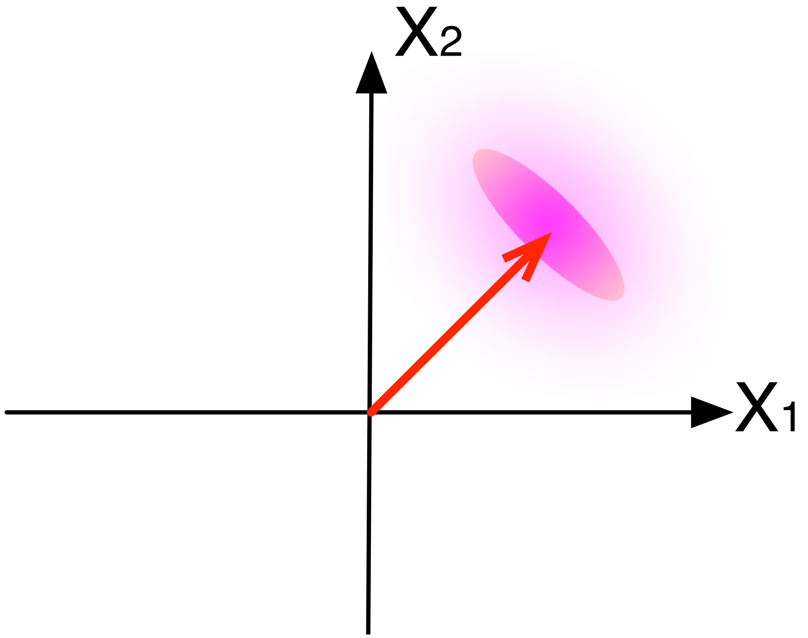
= Squeezed light



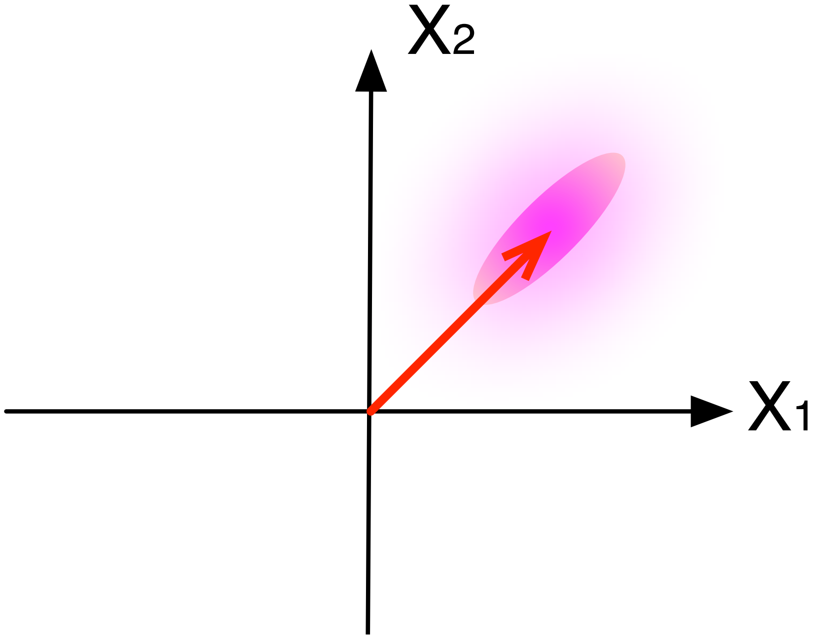
Squeezing

- Particularly useful two states

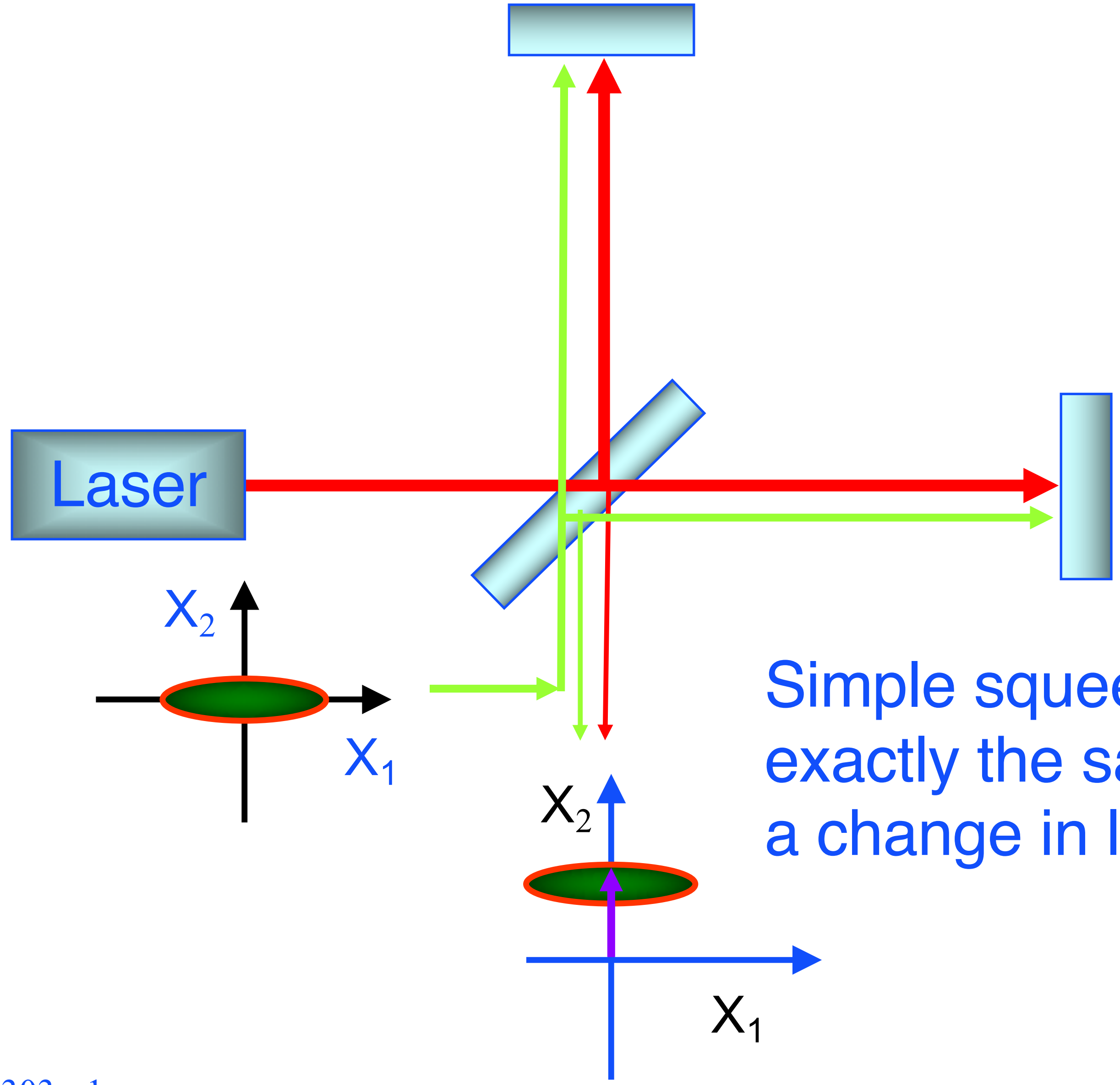
Amplitude squeezing
(Phase anti-squeezing)



Phase squeezing
(Amplitude anti-squeezing)

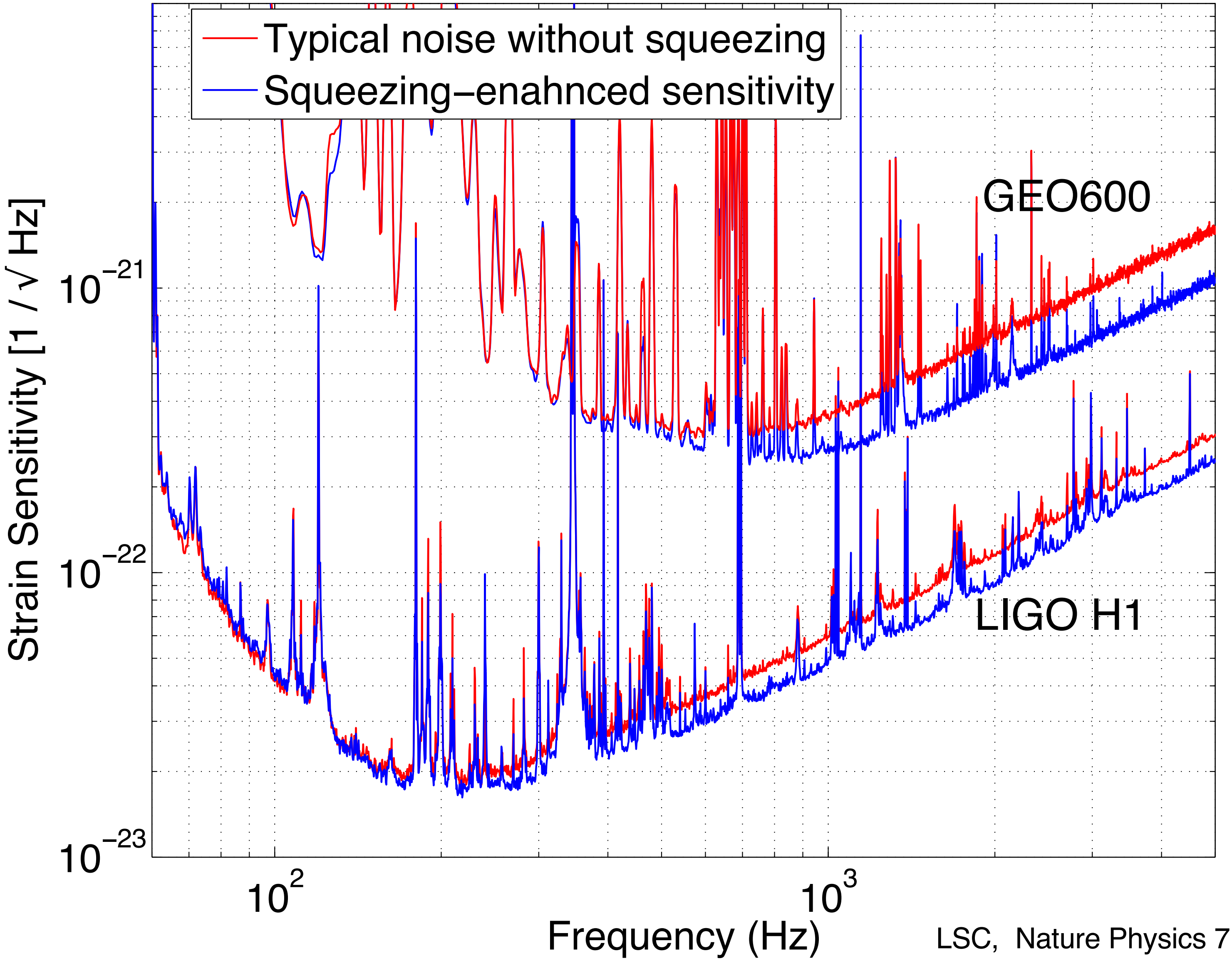


Squeezing in an Interferometer



Simple squeezing gives exactly the same effect as a change in laser power

Does it Really Work?
Squeezing in Action



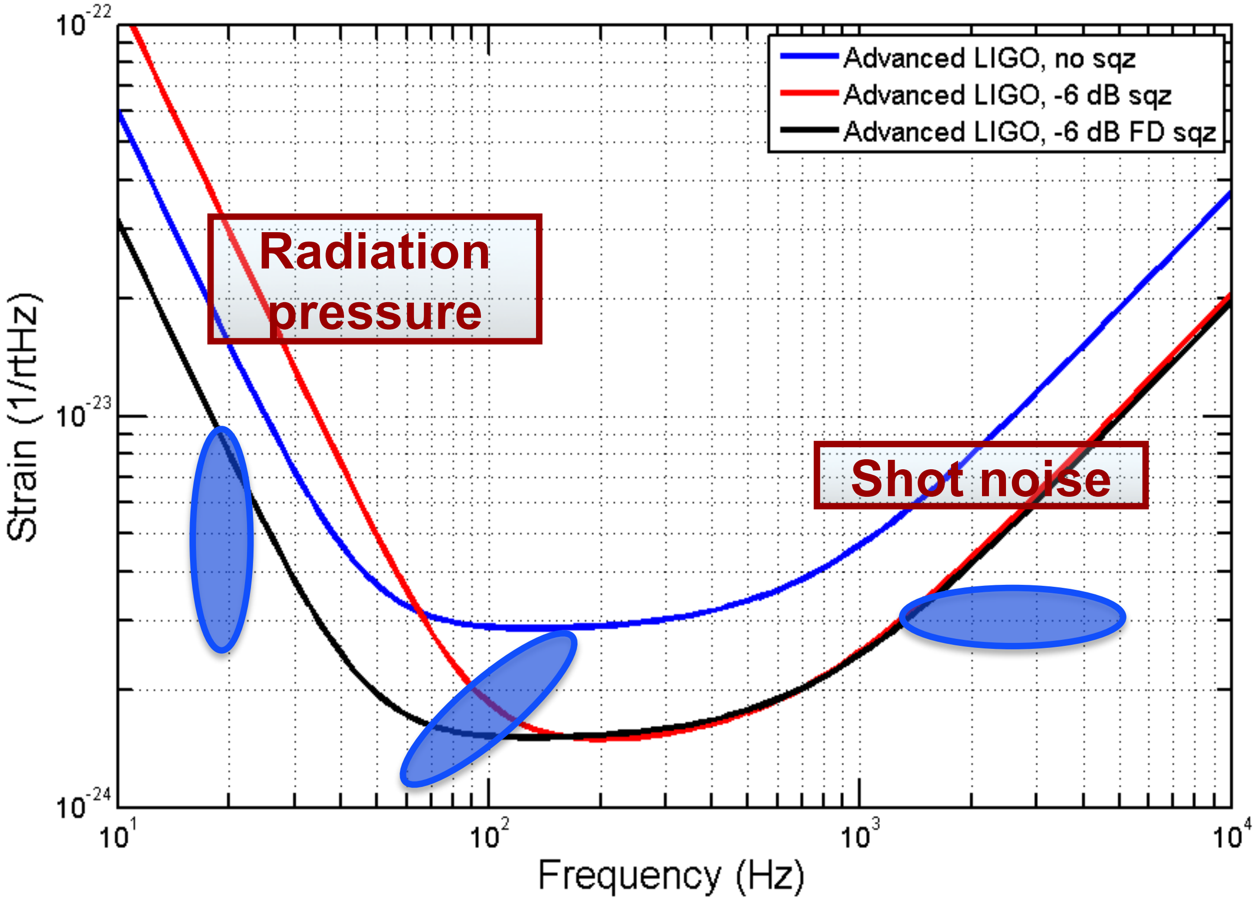
3.5 dB (1/1.5)

2.1 dB (1/1.27)

LSC, Nature Physics 7, 962 (2011)
LSC, Nature Photonics 7, 613–619 (2013)

Best of Both Worlds?

Rotate the squeezing quadrature as a function of frequency



Summing Up

- Detection of gravitational waves is already giving important new information about the Universe on its largest scales

- Made possible by advances in optics and precision interferometry

- Future advances will require us to confront the quantum nature of measurement