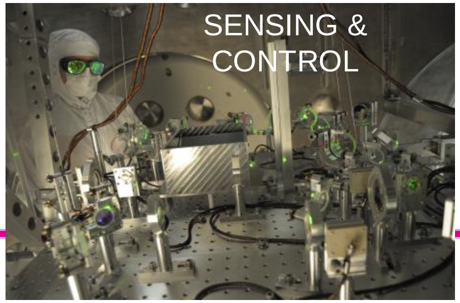
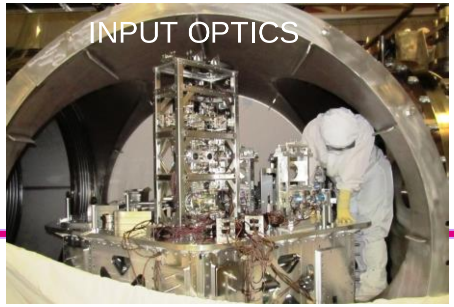
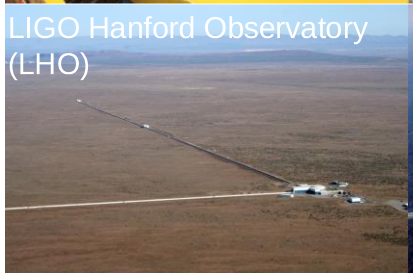


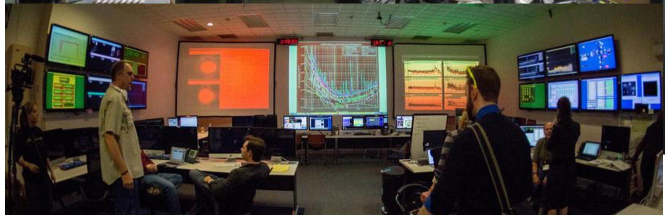
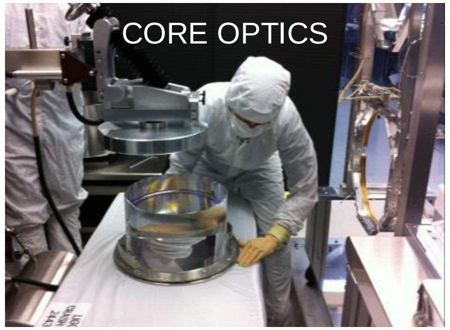


ENGINEERING BEHIND LIGO, the Laser Interferometer Gravitational-wave Observatory

Dennis Coyne
LIGO Laboratory, Caltech
on behalf of the LIGO Scientific Collaboration

A talk to the Southern California Chapter of the American Vacuum Society (AVS),
28 March 2017



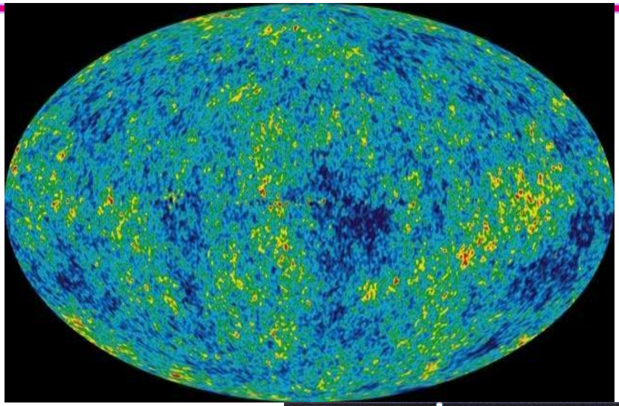



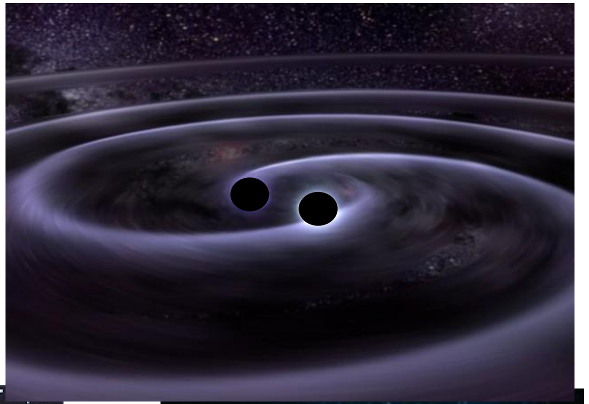
Outline

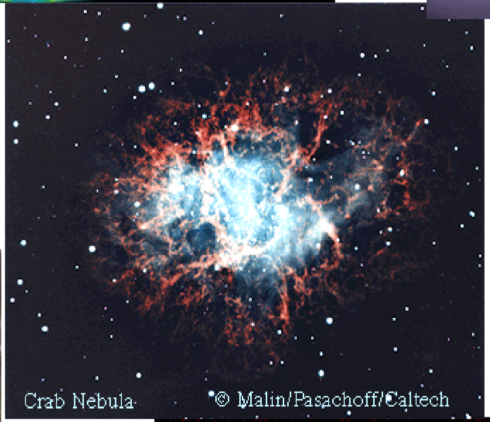
- Why? (the motivation)
  - Gravitation, Gravitational Waves & Astrophysical Sources
- Detection!
- Who?
  - The team
- How? (the engineering)
  - Basic principles of operation
  - Subsystems
- More about the vacuum system
  - a talk by Jon Feicht
- Tours
  - VORTEX (Vapor Outgassing & Reexposure Text Experiment)
  - 40m Lab – a 100th scale version of LIGO

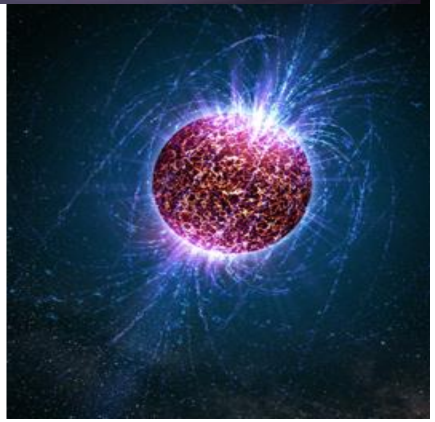
Astrophysical Sources of Gravitational Waves

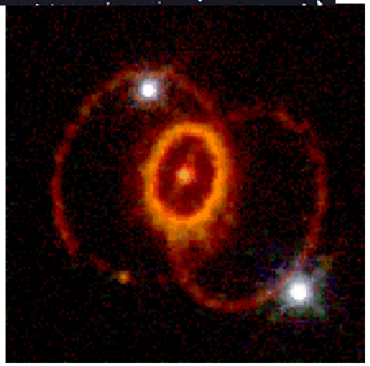
- Compact binary inspiral mergers: template search
  - Neutron star – Neutron star
  - Black hole – Neutron star
  - Black hole – Black hole
- “Burst” Sources: wavelets, T/f clusters
  - Core-collapse supernovae
  - BH normal modes
  - Cosmic Strings
  - The unknown…
- Triggered searches: Multi-modality searches
  - Gamma ray bursts
  - EM transients
- Periodic Sources
  - Pulsars
  - Low mass x-ray binaries (quasi-periodic)
  - Rotating neutron stars
- Stochastic Sources
  - Primordial GW radiation from the Big-Bang
  - Incoherent ensemble of GW emitters: GW radiometry



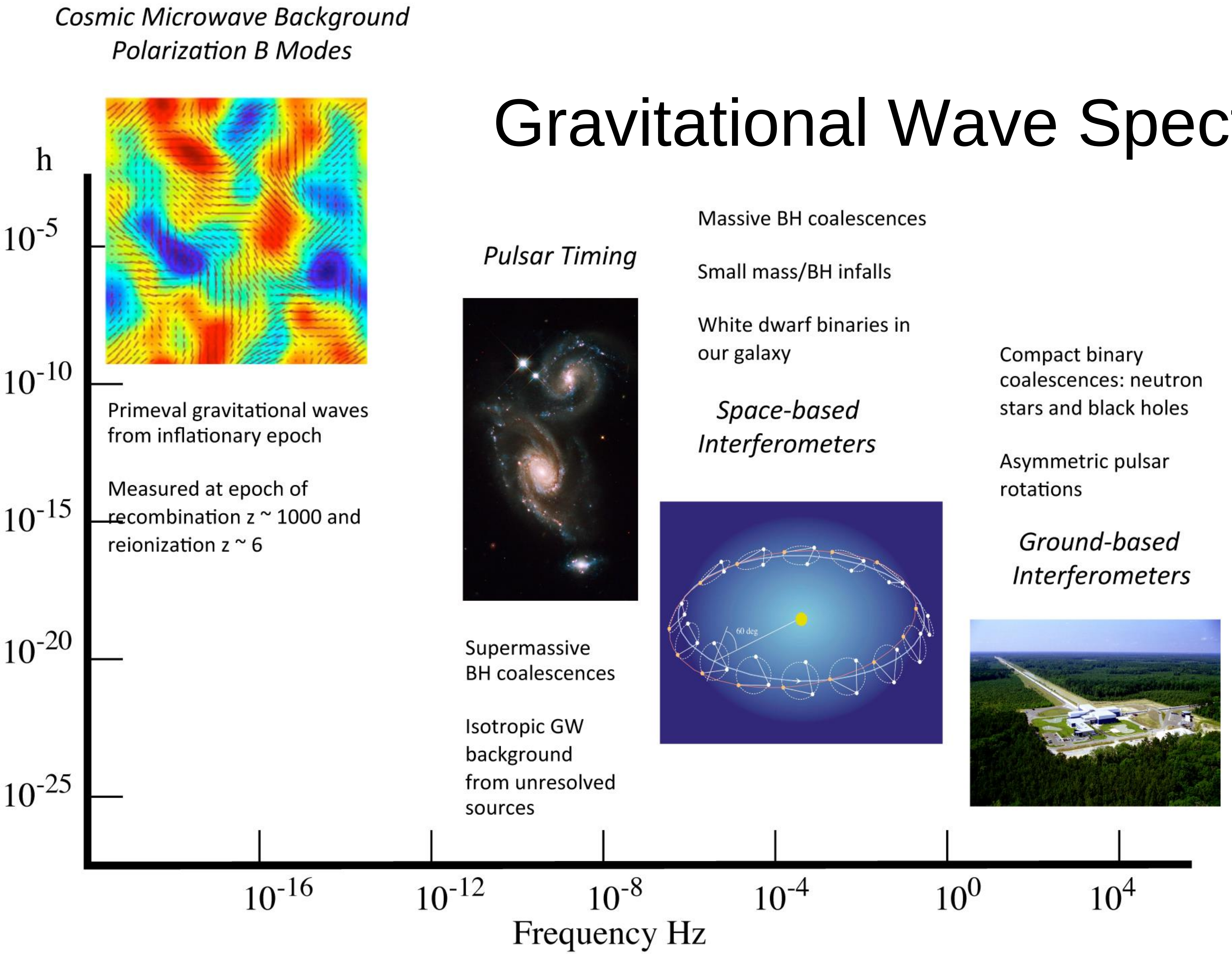




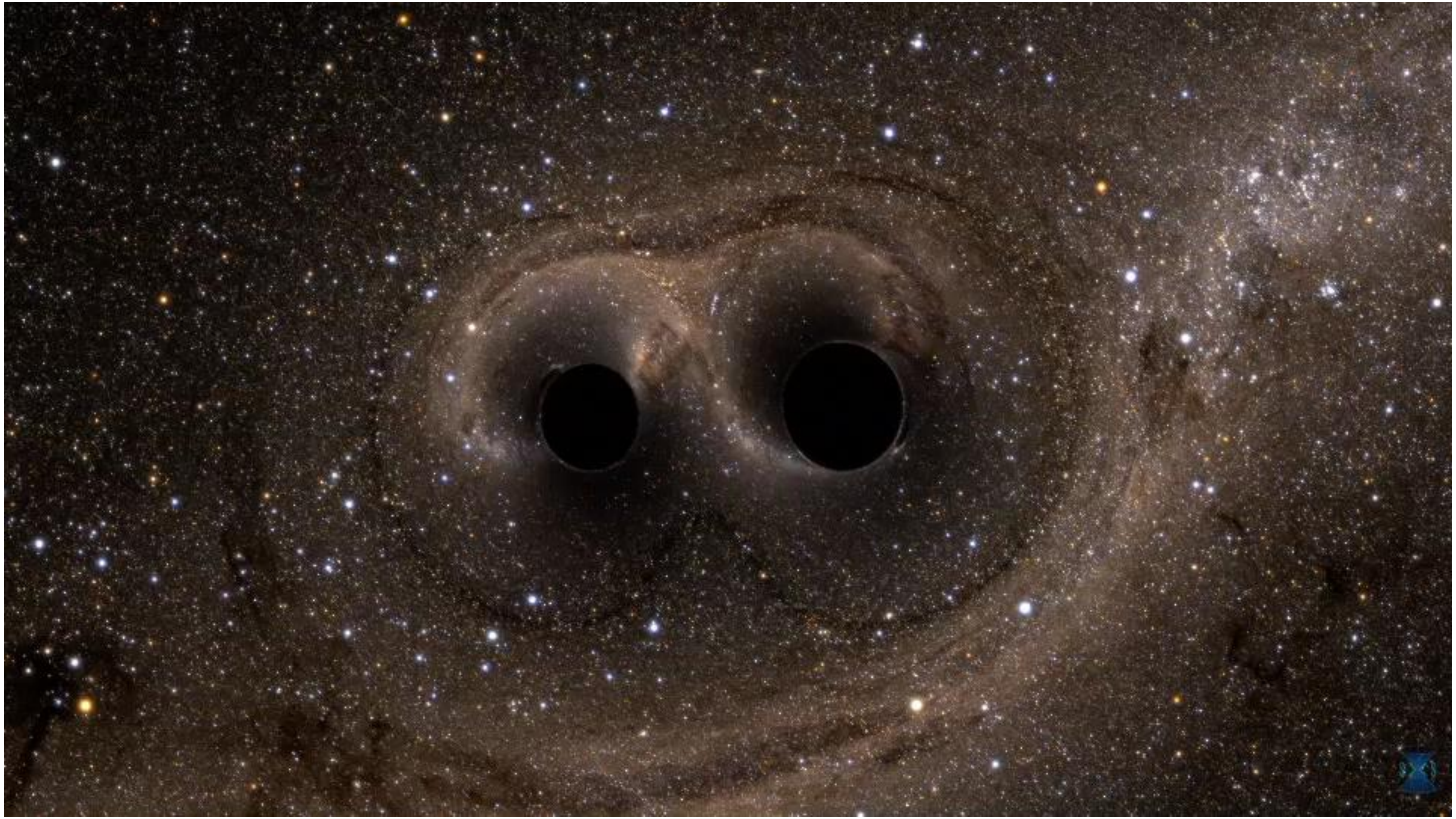




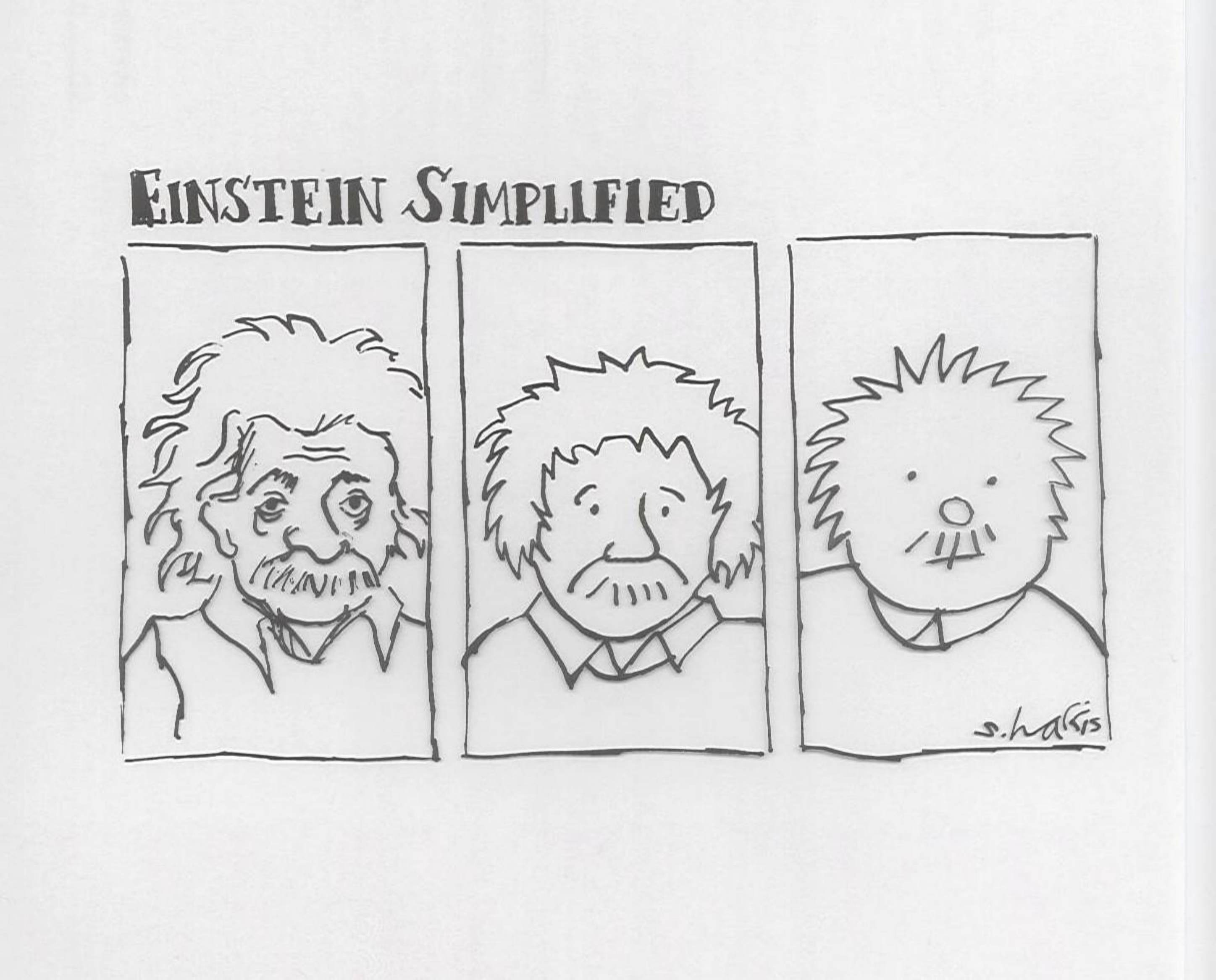
Gravitational Wave Spectrum



Numerical Solution of Einstein Field Equations: Binary Black Hole Merger



Did I Mention that I'm an engineer?



Einstein's General Theory of Relativity

$$\gamma'_{\mu\nu} = \alpha_{\mu\nu} f(x_1 + i x_4) = \alpha_{\mu\nu} f(x - t). \quad (15)$$

Dabei sind die $\alpha_{\mu\nu}$ Konstante; f ist eine Funktion des Arguments $x - t$. Ist der betrachtete Raum frei von Materie, d. h. verschwinden die $T_{\mu\nu}$, so sind die Gleichungen (6) durch diesen Ansatz erfüllt. Die Gleichungen (4) liefern zwischen den $\alpha_{\mu\nu}$ die Beziehungen

$$\left.\begin{array}{l} \alpha_{11} + i\alpha_{14} = 0 \\ \alpha_{12} + i\alpha_{24} = 0 \\ \alpha_{13} + i\alpha_{34} = 0 \\ \alpha_{14} + i\alpha_{44} = 0 \end{array}\right\}. \quad (16)$$

Von den 10 Konstanten $\alpha_{\mu\nu}$ sind daher nur 6 frei wählbar. Wir können die allgemeinste Welle der betrachteten Art daher aus Wellen von folgenden 6 Typen superponieren

$$\left.\begin{array}{lll} \text{a)} \begin{array}{l} \alpha_{11} + i\alpha_{14} = 0 \\ \alpha_{14} + i\alpha_{44} = 0 \end{array} & \begin{array}{l} \text{b)}\ \alpha_{12} + i\alpha_{24} = 0 \\ \text{c)}\ \alpha_{13} + i\alpha_{34} = 0 \end{array} & \begin{array}{l} \text{d)}\ \alpha_{22} \neq 0 \\ \text{e)}\ \alpha_{23} \neq 0 \\ \text{f)}\ \alpha_{33} \neq 0 \end{array} \end{array}\right\}. \quad (17)$$

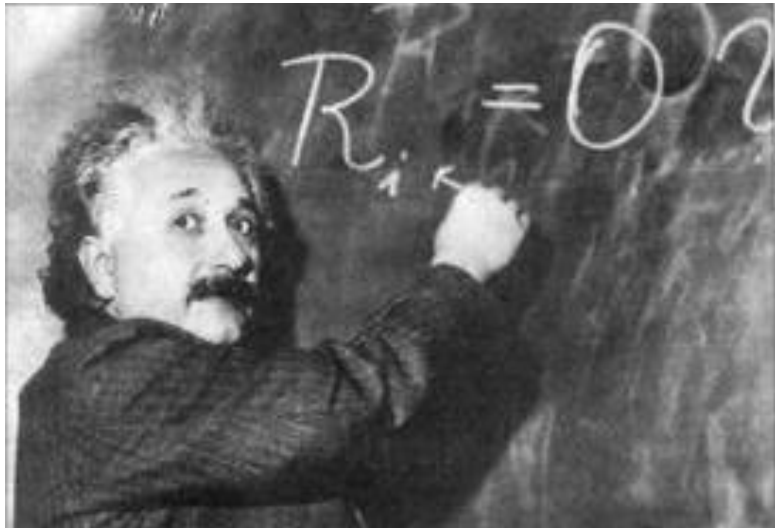
$$\text{d)} \quad \frac{1}{i} t_{22} = \frac{f'^2}{4\varkappa} \alpha_{22}^2 = \frac{1}{4\varkappa} \left(\frac{\partial \gamma'_{22}}{\partial t}\right)^2$$

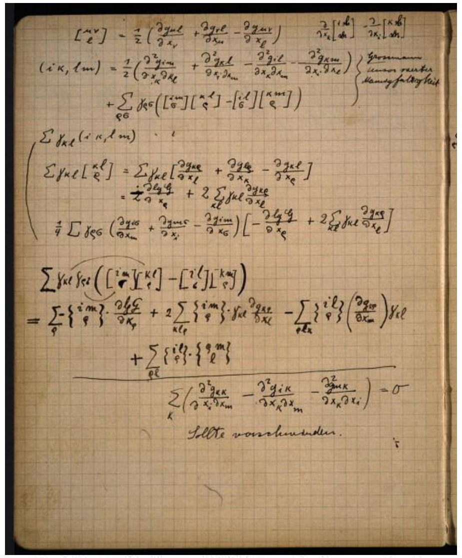
$$\text{e)} \quad \frac{1}{i} t_{23} = \frac{f'^2}{4\varkappa} \alpha_{23}^2 = \frac{1}{4\varkappa} \left(\frac{\partial \gamma'_{23}}{\partial t}\right)^2$$

$$\text{f)} \quad \frac{1}{i} t_{33} = \frac{f'^2}{4\varkappa} \alpha_{33}^2 = \frac{1}{4\varkappa} \left(\frac{\partial \gamma'_{33}}{\partial t}\right)^2$$

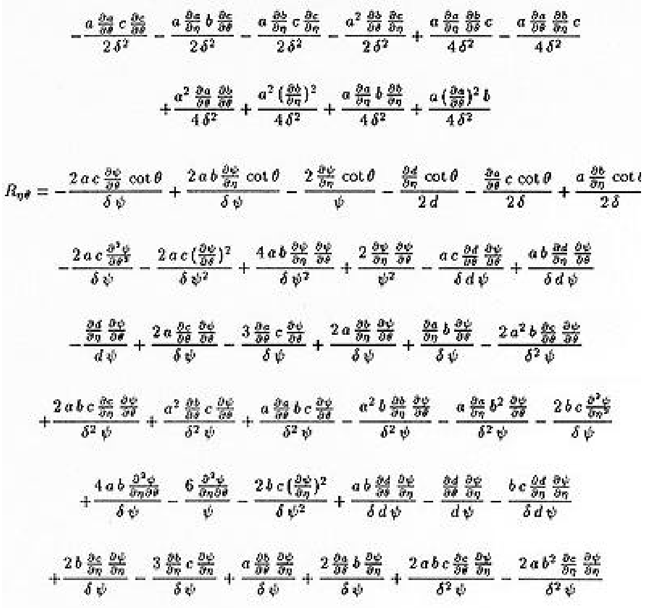
Es ergibt sich also, daß nur die Wellen des letzten Typs Energie transportieren, und zwar ist der Energietransport einer beliebigen ebenen Welle gegeben durch

$$\mathfrak{I}_x = \frac{1}{i} t_{41} = \frac{1}{4\varkappa} \left[\left(\frac{\partial \gamma'_{22}}{\partial t}\right)^2 + 2\left(\frac{\partial \gamma'_{23}}{\partial t}\right)^2 + \left(\frac{\partial \gamma'_{33}}{\partial t}\right)^2\right]. \quad (18)$$





$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

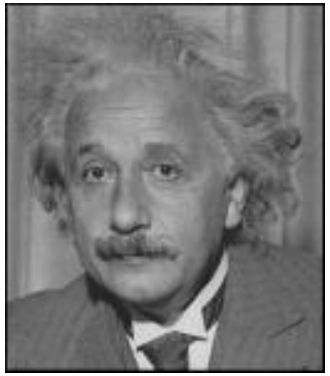


Albert Einstein: "Do not worry about your difficulties in Mathematics. I can assure you mine are still greater."

$$ds^2 = -\left[\left\{1 - \left(\frac{2GM}{rc^2}\right)\right\}^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right]$$

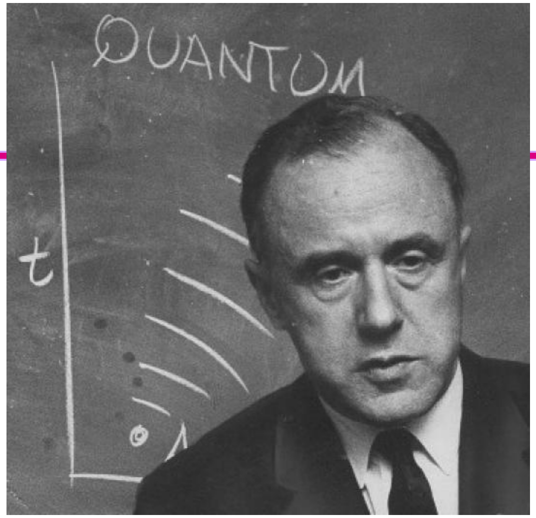
$$+\left\{1 - \left(\frac{2GM}{rc^2}\right)\right\}(cdt)^2 + \left[\left(\frac{G}{c^2}\right) dm\right]^2$$

Newtonian Gravity, General Relativity and Gravitational Waves



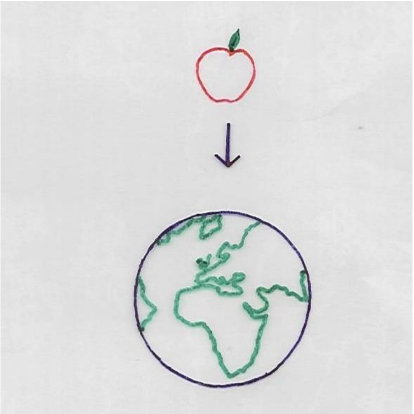
$$\left(-\frac{\partial^2}{\partial t^2}+\nabla^2\right)h^{ab}=0$$

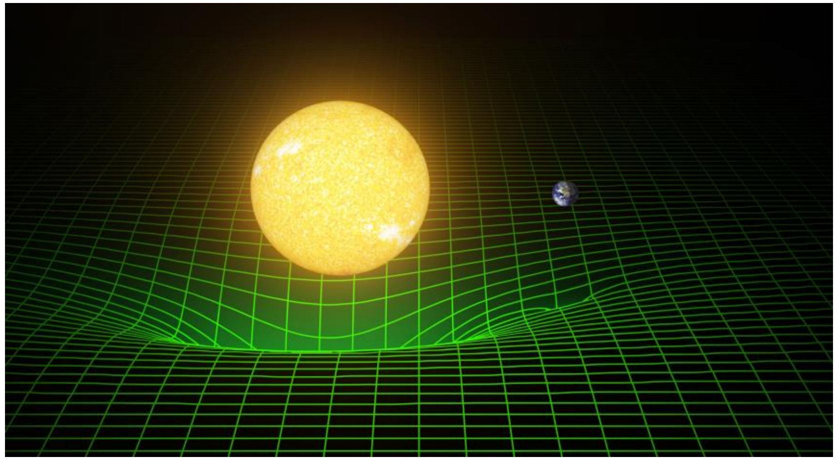
Einstein field equations have wave solution

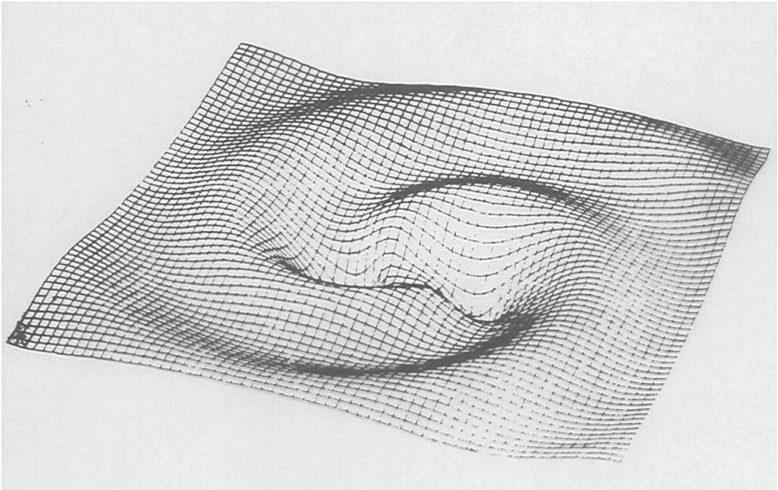


"Mass tells space-time how to curve, and space-time tells mass how to move." John Wheeler

Newtonian Gravity "Spooky action at a distance"







$$F=\frac{GMm}{r^2}$$

$$h=\frac{dL}{L}=G^a c^b M^d R^e D^k f^n$$

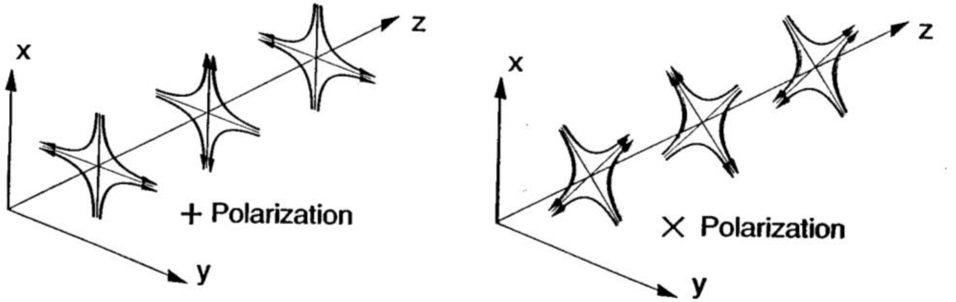
$$=\frac{GMR^2 f^2}{c^4 D}\approx 10^{-22}$$

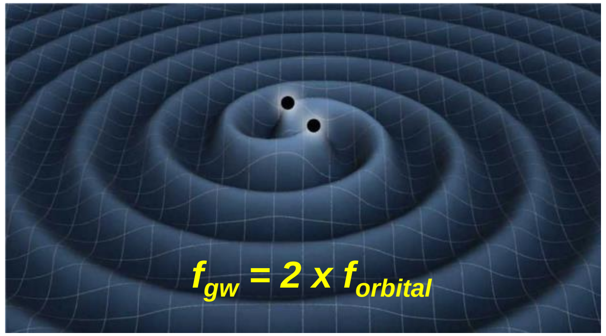
"Like" measuring the distance to the sun to less than the diameter of an atom

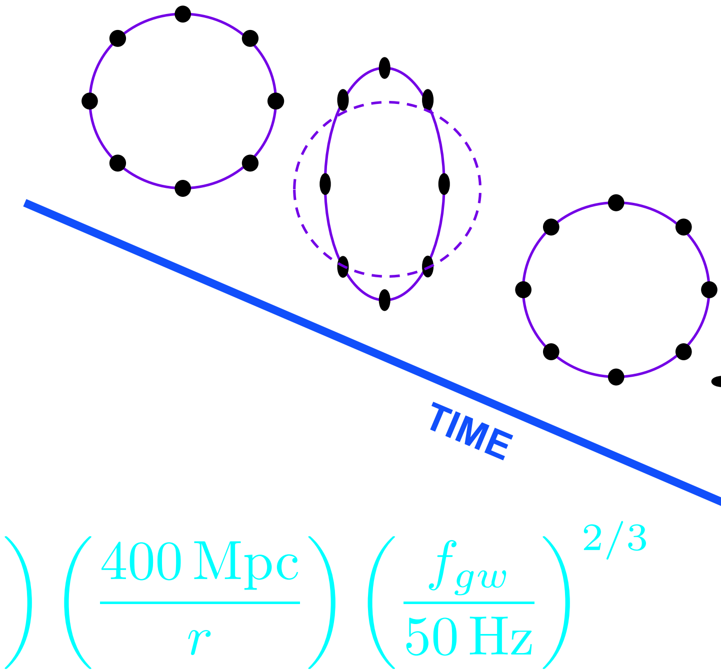
Transverse Quadrupolar Wave

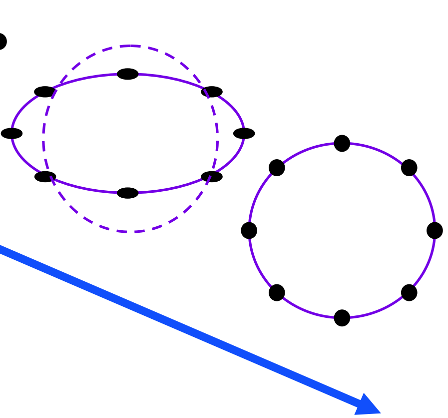
- Gravitational waves are required by all relativistic theories of
  - Sources are accelerated masses
  - Propagation velocity is assumed as c
  - Lowest order source is a quadrupole (general relativity)
- GWs cause geometry/length fluctuations
  - x and + polarizations
- Dimensionless amplitude strain

  h = ΔL/L ~ 10^{-21}
  - $\sim \frac{atomic\ diameter}{earth - sun\ distance} \approx \frac{1\ Angstrom}{150\ Gm}$









metric perturbation

$$h = \frac{2G}{c^4 r}\ddot{I}$$

quadrupole moment

Two masses m in a circular orbit:

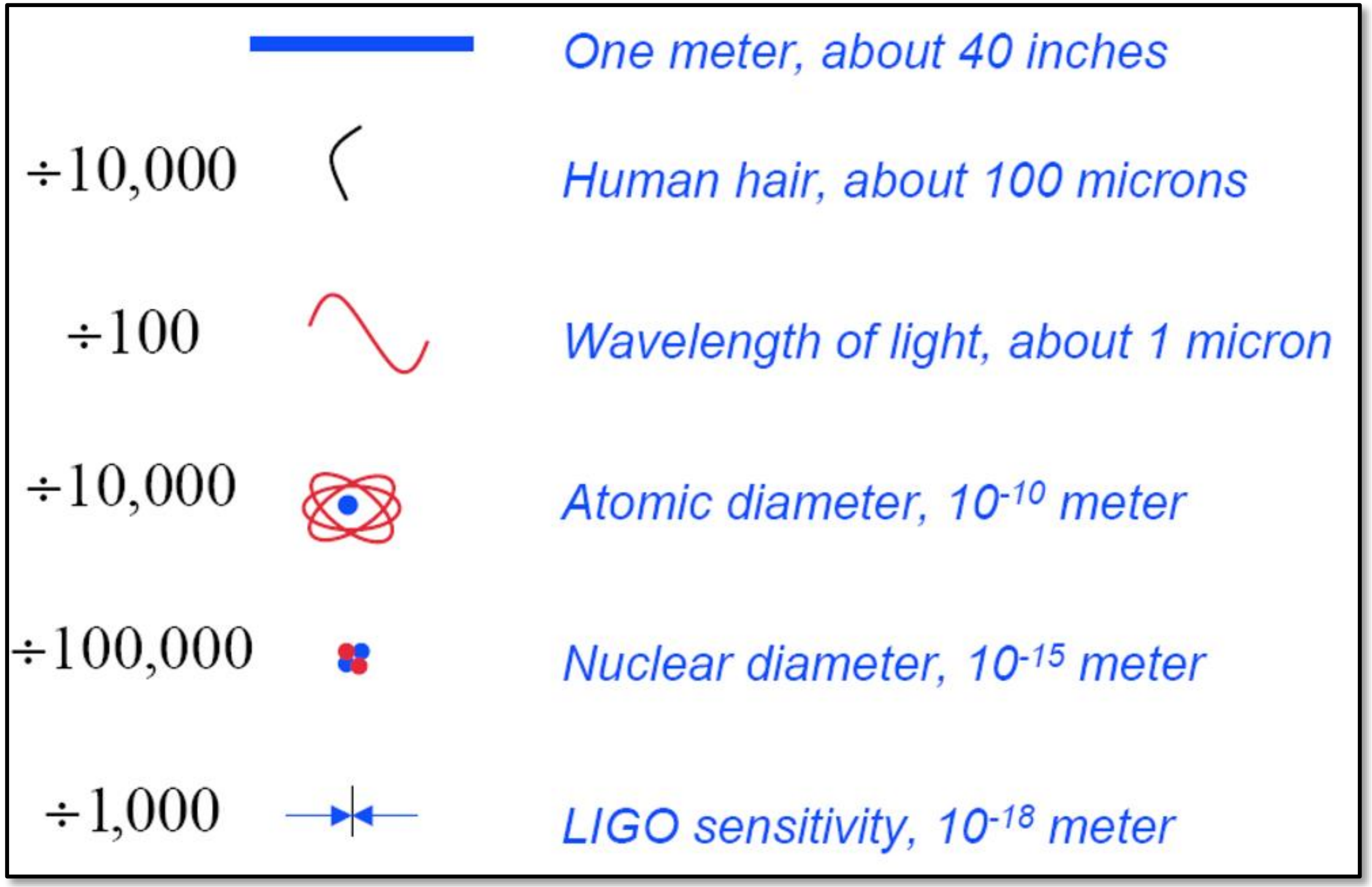
$$h = \frac{2Gm}{c^4 r}(2\pi f_{gw})^{2/3} = 1.5 \times 10^{-21}\left(\frac{m}{30M_\odot}\right)\left(\frac{400\,\mathrm{Mpc}}{r}\right)\left(\frac{f_{gw}}{50\,\mathrm{Hz}}\right)^{2/3}$$

Measurement Challenge

- Needed technology development to measure:

$$h = \Delta L/L < 10^{-21}$$

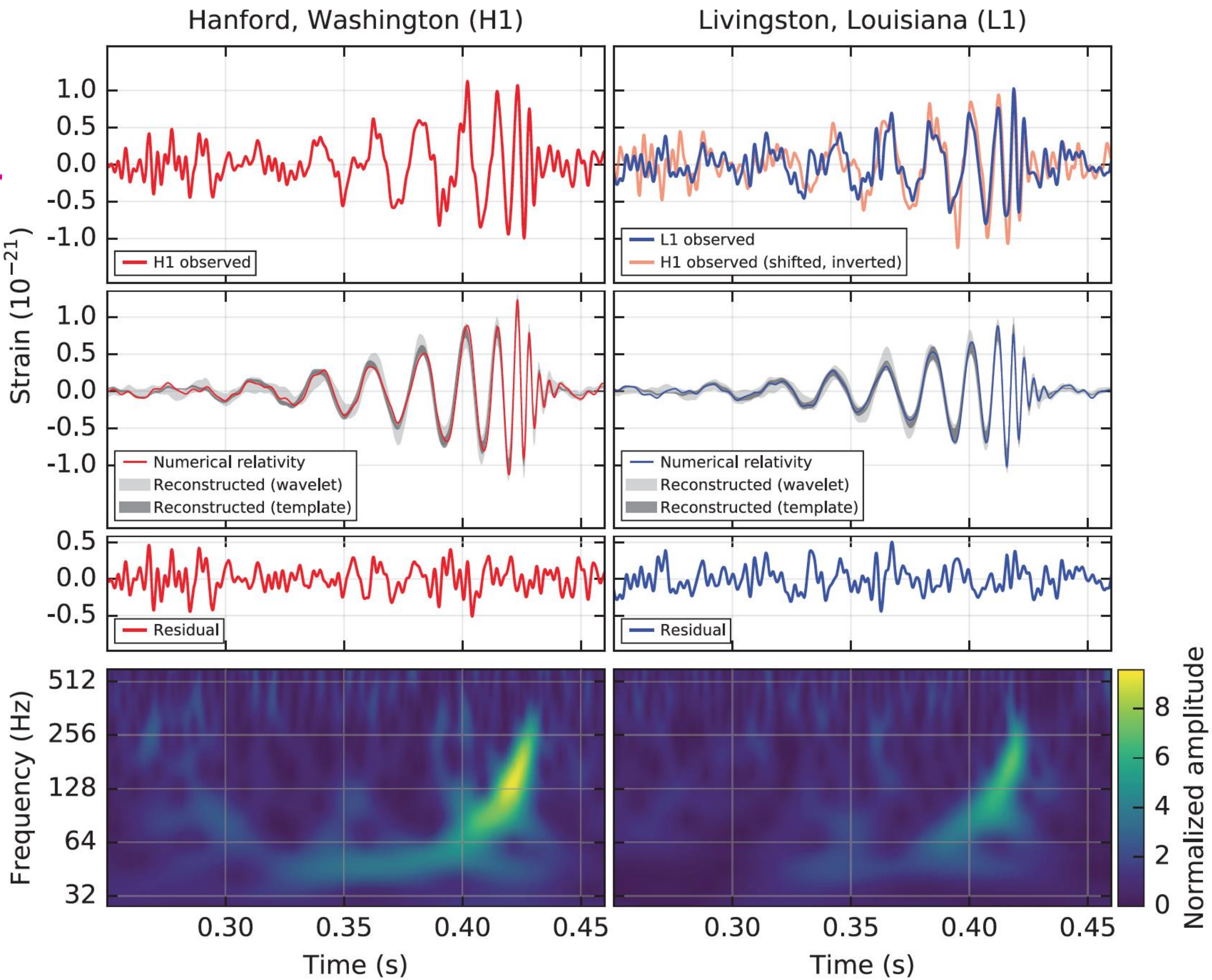
$$\Delta L < 4 \times 10^{-18} \text{ meters}$$

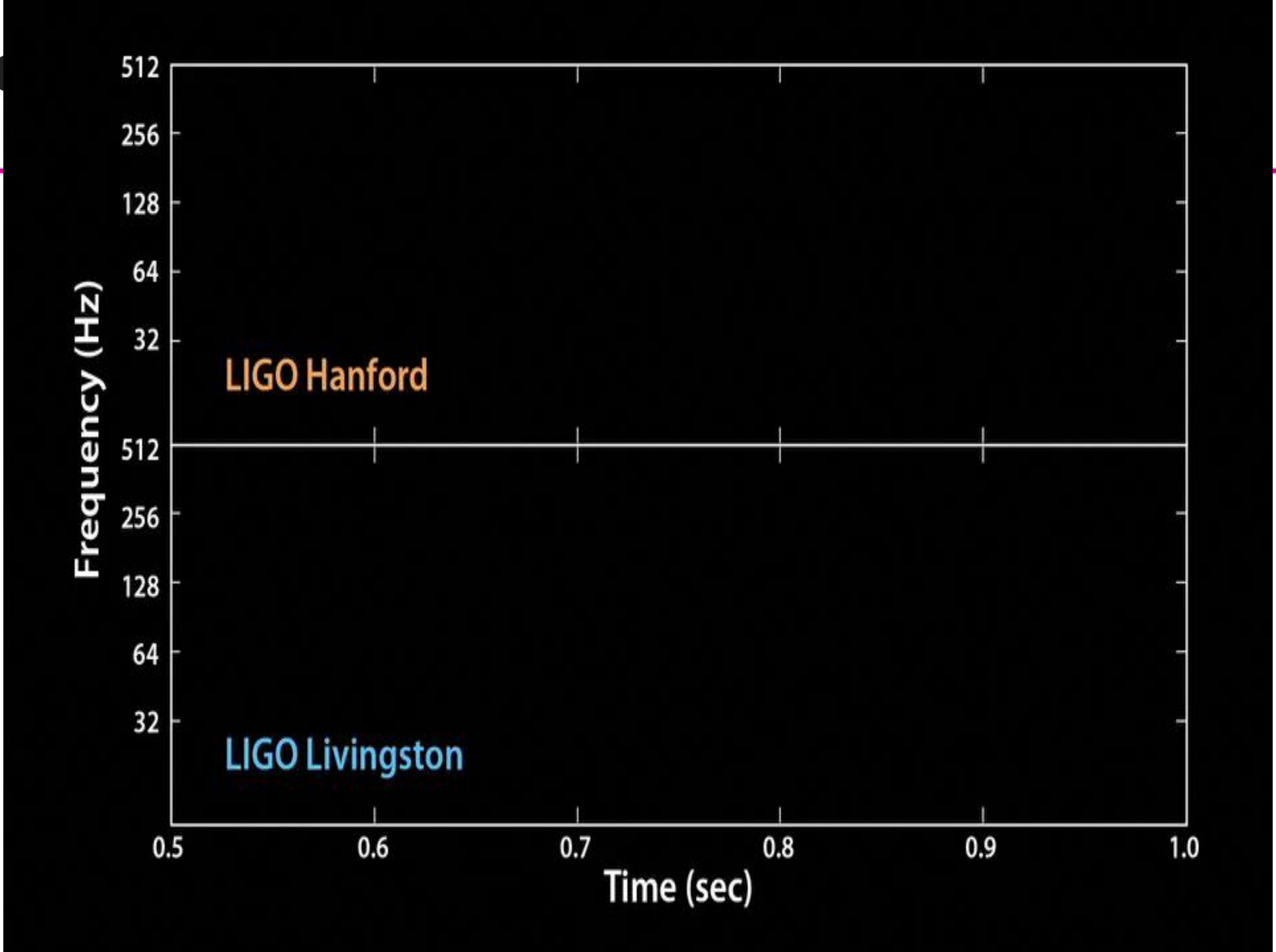


LIGO

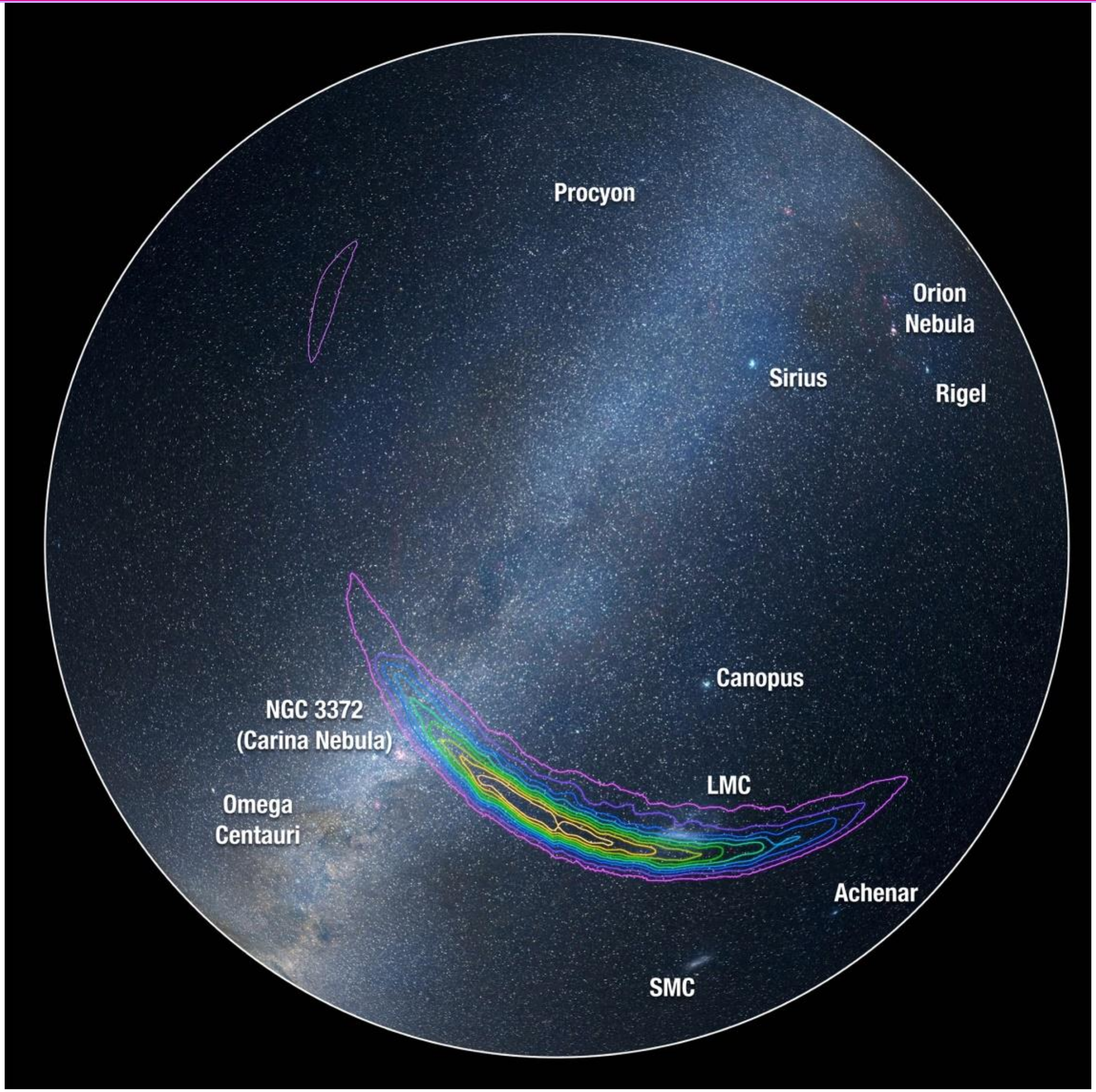
Outline

- Why? (the motivation)
  - Gravitation, Gravitational Waves & Astrophysical Sources
- Detection!
- Who?
  - The team
- How? (the engineering)
  - Basic principles of operation
  - Subsystems
- More about the vacuum system
  - a talk by Jon Feicht
- Tours
  - VORTEX (Vapor Outgassing & Reexposure Text Experiment)
  - 40m Lab – a 100th scale version of LIGO


Hanford, Washington (H1)
Livingston, Louisiana (L1)
H1 observed
L1 observed
H1 observed (shifted, inverted)
Strain (10^{-21})
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Time (s)
Normalized amplitude

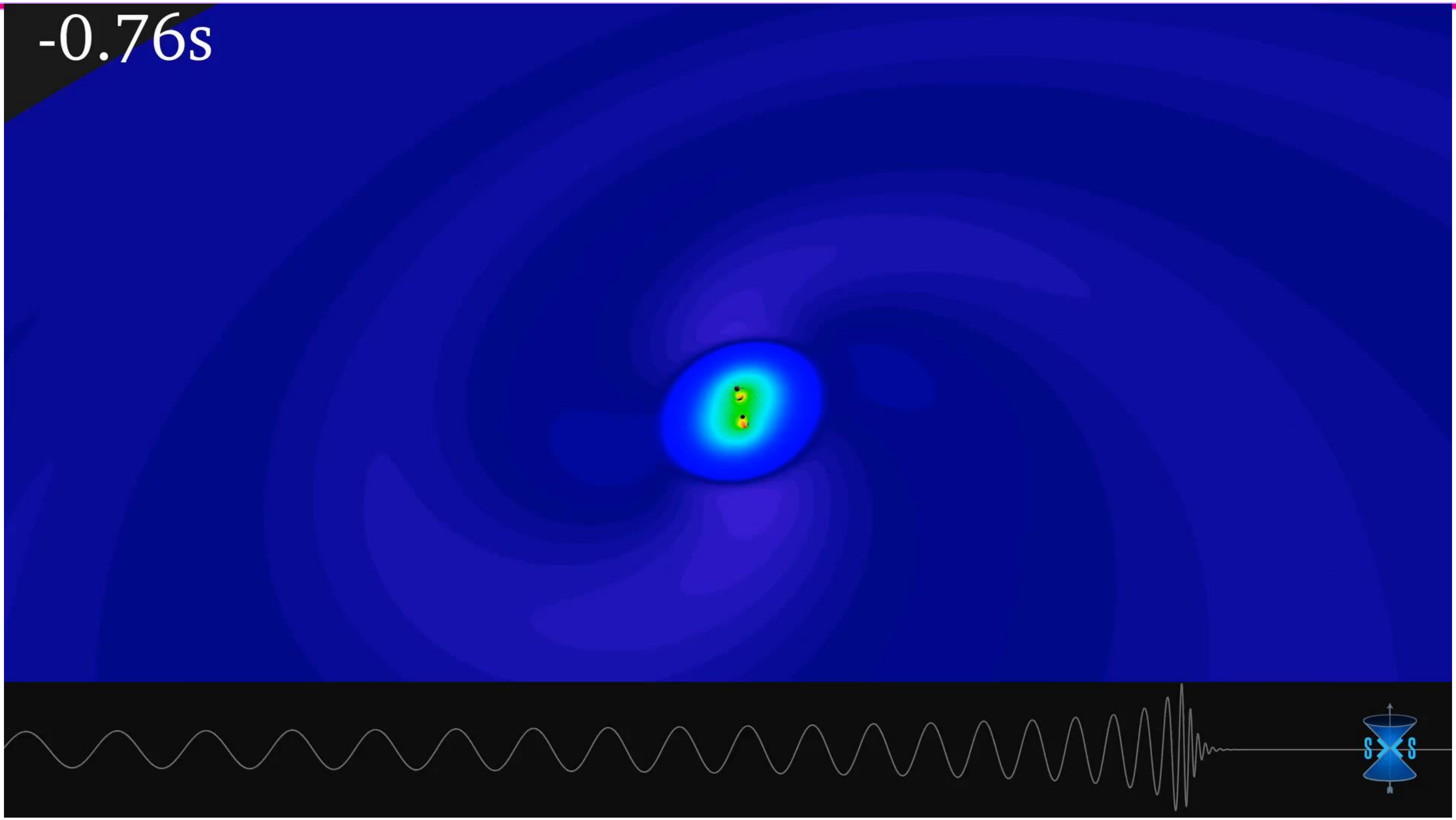

Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

Where was it?



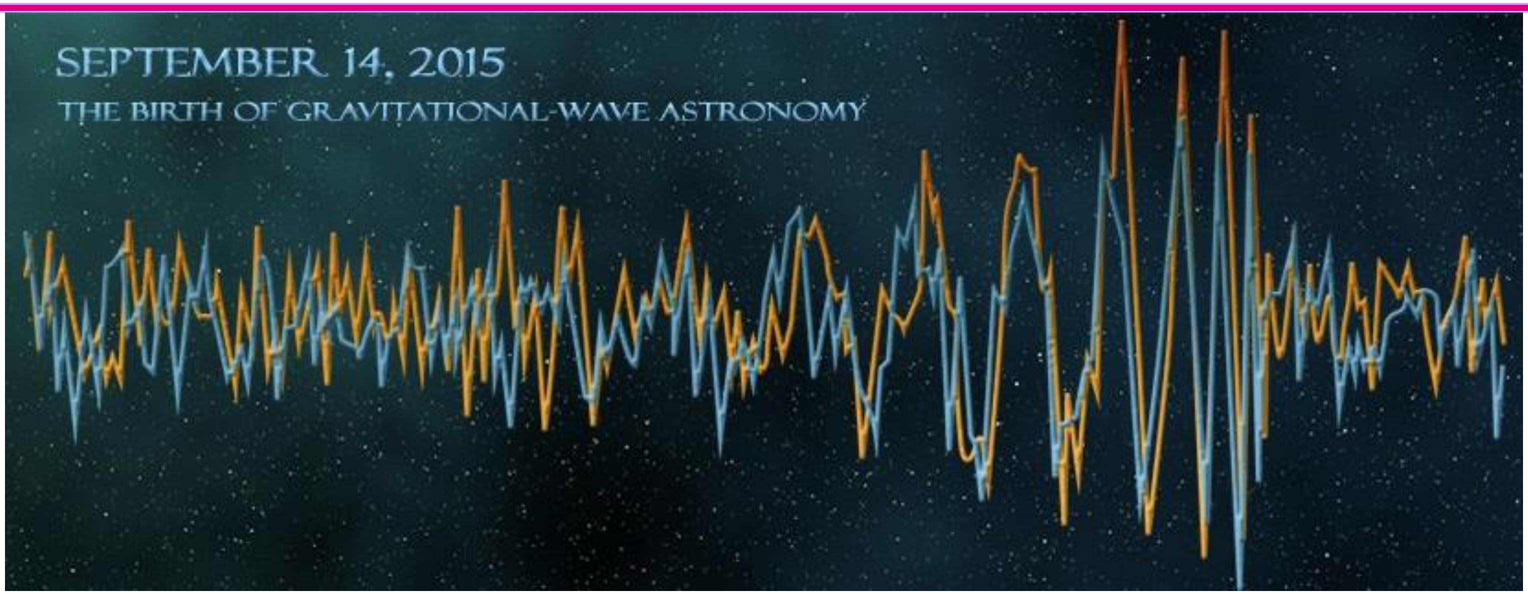
- We can’t localize it very well with only two detectors

Simulating Dynamical Spacetime: Binary Black Hole Merger



Credit: SXS

The First Detection – GW150914



- Initial Black hole masses 36 and 29 Solar masses
- Distance 1.2 Billion light years
- Signal to noise ratio 24, FAR 1 in 203,000 years
- Final Black hole mass 62 solar masses
- Brightness
  - In last 200 msec it was brighter than the rest of the universe
  - In the last 20 msec was 50 times brighter than the rest of the universe
- Agrees with Einstein's General Theory of Relativity

Sounds of Space-Time

LIGO

Outline

- Why? (the motivation)
  - Gravitation, Gravitational Waves & Astrophysical Sources
- Detection!
- Who?
  - The team
- How? (the engineering)
  - Basic principles of operation
  - Subsystems
- More about the vacuum system
  - a talk by Jon Feicht
- Tours
  - VORTEX (Vapor Outgassing & Reexposure Text Experiment)
  - 40m Lab – a 100th scale version of LIGO

LIGO Scientific Collaboration

LIGO

LIGO Laboratory

Caltech

~67 institutions
1523 individuals

The Paper

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].

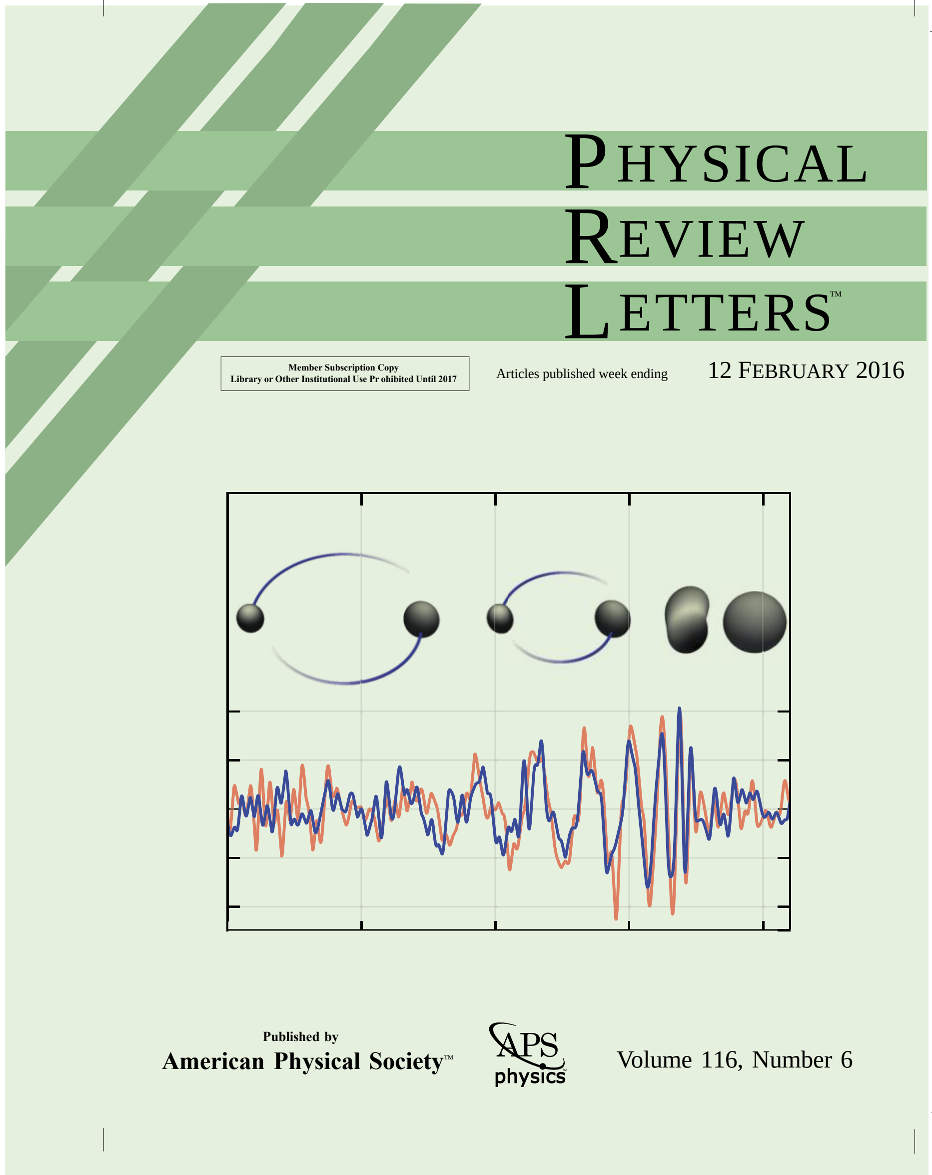
Also in 1916, Schwarzschild published a solution for the field equations [4] that was later understood to describe a black hole [5,6], and in 1963 Kerr generalized the solution to rotating black holes [7]. Starting in the 1970s theoretical work led to the understanding of black hole quasinormal modes [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.

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].

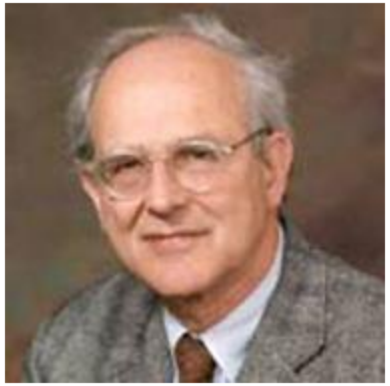
A century after the fundamental predictions of Einstein and Schwarzschild, we report the first direct detection of gravitational waves and the first direct observation of a binary black hole system merging to form a single black hole. Our observations provide unique access to the

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



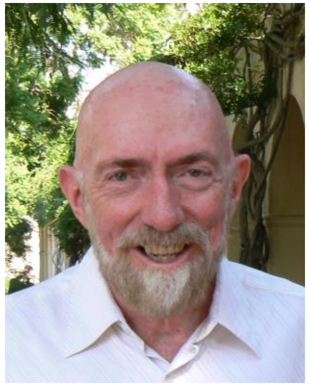
1002 Authors

The “Troika” – originators of LIGO



Rainer Weiss, MIT

Ron Drever, Caltech



Kip Thorne, Caltech

Nominees for the 2016 Nobel Prize in Physics

The NSF and the NSB deserve credit for their vision as well!

The New York Times

New England Edition

Today, sunshine mixing with some clouds, cold, high 26. Tonight, cloudy, a flurry or heavier squall late, low 17. Tomorrow, windy, frigid, high 18. Weather map, Page A18.

FRIDAY, FEBRUARY 12, 2016

$2.50

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most fore-

CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

Long in Clinton's Corner, Blacks Notice Sanders

By RICHARD FAUSSET

ORANGEBURG, S.C. — When Helen Duley was asked whom

Courted Hard in South Carolina, Loyalists

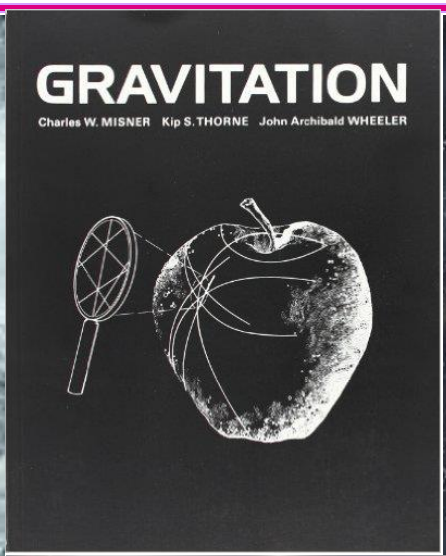
candidate she barely knew. “It makes me feel good,” she said, chuckling, “that young people are listening to the elderly people.” She now said she was an un-

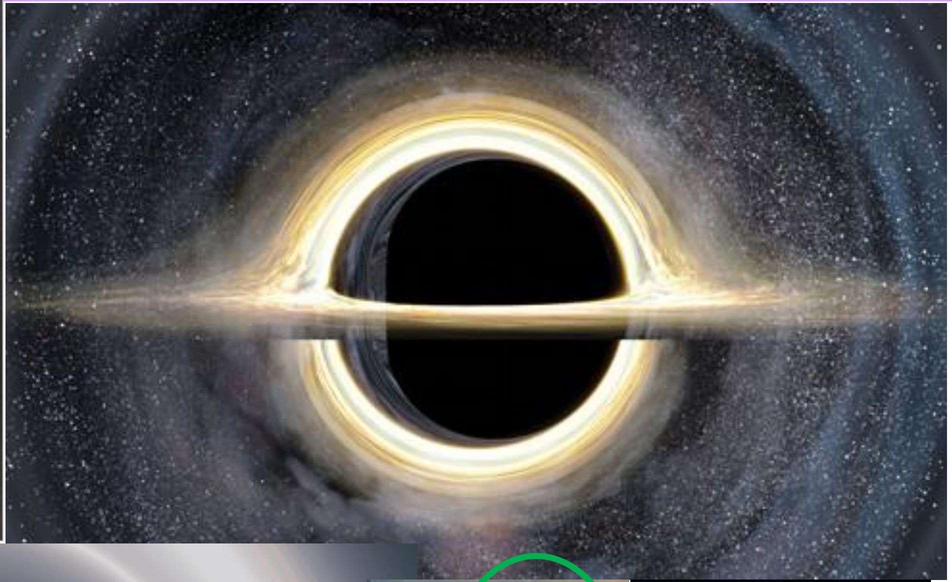
Last Occupier Is Coaxed From Oregon Refuge

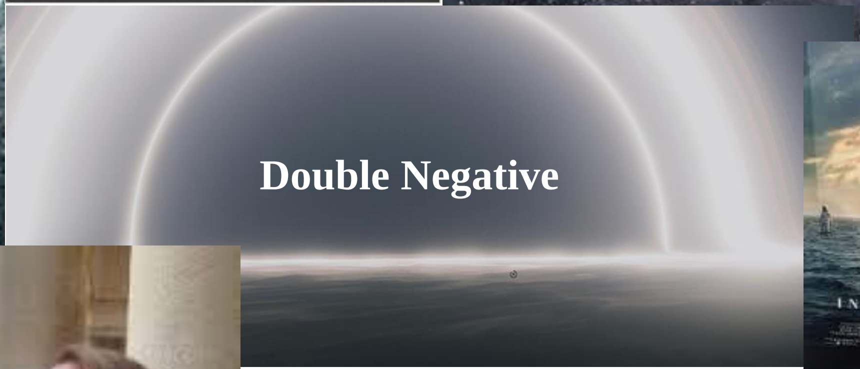
“Me”

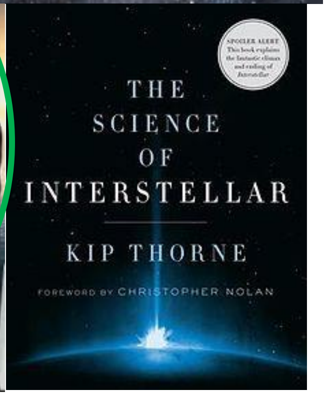
(asserted by all of us who worked in chambers!)

Interstellar







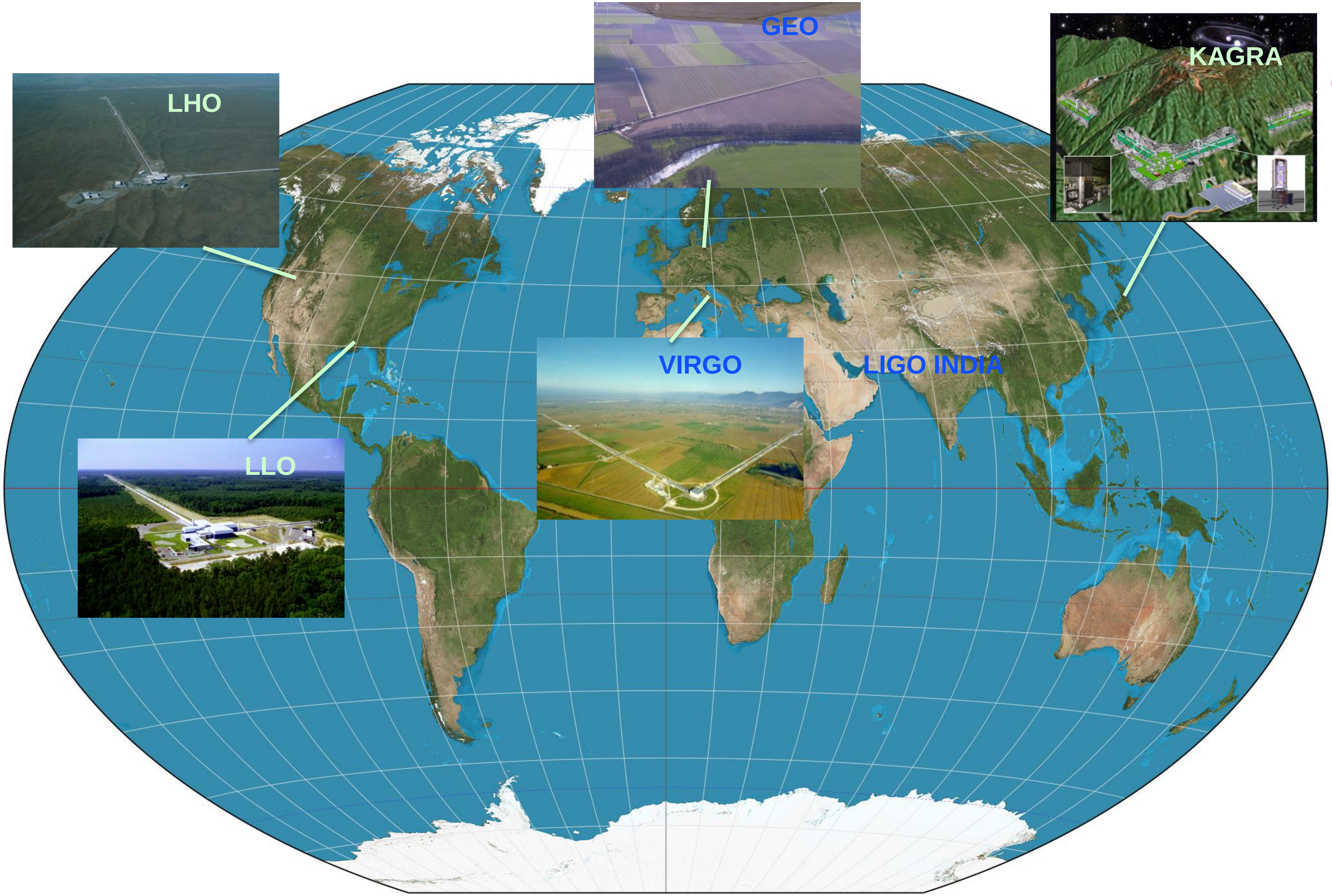


IMDb

Christopher Nolan	Producer
Lynda Obst	Producer
Debbie Schwab	Supervising Producer
Inga Bjork Solnes	Coordinating Producer
Emma Thomas	Producer
Kip Thorne	Executive Producer

Kip Thorne was one of the LIGO originators

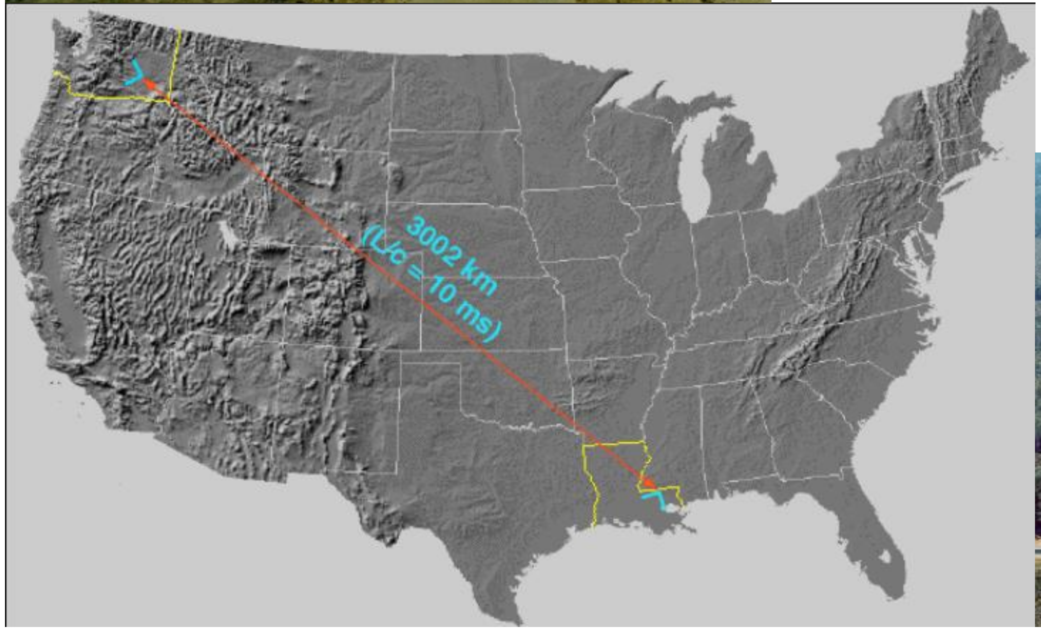
Building a Global Network



LIGO Interferometers

- Interferometers are aligned to be as close to parallel to each other as possible
- Observing signals in coincidence increased the detection confidence
- Determine source location on the sky, propagation speed and polarization of the gravitational wave

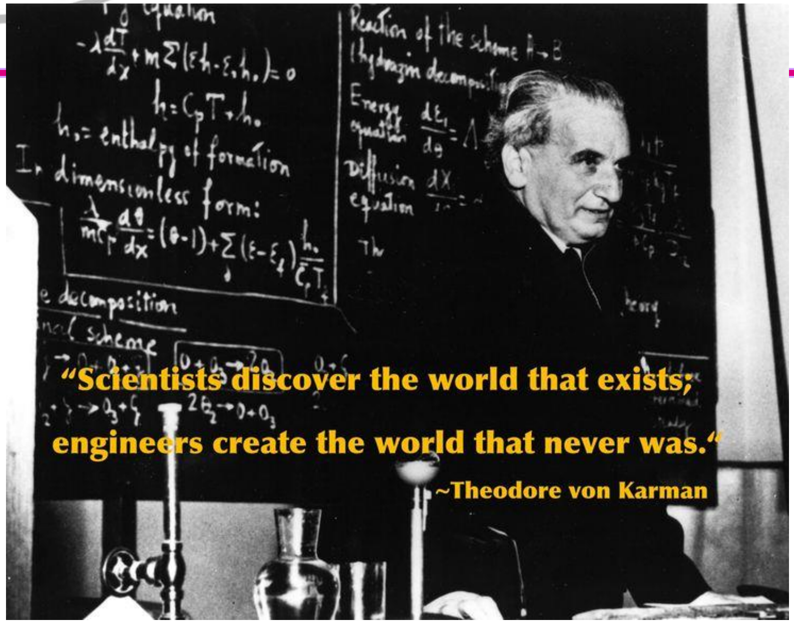
Hanford Nuclear Reservation, Eastern WA (H1 4km)

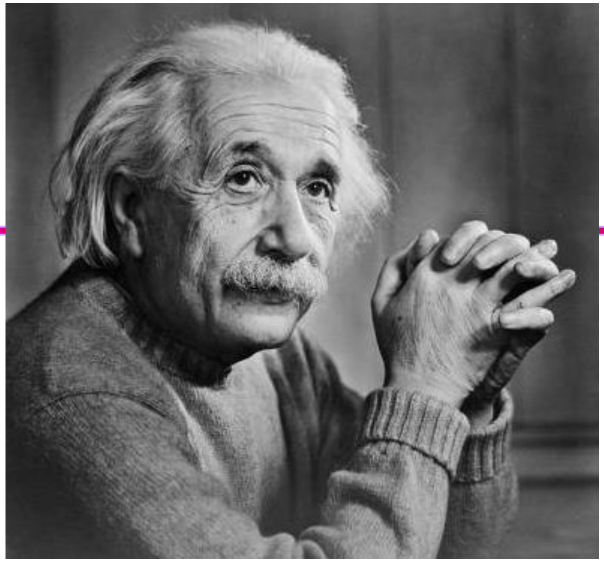


Livingston, LA (L1 4km)

Outline

- Why? (the motivation)
  - Gravitation, Gravitational Waves & Astrophysical Sources
- Detection!
- Who?
  - The team
- How? (the engineering)
  - Basic principles of operation
  - Subsystems
- More about the vacuum system
  - a talk by Jon Feicht
- Tours
  - VORTEX (Vapor Outgassing & Reexposure Text Experiment)
  - 40m Lab – a 100^{th} scale version of LIGO





…such ripples would be "vanishingly small" and nearly impossible to detect.

SCIENTISTS DREAM ABOUT DOING GREAT THINGS. ENGINEERS DO THEM.

James A Michener

"A good scientist is a person with original ideas. A good engineer is a person who makes a design that works with as few original ideas as possible. There are no prima donnas in engineering."

Freeman Dyson

"I don't spend my time pontificating about high-concept things; I spend my time solving engineering and manufacturing problems."

Elon Musk

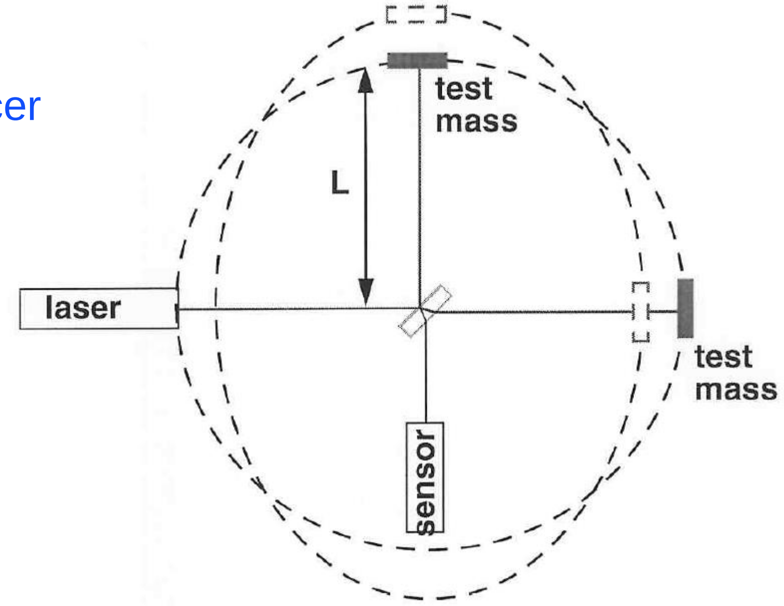
"Don't undertake a project unless it is manifestly important and nearly impossible"
Edwin H. Land

What we usually consider as impossible are simply engineering problems... there's no law of physics preventing them.

Michio Kaku

Basic Concepts

- Optical Interferometery
  - A Michelson interferometer is an ideal transducer for a transverse quadrupolar strain wave
    → two orthogonal arms
  - Laser frequency fluctuations
    → equal arm lengths
  - Minute strain
    → long arms
    (~4km as a practical civil engineering limit for earth curvature)
  - Optical interferometry allows measuring 0.01 nrad of optical phase
  - Optically resonant cavities can amplify the phase shift by ~200x
- Audio frequency measurement
  - Where ground motion is small (and further attenuated by isolators)
- Avoid thermal noise ($k_B T$)
  - Select low loss materials
  - Measure away from mechanical resonances

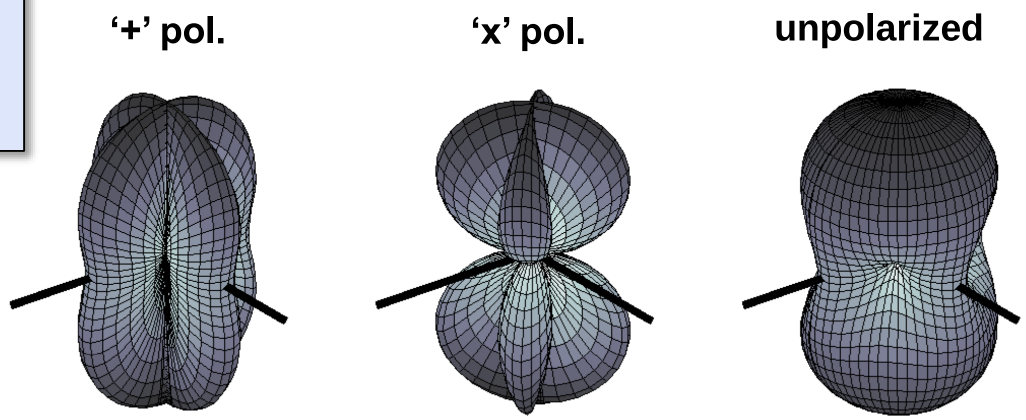


Interferometer Response Function:

$$\delta\varphi = h\frac{\omega L}{c}2\,\mathrm{sinc}\left(\frac{\Omega L}{c}\right)$$

where
$\delta\varphi$ = optical light phase change
ω = laser frequency
Ω = GW frequency
c = speed of light
h = strain amplitude
L = arm length

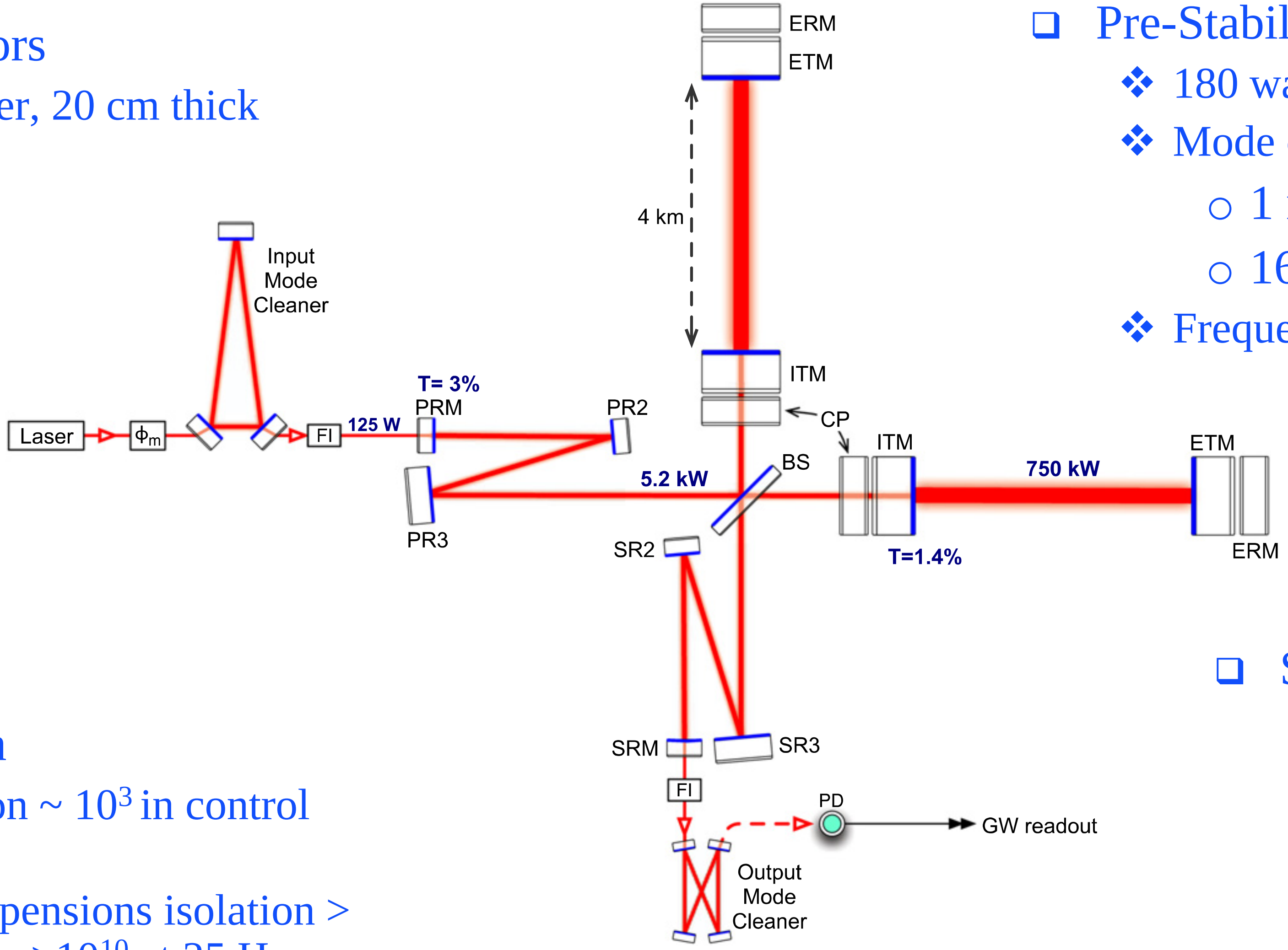
The Michelson Interferometer as a Receiving Antenna – almost omnidirectional



Advanced LIGO Laser Interferometry

- Core Optic Mirrors
  - 34 cm Diameter, 20 cm thick
  - 40 Kg
  - R=99.9996

- Pre-Stabilized Laser
  - 180 watts, Power Recycled
  - Mode cleaning cavity
    - 1 meter table top
    - 16 meter suspended
  - Frequency and Amplitude Stabilized



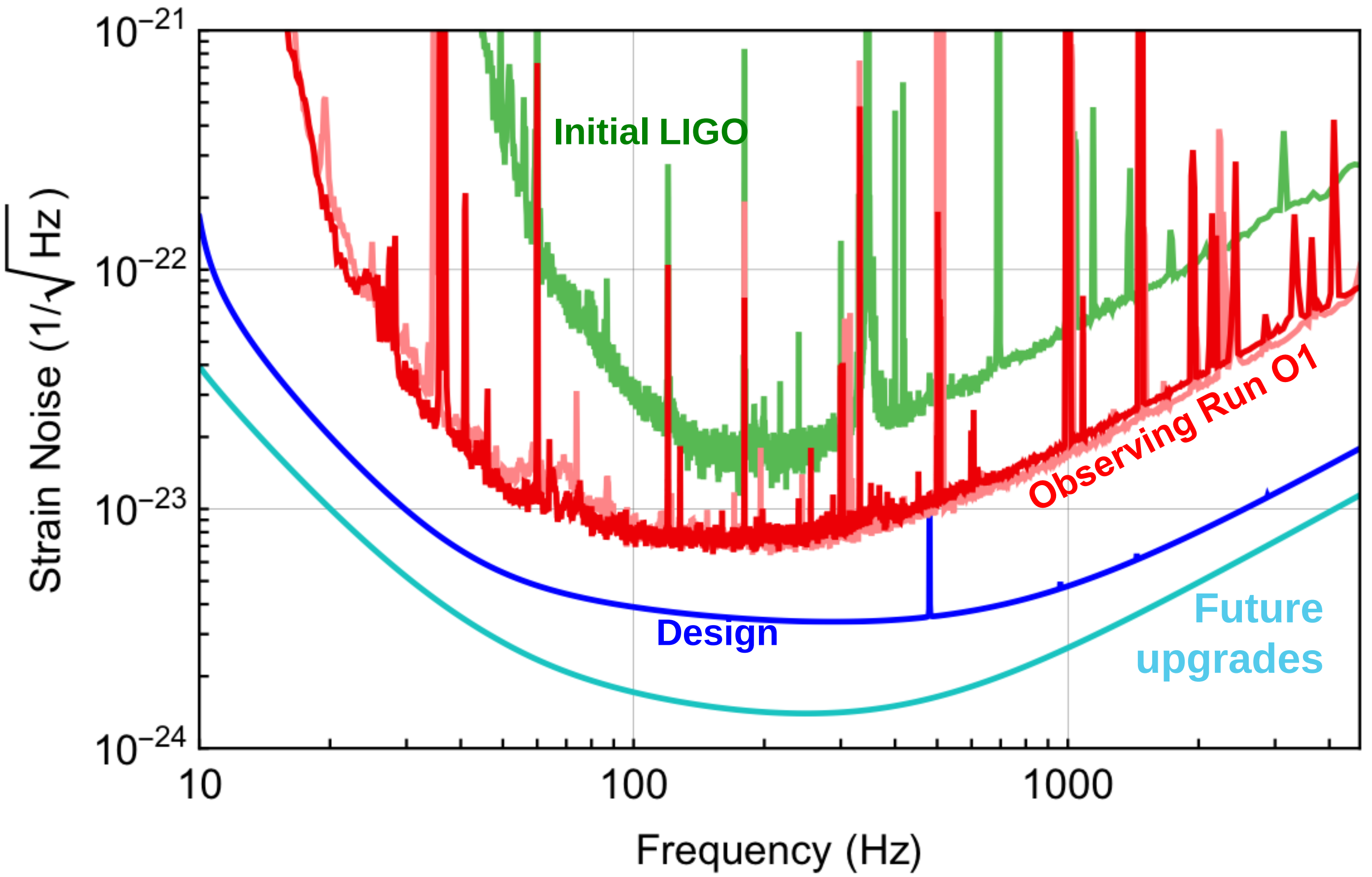
- Seismic Isolation
  - Active Isolation ~ 10^3 in control band
  - Pendulum Suspensions isolation > $3x10^6$ at 10 Hz, >10^{10} at 25 Hz

- Signal Readout
  - Output mode cleaner
  - DC Homodyne
  - Circulating Power 800 kW
  - Signal Recycled

Steps leading to strain measurement of 10^{-23}

- Ability to measure small strains
  - Frequency and amplitude stabilized high power lasers operating at the quantum limit
  - Tailored quantum states to modify momentum and phase noise – "squeezed " light
  - Low loss optics – a few ppm
- Ability to diagnose instrument performance by correlation techniques – digital control and filtering
- Ability to reduce 10^{14} bytes of data per year in the data analysis for gravitational wave signatures
- Ability to reduce stochastic forces
  - Feedback and feed forward from inertial references – reduction in seismic noise
  - Low mechanical loss suspensions and optics with few mechanical resonances in the gravitational wave band - reduction of thermal noise by noise "free" feedback damping.

Advanced LIGO Performance

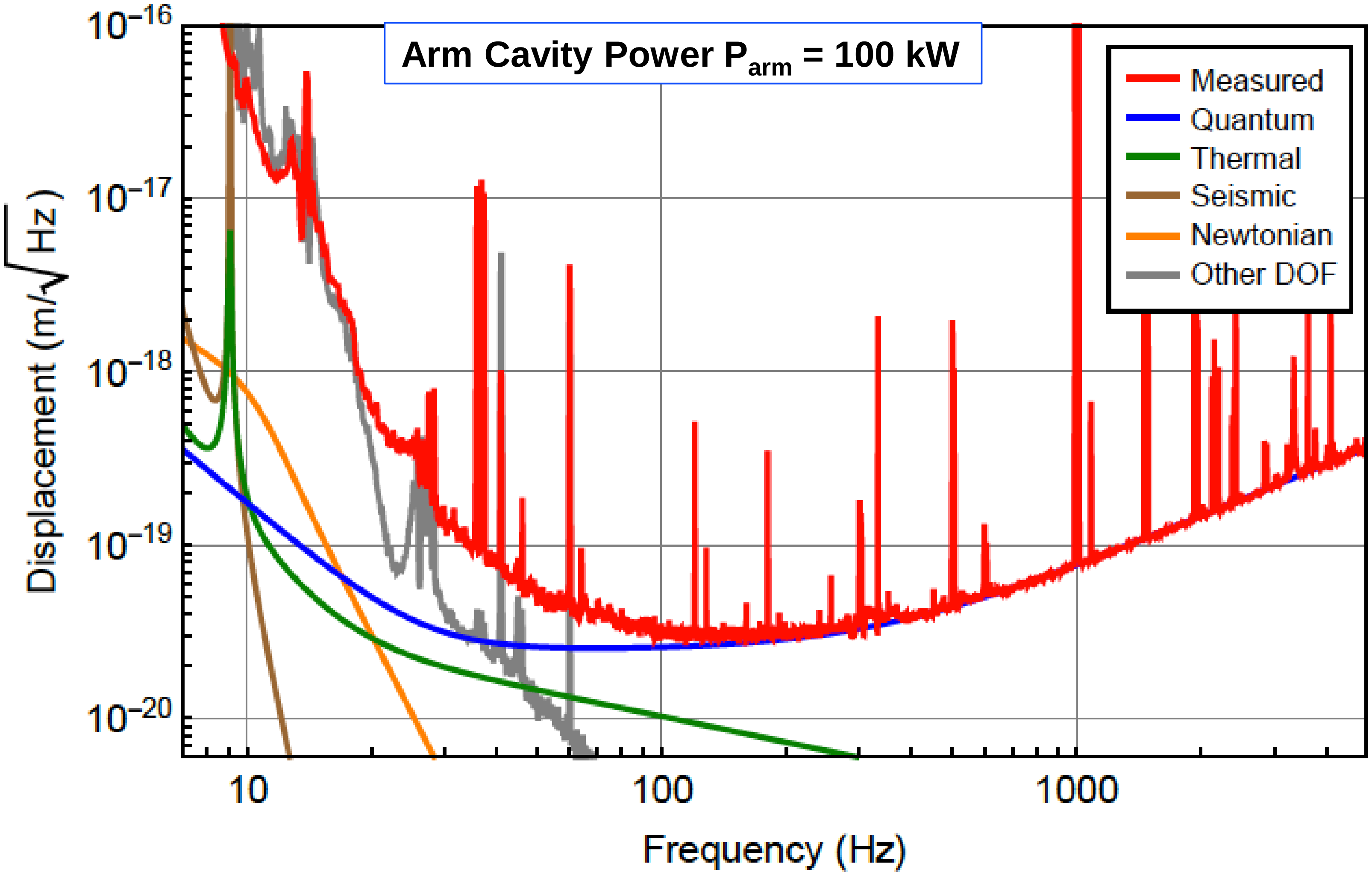


Binary neutron star inspiral range: 70-80 Mpc

RMS strain noise: 1×10^{-22}

GW150914: The Advanced LIGO Detectors in the Era of First Discoveries (Phys. Rev. Lett. 116, 131103)

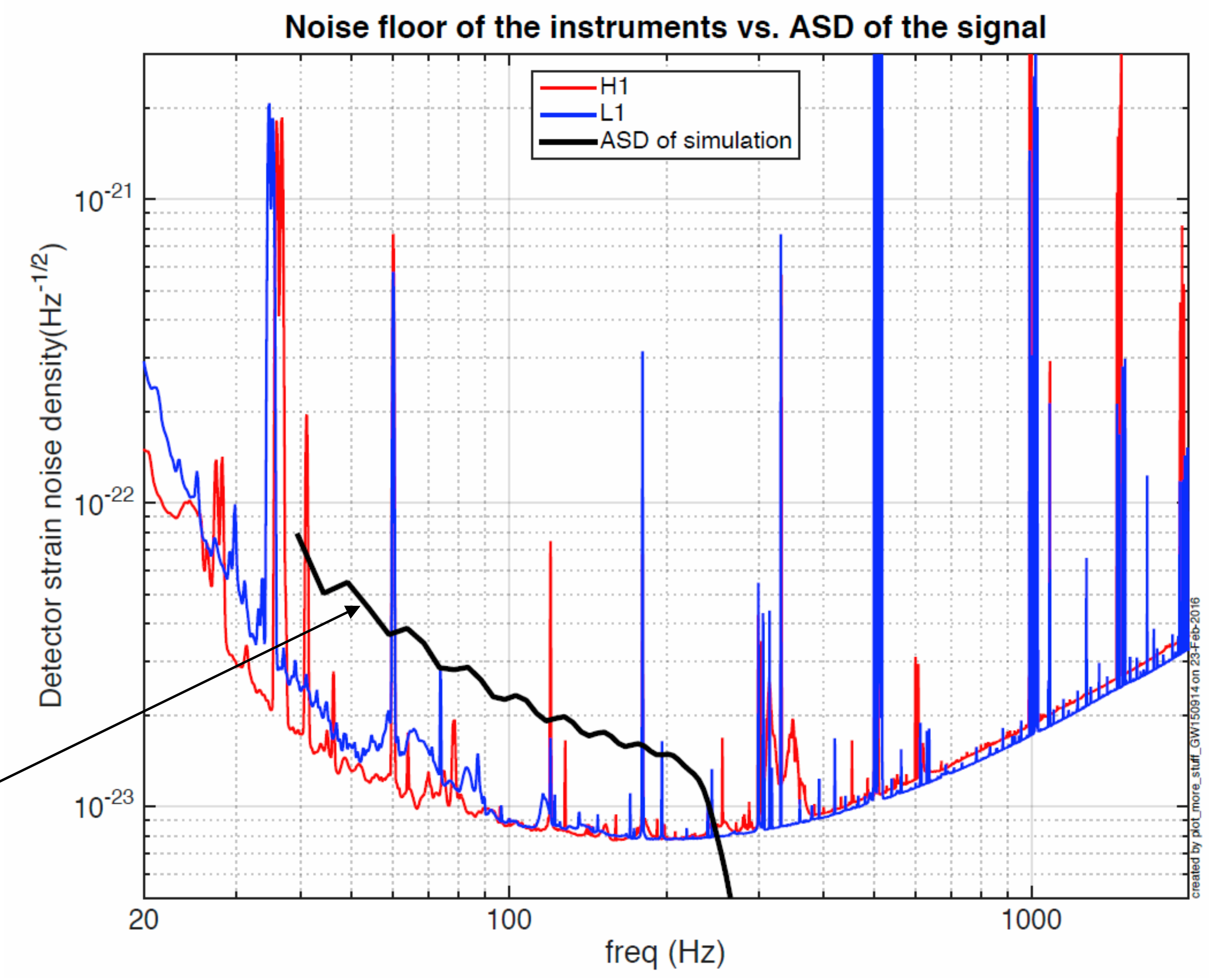
Advanced LIGO Detector Sensitivity During the first observing run (O1)



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).

The Discovery BH-BH Chirp Signal compared to the Instrument Sensitivty

First Observation Run (O1) Instrument Strain Sensitivity



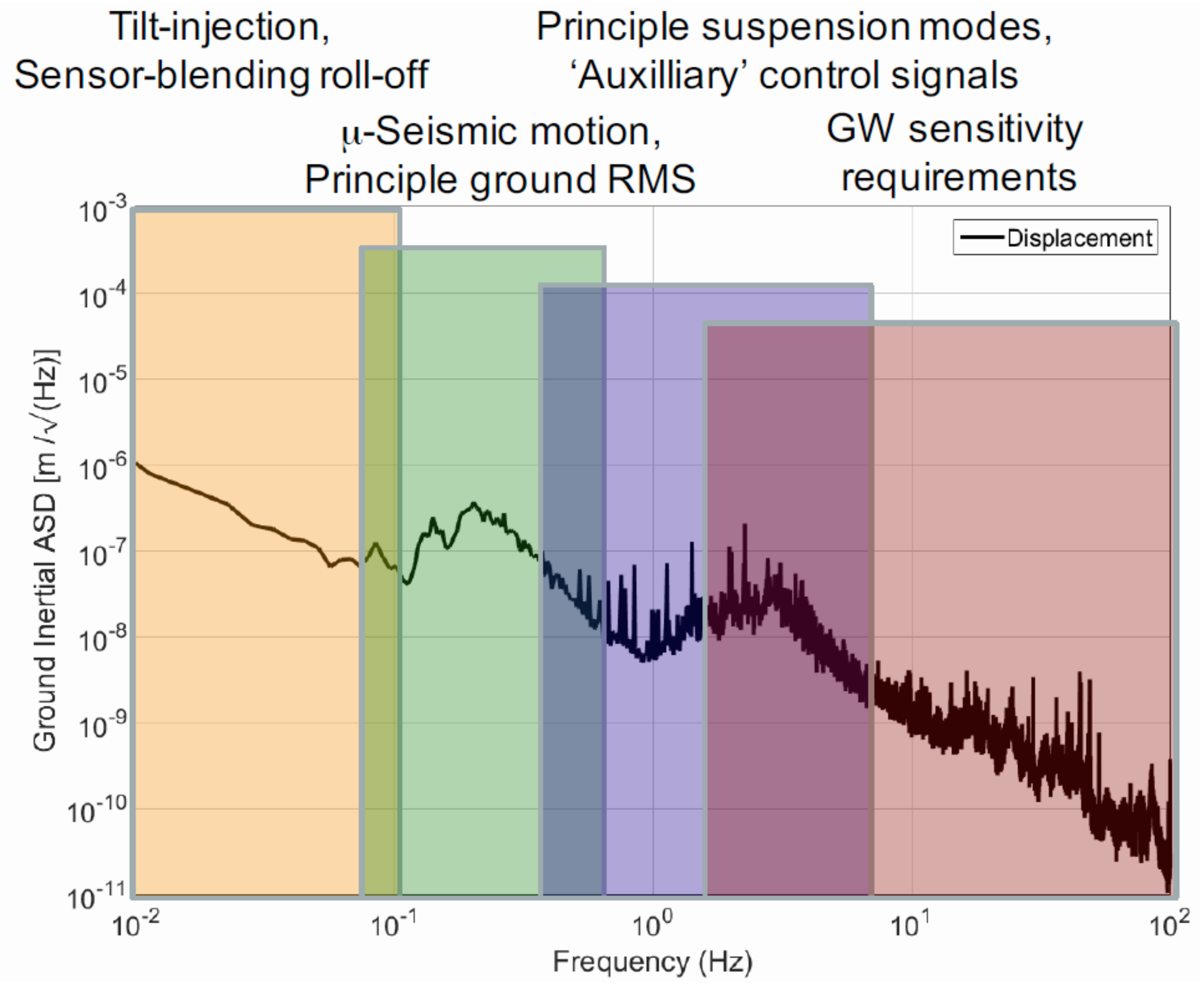
Amplitude Spectral Density (ASD) of the Chirp Signal

Important seismic frequency region: 10mHz – 100Hz

- Ground Motion at 10 [Hz] ~ 10^{-9} [m/rtHz]

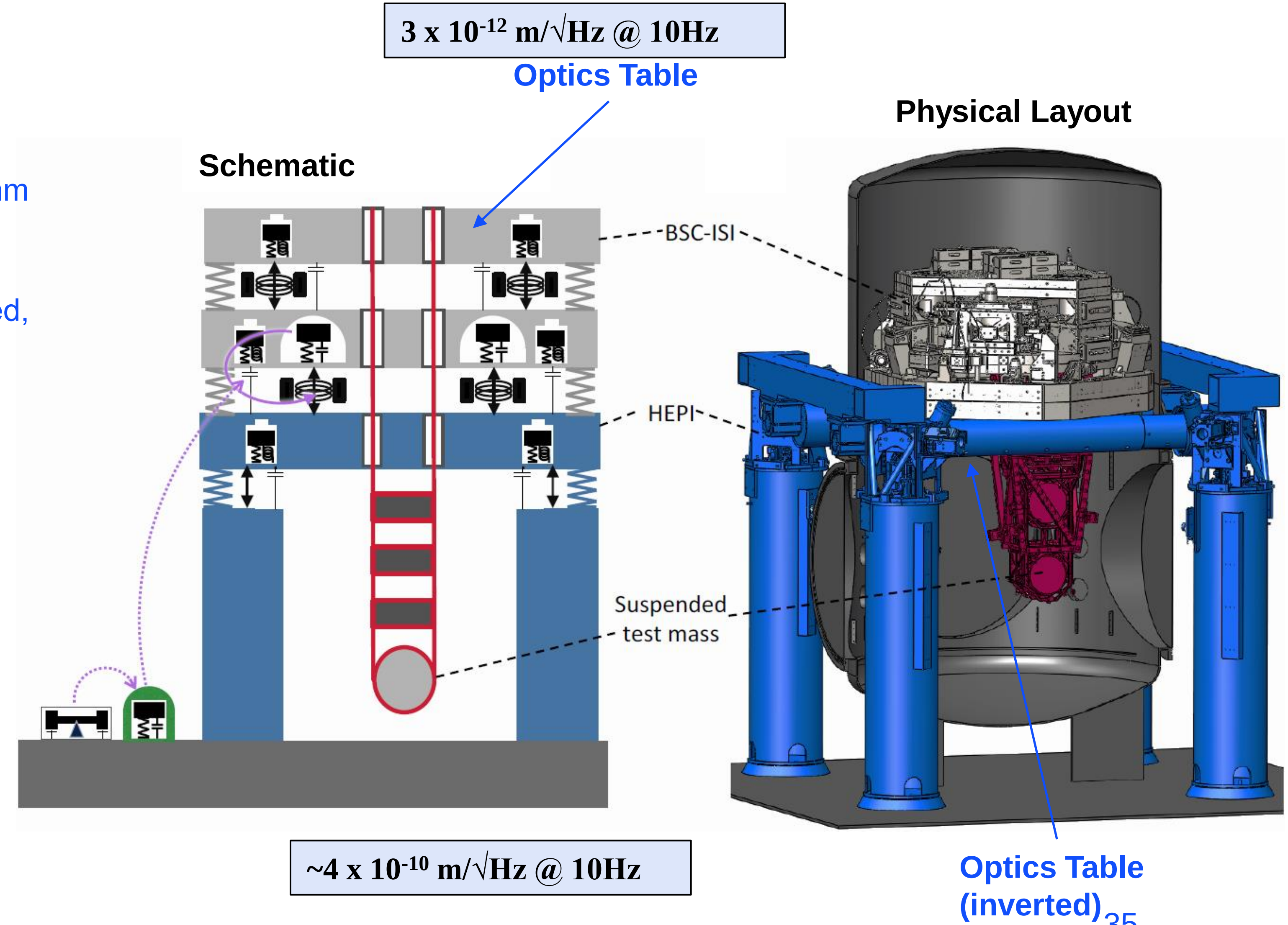
$$\Delta L = h\, L \sim 10^{-19}\, m / Hz^{1/2}$$

- Need 10 orders of magnitude reduction in seismic motion at 10 Hz

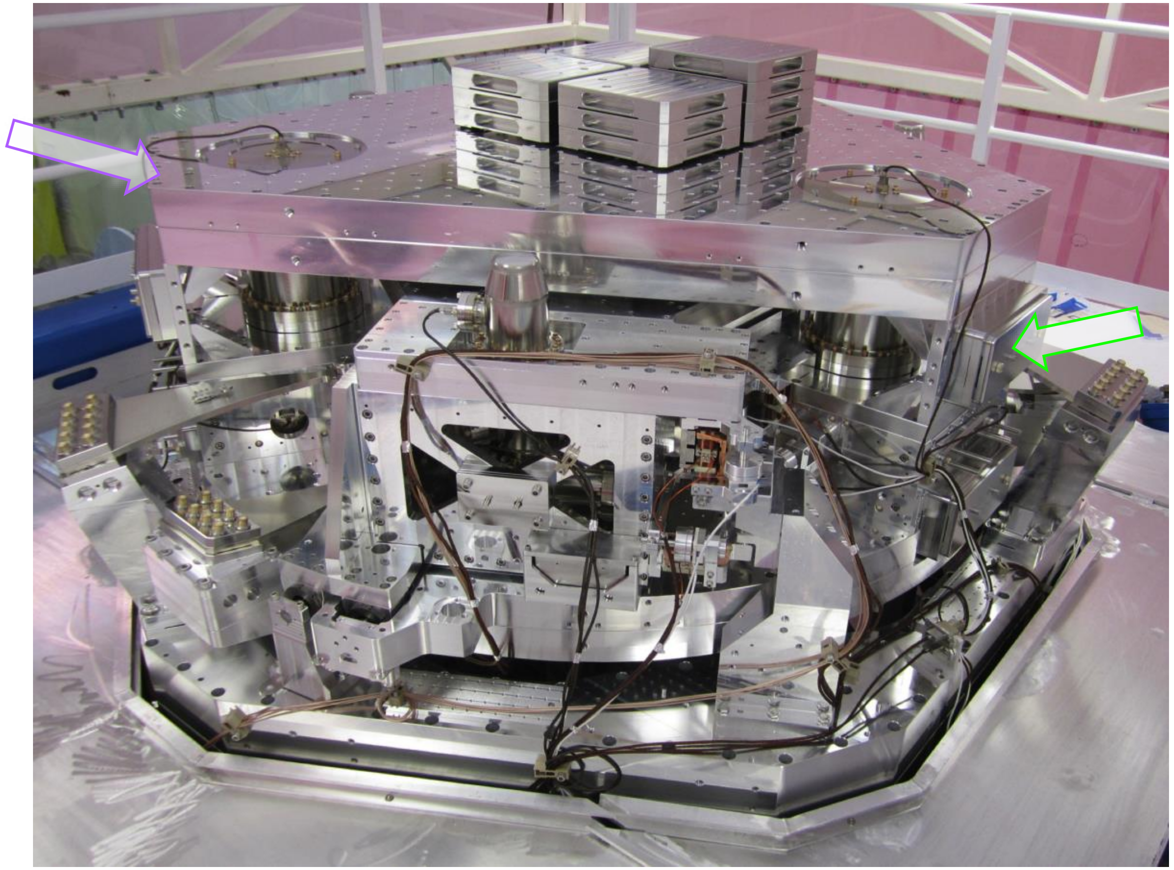


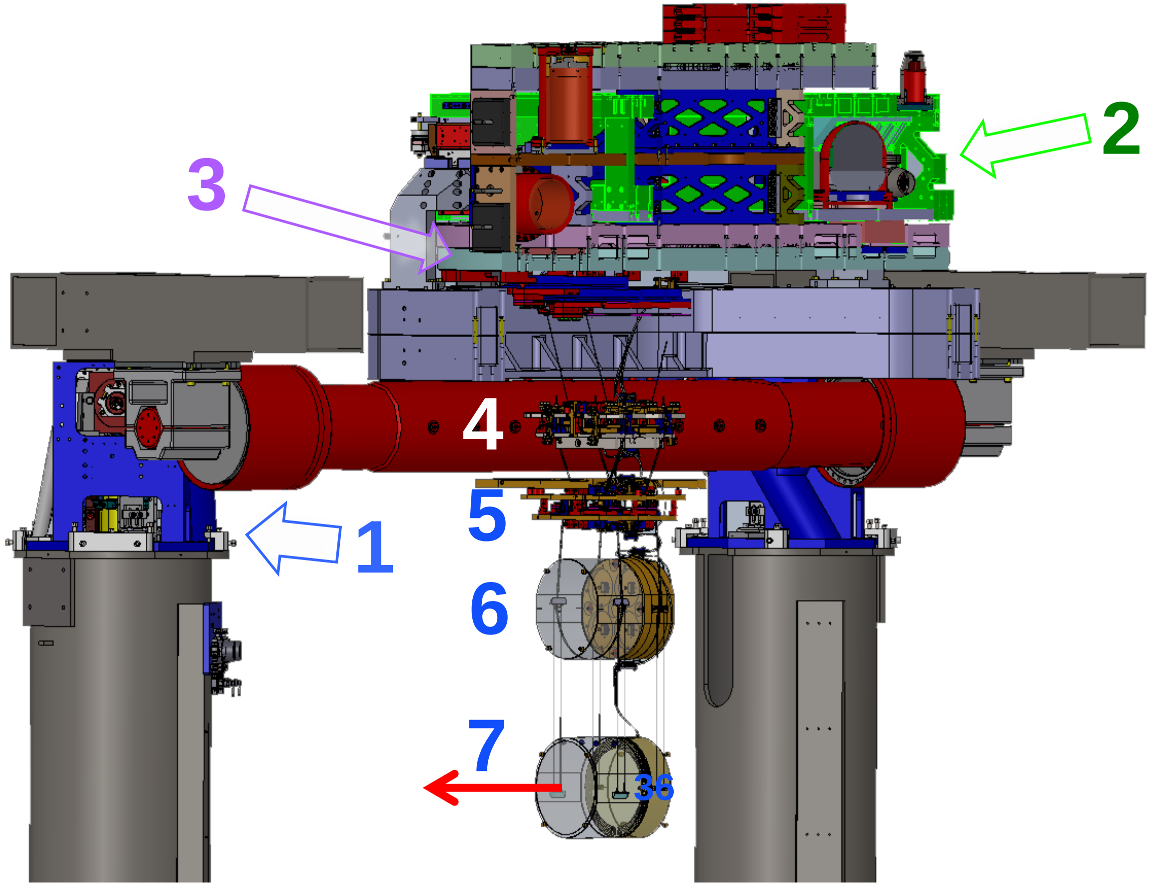
Seismic Isolation & Alignment Systems

- 7 sequential stages of active & passive isolation for the “Test Mass Optics”
- 3 stages to the “optics table”, each 6 dof
  - Exo-vacuum quiet hydraulic pre-isolator with 1 mm dynamic range, inductive position sensors & seismometers
  - Next 2 stages are “hung” on sets of 3 cantilevered, maraging steel springs and flexures (1.3 – 7 Hz)
  - Custom electro-magnetic actuators
  - Low noise, capacitive position sensors and seismometers
  - MIMO feed-back & feed-forward control includes ground tilt and seismometer sensors, 30 Hz BW
  - 1100 kg payload
- The quadruple suspension system comprises the next 4 stages from the “optics table” to the “Test Mass Optic”
- Isolation Systems also provide angular & length alignment/positioning actuators, guided by interferometric sensing



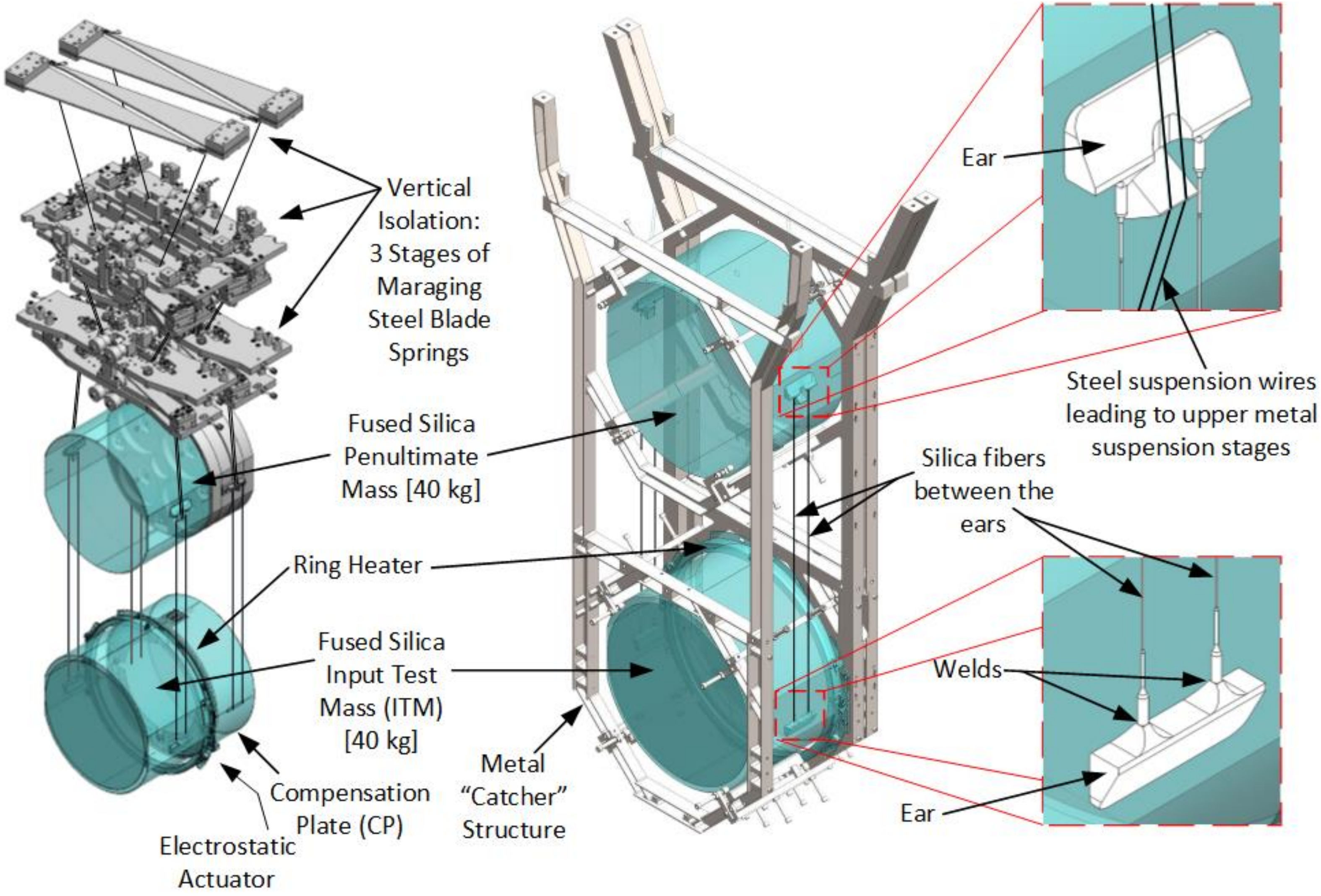
Seismic Isolation



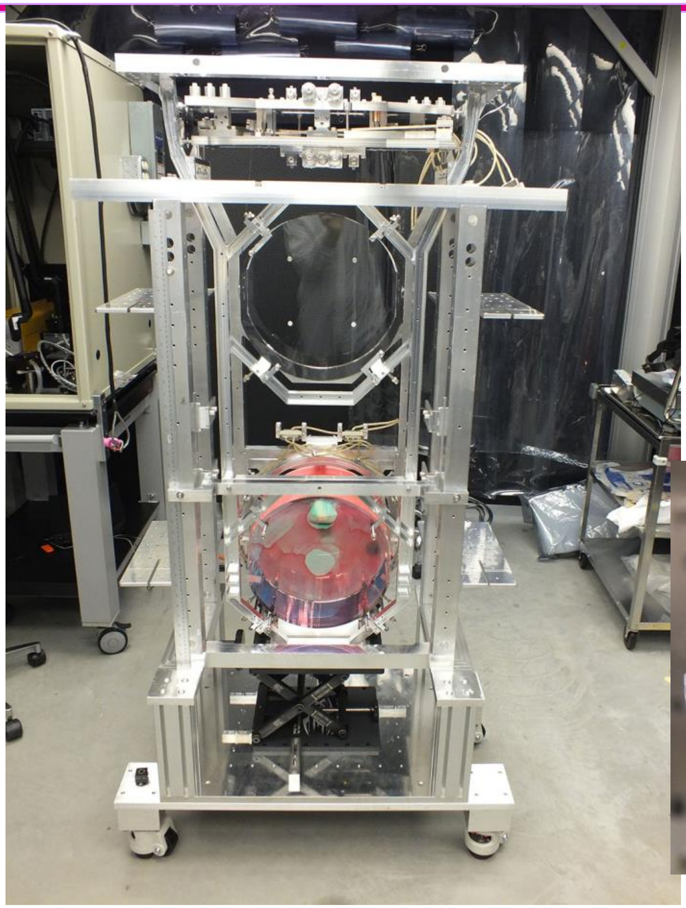


Quadruple Suspension Systems

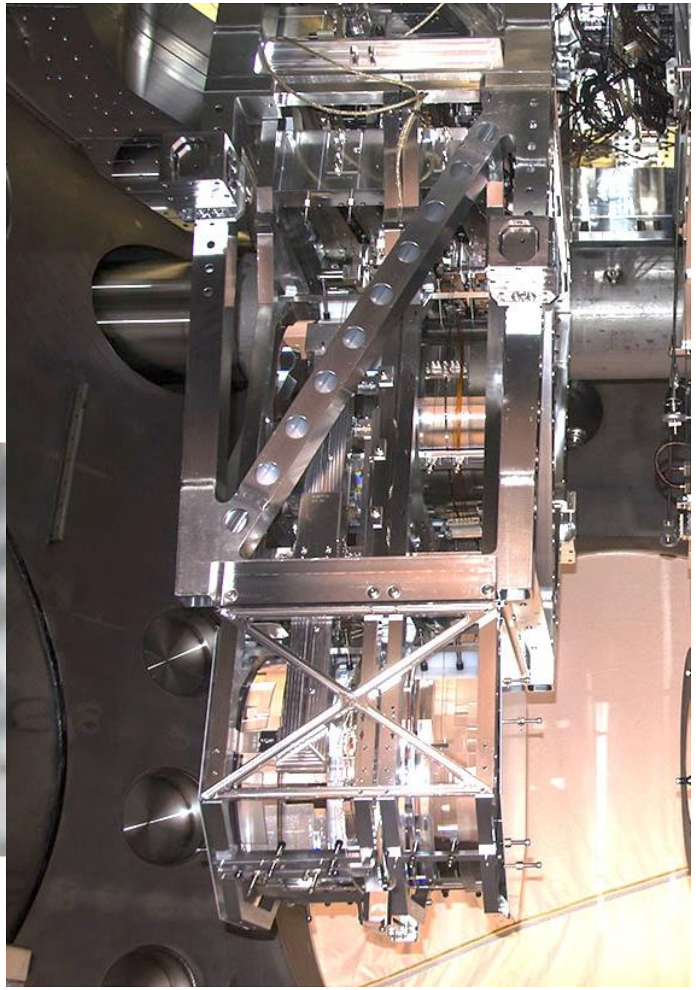
Last two stages are monolithic to improve Brownian noise



Quadruple Pendulums Suspend and Isolate the Test Masses



- Silica Ear Sodium Silicate Bonded to Mirror Substrate
- Horn (3 mm) for fiber welding
- 0.4 mm x 600 mm long silica fiber



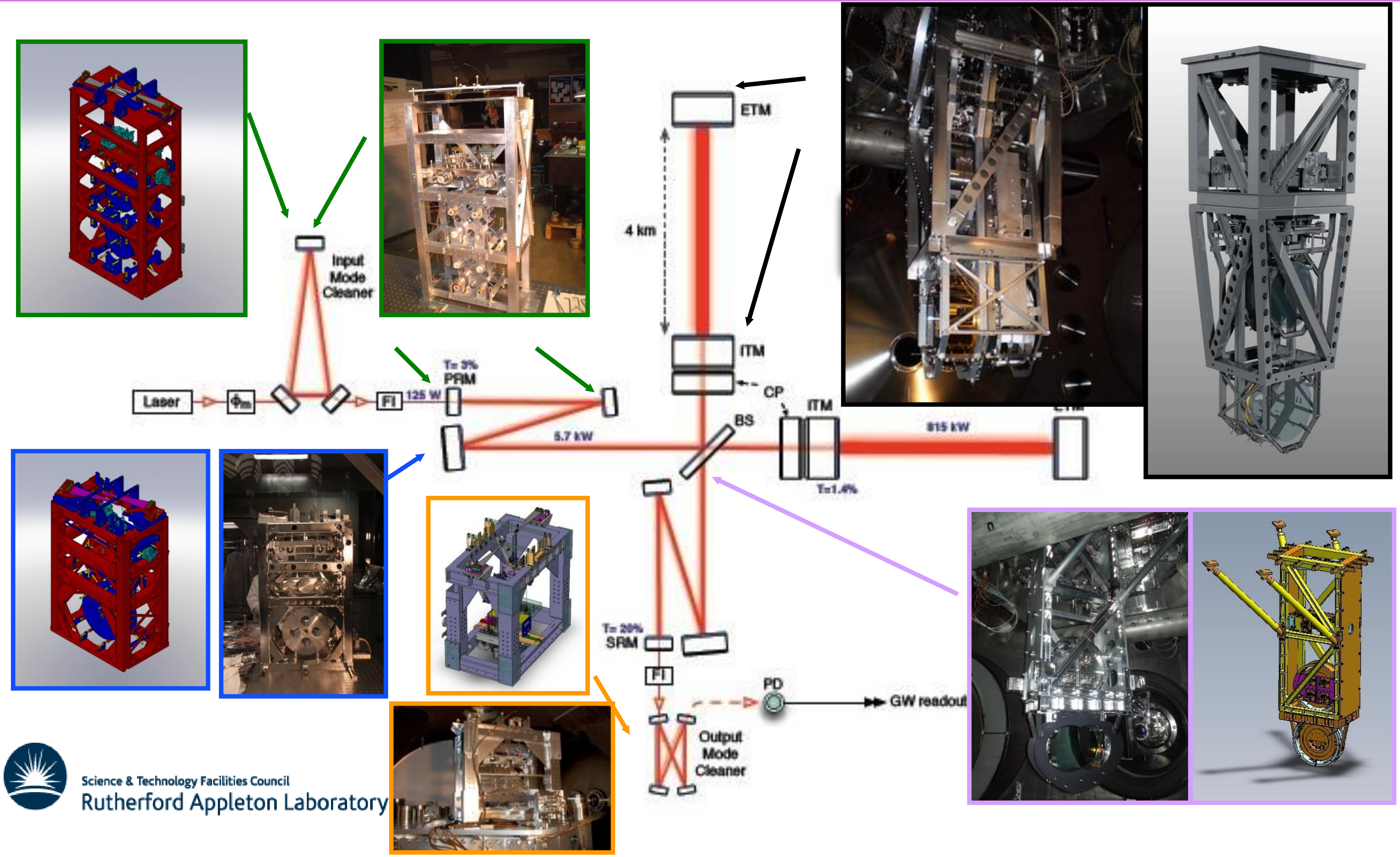
- Test mass & penultimate mass
- All Silica
- First Contact (red)
- $>10^{10}$ Isolation at 25 Hz

- Four stage suspension
- Active 3 stage platform
- Modes coupled throughout

LIGO

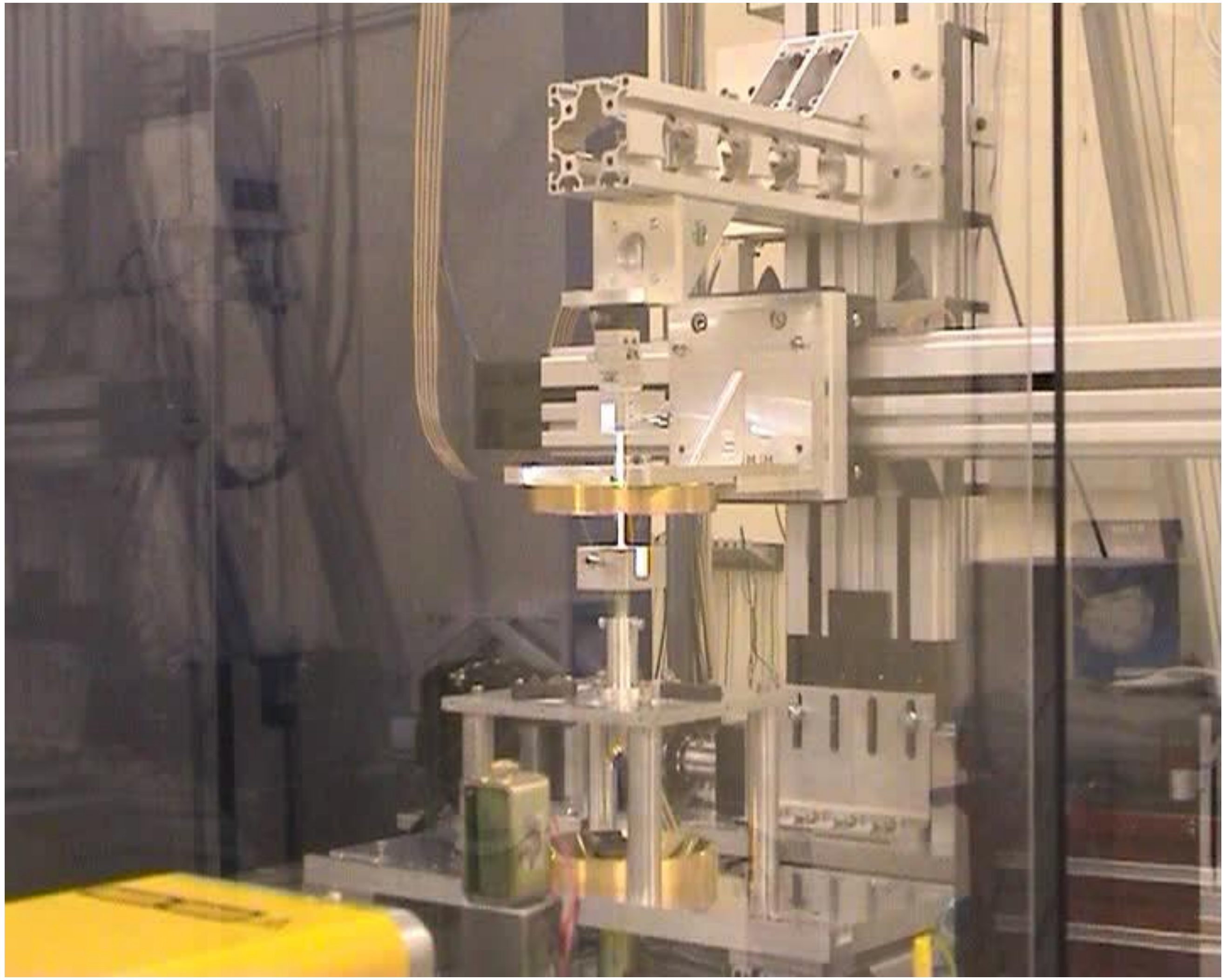
Suspension Designs

a Zoo of Double, Triple and Quadruple Pendulums

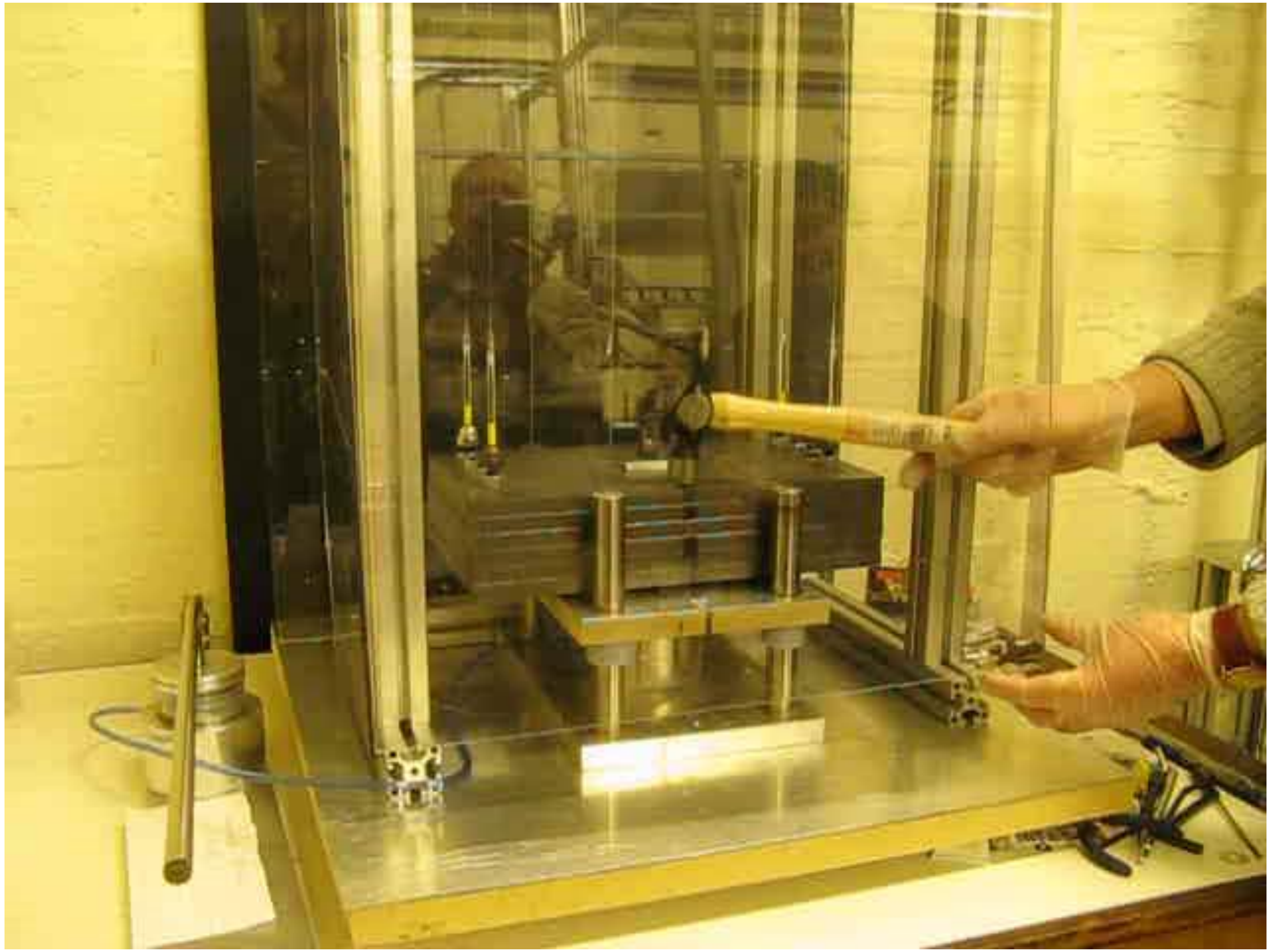


Science & Technology Facilities Council
Rutherford Appleton Laboratory

Silica Fiber Pulling and Polishing Machine

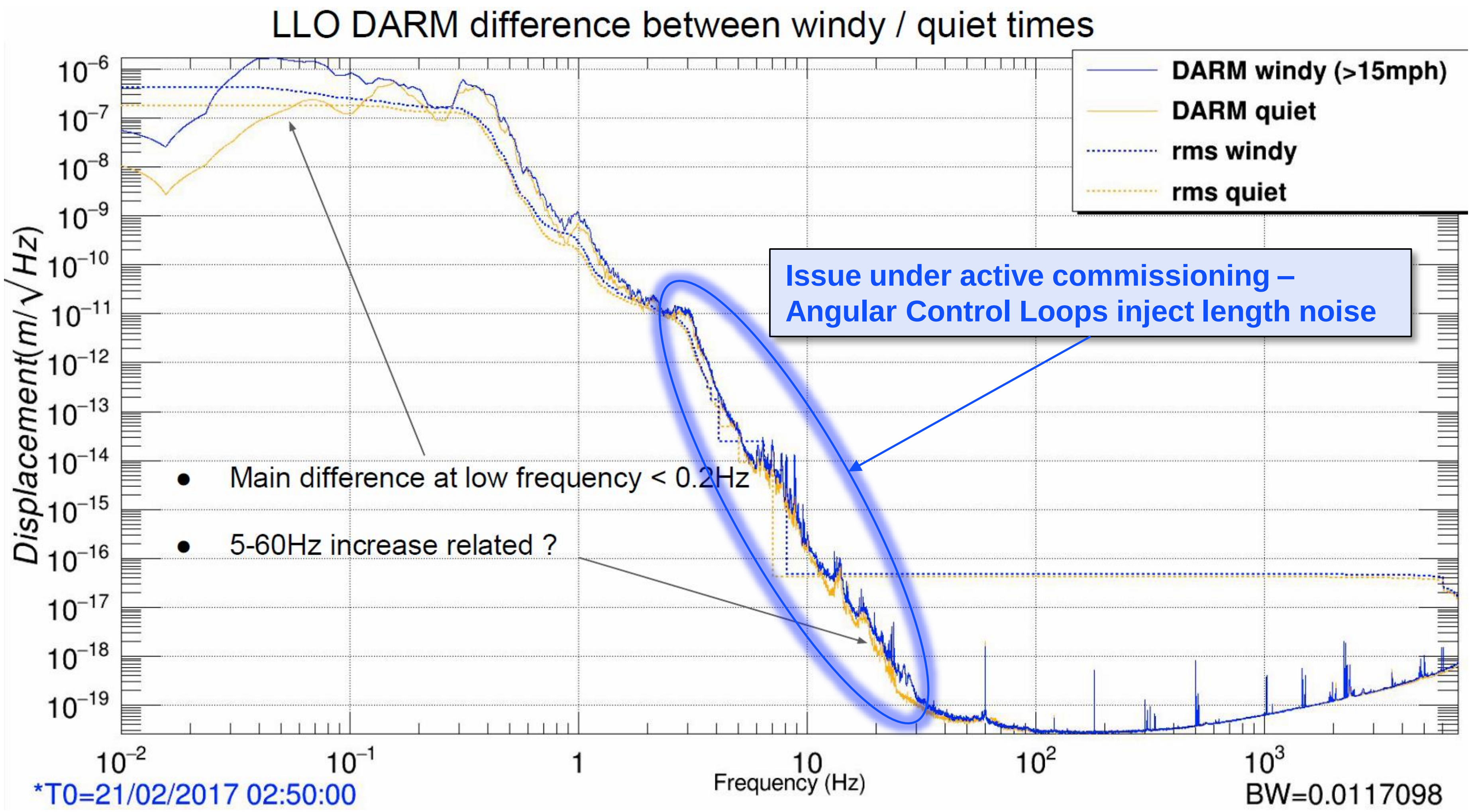


"Testing" Silica Suspension Fiber



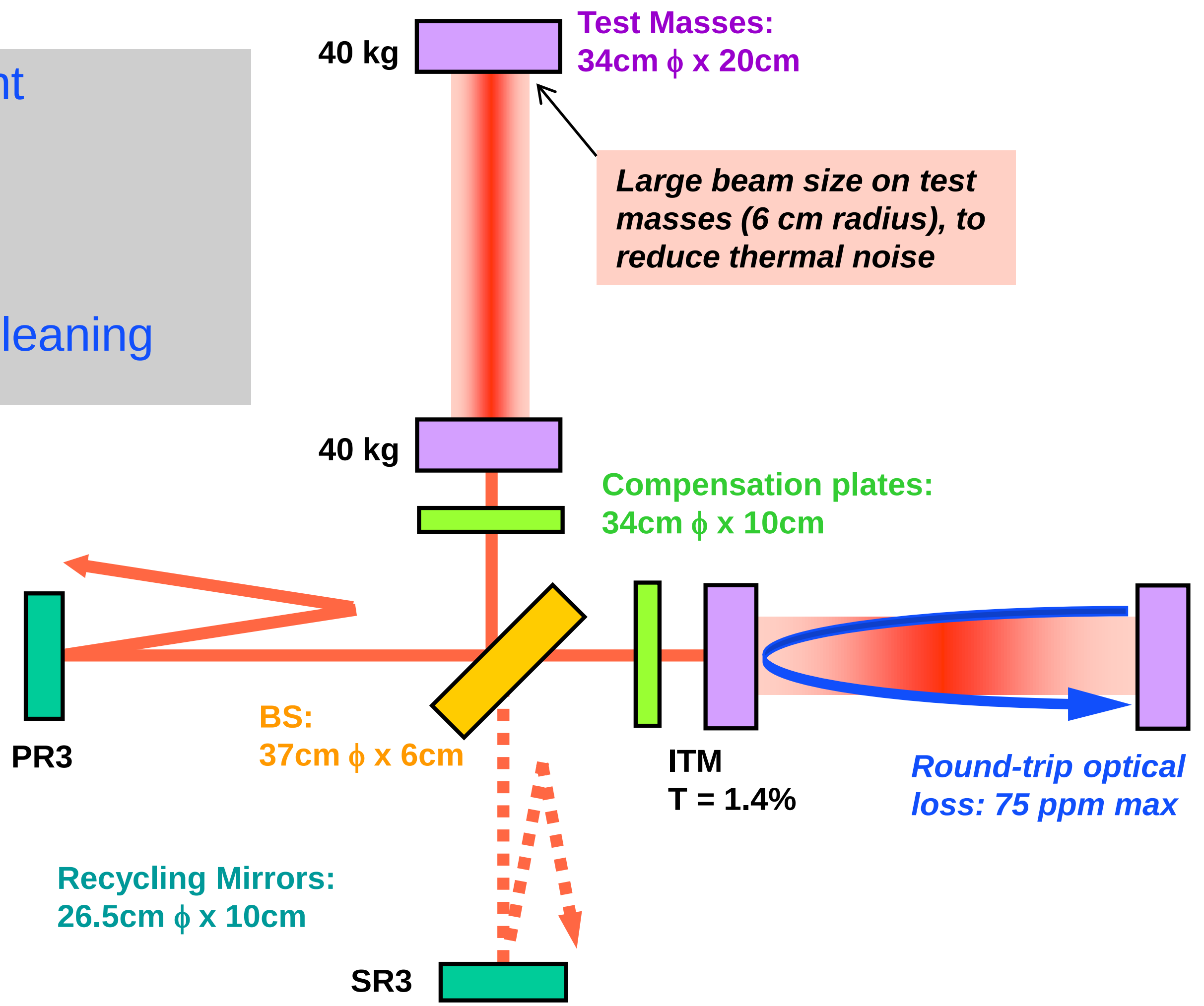
“cartridge” installation

Isolation Performance



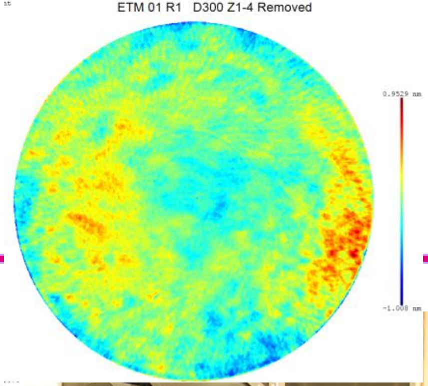
Core Optics Components

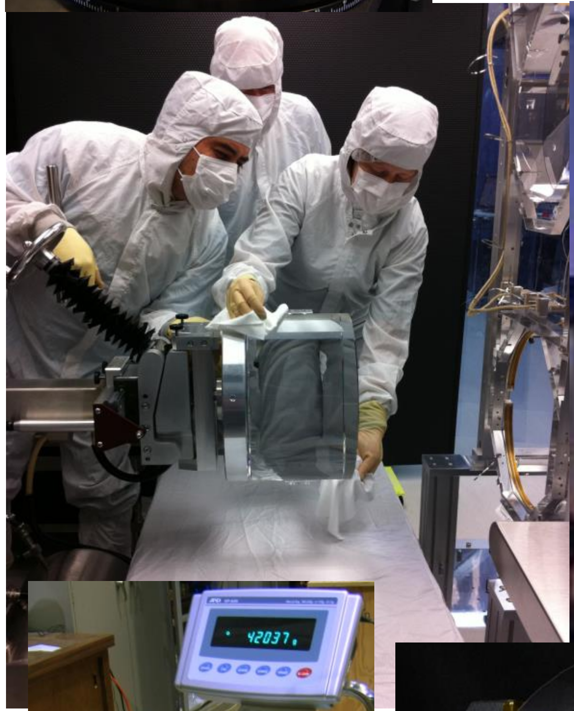
- Substrate procurement
- Substrate polishing
- Dielectric coatings
- Metrology
- Transport, handling, cleaning

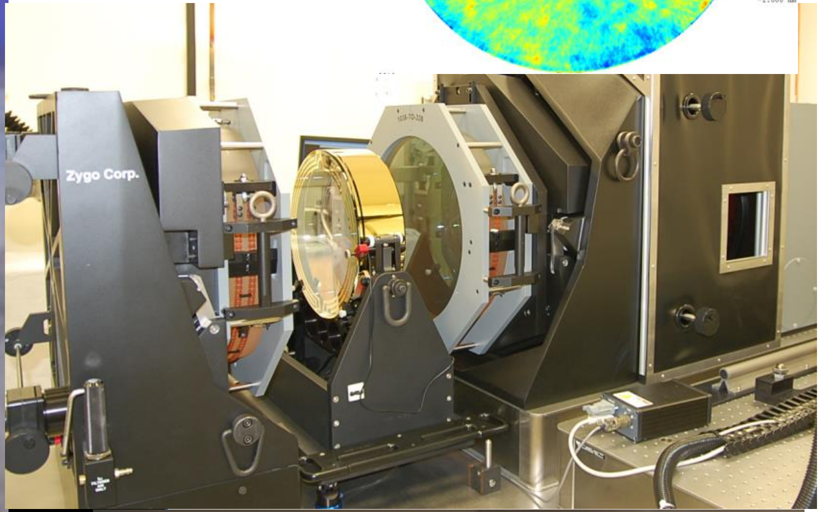


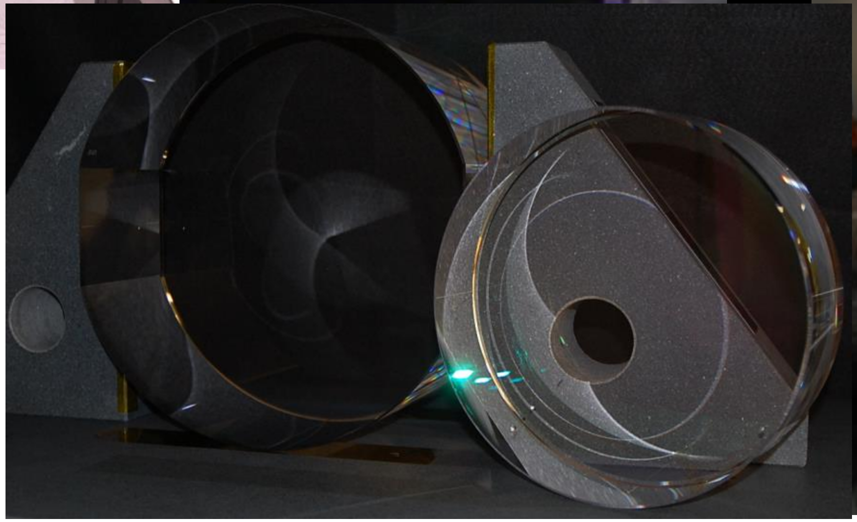
All COC are fused silica substrates with ion-beam sputtered dielectric coatings

Core Optics:
Large Super Mirrors



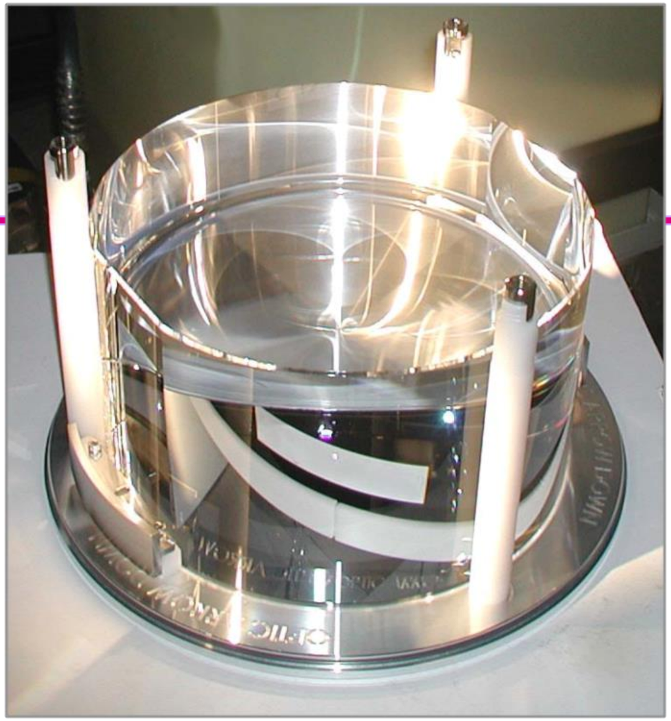


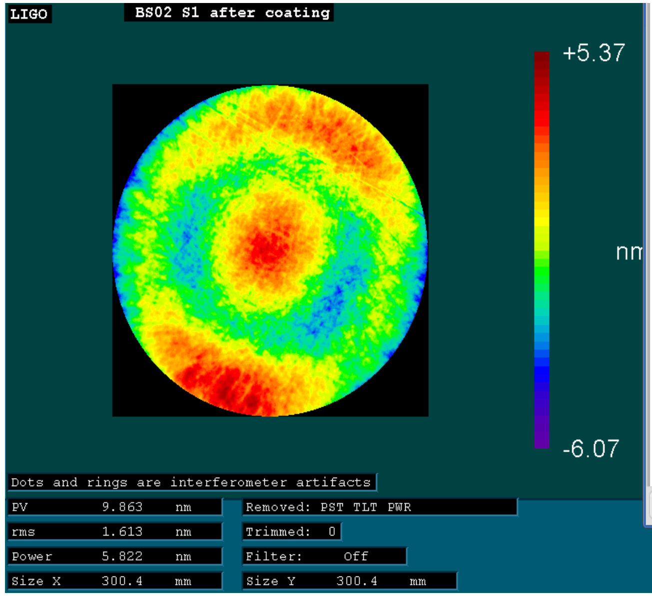


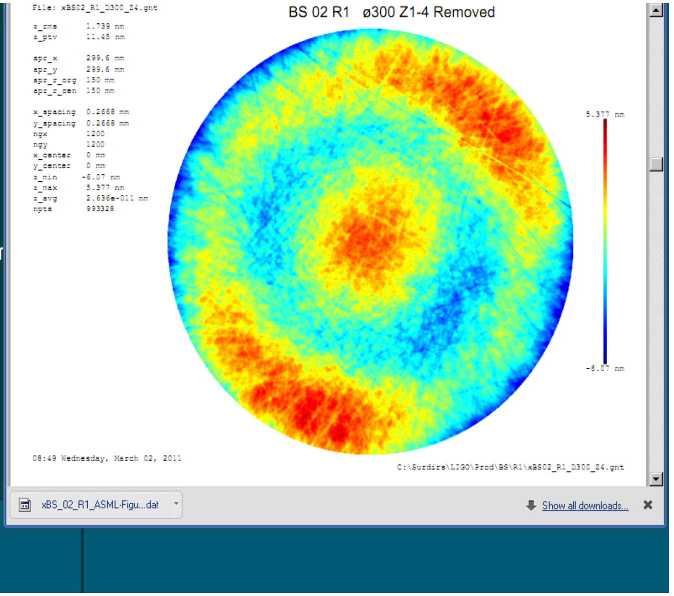


Core Optics Specifications

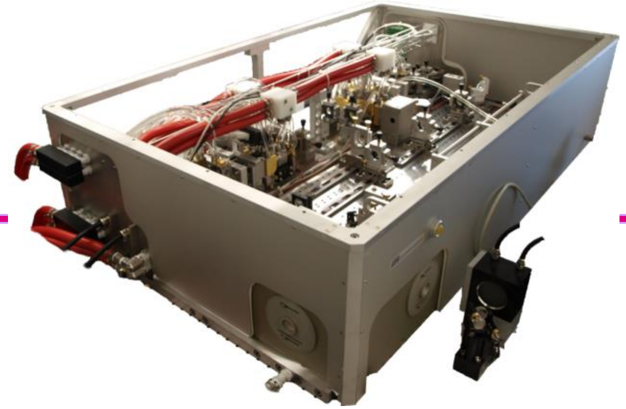
- 2240 m < ROC < 2260 m
- Spatial Freq. Band < 1 mm^{-1}
  - Central 300 mm σ_{rms} < 2.5 nm
  - Central 150 mm σ_{rms} < 0.3 nm
- Spatial Freq. Band 1- 750 mm^{-1}
  - 4 Locations σ_{rms} < 0.16 nm
- R > 0.999996, T < 4 PPM
- Total Cavity Loss < 50 (75) ppm





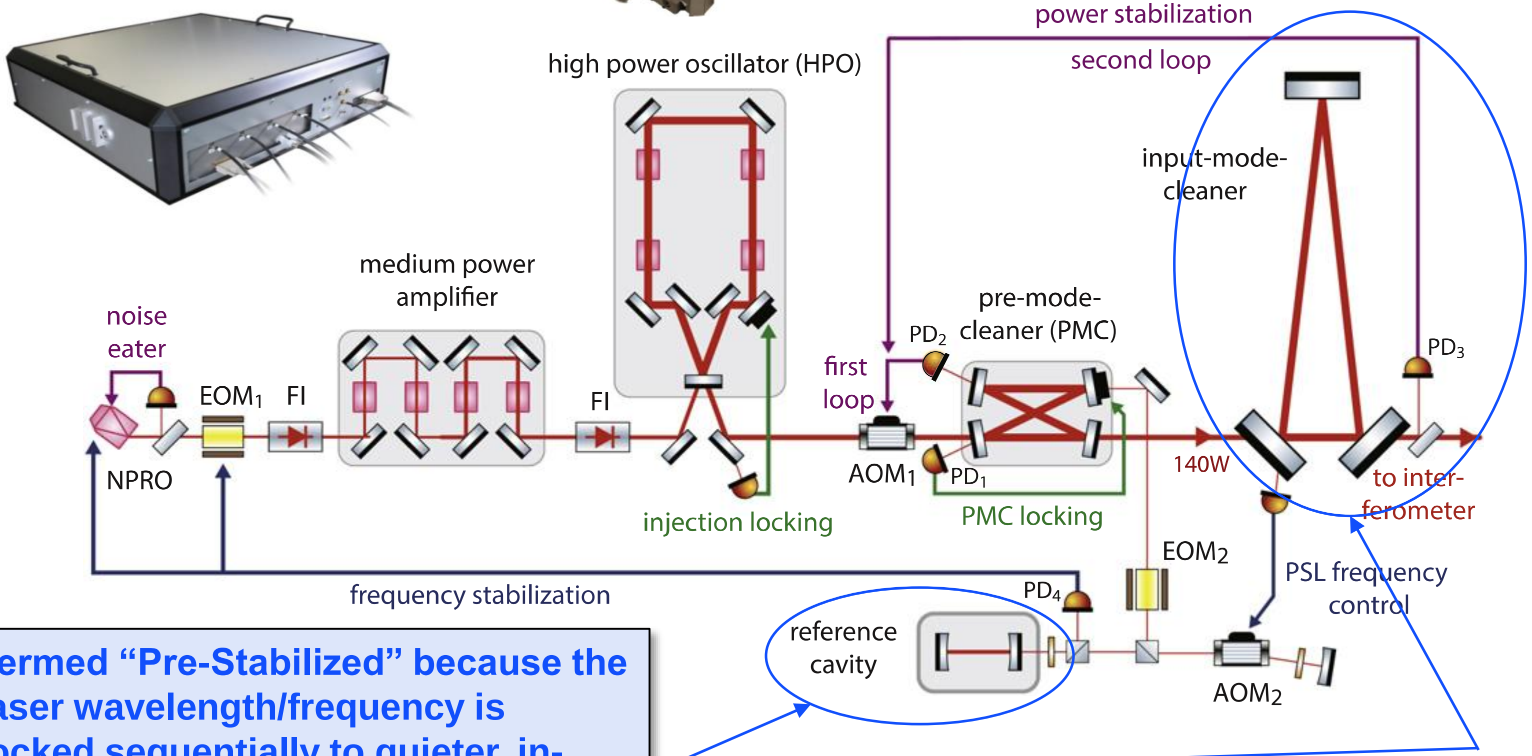


Pre-Stabilized Laser



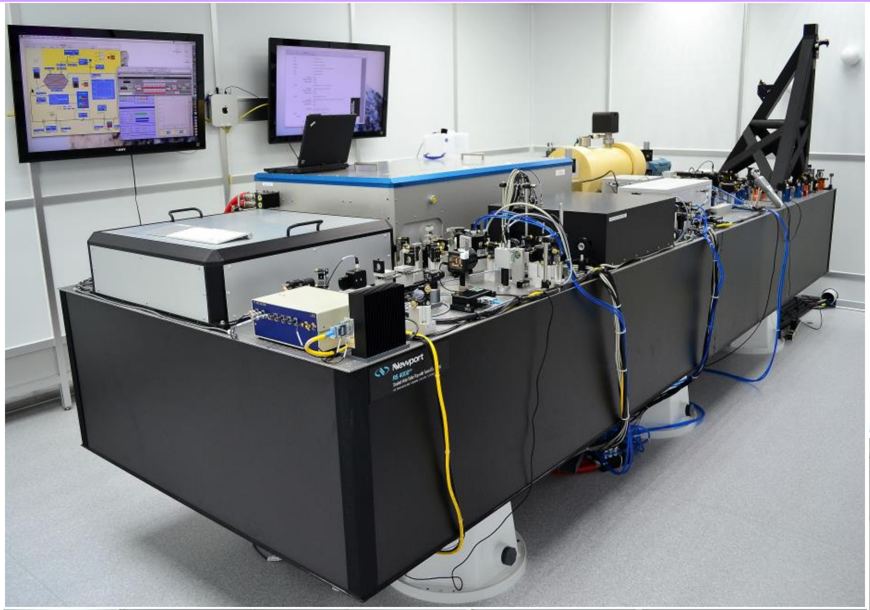
- Contribution from Germany (Albert Einstein Institute, AEI partnered with LZH)
- Custom design/build
- Master Oscillator – 2 W
- 4 Stage intermediate Amplifier – 35 W
- 4 Head Injection Locked Ring – 180 W
- Diagnostic Breadboard
- Pre mode cleaner

Parameter	Specification
1. type of laser	Nd:YAG, Nd:YVO_4
2. wavelength	1064 nm
3. output power	>200 W
4. power in higher order modes	< 20 W
5. polarization extinction ratio	100:1 in the vertical plane
6. relative power fluctuations	$< 10^{-2}$ / √Hz between 0.1 Hz and 10 Hz $< 10^{-5}$ / √Hz between 10 Hz and 10 kHz $< 3.6 \times 10^{-9}$ / √Hz for $f > 9$ MHz (3 dB above shot noise of 50mA photocurrent)
7. frequency fluctuations	$< 1 \times 10^{4}$ Hz / √Hz × [1 Hz / f] between 1 Hz and 10 kHz (same as NPRO free running)

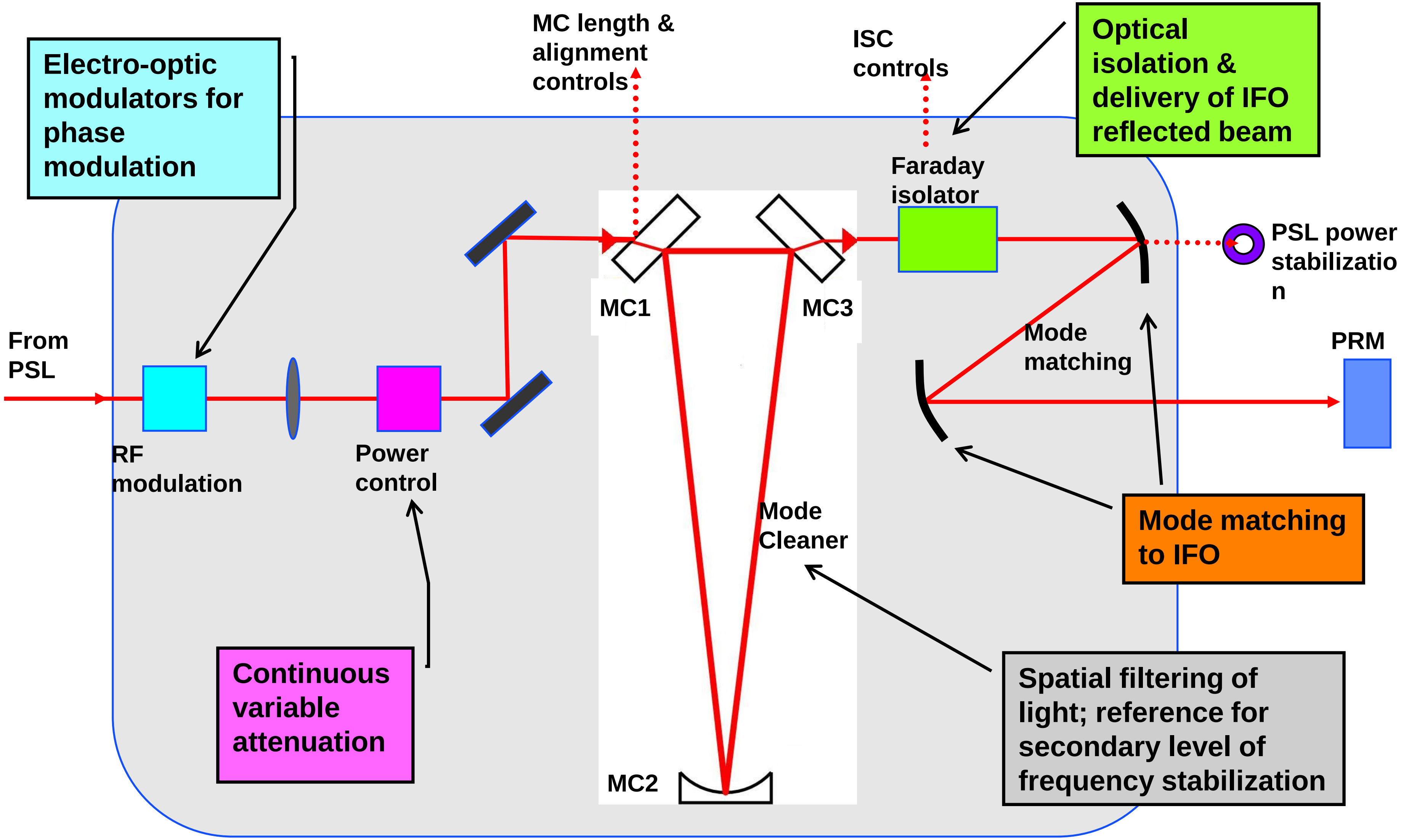


Termed "Pre-Stabilized" because the laser wavelength/frequency is locked sequentially to quieter, in-vacuum cavities & ultimately the Fabry-Perot Arm Cavities (ultimately achieving 1 Hz/√Hz)

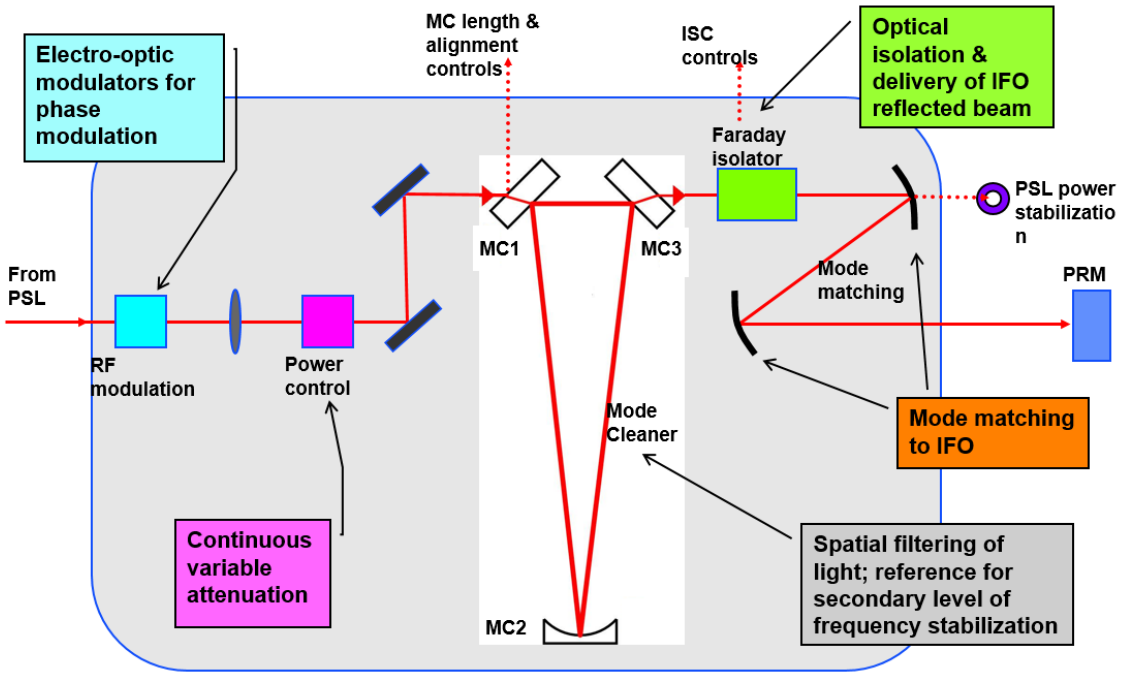
Pre-Stabilized Laser

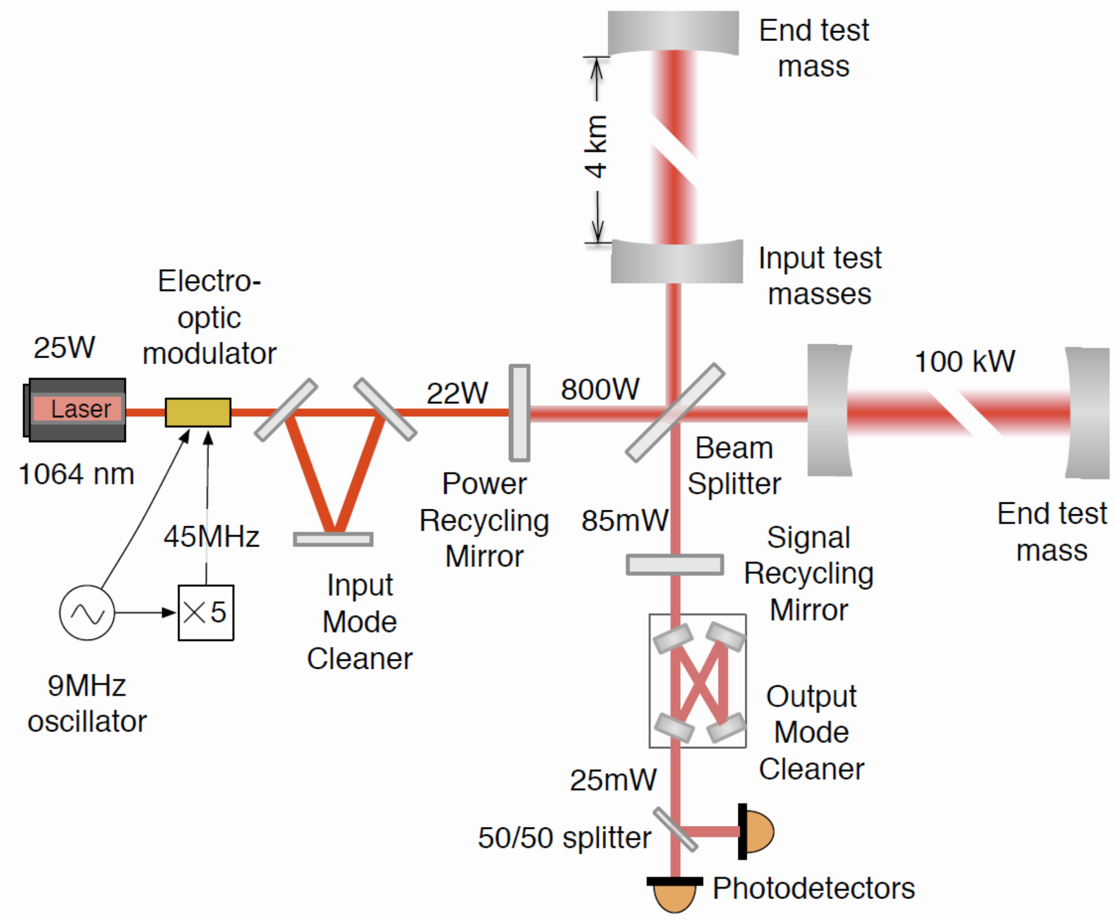


Input Optics



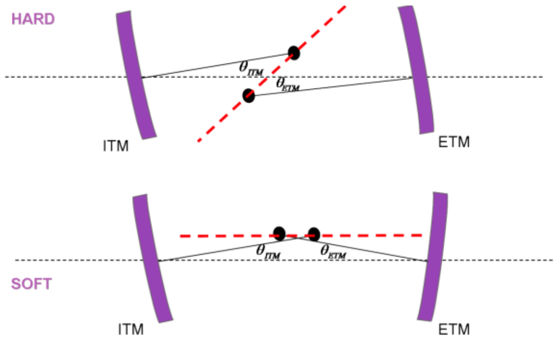
LIGO

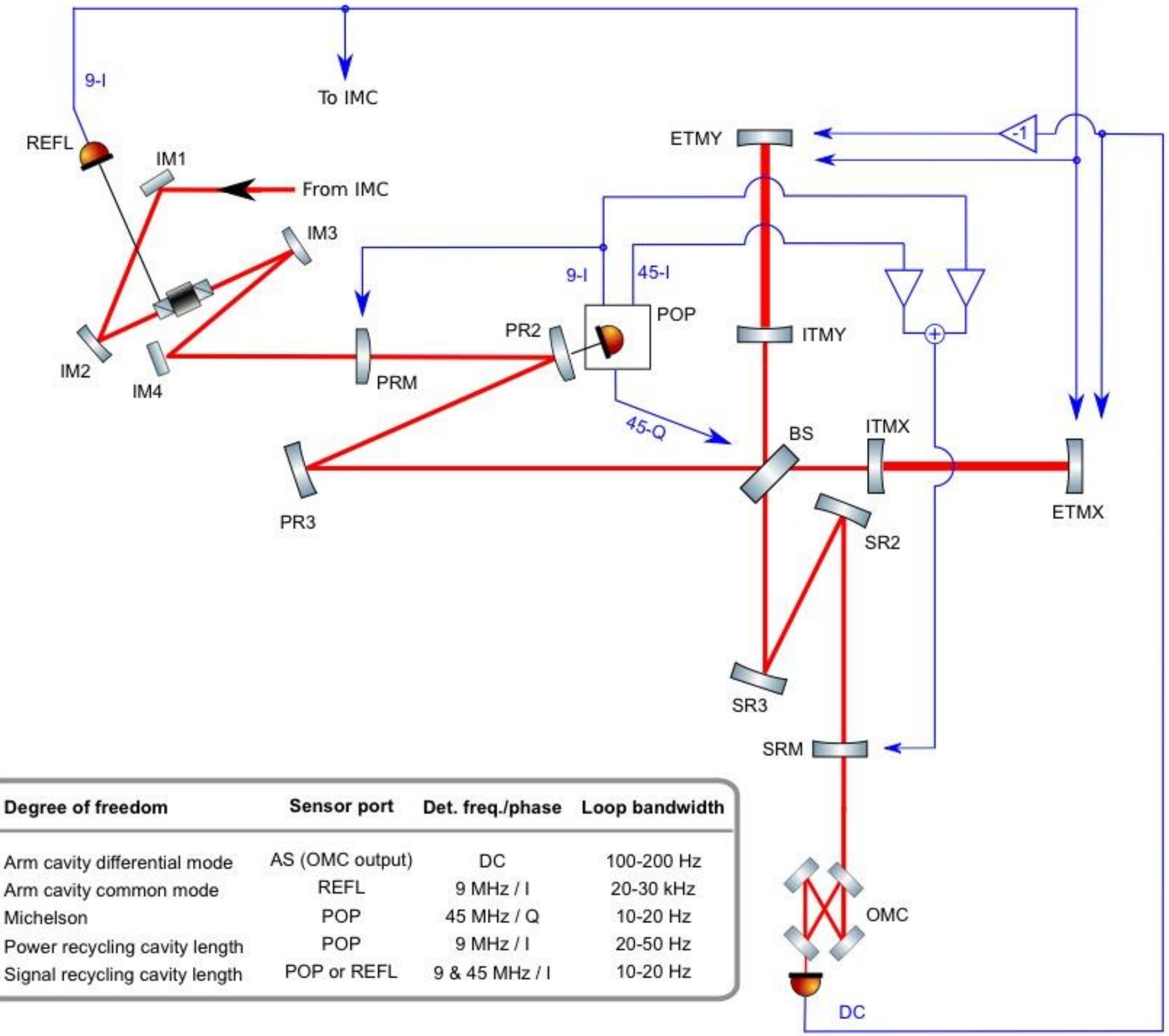

Electro-optic modulators for phase modulation
MC length & alignment controls
ISC controls
Optical isolation & delivery of IFO reflected beam
Faraday isolator
PSL power stabilizatio n
From PSL
MC1
MC3
PRM
Mode matching
RF modulation
Power control
Mode Cleaner
Mode matching to IFO
Continuous variable attenuation
Spatial filtering of light; reference for secondary level of frequency stabilization
MC2


End test mass
4 km
Input test masses
Electro-optic modulator
25W
Laser
1064 nm
22W
800W
100 kW
Beam Splitter
Power Recycling Mirror
85mW
End test mass
45MHz
Signal Recycling Mirror
Input Mode Cleaner
×5
9MHz oscillator
Output Mode Cleaner
25mW
50/50 splitter
Photodetectors

Length Controls

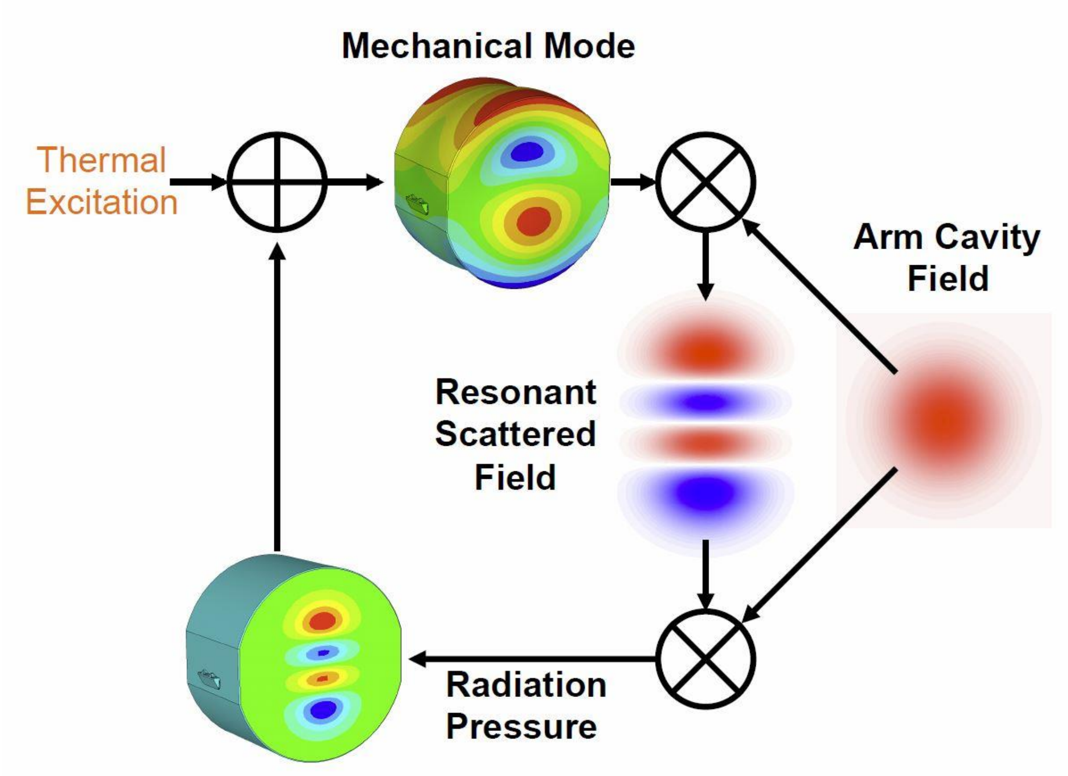
- RF modulation sidebands (9 MHz and 45 MHz)
  - Resonant in PRC, not Arms
  - Michelson contains Schnupp asymmetry so that RF sideband is transmitted to the antisymmetric port even when carier is on a dark fringe
  - Demodulated signals used for digital feedback control at 16k samples/sec
- DC readout of the Differential Arm (DARM) signal is accomplished by intentional offset of ~10 pm
- Radiation pressure effects at high power (>700 kW) cause instability
  - Soft & hard alignment modes





Degree of freedom	Sensor port	Det. freq./phase	Loop bandwidth
Arm cavity differential mode	AS (OMC output)	DC	100-200 Hz
Arm cavity common mode	REFL	9 MHz / I	20-30 kHz
Michelson	POP	45 MHz / Q	10-20 Hz
Power recycling cavity length	POP	9 MHz / I	20-50 Hz
Signal recycling cavity length	POP or REFL	9 & 45 MHz / I	10-20 Hz

High Power Challenges: Parametric Instabilities



mechanical mode Q-factor: ~10 Million

power in the arm cavity: >100 kW

spatial overlap Optical-mechanical mode

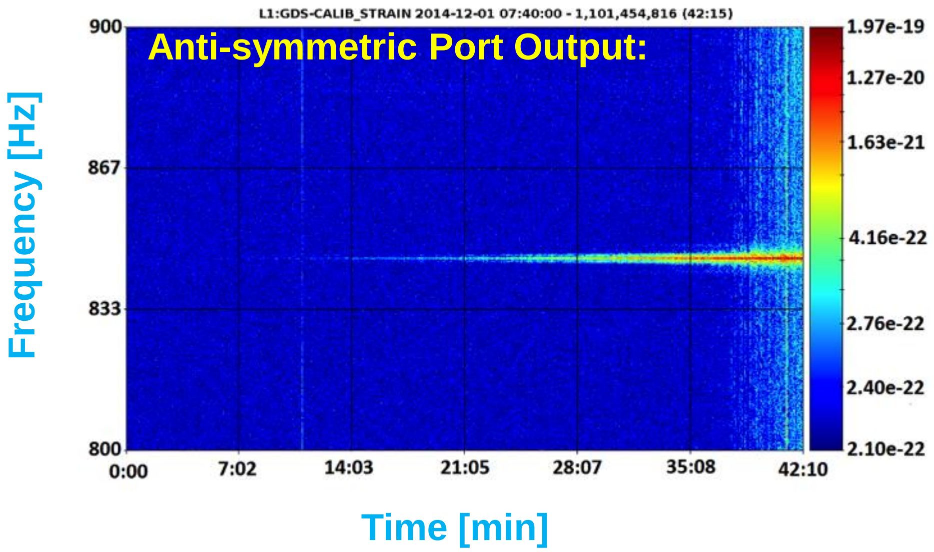
$$R_m = \frac{8\pi Q_m P_{\text{arm}}}{M\omega_m^2 c\lambda} \sum_{n=0}^{\infty} \mathrm{Re}[G_n] B_{m,n}^2$$

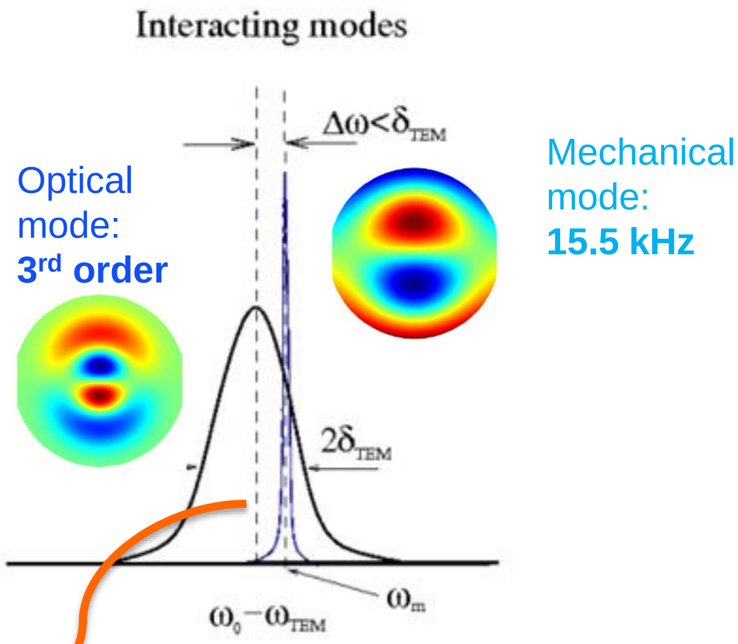
Mirror mass

Acoustic mode frequency

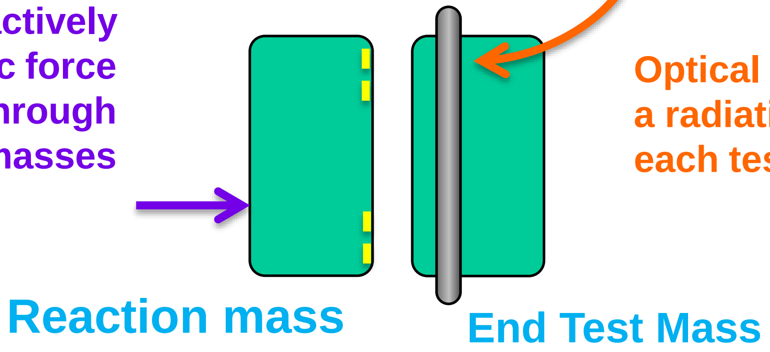
optical mode gain

Controlling Parametric Instabilities

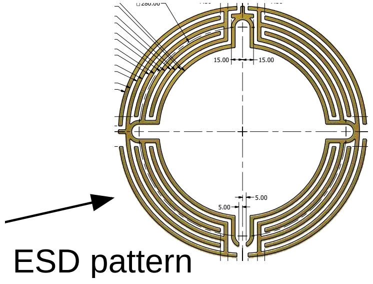




Instabilities can be actively damped with electro-static force feedback applied through reaction masses

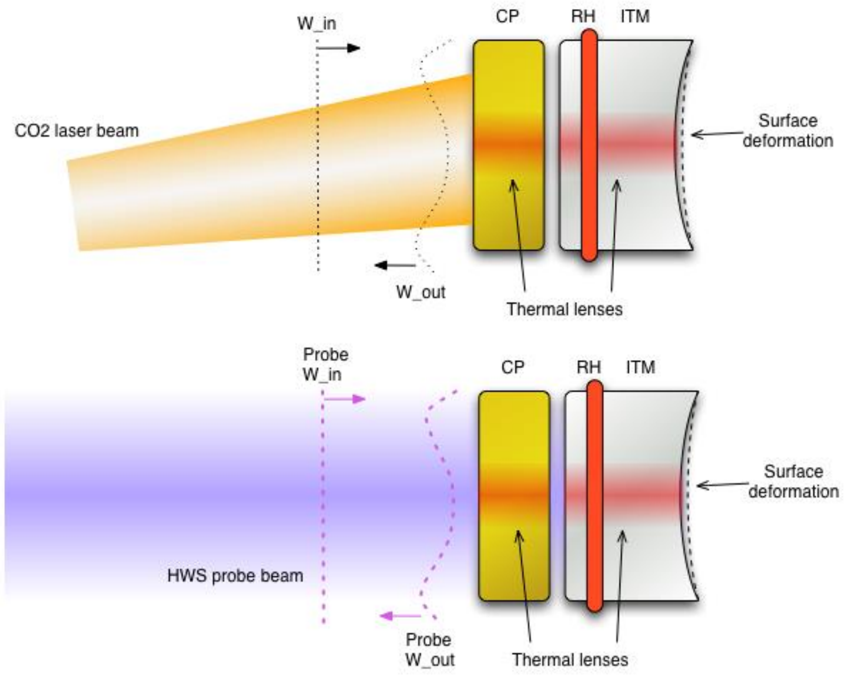


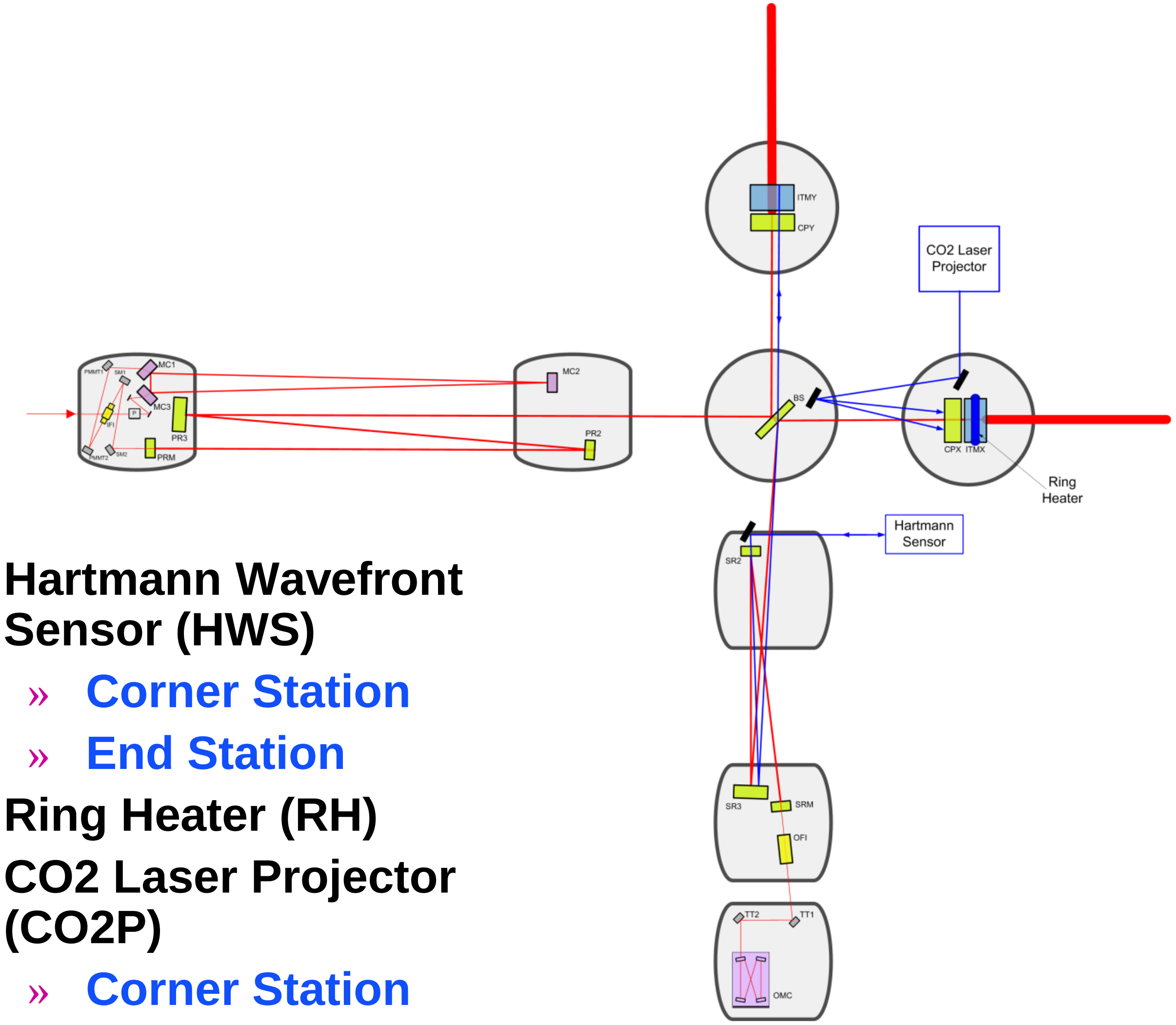
Optical mode can be shifted with a radiative heater that surrounds each test mass



Thermal Compensation System (TCS)

- **Measure & Control thermal lens in the Input Test Mass**
  - » Maintain thermal aberrations to within λ/50
- **Control the Radius Of Curvature (ROC) in the Input & End Test Masses**
  - » Provide 35 km ROC range

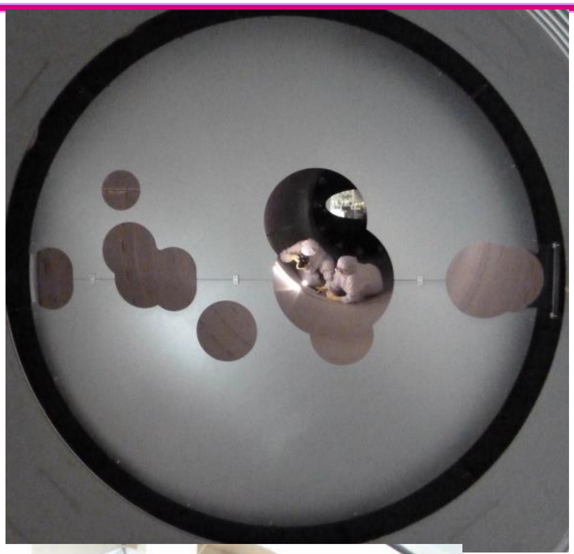
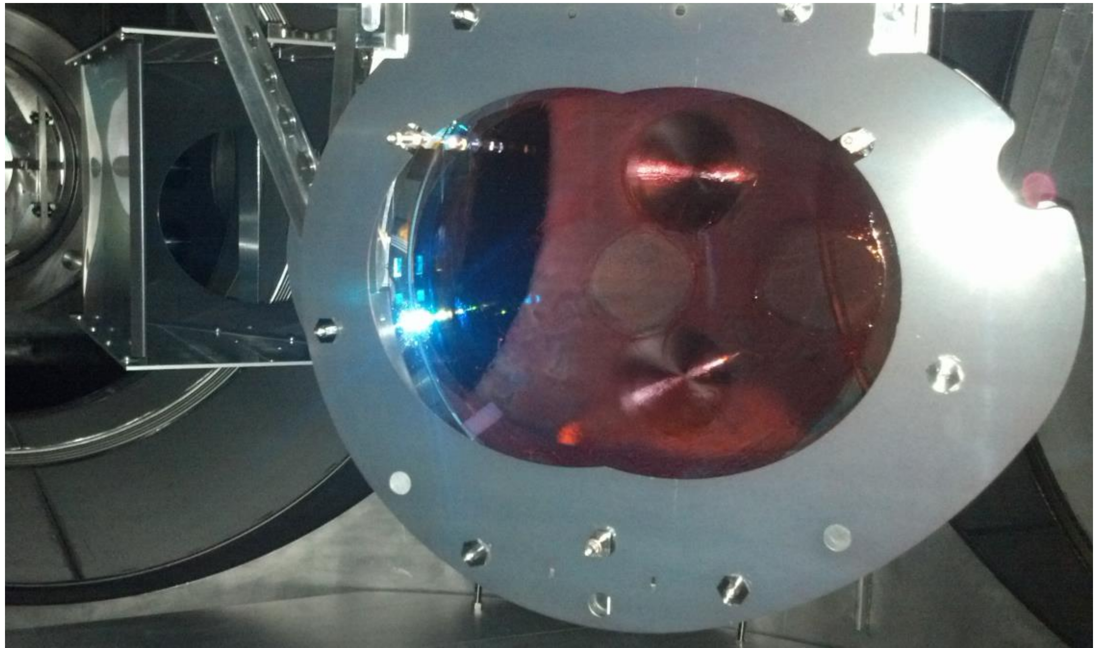
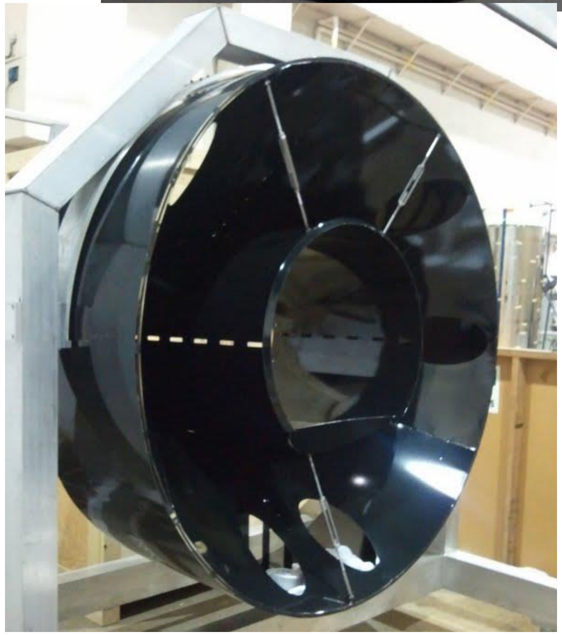




- **Hartmann Wavefront Sensor (HWS)**
  - » Corner Station
  - » End Station
- **Ring Heater (RH)**
- **CO2 Laser Projector (CO2P)**
  - » Corner Station

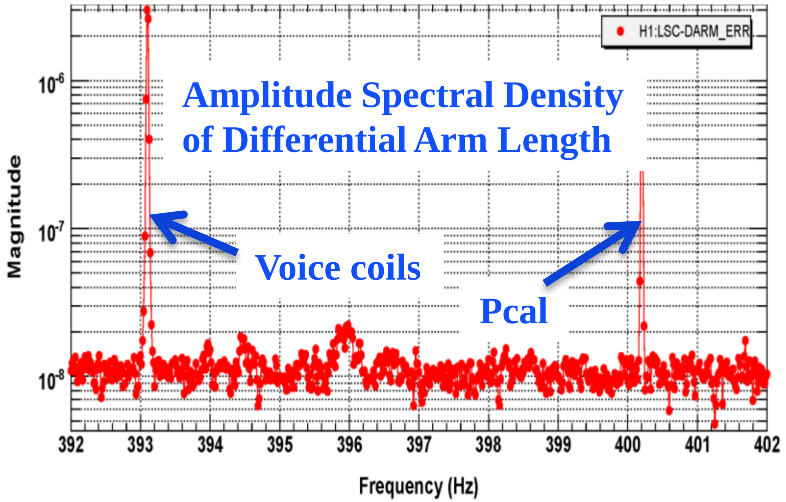
Scattered Light Control: Baffles



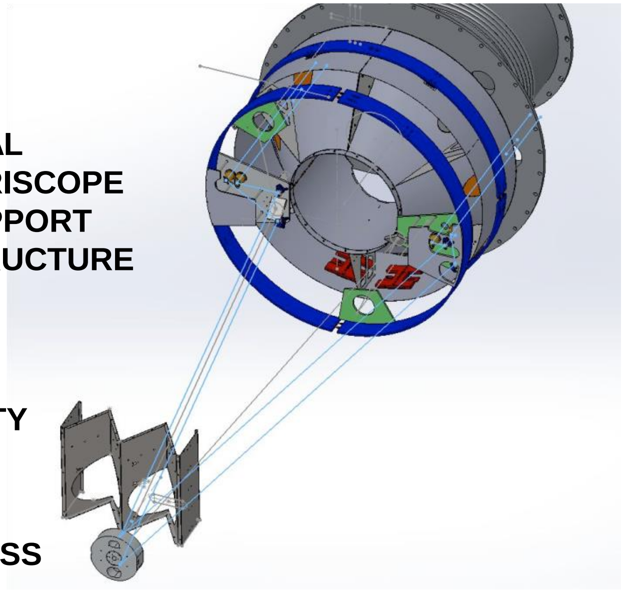




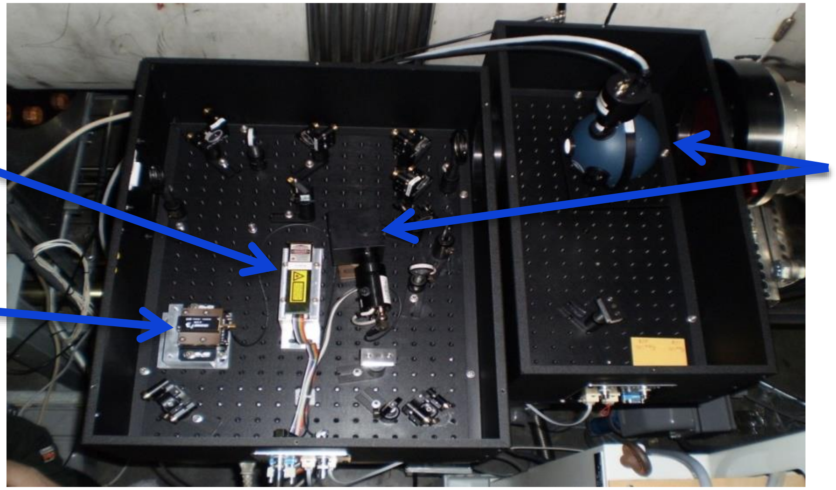
Photon Calibration (Pcal)

- Apply sinusoidal photon pressure to the End Test Masses to calibrate the displacement response of the interferometer
  - SNR>20 over the expected aLIGO sensitivity curve with an integration time of 1 s for frequencies up to 1100 Hz
  - ± 5% calibration accuracy
- Provide an independent timing standard



- **Calibrated receiver**
- **Two beams**
  - **Torque free excitation**
  - **Minimize apparent recoil due to mirror elastic deformation**



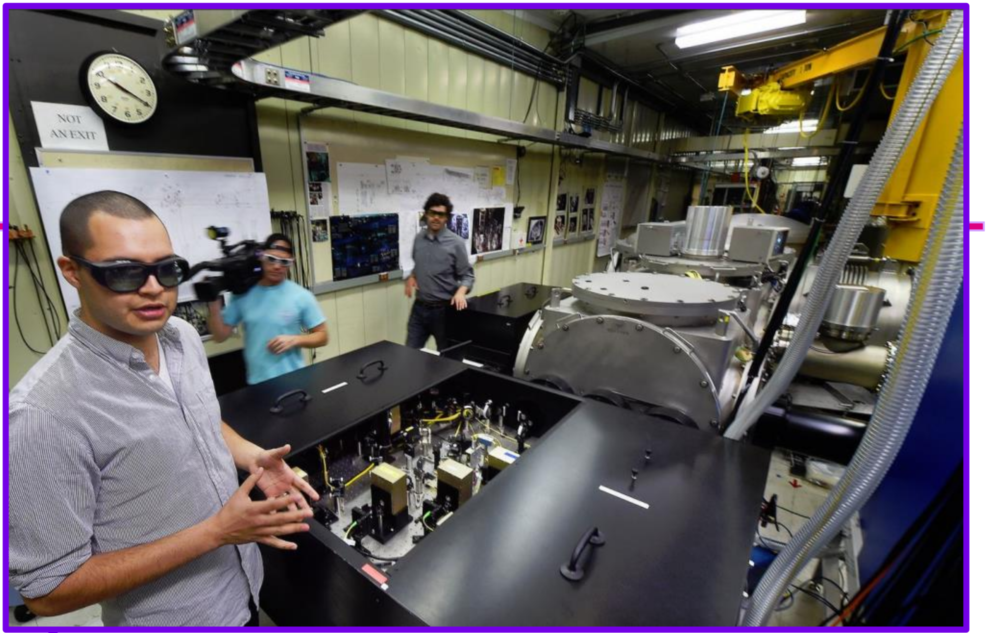


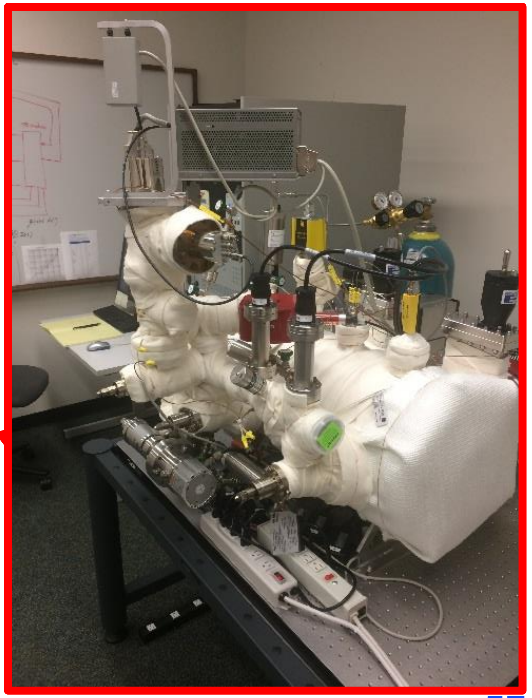
- **Vary the laser power sinusoidally with an acousto-optic modulator**
- **Measure the light power with a NIST traceable integrating sphere**

Outline

- Why? (the motivation)
  - Gravitational Waves & Astrophysical Sources
- Detection!
- Who?
  - The team
- How? (the engineering)
  - Basic principles of operation
  - Subsystems
- More about the vacuum system
  - a talk by Jon Feicht
- Tours
  - 40m Lab – a 100th scale version of LIGO
  - VORTEX (Vapor Outgassing & Reexposure Text Experiment)

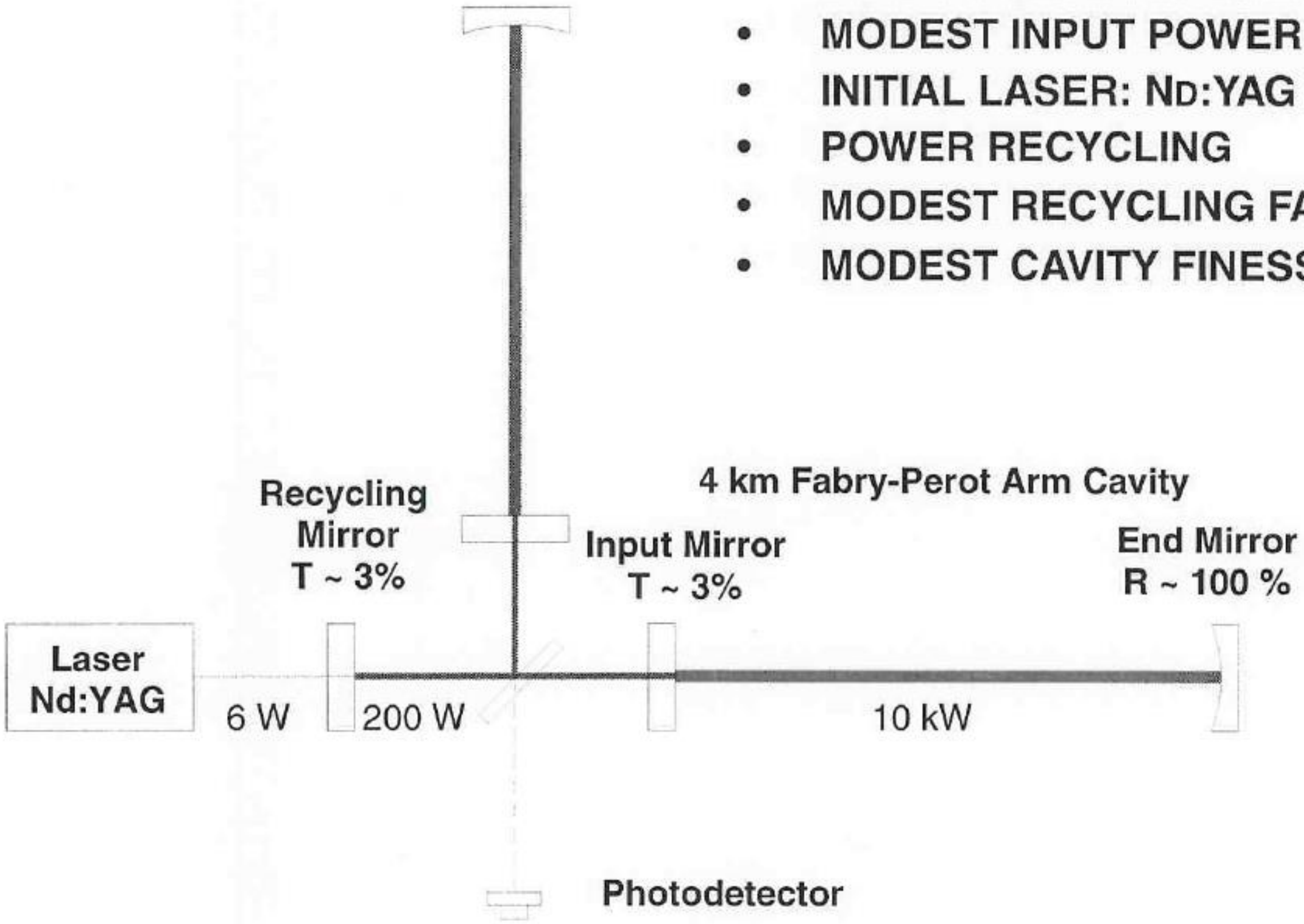
Then we'll split into 2 tour groups





Backup Slides

Initial LIGO Interferometer Configuration



- FABRY-PEROT ARM CAVITIES
- MODEST INPUT POWER (6 W)
- INITIAL LASER: ND:YAG $\lambda = 1.06\ \mu\text{m}$
- POWER RECYCLING
- MODEST RECYCLING FACTOR ($\mathcal{R} \sim 30X$)
- MODEST CAVITY FINESSE ($\mathcal{F} \sim 50$)

Interferometer Response Function:

$$\varphi = h\frac{\omega L}{c}\frac{2F}{\pi\sqrt{1+(\Omega\tau)^2}}$$

where

$\delta\varphi$ = optical light phase change

ω = laser frequency

Ω = GW frequency

c = speed of light

h = strain amplitude

L = arm length

F = Fabry-Perot finesse

τ = Fabry-Perot time constant

Fringe Sensing

wavelength 1×10^{-6} m

$$h = \frac{x}{L} \sim \frac{\lambda}{L b \sqrt{\dot{N}\tau}}$$

arm length = 4000 m

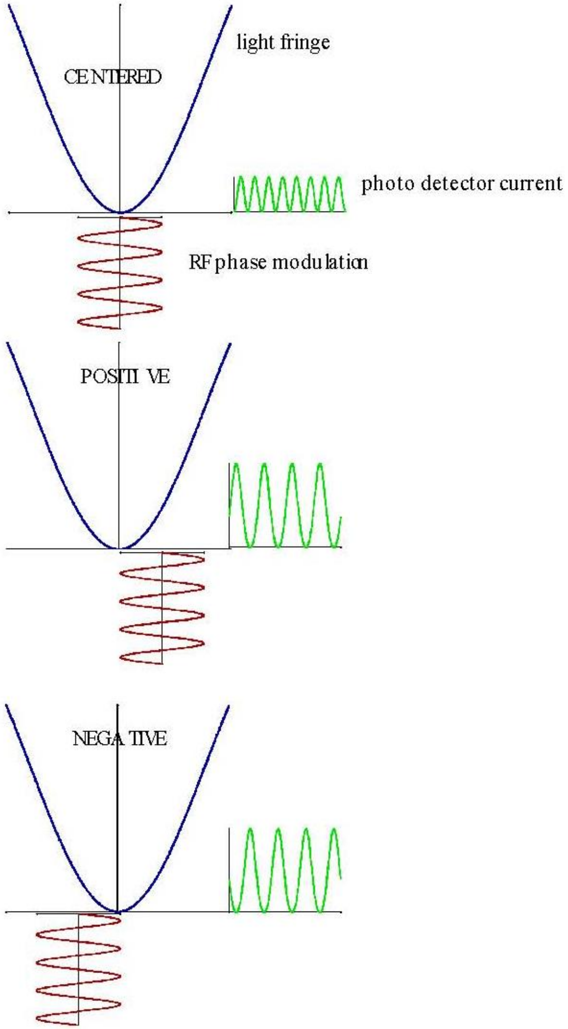
equivalent # of passes = 100

number of quanta/second at the beam splitter

300 watts at beam splitter = 10^{21} identical photons/sec

integration time

$h = 6 \times 10^{-22}$ integration time 10^{-2} sec



Is the Measurement Meaningful?

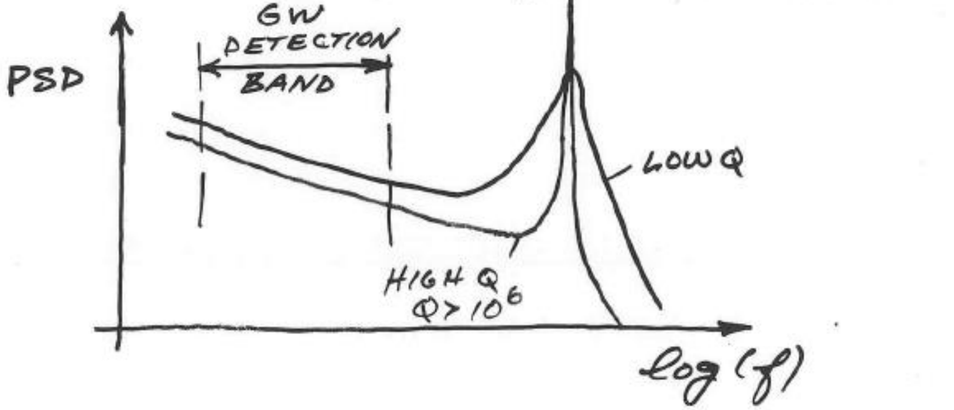
RANDOM, THERMALLY INDUCED MOTIONS OF THE ATOMS IN THE MIRROR FACES >> ΔL

$$\Delta L \sim 10^{-18}\,m \sim \frac{\text{Dia. of Nucleus of Atom}}{1000}$$

YES, IT IS MEANINGFUL!

- ATOMIC MOTIONS OCCUR AT VERY HIGH FREQUENCIES
  - ATOMIC MOTION AVERAGED AWAY DURING THE ~1 ms COLLECTION OF ~10^{16} PHOTONS
- SPATIALLY AVERAGING OVER MANY ATOMS SO THAT ONLY THE LOW SPATIAL ORDER MODES ARE POTENTIALLY SIGNIFICANT (i.e. "Drum Head" modes)
  - MIRROR LOWEST FREQ., f_0 > 10 kHz
  - $\delta x = \frac{(kT/m)^{1/2}}{2\pi f_0} \sim 3 \times 10^{-16}\,m$ for $T = 300K$, $m = 10\,kg$

    $\delta x \sim \frac{\text{dia. of Nucleus of Atom}}{3} \sim 300 \times$ GW signal
  - OUT OF THE GW BAND
  - HIGH Q ASSOCIATED WITH f_0 SO THAT THE "TAIL" OF THE RESONANCE HAS A SMALL EFFECT



Is the measurement possible?

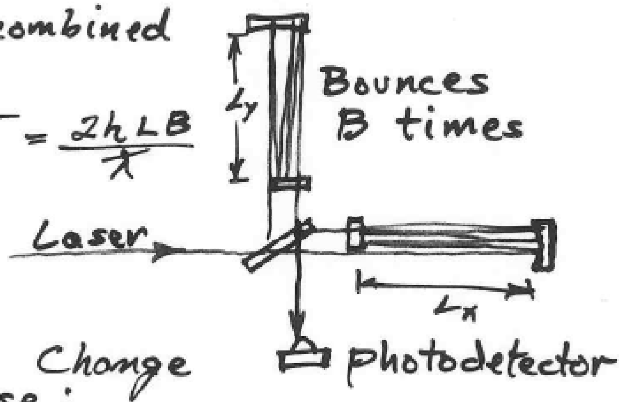
STRAIN, $h = \frac{\Delta L}{L} \sim 10^{-21}$ OR $\Delta L = 4\,km \times 10^{-21}$

$\Delta L \sim 10^{-18} m \sim 10^{-12} \lambda$ (LASER WAVELENGTH $\lambda = 1.06 \mu m$)

OUTRAGEOUS? $\Rightarrow$ NOT AT ALL:

- Phase Difference of Recombined Light:

$$\Delta\varphi = \frac{2B(\Delta L_x - \Delta L_y)2\pi}{\lambda} = \frac{2hLB}{\bar{\lambda}}$$



- Photodetector Intensity Change Limited by Shot Noise:

$$\Delta\varphi \simeq \frac{\Delta I}{I_0} \sim \frac{1}{\sqrt{\#\,photons}}$$

- Photodetector Can Integrate for ½ GW period

$$\frac{1}{2f} \sim 1\,ms$$

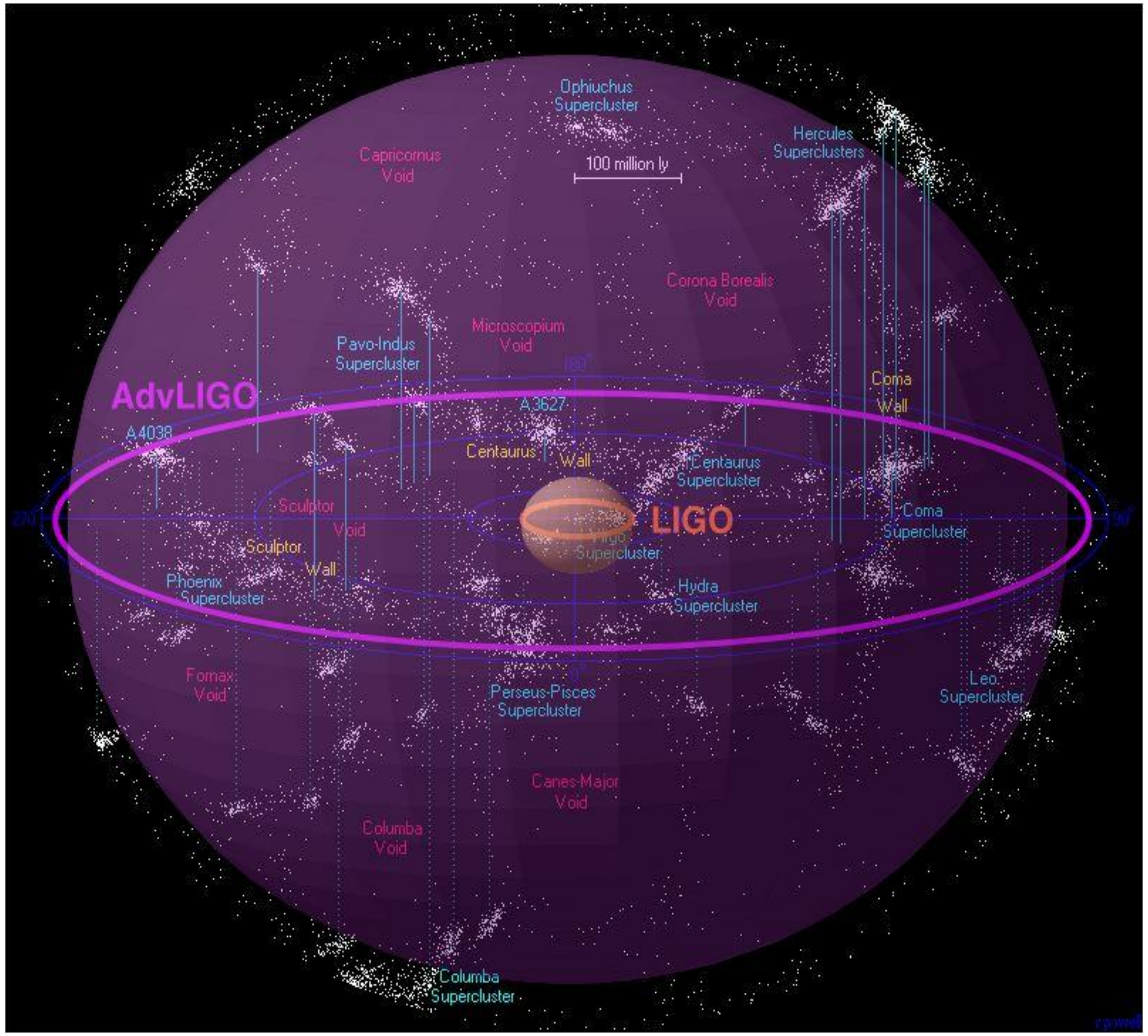
Consequently:

$$h_{min} \simeq \frac{\bar{\lambda}}{2BL}\frac{1}{\sqrt{N}} = \frac{\bar{\lambda}}{2BL}\left(\frac{2\hbar c f}{I_0 \bar{\lambda}}\right)^{1/2}$$

$$h_{min} \simeq \underline{\underline{3 \times 10^{-21}}}\left(\frac{50}{B}\right)\left(\frac{4km}{L}\right)\left(\frac{\lambda}{1.06\mu m}\right)^{1/2}\left(\frac{10W}{I_0}\right)^{1/2}\left(\frac{f}{1000\,Hz}\right)^{1/2}$$

$\therefore$ MEASUREMENT IS POSSIBLE

From LIGO to Advanced LIGO

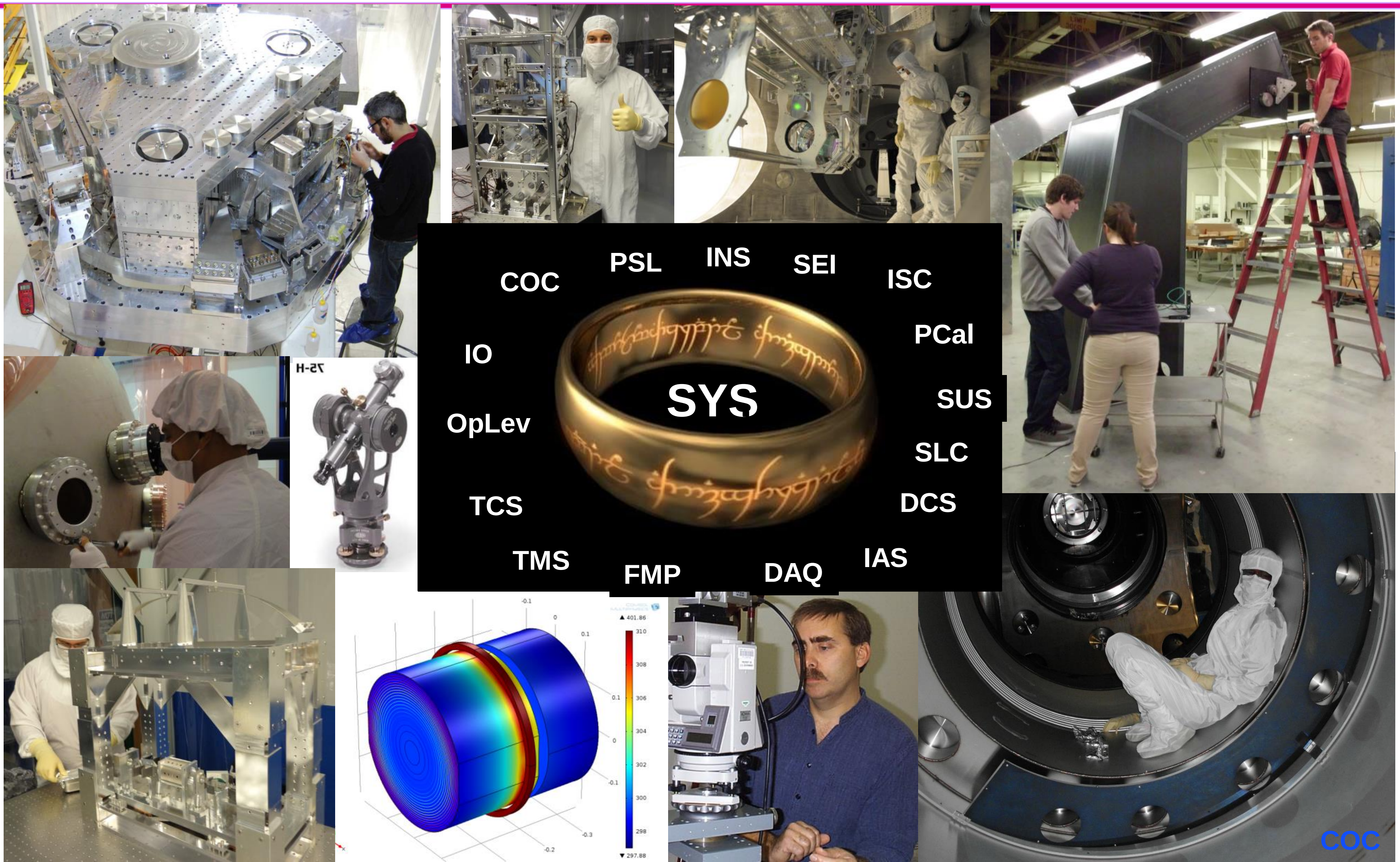


Factor of 10 in sensitivity gives factor of 1000 in volume and hence in event rate

- Advanced LIGO aiming for sensitivity at which several signals per month (or per week) should be detected .
  - Factor of 10 improvement in sensitivity at ~100 Hz
  - Wider bandwidth extending down to ~10 Hz
- US funding approved 2008 (plus contributions from UK, Germany, Australia)
- Construction and installation 2008-2015
- Project completed March 2015
- First observing run scheduled for September 2015

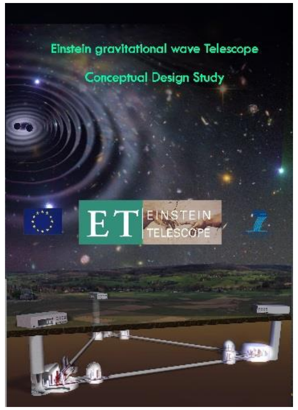
Systems Group

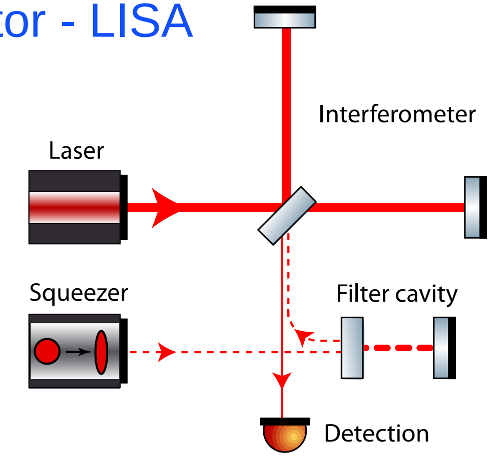
(one group to rule them all)

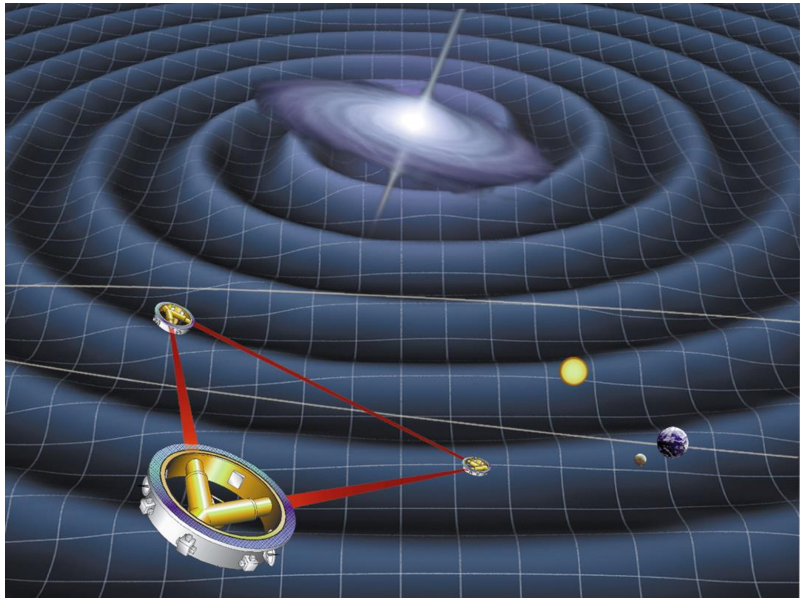


Beyond Advanced LIGO

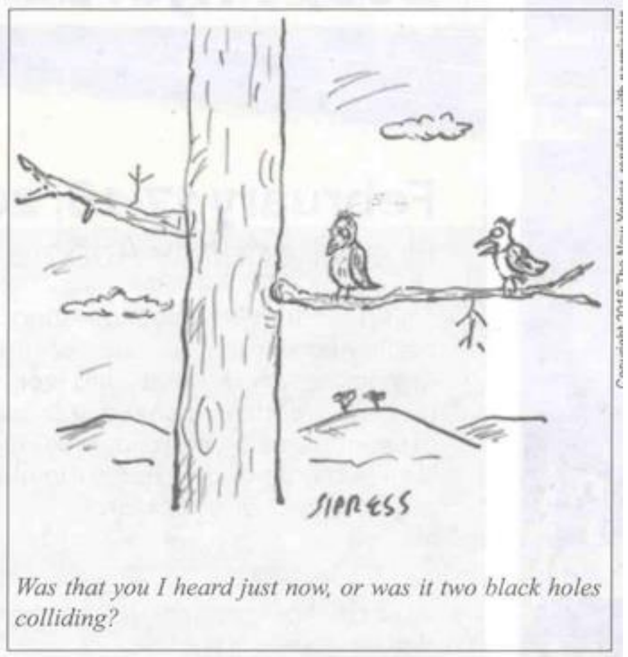
- A+ (~6 year timescale)
  - Improved coatings with reduced mechanical loss (lower thermal noise)
  - Frequency dependent squeezing
- Voyager – at LIGO facilities limit (~10 to 15 year timescale)
  - Cryogenic operation (~ 120K)
  - Large (~200 kg) silicon optics
  - 2 micron lasers
- 20 year timescale: new facilities
  - Cosmic Explorer
    - ~40 km arm lengths
  - Einstein Telescope (Europe)
    - Underground, 10 km arm lengths
- Space Based Detector - LISA







GW150914 in popular culture

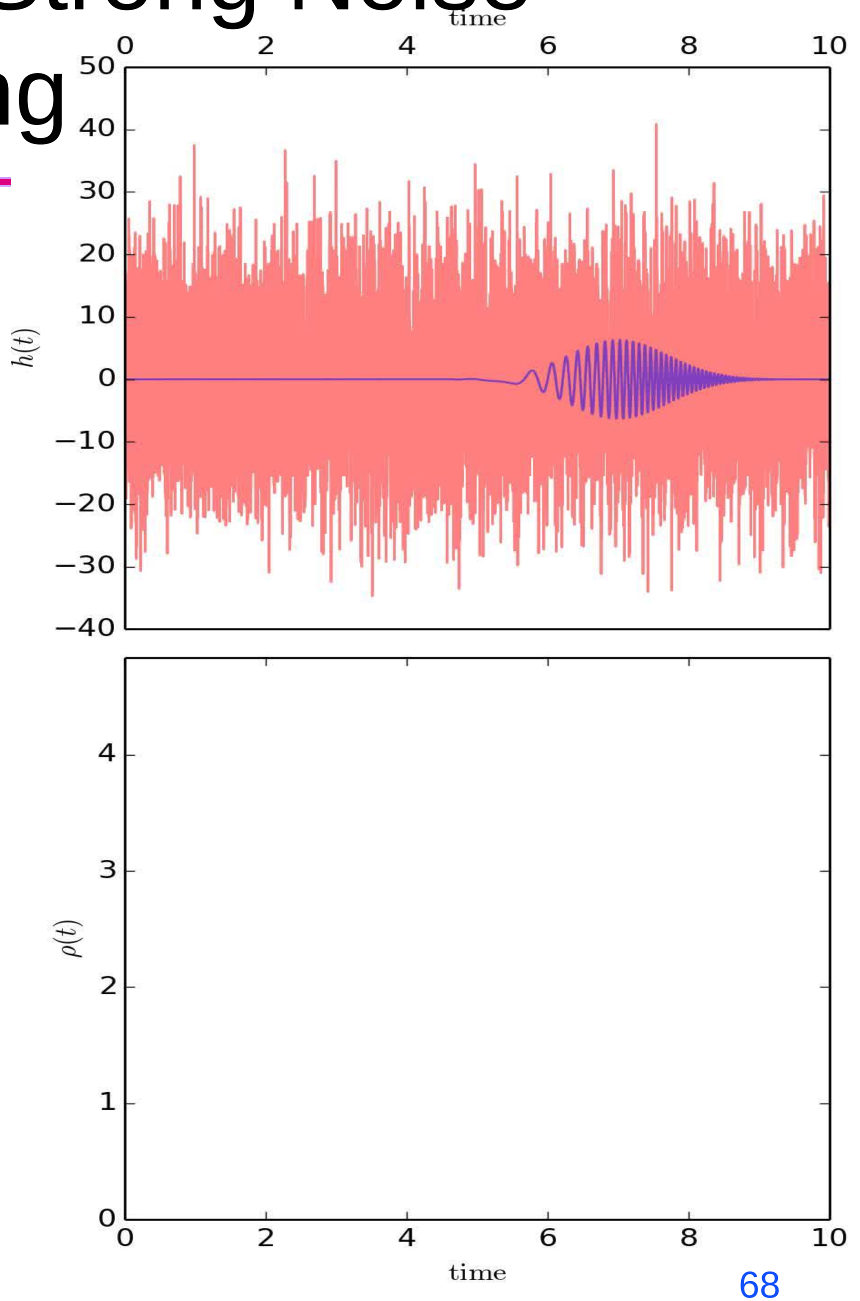


Weak Signal – Strong Noise
Matched Filtering

Matched filtering lets us find a weak signal submerged in noise.

If you know the signal waveform: multiply the waveform by the data, for all possible times when the signal might have arrived.

When there's a match, you can see it.



SIM

G1700601-v1