Gravitational Waves from an experimentalist’s point of view

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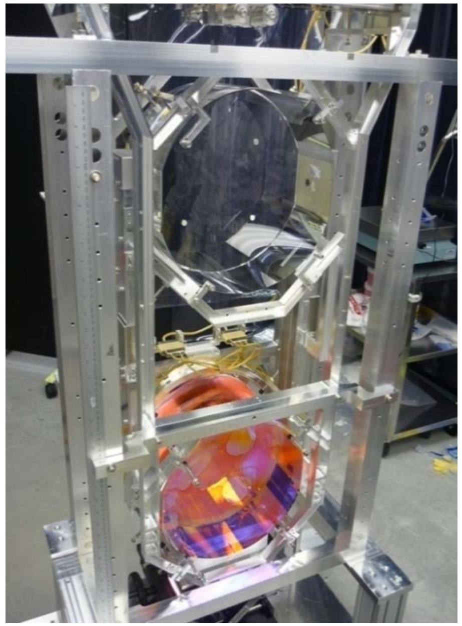
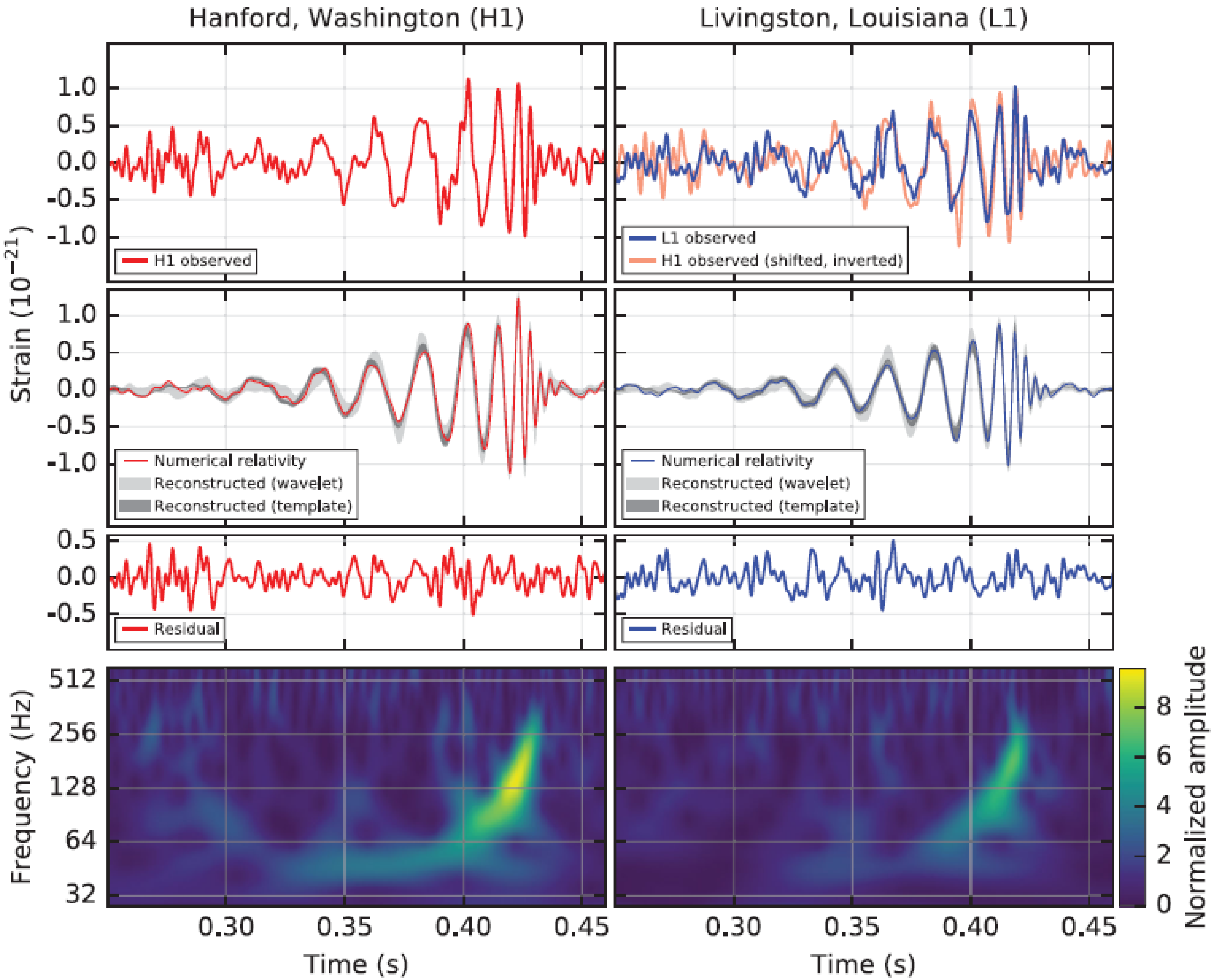
University of Glasgow

For the LIGO Scientific Collaboration and
the Virgo Collaboration

With thanks to Prof Giles Hammond many slides

LIGO-G1700009





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

Overview

- History of gravitational waves
- Ground based detector technology
  - Detector basics
  - Recent upgrades, aLIGO
  - Expectations
- GW150914/GW151226: a pair of black hole binary mergers
- What’s next?

Not the first detection

PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Detection and Generation of Gravitational Waves*

J. Weber
University of Maryland, College Park, Maryland
(Received February 9, 1959; revised manuscript received July 20, 1959)

Methods are proposed for measurement of the Riemann tensor and detection of gravitational waves. These make use of the fact that relative motion of mass points, or strains in a crystal, can be produced by second derivatives of the gravitational fields. The strains in a crystal may result in electric polarization in consequence of the piezoelectric effect. Measurement of voltages then enables certain components of the Riemann tensor to be determined. Mathematical analysis of the limitations is given. Arrangements are presented for search for gravitational radiation.

The generation of gravitational waves in the laboratory is discussed. New methods are proposed which employ electrically induced stresses in crystals. These give approximately a seventeen-order increase in radiation over a spinning rod of the same length as the crystal. At the same frequency the crystal gives radiation which is about thirty-nine orders greater than that of a spinning rod.

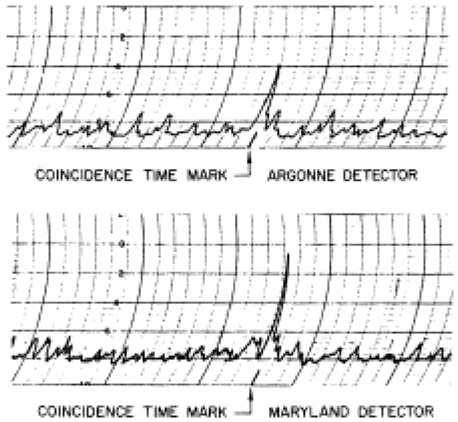
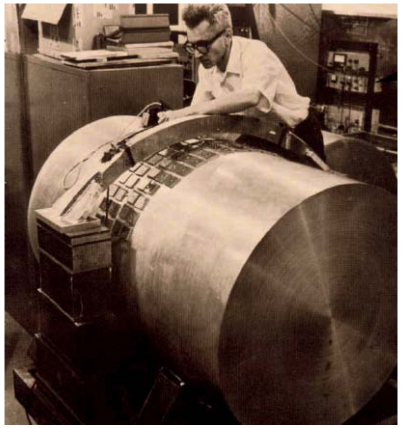


FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

- Two bar detectors ~ 1000 km apart



J. Weber, 1960’s

Volume 22, Number 24 PHYSICAL REVIEW LETTERS 16 June 1969

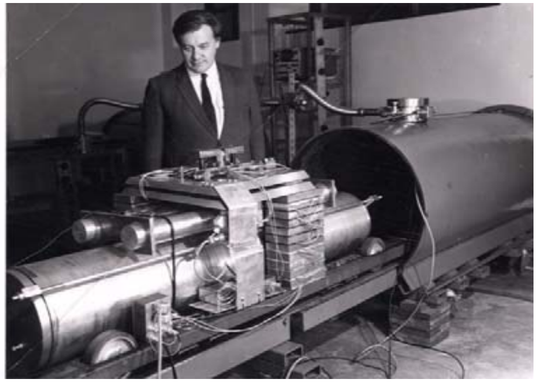
EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

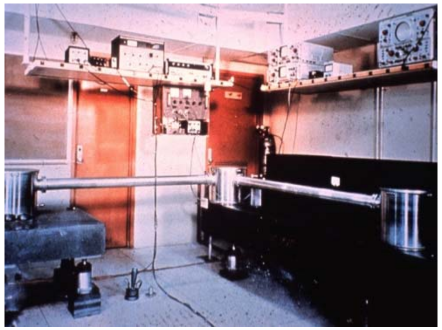
Brief History

Abb. 23: Der Aluminiumzylinder des in München wiederholten Weber-Experimentes mit Heinz Billing, der den Versuchsaufbau leitete. Der Zylinder hängt an einem Stahldraht. Deutlich zu sehen ist die Isolation gegen mechanische Erschütterungen, bestehend aus abwechselnden Lagen von Eisen und Gummi. Im Hintergrund der Vakuumtank und die Elektronik mit einer Antenne für Zeitzeichen.



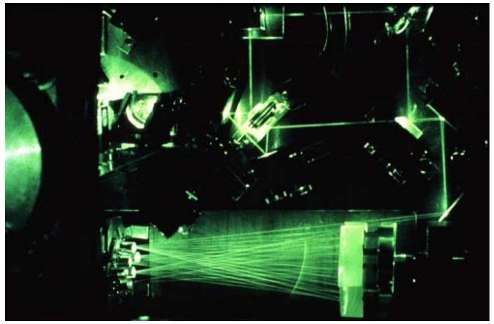
Germany-Italy/UK, 70's-80's

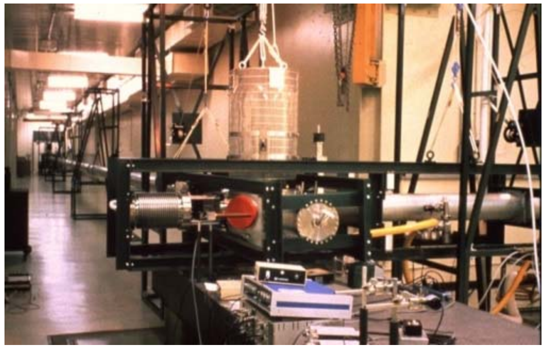
Modern bars
80's-90's



US, 70's-80's, R. Weiss / R. Forward)

Interferometer prototypes,
80's-90's
Glasgow/Garching/Caltech





Brief History

GEO 600 (GEO-HF): 90's-current

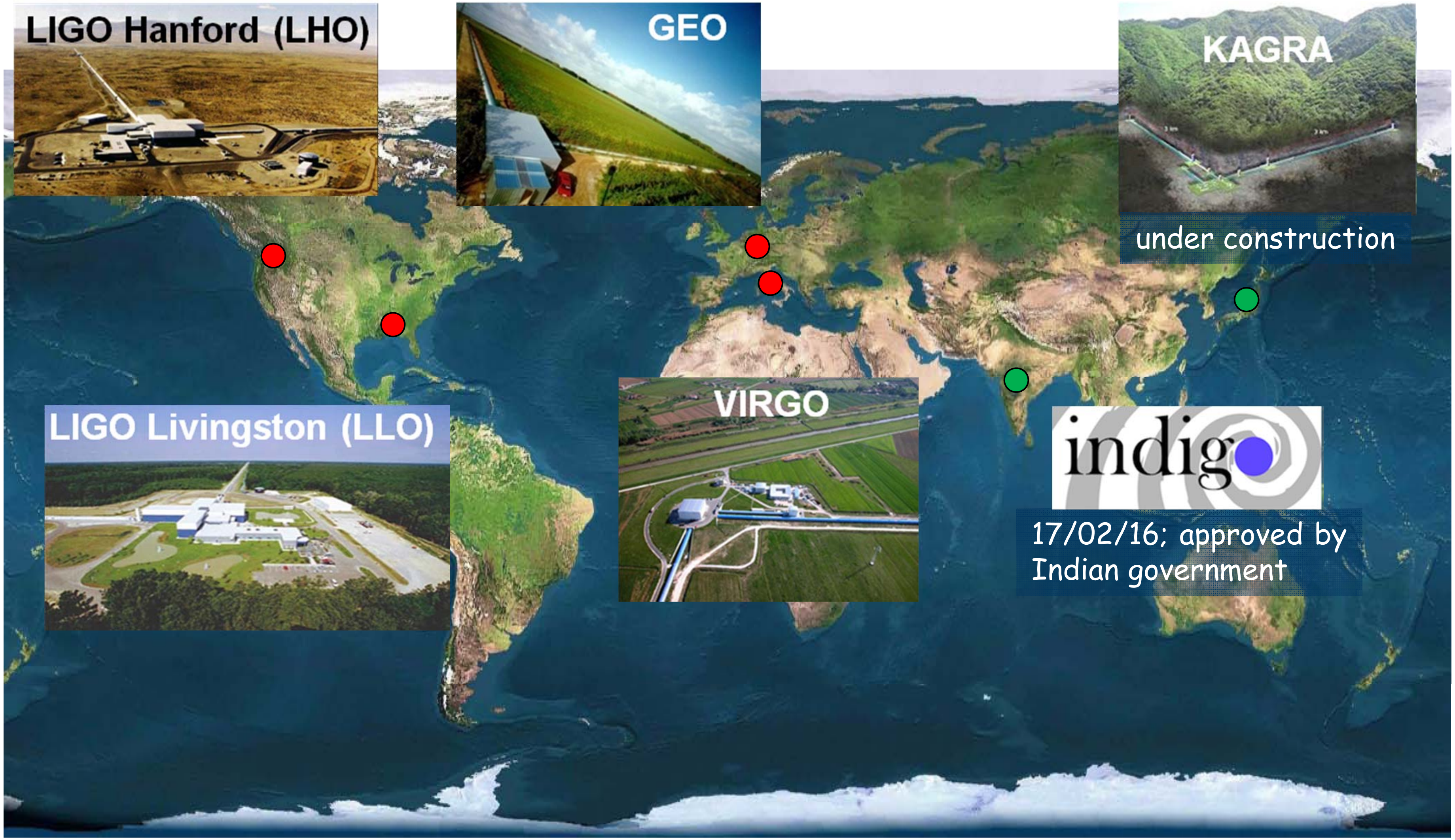
AEI prototype: 2010-current

Glasgow 10m: 1978-current,
this facility from 2003

LIGO/aLIGO: 90's-current

- The UK has a strong history, and continues to have a leadership role in current detector technology and implementation

International Network

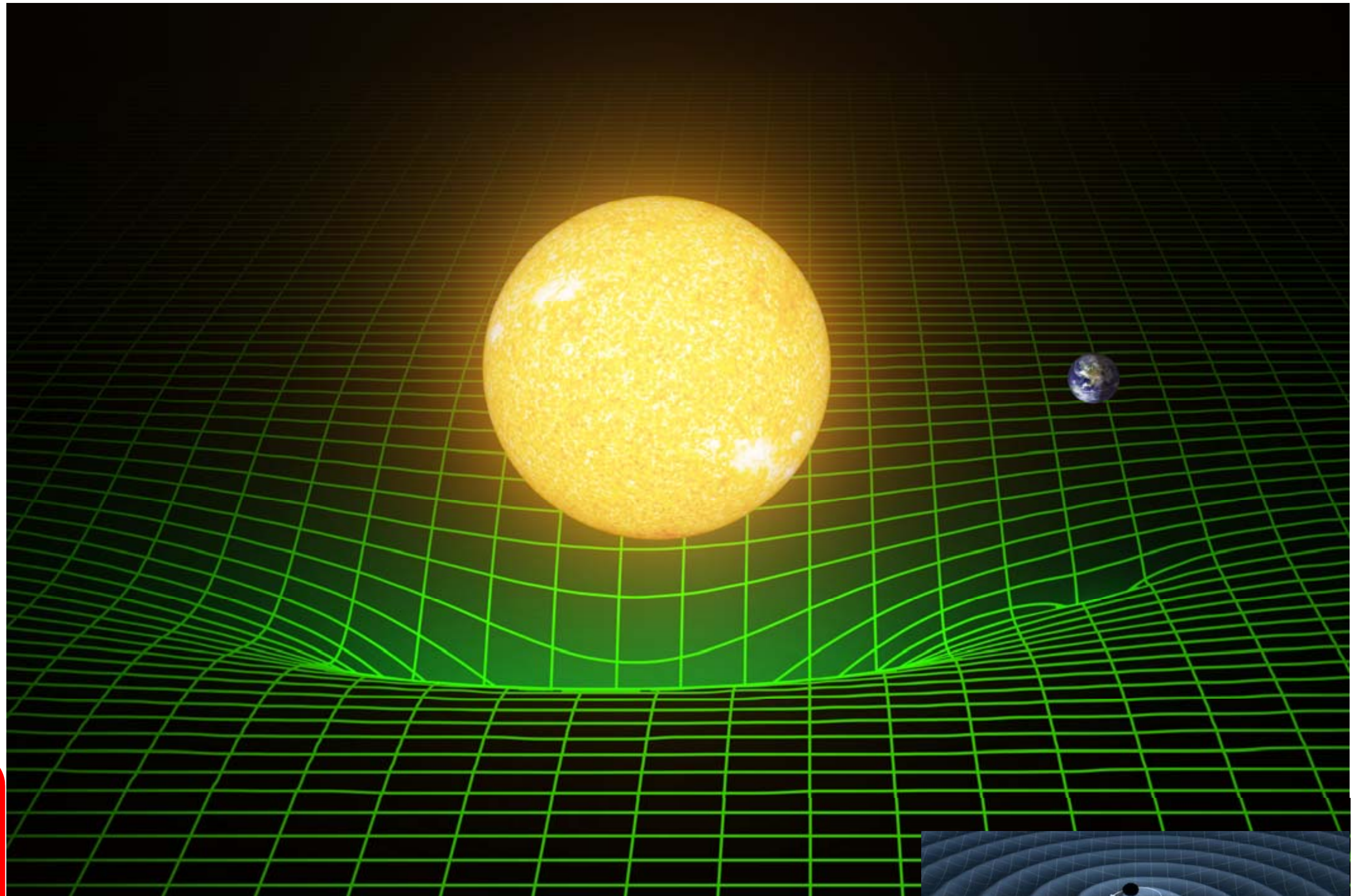


- A network is required to localise the source direction

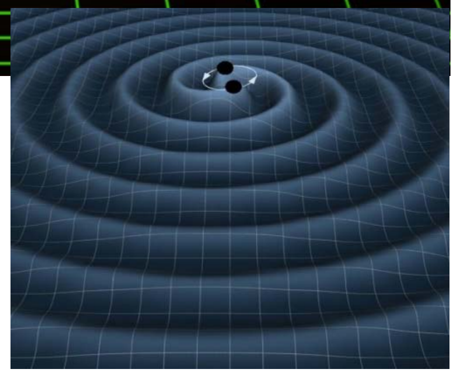
General Relativity & Gravitational Waves

- Gravity is emergent from geometry in GR
- matter/energy curves space-time
- space-time tells light/matter how to move

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$



Changes in space-time curvature travel at the speed of light



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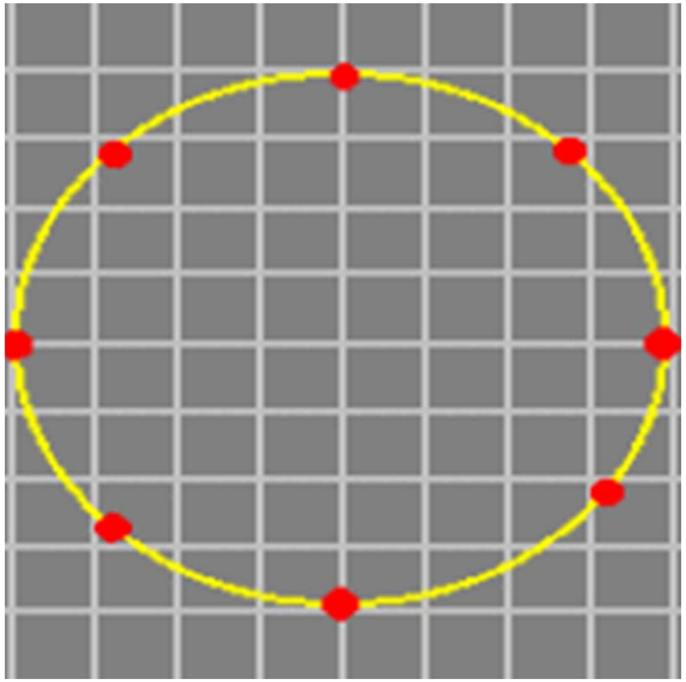
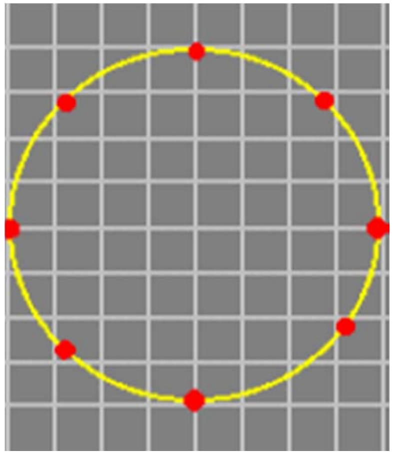
IGR SUPA LSC advancedligo

Effect of GW on space-time

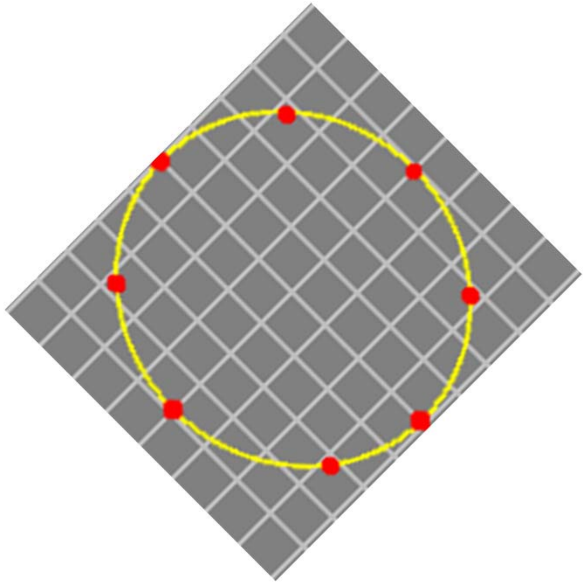
Gravitational Wave travelling into the plane



Ring of free particles



"+" polarisation

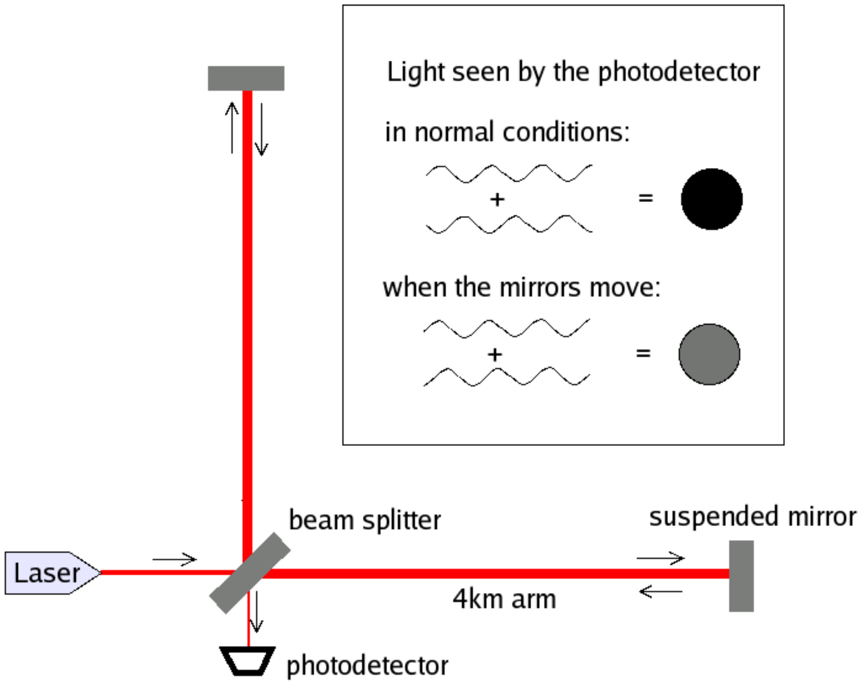


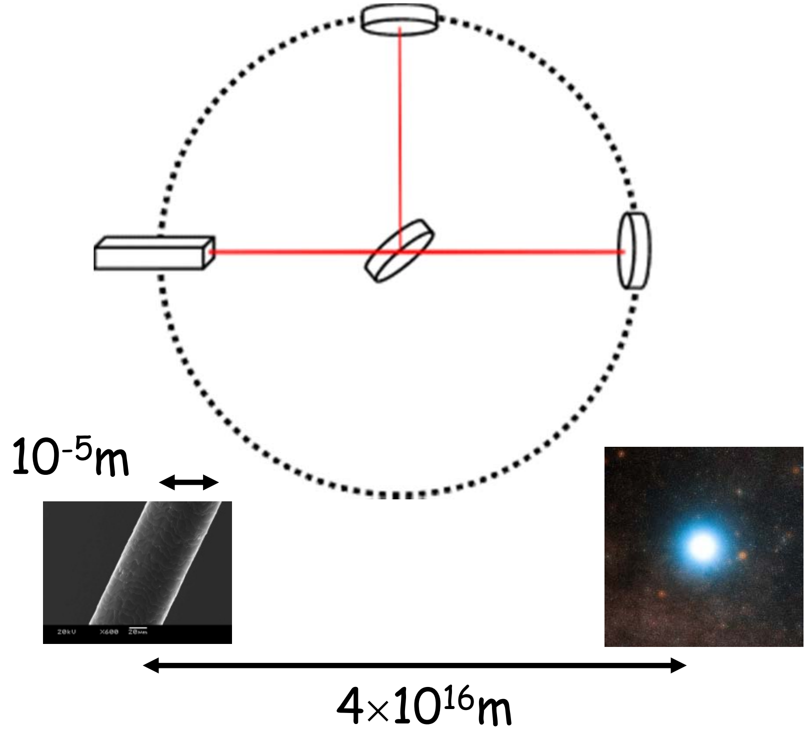
"x" polarisation

We need to measure the ellipticity
[using a ruler that doesn't also stretch]

Interferometric Detectors

- A passing gravitational wave will lengthen one arm and shrink the other arm
- light travelling the two paths from the beam splitter to the test masses (and back) will acquire different phases
- This phase change produces a change in light intensity at output port

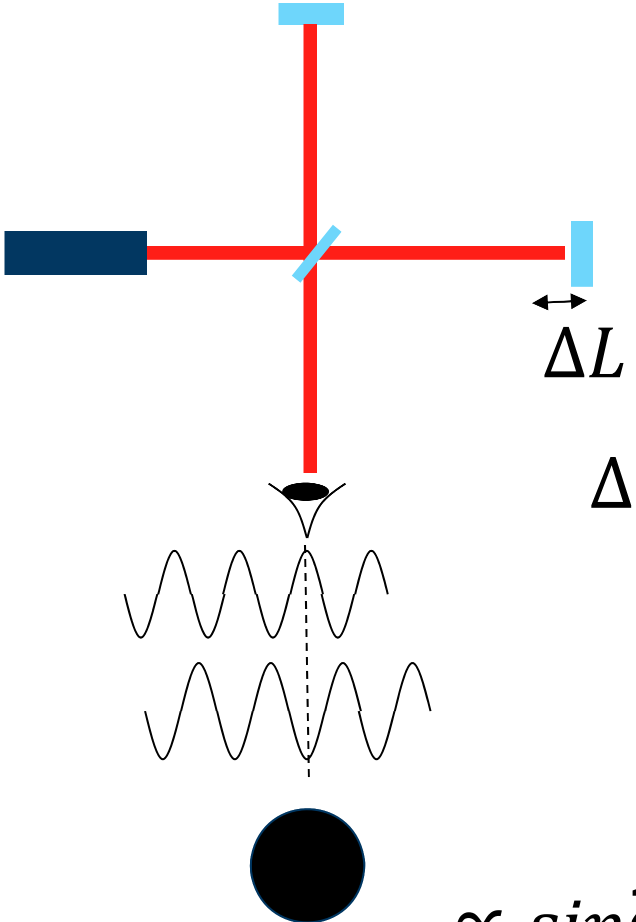




aLIGO specification is 10^{-19} m/√Hz at 10 Hz

Interferometric Detectors

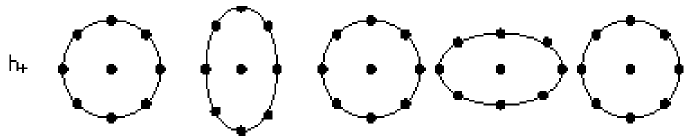
$$h \equiv \frac{\Delta L}{L}$$



$$\Delta\emptyset = \frac{2\pi}{\lambda} 2\Delta L$$

$$h = \frac{1}{2}\frac{\Delta\emptyset_{GW}}{\frac{2\pi}{\lambda}L}$$

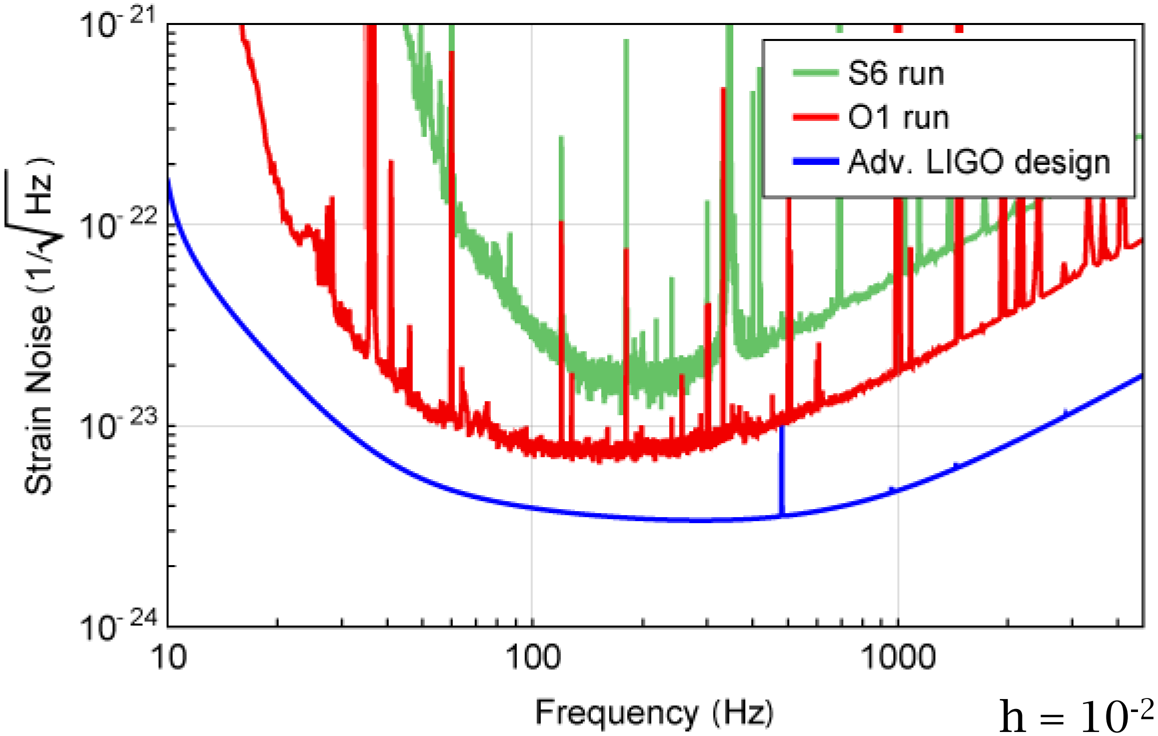
$\propto sin^2 \Delta\emptyset$



Detector Sensitivity

- LIGO ran from 2002 to 2010 – final run S6 ending in 2010
    - No detections made but many upper limits placed on sources

- aLIGO project aim was to increase detection sensitivity by a factor of ~10 – this meant a complete rebuild

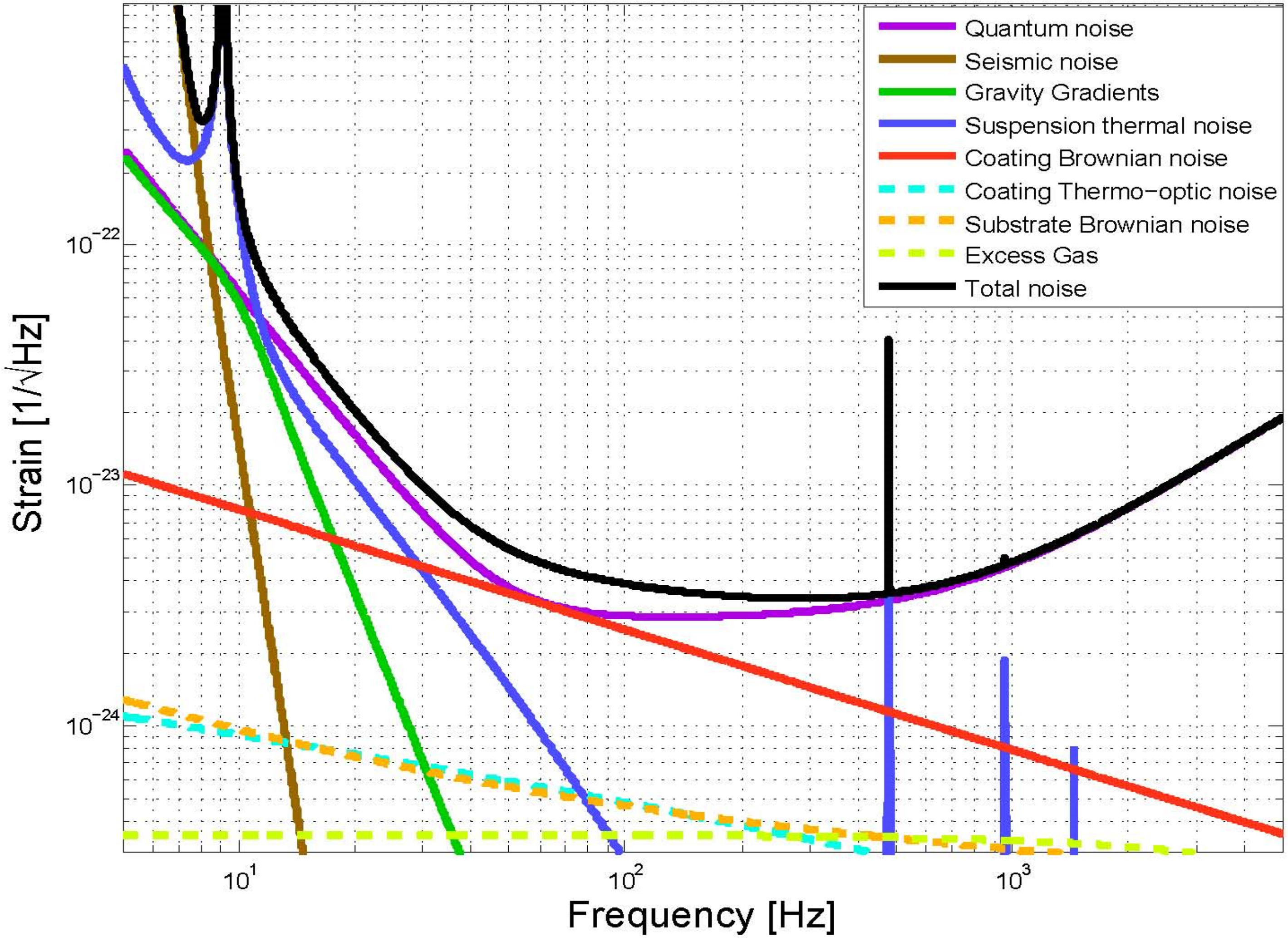


- S6 was final LIGO run
- O1 was first aLIGO run
- Adv LIGO design is final sensitivity goal (2020)

$h = 10^{-23}\ /\sqrt{Hz} \Rightarrow \Delta l = 4\ 10^{-20}\ m/\sqrt{Hz}$

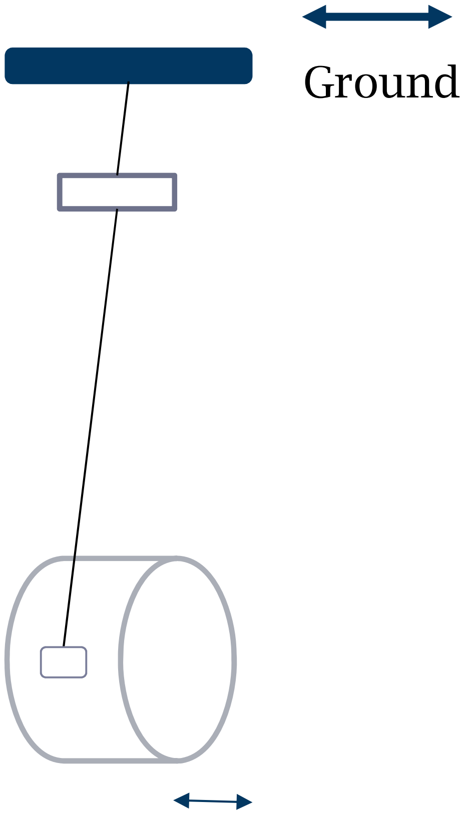
aLIGO Sensitivity

- aLIGO design sensitivity

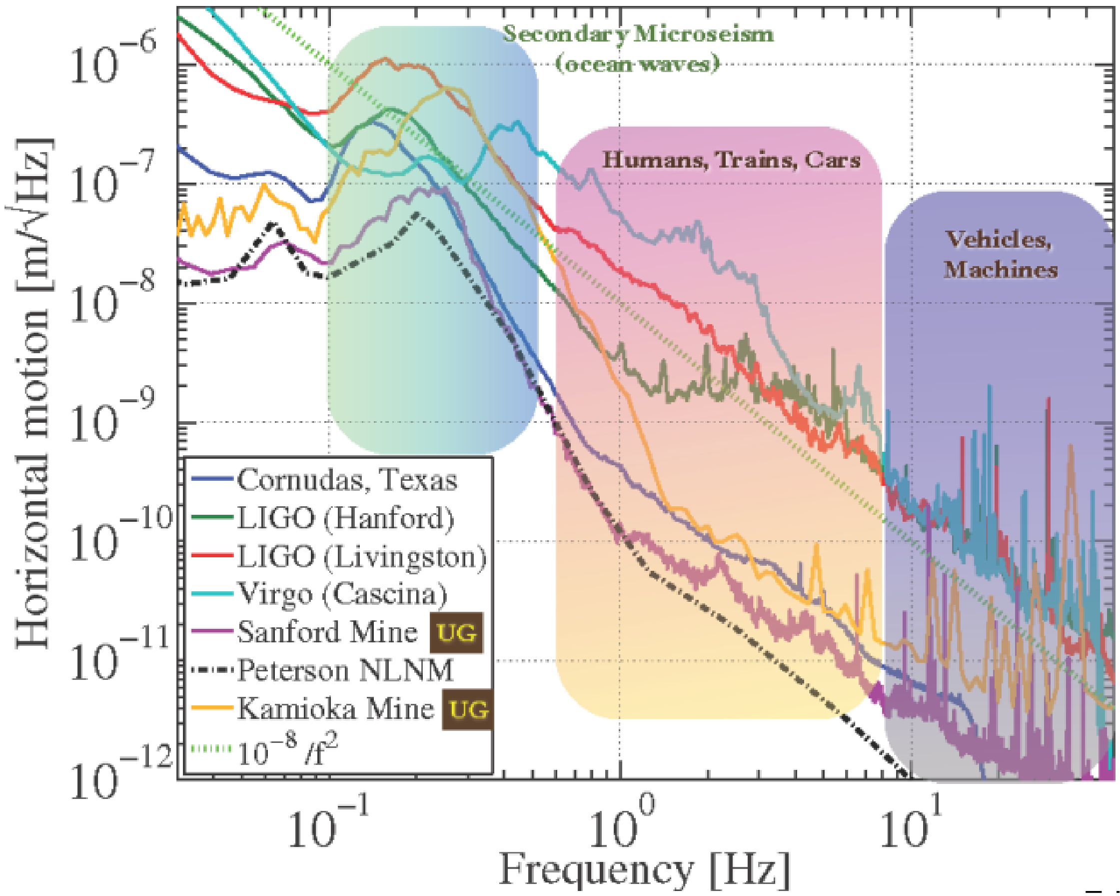


Fundamental Noise Sources

Seismic Noise

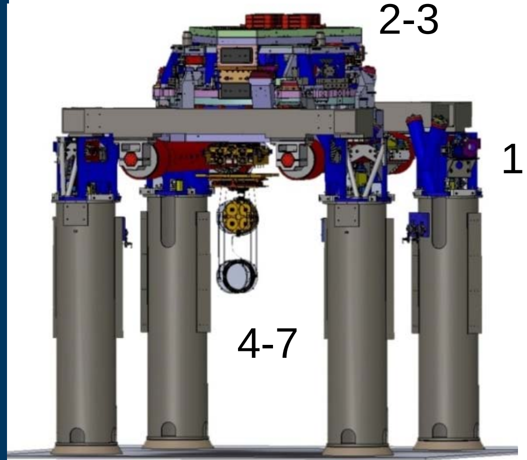


	Requirements
Seismic Noise	10^{-19} m/√Hz at 10Hz (assumes seismic platform noise $2x10^{-13}$ m/√ Hz)

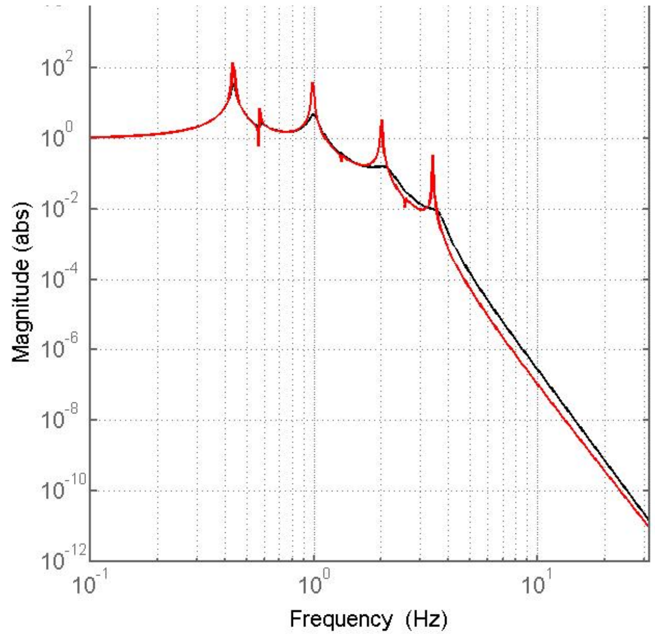


Seismic and Suspensions

- The mirror needs to be suspended to a level 10^{-19} m/√Hz at 10 Hz
- Utilise multiple pendulum systems which are excellent isolators
- aLIGO uses 7 stages (3 seismic active/passive stages + 4 suspension stages)



Transfer function for suspension



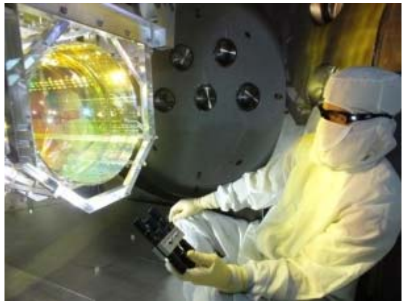
$$\left(\frac{x_{mass}}{x_{ground}}\right) \approx \frac{\omega_0^{\,2}}{\left(\omega_0^{\,2} - \omega^2\right)}$$

$$\left(\frac{x_{mass}}{x_{ground}}\right) \propto \left[\frac{\omega_0^{\,2}}{\omega^2}\right]^N$$

- $(f_0/f)^8$ for 4 stages $\approx (1.5/10)^8 \approx 3e\text{-}7$

Fundamental Noise Sources

Thermal Noise



	Mirror Requirements
Thermal Noise	10^{-19} m/√Hz at 10Hz (longitudinal) 10^{-16} m/√Hz at 10Hz (vertical)

$$S_x(f) = \frac{k_B T}{\pi^2 f^2} \left|\mathrm{Re}\left[Y(f)\right]\right|$$

Everything moves

Even if the external environment was perfectly noise-free, all our internal parts are generating their own displacement noise

Fluctuation–Dissipation theorem relates power spectral density, S_x (m^2/Hz), to mechanical admittance, Y

For the mirror coating, in amplitude terms:

$$A_x(f) \propto \left(T \frac{d}{f w^2} \varphi_c\right)^{1/2} \quad \mathrm{m}/\sqrt{\mathrm{Hz}}$$

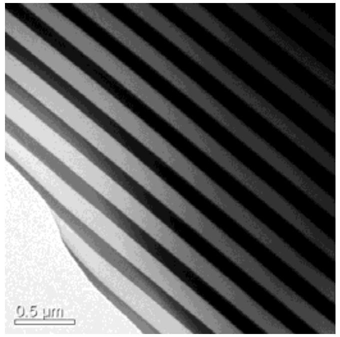
w = laser beam radius

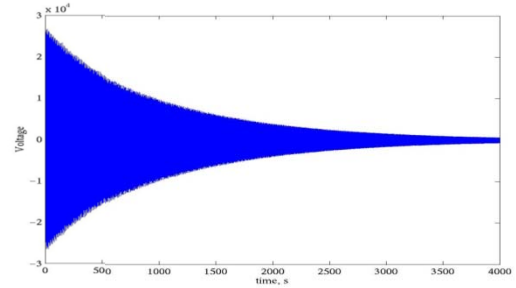
d = coating thickness

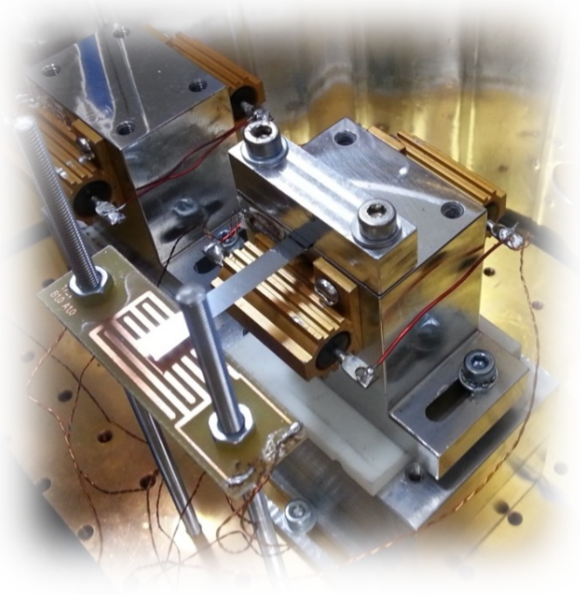
φ_c = mechanical loss

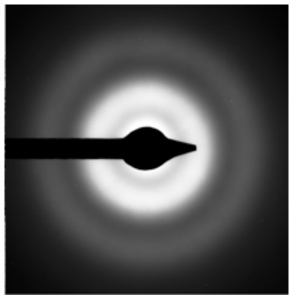
Coating Thermal Noise

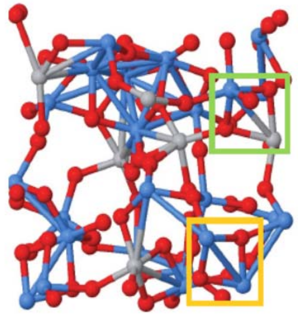
- Brownian thermal noise associated with the mirror coatings will limit design sensitivity of aLIGO at ≈70Hz.
- Amorphous Ion Beam Sputtered coatings are currently the materials of choice for aLIGO;
- Ta_2O_5 (high index) loss is greater than SiO_2 (low index) loss



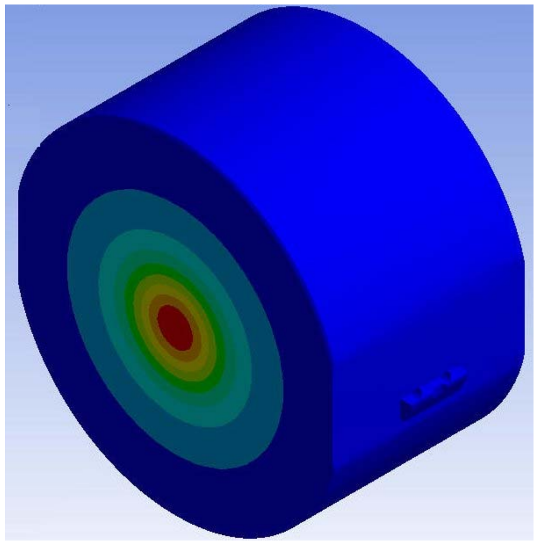






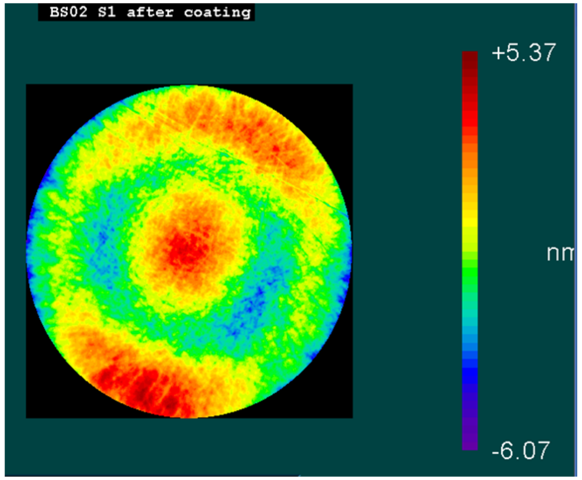


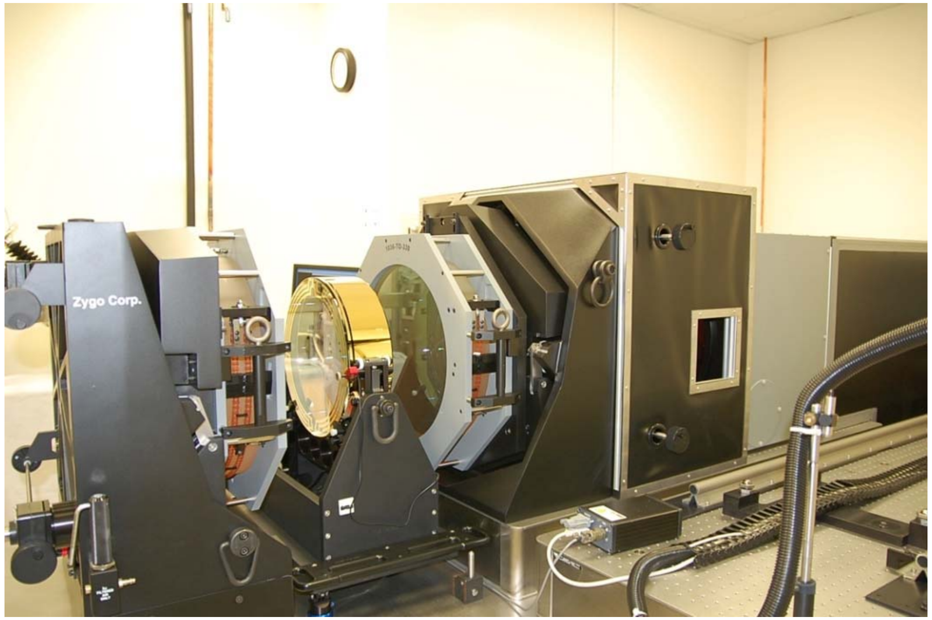
coating microstructure

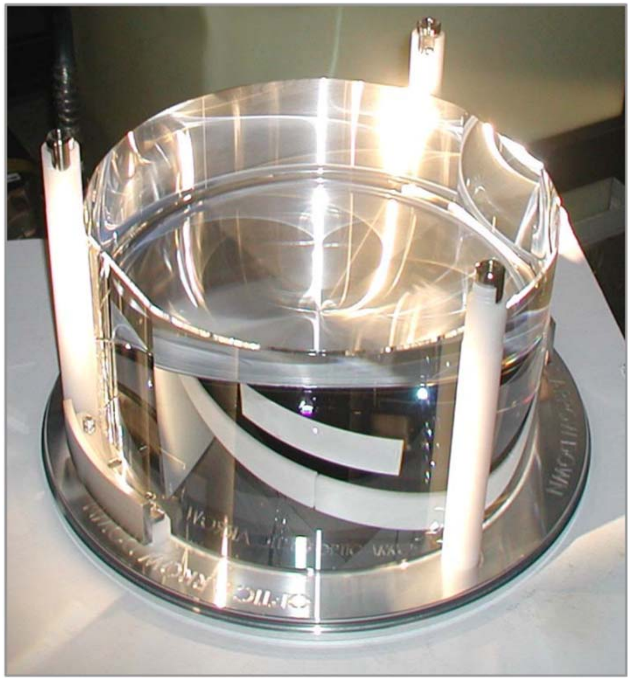


Core Optics

- 40kg test masses are suspended as "free" particles
- Fused silica substrates with low OH content
- Two step polish:
  - Superpolish: ~1 Å microroughness
  - Ion Beam Figuring: corrects figure, maintains microroughness

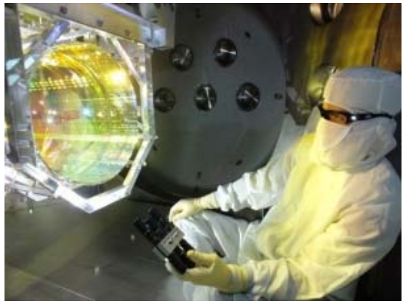



Zygo Interferometer, Caltech



Fundamental Noise Sources

Thermal Noise



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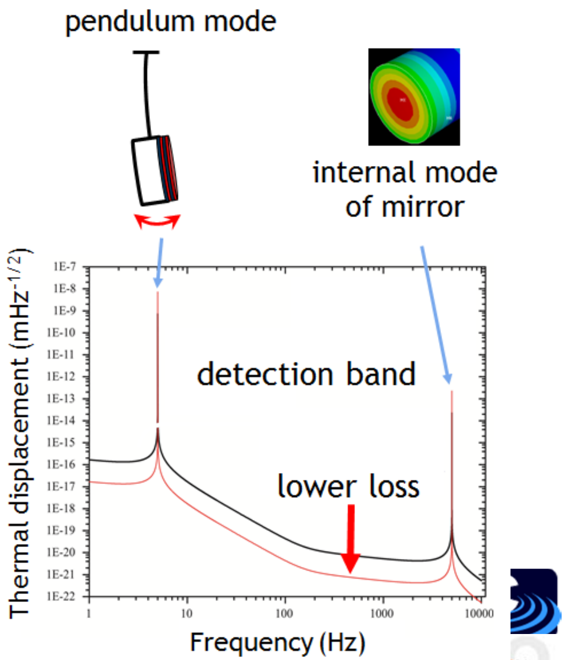
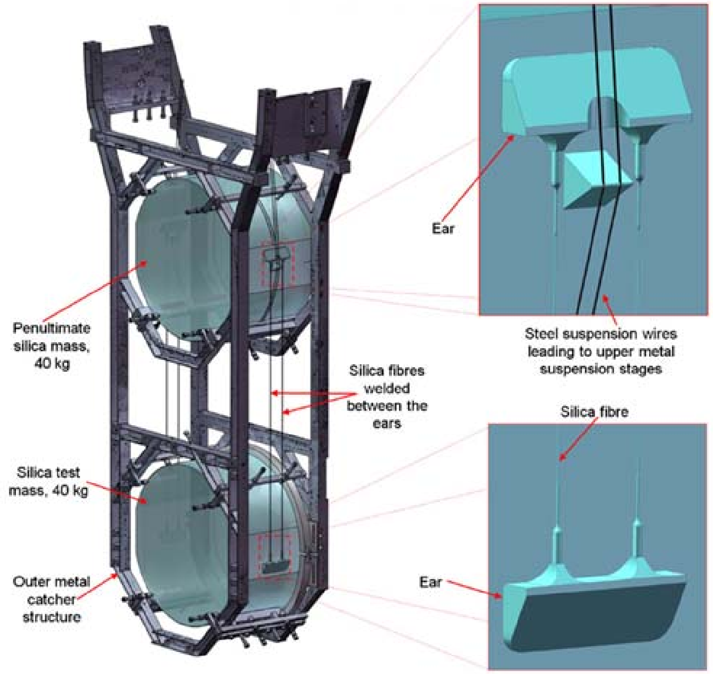
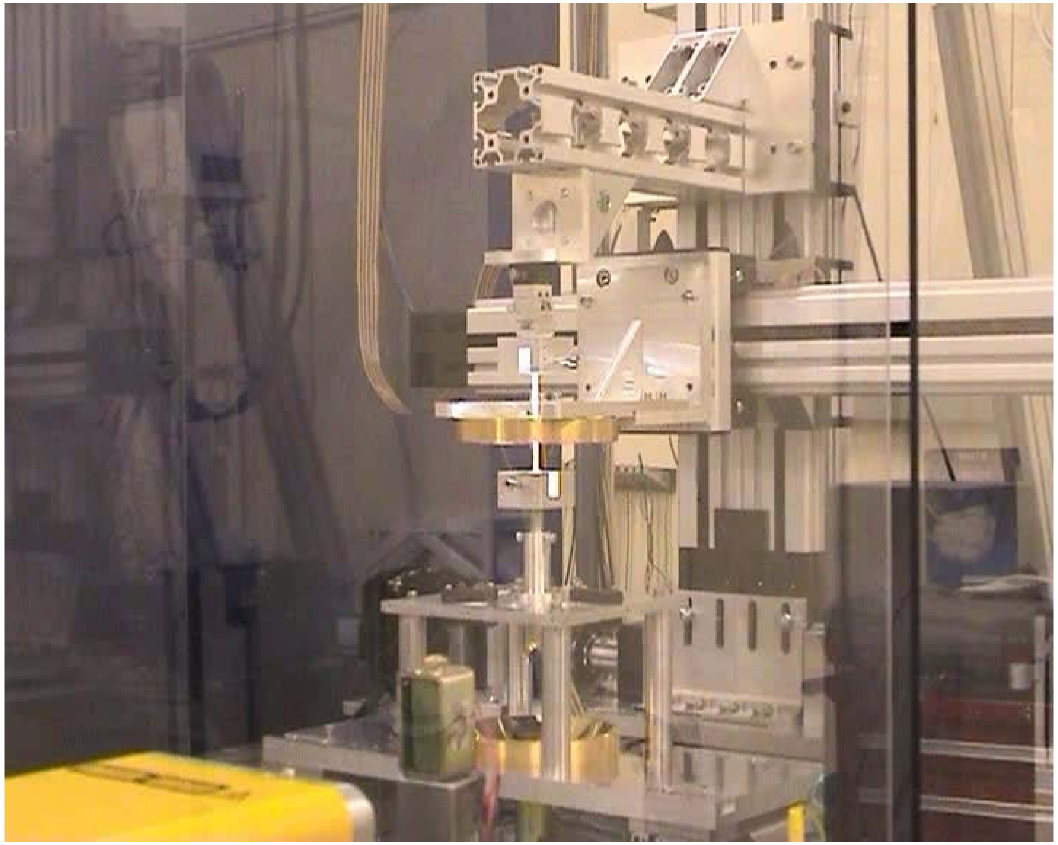


- Pendulum mode 1 Hz
- Suspension violin modes 500 Hz
- Mass internal modes few kHz

We minimise the noise in our detection band by minimising mechanical loss φ_c

Fused Silica Fibre Pulling





Low thermal noise requires ultra-low loss materials => fused silica

Glasgow has supplied the machines used in AdV VIRGO and aLIGO

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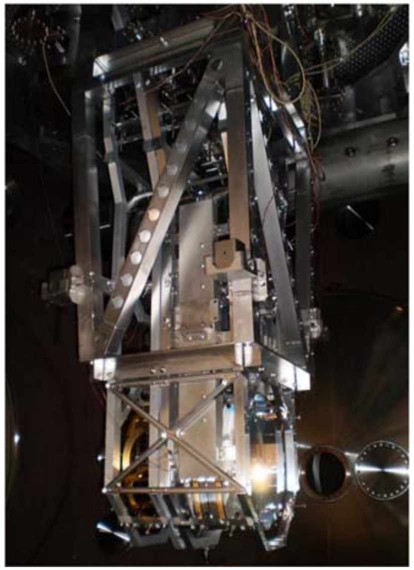
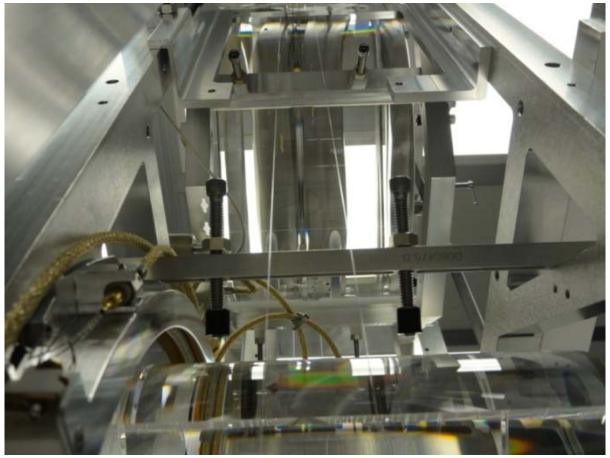
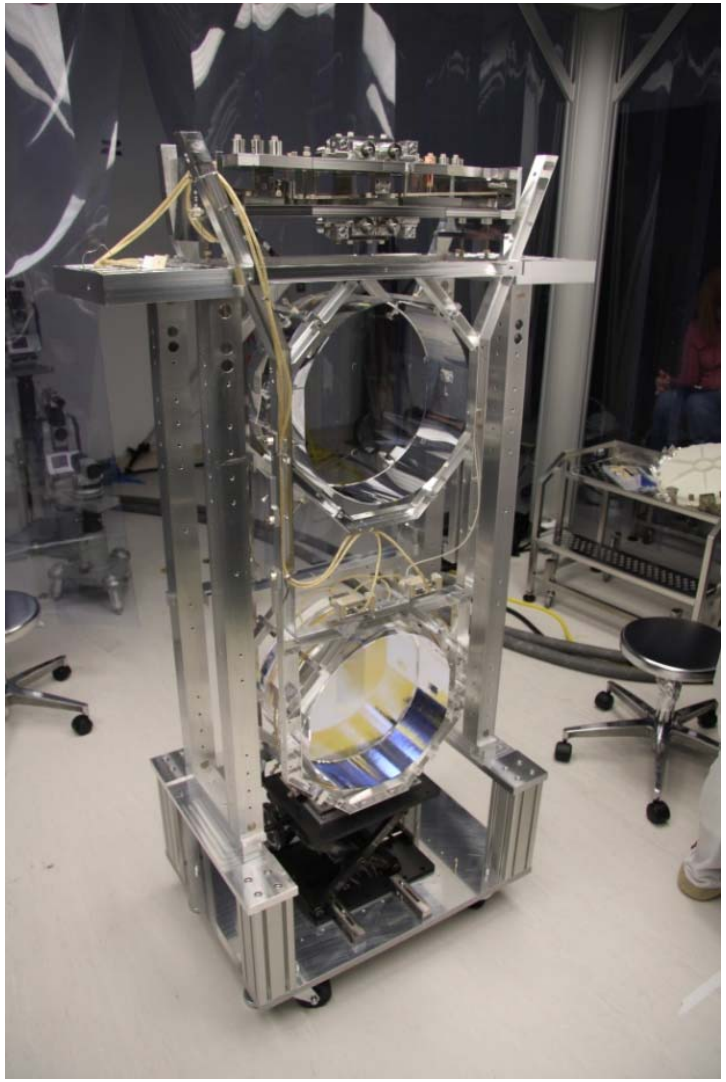
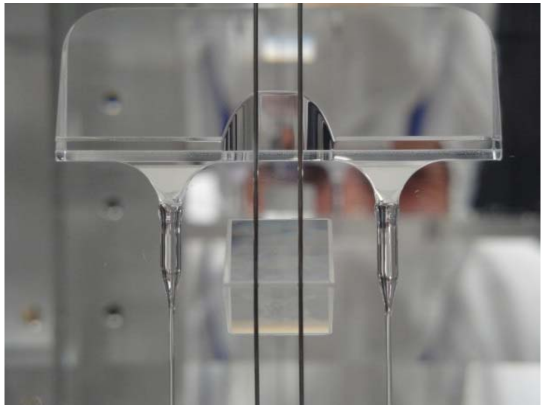
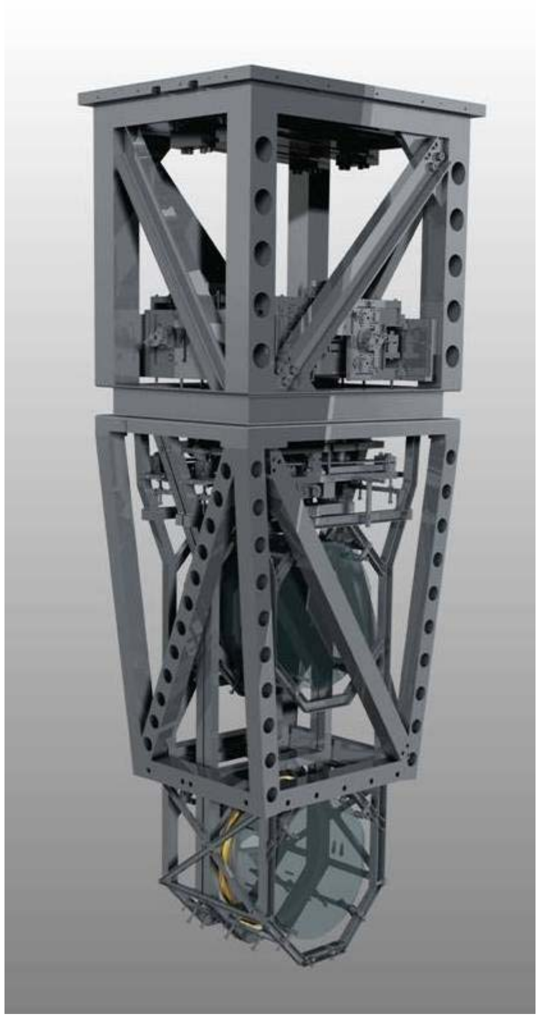
aLIGO Suspensions


Fused silica technology has been essential to meet aLIGO requirements

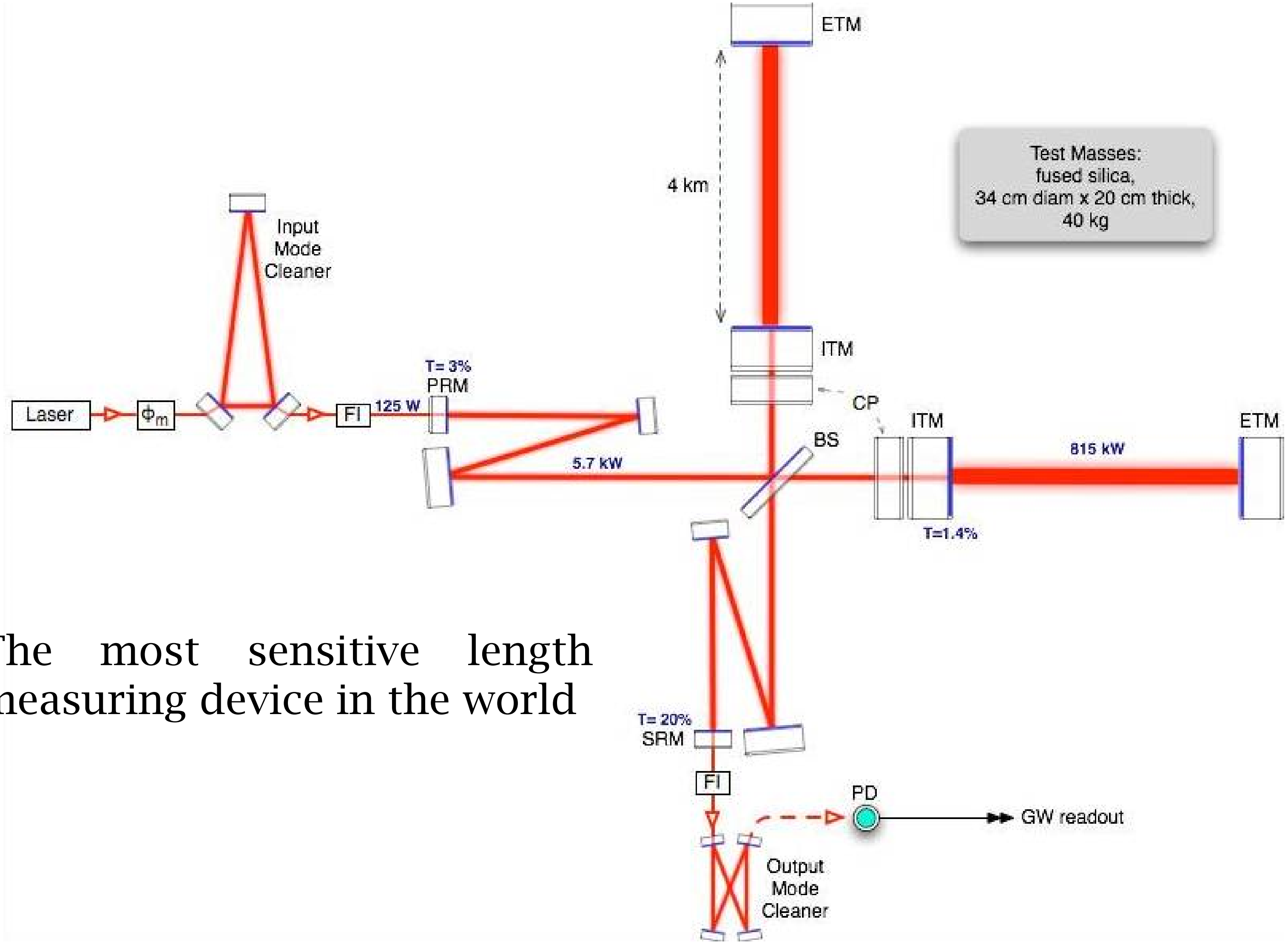
aLIGO Quadruple Suspension

- The input test masses (ITM) and end test masses (ETM) of Advanced LIGO are suspended via a quadruple pendulum system
- **Seismic isolation:** use quadruple pendulum with 3 stages of maraging steel blades for horizontal/vertical isolation
- **Thermal noise reduction:** monolithic fused silica suspension as final stage
- **Control noise minimisation:** use quiet reaction pendulum for global control of test mass position
- **Actuation:** Coil/magnet actuation at top 3 stages, electrostatic drive at test mass



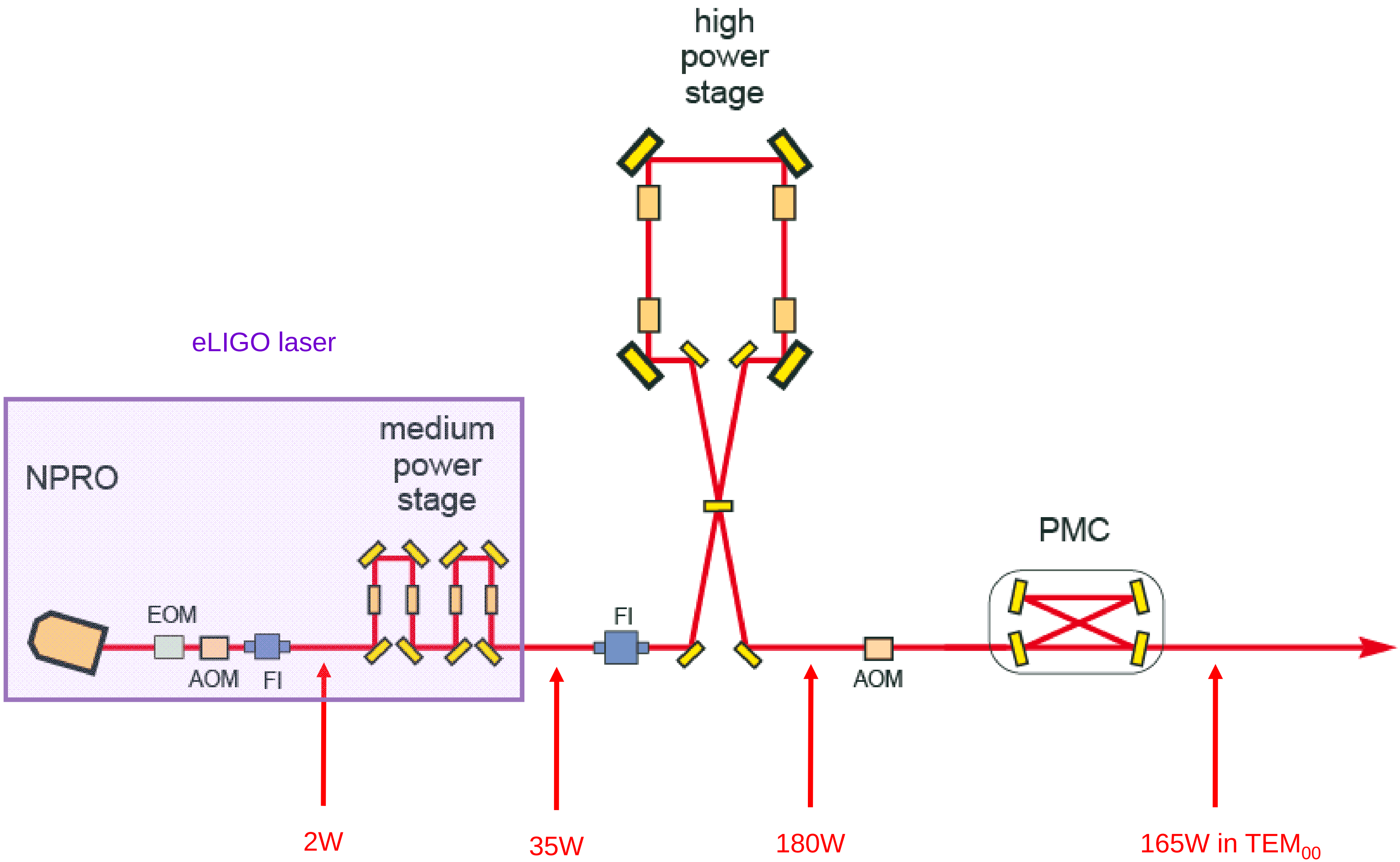
Developed under the ALUK project (Glasgow/RAL/Birmingham/Strathclyde)

A Bit More Detail

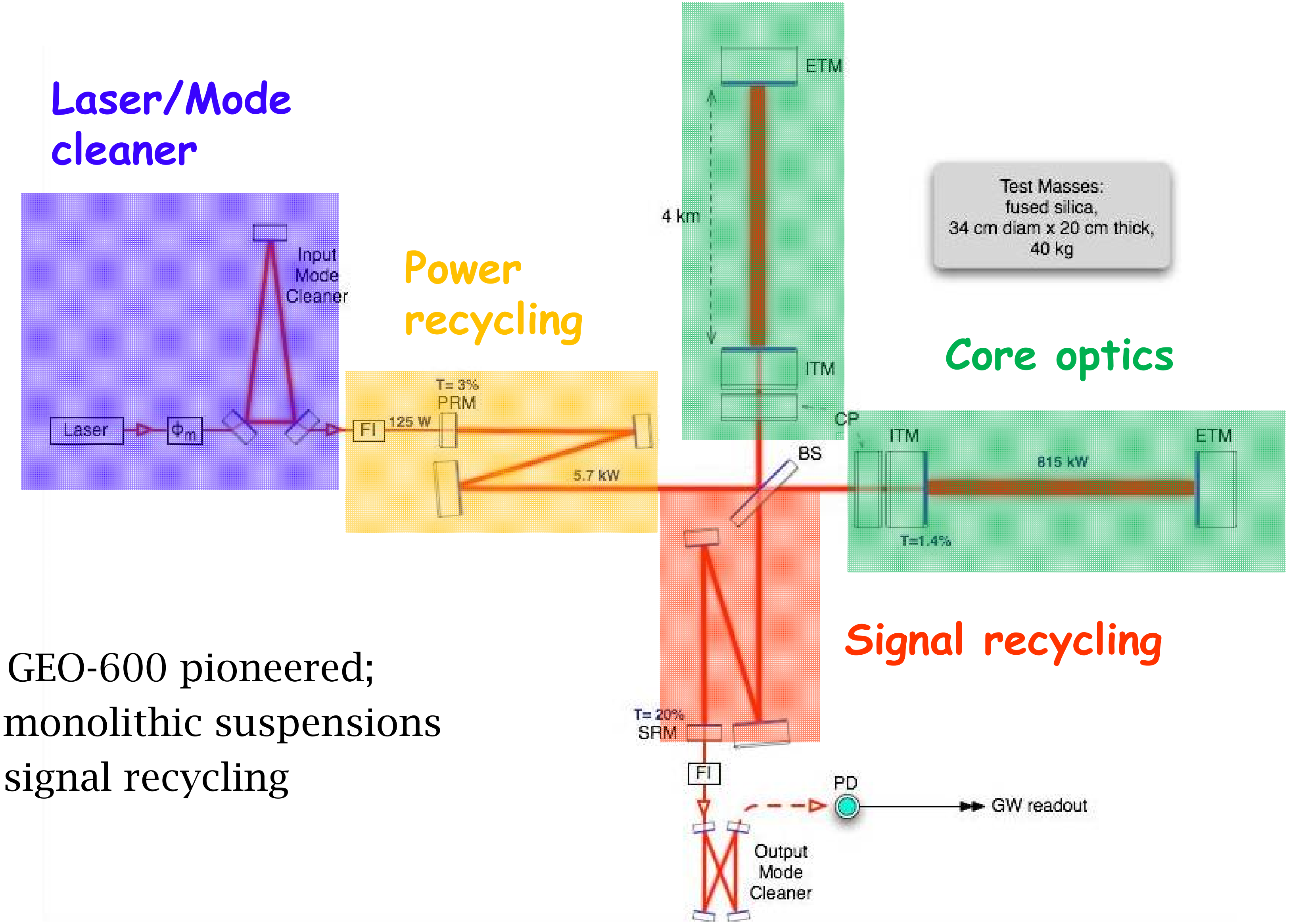


- The most sensitive length measuring device in the world

Laser


high
power
stage
eLIGO laser
NPRO
medium
power
stage
EOM
AOM
FI
FI
PMC
AOM
2W
35W
180W
165W in TEM00

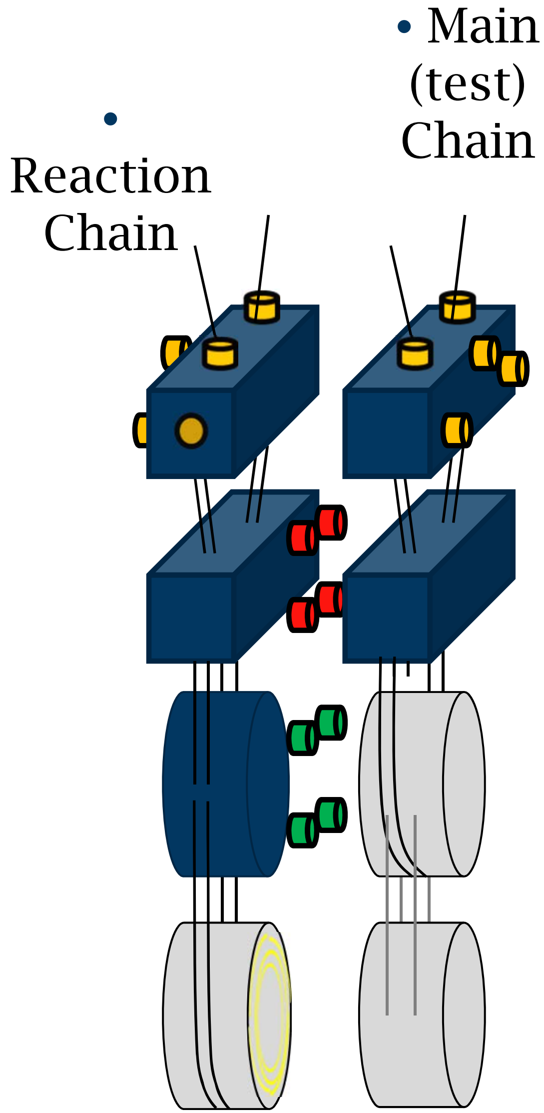
A Bit More Detail

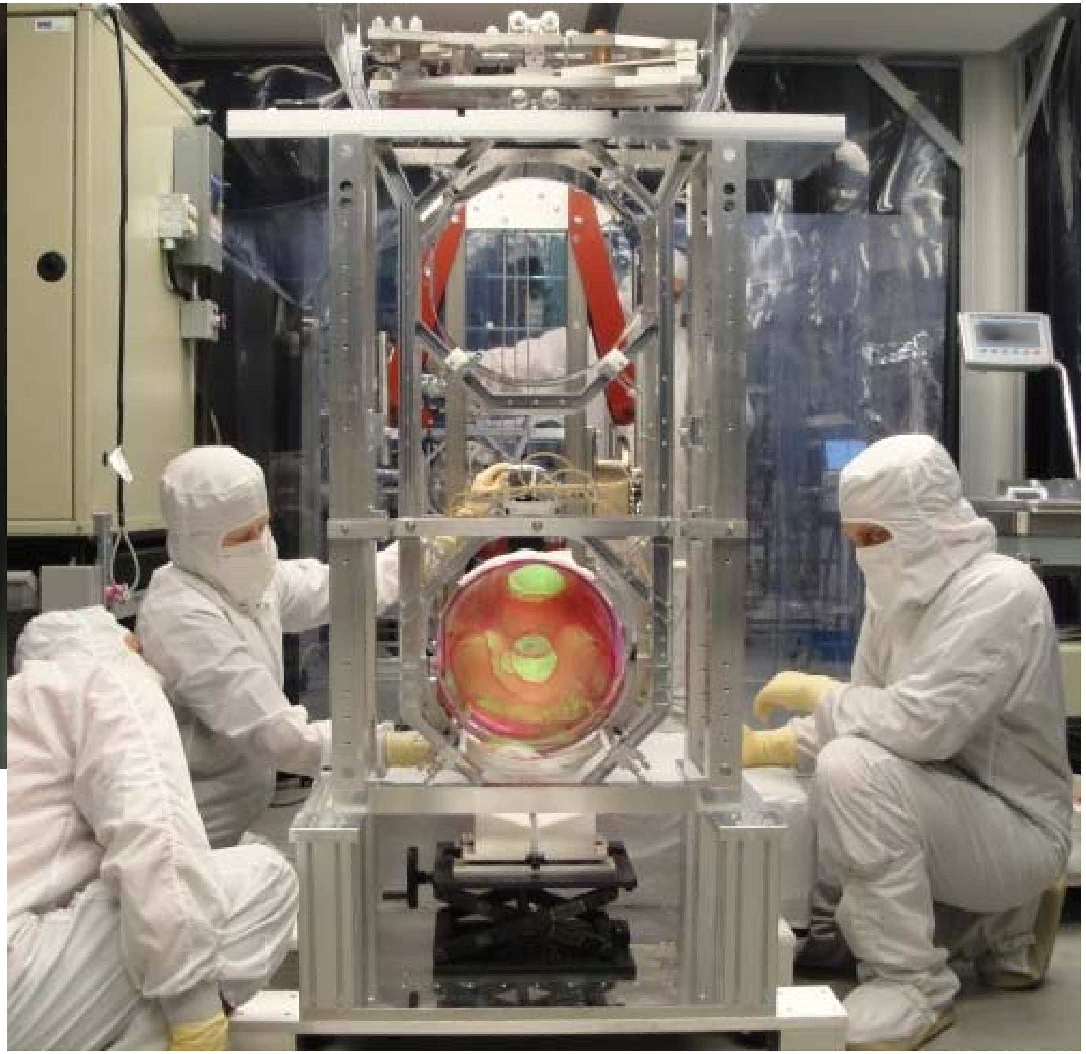


- GEO-600 pioneered;
  - monolithic suspensions
  - signal recycling

Local and Global Control

- Local control: damping at top mass, separately for each chain, using Optical Sensors/Electromagnetic Actuators
- Global control (length and angular) at all four levels
  - Control strength decreases as we go down the chain
  - Electrostatic drive (ESD) using gold pattern on reaction mass/compensator plate at test mass level
- Calibration
  - Direct actuation on the test mass with another laser provides a very well known force

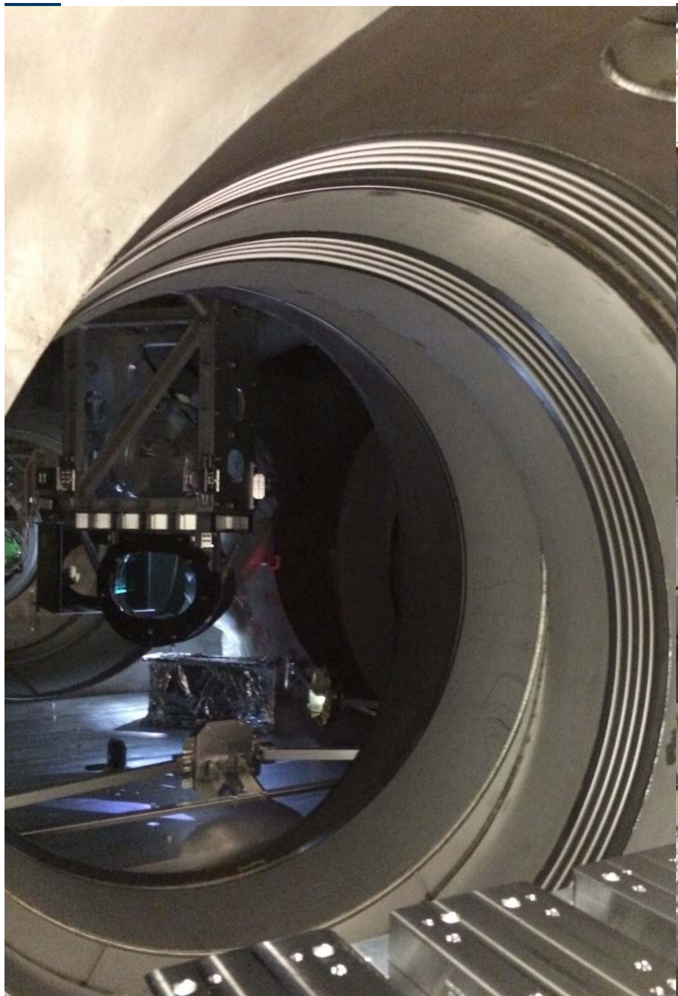


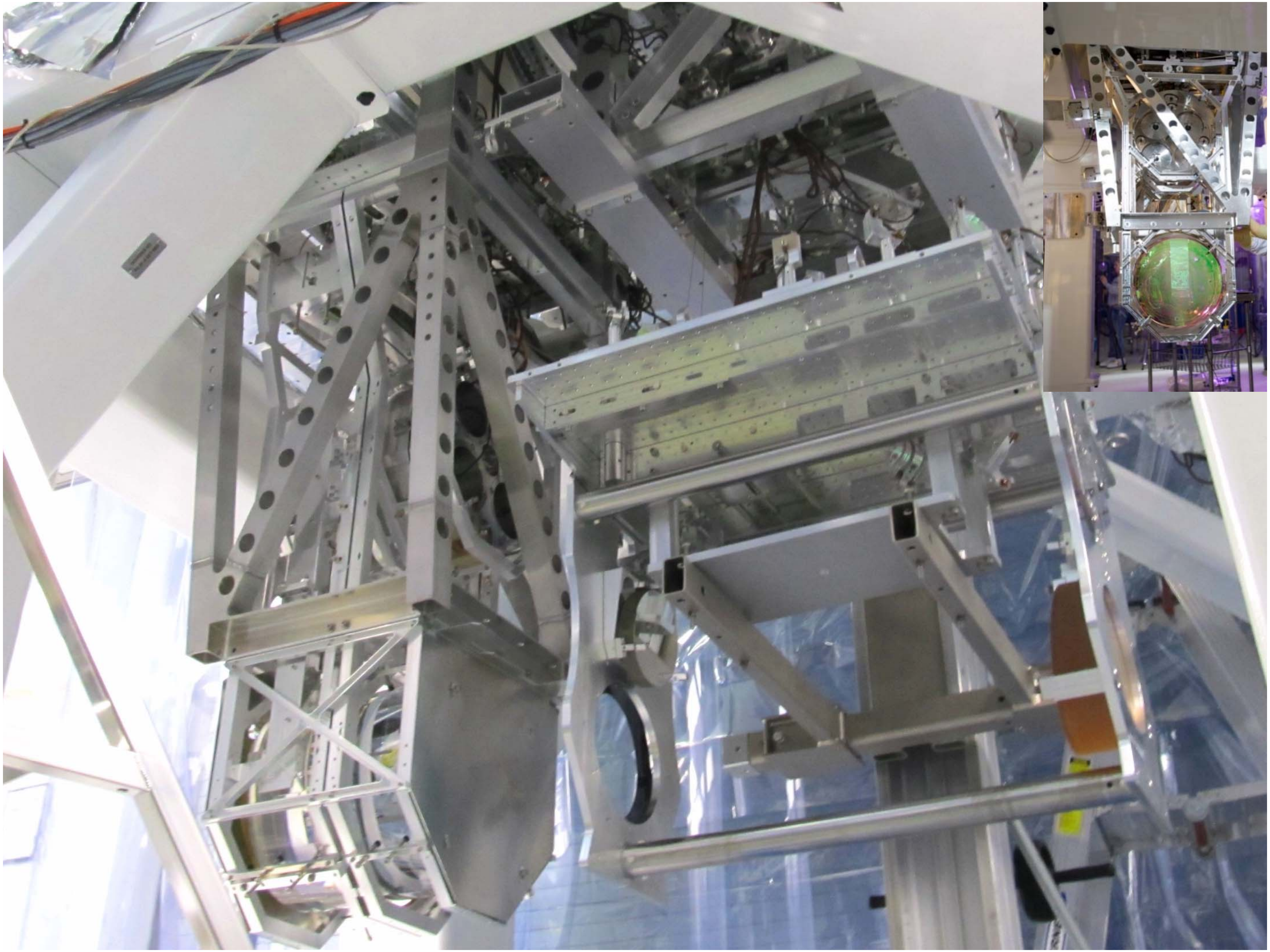


Building and installing quadruple suspension at LIGO Hanford site

University of Glasgow

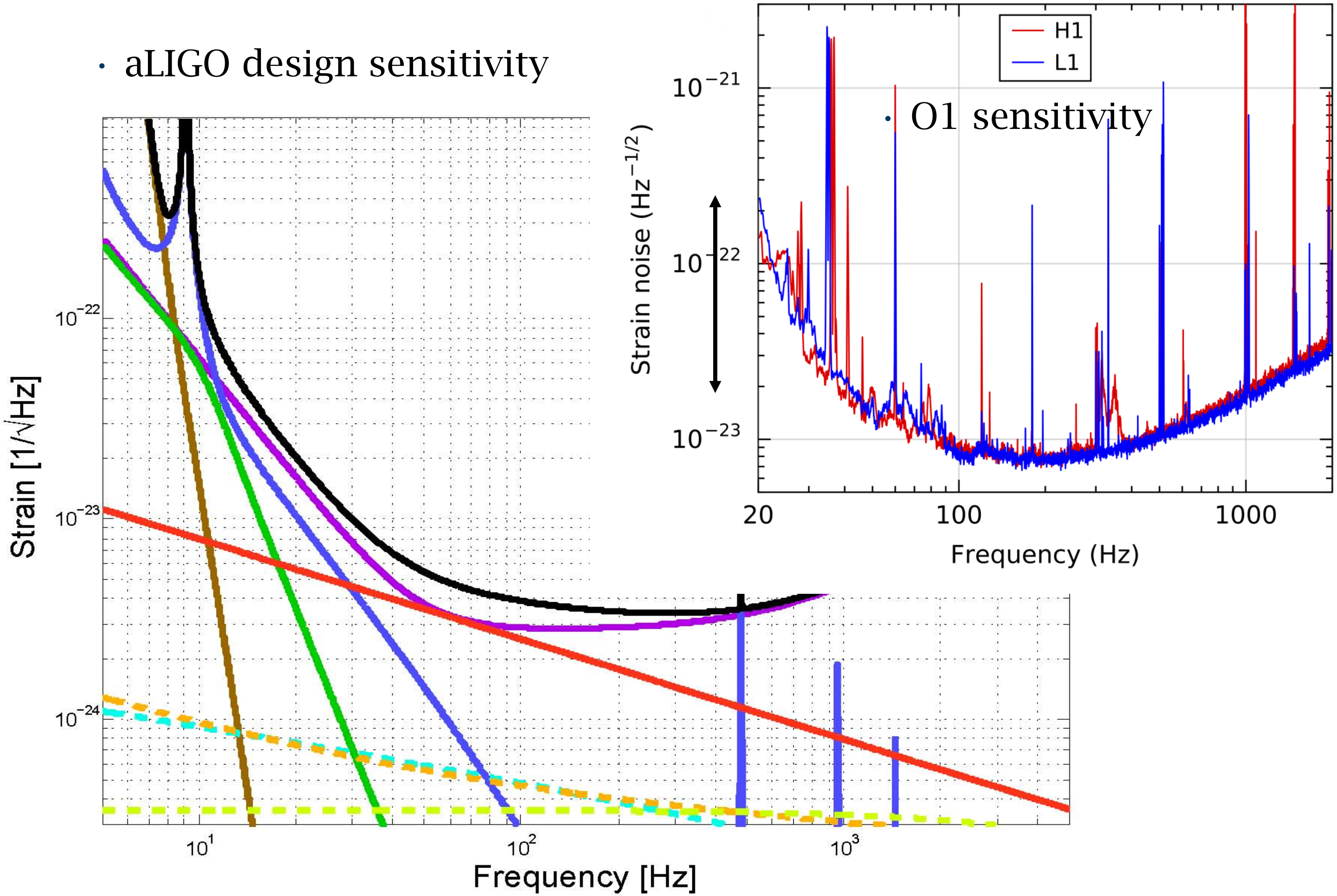
IGR SUPA LSC advancedligo



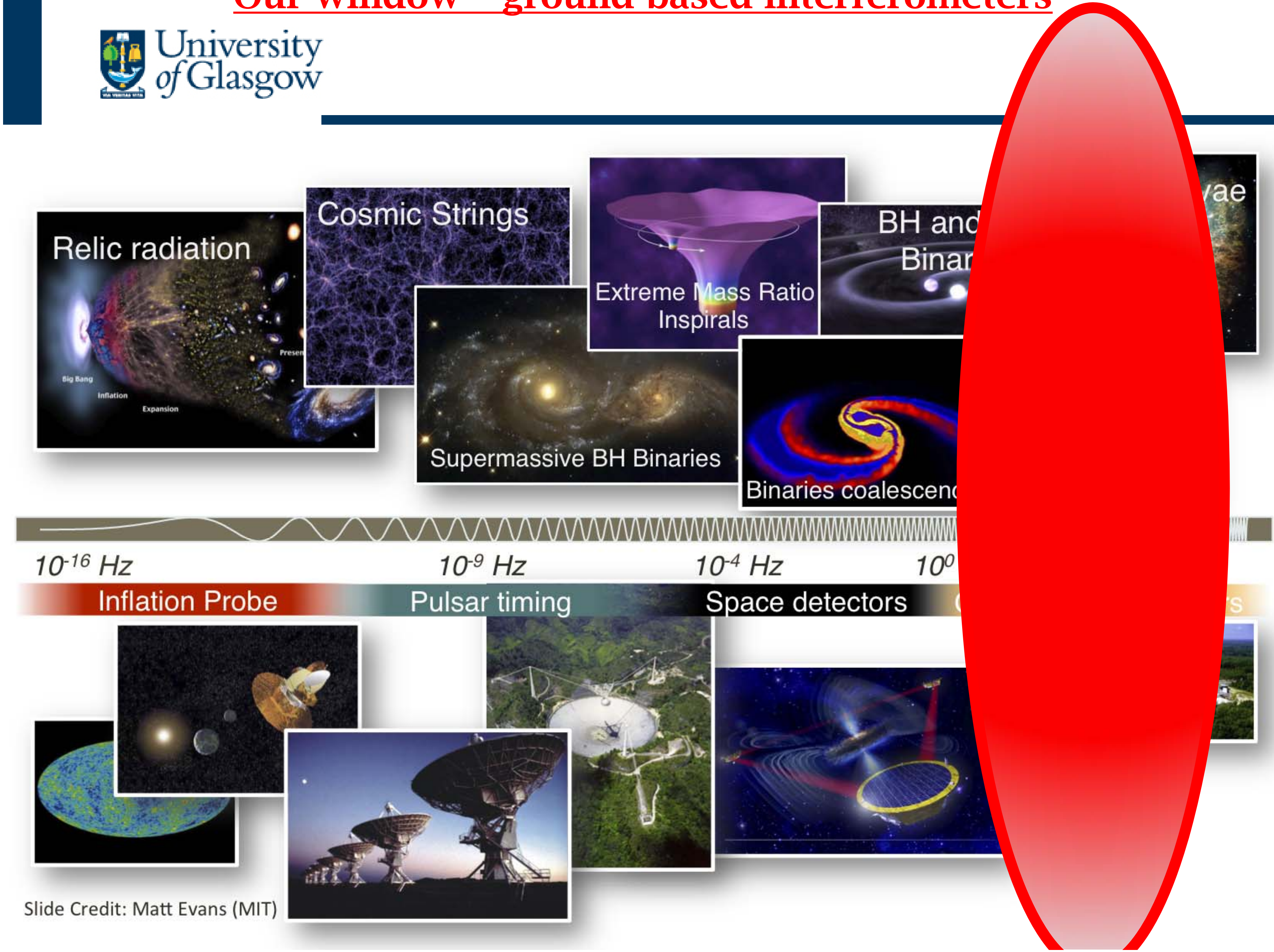
aLIGO Sensitivity

- aLIGO design sensitivity



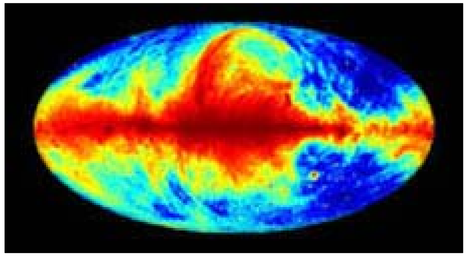
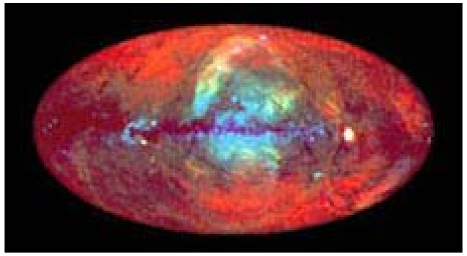
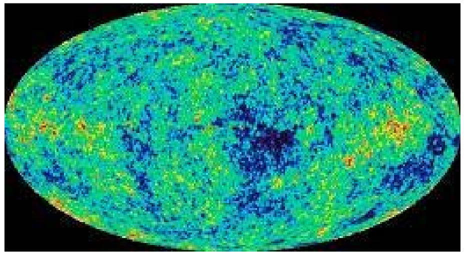
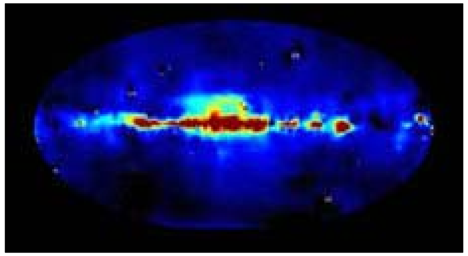
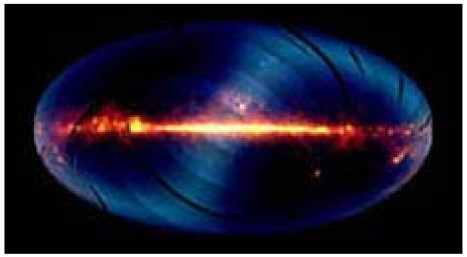
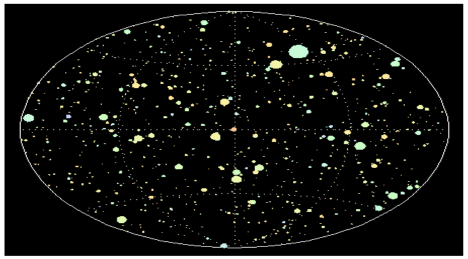
- O1 sensitivity

Our window – ground based interferometers



Slide Credit: Matt Evans (MIT)

A New Probe of the Universe


- Gravitational Waves will give us a different, non electromagnetic view of the universe, and open a new spectrum for observation.
- This will be complementary information, as different from what we know as *hearing* is from *seeing*.

EXPECT THE UNEXPECTED!

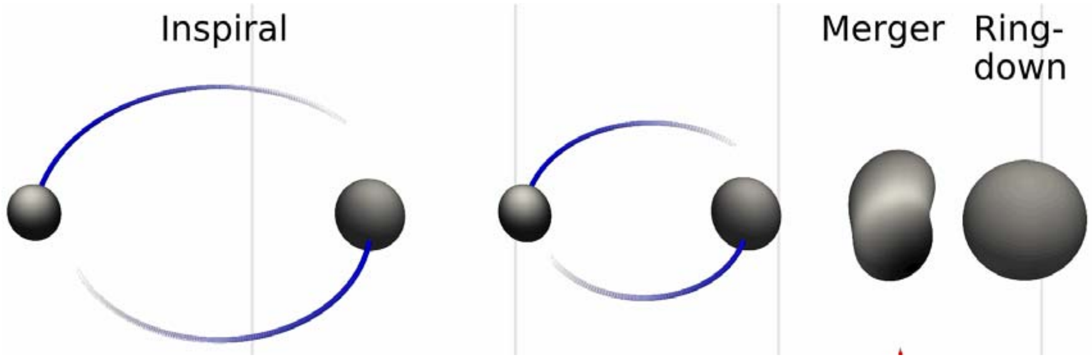
First Detection

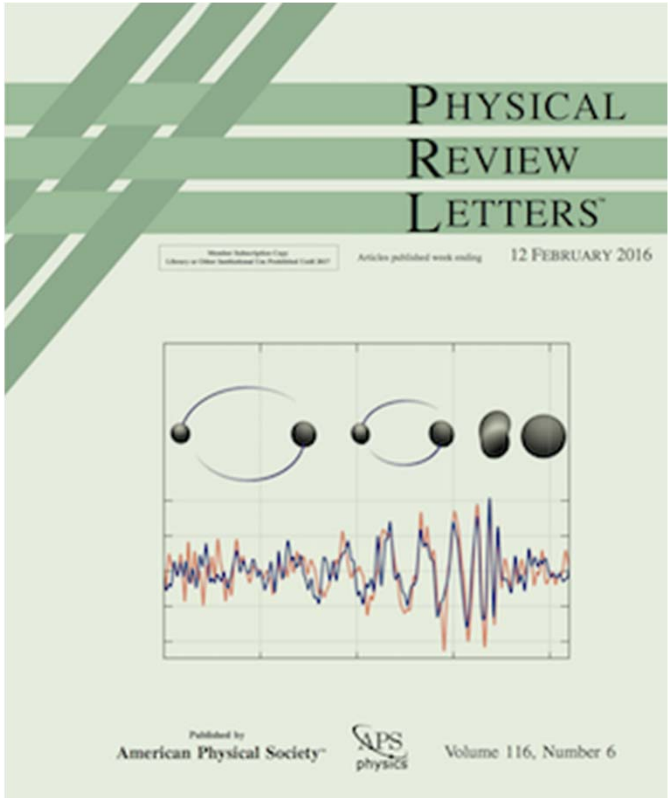
LIGO Update on the Search for Gravitational Waves

GW150914: The Paper

- Excerpt from the detection paper:

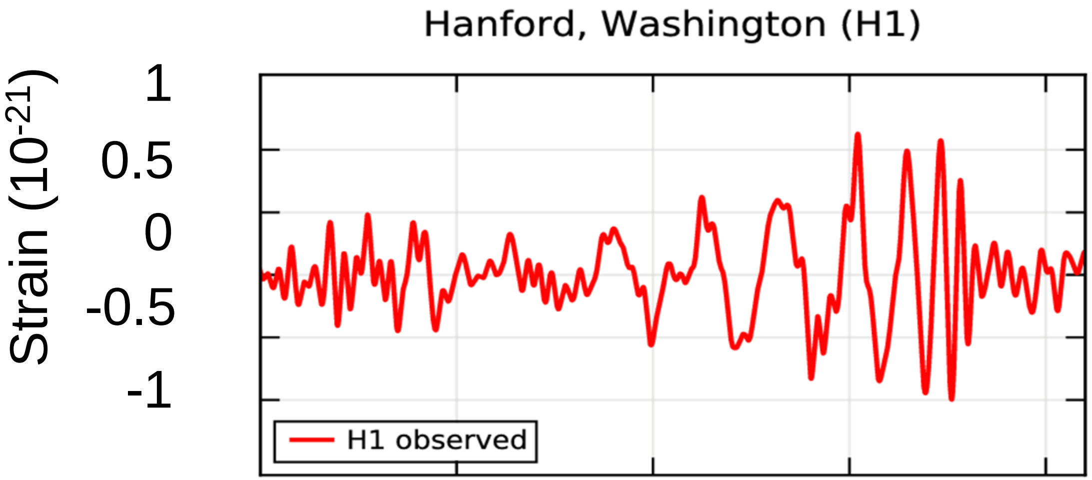
"On September 14, 2015 at 09:50:45 UTC, the LIGO Hanford, WA, and Livingston, LA, observatories detected the coincident signal GW150914 …"

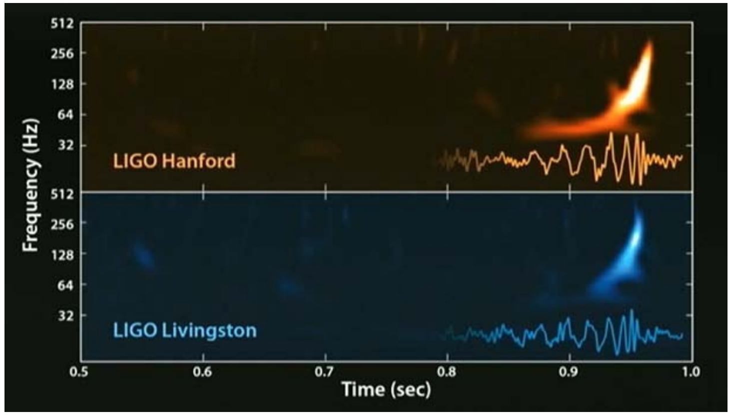


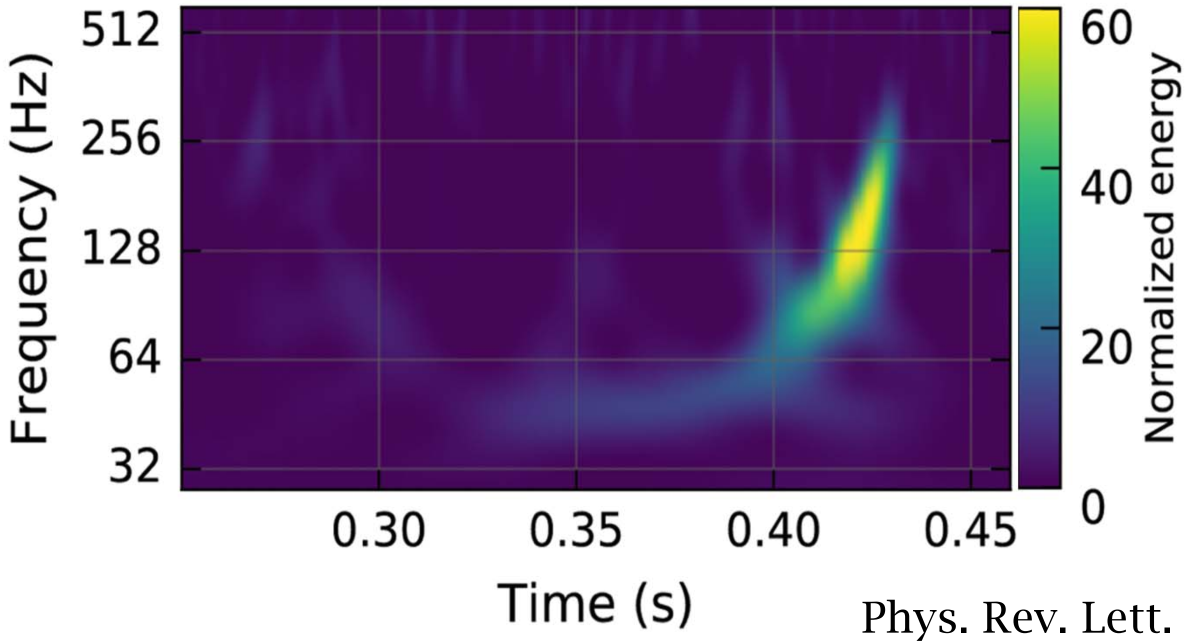


Phys. Rev. Lett. 116, 061102, 2016

GW150914: The Signal







Phys. Rev. Lett. 116, 061102, 2016

Some Facts

- **First direct detection of Gravitational Waves**
  - Confirmation of their existence came from the Hulse-Taylor binary (1975) (and also conformation that they travel unimpeded through space)
- **First direct observation of a black hole**
  - inferred from the characteristic ring-down of the observed signal (and not from the influence on gas surrounding a black hole)
- **First observation of a black hole binary**
  - There is no other way to observe other than via their gravitational wave emission
- **The "brightest" event ever detected: 3.6×10^{49} W**
  - Total radiated energy ~ 3 solar mass
- **Placed constraint on the graviton mass**
  - $\lambda_g > 10^{13}$ km or $m_g < 1.2 \times 10^{-22}$ eV/c^2

GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.
duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

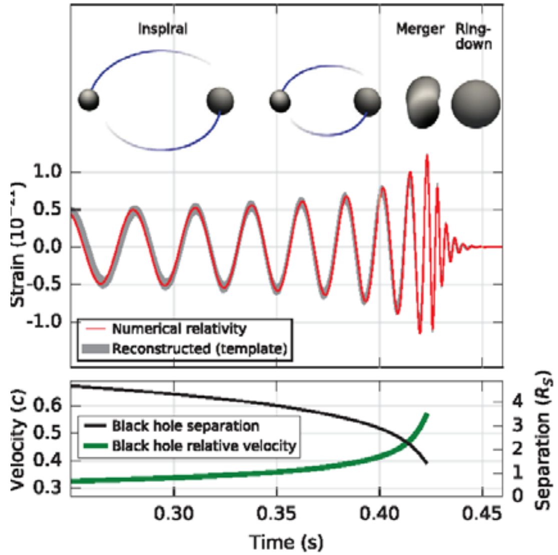
Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds.
Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

LIGO G1600220-v8

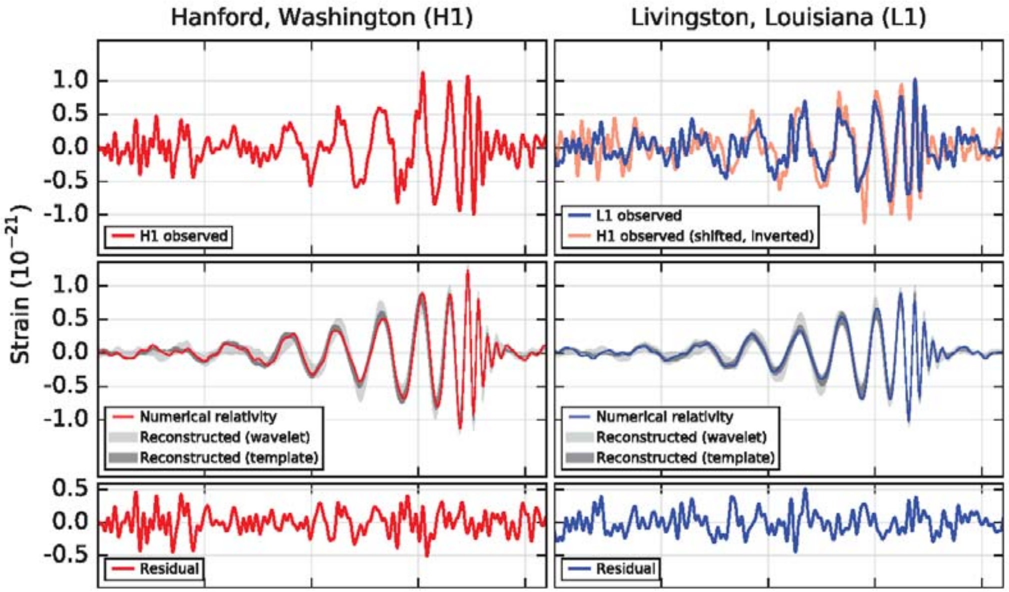
Phys. Rev. Lett. 116, 061102, 2016

GW150914: The Signal

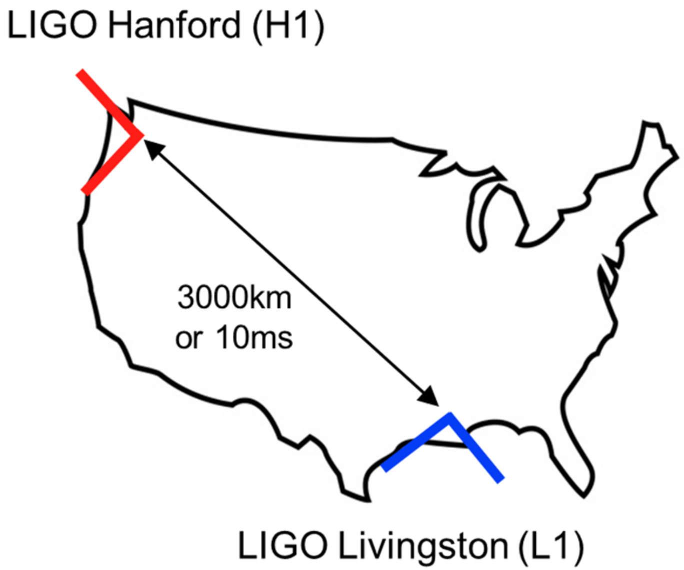
- Numerical relativity models of the BH coalescence
- Over 0.2s the signal increases in frequency and amplitude in about 8 cycles from 35 to 150 Hz
- Effective BH separation in units of Schwarzschild radius $R_s = 2GM_{tot}/c^2 = 210km$

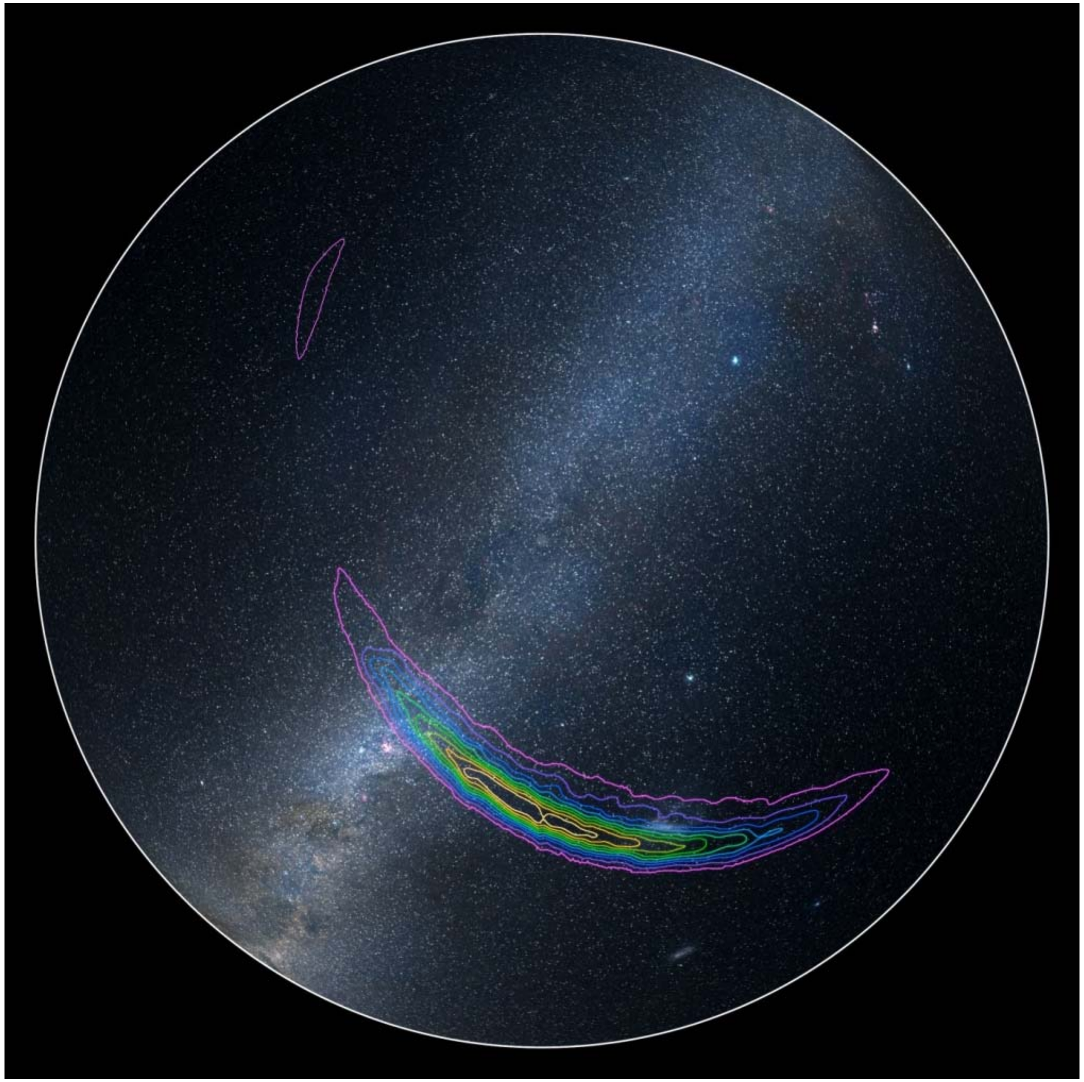


- Binary Black Hole System
- M_1 = 36 +5/-4 M_{sol}
- M_2 = 29 +/- 4 M_{sol}
- Final Mass = 62 +/- 4 M_{sol}
- Distance = 410 +160/-180 Mpc (redshift z = 0.09)



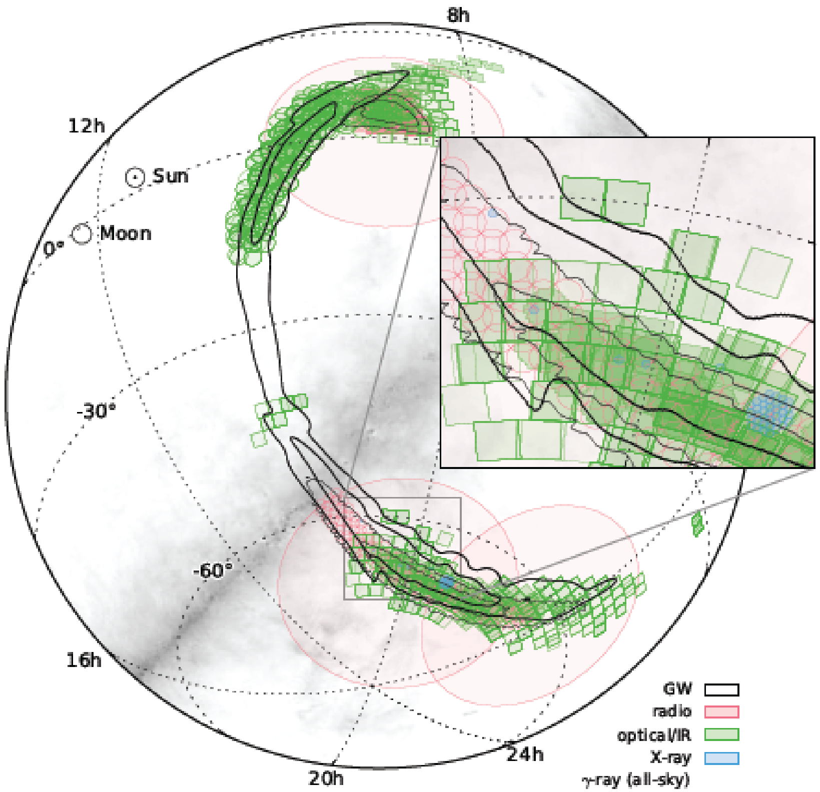
Sky localisation GW150914





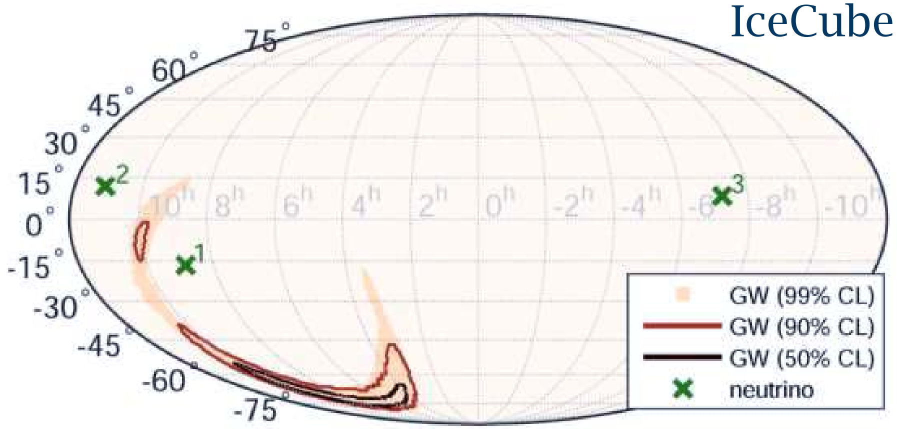
Source position determined mainly by triangulation and signal strength (antenna patterns different due to orientation)

EM and neutrino follow-up



Rapid EM observations in region of GW source – no significant source

IceCube



- Search for coincident high energy neutrino candidates in IceCube and ANTARES data
- Search window ± 500s
- No υ candidate in both temporal and spatial coincidence
- 3 υ candidates in IceCube and 0 υ candidate in ANTARES (consistent with expected atmospheric background)

https://arxiv.org/abs/1602.05411

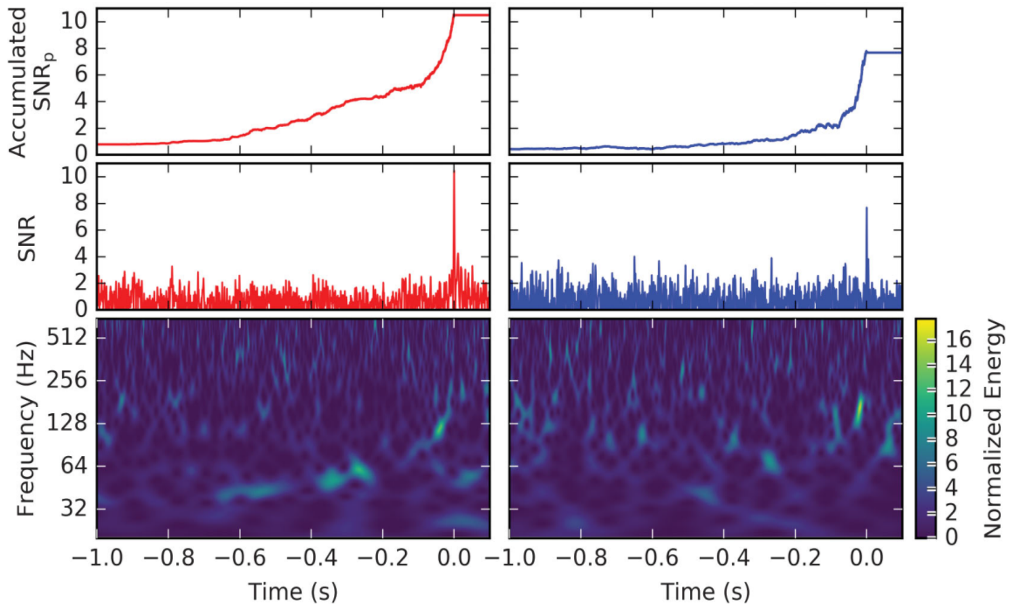
Phys. Rev. Lett. 116, 241103, 2016

University of Glasgow

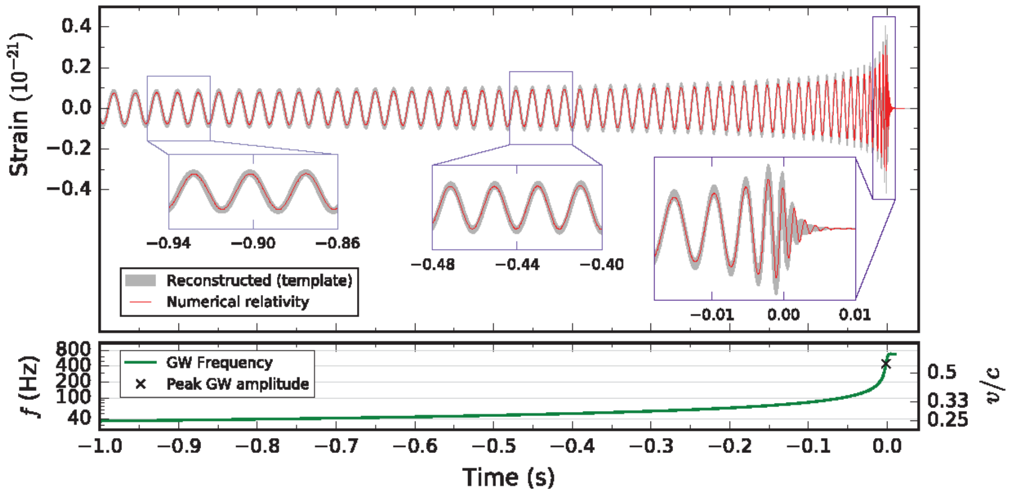
GW151226 2nd detection

- from the detection paper:

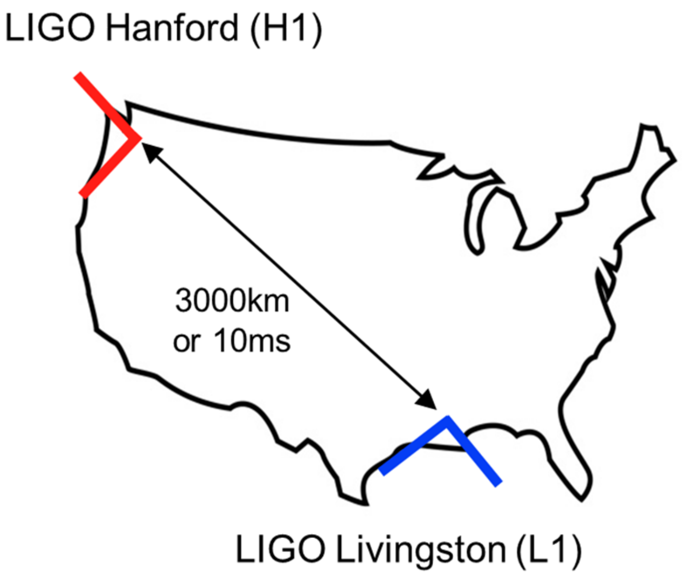
"We report the observation of a gravitational wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC."



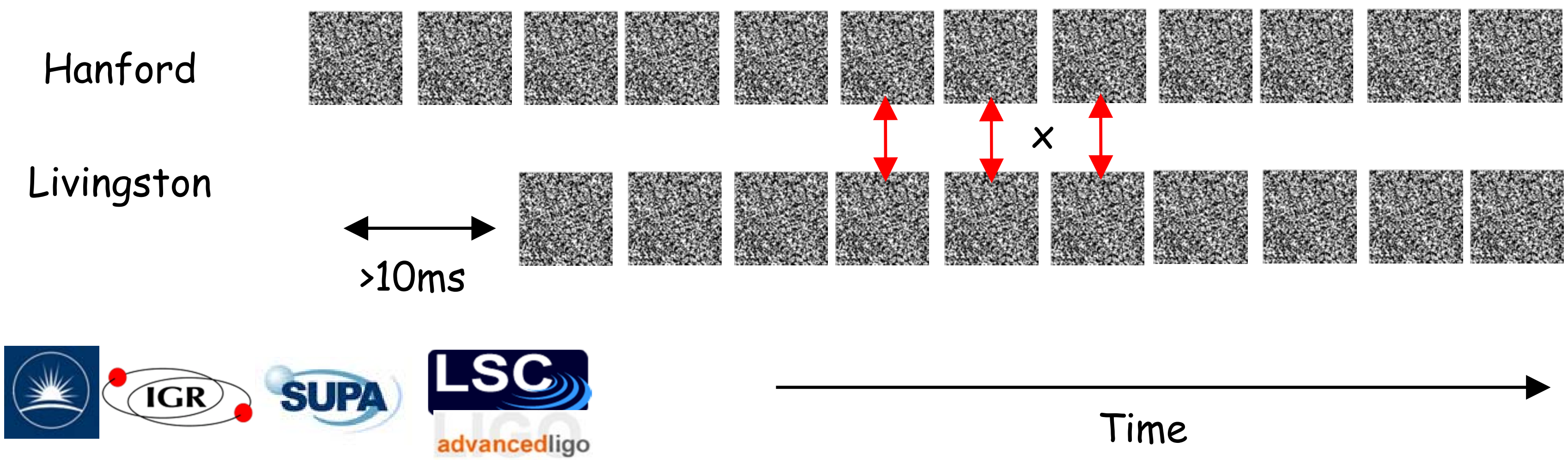
- Second observation of BBH in O1 data
- Firmly establishes field of GW astronomy
- Initial localization: ~1400 deg^2
- Signal increased in frequency anc amplitude over about 55 cycles from 35 to 450 Hz (over ≈1s)



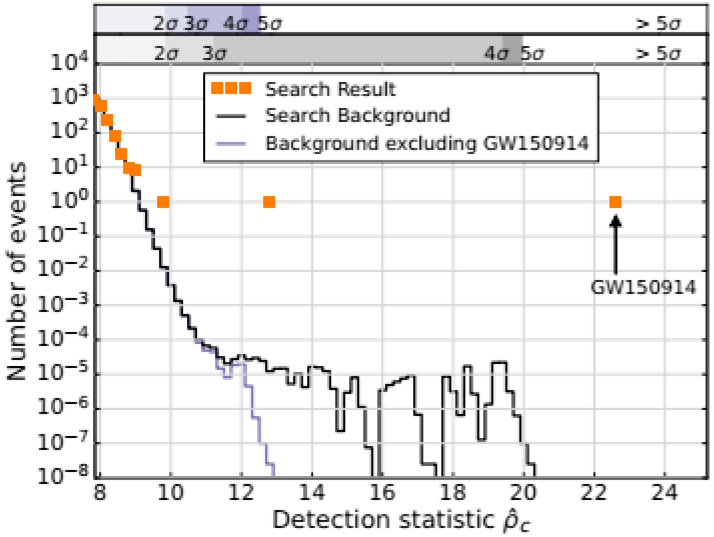
Estimating the Significance

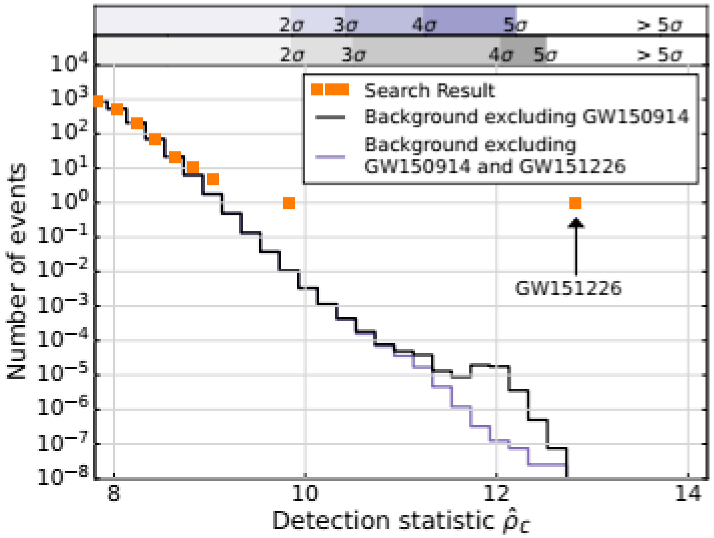


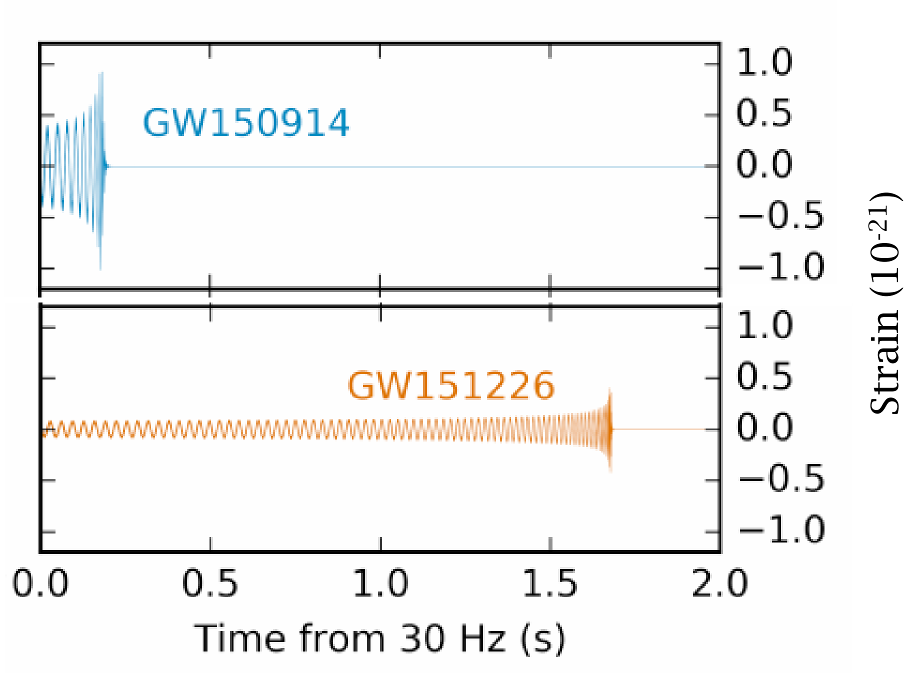
- Time shift the data at both sites by greater than light travel time
- Perform a cross correlation => false alarm rate



Comparing The Events







Event	GW150914	GW151226
Signal-to-noise ratio ρ	23.7	13.0
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$
p-value	7.5×10^{-8}	7.5×10^{-8}
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$

https://arxiv.org/abs/1606.04856 Phys. Rev. Lett. 116, 241103, 2016

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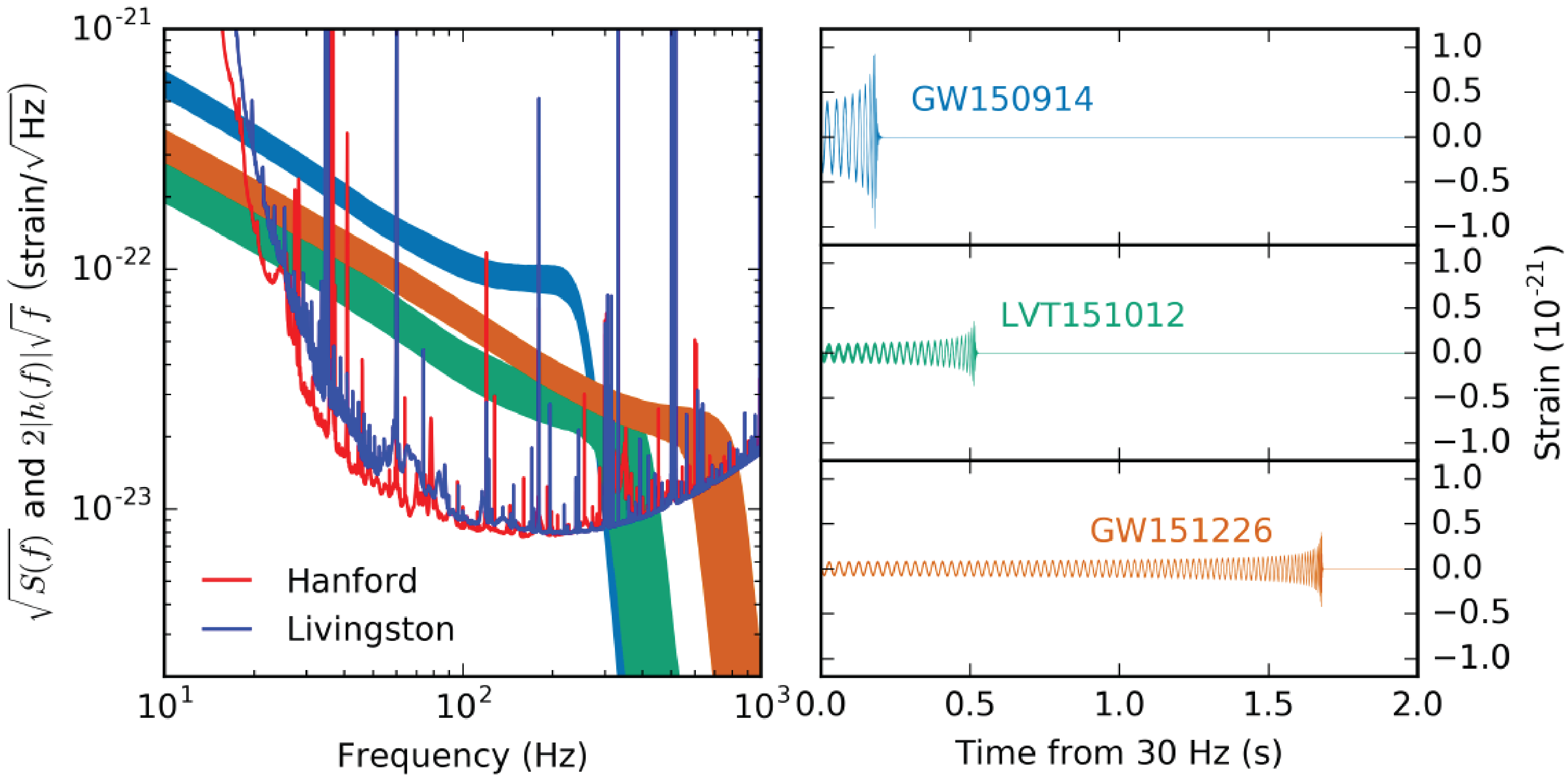
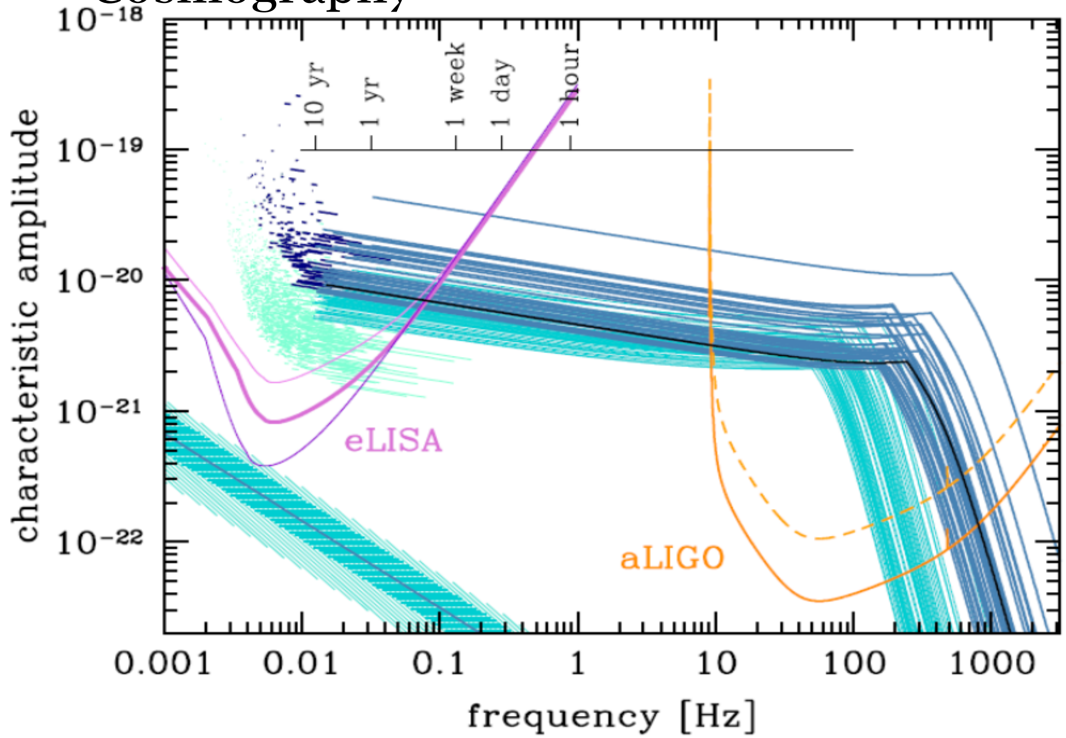
3rd signal



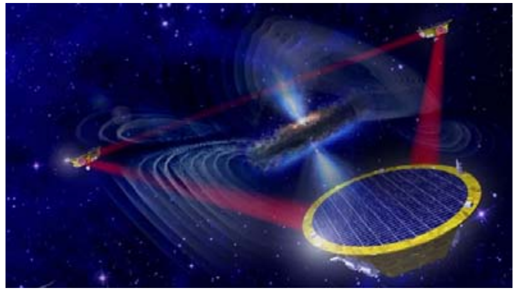
https://arxiv.org/abs/1606.04856

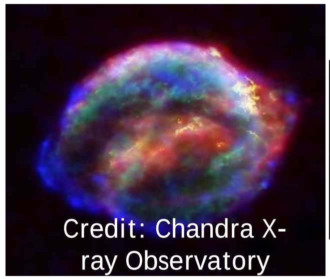
Future of the Field

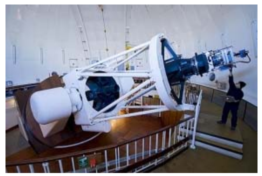
- Multi-Band Multi-Messenger gravitational wave astronomy
  - Compact binary coalescence studies (neutron star EOS/BH populations)
  - Testing gravity/numerical relativity at extremes
  - Continuous waves/Stochastic background
  - Cosmography



Sesana arXiv:1602-06951 (2016)







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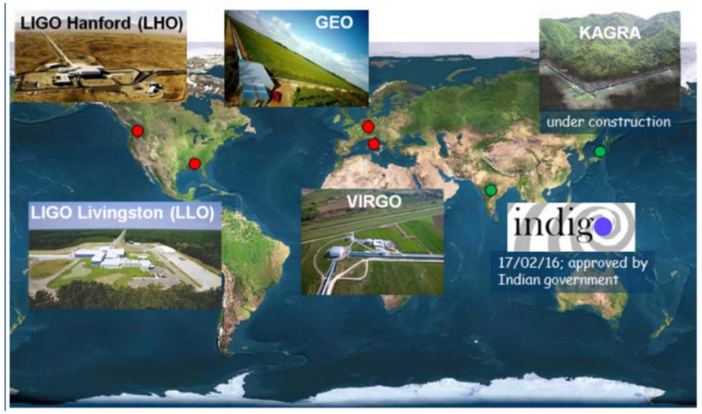
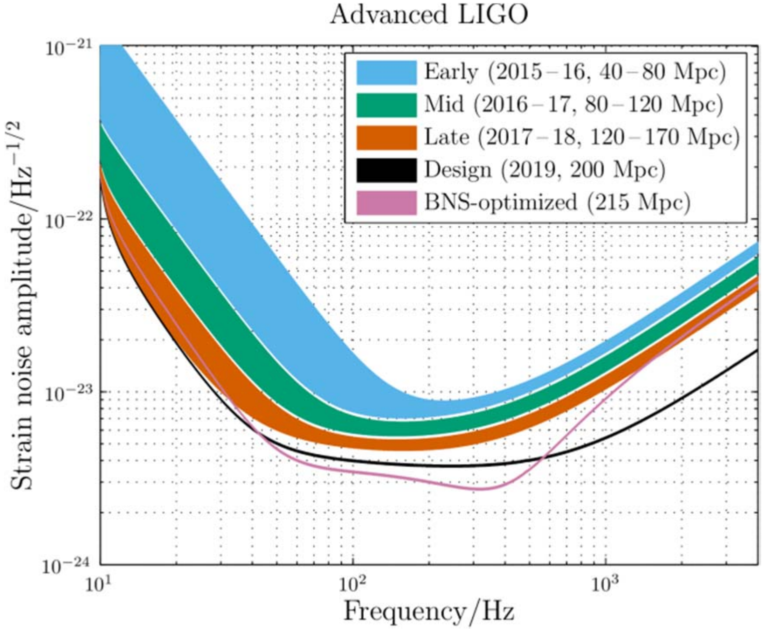
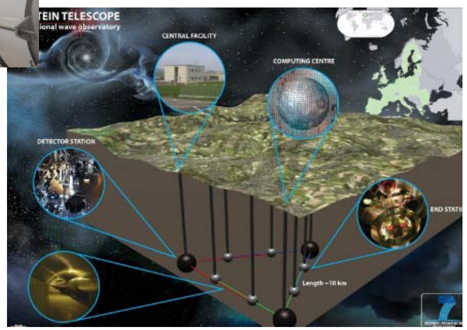
Future of the Field

- A worldwide network of advanced detectors are currently operating/under development

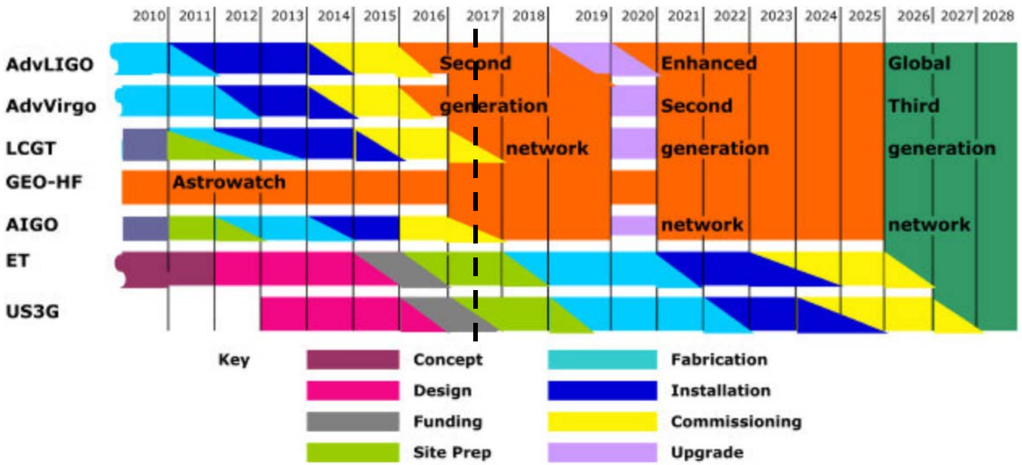




KAGRA (Japan)



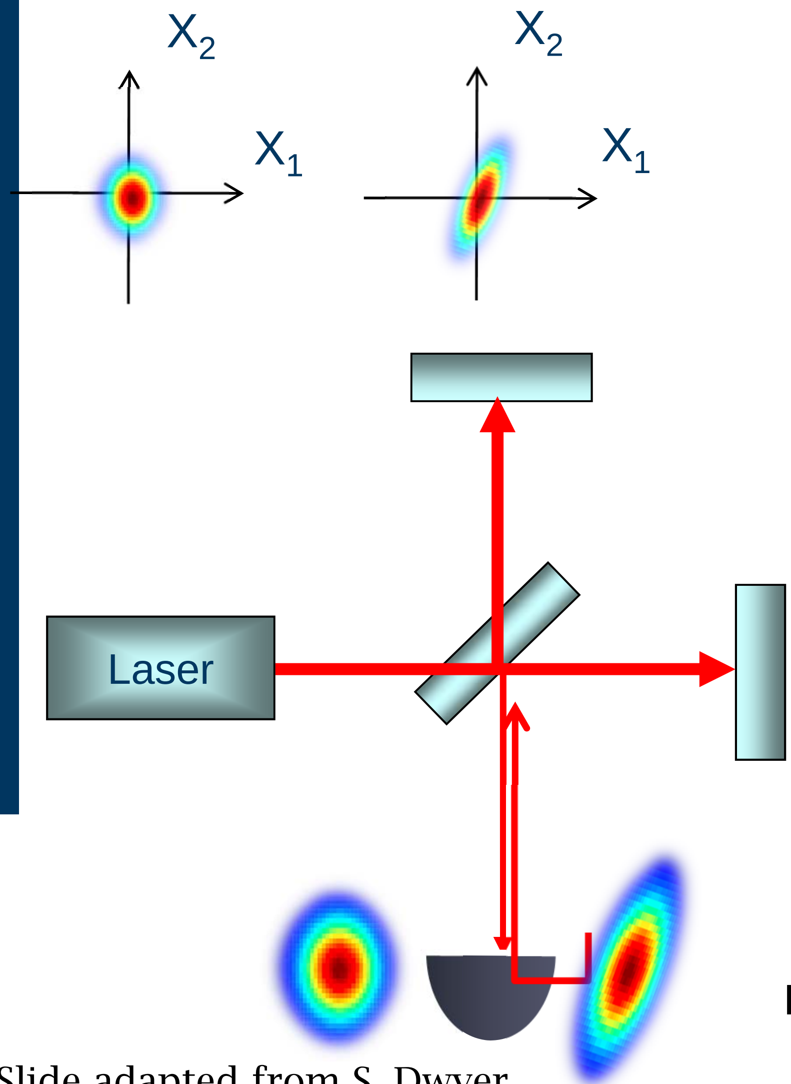
Einstein Telescope (Europe 3G detector)

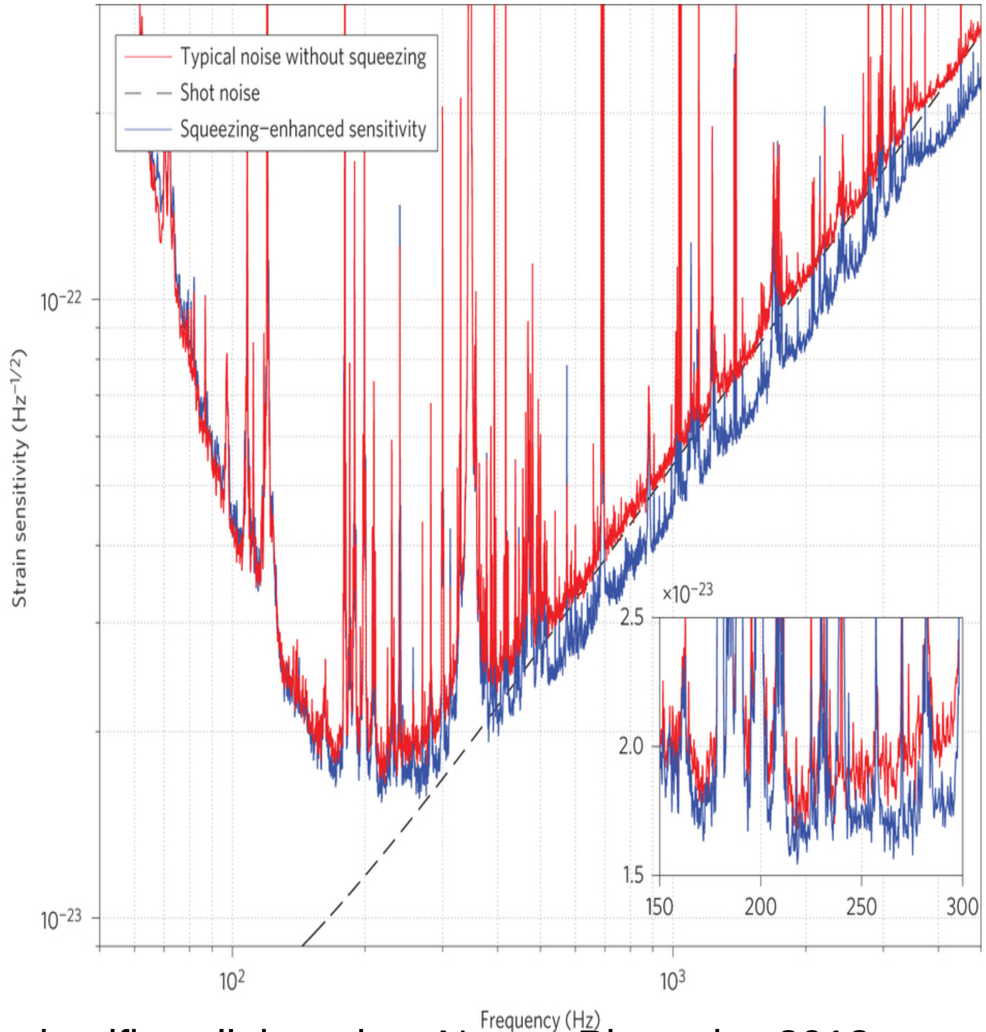


Future upgrades – squeezed light

Vacuum fluctuations

Squeezed Vacuum fluctuations





LIGO scientific collaboration, Nature Photonics 2013

doi:10.1038/nphoton.2013.177

Slide adapted from S. Dwyer

Summary

- This is an extremely exciting time in Gravitational Wave Astronomy with the next observing run of aLIGO (O2) currently underway and AdvVIRGO joining later this year

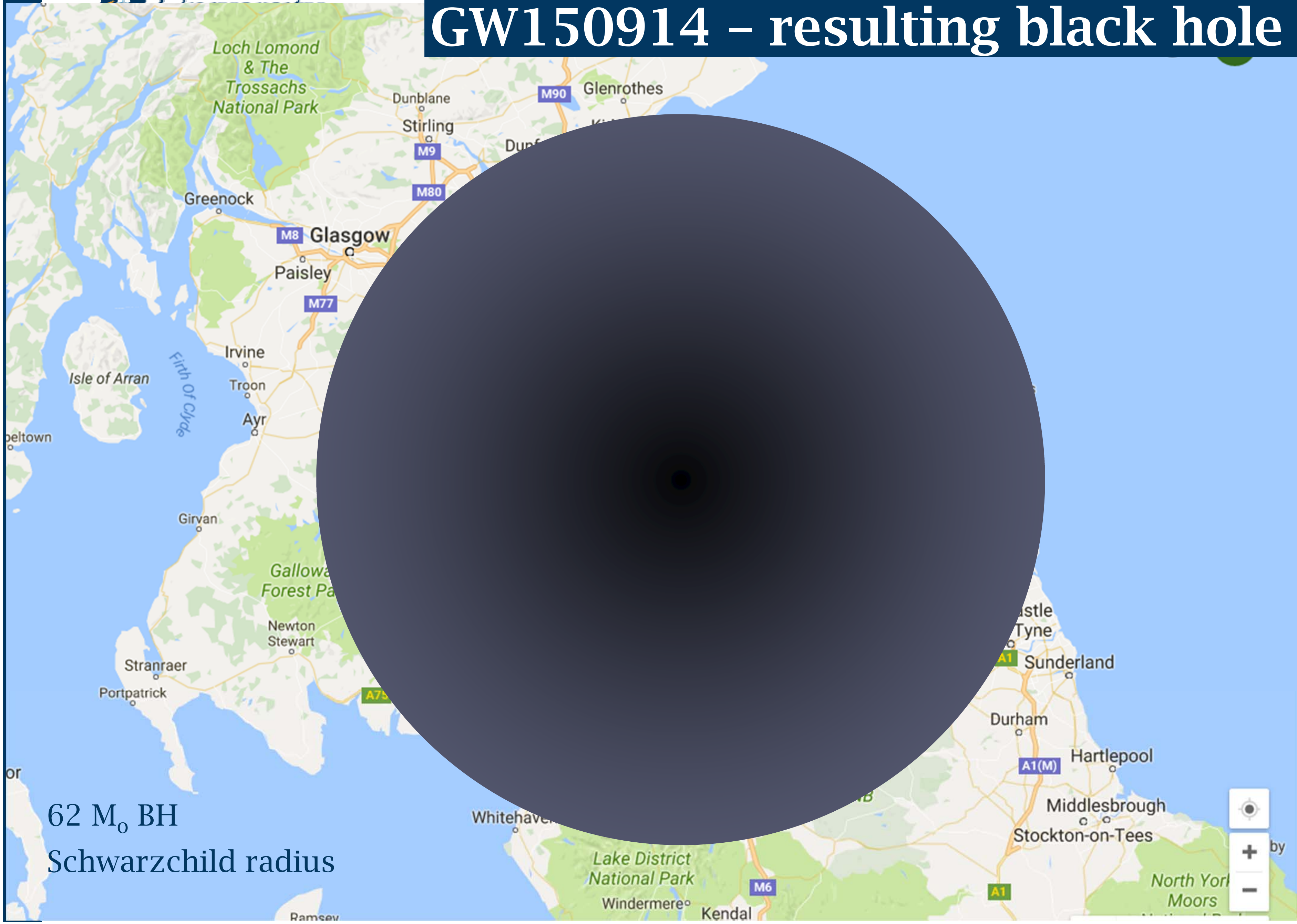
- With 2 detections the Gravitational Wave window has truly been opened

- The detectors are performing well, and UK expertise has been essential to realise aLIGO

- Future 3rd generation detectors will further push technologies and realise improvement in sensitivity/widening of operation bandwidth (>1Hz)


Thank You
Any Questions?

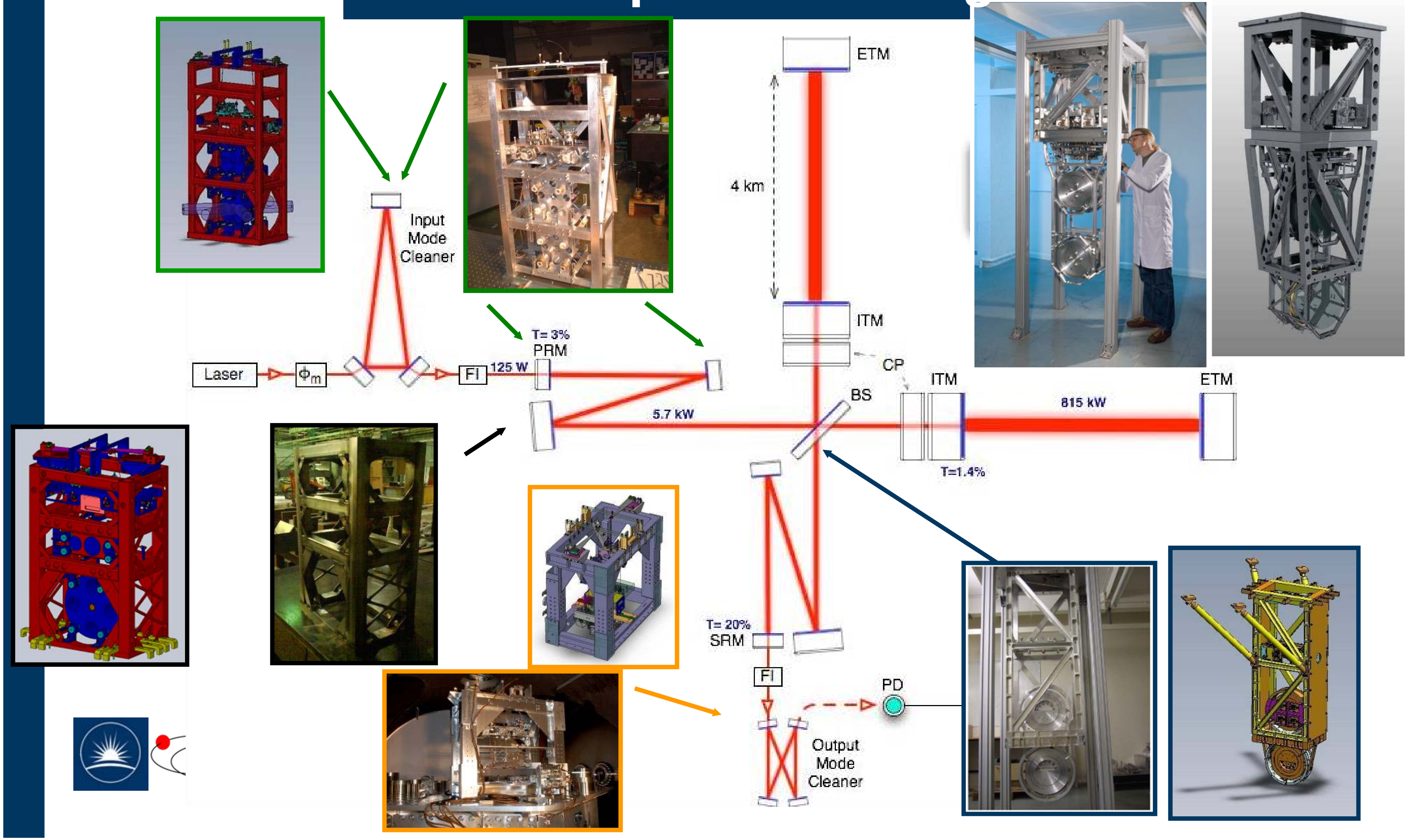
GW150914 – resulting black hole



$62\ M_o$ BH

Schwarzchild radius

aLIGO suspension designs



Strong Evidence for GW

- Hulse-Taylor Binary Pulsar (PSR B1913+16)

- Two neutron stars in very close orbit, loosing energy via GWs
- Matches exactly (99.7%) what GR predicts
- In 300 Myrs the system will coalesce (and produce a massive GW)