Gravitational Physics: a tour of Precision Measurement, Astronomy and Industrial Applications

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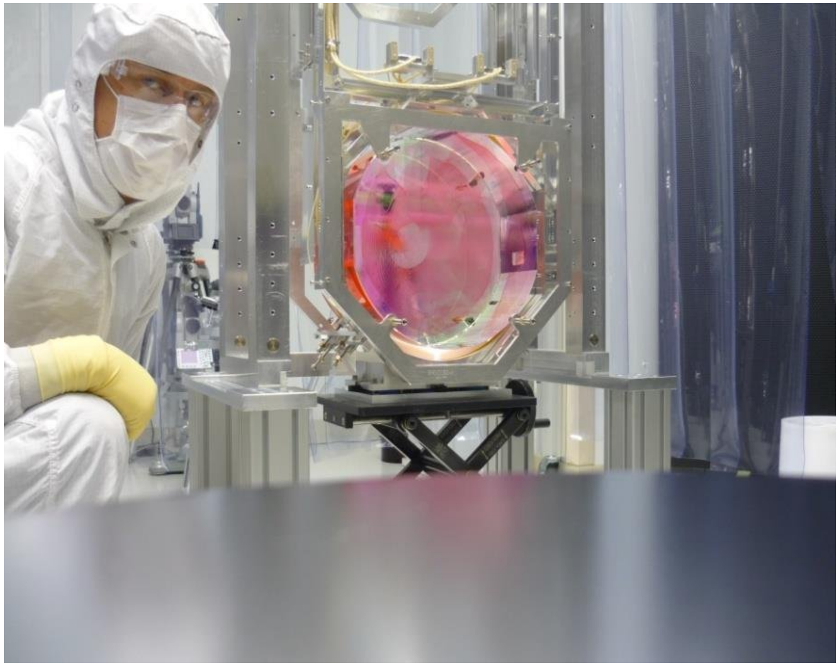
Glasgow, Scotland, UK

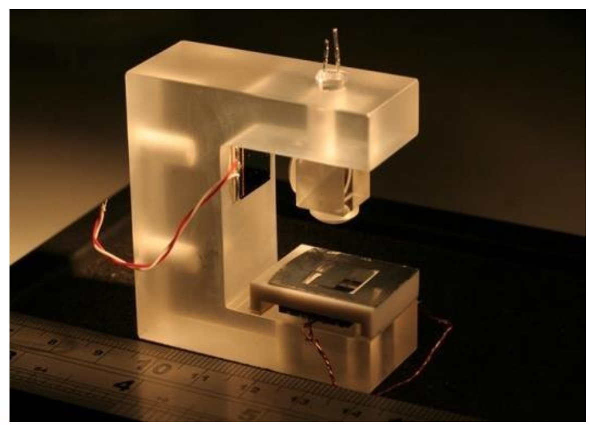
Speaker Bio

- PhD, Birmingham, Experimental gravitational physics (1995-1998)
- Postdoc, JILA/Colorado, Advanced LIGO seismic isolation systems (1998-2001)
- Postdoc, Birmingham, Casimir force measurements (2001-2007)
- Faculty, Glasgow, Advanced LIGO suspensions/MEMS (RCUK fellow; 2007-2011, Reader; 2011-2016, Professor; 2016-present)



Overview

- Astronomy: weighing the Earth
- Precision measurement: aLIGO
- Industrial Applications: MEMS gravimeters



Astronomy: weighing the Earth

Astronomy: weighing the Earth

- Nevil Maskelyne (Astronomer Royal) put in a “proposal” to the Royal Scoiety to weigh the Earth using the gravitational attraction of Schiehallion (Munro 1085m/3553ft)

low country Maiden-pap, but by the neighbouring inhabitants, Schehallien; which, I have ſince been informed, ſignifies in the Erſe language, Conſtant Storm: a name well adapted to the appearance which it ſo frequently exhibits to thoſe who live near it, by the clouds and miſts which uſually crown its ſummit. It had, more-

- Maskelyne spent 17 weeks (July-September 1775) in a bothy measuring star positions

PHILOSOPHICAL TRANSACTIONS:

An Account of Observations Made on the Mountain Schehallien for Finding Its Attraction. By the Rev. Nevil Maskelyne, B. D. F. R. S. and Astronomer Royal

Nevil Maskelyne

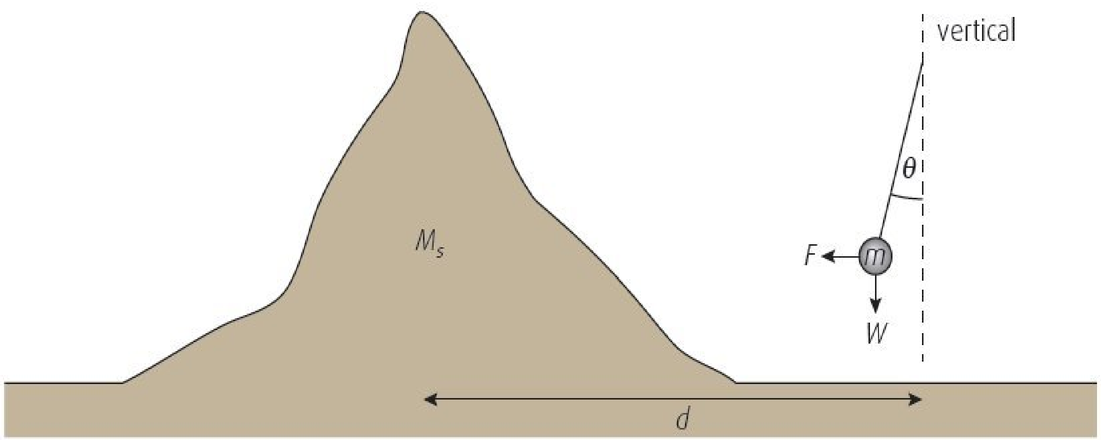
Phil. Trans. 1775 **65**, 500-542, published 1 January 1775

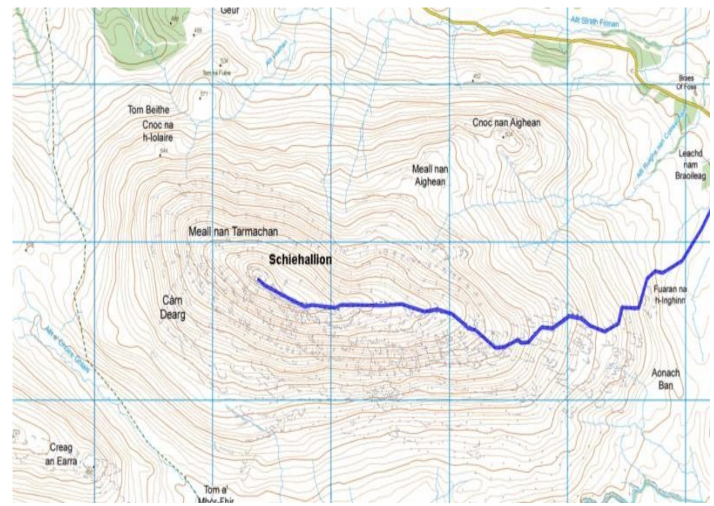
Astronomy: weighing the Earth

- The plan was to compare the attraction of the Earth and the mountain

Astronomy: weighing the Earth

- Plan was to compare the attraction of the Earth and the mountain





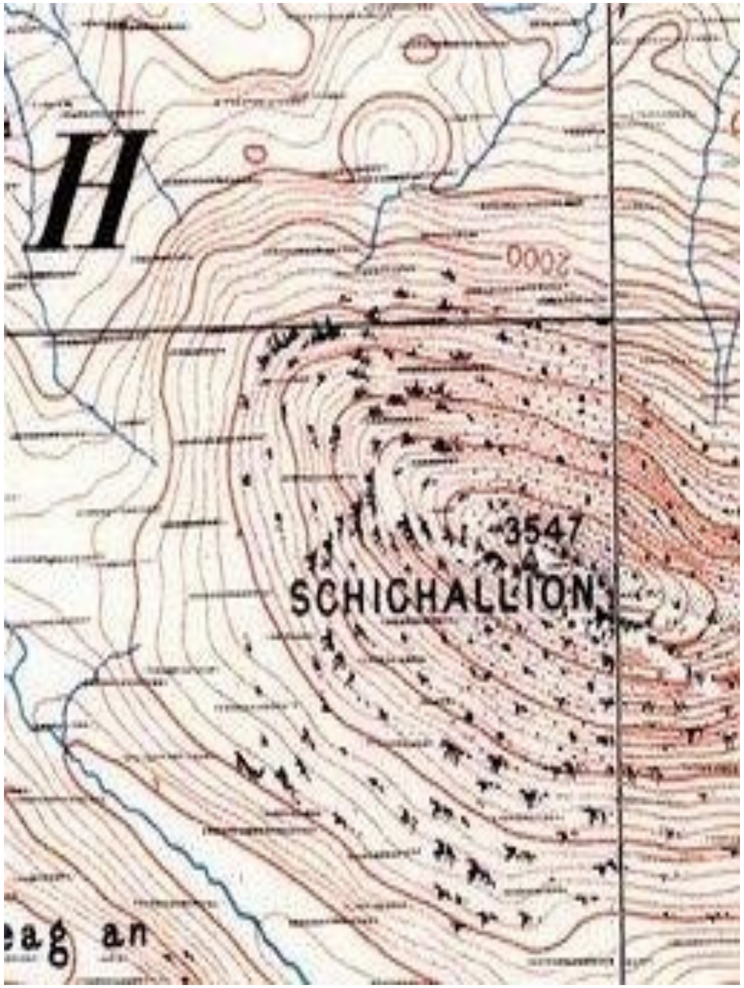
- The deflection of the pendulum was measured relative to the stars

Astronomy: weighing the Earth

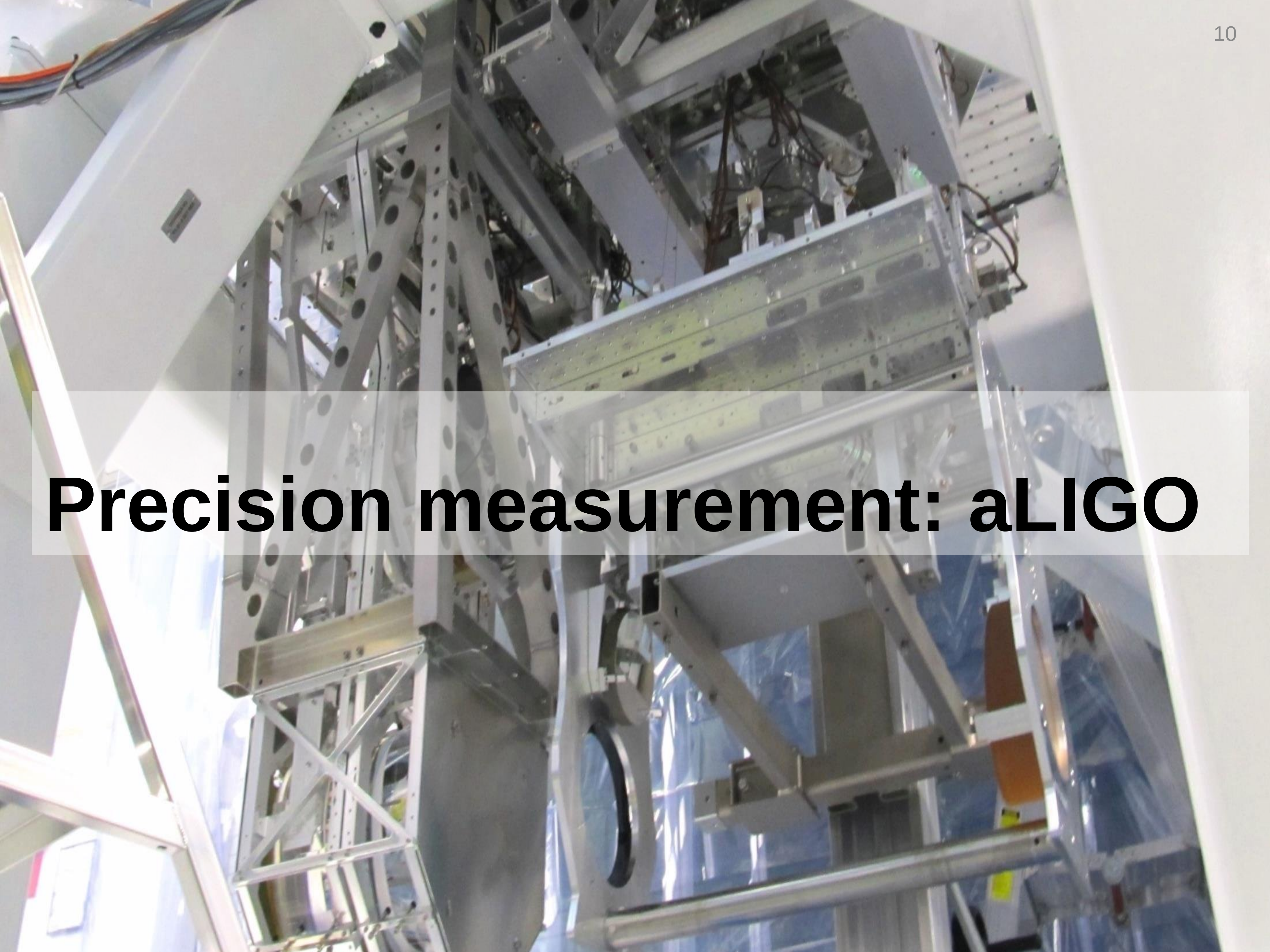
- Maskelyne found that the mass of the Earth was 4.5×10^{24} kg
- The actual value is 5.98×10^{24} kg
- Not bad for the technology of that time
- However, it took him 17 weeks and bankrupted the Royal Society

Astronomy: weighing the Earth

- Charles Hutton (Mathematician / Surveyor) worked on calculating the mass of the mountain
- He split the mountain into chunks of similar height => contour lines

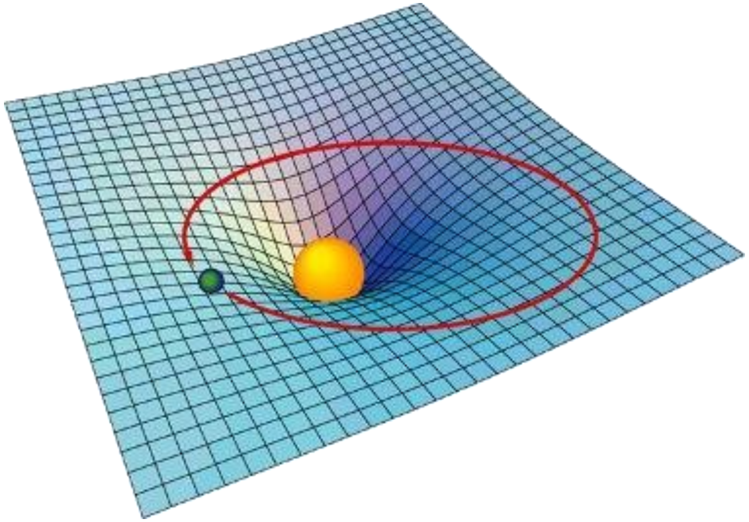


Precision measurement: aLIGO



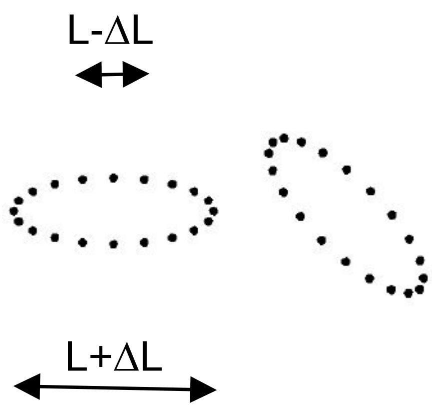
General Relativity/Gravity Waves

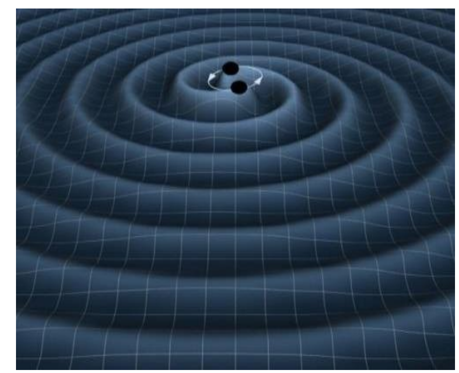
- In General Relativity gravity is described by the curvature of space-time



Matter tells spacetime how to curve.
Spacetime tells matter how to move

- Gravitational waves are ripples in spacetime propagating at the speed of light (according to GR)
- Created by acceleration of massive compact objects

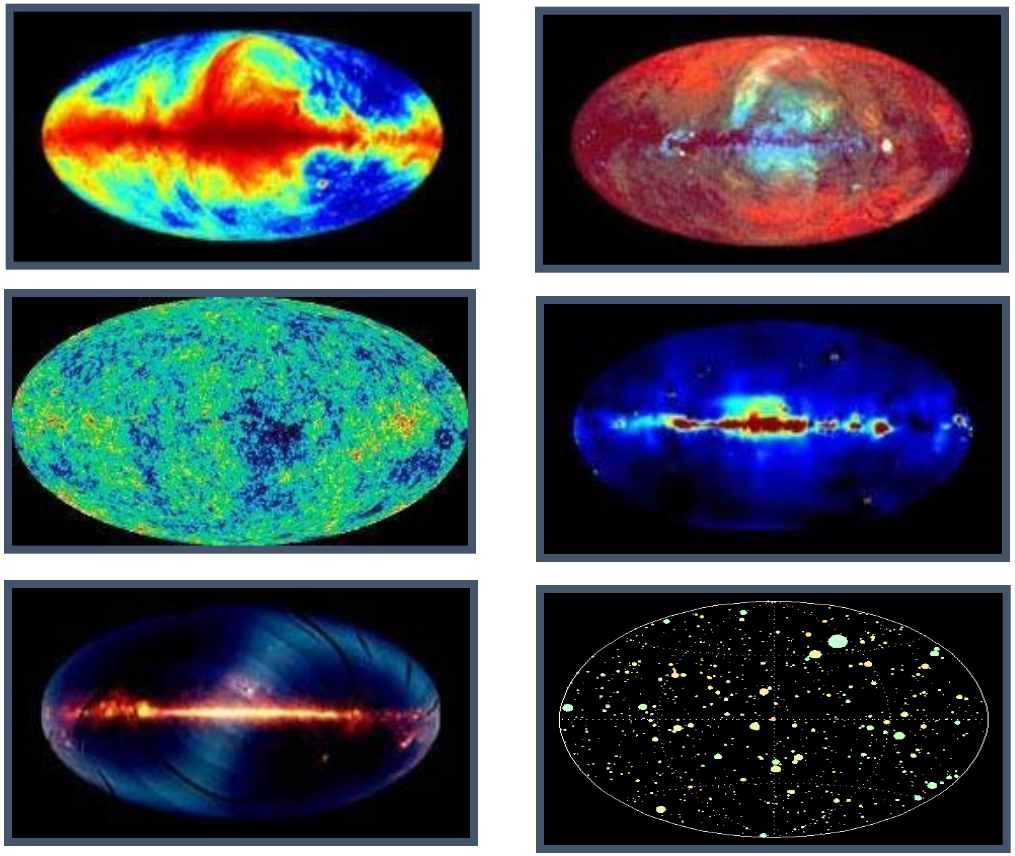




- Gravitational wave detectors measure the separation between free test masses in this spacetime

$$\boxed{h = \frac{2\Delta L}{L}}$$

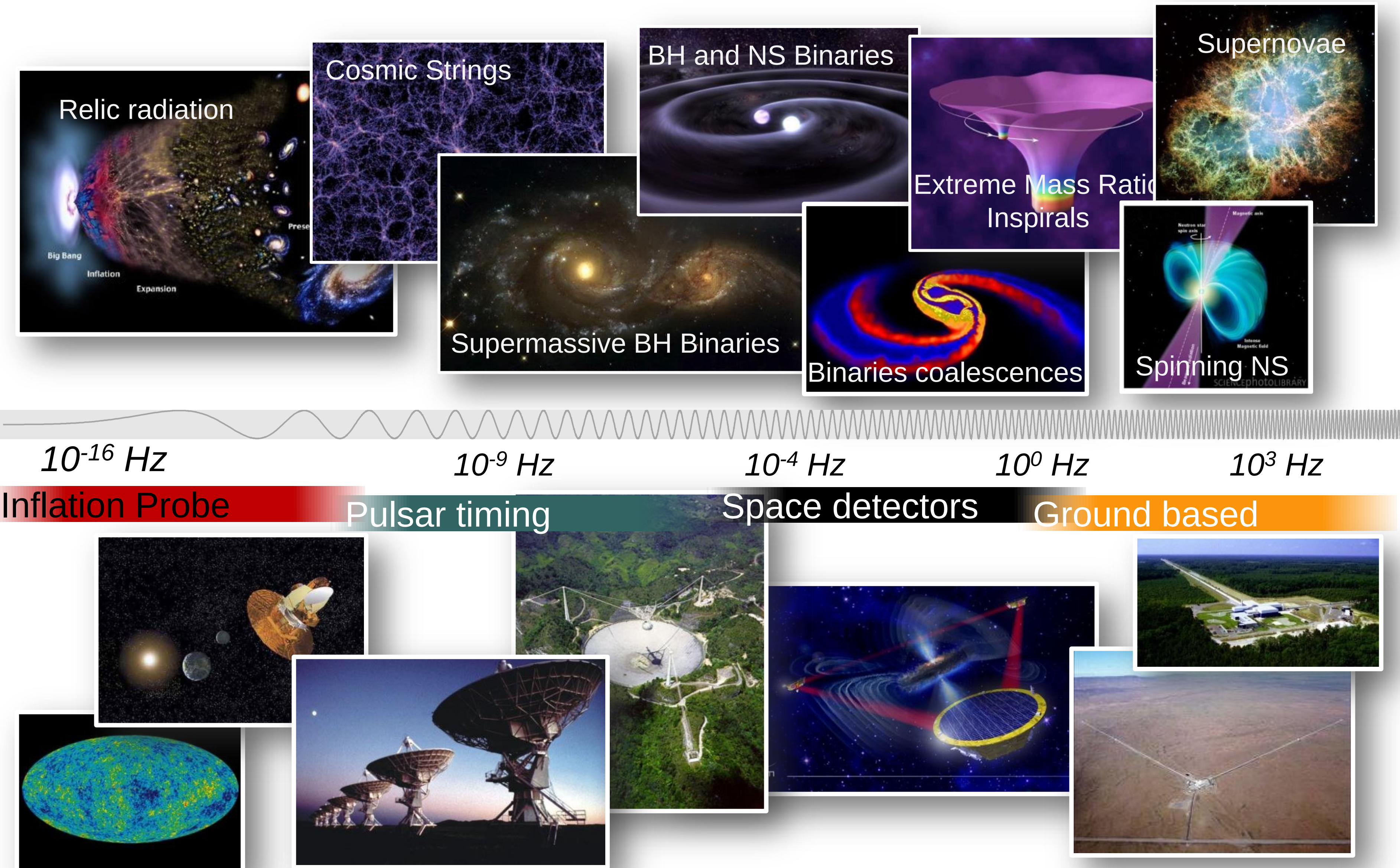
A New Probe of the Universe



- 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*.

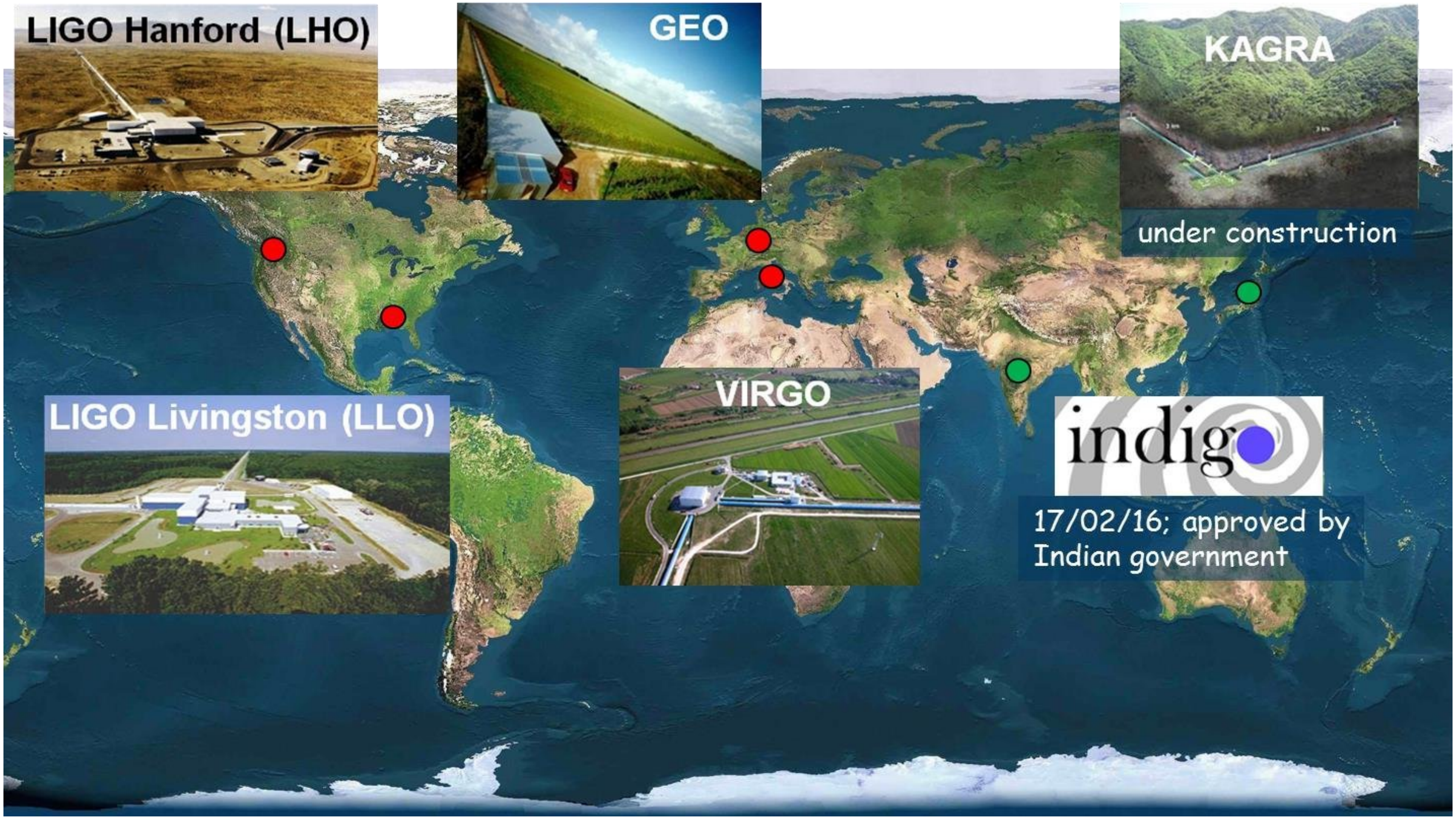
EXPECT THE UNEXPECTED!

The Gravitational Wave Spectrum



- Adapted from M. Evans (LIGO G1300662-v4)

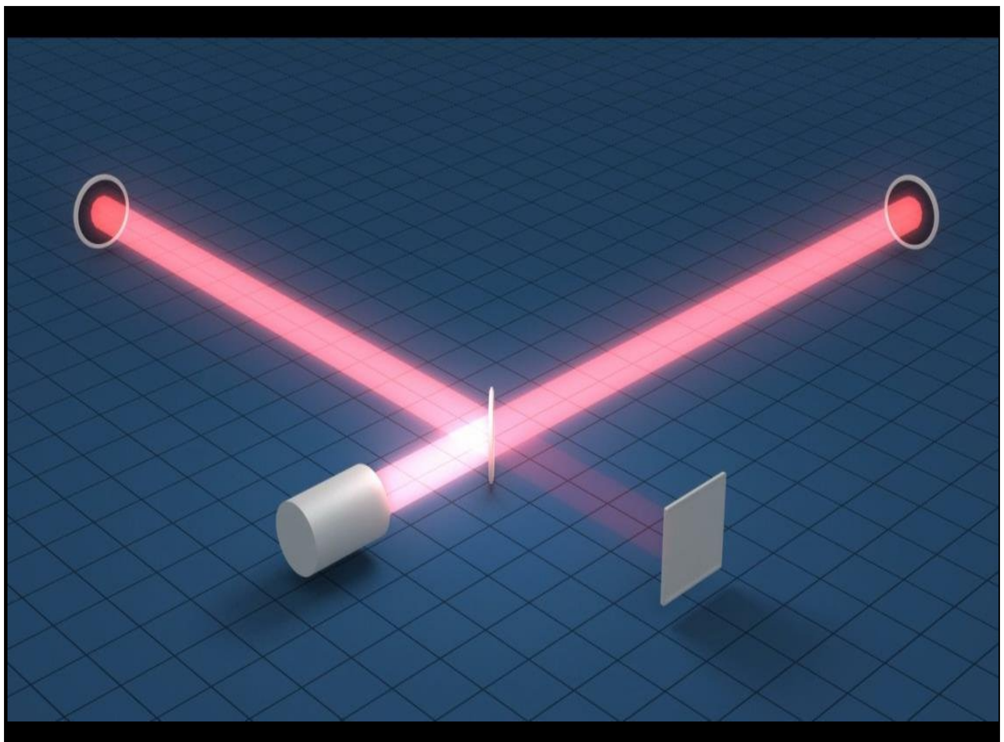
A Worldwide Network



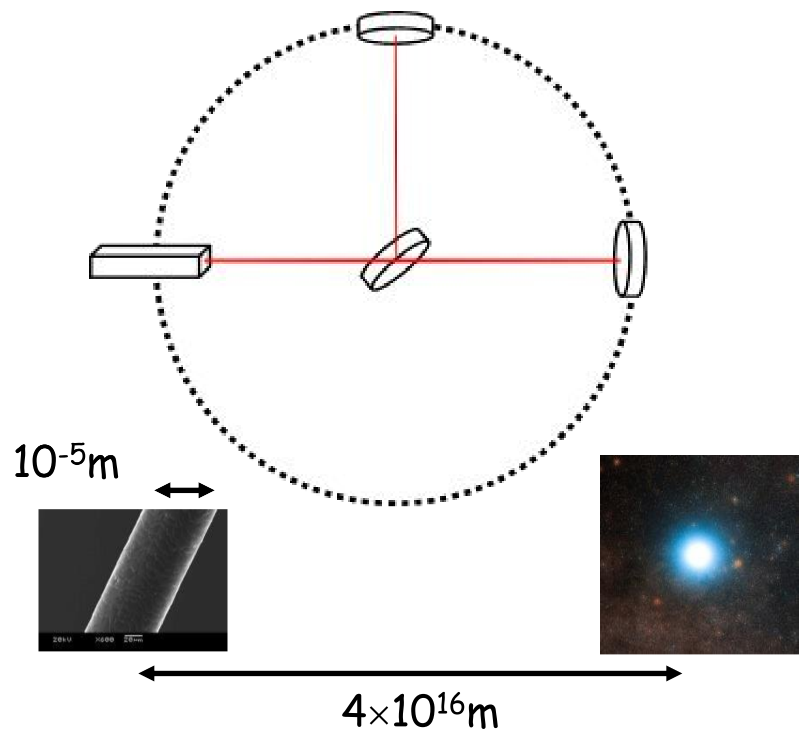
- A network is required to localise the source position

Interferometric Detectors

- Interferometers monitor the position of suspended test masses separated by a few km
- A passing gravitational wave will lengthen one arm and shrink the other arm; transducer of GW strain-intensity (10^{-18} m over 4 km)



https://www.ligo.caltech.edu/gallery



LIGO Livingston

- It is not easy ….

Hanford

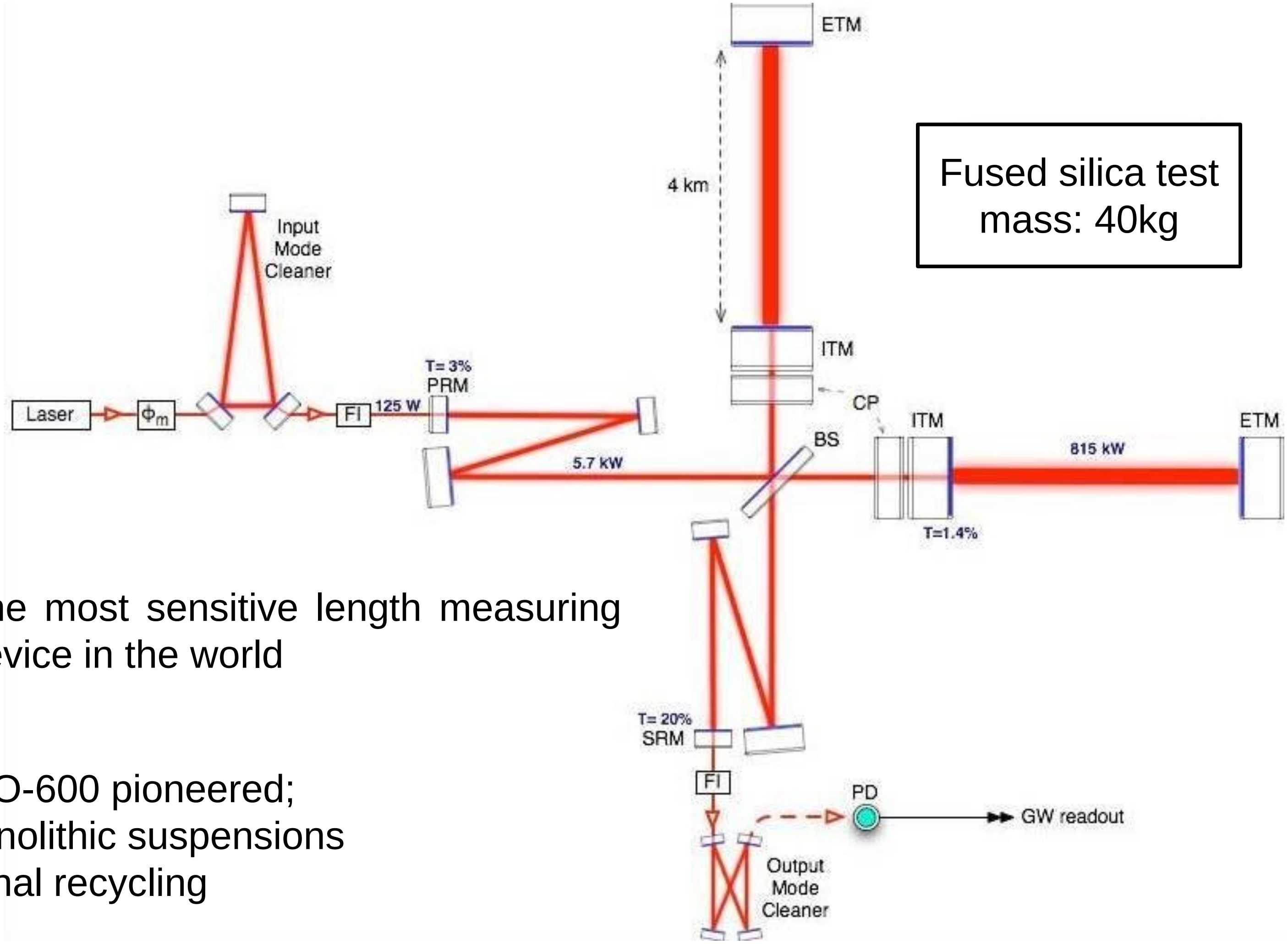
- It is not easy ....

Livingston

- Really not easy ….

Hanford
… again …

Inside the Interferometer



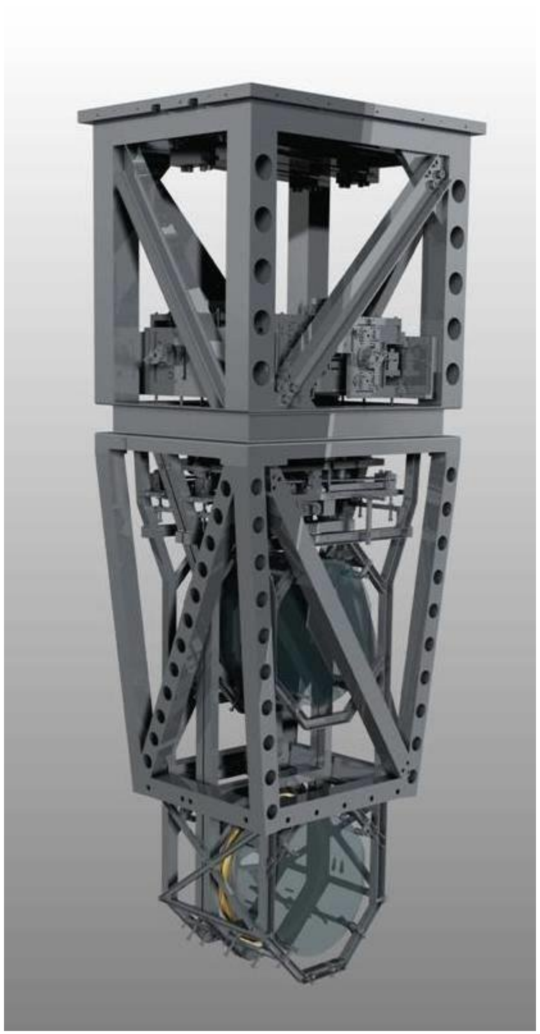
Fused silica test mass: 40kg

- The most sensitive length measuring device in the world

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

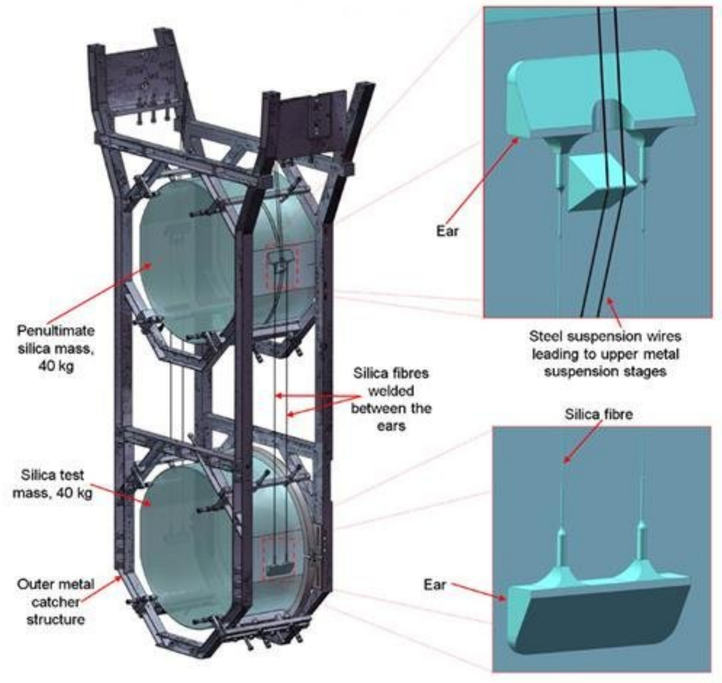
aLIGO Quadruple Suspension

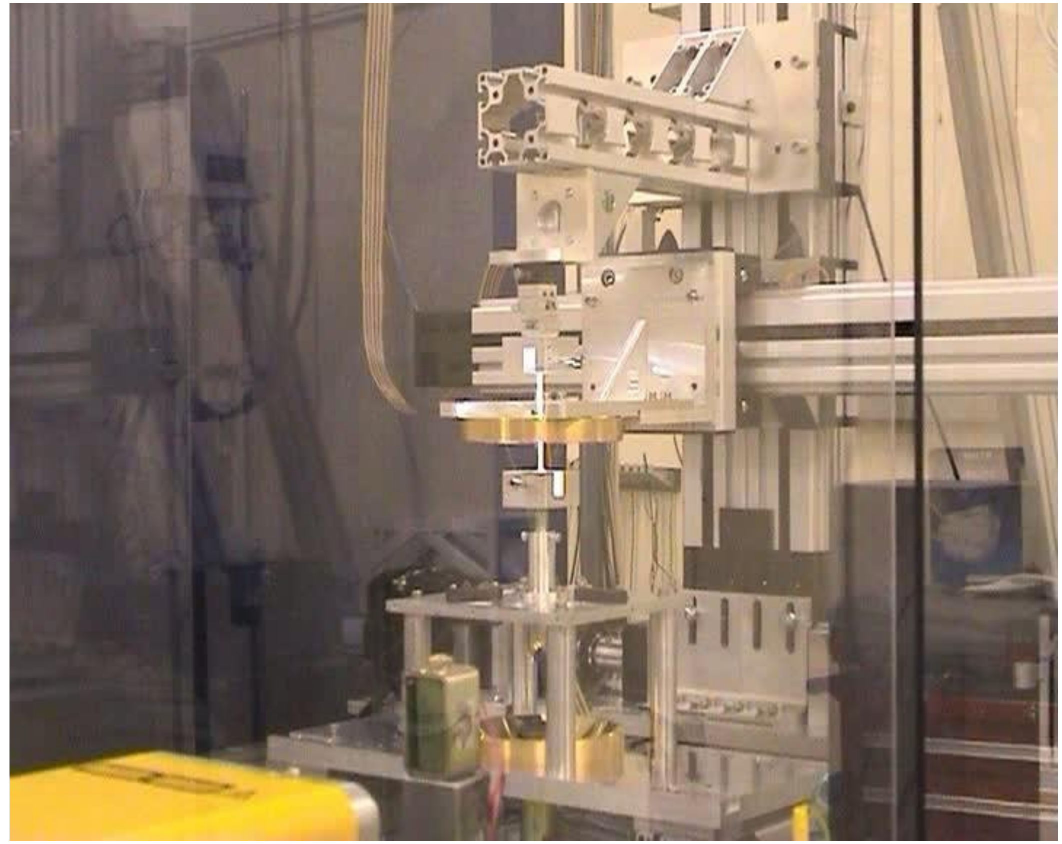
- The input test masses (ITM) and end test masses (ETM) of Advanced LIGO are suspended via a quadruple pendulum system
- **Seismic isolation:** use quadruple pendulum with 3 stages of maraging steel blades for horizontal/vertical isolation
- **Thermal noise reduction:** monolithic fused silica suspension as final stage
- **Actuation:** Coil/magnet actuation at top 3 stages, electrostatic drive at test mass. This is used to align the optical cavity

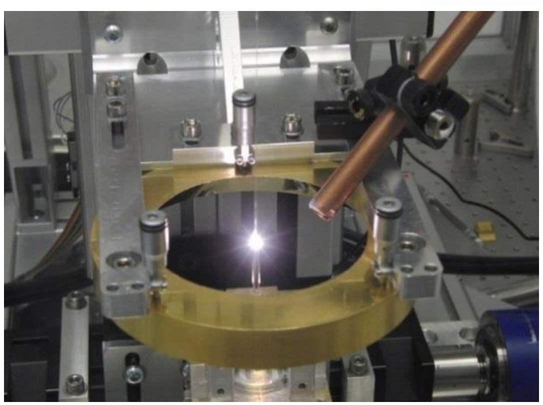


Developed under the ALUK project (Glasgow/RAL/Birmingham/Strathclyde)

Fused Silica Fibre Pulling



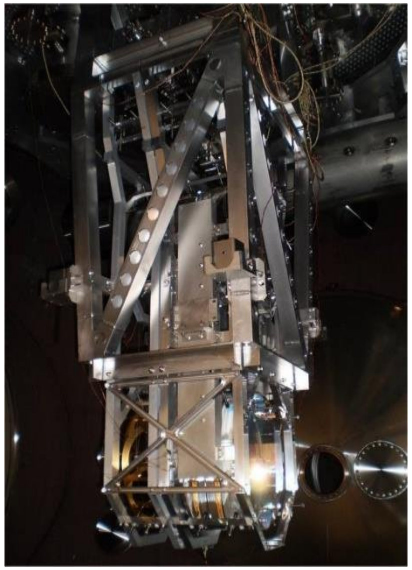


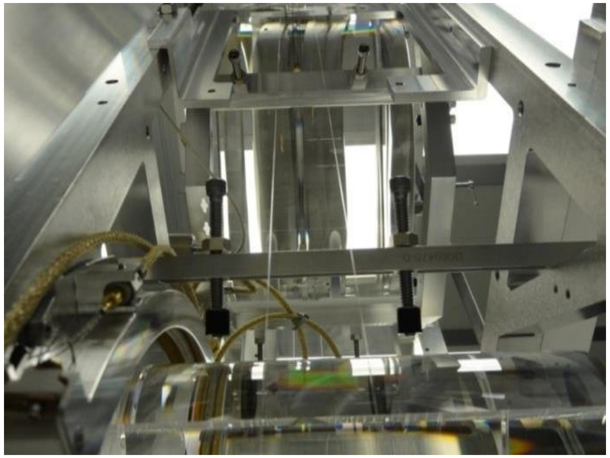


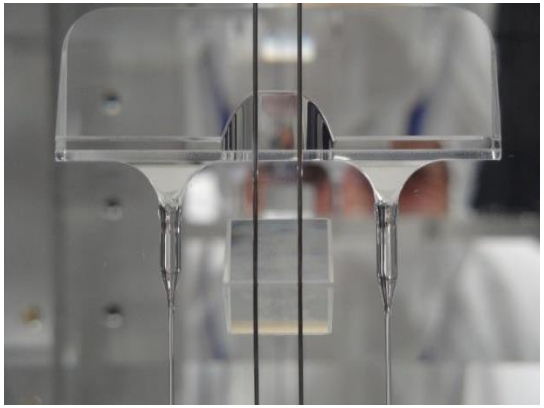
Glasgow has supplied the machines used in AdV VIRGO and aLIGO

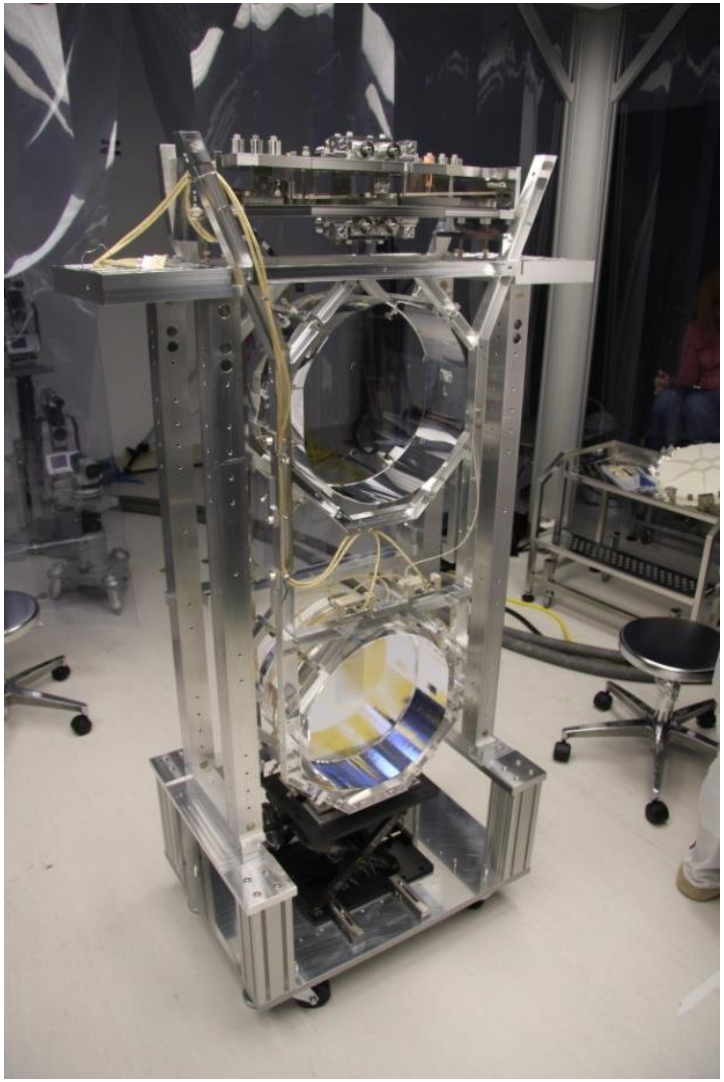
- Low thermal noise requires ultra-low loss materials => fused silica

aLIGO Suspensions





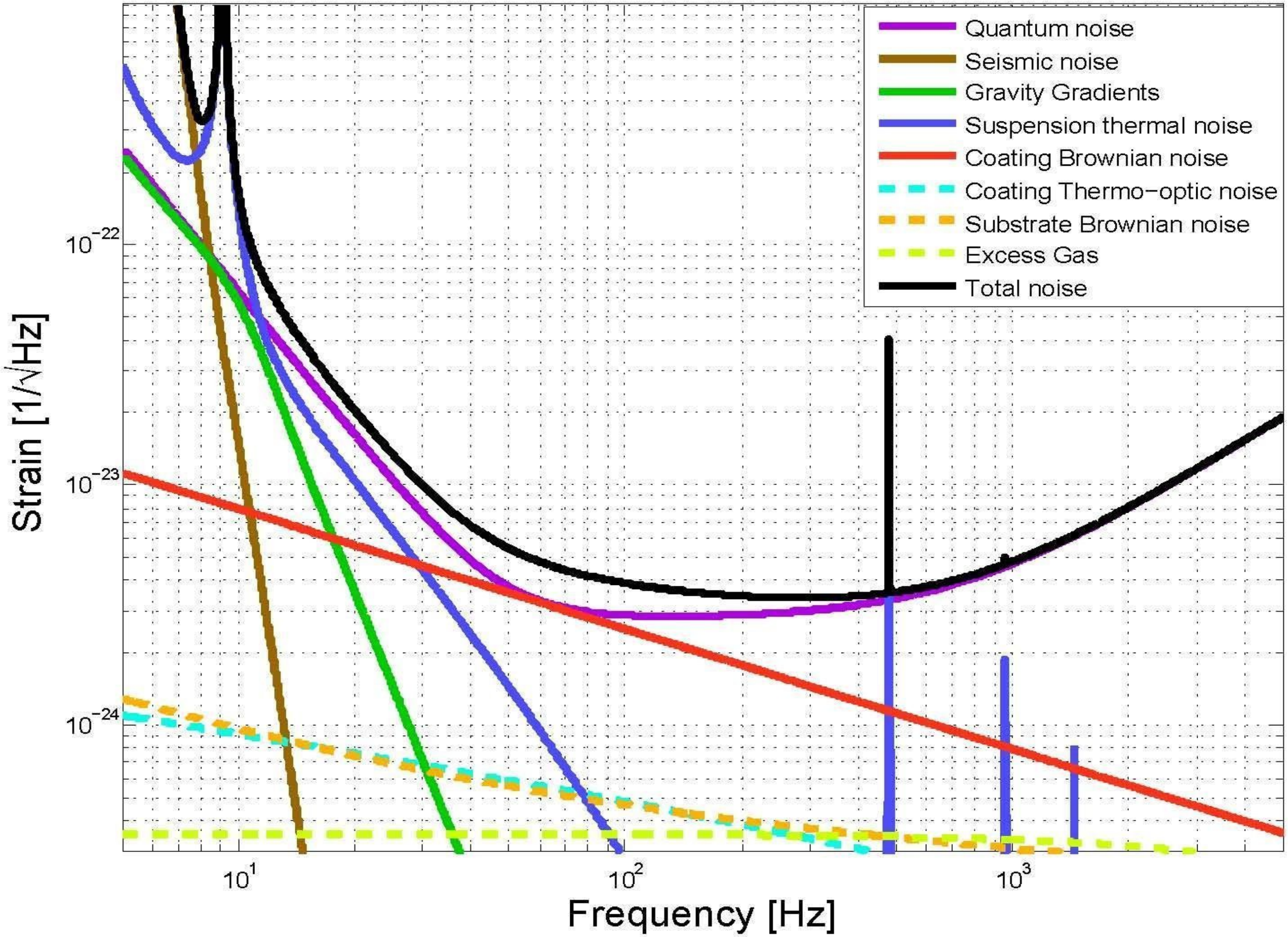




- Fused silica technology has been essential to meet aLIGO requirements

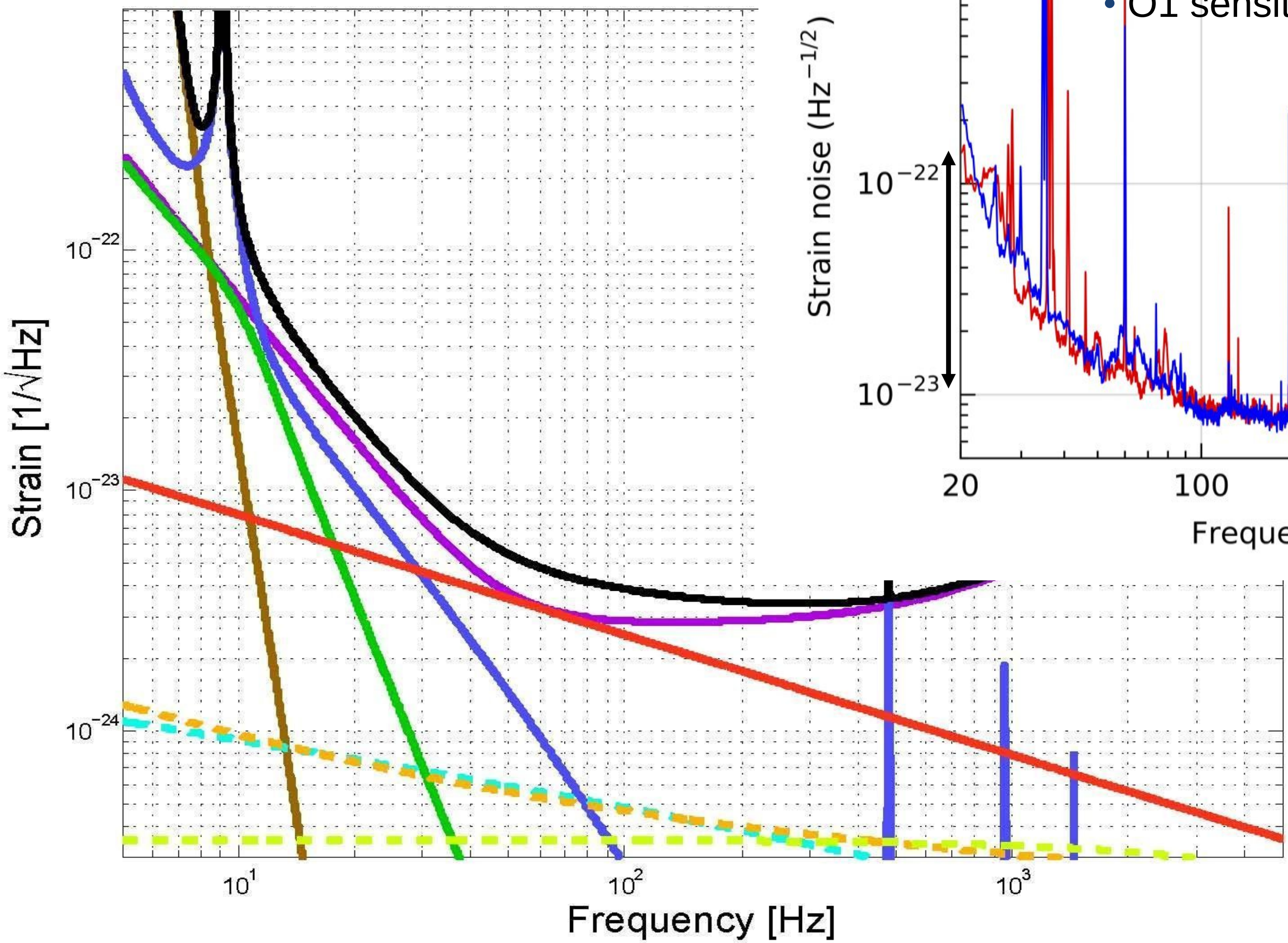
aLIGO Sensitivity

- aLIGO design sensitivity

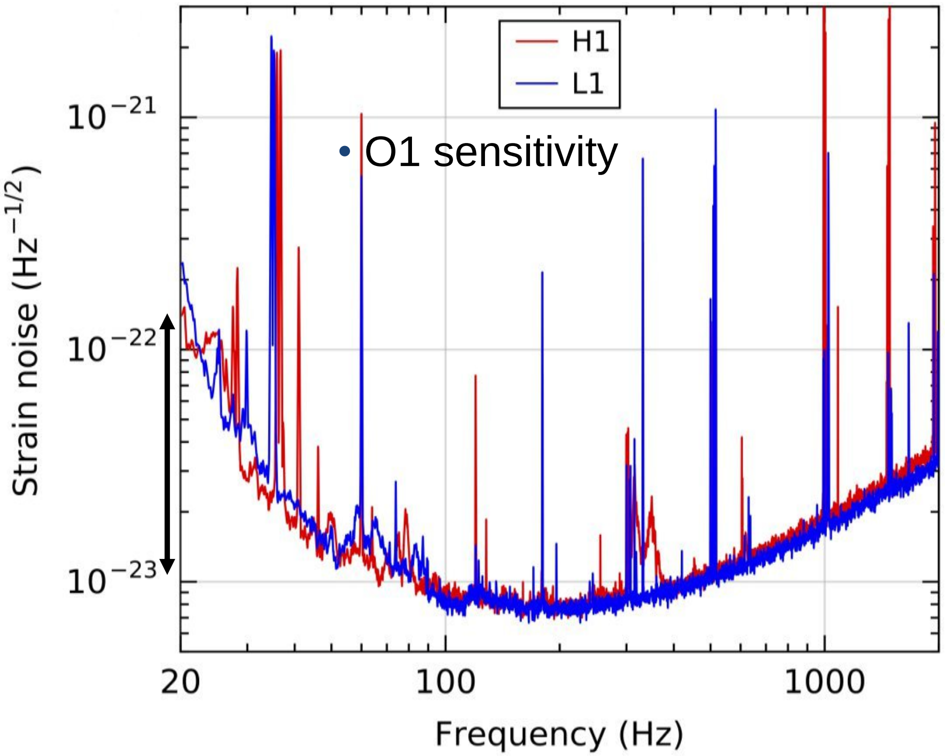


aLIGO Sensitivity

- aLIGO design sensitivity



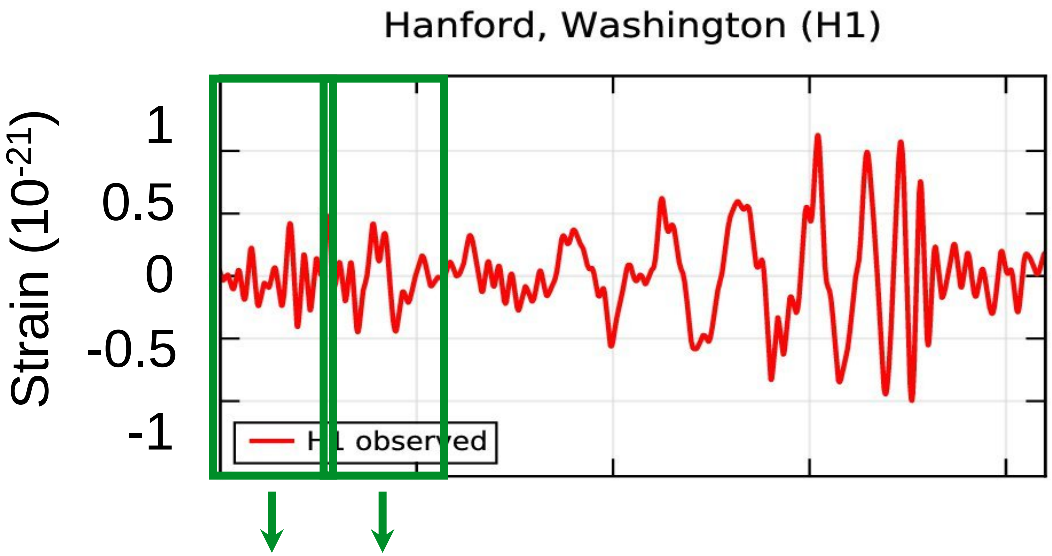
- O1 sensitivity

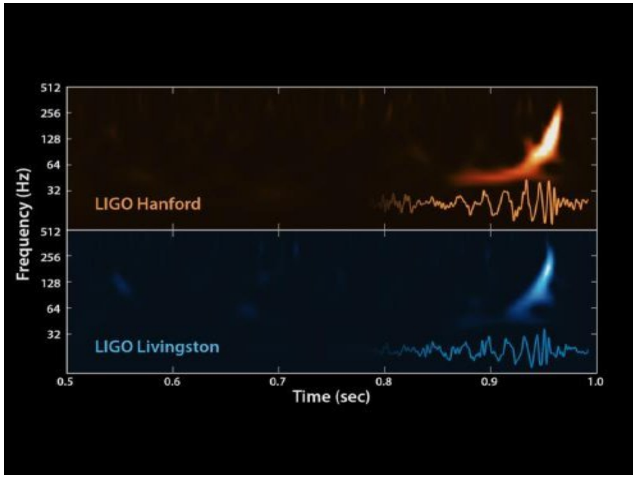


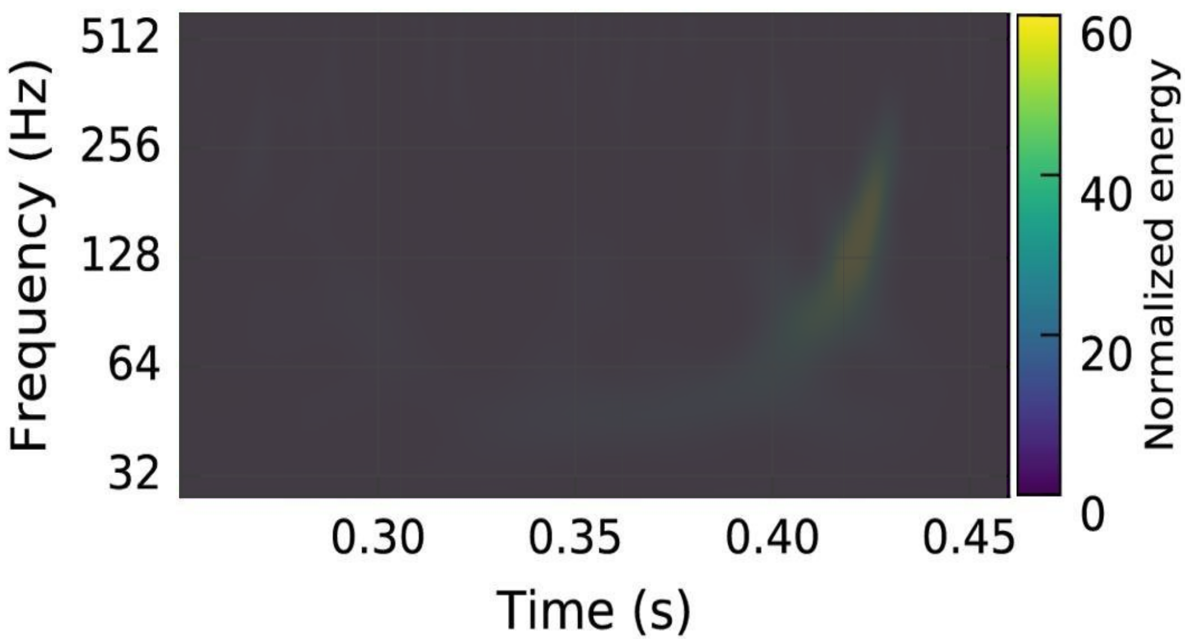
The Industry Steering Committee on Wellbore Survey Accuracy (ISCWSA)

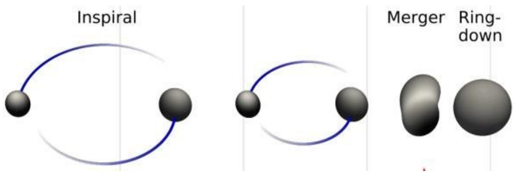
GW150914: The Signal

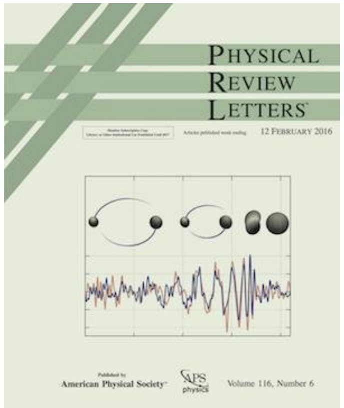
Phys. Rev. Lett. 116, 061102, 2016



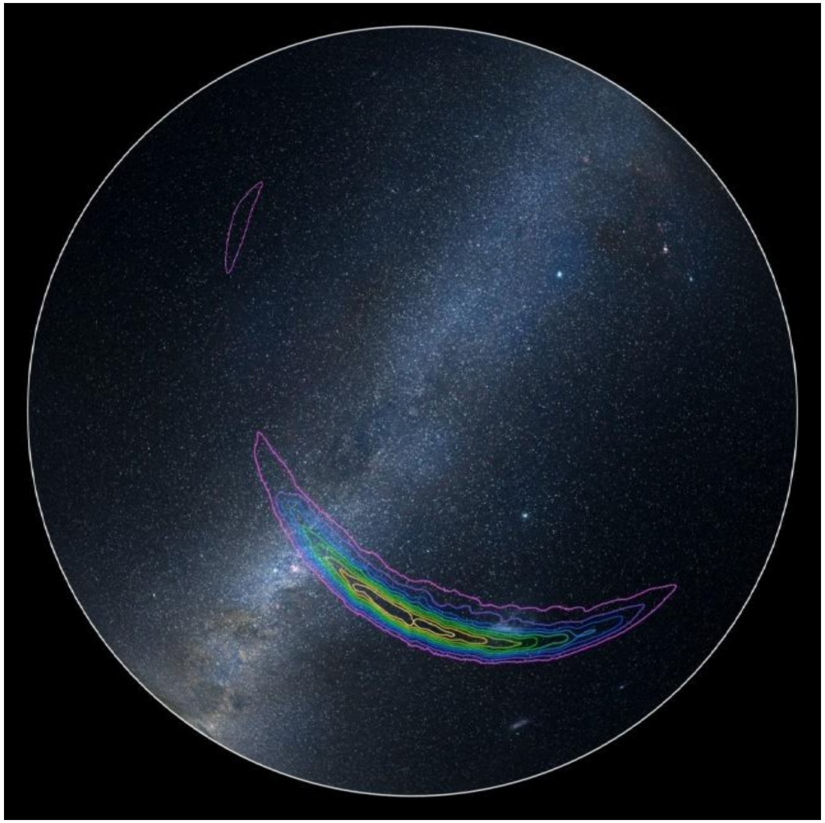




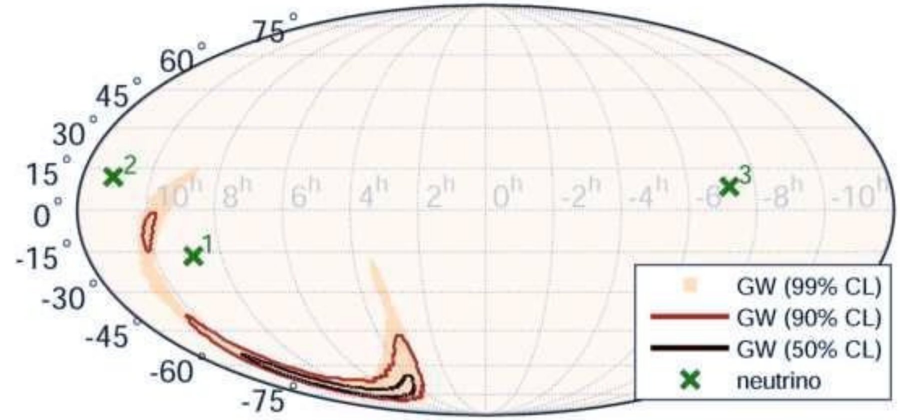




Rapid Source Sky Localisation



GW150914 is localized to an area of approximately 590 deg^2 (90% credible region) in Southern hemisphere



- Trigger sent to astronomer within about 180s of online detection
- But follow up, to assess the signal significance, takes several months
- Search for coincident high energy neutrino candidates in IceCube and ANTARES data (nothing above background)

Some Facts

LIGO G1600220

- **First direct detection of Gravitational Waves**
  - First confirmation of their existence from the Hulse-Taylor binary (1975)
- **First direct observation of a black hole**
  - inferred from the characteristic ringdown 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 most luminous event ever detected: 3.6 x 10^{56} erg/s**
  - Total radiated energy ~ 3 solar mass
- **Placed 2nd strongest 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

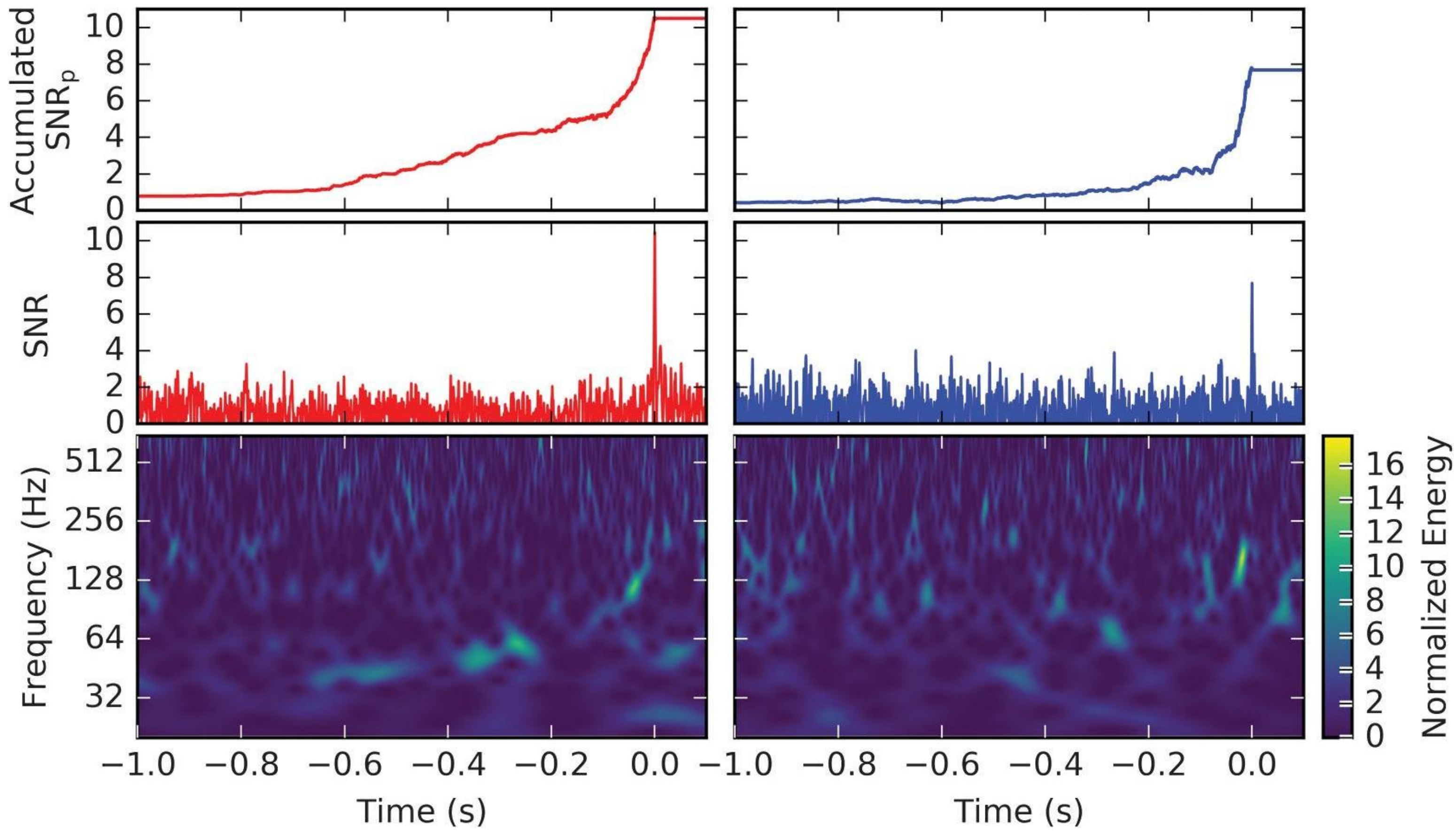
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary 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 x 10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2 x 10^{30} kg

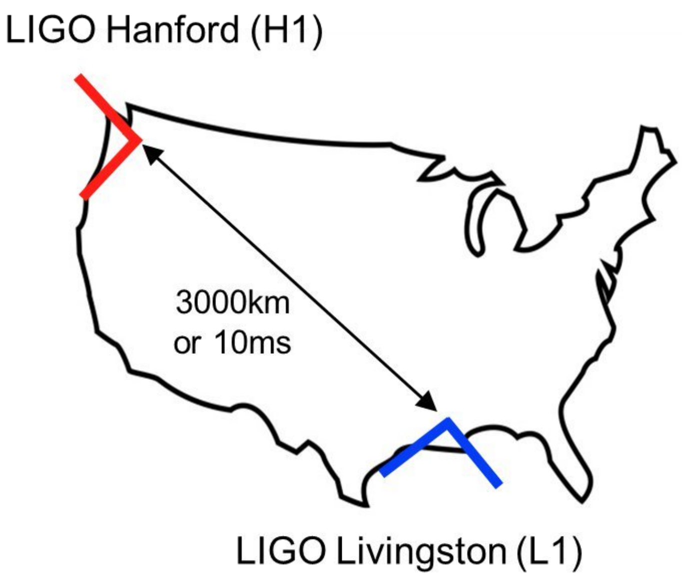
GW151226: The Signal

Phys. Rev. Lett. 116, 241103, 2016

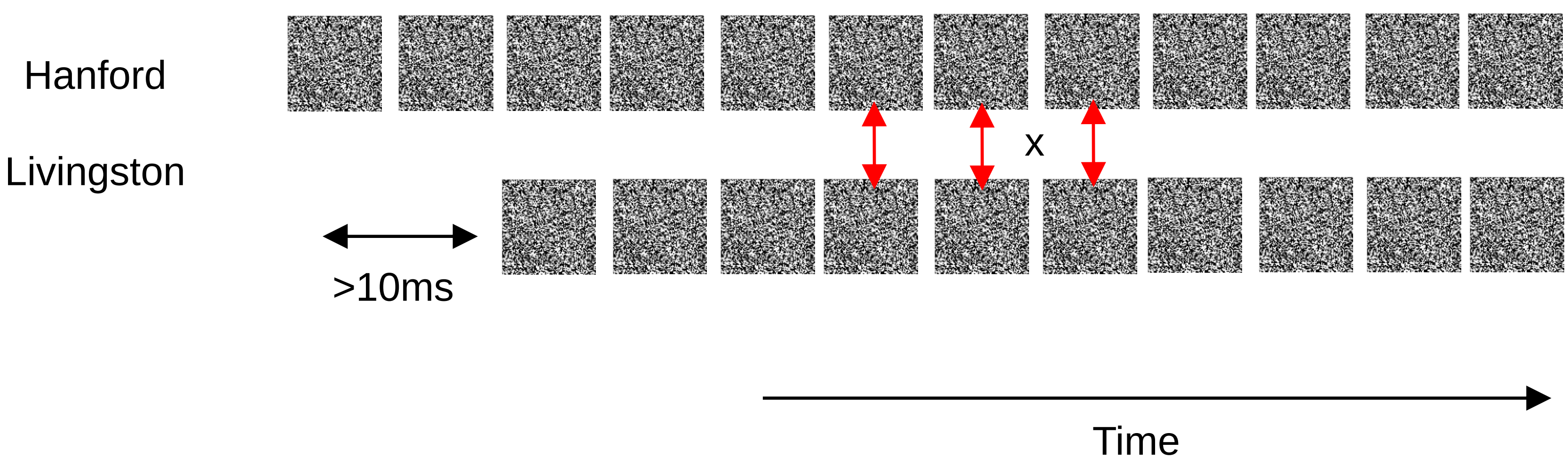


- 2nd most significant event in the O1 data after GW150914

Estimating the Significance

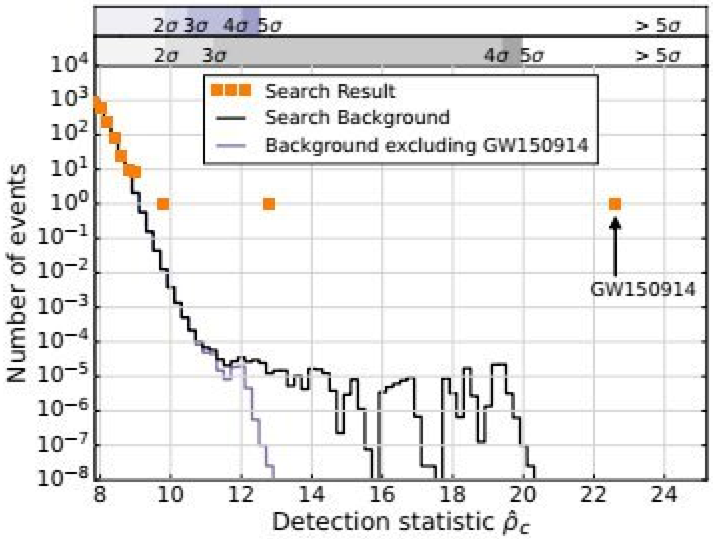


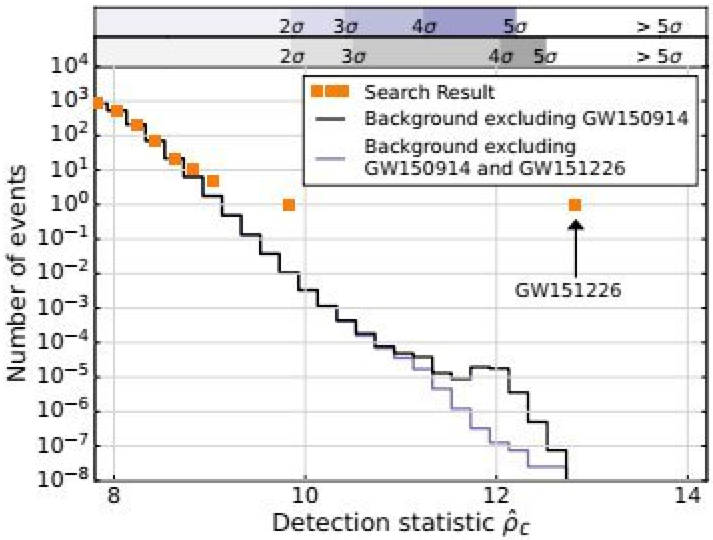
- Time shift the data at both sites by greater than light travel time
- Perform a cross correlation => false alarm rate

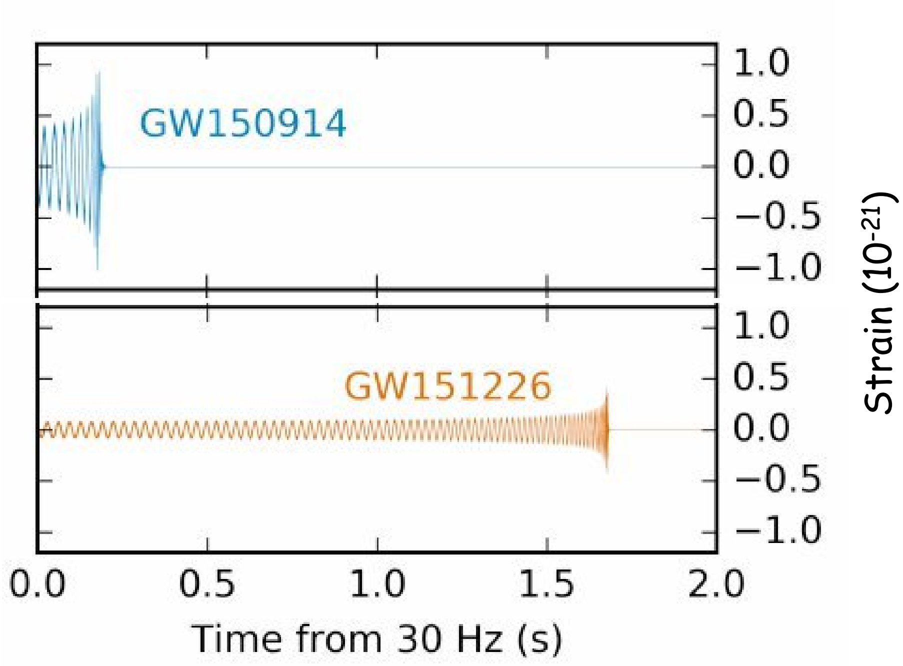


Comparing The Events

Chunglee Kim (Seoul National U.)

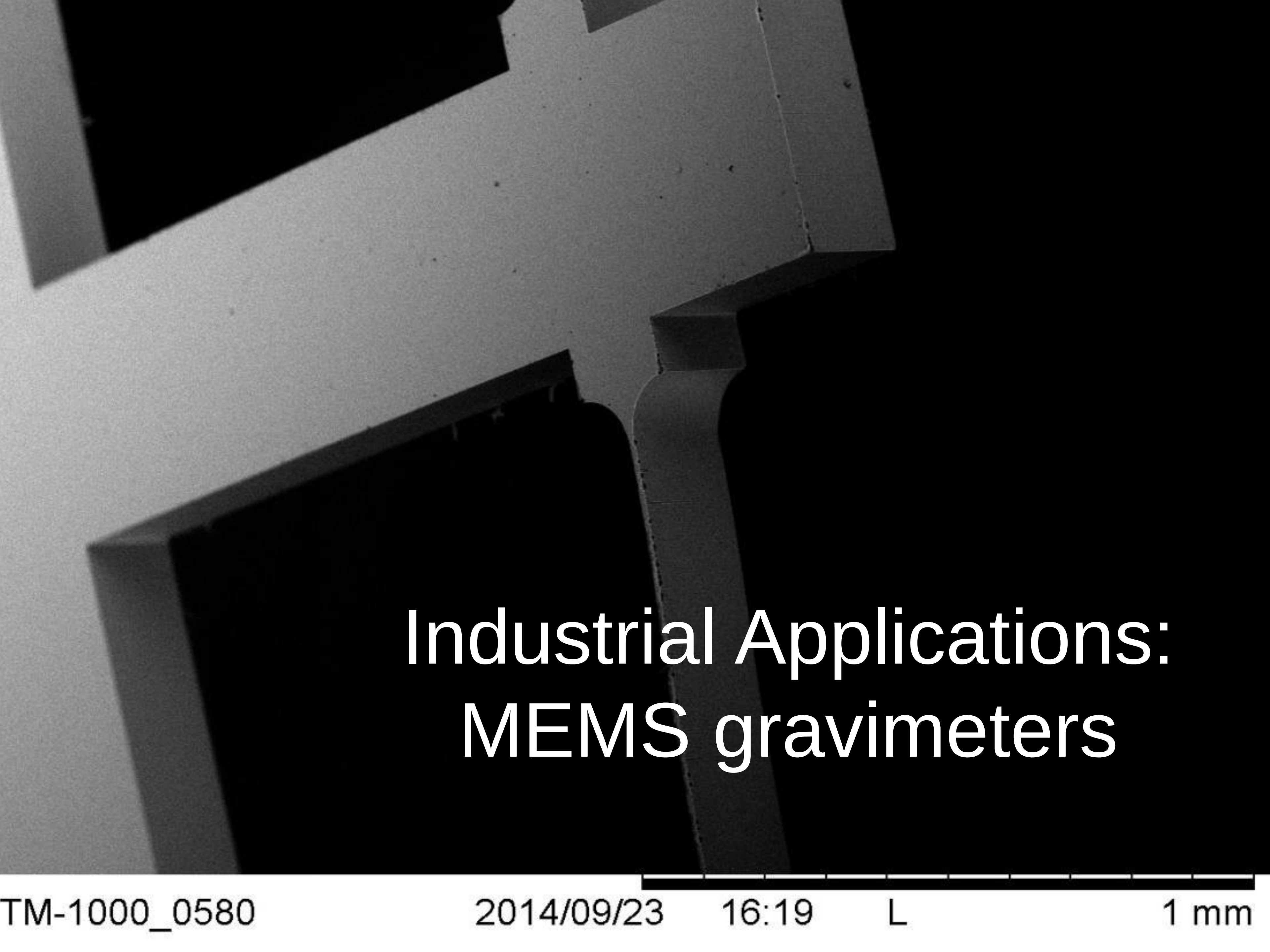






Event	GW150914	GW151226
Signal-to-noise ratio ρ	23.7	13.0
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$
p-value	7.5×10^{-8}	7.5×10^{-8}
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$

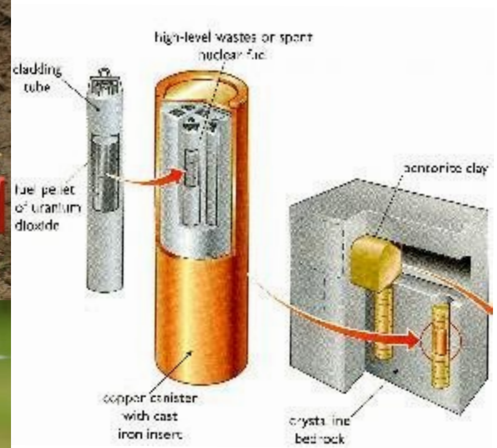
Industrial Applications: MEMS gravimeters



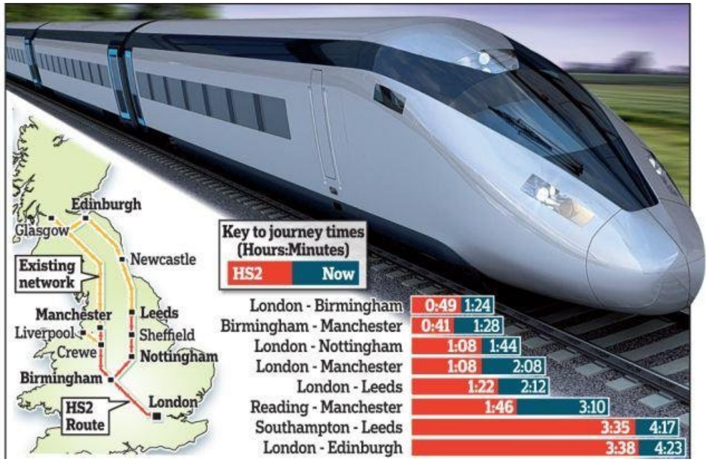
Gravity Imaging Applications

Oil & gas prospecting

Environmental monitoring



HS2

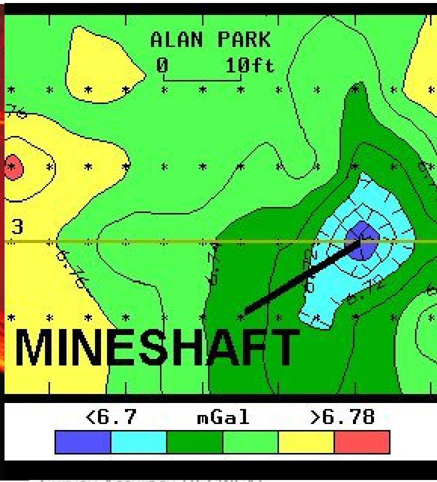


Buried utilities / brown field site

Security & Defence

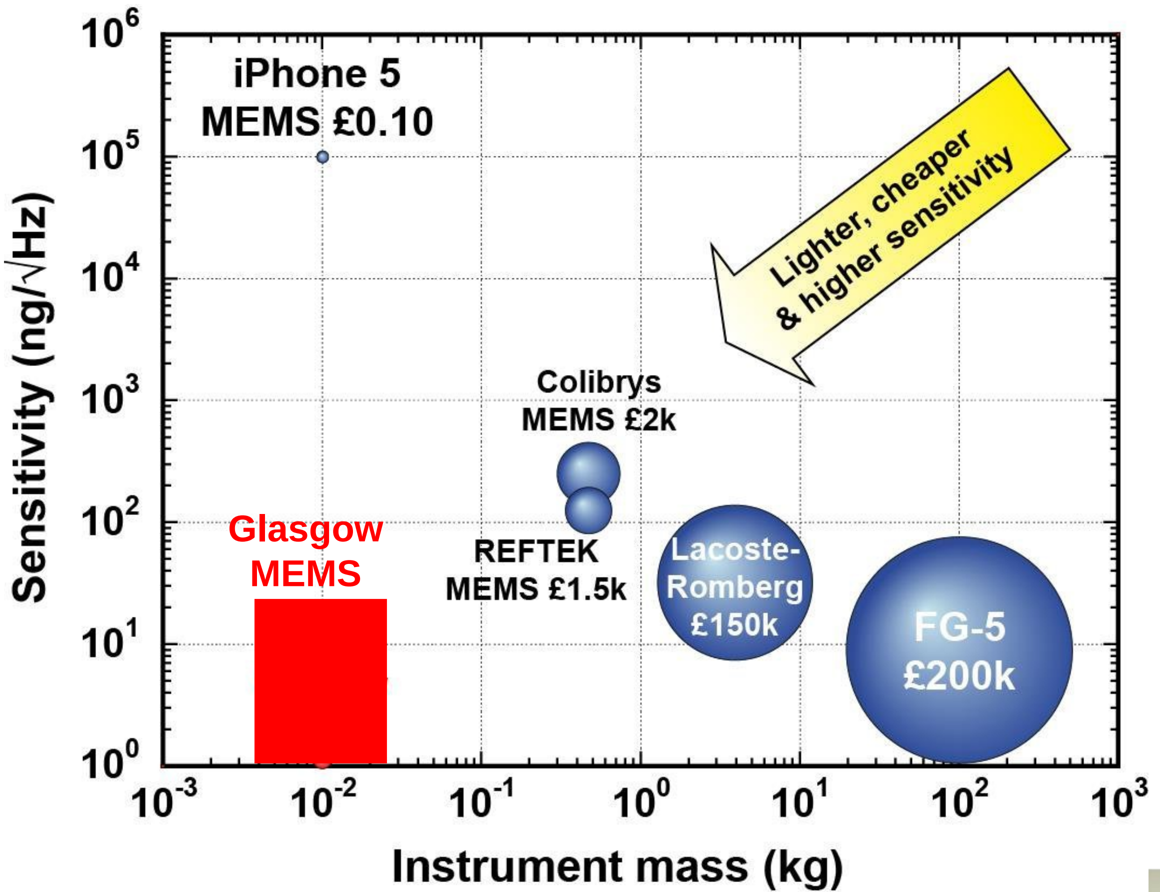
Volcano eruption

Geological hazard detection



Survey Accuracy (ISCWSA)

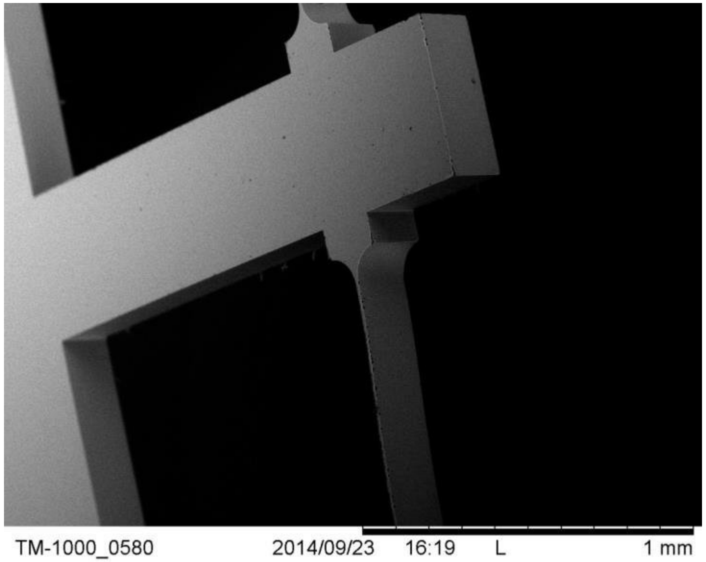
Instruments for Gravity Measurement

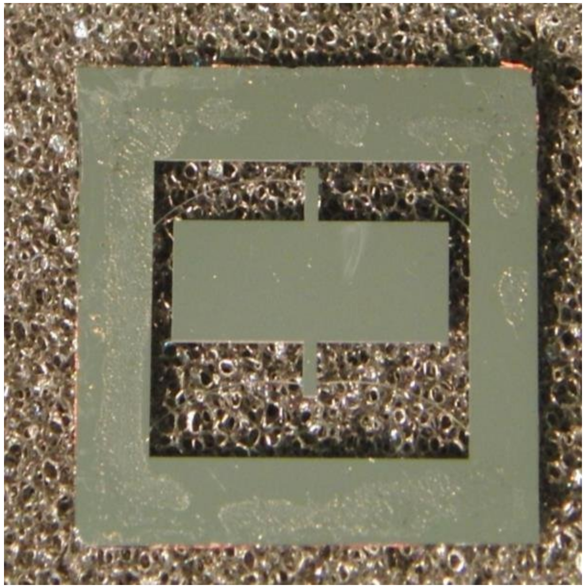


- Explore a new region of sensitivity-cost space

Survey Accuracy (ISCWSA)

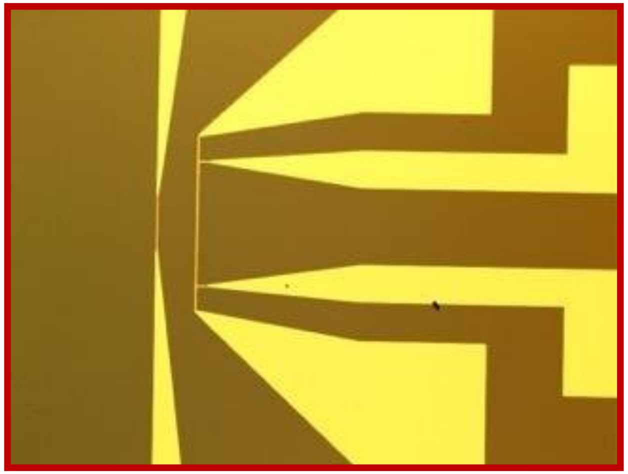
MEMS Fabrication



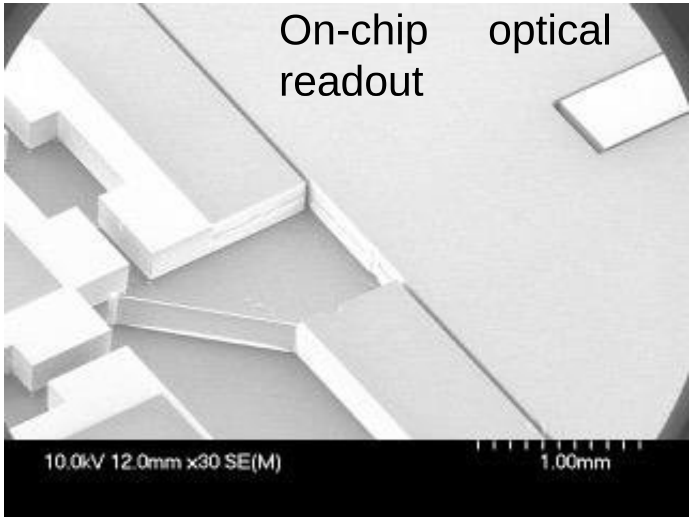


9 mm

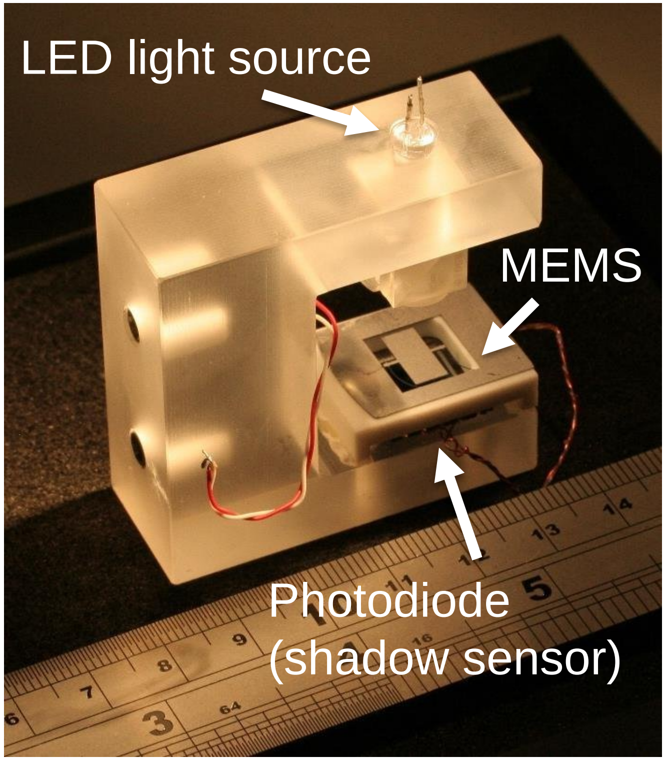
MEMS device

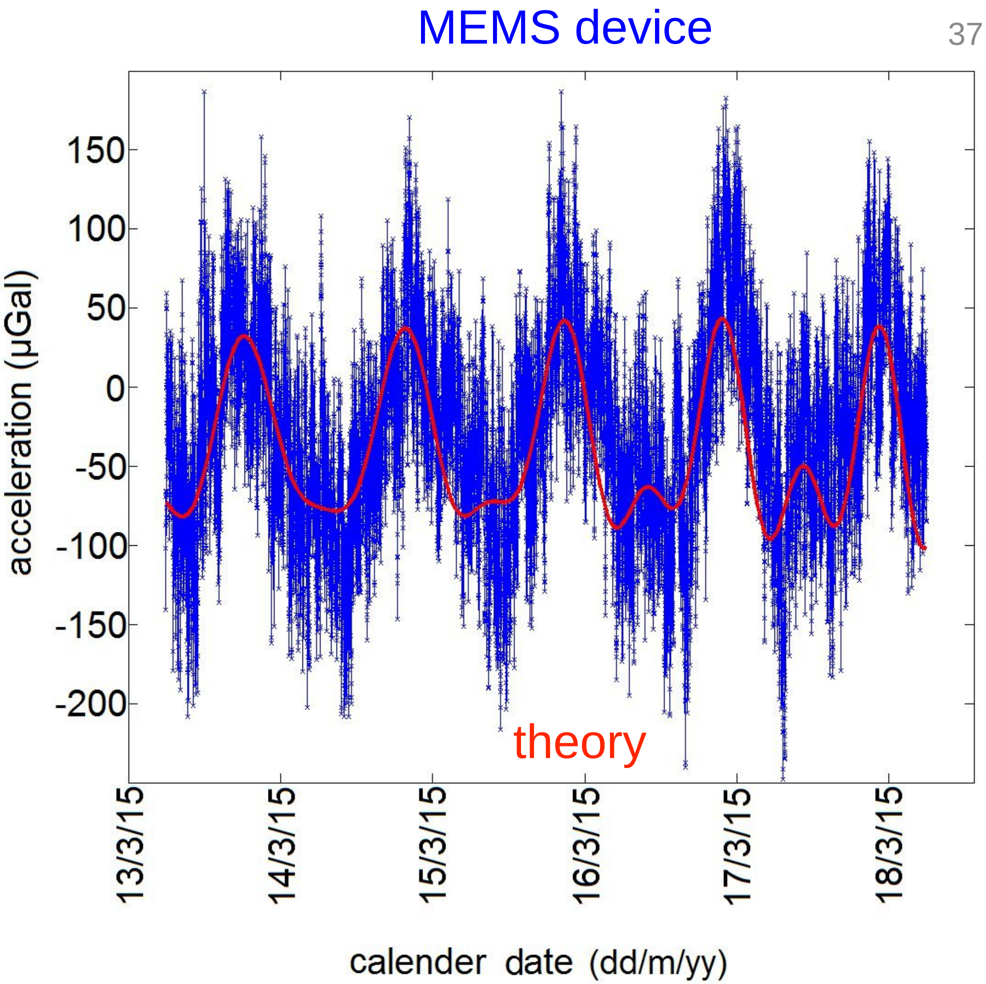


Integrated heater/thermometer



MEMS Gravimeter



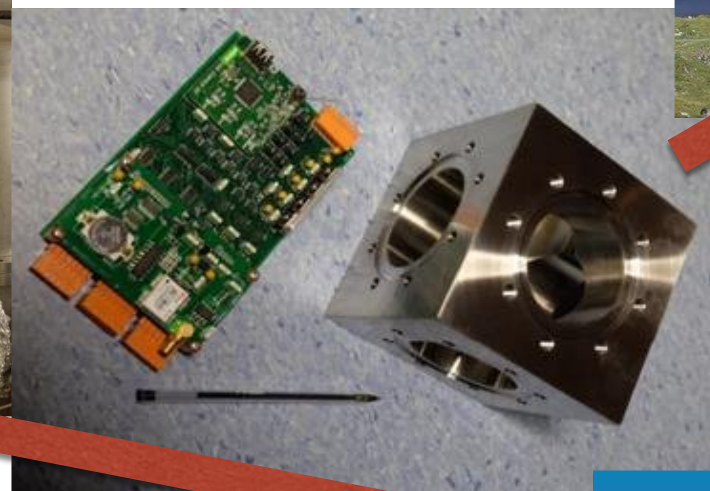


R.P. Middlemiss et al. Nature 531, 614 (2016)

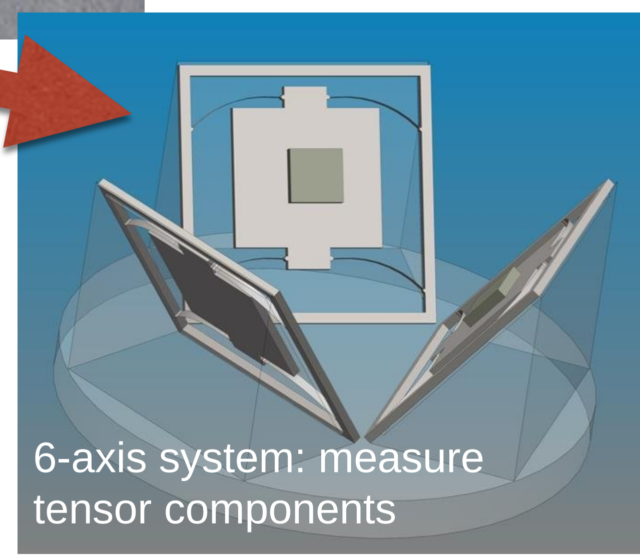
CLYDE SPACE QinetiQ dstl Schlumberger SPE International EPSRC Engineering and Physical Sciences Research Council bridgeporth

Miniaturising the Gravimeter

Aim: shoebox sized field demonstrator (2016)



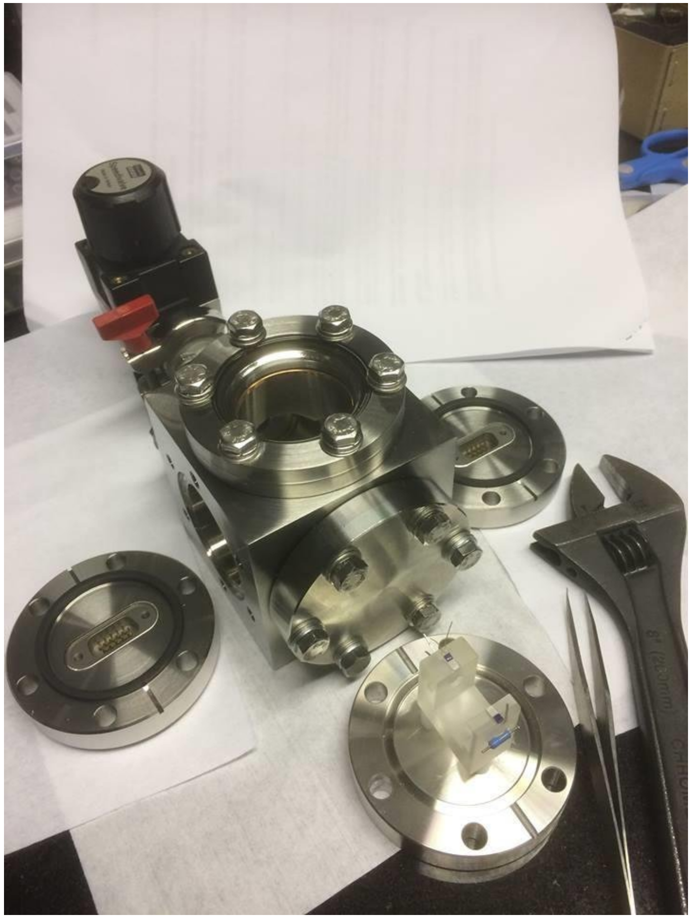
Fully integrated gravity system (2018)

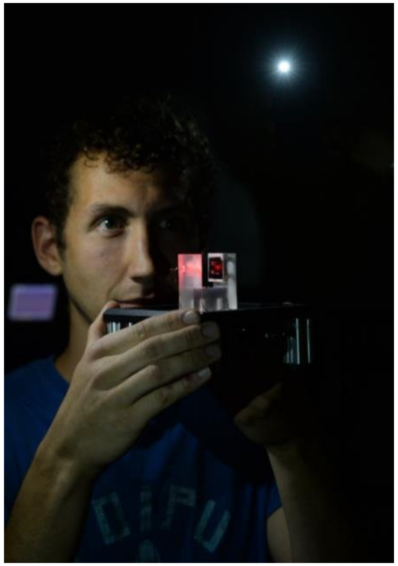


Demonstrator requests:

- oil & gas prospecting
- volcano eruptions
- geophysics (sink holes…….)
- nuclear waste, SNM detection
- security

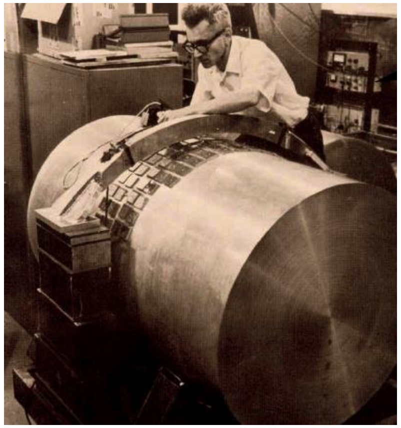
Miniaturising the Gravimeter



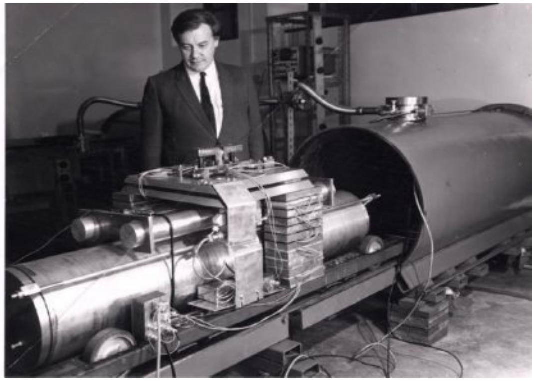


Thank You

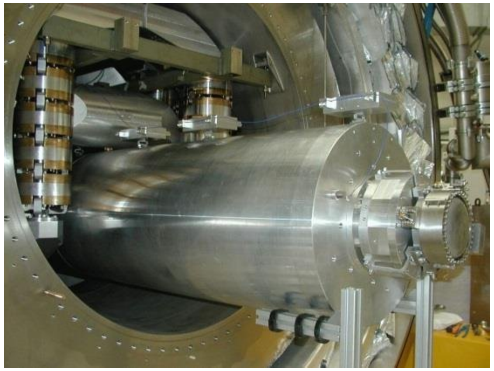
Brief History



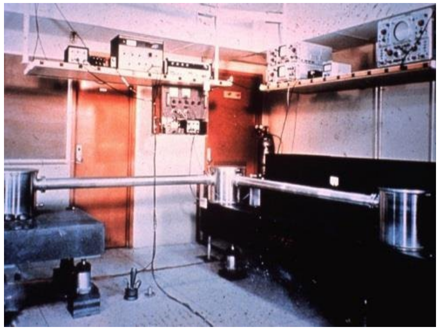
J. Weber, 60’s-80’s



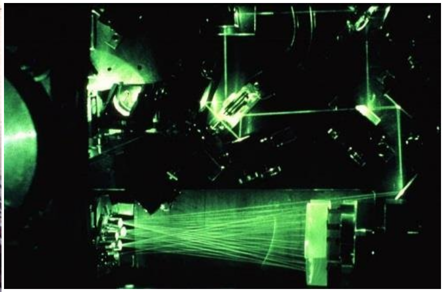
Germany/Italy/UK, 70’s-80’s

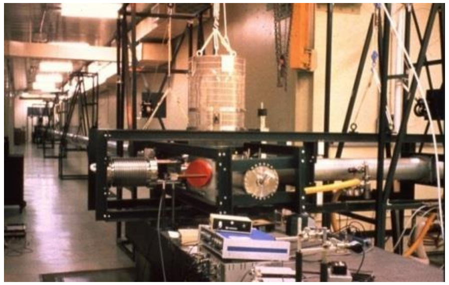


Modern bars
80’s-90’s



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

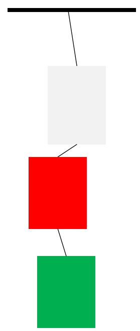
Glasgow 10m: 1978-current

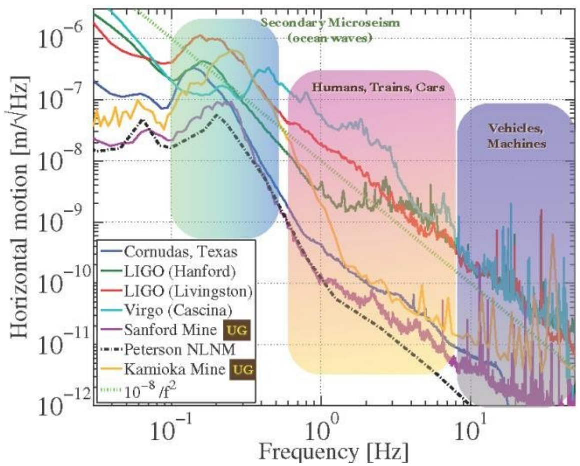
LIGO/aLIGO: 90’s-current

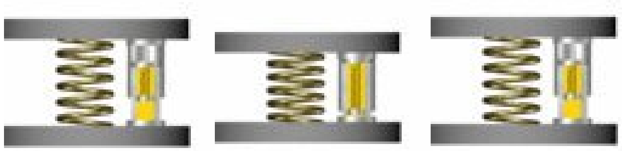
- The UK has a strong history, and continues to have a leadership role in current detector technology and implementation

Fundamental Noise Sources

Seismic Noise

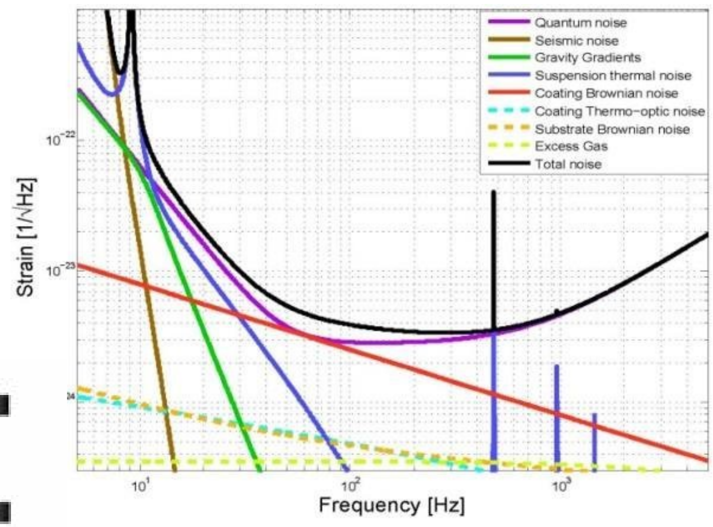




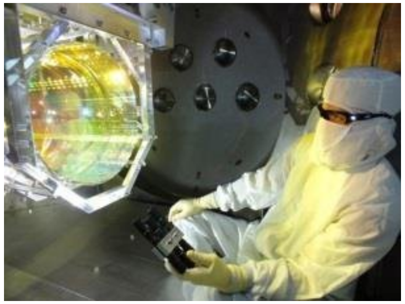


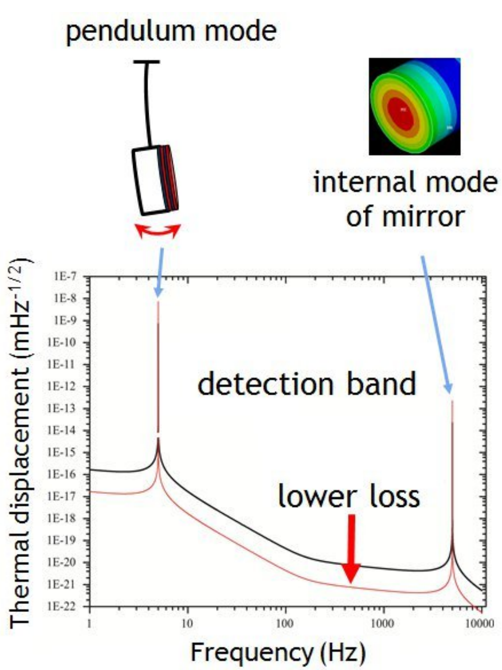
f low resonance f high

	Mirror Requirements
Thermal Noise	10^{-19} m/√Hz at 10Hz (longitudinal) 10^{-16} m/√Hz at 10Hz (vertical)
Seismic Noise	10^{-19} m/√Hz at 10Hz (assumes seismic platform noise 2×10^{-13} m/√ Hz)

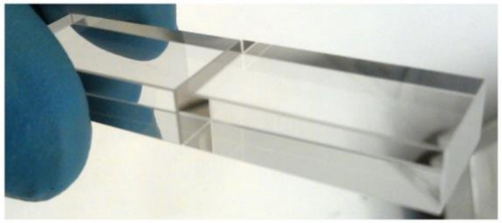


Thermal Noise

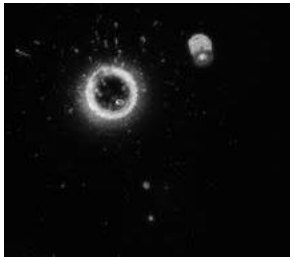




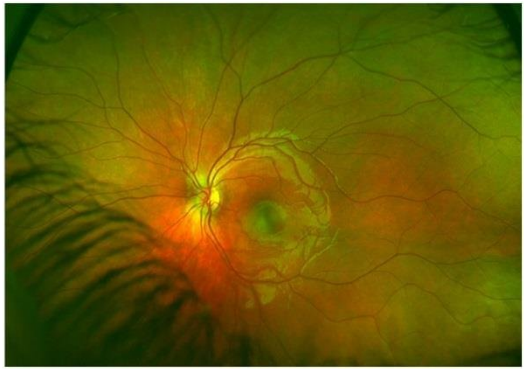
Spin Off Technologies



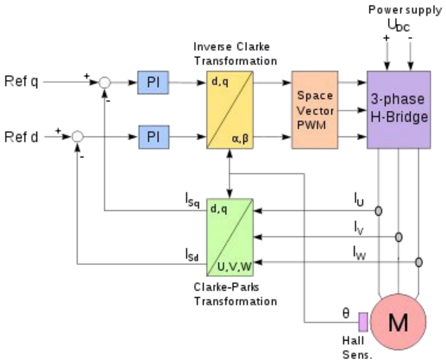
High precision/stability bonding



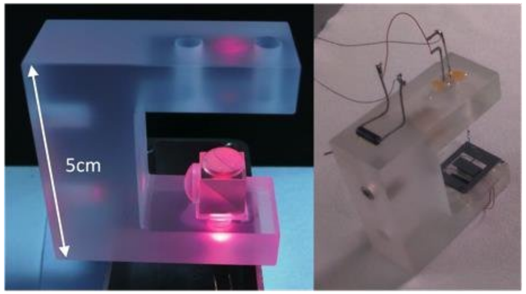
Coating damage



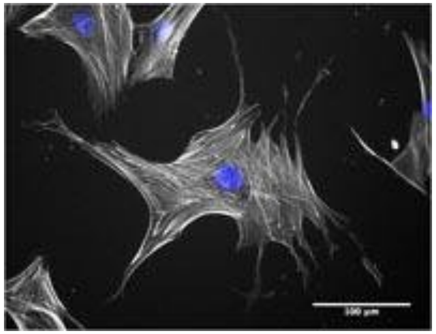
analysis of retinal scans



Motor control



Gravity sensors for environmental monitoring/security/oil & gas



Stem cell differentiation

Gas sensors (GSS)

Weathering of sandstone