Gravitational wave detectors: precision measurement technologies and their applications

Prof Sheila Rowan

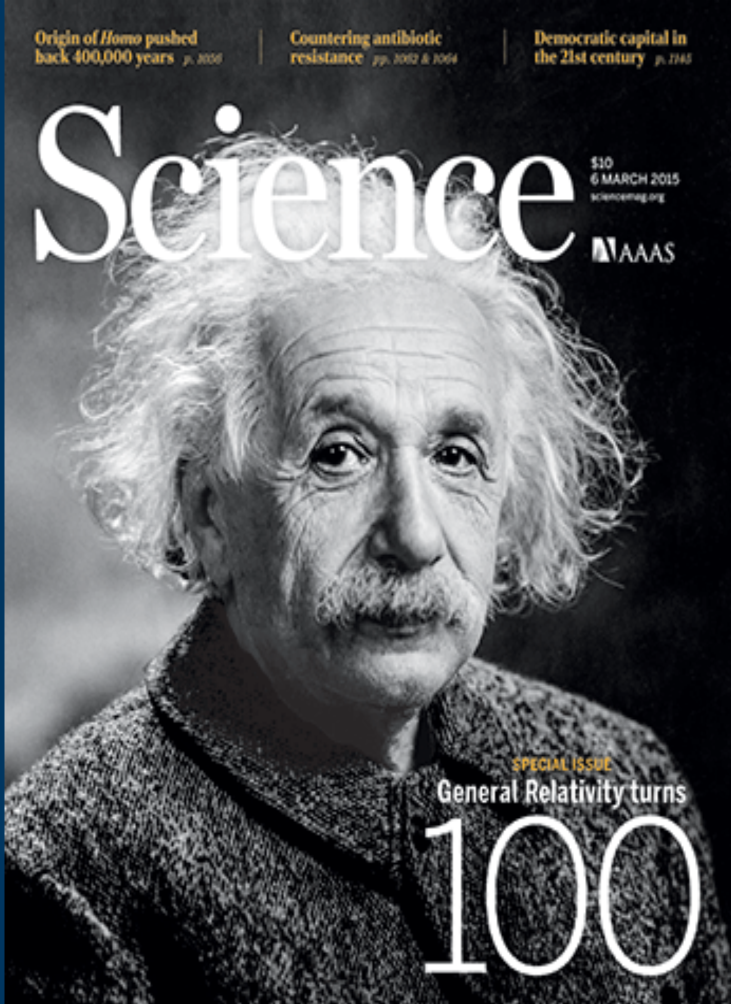
For the LIGO Scientific Collaboration

Winton meeting, Cambridge

1st November 2018

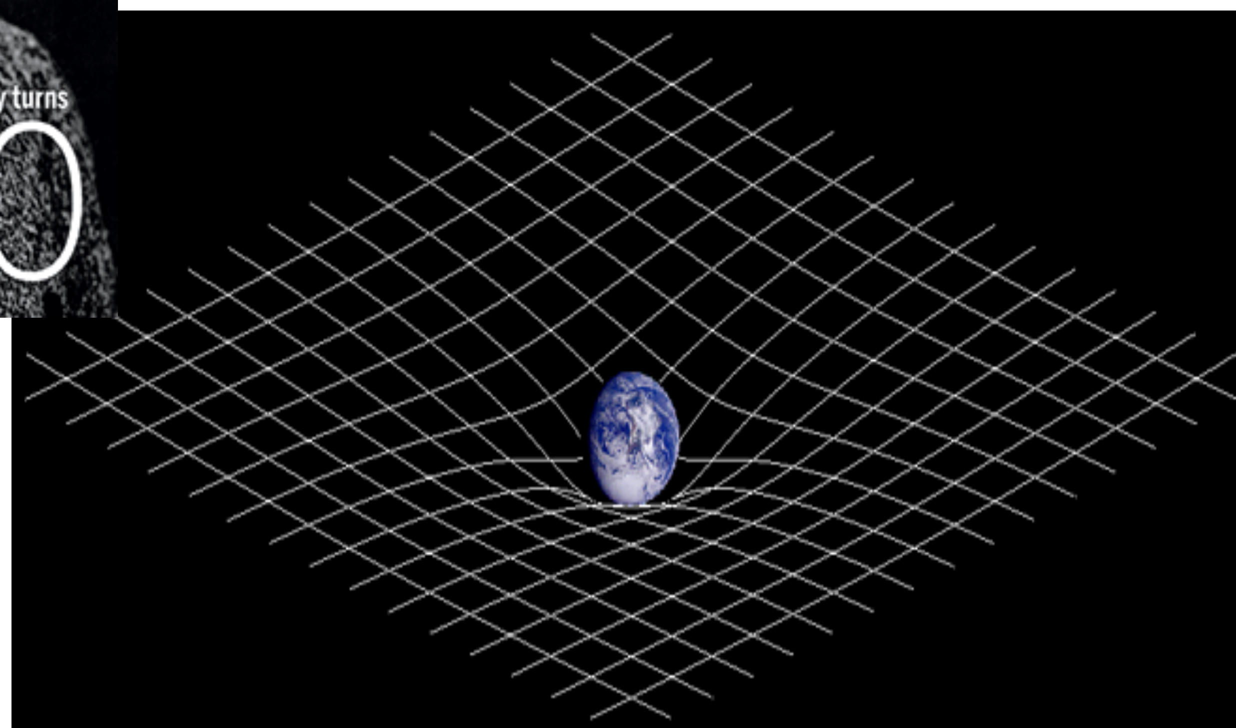
LIGO-G1702161.

Gravity in Einstein's Universe



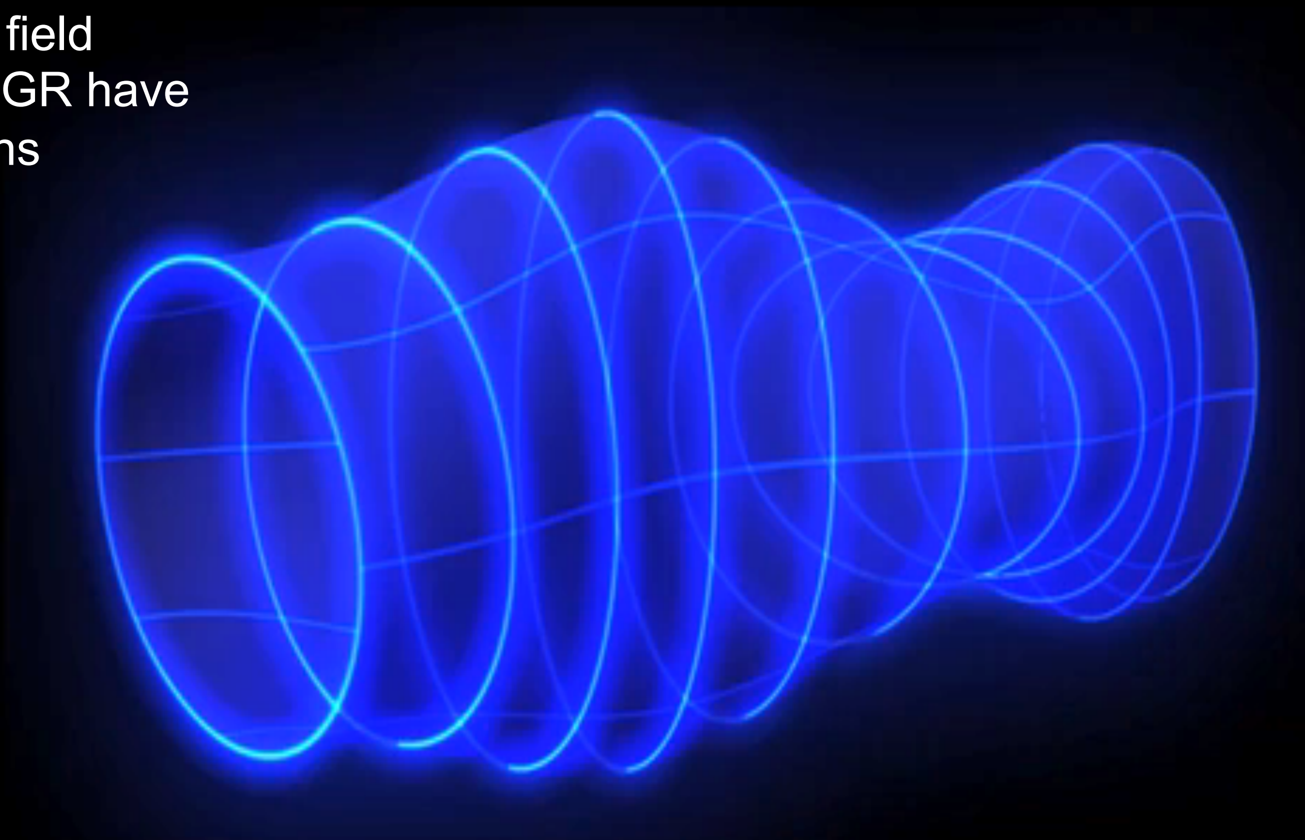
Special Relativity
information cannot be carried faster than speed of light – there must be gravitational radiation

General Relativity:
"Space-time tells matter how to move,
and matter tells space-time how to curve"



General Relativity predicts the physical properties of GWs

The Einstein field equations of GR have wave solutions

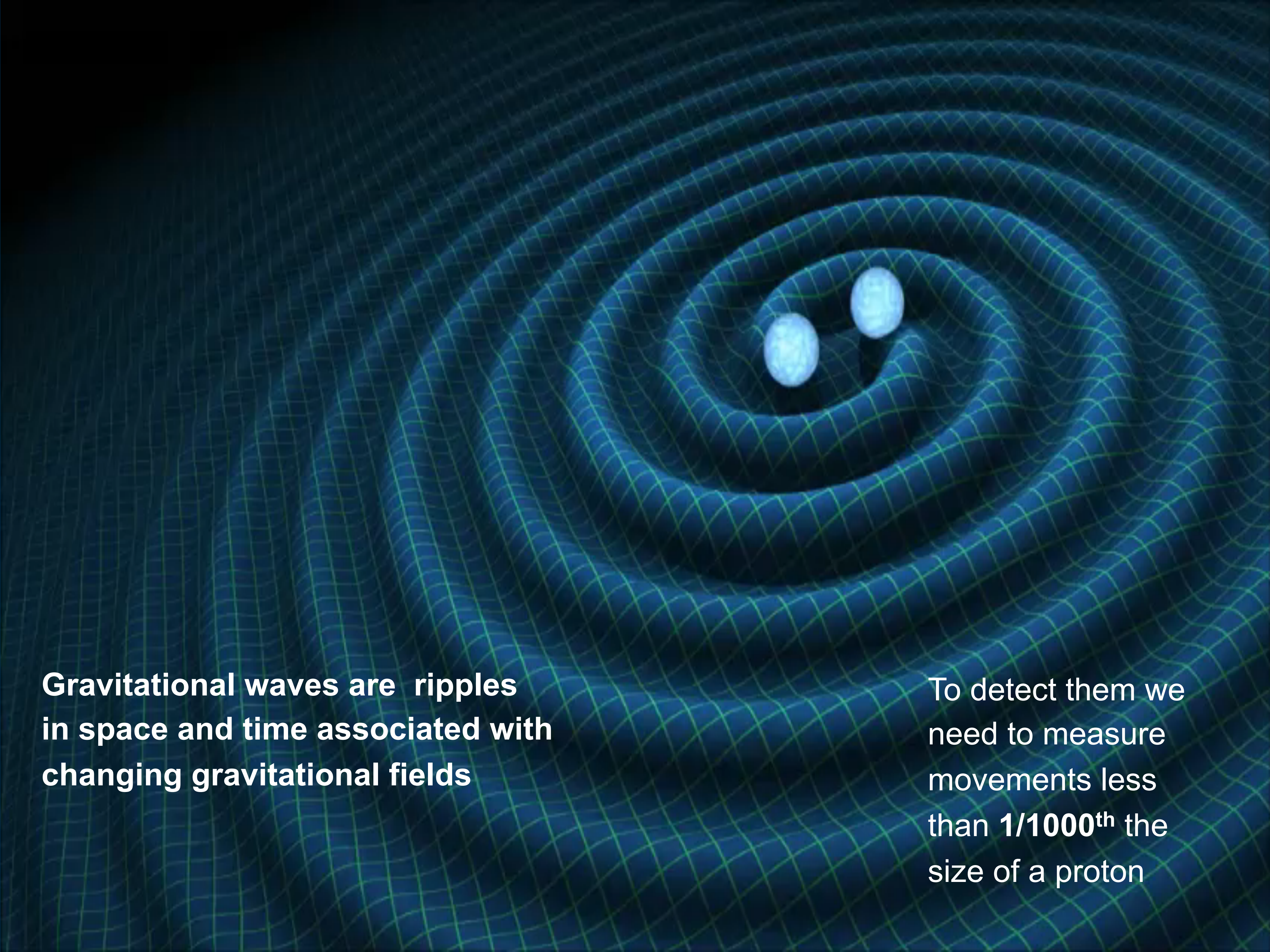


► GWs are em by a rapidly changing configuration of mass

► Travel away the source at th speed of light

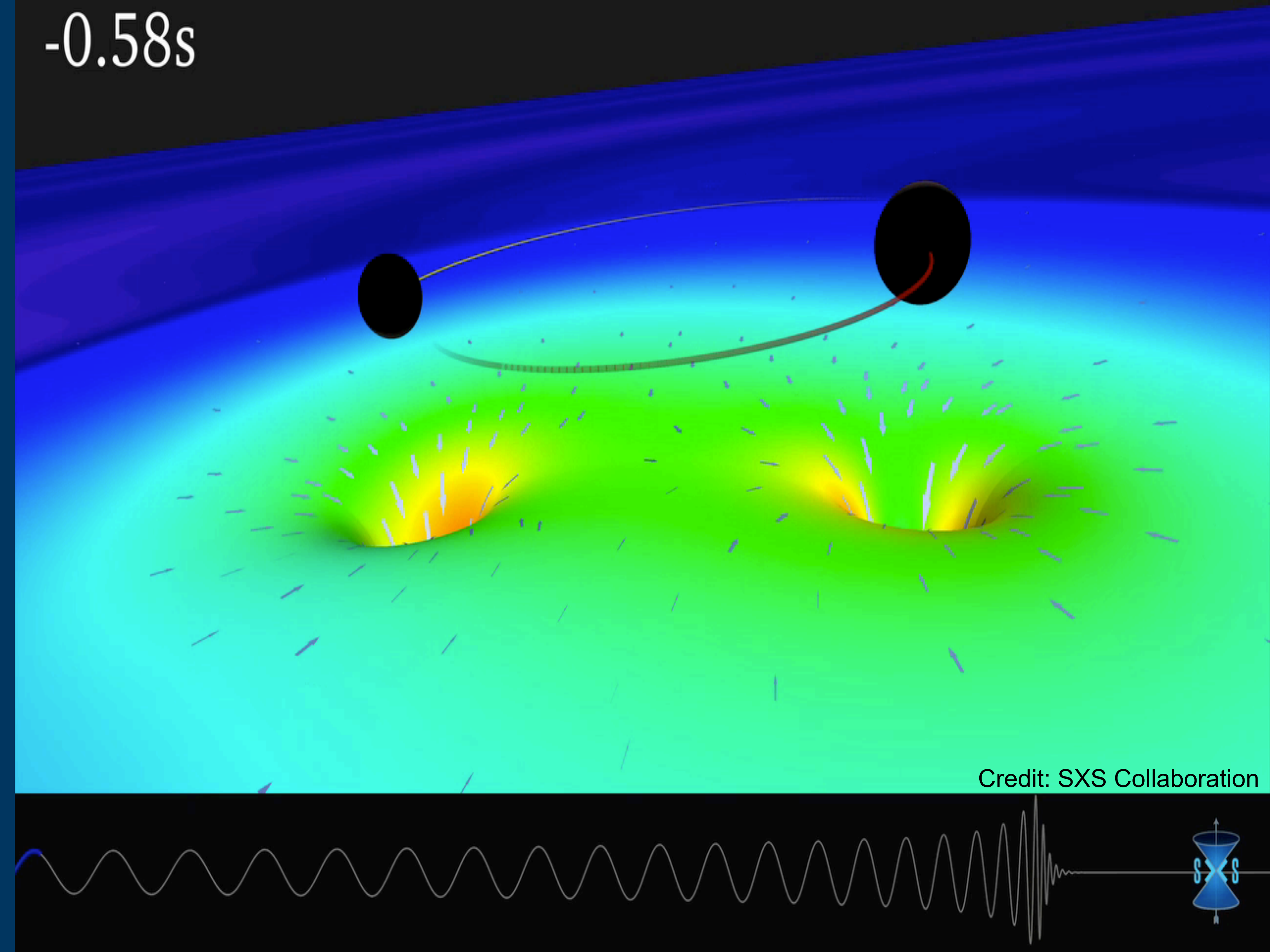
Change the effective distance between inertial points — i.e. the spacetime metric — transverse to the direction of travel

Looking at a fixed place in space while time moves forward, the waves alternately *s t r e t c h* and *shrink* the space



Gravitational waves are ripples in space and time associated with changing gravitational fields

To detect them we need to measure movements less than **$1/1000^{th}$** the size of a proton


-0.58s
Credit: SXS Collaboration
SXS

The LIGO and Virgo collaborations found the first gravitational wave signal – reported in Feb 2016

From exact signal shape we get a wealth of information

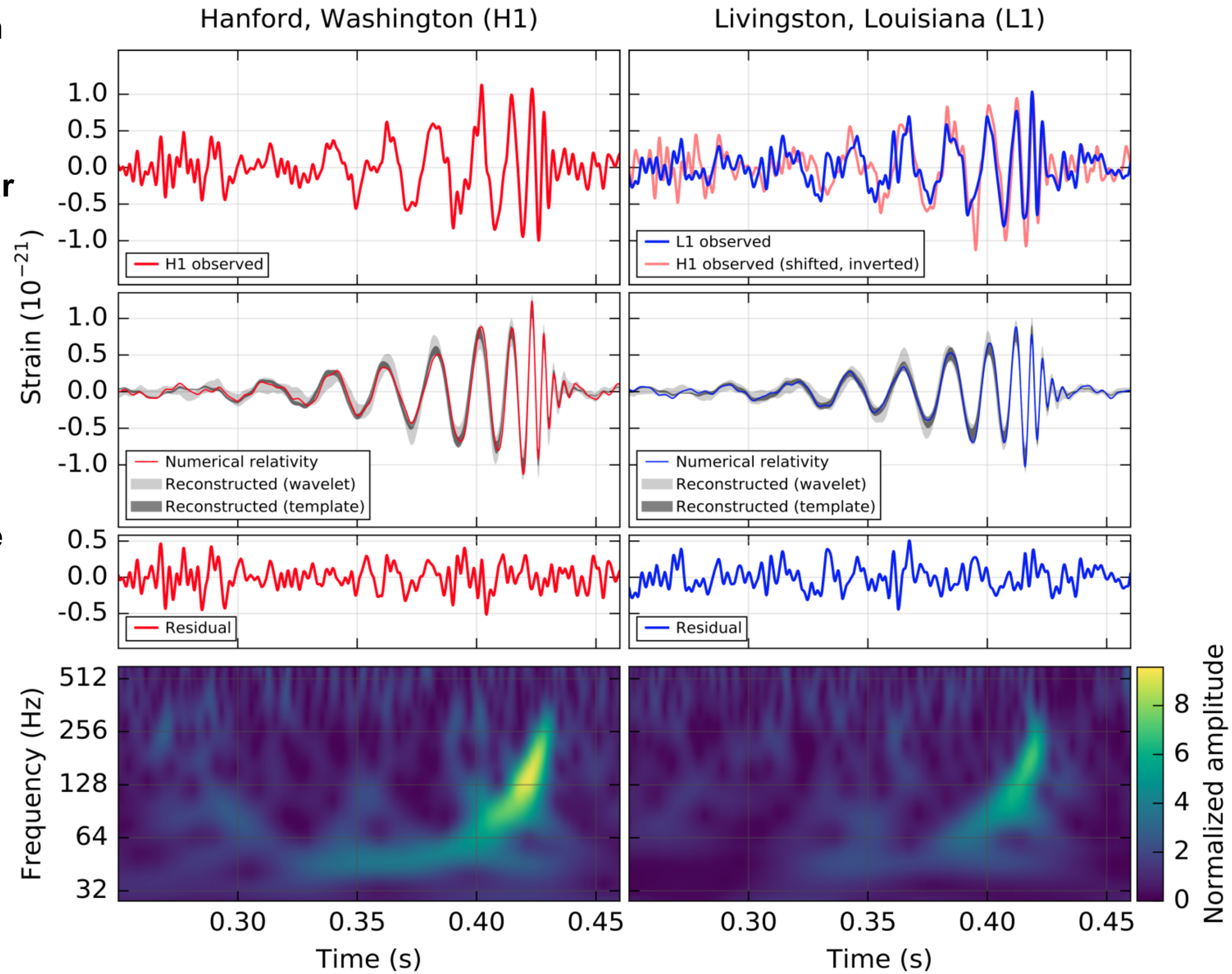
Two black holes colliding - one 36 solar mass, one 29 solar mass

…collided 1.3 billion lights years away…

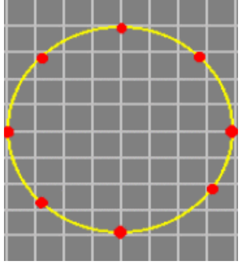
….the final black hole was about 366 km across (about the size of Iceland)

..but 62 times the mass of the sun (about 20 million Earths)…

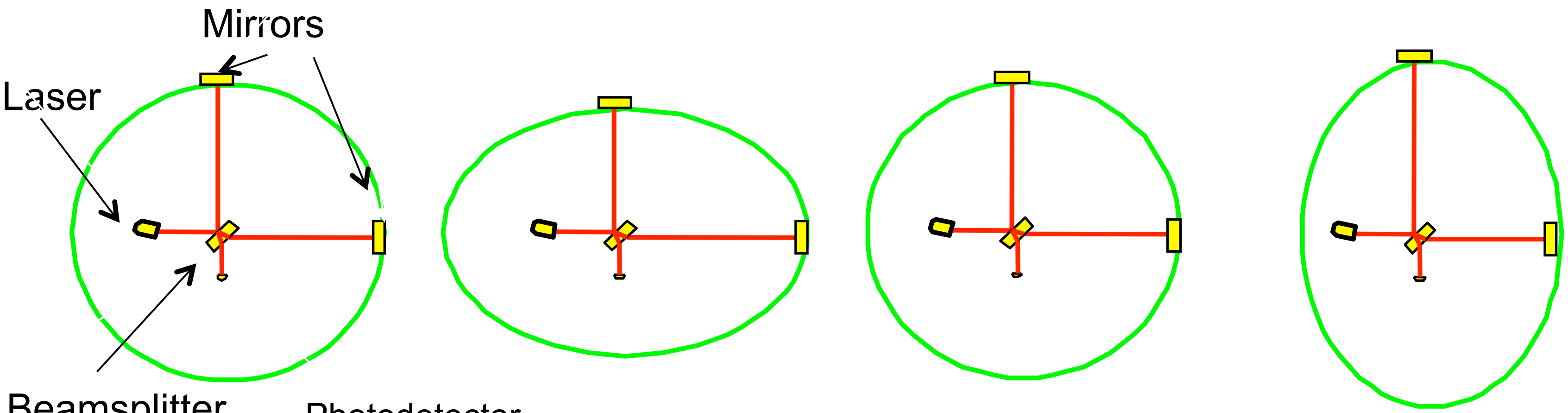
..spinning about 100 times a second at nearly half the speed of light.



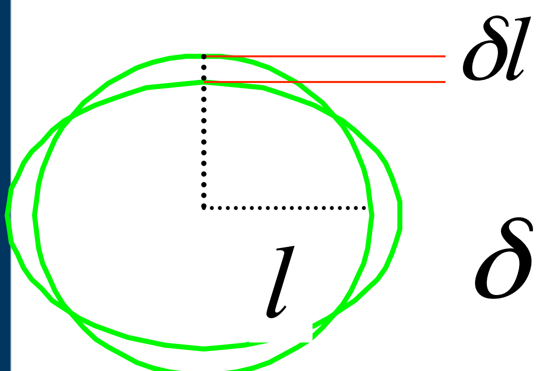
Phys. Rev. Lett. 116 061102 (2016)



Operation of Interferometric Gravitational Wave Detectors



$t = 0$ $\quad t = \frac{\tau}{4}$ $\quad t = \frac{\tau}{2}$ $\quad t = \frac{3\tau}{4}$



For Typical Astronomical sources

$$\delta l = \frac{h}{2} l \qquad h = \frac{2\delta l}{l} \leq 10^{-22}$$

Gravitational wave amplitude

For 1m arm interferometer = δl of 10^{-22} m

These are not tabletop devices….

Main limitations to sensitivity

Photton shot noise (improves with increasing laser power) and

Radiation pressure (becomes worse with increasing laser power)

There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle – the ‘Standard Quantum limit’

Seismic noise (relatively easy to isolate against – use suspended mirrors

Thermal noise (Brownian motion of test masses and suspensions)

Gravitational gradient noise – particularly important at frequencies below ~10 Hz

All point to long arm lengths being desirable

Requires instrument science at the frontiers of fundamental limits In physics

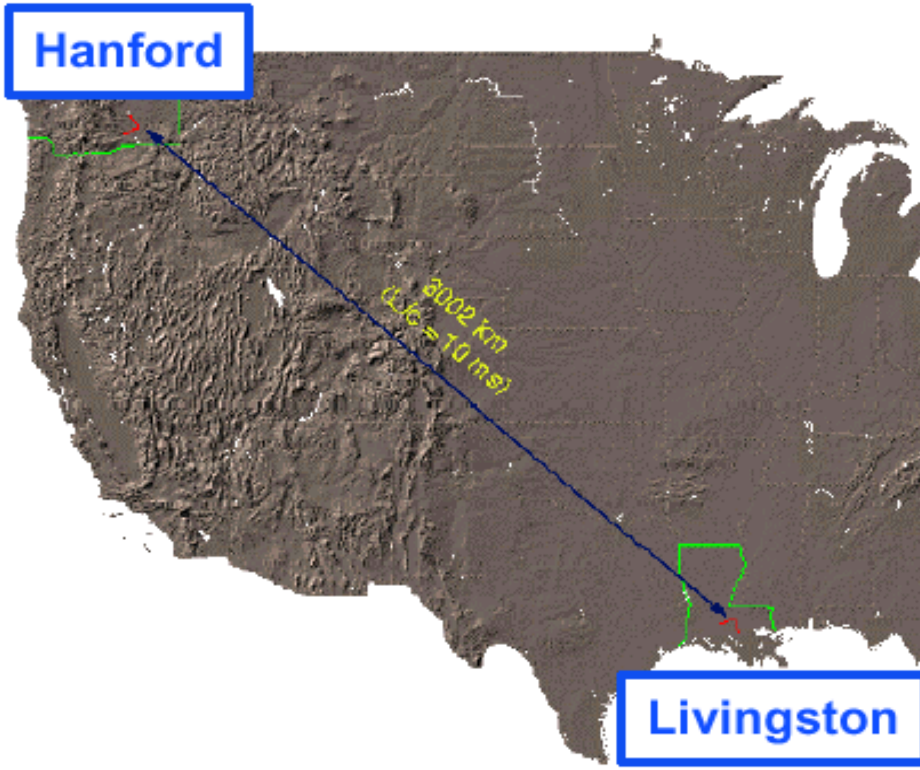
All present technological and engineering challenges, in each case pushing the state-of-the art in the laboratory and commercially

LIGO observatories

LIGO project (USA)

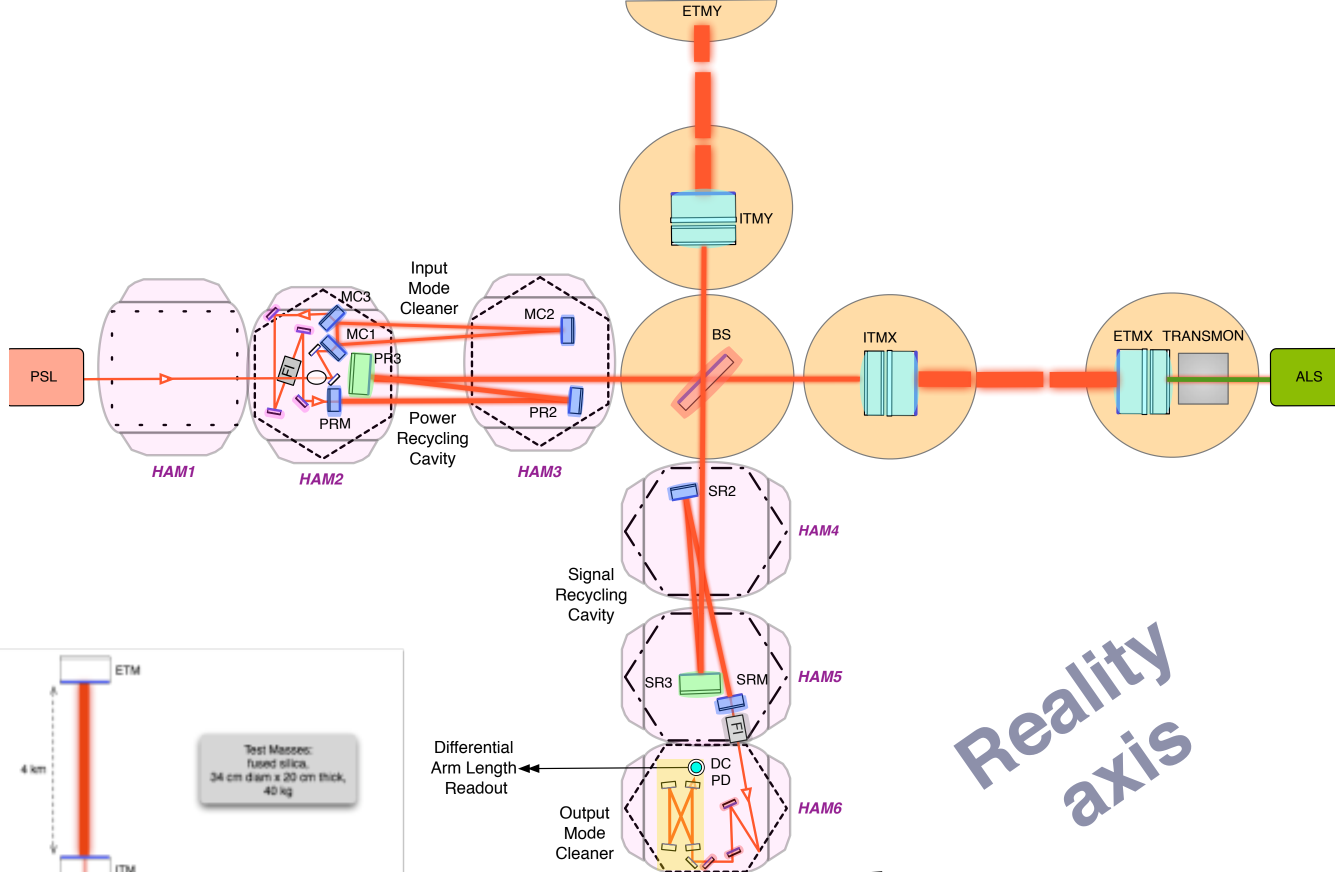
- 2 detectors of 4km arm length

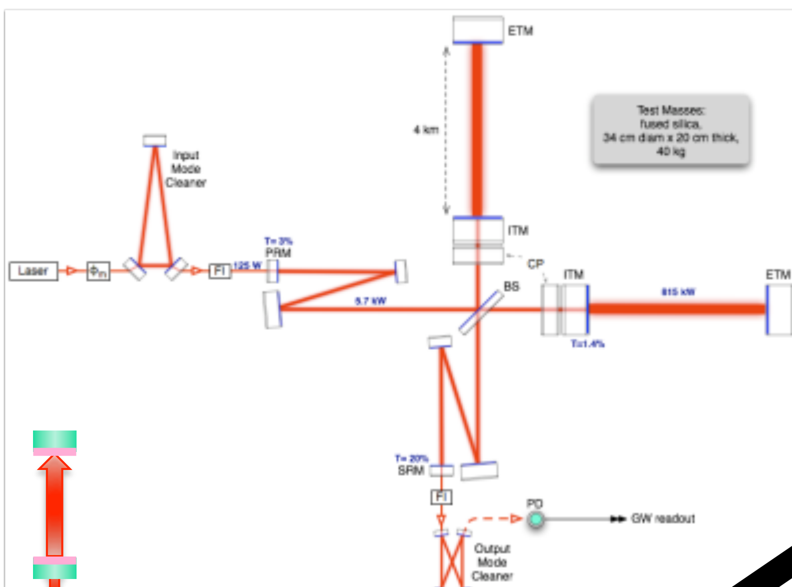
- Observatories jointly managed by Caltech and MIT



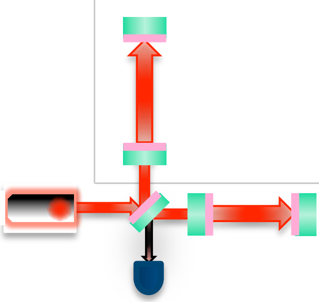
Science of developing and using the observatories: LIGO Scientific Collaboration - <u>a group of 1000+ scientists worldwide</u>

LIGO





Reality axis


photodiode

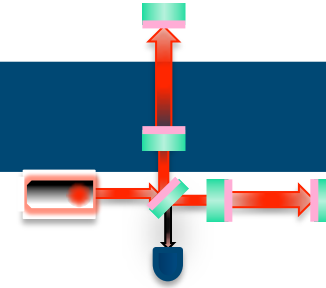
The real instrument is far more complex…

LIGO Infrastructure: 4km "Beam Tubes"

- Light must travel in an excellent vacuum: …10^{-9} torr
  - » Just a few molecules traversing the optical path makes a detectable change in path length, masking Gravitational waves
  - » 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters' bullets and the stray car
- Tube is straight to a fraction of a cm…not like the earth's curved surface

LIGO

Addressing limits to performance



Creating Advanced GW observatories

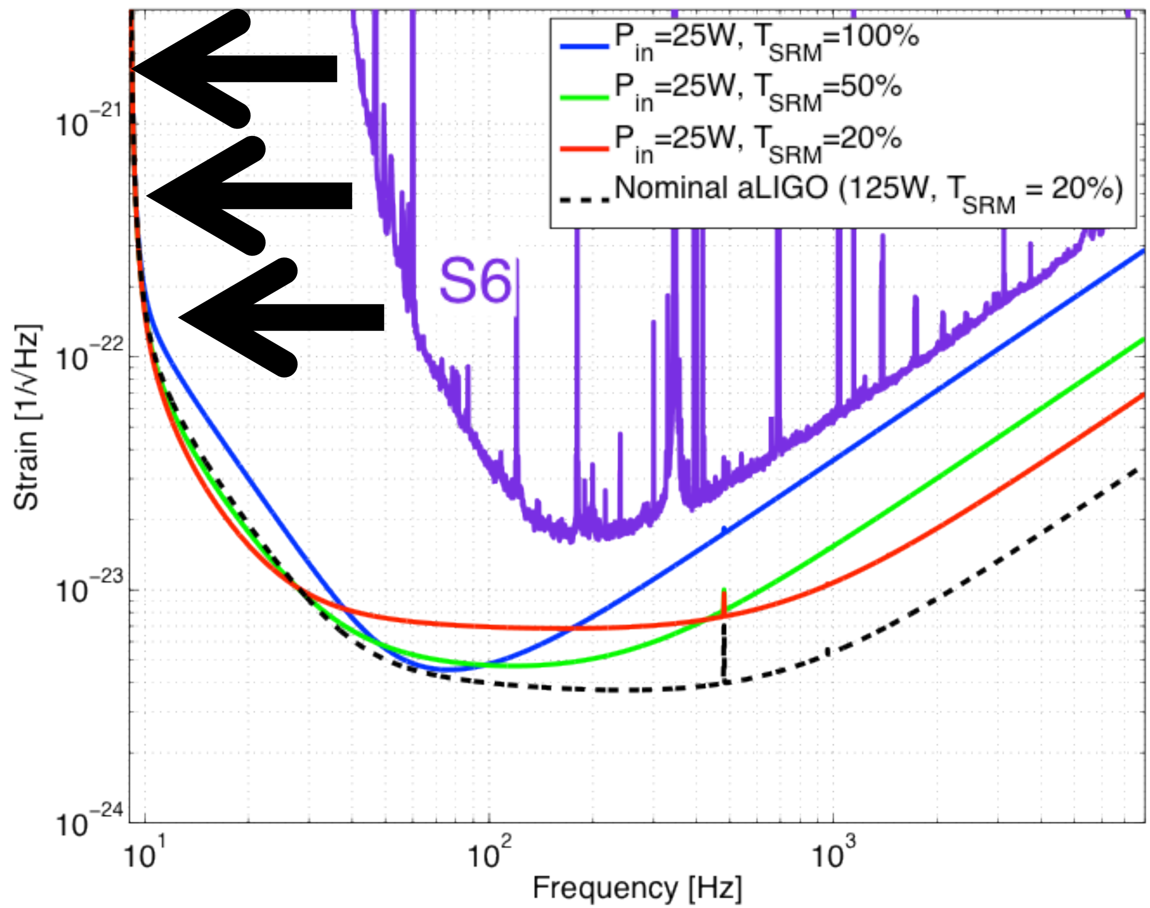
Seismic noise

– must prevent masking of GWs, enable practical control systems

- Motion from waves on coasts…and people moving around

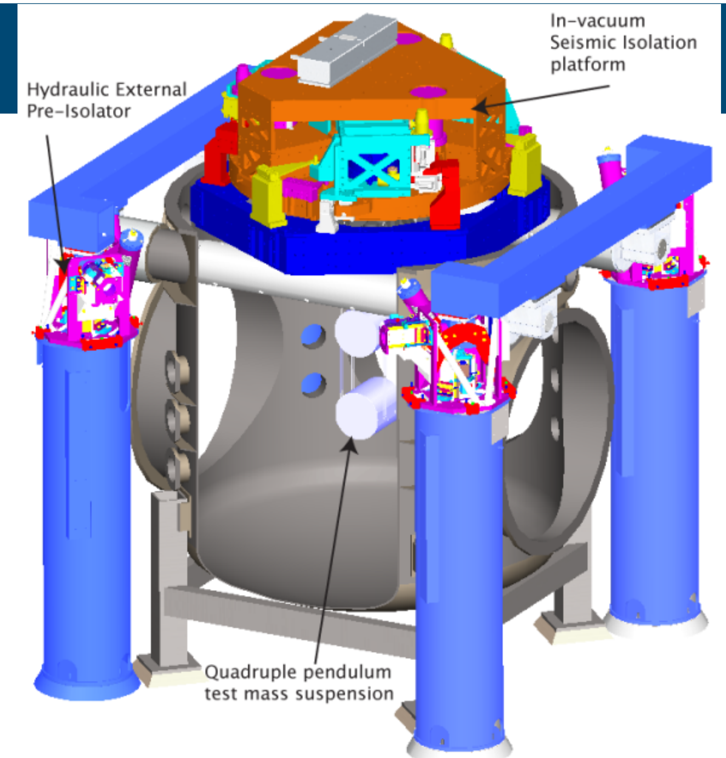
<u>Objectives:</u>

- Render seismic noise a negligible limitation to GW searches: 10 Hz and above
- Reduce actuation forces on test masses - control Band: below 10 Hz – forces needed to hold optics on resonance and aligned



LIGO

Seismic Isolation



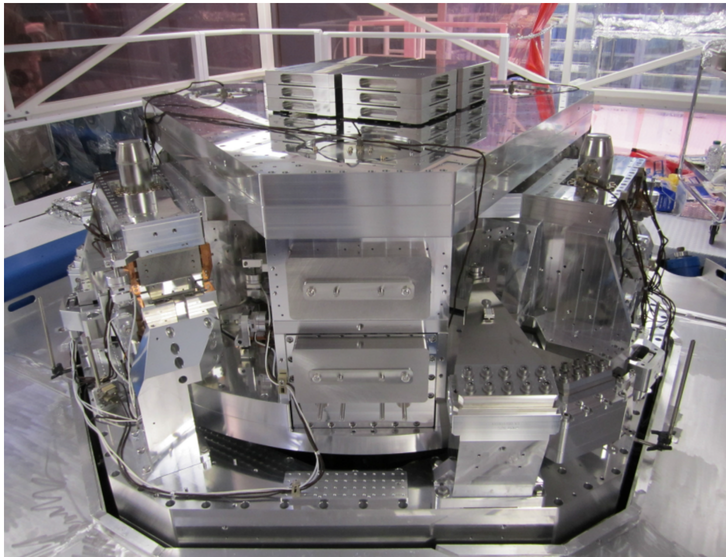
Creating Advanced GW observatories

aLIGO uses **active servo-controlled platforms** and multiple pendulum systems to isolate interferometer mirrors

Choose an active isolation approach, 3 stages of 6 degrees-of-freedom :

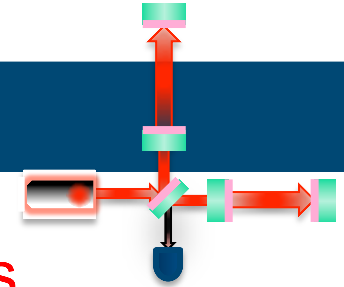
1) **Two Active Stages of Internal Seismic Isolation**
2) **Hydraulic External Pre-Isolation**

Low noise sensors (position, velocity, acceleration) are combined, passed through a servo amplifier, and delivered to the optimal actuator as a function of frequency to hold platform still in inertial space



Limit for earth-based detectors: Newtonian background – wandering net gravity vector; a limit in the 10-20 Hz band

Addressing limits to performance



Creating advanced gravitational wave observatories

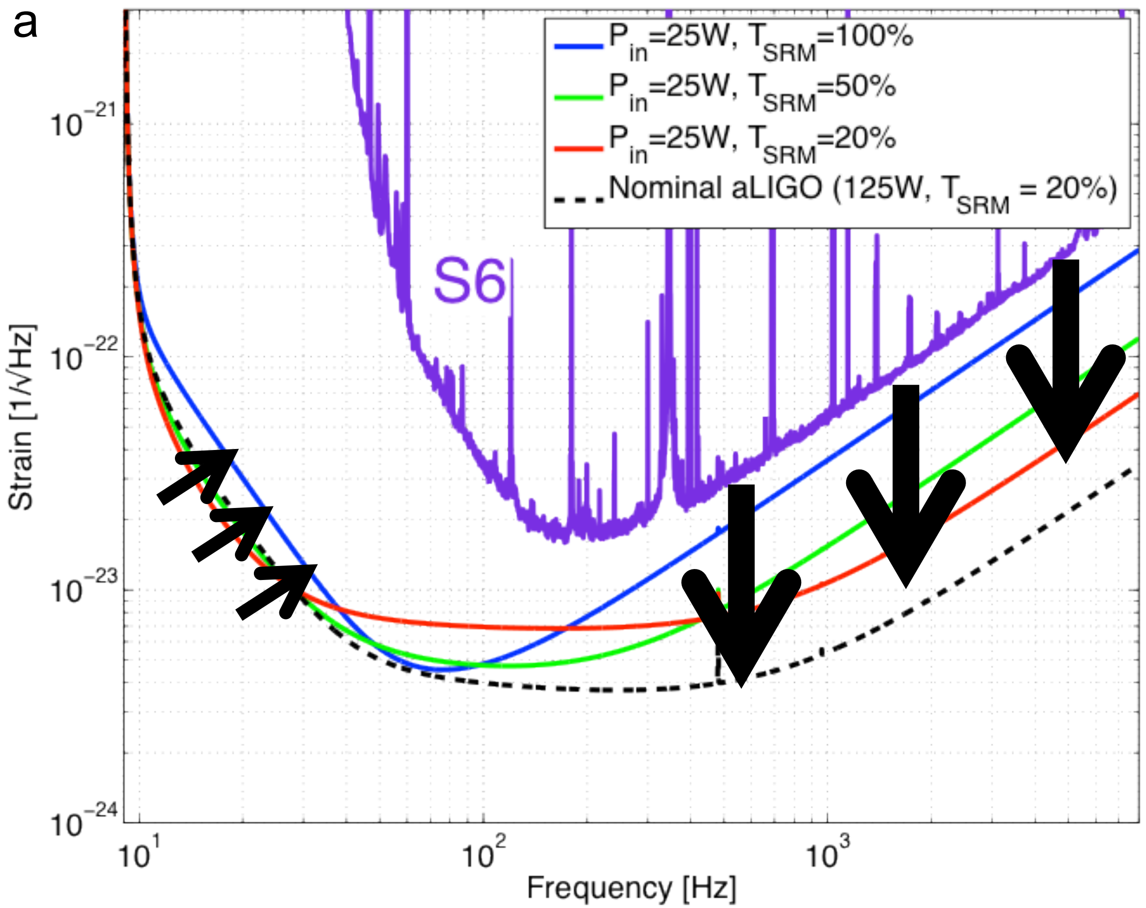
Shot noise – ability to resolve a fringe shift due to a GW (counting statistics)

Fringe Resolution at high frequencies improves as (laser power)$^{1/2}$

Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses

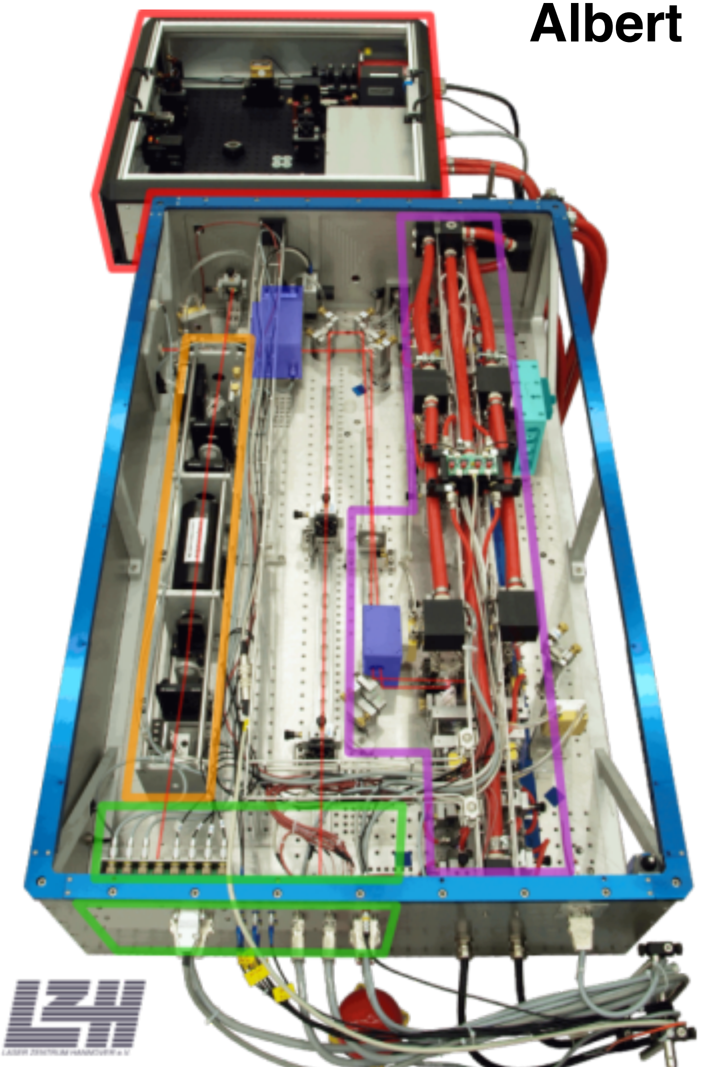
'Standard Quantum Limit'

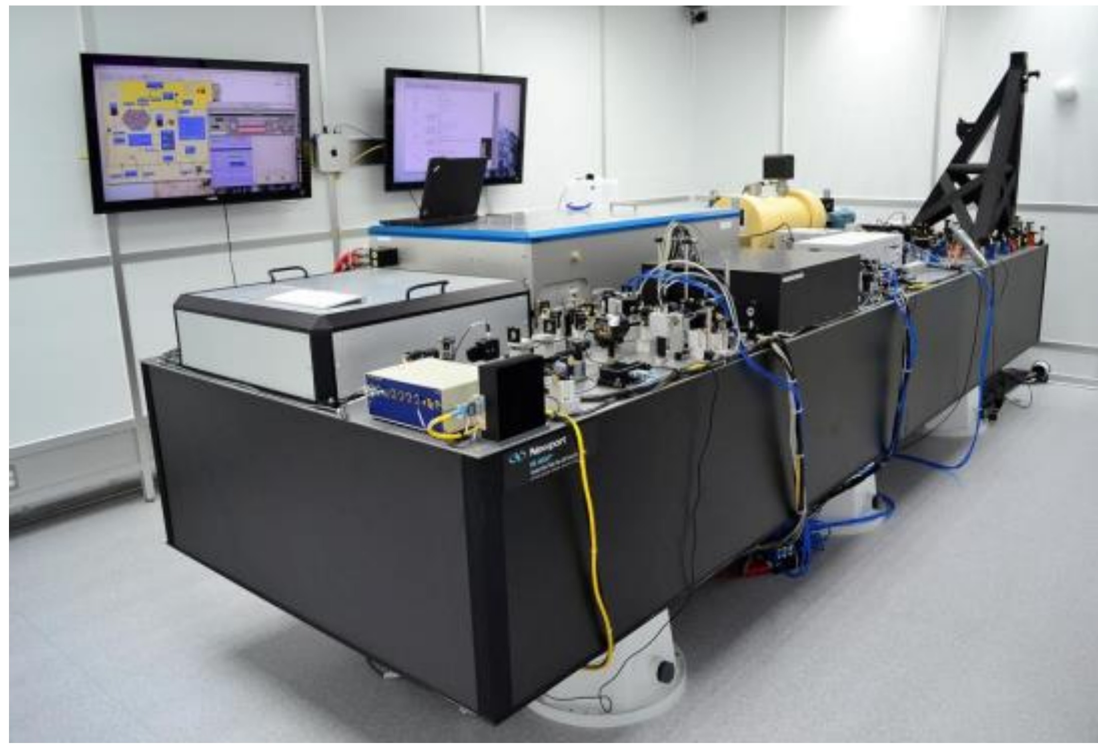
Advanced LIGO reaches this limit with its **200W laser,** 40 kg test masses



200W Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute

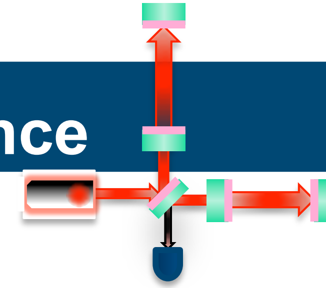




- **Stabilised in power and frequency**
- **Uses a monolithic master oscillator followed by injection-locked rod amplifier**

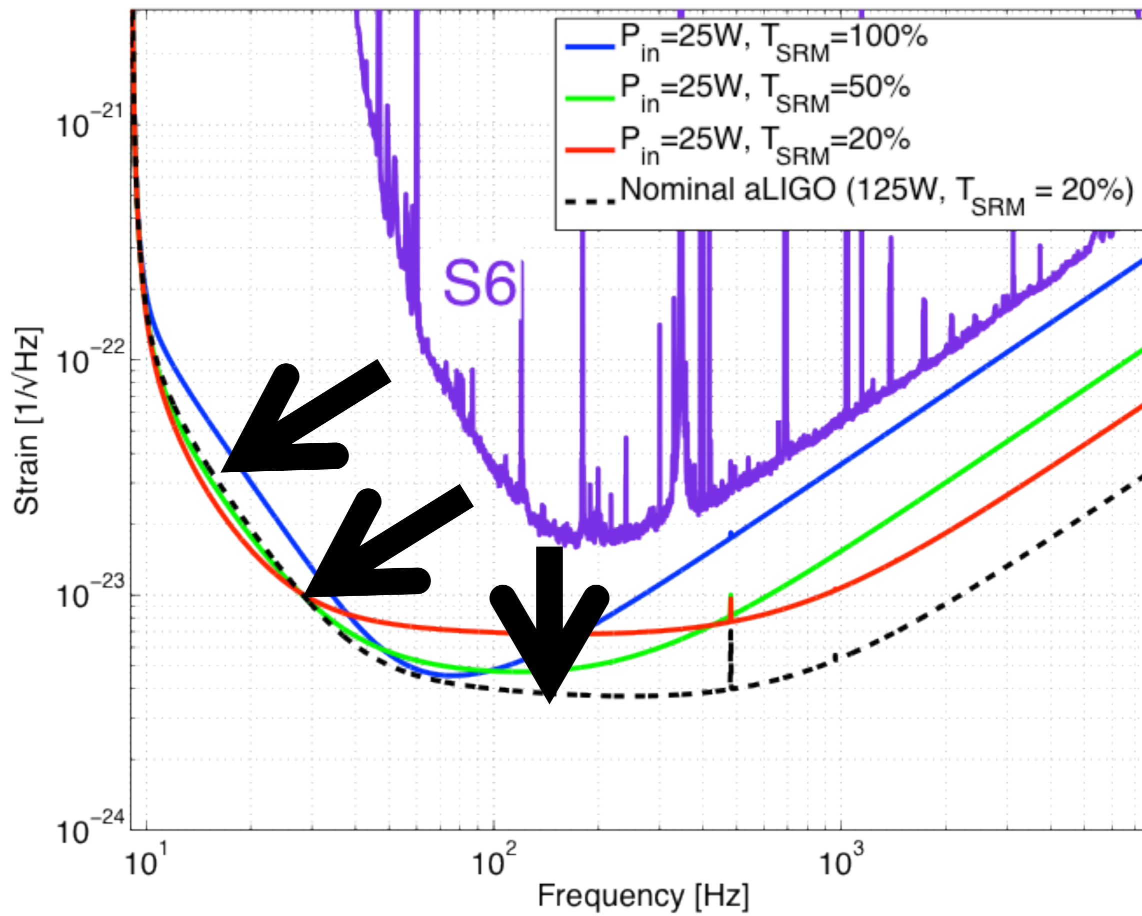
LIGO

Addressing limits to performance



Creating advanced gravitational wave observatories

- **Thermal noise** – kT of energy per mechanical vibrational mode
- Wish to keep the motion of components due to thermal energy below the level which masks GWs
- Low mechanical loss materials
- Realised in aLIGO with an all **fused-silica test mass suspension**

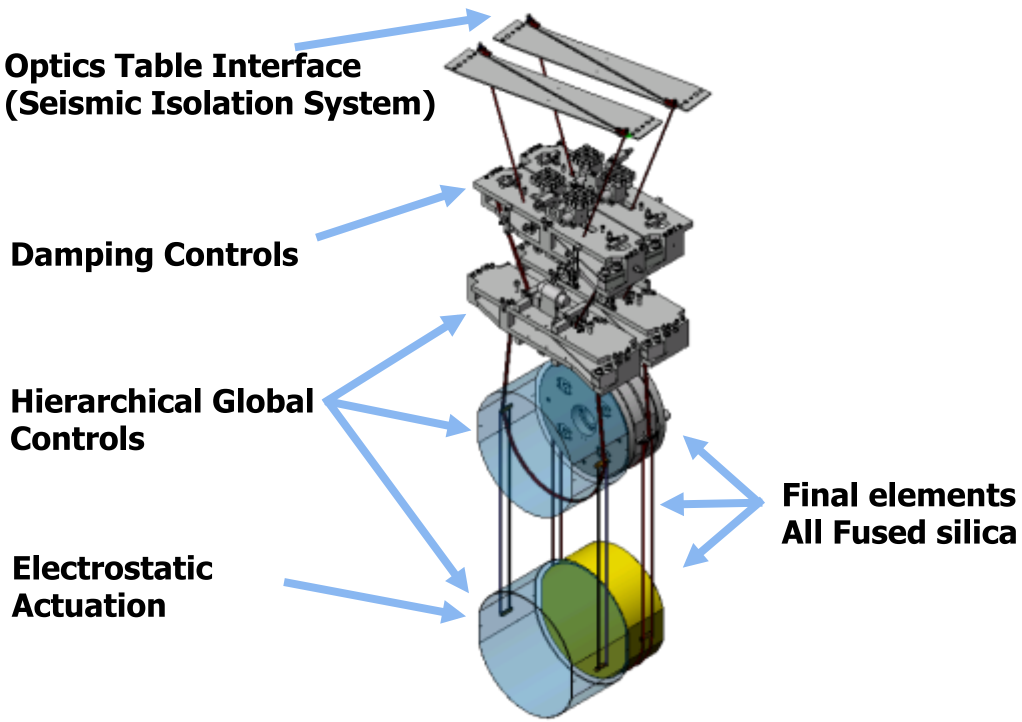


Test Mass Quadruple Pendulum suspension designed jointly by the UK and LIGO lab,

Quadruple pendulum suspensions for the main optics; second ‘reaction’ mass to give quiet point from which to push

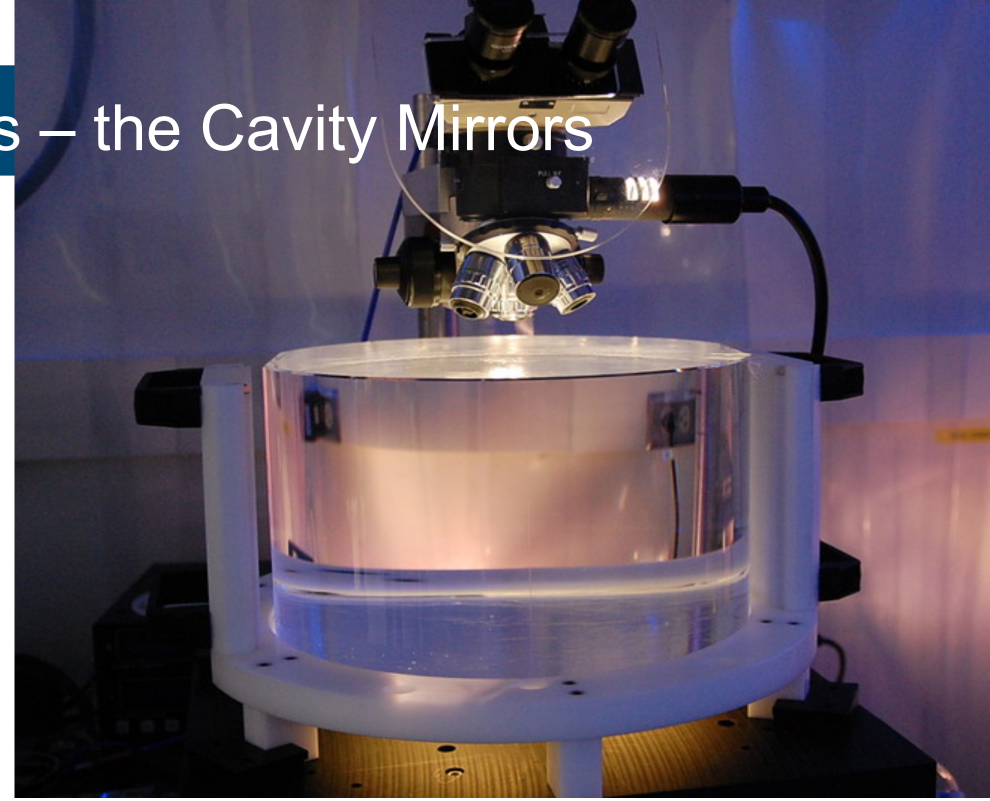
Create quasi-monolithic pendulums using fused silica fibers to suspend 40 kg test mass

- Very low thermal noise



LIGO-G1301277

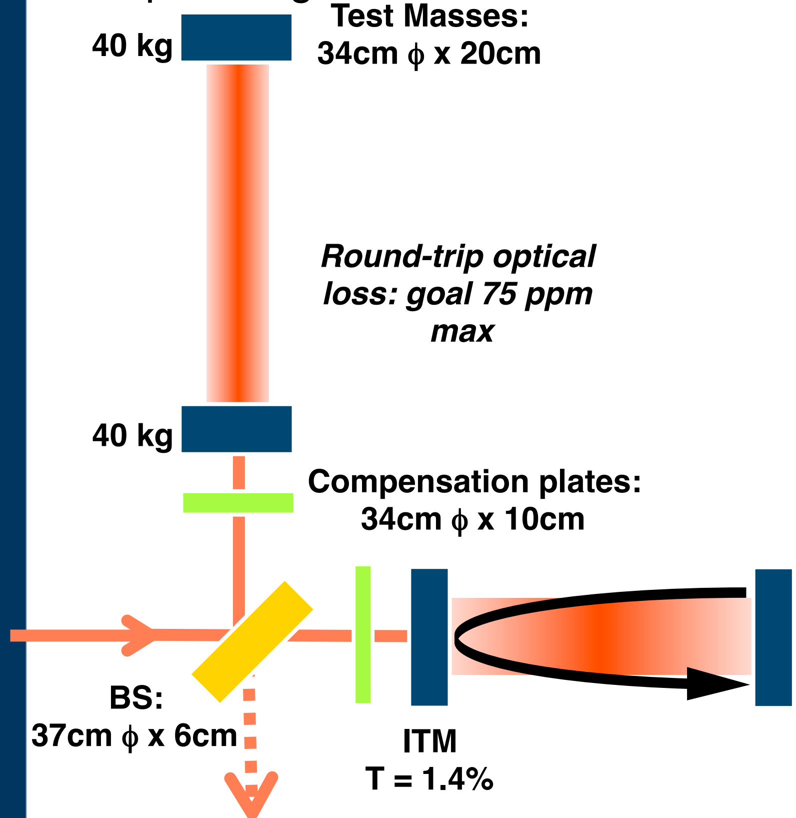
Test Masses – the Cavity Mirrors



Both the physical test mass **– a free point in space-time** – and a crucial optical element (synthetic fused silica)

Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Requires the state of the art in substrates and polishing



- Substrates sub - 0.5 ppm/cm absorption at 1064nm)
- Sub-nm flatness over 300mm
- Radii of curvature: 2245m and 1934m (-5/+15)m
- Beam radii of 6.2 cm /5.3 cm

- Pushes the art for coating: Ion-Beam-Sputtered (LMA, Lyon) Multi-layers of SiO_2 alternating with Ta_2O_5 doped with TiO_2 (~10's%)
- Coating transmission spec. T<5+/1ppm
- Absorption <0.5ppm

Selected for a Viewpoint in *Physics*
PRL **119**, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

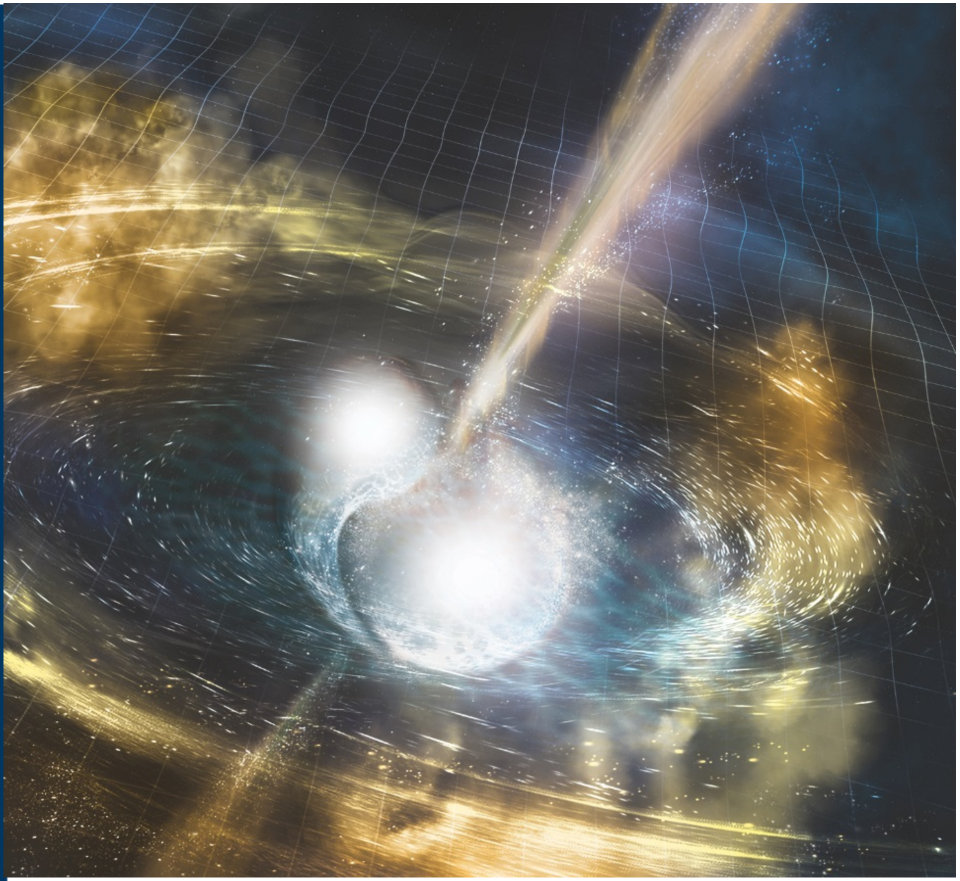
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

LIGO

Sequence of Events



CREDIT: NSF LIGO Sonoma State University
A.Simonnet

August 17th 2017 12:41:04 UTC : GW signal from BNS merger detected

+2 seconds: gamma ray burst detected

+10 hours 52 mins: a new bright optical source detected in NGC 4993

- a “kilonova”

+11 hours 36 mins: infrared emission detected

+ 15 hours: UV emission detected

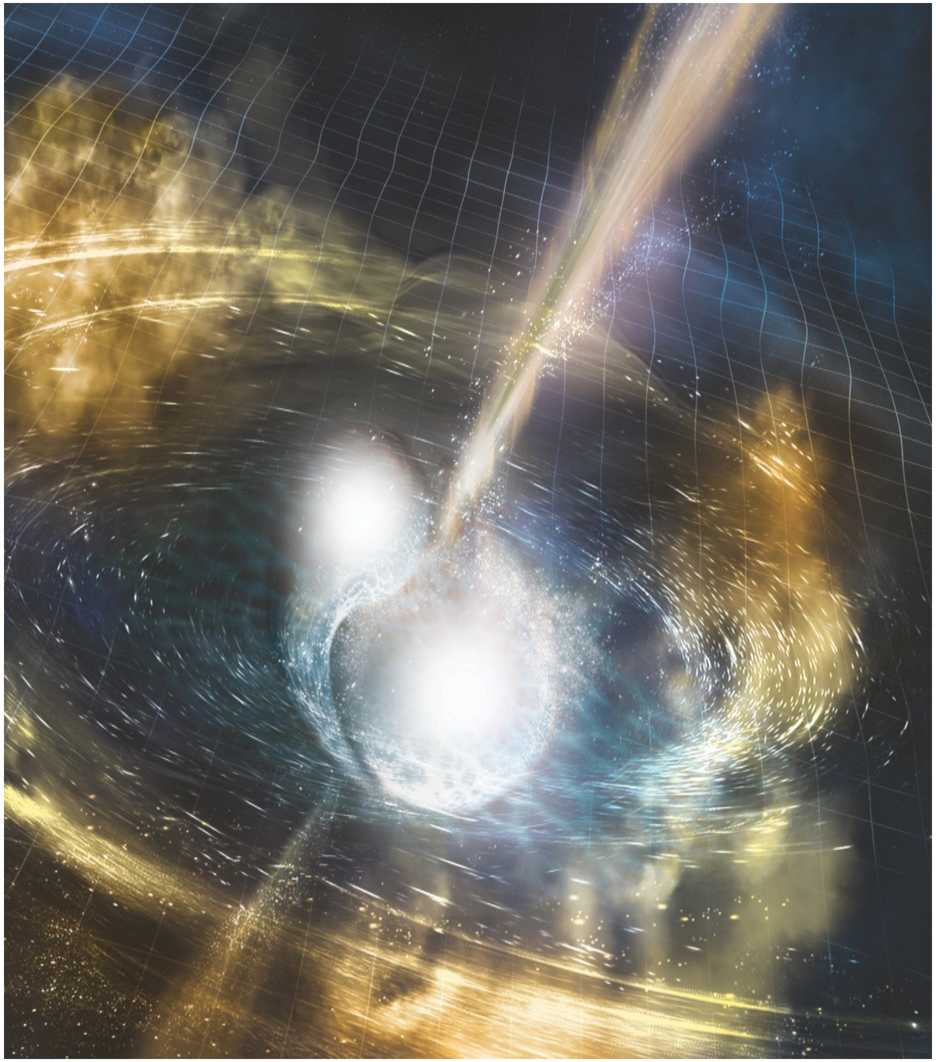
+ 9 days: X-ray emission detected

+ 16 days: radio emission detected

Unprecedented set of observations using EM and GW observatories

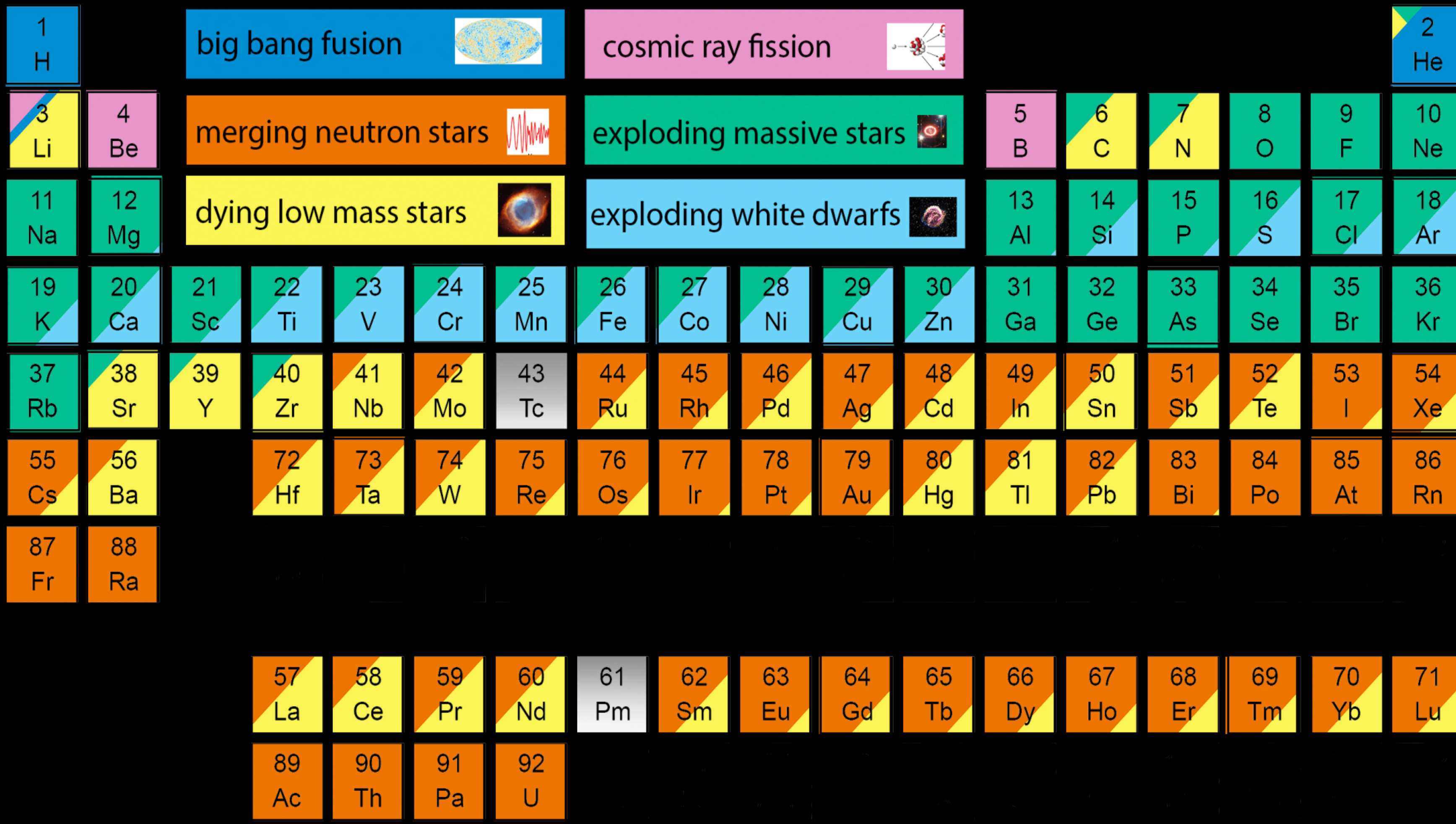
GW170817
Birth of "multi-messenger" gravitational astronomy

- Confirmation of neutron star mergers as cause for short Gamma Ray Bursts
- Testing laws of physics (GR) in the extreme gravity regime
- Hints at "equation of state" for neutron stars
- Speed of Gravitational Waves compared with light
- Independent measure of "Hubble's constant" – expansion rate of the Universe
- Confirmation of "kilonova" scenario – synthesis of heavy elements



NSF/LIGO/Sonoma State University/A. Simonnet

The Origin of the Solar System Elements



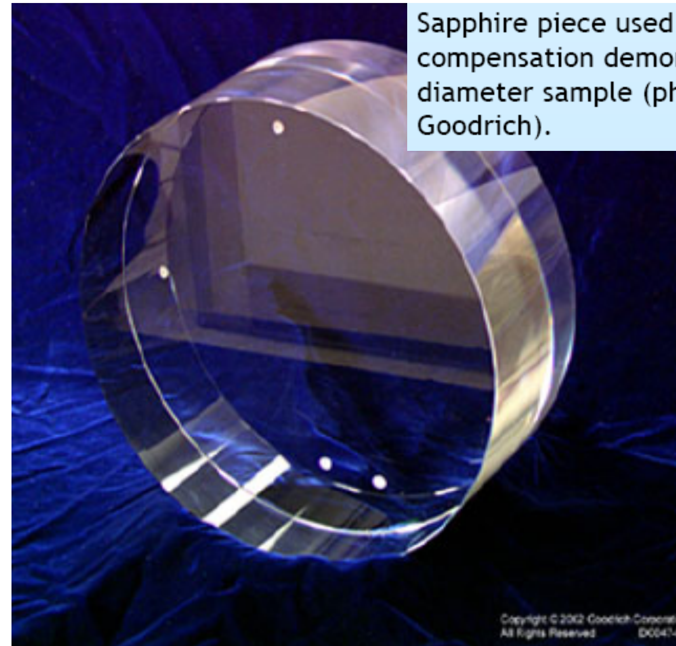
Astronomical Image Credits:
ESA/NASA/AASNova

Graphic created by Jennifer Johnson

What's beyond the Advanced Detectors?
(just time for a flavour of current research directions)

What new technologes are needed

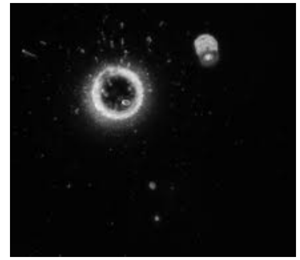
- Longer arms? (10km? 40km?)
- Underground site?
- Higher power than advanced detectors (3 MW)
- Cryogenic optics for low thermal noise (Silicon? Sapphire?)
- Lower thermal noise coatings (AlGaAs? AlGaP?)
- Larger, heavier optics (160kg?)
- Non-Gaussian laser beams?
- Laser wavelength (fused Silica: 1064nm; Silicon:1550nm;)
- Frequency dependent ‚squeezing‘



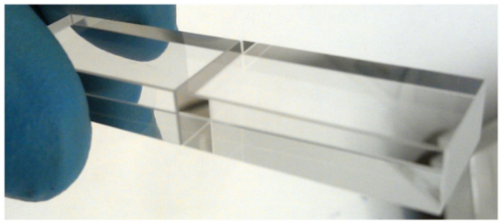
Sapphire piece used in spot polishing compensation demonstration; 25cm diameter sample (photo courtesy Goodrich).

Source: http://www.quora.com/Semiconductors/How-do-silicon-boules-not-break-off-during-semiconductor-fabrication

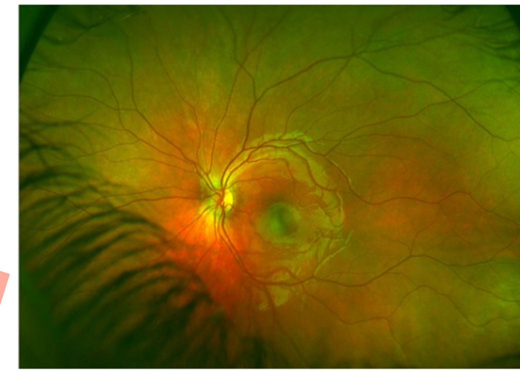
…rich source of technological spin-offs:



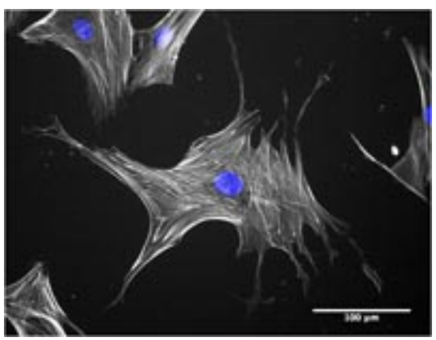
• Coating damage



•High precision/stability bonding

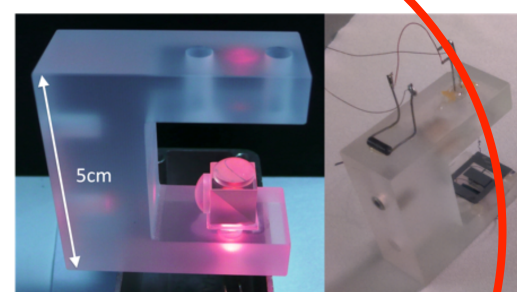


Analysis of retinal scans



• Stem cell differentiation: sensors and actuations for healthcare

• Weathering of sandstone



MEMS Gravity sensors for environmental monitoring/security/oil & gas

MEMS GRAVIMETERS AS A NEW TOOL FOR GRAVITY IMAGING

Giles Hammond (Physics & Astronomy); Doug Paul (Engineering),

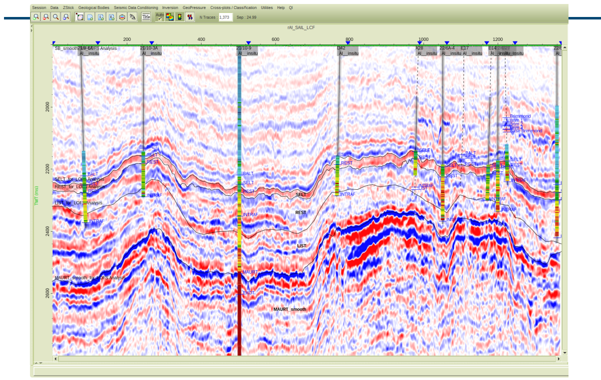
S. G. Bramsiepe, R. Douglas, S. Hild, J. Hough,
R. P. Middlemiss, D. J. Paul, S. Rowan, A. Samarelli

Gravity Imaging Applications

Oil & gas prospecting

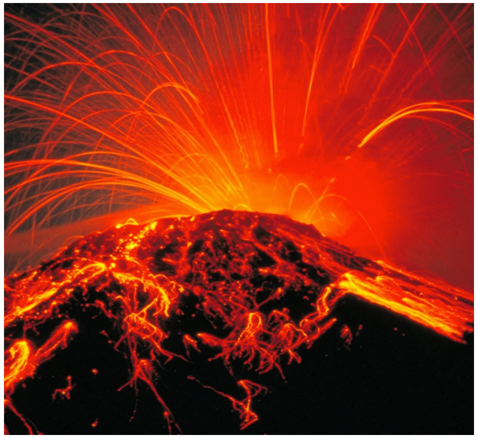
Navigation

Seismic surveys

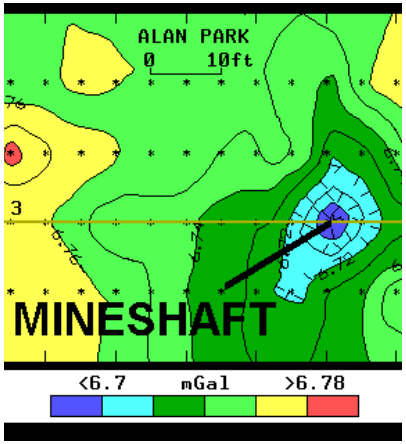


Security & Defence

Environmental monitoring



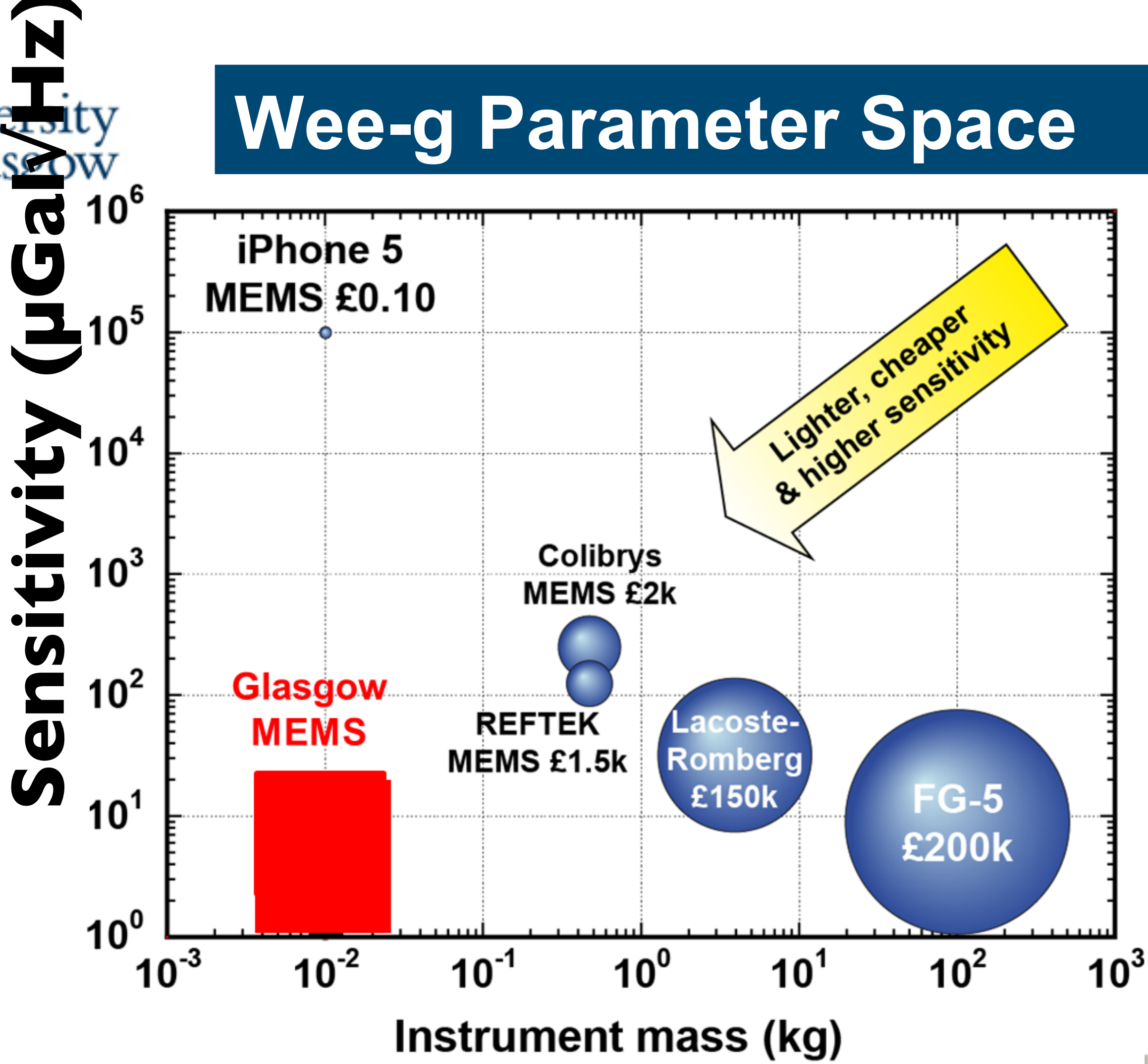
Sink hole detection



Wee-g Parameter Space

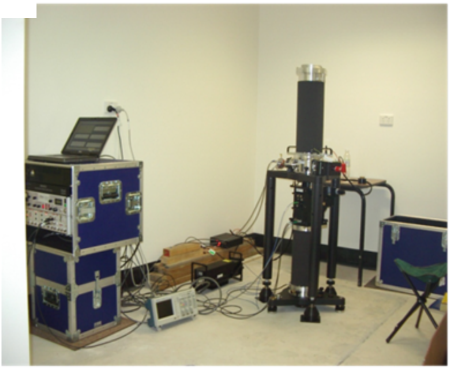
IPhone

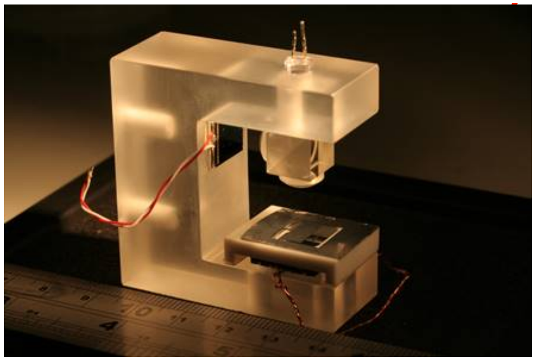
Colibrys

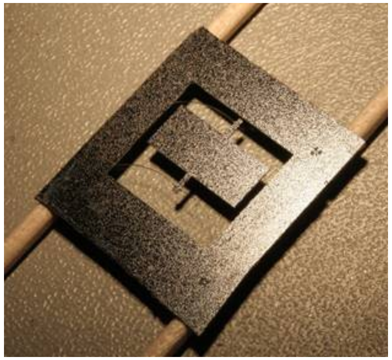


CG-5

FG-5



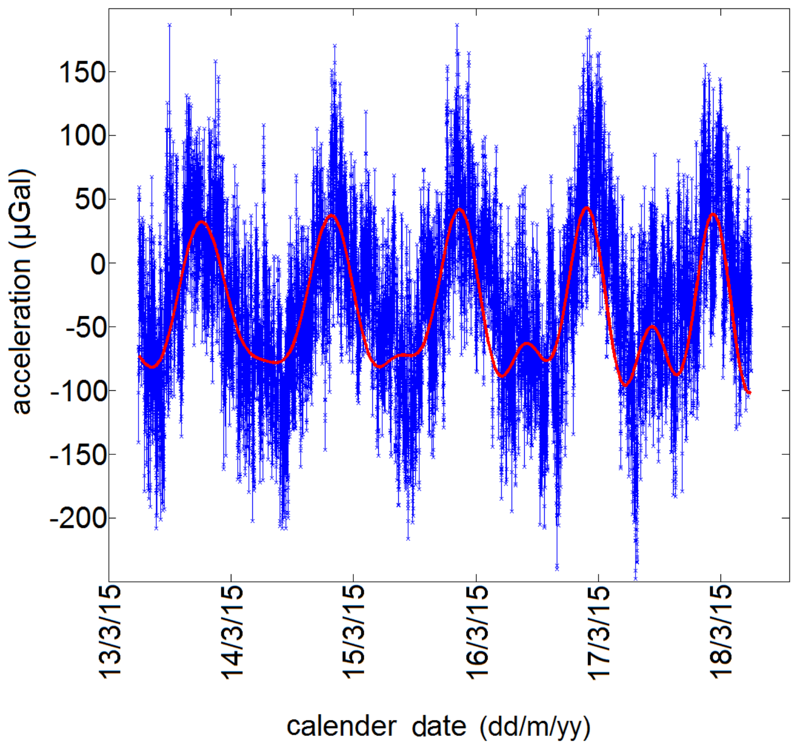


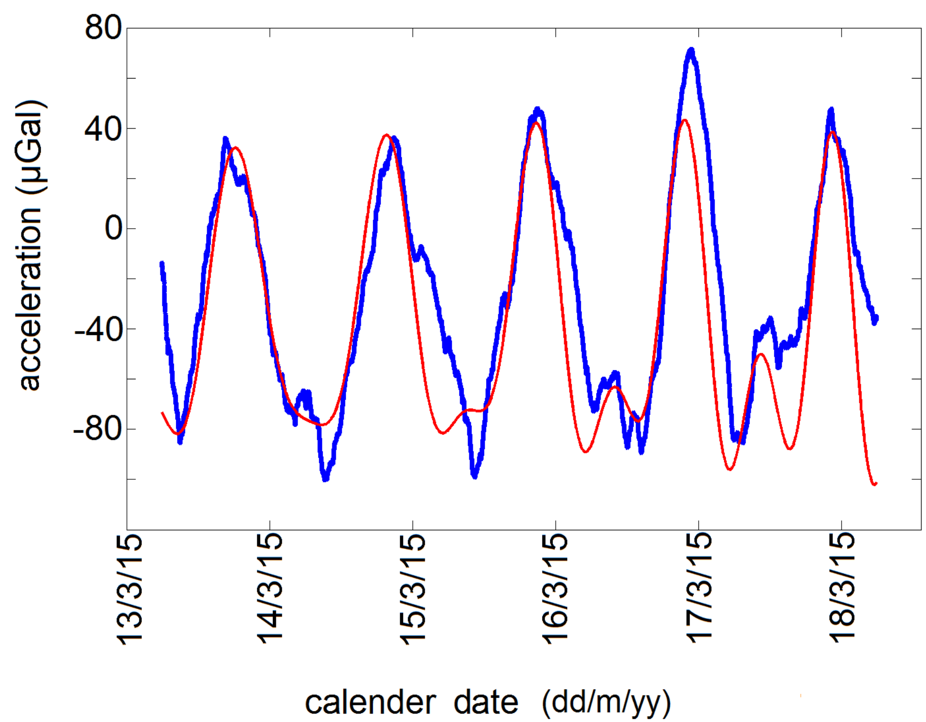


University of Glasgow

Earth Tides

- There is a daily/twice-daily change in the local acceleration of gravity due to the Earth-Moon tidal gravitational potential (250μGal ≈ 250ng maximum variation)
  - due to changing shape of solid earth (Earth tides; 30cm-40cm change in radius)
- This is a good signal to test long term stability. Measured during 2015-2016

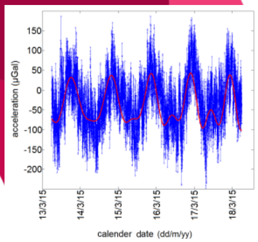




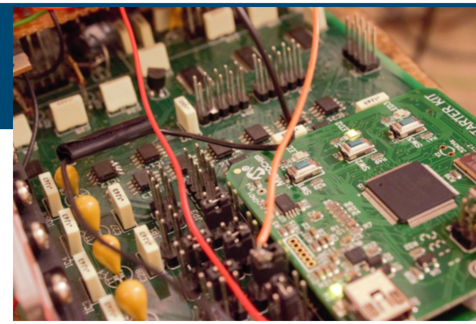
R.P. Middlemiss et al. Nature 531, 614, 2016
Toninelli et al. Optics Express 25 (18), 2017
R.P. Middlemiss et al. MDPI Sensors, *17*(11), 2571, 2017
Bramsiepe et al. IEEE Sensors 18 (10), 2018

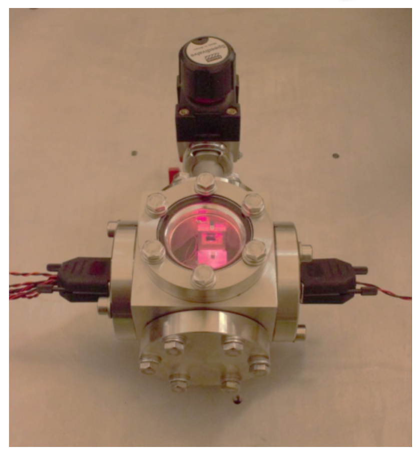
1 μGal =1 cm/s^2= 0.01 m/s^2

Developing a Field Unit



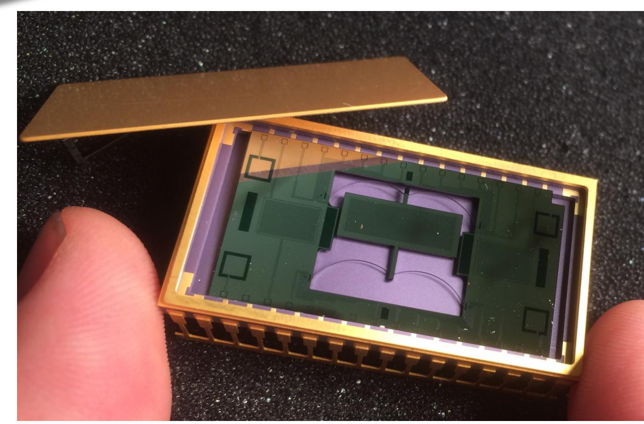
2015: lab based system with mains power, rack mount electronics



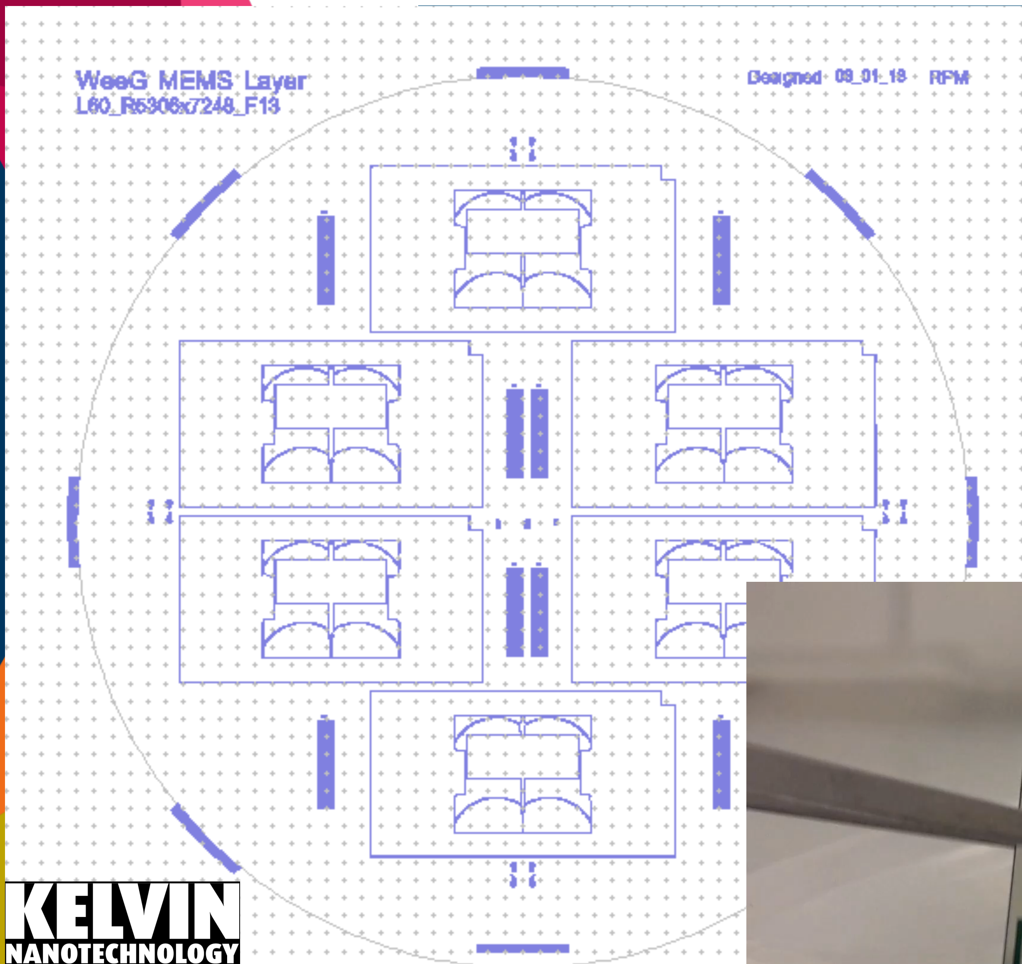


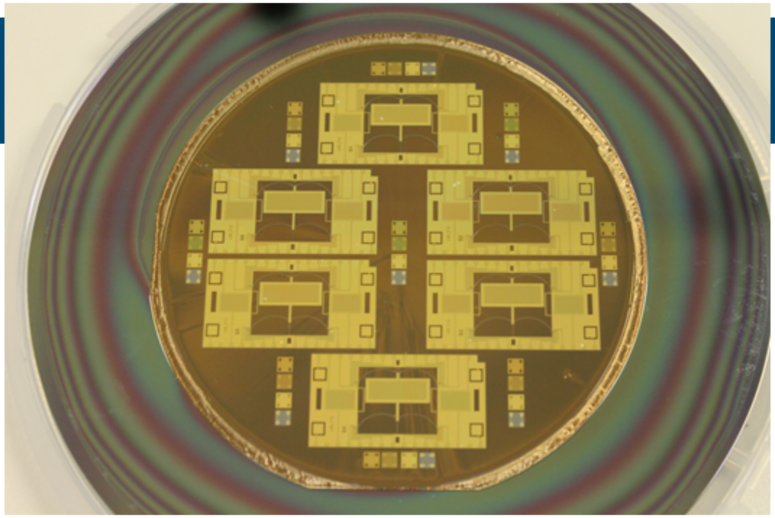
2016: shoebox sized field demonstrator, battery power

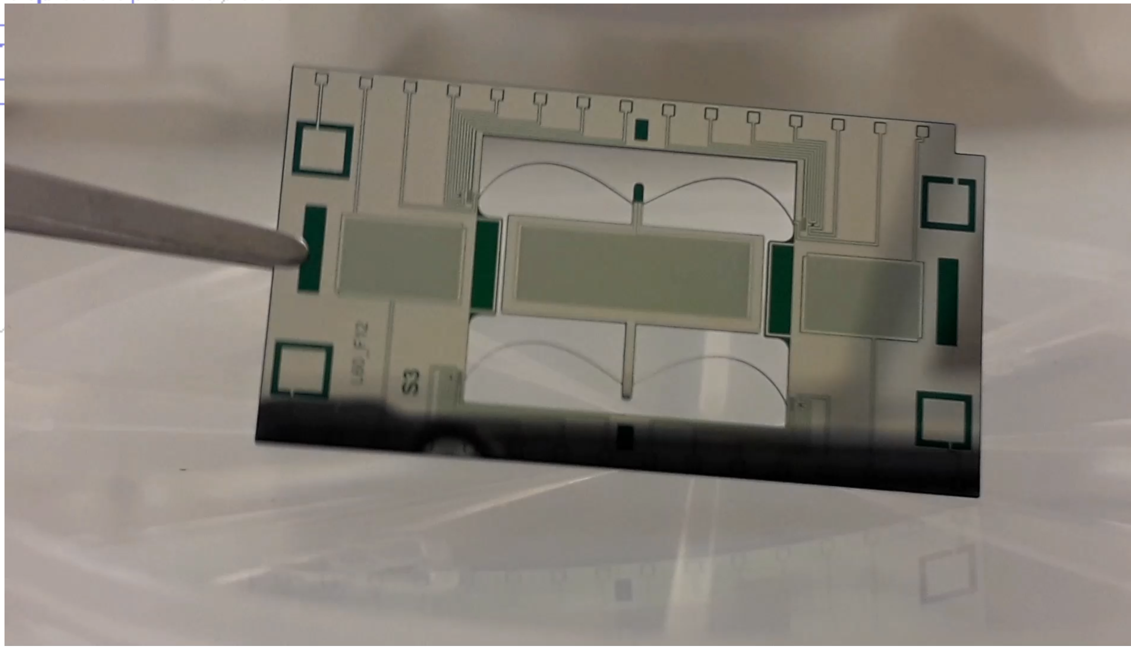
2018/19: packaged device with FPGA readout



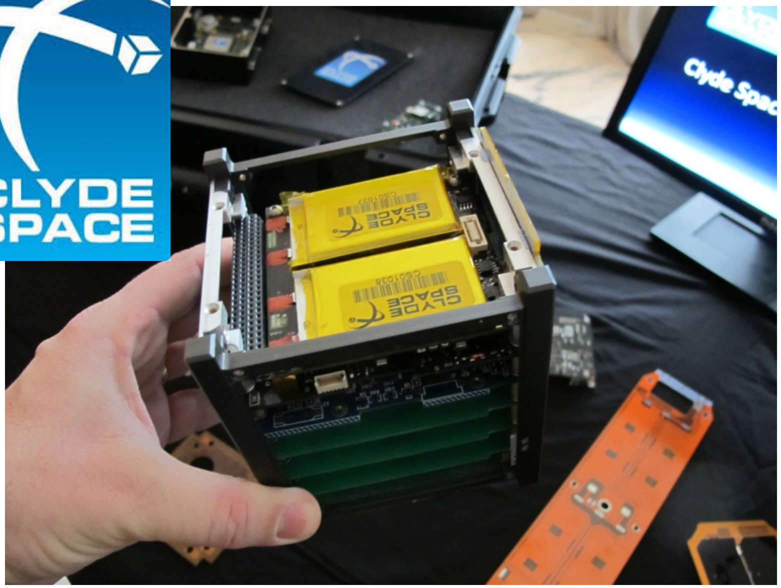
Etching and packaging the Field Prototype



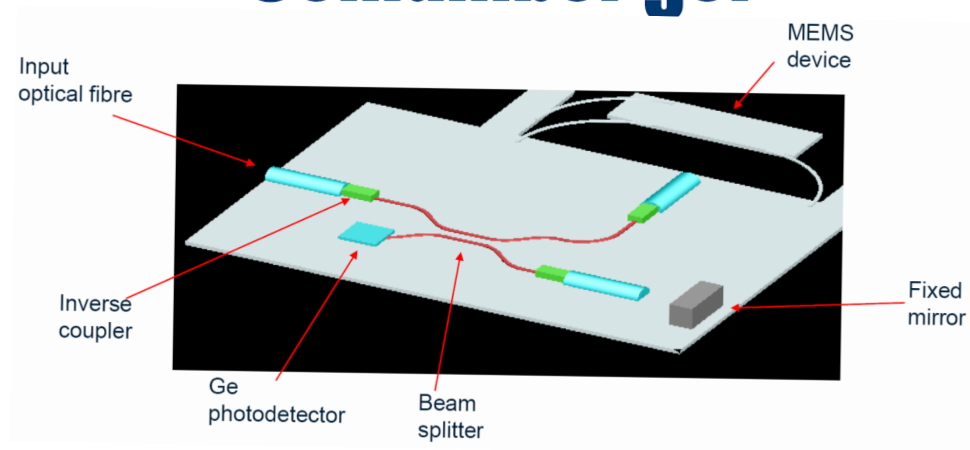




Ongoing Industrial Projects



Attitude control (EngD/CENSIS)



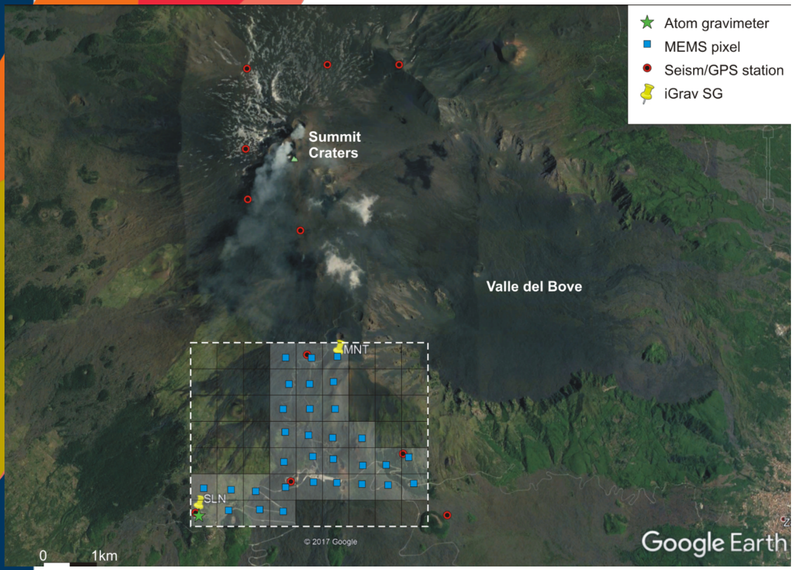
Miniature interferometric sensing

Underwater sensing

Near future

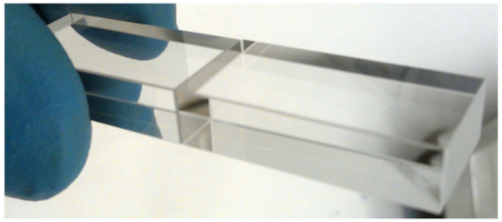
- Studentship with Bridgeporth to test packaged MEMS in Boulby mine
- FET-OPEN H2020 grant to deploy 70 MEMS onto Mt Etna by 2022 (€800k to Glasgow, €3.5 million total)

- DSTL tender secured to deliver gradiometers for drone deployment
- BP field trials to likely start 2018/9

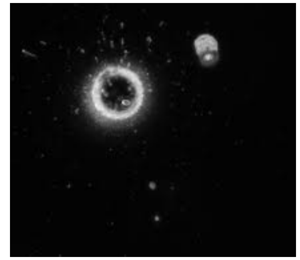


European Commission

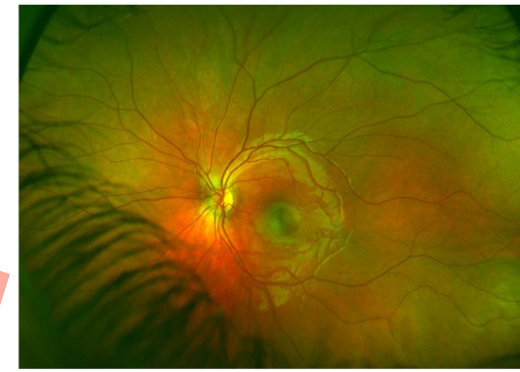
…rich source of technological spin-offs:



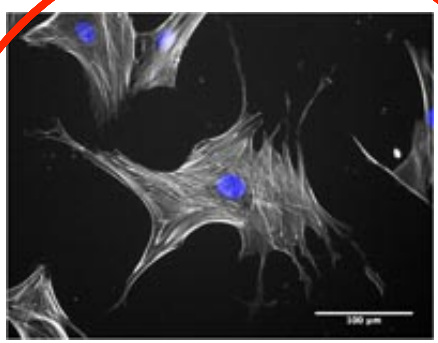
• High precision/stability bonding



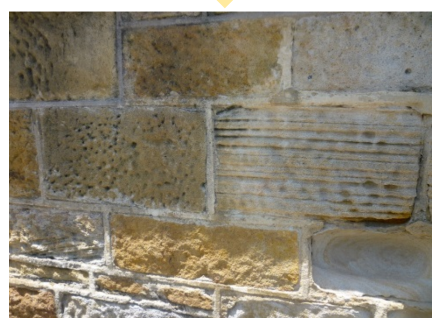
• Coating damage



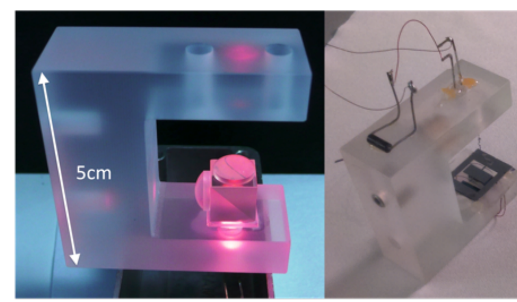
Analysis of retinal scans



• Stem cell differentiation: sensors and actuators for healthcare



• Weathering of sandstone



MEMS Gravity sensors for environmental monitoring/security/ oil & gas

IGR

NANOVIBRATIONAL STIMULATION FOR CONTROLLING STEM CELL BEHAVIOUR

University of Glasgow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5 April 2013 Last updated at 01:01

Stem cells 'nanokicked' to grow new bone

By Ken Macdonald
BBC Scotland Science Correspondent

Cells are vibrated by billionths of a metre, 1,000 times a second

Bone is the second most transplanted tissue after blood

Harnessing the power of stem cells (Stuart Reid & Matthew Dalby)

Through collaboration with GW researchers – a new field in tissue engineering established

First time bone building cells (osteoblasts) have been formed in the lab from a patients stem cells (MSCs) without requirement for drugs/complex scaffolds

Particularly relevant for clinical supply of bone graft, and drug discovery.

University of Strathclyde Glasgow

UWS UNIVERSITY OF THE WEST of SCOTLAND

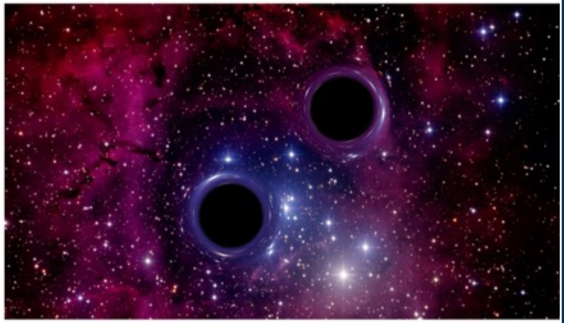
bone building cells

@Nanokicking

Institution of MECHANICAL ENGINEERS

our top 5 UK innovations of the year

Black holes and broken bones



A pair of black holes (Credit: iStock)

Massive, star-consuming and vital for holding some galaxies together, black holes are a continuing fascination for scientists. On Earth, doctors and biomedical engineers search for better ways to fix broken bones ahead of a forecast jump in the number of older people worldwide.

NHS Greater Glasgow and Clyde

University of Glasgow

University of Strathclyde Glasgow

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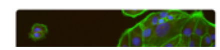
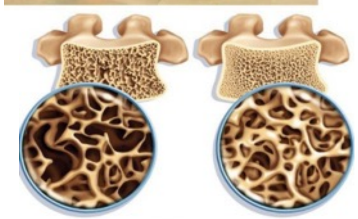
Home / News / Growing human bones using gravitational wave technology

Growing human bones using gravitational wave technology

12 September 2017

Technology originally developed to witness black holes colliding is now being used to grow human bone in a laboratory, which could revolutionise the treatment of bone injuries.





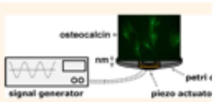
2017: Herald Scotland Awards – best research project

Osteogenesis of Mesenchymal Stem Cells by Nanoscale Mechanotransduction

Habib Nikukar,[†,§] Stuart Reid,[‡,*] P. Monica Tsimbouri,[†] Mathis O. Riehle,[†] Adam S. G. Curtis,[†] and Matthew J. Dalby[†,*]

[†]Centre for Cell Engineering, Institute for Molecular, Cell and Systems Biology, College of Medical, Veterinary and Life Sciences, University of Glasgow, Glasgow G12 8QQ, United Kingdom, [‡]SUPA, Thin Film Centre, University of the West of Scotland, Paisley PA1 2BE, United Kingdom, and [§]Shahid Sadoughi University of Medical Sciences, Yazd, I. R. Iran

ABSTRACT It is likely that mesenchymal stem cells will find use in many autologous regenerative therapies. However, our ability to control cell stem growth and differentiation is presently limited, and this is a major hurdle to the clinical use of these multipotent cells especially when considering the desire not to use soluble factors or complex media formulations in culture. Also, the large number of cells required to be clinically useful is currently a hurdle to using materials-based (stiffness, chemistry, nanotopography, etc.) culture substrates. Here we give a first demonstration of using nanoscale sinus



2D (ASC Nano 2013)

ARTICLES
DOI: 10.1038/s41551-017-0127-4

nature biomedical engineering

Corrected: Publisher correction

Stimulation of 3D osteogenesis by mesenchymal stem cells using a nanovibrational bioreactor

Penelope M. Tsimbouri[1], Peter G. Childs[2,3], Gabriel D. Pemberton[1], Jingli Yang[1], Vineetha Jayawarna[1], Wich Orapiriyakul[1], Karl Burgess[4], Cristina González-García[3], Gavin Blackburn[4], Dilip Thomas[5], Catalina Vallejo-Giraldo[5], Manus J.P Biggs[5], Adam S.G. Curtis[1], Manuel Salmerón-Sánchez[3], Stuart Reid[2,6*] and Matthew J. Dalby[1*]

Bone grafts are one of the most commonly transplanted tissues. However, autologous grafts are in short supply, and can be associated with pain and donor-site morbidity. The creation of tissue-engineered bone grafts could help to fulfil clinical demand and provide a crucial resource for drug screening. Here, we show that vibrations of nanoscale amplitude provided by a newly developed bioreactor can differentiate a potential autologous cell source, mesenchymal stem cells (MSCs), into mineralized tissue in 3D. We demonstrate that nanoscale mechanotransduction can stimulate osteogenesis independently of other environmental factors, such as matrix rigidity. We show this by generating mineralized matrix from MSCs seeded in collagen gels with stiffness an order of magnitude below the stiffness of gels needed to induce bone formation in vitro. Our approach is scalable and can be compatible with 3D scaffolds.

With an ageing population increasing the demand for musculoskeletal surgery, there is a growing need to provide viable bone grafts for clinical use; a wide range of sur- … therefore be advantageous for a new bioreactor to be able to sit in a standard incubator, consist of a few parts, and to use off-the-shelf cell-culture containers that are easy to move between the bioreactor

3D (Nature BME 2017)

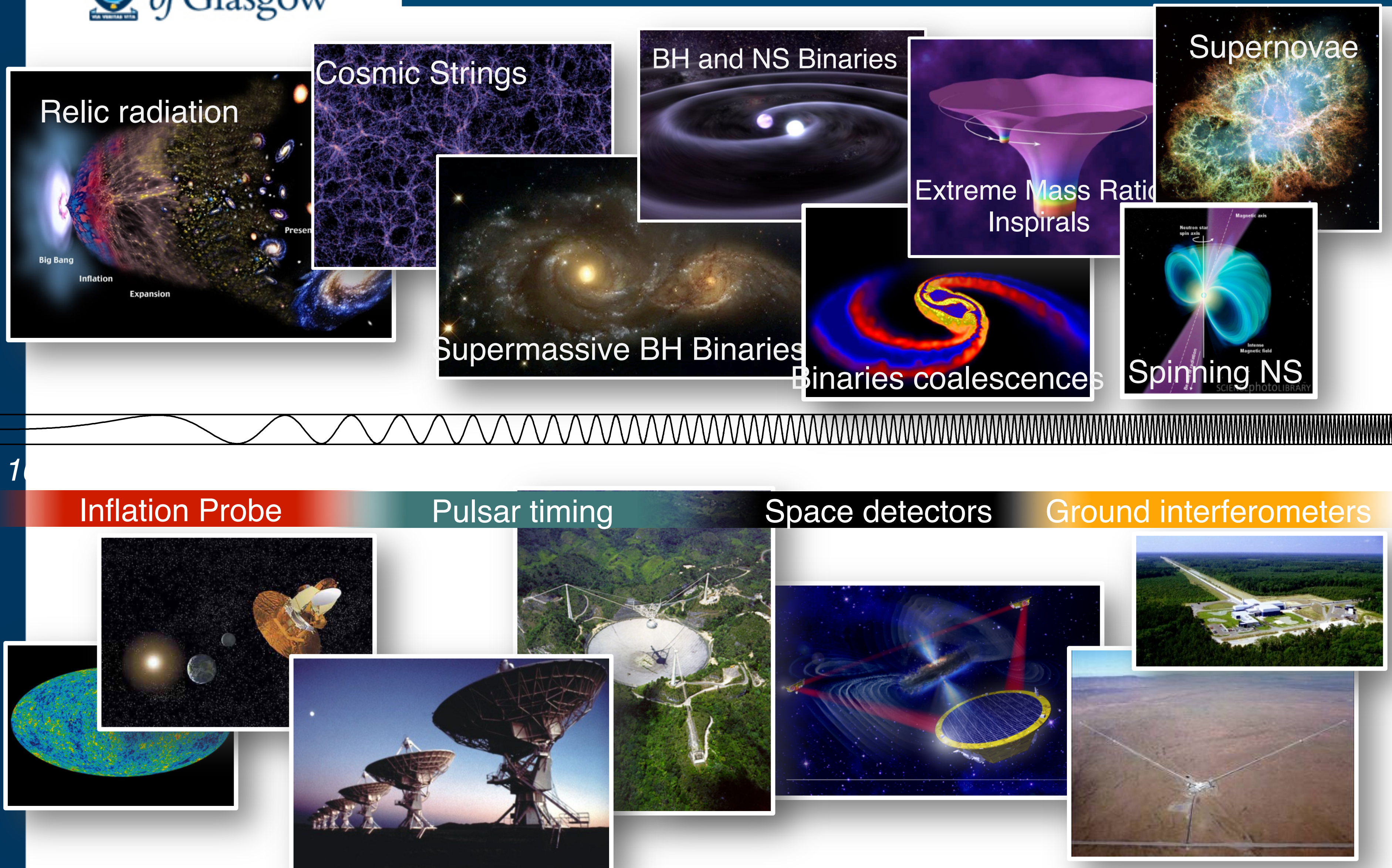
Implantable bone graft trials funded by landmine charity, Find a Better Way, 2020

FIND A BETTER WAY

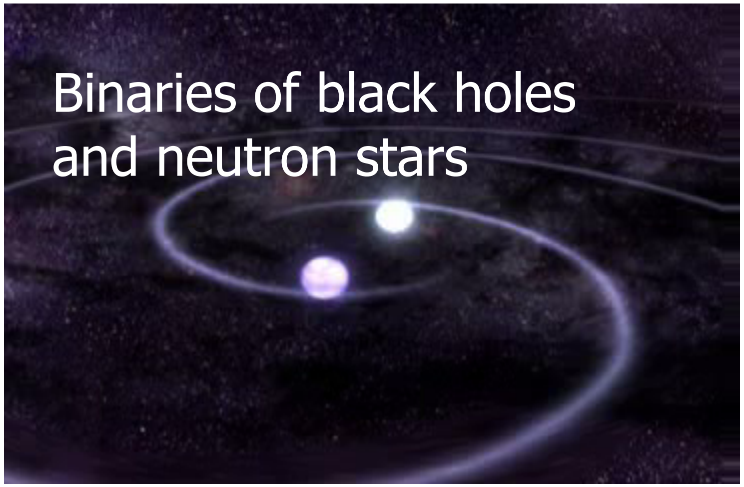
Nanovibrational ***treatment for osteoporosis*** trialled by NHS 2019/20

IGR

The Gravitational Wave Spectrum

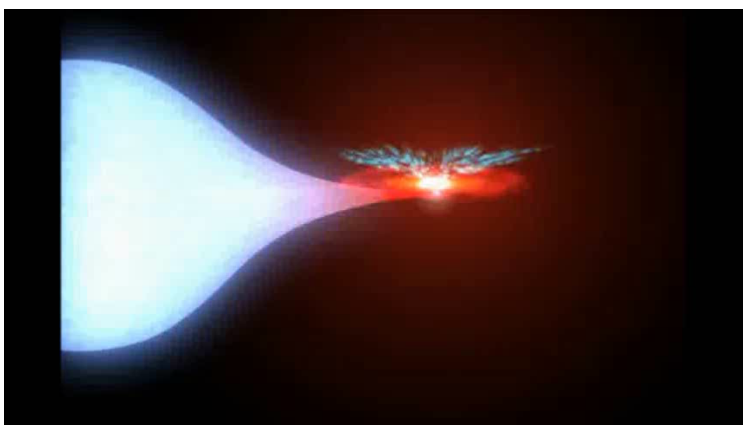


Gravitational wave sources in ground-based detectors

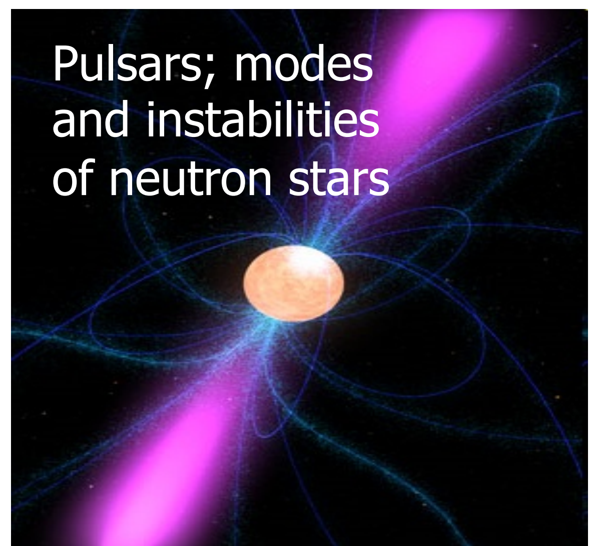


Binaries of black holes and neutron stars

Supernovae and black hole formation



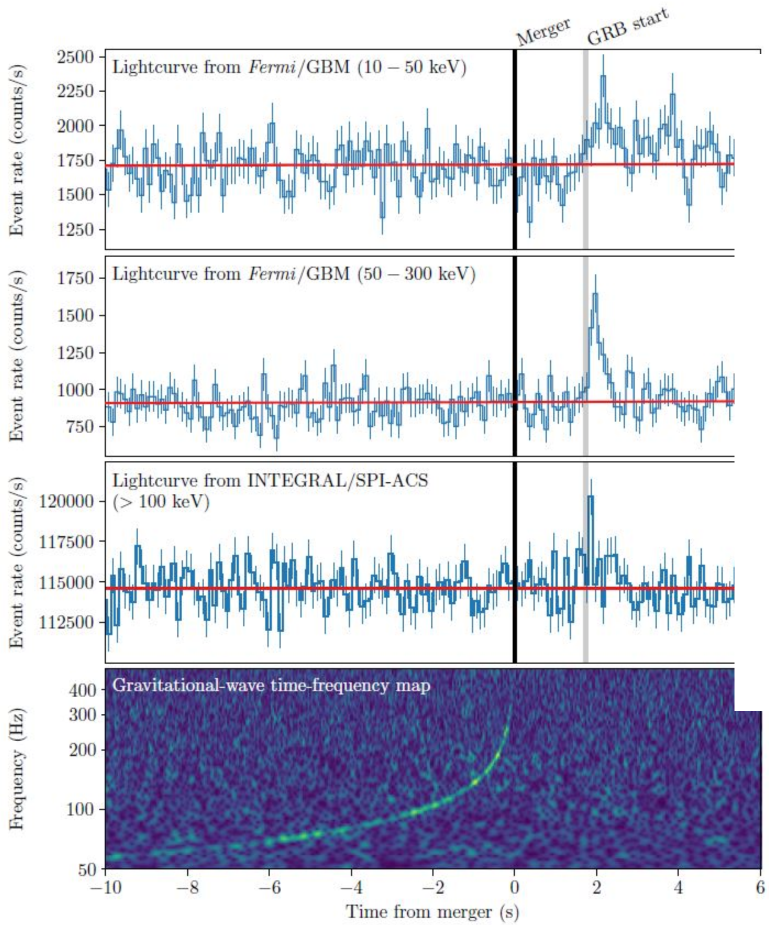
Spinning neutron stars in X-ray binaries

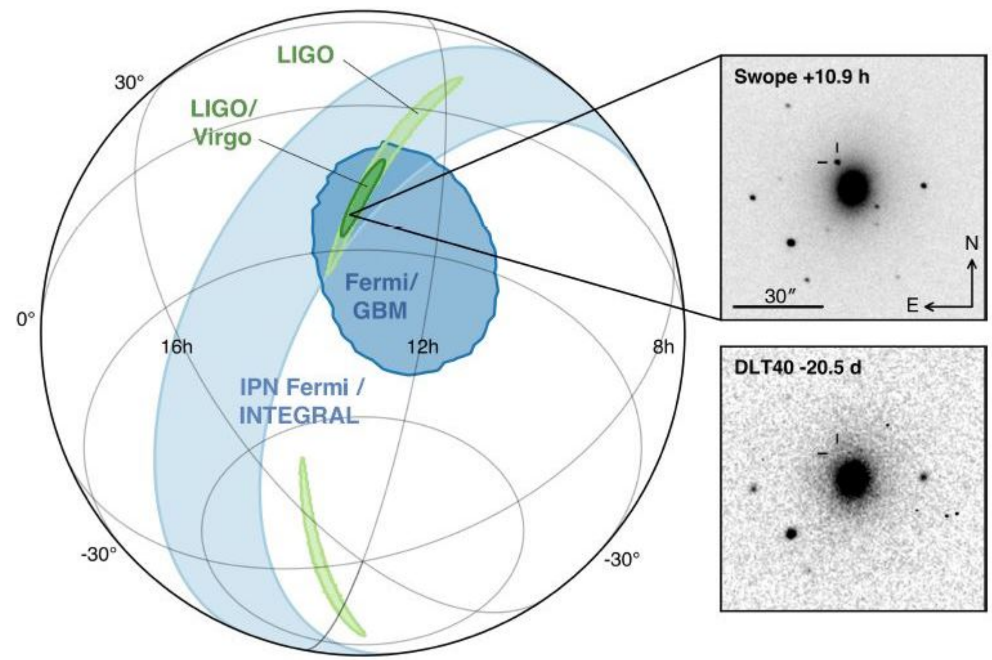


Pulsars; modes and instabilities of neutron stars


BRIGHT
FUTURE
AHEAD

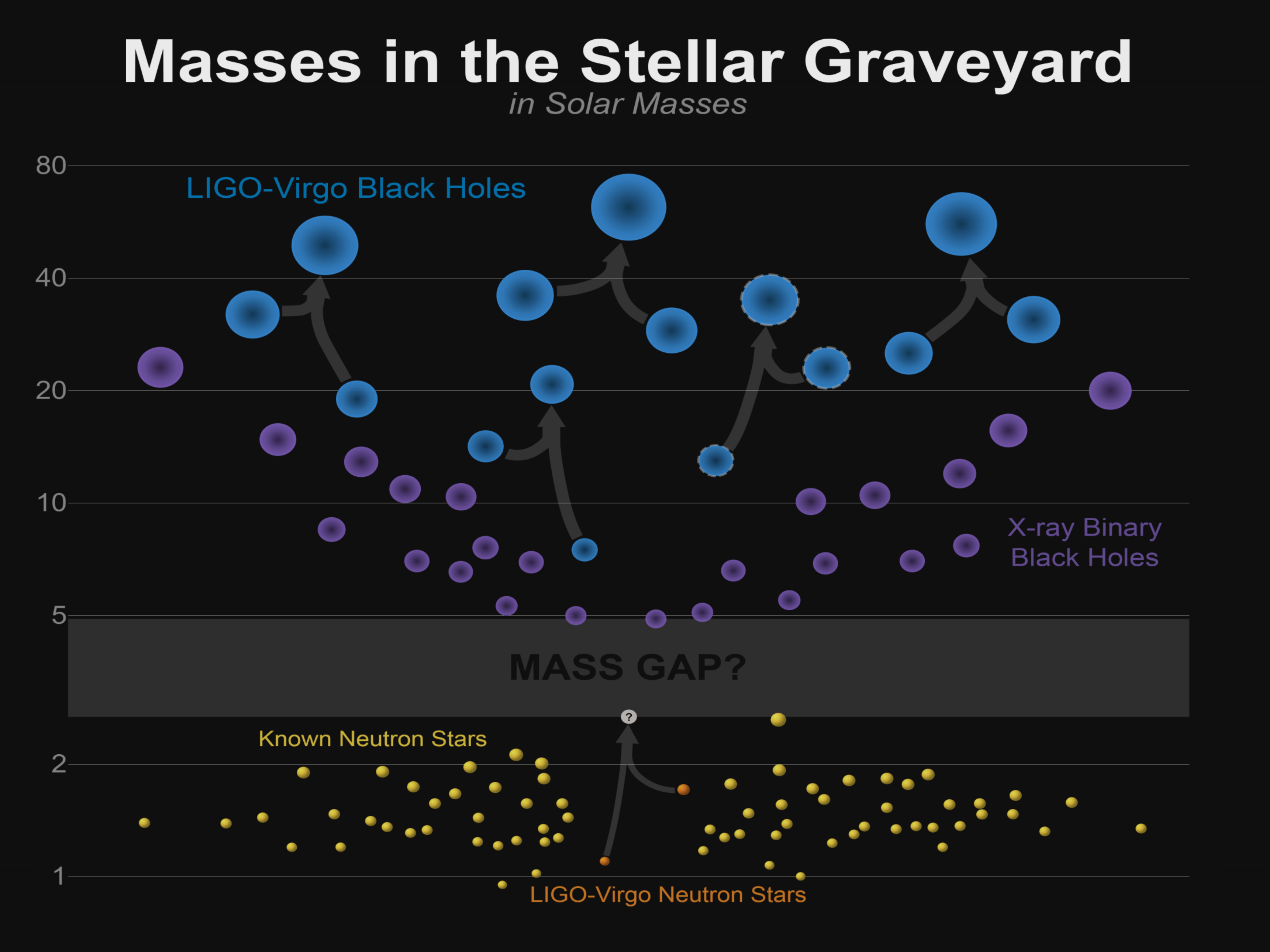
Gravitational Waves, Gamma Rays and More……





Multi-messenger Observations of a Binary Neutron Star Merger
Ap. J. Lett 848:L12, 2017
Many collaborations: ~3500 authors!

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A
Ap. J. Lett., 848:L13, 2017,
(LIGO, Virgo, Fermi and INTEGRAL collaborations)


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary Black Holes
MASS GAP?
?
Known Neutron Stars
LIGO-Virgo Neutron Stars