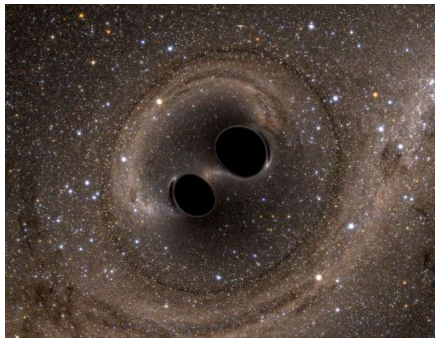
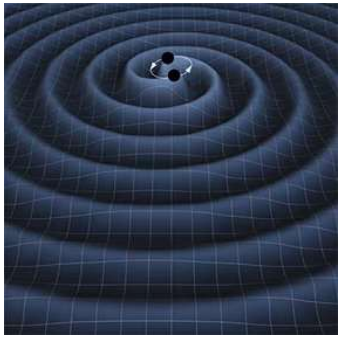
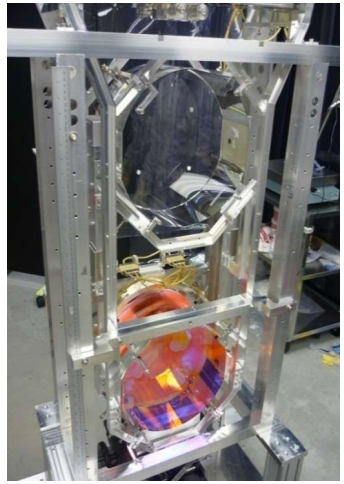
University of Glasgow





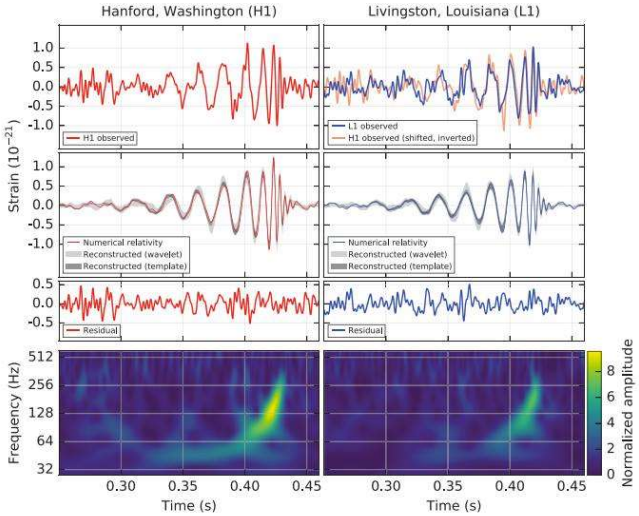


Gravitational Wave Astronomy

Prof. Giles Hammond (giles.hammond@glasgow.ac.uk)

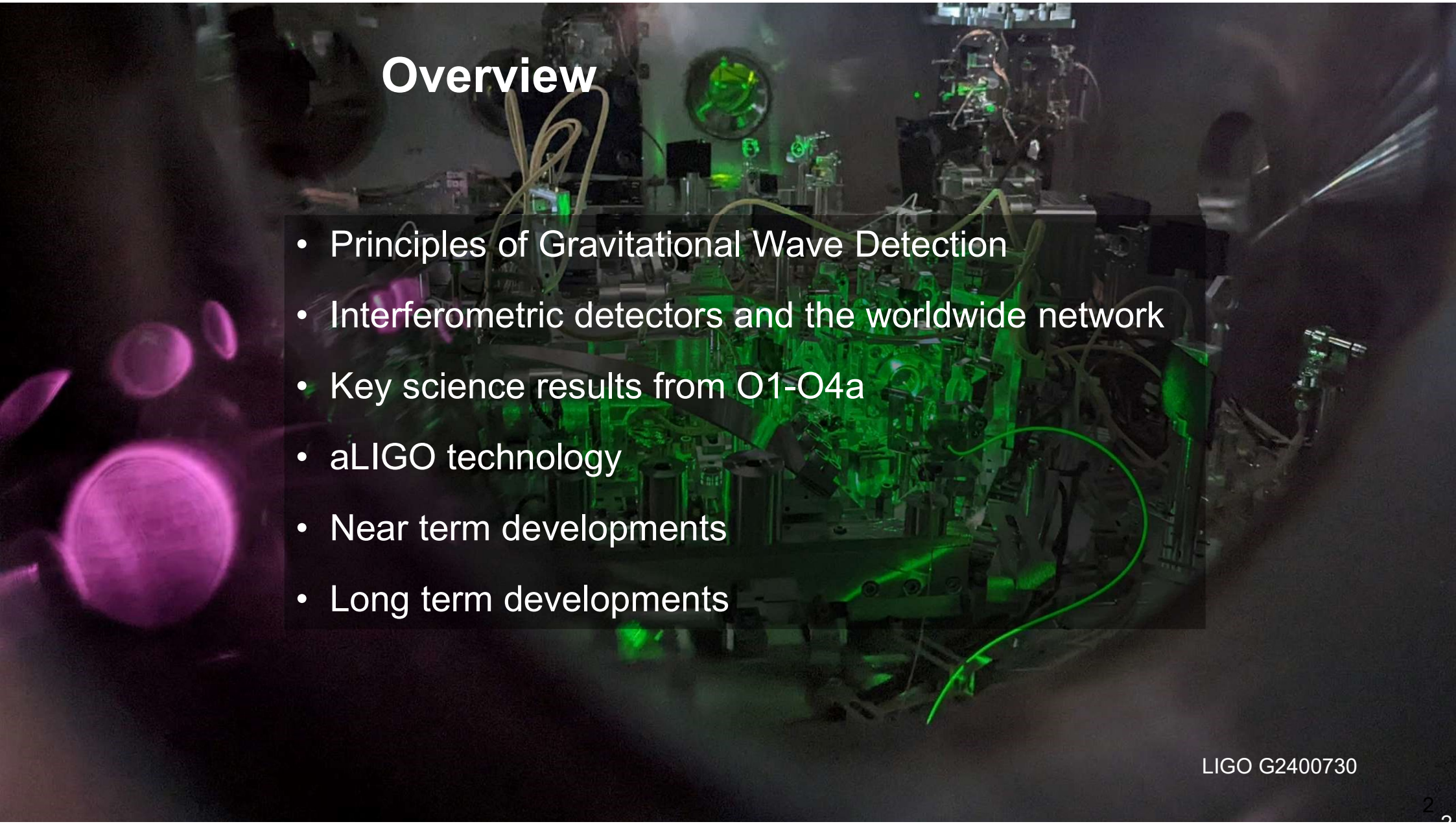
Institute for Gravitational Research

University of Glasgow



LIGO G2400834-v1

IoP APP / HEPP / NP conference
8 – 11 April 2024



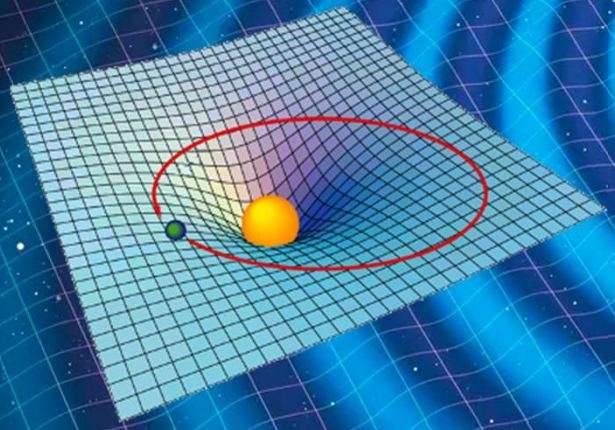
Overview

- Principles of Gravitational Wave Detection
- Interferometric detectors and the worldwide network
- Key science results from O1-O4a
- aLIGO technology
- Near term developments
- Long term developments

Principles of Gravitational Wave Detection

- Gravitational waves (GW) are ripples in spacetime generated by accelerating masses with non-zero quadrupole moment

  e.g. Compact binary coalescences



$$h \approx \frac{G}{c^2}\frac{M}{d}\left(\frac{v}{c}\right)^2$$

- GW induce strain, stretching and compressing spacetime, causing displacements on the order of 10^{-18} m over a 4 km baseline
- To detect GW we measure the displacement of a test mass

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

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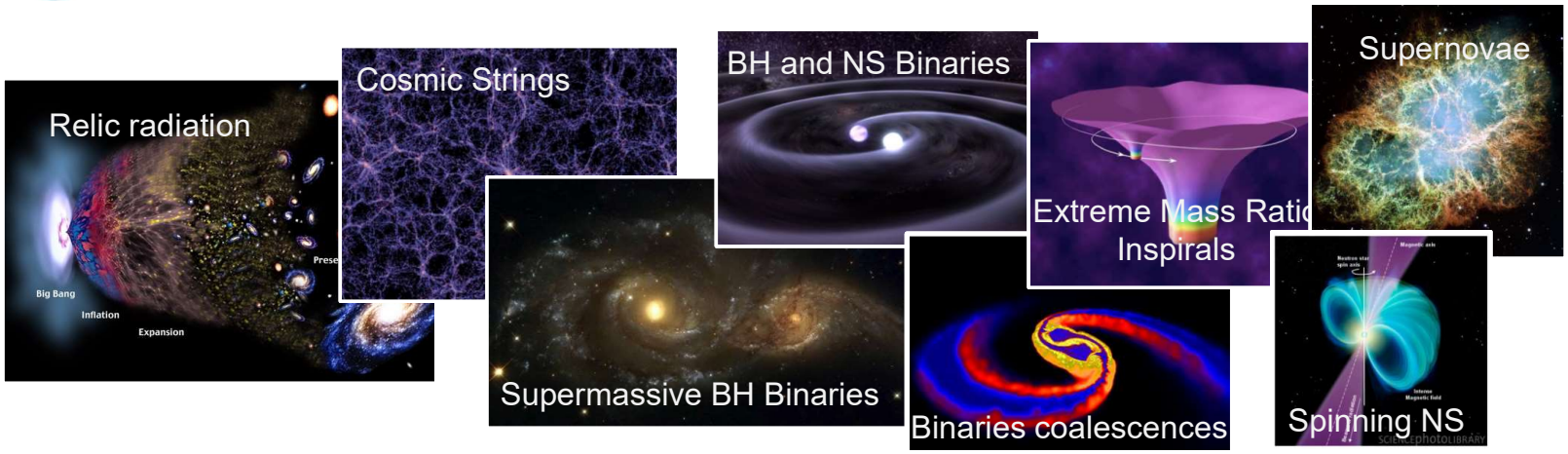
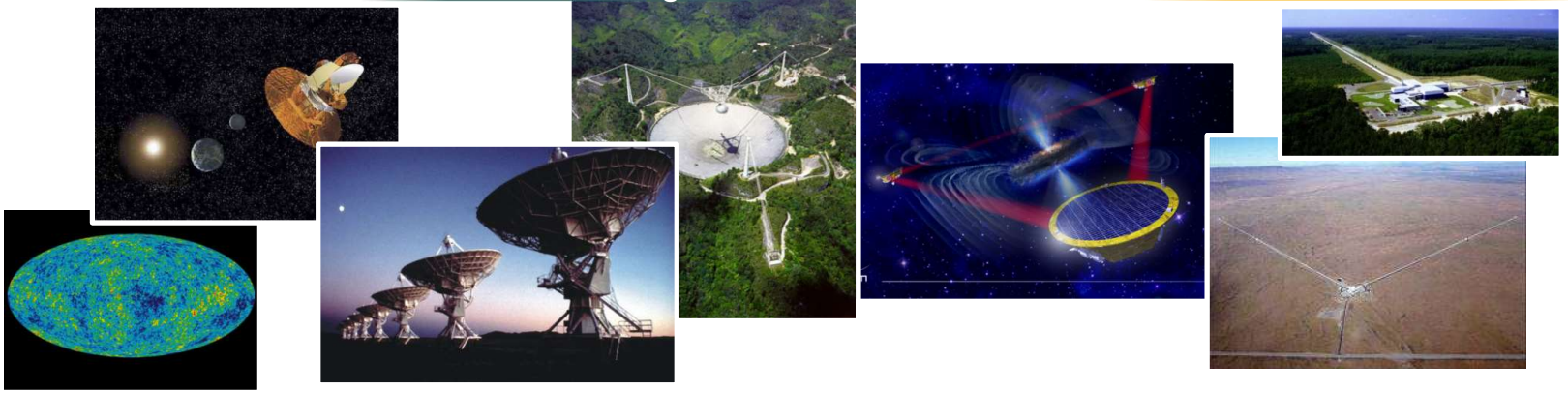
The Gravitational Wave Spectrum



10^{-16} Hz | 10^{-9} Hz | 10^{-4} Hz | 10^{0} Hz | 10^{3} Hz

Inflation Probe | Pulsar timing | Space detectors | Ground based



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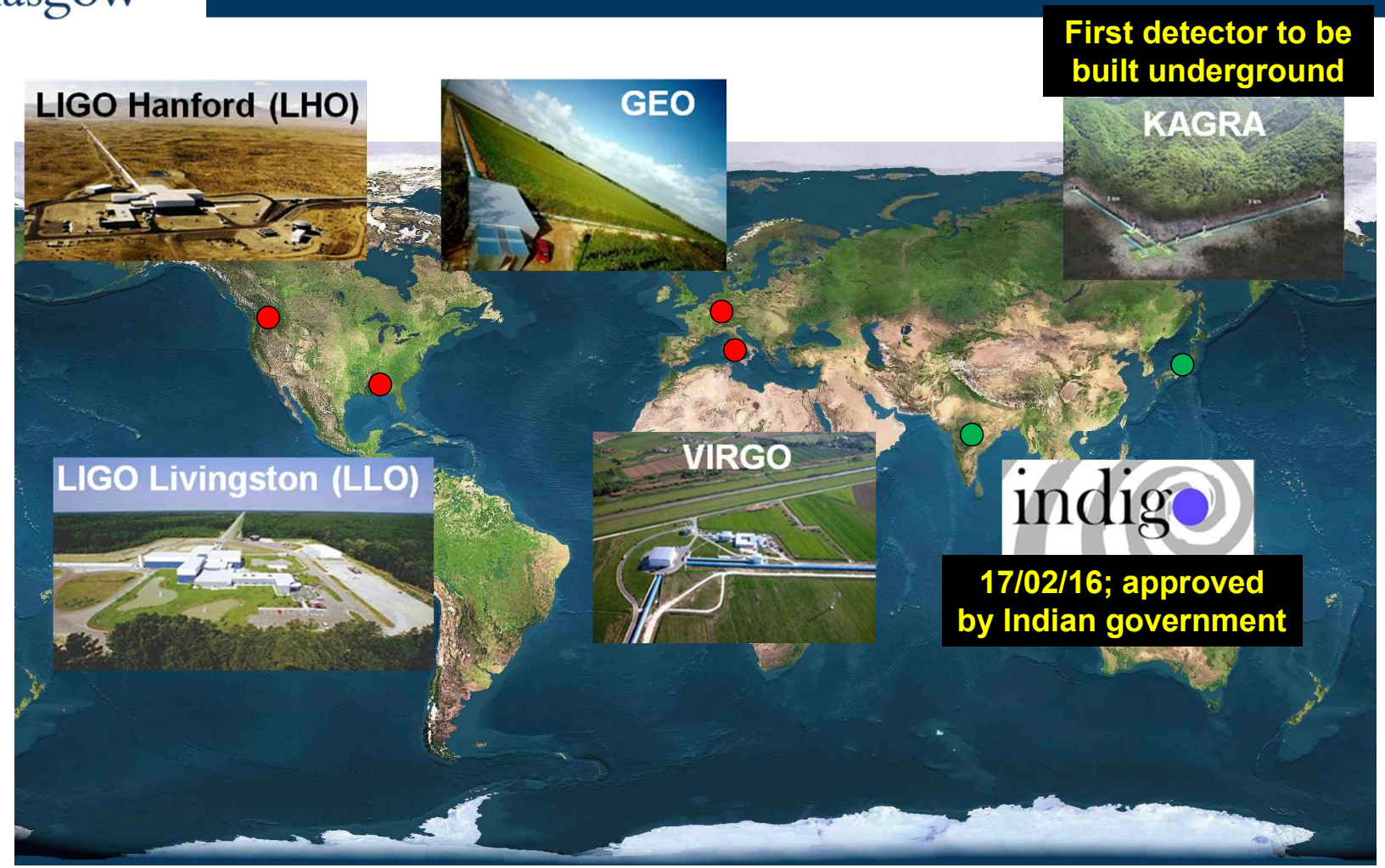
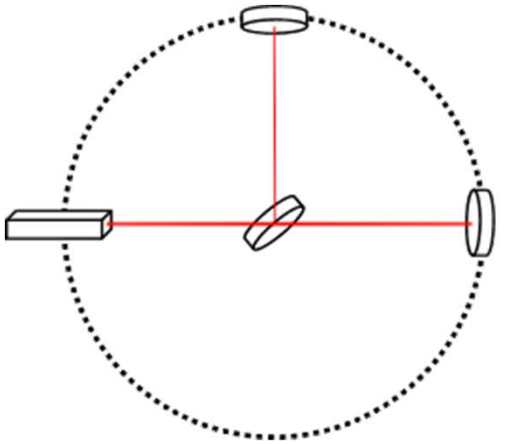
The International Network

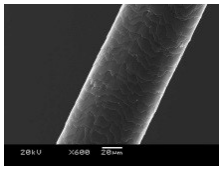


- A network is required to localise the source position

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)



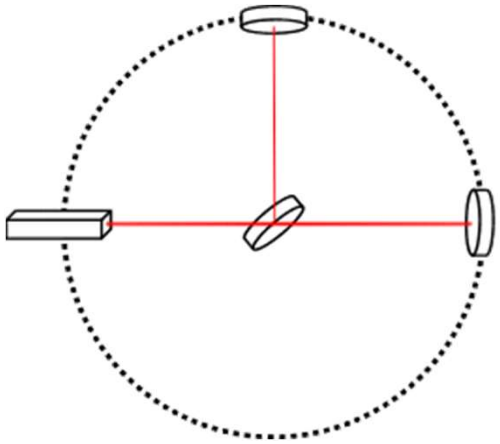


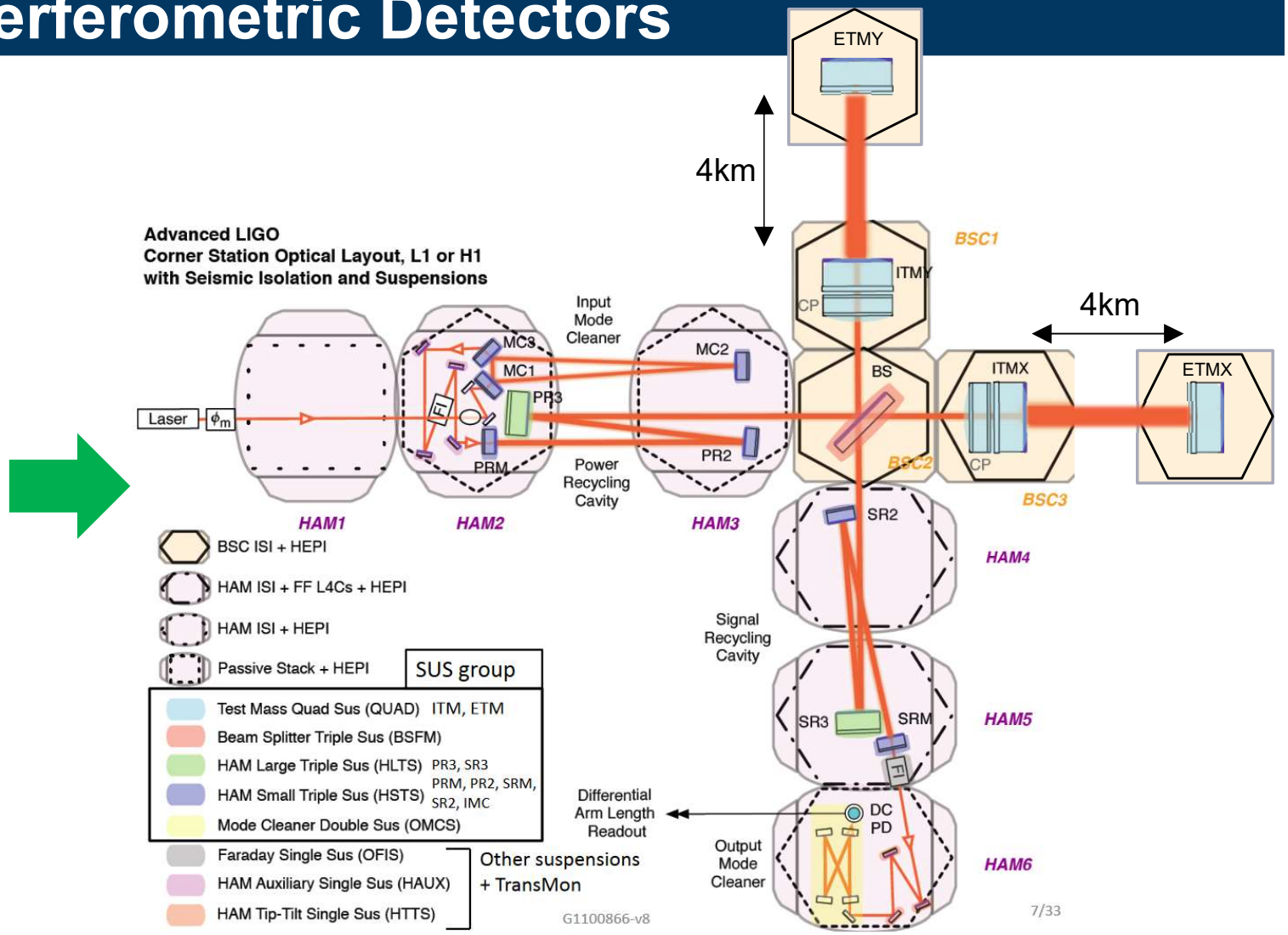
Human hair (10^{-4} m)

Nearest star (3×10^{16} m)

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

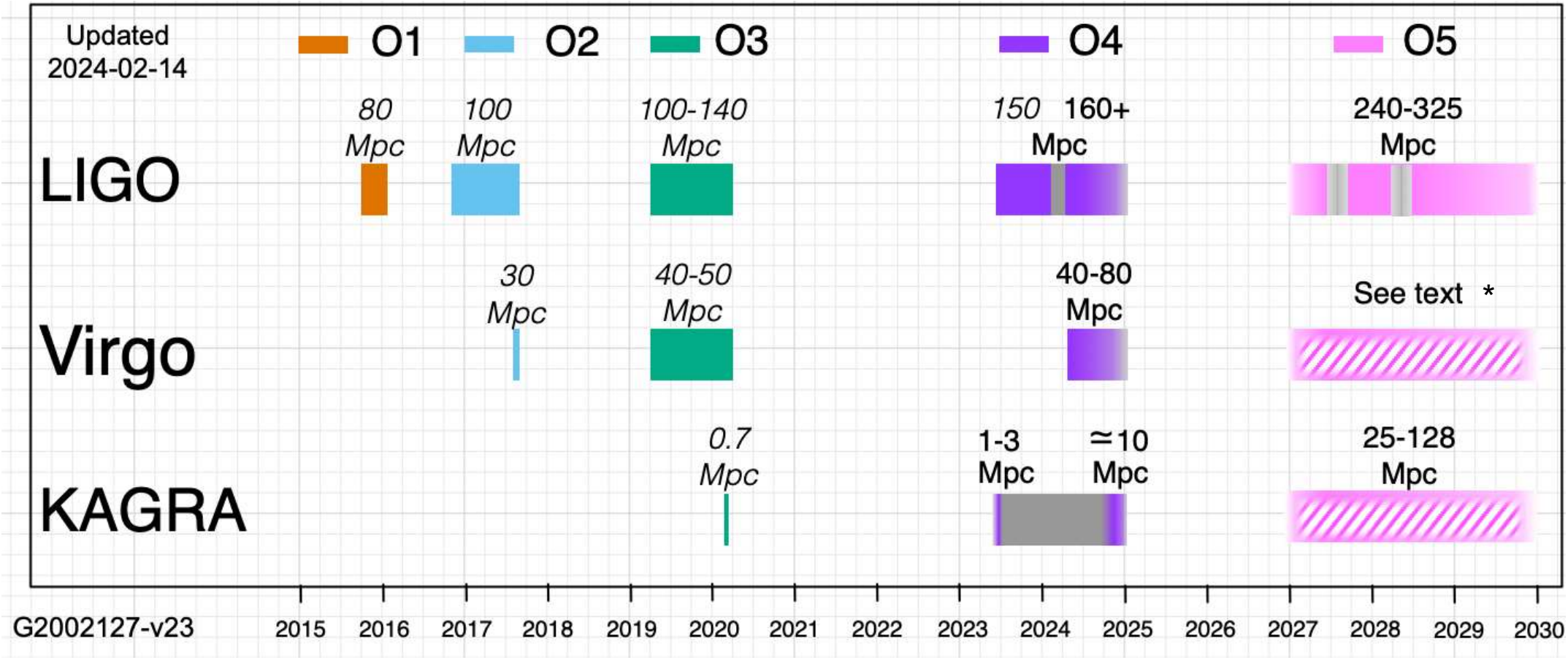
Interferometric Detectors





https://observing.docs.ligo.org/plan/#

Observing Timeline



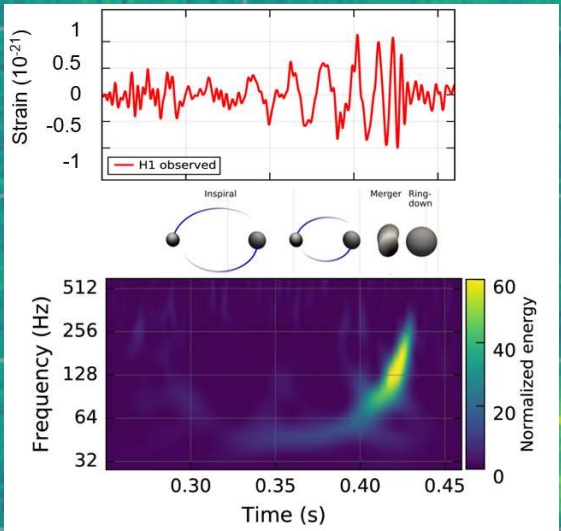
* At the moment, Virgo is reconsidering its plans for O5 and both the date on which it will be able to enter O5 and the target sensitivity are currently unclear.

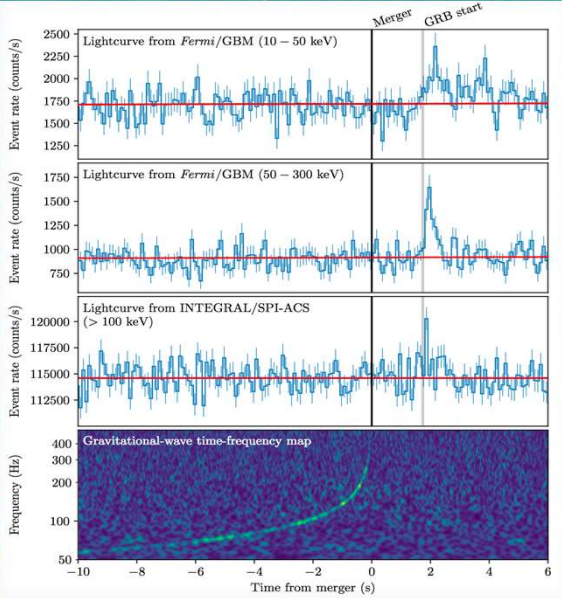
Phys. Rev. Lett. 116, 061102, 2016
Phys. Rev. Lett. 119, 161101, 2017
Phys. Rev. X 13, 041039, 2023

Key Science results O1-O4a

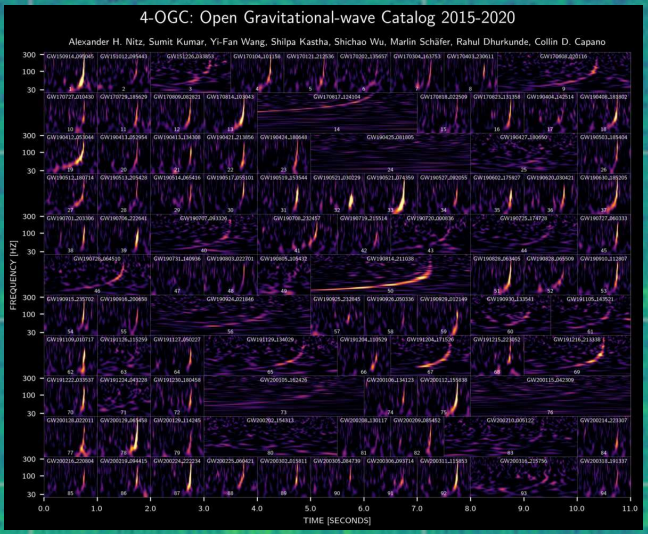
GWTC-3 catalog

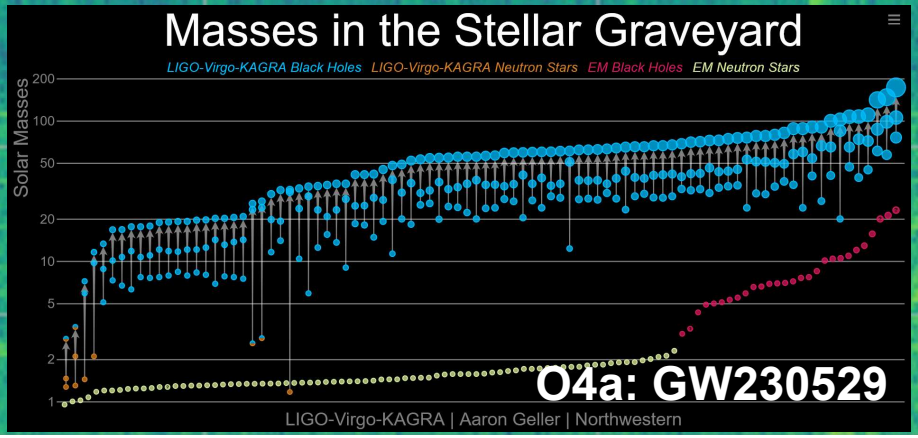
O1: GW150914



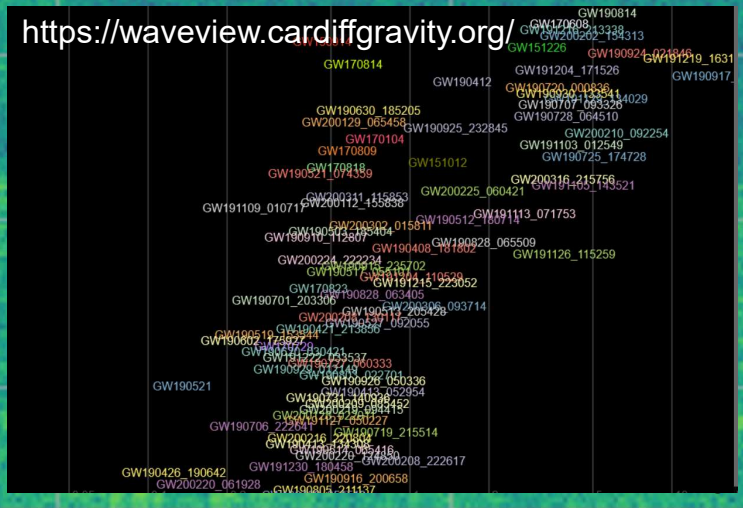


O2: GW170817





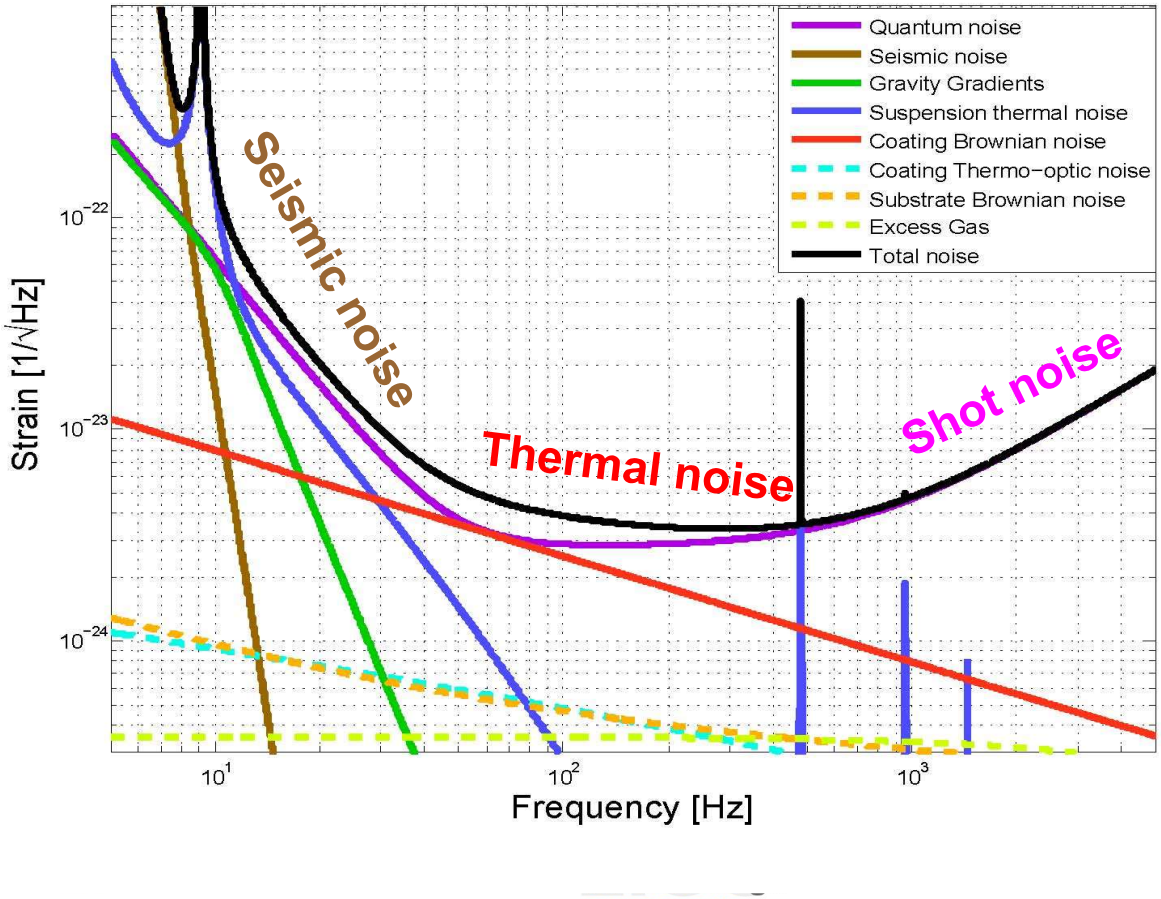
https://waveview.cardiffgravity.org/

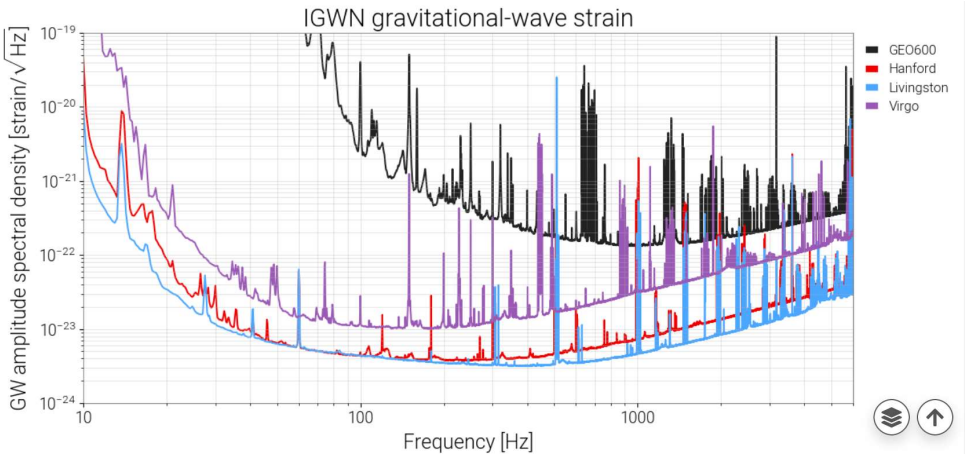


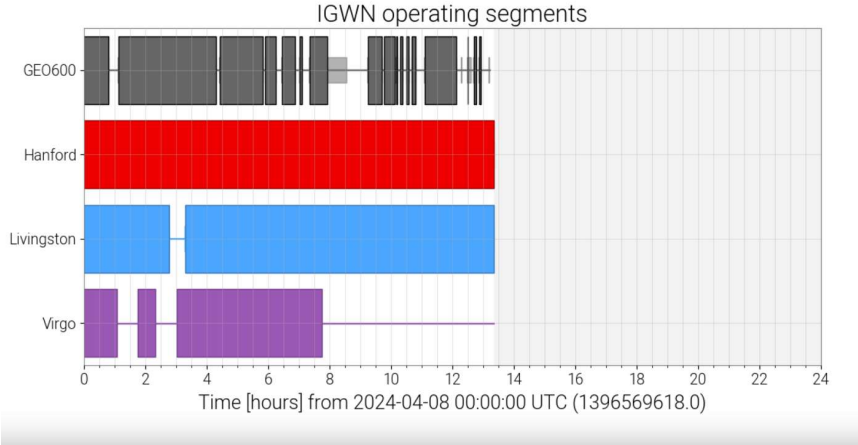
https://gwosc.org/detector_status/day/20240408/

Detector Sensitivity

- aLIGO design sensitivity





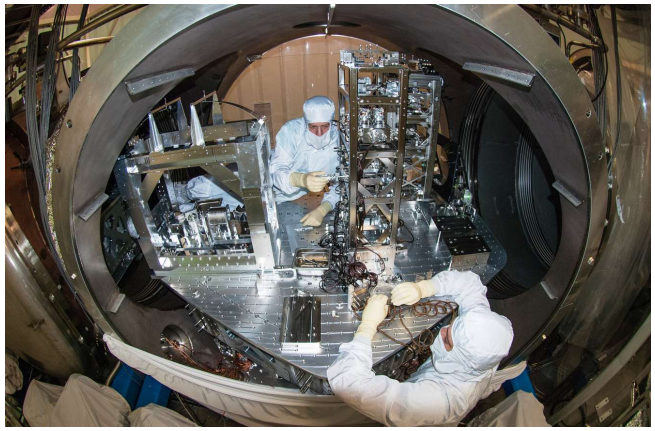


8th April 2024

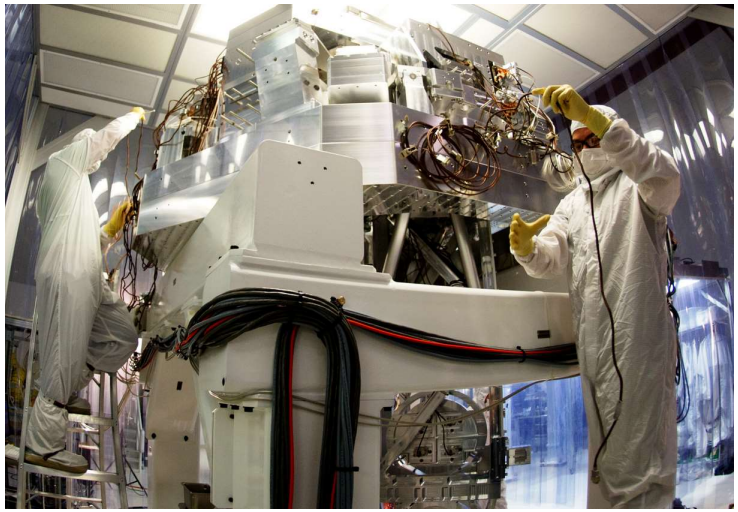
https://www.advancedligo.mit.edu/april_2012_news.html

Seismic Isolation & Suspensions

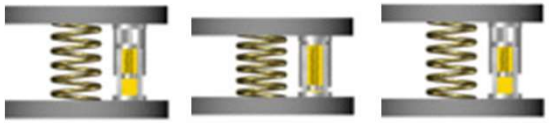
aLIGO Inertial Seismic Isolation (2 active/passive in-vacuum stage)



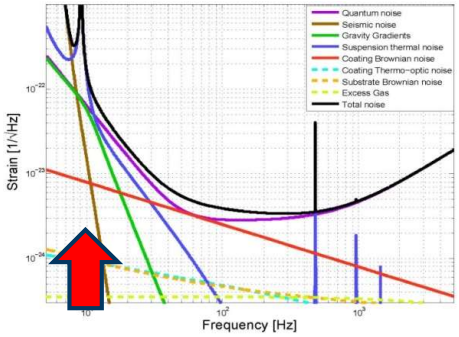
aLIGO HAM5 suspensions



aLIGO QUAD suspension (3/4 stages of vertical/horizontal isolation)

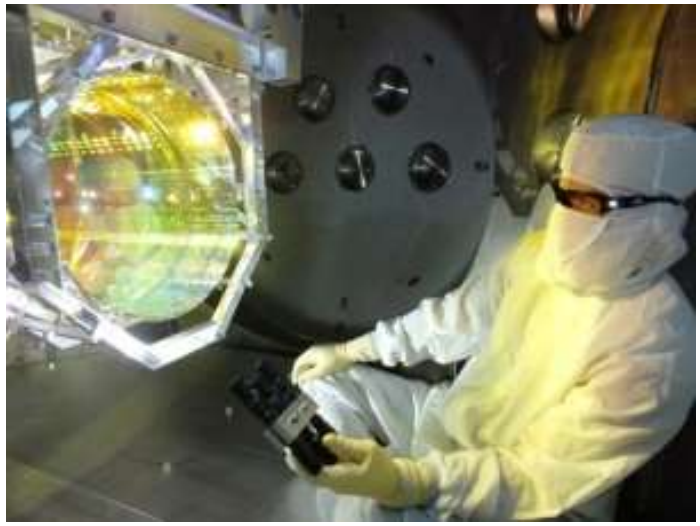


f low resonance f high

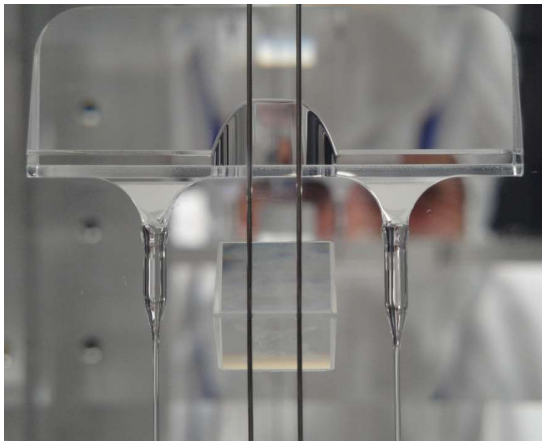


https://dcc.ligo.org/LIGO-G2400504

Thermal Noise

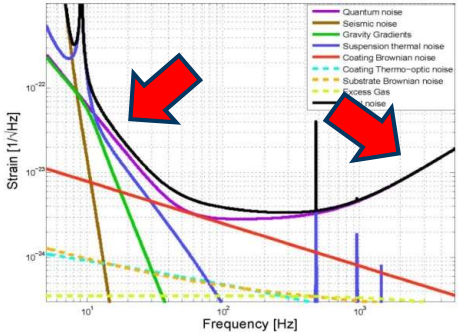


40kg fused silica mirrors



Final mirror suspended by fused silica fibres (Q factor >10^9)

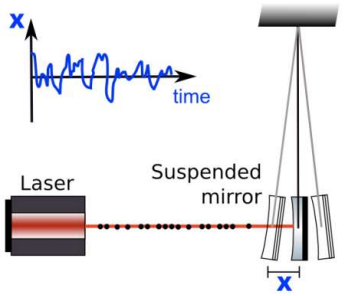
- Low dissipation (loss angle) materials to reduce thermal noise in coatings/suspensions

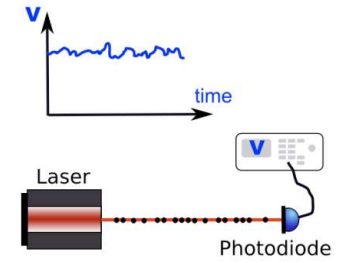


https://dcc.ligo.org/LIGO-P2400059

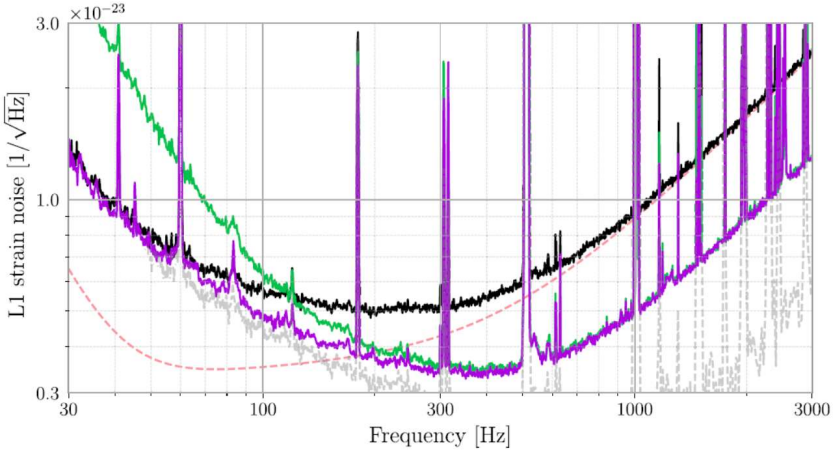
Quantum Noise

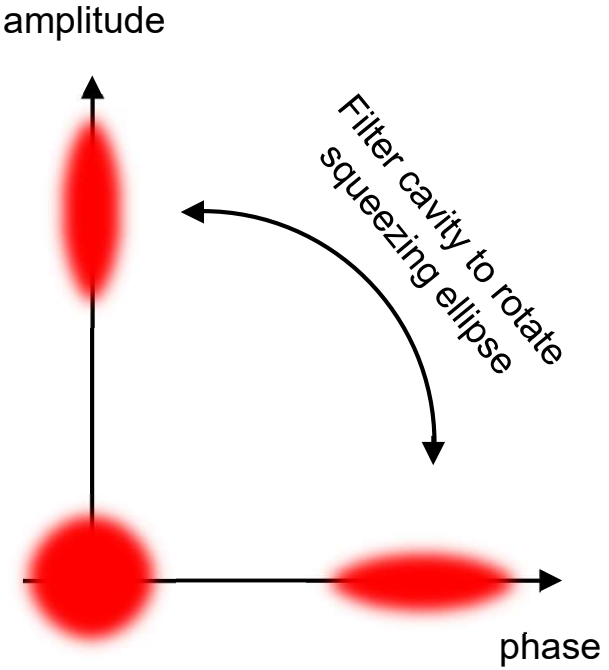
- GW detectors limited by quantum noise
  - Shot noise at high frequency (>80 Hz)
  - Radiation pressure noise at low frequency (<80 Hz)
- Quantum noise is due to the phase and amplitude uncertainty of light (inject light into dark port)

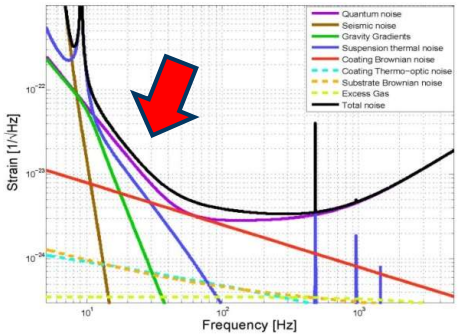




PRX 13, 041021 (2023)

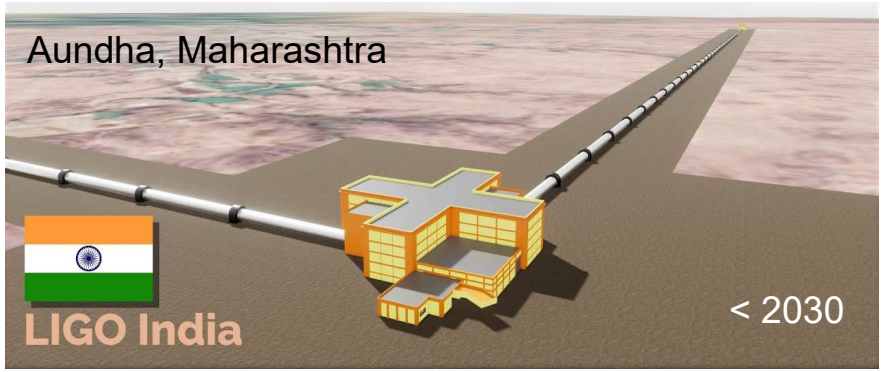




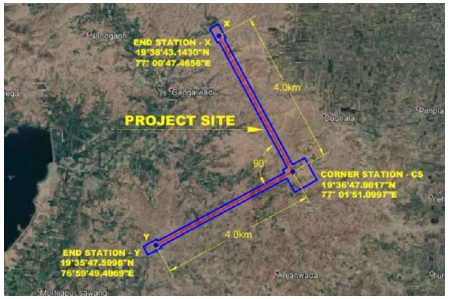


Near Term Developments (next 5-10 years)

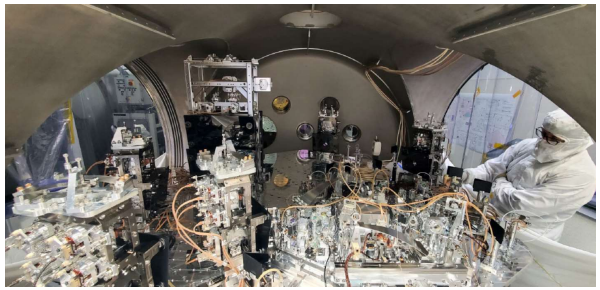
https://dcc.ligo.org/LIGO-G2400725



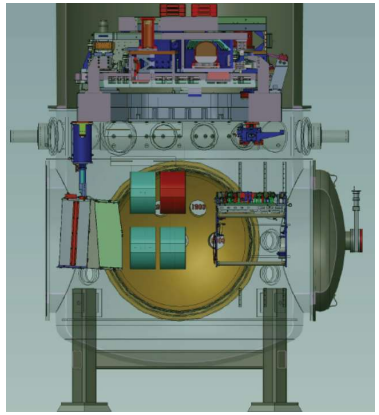
- LIGO India (3rd LIGO detector)



- A+ (O5)



- New 40kg optics
- New coatings with lower scatter/thermal noise
- New suspensions with higher stress silica fibres

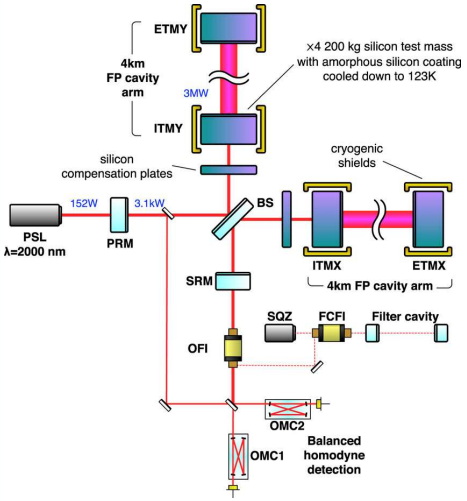


- A#/AdV+ (post O5)
- 100kg suspensions
- Reduced cross-couplings
- Interferometric inertial sensors

https://dcc.ligo.org/LIGO-G2301738

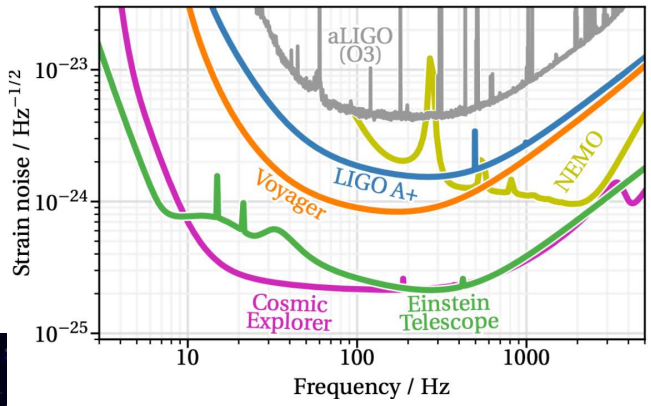
LIGO Voyager, Classical and Quantum Gravity 37(16), 2020

Long Term Developments (>10 years)

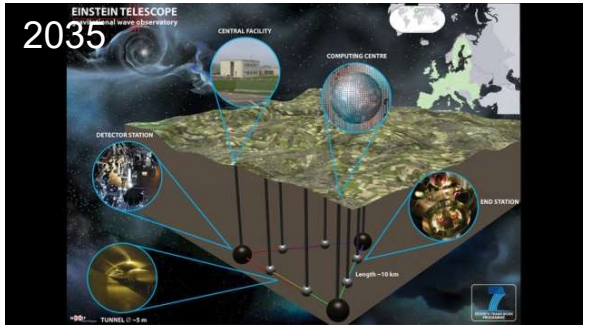


- LIGO Voyager (US)
- 123K detector
- LIGO facility

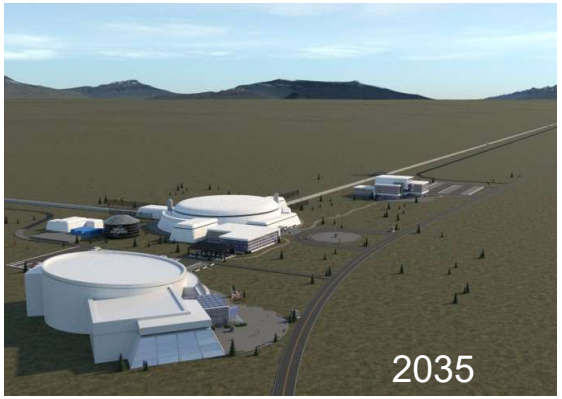
- LISA space-based detector



https://www.et-gw.eu/



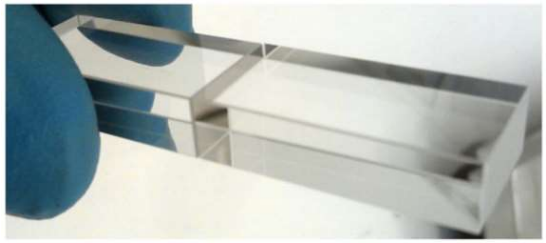
- Einstein telescope (Europe)
- X10 strain improvement
- 300K/20K, underground



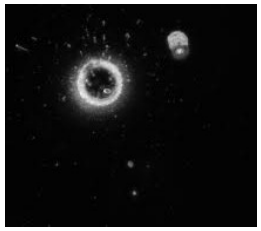
- Cosmic Explorer (US)
- X10 strain improvement
- 300K phase I

https://cosmicexplorer.org/sensitivity.html

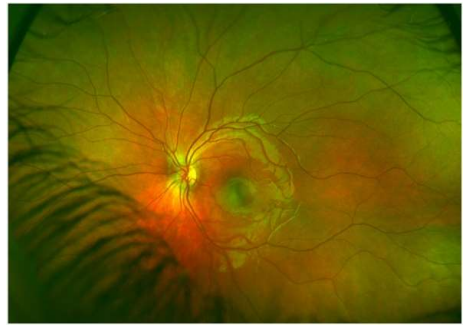
Spin-Off Technologies



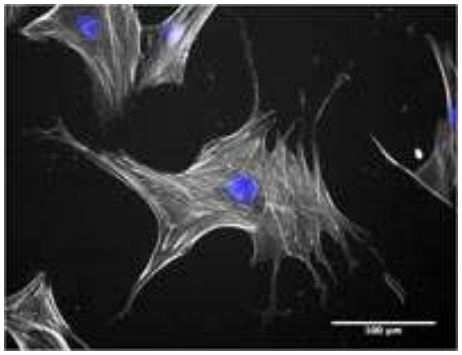
• High precision/stability bonding



• High damage threshold coatings

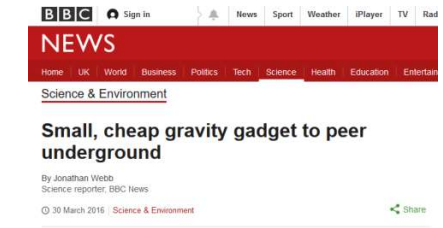


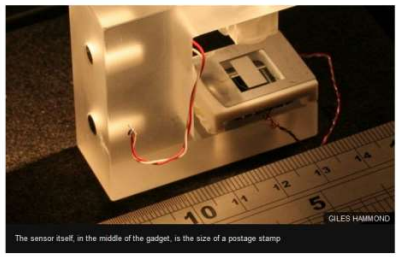
• analysis of retinal scans



• Stem cell differentiation

• Gas Sensing Solutions





• Gravity sensors for environmental monitoring/security/Carbon Capture

- The LIGO-VIRGO Scientific Collaboration is made up of around 1800 members worldwide

Thank You

Any Questions?