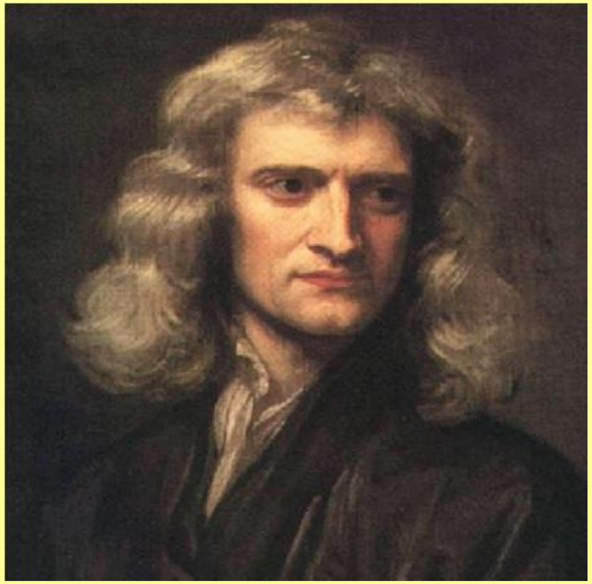
The search for gravitational waves

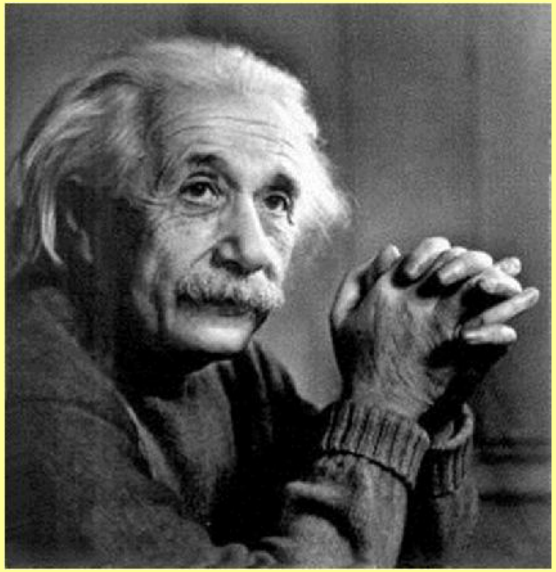
Prof Sheila Rowan
For the LIGO Scientific Collaboration
Director, Institute for Gravitational Research
University of Glasgow
UK

The Indian Physics Association/UK IoP
"Cockcroft and Walton Lectures"
2015

LIGO Document G1501331

Gravitation





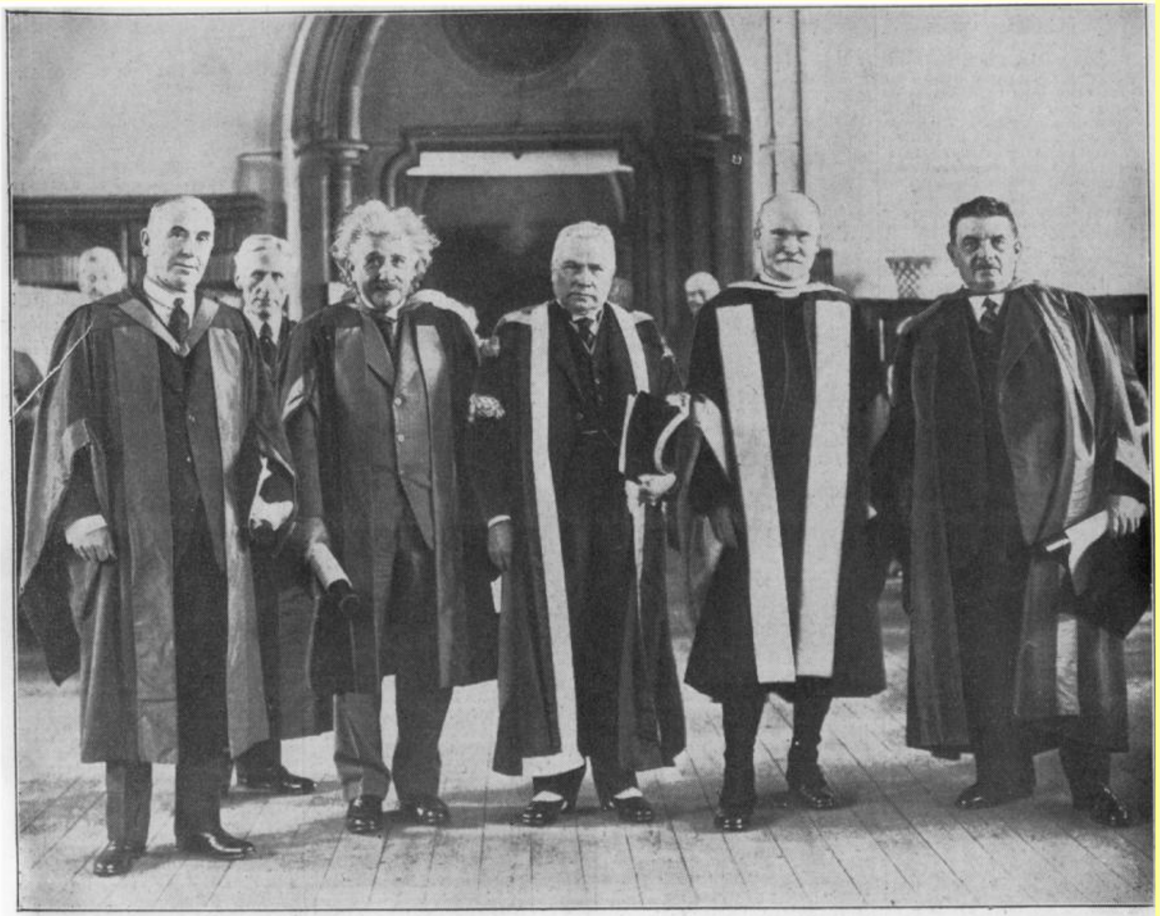
Newton's Theory

"instantaneous action at a distance"

Einstein's Theory

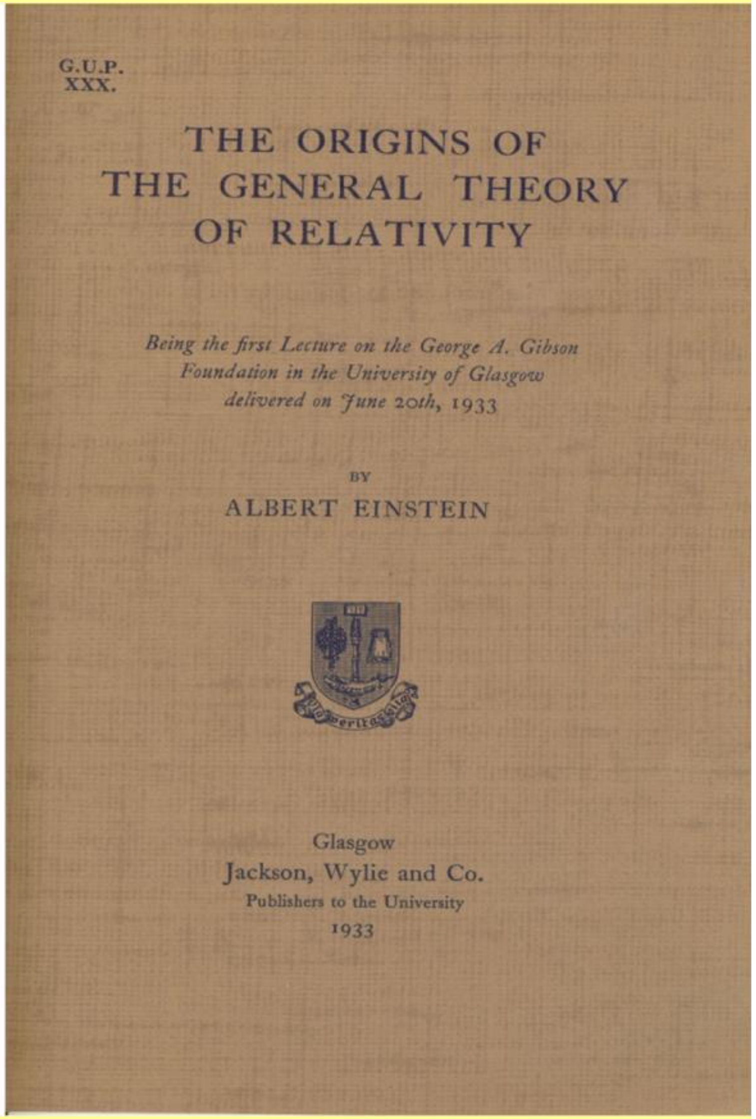
information cannot be carried faster than speed of light – there must be gravitational radiation

Gravitational waves - a prediction of General Relativity (1916)



A group of some of the honorary graduates taken after the ceremony in the Bute Hall of Glasgow University yesterday. Left to right—The Right Hon. Sir Robert S. Horne; Emeritus Professor William Blair-Bell, University of Liverpool; Professor Albert Einstein; Principal Sir Robert S. Rait; the Archbishop of Armagh and Primate of All Ireland; and M. Edouard Herriot, former Prime Minister of France.

Einstein in Glasgow 1933



G.U.P.
XXX.

THE ORIGINS OF THE GENERAL THEORY OF RELATIVITY

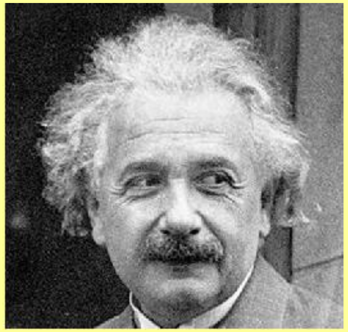
Being the first Lecture on the George A. Gibson Foundation in the University of Glasgow delivered on June 20th, 1933

BY

ALBERT EINSTEIN

Glasgow
Jackson, Wylie and Co.
Publishers to the University
1933

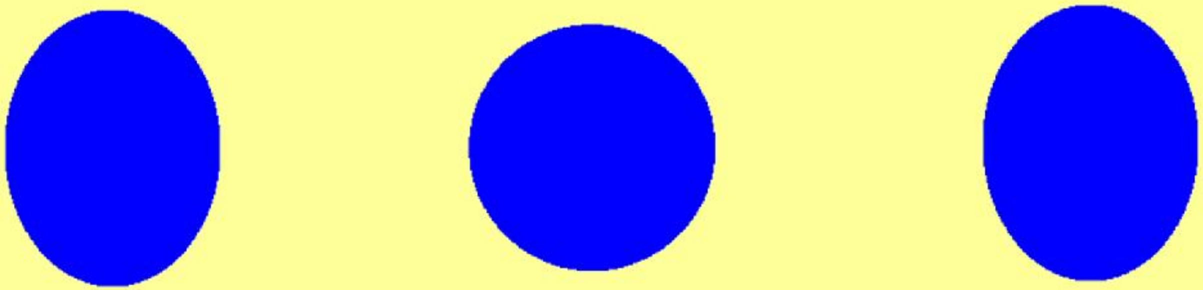
Gravitational Waves



The Einstein field equations of GR have wave solutions

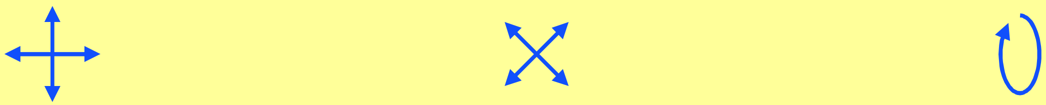
- Emitted by a rapidly changing configuration of mass
- Travel away from the source at the speed of light
- Change the effective distance between inertial points — i.e. the spacetime metric — transverse to the direction of travel

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



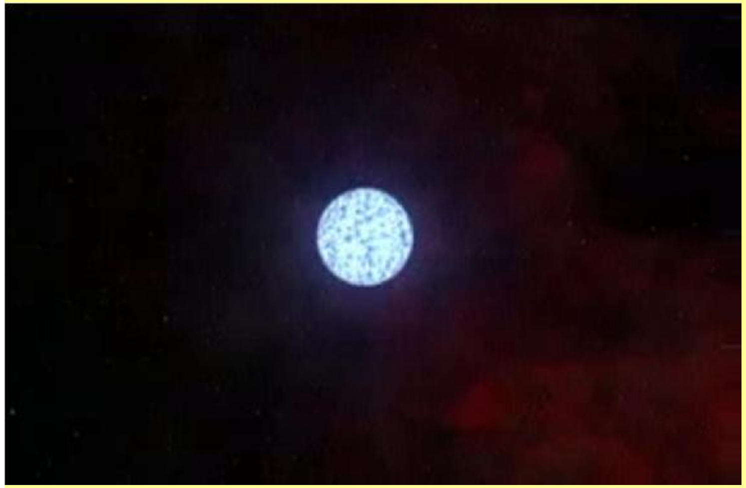
…

“Plus” polarization | “Cross” polarization | Circular polarization

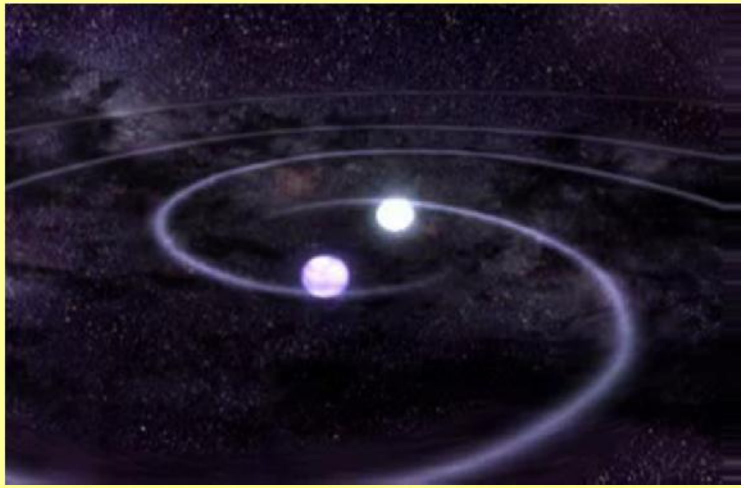


Gravitational wave sources in ground-based detectors

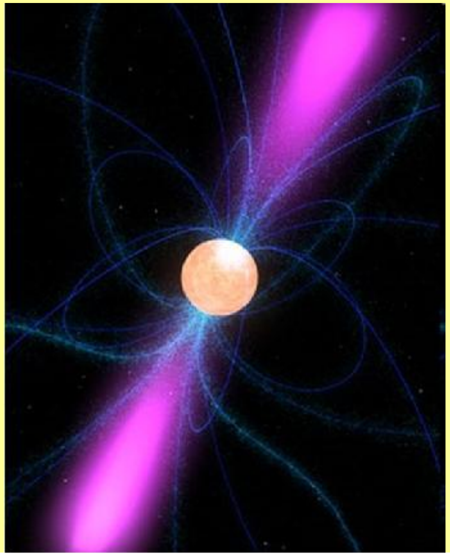
Supernovae and black hole formation



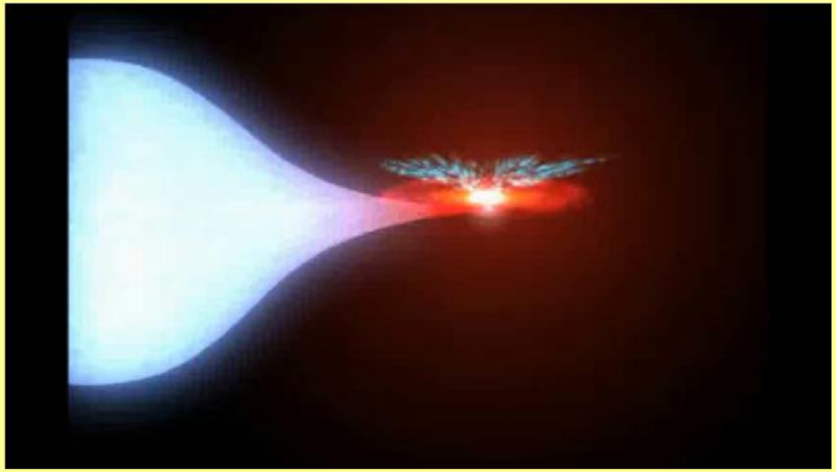
Binaries of black holes and neutron stars



Pulsars; modes and instabilities of neutron stars

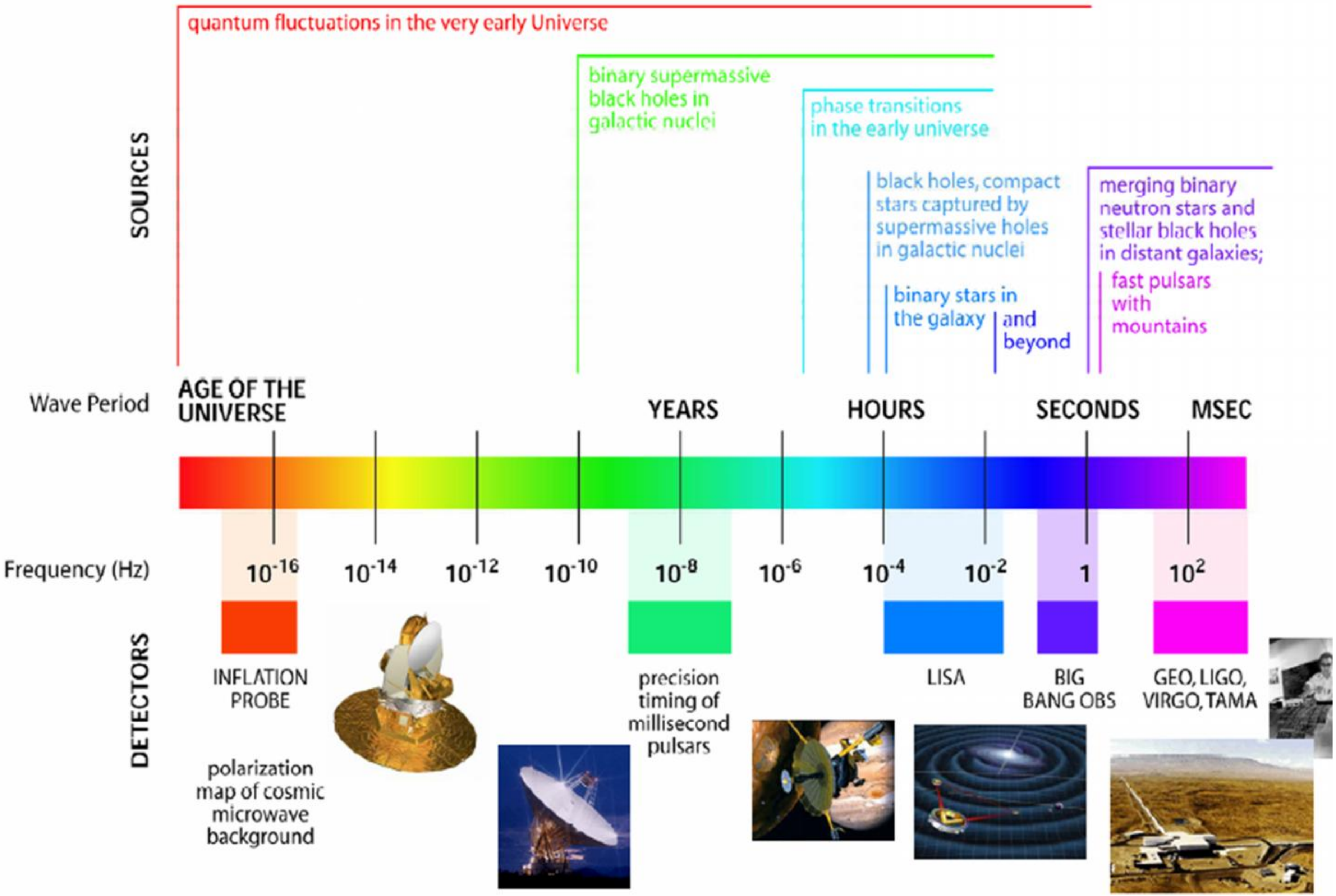


Spinning neutron stars in X-ray binaries

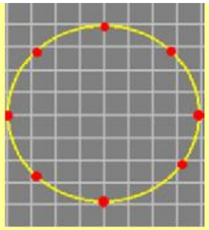


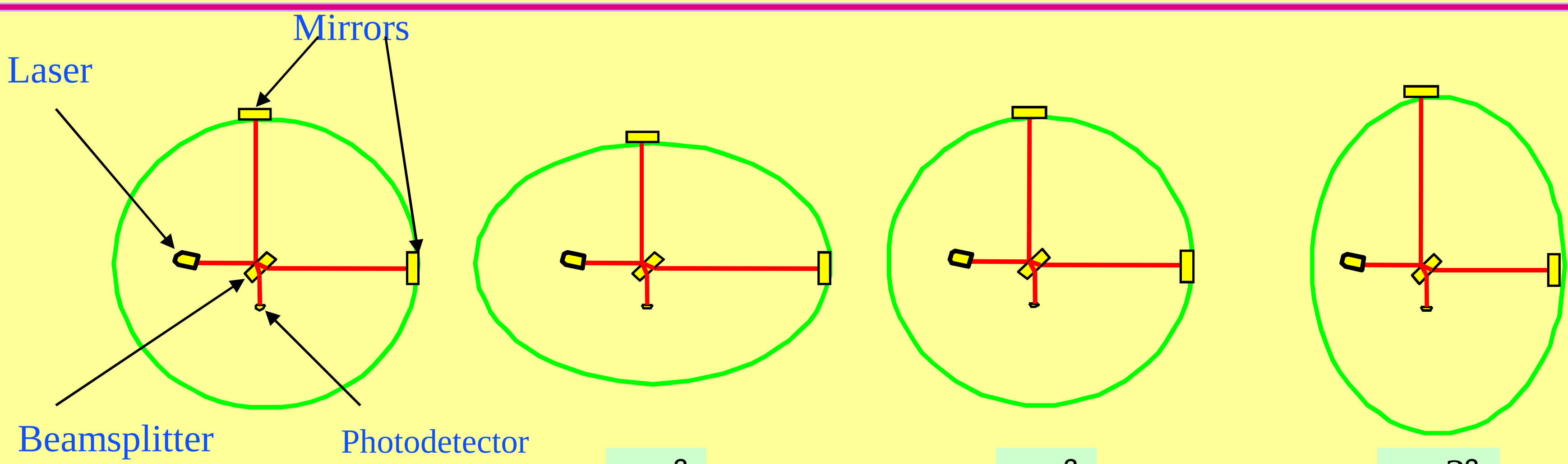
- GWs trace the bulk motion of their source
- Non-imaging
- Very weakly scattered / absorbed.
- Complementary to properties of photons

THE GRAVITATIONAL WAVE SPECTRUM

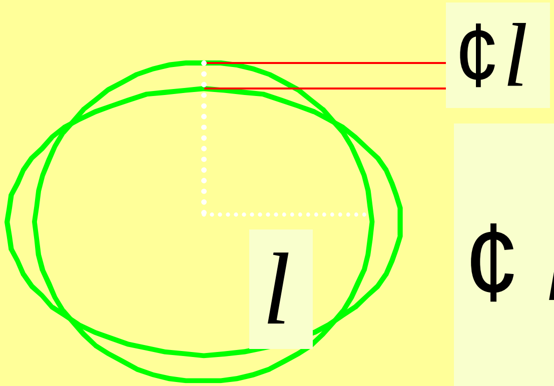


Operation of Interferometric Gravitational Wave Detectors





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



$$¢ l = \frac{h}{2} l$$

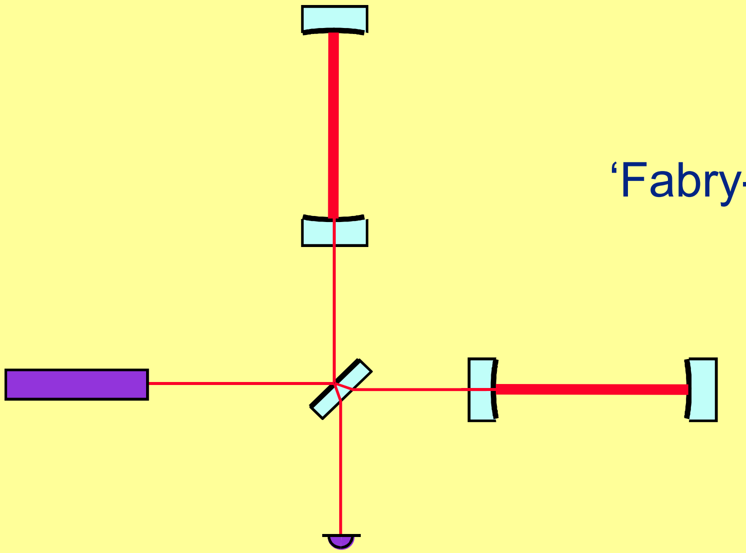
Gravitational wave amplitude

For Typical Astronomical sources

$$h = \frac{2 ¢ l}{l} \leq 10^{-22}$$

Laser Interferometer

- For best performance want arm length ~ λ/4
  - » i.e. for 1kHz signals, length = 75 km
- Such lengths not really possible on earth, but optical path can be folded



'Fabry-Perot Michelson'

- Much longer arm lengths are possible in space

Main limitations to sensitivity

- » Photon shot noise (improves with increasing laser power) and
- » radiation pressure (becomes worse with increasing laser power)

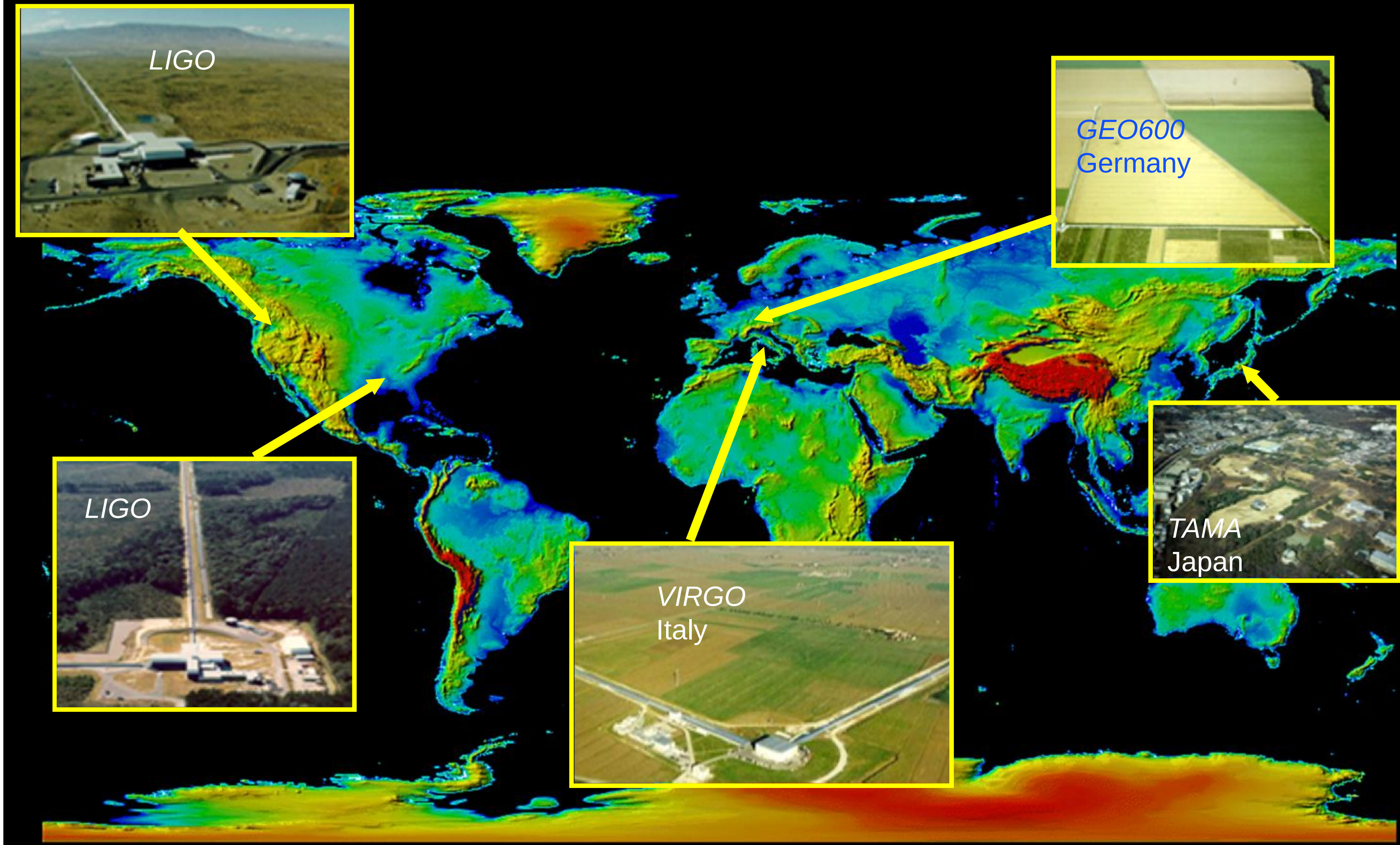
  There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle – the 'Standard Quantum limit'

- » Seismic noise relatively easy to isolate against – use suspended mirrors
- » Gravitational gradient noise – particularly important at frequencies below ~10 Hz
- » Thermal noise – Brownian motion of test masses and suspensions)

All point to long arm lengths being desirable

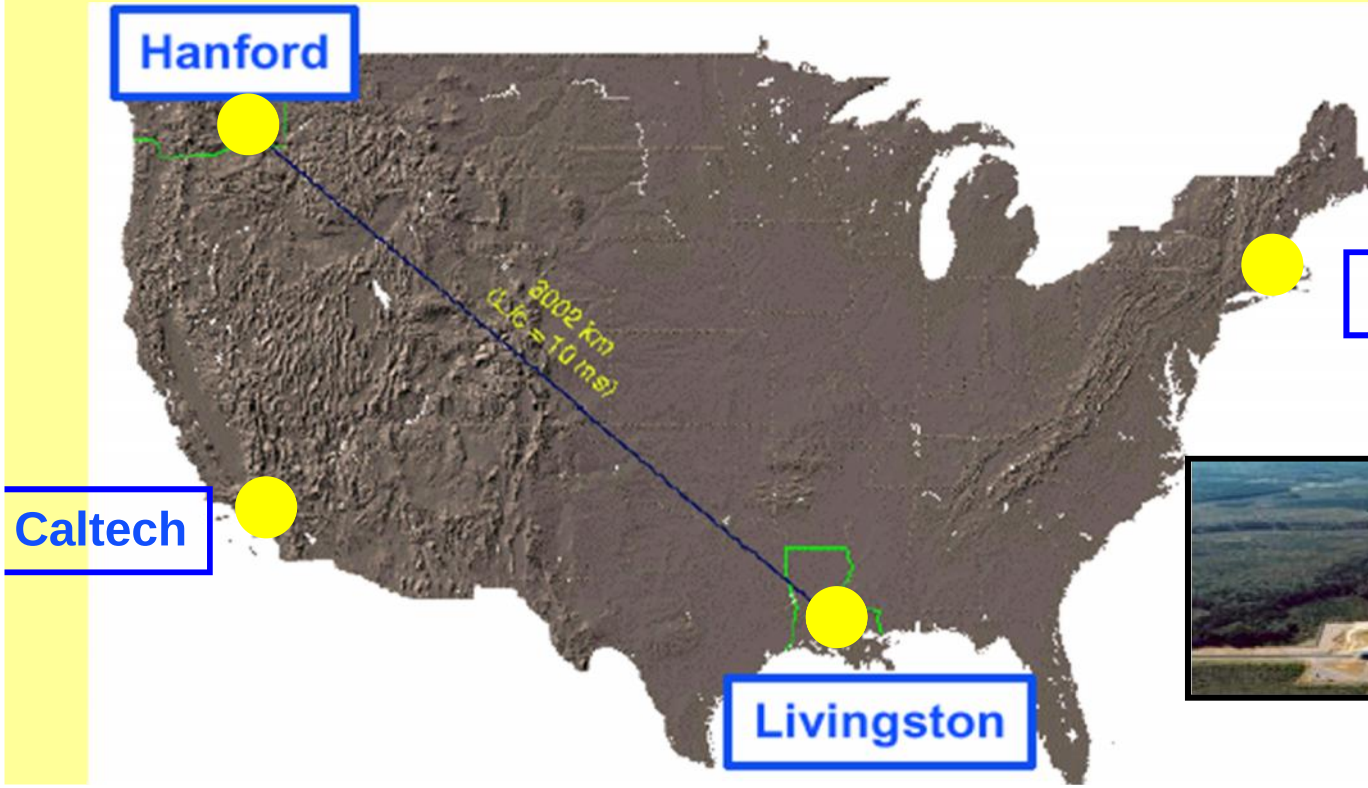
– **Global network of interferometers developed**

The Global Network
of (initial) Interferometric Gravitational Wave Detectors



LIGO Laboratory: two Observatories and Caltech, MIT campuses

- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



https://www.zeemaps.com/map?group=245330

The LIGO Scientific Collaboration: a group of 900+ scientists worldwide

Virgo: The French-Italian Project
3 km armlength at Cascina near Pisa

3km beam tube

GEO 600 : UK/German collaboration

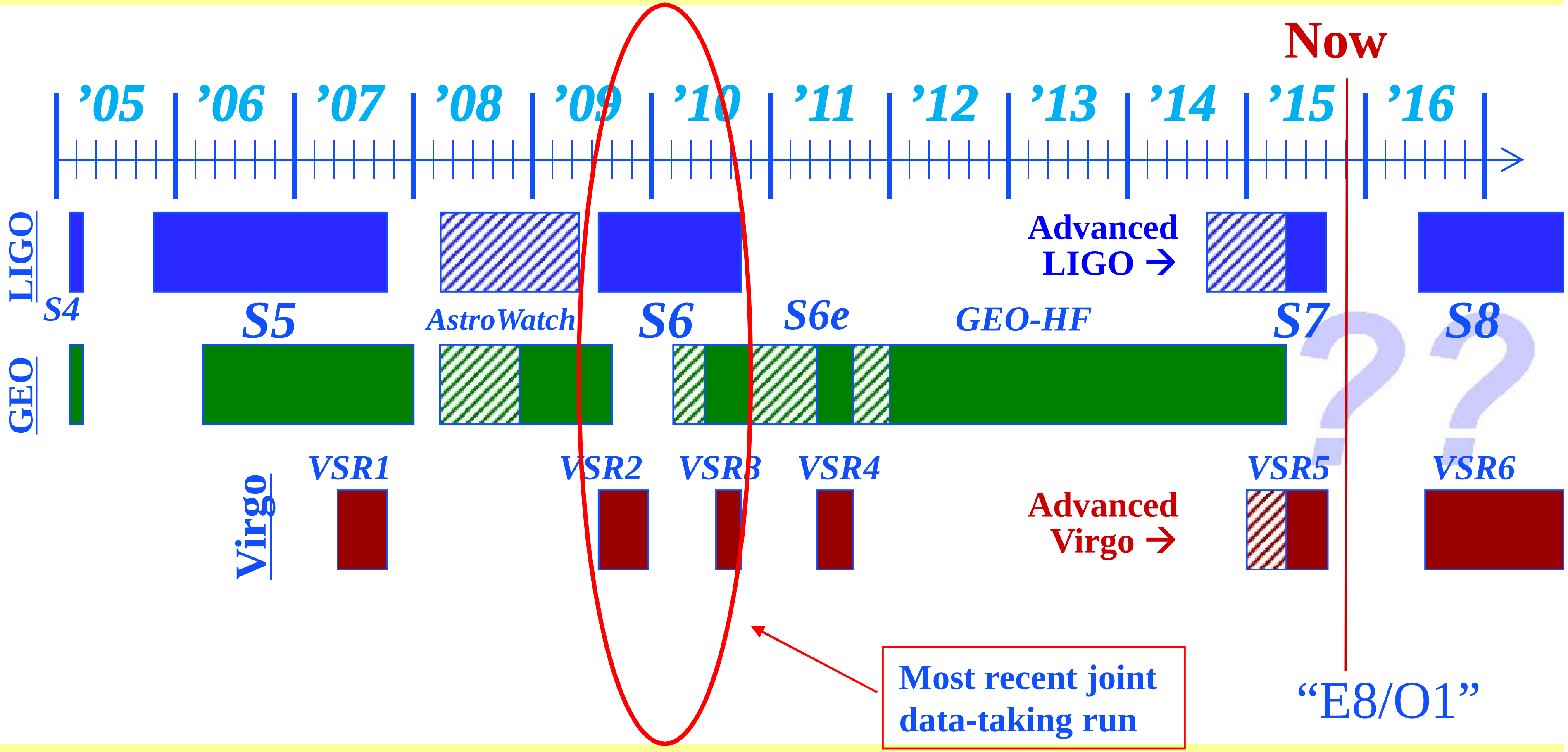
Initial GEO 600 strategy:

to build a low cost detector of comparable sensitivity to the initial LIGO and Virgo detectors to take part in gravitational wave searches in coincidence with these systems

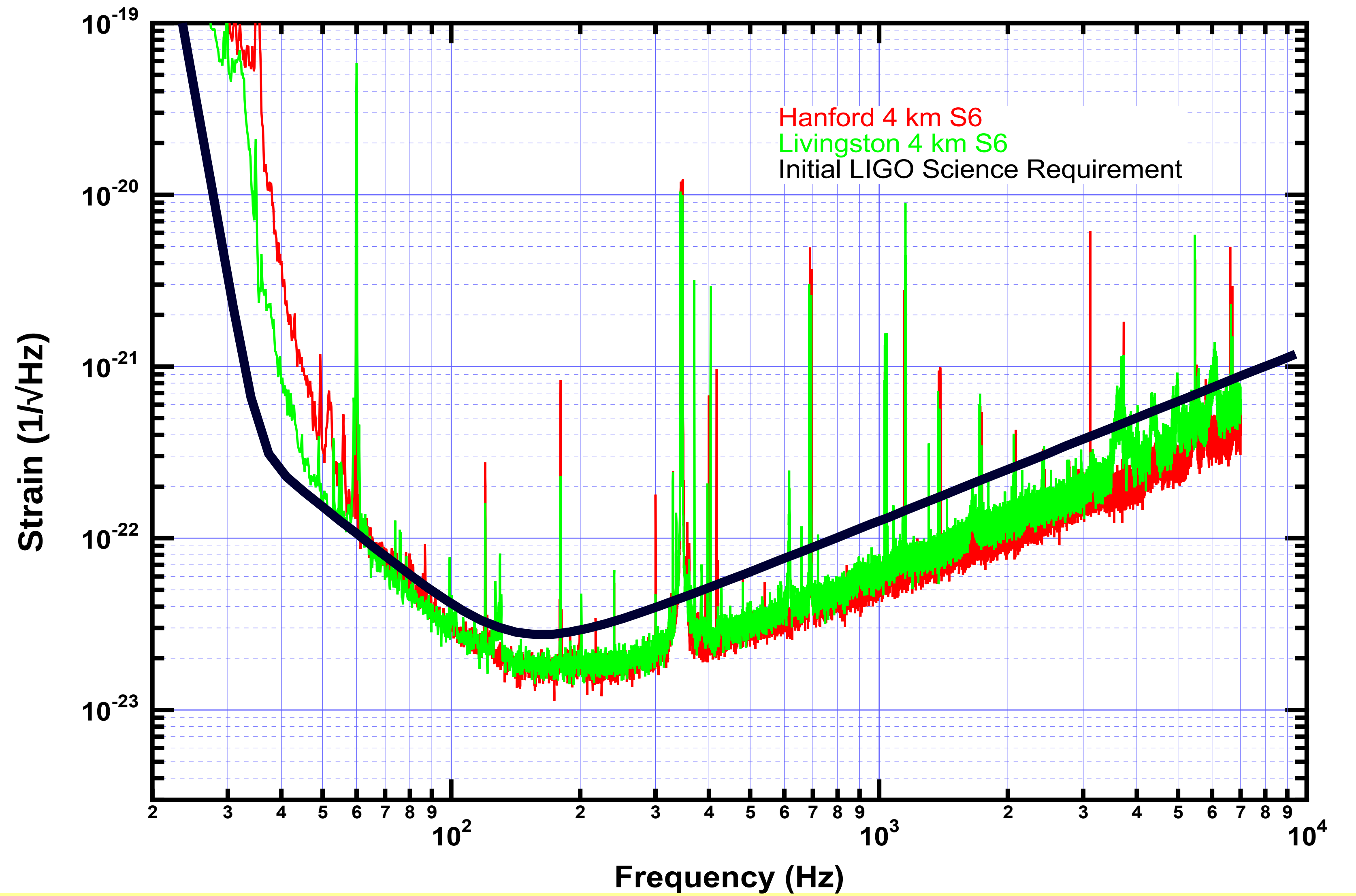
Disadvantage:

For geographical reasons the GEO armlength (600m) cannot be extended to the 3/4kms of Virgo/LIGO

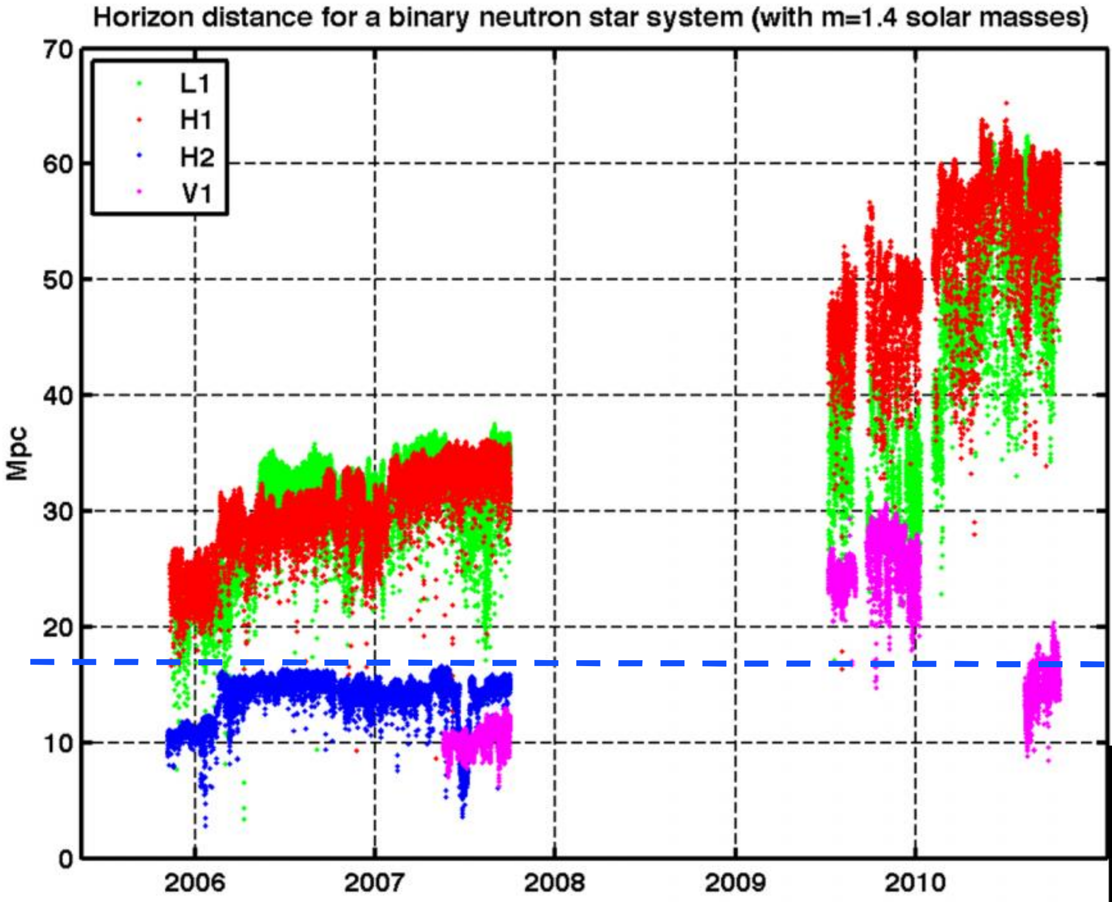
Science Runs: Past, Present & Future



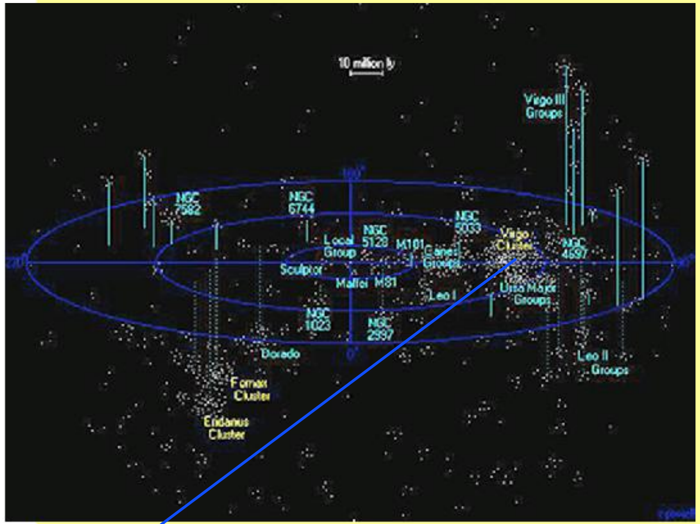
LIGO Detectors 2009-10 (S6)



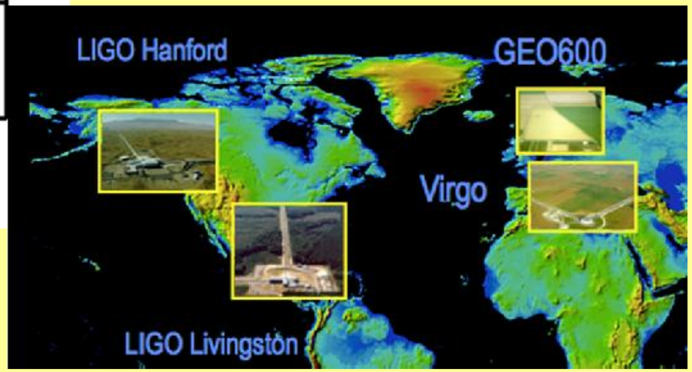
LIGO-Virgo detectors 2005-2011



atlasofthe universe.com



The Virgo Cluster
~16.5 Mpc from earth)



Astrophysical searches

- Six completed science runs to date involving LIGO, Virgo, GEO and (and TAMA) (>80 publications to date)

  see: https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html

- Continuous waves
  - Rapidly rotating deformed neutron stars
    - Known radio pulsars (using radio and X-ray observations to provide signal phase) and unknown sources
  - Targeted (supernova remnants, globular clusters, galactic centre, X-ray sources) and all-sky searches

- Compact binary coalescences
  - late stage neutron star or black hole binary inspirals, mergers and ring-downs

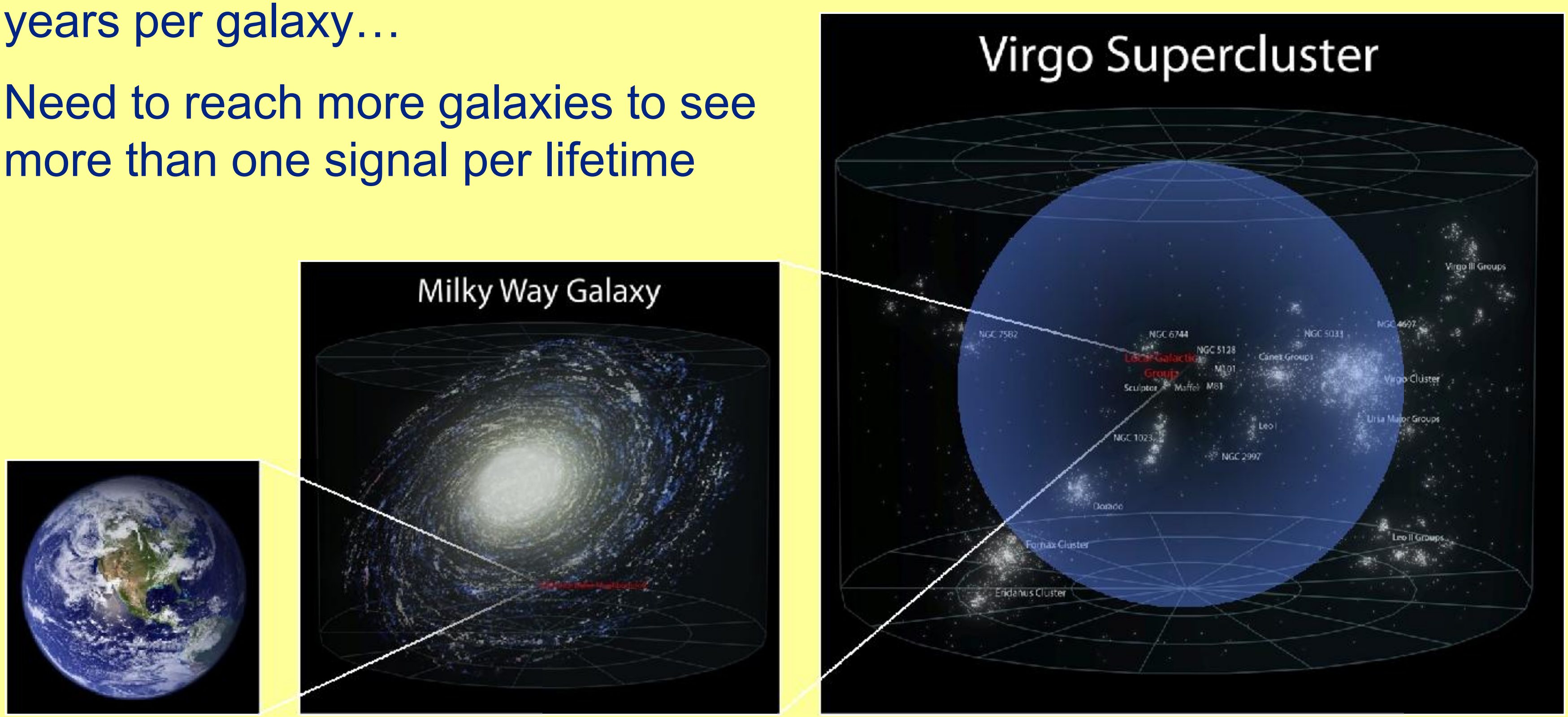
- **Transient ('burst') searches**
  - Coincident excess power from short duration transient sources
  - 'multi-messenger astronomy': Gamma Ray Bursts, X-ray transients, radio transients, supernova, neutrino observations

- Stochastic background
  - Cosmological i.e. from inflation
  - Combined background of astrophysical sources

No detections from those runs…
Why not?

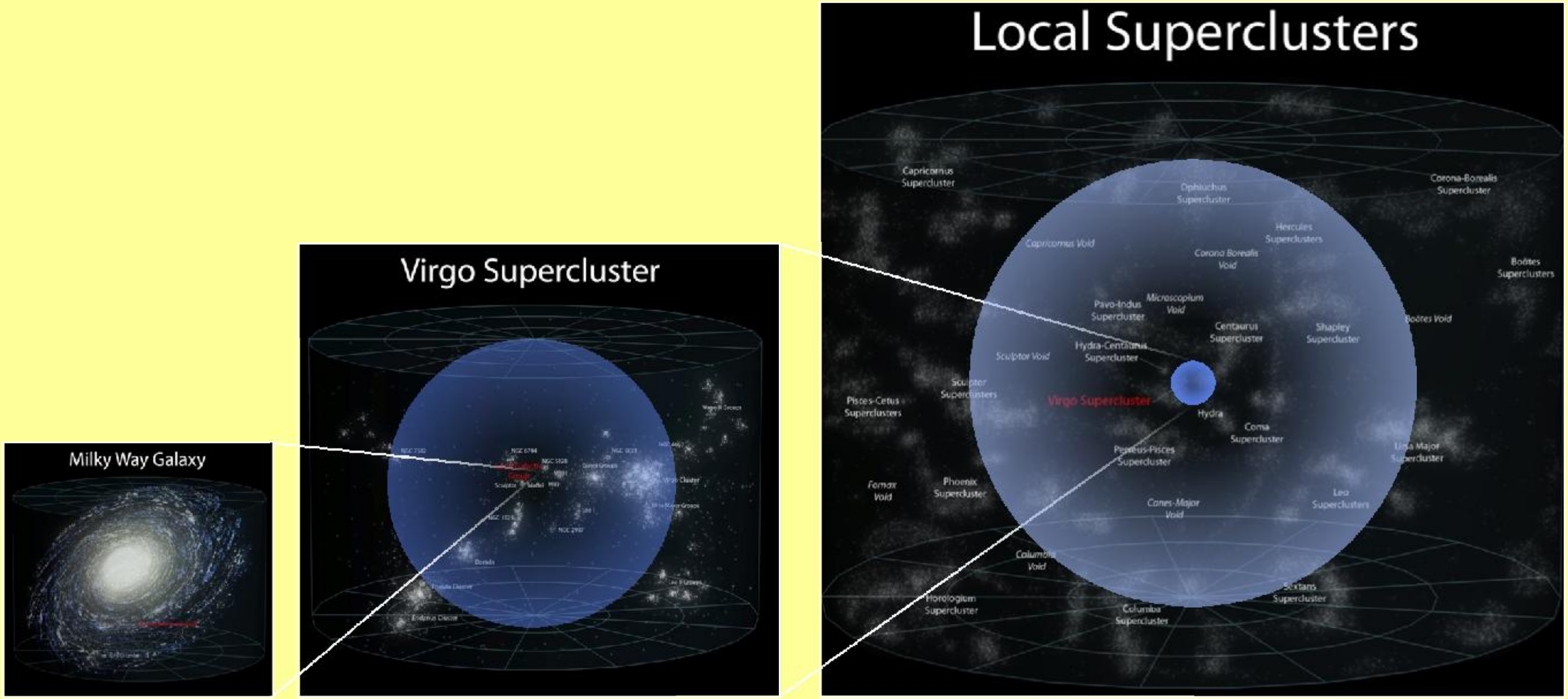
- First generation detectors reached about 100 galaxies
- Events happen once every 10,000 years per galaxy…
- Need to reach more galaxies to see more than one signal per lifetime

(considering mergers of pairs of neutron stars)



Advanced Sensitivity: 10x More Range makes a qualitative difference

- Advanced detectors will reach about 100,000 galaxies
- Events happen once every 10,000 years per galaxy…
- Order of 10’s per year



M. Evans Initial Range Advanced Range

Advanced GW detector era – the coming years (2015-2020)

Advanced GW detector sensitivity 2015-2020 : a significant difference

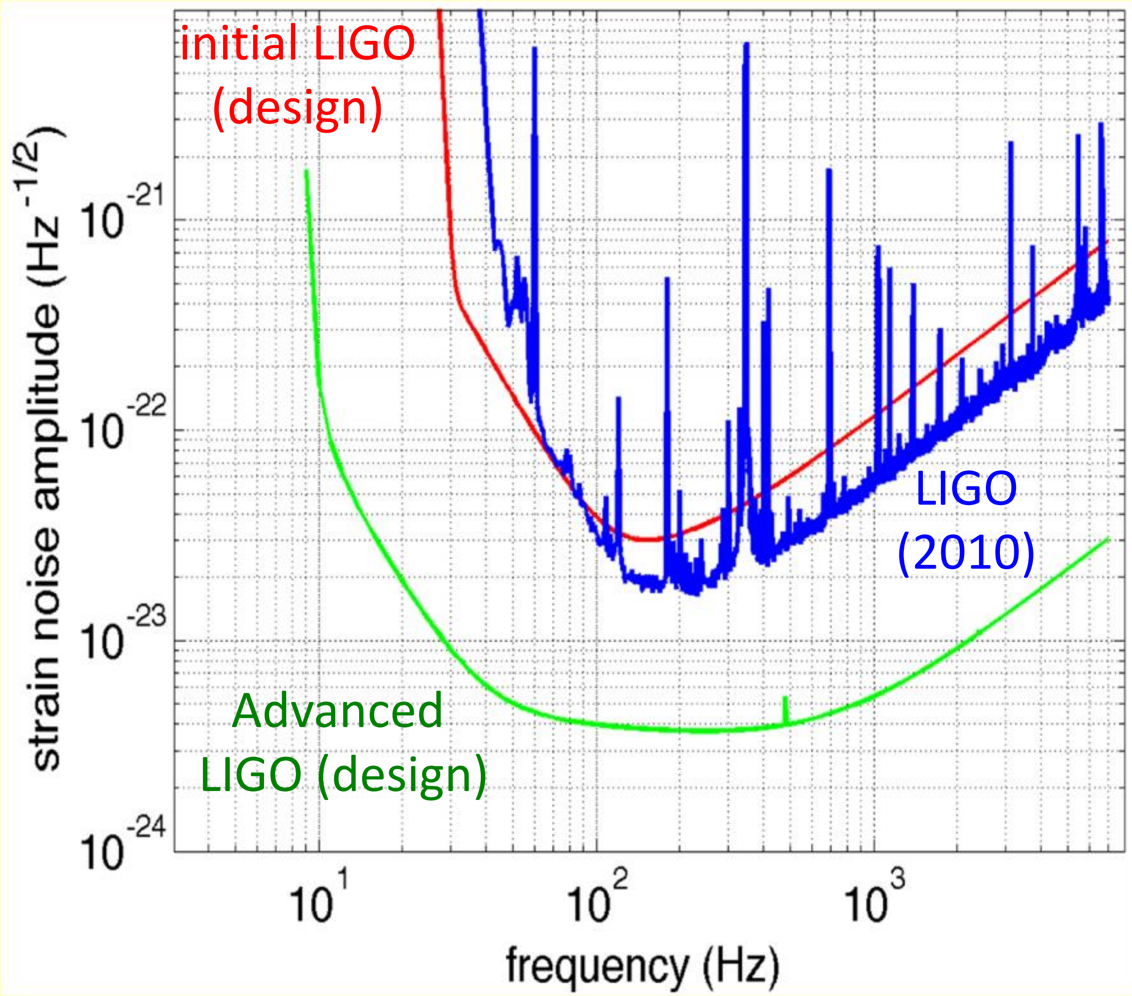
- While observing with initial detectors, parallel R&D led to better concepts

- ' Advanced detectors' are ~10x more sensitive, will reach about 100,000 galaxies

E.g.:

- Maximum sensitive ranges:
  - NS-NS: 450 Mpc
  - NS-BH: 930 Mpc

- Expected detection rates:
  - NS-NS: 0.4 - 400 yr^{-1}
  - NS-BH: 0.2 – 300 yr^{-1}



Abadie et al., arXiv:1003.2480

Hardware upgrades to form aLIGO, aVirgo
(...with Geo-HF and KAGRA to form Advanced detector network)

Timescales Advanced LIGO

- Design began 1999 as a LIGO Scientific Collaboration concept paper
- (Capital contributions via hardware by UK (2003), Germany, Australia)
- **Advanced LIGO Project officially began on April 1, 2008**

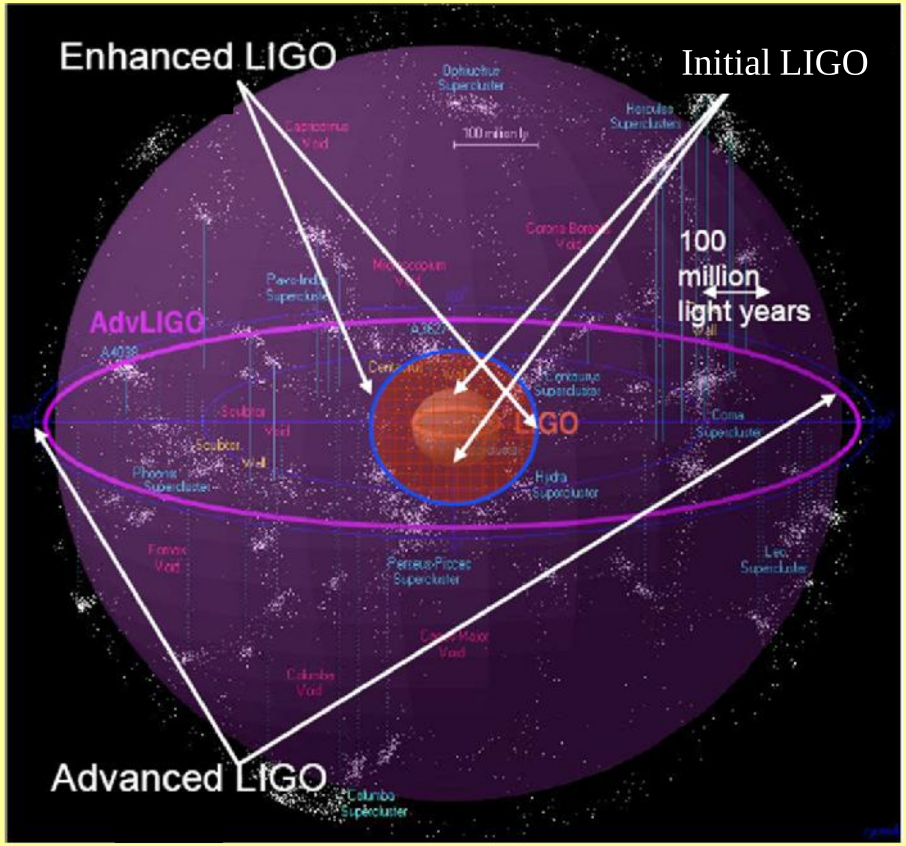
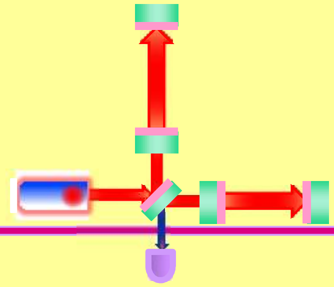
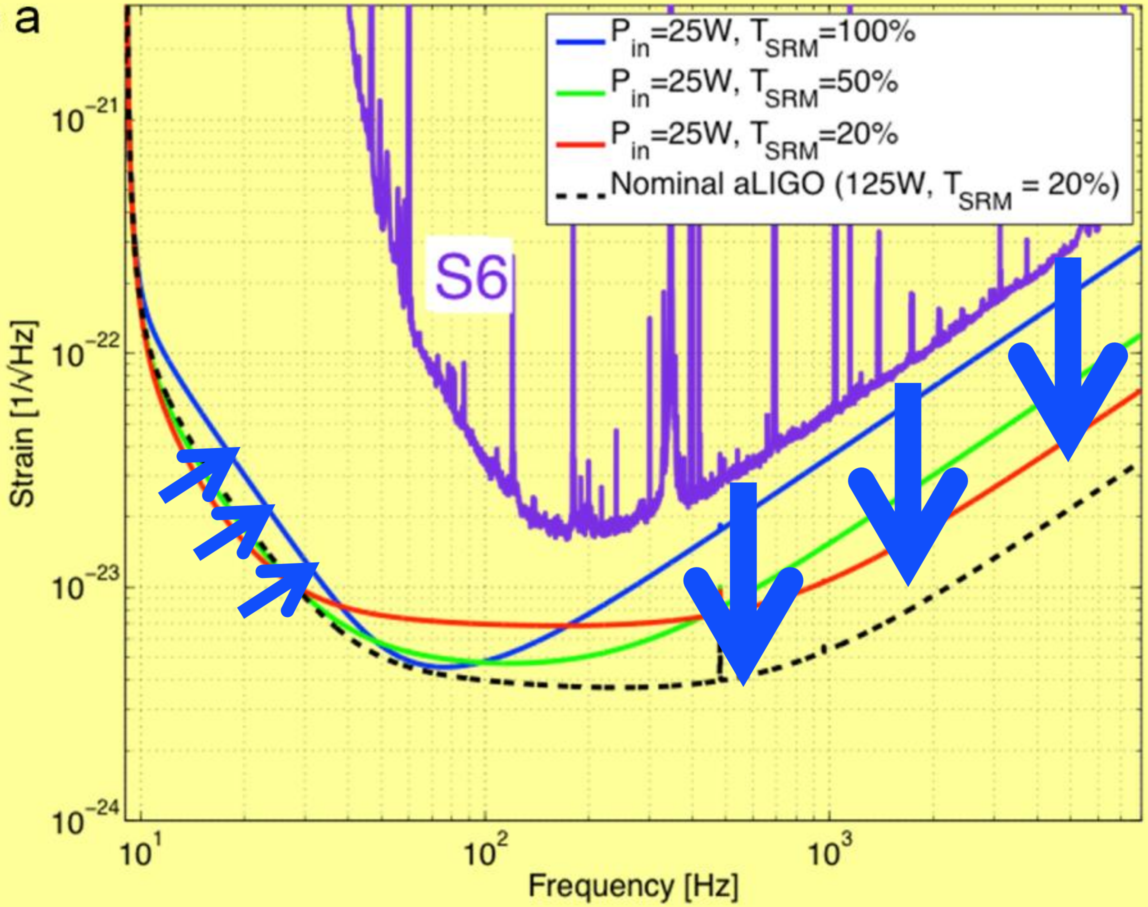


Image courtesy of Beverly Berger
Cluster map by Richard Powell

How to get there: Addressing limits to performance

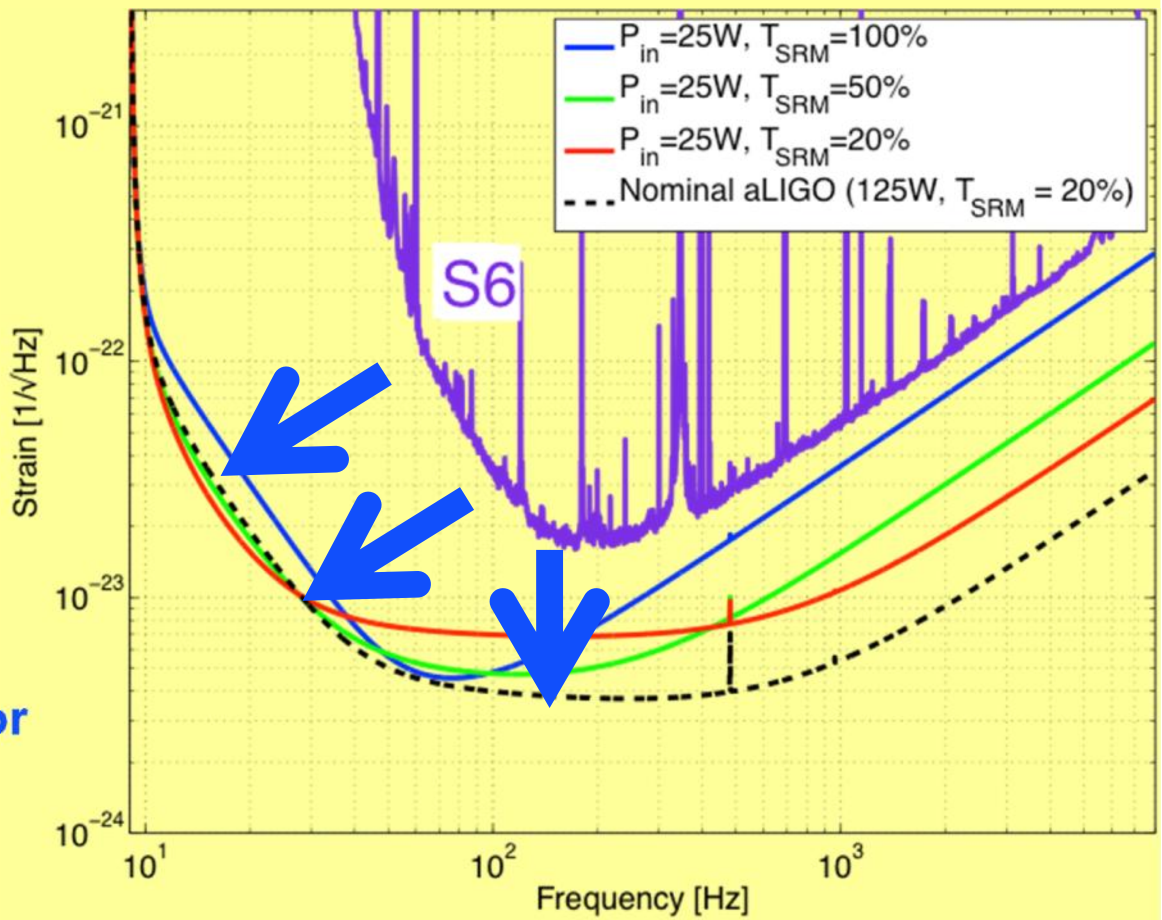


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- Fringe Resolution at high frequencies improves as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses
- 'Standard Quantum Limit'
- Advanced LIGO reaches this limit with its **200W laser, 40 kg test masses**



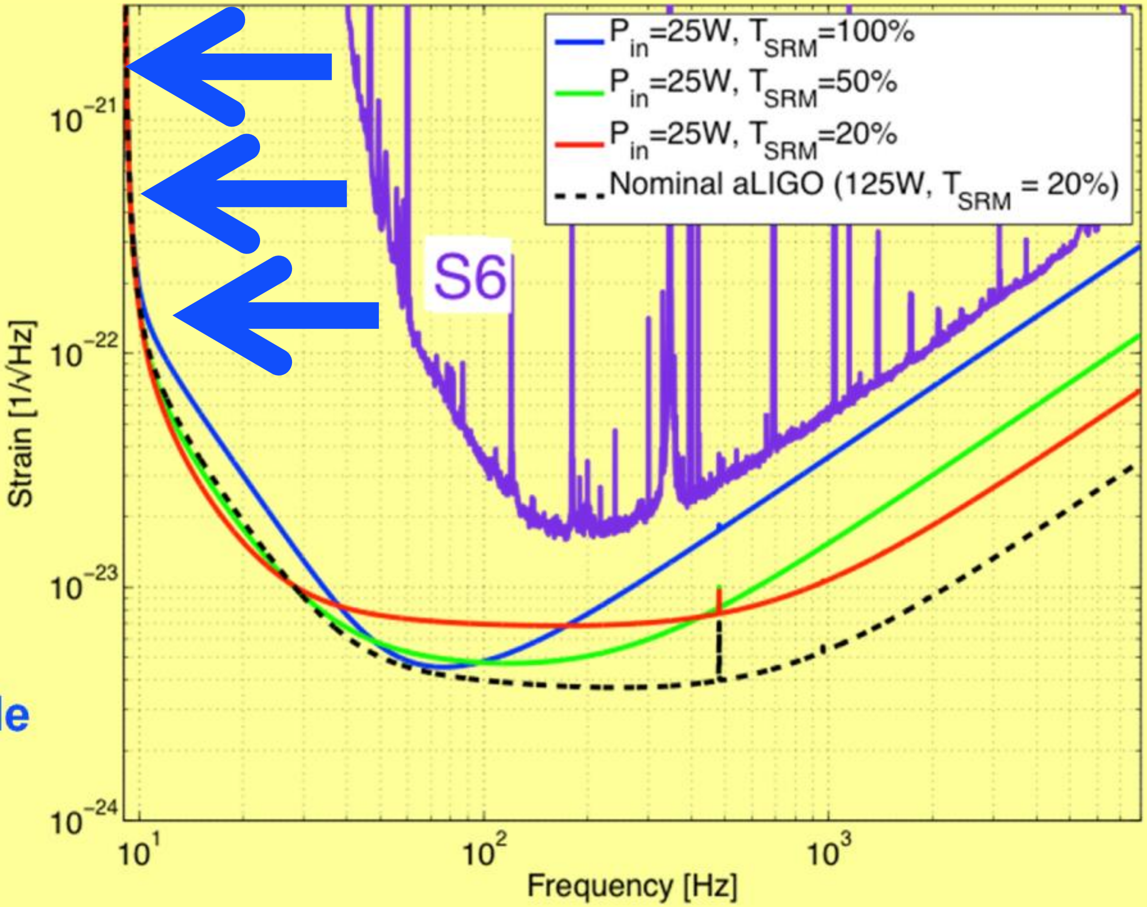
Addressing limits to performance

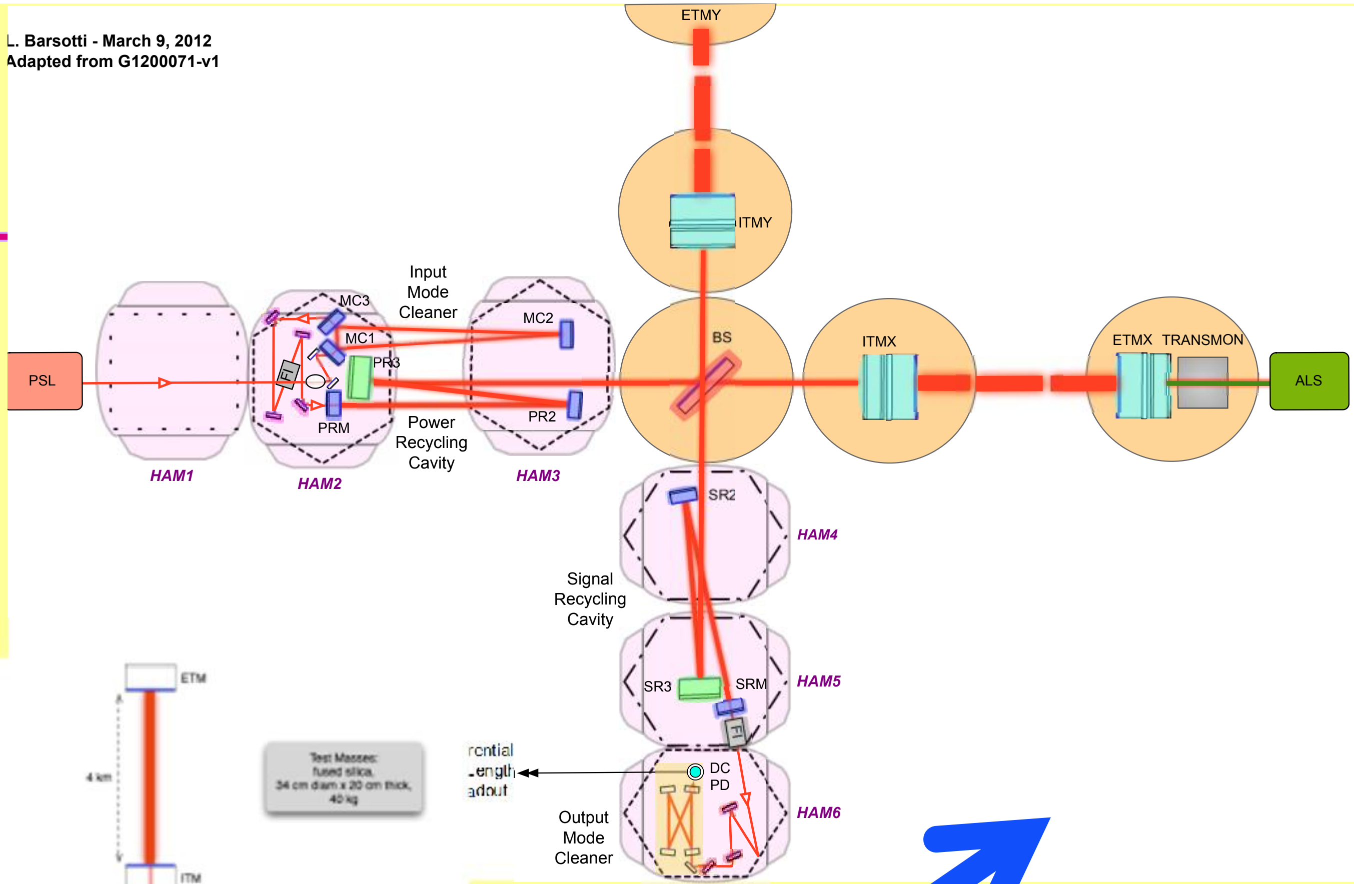
- **Thermal noise** – kT of energy per mechanical mode
- Wish to keep the motion of components due to thermal energy below the level which masks GW
- Low mechanical loss materials
- Realized in aLIGO with an all **fused-silica test mass suspension**
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**

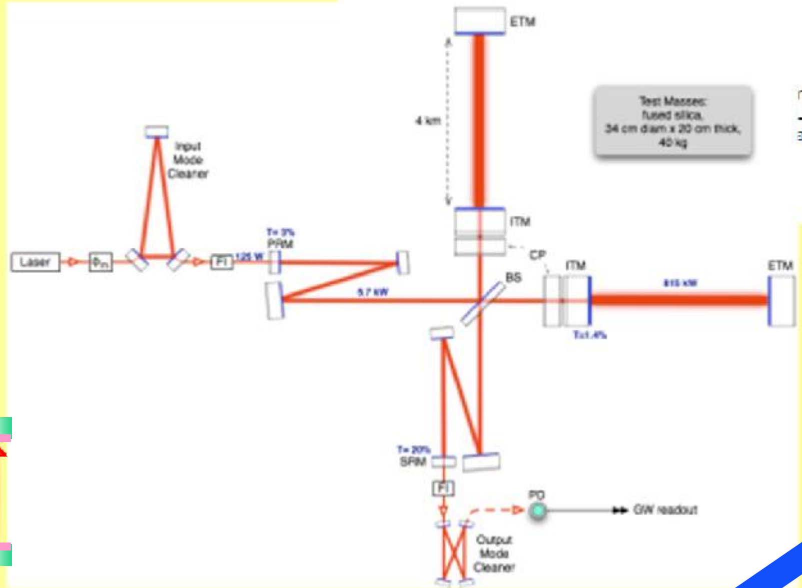


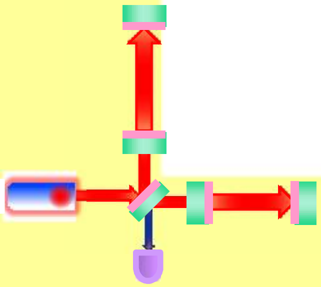
Addressing limits to performance

- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Motion from waves on coasts…and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- Limit on the ground: Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band









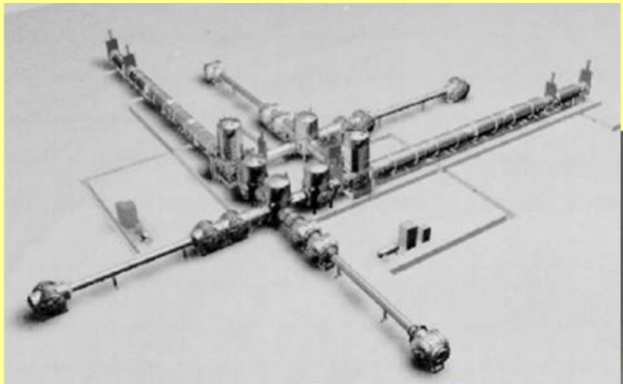
Reality axis

The real instrument is far more complex…

Existing infrastructure : 4km Beam Tubes

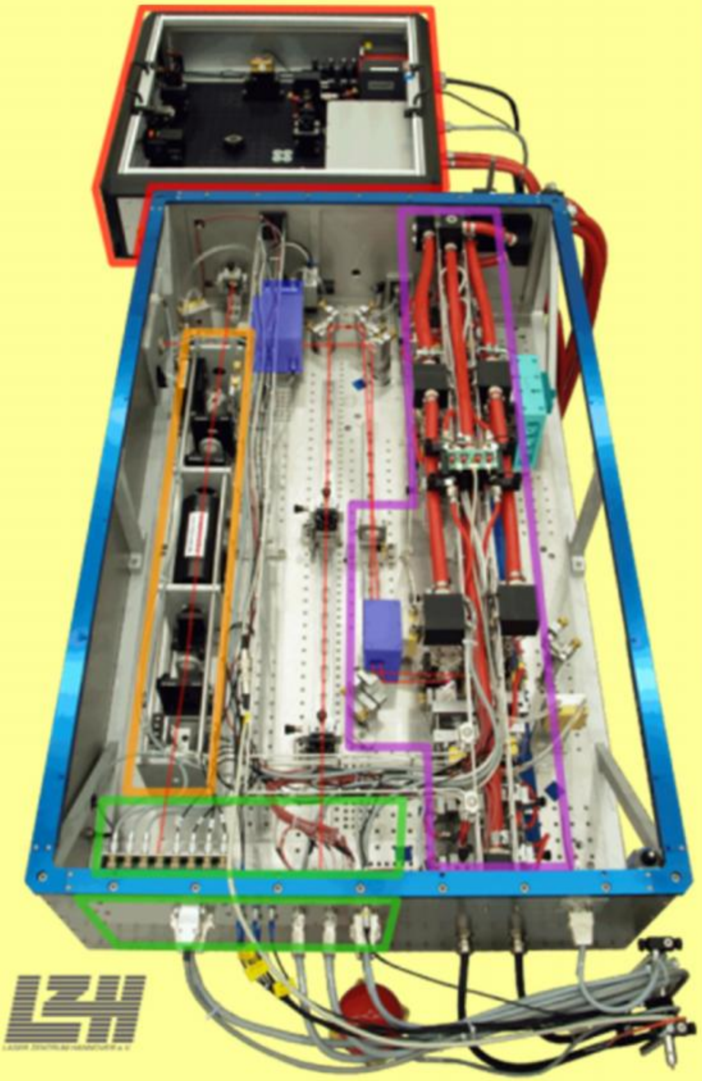
- Light must travel in an excellent vacuum
  - Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs
  - 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters’ bullets and the stray car
- Tube is straight to a fraction of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

LIGO Vacuum Equipment – designed for several generations of instruments



200W Nd:YAG laser

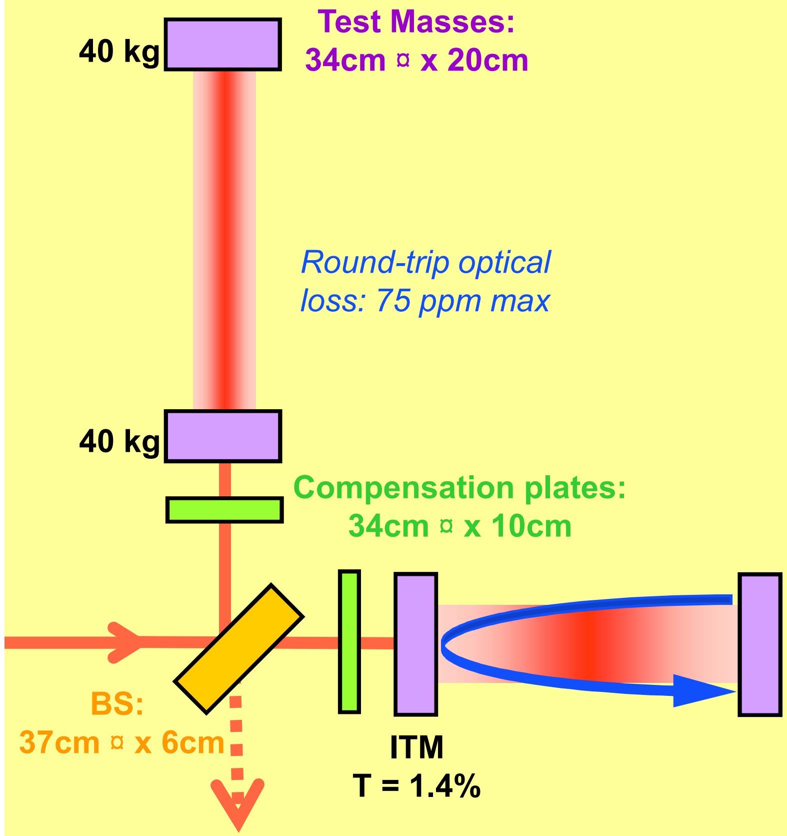
Designed and contributed by
Max Planck Albert Einstein Institute

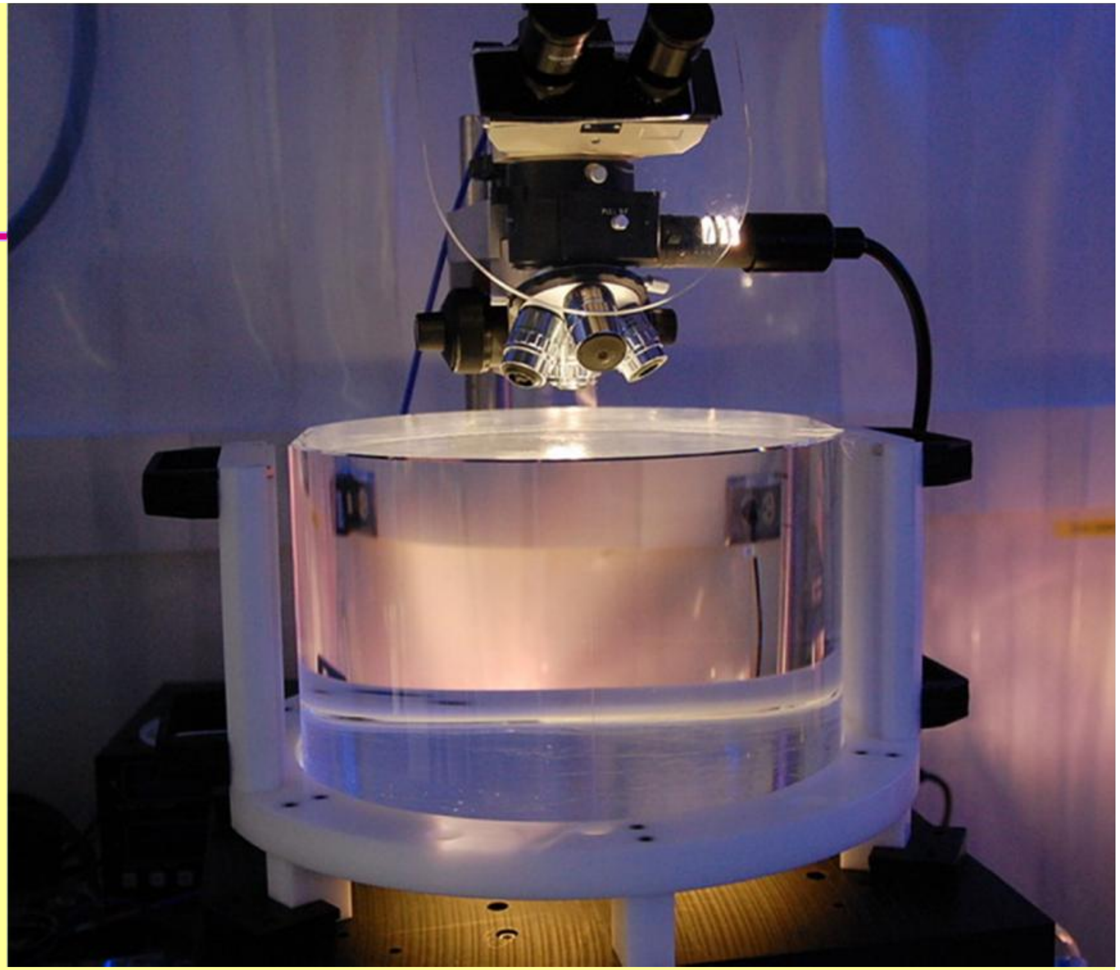


- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

Test Masses

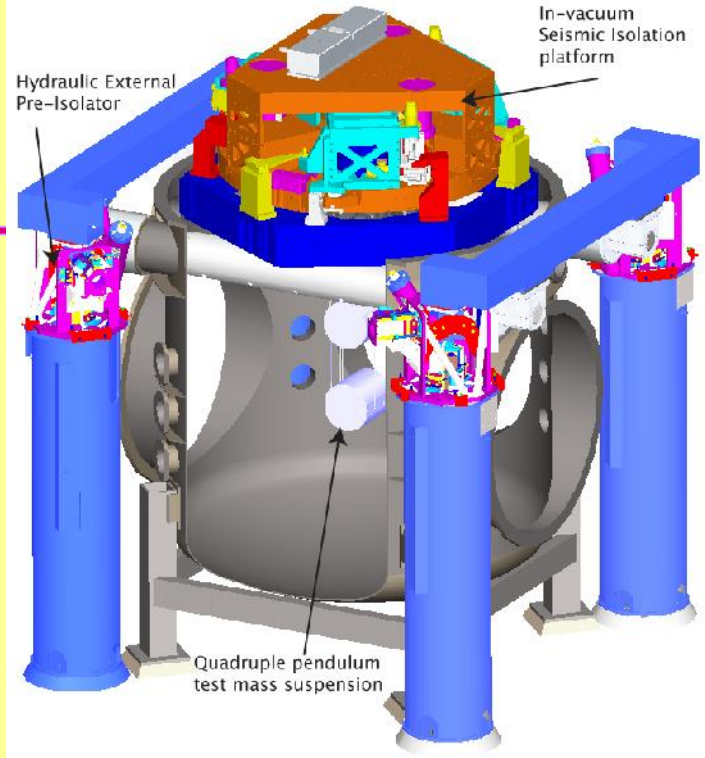
- Requires the state of the art in substrates and polishing
- Pushes the art for coating
- Sum-nm flatness over 300mm



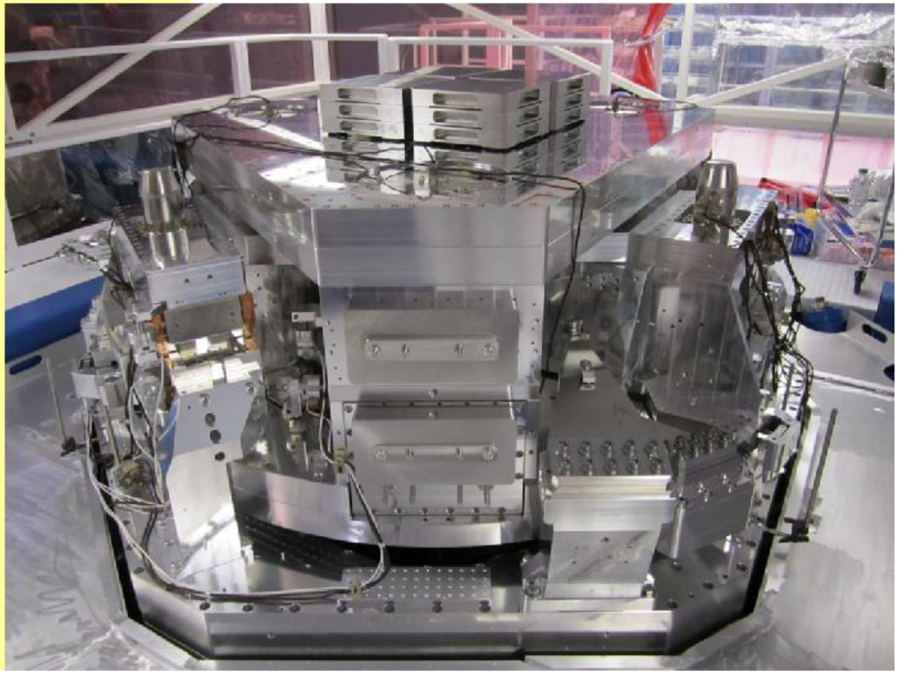


- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Seismic Isolation: Multi-Stage Solution



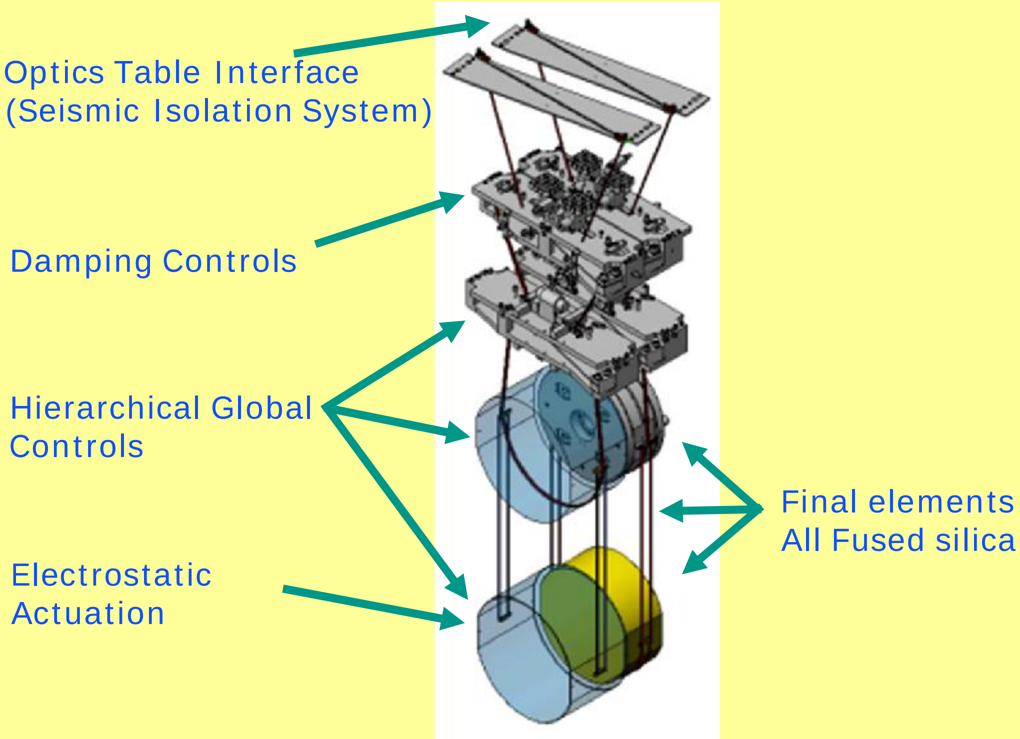
- Objectives:
  - Render seismic noise a negligible limitation to GW searches
  - Reduce actuation forces on test masses
- Both suspension and seismic isolation systems contribute to attenuation
- Choose an active isolation approach, 3 stages of 6 degrees-of-freedom :
  - 1) Hydraulic External Pre-Isolation
  - 2) Two Active Stages of Internal Seismic 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



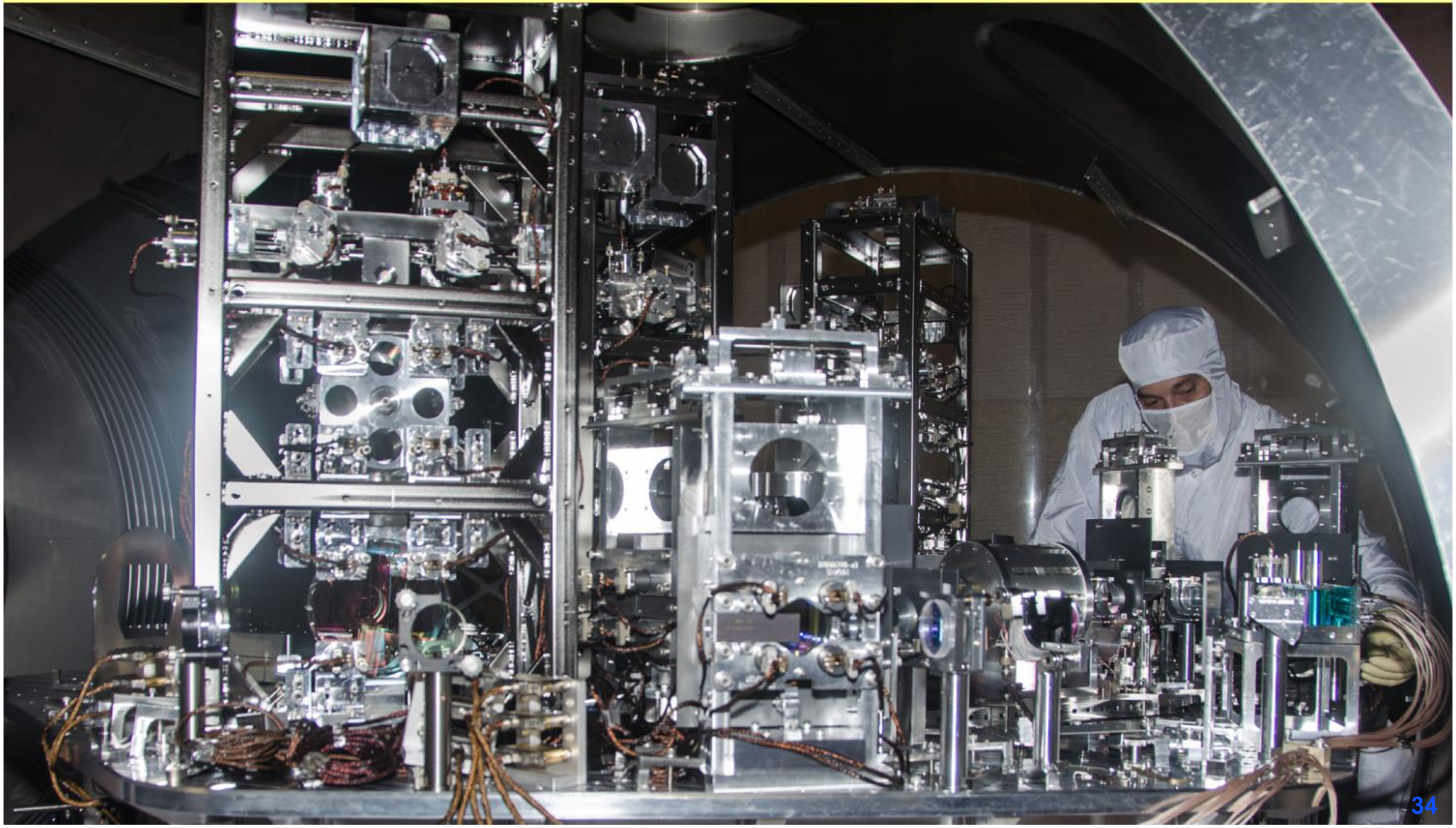
Test Mass Quadruple Pendulum suspension

designed jointly by the UK and LIGO lab,

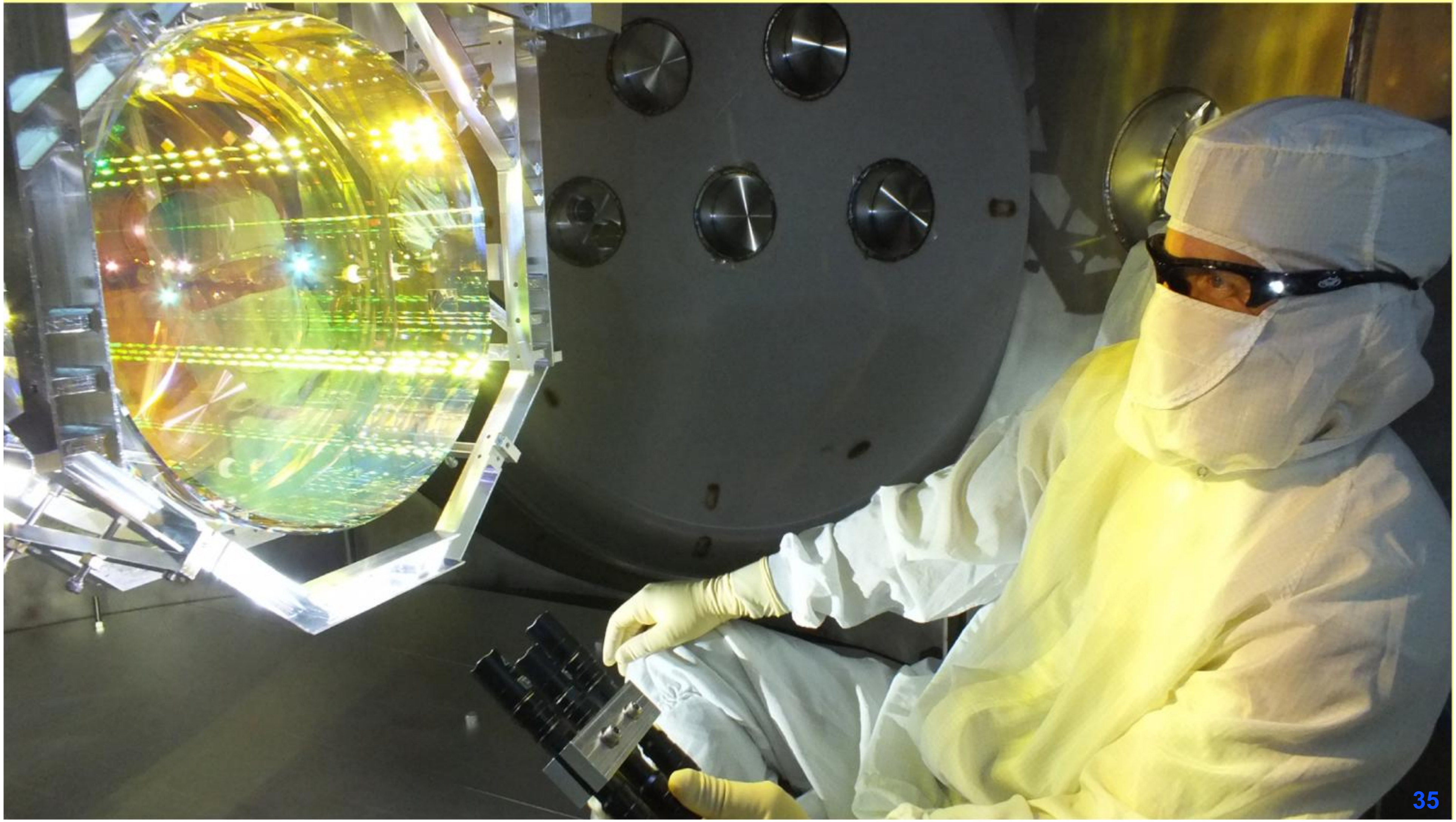
- Quadruple pendulum suspensions for the main optics; second ‘reaction’ mass to give quiet point from which to push
- Create quasi-monolithic pendulums using fused silica fibers to suspend 40 kg test mass
  - » Very low thermal noise



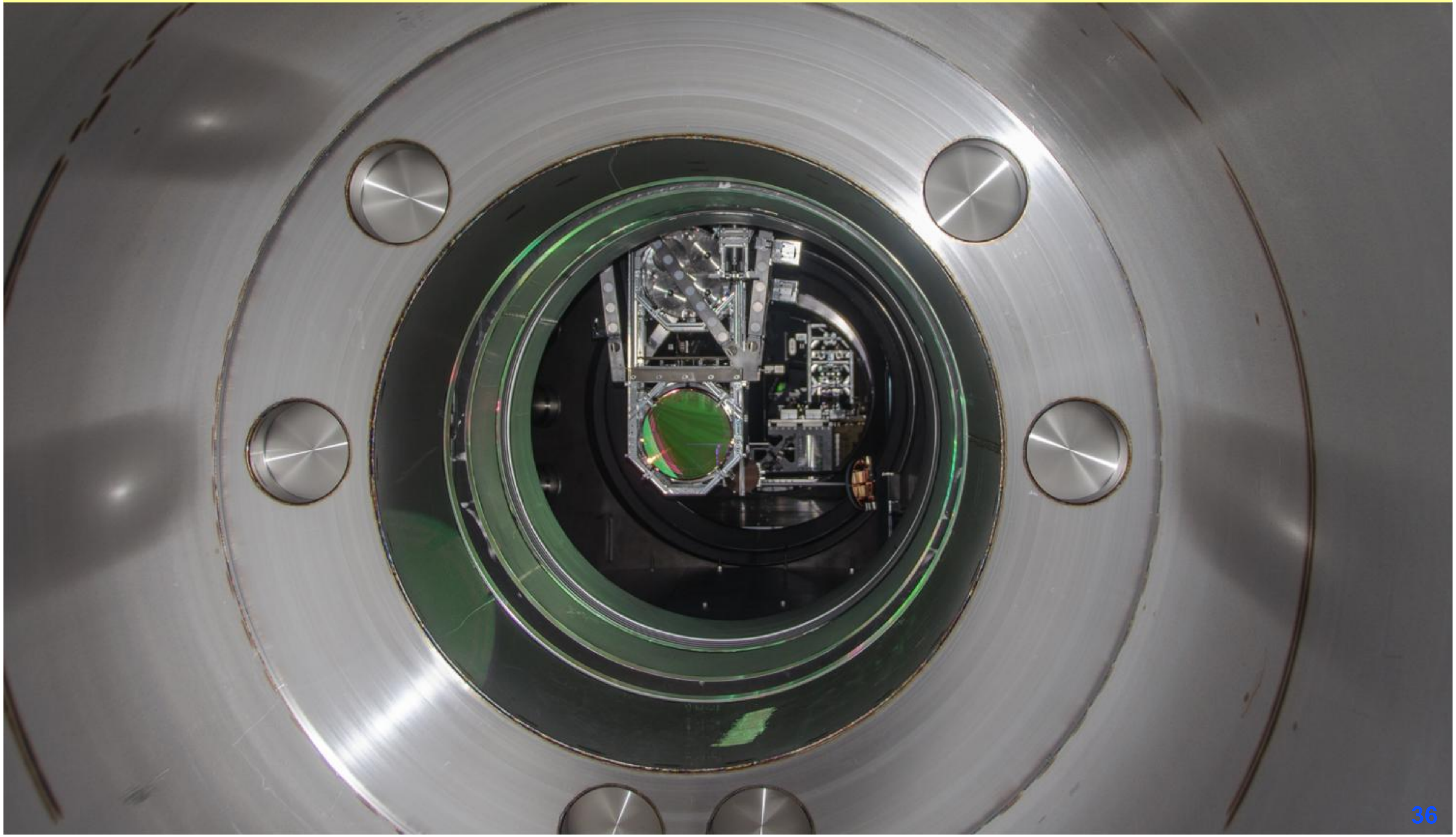
A few family photos:
Livingston site (mode cleaner, recycling optics)



Inspecting an Input Tess Mass surface

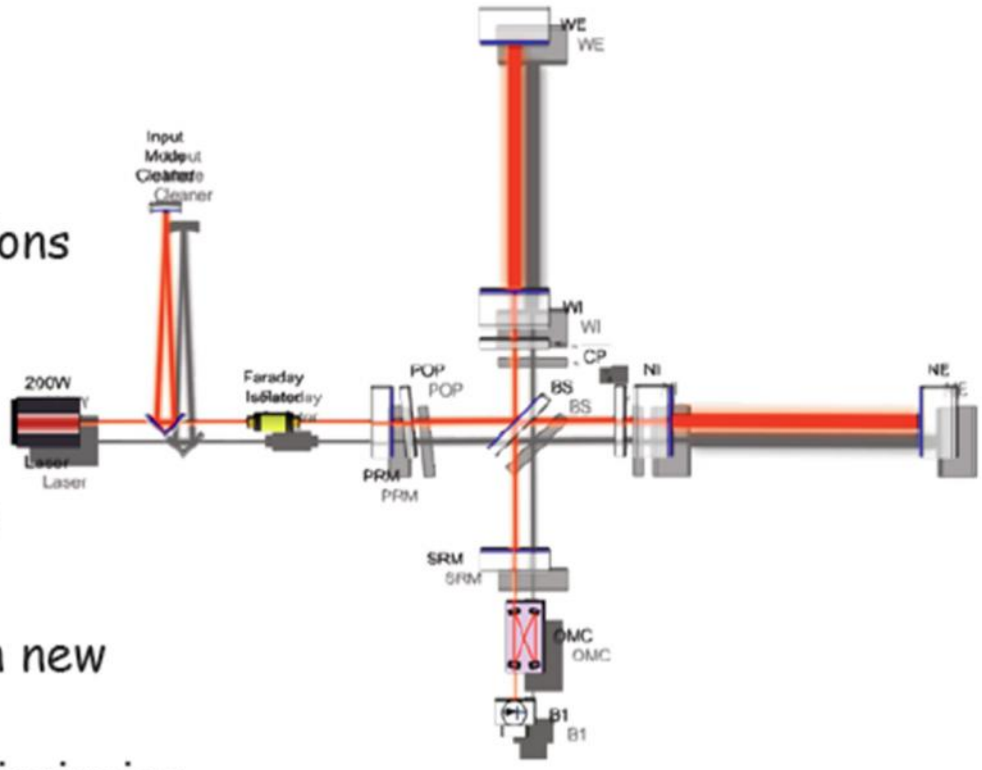


Input Test Mass viewed from the Beam Tube side



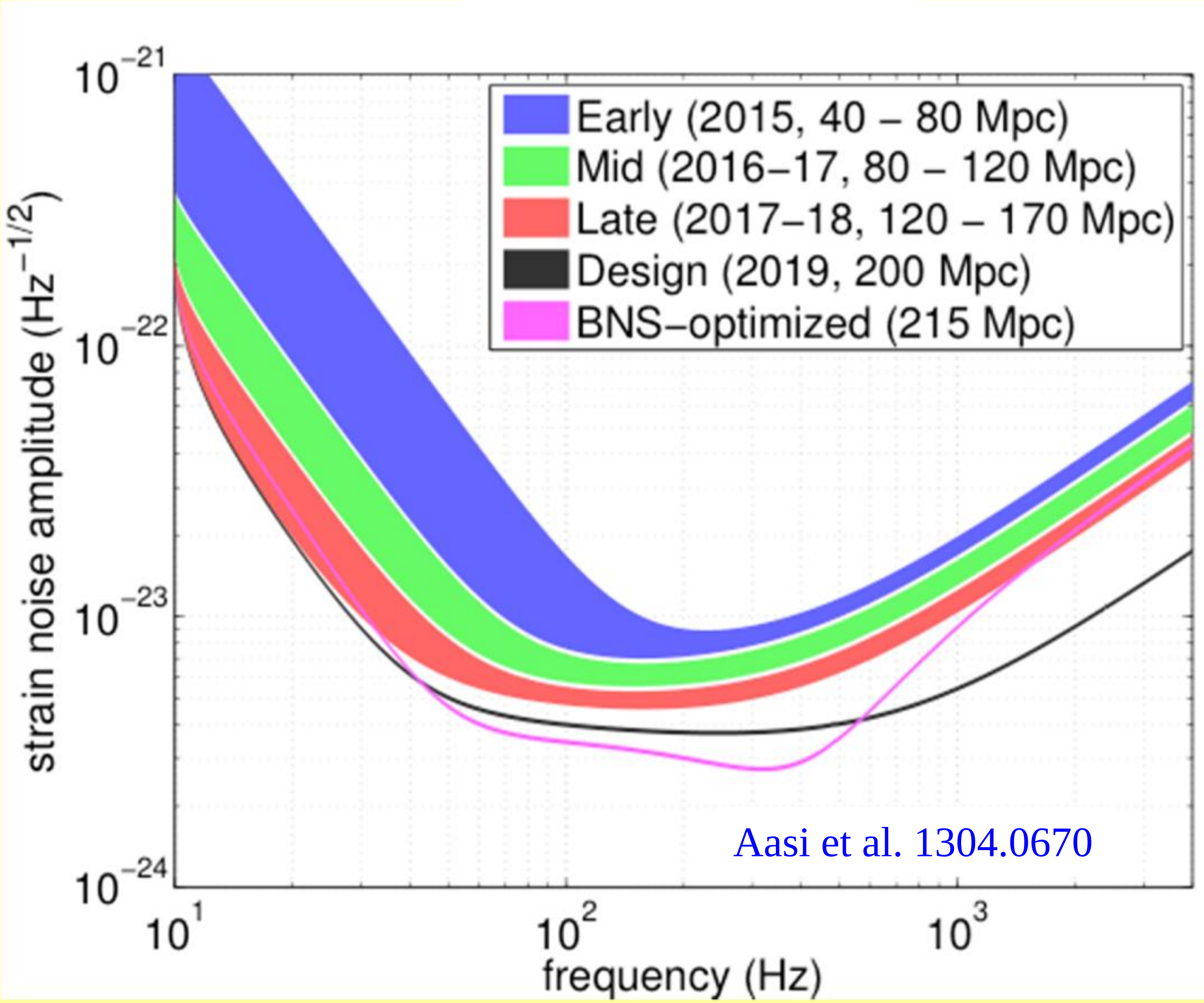
In parallel – Advanced Virgo

- Main changes with respect to VIRGO:
  - larger beam
  - heavier mirrors
  - higher quality optics
  - thermal control of aberrations
  - 200W fiber laser
  - Signal Recycling



- Vibration isolation by VIRGO Superattenuators:
  - performance compliant with new requirements
  - wide experience with commissioning at low frequency

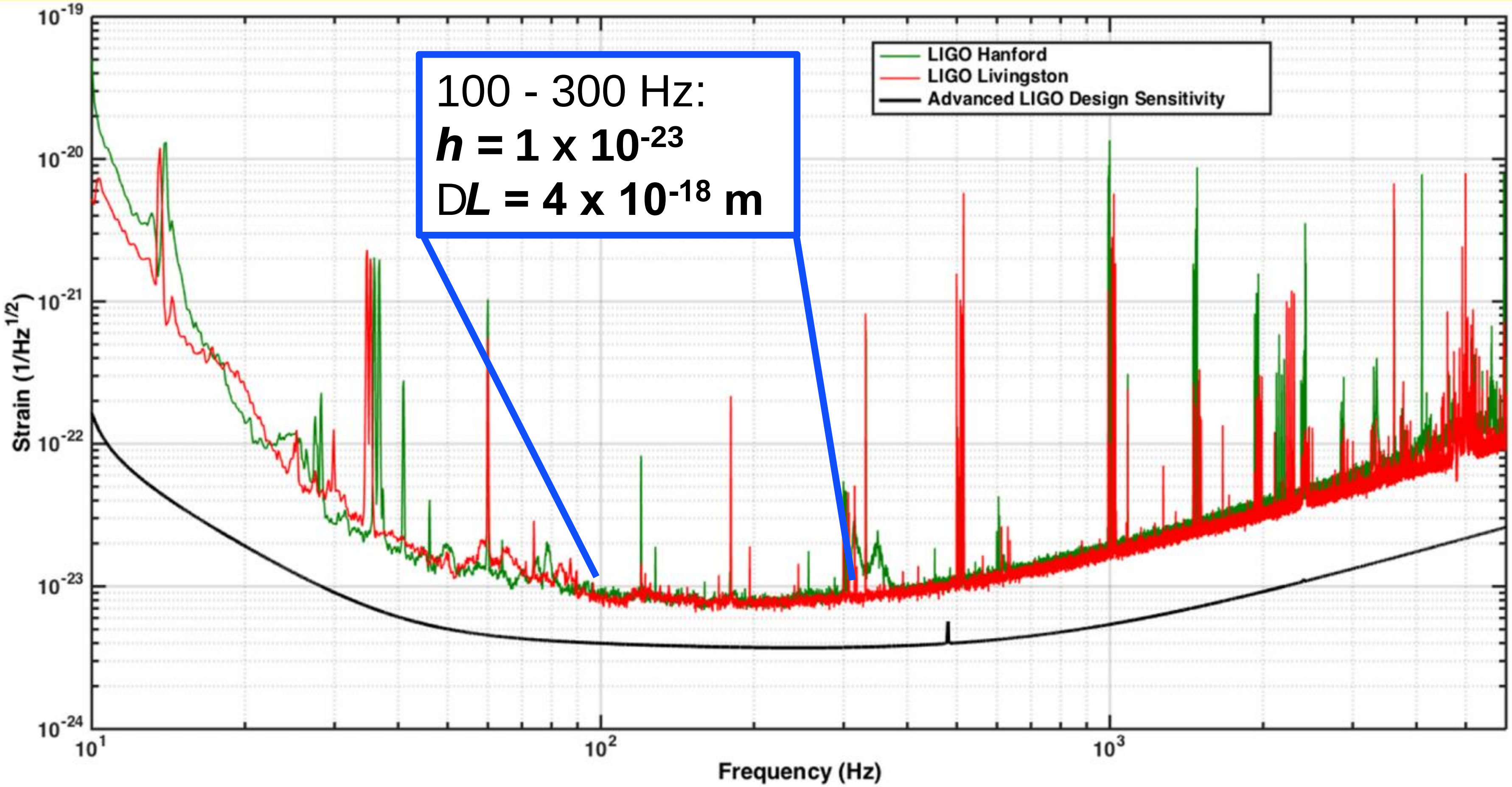
Advanced LIGO Evolution



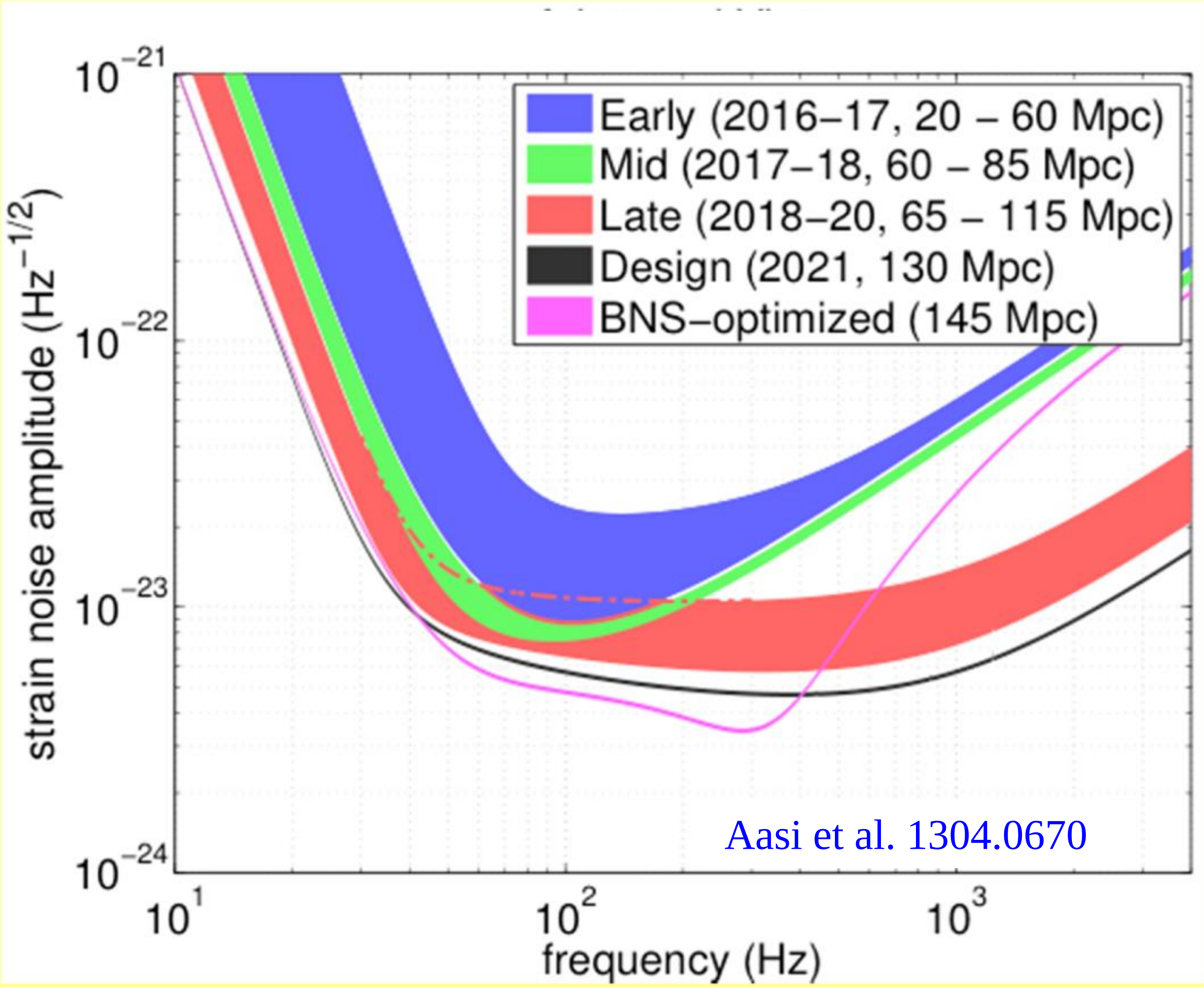
Aasi et al. 1304.0670

Current Advanced LIGO Sensitivity: Observing Run 1

Advanced LIGO Observing Run 1 Began in September 2015



Advanced Virgo Evolution



We are entering a very exciting time

- The baseline Advanced gravitational wave detectors are expected to accomplish the first direct detection of gravitational waves.

Projected ranges and detection rates for binary neutron star inspirals

Epoch	Estimated Run Duration	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections	% BNS Localized within $5\ \mathrm{deg}^2$	% BNS Localized within $20\ \mathrm{deg}^2$
2015	3 months	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	200	130	0.4 – 400	17	48

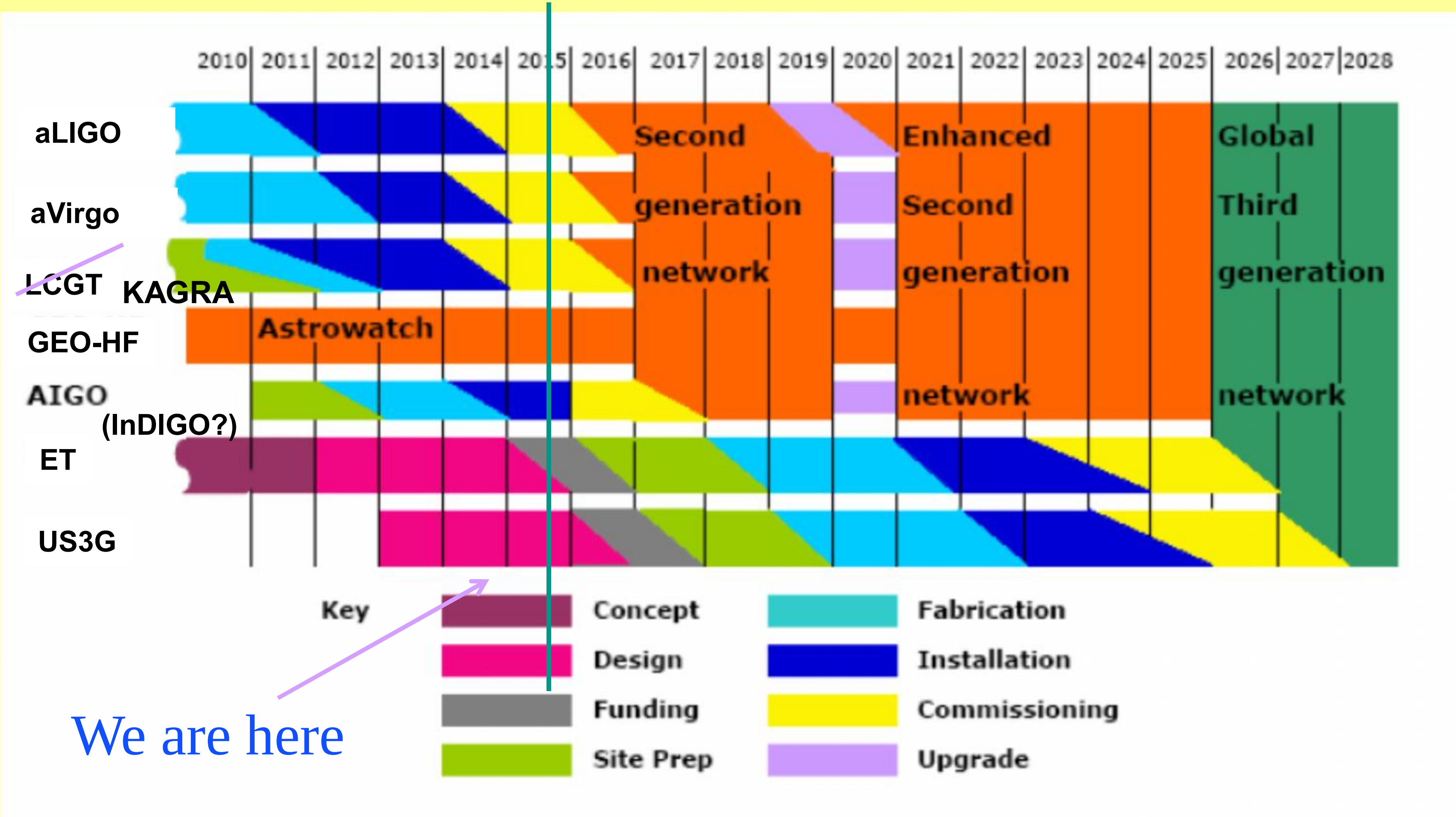
using "low" rate, worst noise curve

using "high" rate, best noise curve

At design sensitivity, advanced detectors have most probable detection rates of order tens per year

The global Gravitational Waves roadmap

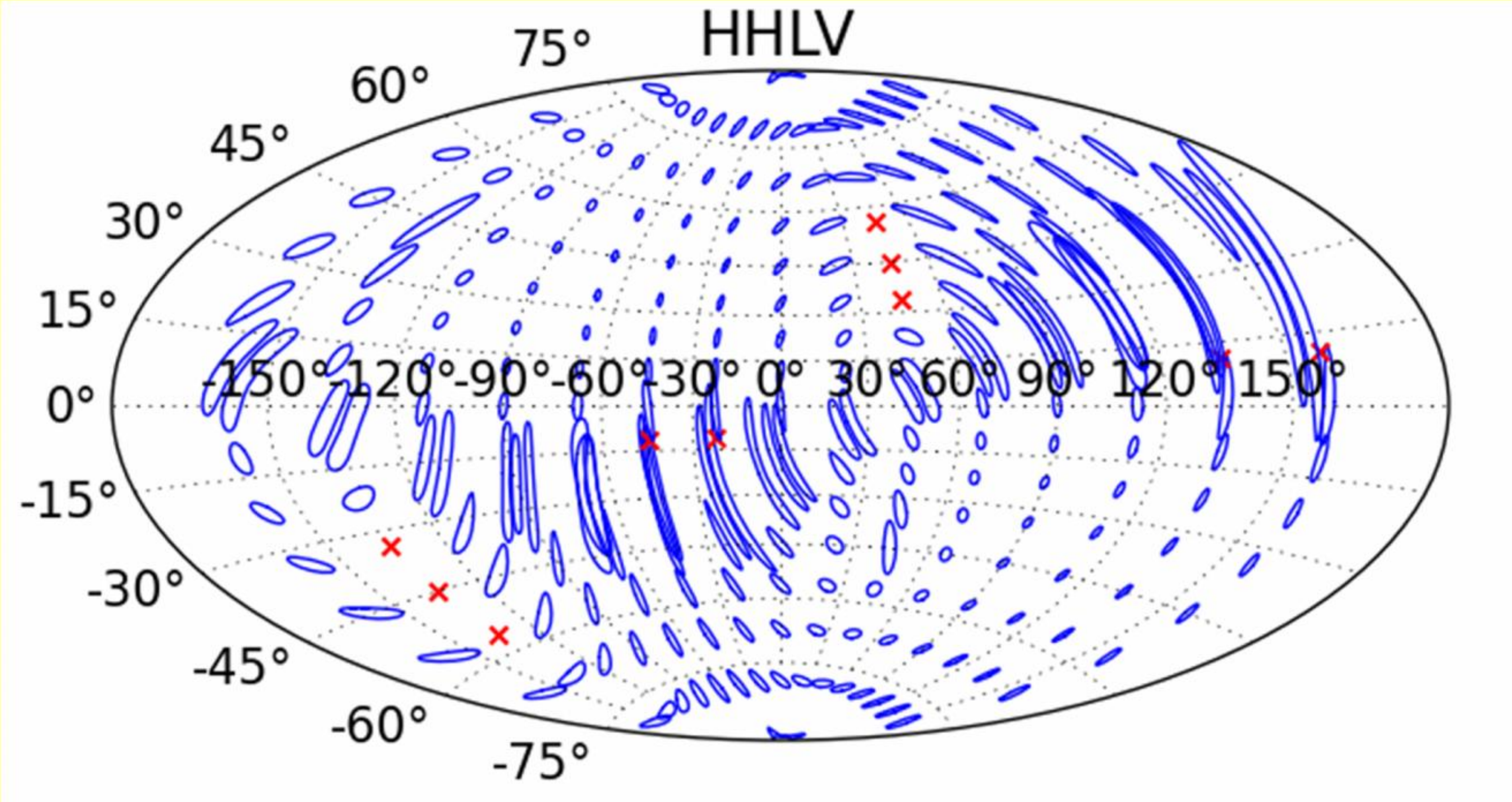
GWIC
Gravitational Wave International Committee



From the Gravitational Wave International Committee (GWIC roadmap - available at: http://gwic.ligo.org/roadmap/)

LIGO-G1301277

Sky localization with 3 sites …

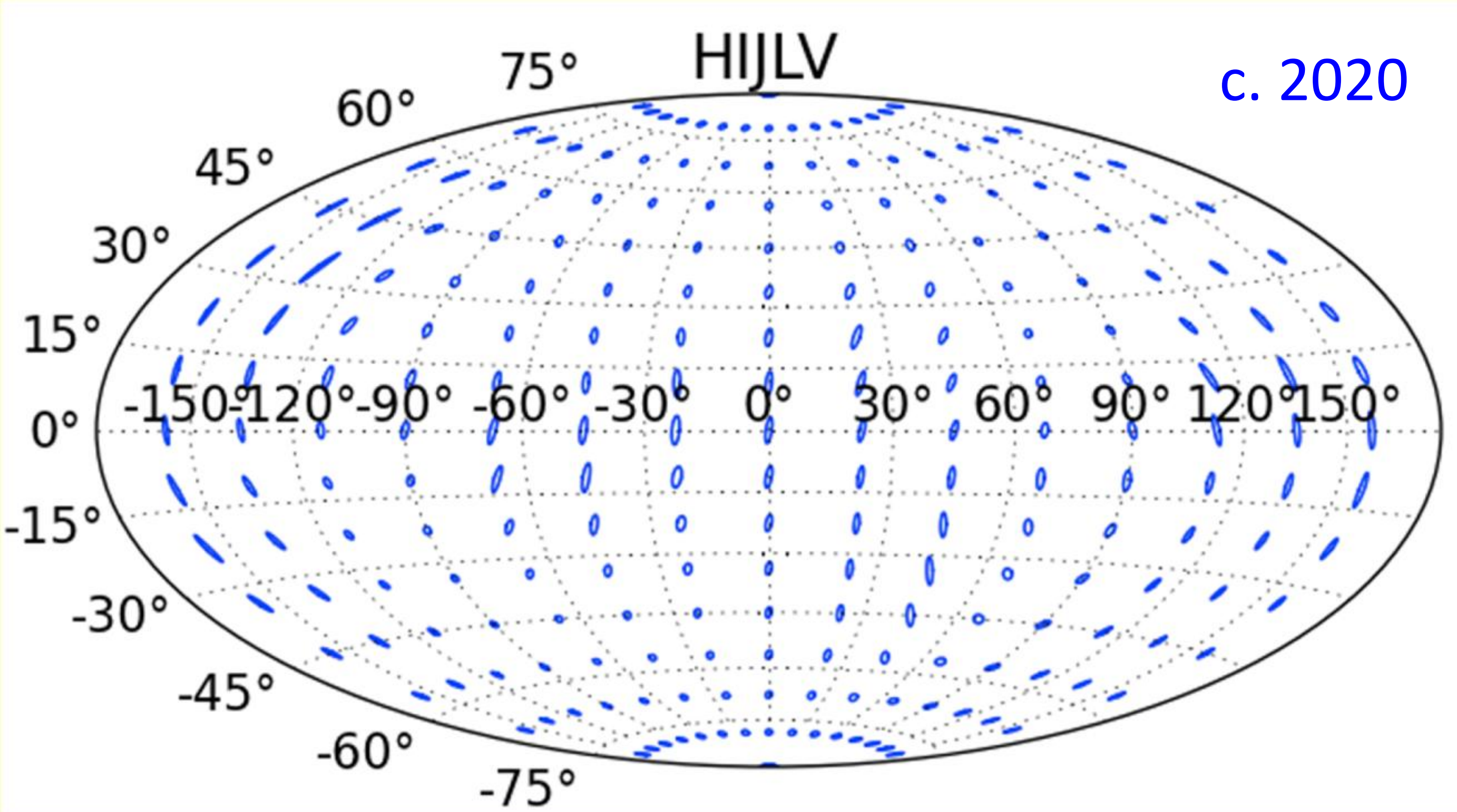


Typical 90% error box areas for NS-NS binaries

» median > 20 sq deg

Fairhurst, CQG 28 105021 (2011)

… and with 5 sites



Fairhurst (2011)

The global Gravitational Waves roadmap

GWIC
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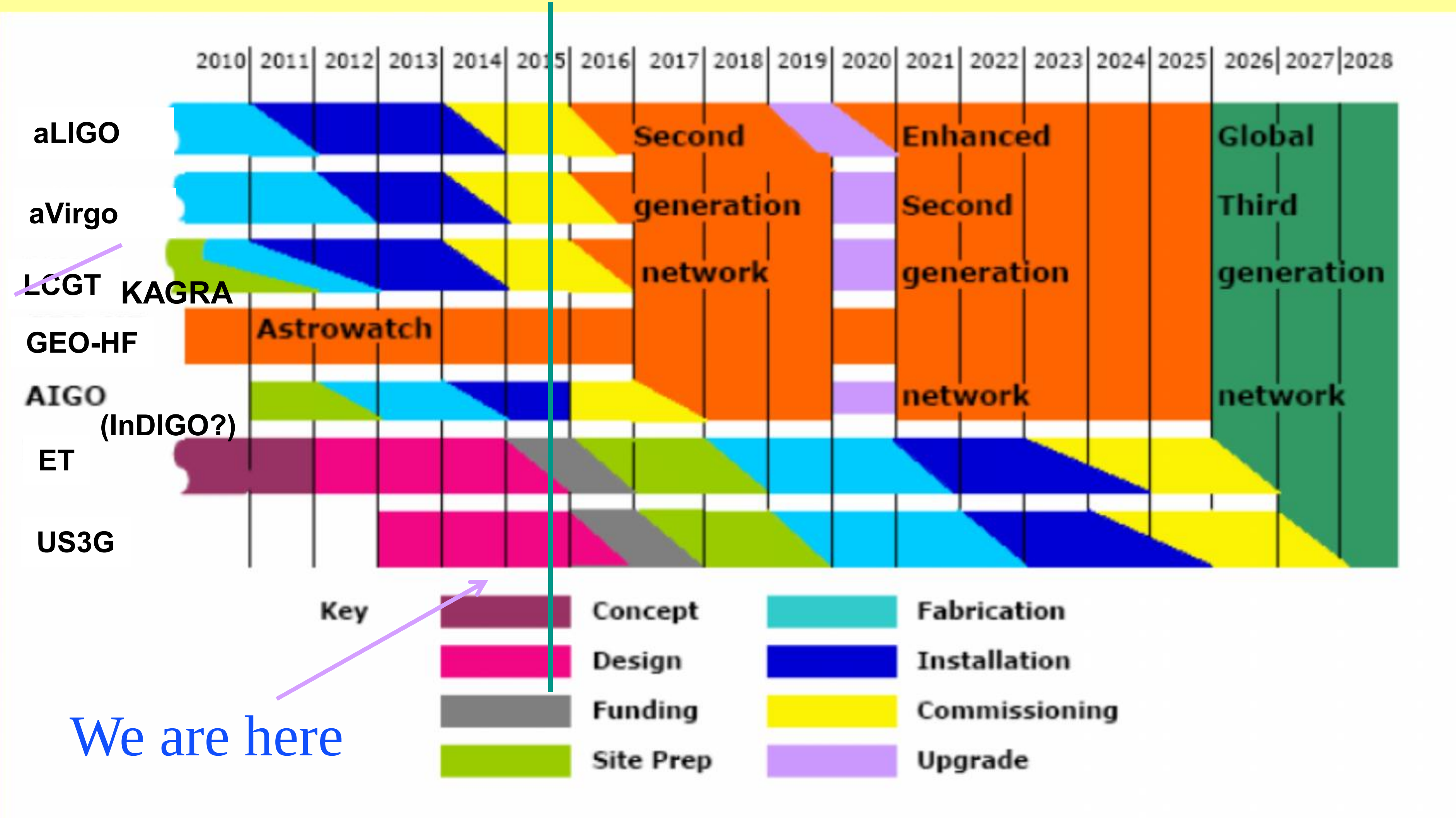

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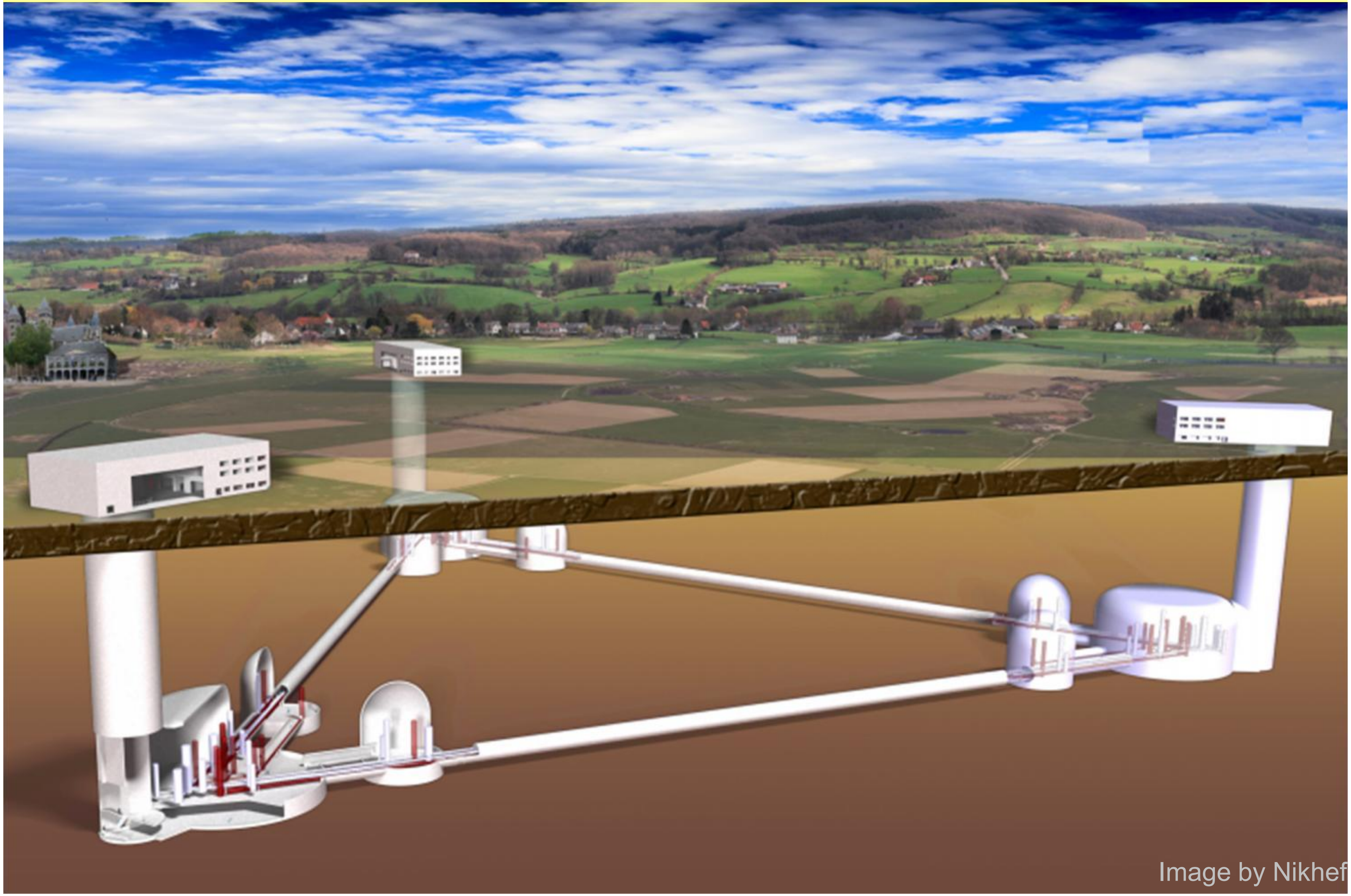
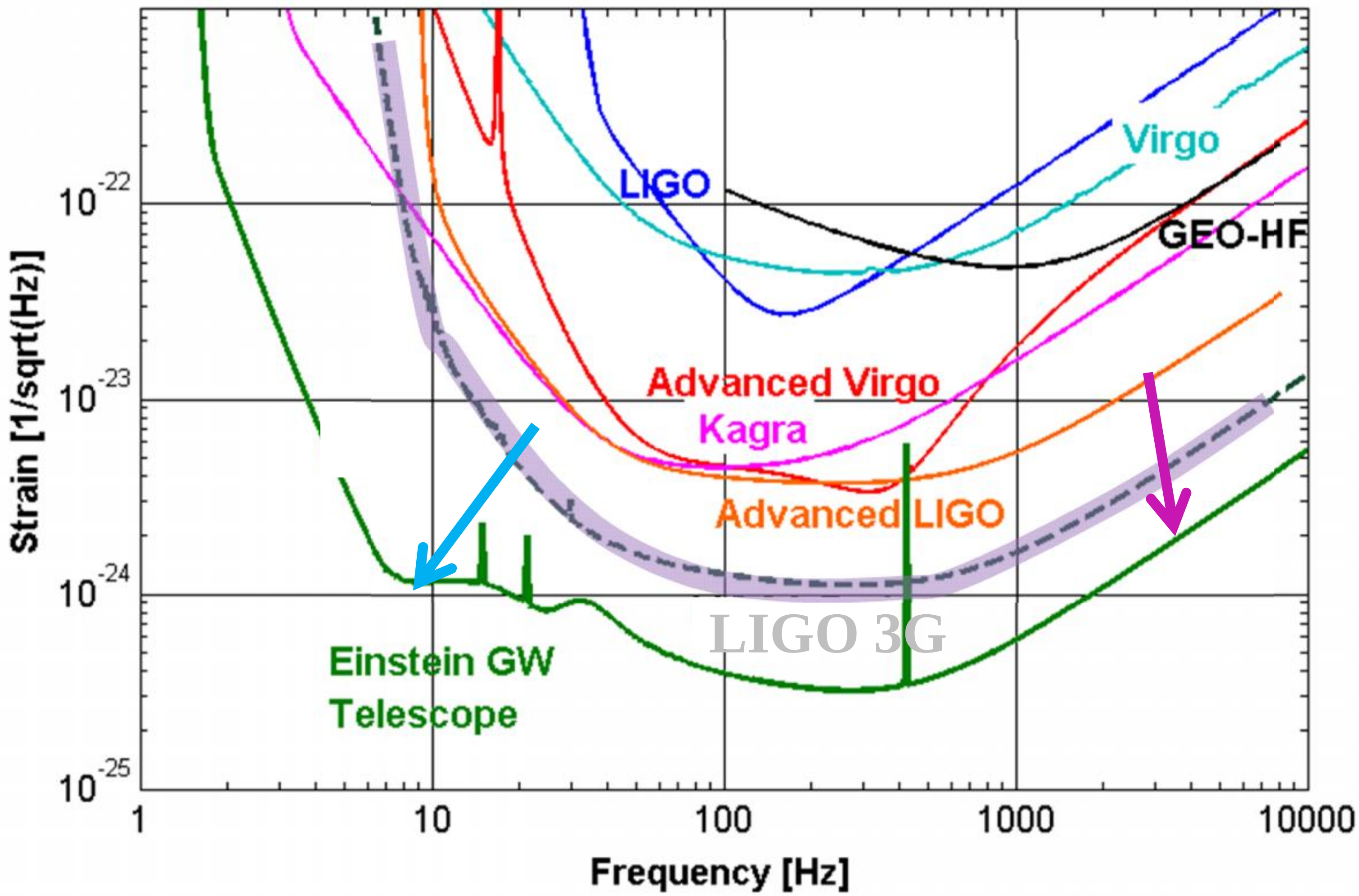
Einstein Telescope



1st, 2nd 2+, and 3rd generation

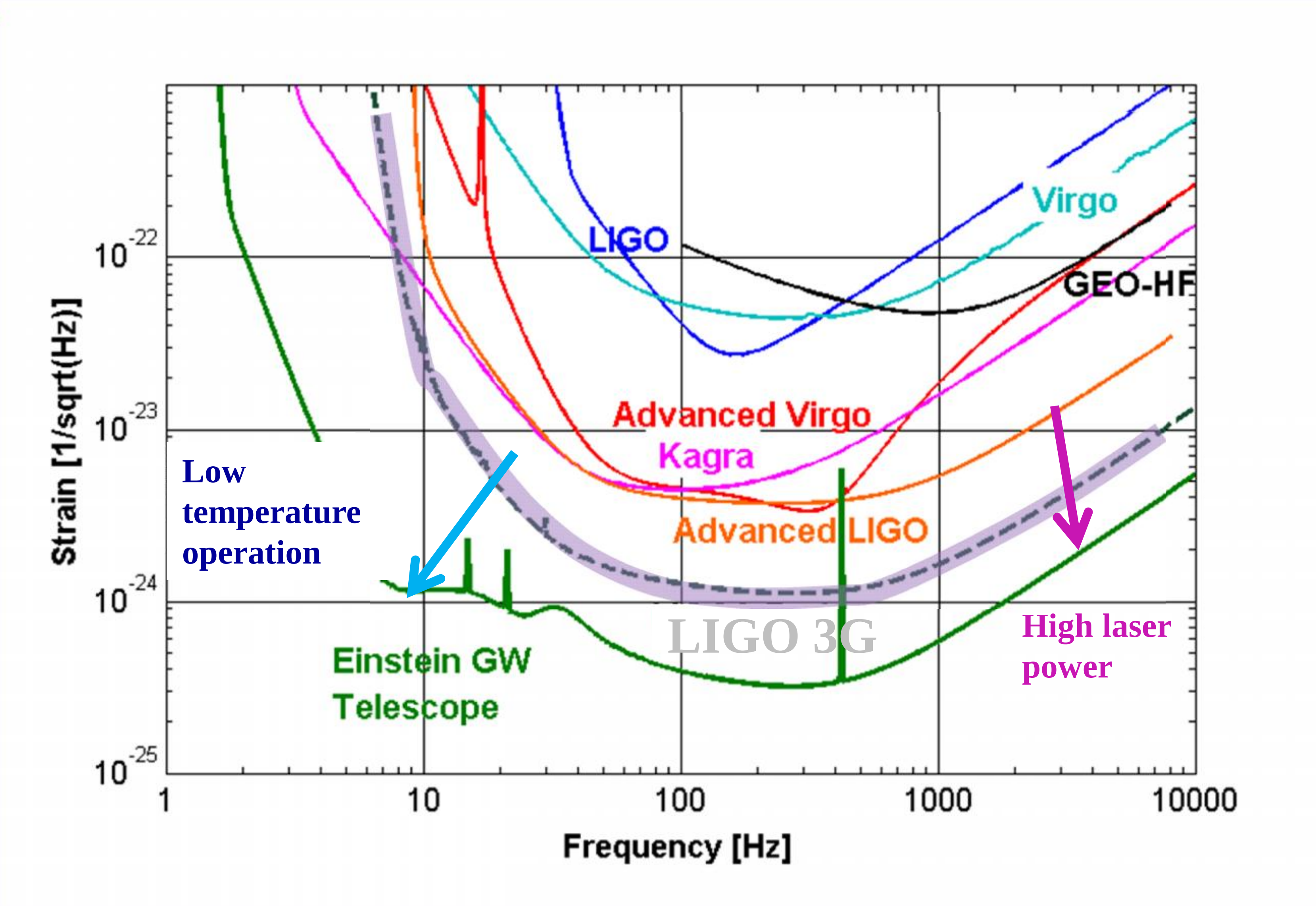


Einstein Telescope – conception and design

- Conceptual Design Study for a future Gravitational Wave interferometer in Europe supported by the European Commission under the Framework Programme 7(2008-11)

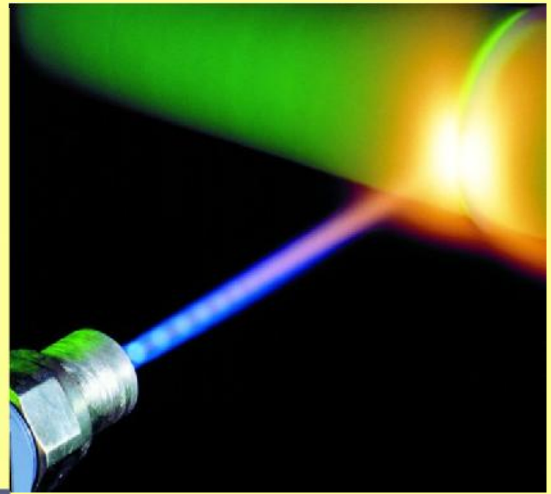
- Proposed by 8 European research institutes involved in experimental gravitational wave research.
  - European Gravitational Observatory
  - Istituto Nazionale di Fisica Nucleare (Italy)
  - Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V., acting through Max- Planck-Institut für Gravitationsphysik (Germany)
  - Centre National de la Recherche Scientifique (France)
  - University of Birmingham (UK)
  - University of Glasgow (UK)
  - NIKHEF (Netherlands)
  - Cardiff University (UK)

1st, 2nd 2+, and 3rd generation



CONFLICT OF INTERESTS

www.miami.com



jgindo.wordpress.com

Need Cryogenics for low**Thermal Noise:** 10K

http://s658.photobucket.com

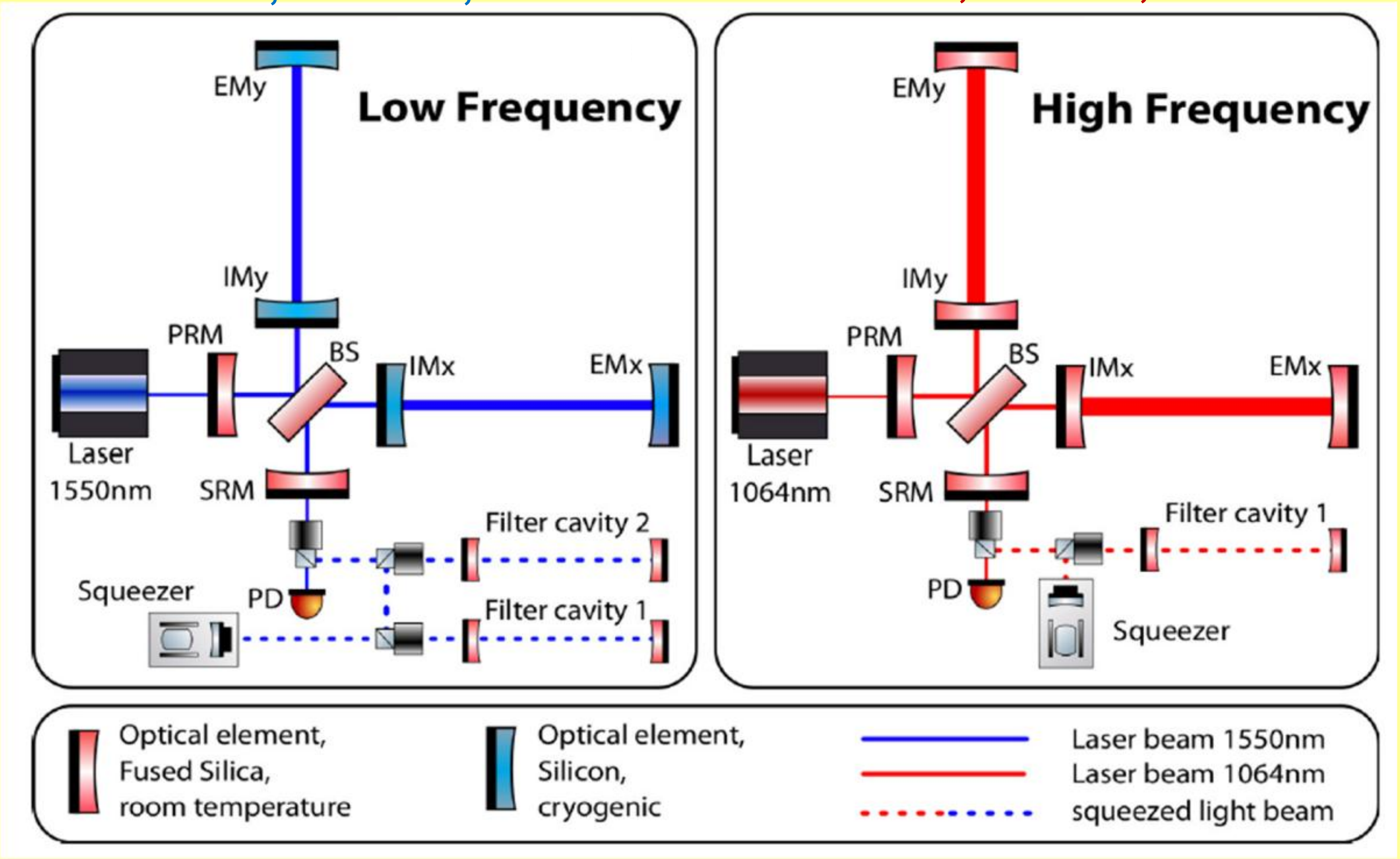
High Power for low **Shot Noise:** 3MW

ET „Xylophone“ Strategy

Split detector into two interferometers optimised for

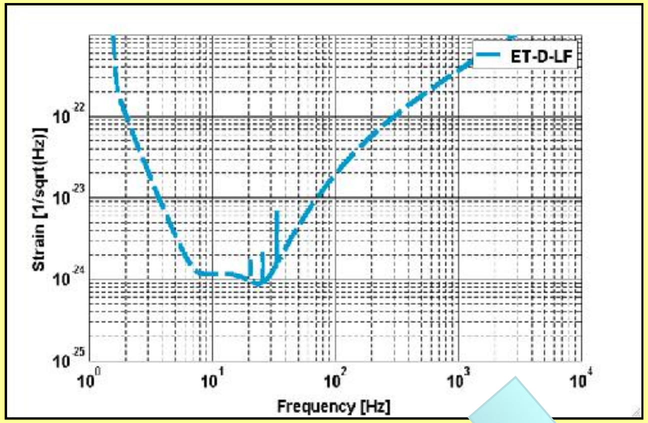
Low Frequencies and High Frequencies

10K, 18kW, 1550nm 300K, 3MW, 1064nm



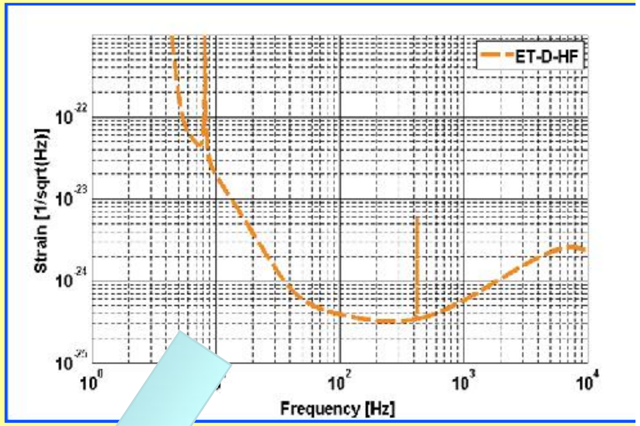
ET Xylophone sensitivity

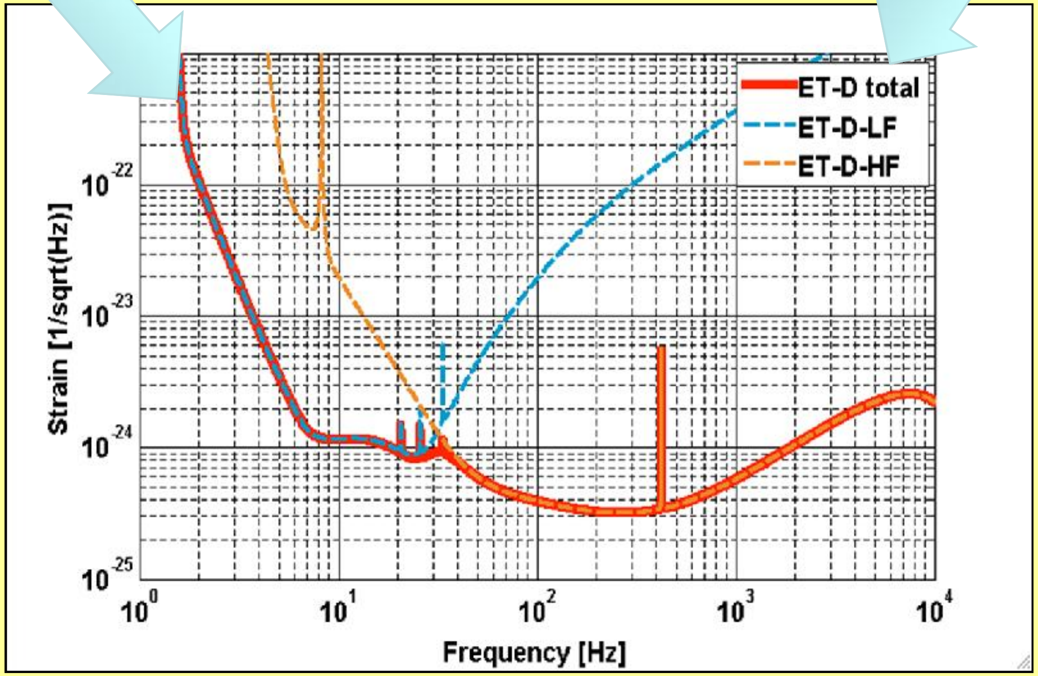
Slide: Christian Gräf, 2013, modified



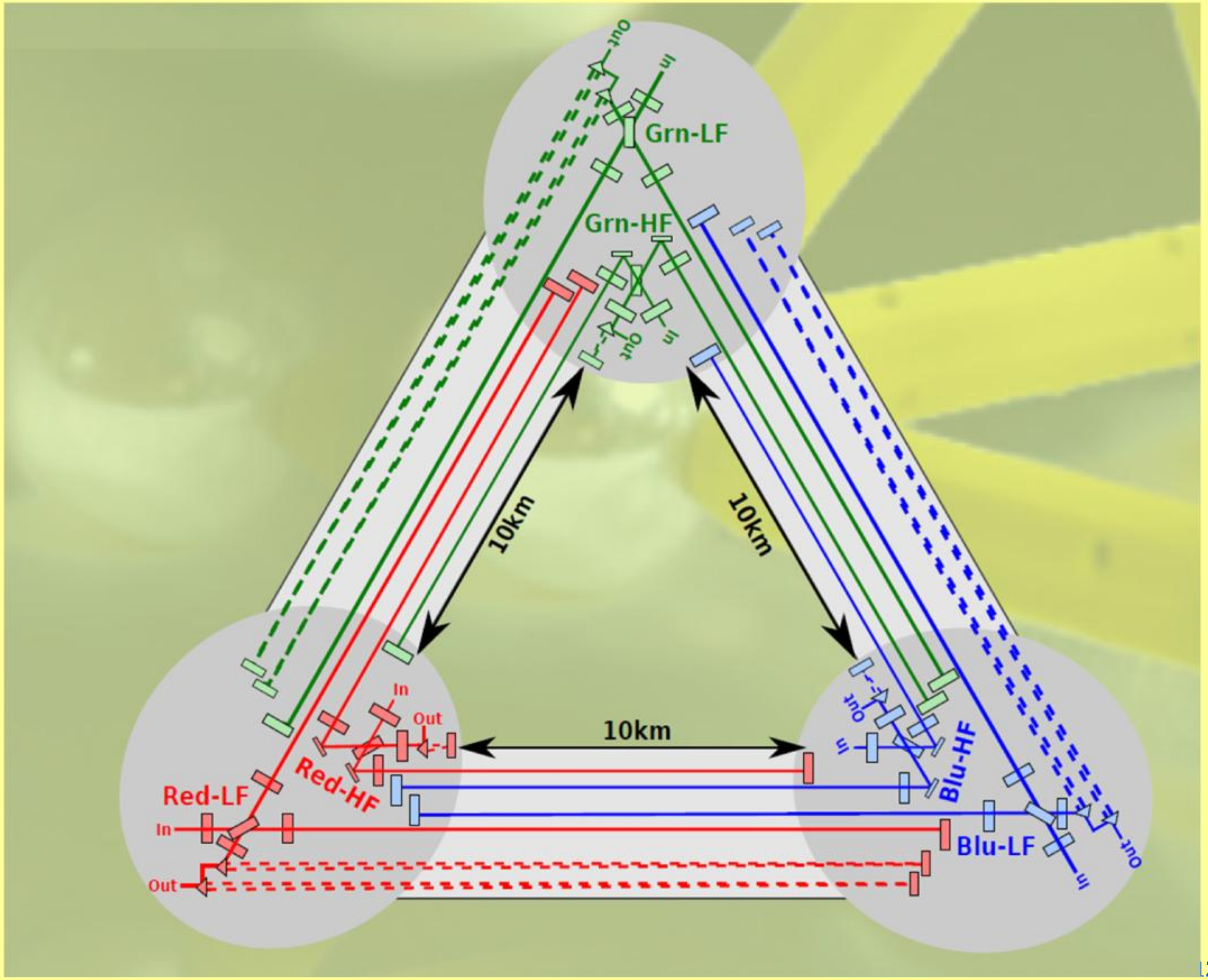
Combining the two interferometers

ET-LF **ET-HF**





Triangular configuration
Six interferometers in total

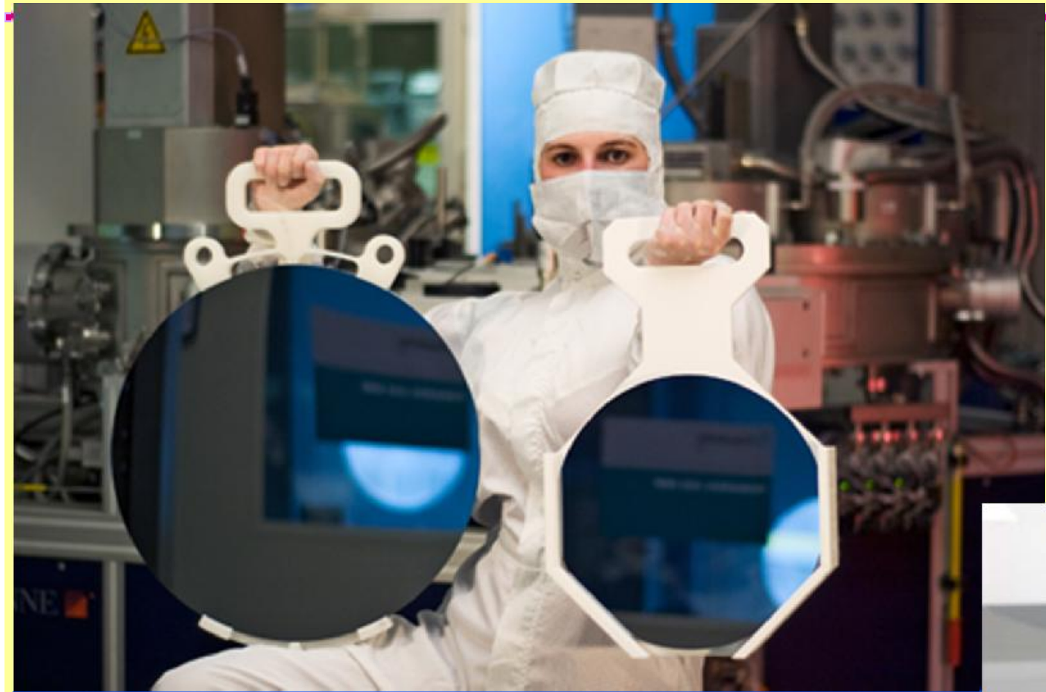


Einstein telescope

What New technologies does it need?

- Longer arms & underground site
- Higher power than advanced detectors (3 MW)
- Cryogenic optics for low thermal noise
  - Split into two (Xylophone) to make Cryogenic operation and high laser powers compatible
- Larger, heavier optics; non-Gaussian laser beams;
- Laser wavelength (Silicon:1550nm; fused Silica: 1064nm)
- Frequency dependent 10 dB ‚squeezing'

R&D Example – properties of Large Silicon Substrates



450 mm 300 mm

Source: http://www.iisb.fraunhofer.de/content/dam/iisb/de/images/geschaeftsfelder/halbleiterfertigungsgeraete_und_methoden/gadest_2011/

Large Silicon Substrates are available but only in Czochralski grown Crystals.
Whether the purity reachable is sufficient is currently under study

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

The global GW roadmap

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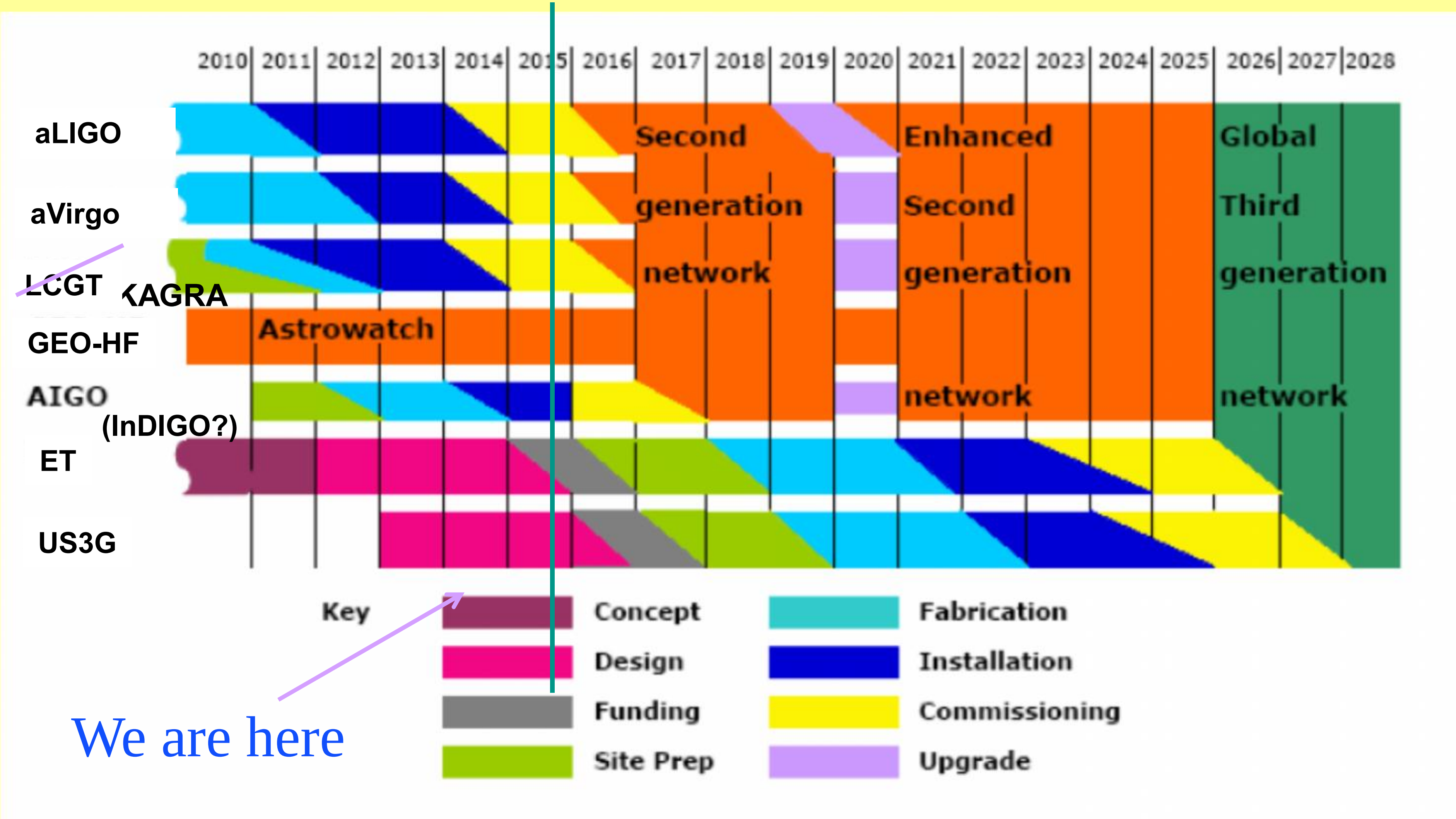

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In Summary


- The next generation of gravitational-wave detectors will have the sensitivity to make frequent detections
- First data taking with the Advanced detectors is underway
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy

Goal: Direct Detection 100 years after Einstein's 1916 paper on GWs ?