Advanced LIGO:
A second-generation gravitational-wave detector

The Violent Universe – Institute of Physics
31 October 2013

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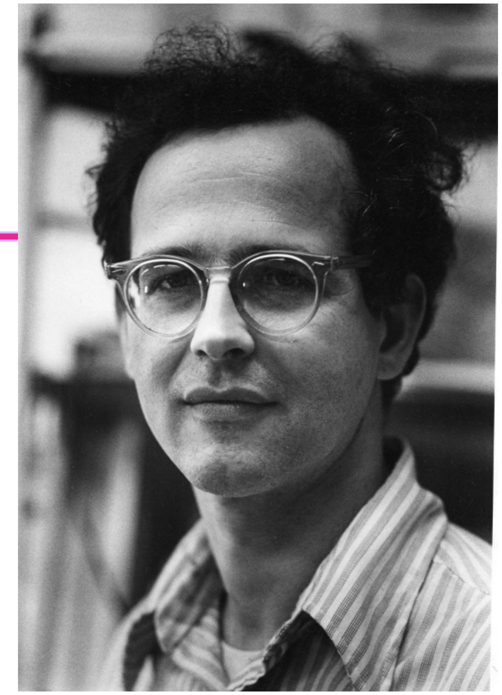
For the LIGO Scientific Collaboration

The starting point for GW detection via Interferometry

- Rai Weiss of MIT was teaching a course on GR in the late ‘60s
- Wanted a good homework problem for the students
- Why not ask them to work out how to use laser interferometry to detect gravitational waves?
- Weiss wrote the instruction book we have been following ever since



QUARTERLY PROGRESS REPORT

No. 105

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RESEARCH LABORATORY OF ELECTRONICS

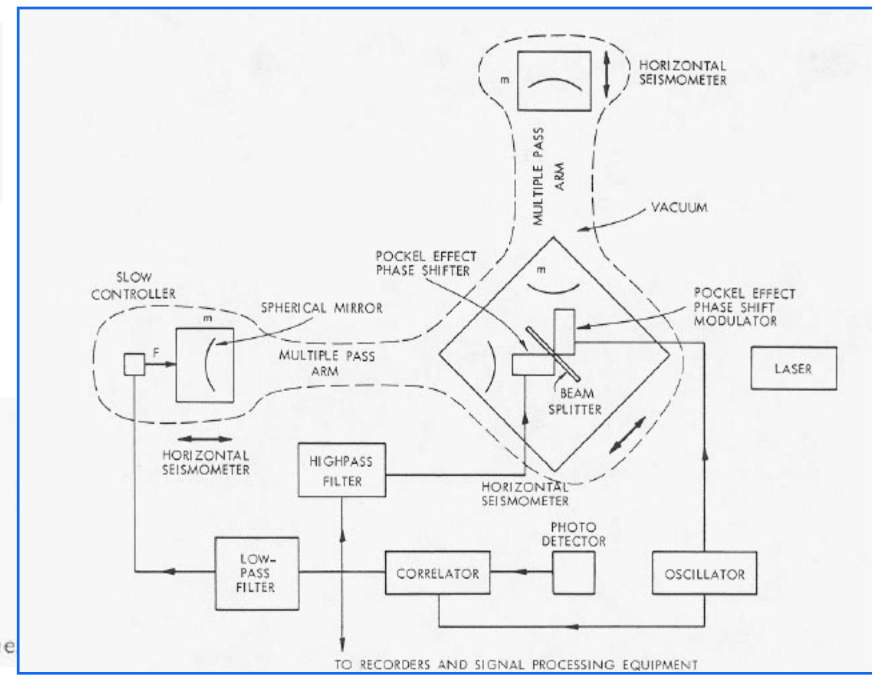
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

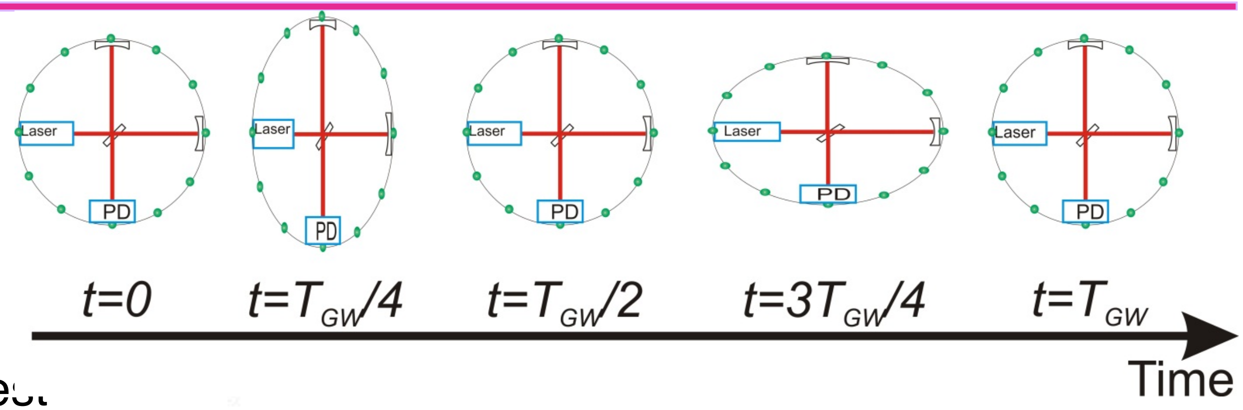
The prediction of gravitational radiation that travels at the speed of light has bee

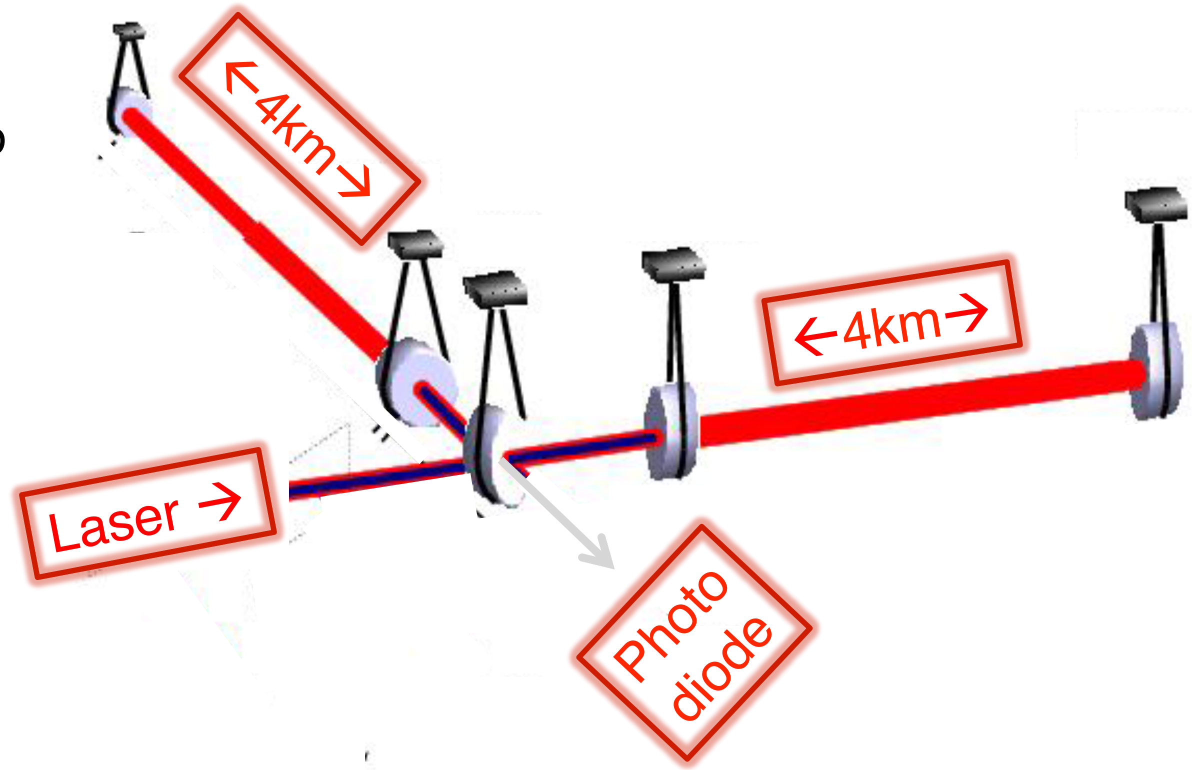


LIGO

Interferometric Gravitational-wave Detectors

- Enhanced **Michelson interferometers**
  - » LIGO, Virgo, and GEO600 use variations
- Passing GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- **Arms are short compared to GW wavelengths, so longer arms make bigger signals → multi-km installations**
- Arm length limited by taxpayer noise….



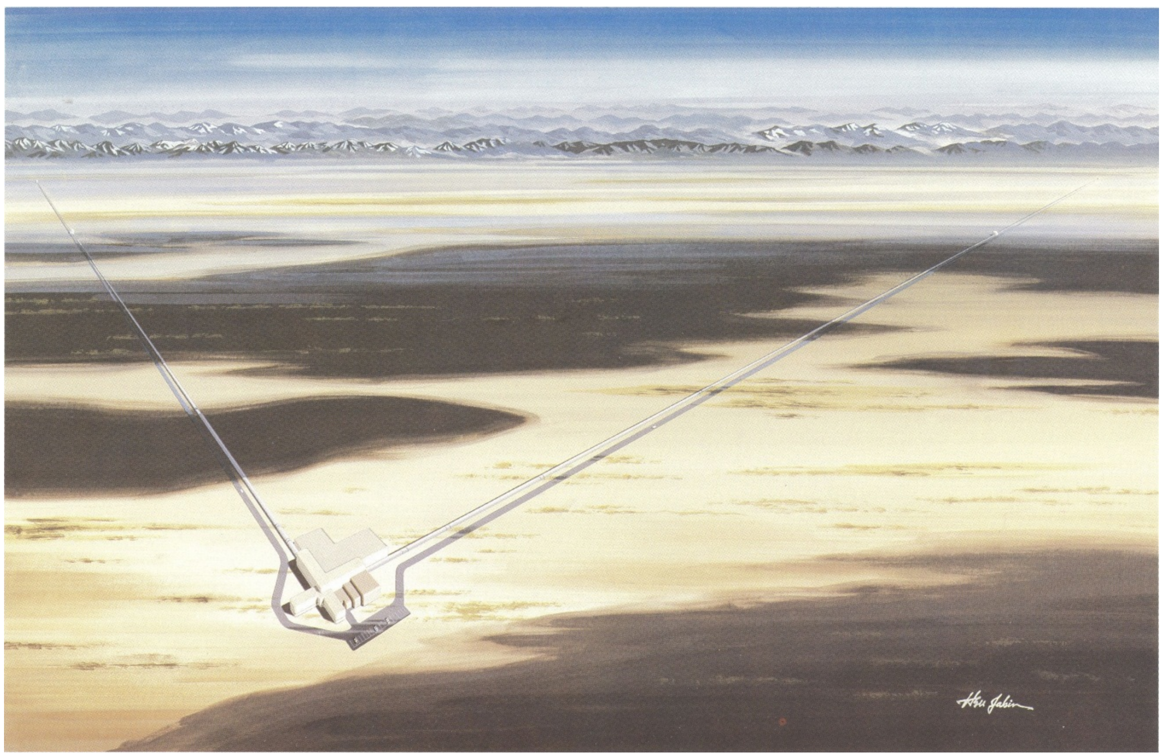


Weiss' groundwork and a worldwide development effort led to a 1989 Proposal to the US NSF

PREFACE

This proposal requests support for the design and construction of a novel scientific facility—a gravitational-wave observatory—that will open a new observational window on the universe.

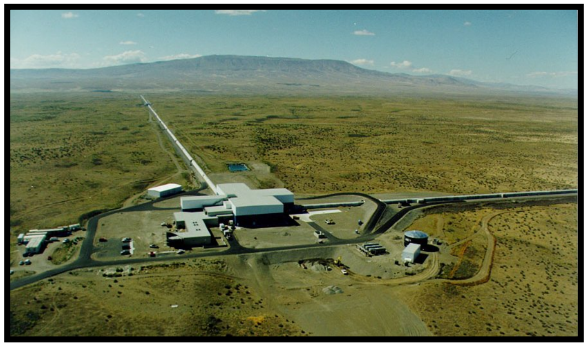
The scale of this endeavor is indicated by the frontispiece illustration, which shows a perspective of one of the two proposed detector installations. Each installation includes two arms, and each arm is 4 km in length.



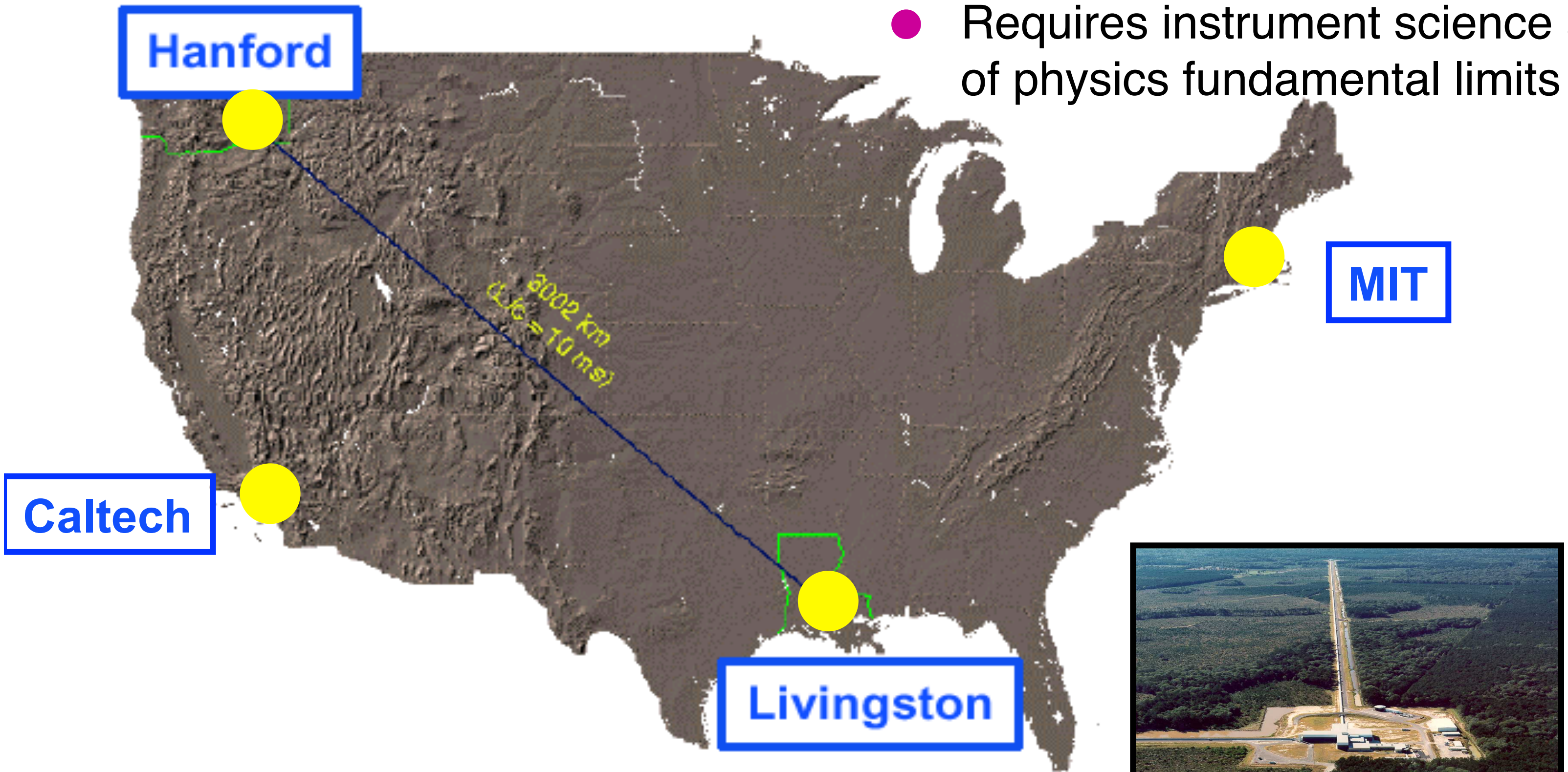
LIGO:
Today, Washington state…

…LIGO in Louisiana

LIGO Laboratory: two Observatories and Caltech, MIT campuses

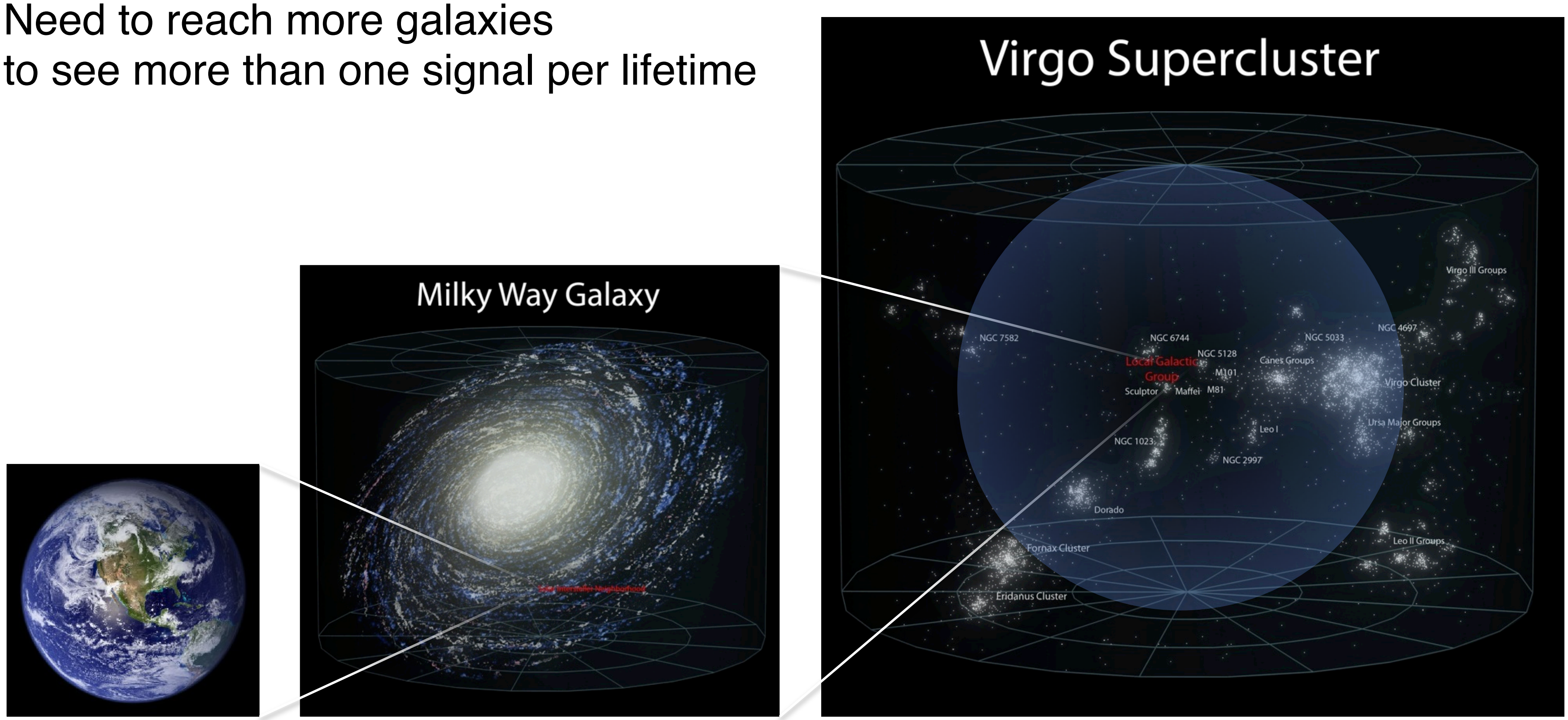


- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT; responsible for operating LIGO Hanford and Livingston Observatories
- Requires instrument science at the frontiers of physics fundamental limits



First generation detectors

- First generation detectors and infrastructure built from mid-'90s to mid-2000; commissioned to design sensitivity; and observed for several years
- Sensitivity sufficient to reach about 100 galaxies; however…
- NS-NS coalescence events happen once every 10,000 years per galaxy…
- Need to reach more galaxies
  to see more than one signal per lifetime

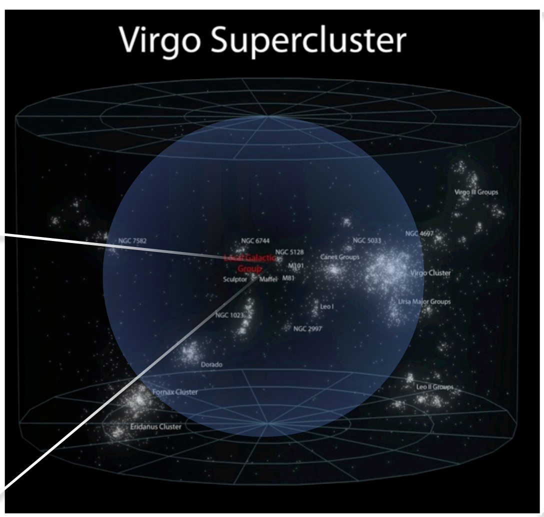


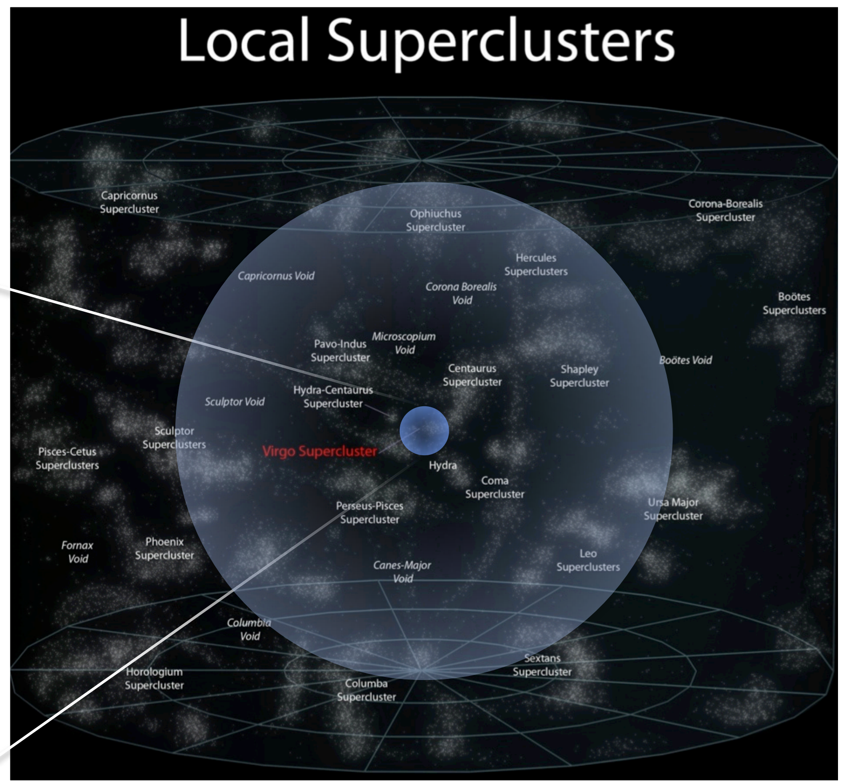
M. Evans

Advanced LIGO Sensitivity: a *qualitative* 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
- Events happen once every 10,000 years per galaxy…
- NS-NS detection rate order of 1 per month...with uncertainties as noted

- Advanced LIGO concept ~1999
- Project start 2008, $205M NSF
- Completion 2015, tuning follows



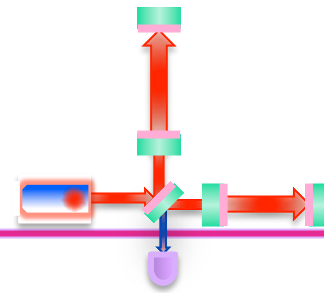


M. Evans

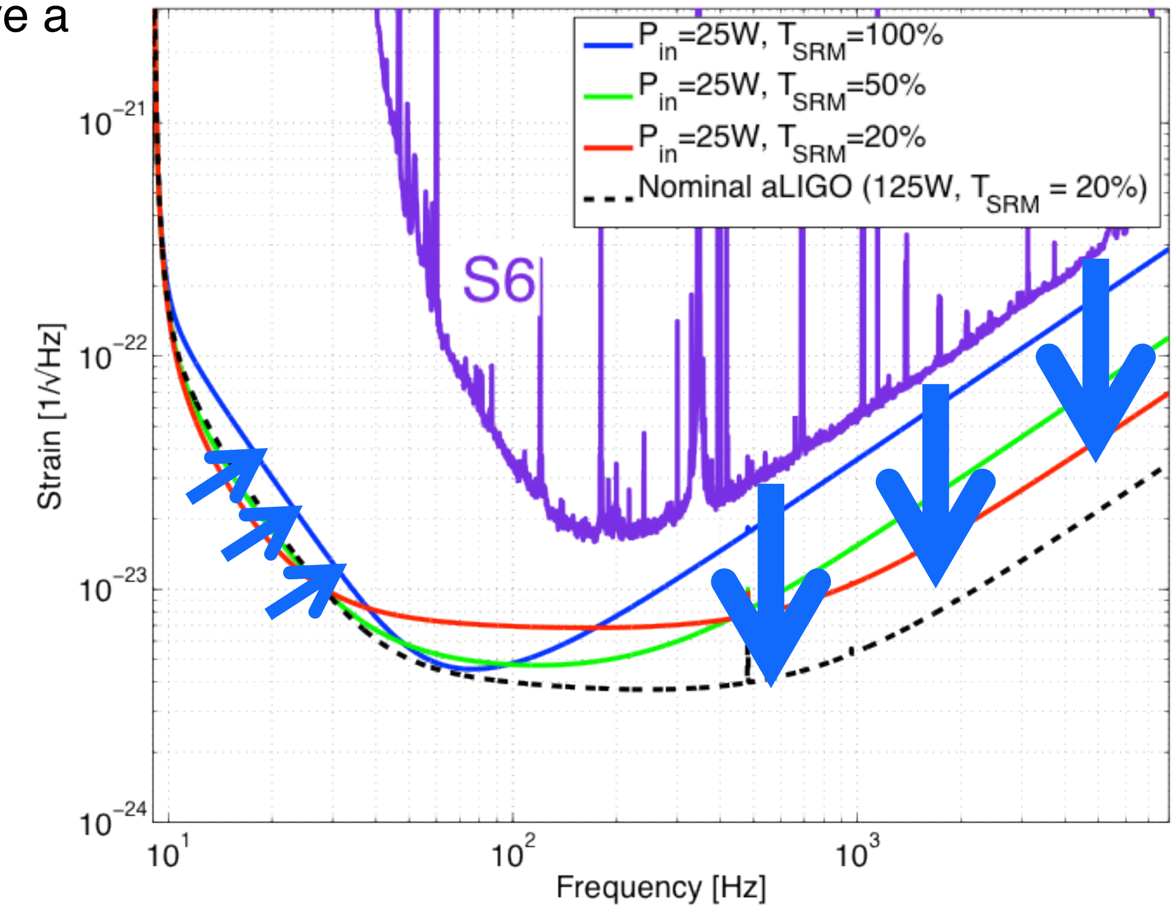
Initial Reach

Advanced Reach

How to get there: Addressing limits to performance

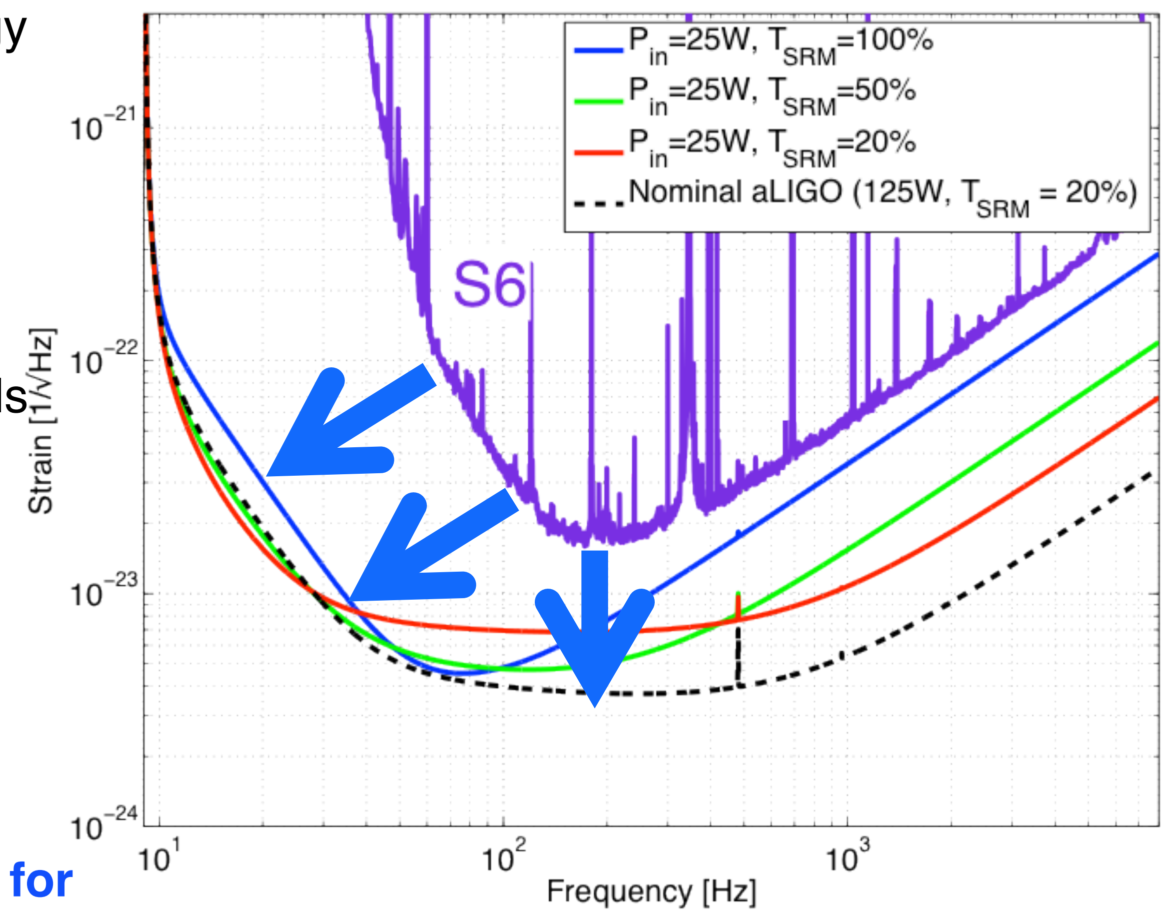


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses!
- 'Standard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



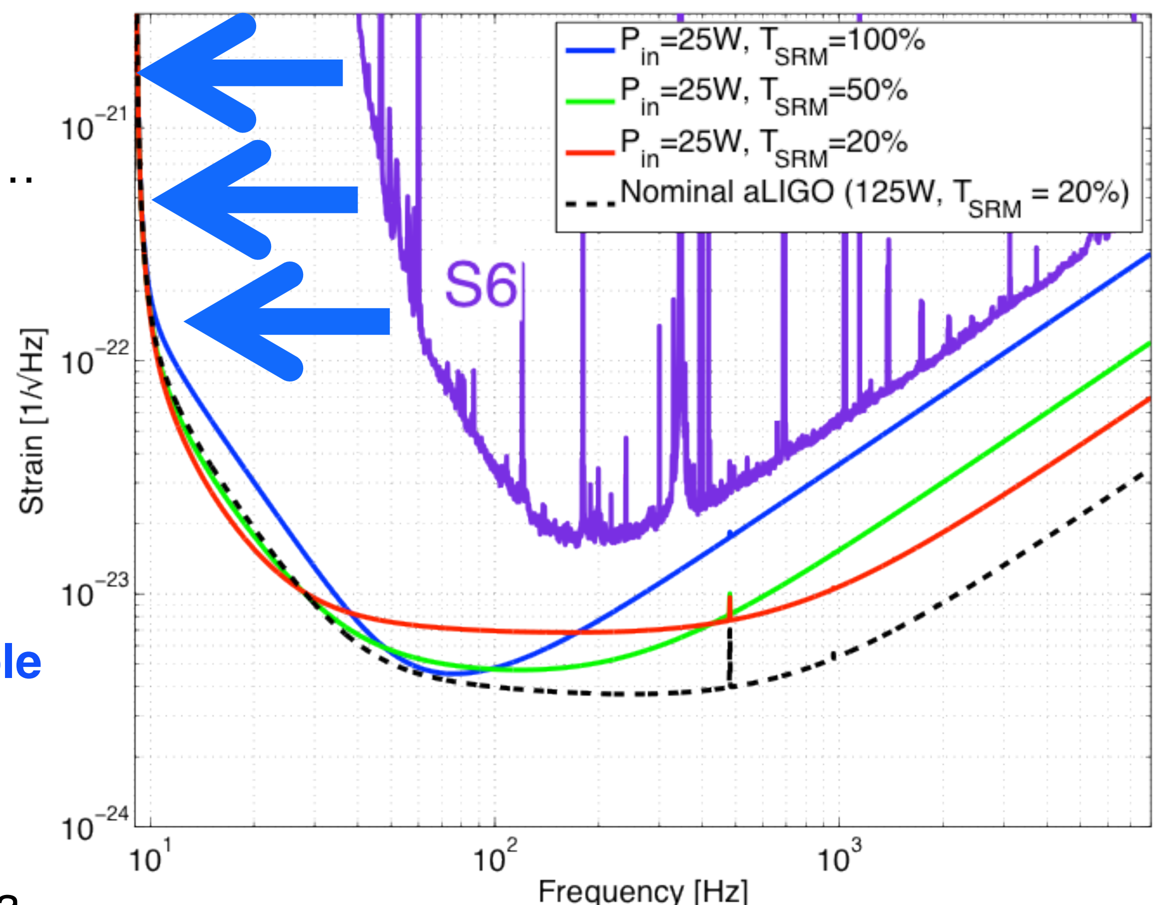
Addressing limits to performance

- **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 gather this motion into a narrow peak at resonant frequencies of system
- Realized in aLIGO with an all **fused-silica test mass suspension** – *Q* of order 10^9
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**

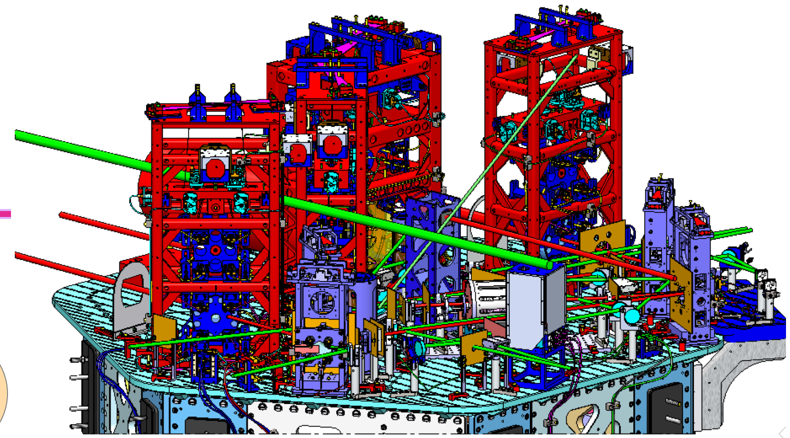


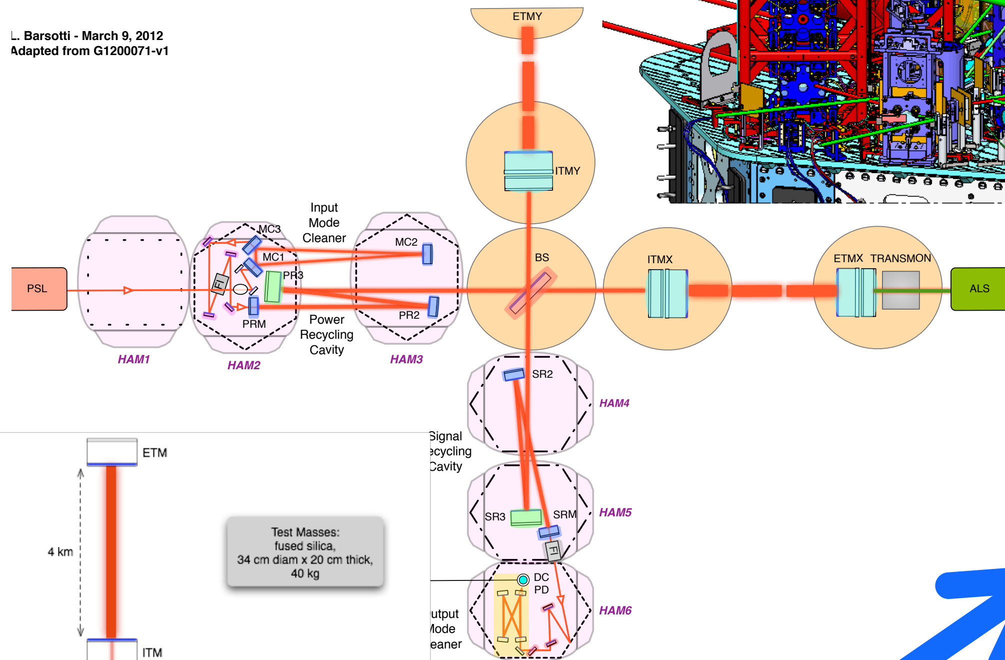
Addressing limits to performance

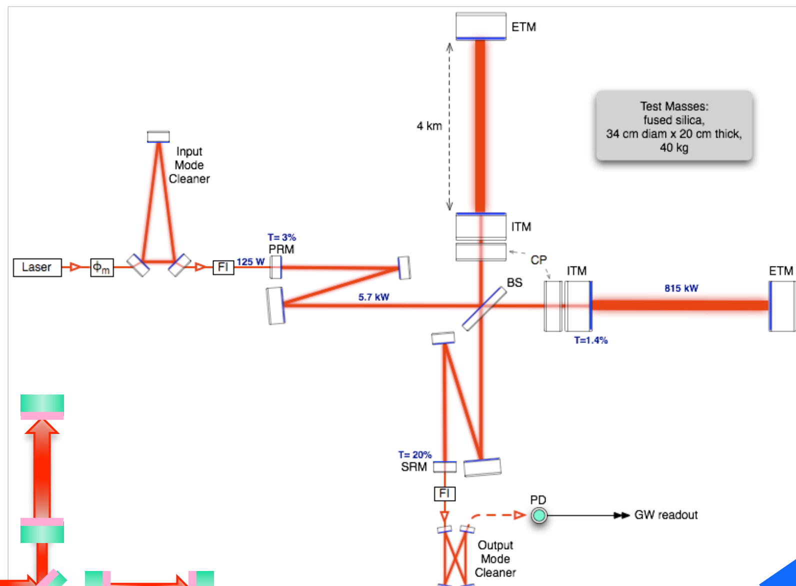
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- Motion from waves on coasts… and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled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

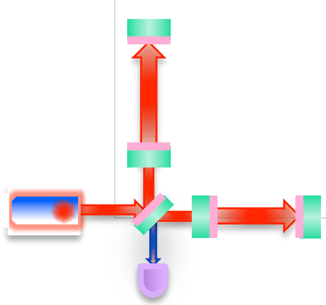


LIGO

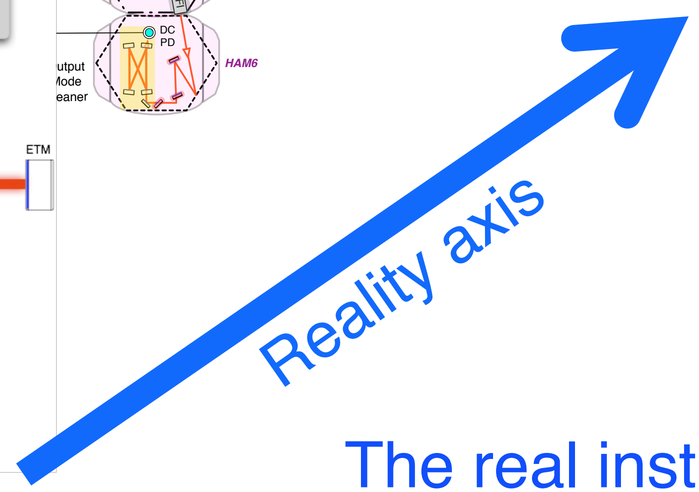






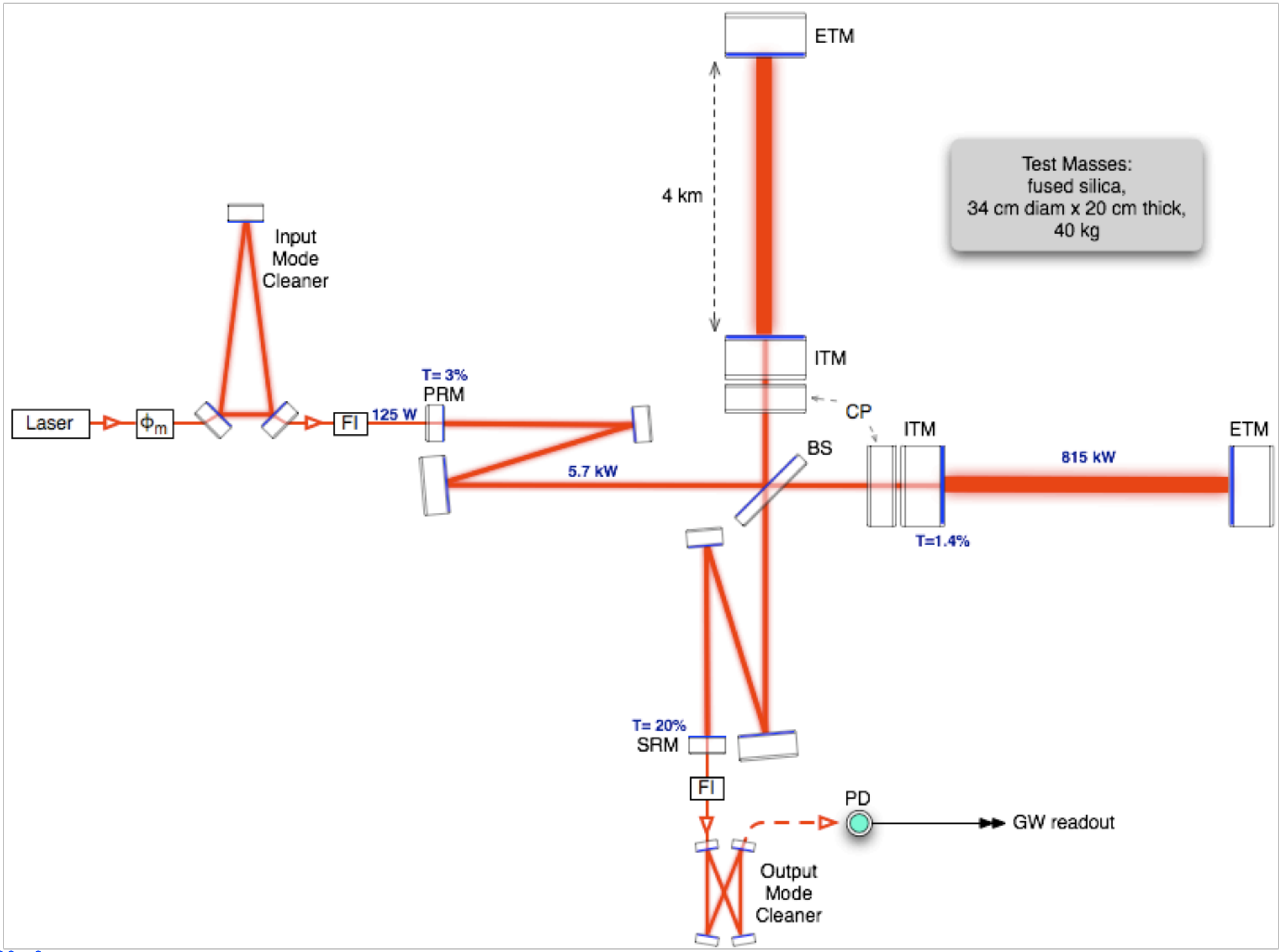


photodiode



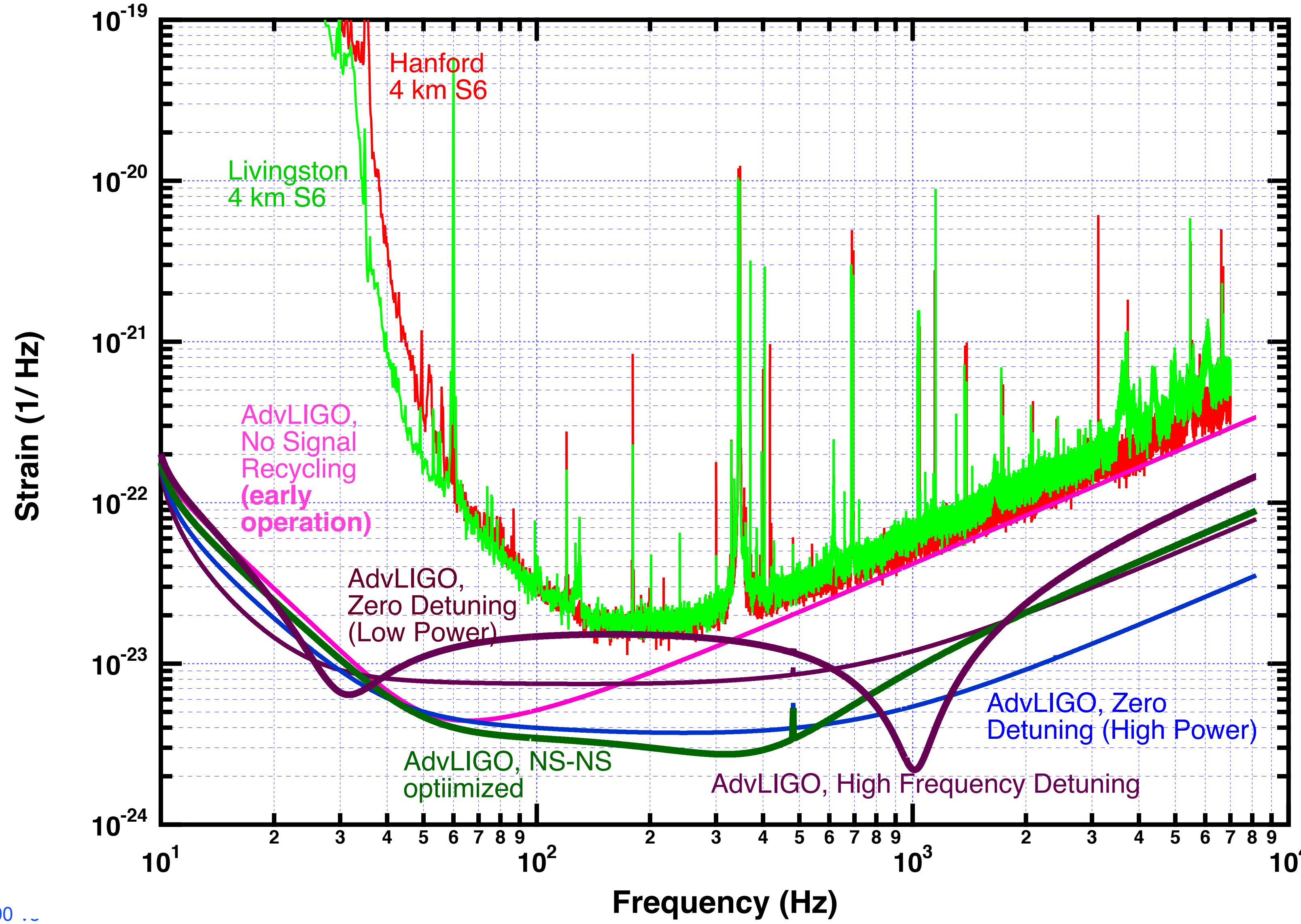
The real instrument is far more complex…

The Design: Optical Configuration



Resulting flexibility in the instrument response

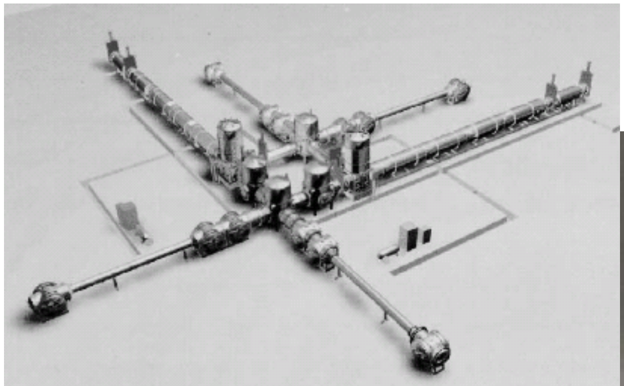
Initial LIGO curves for comparison



4km Beam Tubes

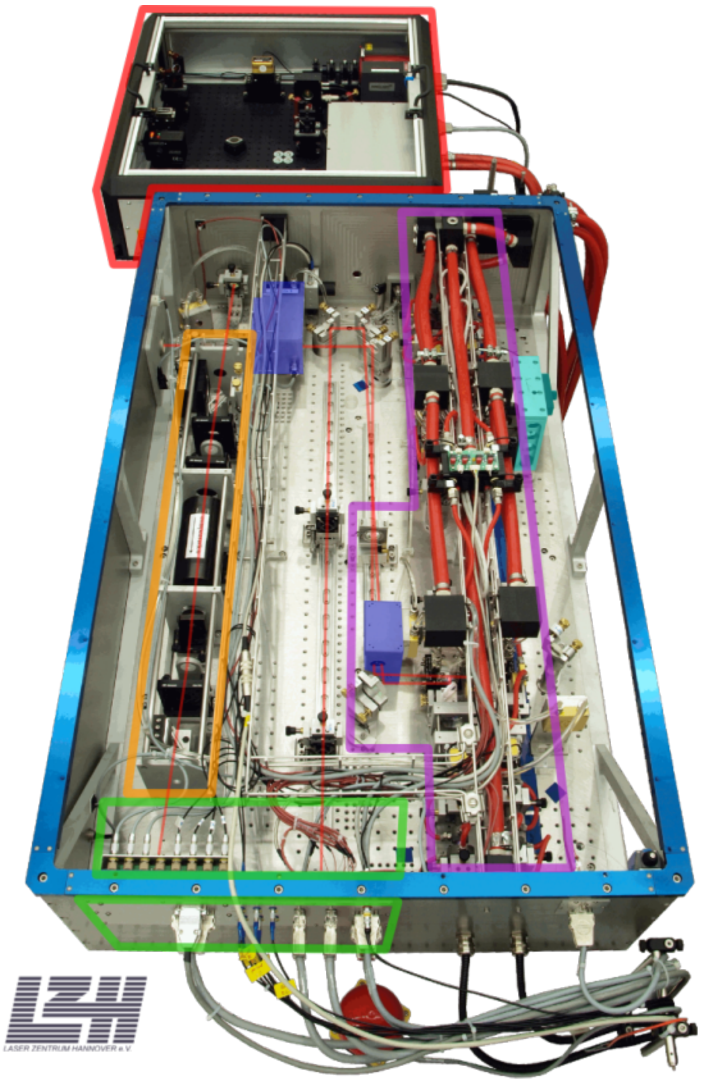
- Light must travel in an excellent vacuum
  - » Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs!
  - » 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters' bullets and the stray car
- Tube is straight to a fraction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

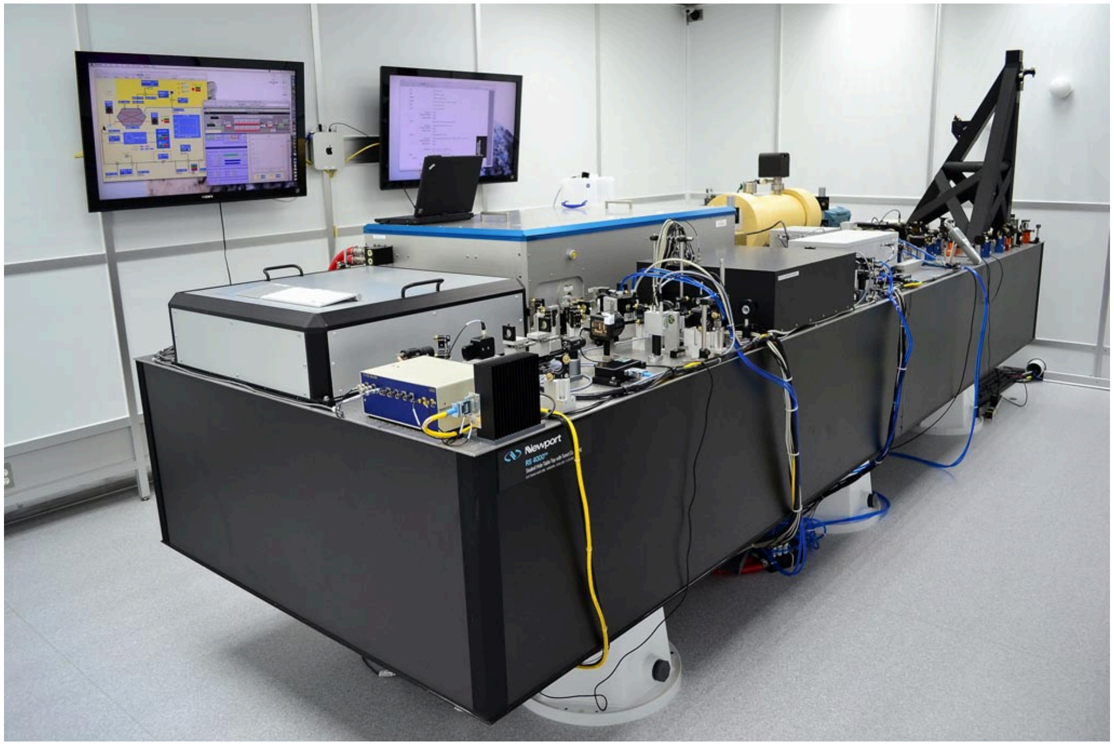
LIGO Vacuum Equipment – designed for several generations of instruments



200W Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute

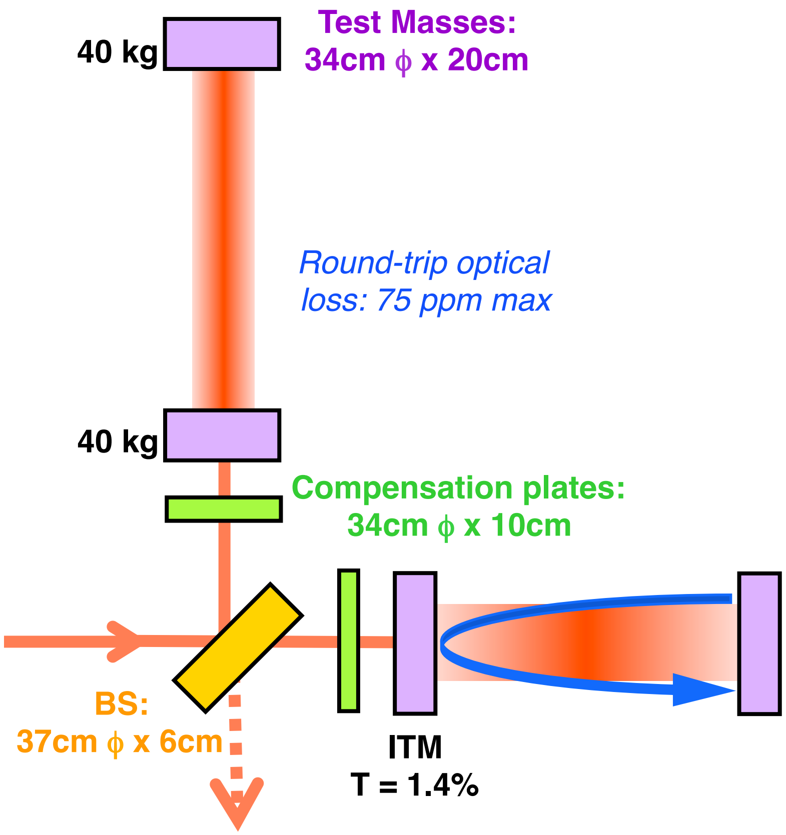


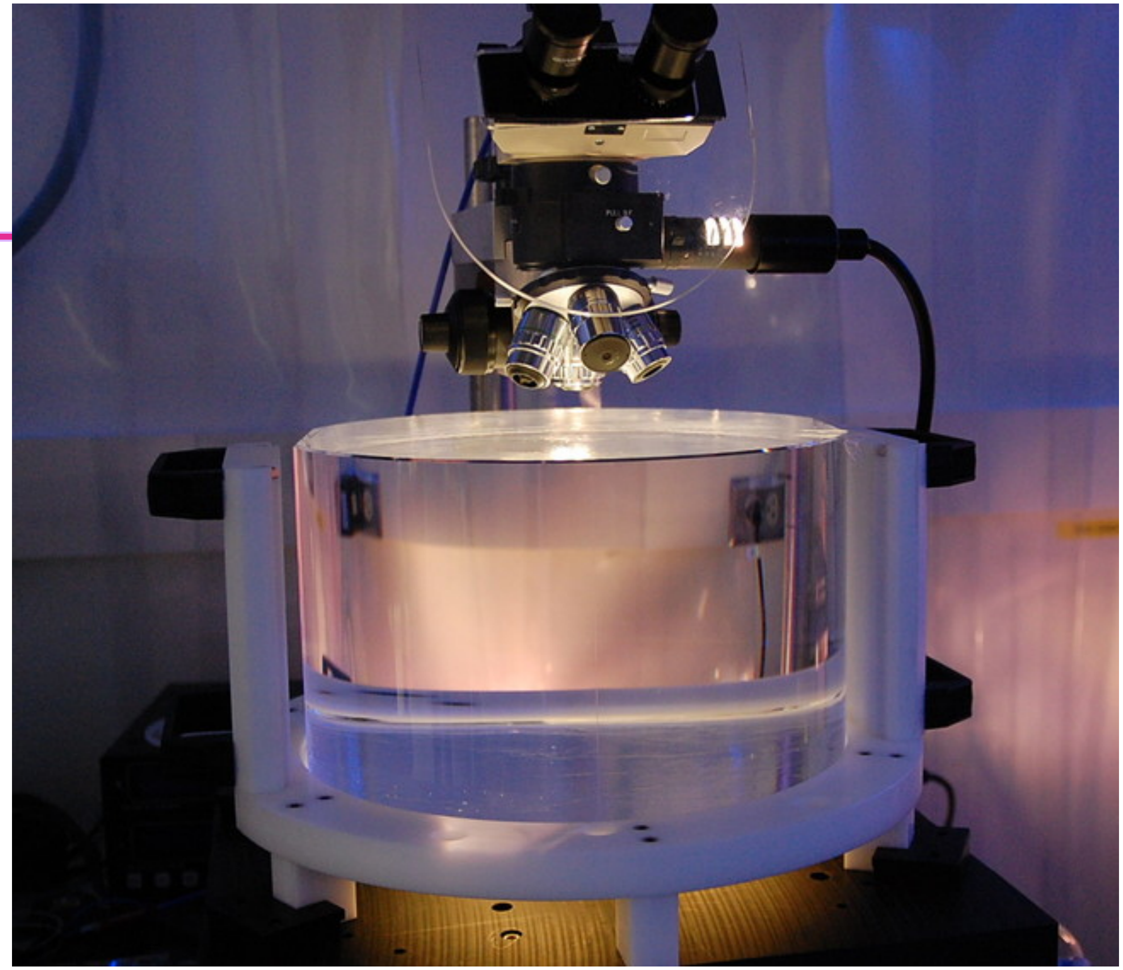


- Stabilized in power and frequency
- Uses a monolithic master oscillator followed by injection-locked rod amplifier

Test Masses

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

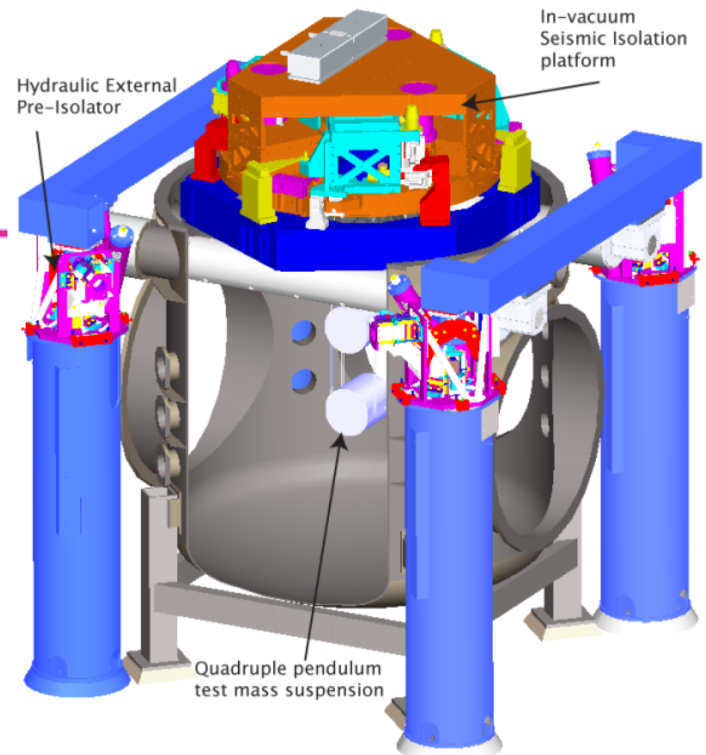


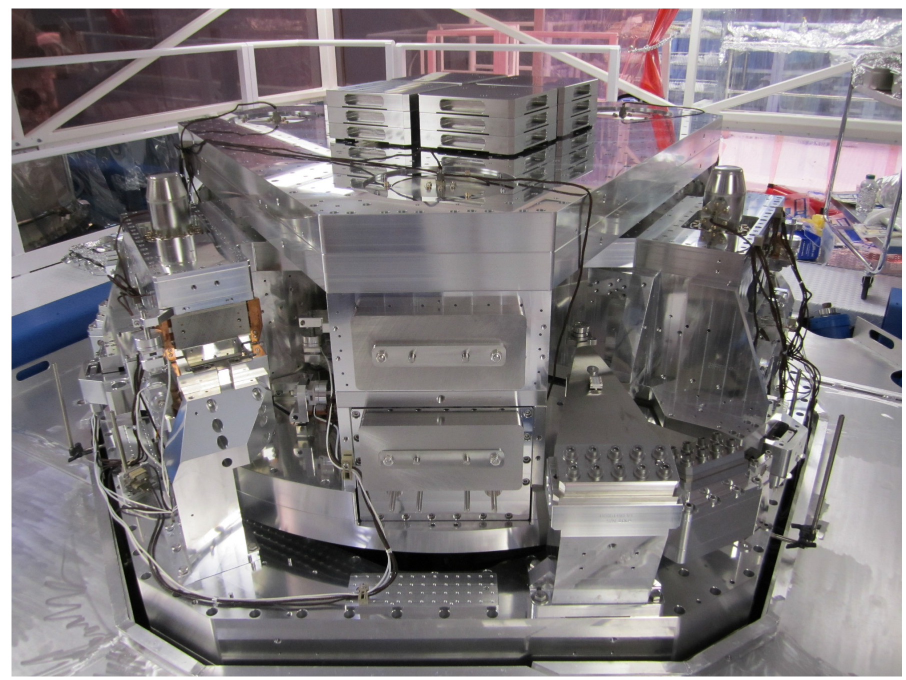


- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

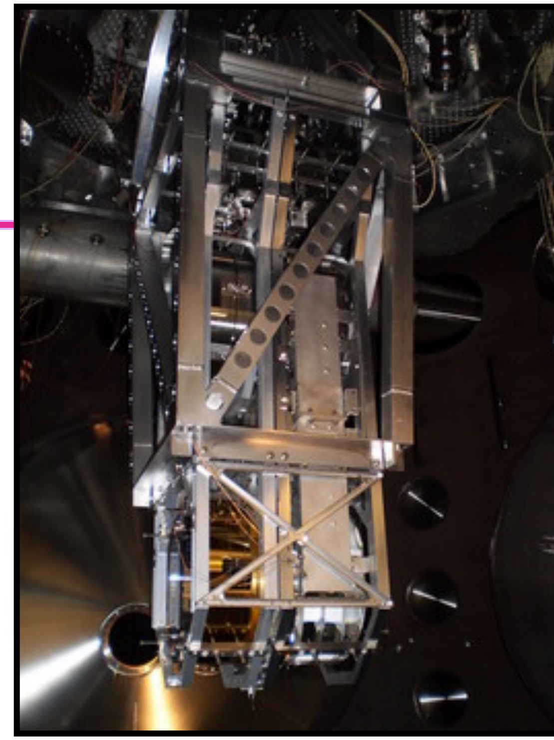
Seismic Isolation: Multi-Stage Solution

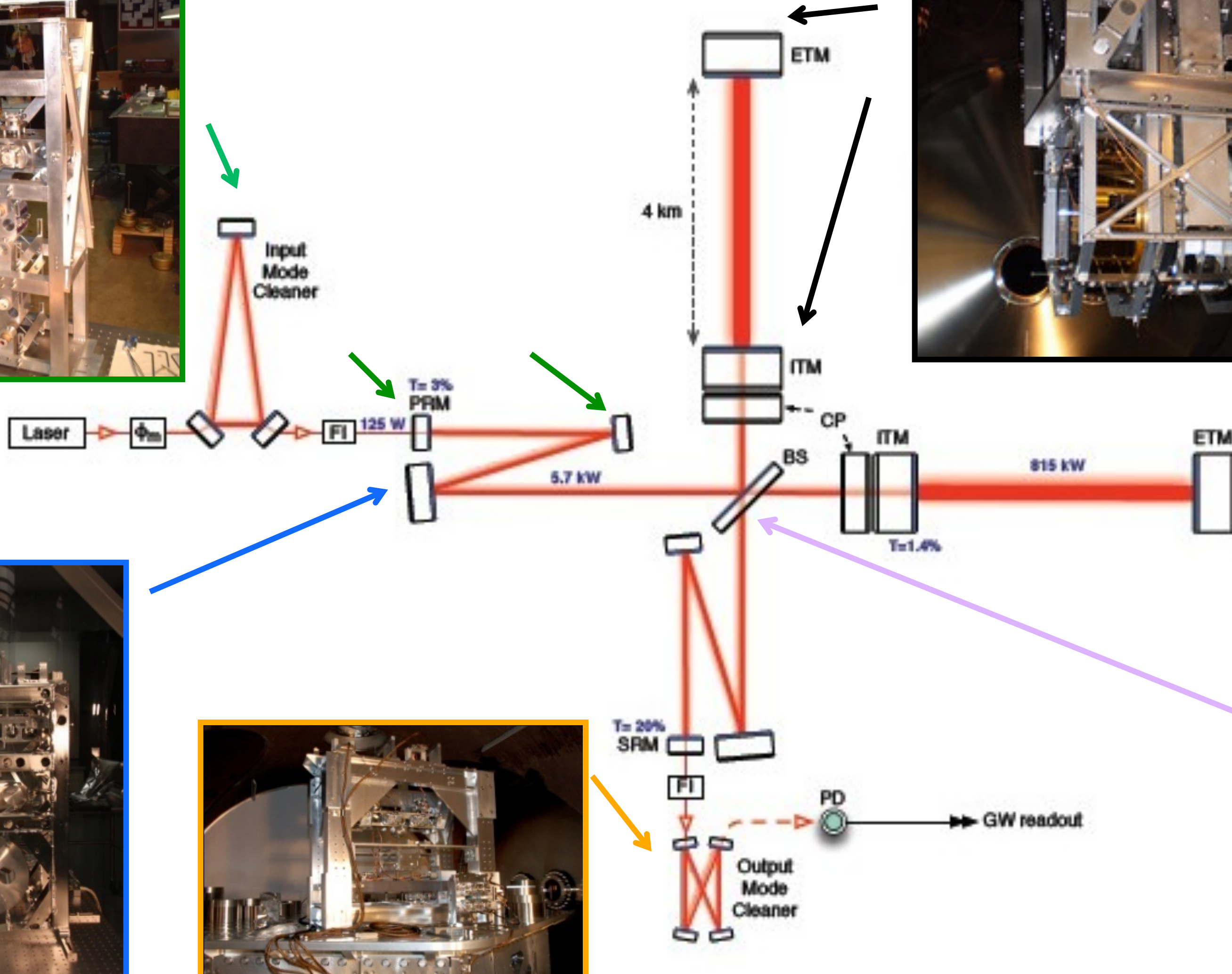
- Objectives:
  - Render seismic noise a negligible limitation to GW searches
  - Reduce actuation forces on test masses
- Both suspension and seismic isolation systems contribute to attenuation
- Choose an active isolation approach, 3 stages of 6 degrees-of-freedom :
  - 1) Hydraulic External Pre-Isolation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

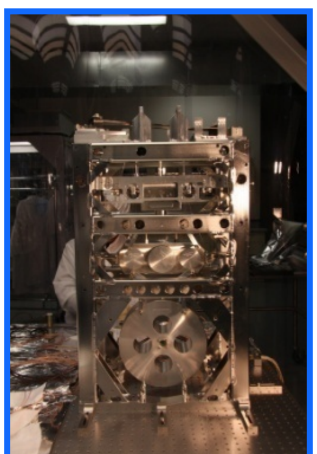


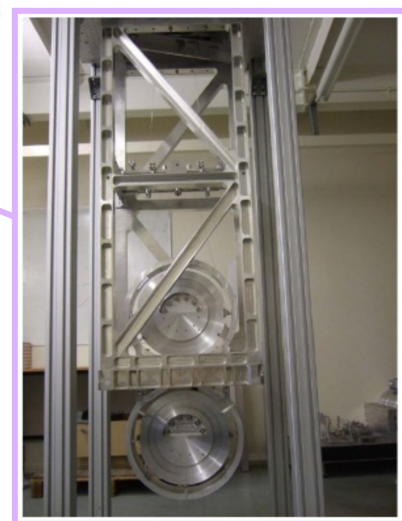


Optics suspensions: Pendulums





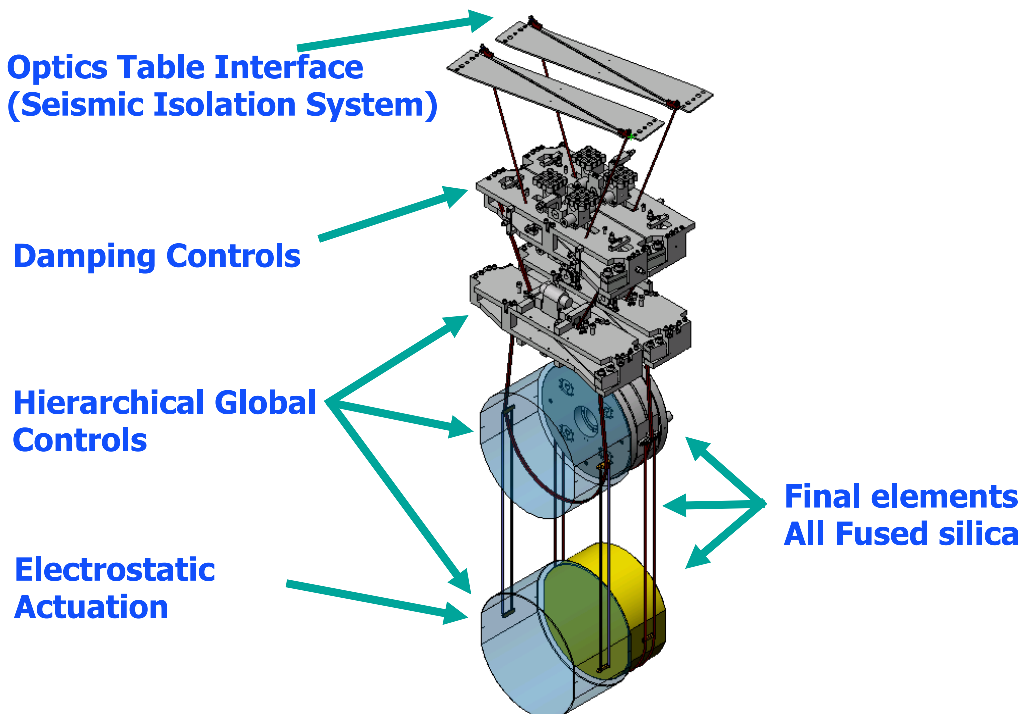




Test Mass Quadruple Pendulum suspension

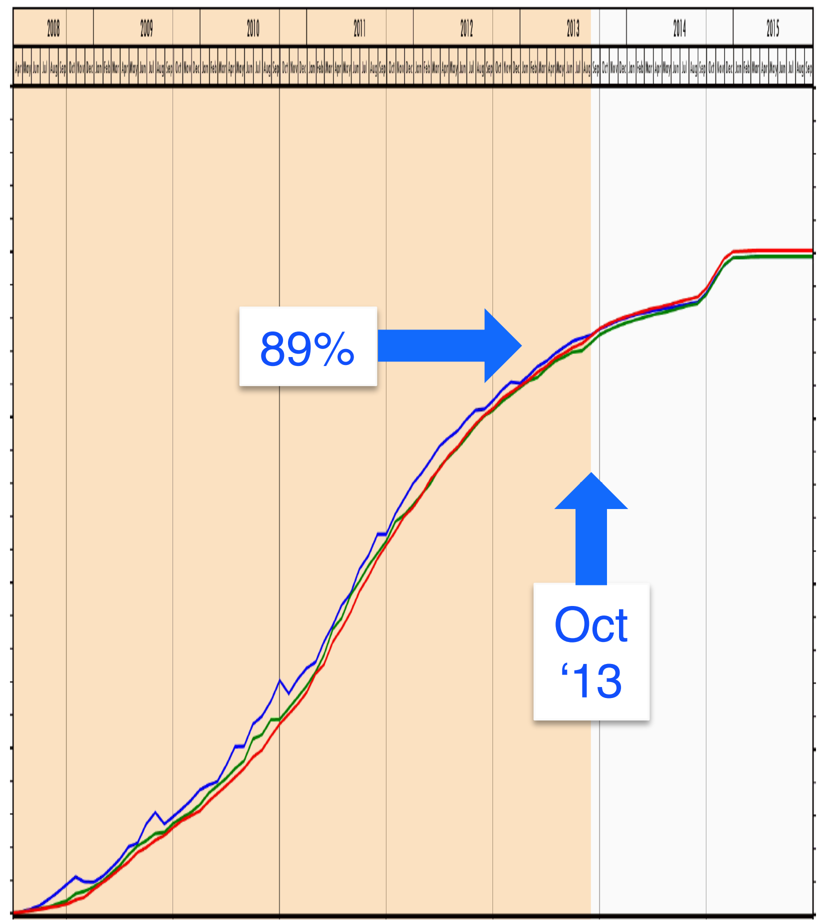
designed jointly by the UK (led by Glasgow) and LIGO lab,
with capital contribution funded by PPARC/STFC

- 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!
- Another element in hierarchical control system

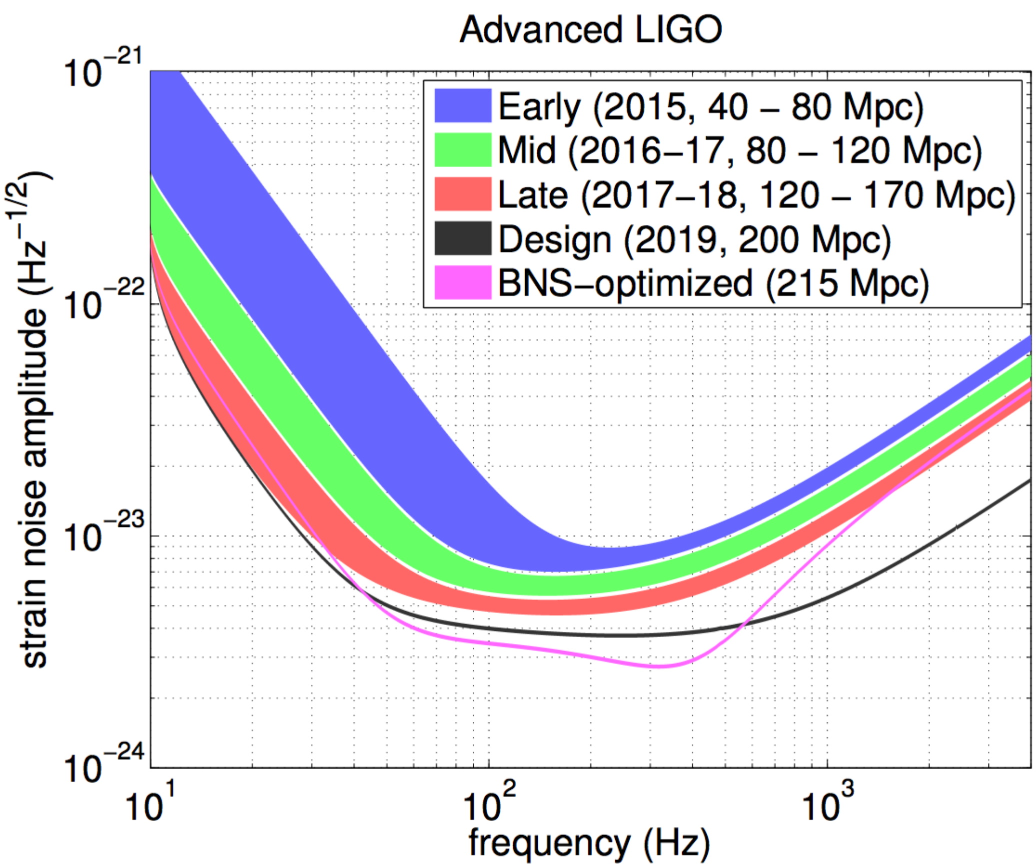


Where are we?

- The detector subsystems are 99.1% complete: procurement, fabrication, cleaning, assembly, and stand-alone testing
- Most of the hardware is now installed; almost every vacuum chamber has almost every component in it
- At both observatories, installation is now interleaved with integrated test – multiple subsystems working together
- Believe we can deliver instruments ready for commissioning on time
  - Have used several months of schedule over last 6 months due to installation hitches, surprises, etc; getting close to the end date…
  - Have some cost contingency remaining to handle problems
  - so far integrated test schedule matches planning, *really* good news



Post-Project commissioning



http://arxiv.org/abs/1304.0670

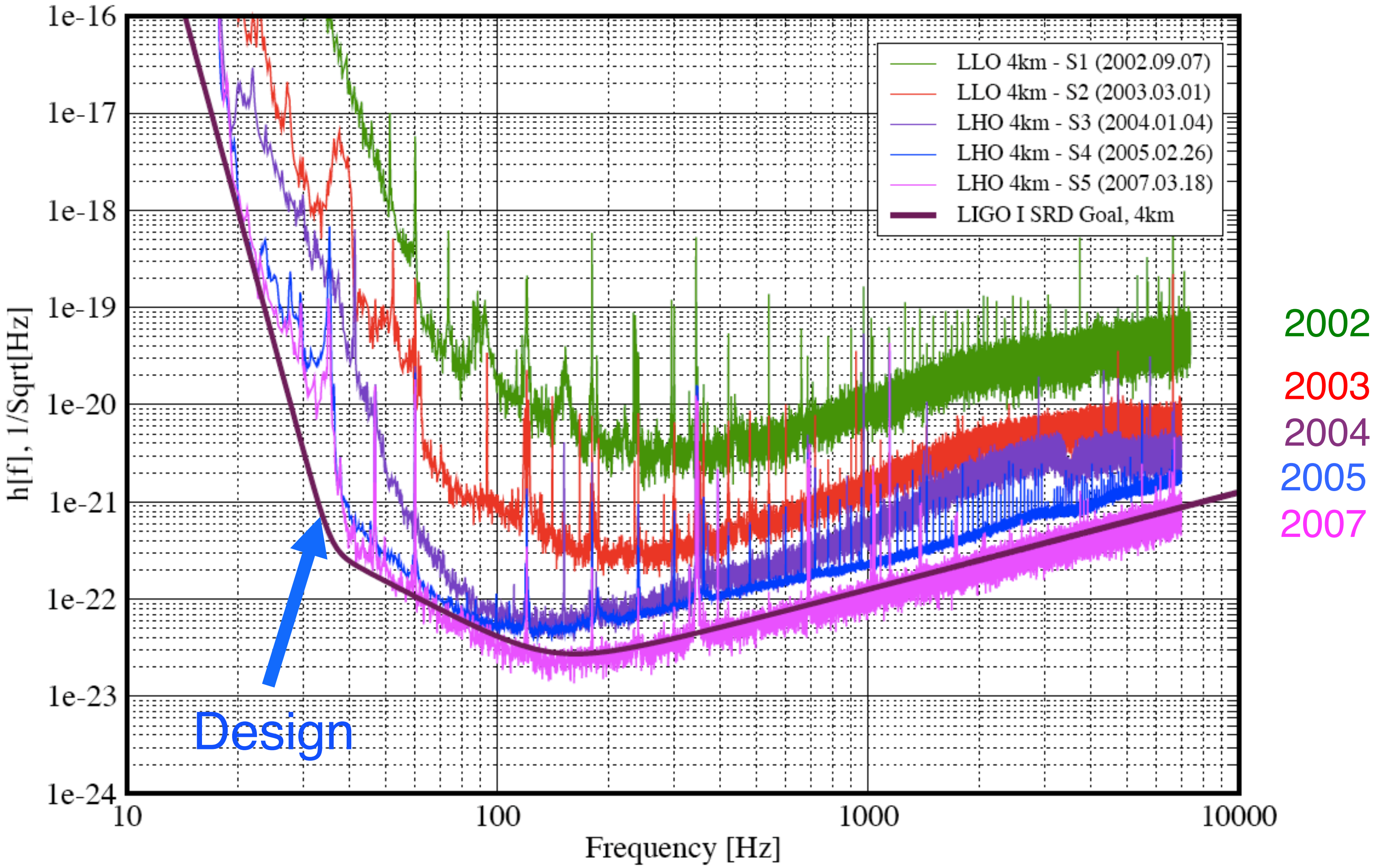
Taking instrument from 2-hour lock to astrophysically interesting sensitivity

TENTATIVE TIMELINE:

- ❖ Complete integration by 2014 (interferometer "locked")
- ❖ "Early" Science Run in 2015 (~60 Mpc)
- ❖ Within a factor of 2 of design sensitivity by 2016 (~100 Mpc)

Interesting to compare with Initial LIGO…

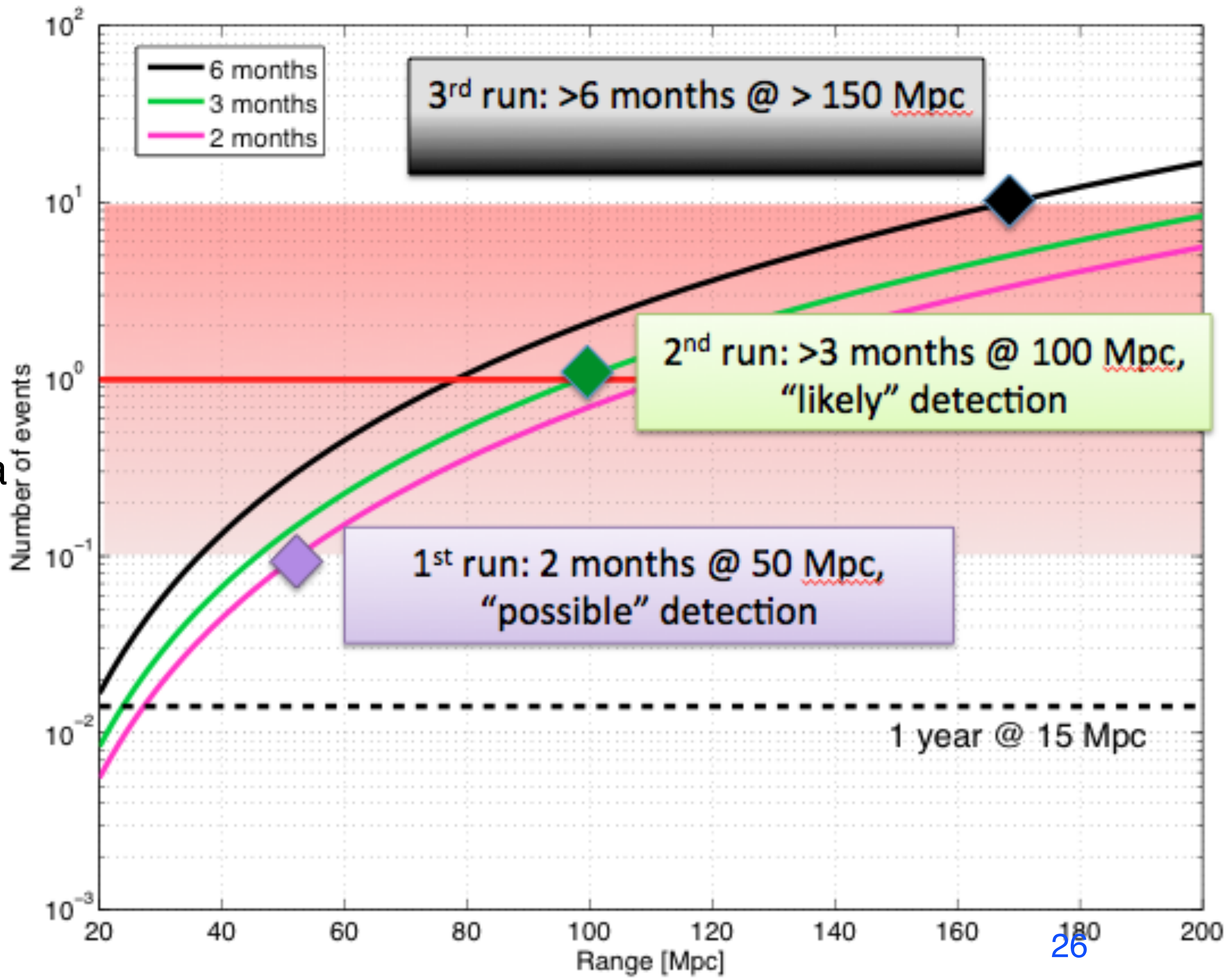
Initial LIGO: first lock in 2000 – 7 years to reach goal



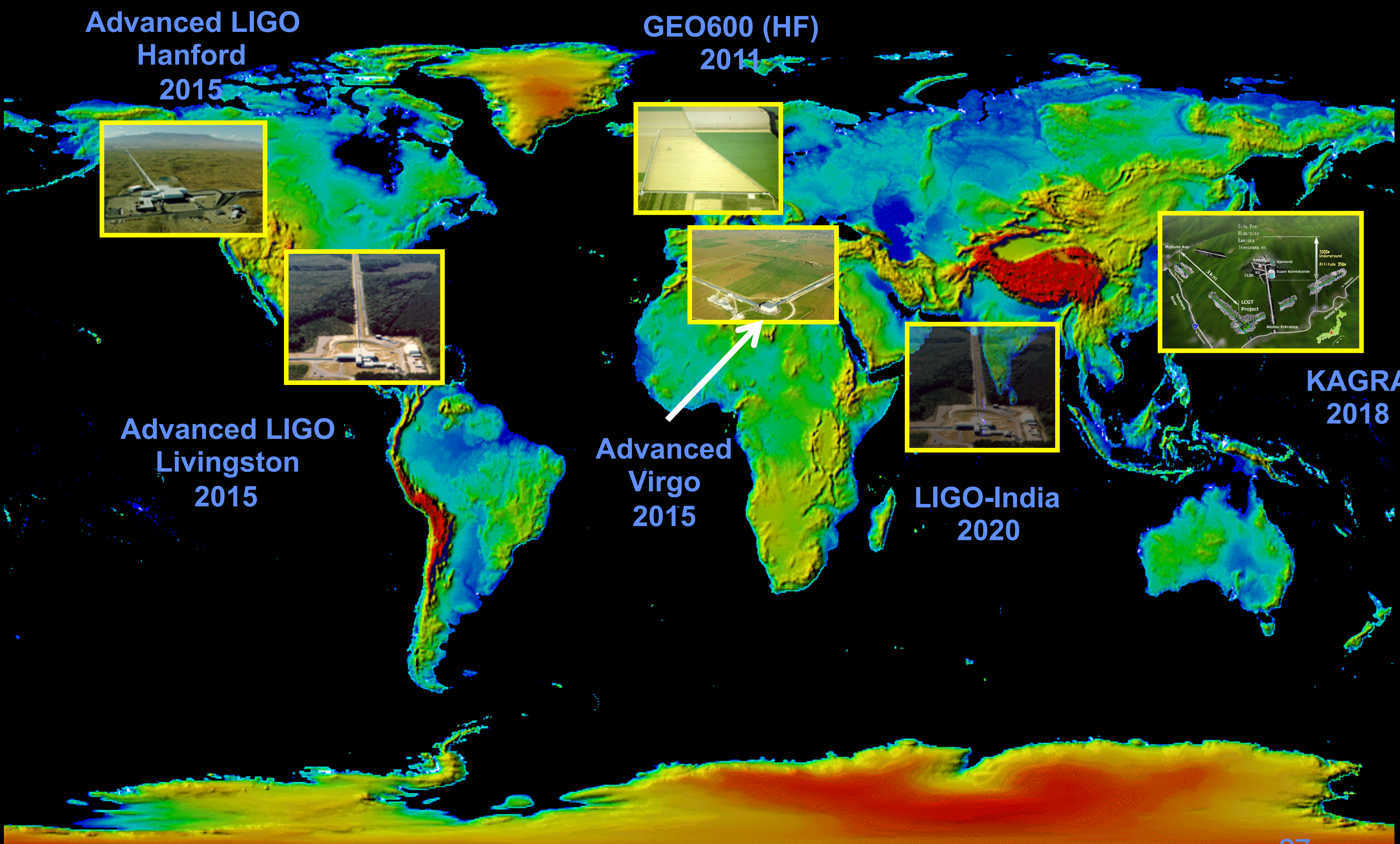
Detection Rate = (Sensitivity)^3 × Time

- Vertical scale is the number of binary inspirals detected
- Rates based on population synthesis, realistic but uncertain
- LIGO Scientific Collaboration (LSC) preparing for the data analysis challenge
- Close collaboration with Virgo
- **Early detection looks feasible**

- arXiv:1304.0670, arXiv:1003.2480



The advanced GW detector network



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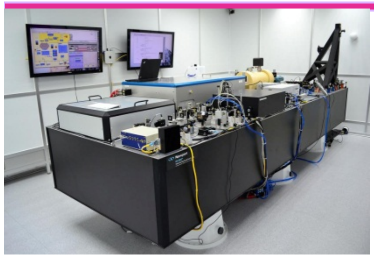

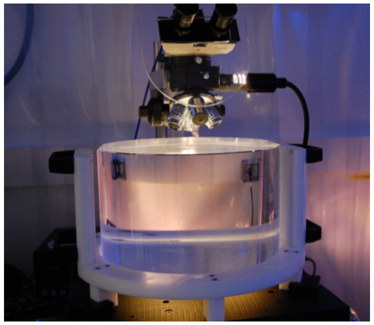

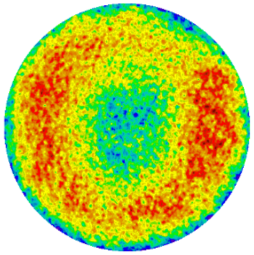

- The next generation of gravitational-wave detectors will have the sensitivity to make frequent detections
- The Advanced LIGO detectors are coming along well, planned to complete in 2015
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy

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