Interferometry and Optics in Advanced LIGO

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For the LIGO Scientific Collaboration

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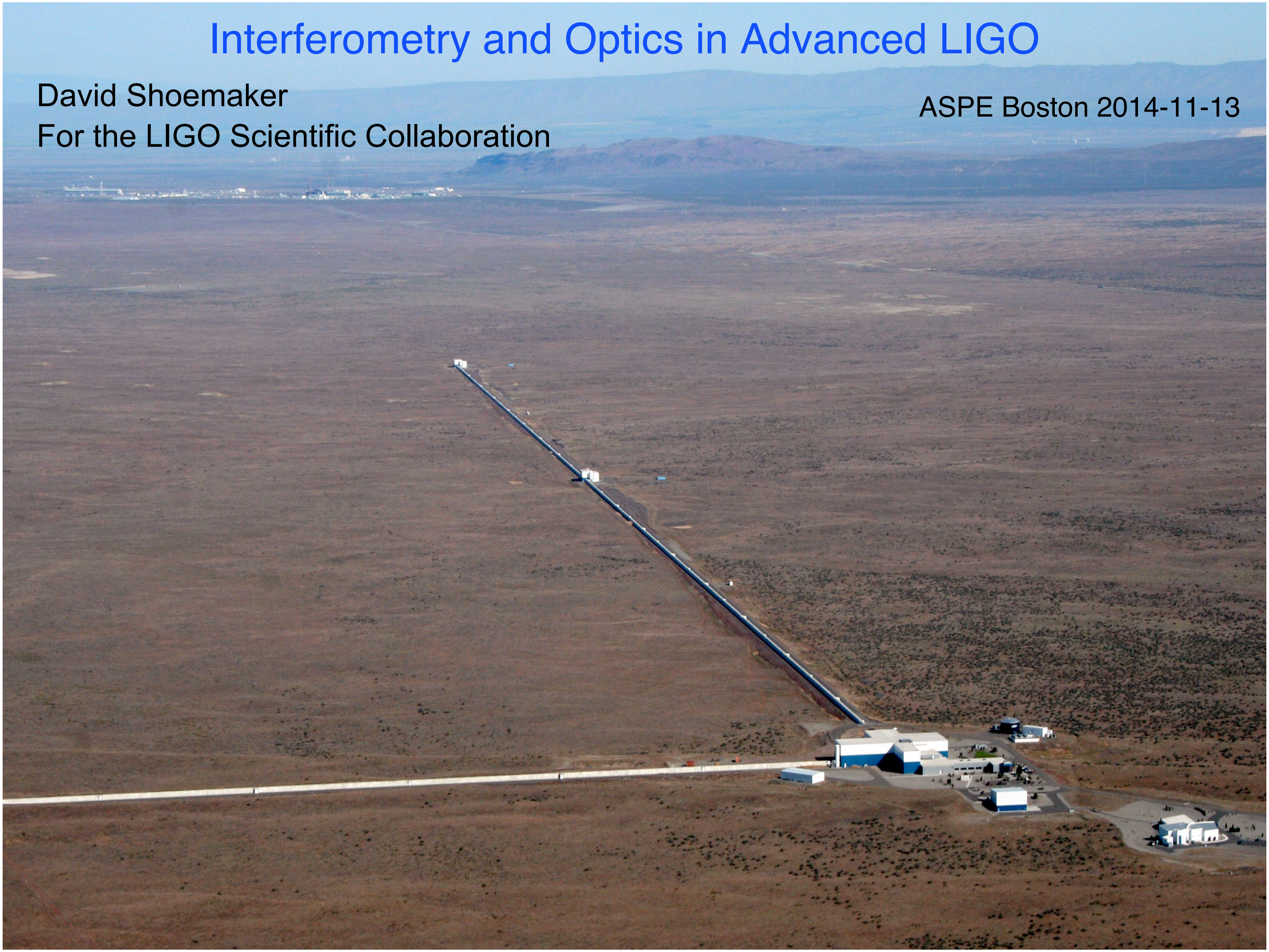
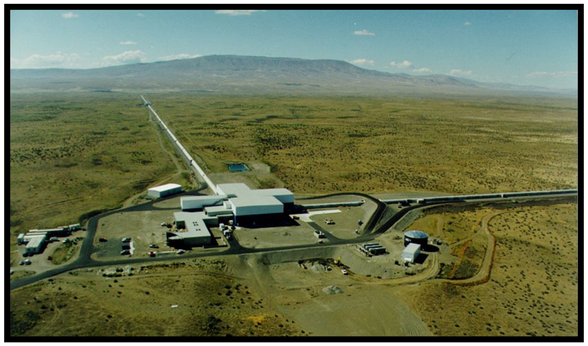
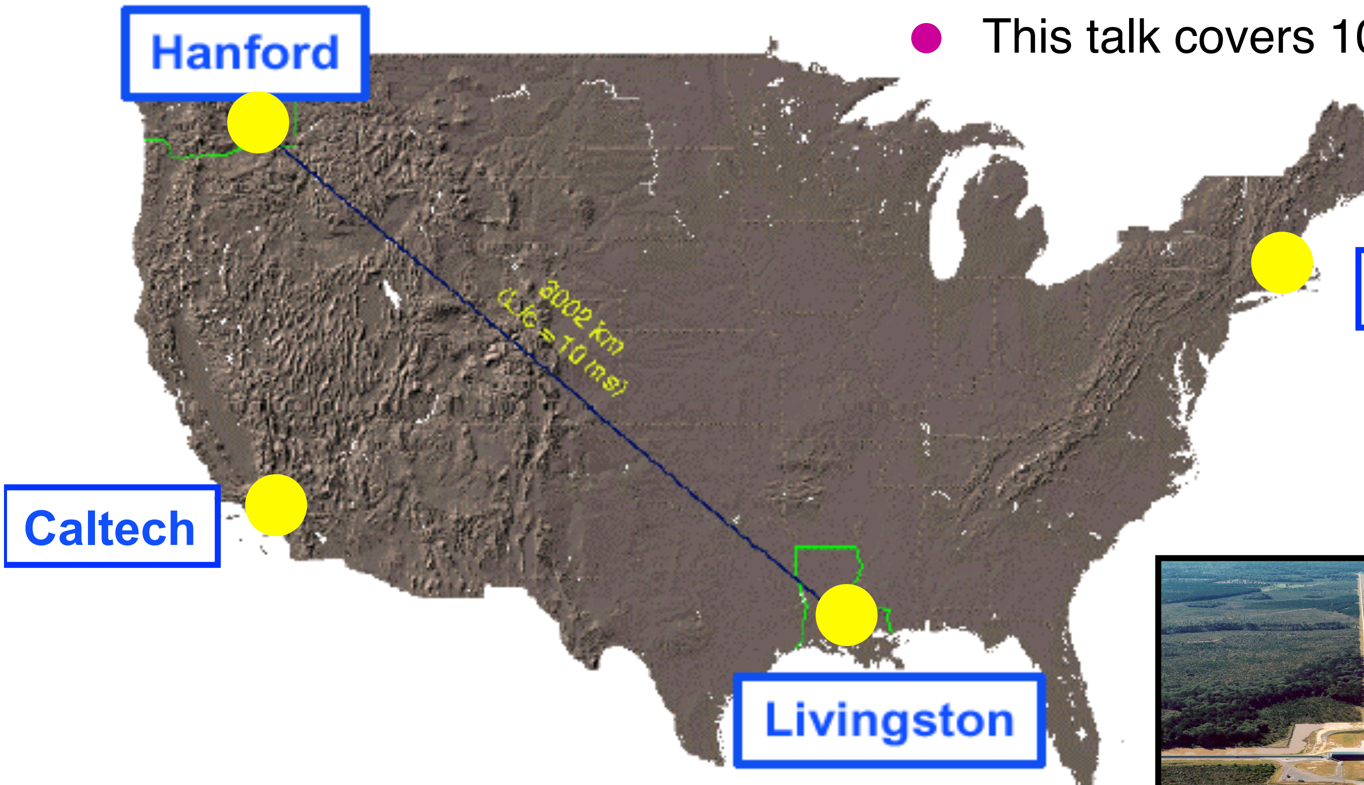


LIGO Laboratory: two Observatories and Caltech, MIT campuses

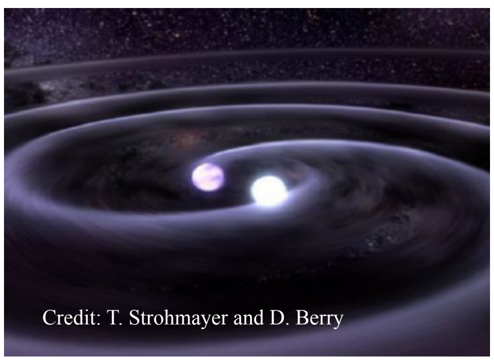


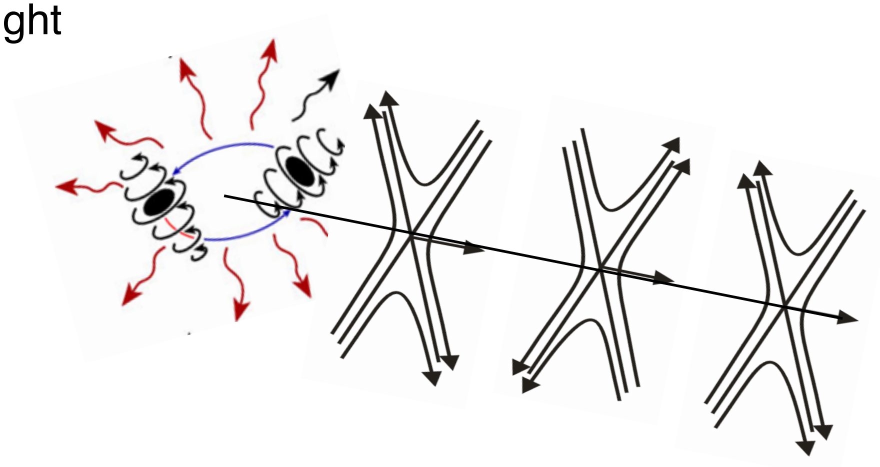
- Mission: Develop gravitational-wave detectors; Operate them as astrophysical observatories
- Jointly managed by Caltech and MIT
- Requires instrument science at the frontiers of physics fundamental limits
- This talk covers 10^{-21} of a very neat story!



Gravitational waves

- Gravitational waves are propagating dynamic fluctuations in the curvature of space-time ('ripples' in space-time)
- Emissions from rapidly accelerating non-spherical mass distributions
  - » Practically, need massive objects moving at speeds approaching the speed of light

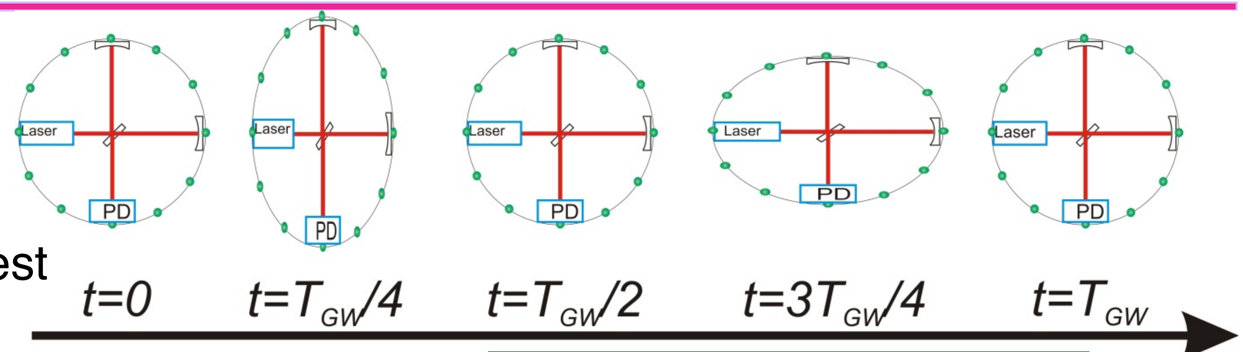




  - » According to GR, GWs propagate at the speed of light
  - » Quadrupolar radiation; two polarizations: h_+ and h_x
  - » **Physically, GWs are strains** → $h = \frac{\Delta L}{L}$
  - » **GWs carry direct information about the dynamics of matter**
  - » **Space is stiff… h is 10^{-21} for a ~monthly signal rate**

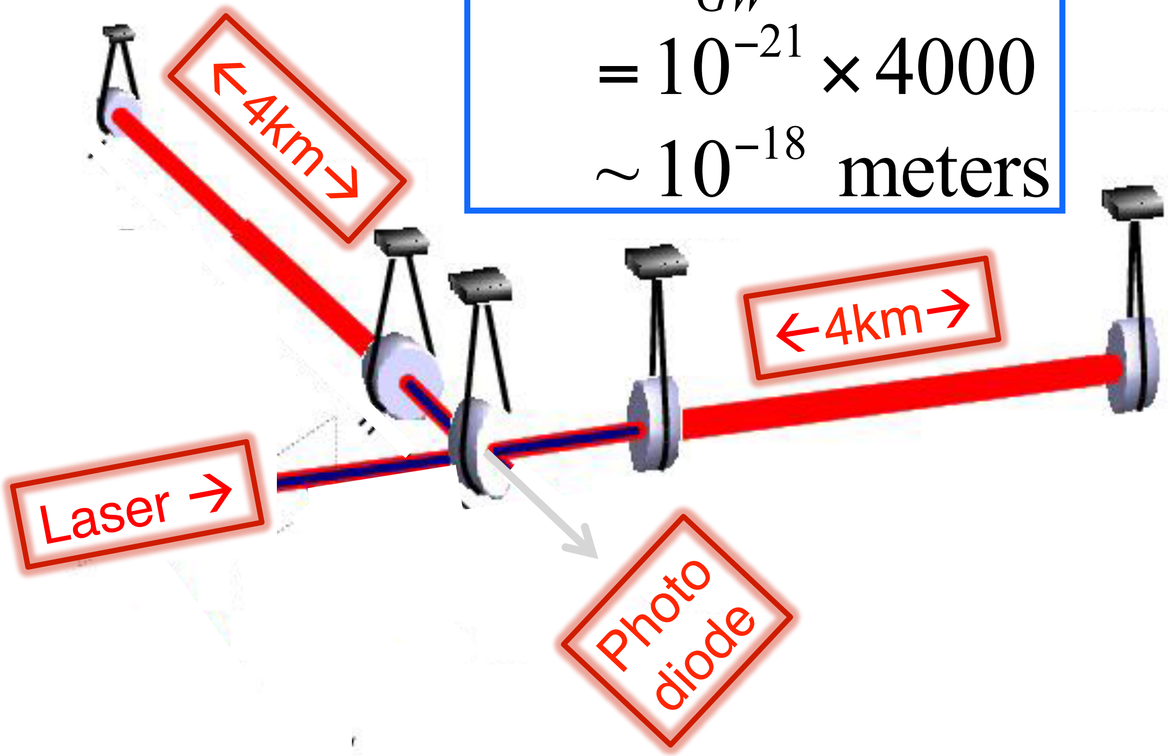
Interferometric Gravitational-wave Detectors

- Enhanced **Michelson interferometers**
- Passing GWs modulate the distance between the end test mass and the beam splitter

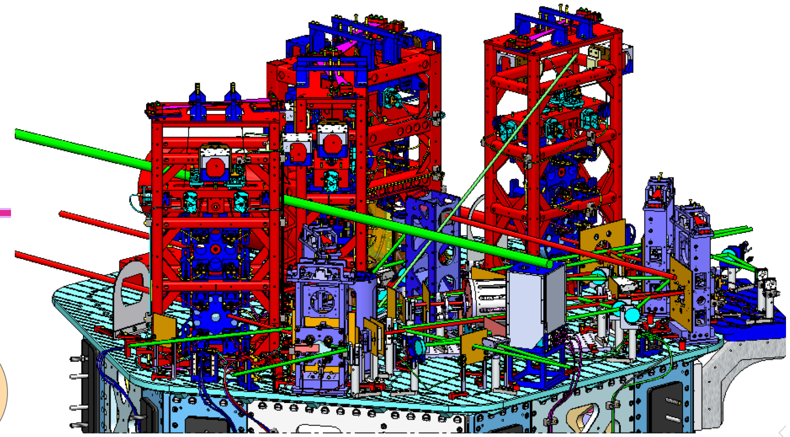


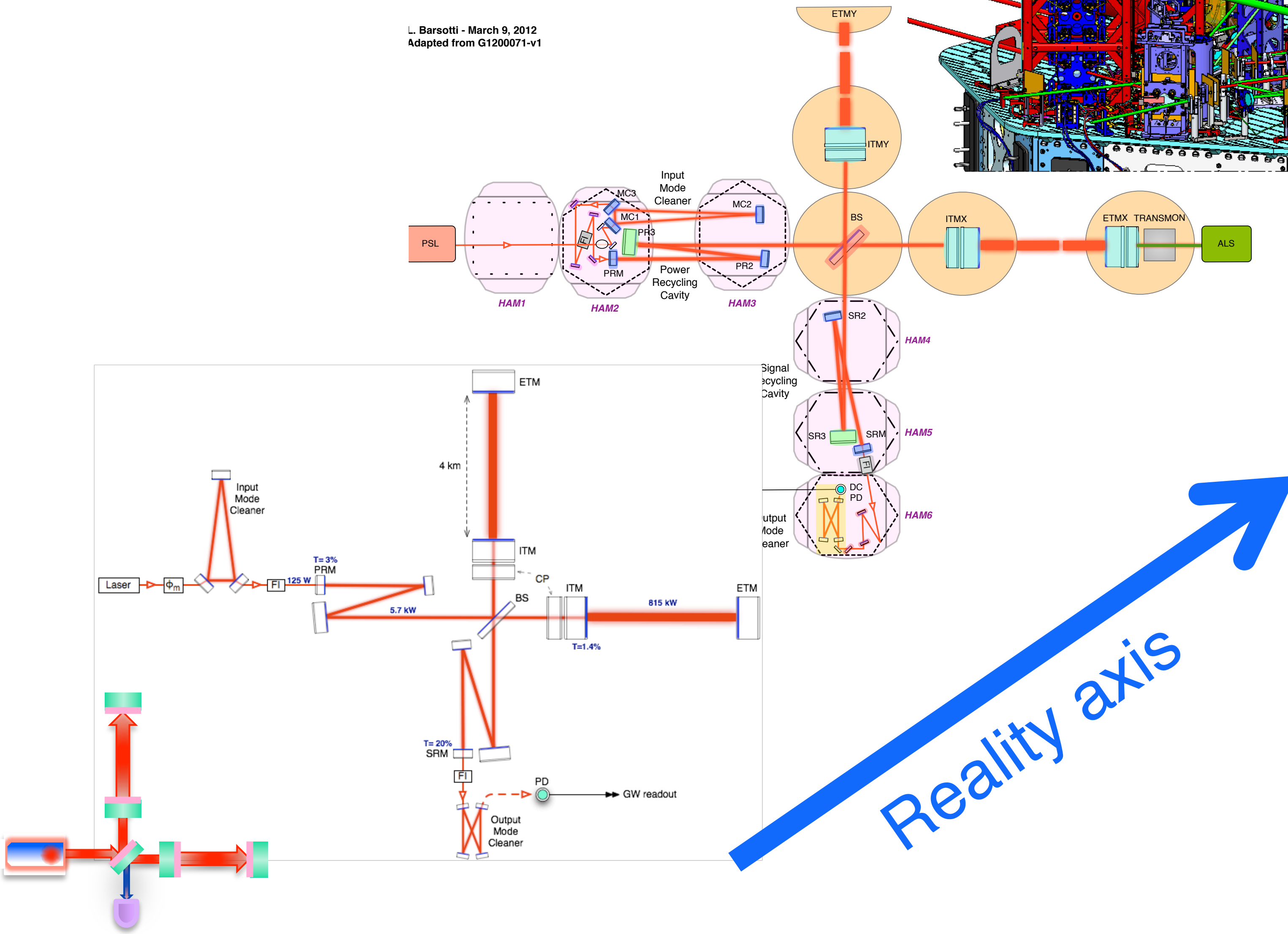
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- **Arms are short compared to GW wavelengths, so longer arms make bigger signals**
  → multi-km installations
- Arm length limited by taxpayer noise….

$$\Delta L = h_{GW} L$$
$$= 10^{-21} \times 4000$$
$$\sim 10^{-18} \text{ meters}$$



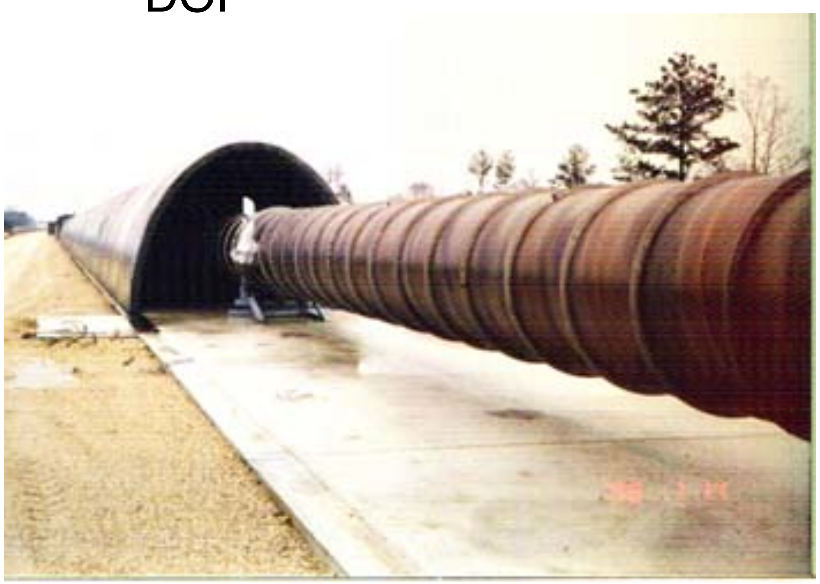
The real instrument is far more complex…





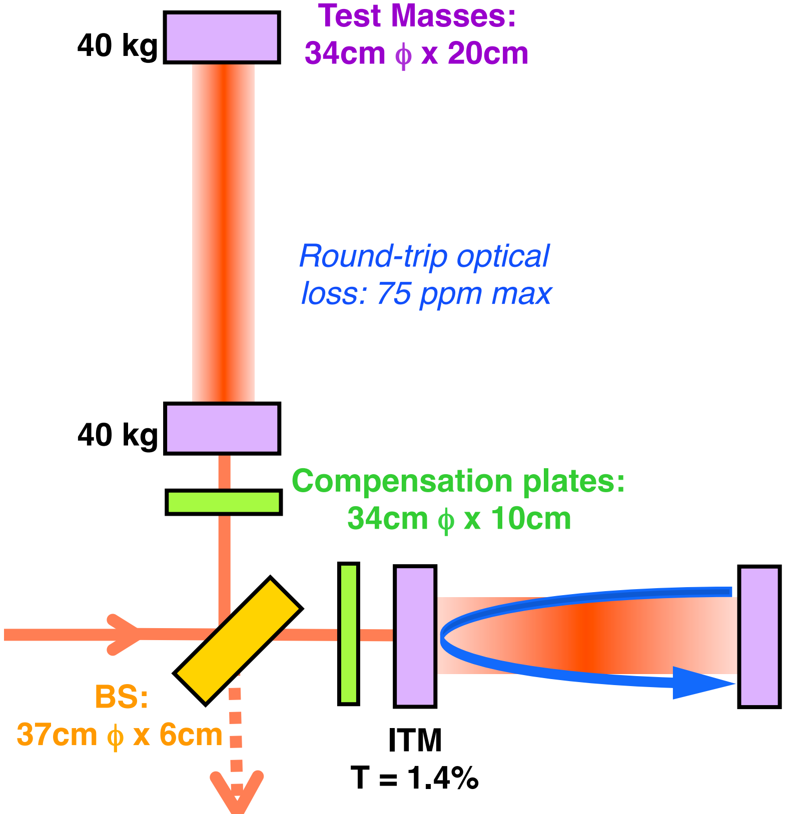
Design drivers

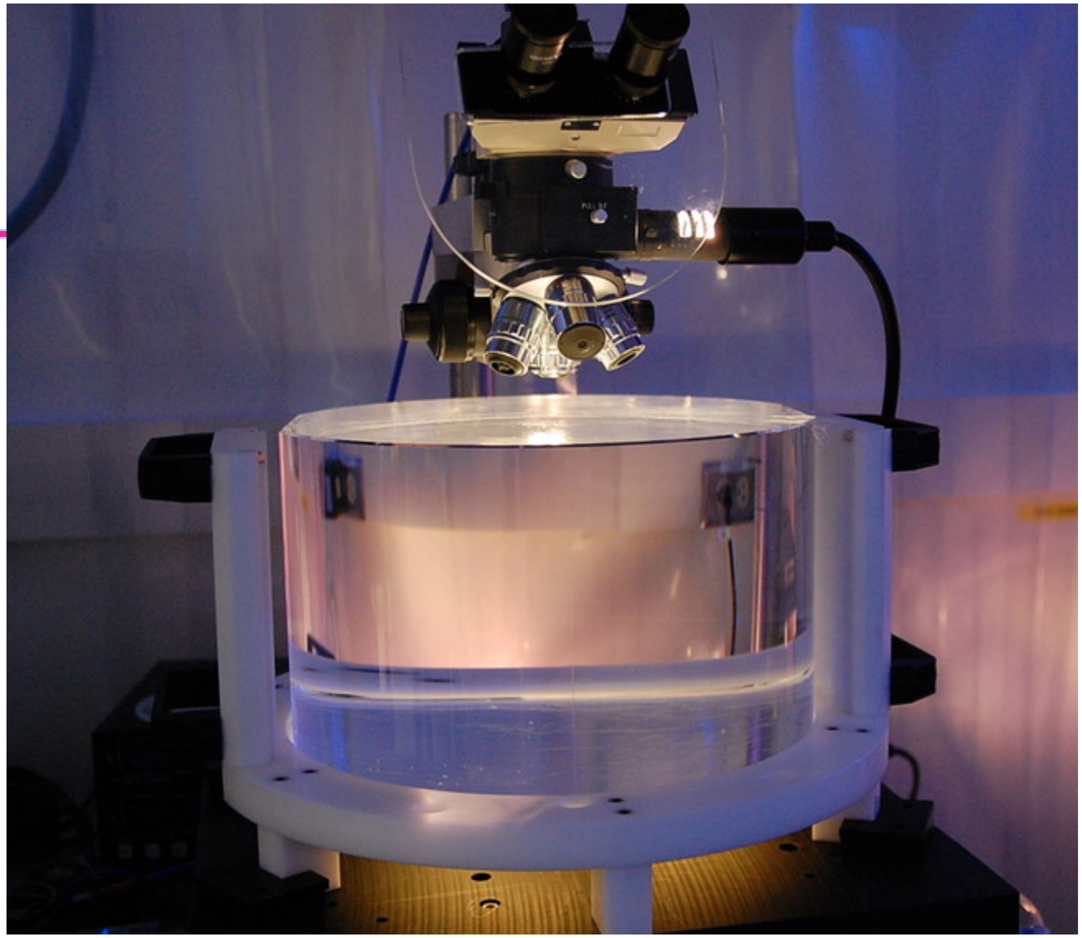
- Long arms and extreme interferometry lead to many design impacts
- World's biggest UHV vacuum system, straighter than earth's curvature
- Optics size – 1064 nm over 4km means beam spots of ~12 cm, 34cm optics
- Readout requirements of one part in 10^{10} of a fringe requires 200W CW Nd:YAG lasers, stabilized in frequency, intensity, and pointing; boosted to ~1 MW with optical resonant cavities
- Pointing and control requirements – hold 4km cavities on resonance to 10^{-15} m; point optics with microradian RMS motion; 5 coupled cavities, 21 coupled DOF
- Suppress seismic and anthropogenic noise input; another 18×5 + 12×5 MIMO DOF



LIGO Test Masses

- Requires the state of the art in substrates, polishing, coating
- Both the physical test mass – a free point in space-time – and a crucial optical element

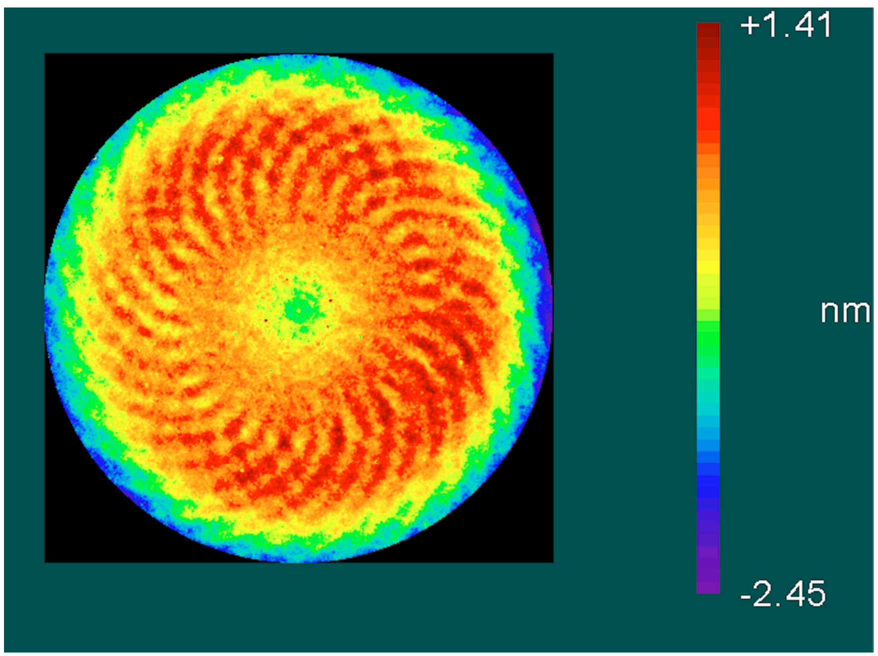


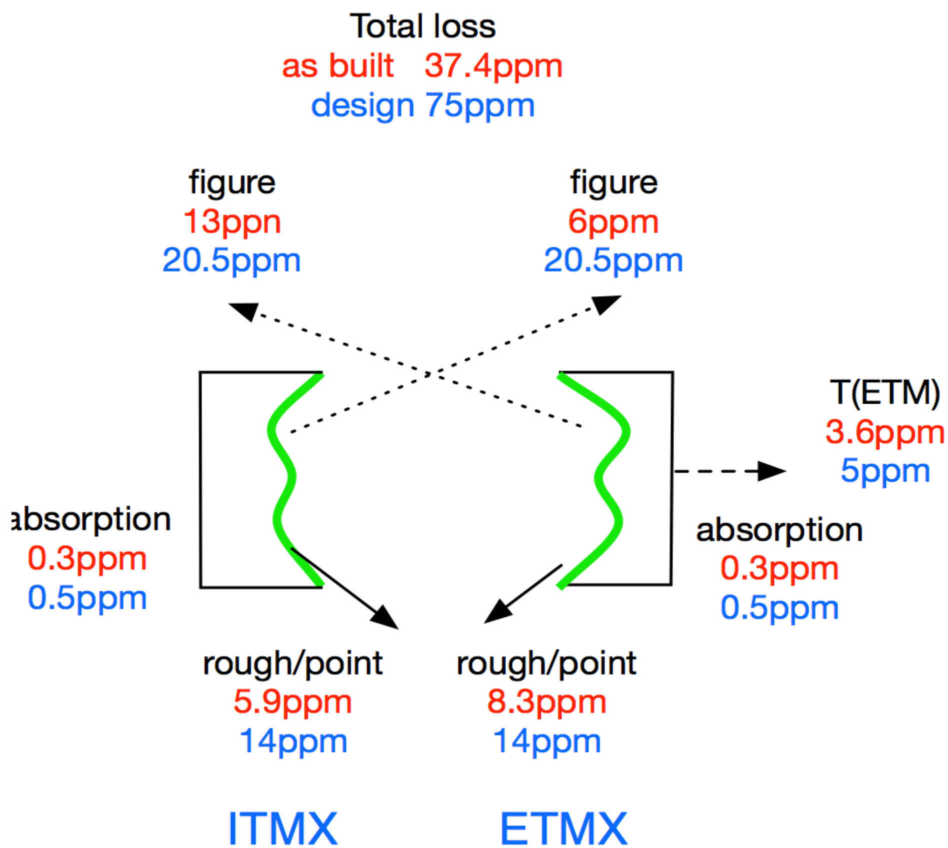


- Half-nm flatness over 300mm diameter
- 0.2 ppm absorption at 1064nm
- Coating specs for 1064 and 532 nm
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency

Test mass Optics figure

- In-house metrology on 300 mm diameter shows 0.66 nm RMS
  - » Note spiral from planetary system; about 0.2 nm pk-pk
- In-situ measurements of as-built 4km cavity show results are better than requirements!

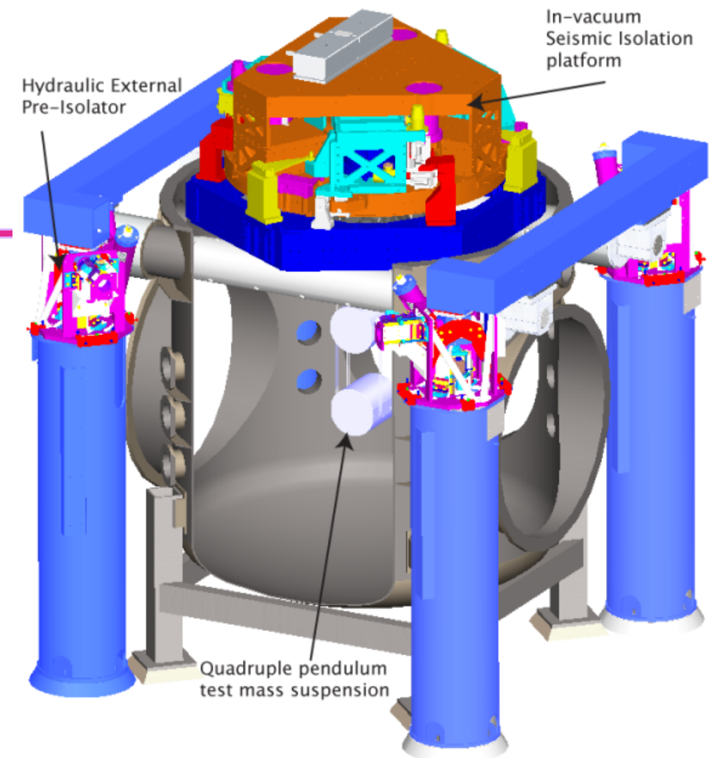


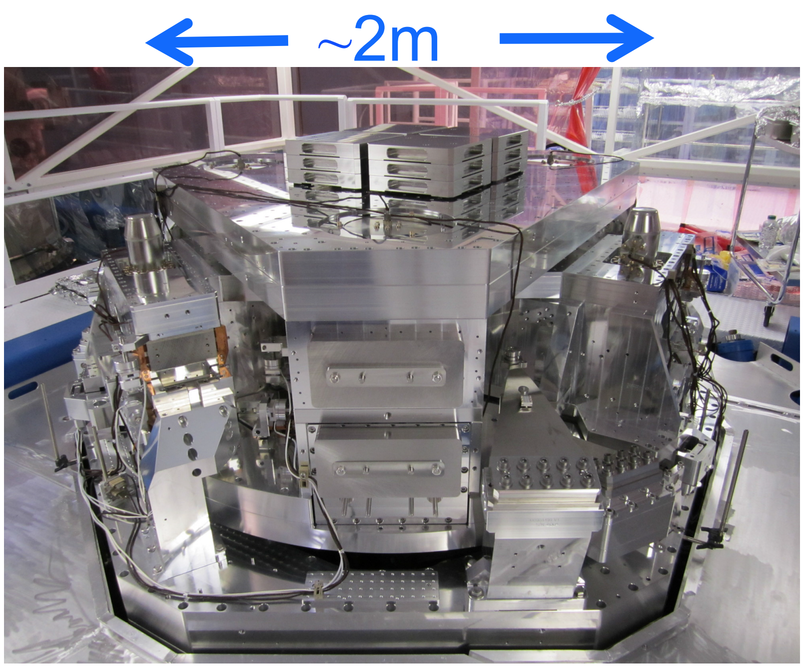


Seismic Isolation: Multi-Stage Solution

(talk by Matichard)

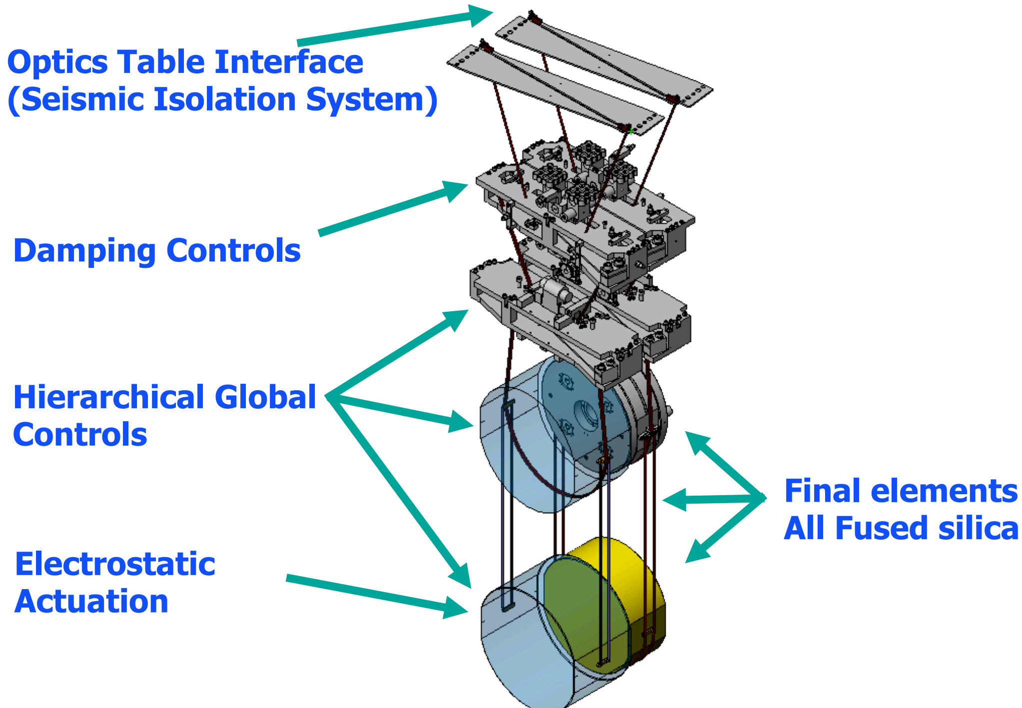
- Objectives:
  - » Render seismic noise a negligible limitation to GW searches
  - » Reduce actuation forces on test masses
- Both suspension and seismic isolation systems contribute to attenuation
- Choose an active isolation approach, 3 stages of 6 degrees-of-freedom :
  - » 1) Hydraulic External 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 and 1-ton payload still in inertial space
- At 10Hz: 10^{-12} m/rHz and -80 dB transmissibility



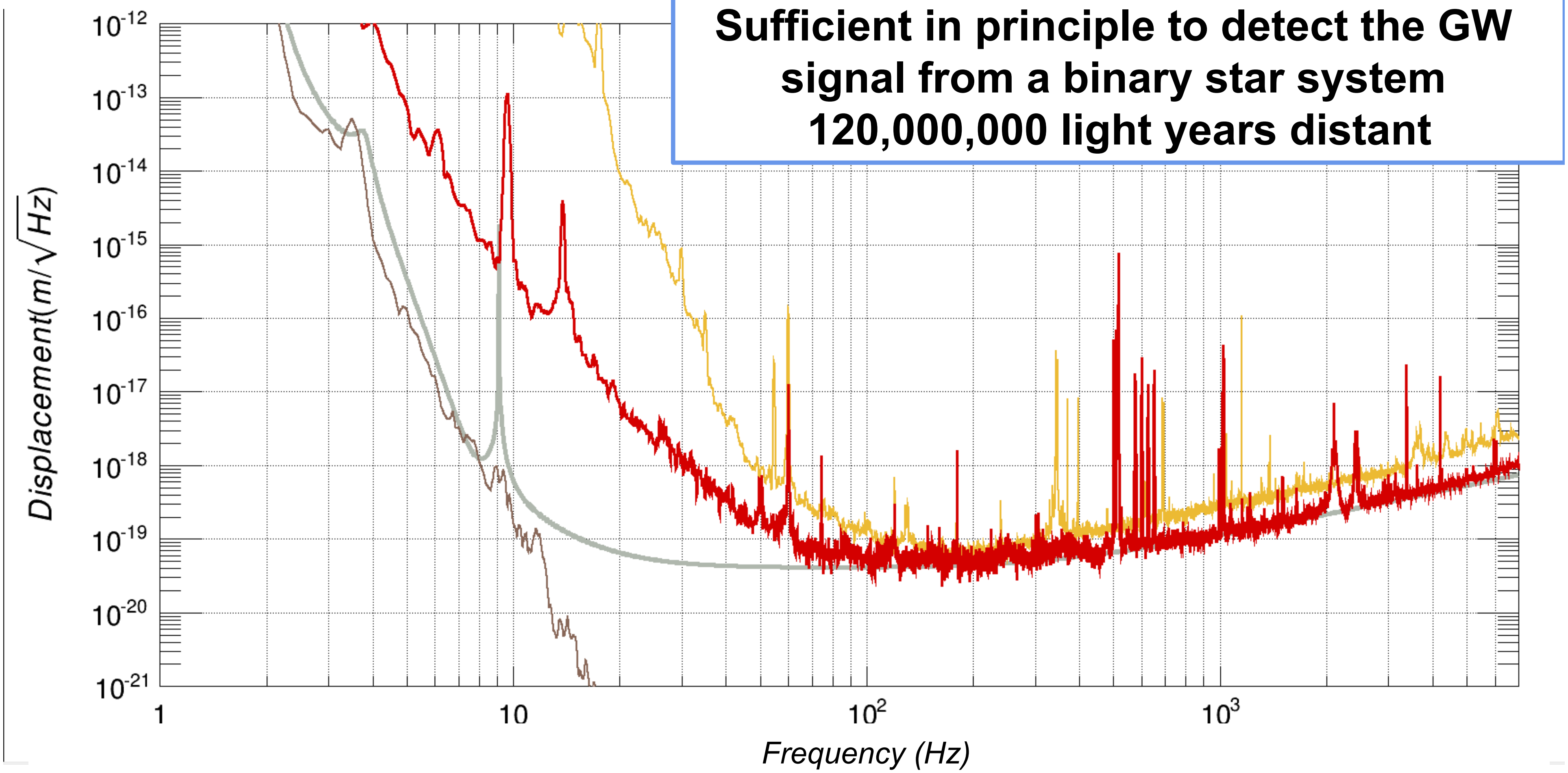


Test Mass Quadruple Pendulum suspension

- Quadruple pendulum suspensions for the test masses; 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! $Q = 10^9$
- Another element in hierarchical control system



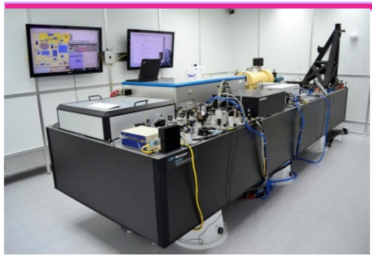
Advanced LIGO commissioning just starting – already more sensitive than any previous detector



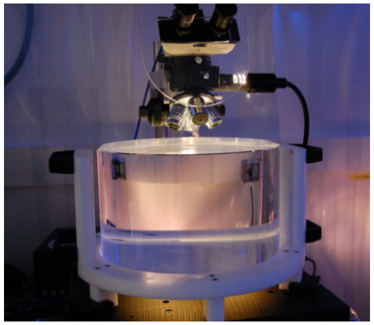
Sufficient in principle to detect the GW signal from a binary star system 120,000,000 light years distant

Accomplished in 4 months what it took ~ 4 years to do in Initial LIGO

The Last Page



- 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 observe in 2015
- The world-wide community is growing, and is working together toward the goal of gravitational-wave astronomy



www.advancedligo.mit.edu

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