Laser Interferometer Gravitational-Wave Detectors

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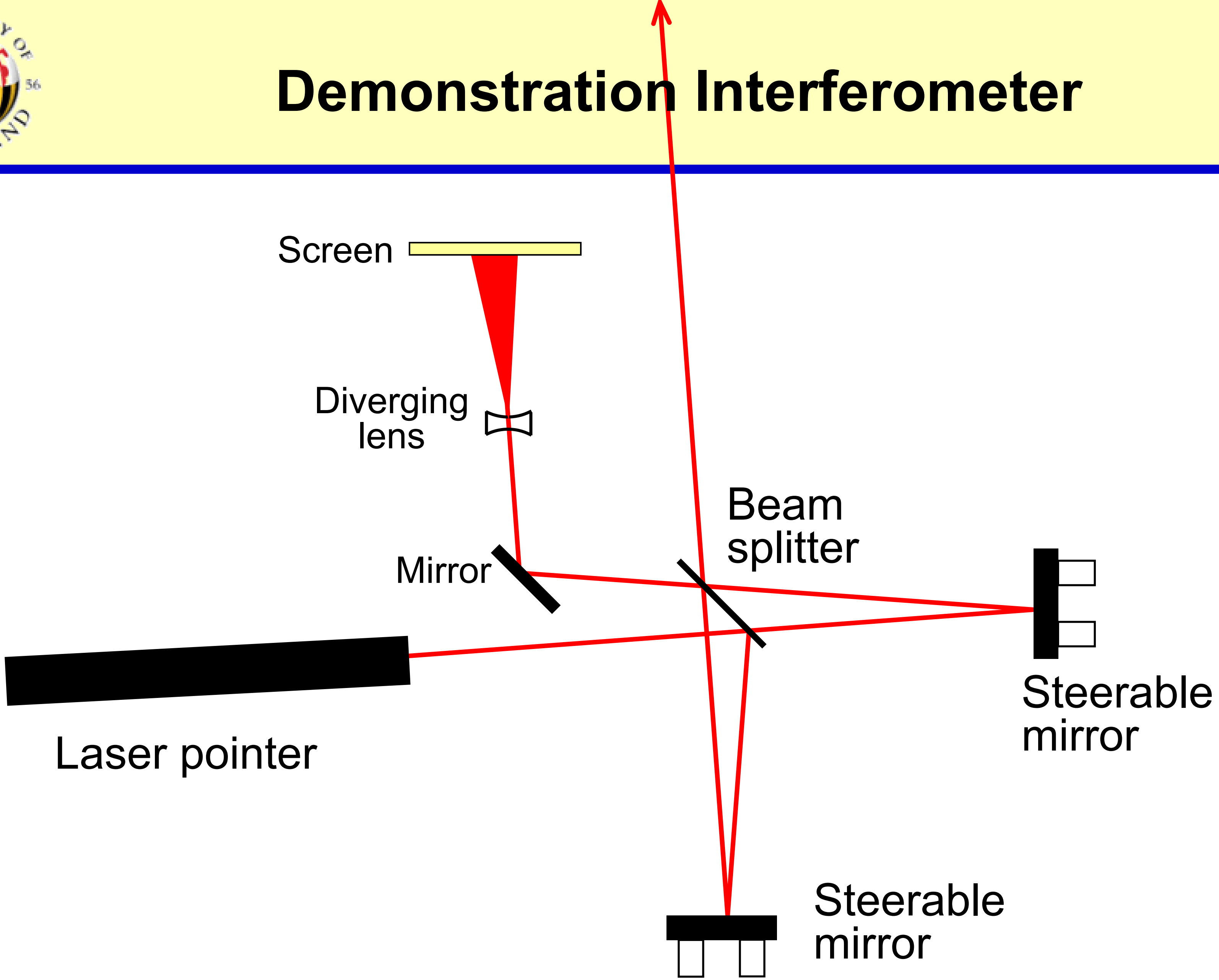
Outline

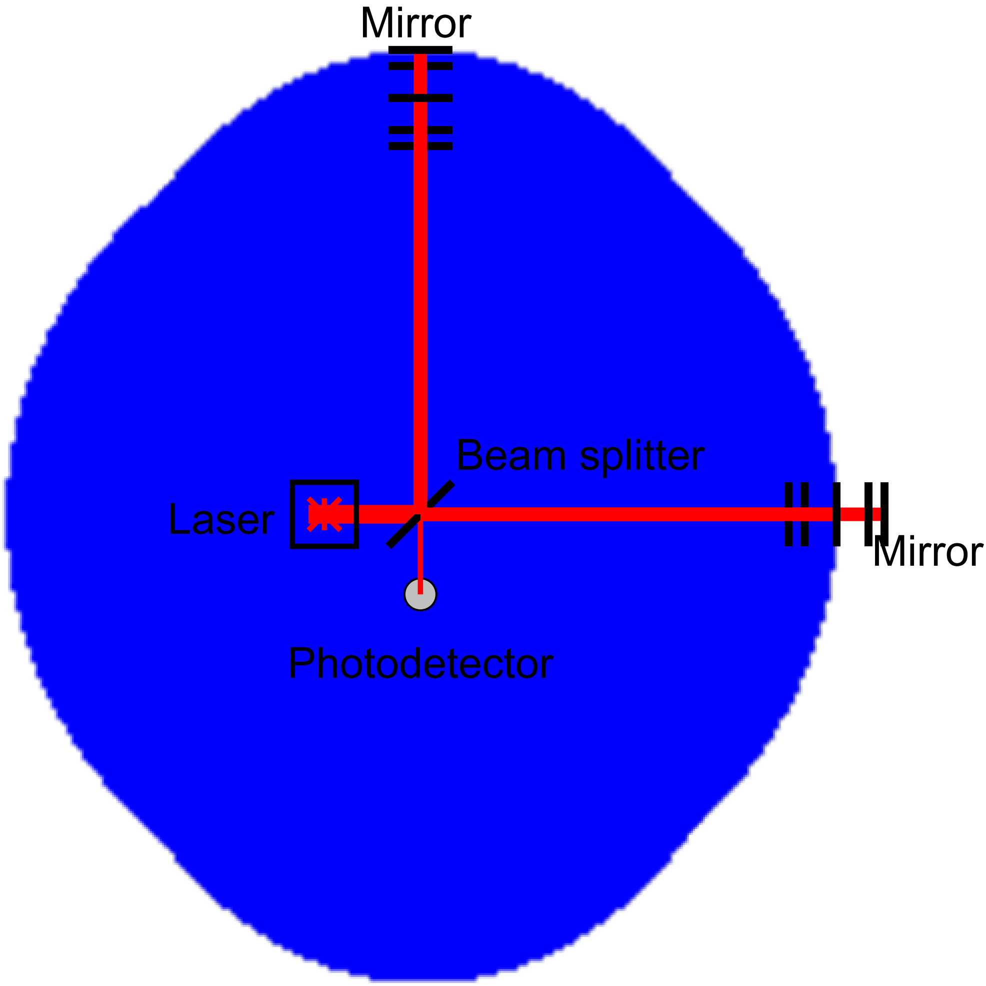
- **Interferometers as gravitational wave detectors**
- **Existing and planned detectors**
- **Instrumentation details** (with focus on LIGO)
  - Vacuum system
  - Laser
  - Optical layout
  - Mirrors
  - Vibration isolation
  - Servo controls
- **Interferometer operation**

Demonstration Interferometer



A Laser Interferometer as a Gravitational-Wave Detector

Measure *difference* in effective arm lengths to a fraction of a wavelength



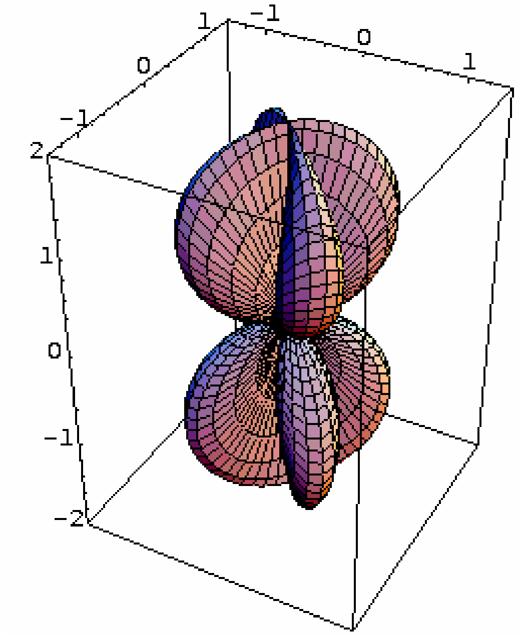
Strain $h = \Delta L / L$

Responds to one polarization projection

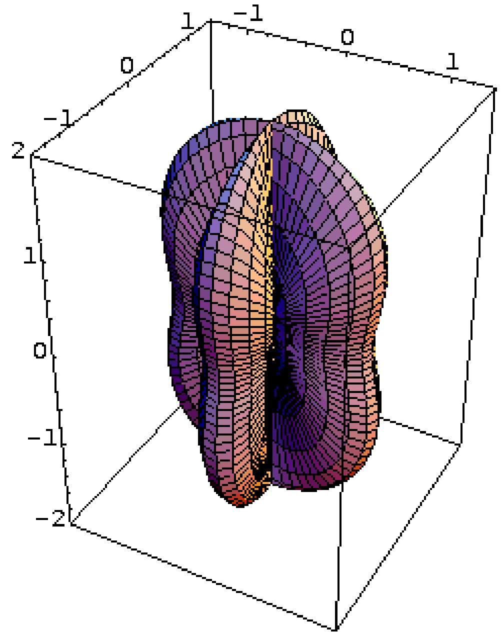
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

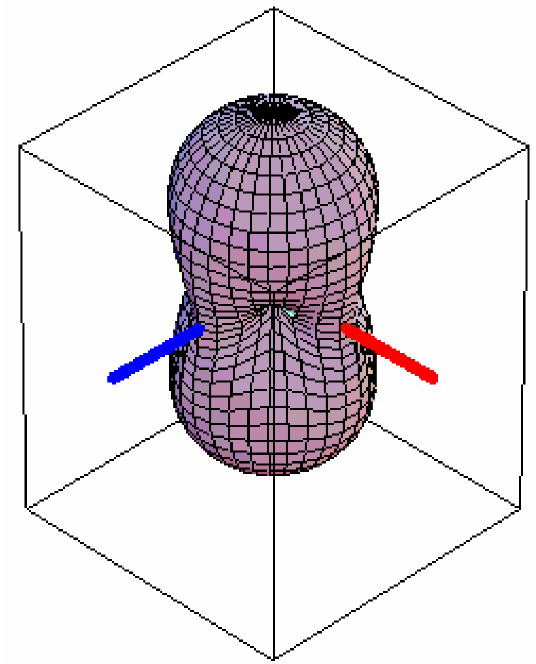
“×” polarization



“+” polarization



RMS sensitivity



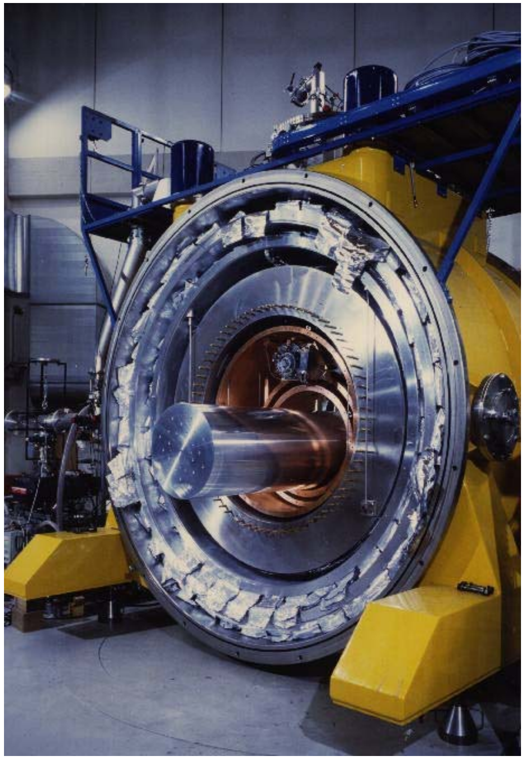
A broad antenna pattern

⇒ **More like a microphone than a telescope**

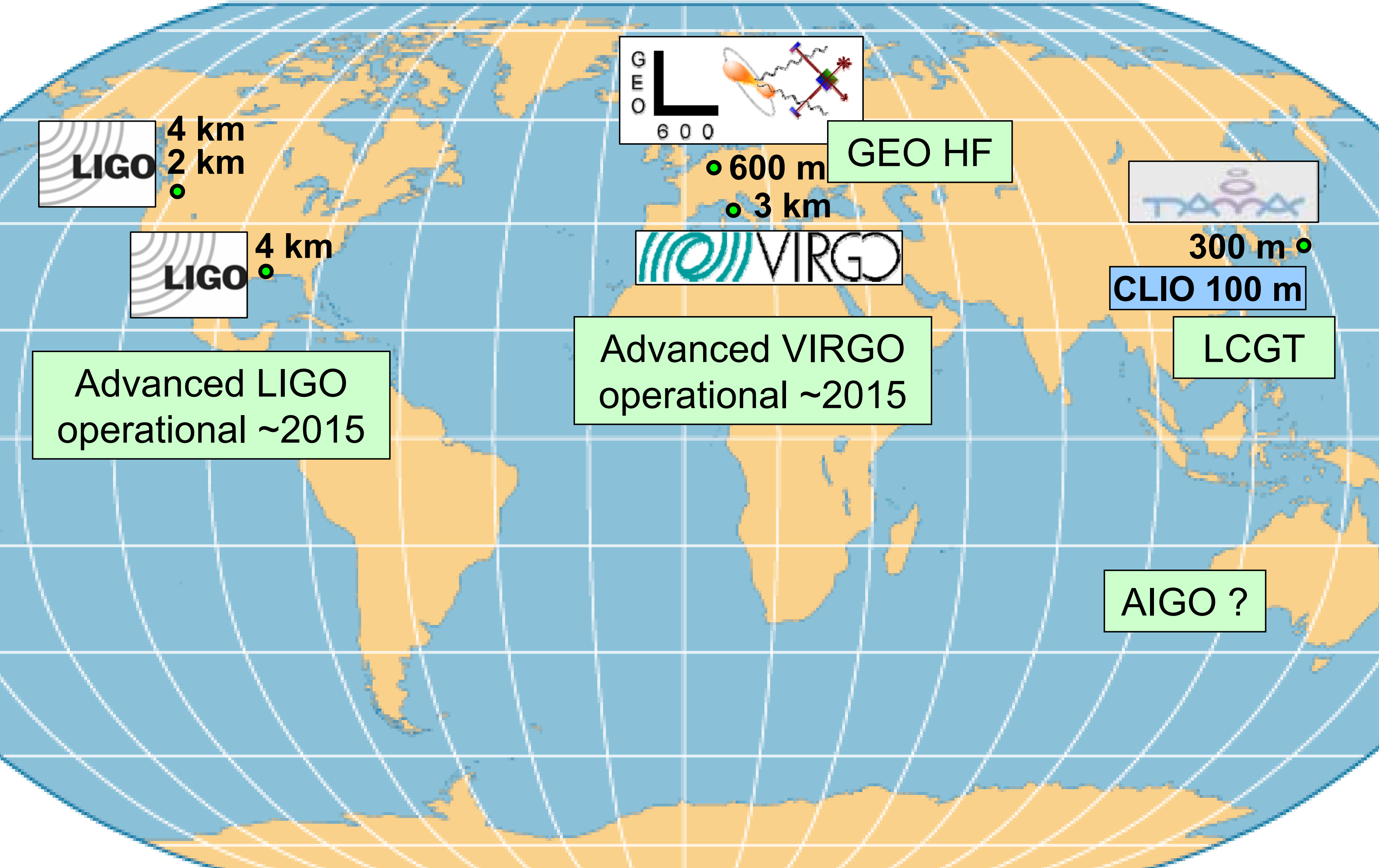
Comparison with Resonant Gravitational-Wave Detectors

Interferometers…

- ► can be made larger
- ► are not so limited by thermal noise
- ► are sensitive over a wider frequency band, including low frequencies
- ► cost more to build and operate



Existing and Planned Detectors



GEO HF

CLIO 100 m

Advanced LIGO operational ~2015

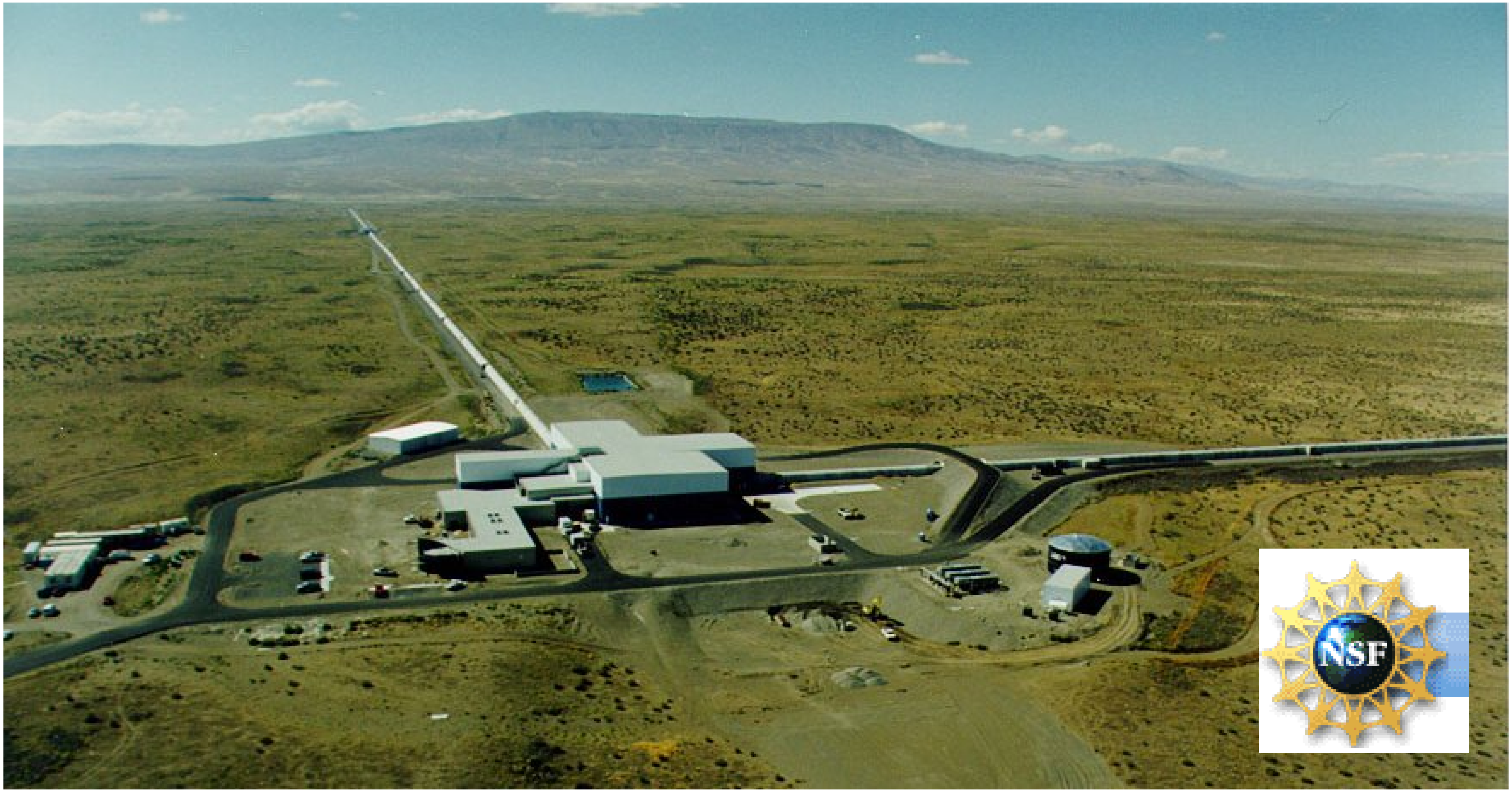
Advanced VIRGO operational ~2015

LCGT

AIGO ?

LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington



Two separate interferometers (4 km and 2 km arms) coexist in the beam tubes

LIGO Livingston Observatory

Located in a rural area of Livingston Parish east of Baton Rouge, Louisiana

One interferometer with 4 km arms

GEO 600

British-German project, located among fields near Hannover, Germany

VIRGO

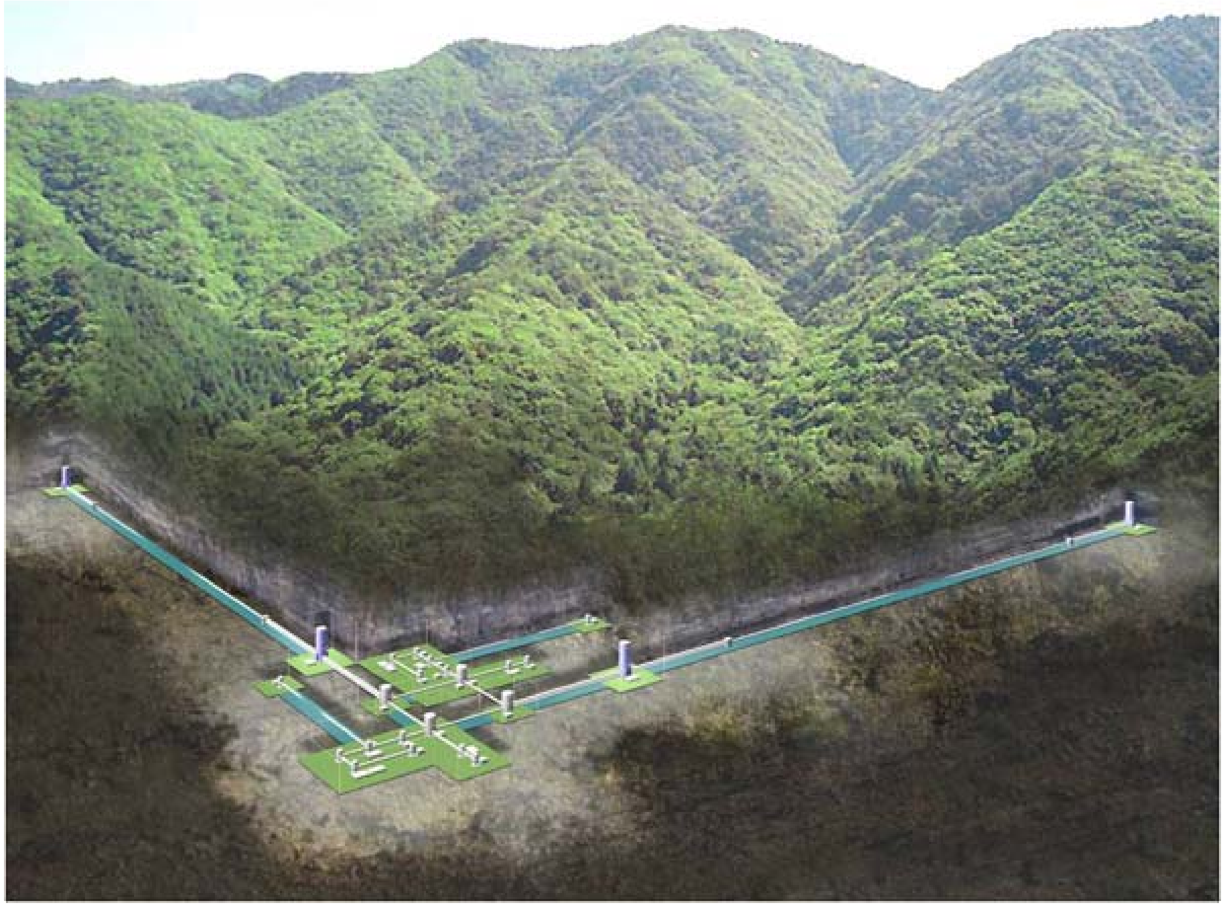
French-Italian project, located near Pisa, Italy

3 km arms

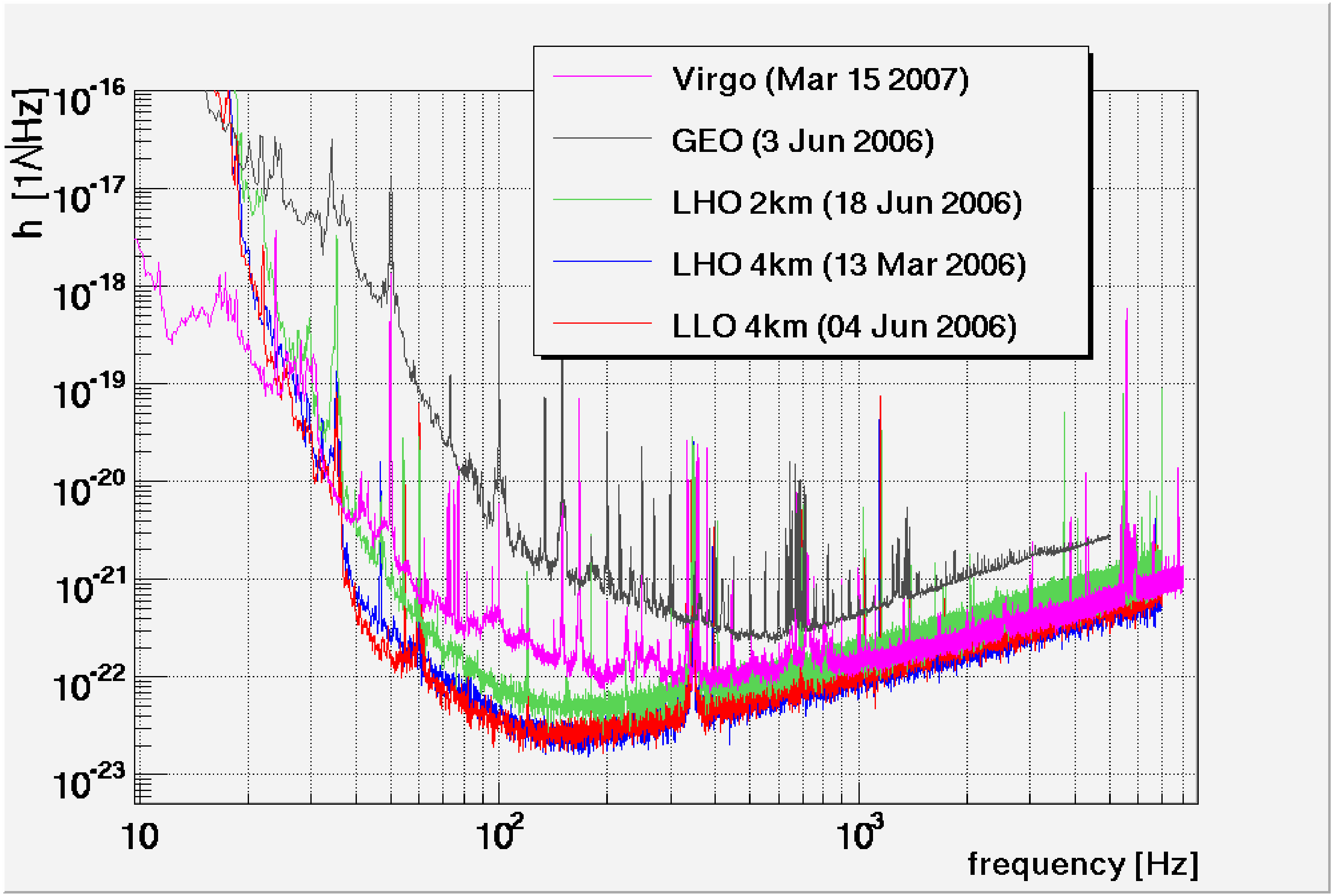
LCGT (Large-scale Cryogenic Gravitational-wave Telescope)

Planned to be constructed inside Kamioka mine

Funding being requested from Japanese government



Current Sensitivities for Gravitational-Wave Strain



Design Requirements

Even with 4-km arms, the length change due to a gravitational wave is *very* small, typically ~ 10^{-18} – 10^{-17} m

Wavelength of laser light = 10^{-6} m

Need a more sophisticated interferometer design to reach this sensitivity

- Add partially-transmitting mirrors to form resonant optical cavities
- Use feedback to lock mirror positions on resonance

Need to control noise sources

- Stabilize laser frequency and intensity
- Use large mirrors to reduce effect of quantum light noise
- Isolate interferometer optics from environment

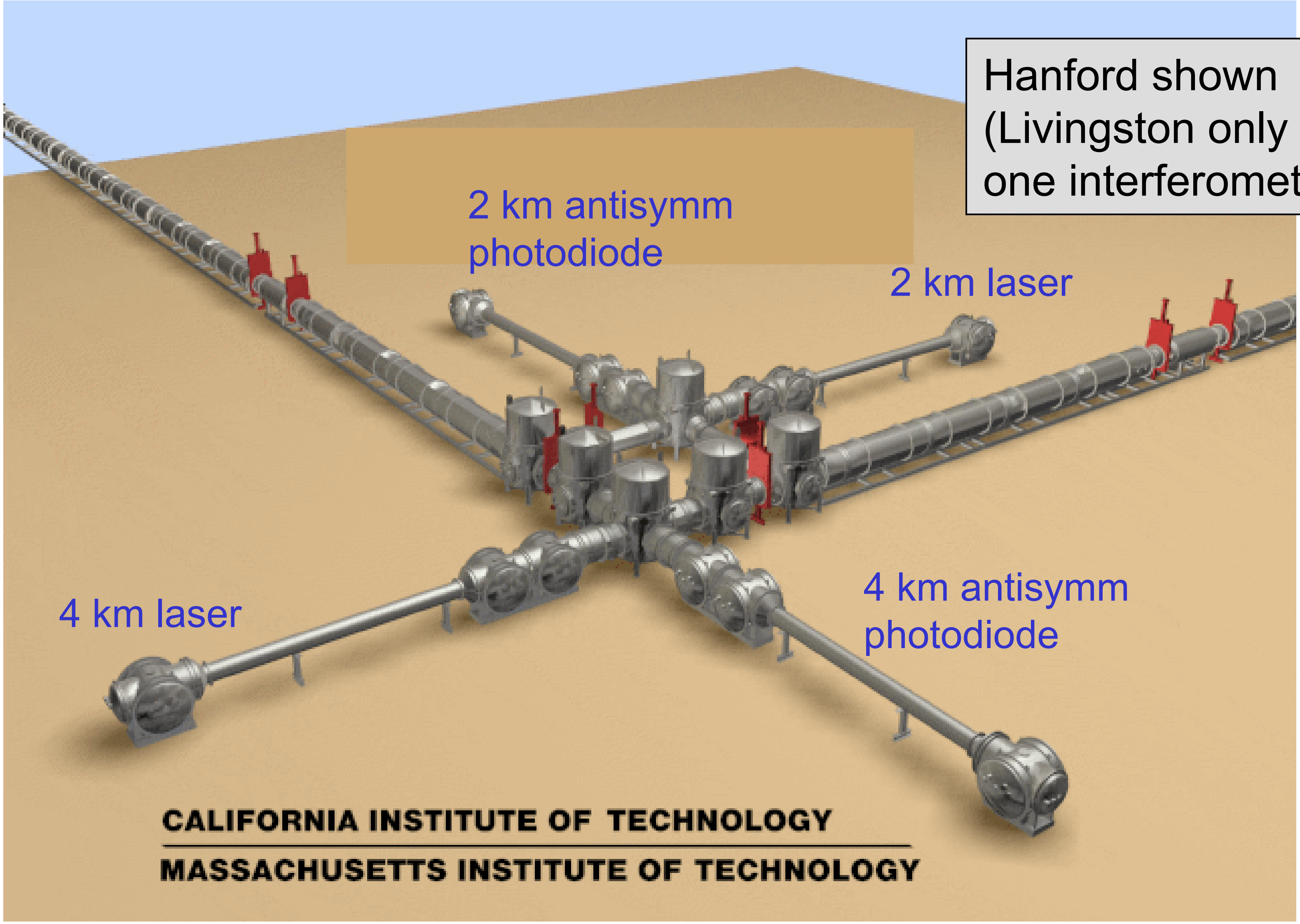
LIGO Beam Tube

Stainless steel, ~1 m in diameter, welded into 2 km lengths

Serrated baffles installed inside to disperse scattered light

Baked to drive off adsorbed water vapor

Vacuum System



Hanford shown (Livingston only has one interferometer)

Vacuum System

Pre-Stabilized Laser

Based on a 10-Watt Nd:YAG laser (infrared)

Uses additional sensors and optical components to locally stabilize the frequency and intensity

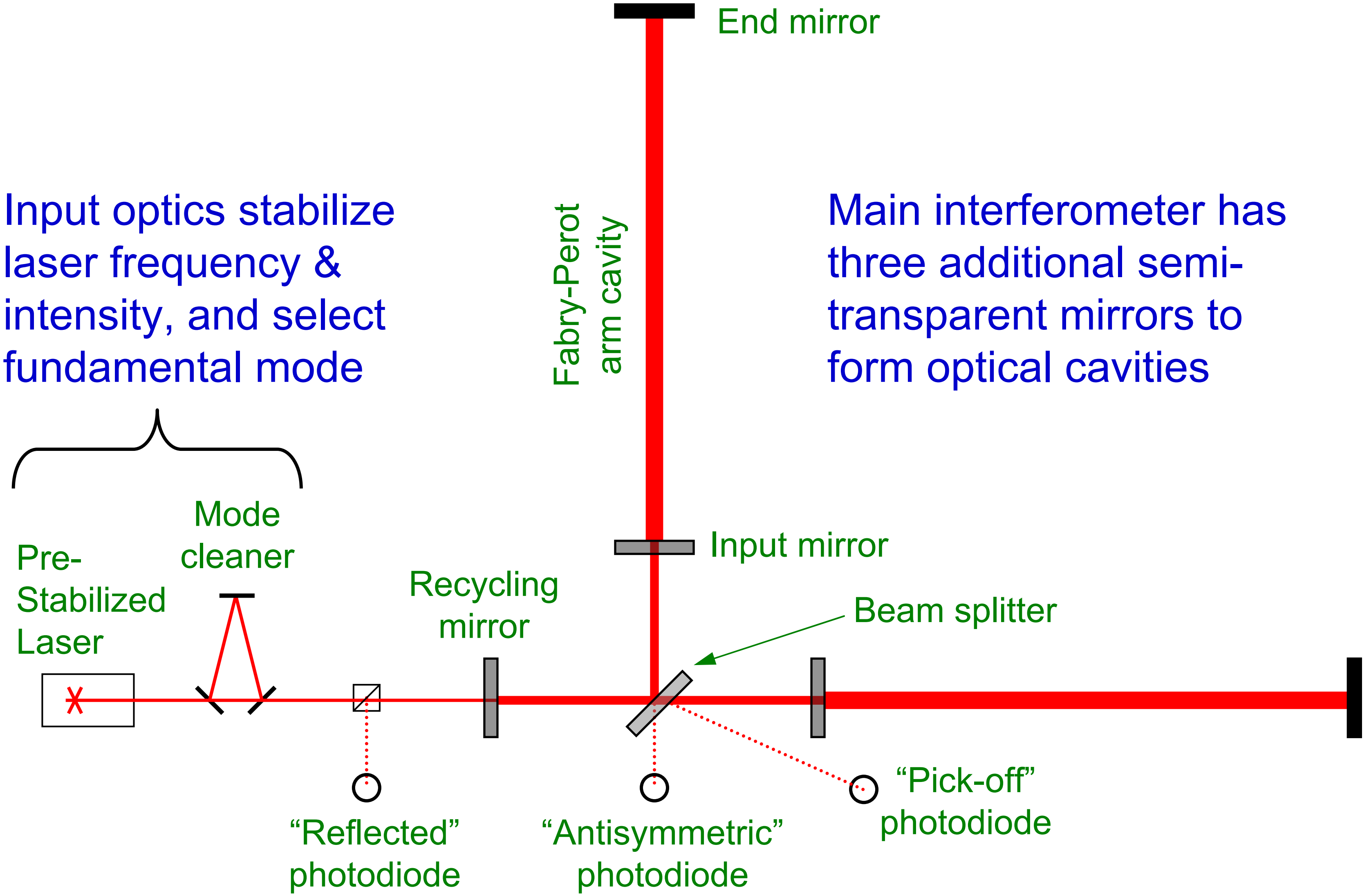

12/15/1998 9:59am

Final stabilization uses feedback from average arm length

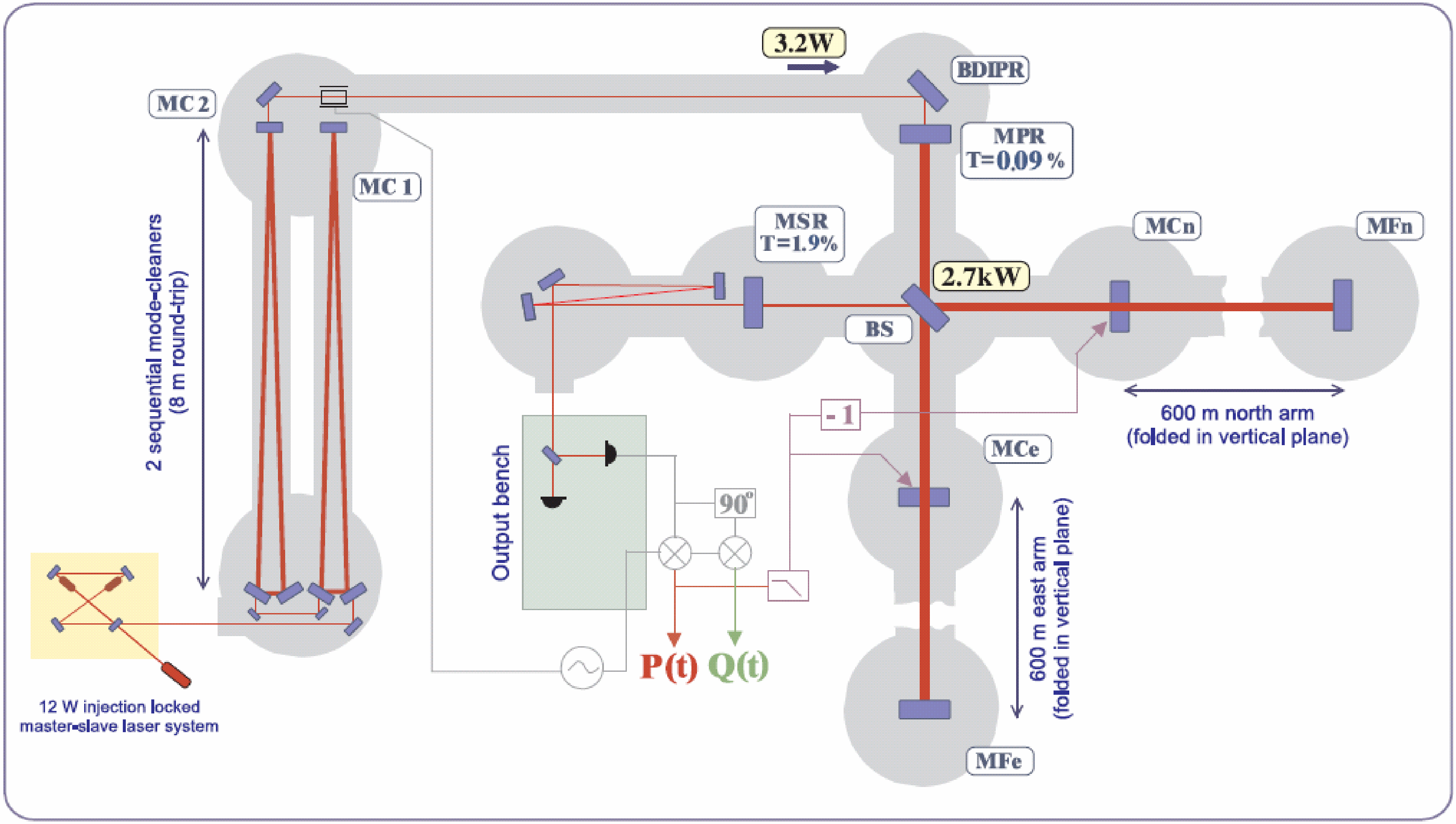
LIGO / VIRGO / TAMA Optical Layout
(not to scale)

Input optics stabilize laser frequency & intensity, and select fundamental mode

Main interferometer has three additional semi-transparent mirrors to form optical cavities



GEO 600 Optical Layout



No Fabry-Perot cavities, but dual recycling

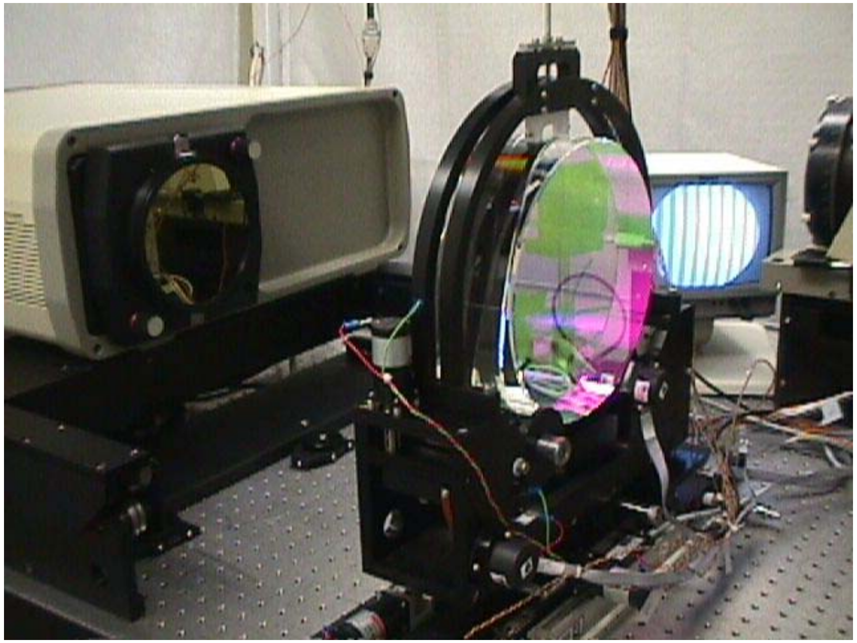
Mirrors

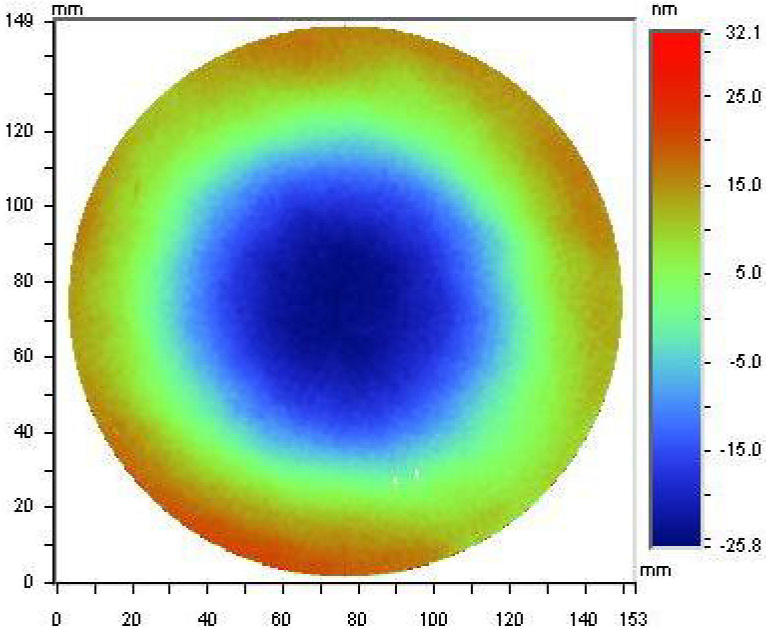
Made of high-purity fused silica

Largest mirrors are 25 cm diameter, 10 cm thick, 10.7 kg

Surfaces polished to ~1 nm rms, some with slight curvature

Coated to reflect with extremely low scattering loss (<50 ppm)





A Mirror *in situ*

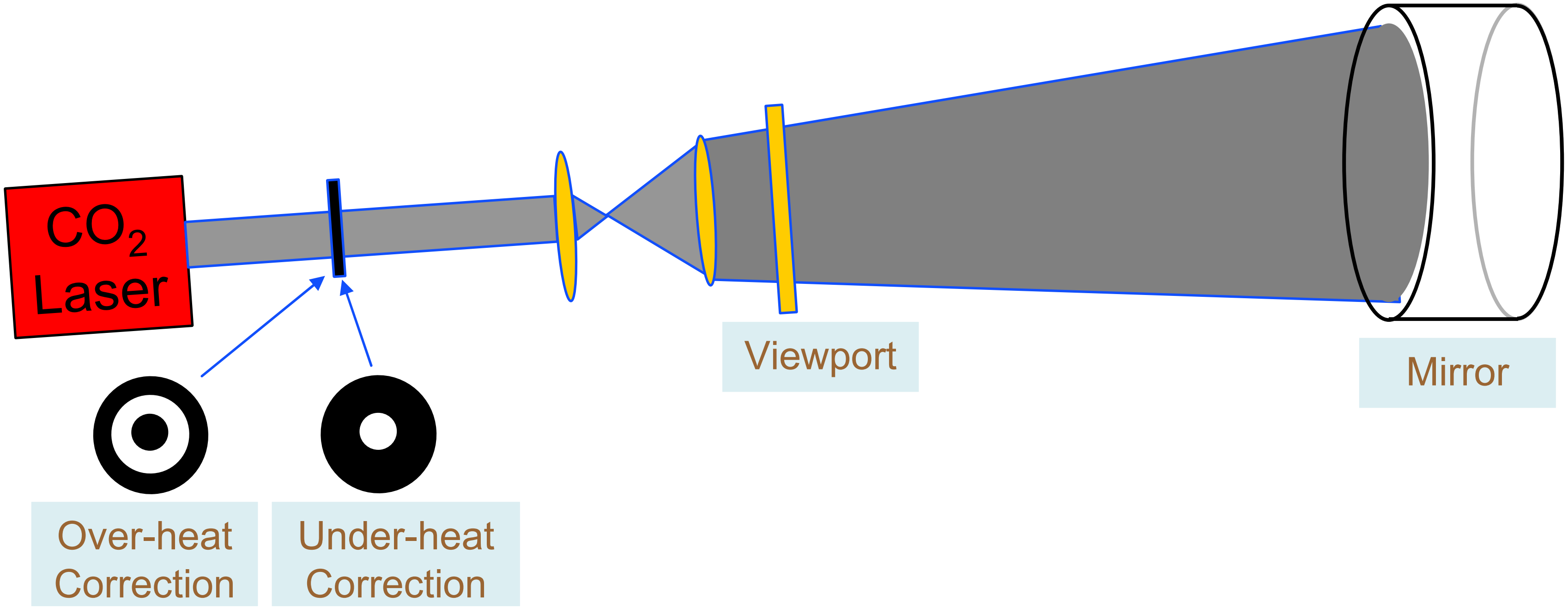
Handling High Laser Power

Use multiple photodiodes to handle increased light

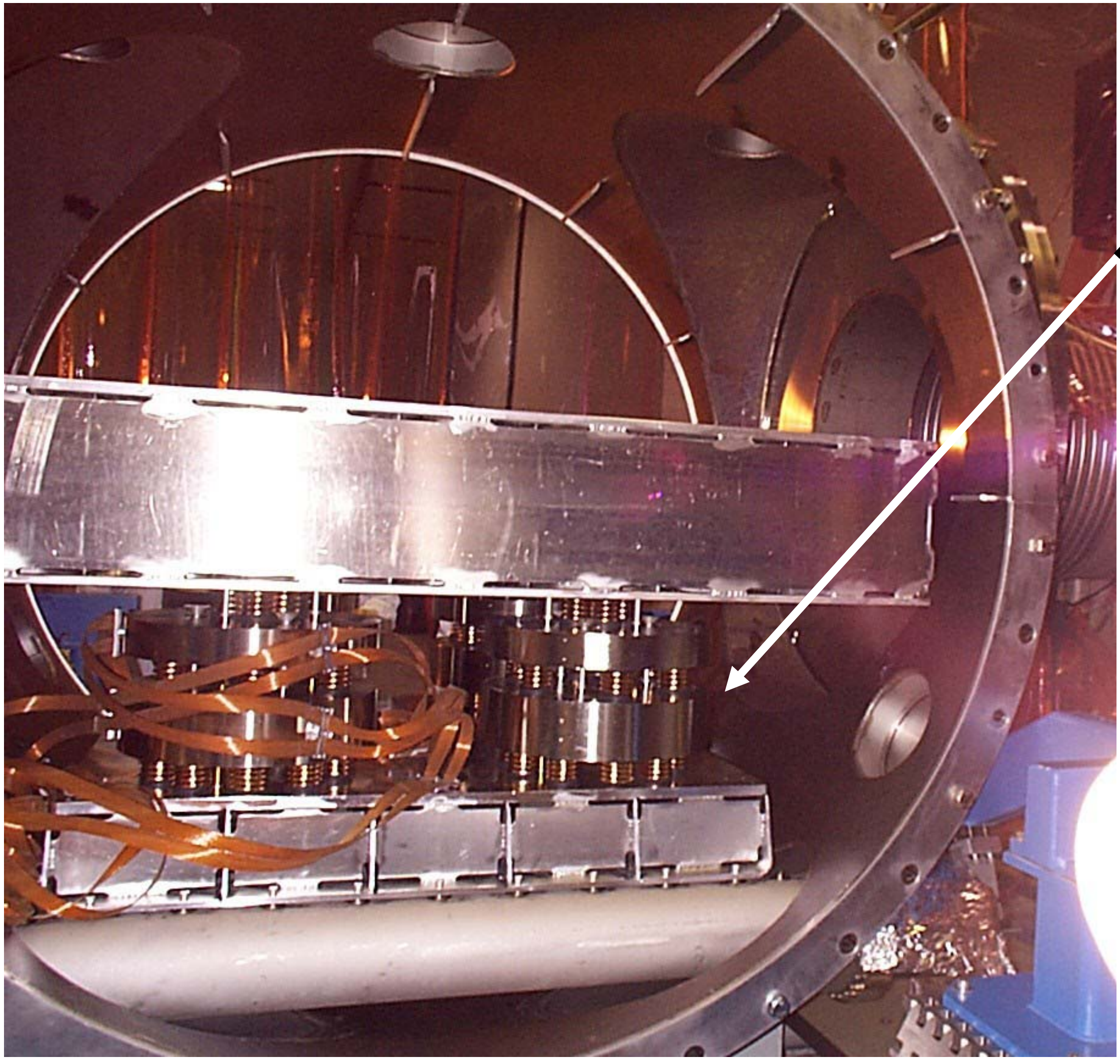
And fast shutters to protect photodiodes when lock is lost !

Compensate for radiation pressure in control software

Correct thermal lensing of mirrors by controlled heating

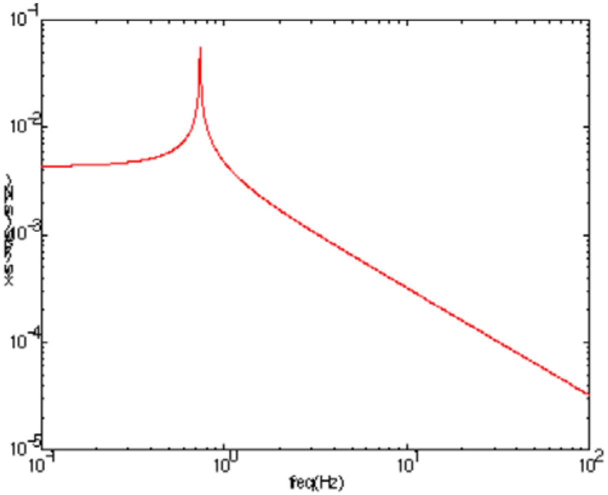


Vibration Isolation

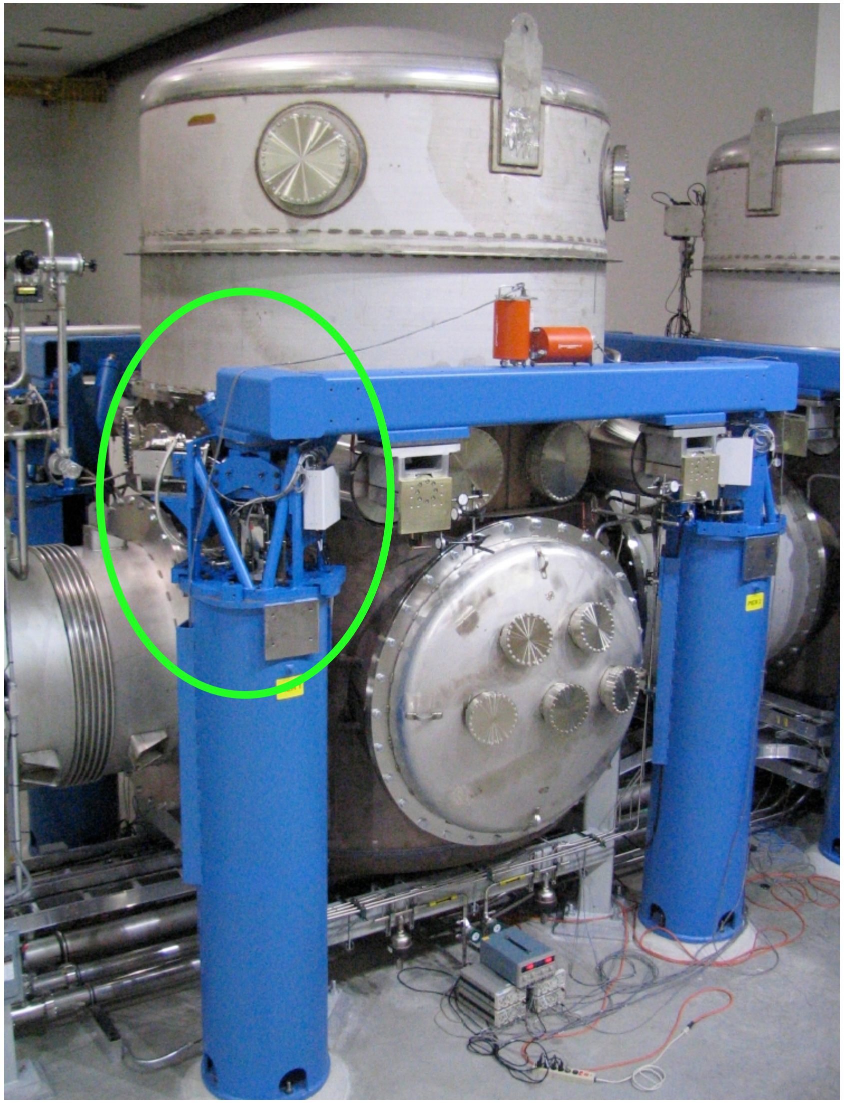


Optical tables are supported on “stacks” of weights & damped springs

Wire suspension used for mirrors provides additional isolation



Active Seismic Isolation at Livingston



Hydraulic external pre-isolator (HEPI)

Signals from sensors on ground and cross-beam are blended and fed into hydraulic actuators

Provides much-needed immunity against normal daytime ground motion at Livingston

Servo Controls

Optical cavities must be kept in resonance

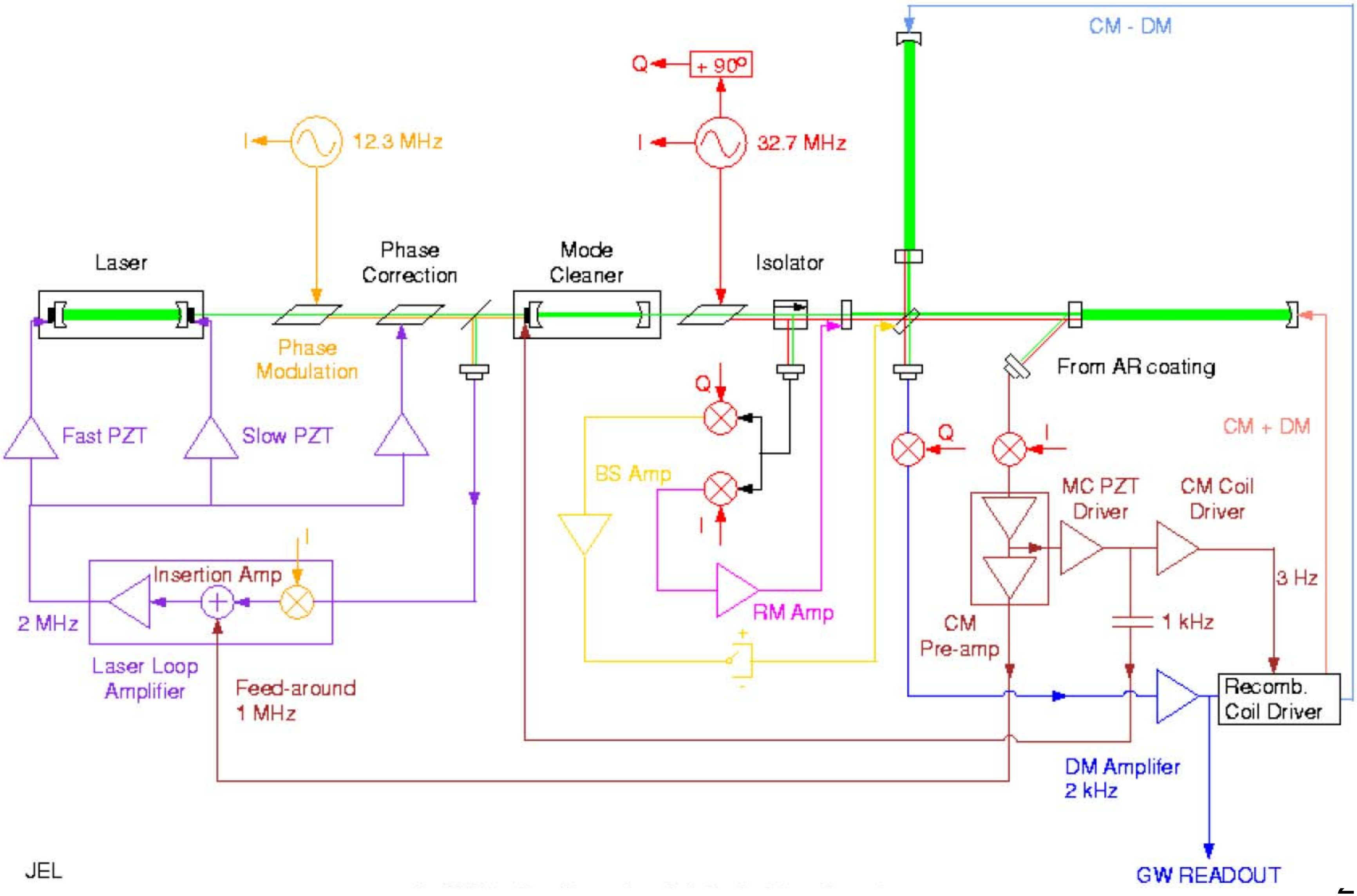
- Need to control lengths to within a small fraction of a wavelength – “lock”
- Nearly all of the disturbance is from low-frequency ground vibrations

Use a clever scheme to sense and control all four length degrees of freedom

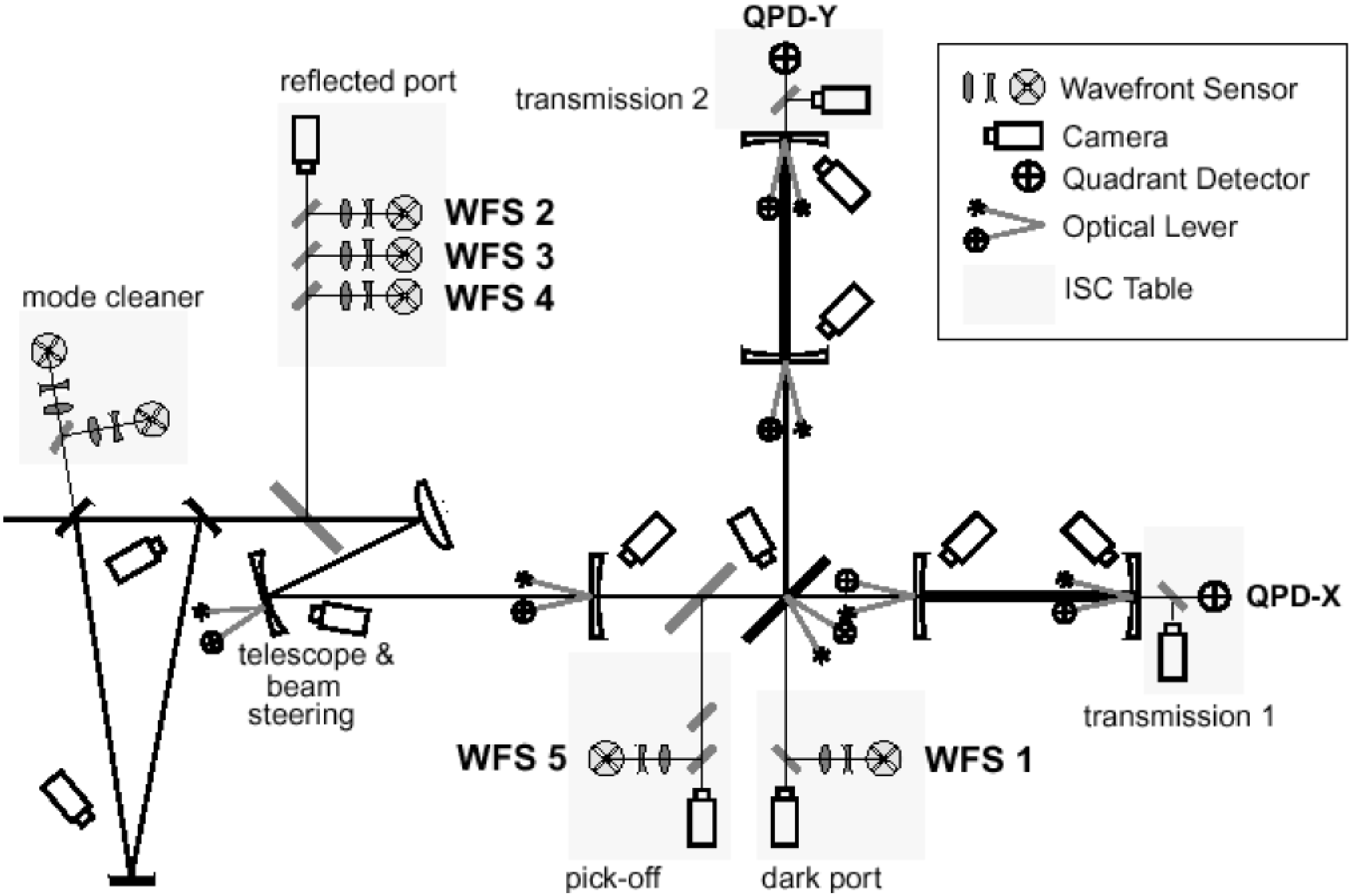
- Modulate phase of laser light at very high frequency
- Demodulate signals from photodiodes
- Disentangle contributions from different lengths, apply digital filters
- Feed back to coil-and-magnet actuators on various mirrors

Arrange for destructive interference at “antisymmetric port”

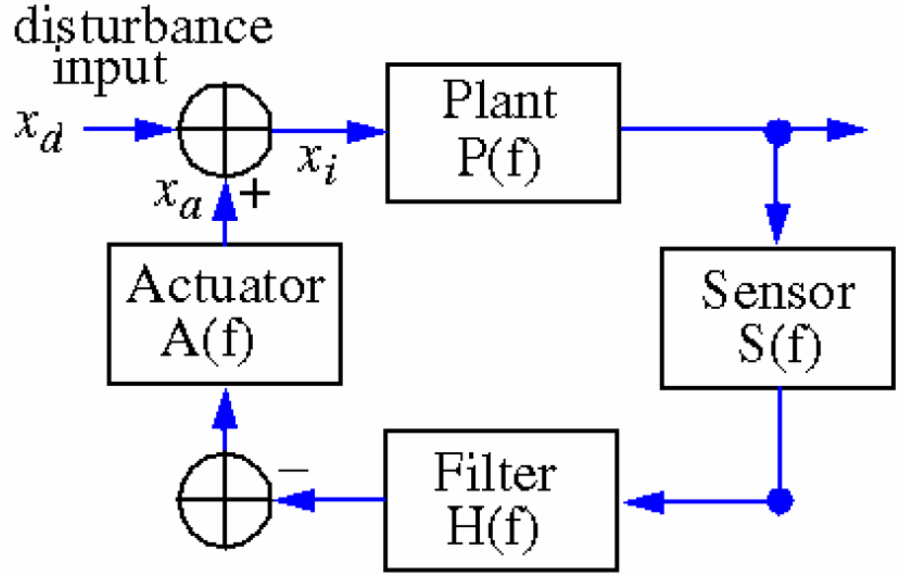
Length Sensing and Control



Alignment Sensing and Control



Feedback Basics



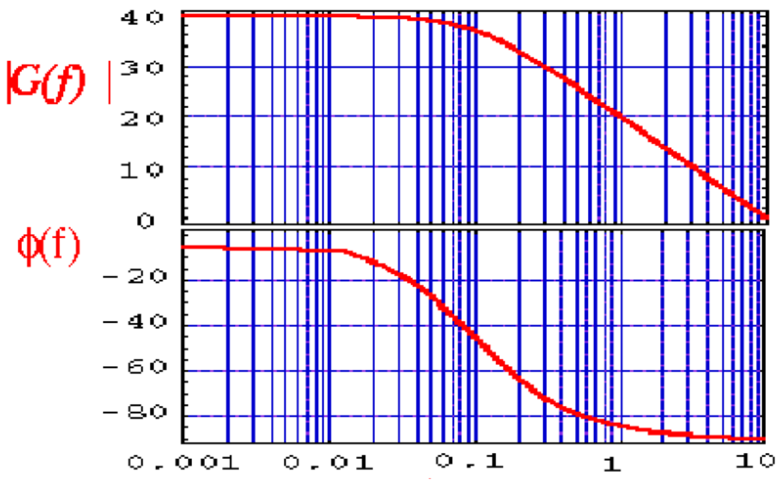
$$x_a = -PSHAx_i$$

$$x_i = x_d + x_a$$

$$x_i = \frac{x_d}{1 + G(f)}$$

where

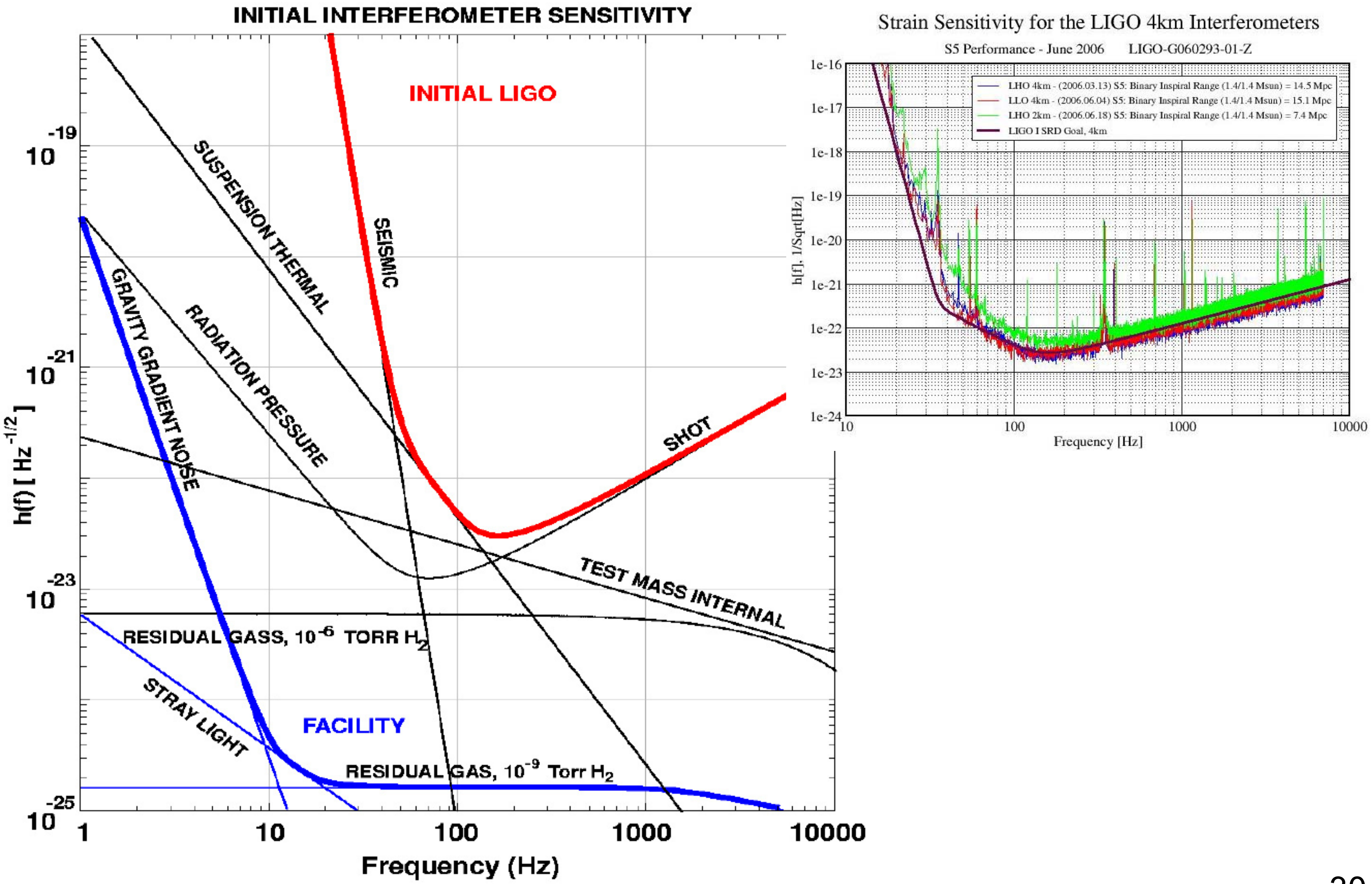
$$G(f) = PSHA$$



High frequency: servo has no effect; measure just the input disturbance

Low frequency: measure the combination of input disturbance and servo; can infer input disturbance

Summary of Noise Sources

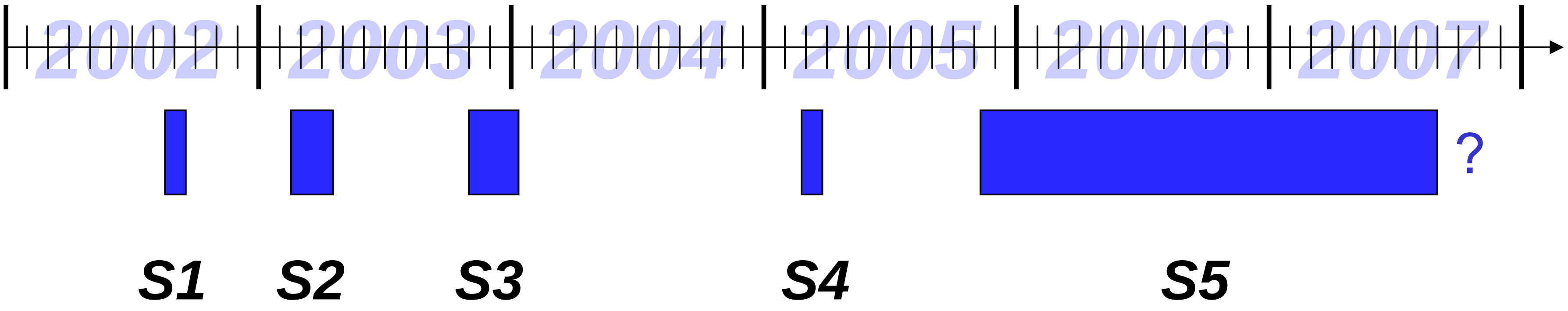


INITIAL INTERFEROMETER SENSITIVITY

Strain Sensitivity for the LIGO 4km Interferometers

S5 Performance - June 2006 LIGO-G060293-01-Z

LIGO Science Runs



Duty factors:					(so far)
H1	59 %	74 %	69 %	80 %	73 %
H2	73 %	58 %	63 %	81 %	77 %
L1	43 %	37 %	22 %	74 %	62 %

Data Collection

Shifts manned by resident “operators” and visiting “scientific monitors”