Initial and Advanced LIGO Detectors

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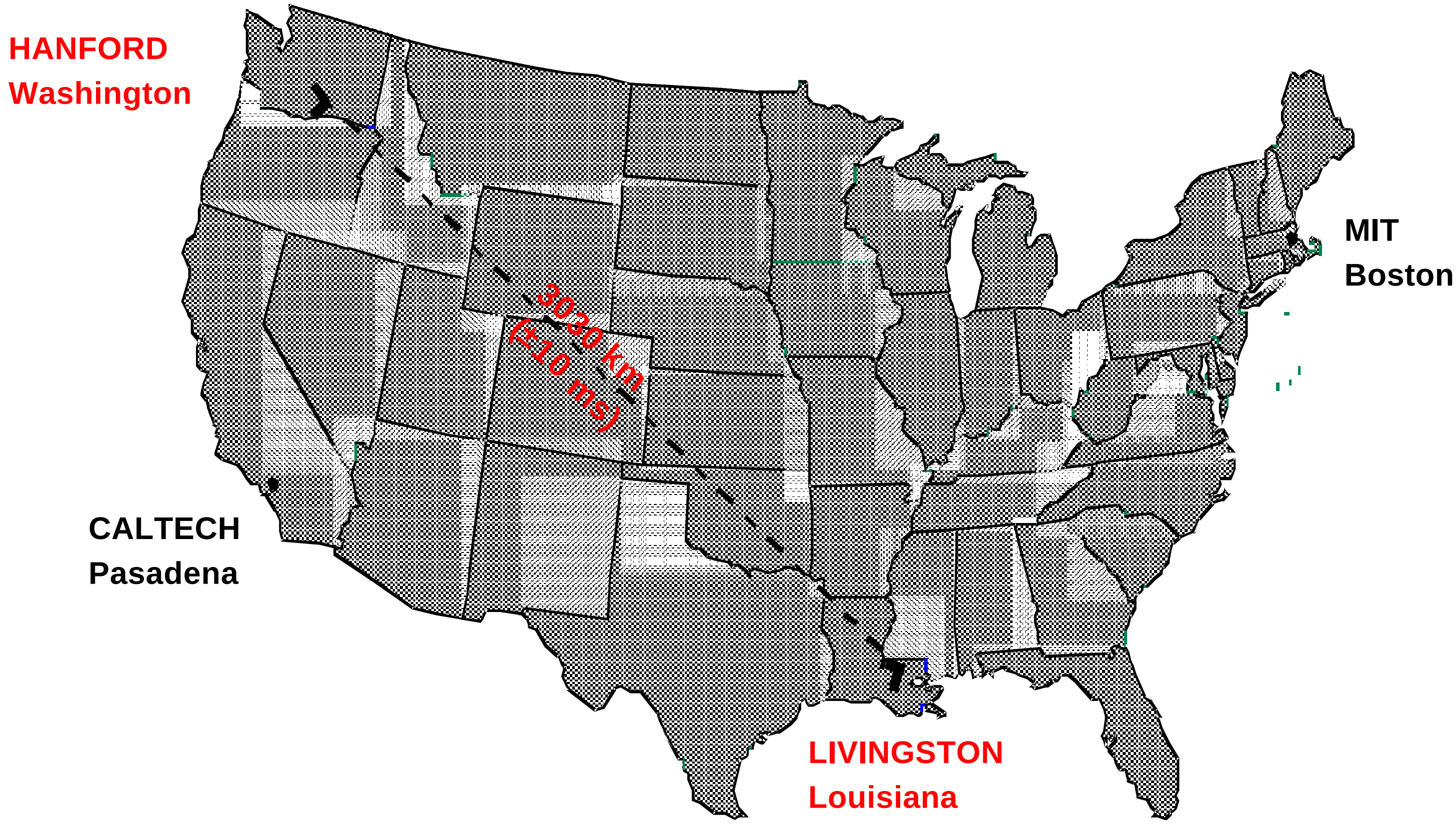
Astro/Phys C285 - Theoretical Astrophysics Seminar
UC Berkeley

LIGO-G010027-00-D

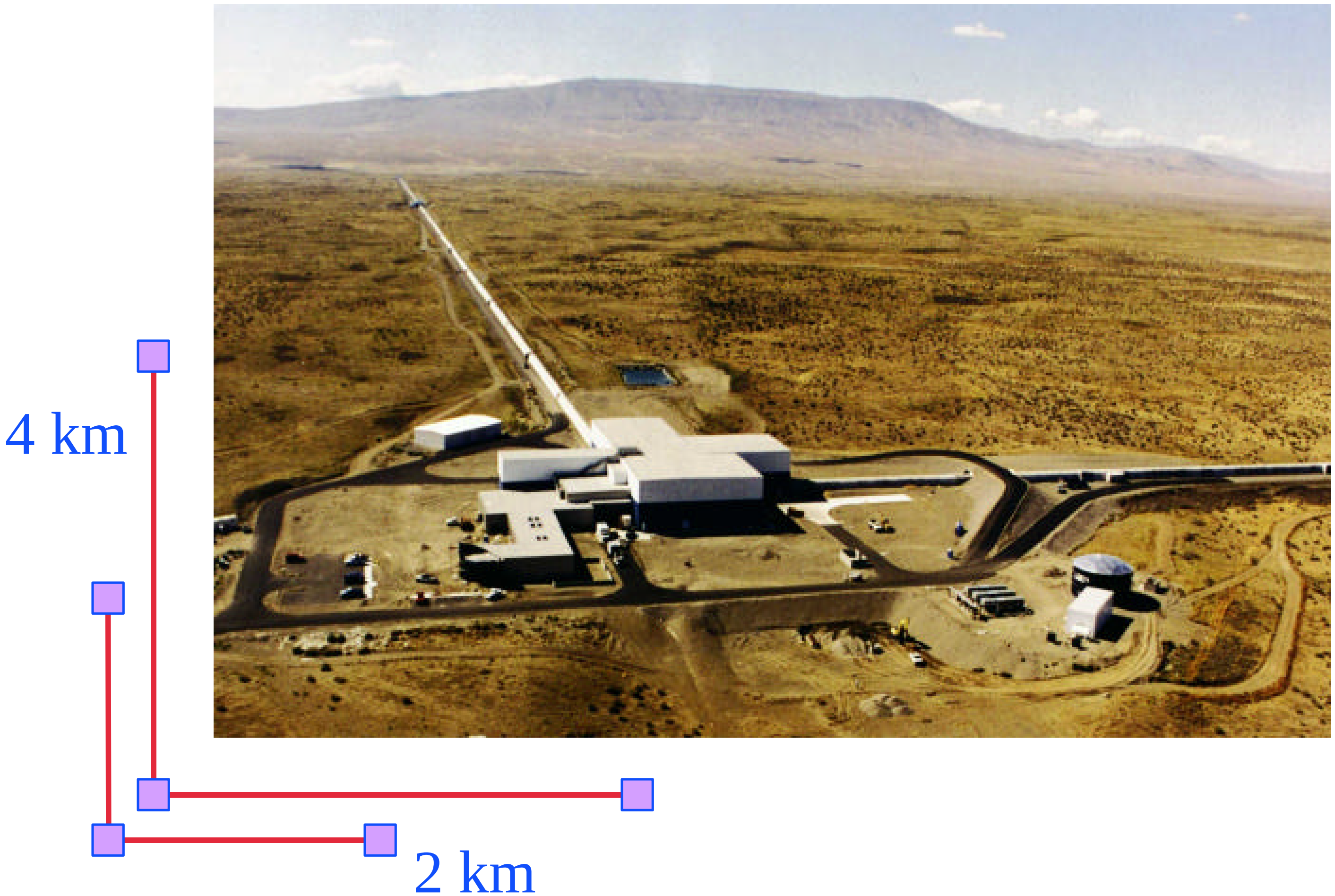
Outline of Talk

- Initial Detector Overview
  - Performance Goals
  - How do they work?
  - What do the parts look like?
- Very Current Status
  - Installation and Commissioning
- Advanced LIGO Detectors

LIGO Observatories

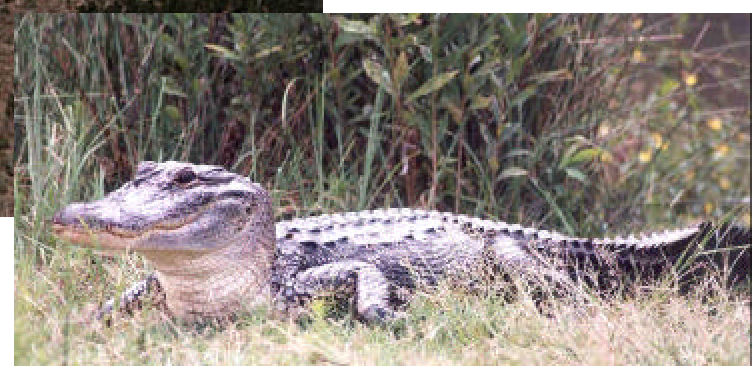


Hanford Observatory



Livingston Observatory

4 km

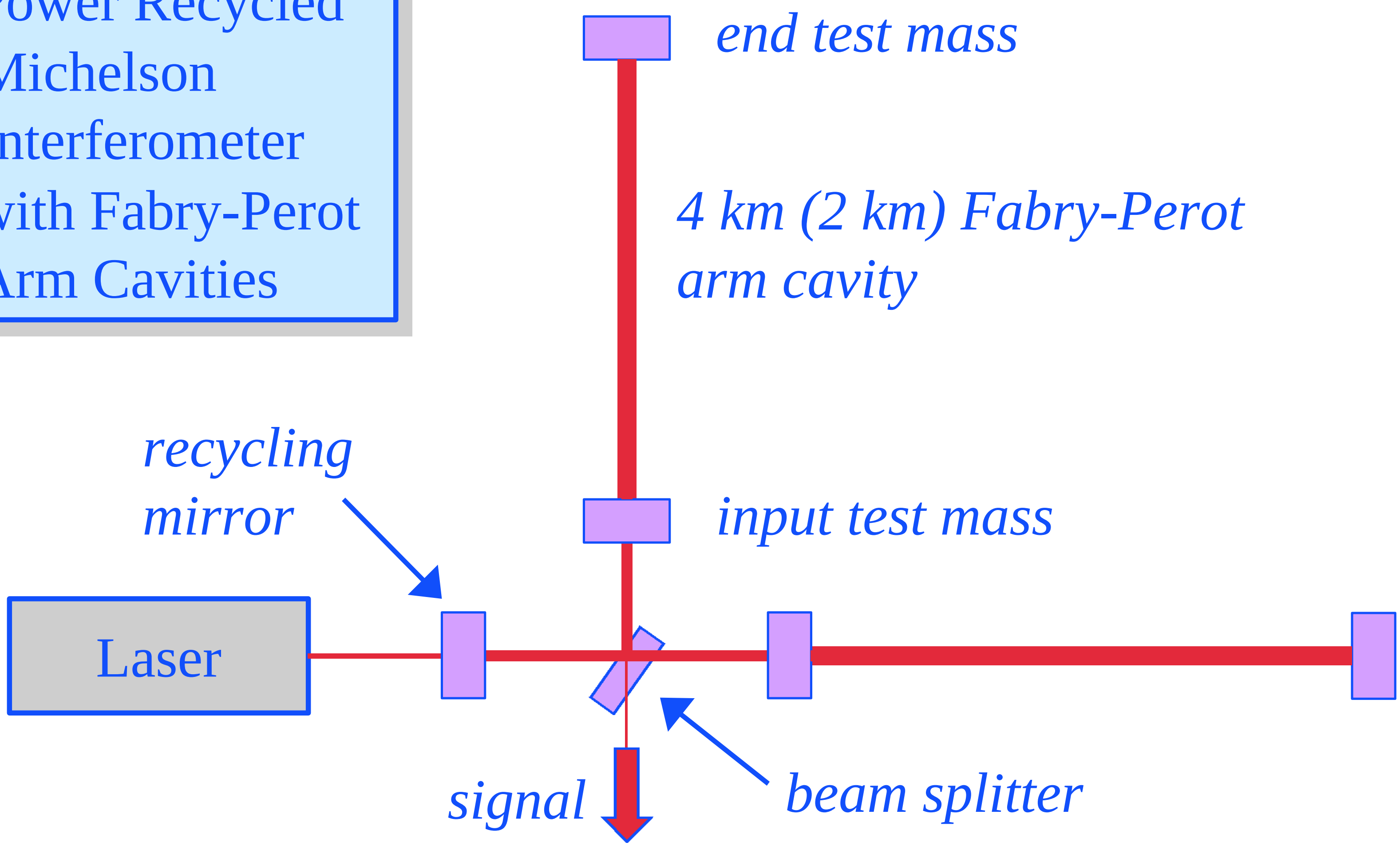


Initial Detectors—Underlying Philosophy

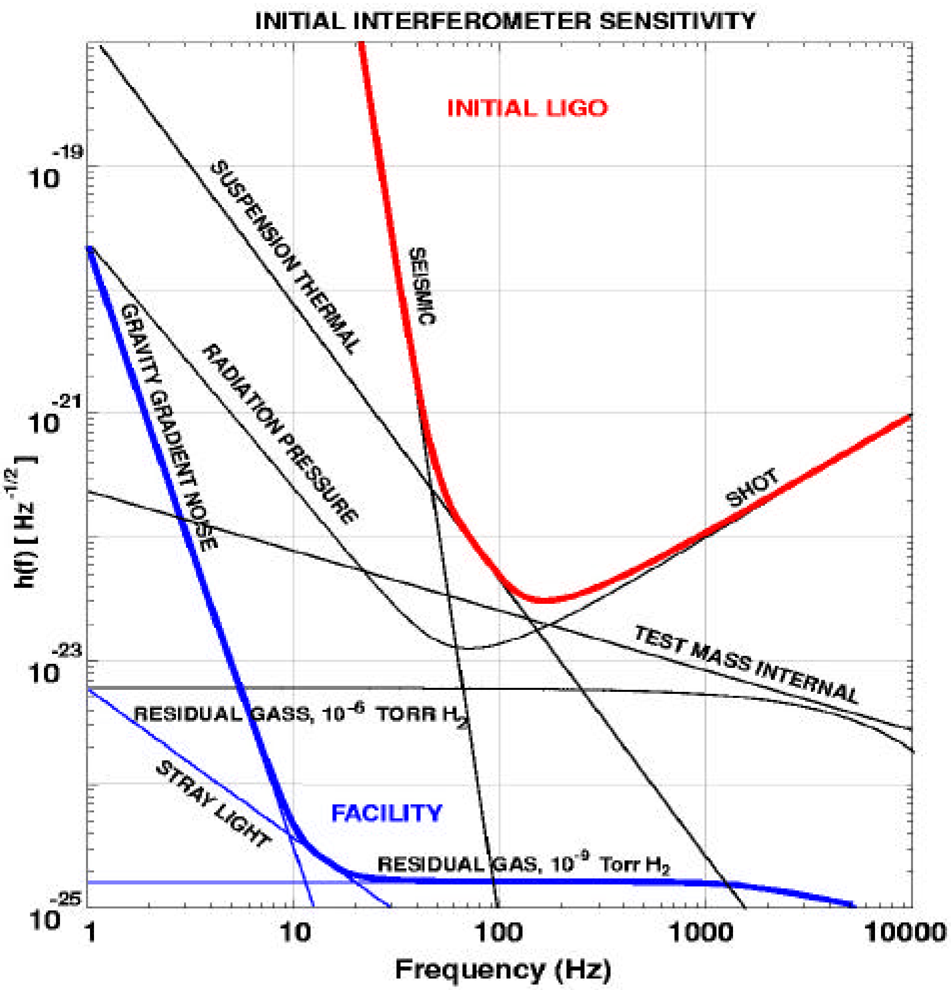
- Jump from laboratory scale prototypes to multi-kilometer detectors is already a BIG challlenge
- Design should use relatively cautious extrapolations of existing technologies
  - » Reliability and ease of integration should be considered in addition to noise performance
    - – “The laser should be a light bulb, not a research project”
      Bob Byer, Stanford
  - » All major design decisions were in place by 1994
- Initial detectors would teach us what was important for future upgrades
- Facilities (big $) should be designed with more sensitive detectors in mind
- Expected 100 times improvement in sensitivity is enough to make the initial searches interesting even if they only set upper limits

Initial LIGO Interferometers

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



Initial LIGO Sensitivity Goal



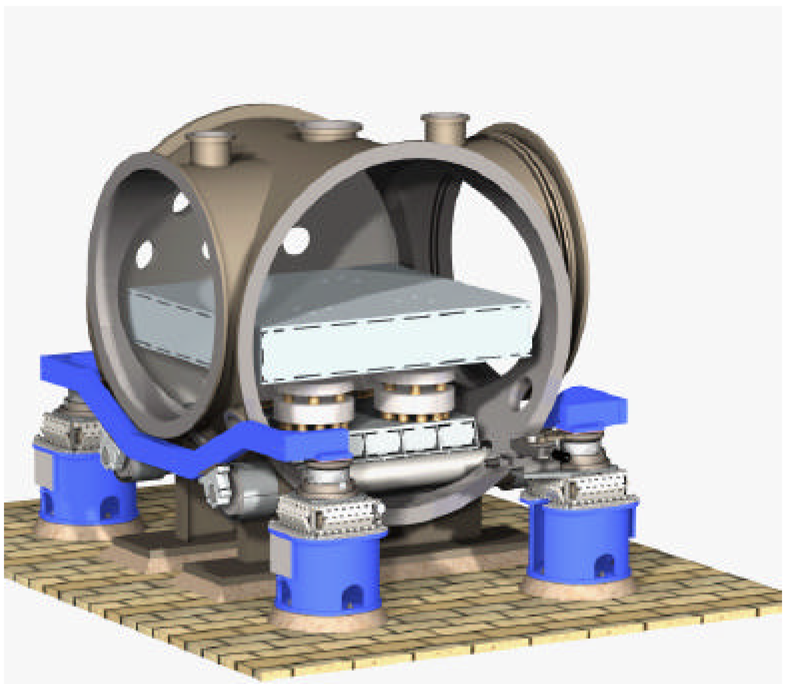
- Strain sensitivity <3x10-23 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

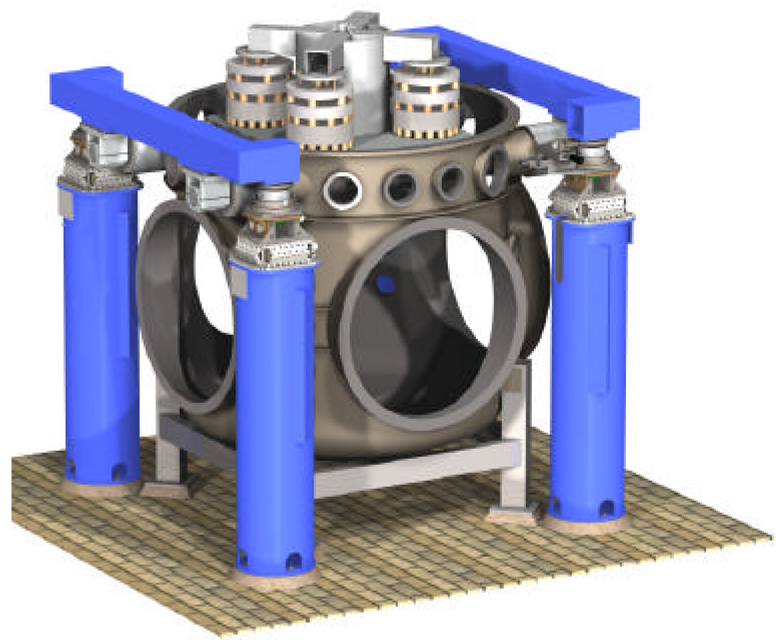
Initial LIGO Detector Status

- Construction project - Finished
  - Facilities, including beam tubes complete at both sites
- Detector installation
  - Washington 2k interferometer complete
  - Louisiana 4k interferometer complete
  - Washington 4k interferometer in progress
- Interferometer commissioning
  - Washington 2k full interferometer functioning
  - Louisiana 4k individual arms being tested
- First astrophysical data run - 2002

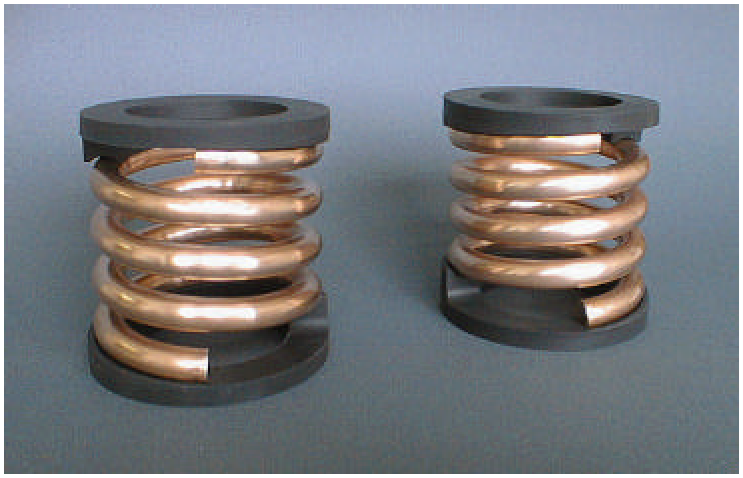
Vibration Isolation Systems

- » Reduce in-band seismic motion by 4 - 6 orders of magnitude
- » Large range actuation for initial alignment and drift compensation
- » Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

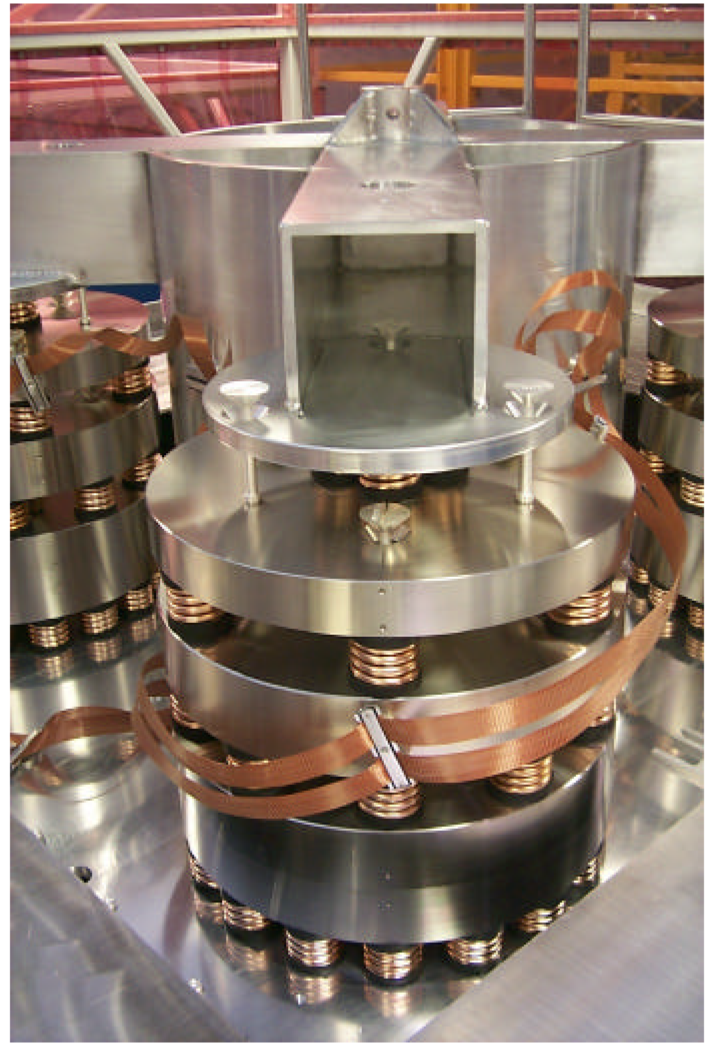




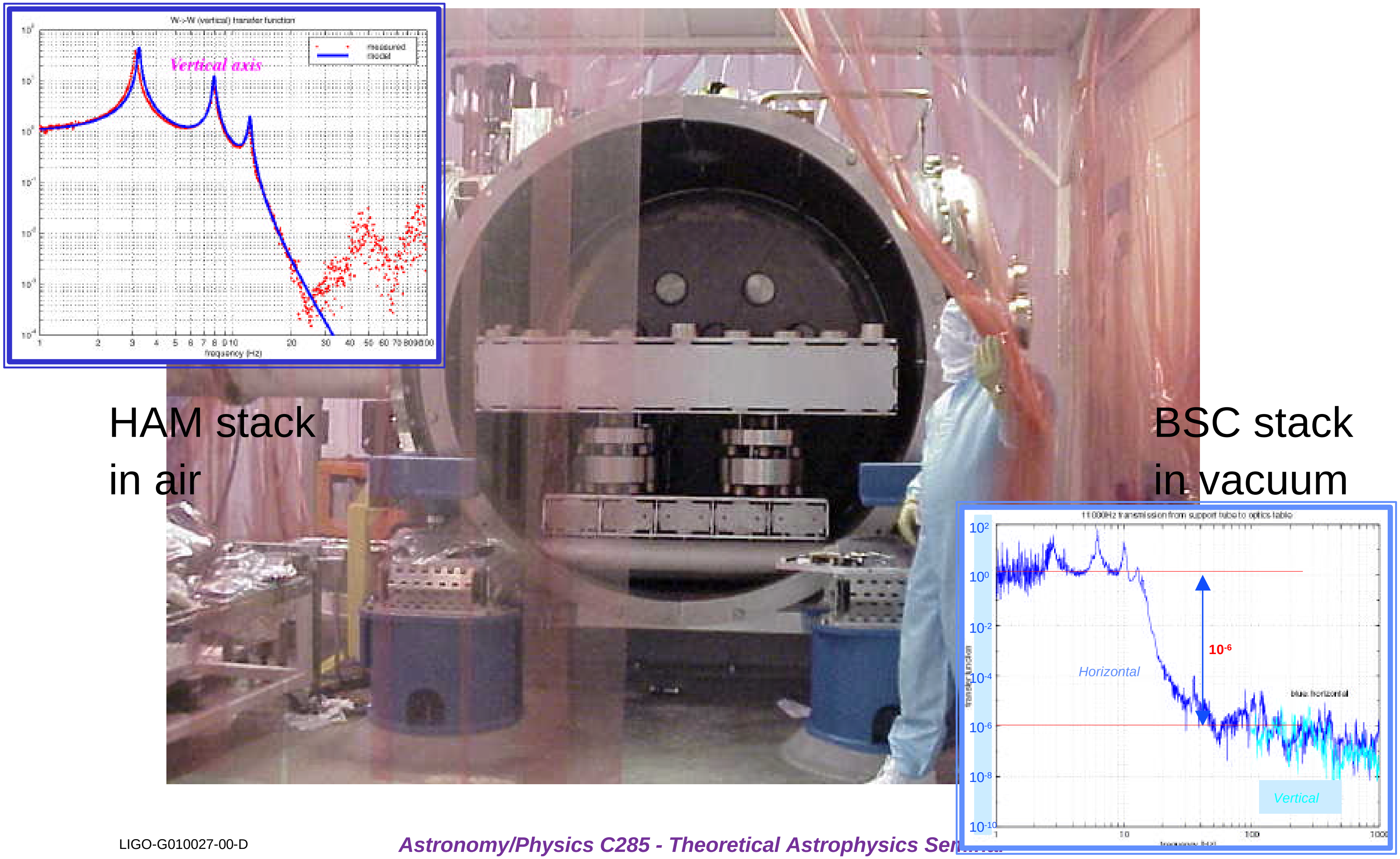
Seismic Isolation – Springs and Masses



damped spring
cross section



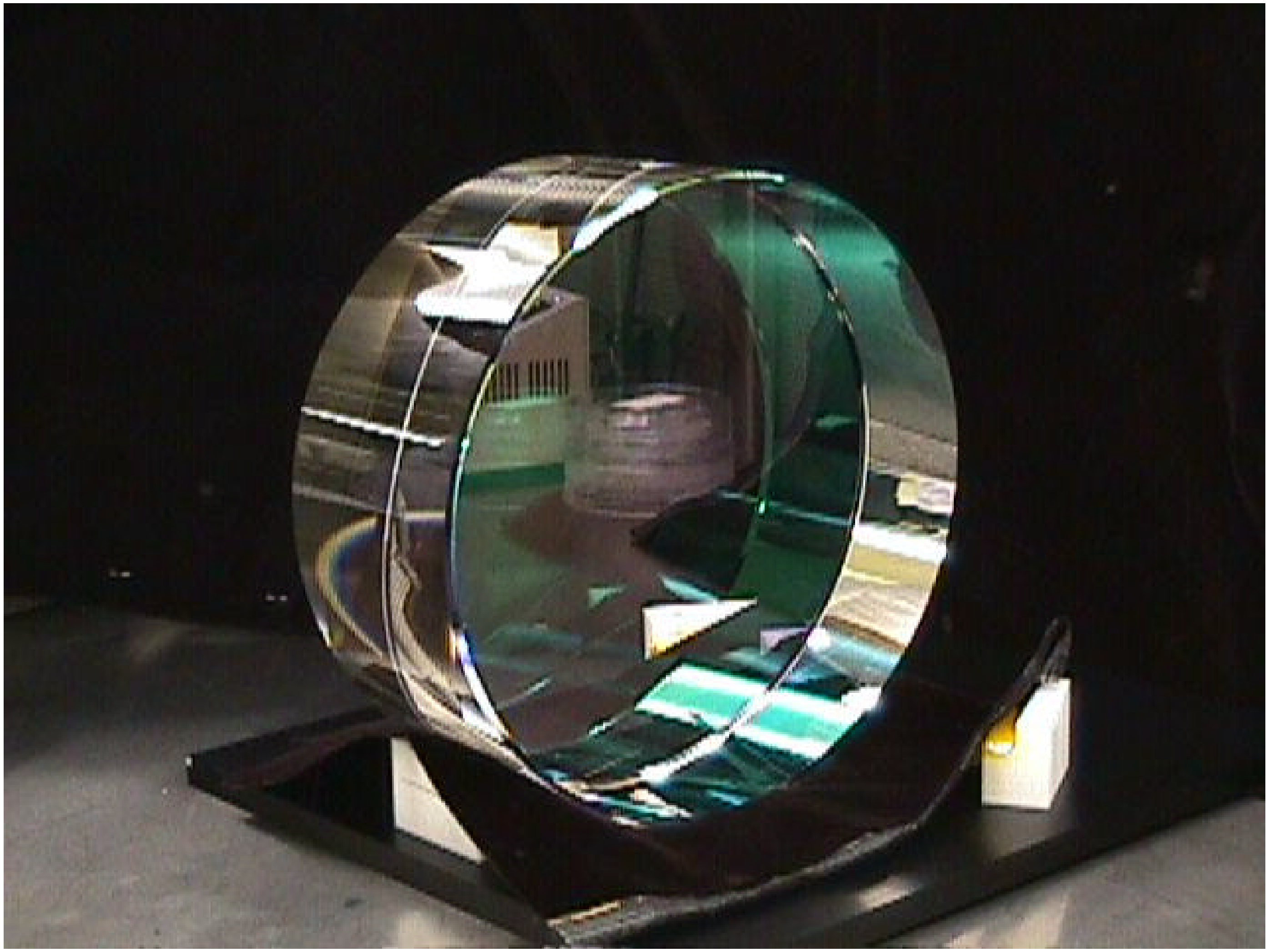
Seismic System Performance



HAM stack
in air

BSC stack
in vacuum

Core Optics

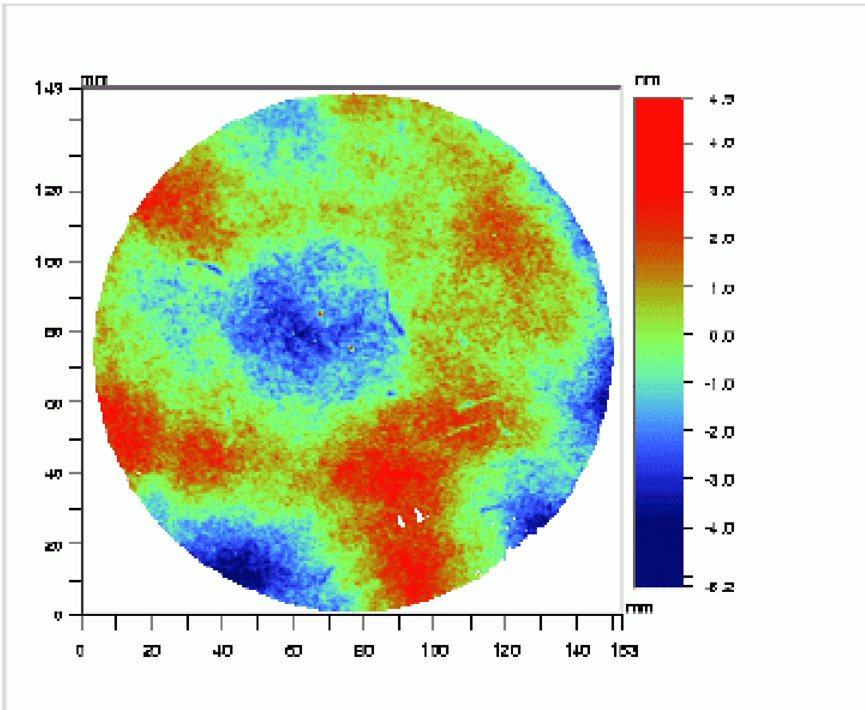


Core Optics Requirements

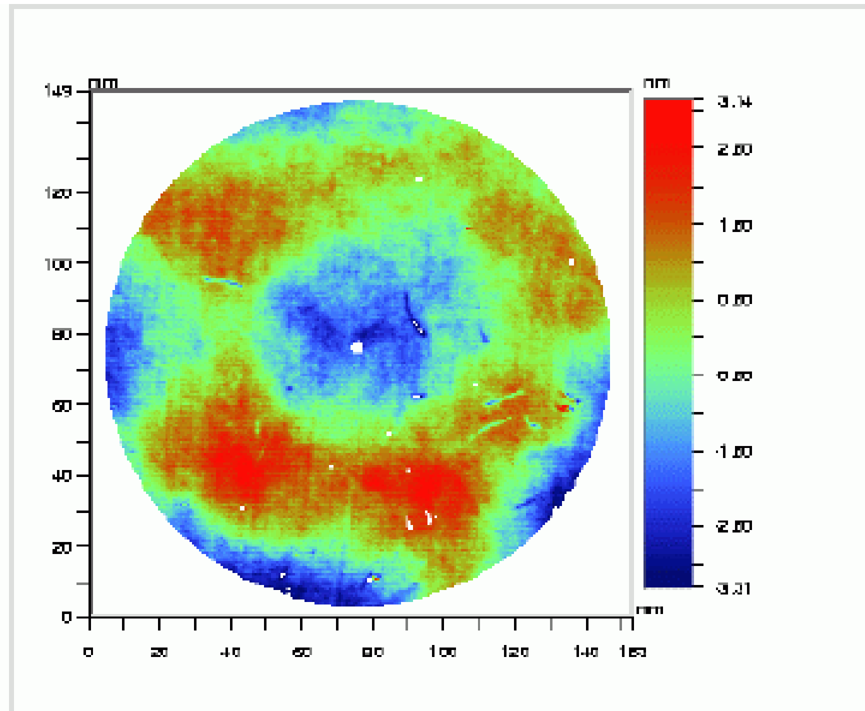
- Substrates
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5 x 10^{-7}
  - Internal mode Q's > 2 x 10^{6}
- Polishing
  - Surface uniformity < 1 nm rms
  - ROC matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity <10^{-3}
- Successful production eventually involved 6 companies, NIST and the LIGO Lab

Core Optic Metrology

- Current state of the art: 0.2 nm repeatability

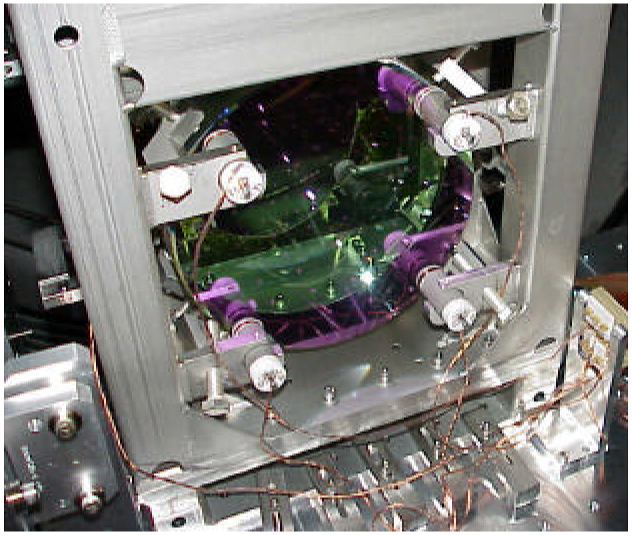


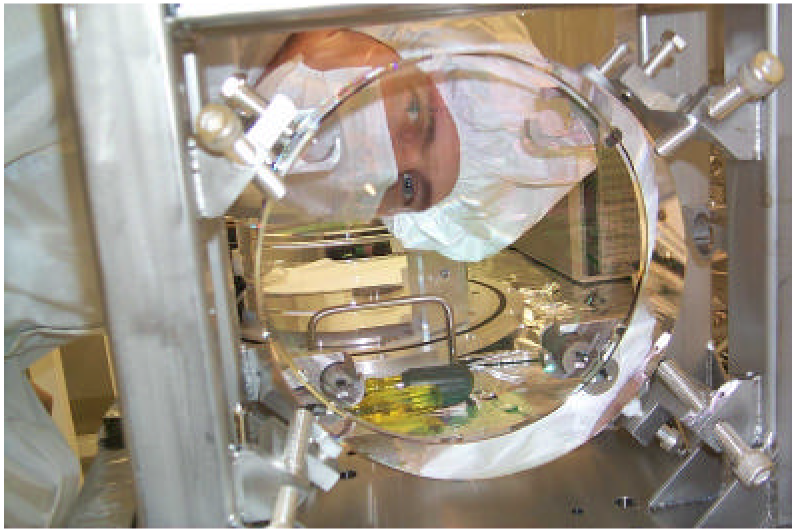
LIGO data (1.2 nm rms)



CSIRO data (1.1 nm rms)

Core Optics Suspension and Control

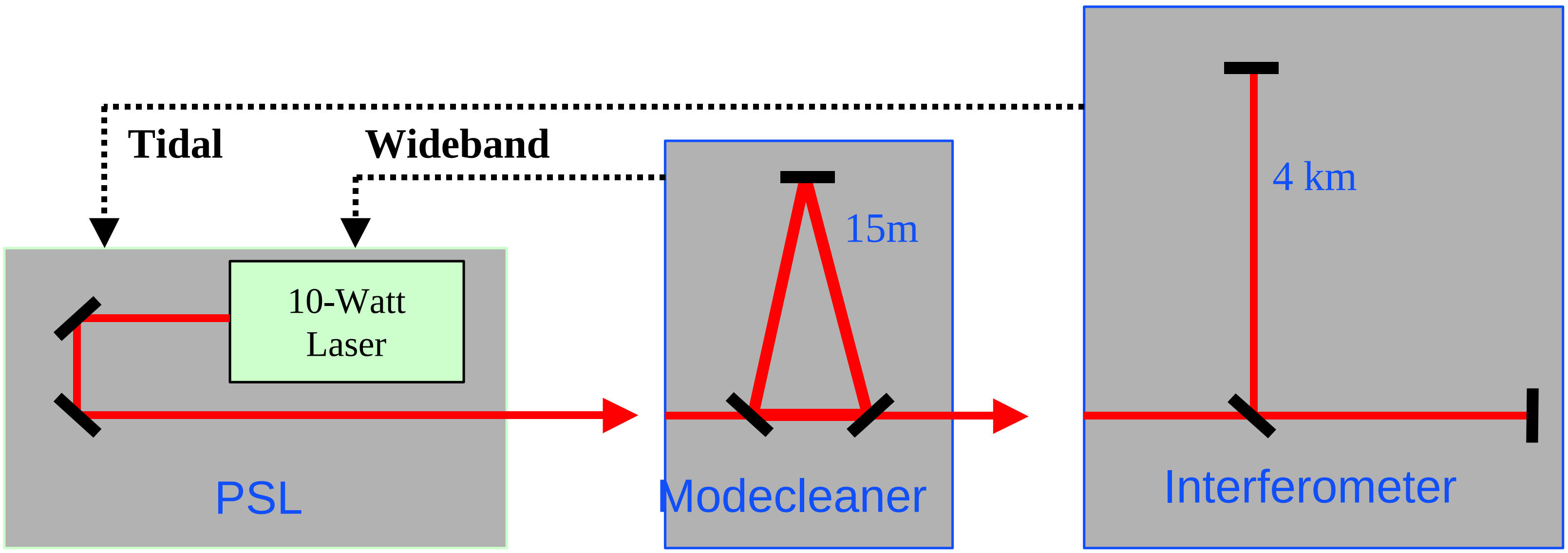




Core Optics Installation and Alignment

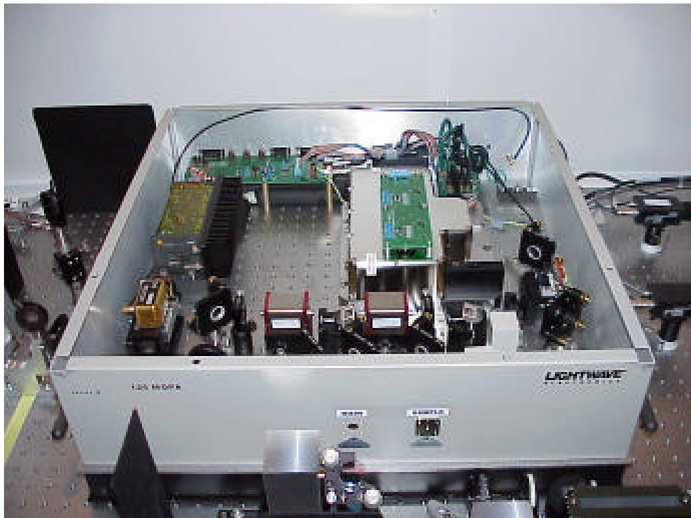
Pre-stabilized Laser

- Deliver pre-stabilized laser light to the 15-m mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Provide actuator inputs for further stabilization
  - **Wideband**
  - **Tidal**

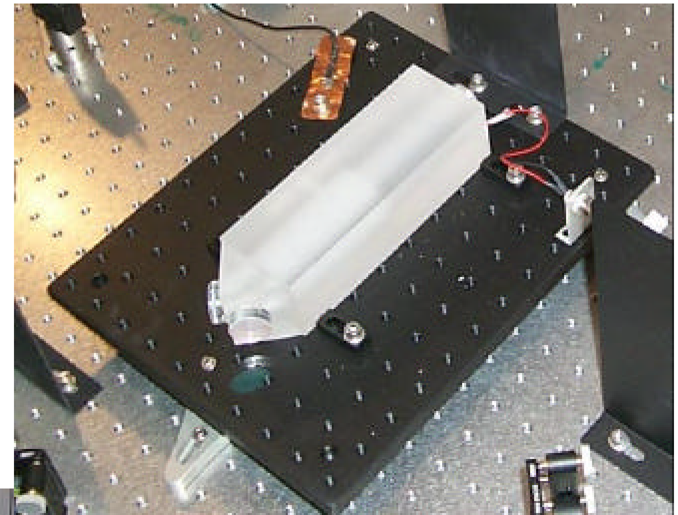


10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/ Hz$^{1/2}$ 10^{-7} Hz/ Hz$^{1/2}$

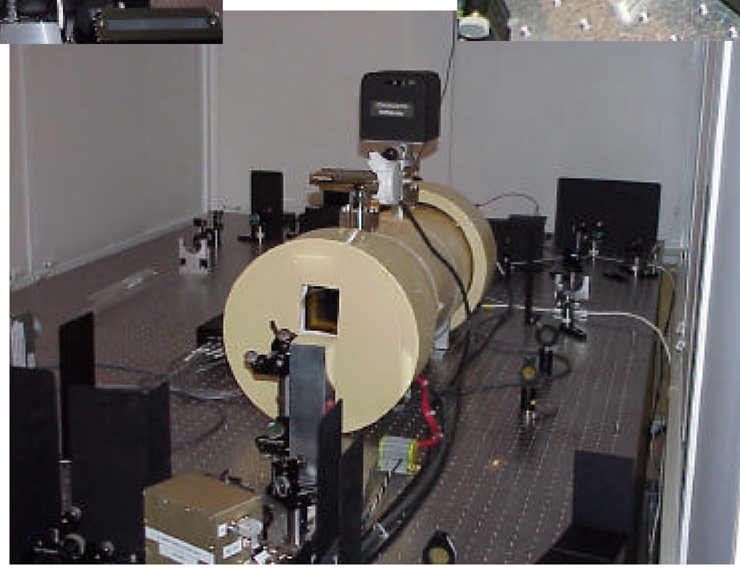
Washington 2k Pre-stabilized Laser



Custom-built
10 W Nd:YAG
Laser

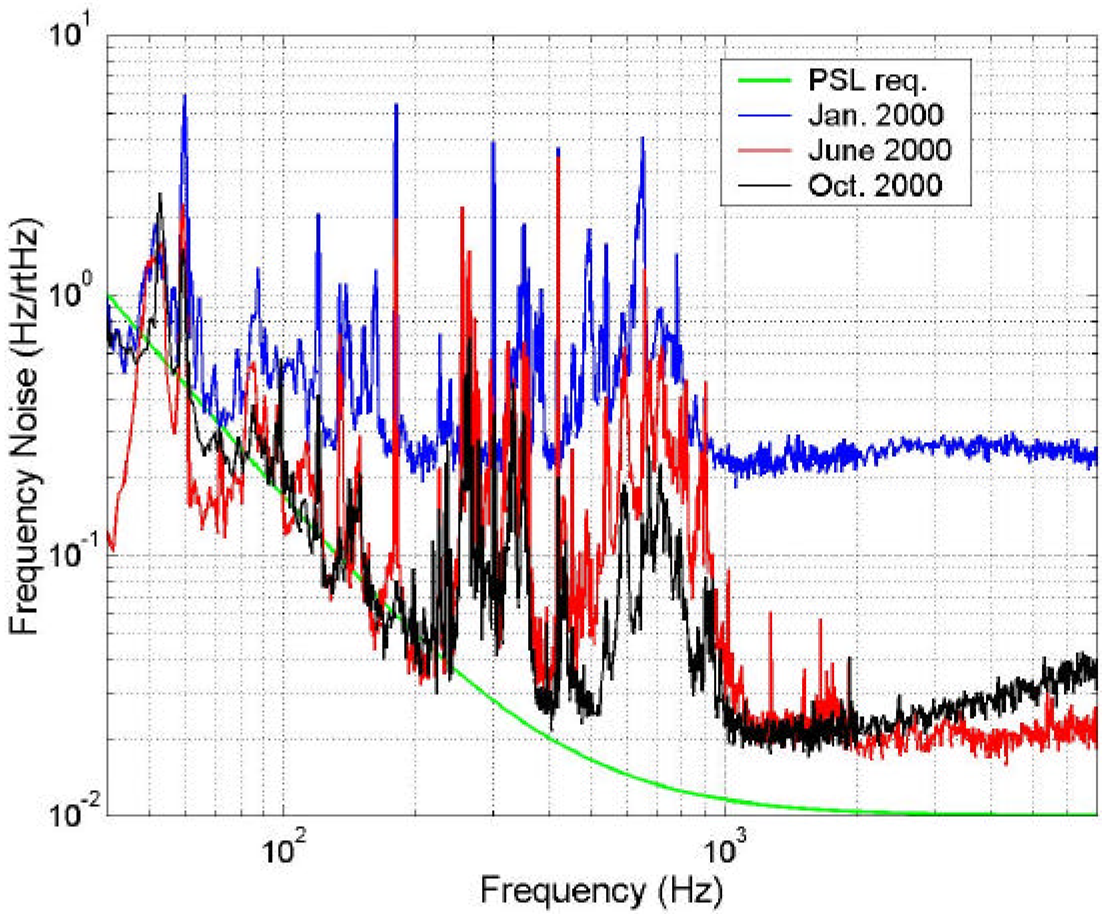


Stabilization cavities
for frequency
and beam shape



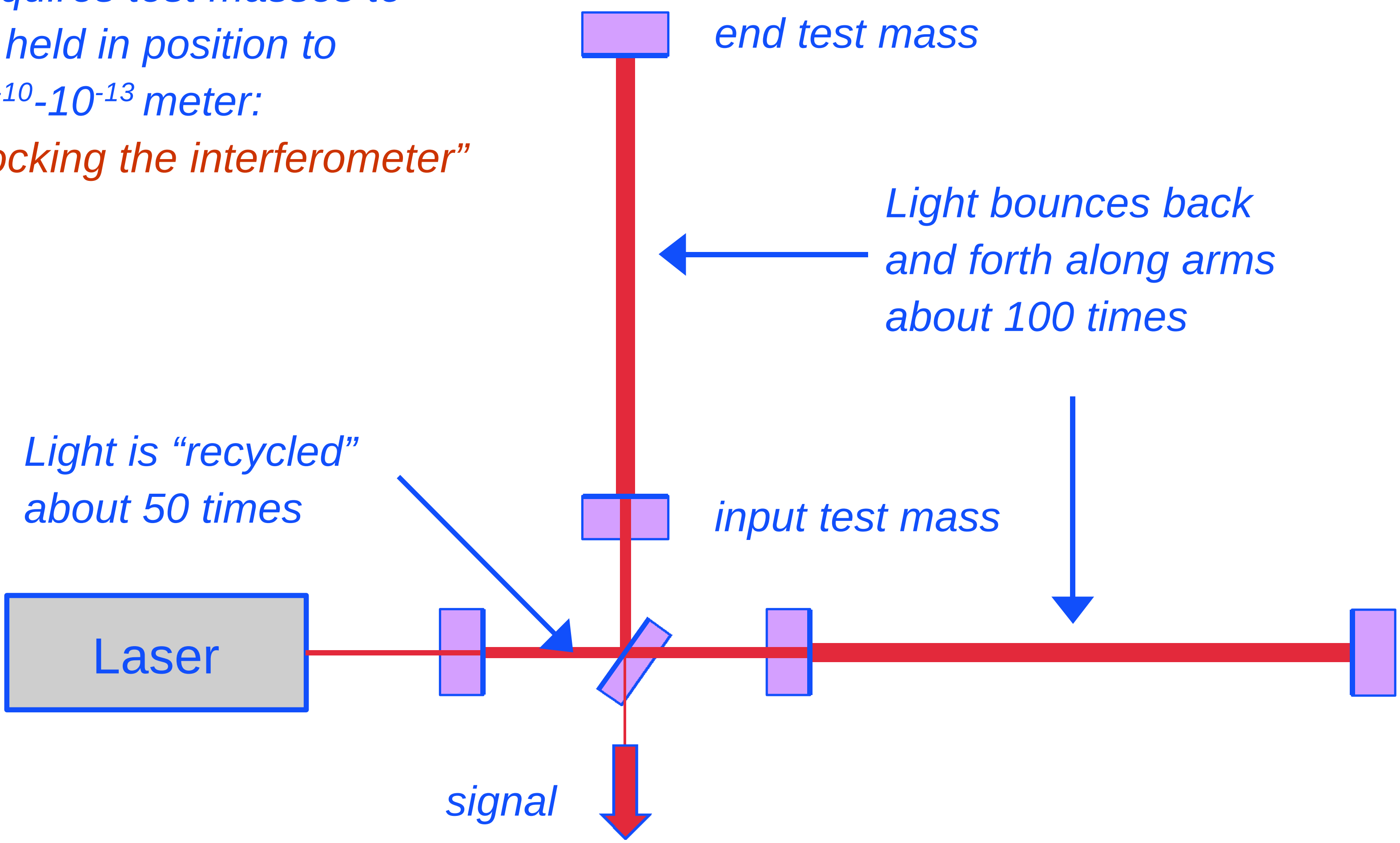
WA 2k Pre-stabilized Laser Performance

- > 20,000 hours continuous operation
- Frequency lock very robust
- TEM_{00} power >8 W delivered to input optics
- Non-TEM_{00} power < 10%
- Improvement in noise performance
  - » electronics
  - » acoustics
  - » vibrations

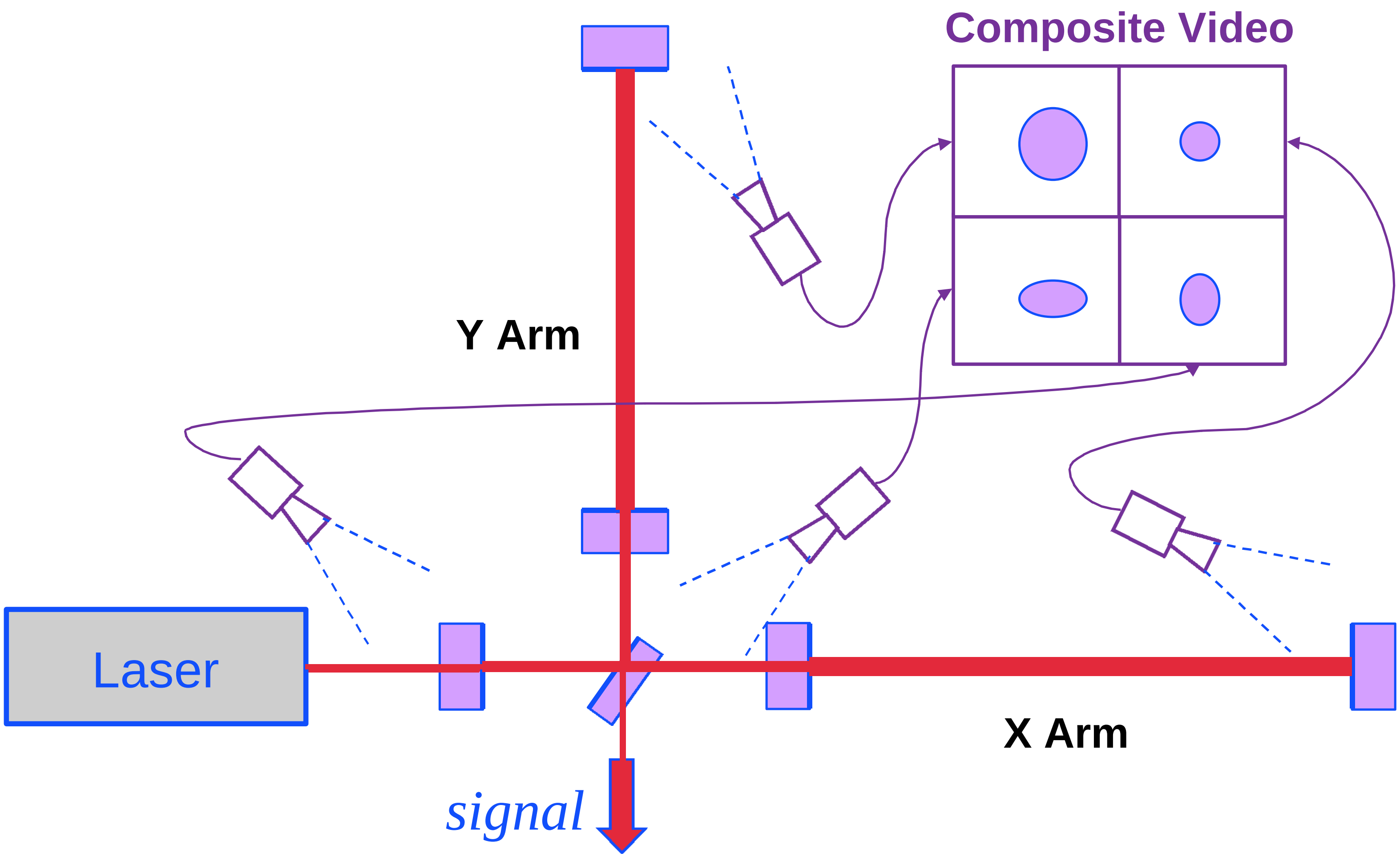


LIGO Interferometers

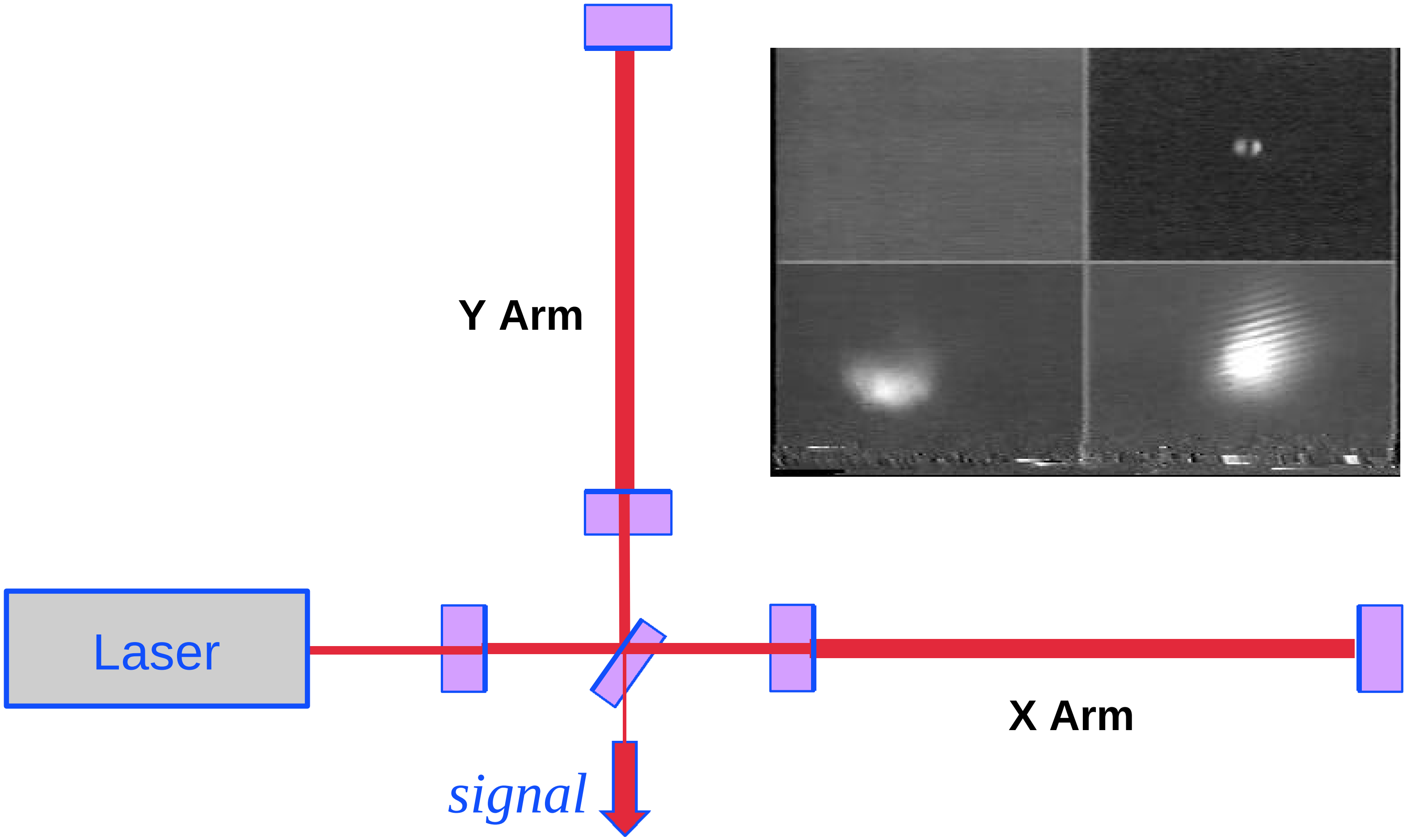
Requires test masses to be held in position to 10^{-10}-10^{-13} meter:
“Locking the interferometer”



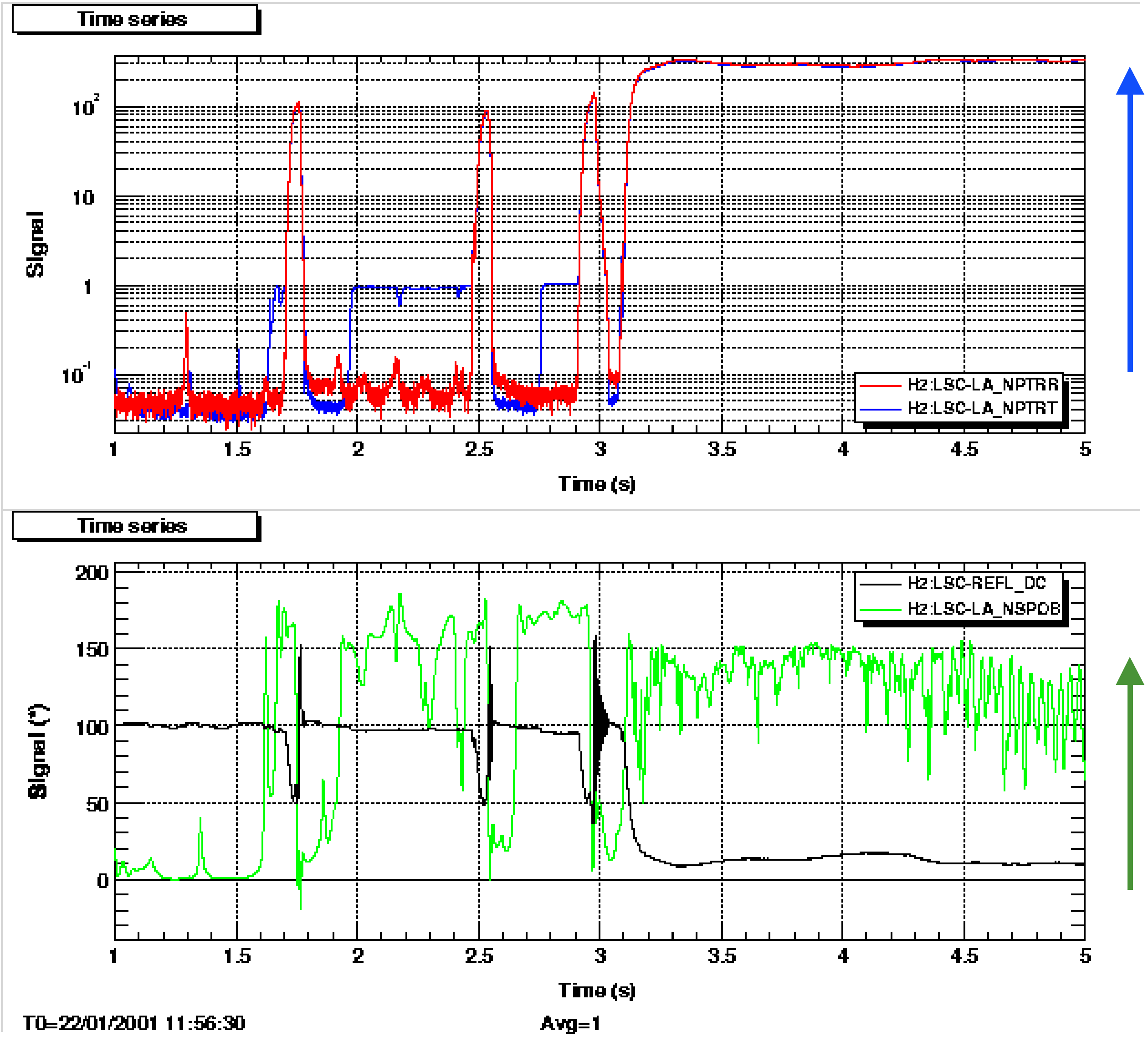
Steps to Locking an Interferometer



Watching the Interferometer Lock



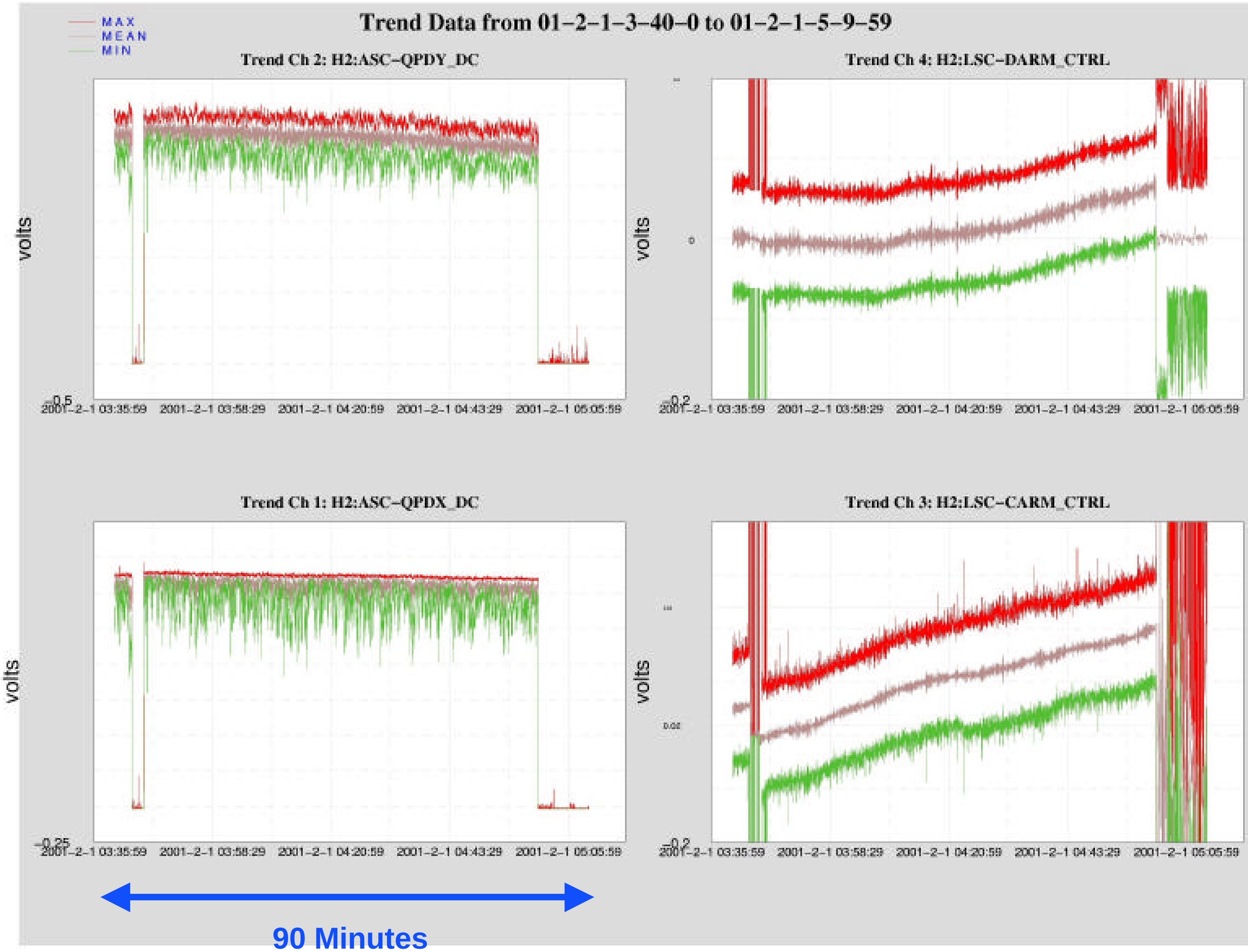
Lock Acquisition Example



Carrier Recycling Gain ~10

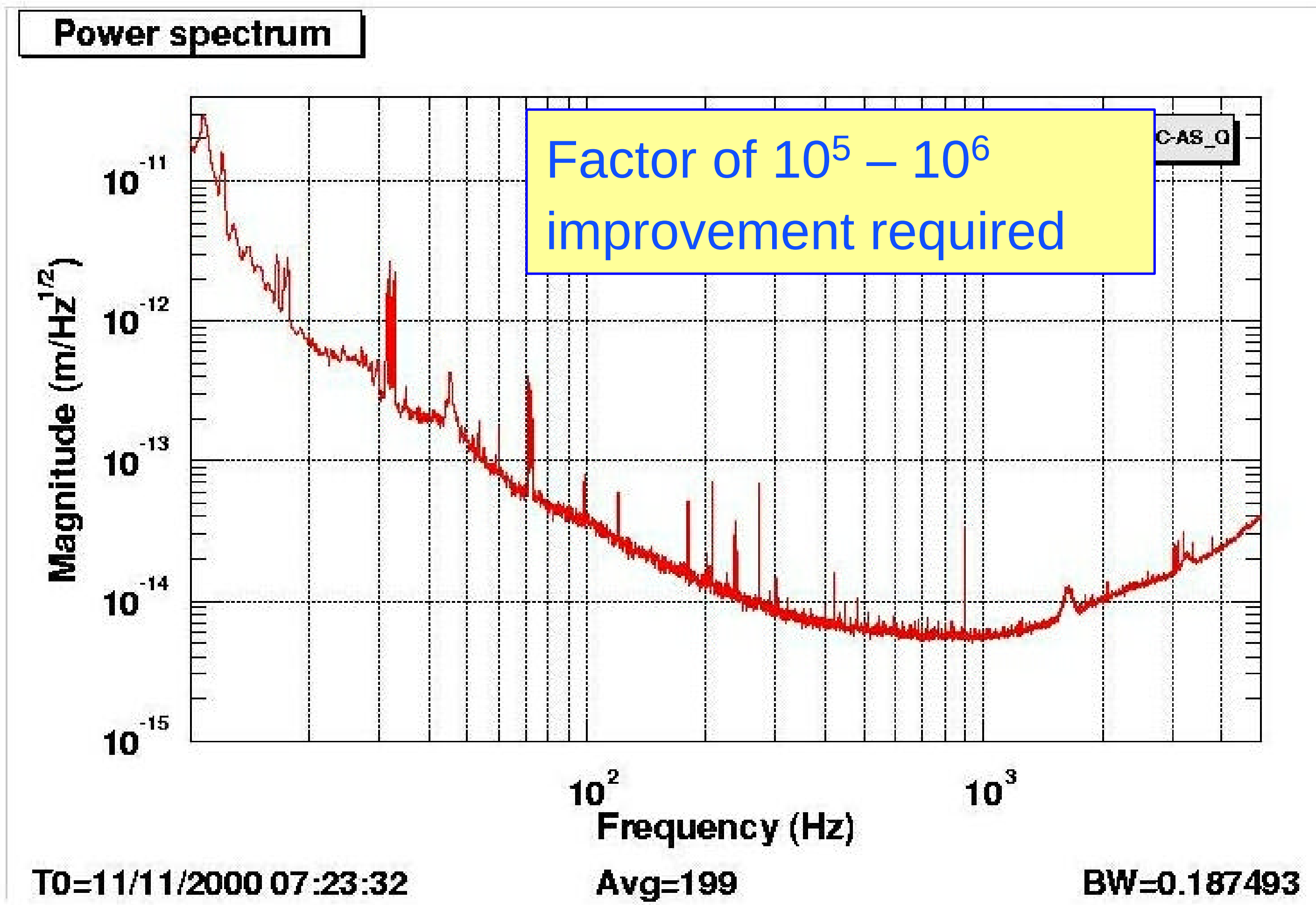
Sideband Recycling Gain ~5

Full Interferometer Locking

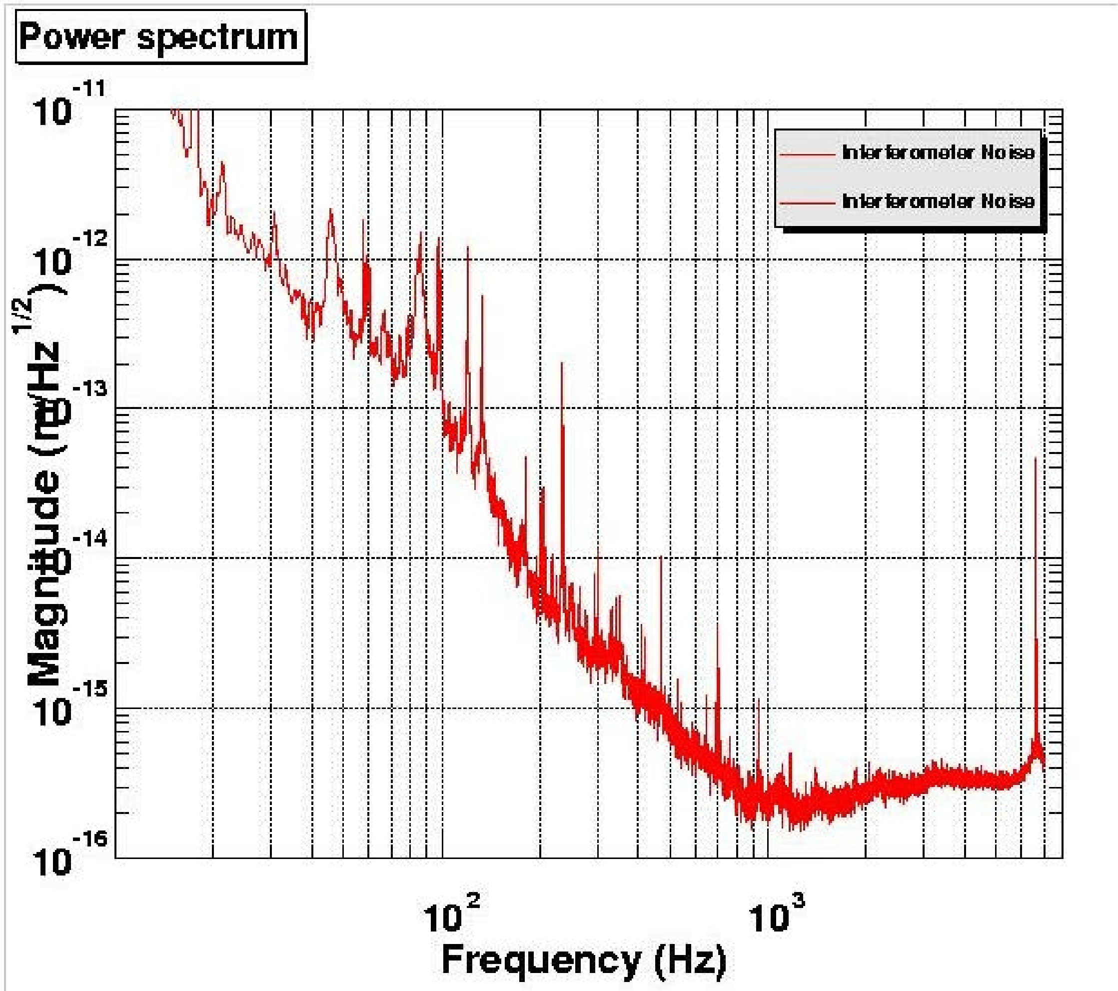


First Interferometer Noise Spectrum

Recombined Michelson with F-P Arms (no recycling) – November 2000



Improved Noise Spectrum

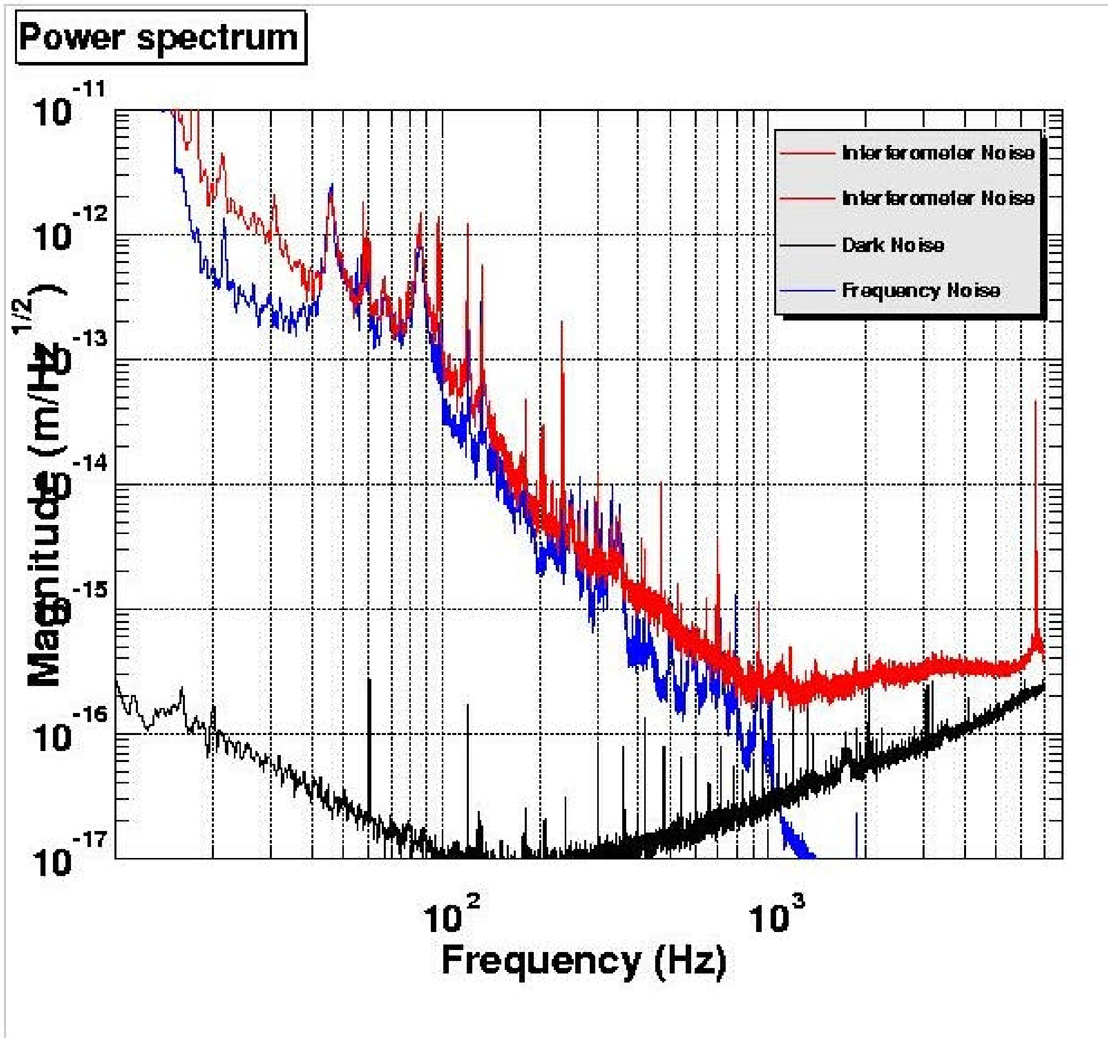


9 February 2001

Improvements due to:

- Recycling
- Reduction of electronics noise
- Partial implementation of alignment control

Known Contributors to Noise

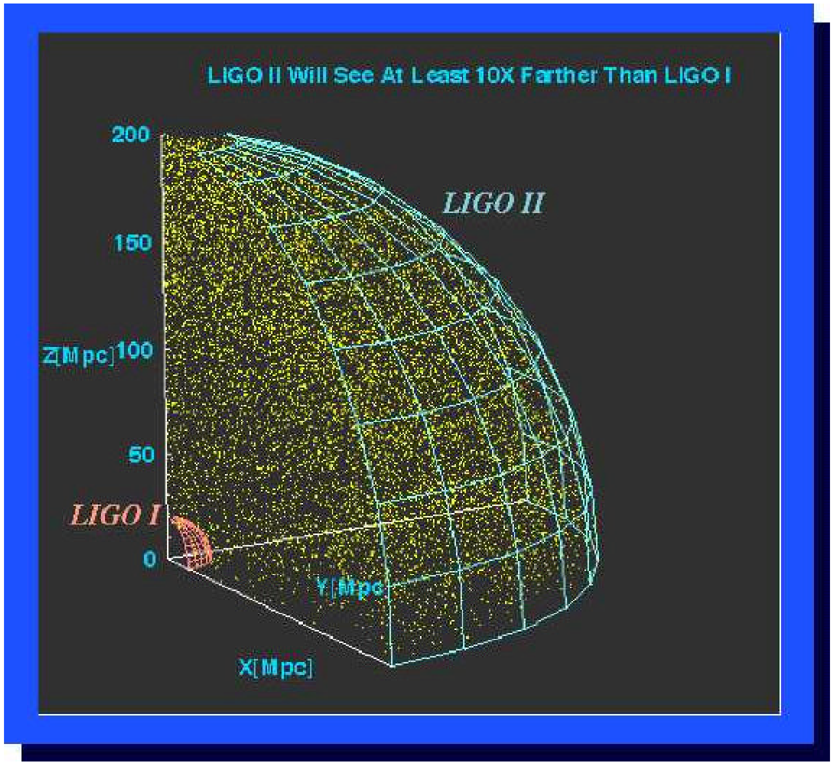


New servo to improve frequency stabilization installed last week

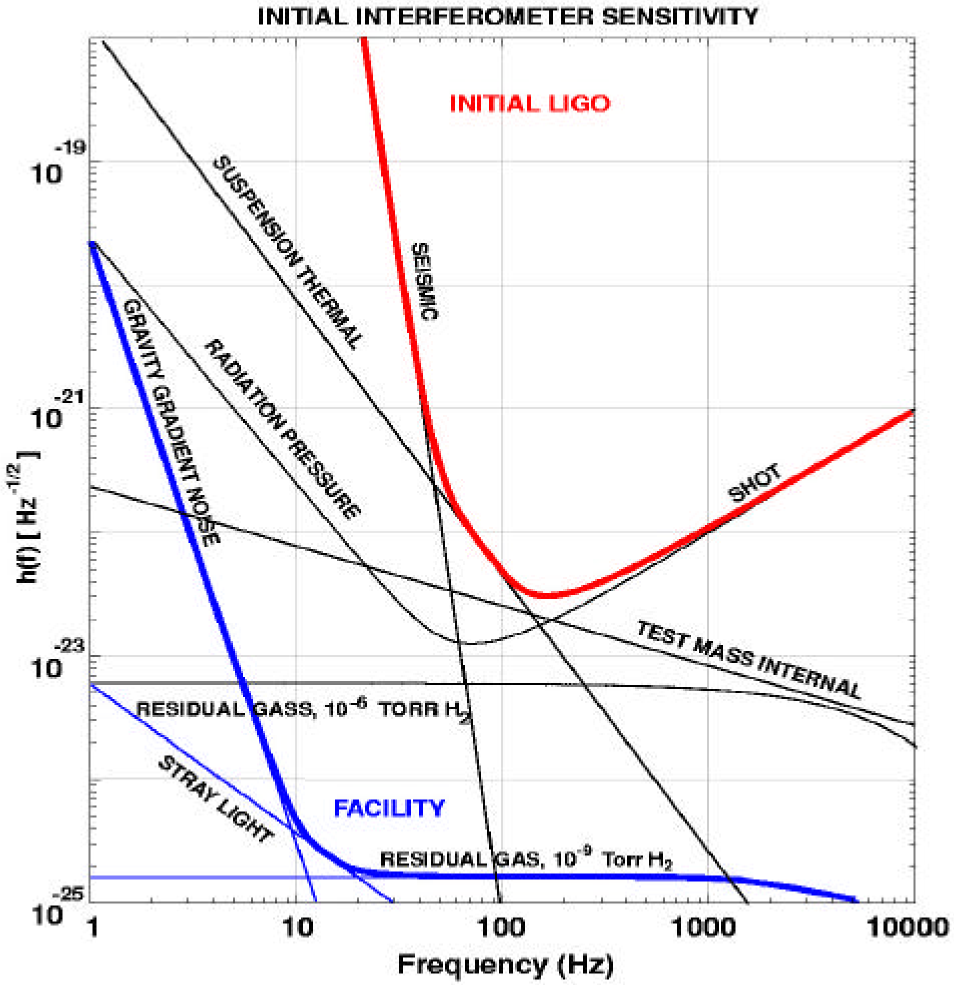
Testing is underway

Advanced LIGO

- Now being designed by the LIGO Scientific Collaboration
- Goal:
  - » Quantum-noise-limited interferometer
  - » Factor of ten increase in sensitivity
  - » Factor of 1000 in event rate. One day > entire 2-year initial data run
- Schedule:
  - » Begin installation: 2006
  - » Begin data run: 2008



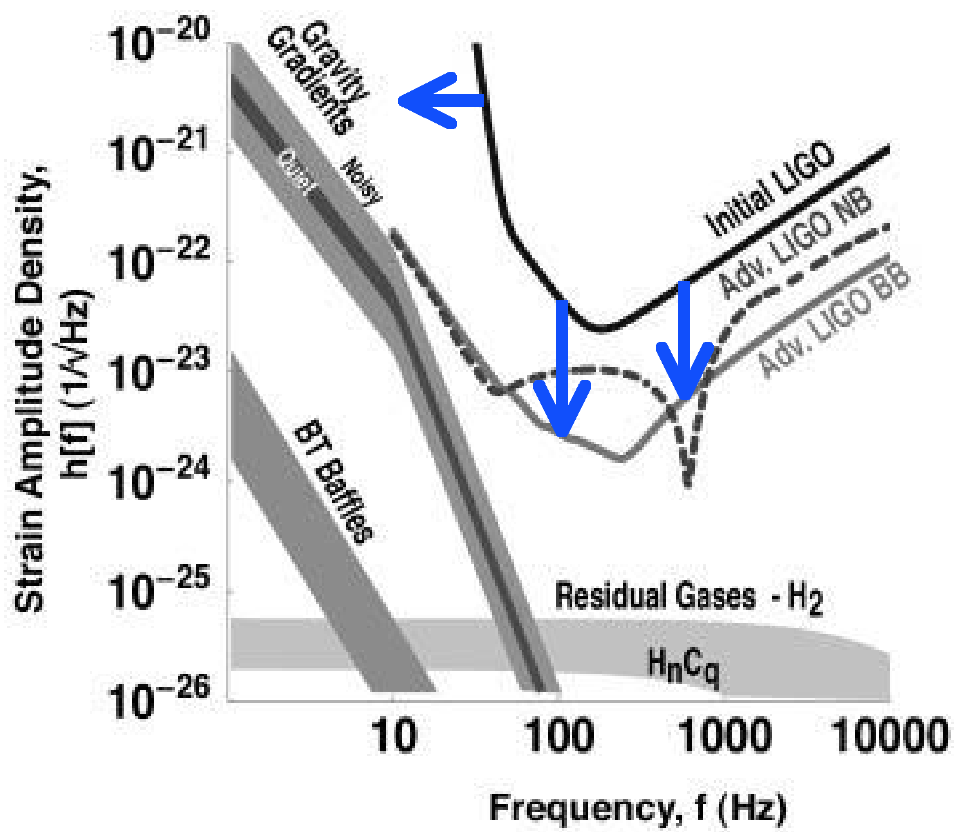
Facility Limits to Sensitivity



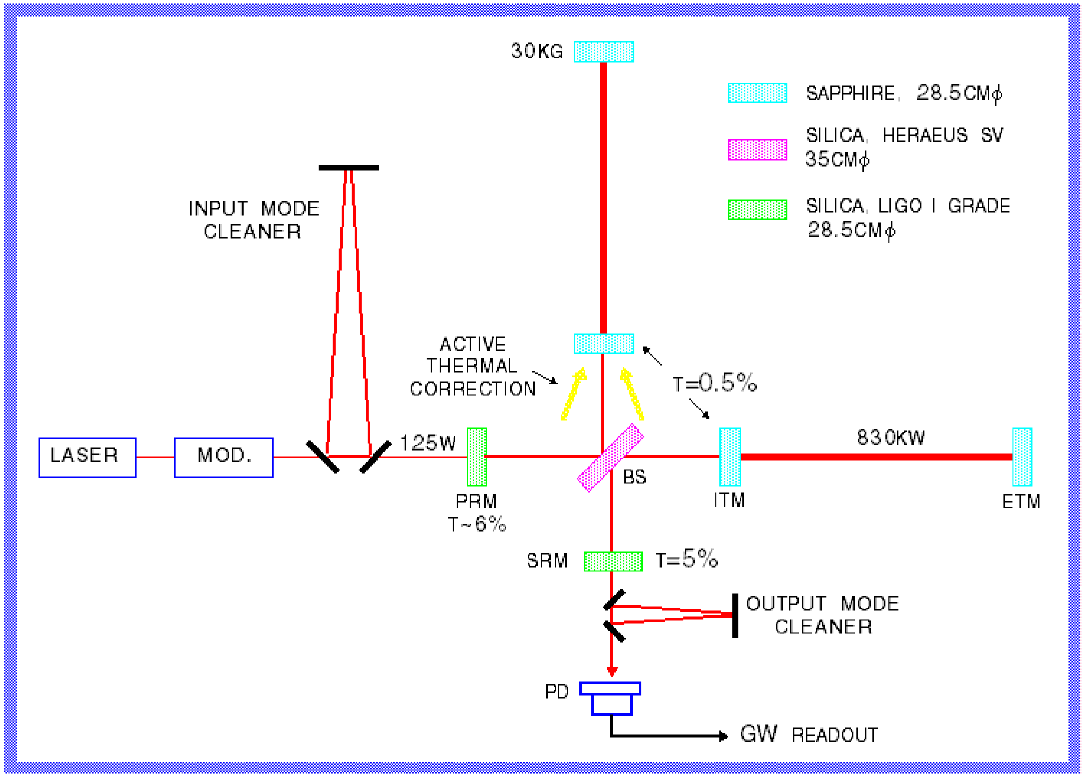
- Facility limits leave lots of room for future improvements

Present and future limits to sensitivity

- Advanced LIGO
  - Seismic noise 40→10 Hz
  - Thermal noise 1/15
  - Shot noise 1/10, tunable
- Facility limits
  - Gravity gradients
  - Residual gas
  - (scattered light)
- Beyond Adv LIGO
  - Thermal noise: cooling of test masses
  - Quantum noise: quantum non-demolition



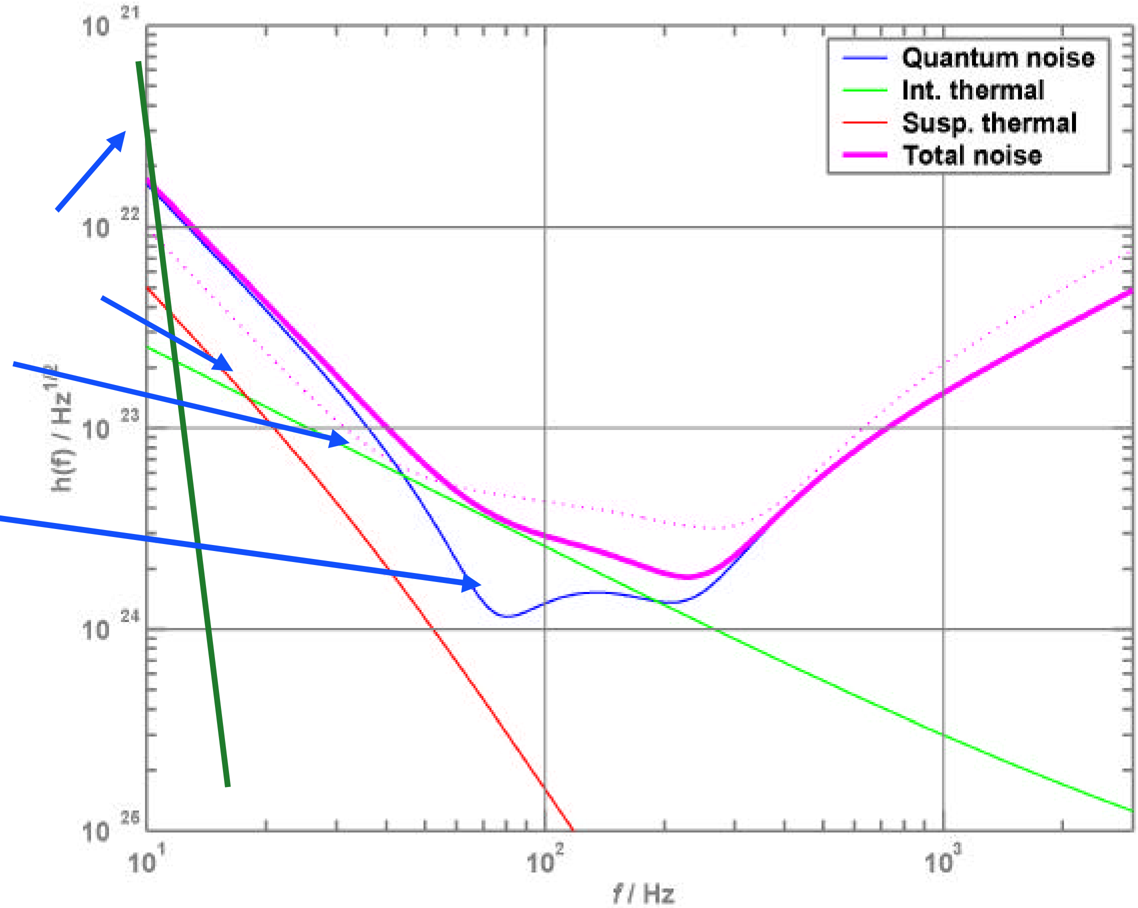
Advanced Interferometer Concept



- »Signal recycling
- »180-watt laser
- »Sapphire test masses
- »Quadruple suspensions
- »Active seismic isolation
- »Active thermal correction

Anatomy of Projected Performance

- Sapphire test mass baseline system
- Silica test mass dotted line
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- 'technical' noise (e.g., laser frequency) levels held in general well below these 'fundamental' noises



System trades

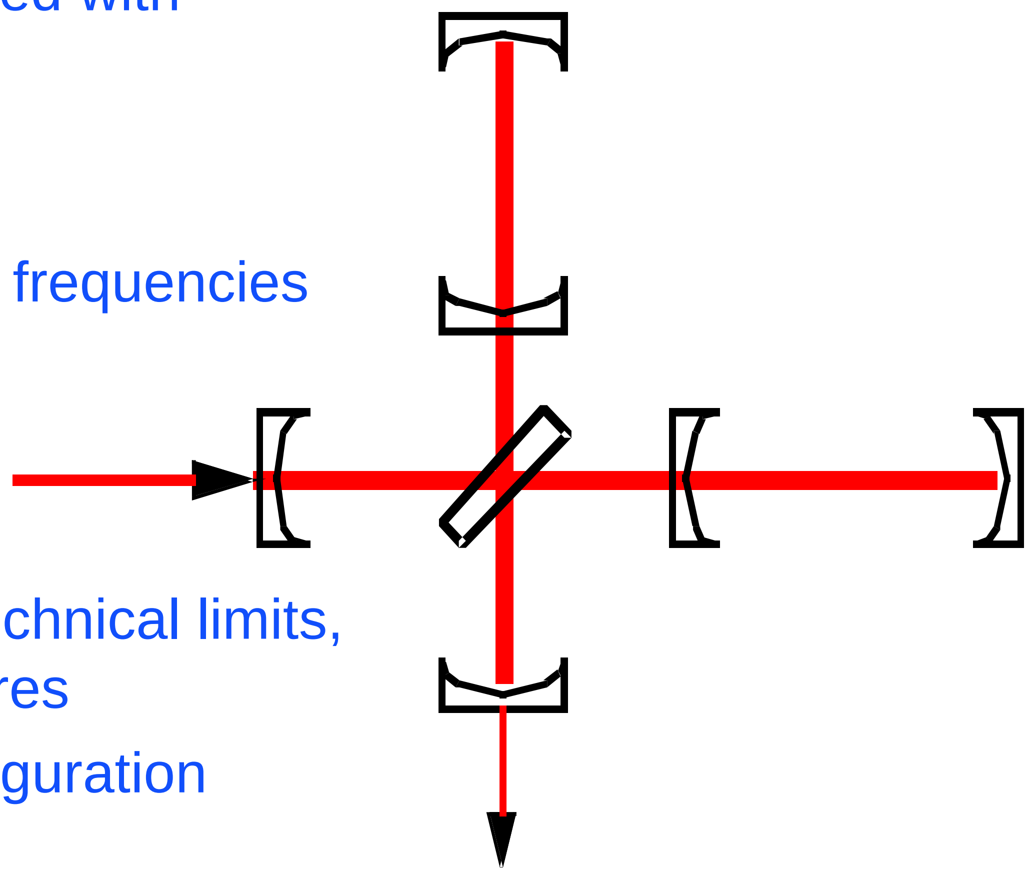
- Laser power
  - Trade between improved readout resolution, and momentum transfer from photons to test masses
  - Distribution of power in interferometer: optimize for material and coating absorption, ability to compensate
- Test mass material
  - Sapphire: better performance, but development program, crystalline nature
  - Fused silica: familiar, but large, expensive, poorer performance
- Lower frequency cutoff
  - Technology thresholds in isolation and suspension design

Nominal top level parameters

	Sapphire	Fused Silica
Fabry-Perot arm length	4000 m	
Laser wavelength	1064 nm	
Optical power at interferometer input	125 W	80 W
Power recycling factor	17	17
FP Input mirror transmission	0.5%	0.50%
Arm cavity power	830 kW	530 kW
Power on beamsplitter	2.1 kW	1.35 kW
Signal recycling mirror transmission	6.0%	6.0%
Signal recycling mirror tuning phase	0.12 rad	0.09 rad
Test Mass mass	40 kg	30 kg
Test Mass diameter	32 cm	35 cm
Beam radius on test masses	6 cm	6 cm
Neutron star binary inspiral range (Bench)	300 Mpc	250 Mpc
Stochastic GW sensitivity (Bench units)	8 x 10-9	3 x 10-9

Tailoring the frequency response

- Signal Recycling
- Additional cavity formed with mirror at output
- Can be resonant,
  or anti-resonant,
  for gravitational wave frequencies

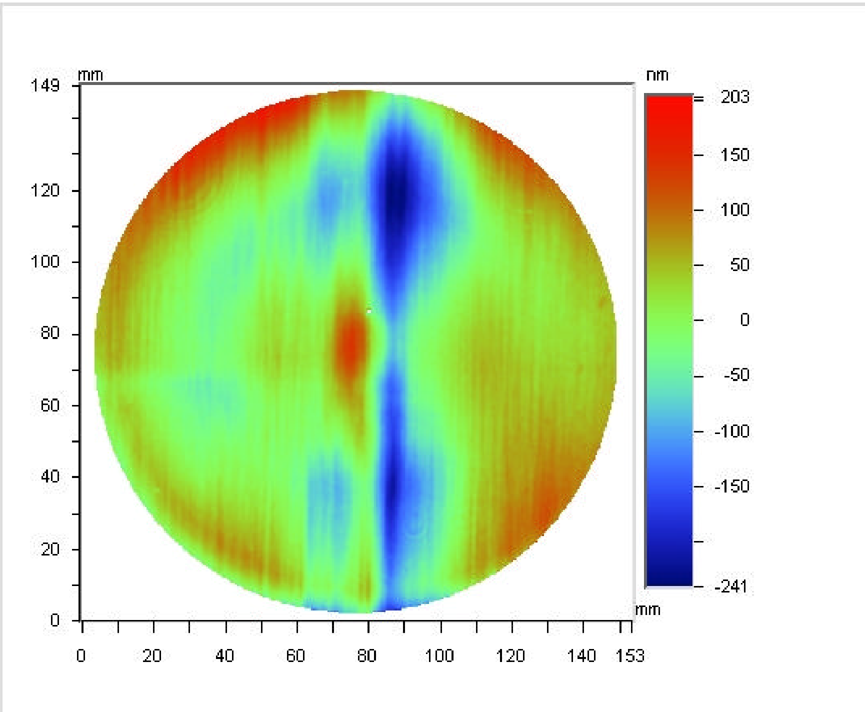


- Allows optimum for technical limits, astrophysical signatures
- Advanced LIGO configuration

Advanced Core Optics

- A key optical and mechanical element of design
  - » Substrate absorption, homogeneity, birefringence
  - » Ability to polish, coat
  - » Mechanical (thermal noise) performance, suspension design
  - » Mass – to limit radiation pressure noise: ~30-40 Kg required
- Two materials under study, both with real potential
  - » Fused Silica: very expensive, very large, satisfactory performance; familiar, non-crystalline
  - » Sapphire: requires development in size, homogeneity, absorption; high density (small size), lower thermal noise

Sapphire substrate homogeneity



Date: 11/08/2000
Time: 13:14:17
Wavelength: 1.064 um
Pupil: 100.0 %
PV: 444.0355 nm
RMS: 65.7678 nm
Rad of curv: 28.13 km

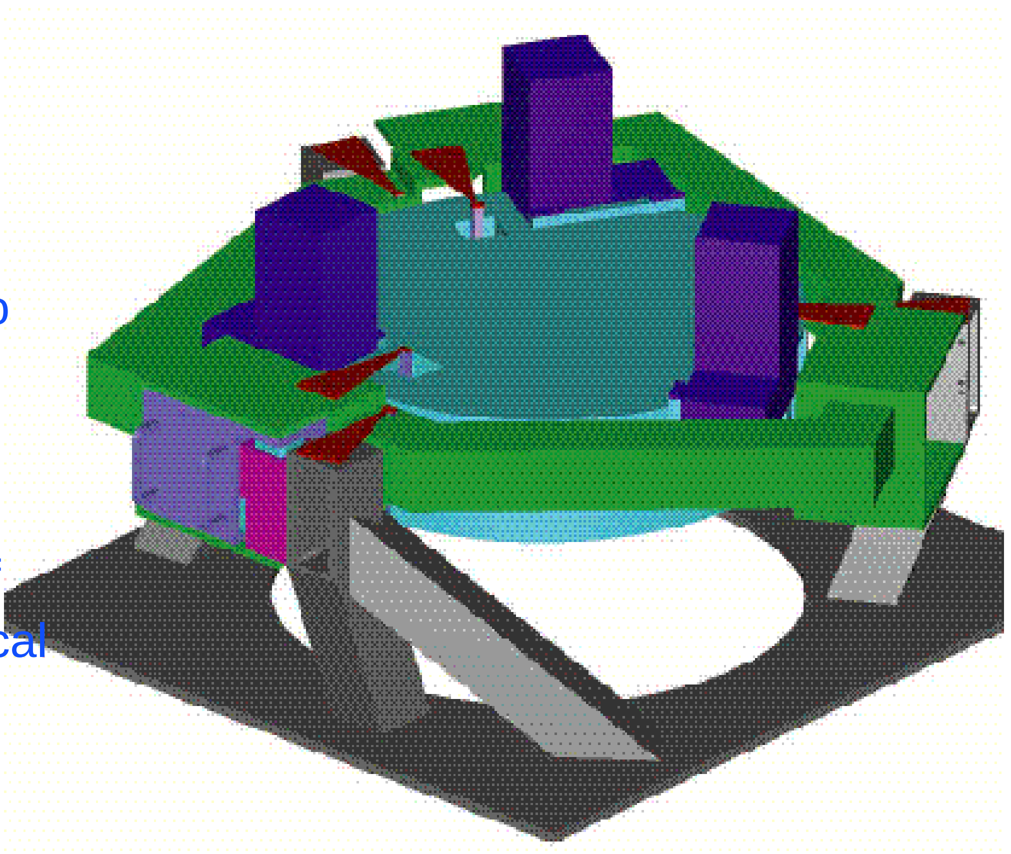
X Center: 287.00
Y Center: 240.00
Radius: 274.00 pix
Terms: Tilt
Filters: None
Masks: Detector Mask
Ref Sub: No

Averages: 8

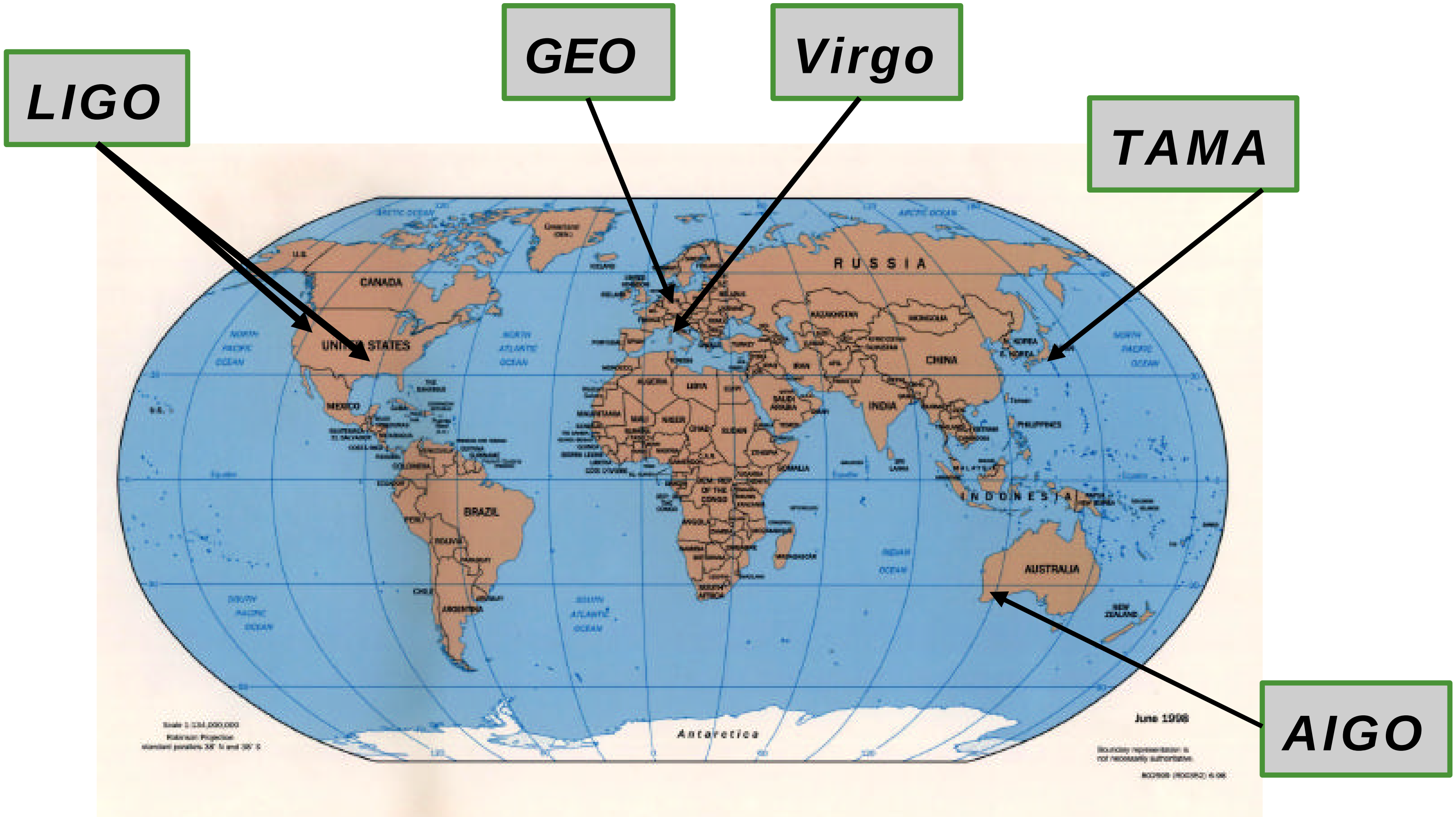
- CIT measurement of a 25 cm m-axis sapphire substrate, showing the central 150mm
- The piece is probed with a polarized beam; the structure is related to small local changes in the crystalline axis
- Plan to apply a compensating polish to side 2 of this piece and reduce the rms variation in bulk homogeneity to roughly 10-20 nm rms

SEI: Conceptual Design

- Two in-vacuum stages in series, external slow correction
- Each stage carries sensors and actuators for 6 DOF
- Stage resonances ~5 Hz
- High-gain servos bring motion to sensor limit in GW band, reach RMS requirement at low frequencies
- Similar designs for both types of vacuum chamber; provides optical table for flexibility



Global Network of GW Detectors



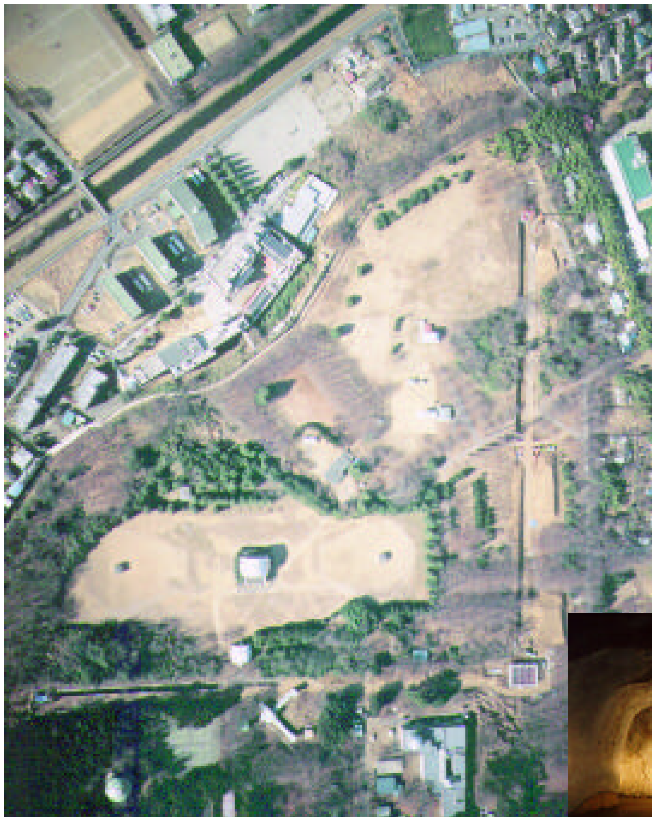
GW Detectors …

AIGO
Australia

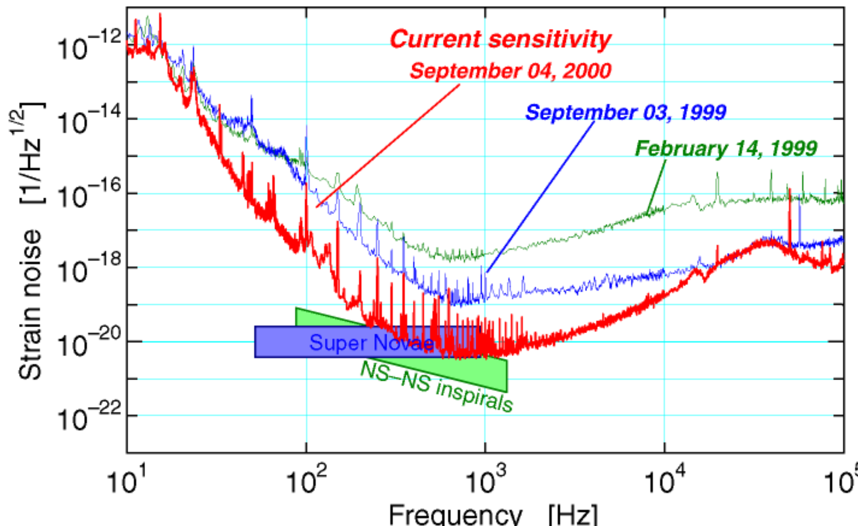
Virgo
Italy

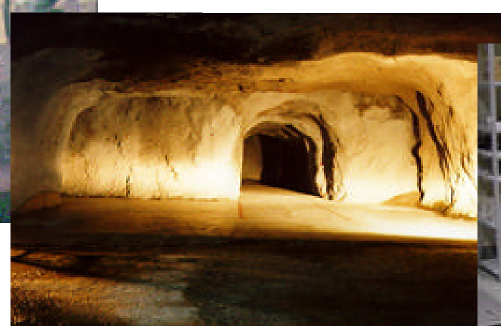
GEO 600
Germany

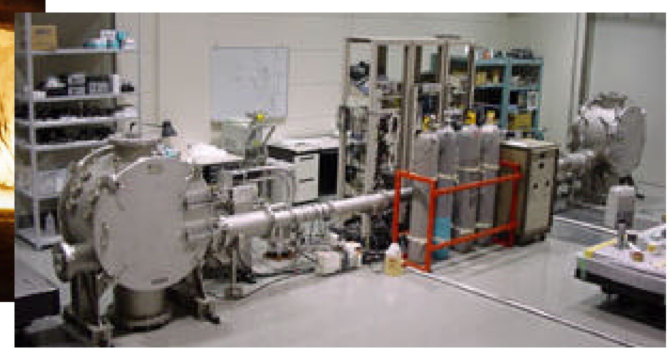
… GW Detectors



TAMA 300 Sensitivity



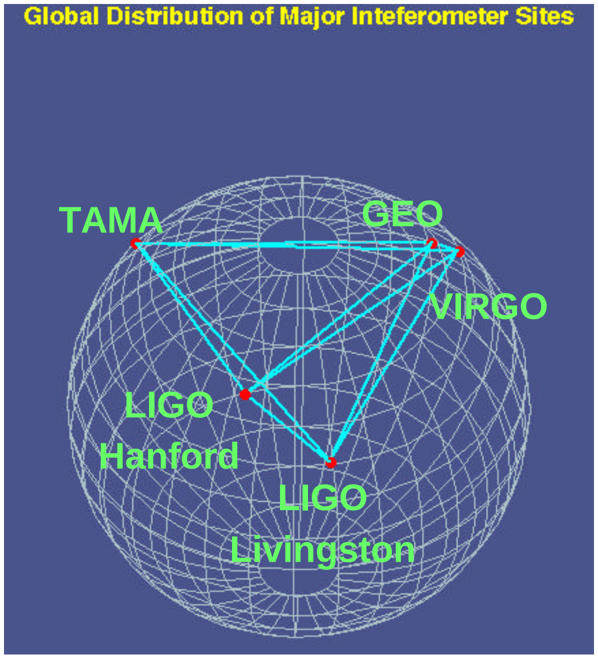


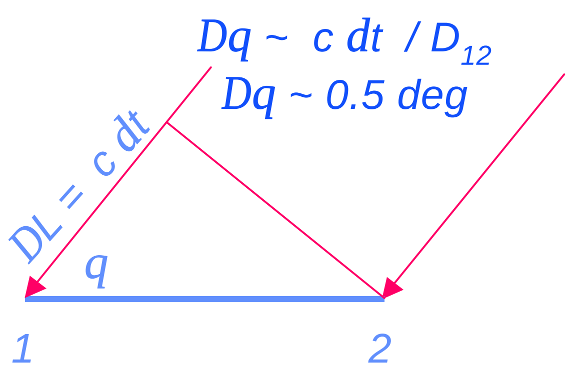


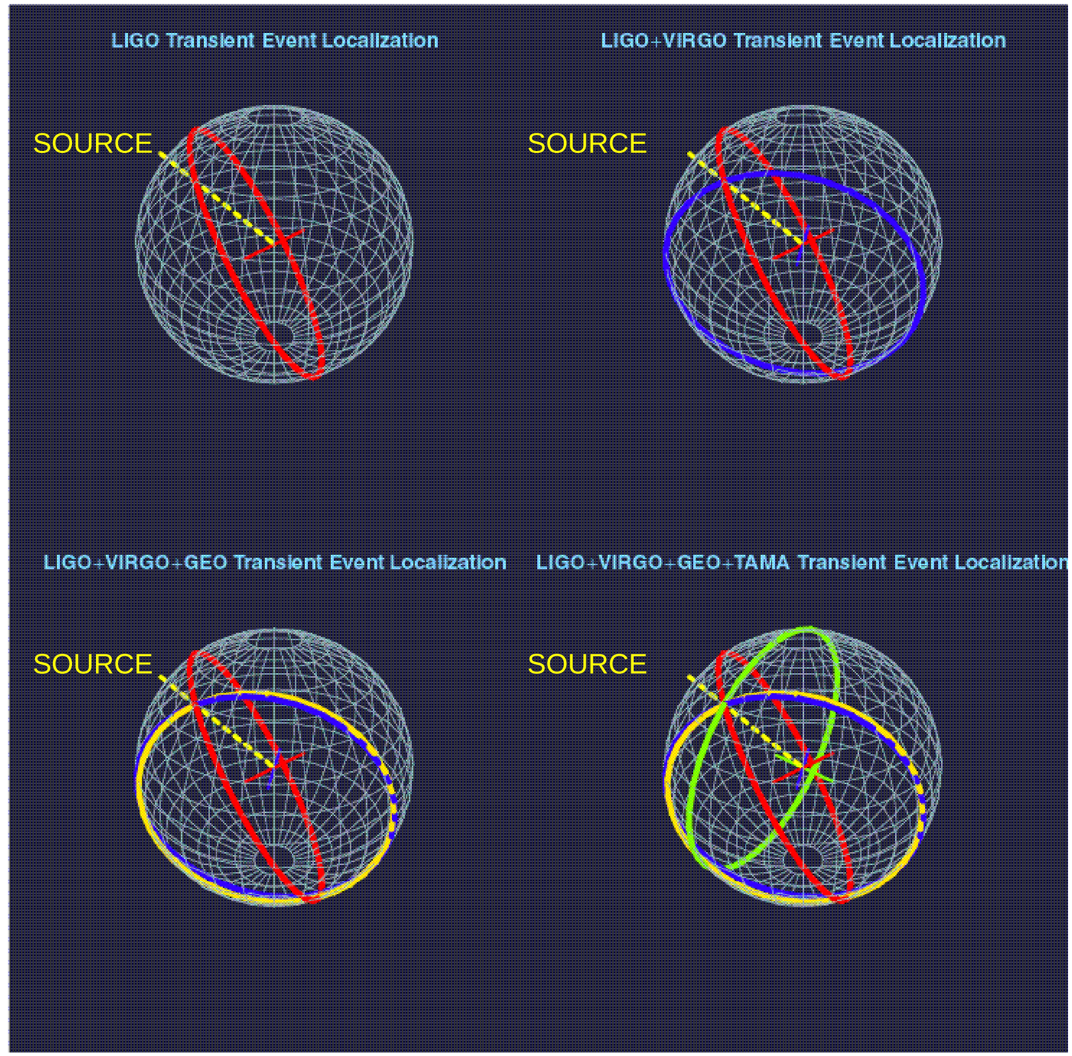
TAMA 300
Japan

LCGT - Kamioka

Event Localization with Array of Detectors

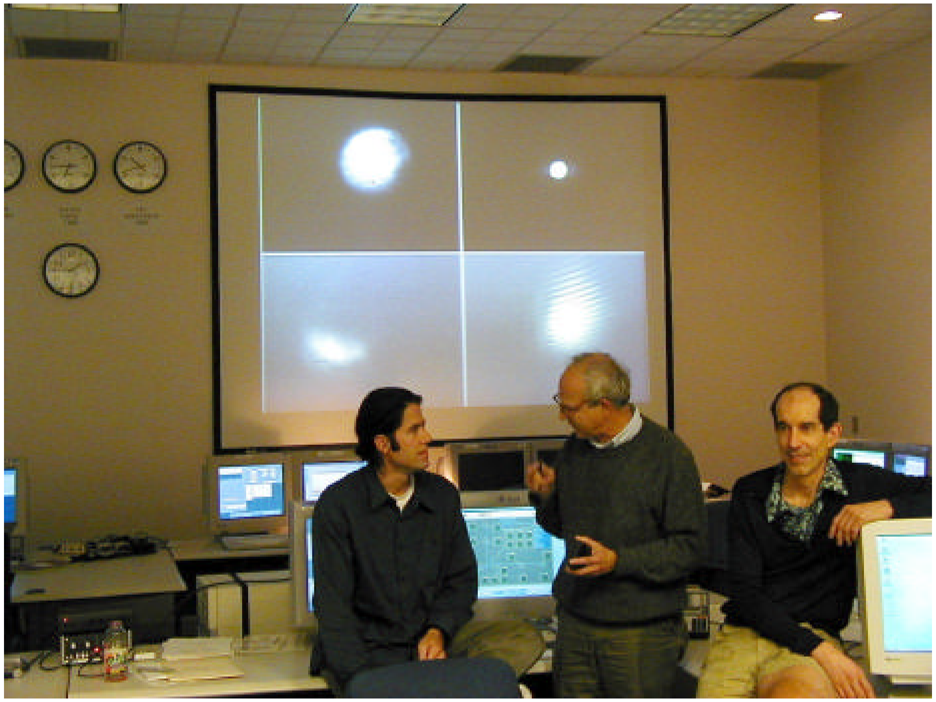






Where do we go from here?

- 2001
  - » Detector commissioning
  - » First coincidence operation
  - » Improve sensitivity/ reliability
  - » Initial data run ("upper limit run")
- 2002
  - » Begin Science Run
  - » Interspersed data taking and machine improvements
- Advanced LIGO R&D



First Lock in the Hanford Observatory control room