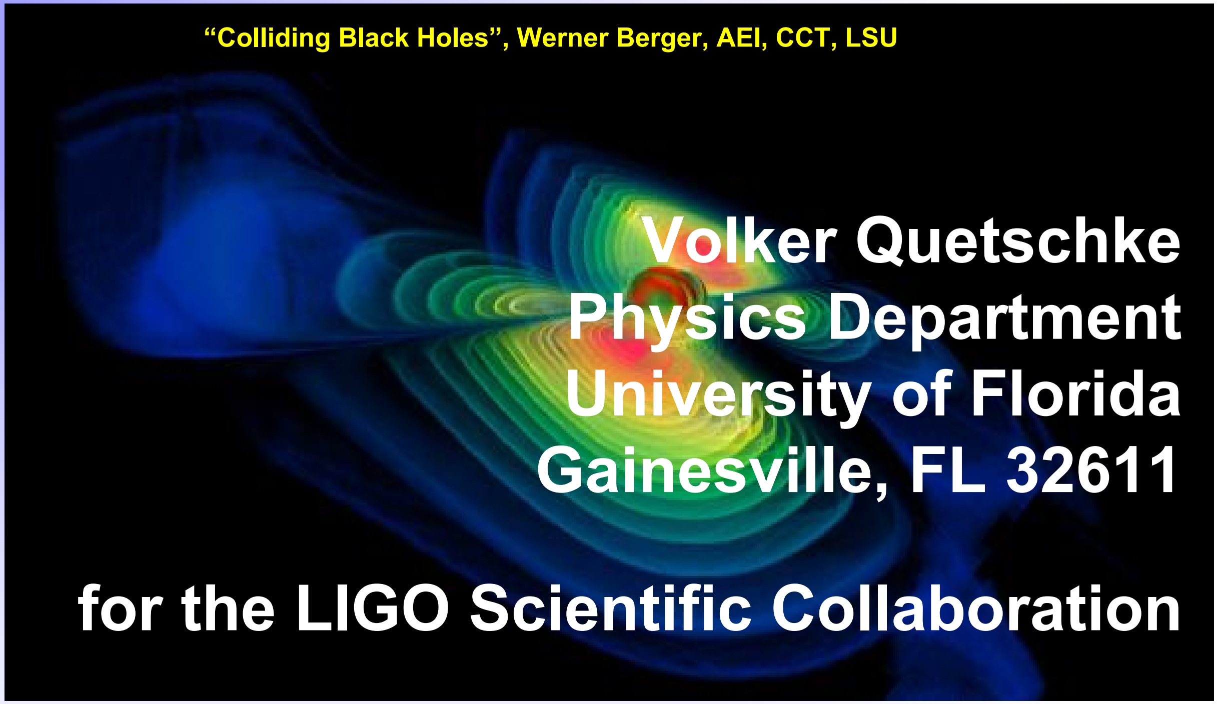
Coherent optical length measurement with 10^{-18} m accuracy



“Colliding Black Holes”, Werner Berger, AEI, CCT, LSU

Volker Quetschke
Physics Department
University of Florida
Gainesville, FL 32611

for the LIGO Scientific Collaboration

14th Coherent Laser Radar Conference, Snowmass, CO

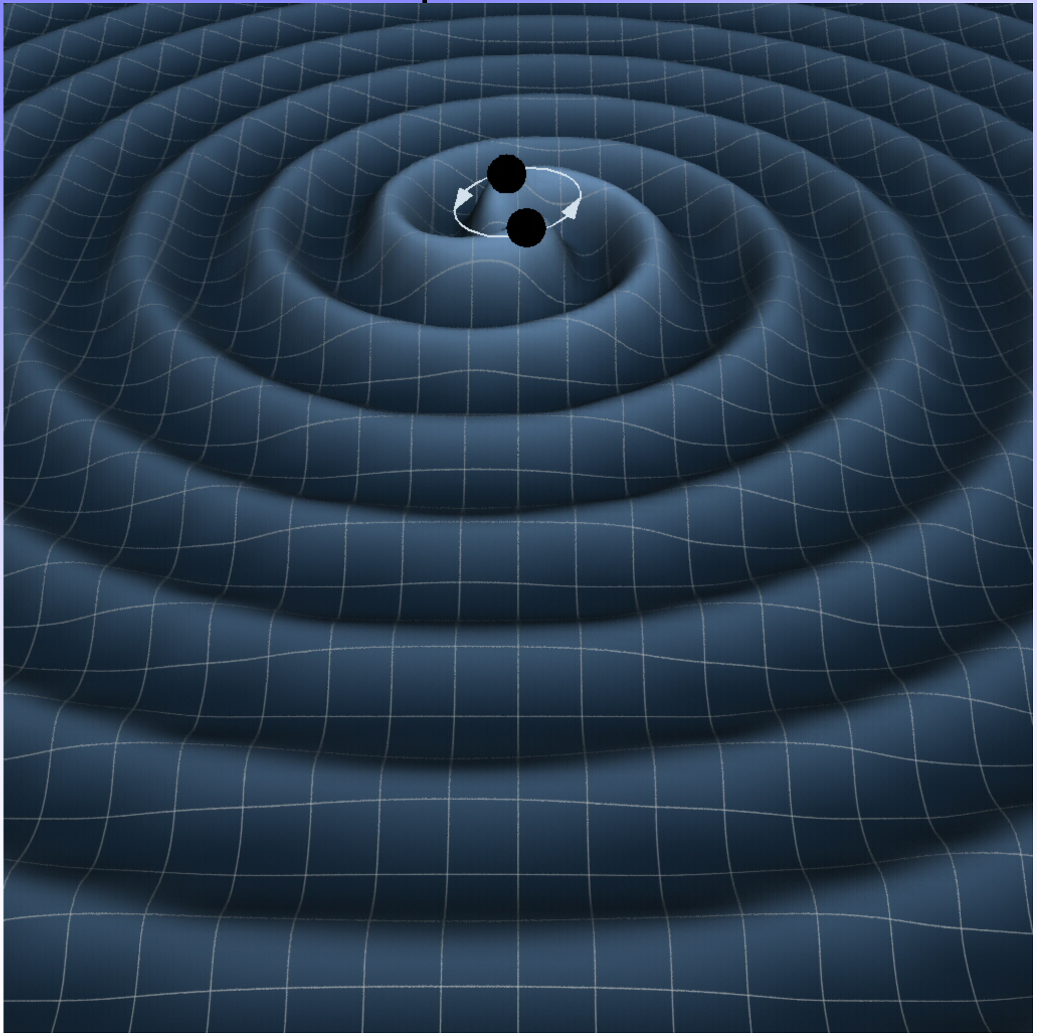
Support: NSF

Outline

- The present: LIGO
  - Gravitational waves
  - Advanced interferometry
  - Noise sources
  - The instrument
    - vacuum system
    - seismic isolation
    - core optics
    - thermal compensation
  - Sensitivity
- The future: Advanced LIGO
- Conclusions

Gravitational waves and astrophysics

Predicted by Einstein in 1916, GWs are propagating fluctuations in the curvature of space-time:



- Perturbations of geometry can be expressed as fractional distortion of proper distances:

$$h = \mathrm{d}x / |x|$$

- Calculate emissions from accelerating non-spherical mass distributions:

$$\Rightarrow \quad h_{\mu\nu}(\omega,t) = \frac{2G}{r\,c^4}\,\ddot{I}_{\mu\nu}(\omega,t)$$

$$\Rightarrow \quad h \approx \frac{4\pi^2 G M R^2 f_{orb}^{\,2}}{c^4 r}$$

K. Thorne (Caltech) , T. Carnahan (NASA GSFC)

Do the math…

A wave's strength is characterized by its *strain*

$$h = \Delta L / L$$

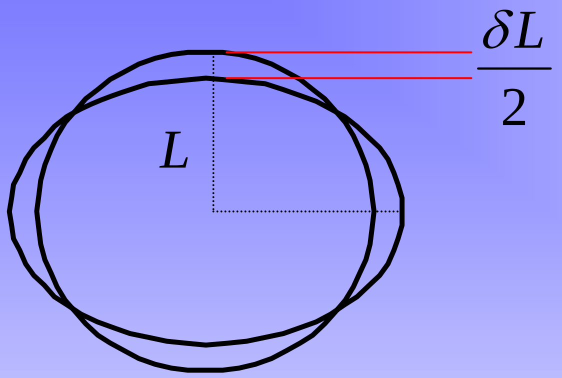
We can calculate the expected strain at Earth for, say, an orbiting binary system:

$$|h| \approx \frac{4\pi^2 G M R^2 f_{orbit}^2}{c^4 r} \approx 10^{-21} \left(\frac{R}{20\mathrm{km}}\right)^2 \left(\frac{M}{M_\Theta}\right) \left(\frac{f_{orbit}}{400\mathrm{Hz}}\right)^2 \left(\frac{10\mathrm{Mpc}}{r}\right)$$

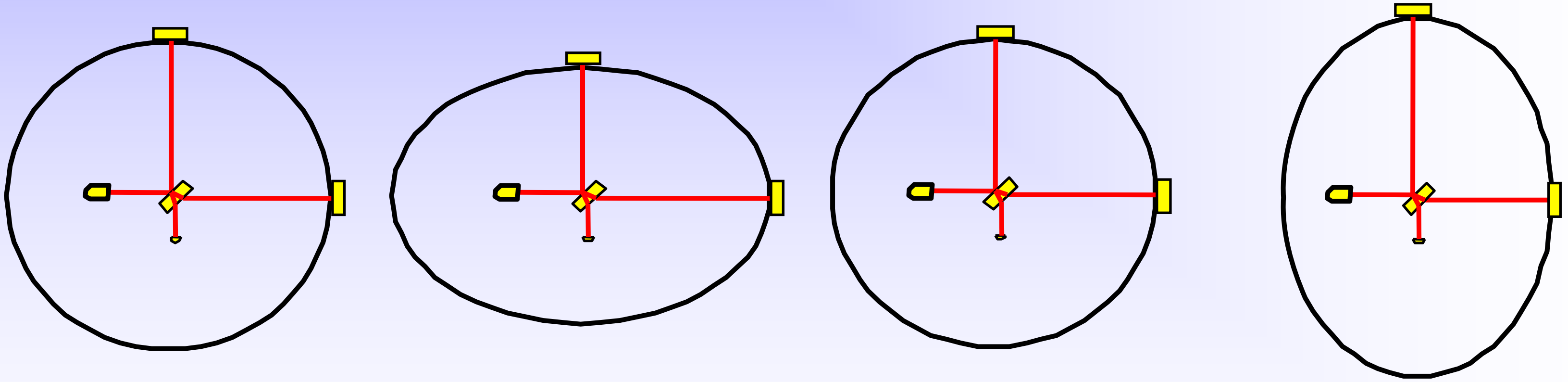
If we make our interferometer very big, say 4,000 meters long, then

$$\Delta L = h \times L \approx 10^{-21} \times 4{,}000\,m \approx 10^{-18}\,m$$

How to Measure Gravitational Waves ?



Effect on a ring of free falling masses: Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.



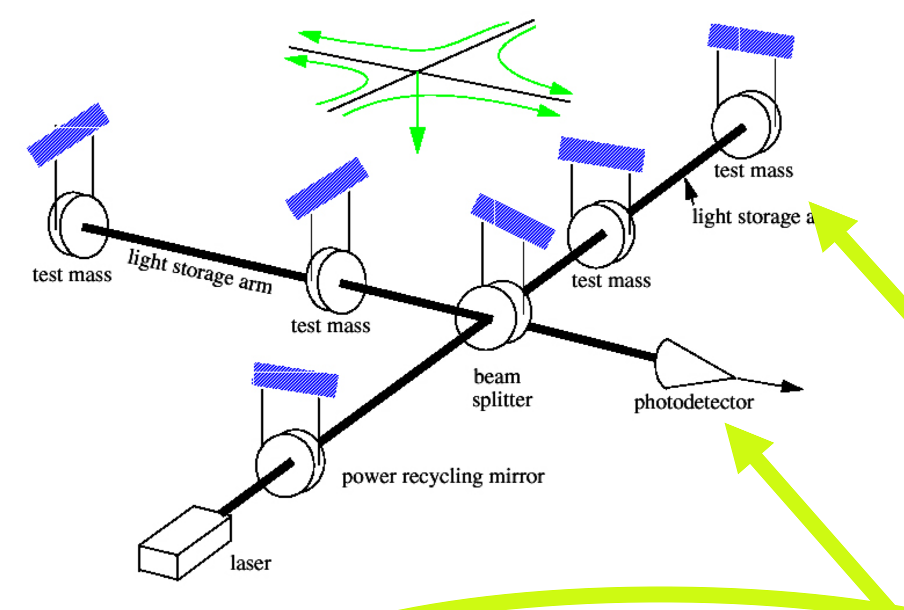
$t = 0$

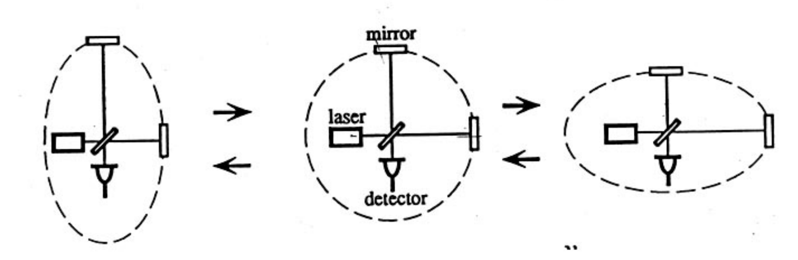
$t = \frac{\tau}{4}$

$t = \frac{\tau}{2}$

$t = \frac{3\tau}{4}$

GW LIGO detectors: interferometers





$h = \Delta L/L \sim 10^{-21}$ and

$L = 4\text{km}$

$\rightarrow \Delta L = h * L \sim 10^{-18}$ m !

suspended test masses
("freely falling objects")

dark port
(RF heterodyne modulation)

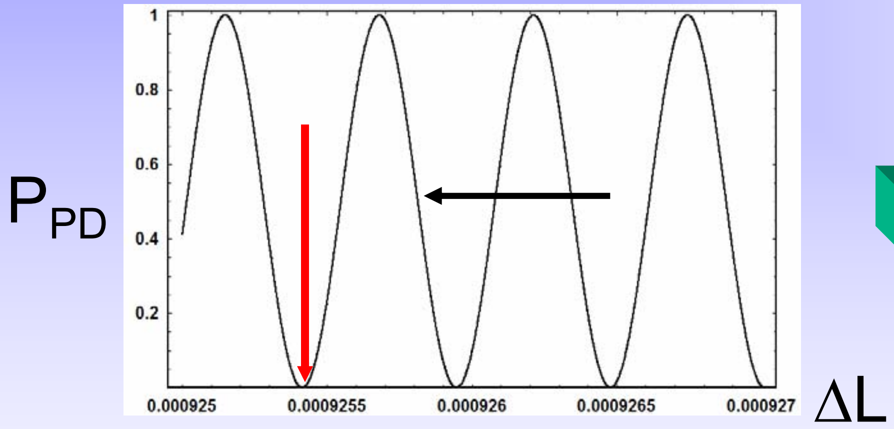
Three LIGO detectors:

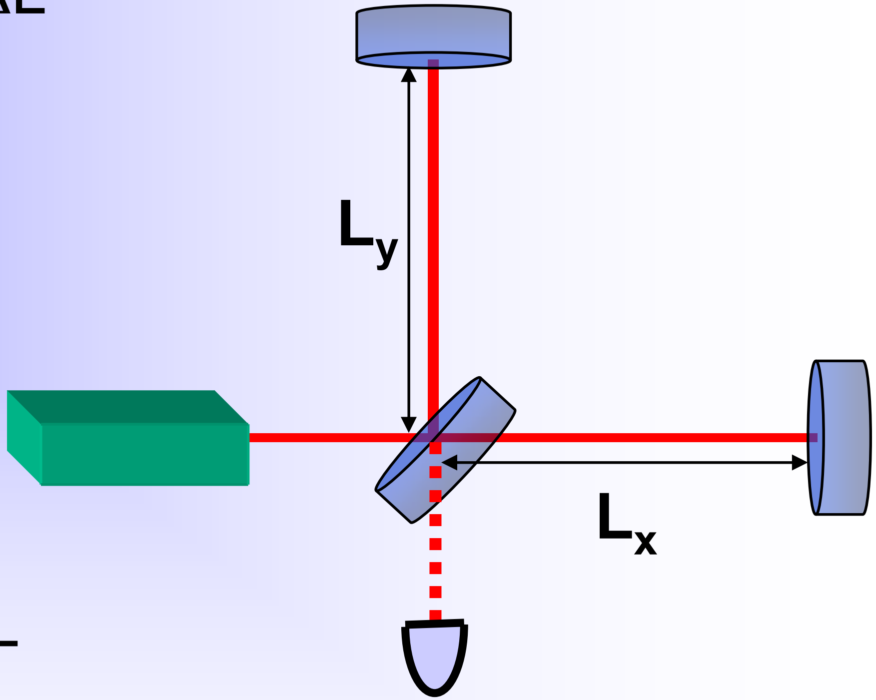
4km long in Livingston, La (L1);

4km and 2km long in Hanford, WA (H1, H2).

Interferometry: the basics

- Simple Michelson
  - Phase: $\phi = 4\pi\,(L_x - L_y)\,/\lambda \sim \Delta L$
  - Power: $P_{PD} = P_{BS}\,\sin^2\phi$
    - $dP/d\phi \sim P_{BS}\,\sin\phi\,\cos\phi$



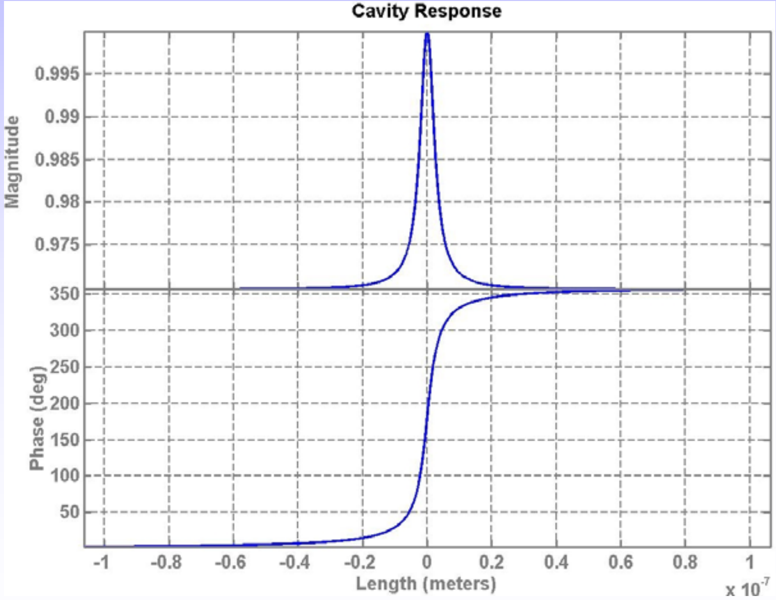


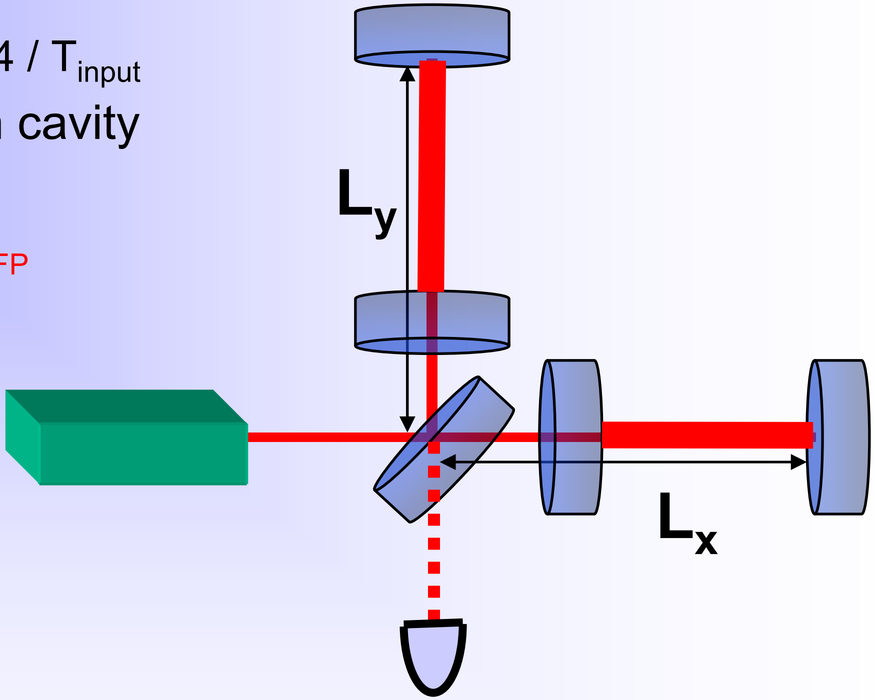
  - Strain: $h = \Delta L/L$
    - Increase sensitivity by using longer arms

$d\varphi/dh \sim L$

Advanced Interferometry I
Fabry-Perot Arm Cavities

- Fabry-Perot cavity
  - Increases power in arms
    - Overcoupled cavity gain: $G_{FP} \sim 4 / T_{input}$
  - Enhances storage time of light in cavity
    - Phase shift on resonance
    - Effectively 'lengthens' arms ~ G_{FP}





$d\varphi/dh \sim G_{FP}$ x L

Advanced Interferometry II: Power Recycling

- 'Recycle' light coming back from beamsplitter
  - Add a mirror which forms a resonant cavity with the rest of the interferometer

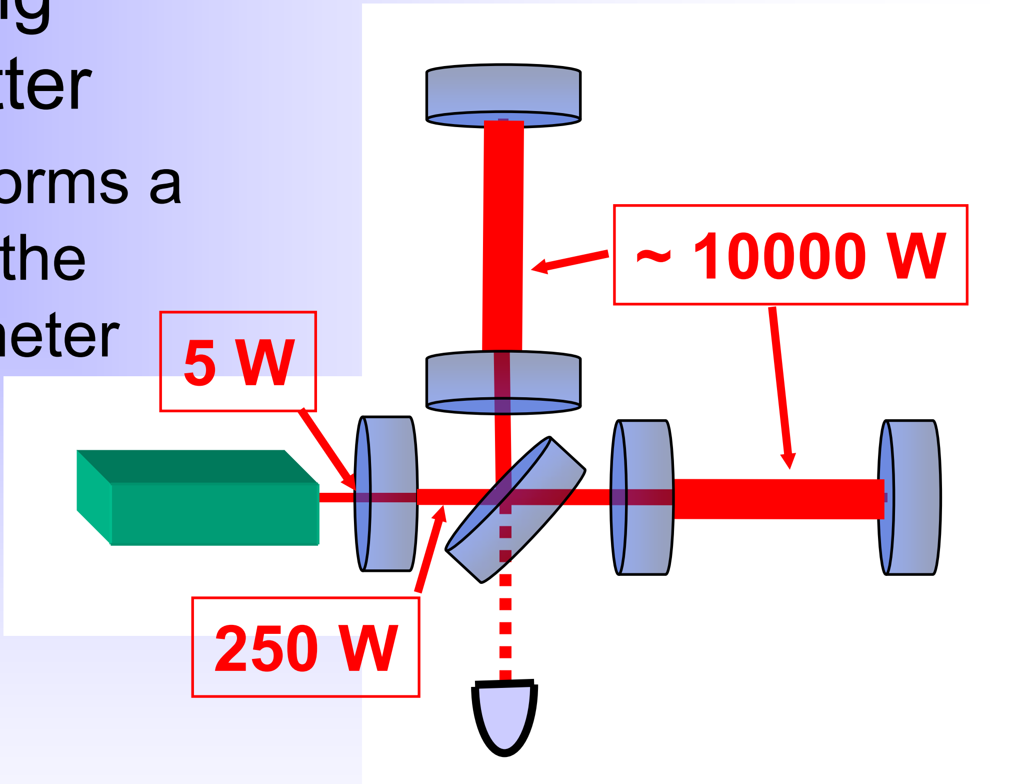
$P_{BS} = G_{RC} P_{input}$

+

$d\varphi/dh \sim G_{FP} \times L$

=>

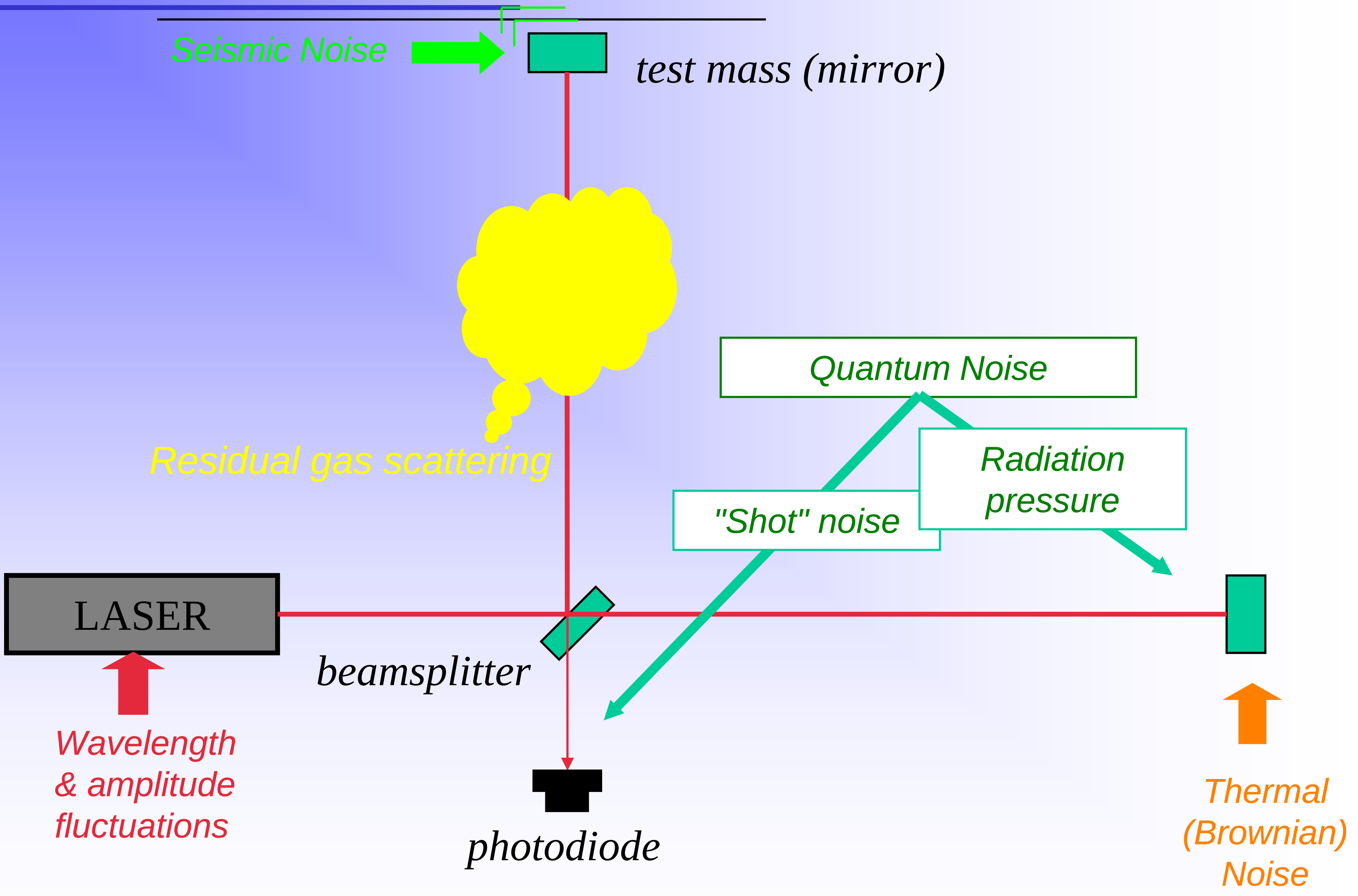
Enhanced Phase Sensitivity!



$G_{RC} \sim 50,\ G_{FP} \sim 80$

LIGO

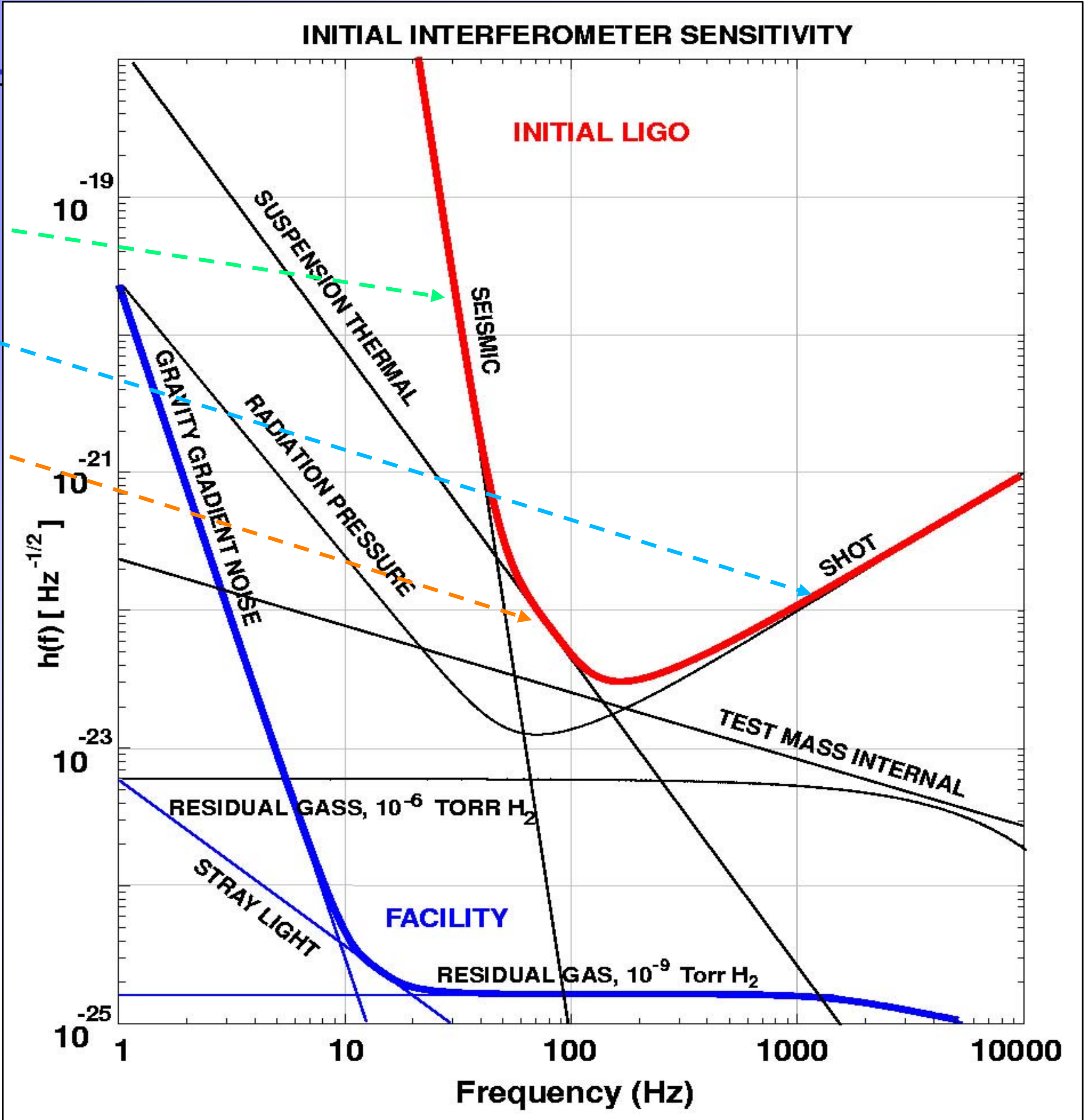
Interferometer Noise



Design Noise Limits

- Initial sensitivity limits
  - **seismic noise** at the lowest frequencies
  - **shot noise** at high frequencies
  - **thermal noise** at intermediate frequencies

- Based on conservative extrapolation of prototype technologies (circa ~'97)



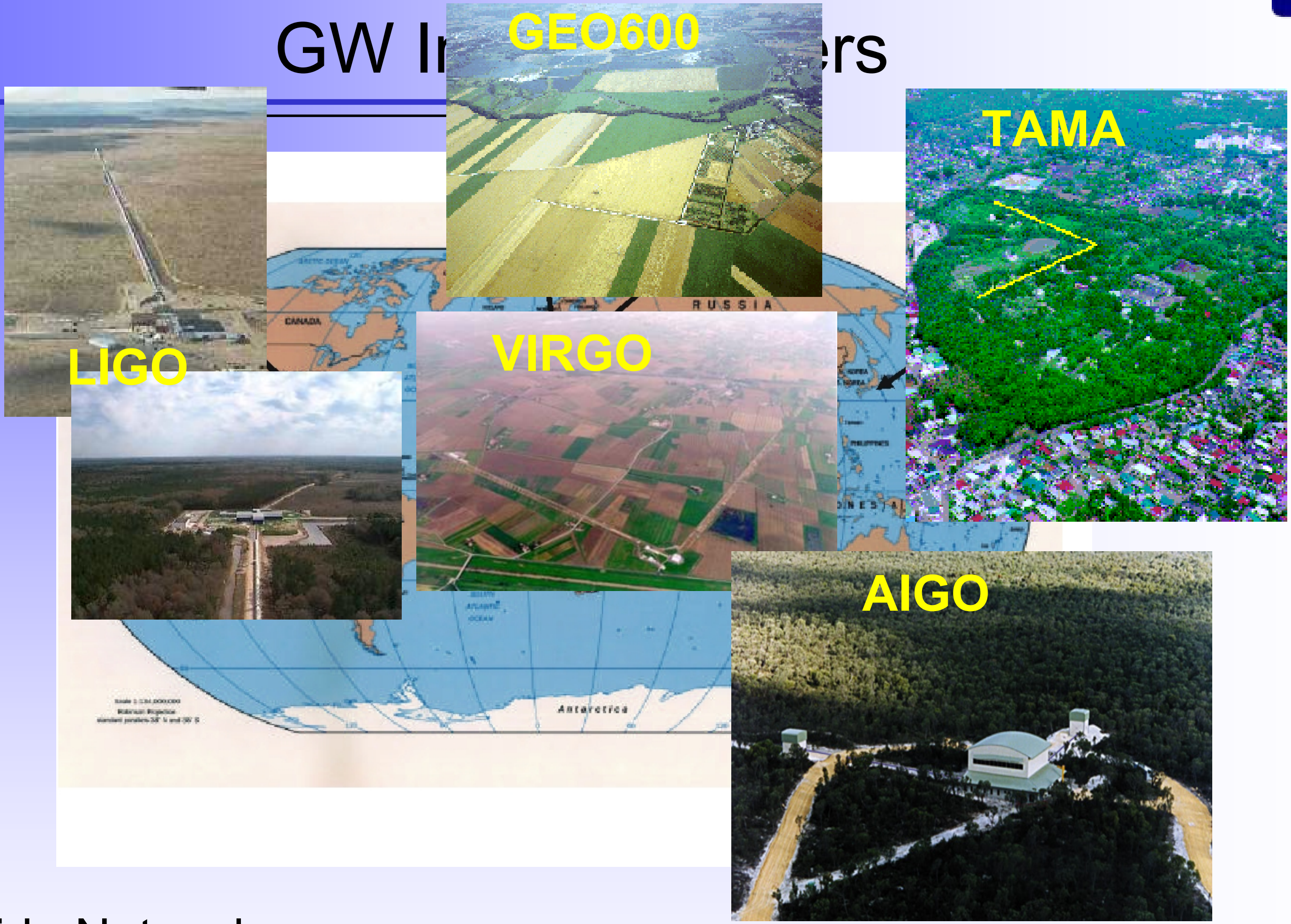
rvatory Sites

great circle connecting the sites

O)

- Coincidence
  - local environments uncorrelated
- Amplitude discrimination
  - half- and full-length IFO's share Hanford site
  - 1:2 ratio required for true signals
- Source triangulation
  - ± 10 ms time of flight
  - ~ arcminute directionality
- Source polarization

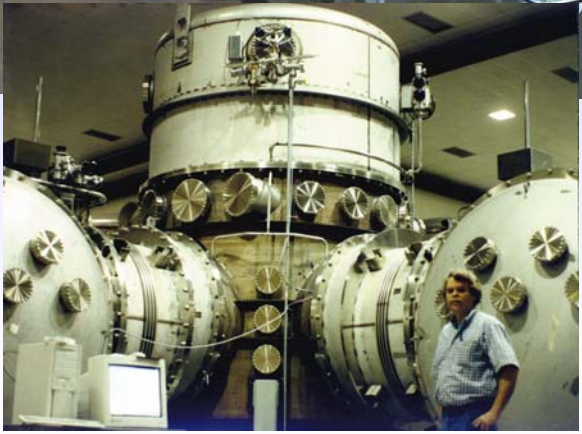
Worldwide Network of GW I ers



- Worldwide Network:
  - We coordinate observations and share data with GEO, TAMA and VIRGO
  - AIGO is still in planning stage

Vacuum Chambers provide housing for the optics

View inside Corner Station



Standing at vertex
beam splitter

Beam Tubes and Enclosures

Precast concrete enclosure: *bulletproof*

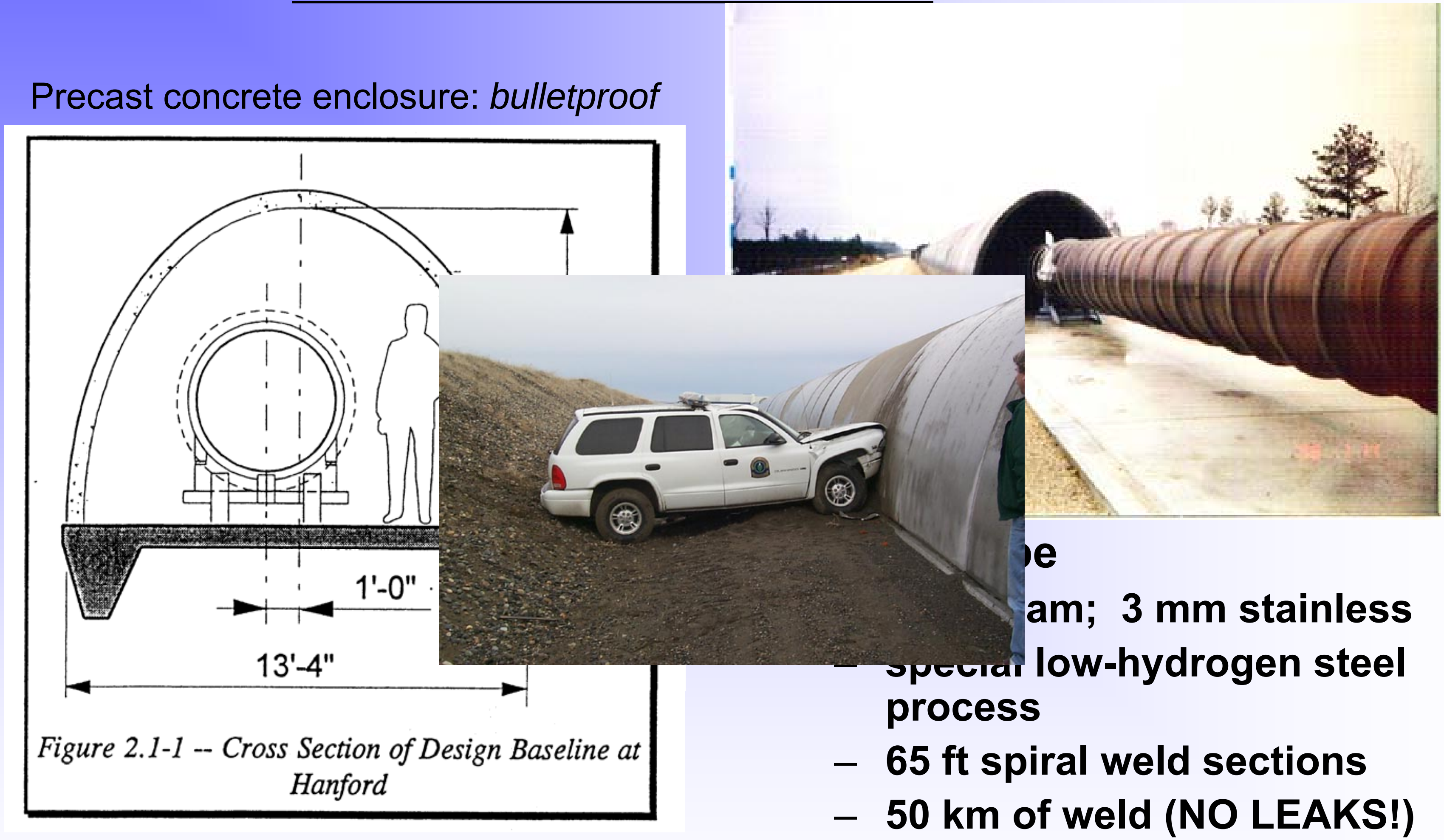


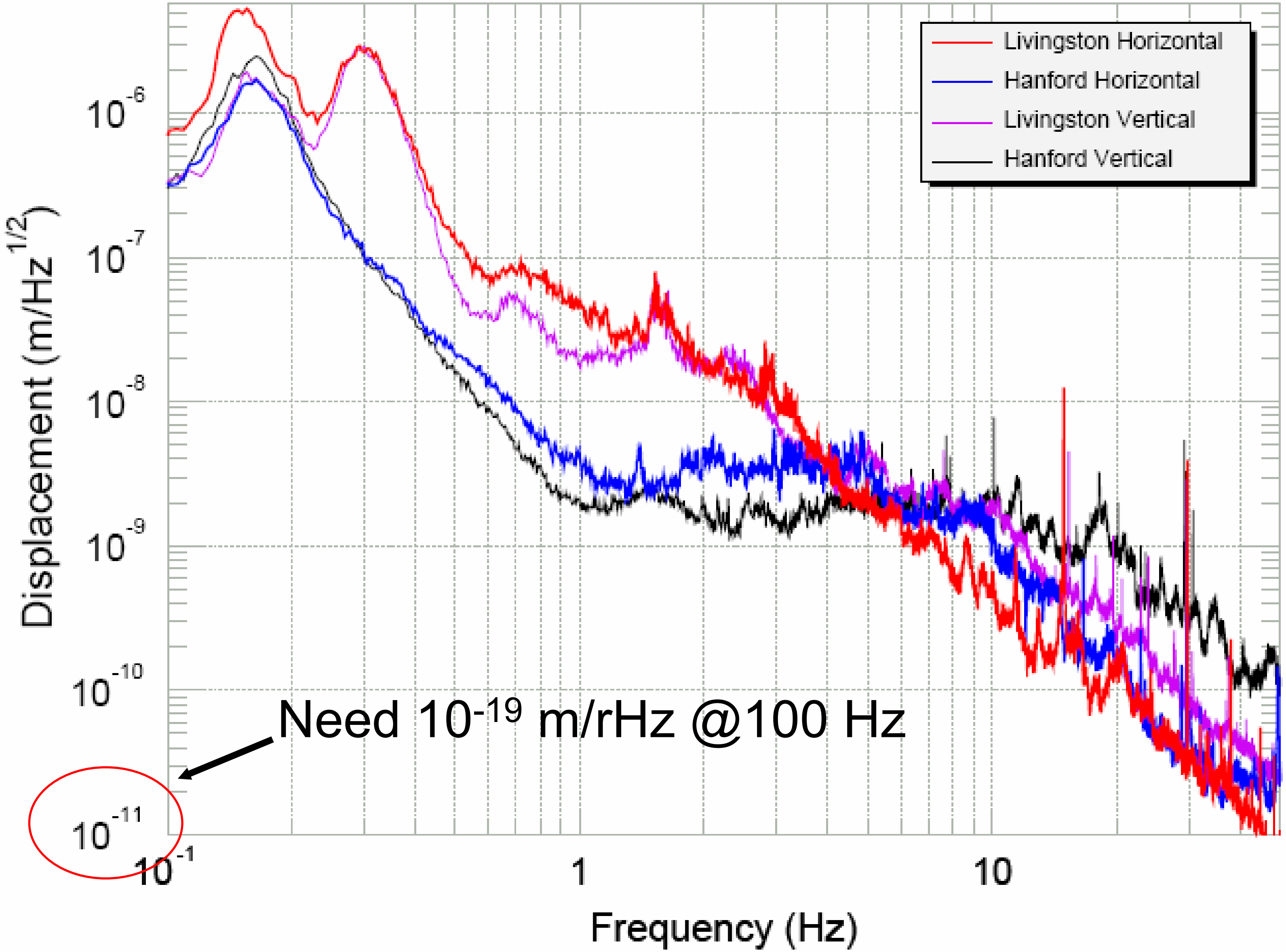
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

be

am; 3 mm stainless

– special low-hydrogen steel process
– 65 ft spiral weld sections
– 50 km of weld (NO LEAKS!)
– 20,000 m^3 @ 10^{-8} torr; earth's largest high vacuum system

Seismic Noise



Need 10^{-19} m/rHz @100 Hz

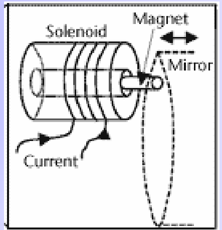
More Seismic isolation

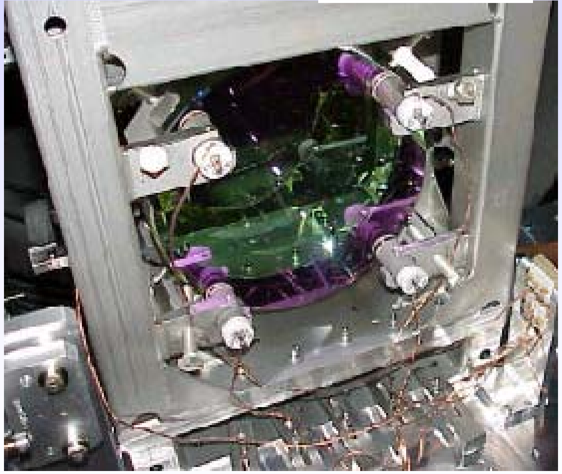
Mirror Suspensions

- pendulum design
- provide 10^2 suppression above 1 Hz
- provide ultraprecise control of optics displacement (< 1 pm)

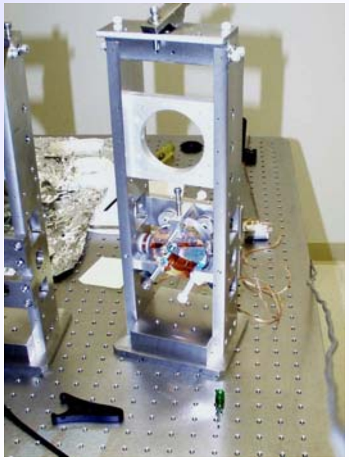
Wire standoff & magnet

"OSEM"



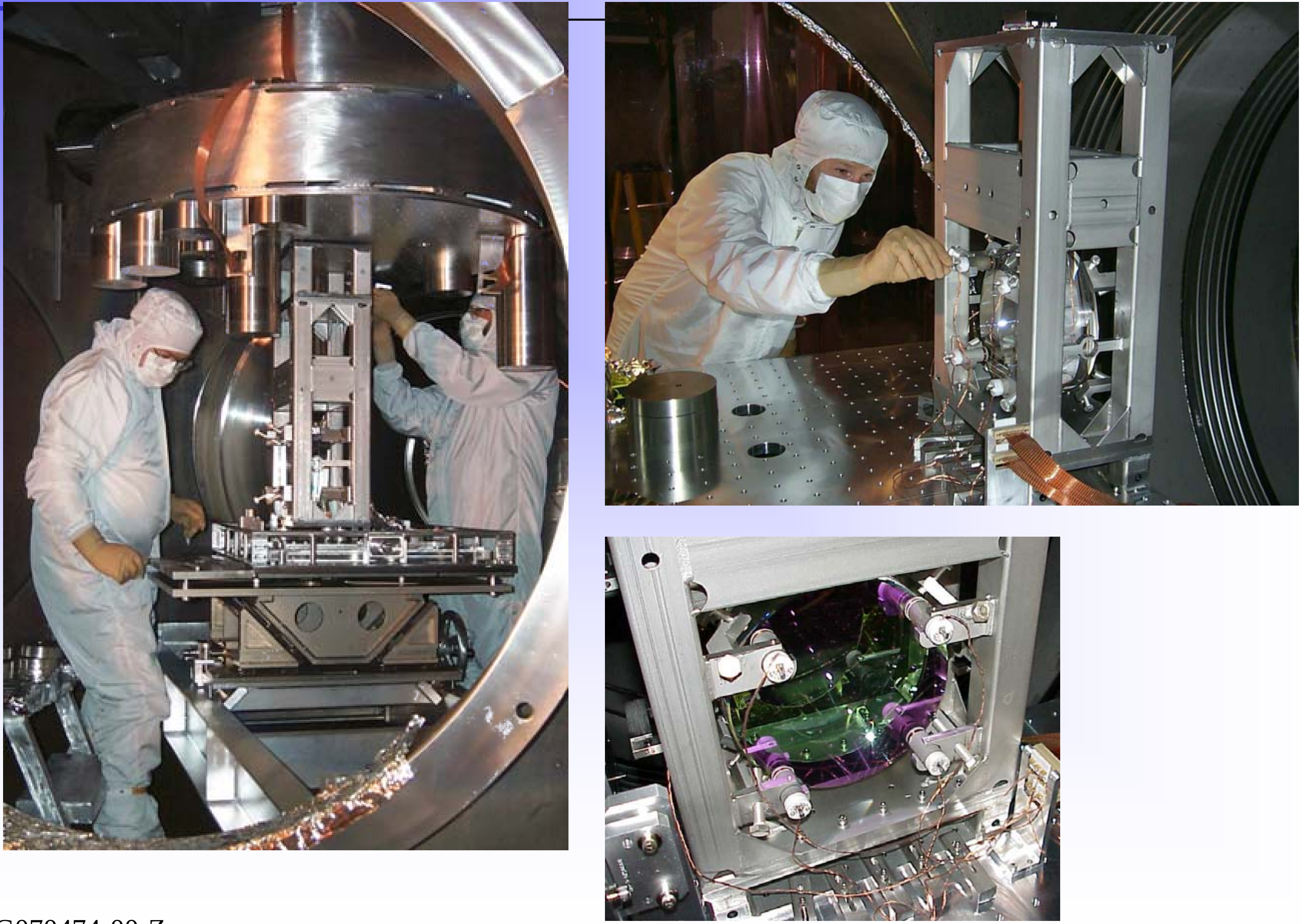


LOS



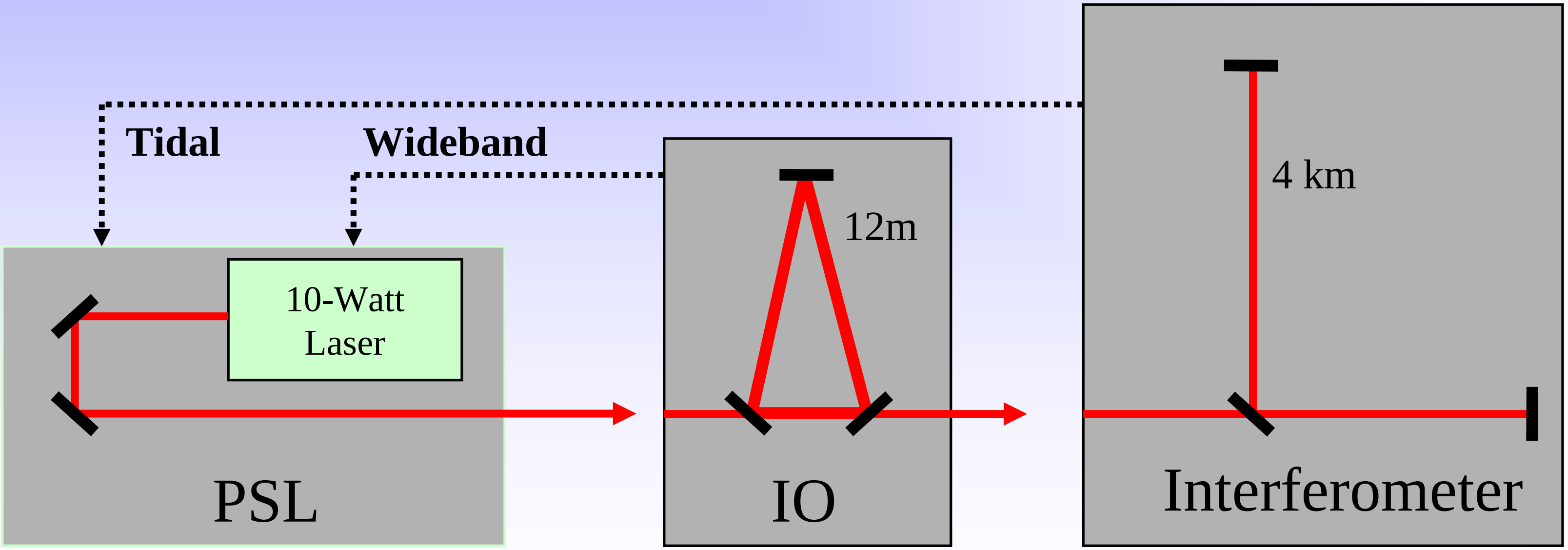
SOS

Core Optic Suspensions

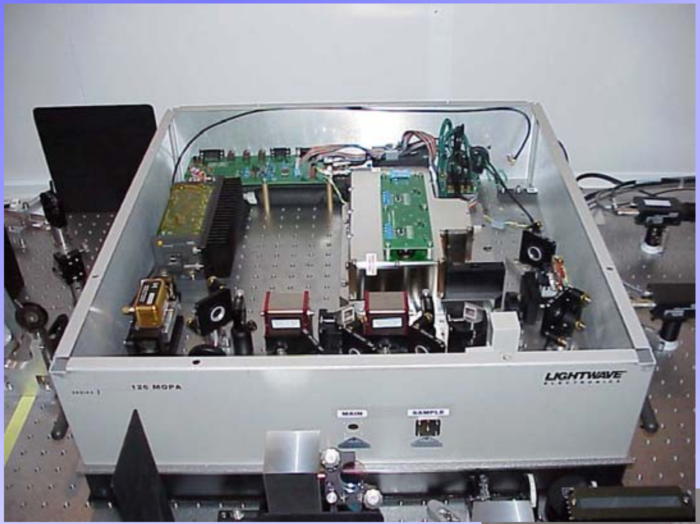


The pre-stabilized Laser System

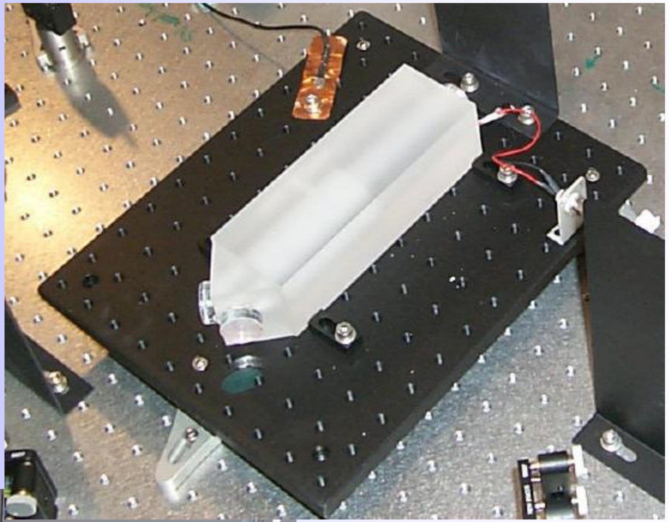
- Deliver pre-stabilized laser light to the long mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Provide actuator inputs for further stabilization
  - **Wideband**
  - **Tidal**



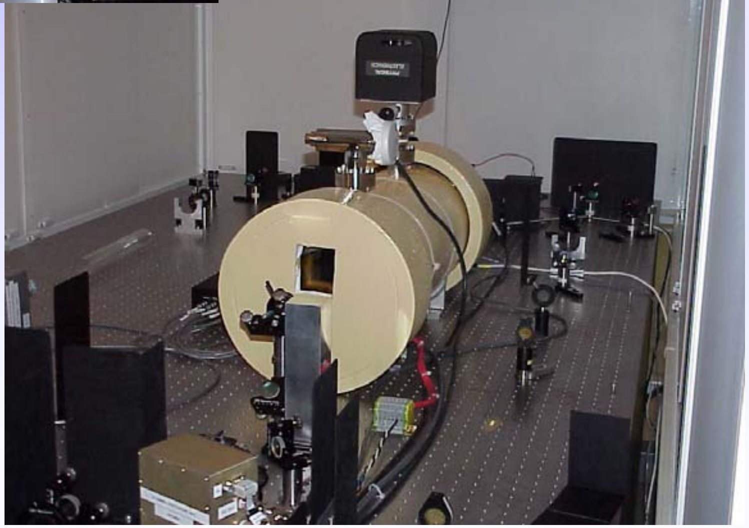
All-Solid-State Nd:YAG Laser



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics



Cavity for
defining beam geometry,
joint development with
Stanford



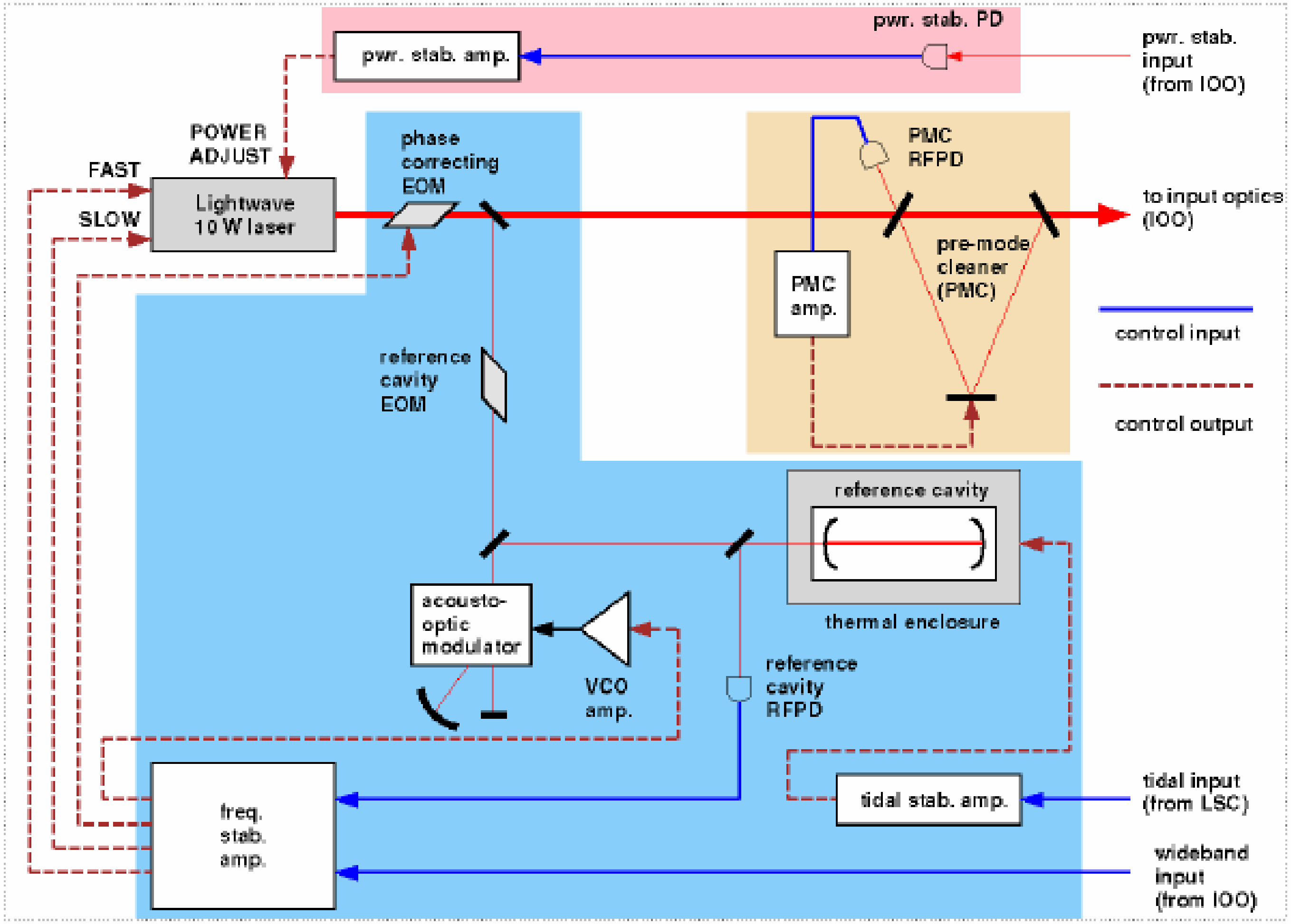
Frequency reference
cavity (inside oven)

LIGO

LIGO Pre-stabilized Laser

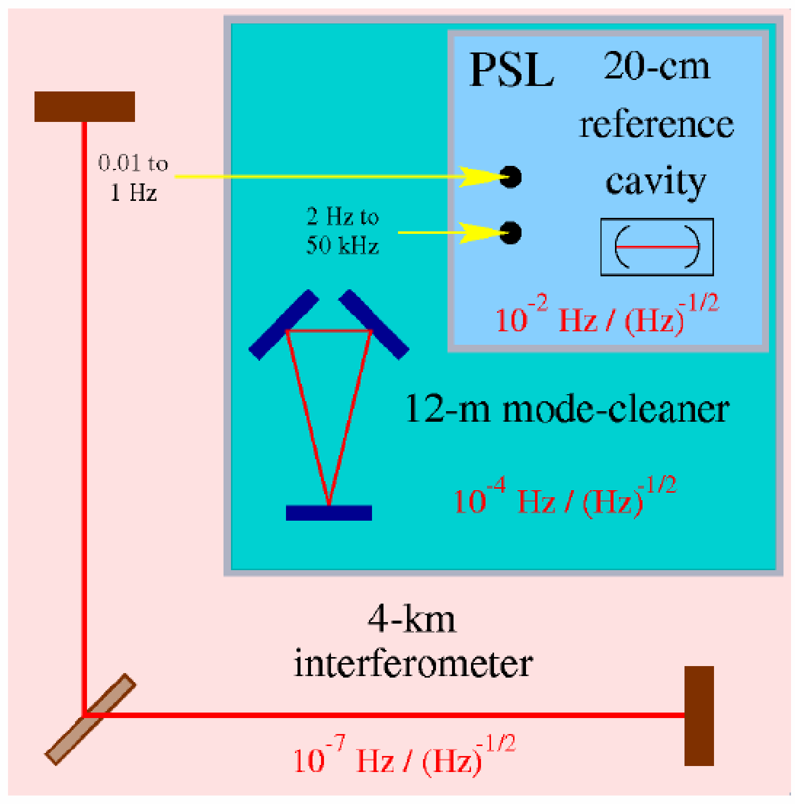
LSC

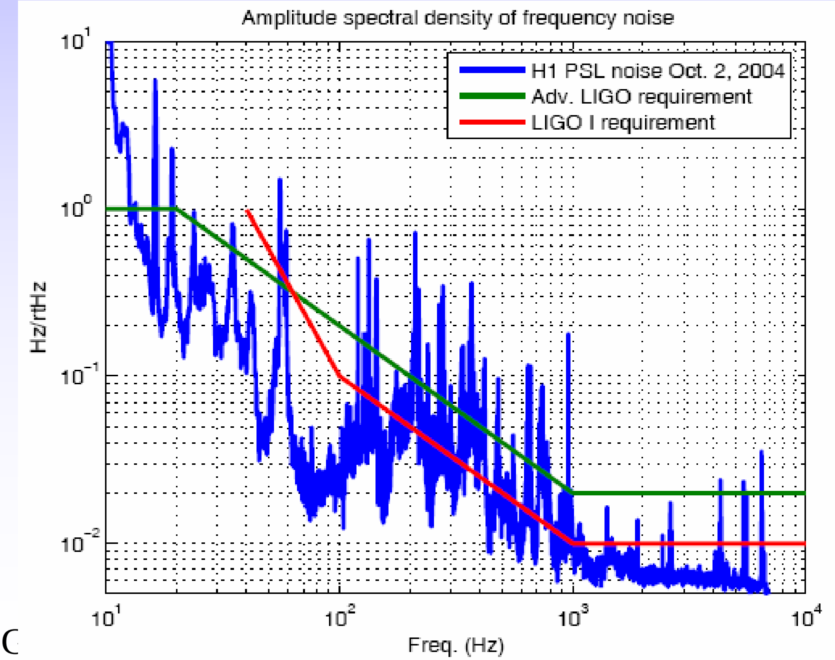
- Laser source
- Frequency pre-stabilization and actuator for further stab.
- Compensation for Earth tides
- Power stab. in GW band
- Power stab. at modulation freq. (~ 25 MHz)



Frequency Stabilization in LIGO

- Nested control loops
  - Stage 1 – thermally-20 cm long stabilized reference cavity
  - Stage 2 – in vacuum suspended 12 or 15 m long “mode cleaner’ cavity
  - Stage 3 – Fabry Perot arm cavities

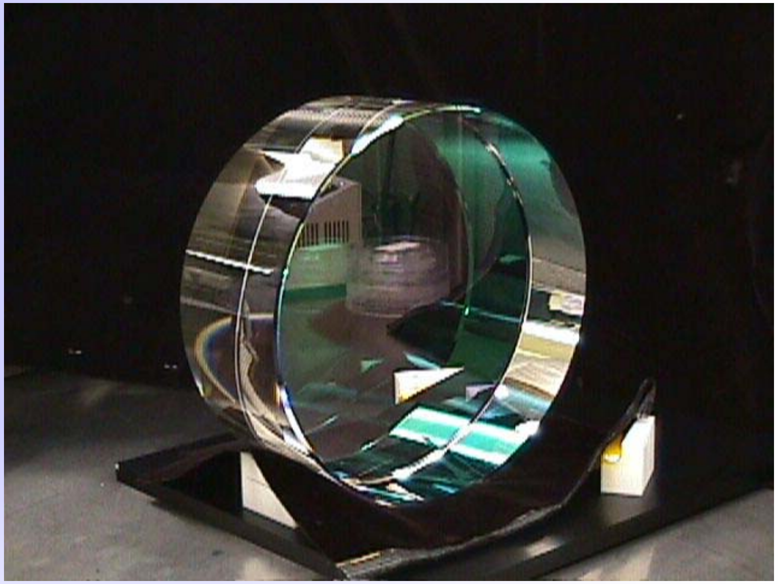




$\Delta f/f \sim 3 \times 10^{-22}$ @ 100 Hz

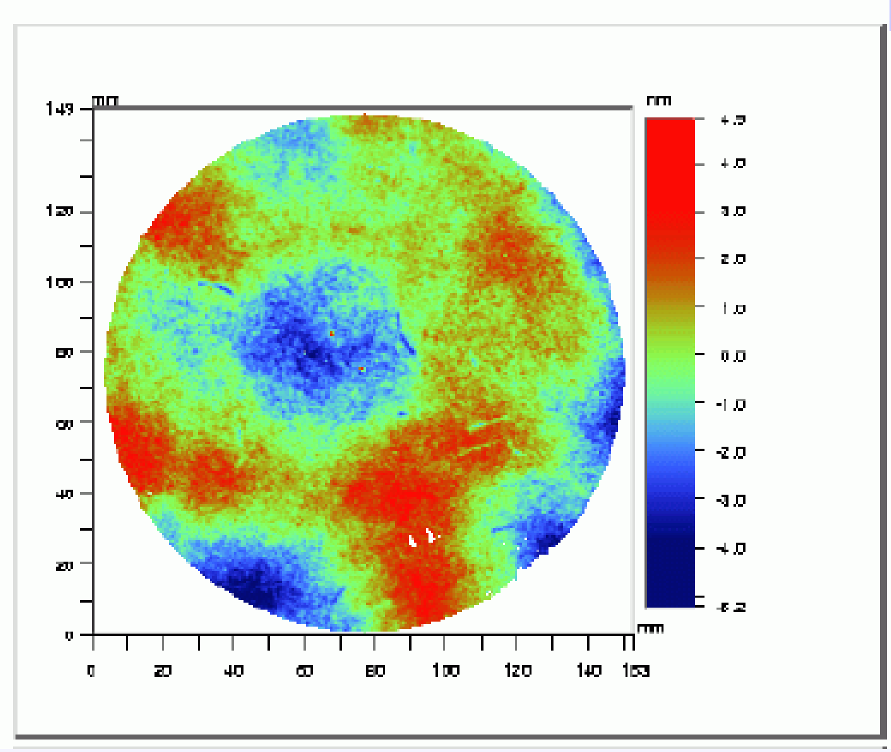
Core Optics

- Substrates: SiO_2
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5×10^{-7}
  - Internal mode Q's > 2×10^{6}
- Polishing
  - Surface uniformity < 1 nm rms
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity $<10^{-3}$
- Production involved 6 companies, NIST, and LIGO

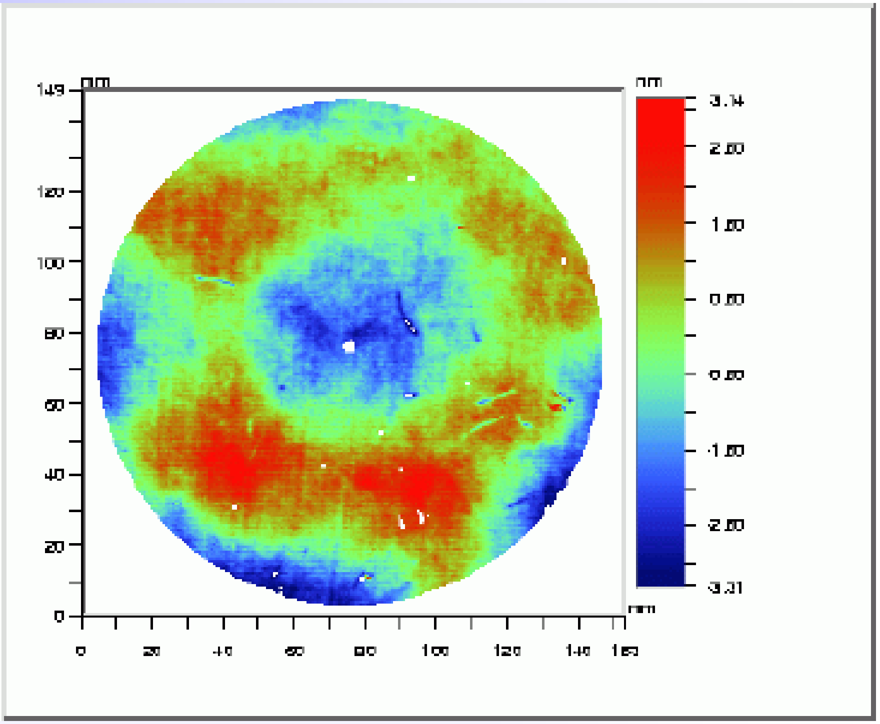


Core Optic Metrology

- Current state of the art: 0.2 nm repeatability



LIGO data (1.2 nm rms)

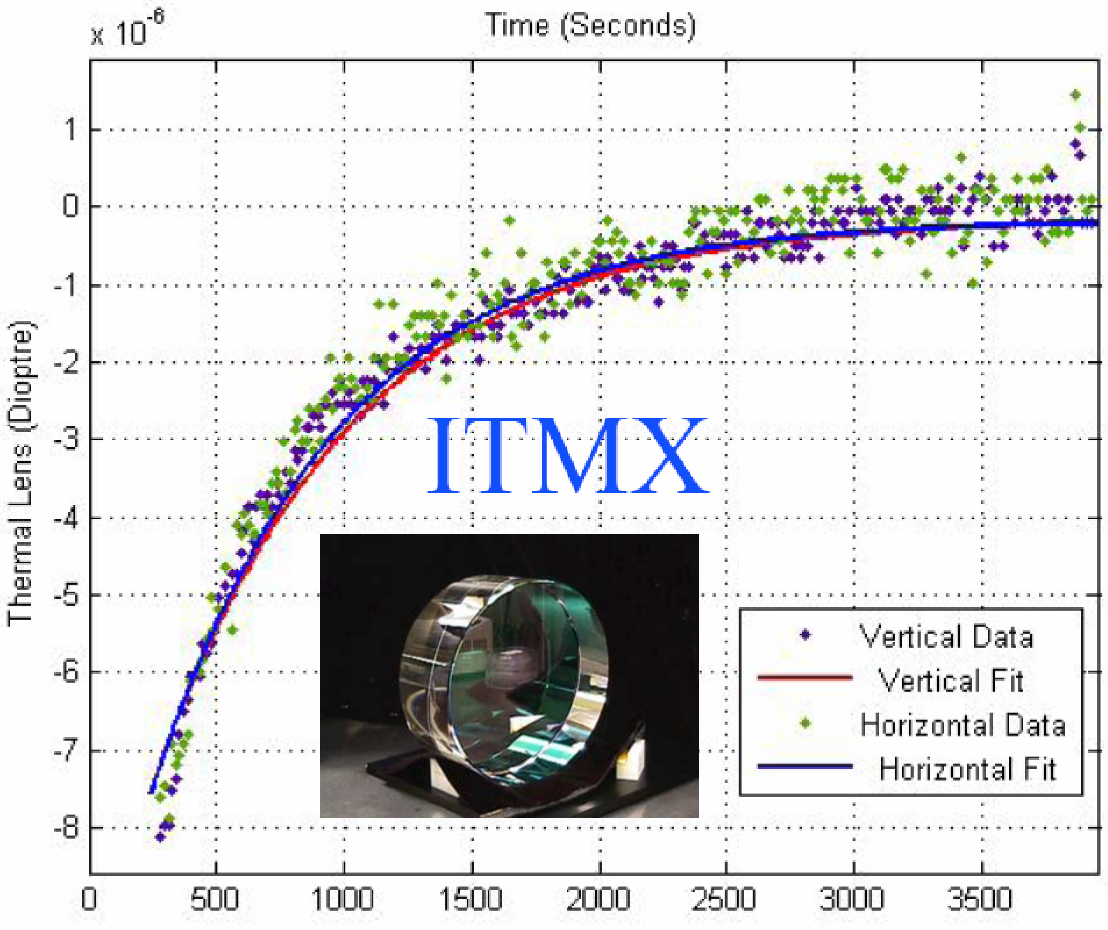


CSIRO data (1.1 nm rms)

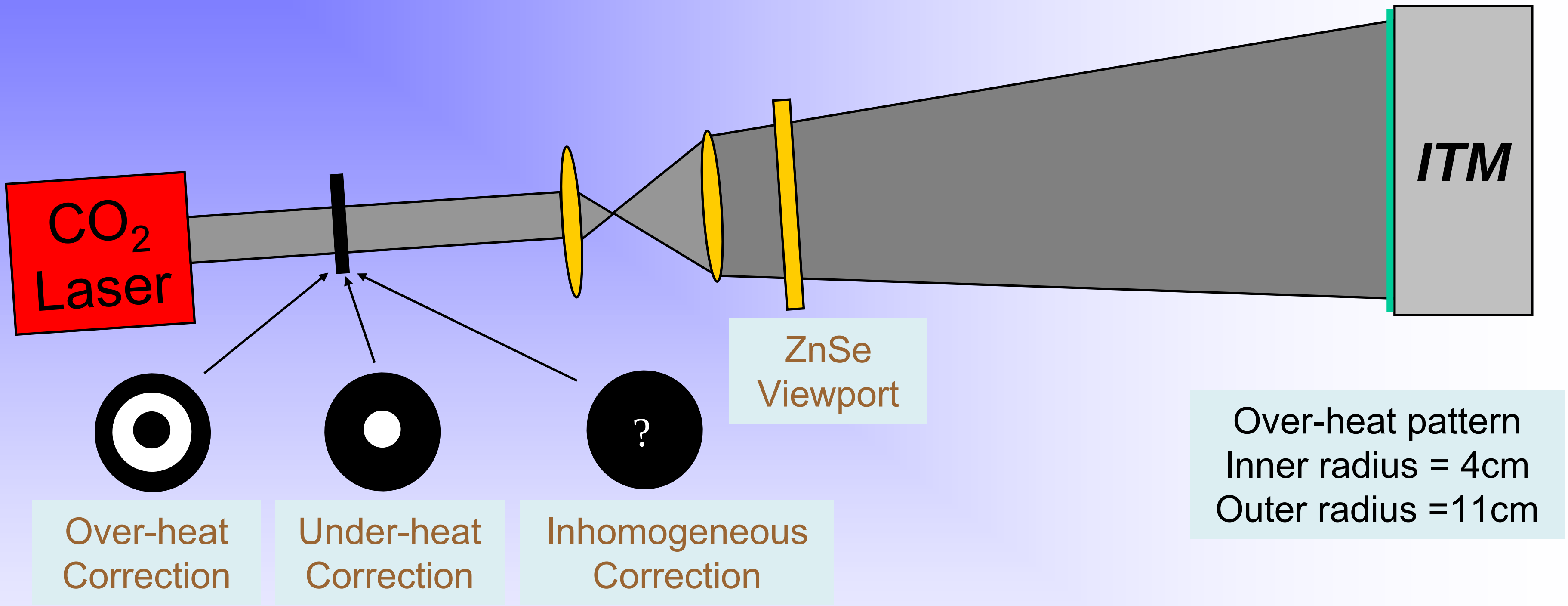
➢ ***Best mirrors are $\lambda/6000$ over the central 8 cm diameter***

Thermal effects in LIGO

- High quality low absorption fused silica substrates
  - ~ 2 -10 ppm/cm bulk absorption
  - ~ 1-5 ppm coating absorption
    - Different for different mirrors
    - Can change with time
  - All mirrors are different
  - Unstable recycling cavity
  - → Requires adaptive control of optical wavefronts
- ~100 mW absorption in current LIGO interferometers
  - Effects are noticeable!



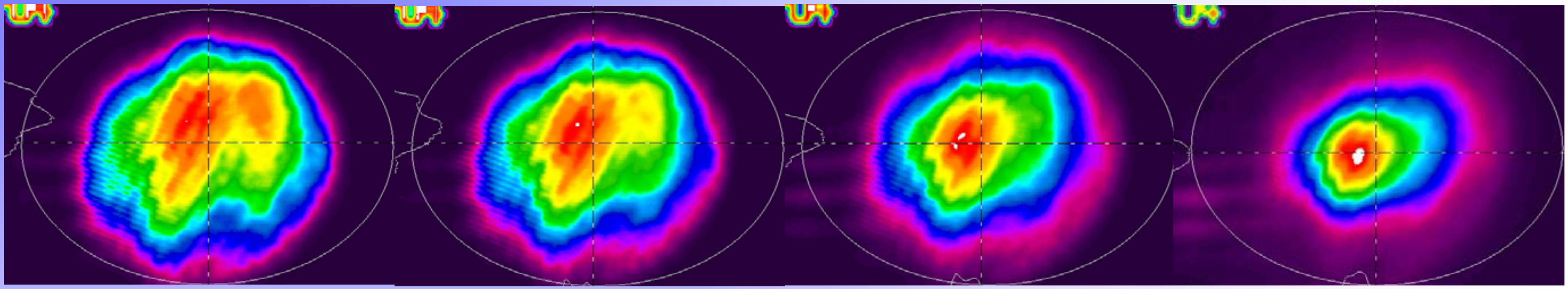
Thermal Compensation System



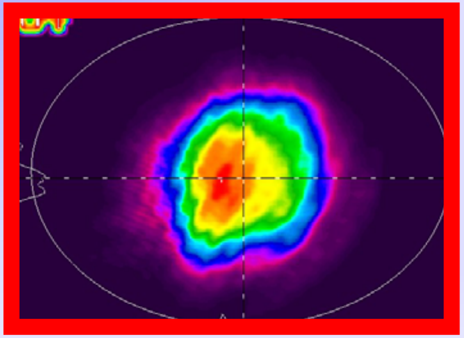
- Cold power recycling cavity is unstable: poor buildup and mode shape for the RF sidebands
- Require 10's of mW absorbed by 1μm beam

Circulating Sideband Mode Profiles vs. Thermal Compensation Power

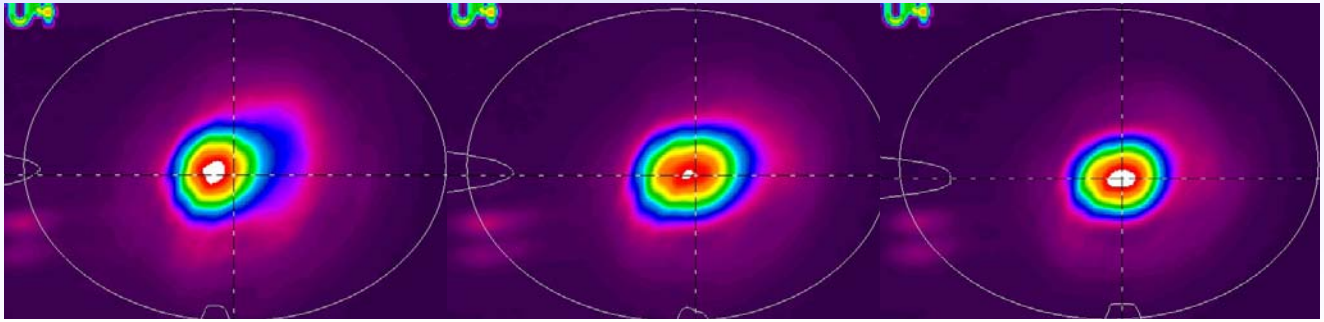
No Heat 30 mW 60 mW 90 mW



Incident beam



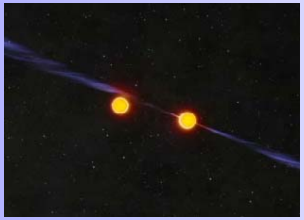
Best match

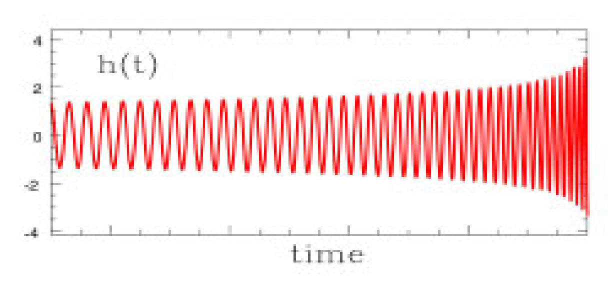


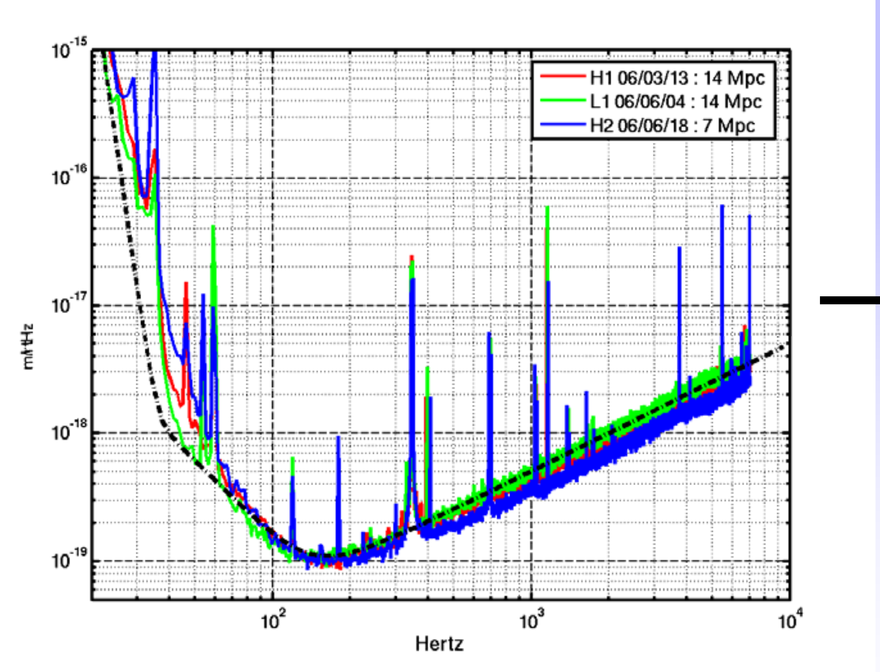
120 mW 150 mW 180 mW

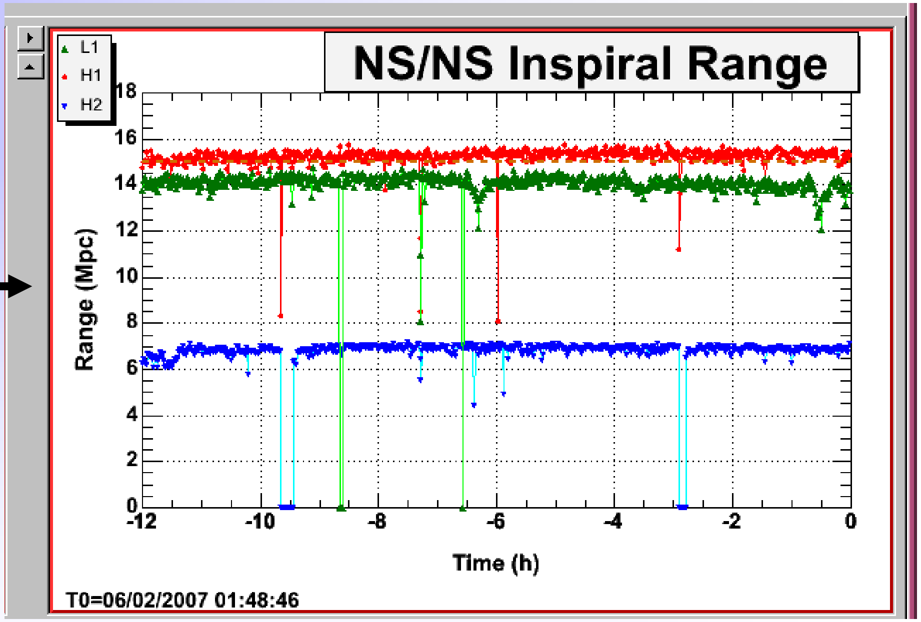
Control room –
Tracking the sensitivity range

Translate strain amplitude of binary system (via calibration lines) into (effective) distance:









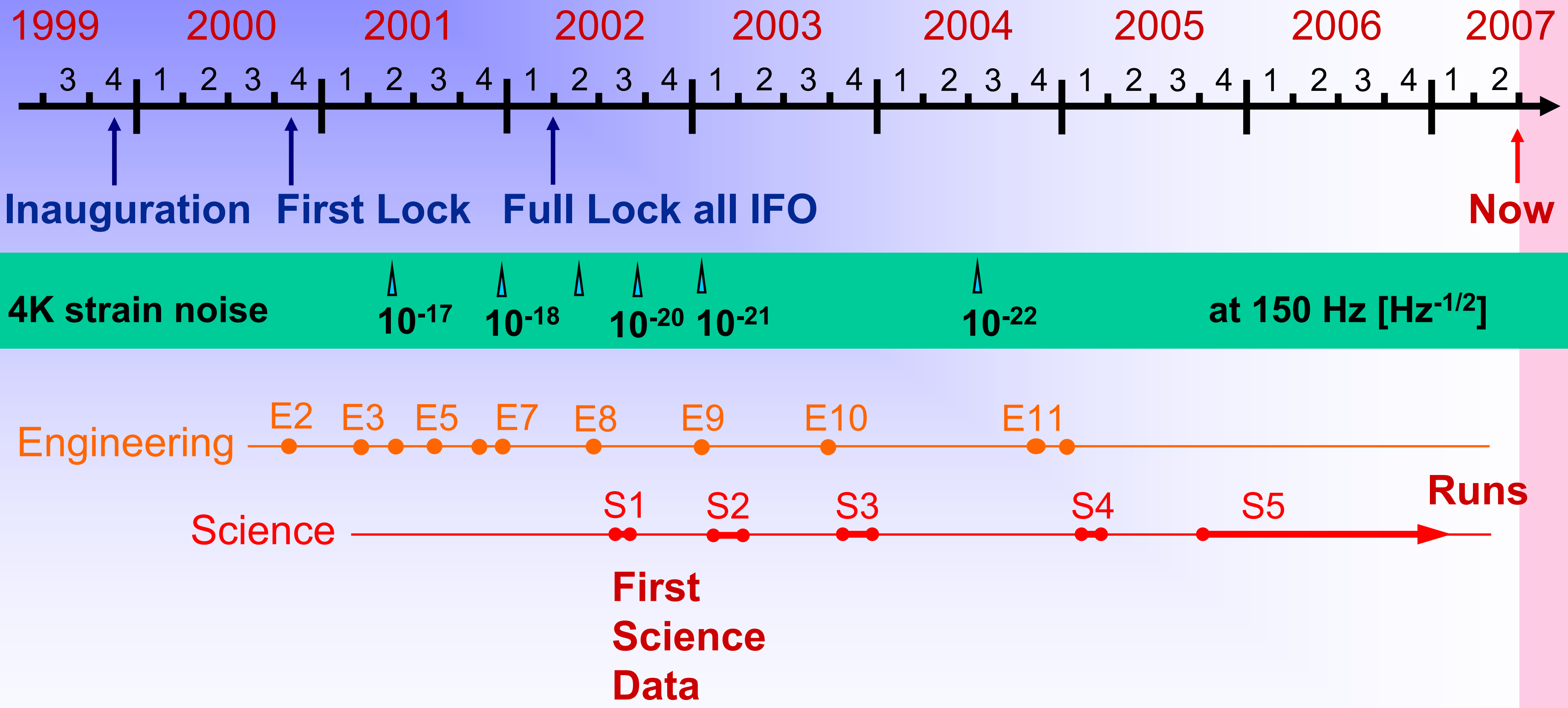
T0=06/02/2007 01:48:46

If system is optimally located and oriented, we can see even further: we are surveying <u>hundreds of galaxies</u>!

Electronic logs are public!
www.ligo.caltech.edu

LIGO

Time Line



Inauguration **First Lock** **Full Lock all IFO** **Now**

4K strain noise **10^{-17}** **10^{-18}** **10^{-20}** **10^{-21}** **10^{-22}** **at 150 Hz [$\mathrm{Hz}^{-1/2}$]**

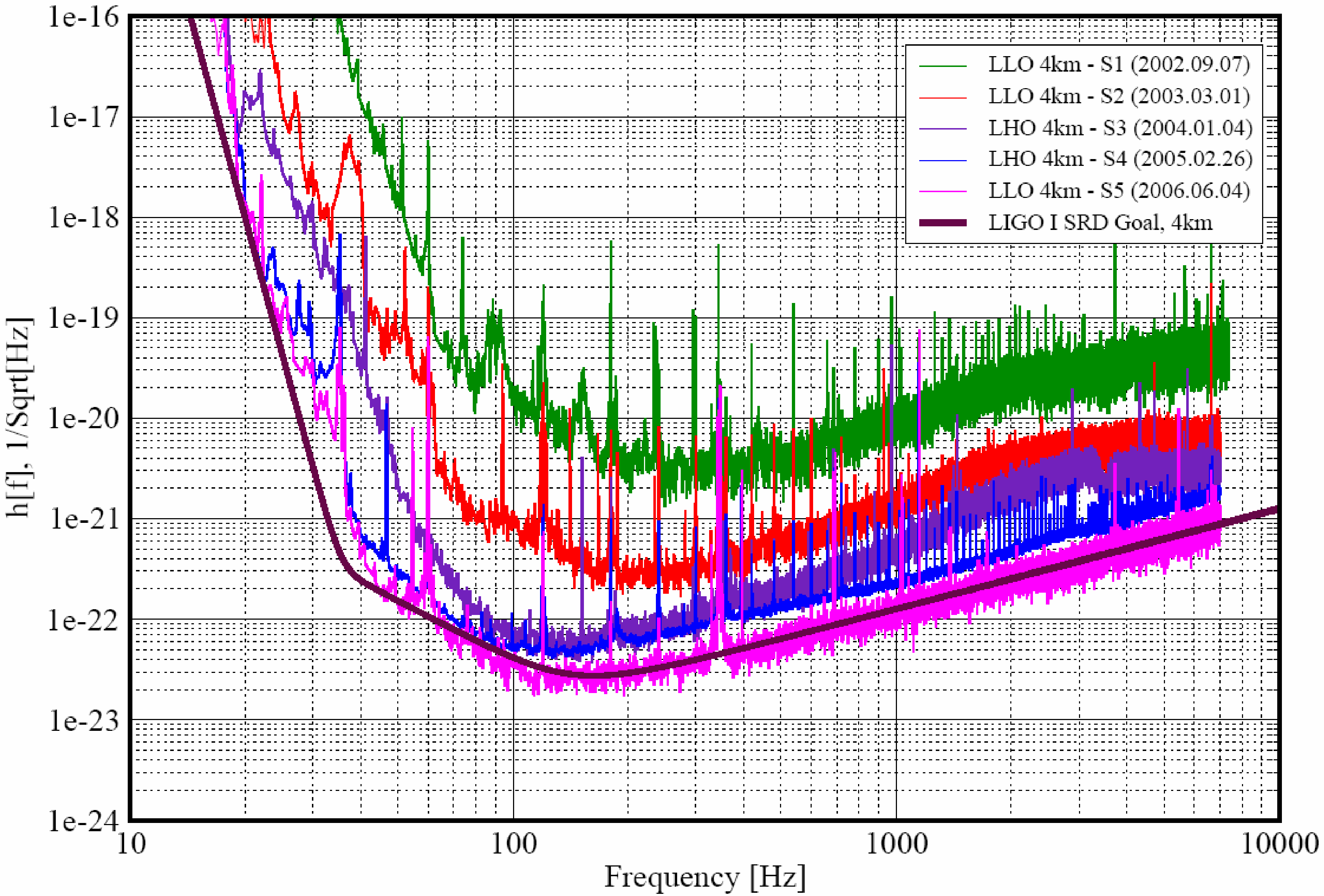
Engineering E2 E3 E5 E7 E8 E9 E10 E11

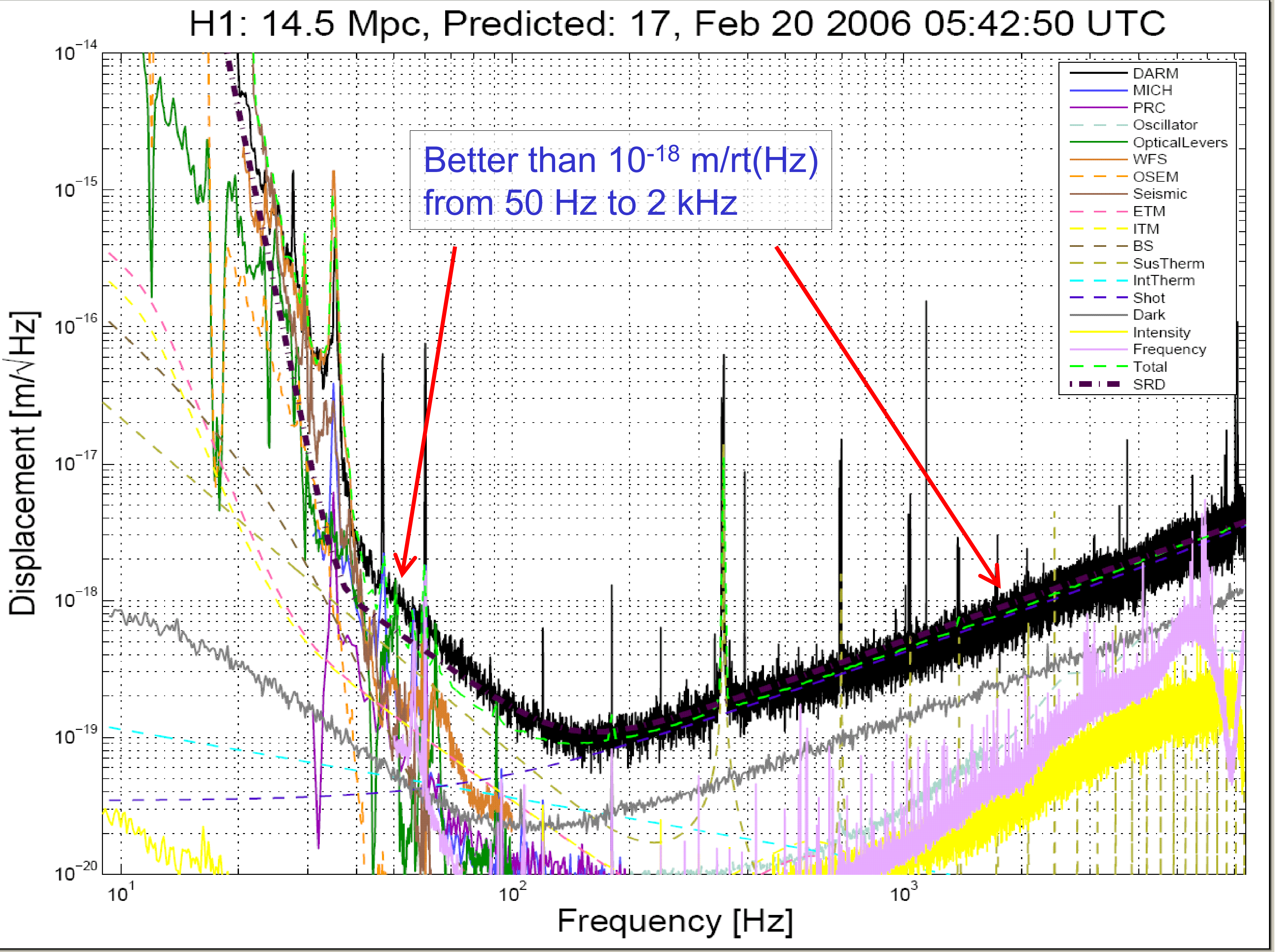
Science S1 S2 S3 S4 S5 **Runs**

First Science Data

Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs   LIGO-G060009-02-Z

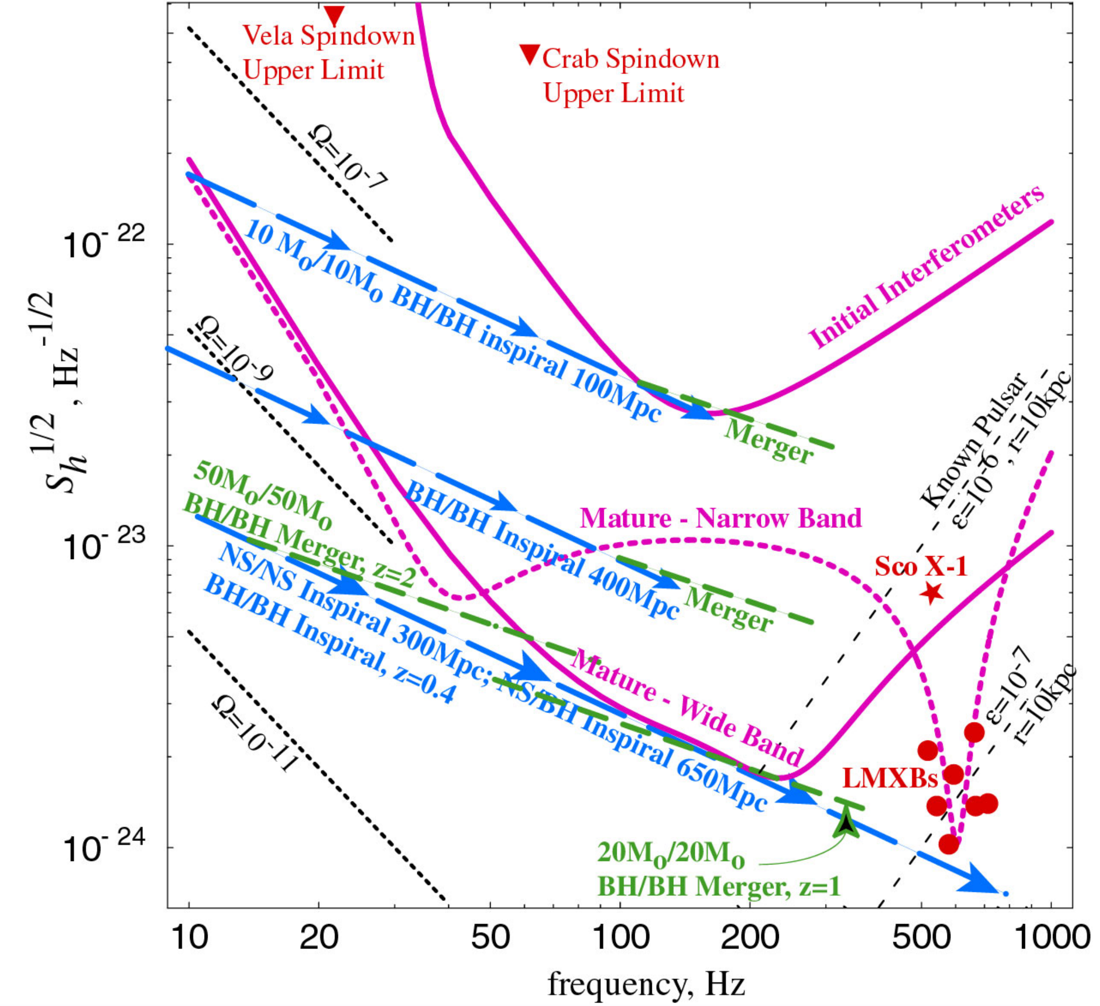




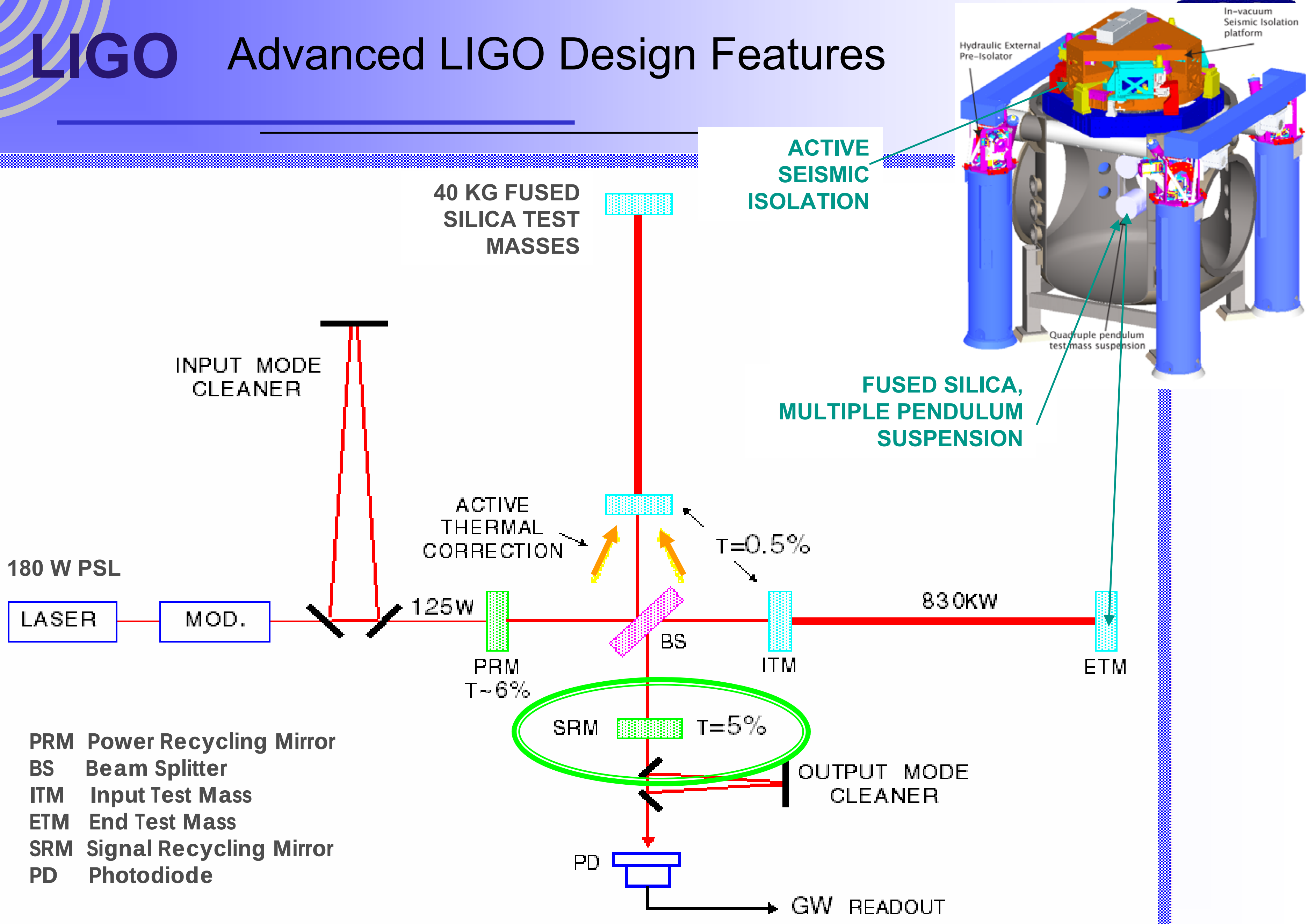
Better than 10^{-18} m/rt(Hz) from 50 Hz to 2 kHz

Advanced LIGO

- At current sensitivity, LIGO detectors are rate-limited
  - 0.01 – 1 event per year
- Advanced LIGO will increase sensitivity, hence range, by 10X over initial LIGO
  - **AdvLIGO rate ~ 500X current LIGO**
    - **At least a few EVENTS per year**
- Anticipate funding to start in 2008, construction to begin in 2011



Advanced LIGO Design Features



ACTIVE SEISMIC ISOLATION

40 KG FUSED SILICA TEST MASSES

FUSED SILICA, MULTIPLE PENDULUM SUSPENSION

INPUT MODE CLEANER

ACTIVE THERMAL CORRECTION

T=0.5%

180 W PSL

LASER

MOD.

125W

PRM T~6%

BS

ITM

830KW

ETM

SRM T=5%

OUTPUT MODE CLEANER

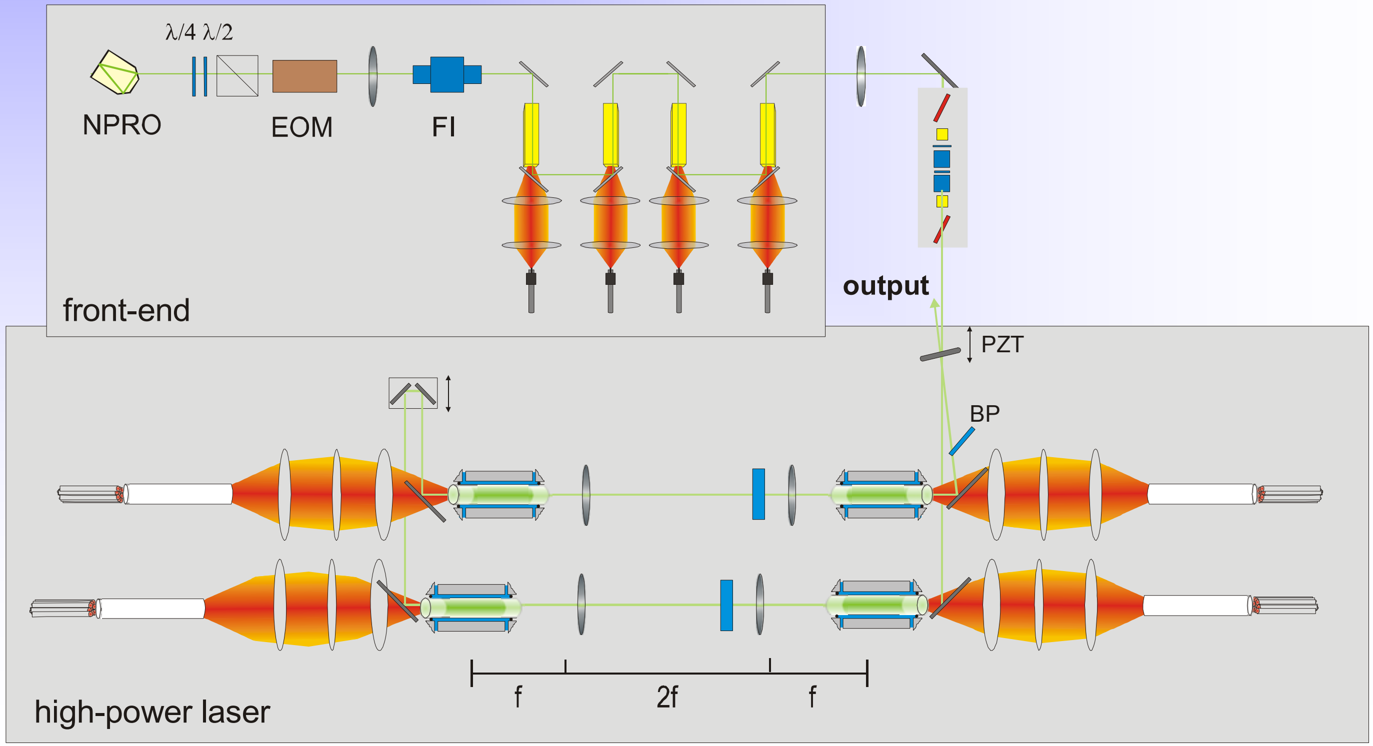
PD

GW READOUT

PRM	Power Recycling Mirror
BS	Beam Splitter
ITM	Input Test Mass
ETM	End Test Mass
SRM	Signal Recycling Mirror
PD	Photodiode

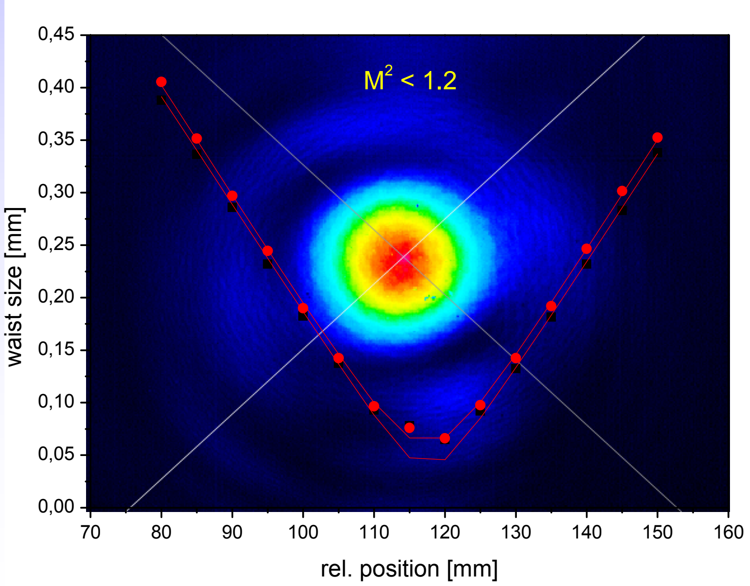
Advanced LIGO Pre-stabilized Laser

- 180 W amplitude and frequency stabilized Nd:YAG laser
- Two stage amplification
  - First stage: either MOPA (NPRO + single pass amplifier) or ring cavity (not shown)
  - Second stage: injection-locked ring cavity
- Developed by Laser Zentrum Hannover (and MPI at Hannover)



Advanced LIGO PSL performance

- Requirements
  - Good spatial mode quality
  - Intensity stabilization < 3 x 10^{-9} /rHz
  - Frequency noise ~ (20 Hz/ *f*) Hz/rHz
- To date
  - 183 W obtained in good spatial mode profile (no spatial filtering)
  - RIN of oscillator @ 3 x 10^{-9} /rHz



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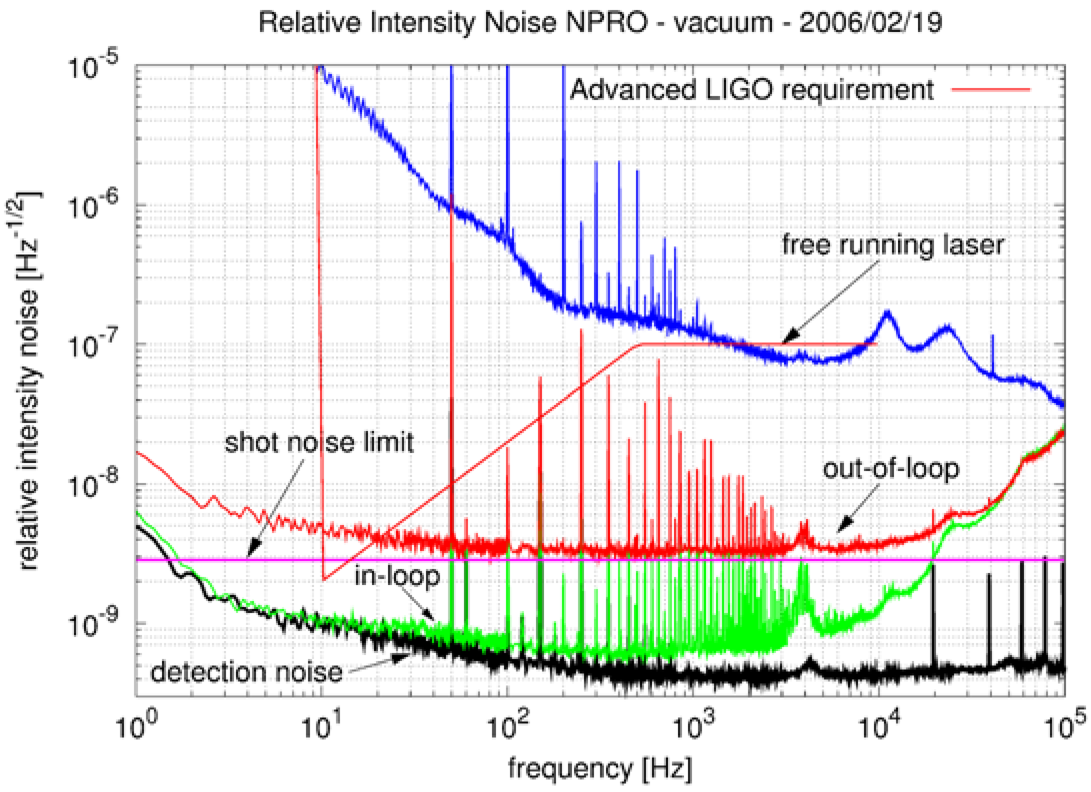
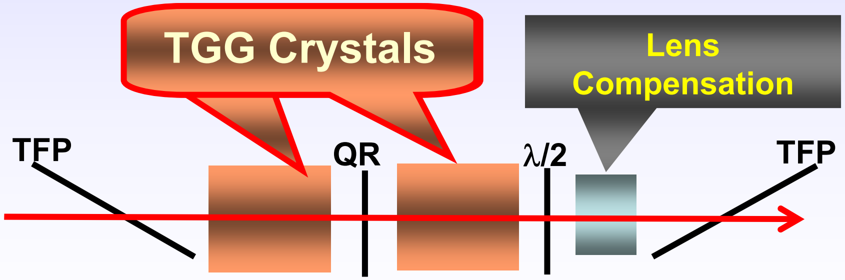
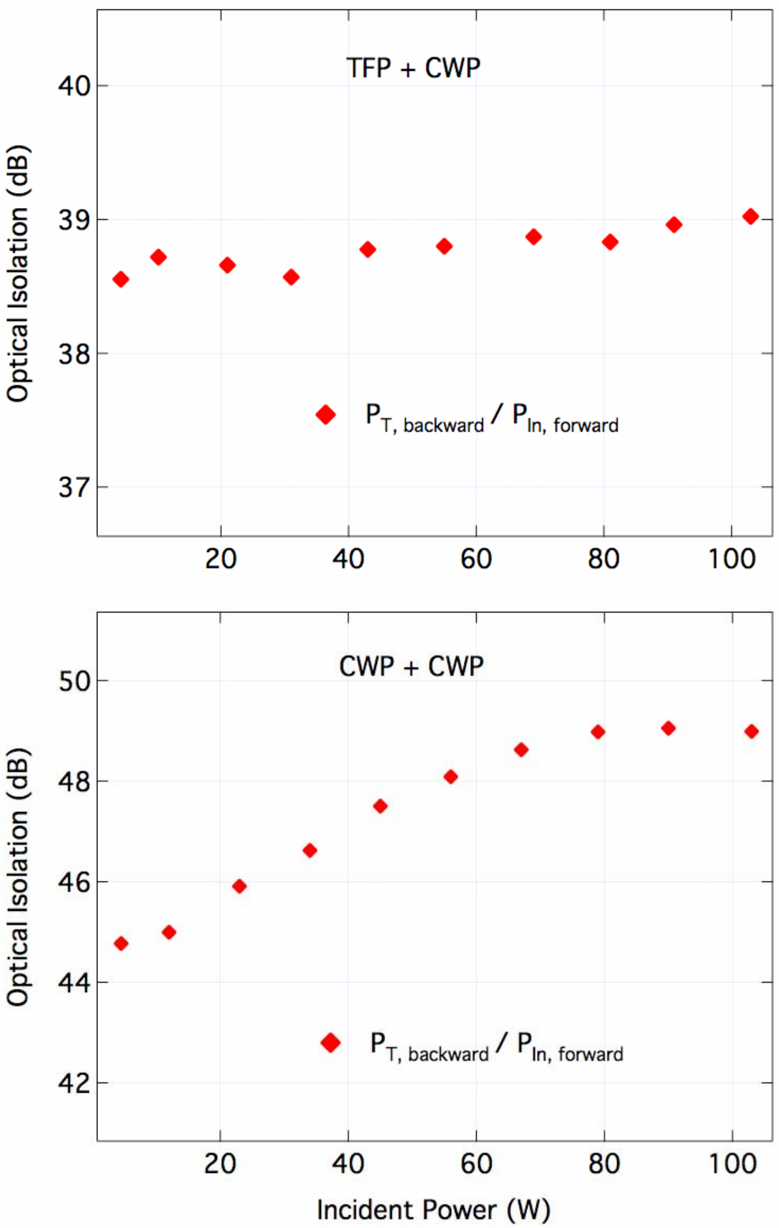

Relative Intensity Noise NPRO - vacuum - 2006/02/19

High Power Faraday Isolators for Advanced LIGO

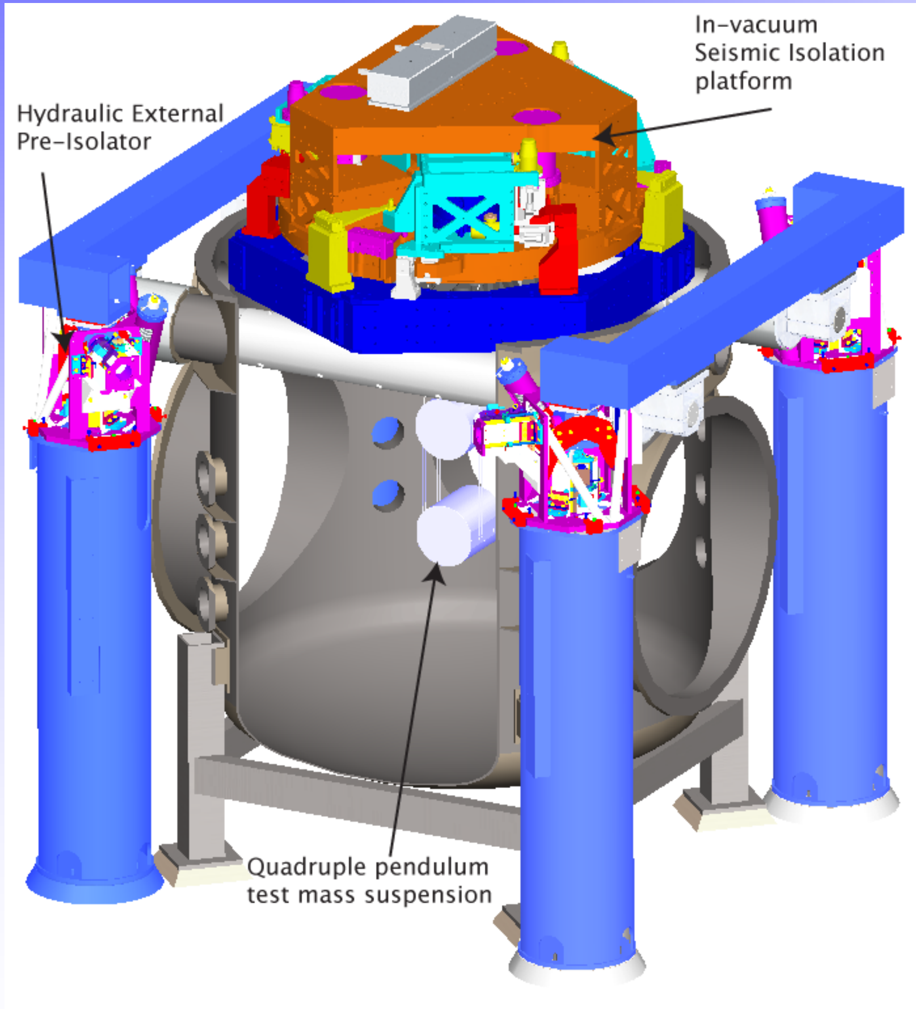
- Faraday Isolator designed to handle high average power
  - **Increased immunity from thermal birefringence**
    - **In excess of 40 dB at 100 W loading**
  - **thermal lensing**
    - **$\lambda/10$ thermal distortions demonstrated**
    - **$< \lambda/20$ possible**

Khazanov, et al., J. Opt. Soc. Am B. 17, 99-102 (2000).
Mueller, et al., Class. Quantum Grav. 19 1793–1801 (2002).
Khazanov, et. al., IEEE J. Quant. Electron. 40, 1500-1510 (2004).





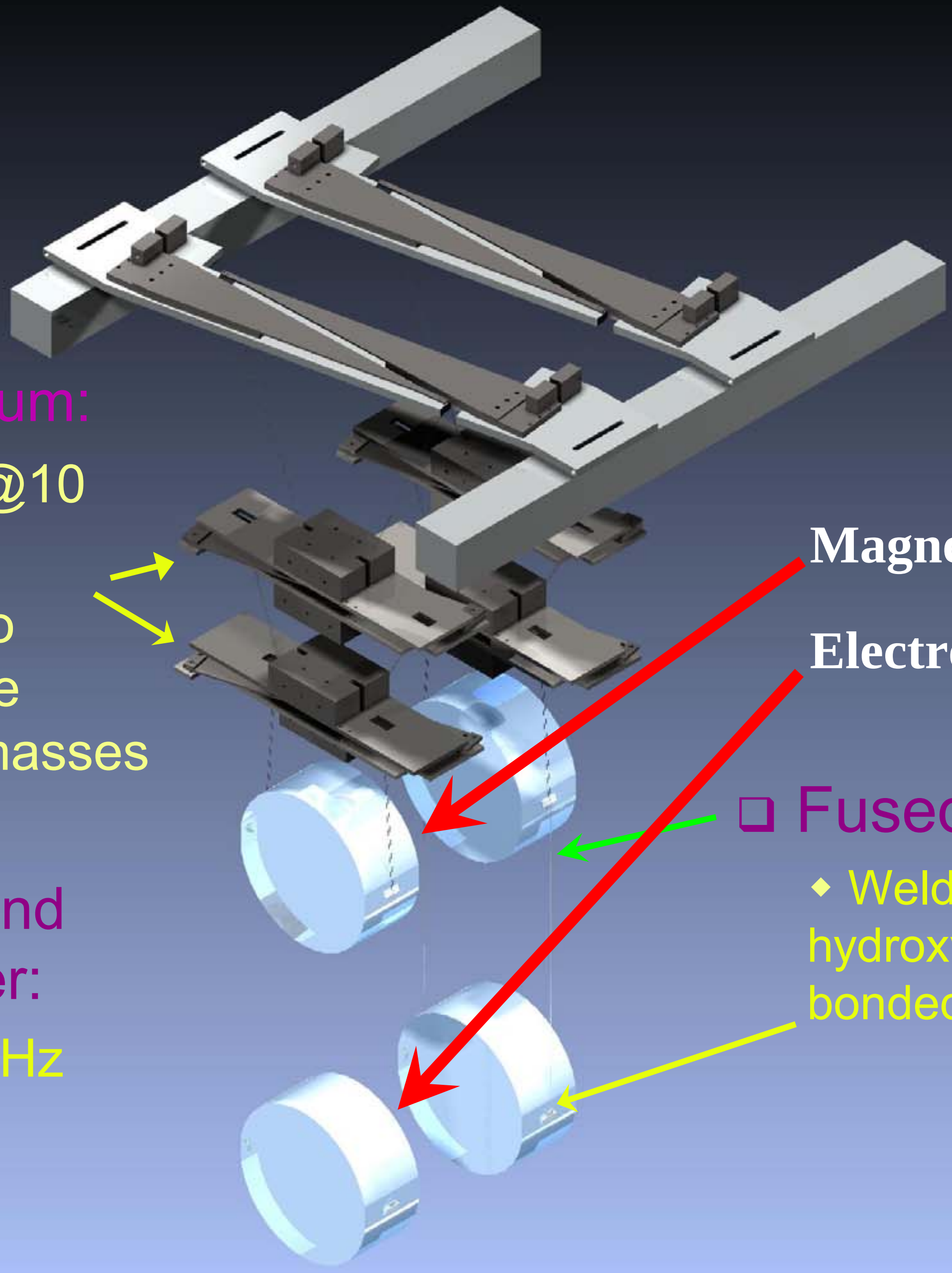
LIGO Seismic Isolation: Active Platform



Requirement	BSC Chamber Value
Payload Mass	**800 kg**
Range	**± 1 mm, ± 0.5 mrad**
Table Noise	**3 x 10^{-13} m/√Hz @10 Hz**
Angular Noise	**10 nrad RMS**

Quad Suspensions

- Quadruple pendulum:
  - ~10^7 attenuation @10 Hz
  - Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - 10^{-19} m/rtHz at 10 Hz



Magnets

Electrostatic

- ❑ Fused silica fiber
  - ◆ Welded to ‘ears’, hydroxy-catalysis bonded to optic

Conclusions

- LIGO is operational and taking data as we speak
  - S5 Science Run will finish soon
- Gravitational wave detection pushes state-of-the art in CW solid state laser technology, optical fabrication and metrology, and control systems
- Advanced LIGO design is well underway

Acknowledgments:

and the Members of the LIGO Laboratory, members of the LIGO Science Collaboration, National Science Foundation

More Information:

- http://www.ligo.caltech.edu; www.ligo.org

Backup slides

Collaborating Institutions

NSF

UTB TSC

Southeastern Louisiana University

Loyola University New Orleans

University of Maryland

Leland Stanford Junior University

LSU

GEO 600

Northwestern University

Universitat de les Illes Balears

Southern University Agricultural & Mechanical College

Hobart and William Smith Colleges

William Smith College

The University of Adelaide Australia

California Institute of Technology 1891

University of Florida

NAOJ 国立天文台

Massachusetts Institute of Technology

University of Wisconsin Milwaukee

Sigill. Coll. Carleton Northfield, Minn. A.D. 1866

Columbia University in the City of New York

The University of Birmingham

The University of Texas at Austin

Syracuse University Founded AD 1870 Suos cultores scientia coronat

IGR

Universität Hannover

Washington State University

Embry-Riddle Aeronautical University

Cardiff University

The University of Western Australia

Michigan

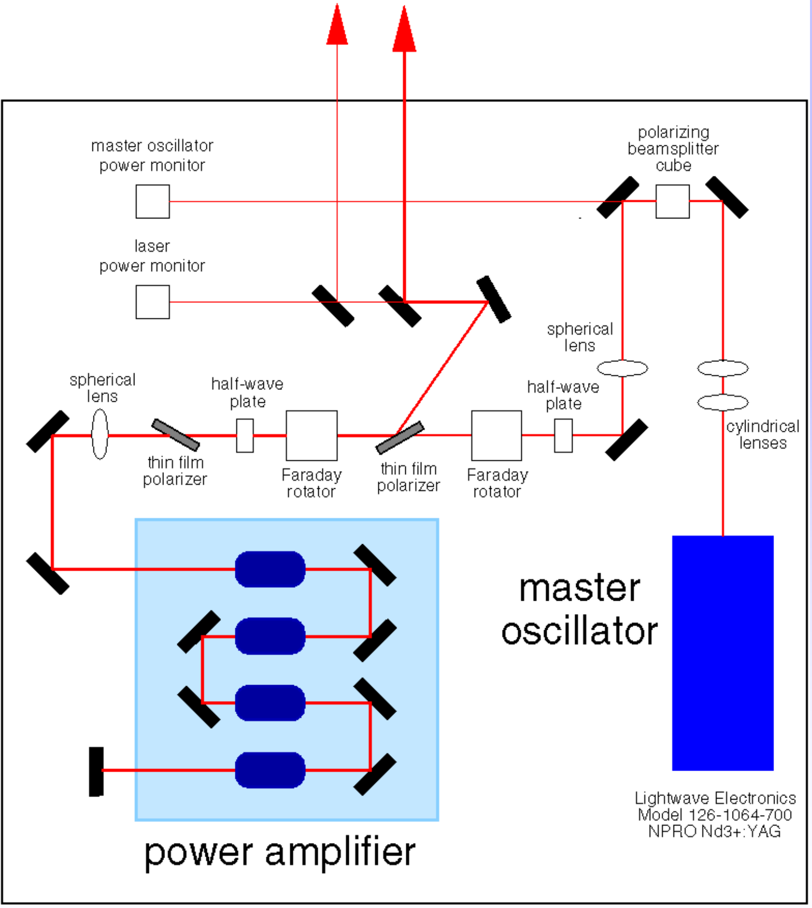
The Physics of the Universe PPARC

PAH

PennState 1855

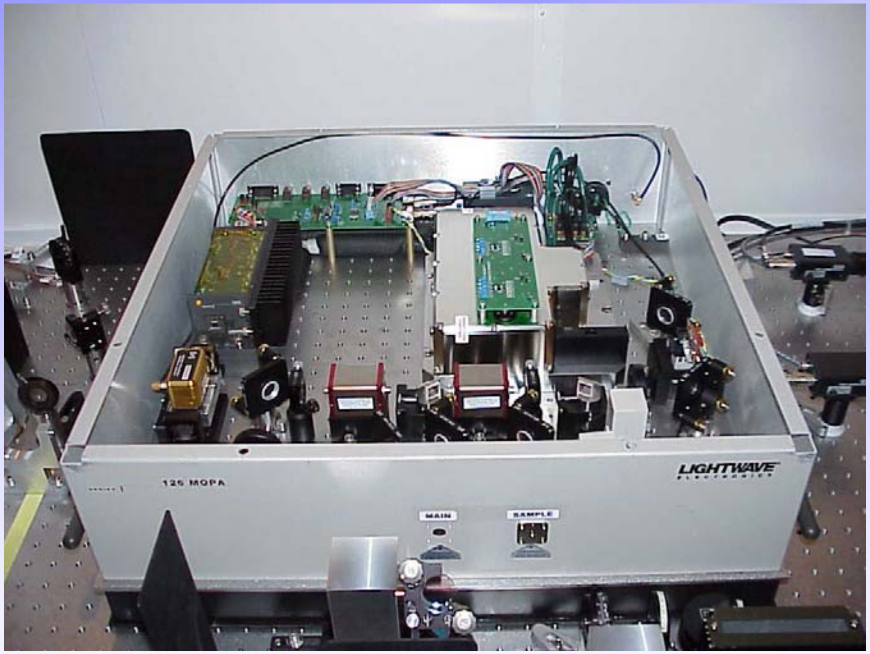
University of Glasgow

LIGO 10-Watt Laser



- Master Oscillator Power Amplifier configuration
- Lightwave Model 126 non-planar ring oscillator
- Double-pass, four-stage amplifier
- All solid state:
amplifier utilizes 160 watts of laser diode pump power

Performance of the LIGO 10-W Laser



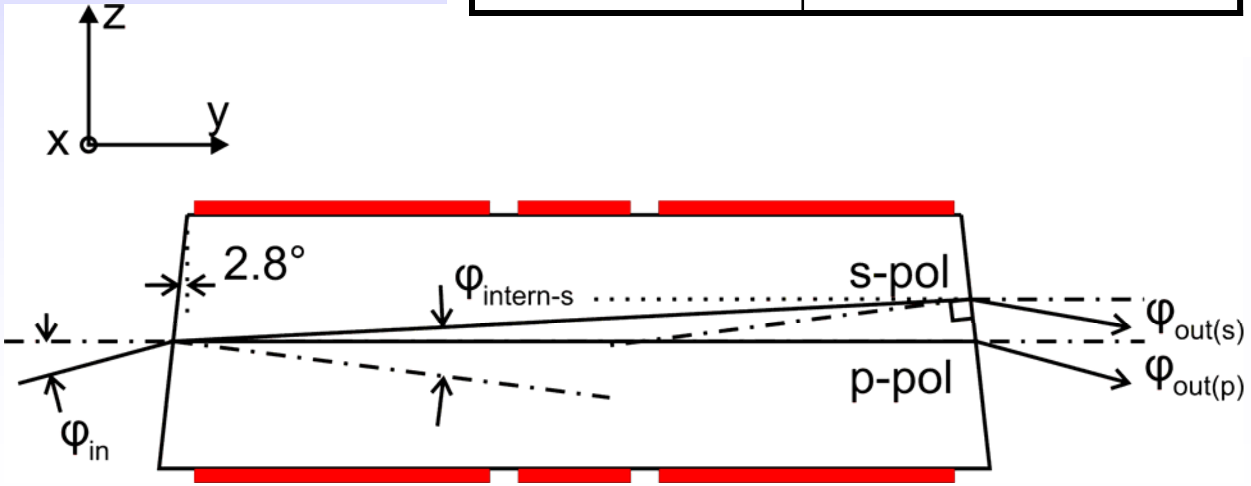
- WA-2k PSL > 15,000 hours continuous operation
  - Two power supply failures
- TEMoo power > 8 watts
- Non-TEMoo power < 10%
- Free-running frequency noise ~100 Hz/rtHz at 100 Hz. Falling as 1 / f
- Six units delivered to LIGO to date.

Wedged RTP crystal

- Wedged crystal separates the polarizations and acts as a polarizer.
  - This avoids cavity effects and reduces amplitude modulation.

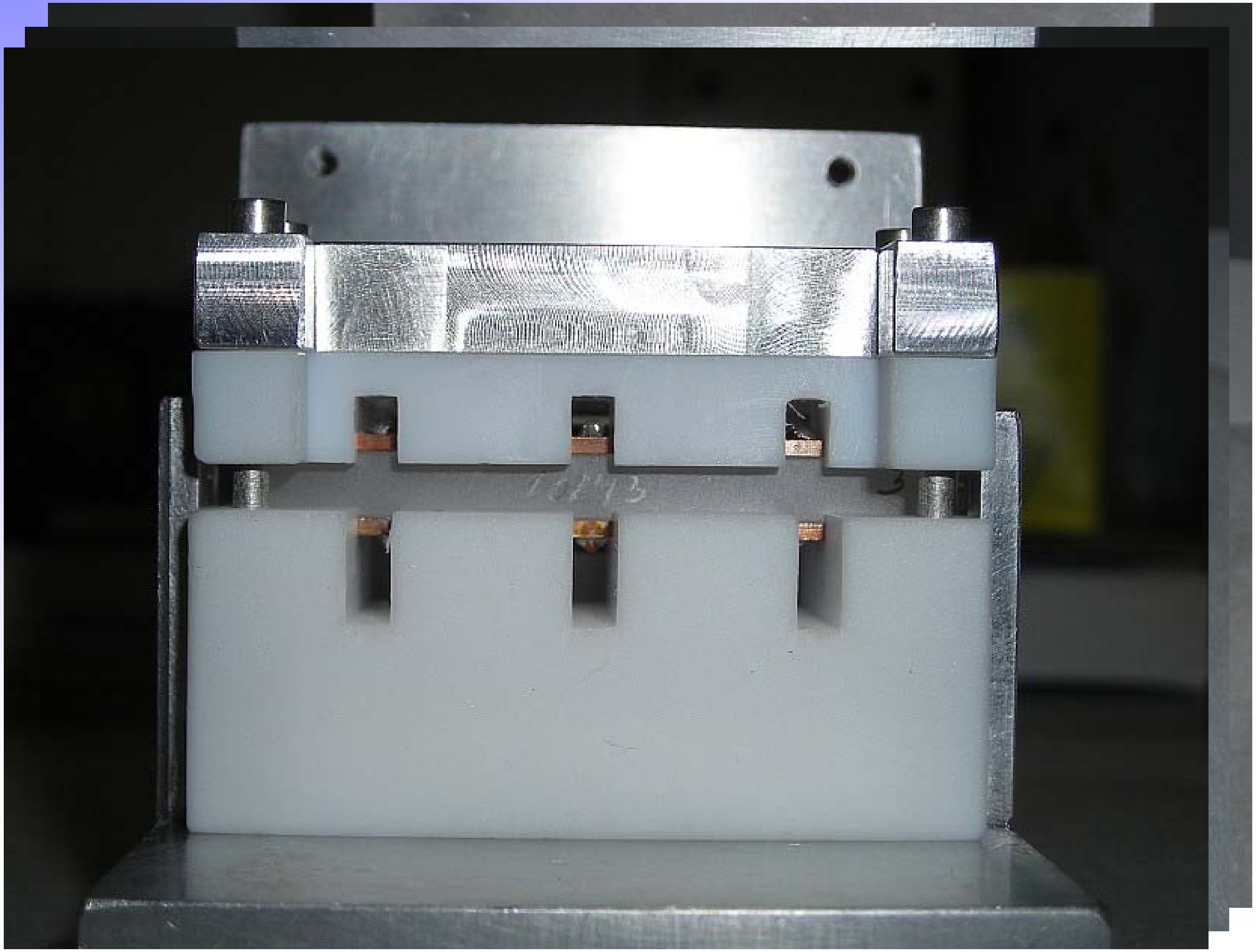
Polarization	Angle [degrees]
p	4.81
s	4.31

- AR coatings (< 0.1%) on crystal faces.



Three Modulations / Single Crystal design

- Use one crystal but three separate pairs of electrodes to apply three different modulation frequencies at once.



Modular housing

- Separate the crystal housing from the housing of the electronic circuits to maintain maximum flexibility.