Gravitational Wave Interferometry: how does it work?

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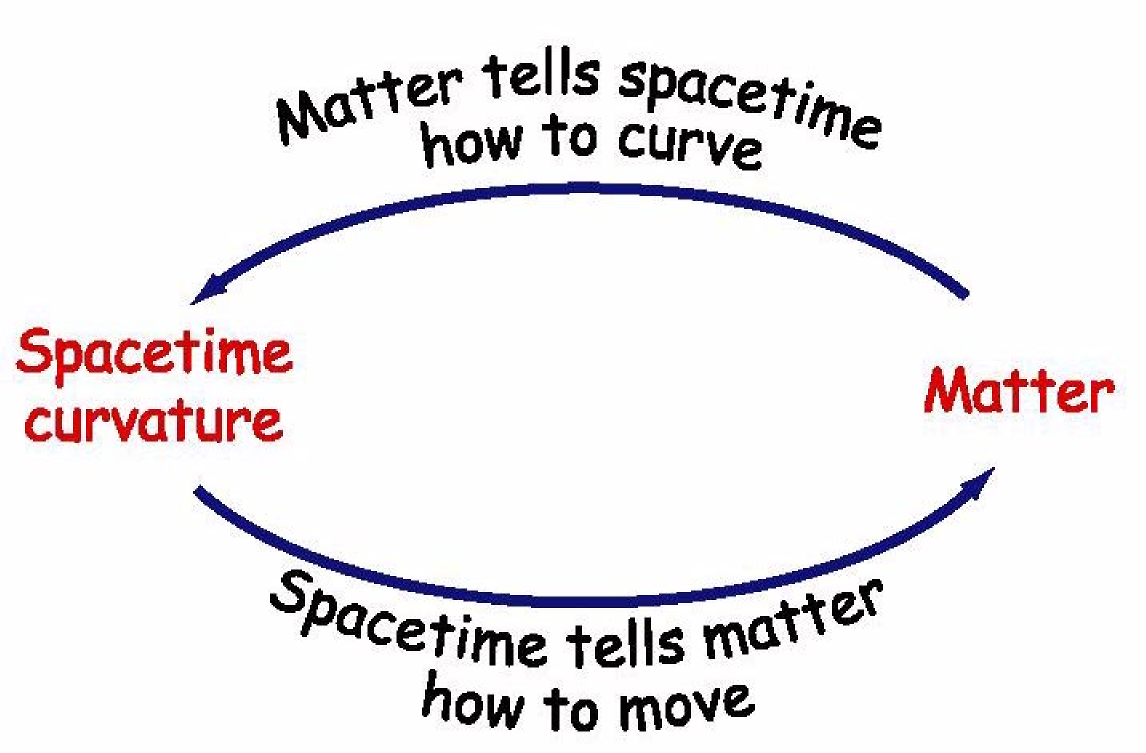
LIGO Project

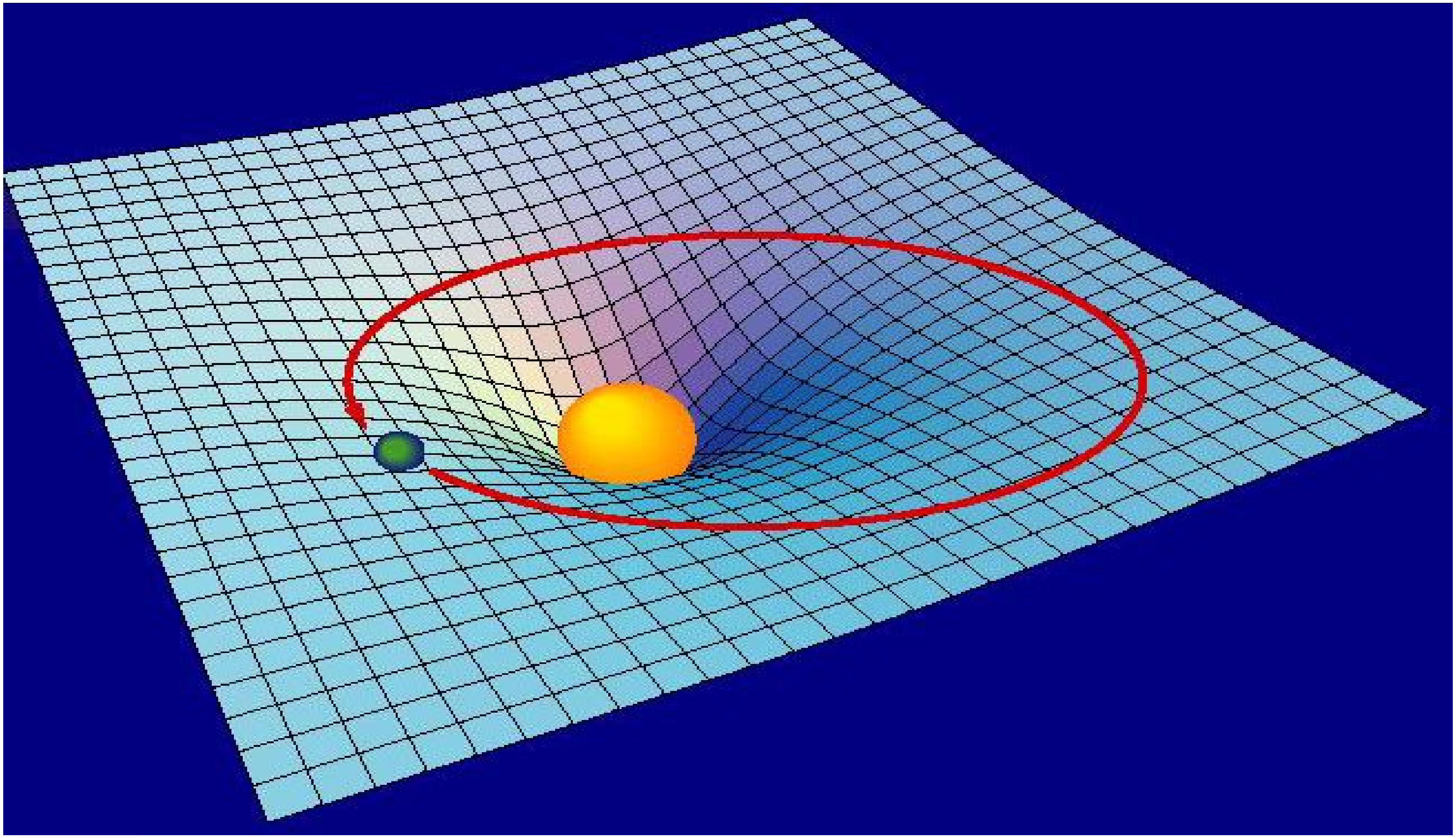
http://ligo.caltech.edu/

General Relativity

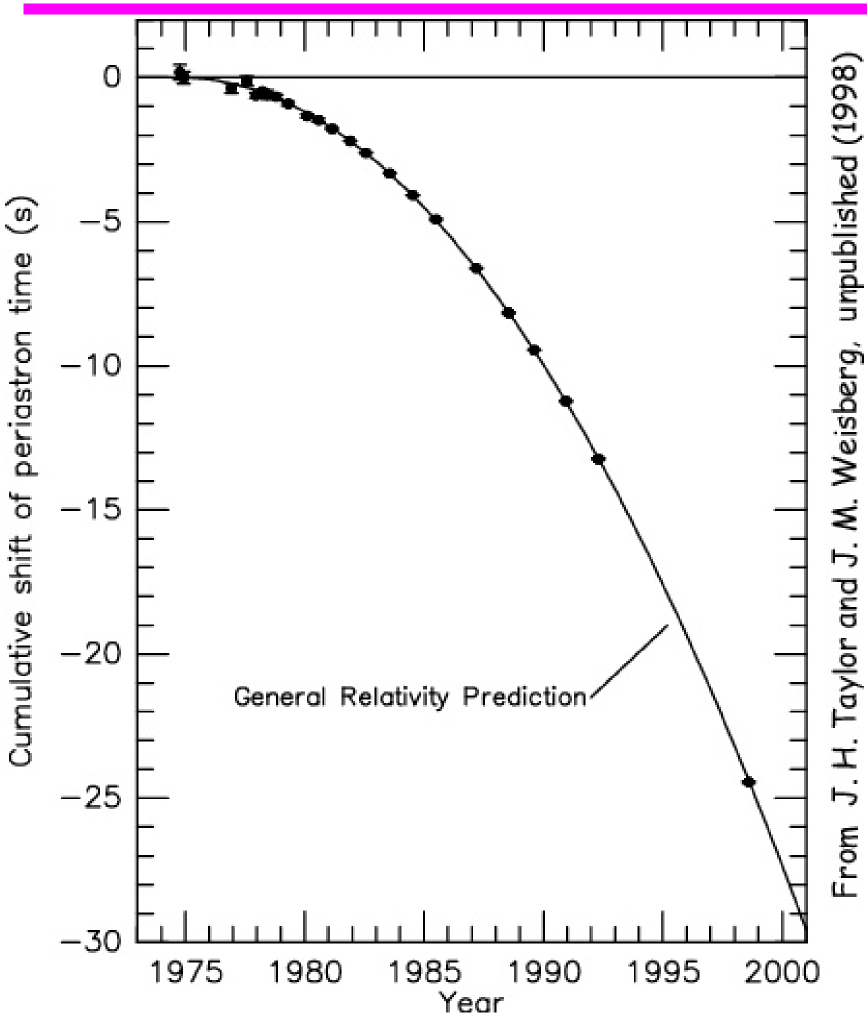
- November 1915 - "Der Feldgleichungen der Gravitation" is submitted by Albert Einstein. In this paper he presents the Gravitational Field equations.



Spacetime Curvature



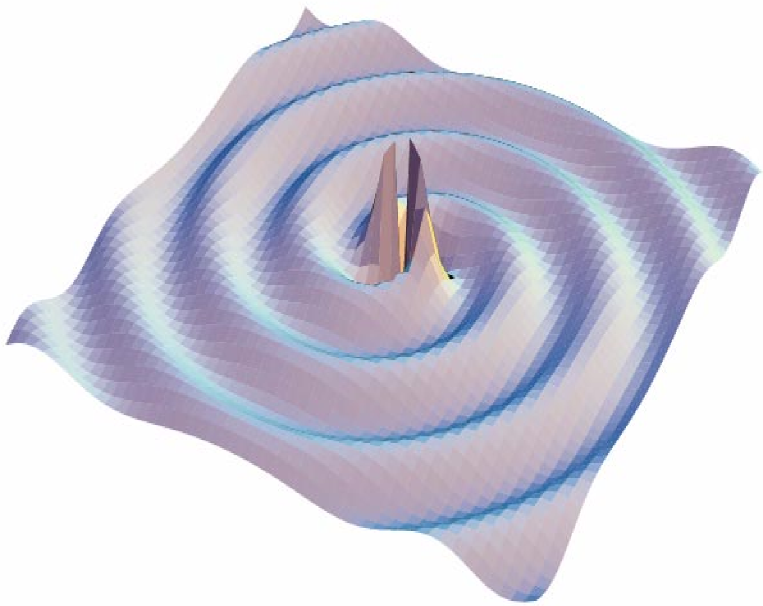
Evidence: Energy lost to Gravitational Waves



- 1993 - Hulse and Taylor are awarded the Nobel Prize for

  "*the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation*"

Gravitational Waves...



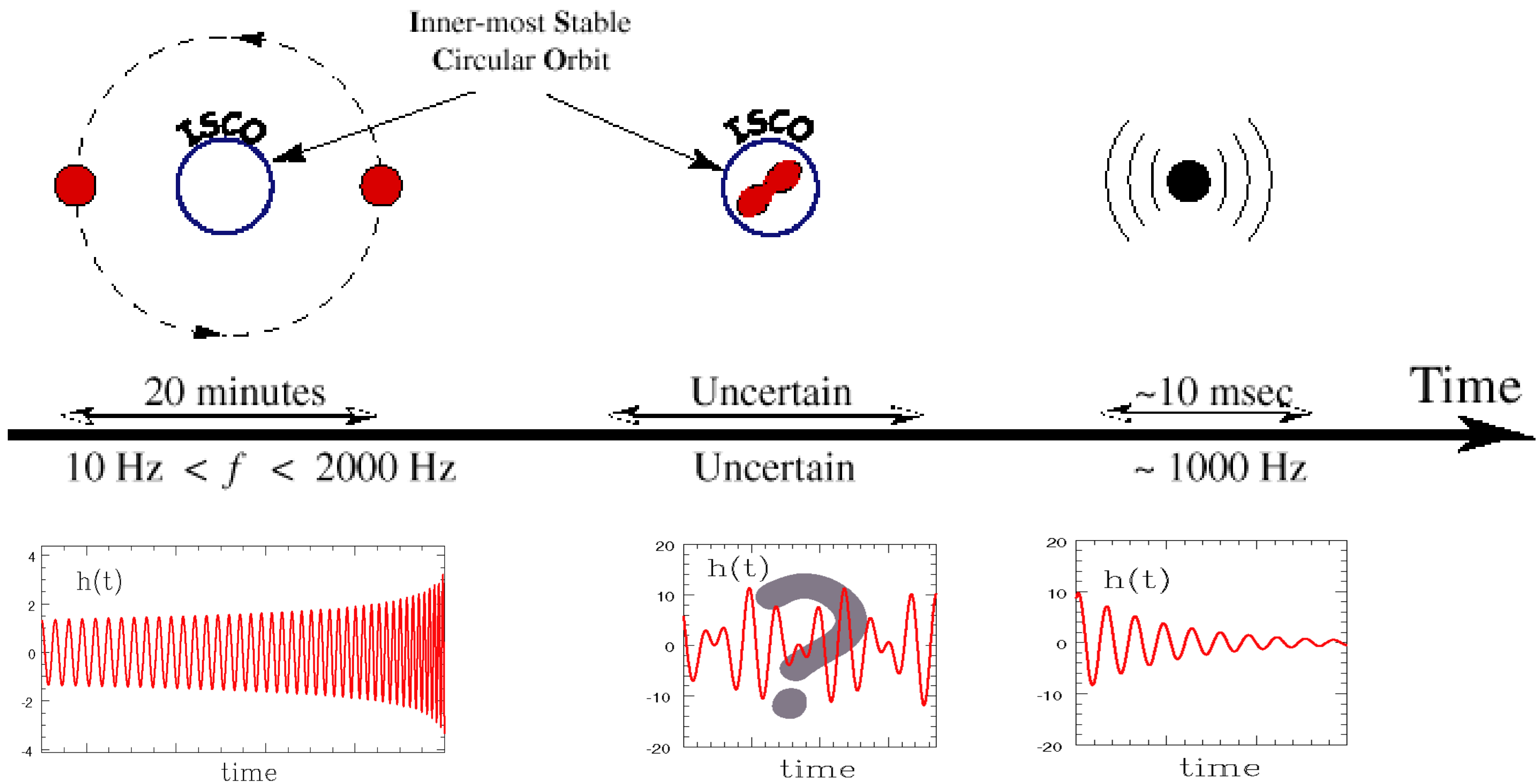
- Are transverse
- Propagate at the speed of light
- Have two polarization states, generally denoted h_+ and h_x
- $h \sim \frac{\Delta L}{L} \sim \frac{4G\left(E_{kinetic}^{ns}/c^2\right)}{c^2 r}$

Why the interest?
Astrophysics

- Coalescing Compact Binary systems
  - Neutron Star / Neutron Star
  - Neutron Star / Black Hole
  - Black Hole / Black Hole
- Continuous Wave Sources
  - Rapidly rotating Neutron Stars
  - Unstable modes / Shear stress in the stellar crust
- Other Burst Sources
  - Supernova core collapse and bounce
  - Boiling of a newborn Neutron Star
- Stochastic Backgrounds
  - 10^{-43} Seconds after the Big Bang

Coalescing Compact Binaries

Inspiral | Merger | Ringdown



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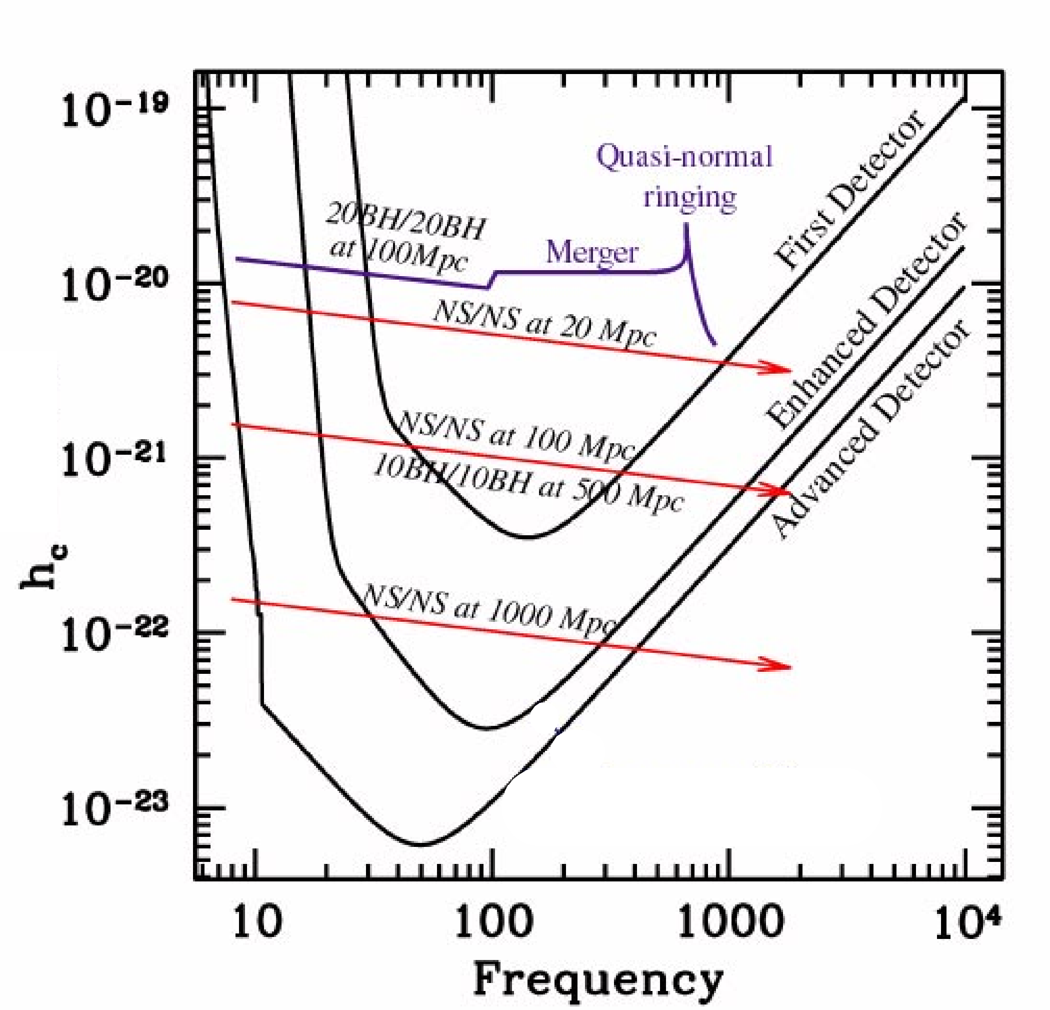
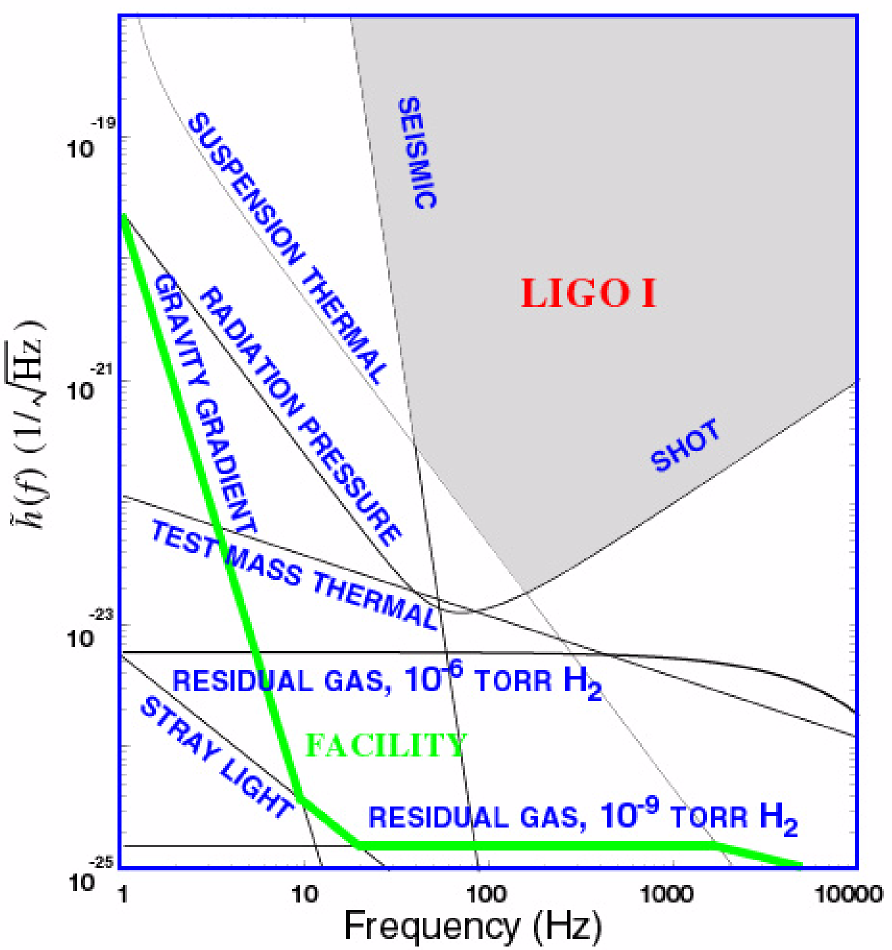
AND...?

Gravitational Lens, Galaxy Cluster 0024 +1654, Hubble Space Telescope WFPC2

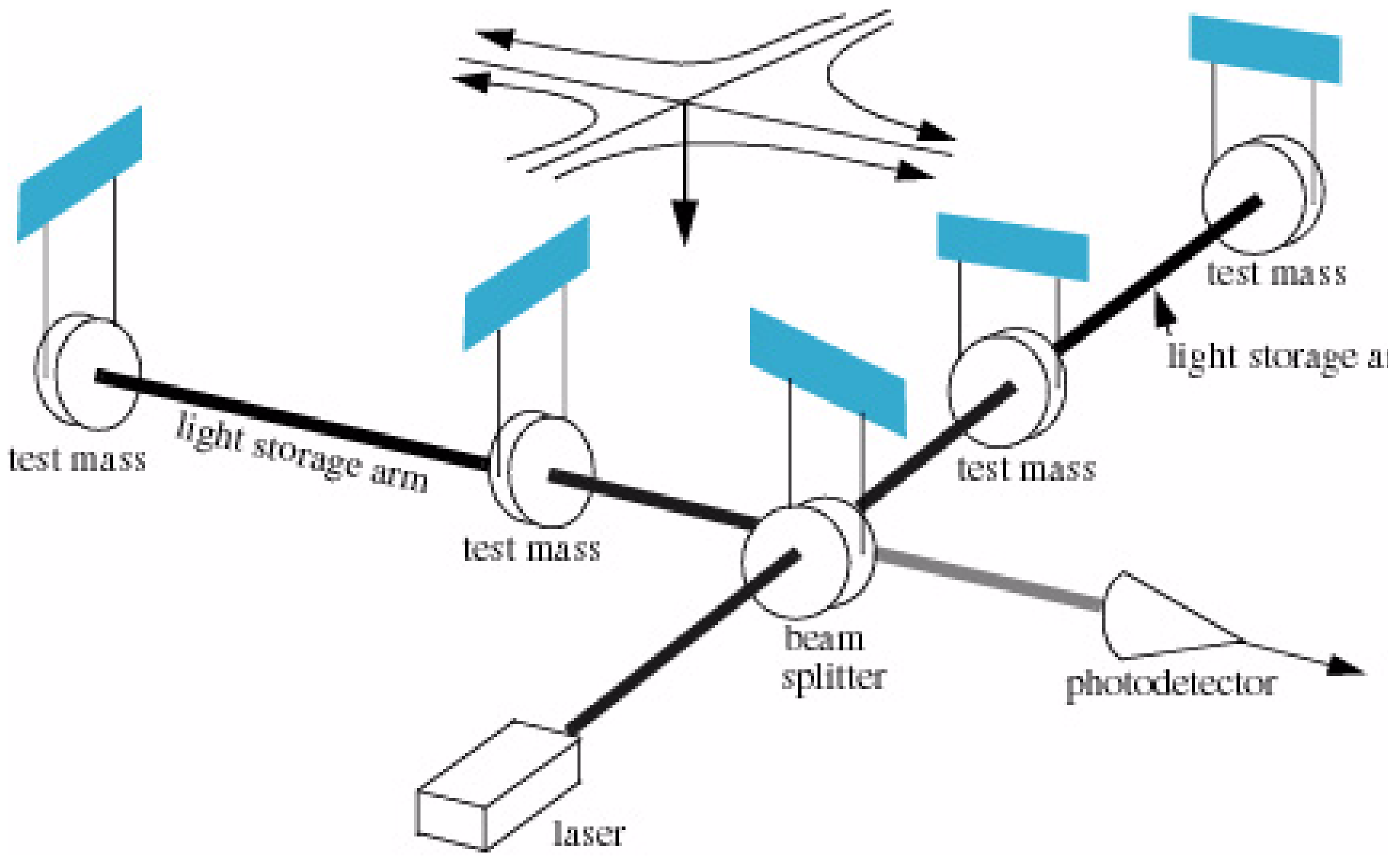
Detection Levels
LIGO Sensitivity to Coalescing Binaries



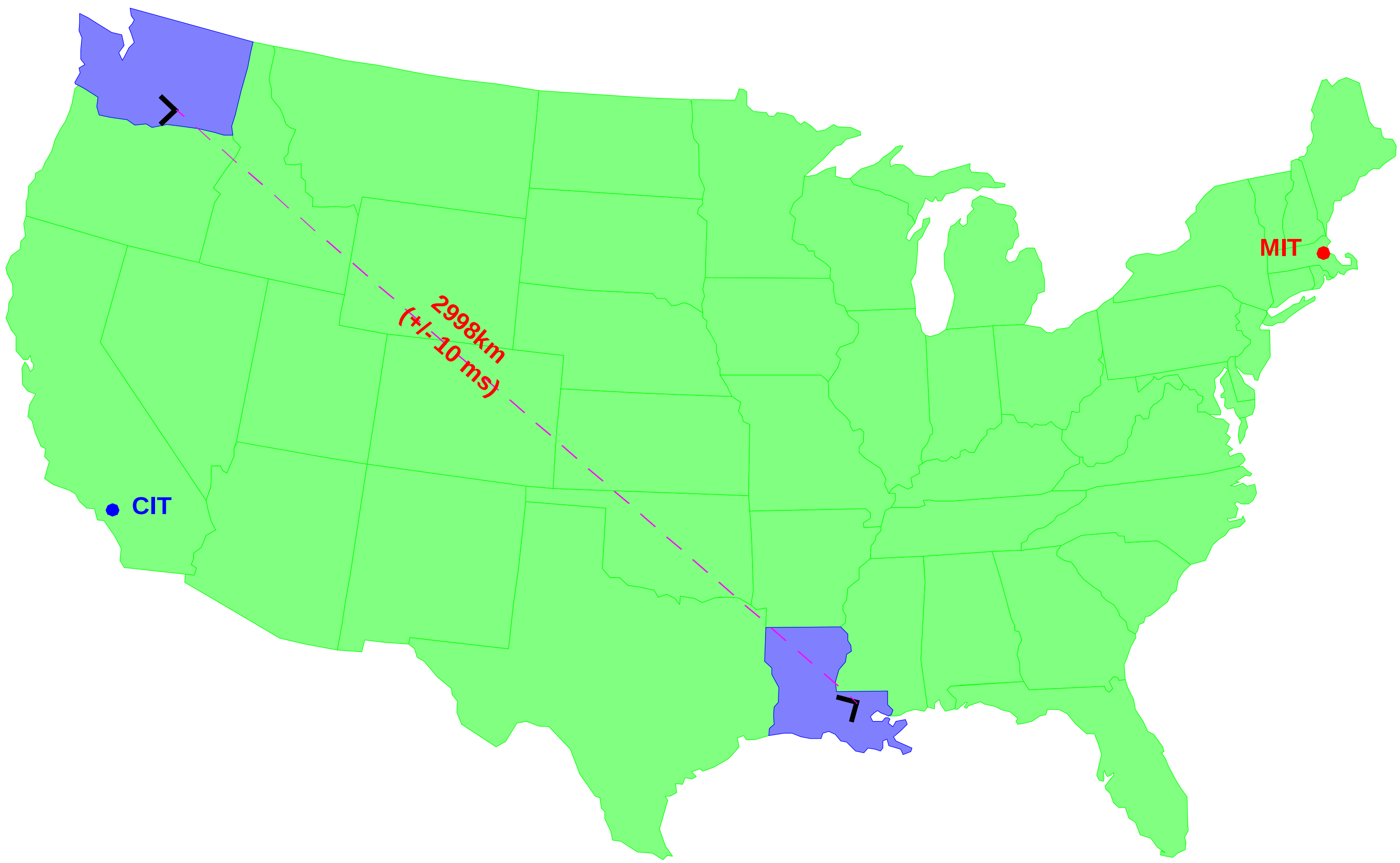
Detection Levels are limited by Noise Sources

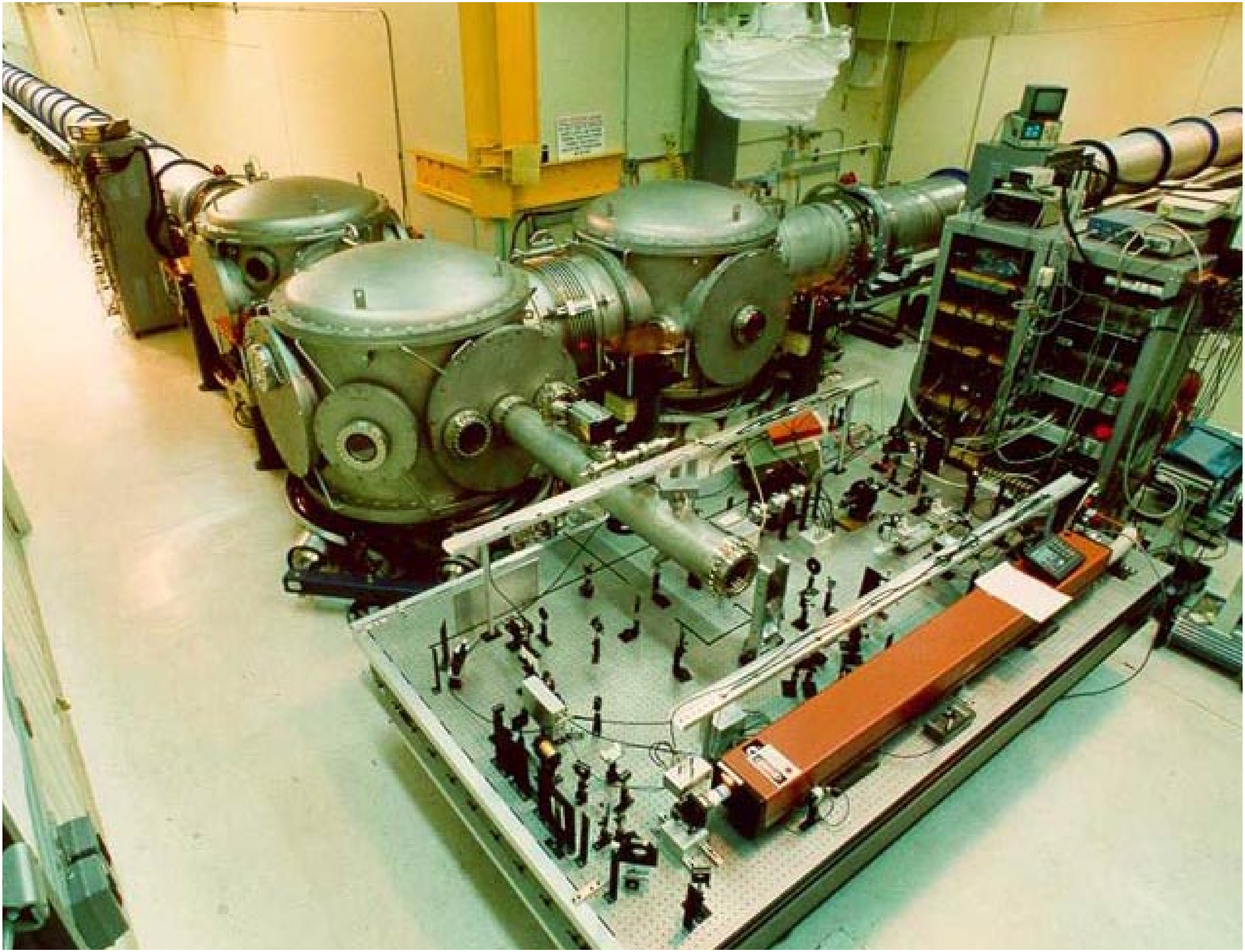


The Basic Interferometer



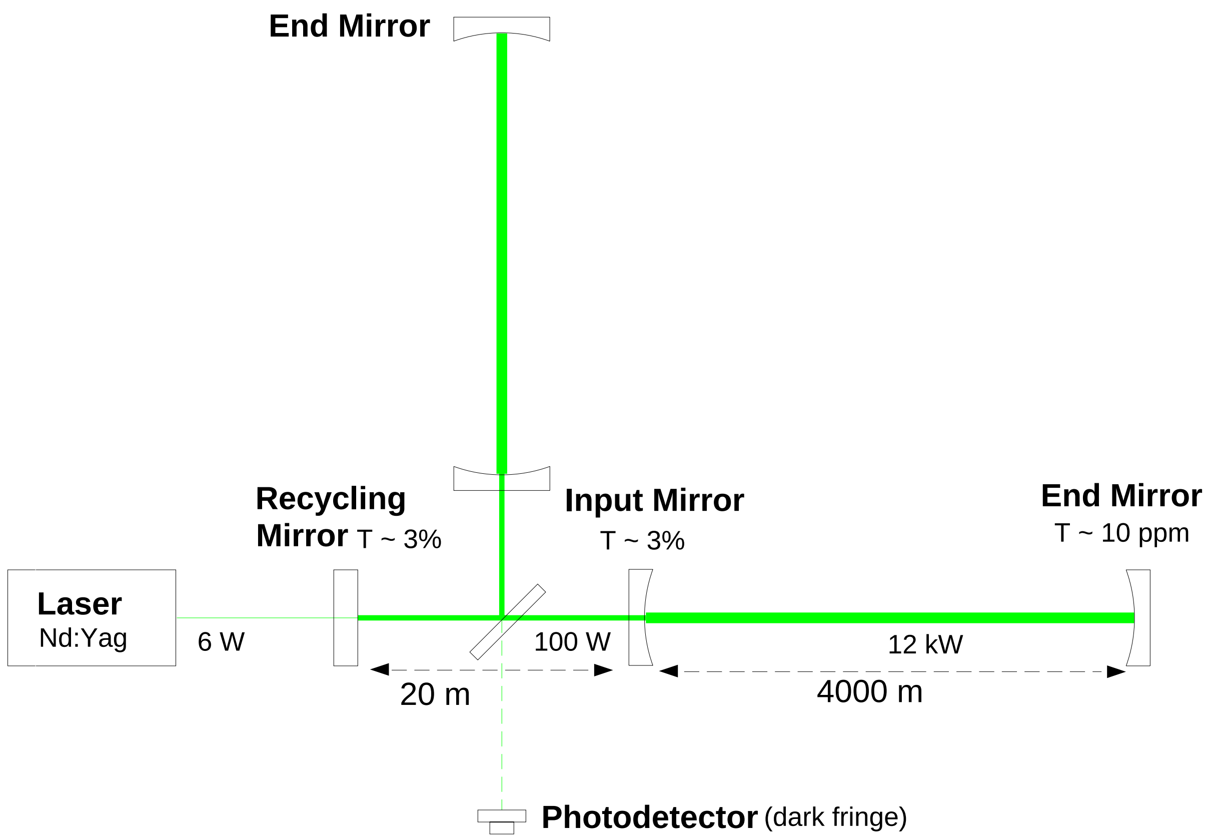
3 Interferometers
2 Sites





Large Optical Components ("Core Optics")

- ››Input Power
  (6 w) Nd:YAG
  λ= 1.06 µm
- ›› Recycling Gain
  ($R \sim 30X$)
- ››Cavity Finesse
  ($F \sim 50$)
- ››20 optics Installed
  20 spares



Core Optics Requirements

- High purity fused silica
  - ››Beams fill some optics (to ~1ppm level)
  - ››1064 nm HR mirrors and AR second surface coatings.
- Principal performance requirements:
  - ››< 50 ppm loss per surface (limits resonant stored energy: shot noise)
  - ››Surface figure errors to scatter negligible power from TEM_{oo} (best dark fringe)
    - – Similar requirement for bulk inhomogeneity
  - ››High mechanical Q to "suppress" thermal noise ($Q \geq$ few x 10^6)

Low bulk (<~5ppm/cm) and coating (<2ppm) absorption (thermal lensing limit to beam power and dark fringe contrast).

Core Optics Requirements

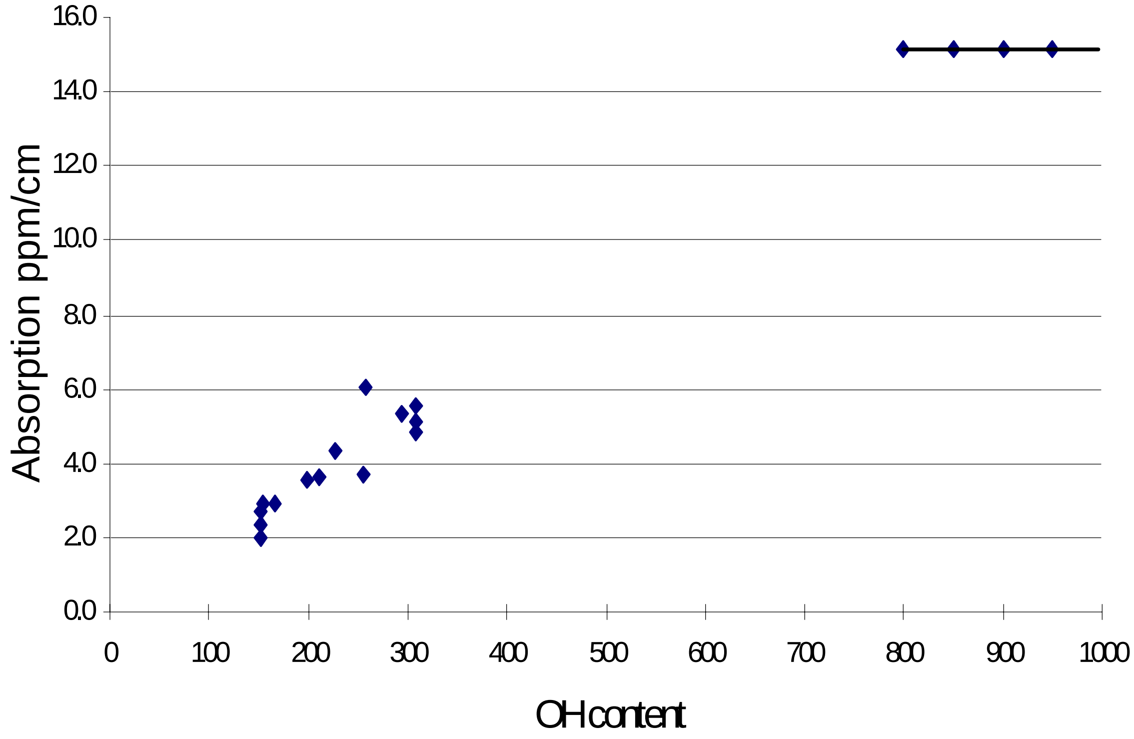
Tight matching of all optical parameters arm to arm

Physical Quantity	***Test Mass*** ***End***	***Input***	***Beam splitter***	***Recycling mirror***
Diameter of substrate, ϕ_S (cm)	**25**	**25**	**25**	**25**
Substrate Thickness, d_S (cm)	**10**	**10**	**4**	**10**
1 ppm intensity contour diameter (cm)	**24**	**19.1**	**30.2**[a]	**19.2**
Lowest internal mode frequency (kHz)	**6.79**	**6.79**	**3.58**	**6.79**
Mass of Suspended Component (kg)	**10.7**	**10.7**	**6.2**	**10.7**
Nominal surface 1 radius of curvature (m)	**7400**	**14180**	**∞**	**14900**
Surface error in the central 80mm diameter after removing TPA (nm rms)	**0.8**	**0.8**	**1.6**	**1.6**
Surface roughness (nm)	**0.2**	**0.2**	**0.4**	**0.4**
Bulk absorption (ppm/cm)	**-**	**<5**	**<5**	**<20**

a. For these 45^o angle of incidence optics, this is the smallest diameter circle centered on the optic face which is everywhere outside of the 1 ppm intensity field.

Absorption in Fused Silica

- Measured in collaboration with VIRGO: Boccara, Loriette, Daban, Cleva

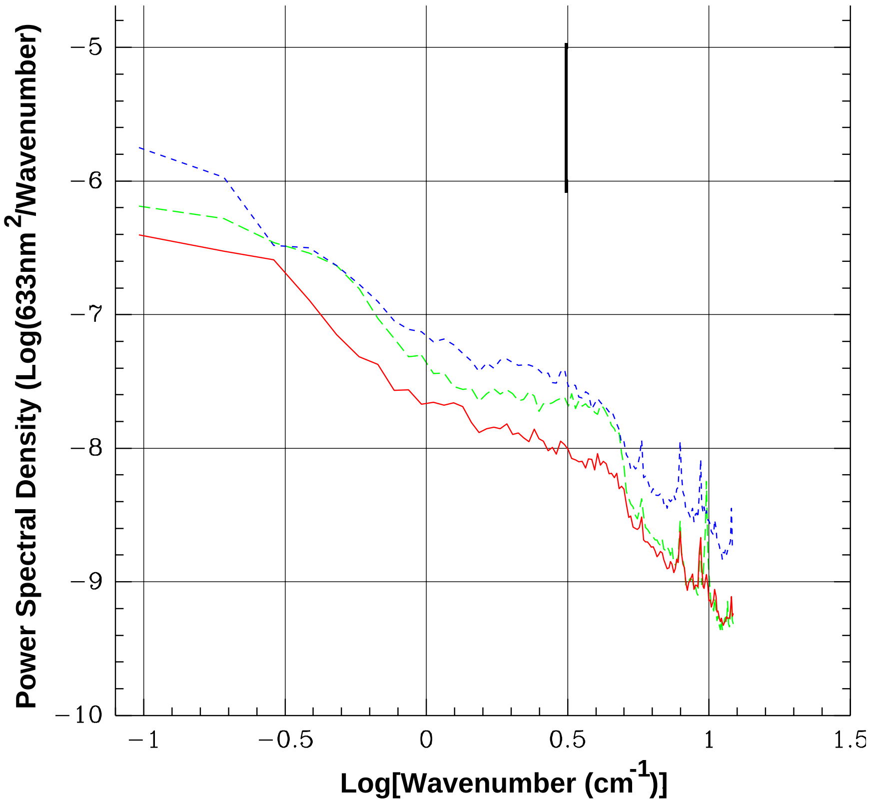


Optics Development Program ("Pathfinder")

- Purchase and evaluate fused silica blanks
  - ››Corning 7940 OAA Grade
- Best effort polishing of substrates
  - ››Commonwealth Scientific and Industrial Research Organization (CSIRO)
  - ››General Optics (GO)
  - ››Hughes-Danbury Optical Systems (HDOS)
- Independent substrate metrology
  - ››National Institute of Standards and Technology (NIST)
- Coating uniformity development
  - ››Research Electro Optics (REO)
- Coated optic metrology (NIST)

Pathfinder Polishing Surface Figure Results

- NIST measurements of CSIRO and GO parts



One dimensional power spectra from NIST metrology of curved surfaces. Z(0,0),Z(1,1) Z(2,0),Z(2,2),Z(3,1),Z(3,3),Z(4,0) removed

Fused Silica Glass

- Corning 7980
  - 21 pieces
    - End Test Masses
    - Recycling Mirrors
    - Folding Mirrors
- Heraeus 311
  - 6 Beamsplitter blanks
- Heraeus 312
  - 13 Input Test Mass blanks

Polishing

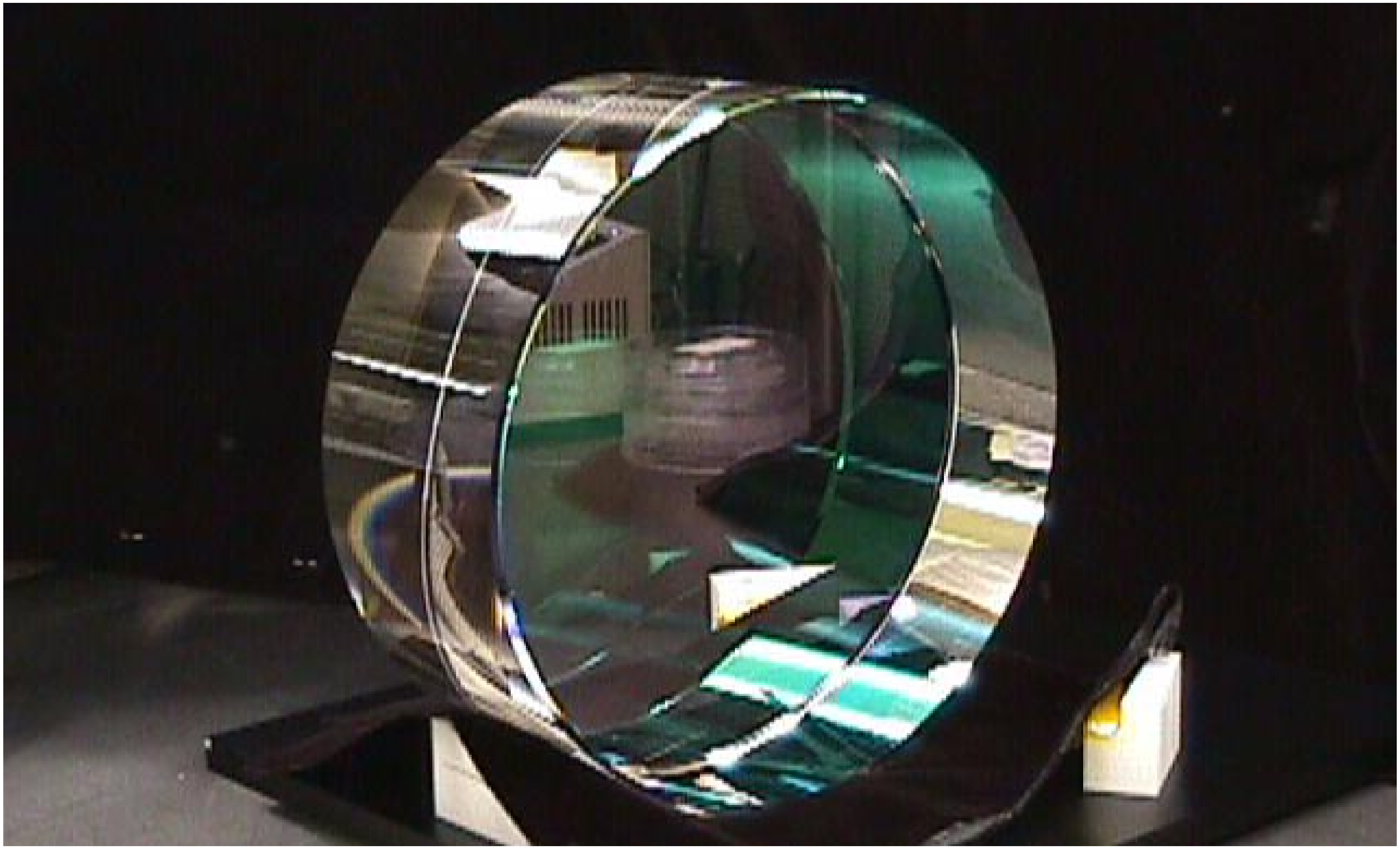
- CSIRO - ETM, ITM, RM, BS, FM
- General Optics - ETM
- Test Masses have the most stringent requirements
  - ››ETM radii of curvature 7,400 m must match within 110m
  - ››RMS surface error after removal of Z3, Z4, Z5 is <0.8 nm over the central 80 mm
- Stability of the Recycling cavity is also important
  - ››ITM side 2 is polished to correct for spherical inhomogeneity in the glass
  - ››RM are polished with a radius of curvature which will match the ITM side 1 radius as it appears under conditions of thermal lensing

Coating

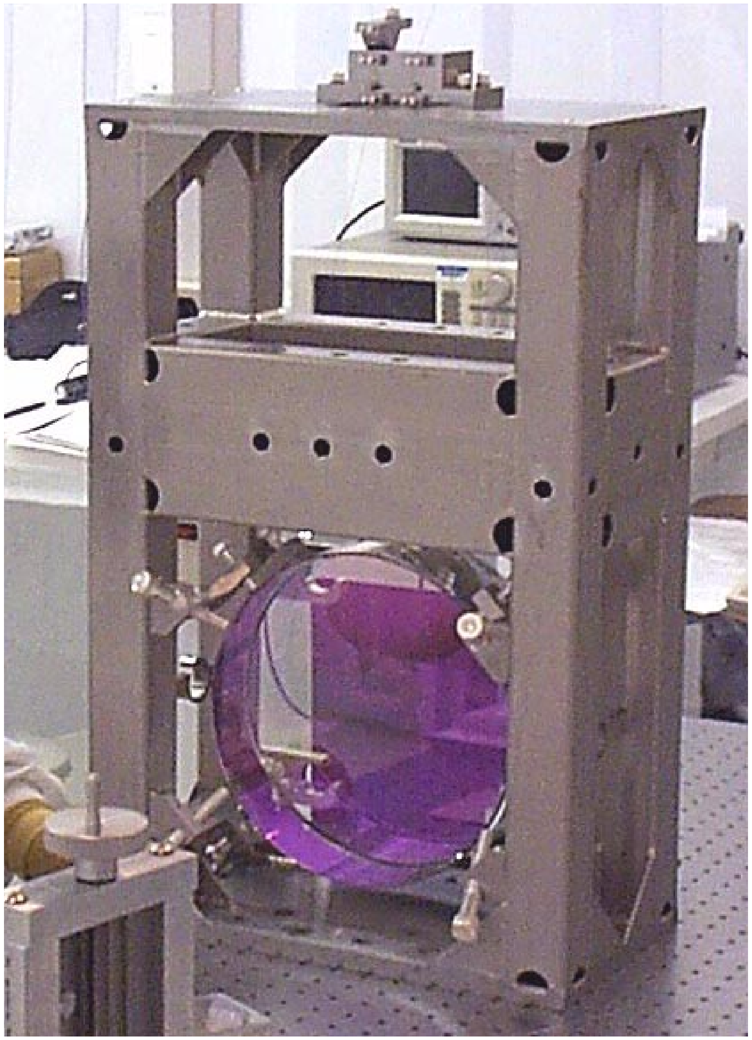
- Research Electro Optics
- Ion Beam Deposition
- Scatter and absorption loss measured at ~ 1ppm
- Coating uniformity ~0.5%
- Beamsplitter requirements
  - Side 1 reflectivity: 50% ± 1%
  - Side 2 reflectivity: <100ppm

Beamsplitter

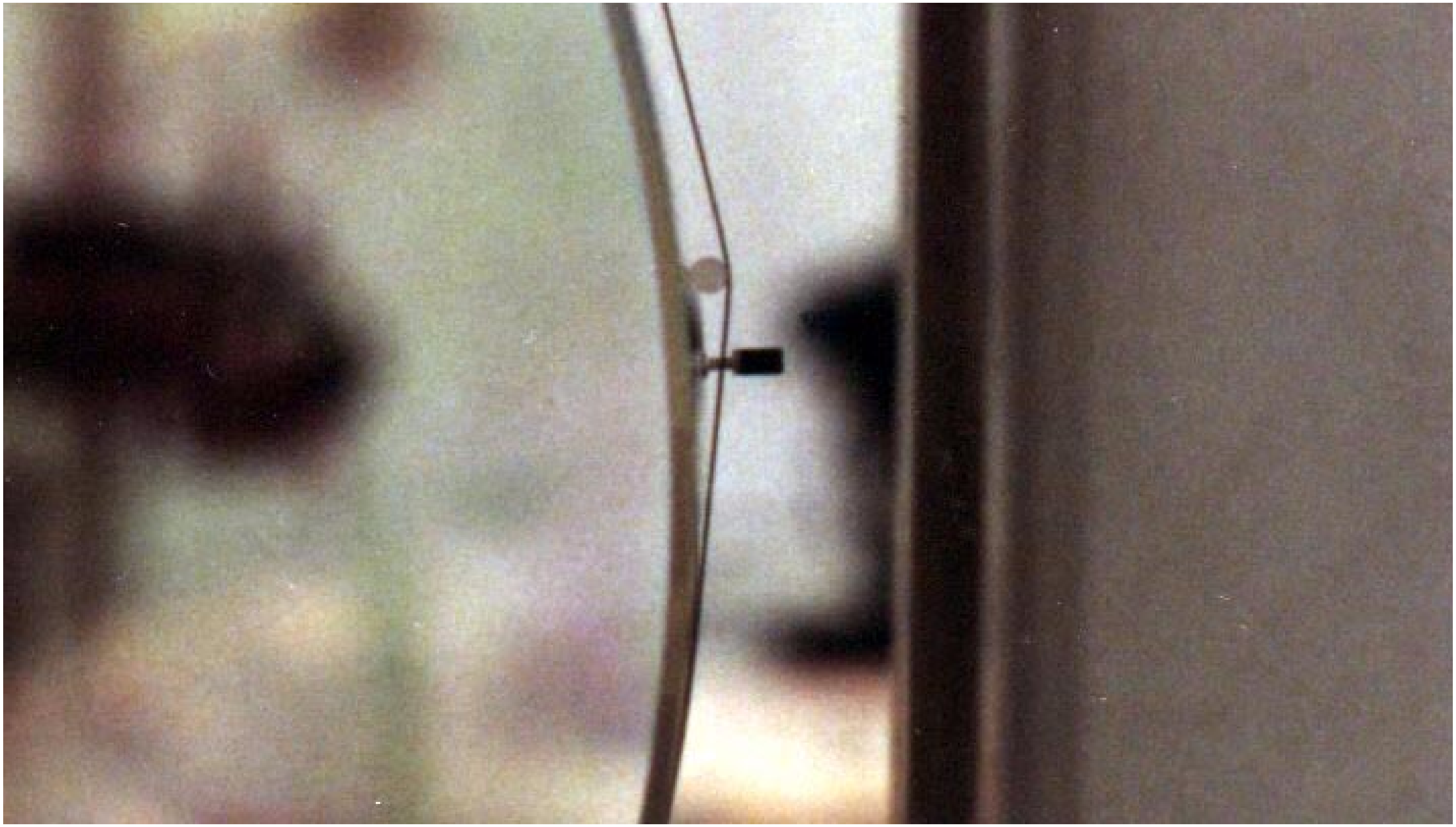
Test Mass



Vibration Isolation
Starts with suspension

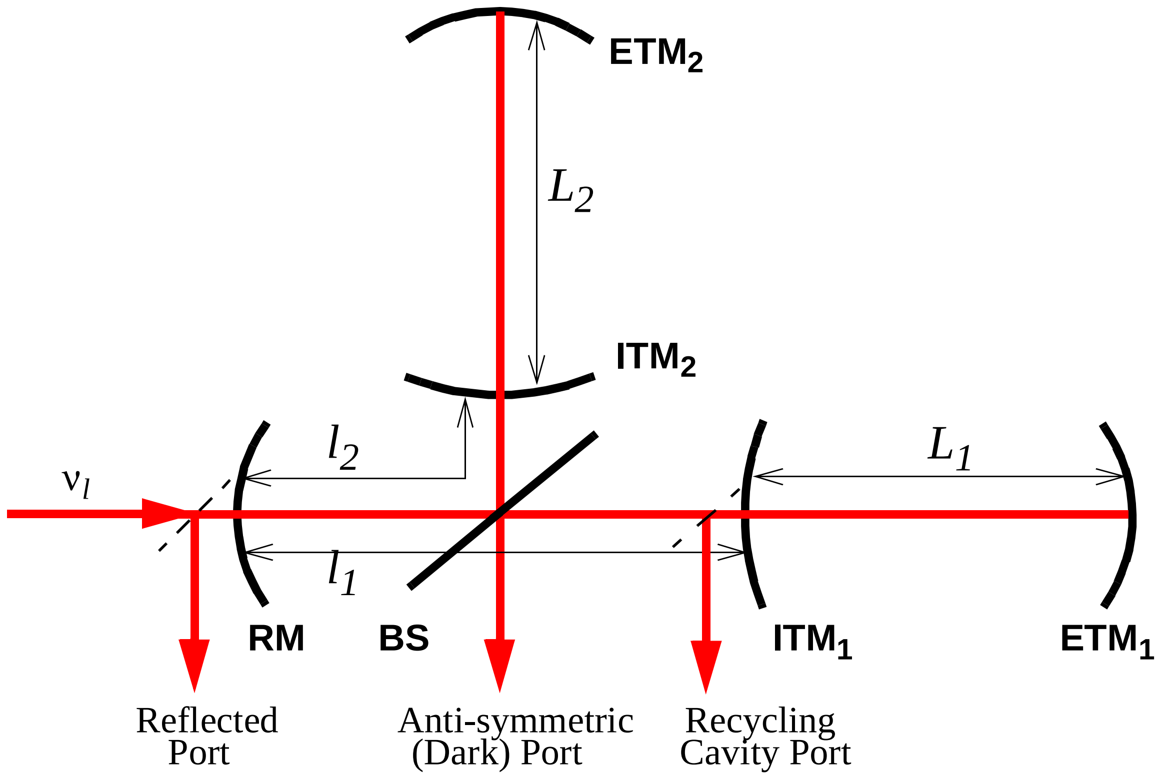


Alignment control and noise suppression



More alignment control and noise suppression

Alignment Sensing and Control



The control Matrix

Port/Signal	L_1+L_2	l_1+l_2	L_1-L_2	l_1-l_2
Reflection	**-62000**	**-560**	**0**	**0**
Recycling Cavity P.O.	**5200000**	**17000**	**0**	**0**
Anti-symmetric	**0**	**0**	**23000**	**180**
Reflection	**0**	**0**	**0**	**19**
Recycling Cavity P.O.	**0**	**0**	**0**	**4900**

Other Interferometric GW Detectors

Project	Country	Number of IFOs	Arm Length (km)
LIGO	United States	2 1	4.0 2.0
VIRGO	Italy & France	1	3.0
GEO600	Germany & Britain	1	0.6
TAMA	Japan	1	0.3
AIGO	Australia	1	1.0

LIGO Timeline

- 1996 Construction Underway - mostly civil
- 1997 Facility Construction - beam pipe and enclosure
- 1998 Construct Detectors - completion of vacuum systems
- 1999 Install Detectors - interferometers in vacuum
- 2000 Commission Detectors - first light in arms; subsystem testing
- 2001 Engineering Tests - sensitivity: engineering run
- 2002 LIGO I Run Begins $h \sim 10^{-21}$

Acknowledgments