Searching for Gravitational Waves with LIGO
(Laser Interferometer Gravitational-wave Observatory)

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Outline of Talk

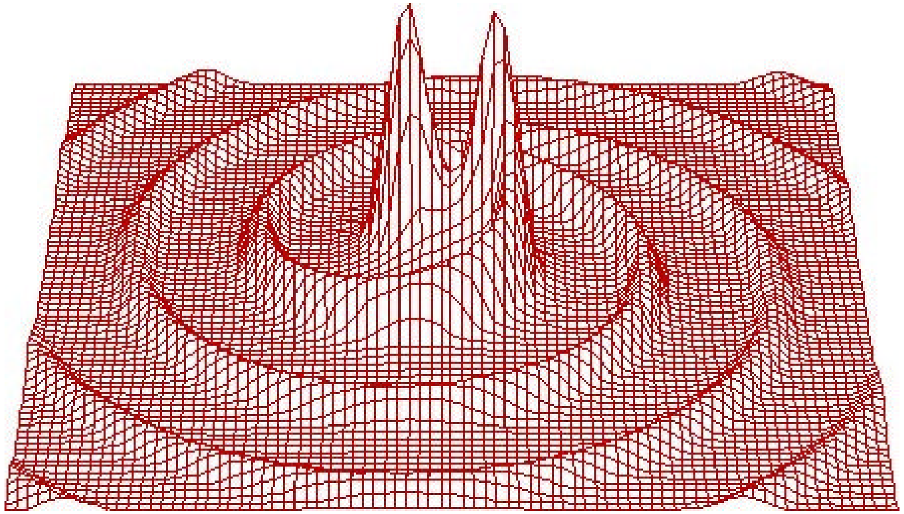
- Quick Review of GW Physics
- LIGO Detector Overview
  - » Performance Goals
  - » How do they work?
  - » What do the parts look like?
- Current Status
  - » Installation and Commissioning
  - » First Science Run
- Global Network
- Advanced LIGO Detectors

Gravitational Waves

- **Einstein in 1916 and 1918 recognized gravitational waves in his theory of General Relativity**

- **Necessary consequence of Special Relativity with its finite speed for information transfer**

- **Time-dependent distortion of space-time created by the acceleration of masses that propagates away from the sources at the speed of light**



gravitational radiation
binary inspiral of compact objects
(blackholes or neutron stars)

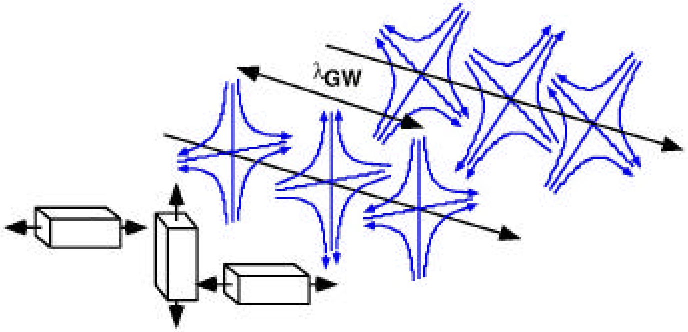
Physics of Gravitational Waves

- In the Minkowski metric, space-time curvature is contained in the metric as an added term, h_{mn}

- In the weak field limit and the *transverse traceless gauge,* the formulation becomes a familiar wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{mn} = 0$$

- Strain h_{mn} takes the form of a transverse plane wave propagating with the speed of light (like EM)

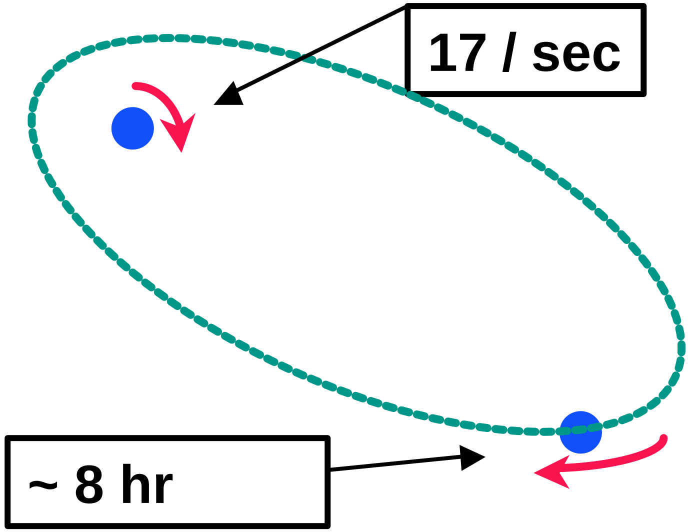


- Since gravity is described by a tensor field (EM is a vector field),
  - » gravitons have spin 2 (cf. spin 1 for photons)
  - » the waves have two polarization components, but rotated by 45^0 instead of 90^0 from each other (as in EM)

Evidence for Gravitational Waves

Neutron Binary System

PSR 1913 + 16

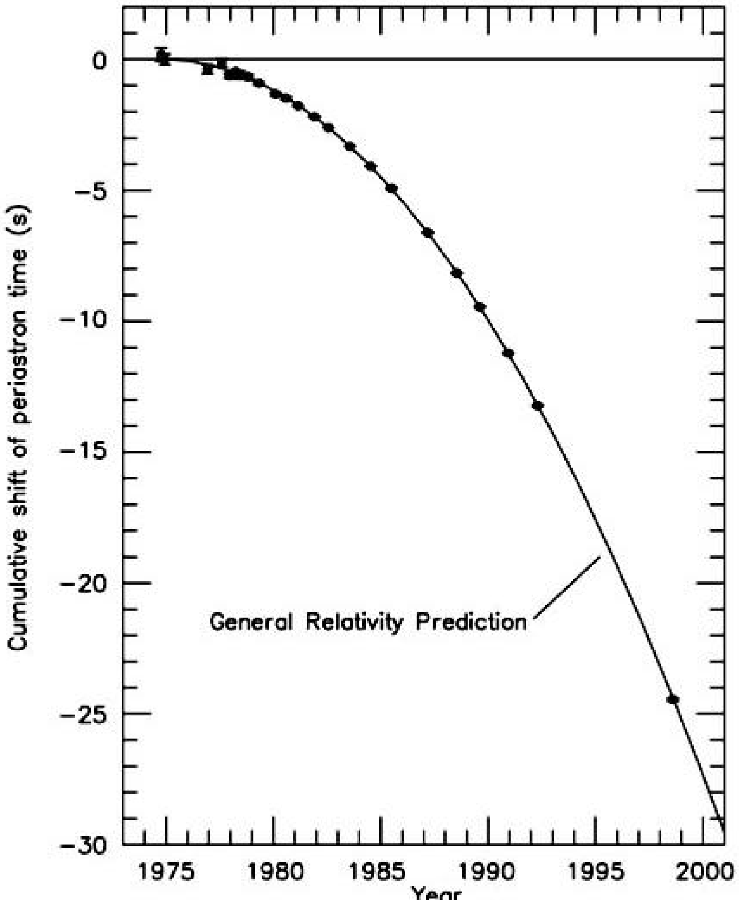


- **Discovered by Hulse and Taylor in 1975**
- **Unprecedented laboratory for studying gravity**
  - **Extremely stable spin rate**
- **Possible to repeat classical tests of relativity (bending of "starlight", advance of "perihelion", etc.**

Binary Pulsar Timing Results

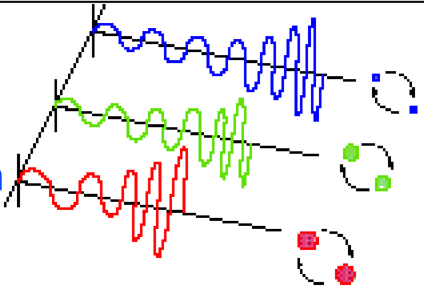
- After correcting for all known relativistic effects, observe loss of orbital energy
- Advance of periastron by an extra 25 sec from 1975-98
- Measured to ~50 msec accuracy
- Deviation grows quadratically with time

=> <u>emission of gravitational waves</u>

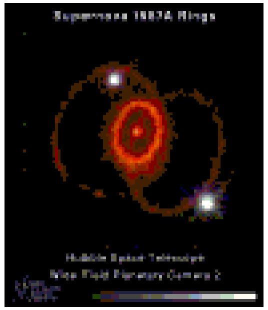


Astrophysical Sources of GWs

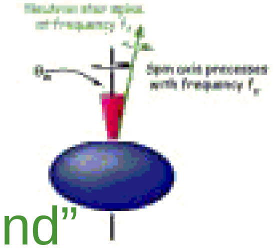
- Compact binary inspiral: “chirps”
  - » **NS-NS binaries well understood**
  - » **BH-BH binaries need further calculation, spin**
  - » **Search technique: matched templates**



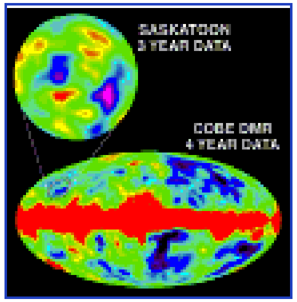
- Supernovas or GRBs: “bursts”
  - » **GW signals observed in coincidence with EM or neutrino detectors**
  - » **Prompt alarm for supernova? (~1 hour?)**



- Pulsars in our galaxy: “periodic waves”
  - » **Search for observed neutron stars (frequency, doppler shift known)**
  - » **All sky search (unknown sources) computationally challenging**
  - » **Bumps? r-modes? superfluid hyperons?**



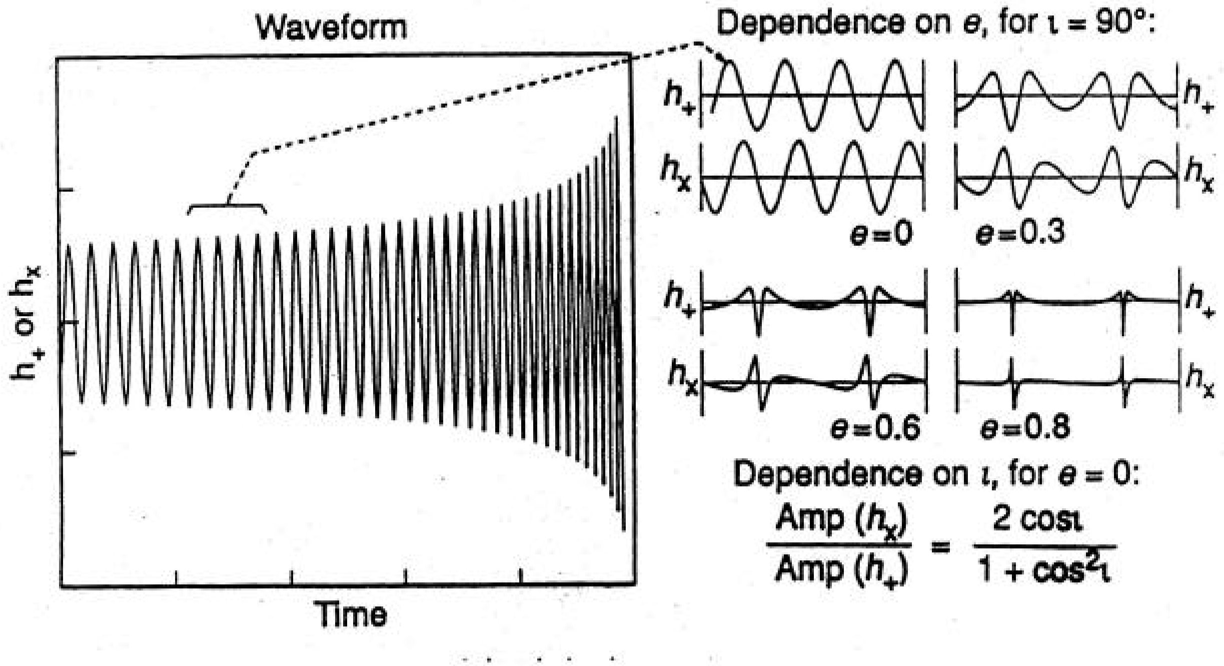
- Cosmological: “stochastic background”
  - » **Probing the universe back to the Planck time (10^{-43} s)**



Using GWs to Learn about the Sources: an Example

Chirp Signal

binary inspiral



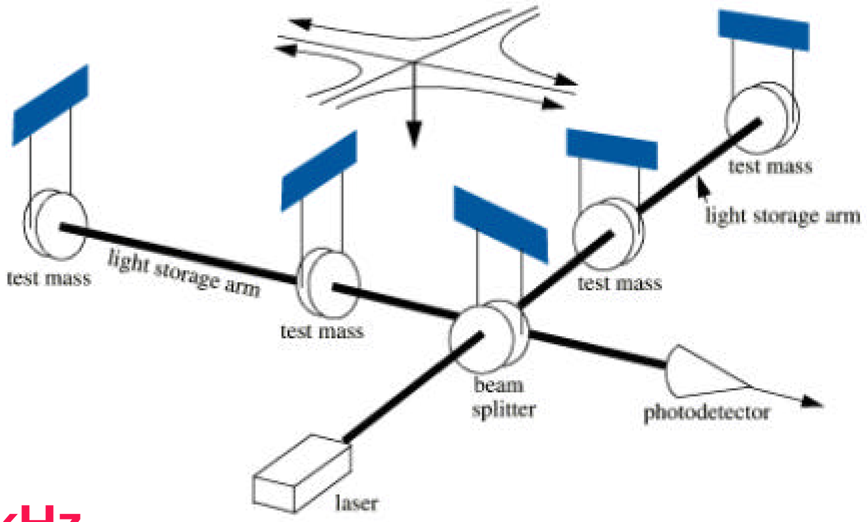
<u>Can determine</u>

- **Distance from the earth r**
- **Masses of the two bodies**
- **Orbital eccentricity e and orbital inclination *i***

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies f >> f_{pend}

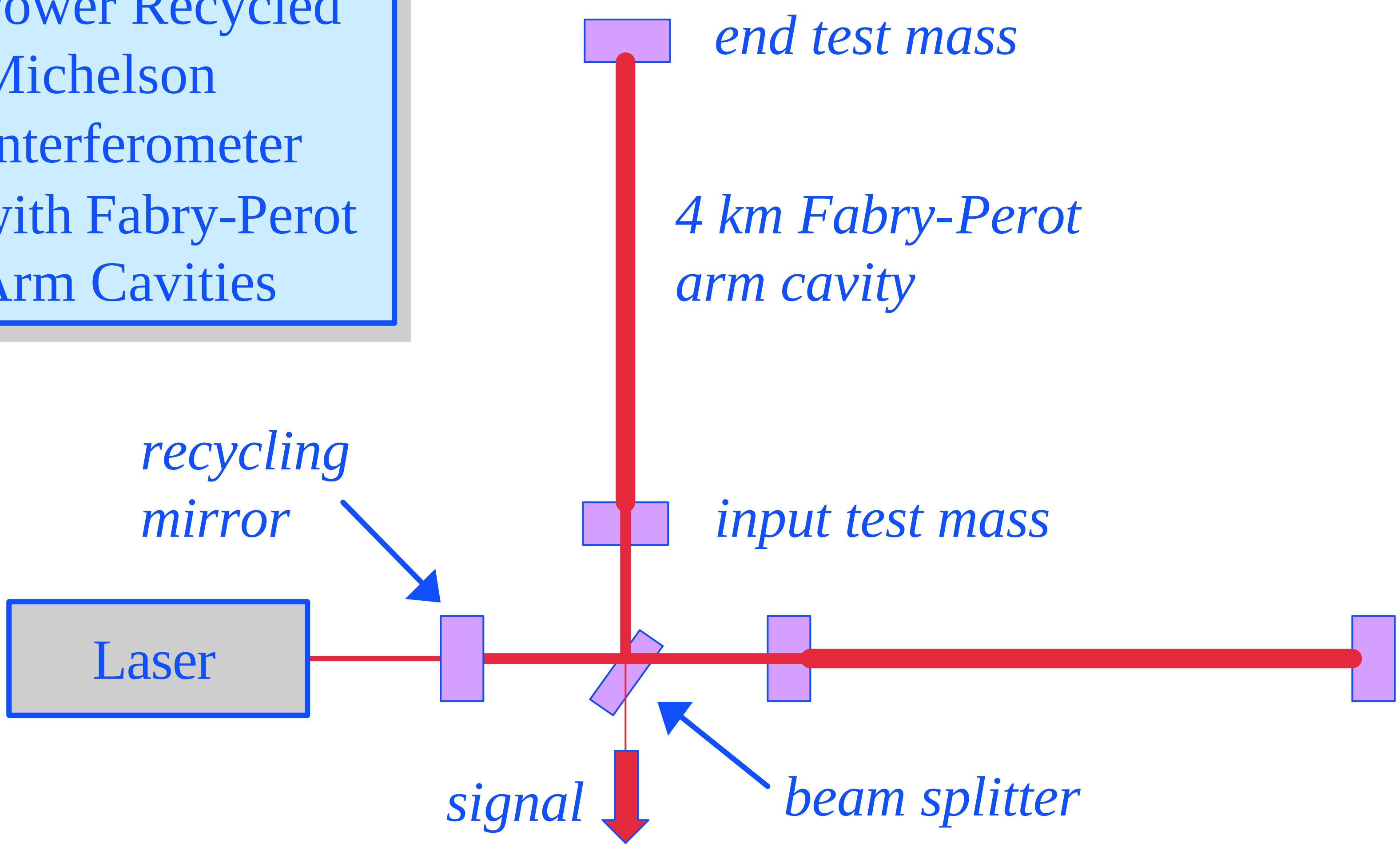
$$h = \Delta L / L$$



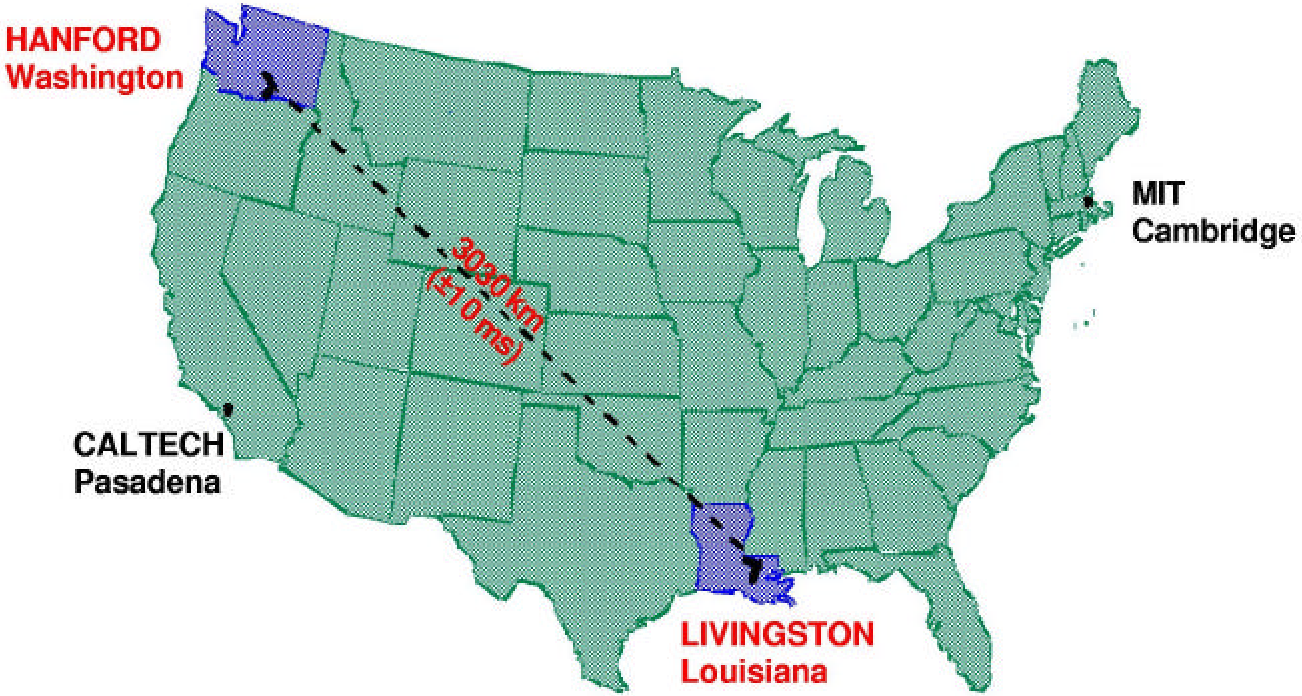
Terrestrial detector,
L ~ 4 km (LIGO)
For $h \sim 10^{-22} - 10^{-21}$
$\Delta L \sim 10^{-18}$ m
Useful bandwidth 10 Hz to 10 kHz, determined by "unavoidable" noise (at low frequencies) and expected maximum source frequencies (high frequencies)

Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



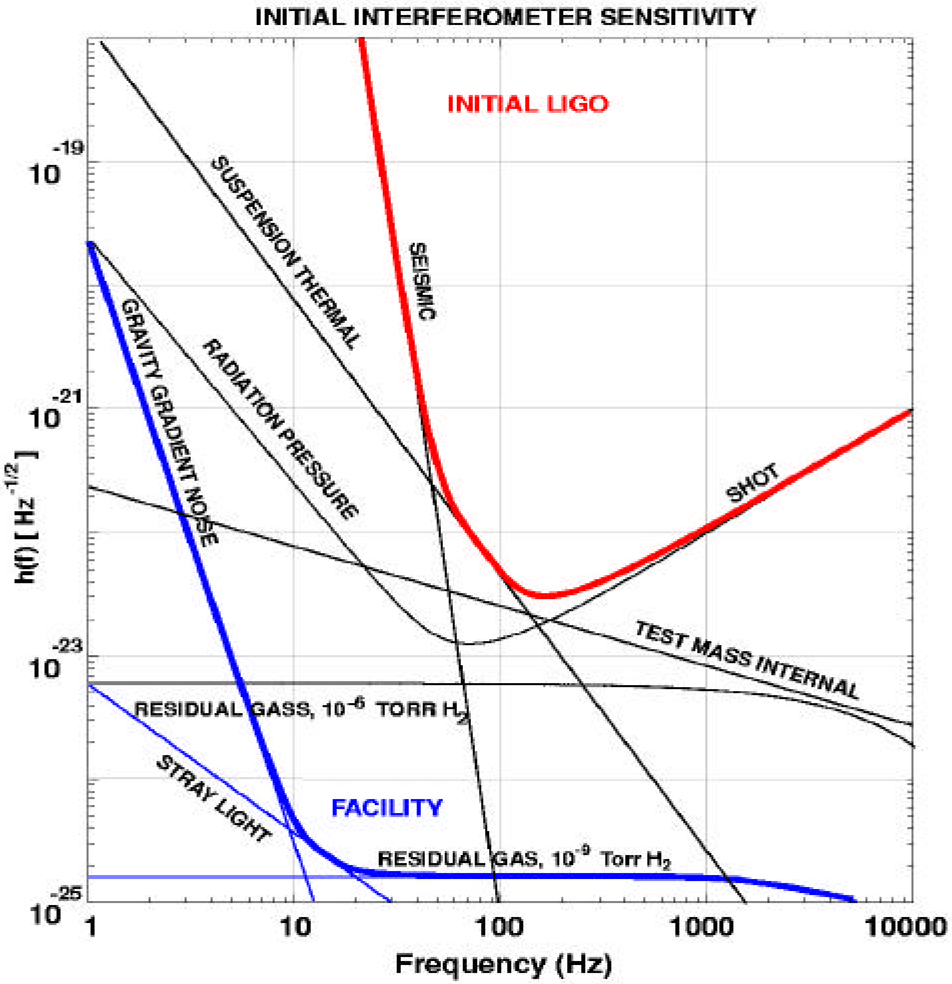
LIGO Observatories



Initial Detectors—Underlying Philosophy

- Jump from laboratory scale prototypes to multi-kilometer detectors is already a BIG challenge
- Design should use relatively cautious extrapolations of existing technologies
  - » Reliability and ease of integration should be considered in addition to noise performance
  - » 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

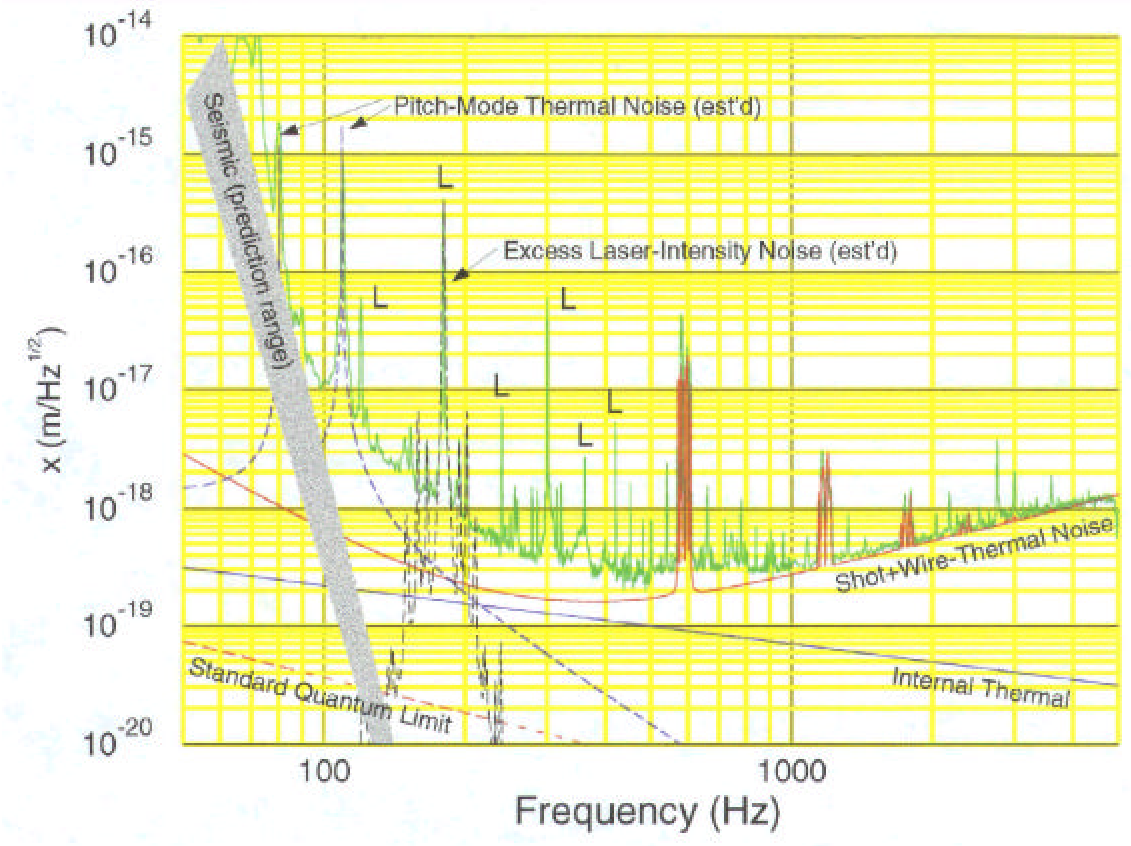
Initial LIGO Sensitivity Goal



- Strain sensitivity $<3\times10^{-23}$ $1/\mathrm{Hz}^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

Can you REALLY measure 10^{-18} m?

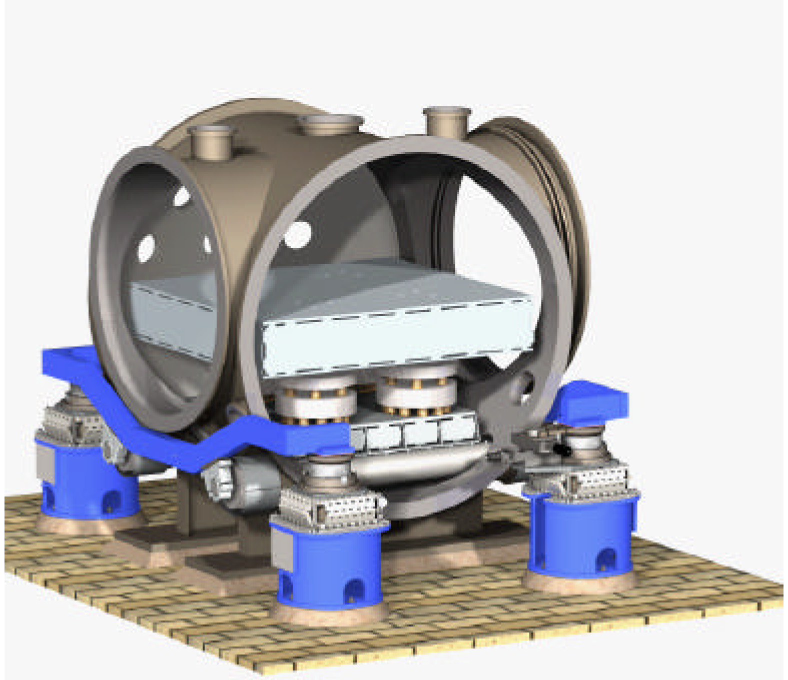
Sensitivity Demonstration

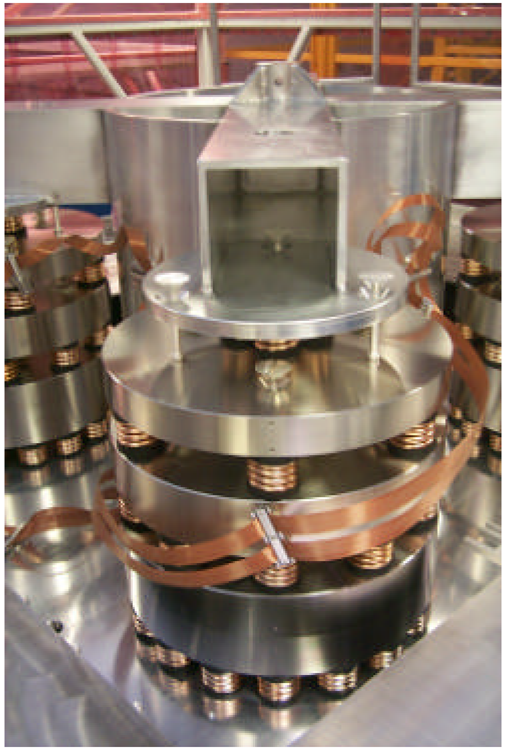


- 40 m prototype interferometer (1992)
- Displacement sensitivity comparable to LIGO requirement
- Understanding of contributing noise sources

Vibration Isolation Systems

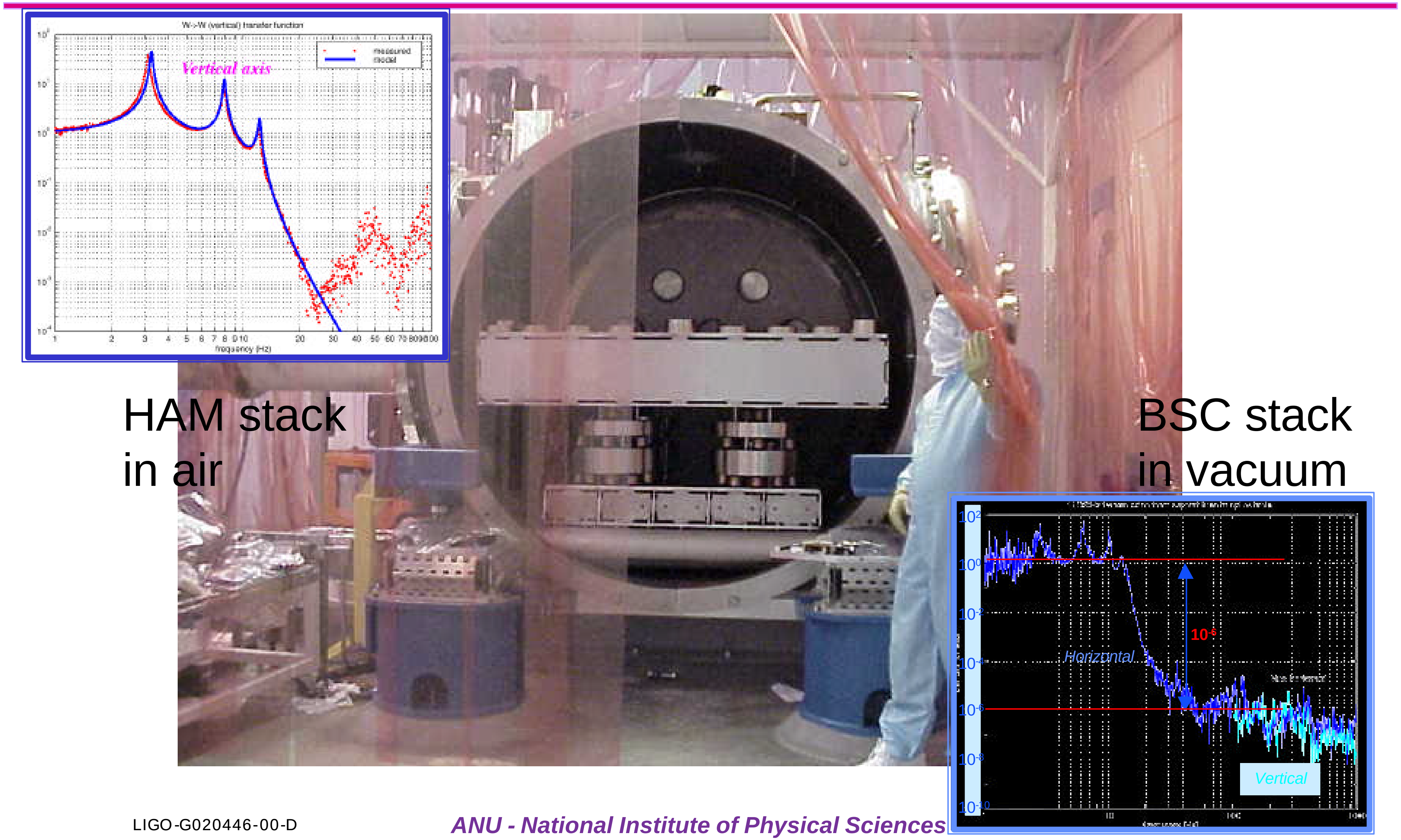
- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Springs and masses
- Large range actuation for initial alignment and drift compensation





- Quiet actuation to correct for Earth tides and microseismic motion at 0.15 Hz during observation

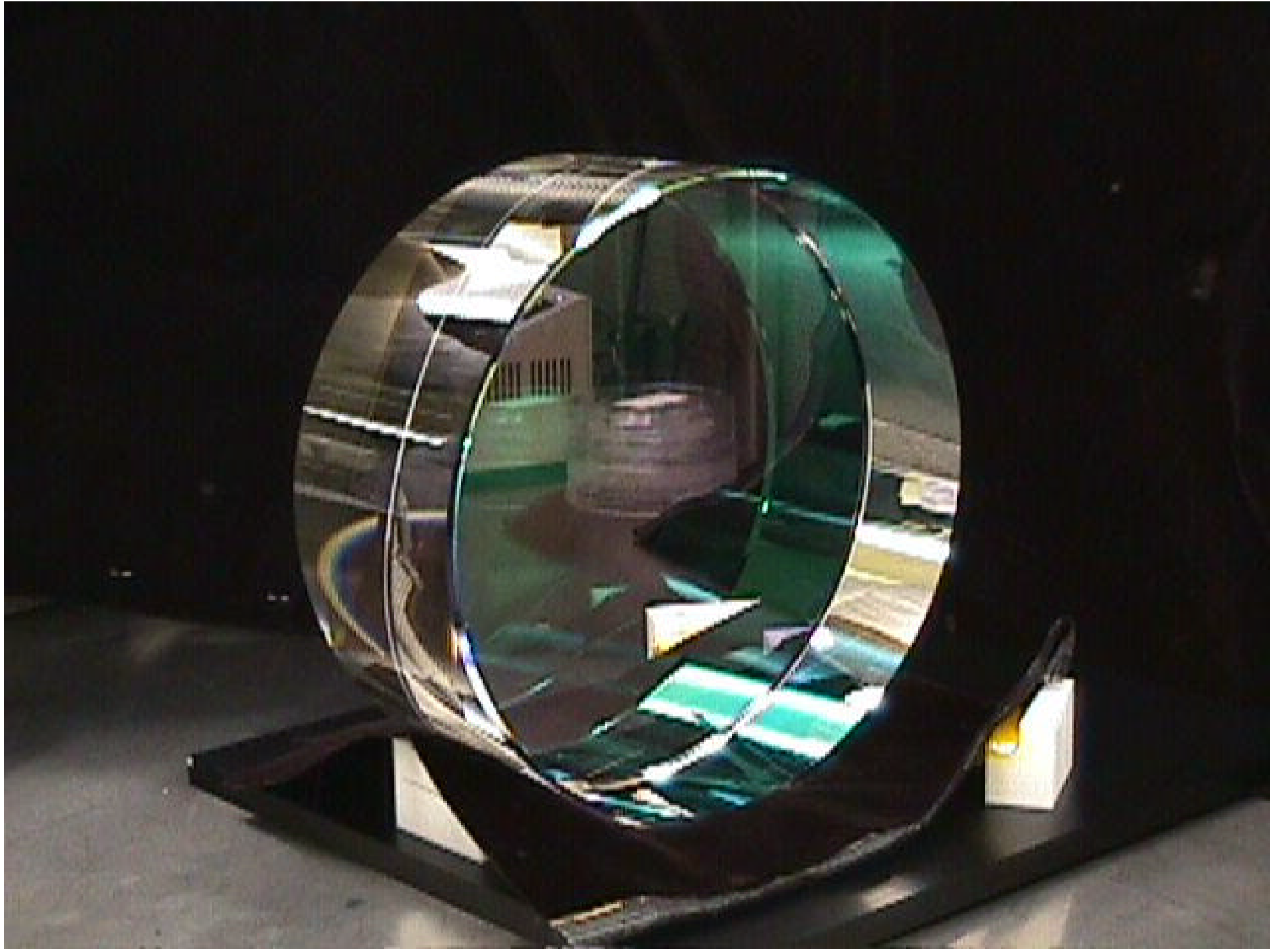
Vibration Isolation System



HAM stack
in air

BSC stack
in vacuum

Test Mass

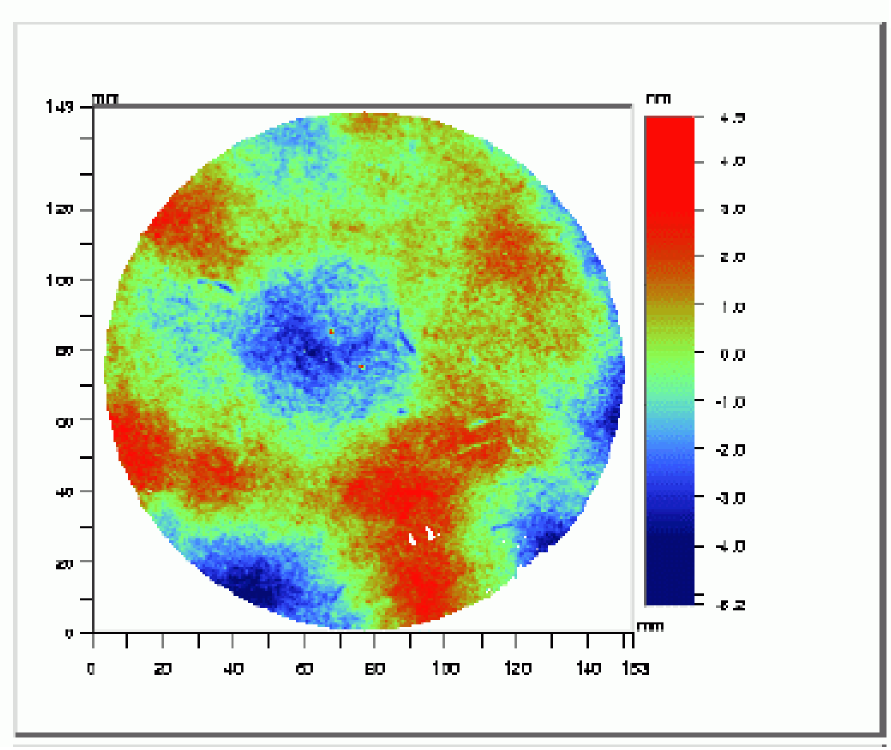


Test Mass Optical Requirements

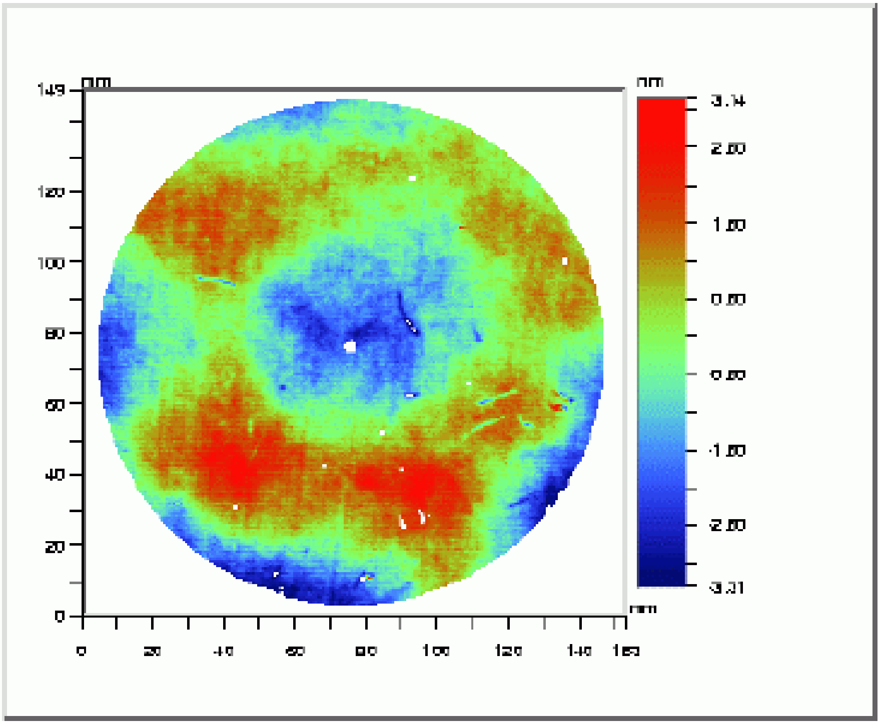
- Substrates
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity $< 5 \times 10^{-7}$
  - » Internal mode Q's $> 2 \times 10^{6}$
- Polishing
  - » Surface uniformity < 1 nm rms
  - » ROC matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity $<10^{-3}$
- Successful production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

Test Mass Metrology

- Current state of the art: 0.2 nm repeatability

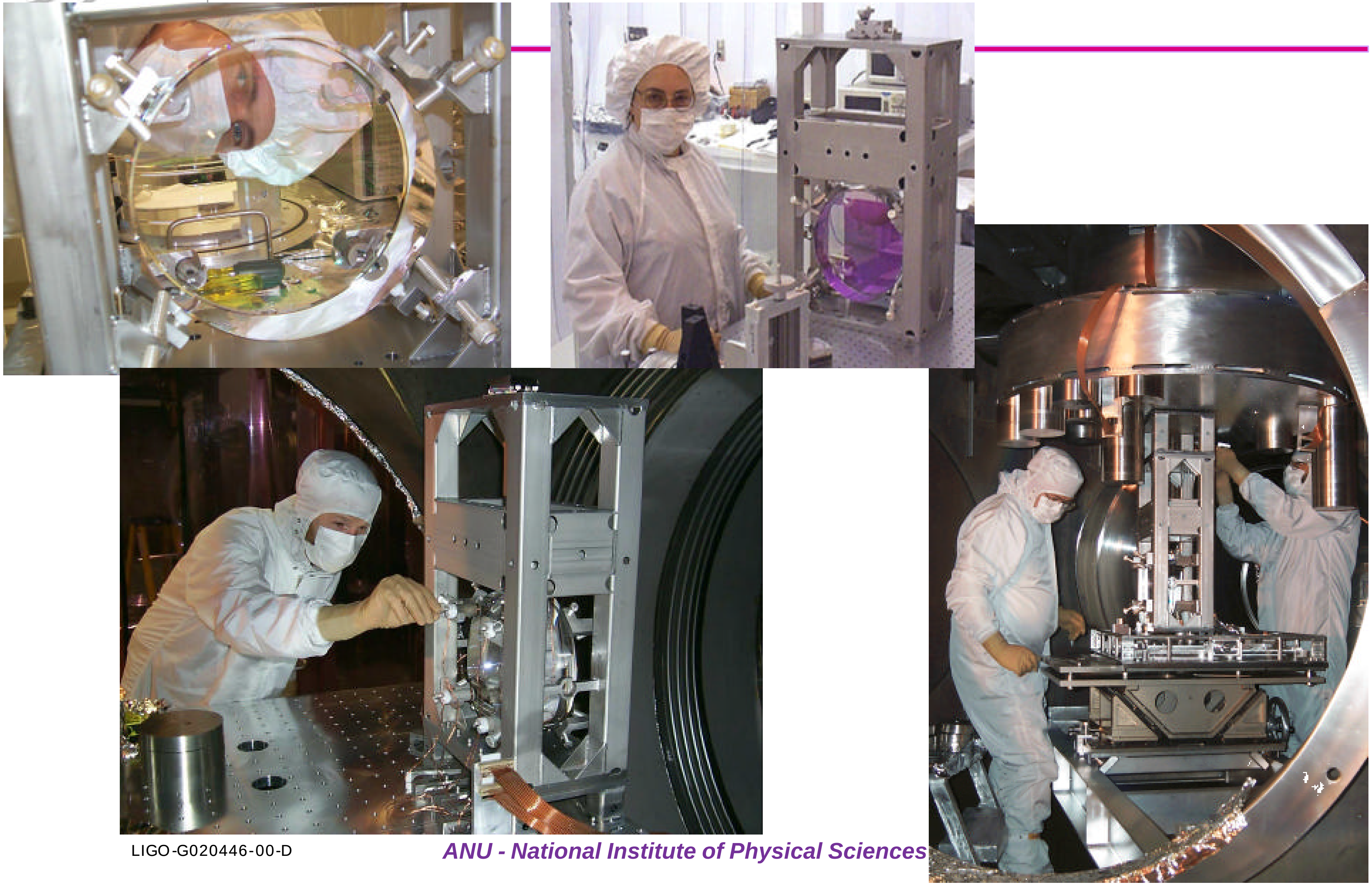


LIGO data (1.2 nm rms)



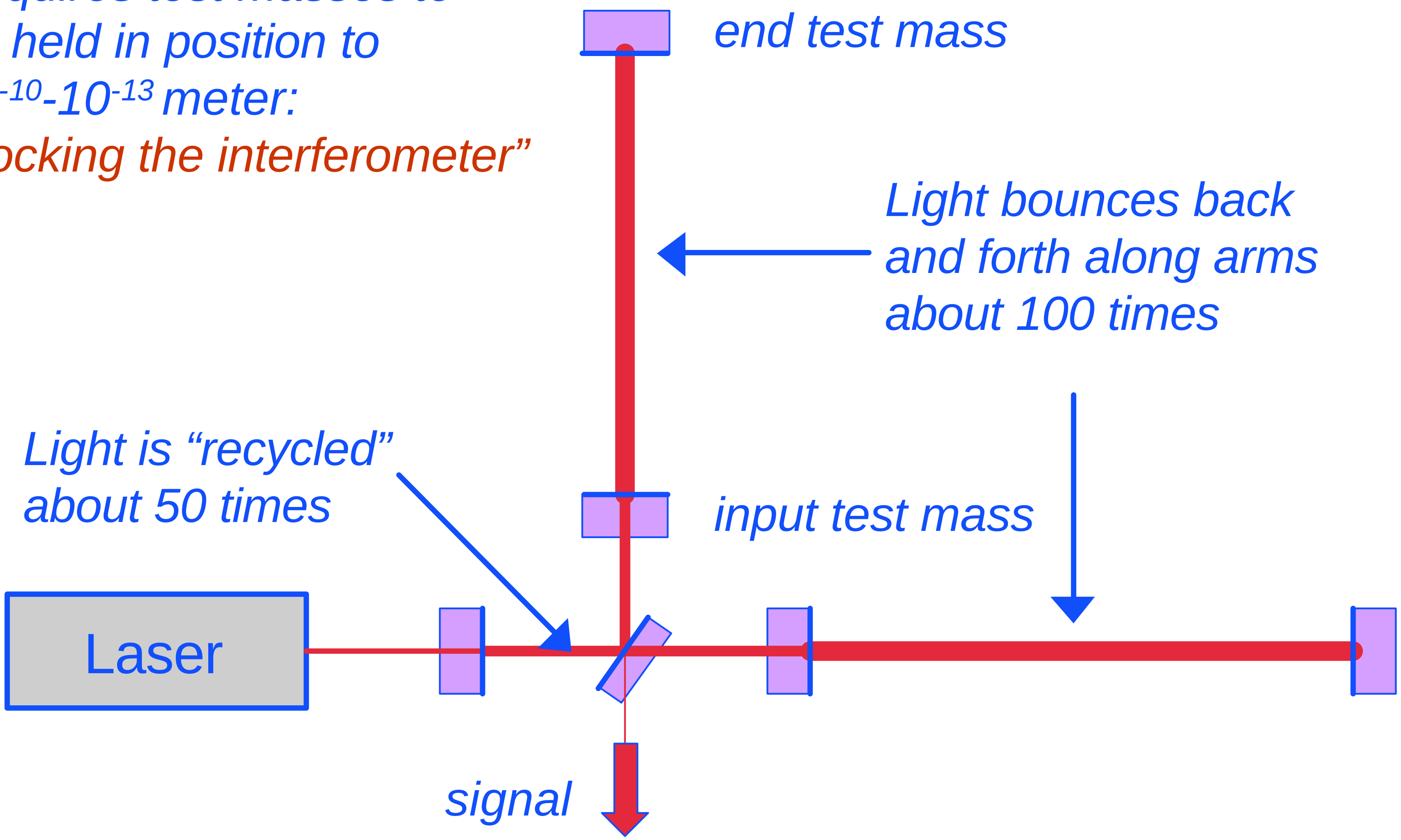
CSIRO data (1.1 nm rms)

Test Mass Suspension and Control



Control Systems

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



First Science Run (S1)

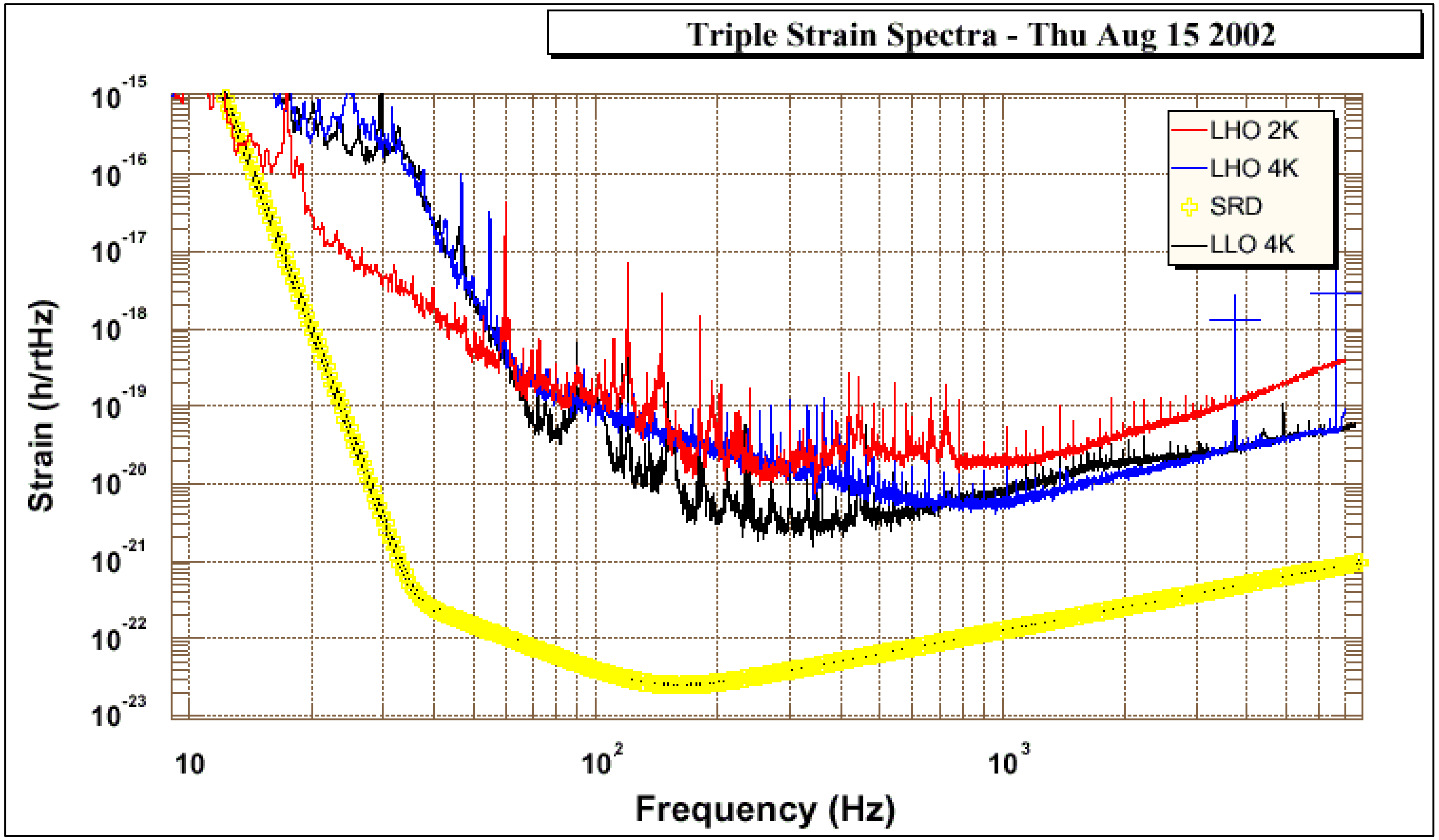
- August 23 - September 9, 2002 (~400 hours)
- Three LIGO interferometers, plus GEO (Europe) and TAMA (Japan)
- Steady improvement in sensitivity continues
  - » Range for binary neutron star inspiral ~ 40-100 kpc
- “Glitch” rate reduced compared with previous engineering runs
- Hardware reliability good for this stage in the commissioning
- Analysis results (upper limits for several types of sources) expected by early 2003
- Next science run early 2003 (longer, more sensitive)

S1 Duty Cycle

	LLO-4K	LHO-4K	LHO-2K	All three together
Integrated lock time (>300 sec per segment)	169 hours	232 hours	288 hours	96 hours
Duty cycle (cf. 400 hour run time)	43%	59%	73%	24%

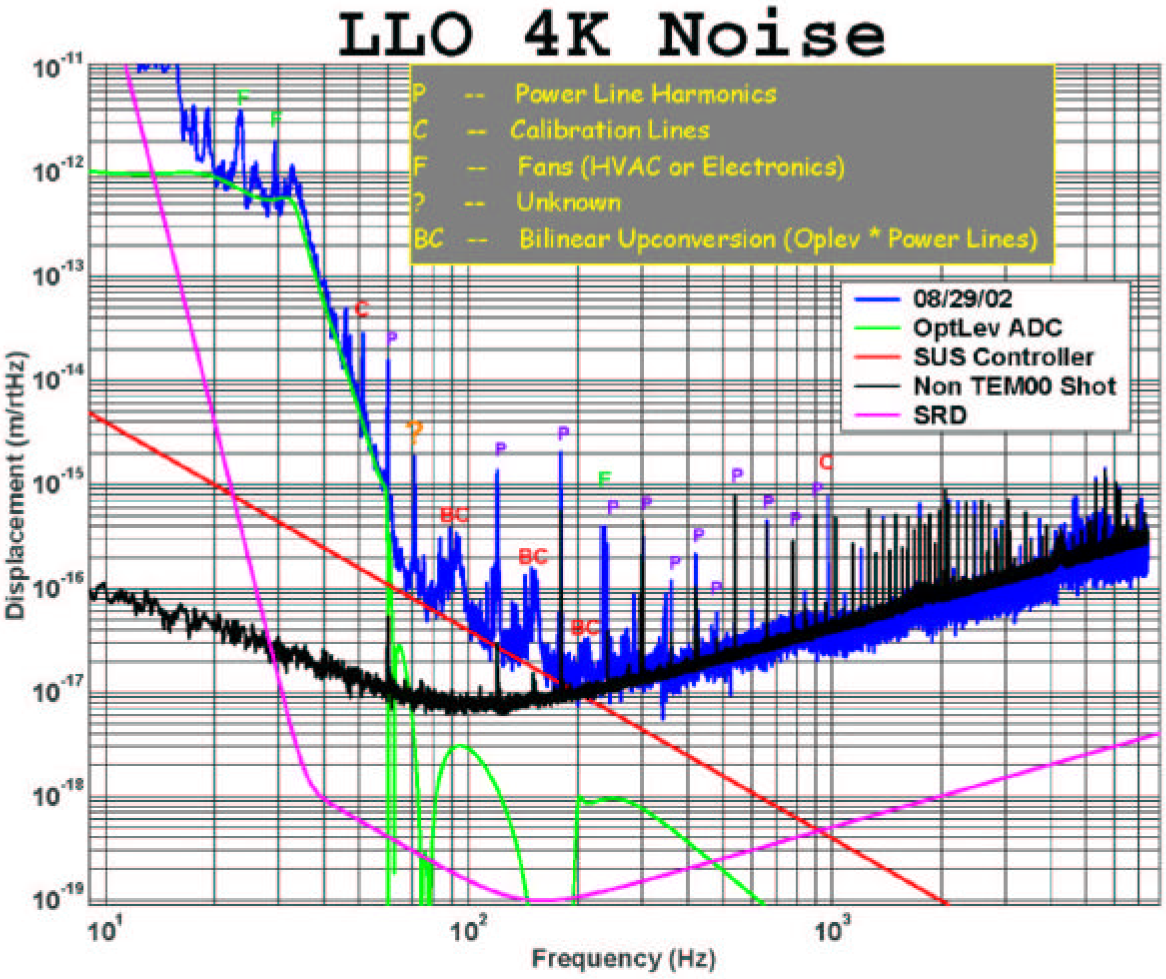
- Longest locked section for individual interferometer: 21 hrs (11 in “Science mode”)
- Need to improve low frequency seismic isolation – protection from local anthropogenic noise

S1 Sensitivities



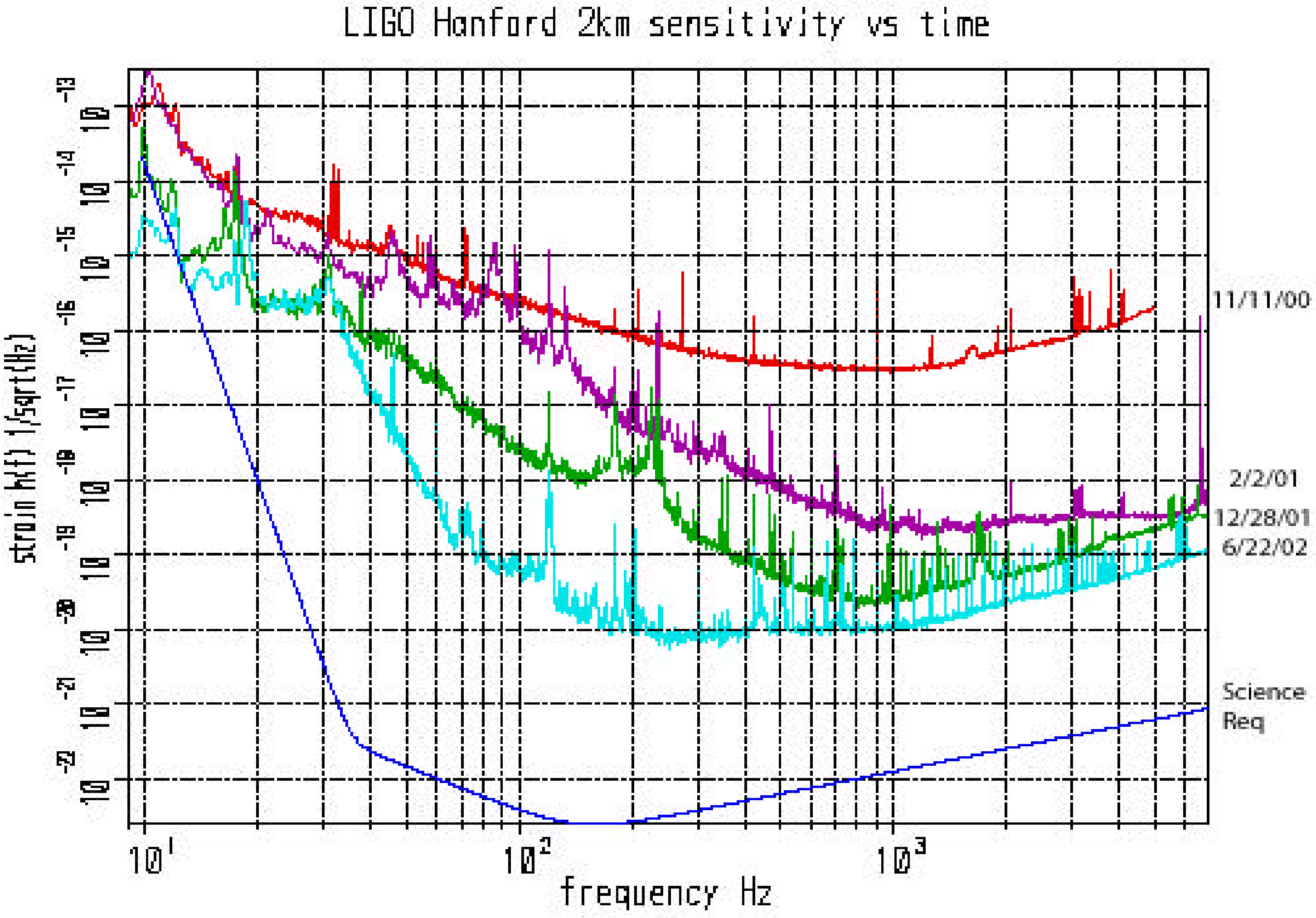
Will provide improved upper limits for the GW flux from sources over a relatively broad frequency band

Improving the Noise



- Understand limiting noise sources
  - »Maintain a working model of dominant noise sources to guide future improvements
- Eliminate the most important noise sources in turn

Example of Progress toward Design Sensitivity



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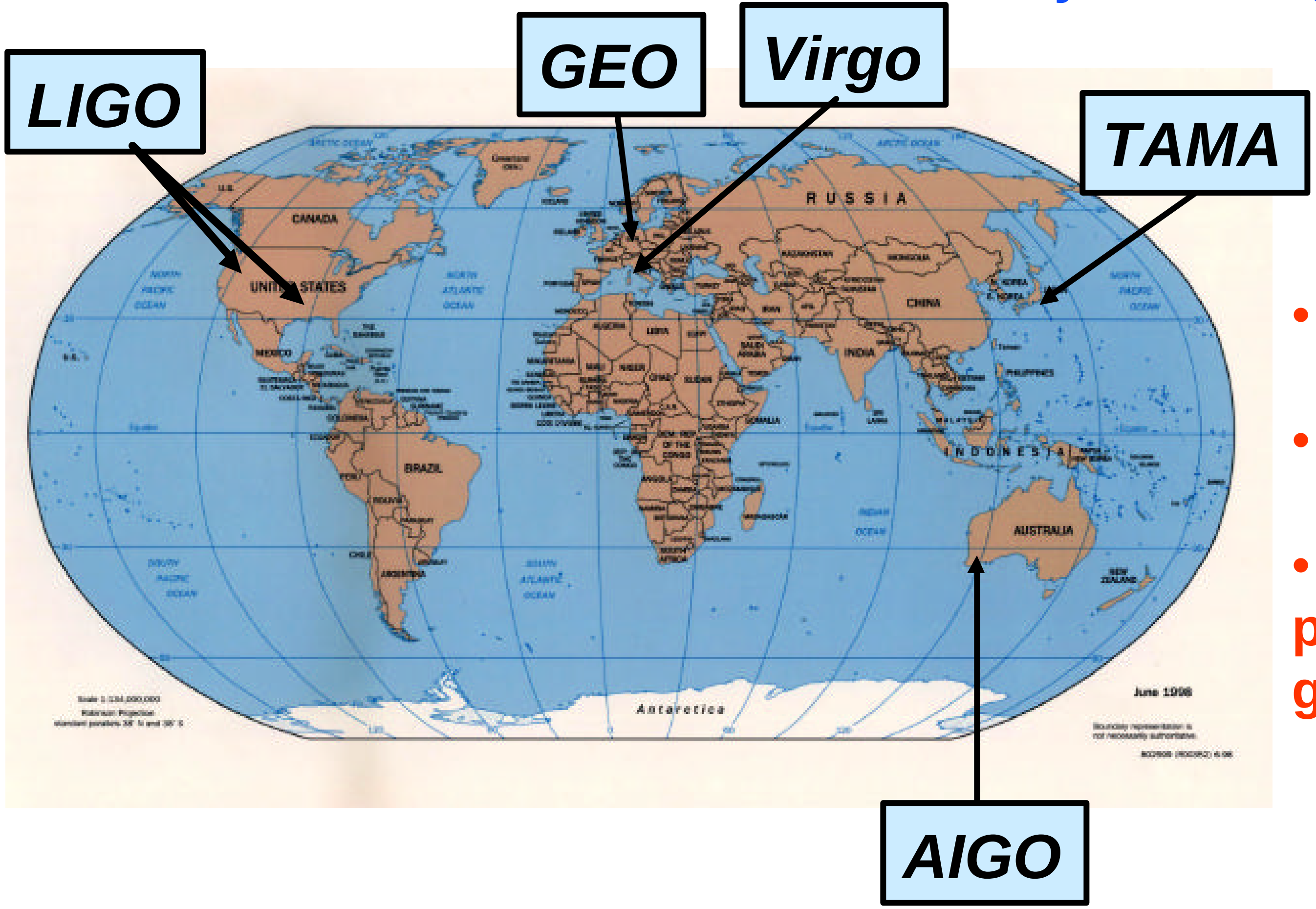
Toward a Global Network of GW Detectors

Simultaneously detect signal (within msec)



LIGO

GEO

Virgo

TAMA

AIGO

- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves

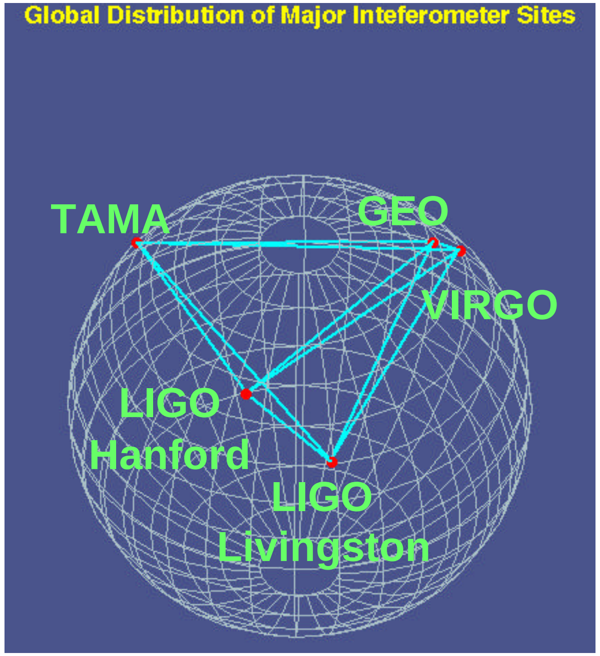
GW Detectors around the World

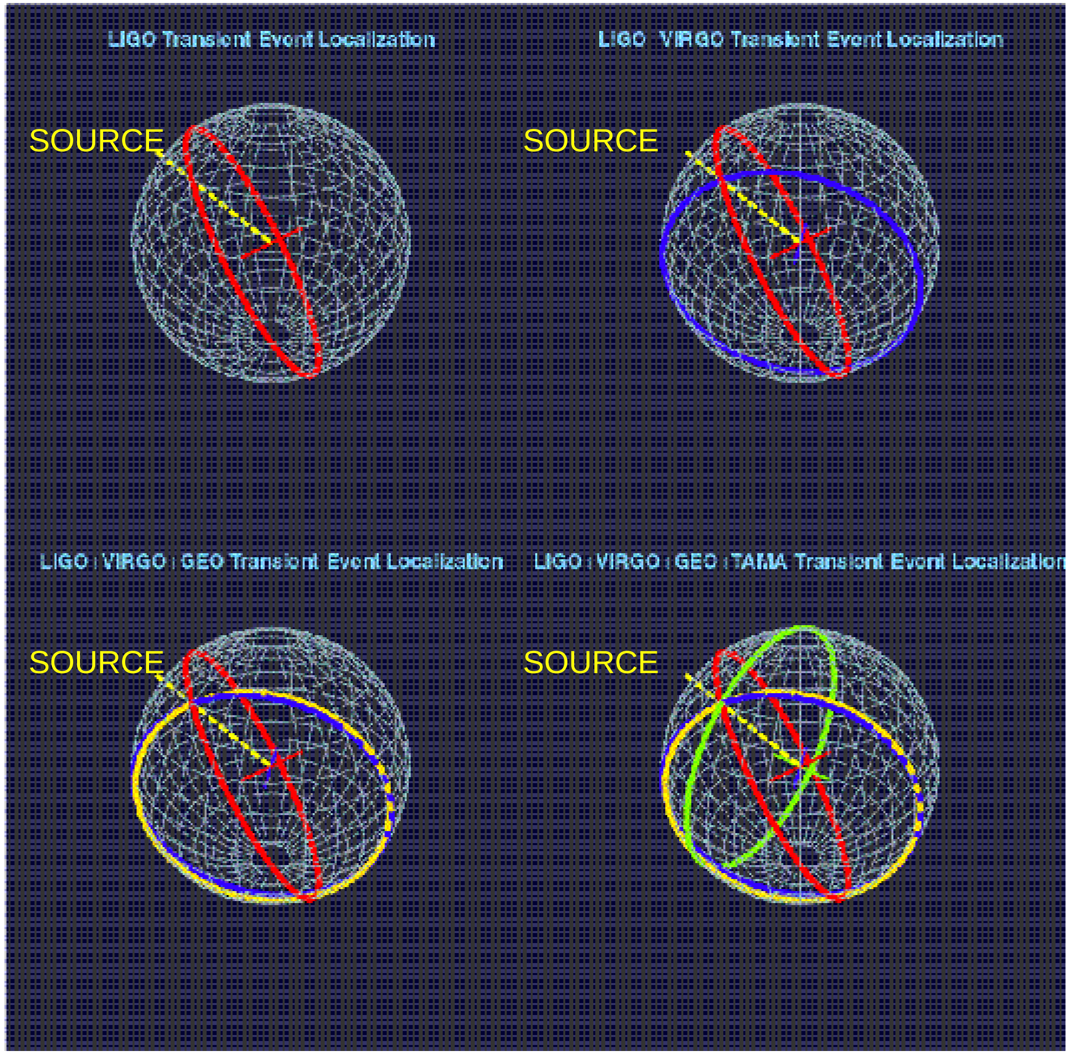
AIGO
Australia

Virgo
Italy

GEO 600
Germany

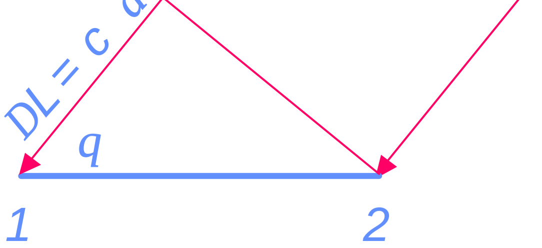
Event Localization with Array of Detectors





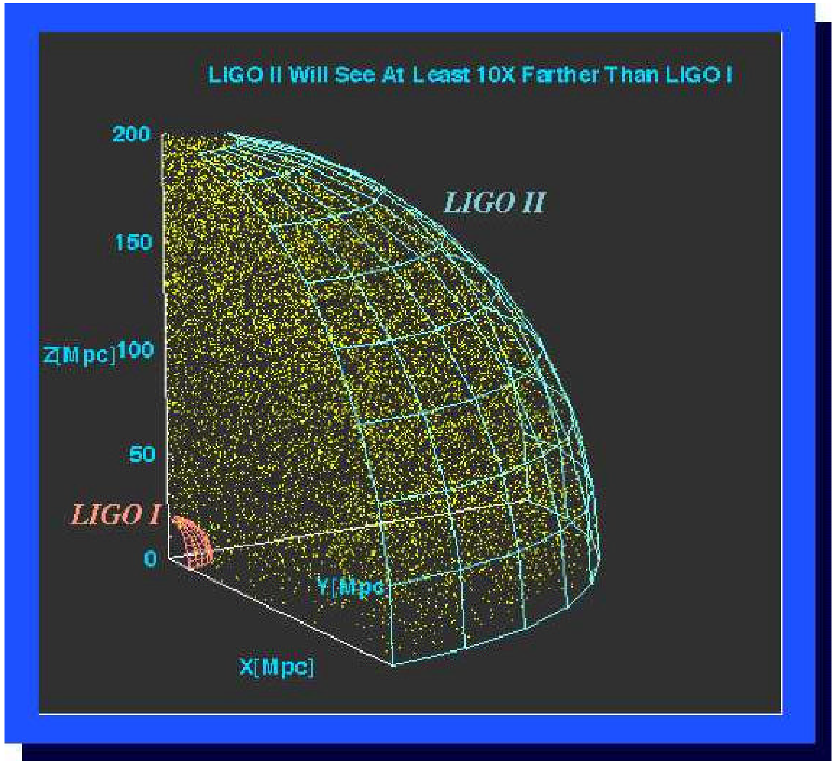
$Dq \sim c\ dt\ / D_{12}$

$Dq \sim 0.5\ deg$

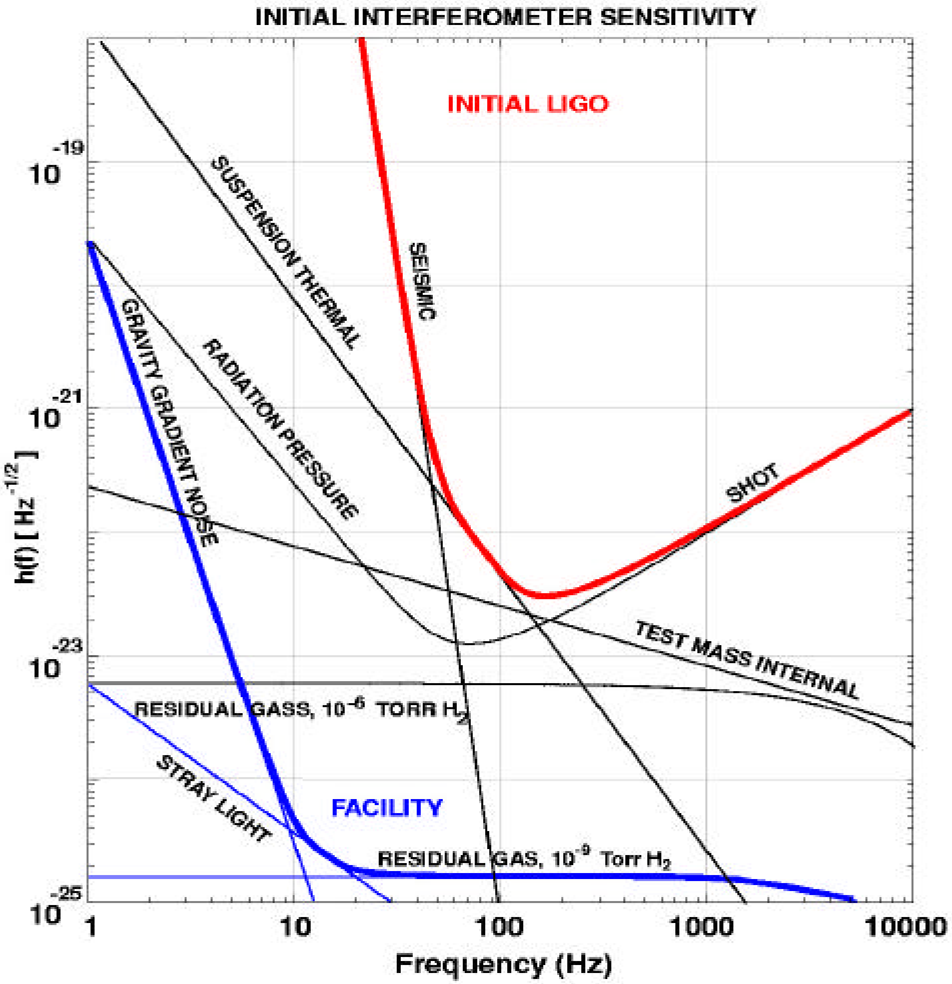


Advanced LIGO

- 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 initial LIGO data run
- Schedule:
  - Begin installation: 2006-7
  - Operational: 2008-9



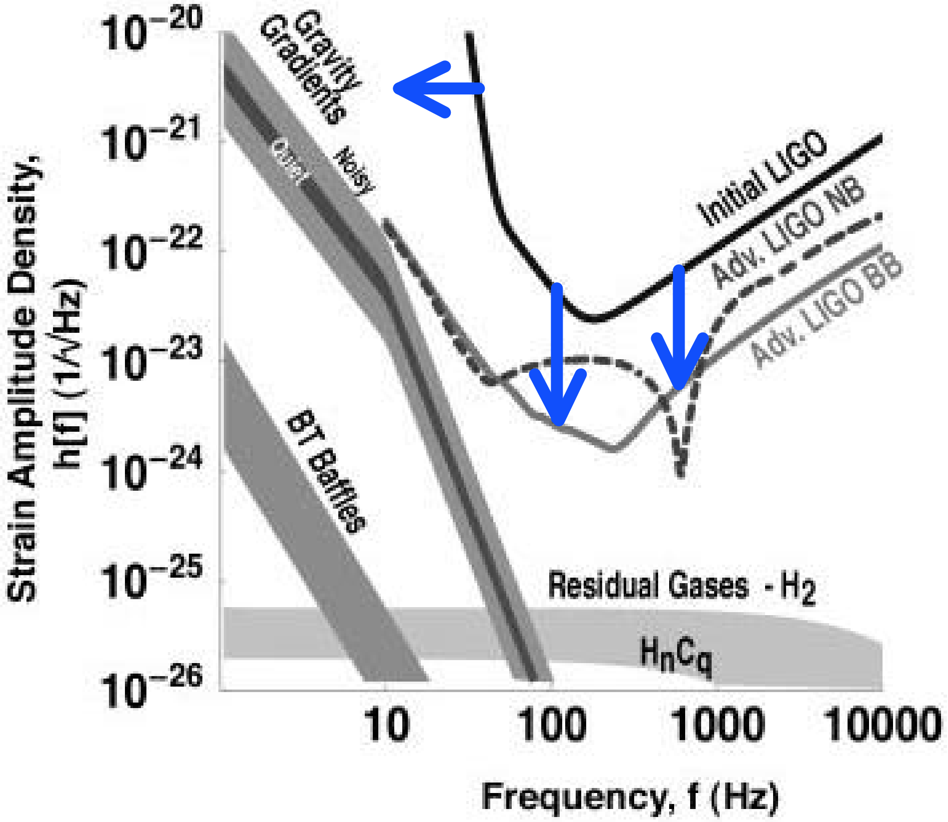
Facility Limits to Sensitivity



- Facility limits leave lots of room for future improvements

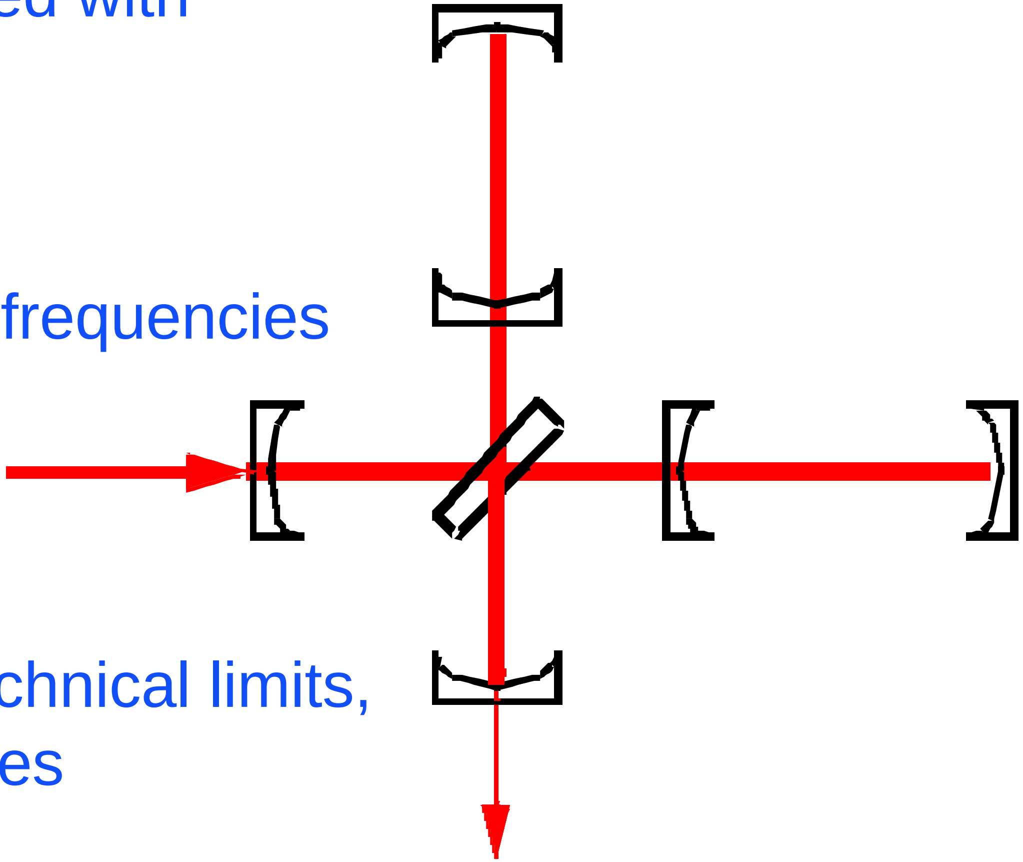
Present and future limits to sensitivity

- Advanced LIGO
  - » Seismic noise 40→10 Hz
  - » Thermal noise 1/15
  - » Shot noise 1/10, tunable
- Facility limits
  - » Gravity gradients
  - » Residual gas
  - » (scattered light)



Tailoring the frequency response

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



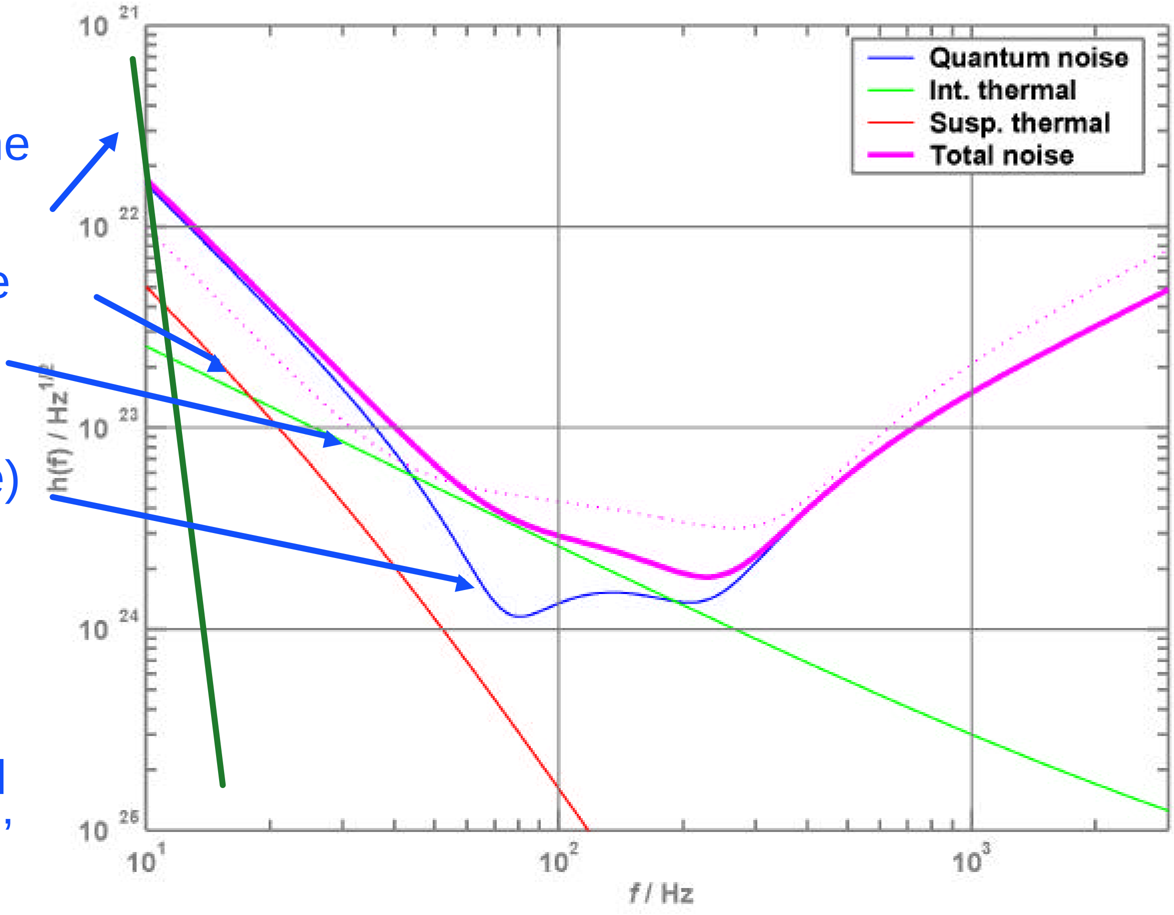
- Allows optimum for technical limits, astrophysical signatures

Advanced 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

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
- Quantum noise (shot + radiation pressure) dominates at most frequencies
- ‘technical’ noise (e.g., laser frequency) levels held in general well below these ‘fundamental’ noises



So, what is this bloke doing in Australia?

- Third generation GW interferometers will have to confront (and beat) the uncertainty principle
- Standard Quantum Limit (early 1980's)
  - » Manifestation of the "Heisenberg microscope"
  - » Shot noise ~ $P^{-1/2}$
  - » Radiation pressure noise ~ $P^{1/2}$
  - » Together define an optimal power and a maximum sensitivity for a "conventional" interferometer
- Resurgent effort around the world to develop sub-SQL measurements ("quantum non-demolition")
  - » Require non-classical states of light, special interferometer configurations, …
  - » ANU has a unique combination of expertise in quantum optics and gravitational wave detection
- But that's a story for another time….

Final Thoughts

- We are on the threshold of a new era in GW detection
- First results from LIGO and the other large interferometers should be available within the next 3-4 months
  - » Upper limits initially
- 20+ years of giving talks on the great potential of interferometers for GW detection will give way to Results