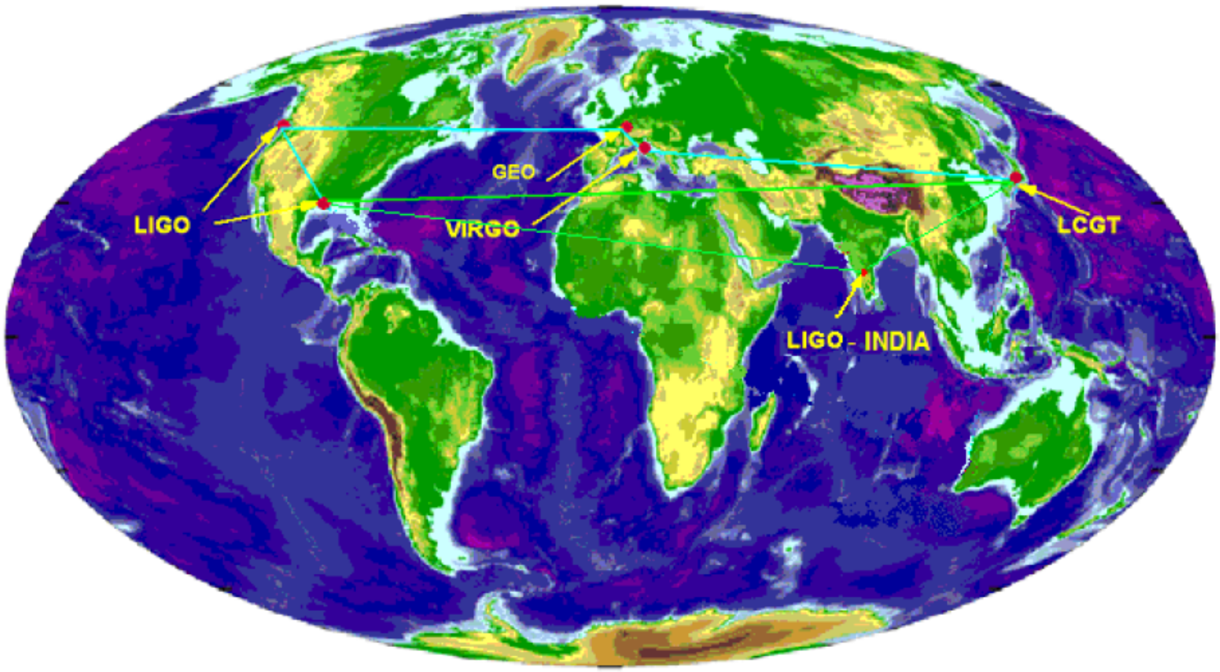
Laser Interferometer Gravitational-wave Detectors: Advancing toward a Global Network



Stan Whitcomb
LIGO/Caltech

ICGC, Goa, 18 December 2011

LIGO-G1101272-v1

Outline

- The Challenge of GW Detection
  - » What has been accomplished?
  - » What comes next?
- A peek at Results from First Generation
- Importance of a Global Network
  - » What do we need?
  - » What do we have?
- LIGO-India
  - » A new opportunity

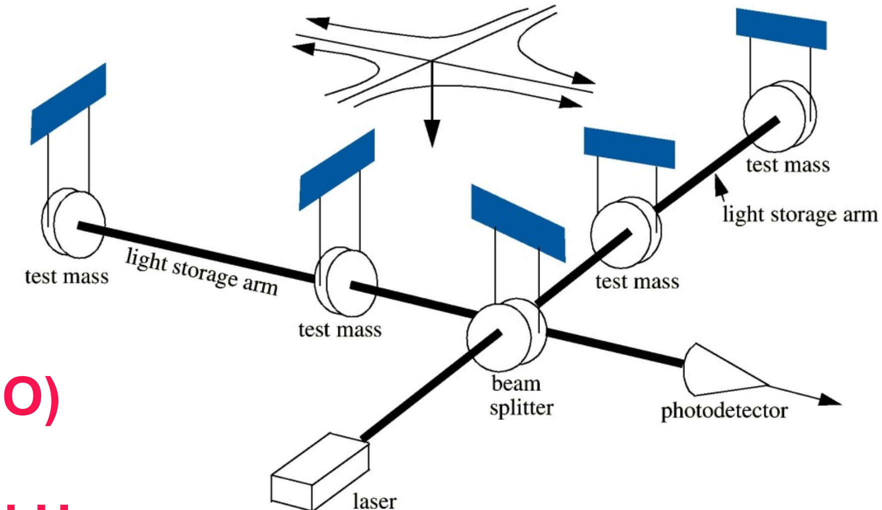
Caveat: Ground-based interferometers

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses

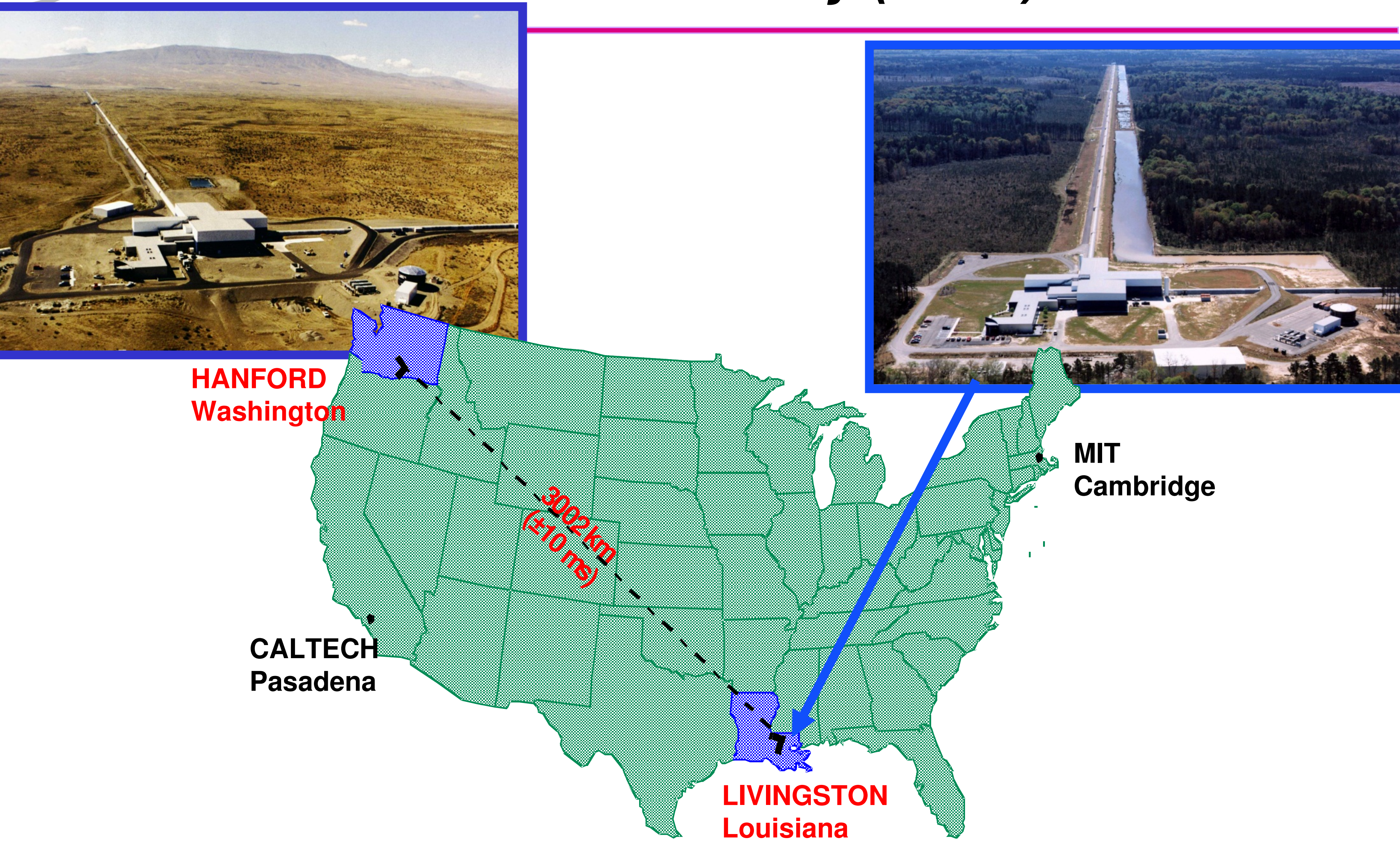
in horizontal plane for frequencies $f >> f_{pend}$

$$h = \Delta L / L$$



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

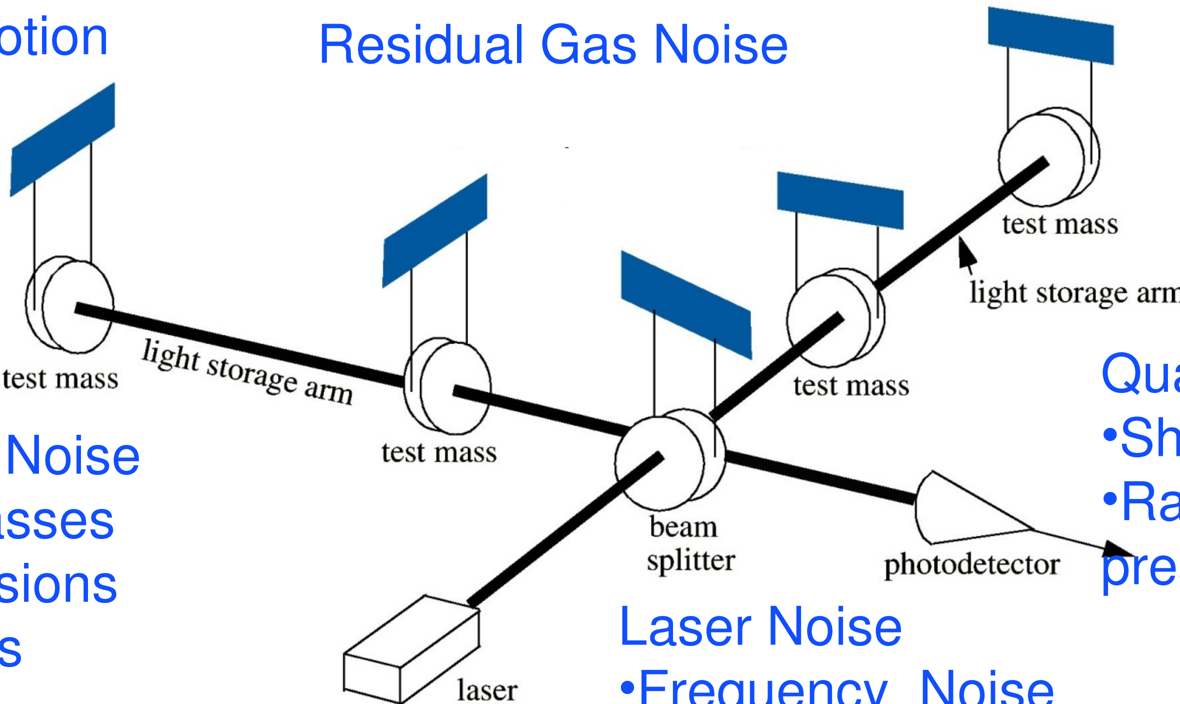
Laser Interferometer Gravitational-wave Observatory (LIGO)



Limits to Sensitivity

Vibrational Noise
•Ground motion
•Acoustic

Residual Gas Noise

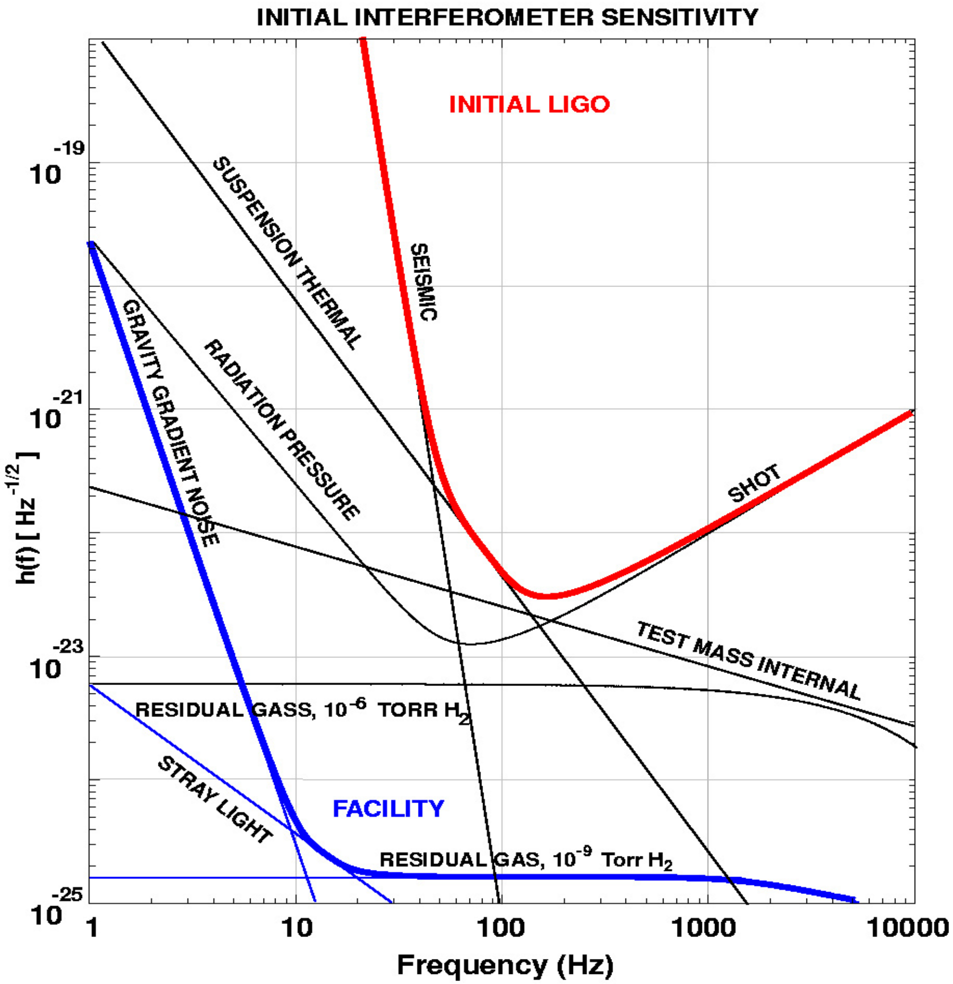


Thermal Noise
•Test masses
•Suspensions
•Coatings

Quantum Noise
•Shot Noise
•Radiation pressure Noise

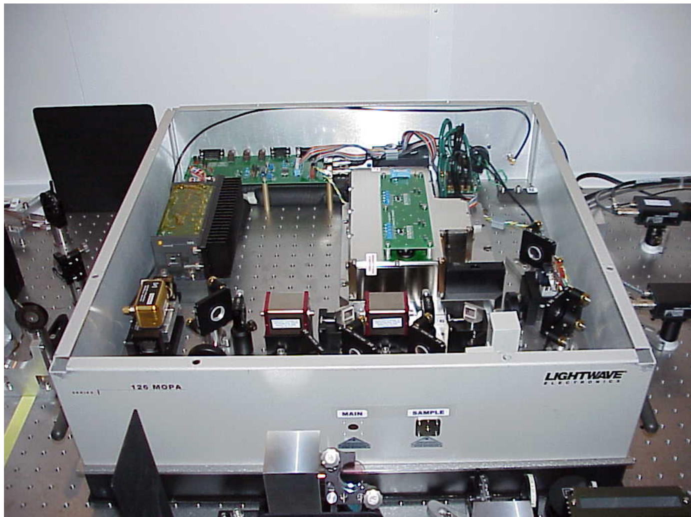
Laser Noise
•Frequency Noise
•Intensity Noise

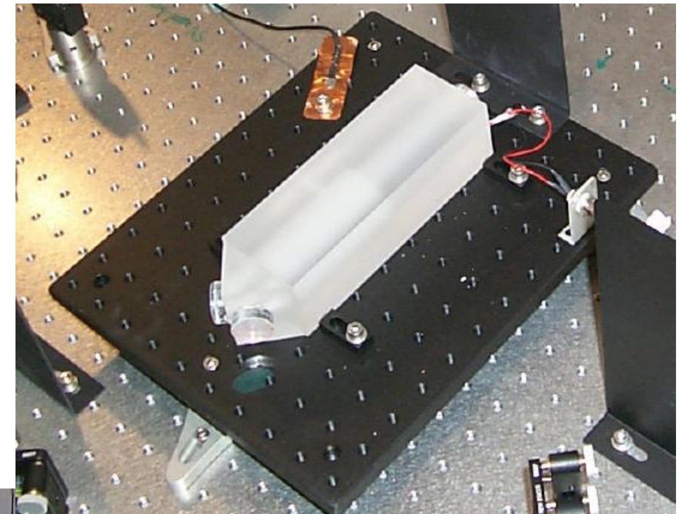
Initial LIGO Sensitivity Goal



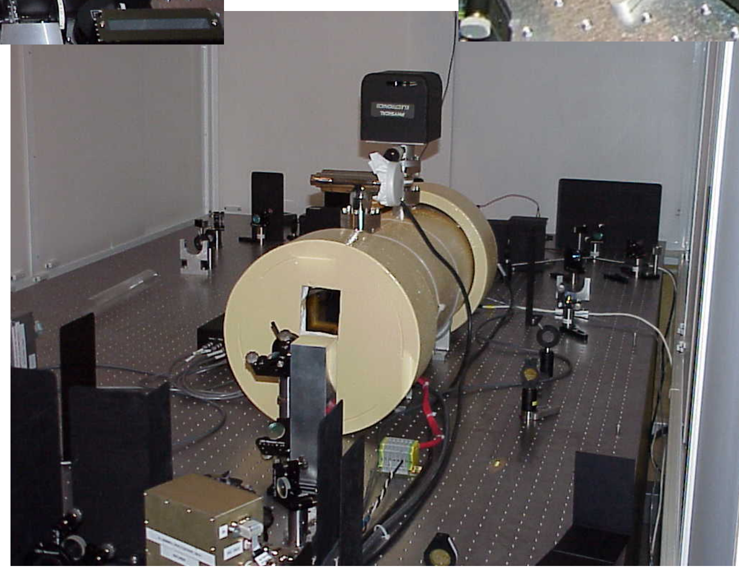
- Strain sensitivity $<3\times10^{-23}$ 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

Initial LIGO Laser



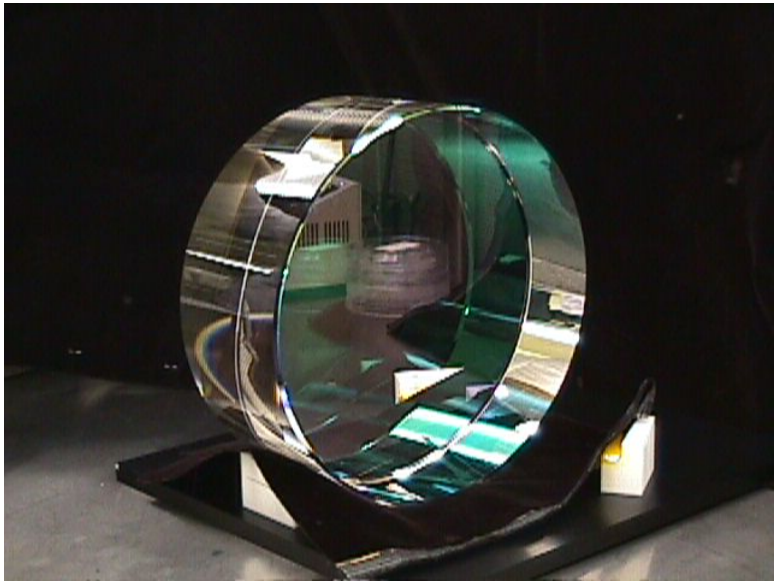


Custom-built
10 W
Nd:YAG
Laser



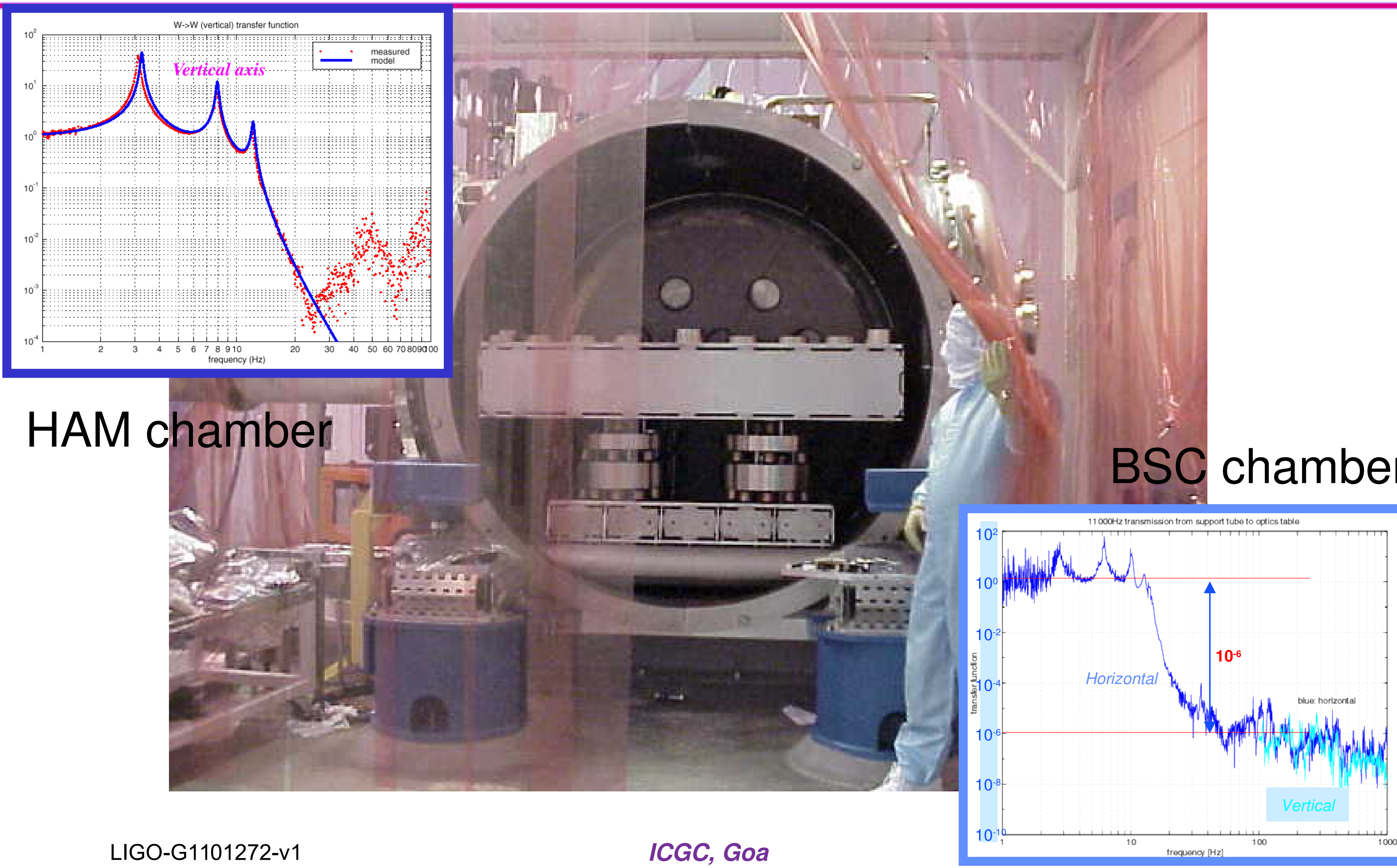
Stabilization
cavities
for frequency
and beam shape

Initial LIGO Mirrors



- Substrates: SiO_2
  - » 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 (λ / 1000)
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}
- Production involved 5 companies, CSIRO, NIST, and LIGO

Initial LIGO Vibration Isolation

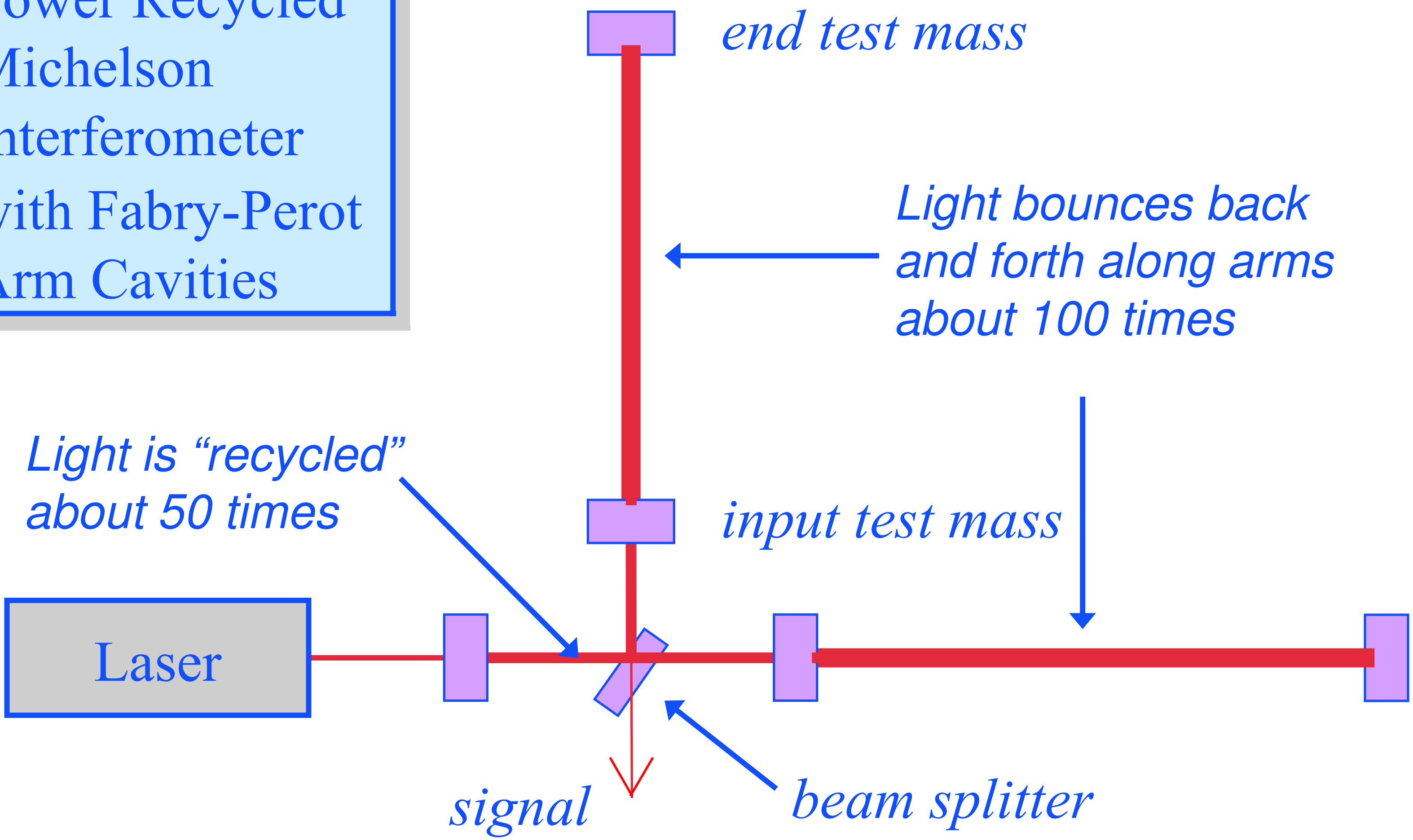


Initial LIGO Test Mass Suspension

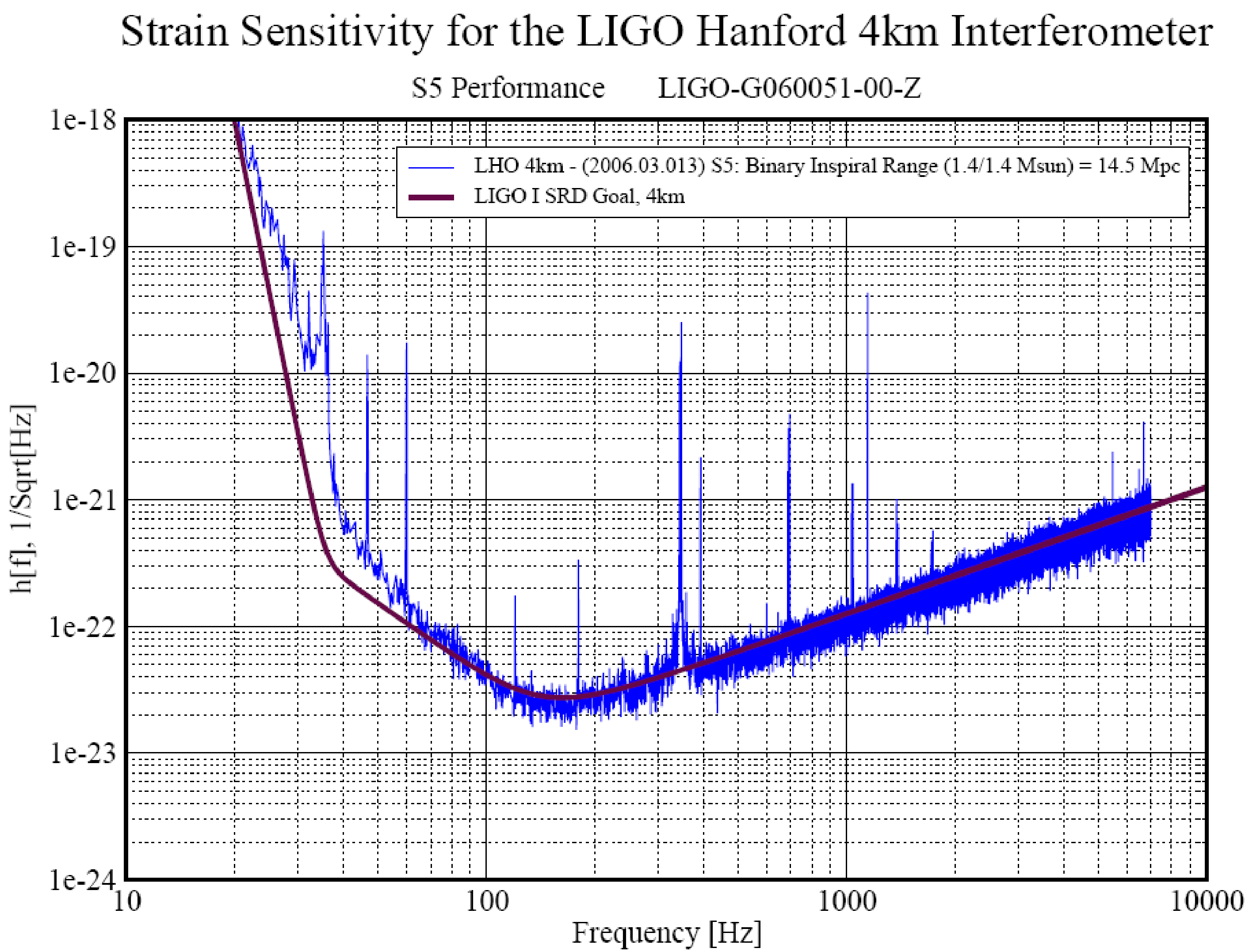
- Simple single-loop pendulum suspension
- Low loss steel wire
  - » Adequate thermal noise performance, but little margin
- Magnetic actuators for control

Initial LIGO Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



Initial LIGO Sensitivity



Results from Initial Detectors: Some highlights from LIGO and Virgo

Several ~year long science data runs by LIGO and Virgo

Since 2007 all data analyzed jointly

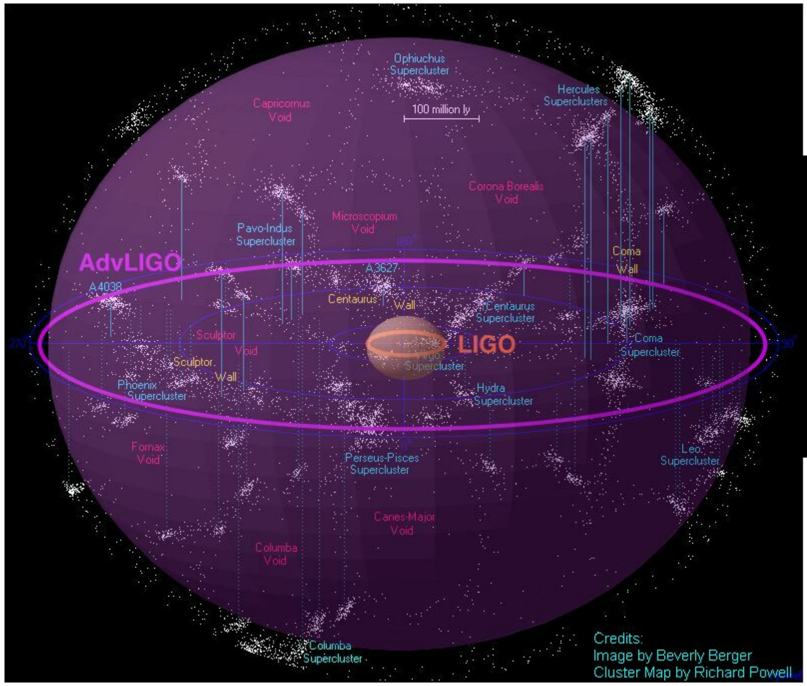
Virgo

LSC

- Limits on GW emission from known msec pulsars
  - » Crab pulsar emitting less than 2% of available spin-down energy in gravitational waves
- Limits on compact binary (NS-NS, NS-BH, BH-BH) coalescence rates in our local neighborhood (~20 Mpc)
- Limits on stochastic background in 100 Hz range
  - » Limit beats the limit derived from Big Bang nucleosynthesis

Advanced LIGO

- Take advantage of new technologies and continuing R&D
- Reuse facilities, vacuum system
- Replace all three initial LIGO detectors



x10 better amplitude sensitivity

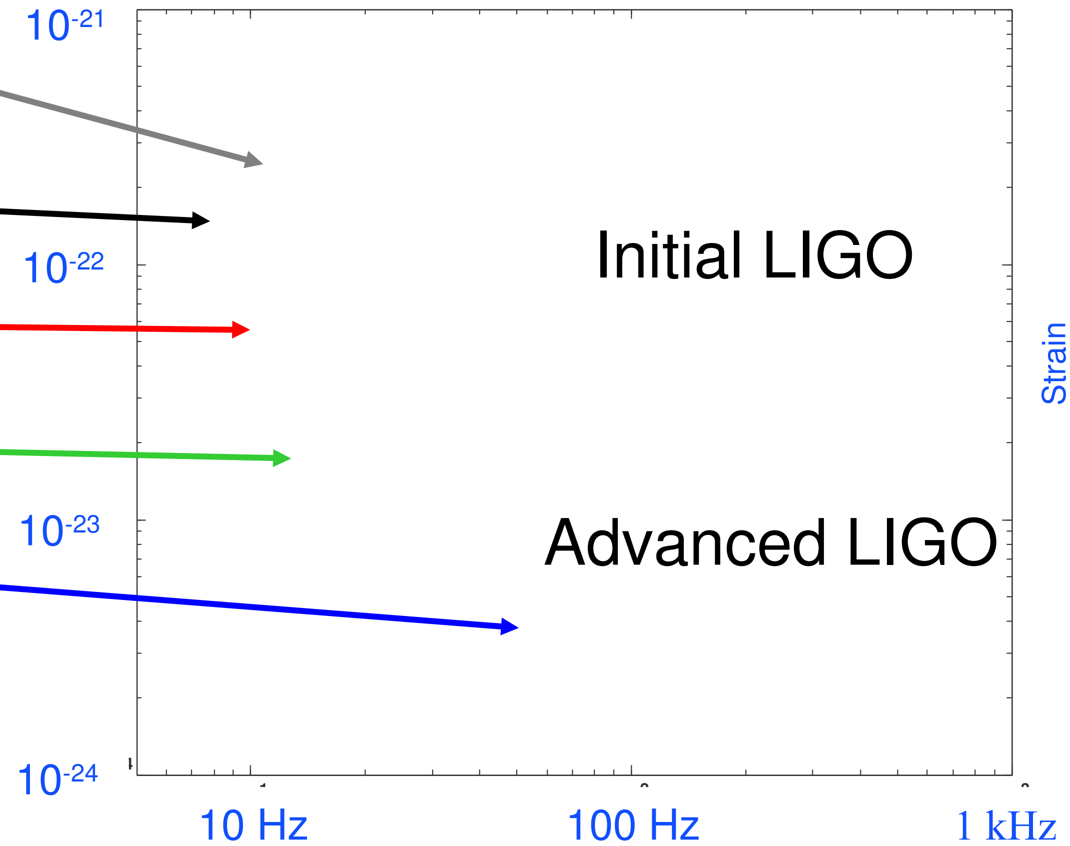
$\Rightarrow$ x1000 rate=(reach)^3

$\Rightarrow$ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

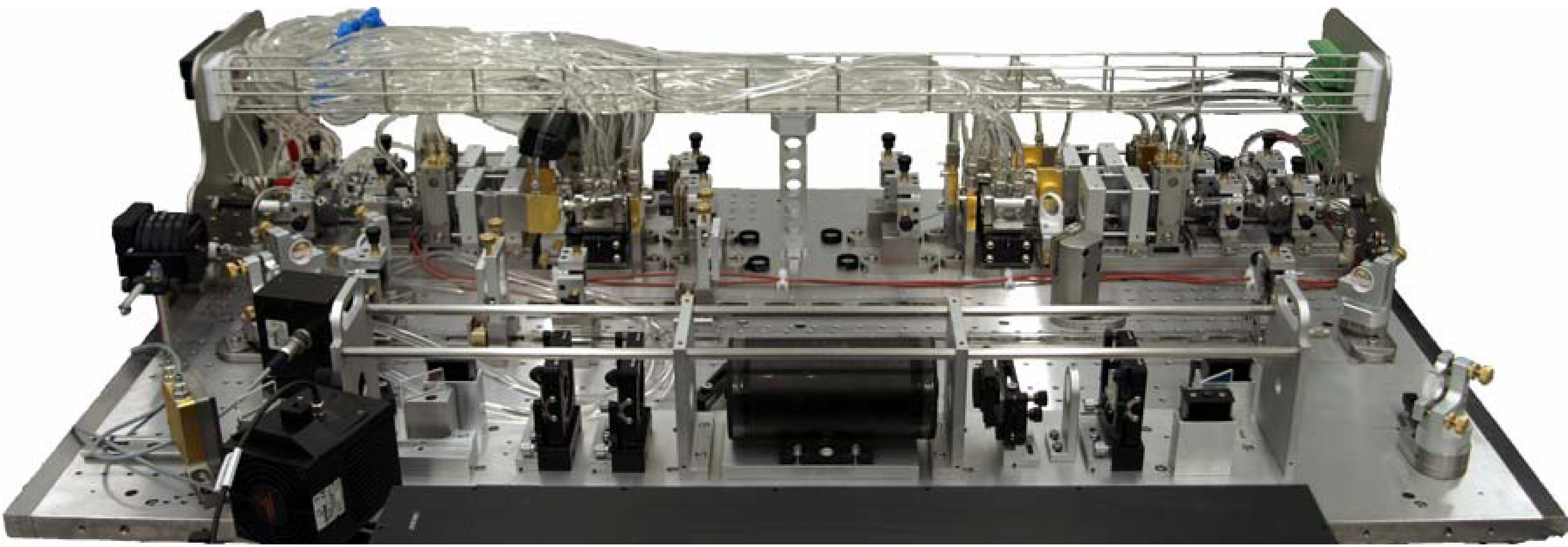
Advanced LIGO Performance

- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Quantum noise dominates at most frequencies

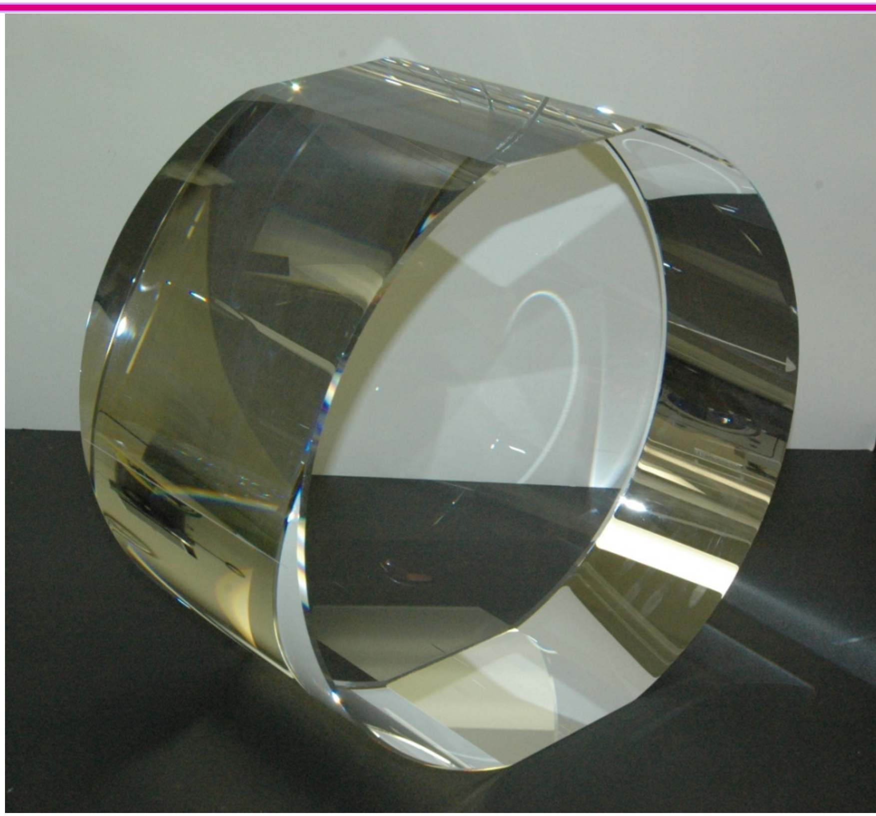


Advanced LIGO Laser

- Designed and contributed by Albert Einstein Institute
- Higher power
  - » 10W -> 180W
- Better stability
  - » 10x improvement in intensity and frequency stability



Advanced LIGO Mirrors

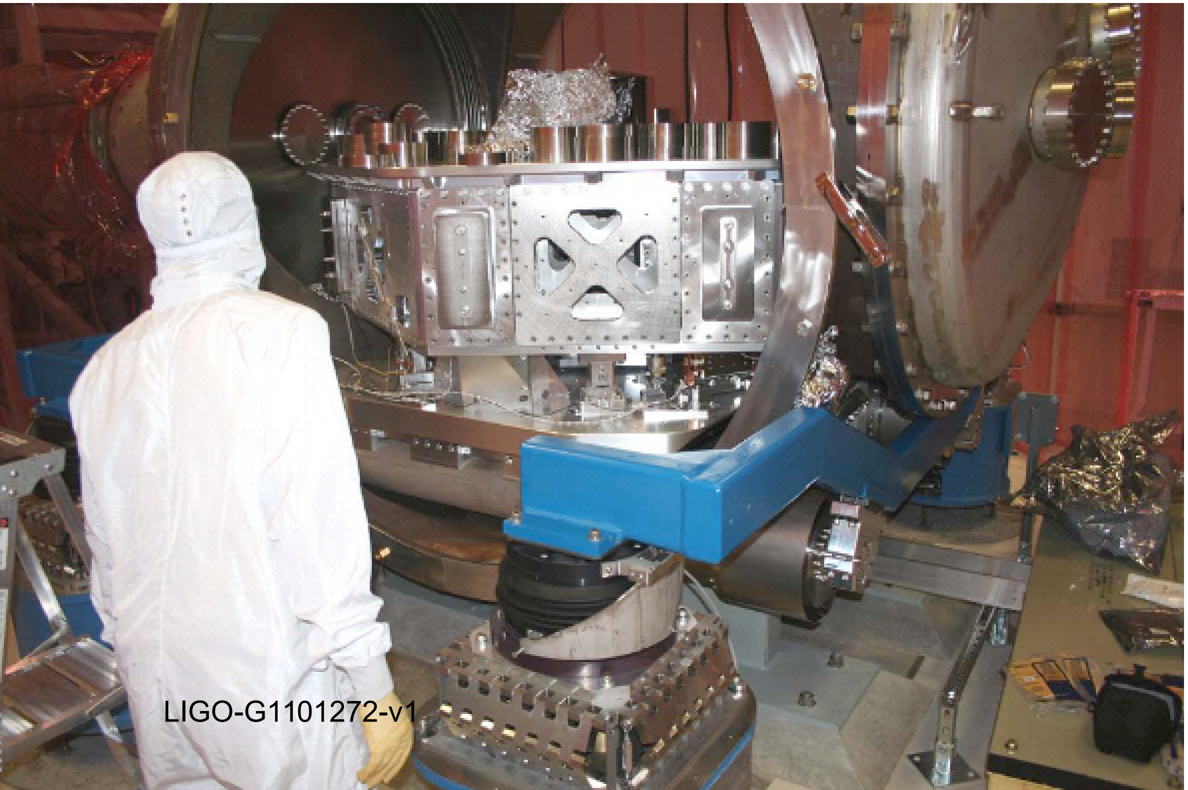


- Larger size
  - » 11 kg -> 40 kg
- Smaller figure error
  - » 0.7 nm -> 0.35 nm
- Lower absorption
  - » 2 ppm -> 0.5 ppm
- Lower coating thermal noise

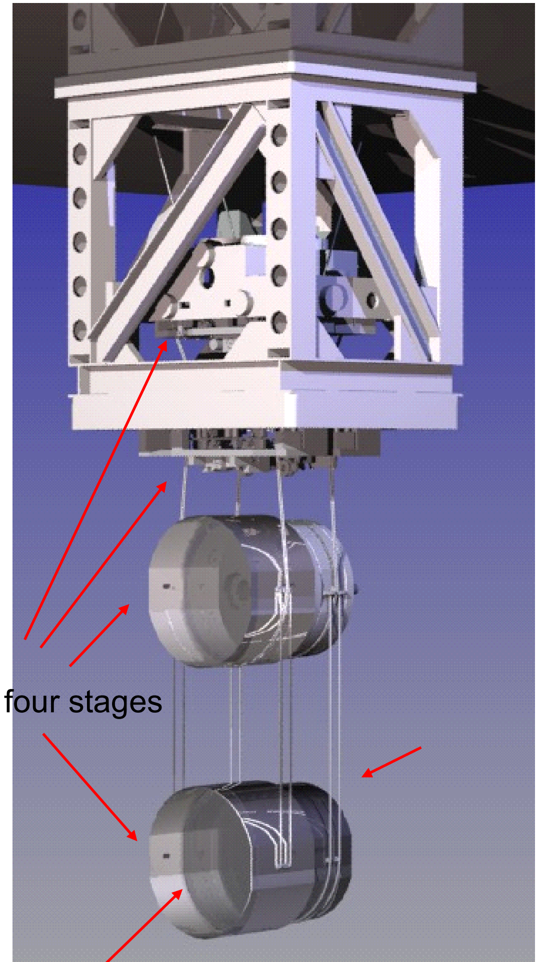
- All substrates delivered
- Polishing underway
- Reflective coating process underway

Advanced LIGO Seismic Isolation

- Two-stage six-degree-of-freedom active isolation
  - » Low noise sensors, Low noise actuators
  - » Digital control system to blend outputs of multiple sensors, tailor loop for maximum performance
  - » Low frequency cut-off: 40 Hz -> 10 Hz



Advanced LIGO Suspensions



four stages

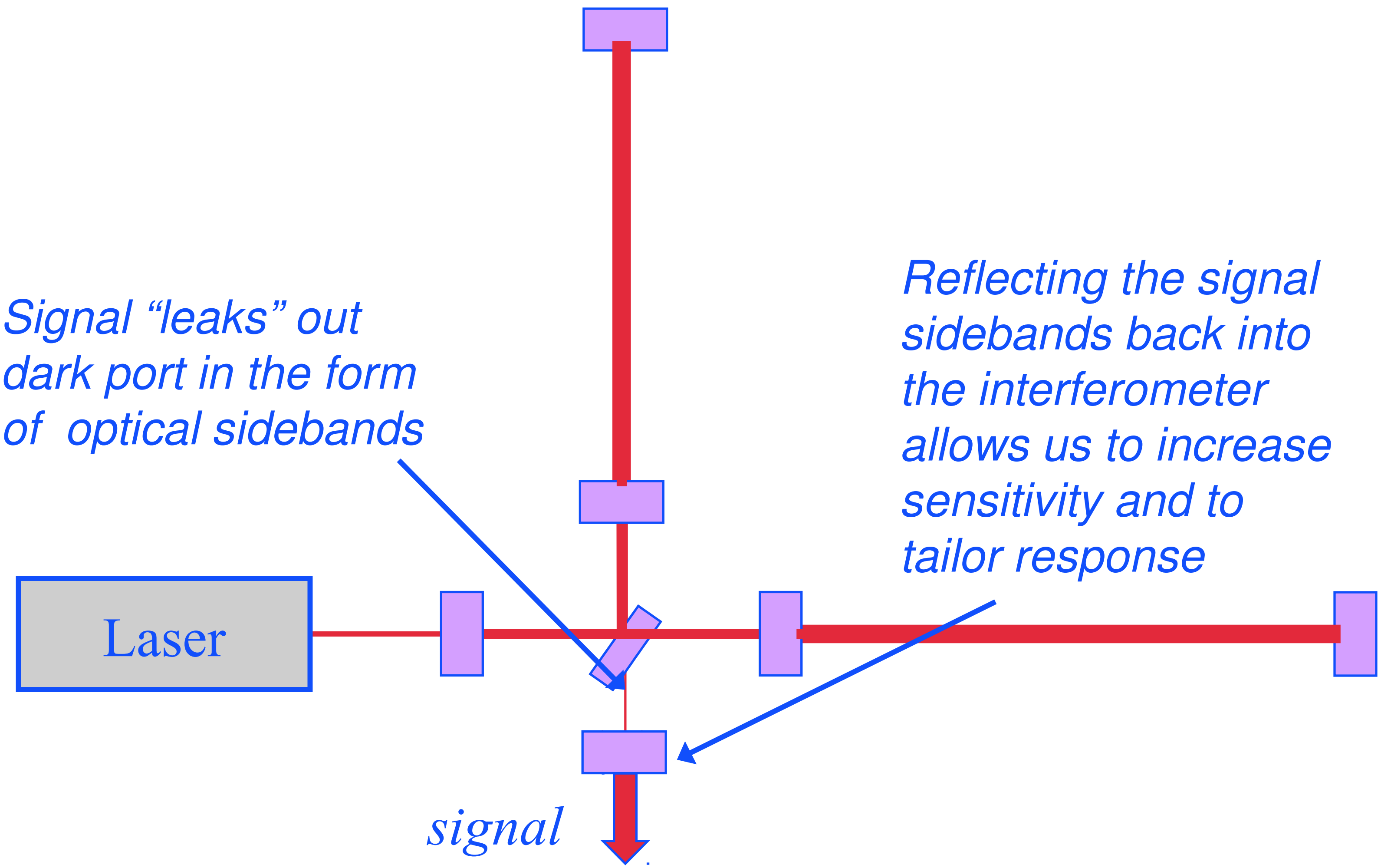
40 kg silica
test mass

- UK designed and contributed test mass suspensions
- Silicate bonds create quasi-monolithic pendulums using ultra-low loss fused silica fibers to suspend interferometer optics
  - » Pendulum Q ~10^5 -> ~10^8
- Electrostatic actuators for alignment and length control

Advanced LIGO Optical Configuration

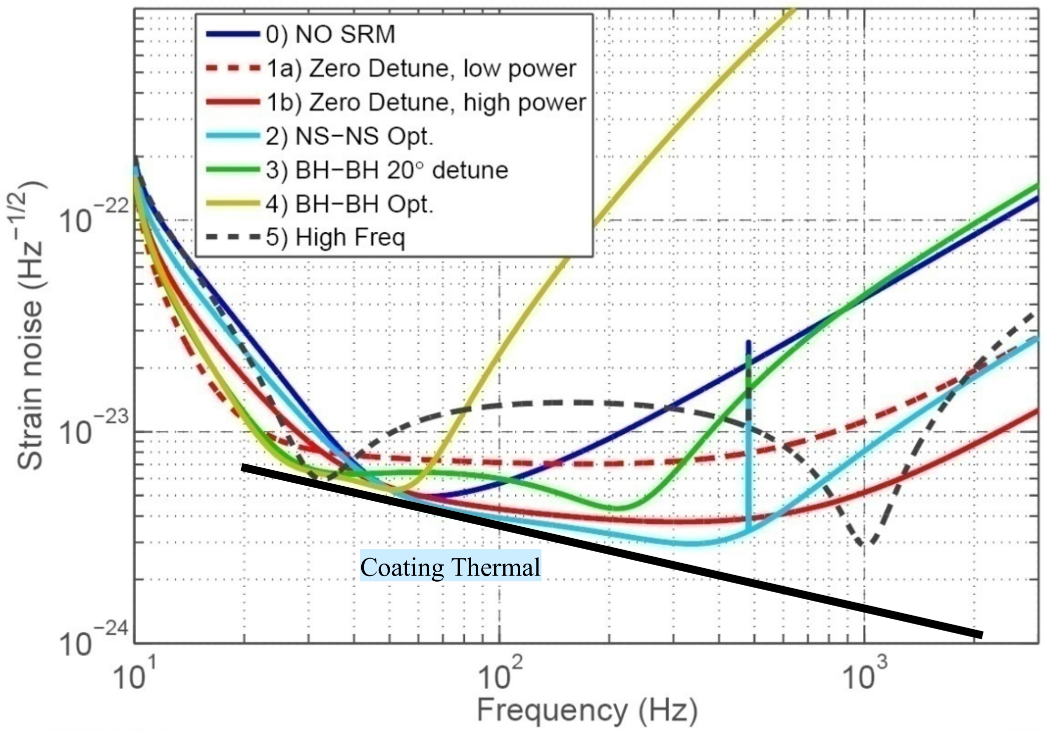
Signal "leaks" out dark port in the form of optical sidebands

Reflecting the signal sidebands back into the interferometer allows us to increase sensitivity and to tailor response



Tailoring the Sensitivity

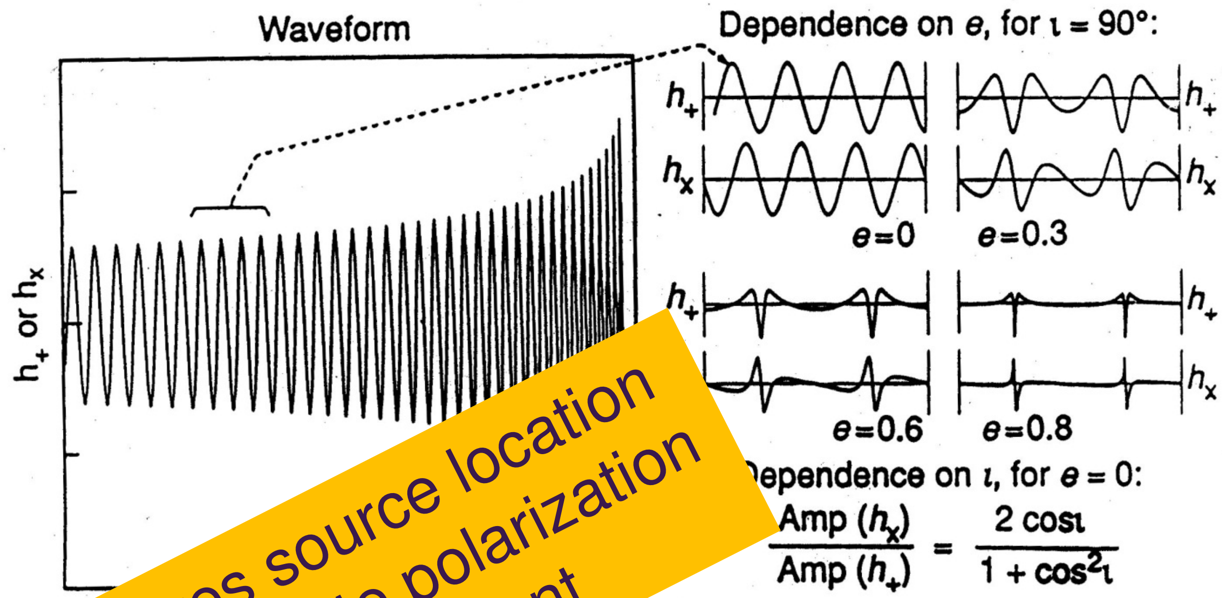
- Flexibility of tuning will allow a range of responses
- Tuning involves microscopic tuning of signal recycling mirror location (controls the frequency of maximum sensitivity) and tuning of signal recycling mirror reflectivity (controls width of sensitive frequency region)



Using GWs to Learn about the Sources: an Example

Chirp Signal

binary inspiral

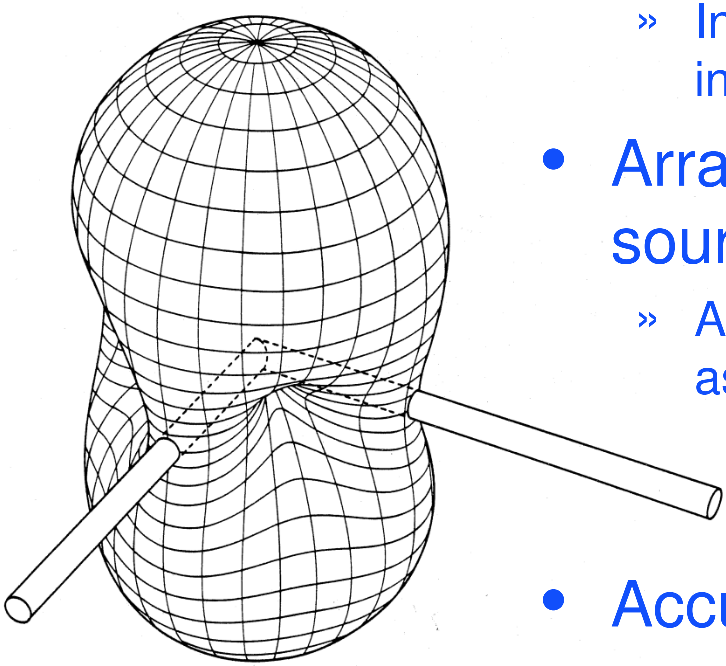


Requires source location and complete polarization measurement

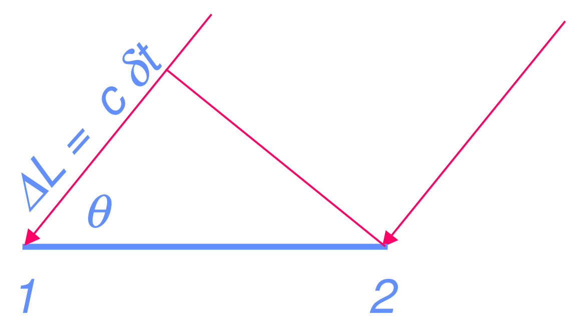
...termine

- **Dist... om the earth r**
- **Mass... s of the two bodies**
- **Orbital eccentricity e and orbital inclination *i***

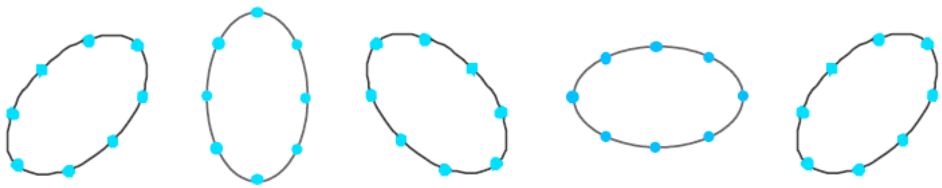
A Global Array of GW Detectors: Source Localization



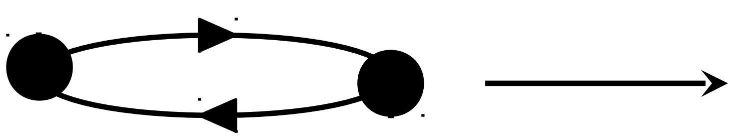
- Detectors are nearly omni-directional
  - Individually they provide almost no directional information
- Array working together can determine source location
  - Analogous to “aperture synthesis” in radio astronomy
- Accuracy tied to diffraction limit

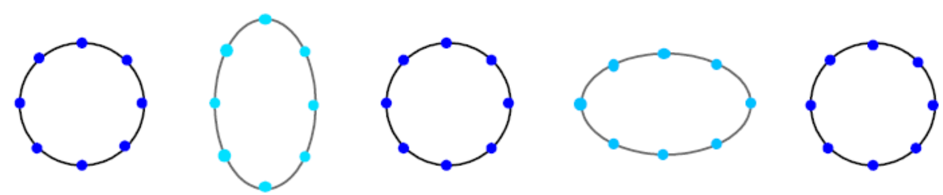


A Global Array of GW Detectors: Polarization Coverage

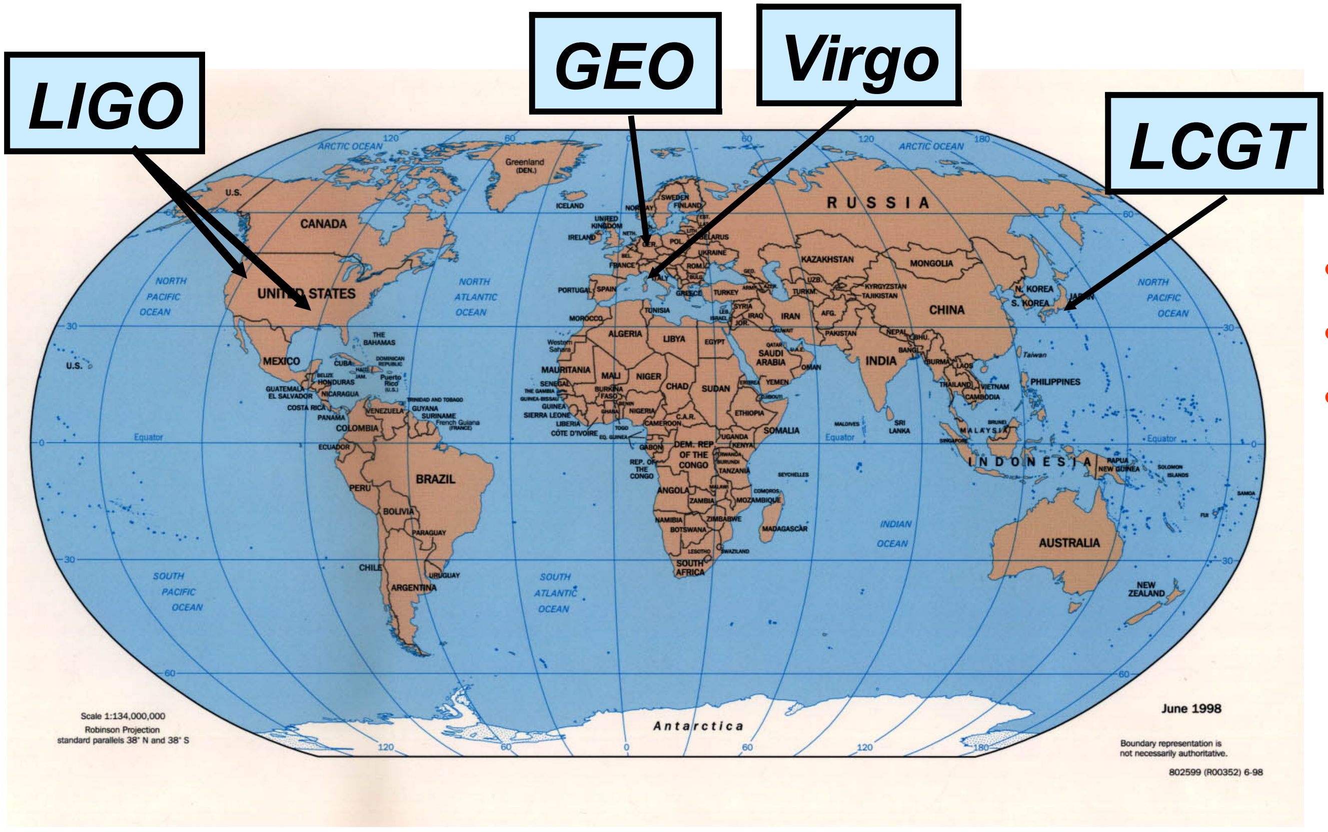


- Sources are polarized
  - » Need complete polarization information to extract distances, energies, other details of sources
- Detectors are polarization selective
  - » Completely insensitive to one linear polarization
- Must have a three dimensional array of detectors to extract maximum science





A Global Array of GW Detectors



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

Virgo

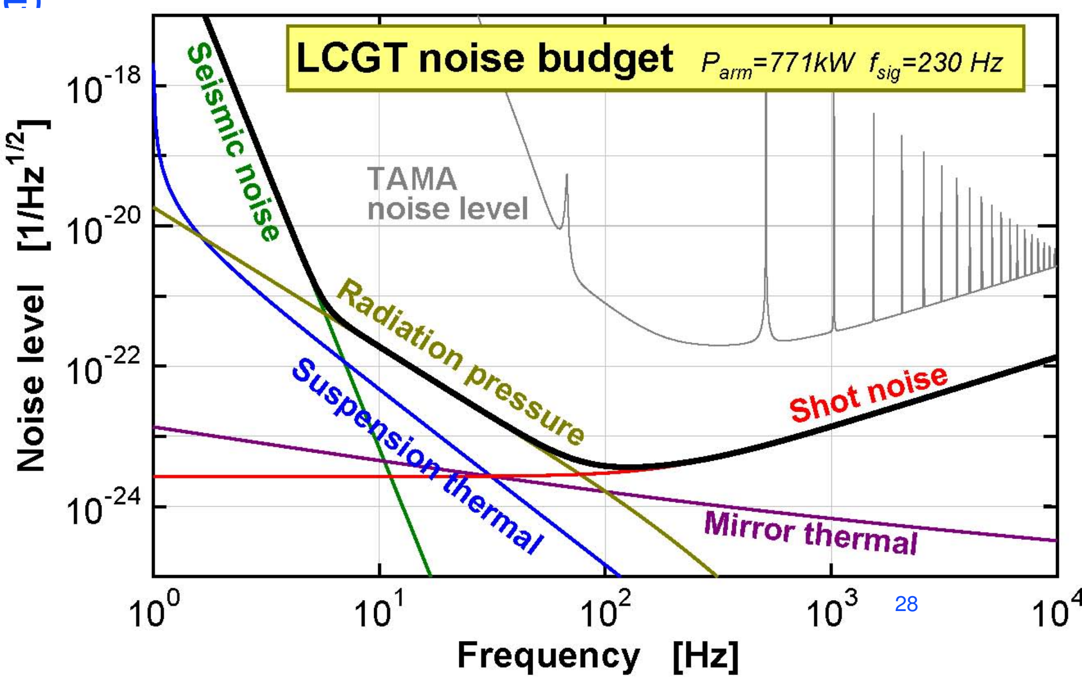
- Virgo
  - » European collaboration, located near Pisa
  - » Single 3 km interferometer, similar to LIGO in design and specification
  - » Advanced seismic isolation system (“Super-attenuator”)
- Advanced Virgo
  - » Similar in scope and schedule to Advanced LIGO
- Joint observations with LIGO since May 2007

GEO

- GEO Collaboration
  - GEO as a whole is a member of the LIGO Scientific Collaboration
  - GEO making a capital contribution to Advanced LIGO
- GEO600
  - Near Hannover
  - 600 m arms
  - Signal recycling
  - Fused silica suspensions
- GEO-HF
  - Up-grade underway
  - Pioneer advanced optical techniques

Large Cryogenic Gravitational-wave Telescope (LCGT)

- Project approved July 2010
- LCGT Project
  - » Lead institution: Institute for Cosmic Ray Research
  - » Other participants include University of Tokyo, National Astronomical Observatory of Japan, KEK, …
- Key Design Parameters
  - » Underground (Kamioka mine)
  - » Sapphire test masses cooled to <20K
  - » 150W Nd:YAG laser
  - » Five stage low frequency (soft) suspension
  - » Promises sensitivity similar to Advanced LIGO

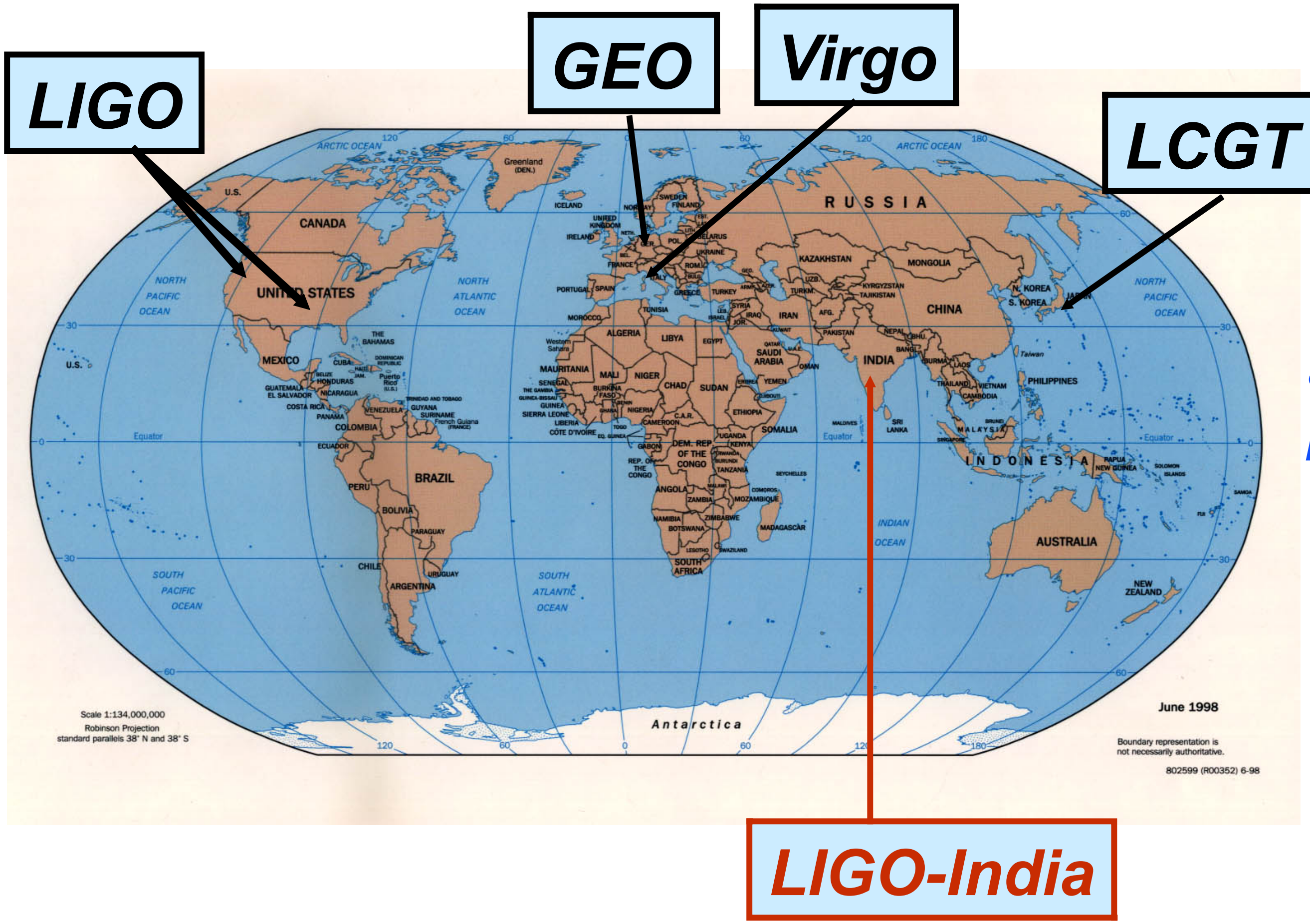


Large Cryogenic Gravitational-wave Telescope

Large Cryogenic Gravitational-wave Telescope (LCGT)

- LCGT project schedule
  - ~$100M approved for LCGT construction June 2010, no tunneling and cryogenic costs (~$60M)
  - Configured project in two stage plan: room temperature operation followed by cryogenic operation
  - Tunnel costs to have been granted April 2011--delayed ~6 months
  - 2017: Start of cryogenic observations

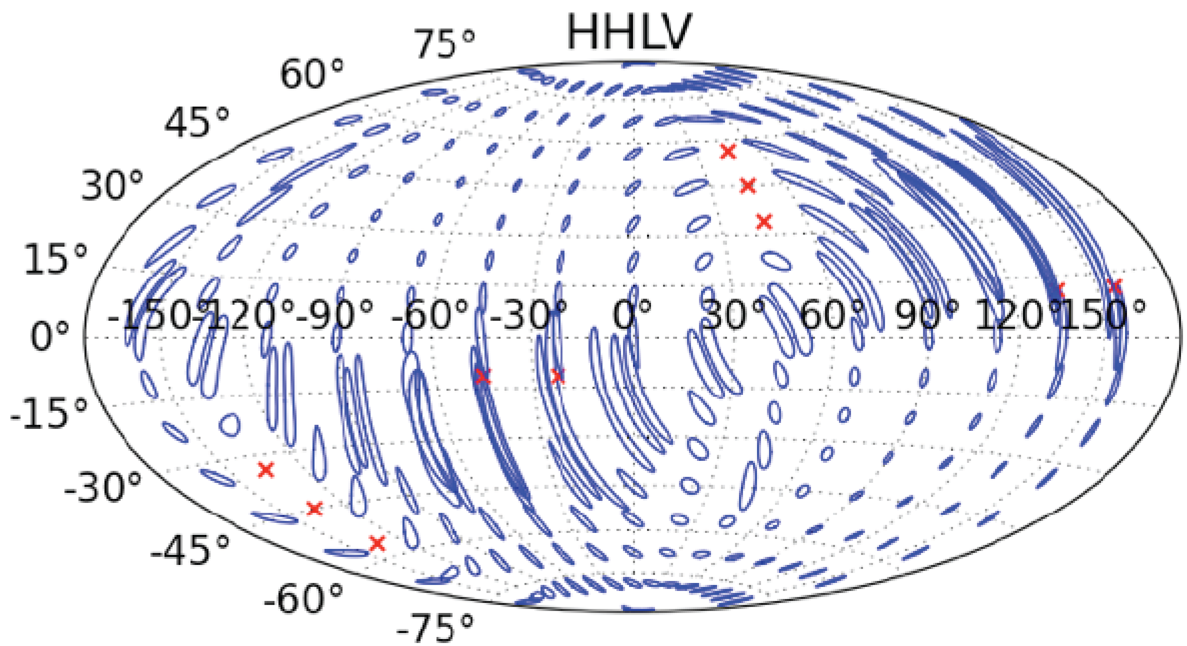
Completing the Global Network



Planned detectors are very close to co-planar—not optimal for all-sky coverage

Large increase to science capability from a southern node in the network

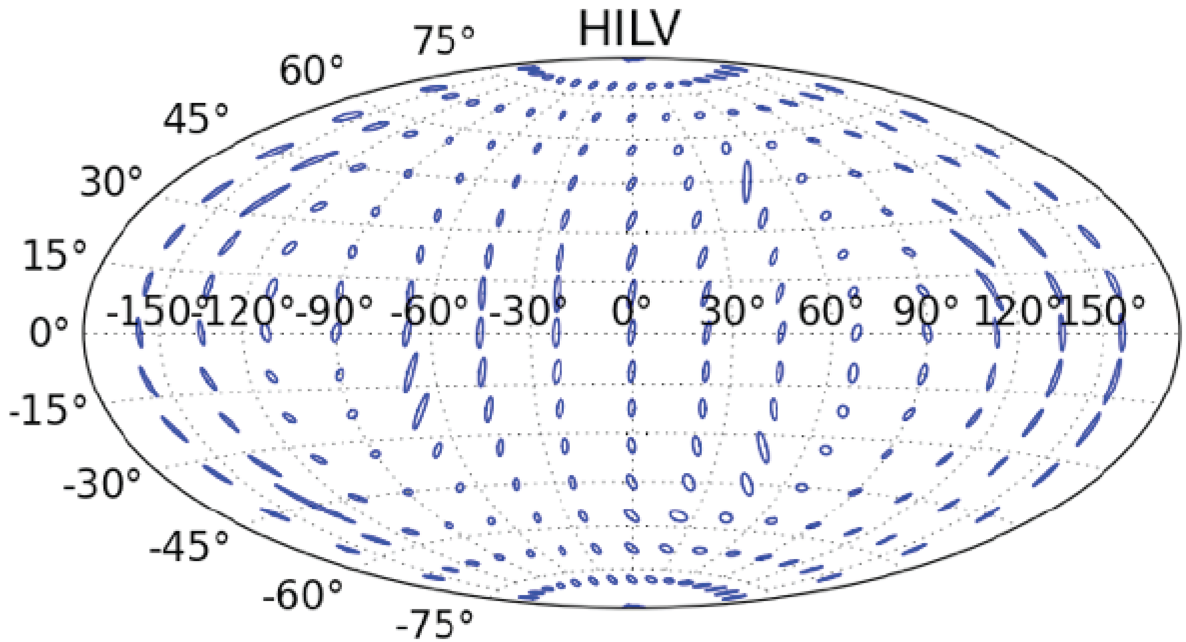
Localization capability: LIGO-Virgo only



Fairhurst 2011

Red crosses denote regions where the network has blind spots

Localization capability: LIGO-Virgo plus LIGO-India



Fairhurst 2011

LIGO-India Concept

- A direct partnership between LIGO Laboratory and IndIGO collaboration to build an Indian interferometer
  - » LIGO Lab (with its UK, German and Australian partners) provides components for one Advanced LIGO interferometer from the Advanced LIGO project
  - » India provides the infrastructure (site, roads, building, vacuum system), “shipping & handling,” staff, installation & commissioning, operating costs
- LIGO-India would be operated as part of LIGO network to maximize scientific impact
- Key deadline: LIGO needs a commitment from India by March 2012—otherwise, LIGO must continue installation at US site

Indian Initiative in Gravitational-wave Observations

- Established in August 2009 to coordinate the Indian GW community to participate in GW research
- Builds on long-standing research efforts of Dhurandhar and Iyer, and recent appointments in India of younger scientists with experience from LIGO and Virgo
- Continues to grow--several new institution this year
- Guided by National Steering Committee and International Advisory Committee
- Recently accepted as LIGO Scientific Collaboration member group
  - » Proposed to establish Tier 2 data center at IUCAA
- Long-term goal to build a GW detector in India

Open Questions about LIGO-India

- Funding
  - » Presented to Planning Commission
  - » Under consideration as a Mega-Science project
- Site
  - » Identify, characterize, acquire
- Identify who will do it
  - » Lead Indian institution?
  - » Project management?
- Formal approvals and agreements

NSF Review of LIGO-India science and motivation

“…the science case for LIGO-India is compelling, …“

Beyond the Advanced Detectors

Advanced LIGO, Advanced Virgo, LCGT
are not the end!

Future detectors will require much further development

- Squeezed light, entanglement, macroscopic quantum mechanical techniques
- Unconventional optics: gratings, cryogenic optics, new shapes
- New materials for substrates and coatings
- New interferometer configurations
- Lasers: higher power, greater stability, new wavelengths

Final Thoughts

- We are on the threshold of a new era of gravitational wave astrophysics
- First generation detectors have broken new ground in optical sensitivity
  - » Initial detectors have proven technique
- Second generation detectors are starting installation
  - » Will expand the “Science” (astrophysics) by factor of 1000
- In the next decade, emphasis will be on the *NETWORK*
  - » Groundwork has been laid for operation as a worldwide network
  - » India could play a key role
- Will continue to drive developments in optical technology and optical physics for many years