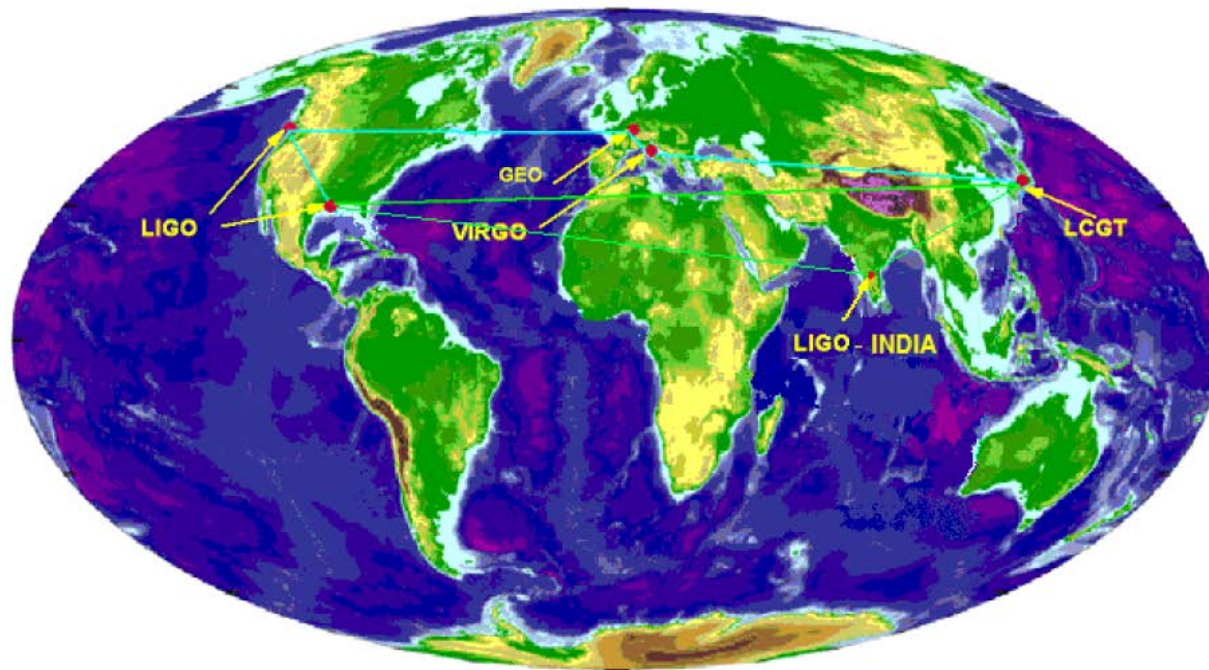


LIGO: On the Threshold of Gravitational-wave Astronomy



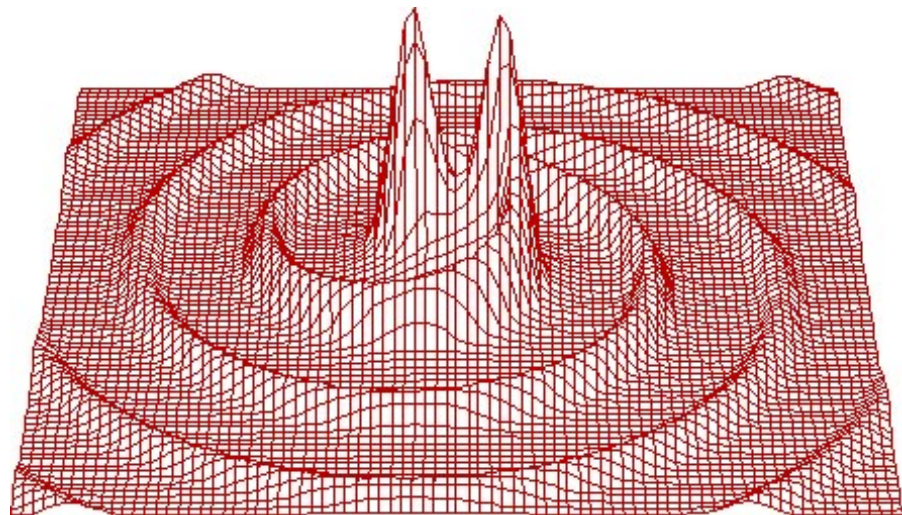
Stan Whitcomb

LIGO/Caltech

IIT, Kanpur 18 December 2011

Outline of Talk

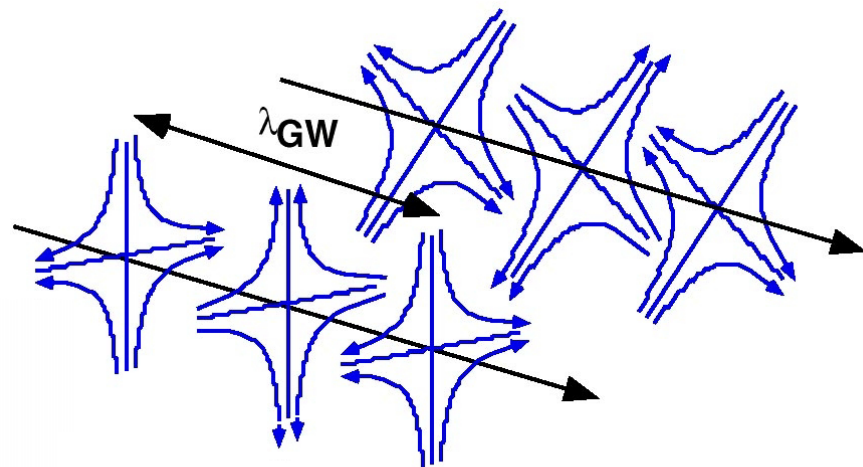
- Quick Review of GW Physics and Astrophysics
- LIGO Overview
 - » Initial Detectors
 - » Initial Results
- The Future
 - » Advanced LIGO
- Importance of a Global Network
- LIGO-India



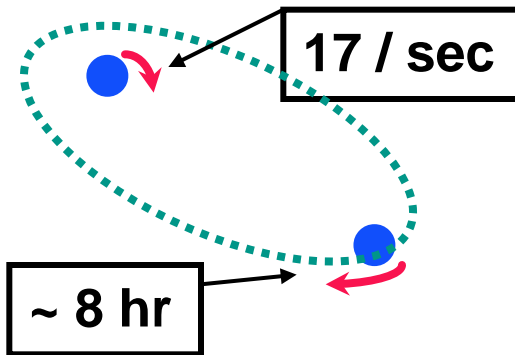
**gravitational radiation
binary inspiral of compact objects
(blackholes or neutron stars)**

- Einstein (in 1916) recognized gravitational waves in his theory of General Relativity
 - » Necessary consequence of Special Relativity with its finite speed for information transfer
 - » Most distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by the acceleration of masses
 - » Propagate away from the sources at the speed of light
 - » Pure transverse waves
 - » Two orthogonal polarizations

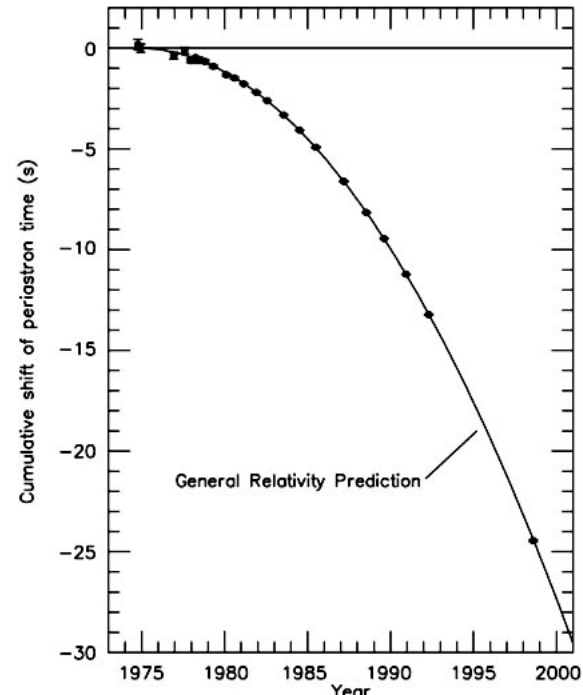
$$h = \Delta L / L$$



Evidence for Gravitational Waves: Binary Pulsar PSR1913+16



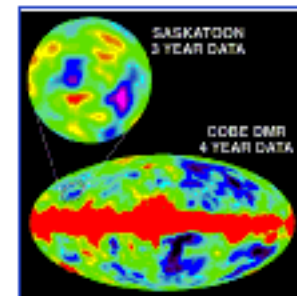
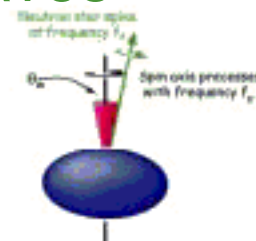
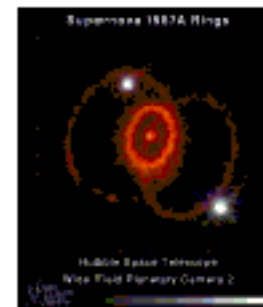
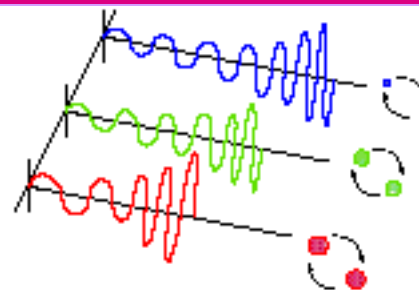
- Discovered by Hulse and Taylor in 1975
- Unprecedented laboratory for studying gravity
 - » Extremely stable spin rate
- Possible to repeat classical tests of relativity (bending of “starlight”, advance of “perihelion”, etc.)



- After correcting for all known relativistic effects, observe loss of orbital energy
=> **Emission of GWs**

Astrophysical Sources for Terrestrial GW Detectors

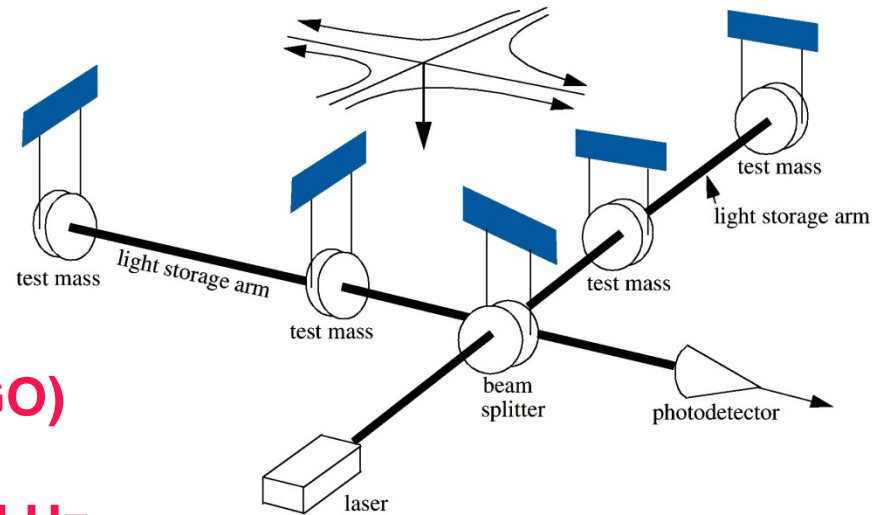
- Compact binary inspiral: “chirps”
 - » NS-NS, NS-BH, BH-BH
- Supernovas or GRBs: “bursts”
 - » GW signals observed in coincidence with EM or neutrino detectors
- Pulsars in our galaxy: “periodic waves”
 - » Rapidly rotating neutron stars
 - » Modes of NS vibration
- Cosmological: “stochastic background”
 - » Probe back to the Planck time (10^{-43} s)



Suspended mirrors act as “freely-falling” test masses in horizontal plane for frequencies $f \gg f_{\text{pend}}$

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

$$h = \Delta L / L$$





Laser Interferometer Gravitational-wave Observatory (LIGO)



HANFORD
Washington

CALTECH
Pasadena

MIT
Cambridge

LIVINGSTON
Louisiana

IIT, Kanpur

3002 km
(± 10 ms)

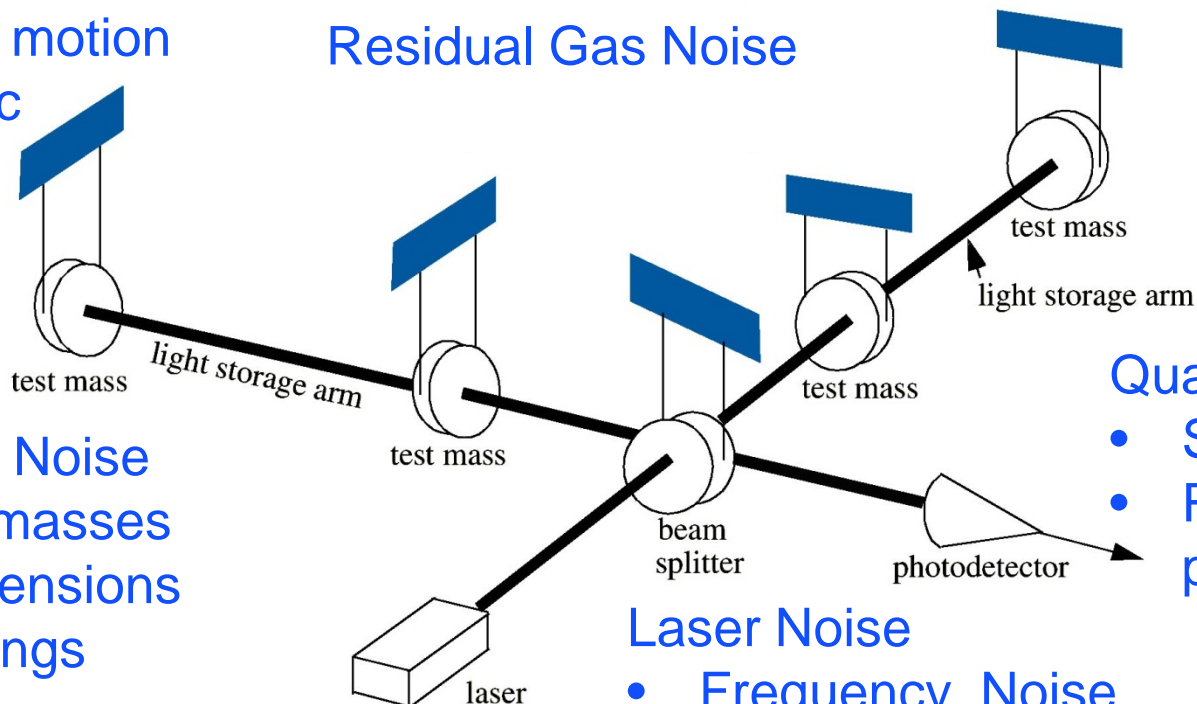
Vibrational Noise

- Ground motion
- Acoustic

Residual Gas Noise

Thermal Noise

- Test masses
- Suspensions
- Coatings



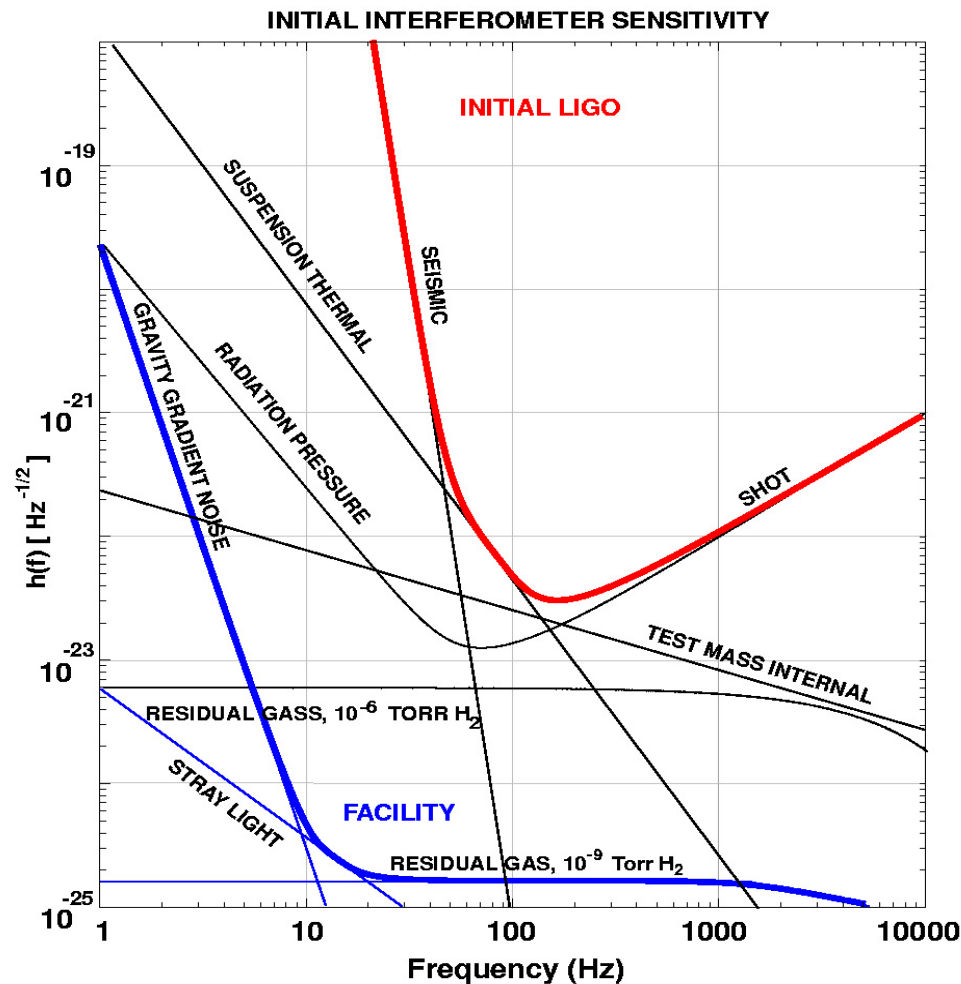
Quantum Noise

- Shot Noise
- Radiation pressure Noise

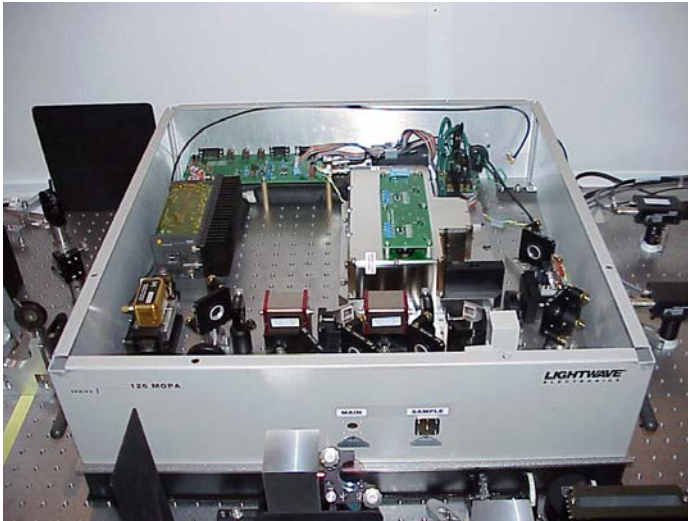
Laser Noise

- Frequency Noise
- Intensity Noise

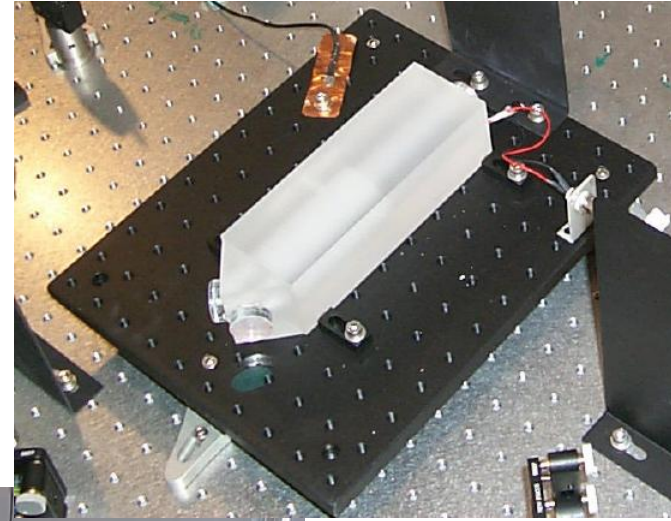
Initial LIGO Sensitivity Goal



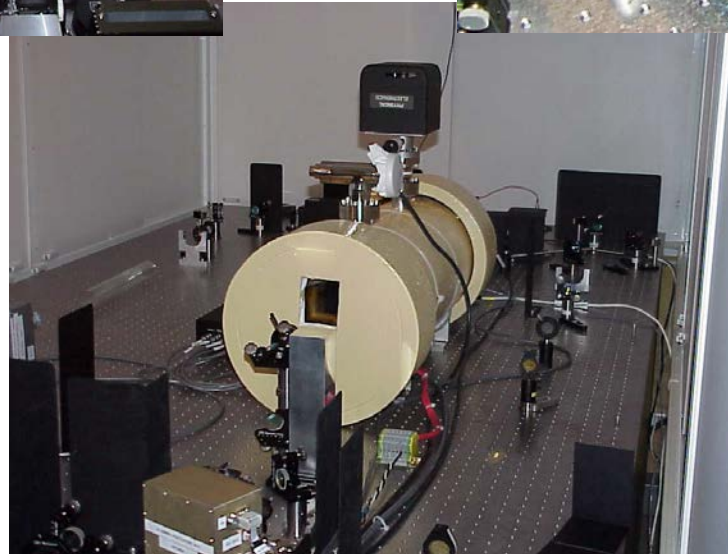
- Strain sensitivity
 $< 3 \times 10^{-23} \text{ 1/Hz}^{1/2}$
 at 200 Hz
- Sensing Noise
 - » Photon Shot Noise
 - » Residual Gas
- Displacement Noise
 - » Seismic motion
 - » Thermal Noise
 - » Radiation Pressure



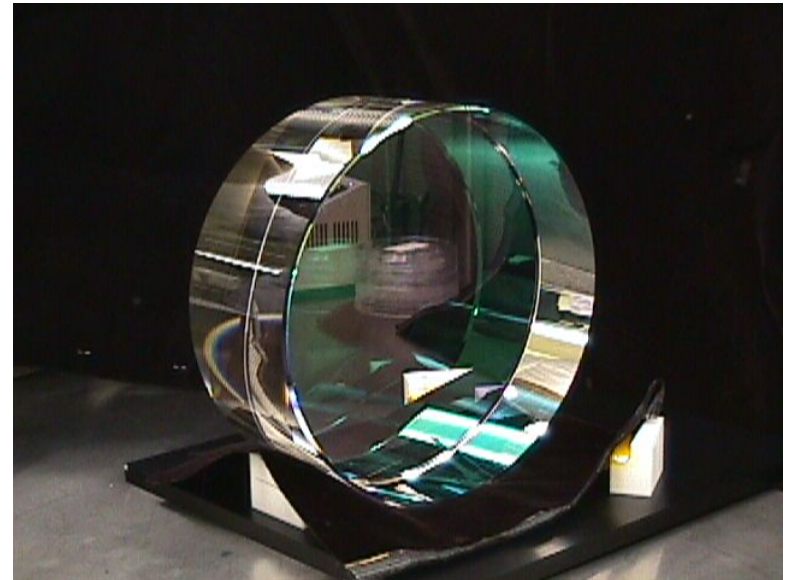
Custom-built
10 W
Nd:YAG
Laser

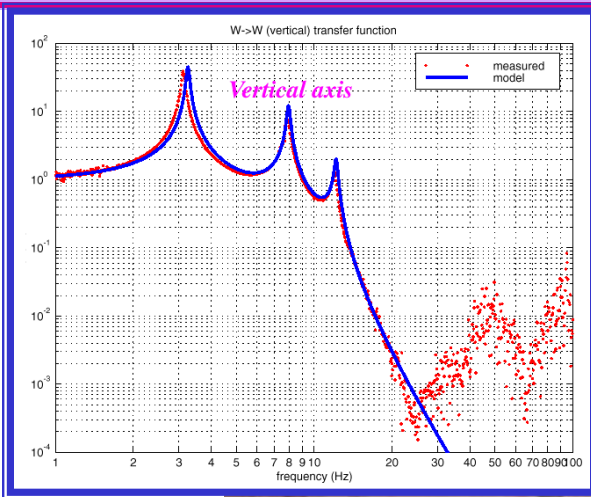


Stabilization
cavities
for frequency
and beam shape

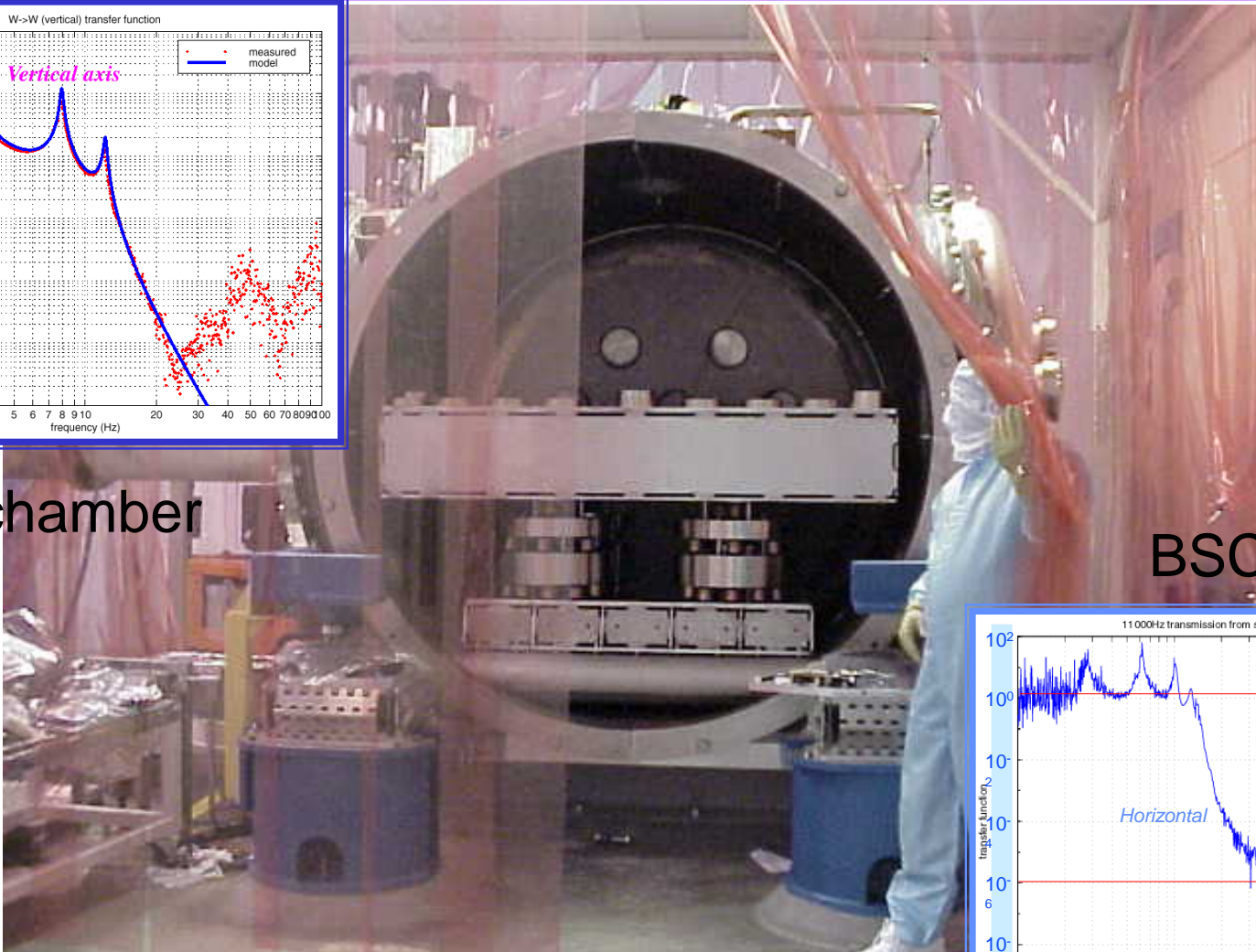


- Substrates: SiO_2
 - » 25 cm Diameter, 10 cm thick
 - » Homogeneity $< 5 \times 10^{-7}$
 - » Internal mode Q's $> 2 \times 10^6$
- Polishing
 - » Surface uniformity $< 1 \text{ nm rms}$
($\lambda / 1000$)
 - » Radii of curvature matched $< 3\%$
- Coating
 - » Scatter $< 50 \text{ ppm}$
 - » Absorption $< 2 \text{ ppm}$
 - » Uniformity $< 10^{-3}$
- Production involved 5 companies, CSIRO, NIST, and LIGO

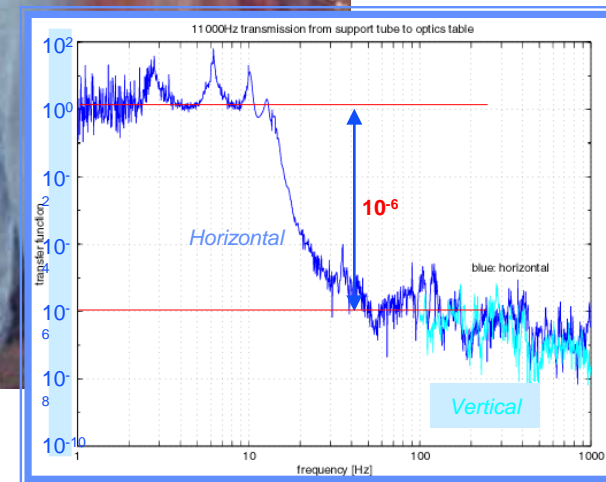




HAM chamber



BSC chamber



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



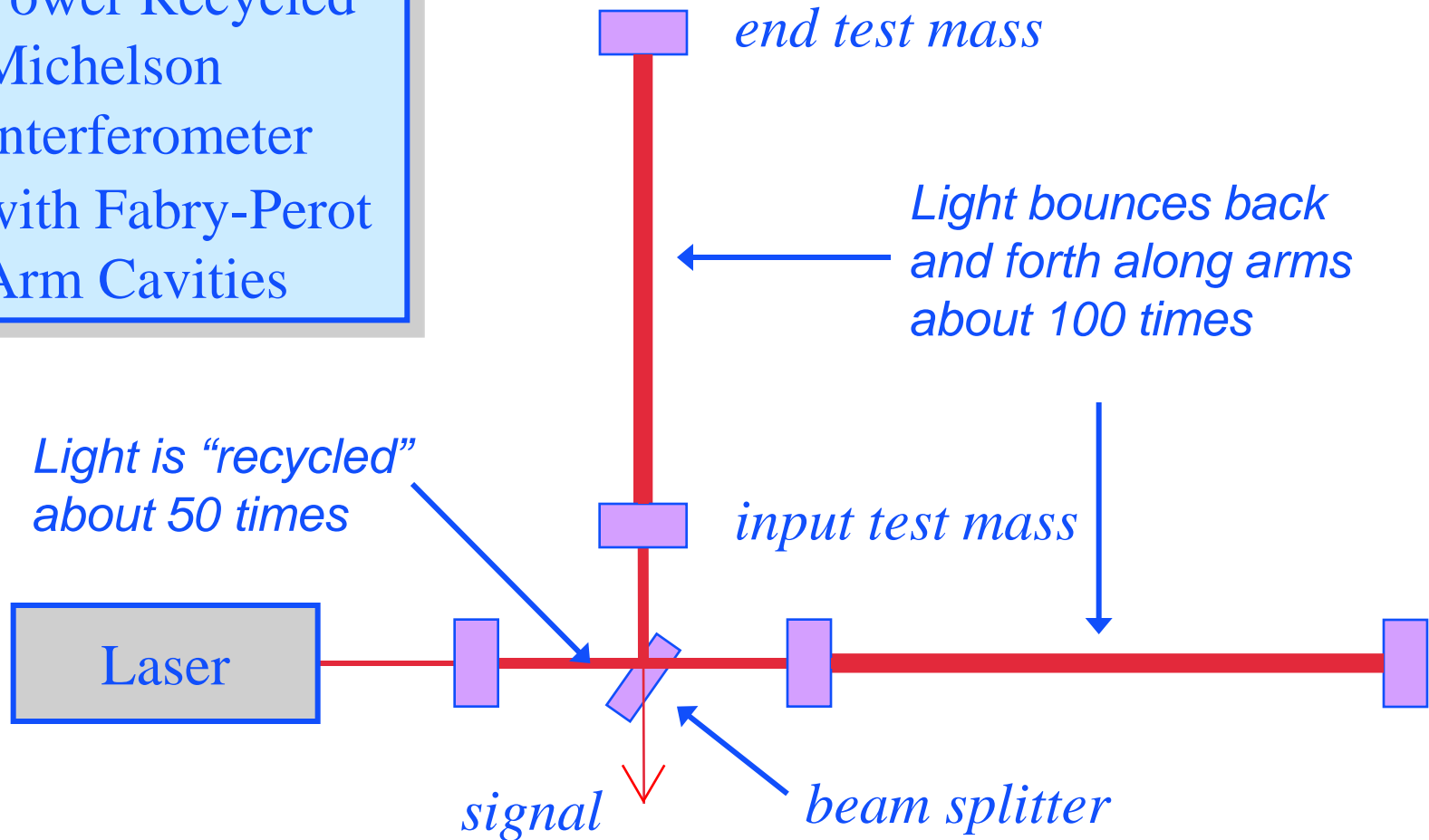
LIGO-G1401143-v1

IIT, Kanpur



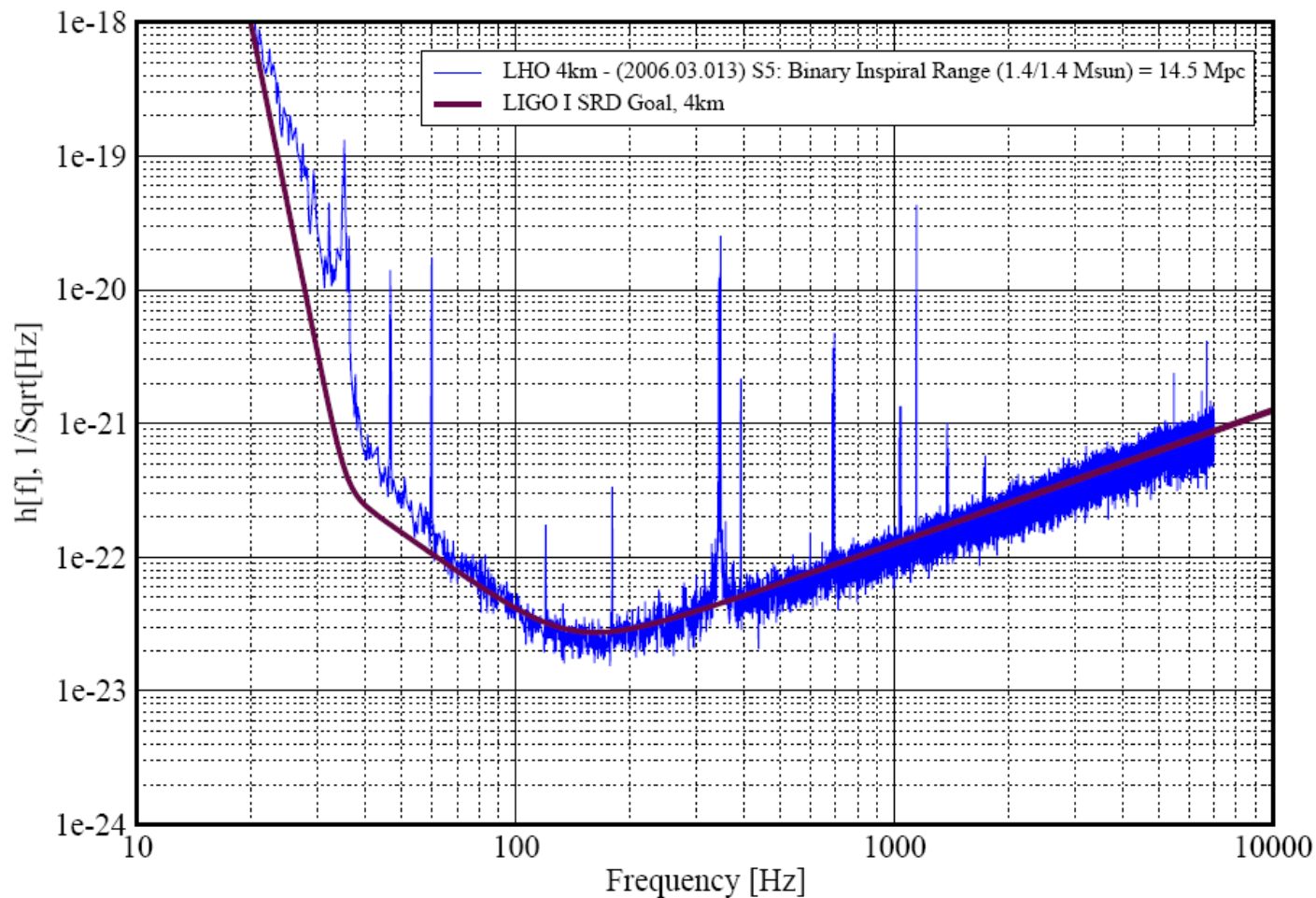
Initial LIGO Optical Configuration

Power Recycled
Michelson
Interferometer
with Fabry-Perot
Arm Cavities



Strain Sensitivity for the LIGO Hanford 4km Interferometer

S5 Performance LIGO-G060051-00-Z



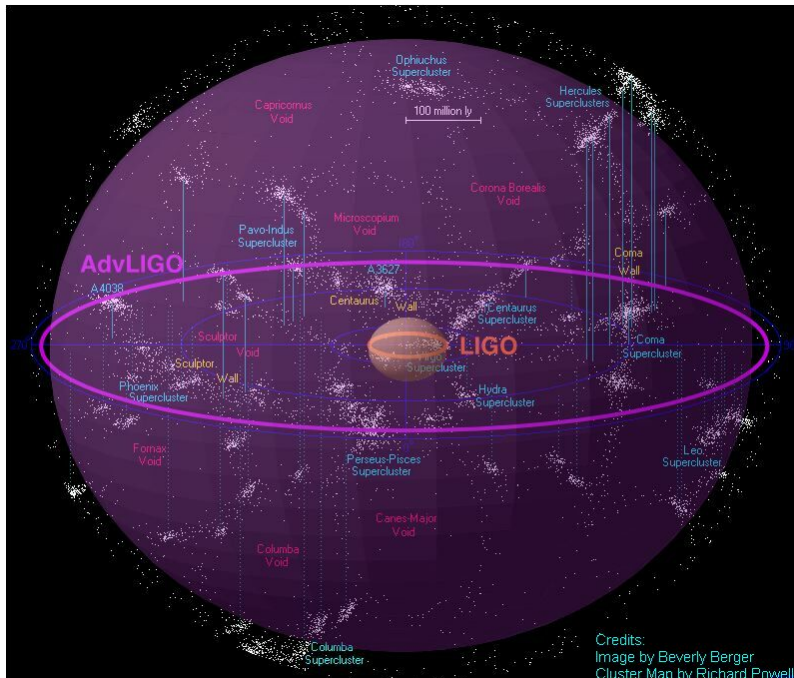
Results from Initial Detectors: Some highlights from LIGO and Virgo

Several ~year long science data runs by LIGO and Virgo
Since 2007 all data analyzed jointly



- 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

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



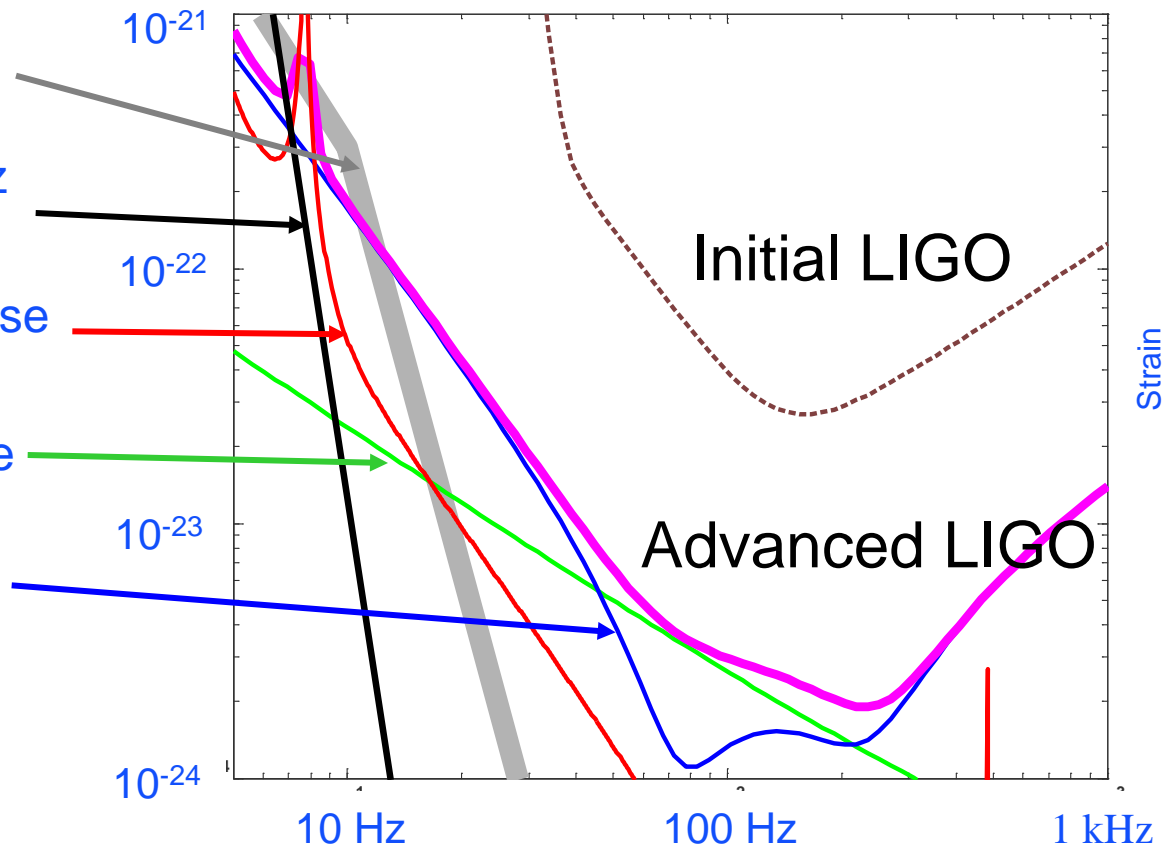
x10 better amplitude sensitivity

⇒ **x1000** rate=(reach)³

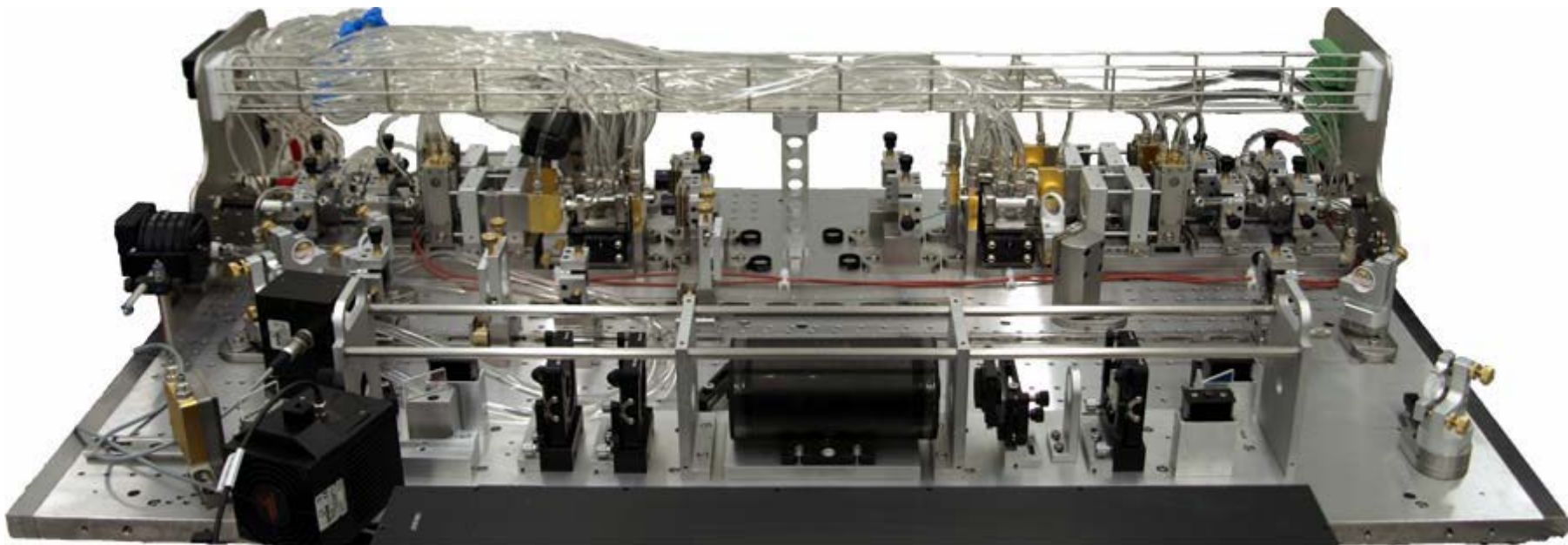
⇒ 1 day of Advanced LIGO

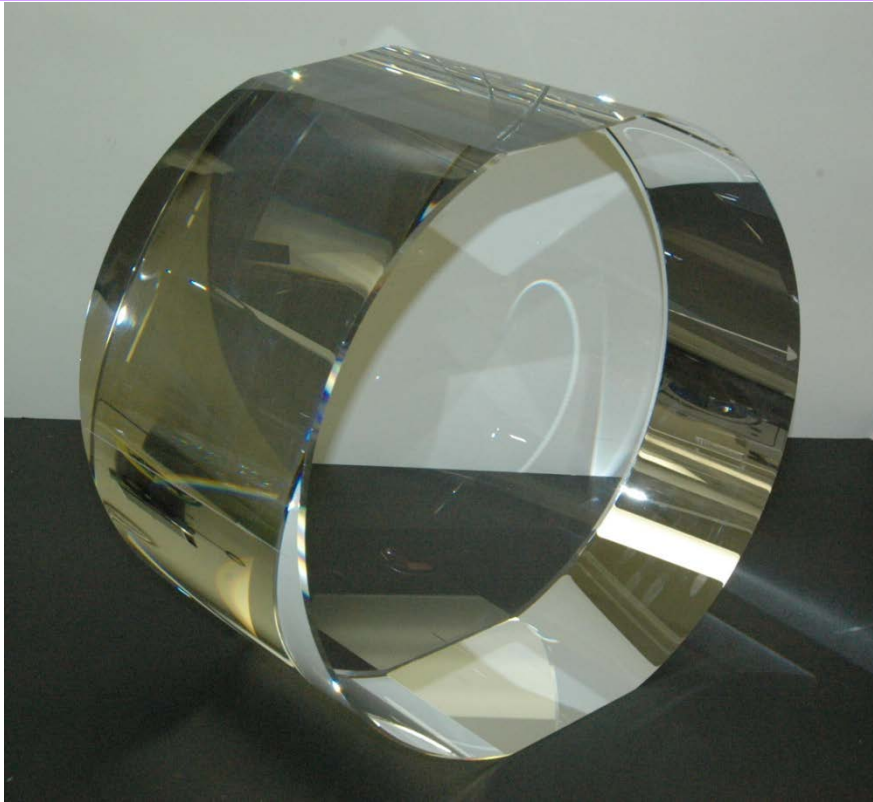
» 1 year of Initial LIGO !

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



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





- 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

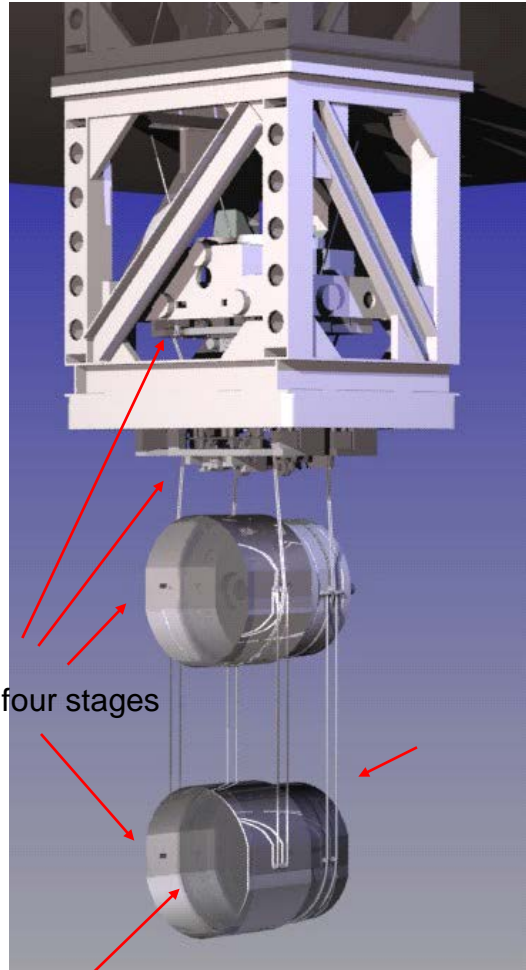


- Two-stage six-degree-of-freedom active isolation
 - » Low noise sensors, Low noise actuators
 - » Digital control system to blend outputs of multiple sensors, tailor loop for maximum performance
 - » Low frequency cut-off: 40 Hz \rightarrow 10 Hz



LIGO-G1401143-v1





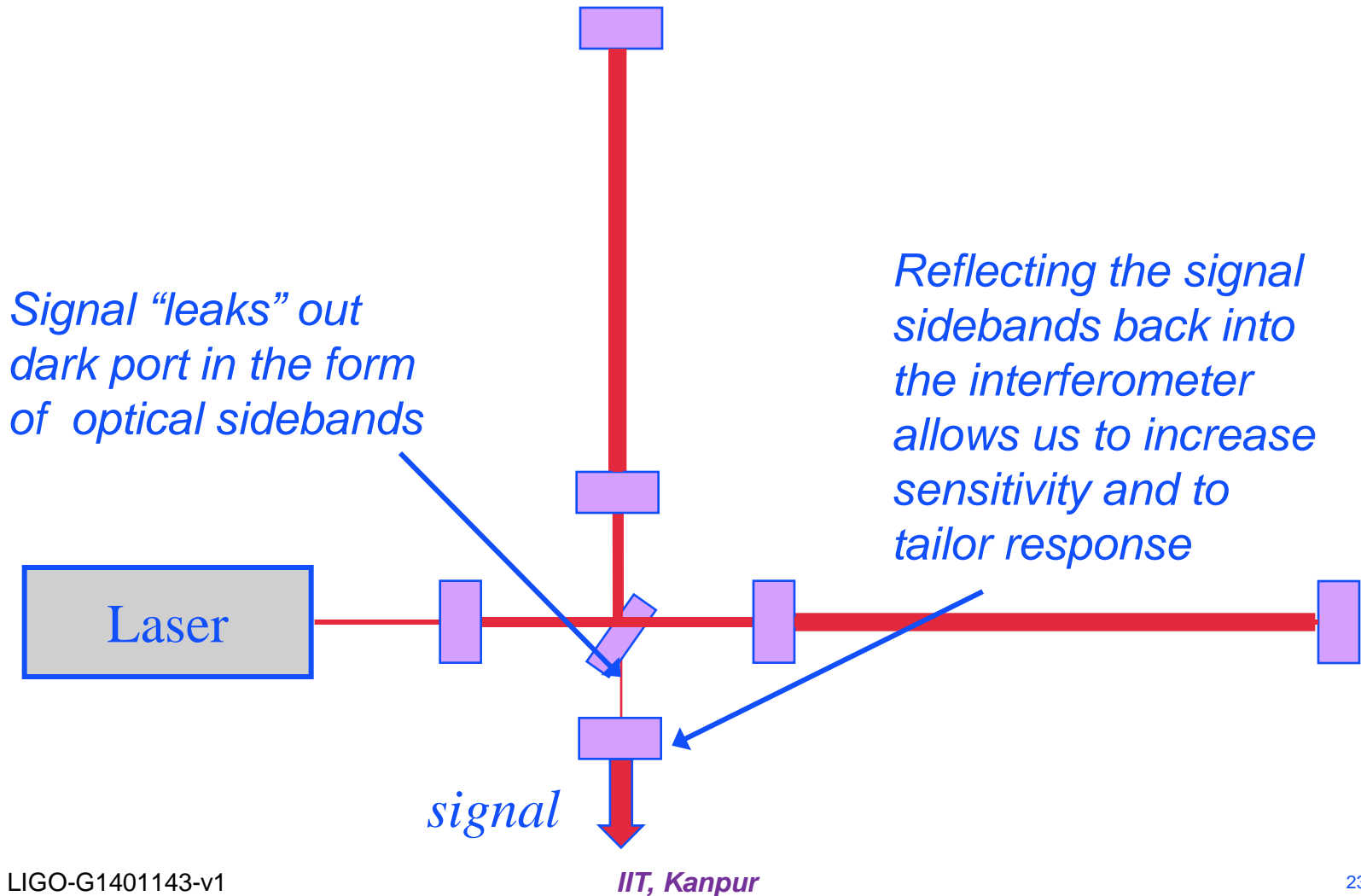
- UK designed and contributed test mass suspensions
- Silicate bonds create quasi-monolithic pendulums using ultra-low loss fused silica fibers to suspend interferometer optics
 - » Pendulum $Q \sim 10^5 \rightarrow \sim 10^8$
- Electrostatic actuators for alignment and length control

40 kg silica
test mass

LIGO-G1401143-v1

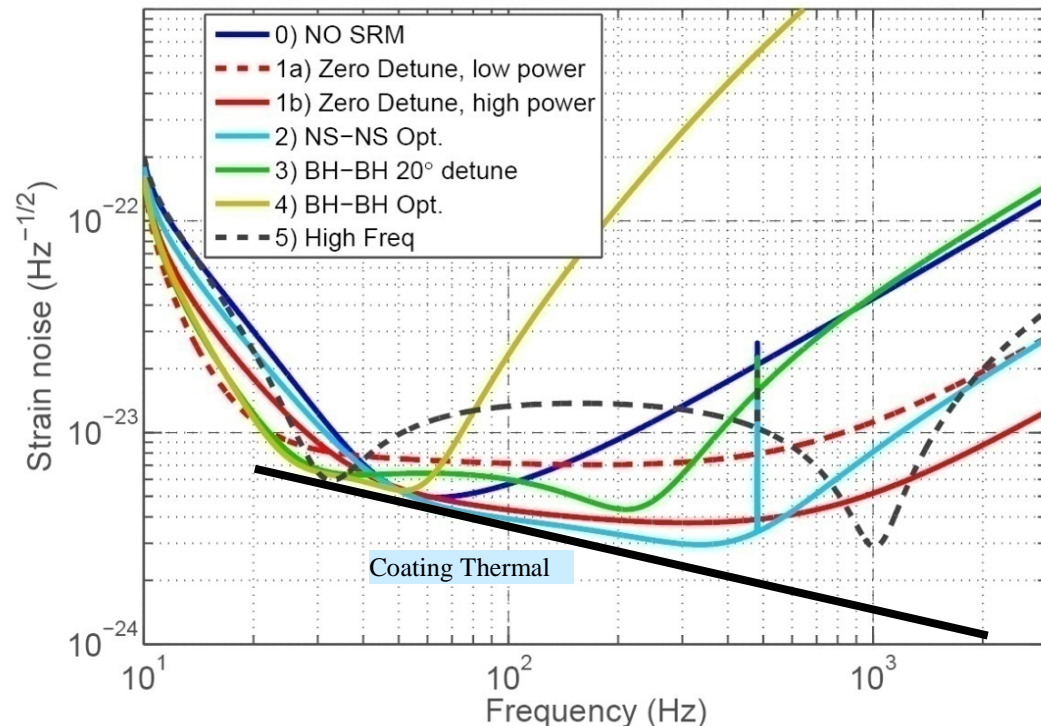


Advanced LIGO Optical Configuration



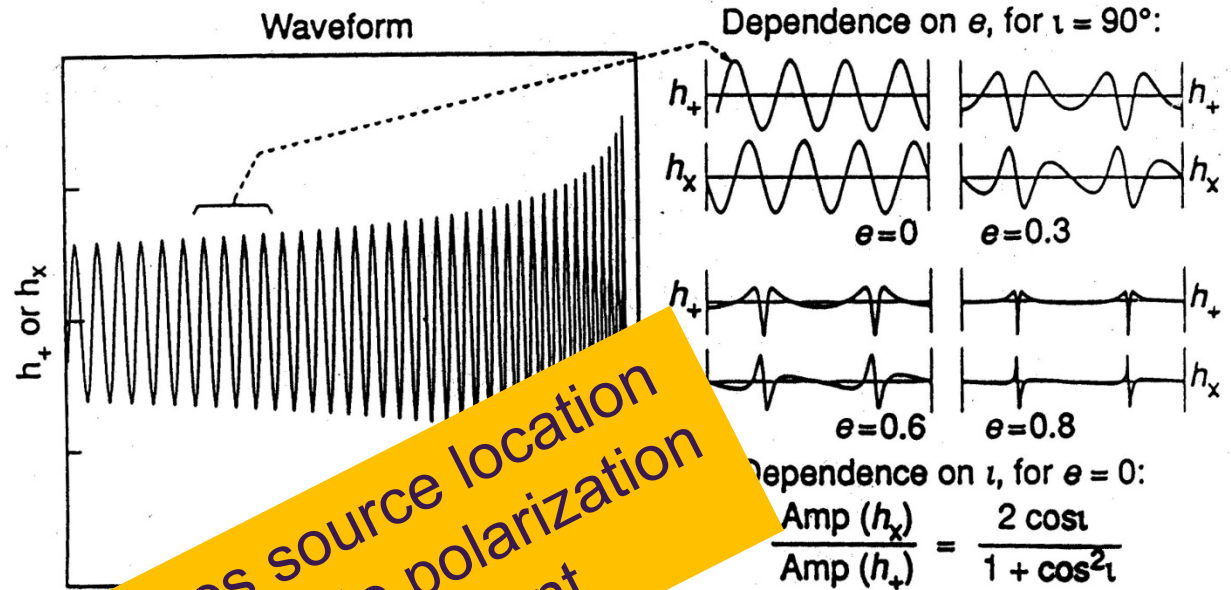
Tailoring the Sensitivity

- 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)



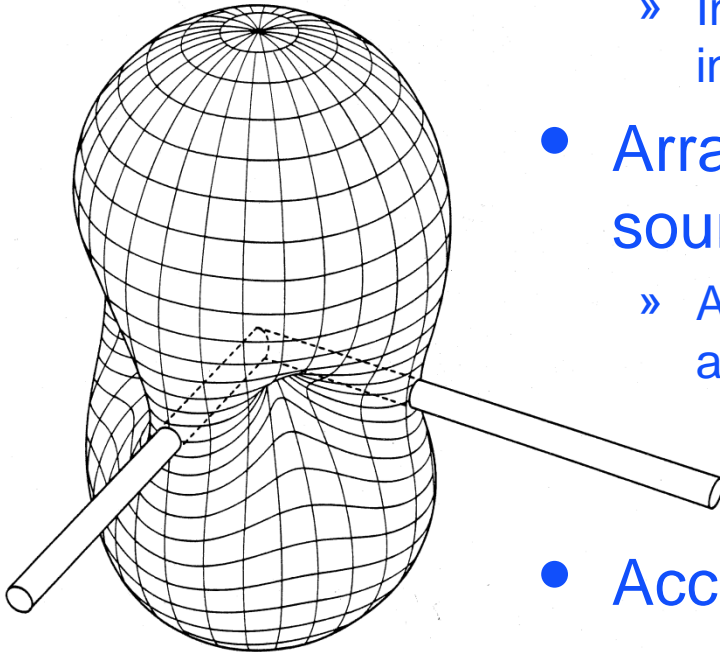
Using GWs to Learn about the Sources: an Example

Chirp Signal binary inspiral

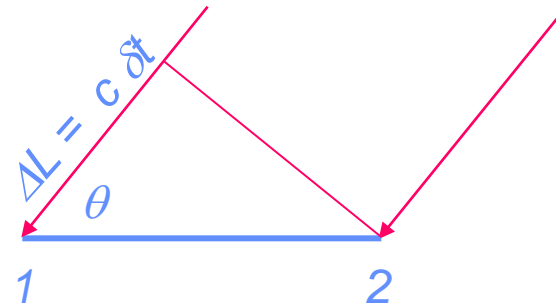


- Requires source location and complete polarization measurement to determine**
- Distance from the earth r
 - Masses of the two bodies
 - Orbital eccentricity e and orbital inclination i

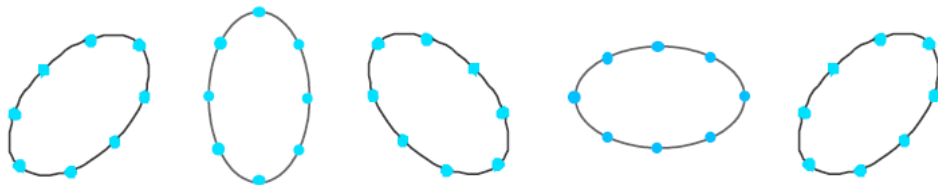
A Global Array of GW Detectors: Source Localization



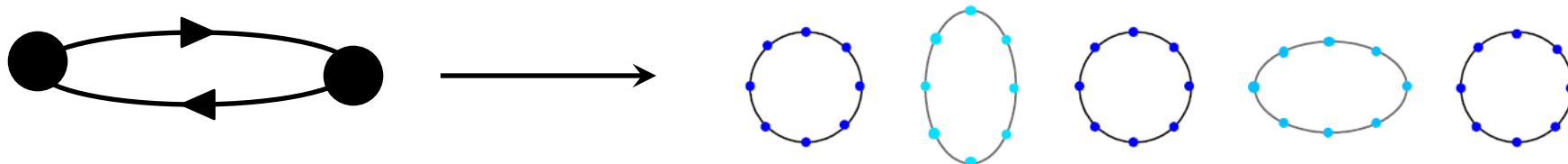
- Detectors are nearly omni-directional
 - » Individually they provide almost no directional information
- Array working together can determine source location
 - » Analogous to “aperture synthesis” in radio astronomy
- Accuracy tied to diffraction limit



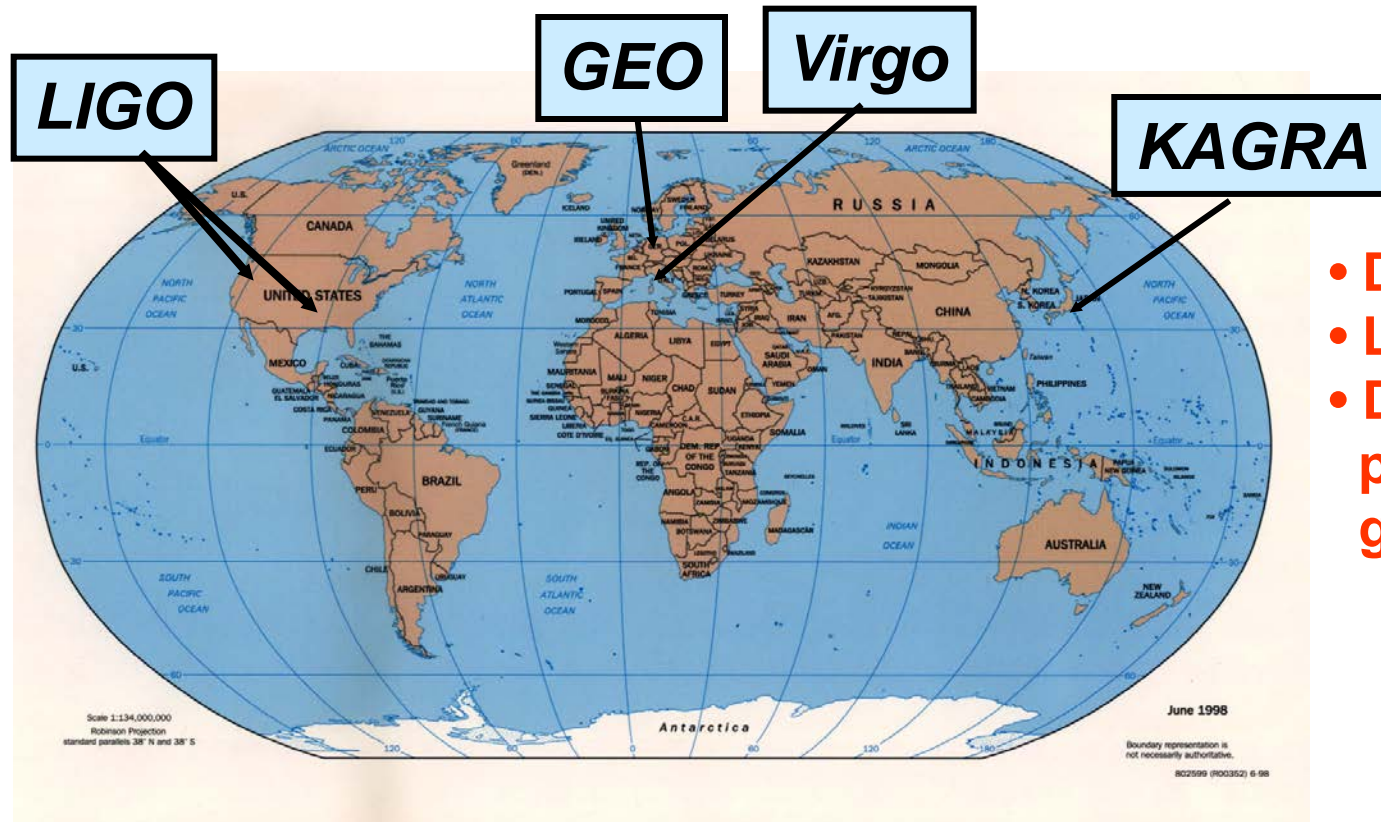
A Global Array of GW Detectors: Polarization Coverage



- 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
 - » 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 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
 - » Pioneered advanced optical techniques
 - » Squeezing

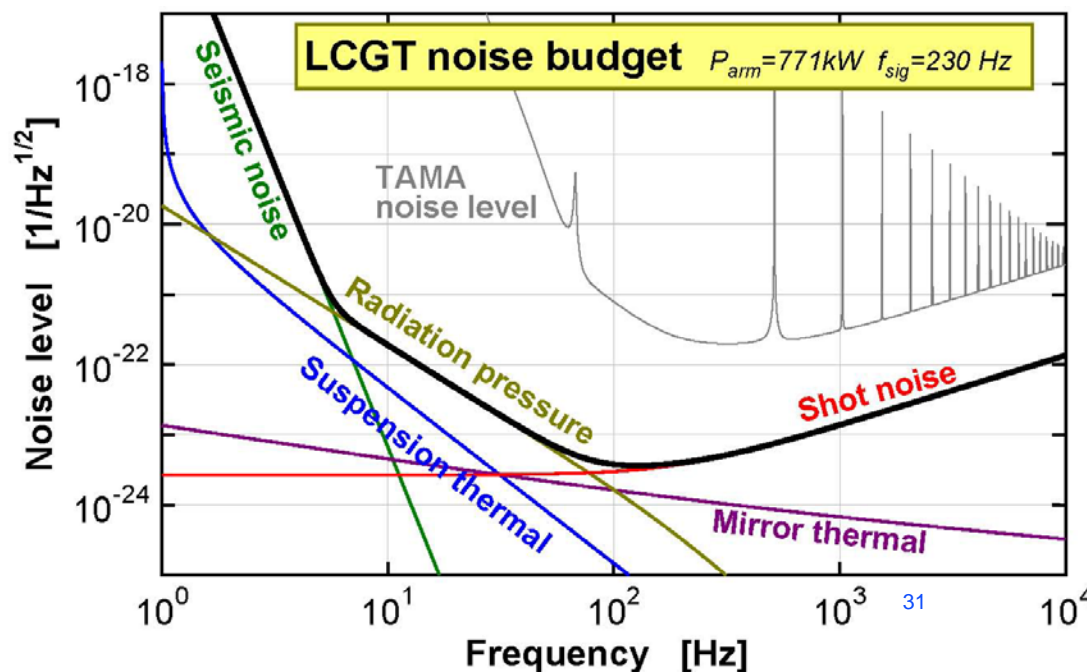


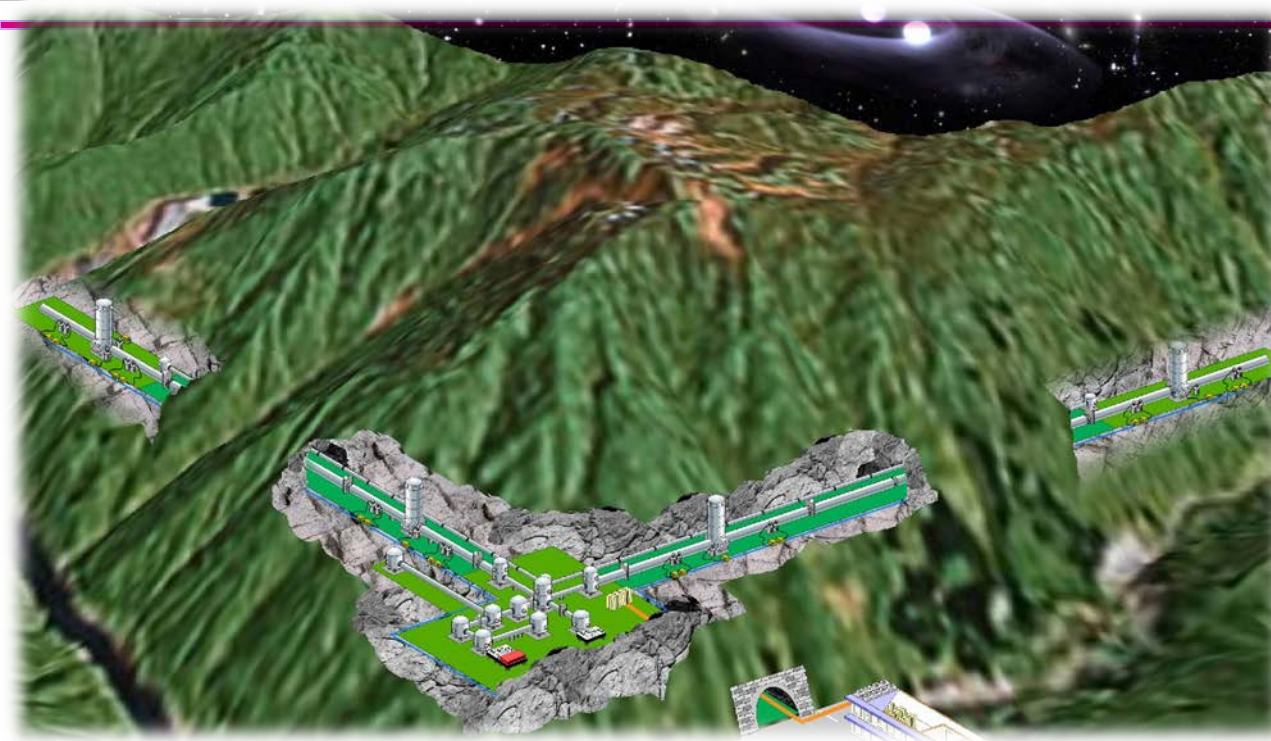
- KAGRA Project

- » Lead institution: Institute for Cosmic Ray Research
- » Other participants include University of Tokyo, National Astronomical Observatory of Japan, KEK,
- » Project approved July 2010...

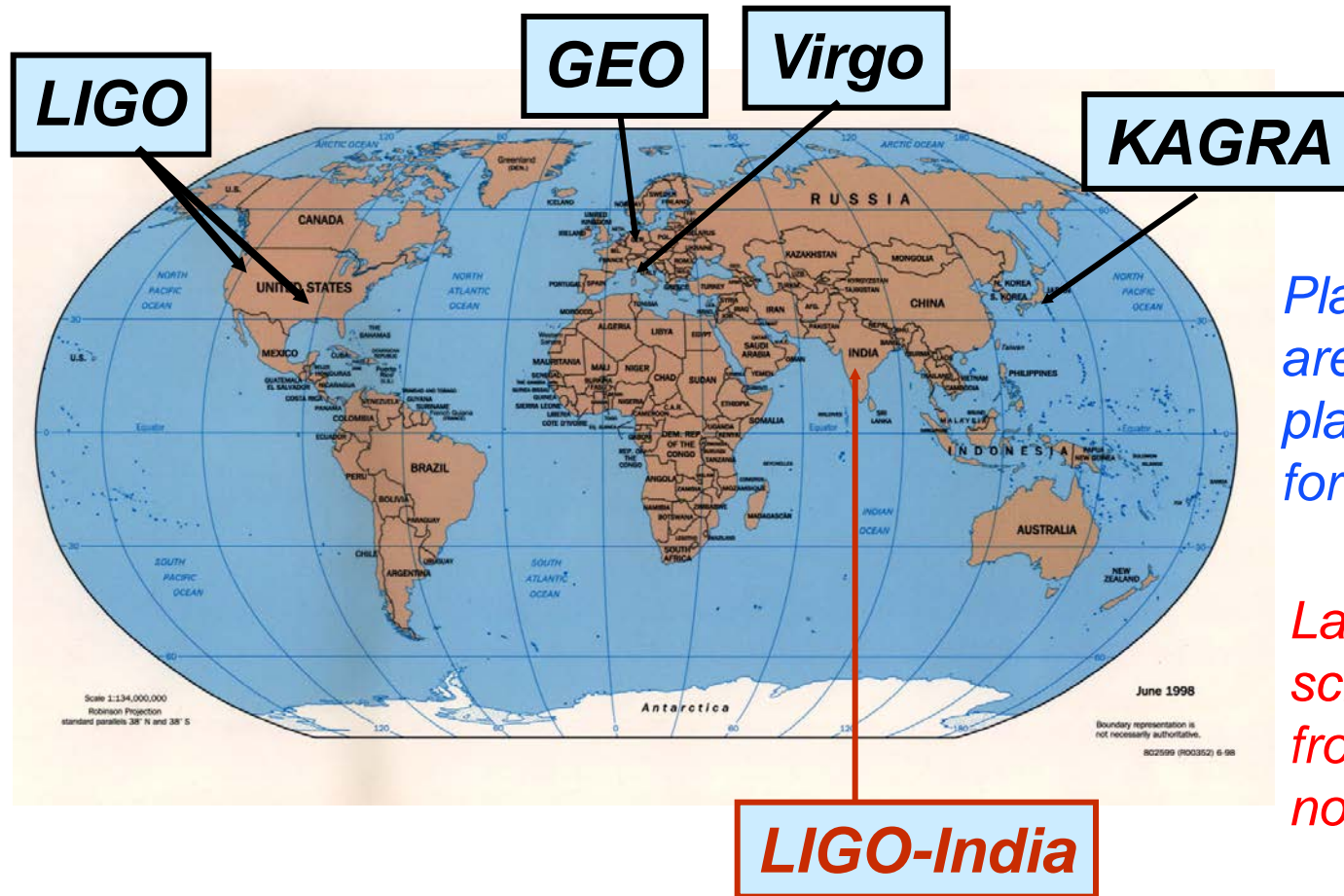
- Key Design Parameters

- » Underground (Kamioka mine)
- » Sapphire test masses cooled to $<20\text{K}$
- » 150W Nd:YAG laser
- » Five stage low frequency (soft) suspension
- » Planning sensitivity similar to Advanced LIGO





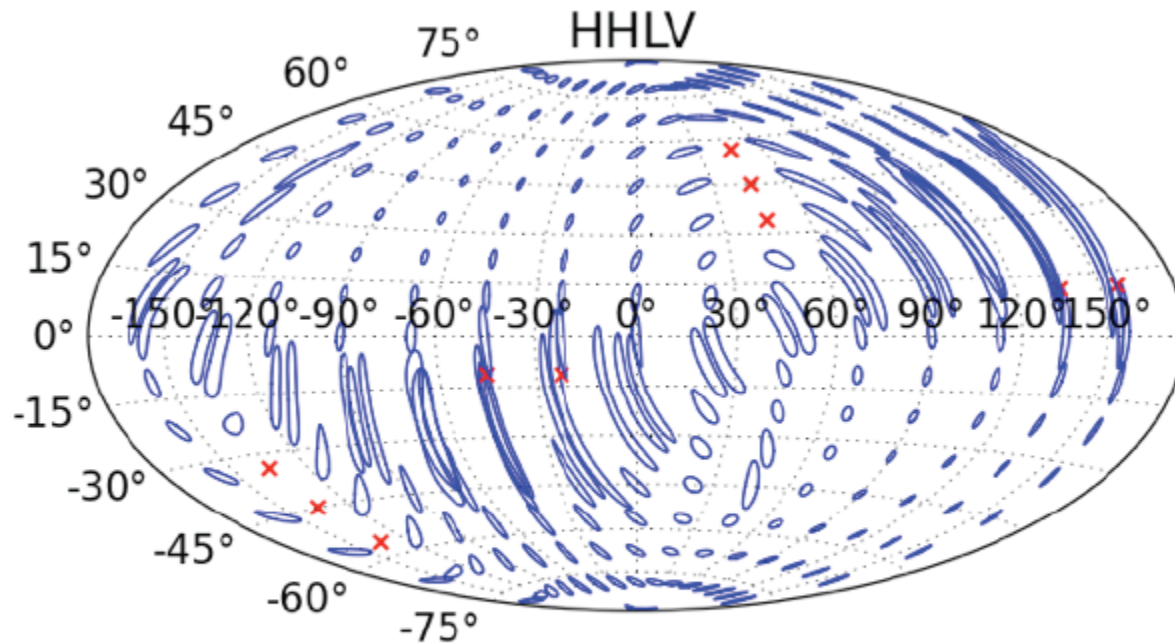
- KAG project schedule
 - » Configured project in two stage plan: room temperature operation followed by cryogenic operation
 - » All tunneling completed; first vacuum tanks to be installed this year
 - » 2018: Start of cryogenic operations—very aggressive schedule



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*

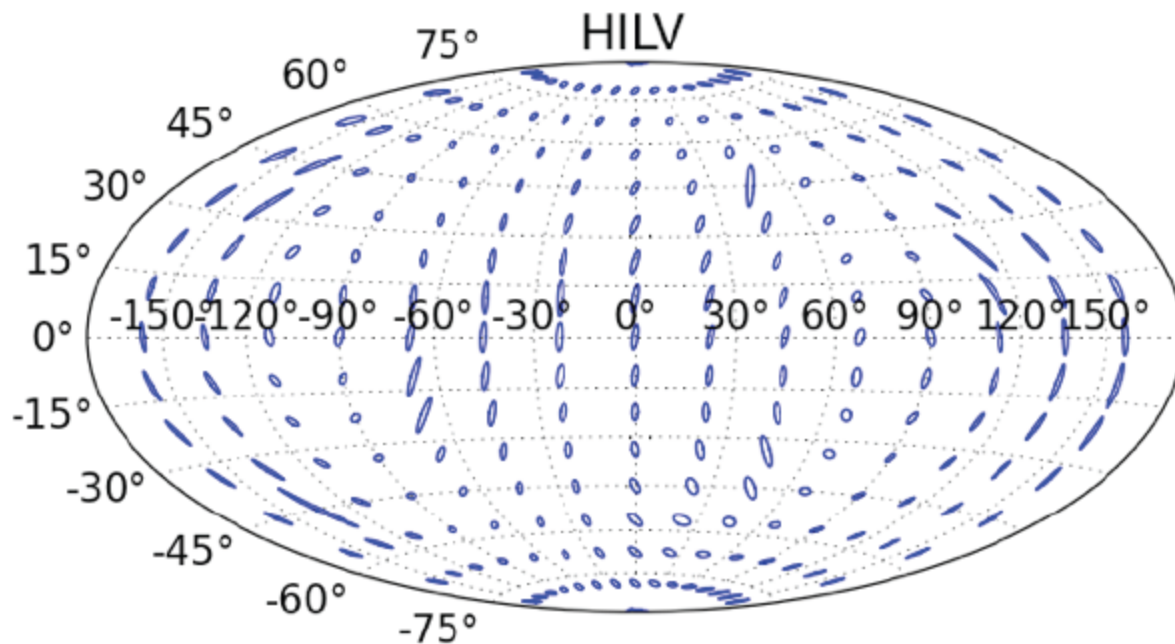


Fairhurst 2011

Red crosses denote
regions where the
network has blind spots

10

Localization capability: *LIGO+Virgo plus LIGO-India*



Fairhurst 2011

- 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
- Joint project of DAE and DST, with DAE taking the lead
- Nodal Institutions in India: IPR, RRCAT, IUCAA
- Project is in final approval stages with Cabinet

Advanced LIGO, Advanced Virgo, KAGRA
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

- 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 commissioning
 - » 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 can play a key role
- Will continue to drive developments in optical technology and optical physics for many years