Gravitational wave detection via optical interferometry

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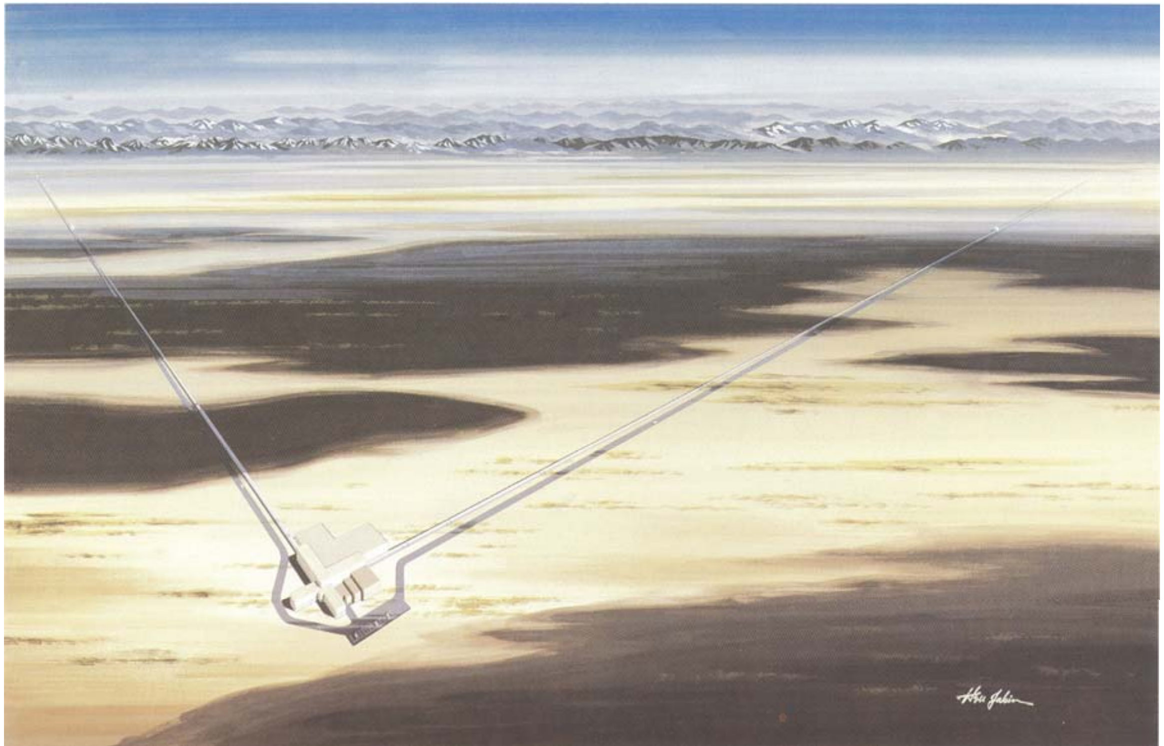
For the LIGO Scientific Collaboration

LIGO: 1989 Proposal to the US NSF

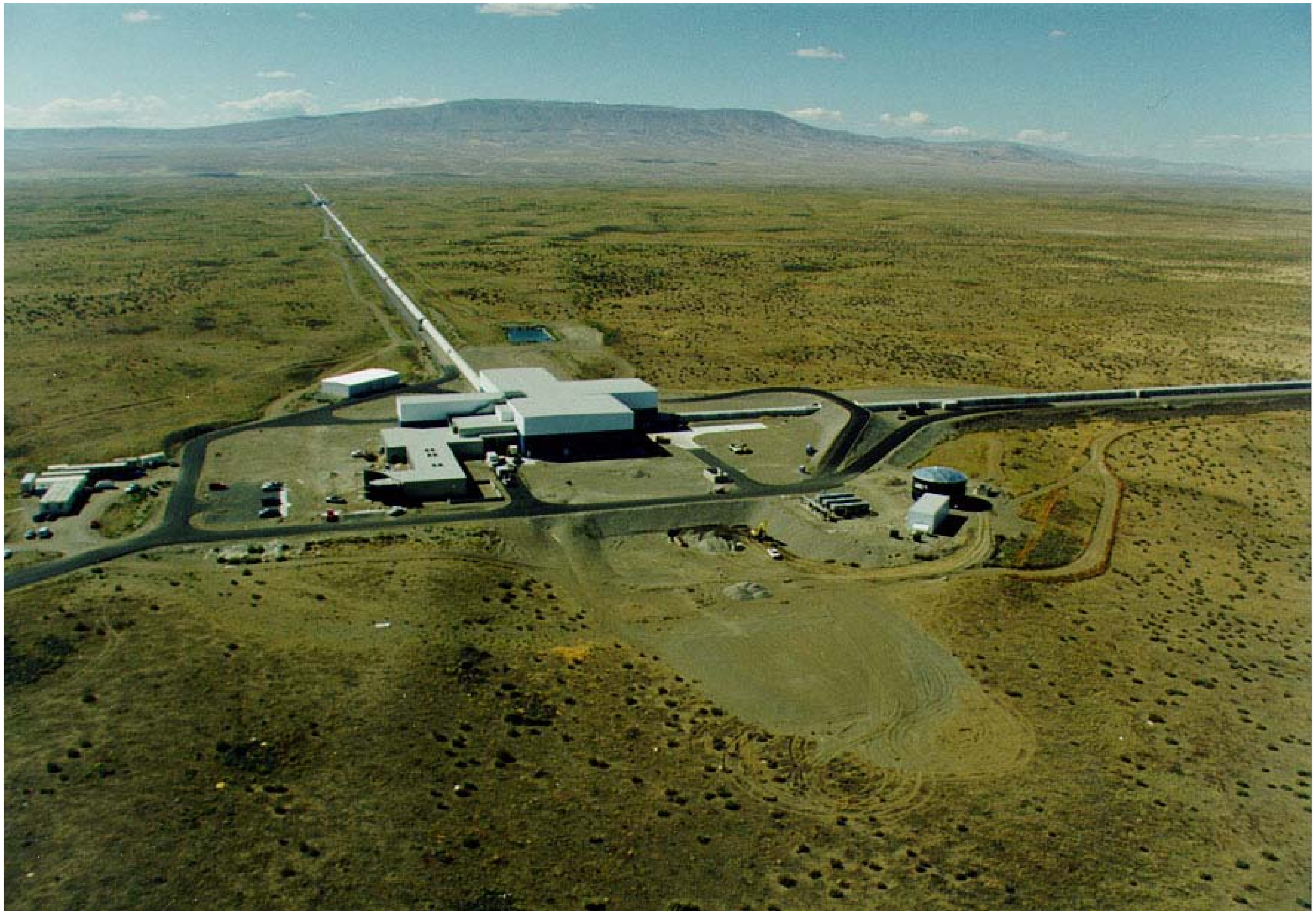
PREFACE

This proposal requests support for the design and construction of a novel scientific facility—a gravitational-wave observatory—that will open a new observational window on the universe.

The scale of this endeavor is indicated by the frontispiece illustration, which shows a perspective of one of the two proposed detector installations. Each installation includes two arms, and each arm is 4 km in length.

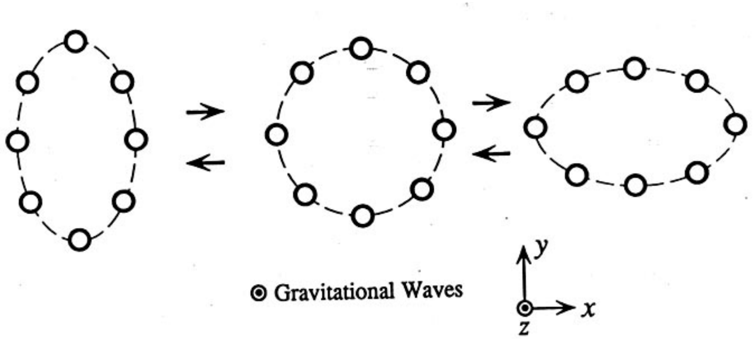


LIGO:
Today, Washington state…



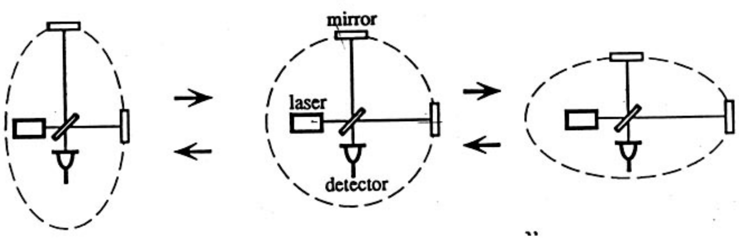
…LIGO in Louisiana

Gravitational Waves



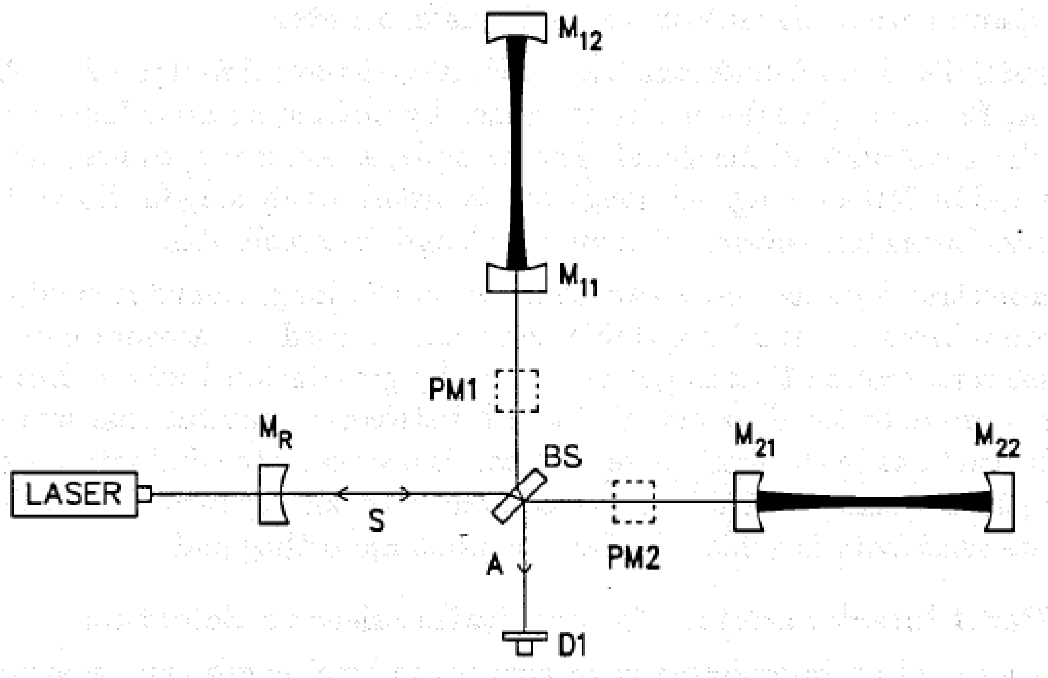
Gravitational waves are quadrupolar distortions of distances between freely falling masses: "ripples in space-time"

Michelson-type interferometers can detect space-time distortions, measured in "strain" h=ΔL/L.



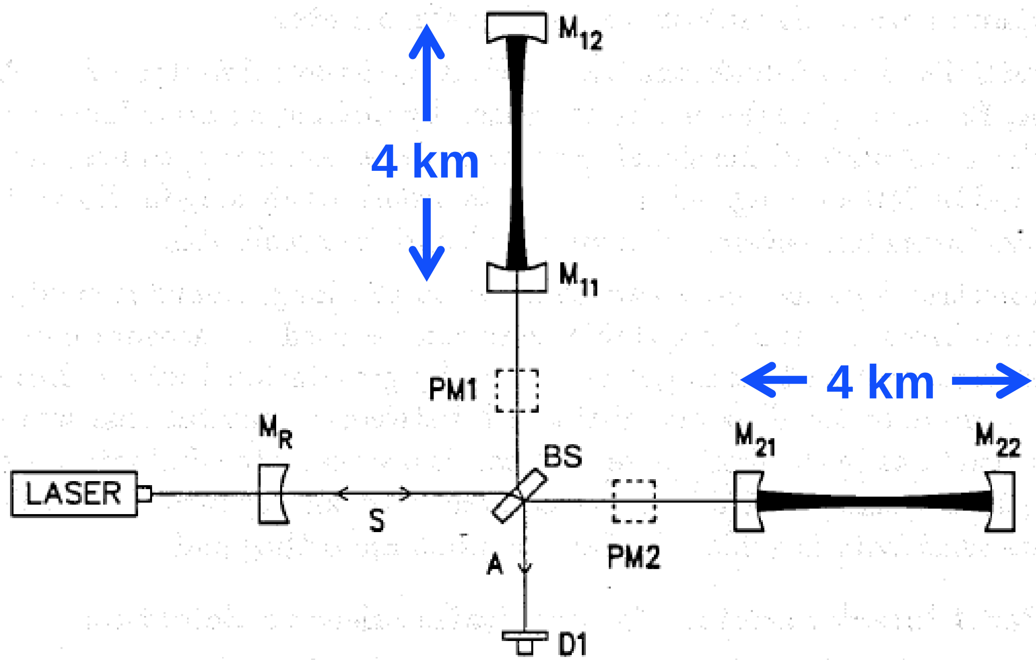
Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have h=~L/L~10^{-21}

A LIGO Detector, 1989 Proposal



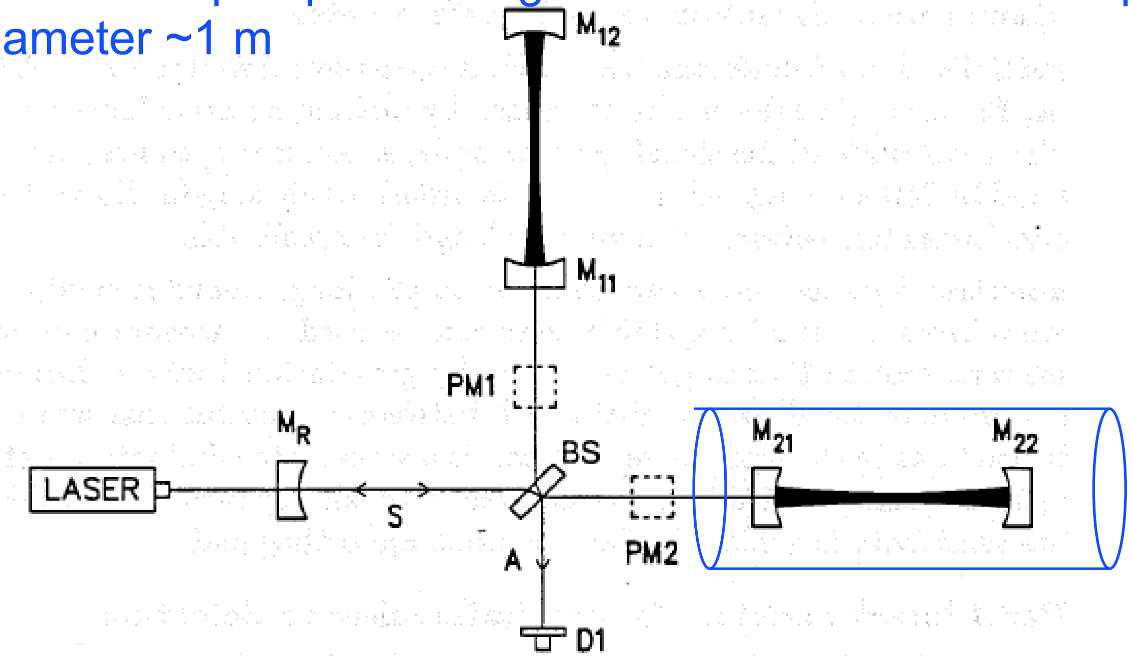
Basic elements: Length

- Length:
  - $\lambda_{GW} = c/f \sim 3000$ km for LIGO frequencies of 100 Hz
  - Short antenna limit, so..
  - Perceived length change $\Delta L = h/L$, L arm length
  - The longer the better
  - LIGO: 4km arms; Virgo: 3km arms



Basic elements: Vacuum system

- Air molecules passing through beam in arm change apparent length of arm
  - Polarizability, or 'index'
  - A stochastic process → noise
  - Establishes vacuum requirements for beam path
  - UHV – 10^{-7} torr
- Need to avoid scattered light from walls of vacuum tube
  - Light wavelength λ ~ 1 micron, diffraction limit leads to ~10cm beams
  - …less expensive to pump out a large diameter tube with fewer pumps!
  - → Tube diameter ~1 m

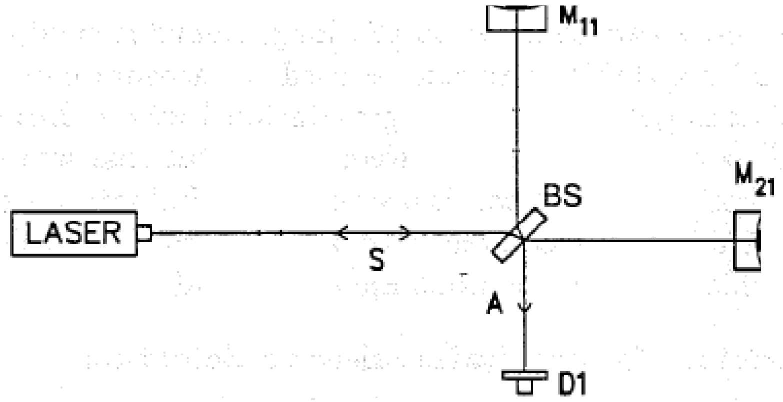


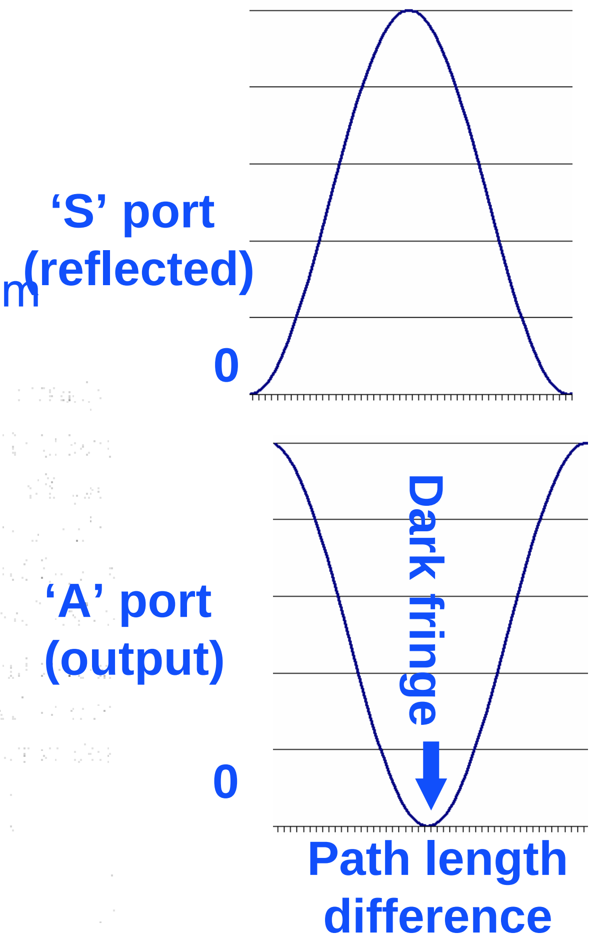
LIGO Beam Tube

- 1.2 m diameter
  - Multiple beams can be accommodated
  - Optimum also for cost considering pumping
- Aligned to within mm over km (correcting for curvature of the earth)
- Total of 16km fabricated with no leaks
- Cover needed (hunters…)

Basic elements: Michelson Interferometer

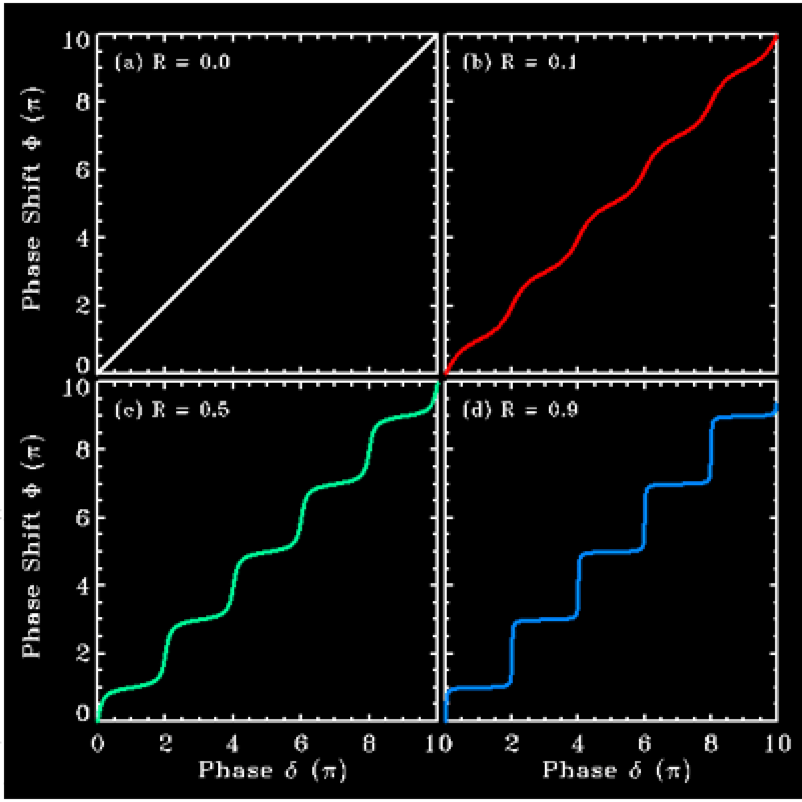
- Could use at mid-fringe
  - Slope ($\delta I/\delta x$) proportional to laser Power
  - Fluctuations proportional to $\sqrt{\text{Power}}$
  - Gain as square root of laser power
- Use at dark fringe, using modulation around the minimum
  - Gives same sensitivity,
    other advantages (later…)
- Complementary ports also used…





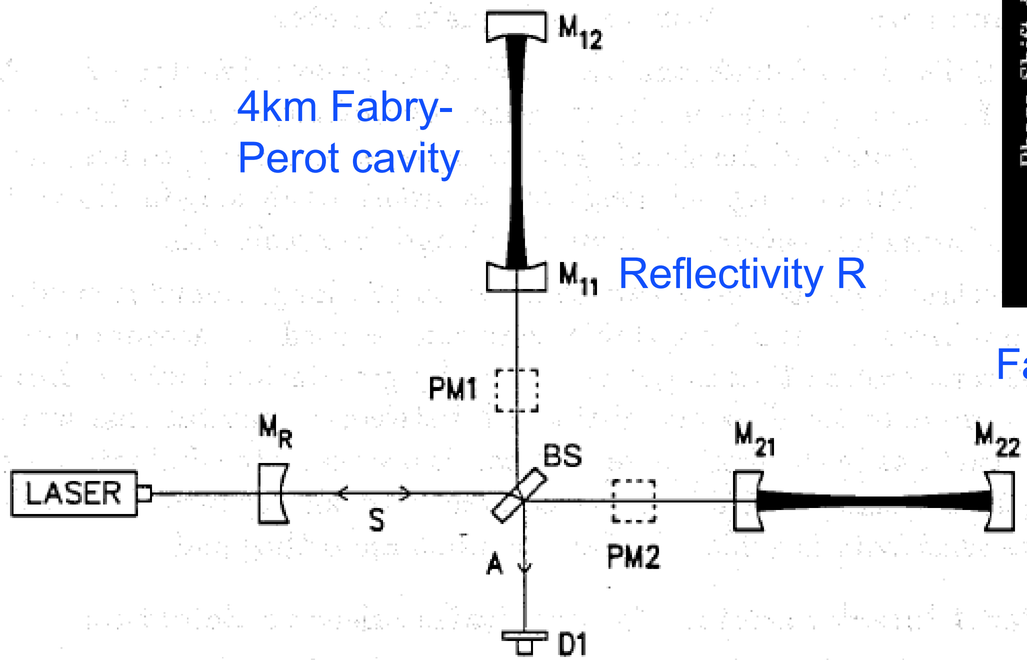
Basic elements: Fabry-Perot cavities

- Desire large phase shift for small length change
- Use Fabry-Perot cavities in arms, operate at point of maximum slope (on resonance)
- Increases phase change by ~100



Fabry-Perot phase shift per length change

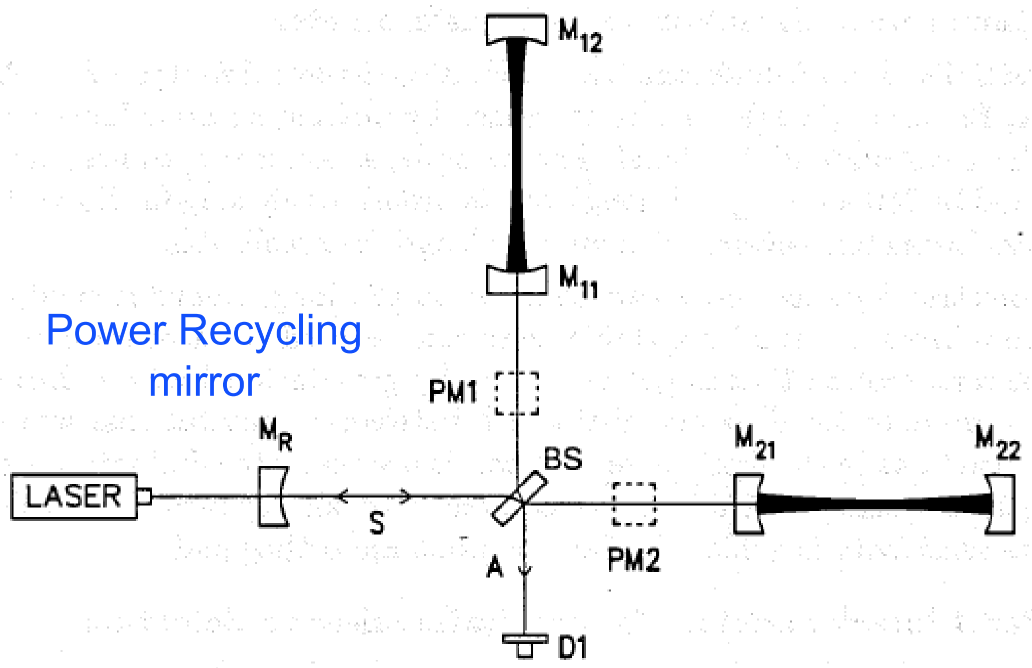
4km Fabry-Perot cavity



Basic elements: Power Recycling

- Shot noise limited sensitivity of fringe interrogation
  - Resolution scales with √Power
  - …or equivalently $\sqrt{2eI}$ – the shot noise in the photodiode current
- Maximize laser power (for now…)
- Build resonant cavity with Michelson and semi-transparent mirror – another Fabry-Perot cavity; can also be seen as impedance matching
- Can achieve 'power recycling factor' of ~50

Power Recycling mirror



The LIGO Detectors: motions which mask GWs

$h = \Delta L/L$

L ~ 4 km

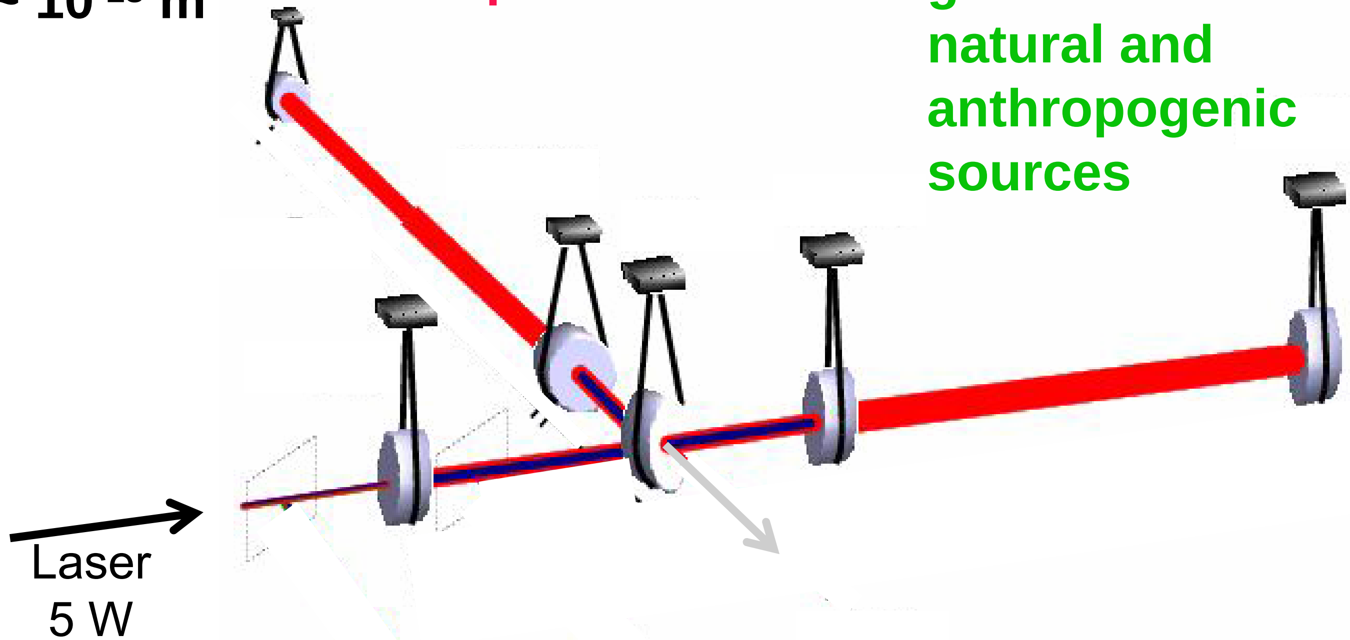
We need $h \sim 10^{-21}$

We have L ~ 4 km

We see $\Delta L \sim 10^{-18}$ m

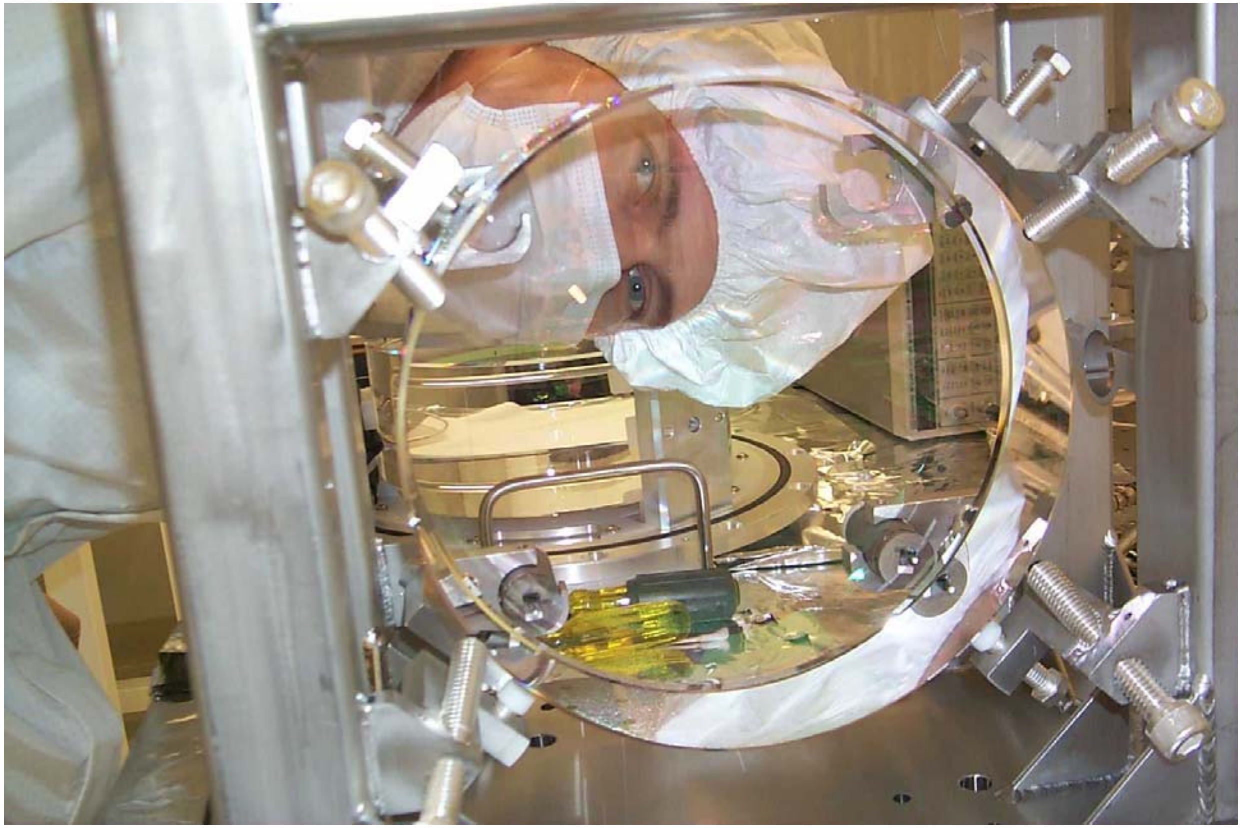
Thermal noise -- vibrations due to finite temperature

Seismic motion -- ground motion due to natural and anthropogenic sources

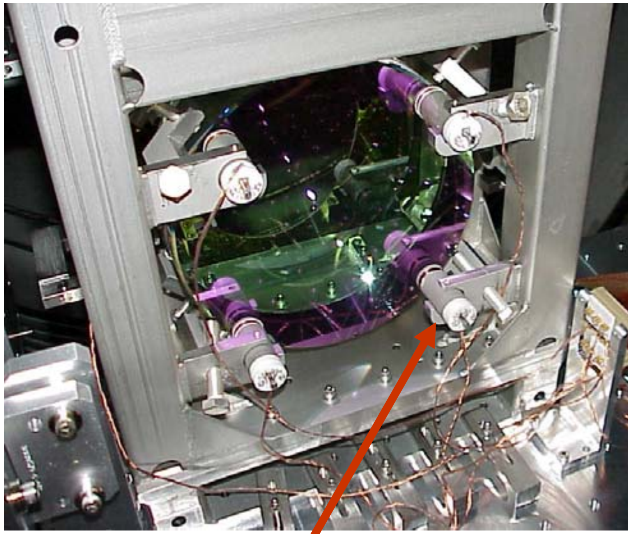


Test Masses

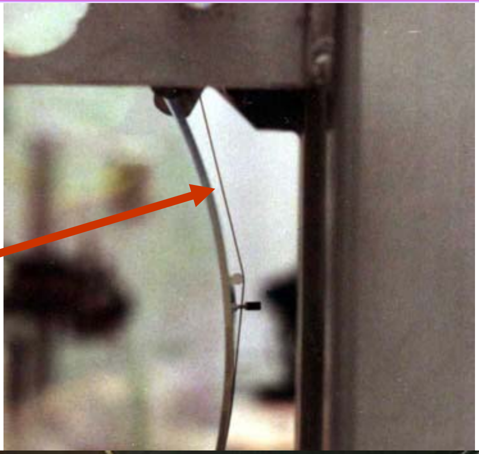
Fused Silica, 10 kg, 25 cm diameter and 10 cm thick
Polished to $\lambda/1000$ (1 nm)



Test mass suspensions

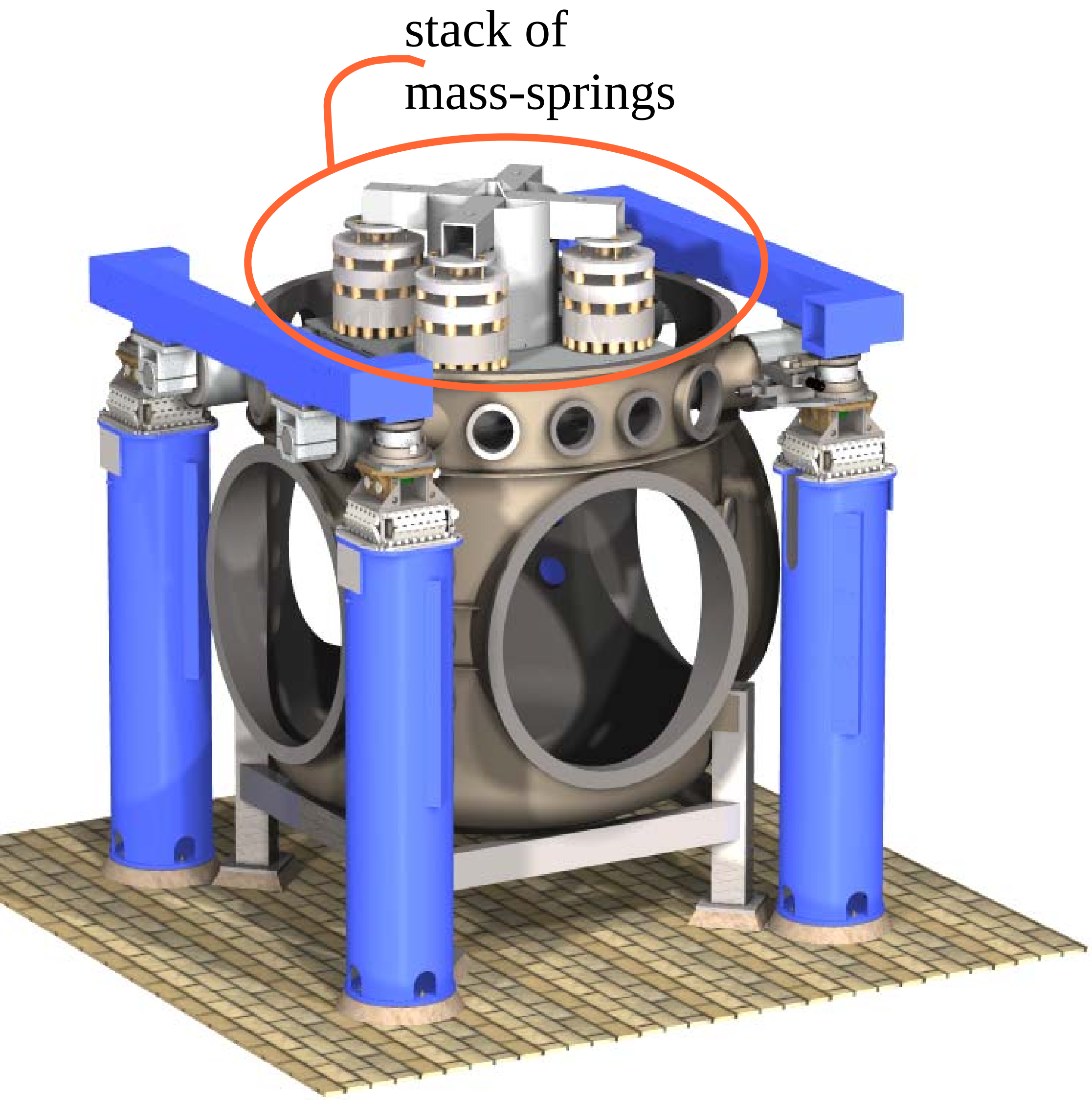


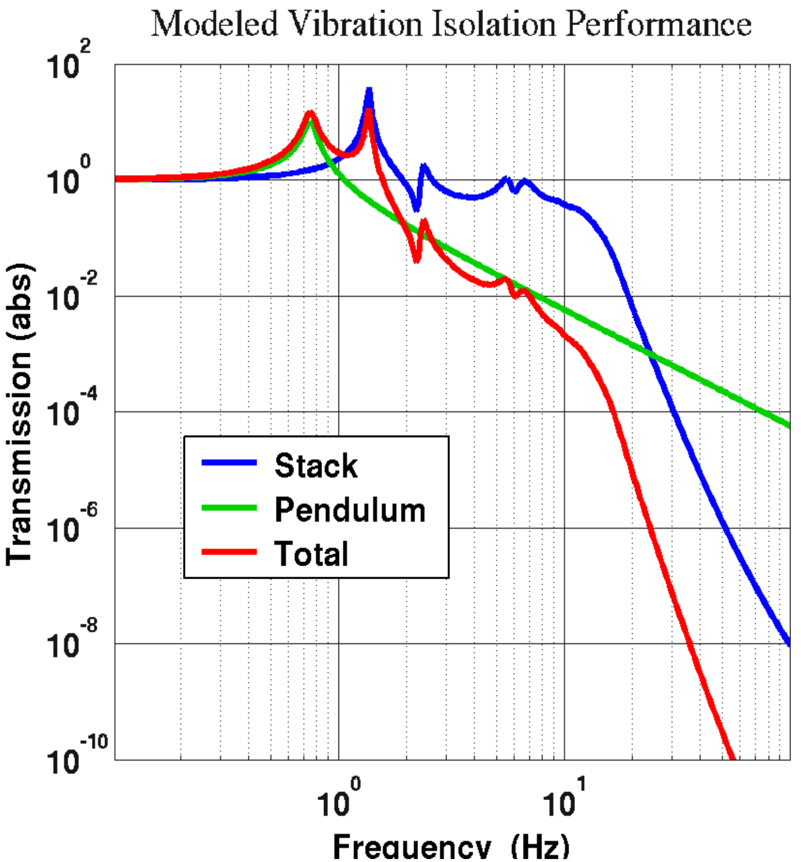
Optics suspended as simple pendulums



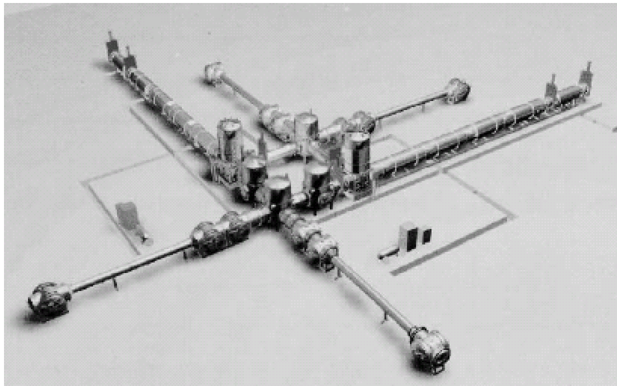
Shadow sensors & voice-coil actuators provide damping and control forces

Seismic Isolation

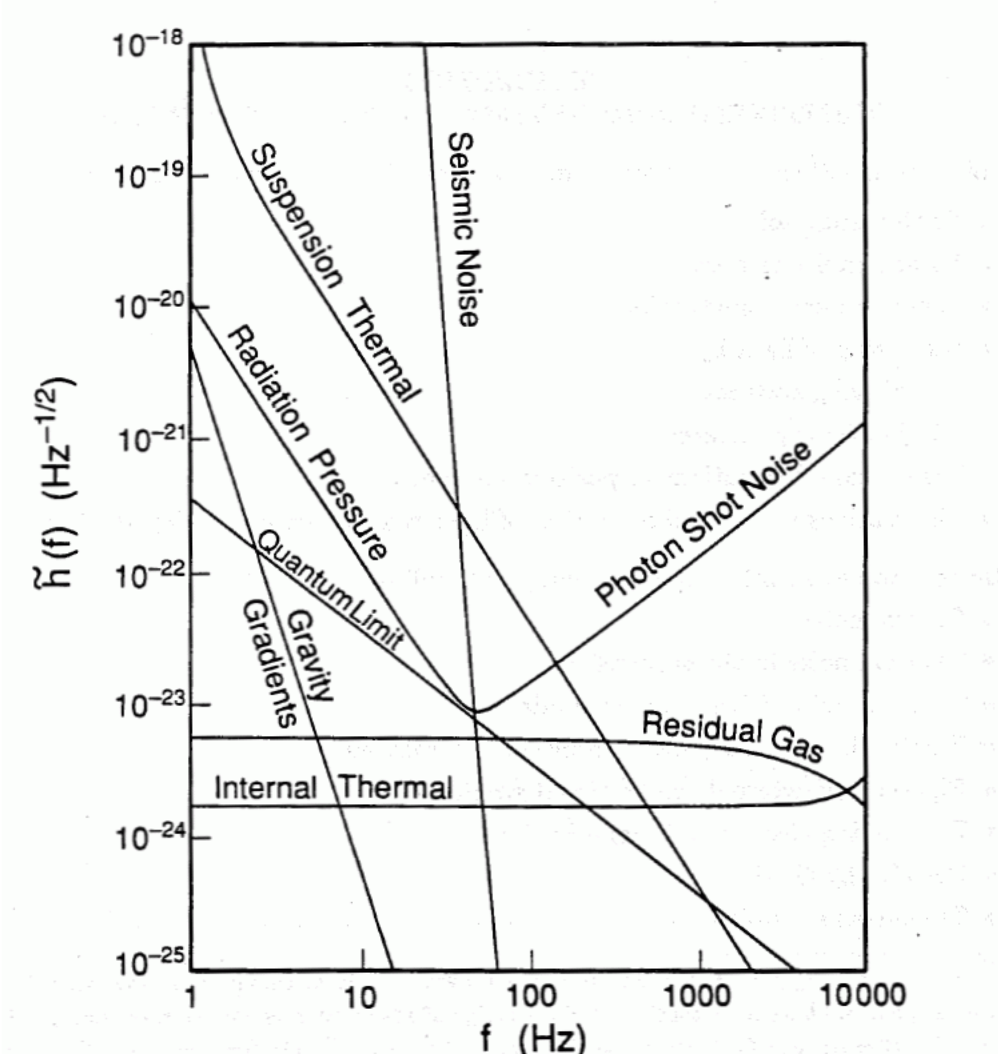




LIGO Vacuum Equipment

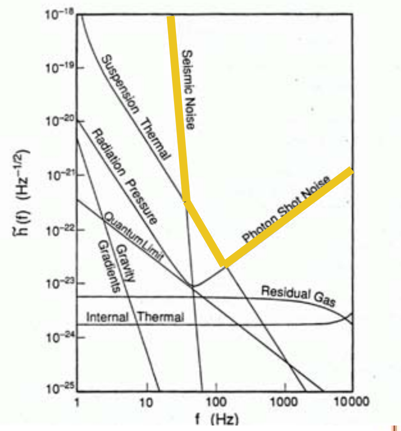


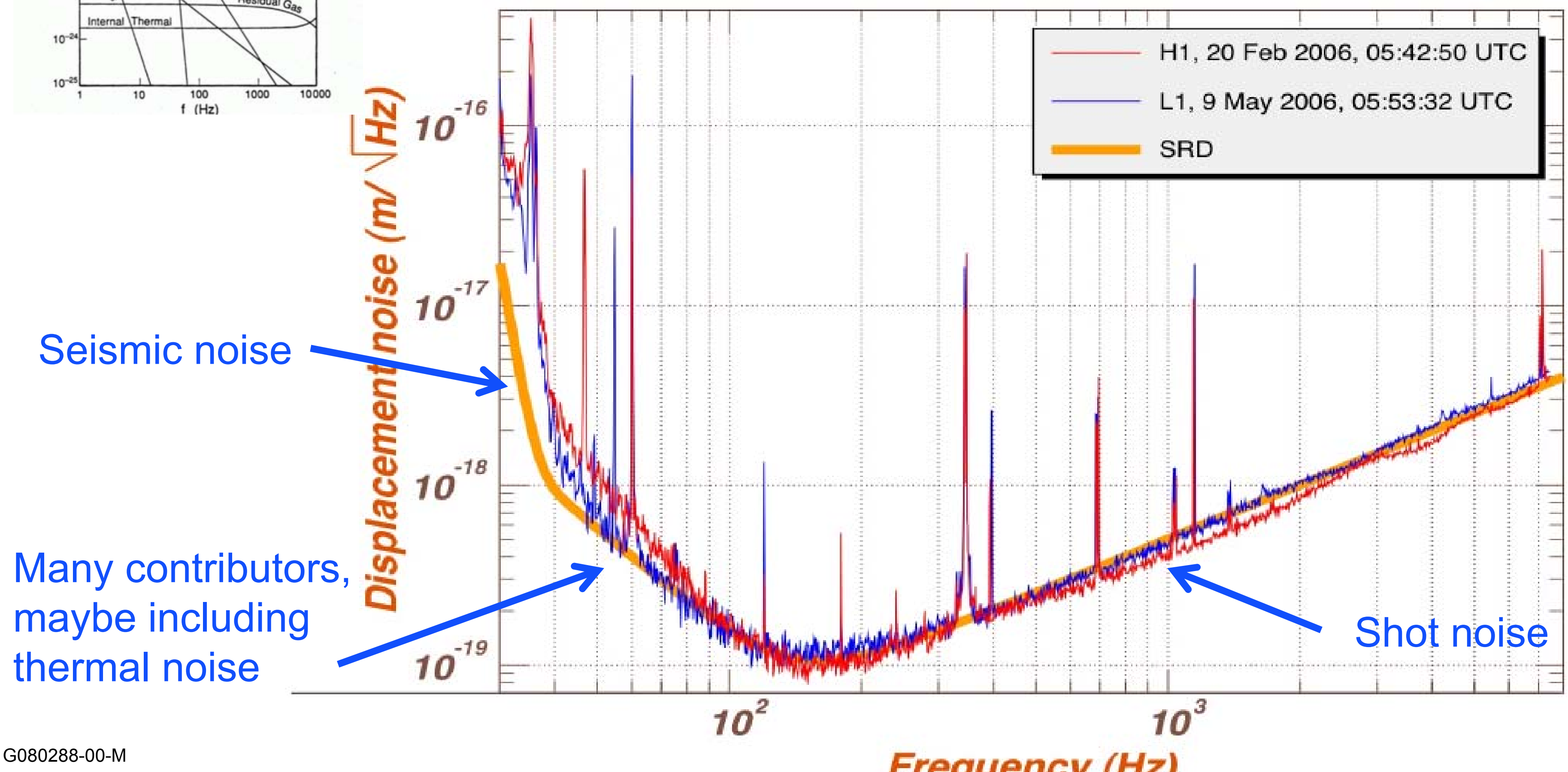
The planned sensitivity of LIGO, 1989 Proposal



The sensitivity of initial LIGO

- SRD: Science Requirements Document target
- Initial LIGO performance requirement: $h_{RMS} \leq 10^{-21}$ over 100Hz Bandwidth
- Current performance ~ $h_{RMS} \approx 4 \times 10^{-22}$
- **Success!**





LIGO in the larger context, 1989 Proposal

B. National Context

We envision the LIGO as an initial quasi-experimental project, focused upon the invention, development, verification, and first use of technologies for laser interferometer gravitational-wave astronomy, with a gradual transition to a mature facility. The early stages of evolution will be conducted primarily by the Caltech/MIT LIGO team, followed by a gradual transition to broader-based national and international participation.

Caltech and MIT, with the principal support of the National Science Foundation (NSF), have invested close to two decades of effort in developing a laser interferometer for gravitational-wave astronomy. The two institutions are committed to continuing a vigorous program leading to the establishment of the LIGO and gravitational-wave astronomy, and subsequently developing, operating, and maintaining LIGO under NSF sponsorship in the interest of the scientific community.

Completion of the LIGO, bringing it to operational readiness in the course of the early search for gravitational waves and, ultimately, conversion to a broadly accessible facility, will require the full commitment and expertise of the Caltech/MIT team. It is expected that once a firm NSF commitment towards construction and operation of the LIGO exists, a broader-based national scientific community will be interested in participation.

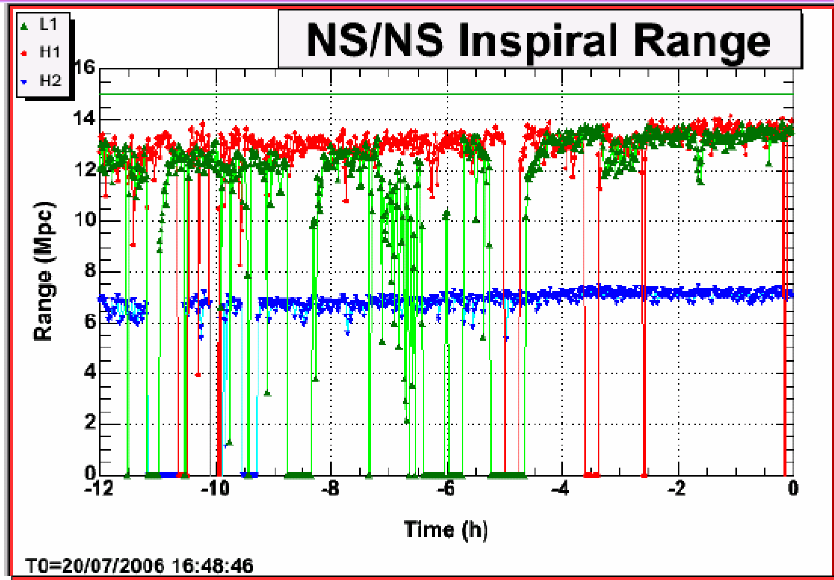
LIGO today is the Lab plus The LIGO Scientific Collaboration (LSC)

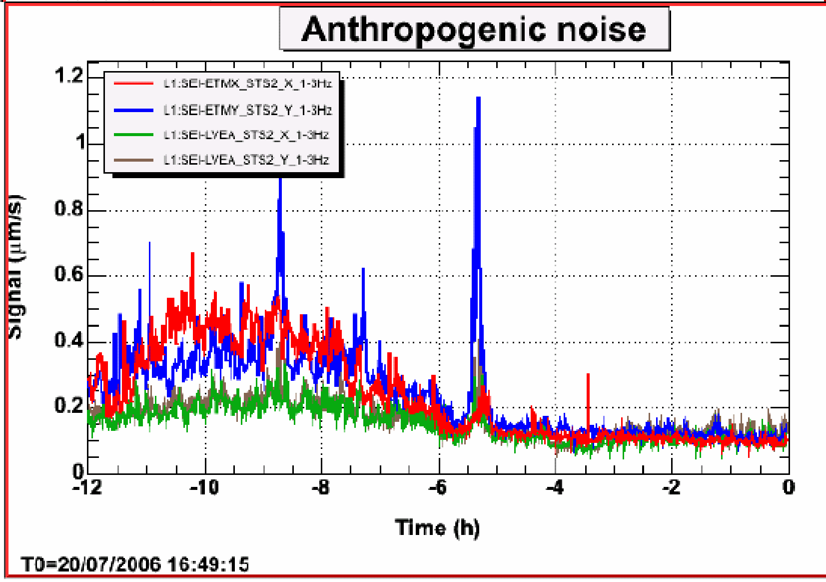
- The LSC carries out the scientific program of LIGO – instrument science, data analysis.
- US Support from the **NSF – THANKS!**
- The 3 LIGO interferometers and the German/UK GEO600 instrument are analyzed as one data set
- 624 members as of this morning…
- 44 institutions plus the LIGO Laboratory, scattered around the world
- Sharing all data and planning also with the **Virgo Collaboration** (France/Italy/Netherlands)

…let's look at their activities….

Astrophysical interpretation of data

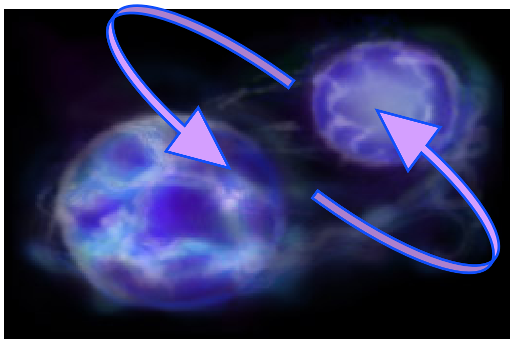
- First effort is to understand instrument and deviations from ideal behavior
  - » Extensive ‘Detector Characterization’ tools and intelligence
- Analysis Working groups formed by instrument scientists and analysts
- Groups organized around the LIGO instruments, GEO600, Virgo
- Concentrating on classes of sources:
  - » Bursts, with or without triggers from other observations
  - » Binary inspirals, of various objects
  - » Periodic sources of GWs
  - » Stochastic backgrounds



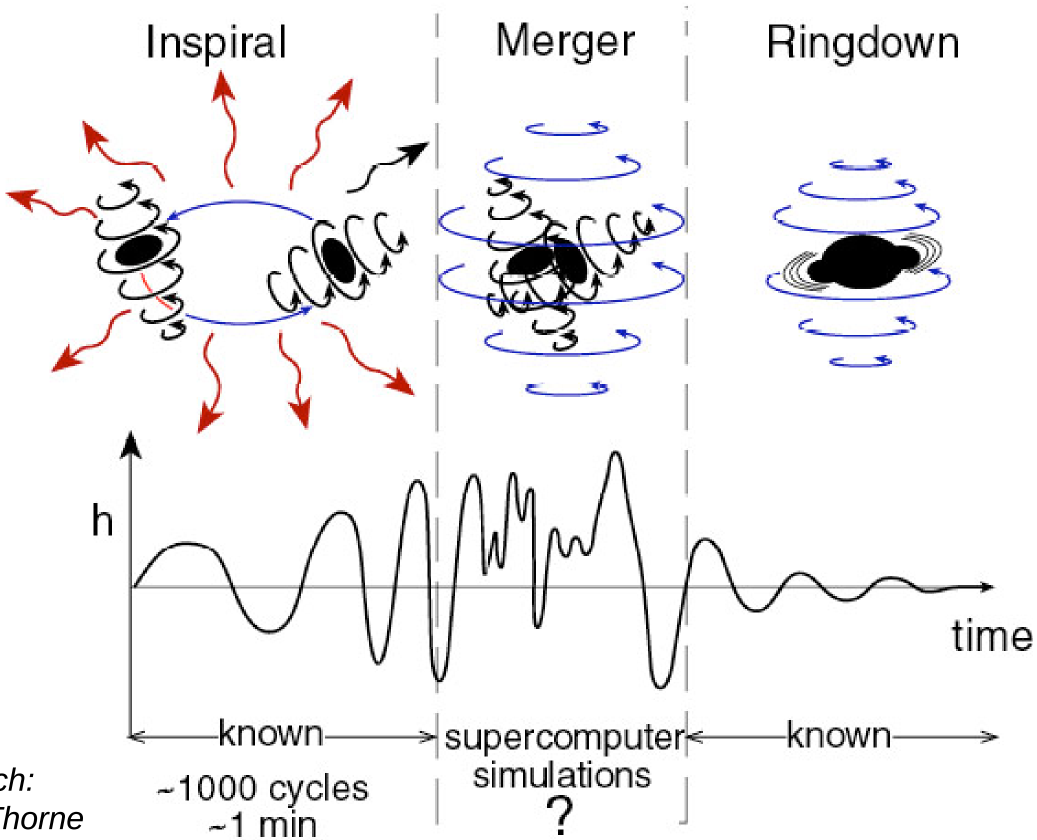


What kinds of signals?

- E.g., inspiral and merger of neutron stars or black holes
- Early ‘chirp’ and resulting black hole ‘ringing’ are well known and a good source for templates
- Can learn about the complicated GR in the middle…



Credit: Jillian Bornak

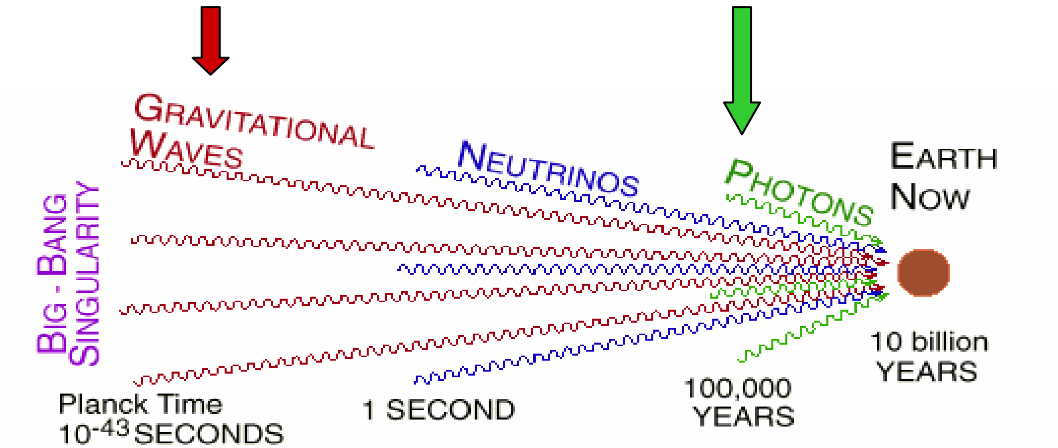


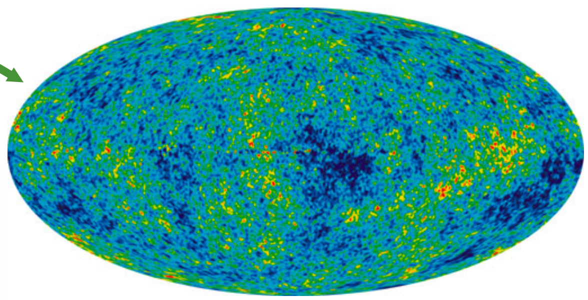
Sketch: Kip Thorne

One example: Stochastic sources

cosmic gravitational-wave background (10^{-22}s)

cosmic microwave background (10^{+12}s)

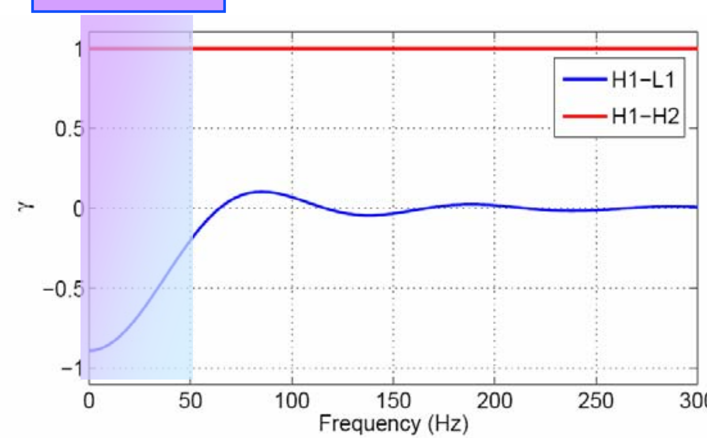




- Cosmological background from Big Bang (analog of CMB) most exciting potential origin, but not likely at a detectable level
- …or, Astrophysical backgrounds due to unresolved individual sources
- All-sky technique: cross-correlate data streams; observatory separation and instrument response imposes constraints
- Crucial to have two separated detectors!

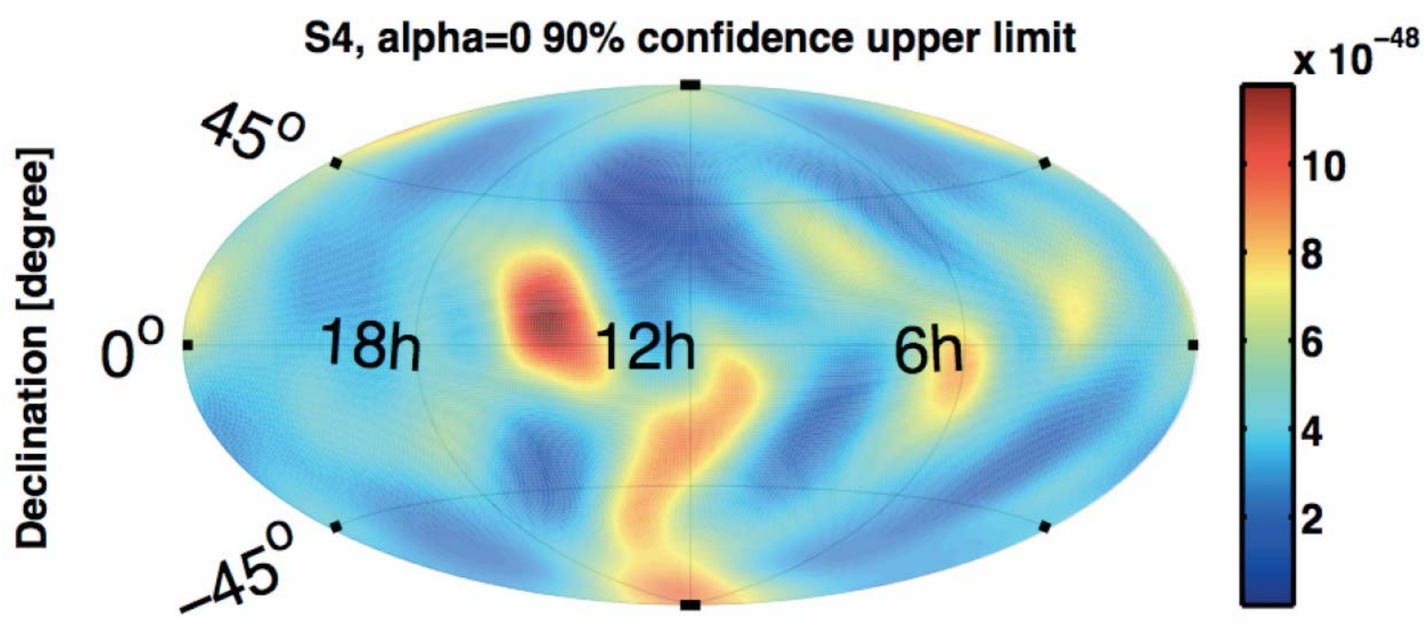
Seismic wall

“Overlap Reduction Function”
(determined by network geometry)



Stochastic sources

Upper limit map of gravitational wave stochastic background (using pair of instruments to ‘point’)



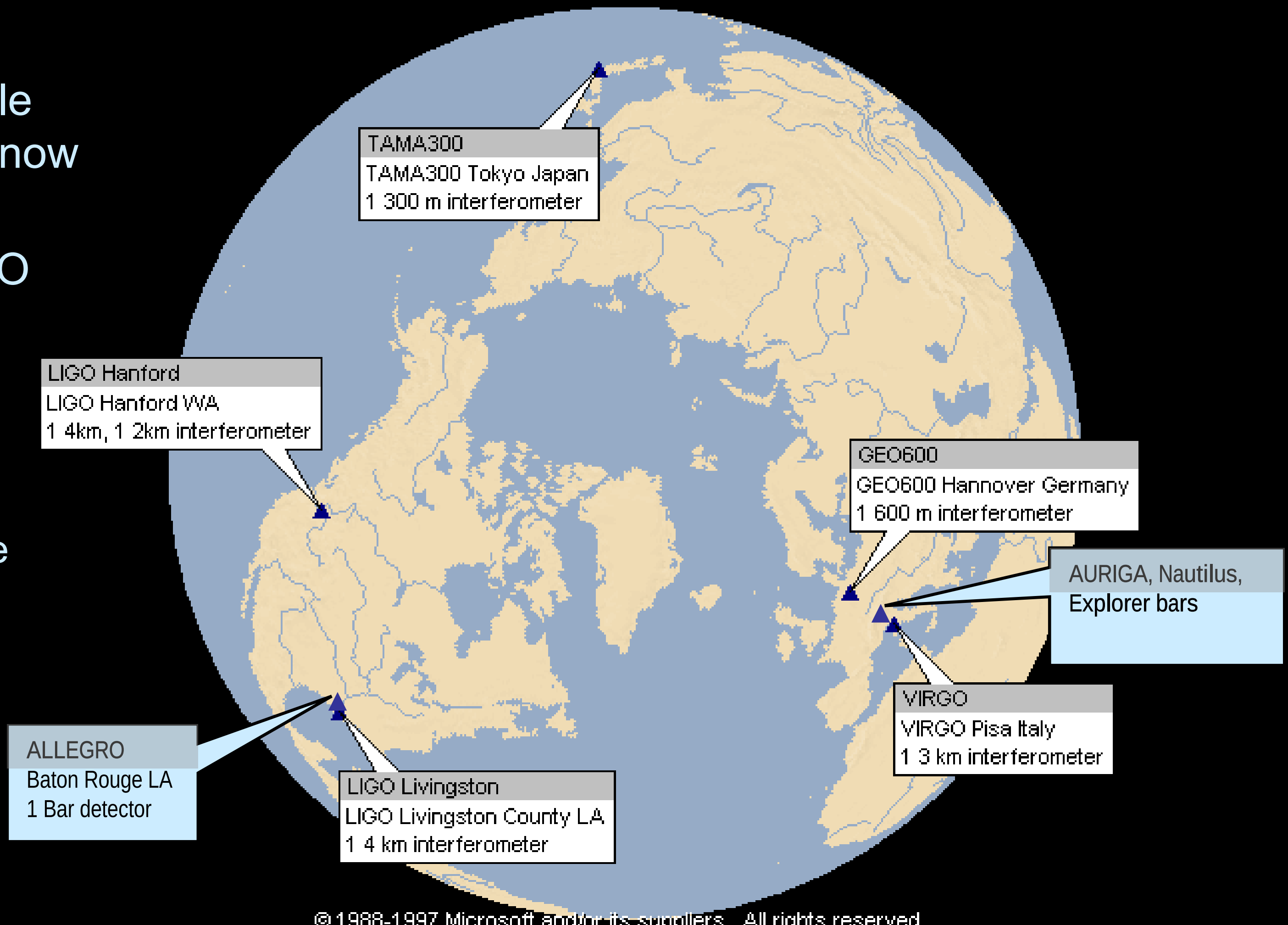
Current upper limit on gravitational wave stochastic background (preliminary):

$\Omega_{GW} < 9 \times 10^{-6}$

Comparable to Big Bang Nucleosynthesis upper limit;

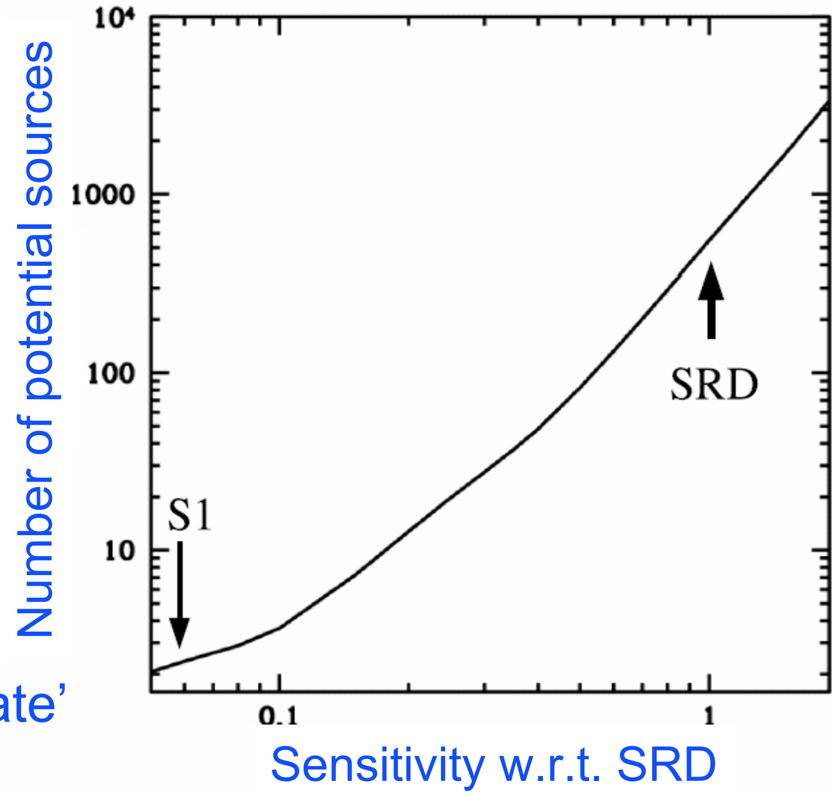
Observation with the Global Network

- Several km-scale detectors, bars now in operation
- Virgo-LIGO-GEO working closely
- Network gives:
  - » Detection confidence
  - » Sky coverage
  - » Duty cycle
  - » Direction by triangulation
  - » Waveform extraction

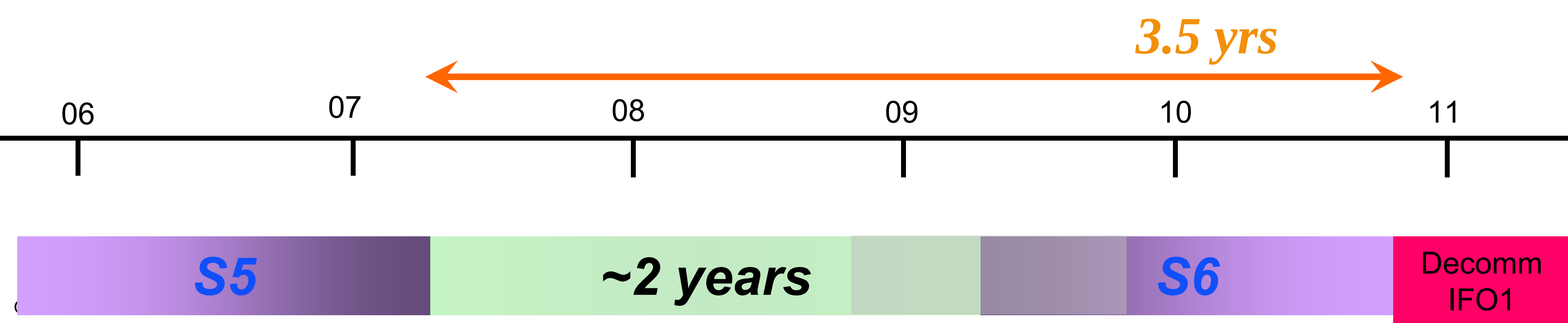


Moving beyond non-detections…

- Increases in sensitivity lead to (**Increases**)$^{\sim 3}$ in rate, so…
- Some enhancements to initial LIGO currently underway
- Increased laser power, associated technical changes
- Expect ~factor 2 in sensitivity, ~8 in 'rate'



- Install, commission during 2 years, then observe for ~1.5 years
- Be ready to decommission for start of **Advanced LIGO** installation



Advanced LIGO: 1989 Proposal

B. Evolution of LIGO Interferometers

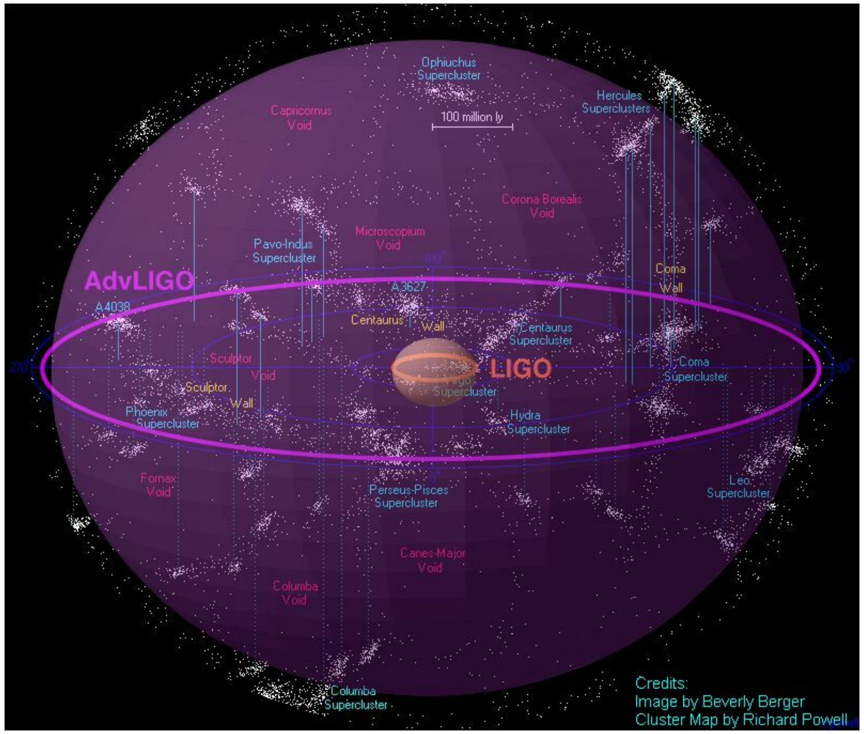
To detect gravitational waves, the use of high performance detectors in extended observational runs is necessary. Development of better detectors that enhance our ability to make new discoveries is also vital. A continuing detector development program is planned to improve LIGO capabilities. The design of the first LIGO interferometer emphasizes simplicity, so that we may place a detector in service as rapidly as possible; succeeding generations of interferometers will more fully exploit the unique capabilities of the LIGO.

2. Development of the second-generation LIGO detector

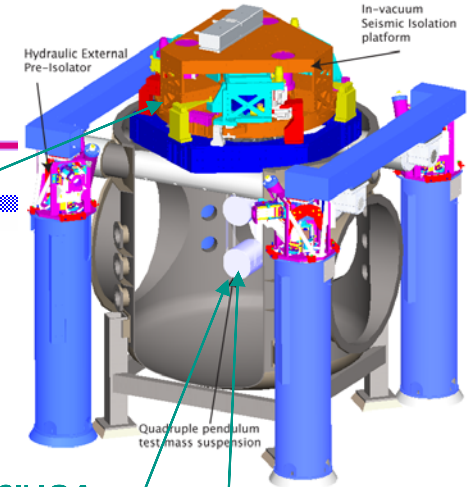
While the Mark I detector is going into operation, campus development of the second-generation LIGO detector, Mark II, will be proceeding. The Mark II design will include options not incorporated in Mark I and improvements based on the experience gained from operating Mark I. The advantages of new technology, made available after the Mark I design freeze, will be evaluated.

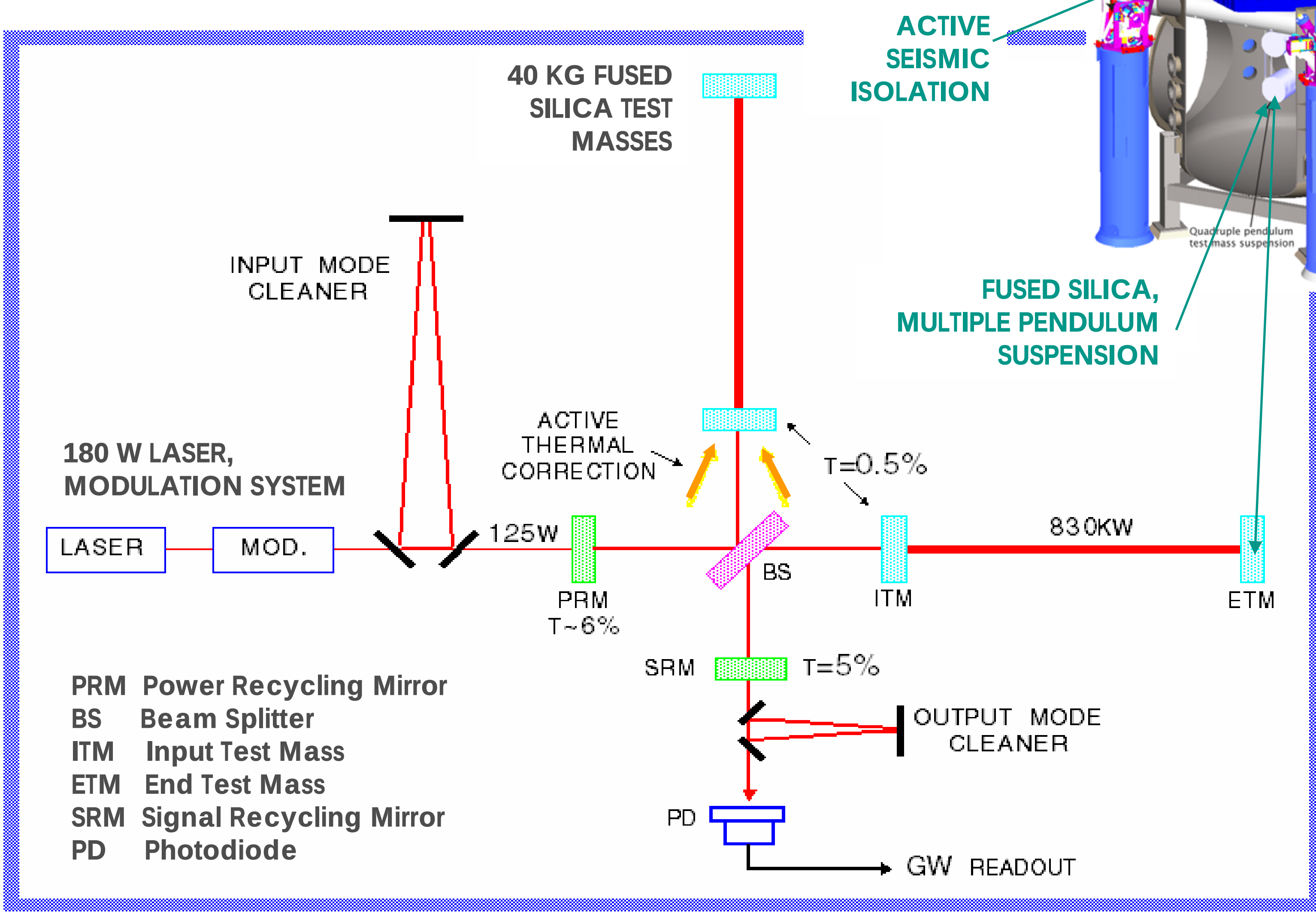
Advanced LIGO

- A significant step forward toward an astronomy of gravitational wave sources
- A factor of 10 in sensitivity, thus a factor of 1000 in rate
- …a year of observation with initial LIGO is equivalent to just several hours of observation with Advanced LIGO



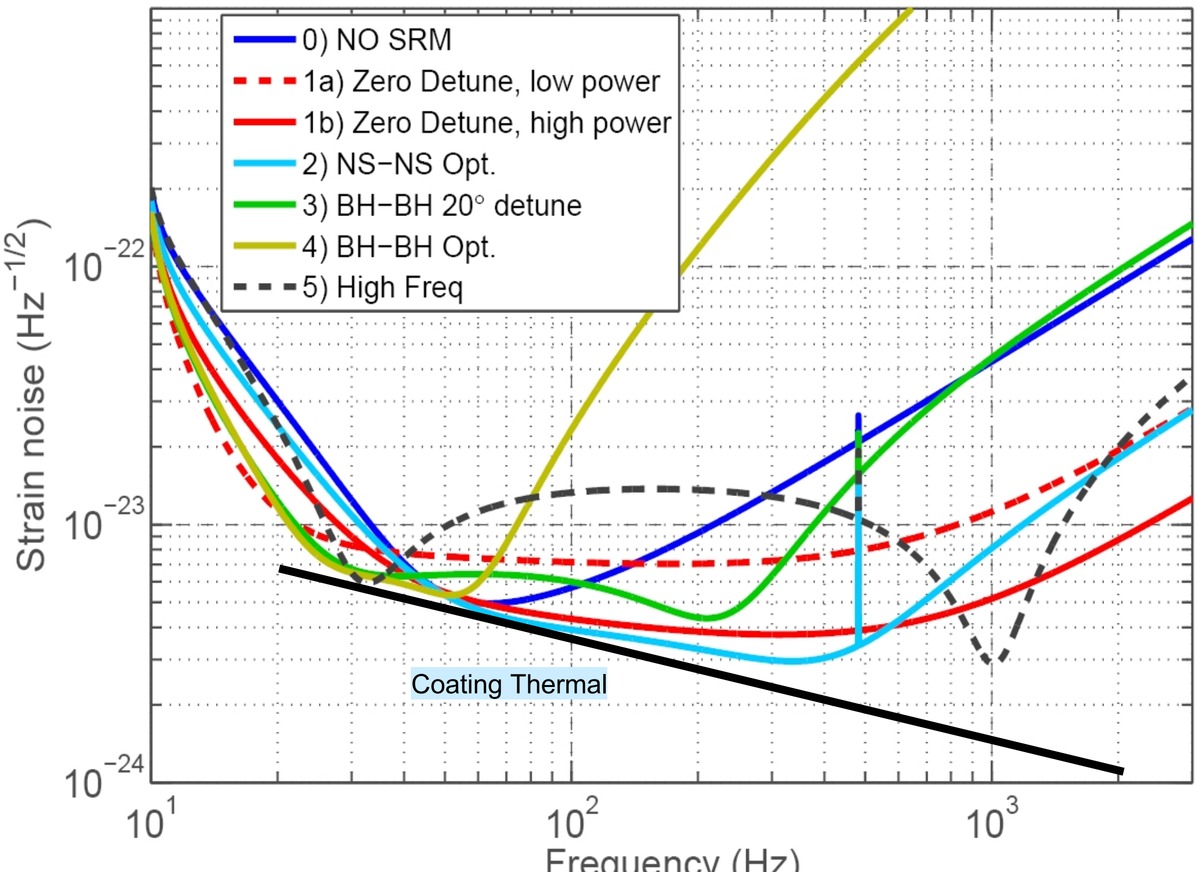
Advanced LIGO Design Features





Instrument tunabilty

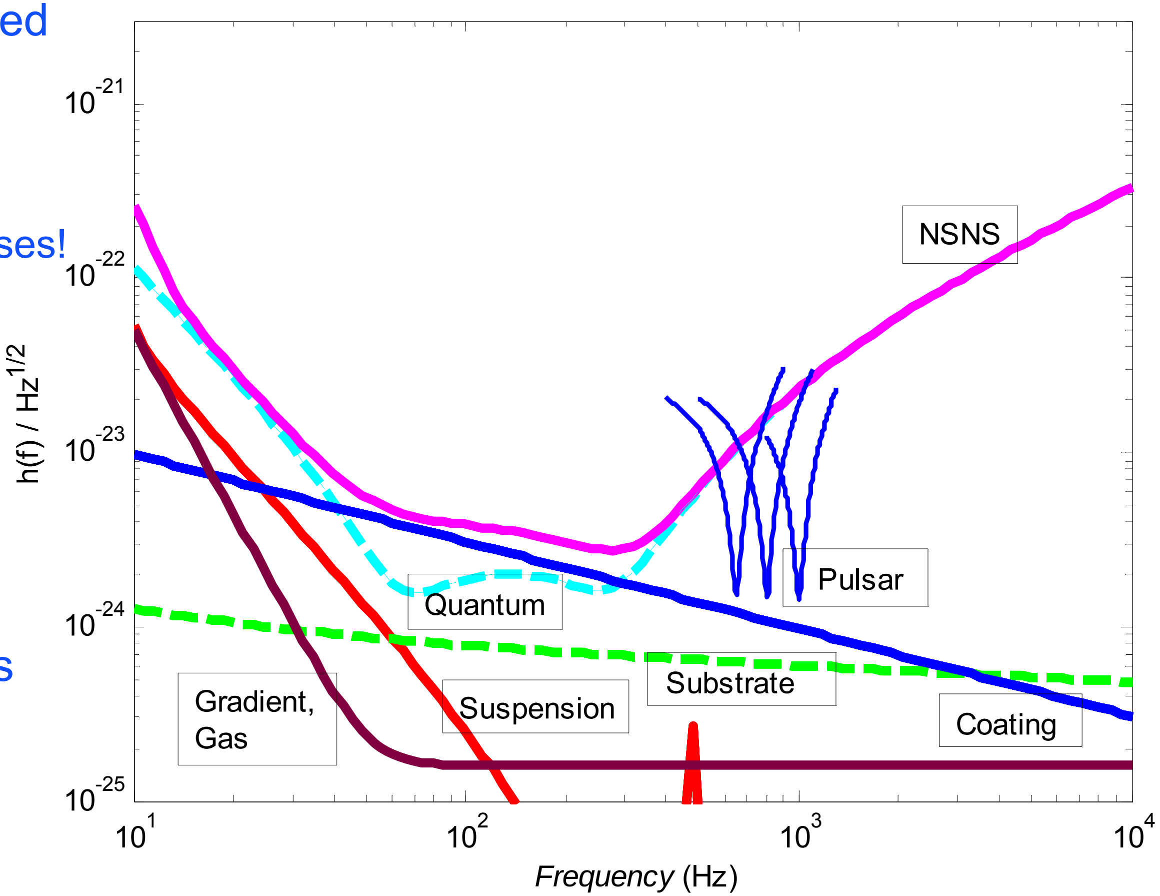
- Signal recycling cavity can cause GW-induced sidebands to resonate or not – allows targeting specific sources
- Creates an optical 'spring' due to photon pressure, coupling light phase and amplitude (and thus optomechanically 'squeezing' the light)



LIGO

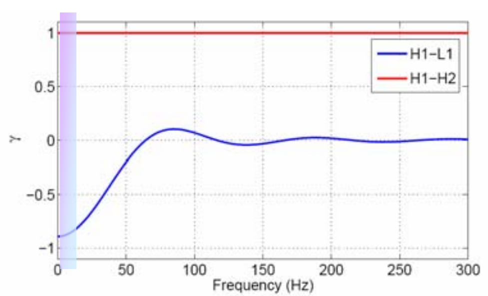
Instrumental limits

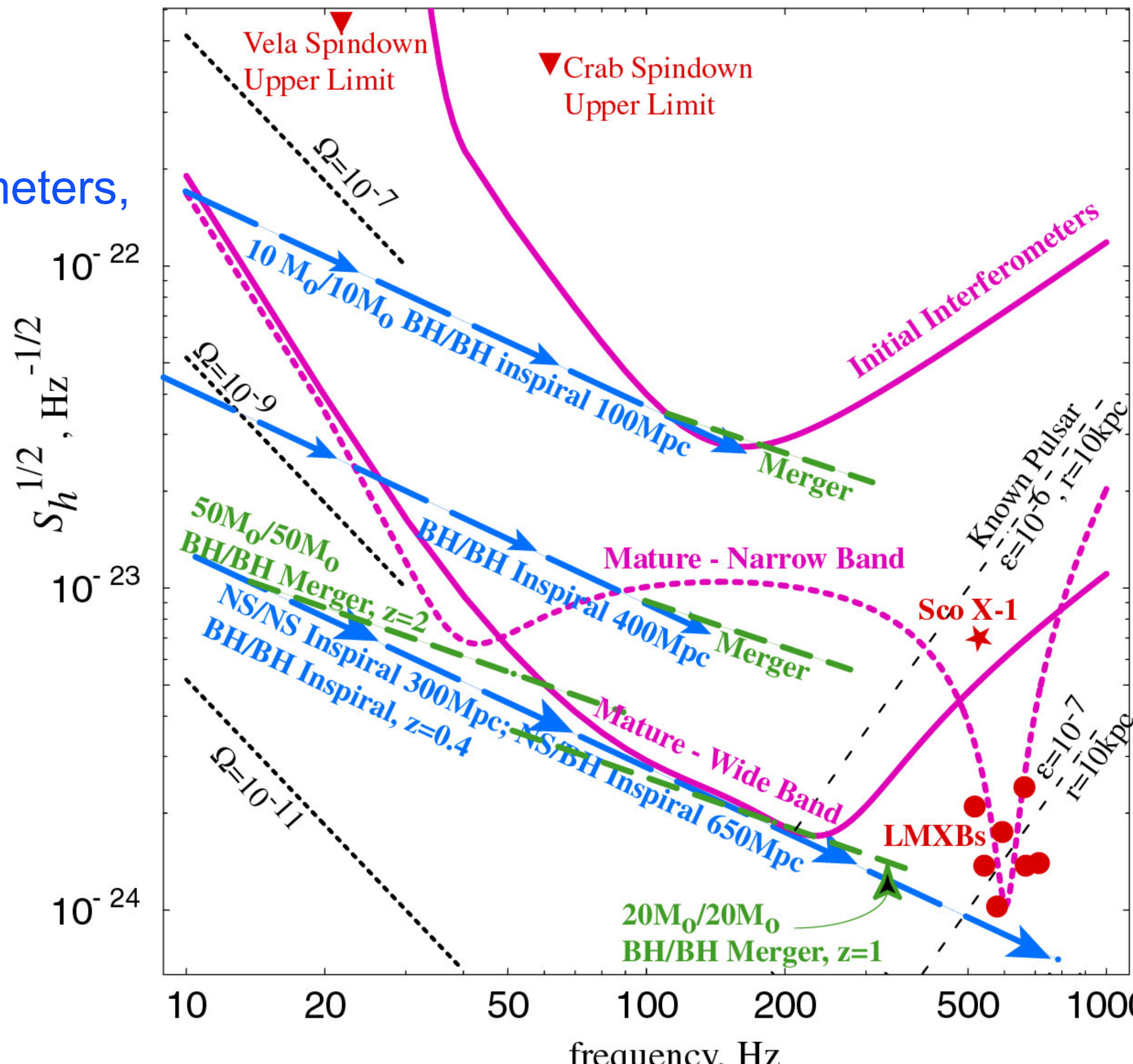
- Low-frequency performance limited by suspension thermal noise, gravity gradients, and buffeting by photons
  - » Measurable motion of 40kg masses!
- Mid-band performance limited by coating thermal noise – a clear opportunity for further development
- Performance at other frequencies limited by quantum noise (shot, or photon pressure)



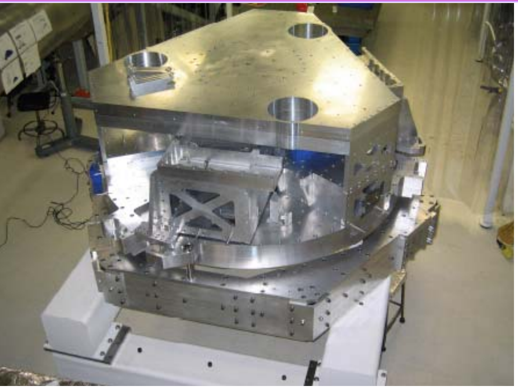
Advanced LIGO sensitivity

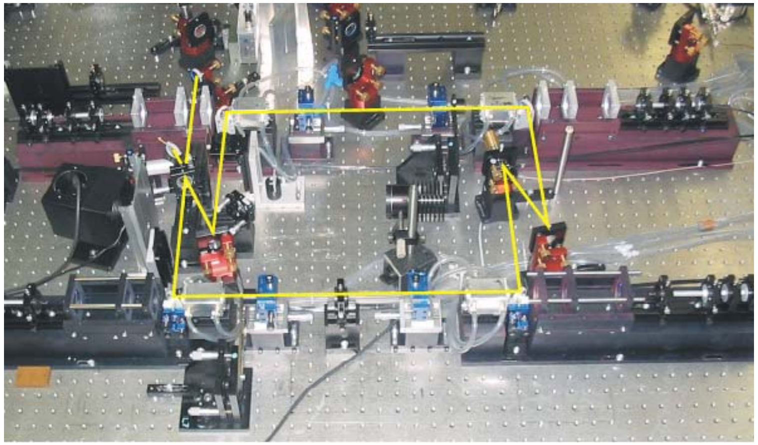
- Factor 10 better amplitude sensitivity
  - » (Reach)^3 = rate
- Factor 4 lower frequency bound
- Tunable for various sources
- NS Binaries: for three interferometers,
  - » Initial LIGO: ~20 Mpc
  - » Adv LIGO: ~300 Mpc, expect one event/week or so
- BH Binaries:
  - » Initial LIGO: 10 M_o, 100 Mpc
  - » Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - » Initial LIGO: Ω~3e-6
  - » Adv LIGO ~3e-9

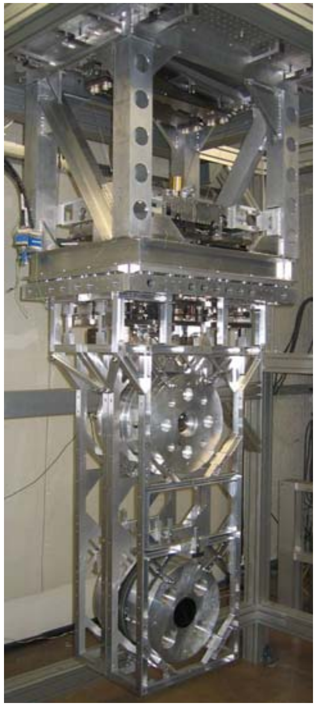


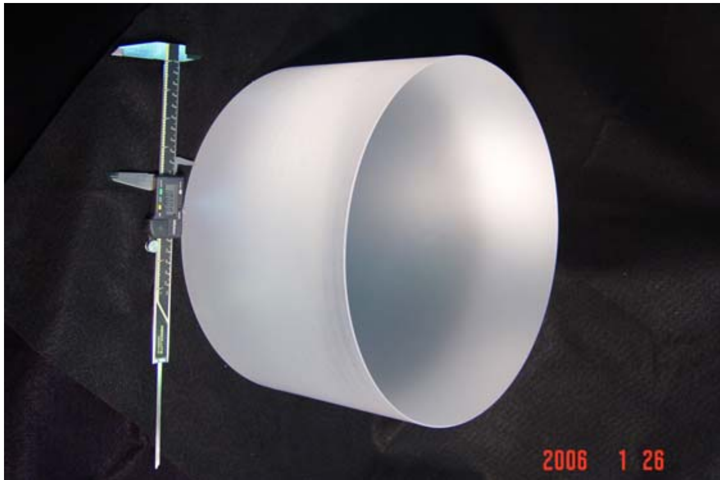


Advanced LIGO Prototypes





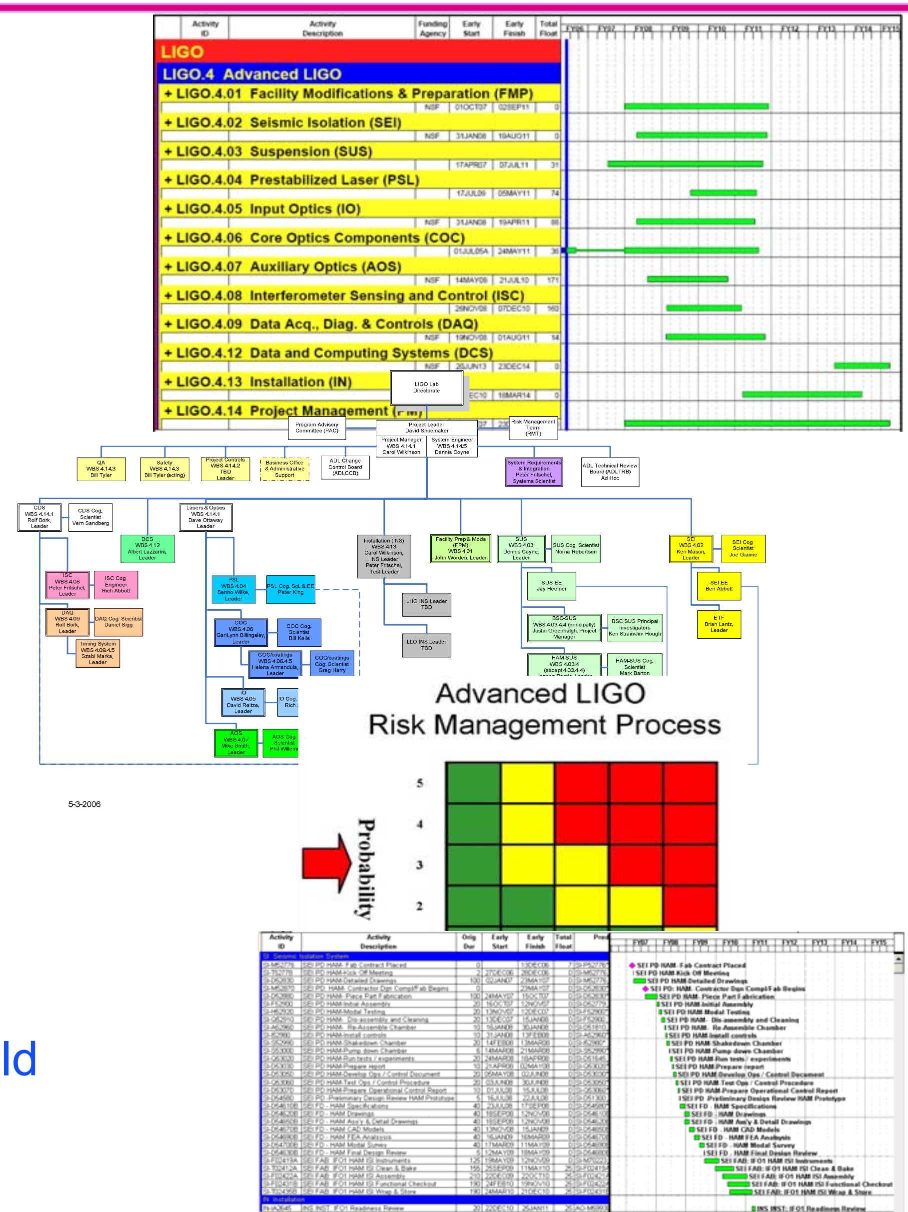




LIGO

Advanced LIGO status and timing

- International team of LIGO Laboratory, Scientific Collaboration scientists
- Supported by the US National Science Foundation ($205M), with additional contributions by UK PPARC and German Max Planck Society ($12M)
- Project started 1 April 2008 (no joke!)
- Decommissioning of initial LIGO in early 2011
- First Advanced LIGO instruments starting up in 2013
- Hoping, and planning, on parallel developments in other ‘advanced’ instruments to help form the second generation Network
- Advanced Virgo in planning stages, should be similar in sensitivity and schedule



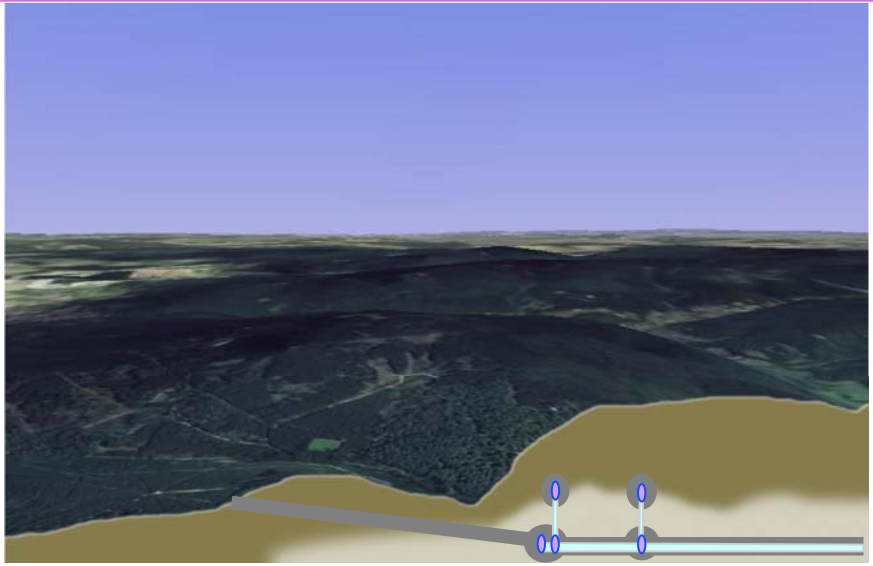
Roadmap for future Gravitational wave Observatories

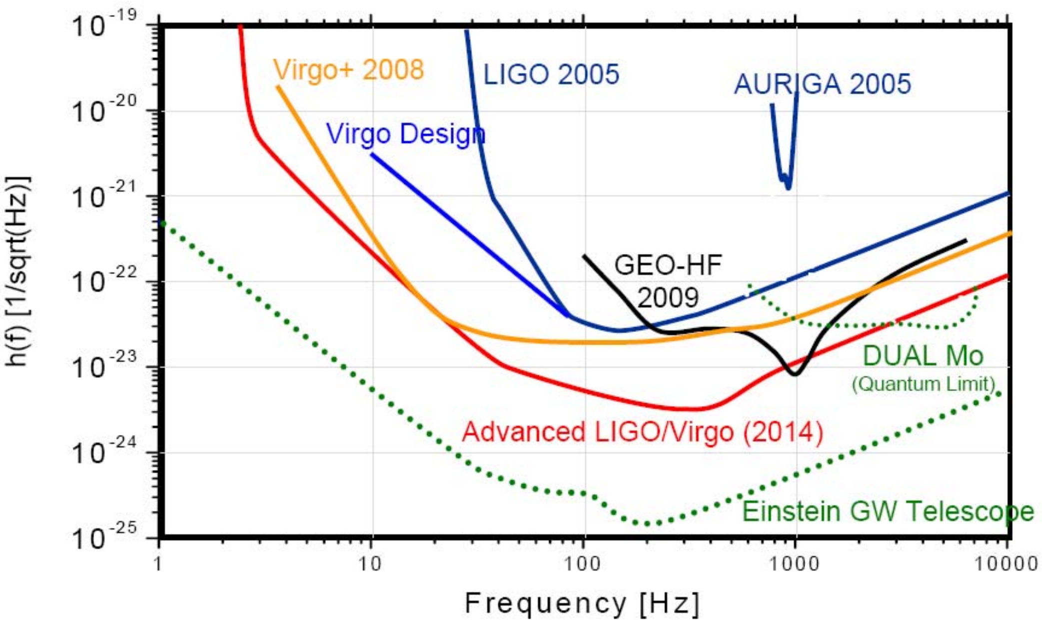
- Technical path understood for further significant improvements
- Interest in Europe, Asia, Australia, States
- Strong interest in a unified, coordinated program

…here is a sampling on a few pages….

- Einstein Observatory
  European 3rd generation detector –
  » Underground
    (lower seismic noise)
  » Cryogenic
    (lower thermal noise)
  » 30km arms
    (larger signals)

- Design study underway



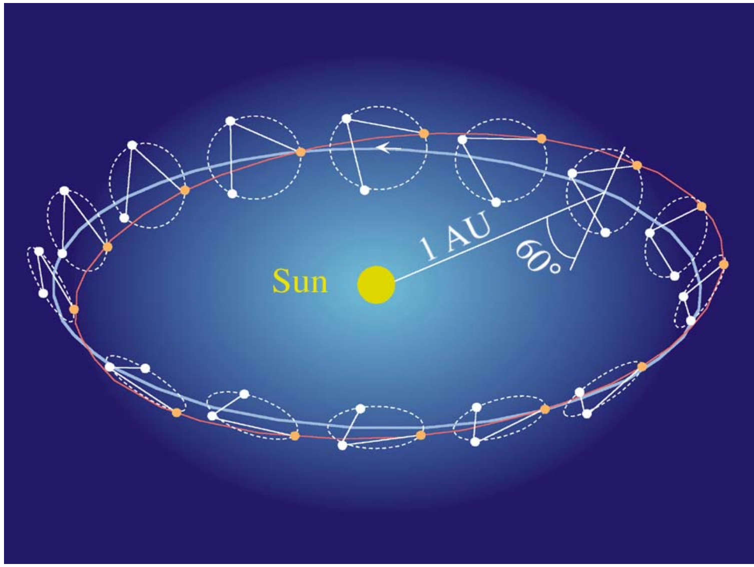


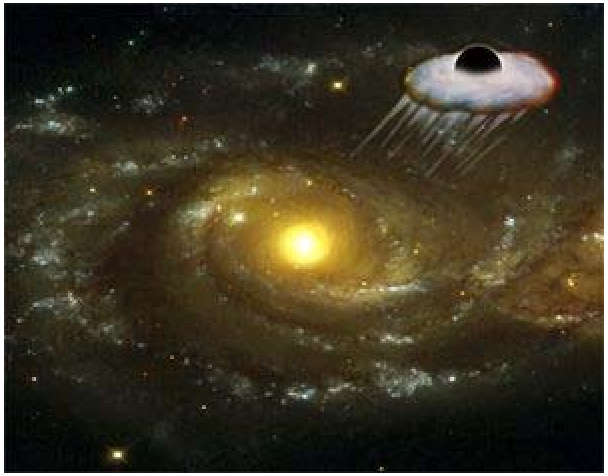
LIGO

LISA

Laser Interferometer Space Antenna

- Space-based antenna
  - » Three satellites in stable 1 AU orbit
  - » Great length → great strain sensitivity at low freqs.
- Sources by the thousands!
  - » Massive black holes: 10^2 - 10^7 $M_\odot$, $z < 20$, 10's to 100 per year
  - » Extreme mass ratio inspirals: ~$10/10^6$ $M_\odot$, $z < 1$, 10's to 100 per year
  - » Ultra-compact binaries: galactic and extra-galactic, 10,000's, confusion foreground
  - » Cosmological back-grounds, bursts and unforeseen sources
- LISA Pathfinder – technology demonstration
  - » Launch date: July 2010
  - » ESA led, with NASA microthruster package
- LISA
  - » Planned launch: 2018, in Phase A
  - » NASA: Physics of the Cosmos
  - » ESA: Cosmic Vision Programme





Ejection from the nucleus: for the first time in nature, astronomers have observed a supermassive black, which - propelled by gravitational waves - leaves its parent galaxy. The illustration depicts this scenario. ApJ Lett, 10May08

Future potential for space missions: **DECIGO**

FP-Michelson interferometer

Arm length: 1000 km

Laser power: 10 W

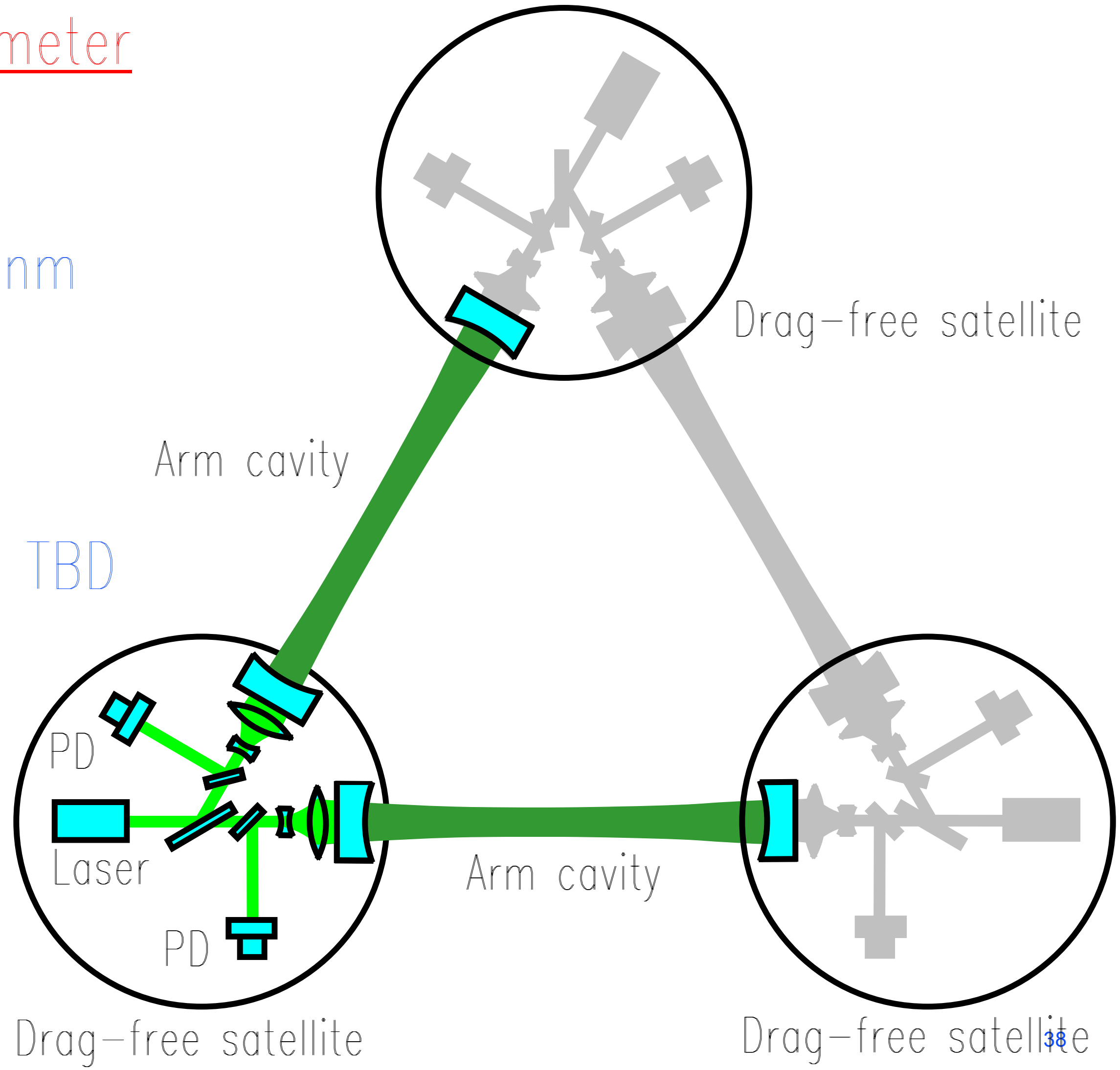
Laser wavelength: 532 nm

Mirror diameter: 1 m

Mirror mass: 100 kg

Finesse: 10

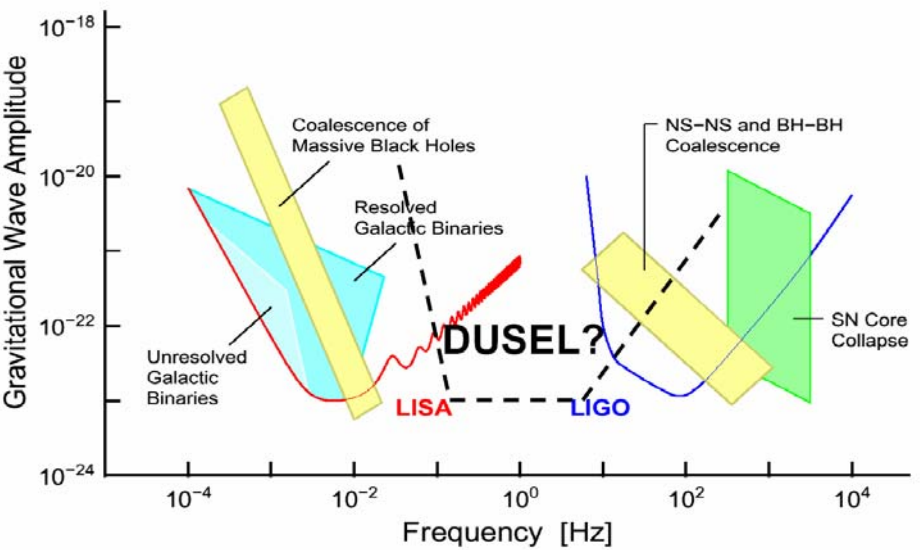
Orbit and constellation: TBD

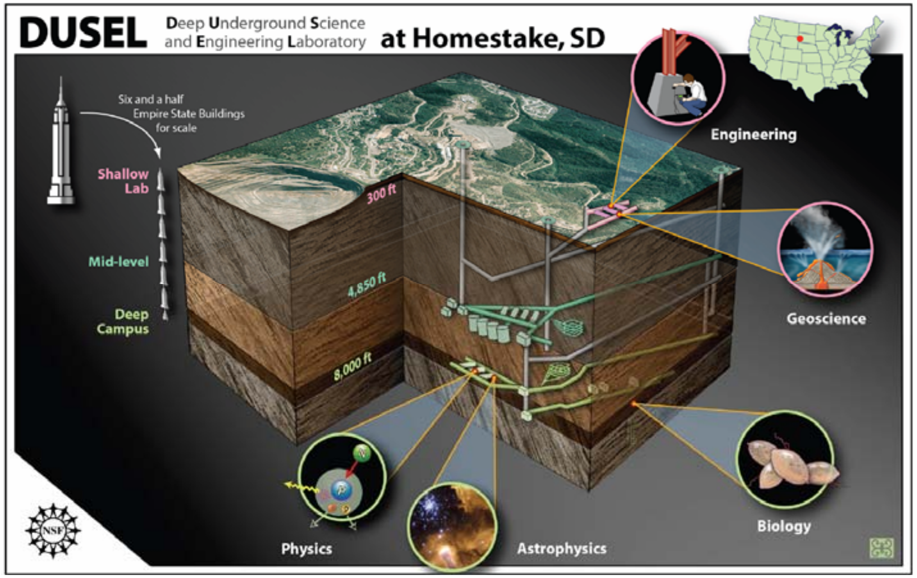


Kawamura, et al., CQG 23 (2006) S125-S131

"DUSELdorf"

- Characterization of (proposed) DUSEL as a possible underground site for US 3rd generation instrument

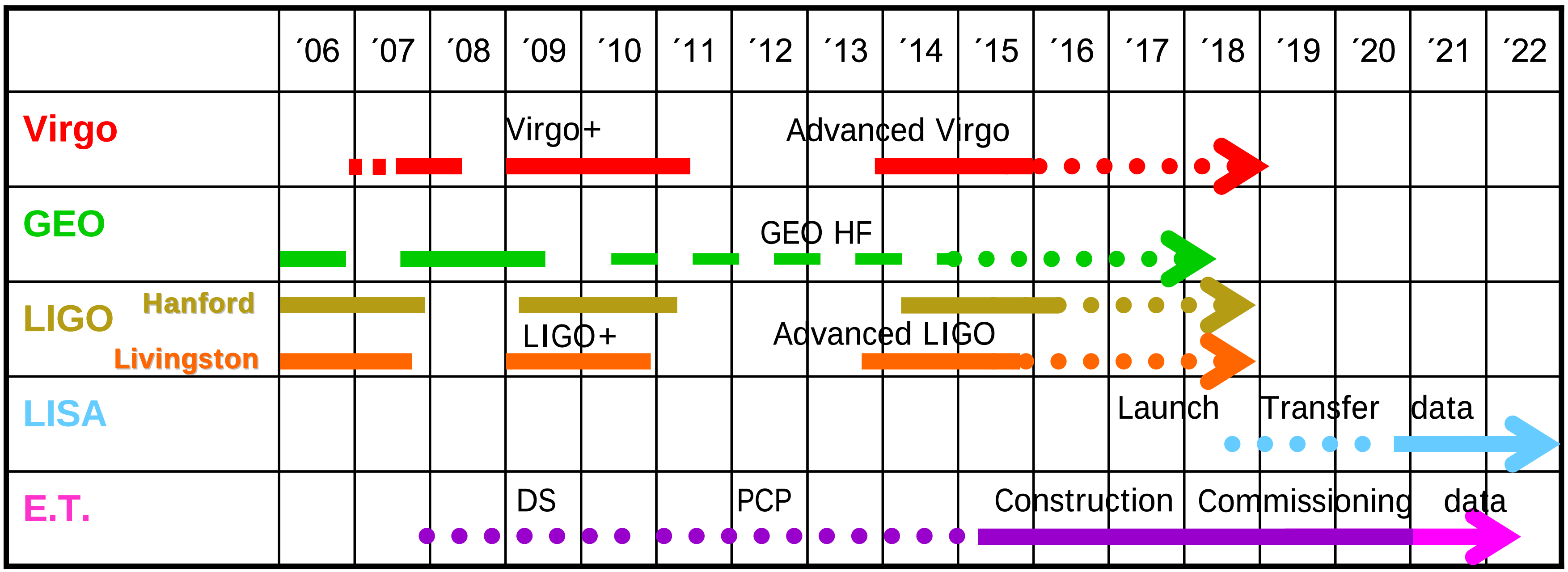




- Seismic noise, and (more importantly) gravity gradients much smaller
- May allow detection of the gravitational wave cosmological ('Big Bang') stochastic background from the ground

When could all this happen?

- Virgo, GEO, LIGO timelines rather definite
- LISA , DECIGO, and Einstein Telescope (‘E.T’) rather less so…
- Can say with some confidence that detections by the former will be a strong boost to the latter



Gravitational wave Detection

- LIGO – the Lab, the Collaboration, and the instruments – are in full swing

- Sensitivity (along with data quality, duty cycle, and duration) is such that detections are plausible – some reasonable expectation that a LIGO presentation soon will be able to include this 'little step forward'

- A network of instruments is growing, allowing broad physics to be extracted from the detectors, and LIGO is pleased to be a central element

- Steps forward in sensitivity are currently in construction which should move us from novelty detection to astrophysical tool