# Gravitational wave detectors

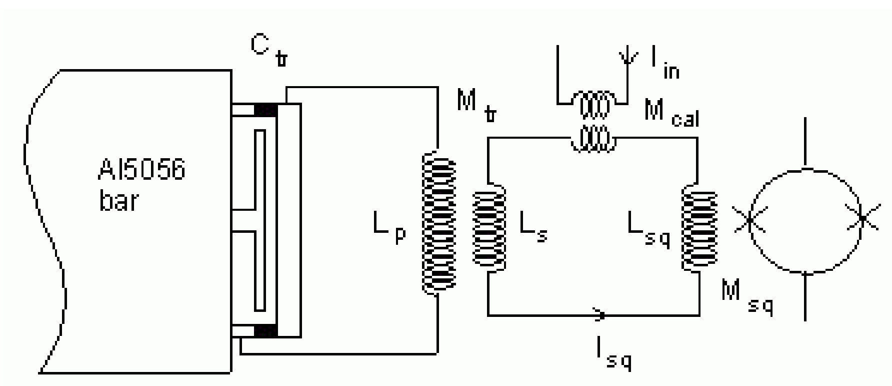
- Bar detectors
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large "bell", set ringing (at ~ 900 Hz) by GW
  - Won't discuss any further, here
- Michelson interferometers
  - At least 4 independent discovery of method:
  - Pirani `56, Gerstenshtein and Pustovoit, Weber, Weiss `72
  - Pioneering work by Weber and Robert Forward, in 60's

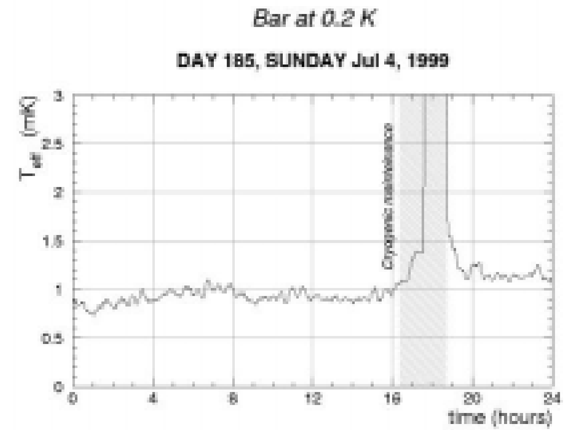
# Resonant bar detectors

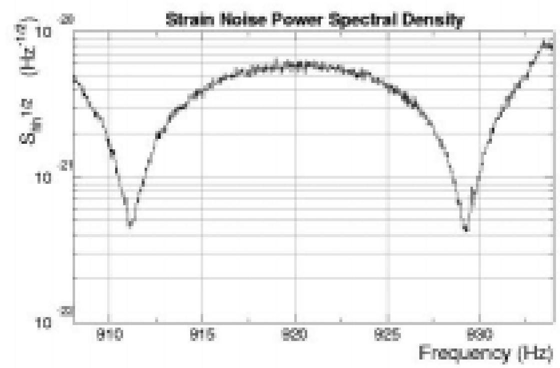
- AURIGA bar near Padova, Italy
(typical of some ~6 around the world – Maryland, LSU, Rome, CERN, UWA)
- 2.3 tons of Aluminum, 3m long;
- Cooled to 0.1K with dilution fridge in LiHe cryostat
- $Q = 4\times10^6$ at < 1K
- Fundamental resonant mode at ~900 Hz; narrow bandwidth
- Ultra-low-noise capacitive transducer and electronics (SQUID)

# AURIGA Resonant bar sensitivity

- Capacitive resonant transducer
- Superconducting matching transducer
- dc-SQUID amplifier

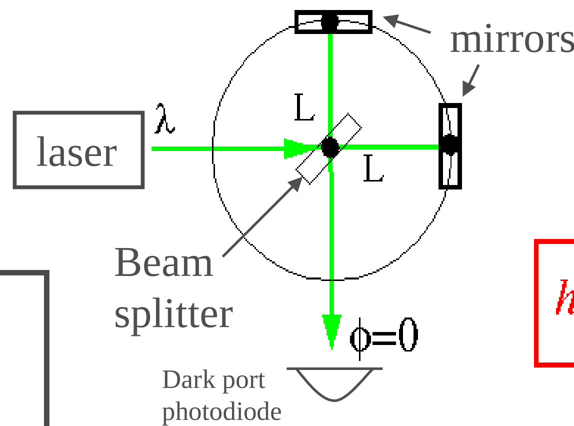


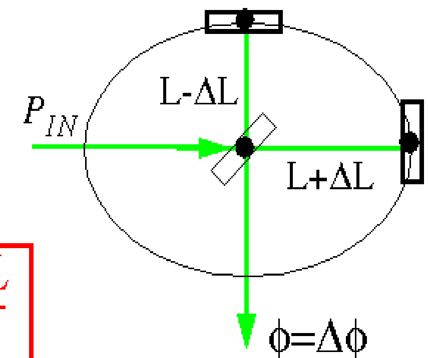



# Interferometric detection of GWs

GW acts on freely falling masses:



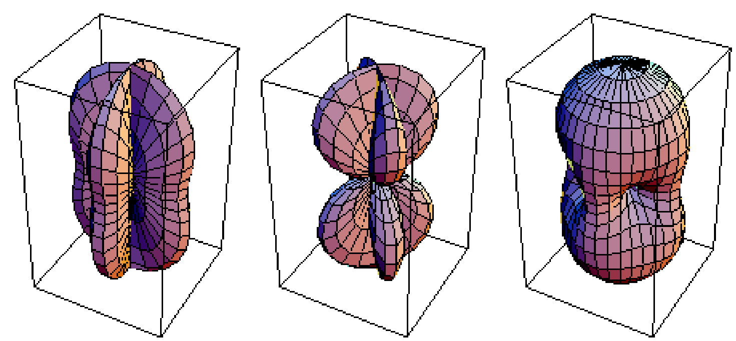




$$h = \frac{\Delta L}{L}$$

For fixed ability to measure *ΔL*, make *L* as big as possible!

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

Antenna pattern:
(not very directional!)

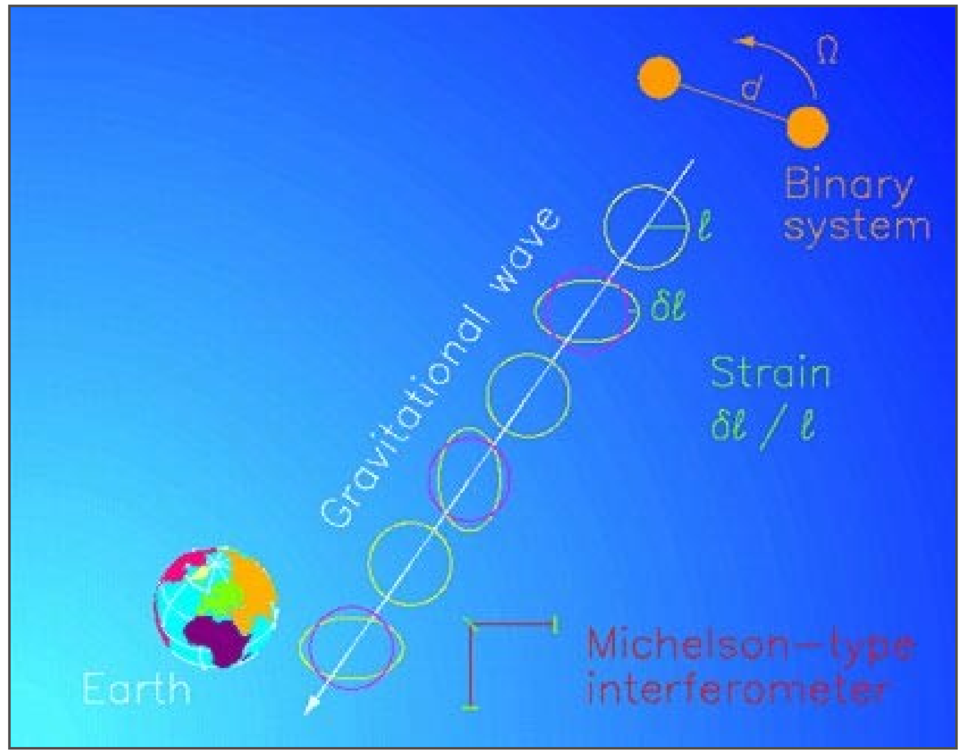


+ polarization × polarization unpolarized

# Terrestrial Interferometers

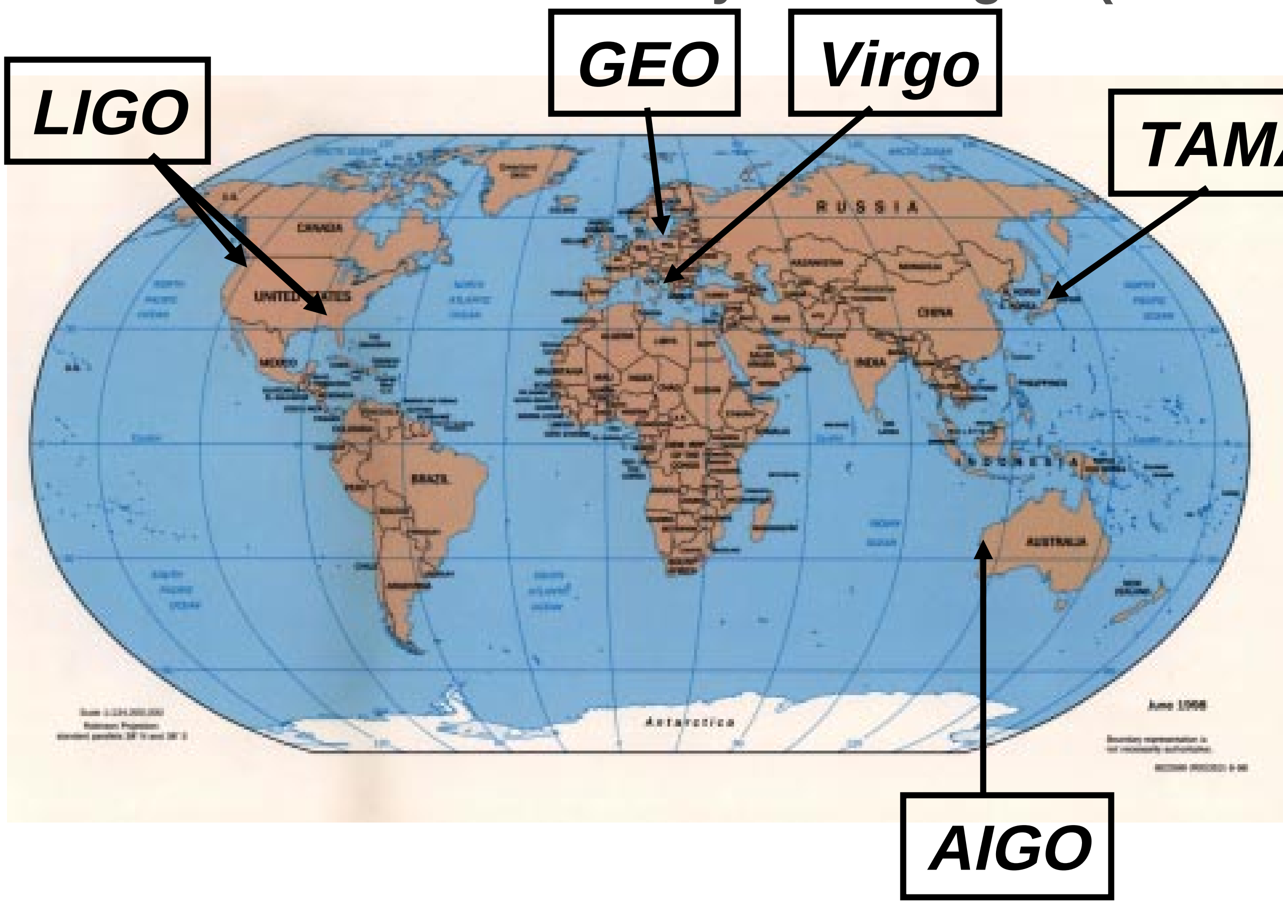
**Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources**

**International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.**



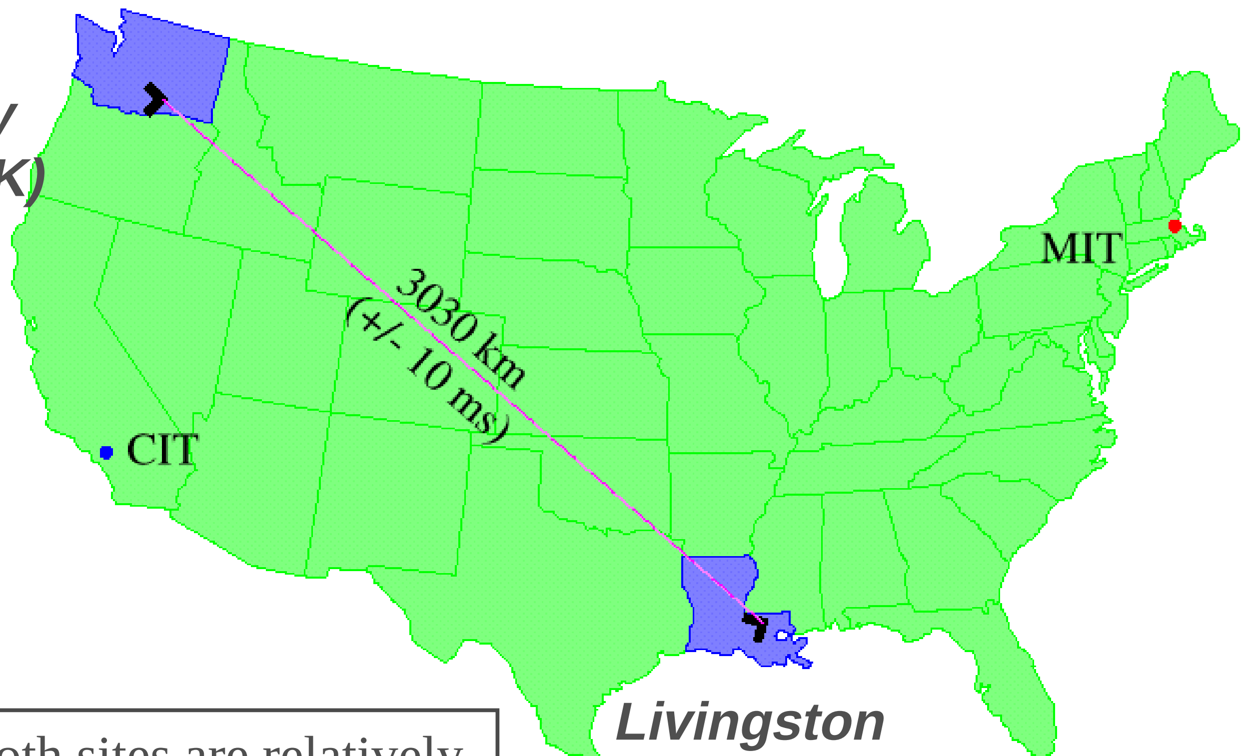
# International network

**Simultaneously detect signal (within msec)**




- **detection confidence**
- **locate the sources**
- **verify light speed propagation**
- **decompose the polarization of gravitational waves**

# LIGO sites




***Hanford Observatory (H2K and H4K)***

Hanford, WA (LHO)

- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA
- Two IFOs: H2K and H4K

Livingston, LA (LLO)

- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA
- One L4K IFO

Both sites are relatively seismically quiet, low human noise

***Livingston Observatory***

# LIGO Livingston (LLO)

- 30 miles from Baton Rouge, LA (LSU)
- forested, rural area
- Commercial logging, wet climate
- need moats (with alligators)
- Seismically quiet, low human noise level

# LIGO Hanford (LHO)

• DOE nuclear reservation

• treeless, semi-arid high desert

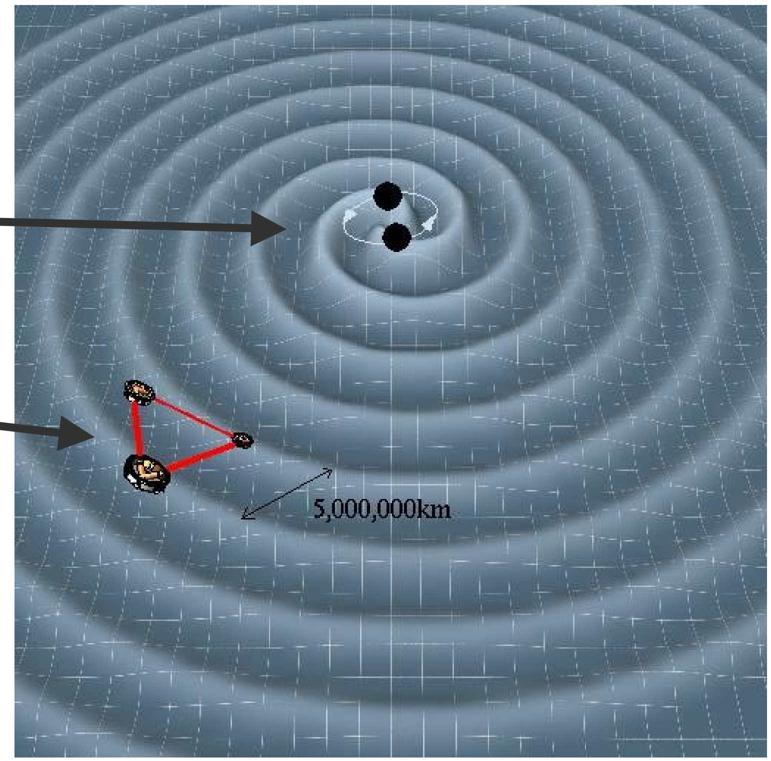
• 15 miles from Richmond, WA

•Seismically quiet, low human noise level

# Laser Interferometer Space Antenna (LISA)

**Radiation of Gravitational Waves from binary inspiral system**

***LISA***

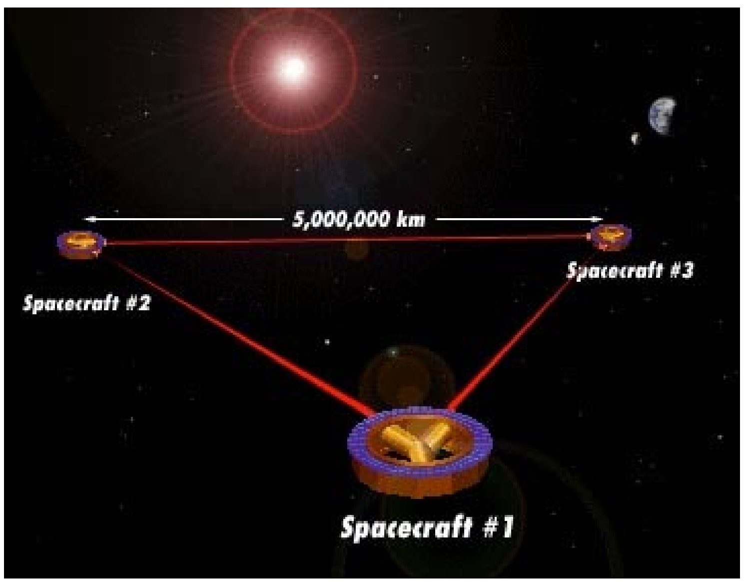


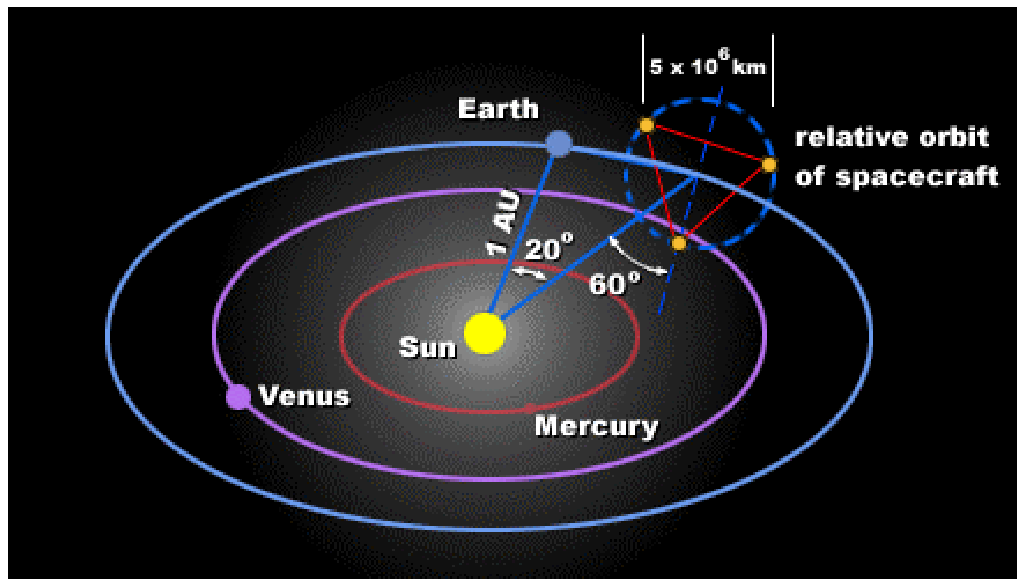

| | | |
|---|---|---|
| Coalescence of massive black holes during collisions between galaxies, perhaps in formation of massive black holes, probing the central engines powering quasars. | Black holes orbiting massive black holes, providing precision tests of gravitational theory in the high-field limit. | Hundreds of galactic binary star systems, many containing neutron stars or black holes, including several known binary systems. |

# The Laser Interferometer Space Antenna
# LISA

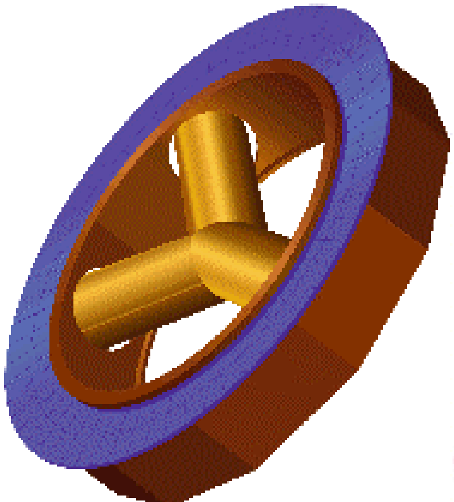
Three spacecraft in orbit about the sun, with 5 million km baseline

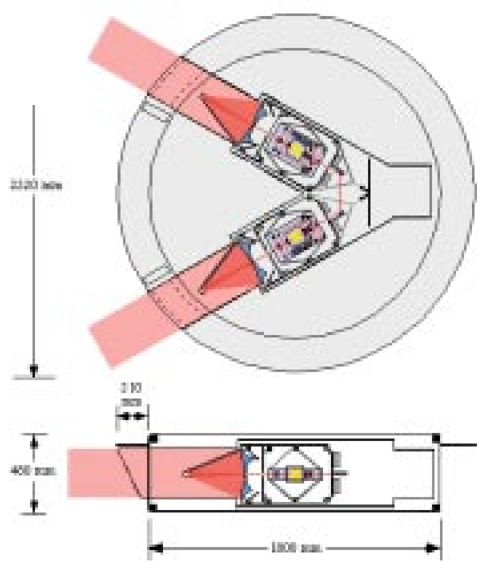
The center of the triangle formation will be in the ecliptic plane 1 AU from the Sun and 20 degrees behind the Earth.

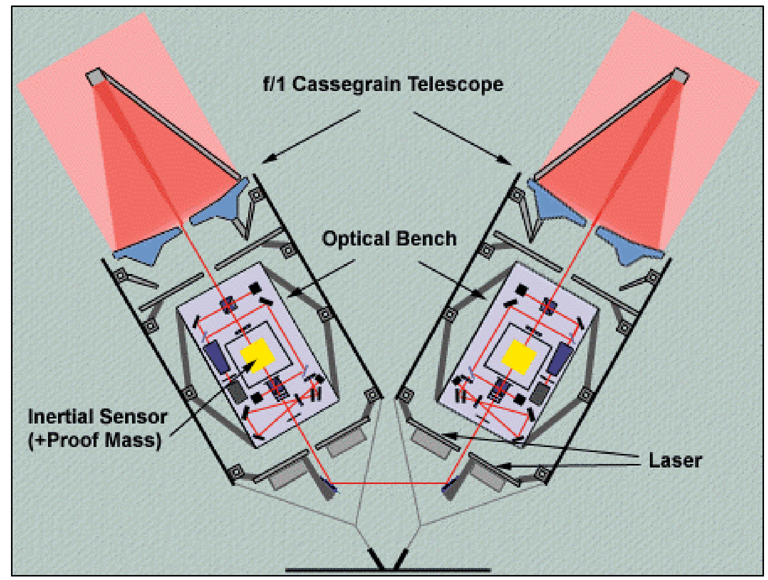


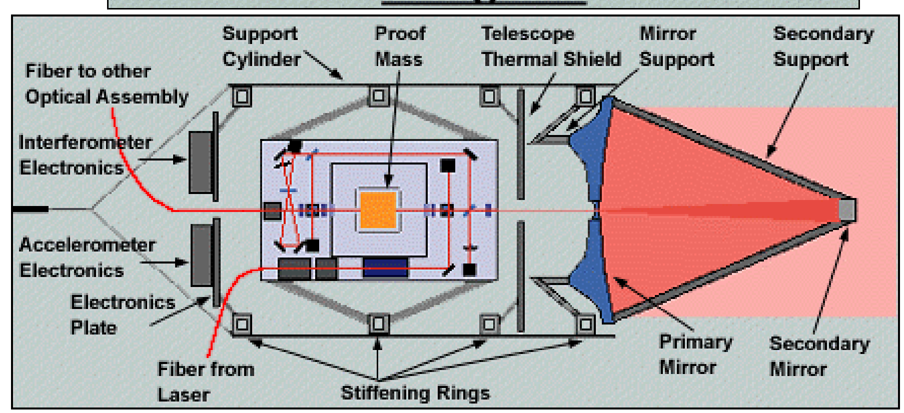



# LISA Spacecraft



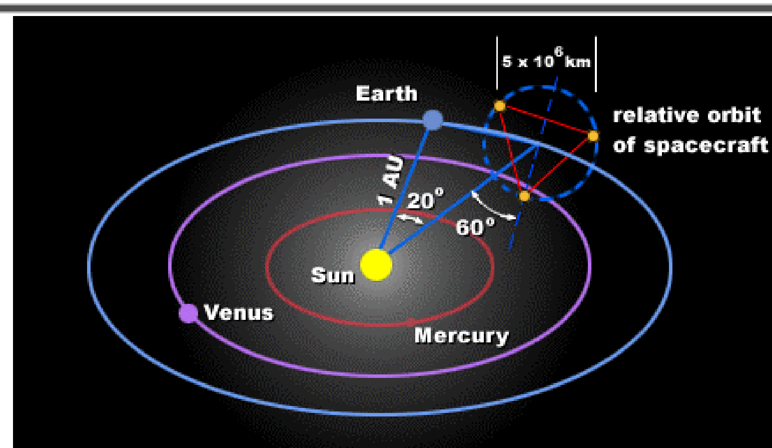


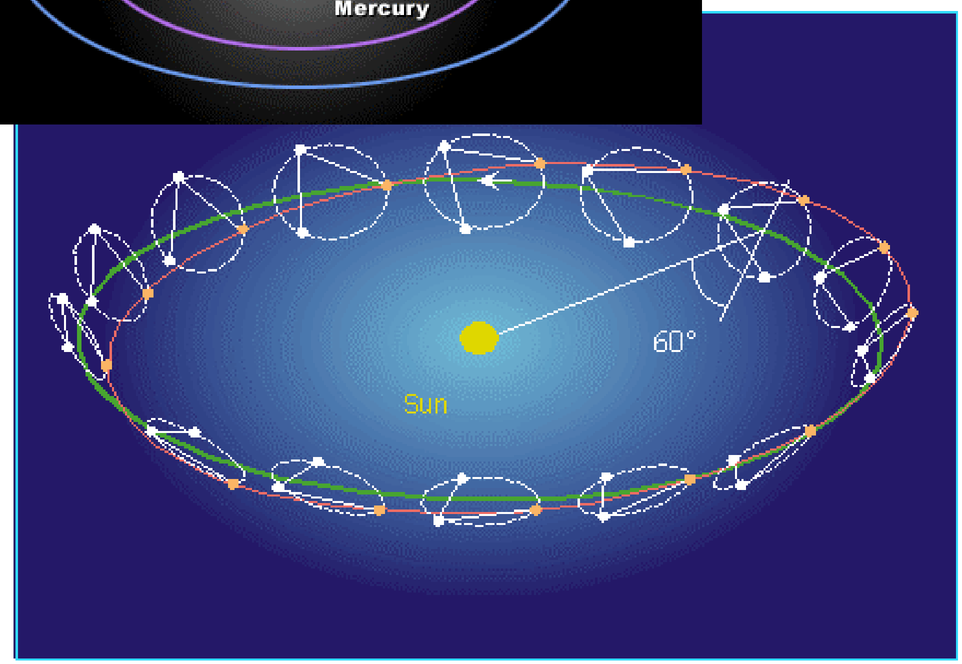


# LISA orbit

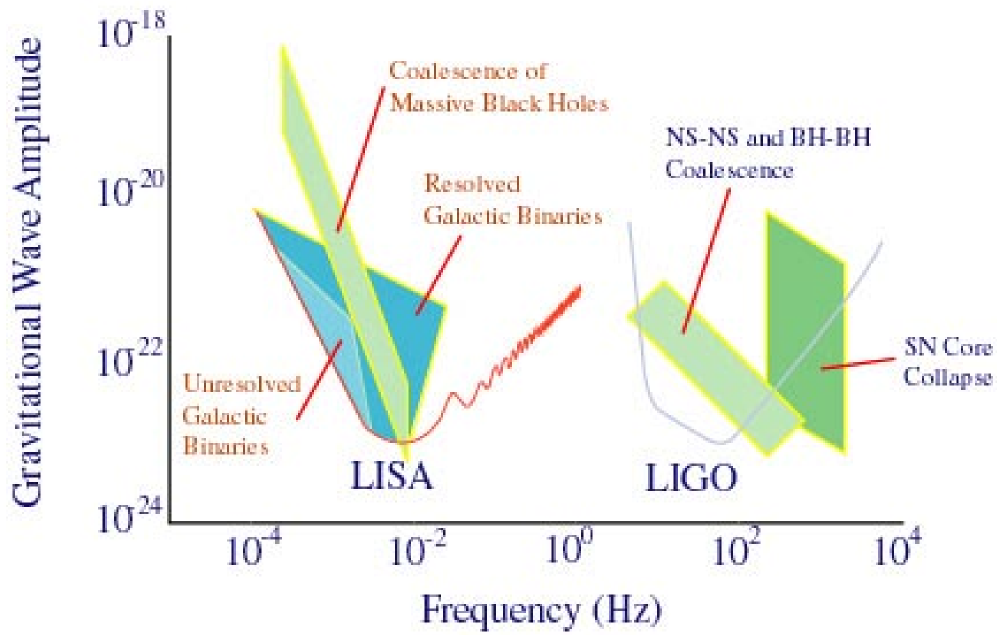
The orbit of the "triangle" of spacecraft *tumbles* as it orbits the sun, to be sensitive to all directions in the sky, and to even out the thermal load (from the sun) on the three spacecraft.



# Sensitivity bandwidth

- EM waves are studied over ~20 orders of magnitude
  - » (ULF radio –> HE $\gamma$ rays)
- Gravitational Waves over ~10 orders of magnitude
  - » (terrestrial + space)

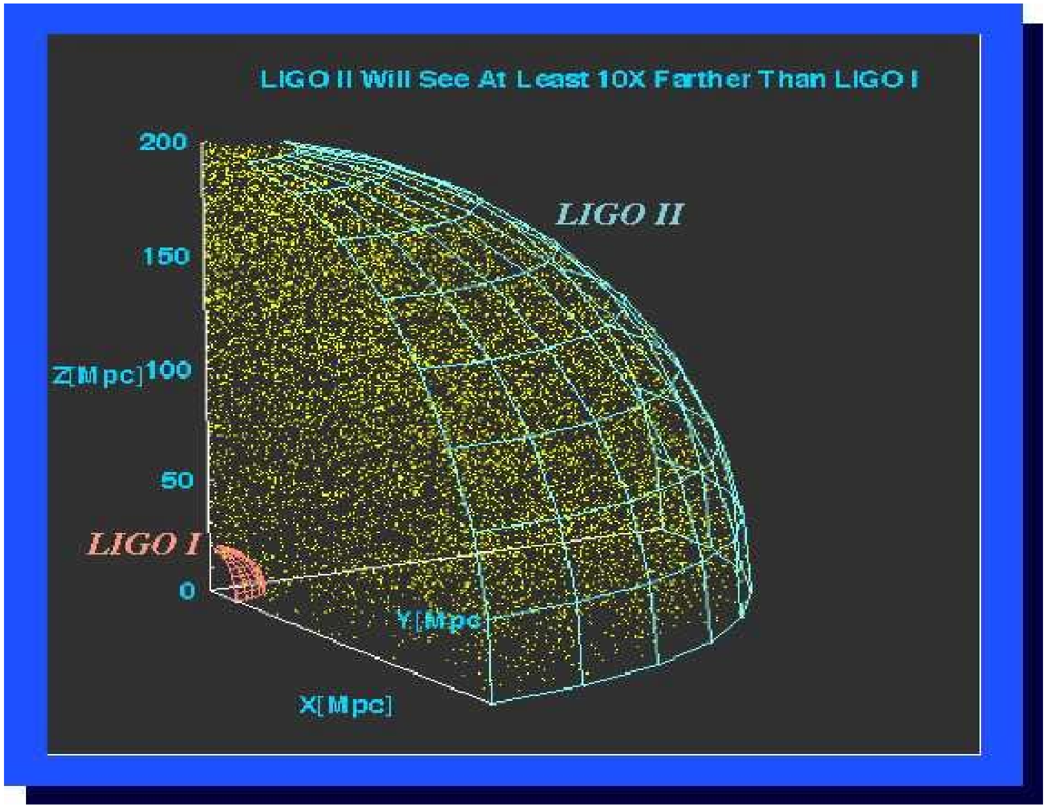


# How far out can we see?

**Improve sensitivity by a factor of 2x, and…**

⇒ Improve sensitivity to distance by 2x ($h \sim 1/r$)

⇒ Number of sources goes up 8x ($1/r^3$) !



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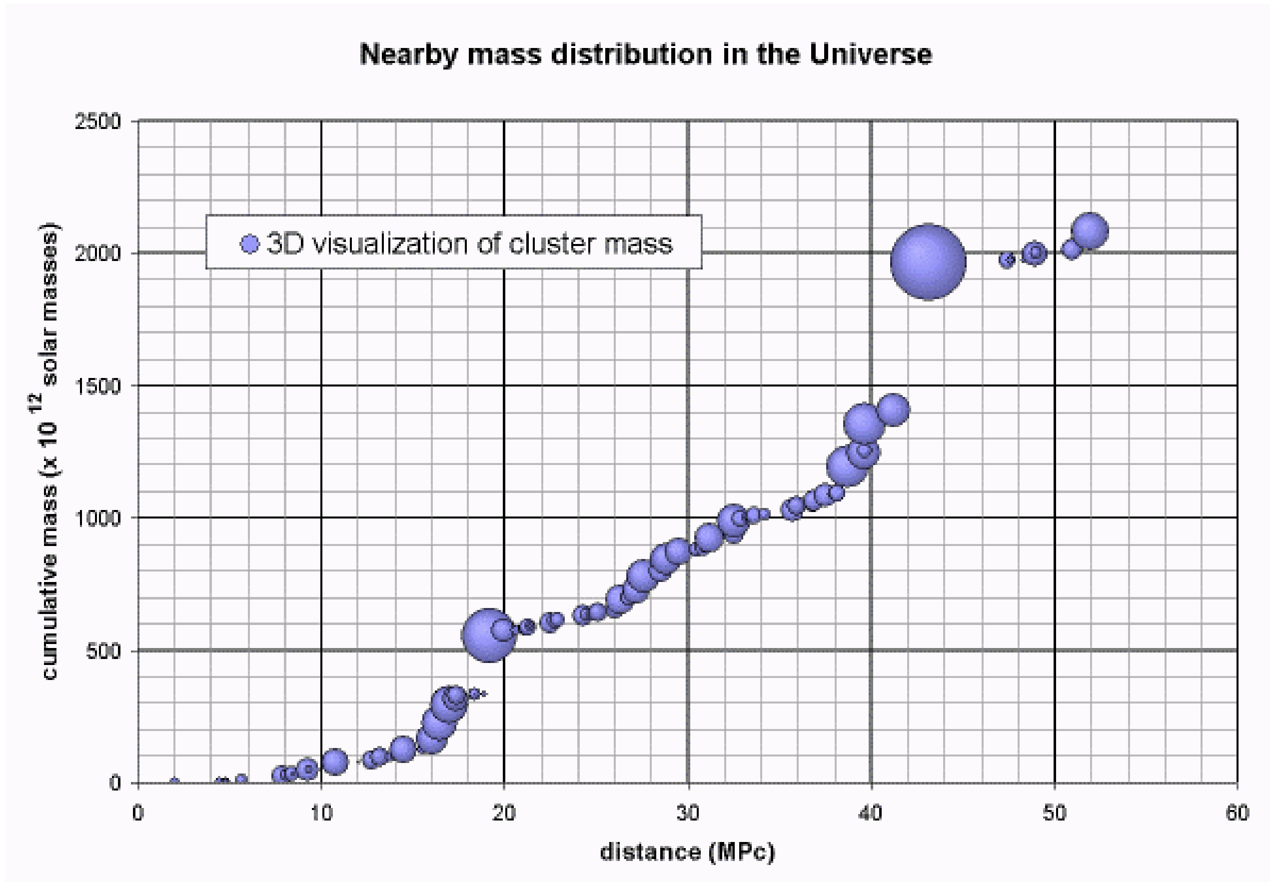
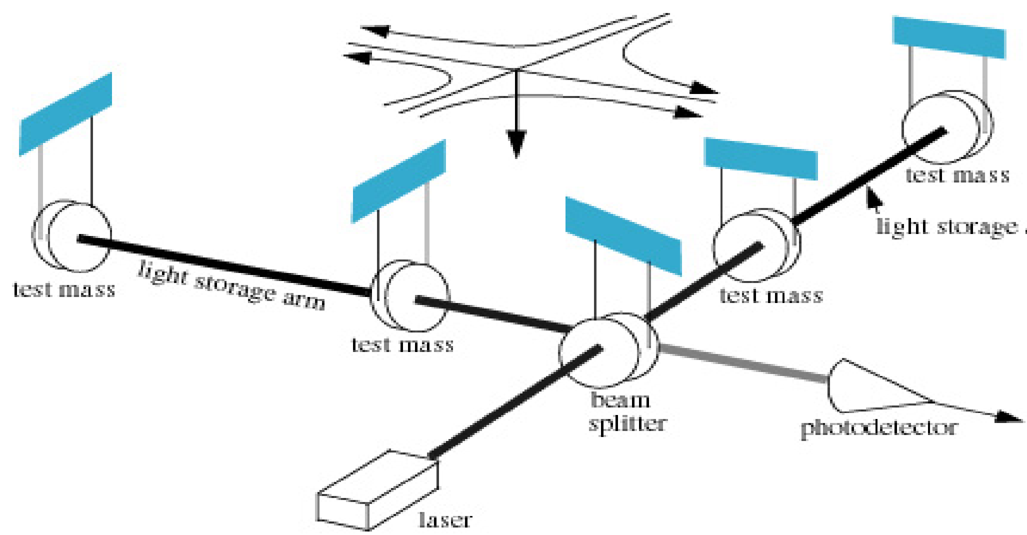
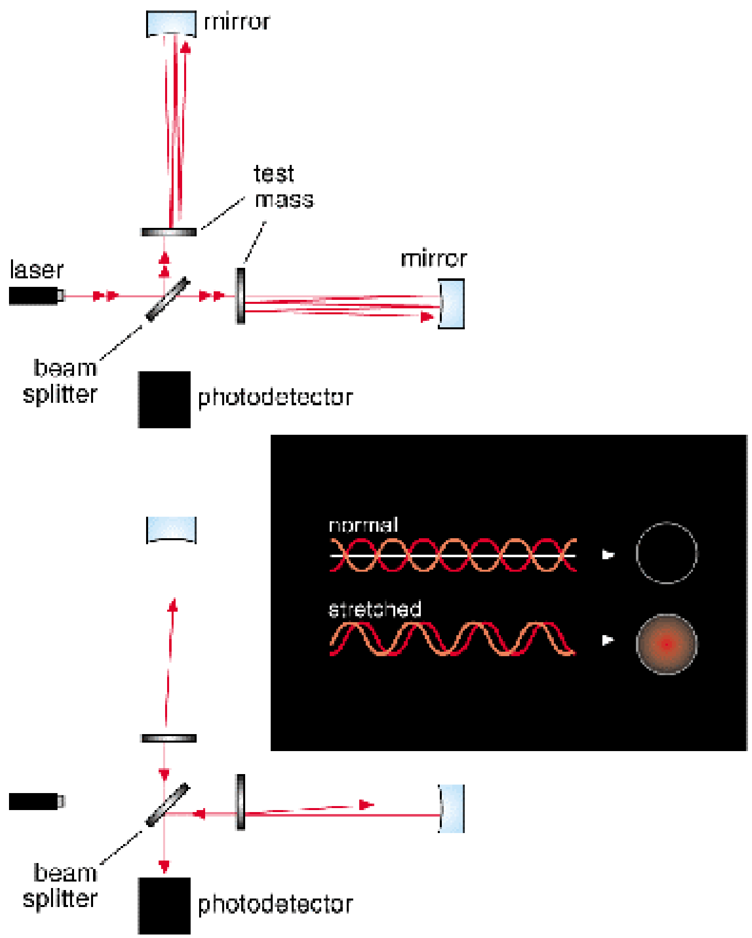


# Interferometer for GWs

- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in $10^{10}$, in order to obtain the required sensitivity.



# Interferometric phase difference




**The effects of gravitational waves appear as a deviation in the phase differences between two orthogonal light paths of an interferometer.**

**For expected signal strengths, The effect is *tiny*:**

**Phase shift of ~$10^{-10}$ radians**

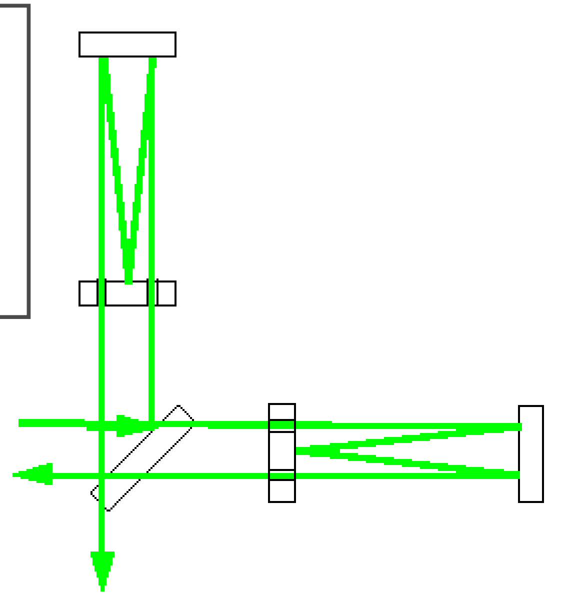
**The longer the light path, the larger the phase shift…**

**Make the light path as long as possible!**

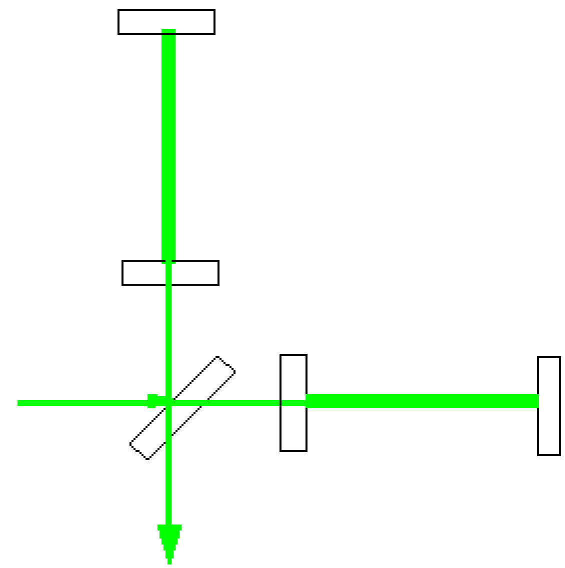
# Light storage: folding the arms

How to get long light paths without making *huge* detectors:

**Fold the light path!**




Simple, but requires large mirrors; limited $\tau_{stor}$




(LIGO design) $\tau_{stor} \sim 3\ msec$

More compact, but harder to control

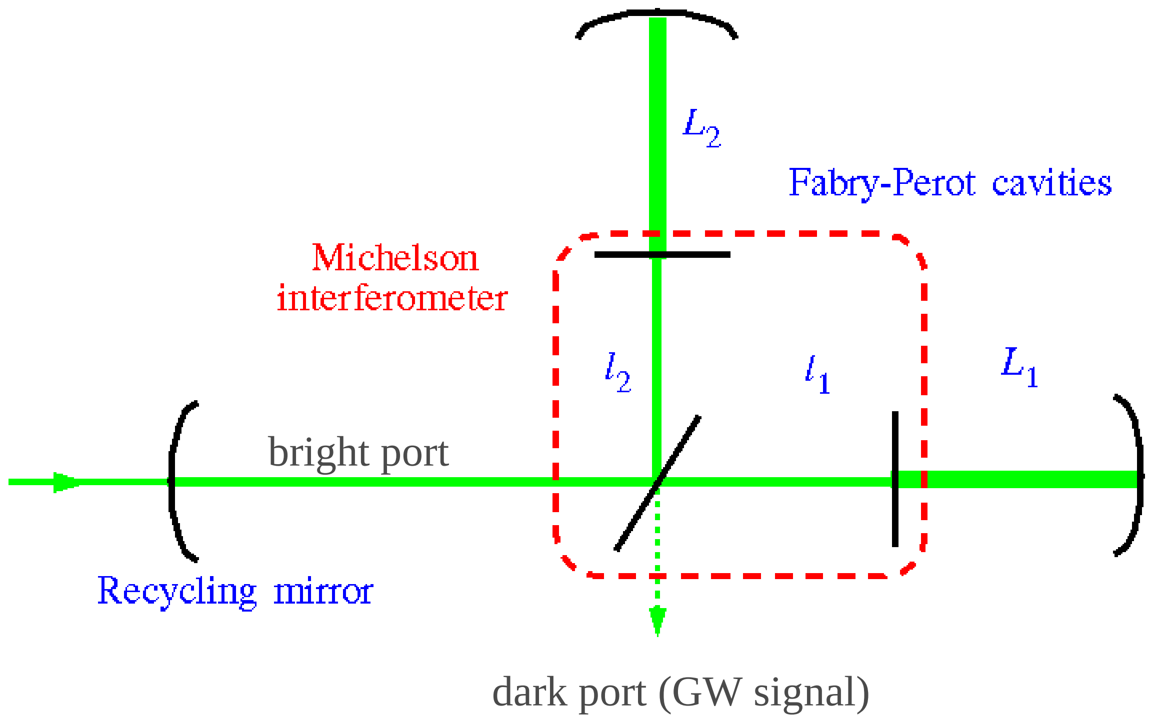
# Limit to the path length

- Can't make the light path arbitrarily long!
- Time for light wave front to leave BS and return: $\tau_{stor} \sim 2NL/c$; $N$ is number of round trips in arms
- During that time, GW may reverse sign, canceling the effect on the light phase: $\tau_{rev} \sim T_{period}/2 = 1/2f$
- LIGO is sensitive to GW's of frequency $f < 3000$ Hz but the best sensitivity is at $f_{pole} \sim 100$ Hz ("knee")
- So, keep $\tau_{stor} < 1/2f_{pole}$, or $N < c/4Lf_{pole} \approx 200$ for LIGO
- For LISA, $L=5\text{x}10^9$ m, $N=1 \Rightarrow f_{pole} \approx 0.01$ Hz

# LIGO I configuration

## Power-recycled Michelson with Fabry-Perot arms:

- Fabry-Perot optical cavities in the two arms store the light for many (~200) round trips
- Michelson interferometer: change in arm lengths destroy destructive interference, light emerges from dark port
- Normally, light returns to laser at bright port
- Power recycling mirror sends the light back in (coherently!) to be reused



# LIGO I schedule

| | |
|---|---|
| 1996 | Construction Underway (mostly civil) |
| 1997 | Facility Construction (vacuum system) |
| 1998 | Interferometer Construction (complete facilities) |
| 1999 | Construction Complete (interferometers in vacuum) |
| 2000 | Detector Installation (commissioning subsystems) |
| 2001 | Commission Interferometers (first coincidences) |
| 2002 | Sensitivity studies (initiate LIGO I Science Run) |
| 2003+ | LIGO I data run (one year integrated data at $h \sim 10^{-21}$) |
| | |
| 2005 | Begin LIGO II installation |