

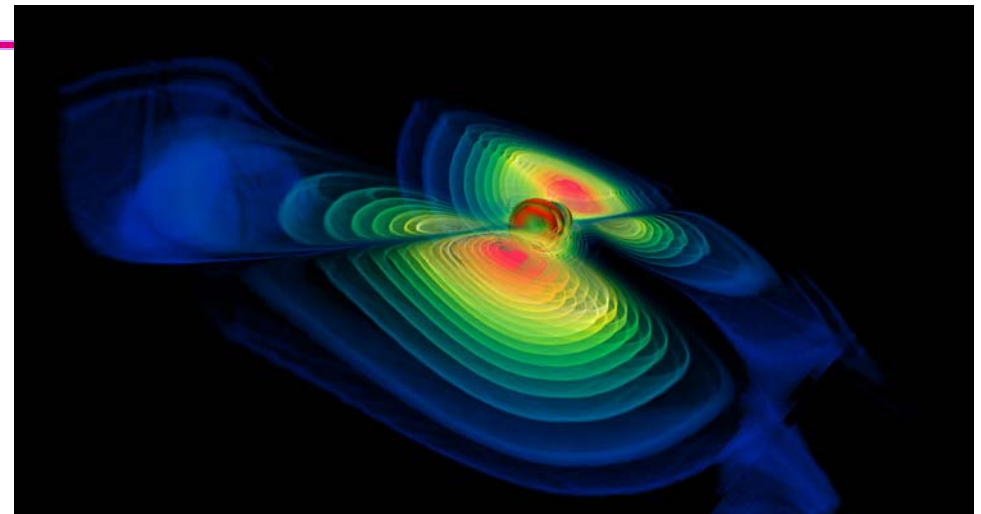


# The technology behind LIGO: how to measure displacements of $10^{-19}$ meters

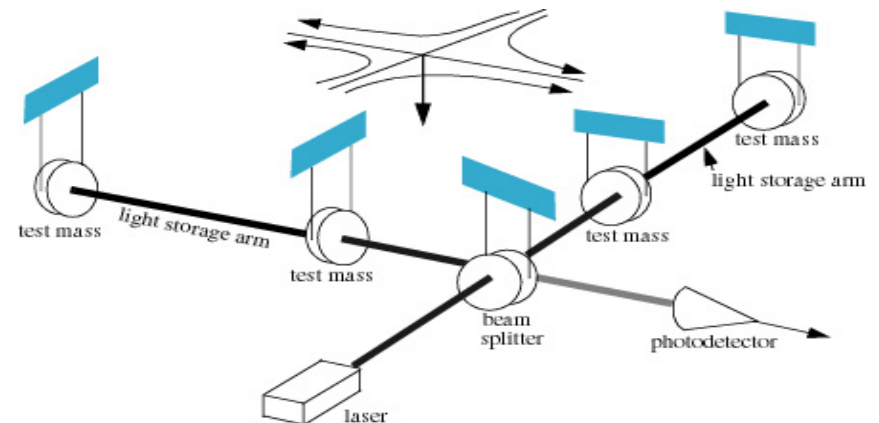
- The LIGO interferometers
- Interferometry: displacement sensing
- Noise limits
- Advanced LIGO

- 4pm today, 1 West:  
Results from science runs

Alan Weinstein, Caltech



"Colliding Black Holes"  
National Center for Supercomputing Applications (NCSA)



AJW, UTeV, October 28, 2005



# Gravitational wave detectors

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- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large “bell”, set ringing (at  $\sim 900$  Hz) by GW
  - Challenge: reduce noise (thermal ringing, readout)
- **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
  - Now: large, earth-based detectors. Soon: space-based (LISA).

# Resonant bar detectors

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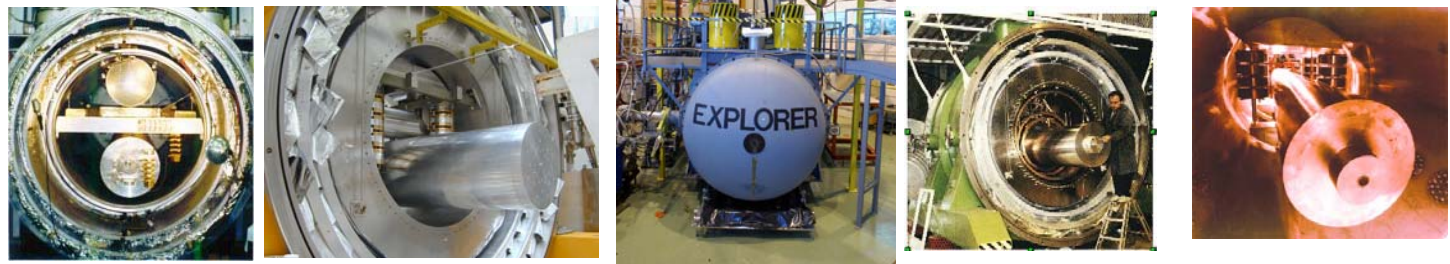
- AURIGA bar near Padova, Italy (typical of some ~5 around the world – Maryland, LSU, Rome, CERN, UWA)
- 2.3 tons of Aluminum, 3m long;
- Cooled to 0.1K with dilution fridge in LHe cryostat
- $Q = 4 \times 10^6$  at  $< 1\text{K}$
- Fundamental resonant mode at ~900 Hz; narrow bandwidth
- Ultra-low-noise capacitive transducer and electronics (SQUID)





# Resonant Bar detectors around the world

## International Gravitational Event Collaboration (IGEC)



detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Mode frequencies [ $Hz$ ]	895, 920	912, 930	905, 921	908, 924	694, 713
Bar mass $M$ [ $kg$ ]	2296	2230	2270	2260	1500
Bar length $L$ [ $m$ ]	3.0	2.9	3.0	3.0	2.75
Bar temperature [ $K$ ]	4.2	0.2	2.6	0.1	5.0
Longitude	91°10'44" <i>W</i>	11°56'54" <i>E</i>	6°12' <i>E</i>	12°40'21" <i>E</i>	115°49' <i>E</i>
Latitude	30°27'45" <i>N</i>	45°21'12" <i>N</i>	46°27' <i>N</i>	41°49'26" <i>N</i>	31°56' <i>S</i>
Azimuth	40° <i>W</i>	44° <i>E</i>	39° <i>E</i>	44° <i>E</i>	0°

**Baton Rouge,  
LA USA**

**Legarno,  
Italy**

**CERN,  
Suisse**

**Frascati,  
Italy**

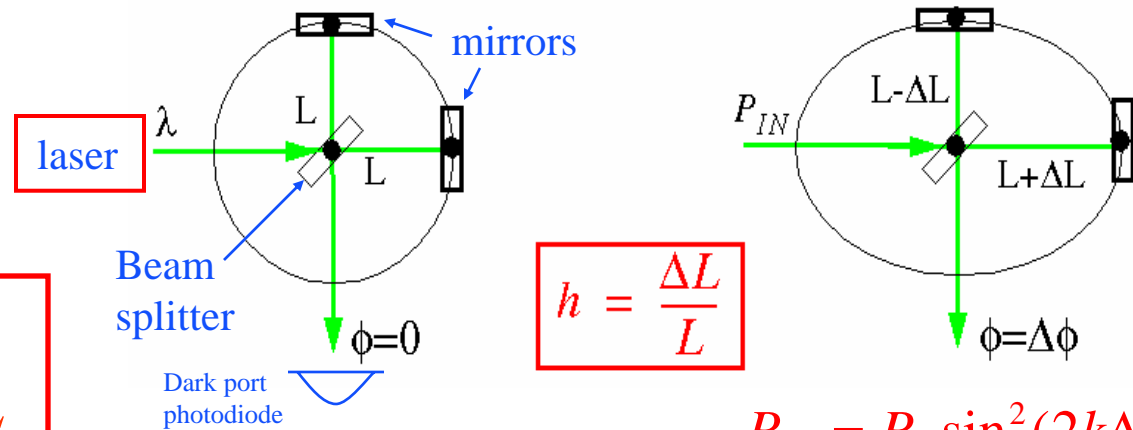
**Perth,  
Australia**

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# Interferometric detection of GWs

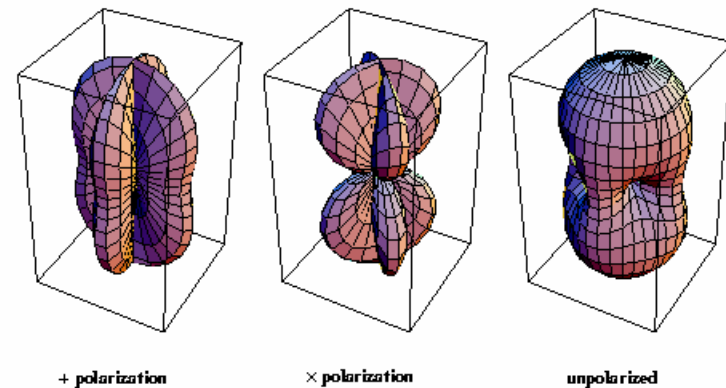
GW acts on freely falling masses:

For fixed ability to measure  $\Delta L$ , make  $L$  as big as possible!



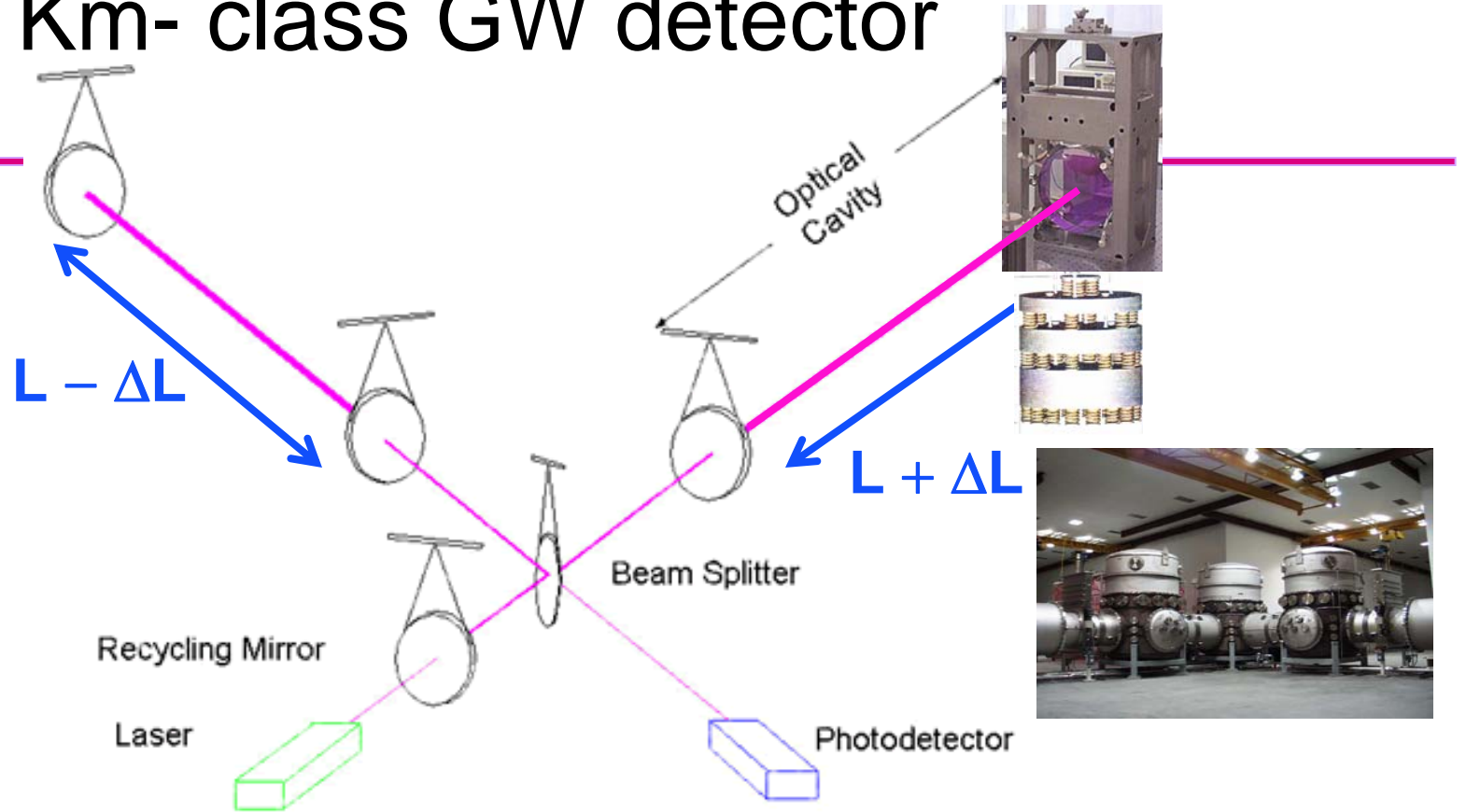
$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

Antenna pattern:  
(not very directional!)





# LIGO – the first Km- class GW detector

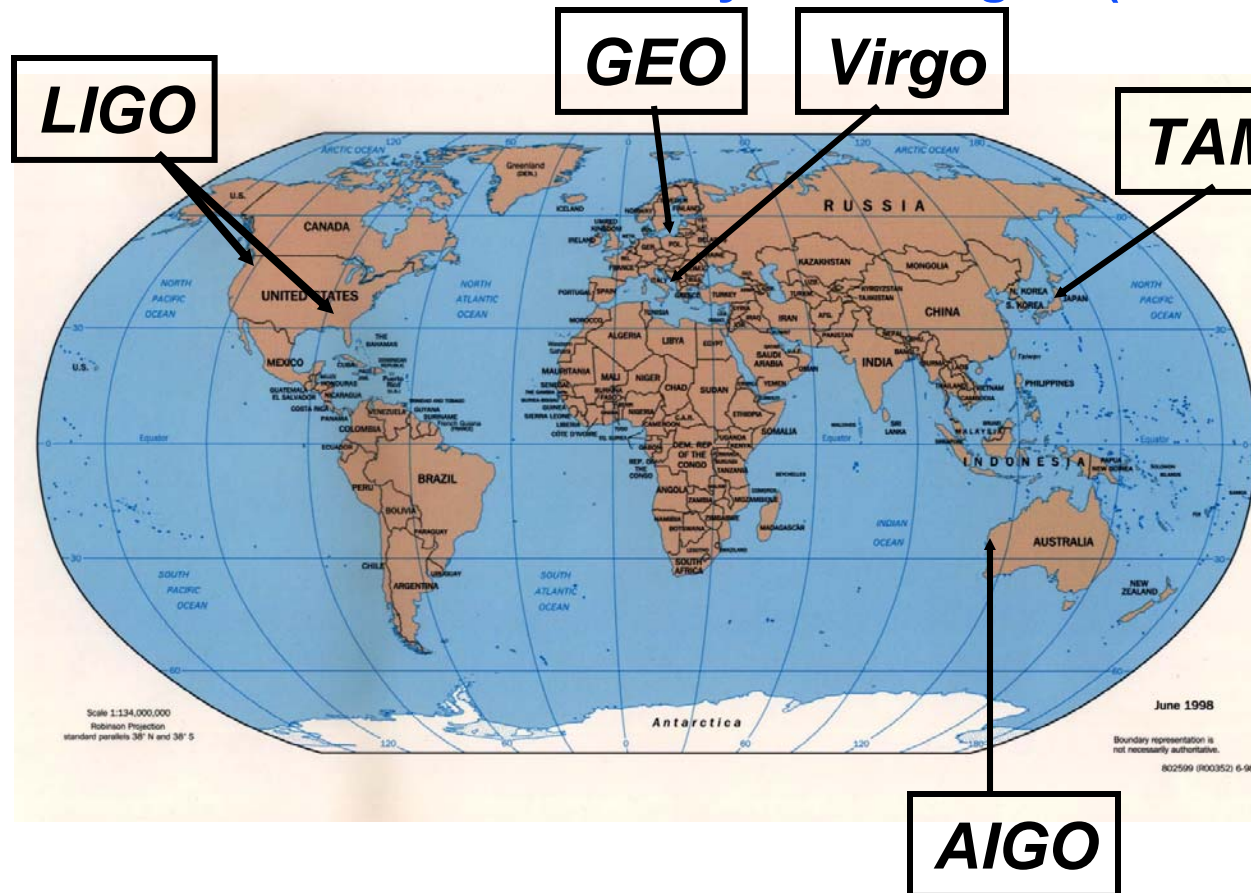


want to get  $h \leq 10^{-22}$ ;  
can build  $L = 4$  km;  
must measure  $\Delta L = h L \leq 4 \times 10^{-19}$  m



# International network

Simultaneously detect signal (within msec)



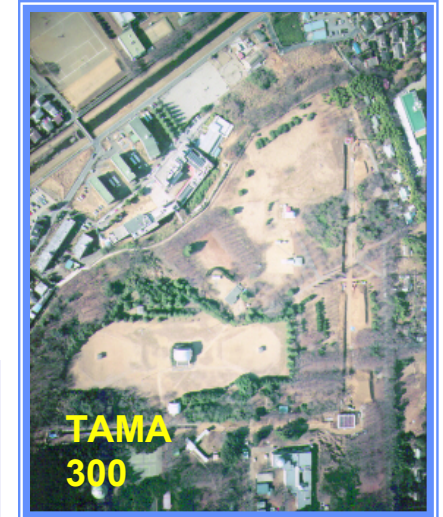
- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- Open up a new field of astrophysics!

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# LIGO, VIRGO, GEO, TAMA ...

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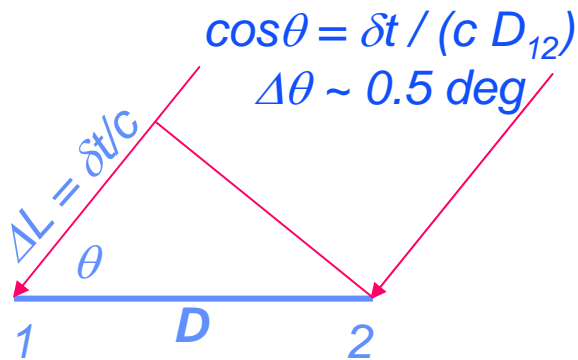


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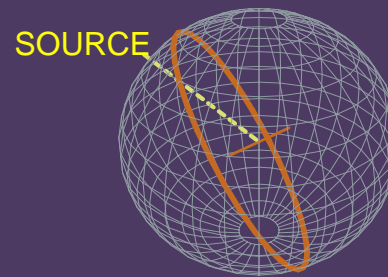


# Event Localization With An Array of GW Interferometers

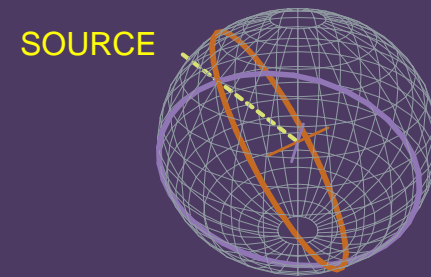
Global Distribution of Major Interferometer Sites



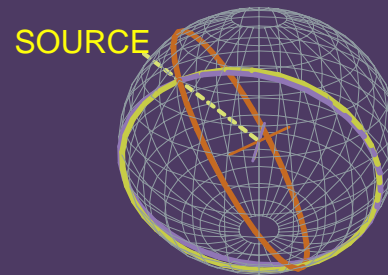
LIGO Transient Event Localization



LIGO+VIRGO Transient Event Localization



LIGO+VIRGO+GEO Transient Event Localization

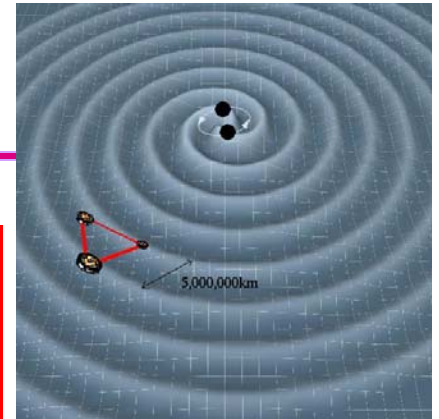


LIGO+VIRGO+GEO+TAMA Transient Event Localization



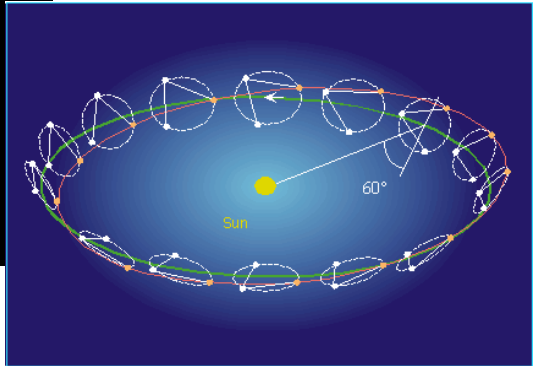
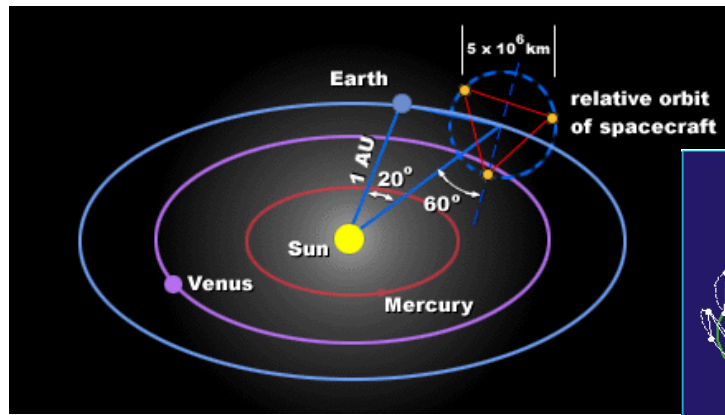
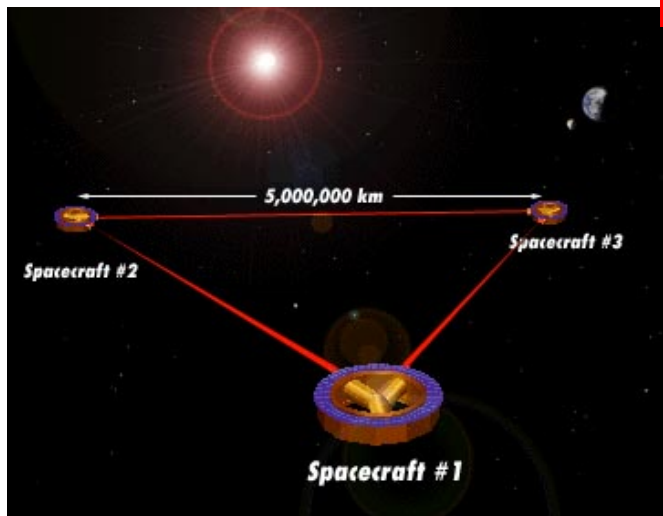


# The Laser Interferometer Space Antenna LISA



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.

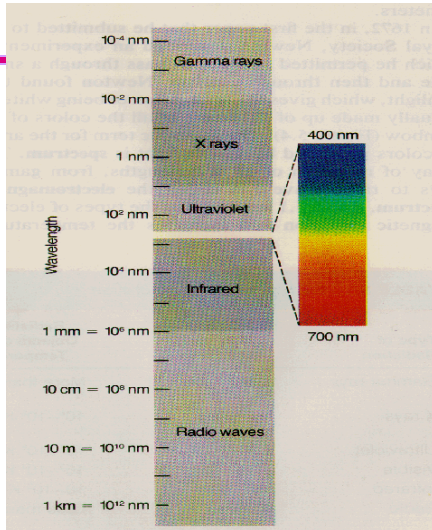


LISA (NASA/JPL, ESA) may fly in the next 10 years!

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# Frequency range of GW Astronomy

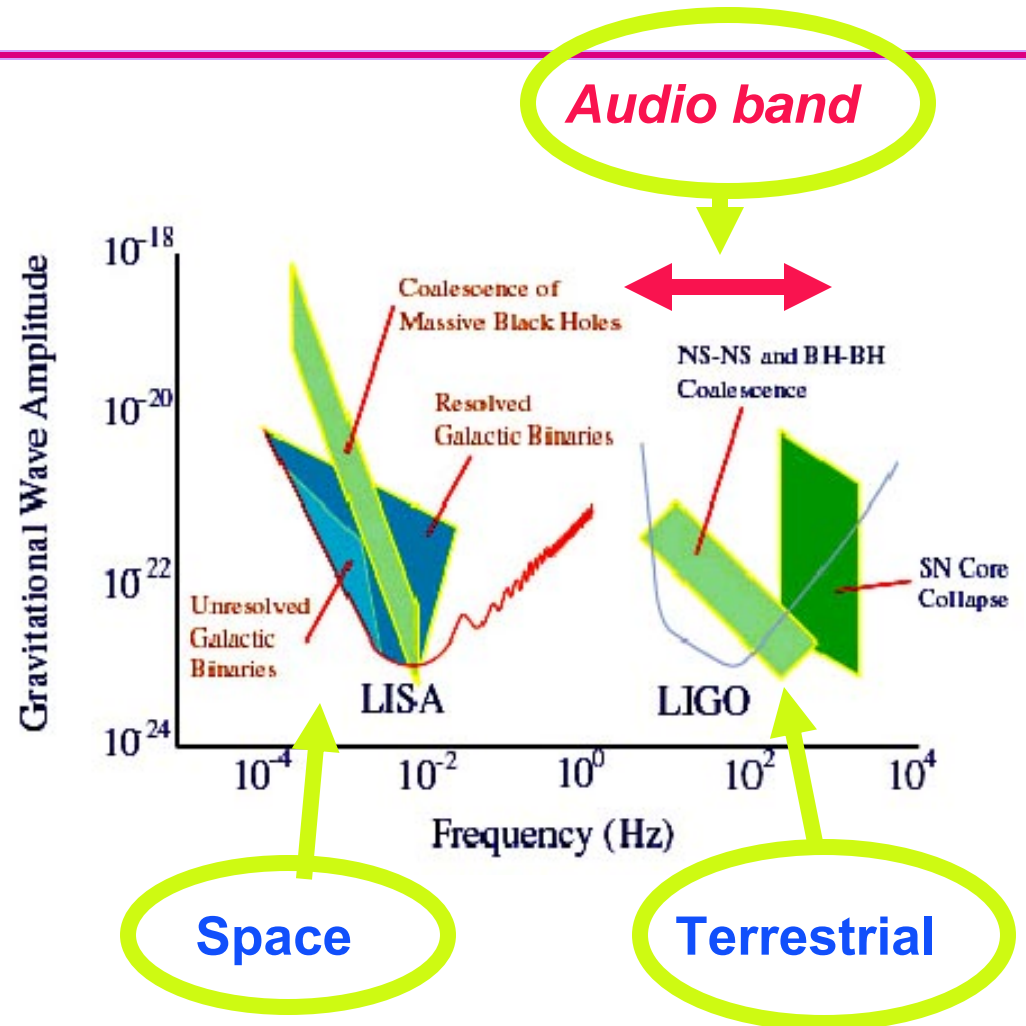


## Electromagnetic waves

- over ~16 orders of magnitude
- Ultra Low Frequency radio waves to high energy gamma rays

## Gravitational waves

- over ~8 orders of magnitude
- Terrestrial + space detectors





# LIGO Observatories



Hanford (LHO) :  
two interferometers in same  
vacuum envelope



Both sites are relatively  
seismically quiet,  
low human noise



4 km

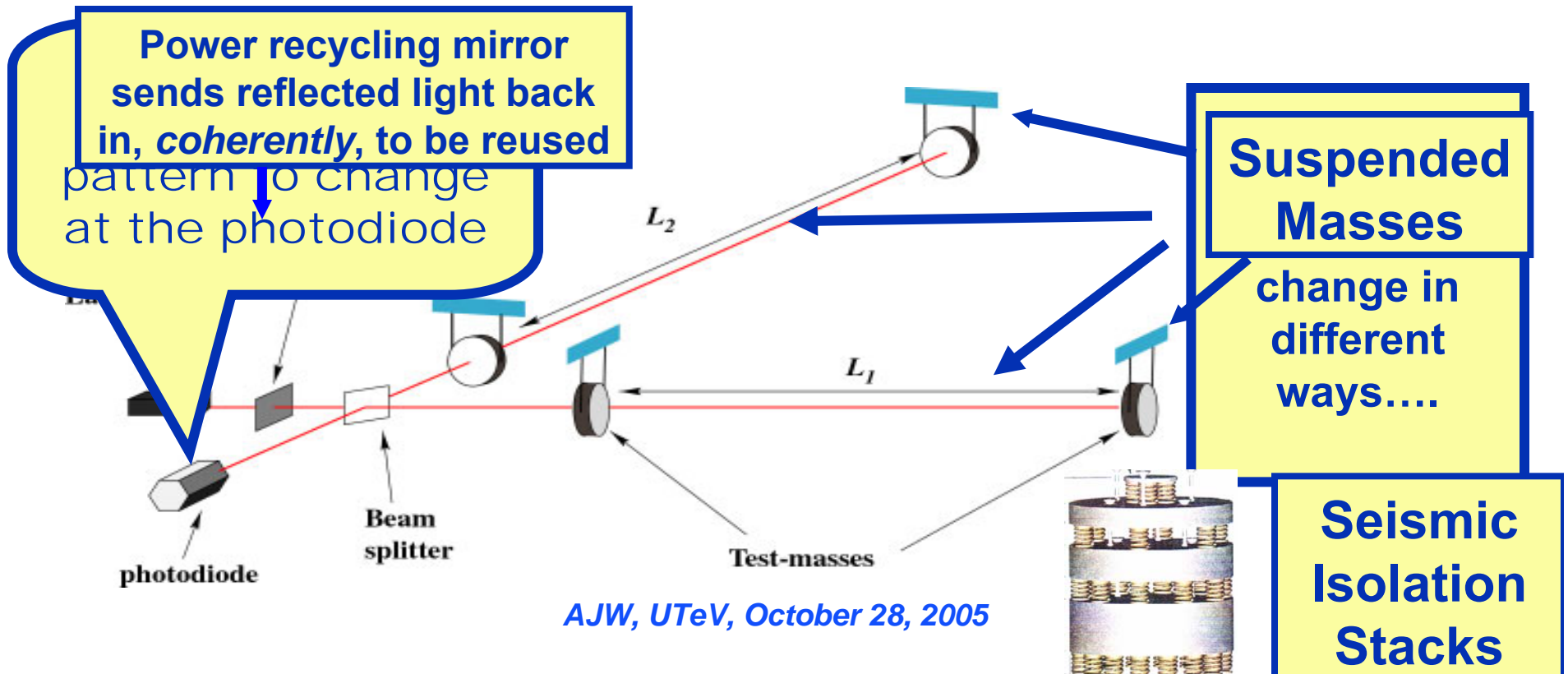
Livingston (LLO):  
one interferometer

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# Interferometer Concept

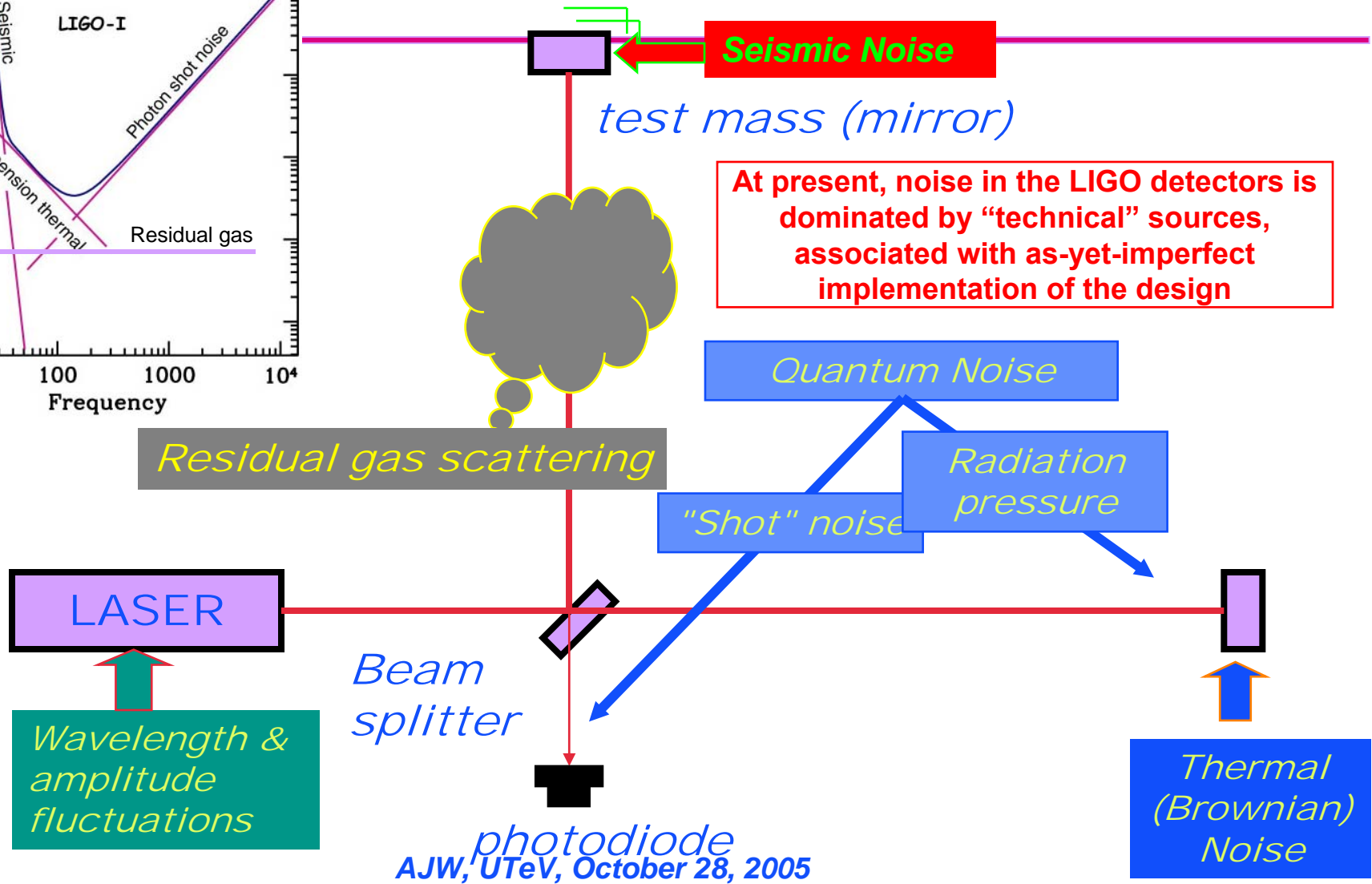
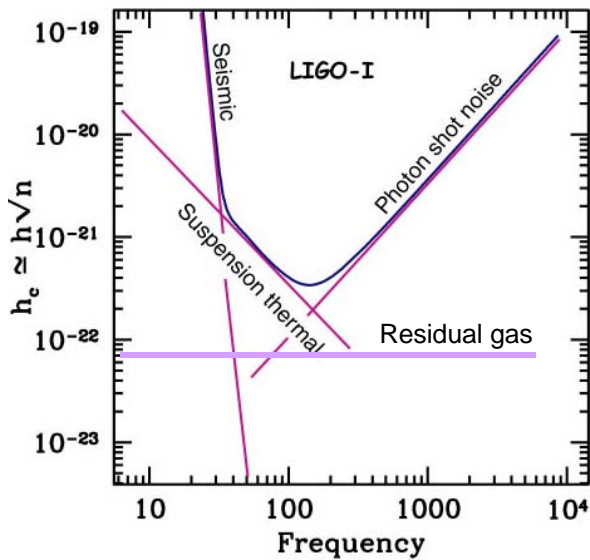
- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4km
- Measure *difference in length to < one part in  $10^{21}$  or  $10^{-18}$  meters*



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# Interferometer Noise Limits



At present, noise in the LIGO detectors is dominated by "technical" sources, associated with as-yet-imperfect implementation of the design

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Despite a few difficulties, science runs started in 2002.



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# Logging at Livingston



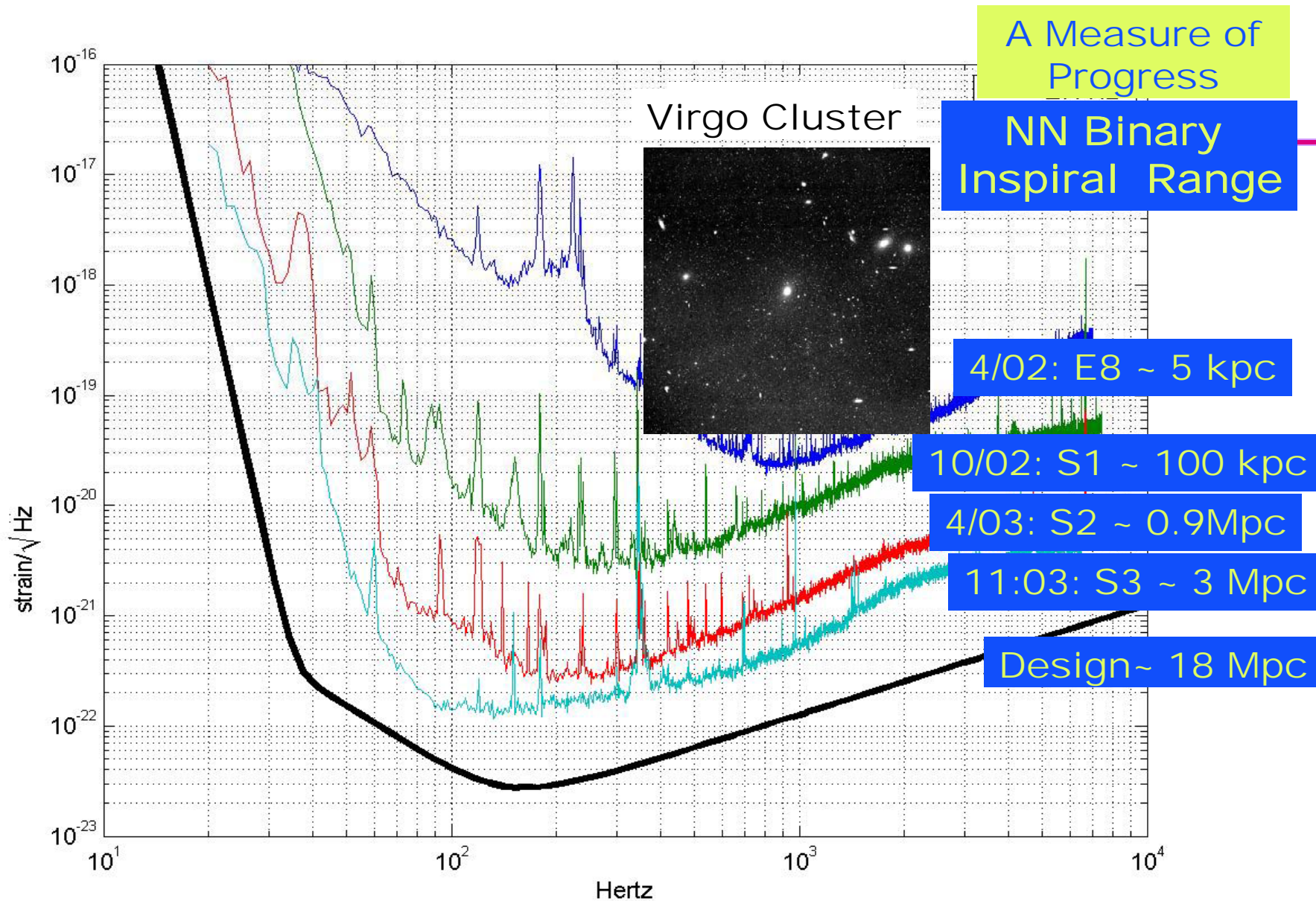
Less than 3 km away...  
Dragging big logs ...  
Remedial measures at LIGO are in progress;  
this will not be a problem in the future.



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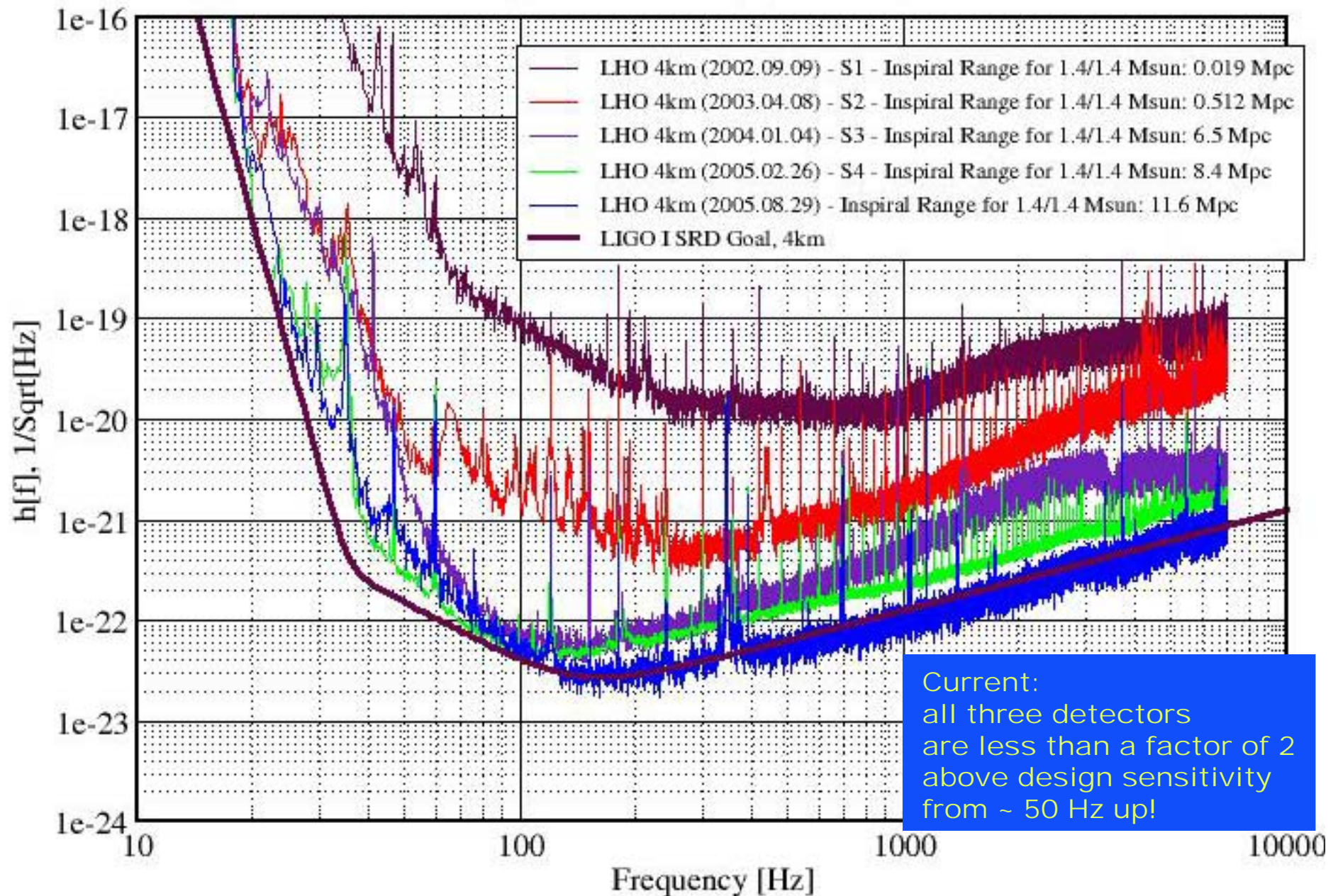
# Science Runs



# Strain Sensivities for the LIGO Interferometers

H1 Performance Comparison: S1 through post S4


LIGO-G050483-01-Z





# LIGO schedule

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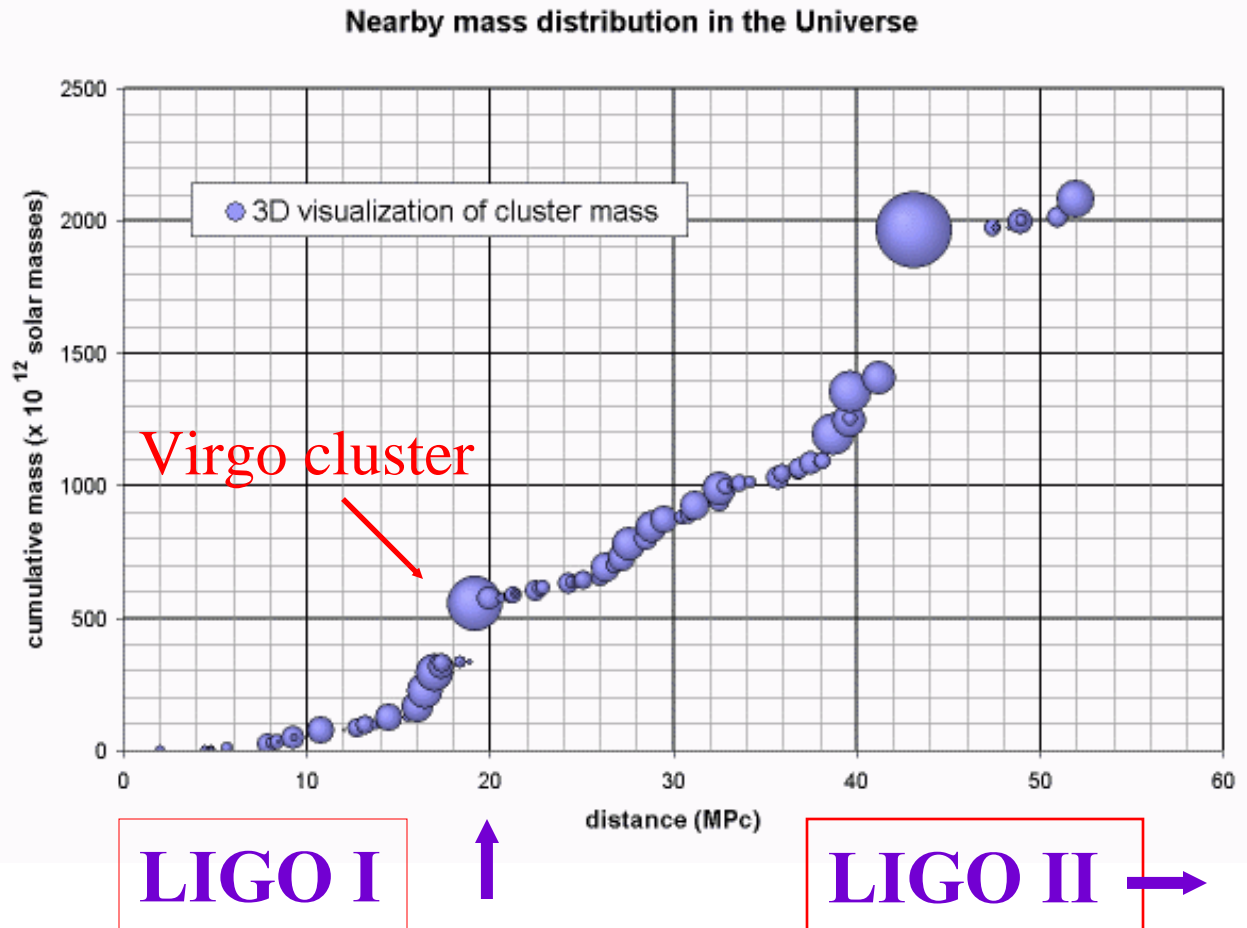
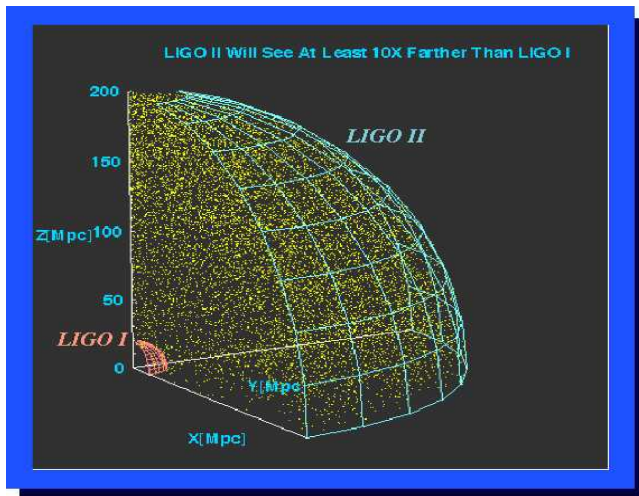
1995	NSF funding secured (\$360M)
1996	Construction Underway (mostly civil)
1997	Facility Construction (vacuum system)
1998	Interferometer Construction (complete facilities)
1999	Construction Complete (interferometers in vacuum)
2000	Detector Installation (commissioning subsystems)
2001	Commission Interferometers (first coincidences)
2002	Sensitivity studies (initiate LIGO I Science Run)
2003-4	LIGO I data runs (S1, S2, S3, S4)
 2005+	LIGO I data run (one year integrated data at $h \sim 10^{-21}$ )
2004	Advanced LIGO approved by the NSB
2007...	Begin Advanced LIGO upgrade installation
2010...	Begin Advanced LIGO observations...



# Improvement of reach with Advanced LIGO

Improve amplitude sensitivity by a factor of 10x, and...

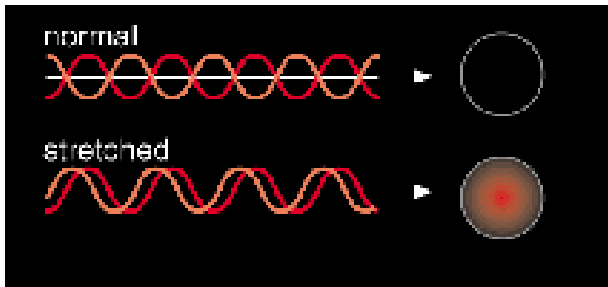
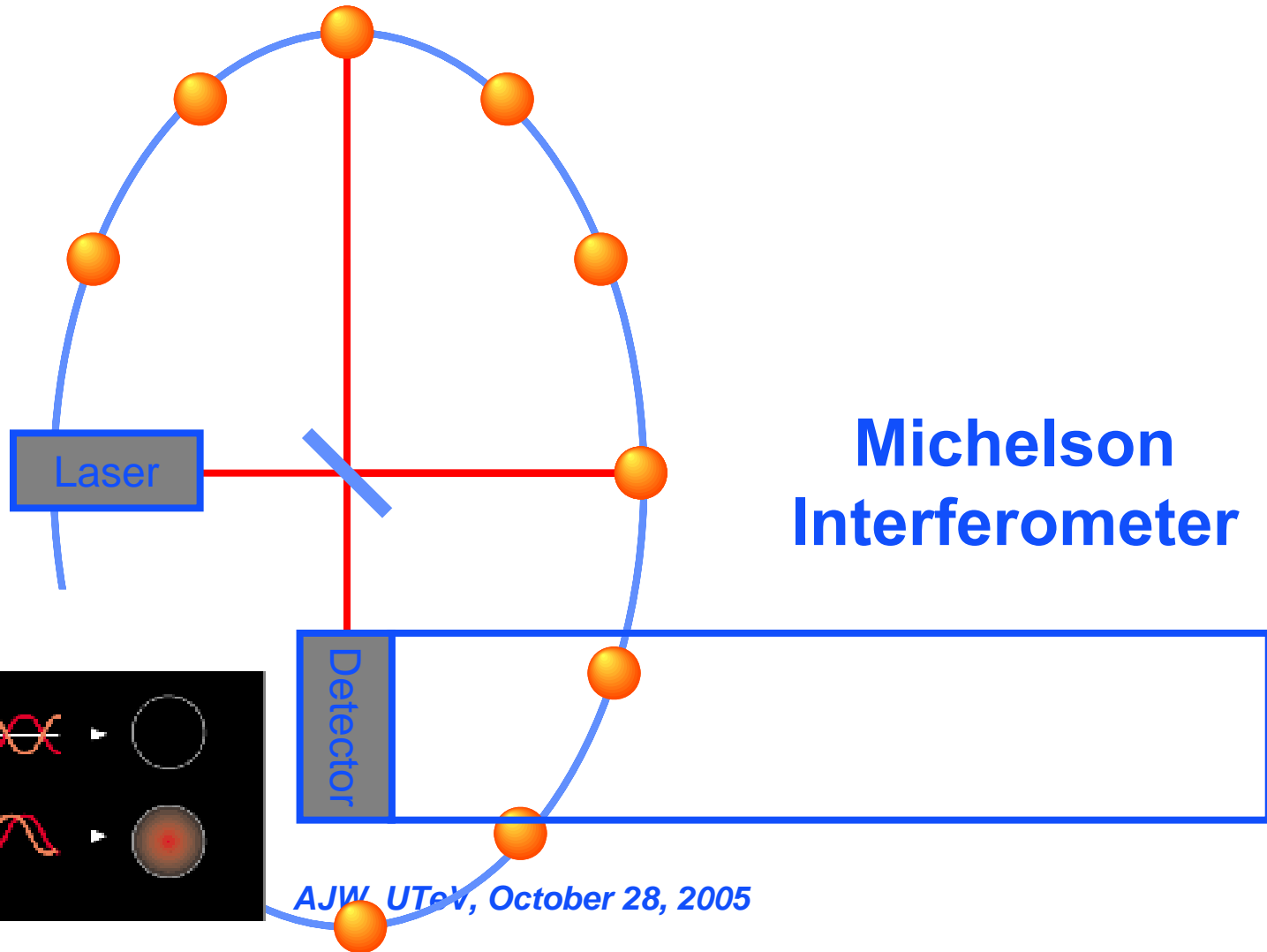
⇒ Number of sources goes up 1000x!



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# Detecting a passing gravitational wave



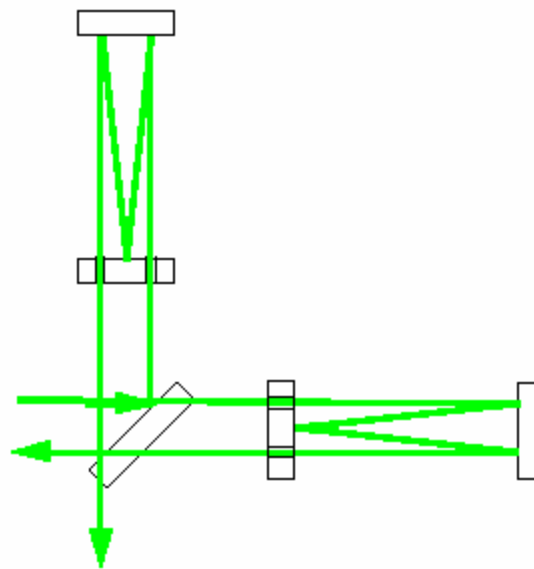
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# Light storage: folding the arms

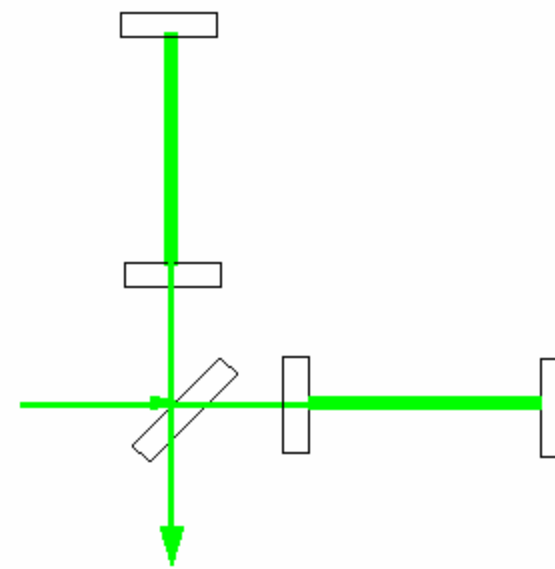
How to get long light paths without making *huge* detectors:

**Fold the light path!**

The laser measures the displaced mirrors many times before returning to the beamsplitter.



**Delay line interferometer**



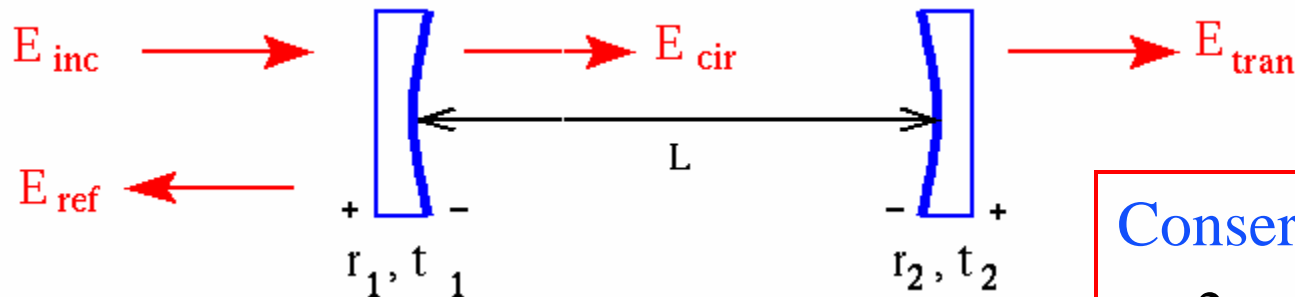
**Fabry Perot interferometer**

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

(LIGO design)  $\tau_{stor} \sim 10 \text{ msec}$   
More compact, but harder to control



# Fabry-Perot Optical Resonator Cavities



Conservation of energy:

$$r_i^2 + t_i^2 + L_i = 1$$

$$R_i + T_i + L_i = 1$$

$$E_{cir} = t_1 E_{inc} + r_1 r_2 e^{-2ikL} E_{cir} = \frac{t_1}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{ref} = r_1 E_{inc} - t_1 r_2 e^{-2ikL} E_{cir} = \frac{r_1 - r_2 (1 - L) e^{-2ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{tran} = t_2 e^{-ikL} E_{cir} = \frac{t_1 t_2 e^{-ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

When  $2kL = n(2\pi)$ , (ie,  $L = n\lambda/2$ ),

$E_{cir}$ ,  $E_{tran}$  maximized  $\Rightarrow$  resonance!



# FP circulating field

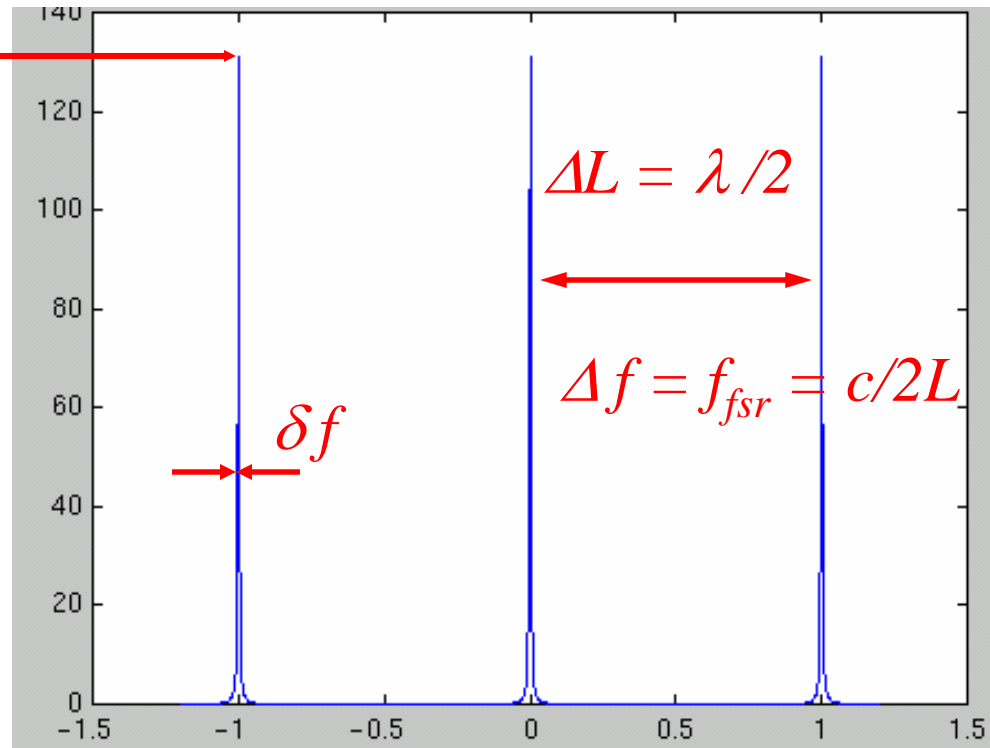
Power Gain

$$\left| \frac{E_{circ}}{E_{in}} \right|^2$$

Free Spectral Range:

$$f_{FSR} = c/2L$$

$$Finesse = \delta f / f_{fsr}$$



$$\Delta \nu = \Delta(2kL)/2\pi = \Delta f / f_{fsr} = \Delta L / (\lambda / 2)$$



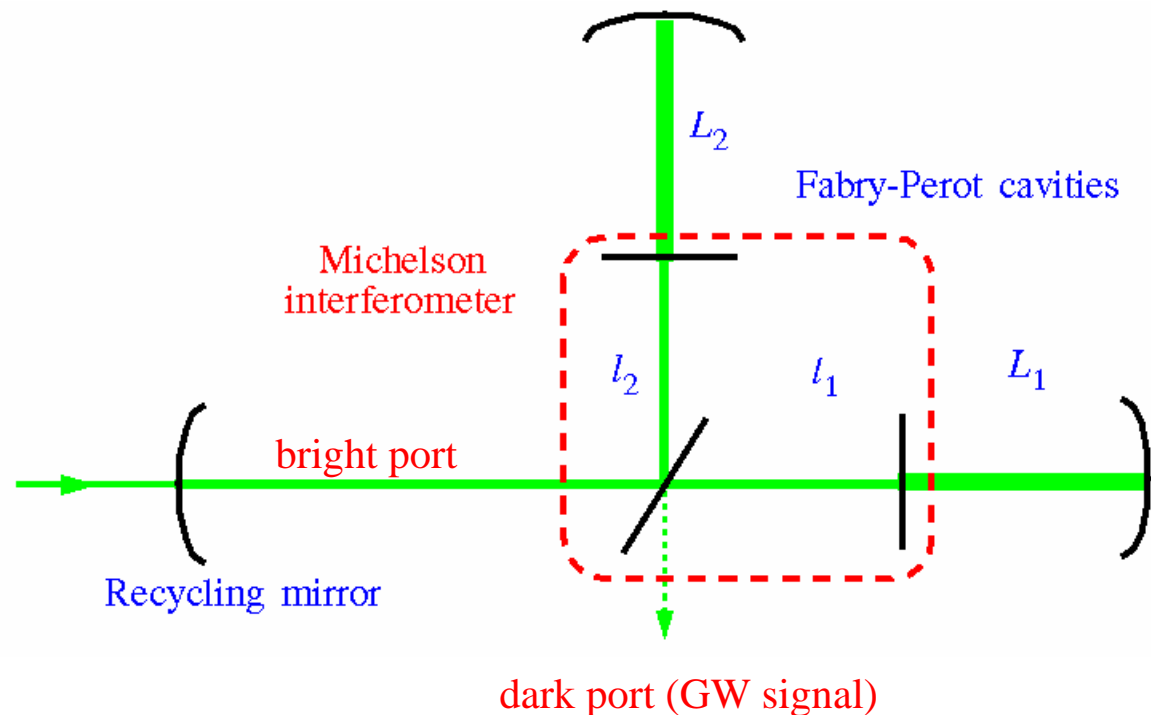
# What do high-finesse optical cavities do for you?

- They are incredibly sensitive **measuring devices and/or filters!**
- They measure  $\Delta\nu = \Delta(2kL)/2\pi = \Delta f/f_{fsr} = \Delta L/(\lambda/2)$
- If you know  $L$  very well (a *length reference*), they **measure the frequency of your laser** very accurately!
  - » In LIGO, we use a sequence of ever-longer optical cavities to measure  $\Delta f$  from the laser, then feed back on the laser to stabilize it. Ultimately, we use the 4-km arms (in *common mode*) to make the world's most stable laser.
- If you have a very stable laser frequency, can **measure  $\Delta L$  very accurately!**
  - » In LIGO, we use the 4-km arms (in differential mode) to measure  $\Delta L$  to an accuracy of  $10^{-19}$  m
  - » We accentuate the effect of  $\Delta L$  on the phase shift of the light in the arms, by having the light bounce back and forth many times
  - » Can't have arbitrarily large number of bounces: when light storage time  $>$  GW period, the effect cancels and we lose sensitivity! For LIGO, this starts happening at  $\sim 100$  Hz.
- If you know both  $L$  and  $f$  very well, can measure ***optical thickness of sample*** placed in one arm – often used in materials science, etc.
- If you send in light with a broad range of frequencies, it **only transmits one frequency**: a filter!
- If one of the mirrors is curved, and you send in light with a messy transverse profile, it only transmits light with a single transverse *mode*: a *mode cleaner*.

# LIGO I configuration

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

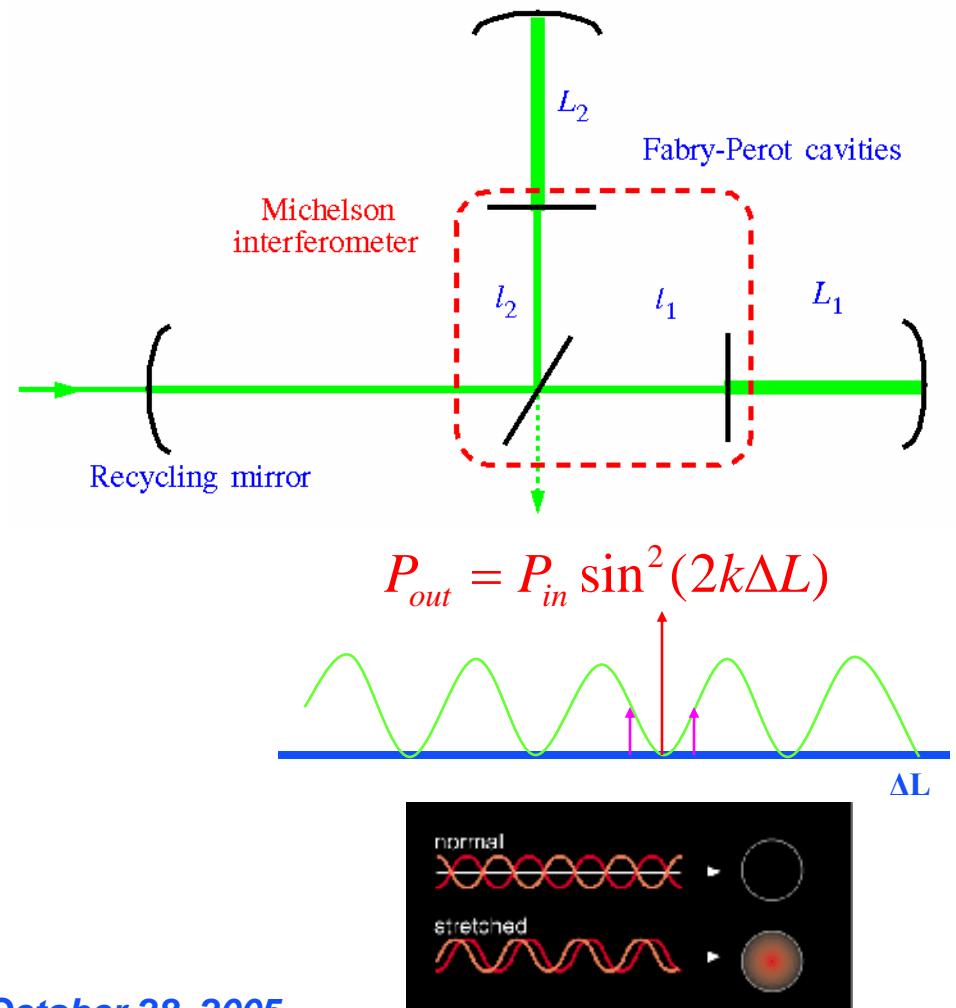
- Fabry-Perot optical cavities in the two arms store the light for many (~200) round trips
- Michelson interferometer: change in arm lengths destroy destructive interference, light emerges from dark port
- Normally, light returns to laser at bright port
- Power recycling mirror sends the light back in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





# LIGO as a “Null” instrument

- Power at output port of the Michelson depends most sensitively on  $\Delta L$  at “mid-fringe”
- But LIGO operates the Michelson on a dark fringe, where power depends on  $(\Delta L)^2$  !
- Why? Because at mid-fringe, power fluctuations would “fake” the GW signal, and they are a *huge* source of noise
- Instead, we extract a signal from the light at the dark fringe, which is linear in  $\Delta L$ , using a clever technique invented by Pound, Drever, Hall (Nobel 2005), to be described in a bit.
- Now we are insensitive to power fluctuations, and sensitive to  $\Delta L$ .
- We want to stay dark, even when the GW signal is present: so we servo out the signal!
- That’s fine; the servo correction signal is neatly linear with  $\Delta L$ .
- Null instrument: one of the many powerful techniques in precision measurement science that makes LIGO possible.



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# Suspended test masses

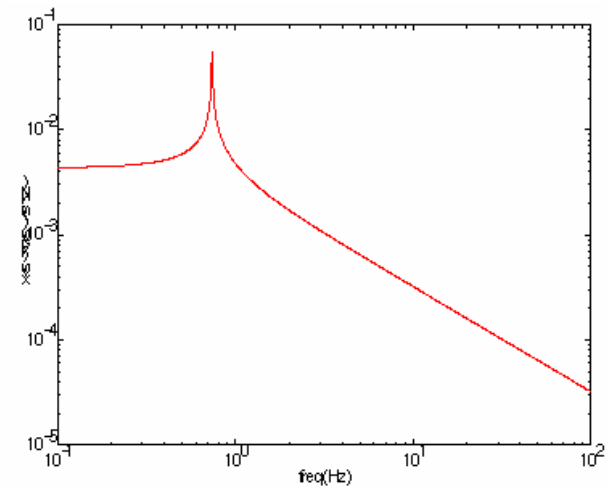
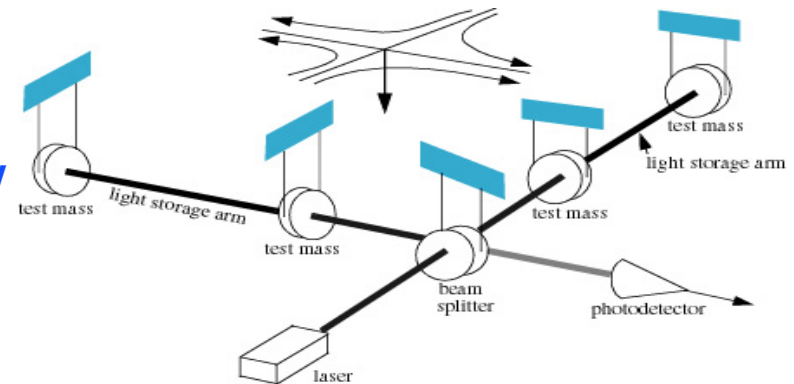
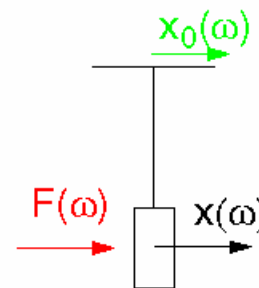
- To respond to the GW, test masses must be “free falling”
- On Earth, test masses must be supported against DC gravity field
- The Earth, and the lab, is vibrating like mad at low frequencies (seismic, thermal, acoustic, electrical);

- can’t simply bolt the masses to the table (as in typical ifo’s in physics labs)

- So, IFO is insensitive to low frequency GW’s
- Test masses are suspended on a pendulum resting on a seismic isolation stack

- “fixed” against gravity at low frequencies, but
  - “free” to move at frequencies above  $\sim 100$  Hz

“Free” mass: pendulum at  $f \gg f_0$





# The LIGO detectors

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- They employ a wide range of clever techniques to overcome the noise that surrounds us, ultimately limited by quantum effects.
- They are great examples of the art and science of precision measurement.
- They are marvels of engineering, in service to marvelous science.
- They *work*, and they will detect GWs soon!