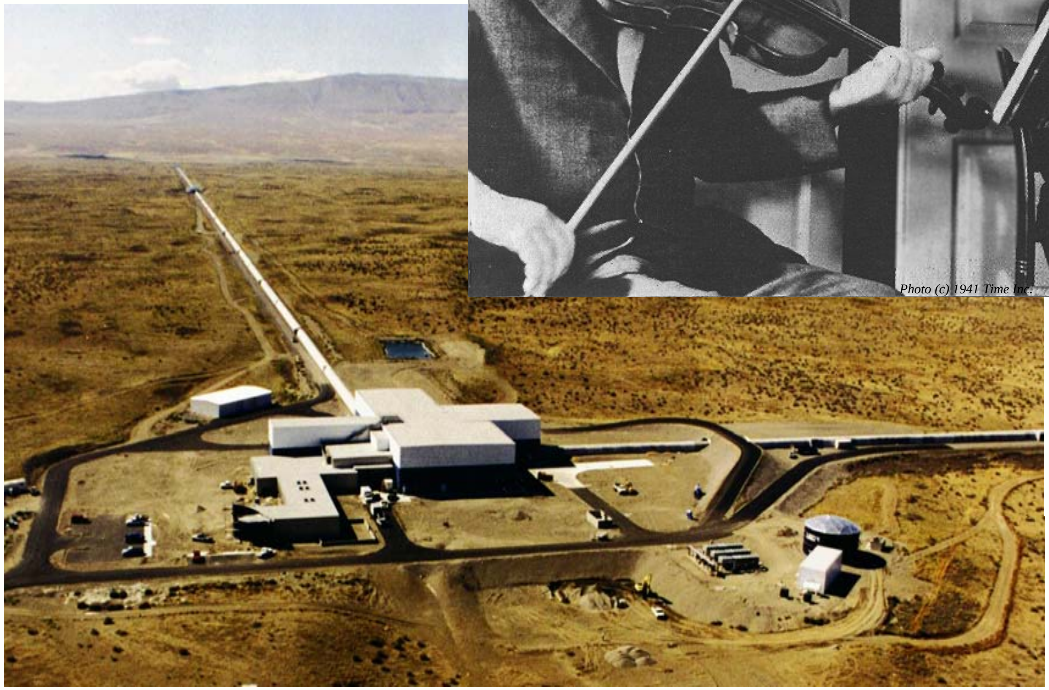
LIGO LISTENS



Mike Zucker

LIGO Livingston Observatory

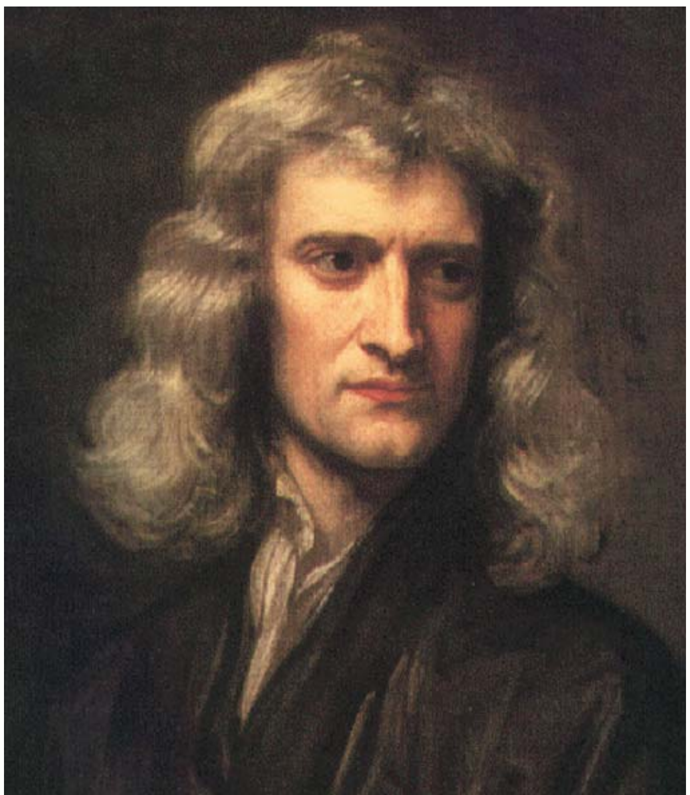
LSU Physics Colloquium

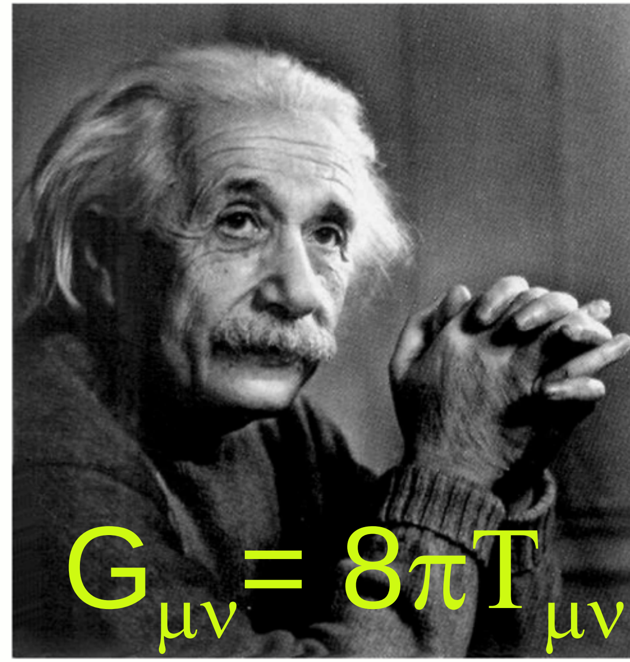
2 March, 2006

LIGO-G060031-05-L

Why must there be gravitational waves?

Newton's puzzle:
"instantaneous action at a distance"



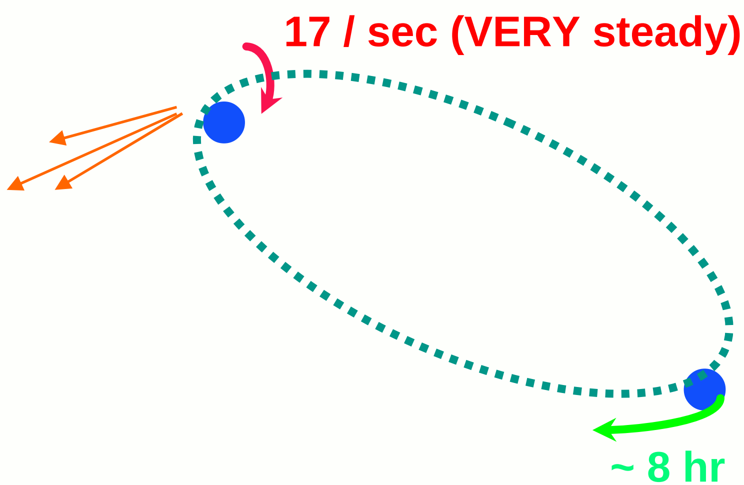


General Relativity
Spacetime itself is a medium
Geometry carries information
Wave equation gives speed c!

Gravitational Waves
the evidence

Neutron Star Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



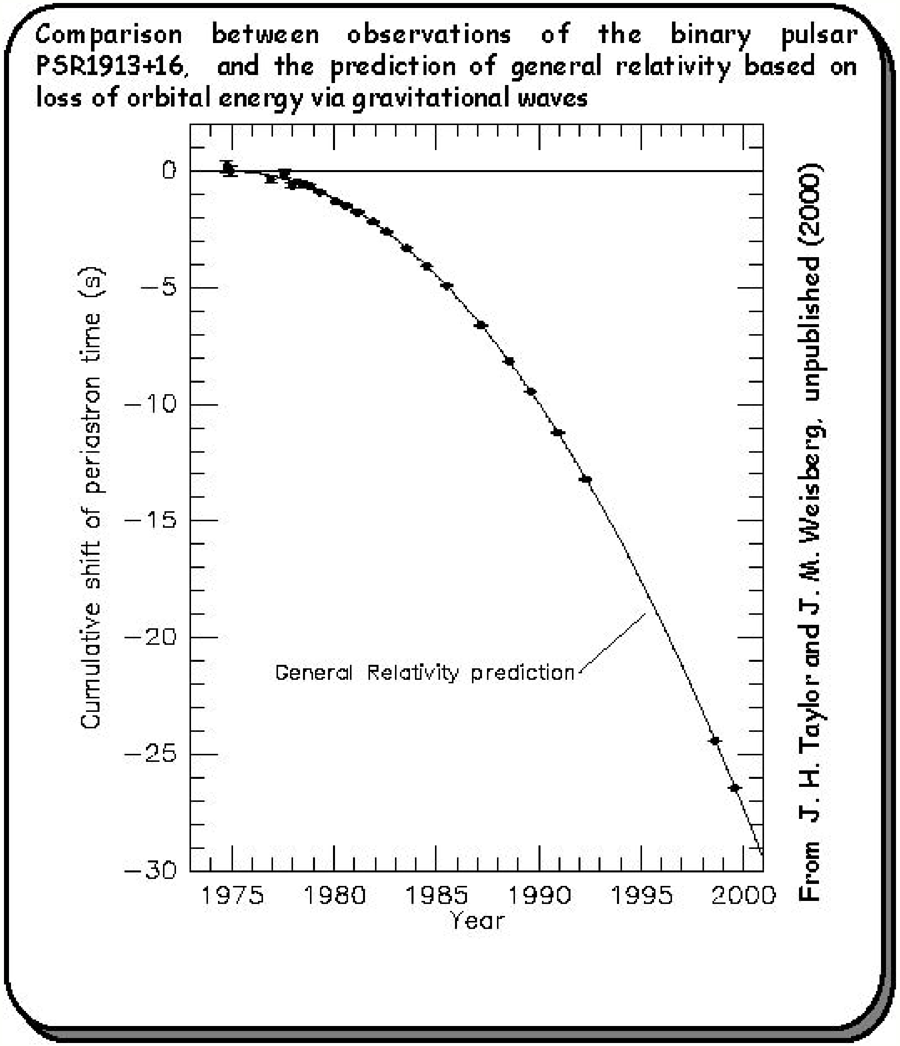
Neutron Star Binary System

- **separated by 10^6 miles**
- **$m_1 = 1.4 m_\odot$; $m_2 = 1.36 m_\odot$; $\varepsilon = 0.617$**

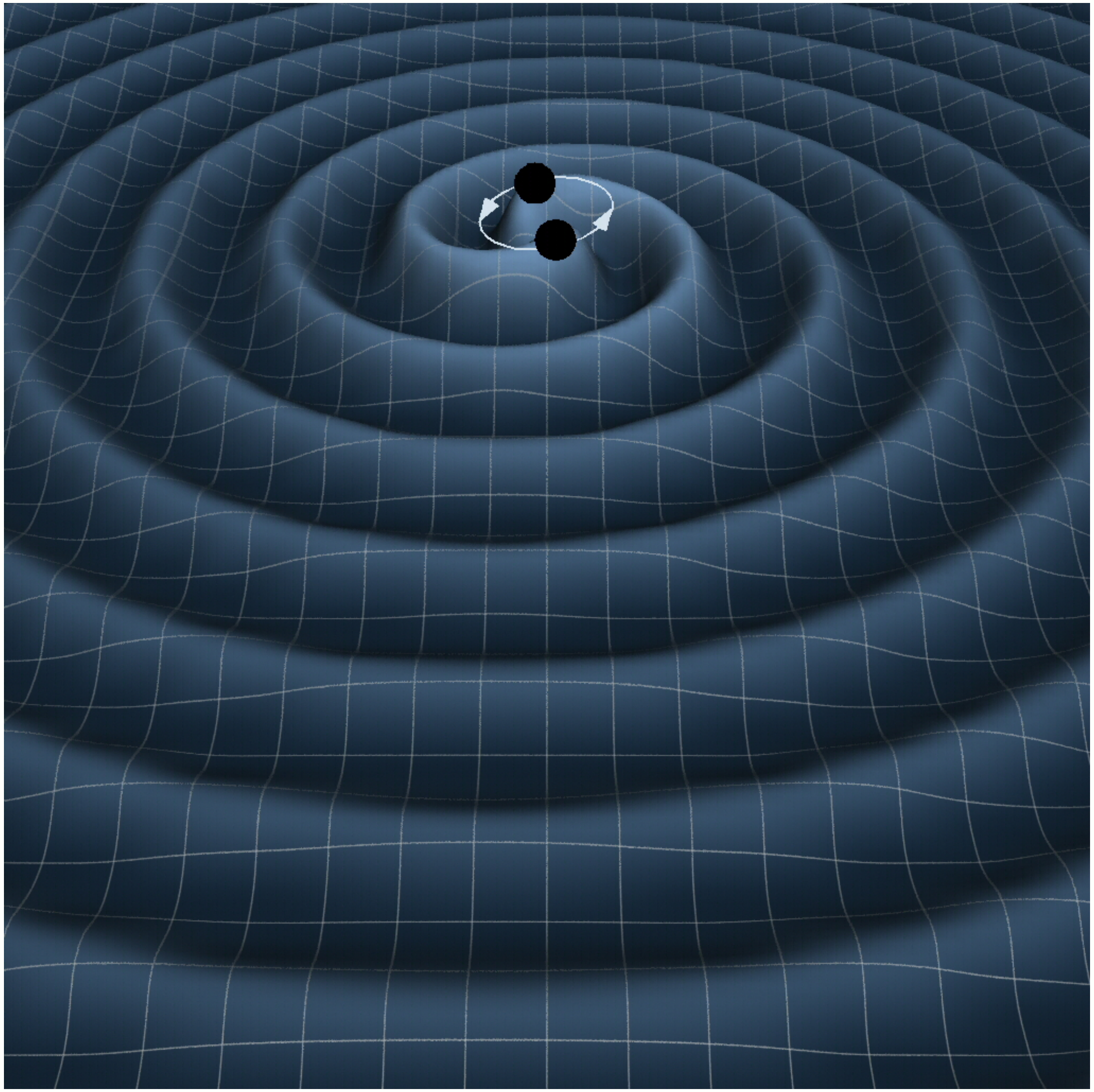
Exact match to general relativity

- **spiral in by 3 mm/orbit**
- **shortening of orbital period**

Emission of gravitational waves



Gravitational Waves



Perturbations of geometry can be expressed as *fractional distortion* of proper distances:

$$\boldsymbol{h} = d\boldsymbol{x}/|\boldsymbol{x}|$$

For varying source quadrupole moment $\boldsymbol{Q}$

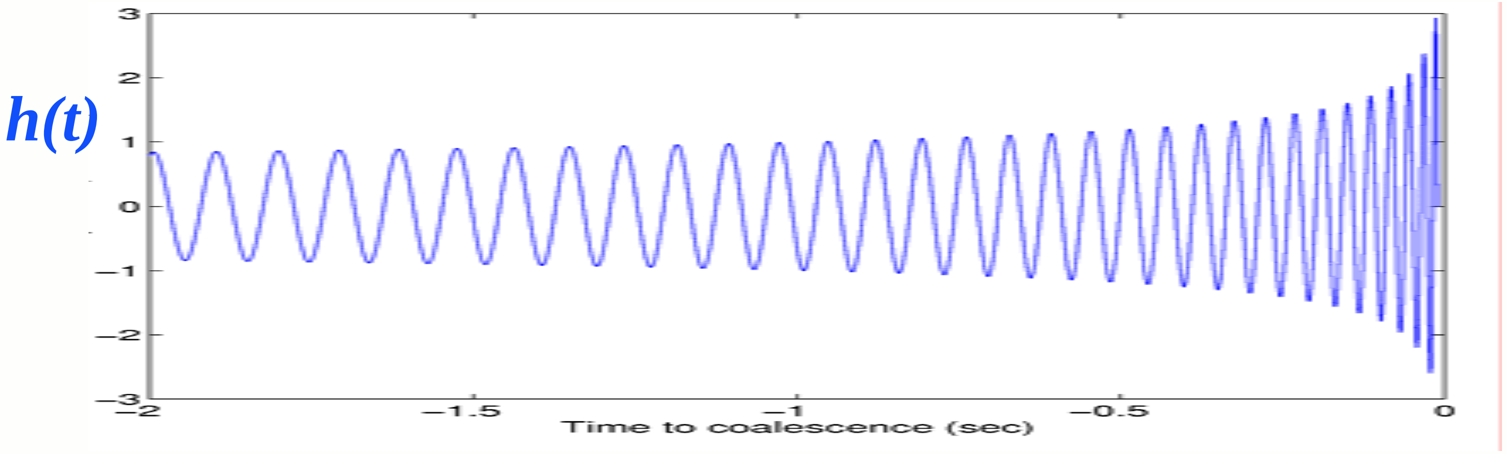
$$h \approx \frac{2G}{3c^4 r}\ddot{Q} \quad \textit{amplitude of wave}$$

$$\left|\dot{E}\right| \approx \frac{G}{45c^5}\dddot{Q} \quad \textit{radiated power}$$

K. Thorne (Caltech) , T. Carnahan (NASA GSFC)

The Fate of B1913+16

- Gravitational waves carry away energy and angular momentum
- Orbit will continue to decay over the next ~300 million years, until…



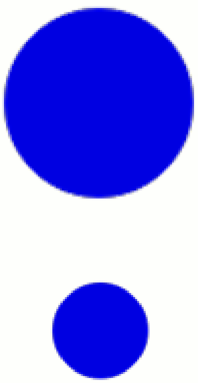
The “inspiral” will accelerate at the end, when the neutron stars coalesce

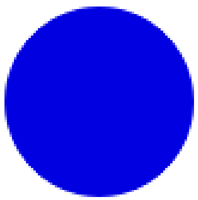
Gravitational wave emission will be strongest near the end

Gravitational Waves in Action

Two massive, compact objects in orbit

deform space (and any object in it) with a frequency which is twice the orbital frequency

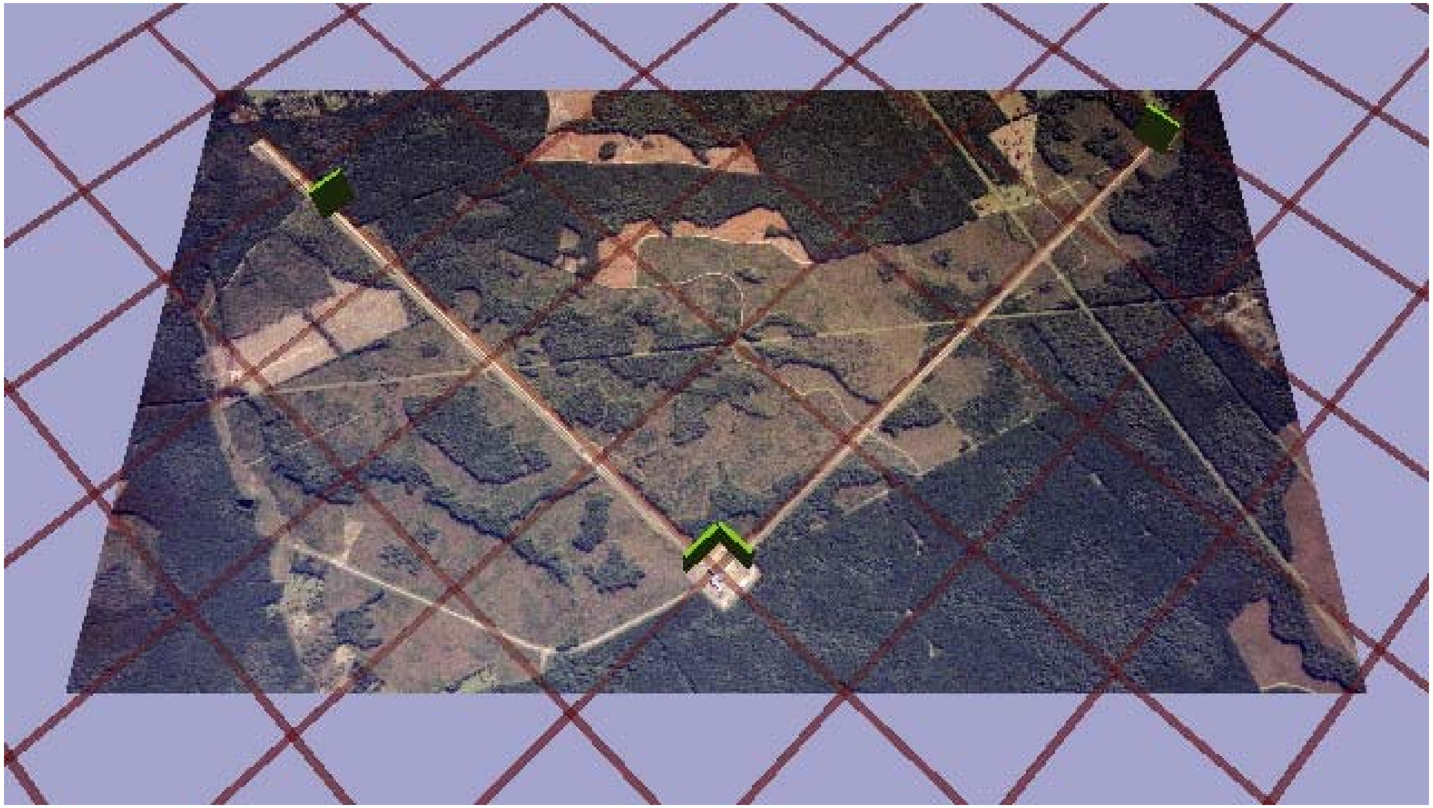




The stretching is described by a dimensionless strain, $h = \Delta L / L$

h is inversely proportional to the distance from the source

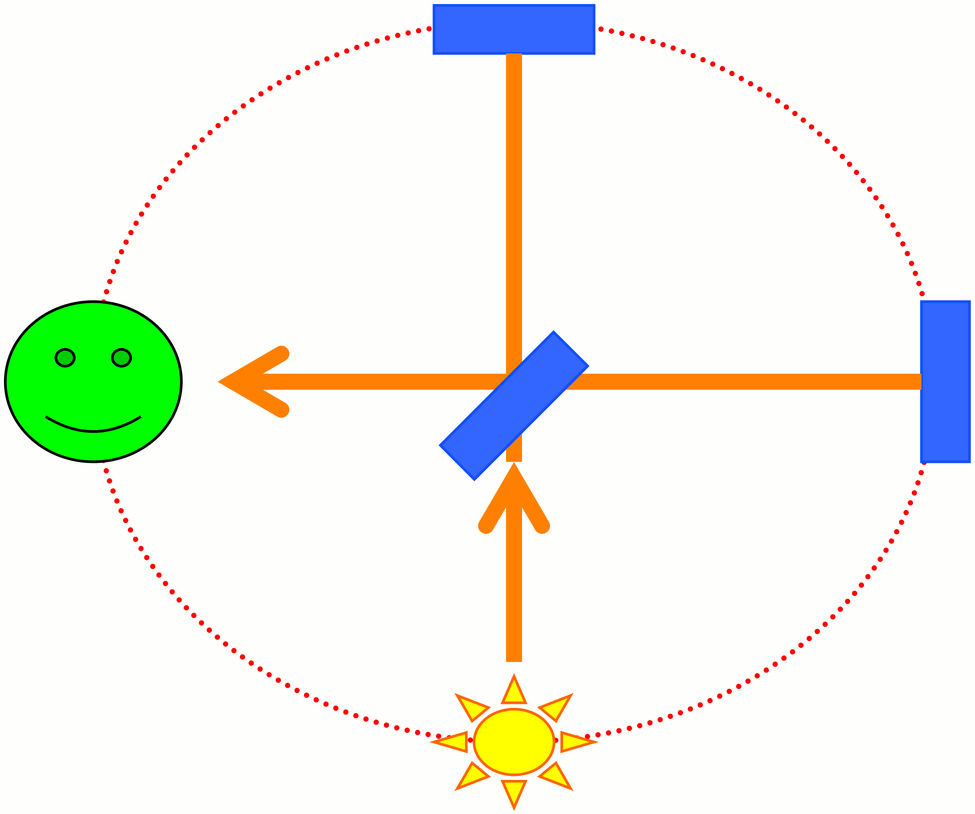
On a small planet in a spiral galaxy far far away…



How can we measure these waves?

Use a Michelson interferometer

Automatically compares orthogonal geodesics using light beams



So what's the catch?

Doing the math…

A wave's strength is characterized by its *strain*

$$h = \Delta L / L$$

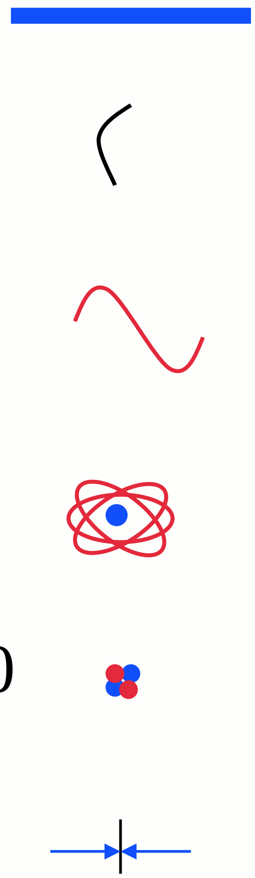
We can calculate the expected strain at Earth for, say, an orbiting binary system;

$$|h| \approx 4\pi^2 GMR^2 f_{orbit}^2 / c^4 r \approx 10^{-21} \left(\frac{R}{20\text{km}}\right)^2 \left(\frac{M}{M_\Theta}\right) \left(\frac{f_{orbit}}{400\,\text{Hz}}\right)^2 \left(\frac{10\text{Mpc}}{r}\right)$$

If we make our interferometer very big, say 4,000 meters long, then

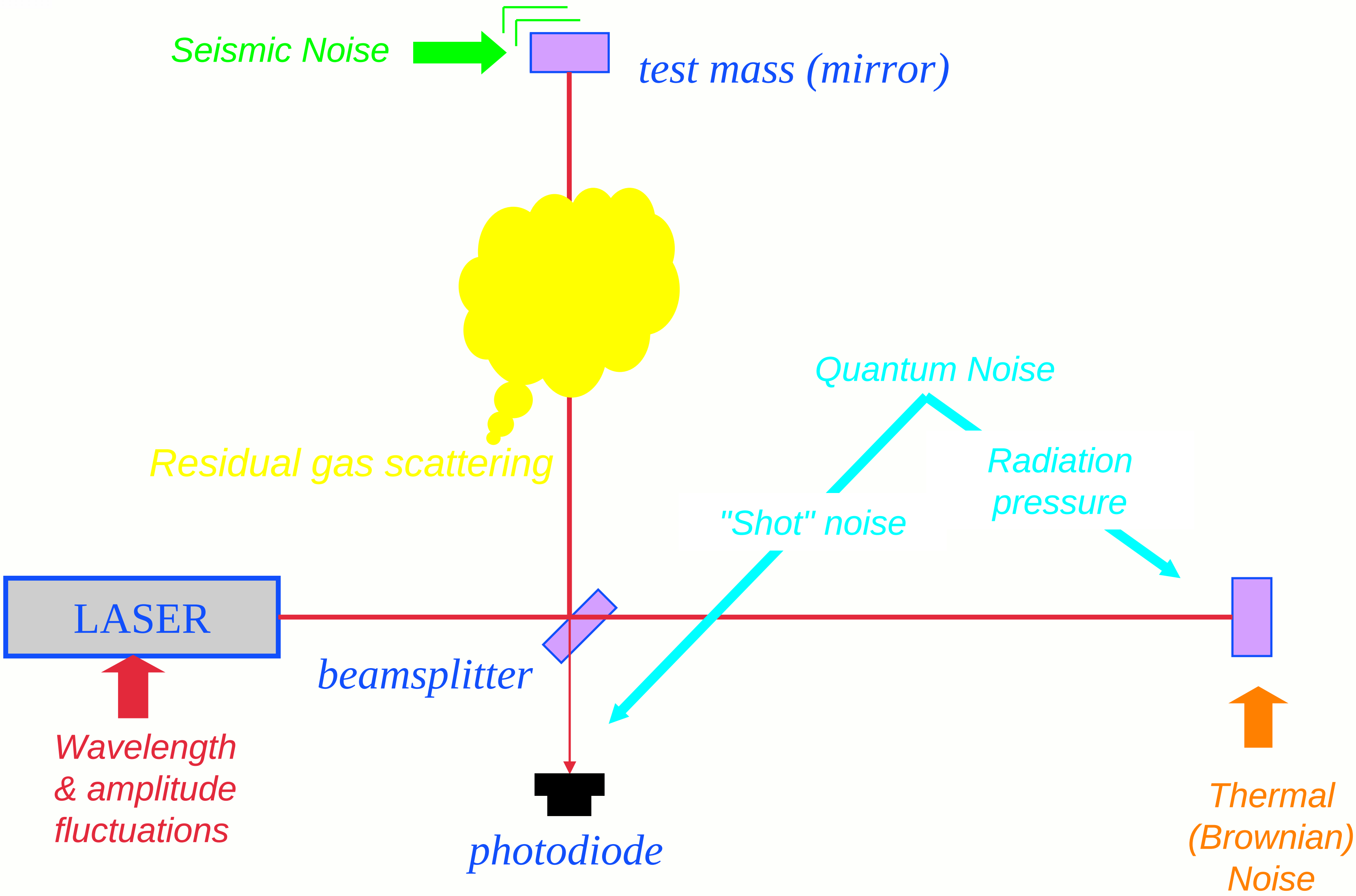
$$\Delta L = h \times L \approx 10^{-21} \times 4{,}000\, m \approx 10^{-18}\, m$$

How Small is 10^{-18} Meter?

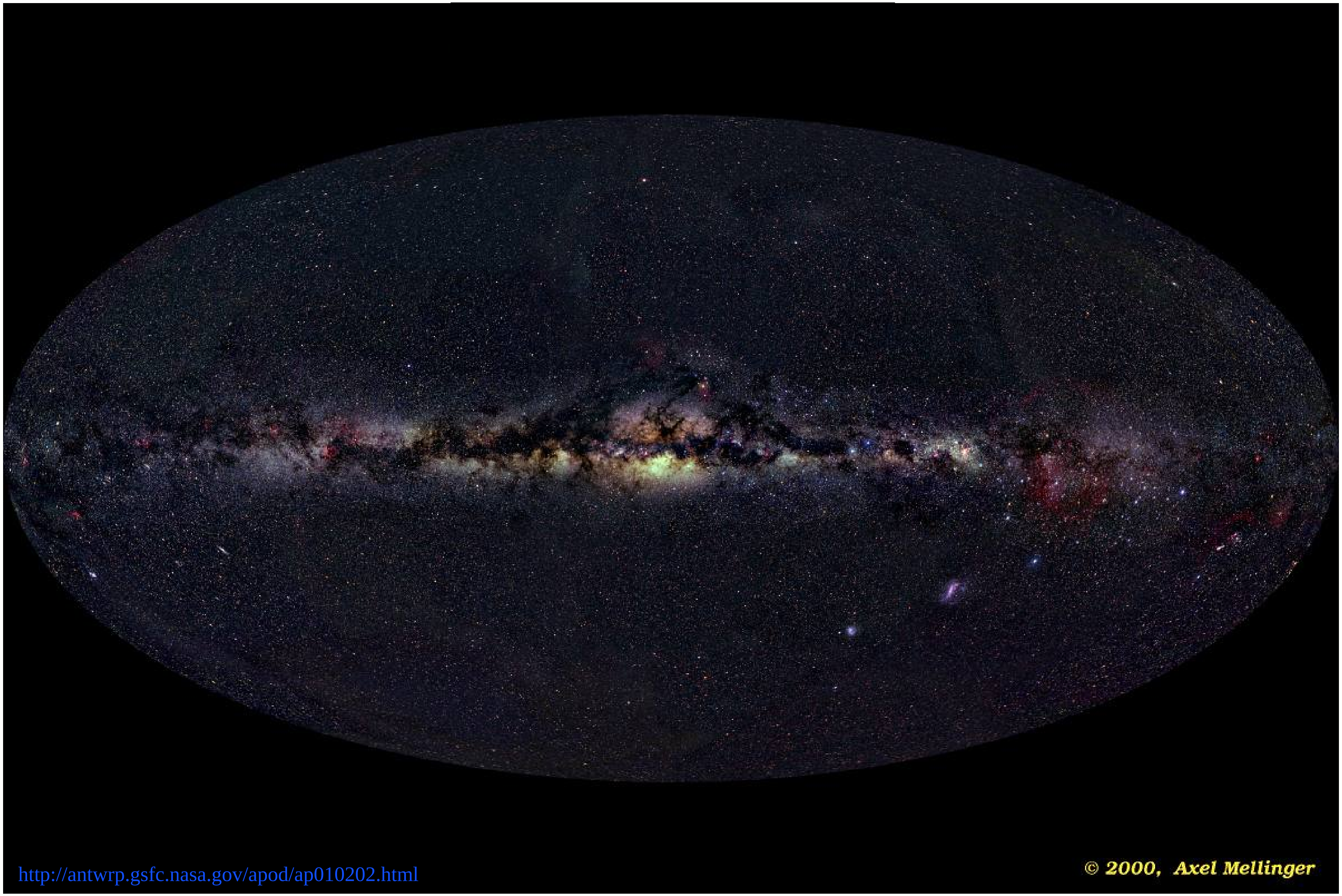


	One meter, about 40 inches
÷10,000	Human hair, about 100 microns
÷100	Wavelength of light, about 1 micron
÷10,000	Atomic diameter, 10^{-10} meter
÷100,000	Nuclear diameter, 10^{-15} meter
÷1,000	LIGO sensitivity, 10^{-18} meter

Interferometer Noise



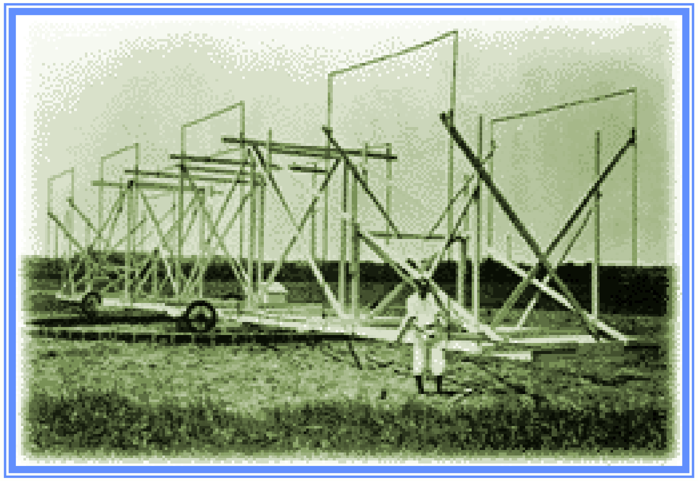
SO WHY ARE WE DOING THIS??



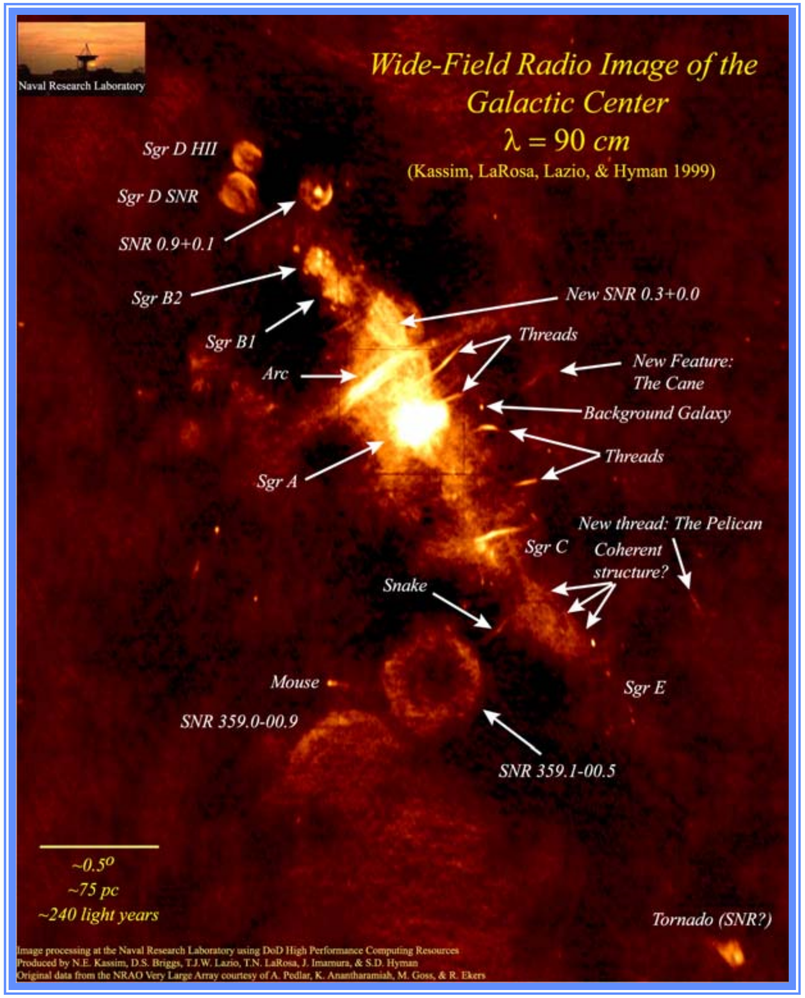
http://antwrp.gsfc.nasa.gov/apod/ap010202.html

New Instrument
‘New’ Universe!

- Janksy, 1933: antenna built to diagnose transatlantic phone interference **accidentally discovers radio emissions from the galactic center**
- Revolution: unforeseen objects & underlying principles
- Entire history of astronomy turned out to be a myopic selection: ‘looking under the lamppost’

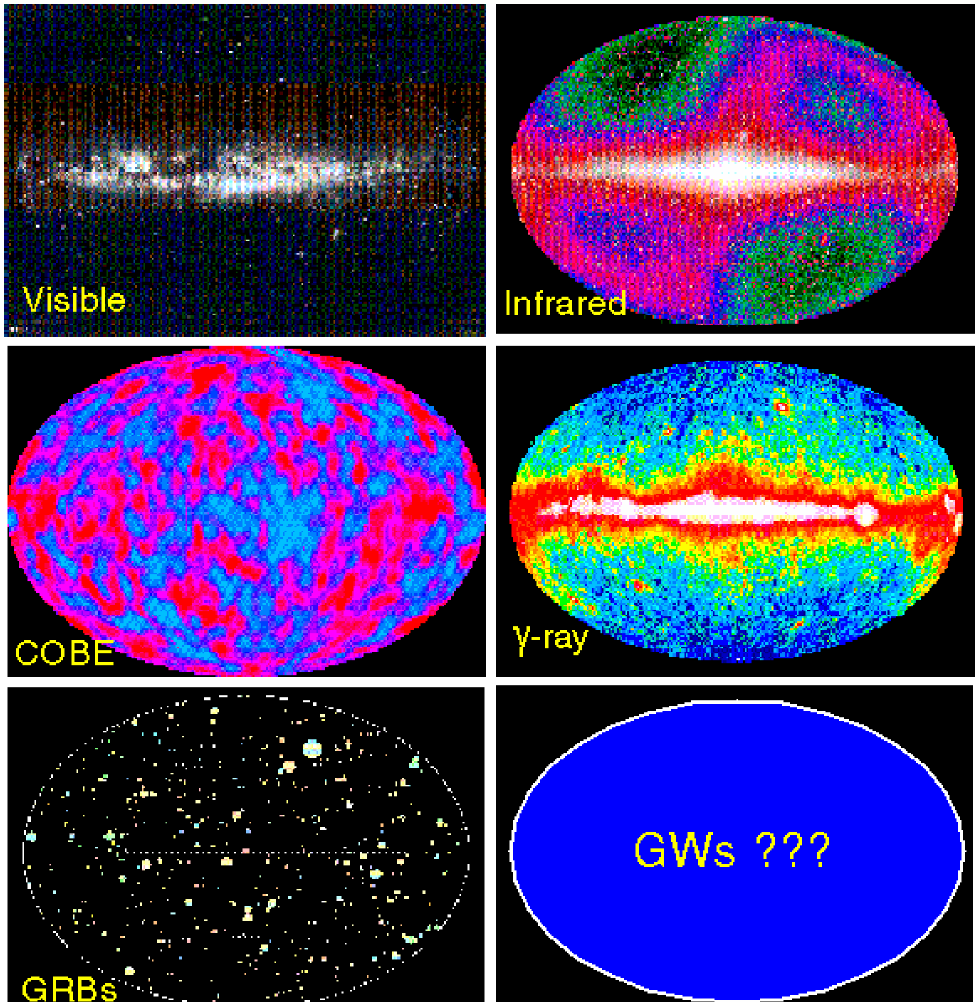


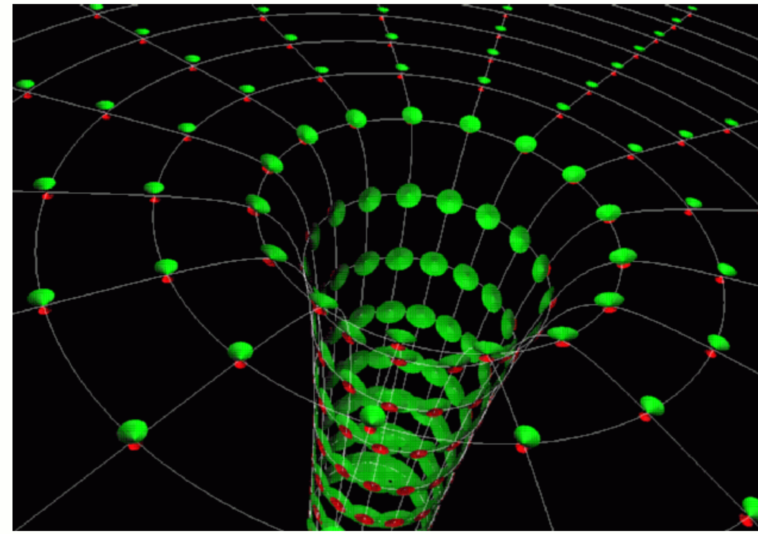
http://www.lucent.com/museum/1933rt.html



//http://rsd-www.nrl.navy.mil/7213/lazio/GC/

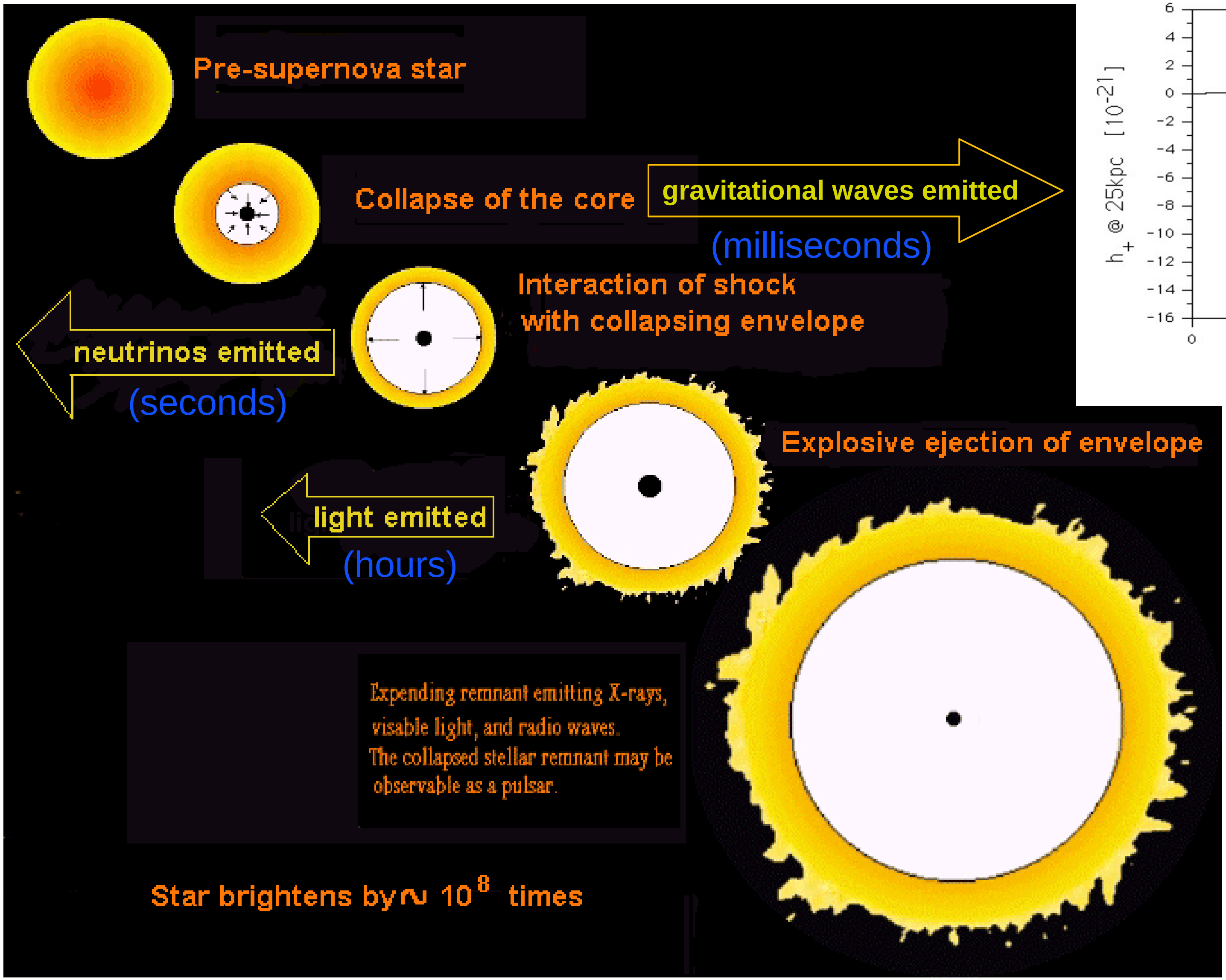
A New 'Sense'- A New Universe

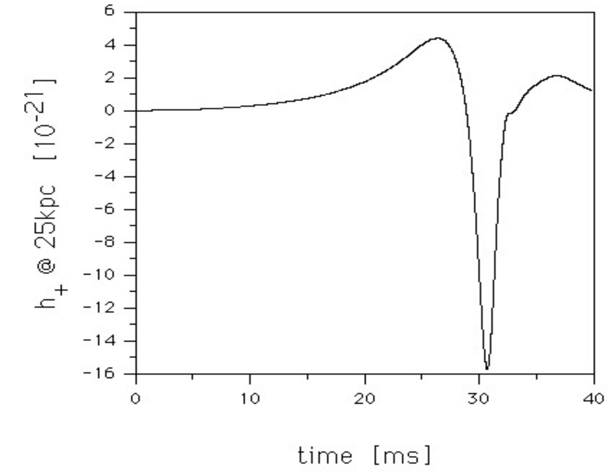




Gravitational Waves will provide complementary information, as different from what we know as sound is from sight.

Nonaxisymmetric supernova

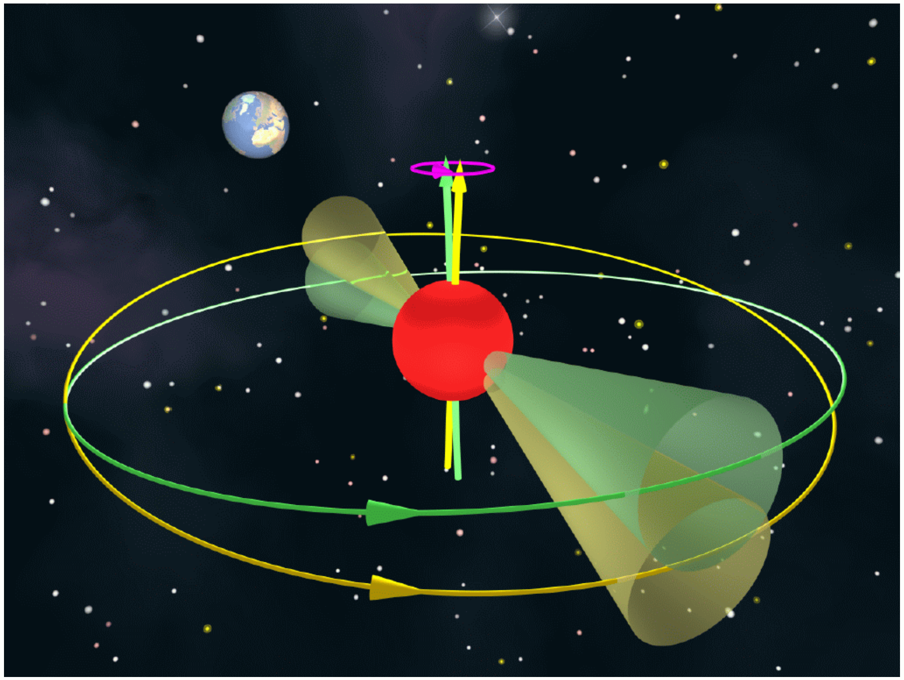




computed strain waveform

Zwerger & Mueller, Astron. Astrophys. 320, 209 (1997)
Dimmelmeier, Font & Mueller, Astrophys.J. 560 (2001) L163-L166

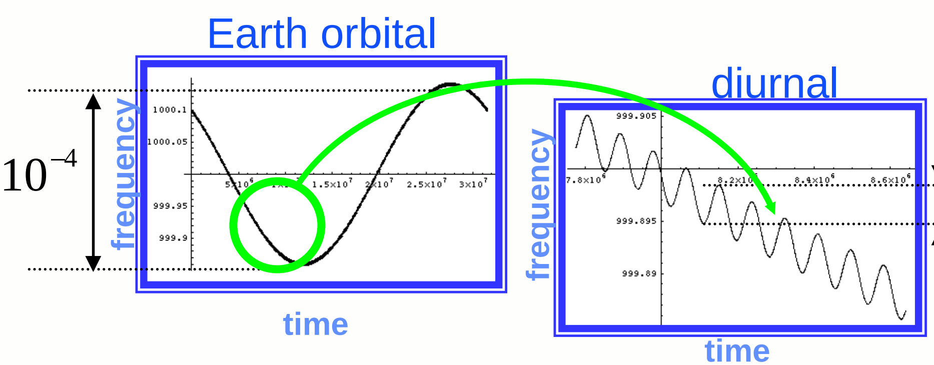
Periodic ("CW") Signals



Jodrell Bank Observatory

- Many fast radio pulsars now known with rotation rates (x2) in LIGO frequency band
- Eccentricity $10^{-4} < \varepsilon < 10^{-6}$ possible from
  - oblateness x axis wobble
  - accretion-driven surface waves
  - GW-driven body waves
- Signal always "on", coherent integration continually improves SNR
  - Doppler shift from Earth and/or source motion requires specific phase ephemeris
  - Unbiased all-sky all-frequ ency search computationally "interesting"

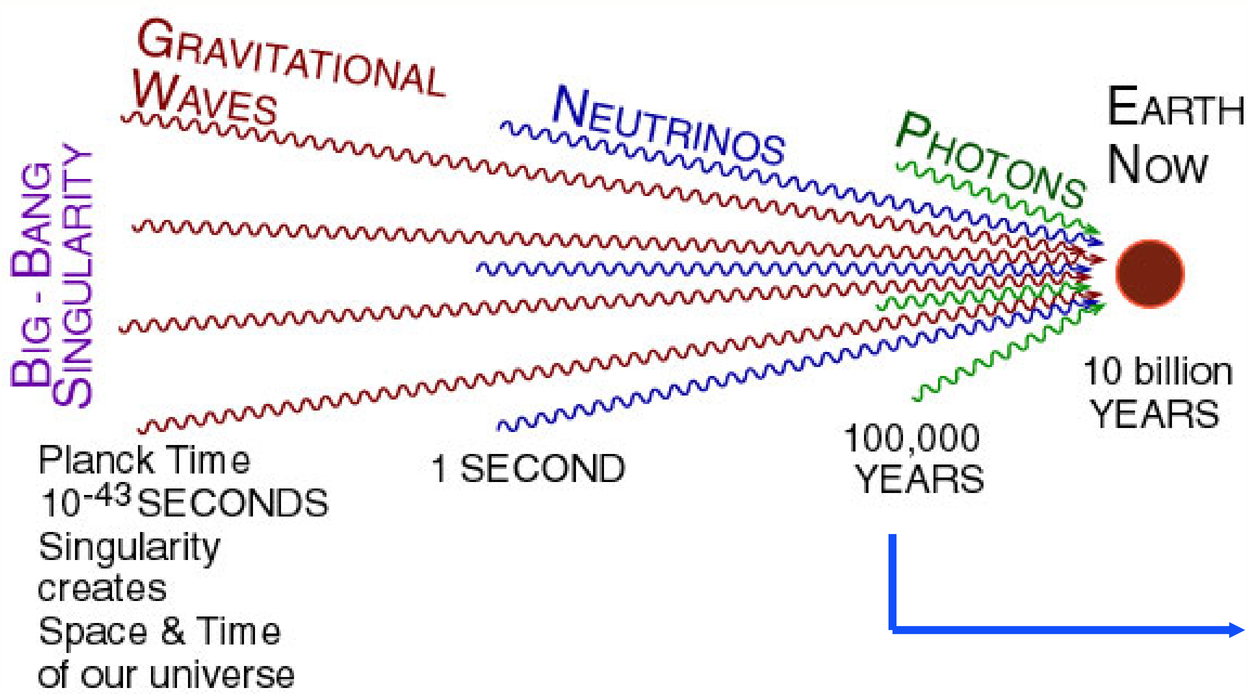
$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$



$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

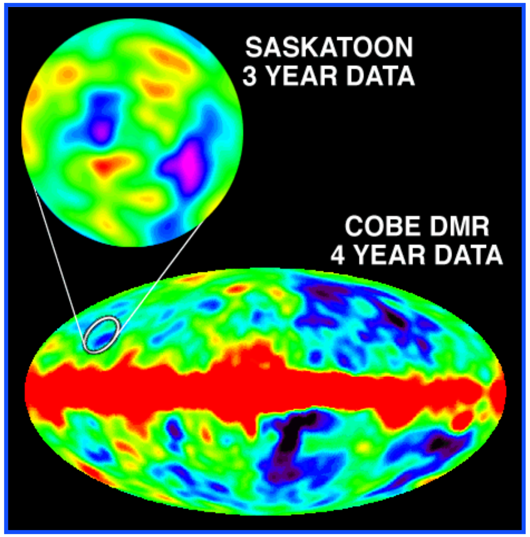
Stochastic GW Background from the Early Universe

- GWs probe the earliest universe; "transparency" at the Planck time
- Constraints from other physics imply GW background weak, but more pronounced mechanisms proposed (primordial strings)



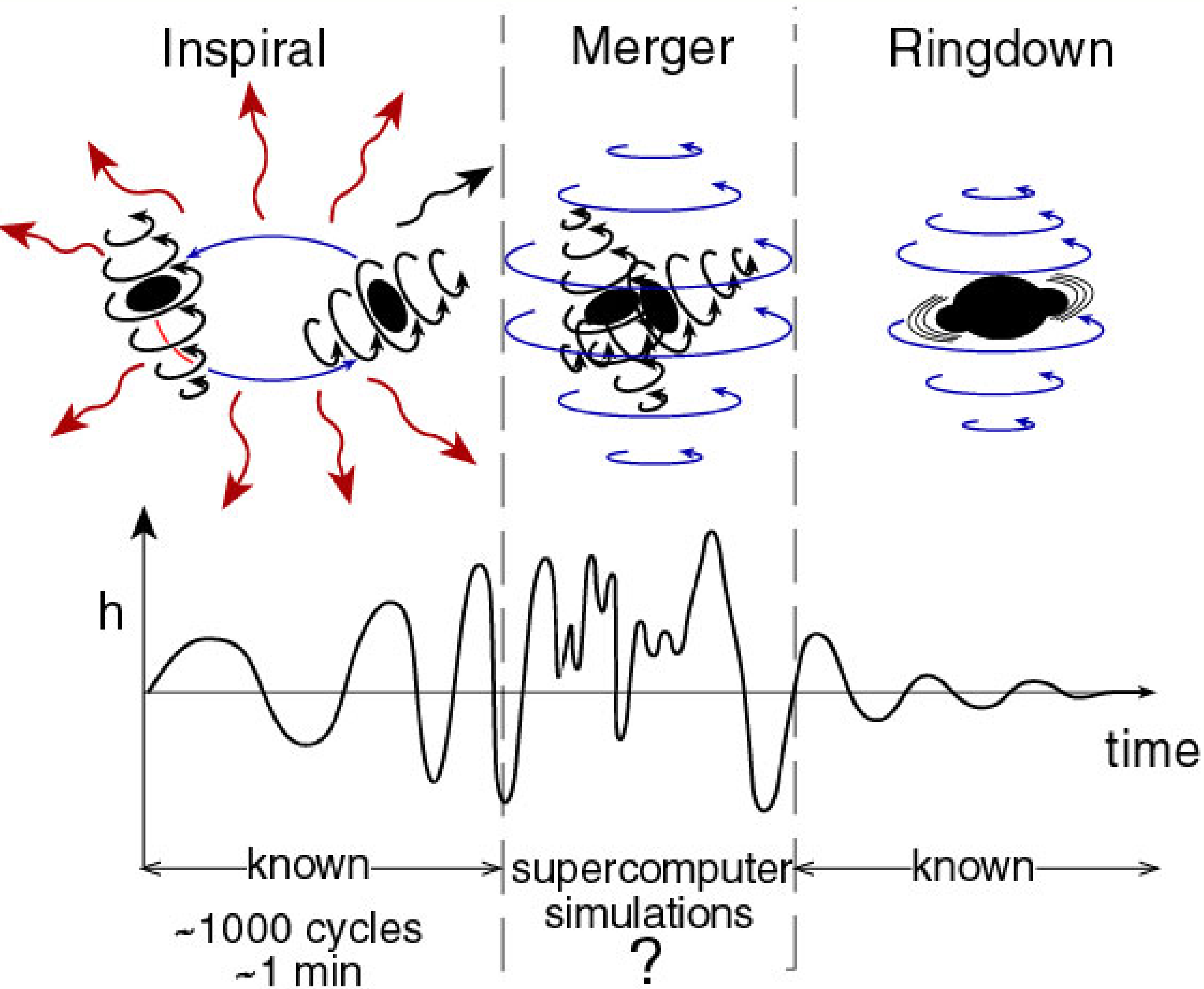
?

Cosmic microwave background



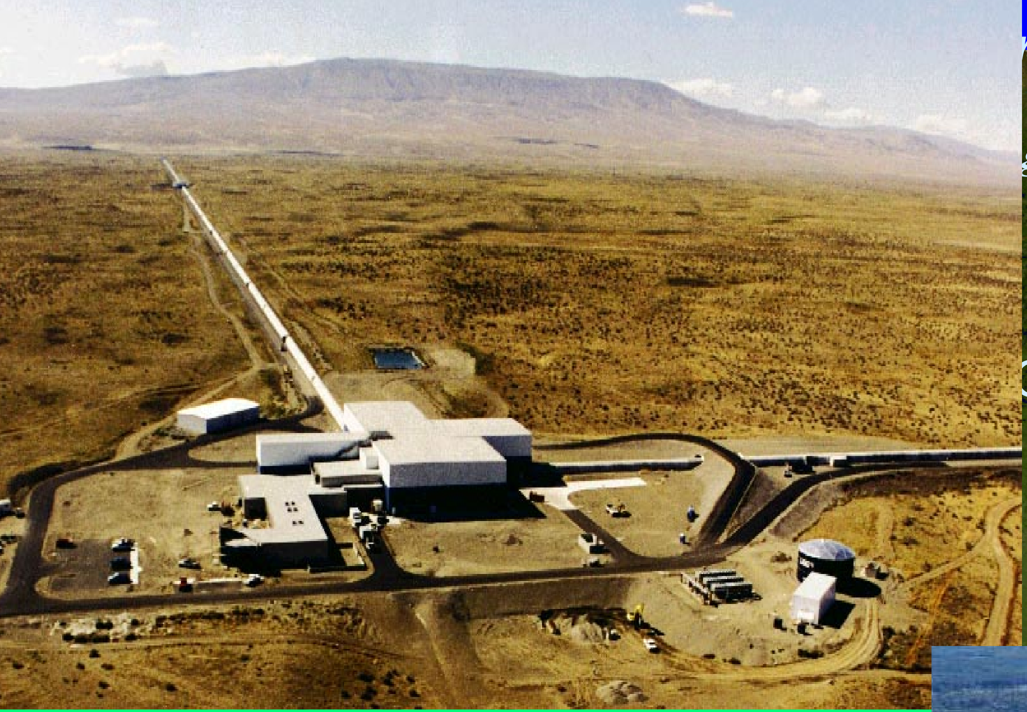
Allen & Romano, gr-qc/9710117
Maggiore, gr-qc/9909001

Example: BH/BH Mergers Producing Dynamic Spacetime Warpage



GW's

- reveal dynamic object cores, not luminous surfaces;
- all mass, not specific species, reactions or temperatures
- pass unabated through intervening matter
- prominent sources may well turn out to be *unpredicted* from what is known by other methods

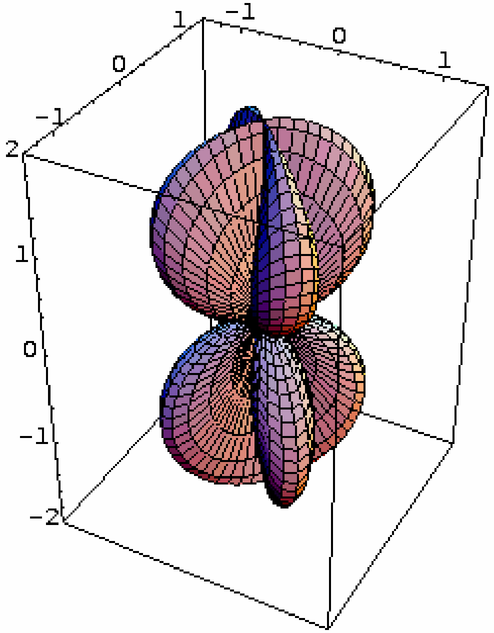


- Coincidence
  - local environments uncorrelated
- Amplitude discrimination
  - half- and full-length IFO's share Hanford site
  - 1:2 ratio required for true signals
- Source triangulation
  - ± 10 ms time of flight
  - ~ arcminute directionality
- Source polarization

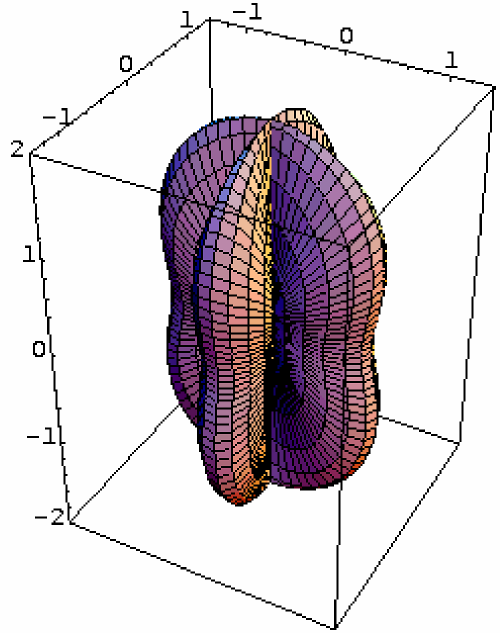
Antenna Pattern of a Laser Interferometer

- Directional sensitivity depends on polarization of waves

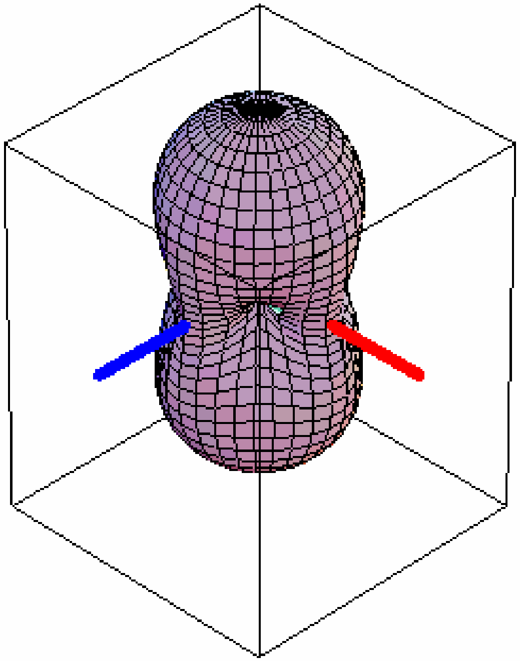
“×” polarization



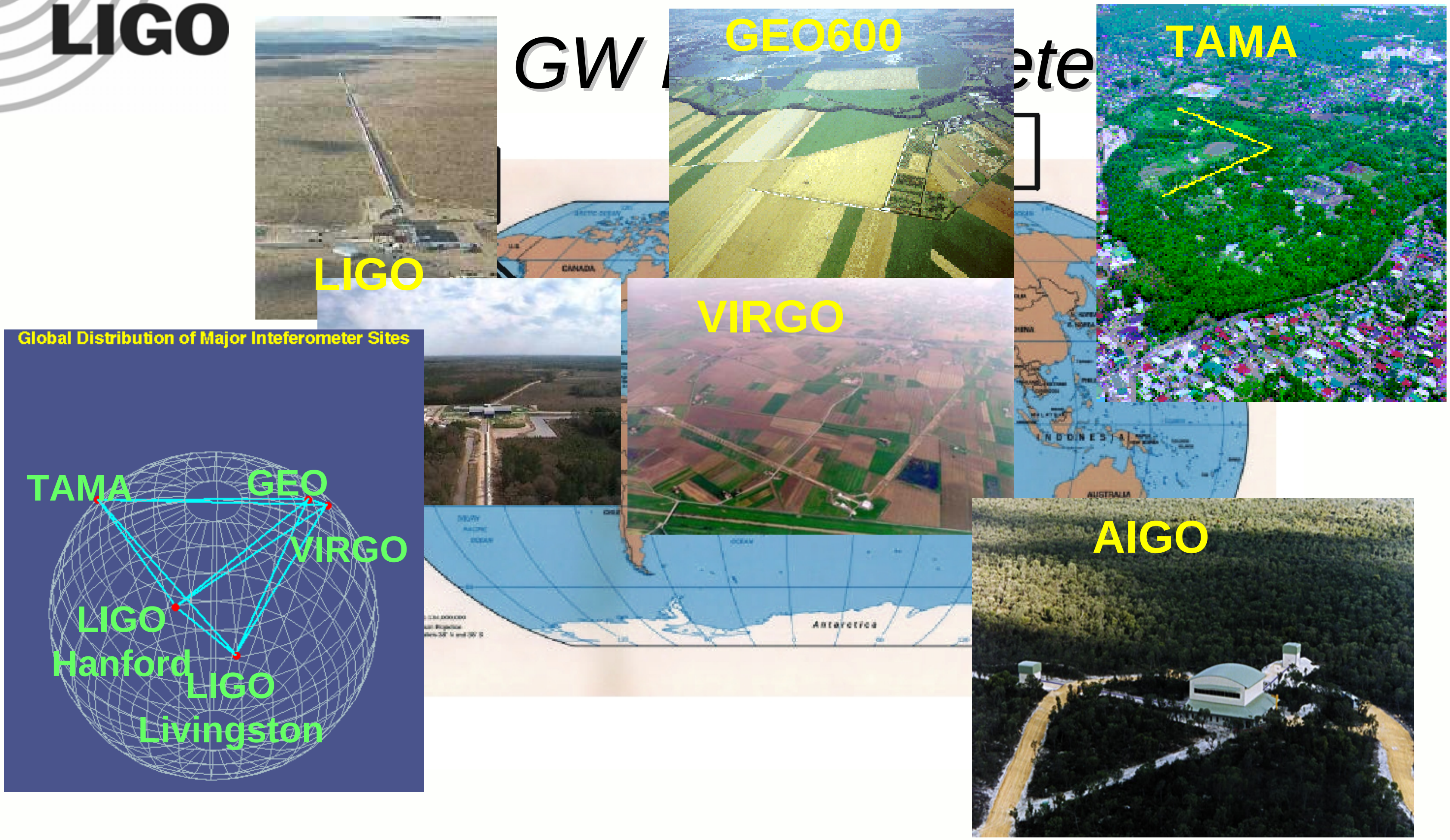
“+” polarization



RMS sensitivity

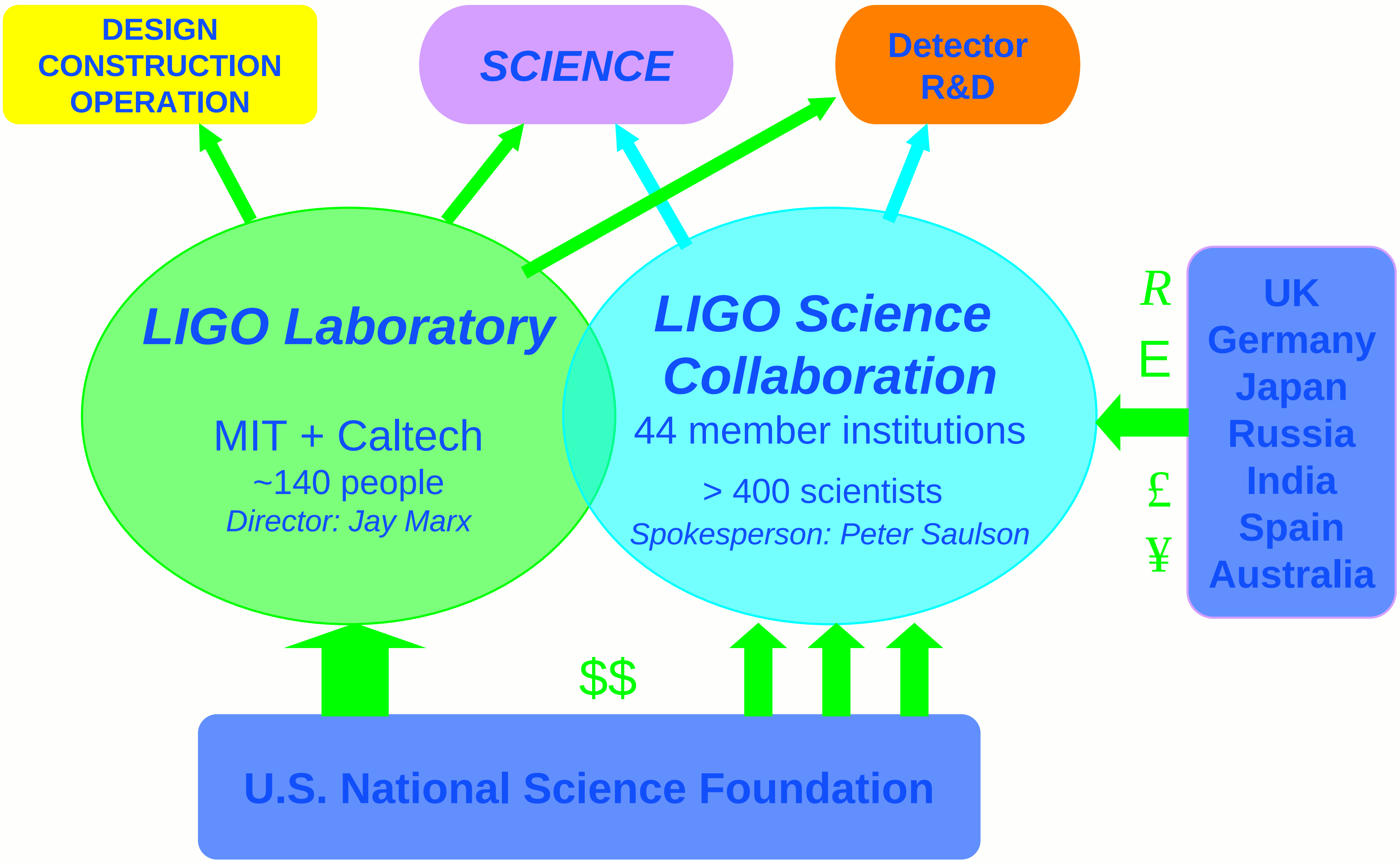


- A broad antenna pattern
  $\Rightarrow$ More like a microphone than a telescope



- Worldwide Network:
  - We coordinate observations and share data with TAMA and GEO
  - We are just finalizing similar agreements with VIRGO
  - AIGO is still in planning stage; AIGO personnel currently share in LIGO operation

LIGO Organization & Support

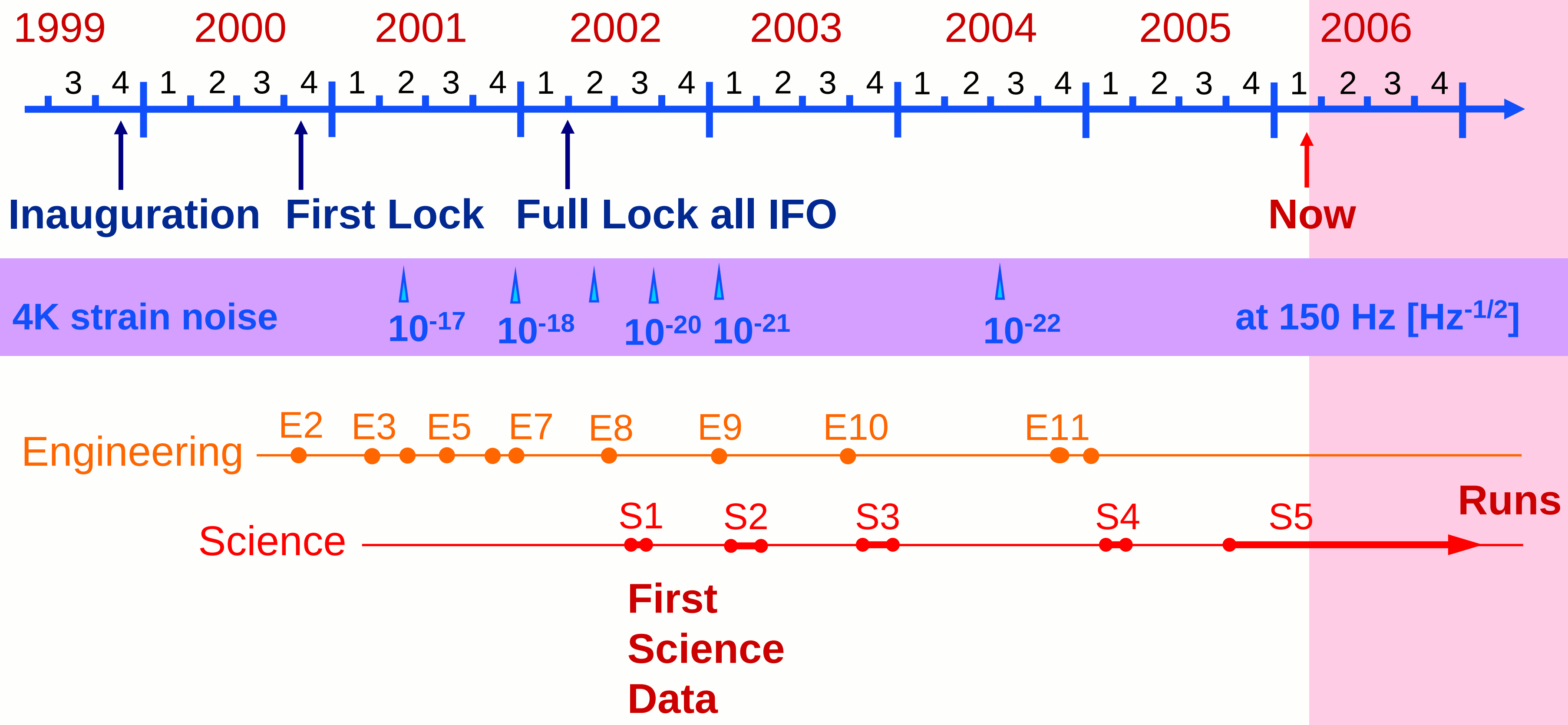


LIGO

Collaborating Institutions

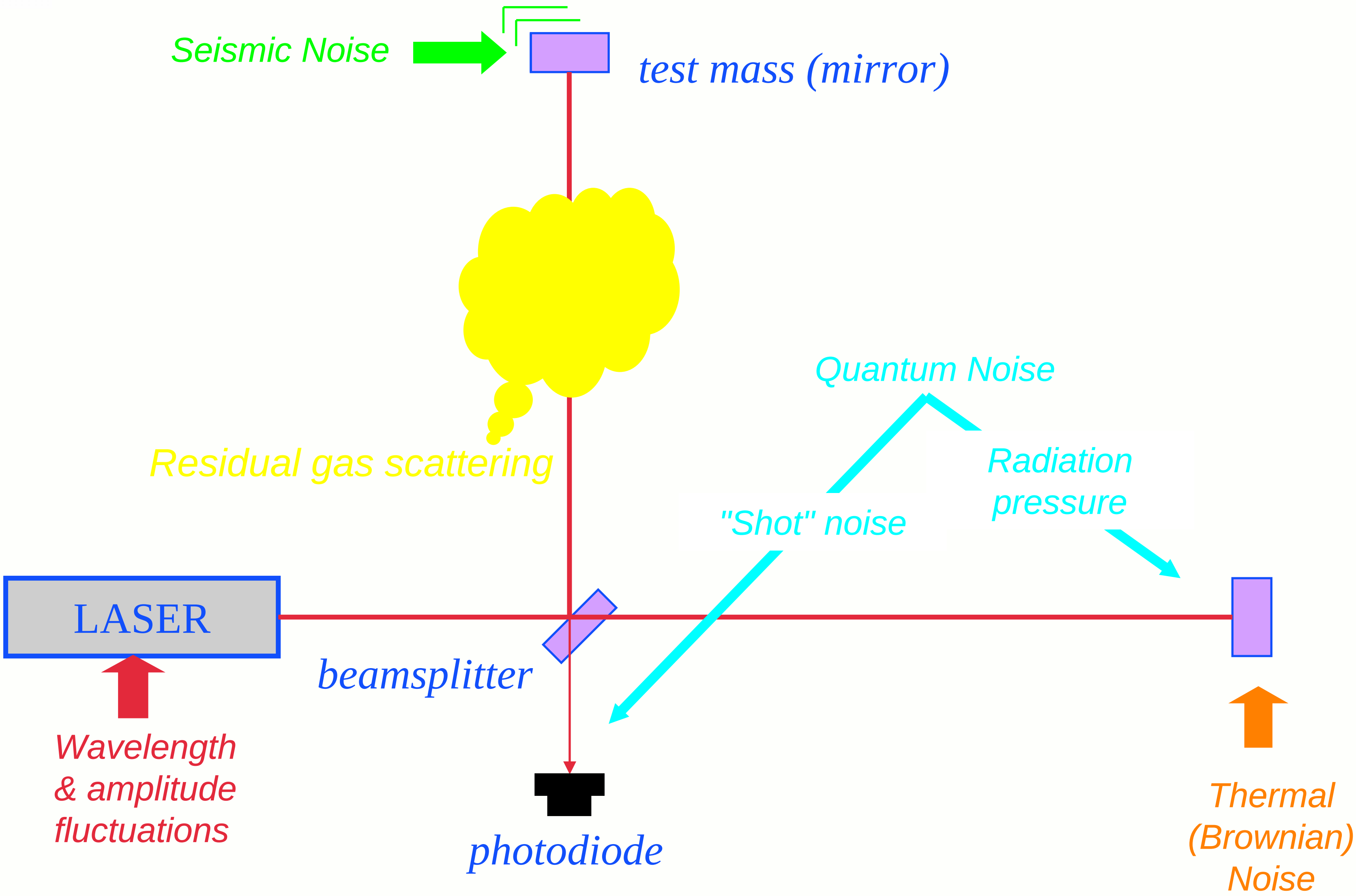
NSF
UTB TSC
Southeastern Louisiana University
Loyola University New Orleans
University of Maryland
LSU
GEO 600
Northwestern University
Universitat de les Illes Balears
Hobart and William Smith College
Southern University
NAOJ 国立天文台
The University of Adelaide Australia
California Institute of Technology
University of Florida
Massachusetts Institute of Technology
University of Wisconsin Milwaukee
Columbia University in the City of New York
The University of Birmingham
The University of Texas at Austin
Syracuse University Founded AD 1870
IGR
Universität Hannover
Washington State University
Embry-Riddle Aeronautical University
Cardiff University
The University of Western Australia
Michigan
The Physics of the Universe PPARC
PAH
Penn State 1855
University of Glasgow

Time Line

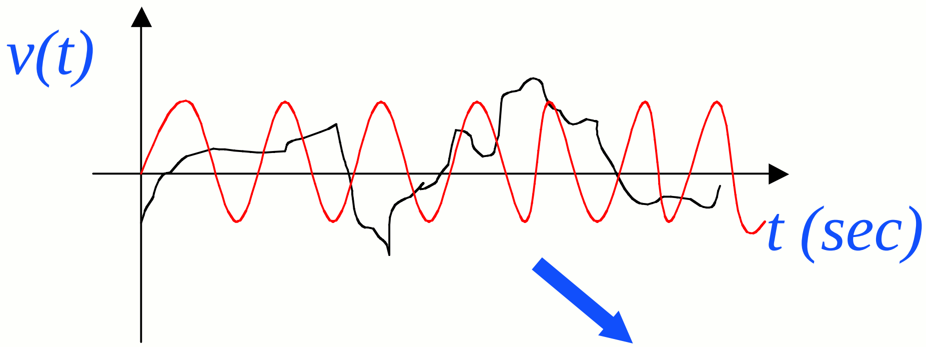


1999
2000
2001
2002
2003
2004
2005
2006
3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Inauguration
First Lock
Full Lock all IFO
Now
4K strain noise
10^{-17}
10^{-18}
10^{-20}
10^{-21}
10^{-22}
at 150 Hz [$Hz^{-1/2}$]
Engineering
E2
E3
E5
E7
E8
E9
E10
E11
Science
S1
S2
S3
S4
S5
Runs
First Science Data

Interferometer Noise Limits



Detour: Power Spectra

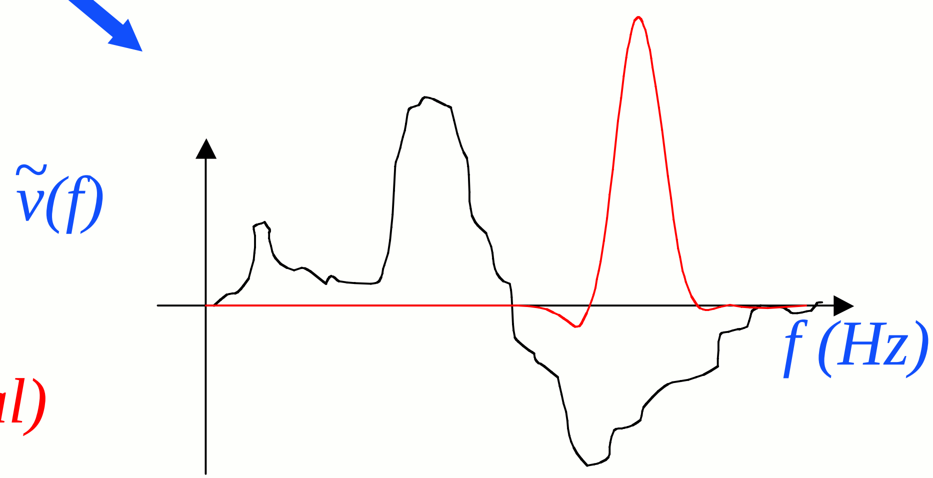


Energy ~ <v^2> Δt

Power ~ <v^2>

(energy per unit time)

Fourier transform



Spectral Density

$$S_v(f) = \lim_{T\to\infty} \frac{1}{T} \left| \int_{-T}^{T} v(t) e^{-i2\pi f t} dt \right|^2$$

(energy per unit frequency interval)

$$\int_0^\infty df\, S_v(f) = \int_0^\infty dt\, v^2(t)$$

Power Spectra (2)

- White noise: $S(f)$ = constant
- A filter passing only signals in interval $\{f_1, f_2\}$ will let through power $S(f) * (f_2 - f_1)$
- Sometimes we talk about the "root mean square" or RMS of a process;

$$v_{RMS} = \sqrt{< v^2(t) >}$$

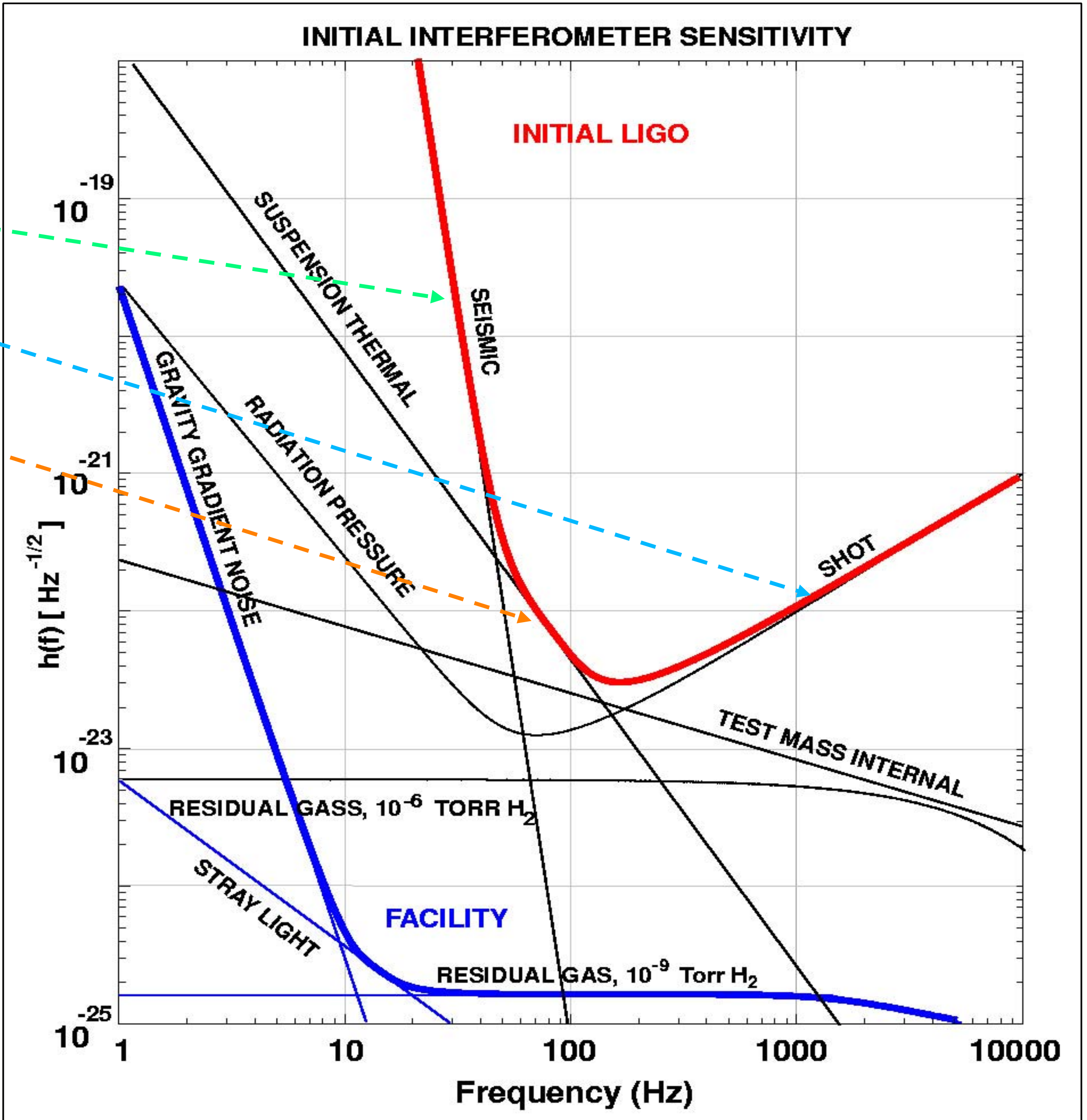
- Similarly, we can talk about an "amplitude spectral density"

$$\hat{v}(f) = \sqrt{S_v(f)}$$

- This beast will have units of $\dfrac{[v]}{\sqrt{\text{Hz}}}$

Design Noise Limits

- Initial sensitivity limits
  - **seismic noise** at the lowest frequencies
  - **shot noise** at high frequencies
  - **thermal noise** at intermediate frequencies
- Based on conservative extrapolation of prototype technologies (circa ~'97)
- Facility limits designed much lower to allow improvement as detector technology advances



Beam Tubes and Enclosures

Precast concrete enclosure: *bulletproof*

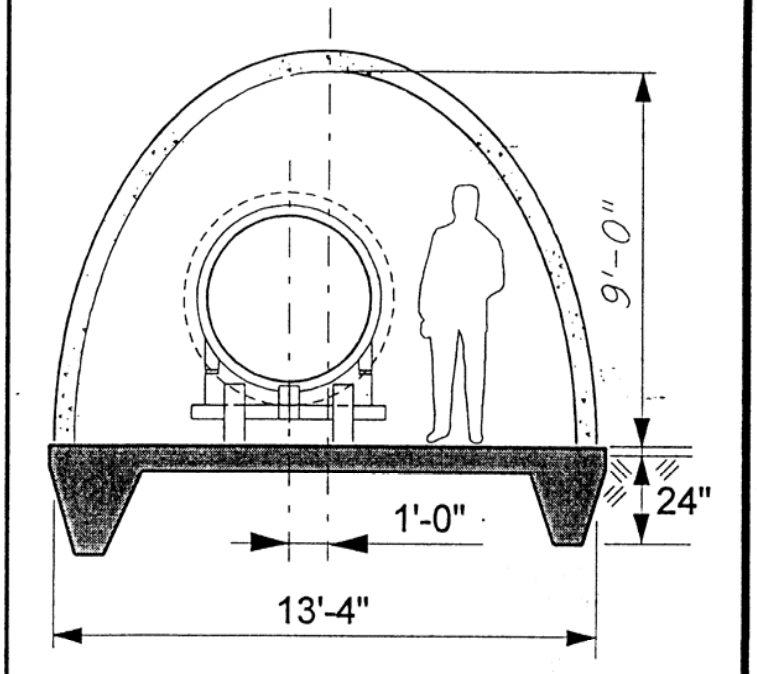


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

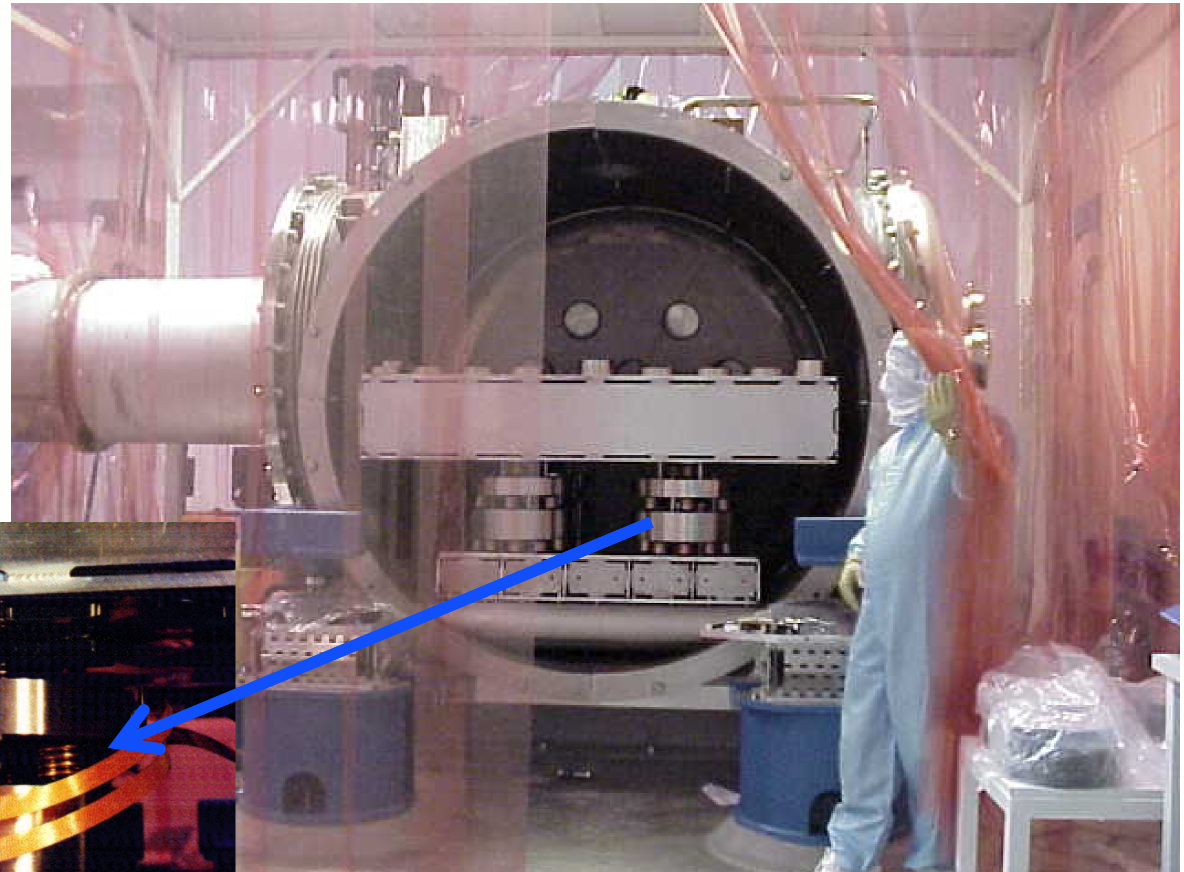
- **Beam Tube**
  - **1.2m diam; 3 mm stainless**
  - **special low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **20,000 m^3 @ 10^{-8} torr; earth's largest high vacuum system**

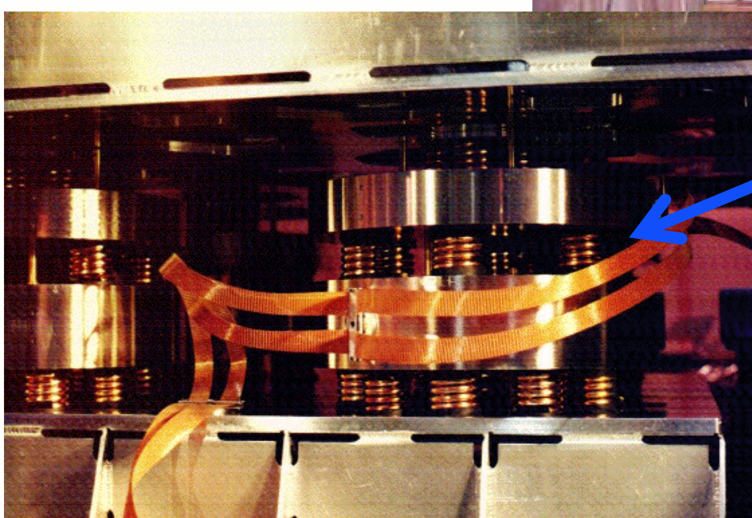
Vacuum Equipment

LIGO

Seismic Isolation System

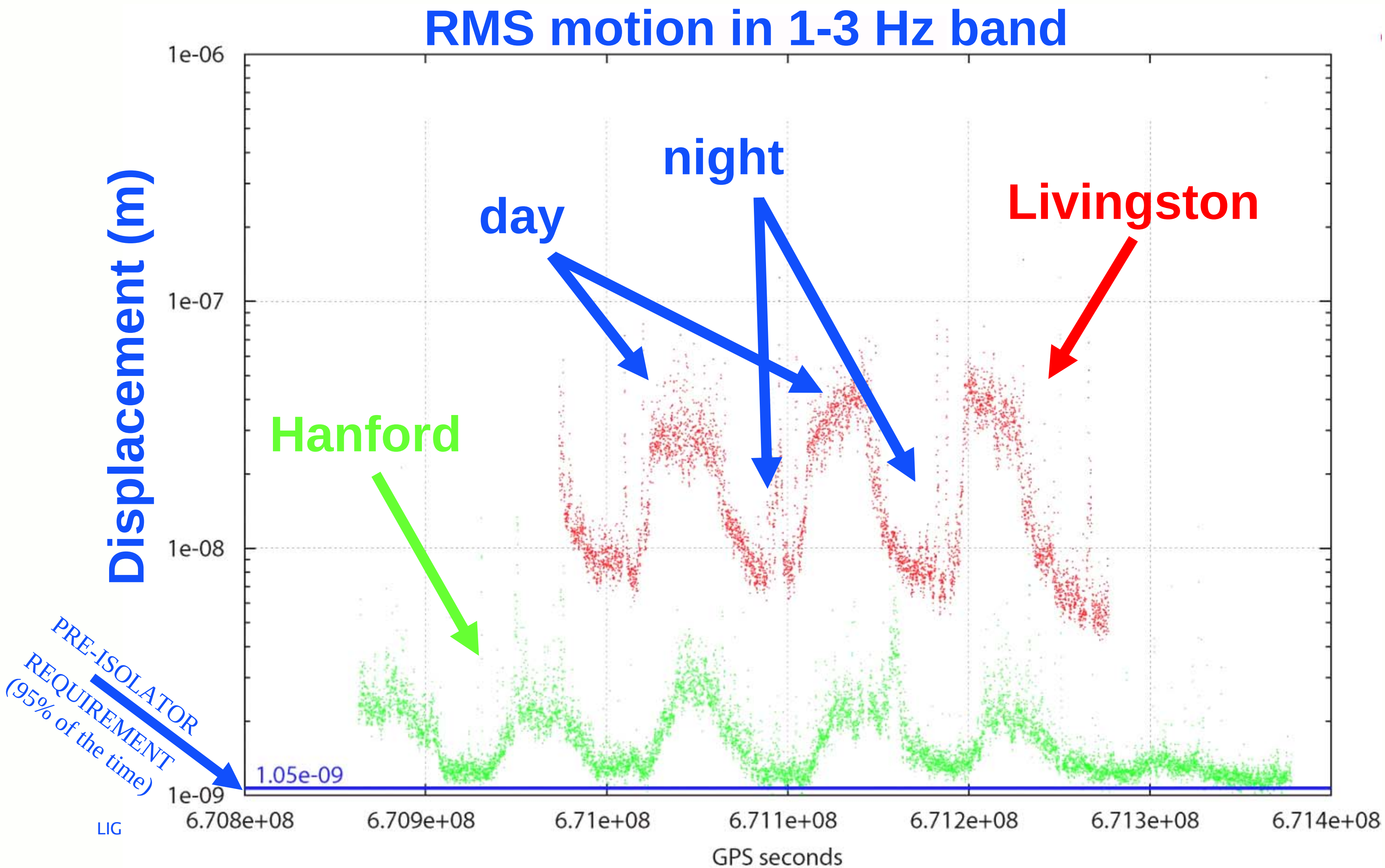
Tubular coil springs with internal constrained-layer damping, layered with reaction masses





Isolation stack in chamber

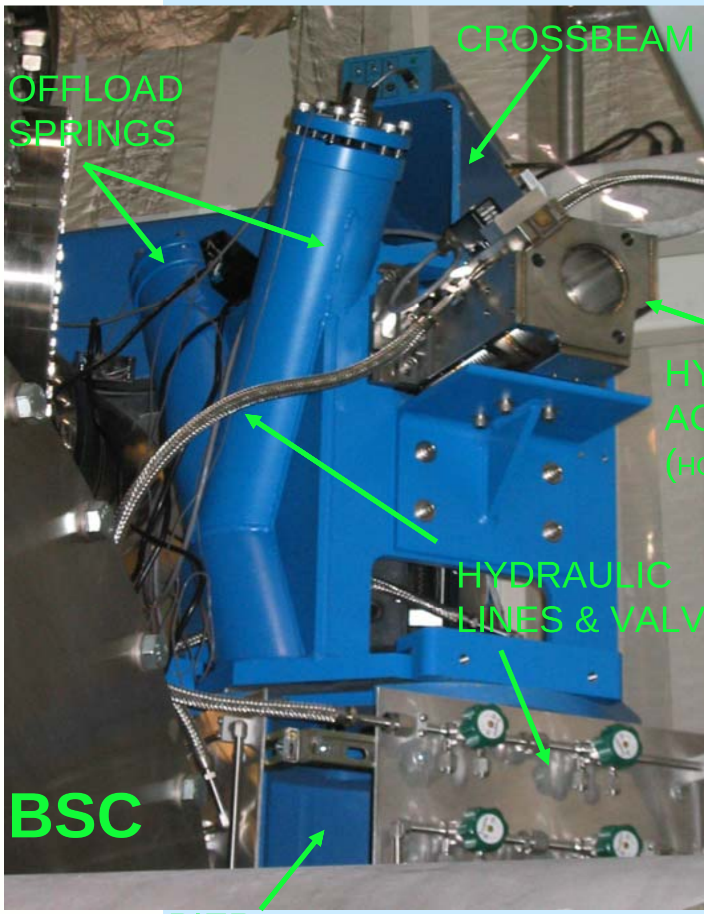
Seismic Noise

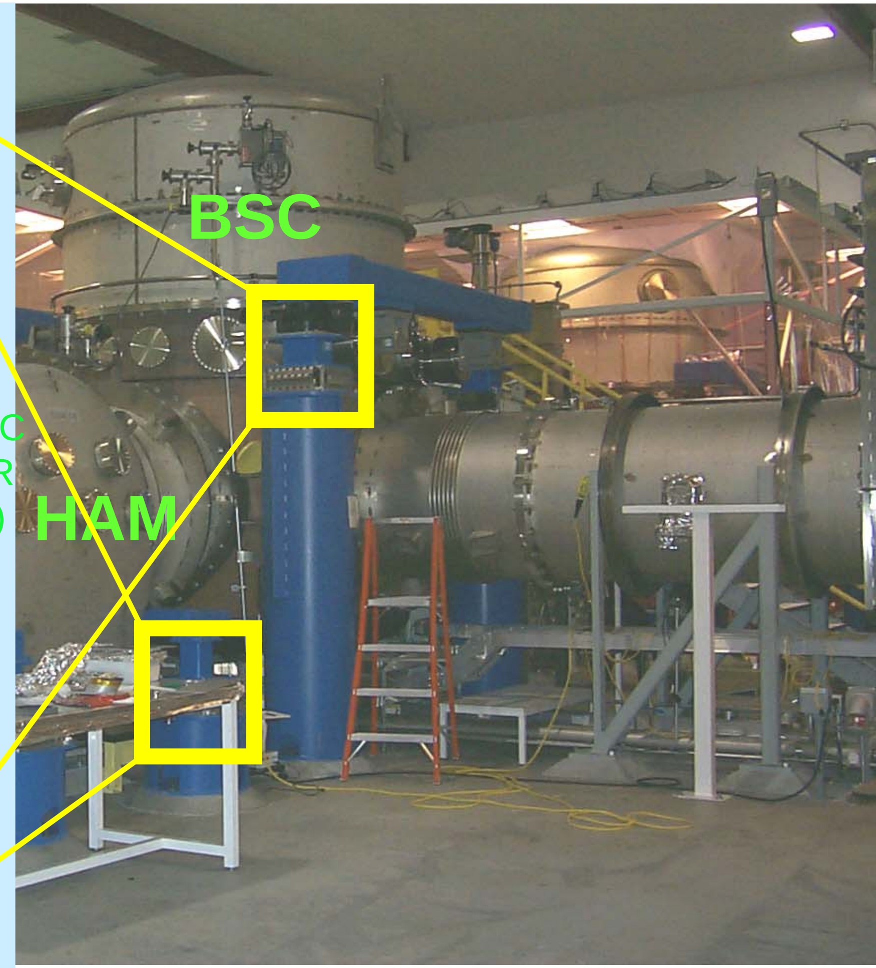


LIGO

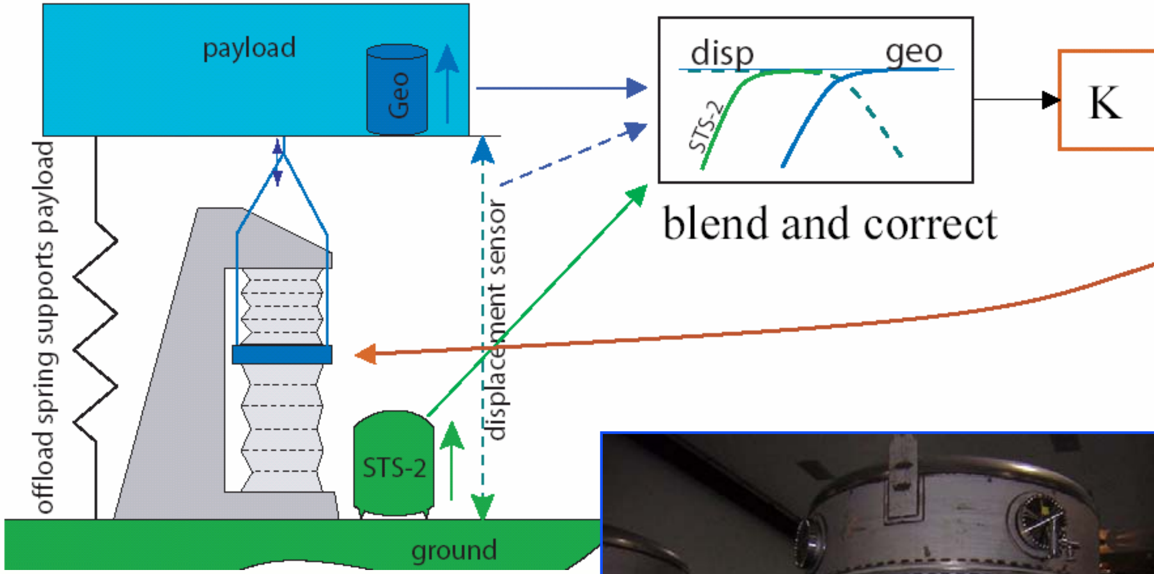
Active Seismic Isolation

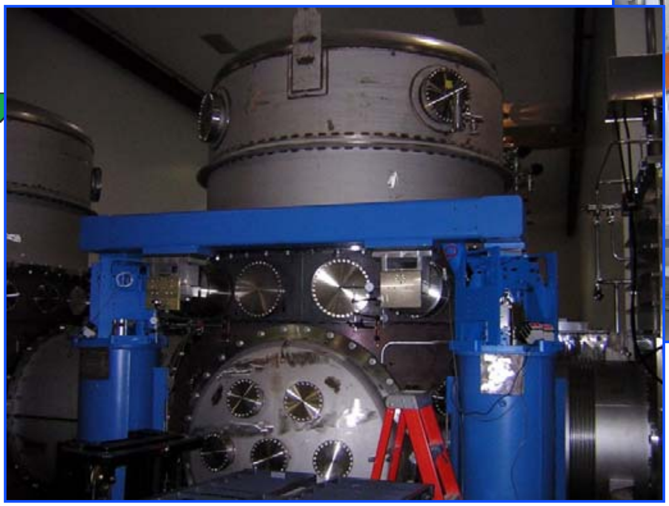
Hydraulic External Pre-Isolator (HEPI)



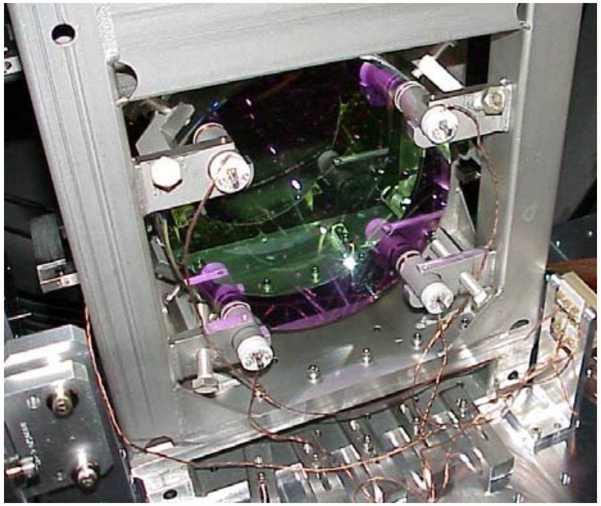


Installation of HEPI at Livingston has improved the stability of L1

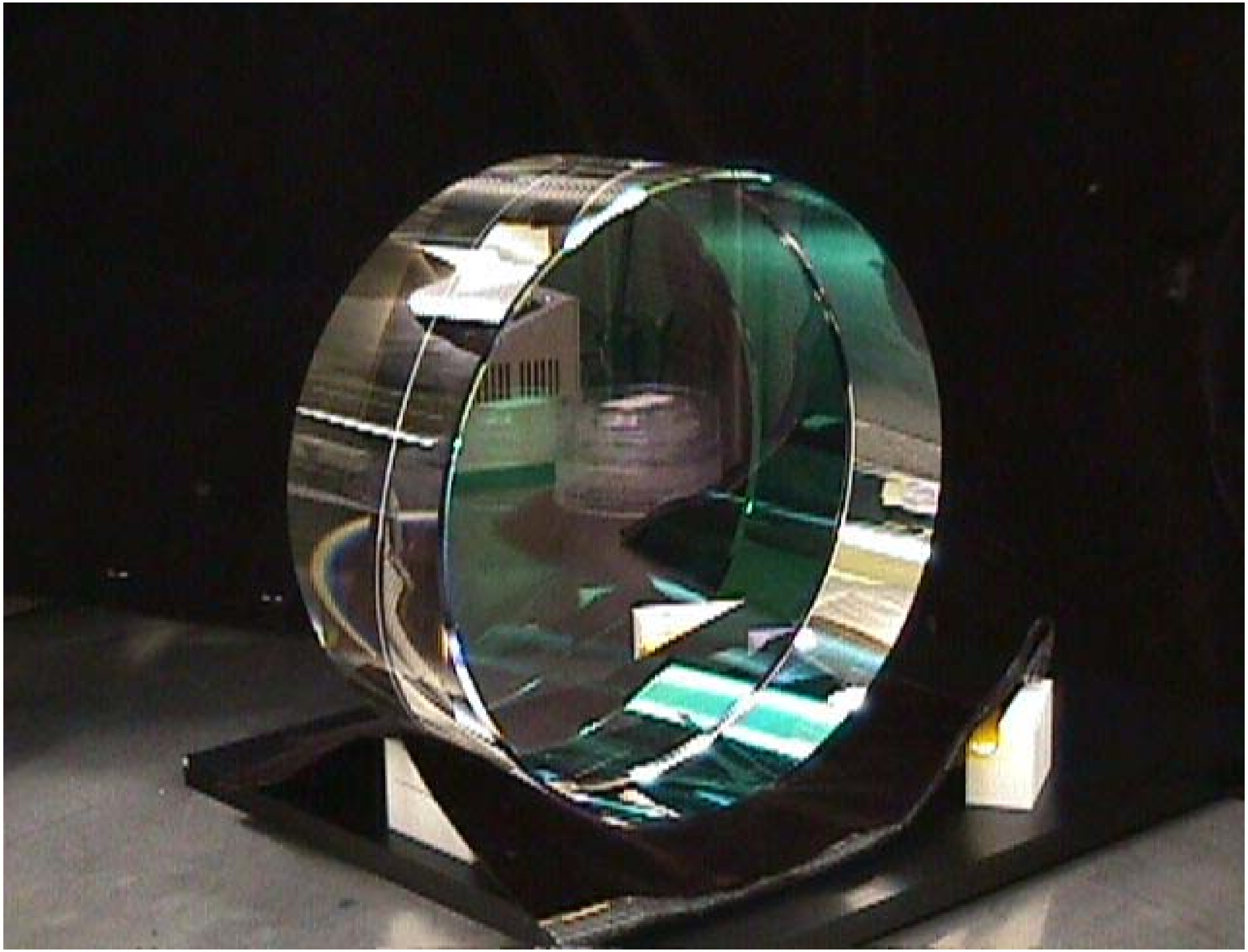




Core Optic Suspensions

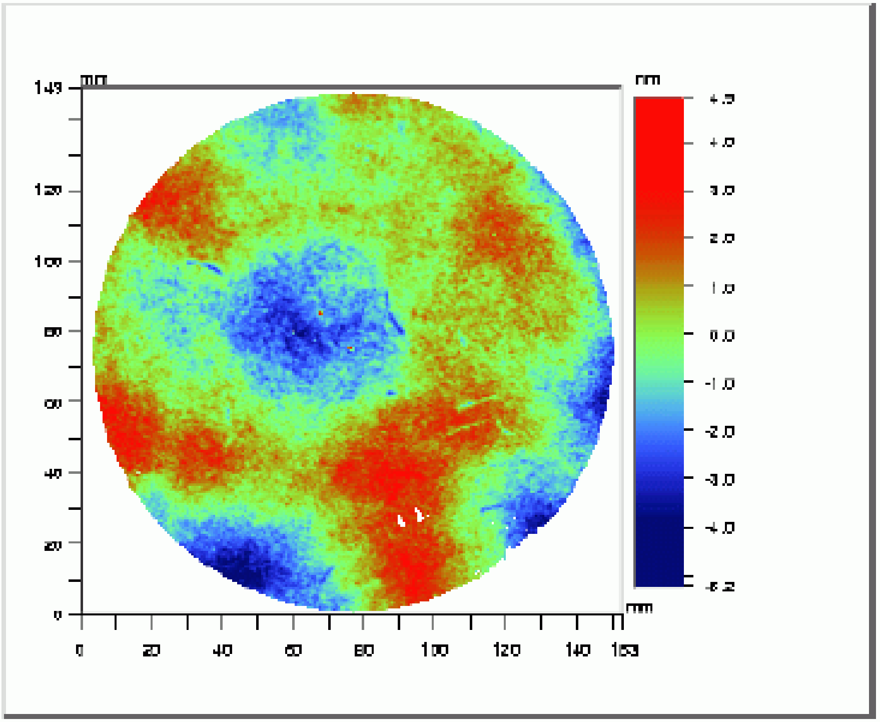


Core Optics

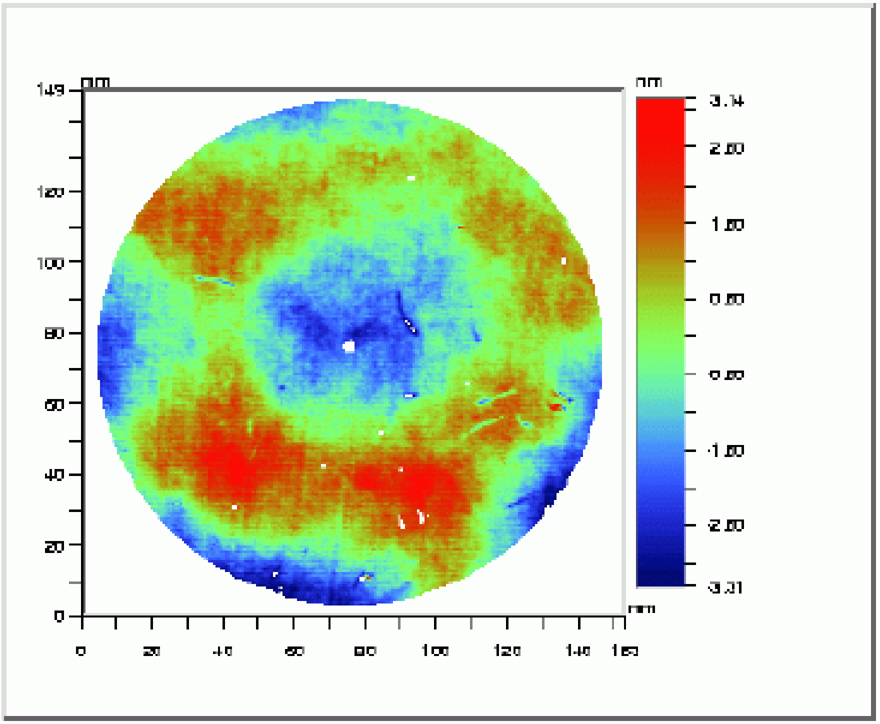


Core Optic Metrology

- Current state of the art: 0.2 nm repeatability



LIGO data (1.2 nm rms)



CSIRO data (1.1 nm rms)

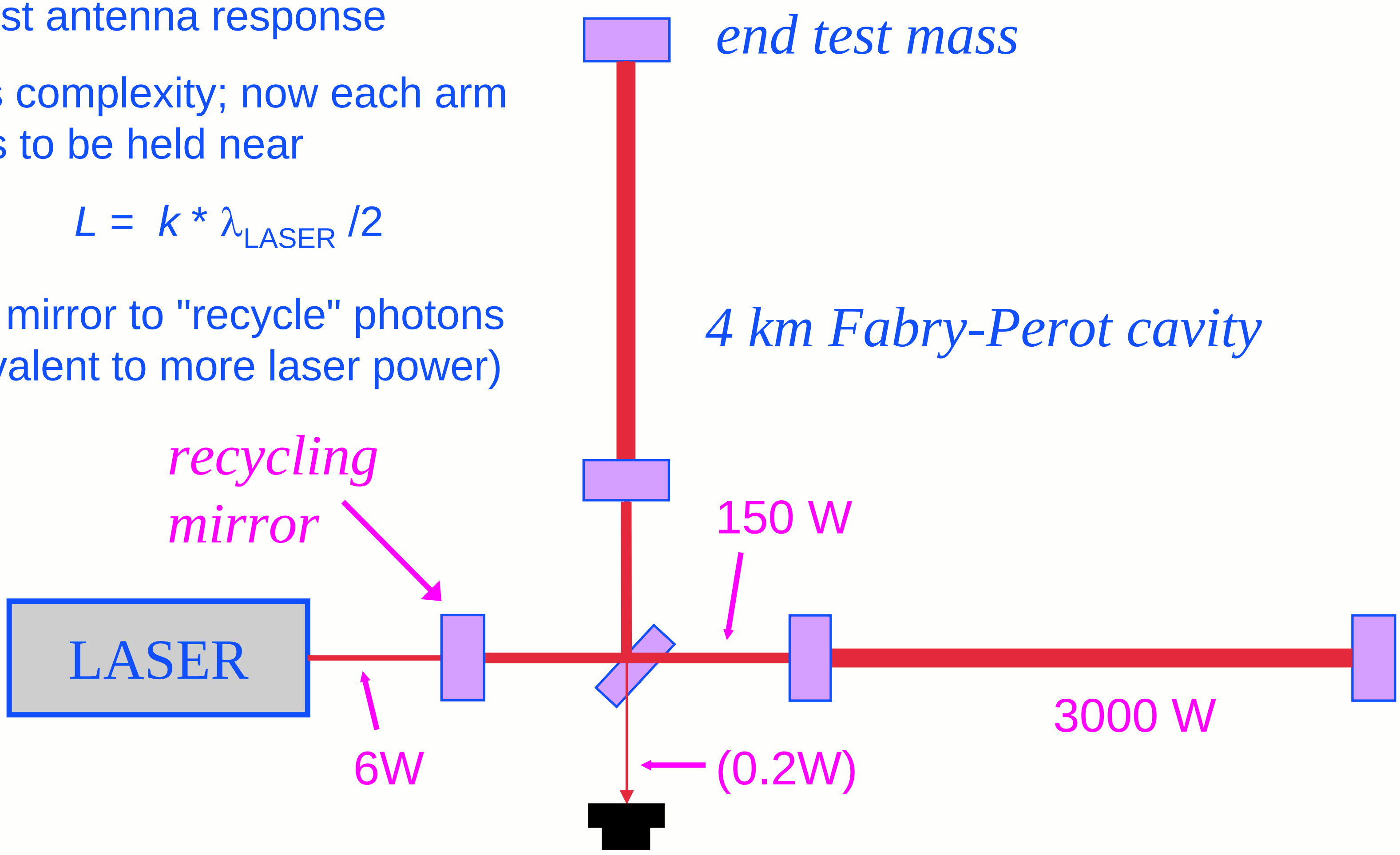
➢ ***Best mirrors are λ/6000 over the central 8 cm diameter***

LIGO Interferometer

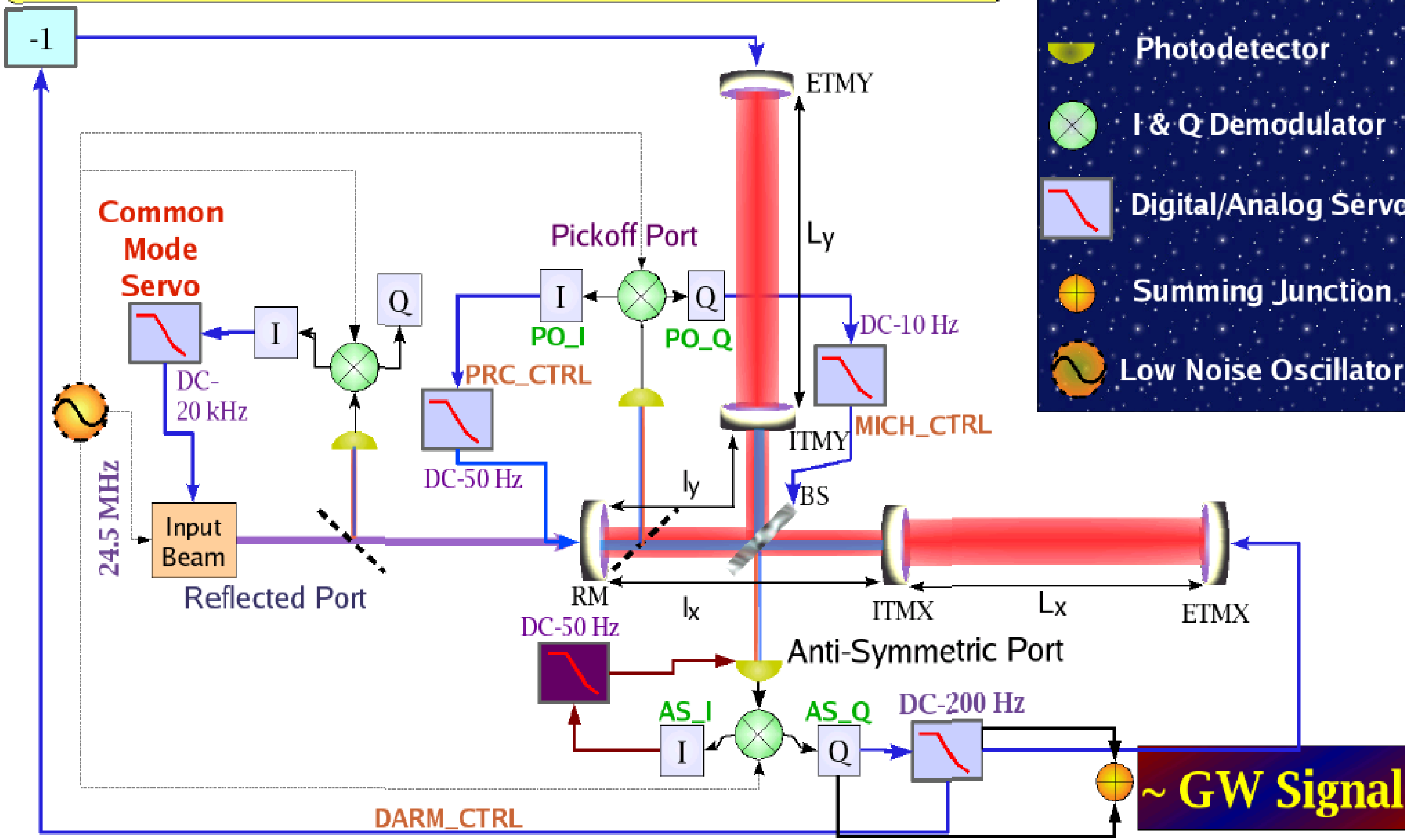
- Want "optical" arm length ~ λ_{GW} /4 for best antenna response
- Adds complexity; now each arm needs to be held near

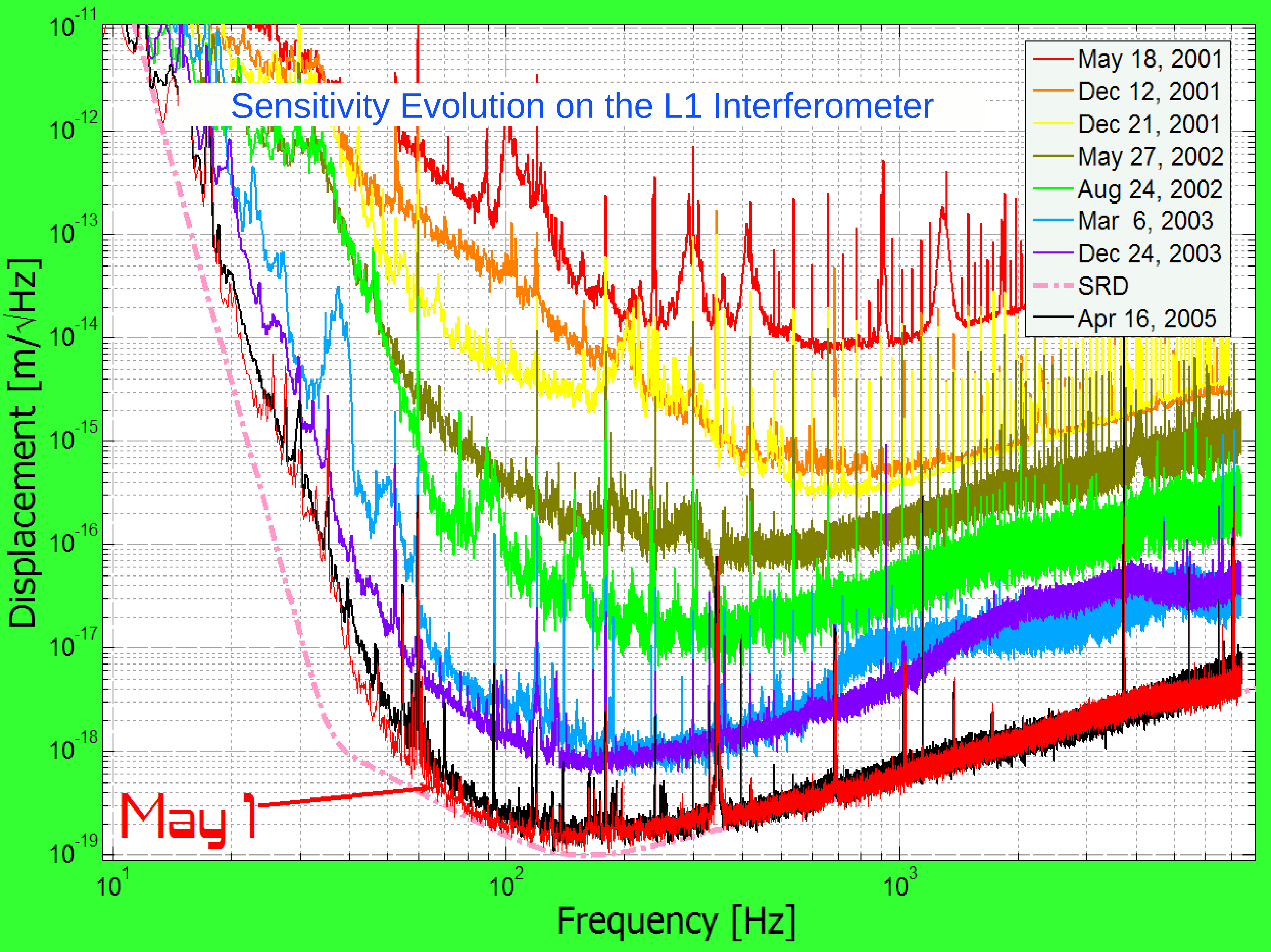
$$L = k * \lambda_{LASER} /2$$

- Add mirror to "recycle" photons (equivalent to more laser power)



Length Readout & Controls




Sensitivity Evolution on the L1 Interferometer
May 18, 2001
Dec 12, 2001
Dec 21, 2001
May 27, 2002
Aug 24, 2002
Mar 6, 2003
Dec 24, 2003
SRD
Apr 16, 2005
May 1
Displacement [m/√Hz]
Frequency [Hz]
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^1
10^2
10^3

PRELIMINARY

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

S5 Performance So Far

NS-NS Inspiral Range Histogram

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Coincidence Factor by Week

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

start delay

commissioning break

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Public Education and Outreach

LIGO Science Education Center at Livingston Observatory

- 8000 ft^2 facility with ~50 hands-on exhibits illustrating LIGO science themes
- School group, family, club visits
- Science teacher professional development
- *Under construction!*

STATUS

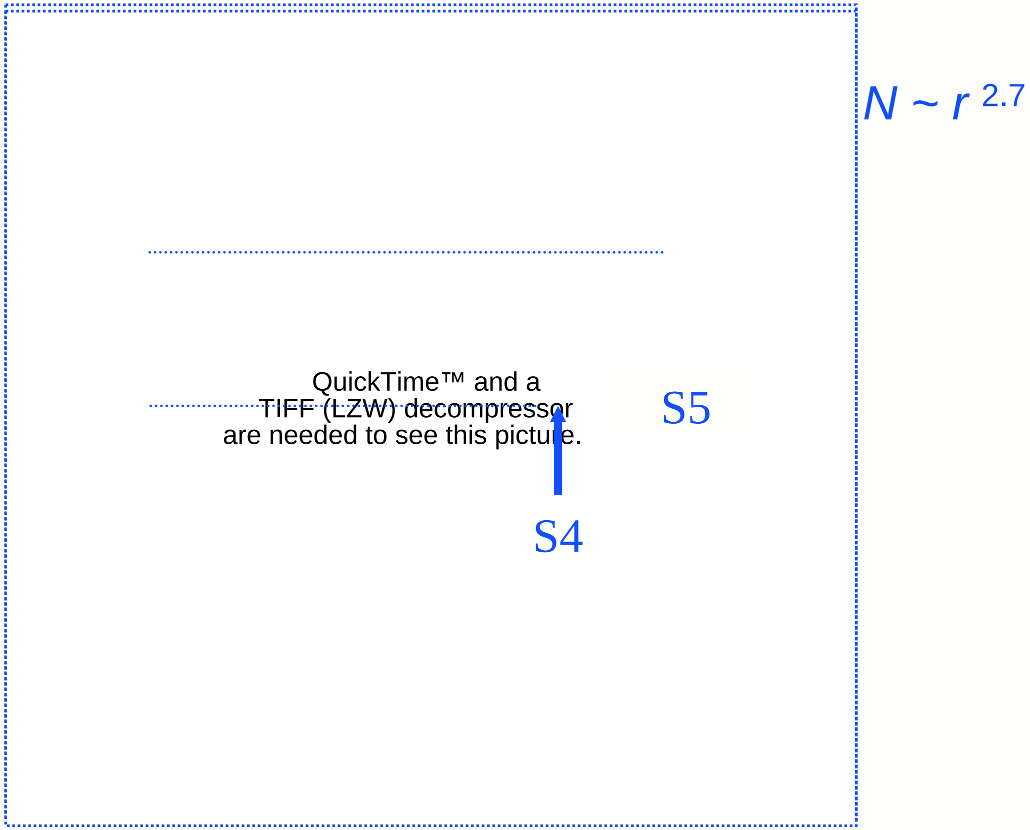
- LIGO completed S1, S2, S3, S4 science data runs at successively higher sensitivities

No confirmed detections yet

- ALL 3 LIGO INTERFEROMETERS NOW OPERATING AT DESIGN SENSITIVITY
- Sharing data, coordinated operation w/ GEO, TAMA (soon also VIRGO)
- Upper limits published on periodic, burst, stochastic and binary signals
- S5 science run is in progress: “1 year at design sensitivity”
- We think we can milk ~ factor of 2 better *h* ; may break for some modest detector enhancements and resume running
- Good chance we’ll confirm detections, but we want MORE…

Perspective: why not just sit tight ?

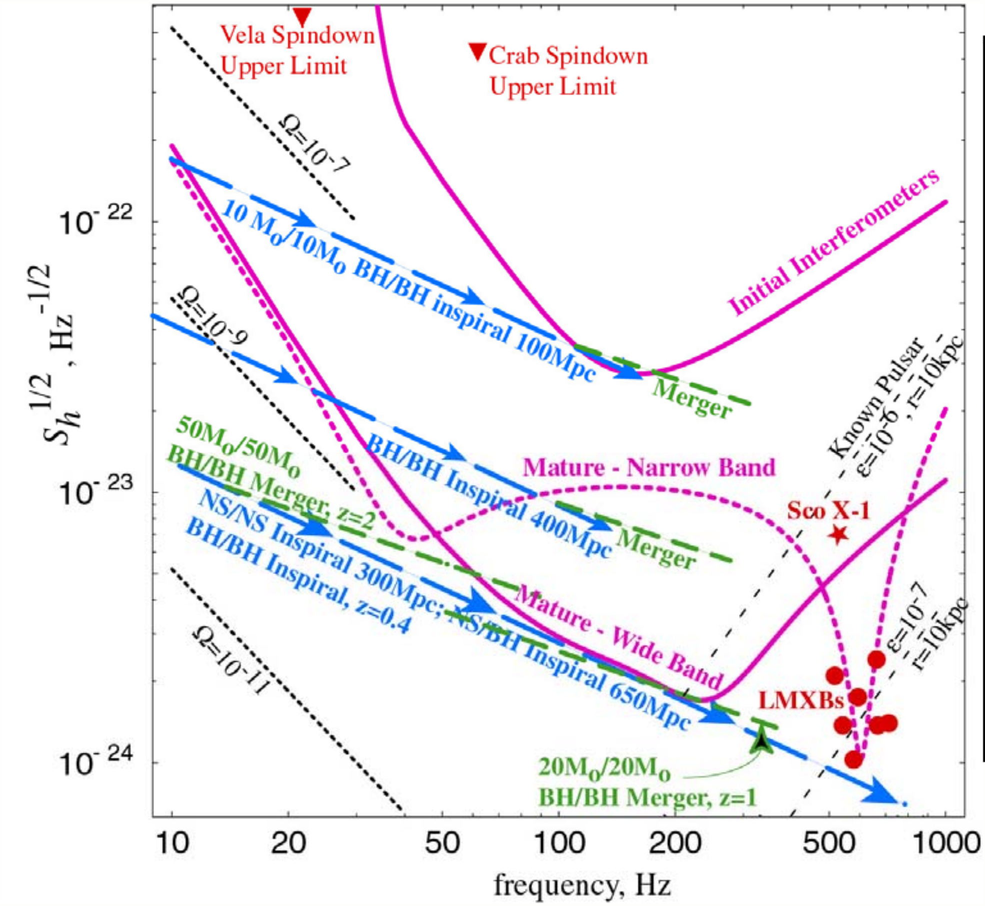
- BNS inspiral detection range is now well into VIRGO cluster

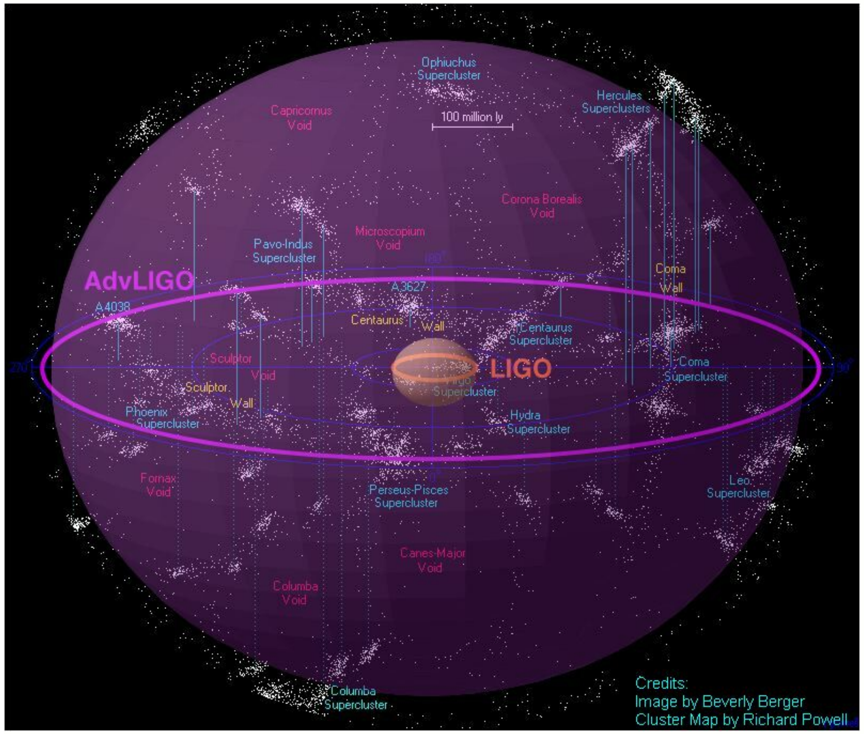


Nutzman et al., arXiv:astro-ph/0402091 v2, 28 Jun 2004

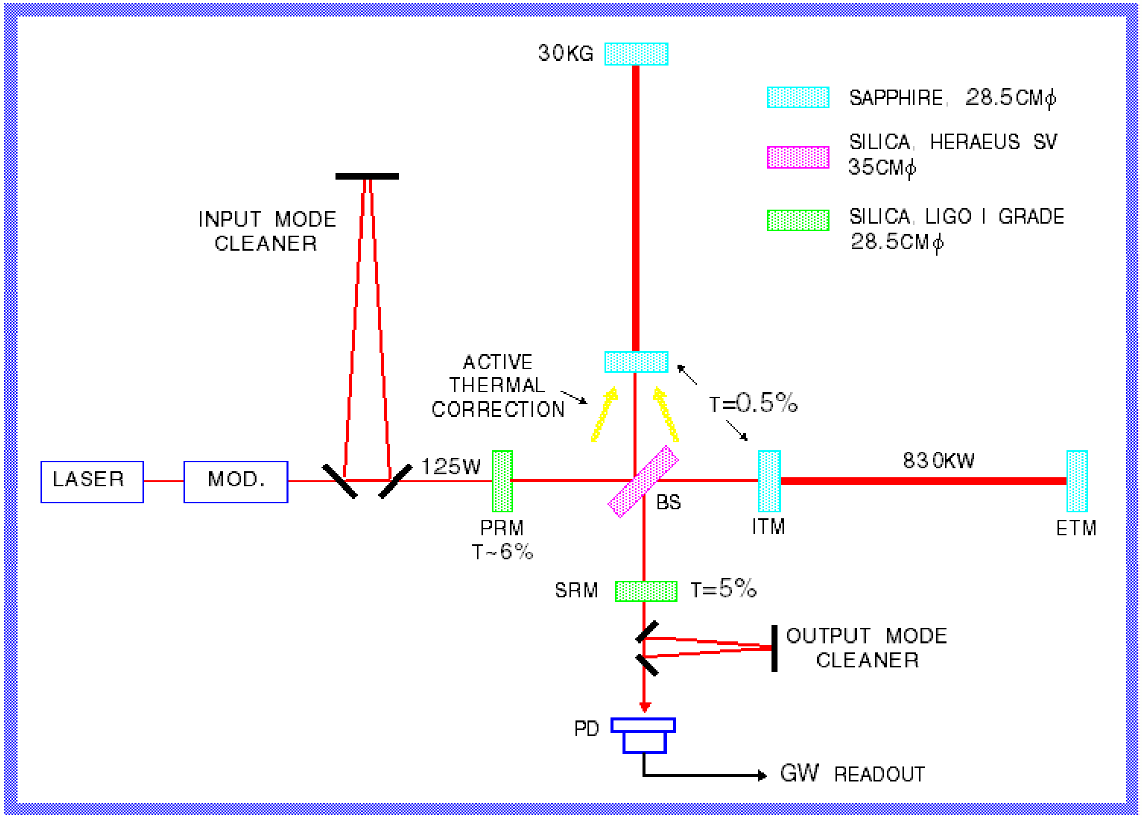
Advanced LIGO

- Approved for FY2008 start





Advanced Interferometer Concept



» Signal recycling

» 180-watt laser

» Sapphire test masses

» Quadruple suspensions

» Active seismic isolation

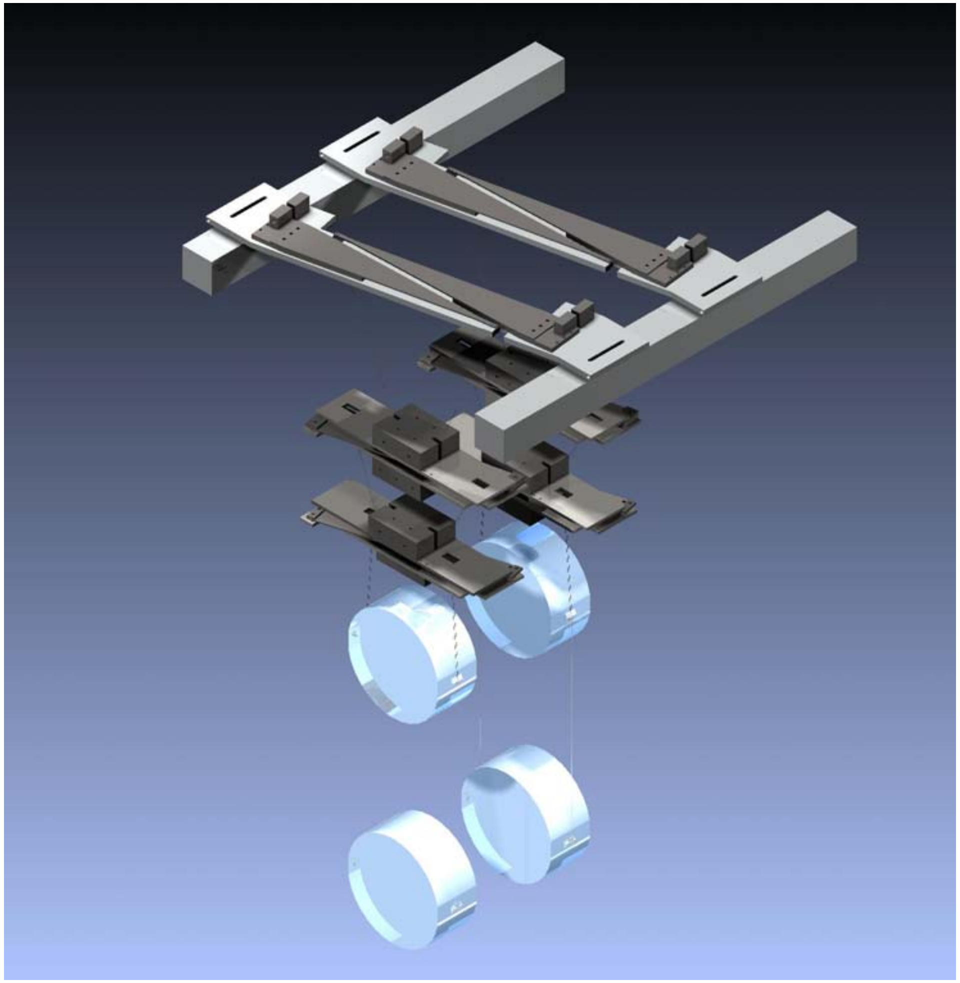
» Active thermal correction

Active Seismic Isolation

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- 2-stage internal active stack w/blade springs & flexures
- 6 degrees of freedom each stage
- Sensors encapsulated in airtight ‘pods’
- Magnetic voice coil forcers
- Digital MIMO control system
- Isolation extends down to 10 Hz

Advanced Suspensions



- Based on successful GEO triple pendulum design
- Quad pendula for TM, BS; Triples for input optics
- Blade springs for vertical isolation
- Indirect damping through upper stage recoil
- Electrostatic or photon drive for fast control at final stage; reaction mass for ES recoil

Concluding Remarks

- LIGO is **on the air at design sensitivity**
- We already have at least 20x more coverage than any previous GW search; a confirmed detection is a *strong possibility*
- As we search, we're designing more powerful instruments to install in 2012; technology has advanced enough to improve by a factor of >10 in *h* or >1000 in event rate
- Each new form of ‘vision’ invented over the last century has revealed a new, unknown universe; we only just started *listening to gravity.*

WHAT CAN WE HEAR?