Gravitation Wave Detection with LIGO

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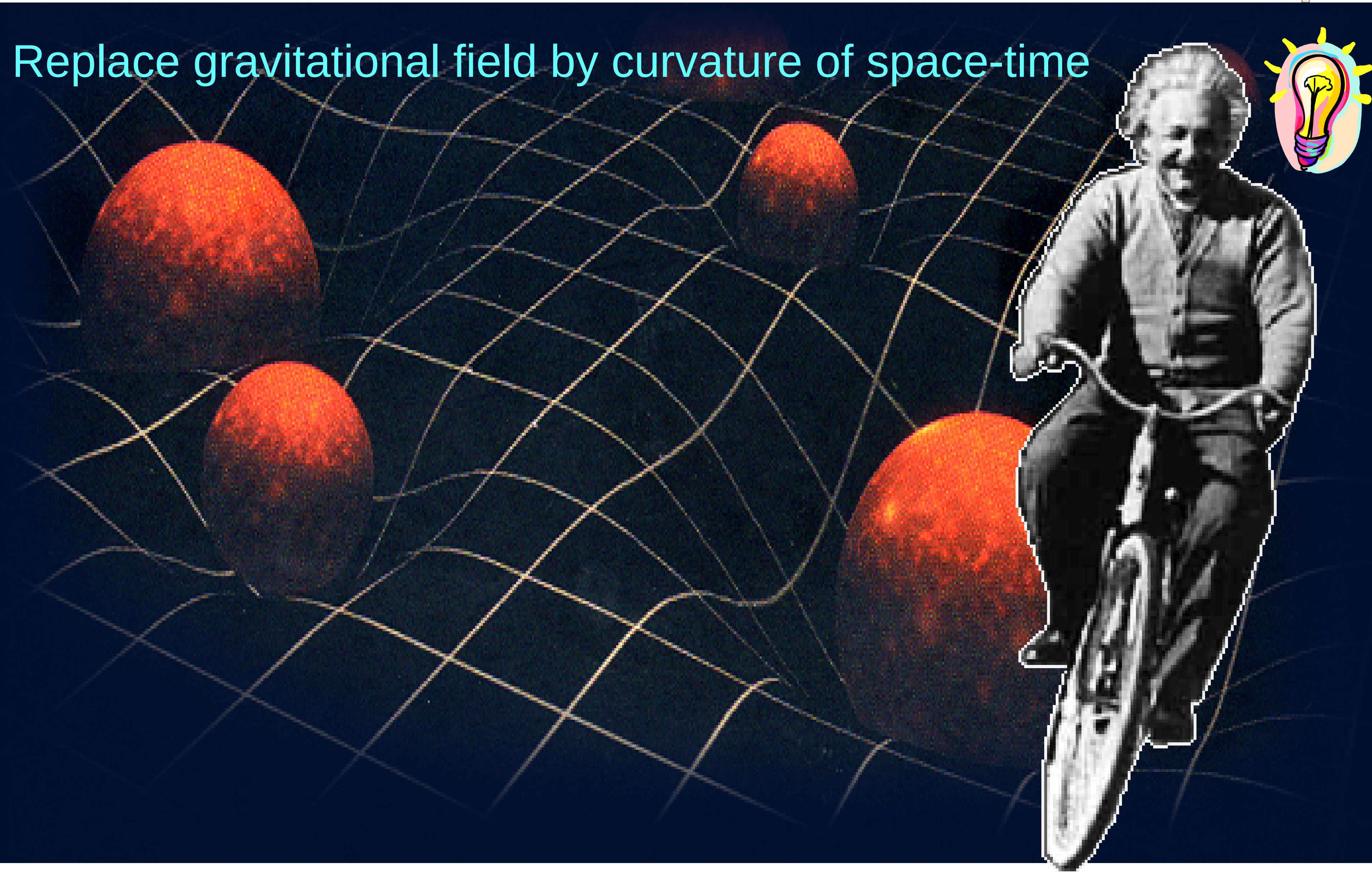
Gravitation Wave Workshop
Beijing, China

Outline

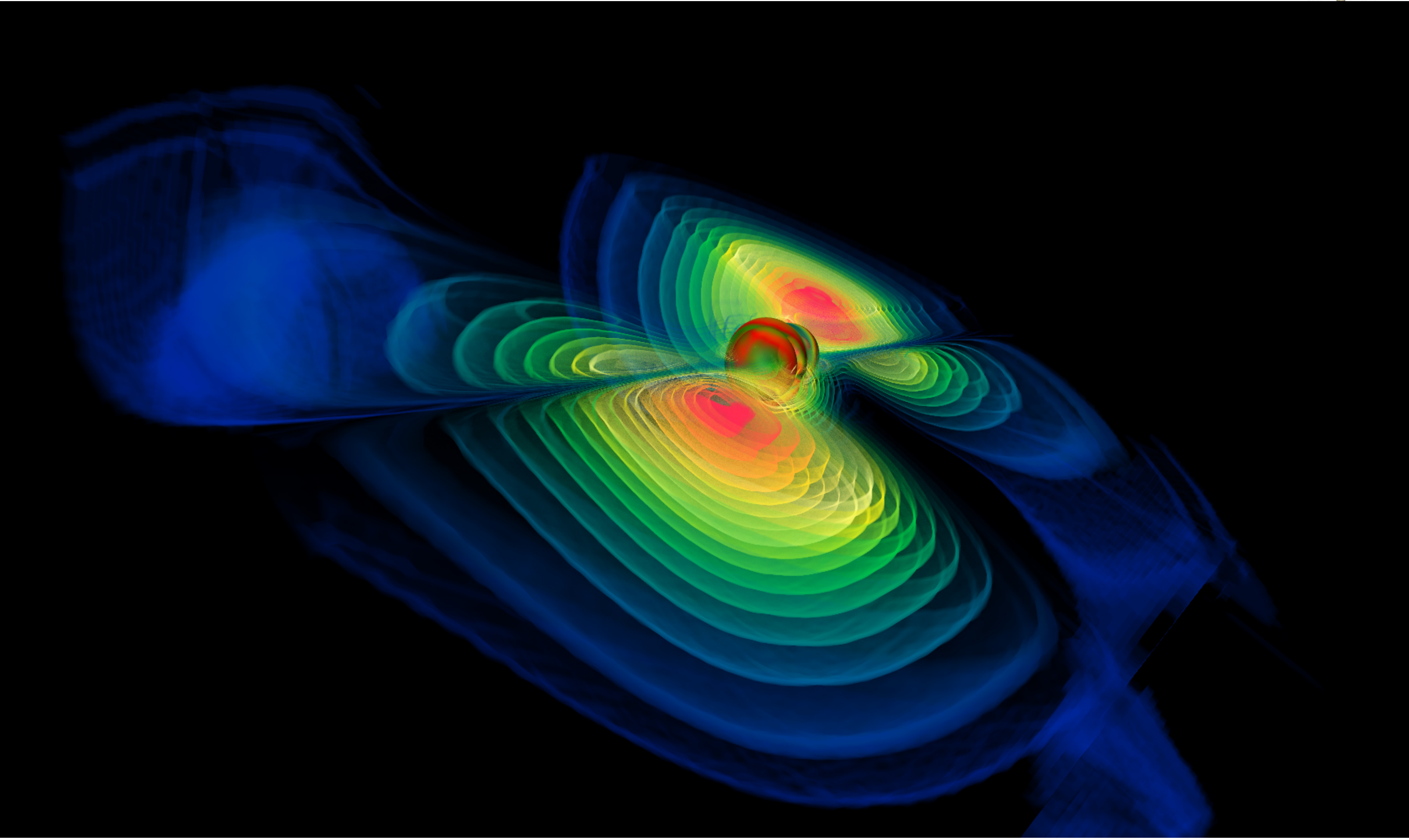
- Gravitation waves
- LIGO: a terrestrial GW detector
- Detector performance and initial scientific result
- Advanced LIGO
- Welcome Chinese colleagues

Gravitational Waves

Replace gravitational field by curvature of space-time



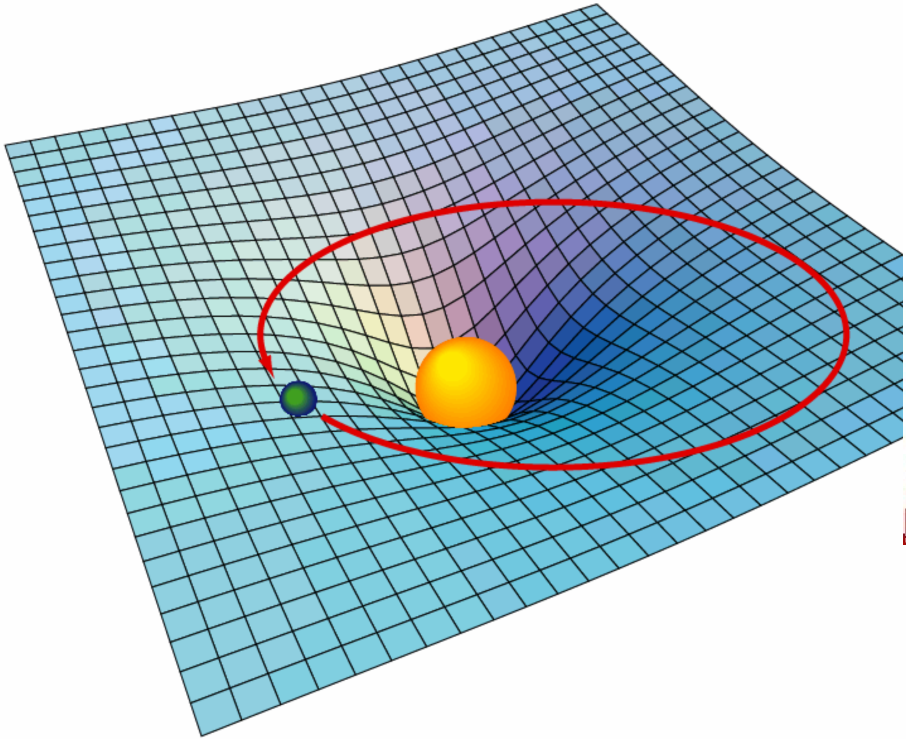
“Colliding Black Holes”

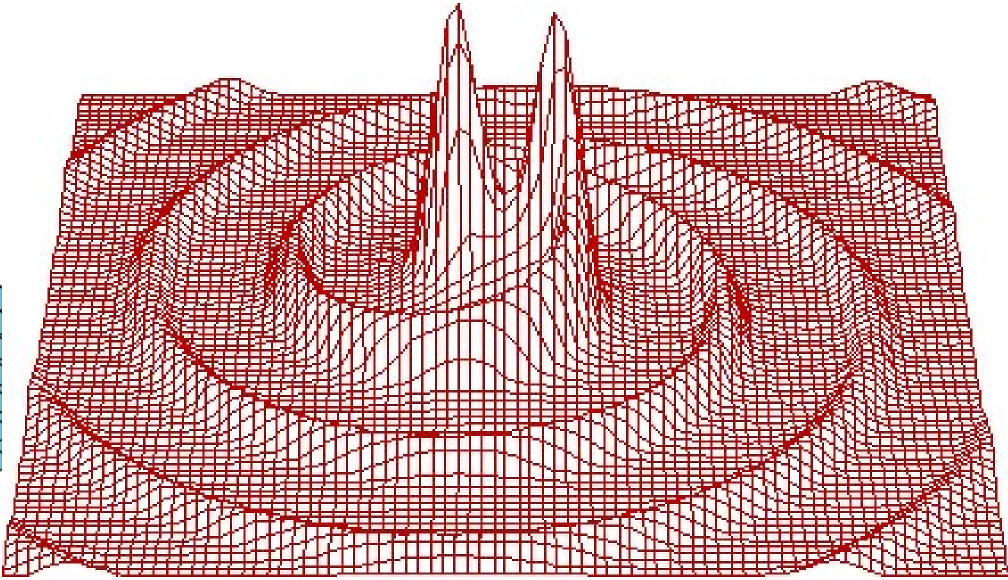


Credit: National Center for Supercomputing Applications (NCSA)

Gravitational Radiation

Propagating Waves of Space-Time Curvature



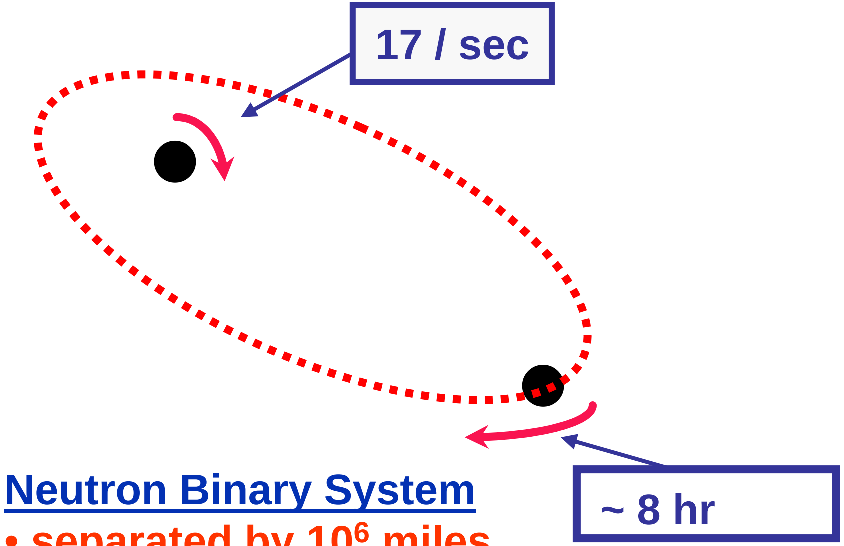


gravitational radiation from inspiral of compact stellar-mass binary objects (black holes, neutron stars)

Evidence for Gravitational Waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



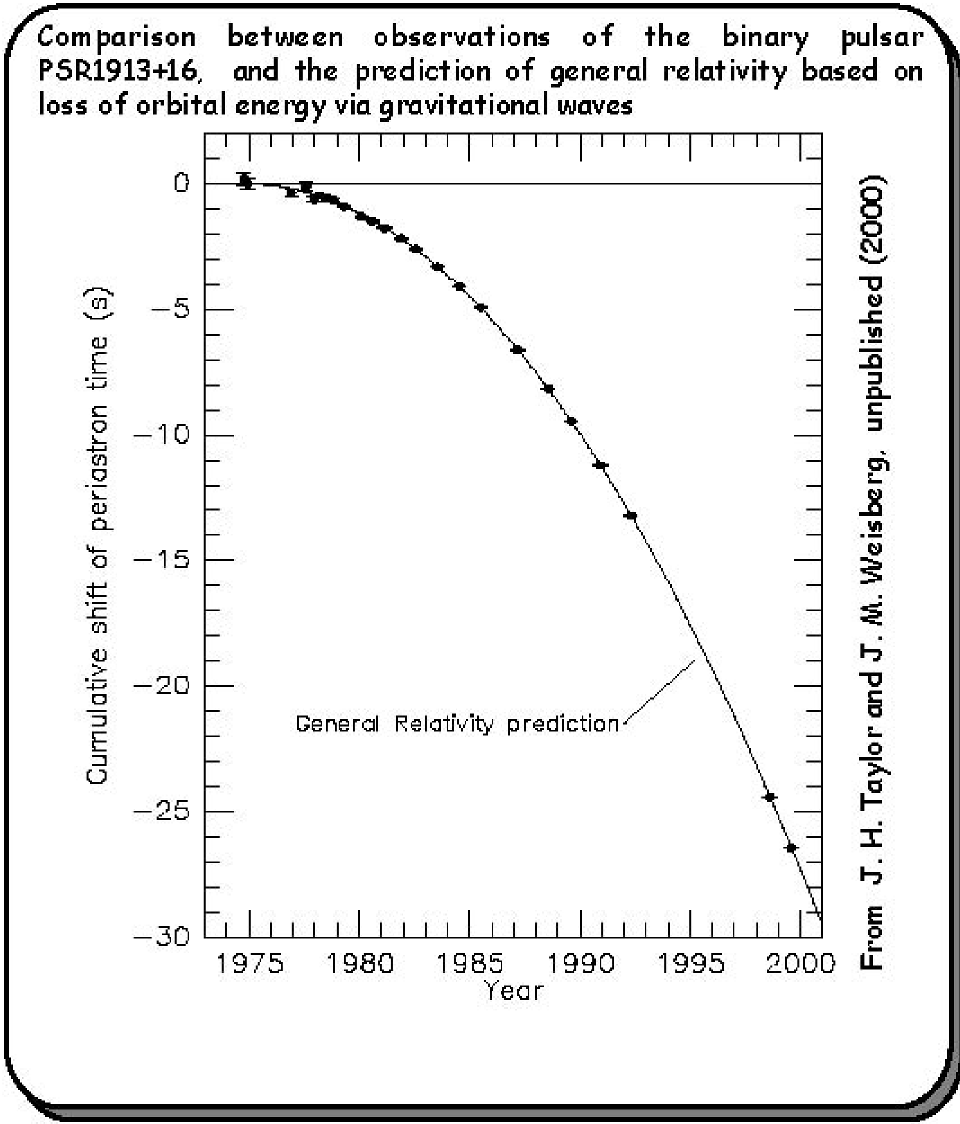
Neutron Binary System

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

Prediction from general relativity

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

Emission of gravitational waves

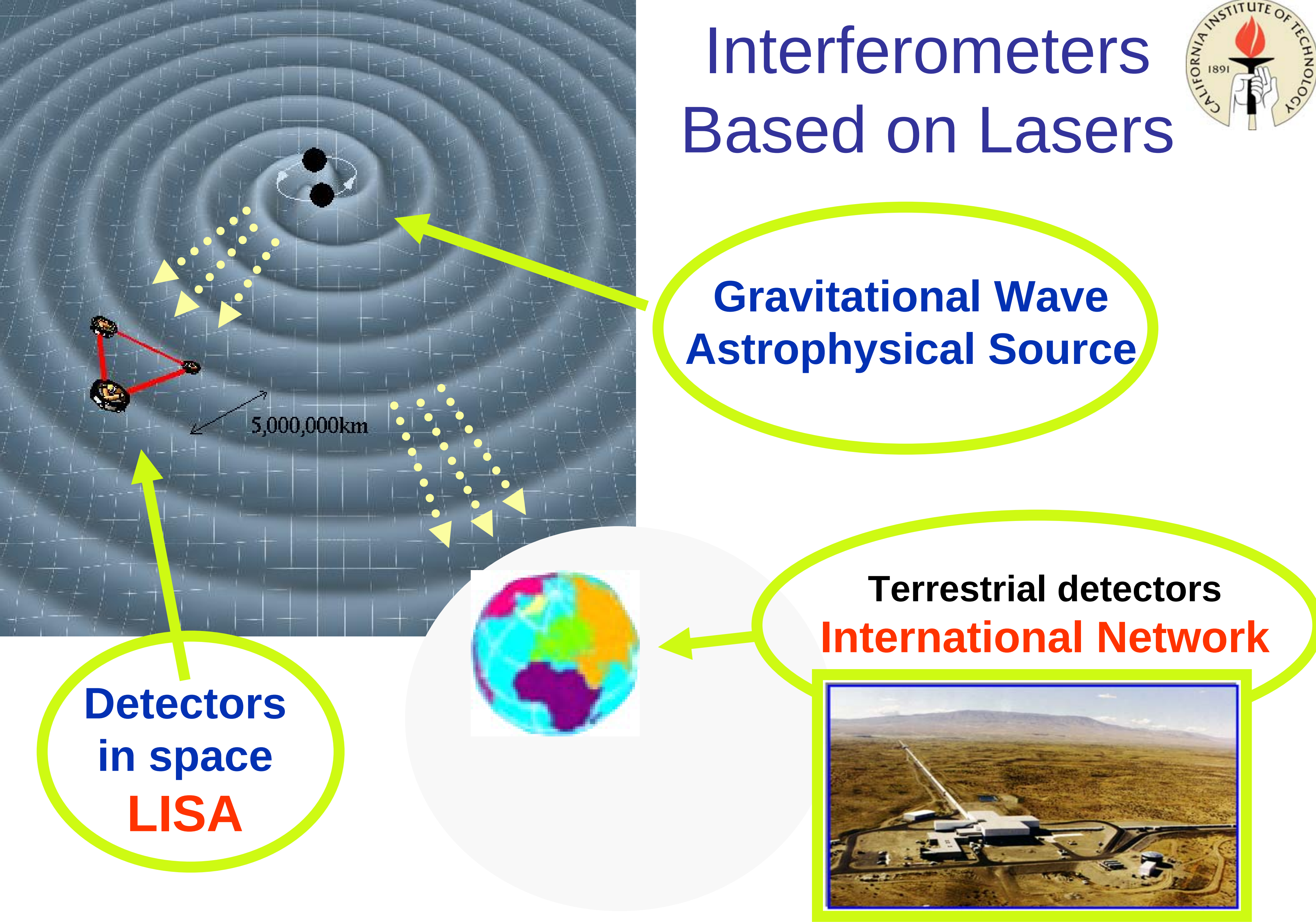


Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Gravitational Wave Detectors

Interferometers Based on Lasers



Gravitational Wave Astrophysical Source

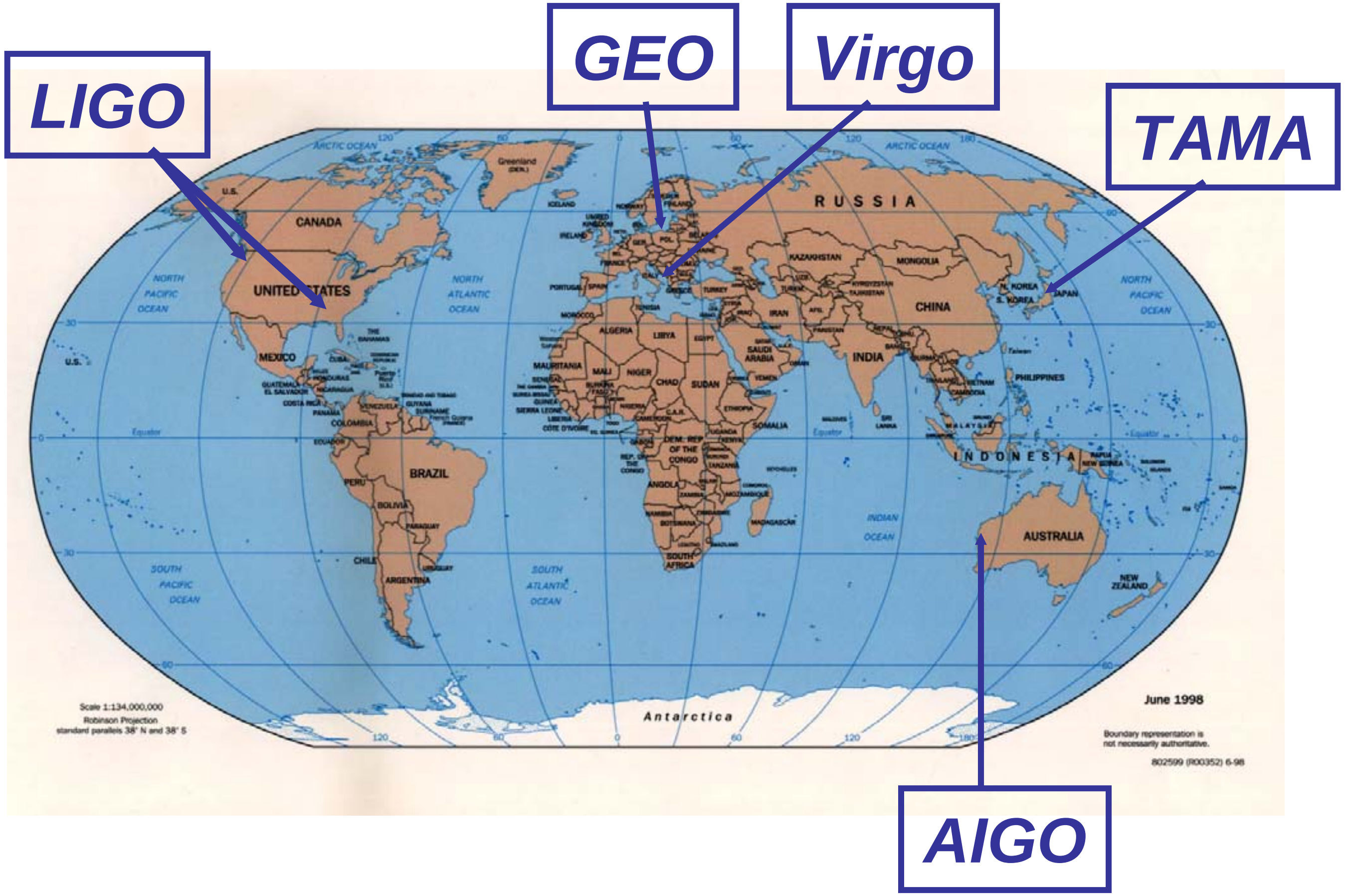
Detectors in space
LISA

Terrestrial detectors
International Network

International Network

Simultaneously detect signal (within msec)

Gravitational Wave International Committee (GWIC)

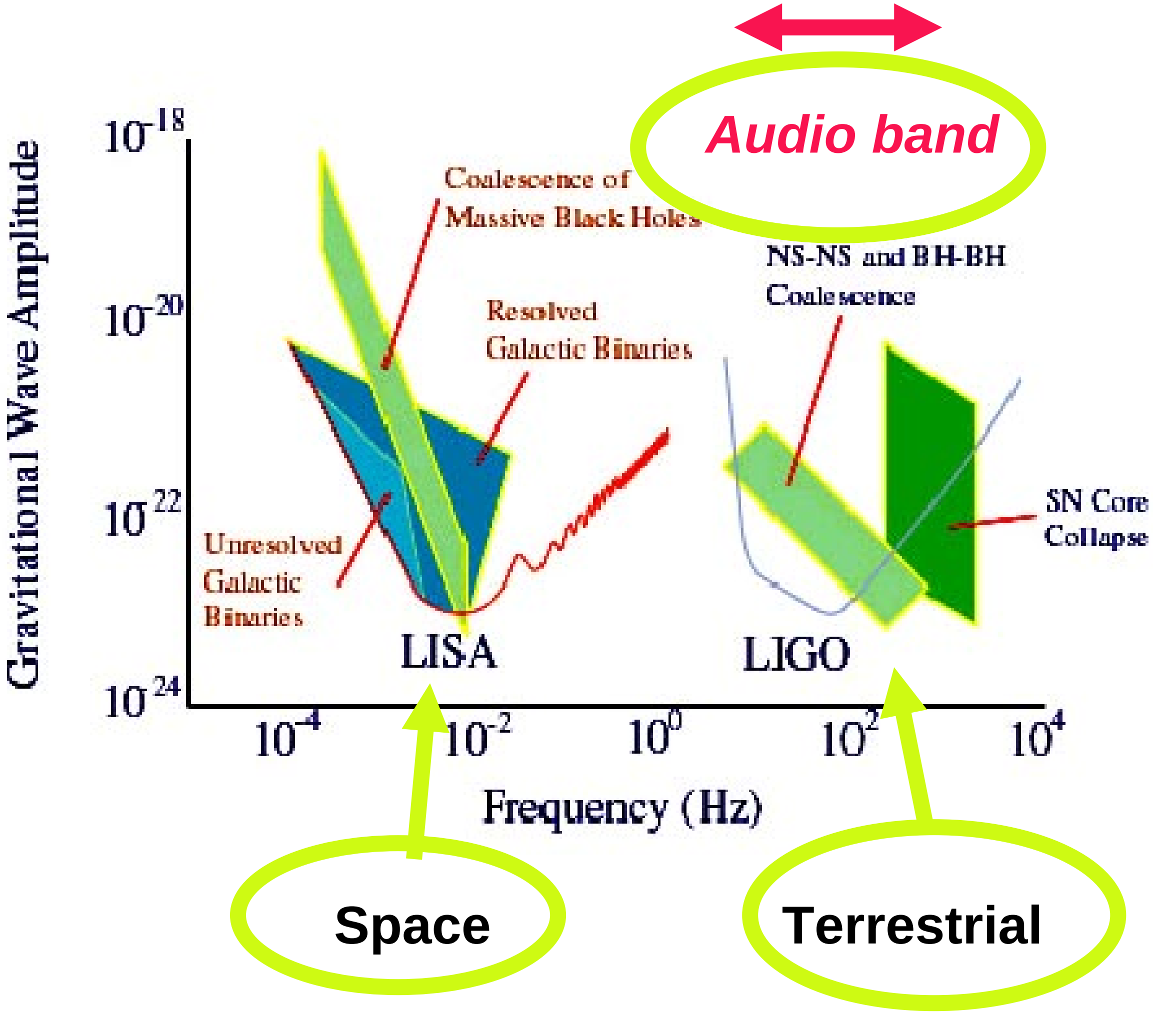


- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- Open up a new field of astrophysics!

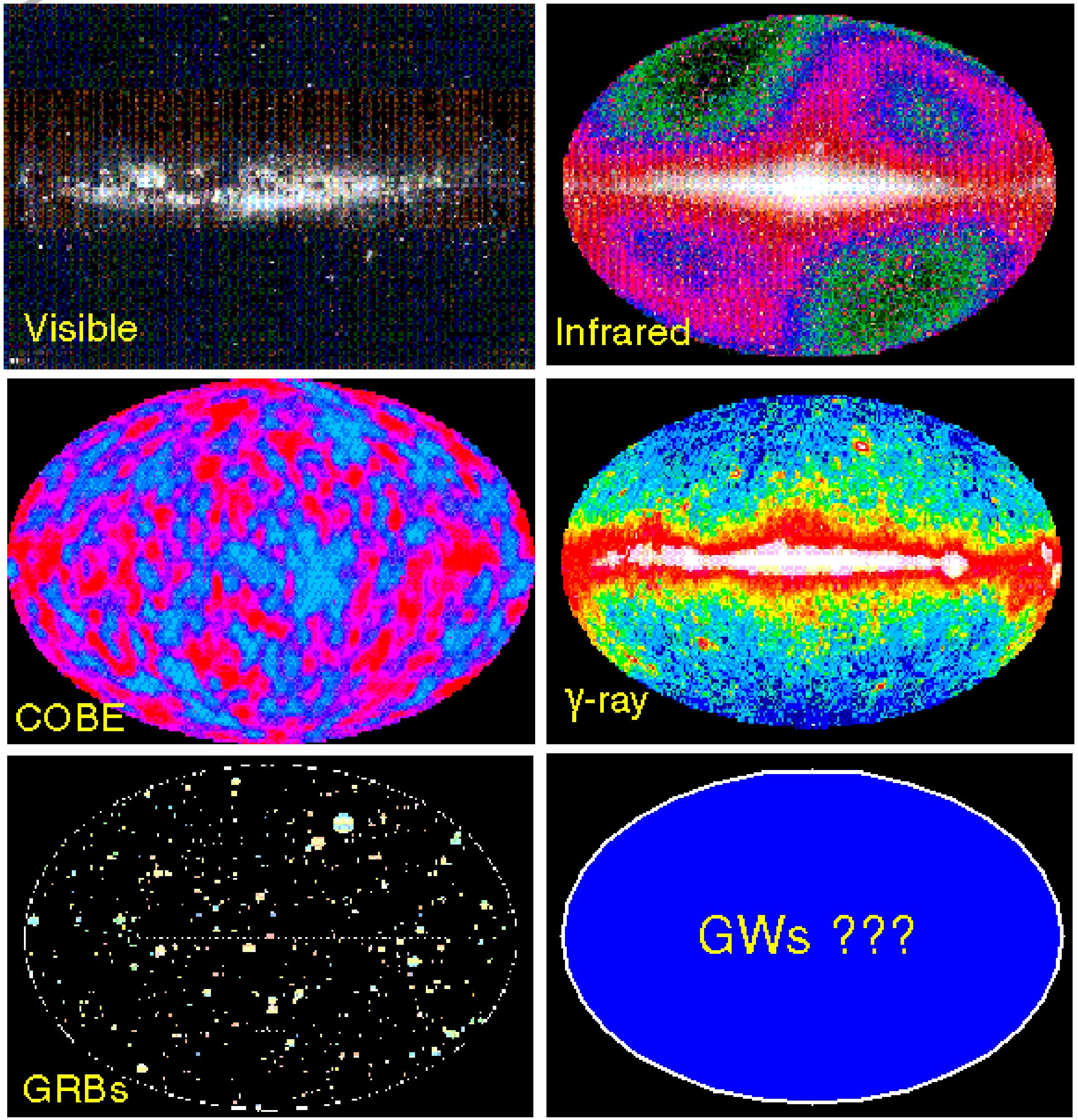
LIGO, VIRGO, GEO, TAMA …
International network

Astrophysics Sources by Frequency

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



A New Window on the Universe



Gravitational wave observations will provide a new way to view the dynamics of the Universe

Nature of Gravitational Radiation

General Relativity predicts :

- Transverse space-time distortions, freely propagating at speed of light

Mass of graviton = 0

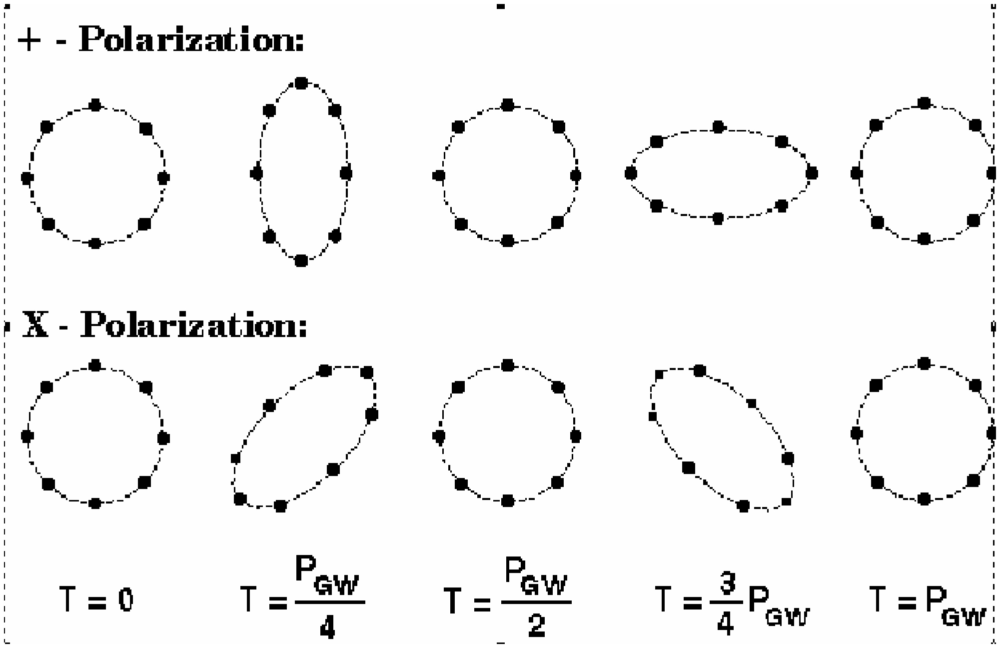
- Stretches and squashes space between "test masses" – strain

$$\boxed{h = \Delta L/L}$$

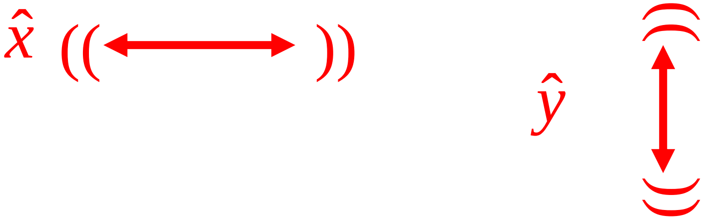
- Conservation laws:
  - cons of energy ⇒ no monopole radiation
  - cons of momentum ⇒ no dipole radiation
  - quadrupole wave (spin 2) ⇒ two polarizations

plus (⊕) and cross (⊗)

Spin of graviton = 2

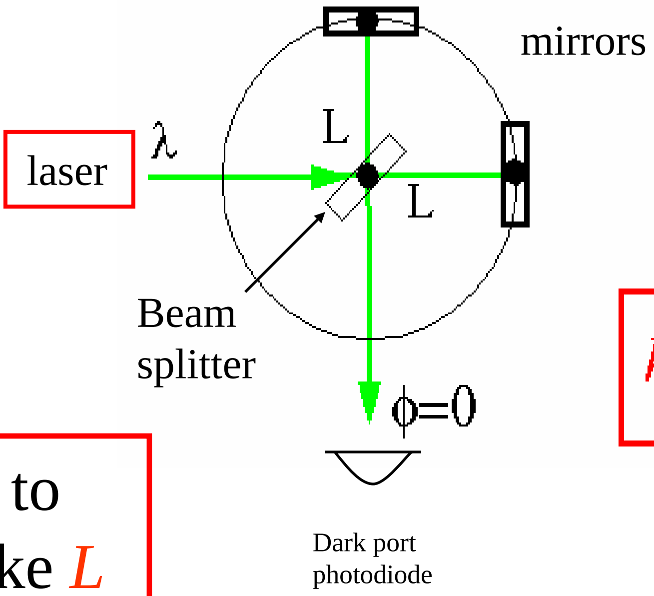


Contrast with EM dipole radiation:

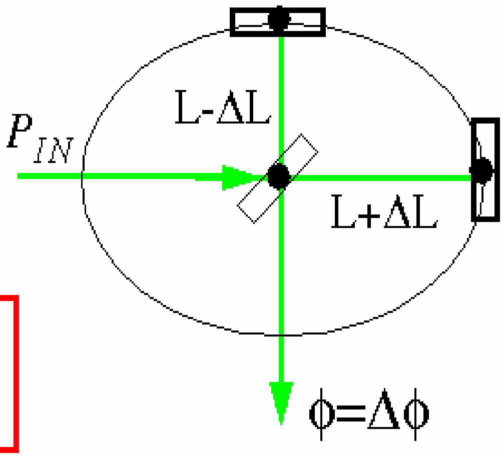


Interferometric Detection of GWs

GW acts on freely falling masses:



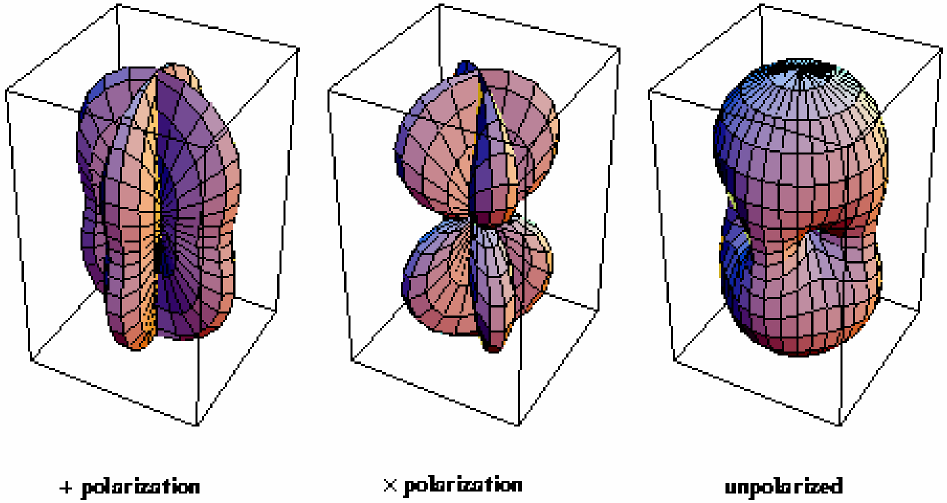
$$h = \frac{\Delta L}{L}$$



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

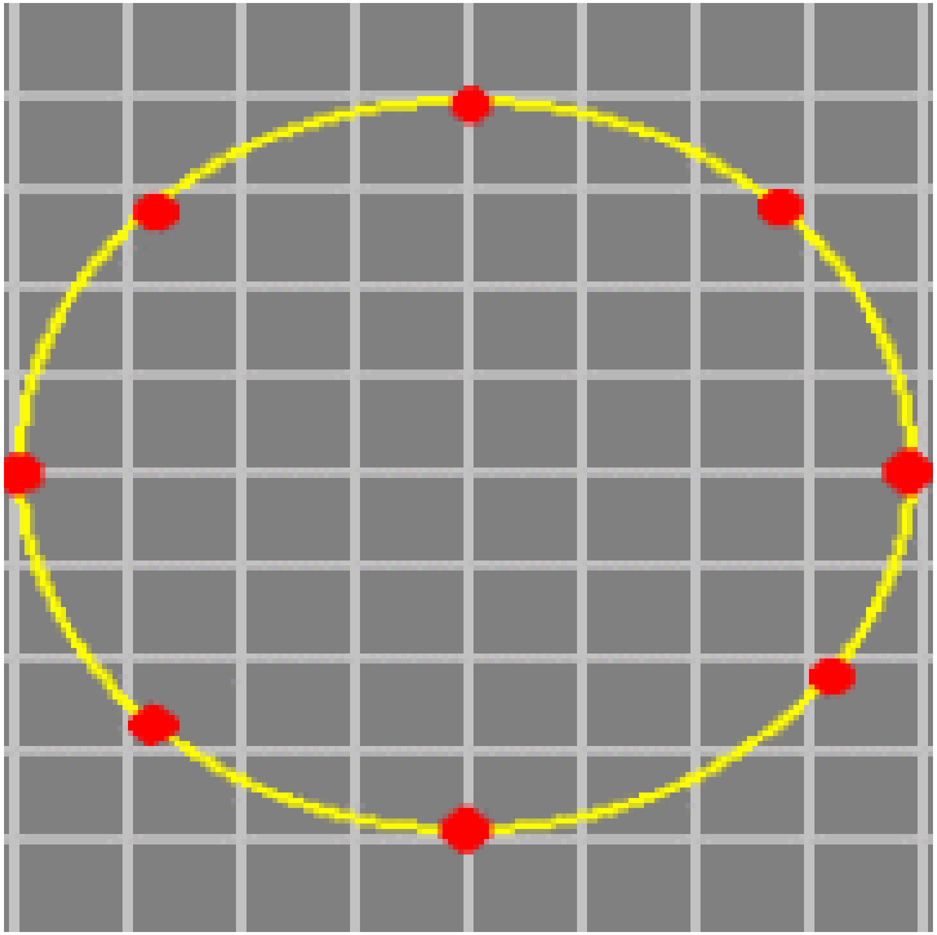
For fixed ability to measure ΔL, make L as big as possible!

Antenna pattern:
(not very directional!)



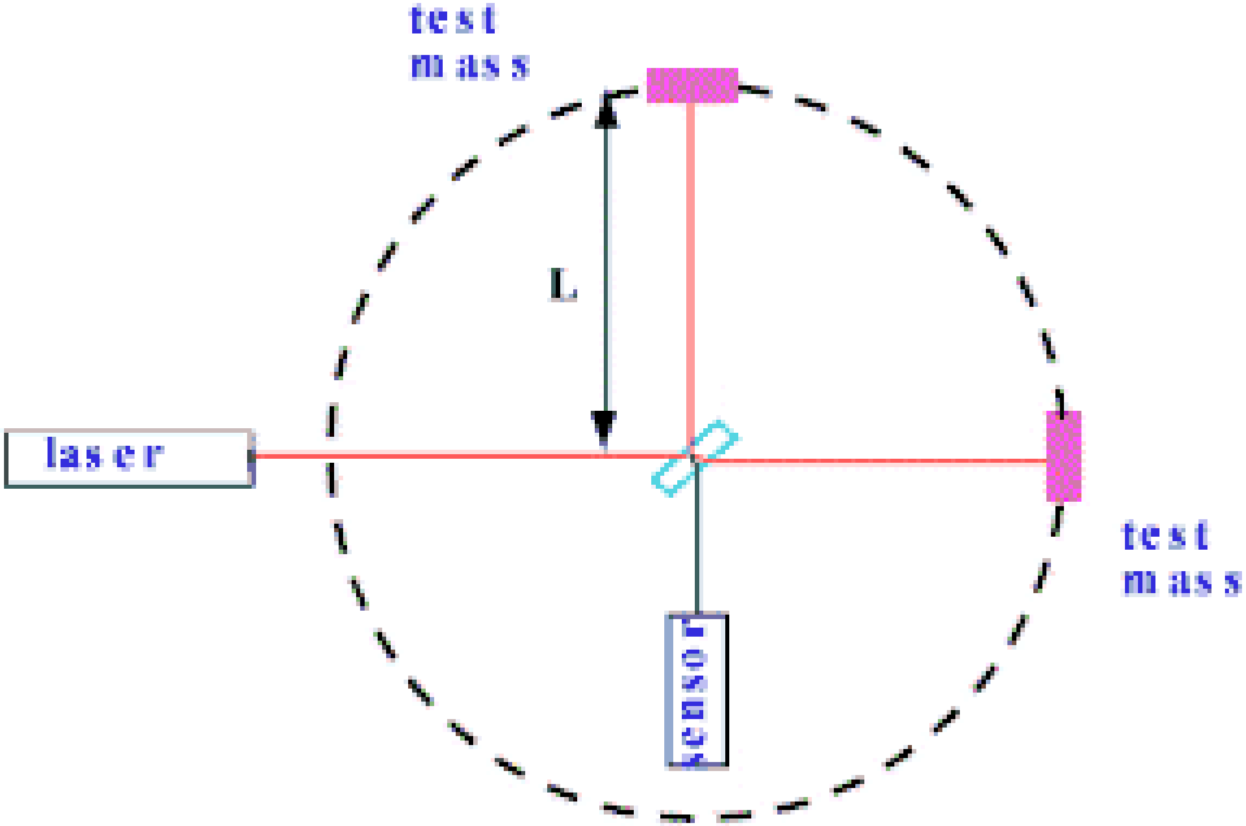
Detecting a Passing Wave

Free masses



Detecting a Passing Wave

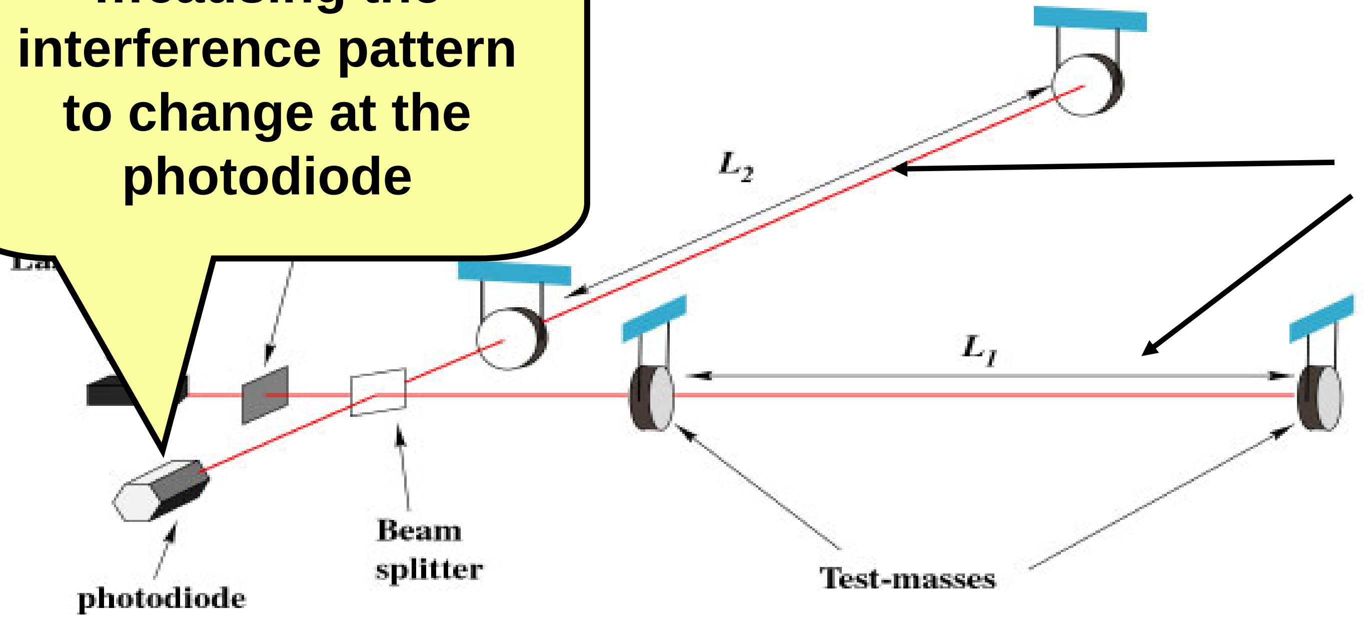
Interferometer



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***



…causing the interference pattern to change at the photodiode

As a wave passes, the arm lengths change in different ways….

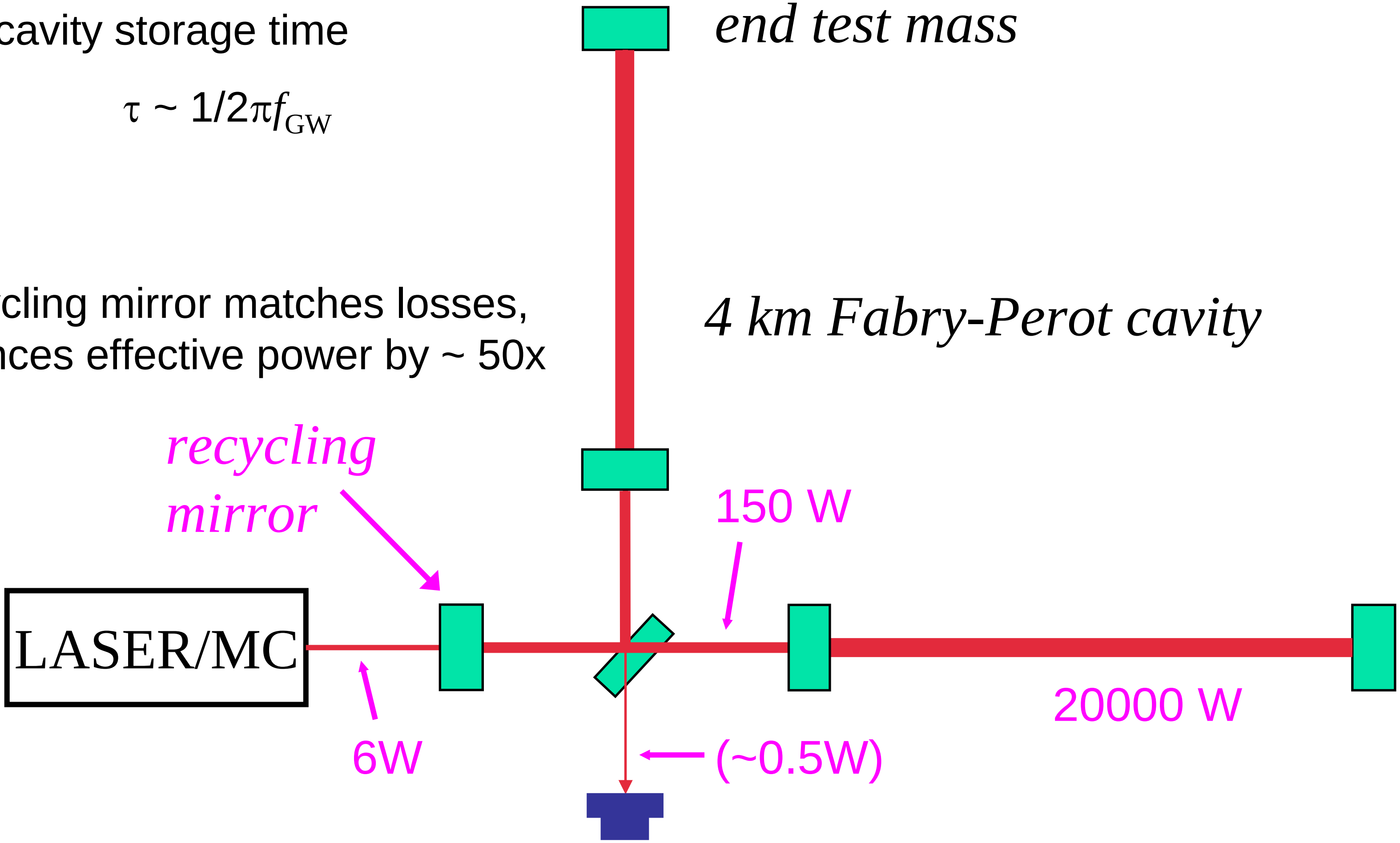
LIGO Optical Scheme

Michelson interferometer with Fabry-Perot arm cavities

- Arm cavity storage time

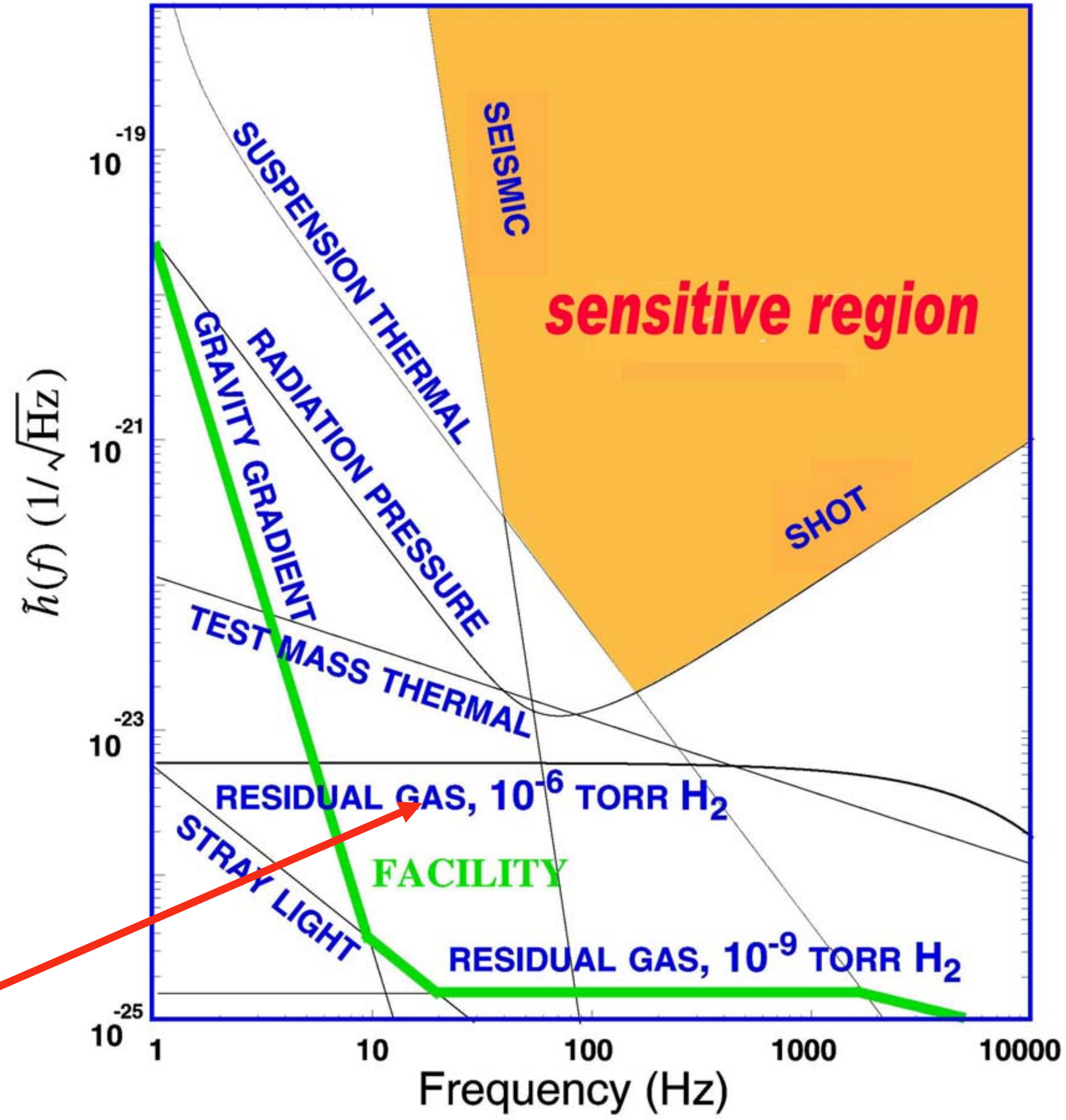
$\tau \sim 1/2\pi f_{GW}$

- Recycling mirror matches losses, enhances effective power by ~ 50x



What Limits Sensitivity?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



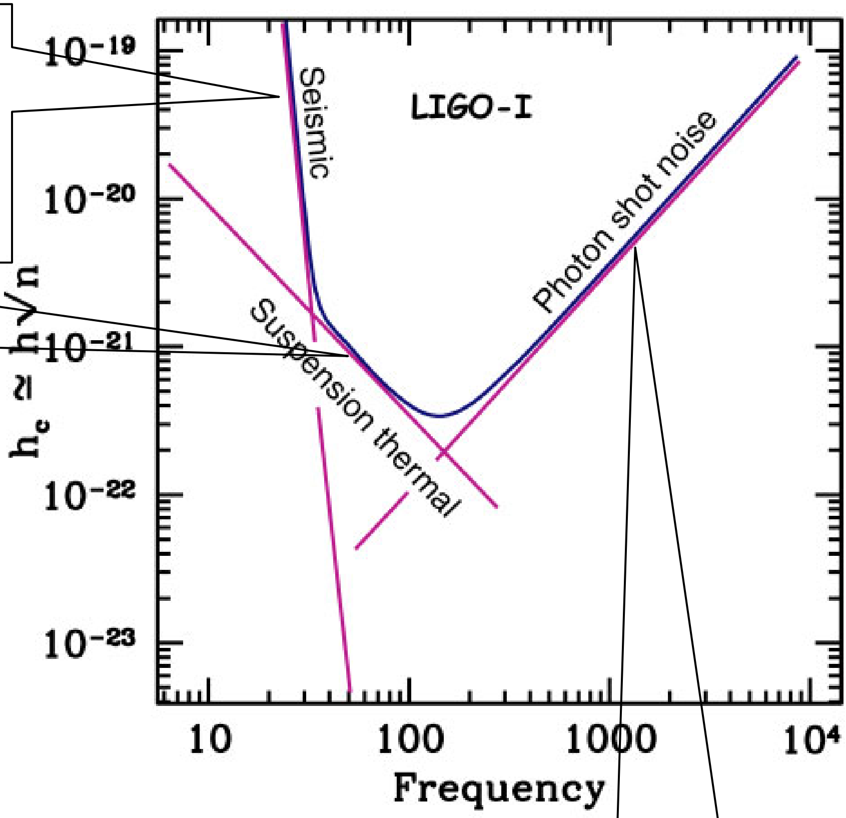
Running at 10^{-7}

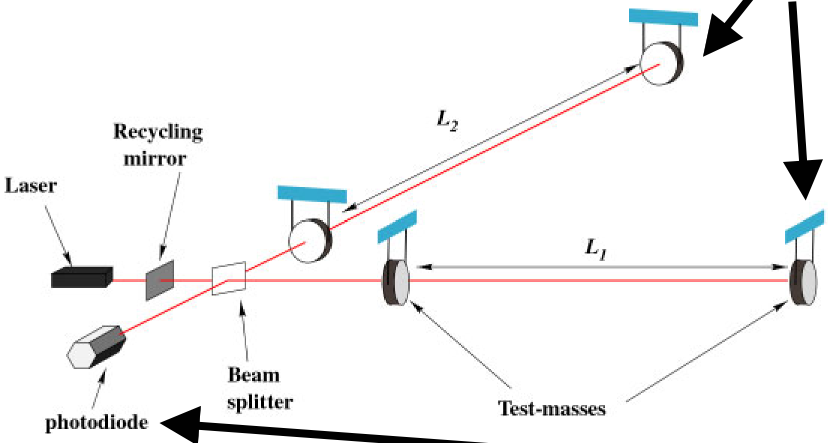
LIGO Noise-limited Sensitivity

The noise in the LIGO interferometers is dominated by three different processes depending on the frequency band

Shaking of ground transfers through the suspension into movement of the test mirrors

thermal noise in mirrors and suspensions



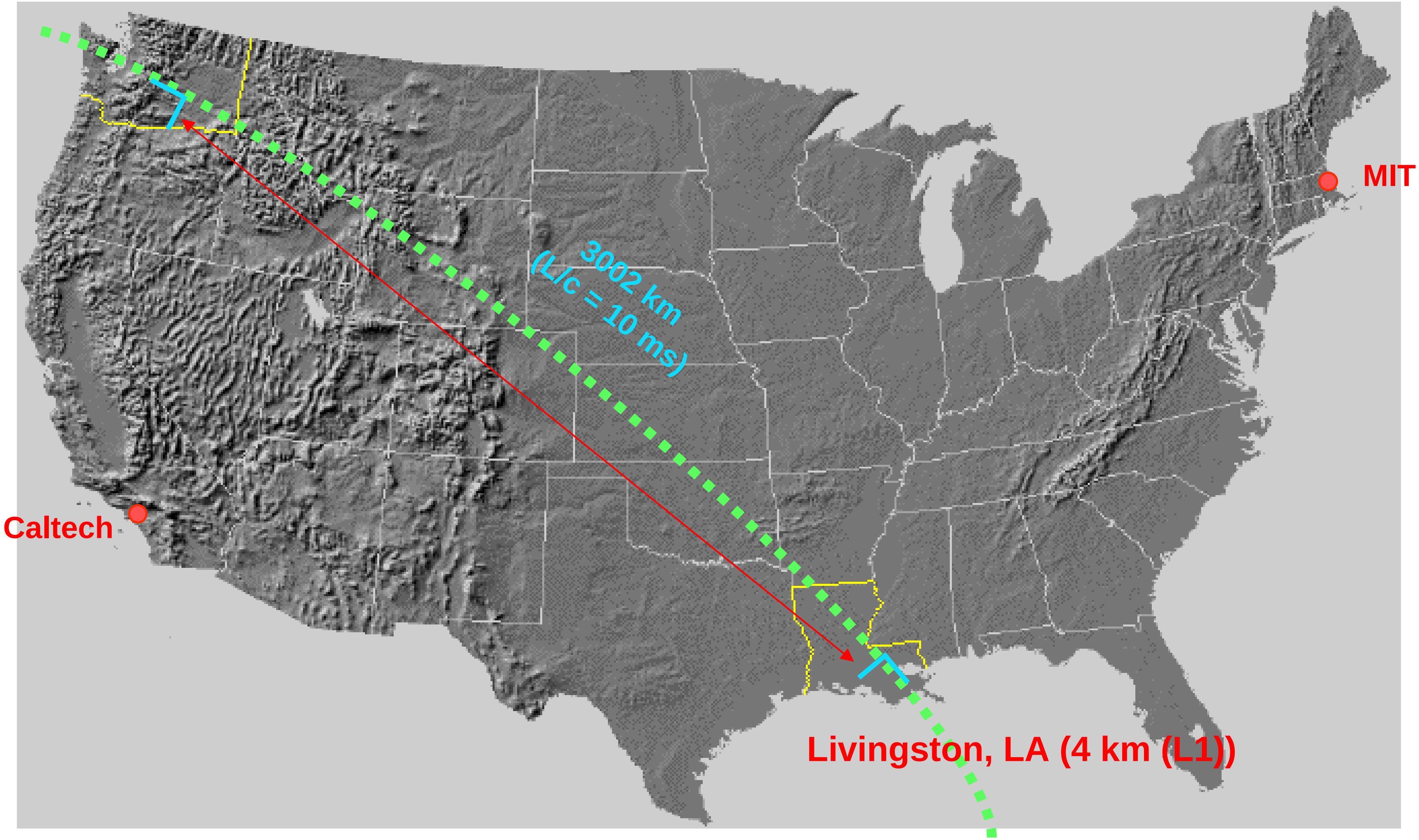


Fluctuations in the number of photons arriving at the photodiode

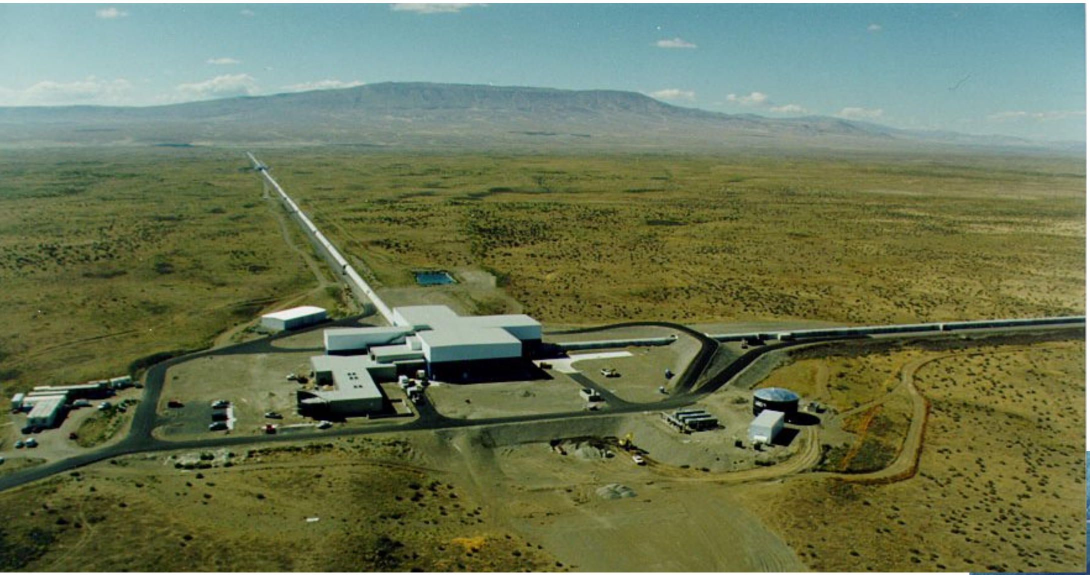
At present, noise in the LIGO detectors is dominated by "technical" sources, associated with as-yet-imperfect implementation of the design

LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites



LIGO Observatories



GEODETIC DATA (WGS84)

h: -6.574 m	***X arm: S72.2836°W***
ϕ: N30°33’46.419531”	***Y arm: S17.7164°E***
λ: W90°46’27.265294”	

Livingston Observatory
Louisiana
One interferometer (4km)

Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

GEODETIC DATA (WGS84)

h: 142.555 m	***X arm: N35.9993°W***
ϕ: N46°27’18.527841”	***Y arm: S54.0007°W***
λ: W119°24’27.565681”	

LIGO Beam Tube

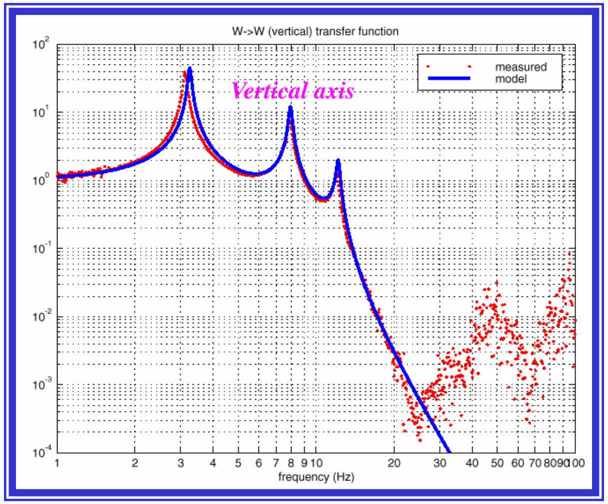
1.2 m diameter - 3mm stainless
50 km of weld

NO LEAKS !!

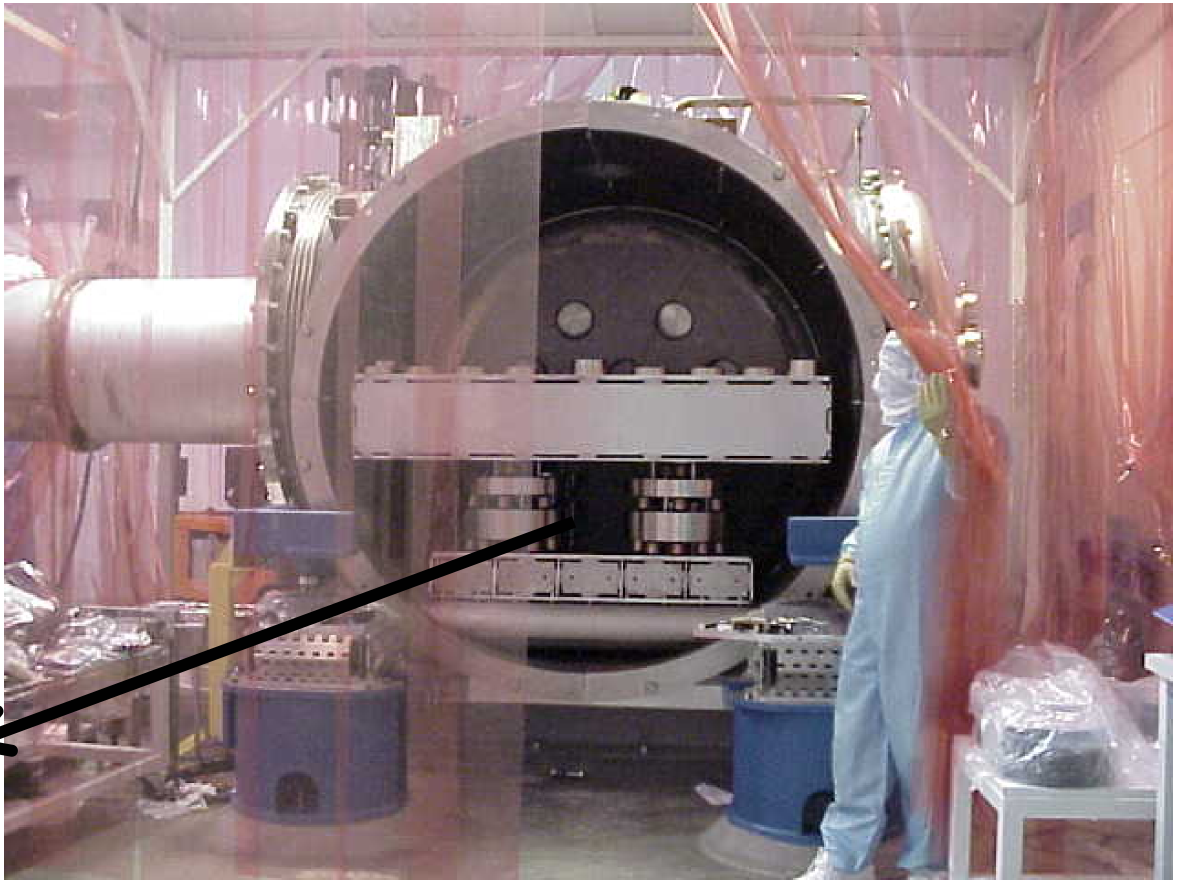
- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

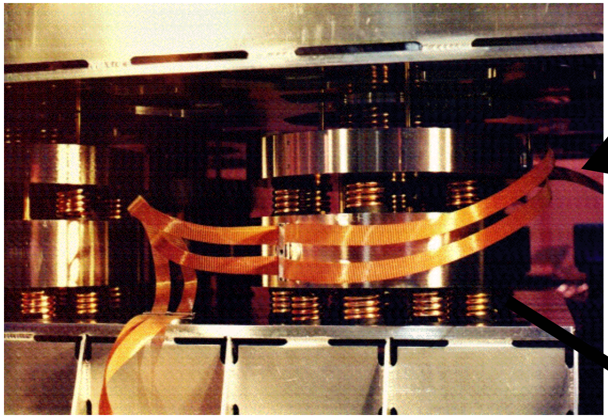
LIGO Vacuum Equipment

Seismic Isolation System



Isolation Performance





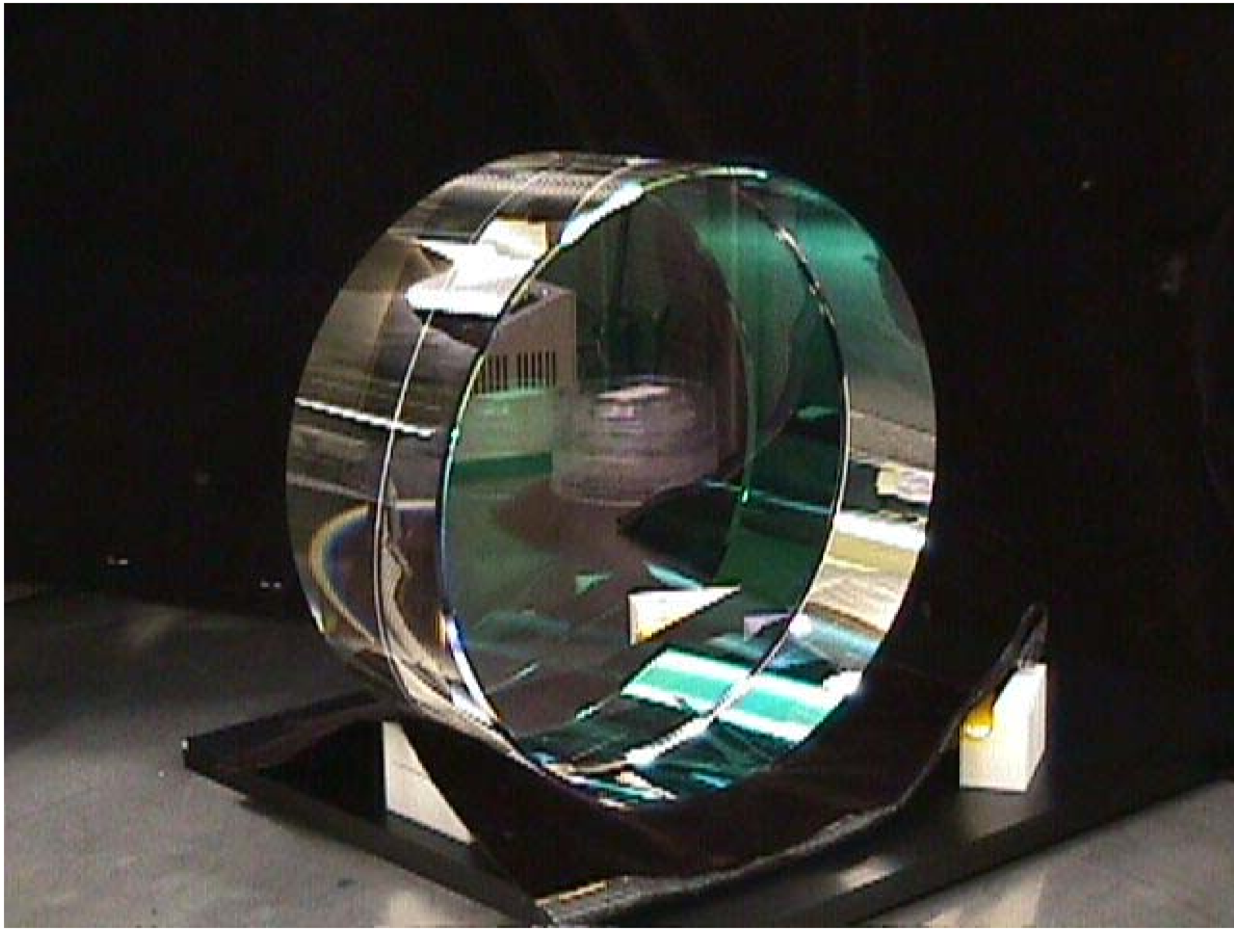
Tubular coil springs with internal damping, layered between steel reaction masses

A LIGO Quartz Mirror

Substrates: SiO_2

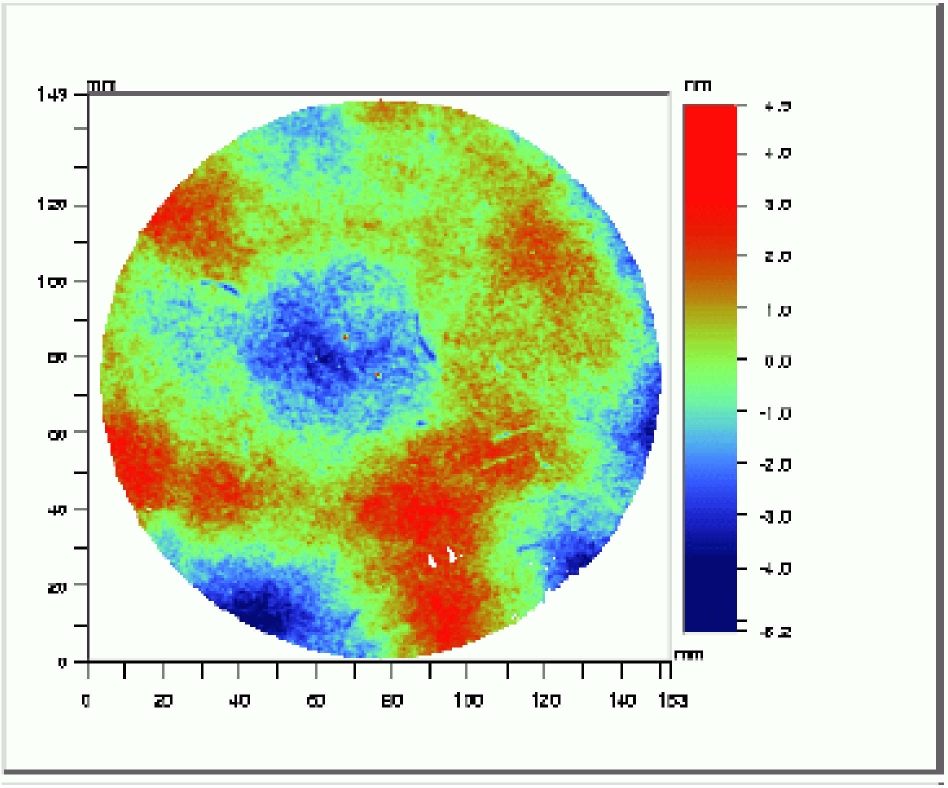
25 cm Diameter
10 cm thick
Homogeneity < 5 x 10^{-7}
Internal mode Q>2x10^{6}

Polishing Surface:
Uniformity < 1 nm rms
Radii of curvature
matched < 3%
Coating Scatter< 50 ppm
Absorption < 0.5 ppm
Uniformity <10^{-3}

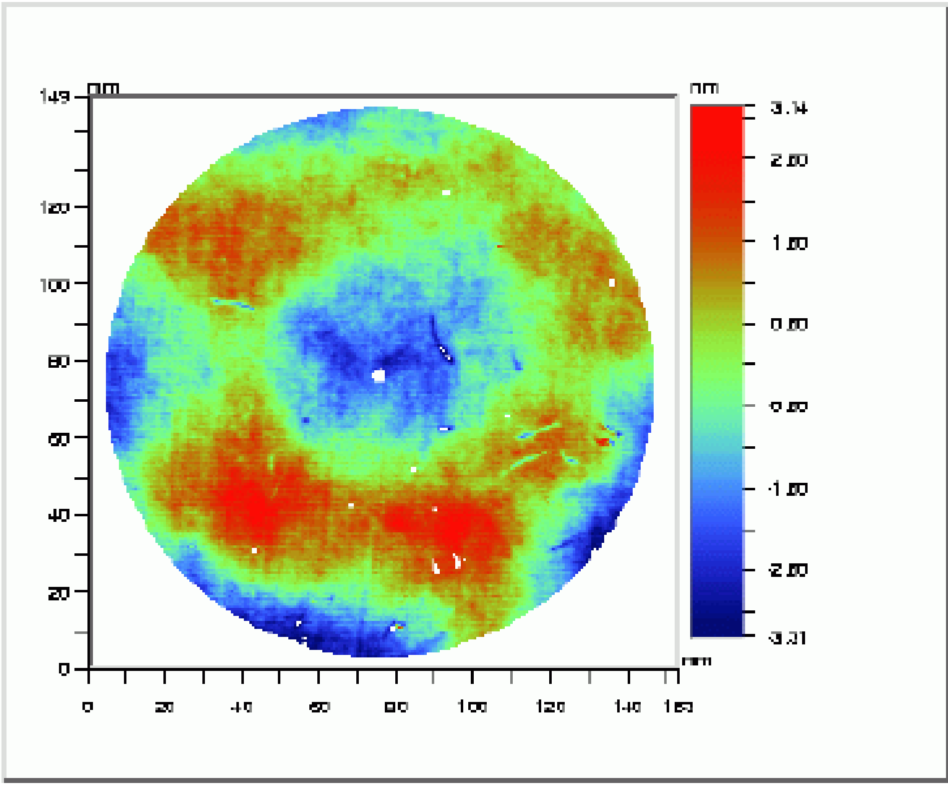


Core Optics Metrology

Current state of the art: 0.2 nm repeatability



LIGO data (1.2 nm rms)



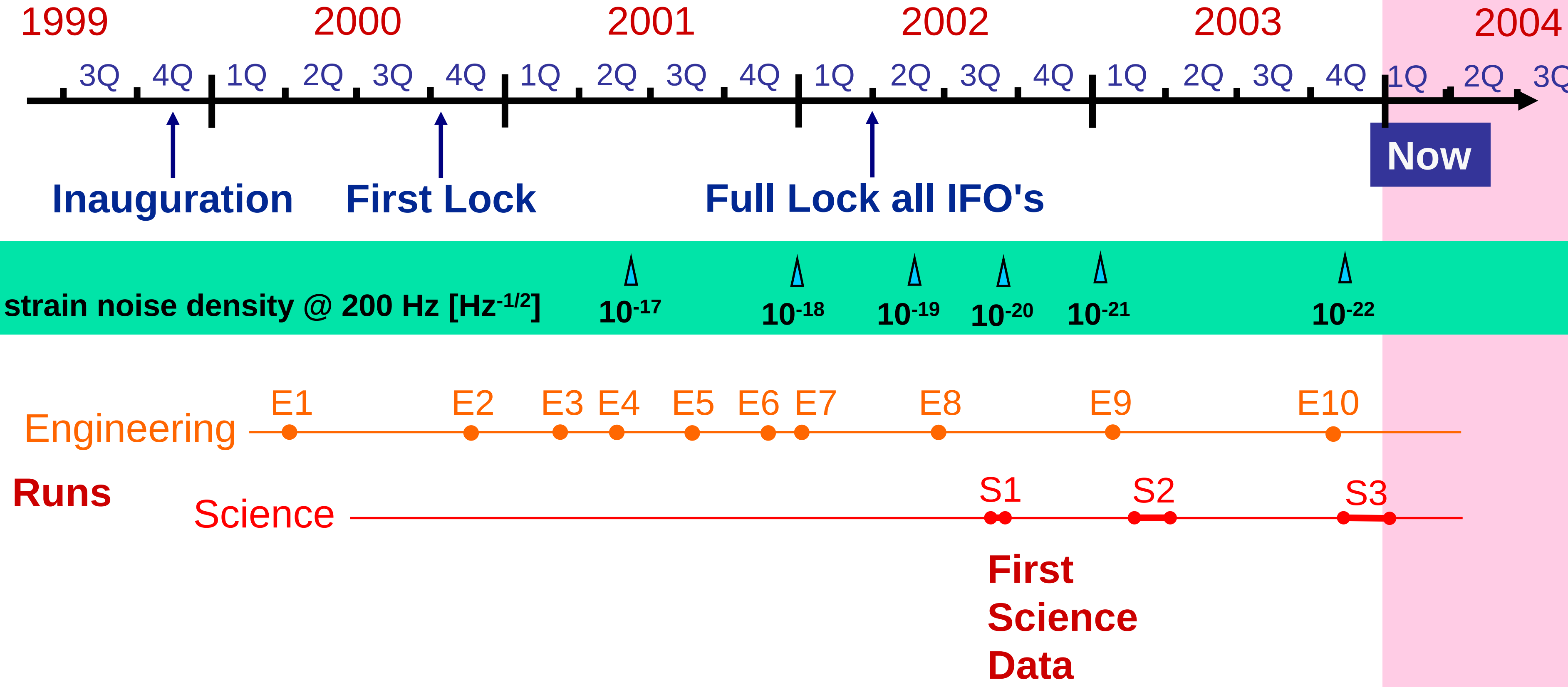
CSIRO data (1.1 nm rms)

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

Core Optics

installation and alignment

Commissioning and Science Runs



1999 2000 2001 2002 2003 2004

3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q

Now

Inauguration

First Lock

Full Lock all IFO's

strain noise density @ 200 Hz [Hz$^{-1/2}$] **10^{-17}** **10^{-18}** **10^{-19}** **10^{-20}** **10^{-21}** **10^{-22}**

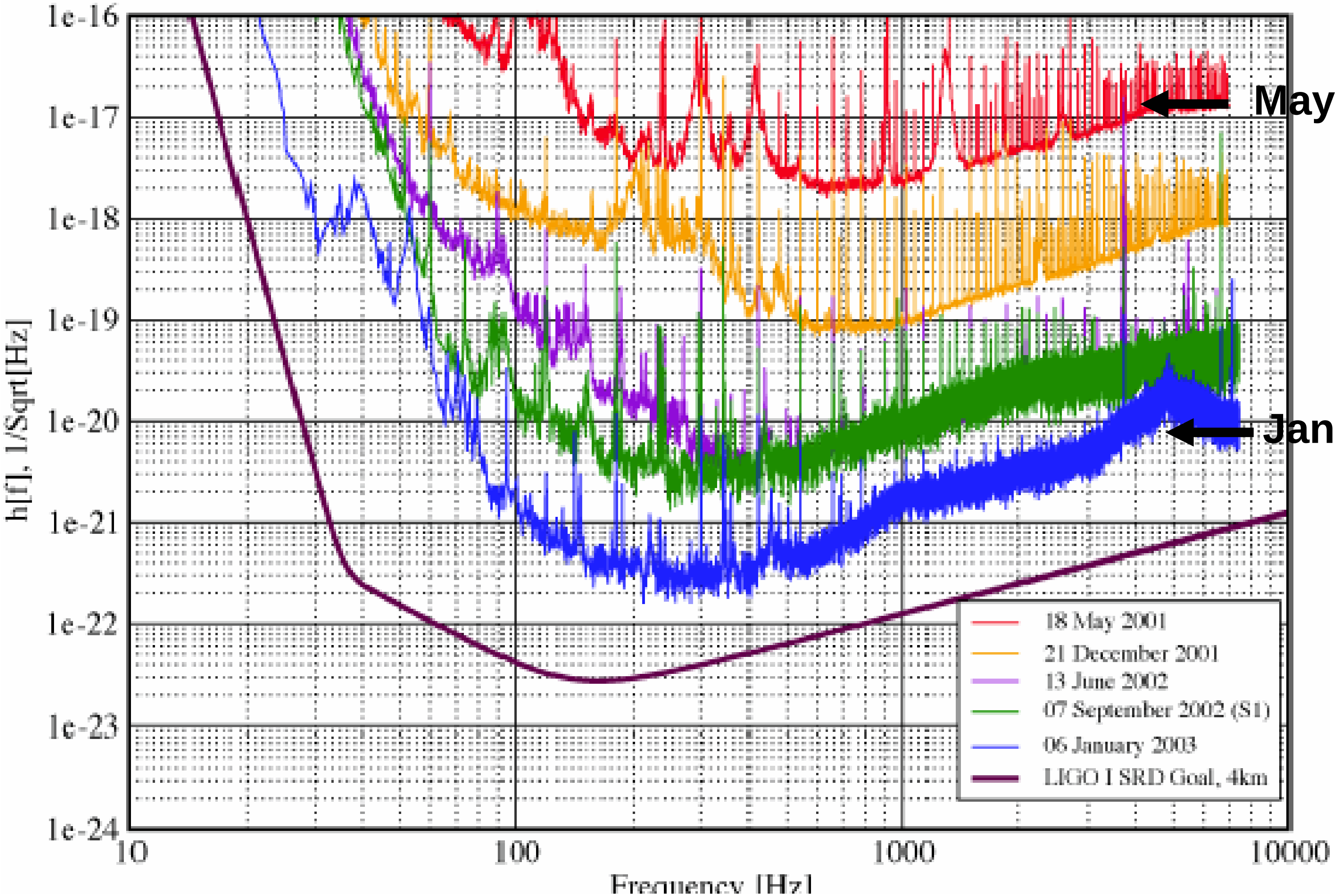
Engineering E1 E2 E3 E4 E5 E6 E7 E8 E9 E10

Runs

Science S1 S2 S3

First Science Data

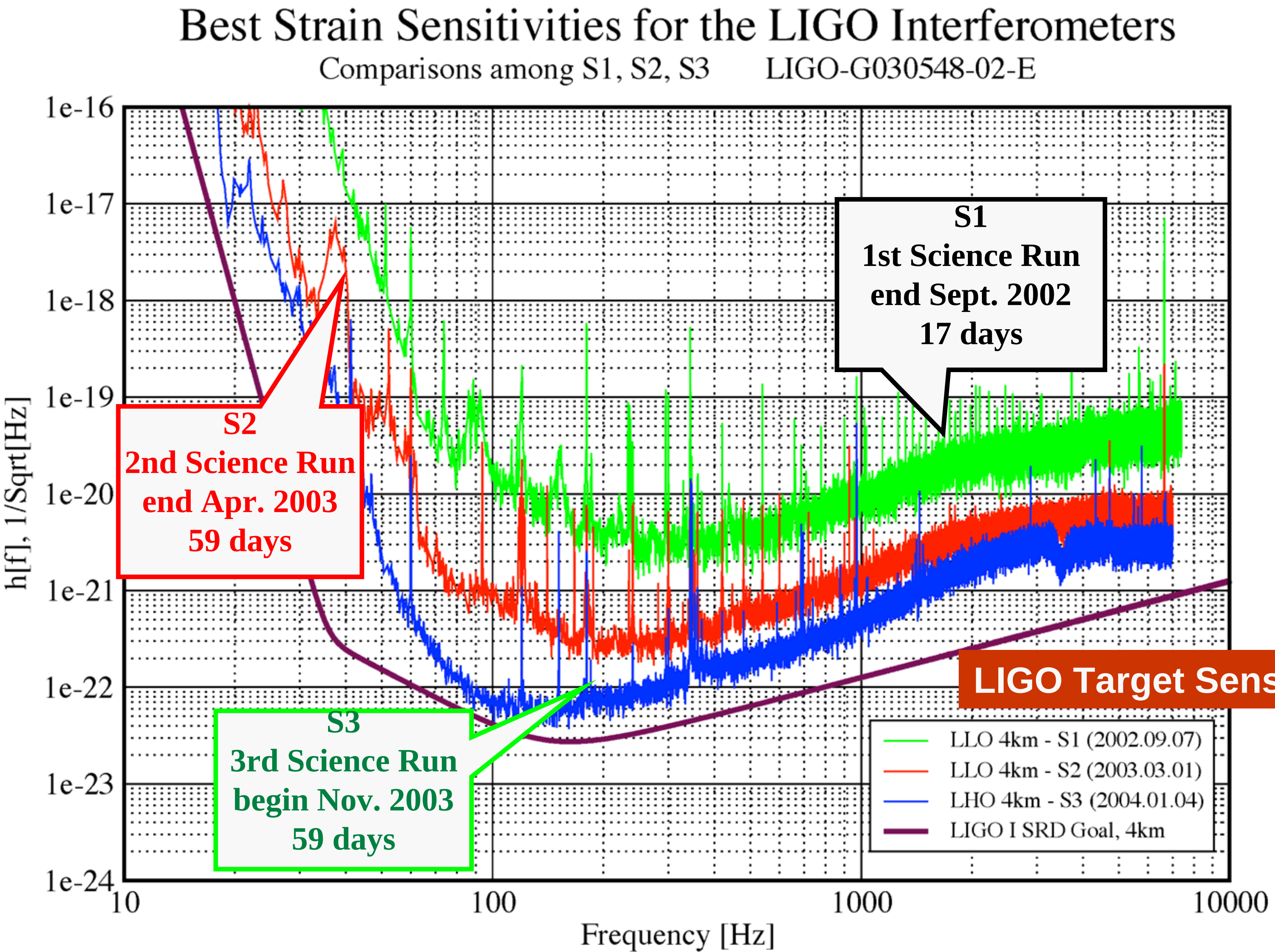
LLO 4km Sensitivity



May 2001

Jan 2003

Sensitivity and 3 Science Runs



S1
1st Science Run
end Sept. 2002
17 days

S2
2nd Science Run
end Apr. 2003
59 days

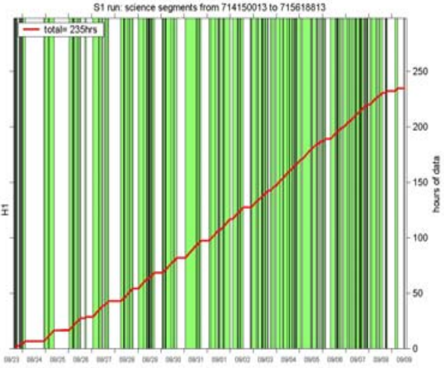
S3
3rd Science Run
begin Nov. 2003
59 days

LIGO Target Sensitivity

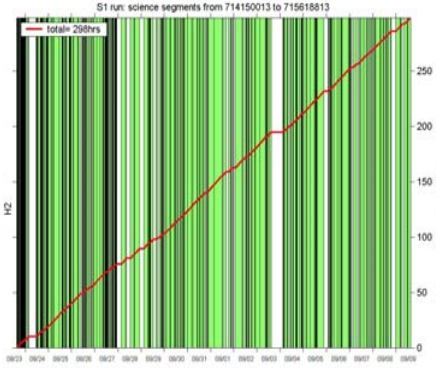
In-Lock Data Summary from S1

Red lines: integrated up time Green bands (w/ black borders): epochs of lock

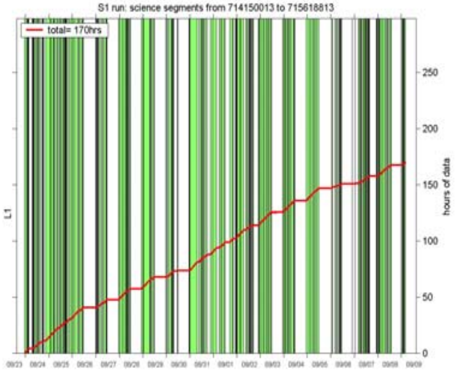
H1: 235 hrs



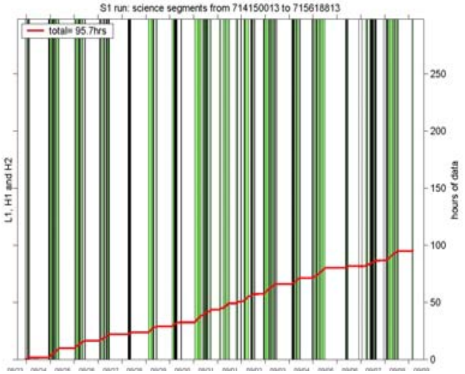
H2: 298 hrs



L1: 170 hrs



3X: 95.7 hrs



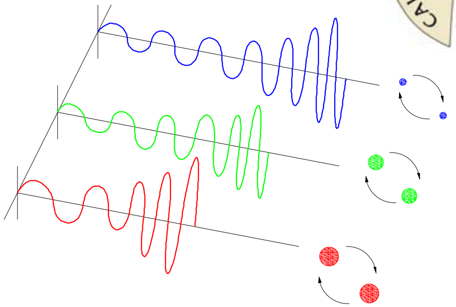
- August 23 – September 9, 2002: 408 hrs (17 days).
  - H1 (4km): duty cycle 57.6% ; Total Locked time: 235 hrs
  - H2 (2km): duty cycle 73.1% ; Total Locked time: 298 hrs
  - L1 (4km): duty cycle 41.7% ; Total Locked time: 170 hrs

- Double coincidences:
  - L1 && H1 : duty cycle 28.4%; Total coincident time: 116 hrs
  - L1 && H2 : duty cycle 32.1%; Total coincident time: 131 hrs
  - H1 && H2 : duty cycle 46.1%; Total coincident time: 188 hrs

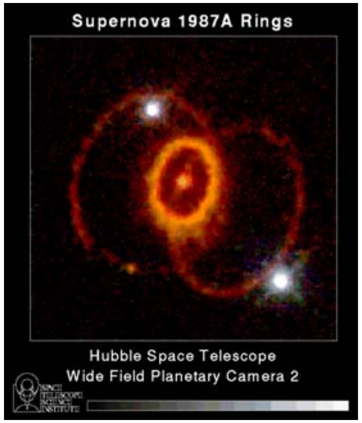
- Triple Coincidence: L1, H1, and H2 : duty cycle 23.4% ;
  - Total coincident time: 95.7 hrs

Astrophysical Sources of GW

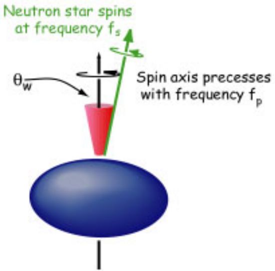
- Compact binary inspiral: ***"chirps"***
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



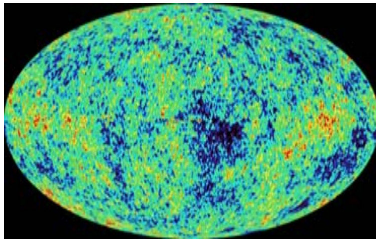
- Supernovae / GRBs: ***"bursts"***
  - burst signals in coincidence with signals in electromagnetic radiation
  - Challenge to search for untriggered bursts



- Pulsars in our galaxy: ***"periodic signals"***
  - search for observed neutron stars (frequency, Doppler shift)
  - all sky search (computing challenge)
  - r-modes

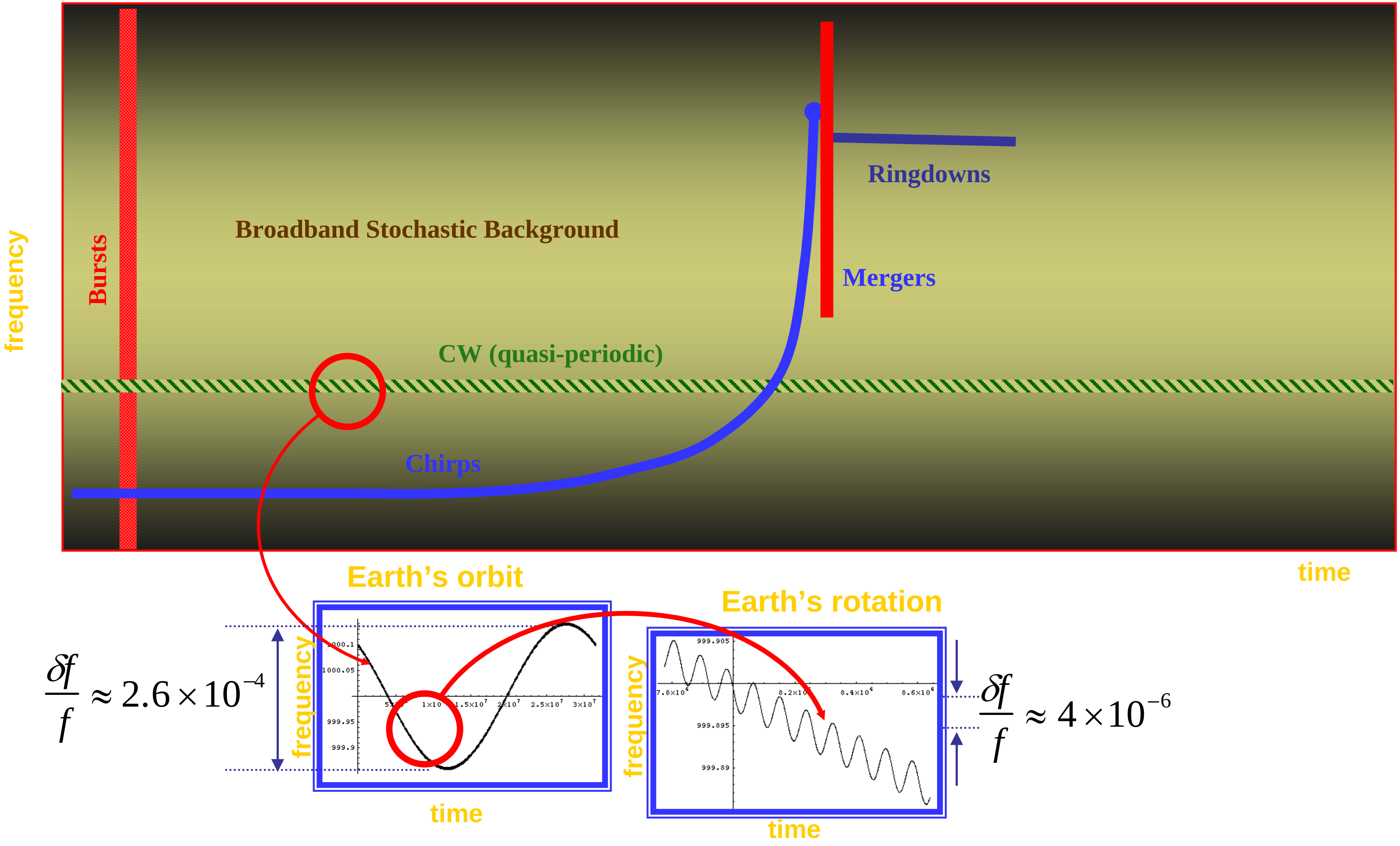


- Cosmological Signals ***"stochastic background"***



Analog from cosmic microwave background -- WMAP 2003

Frequency-Time Characteristics



$$\frac{\delta f}{f} \approx 2.6\times10^{-4}$$

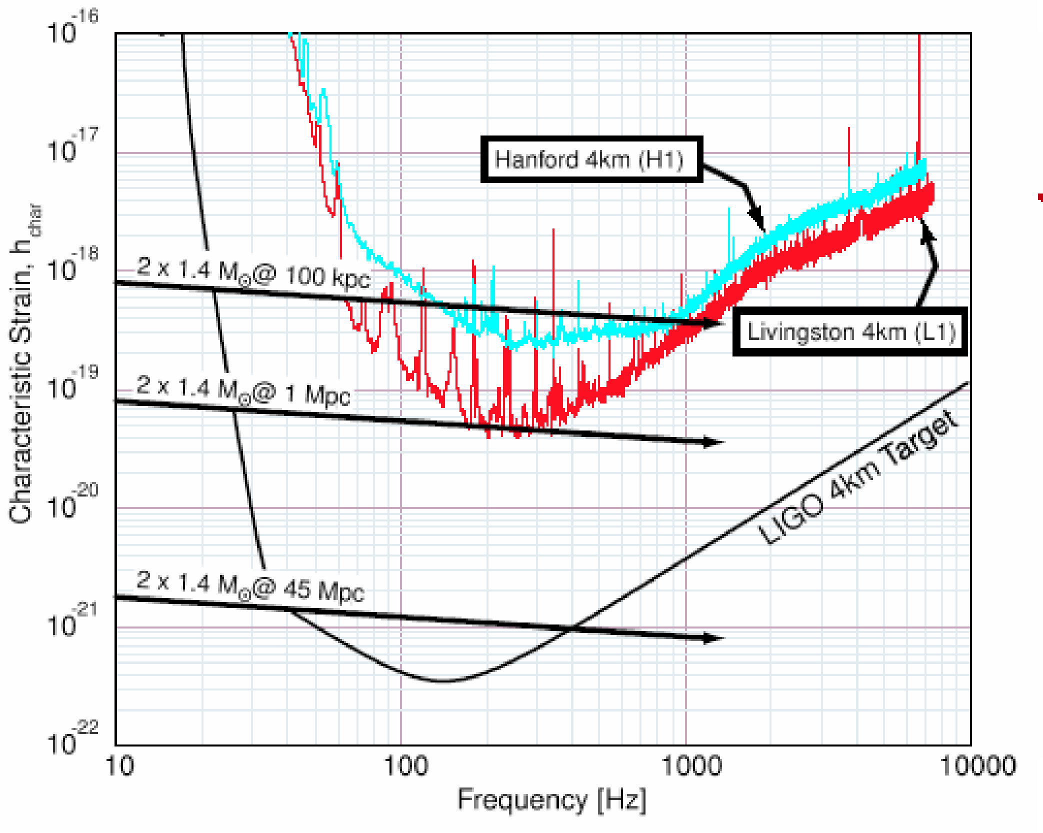
$$\frac{\delta f}{f} \approx 4\times10^{-6}$$

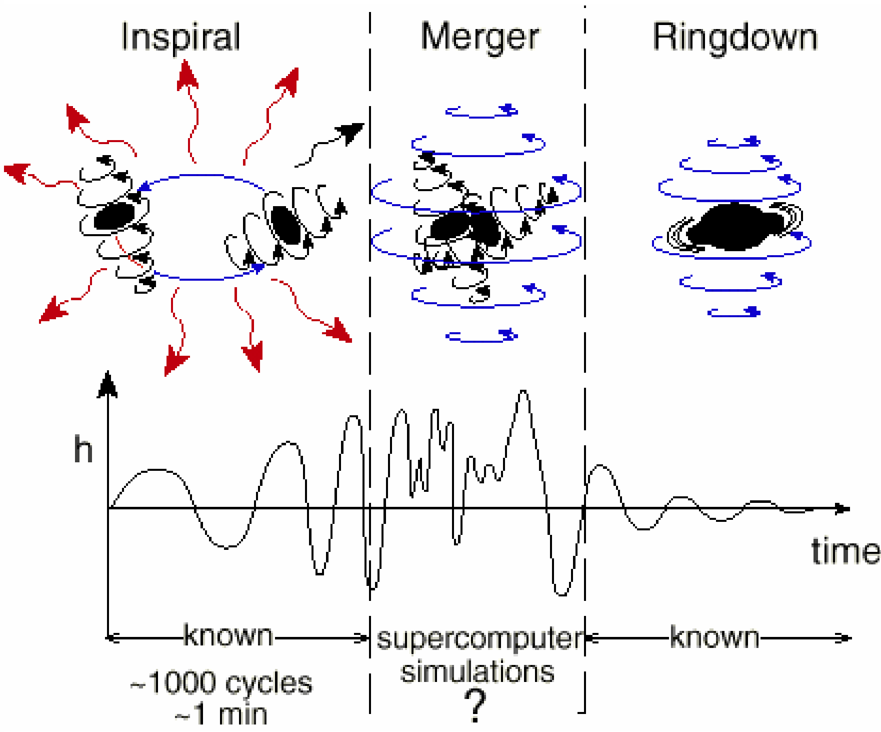
1. Compact binary sources

Coalescence inspirals

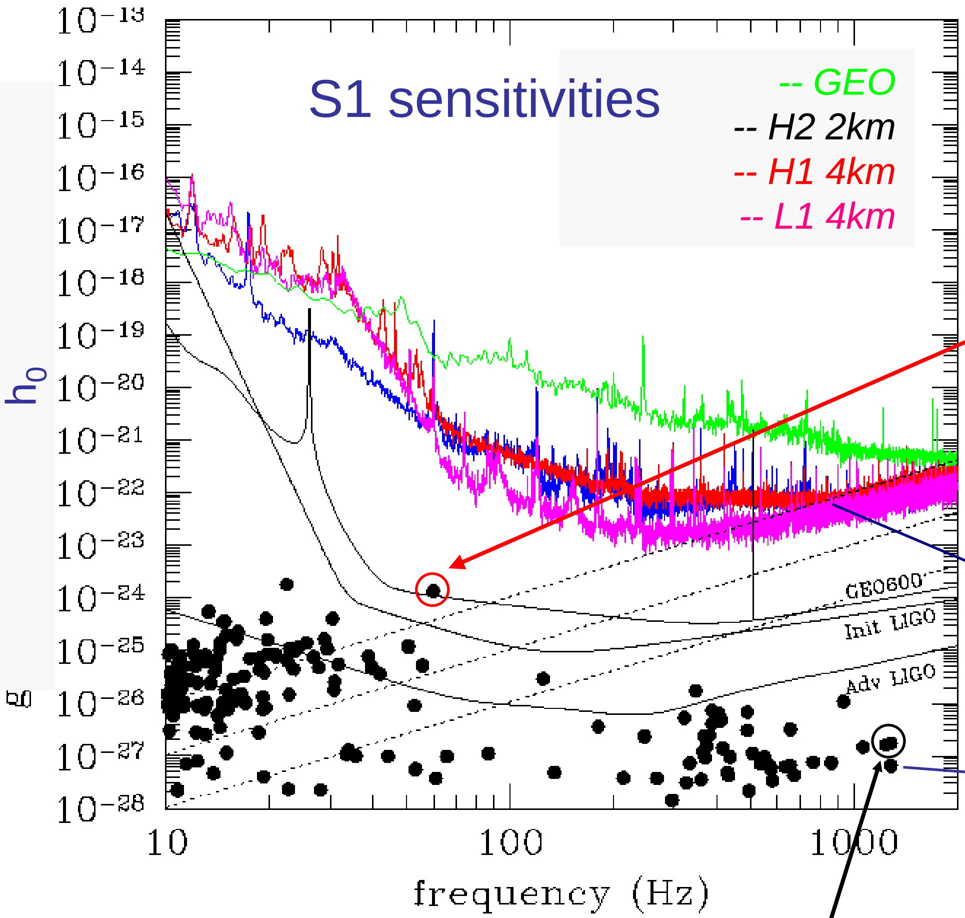
Detectability of coalescing binary sources during S1

(for optimal location & orientation relative to antenna pattern)

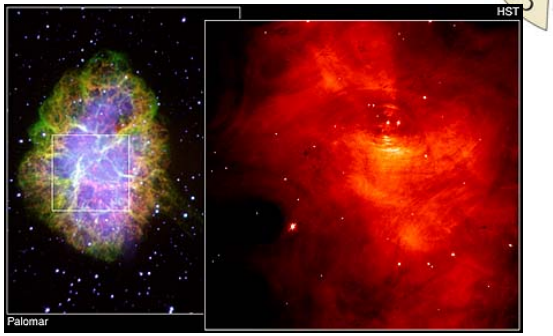




2. Periodic sources



PSR J1939+2134
P = 0.00155781 s
f_{GW} = 1283.86 Hz
$\dot{P}$ = 1.0519 10^{-19} s/s
D = 3.6 kpc



Crab pulsar

- h_0: Amplitude detectable with 99% confidence during observation time T

$$\langle h_0 \rangle = 11.4\sqrt{S_n(f_s)/T}$$

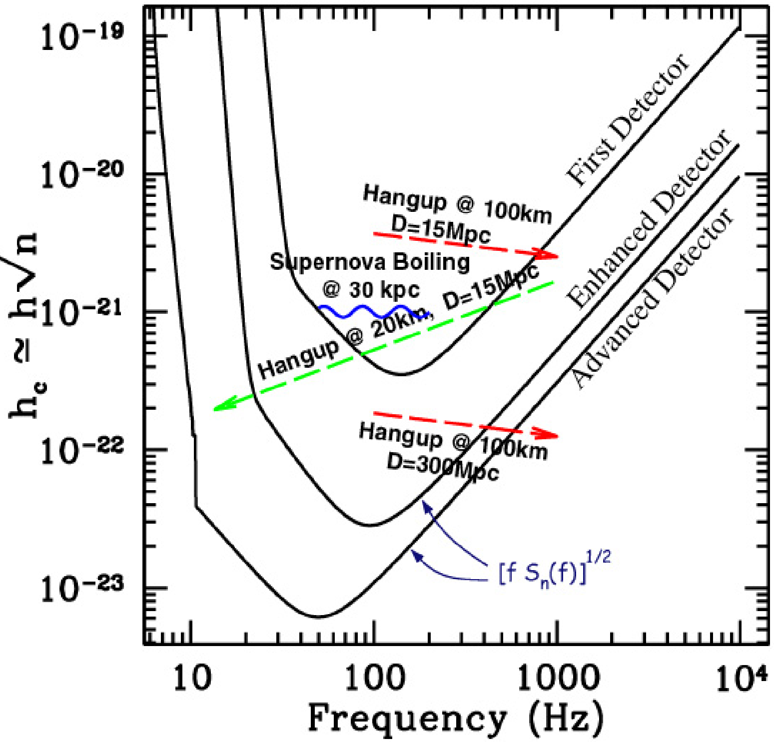
- *Limit of detectability for rotating NS with equatorial ellipticity, $\varepsilon = \delta I/I_{zz}$:*

  10^{-3} , 10^{-4} , 10^{-5} @ 10 kpc

- ***Known** EM pulsars*
  - *Values of h_0 derived from measured spin-down*
    - *IF spin-down were entirely attributable to GW emissions*
    - *Rigorous astrophysical upper limit from energy conservation arguments*

3. Burst sources

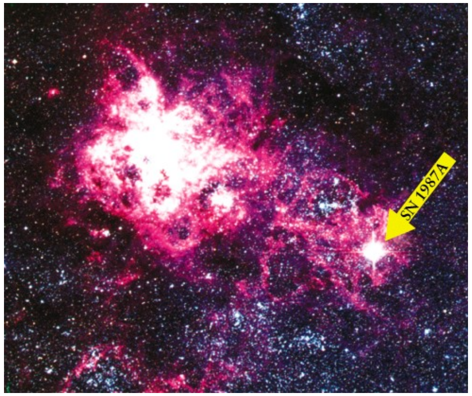
Sensitivity of LIGO to burst sources



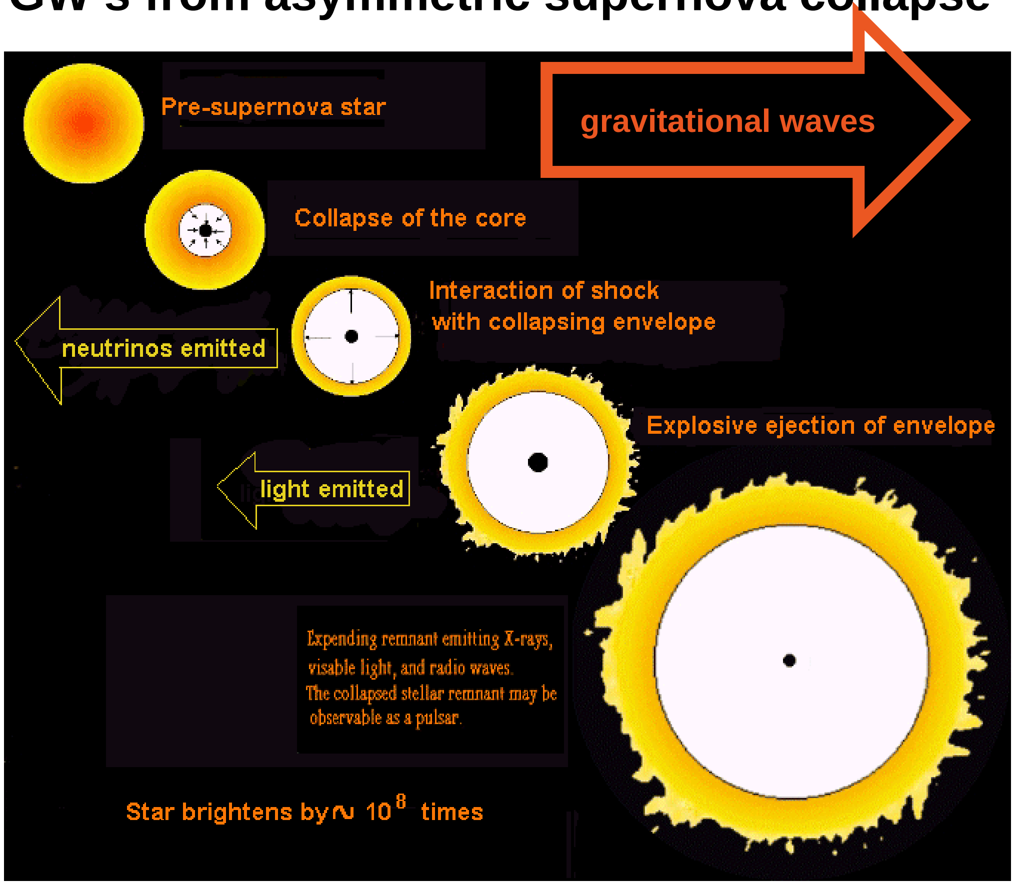
Expected SNe Rate

1/50 yr - our galaxy

3/yr - Virgo cluster



GW's from asymmetric supernova collapse



Pre-supernova star

gravitational waves

Collapse of the core

Interaction of shock with collapsing envelope

neutrinos emitted

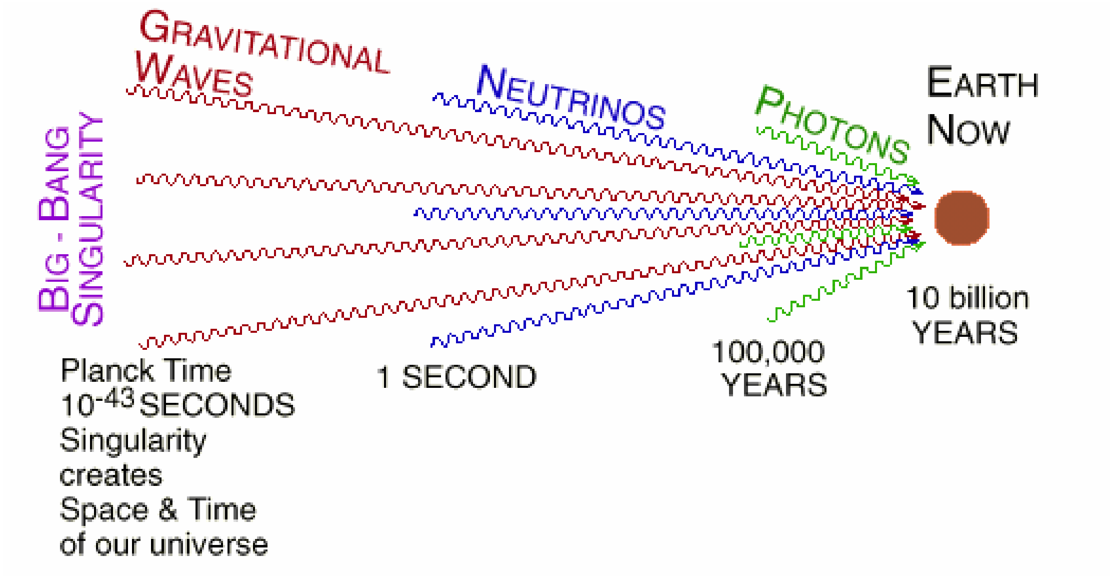
Explosive ejection of envelope

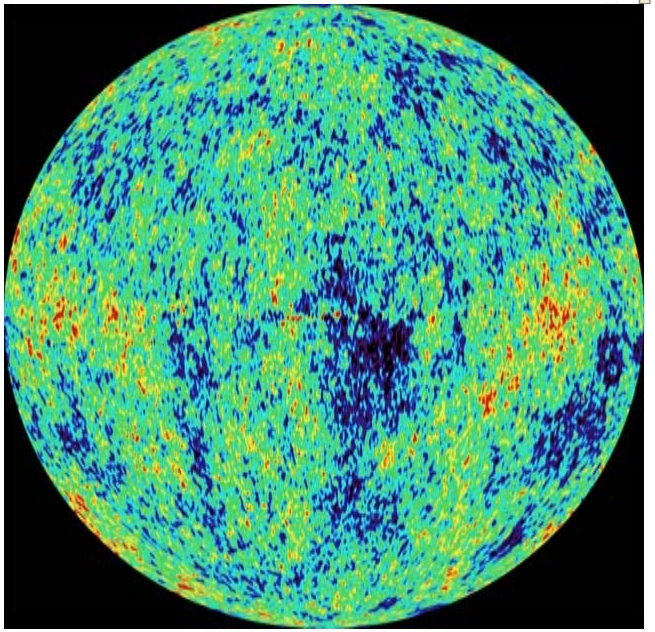
light emitted

Expending remnant emitting X-rays, visable light, and radio waves. The collapsed stellar remnant may be observable as a pulsar.

Star brightens by ~ 10^8 times

4. Stochastic GW Background





Analog from cosmic microwave background -- WMAP 2003

Sources

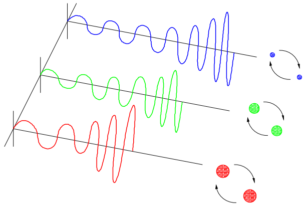
- Early universe sources (inflation, cosmic strings, etc) produce very weak, non-thermal (eg, power-law spectrum), unpolarized, isotropic, incoherent (stochastic) background spectrum
- Contemporary sources (unresolved SN & inspiral sources) produce power-law spectrum

$$\int_0^\infty d(\ln f)\ \Omega_{GW}(f) = \frac{\rho_{GW}}{\rho_{critical}}$$

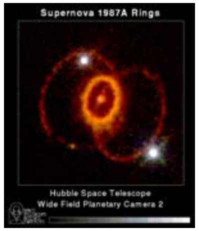
The integral of [$1/f \bullet \Omega_{GW}(f)$] over all frequencies corresponds to the fractional energy density in gravitational waves in the Universe

LIGO Data Analysis Groups

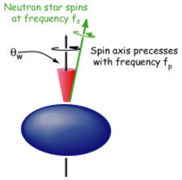
- LIGO Scientific Collaboration (LSC) Analysis Groups
  - Typically ~30 physicists / group
  - One experimentalist / One theorist co-lead each group
- Compact binary inspiral: *“chirps”*



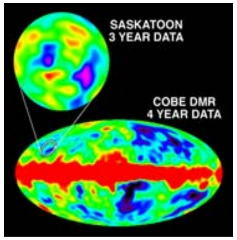
- Supernovae / GRBs / mergers: *“bursts”*



- Pulsars in our galaxy: *“periodic”*



- Cosmological Signal *“stochastic background”*



LIGO Data Analysis

- LIGO is a broad-band detector, measures waveforms.
- The experimentalist thinks not in terms of astrophysical sources, but in terms of waveform morphologies.
- Specific astrophysical sources suggest specific waveforms, but we don’t want to miss the unexpected!
- Four different waveform morphologies being considered:
  - Bursts (of limited duration), for which we have models (chirps, ringdowns)
  - Bursts, for which we have no reliable models (supernovas, …)
  - Continuous waves, narrow bandwidth - periodic (pulsars)
  - Continuous waves, broad bandwidth - stochastic (BB background)
- Each requires radically different data analysis techniques.
- Algorithms and implementation are under development.
- Marching into the unknown – look out for surprises!

Summary of S1

- The first upper limits results have been obtained using the LIGO interferometers in coincidence. These have resulted in four ***methodology*** papers:

  Papers submitted to *Physical Review D*:

  - ‡ ***"Analysis of LIGO data for gravitational waves from binary neutron stars", gr-qc/0308069***
  - ‡ ***"Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO600 and LIGO detectors", gr-qc/0308050***
  - ‡ ***"First upper limits on gravitational wave bursts from LIGO"***
  - ‡ ***"Analysis of First LIGO Science Data for Stochastic Gravitational Waves***
- A paper describing the instruments has also been written.
  - ‡ ***"Detector Description and Performance for the First Coincidence Observations between LIGO and GEO", gr-qc/0308043, accepted for publication by Nuclear Instruments and Methods***

Papers in Publication

1. gr-qc/0312088 [abs, ps, pdf, other] :

Title: Analysis of First LIGO Science Data for Stochastic Gravitational Waves
Authors: LIGO Scientific Collaboration: B. Abbott, et al
Comments: 26 pages, 17 figures

2. gr-qc/0312056 [abs, ps, pdf, other] :

Title: First upper limits from LIGO on gravitational wave bursts
Authors: LIGO Scientific Collaboration: B. Abbott, et al
Comments: 21 pages, 15 figures, for submission to Phys Rev D

3. gr-qc/0308069 [abs, ps, pdf, other] :

Title: Analysis of LIGO data for gravitational waves from binary neutron stars
Authors: The LIGO Scientific Collaboration: B.Abbott, et al
Comments: 17 pages, 9 figures

4. gr-qc/0308050 [abs, ps, pdf, other] :

Title: Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO600 and LIGO detectors
Authors: The LIGO Scientific Collaboration: B.Abbott, et al
Comments: 16 pages,8 figures

5. gr-qc/0308043 [abs, ps, pdf, other] :

Title: Detector Description and Performance for the First Coincidence Observations between LIGO and GEO
Authors: The LIGO Scientific Collaboration: B. Abbott, et al
Comments: 41 pages, 9 figures 17 Sept 03: author list amended, minor editorial changes

300 physicists and engineers; 40 institutions from eight countries

Analysis of First LIGO Science Data for Stochastic Gravitational Waves

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Libbrecht,[13] P. Lindquist,[13] S. Liu,[13] J. Logan,[13,r] M. Lormand,[16] M. Lubinski,[15] H. Lück,[32,2] T. T. Lyons,[13,r] B. Machenschalk,[1] M. MacInnis,[14] M. Mageswaran,[13] K. Mailand,[13] W. Majid,[13,h] M. Malec,[32] F. Mann,[13] A. Marin,[14,s] S. Márka,[13] E. Maros,[13] J. Mason,[13,t] K. Mason,[14] O. Matherny,[15] L. Matone,[15] N. Mavalvala,[14] R. McCarthy,[15] D. E. McClelland,[3] M. McHugh,[19] P. McNamara,[36,u] G. Mendell,[15] S. Meshkov,[13] C. Messenger,[34] V. P. Mitrofanov,[21] G. Mitselmakher,[35] R. Mittleman,[14] O. Miyakawa,[13] S. Miyoki,[13,v] S. Mohanty,[1,w] G. Moreno,[15] K. Mossavi,[2] B. Mours,[13,x] G. Mueller,[35] S. Mukherjee,[1,w] J. Myers,[15] S. Nagano,[2] T. Nash,[10,y] H. Naundorf,[1] R. Nayak,[12] G. Newton,[36] F. Nocera,[13] P. Nutzman,[24] T. Olson,[25] B. O'Reilly,[16] D. J. Ottaway,[14] A. Ottewill,[40,z] D. Ouimette,[13,q] H. Overmier,[16] B. J. Owen,[29] M. A. Papa,[1] C. Parameswariah,[16] V. Parameswariah,[15] M. Pedraza,[13] S. Penn,[11] M. Pitkin,[36] M. Plissi,[36] M. Pratt,[14] V. Quetschke,[32] F. Raab,[15] H. Radkins,[15] R. Rahkola,[38] M. Rakhmanov,[35] S. R. Rao,[13] D. Redding,[13,h] M. W. Regehr,[13,h] T. Regimbau,[14] K. T. Reilly,[13] K. Reithmaier,[13] D. H. Reitze,[35] S. Richman,[14,aa] R. Riesen,[16] K. Riles,[37] A. Rizzi,[16,bb] D. I. Robertson,[36] N. A. Robertson,[36,27] L. Robison,[13] S. Roddy,[16] J. Rollins,[14] J. D. Romano,[30,cc] J. Romie,[13] H. Rong,[35,m] D. Rose,[13] E. Rotthoff,[29] S. Rowan,[36] A. Rüdiger,[20,2] P. Russell,[13] K. Ryan,[15] I. Salzman,[13] G. H. Sanders,[13] V. Sannibale,[13] B. Sathyaprakash,[7] P. R. Saulson,[28] R. Savage,[15] A. Sazonov,[35] R. Schilling,[20,2] K. Schlaufman,[29] V. Schmidt,[13,dd] R. Schofield,[38] M. Schrempel,[32,ee] B. F. Schutz,[1,7] P. Schwinberg,[15] S. M. Scott,[3] A. C. Searle,[3] B. Sears,[13] S. Seel,[13] A. S. Sengupta,[12] C. A. Shapiro,[29,ff] P. Shawhan,[13] D. H. Shoemaker,[14] Q. Z. Shu,[35,gg] A. Sibley,[16] X. 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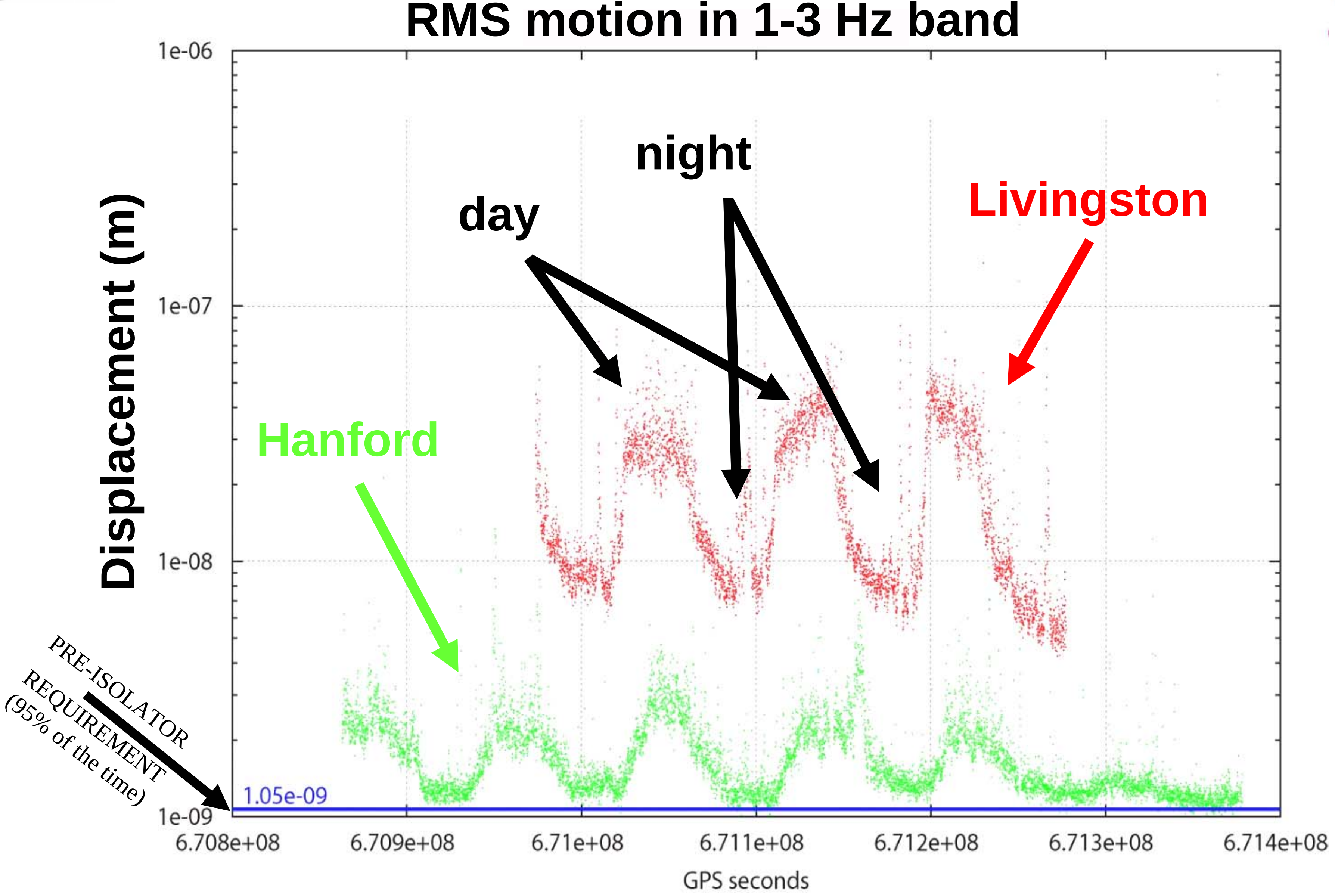
Seismic Environment at LLO

- Spiky impulsive seismic noise in 1-3 Hz band
  - Related to human activity – mostly lumber industry
  - Dominant frequencies accidentally coincide with stack resonances
  - Impedes interferometer locking during weekdays
- Large & variable microseism
  - Ocean waves excite double frequency (DF) surface waves on land
    - Fraction to several microns RMS; frequency: ~ 0.15 - 0.25 Hz
    - Wavelength ~ kilometers ➔ L1 arm length change several microns
- Strategy for recovering full-time duty at LLO
  - Active Hydraulic External Pre-Isolator system
    - 6 D.O.F active stabilization of seismic supports (External Pre-Isolator)
  - Prototype demonstrated at Stanford and MIT
  - Now in full production for January installation start at LLO

Daily Variability of Seismic Noise



RMS motion in 1-3 Hz band

day

night

Livingston

Hanford

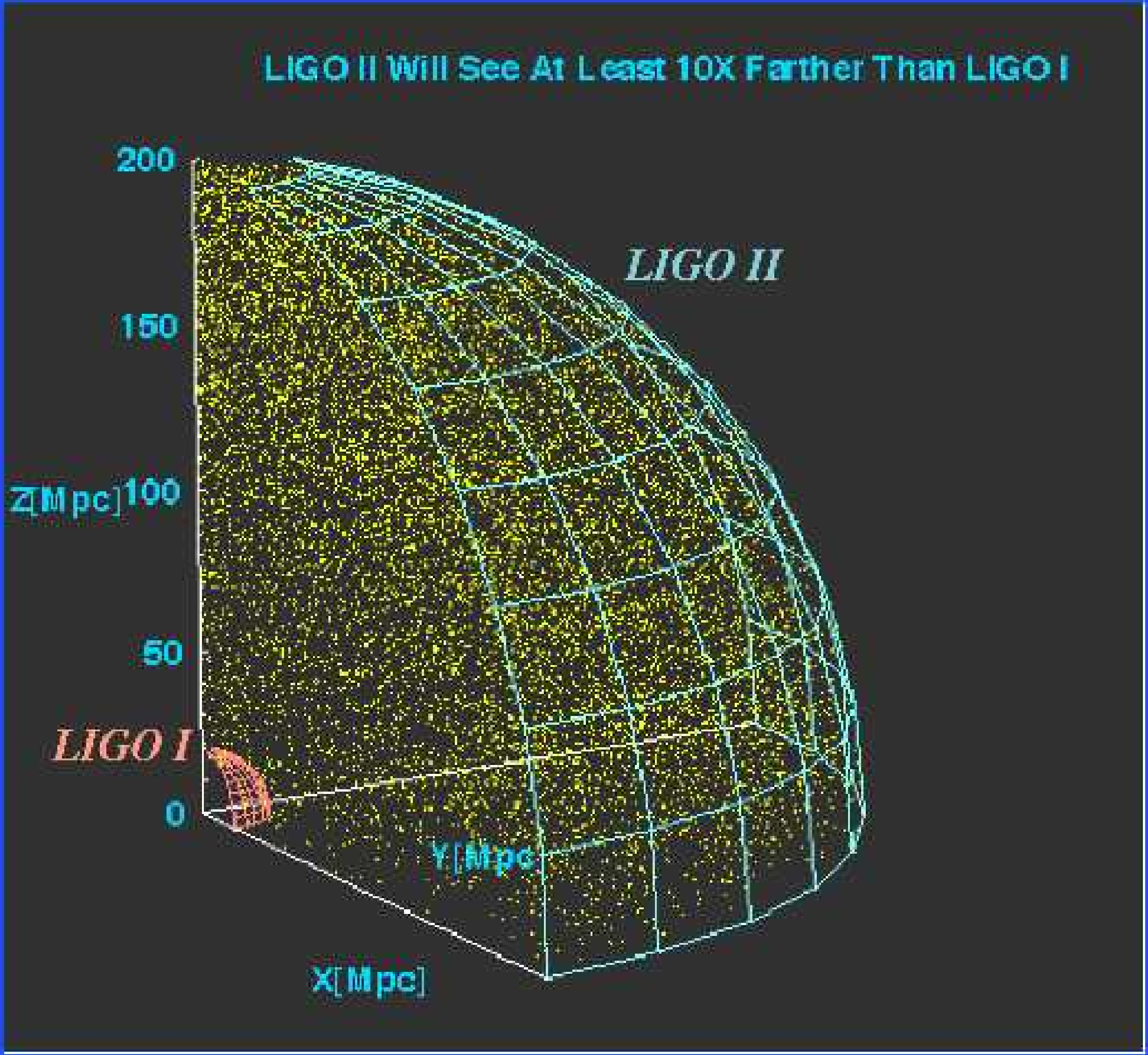
PRE-ISOLATOR REQUIREMENT (95% of the time)

LIGO Plans

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 $h \sim 10^{-21}$)
2007+	Begin 'advanced' LIGO installation

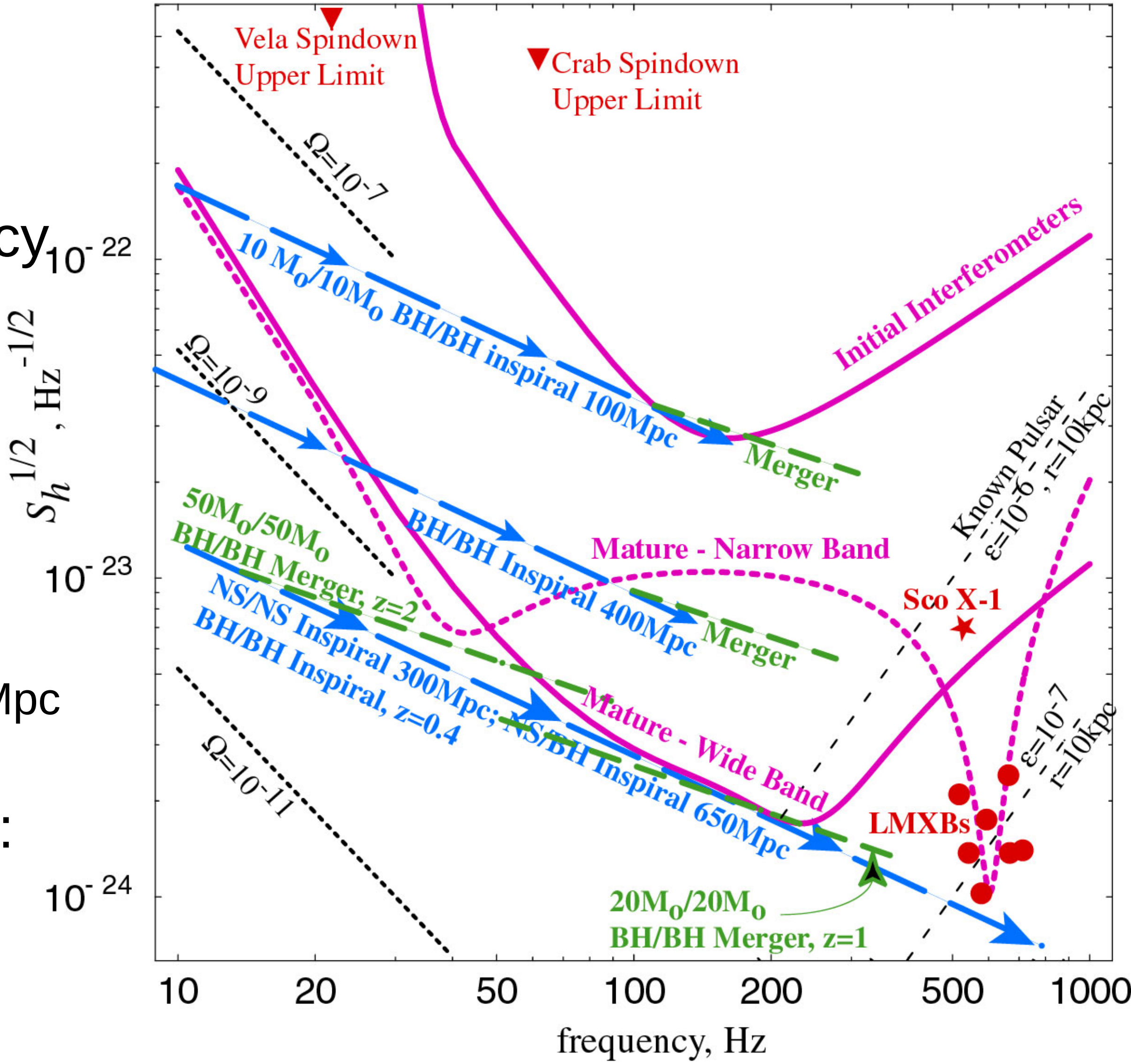
Advanced LIGO Reach



The scientific reach of a few hours of advanced LIGO is comparable to 1 year of initial LIGO

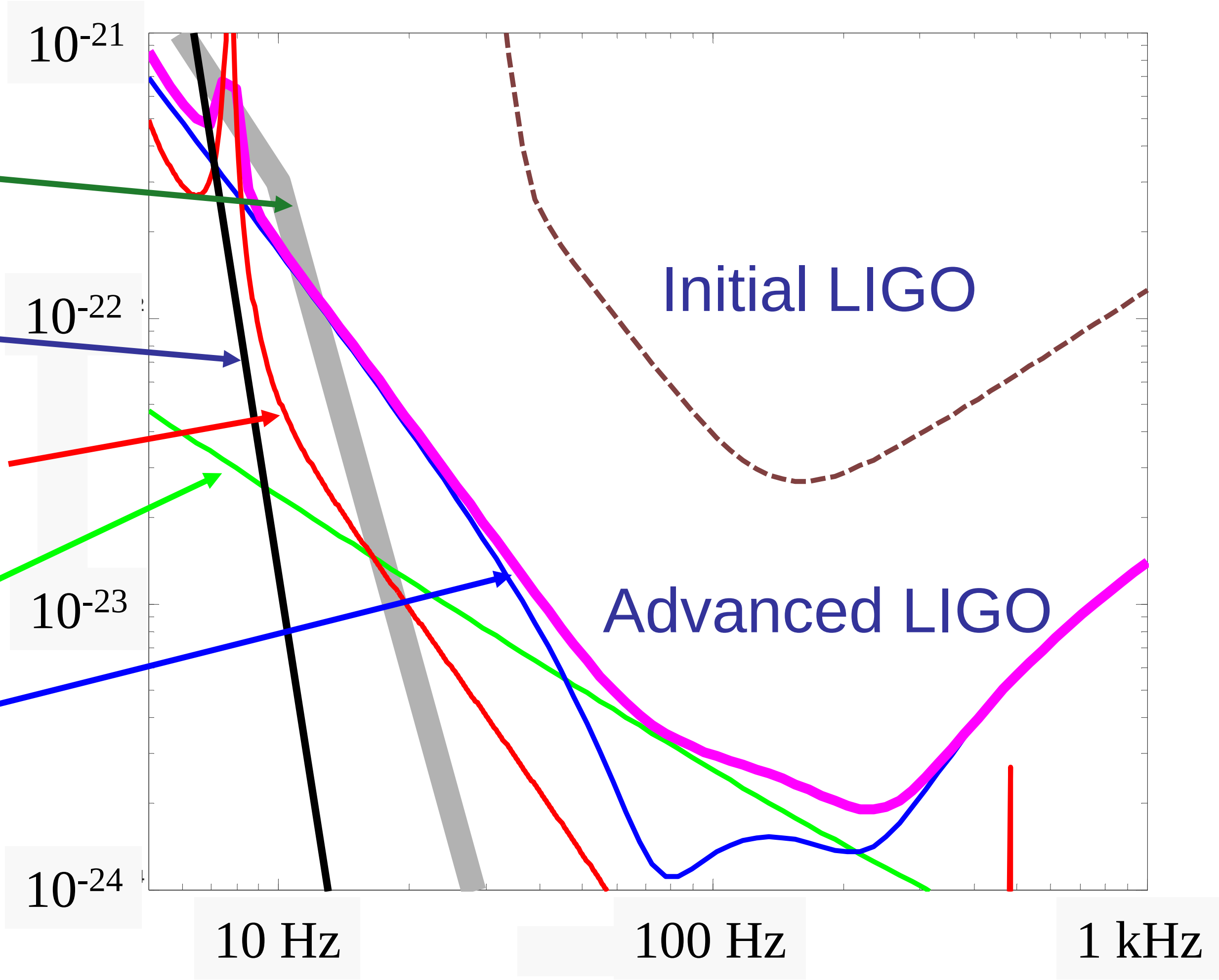
Initial and Advanced LIGO

- Factor 10 better amplitude sensitivity
  - $(\text{Reach})^3$ = rate
- Factor 4 lower frequency bound
- NS Binaries: for three interferometers,
  - Initial LIGO: ~20 Mpc
  - Adv LIGO: ~350 Mpc
- BH Binaries:
  - Initial LIGO: 10 M_o, 100 Mpc
  - Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - Initial LIGO: ~3e-6
  - Adv LIGO ~3e-9



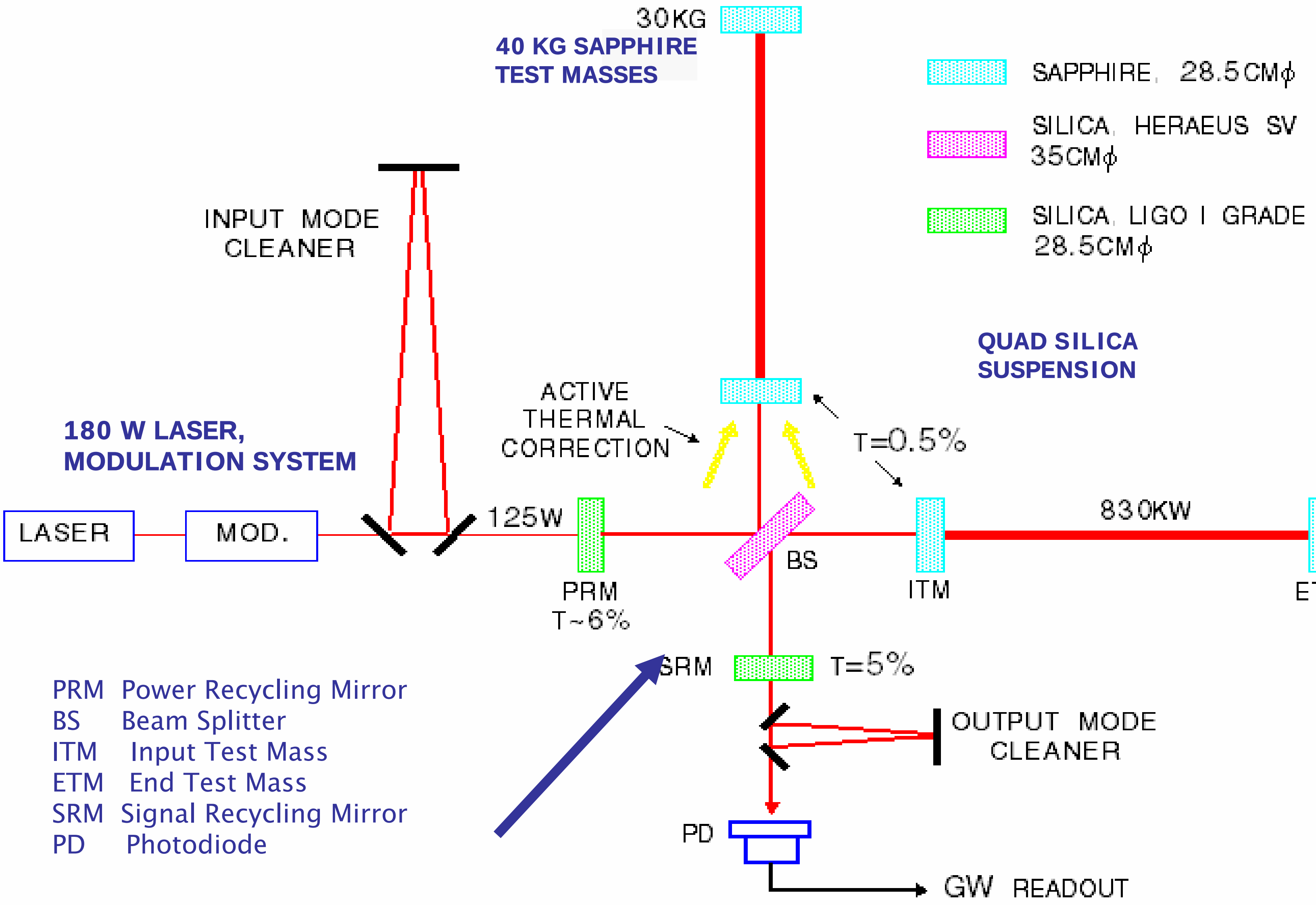
Projected Advanced LIGO

- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



- Advanced LIGO's Fabry-Perot Michelson Interferometer is flexible – can tailor to what we learn before and after we bring it on line, to the limits of this topology

Design features



40 KG SAPPHIRE TEST MASSES

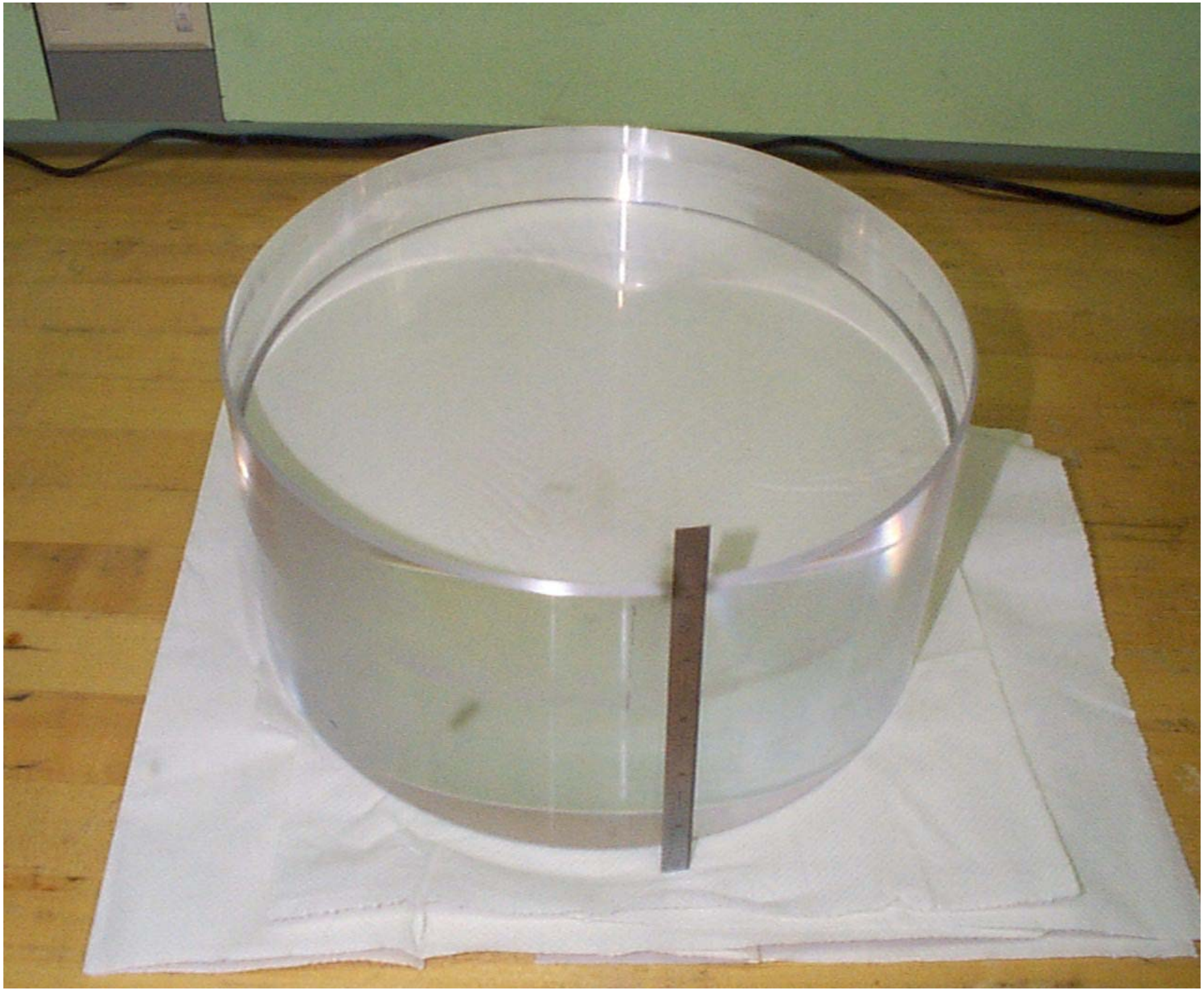
QUAD SILICA SUSPENSION

180 W LASER, MODULATION SYSTEM

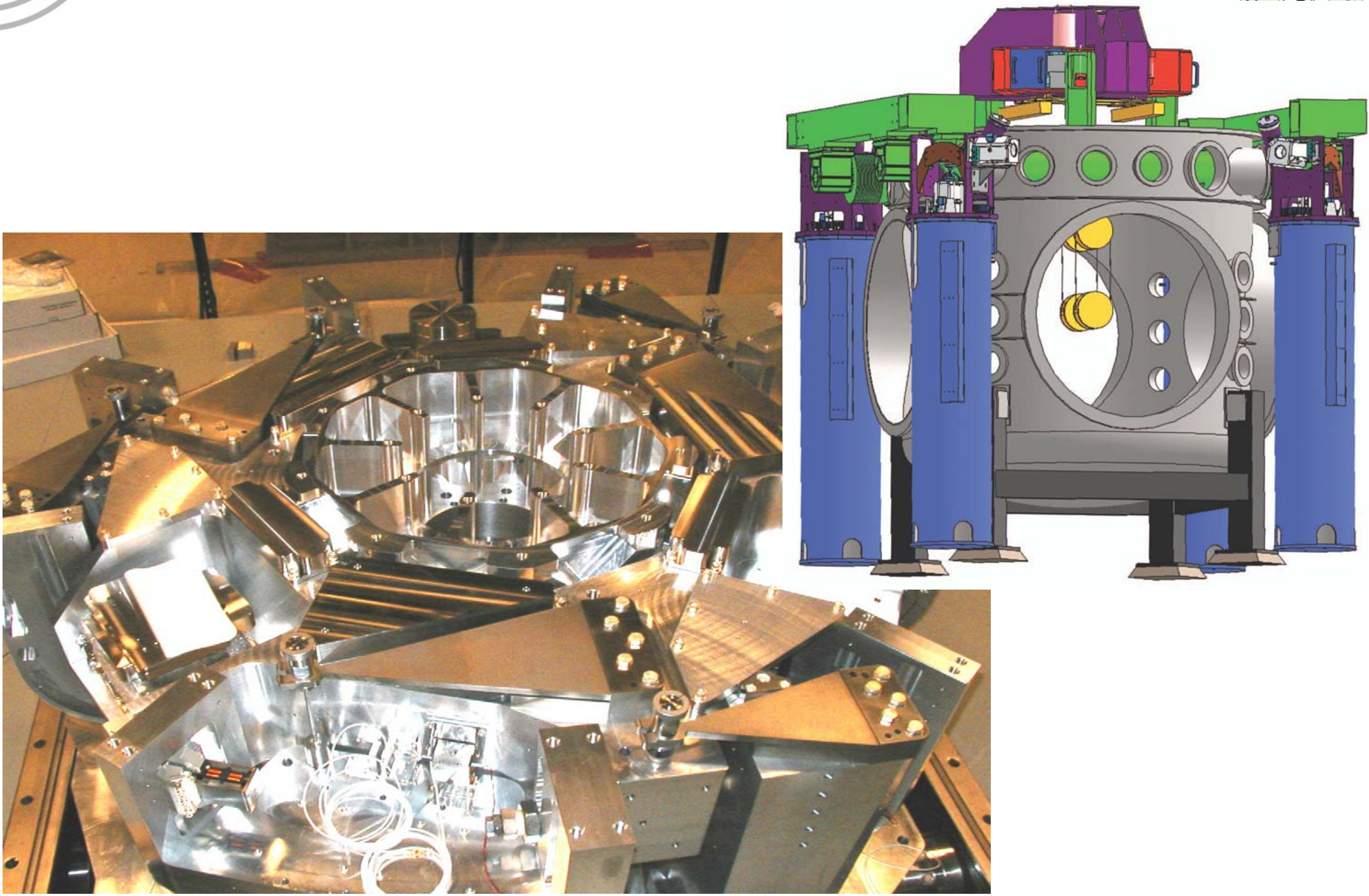
PRM	Power Recycling Mirror
BS	Beam Splitter
ITM	Input Test Mass
ETM	End Test Mass
SRM	Signal Recycling Mirror
PD	Photodiode

Test Masses / Core Optics

Full-size Advanced LIGO Sapphire Substrate



Isolation: multi-stage solution



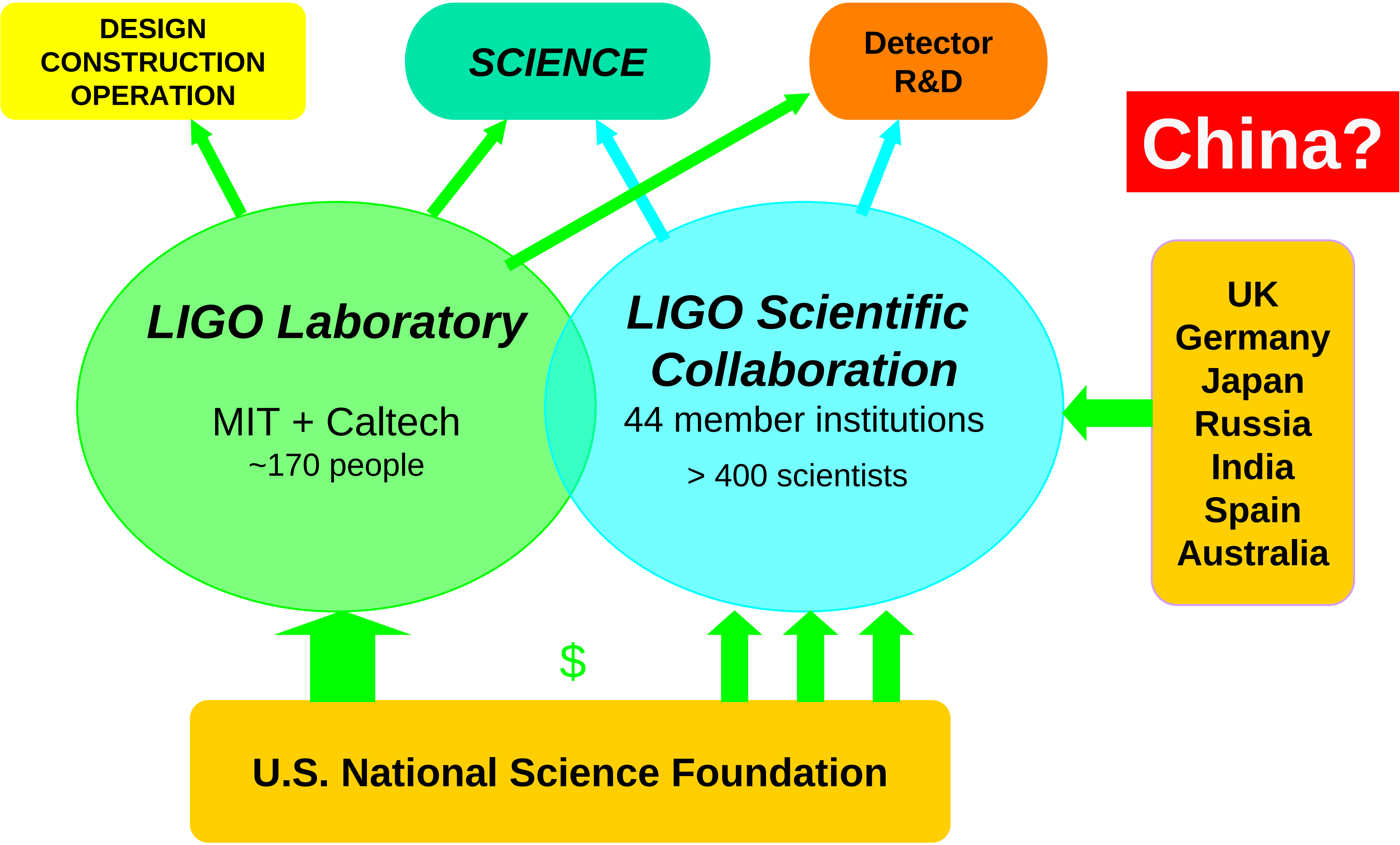
Suspensions

Prototype triple pendulum suspension

Advanced LIGO R&D

- Laser:
  - selected baseline power head design,
  - Prototyping: observe >1/2 final power goal in ½ of system.
  - Intensity stabilization to requirements (> 40Hz), within factor of 5 (10 Hz)
- Substrates:
  - Received full-size 40 kg, 32 cm diameter sapphire substrates
  - Found mechanical losses in these substrates to meet requirements
  - Characterized absorption in these substrates, supported successful annealing techniques on smaller pieces to reduce absorption
  - New high Q measurements of small (200e6) and LIGO-sized (120e6) of fused silica; annealing on small pieces to reduce mechanical losses
- Coatings:
  - Refined models for coating thermal noise
  - Observed coating thermal noise in two experiments, consistent with theory
  - Measured and supported measurements of mechanical losses on trial coatings
  - Developed strategy for coating development, put plan into motion

LIGO Organization & Support



DESIGN
CONSTRUCTION
OPERATION

SCIENCE

Detector
R&D

China?

LIGO Laboratory

MIT + Caltech
~170 people

LIGO Scientific Collaboration

44 member institutions

> 400 scientists

UK
Germany
Japan
Russia
India
Spain
Australia

$

U.S. National Science Foundation

Summary

- To study gravitation wave astronomy, a laser based interferometer technology has been developed in the last decade. As of today, LIGO is approaching its initial scientific design goal and is publishing scientific result.
- Advanced LIGO is planned to expand the observation reach by a factor of ten, or the volume by 1,000.
- Similar to ICFA for high energy physics, a world wide scientific collaboration on gravitation wave detection (GWIC) has been established.
- A Chinese gravitation wave observatory will play an important role in this coordinated international effort.
- Prof. B. Barish, Director of LIGO, would like to express his warm welcome to our Chinese colleagues. He will support a bi-lateral collaboration between US and China in this effort, and will start this collaboration with a US NSF supported visitors program.