Quantum Noise Limited Lasers and The Search for Gravitational Waves

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Department of Applied Physics
Stanford University

Abstract

Einstein formulated the general theory of relativity near 100 years ago and showed that gravity is curvature in space-time and further that ripples in space-time, gravitational waves, travel at the speed of light. Today the **L**aser **I**nterferometer **G**ravitational Wave **O**bservatory, **LIGO**, project is using ground based 4km long interferometers to search for gravitational waves. The progress for LIGO and other earth based gravitational wave interferometers will be reviewed.

This summer the **L**aser **I**nterferometer in **S**pace **A**ntenna, **LISA**, project, joint between NASA and ESA, will hold its 8th International meeting at Stanford. The design of the space-based 5 million kilometer path length LISA interferometer, scheduled for launch in 2020, will be discussed.

The detection of gravitational waves requires the ultimate in precision measurement. The 'ruler' used to detect oscillations in space-time is the constant; the speed of light. The light source is a very stable diode-pumped Nd:YAG solid state laser oscillator-amplifier that operates reliably at the quantum limit in phase and amplitude.

AAAS 2010 Annual Meeting
San Diego, CA
February 21, 2010

Outline

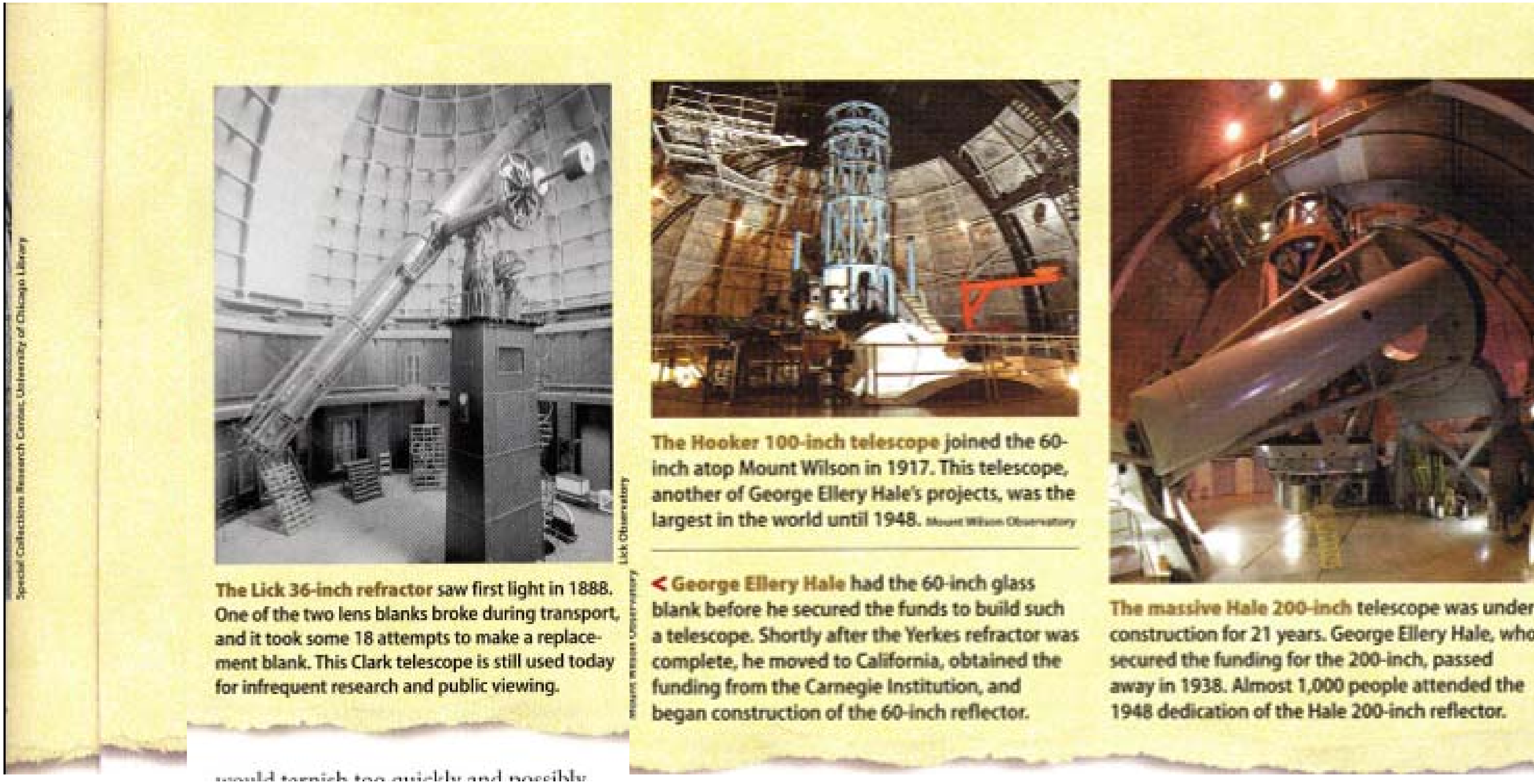
Prelude: California – a leader in science and technology

LIGO & LISA: Early History and Concepts
- LIGO and LISA at the beginning
- Gravitational Waves and Sources

The LIGO Observatory
- LIGO Interferometers
  - Measurements
  - Technical progress
  - Science Runs - LIGO begins Science Run #6
- Advanced LIGO Interferometer
  - Sensitivity Improvement
  - Detection rates
  - Schedule for completion

Future concepts
- LISA an Interferometer in Space
- LISA performance & technology development

California – Leader in advanced telescopes for astronomy



Special Collections Research Center, University of Chicago Library

The Lick 36-inch refractor saw first light in 1888. One of the two lens blanks broke during transport, and it took some 18 attempts to make a replacement blank. This Clark telescope is still used today for infrequent research and public viewing.

Lick Observatory

The Hooker 100-inch telescope joined the 60-inch atop Mount Wilson in 1917. This telescope, another of George Ellery Hale's projects, was the largest in the world until 1948. Mount Wilson Observatory

< **George Ellery Hale** had the 60-inch glass blank before he secured the funds to build such a telescope. Shortly after the Yerkes refractor was complete, he moved to California, obtained the funding from the Carnegie Institution, and began construction of the 60-inch reflector.

Mount Wilson Observatory

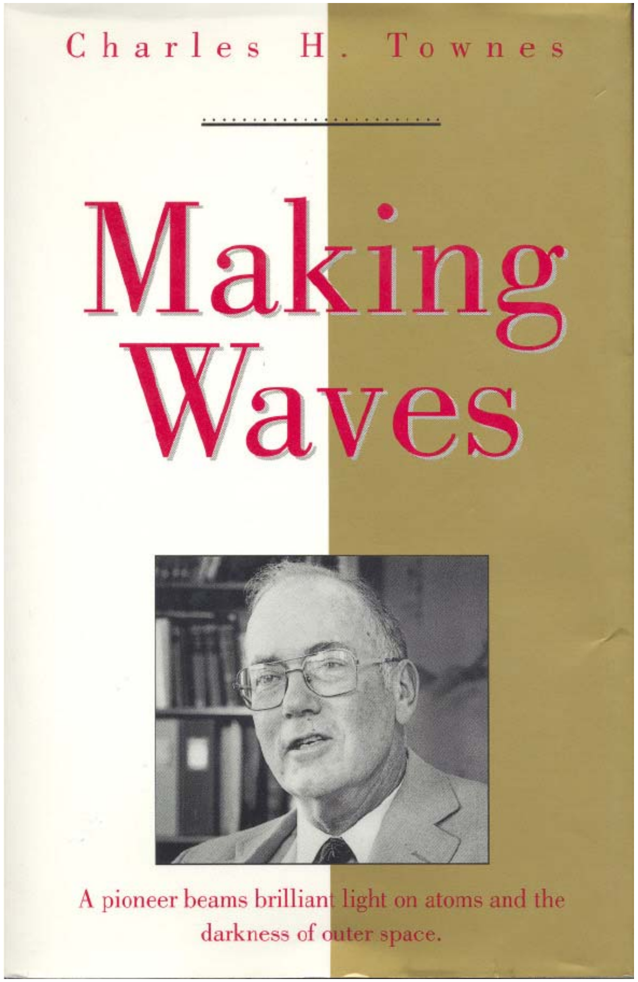
The massive Hale 200-inch telescope was under construction for 21 years. George Ellery Hale, who secured the funding for the 200-inch, passed away in 1938. Almost 1,000 people attended the 1948 dedication of the Hale 200-inch reflector.

Lick 36 inch refractor 1888

The Mount Wilson 100 inch 1917

The Palomar 200 inch 1948

Lightwaves



Prelude

Introduction — *Making Lightwaves*

Scientific Applications of Lasers — *Riding Lightwaves*

Future Directions — *Surfing Lightwaves*

Charlie is still contributing to Science at
The University of California at Berkeley

The Ruby Laser

Art Schawlow with Mickey Mouse Balloon and Ruby Laser

Retinal Attachment

"If I had set out to invent a method of re-attaching the retina, I would not have invented the laser"

Laser Eraser

"The "Laser Eraser" may not find any near term application, but it is interesting."

The first Ruby laser was demonstrated in 1960 by Ted Maiman
Hughes Research Labs in Los Angeles

California – Leader in advanced lasers

Concept of the Optical Maser	Schawlow & Townes	1958
Ruby Laser	Ted Maiman	1960

Nobel Prize awarded in 1964 Townes, Prokhorov and Basov

Hg+ Ion Laser	Earl Bell	1965
Argon Ion Laser	Bill Bridges	
Unstable Resonator	Tony Siegman	
Tunable cw parametric Laser	Steve Harris	1968
Diode bar 1Watt Laser	Scifres	1978
Diode Pumped Nd:YAG (NPRO)	Byer	1984

2009 a special year

105kW cw Nd:YAG Slab Laser	NGST	January
4 MJ IR, 2MJ UV NIF Laser	LLNL	March
1mJ 10Hz 1A Coh X-ray Laser	SLAC	April

2010 LaserFest

Motivation..
Scientific Applications of Lasers

"Don't undertake a project unless it is manifestly important and nearly impossible." Edwin Land - 1982

Scientific Applications of Lasers

Atmospheric Remote Sensing

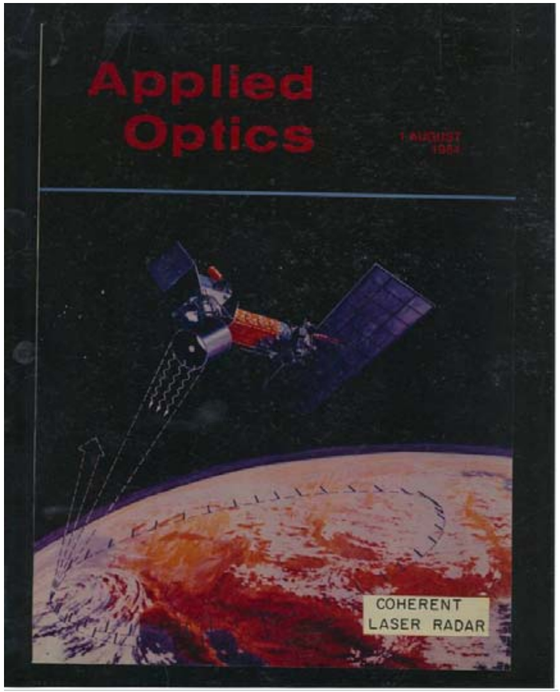
Quanta Ray 1J Unstable resonator
Nd:YAG Laser
1.4 to 4.3 micron Tunable LiNbO3 OPO

Global Wind Sensing

Laser Diode pumped Nd:YAG
Single Frequency Oscillator (NPRO)

LIGO and LISA & Gravitational Waves

10 W Nd:YAG slab MOPA for LIGO
200W Nd;YAG Advanced LIGO
1W Iodine Stabilized Nd:YAG LISA



Global remote sensing 1980 – Needed a coherent laser oscillator.

One thing leads to another….. from coherent laser radar to LISA and LIGO

The Non-Planar Ring Oscillator - 1984

1984

Reprinted from Optics Letters, Vol. 10, page 65, January 1985

Δν<10kHz

Monolithic, unidirectional single-mode Nd:YAG ring laser

Thomas J. Kane and Robert L. Byer

Ginzton Laboratoory, Stanford University, Stanford, California 94305

Receieved October 1, 1984; accepted November 26, 1984

We have built a nonplanar ring oscillator with the resonator contained entirely within a Nd:YAG crystal. When the oscillator was placed in a magnetic field, unidirectional oscillation was obtained with a pump-limited, single-axial-mode output of 163 mW.

In this Letter, we describe a new solid-state laser design that achieves high single-mode output power by using a unidirectional nonplanar resonator. Excellent frequency stability is achieved because the ring resonator is constructed from a single Nd:YAG crystal. We refer to the design as a MISER (Monolithic Isolated Single-mode End-pumped Ring) design. We developed this source as an oscillator for a long-range coherent Doppler anemometer.[1] Other applications areas include coherent communications, coherent optical radar, and inertial rotation sensing.

Ideally, a continuous-wave homogeneously broadened laser should oscillate in a single axial mode. The laser transitions in Nd:YAG are primarily phonon broadened, so the assumption of homogeneity is met. However, when a Nd:YAG laser is contructed with a standing-wave linear resonator, the threshold of the second axial mode is near that of the first. At the nulls of the standing wave created by the initial axial mode, stimulated emission does not take place, and the gain is not saturated. This spatially modulated gain, termed spatial hole burning, allows other axial modes to reach threshold and oscillate.[2]

A unidirectional ring resonator has no standing wave, and therefore spatial hole burning is eliminated. Much higher single-mode power is available from a ring than from a linear resonator even without the addition of selective loss elements, such as étalons. Successful high-power, single-mode operation of unidirectional rings has been achieved with arc-lamp-pumped Nd:YAG oscillators[3] and with commercial dye lasers.[4]

Excellent frequency stability is possible when the resonator of a Nd:YAG laser is monolithic, that is, when it consists of reflective coatings applied directly to the surfaces of the Nd:YAG. Even better stability is possible when the pump source of the laser is a laser diode with stable output power. We recently reported a laser-diode-pumped Nd:YAG rod laser that has a frequency jitter in 0.3 sec of less than 10 kHz.[5] Because of spatial hole burning, output power in a single axial mode has been limited to 8 mW.

The objective of this work is to combine the advantages of ring lasers and monolithic lasers by constructing a unidirectional resonator entirely internal to a single crystal of Nd:YAG. The conventional way to design a unidirectional laser is to include a polarizer, a Faraday rotator, and a nonmagnetic polarization rotator, such as a half-wave plate in the resonator. All three of these functions, which together form an optical diode,[6] are incorporated into the MISER resonator design. As is shown in Fig. 1, the resonator is a single block of Nd:YAG incorporating four reflecting surfaces, which act as mirrors. The front face is convex to provide resonator stability and is coated to be a partially transmitting output coupler. The other three faces are flat and totally internally reflecting.

Most ring lasers use a resonator that is entirely within a plane. There are sometimes advantages to a nonplanar geometry that are worth the greater complexity. Dorschne at Raytheon has described a nonplanar helium–neon ring laser that, when used as a gyroscope, overcomes the problem of self-locking or lock-in.[7] Researchers in the Soviet Union have built nonplanar Nd:YAG ring lasers and have studied the mode structure, temporal dynamics, and polarization of these lasers.[8] Biraben[9] suggested that single-mode dye lasers

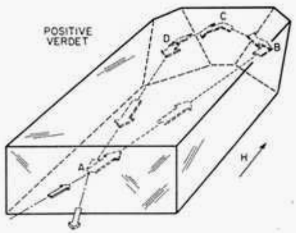
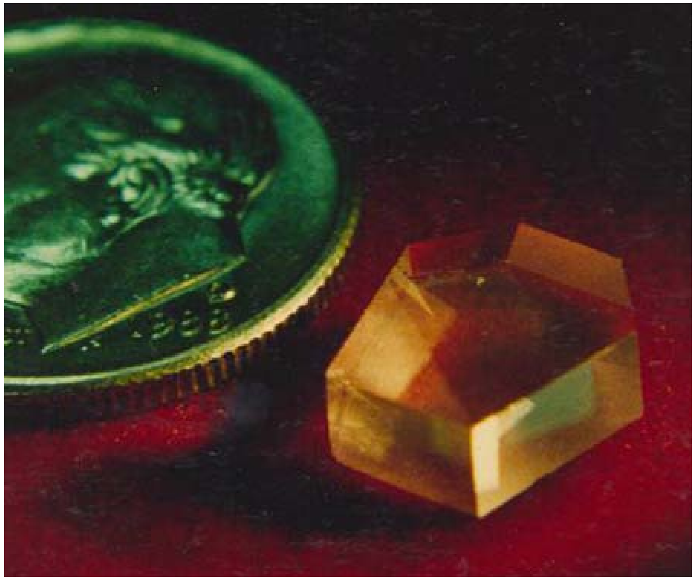


Fig. 1. The MISER laser design. Polarization selection takes place at the curved, partially transmitting face (point A). At points B, C, and D, total internal reflection occurs. A magnetic field H is applied to establish unidirectional oscillation. Magnetic rotation takes place along segments AB and DA. The focused pump laser beam enters the crystal at point A, and the output beam emerges at the same point.

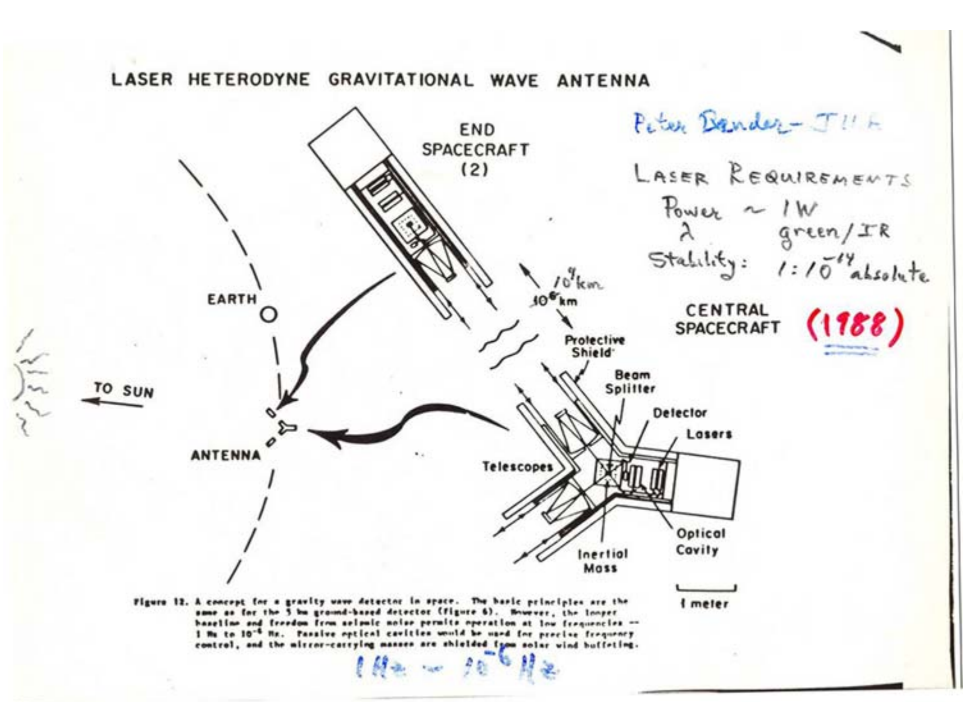
0146-9592/85/020065-03$2.00

Tom Kane, R. L. Byer
"Monolithic, unidirectional
Single-mode Nd:YAG ring laser"
Opt. Lett. 10,65,1985

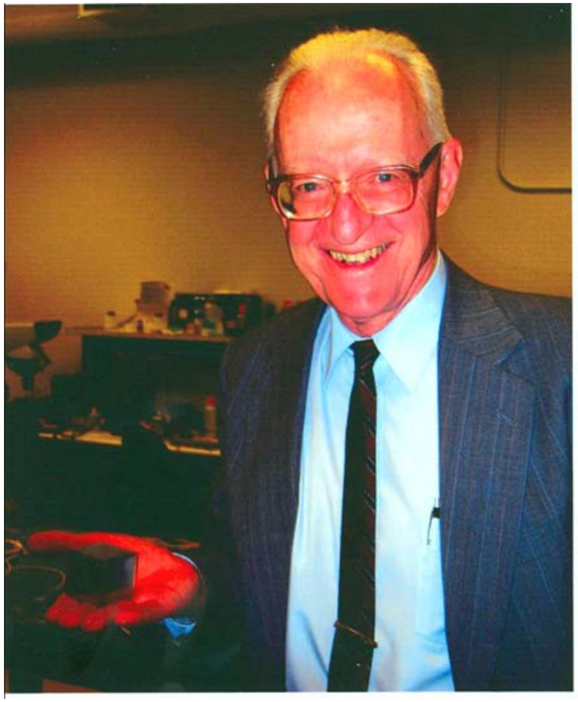


NonPlanar Ring Oscillator
Single frequency: <10kHz

LISA Concept – Peter Bender JILA 1988

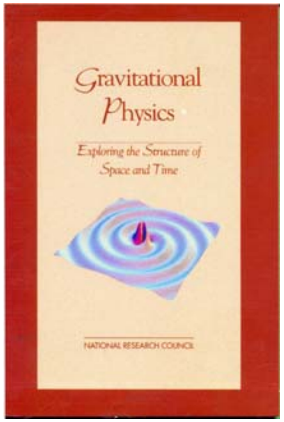


Schematic of LISA in 1988



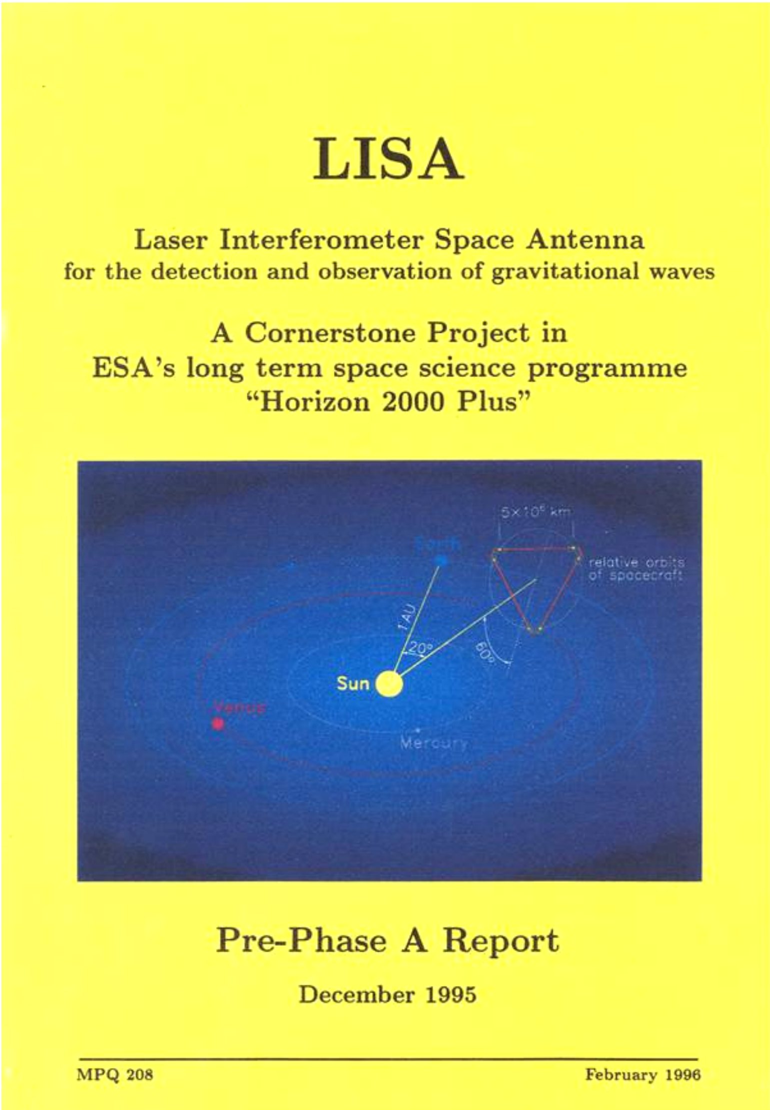
Peter Bender holding 4x4cm Au/Pt cube

Expected Launch date of 1998 (now 2020)
- Laser power 1W
- Laser stability extremely high
- Laser reliability > 5 years



Gravitational waves open a new window on universe

Detect amplitude and phase of gravitational waves with sensitivity to detect back the era of galaxy formation.



LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

A Cornerstone Project in
ESA's long term space science programme
"Horizon 2000 Plus"

Pre-Phase A Report

December 1995

MPQ 208 February 1996

LISA - Laser Interferometer Space Antenna

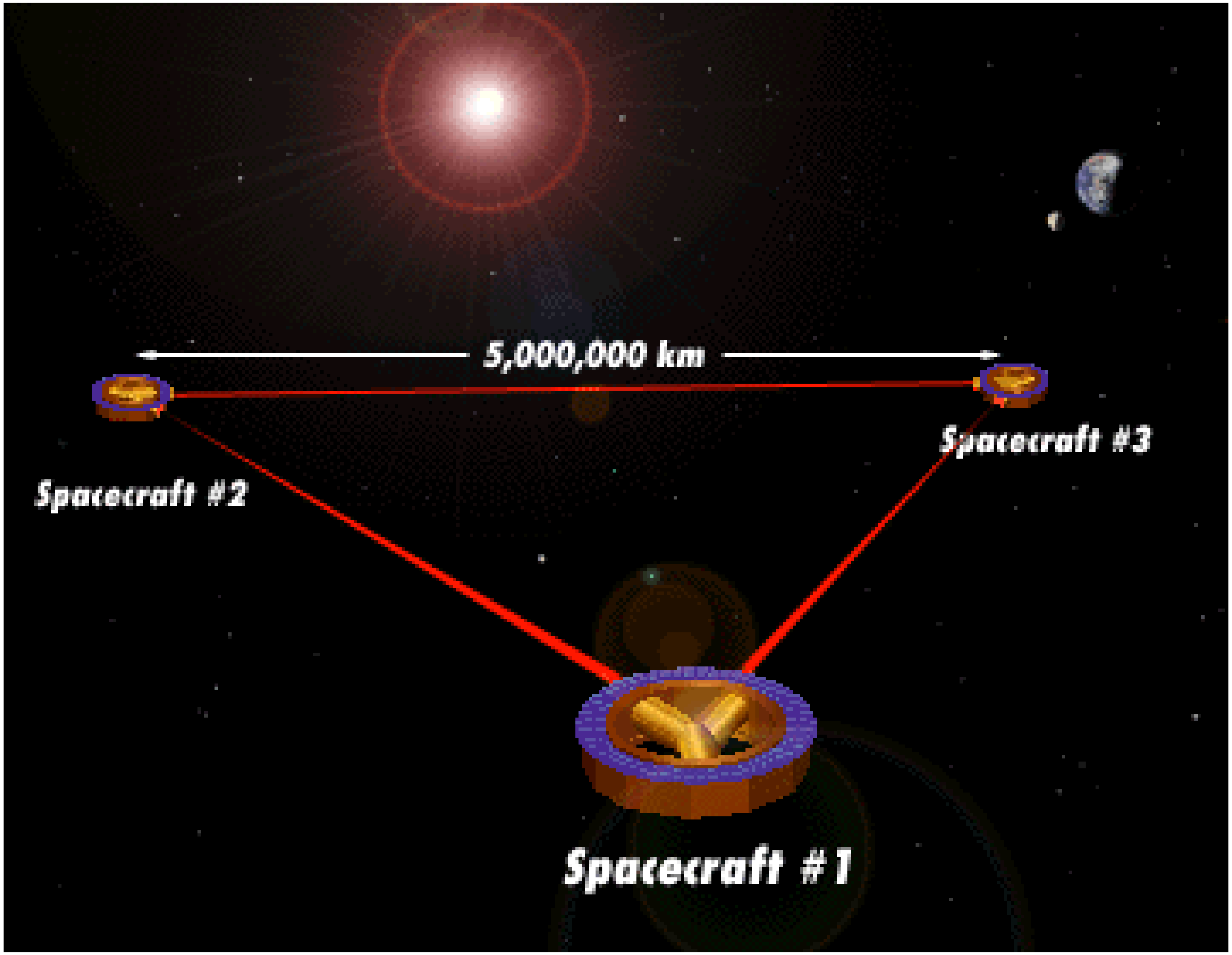
Phase A Study - 1995
Joint mission NASA and ESA

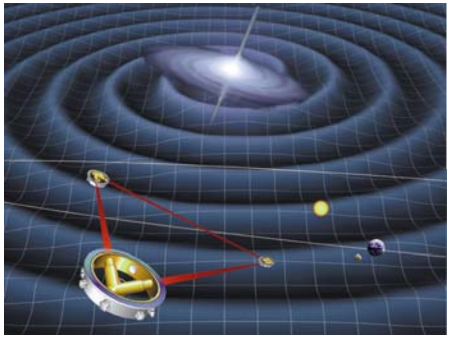
3 satellites in solar orbit
1 W laser - Nd:YAG NPRO
5 million km interferometer path
30 light seconds round trip delay

Scheduled for launch in 2020
1 year to station, 5 year mission

Will detect binaries in our galaxy
Will detect massive Black Holes at
Cores of most galaxies

LISA Interferometer Space Antenna



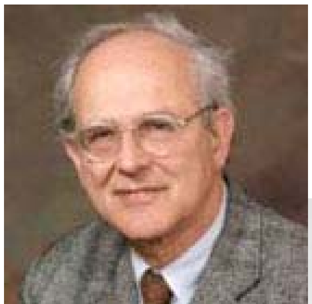


LIGO Interferometer

How to detect gravitational waves

QUARTERLY PROGRESS REPORT
APRIL 15, 1972
No. 105

ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA



Rai Weiss, MIT

Maryland

Ron Drever, Caltech

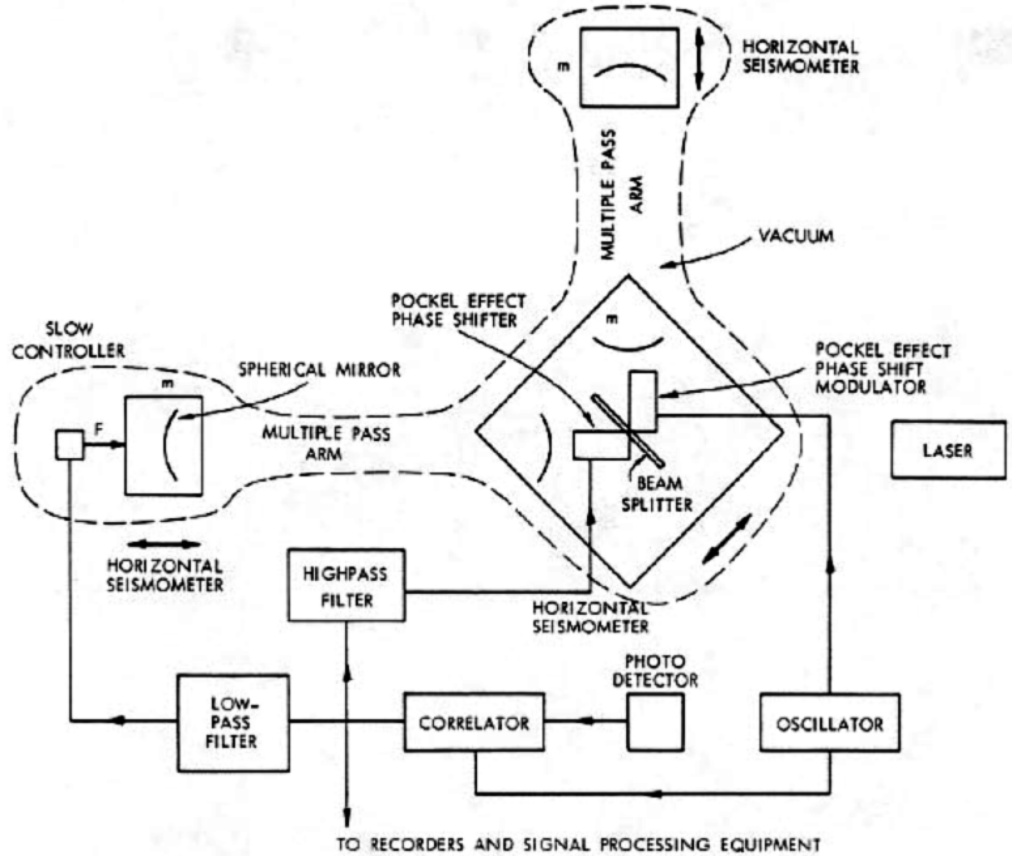
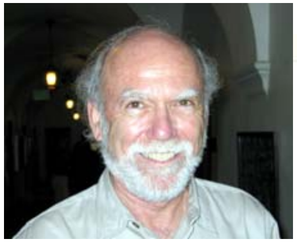


Fig. V-20. Proposed antenna.

LIGO Observatory Sites



Barry Barish*

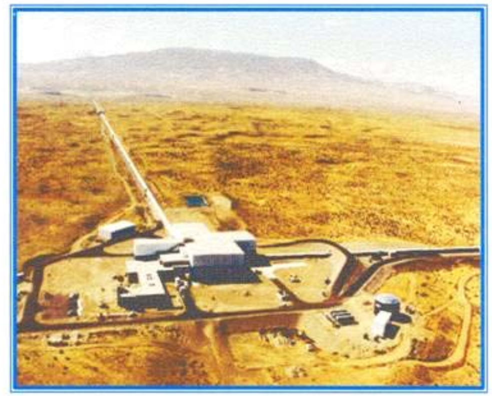
LIGO Sites

* Jay Marx joined LIGO as Director – Jan 2006

LIGO-G9900XX-00-M NSF LIGO II Review 5

Rai Weiss
MIT

LIGO
sites



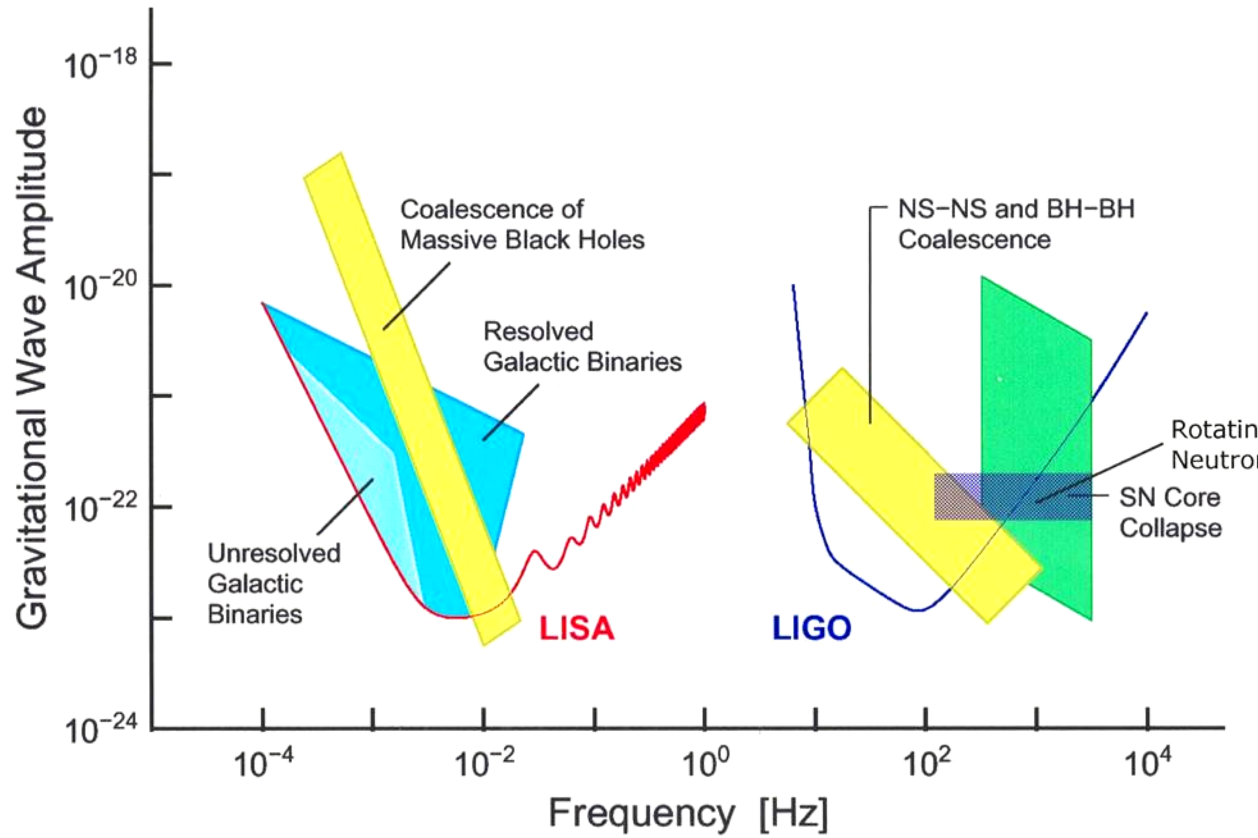
- Hanford Observatory

- Livingston Observatory

LIGO-G9900XX-00-M NSF LIGO II Review 12

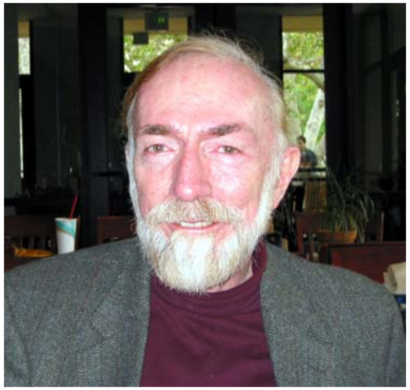
LISA and LIGO Detection Bands

(LISA) Space-& (LIGO) Ground-Based Detectors



(LISA Science & Technology Study)

ISA 40

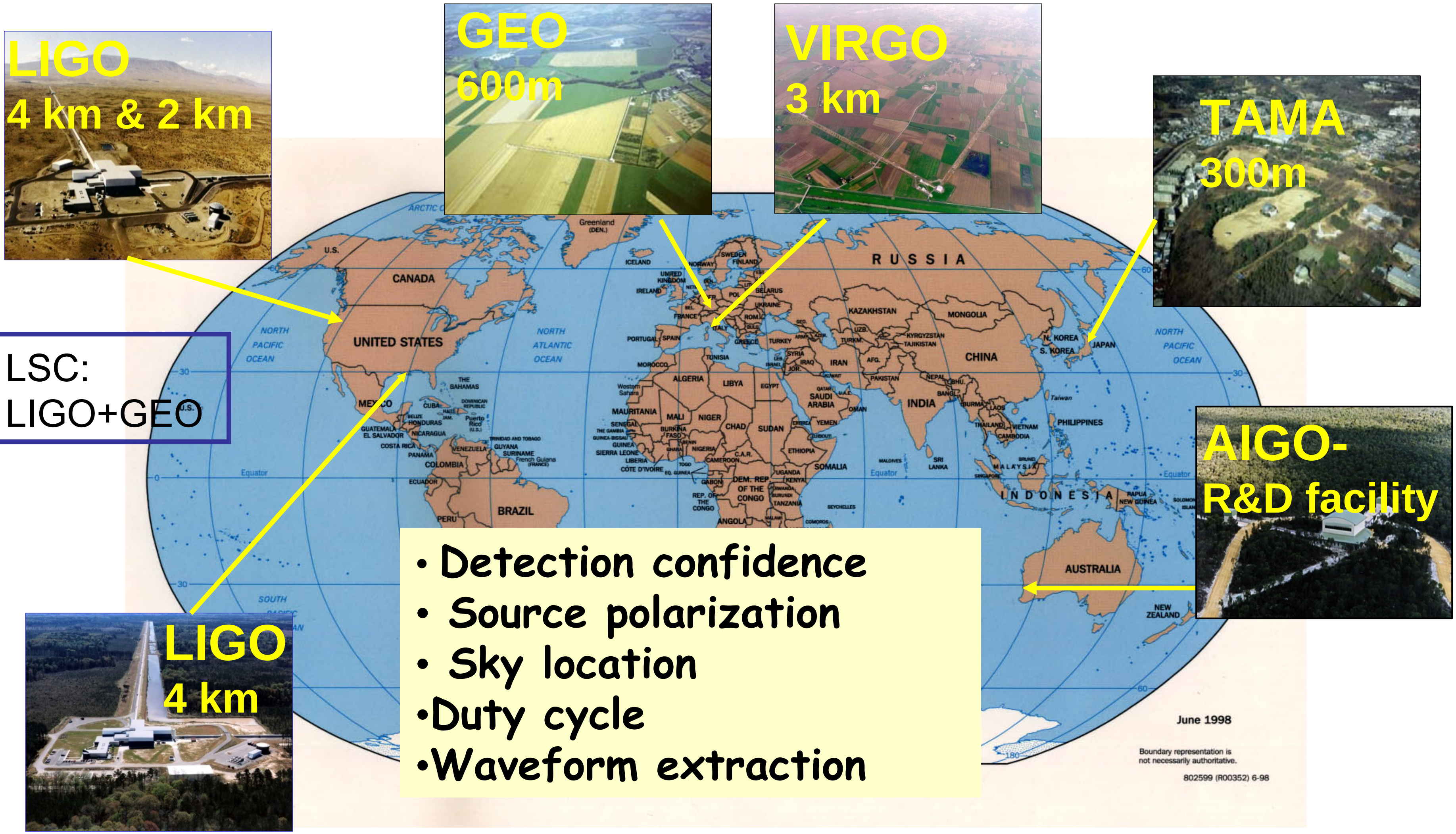


Kip Thorne,
CalTech

Laser Interferometer Gravitational-wave Observatory

- Managed and operated by Caltech & MIT with funding from NSF
- Ground breaking 1995
- 1st interferometer lock 2000
- design sensitivity 2005
- LIGO Scientific collaboration: 45 institutions, world-wide

Global network of interferometers



- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Waveform extraction

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Stuart Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

One thing leads to another…
from Lasers to LIGO to LISA…

Prelude: California – a leader in science and technology

LIGO & LISA: Early History and Concepts
- LIGO and LISA at the beginning
- **Gravitational Waves and Sources**

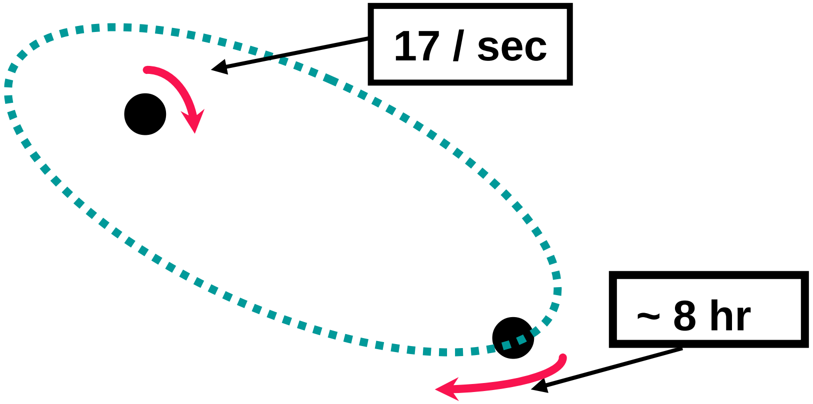
The LIGO Observatory
- LIGO Interferometers
  - Measurements
  - Technical progress
  - Science Runs - LIGO begins Science Run #6
- Advanced LIGO Interferometer
  - Sensitivity Improvement
  - Detection rates
  - Schedule for completion

Future concepts
- LISA an Interferometer in Space
- LISA performance & technology development

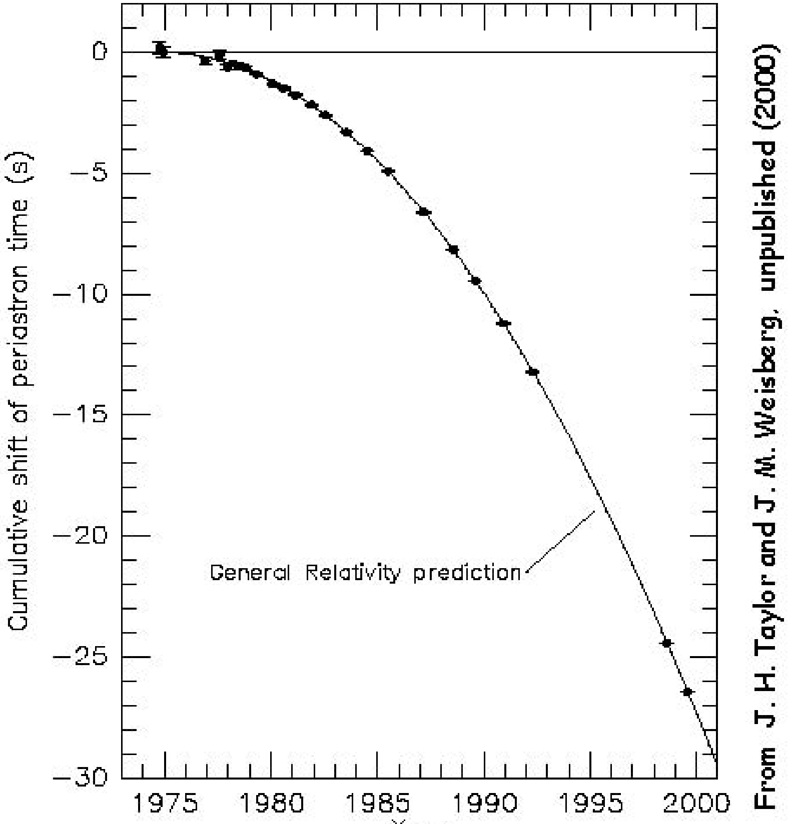
Existence proof: PSR 1913+16

Joseph Taylor

Russell Hulse



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



- What are GW?
  - waves in curvature of space-time
  - a prediction of general relativity
  - produced by acceleration of mass

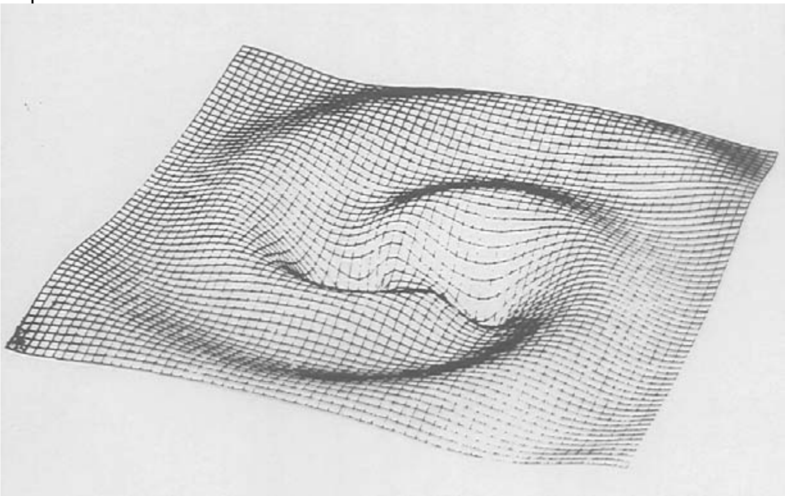
    (c.f. EM waves produced by accelerated charge)
  - travel at speed of light

BUT

  - gravitational interactions are very weak
  - no dipole radiation (due to conservation of momentum and mass of only one "sign")

To produce significant flux requires asymmetric accelerations of large masses

→ Astrophysical Sources



Gravitational Waves

In the weak field approximation gravitational waves can be represented as a perturbation to the Minkowski flat space-time

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$g_{\mu\nu}$ *Minkowski space perturbed by gravitational waves*
$\eta_{\mu\nu}$ *Minkowski space*
$h_{\mu\nu}$ *gravitational waves perturbation*

Using the transverse traceless gauge the field equation for $h_{\mu\nu}$ is:

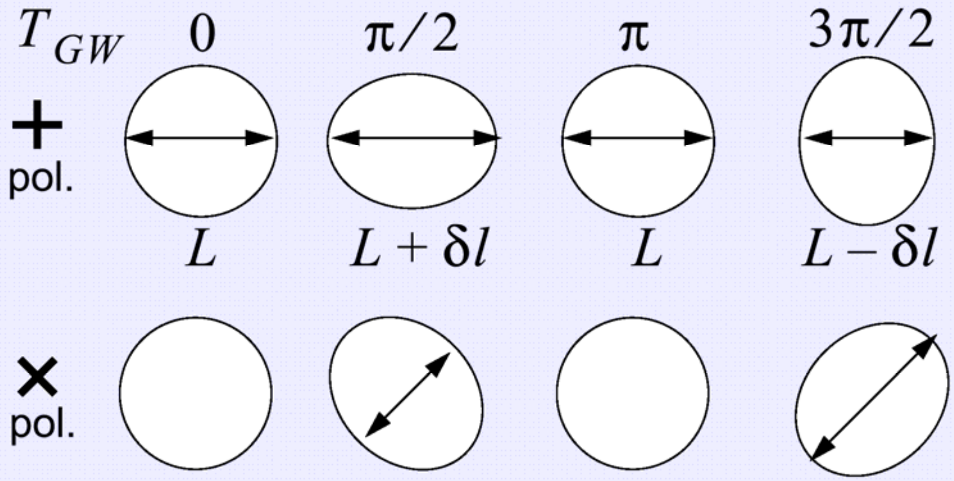
$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial^2 t^2}\right) h_{\mu\nu} = \frac{G}{c^4} S$$

S *Energy densities and stresses*

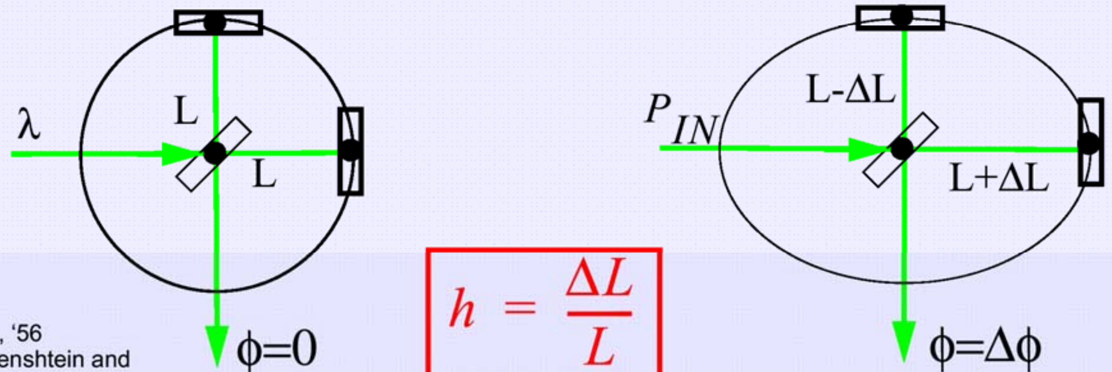
In **GR** $h_{\mu\nu}$ results in two plane waves with polarizations at 45°

$$h_{\mu\nu} = a\hat{h}_+\left(t - \frac{z}{c}\right) + b\hat{h}_\times\left(t - \frac{z}{c}\right)$$

❑ Two polarizations of GWs



❑ Laser interferometer



Pirani, '56
Gertsenshtein and Pustovoit, '62
Weiss, '72
Forward, '72

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

$$P_{OUT} = P_{IN} \cos^2(2k\Delta L)$$

How Precise must LIGO/LISA be? (Answer: Very, very Precise!!!!)

1 part in 10^{21} strain

10^{21}= 1,000,000,000,000,000,000,000

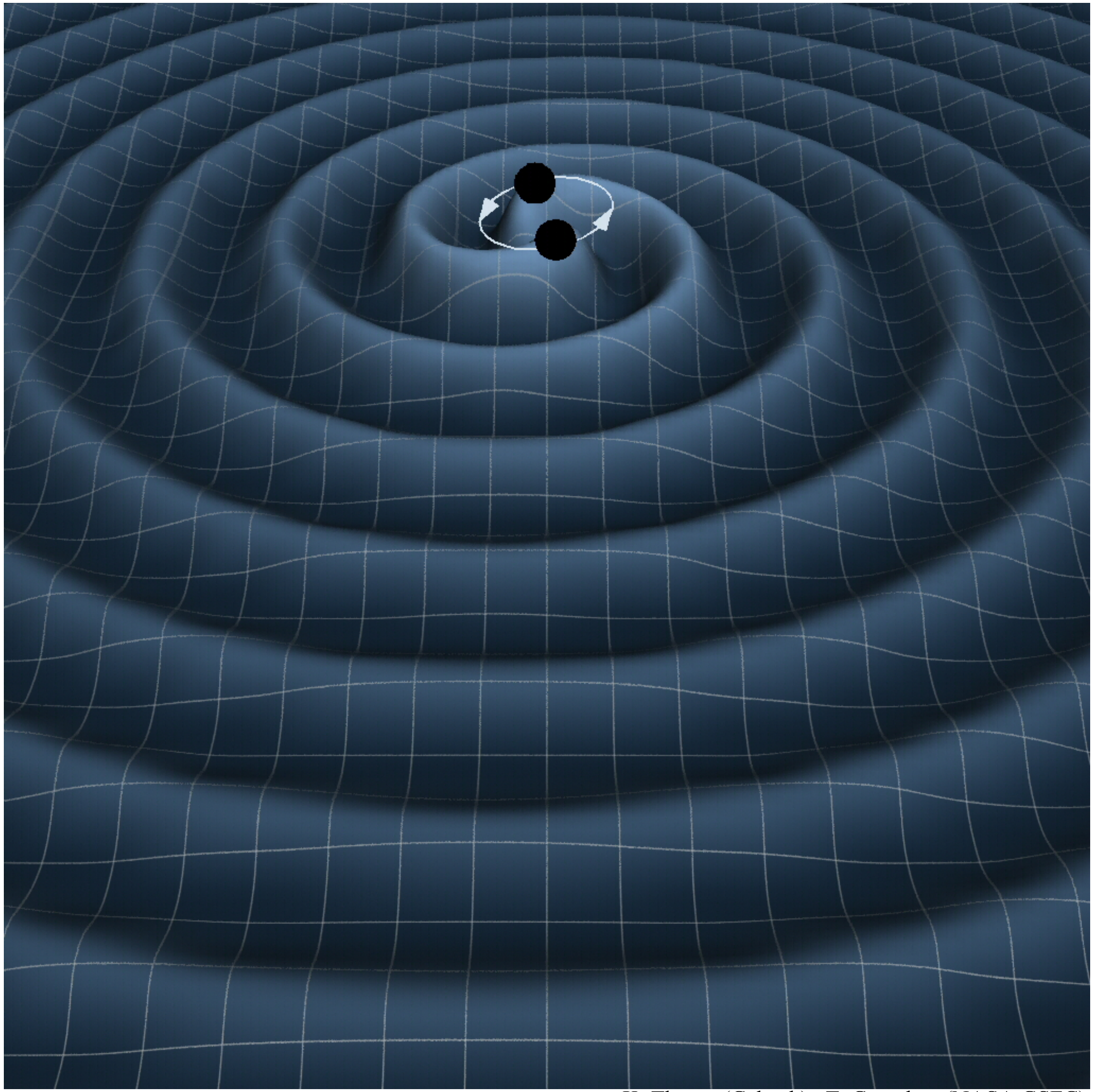
Alpha Centauri: 4.4 light years = 4 x 10^{16} meters

Alpha Centauri
(one of the nearest stars)

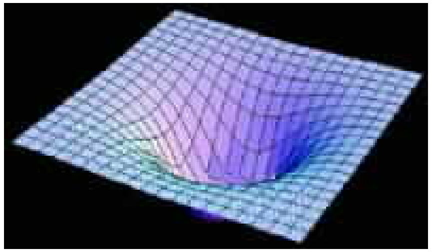
Strain sensitivity analogous to
10^{-21} x 4 x 10^{16} m = 4 x 10^{-5} m ~ 40 microns!

Like measuring the distance to a nearby star to the diameter of a human hair !
(~100 microns)

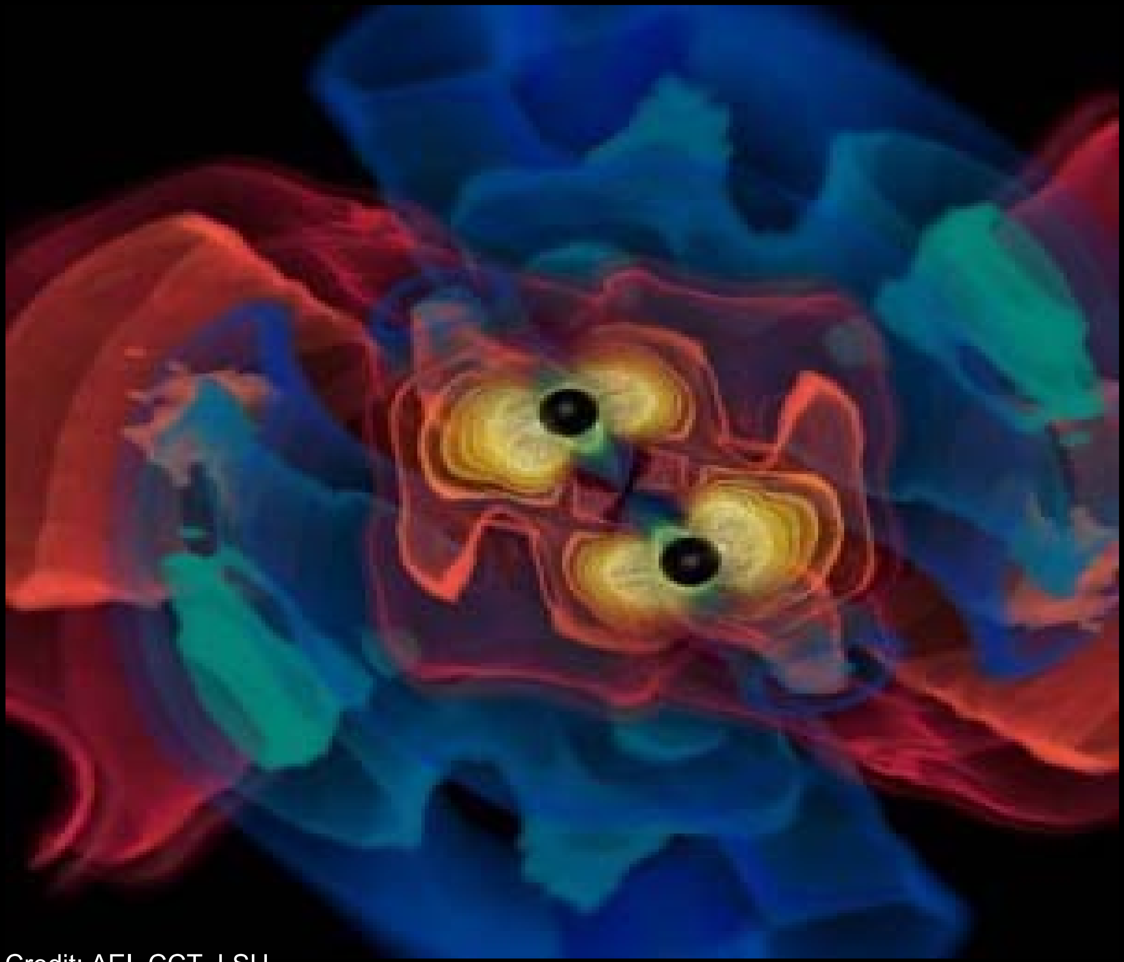
Watching Two Black Holes Merge



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

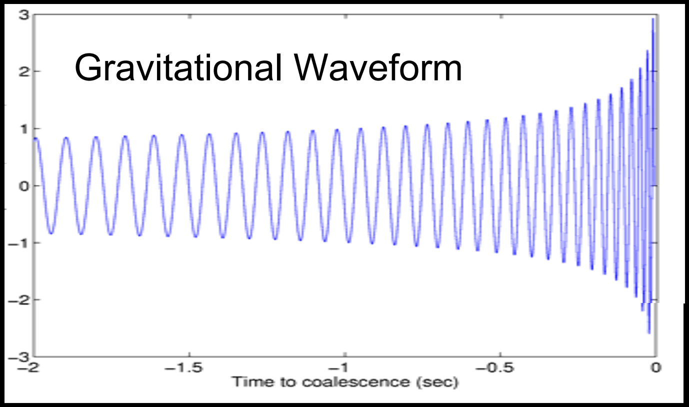


The astrophysical gravitational wave source catalog



Credit: AEI, CCT, LSU

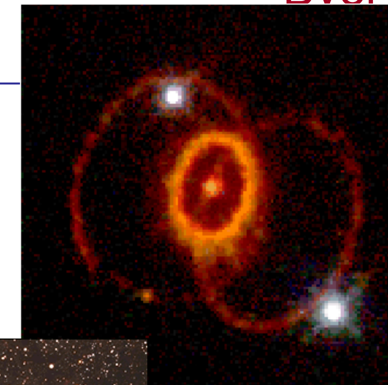
- Neutron stars, black holes
- ‘chirped’ waveform



http://www.ligo.org/science/GW-Overview/sounds/chirp40-1300Hz.wav

Gravitational Wave Sources

- ***Bursts***
  - catastrophic stellar collapse to form black holes or neutron stars
  - final inspiral and coalescence of neutron star or black hole binary systems – possibly associated with gamma ray bursts
- ***Continuous***
  - pulsars (e.g. Crab)
  (sign up for Einstein@home)
  - low mass X-ray binaries Sco-X1)
- ***Stochastic Background***
  - random background "noise" associated with cosmological processes, e.g. inflation, cosmic strings…..



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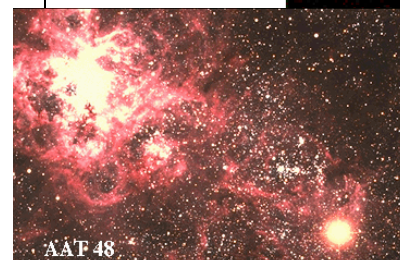
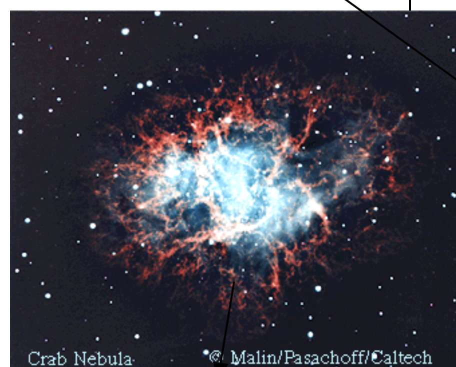
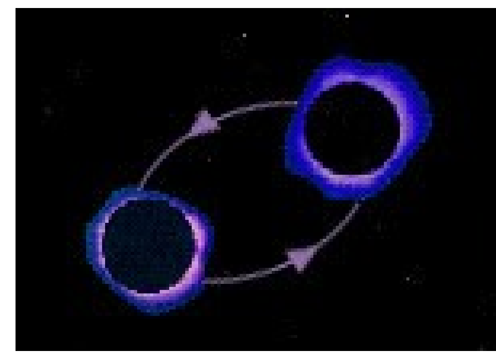




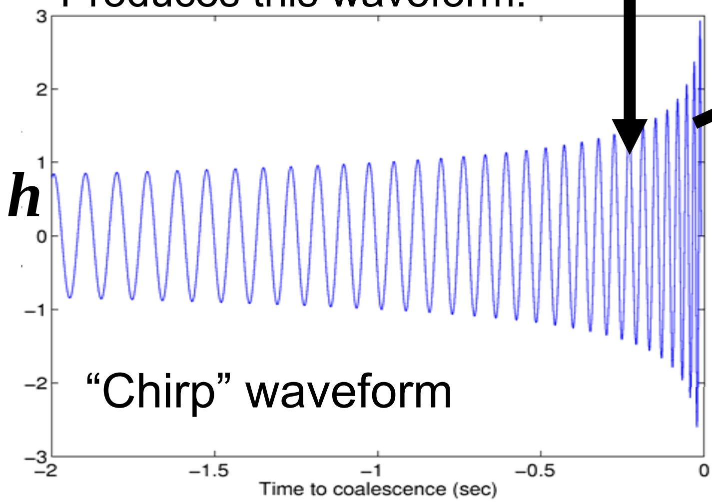


A New Astronomy

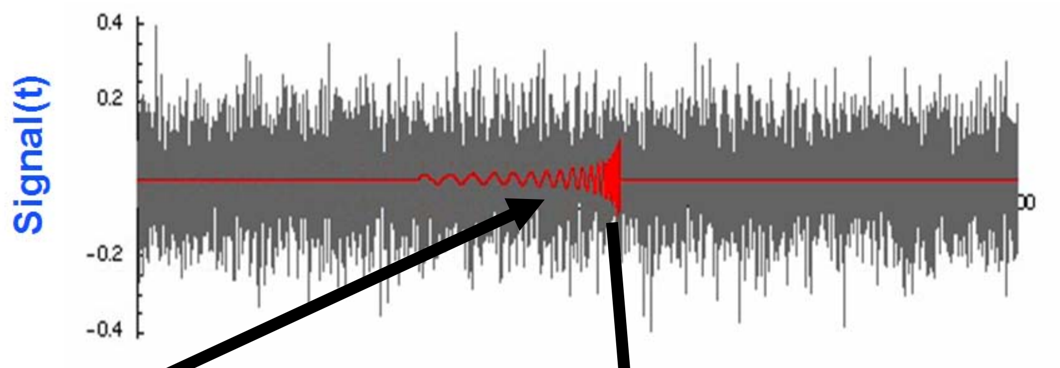
The challenge of LIGO data analysis

This source:

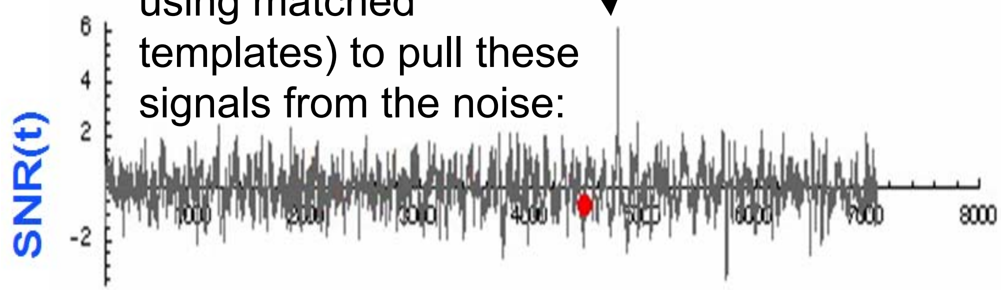
Produces this waveform:



Embedded in this noise stream:



We use different methods (in this case optimal Weiner filtering using matched templates) to pull these signals from the noise:



The problem is that non-astrophysical sources also produces signals (false positives)

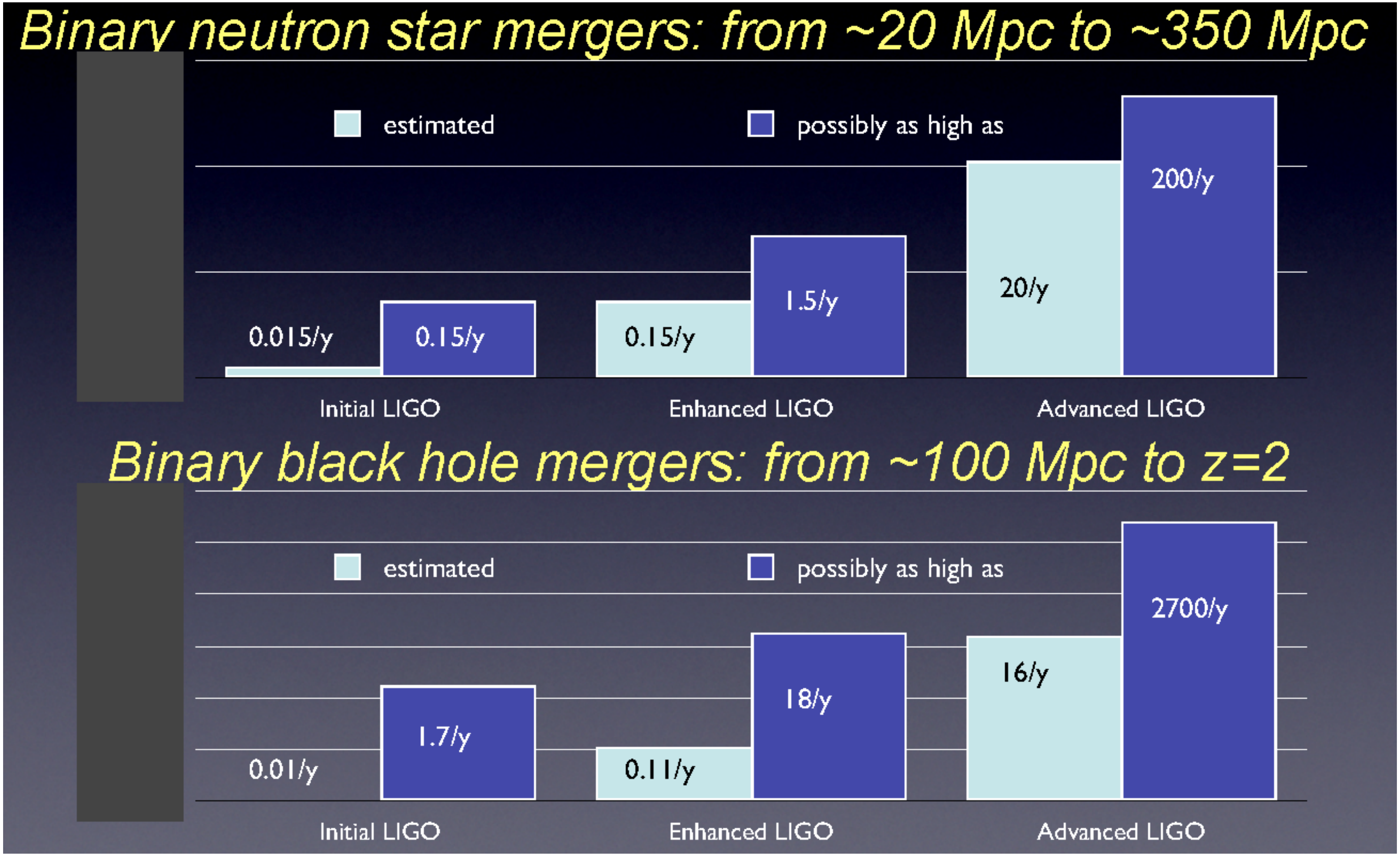
Has LIGO detected a gravitational wave yet?

- No, not yet.
- When will LIGO detect a gravitational wave?
- "Predictions are difficult, especially about the future"
  - » (Yogi Berra)

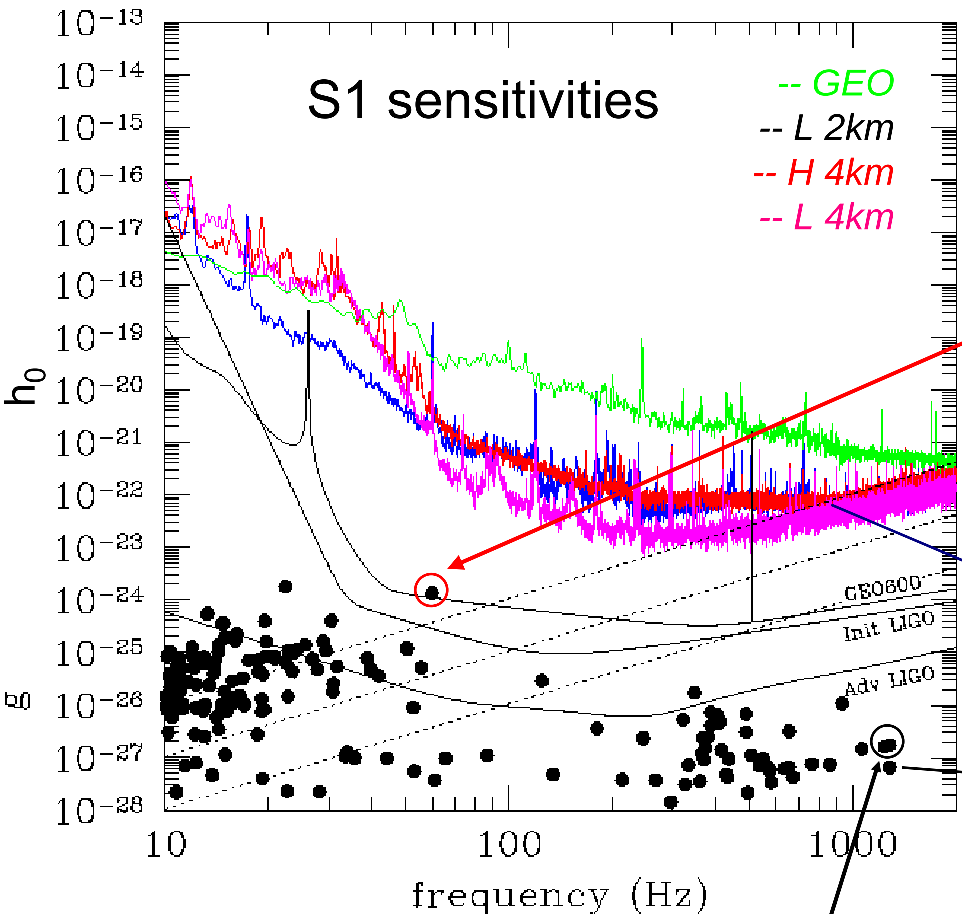
TABLE V: Detection rates for compact binary coalescence sources.

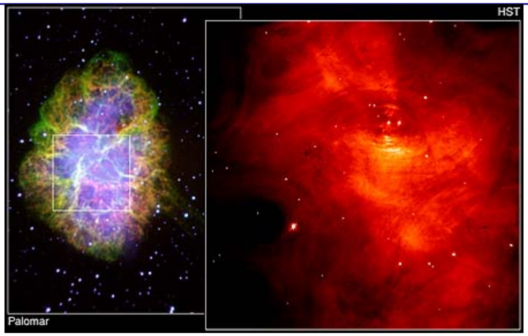
IFO	Source	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm pl}$ yr^{-1}	$\dot{N}_{\rm up}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

Prospective rates for binary mergers



Periodic sources





- 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, $\varepsilon = \delta I/I_{zz}$:*

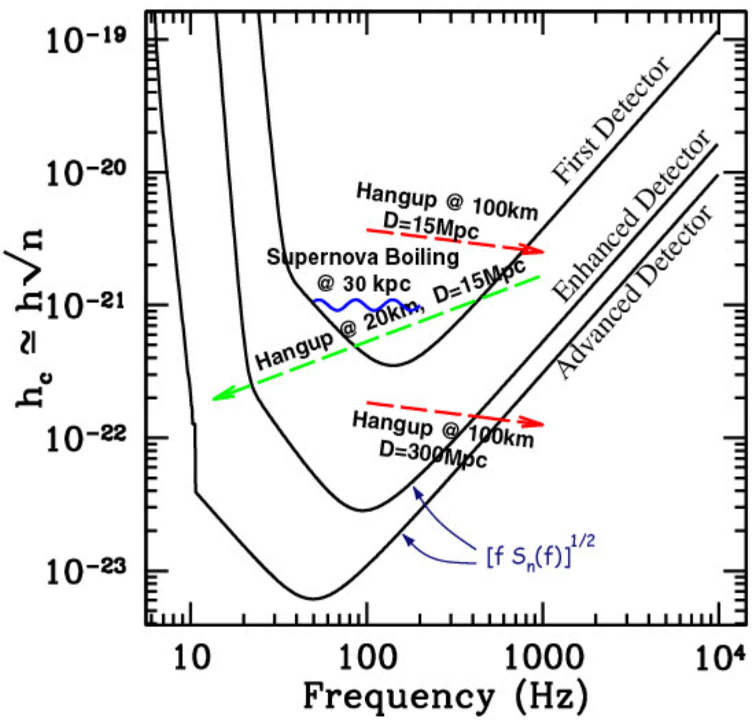
  10^{-3} , 10^{-4} , 10^{-5} @ 10 kpc

- ***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*

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

Burst sources

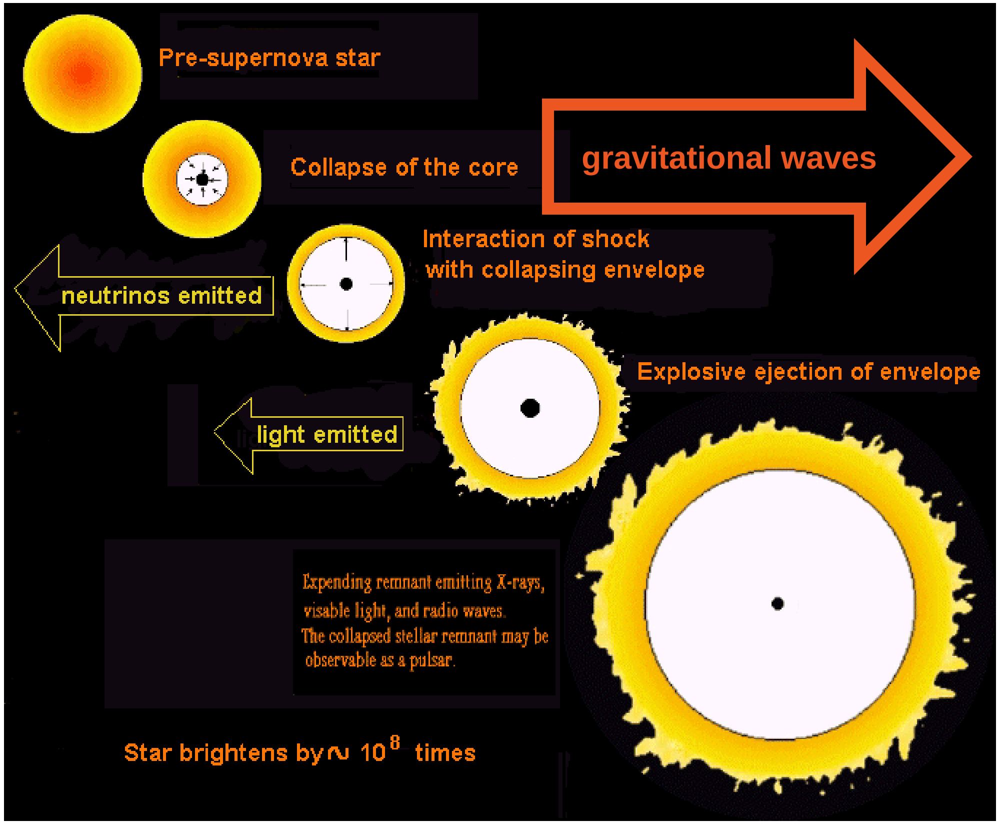
Sensitivity of LIGO to burst sources



Expected SNe Rate

1/50 yr - our galaxy

3/yr - Virgo cluster



Outline

Prelude: California – a leader in science and technology

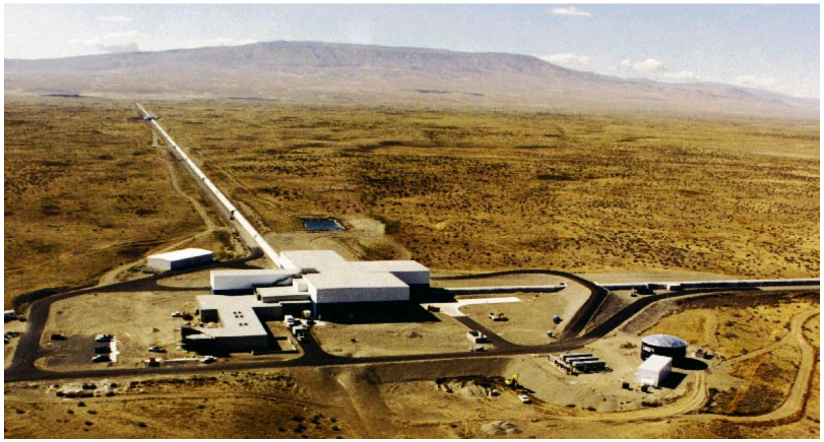
LIGO & LISA: Early History and Concepts
- LIGO and LISA at the beginning
- Gravitational Waves and Sources

The LIGO Observatory
- LIGO Interferometers
  - Measurements
  - Technical progress
  - Science Runs - LIGO begins Science Run #6
- Advanced LIGO Interferometer
  - Sensitivity Improvement
  - Detection rates
  - Schedule for completion

Future concepts
- LISA an Interferometer in Space
- LISA performance & technology development

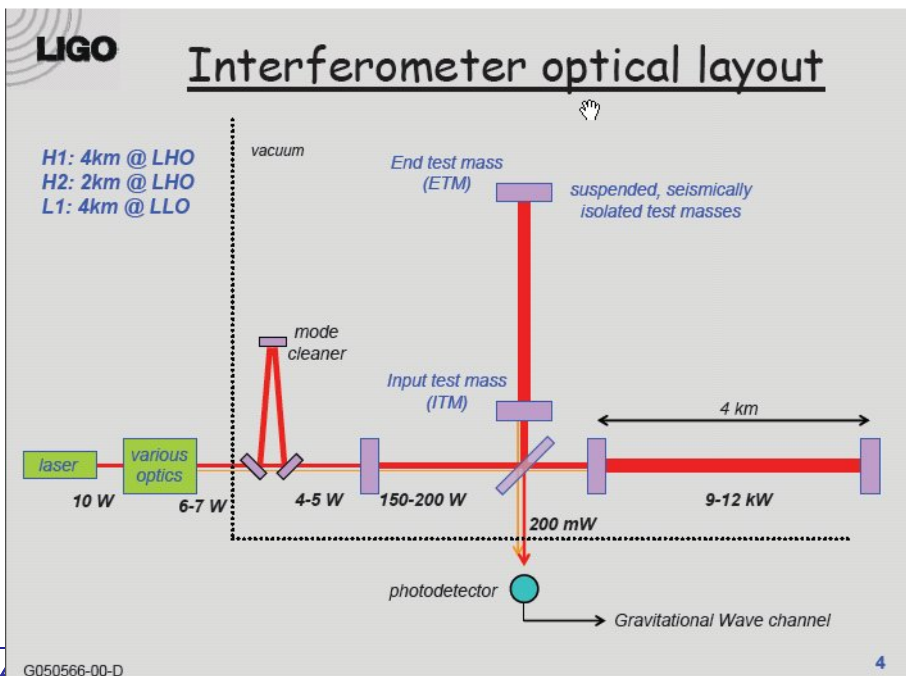
LIGO Observatories

Byer Group



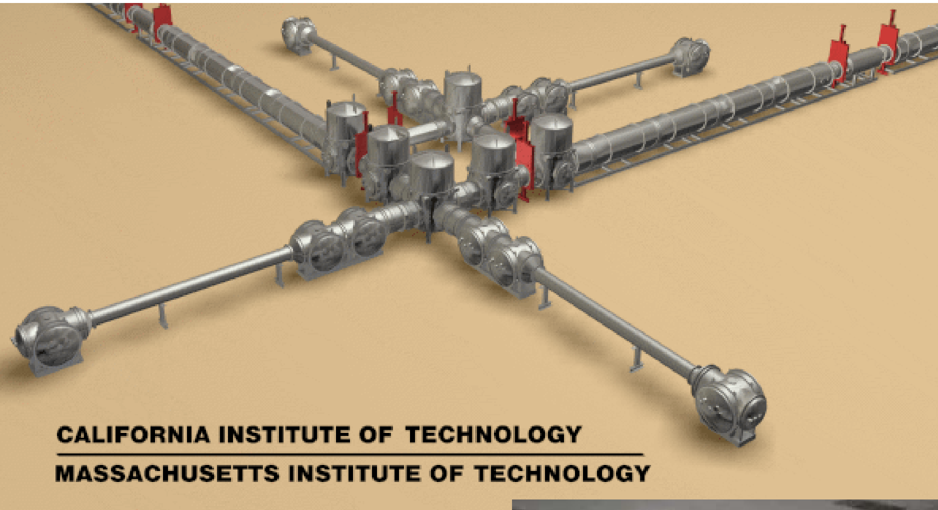
LIGO Hanford Observatory, WA

LIGO Livingston Observatory, LA



LIGO = **L**aser **I**nterferometer **G**ravitational Wave **O**bservatory

LIGO Vacuum Equipment

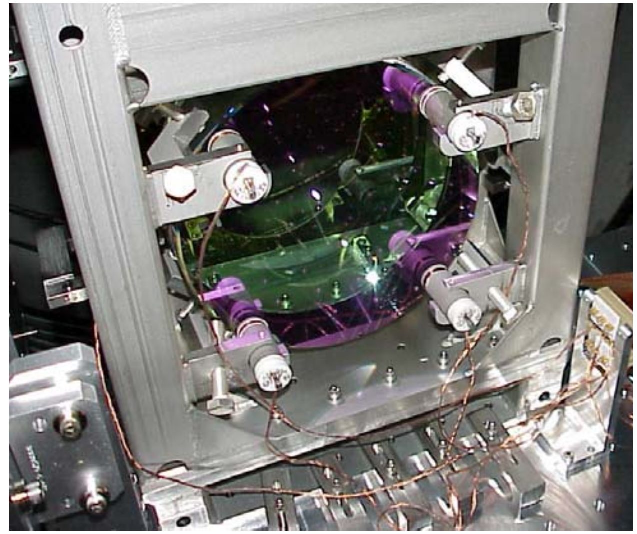


- 1.2 m diameter
- Aligned to a mm
- Total of 16km fabricated with no leaks
- 1 nTorr (!)
- few, remote pumps
- Cover…

Vacuum tube enclosures test

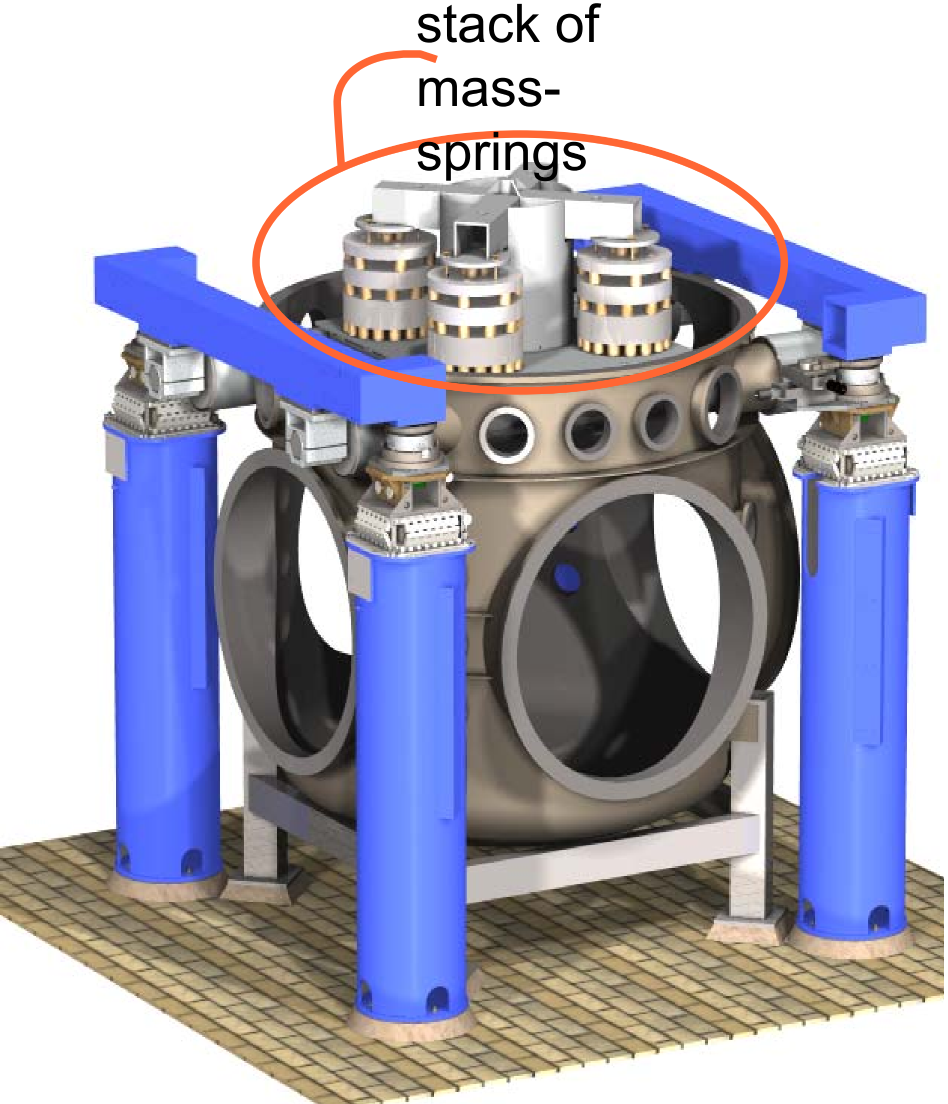
Test Masses

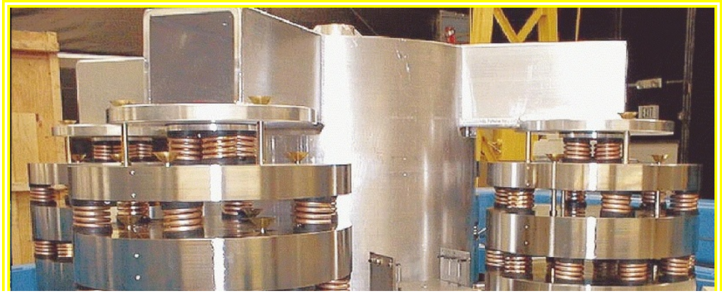
Byer Group

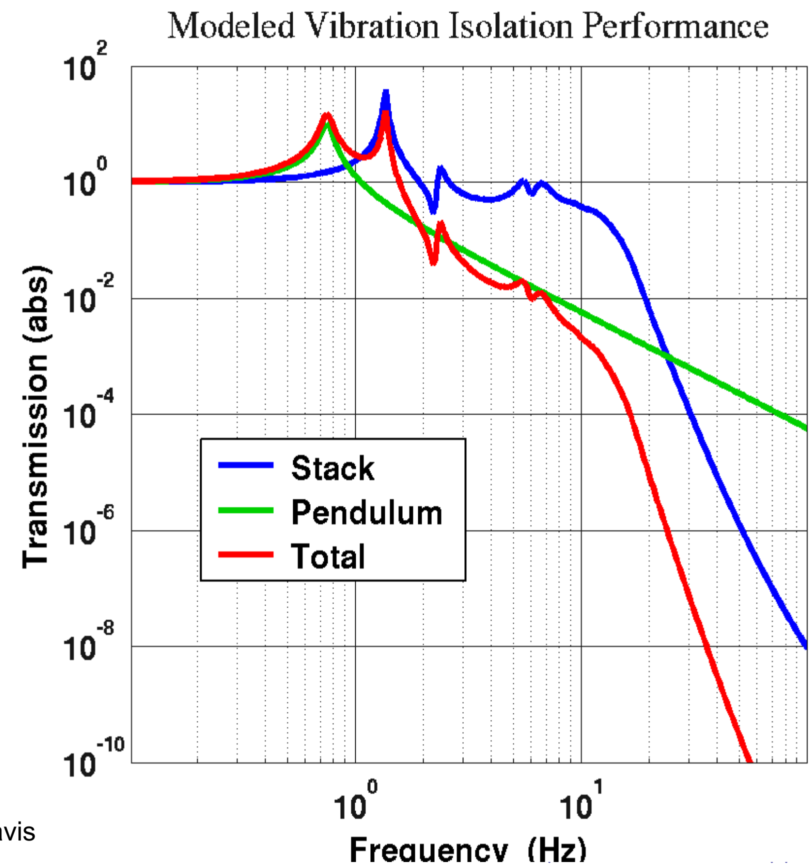


Fused Silica, 10 kg, 25 cm diameter
and 10 cm thick
Polished to λ/1000 (1 nm)

Seismic Isolation – Dan Debra and Brian Lantz



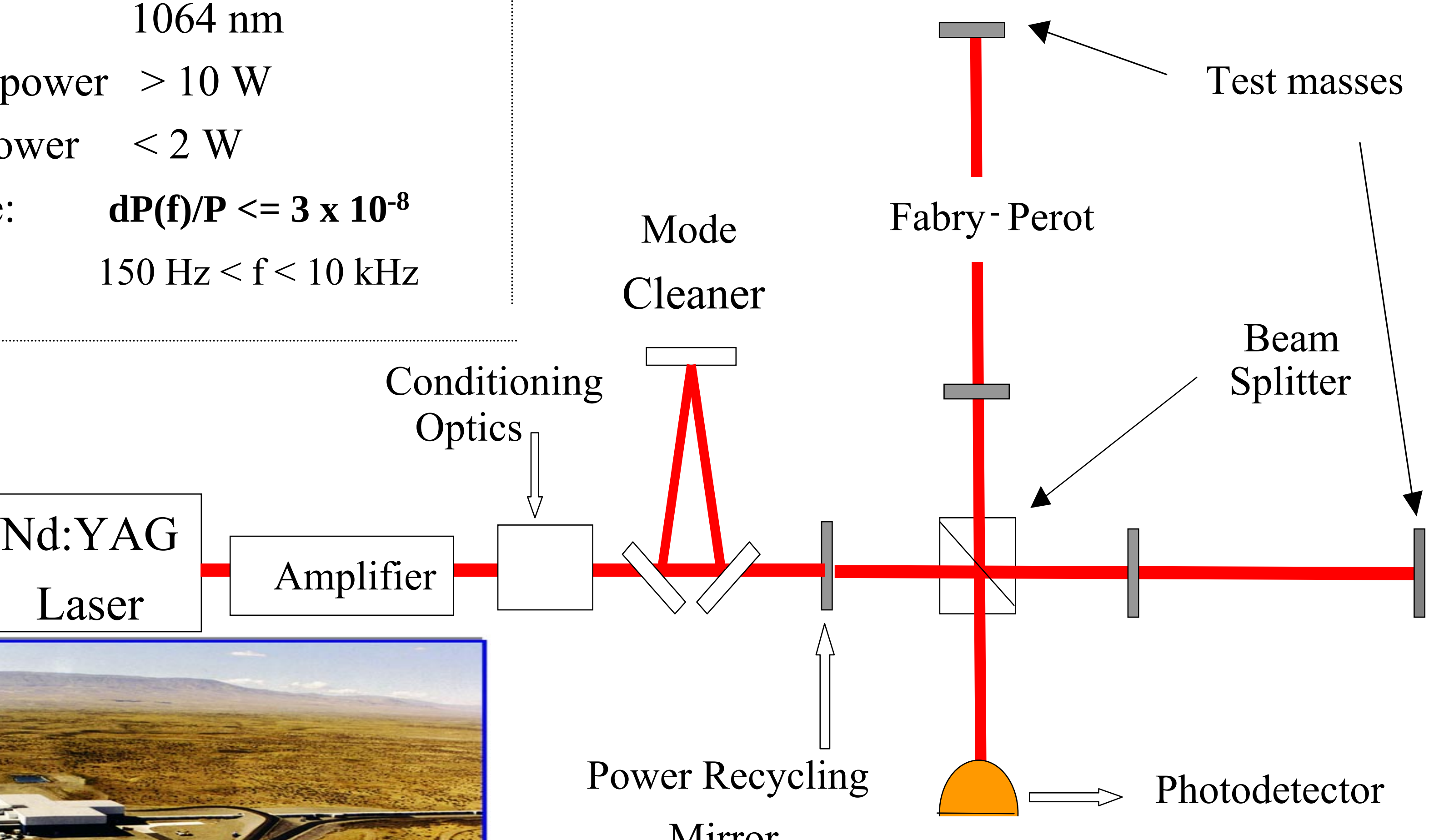




Lasers for the LIGO interferometer

Laser Characteristics

Wavelength	1064 nm
TEM_{00} output power	> 10 W
Non-TEM_{00} power	< 2 W
Intensity noise:	**$dP(f)/P <= 3 \times 10^{-8}$**
	150 Hz < f < 10 kHz



Strain sensitivity ~ 10^{-22}

1984

Reprinted from Optics Letters, Vol. 10, page 65, January 1985

Δν < 10kHz

Monolithic, unidirectional single-mode Nd:YAG ring laser

Thomas J. Kane and Robert L. Byer

Ginzton Laboratoory, Stanford University, Stanford, California 94305

Receieved October 1, 1984; accepted November 26, 1984

We have built a nonplanar ring oscillator with the resonator contained entirely within a Nd:YAG crystal. When the oscillator was placed in a magnetic field, unidirectional oscillation was obtained with a pump-limited, single-axial-mode output of 163 mW.

In this Letter, we describe a new solid-state laser design that achieves high single-mode output power by using a unidirectional nonplanar resonator. Excellent frequency stability is achieved because the ring resonator is constructed from a single Nd:YAG crystal. We refer to the design as a MISER (Monolithic Isolated Single-mode End-pumped Ring) design. We developed this source as an oscillator for a long-range coherent Doppler anemometer.[1] Other applications areas include coherent communications, coherent optical radar, and inertial rotation sensing.

Ideally, a continuous-wave homogeneously broadened laser should oscillate in a single axial mode. The laser transitions in Nd:YAG are primarily phonon broadened, so the assumption of homogeneity is met. However, when a Nd:YAG laser is contructed with a standing-wave linear resonator, the threshold of the second axial mode is near that of the first. At the nulls of the standing wave created by the initial axial mode, stimulated emission does not take place, and the gain is not saturated. This spatially modulated gain, termed spatial hole burning, allows other axial modes to reach threshold and oscillate.[2]

A unidirectional ring resonator has no standing wave, and therefore spatial hole burning is eliminated. Much higher single-mode power is available from a ring than from a linear resonator even without the addition of selective loss elements, such as étalons. Successful high-power, single-mode operation of unidirectional rings has been achieved with arc-lamp-pumped Nd:YAG oscillators[3] and with commercial dye lasers.[4]

Excellent frequency stability is possible when the resonator of a Nd:YAG laser is monolithic, that is, when it consists of reflective coatings applied directly to the surfaces of the Nd:YAG. Even better stability is possible when the pump source of the laser is a laser diode with stable output power. We recently reported a laser-diode-pumped Nd:YAG rod laser that has a frequency jitter in 0.3 sec of less than 10 kHz.[5] Because of spatial hole burning, output power in a single axial mode has been limited to 8 mW.

The objective of this work is to combine the advantages of ring lasers and monolithic lasers by constructing a unidirectional resonator entirely internal to a single crystal of Nd:YAG. The conventional way to design a unidirectional laser is to include a polarizer, a Faraday rotator, and a nonmagnetic polarization rotator, such as a half-wave plate in the resonator. All three of these functions, which together form an optical diode,[6] are incorporated into the MISER resonator design. As is shown in Fig. 1, the resonator is a single block of Nd:YAG incorporating four reflecting surfaces, which act as mirrors. The front face is convex to provide resonator stability and is coated to be a partially transmitting output coupler. The other three faces are flat and totally internally reflecting.

Most ring lasers use a resonator that is entirely within a plane. There are sometimes advantages to a nonplanar geometry that are worth the greater complexity. Dorschne at Raytheon has described a nonplanar helium–neon ring laser that, when used as a gyroscope, overcomes the problem of self-locking or lock-in.[7] Researchers in the Soviet Union have built nonplanar Nd:YAG ring lasers and have studied the mode structure, temporal dynamics, and polarization of these lasers.[8] Biraben[9] suggested that single-mode dye lasers

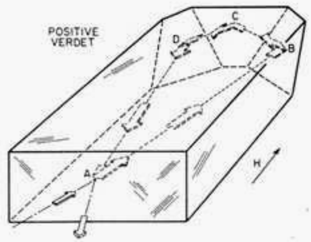


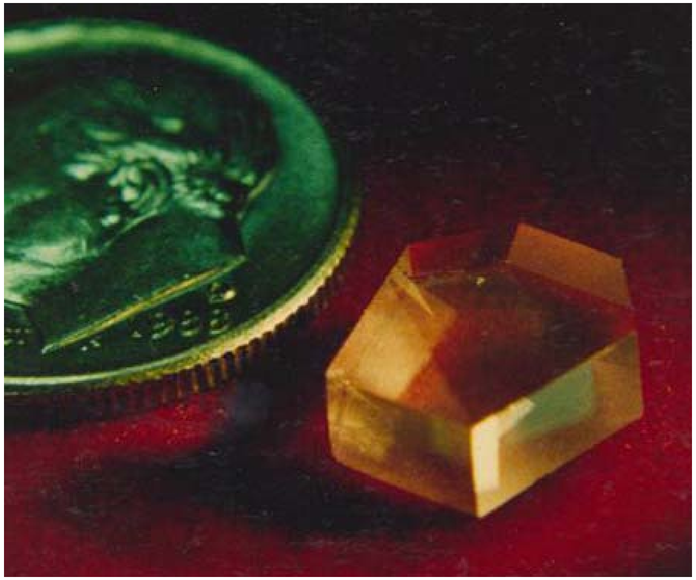
Fig. 1. The MISER laser design. Polarization selection takes place at the curved, partially transmitting face (point A). At points B, C, and D, total internal reflection occurs. A magnetic field H is applied to establish unidirectional oscillation. Magnetic rotation takes place along segments AB and DA. The focused pump laser beam enters the crystal at point A, and the output beam emerges at the same point.

0146-9592/85/020065-03$2.00

Tom Kane, R. L. Byer

"Monolithic, unidirectional Single-mode Nd:YAG ring laser"

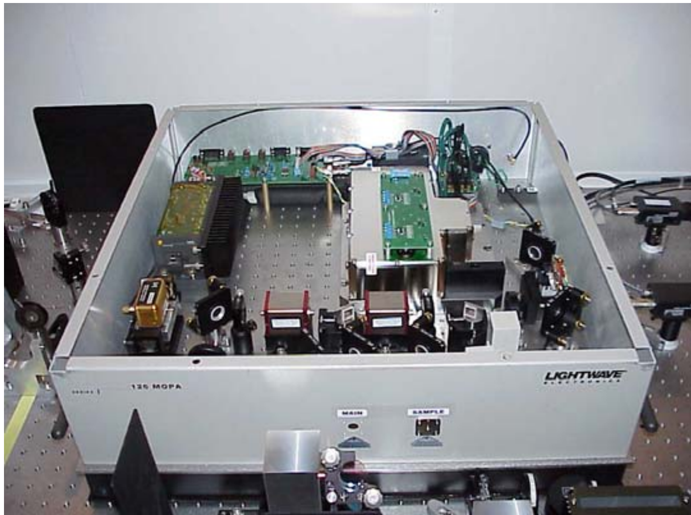
Opt. Lett. 10,65,1985



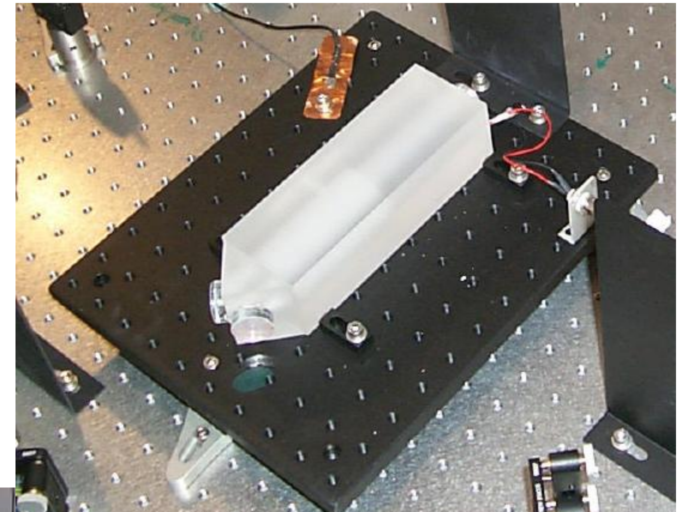
NonPlanar Ring Oscillator

Single frequency: <10kHz

10 Watt All-Solid-State Nd:YAG Laser



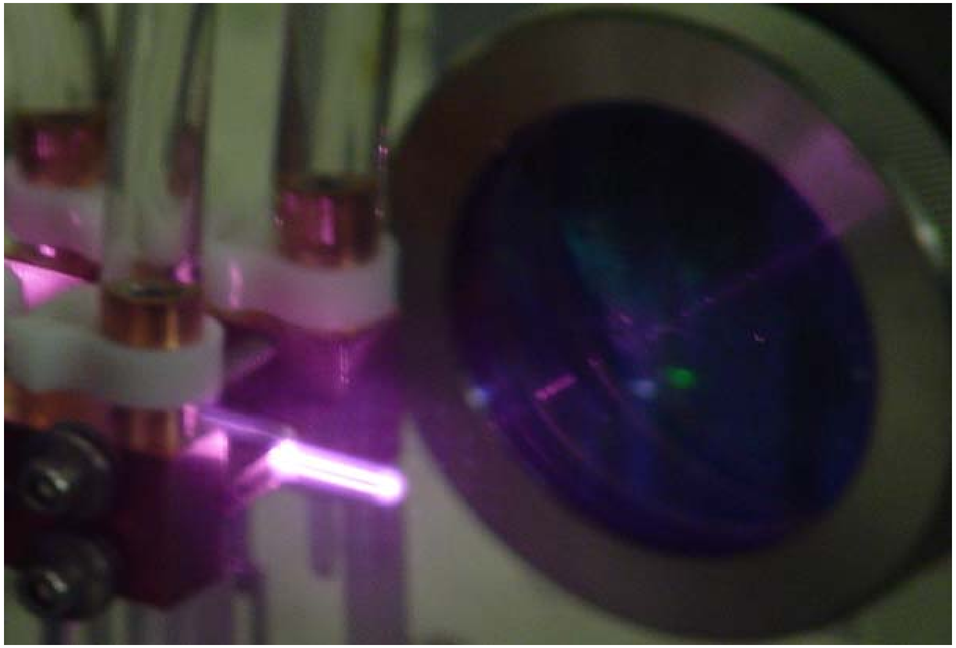
Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics



Cavity for
defining beam geometry,
joint development with
Stanford

Frequency reference
cavity (inside oven)

Quantum Noise Limited End pumped slab Amplifier



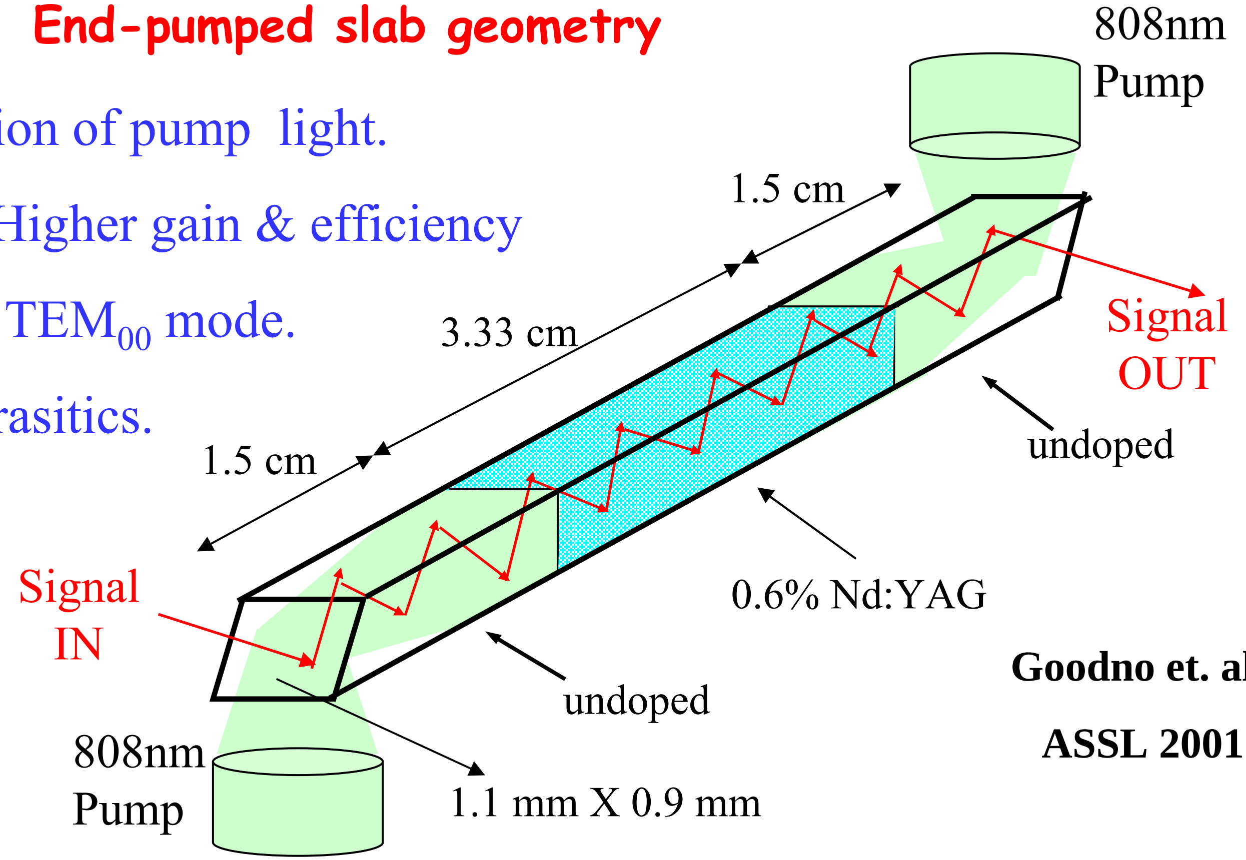
Photograph of end pumped Nd:YAG Slab amplifier

Shally Saraf

Optics Letters May 2005
"Quantum Noise Measurements In a cw laser diode pumped Nd:YAG saturated amplifier"

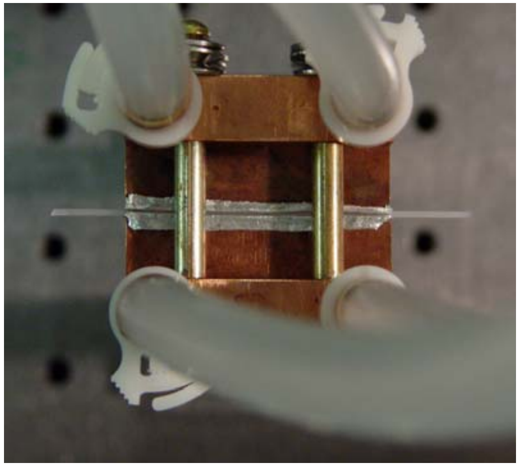
End-pumped slab geometry

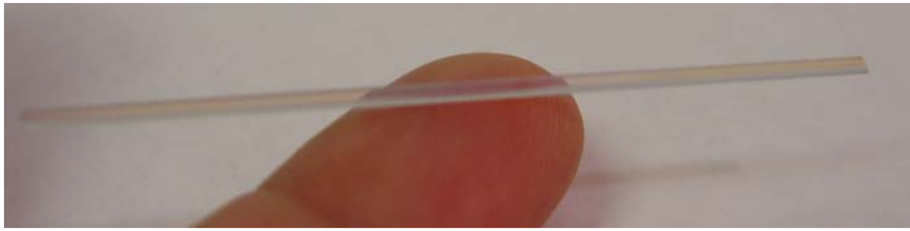
- Nearly complete absorption of pump light.
- Better mode overlap => Higher gain & efficiency
- Square geometry prefers TEM_{00} mode.
- Rough sides suppress parasitics.



Goodno et. al.,

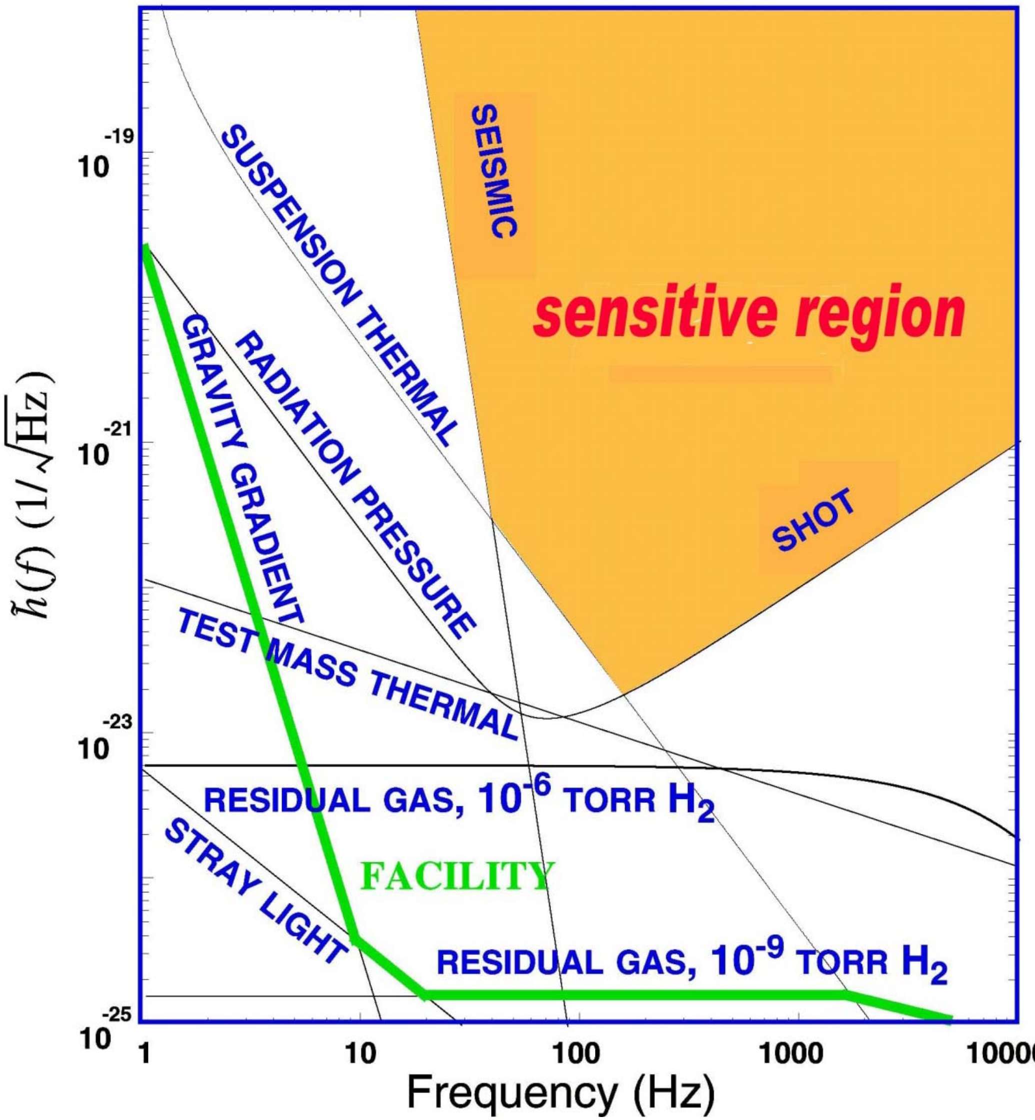
ASSL 2001





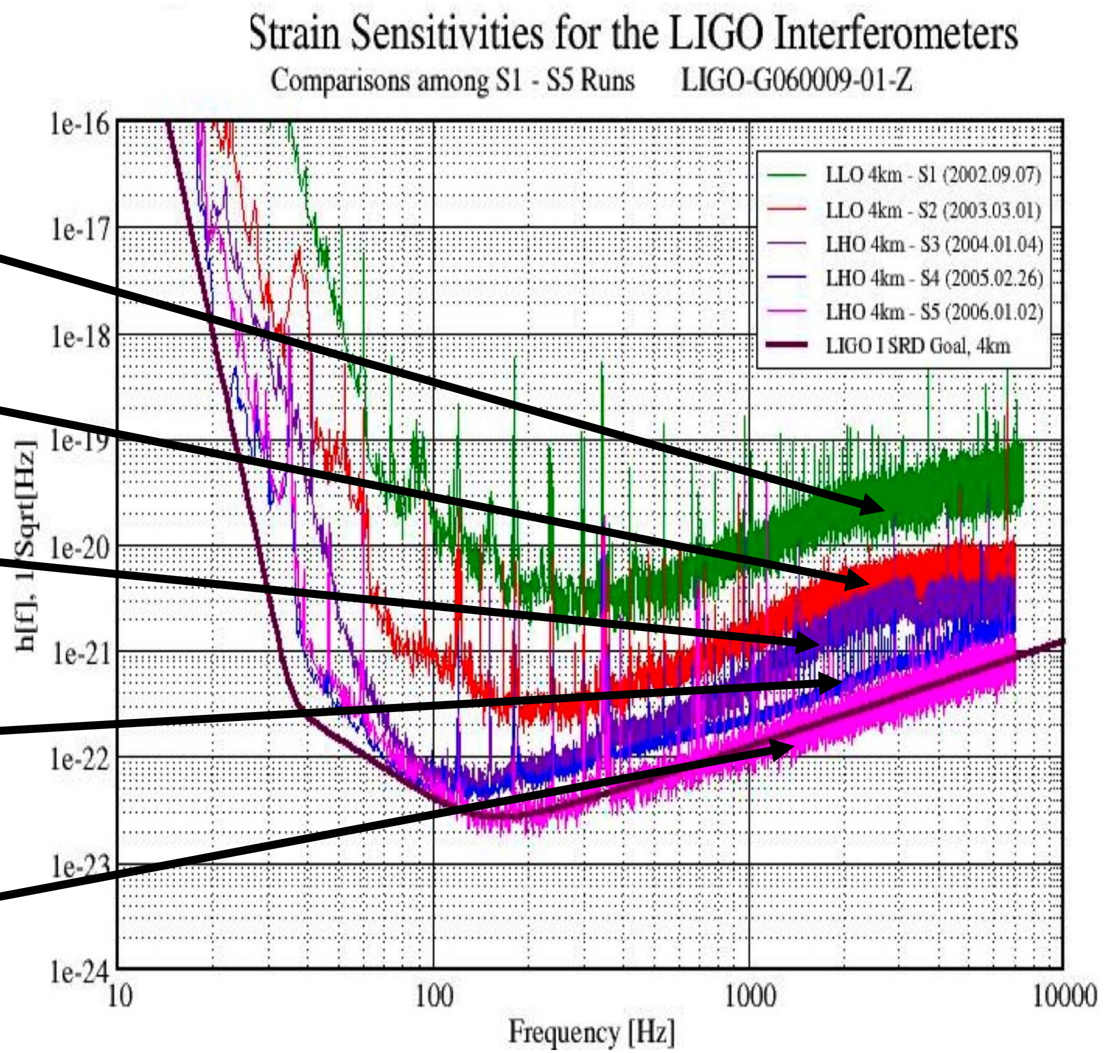
What Limits Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Thermal noise of suspensions and test masses
- Quantum nature of light (Shot Noise) limits at high frequencies
- Limitations of facilities much lower

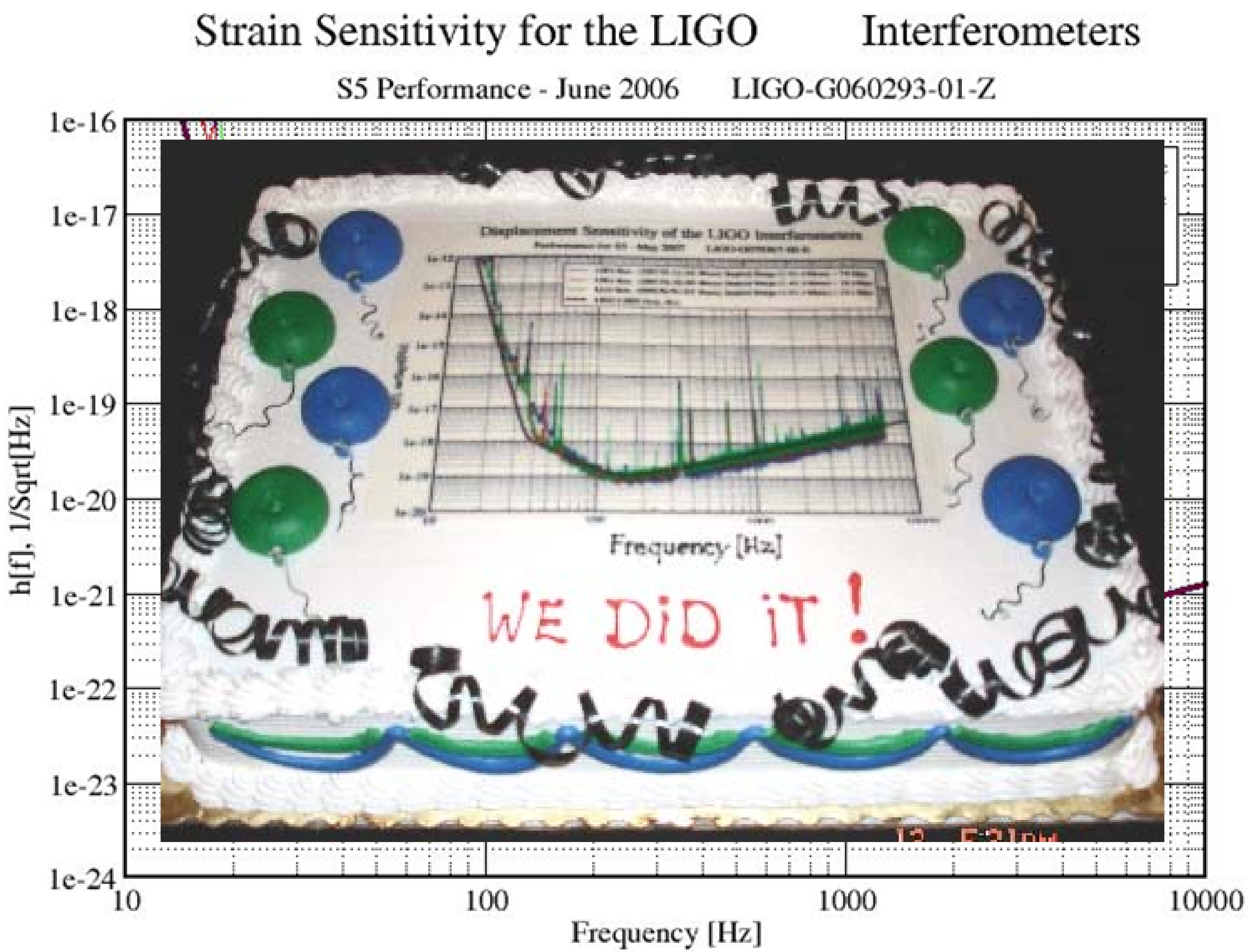


Science runs and sensitivity

Run	# days
S1 Sept '02	17
S2 Feb 03-Apr 03	59
S3 Nov 03-Jan 04	70
S4 Feb- March 05	30
S5 Nov 05 - Sep 07	2 y (1y coincident)



S5 Science Run: LIGO at Design Sensitivity



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  - Detection rates
  - Schedule for completion

Future concepts
- LISA an Interferometer in Space
- LISA performance & technology development

The Future: Enhanced and Advanced LIGO

S5 Run | S6 | S7?

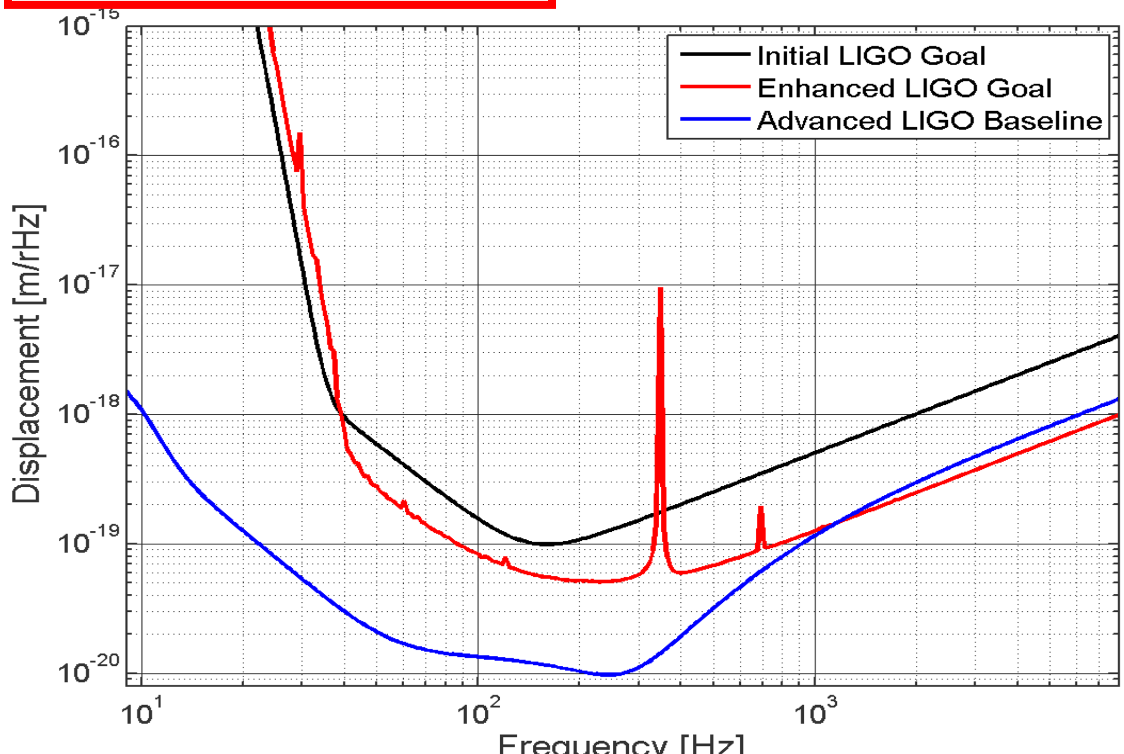
2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014

LIGO — ***enhanced* LIGO**

Advanced LIGO

build hardware | installation | science

Advanced LIGO funded as of 2008



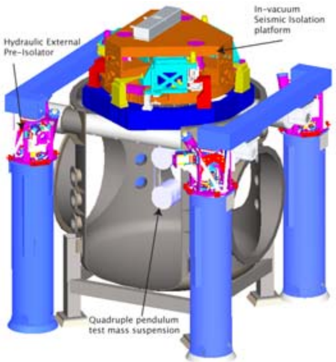
Enhanced LIGO (S6)

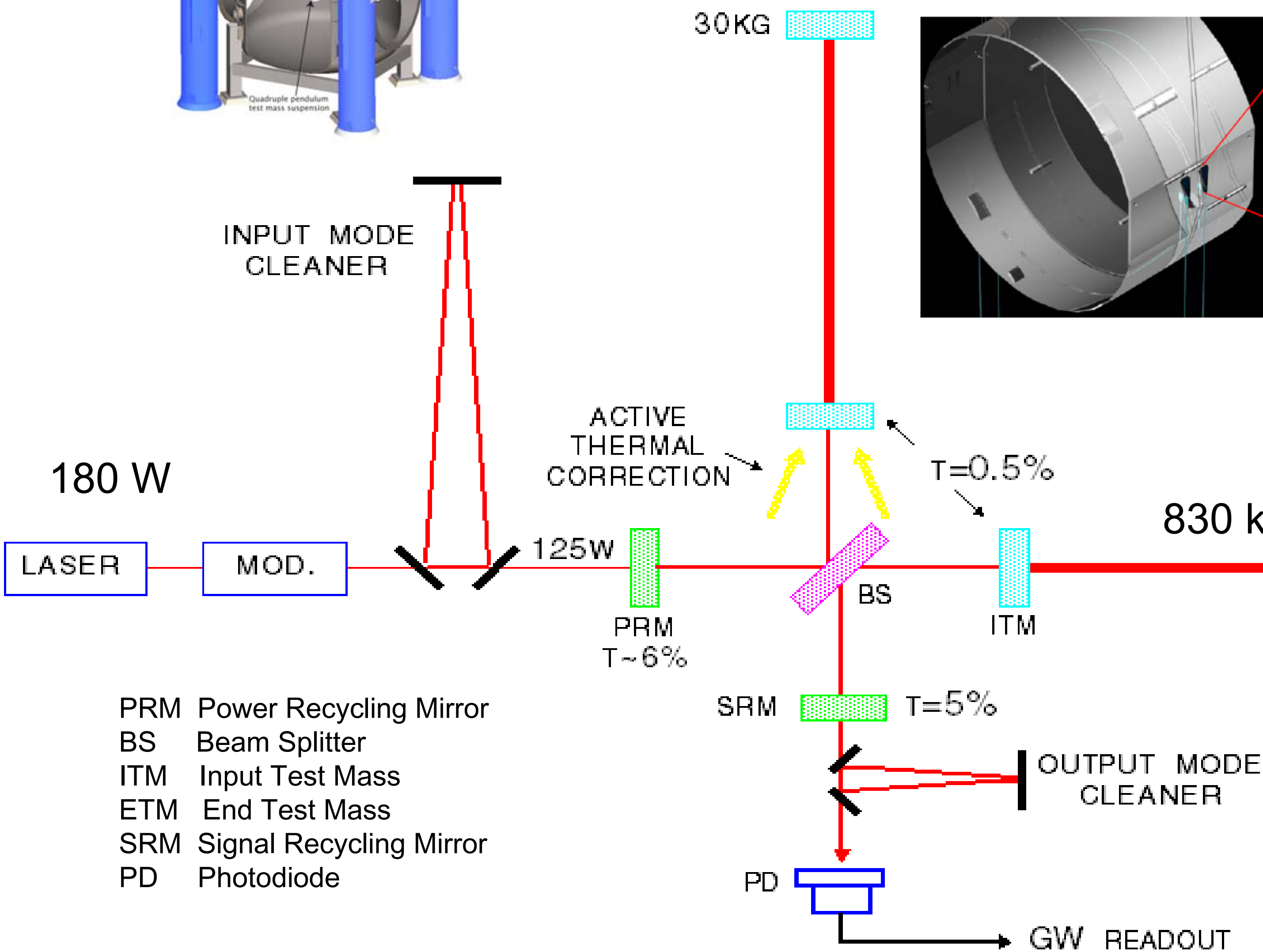
- readout noise; laser power
- ×2 better sensitivity
- commission AdLIGO DC readout with real IFOs
- reduce AdLIGO startup time

Advanced LIGO

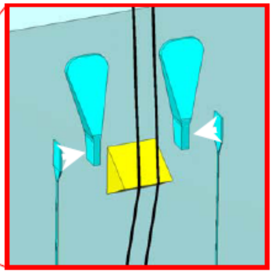
- Major upgrades: optics, lasers, suspensions, ...
- ×10 better sensitivity

Advanced LIGO

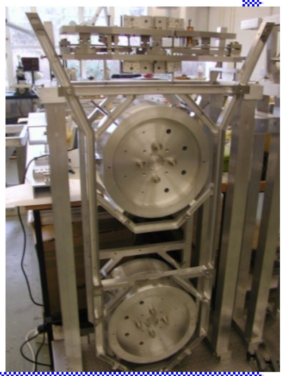




PRM Power Recycling Mirror
BS Beam Splitter
ITM Input Test Mass
ETM End Test Mass
SRM Signal Recycling Mirror
PD Photodiode



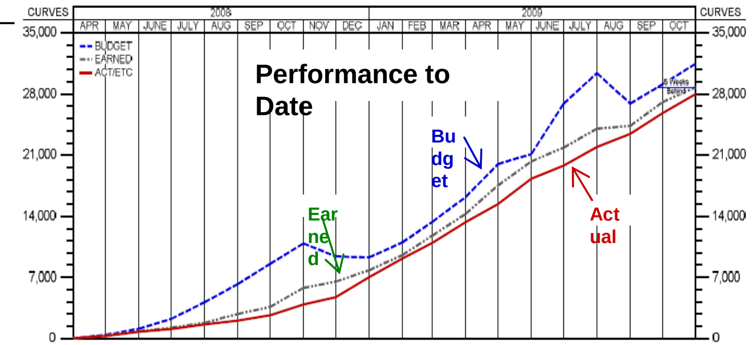
Ribbons welded to silica ears bonded to mass



Advanced LIGO is advancing!

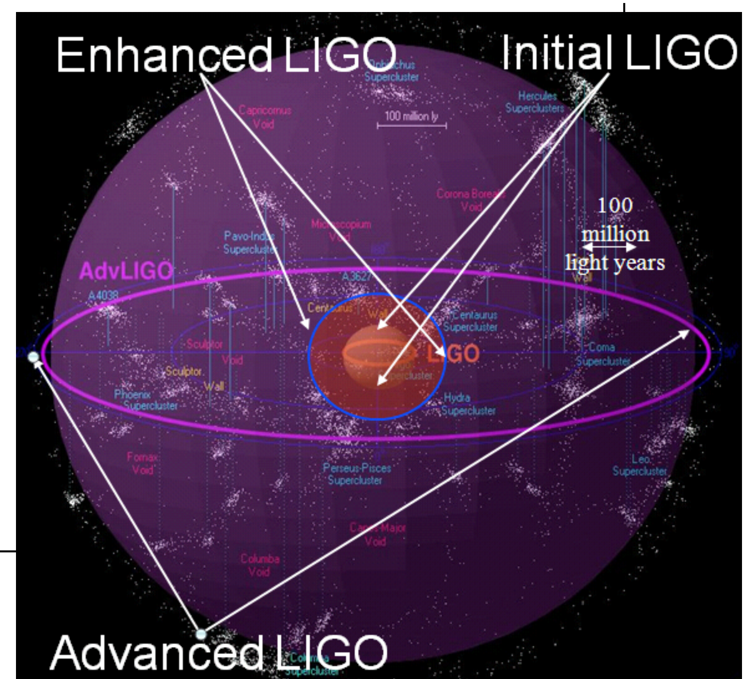
David Shoemaker - MIT

- **Started April 2008, scheduled to wrap up in 2015 with installation of the computing cluster**
- About 1/5 of the way through the Project in terms of 'earned value', pretty close to planned status
- Costs are ok (a little under due to soft economy); allows hiring people to solve problems



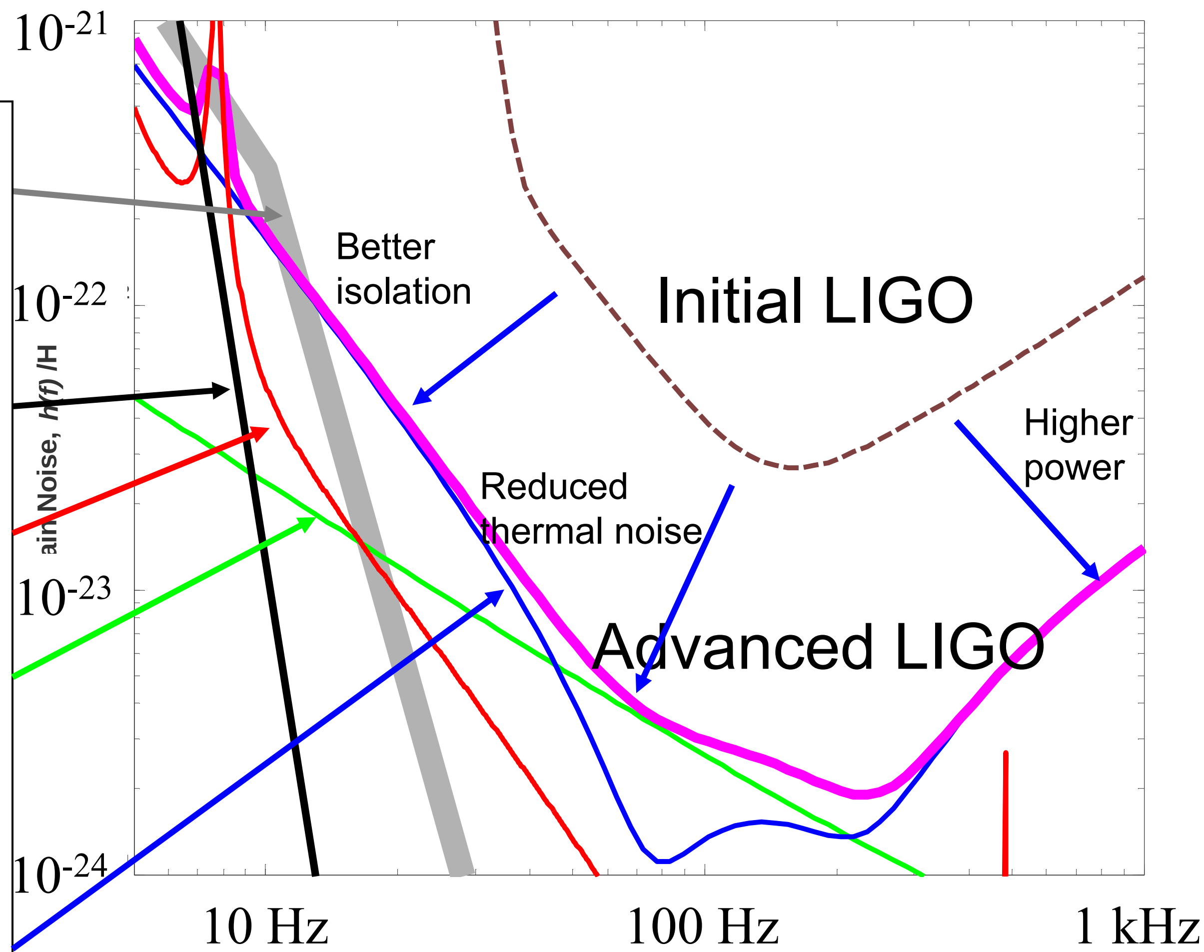
(COST IN USD x1,000)	BUDGET	EARNED	ACTUAL	S.V.	C.V.	S.P.I.	C.P.I.		
PREVIOUS PERIODS	29,111	27,067	25,814	-2,044	1,253	0.93	1.05	BUDGET:	167,789
CURRENT PERIOD	2,383	1,737	2,167	-646	-430	0.73	0.80	E.A.C.:	167,789
TO DATE	31,494	28,804	27,981	-2,690	823	0.91	1.03	SCHED. % COMP.:	18.77
								ACTUAL % COMP.:	17.17

- **No significant new noise sources or problems – should be able to get to that promised factor-of-10 in sensitivity**
- Design is wrapping up; big ticket/long schedule items mostly underway
- Modifications of Observatories for assembly, cleaning, storage complete
- Fabrication is underway of interferometer components



Projected Advanced LIGO performance

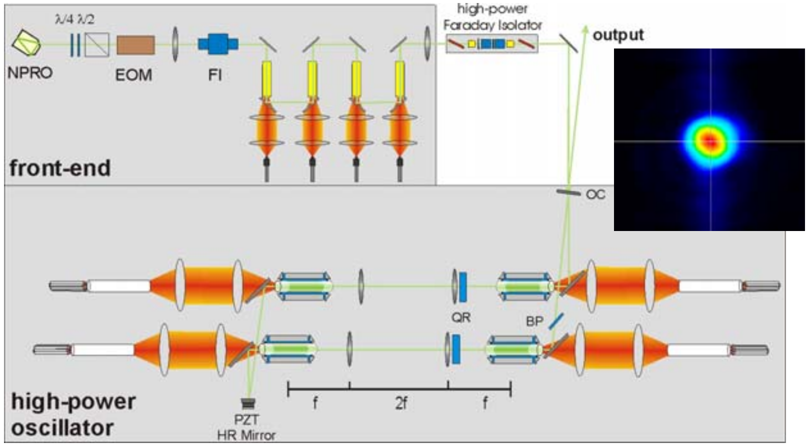
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



David Shoemaker/adapted

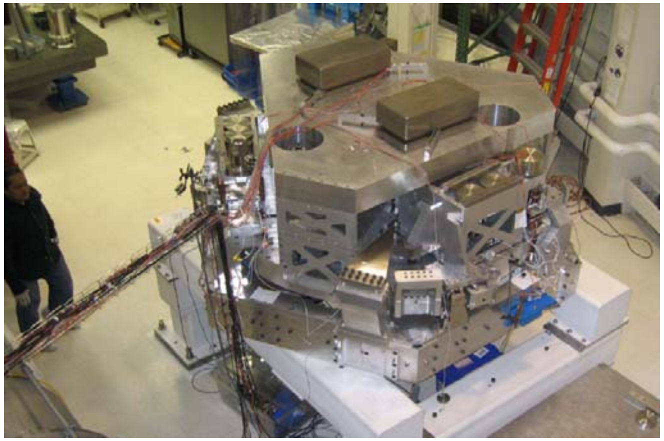
Advanced LIGO - Key subsystems

180 W laser

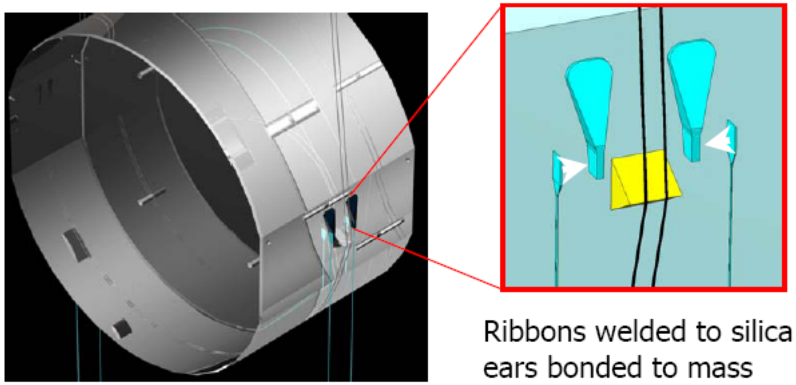


Mirror Suspensions

Seismic isolation

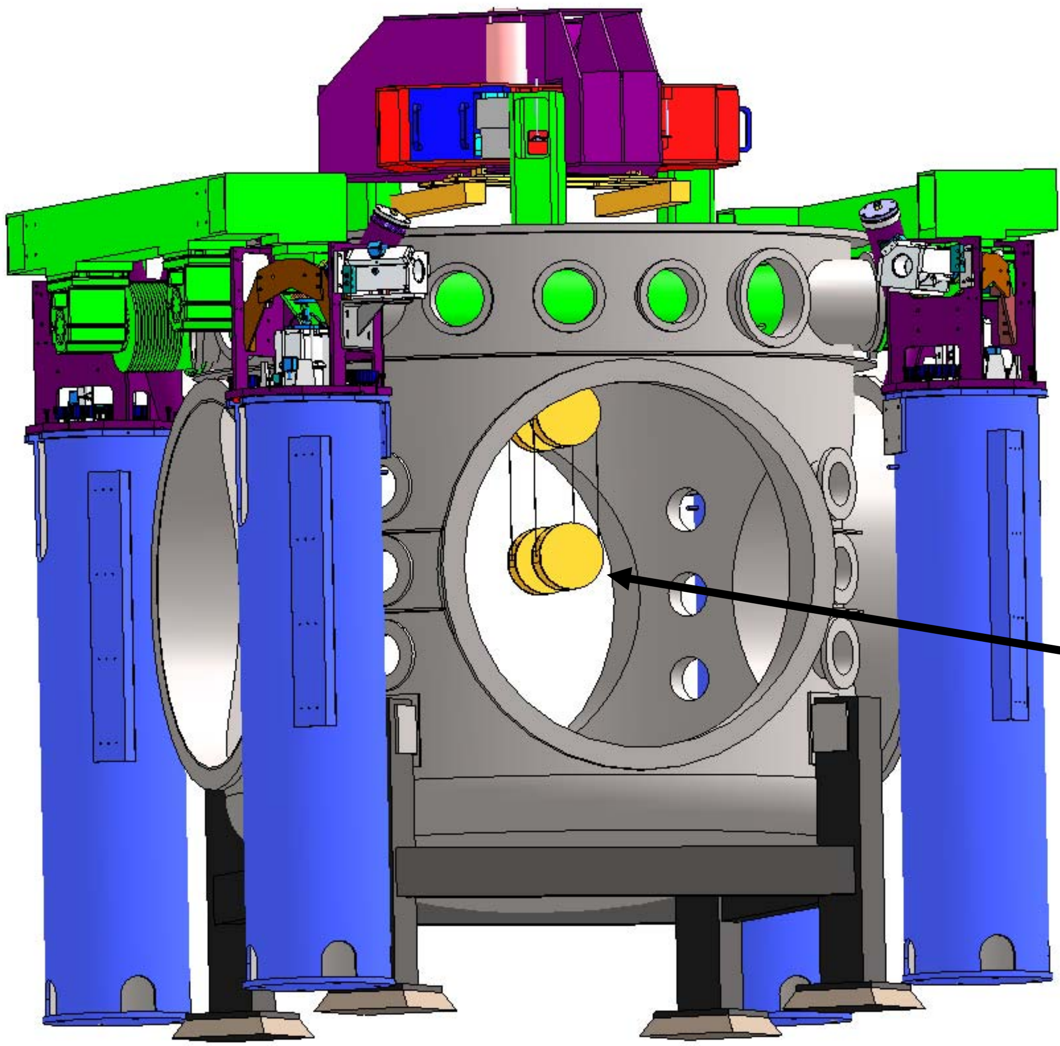


Mirrors



Ribbons welded to silica ears bonded to mass

Advanced LIGO Suspension+ Isolation



active isolation platform
(Stanford)

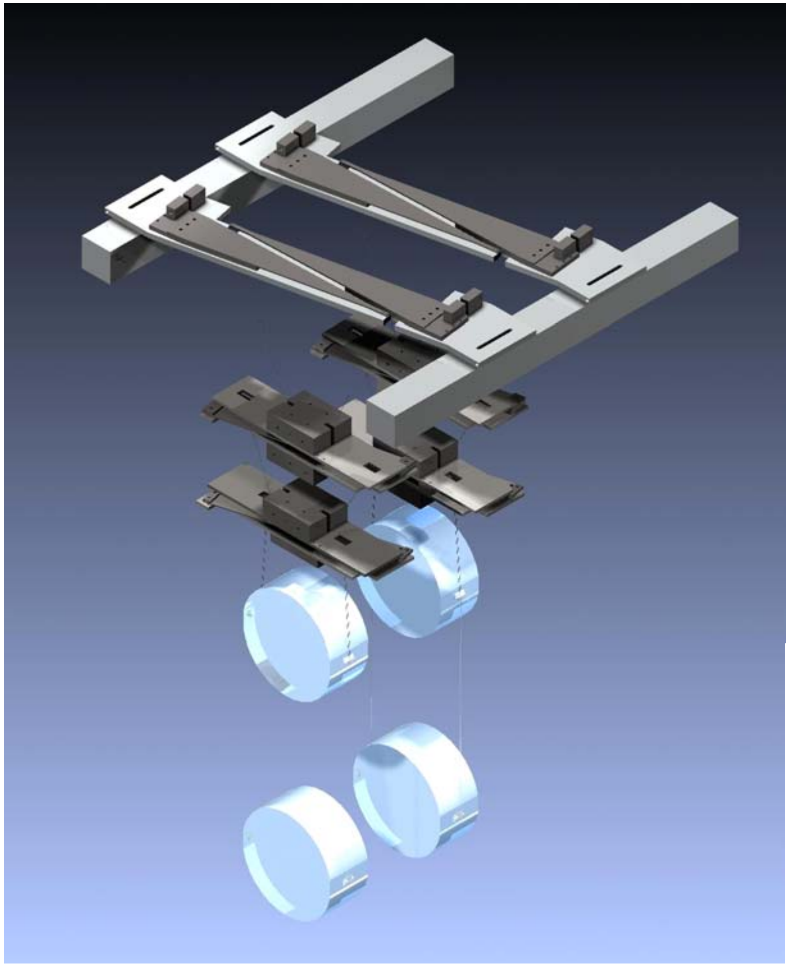
Hydraulic pre-isolator (HEPI)
(Stanford)

quad pendulum

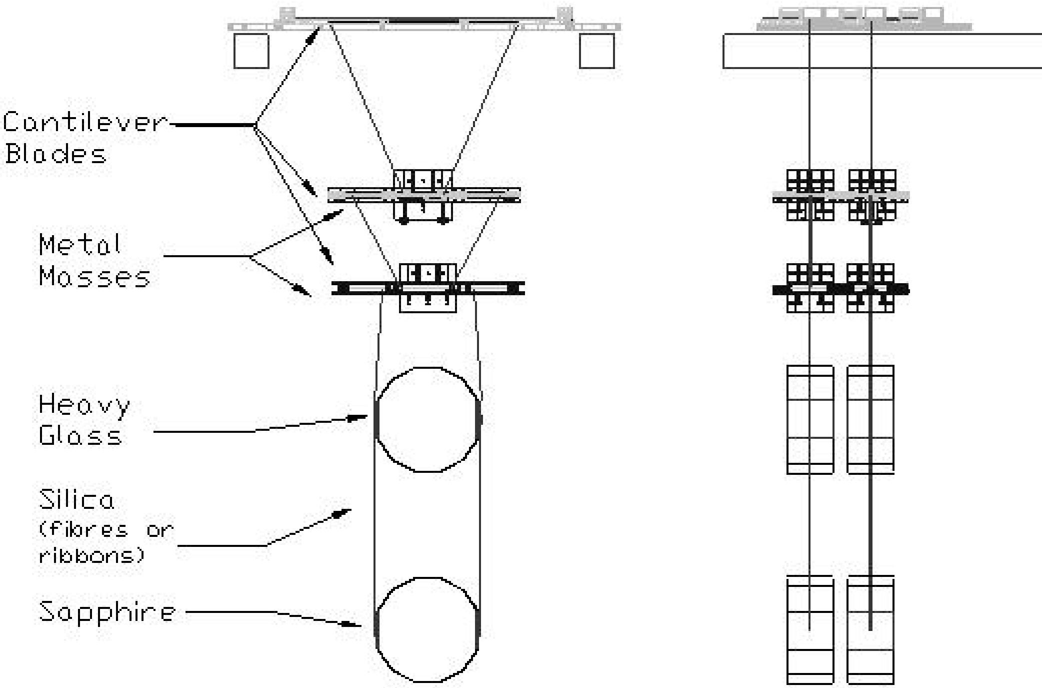
(Glasgow Univ)

Corwin Hardham

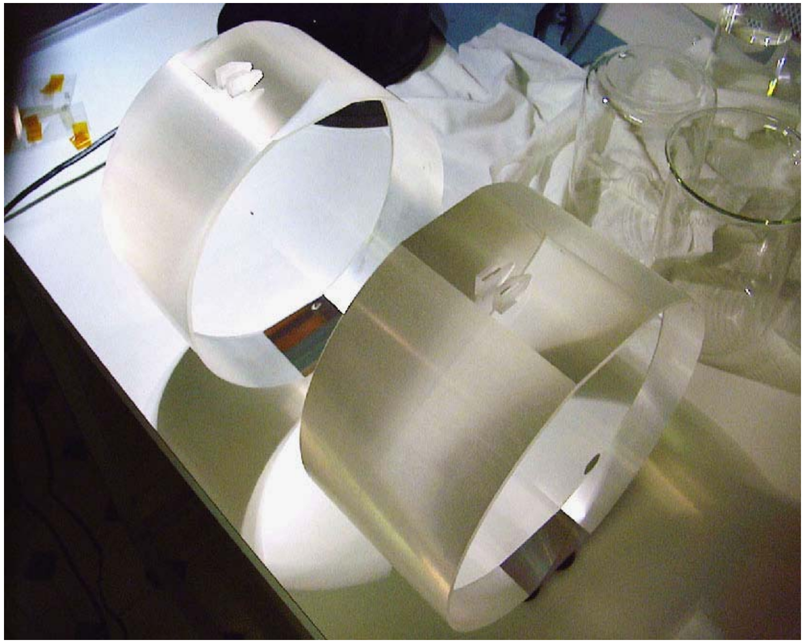
Quadruple Suspension for Advanced LIGO



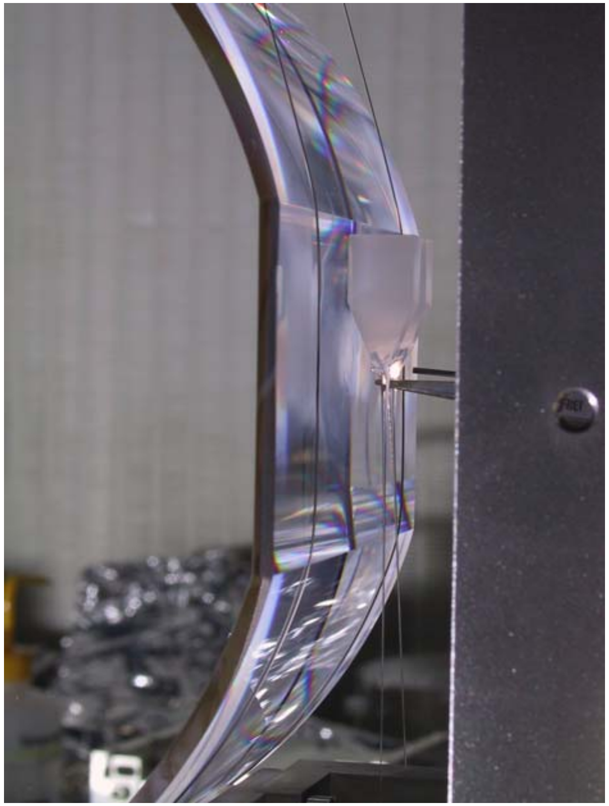
C Torrie, M Perreur-Lloyd, E Elliffe, R Jones



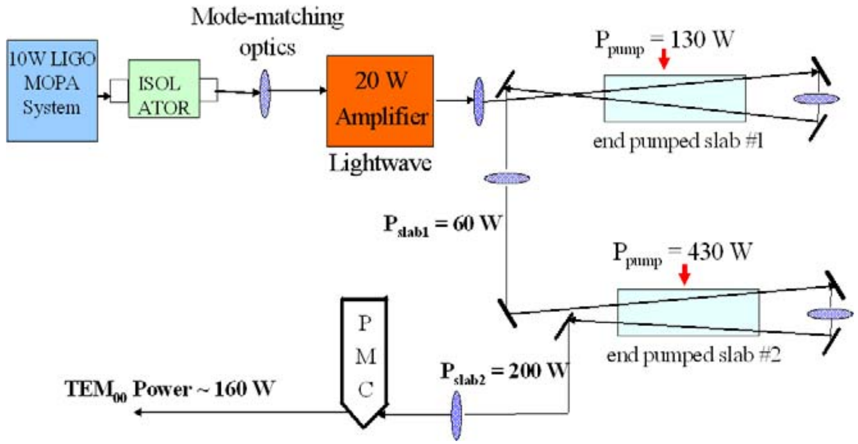
Monolithic Suspension - Assembly



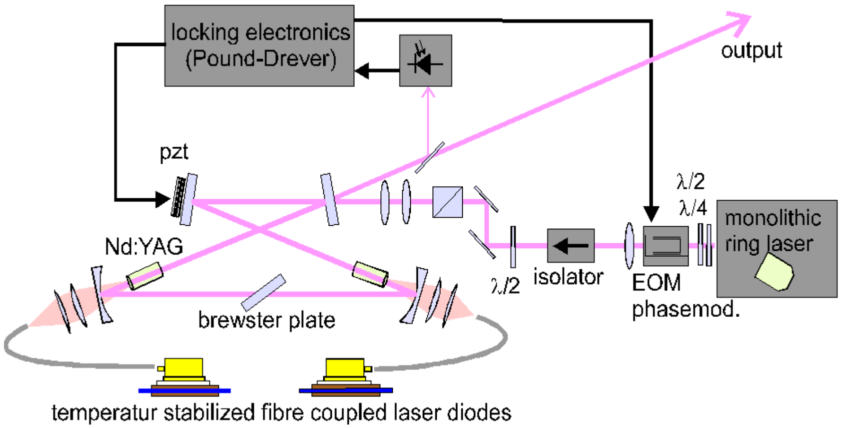
Bonding of ears



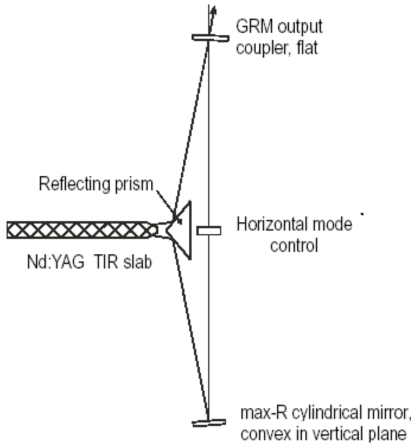
Welding of fibres



Edge Pumped Nd:YAG slab - Stanford



Injection locked Nd:YAG oscillators Hannover



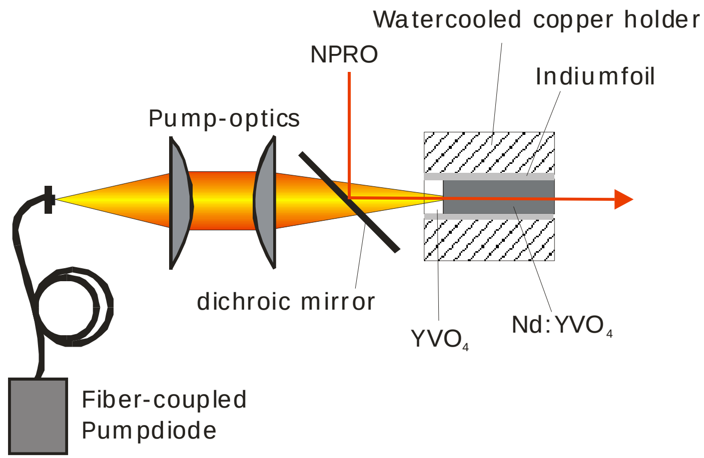
Unstable resonator -- Adelaide

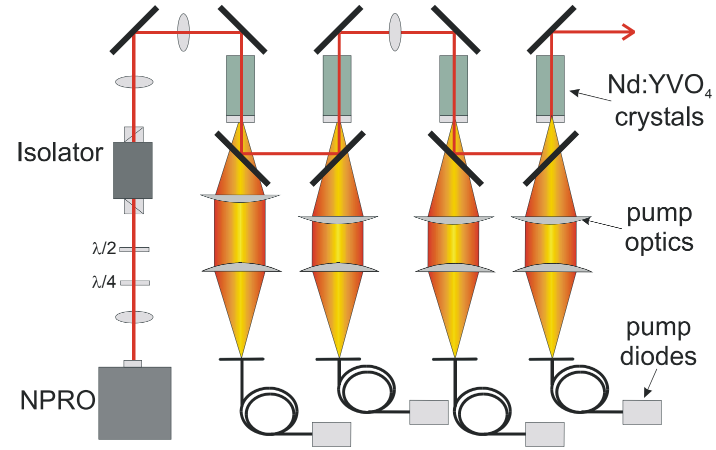
Benno Willke
Hannover

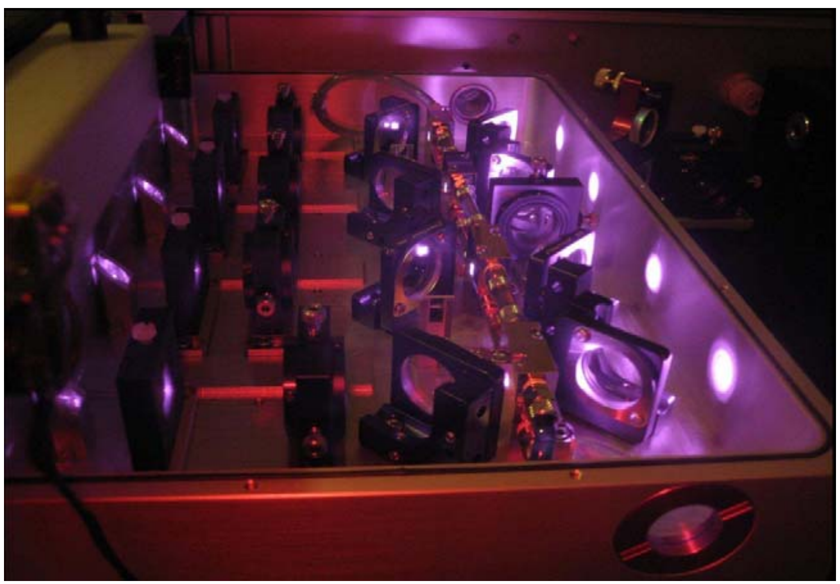
In charge of 200W Laser program for Advanced LIGO

35W amplifier design

Byer Group





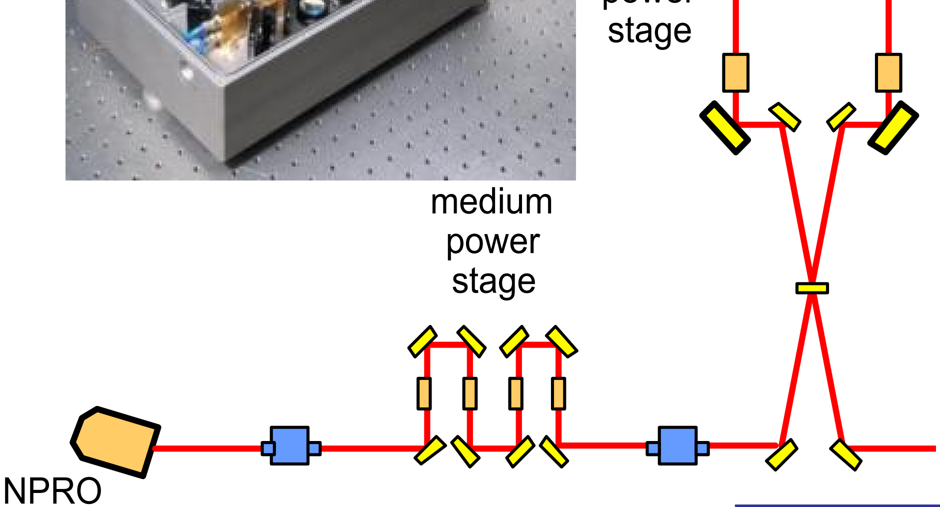


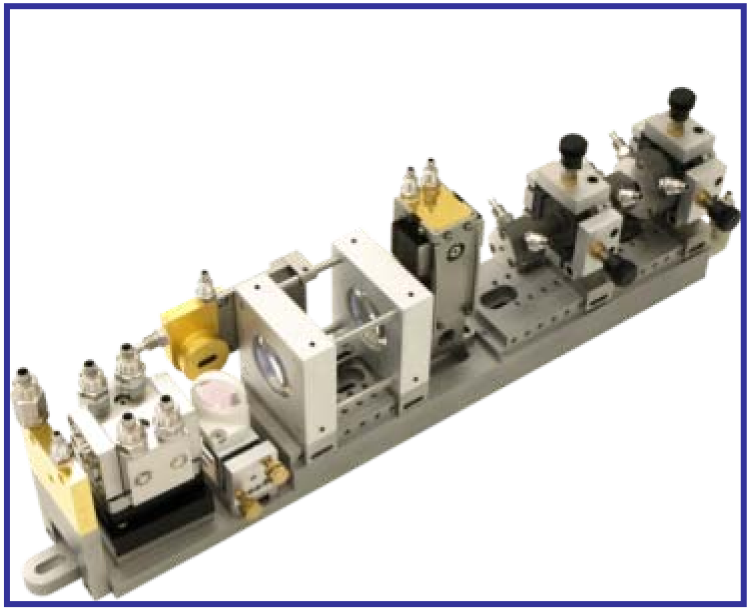
- Crystal:
  3 x 3 x 10 mm^3 Nd:YVO$_4$
  8 mm 0,3 % dot.
  2 mm undoped endcap
- Pump diode:
  808 nm, 45 W
  400 μm fiber diameter
  NA=0,22
- amplifier:
  38W for 2W seed and 150W pump

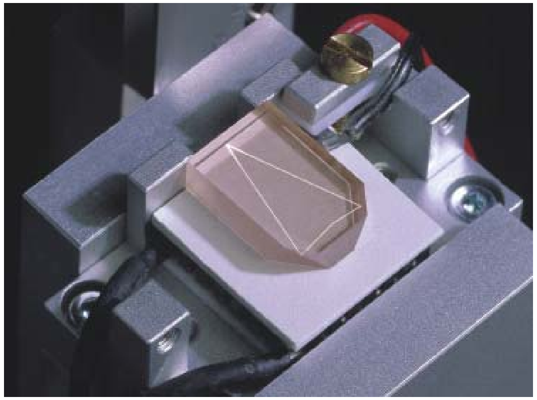
Frede et al, *Opt. Express* **22** p459 (2007)

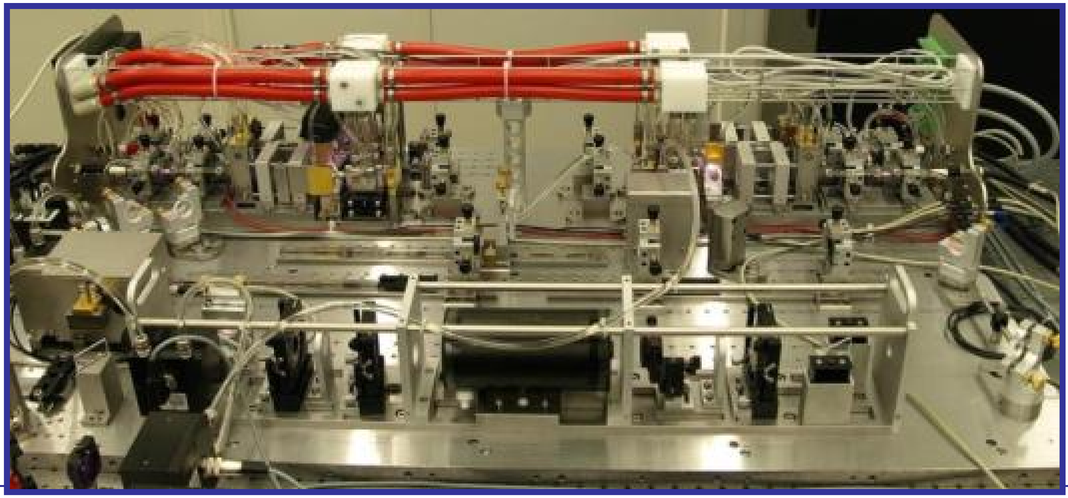
180W prototype - layout

Byer Group





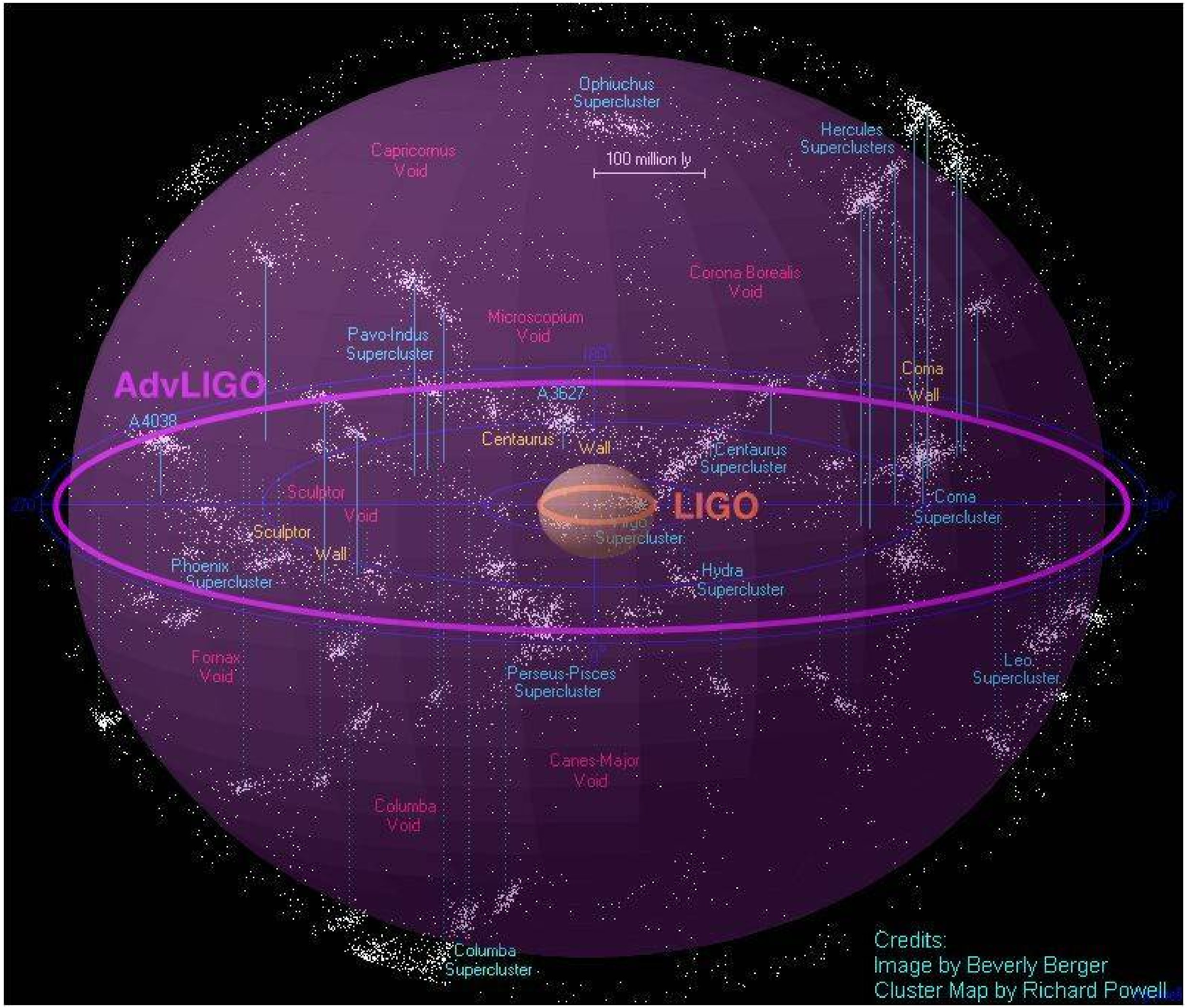




Advanced LIGO: 2011 – 2015 installation

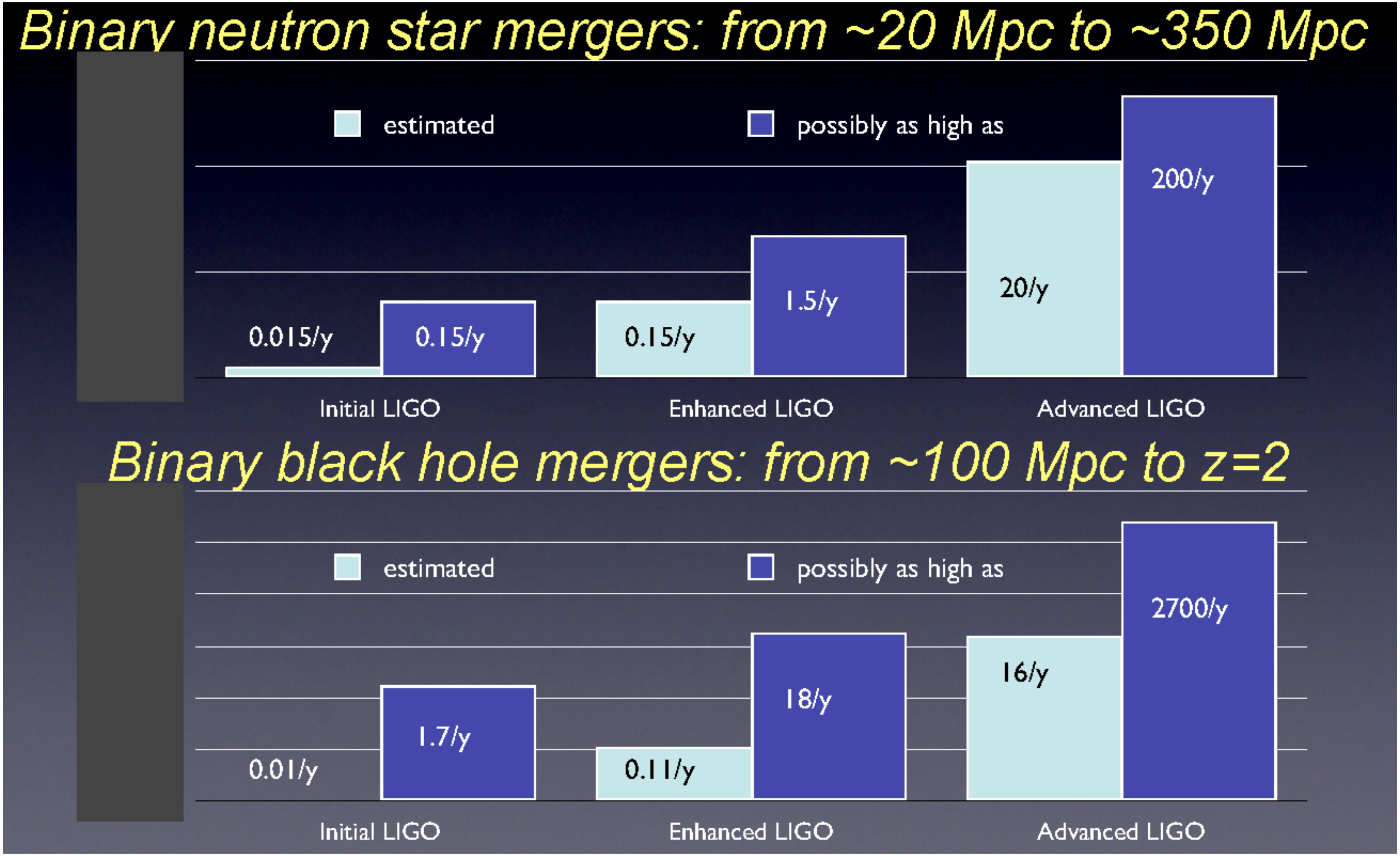
Byer Group

- Current LIGO is 'rate-limited'
  - Detection of a gravitational wave is 'possible', but not 'likely'
- Detector upgrade is planned for 2011-2015
  - Factor of 10 increase in distance probed ('reach')
  - Factor of 1000 increase in event rate

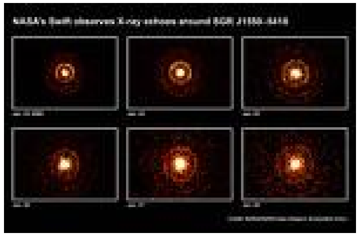


Prospective rates for binary mergers

Byer Group



Multi-messenger astronomy



- Externally triggered searches – electromagnetic
  - GRBs
  - SGRs
- Externally triggered searches – neutrinos
  - High-energy neutrinos (Ice Cube, Antares, …)
    - GRBs, SGR flares, microquasers, ?
  - Low-energy neutrinos (Super-K, LVD, Borexino,…)
    - Core-collapse supernovae
- Electromagnetic follow-ups of GW triggers
  - Requires fast (~10 min) id and distribution of LIGO-Virgo trigger (for S6)
    - ~few degree resolution with LIGO-Virgo network
  - Swift ToO – XRT
  - Wide-angle optical telescopes (SkyMapper, ROTSE, TAROT, Quest)
  - Radio

Summary

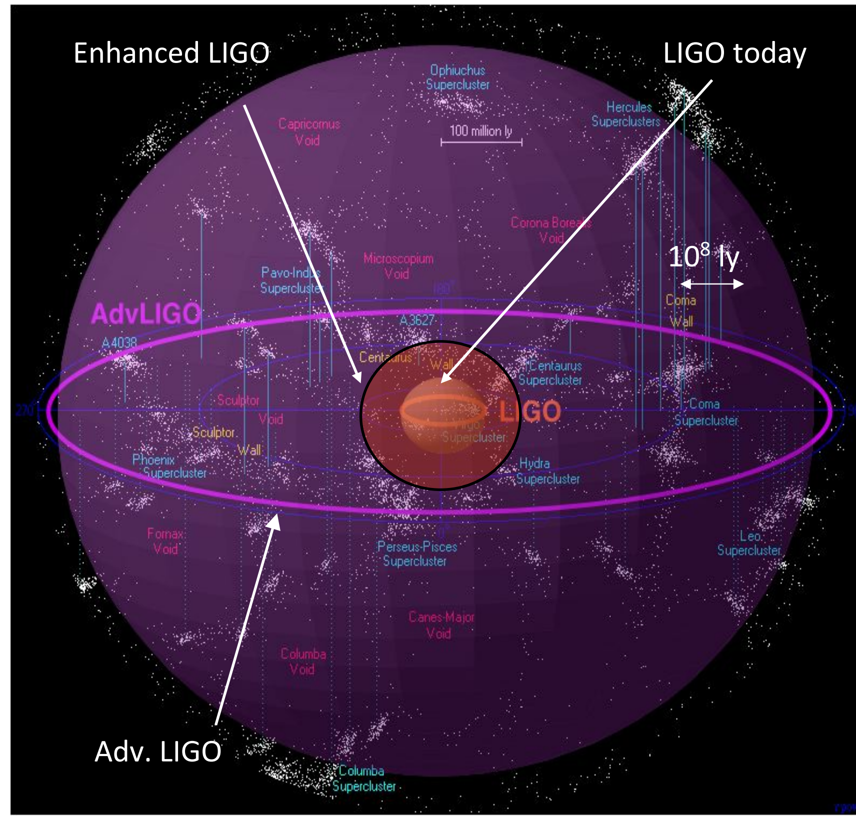
- LIGO is now a powerful scientific instrument with "reasonable" sensitivity to astrophysical GW sources
- The S5 run at design sensitivity is completed
  - No detections yet, but starting to make interesting statements:
    - GRB 070201; Crab spindown limit; cosmic GW limit < BBN
- Enhanced LIGO (x2 sensitivity) run started Summer 2009
- Now it is up to nature...run to be completed in October 2010
- Advanced LIGO is funded and proceeding on track (x10 sensitivity)
- Expect detections to become "routine" → GW science & astronomy
  - numerical relativity
  - multi-messenger astronomy
  - a new, exciting field

Next generation detectors are being considered:
Squeezed light, improved thermal control, improved isolation...

Gravitational Waves: From Discovery to Astronomy

2nd generation:
Advanced LIGO

GOAL:
sensitivity 10x better →
look 10x further →
Detection rate 1000x larger



Credit: R.Powell, B.Berger

Outline

Prelude: California – a leader in science and technology

LIGO & LISA: Early History and Concepts

- LIGO and LISA at the beginning
- Gravitational Waves and Sources

The LIGO Observatory

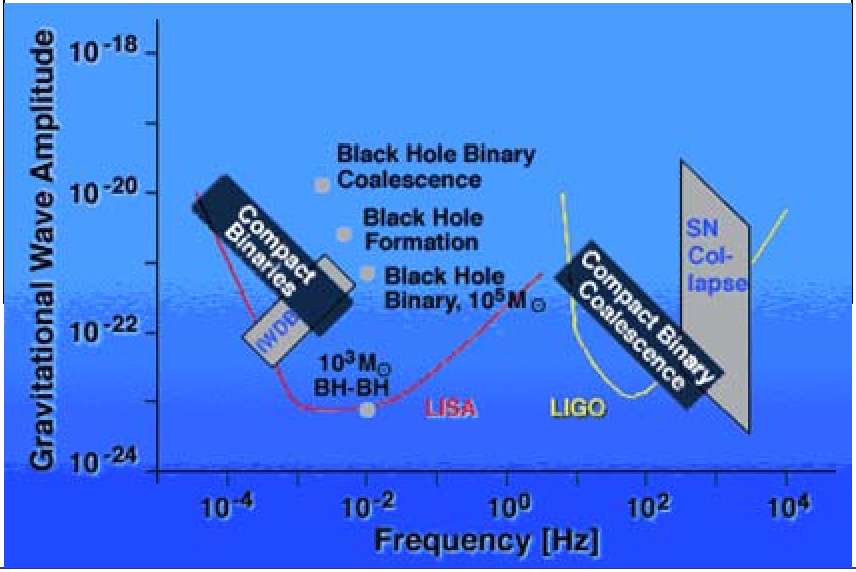
- LIGO Interferometers
  - Measurements
  - Technical progress
  - Science Runs - LIGO begins Science Run #6
- Advanced LIGO Interferometer
  - Sensitivity Improvement
  - Detection rates
  - Schedule for completion

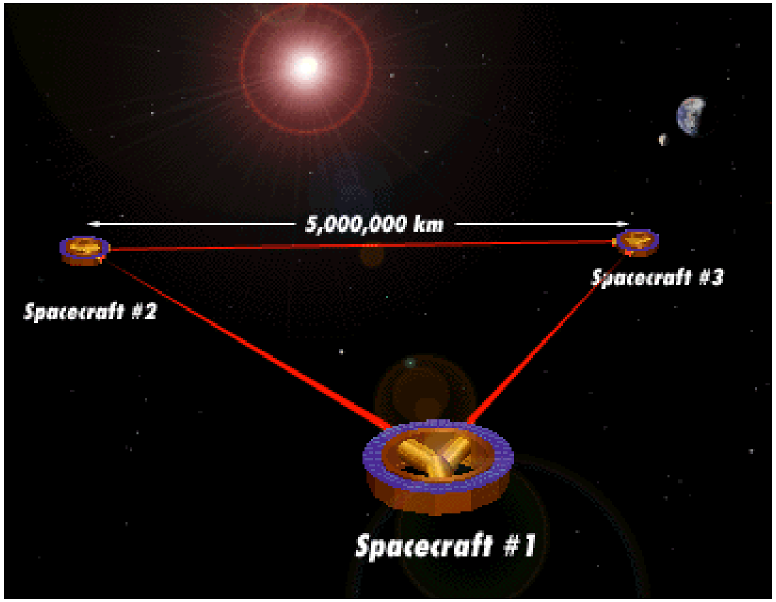
Future concepts

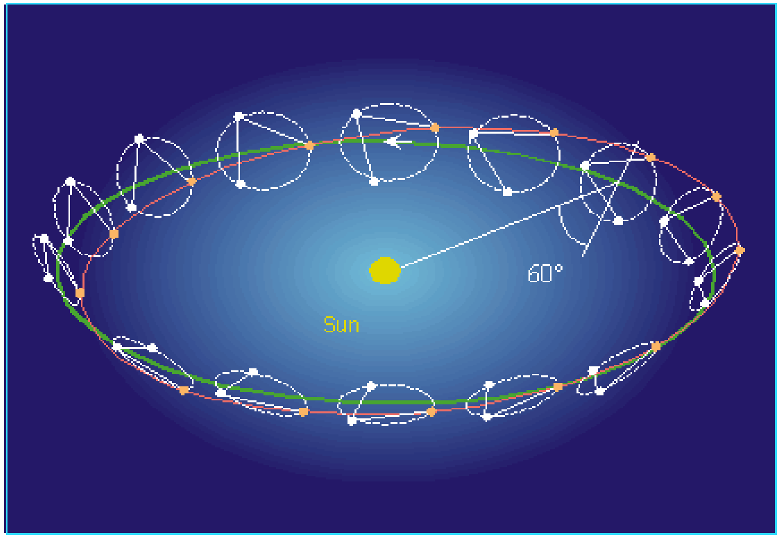
- LISA an Interferometer in Space
- LISA performance & technology development

LISA
Laser Interferometer Space Antenna

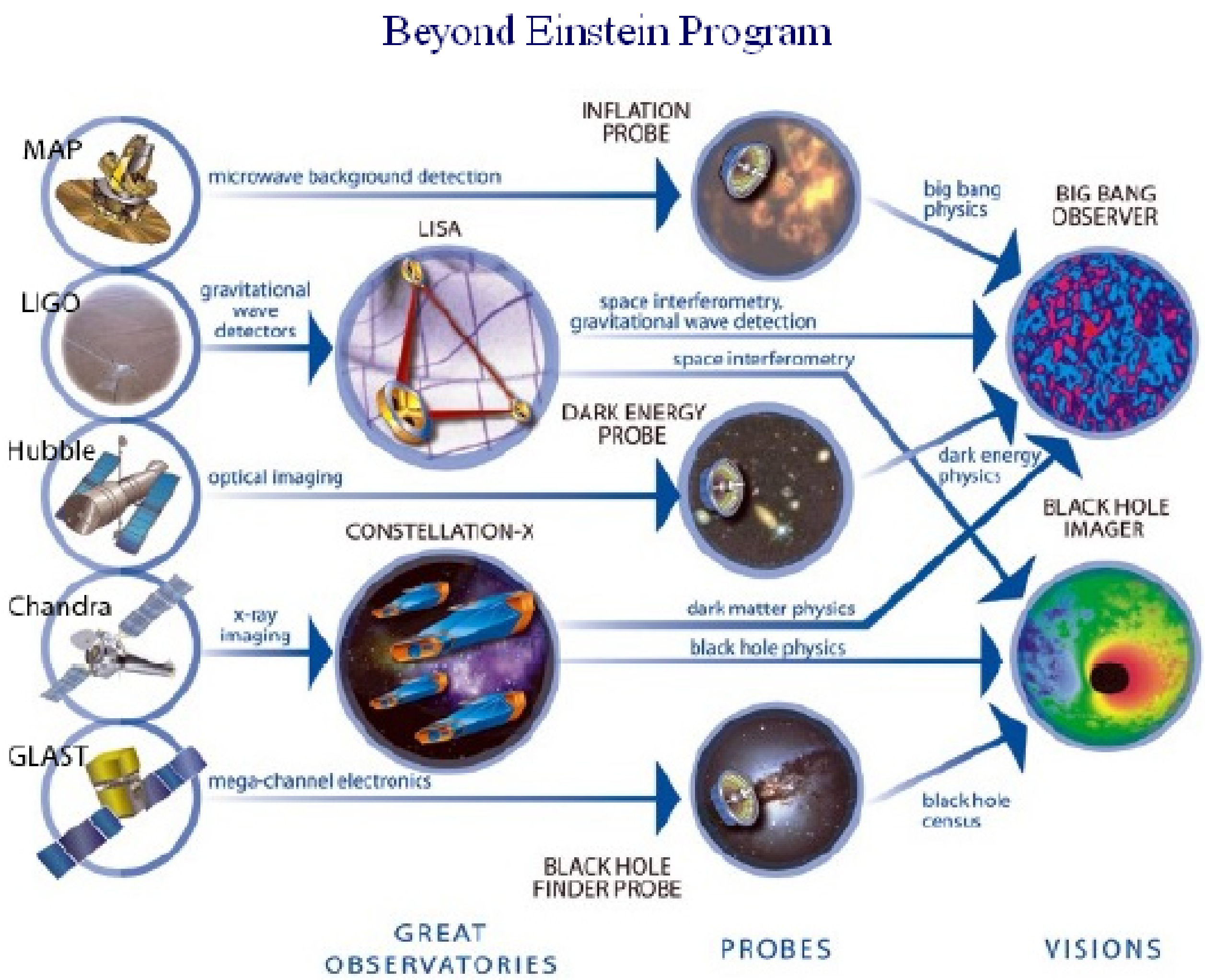
- a proposed joint ESA/NASA mission
- sensitive to low frequency signals - complementary to the ground-based detectors
- science objectives:
  - observations of interactions of massive black holes
  - observations of galactic binary star systems



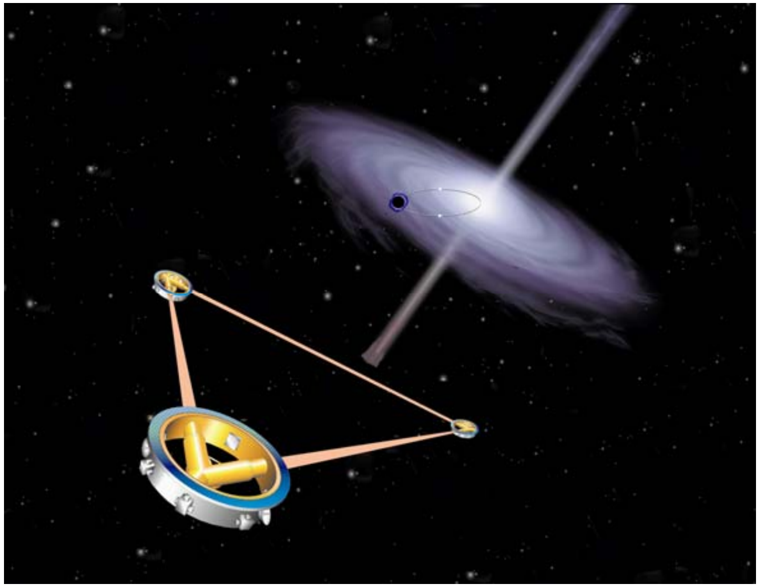




One year orbit around Sun


Beyond Einstein Program
MAP
microwave background detection
INFLATION PROBE
big bang physics
BIG BANG OBSERVER
LIGO
gravitational wave detectors
LISA
space interferometry, gravitational wave detection
space interferometry
DARK ENERGY PROBE
Hubble
optical imaging
dark energy physics
BLACK HOLE IMAGER
CONSTELLATION-X
Chandra
x-ray imaging
dark matter physics
black hole physics
GLAST
mega-channel electronics
black hole census
BLACK HOLE FINDER PROBE
GREAT OBSERVATORIES
PROBES
VISIONS

LISA Mission

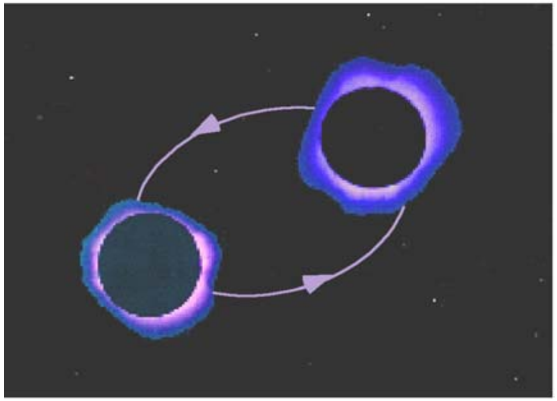


LISA: Exploring Black Holes, Space-Time, and the Beginning of the Universe

- **Status:**
- Ranked as high-priority mission in US and Europe
- Currently in technology development phase in US; approved "Cornerstone" mission in Europe
- Technology development validation flight on ESA Smart-II spacecraft in 2008 (Stanford University was a participant)
- LISA currently "on the books" for 2020 launch

If we achieve our goals, what will LISA be able to "see"?

- **No limits!**
  - LISA will be able to see supermassive black hole mergers back to the beginning of the universe (if they are there)



How many are predicted?

As many as 10 supermassive black hole mergers observable per year (Maybe lots more!?)

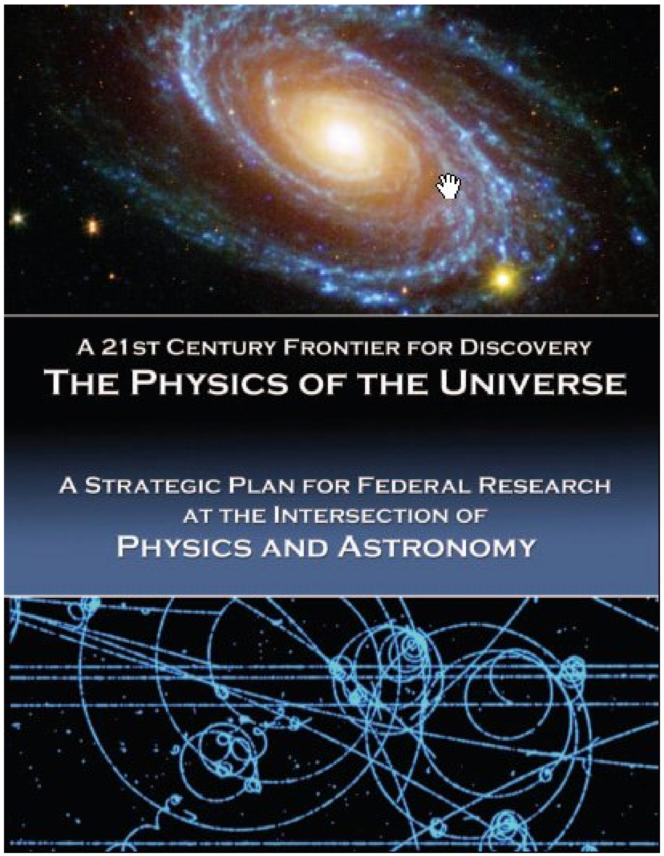
Most powerful events in the universe!

Release a billion times more energy in a minute than our sun does in its lifetime!

LISA will probe the ultimate limits of mass, energy, & gravity!

Conclusion

- Gravitational wave detection is recognized as a key research area: exciting times ahead!



Report from Interagency Working Group, Feb 2004

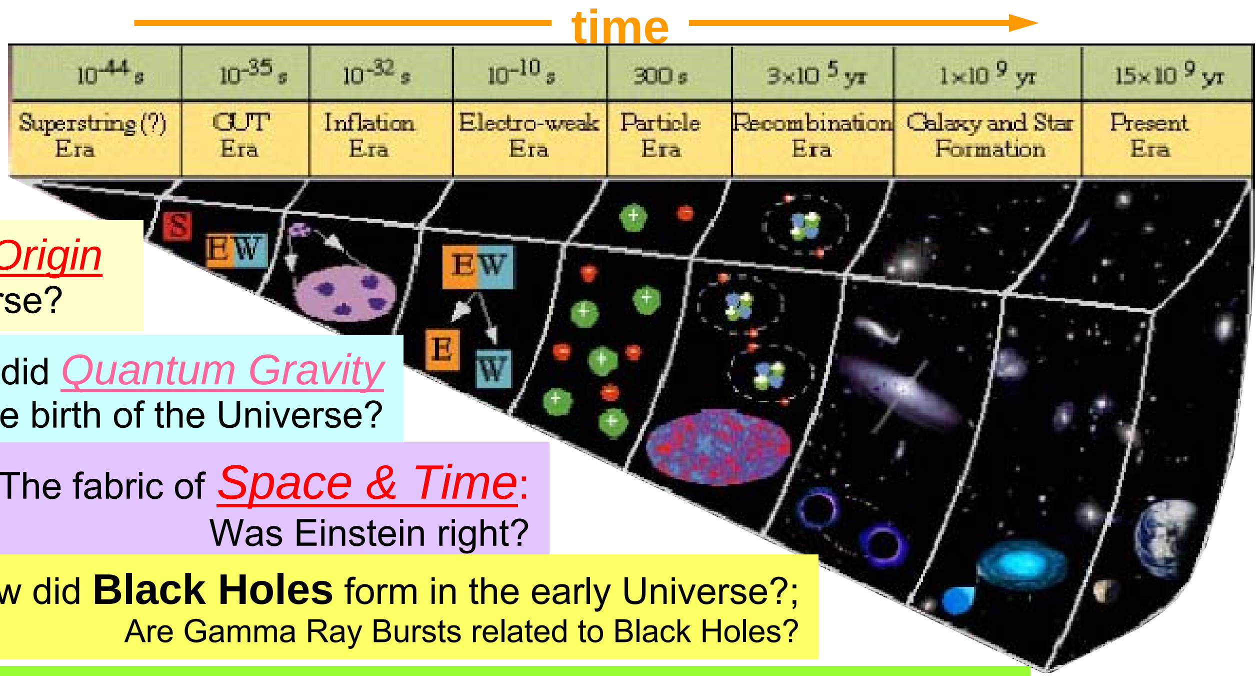
Recommendations

* NSF, NASA, and DOE will strengthen numerical relativity research in order to more accurately simulate the sources of gravitational waves.

* The timely upgrade of LIGO and execution of the LISA mission are necessary to open this powerful new window on the universe and create the new field of gravitational wave astronomy.

Exploration of the Universe -The BIG questions

Byer Group



?

What is the *Origin* of the Universe?

What role did *Quantum Gravity* play in the birth of the Universe?

The fabric of *Space & Time*: Was Einstein right?

How did **Black Holes** form in the early Universe?; Are Gamma Ray Bursts related to Black Holes?

What is **Dark Matter**? Does **Dark Energy** really exist?

How did **Galaxies** form? Which came first, Black Holes or Galaxies?

How does our star work? Is **Life** in our galaxy unique?

What is the future **fate** of the Universe?

The Universe is our ultimate Laboratory!

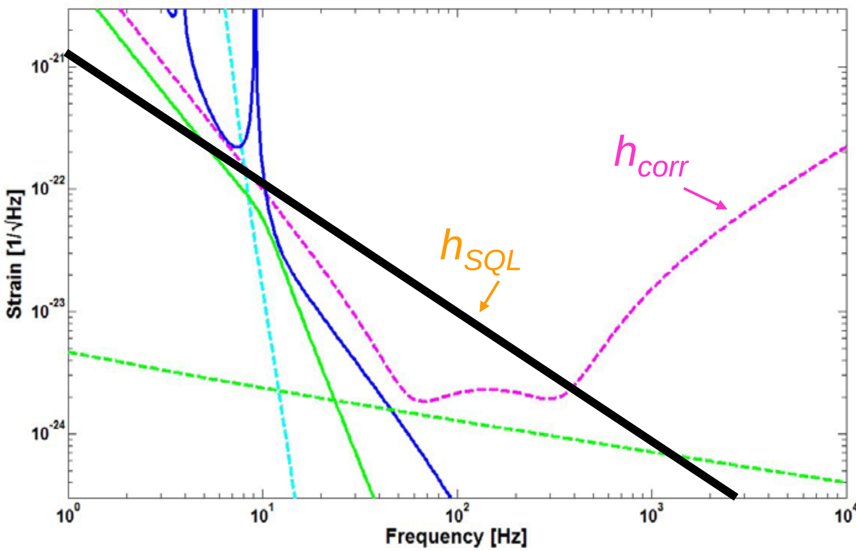
Back Up Slides

- Back Up Slides

LIGO as a quantum system

- LIGO test masses are μK oscillators
- Position sensitivity limited by Heisenberg: $\Delta x_{\text{SQL}} = [\hbar\tau/M]^{1/2}$
- Quantum noise limits Advanced LIGO sensitivity over much of band
  - Radiation pressure + shot noise

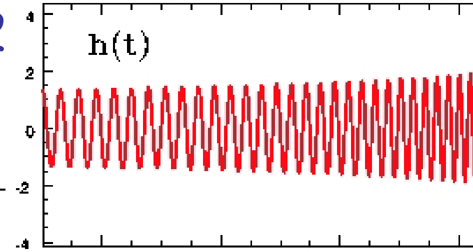
A. Buonanno and Y. Chen, PRD (2001)



- **Beating the SQL**
  - Introduce correlation between RP and shot noise (Signal Recycling)
  - Squeezed light

Science reach examples

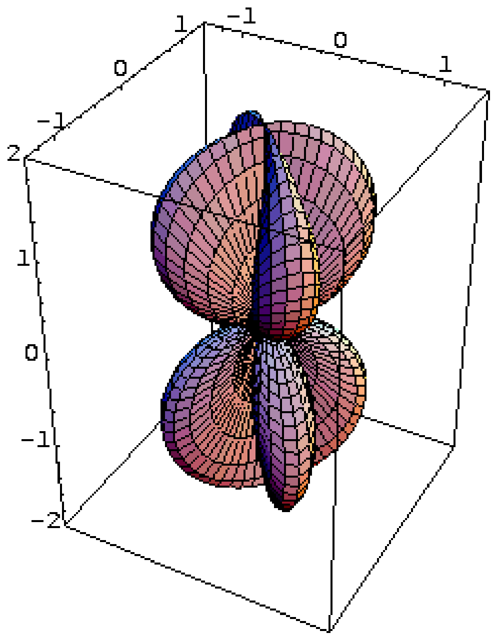
- GWs: fundamental test of General Relativity
- Detailed tests of strong-field gravity via numerical relativity
  - e.g. BH-BH mergers
- Astrophysics of gamma-ray bursts
  - Progenitors identified: binary mergers vs hypernovae
- Astrophysics of extreme stellar systems
  - Direct probe of core-collapse (with neutrinos)
  - Neutron stars: pulsars, soft-gamma repeaters (SGRs)
- Early universe
  - A cosmic background of GWs; cosmic strings
- Cosmology
  - GWs of merging binaries encode mass, z, orientation, position, D_l
  - Independent cosmological distance ladder to z ≈1-2
  - short GRBs will help (arXiv:0904.1017, ApJ)



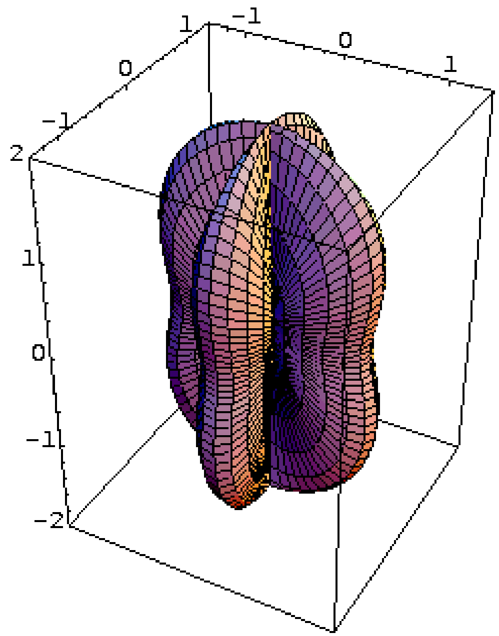
Antenna Pattern

GWs are transverse, with x and + polarizations: $h_x(t)$, $h_+(t)$

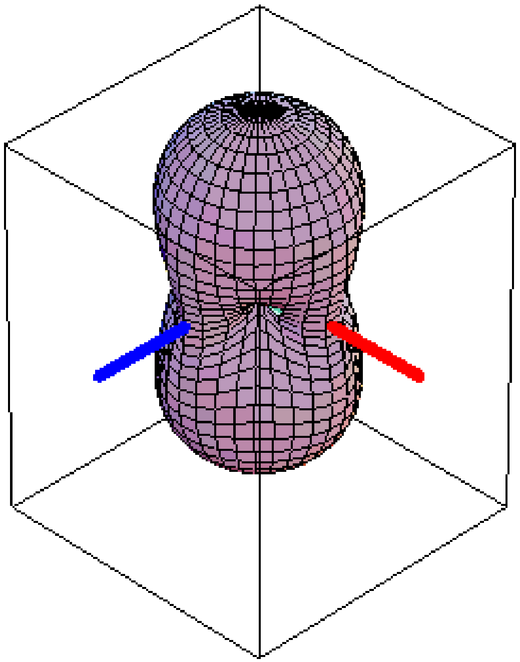
"×" polarization



"+" polarization



RMS sensitivity



Detector response

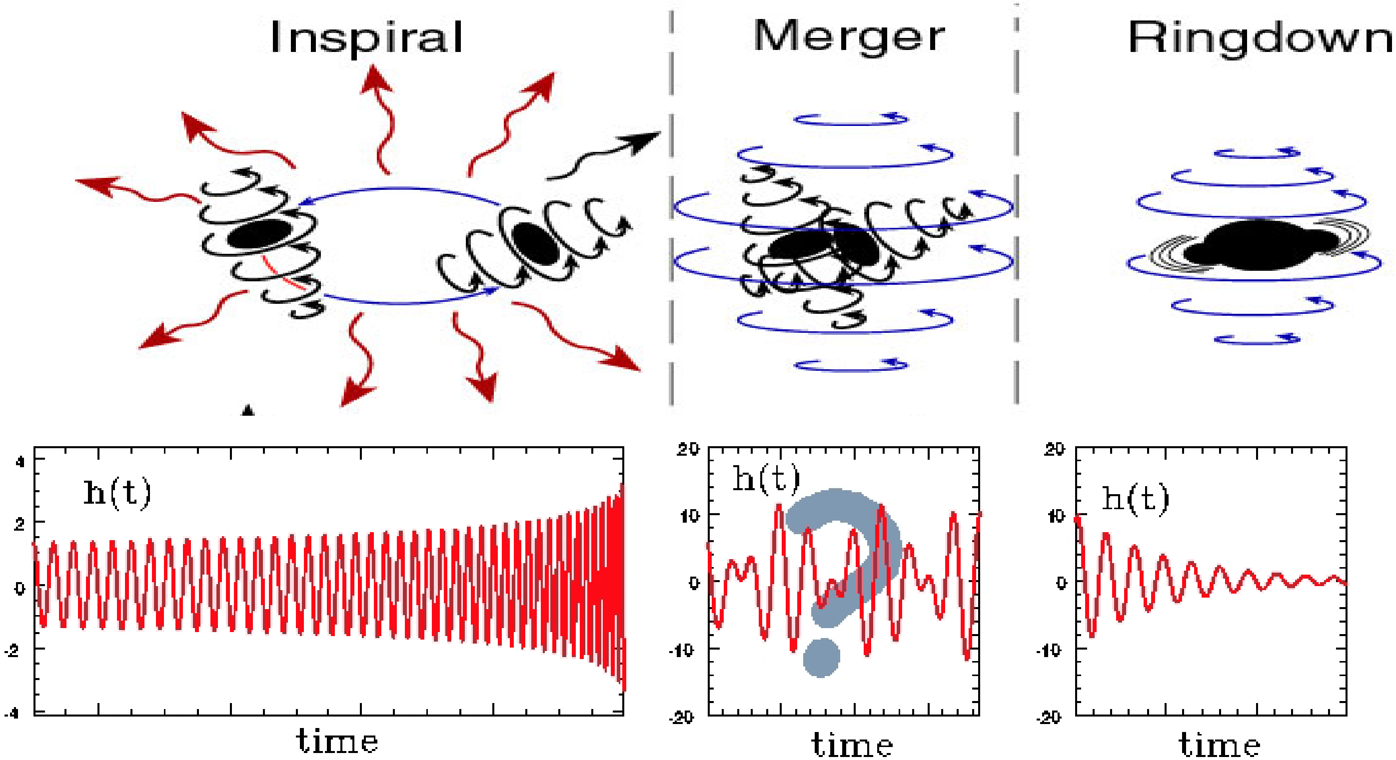
$$h(t) = F_x\, h_x(t) + F_+\, h_+(t)$$

Recent observational results

- Some, but not all, results from S5 data are public.
- No GW detection yet, but results are becoming astrophysically interesting. Highlight 3 such results:
  - Crab spindown
  - Cosmic GW background radiation
  - GRB 070201
- Other emerging S5 results
  - Compact binary inspirals and mergers (NS-NS, NS-BH, BH-BH)
  - Bursts/GRBs

Coalescing Compact Binaries

NS-NS, BH-BH, (BH-NS) binary systems

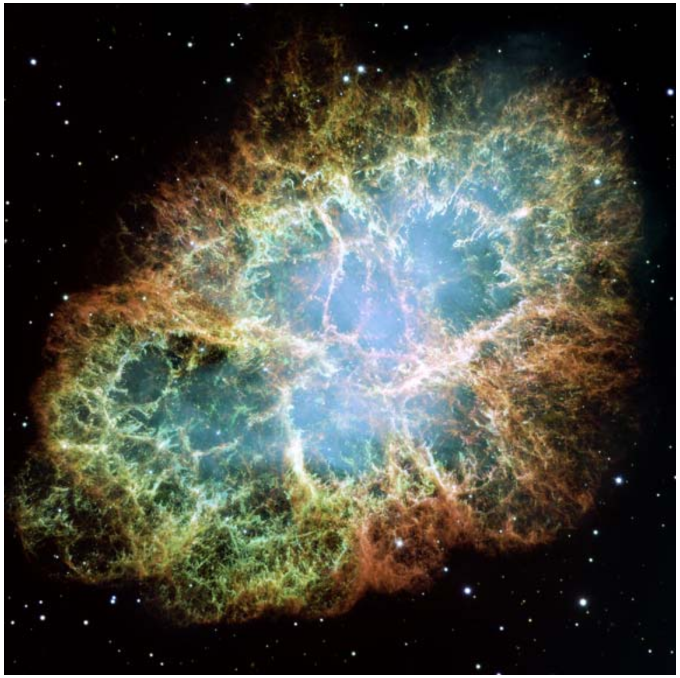


Matched filter

Template-less

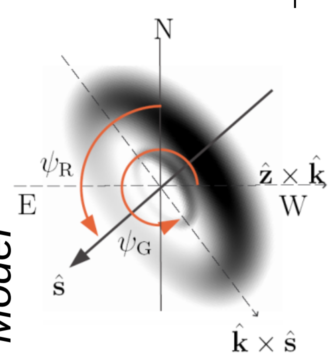
Matched filter

Beating the Crab Spindown



Chandra image

Model



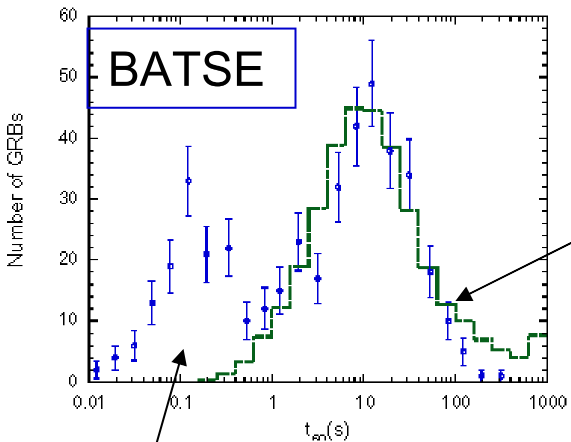
(Ap. J. Lett. 683, 45 (2008))

- Crab pulsar's spin rate is gradually slowing down
  - $\dot{f} \approx -3.7 \times 10^{-10}$ Hz s^{-1}
- The energy loss goes into EM and GW emission
- All into GW?

No. In fact, LIGO limit implies GW emission accounts for ≤ 4% of total spin-down power

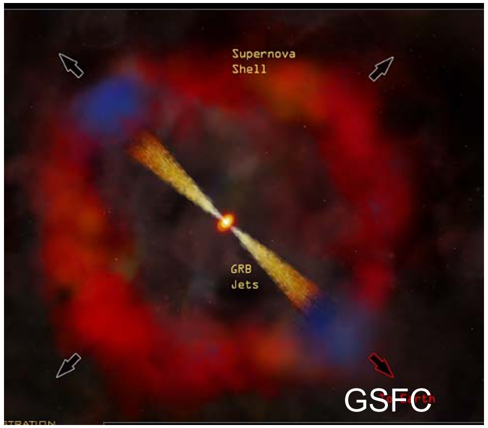
Getting close to spindown sensitivity for several other pulsars

Gamma-ray Bursts



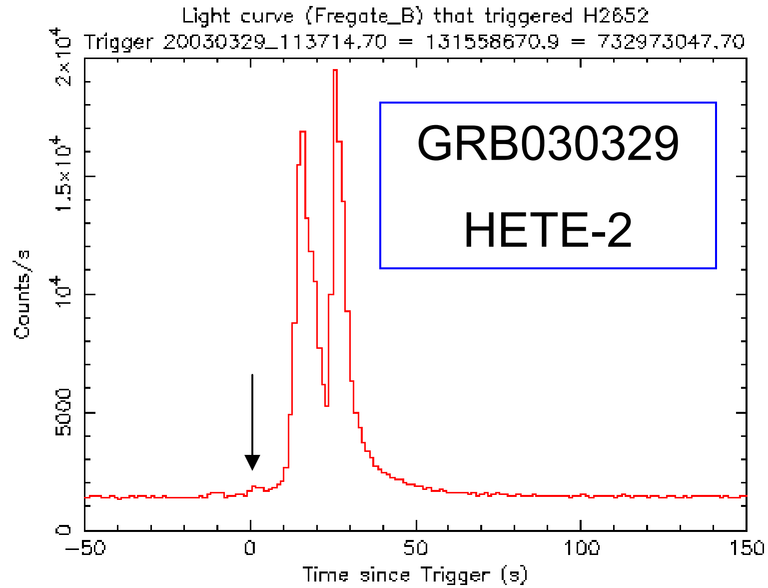
Long-duration GRBs

- Stronger afterglows → z
- SNe or "hypernovae"
- mean z ≈ 2.3



Short-duration GRBs

- Until 2005, no measured z's → enter **Swift**
- Now: some z's → "compact binary mergers"



Oct 6, 2005

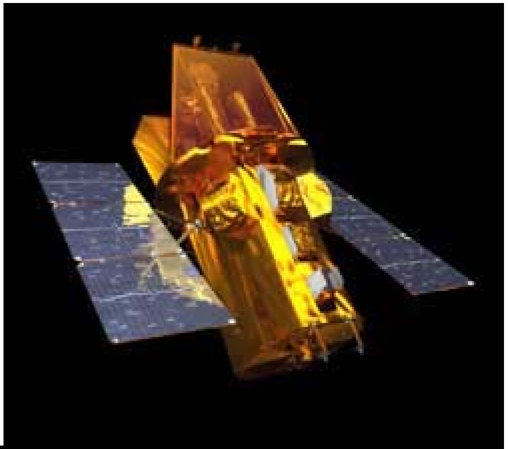
- mergers are efficient GW radiators
- much smaller z's (mean ≈ 0.6)

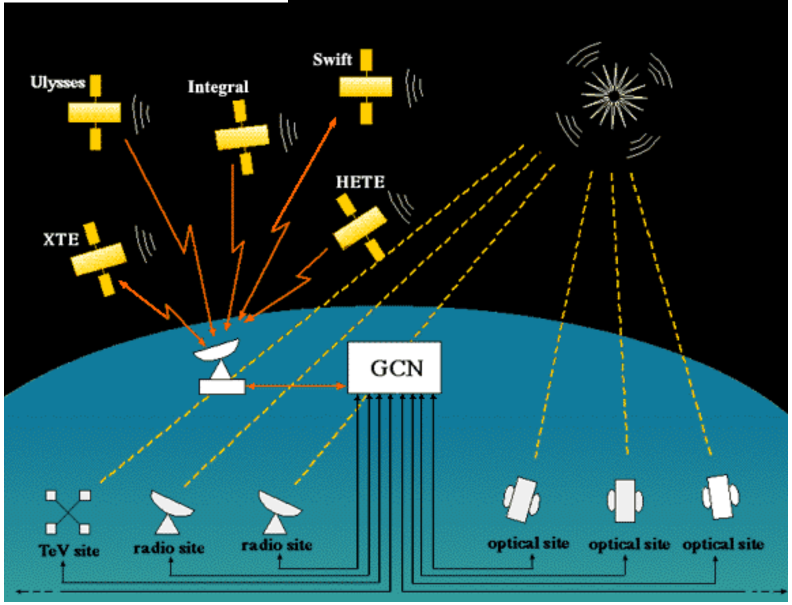
The GRB sample for the S5/VSR1 run

- **212 GRB triggers** from Nov. 4, 2005 to Oct. 1, 2007
  - 70% with double-IFO coincidence LIGO data
  - 45% with triple-IFO coincidence LIGO data
  - 15% short-duration GRBs
  - 25% with redshift
  - 20% fall in joint LIGO-Virgo times
  - all but a handful have accurate position information

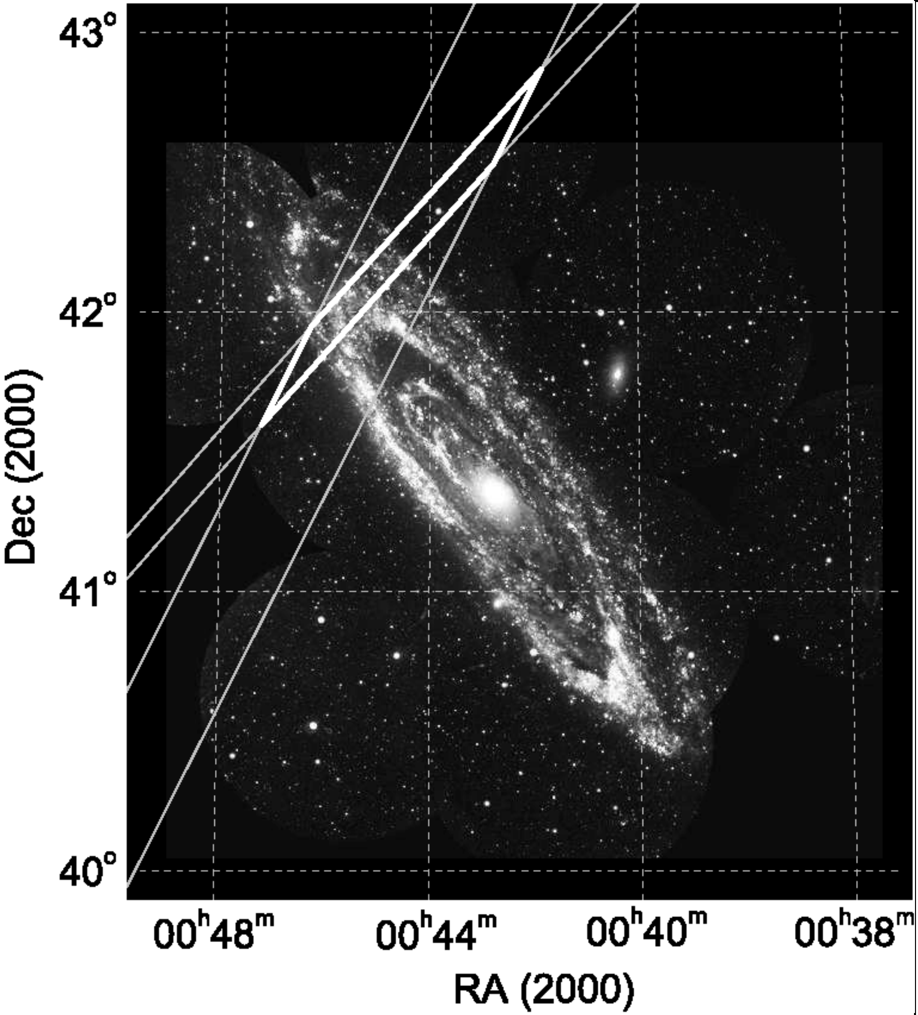
burst analysis has been completed; paper due out soon

GRB triggers were mostly from Swift; some were from IPN3, INTEGRAL, HETE-2





GRB 070201



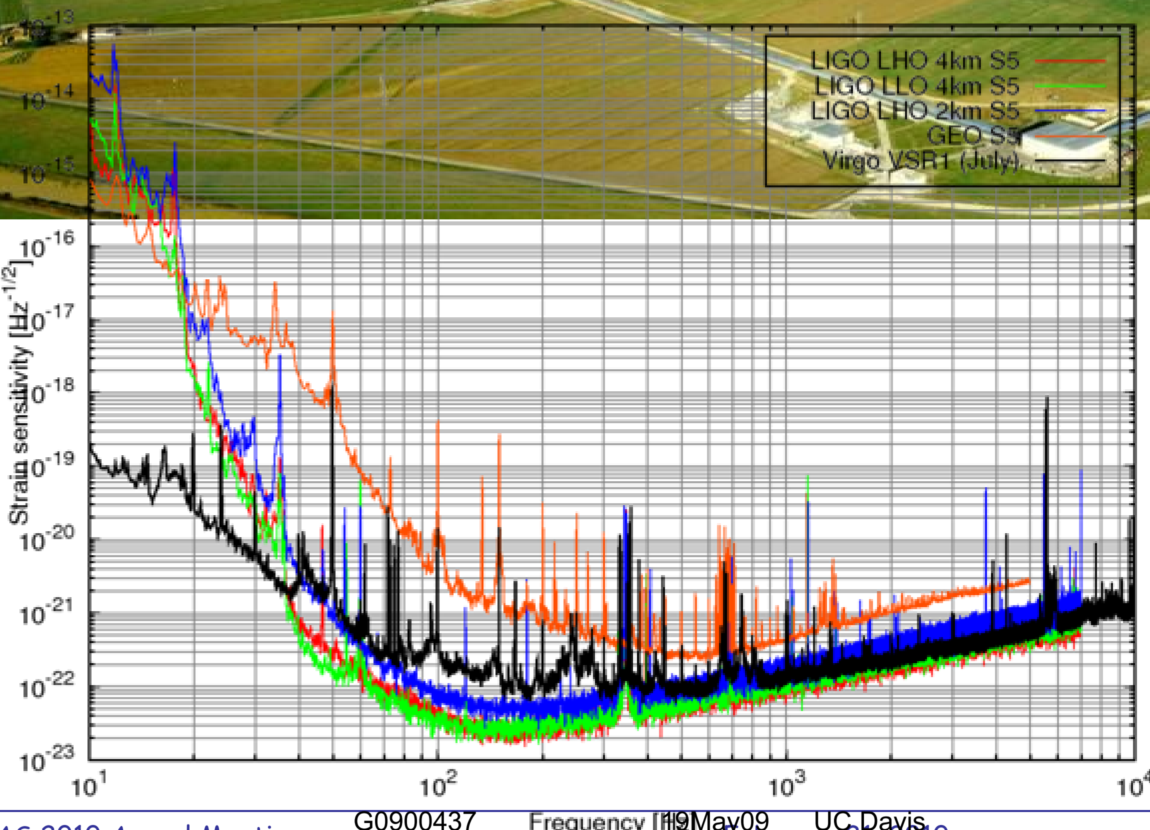
Revised error box: arXiv:0712.1502

- GRB 070201 – a short-duration gamma-ray burst with position consistent with M31 (Andromeda)
- Such a nearby GRB would have easily been observed by LIGO if due to a binary merger
- This hypothesis ruled out at ~99% CL
- Alternatives: a GRB behind M31 or an SGR in M31
- Astrophys. J. 681 (2008) 1419

Virgo

French-Italian project, located near Pisa, Italy; 3 km arms

Joint data-sharing agreement with the LSC, started 2007



LIGO, GEO, Virgo, July 2007

G0900437 19May09 UC Davis