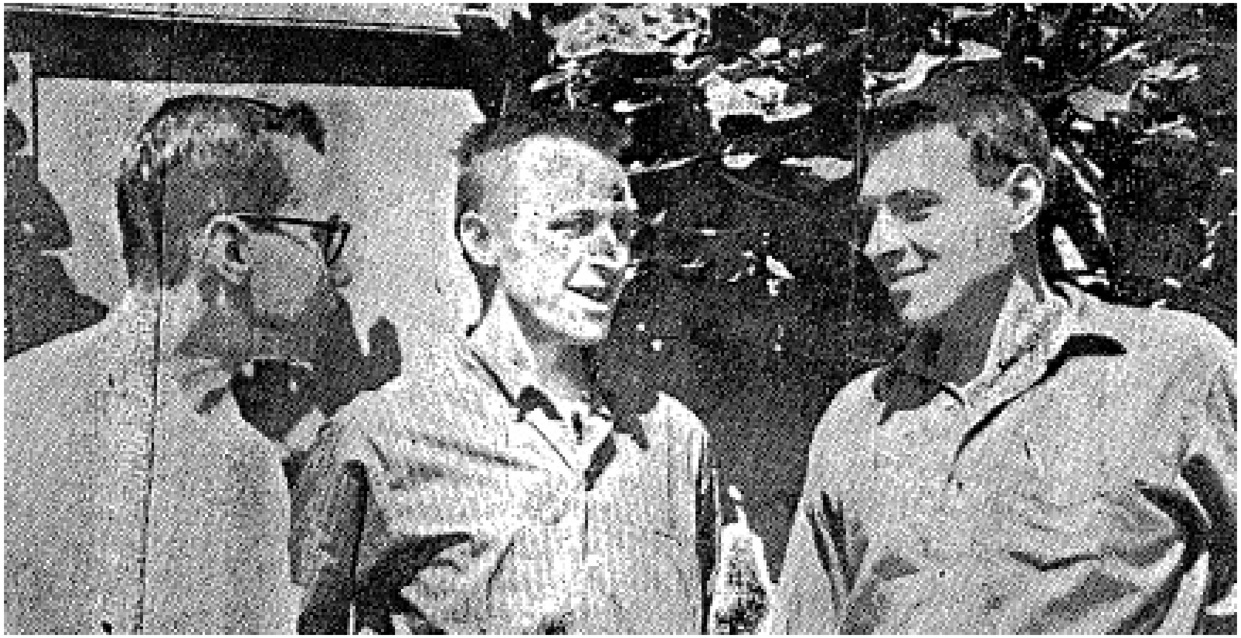
The Current State of Gravitational Wave Detection

R. Weiss , MIT

ADM-50 Texas A&M

November 8, 2009



1. History of Sub-Panel

This report is a summary of the deliberations and the recommendations of a Sub-Panel of the Management and Operations Working Group in Shuttle Astronomy commissioned by Dr. Nancy G. Roman of NASA Headquarters to consider the role of the space program in the field of experimental relativity and gravitation.

The panel members are Professors Peter Bender of the University of Colorado and the National Bureau of Standards, Charles Misner of the University of Maryland, Robert V. Pound of Harvard University and Rainer Weiss of M.I.T., chairman.

The panel met 4 times during 1975, and at several of the meetings it was joined by visitors interested in the field. The visitors were Dr. Rudolf Decher of NASA Huntsville, Dr. Nancy Roman, NASA Headquarters, Professors James Peebles of Princeton University, Irwin Shapiro of M.I.T. and Kip Thorne of Cal Tech.

The report introduces the reader to the fundamental problems in experimental relativity and gravitation and then follows with sections on various areas in the field. Each section reviews the present status of research and brings forward suggestions where the space program may have an impact.

2. Introduction

Gravitation is at the same time the dominant force in the universe for matter in the large as well as the weakest known fundamental interaction in nature. Gravitation opened the era

TABLE OF CONTENTS

1. History of Sub-Panel 1

2. Introduction 1

3. Fundamental Issues in Relativity and Gravitation . . . 4

4. Solar System Measurements of Relativistic Gravitational Effects 10

   a) Planetary Ranging Experiments 11

      1) Mercury Orbiter Mission 17
      2) Close Solar Probe Mission 20

   b) Deflection of Electromagnetic Waves by the Sun 22

   c) The Gyroscope in Orbit 24

5. Tests of the Principle of Equivalence 28

   a) "Eötvös" Experiments 28

   b) Red Shift Measurements 31

   c) Other Clock Experiments 33

   d) Second Order Red Shift 35

6. Gravitational Radiation 35

7. Search for Highly Condensed Objects--Black Holes . . . 43

8. Cosmology and Gravitation 45

9. Summary and Recommendations 48

NATIONAL SCIENCE FOUNDATION
ADVISORY COMMITTEE FOR PHYSICS

December 12-13, 1983
1800 G Street, N.W.
ROOM 540

Tentative Discussion Schedule

MONDAY, DECEMBER 12

9:00 a.m.	Introductions and Remarks - J. Armstrong, M. Bardon
9:30 a.m.	Oversight Review of the NSF Elementary Particle Physics Program
	NSF Role in Elementary Particle Physics - D. Berley
10:00 a.m.	DOE and Elementary Particle Physics - W. Wallenmeyer
10:30 a.m.	Report of Subcommittee for Review of NSF Elementary Particle Physics Program - R. Schwitters
11:00 a.m.	Discussion of Oversight Review
12:00 Noon	Lunch
1:30 p.m.	Cornell Upgrading - B. McDaniel
2:30 p.m.	Discussion of Elementary Particle Physics Program and Related Issues
6:00 p.m.	Adjourn

TUESDAY, DECEMBER 13

9:00 a.m.	Funding Pressures for FY 1984/1985 and Planning of Major Projects in Physics Division - M. Bardon
9:30 a.m.	University of Illinois Microtron - L. Cardman
10:30 a.m.	MIT/Caltech Laser Interferometer Project - R. Drever/R. Weiss
12:00 Noon	Lunch
1:30 p.m.	Report of Review Subcommittee - R. Schwitters
2:00 p.m.	Discussion of Long Range Plans
3:00 p.m.	Discussion with NSF Director, E. Knapp
3:30 p.m.	Continuation of Long Range Plan Discussion and Other Committee Business
6:00 p.m.	Adjourn

ADVISORY COMMITTEE FOR PHYSICS

(Chairman: Dr. John A. Armstrong)

Dr. Ralph D. Amado
Department of Physics
University of Pennsylvania
Philadelphia, Pennsylvania 19104
(215, 898-8147)

Dr. John A. Armstrong
IBM Corporation
T. J. Watson Research Center
PO Box 218, Dept. 460, Location 16-112
Yorktown Heights, New York 10598
(914, 945-1228)

Dr. Sam M. Austin
Department of Physics
and Astronomy
Michigan State University
East Lansing, Michigan 48824
(517, 353-7602)

Dr. Gordon A. Baym
Department of Physics
University of Illinois
Urbana, Illinois 61801
(217, 333-4363)

Dr. George B. Benedek
Department of Physics 13-2005
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617, 253-4828)

Dr. Peter G. Bergmann
Department of Physics
New York University
New York, New York 10003
(212, 598-7634)

Dr. Richard Blankenbecler
Stanford Linear Accelerator Center
Post Office Box 4349
Stanford, California 94305
(415, 854-3300 x2670)

Dr. Eugene D. Commins
Department of Physics
University of California
Berkeley, California 94720
(415, 642-2321)

Dr. Stanley Deser
Department of Physics
Brandeis University
Waltham, Massachusetts 02254
(617, 647-2845)

Dr. William A. Fowler
W. K. Kellogg Radiation Laboratory 106-38
California Institute of Technology
Pasadena, California 91125
(213, 356-4272)

Dr. Lee G. Pondrom
Department of Physics
University of Wisconsin
Madison, Wisconsin 53706
(608, 262-2284)

Dr. Roy F. Schwitters
*Fermi National Accelerator Laboratory
Post Office Box 500
Batavia, Illinois 60510
(312, 840-4590 FTS: 370-4590)
*TEMPORARY, 1982-83

Dr. John F. Waymouth
Laboratory Director
Lighting Products Group
GTE Products Corporation
Sylvania Lighting Center
Danvers, Massachusetts 01923
(617, 777-1900)

(November 1983)

Subcommittee:

G. Baym

S. Deser

R. Schwitters

(1) Final, unanimously appr. 12/1

¶ The committee is impressed with the long-range scientific potential of gravitational wave detection. It will not only test our basic understanding of gravitation, but provide an entirely new window on the Universe. ¶ We have considered the major interferometric laser detection system now being developed by the Caltech and MIT groups. ¶ ~~As with~~

We note that not only is this an outstanding scientific opportunity, but the Foundation is the only source of support for ground-based gravitational physics.

¶ As with any attempt at a qualitative advance, there are risks: ~~[illegible]~~ Here the uncertainties involve both the magnitude of the signals to be detected and the large extrapolation of known experimental technique inherent in the proposed scale.

(2)

~~The committee~~, We find, however, the fundamental scientific merits of such an investigation so important as to be worth a substantial investment.

LIGO Scientific Collaboration

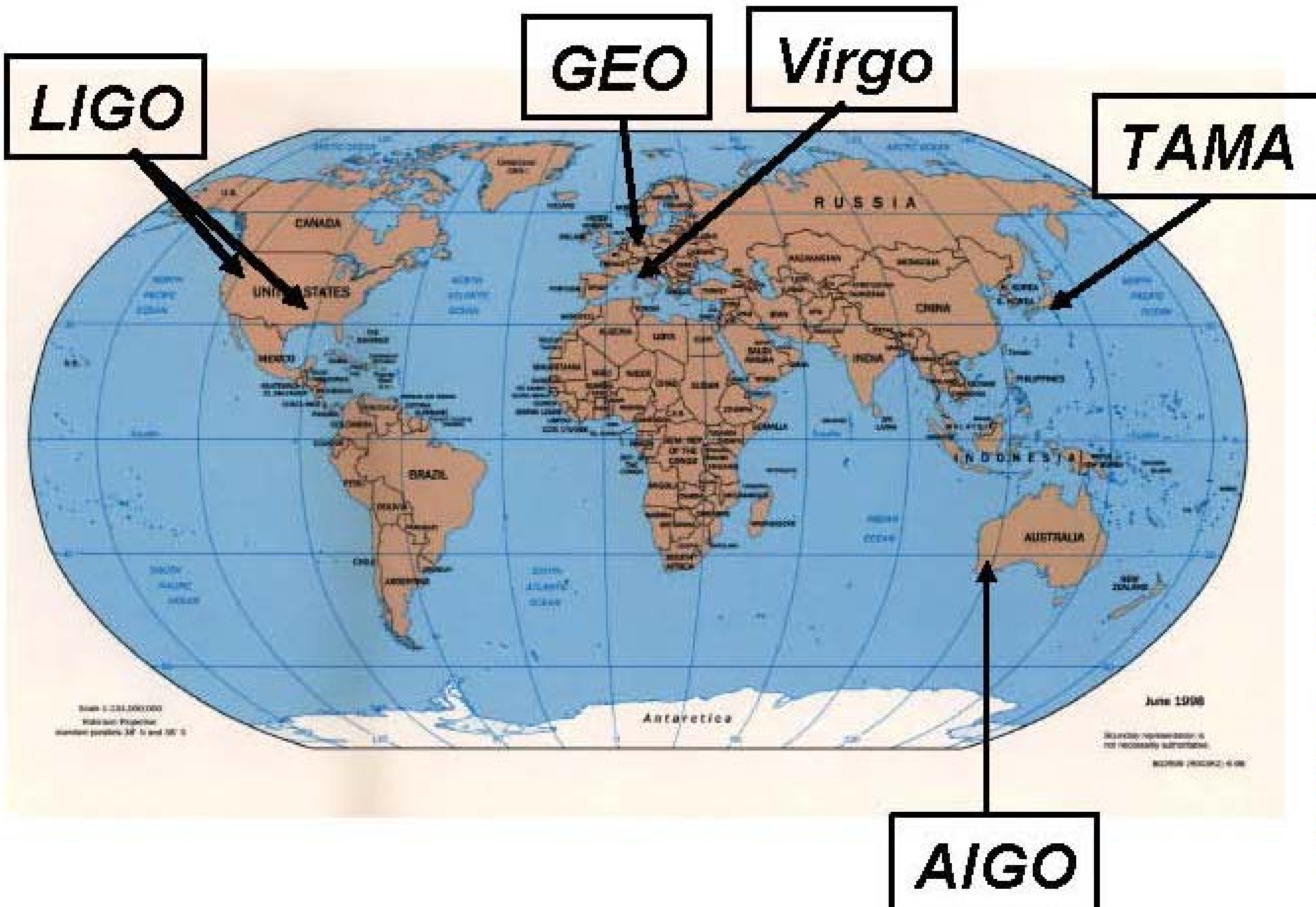
- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle 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 Gravit

- University of Michigan
- University of Minnesota
- The University of Mississippi
- 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 Washingto

Interferometers

international network

Simultaneously detect signal (within msec)



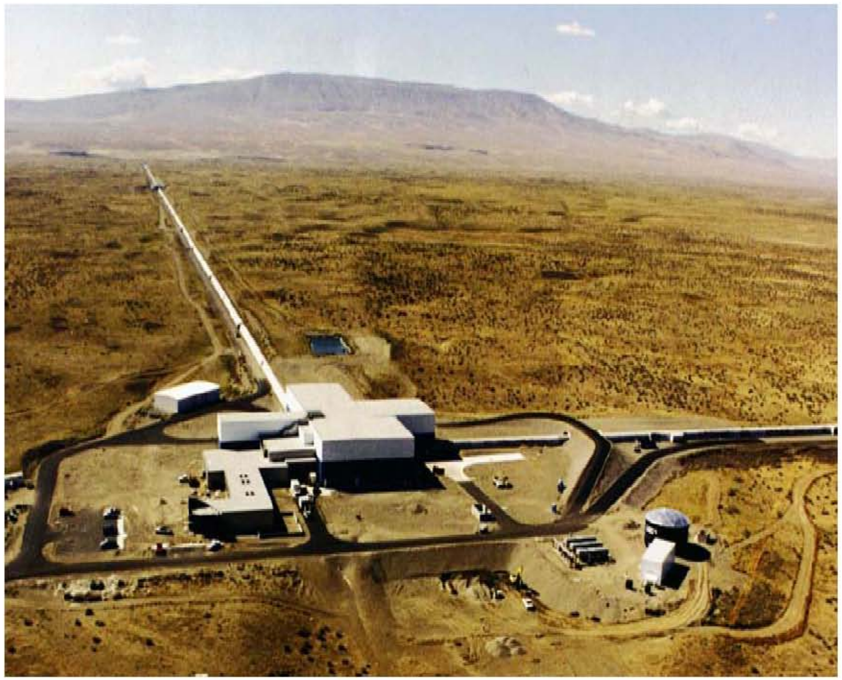
detection confidence

locate the sources

decompose the polarization of gravitational waves

VIRGO Interferometer   Cascina, Italy

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

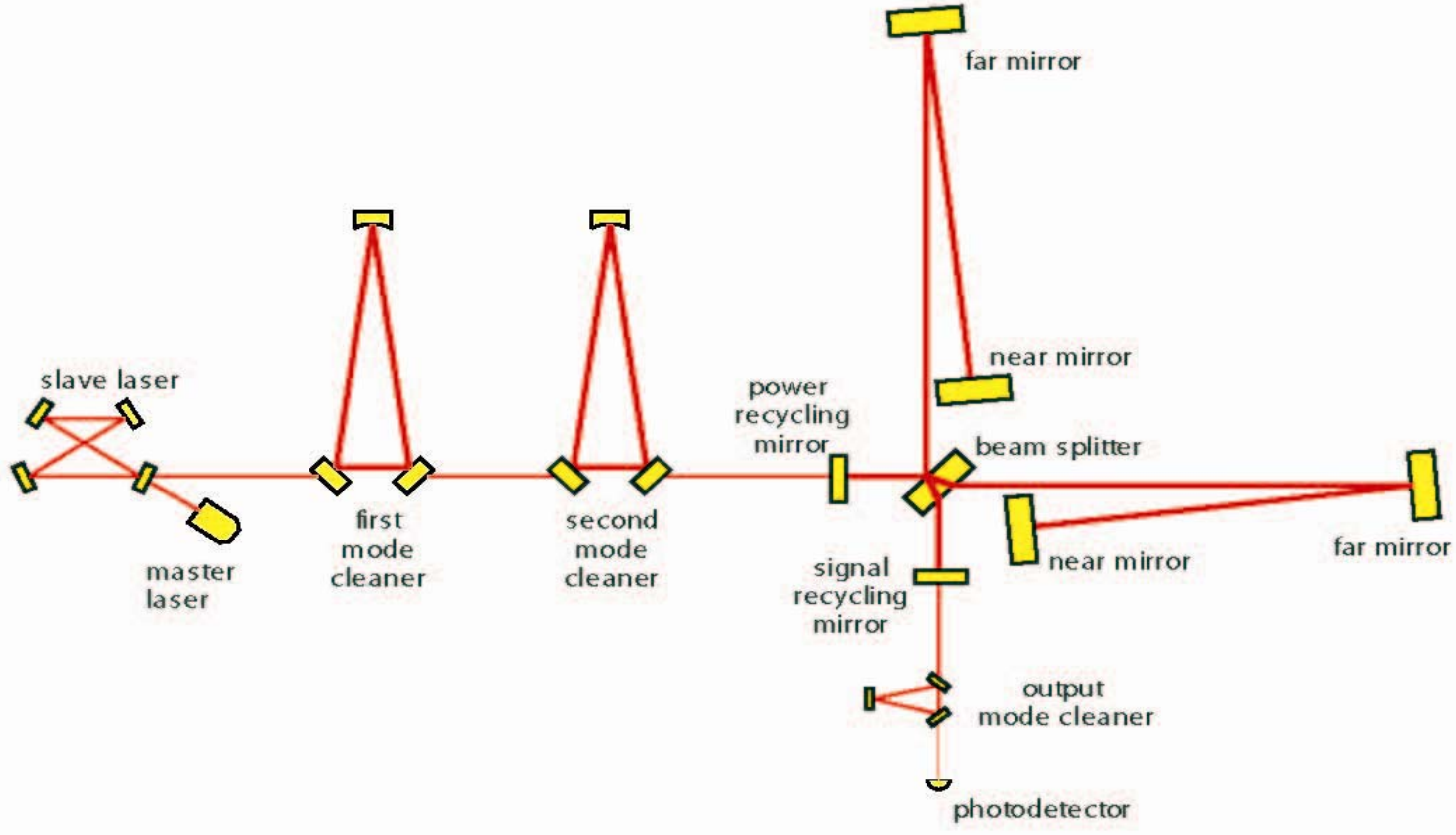
2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer

GEO Interferometer Hannover, Germany



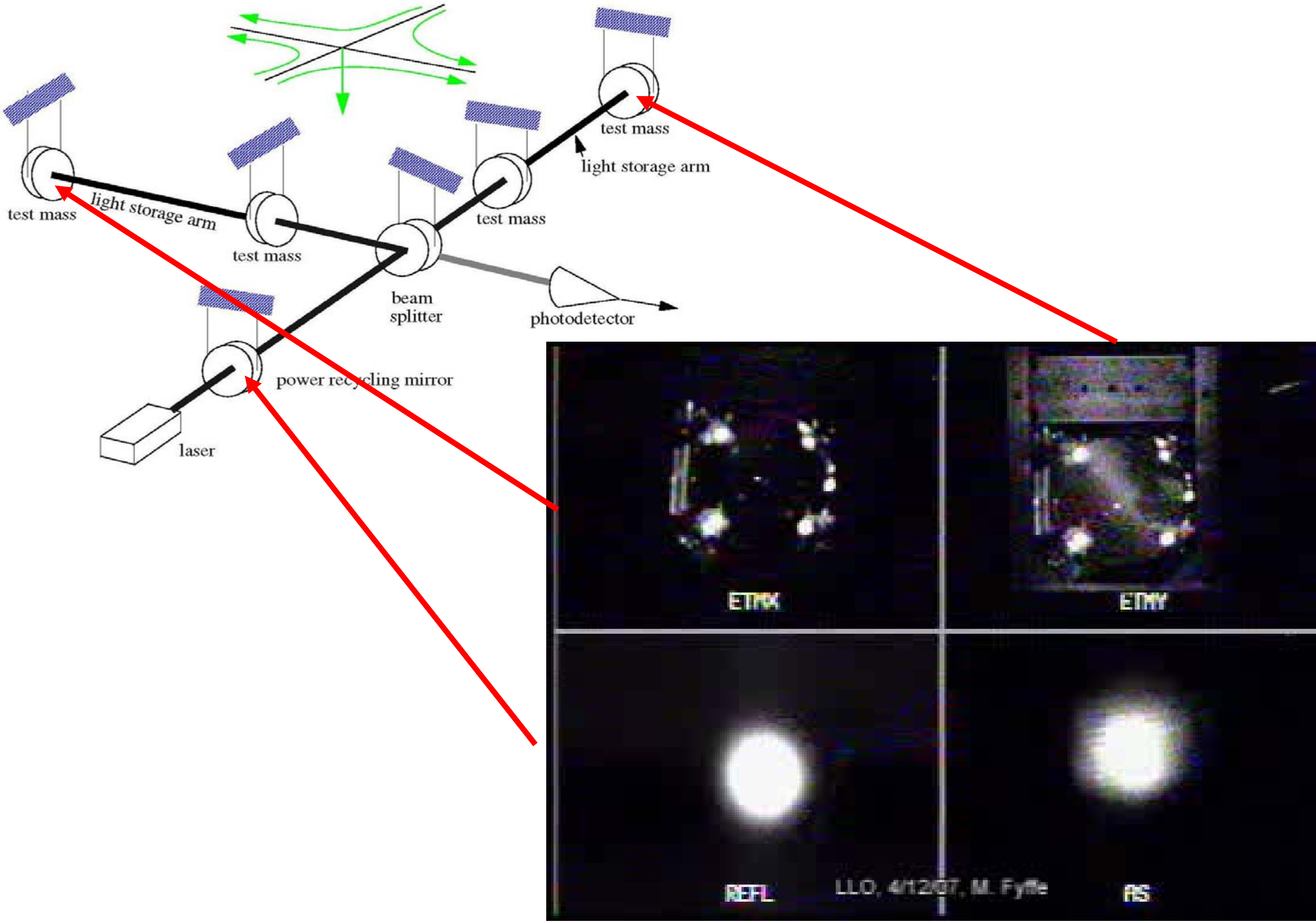
GEO Interferometer Configuration

Measurement challenge

- Needed technology development to measure:

$$h = \Delta L/L < 10^{-21}$$

$$\Delta L < 4 \times 10^{-18} \text{ meters}$$


test mass
light storage arm
test mass
test mass
test mass
light storage arm
beam splitter
photodetector
power recycling mirror
laser
ETMX
ETMY
REFL
LLO, 4/12/07, M. Fyffe
AS

NOISE SOURCES

Noise Terms Influencing the Strain Measurement

* Shot (Poisson) Noise

Light Amplitude Noise

Laser Frequency Fluctuations

Scattering of Light by

1) Moving Sources
2) Stationary Sources

Laser Beam Position and Angle Jitter

Residual Gas Column Density Fluctuations

Fluctuation Forces Moving the End Points

* Seismic Noise

* Thermal Noise in the Suspension Elements

Thermal Noise Driving the Mirror Normal Modes

Optical / Mechanical Imbalance Radiation Pressure Force

"Radiometer" Force Driven by Light Amplitude Noise

Fluctuating External Gravitational Gradients

Fluctuating "Patch" Electric Fields

Fluctuating Magnetic Fields Acting on Iron Impurities

Cosmic Ray Muons

The "Naive" Quantum Limit

* Important Terms Influencing *Initial* Sensitivity Goals

FRINGE SENSING

wavelength 1×10^{-6} m

$$h = \frac{x}{L} \sim \frac{\lambda}{Lb\sqrt{\dot{N}\tau}}$$

arm length = 4000 m

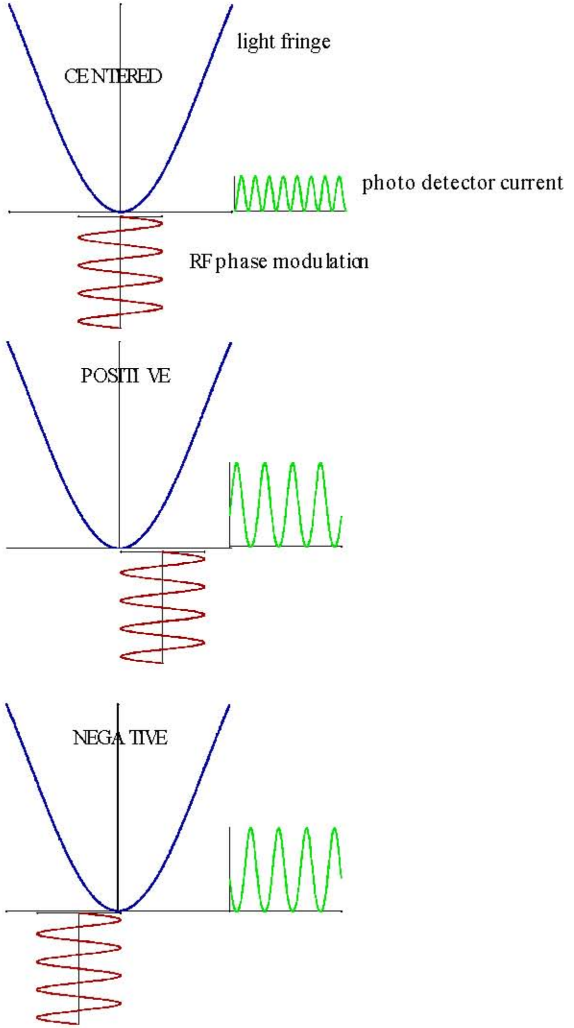
equivalent # of passes = 100

number of quanta/second at the beam splitter

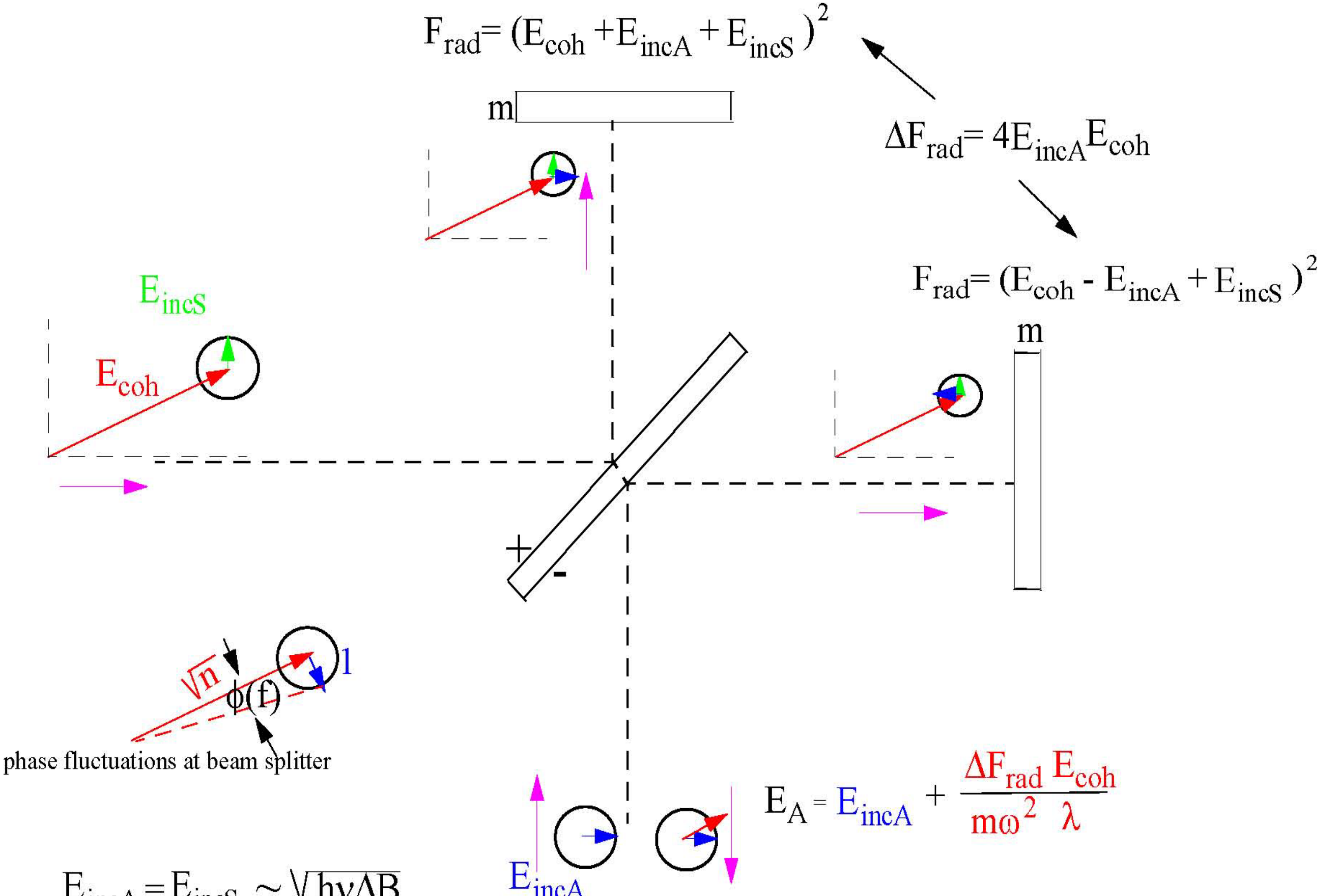
integration time

300 watts at beam splitter = 10^{21} identical photons/sec

$h = 6 \times 10^{-22}$ integration time 10^{-2} sec



Quantum Noise in the Michelson Interferometer



$E_{incA} = E_{incS} \sim \sqrt{h\nu\Delta B}$

$E_{coh} \sim \sqrt{nh\nu}$

Prof Robert Pound smelled a rat in 1975

Carlton Caves got it right in 1980

PENDULUM THERMAL NOISE

Pendulum Brownian motion

Dissipation leads to fluctuations

τ = coherence or damping time

= Q x period of oscillator

Exchange with surroundings:

$$E(\text{thermal}) = \frac{kT\ t}{\tau}$$

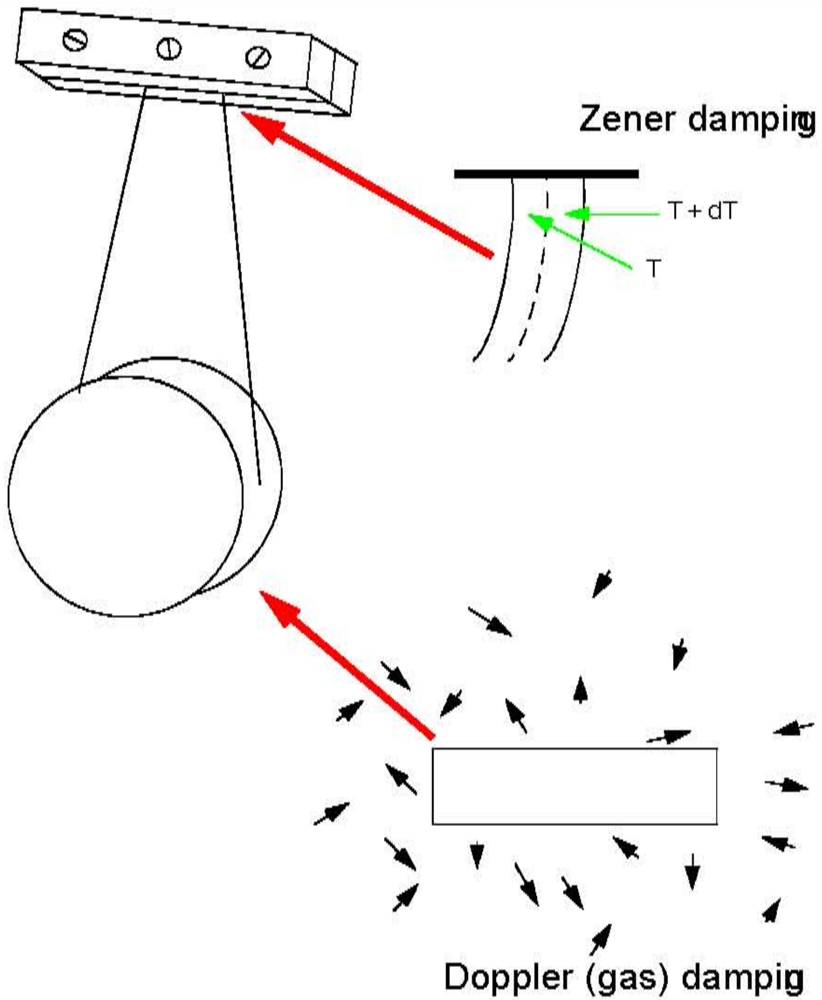
Large τ => smaller fluctuations

Mechanisms

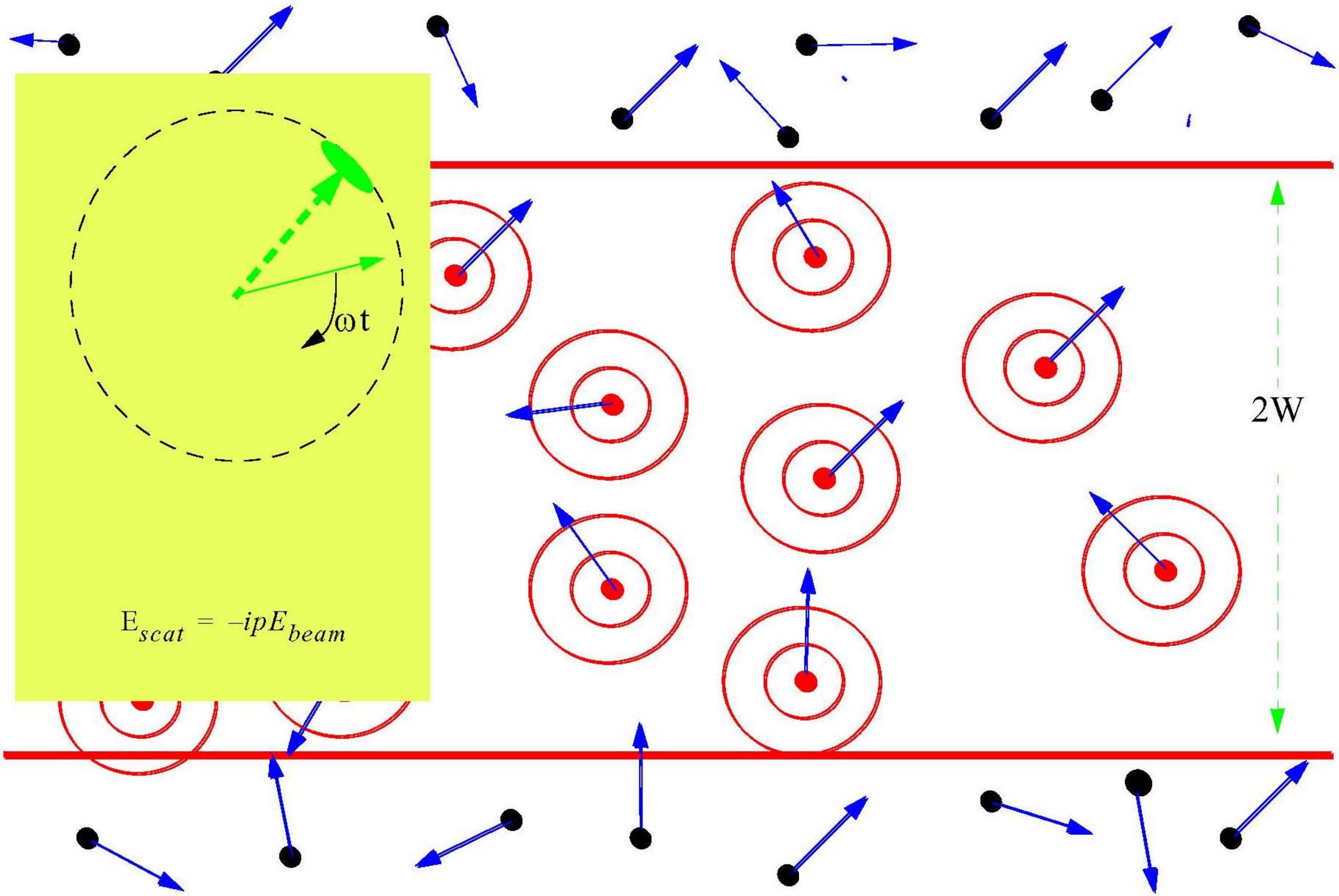
velocity dependent – viscous

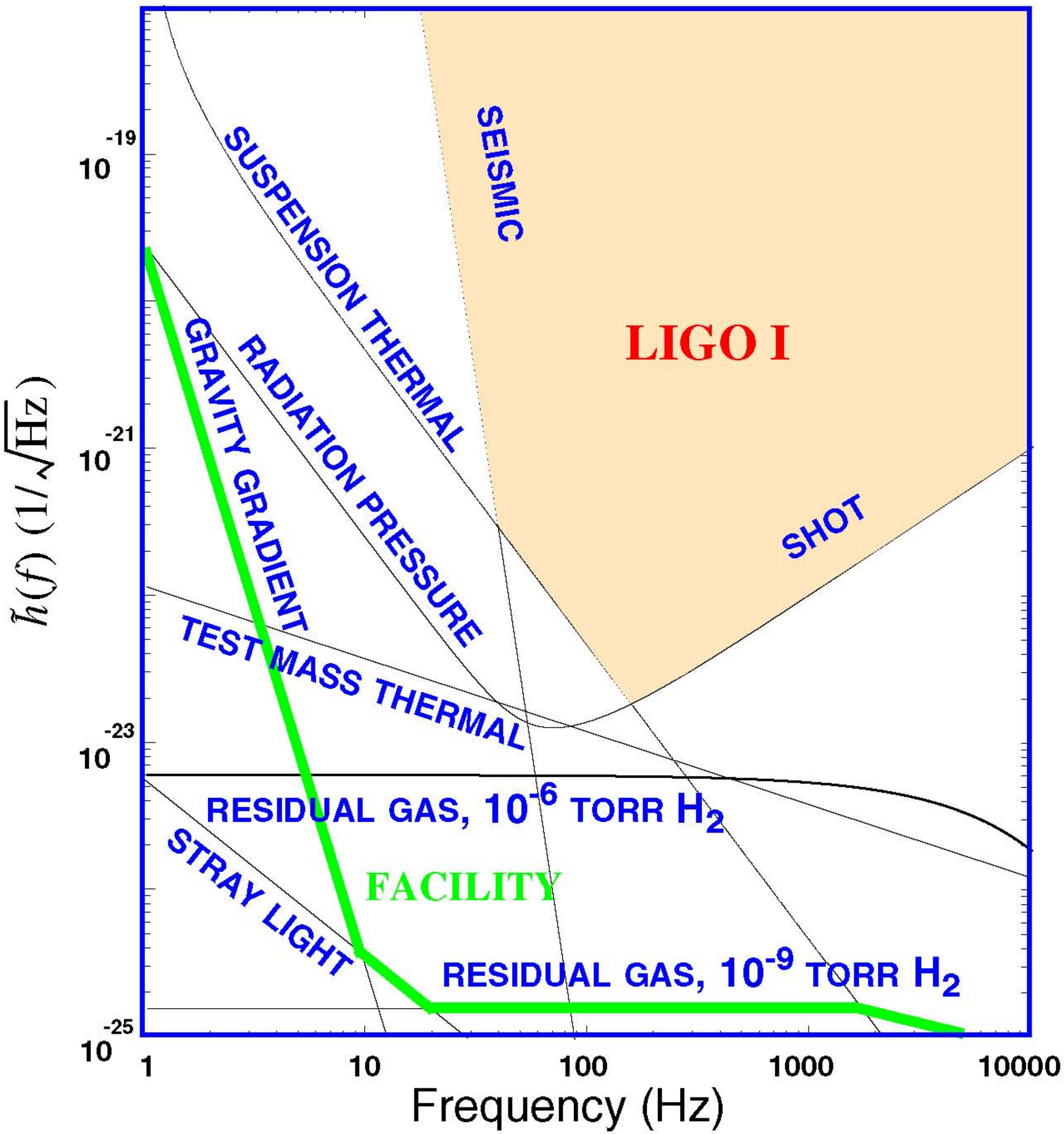
position dependent lag – structure

thermo-elastic - Zener



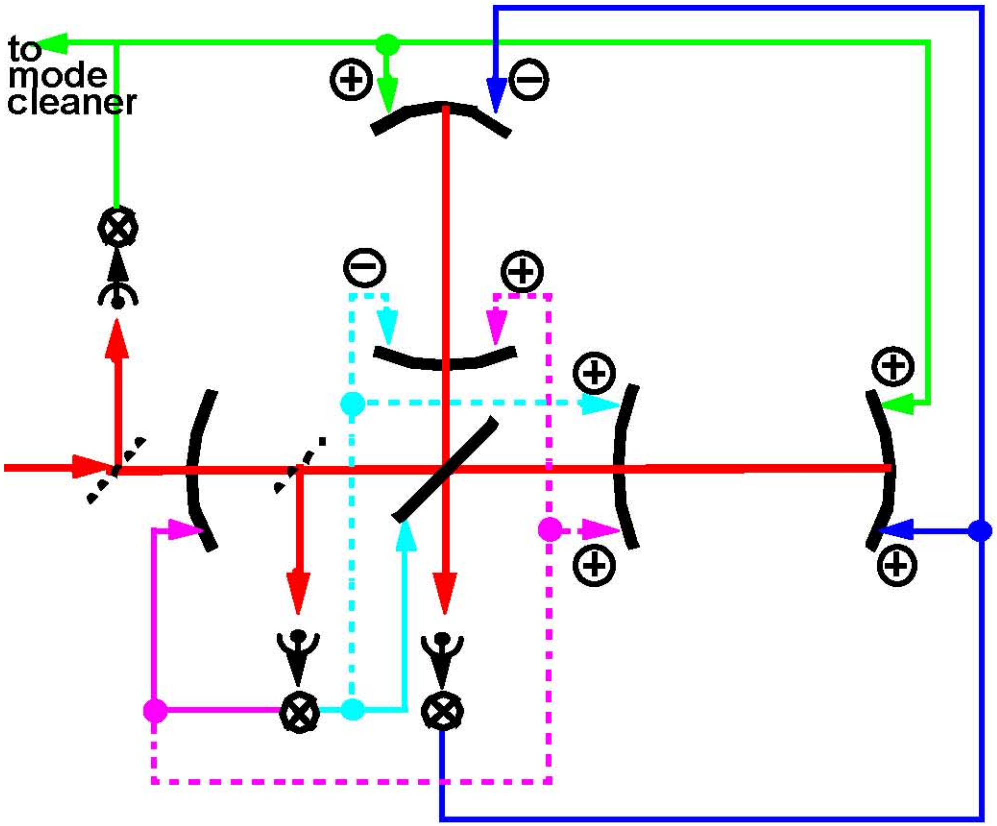
Phase noise from molecular scattering





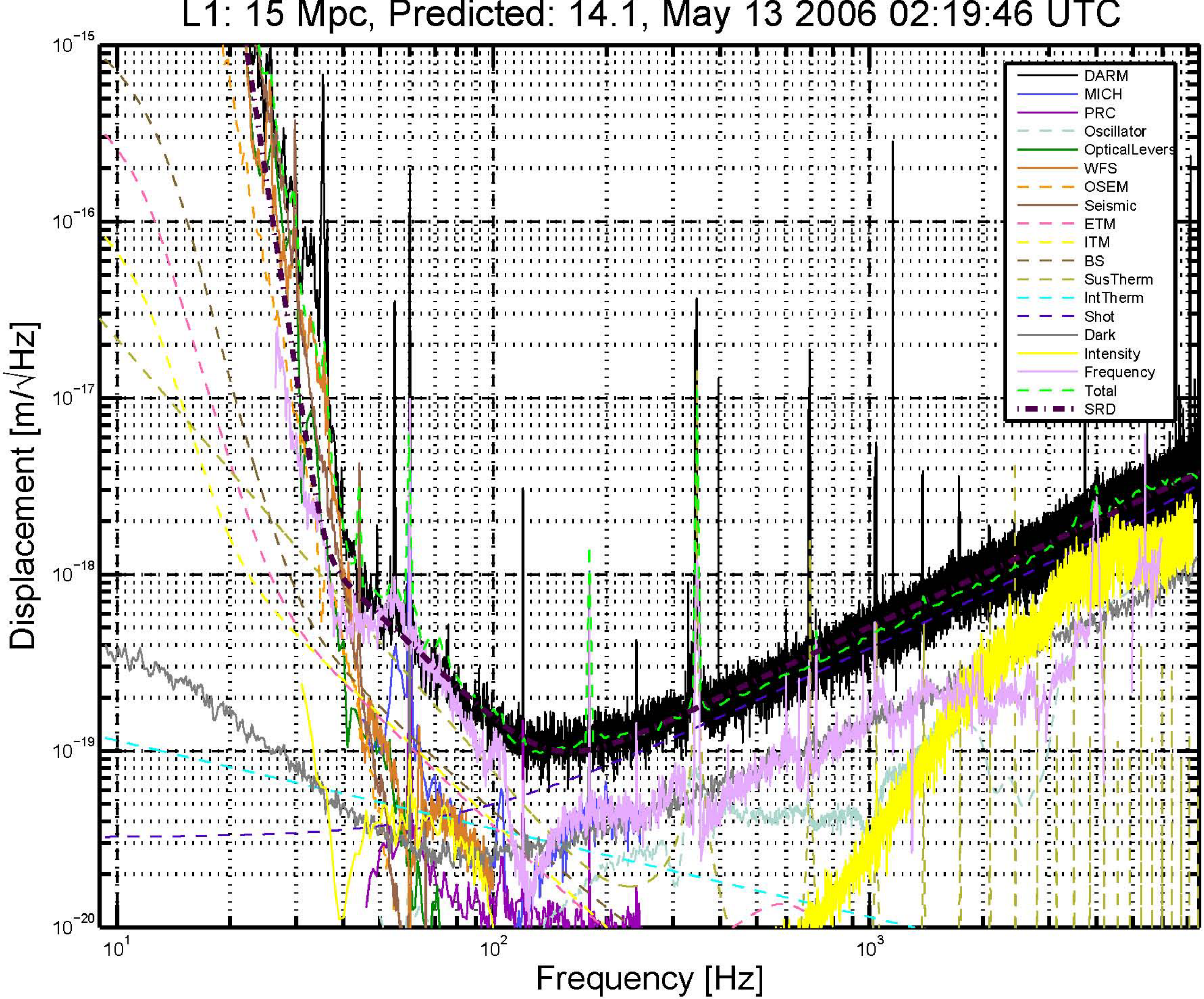
LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10-6 TORR H2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10-9 TORR H2
10-19
10-21
10-23
10-25
1
10
100
1000
10000
Frequency (Hz)
h̃(f) (1/√Hz)

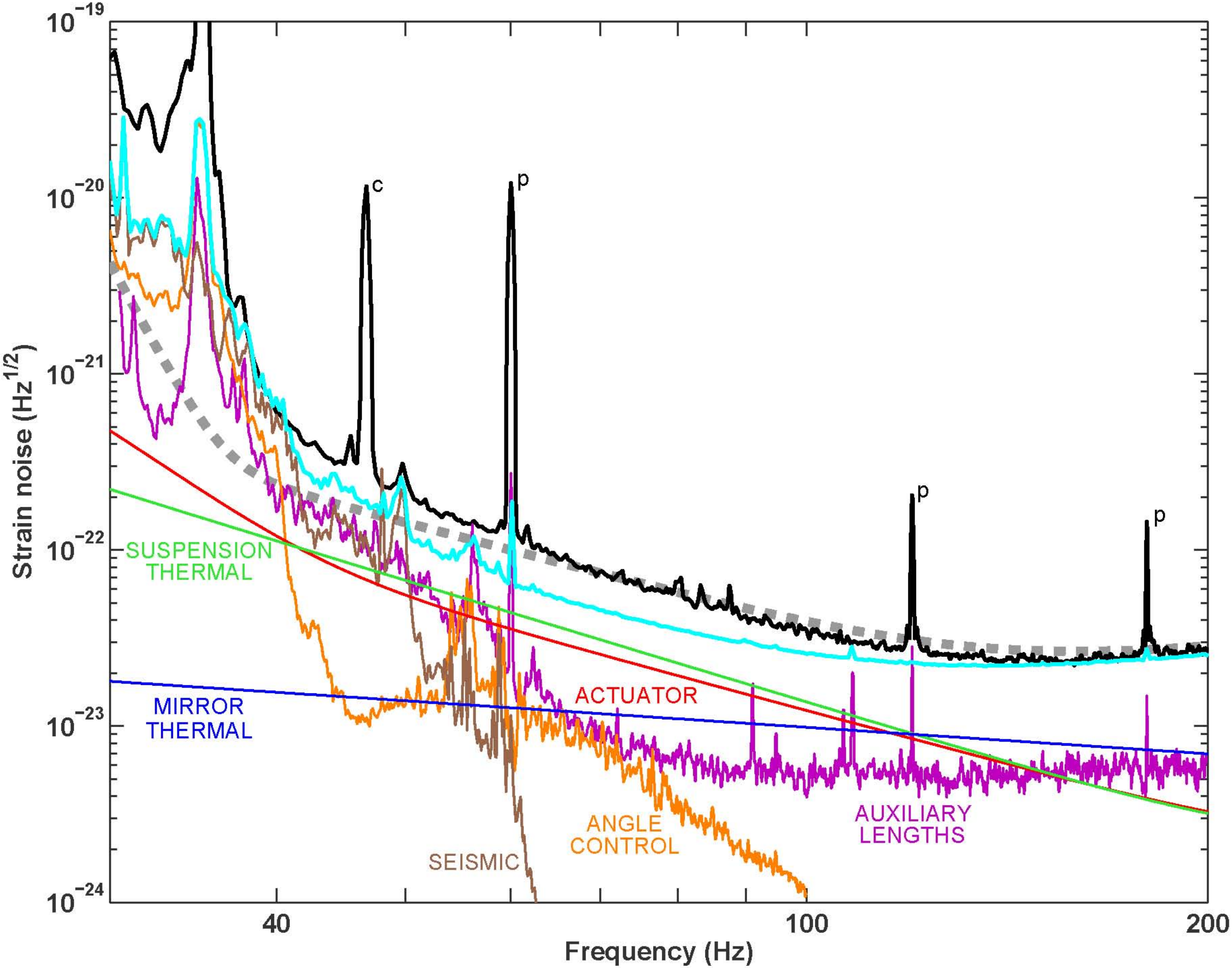
Feedback Control Systems



example: cavity length sensing & control topology

- Array of sensors detects mirror separations, angles
- Signal processing derives stabilizing forces for each mirror, filters noise
- 5 main length loops shown; total ~ 25 degrees of freedom
- Operating points held to about 0.001 Å, .01 μrad RMS
- Typ. loop bandwidths from ~ few Hz (angles) to > 10 kHz (laser wavelength)


L1: 15 Mpc, Predicted: 14.1, May 13 2006 02:19:46 UTC
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD
Displacement [m/√Hz]
Frequency [Hz]
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^1
10^2
10^3



Strain noise (Hz^1/2)
Frequency (Hz)
10^−19
10^−20
10^−21
10^−22
10^−23
10^−24
40
100
200
c
p
p
p
SUSPENSION
THERMAL
MIRROR
THERMAL
ACTUATOR
SEISMIC
ANGLE
CONTROL
AUXILIARY
LENGTHS

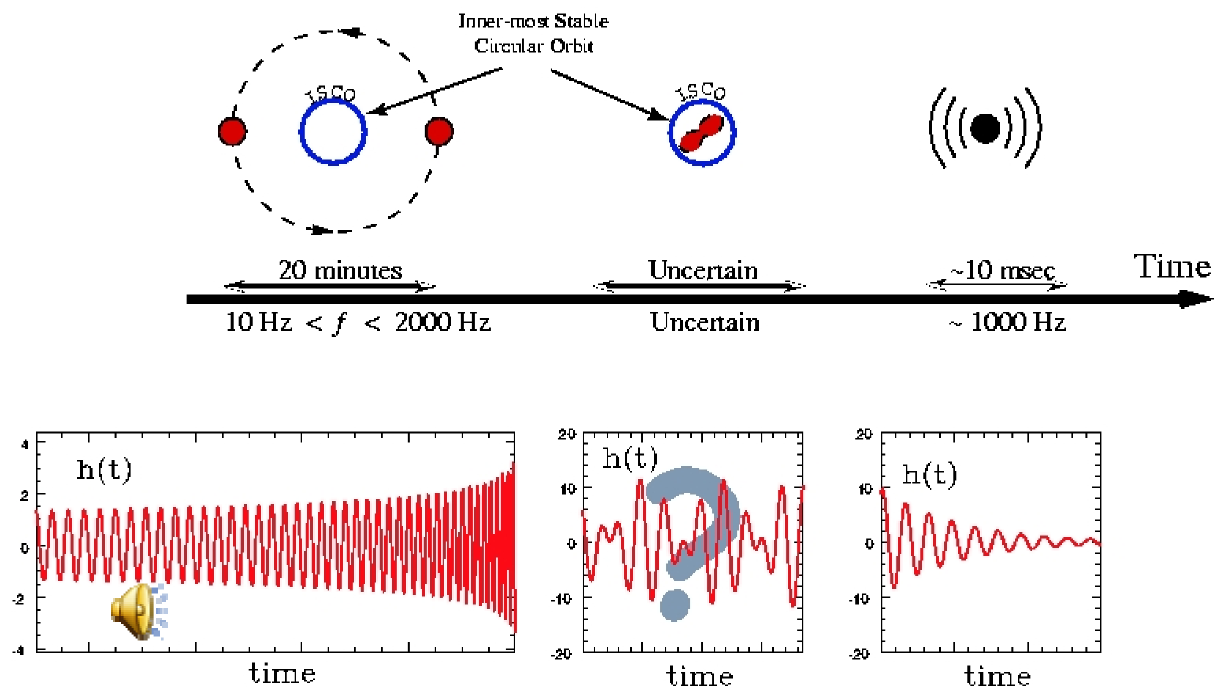
Classes of sources and searches

inspiral S5

- Compact binary inspiral: template search
  - BH/BH
  - NS/NS and BH/NS
- Low duty cycle transients: wavelets,T/f clusters
  - Supernova
  - BH normal modes
  - Unknown types of sources
- Externally triggered searches
  - Gamma bursts
  - EM transients
- Periodic CW sources
  - Pulsars
  - Low mass x-ray binaries (quasi periodic)
- Stochastic background
  - Cosmological isotropic background
  - Foreground sources : gravitational wave radiometry

Gravitational waves from compact binaries

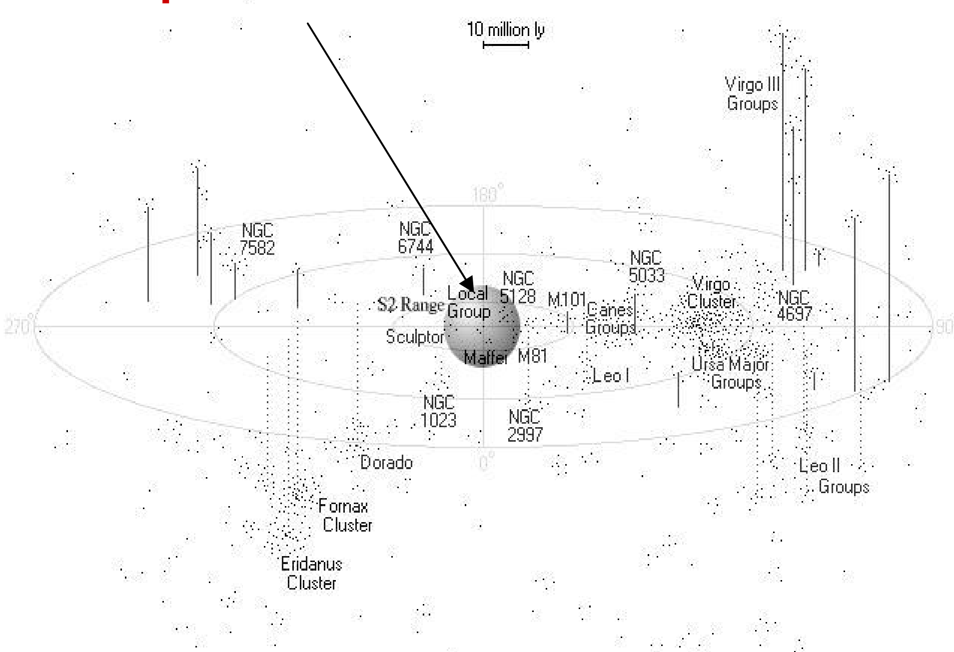
- LIGO is sensitive to gravitational waves from binary systems with neutron stars & black holes
  - Waveforms depend on masses and spins.
- Binary neutron stars
  - Estimates give upper bound of 1/3 yr in LIGO S5
- Binary black holes
  - Estimates give upper bound of 1/yr in LIGO S5



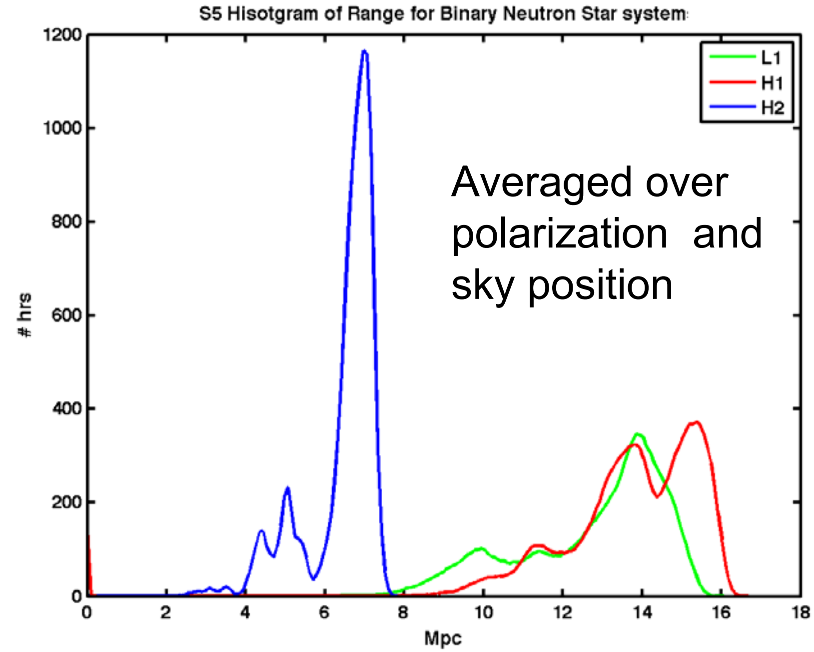
P. Brady

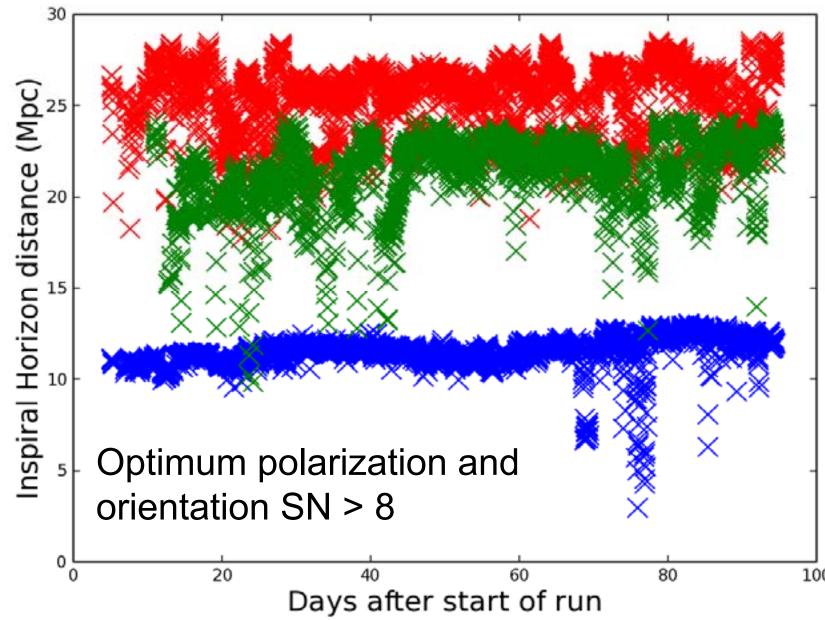
Binary Neutron Stars: S5 Search (Preliminary)

S2 Horizon Distance
1.5 Mpc

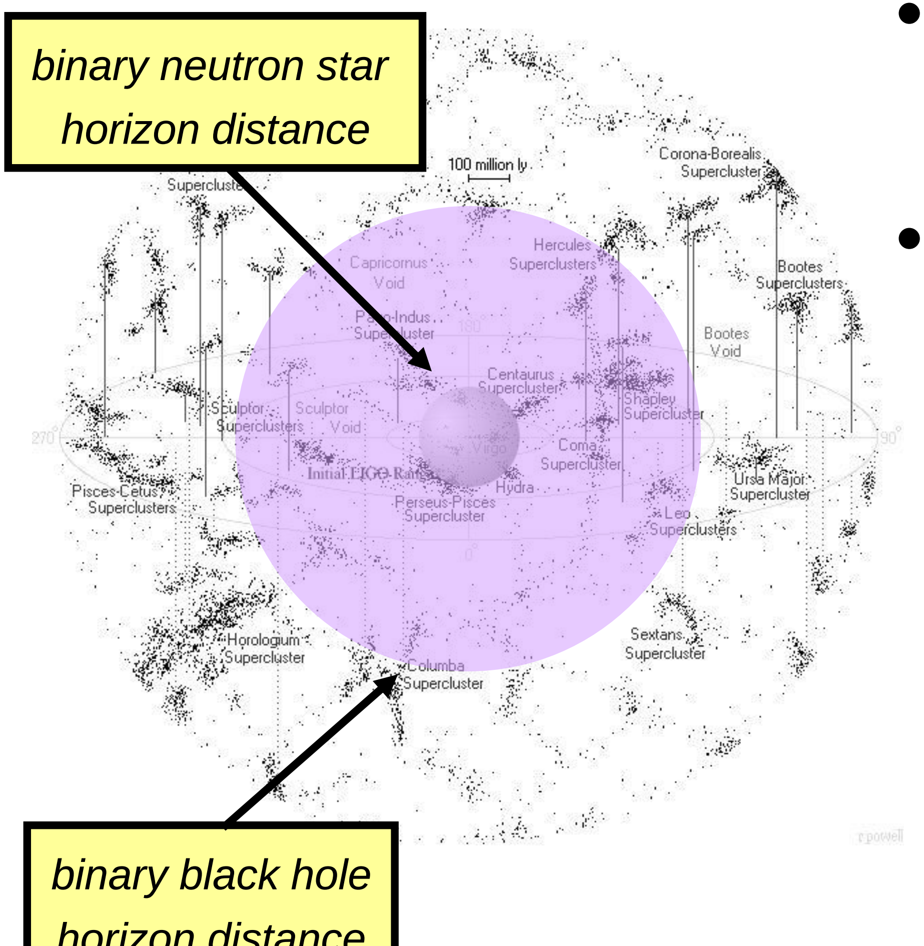


P. Brady, G. Gonzalez

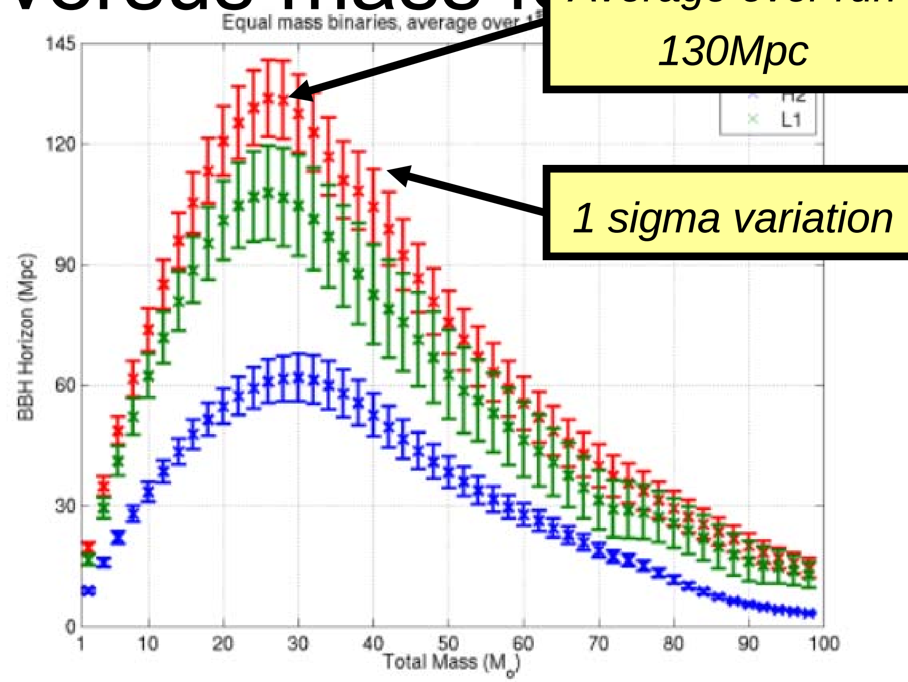




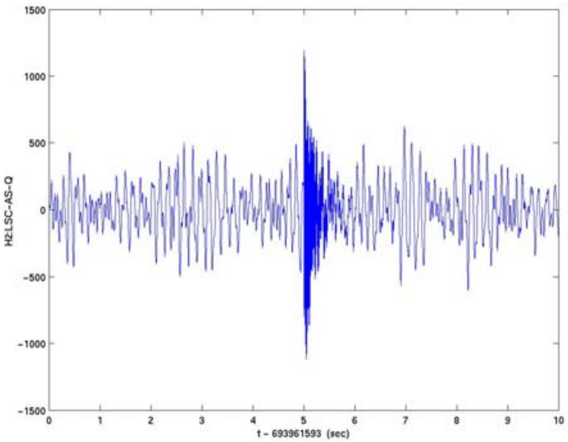
Binary Black Holes
S5 Search

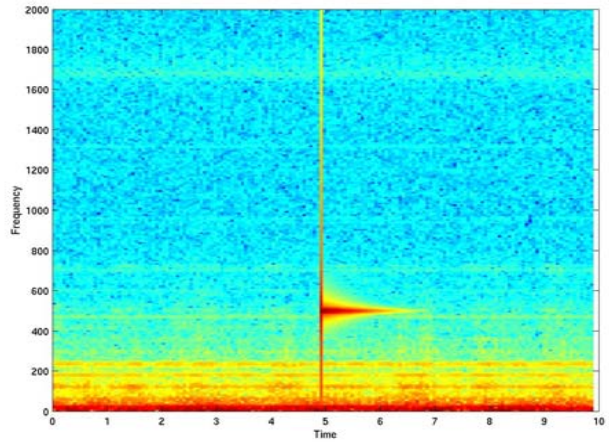


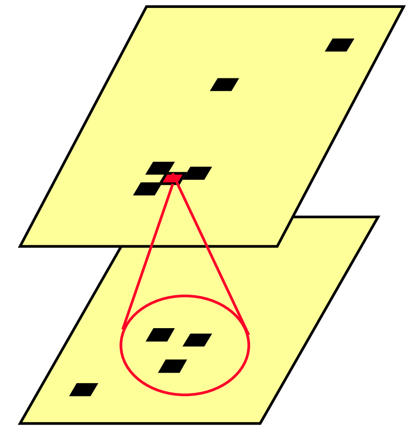
- 3 months of S5 analyzed
- Horizon distance versus mass fo



Burst search: a time-frequency method



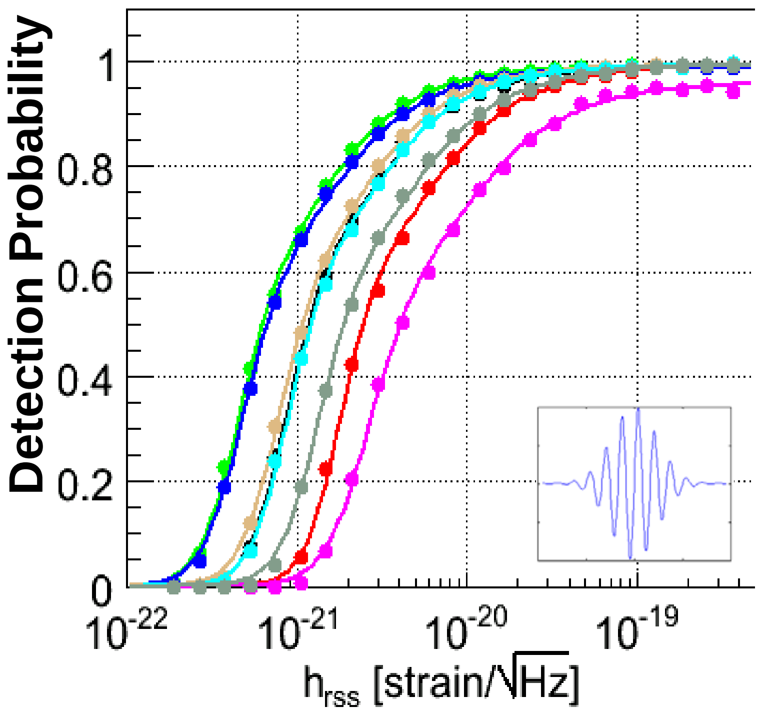


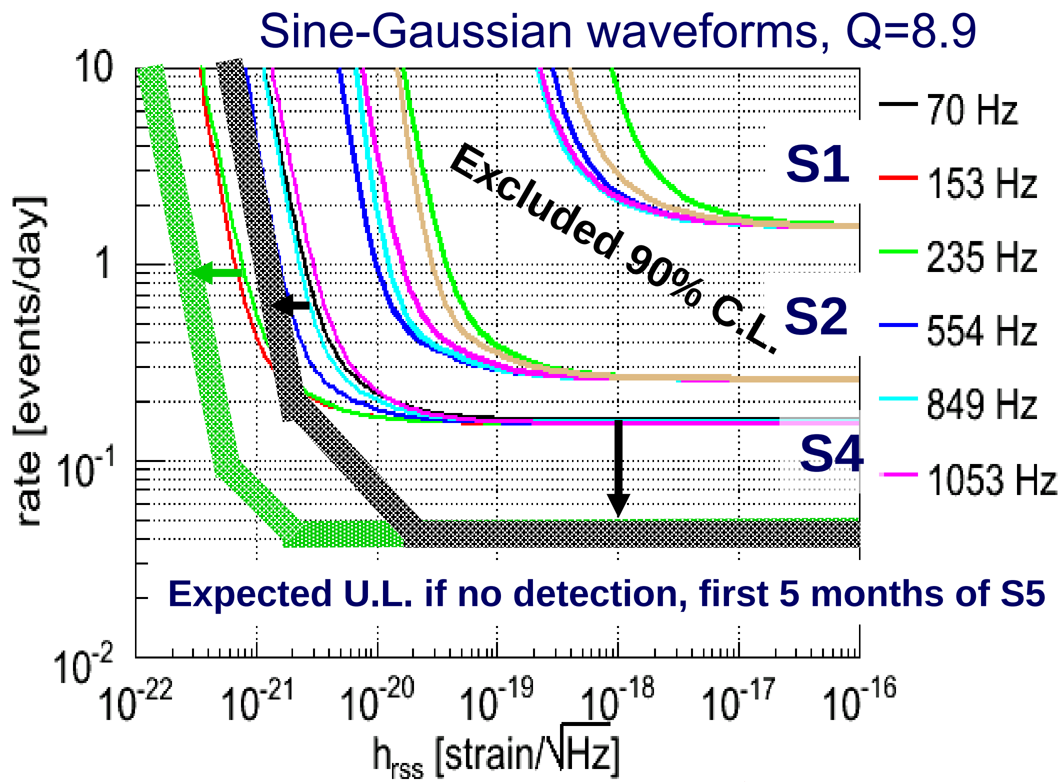


- Compute time-frequency decomposition in a Fourier or wavelet basis
- Threshold on power in a pixel; search for clusters of pixels
- Basic assumption: multi-interferometer response consistent with a plane wave-front incident on network of detectors:
  - use temporal coincidence of the 3 interferometer's 'loudest pixels'
  - correlate frequency features of candidates (time-frequency domain analysis)
  - check consistency of the signal amplitude
  - test the list of coincident event candidates for waveform consistency (correlation) between signals from three LIGO interferometers.
- End result of analysis pipeline: number of triple coincidence events

E. Katsavounidis

Preliminary detection efficiency and upper limit reach for initial part of S5





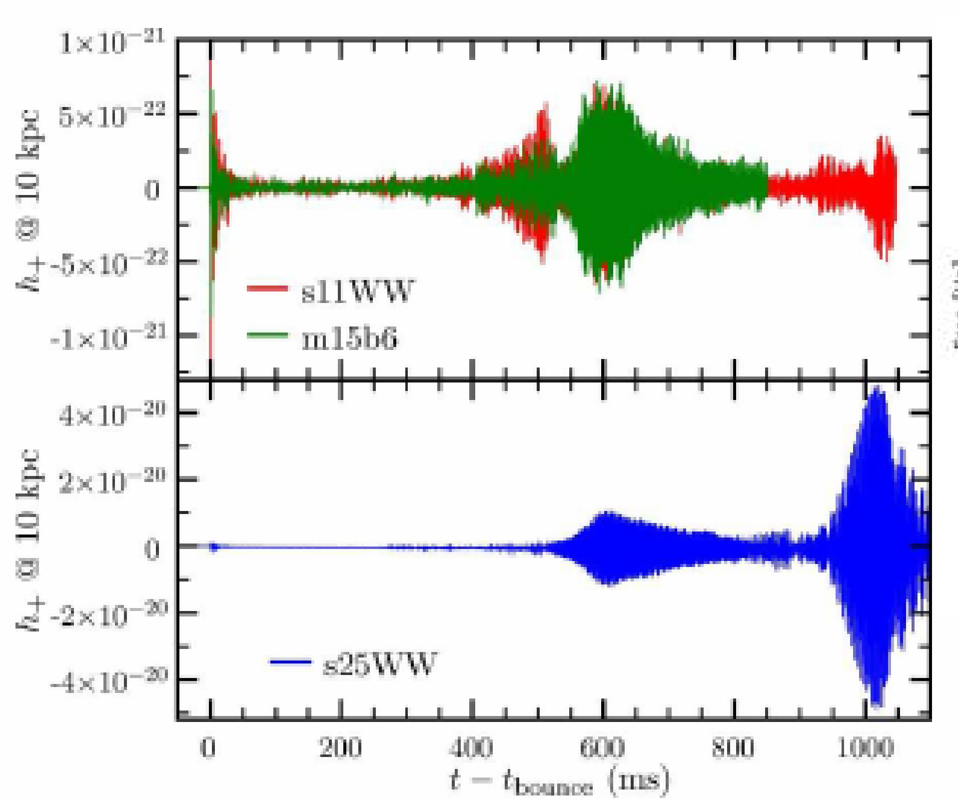
$$h_{\rm rss} \equiv \sqrt{\int (|h_+(t)|^2 + |h_\times(t)|^2)\, dt}$$

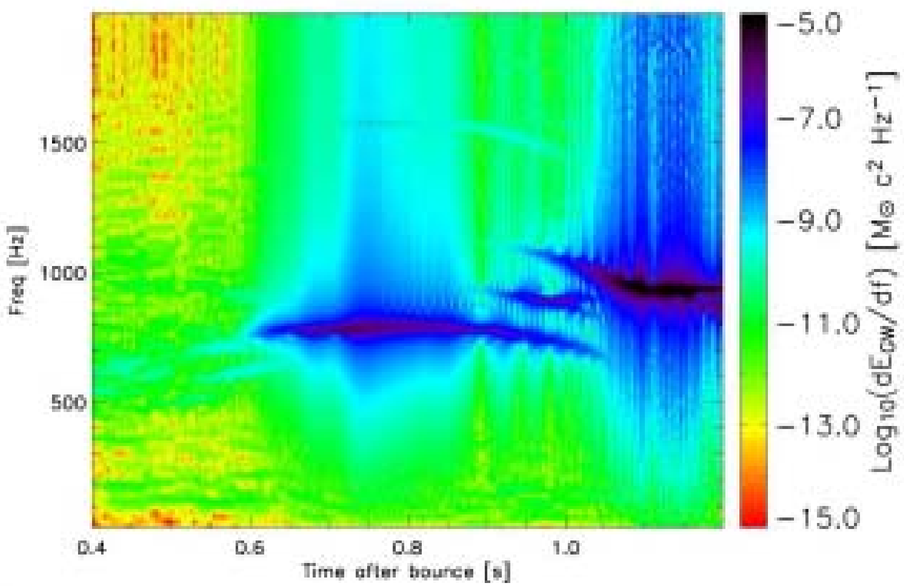
PRELIMINARY

E. Katsavounidis

Possible supernova explosion model

- Burrows, Livne, Dessart, Ott, Murphy (ApJ 2006) and Ott, Burrows, Dessart, Livne (PRL 2006)
  - Axisymmetric simulations with non-rotating progenitor
  - In-falling material eventually drives oscillations of the core
  - Hundreds of ms after the bounce and lasting several hundred ms



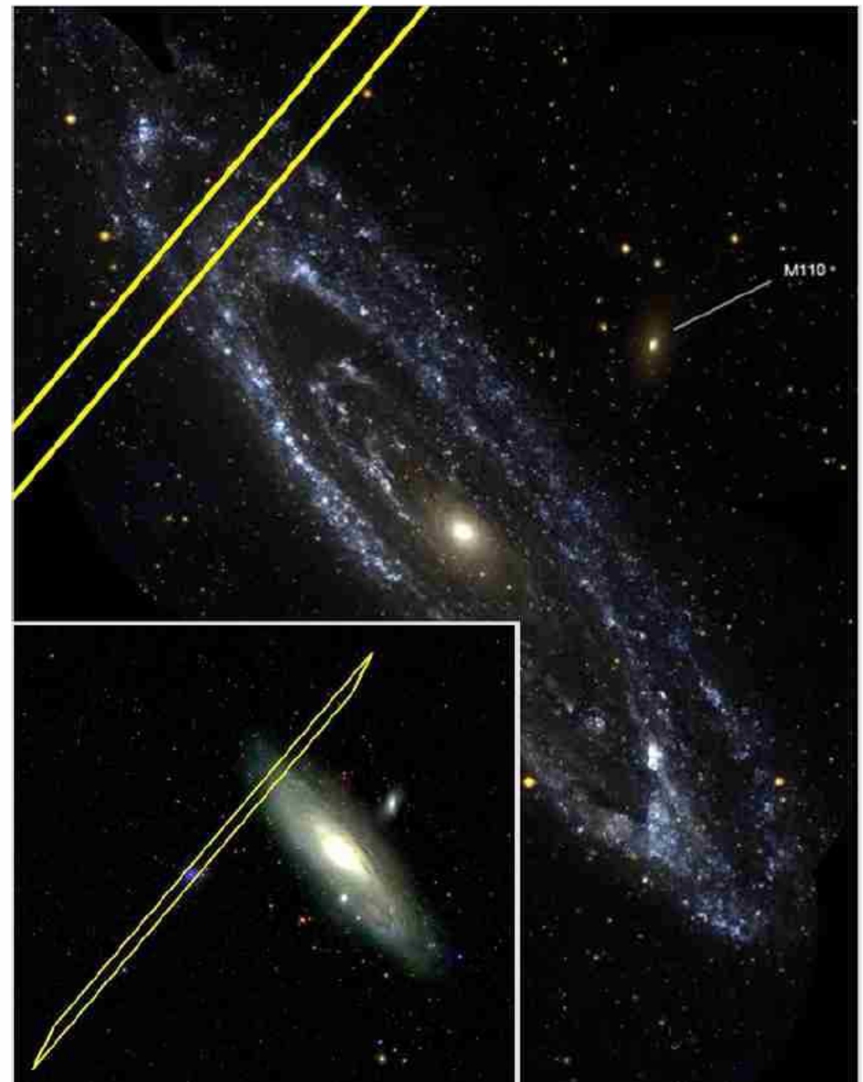


Ott, Burrows, Lessart, Livne, PRL 2006

E. Katsavounidis

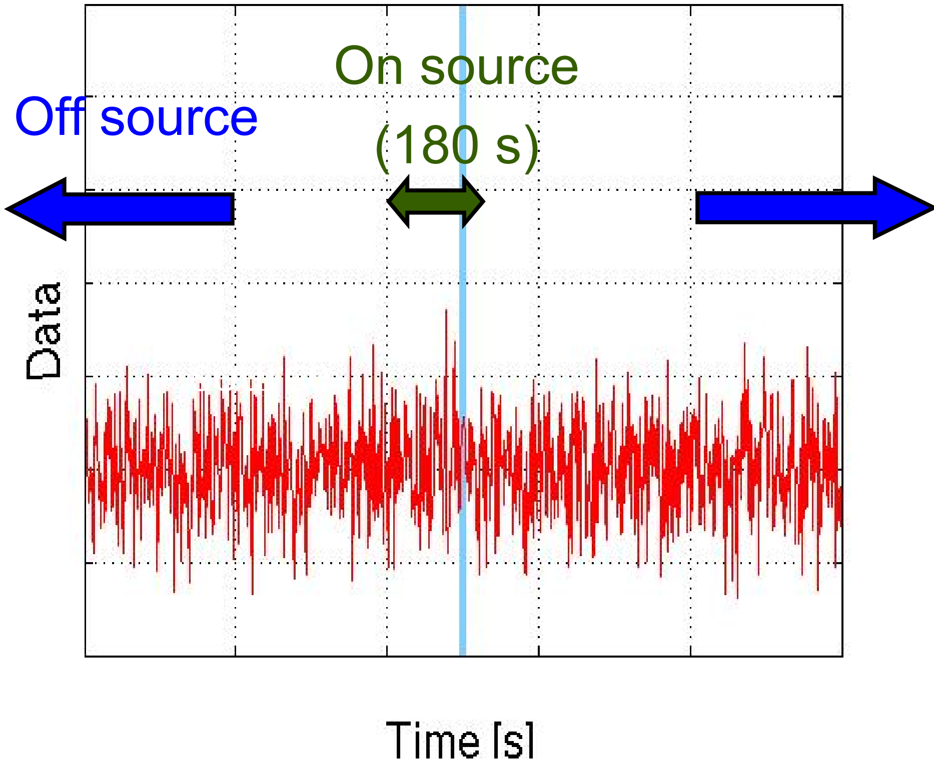
GRB 070201

- Feb 1, 2007: short hard γ burst
- Observed by five spacecraft
- Location consistent with M31spiral arms (0.77 Mpc)
- At the time of the event, both Hanford instruments were recording data (H1, H2), while others were not (L1, V1, G1)



Inspiral and burst analyses

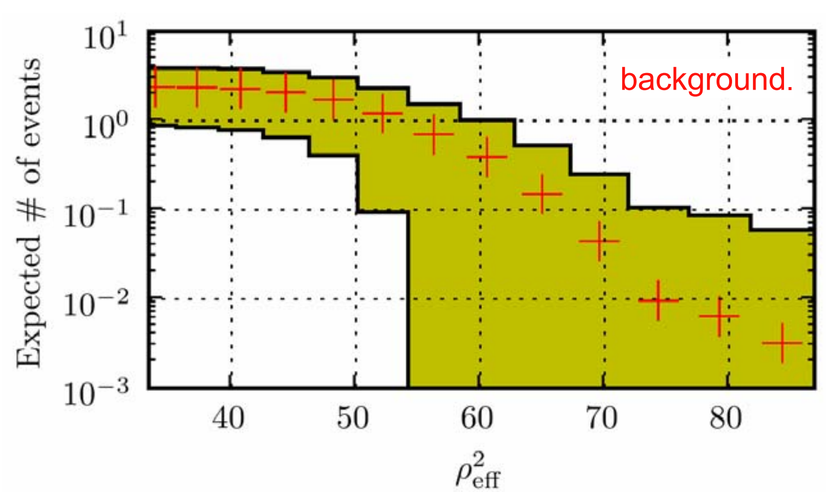
- On source data: 180s around GRB
- Off source, for background est.
  - inspiral: -14h, +8h
  - burst: -1.5h, +1.5h
- Some (.9%) off source data excluded, based on data quality cuts obtained from playground studies (e.g. excess seismic noise, digital overflows, hardware injections of fake signals)
- Assume gravitational waves travel at the speed of light

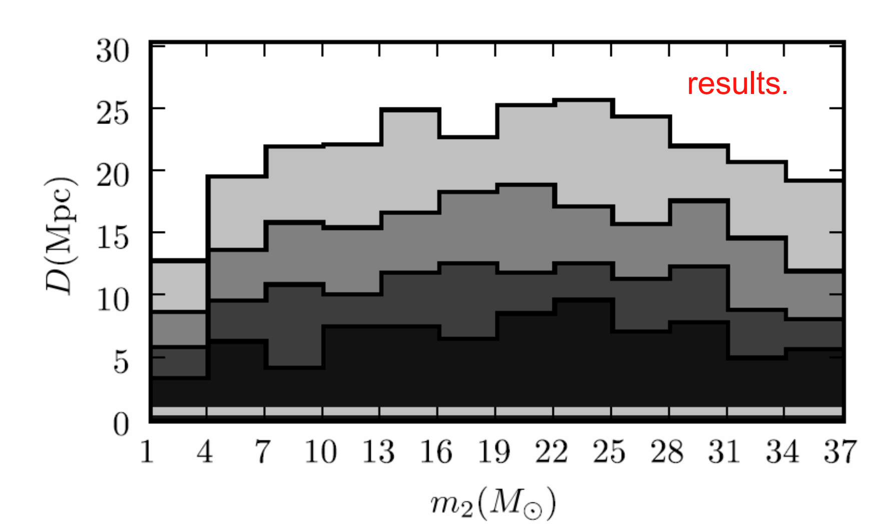


M. Landry

Inspiral search - GRB 070201

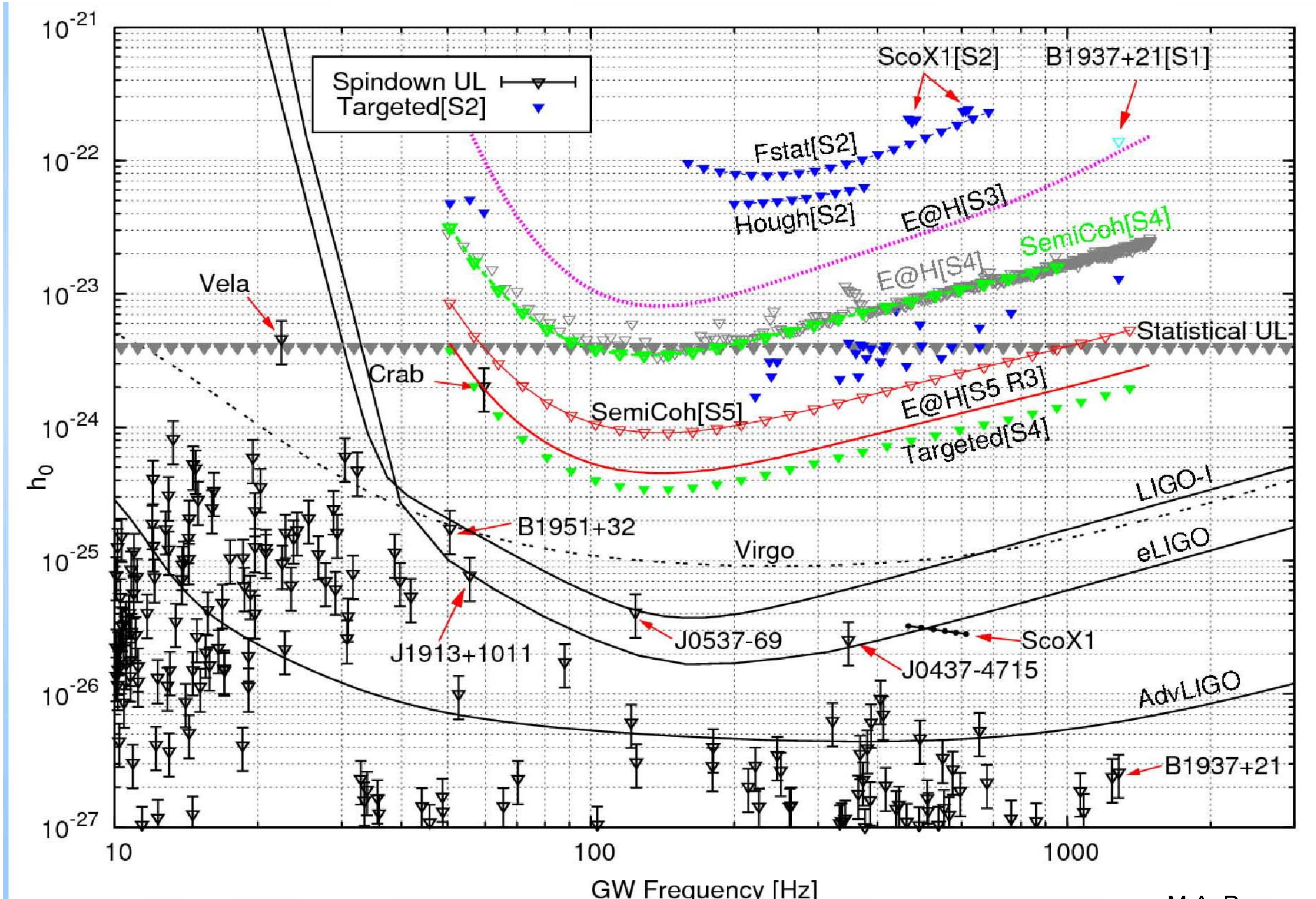
- Matched template analysis, $1M_O < m_1 < 3M_O$, $1M_O < m_2 < 40M_O$
- H1 ~ 7200 templates, H2 ~ 5400 templates, obtain filter SNR
- Require consistent timing and mass parameters between H1, H2
- Additional signal-based tests : χ^2, and r^2 veto
- SNR and χ^2 combined into effective SNR ρ_{eff}
- No gravitational wave candidates found
- Compact binary in M31 excluded at 99% confidence



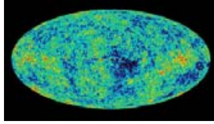


M. Landry

Summary of Periodic Sources and Detection Sensitivity

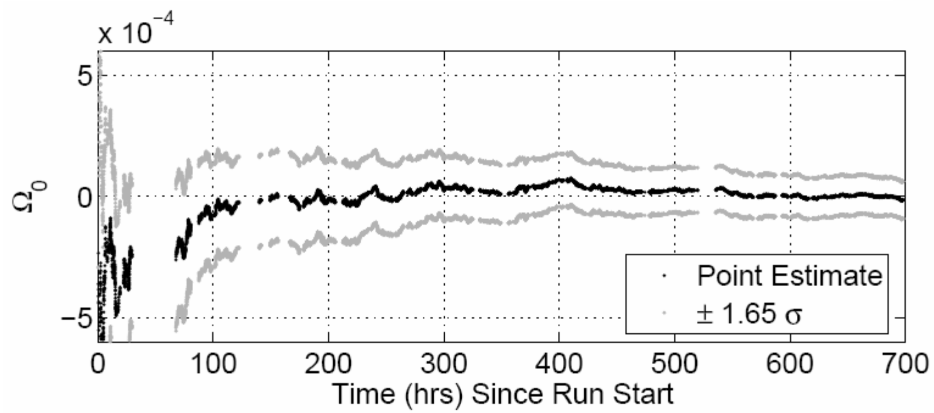


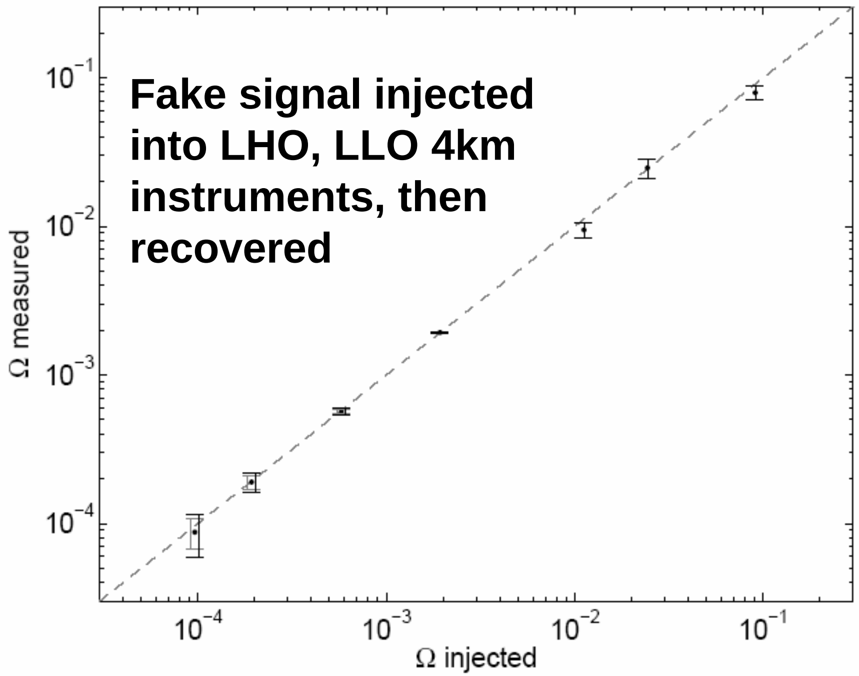
M.A. Papa



Isotropic Stochastic Background

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}$$



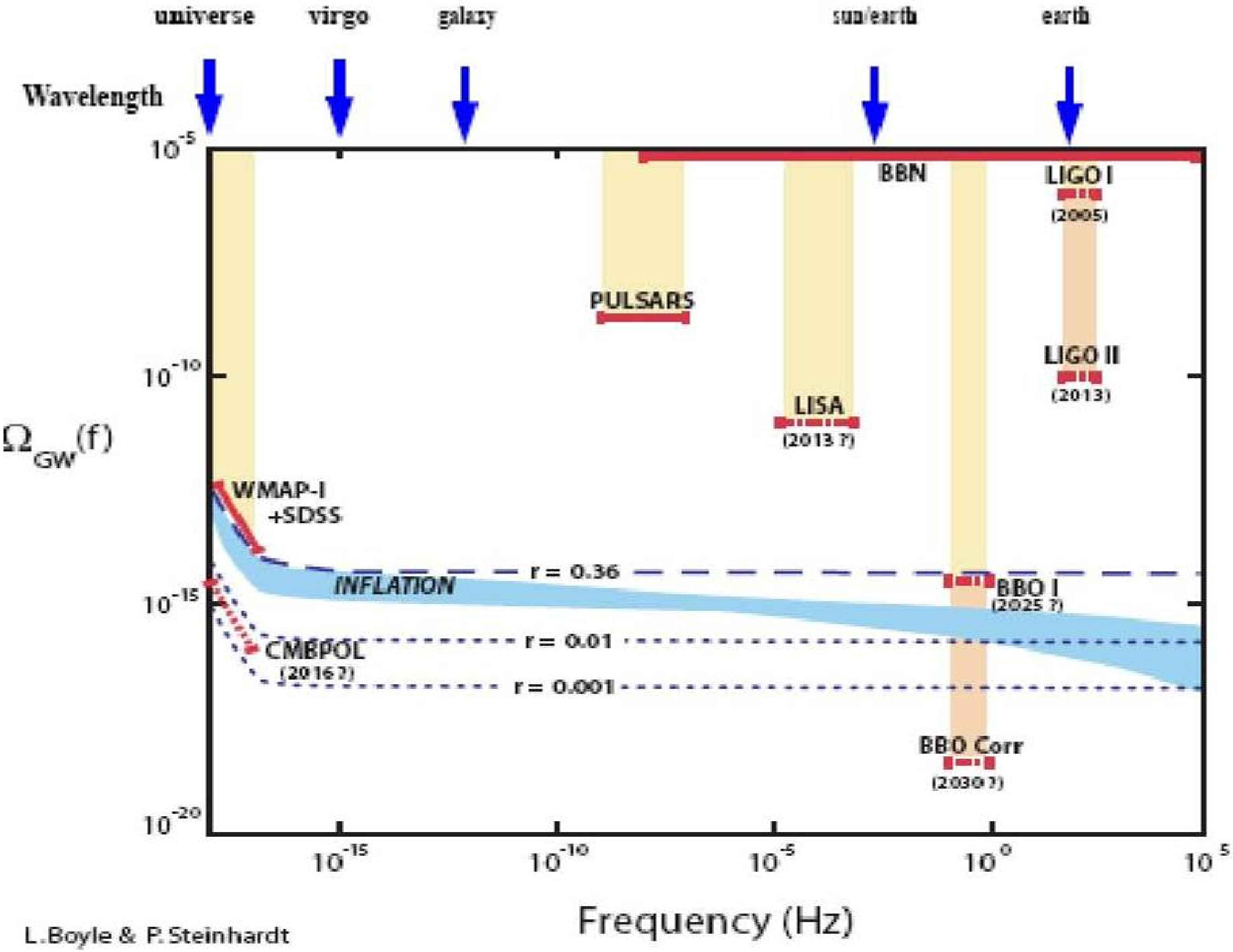


S4 result

Ap. J., 659 (2007) 082003 (astro-ph/0608606): $\Omega_{GW} < 6.5 \times 10^{-5}$

Bayesian 90% U.L.

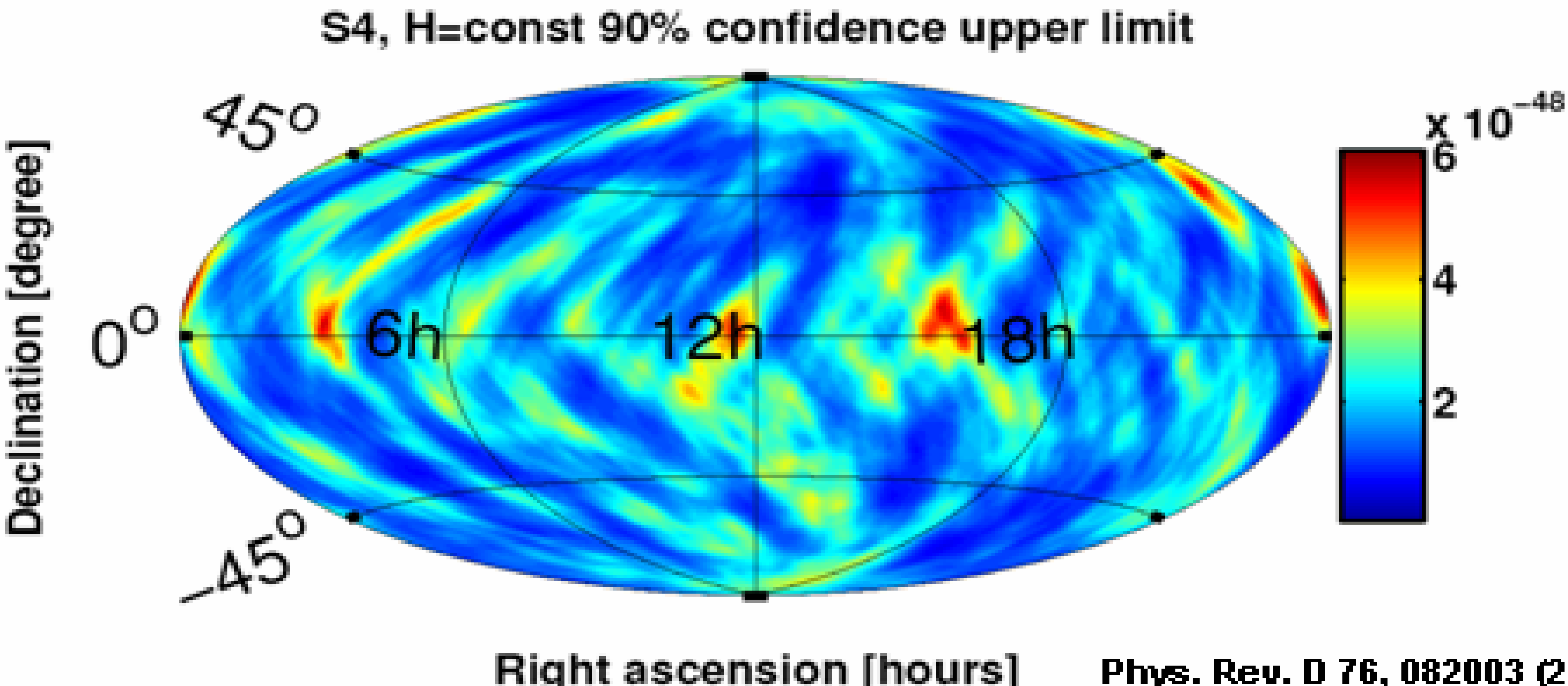
Estimates for a Cosmological Background of Gravitational Waves



CMB Task Force Report (2006)

Gravitational Wave “Radiometer”

S4 Result:
Limit on Point Sources



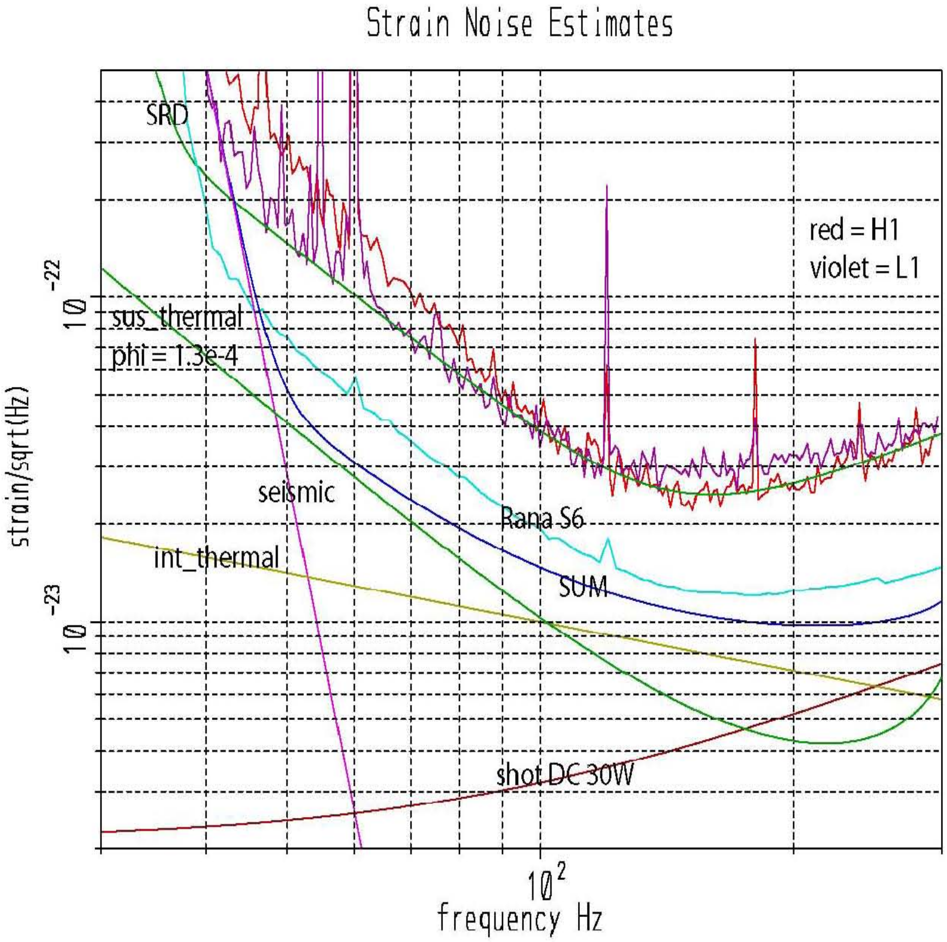
Phys. Rev. D 76, 082003 (2007

$$H_{90\%} = (0.85 - 6.1) \times 10^{-48} \, Hz^{-1}$$

Program of detector improvements

- **Major steps between initial and advanced LIGO**
  - Increase laser input power 10 to 180 watts in stages
  - Incorporation of an output mode cleaner
  - Output optics and electro-optics chain in vacuum
  - DC (carrier offset) “modulation” technique
  - Reduction in thermal noise
    - Steel wire to fused quartz ribbon suspension elements
    - Lower mechanical dissipation optical coatings
    - Larger fused silica test masses : 10 kg to 40 kg
  - Improved active seismic isolation – extend sensitivity to 15Hz
  - Tunable dual recycling interferometer configuration
  - Quantum limited operation over significant band

BEGIN
IN
ENHANCED
LIGO



Estimates by Ilya Mandel, Richard Shaughnessy, Vicky Kalogera Jan 2008

Horizon Distance Mpc

curve	NS/NS	10/10BH	30/30BH	60/60BH
H1 S5	32	160	169	57
L1 S5	31	157	215	83
SRD	34	170	219	127
Rana S6	71	349	443	208
SUM	92	450	638	209

Detection Rate relative to SRD

curve	NS/NS	10/10BH	30/30BH	60/60BH
H1 S5	0.84	0.83	0.46	0.09
L1 S5	0.79	0.79	0.94	0.28
Rana S6	9.1	8.7	8.2	4.4
SUM	20	19	23	4.5

NS/NS detection rates using 100 NS/NS mergers per Myr in MWEG and 0.01 MWEG/Mpc^3

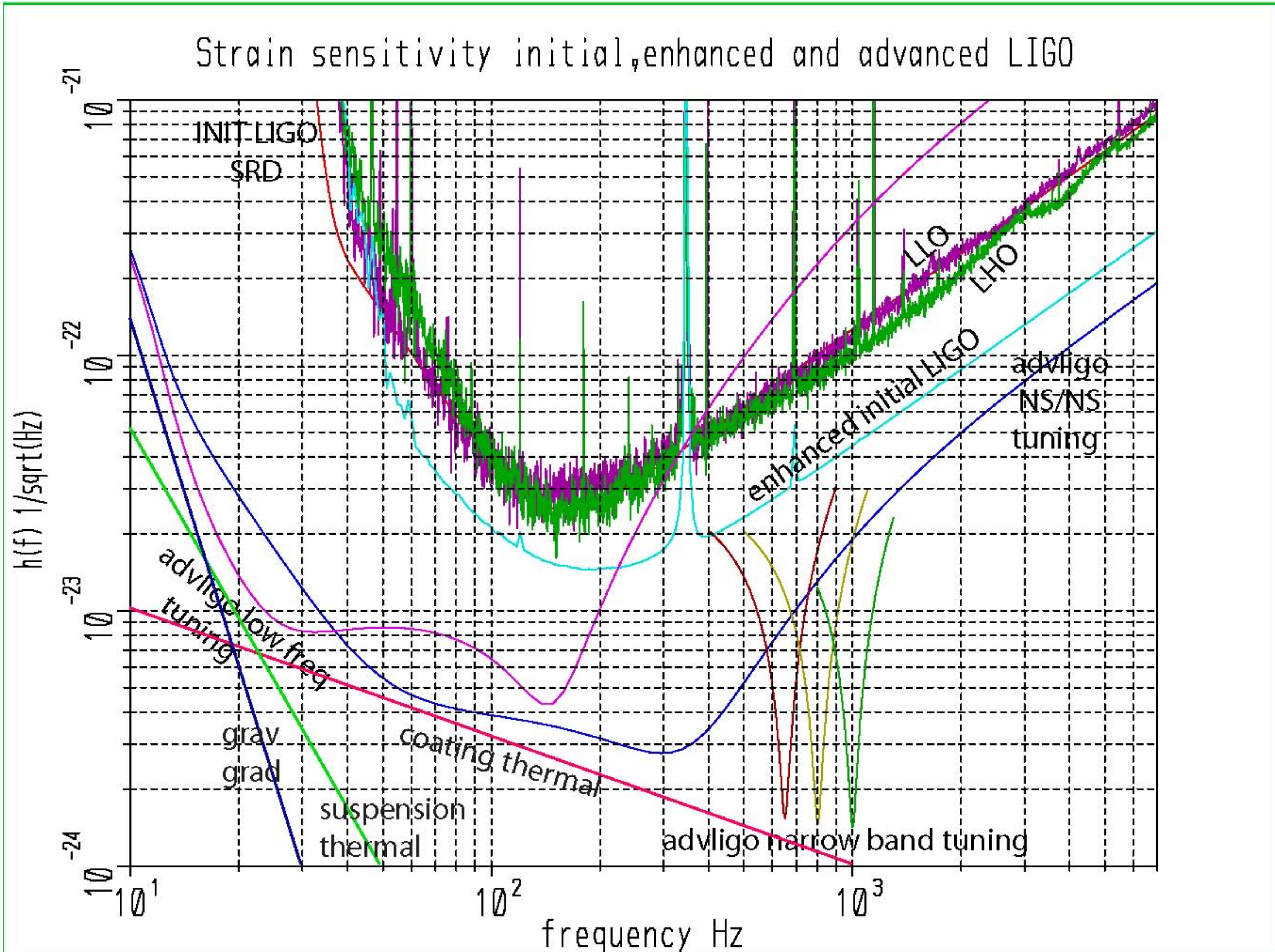
H1 S5 => 0.012/year

L1 S5 => 0.011/year

SRD => 0.014/year

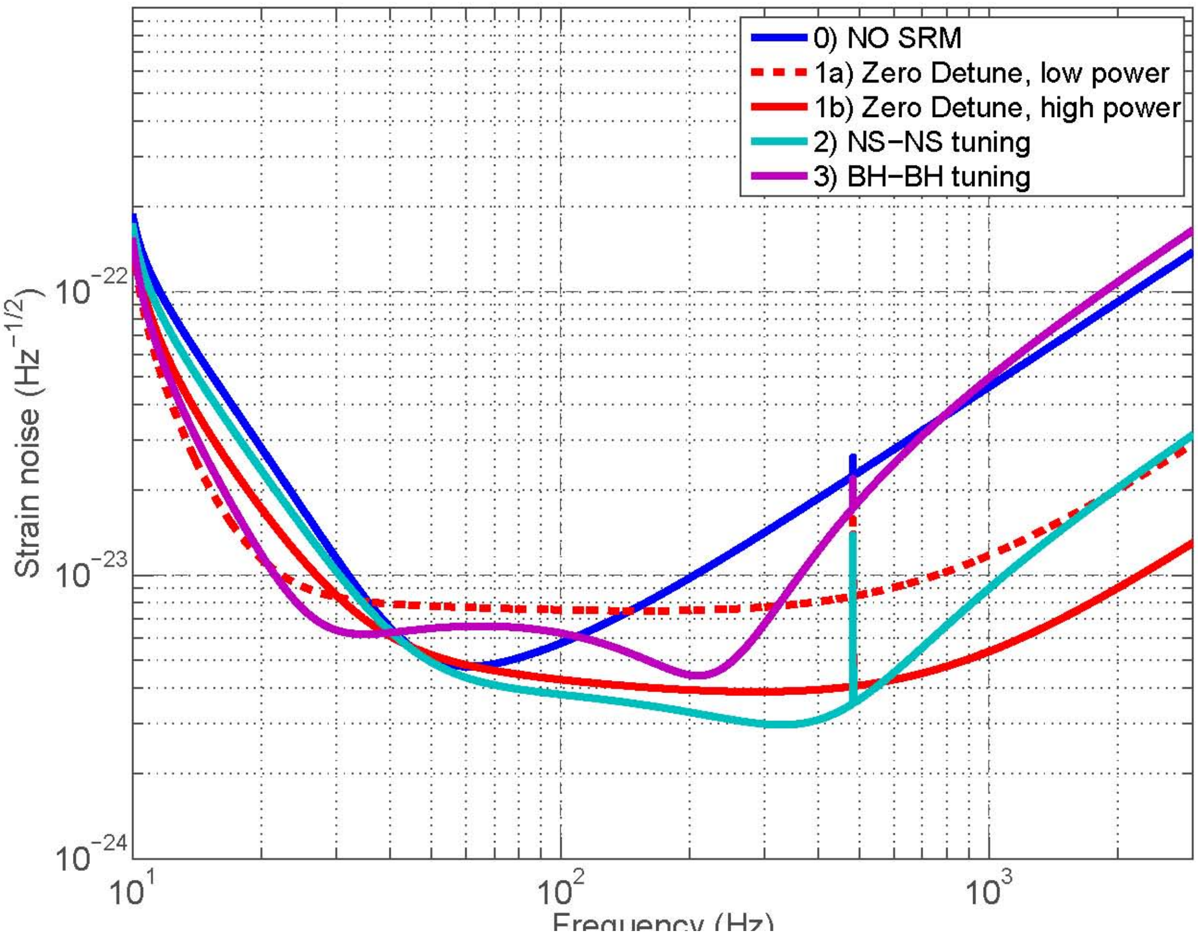
Rana S6 => 0.13/year

SUM => 0.28/year



Strain sensitivity initial,enhanced and advanced LIGO
INIT LIGO SRD
LLO
LHO
enhanced initial LIGO
advligo NS/NS tuning
advligo low freq tuning
gray grad
suspension thermal
coating thermal
advligo narrow band tuning
h(f) 1/sqrt(Hz)
frequency Hz

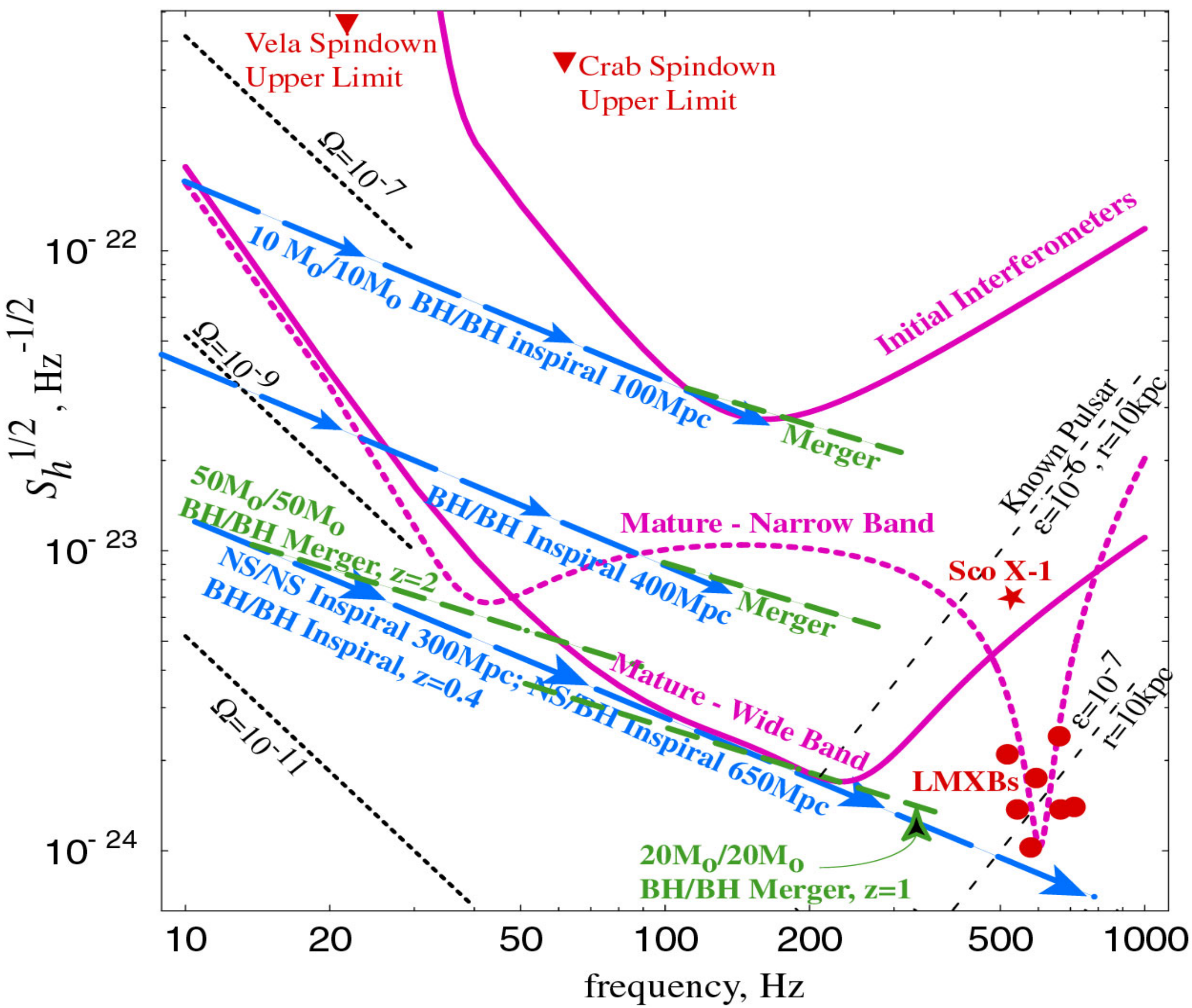
Advanced LIGO modes of operation



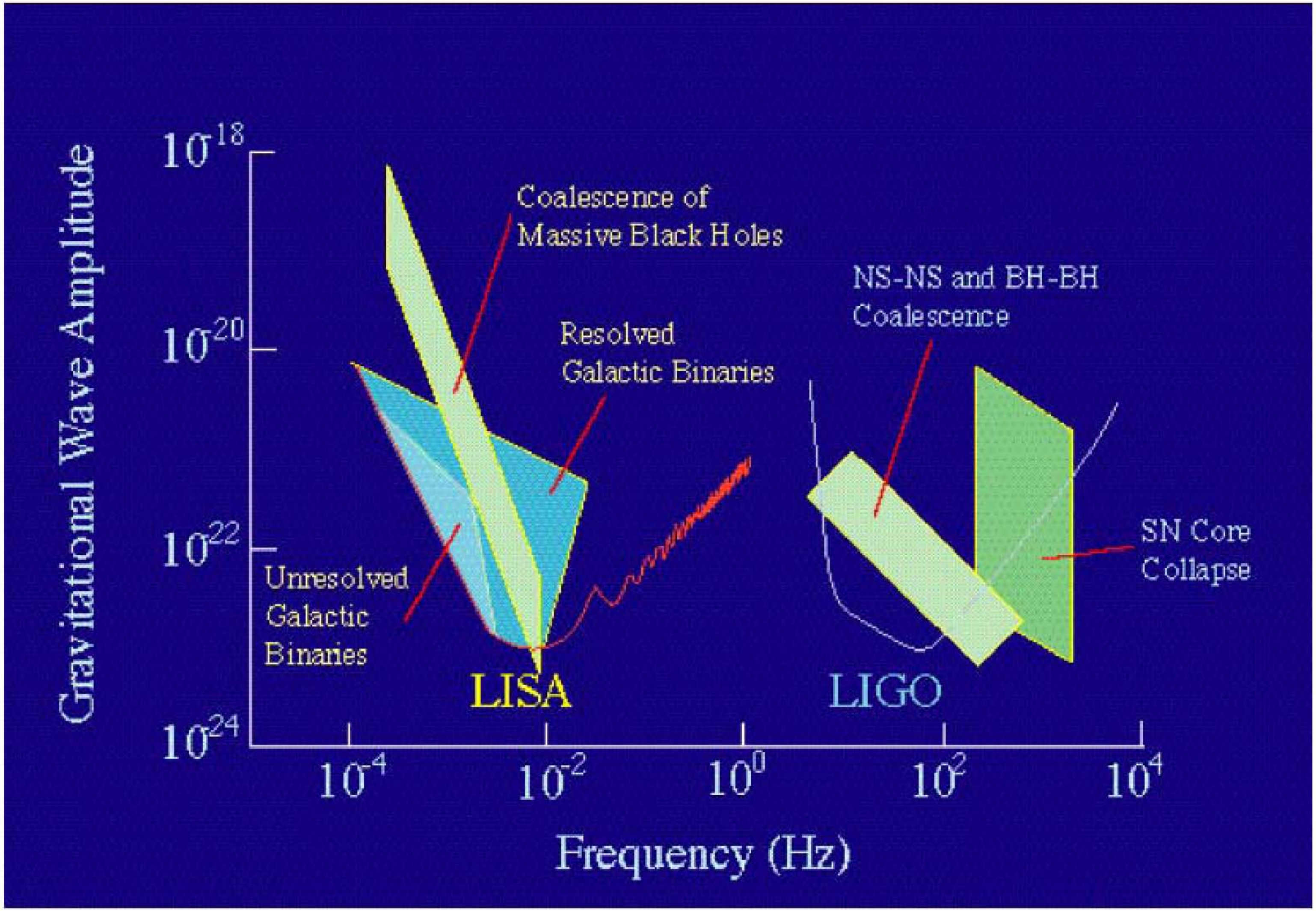
Mode	*NS-NS Range*	*BH-BH Range*	P_{in}	T_{SRM}	ϕ_{SRC}	h_{RMS}, 10^{-22} (band)
0	143 Mpc	1.28 Gpc	25 W	100%	–	0.57 (40–140 Hz)
1a	145 Mpc	1.48 Gpc	25 W	20%	0 deg.	0.75 (120–220 Hz)
1b	180 Mpc	1.32 Gpc	125 W	20%	0 deg.	0.39 (265–365 Hz)
2	186 Mpc	1.13 Gpc	125 W	20%	11 deg.	0.30 (285–385 Hz)
3	170 Mpc	1.68 Gpc	20 W	20%	20 deg.	0.47 (155–255 Hz)

Peter Fritschel

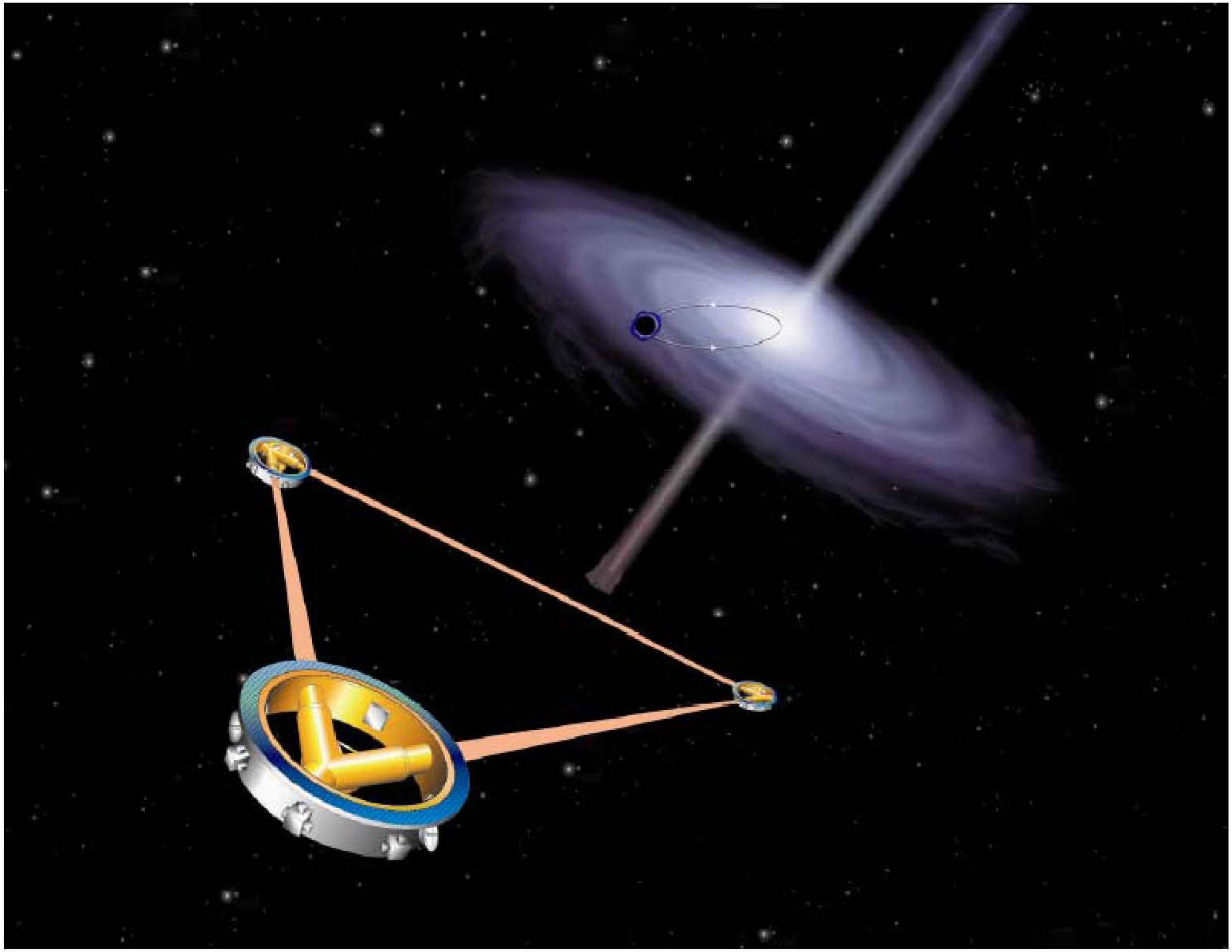
Projections for Advanced LIGO : sensitivity and sources



The Gravitational-Wave Spectrum

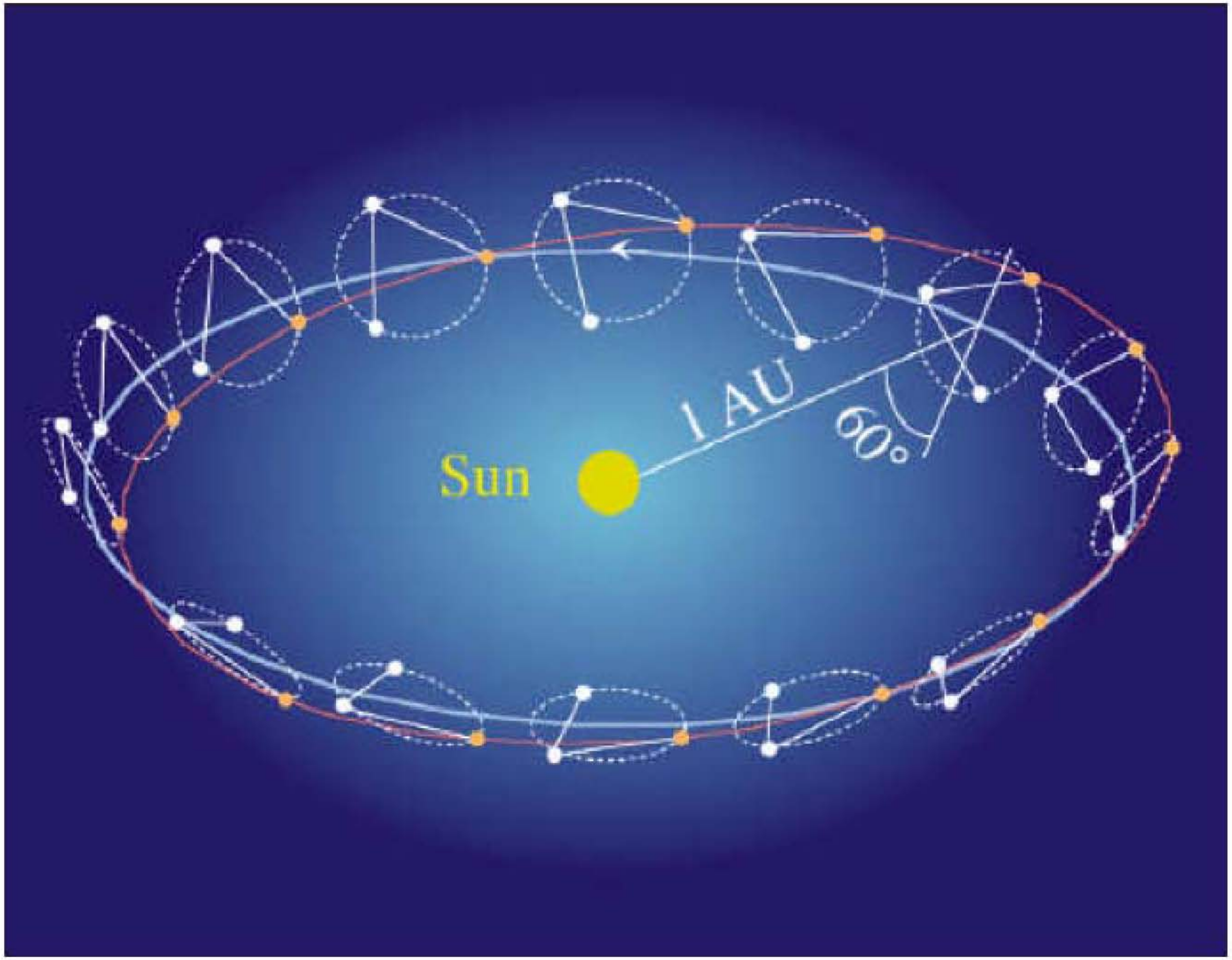


Mission Concept

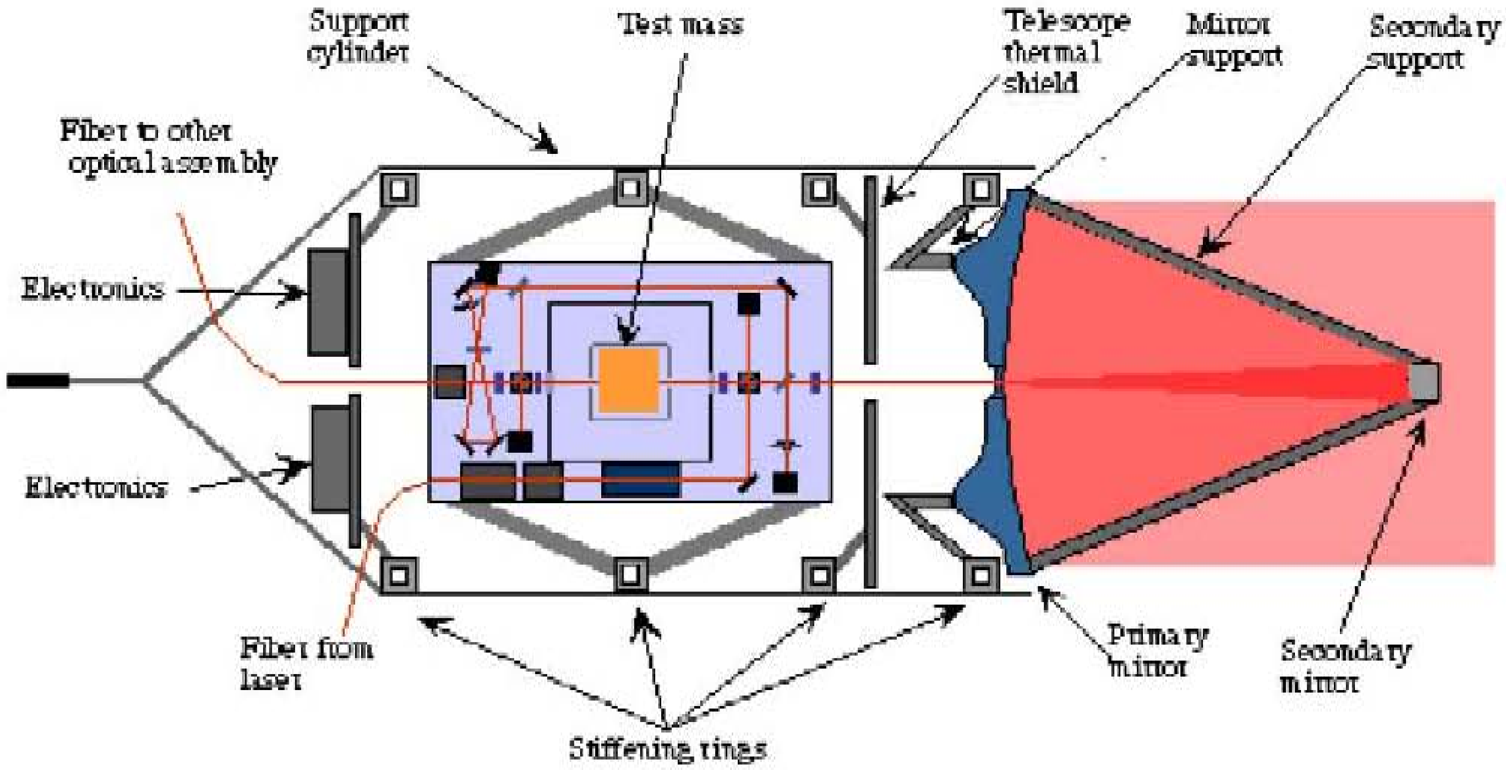


Spacecraft Orbits

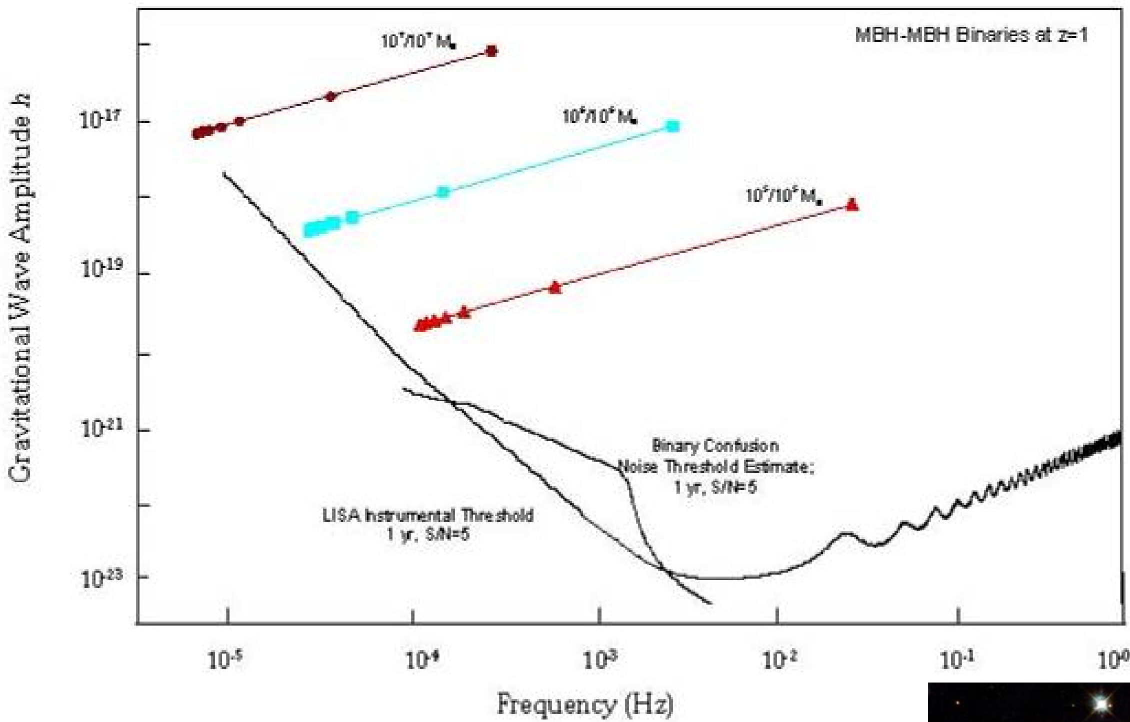
- Spacecraft orbits evolve under gravitational forces only
- Spacecraft fly "drag-free" to shield proof masses from non-gravitational forces

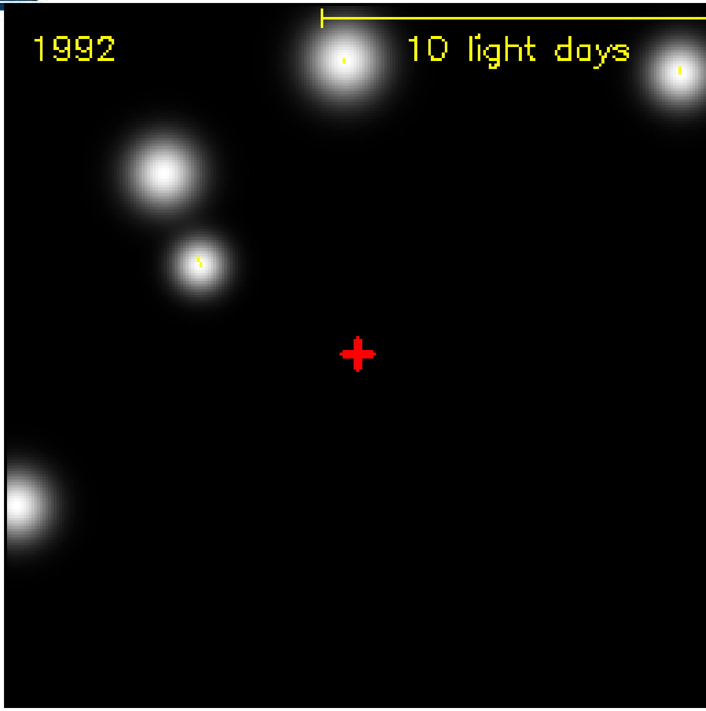


Optical System



Massive Black Holes in Merging Galaxies





R. Genzel

Hubble Space Telescope

Power and signal recycling configuration