Interferometric GW detectors:
the near term prospects for detection

Rainer Weiss, MIT on behalf of the
VIRGO/LIGO Scientific Collaboration

GR 19, Mexico City
July 6, 2010

~100 years since 1916

- B modes in the Cosmic Background
  - periods of 10^{10} years
- Timing with millisecond pulsars
  - periods of ~ year
- LISA
  - periods of hours to minutes
- Ground based interferometers
  - periods of 100 to 0.1 milliseconds

Outline

- Current state of the detectors
- Steps to improve the sensitivity
- Modes to run improved detectors
- Detection of NS/NS coalescences

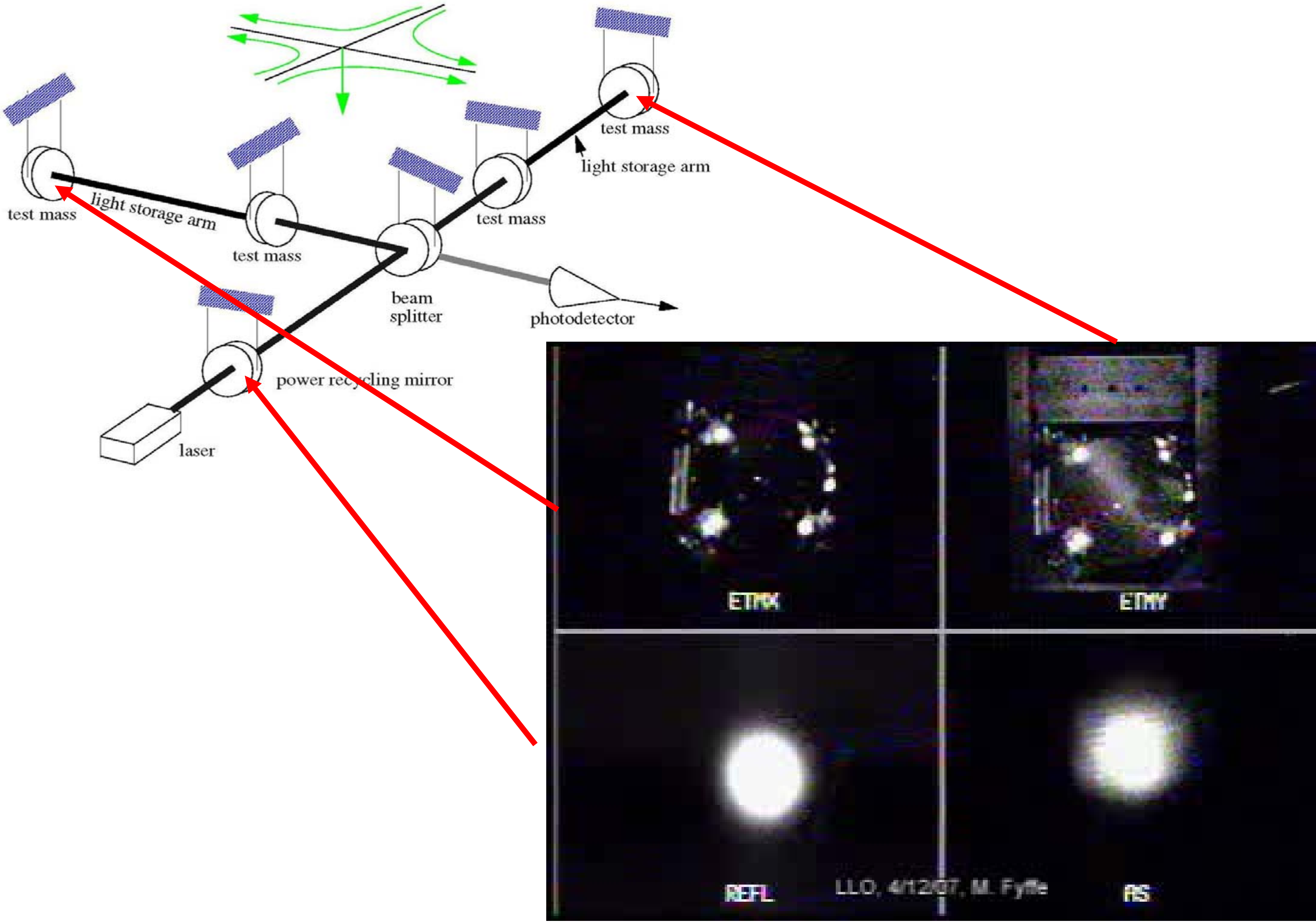
Talks at GR19 on ground based detectors

Thursday Afternoon Sessions C1 and C3

• A. Krolak	14:00	Status of Virgo
• V. Frolov	14:30	Status of LIGO
• J. Hough	15:00	GEO 600
• S. Miyoki	15:30	CLIO
• P. Fritschel	16:30	Advanced LIGO
• S. Miyoki	17:00	LCGT
• T. Corbitt	17:30	QND Experiments
• Y. Chen	18:00	QND Theory

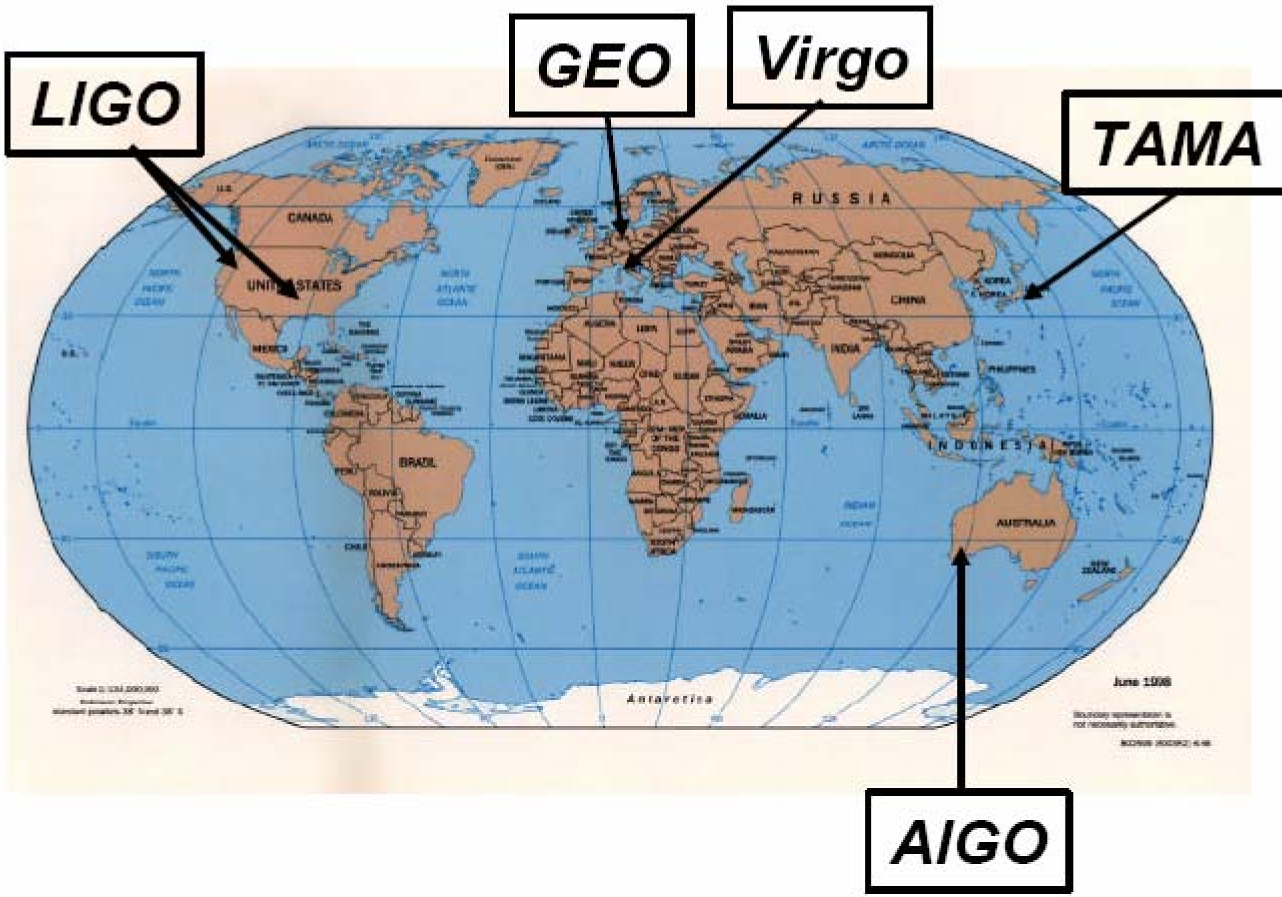
LIGO Scientific Collaboration

- 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


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

Interferometers
international network

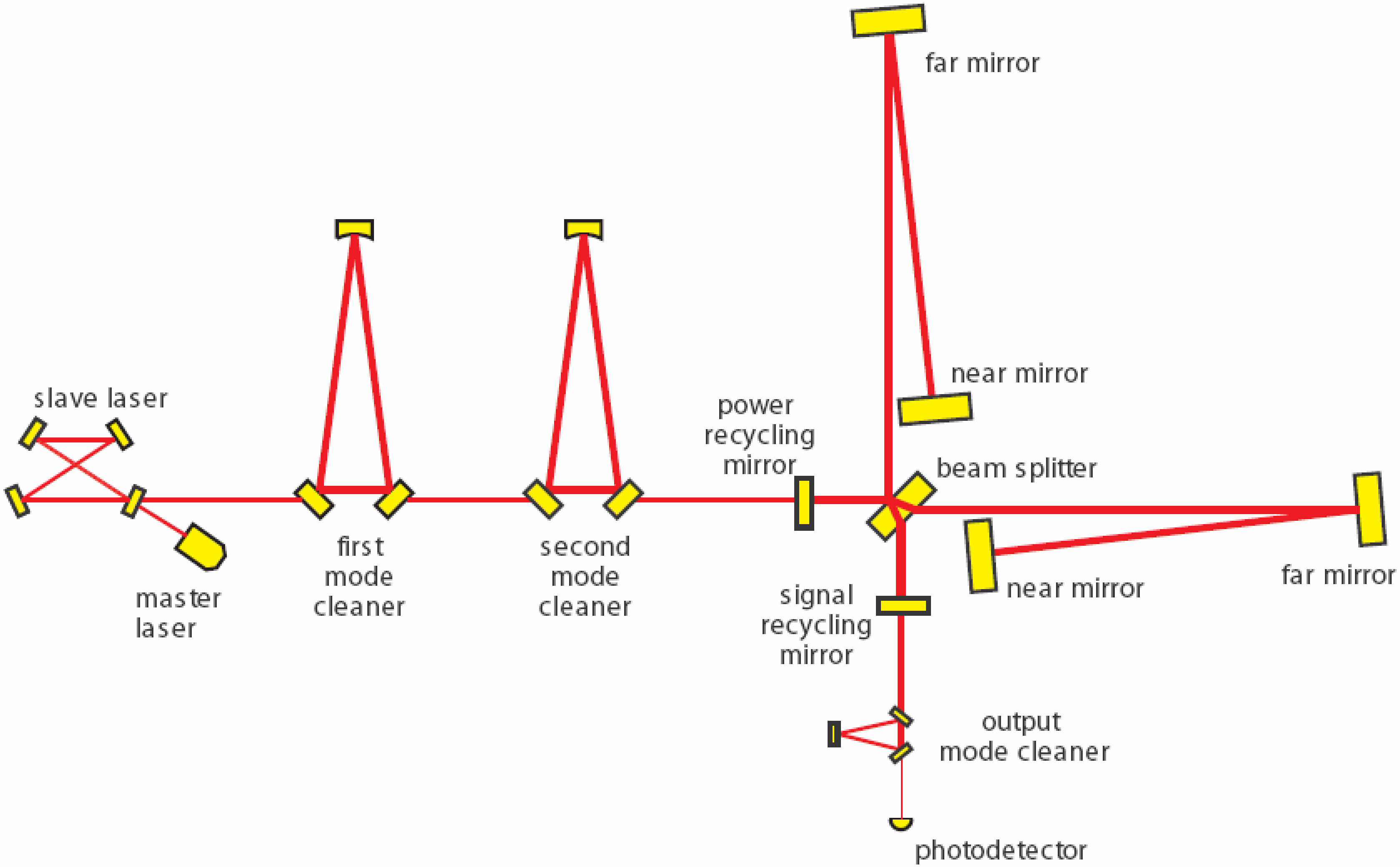
Simultaneously detect signal (within msec)



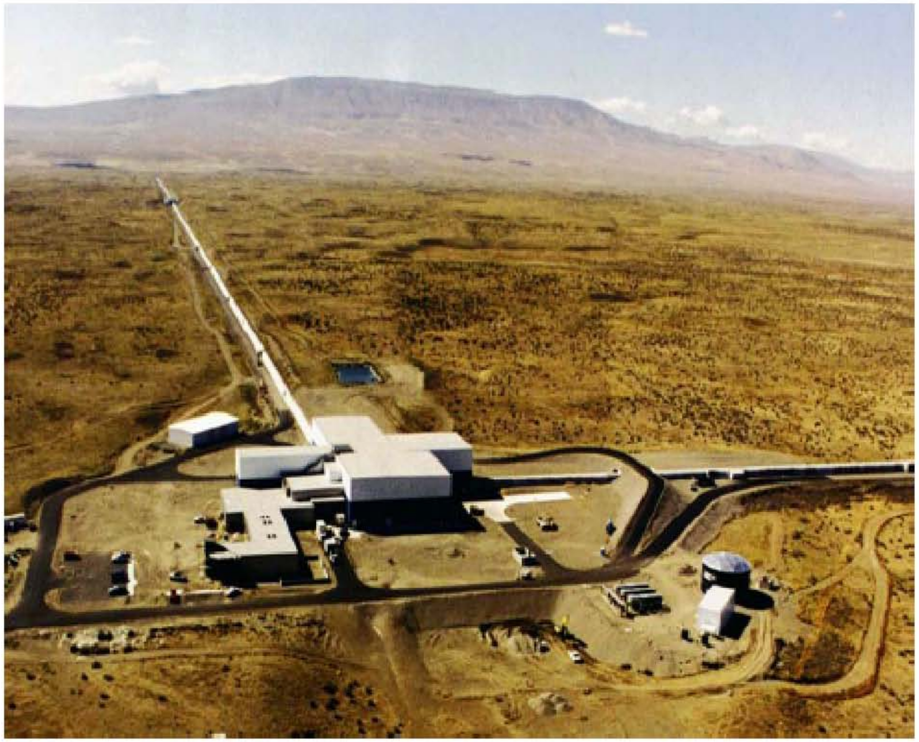
detection confidence

locate the sources

decompose the polarization of gravitational waves


far mirror
near mirror
slave laser
power
recycling
mirror
beam splitter
first
mode
cleaner
second
mode
cleaner
master
laser
signal
recycling
mirror
near mirror
far mirror
output
mode cleaner
photodetector

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

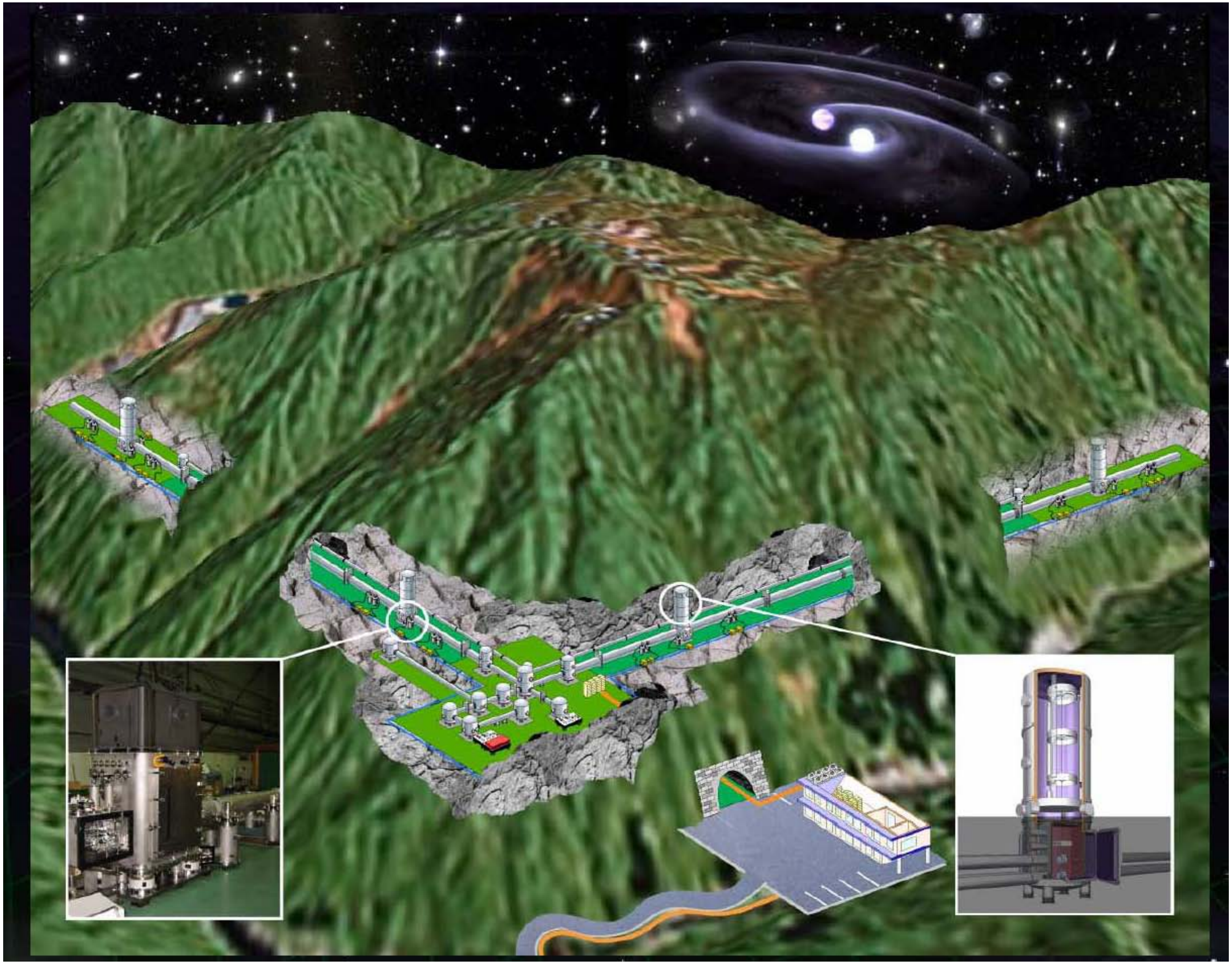
26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

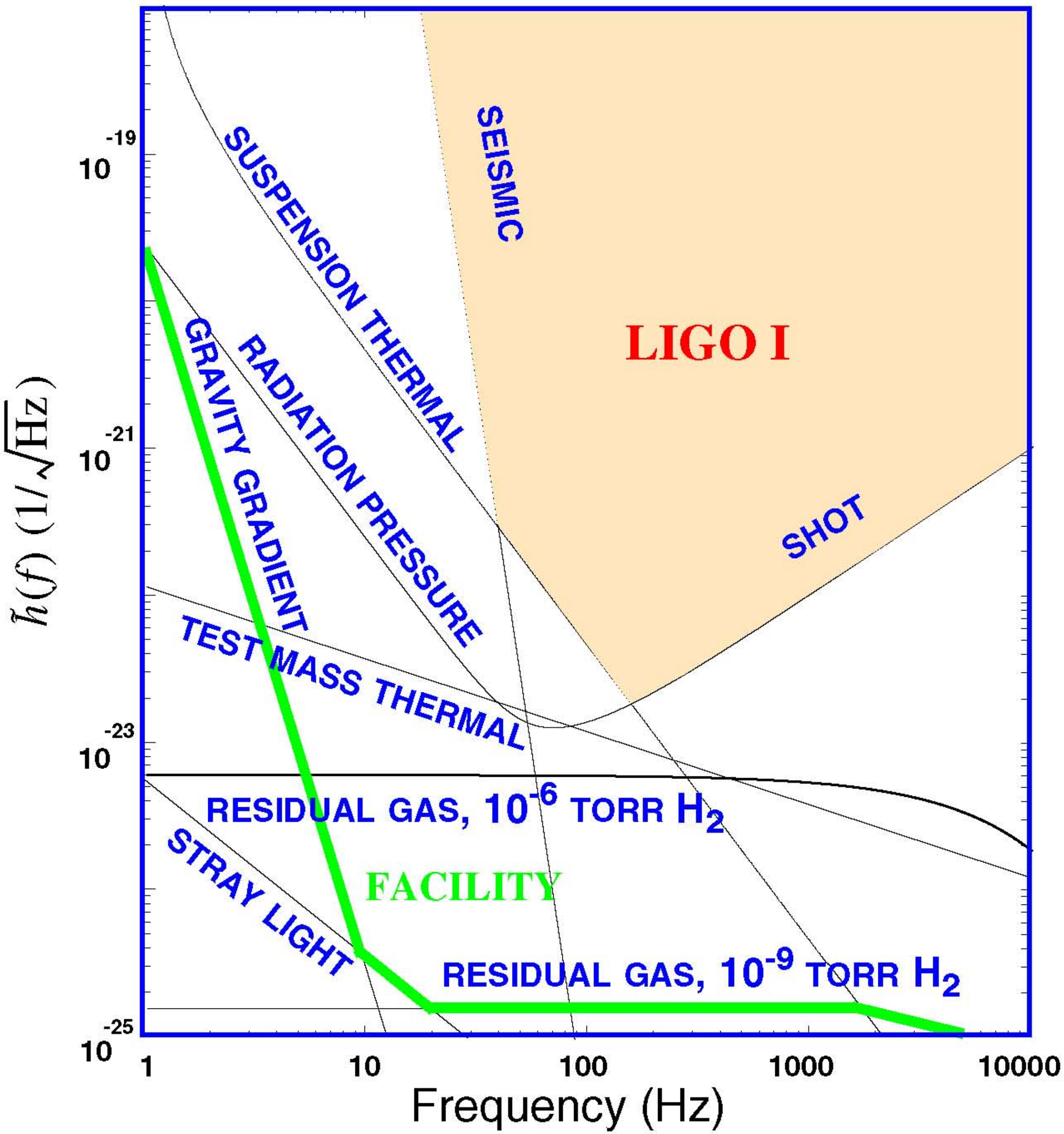
Single 4 km interferometer

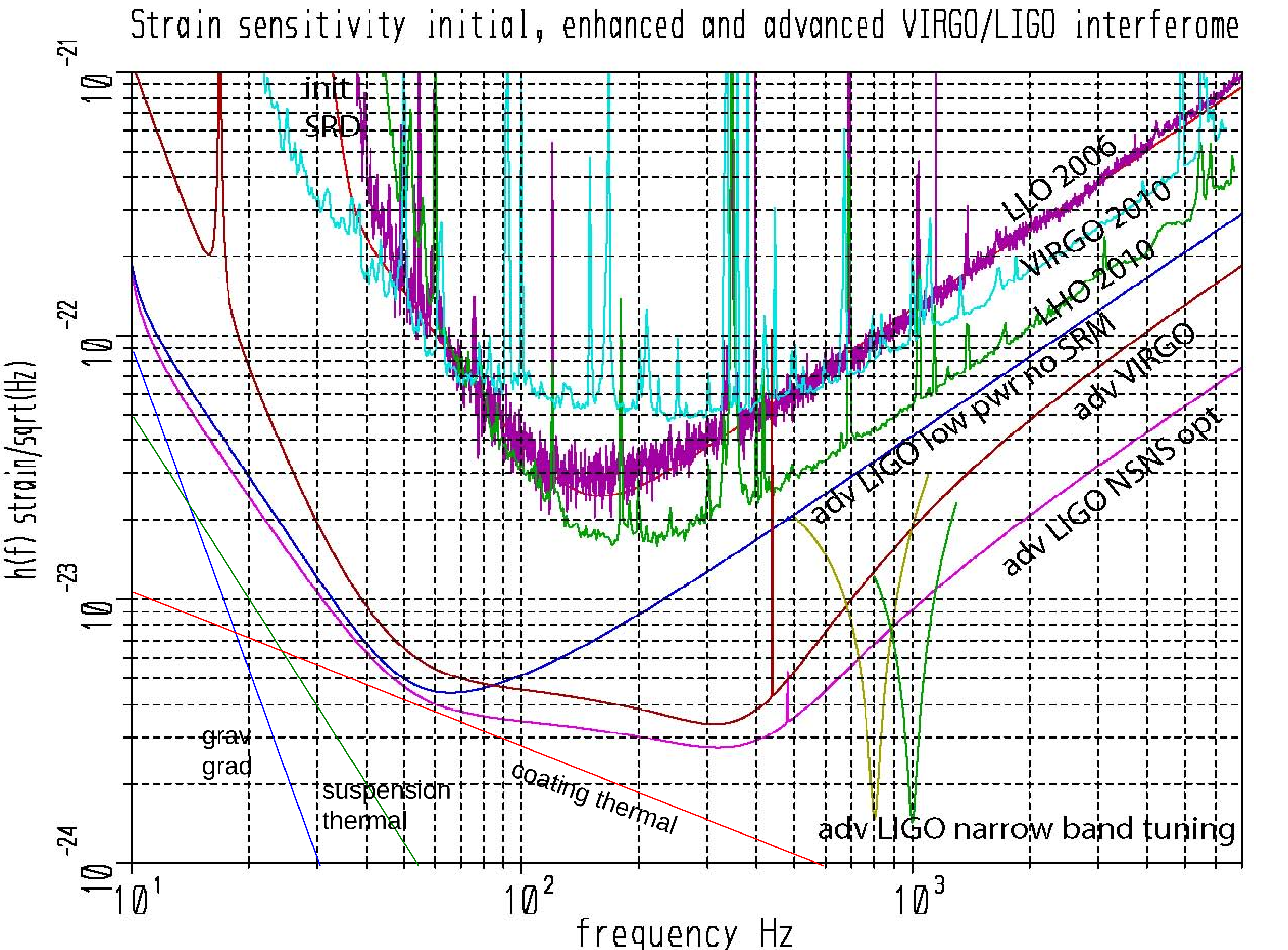


Broad overview of the projects

- GEO
  - Developed :fused silica suspensions,signal recycling
  - Future: squeezed light interferometry, high frequency detection
- CLIO/LCGT
  - Current and future: cryogenic suspensions and optics,underground operations
  - Future: long baseline cryogenic underground detector
- ACIGA/AIGO
  - Current: study of high power, parametric instability
  - Future: 4km detector
- VIRGO
  - Advanced detector
- LIGO
  - Advanced detector

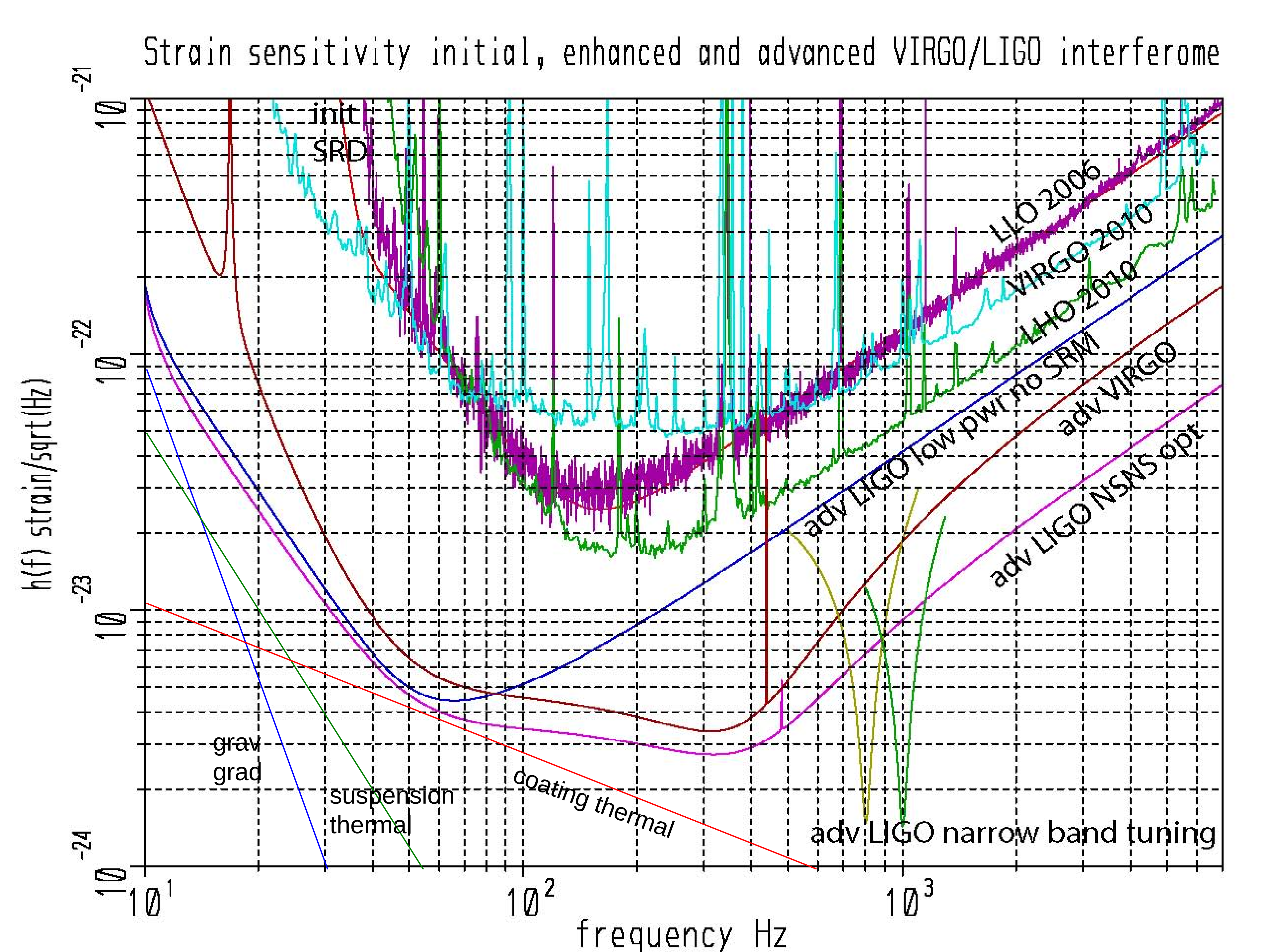
Mostly idealized and fundamental noise




Strain sensitivity initial, enhanced and advanced VIRGO/LIGO interferome
h(f) strain/sqrt(Hz)
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3
frequency Hz
init
SRD
LLO 2006
VIRGO 2010
LHO 2010
adv LIGO low pwr no SRM
adv VIRGO
adv LIGO NSNS opt
grav
grad
suspension
thermal
coating thermal
adv LIGO narrow band tuning

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 silica fiber 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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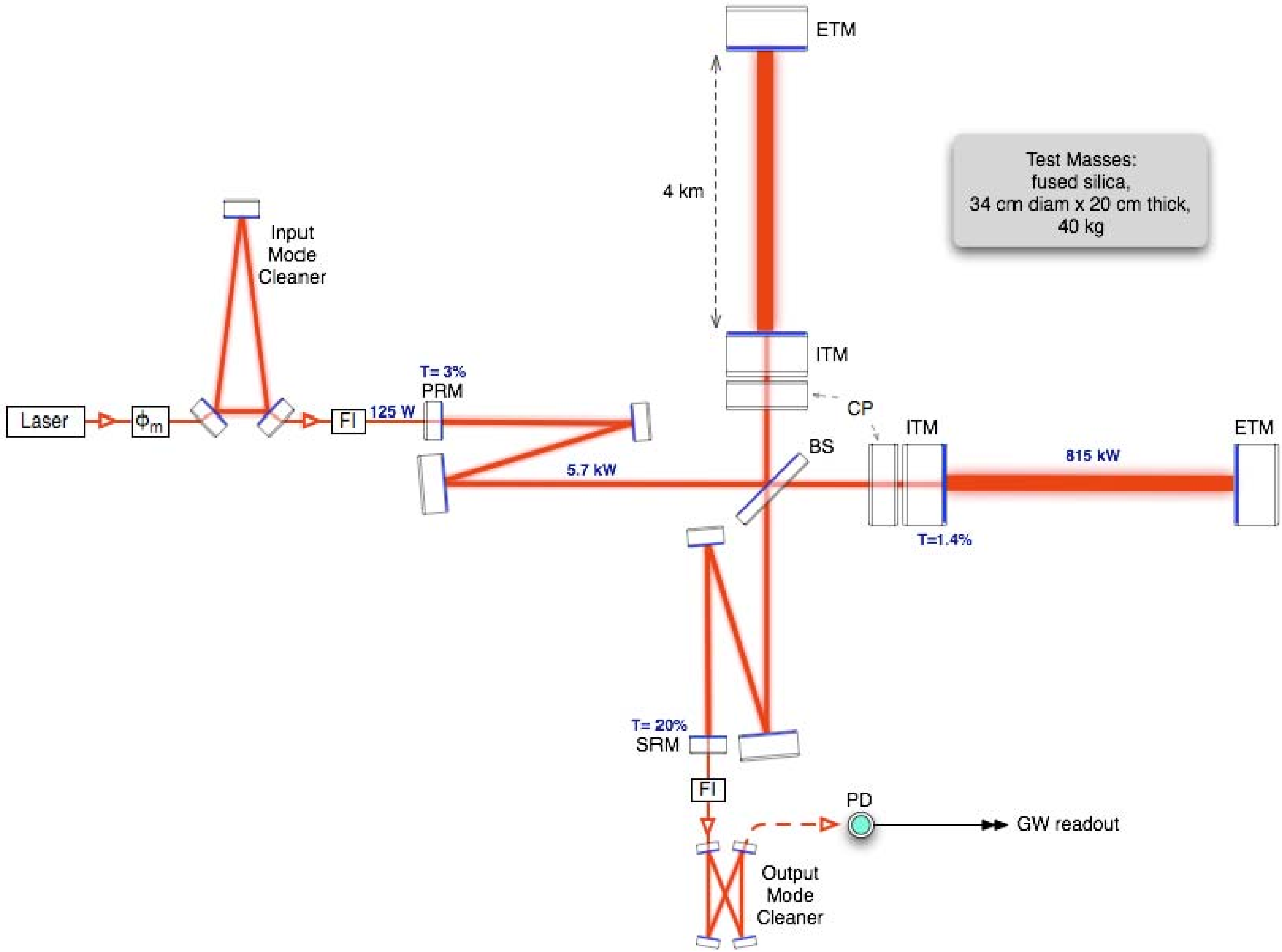
Systems: Interferometer Design



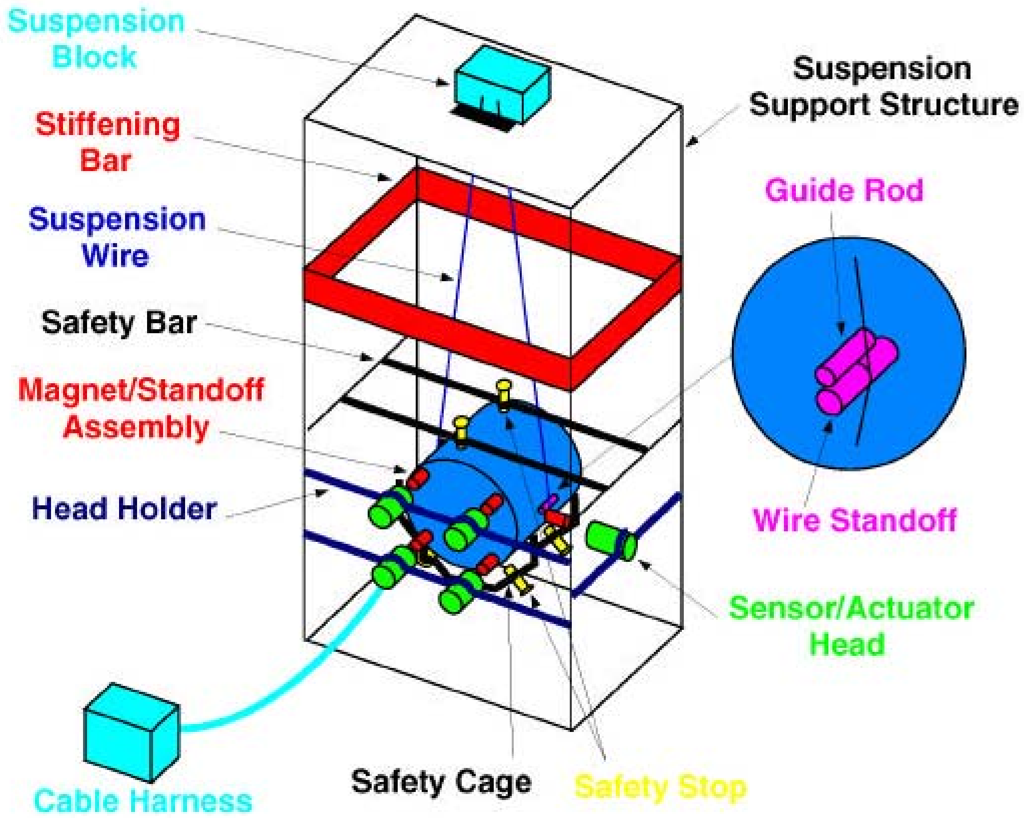
Seismic Isolation

Springs and Masses

Seismic Isolation

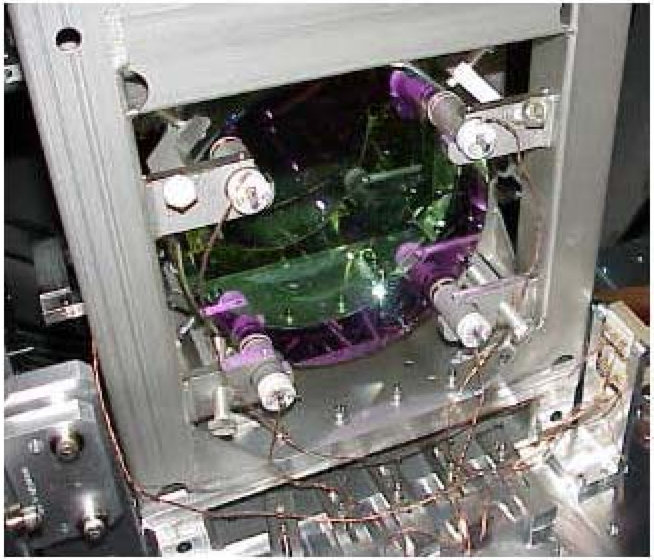
suspension system

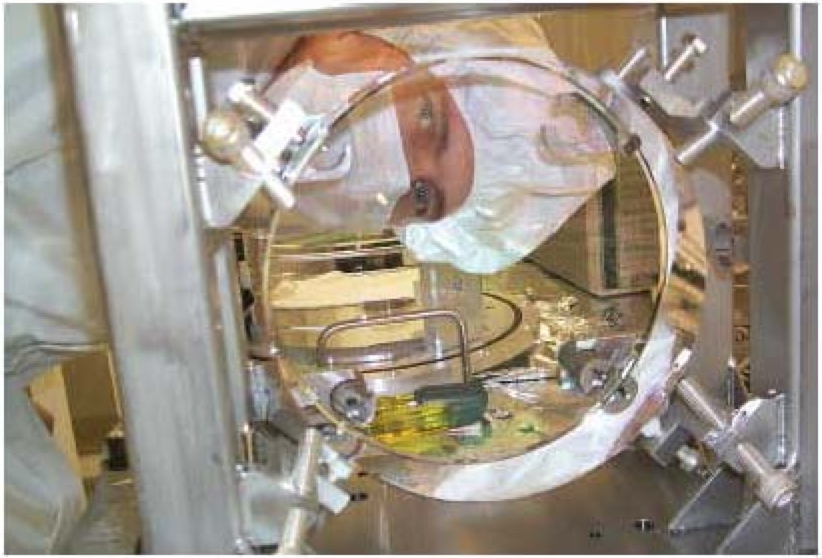
suspension assembly for a core optic



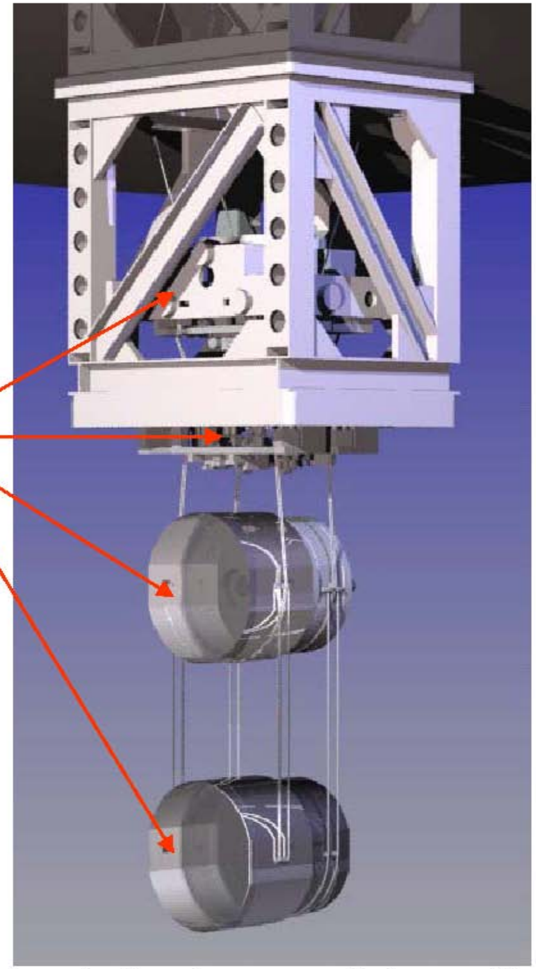
Core Optics

Suspension





Schematic

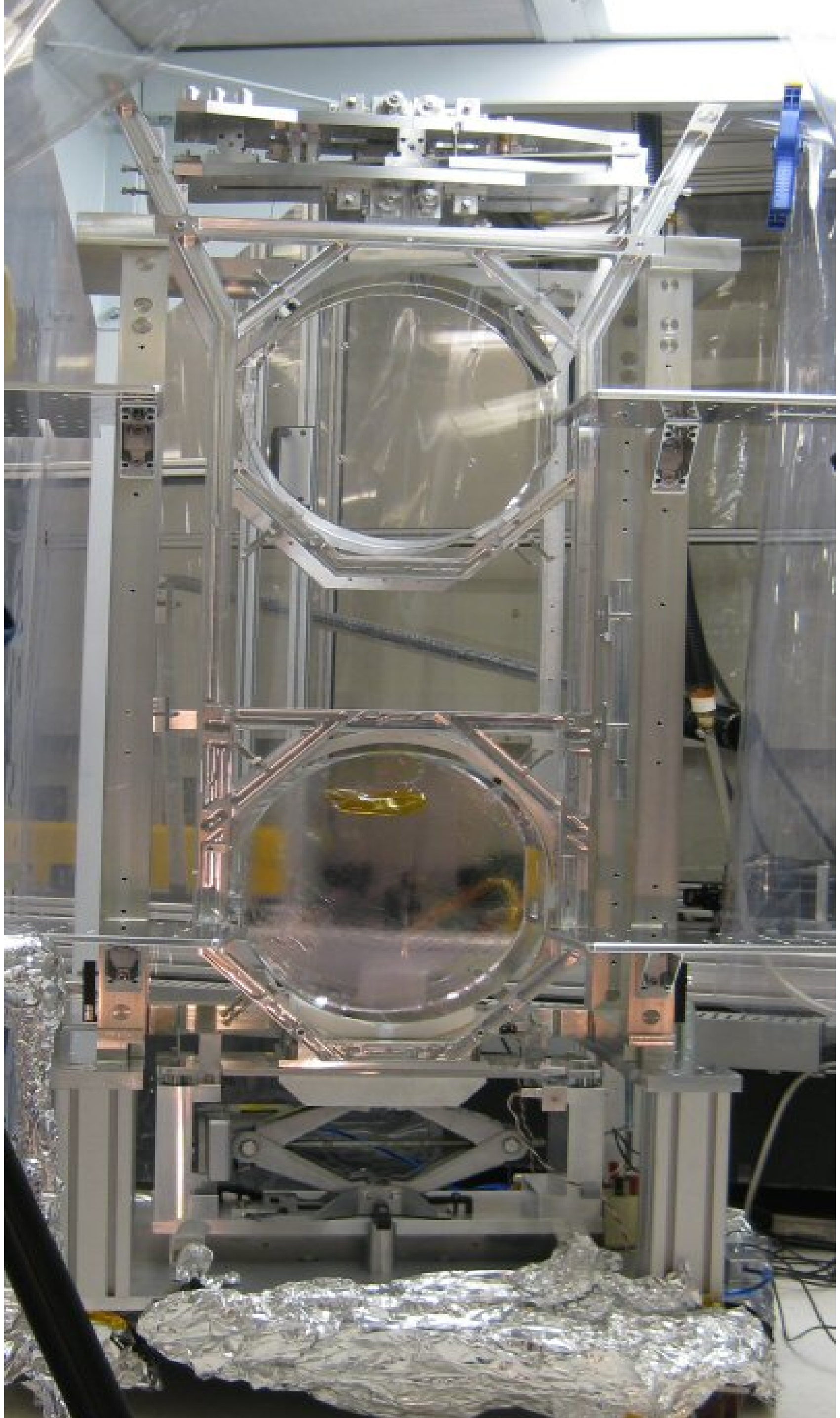


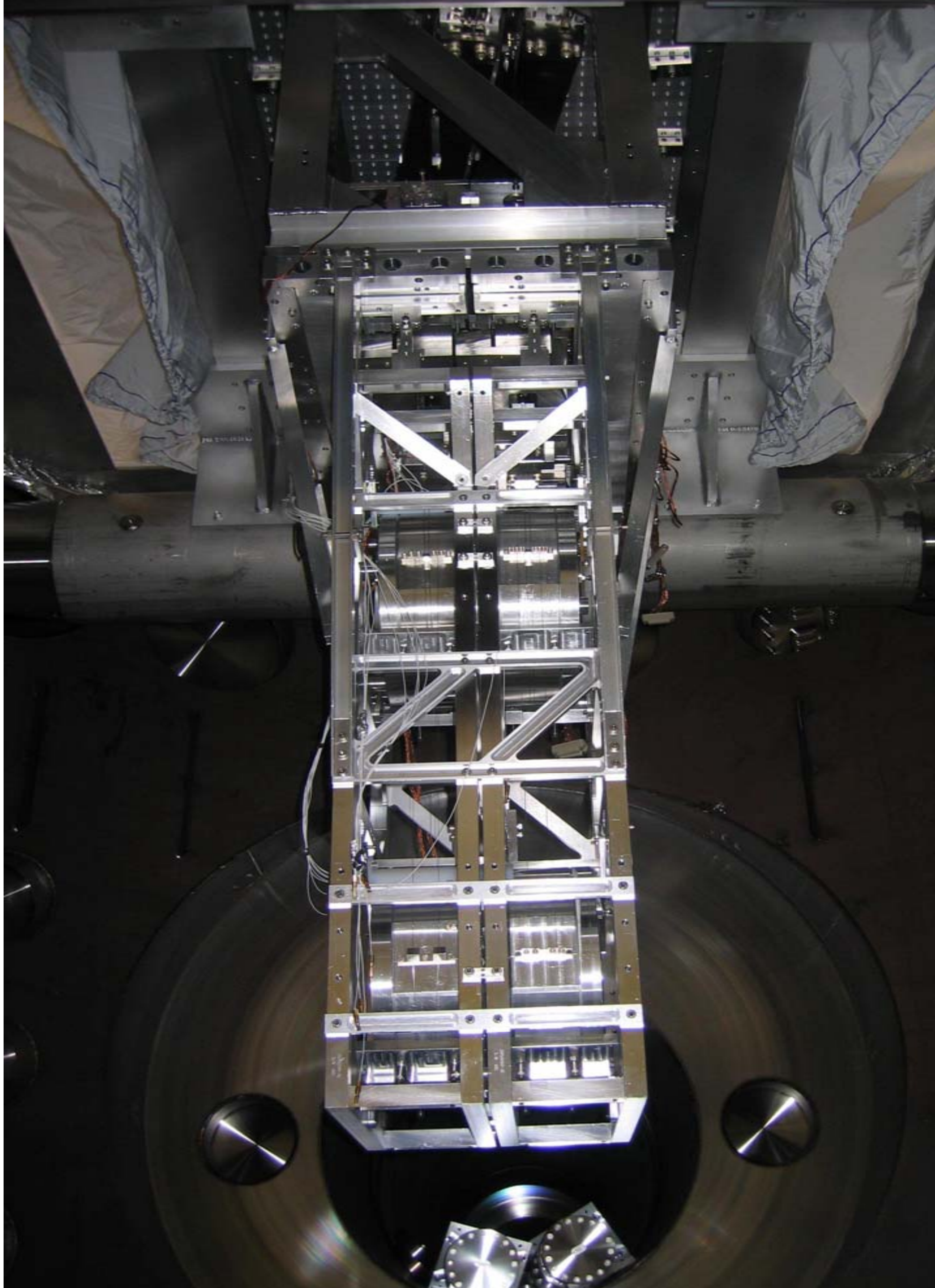
Four stages

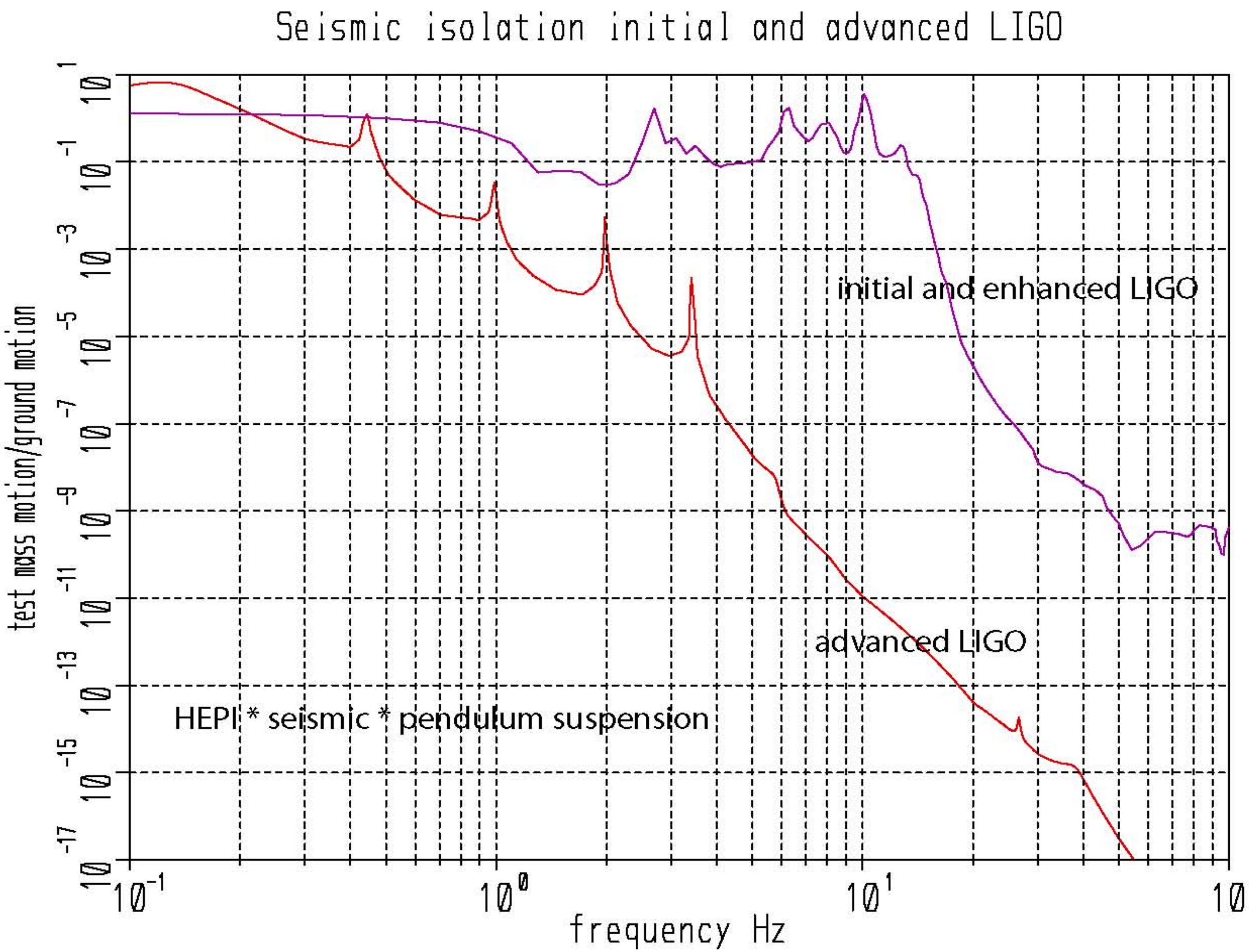
Damping applied at top stage

Main chain plus parallel reaction chain for control actuation

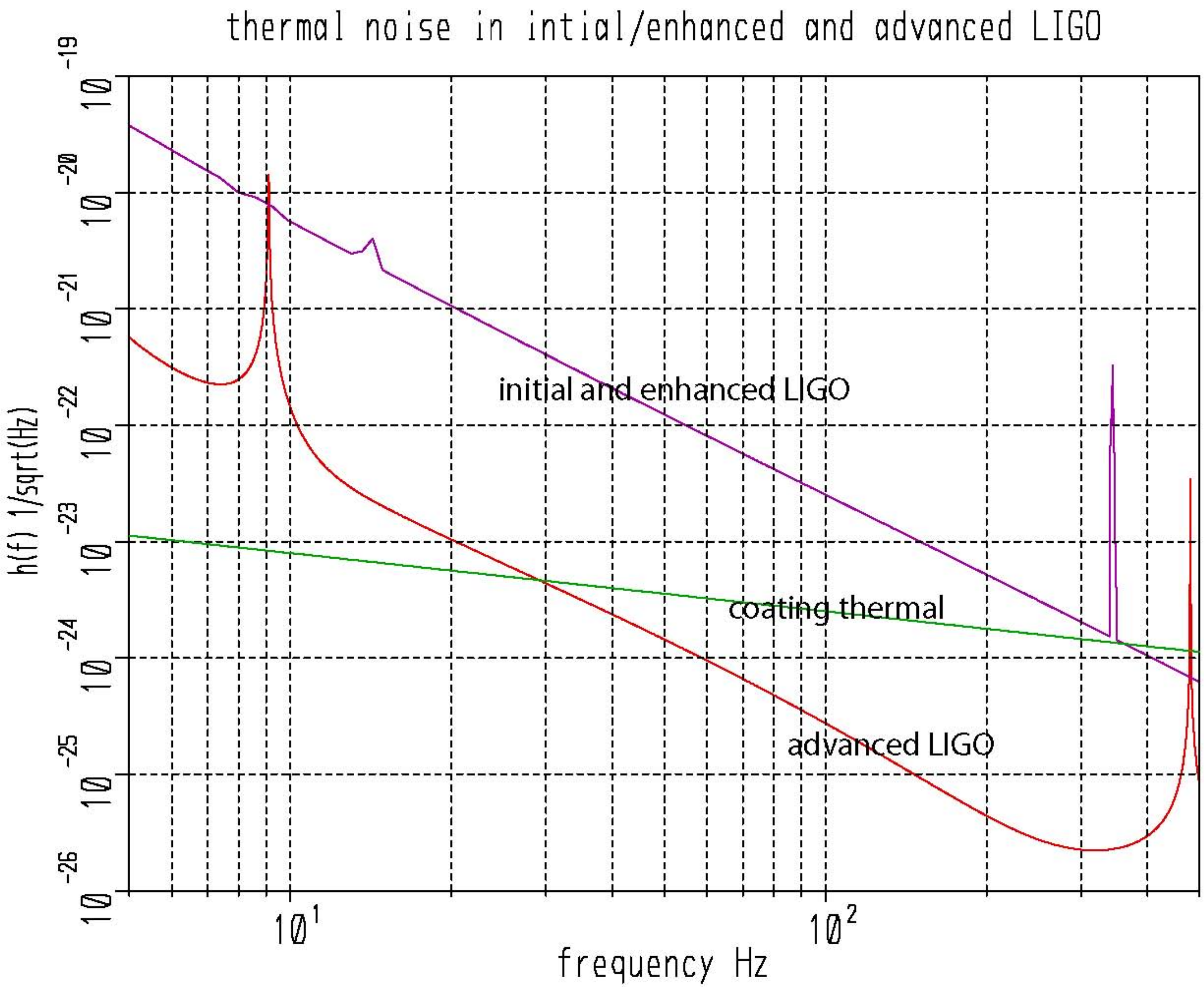
(Lower support structure removed for clarity)



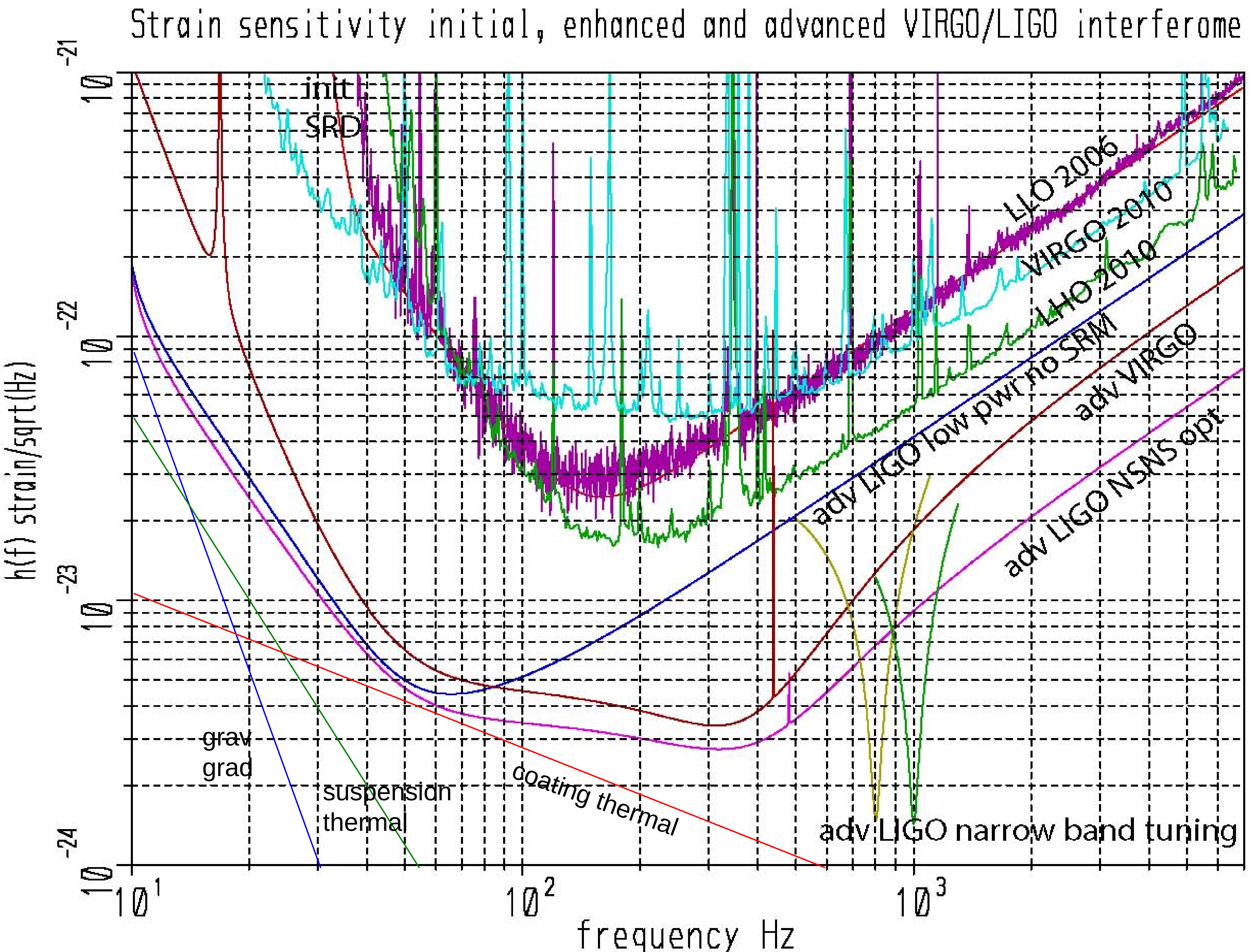




Seismic isolation initial and advanced LIGO
test mass motion/ground motion
frequency Hz
initial and enhanced LIGO
advanced LIGO
HEPI * seismic * pendulum suspension



thermal noise in intial/enhanced and advanced LIGO
initial and enhanced LIGO
coating thermal
advanced LIGO
h(f) 1/sqrt(Hz)
frequency Hz
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^-25
10^-26
10^1
10^2



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grav
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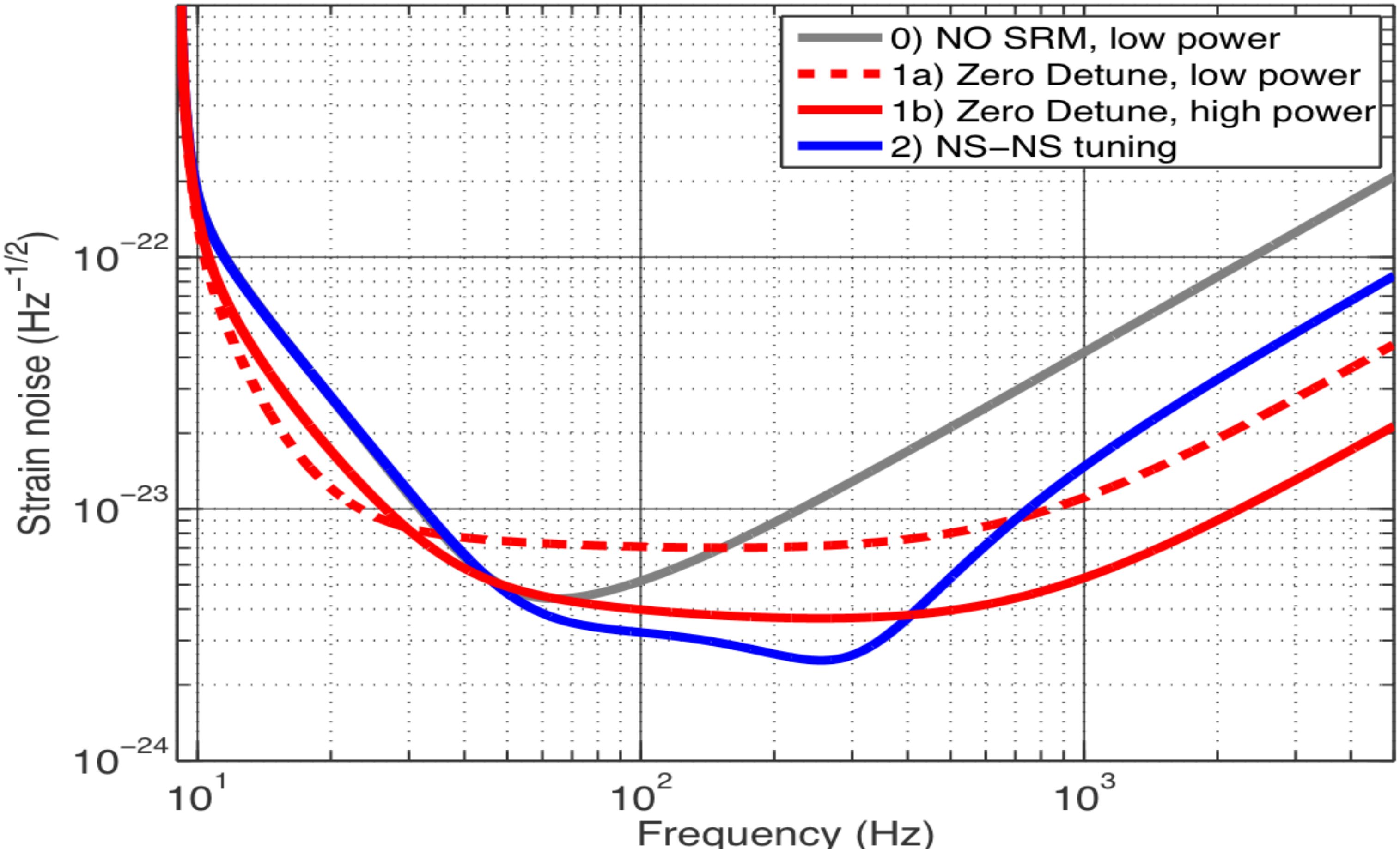
thermal
coating thermal
adv LIGO narrow band tuning

Advanced LIGO broadband operational modes



P.Fritschel Advanced LIGO Systems Design (2009)

Mode	*NS-NS Range*	*BH-BH Range*	P_{in}	T_{SRM}	ϕ_{SRC}	h_{RMS}, 10^{-22} (band)
0	150 Mpc	1.60 Gpc	25 W	100%	–	0.53 (40 – 140 Hz)
1a	145 Mpc	1.65 Gpc	25 W	20%	0 deg.	0.70 (110 – 210 Hz)
1b	190 Mpc	1.85 Gpc	125 W	20%	0 deg.	0.37 (205 – 305 Hz)
2	200 Mpc	1.65 Gpc	125 W	20%	16 deg.	0.25 (205 – 305 Hz)

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
- Triggered searches
  - Gamma ray bursts
  - EM transients
- Periodic CW sources
  - Pulsars
  - Low mass x-ray binaries (quasi periodic)
- Stochastic background
  - Cosmological isotropic background
  - Foreground sources : gravitational wave radiometry

P. Brady Plenary talk on Friday

Session C2 Friday

R = horizon distance

Binary NS coalescences 1.4Mo / 1.4 Mo

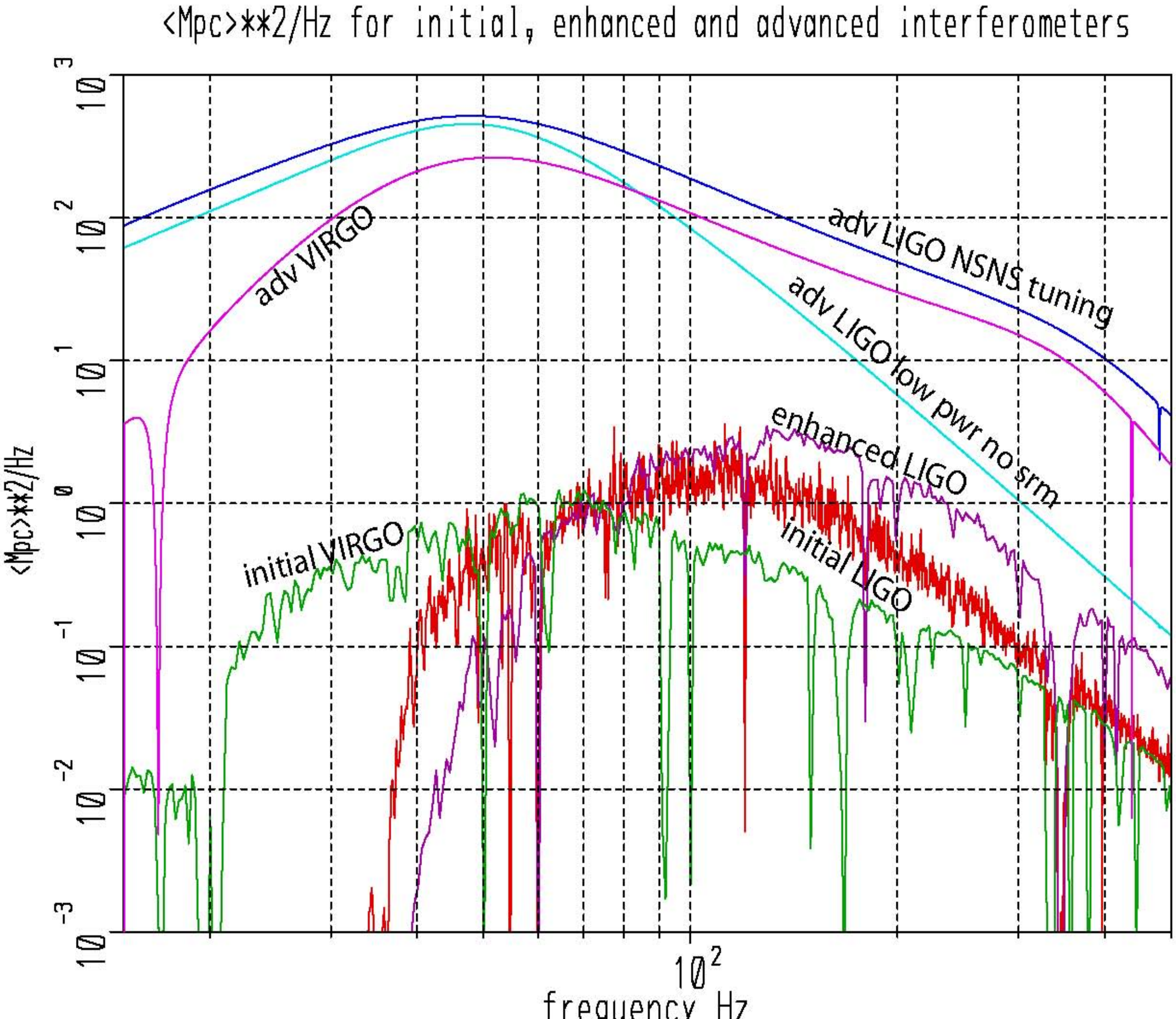
Strain vs time

$$h(t) = \frac{2G}{Rc^4}\left(\frac{m_1 m_2}{m_1 + m_2}\right)(\pi G(m_1 + m_2)f(t))^{\frac{2}{3}} = 1.8\times 10^{-23} \quad f = 100\text{Hz} \quad R = 100\text{Mpc}$$

$$f(t) = \frac{1}{\pi}\left(\frac{5}{256\tau}\right)^{\frac{3}{8}}\left(\frac{c^3}{G M_{chirp}}\right)^{\frac{5}{8}} = \frac{134\text{Hz}}{\tau^{\frac{3}{8}}} \qquad M_{chirp} = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}} \qquad \tau = (t_{end} - t)$$

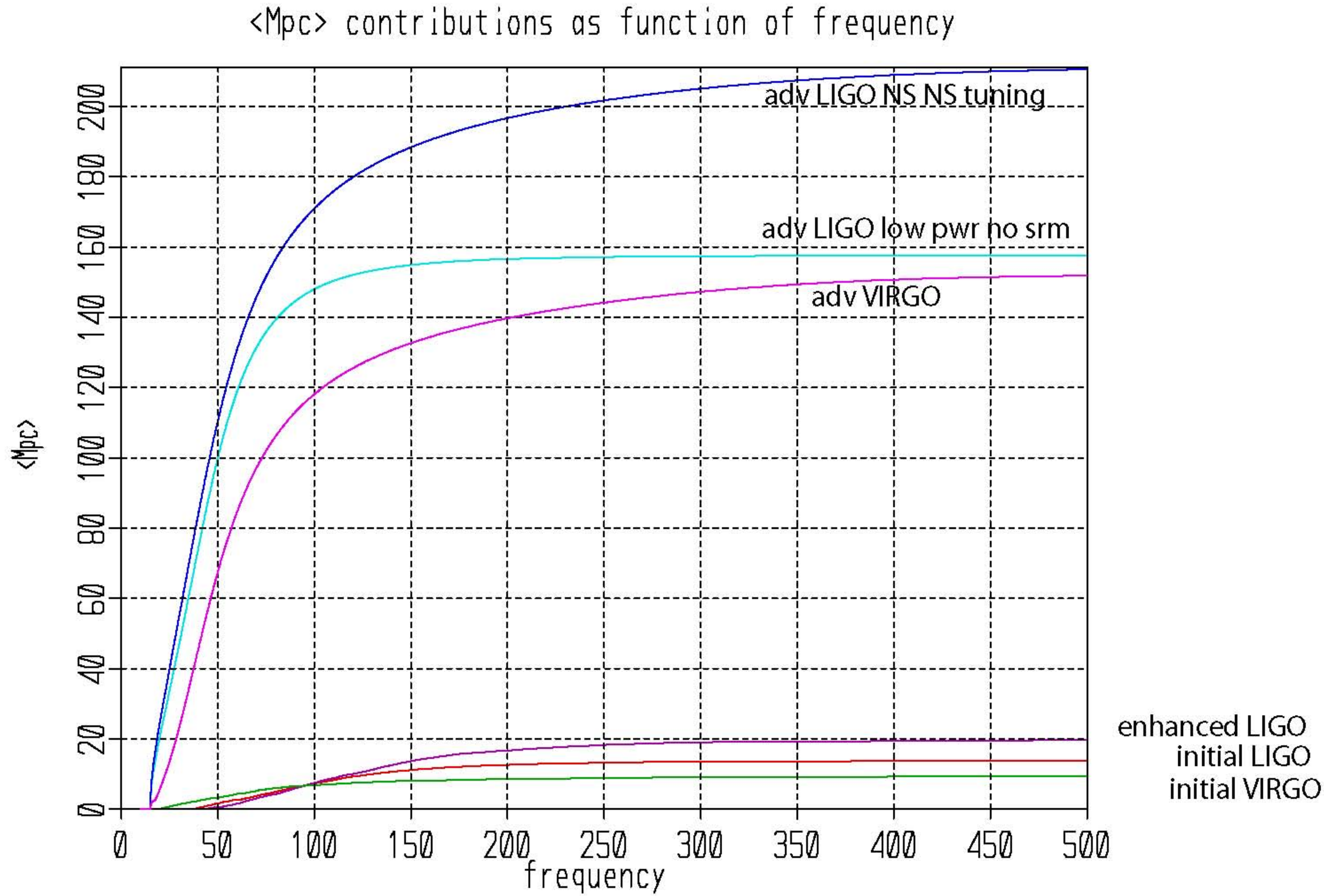
Frequency spectrum

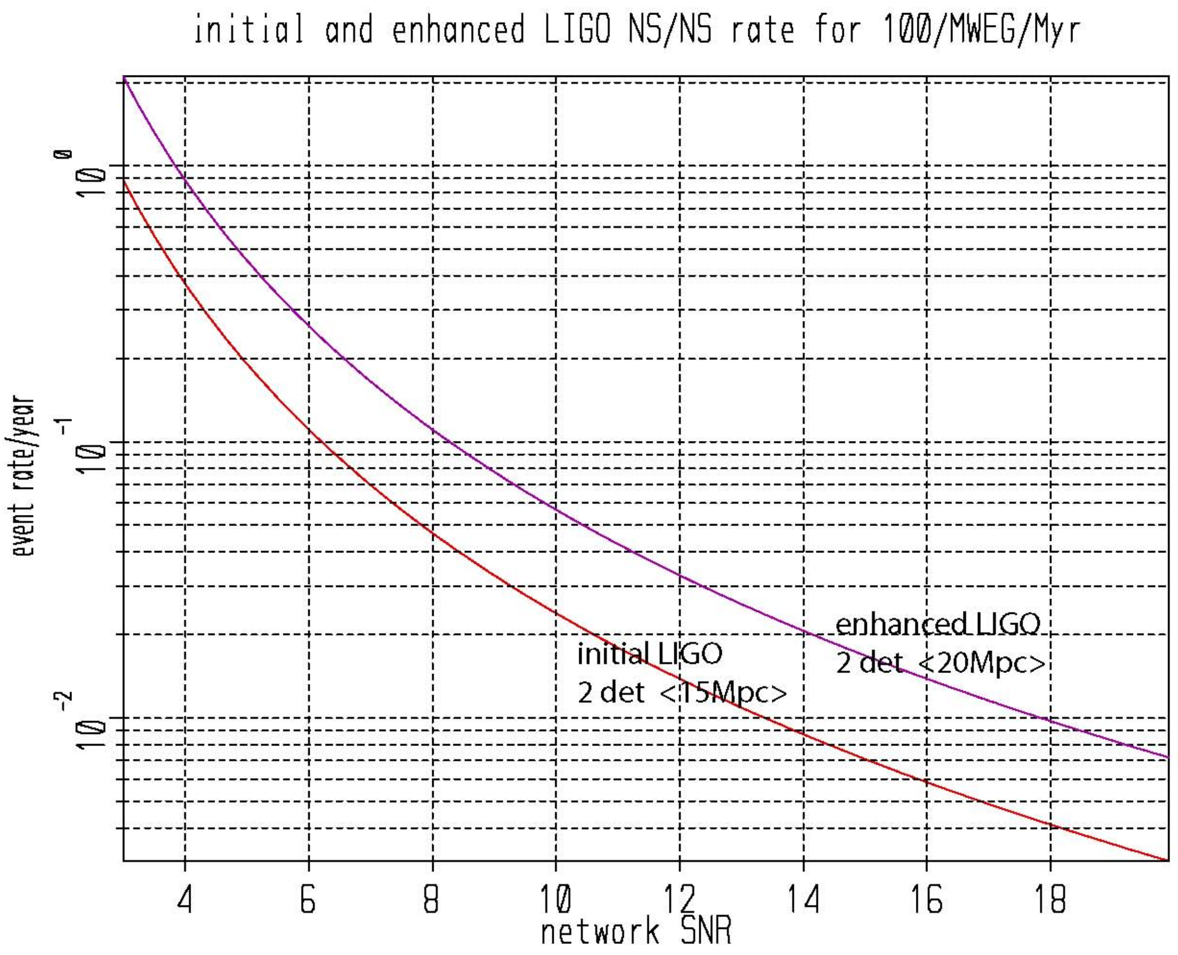
$$h(f) = \frac{1}{\pi^{\frac{2}{3}}}\sqrt{\frac{5}{24}}\left(\frac{c}{R}\right)\left(\frac{G M_{chirp}}{c^3}\right)^{\frac{5}{6}}\left(\frac{1}{f^{\frac{7}{6}}}\right) = \frac{9.1\times 10^{-22}}{f^{\frac{7}{6}}}\text{strain/Hz} \quad R = 100\text{Mpc}$$



$$h_{signal}(f) = \sqrt{h_x^2(f) + h_+^2(f)}$$

$$SNR^2 = 2\int_0^{\infty} \frac{h_{signal}^2(f)}{h_{noise}^2(f)} df$$


<Mpc> contributions as function of frequency
adv LIGO NS NS tuning
adv LIGO low pwr no srm
adv VIRGO
enhanced LIGO
initial LIGO
initial VIRGO
<Mpc>
frequency
0
20
40
60
80
100
120
140
160
180
200
0
50
100
150
200
250
300
350
400
450
500

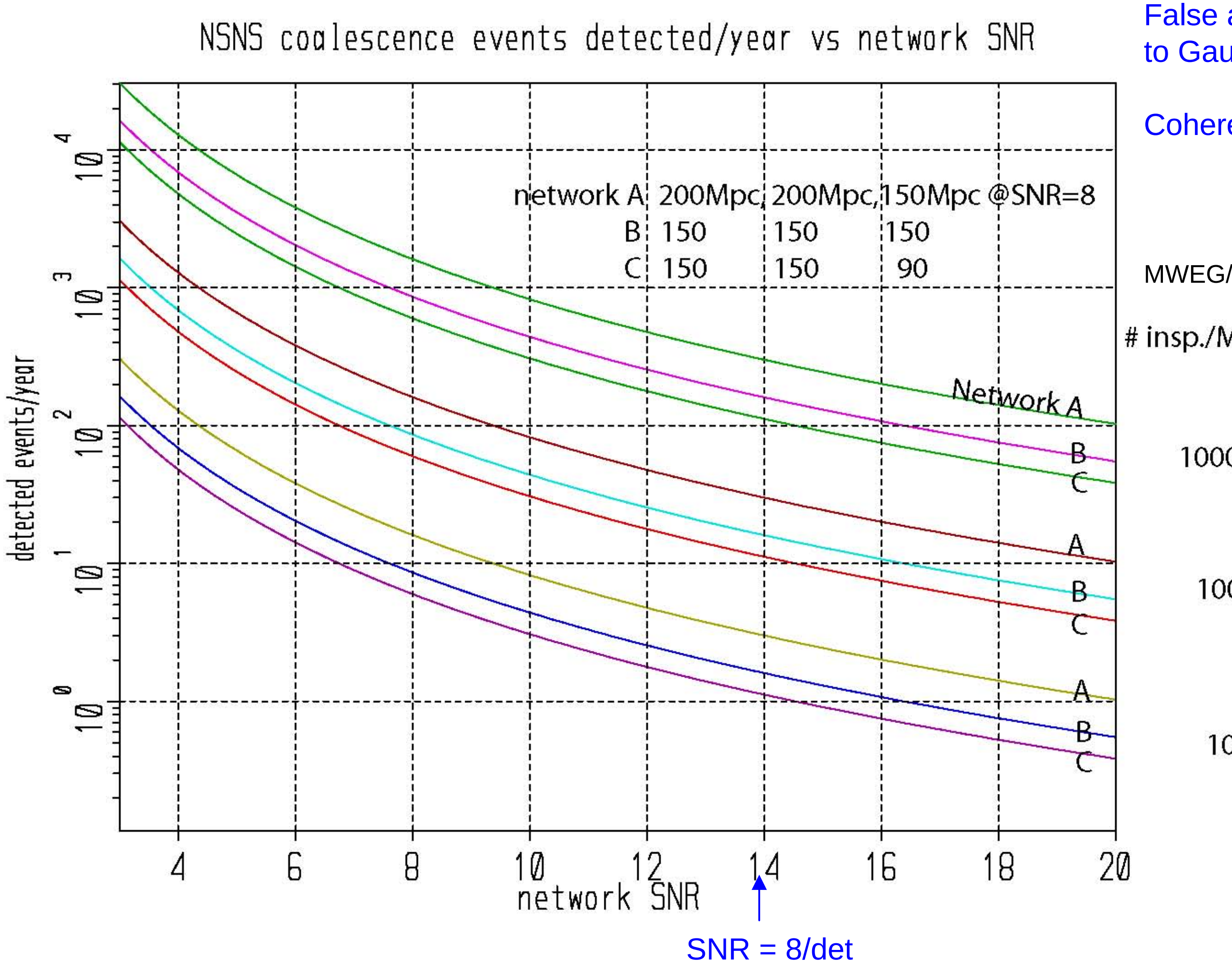


initial and enhanced LIGO NS/NS rate for 100/MWEG/Myr
event rate/year
10^0
10^-1
10^-2
4
6
8
10
12
14
16
18
network SNR
initial LIGO
2 det <15Mpc>
enhanced LIGO
2 det <20Mpc>

Conditions:

False alarm rates reduced to Gaussian statistics.

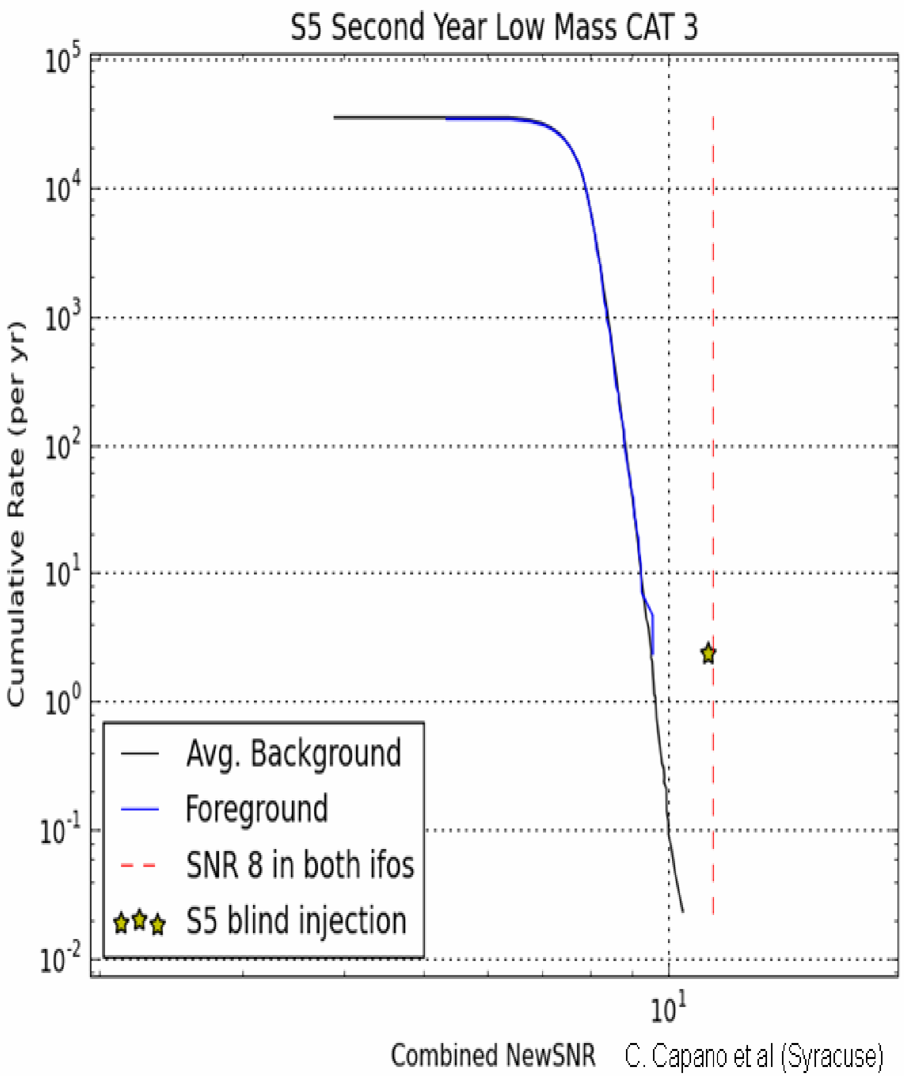
Coherent detection

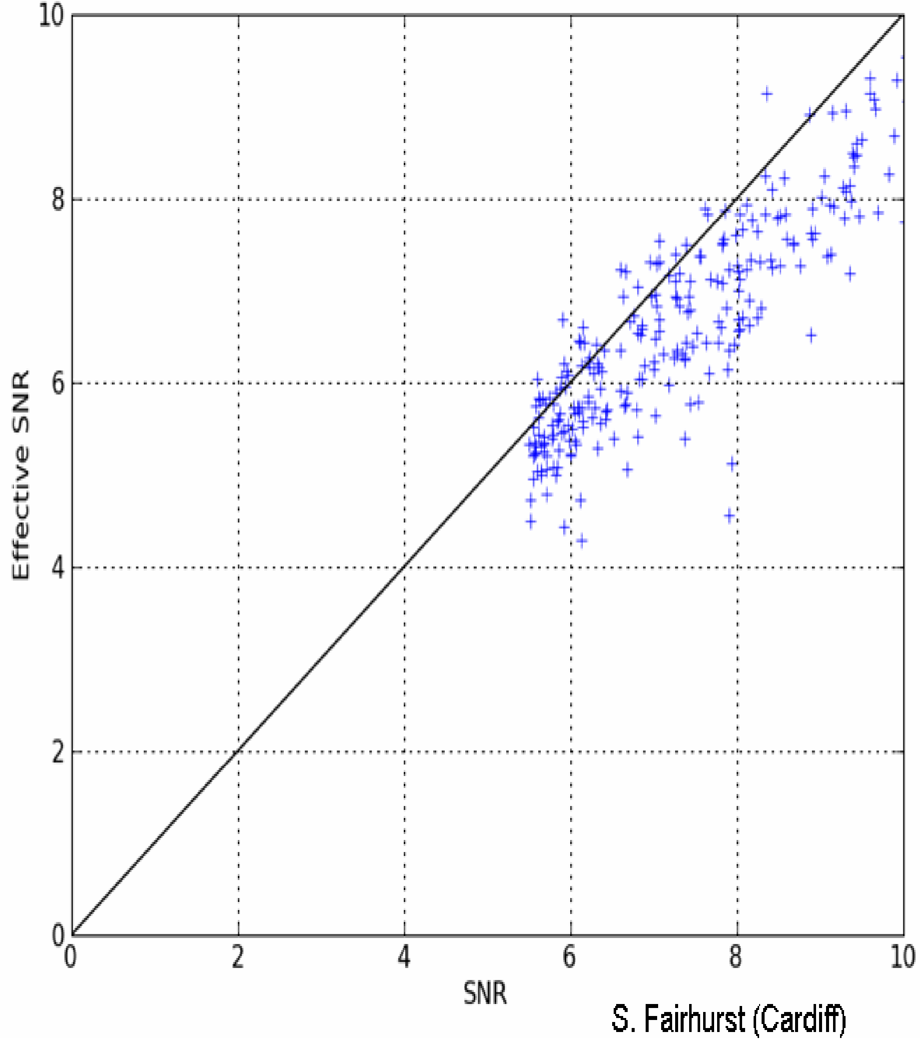


$$\text{NSNS events/year} = \frac{4\pi}{3}\left(\frac{8}{\text{SNR}_{\text{network}}}\sqrt{\sum_{1}^{\text{n det}}\left\langle \text{R(Mpc)}\right\rangle^2_{\text{SNR=8}}}\right)^3\left(\frac{\text{MWEG}}{\text{Mpc}^3}\right)\left(\frac{\text{\#NSNS insp}}{\text{MWEG/yr}}\right)$$

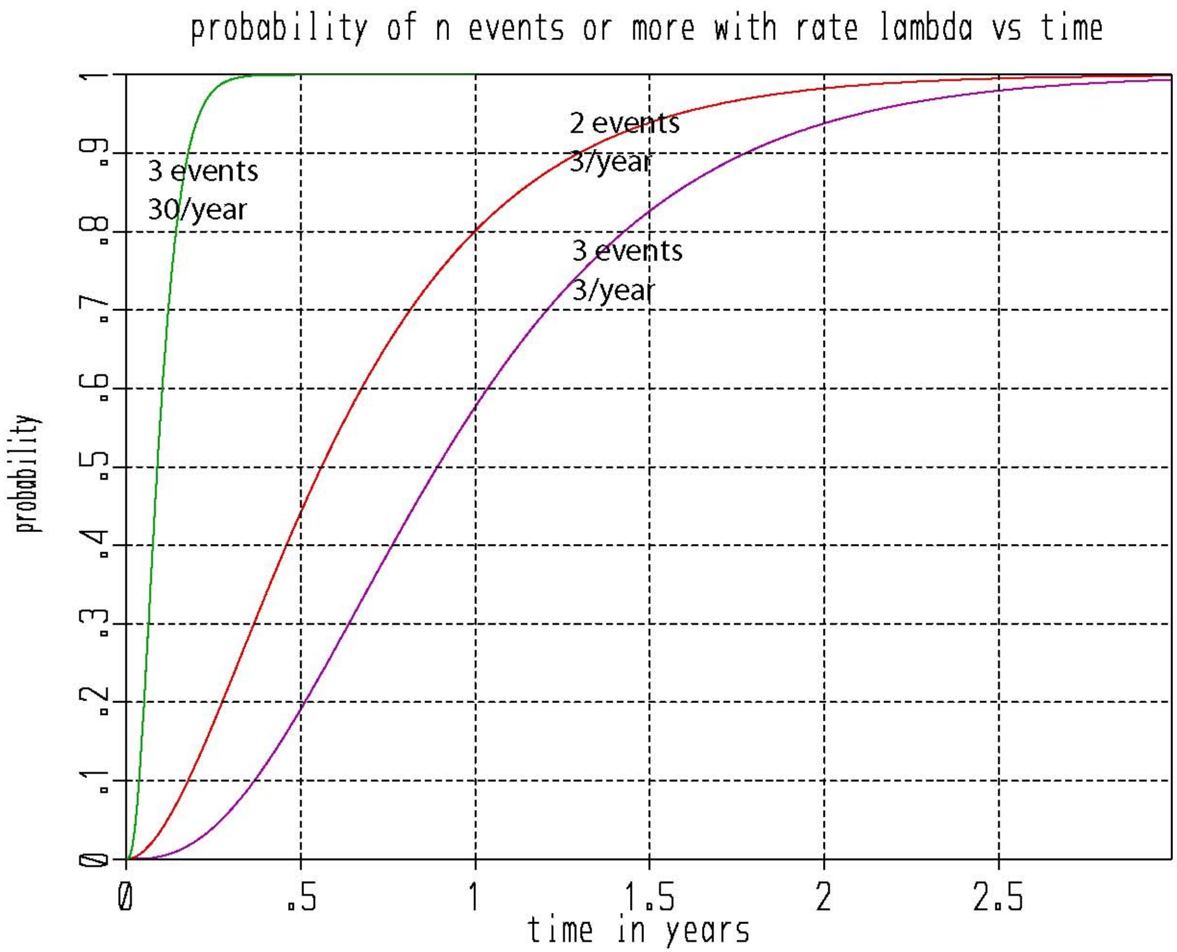
Physical Environment Monitoring

- Seismic motion
  - xyz seismometer/building
- Motion of test mass chambers
  - xyz accelerometers/chamber
- Acoustic excitation
  - microphone/building
- Magnetic fields
  - xyz magnetometer/building
  - xyz high sensitivity coil/site
- Radio Frequency interference
  - multiband 30kHz -100MHz receiver/site
- Main AC power monitor
  - 3 phase monitor/building
- Muon shower detector
  - scintillator-PM tube/site


S5 Second Year Low Mass CAT 3
Cumulative Rate (per yr)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Avg. Background
Foreground
SNR 8 in both ifos
S5 blind injection
10^1
Combined NewSNR
C. Capano et al (Syracuse)


Effective SNR
SNR
0
2
4
6
8
10
S. Fairhurst (Cardiff)

Spare slides follow

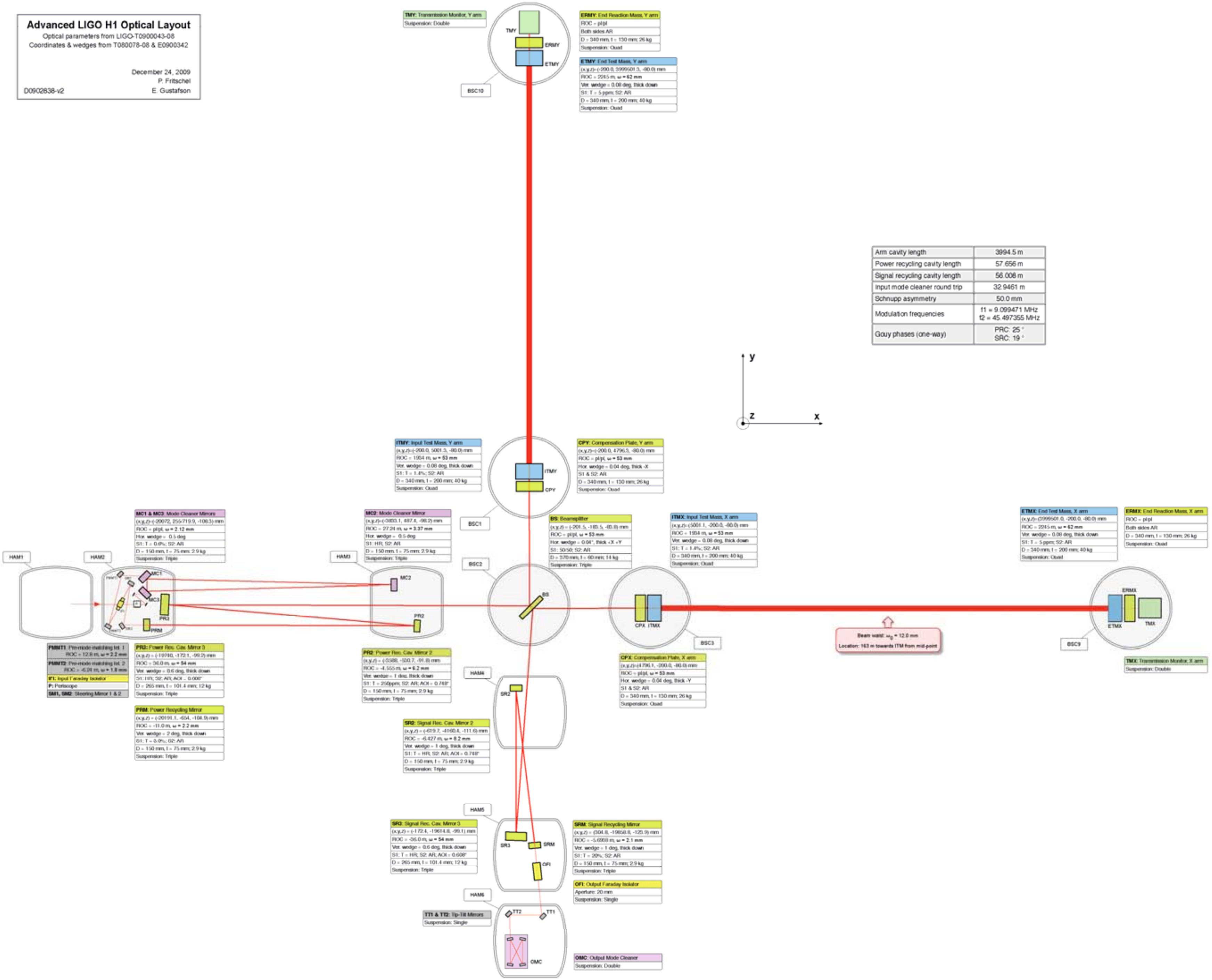

probability of n events or more with rate lambda vs time
probability
time in years
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
.5
1
1.5
2
2.5
3 events
30/year
2 events
3/year
3 events
3/year

Advanced LIGO H1 Optical Layout

Optical parameters from LIGO-T0900043-08
Coordinates & wedges from T080078-08 & E0900342

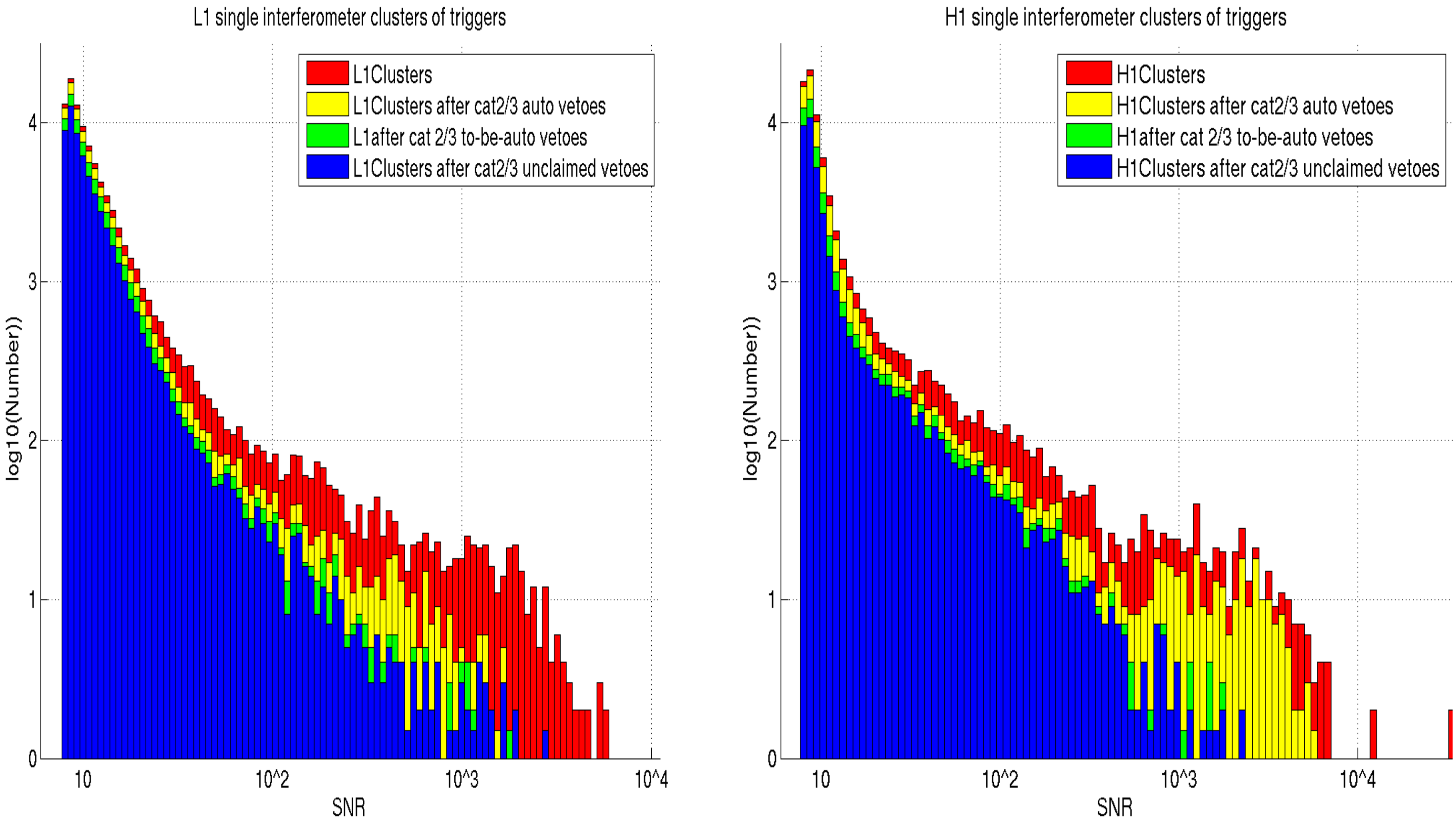
December 24, 2009
P. Fritschel
E. Gustafson

D0902838-v2

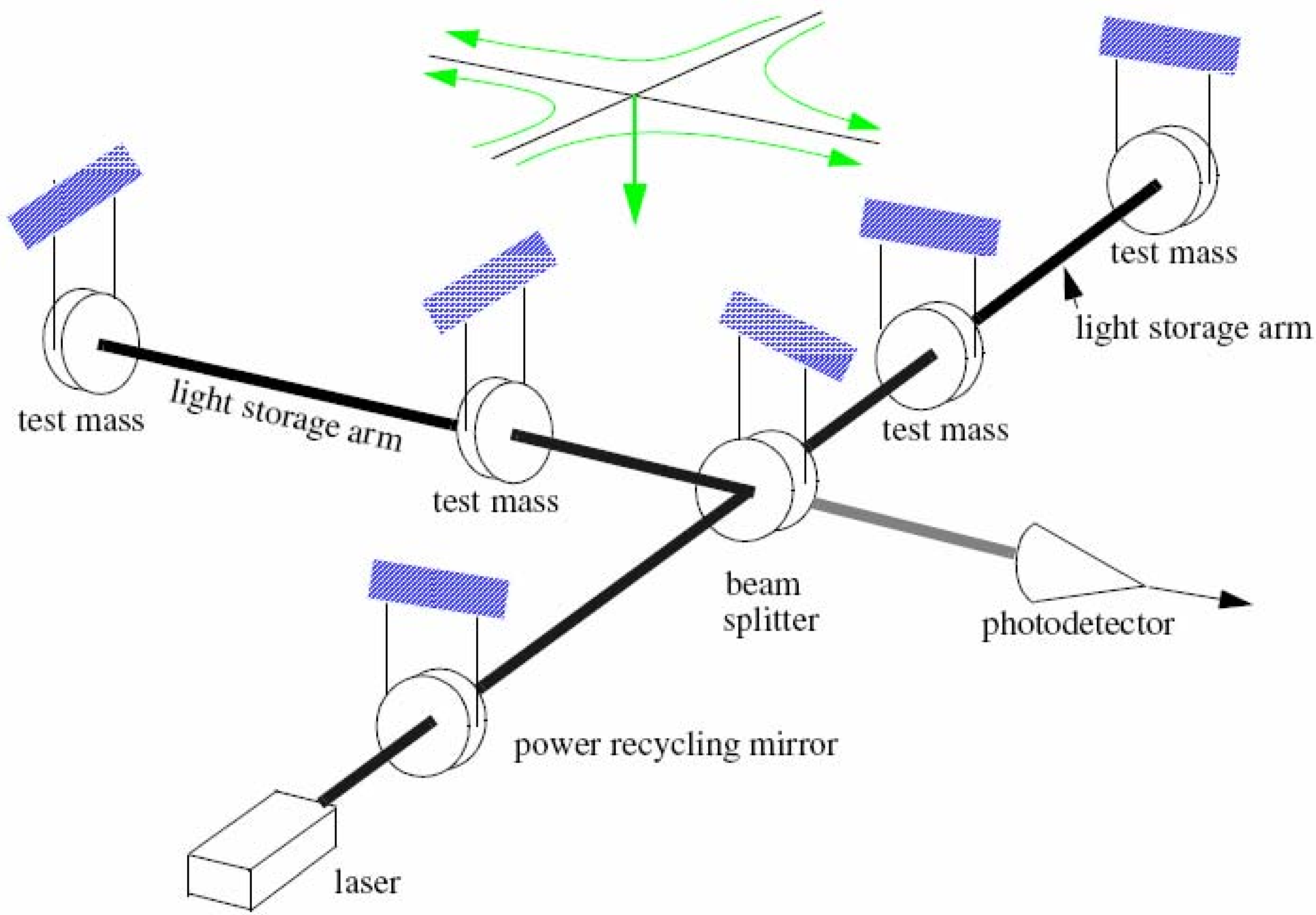


Arm cavity length	3994.5 m
Power recycling cavity length	57.656 m
Signal recycling cavity length	56.008 m
Input mode cleaner round trip	32.9461 m
Schnupp asymmetry	50.0 mm
Modulation frequencies	f1 = 9.099471 MHz f2 = 45.497355 MHz
Gouy phases (one-way)	PRC: 25° SRC: 19°

NS/NS binary inspiral triggers in the year 1 of S5 in L1 and H1



Jake Slutsky LSU


test mass
light storage arm
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splitter
photodetector
power recycling mirror
laser