The Current State of the LIGO Detectors

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Outline

- Gravitational waves and amplitude
- Noise sources limiting detection sensitivity
- LIGO performance
  - Sensitivity
  - Duty cycle
  - Binary neutron star inspiral range
- Near term LIGO improvements

The LIGO Scientific Collaboration (LSC)

- The LSC carries out the scientific program of LIGO – instrument science, data analysis.
- The 3 LIGO interferometers and the GEO600 instrument are analyzed as one data set
- Approximately 540 members
- ~ 35 institutions plus the LIGO Laboratory.
- Participation from Australia, Germany, India, Italy, Japan, Russia, Spain, the U.K. and the U.S.A.

Direct detection of gravitational waves from astrophysical sources

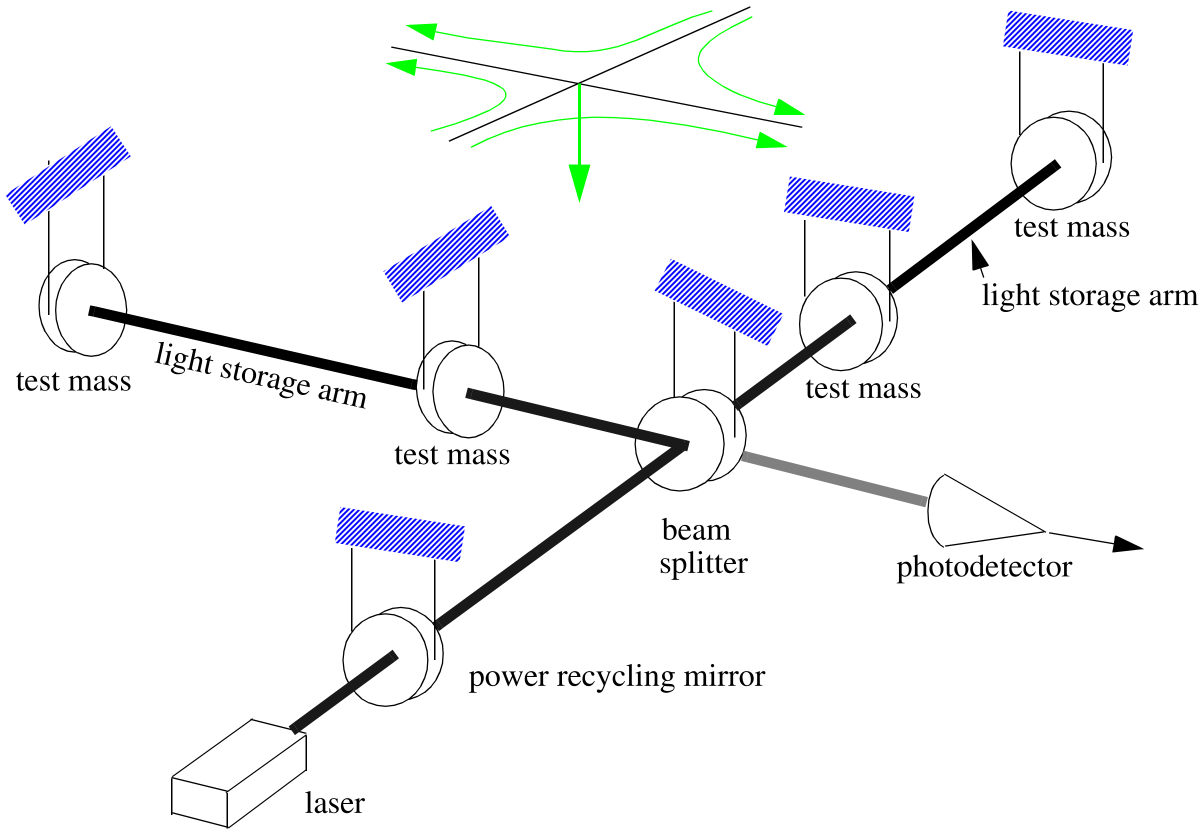
- Physics
  - Observations of gravitation in the strong field, high velocity limit
  - Determination of wave kinematics – polarization and propagation
  - Tests for alternative relativistic gravitational theories
- Astrophysics
  - Measurement of coherent inner dynamics – stellar collapse, pulsar formation….
  - Compact binary coalescence – neutron star/neutron star, black hole/black hole
  - Neutron star equation of state
  - Primeval cosmic spectrum of gravitational waves
- Gravitational wave survey of the universe

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

LIGO

LIGO Optic

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity $< 5 \times 10^{-7}$

Internal mode Q's $> 2 \times 10^{6}$

Polishing

Surface uniformity < 1 nm rms

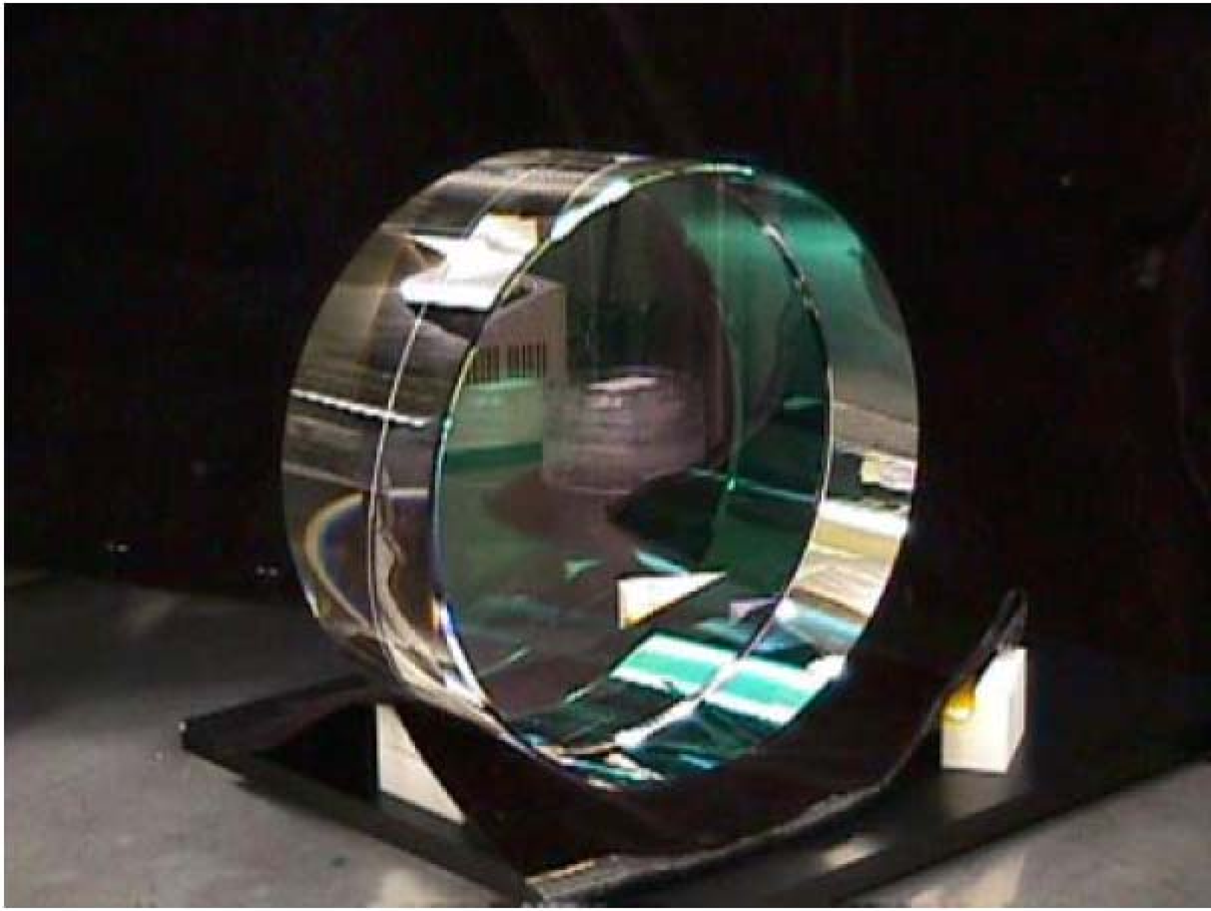
adii of curvature matched < 3%

Coating

Scatter < 50 ppm

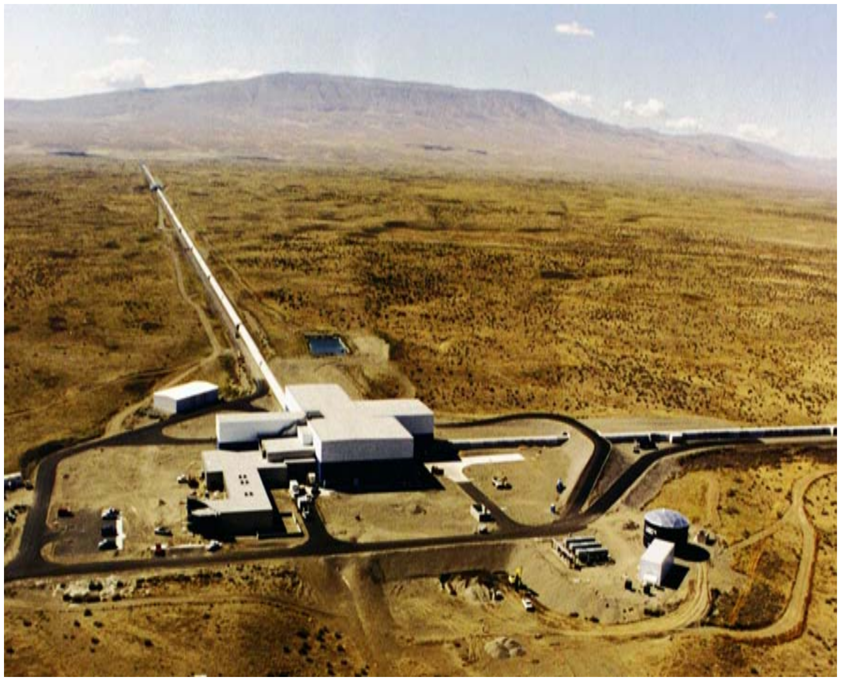
Absorption < 2 ppm

Uniformity $<10^{-3}$



Core Optics
installation and alignment

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

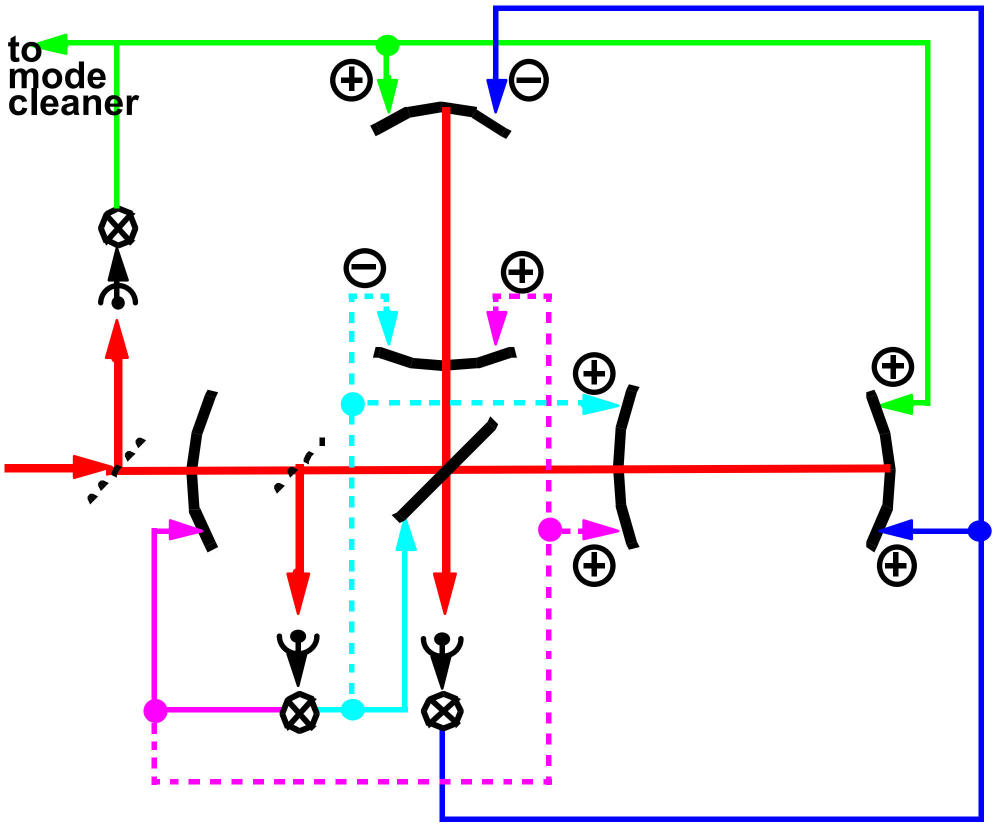
2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

Single 4 km interferometer

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)

FRINGE SENSING

wavelength 1×10^{-6} m

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

arm length = 4000 m

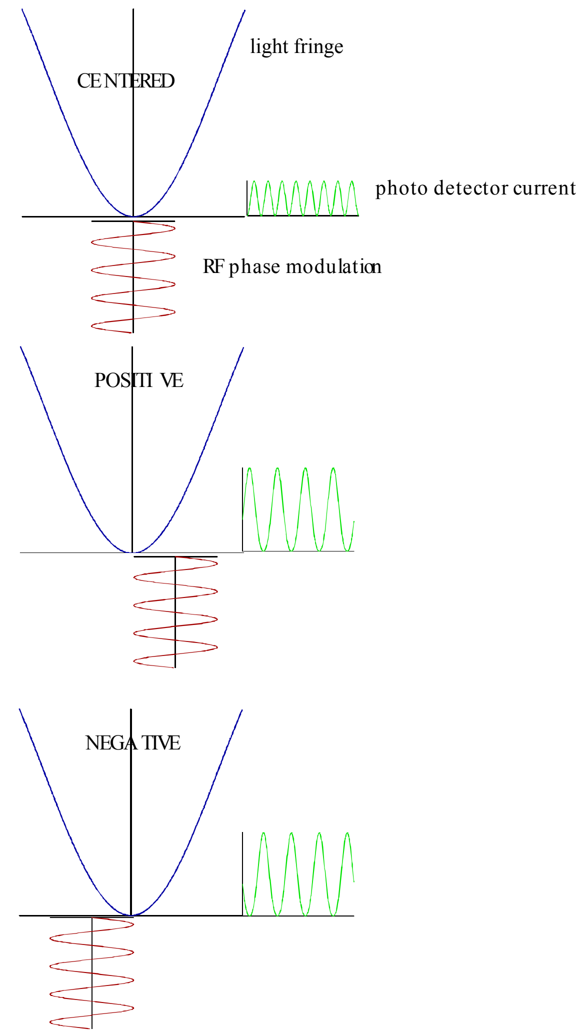
equivalent # of passes = 100

number of quanta/second at the beam splitter

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

integration time

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



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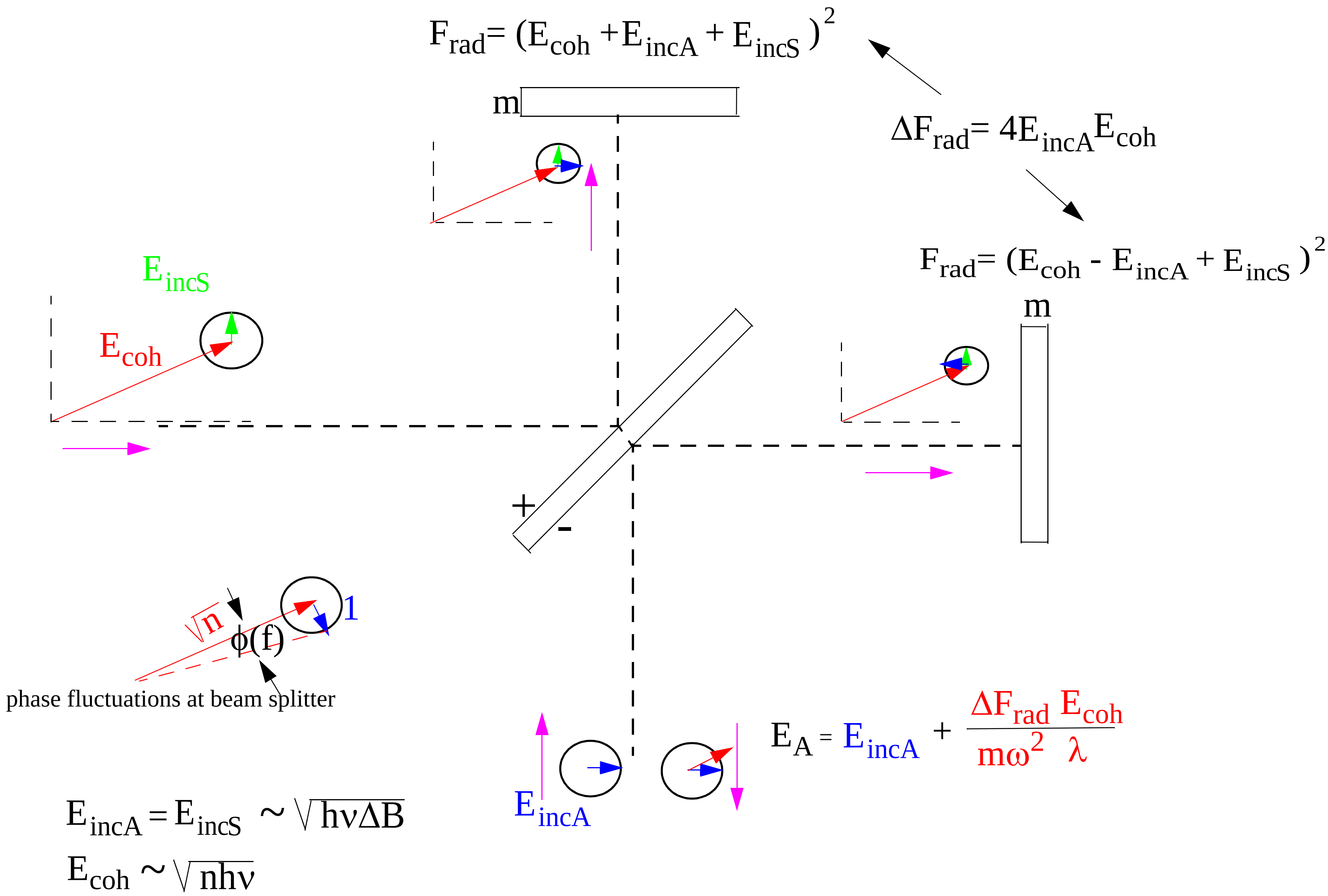
Quantum Noise in the Michelson Interferometer



ττ=

PENDULUM THERMAL NOISE

Pendulum Brownian motion

Dissipation leads to fluctuations

τ = coherence or damping time

= Q x period of oscillator

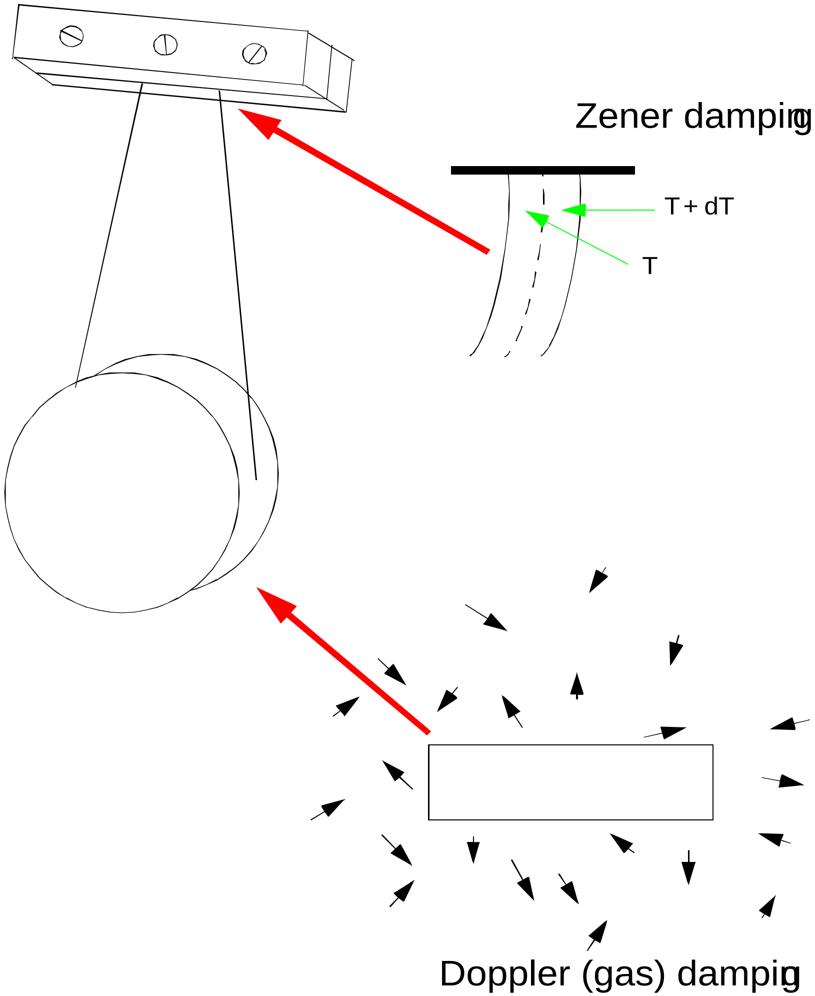
Exchange with surroundings:

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

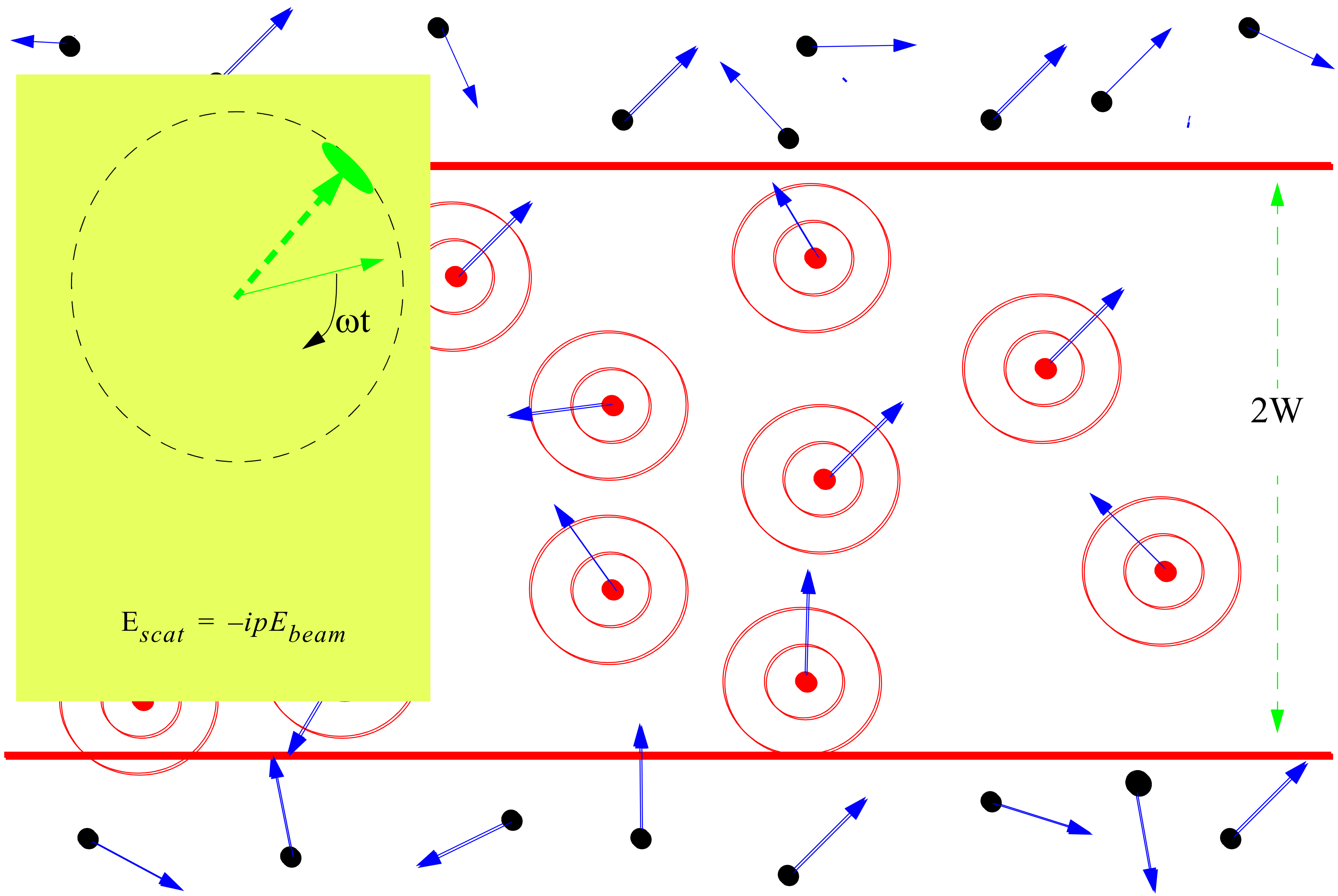
Large τ => smaller fluctuations

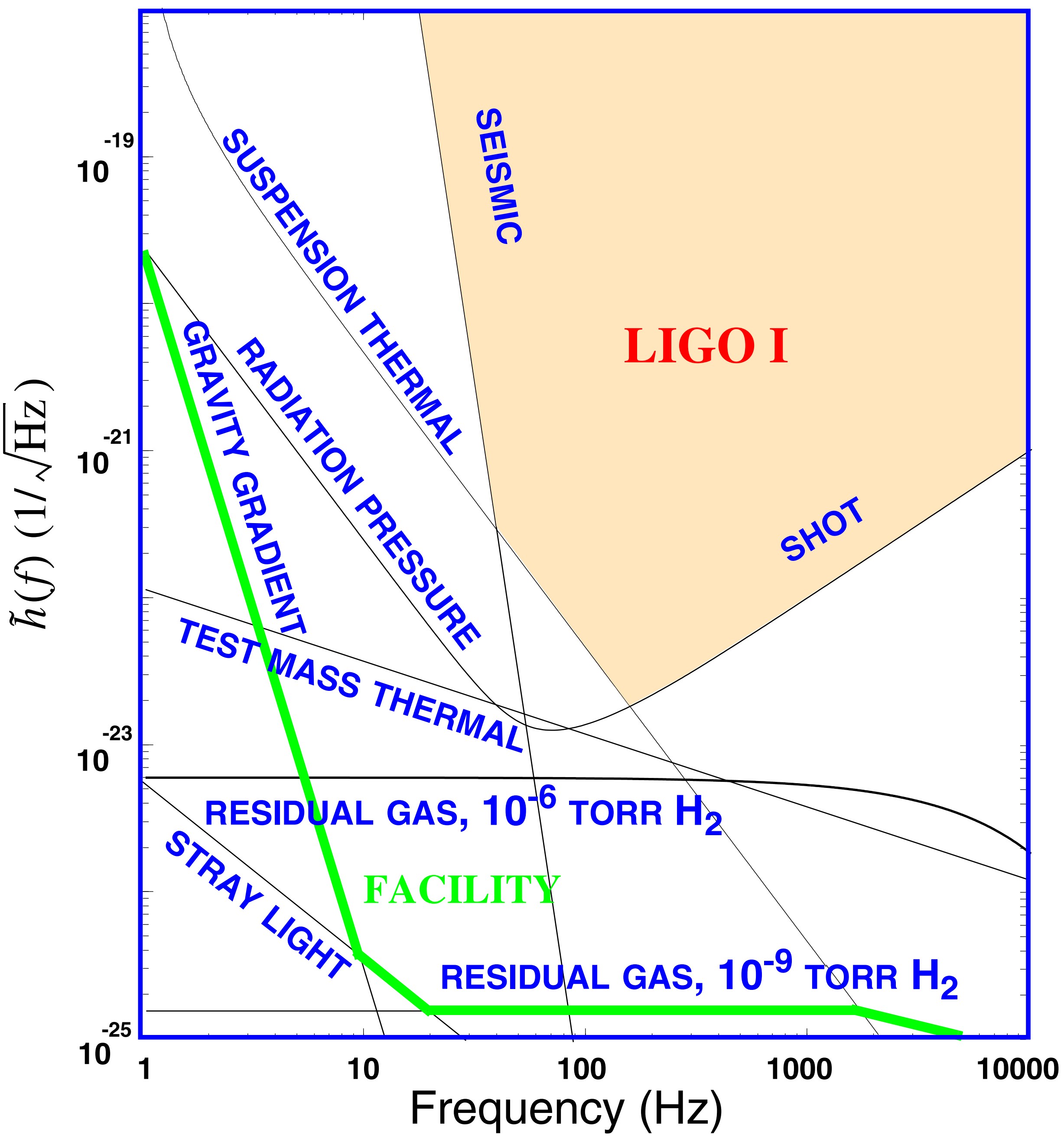
Mechanisms

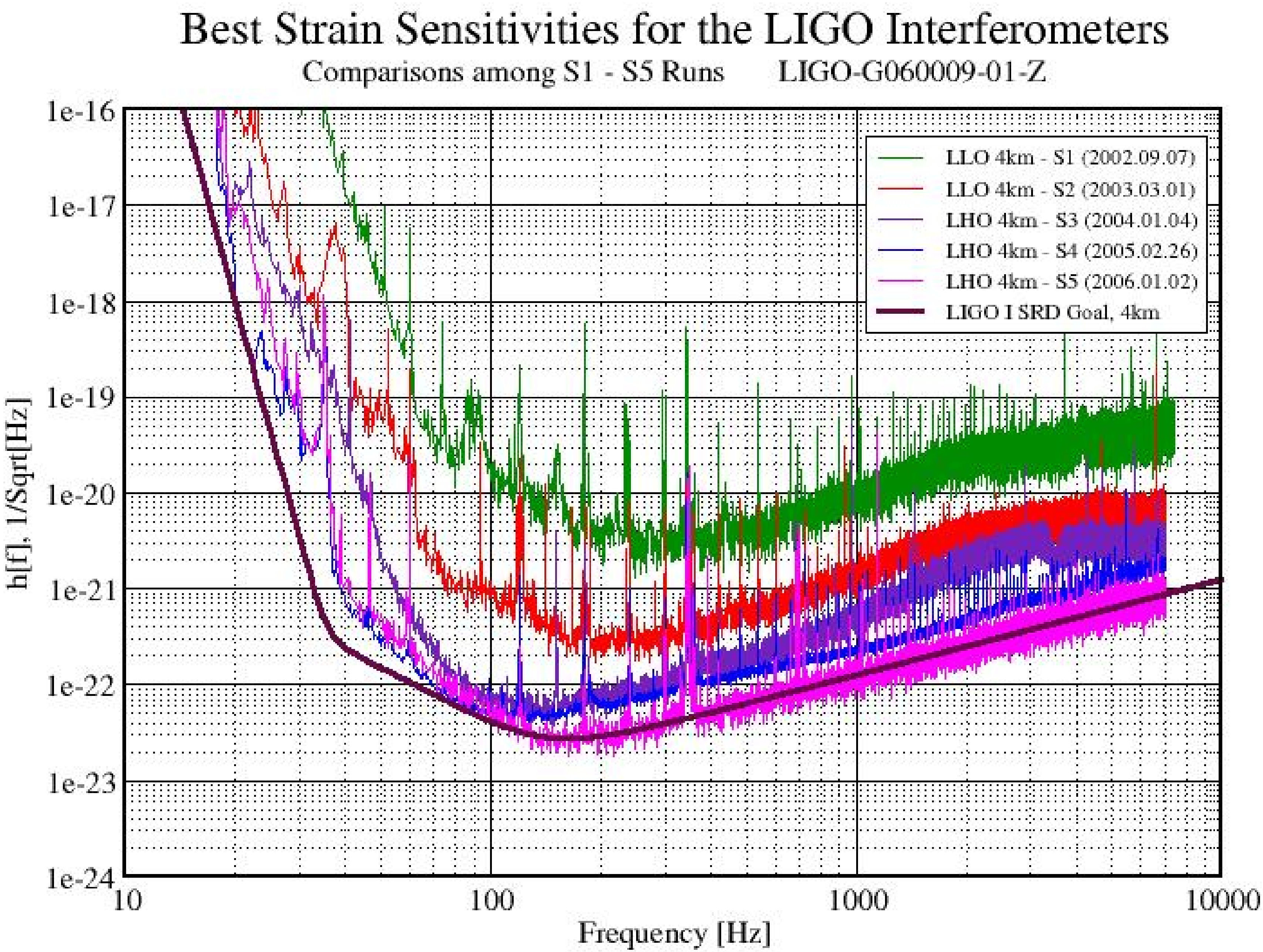
- velocity dependent – viscous
- position dependent lag – structure
- thermo-elastic - Zener

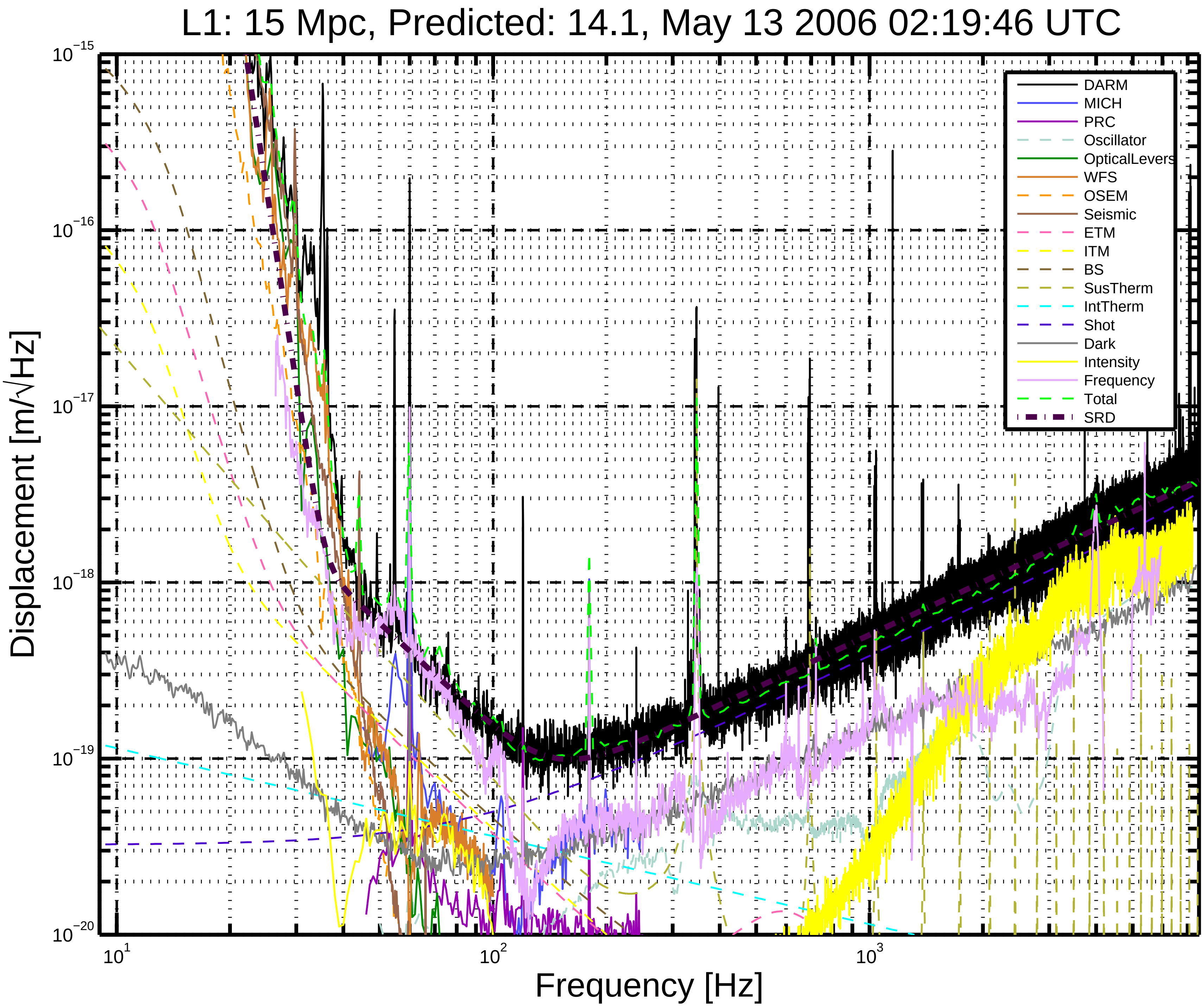


Phase noise from molecular scattering

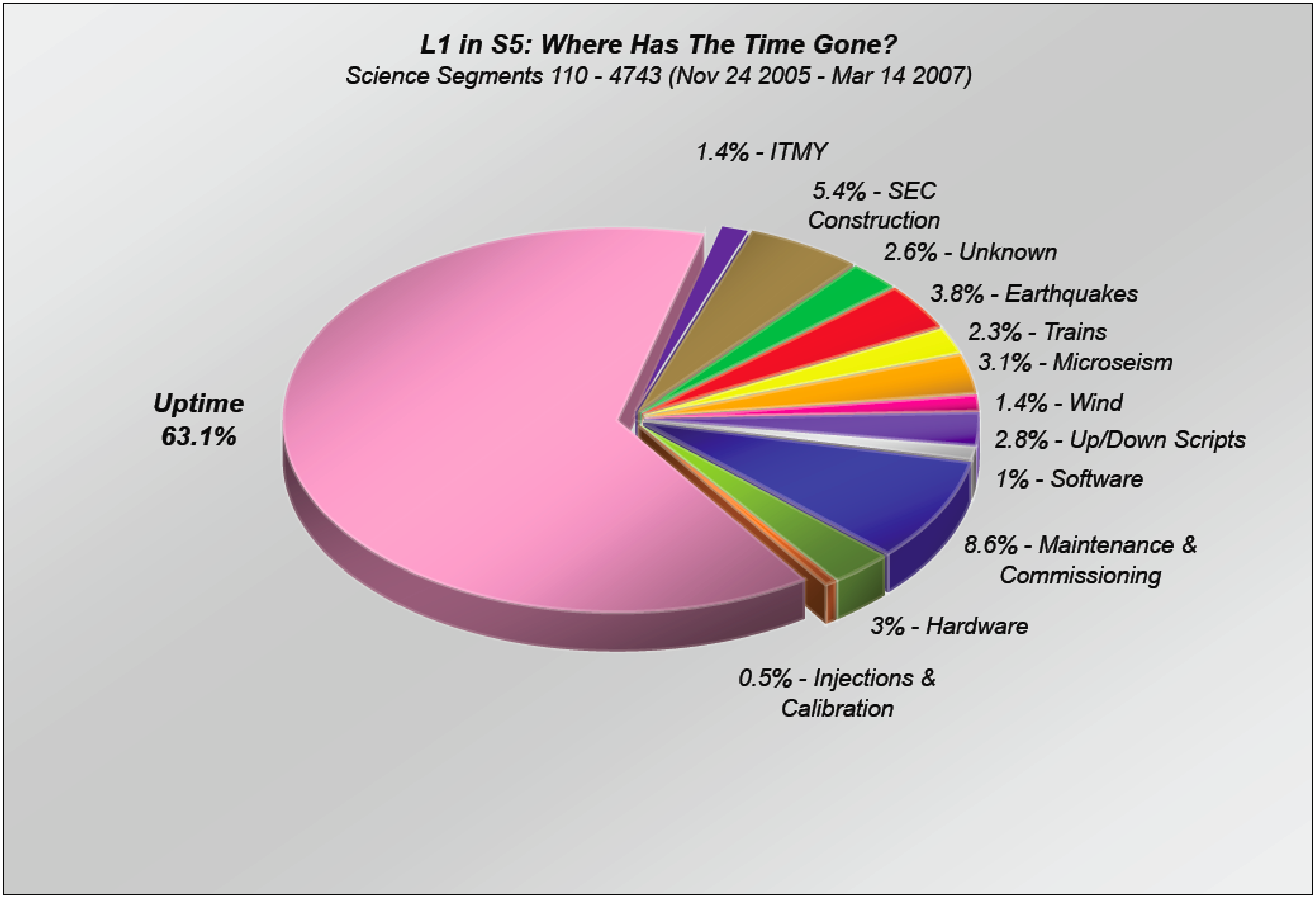



LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^-6 TORR H_2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^-9 TORR H_2
10^-19
10^-21
10^-23
10^-25
1
10
100
1000
10000
Frequency (Hz)
h̃(f) (1/√Hz)


Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs
LIGO-G060009-01-Z
LLO 4km - S1 (2002.09.07)
LLO 4km - S2 (2003.03.01)
LHO 4km - S3 (2004.01.04)
LHO 4km - S4 (2005.02.26)
LHO 4km - S5 (2006.01.02)
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

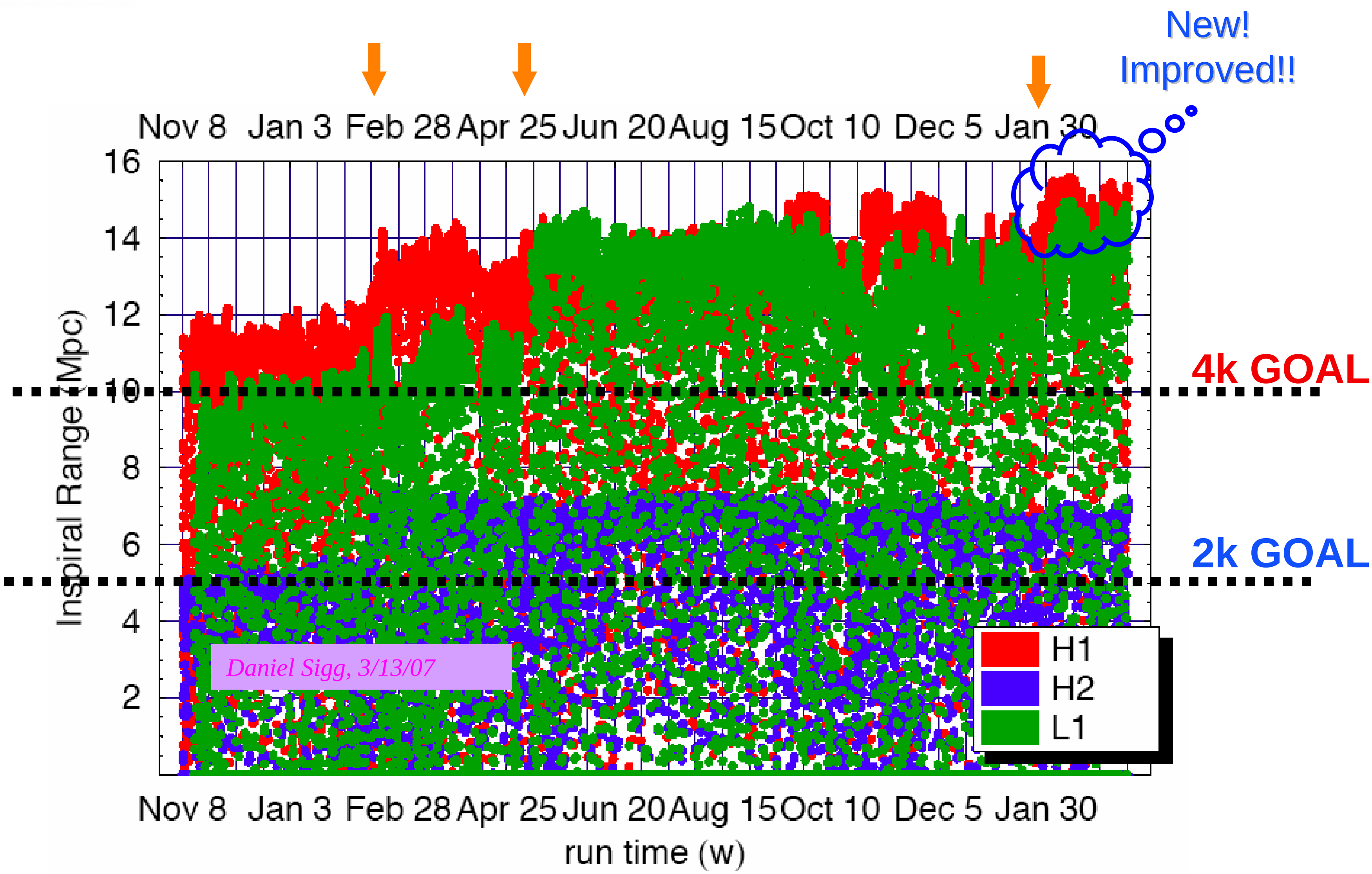


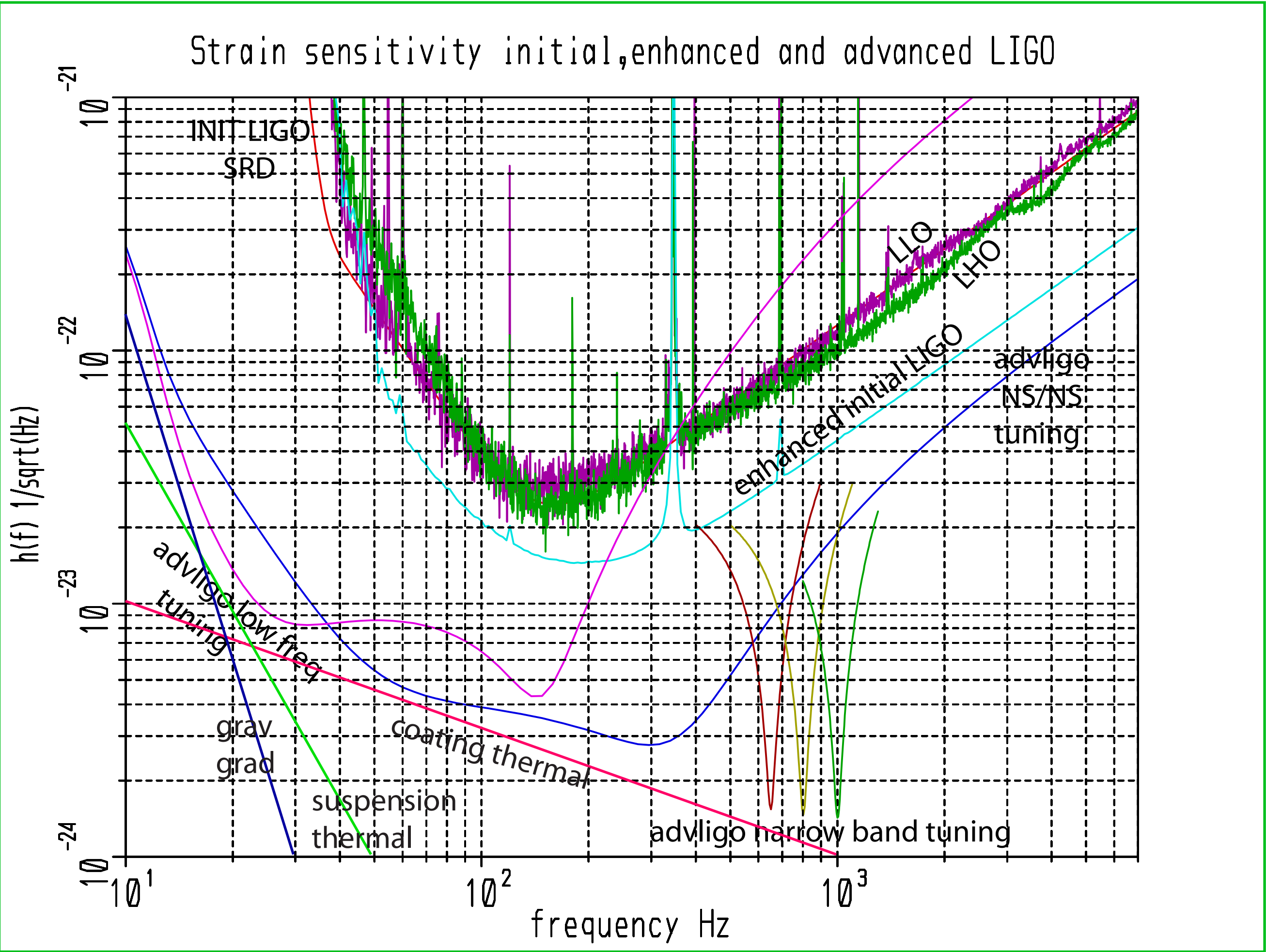
L1: 15 Mpc, Predicted: 14.1, May 13 2006 02:19:46 UTC
Displacement [m/√Hz]
Frequency [Hz]
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD



L1 in S5: Where Has The Time Gone?
Science Segments 110 - 4743 (Nov 24 2005 - Mar 14 2007)
1.4% - ITMY
5.4% - SEC Construction
2.6% - Unknown
3.8% - Earthquakes
2.3% - Trains
3.1% - Microseism
1.4% - Wind
2.8% - Up/Down Scripts
1% - Software
8.6% - Maintenance & Commissioning
3% - Hardware
0.5% - Injections & Calibration
Uptime 63.1%

BNS Sensitivity History




Strain sensitivity initial,enhanced and advanced LIGO
h(f) 1/sqrt(Hz)
frequency Hz
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^1
10^2
10^3
INIT LIGO SRD
LLO
LHO
enhanced initial LIGO
advligo NS/NS tuning
advligo low freq tuning
grav grad
suspension thermal
coating thermal
advligo narrow band tuning