CURRENT STATUS AND NEAR TERM PROSPECTS FOR LIGO

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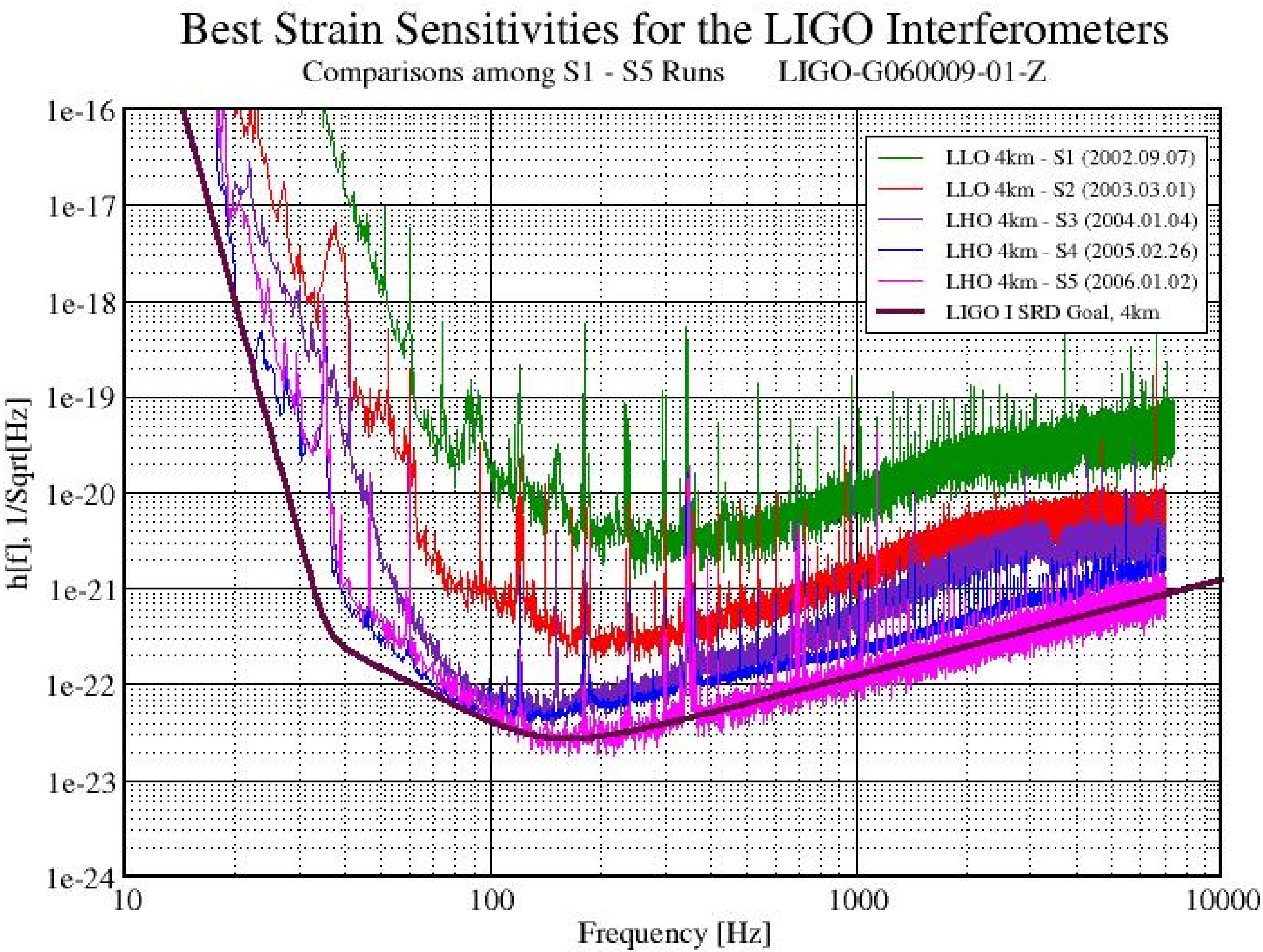
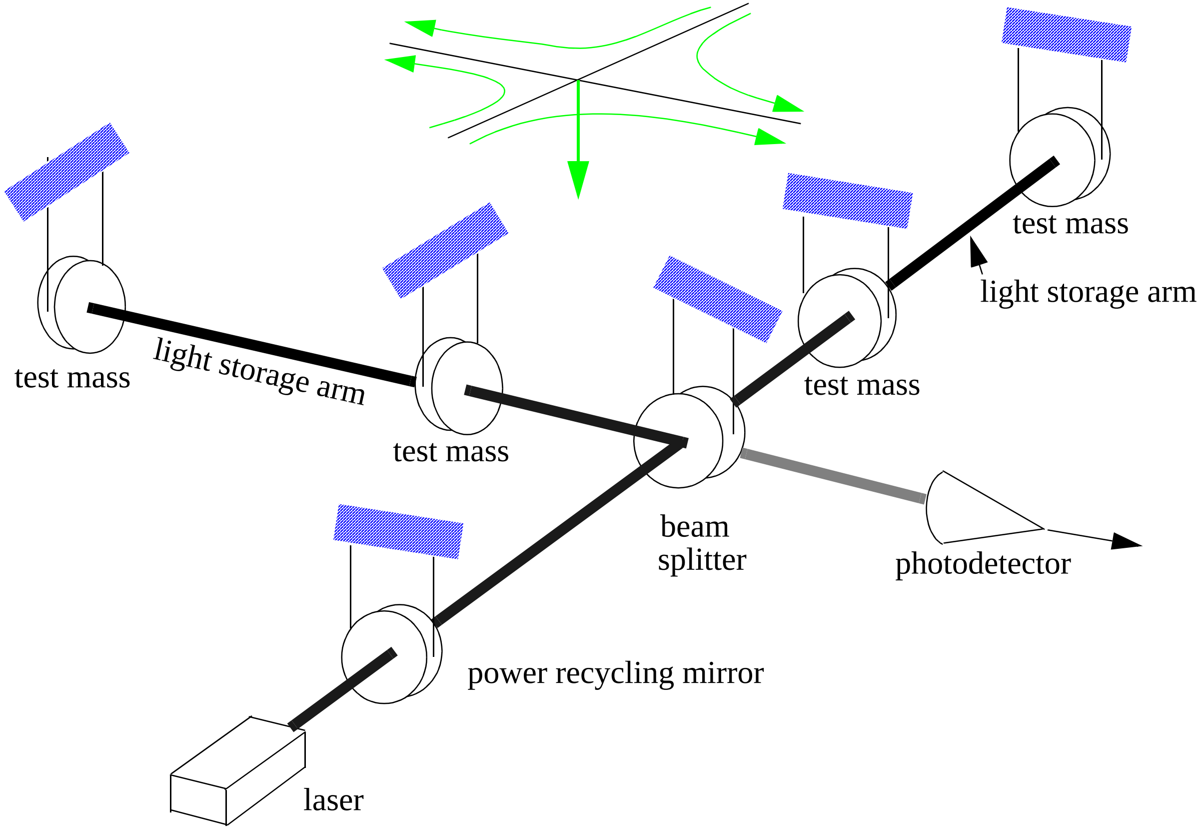
Outline

- Evolution of the initial LIGO sensitivity
- Noise in the initial LIGO
- Program for improvements in sensitivity and duty cycle
- Enhanced initial LIGO
- Advanced LIGO
- Evolution of the capability for detection


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]


test mass
light storage arm
test mass
test mass
light storage arm
test mass
beam
splitter
photodetector
power recycling mirror
laser

FRINGE SENSING

wavelength 1×10^{-6} m

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

arm length = 4000 m

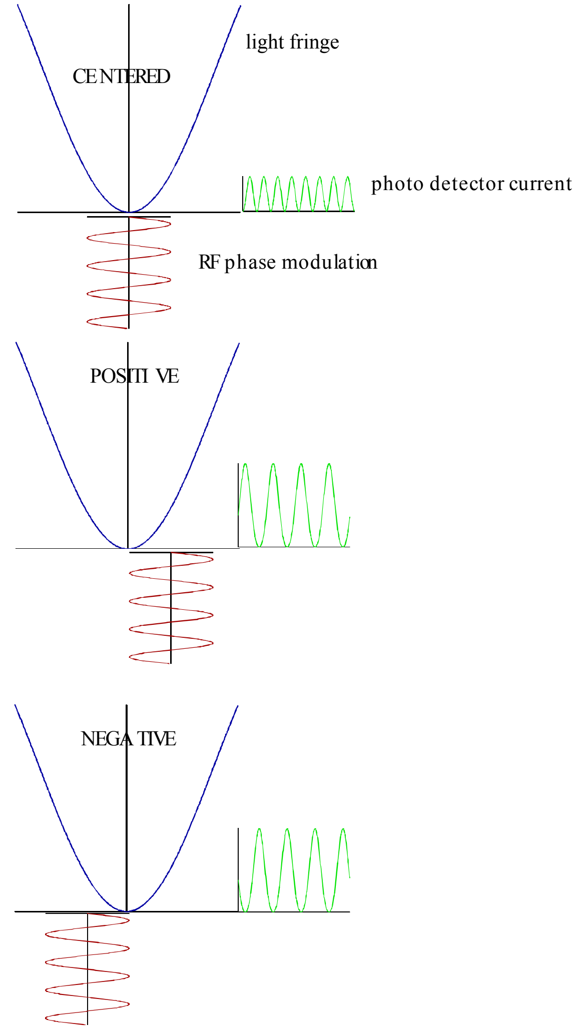
equivalent # of passes = 100

integration time

number of quanta/second at the beam splitter

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

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



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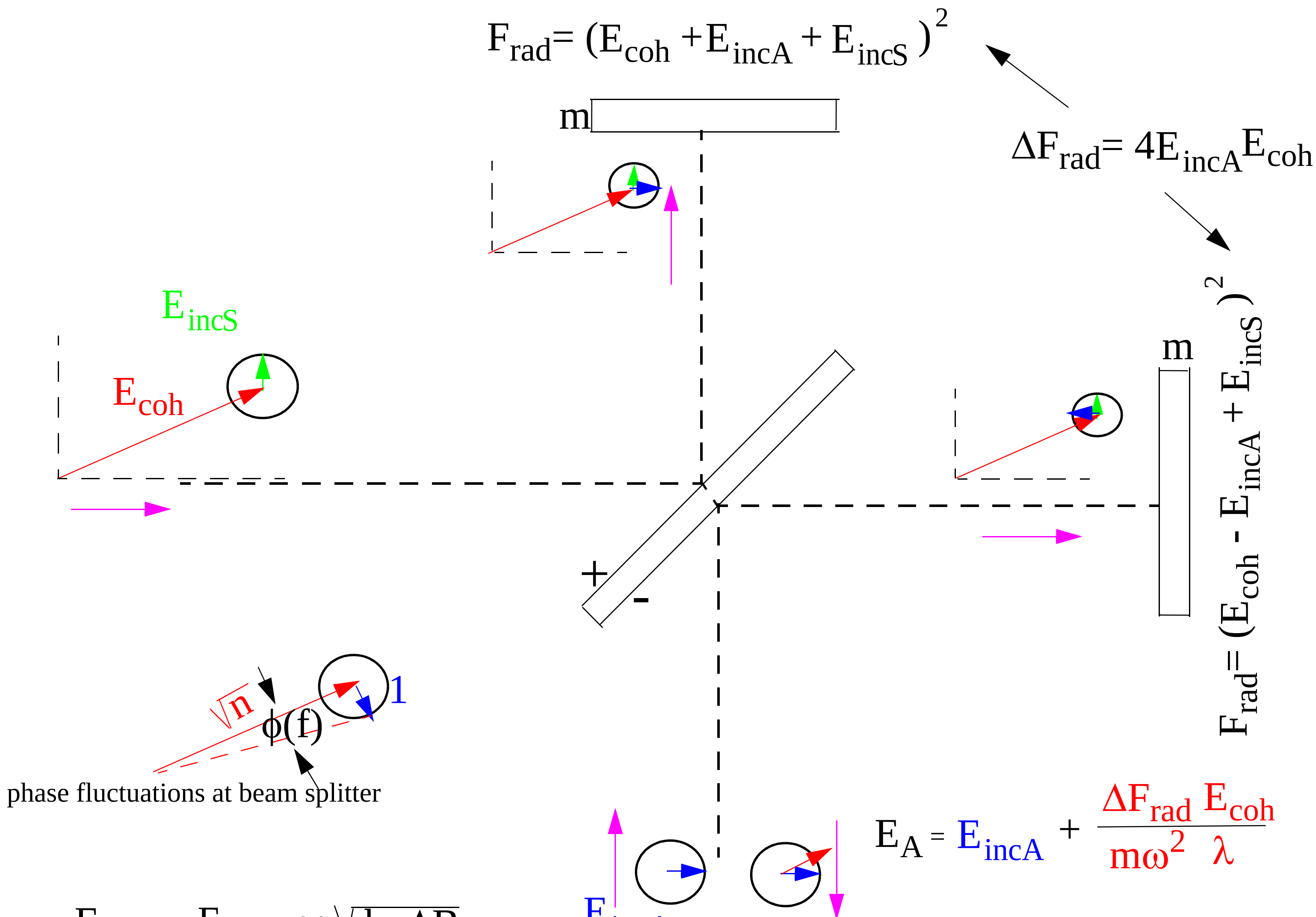
Quantum Noise in the Michelson Interferometer



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

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

PENDULUM THERMAL NOISE

Pendulum Brownian motion

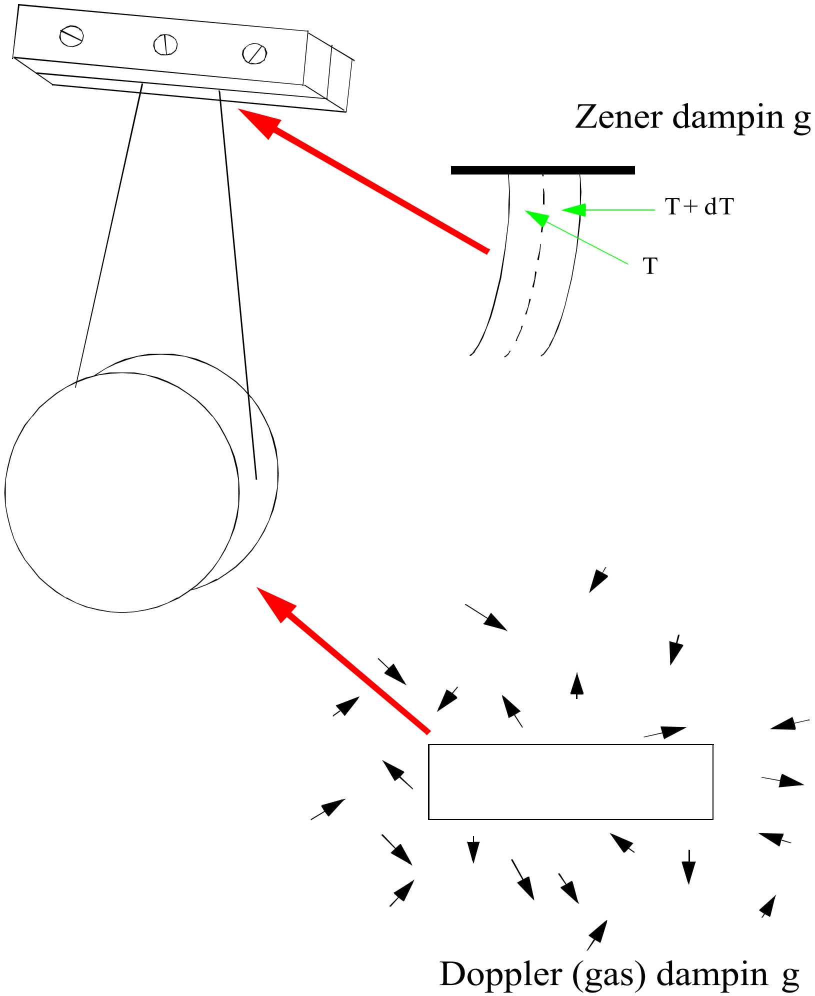
Dissipation leads to fluctuations

Tc = coherence or damping time
= Q x period of oscillator

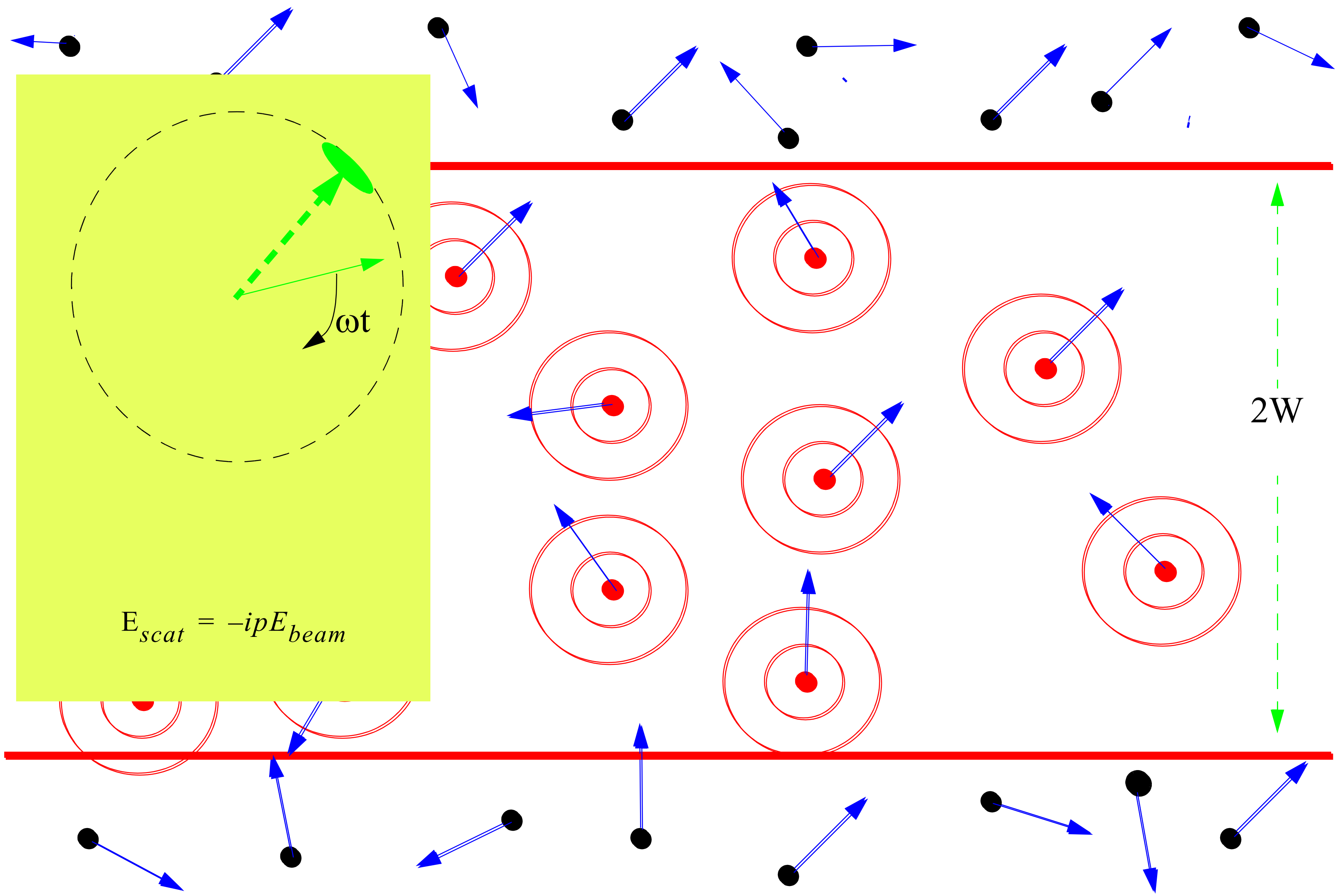
Exchange with surroundings:

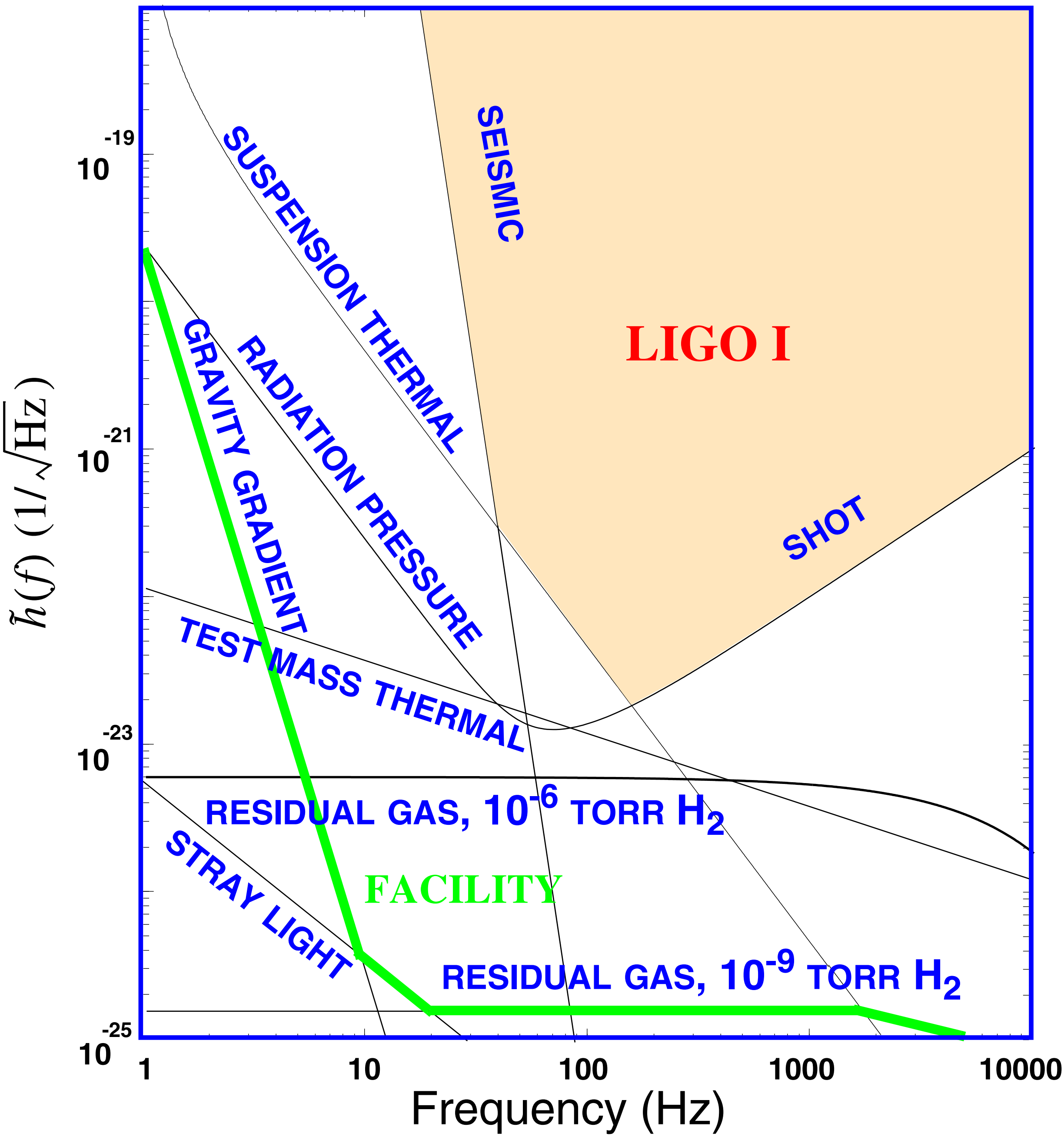
$$E(\text{thermal}) = \frac{kT\ t}{Tc}$$

Large Tc => smaller fluctuations

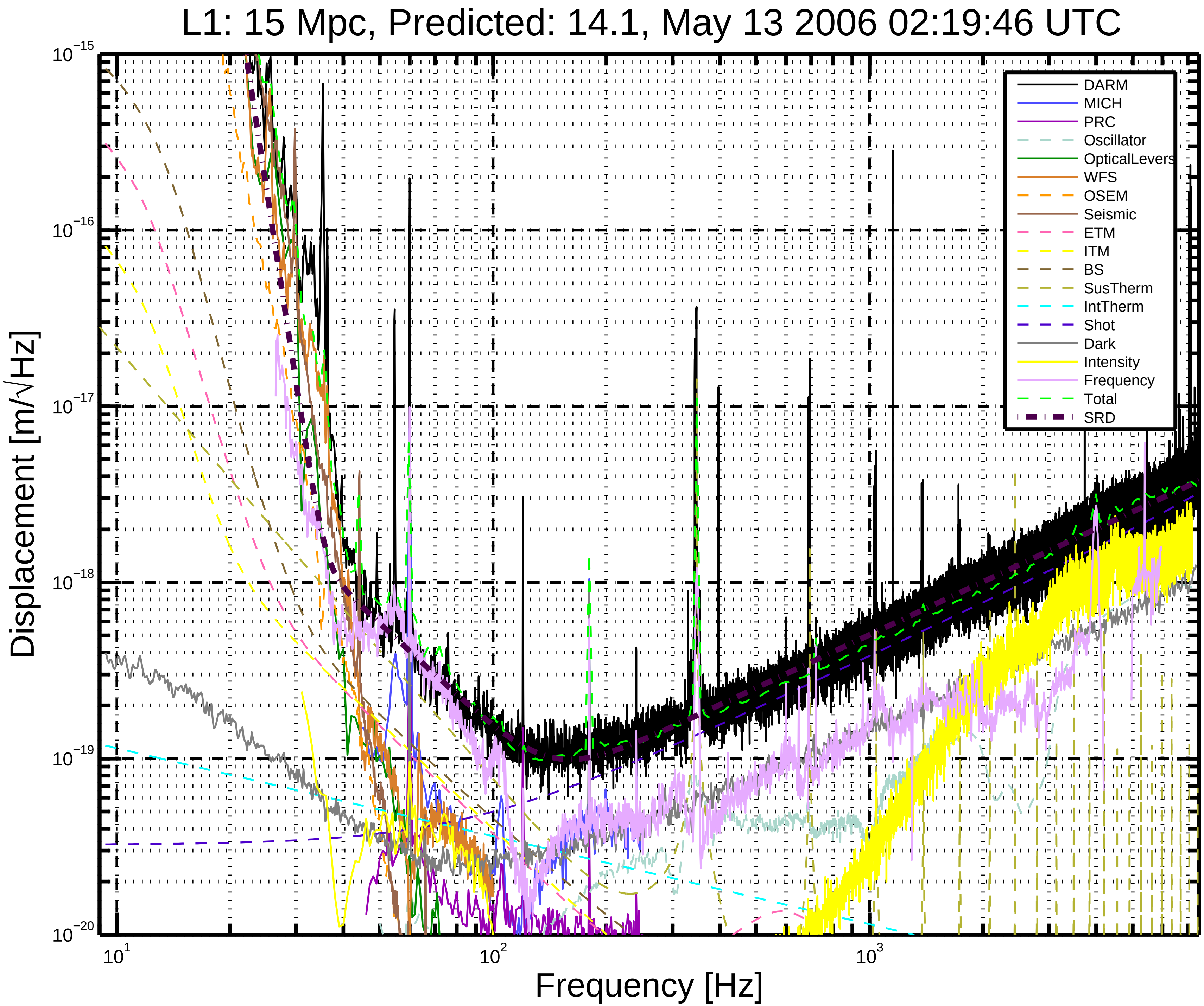


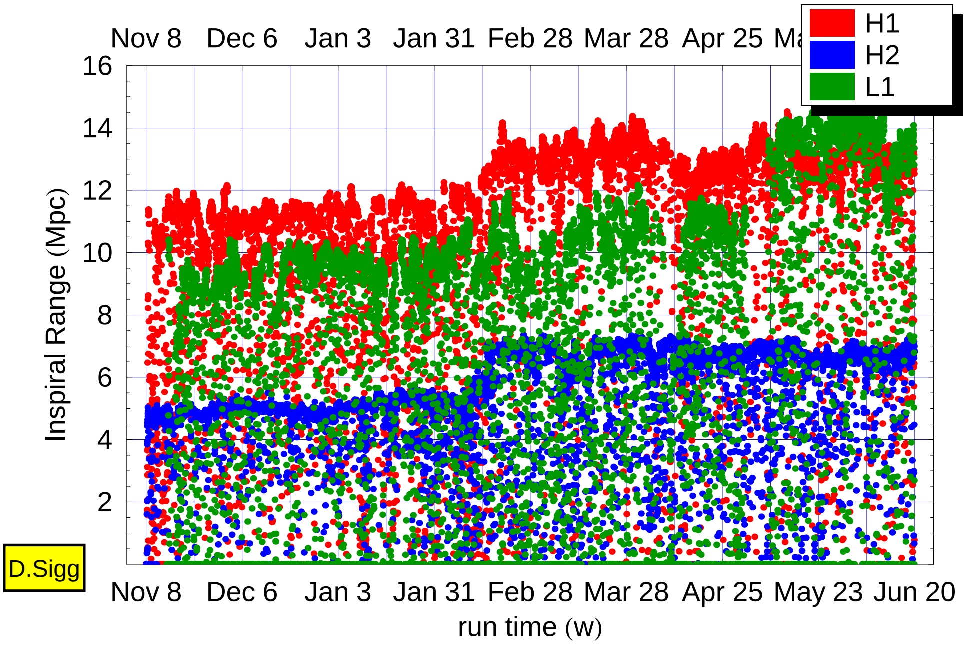
Phase noise from molecular scattering



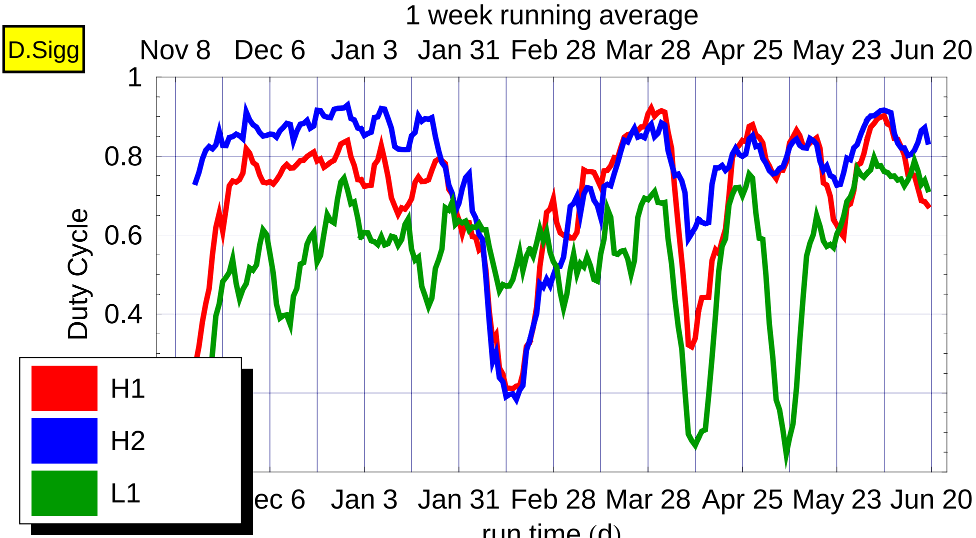


LIGO I
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
STRAY LIGHT
FACILITY
RESIDUAL GAS, 10^{-9} TORR H_2
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
Frequency (Hz)
$\tilde{h}(f)$ $(1/\sqrt{\mathrm{Hz}})$

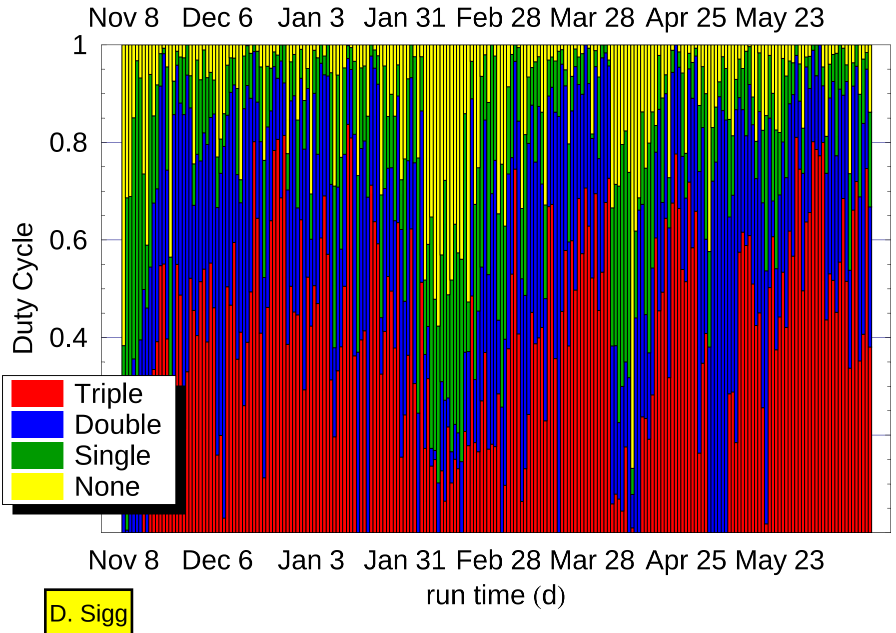

L1: 15 Mpc, Predicted: 14.1, May 13 2006 02:19:46 UTC
Displacement [m/√Hz]
Frequency [Hz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{1}
10^{2}
10^{3}
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

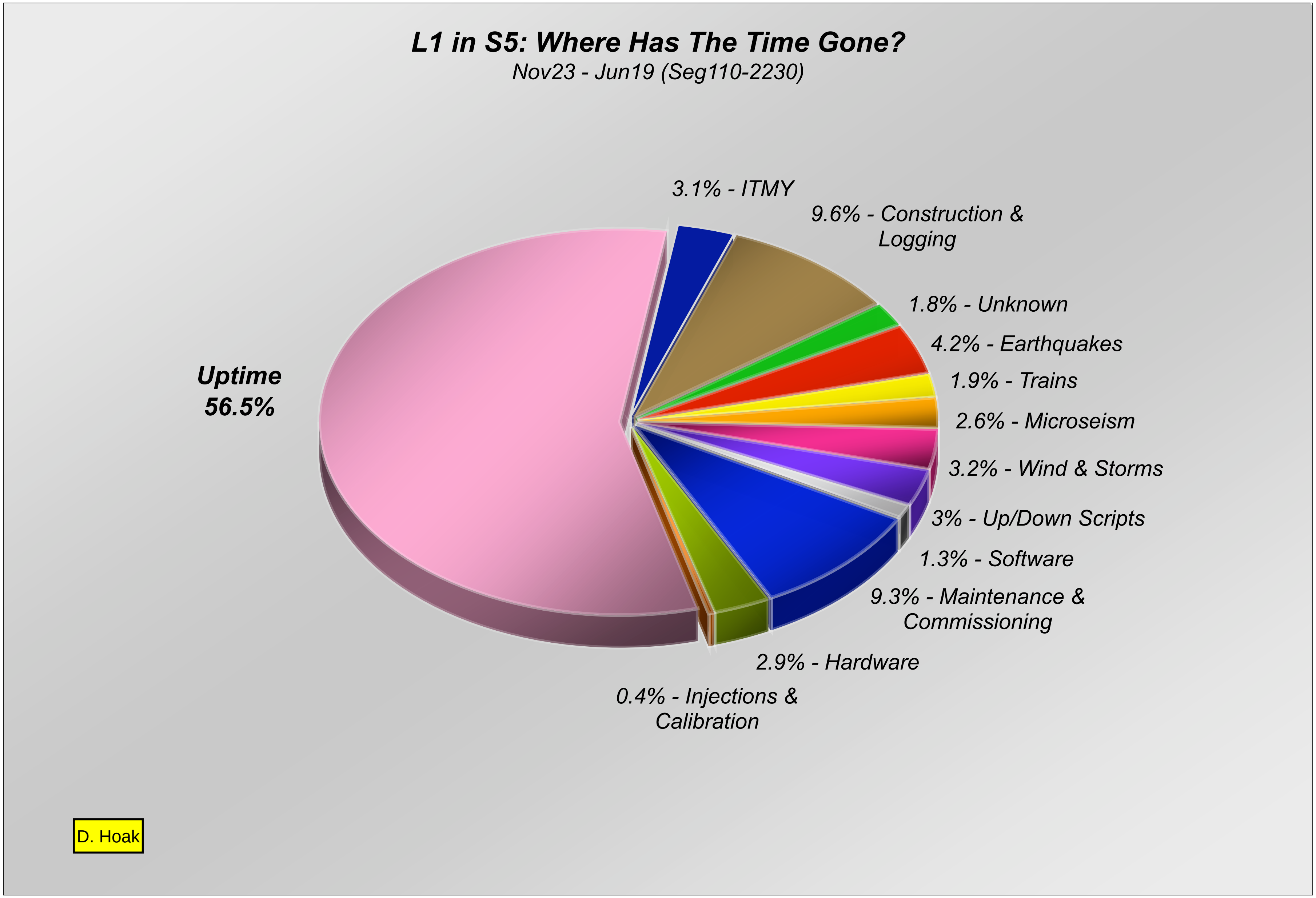


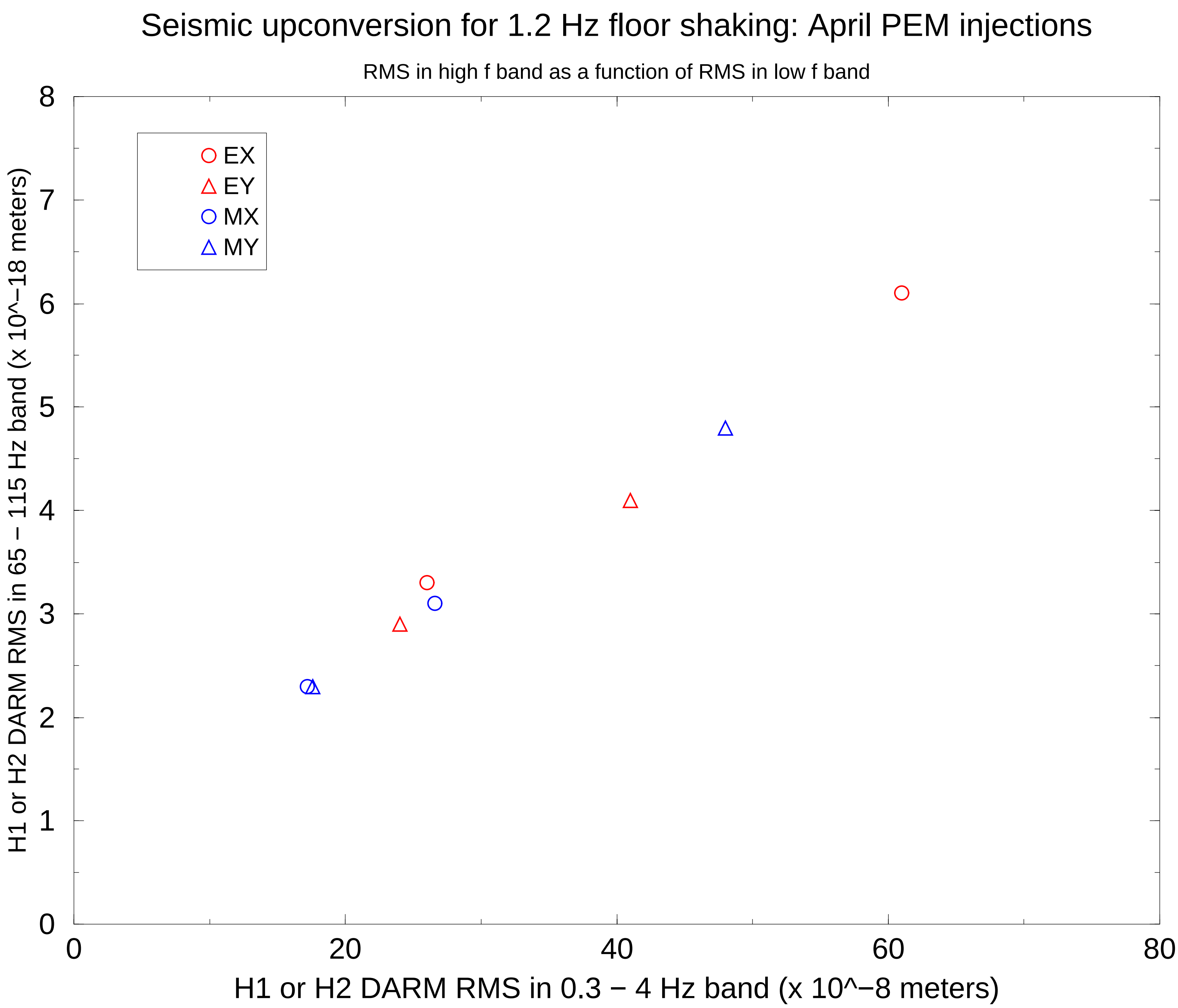
H1
H2
L1
Nov 8
Dec 6
Jan 3
Jan 31
Feb 28
Mar 28
Apr 25
May 23
Jun 20
16
14
12
10
8
6
4
2
Inspiral Range (Mpc)
run time (w)
D.Sigg



D.Sigg
1 week running average
Nov 8
Dec 6
Jan 3
Jan 31
Feb 28
Mar 28
Apr 25
May 23
Jun 20
1
0.8
0.6
0.4
Duty Cycle
H1
H2
L1
ec 6
Jan 3
Jan 31
Feb 28
Mar 28
Apr 25
May 23
Jun 20
run time (d)


Nov 8
Dec 6
Jan 3
Jan 31
Feb 28
Mar 28
Apr 25
May 23
1
0.8
0.6
0.4
Duty Cycle
Triple
Double
Single
None
run time (d)
D. Sigg


L1 in S5: Where Has The Time Gone?
Nov23 - Jun19 (Seg110-2230)
3.1% - ITMY
9.6% - Construction & Logging
1.8% - Unknown
4.2% - Earthquakes
1.9% - Trains
2.6% - Microseism
3.2% - Wind & Storms
3% - Up/Down Scripts
1.3% - Software
9.3% - Maintenance & Commissioning
2.9% - Hardware
0.4% - Injections & Calibration
Uptime 56.5%
D. Hoak


Seismic upconversion for 1.2 Hz floor shaking: April PEM injections
RMS in high f band as a function of RMS in low f band
EX
EY
MX
MY
H1 or H2 DARM RMS in 65 − 115 Hz band (x 10^−18 meters)
H1 or H2 DARM RMS in 0.3 − 4 Hz band (x 10^−8 meters)
0
20
40
60
80
0
1
2
3
4
5
6
7
8

R. Scofield

Sensors to Broadband DARM

8 averages of

- 8192 seconds of
- 8 sec FFTs

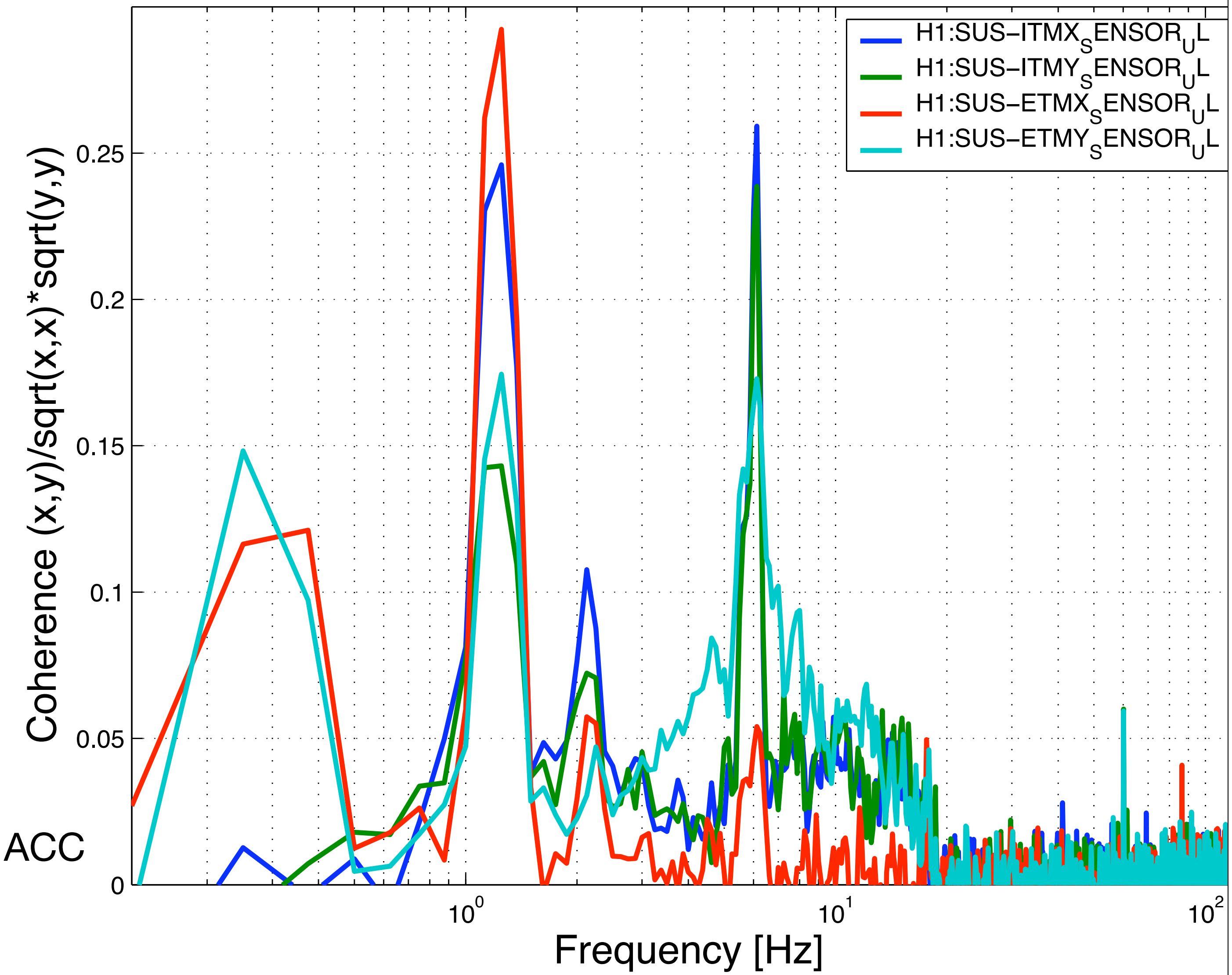
Correlated with

- 70 - 110 Hz RMS
  - DARM_ERR

Higher bandwidth,

- less statistics,
- longer correlations

Visible in Seismic and ACC



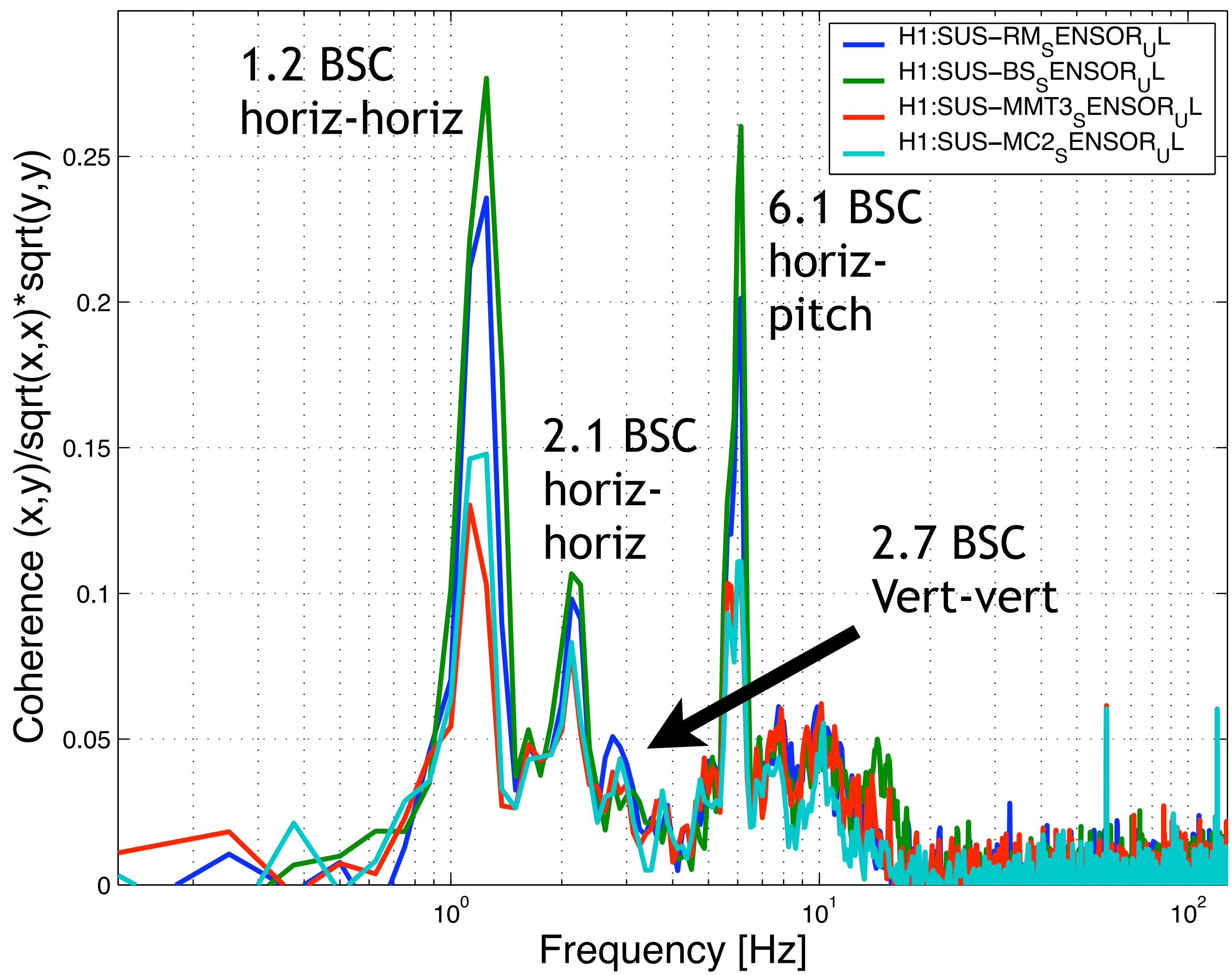
S. Waldman

Auxiliary optics

Some other channels

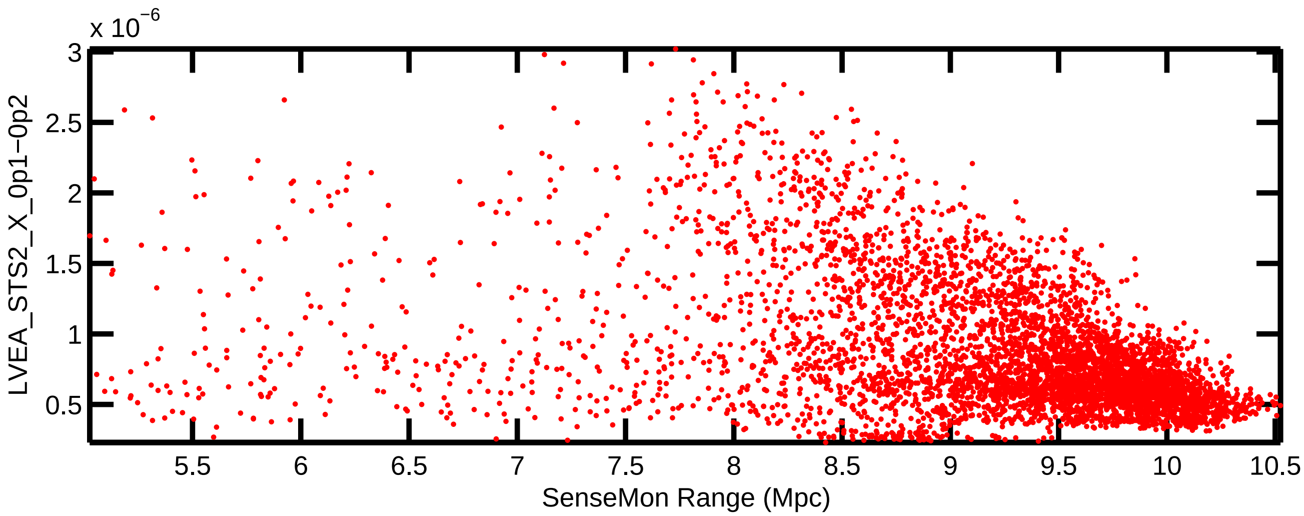
Note differences in LVEA, EX and EY

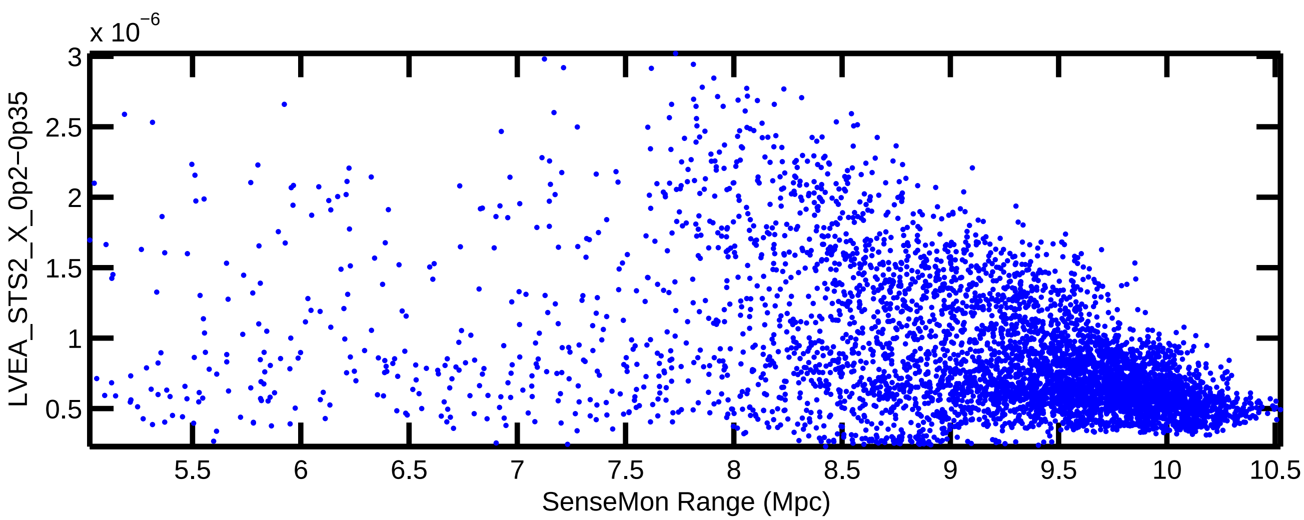
Most likely reflects optic motion



S. Waldman

Brian O'Reilly
llo elog
01/24/2006





Sources of Up-conversion

- Non-linearity in the fringe
- Non-linearity in the servo drive electronics
- Optical scattering (fringe wrapping)
- Creaking in the isolation system
- Rubbing in the suspension
- Barkhausen noise in the magnets
- ????

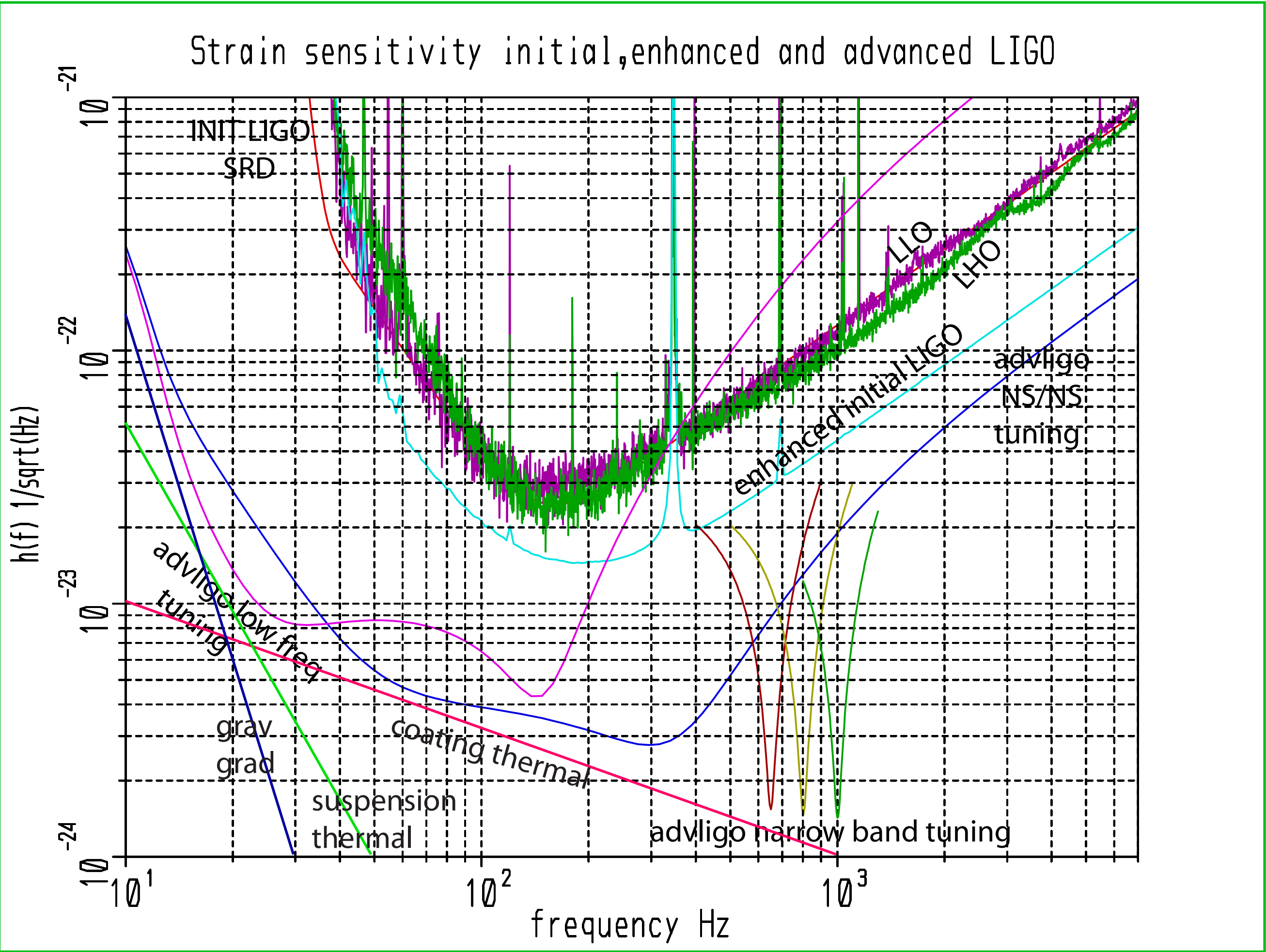
Program of improvements

- **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 test masses : 10 kg to 40 kg
  - Improved seismic isolation – extend sensitivity to 15Hz
  - Tunable dual recycling interferometer configuration
  - Quantum limited operation over significant band

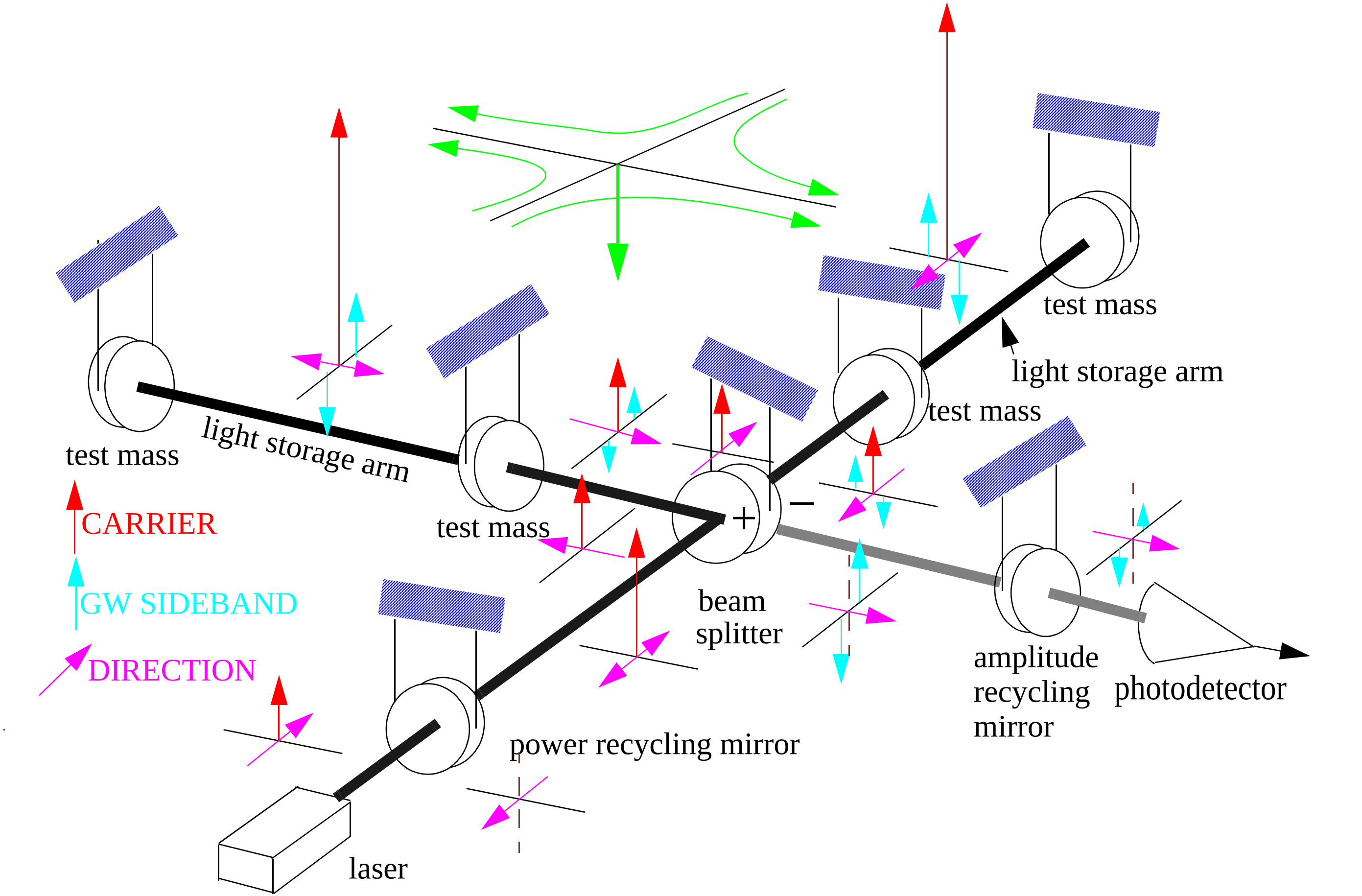
BEGIN
IN
ENHANCED
LIGO

Considerations

- Advantages for the science from phasing
  - Operations now in regime where rate of events ~ $(1/\text{sensitivity})^3$
  - Reasonable probability of a detection
  - Maintain the data analysis effort
- Advantages for the technical program from phasing
  - Early trials
  - Reduction in installation and commissioning time



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


test mass
light storage arm
test mass
test mass
light storage arm
test mass
CARRIER
GW SIDEBAND
DIRECTION
+
−
beam
splitter
amplitude
recycling
mirror
photodetector
power recycling mirror
laser

Classes of sources

- 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
- Periodic CW sources
  - Pulsars
  - Low mass x-ray binaries (quasi periodic)
- Stochastic background
  - Foreground sources : gravitational wave radiometry
  - Cosmological isotropic background

Binary Coalescence Sources & Science:

Binary Neutron Stars: LIGO Range

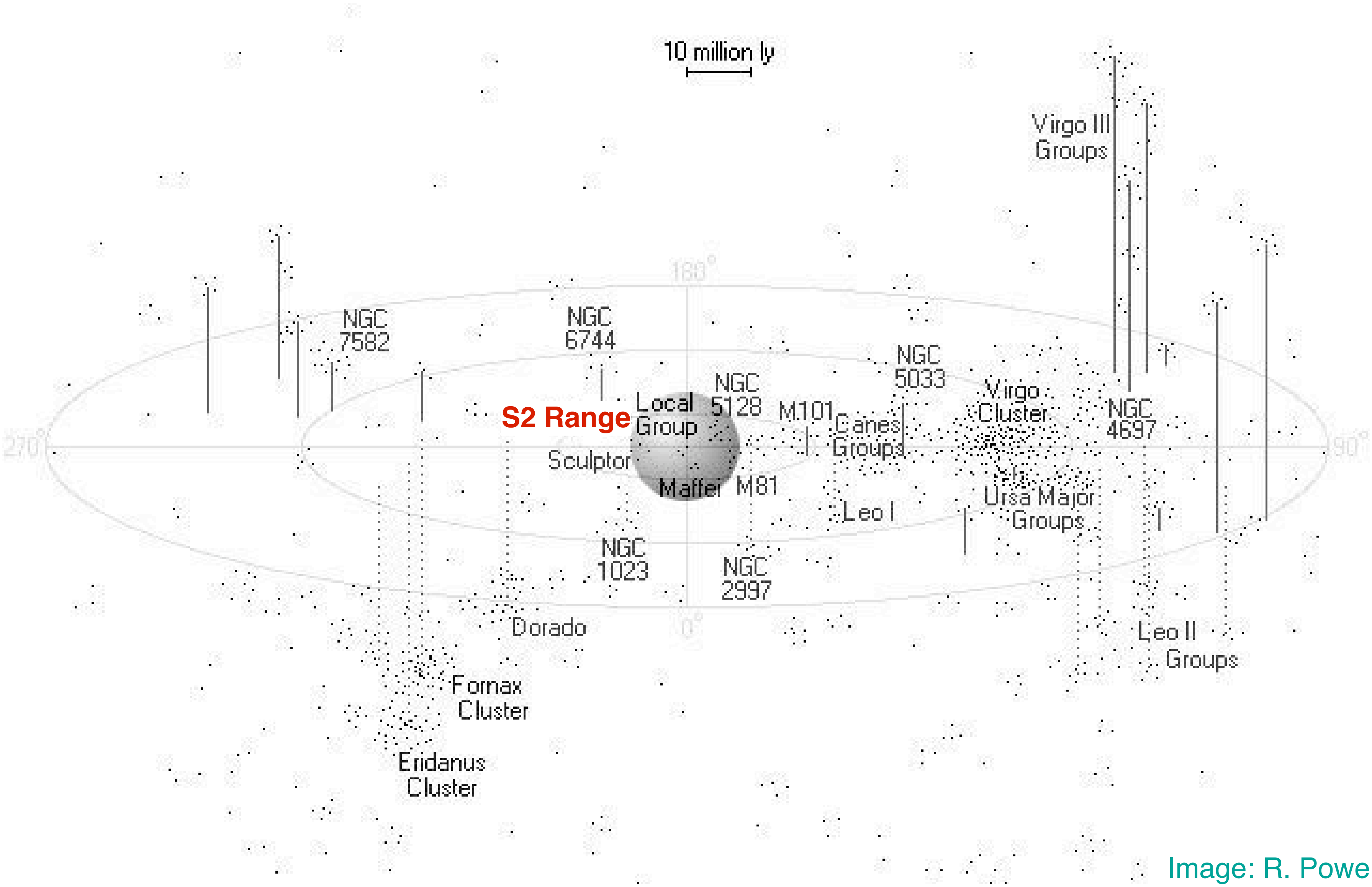


Image: R. Powell

Binary Coalescence Sources & Science:
Binary Neutron Stars: AdLIGO Range

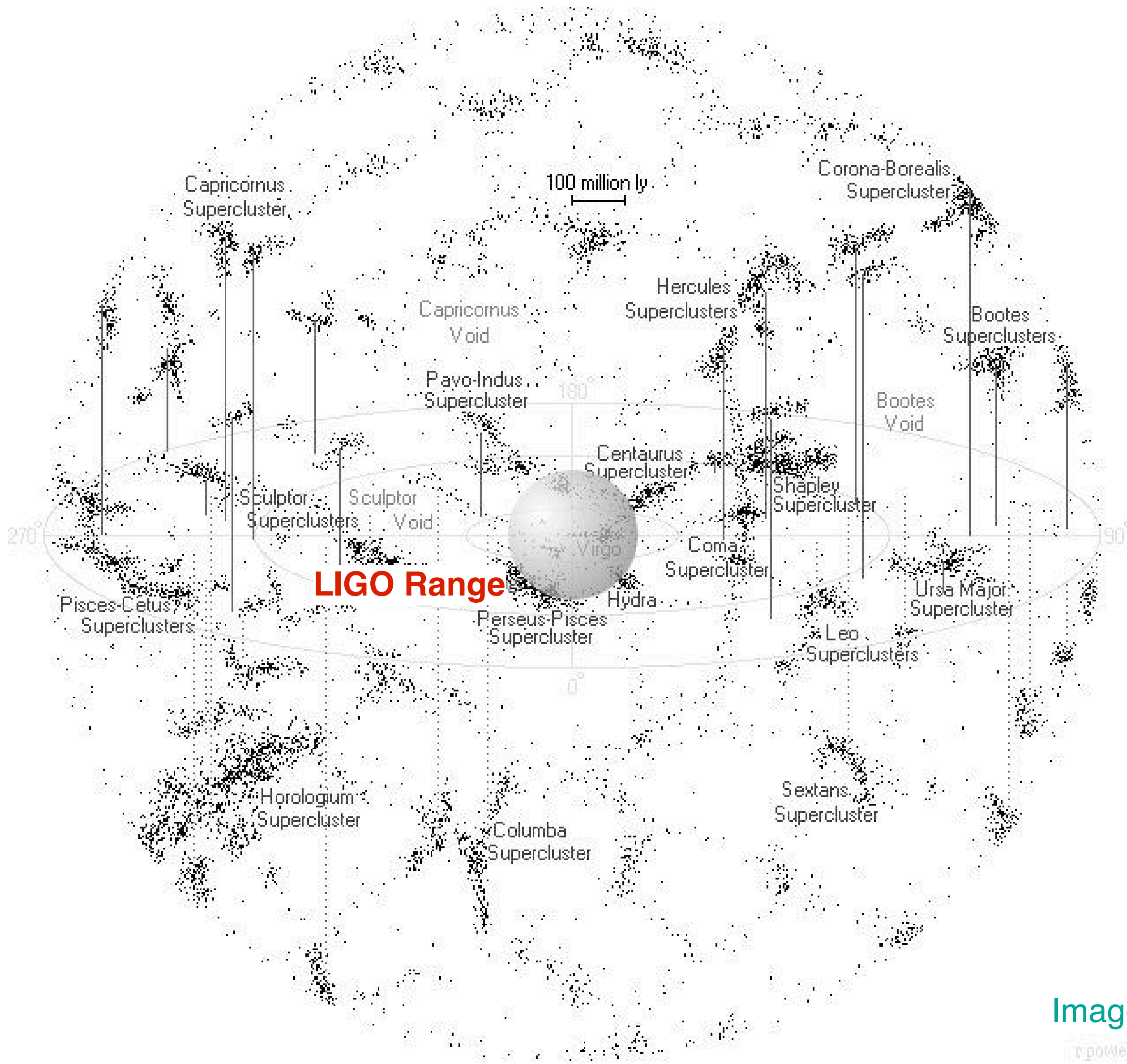
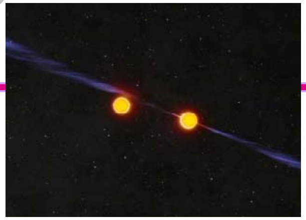


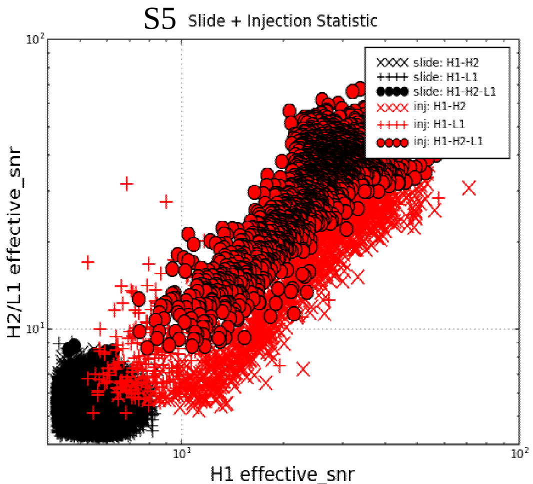
Image: R. Powell

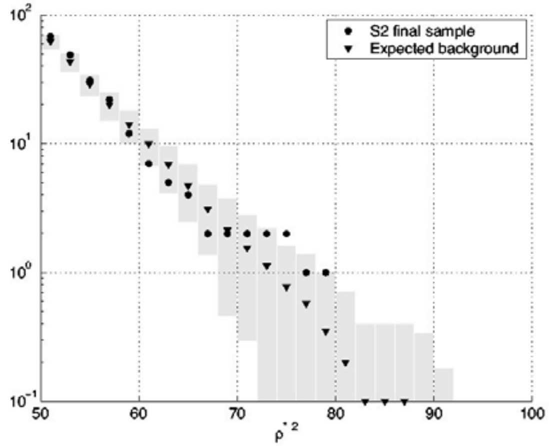
Search for binary systems

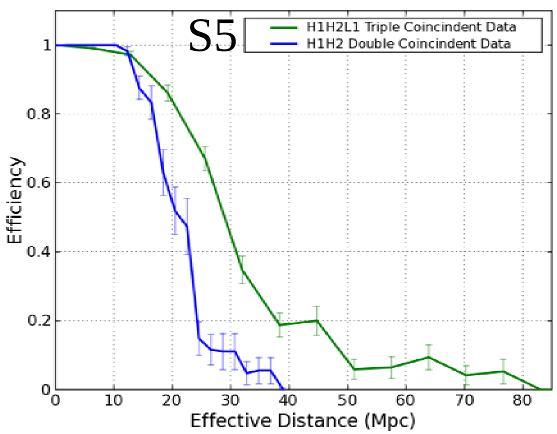


John Rowe, CSIRO

- Search for double or triple coincident “triggers”
- Estimate false alarm probability of resulting candidates: detection?
- Compare with expected efficiency of detection and surveyed galaxies: upper limit







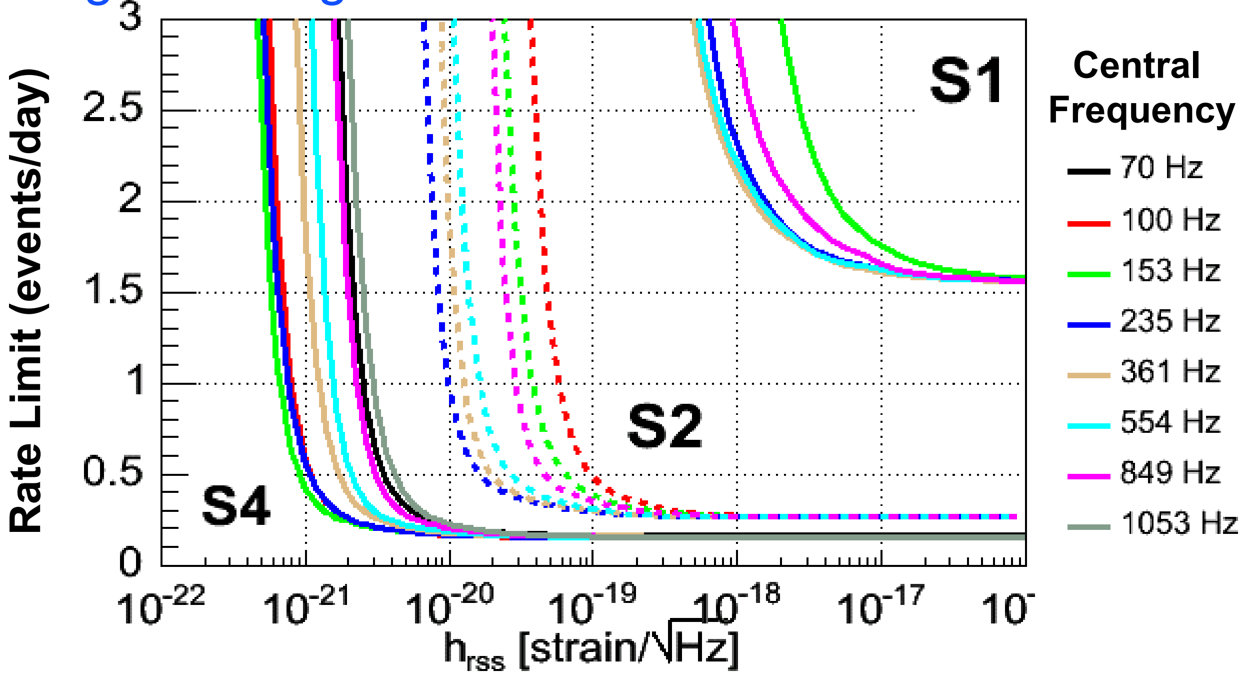
B. Abbott et al. (LIGO Scientific Collaboration):
- S1: Analysis of LIGO data for gravitational waves from binary neutron stars, Phys. Rev. D 69, 122001 (2004)
- S2: Search for gravitational waves from primordial black hole binary coalescences in the galactic halo, Phys. Rev. D 72, 082002 (2005)
- S2: Search for gravitational waves from galactic and extra-galactic binary neutron stars, Phys. Rev. D 72, 082001 (2005)
- S2: Search for gravitational waves from binary black hole inspirals in LIGO data, Phys. Rev. D 73, 062001 (2006)
- S2: Joint Search for Gravitational Waves from Inspiralling Neutron Star Binaries in LIGO and TAMA300 data (LIGO, TAMA collaborations), PRD, in press
- S3: finished searched for BNS, BBH, PBBH: no detection
- S4, S5: searches in progress.

Progress in Upper Limits

No GWBs detected through S4. So, set limit on GWB rate vs. signal strength:

$$R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$$

η = upper limit on event number
T = observation time
$\varepsilon(h_{rss})$ = efficiency vs strength



Progress:

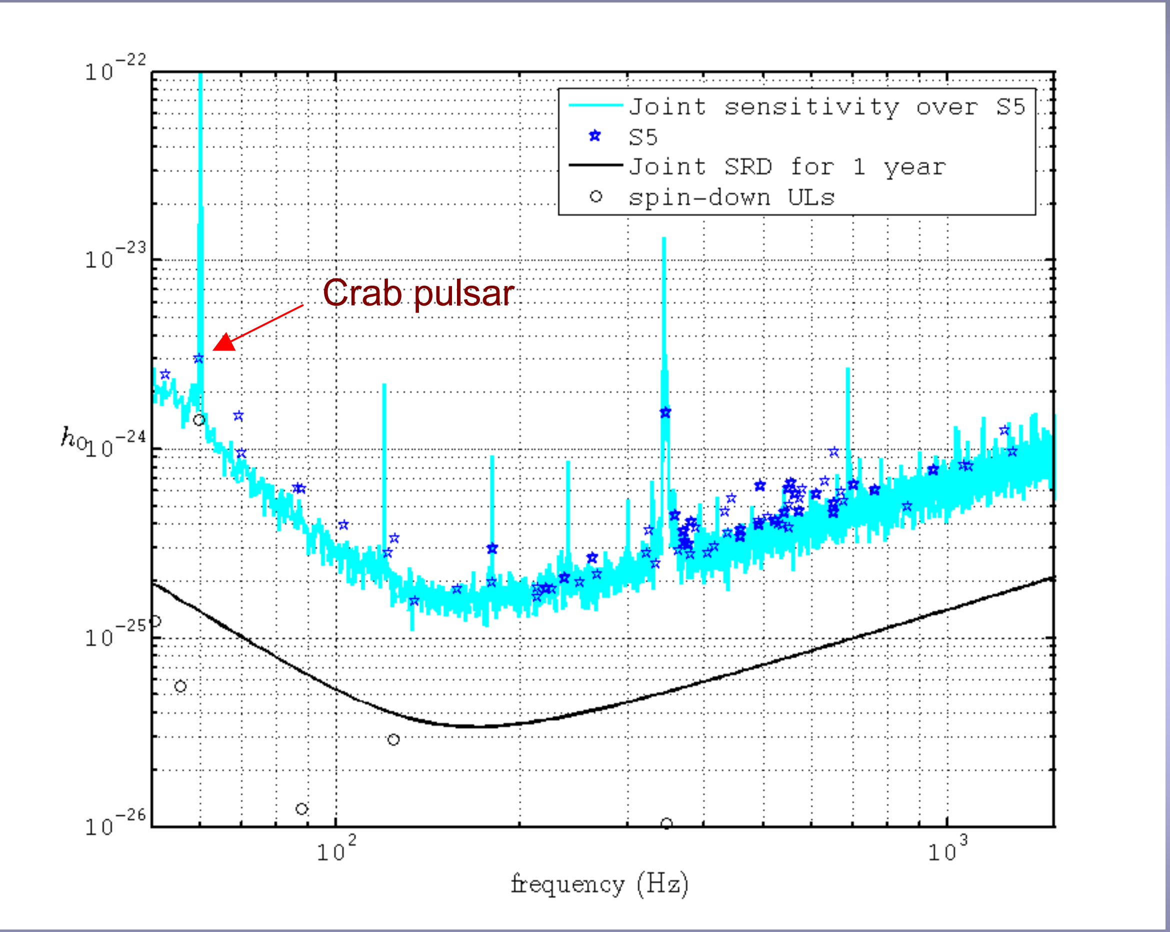
Lower rate limits from longer observation times

Lower amplitude limits from lower detector noise

Latest (unpublished) results in Session W11:
Shawhan – Science Run 4
Yakushin – Science Run 5

h_0 Results

- Spin-down upper limit calculated with intrinsic spin-down value if available i.e. corrected for Shklovskii transverse velocity effect
- Closest to spin-down upper limit
  - Crab pulsar ~ **2.1** times greater than spin-down (f_{gw} = 59.6 Hz, dist = 2.0 kpc)
  - $h_0 = 3.0\text{x}10^{-24}$, $\varepsilon = 1.6\text{x}10^{-3}$
  - Assumes $I = 10^{38}$ kgm^2



- Sensitivity curves use:

$$S(f) = \left(\frac{T_{\text{obs H1}}}{S_h(f)_{\text{H1}}} + \frac{T_{\text{obs H2}}}{S_h(f)_{\text{H2}}} + \frac{T_{\text{obs L1}}}{S_h(f)_{\text{L1}}} \right)^{-1}$$

$$h_0^{95\%} = 10.8\sqrt{S(f)}.$$

S5 Results – 95% upper limits

h_0	Pulsars
$1\times10^{-25} < h_0 < 5\times10^{-25}$	44
$5\times10^{-25} < h_0 < 1\times10^{-24}$	24
$h_0 > 1\times10^{-24}$	5

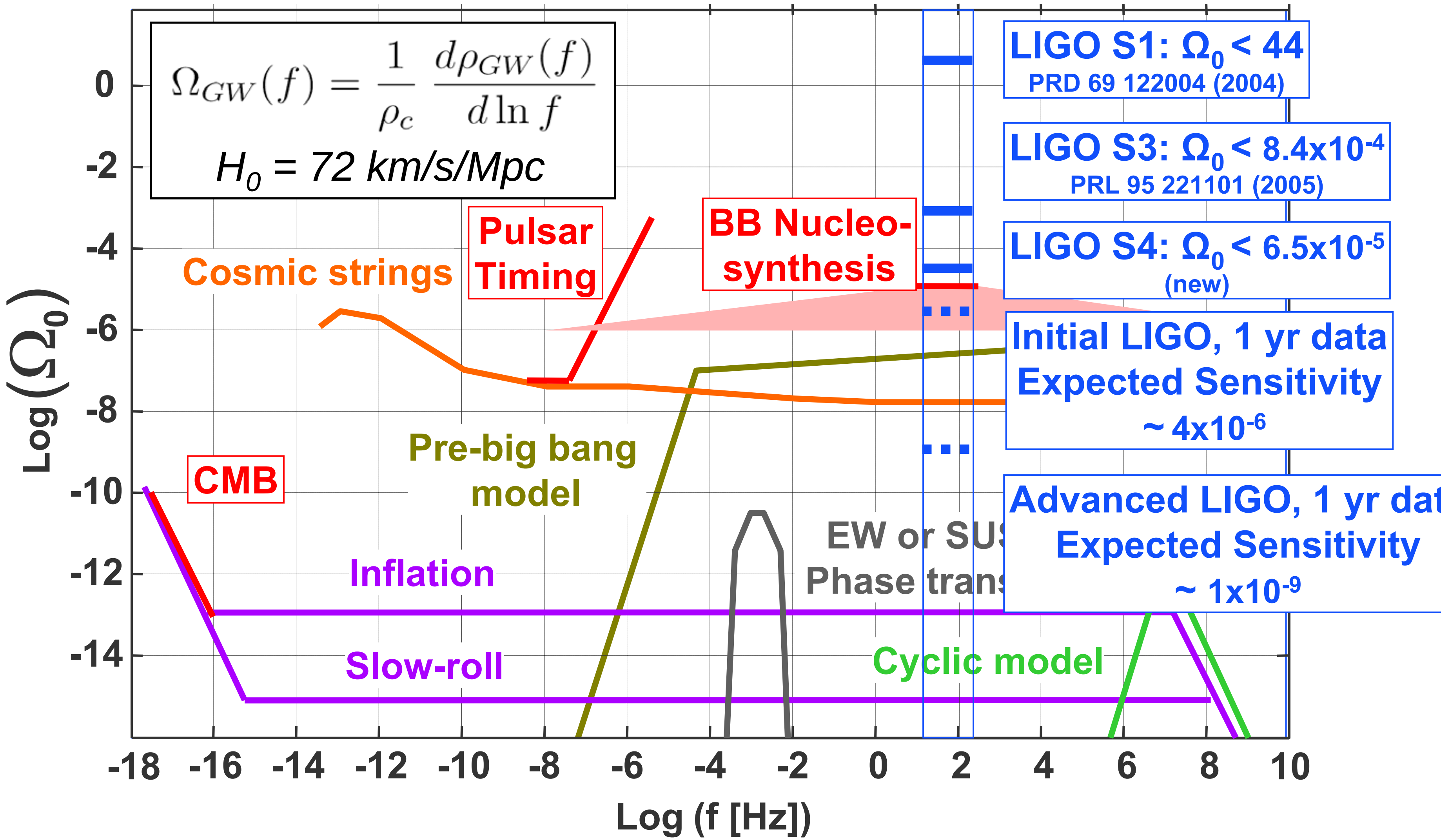
Lowest h_0 upper limit:
PSR J1603-7202 (f_{gw} = 134.8 Hz, r = 1.6kpc) h_0 = 1.6×10^{-25}
Lowest ellipticity upper limit:
PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) ε = 4.0×10^{-7}

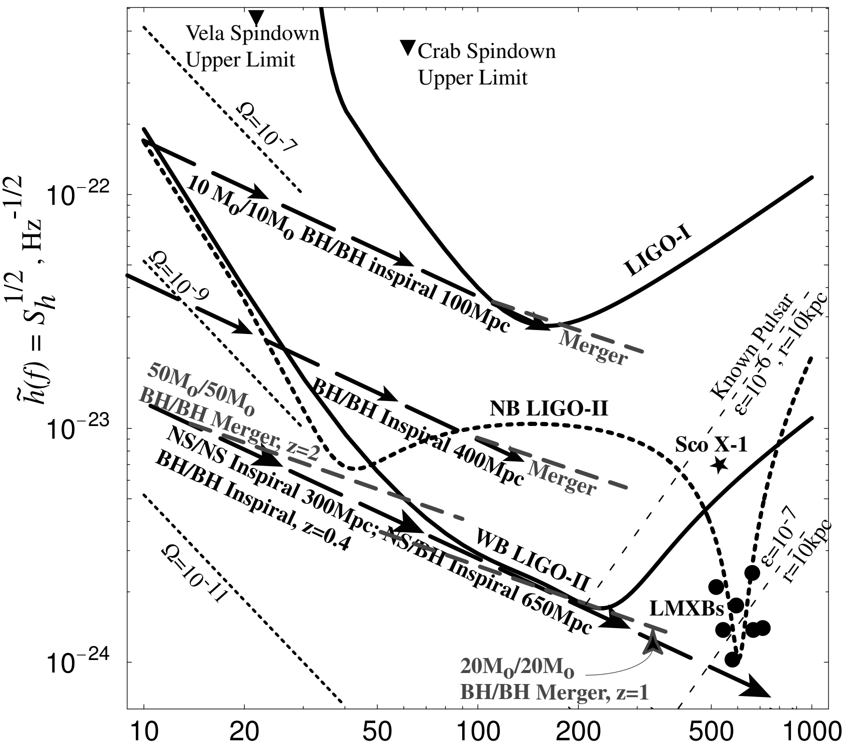
Ellipticity	Pulsars
$\varepsilon < 1\times10^{-6}$	6
$1\times10^{-6} < \varepsilon < 5\times10^{-6}$	28
$5\times10^{-6} < \varepsilon < 1\times10^{-5}$	13
$\varepsilon > 1\times10^{-5}$	26

All values assume I = 10^{38} kgm^2 and no error on distance

$$\varepsilon = 0.237 \frac{h_0}{10^{-24}} \frac{r}{1\text{kpc}} \frac{1\text{Hz}^2}{\nu^2} \frac{10^{38}\,\text{kgm}^2}{I_{zz}}$$

Predictions and Limits





Cutler and Thorne 2003