SENSITIVITY IMPROVEMENT AND GRAVITATIONAL WAVE DETECTION

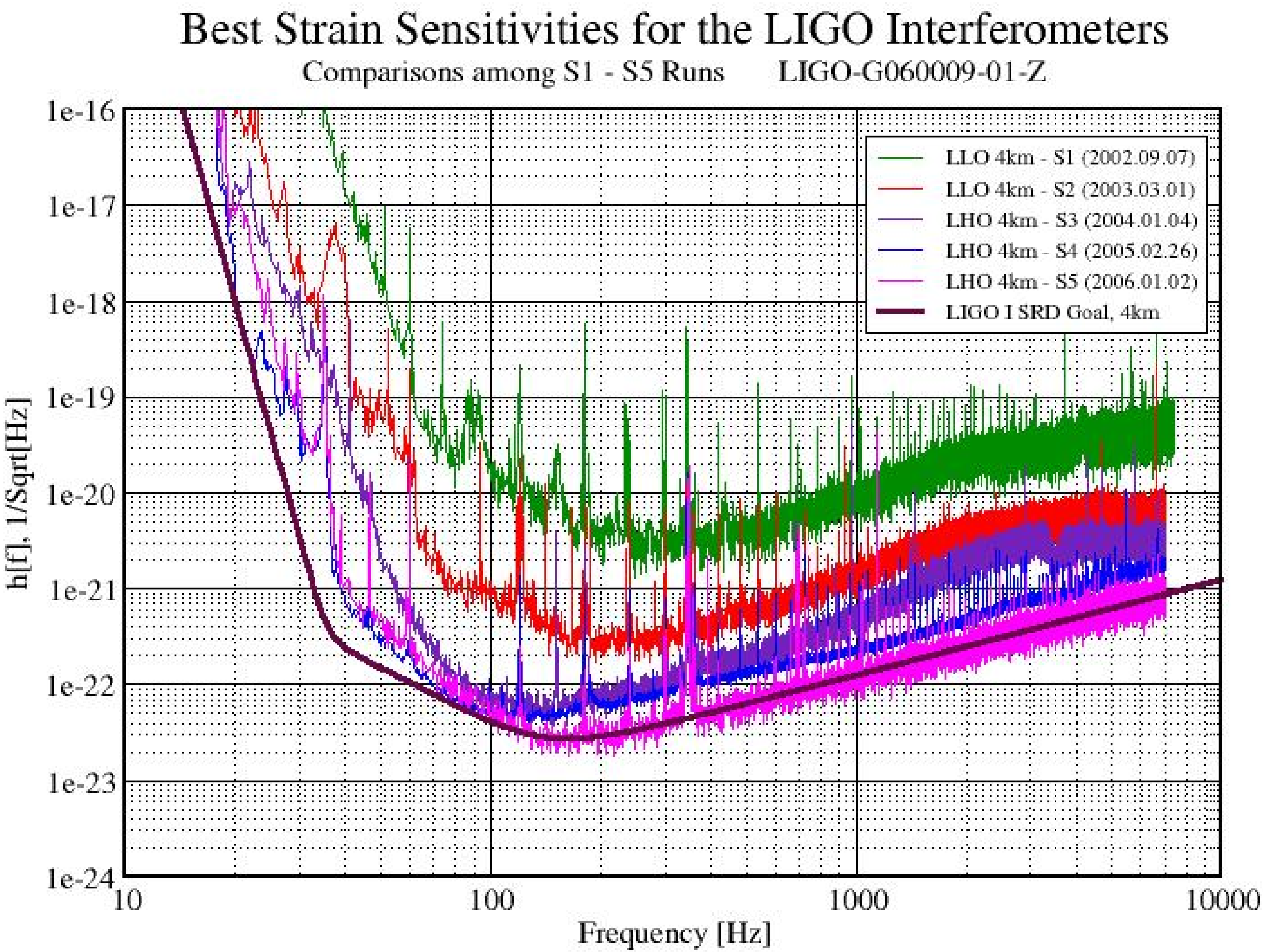
Rainer Weiss, MIT

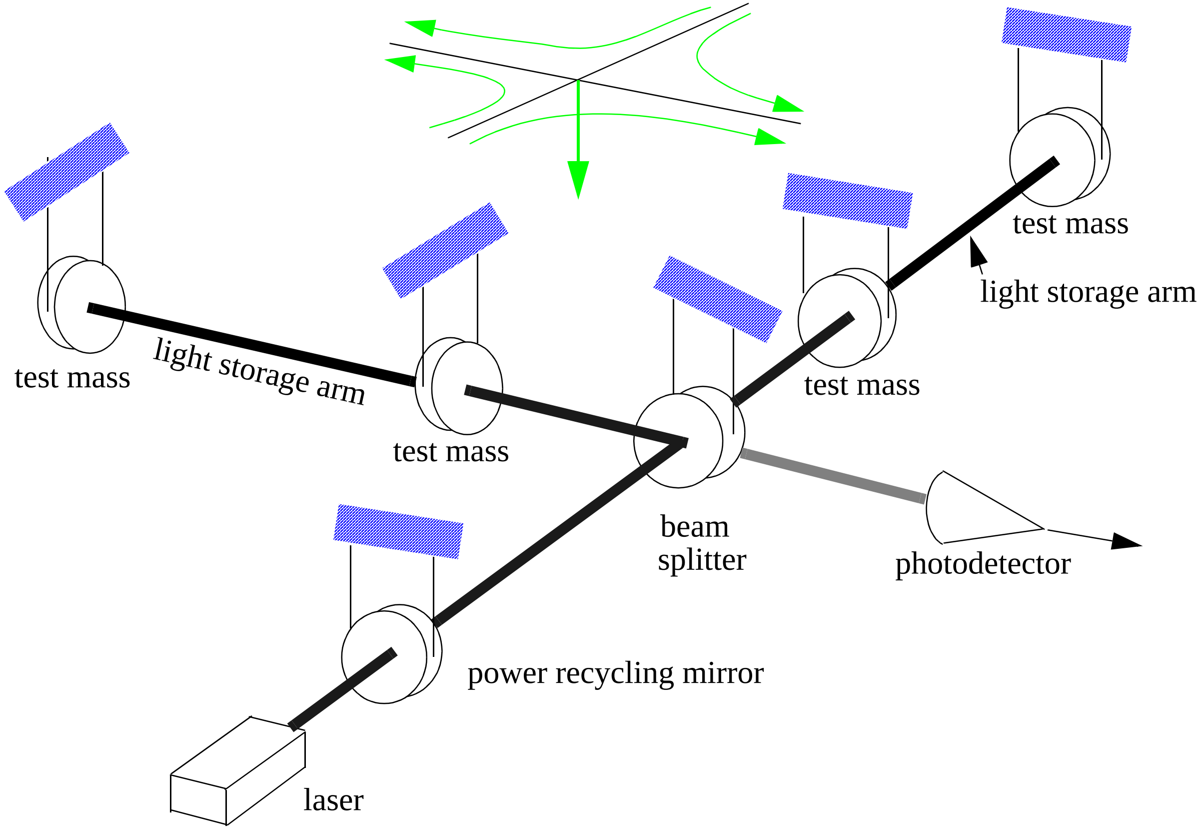
NSF Advanced LIGO Review

May 31, 2006

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

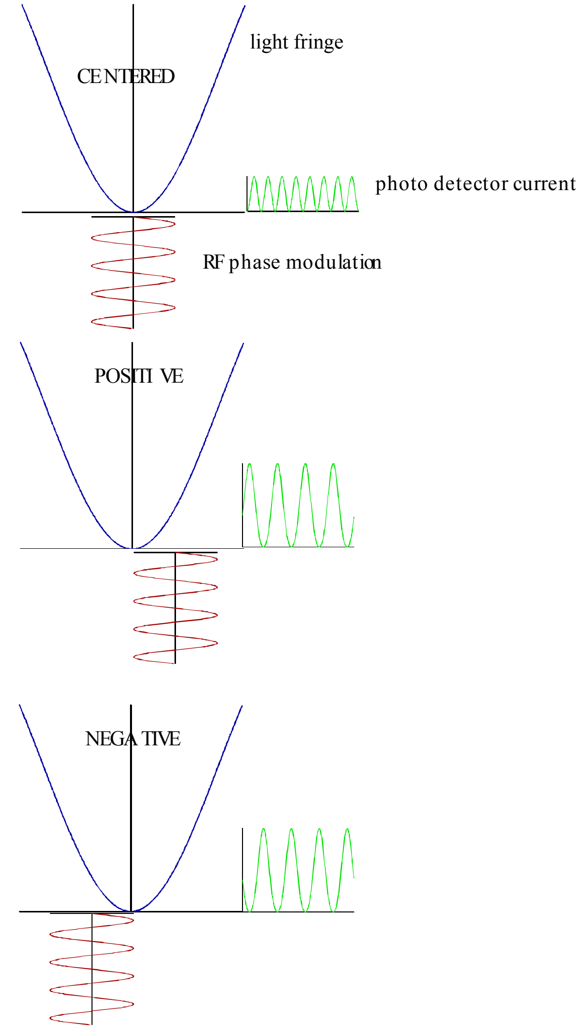
equivalent # of passes = 100

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



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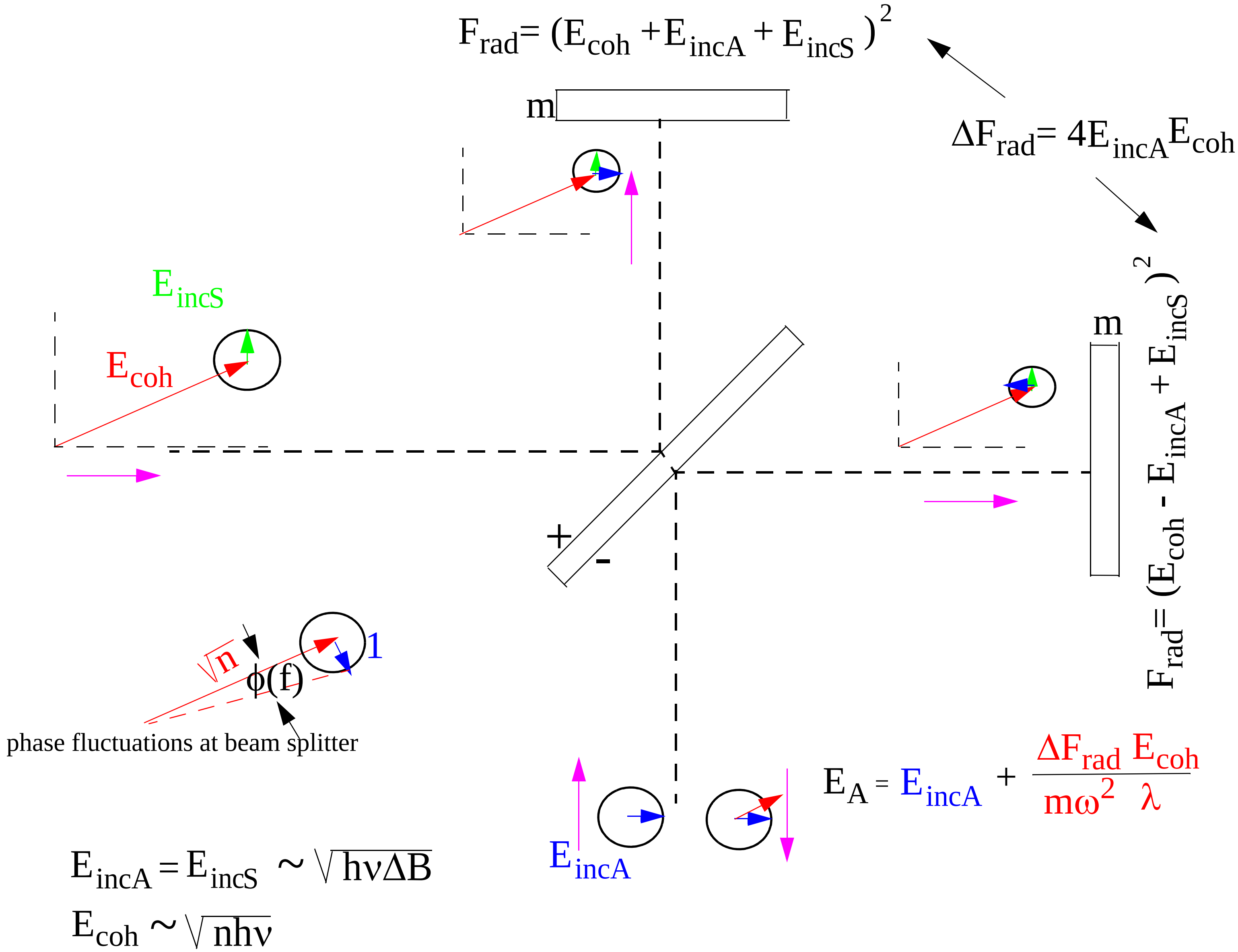
Quantum Noise in the Michelson Interferometer



PENDULUM THERMAL NOISE

Pendulum Brownian motion

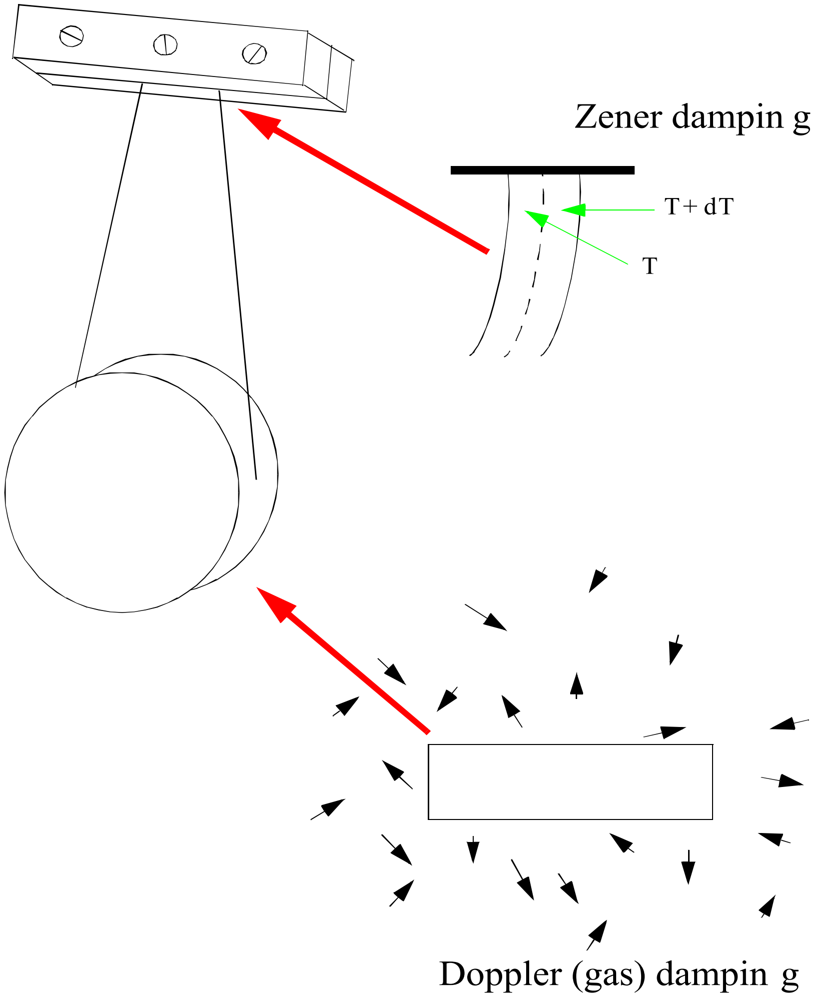
Dissipation leads to fluctuations

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

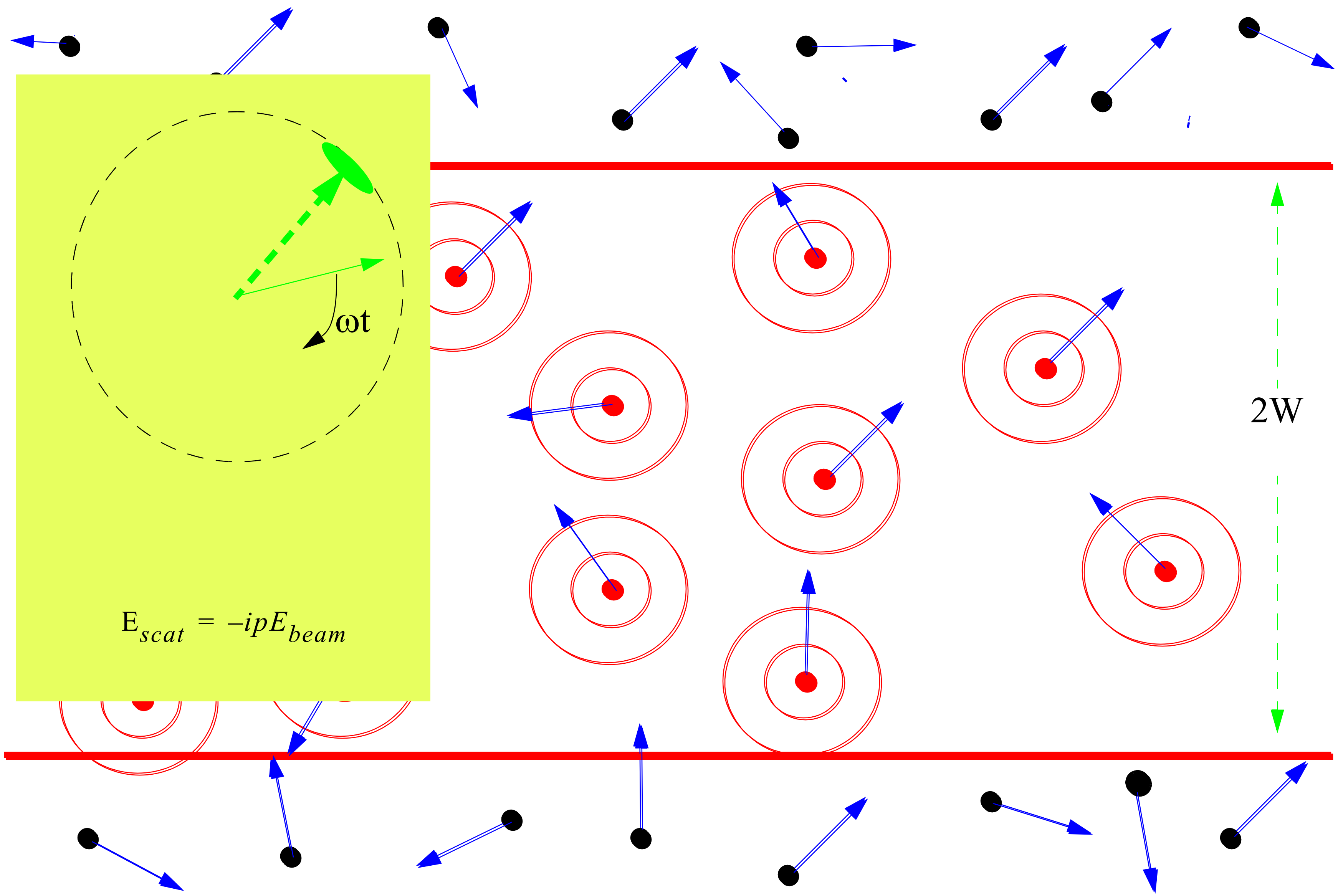
Exchange with surroundings:

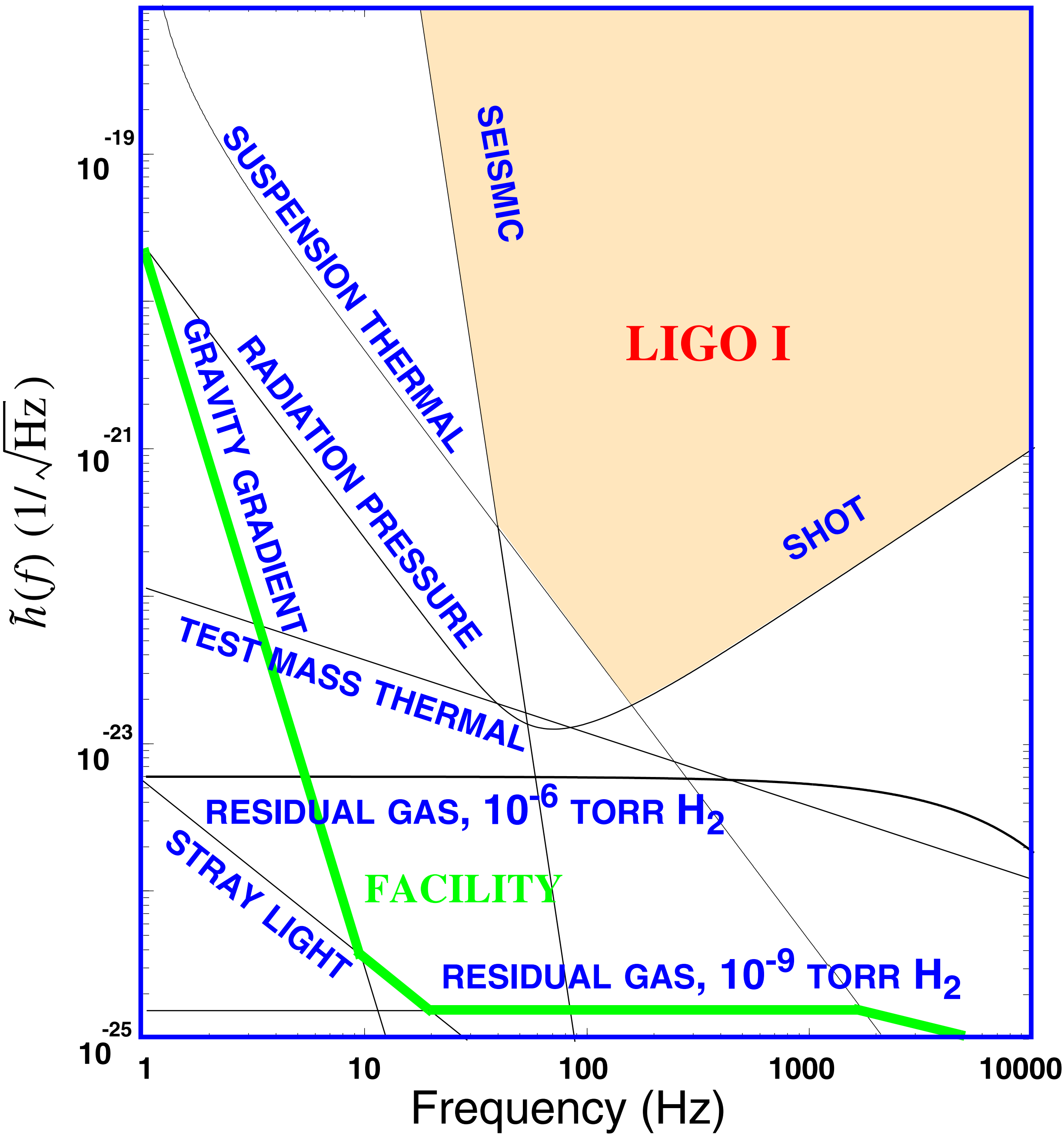
$$E(\text{thermal}) = \frac{kT\ t}{Tc}$$

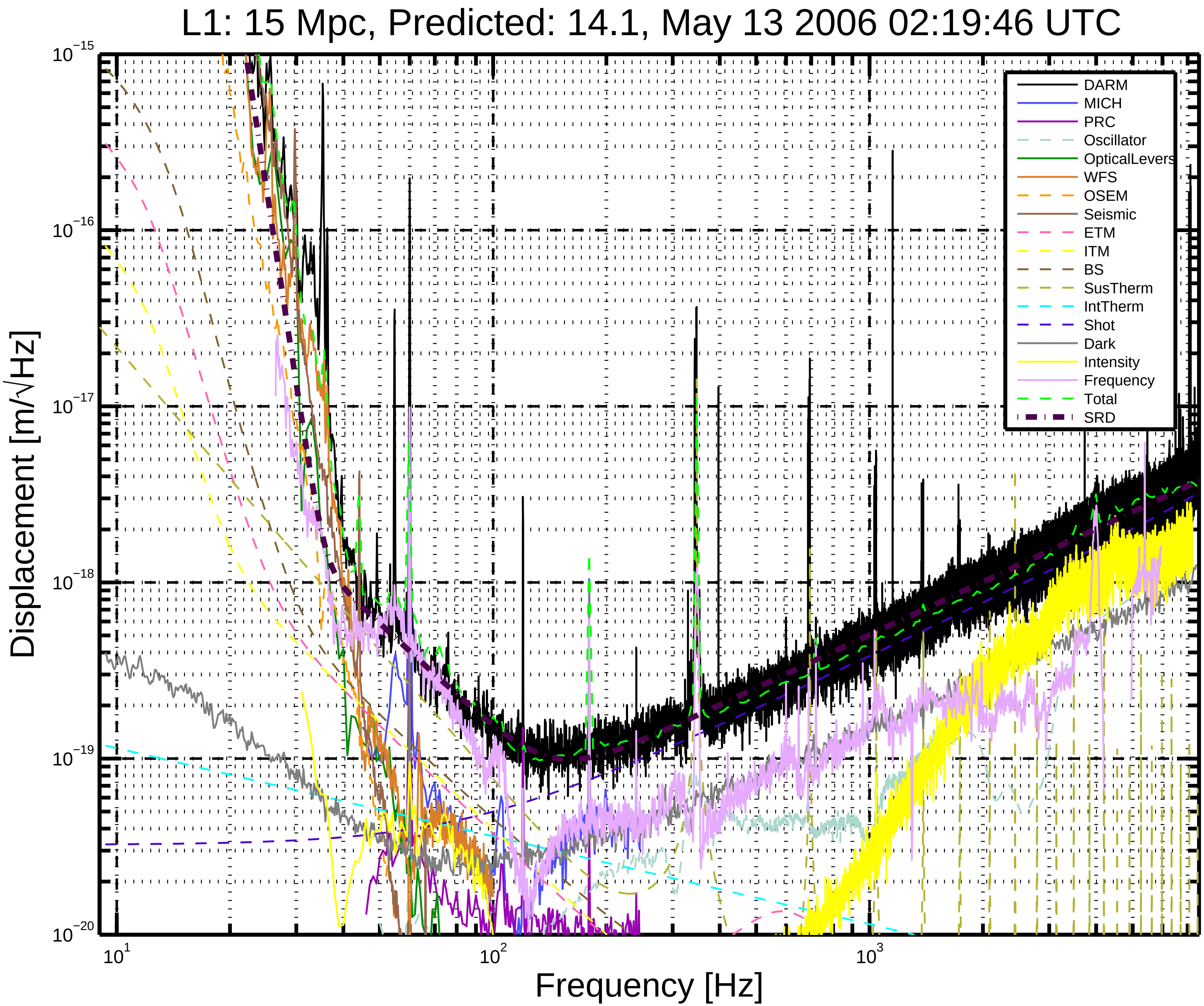
Large Tc => smaller fluctuations



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
$\tilde{h}(f)$ $(1/\sqrt{\mathrm{Hz}})$
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
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

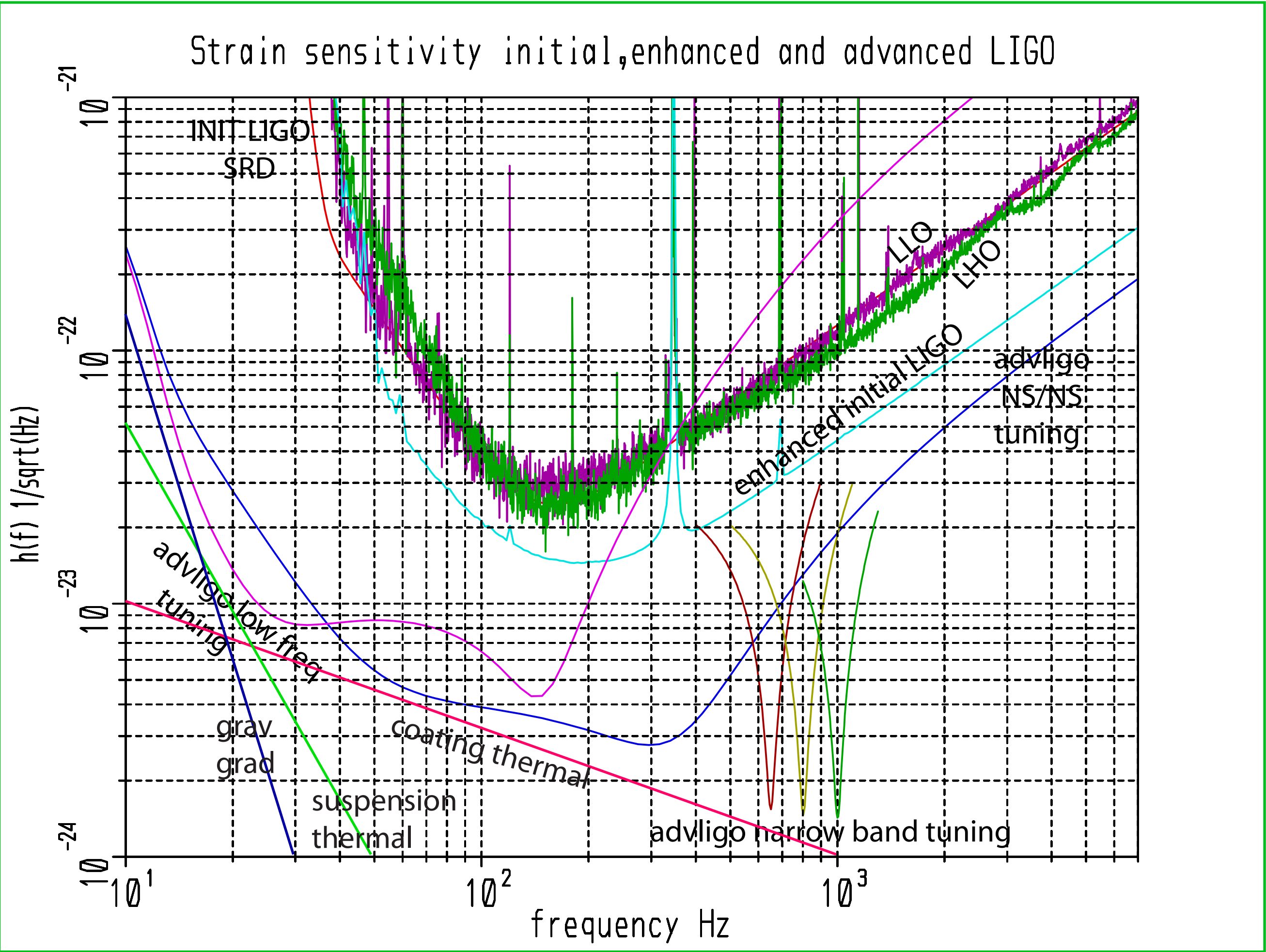
Program of improvements

- **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

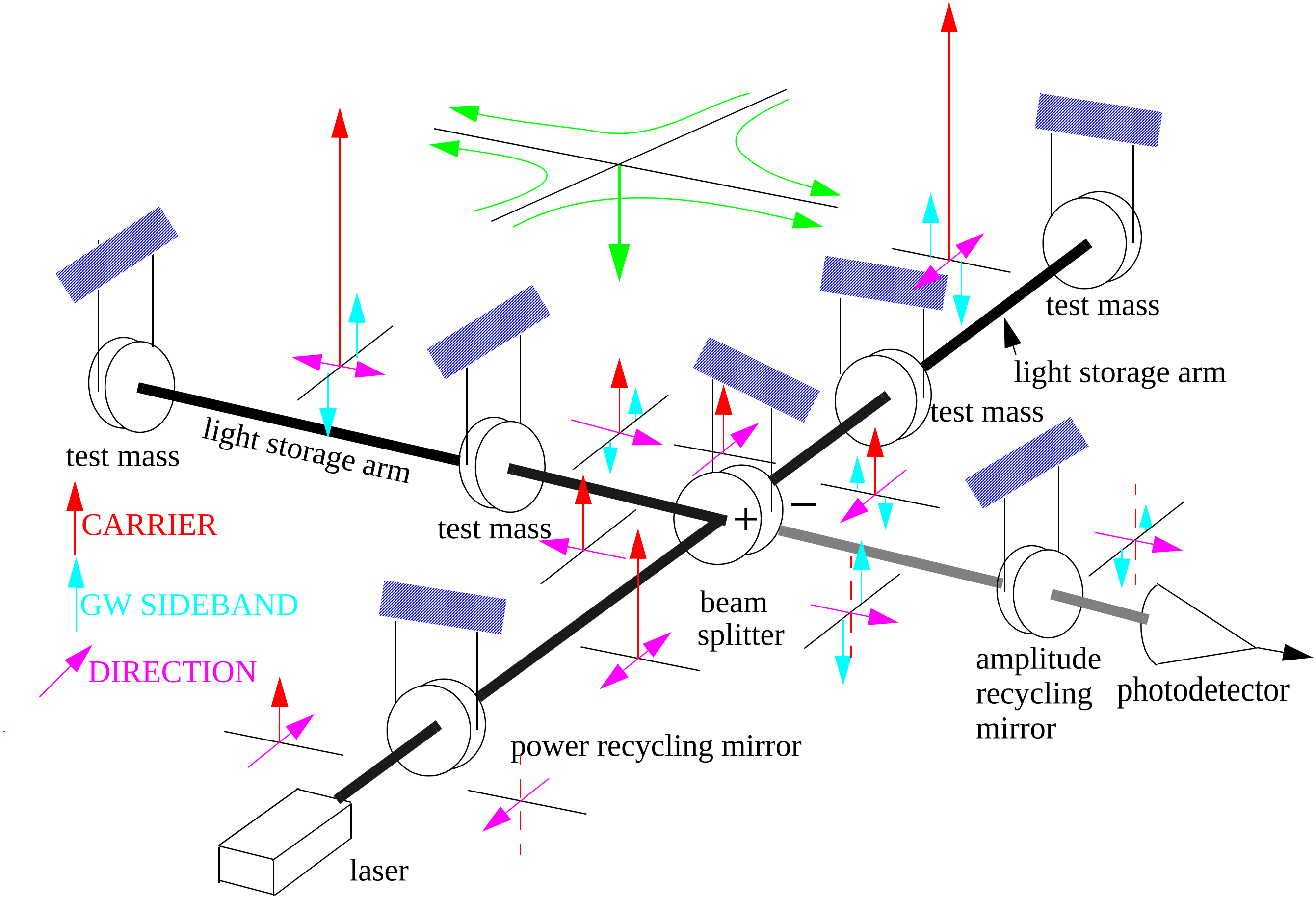
BEGIN IN ENHANCED LIGO

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
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^1
10^2
10^3


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

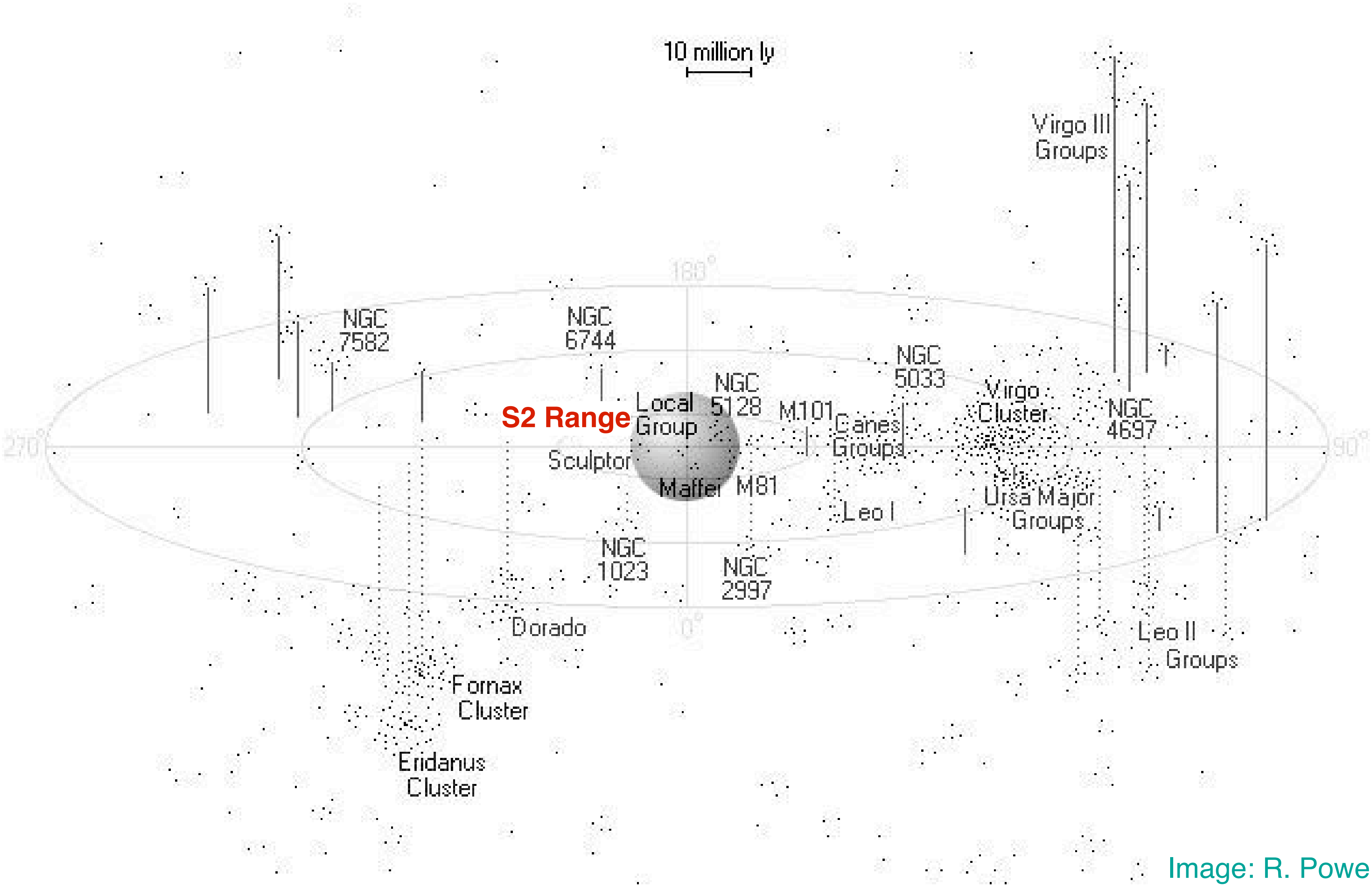


Image: R. Powell

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

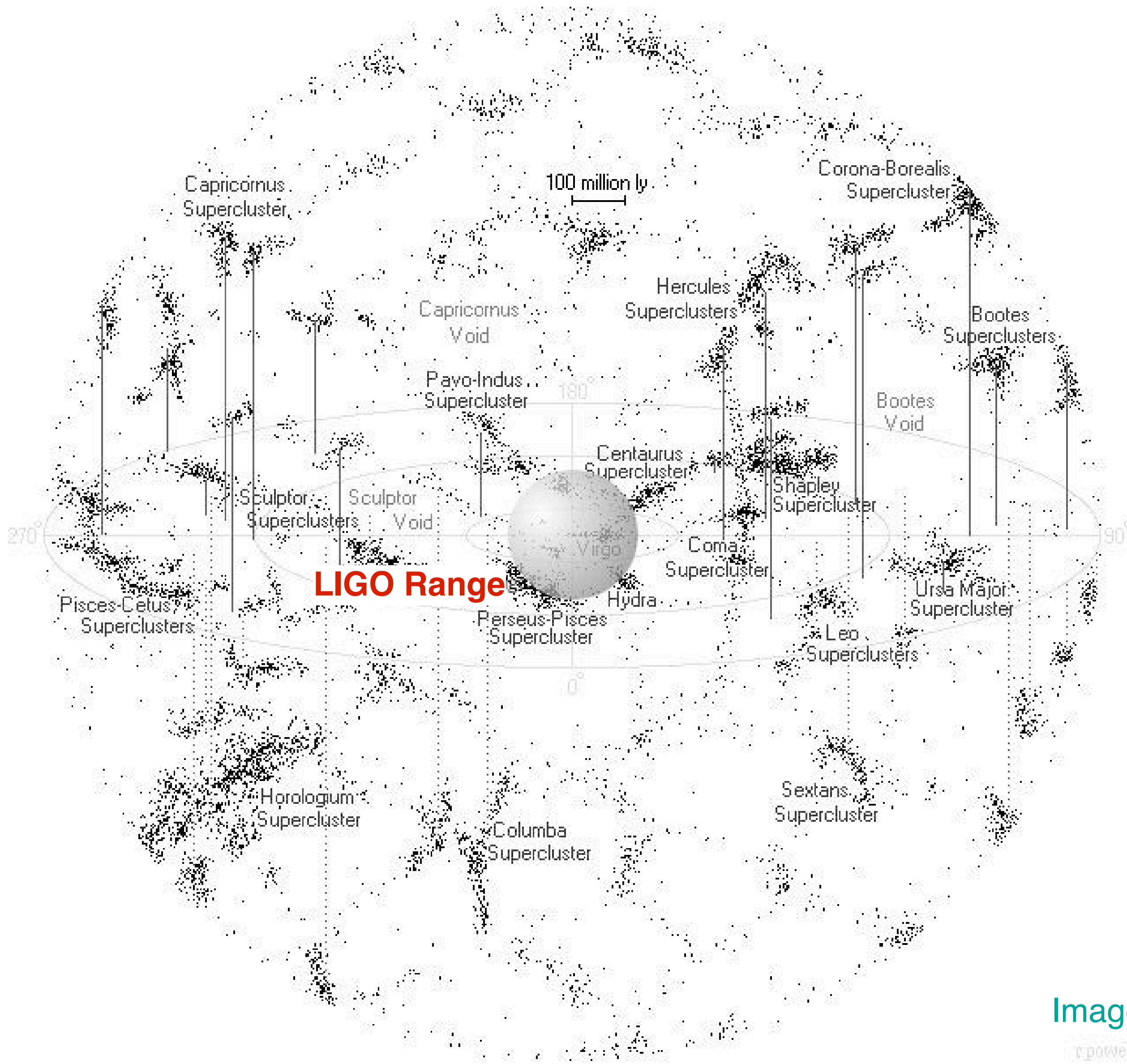
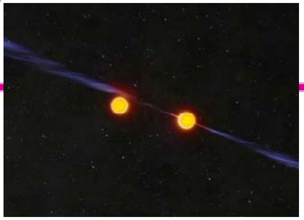


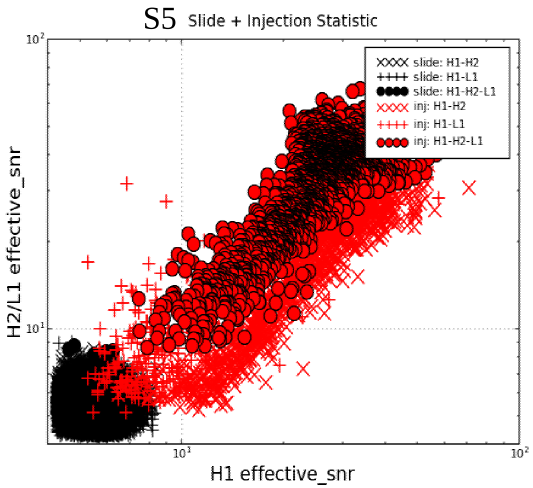
Image: R. Powell

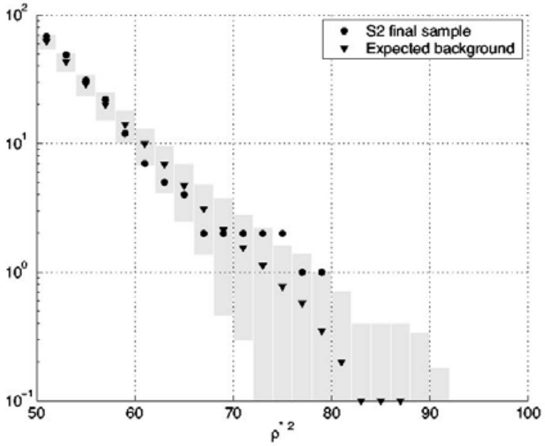
Search for binary systems

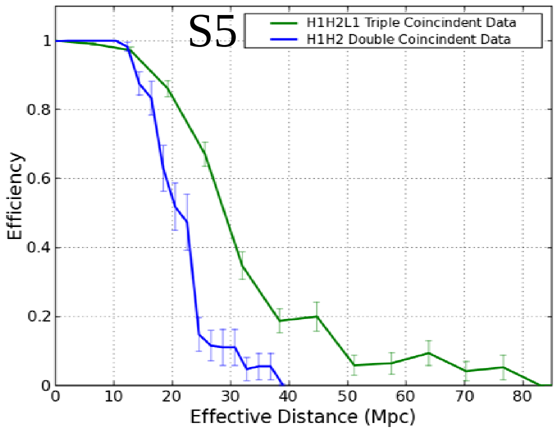


John Rowe, CSIRO

- 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):

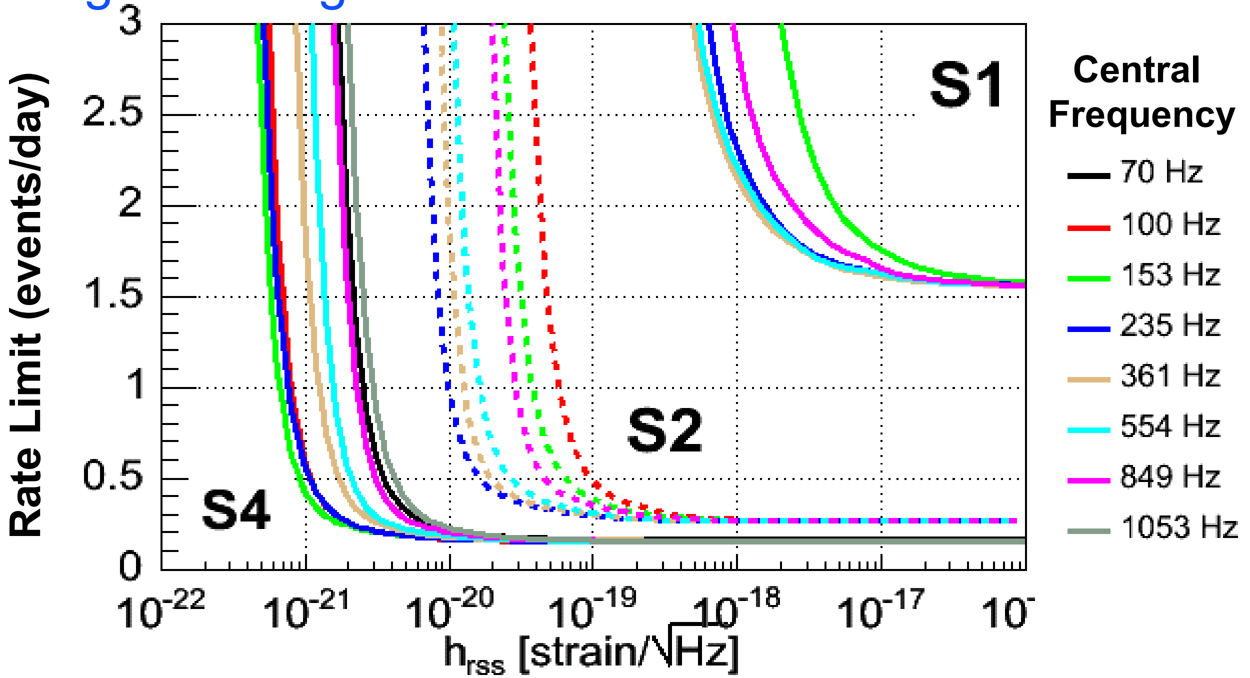
- S1: Analysis of LIGO data for gravitational waves from binary neutron stars, Phys. Rev. D 69, 122001 (2004)
- S2: Search for gravitational waves from primordial black hole binary coalescences in the galactic halo, Phys. Rev. D 72, 082002 (2005)
- S2: Search for gravitational waves from galactic and 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:

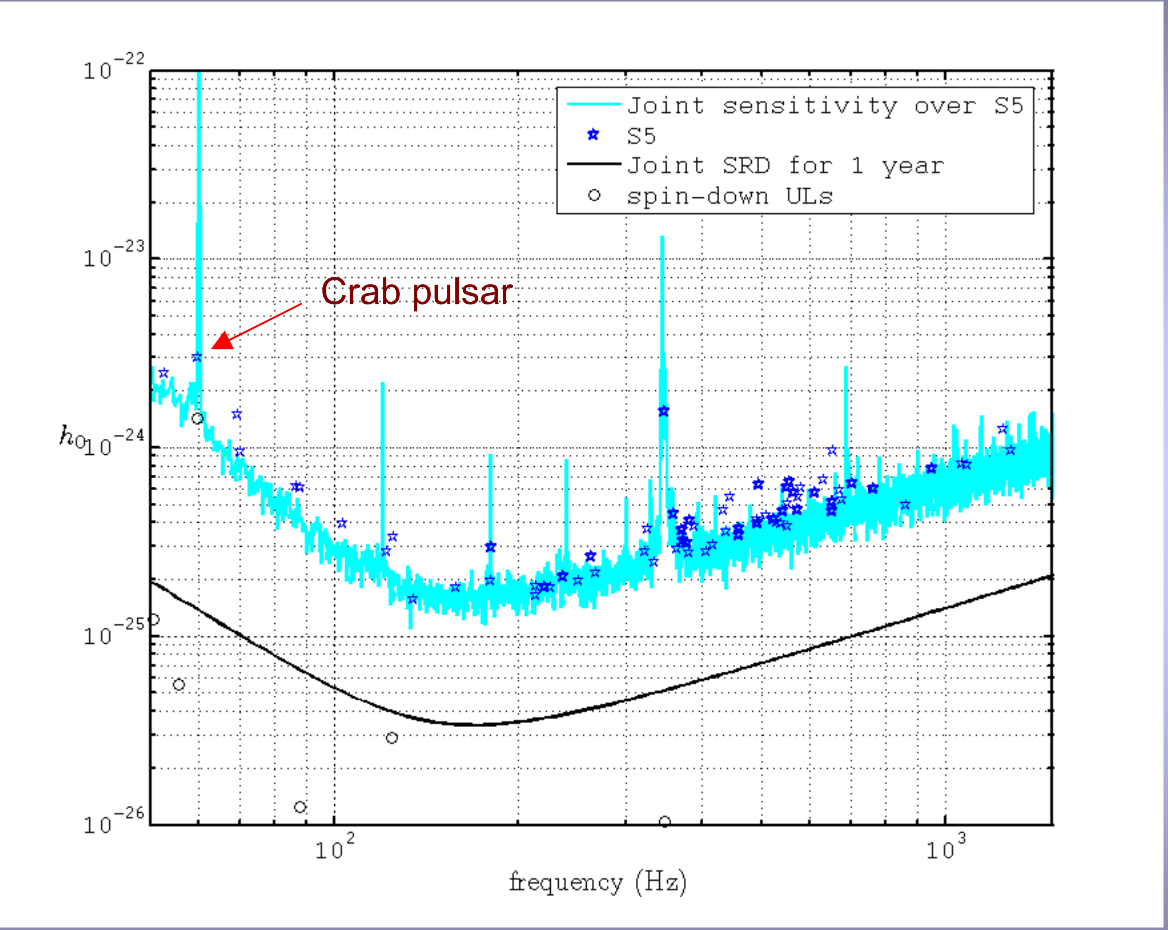
Lower rate limits from longer observation times

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)
  - $h_0 = 3.0\times10^{-24}$, $\varepsilon = 1.6\times10^{-3}$
  - Assumes $I = 10^{38}$ kgm^2



- Sensitivity curves use:

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

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

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

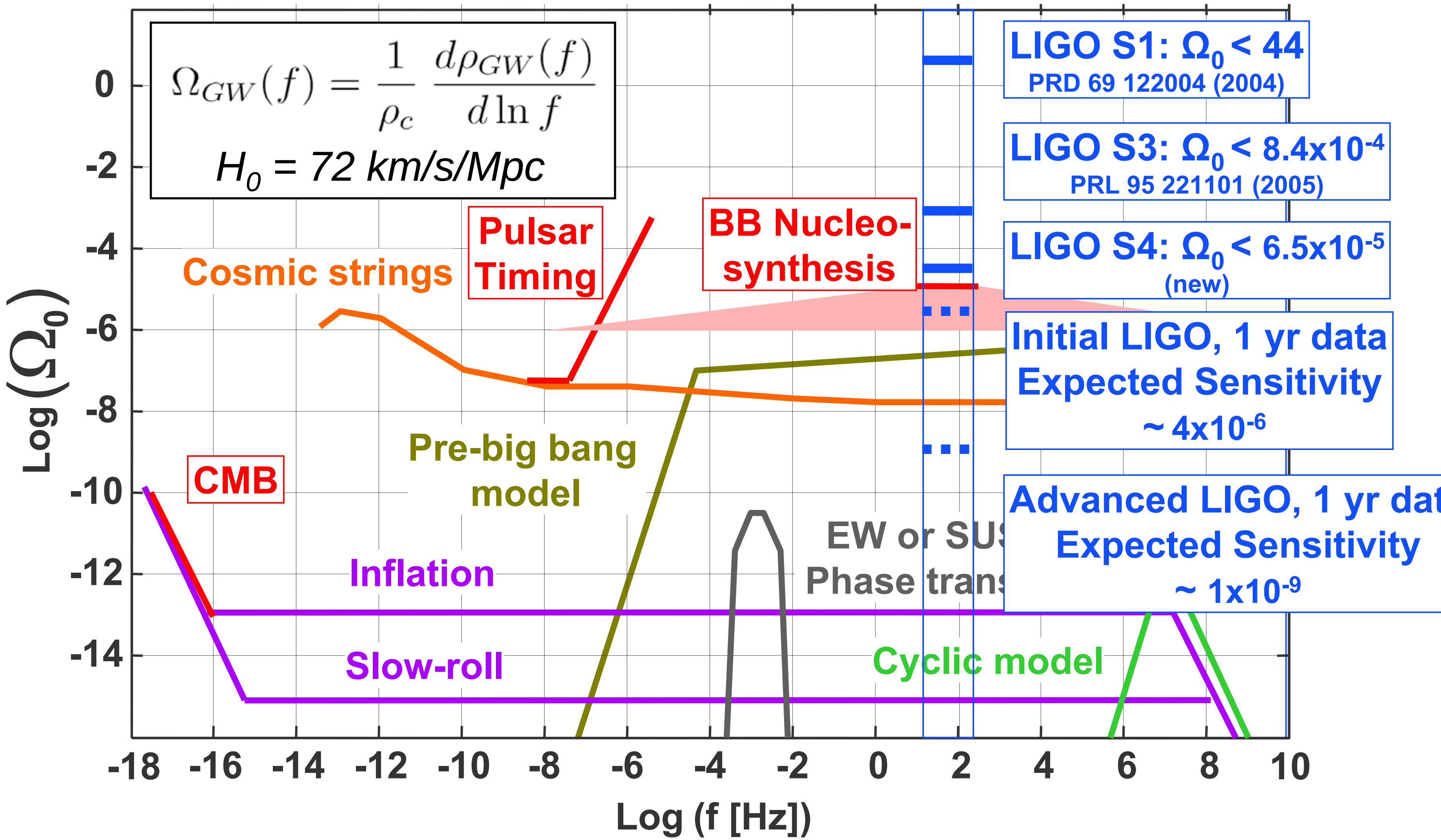
Lowest h_0 upper limit:
PSR J1603-7202 (f_{gw} = 134.8 Hz, r = 1.6kpc) $h_0 = 1.6\times10^{-25}$
Lowest ellipticity upper limit:
PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) $\varepsilon = 4.0\times10^{-7}$

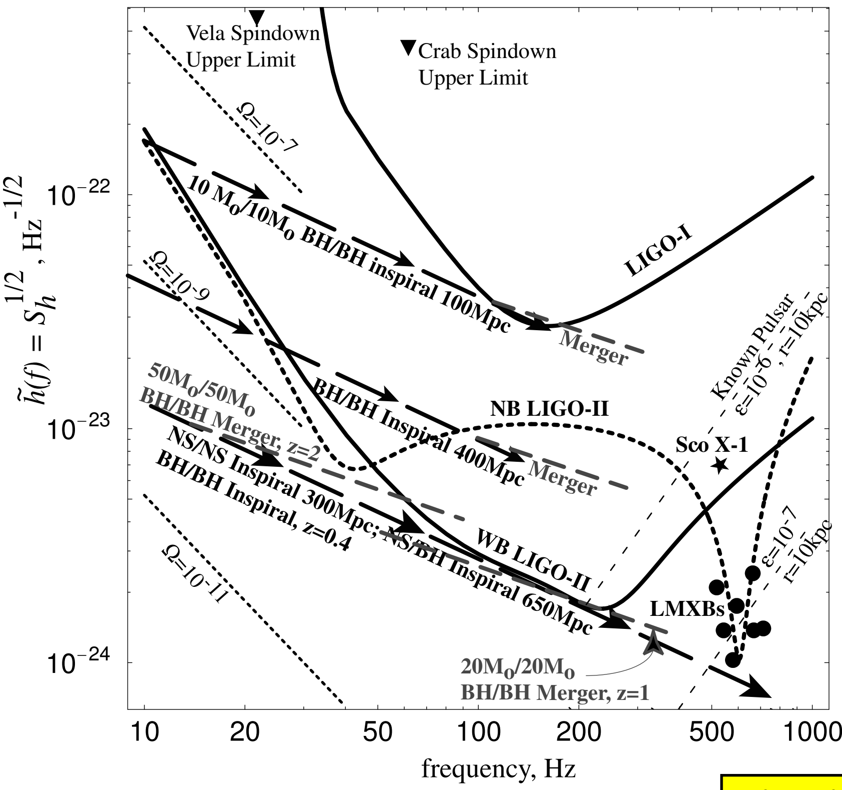
Ellipticity	Pulsars
$\varepsilon < 1\times10^{-6}$	6
$1\times10^{-6} < \varepsilon < 5\times10^{-6}$	28
$5\times10^{-6} < \varepsilon < 1\times10^{-5}$	13
$\varepsilon > 1\times10^{-5}$	26

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