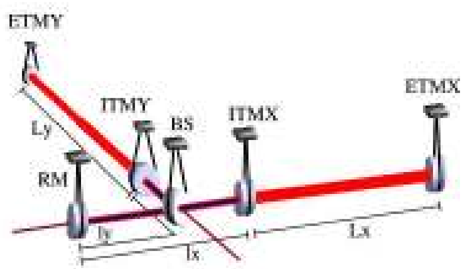
Status of the LIGO interferometers

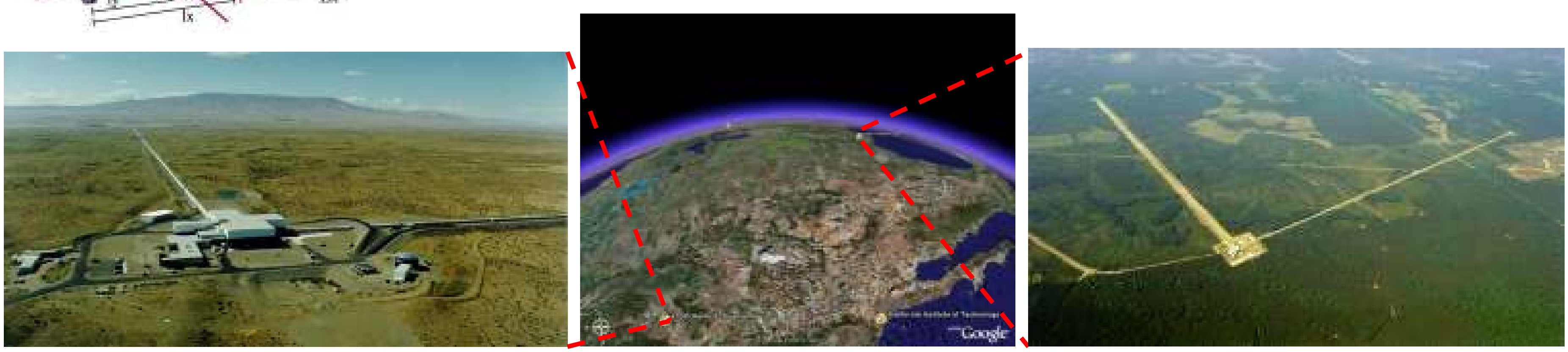
Stefan Ballmer
On behalf of the LSC

Presented at the

11th Marcel Grossmann Meeting on General Relativity

July 24th 2006, Berlin Germany





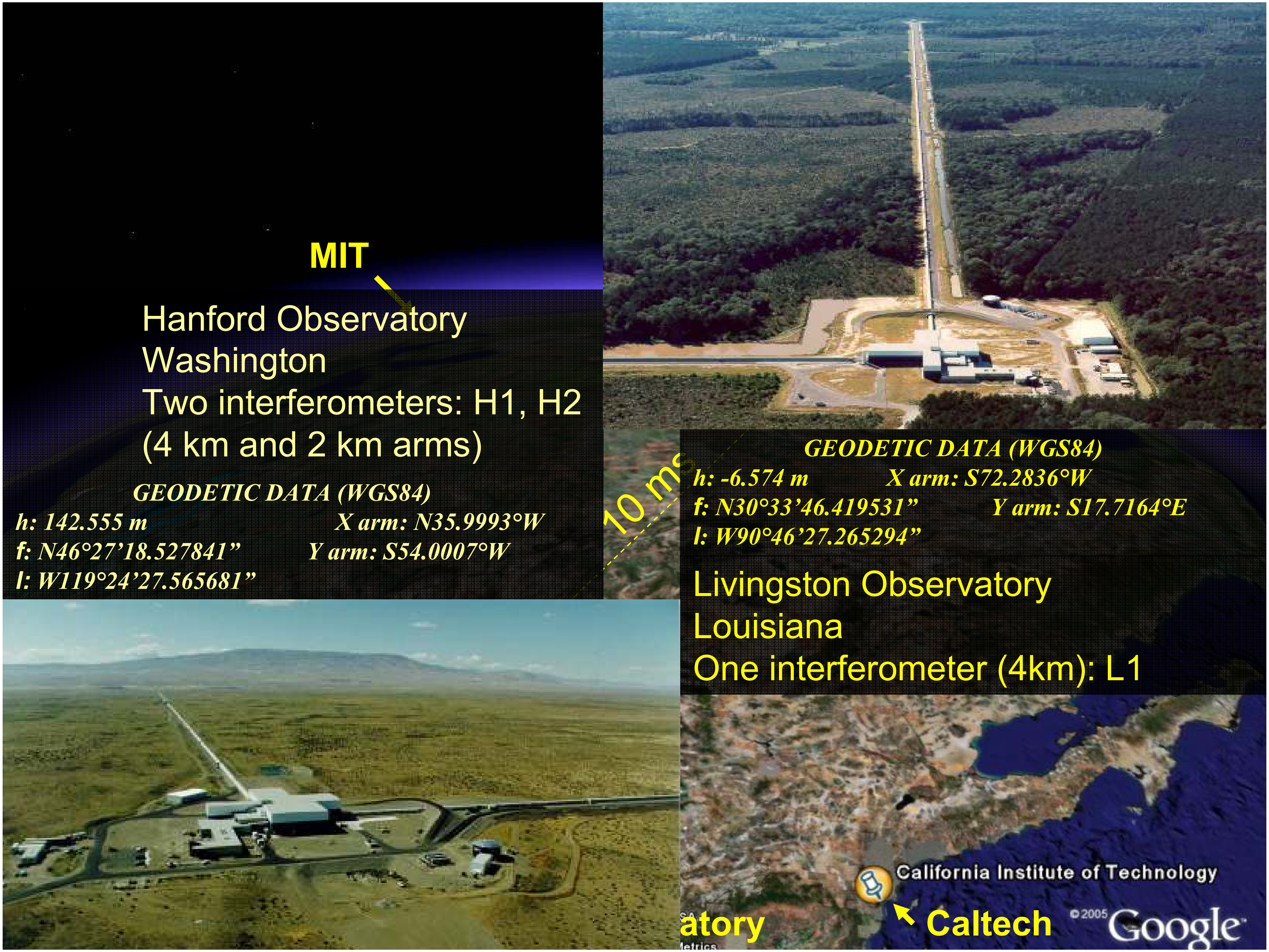
Outline

i. Introduction: The LIGO Interferometers

ii. Current Performance

iii. S5 science run progress

iv. Enhanced LIGO plans


MIT
Hanford Observatory
Washington
Two interferometers: H1, H2
(4 km and 2 km arms)
GEODETIC DATA (WGS84)
h: 142.555 m
X arm: N35.9993°W
f: N46°27'18.527841"
Y arm: S54.0007°W
l: W119°24'27.565681"
10 ms
GEODETIC DATA (WGS84)
h: -6.574 m
X arm: S72.2836°W
f: N30°33'46.419531"
Y arm: S17.7164°E
l: W90°46'27.265294"
Livingston Observatory
Louisiana
One interferometer (4km): L1
California Institute of Technology
Caltech
atory
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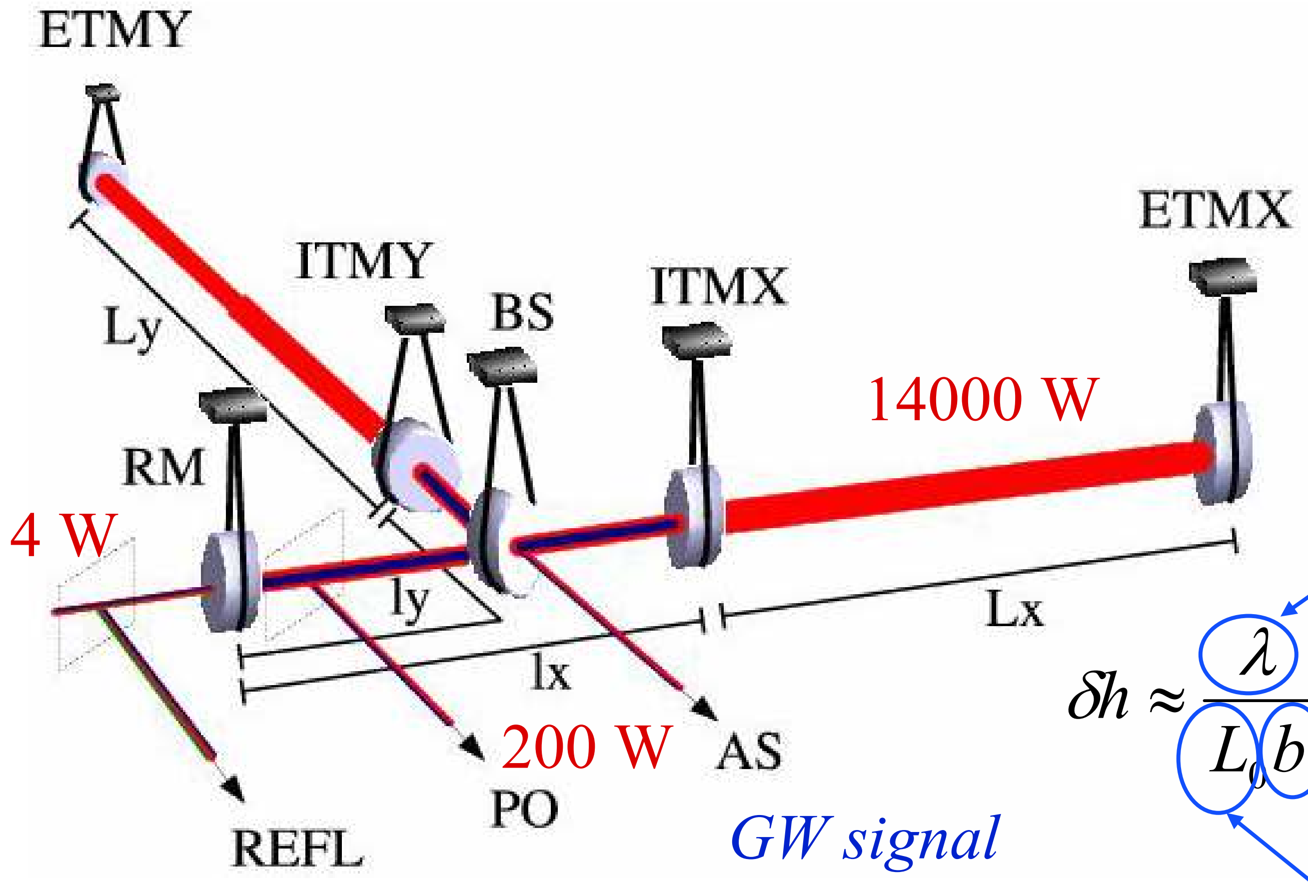
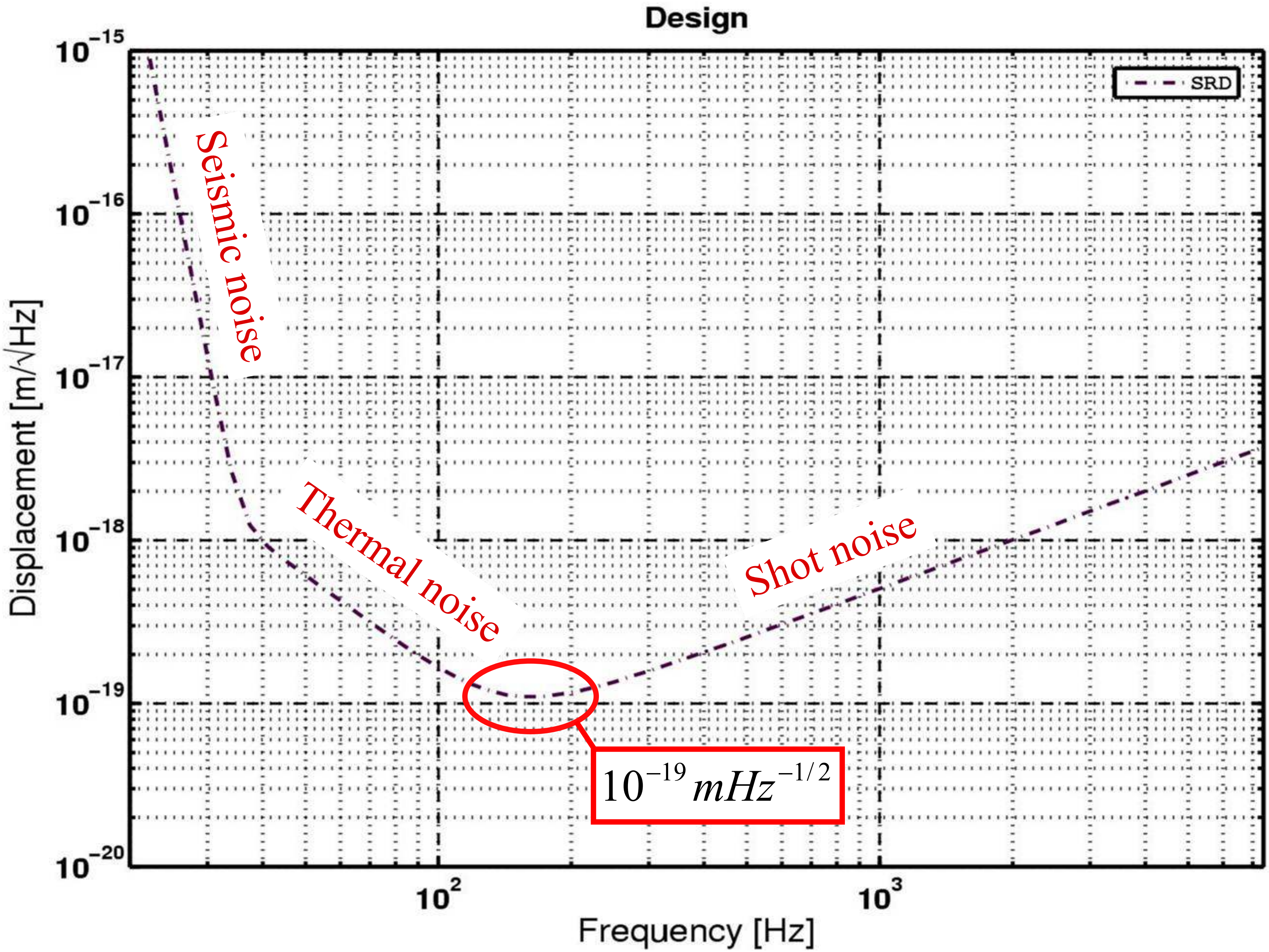
Displacement Sensitivity



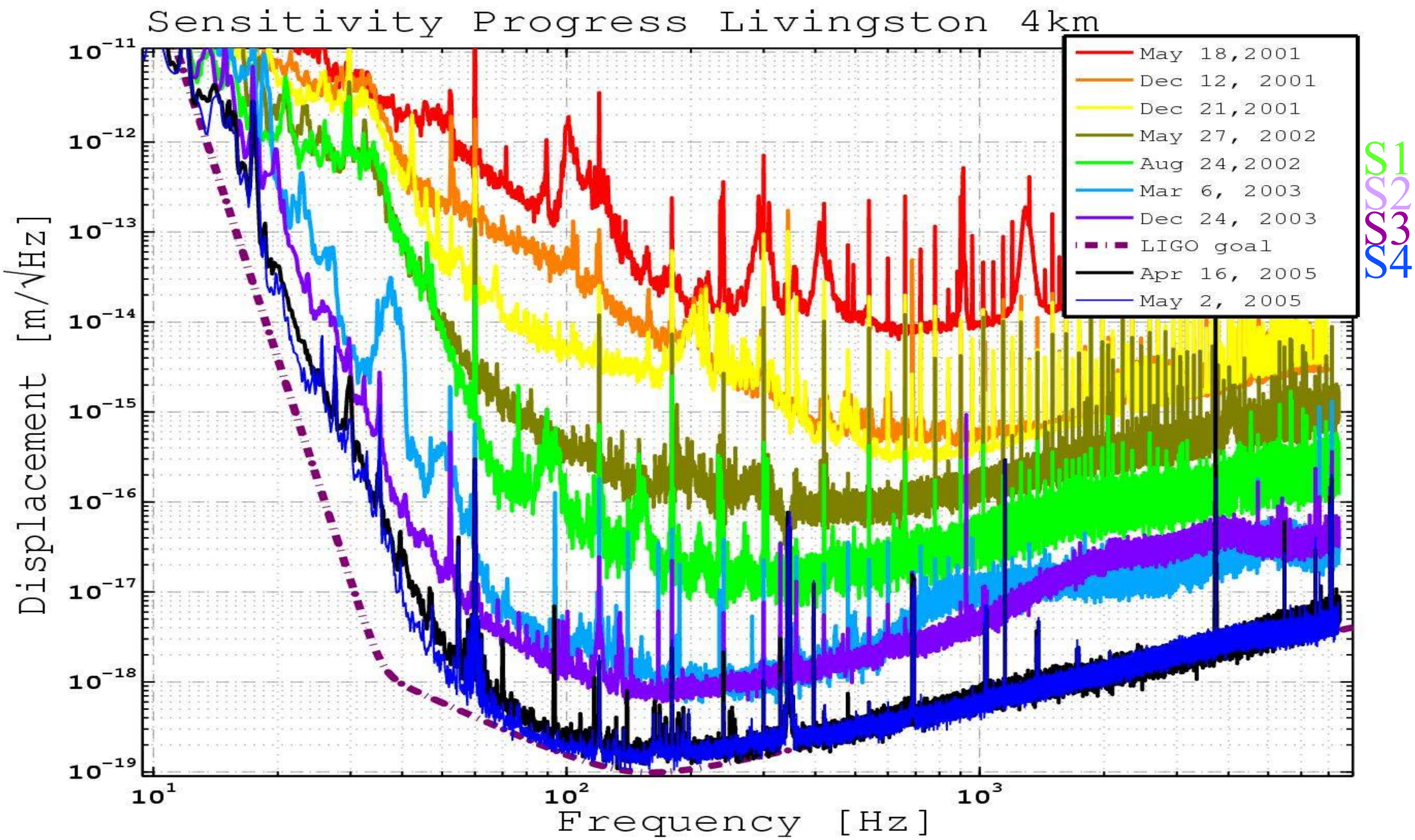
$$\delta h \approx \frac{\lambda}{L_0 b} \Delta\phi \approx 2.5 \times 10^{-23}\ Hz^{-1/2} \approx 10^{-19}\ Hz^{-1/2}\ \frac{m}{L}$$

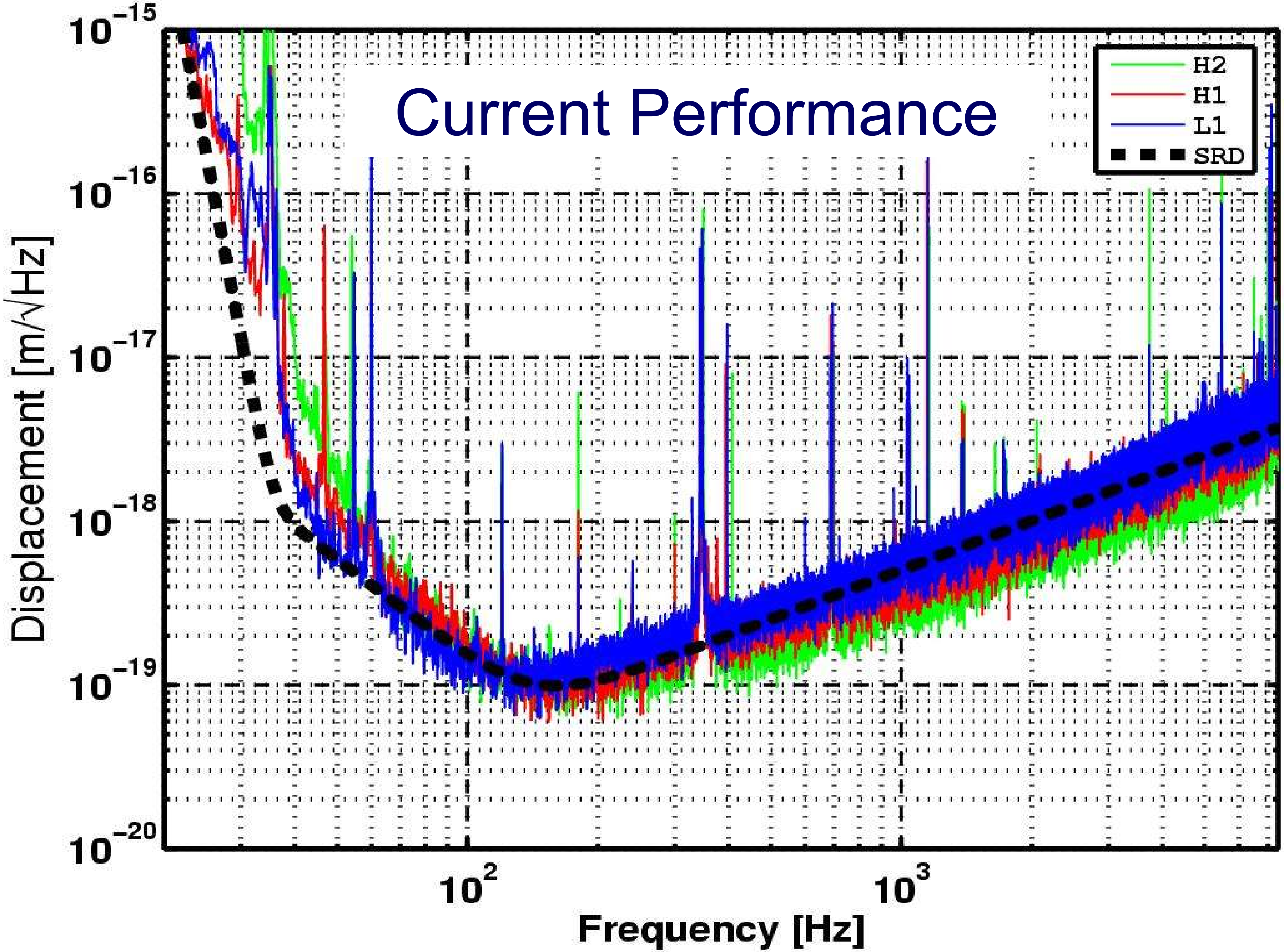
- λ: 1064 nm
- $\Delta\phi$: $\sim 10^{-11} Hz^{-1/2}$
- L_0: 4000 m
- b: 140



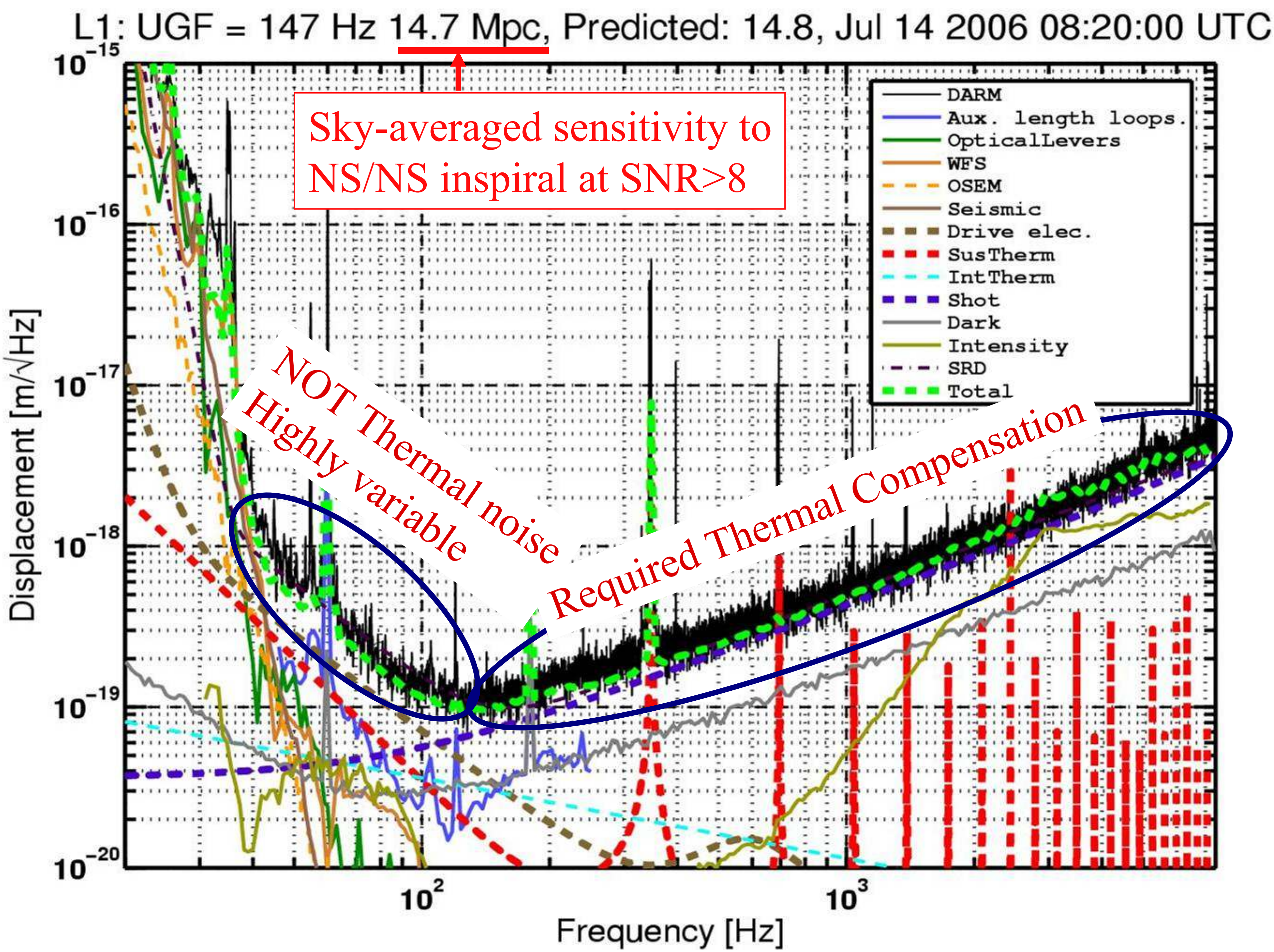
Design
SRD
Seismic noise
Thermal noise
Shot noise
$10^{-19} mHz^{-1/2}$
Displacement [m/√Hz]
Frequency [Hz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{2}
10^{3}

Early Noise Progression Livingston 4km





Current Performance
H2
H1
L1
SRD
Displacement [m/√Hz]
Frequency [Hz]
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
10^2
10^3



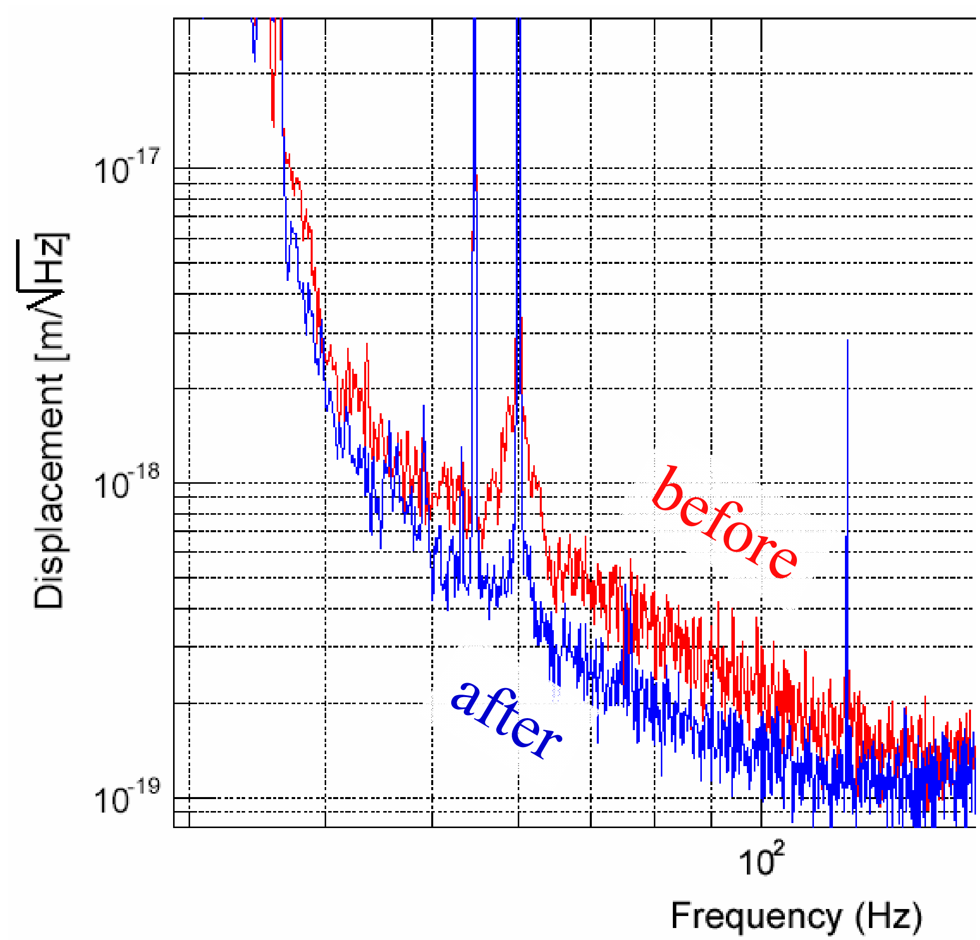
L1: UGF = 147 Hz 14.7 Mpc, Predicted: 14.8, Jul 14 2006 08:20:00 UTC
Sky-averaged sensitivity to NS/NS inspiral at SNR>8
DARM
Aux. length loops.
OpticalLevers
WFS
OSEM
Seismic
Drive elec.
SusTherm
IntTherm
Shot
Dark
Intensity
SRD
Total
NOT Thermal noise
Highly variable
Required Thermal Compensation
Displacement [m/√Hz]
Frequency [Hz]

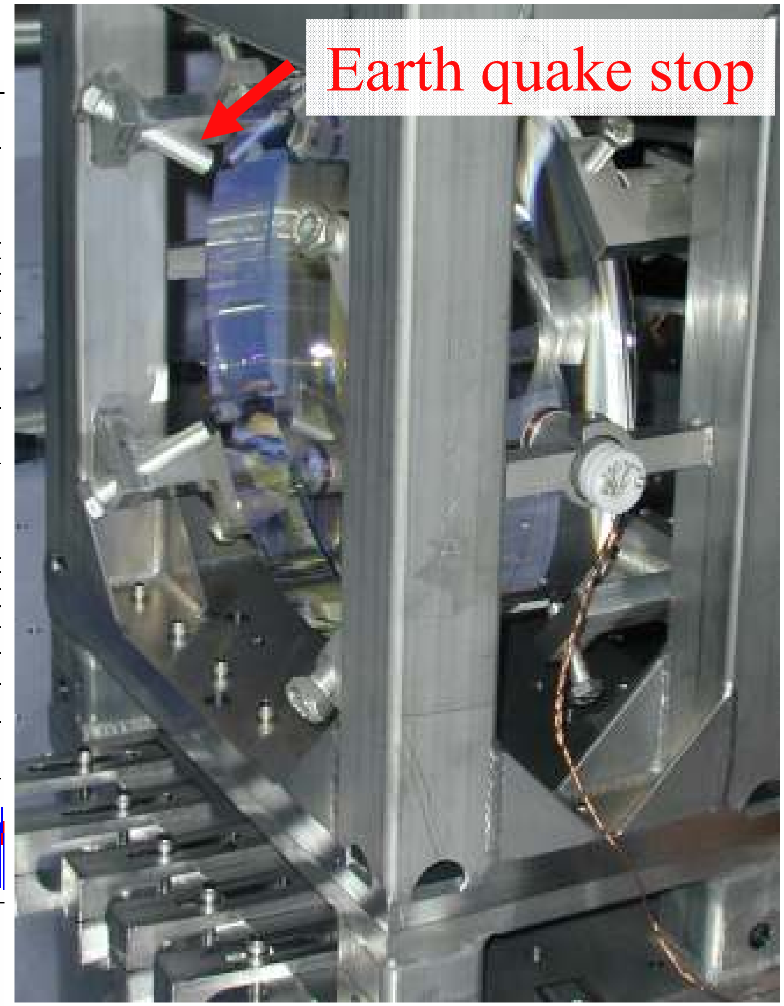
Low Frequency Up-conversion

- Band: ~40 Hz – 120 Hz
- Up-converted from Seismic Noise (below ~3 Hz)
- Lots of investigations, but no break-trough
  - Problem somewhere in actuation chain

- Bizarre incident with earth quake stop in Livingston
  - Optic got stuck on one earth quake stop
  - Vent was required to release optic
  - Earth quake stop retracted to nominal 0.5mm separation
  - ➔ ~x2 improvement in low frequency sensitivity!?!

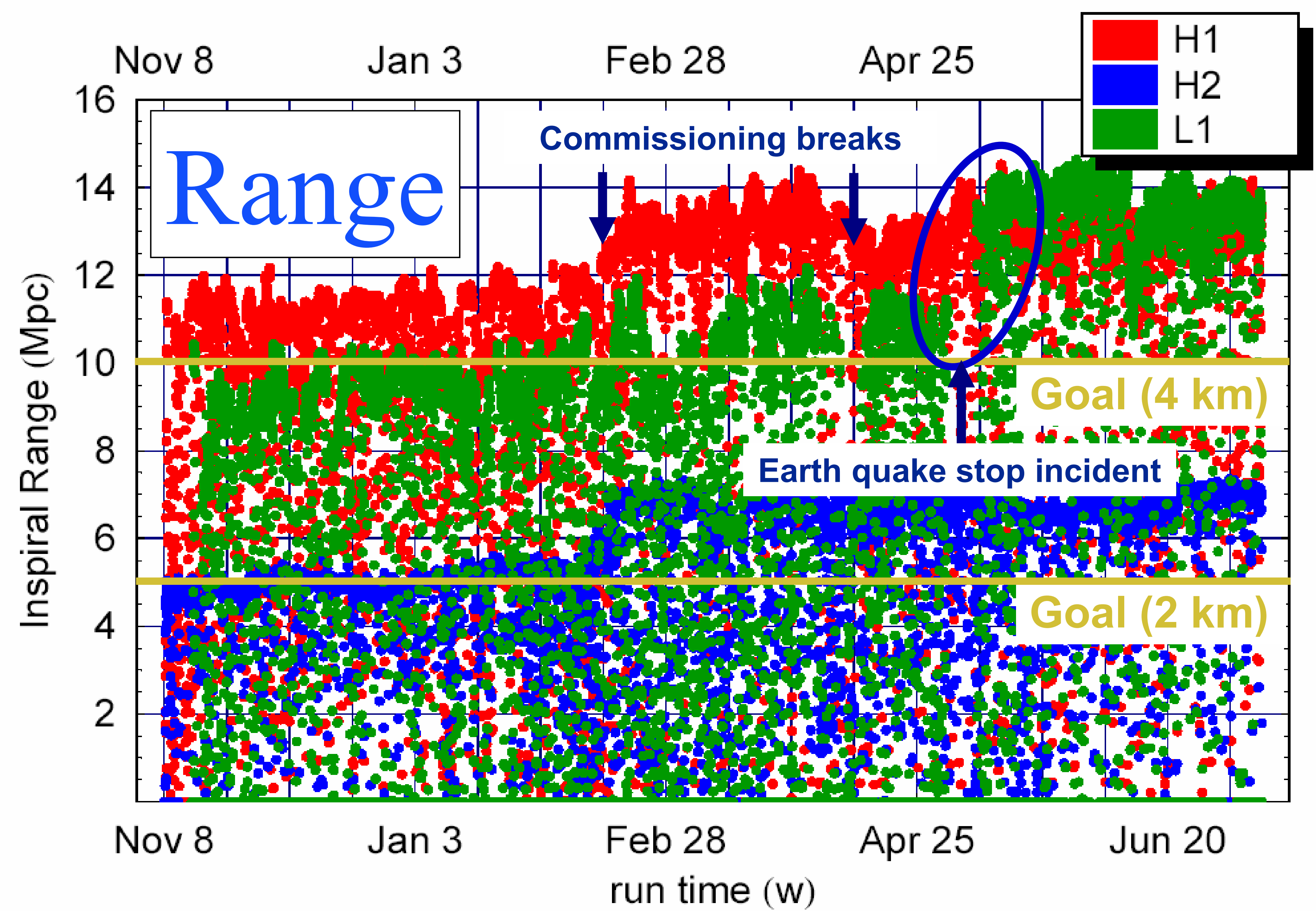
Before/after incident



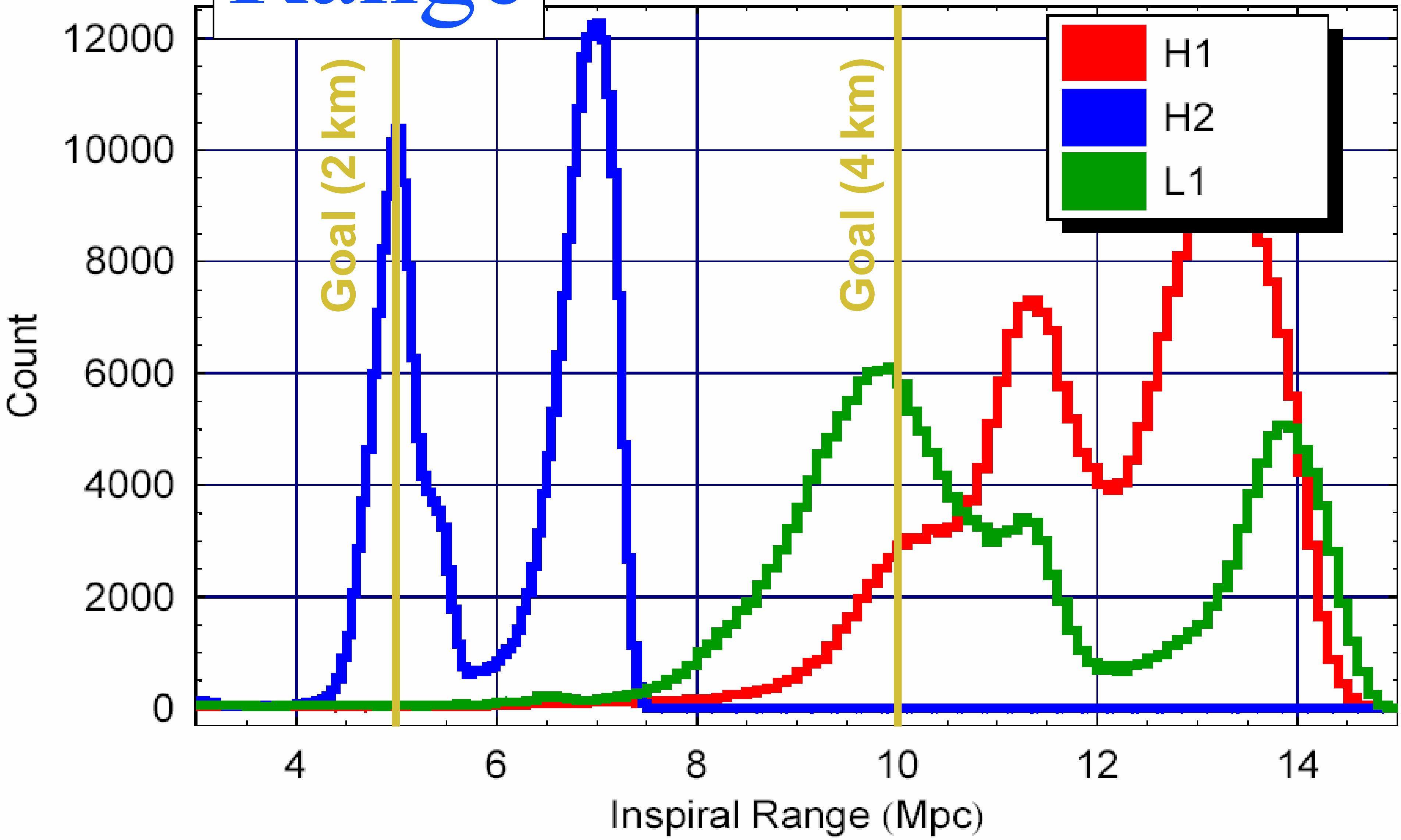


S5 Science Run

- Started in Nov 2005
- Goals:
  - *"Collect at least a year's data of coincident operation at the science goal sensitivity"*
  - NS/NS Range:
    - 4K ~ 10Mpc
    - 2K ~ 5Mpc
  - 85% single interferometer duty cycle (70% triple coincidence)

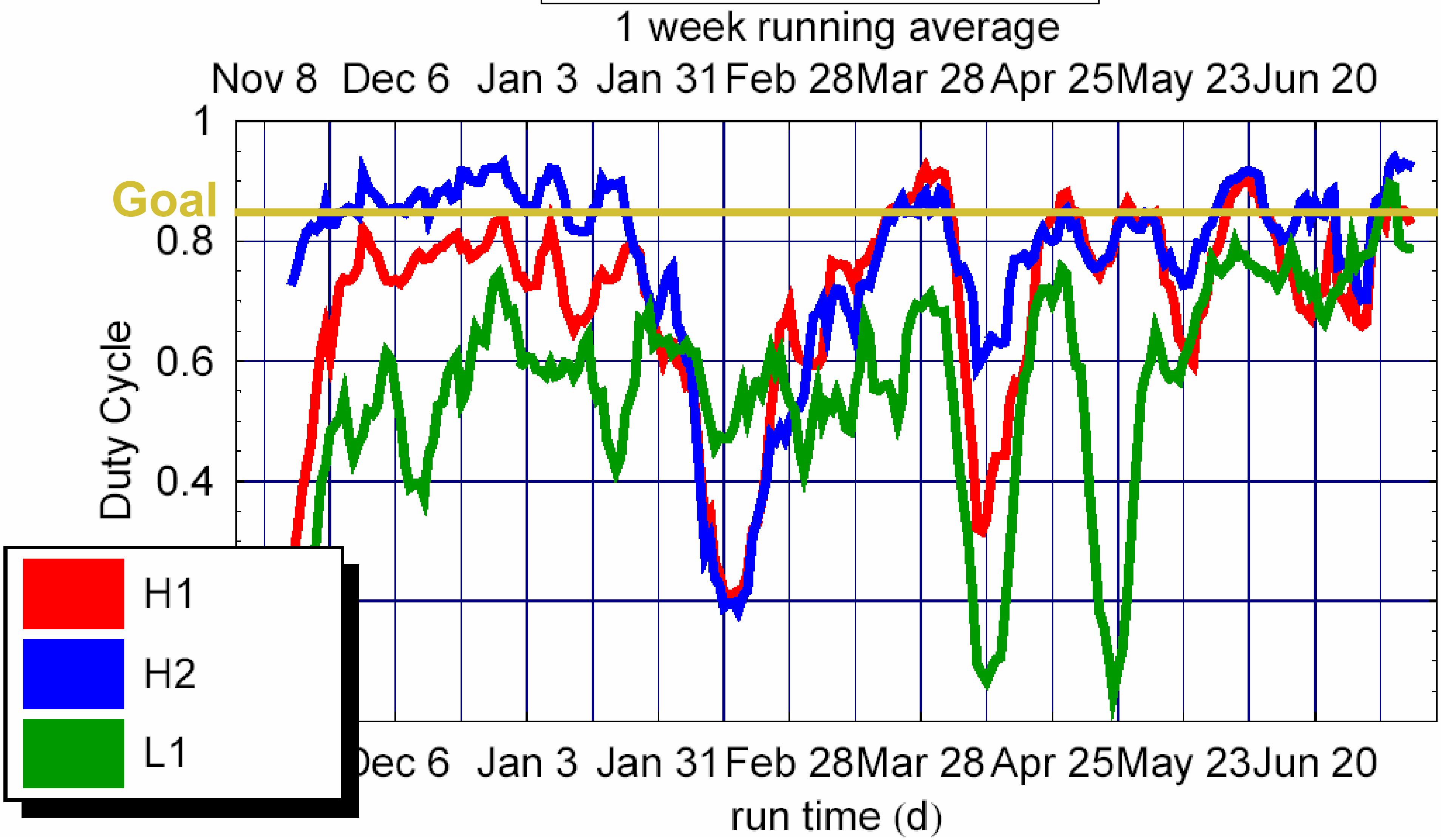

Range
H1
H2
L1
Nov 8
Jan 3
Feb 28
Apr 25
Jun 20
16
14
12
10
8
6
4
2
Inspiral Range (Mpc)
run time (w)
Commissioning breaks
Goal (4 km)
Earth quake stop incident
Goal (2 km)

Range



Goal (2 km)
Goal (4 km)
H1
H2
L1
12000
10000
8000
6000
4000
2000
0
Count
4
6
8
10
12
14
Inspiral Range (Mpc)

Duty cycle

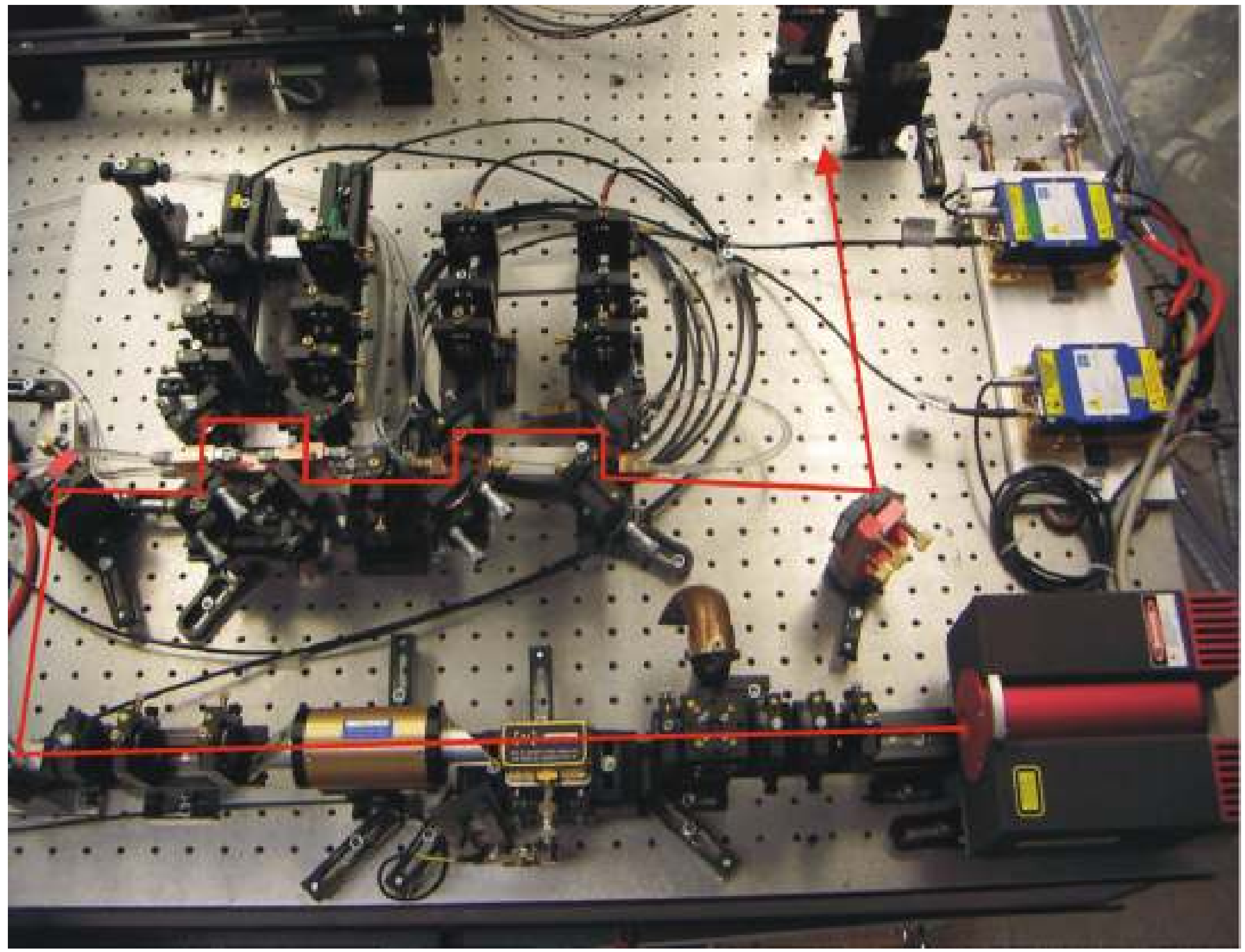

1 week running average
Nov 8 Dec 6 Jan 3 Jan 31 Feb 28 Mar 28 Apr 25 May 23 Jun 20
1
Goal
0.8
0.6
0.4
Duty Cycle
H1
H2
L1
Dec 6 Jan 3 Jan 31 Feb 28 Mar 28 Apr 25 May 23 Jun 20
run time (d)

The near term future

- S5 science run ongoing
  - Goal: 1 year of data at design sensitivity
  - Short commissioning breaks may be scheduled if required
    - Aimed at duty cycle improvements
- Current interferometers can do better
  - Design sensitivity is not a fundamental limit
  - Increase circulating power
    → doubling sensitivity possible (x8 in event rate)
    - Requires:
      - New Laser (30 Watt)
      - In-vacuum detection & output mode cleaner
    - Plans to do this after S5

30Watt MOPA from LZH, Germany

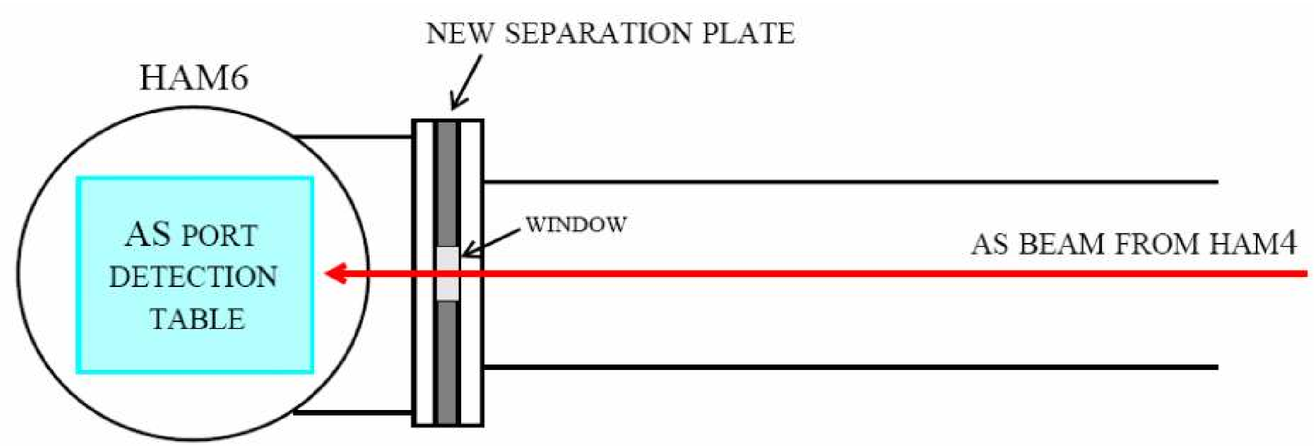
- Front-end of AdvLIGO high power laser



In-vacuum detection bench

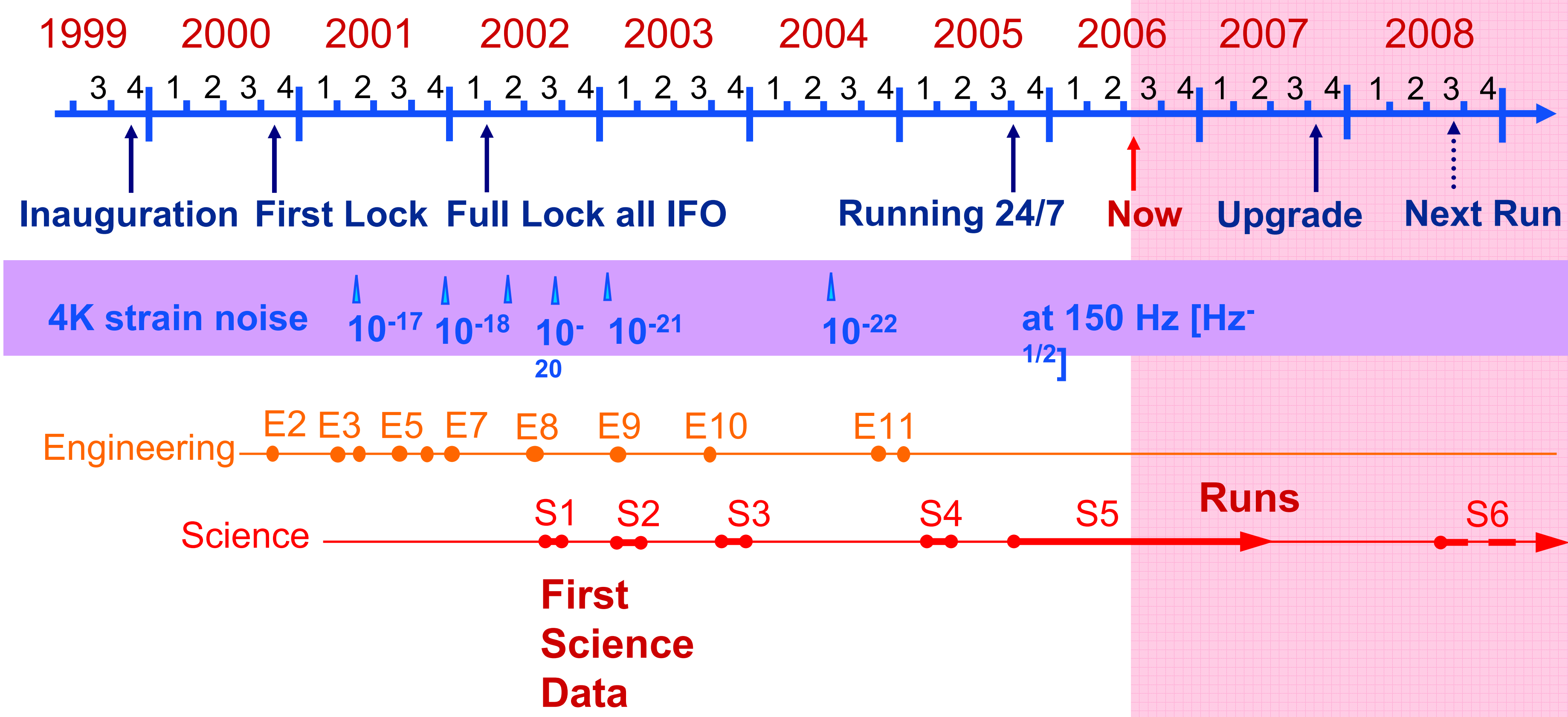
- Provides seismic and acoustic isolation for
  - Output Mode Cleaner
  - Detection bench optics and photo diodes

- Switch to DC readout scheme



LIGO

Time Line



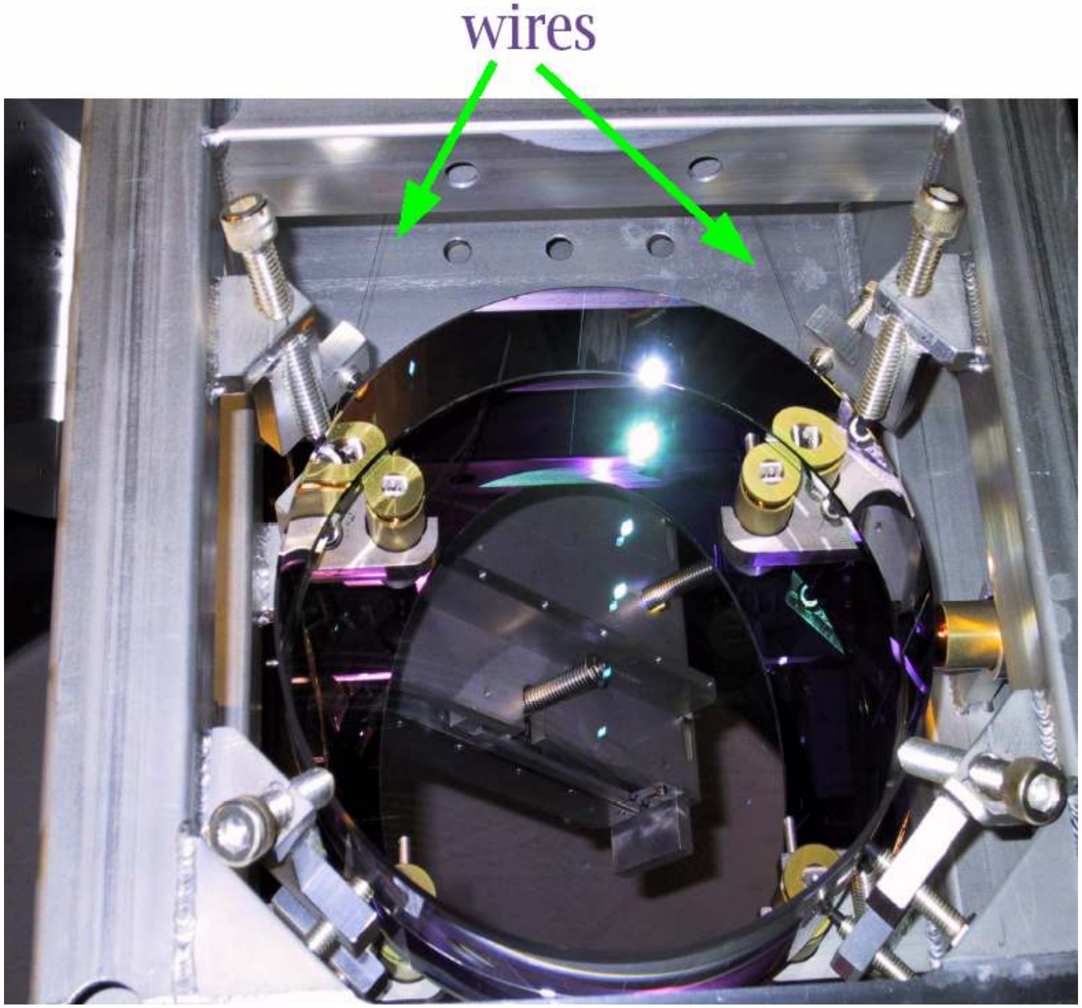
Summary

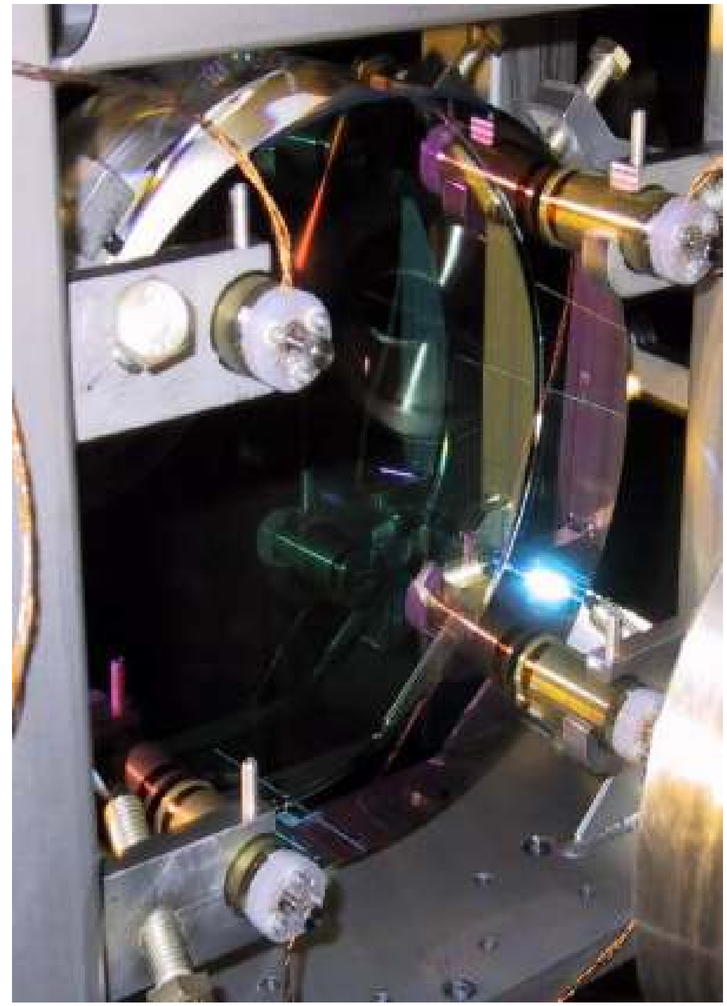
- LIGO has achieved its design sensitivity
- One third into S5 science run
  - Goal: 1 year of coincidence data at design sensitivity
- Upgrade planned after S5
  - Laser upgrade
  - Output mode cleaner
  - In-vacuum DC-readout

The End of my talk

The Beginning of GW astronomy

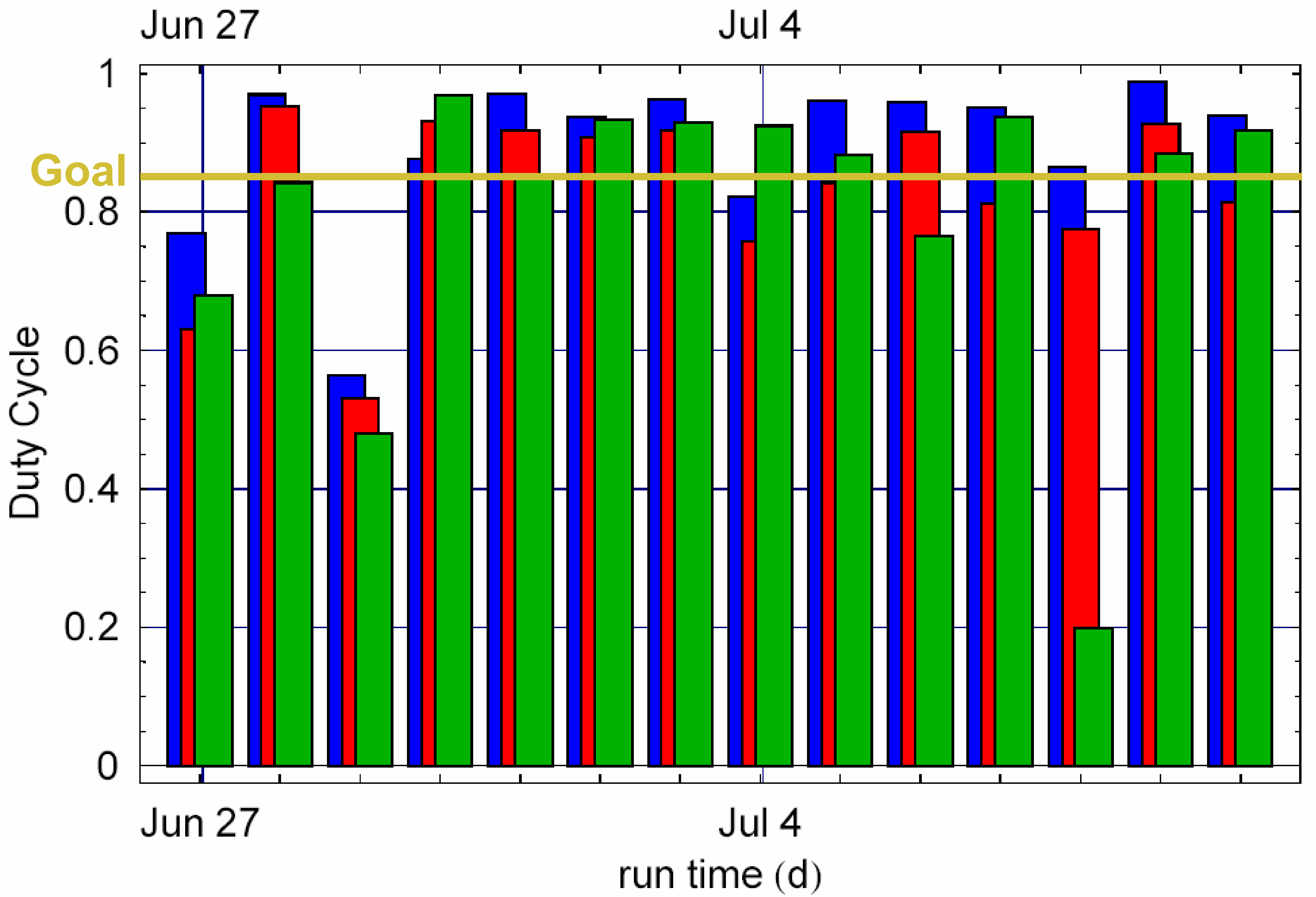
Optics





Seismic Isolation

Stefan Ballmer, Caltech


Jun 27
Jul 4
Goal
Duty Cycle
1
0.8
0.6
0.4
0.2
0
Jun 27
Jul 4
run time (d)

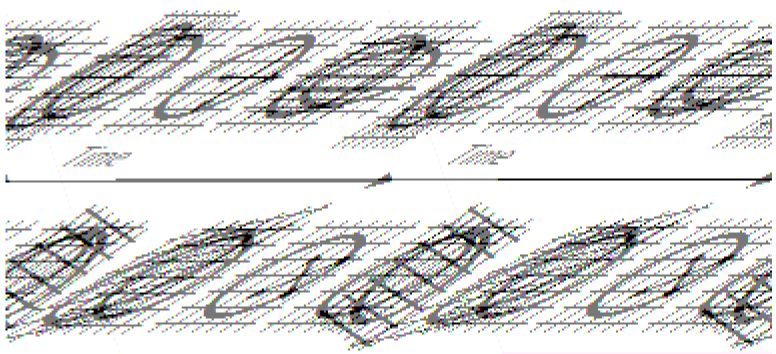
S5 Goals

- *"Collect at least a year's data of coincident operation at the science goal sensitivity"*
- Expect S5 to last about 1.5 yrs
- 4K ~ 10Mpc
- 2K ~ 5Mpc
- Range:
  - Sky-averaged NS/NS inspiral at SNR 8

Run	*S2*	*S3*	*S4*	*S5 Target*
L1	37%	22%	75%	85%
H1	74%	69%	81%	85%
H2	58%	63%	81%	85%
3-way	22%	16%	57%	70%

Gravitational Waves

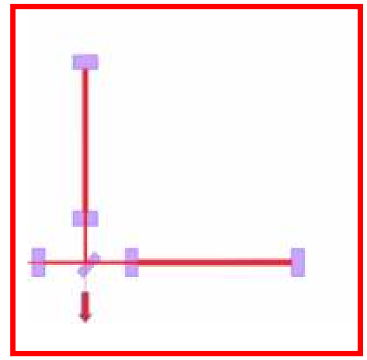
- Field:
  - Distortions of space-time
  - Massless (v=light speed)
  - Spin 2 symmetry,
    but only 2 polarizations ("plus" and "cross")
- Effect:
  - Stretches/contracts space perpendicular to propagation



"Plus"

"Cross"

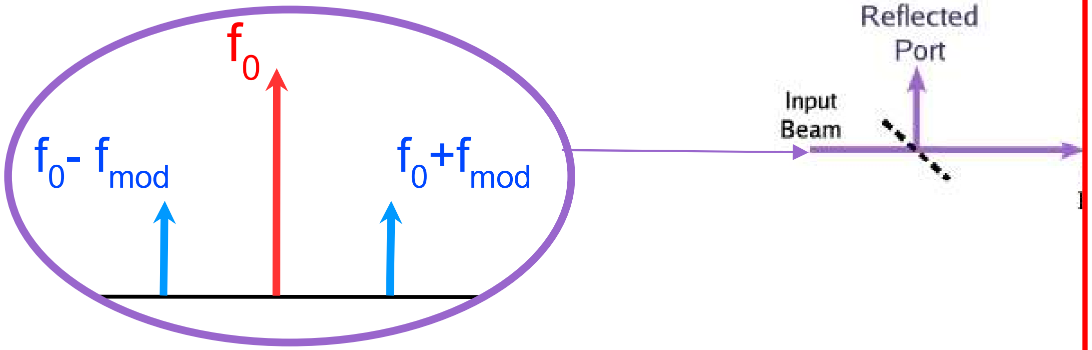
Image credit: Google

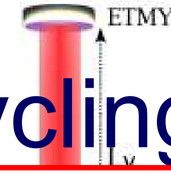


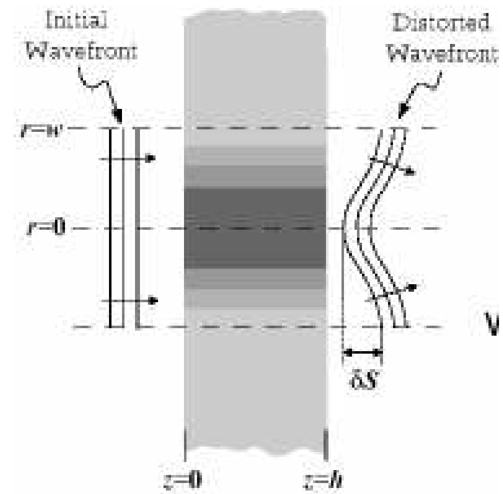
Amplitude:

dL/L = h/2

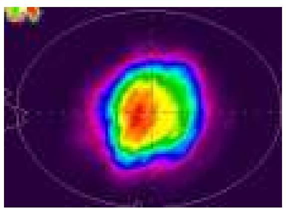
Thermal Lens in Recycling Cavity



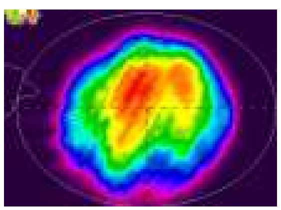




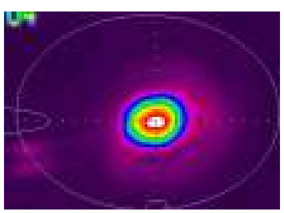
Thermal lens in ITMs



Carrier (defined by arms)



Sideband COLD



Sideband HOT

Output Signal, AS_Q proportional to field overlap
Strain Signal ~ CR_{00} * SB_{00}

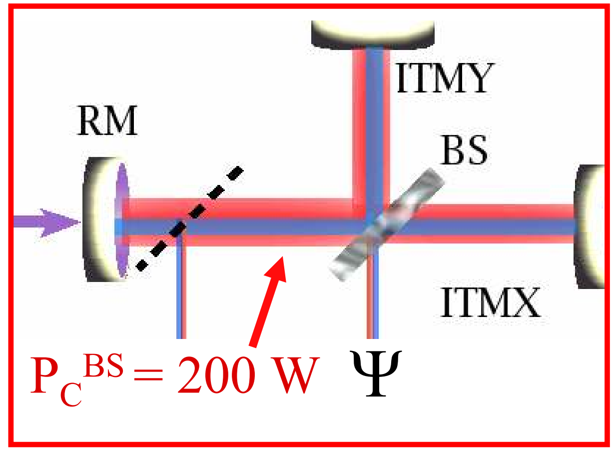
Shot Noise doesn't care about overlap
Strain noise ~ $(CR^2 + 3 * SB^2)^{1/2}$

Phase Sensitivity (RF readout)

- Field at dark port: $\Psi = A_{SB} \sin \omega_m t + (A_C^{BS} \sin \delta\phi)$

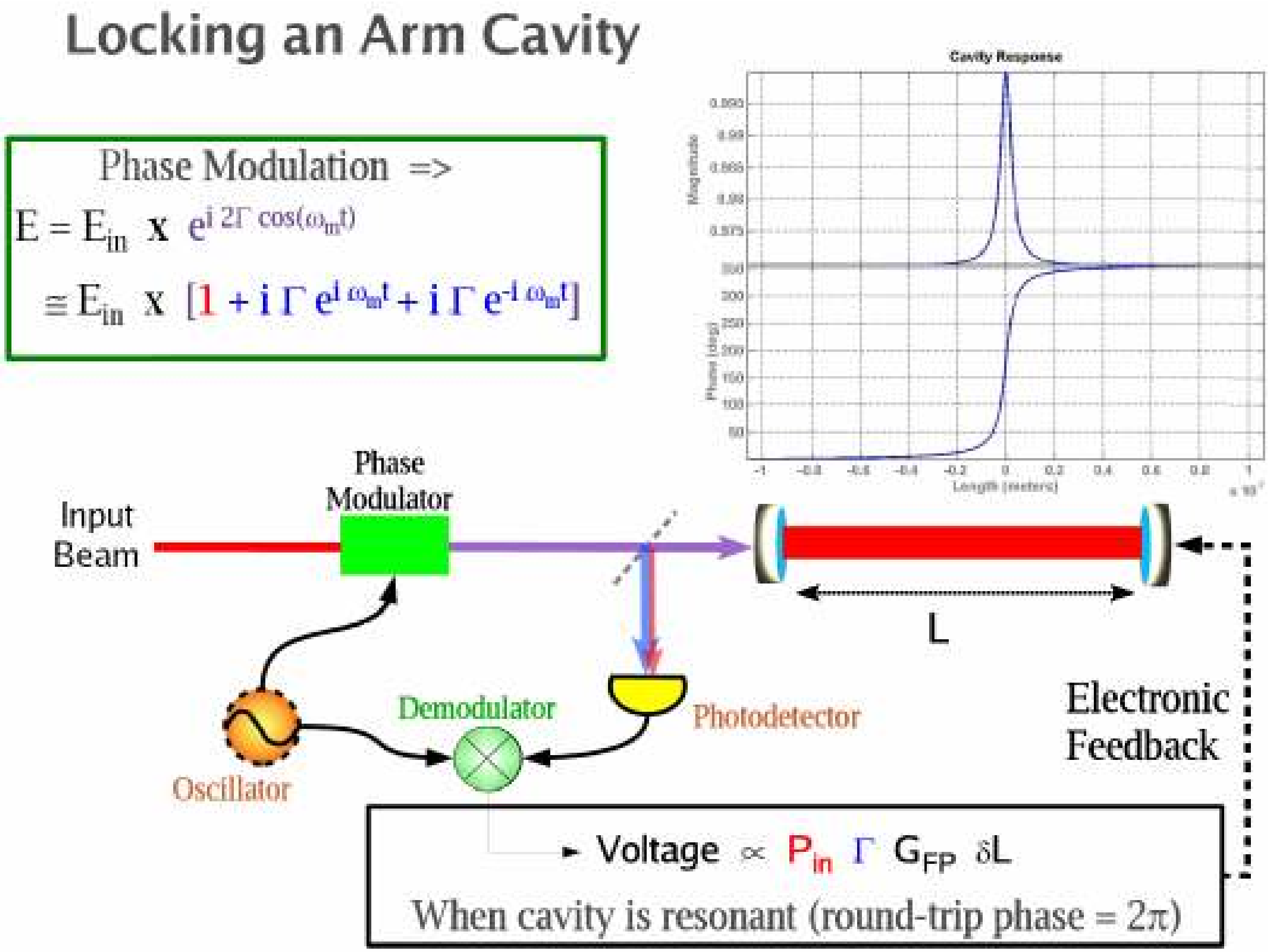
→Signal at ω_m: $\delta P_{\omega_m} = 2 A_C^{BS} A_S \delta\phi$

→Shot noise: $S_P^{shot} \approx \sqrt{2 h \nu \frac{|A_S|^2}{2}}$

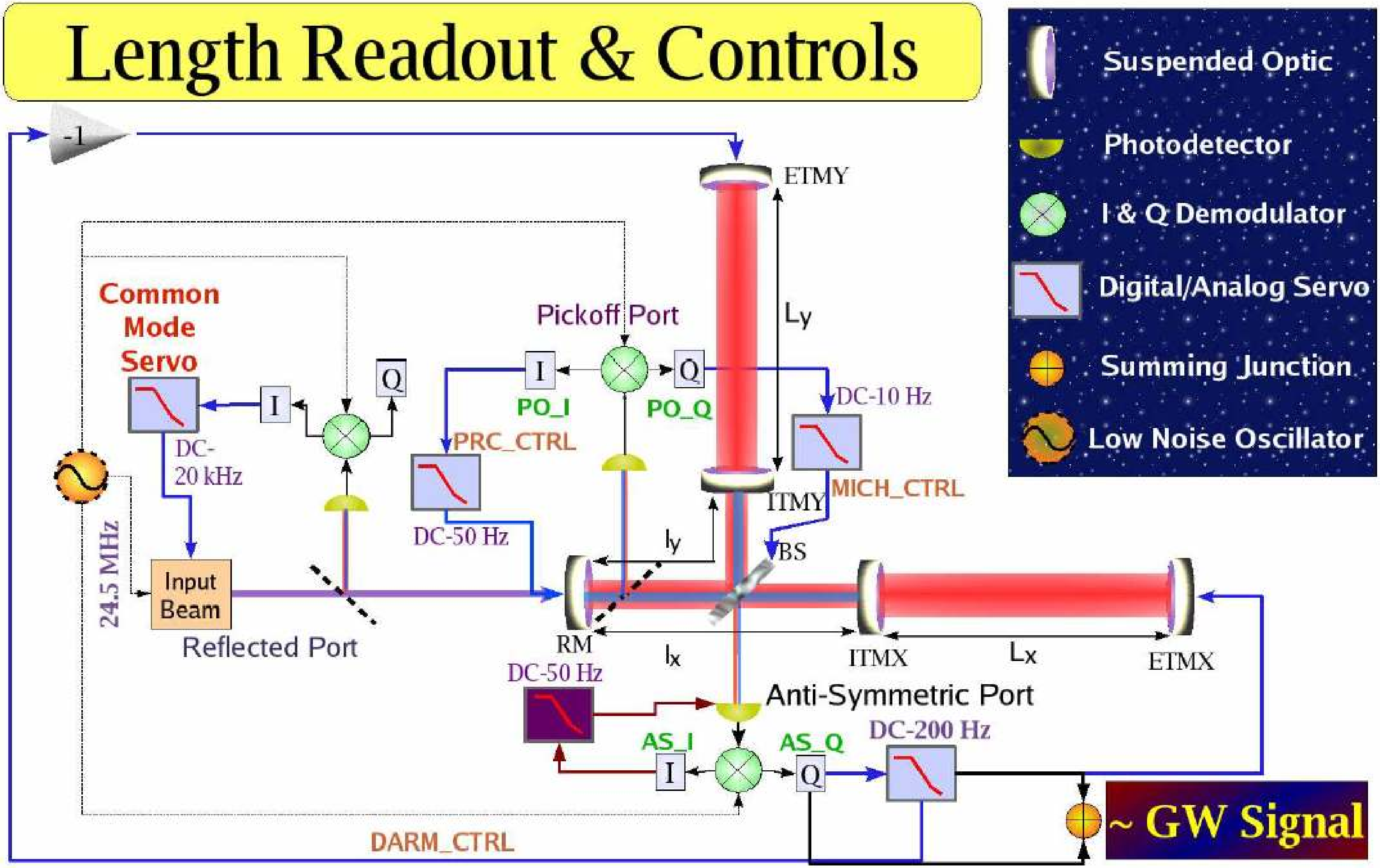


→Phase sensitivity: $\delta\phi_{shot} \approx \sqrt{\frac{h\nu}{4 P_C^{BS}}} \approx 1.5 \times 10^{-11} Hz^{-\frac{1}{2}}$

Locking a single cavity

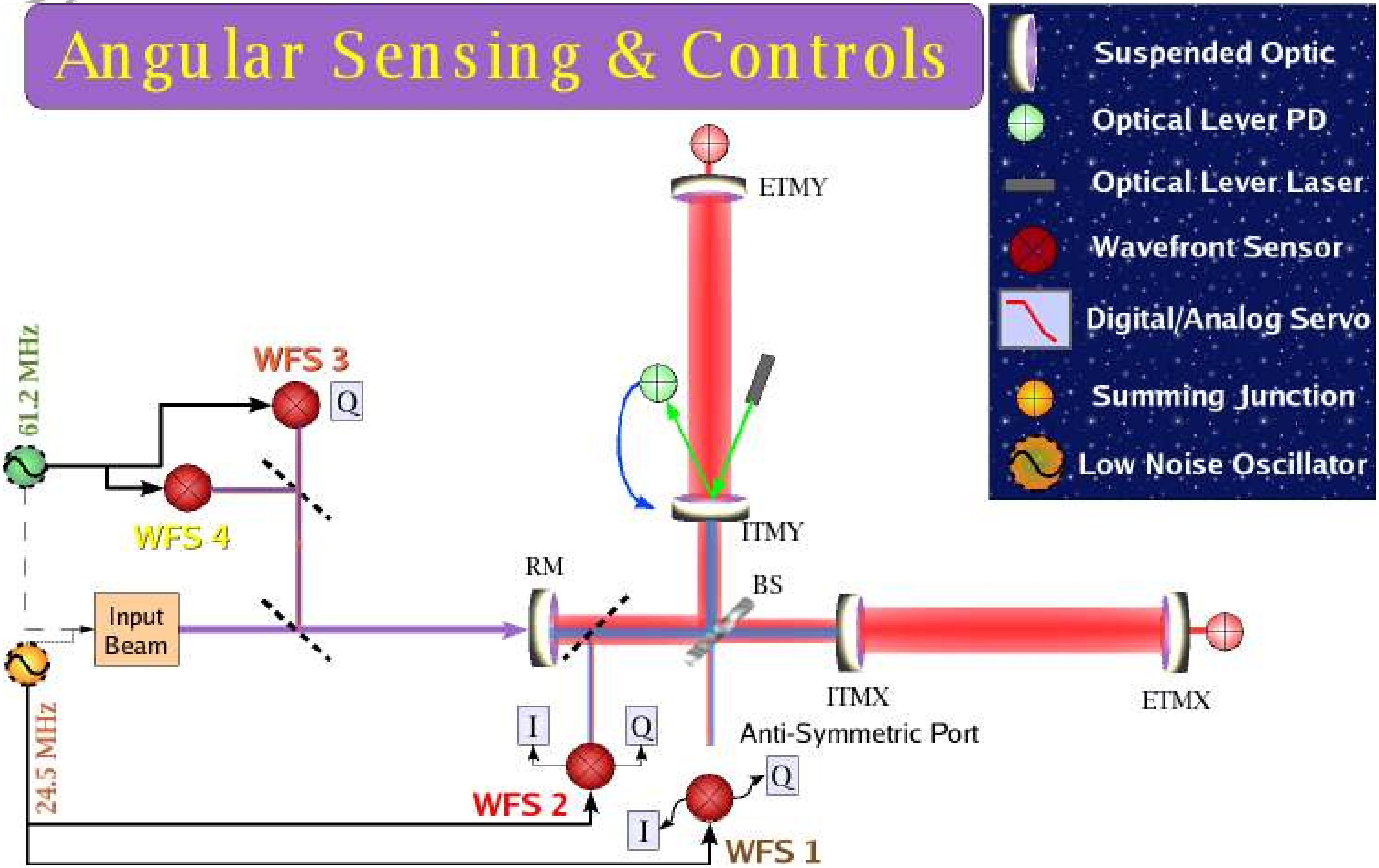


Length Readout & Controls



LIGO

Angular Sensing & Controls

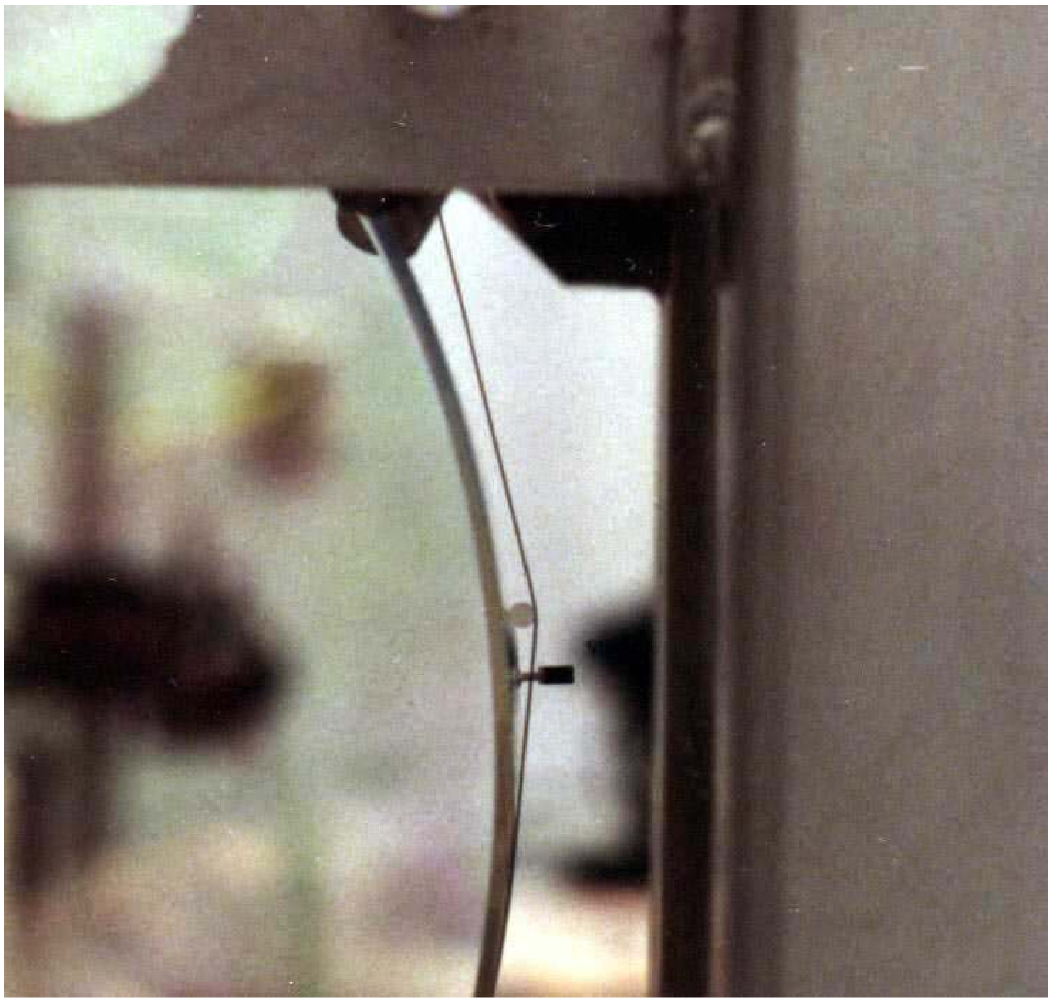


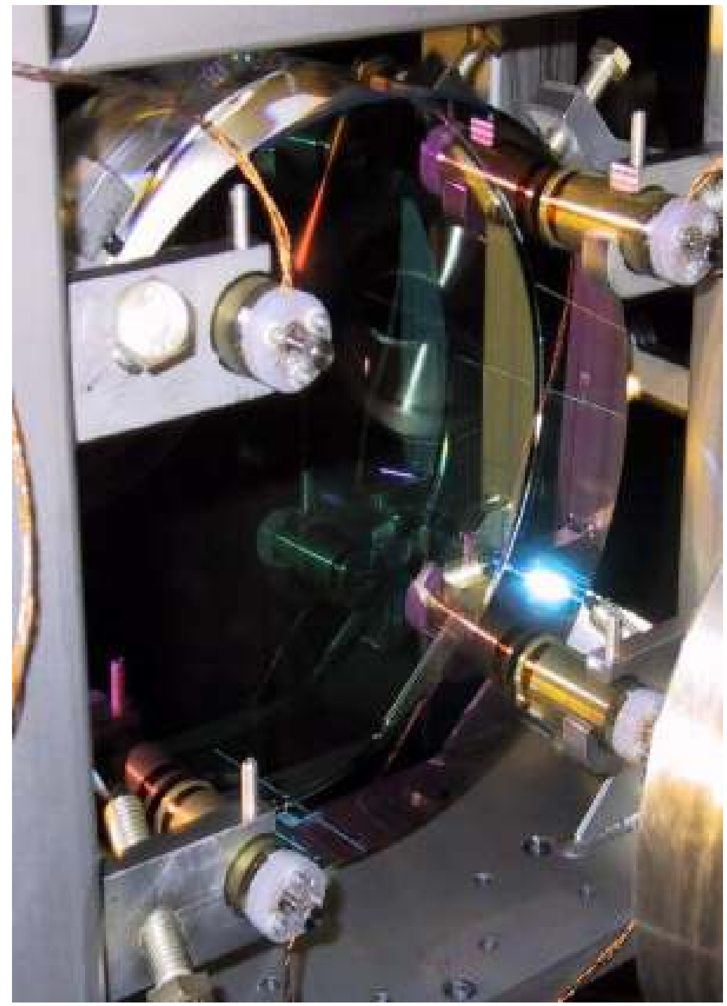
Seismic Isolation & Suspension

BSC8 Looking South. FMy at left, ITMy at right with COS Elliptical Baffle on AR/rear side.

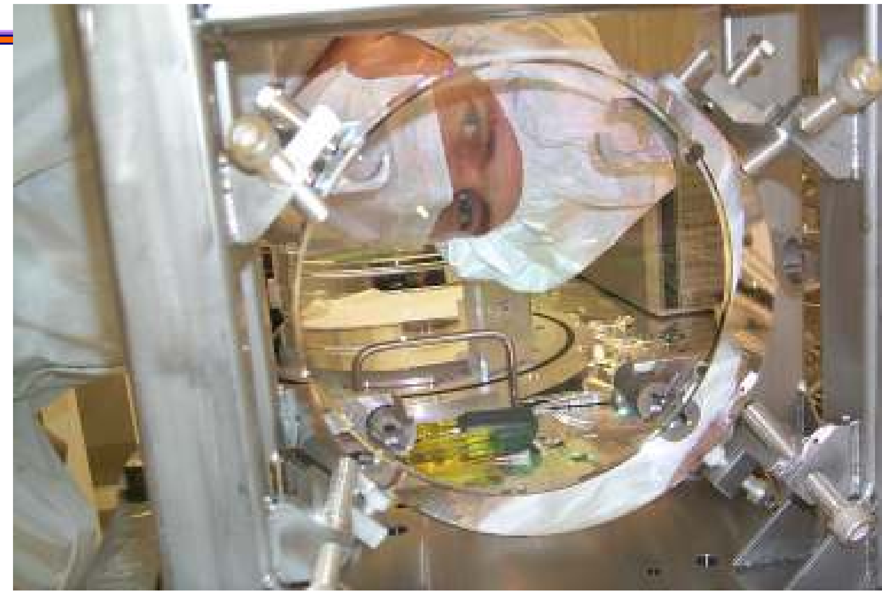
Vacuum “Envelope”

Optics





Optic Suspension



- Magnets and coils control position and angle of mirrors
- Suspension provides $1/f^2$ attenuation above the pendulum resonance ~0.75 Hz.
- Suspension is critical to controlling thermal noise.

Optics

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5 x 10^{-7}

Internal mode Q's > 2 x 10^{6}

Polishing

Accuracy < 1 nm

Micro-roughness < 0.1 nm

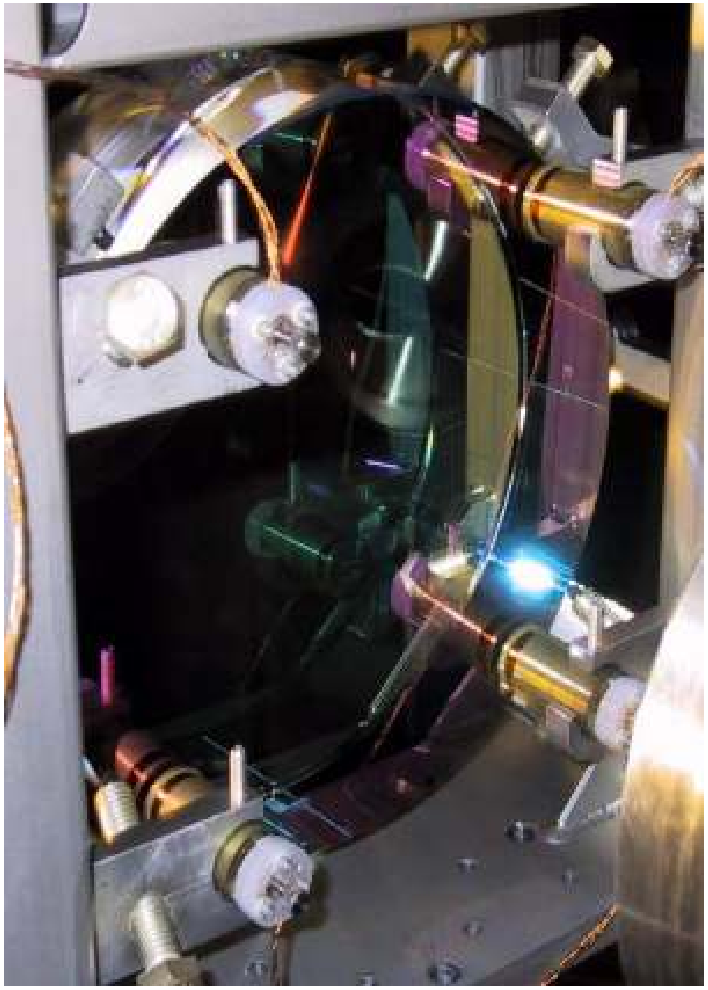
Radii of curvature matched < 3%

Coating

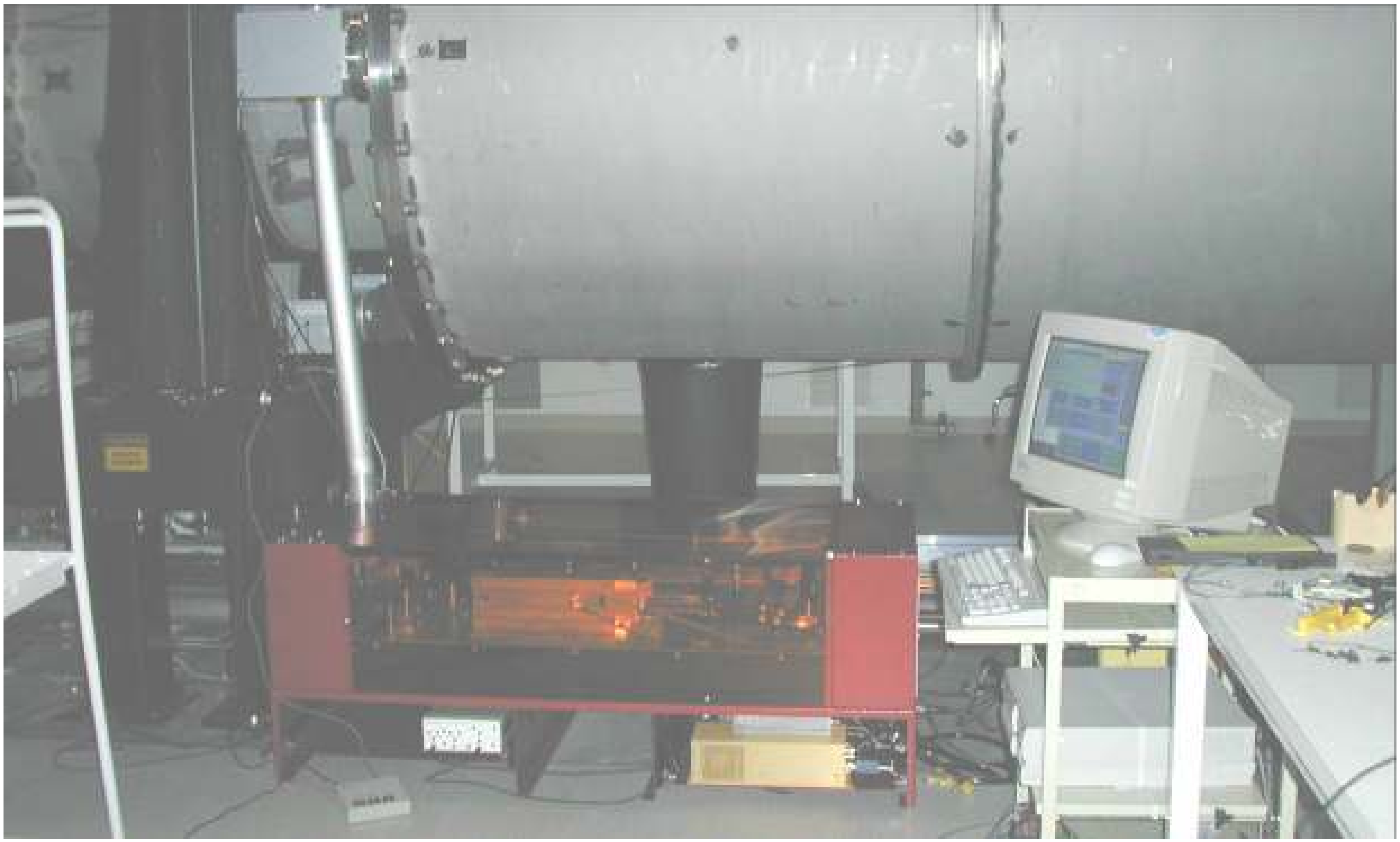
Scatter < 50 ppm

Absorption < 0.5 ppm

Uniformity <10^{-3} (~1 atom/layer)



The Hardware



H1 absorption measurement

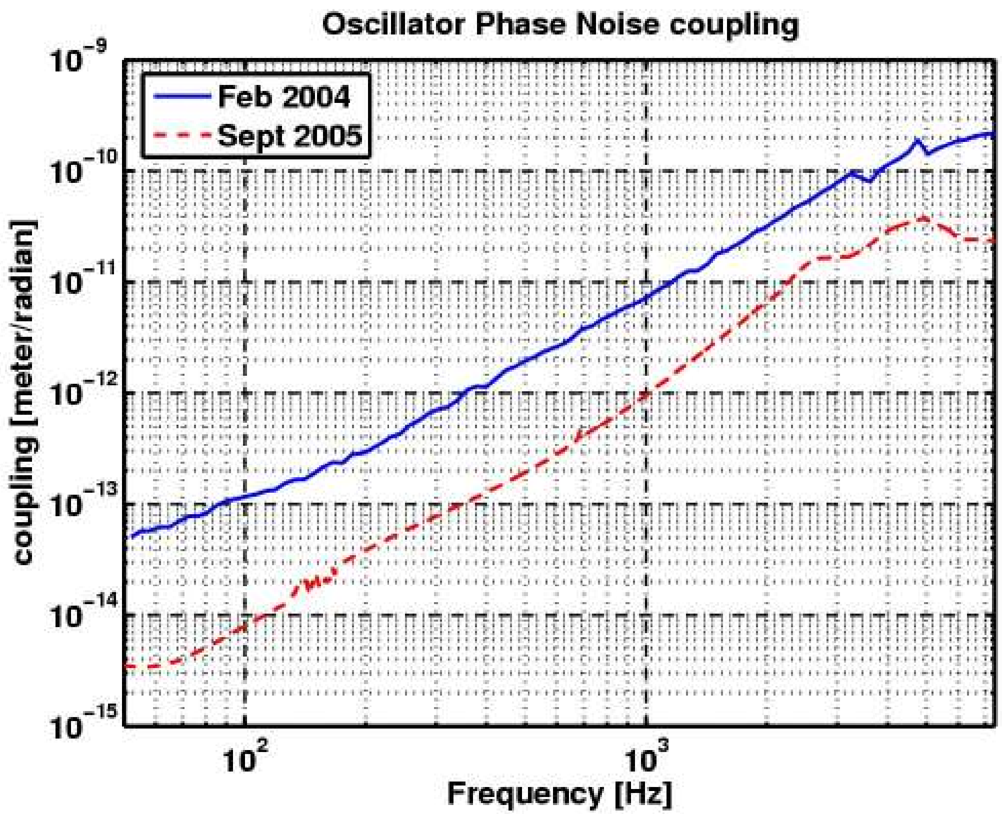
- ITMX coating: 15 ppm (nominal ~1ppm)
- ITMY coating: 5.5 ppm (“)
- RM and BS irrelevant

- On June 30 2005: Vacuum broken
  - ITMX replaced
  - ITMY drag-wiped

- Now both ITMs: <1.3 ppm coating absorption
  - TCS now run in central heating mode
  - still required for optimal Sideband recycling gain

Oscillator Phase Noise Coupling Reminder

- Facts from the last 3 years:
  - Notches at 3.3kHz and 5.5kHz are due to l=2 modes resonating in the arms
  - Pole lower than 4.5kHz (MC) and no big effect from MC pole compensation filter
  - High variability
    - Sensitive to differential TCS
    - Episode with L1 MC: x10 (!)
- Only MC and RC in the path
  - RC pole is: 71kHz (no ETM)
    48kHz (r_c=1)
    - This simple picture is wrong…



Double Cavity for SB

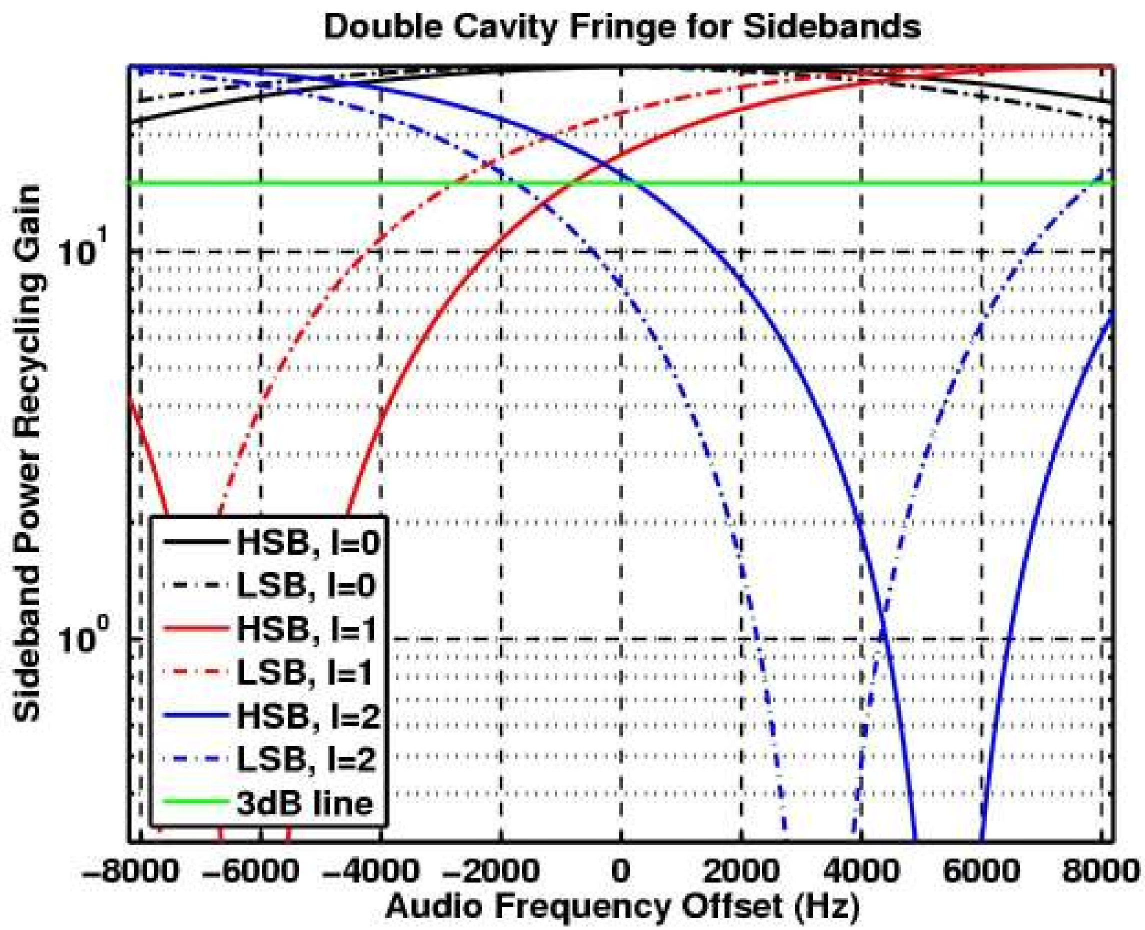
- RC round trip phase dominated by phase change of arm reflectivity

$$\phi_{RC}^{RT} = 2\pi \frac{f}{FSR} + \boxed{angle\left(r_c^l(f)\right)}$$

- Higher order modes (l>0) pick up additional frequency shift proportional to l x f_{TM}

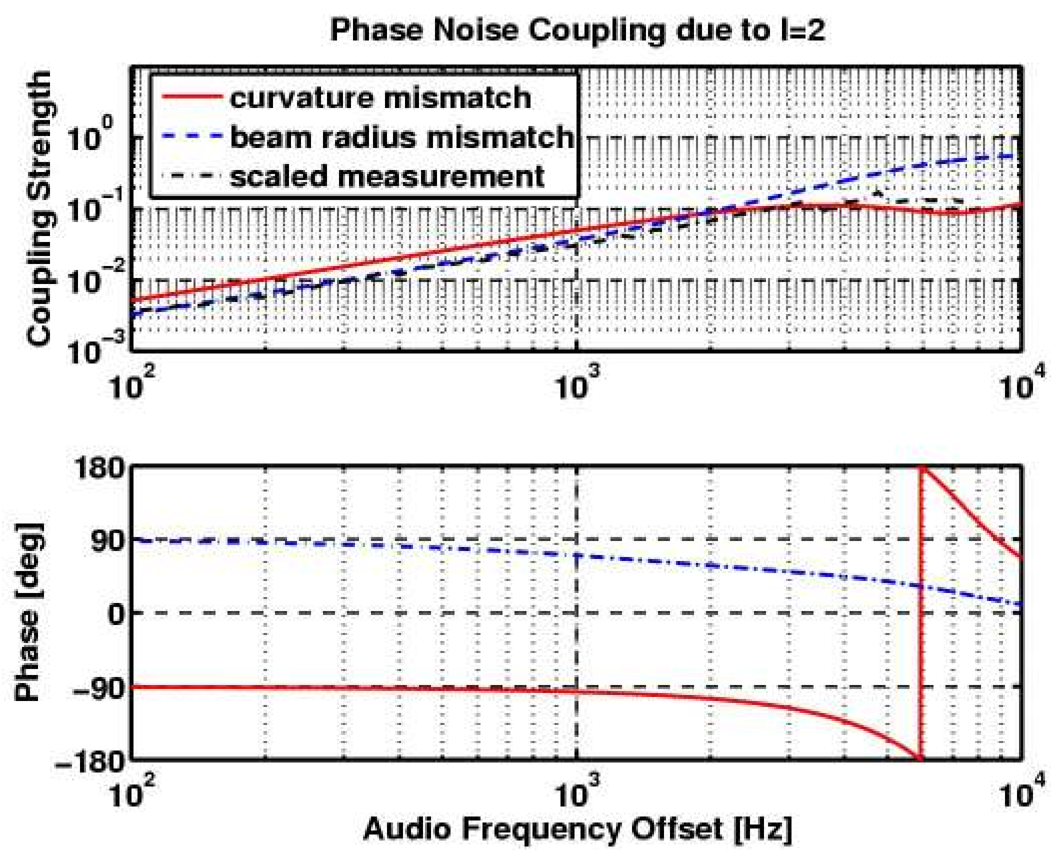
- RC pole: ~12kHz for l=0
  below that for l>0
  as low as ~3kHz for l=2

Double Cavity fringe for SB with l=0,1,2



Phase noise coupling for l=2

- Significant contribution from l=1 and l=2
- For l>0:
  - Residual carrier can exist in both quadratures
  - For l=2: "curvature mismatch"
    "beam size mismatch"
  - Different contributions can interfere
- Shown coupling for l=2 only (MC pole included)



The Math

SB recycling gain:

$$f_{TM} = \frac{\mathrm{FSR}}{\pi}\mathrm{acos}\left((1 - L/\mathrm{RoC}_{ITM})^{\frac{1}{2}}(1 - L/\mathrm{RoC}_{ETM})^{\frac{1}{2}}\right)$$

$$\phi = 2\pi\frac{f \pm f_{SB} - (l \times f_{TM})}{\mathrm{FSR}}$$

$$r_c = \left(-\frac{T_{ITM}\sqrt{R_{ETM}}e^{i\phi}}{1 - \sqrt{R_{ITM}R_{ETM}}e^{i\phi}} + \sqrt{R_{ITM}}\right)$$

$$\phi_{RC} = 2\pi\frac{f \pm f_{SB}}{\mathrm{FSR}_{RC}} + \pi$$

$$g_{sb} = \frac{\sqrt{T_{RM}}}{1 - \sqrt{R_{RM}}r_M r_c e^{i\phi_{RC}}}.$$

Osc. Phase noise:

$$\propto [\mathrm{Carrier}]^* \left[(+g_{sb}^{-f_{SB}-f} + g_{sb}^{-f_{SB}+f} - g_{sb}^{+f_{SB}-f} - g_{sb}^{+f_{SB}+f} - 2 * g_{sb}^{-f_{SB}} + 2 * g_{sb}^{+f_{SB}}) + i(+g_{sb}^{-f_{SB}-f} - g_{sb}^{-f_{SB}+f} - g_{sb}^{+f_{SB}-f} + g_{sb}^{+f_{SB}+f})\right].$$