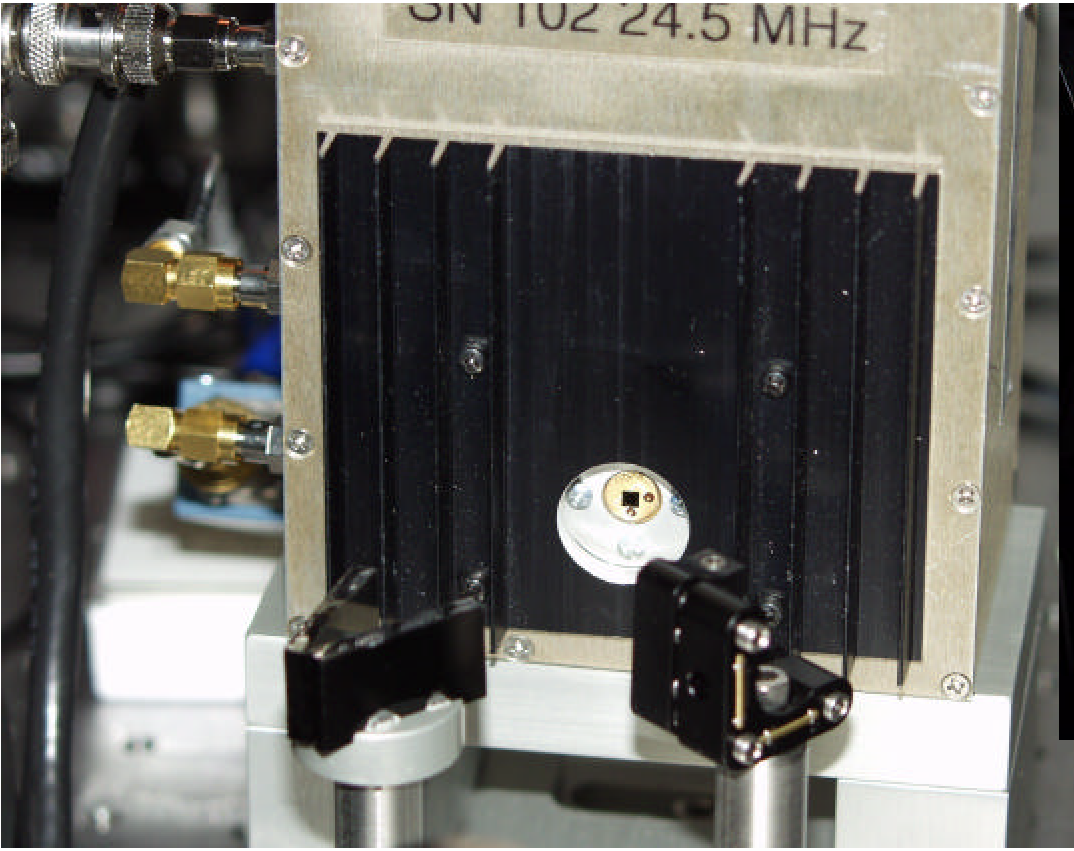
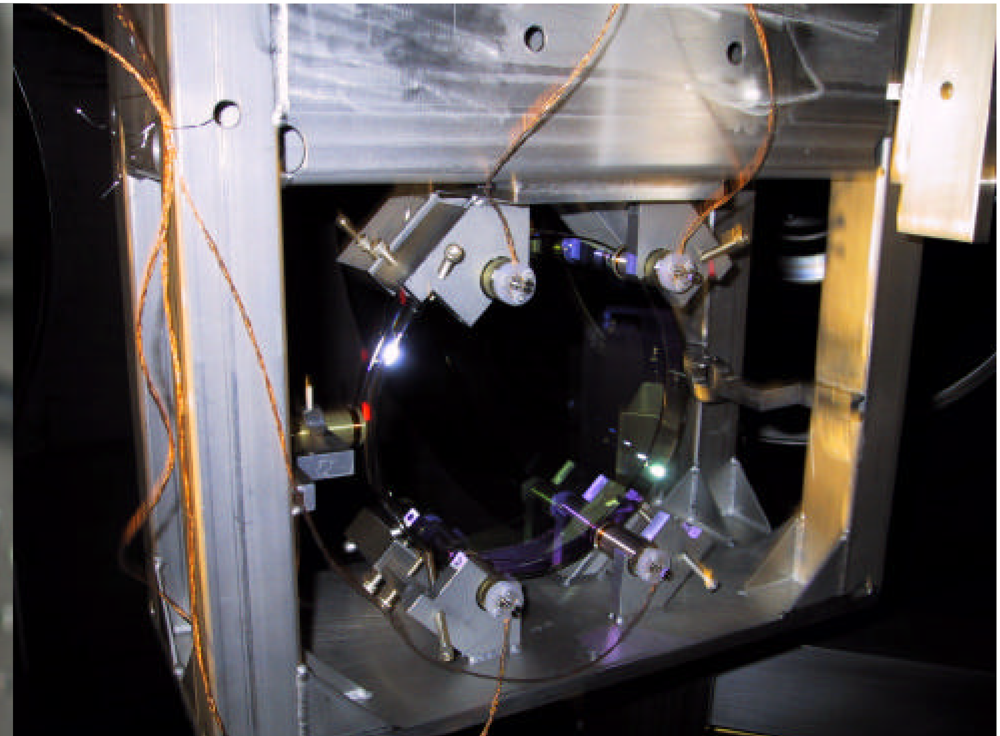
LIGO- I:
Breaking the Sensitivity Barrier





March 2nd, 2004
Rana Adhikari
MIT

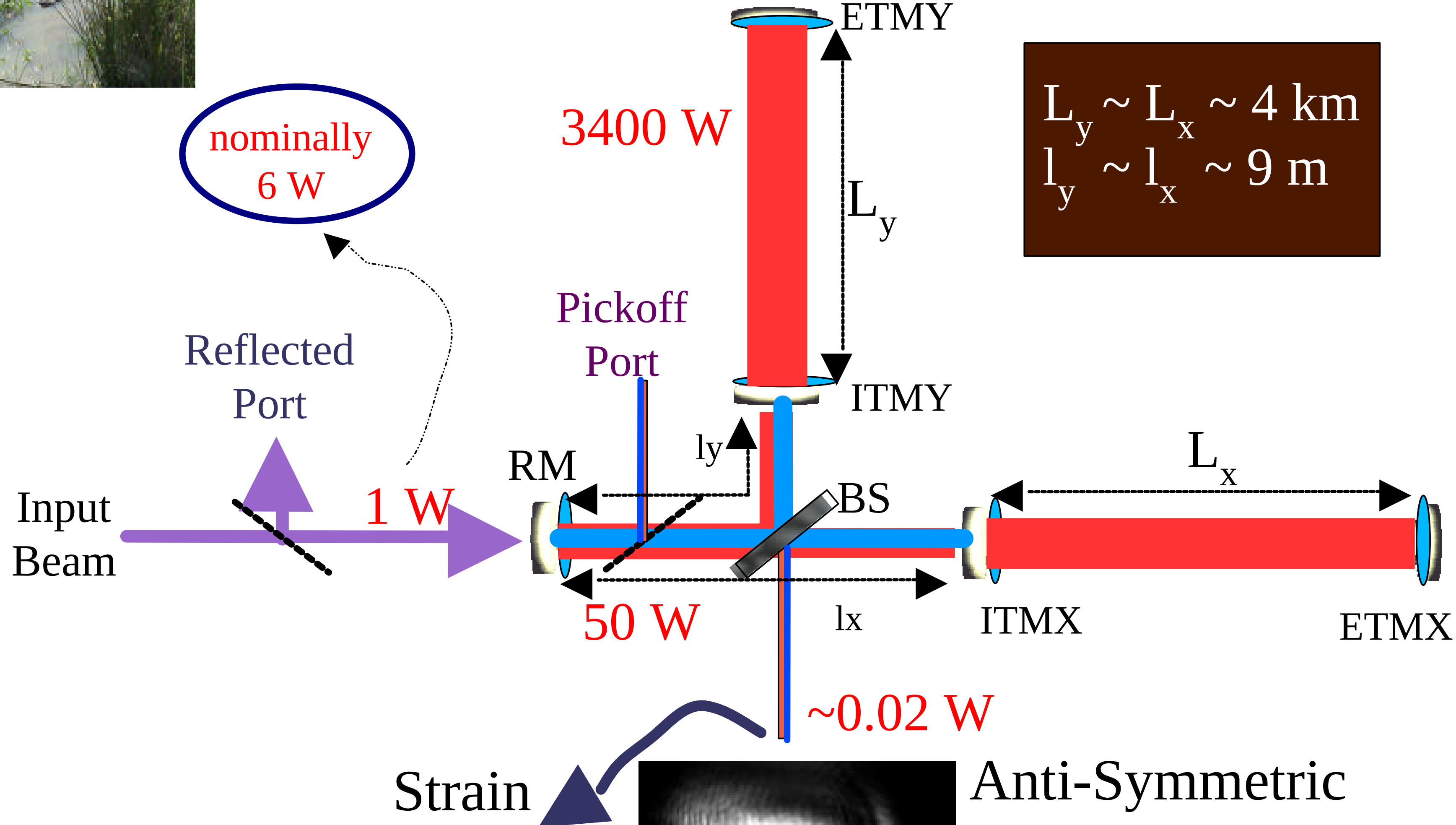
LIGO-G040557-00-D

OUTLINE

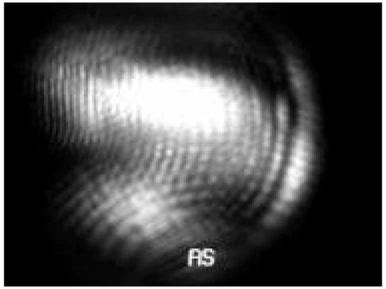
- What is the noise in the interferometers now?
- *Where does the SRD Curve come from?*
- What we know about the 'fundamental' noises.
- **Can we ever reach the SRD ?**
- What do we do about it?

The INTERFEROMETER

$L_y \sim L_x \sim 4$ km
$l_y \sim l_x \sim 9$ m



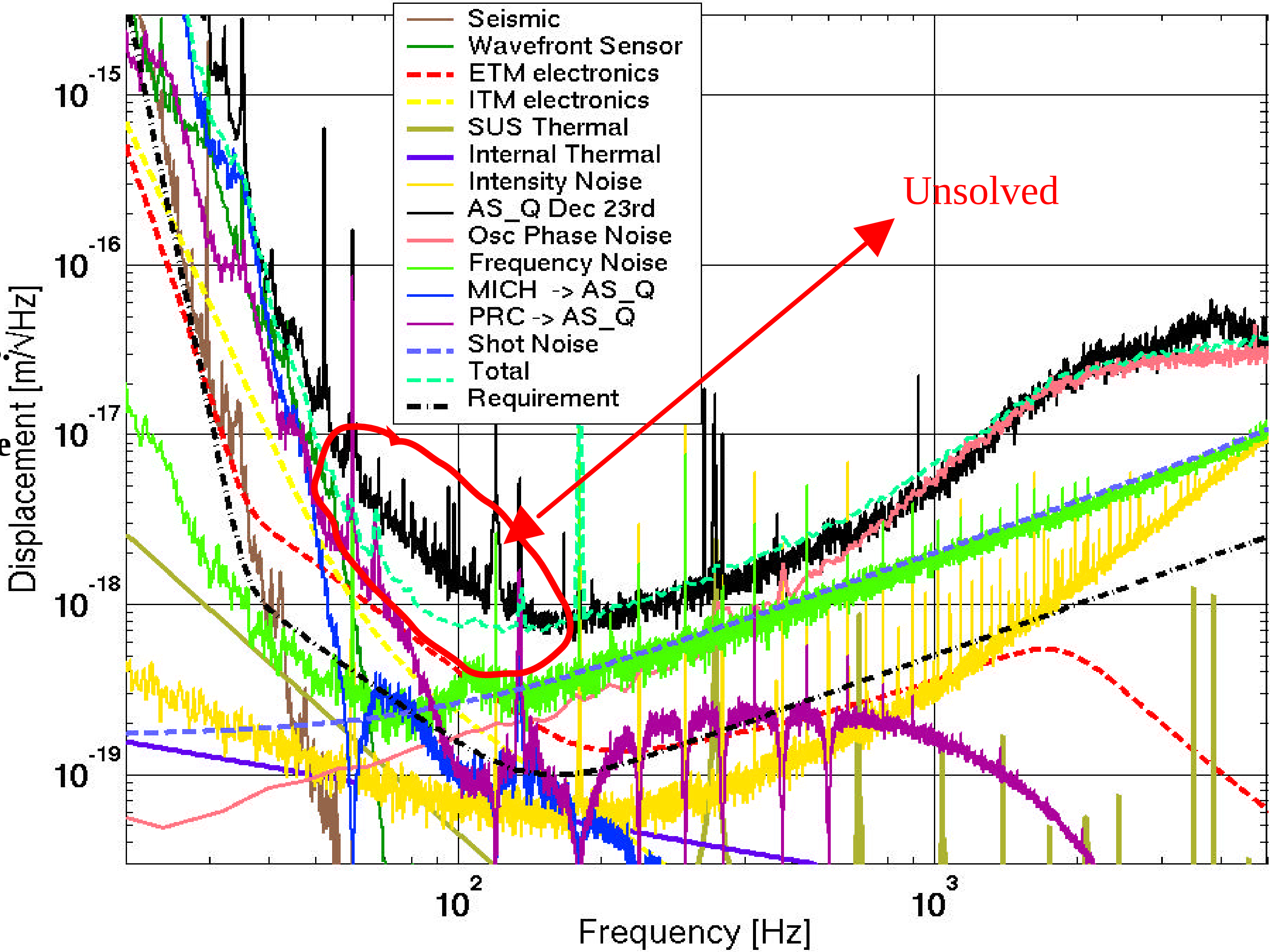
Strain
Readout
(AS_Q)
? $(L_y - L_x)$



Anti-Symmetric
Port

The Noise in Livingston

- ~10X higher than design...
- ~10^5 X lower than a few years ago.
- Most of the noise is explained by the models.
- Plans are in place to reduce each noise source above SRD.



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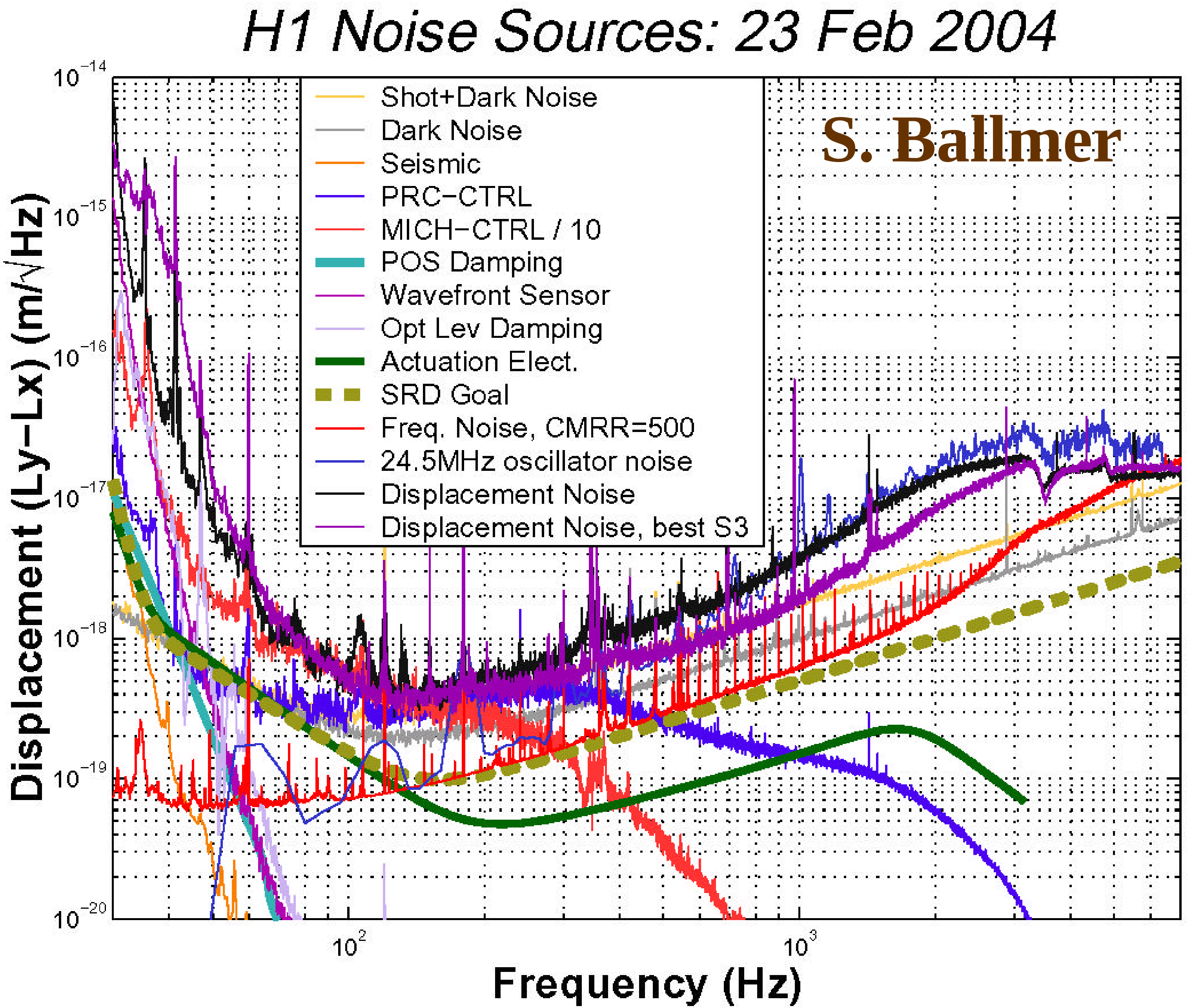


Science Requirements Doc:
The LIGO-I Sensitivity Goal

Seismic:

“Standard” spectrum

h(f) µ f^{-2}

filtered by an isolation stack and a 1 Hz pendulum

Suspension Thermal:

Viscously damped harmonic oscillator:

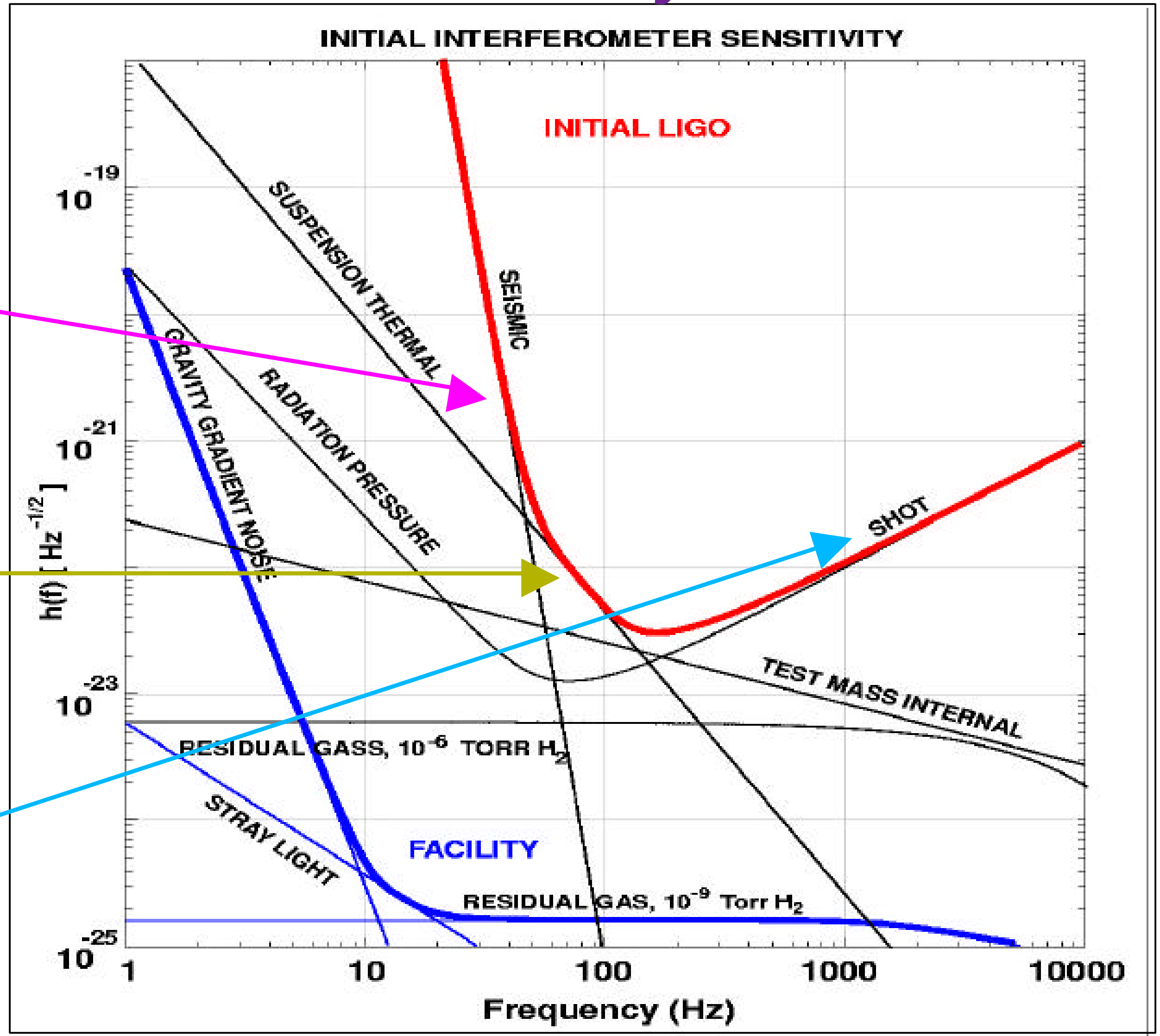
h(f) µ f^{-2}

Shot Noise:

'Mediocre' optics give:

- Recycling gain ~ 30
- Contrast ~ 3 x 10^{-3}

h(f) µ f^{-1}

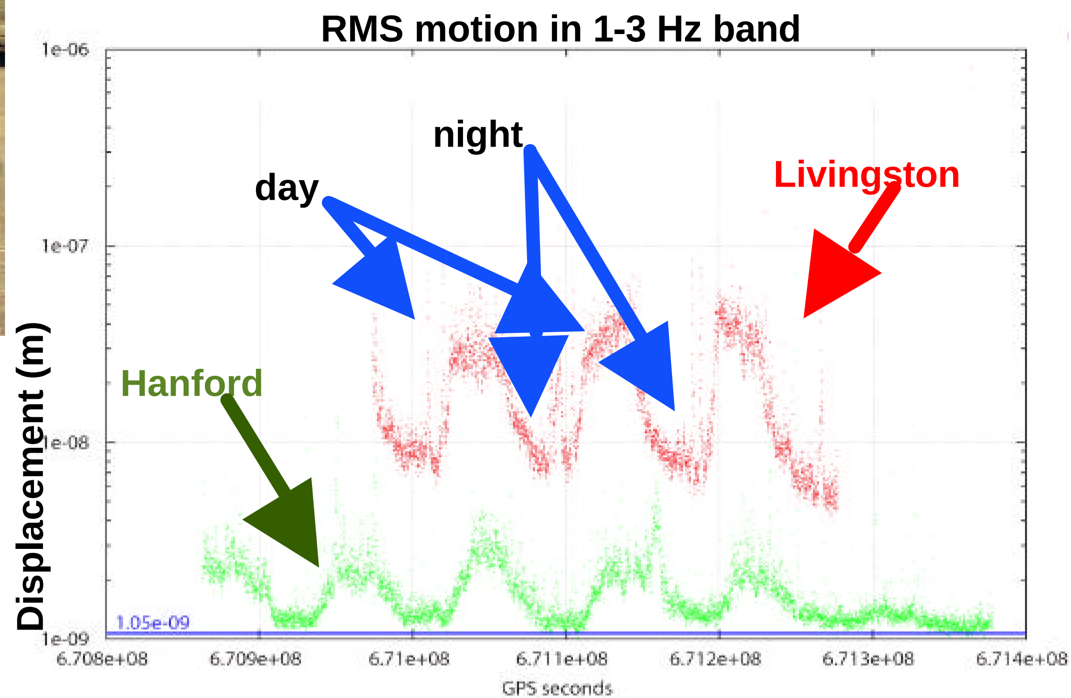


Seismic Noise

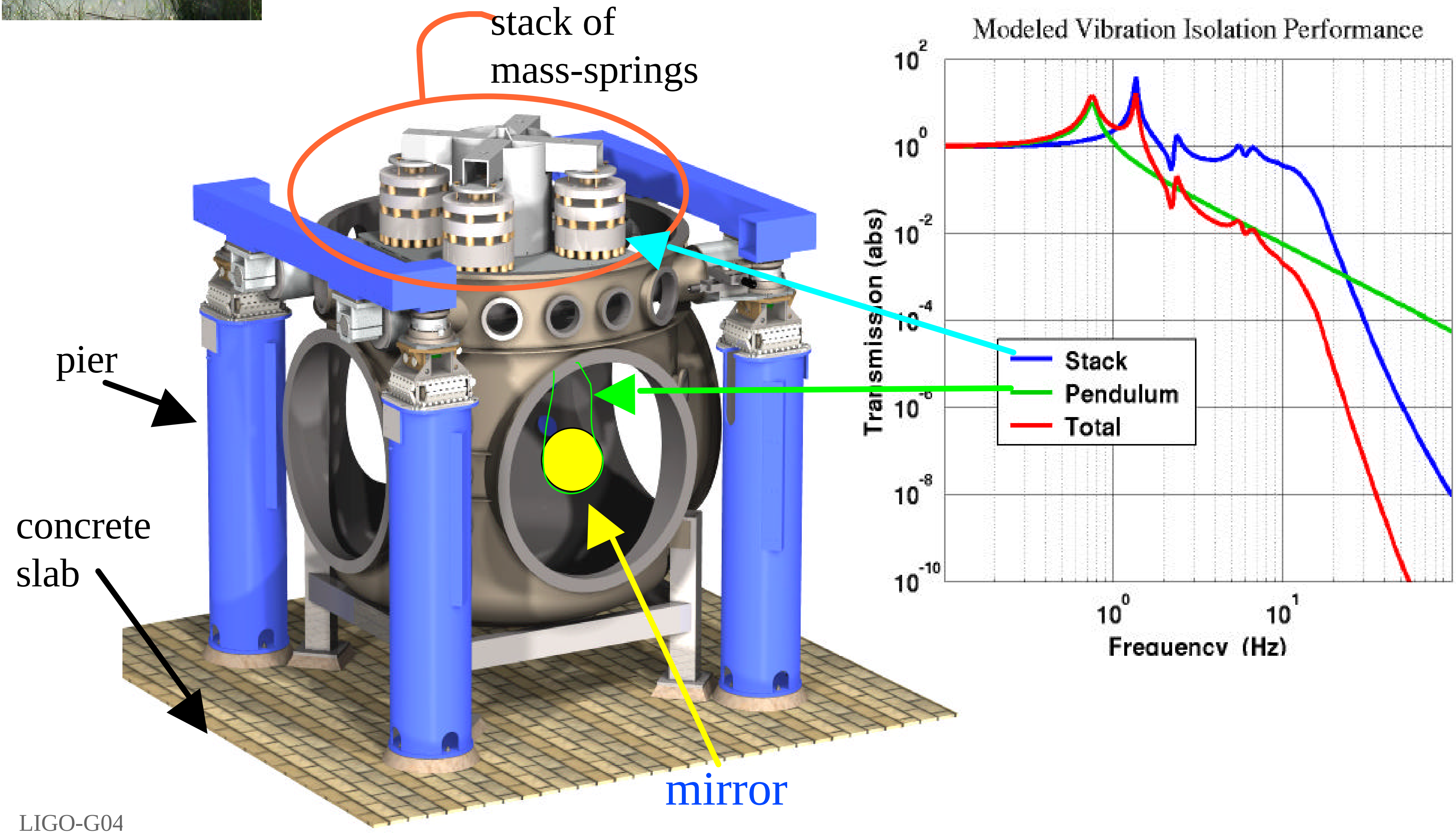
Large day/night variability due mostly to noise made by people:
-- Logging
-- Traffic
-- Construction

Seismic noise in GW band is mostly independent of human activity.

Variability is mostly for f < 10 Hz

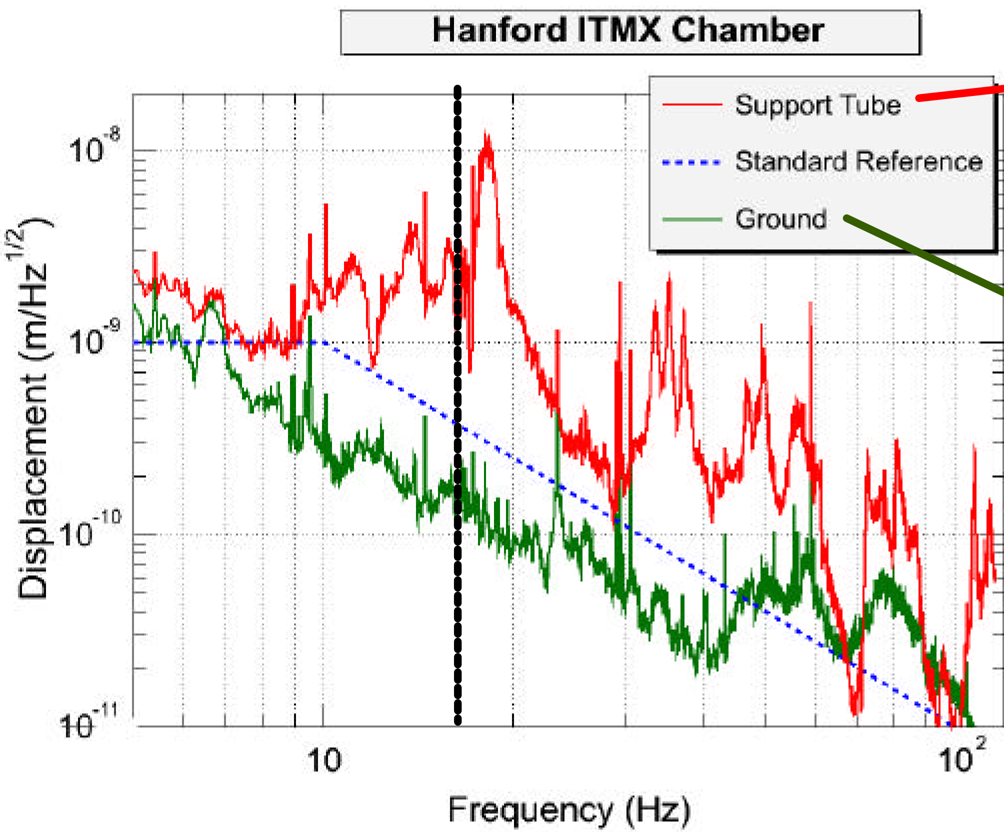


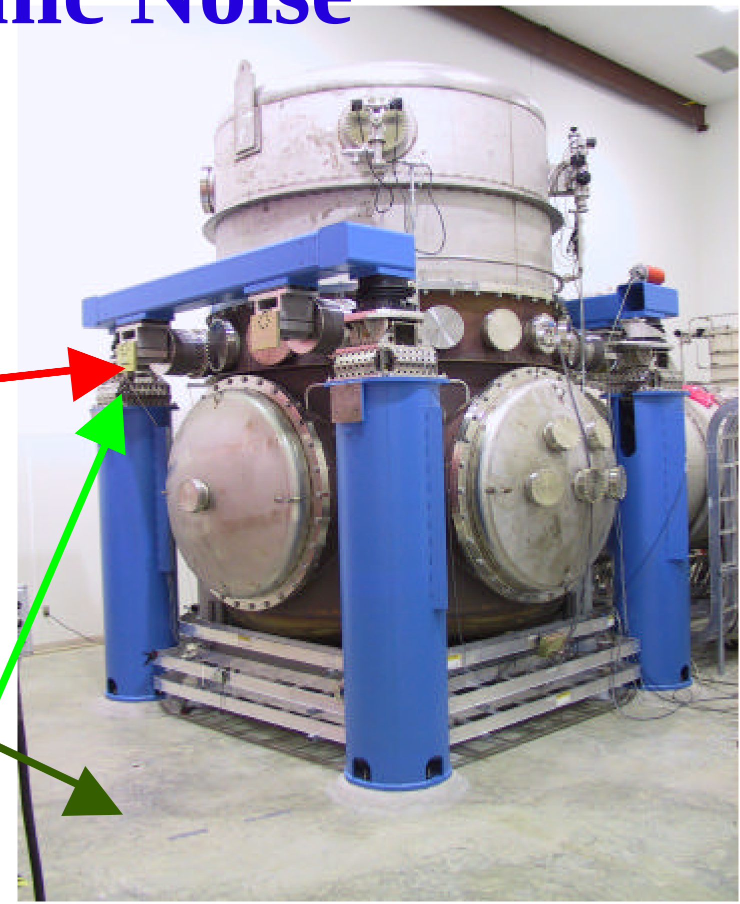
Seismic Noise



Measurements:
Seismic Noise

- **Ground noise is higher than expected.**
- **0.1 < f < 4 Hz excess @ LLO: Hydraulic Pre-Isolator**
- **f > 5 Hz narrow features from HVAC at both sites. Being investigated at LHO.**



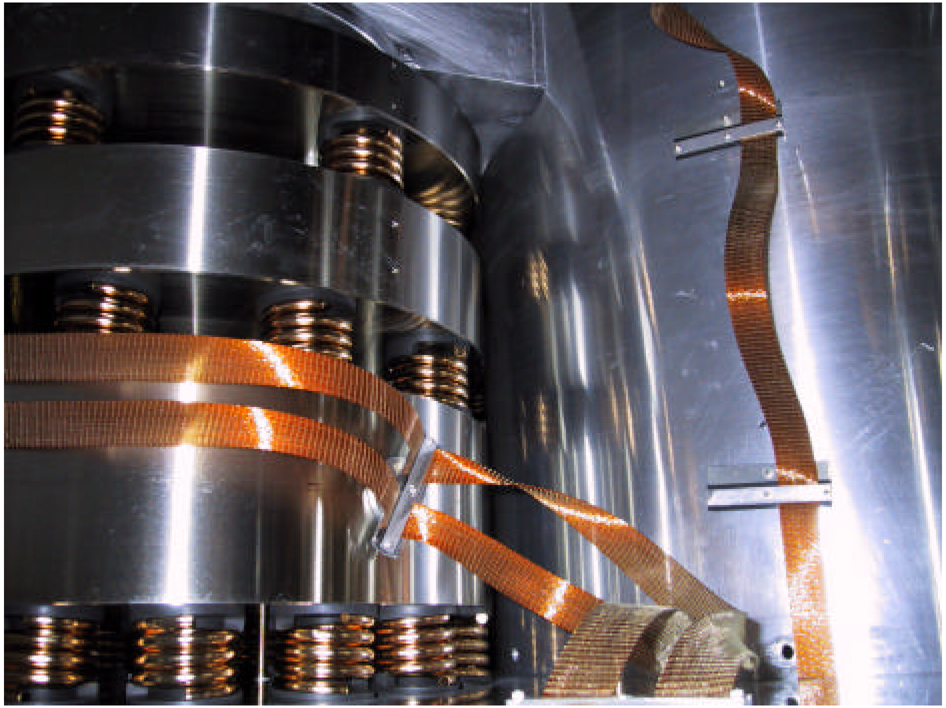


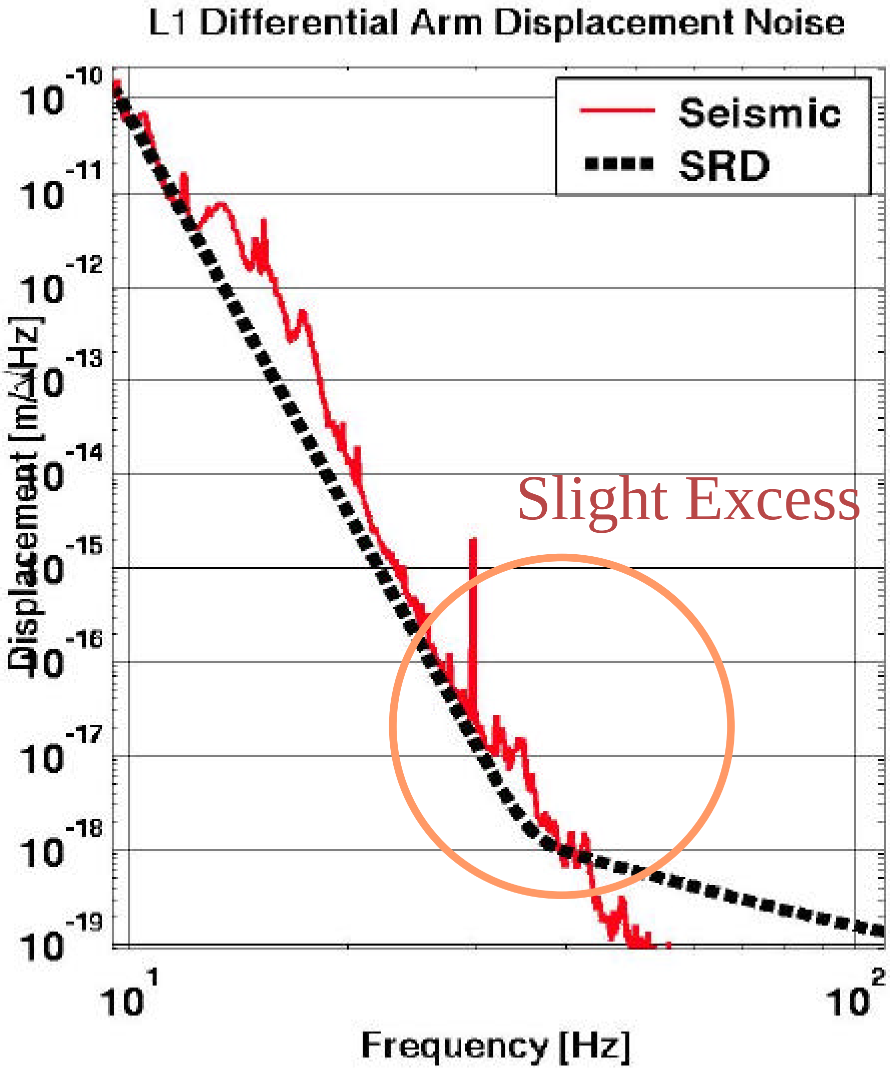
Accelerometers at the top of the piers are **<u>10-100x</u>** noisier than the ground at some frequencies from 10-100 Hz!

Studies at LASTI say that its mostly tilt. Could also be partly acoustic above 30 Hz.

Measurements:
Seismic Noise

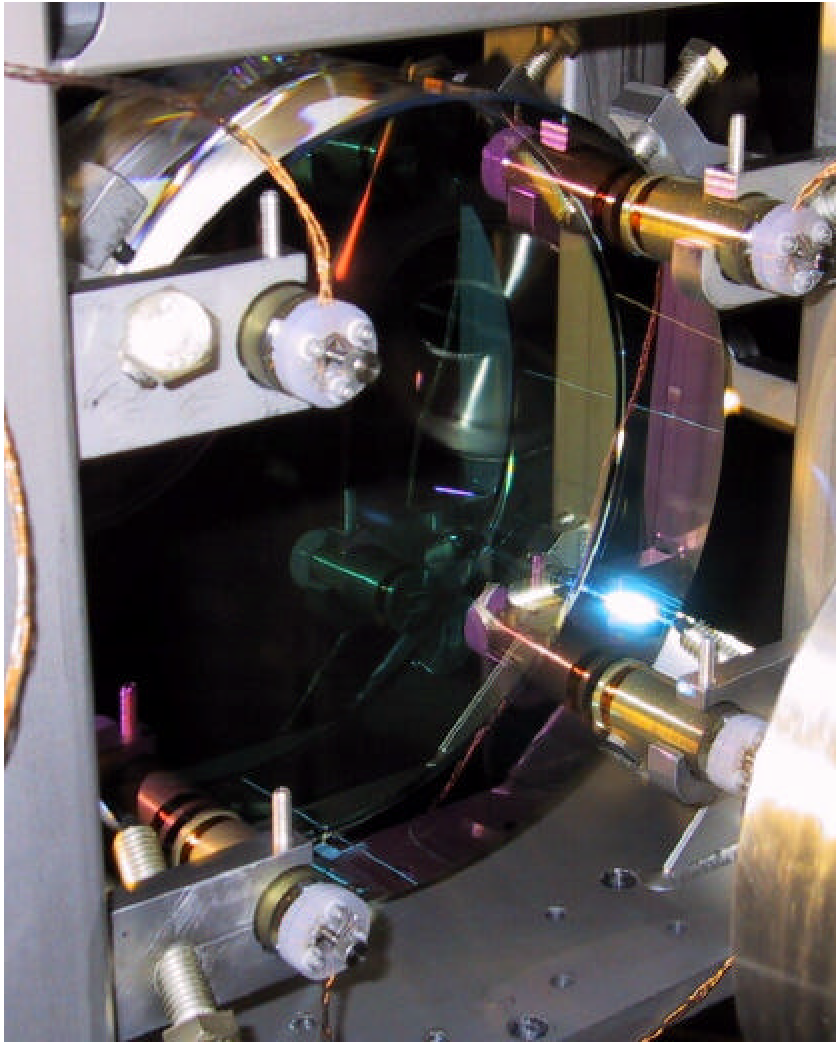
- Take measurements at the top of the piers.
- Use the Hytec BSC model and the locally damped suspension model to get the TF.





Test Mass Thermal Noise I

Measurements:



- Need to know the loss angle in the mirror substrate and in the coating.
- Measure ~10 Q's on every test mass mirror.
- Use highest Q to set lower limit on internal loss of the fused silica substrate. Assumes coating loss does not contribute to the highest Q mode.
- Use energy ratios from Dennis' FEA voodoo to get the loss angle of the coating.
- Take loss angles of the substrate and coating, plugin to formula from A. Gretarsson's thesis to get test mass displacement
- Method verified by experiment --- *K. Numata, et al. PRL (2003)*
- **This method gives a lower strain noise than what's obtained by doing the traditional summation over normal modes.**

Details in Gregg Harry's March 2003 LSC Talk

Results: $\phi_{Substrate} < 1 \times 10^{-7}$

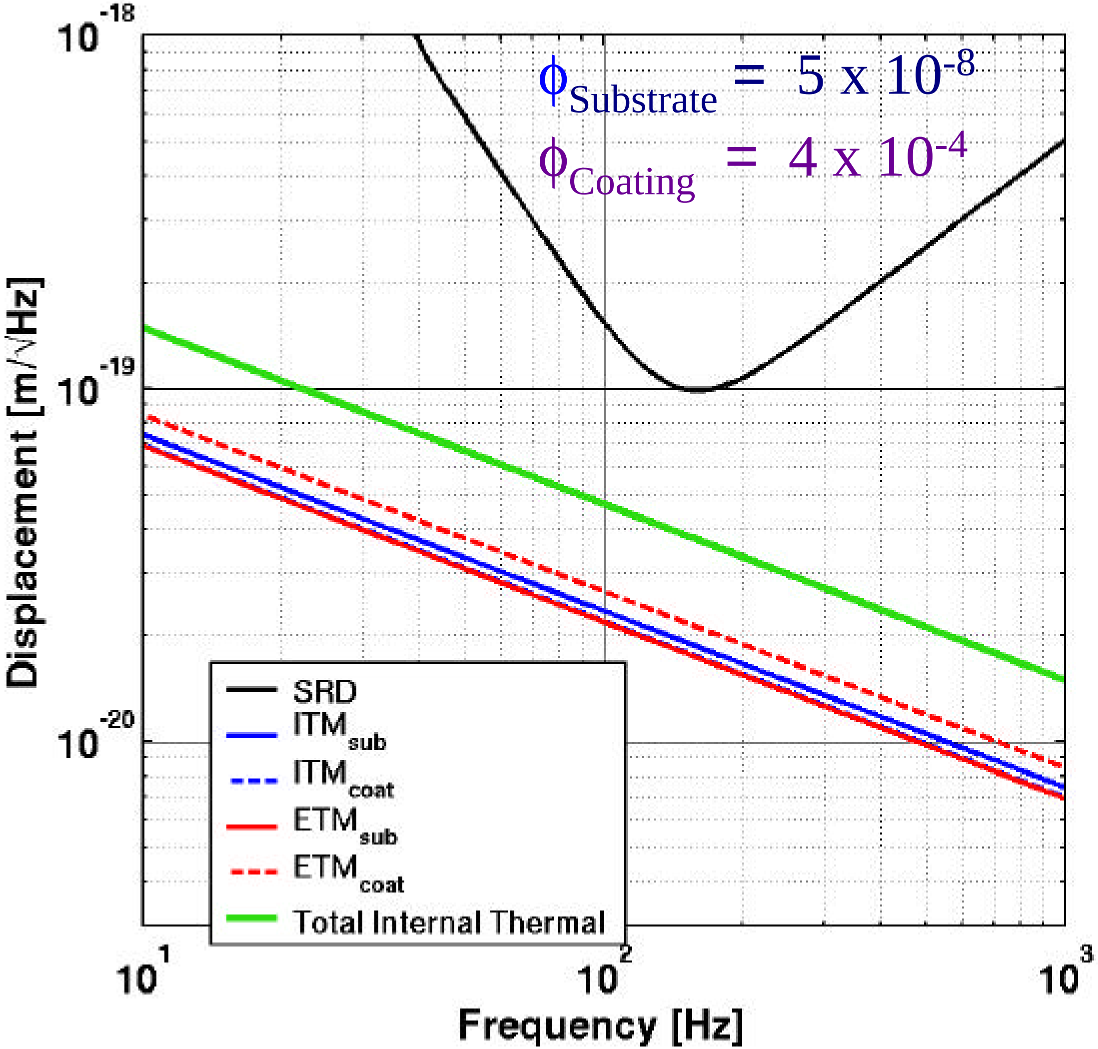
$\phi_{Coating} \sim< 4 \times 10^{-4}$

 LLO ETMY

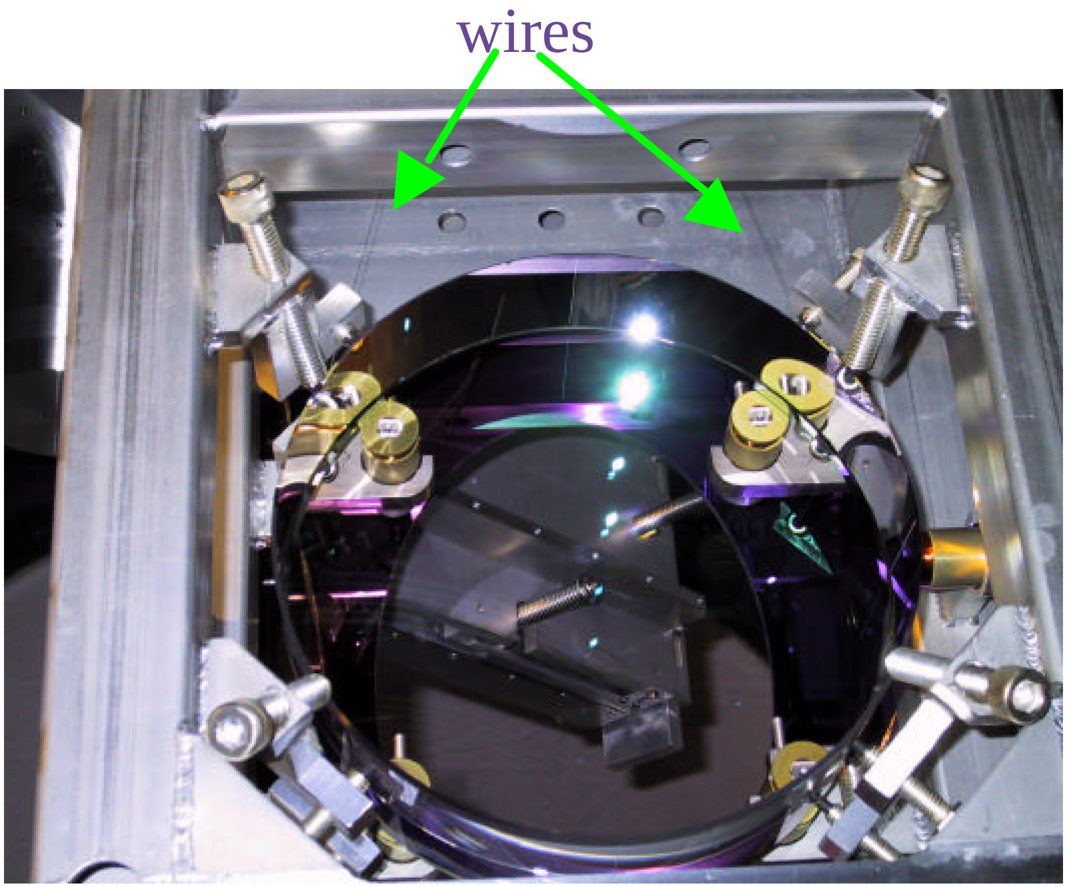
Test Mass Thermal Noise I

Predictions:

- Can calculate the thermal noise contributions from the substrate and coating separately.
- ETMs have twice as many coating layers as the ITMs.
- Beam is slightly bigger on the ETMs.
- $x_{coating}(f) \propto (\text{thickness})^{1/2} * (\text{spot size})^{-1}$
- $x_{substrate}(f) \propto (\text{spot size})^{-1/2}$
- ~2x **lower** than SRD estimate



Suspension Thermal Noise I
Not Viscous Damping

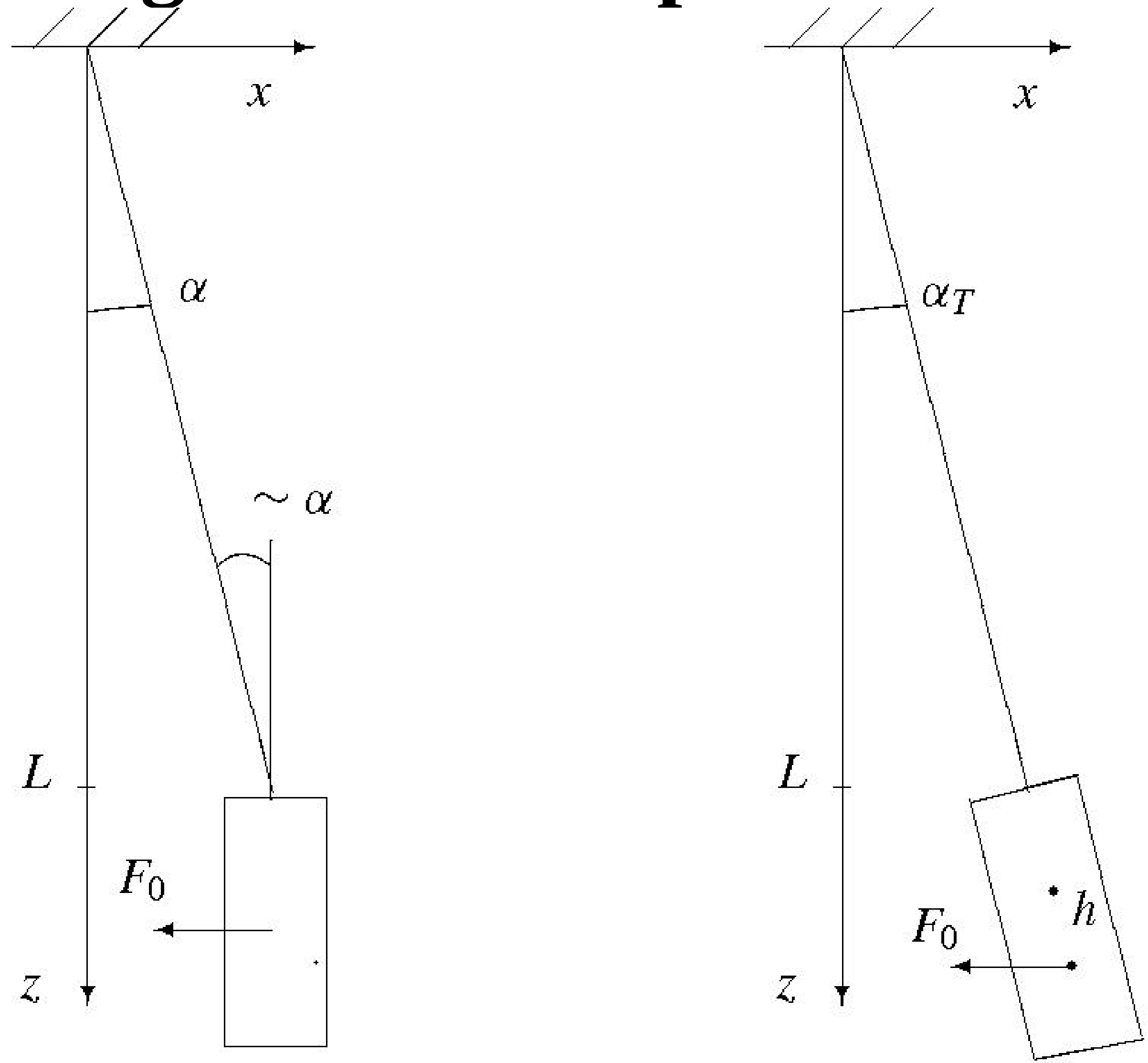


- SRD estimate assumed a viscously damped harmonic oscillator: $\mathbf{x(f)} \propto \mathbf{f^{-2}}$.
- We know now that its due to internal friction of the steel wire: $\mathbf{x(f)}\ \mu\ \mathbf{f^{-5/2}}$.
- 'Low' loss steeel music wire: $\phi_{wire} \sim 5 \times 10^{-4}\ -\ 1.3 \times 10^{-3}$

Suspension Thermal Noise II
Finding the Sweet Spot

- **Pitch & Piston thermal noise are correlated.**
- **Both caused by thermal forces generated where the wire bends.**
- **Calculate both, move the beam, minimize the readout noise.**
- **Reduces coupling from bottom part of the wire *at some frequencies*.**
- d ~ 1 cm
- $x_{sus}(f)$ reduced by ~20%

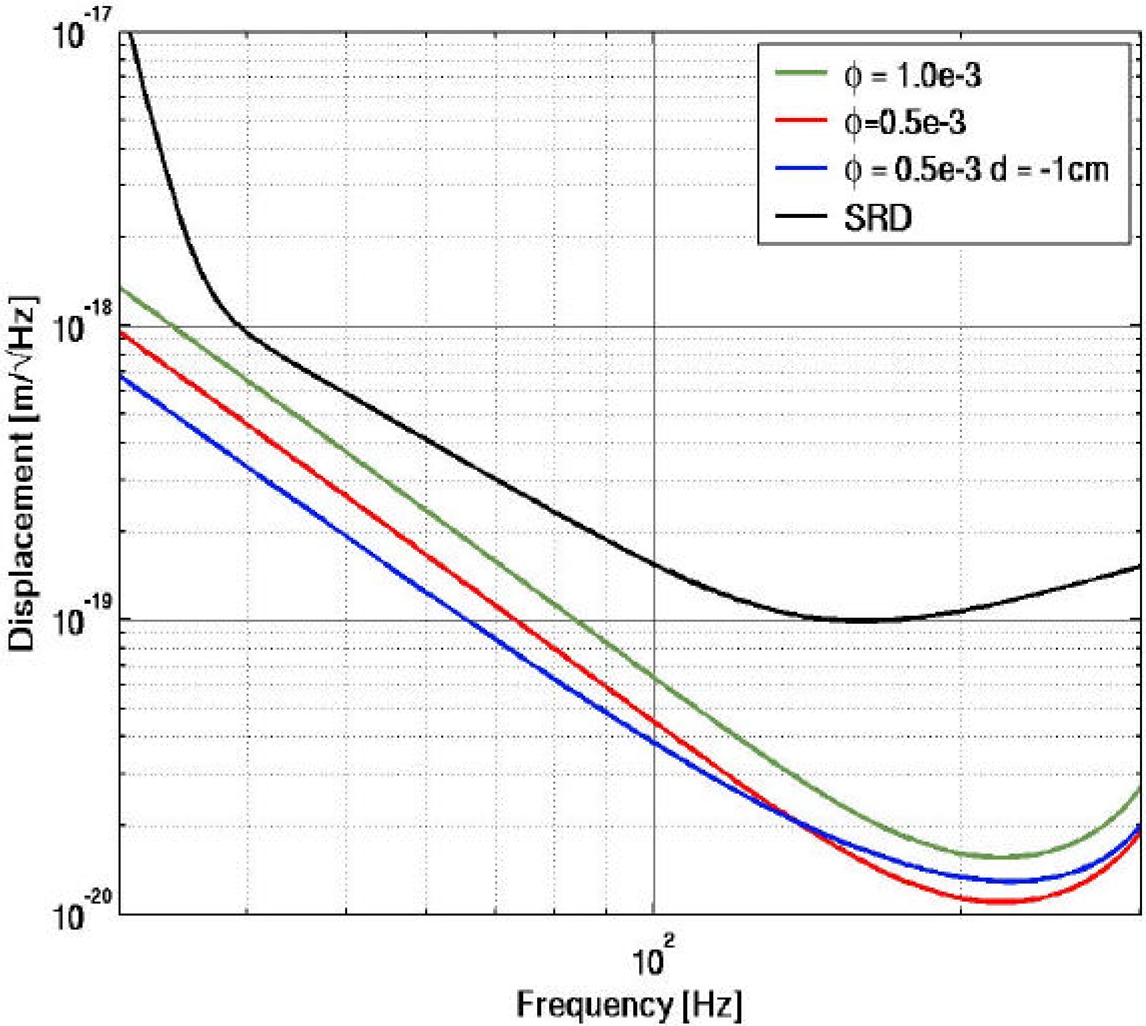
Braginsky, Levin, Vyatchanin (1999)
Gonzalez (2000)



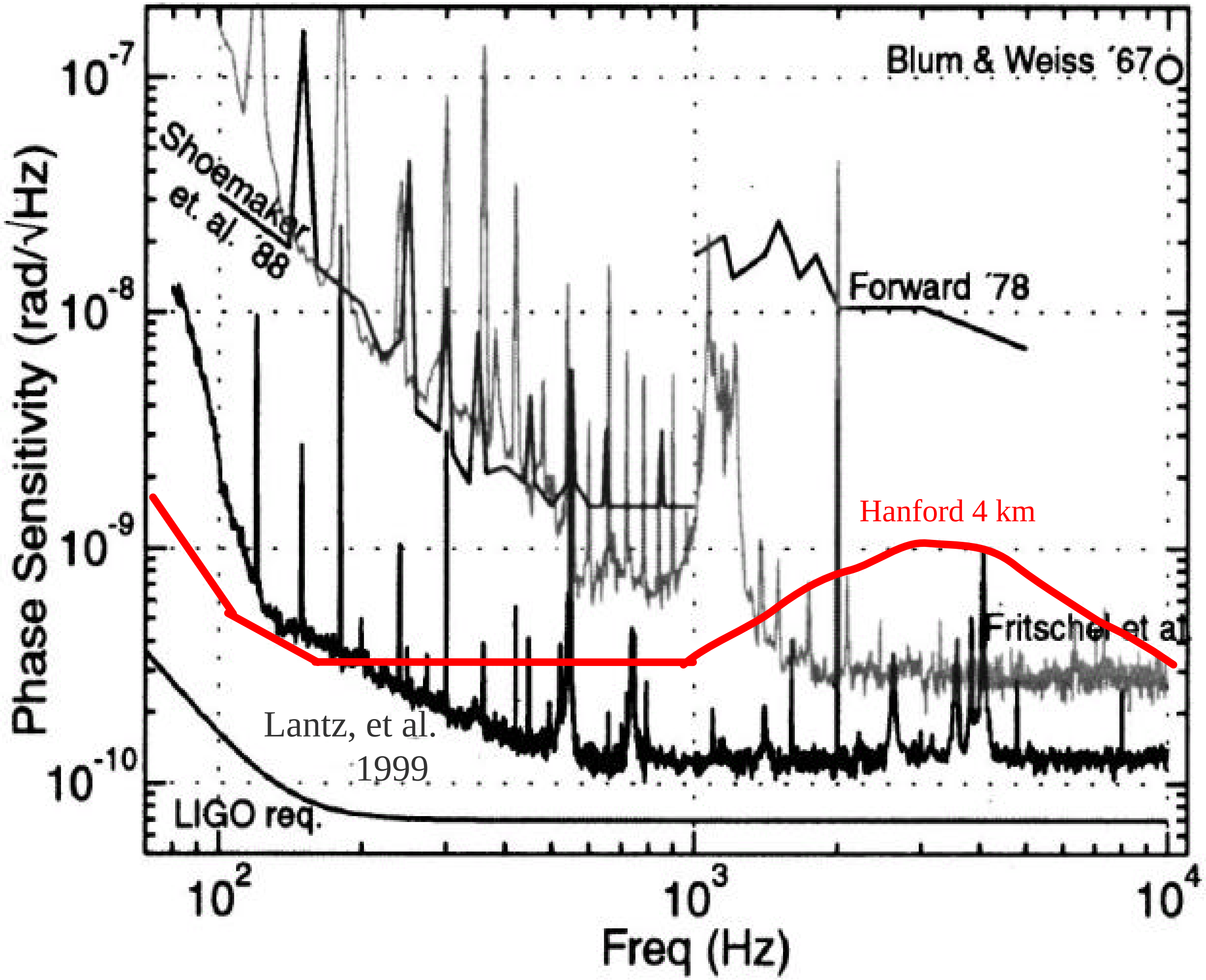
Measurements:
Suspension Thermal Noise I

- Assumes NO loss except for the internal wire friction:
  Good clamps, no rubbing.

  Not yet verified.
- High upper limit of 1.3×10^{-3} set by measuring in lock linewidth of violin modes.
- Linewidths limited by temperature drift of ~1 deg.
- Violin mode ringdown measurements take minutes, not hours.
- *Need to remove systematics*: amplitude dependence, servo feedback.
- **May turn out to be ~3-4x less than SRD.**



Shot Noise



- Gaussian, white noise in the detected photocurrent from the random photon arrival rate.
- By using high power in the IFO we get a large optical phase gain: many Watts/Radian
- But we need to reduce the spurious light which makes shot noise but doesn't help the signal strength.
- **SRD curve makes some assumptions about both:**
- **Laser Power x Buildup**
- **Spurious light due to imperfect dark fringe.**

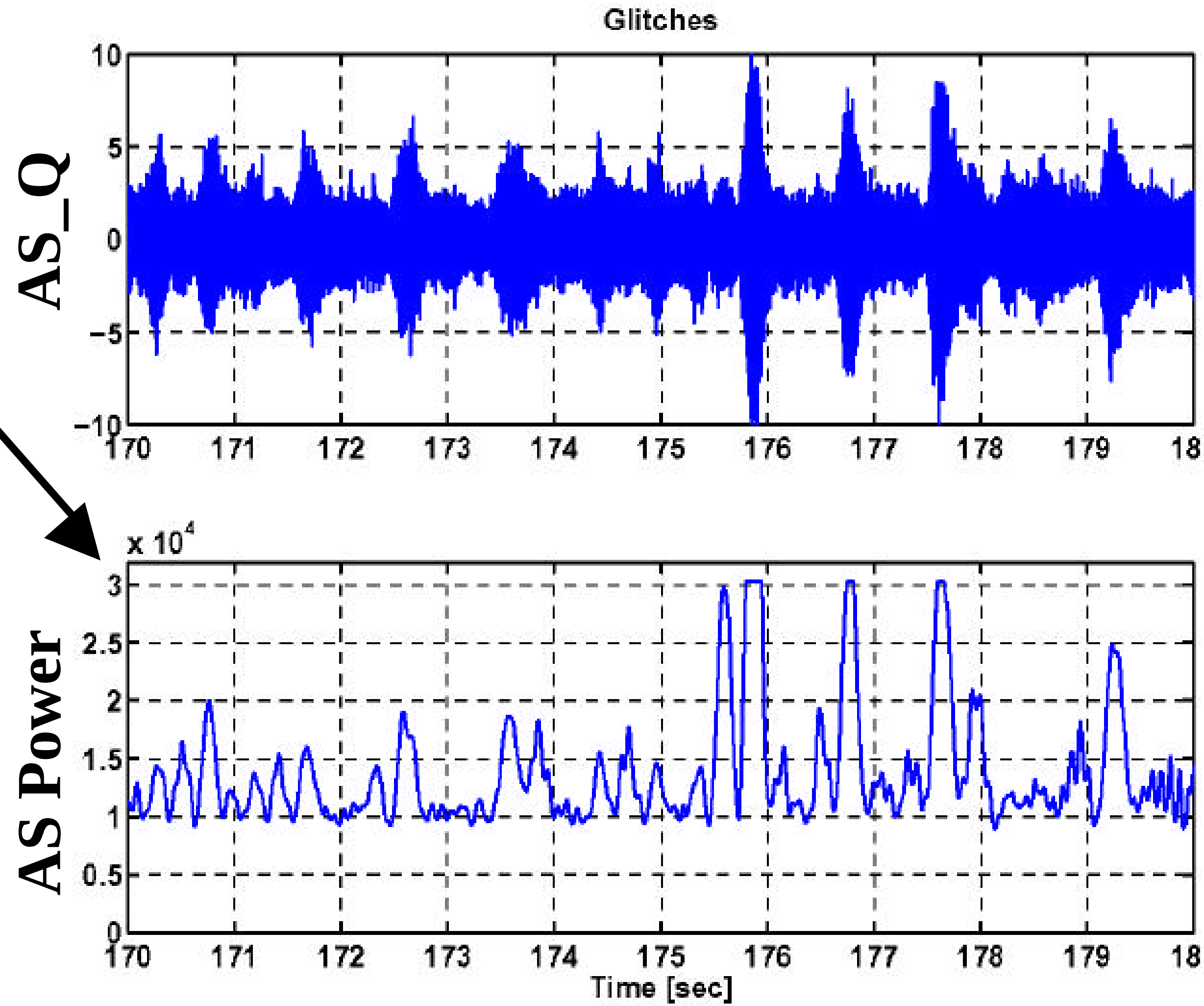
Why is the sensitivity (above 100 Hz) not better?

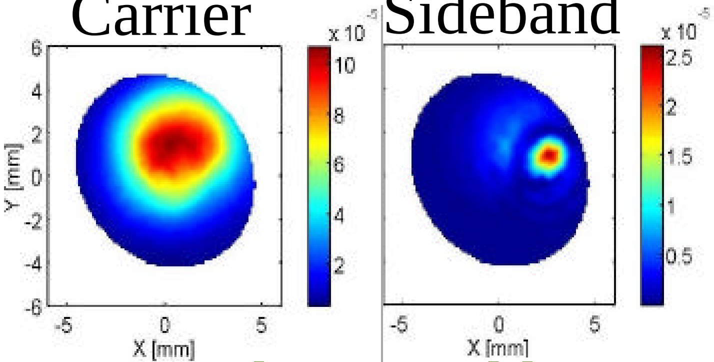
- Low Optical Gain: Low laser power, low sideband transmission, and poor overlap.
- The noise is too high: The Dark port is not dark. The mismatched SB and the mismatched carrier make shot noise.

Measurements:
Shot Noise

Angular fluctuations can cause large power fluctuations.

Must reduce this:
- Better angular controls
- Seismic isolation (HEPI)
- <u>Output mode cleaner</u>





Poor overlap in Cold IFO

example image
of hot PRM
goes here

Good overlap in Hot IFO

Shot Noise

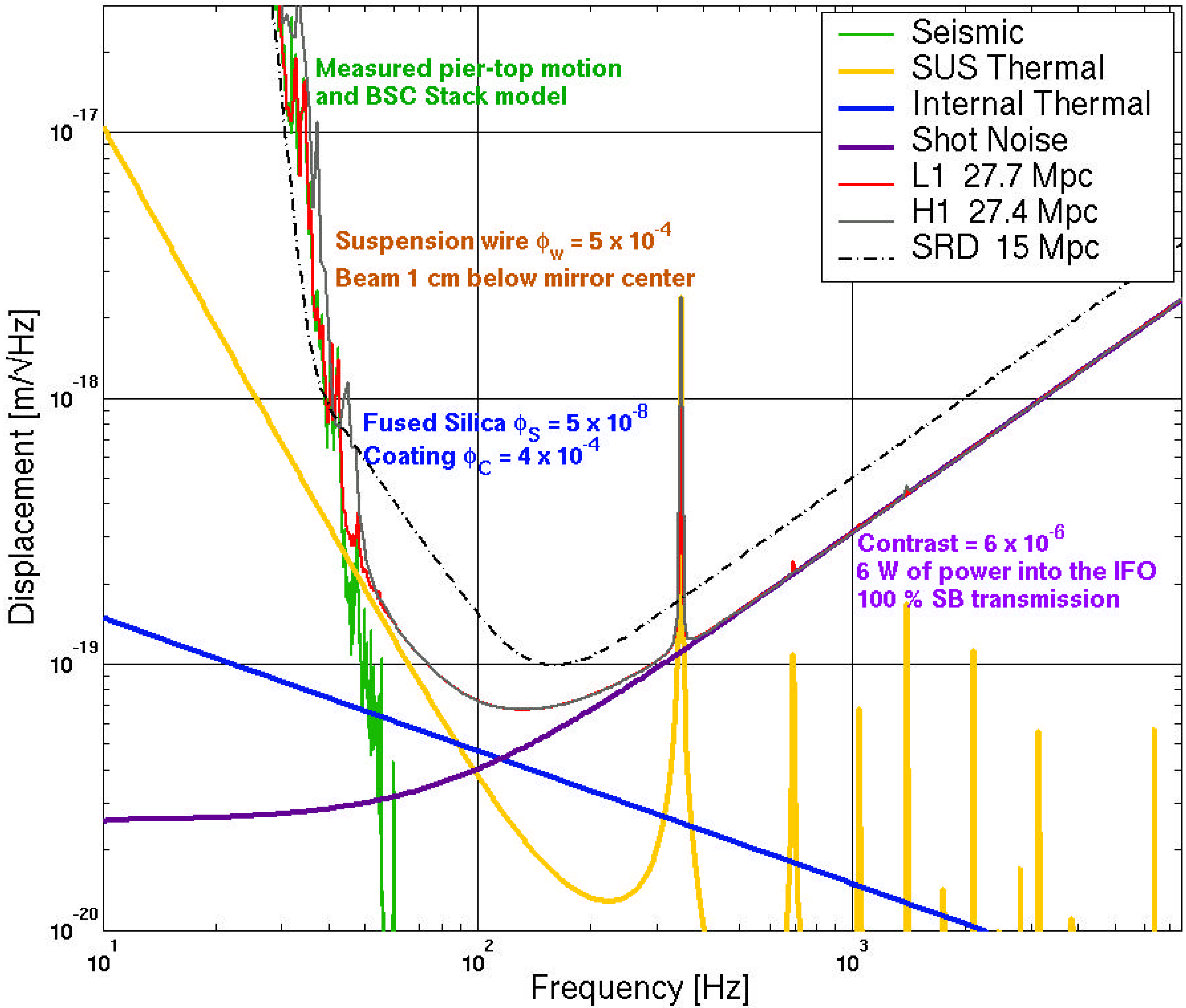
Thermal Lensing:

- Measured power gains (~45-50) are higher than the design (30). Limited by the excess scatter loss on the test masses (~70 ppm/mirror).
- Measured contrasts (L1 = 30 ppm, H1 = 700 ppm) better than SRD (3000 ppm).
- New output mode cleaner will remove all higher order contrast defects.
- Residual contrast defect will be TEM_{00} defect (6 ppm) due to loss imbalance (L1 ~ 70 ppm, H1 ~ 35 ppm).
- RF modulation depth then lowered to optimize SNR. Goes to ~0.15 radians from ~0.45 radians (design)
- Assumes 100% sideband transmission to AS port. Original requirement is > 75%.
- Means perfect thermal compensation (TCS) and all SB power in TEM_{00} mode.
- 'Hot' off the press: H1 SB transmission ~ 87%

The TCS is doing a fairly good job of correcting the phase front curvature error in the PRM.
- Daniel Sigg, Hanford elog Feb 27th, 2004

The Noise Spectrum

- Identical Thermal Noise assumed for both IFOs
- Slightly more seismic noise in Hanford than in Livingston !
- Nice improvement in NS/NS Inspiral Range.
- S4? S5?



Summary

- *What is the noise in the interferometers now?*

  - Mostly known. Not unfixable.

- *Where does the SRD Curve come from?*

  - Conservative estimates that look pretty close.

- *What do we know about the 'fundamental' noises?*

  - The Seismic may be a little high, the others look good.

- *Can we ever reach the SRD ?*

  - Yes, but that's easy.

- *What do we do about it?*

  - Continue as planned, re-evaluate technical sources

  + next page...

Near Term Measurements: Characterize Thermal Noise

- Continue internal mode Q measurements on all 3 IFOs to get better handle on losses. So far only a few optics have gotten several Q's measured. Also, no substantial Q measurements on Super Polished ETMs (L1 & H2) .
- Even worse situation on Suspension thermal noise. Need to measure the first 3 harmonics of the violin modes on *every* test mass. Needs to be done at low amplitudes and with no servo feedback.
- Maybe look for anharmonicity in the violin modes to establish that its internal friction.

Near Term Noise Reduction: Optical Phase Noise

- Thermal Compensation
- Apply heat to make T_SB > 75%
- Tweak up lasers for > 8W into the MC
- REFL signal goes down with heat: Implement NRSB scheme to increase phase sensitivity at REFL port. Reduces frequency noise.
- POB SNR goes like ~Pin*$(G\_SB)^2$:
- -> 20x reduction of POB noise.

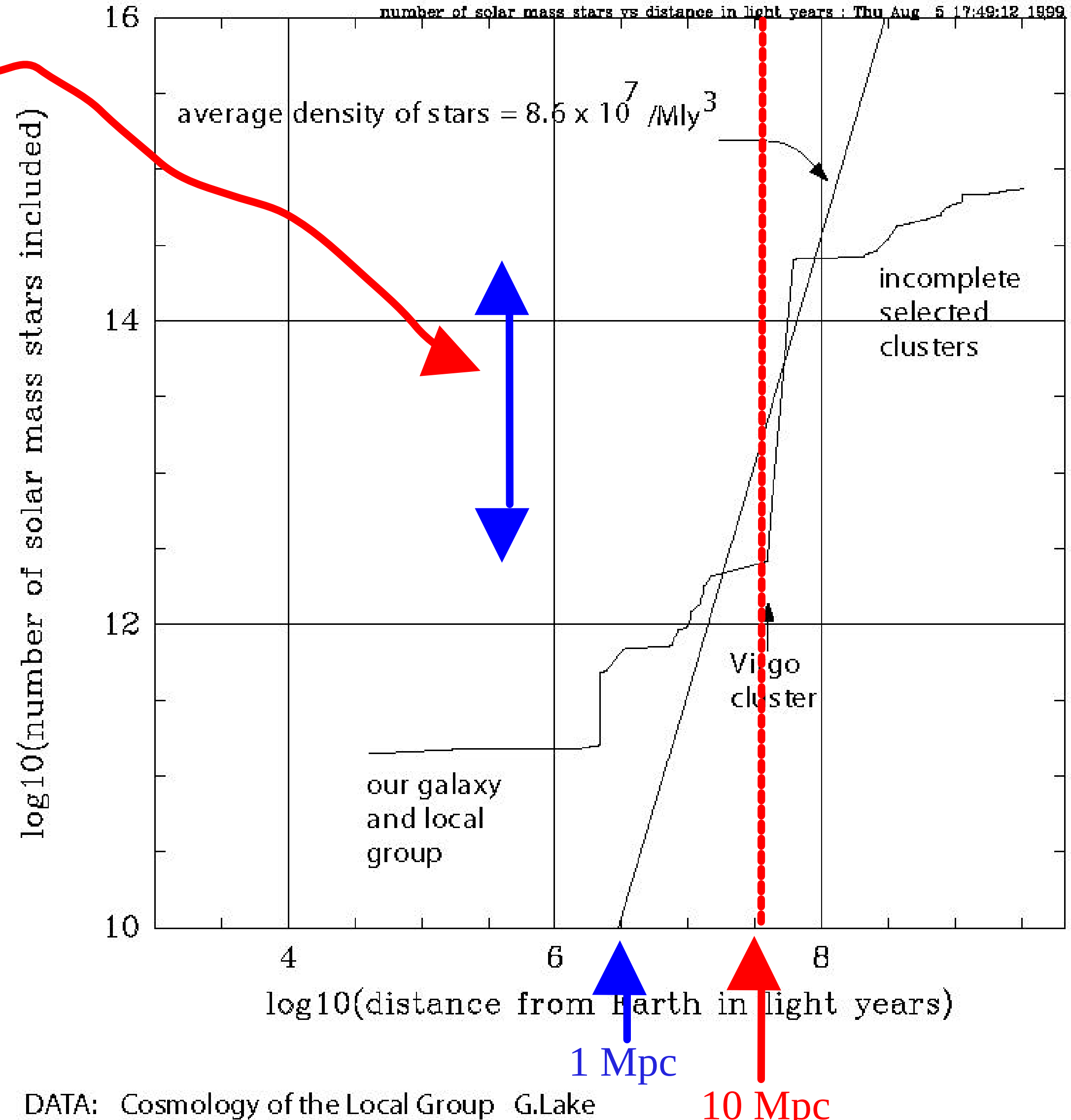
Near Term Noise Reduction: Oscillator Phase Noise

- Oscillator noise is OK: 4×10^{-7} rad/rHz
- Coupling is ~100X higher than design.
- LO & RF SB follow *different* paths.
- Custom low noise OCXO: 1×10^{-8} rad/rHz
- LO filter to symmetrize the RF paths.

Big Payoff !

100 X more mass

for a small noise reduction



DATA: Cosmology of the Local Group G.Lake
Astrophysical Quantities C.W. Allen