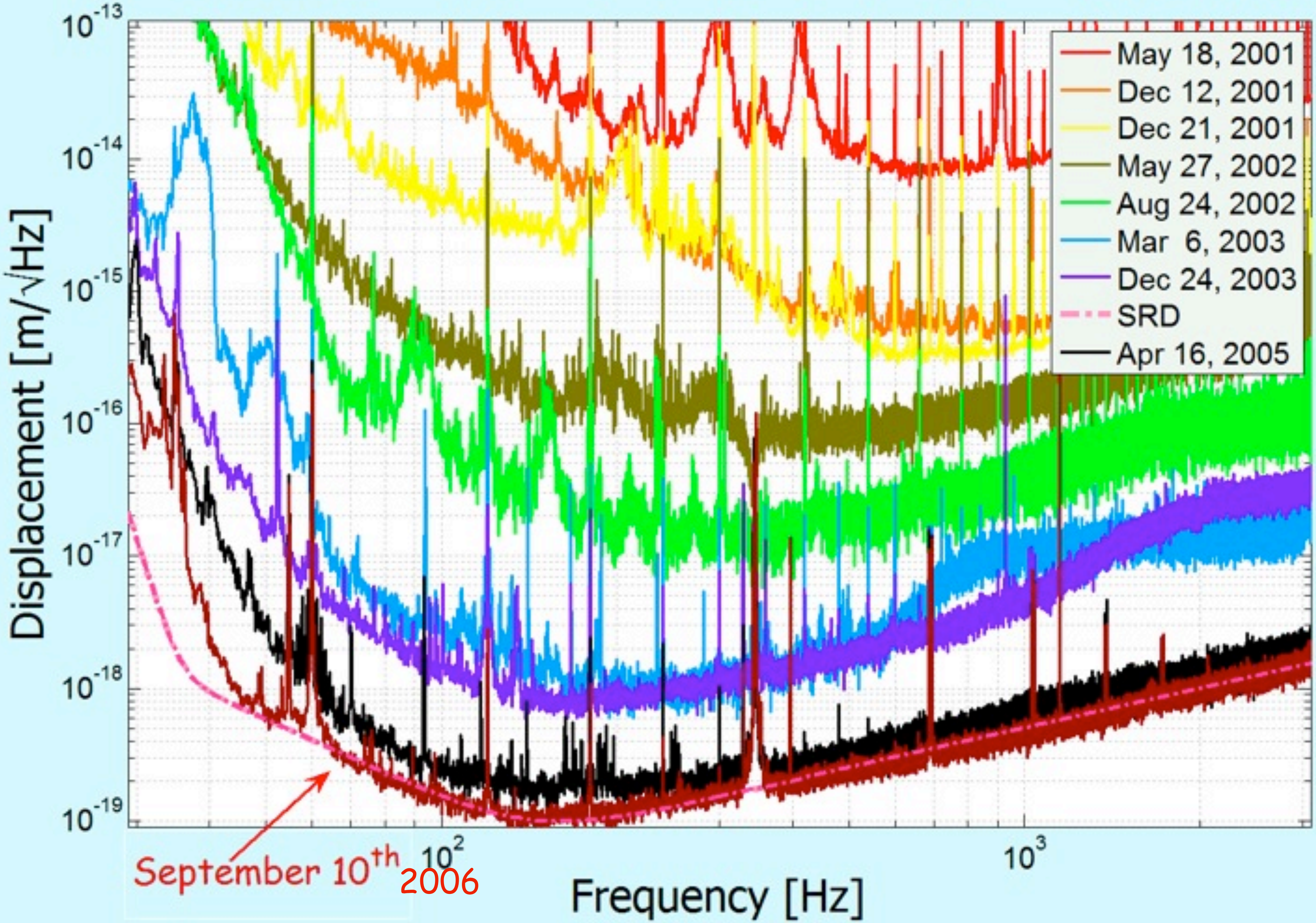
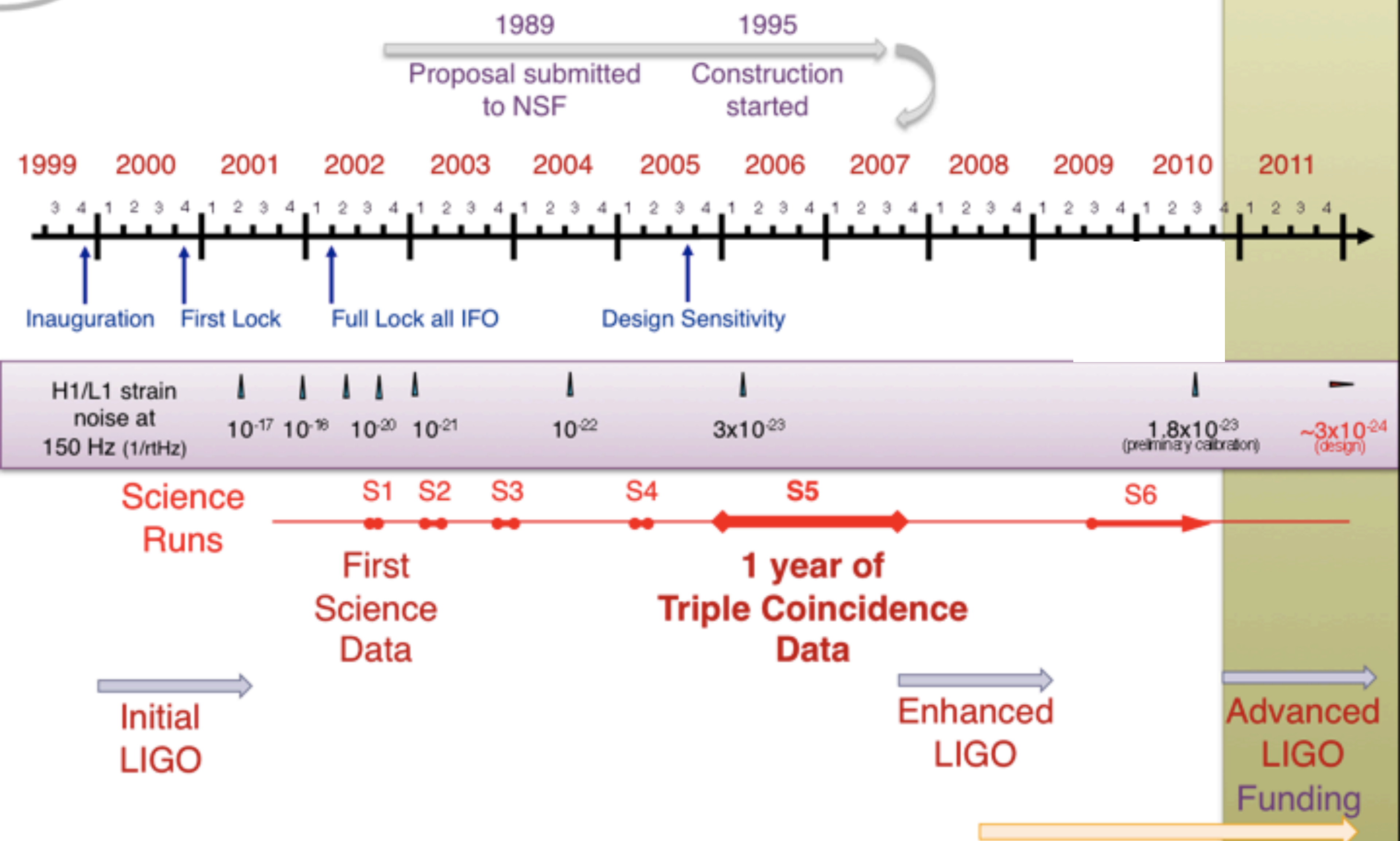

Displacement [m/√Hz]
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{2}
10^{3}
Frequency [Hz]
May 18, 2001
Dec 12, 2001
Dec 21, 2001
May 27, 2002
Aug 24, 2002
Mar 6, 2003
Dec 24, 2003
SRD
Apr 16, 2005
September 10^{th} 2006

LIGO Time Line



from V. Frolov

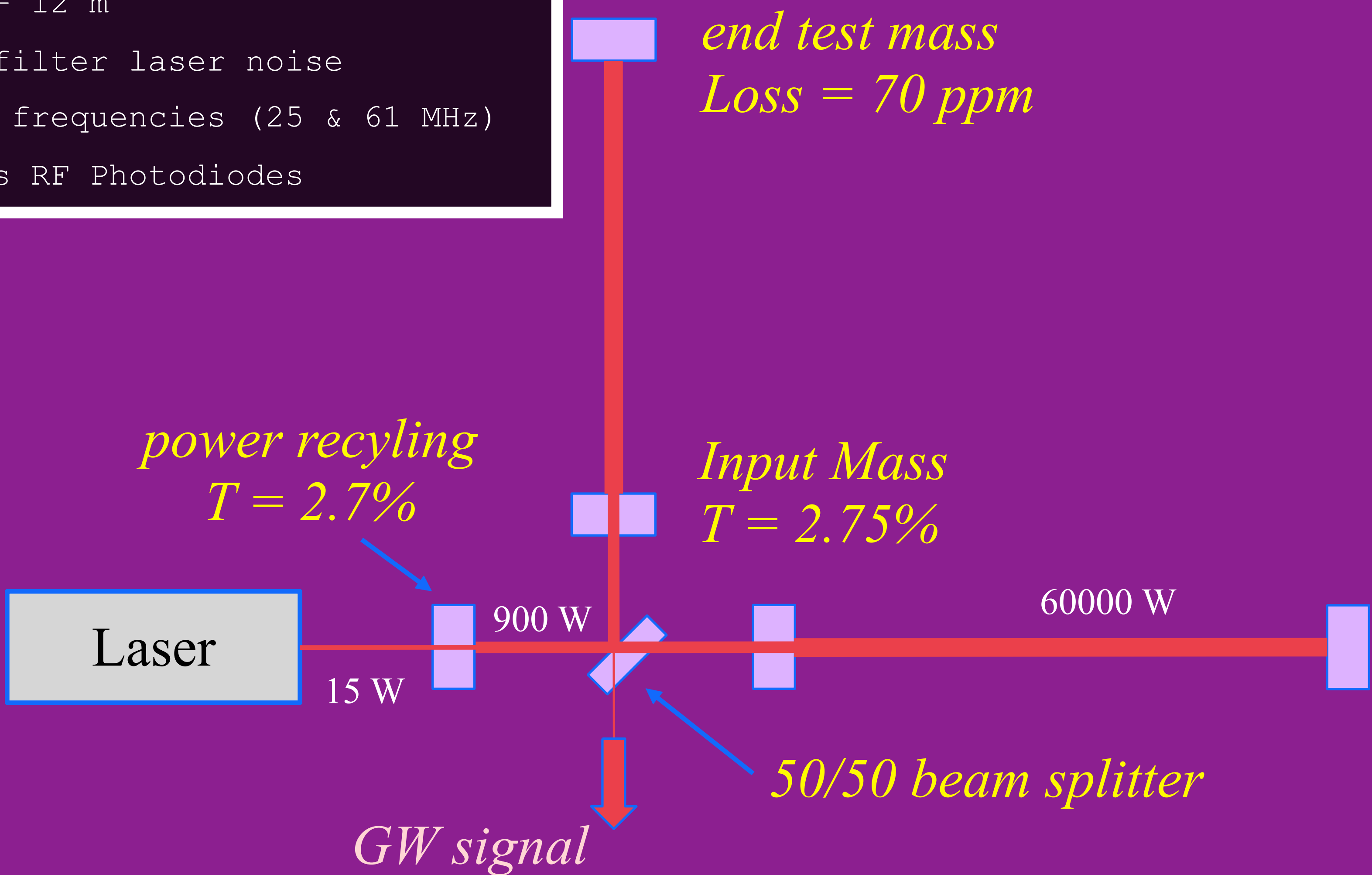
Not Really Mistakes

- **iLIGO was a first**: 10^{-19} m/rHz and 10^{-10} rad/rHz @100 Hz
- **HUGE Vacuum System, HUGE Optics + Large power**
- **>100 servo loops: low-noise, real-time, high speed**
- First U.S. experience w/ PR FPMI w/ frontal modulation
- First scaling from ‘table-top’ experiments to large scale observatories: large staff, big budget, high profile
- But still...design was very idealistic and inflexible. GW interferometery is a dynamic research effort: has to be made flexible because no one is smart enough.

Hanford Security during an anti-terrorist exercise...
LIGO not on Dep. of Energy maps

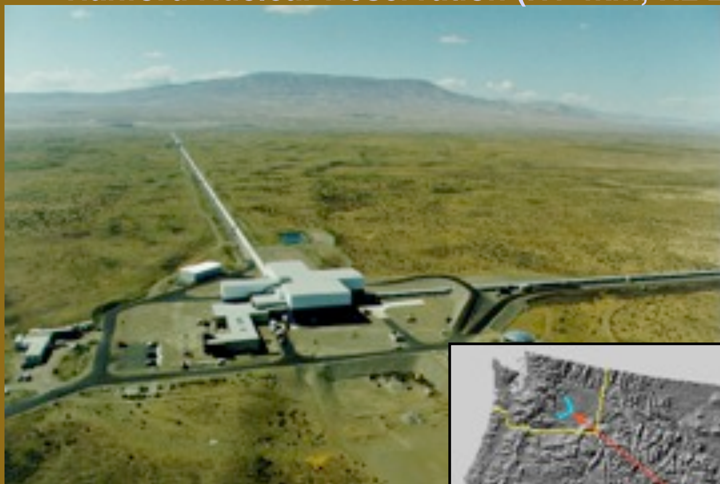
eLIGO

- 10 kg mirrors (25 cm dia.)
- Arm Cavity finesse = 220
- 35 W laser --- 16 W into PR
- Critical Schnupp (~35 cm, Tsb = 3%)
- Short IMC - 12 m
- Pre-MC to filter laser noise
- Modulation frequencies (25 & 61 MHz)
- 2 mm InGaAs RF Photodiodes



LIGO Observatories

Hanford Nuclear Reservation (H1 4km, H2 2km)



Initial Rules

- "Far away" from people
- Infrastructure compatible with 3rd Gen.
- 20 year minimum lifetime
- Observatory, laboratory, office, school

LHO (reality):

- Excellent seismic noise
- Scientists in local area => good primary schools
- No University = No Graduate Students
- Terrible Food, No nightlife

LLO (reality):

- Horrible seismic noise, unreliable power
- No scientists in local area => bad primary schools
- Several Universities = Many Graduate Students
- Best Food in the U.S., Great music/nightlife
- Very affordable (postdoc can buy a house)

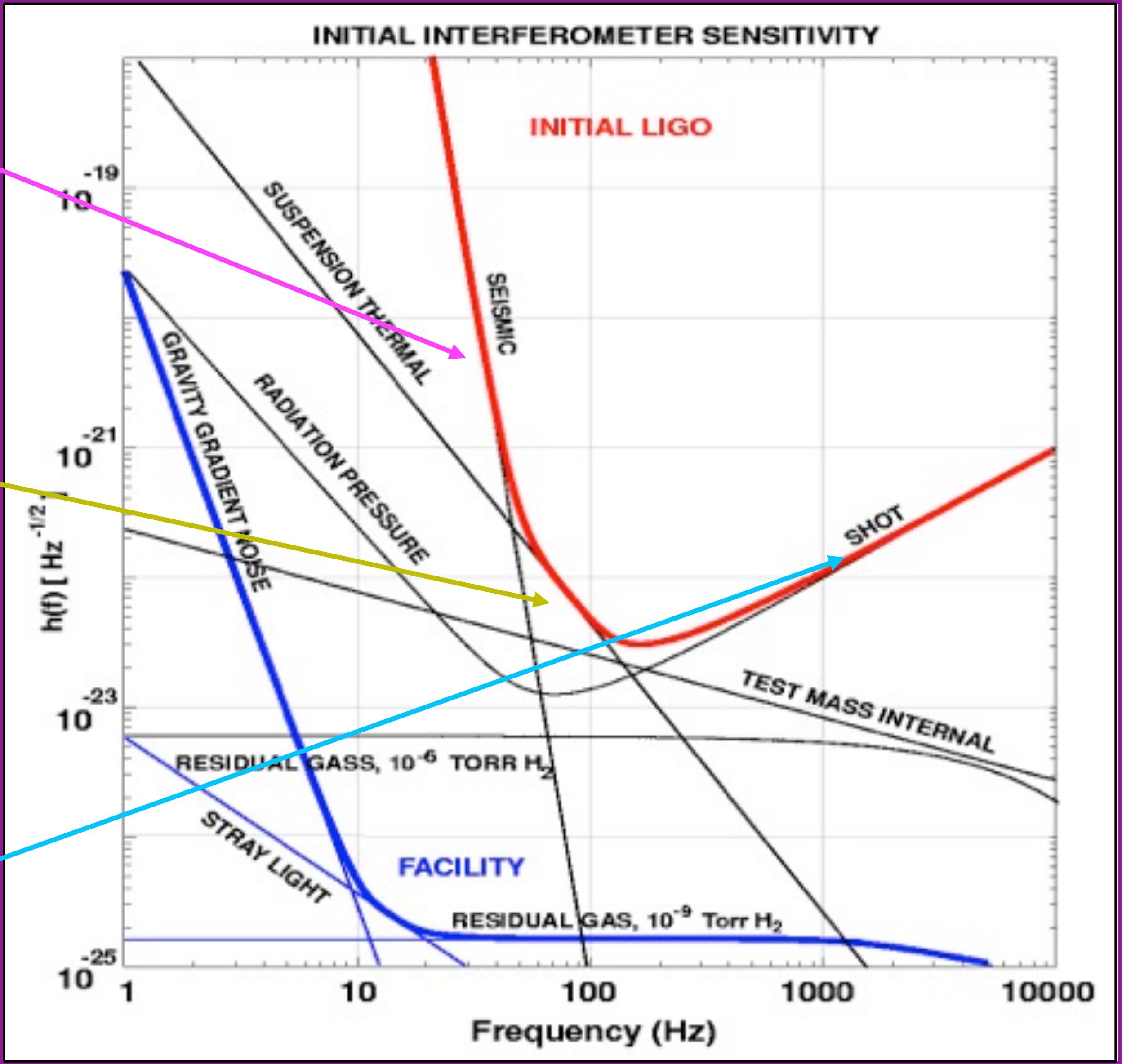
Science Requirements Doc: The LIGO-I Sensitivity Goal

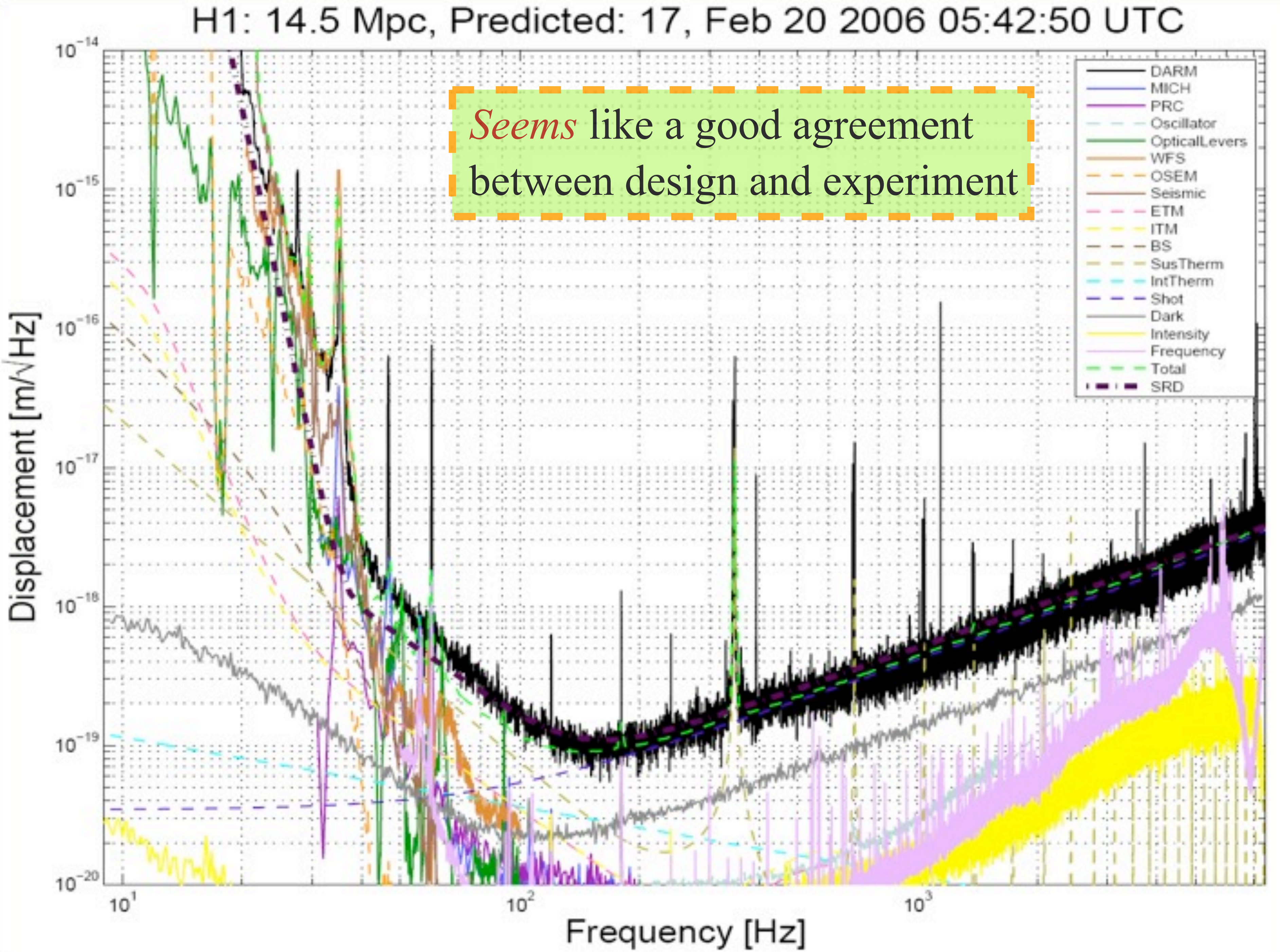
Seismic:
Ground noise filtered by seismic stack. Overkill above 20 Hz and makes noise below 2 Hz.

Thermal:
Brownian noise in the mirrors and in the mirrors' steel suspension wires. Depends mostly on internal rubbing in the suspension wires.

Shot Noise:
Photon counting statistics --
> 10 kW in the cavities
~ 200 mW detected power

- Goes down with increased laser power and better fringe contrast



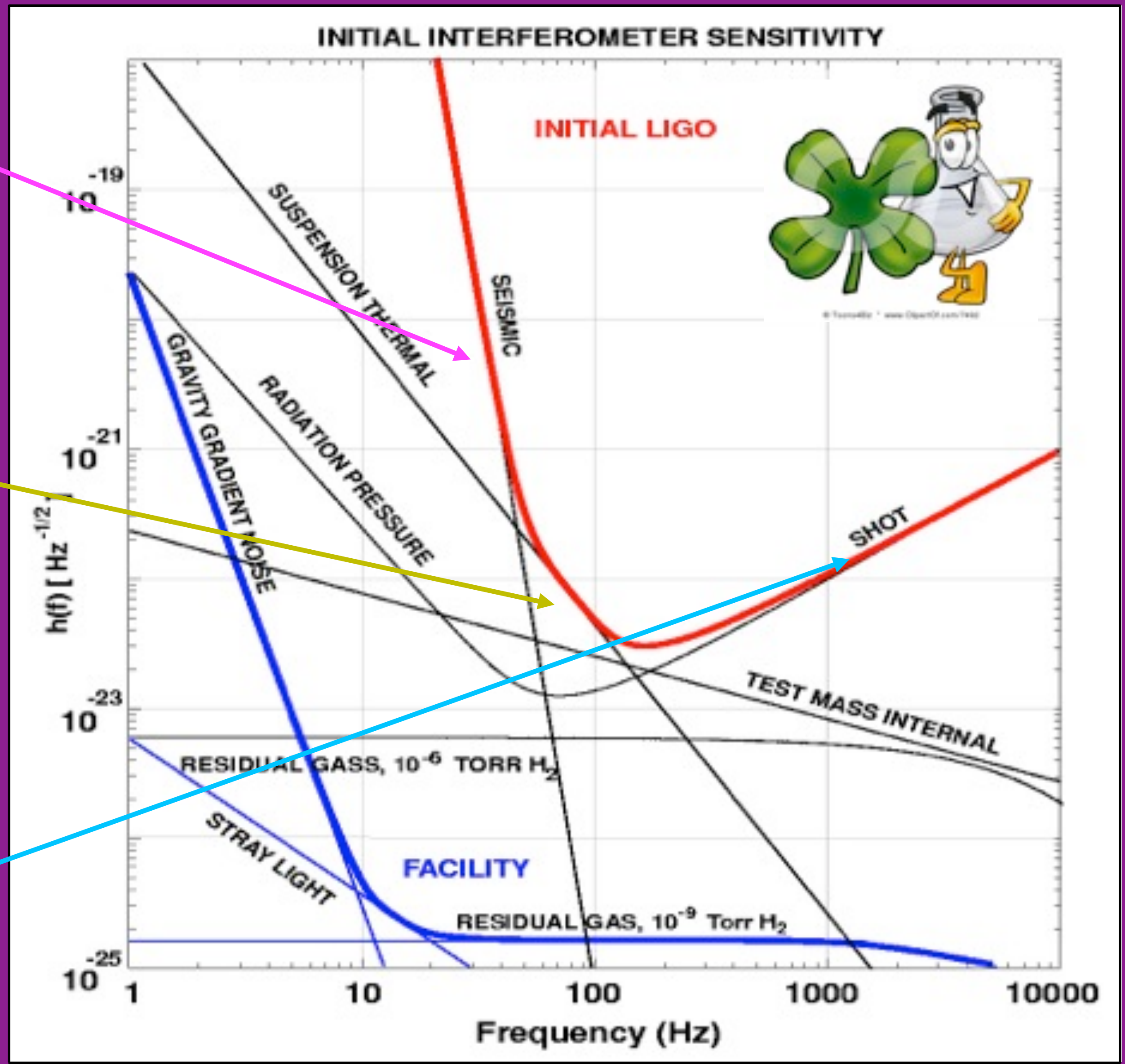

H1: 14.5 Mpc, Predicted: 17, Feb 20 2006 05:42:50 UTC
Seems like a good agreement between design and experiment
Displacement [m/√Hz]
Frequency [Hz]
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{1}
10^{2}
10^{3}
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

Science Requirements Doc: **~ correct**

Seismic:
Ground noise is actually amplified by **10-30x** by **vacuum system** and **piers.**

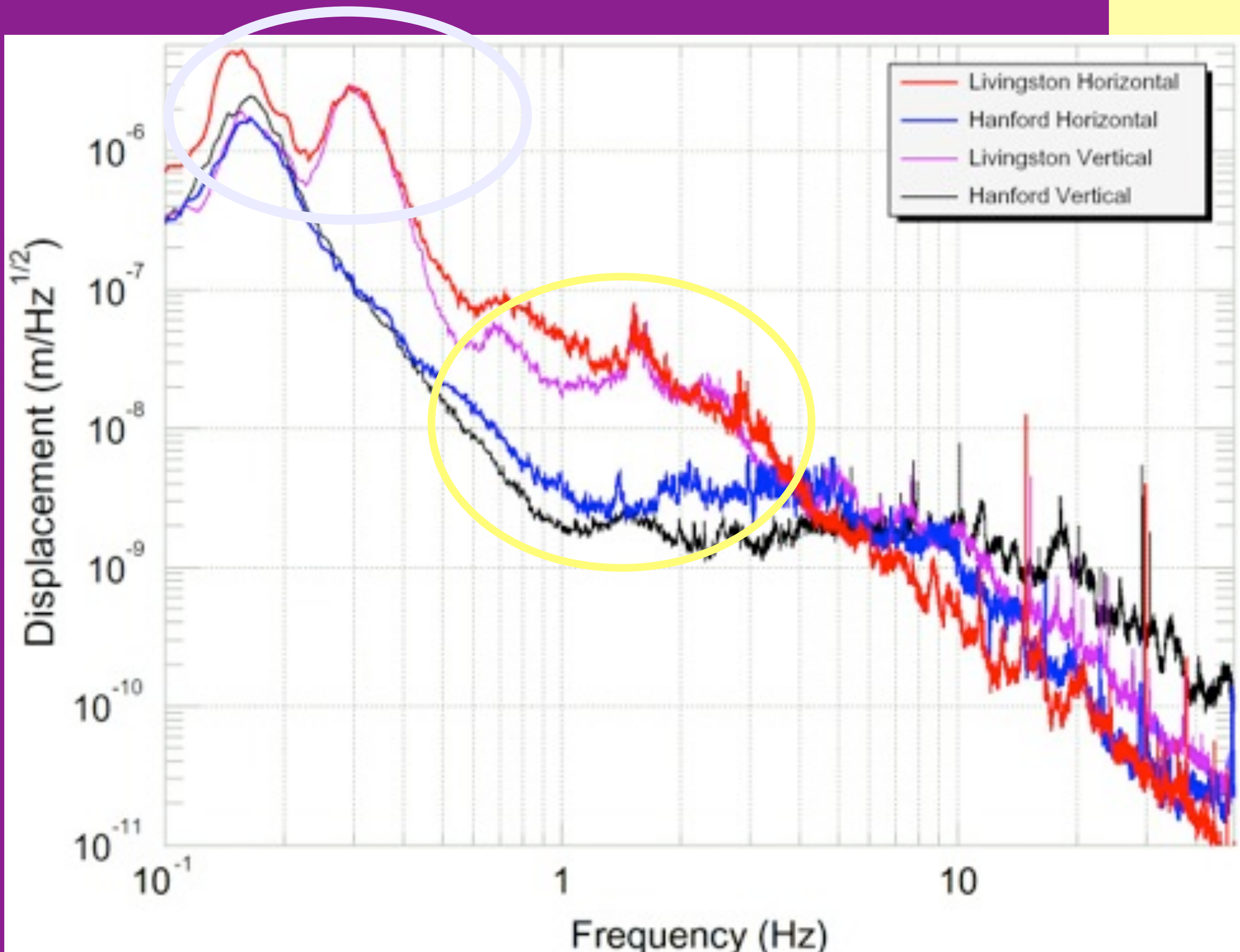
Thermal:
Wrong suspension thermal noise model. Suspension design has **excess** thermal noise. **Coating noise** missing.

Shot Noise:
- Recycling gain off by 2x.
- **Contrast Defect better**
- **SB and CR overlap unknown.**
- **Degenerate recycling cavity.**



Seismic Noise

Ocean activity, hurricanes

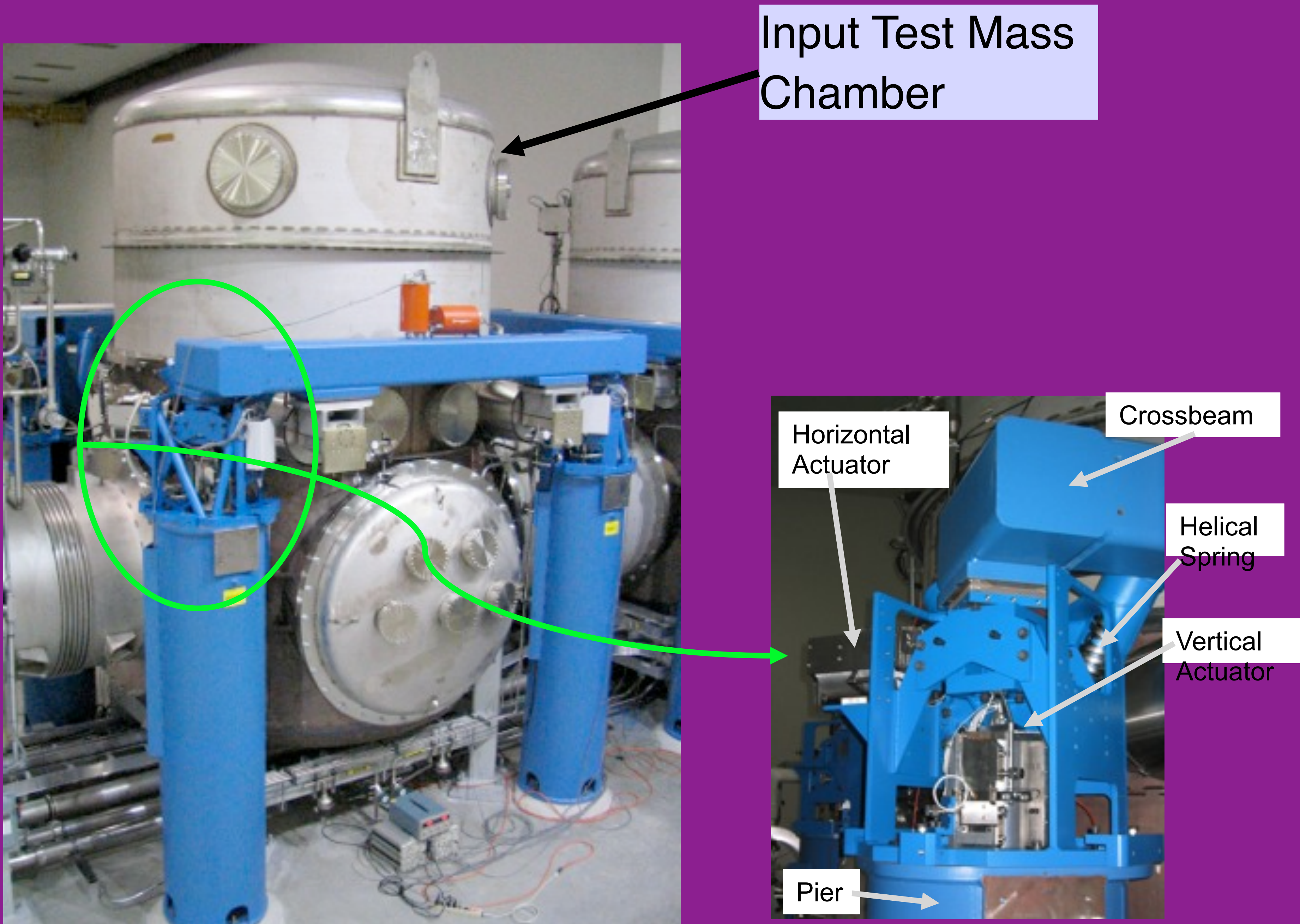


Caused by human activity:
Cars,
Trains,
Trucks,
Logging,
Well Drilling,
Oil Pipeline

Amplified by internal isolation stack resonances

Major Changes from Baseline

- Digital Controls for Suspensions
- Thermal Compensation for ITM Absorption
- Hydraulic Active Isolation (~3 M$)
- EMI Retrofit of Electronics (~2 M$)
- Multiple Upgrade of SUS Electronics
- LSC RFPDs (multiple upgrades)
- ASC WFS RFPDs
- Acoustic Enclosures for ISC Sensing Tables
- Enhanced LIGO (2007-2008): DC Readout, High Power = 2x in high frequency sensitivity.



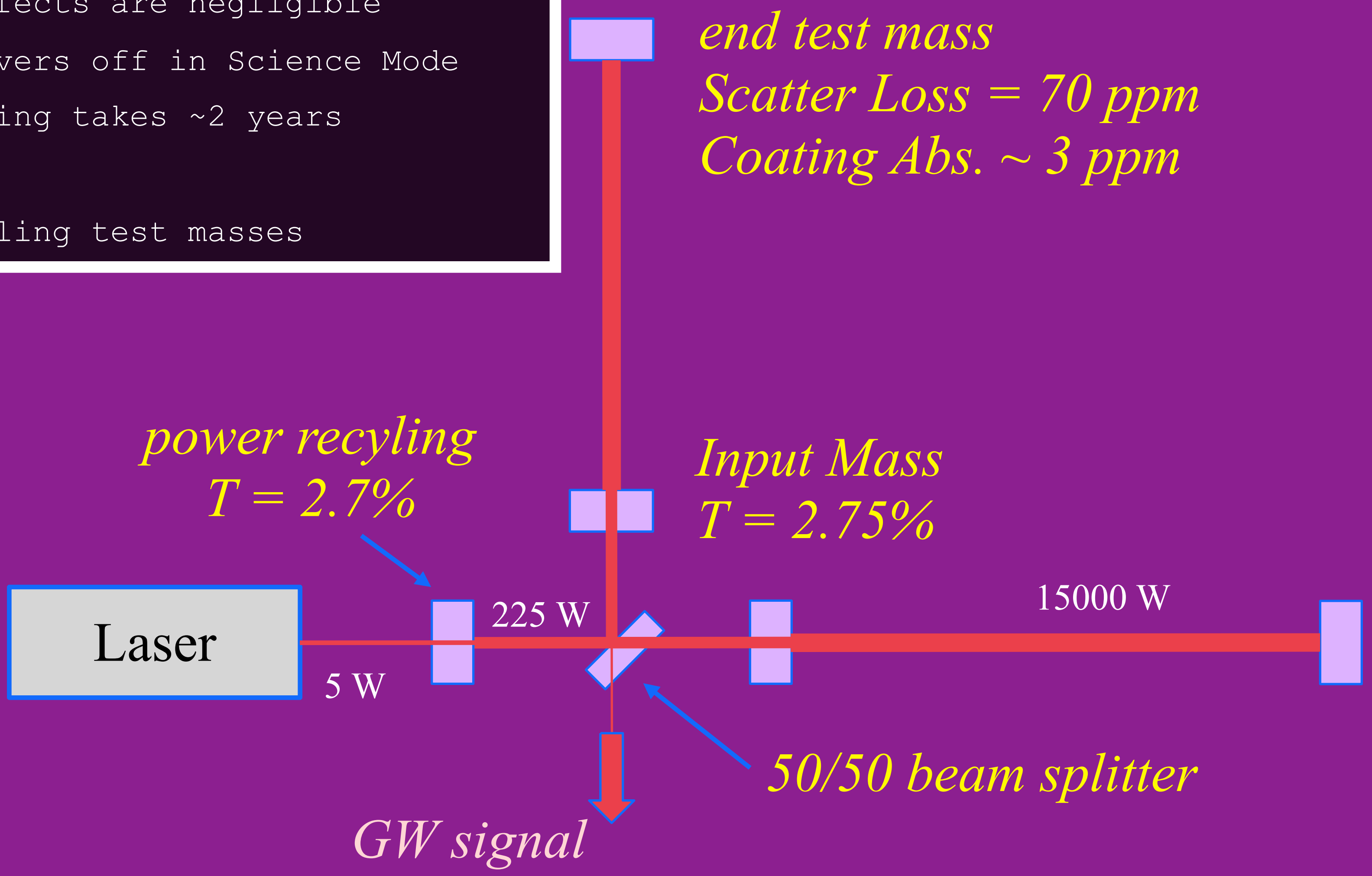
Input Test Mass Chamber
Horizontal Actuator
Crossbeam
Helical Spring
Vertical Actuator
Pier

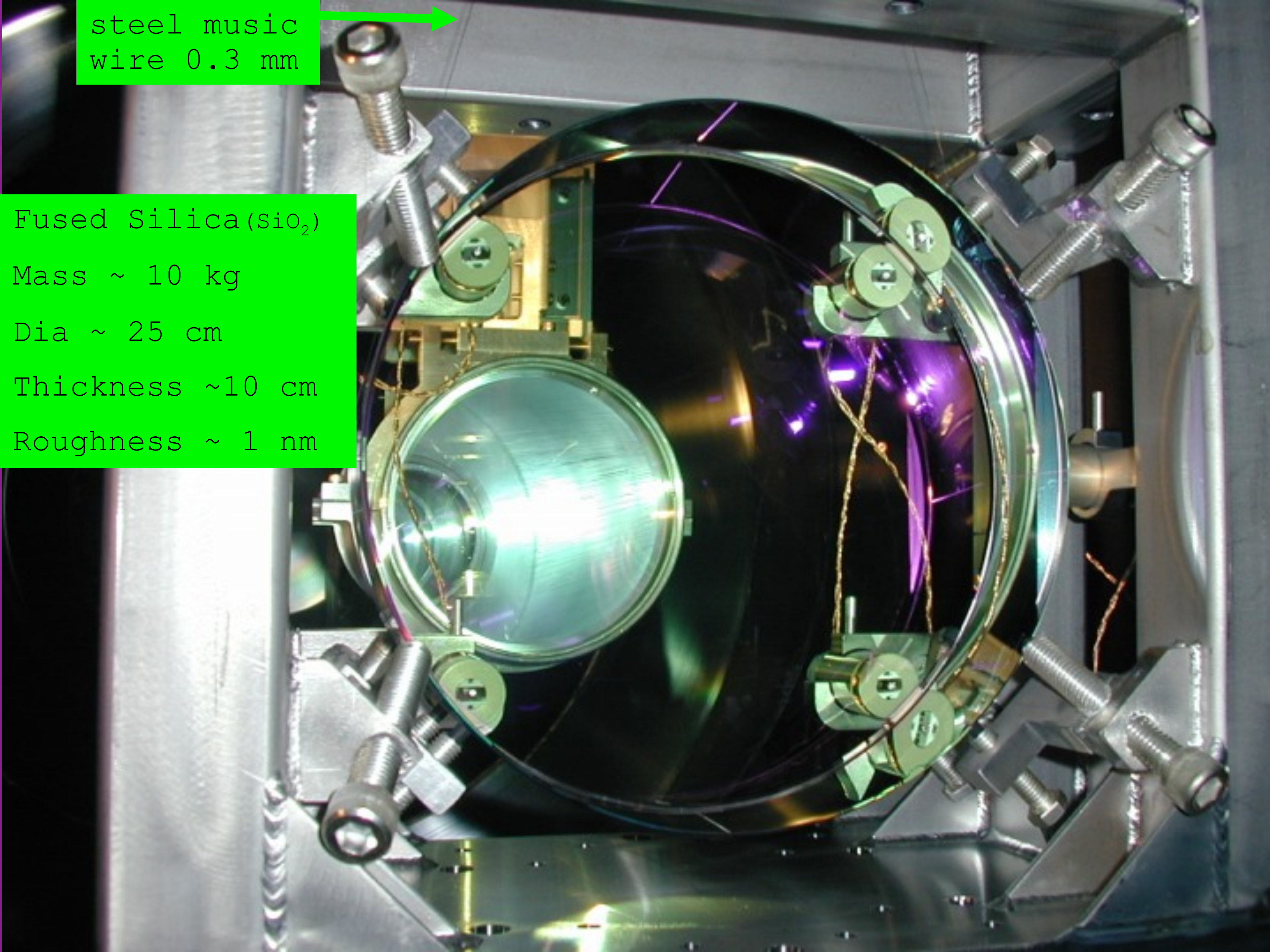
Seismic Isolation Problems

- Rubber in stacks for holding springs: absorbs lots of water and leads to long pump down times (to avoid contaminating arms) = Long Commissioning Time
- Low frequency (~1-2 Hz), high Q (~20-30) resonances
  - Huge noise amplification: SUS coil drivers don't work, Lock acquisition difficult, Angular controls impossible, redesign optical lever for damping, Barkhausen noise, large beam motion on mirrors
- Pier/chamber amplification
  - x10-30 amplification of 10-30 Hz noise
  - Seismic model should include floor+chambers+piers
  - Saturation in POB/POP/WFS => increase BW of MICH/PRC servos, redesign RFPD for better notch, use low Q photodiodes
- Vacuum: Cheap pneumatic gate valves; may fail. Should have used double electric/pneumatic valves to allow valve replacement.

LIGO Myths

- xxx DOF does not couple to yyy
- Limited by fundamental noises
- Passive seismic attenuation
- Stays "locked" for 40 days and nights
- Thermal effects are negligible
- Optical Levers off in Science Mode
- Commissioning takes ~2 years
- 10 W laser
- Freely falling test masses





steel music wire 0.3 mm
Fused Silica(SiO_2)
Mass ~ 10 kg
Dia ~ 25 cm
Thickness ~10 cm
Roughness ~ 1 nm

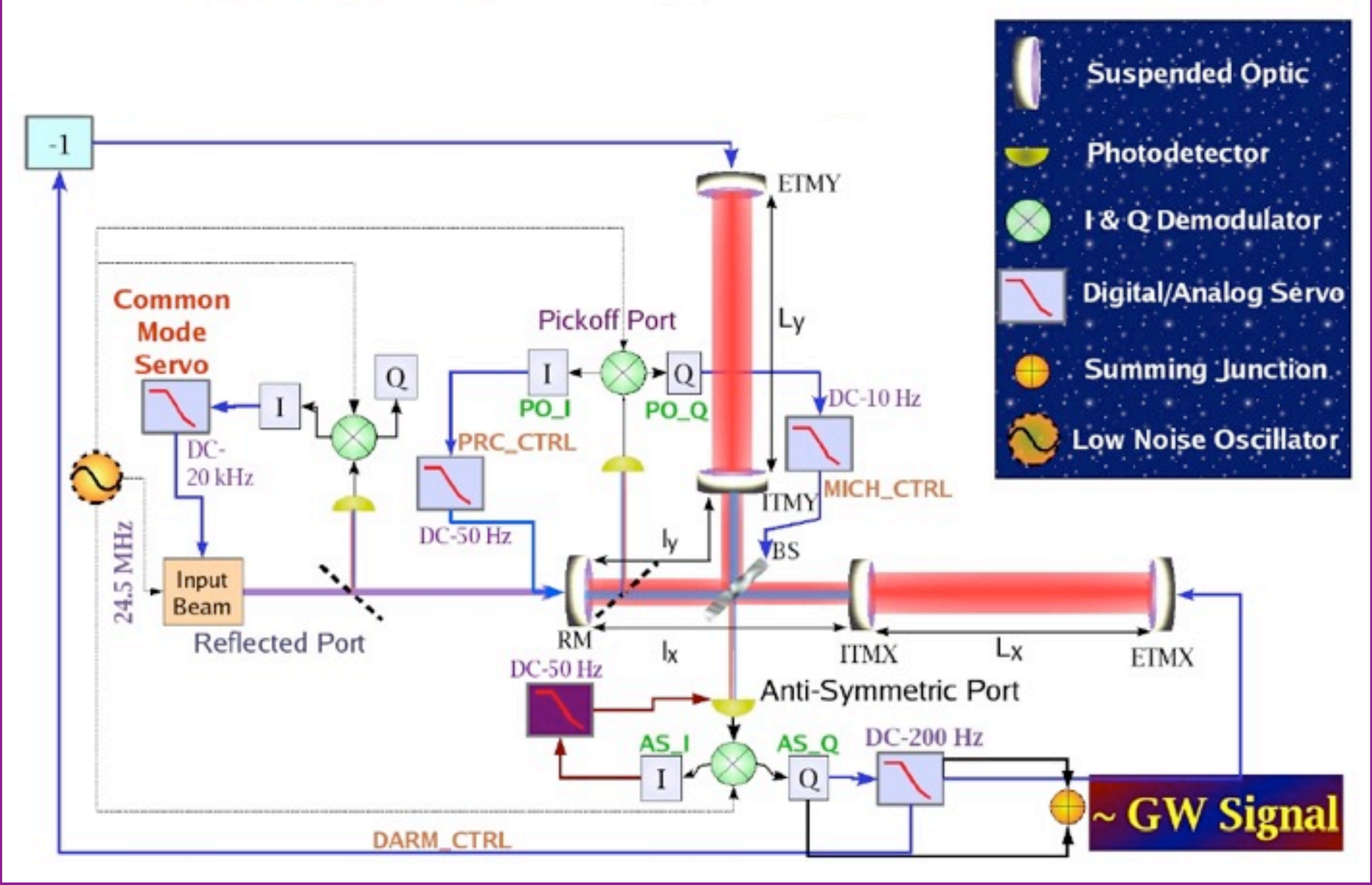
Suspension Problems

- **Top attachment has bad clamp**; clamps re-used, non-deterministic noise
- **Metal Spring EQ stops:** Q too high, mirror bounces, broken magnets.
  - Try Rubber stops: better damping, but static charge problems
  - Try Glass stops: less charging, but some glass grinding dust
- **Bottom attachment bad.** Poor contact at standoff and around barrel. Excess 'thermal noise'
- **Bad magnets: Barkhausen noise from NdFeB magnets**. Replaced with SmCo. Should use plated magnets to reduce 'hair' noise.
- **Shadow Sensors (980 nm) sensitive to 1064 nm laser.**
  - Change to 880nm + added lens + 40 dB filter = 60 dB better
- **Single Loop Bad:** 10-6m @ 0.1 Hz and 10-19m @ 100 Hz. Too much dynamic range in 1 stage. Too hard for the electronics.
- Needed **FD coil balancing** to reduce ~1 Hz angular noise. Extra angular noise put too much load on WFS/OL systems.
- Poor **QC in shadow sensors**: non-aligned beams = cross-coupling in damping

Optics Problems

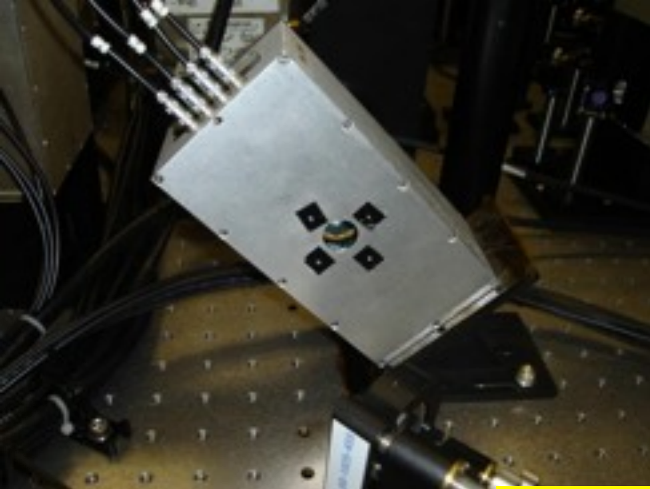
- Metrology has systematics = no reliable FFT model with real phase maps; cannot predict losses, contrast, etc.
- Phase map PSD estimate bad: procedure to remove power/tilt wrong.
- **Schnupp asymmetry wrong** for 4k IFO (copy/paste error from 2k)
- PRC length wrong by ~1 cm at LLO (surveying error; LLO made their own equipment...)
- Unstable/Degenerate PRC - unstable sidebands
- Design for fixed absorption - absorption is variable - more unstable
- Turns out that we needed **Thermal Compensation System** (TCS). Basic TCS existed because of aLIGO research. However
  - Hacky system; no requirements; bad beam pattern, much intensity noise, much beam jitter.
  - Installed in 2004 - commissioning finished in ~2009.
- Optics Cleaning Procedure (liquinox) damages AR coatings
- Wrong TM RoC (g-factor) to minimize Sigg-Sidles Angular Instability

Global Length Controls



LSC Problems

- Schnupp Asymmetry Wrong
- **Digital Control System inflexible**: hard-coded filter coefficients, can't switch without killing lock.
- Digital Control System: single precision computation = noise
- Design of RFPDs: Oscillations, extra noise
- Orthogonal Phase Unsuppressed ("AS_I problem")
  - 3 PDs x 2 RF quadratures = 6 signals (but only 4 servos)
  - Max laser power ~100 mW (instead of 10W) before saturation
  - Design ASI servo (reverse modulator/amplifier) to subtract ASI
- **PRC couples to DARM!** (PRC puts phase modulation on SBs)
  - implement a Feed Forward to cancel / redesign RFPD
- **Lock Acquisition:** Slow LA makes people afraid to try new things
  - e2e model / Matt Evans => success, but still not very good.
- **No Noise Budget! (saved by input from TAMA)**

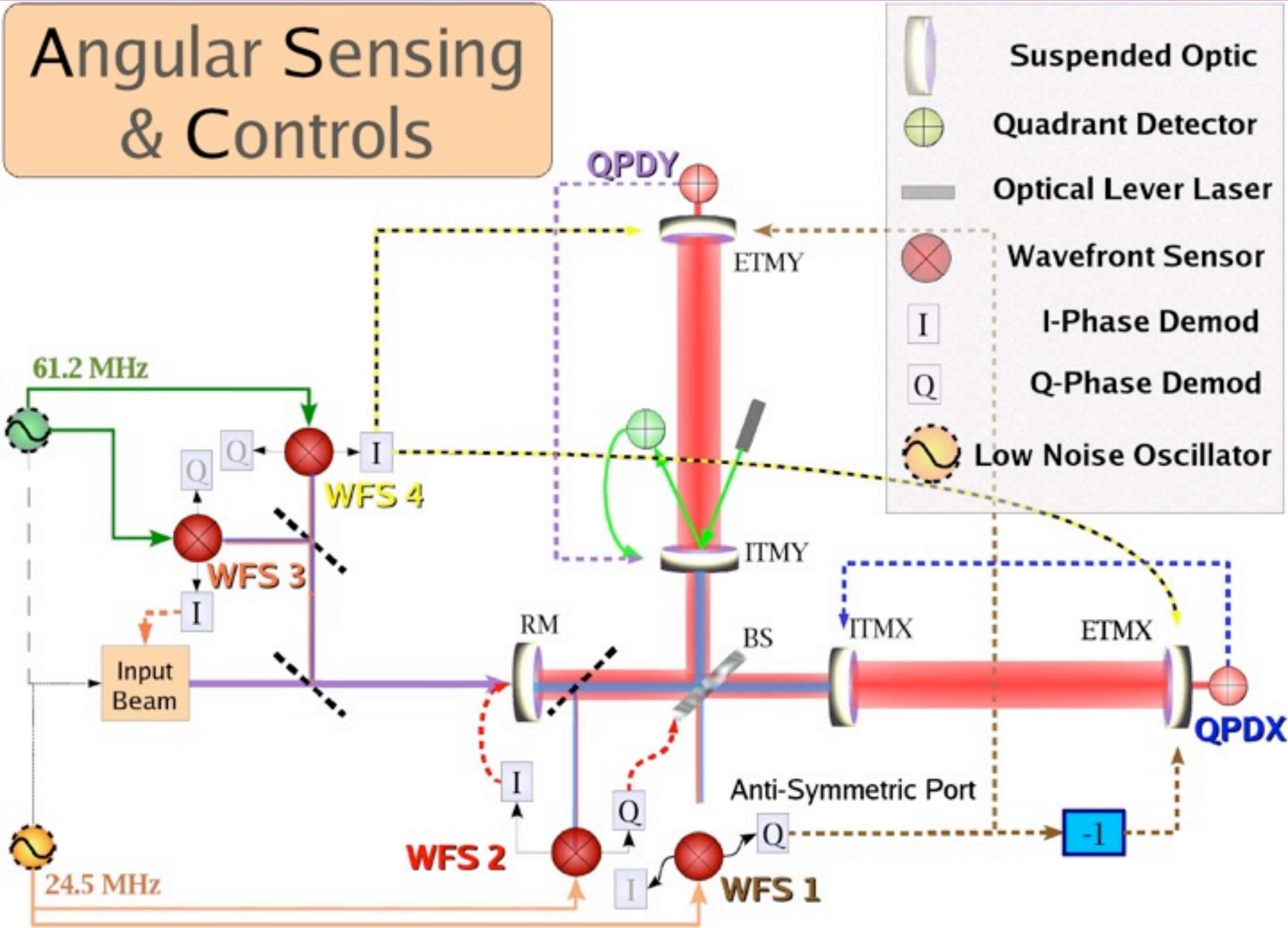


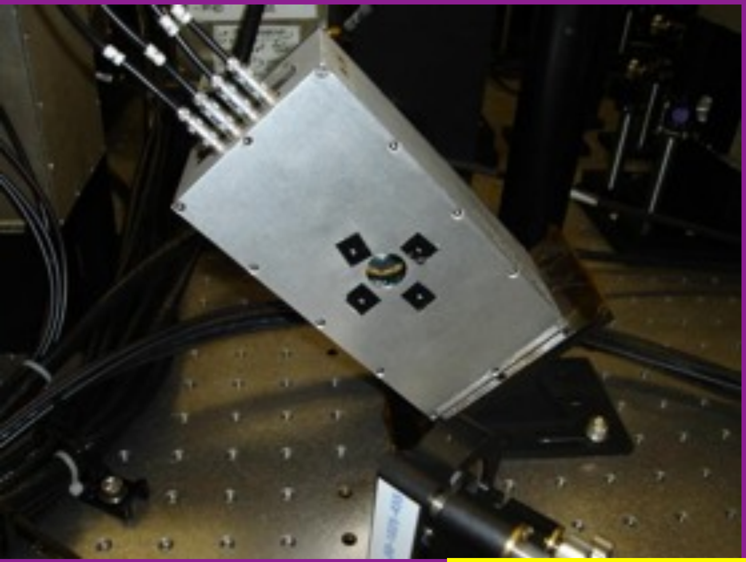
Alignment Control

(the hardest servo problem in LIGO)

- Controllability
  - 8(x2 DOF) sensors
  - Sensing matrix is not diagonal
  - Works along with non-diagonal optical levers
  - Sensing matrix is not constant (thermal stuff)
  - Radiation pressure instability (Sigg-Sidles Springs)
- Noise
  - Feedback w/ 5-10 Hz bandwidth
  - Make less than 10^{-19} m/rHz of noise at 40 Hz.
- Mirrors wiggle by a few nanoradians (RMS)

Angular Sensing & Controls





Alignment Control

(the hardest servo problem in LIGO)

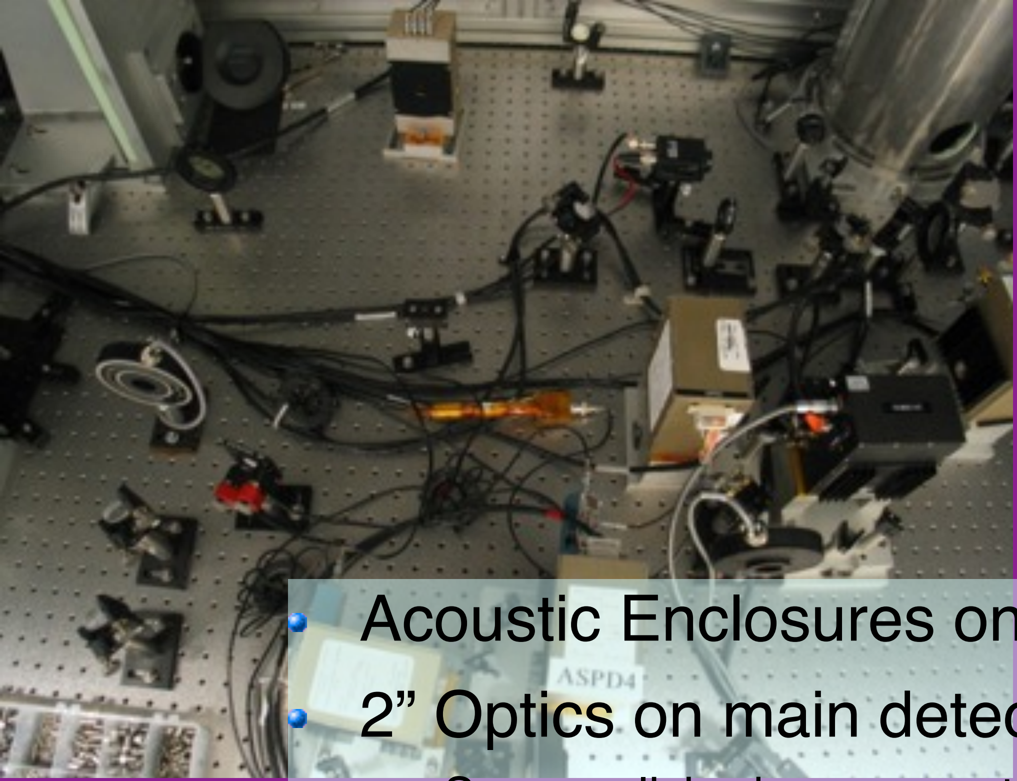
Rai Weiss

Hartmut Grote

Matt Evans

oops

- Sensing Noise = ~10^{-13} – 10^{-14} rad/rHz
  - Oscillating RF amps, noisy demod, Bouchon Compression, ADC
- Gouy phase telescope for Dark Port was 88 deg. wrong
  - New 3 lens solution for hot ITFb
- Non-diagonal Sensing Matrix
  - Years and years of suffering => (Simple Matrix Adjustment Concept)
- Sigg-Sidles Instability: Radiation Pressure induced torque
  - low frequency phase margin reduction



Scattering / Clipping

Lesson Learned:

put all detectors in vacuum

- Acoustic Enclosures on Detection Tables: -40 dB
- 2” Optics on main detections paths (every beam)
  - Super polished, super coated from REO (CVI AR = 0.5 %)
- Clean Detection Optics
  - Good optics practice (gloves, hats, coats, etc.)
  - ‘Mouse’ maze (plexi-glass box for the B1 beam)
  - HEPA filtered air for mouse. Very soft laminar flow.
- Stiff Mounts
  - Main resonance from ‘flagpole’ resonance
- Floating tables
  - Pressure regulated air legs

Electronics / Controls Problems

- Point Design: Low noise electronics not tested in 'real' field conditions (long cables, noisy RFI environment, physicist abusing connections)
- Point Design: Whole LIGO design only works at design sensitivity. No good phased plan to progress in noise hunting
- Oscillations and Noise in SUS coil drivers: changed many times
- Design of RFPDs: Oscillations, extra noise
- Unlocked RF oscillators produce beat frequencies and can be demodulated into the GW signal => "wandering lines" in the pulsar search.
- All ADCs/DACs/etc/ have cheap crystal oscillators that beat with us.
- ADC/DAC have upconversion due to lack of high frequency dither signal; dither included in old Pentek ADC, but not new aLIGO style ADC.

Electronics II

- **To avoid some of, the unnecessary problems from iLIGO, these documents have been used for standards:**
  - Standard LIGO Electrical Interfaces: https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=3693
  - PCB Design Checklist for Manufacturing: https://dcc.ligo.org/cgi-bin/private/DocDB/ShowDocument?docid=13944
- These 'quasi-rules' are also mostly adopted (by the aLIGO team) from the experience of the iLIGO:

1. The merit of choosing simple solutions (OP27 etc). Initially, robust but simple solutions let you see where you want to go faster.
2. Parts availability, be sure you don't choose weird parts or values.
3. In a world of arbitrary choices, tend to make component values equal to avoid unnecessary complexity.
4. Beware of slew rate, even though you don't use response at 10 MHz in your servo, noise does.
5. Don't miss the boat on power density for circuit boards. Be sure to add up the total DC power used, and figure you have to dissipate it in a closed box.
6. Avoid fans, they never seem to work in the end.
7. Don't use op-amps for RF work unless you absolutely have to. RF amplification should be done with 50 ohm RF amplifiers, which can be cascaded easily.
8. Watch out for ceramic capacitors, and thick film resistors. These parts can make for some complicated excess noise problems.
9. LEMO connectors are weak and bad for RF. Physicists break them. Choose connectors with strain relief suitable for children.
10. Own electronics solutions from the physics requirements they serve, to the final product. If you don't, you will end up building some physicists view of the ideal electronics solution, which can be less optimal.
11. No up downs (Seiji et al.).
12. In a demanding system, put most of your energy into the sensors. Once the sensors work well, the rest is usually not so bad.
13. Develop standard packaging solutions early in the project.
14. Set up a nice way of putting serial numbers on electronics early.
15. Set up standards for storing test data and life history on electronics early.
16. Early on, foster a relationship with other GW labs as far as electronics is concerned. Don't reinvent the wheel.

Summary

- Main Flaw: Inflexible design; no plan for mistakes. After several years, LIGO is no longer afraid of mistakes.
- No Model: Some models, but no check with experiment. New way (see Koji Arai, Joe Betsweiser talks): SimPlant
- Grad Student involvement important at early phase; students can work more intensively than older scientists
- Diagnostic Capabilities Vital: How to check that each piece is working correctly? In principle, everything works perfectly anywhere anytime. In practice,...diagnostics must be designed in from the start.
- ...

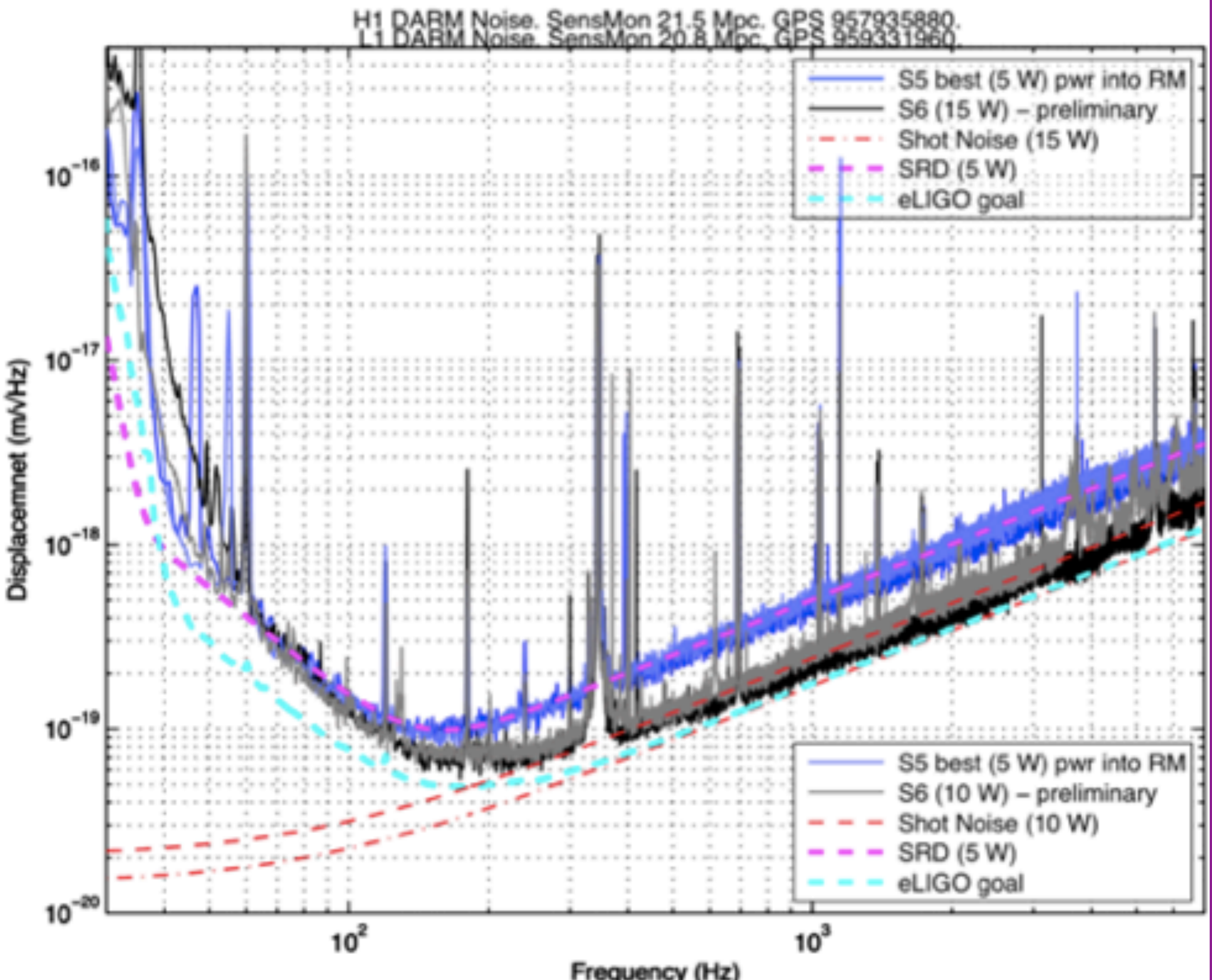
Shot Noise Improvement

For a given incident laser power the ideal shot noise ratio (no contrast defect):

$$\frac{X(f)_{RF}}{X(f)_{DC}} = \sqrt{\frac{3}{2}}$$

- OMC reduces CD from ~10^{-3} (HOM) to ~10^{-6} (TEM00)
- Optical gain: CR/SB overlap vs OMC mode matching

- <u>Extra bonus:</u> DC readout is more suitable for squeezing. Only one vacuum field.
- Squeezing experiment will be installed on H1 after L1 shutdown and run April-September 2011.



Power recycling gain H1:63 L1:42