Sensitivity Improvements in the LIGO Interferometers

Rana Adhikari

December 7, 2004

G040554-00-D

Outline

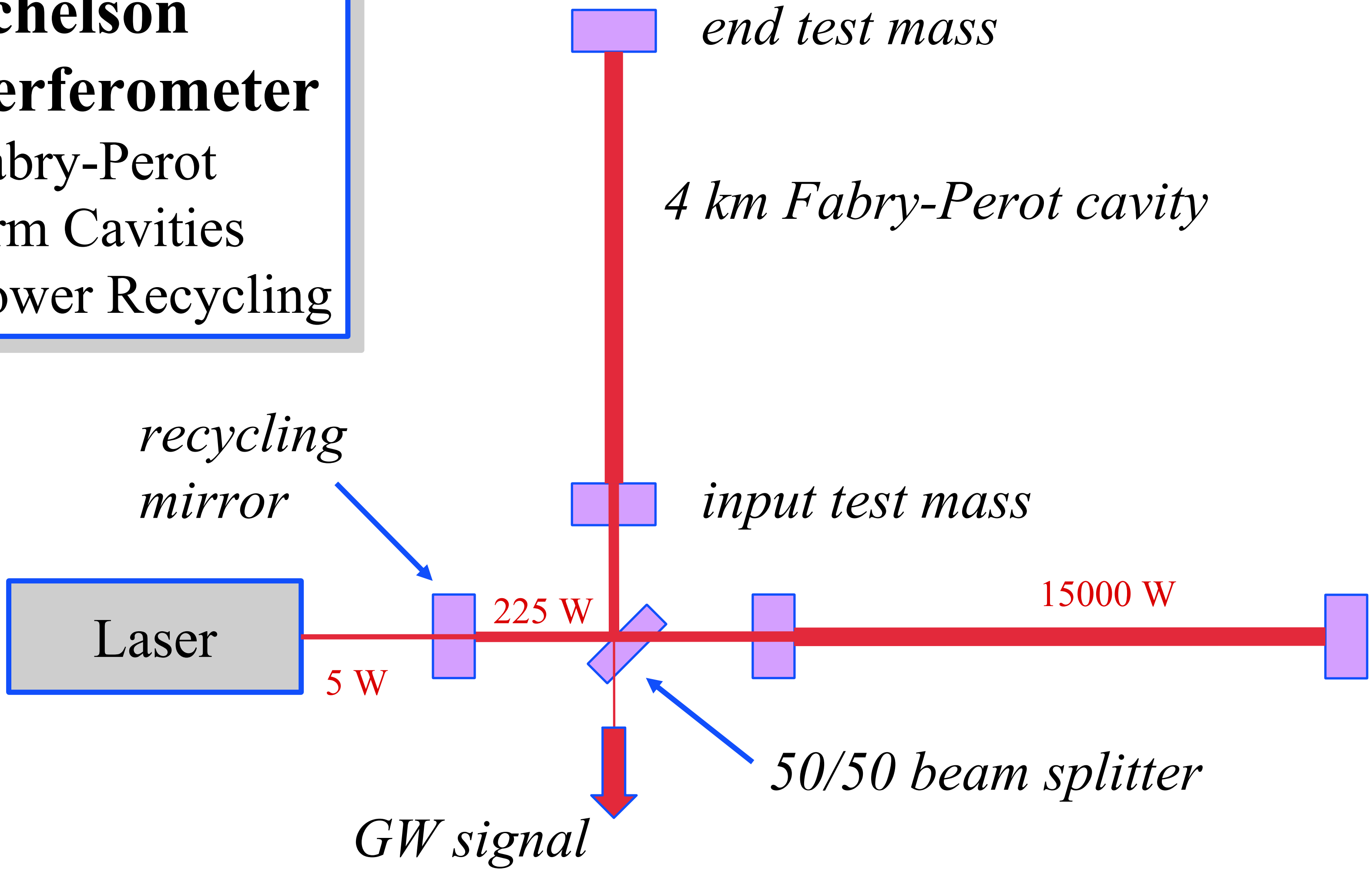
- Sensitivity & Duty Cycle in the last Science Run
- **Louisiana:** *Active Seismic Isolation*
- **Washington**
  - High Power Operations
  - Active Thermal Compensation
  - Reduction of several noise sources
- Near term plans

LIGO Interferometers

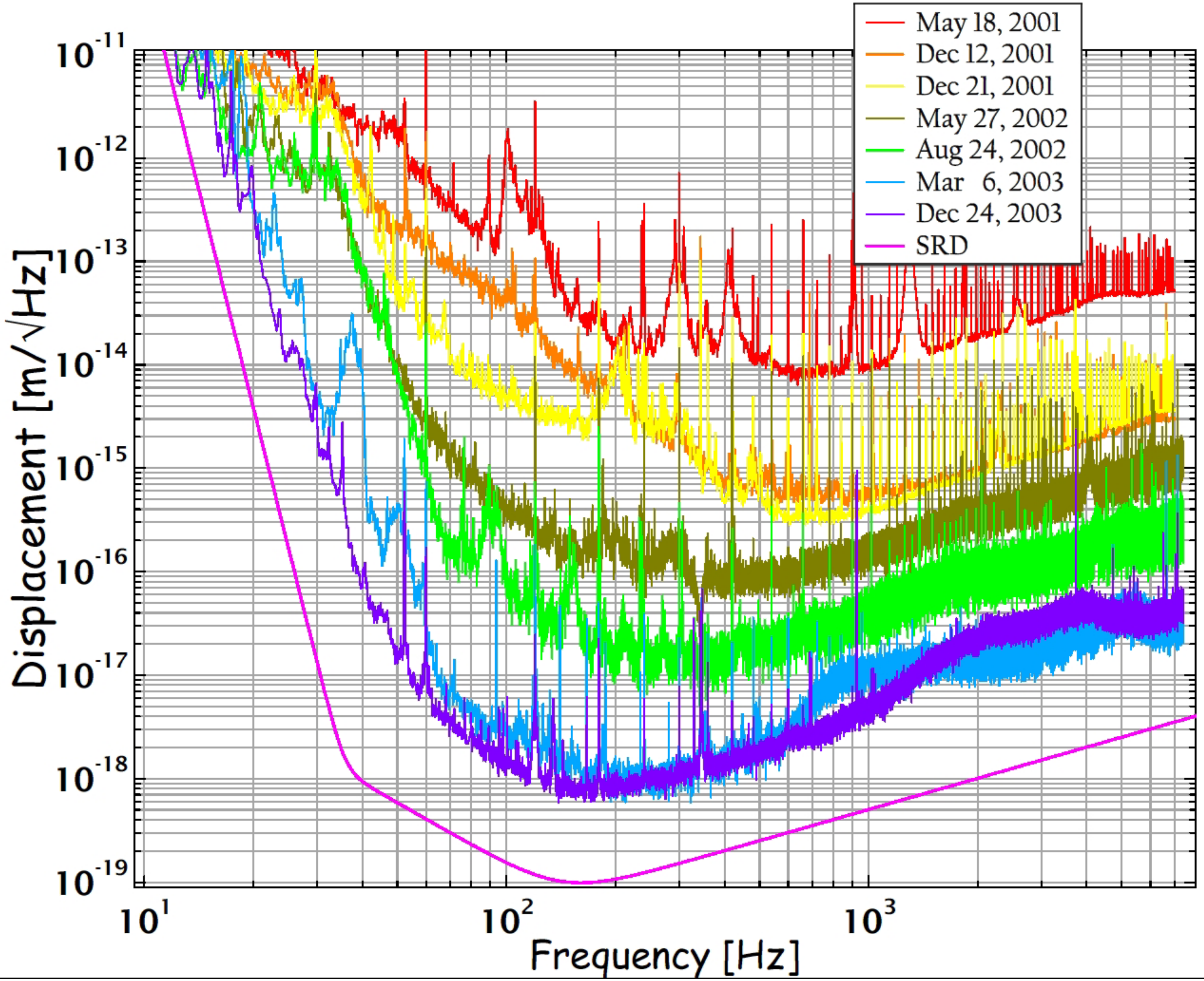
Michelson Interferometer

+ Fabry-Perot Arm Cavities

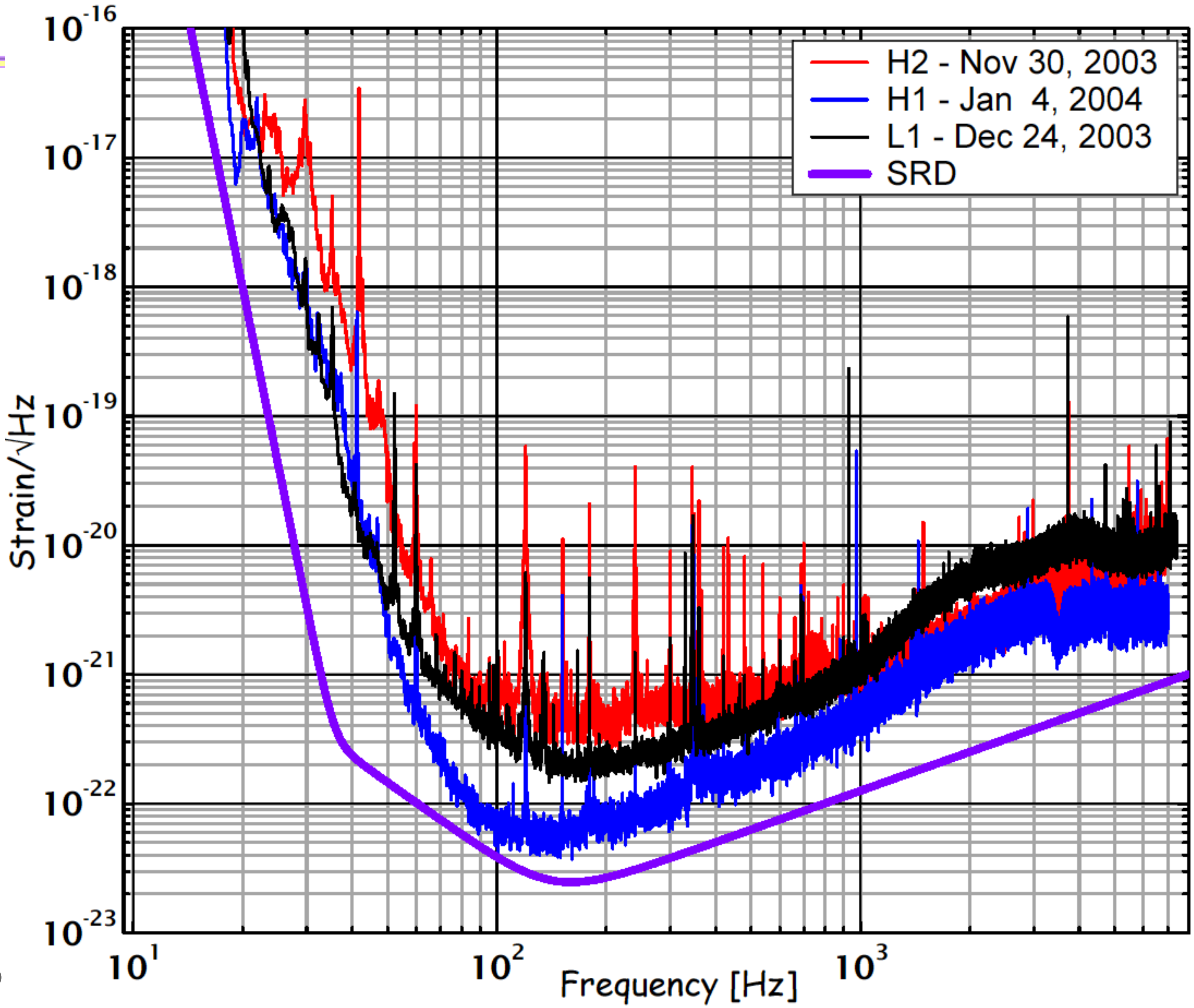
+ Power Recycling



Noise Progression of the Livingston Interferometer

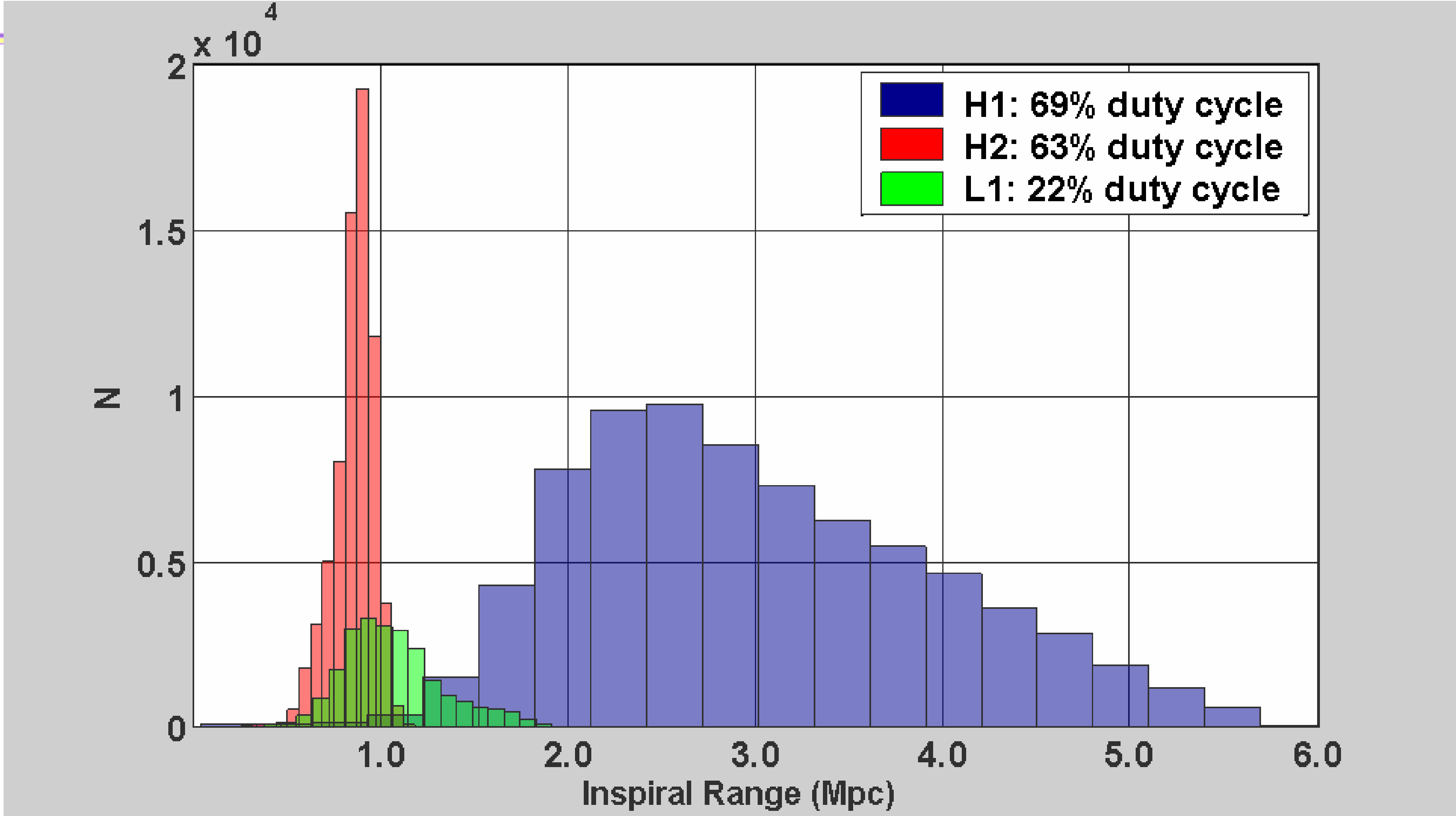


Science Run 3: best sensitivities



LIGO

S3: reliability & stability



Average Effective Distance to see a 1.4/1.4 NS/NS Inspiral with SNR>8

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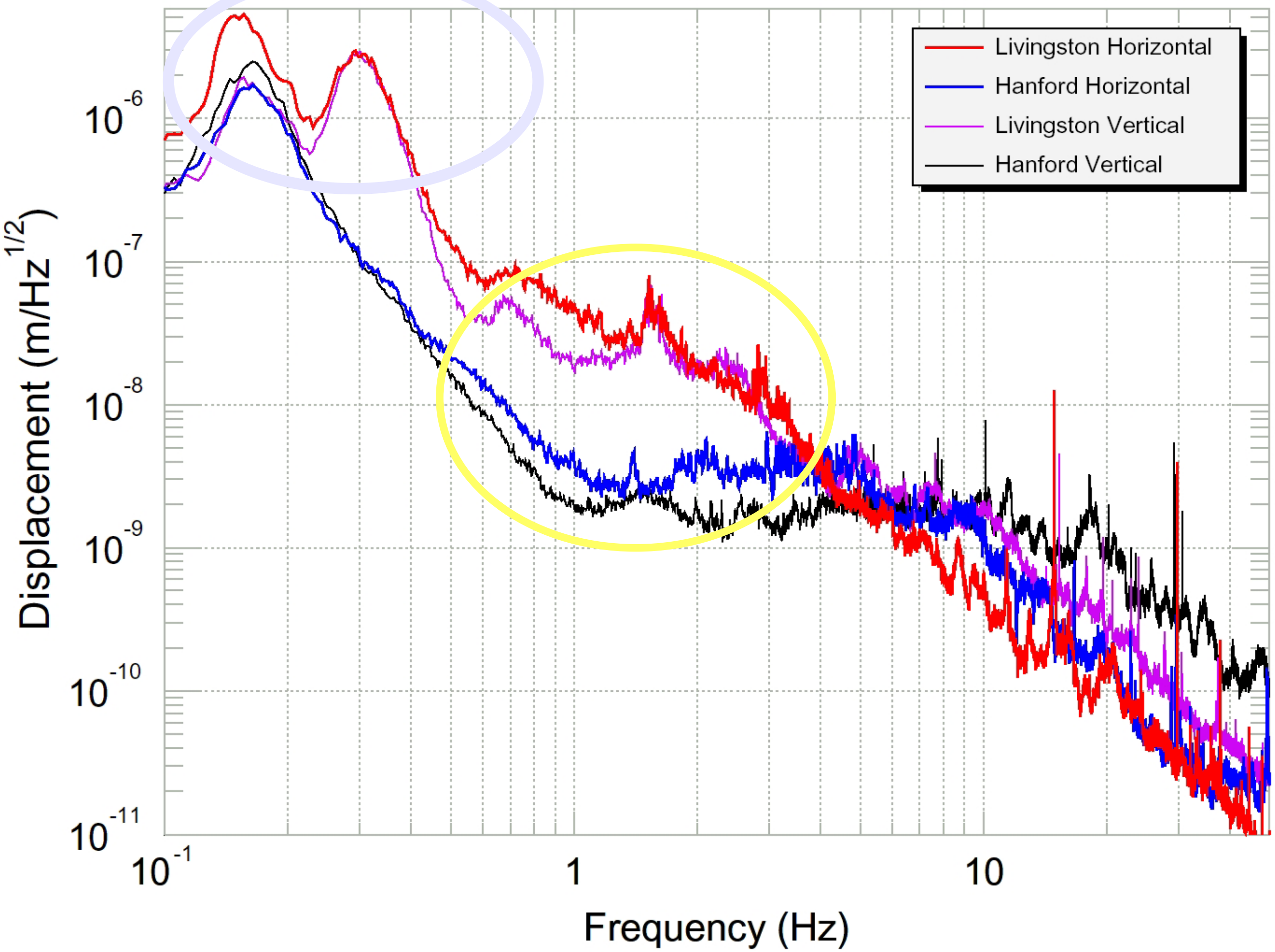
Seismic Noise

Ocean activity, hurricanes



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

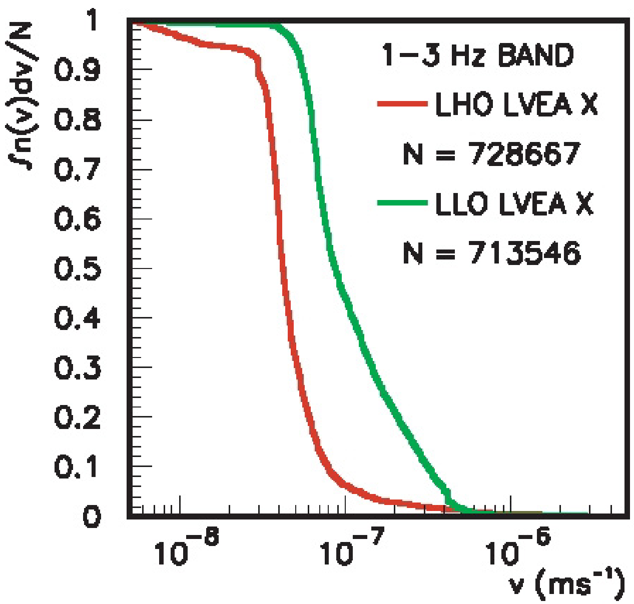
Amplified by internal isolation stack resonances

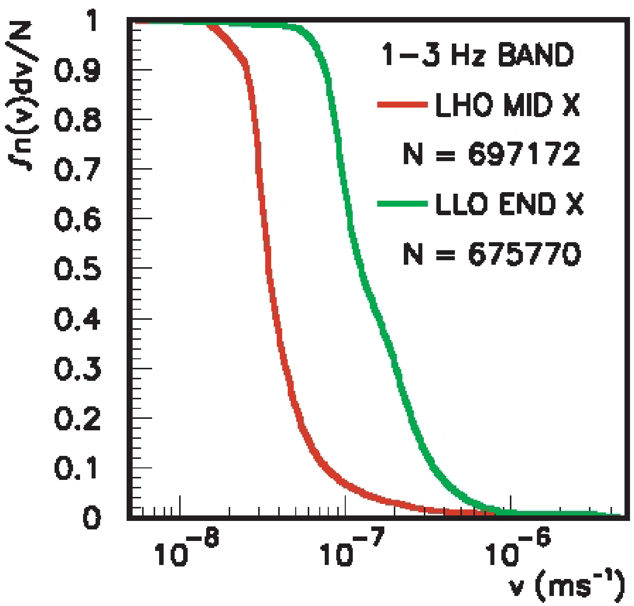
Seismic Noise Statistics

Ground velocity statistics measured over 600 days

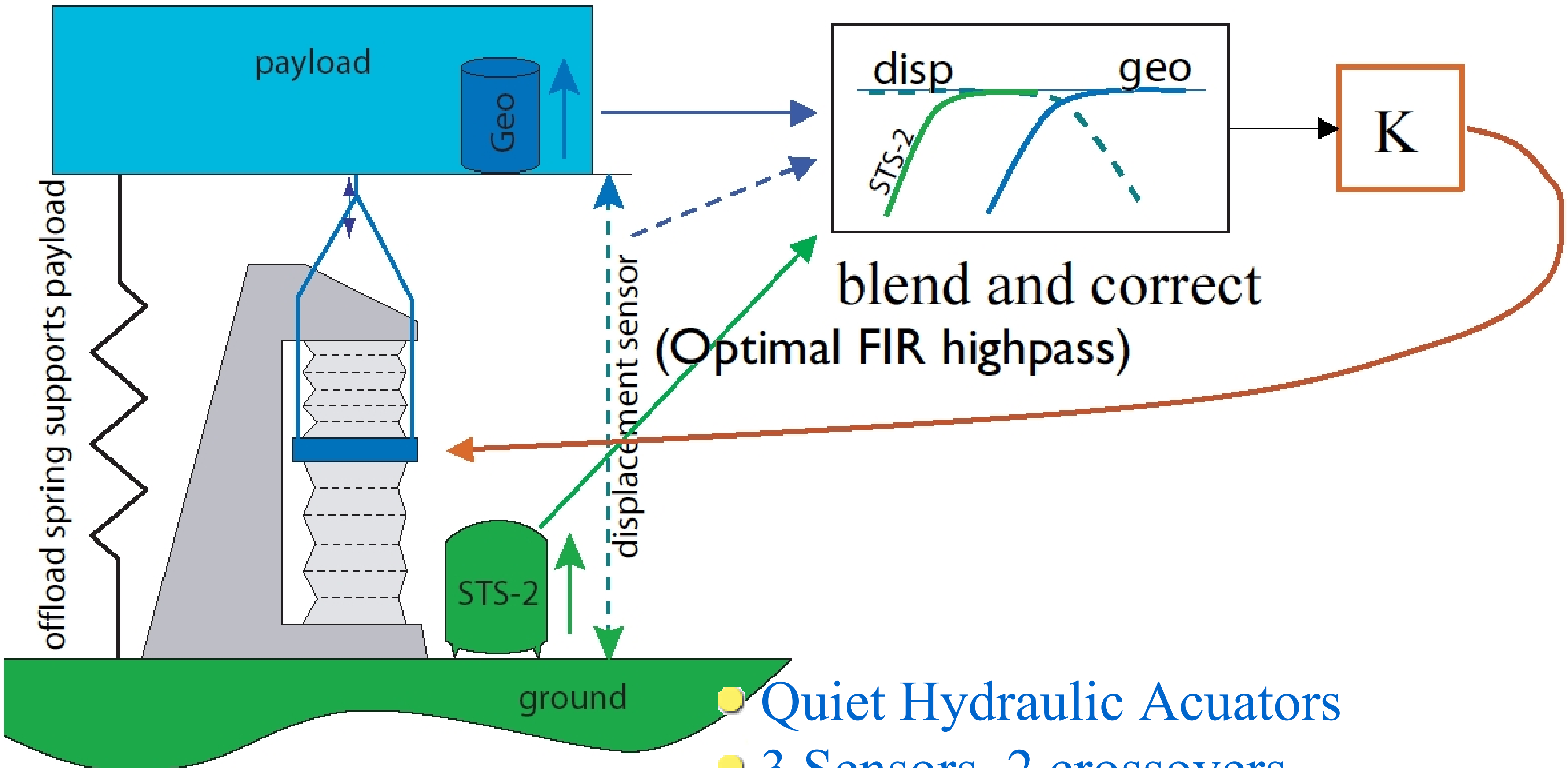
example: 1–3 Hz 90th percentile values

site	chan	90%, µm/s	llo/lho
LLO	lvea x	0.31	4.0
	lvea y	0.29	3.6
	ex x	0.34	4.5
	ey y	0.75	7.3
LHO	lvea x	0.078	
	lvea y	0.083	
	mx x	0.077	
	my y	0.10	

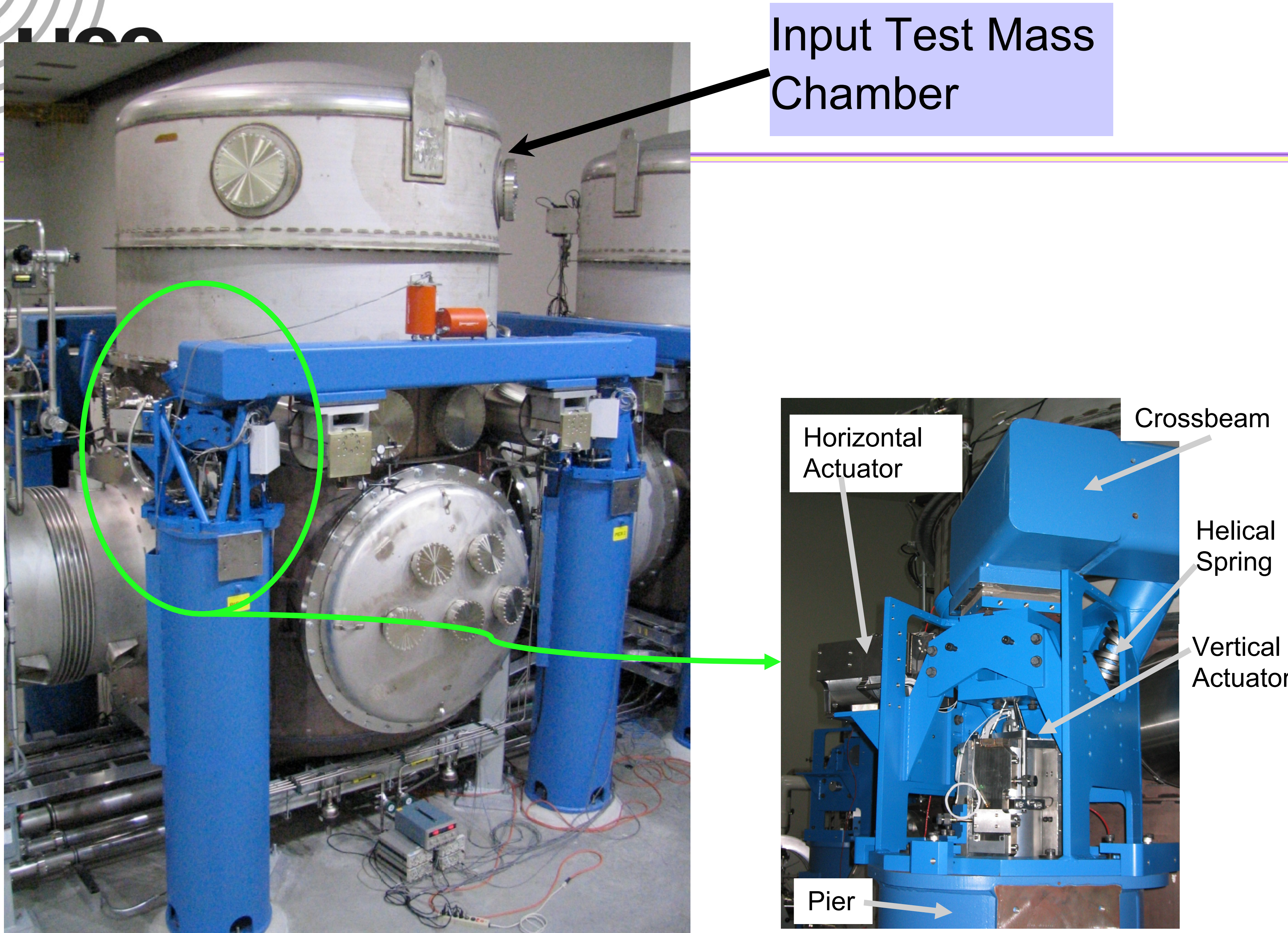




Active Seismic Isolation



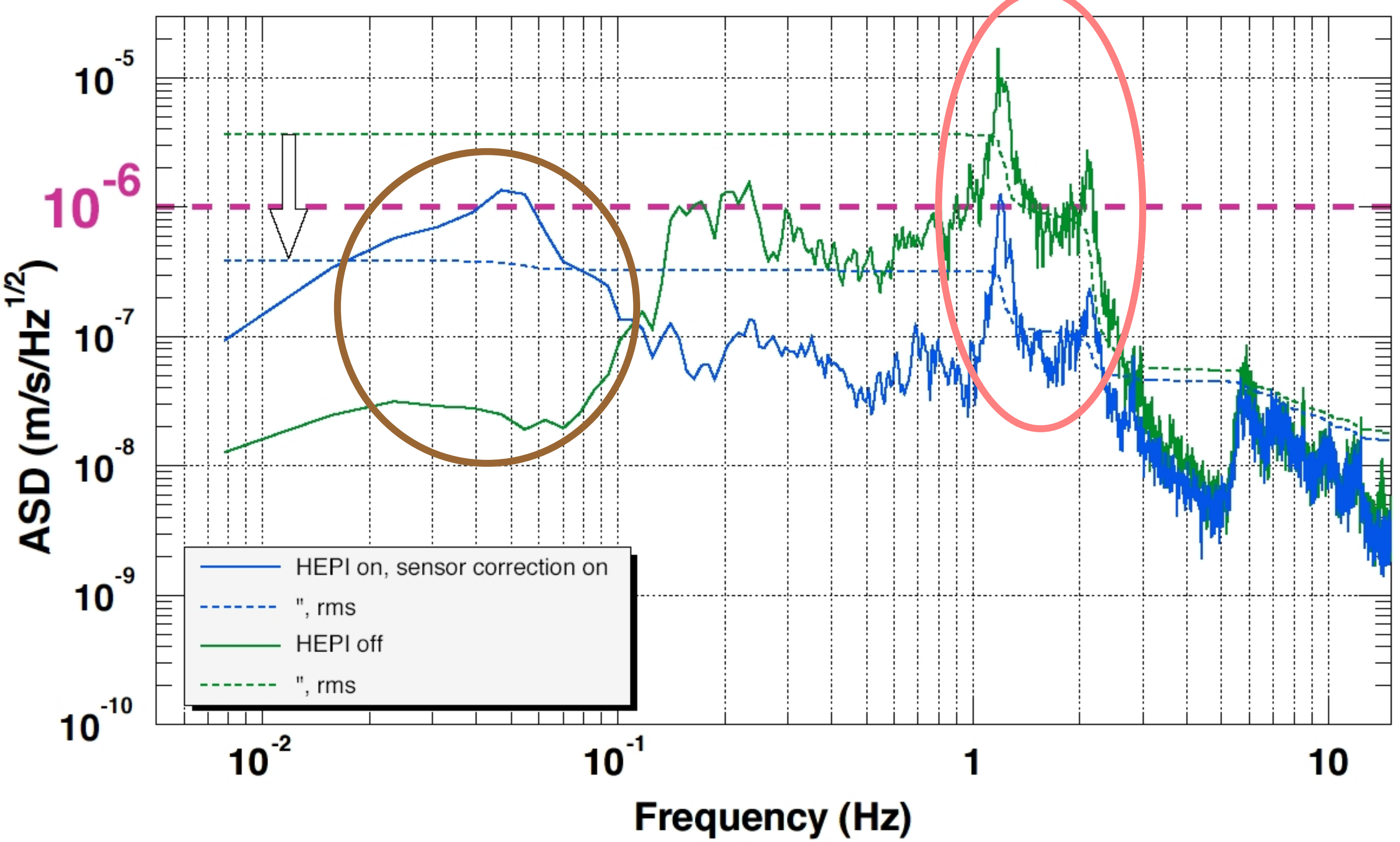
- Quiet Hydraulic Acuators
- 3 Sensors, 2 crossovers
- Position sensors for DC lock
- Ground sensor for low freq. correction
- Payload geophone for high frequencies


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

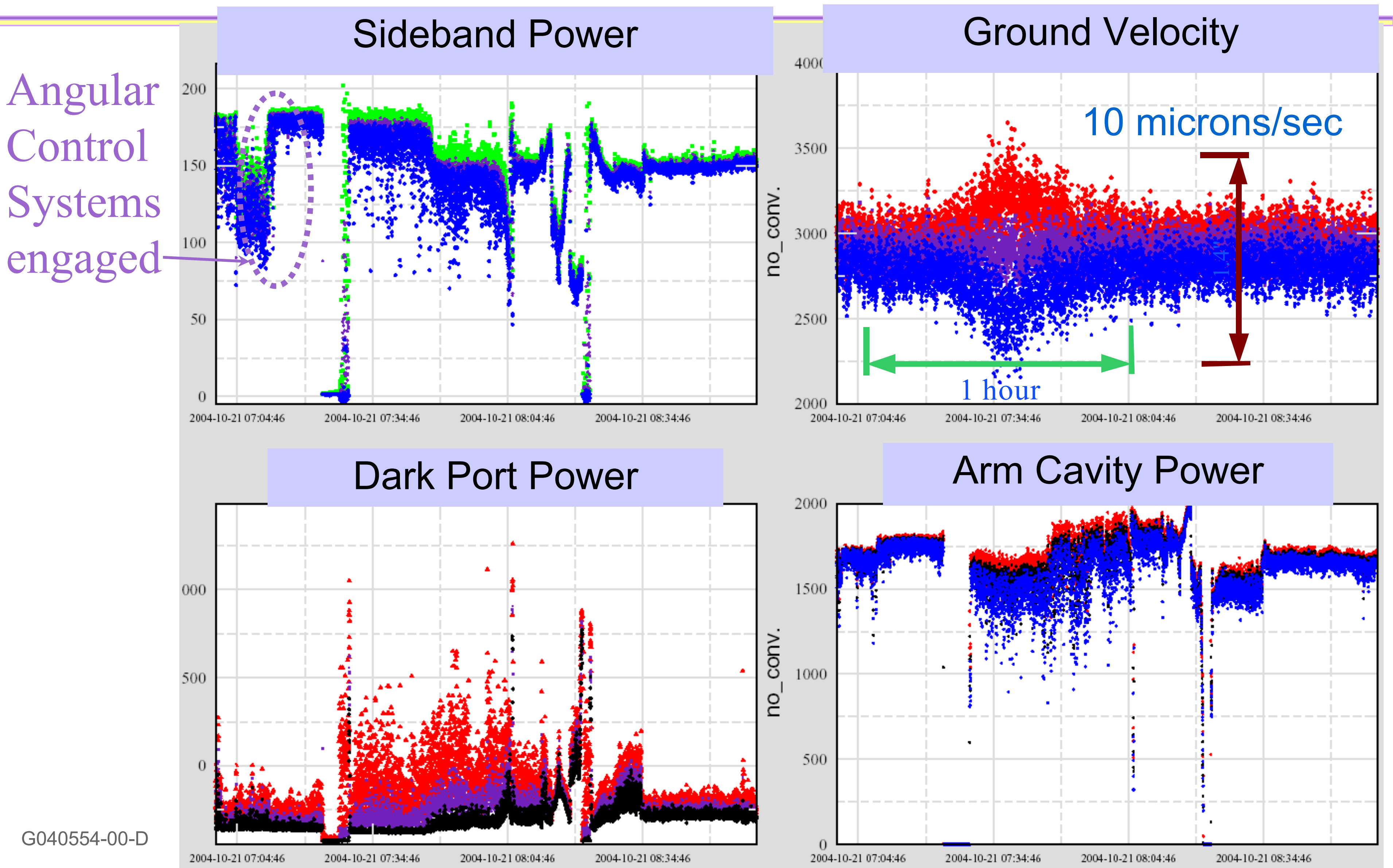
Isolation Performance on a noisy afternoon

Amplification in the earthquake band: automatic fade-out during earthquakes

10x reduction in the crucial frequency band



Test of Full Interferometer: First lock through a train



Isolation Status

- All hardware installed
  - 16 sensors + 8 actuators per chamber
  - 9 chambers
  - 3 ground seismometers
- All chambers locked at DC with PS servo loops
  - 3 (test-mass) chambers fully isolated
  - 3 other chambers have limited 1-3 Hz isolation
  - Servo tuning knowledge is being spread
- Some control authority re-allocation done
  - Suspension angle bias relieved (allows lower noise electronics)
  - Earth tide motions (~0.5 mm) (allows uninterrupted locking)

Interferometer can now be worked on in the daytime !!

Outline

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- Louisiana
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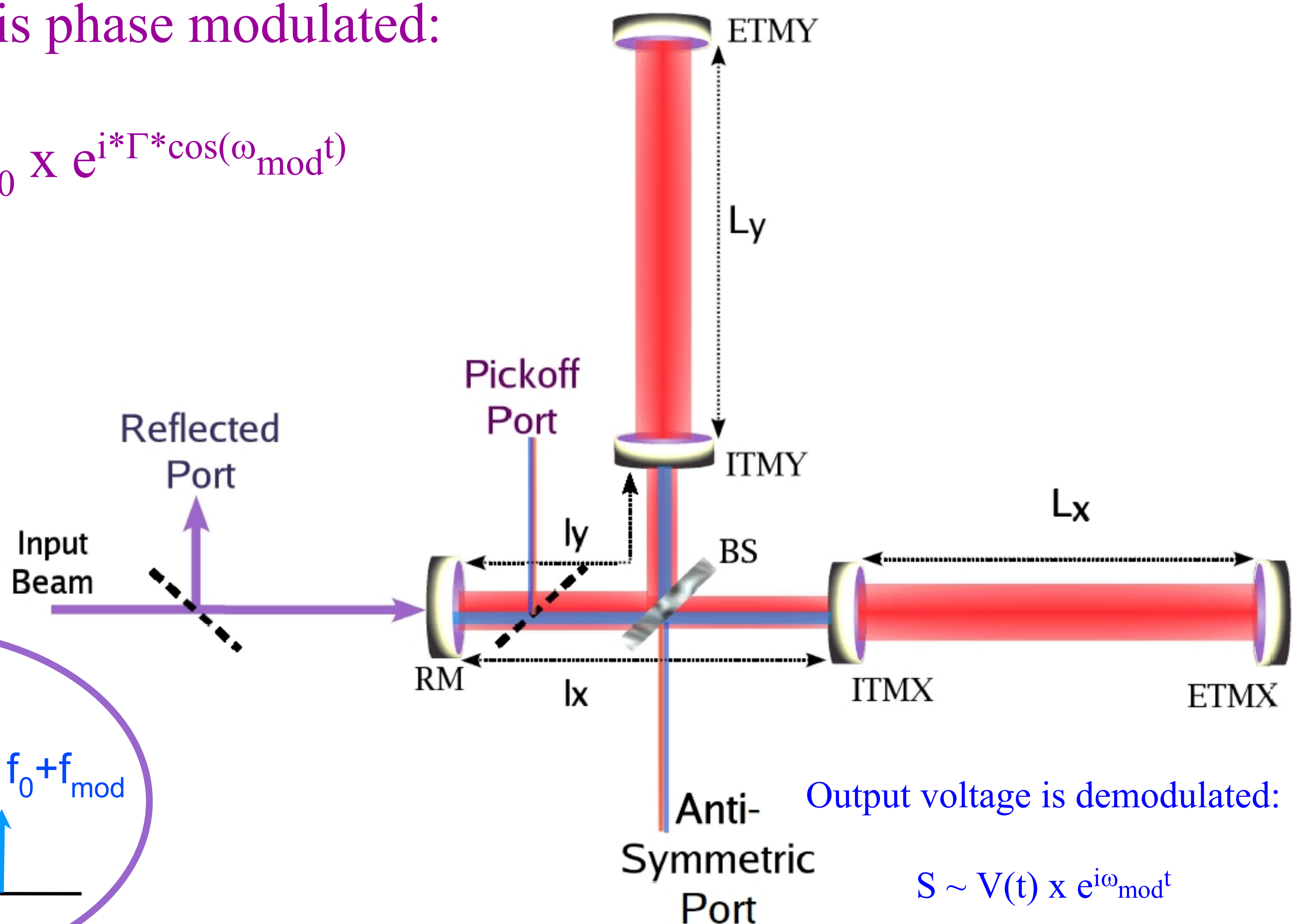
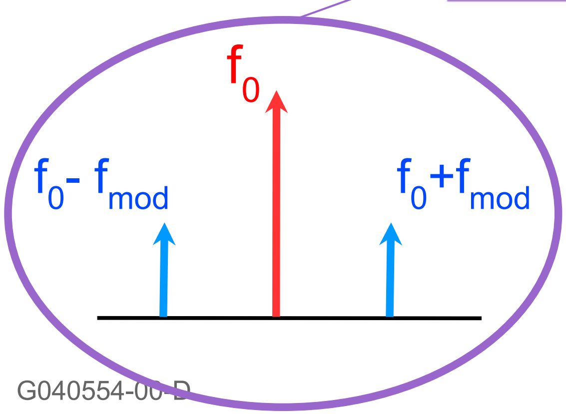
  - Angular Control System (wavefront sensing)
- **Washington**
  - High Power Operations
  - Active Thermal Compensation
  - Reduction of several noise sources
- Near term plans

Optical Schematic

Input field is phase modulated:

$$E_{in} = E_0 \text{ x } e^{i*\Gamma*\cos(\omega_{mod}t)}$$

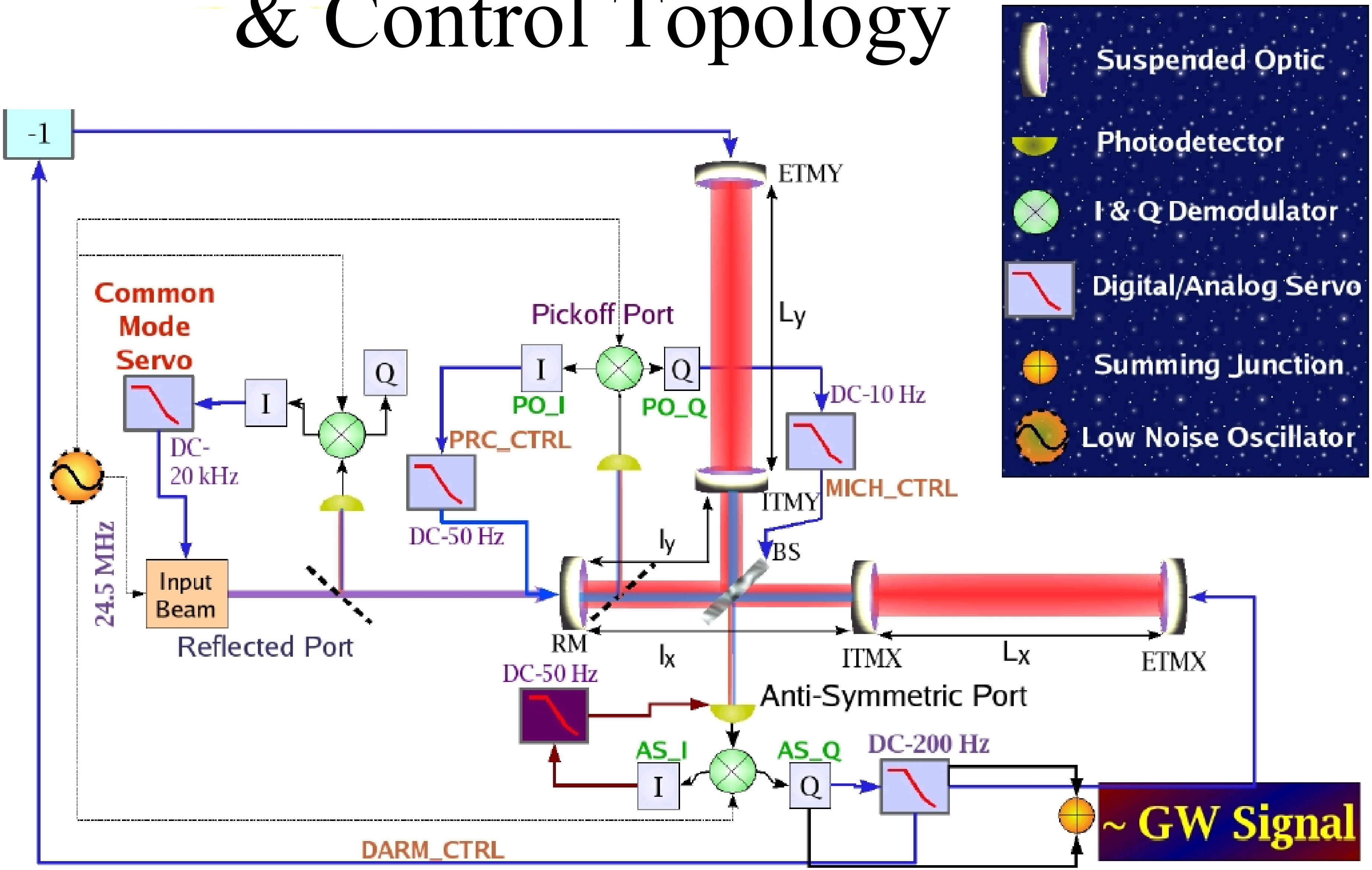




Output voltage is demodulated:

$$S \sim V(t) \text{ x } e^{i\omega_{mod}t}$$

Optical Layout & Control Topology



LIGO

High Power Interferometry

- Getting High Power
  - **Laser Power has declined over the 1000's of hrs. of laser life**
  - Previously could not handle the high power
  - Rebuild / Tune up lasers. Diagnose losses in the input optics.
- Detecting all the light
  - **Acquisition/Detection modes: large transients / low noise**
  - Dark port power split -> 4+1 photodetectors
  - Fast Mechanical Shutter to protect diodes from lock loss 'burp'
  - New gain ramping software allows smooth PD handoff
- Radiation Pressure
  - **Significant torque from off center beams**
  - Stage power up: Lock at low power, engage alignment controls, crank up the power
  - Software installed to compensate 'optical spring'
- Thermal Lensing
  - **Deposited heat in optics forms a thermal lens** ($dn/dT = 10^{-5}$)
  - Active curvature correction using an external heating laser

Laser Power Levels

- Hanford 4km power levels

	S3	Now	Design
Laser output	5 W	10 W	*10 W*
Mode cleaner input	3.1 (2.2) W	7.5 W	*8 W*
Recycling mirror input	2.0 (1.4) W	4.8 W	*6 W*

- Plan
  - Tune up other lasers or send back for rebuild
  - Diagnose pre-mode cleaner loss (typically 10-15% lost)
  - Loss in input electro-optic modulators: reduce number from 3 to 1
  - Diagnose suspended mode cleaner loss (20-30% lost)

Handling High Power

- Detecting all the light
  - **Acquisition/Detection modes: large transients / low noise**
  - Dark port power split -> 4+1 photodetectors
  - Fast Mechanical Shutter to protect diodes from lock loss 'burp'
- Radiation Pressure
  - **Significant torque from off center beams**
  - Scripted power up
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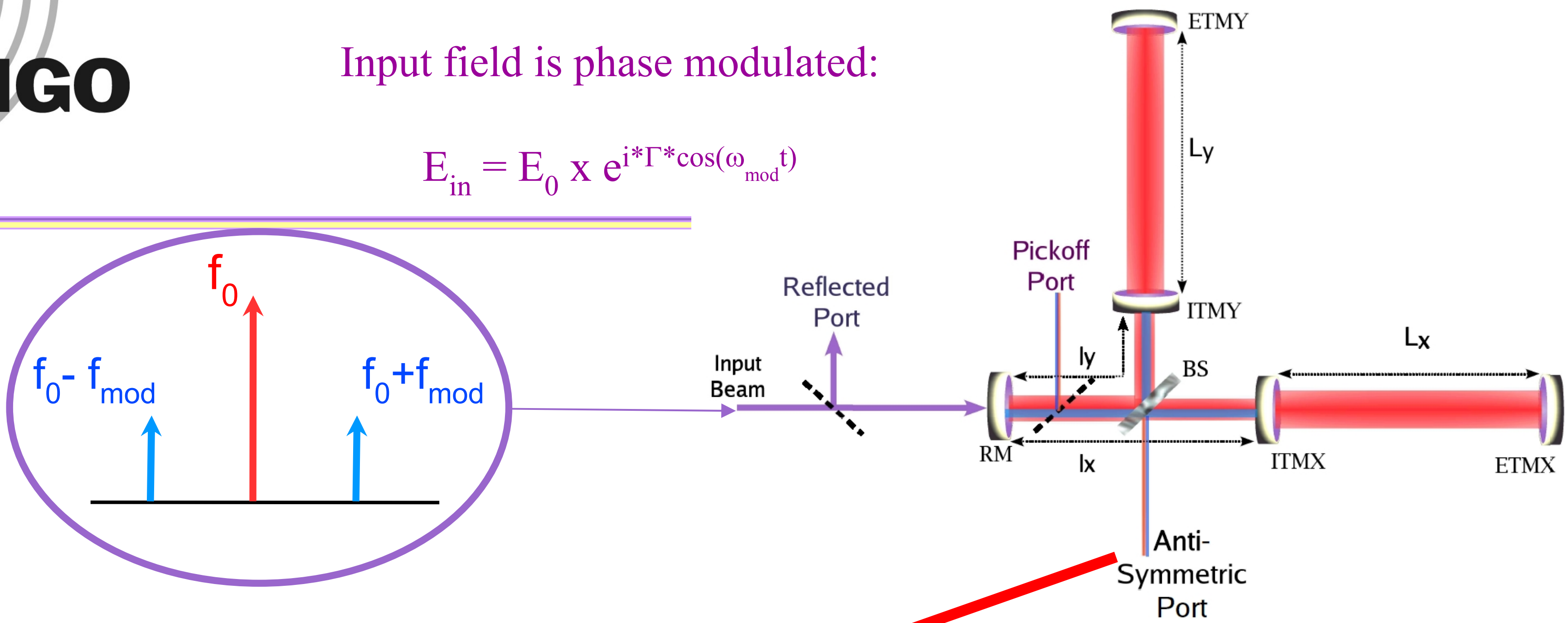
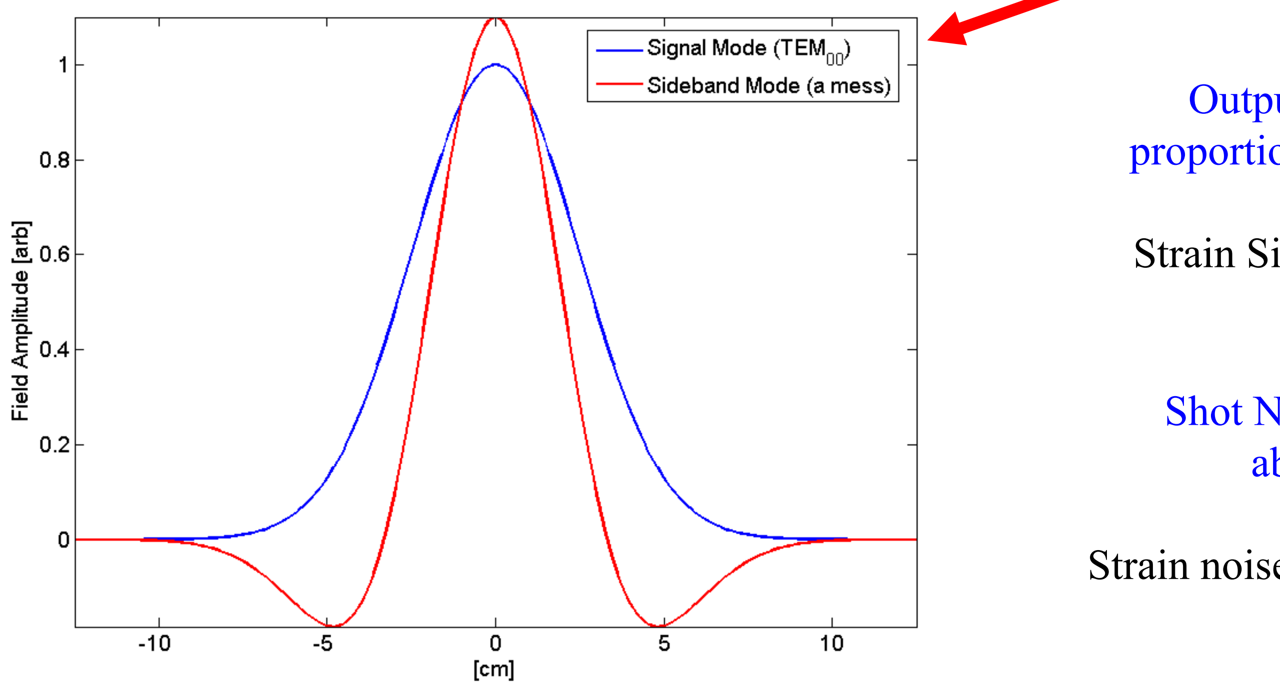




Output Signal, AS_Q proportional to field overlap

Strain Signal ~ $CR_{00} * SB_{00}$

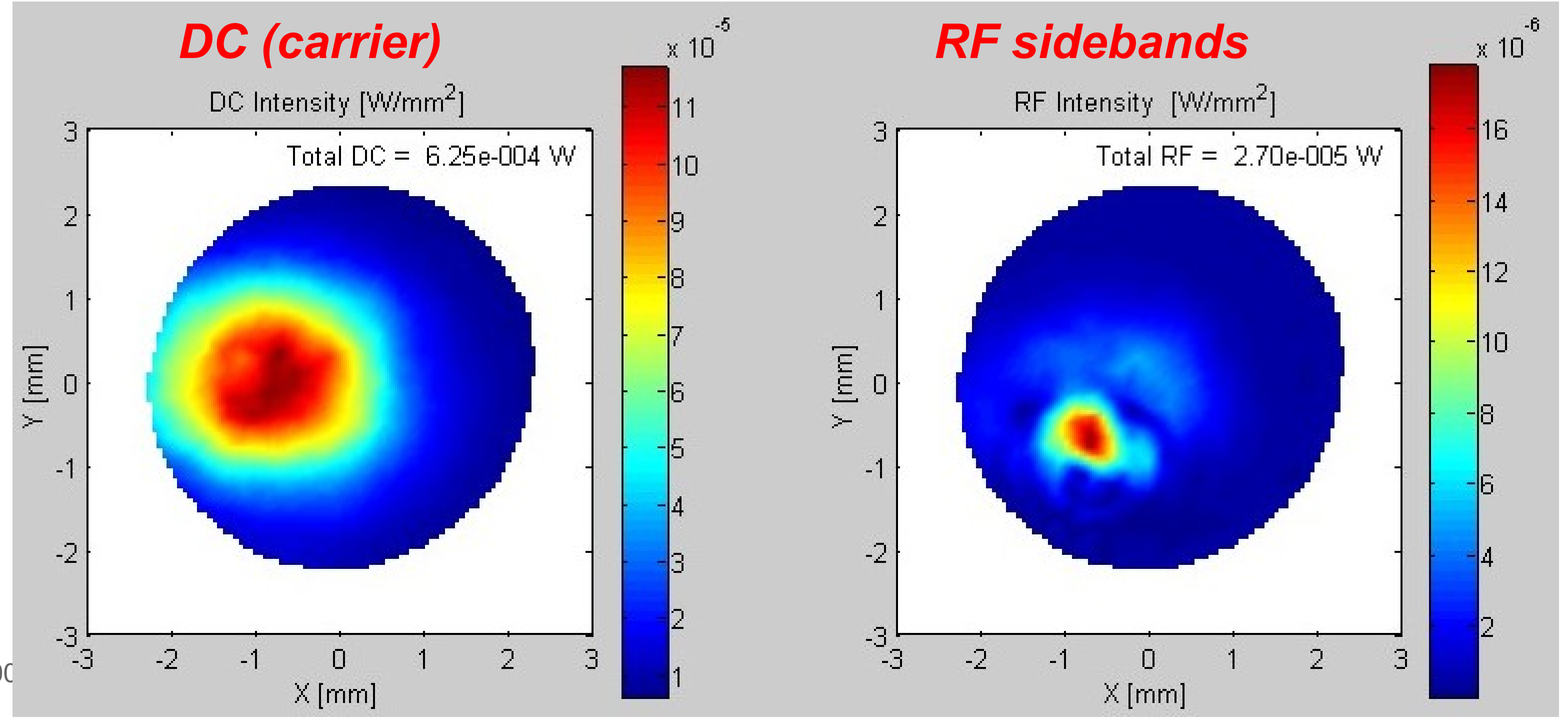
Shot Noise doesn't care about overlap

Strain noise ~ $(CR^2 + 3 * SB^2)^{1/2}$

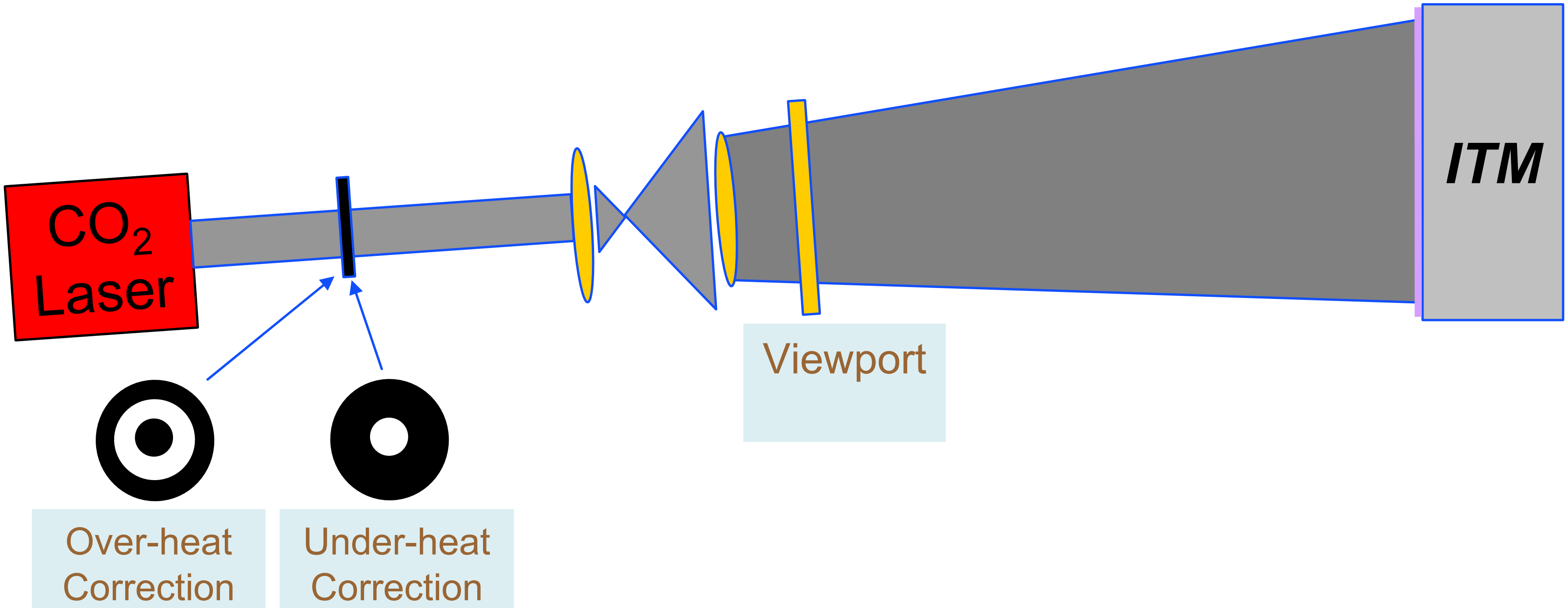
Recycling Cavity Degeneracy

- 'Frontal modulation' scheme depends on efficient coupling
  - Local oscillator field generated at laser, coupled into recycling cavity (not co-resonant in arm cavities)
  - Recycling cavity is **nearly degenerate** ($ROC_{[cold]}$ ~ 15 km, length ~ 9 m)
  - Original design depends on specific, balanced **thermal lensing**
- RF sideband efficiency found to be very low
  - H1 efficiency: ~6% (anti-symmetric port relative to input)
  - incorrect/insufficient ITM thermal lens makes $g_1 \cdot g_2 > 1$ (unstable resonator)

$\Rightarrow$**Bad mode overlap!**



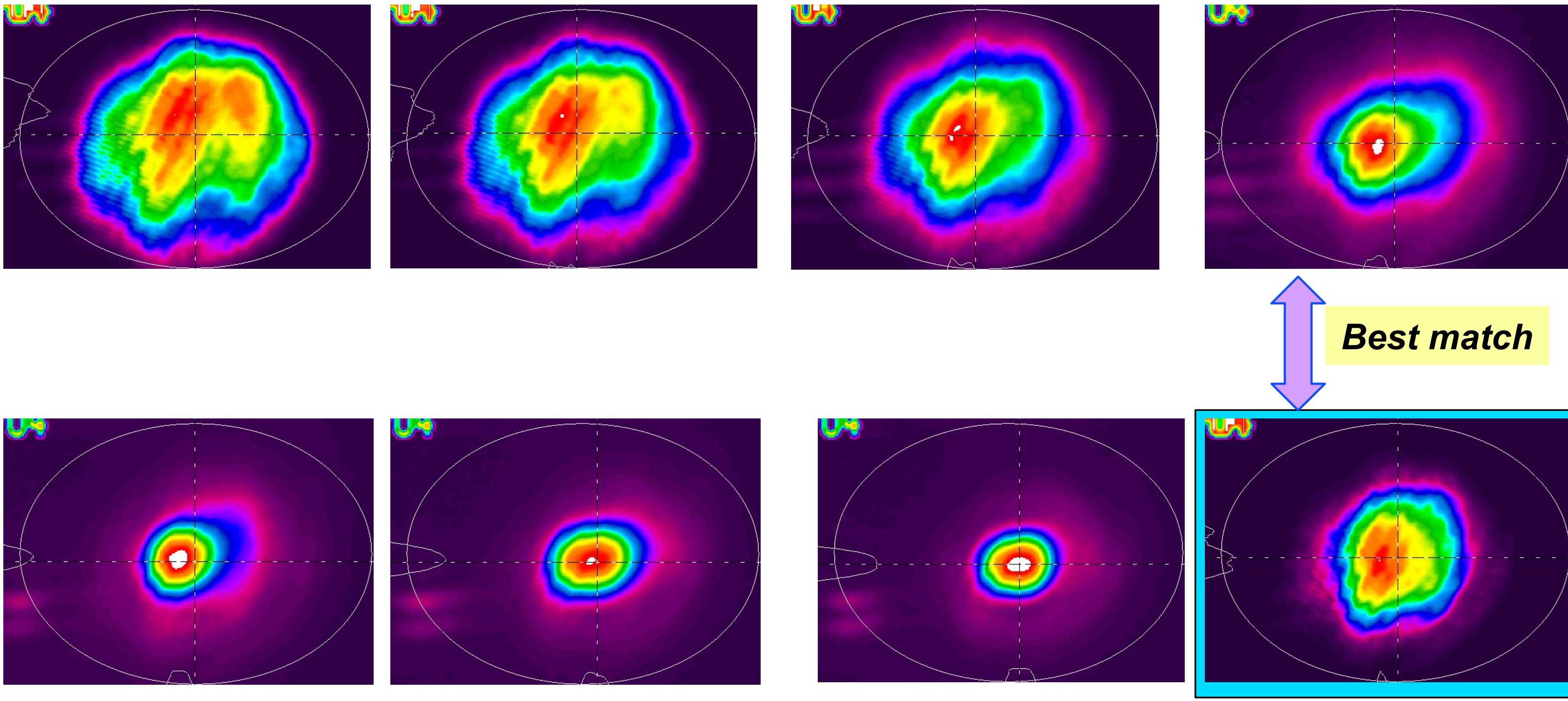
Thermal Compensation



- Heat/'Cool' the Recycling cavity
  - Increase the buildup and correct the mode shape for the RF sidebands
  - Increase the fields' overlap; increase of shot-noise limited sensitivity
- ~100 mW of power required to correct curvature

Sideband beam images at the dark port

No Heating | 30 mW | 60 mW | 90 mW



120 mW | 150 mW | 180 mW | Input beam

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  - **Reduction of several noise sources**
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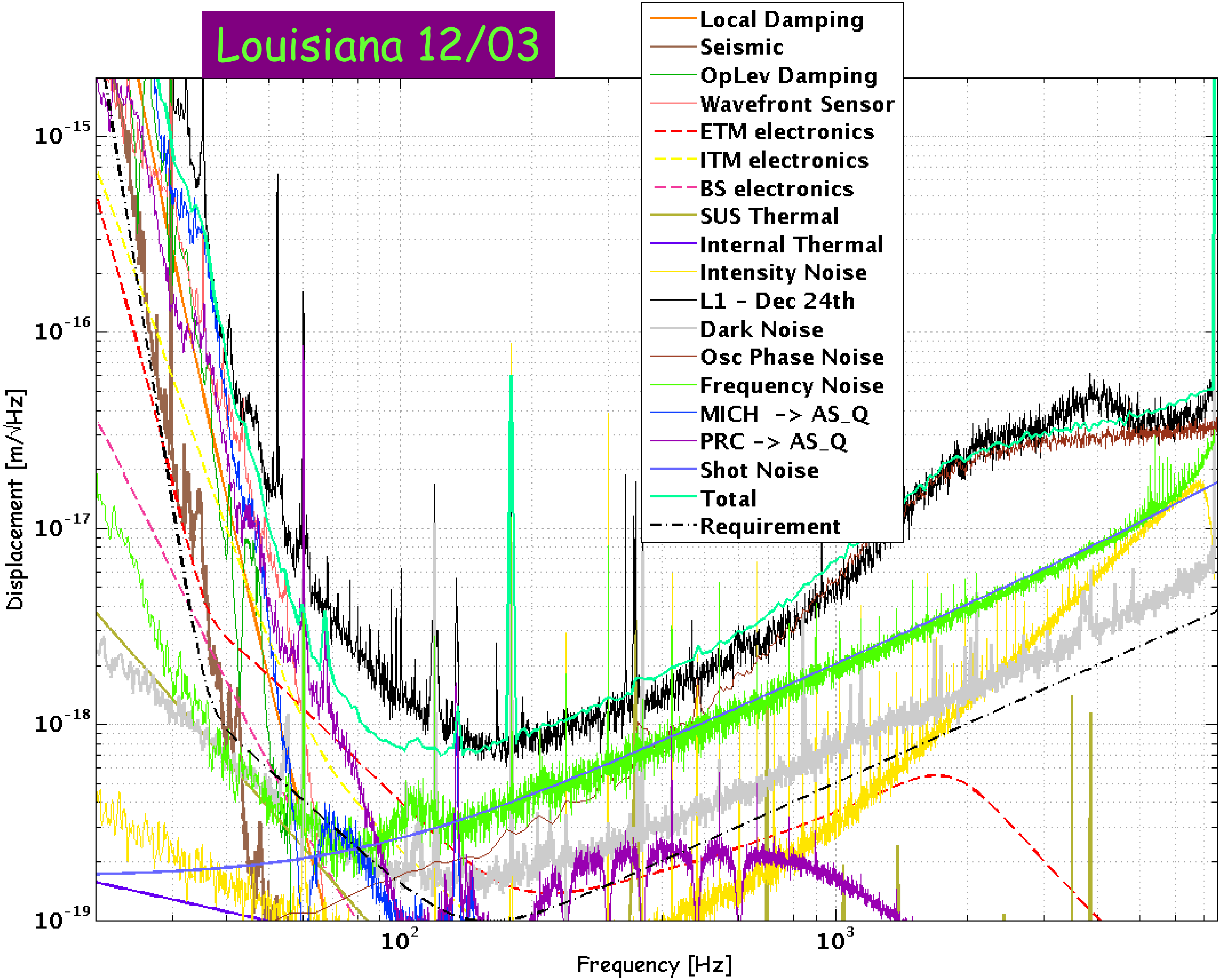
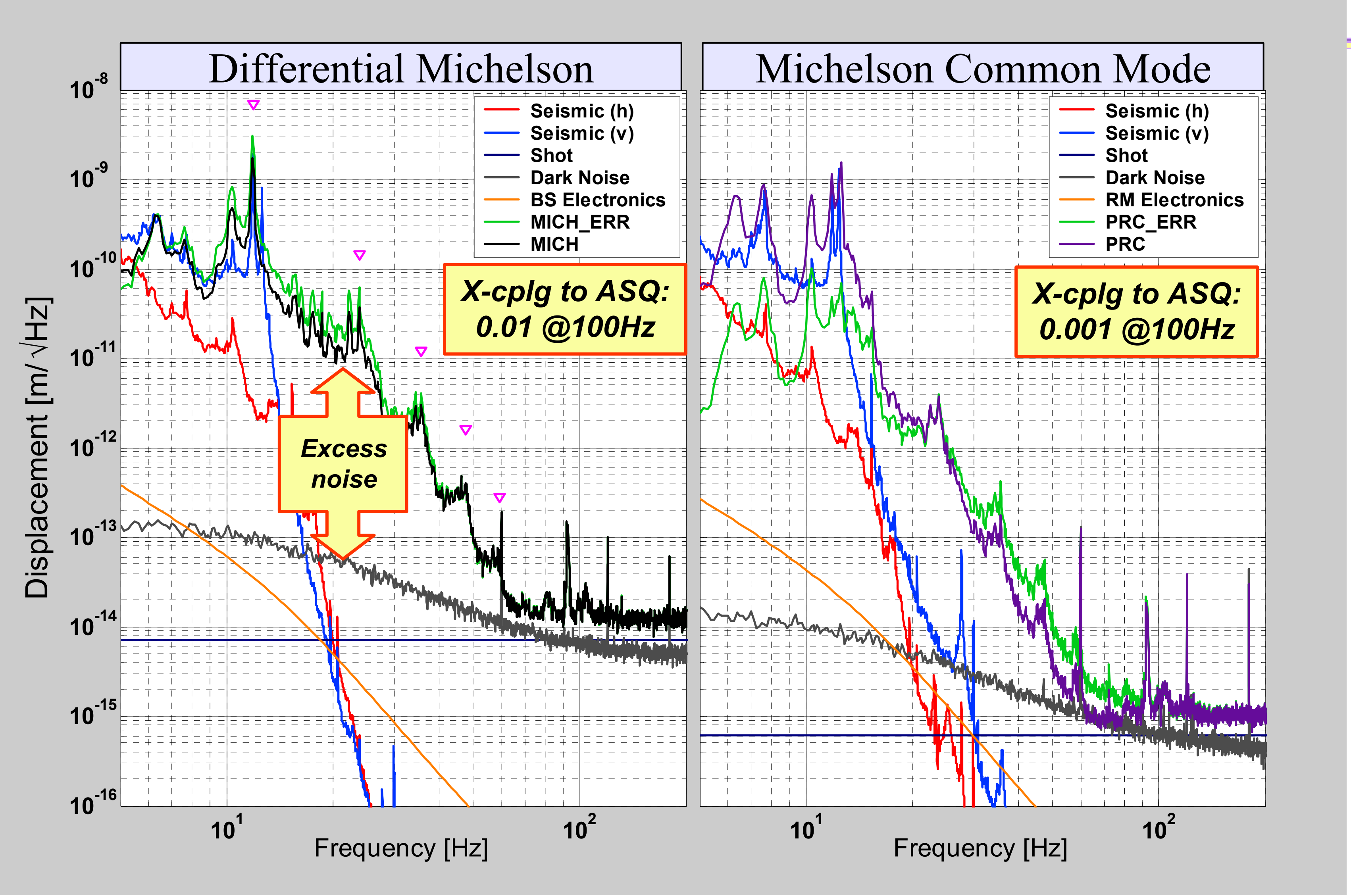
Louisiana 12/03



Noise Reduction

- Auxiliary length loops: a change in strategy
  - Reduced sensing noise: more power, thermal compensation
  - High gain -> reduced nonlinear upconversion
  - Off-diagonal correction paths (“feed-forward”)
- Angular controls noise => apparent cavity length
  - Coupling: spot mis-centering or coil/magnet gain imbalance
  - Output of software 'lock-in' used to servo coil gains
  - Automated procedure (easy to modify shell scripts)
- Photodetector saturation at 2 x fmod
  - Circuit modified with an 'active' notch
- RF oscillator phase noise
  - Dedicated crystal oscillator (OCXO)
  - Coupling reduced through differential thermal lensing

Auxiliary degrees-of-freedom: small coupling, but very noisy

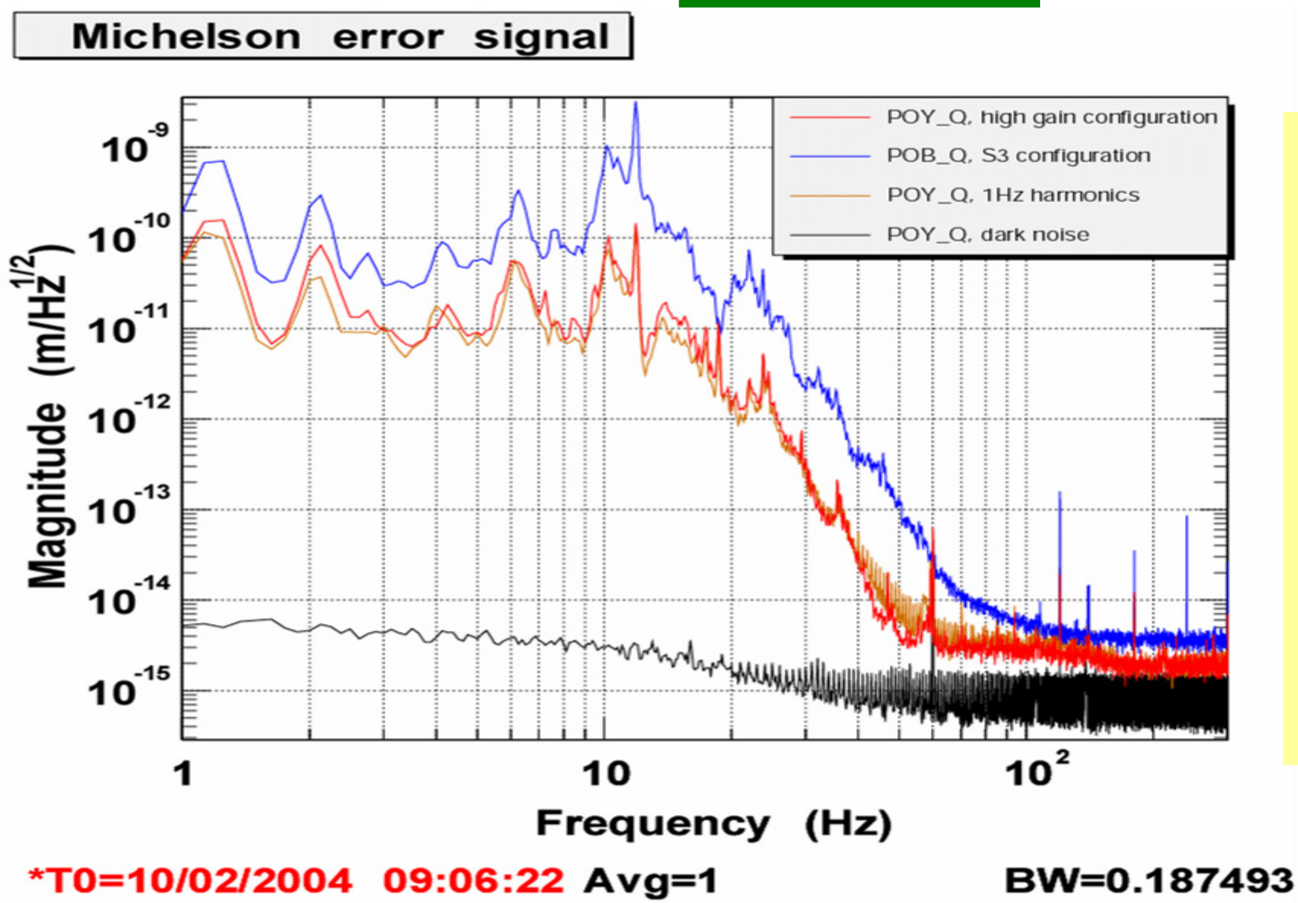


Excess noise: optical gain modulation

- *Signal* $\propto$ *(sideband field)·(length deviation)*

Intermodulation

Reduce these by increasing loop gain



Effects of increased servo gain:

- 10x noise reduction in the recycling cavity loops: MICH, PRC, & WFS

- noise small enough to use the 'high power' PickOff

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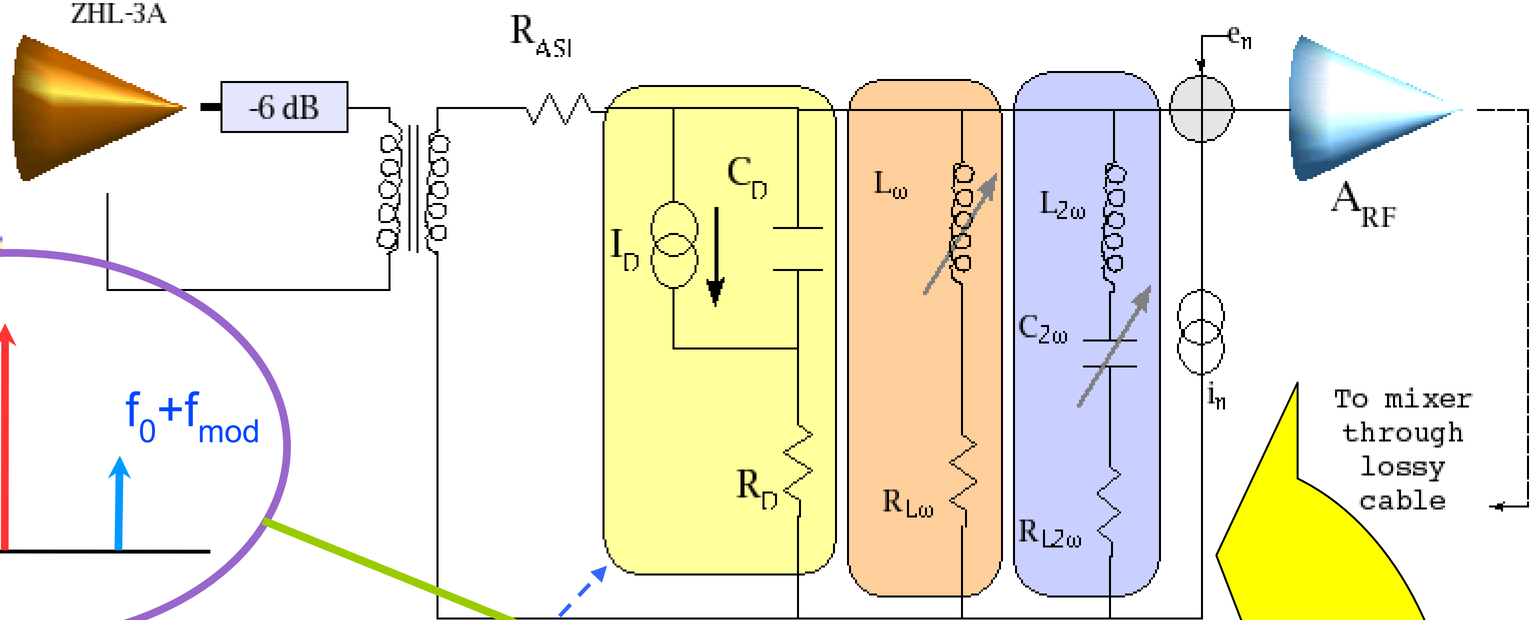
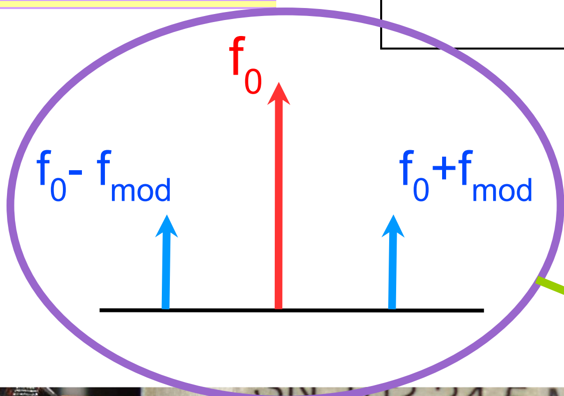
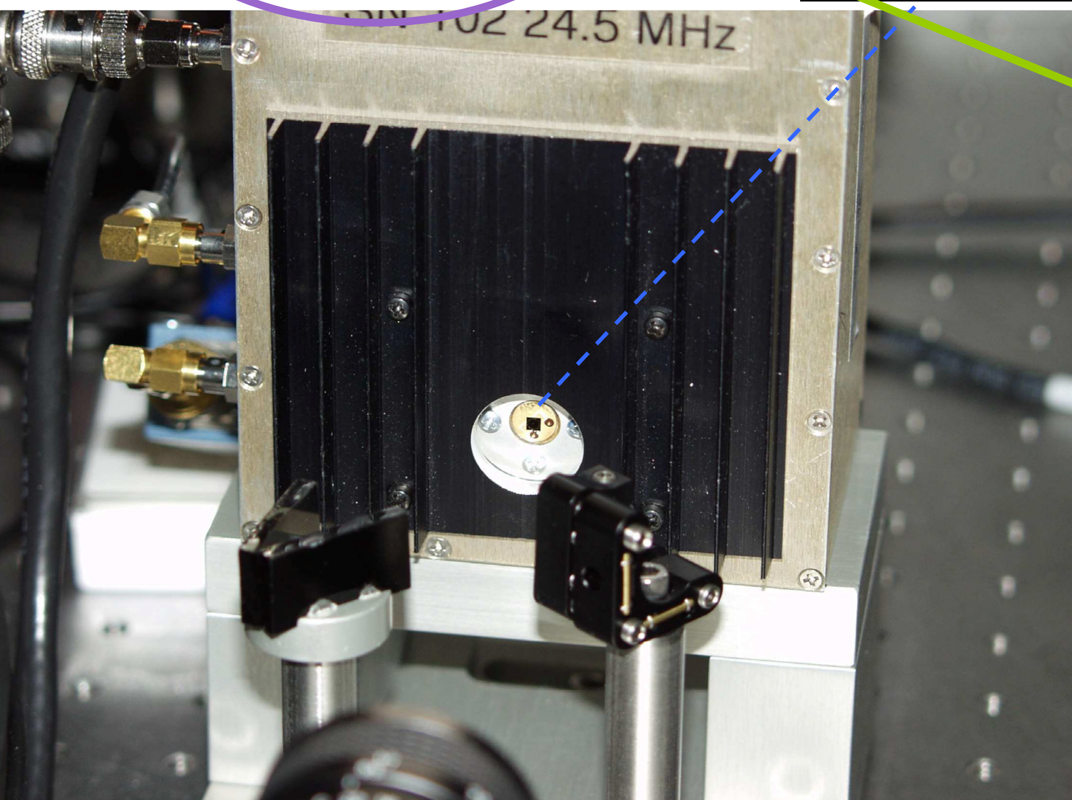
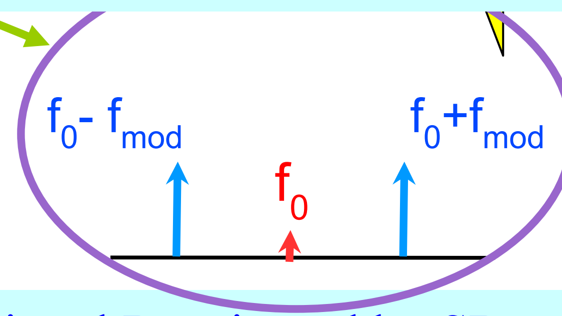
LIGO







Dark Port = No Carrier



Signal Dominated by SBs

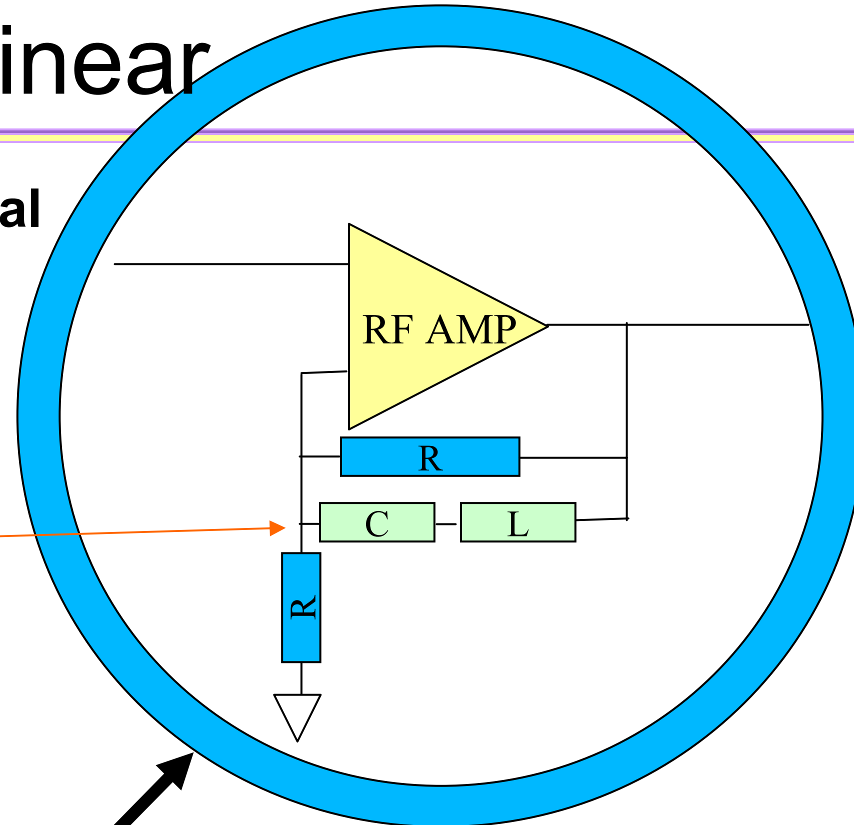
at $2 \times f_{mod}$

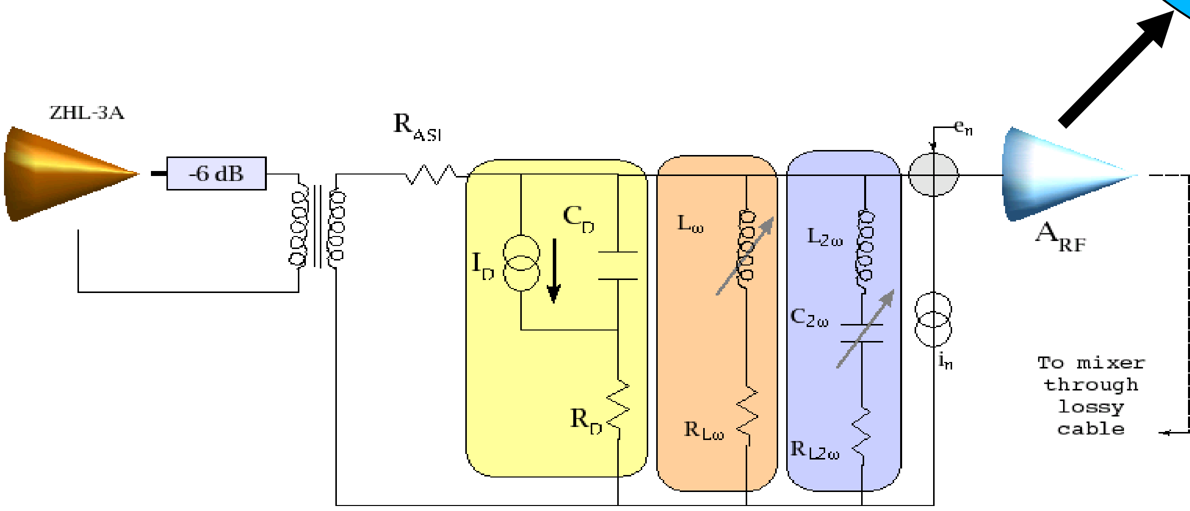
Initial notch

design not good enough

The photodetector is ALWAYS nonlinear

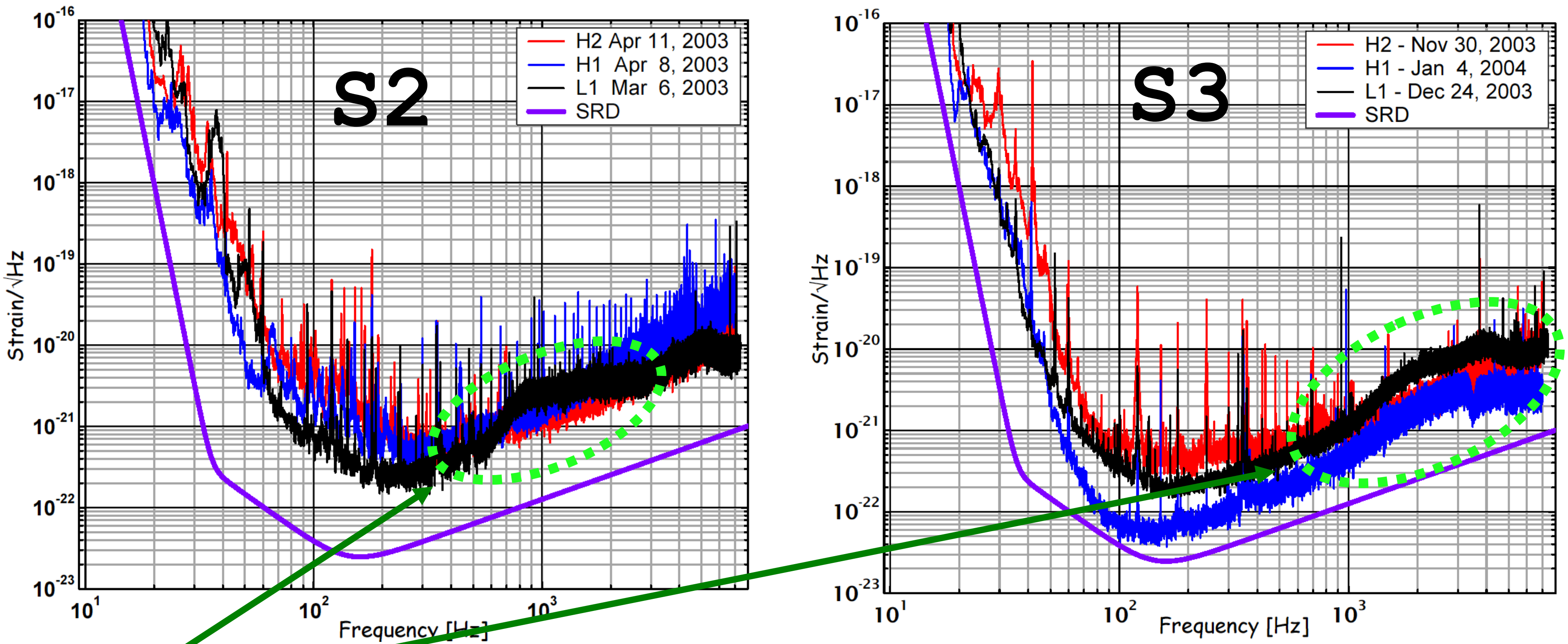
- **RF amplifier saturated by 50 MHz signal**
  - Nonlinear behavior over a wide range of signal levels… ?
- Passive notch only gives -40 dB
- Active notch gives another -20 dB





LIGO

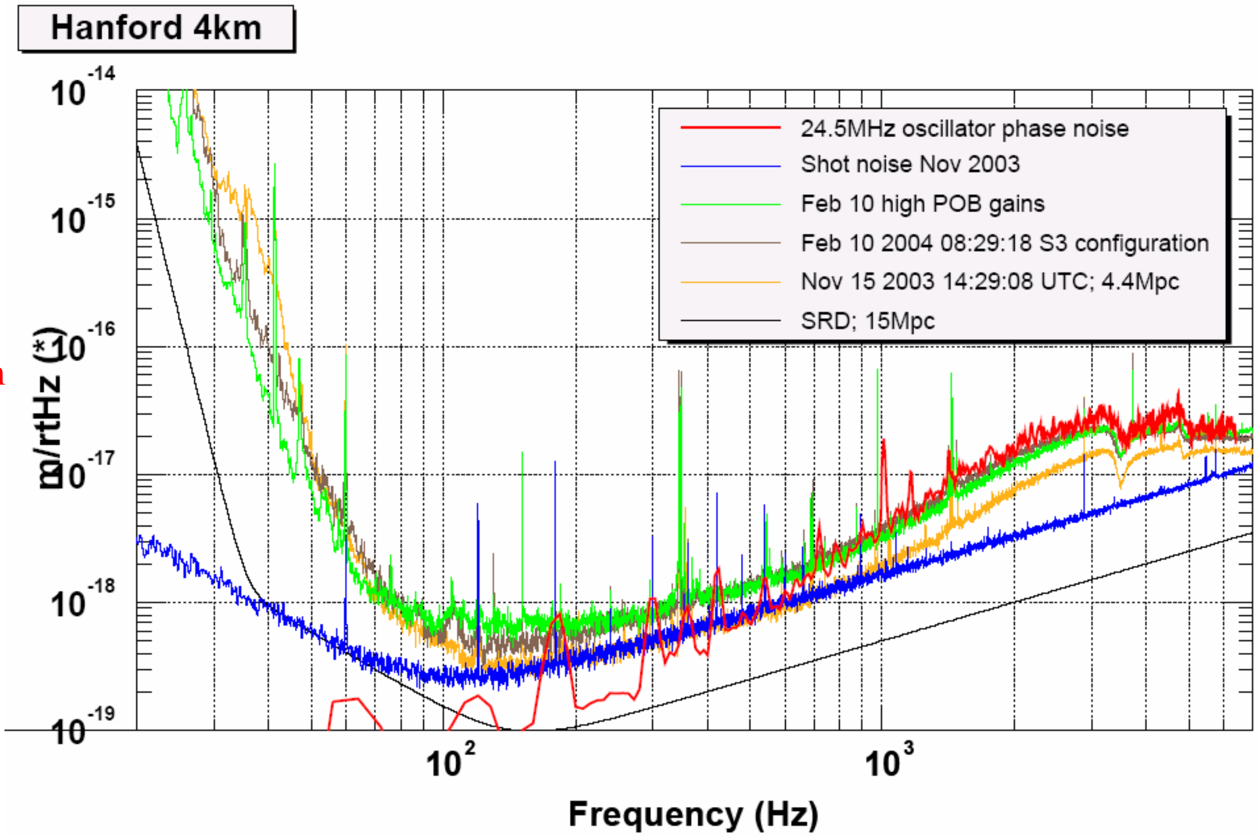
Mysterious ~kHz noise bumps



- *Present in noise curves since early '03*
- *Does not scale with laser power*

RF Oscillator Phase Noise

- Modulation phase noise appears on demodulation signal (LO) too – no big deal
- True at low frequencies, but... mode cleaner shifts phase of modulation fields – doesn't cancel out at higher frequencies
- Solutions:
  - Replaced commercial "low noise" Marconi with an Ultra-low phase noise crystal oscillator (-160 dBc/rHz)
  - Differential thermal lensing in the recycling cavity balances the RF sidebands and reduces the coupling

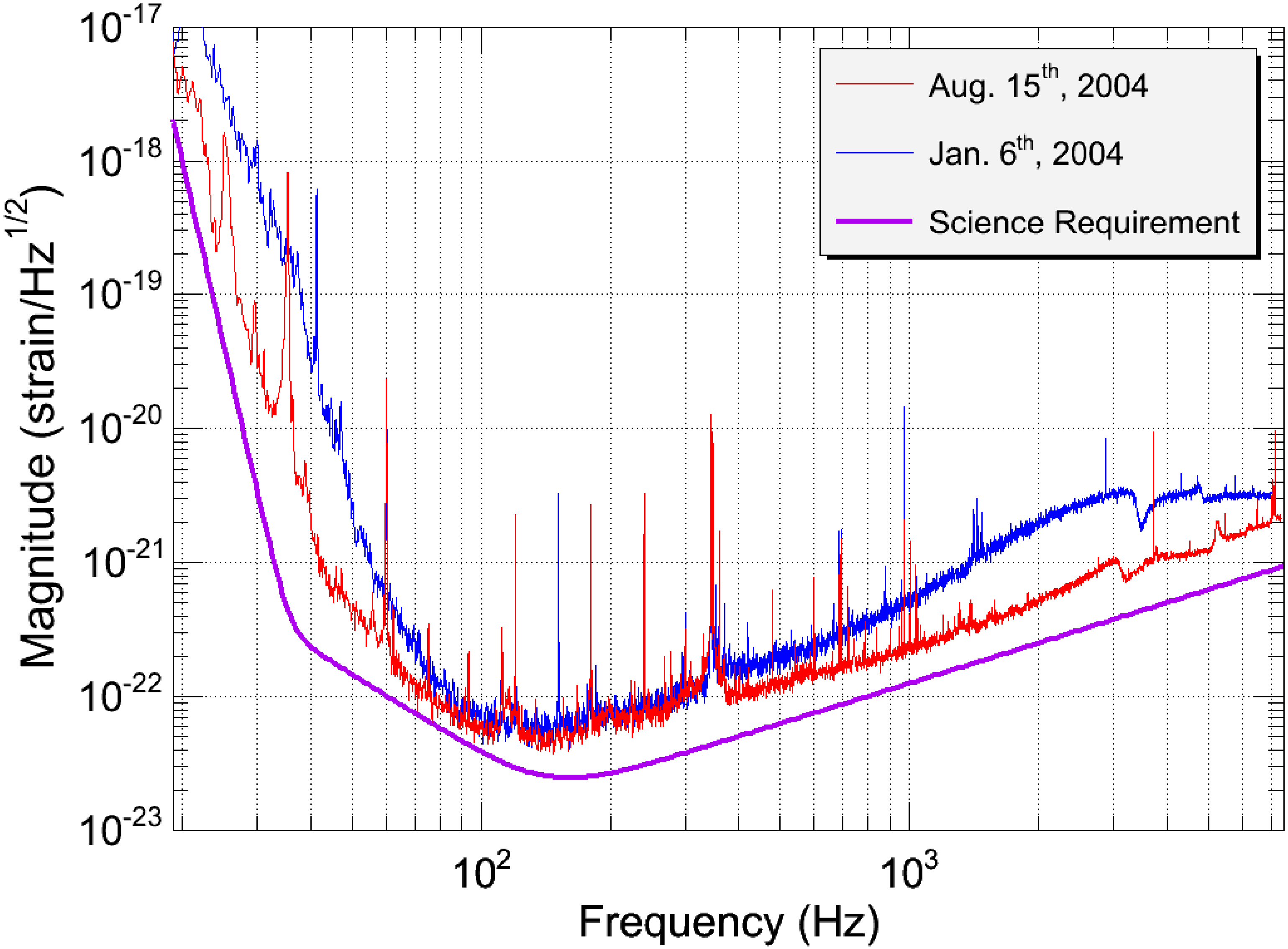


Noise Reduction

- Auxillary length loop noise
- Angular controls noise => apparent cavity length
- RF Photodetector saturation at 2 x f_{mod}
- RF Oscillator Phase Noise

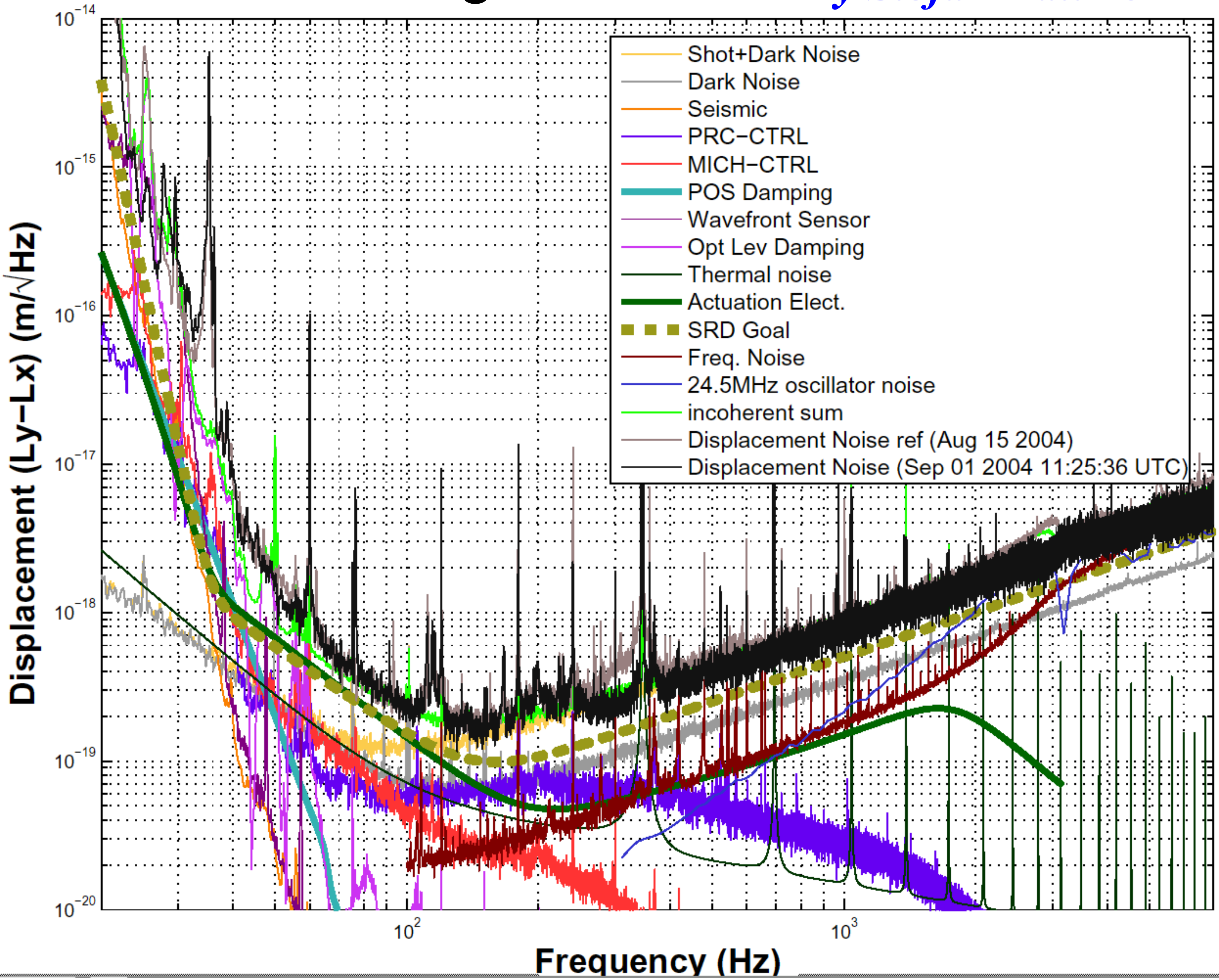
- Many noise sources of comparable level
- Noise reduction only obvious when all of the fixes are in...

Very Good Sensitivity



Noise Budget

By Stefan Ballmer



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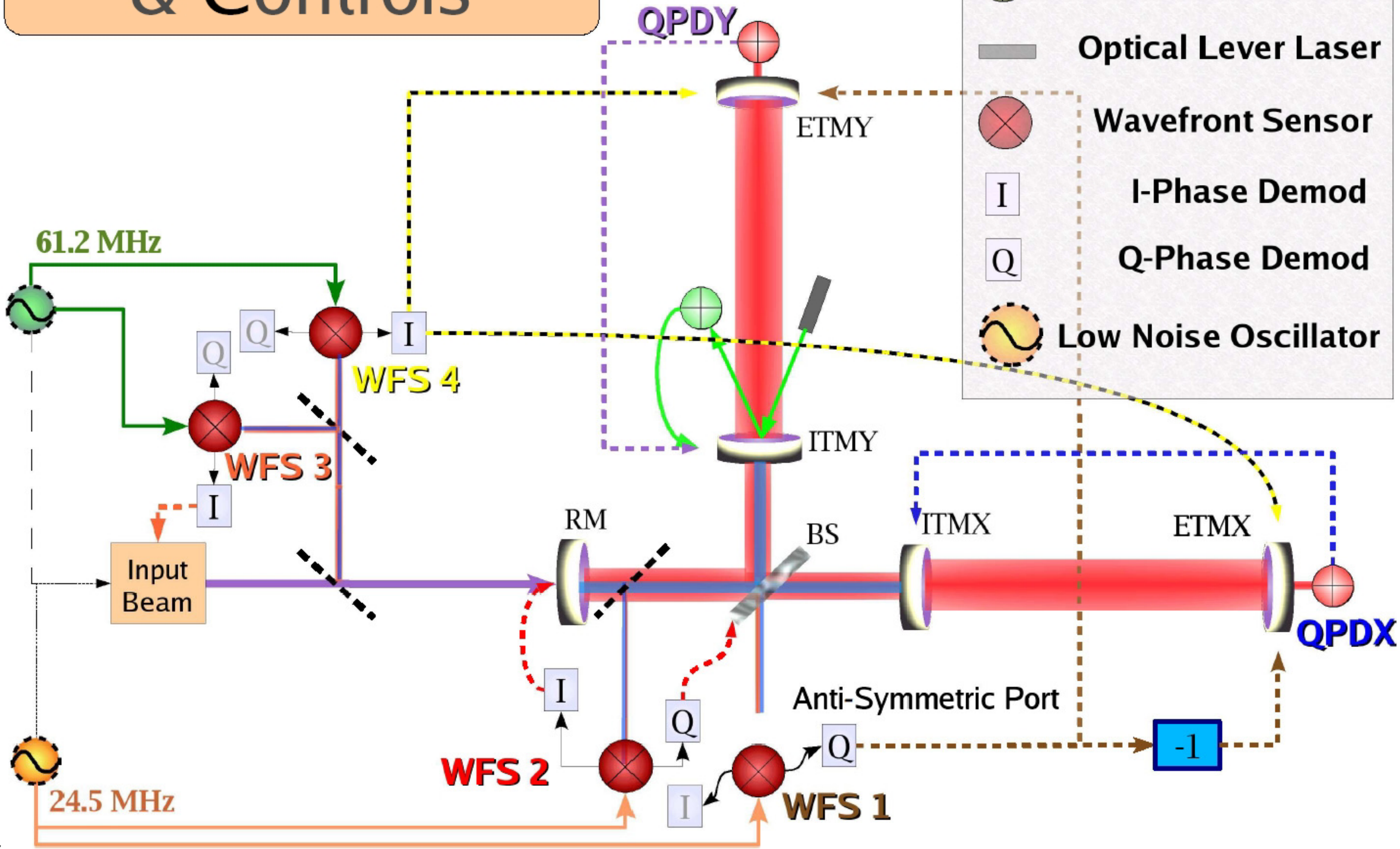
Alignment Controls

LIGO

Angular Sensing & Controls

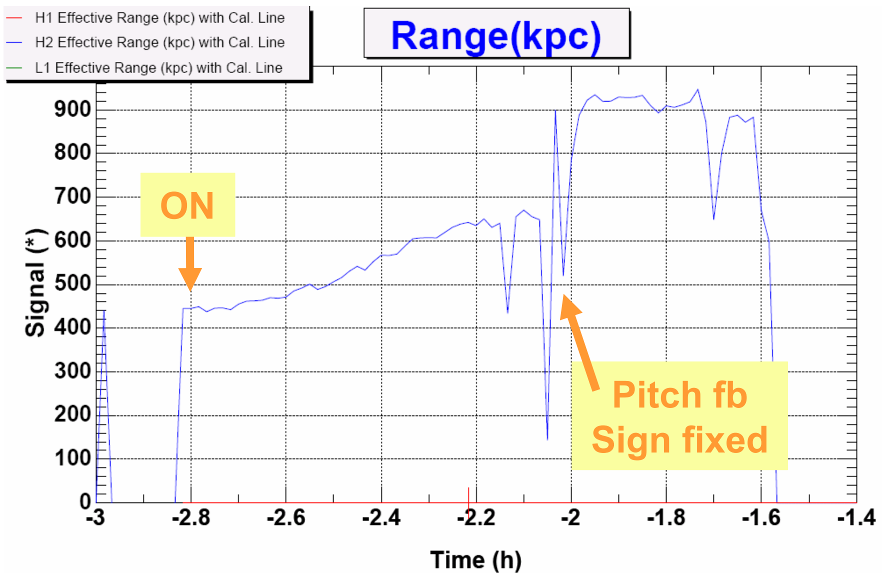


Alignment Control

- Continued progress…
  - Goals:
    - Increase gain to reduce power fluctuations to ~1%
    - Manage angular noise & coupling to strain readout
  - Status:
    - **H1:** ~few Hz BW for all loops, high power characterization ongoing
    - **H2:** All loops closed, high power characterization ongoing
    - **L1:** Recently closed all angular control loops.
  - Recent work:
    - Dynamic input matrix (compensates optical gain fluctuations)
    - Electronics noise reductions
    - More MIMO system => higher bandwidth servos
    - Beam centering …

Beam Centering

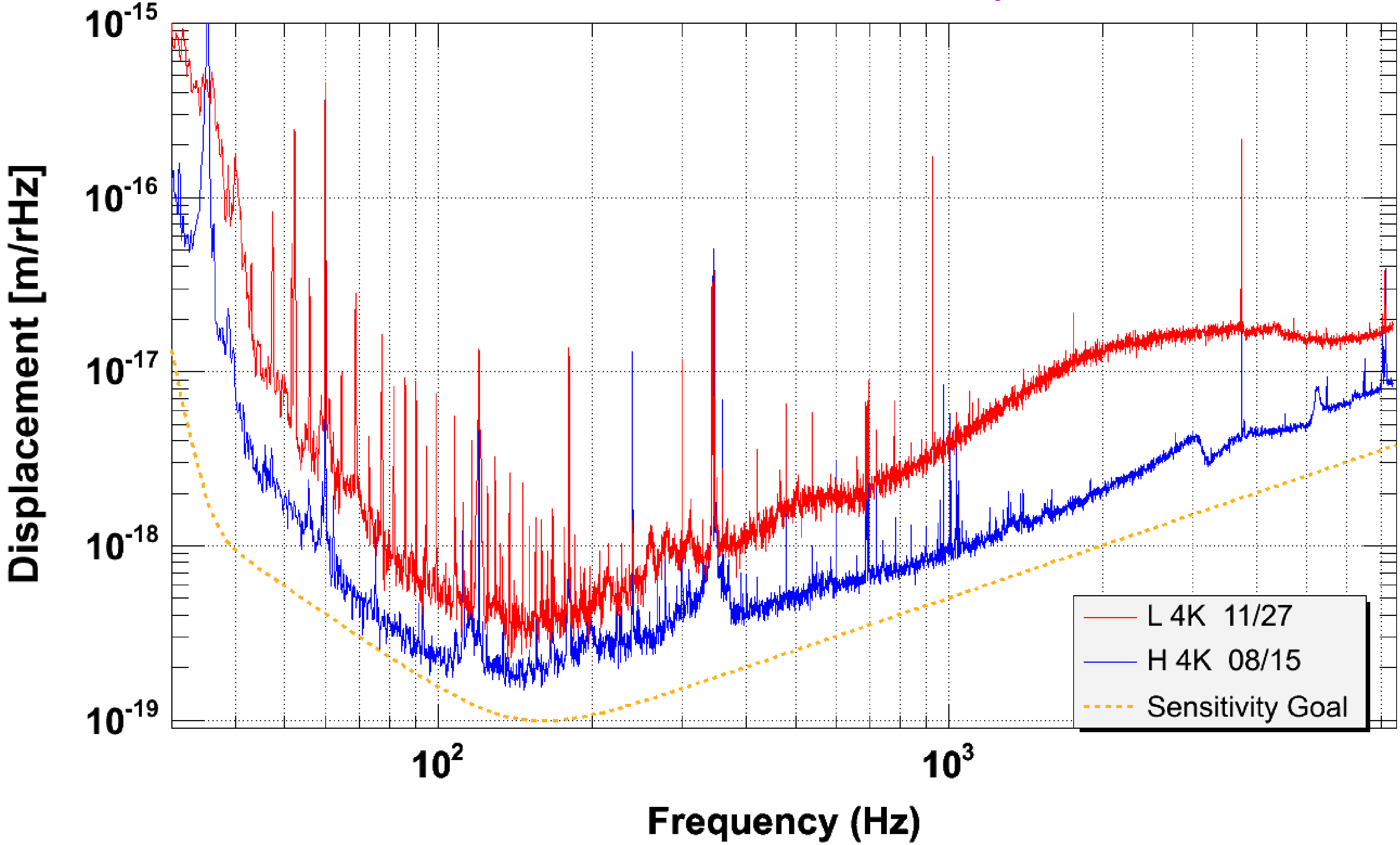
- Transmission QPDs hold the beam position fixed at the ETMs
  - Need to independently find the right spot (w/in 1mm of center)
- WFS control all mirror angles: only DOF left is the beam position in the corner
- New servo:
  - Capture image of beam scatter from BS face
  - Image processing to determine position of beam center
  - Slow feedback to input telescope to fix BS beam position



Pre-S4 Steps

	Next **~3 months**
L 4k	➔ Thermal Lensing compensation -- in progress ➔ Increase the laser power from 1-4 W -- Thursday ➔ Copy noise improvements from H 4K -- 3 out of 4
H 4k	▶ Stability and duty cycle studies ▶ Wideband angular control at high power ▶ Microseismic feedback and FF
H 2k	❑ All of the above

Catching Up…

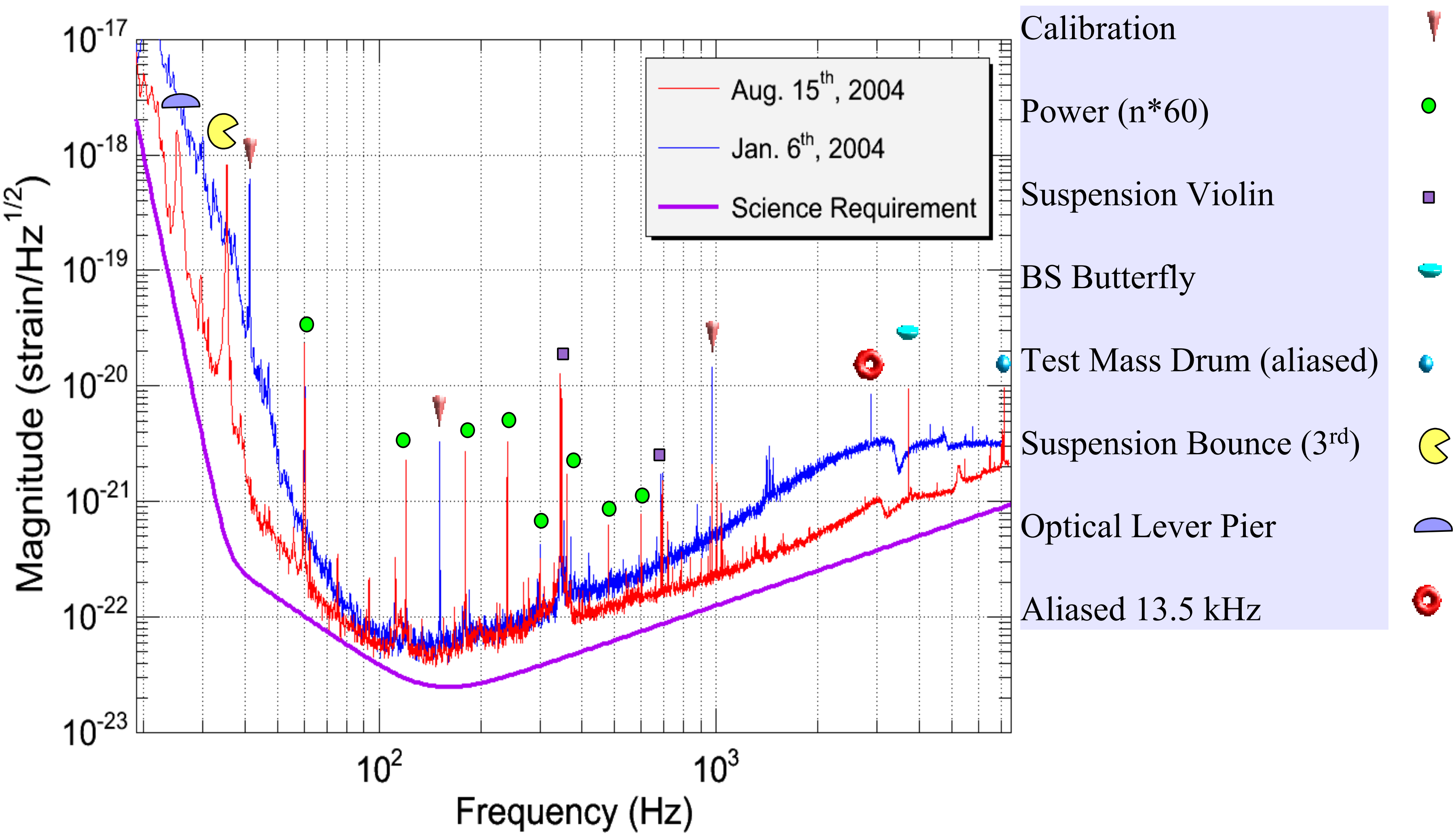


Displacement [m/rHz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{2}
10^{3}
Frequency (Hz)
L 4K 11/27
H 4K 08/15
Sensitivity Goal

Conclusions

- All interferometers can now run **all day and night**
- All interferometers have all lengths and angles under control
=> **repeatable, stable operation**
- Sensitivity is very close to the design goal on one interferometer
  - No show stoppers
- ...

Lines



Aug. 15th, 2004
Jan. 6th, 2004
Science Requirement
Magnitude (strain/Hz^1/2)
Frequency (Hz)
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^2
10^3
Calibration
Power (n*60)
Suspension Violin
BS Butterfly
Test Mass Drum (aliased)
Suspension Bounce (3rd)
Optical Lever Pier
Aliased 13.5 kHz