LIGO

Recent Improvements in the LIGO Interferometers

Rana Adhikari

February 18, 2005

G050081-00-D

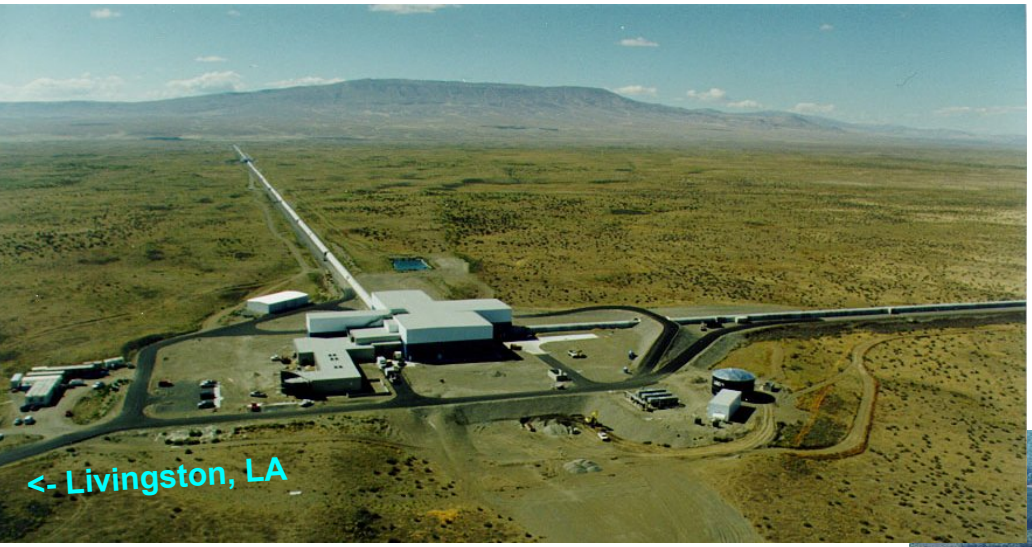
LIGO

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

- Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov
- NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

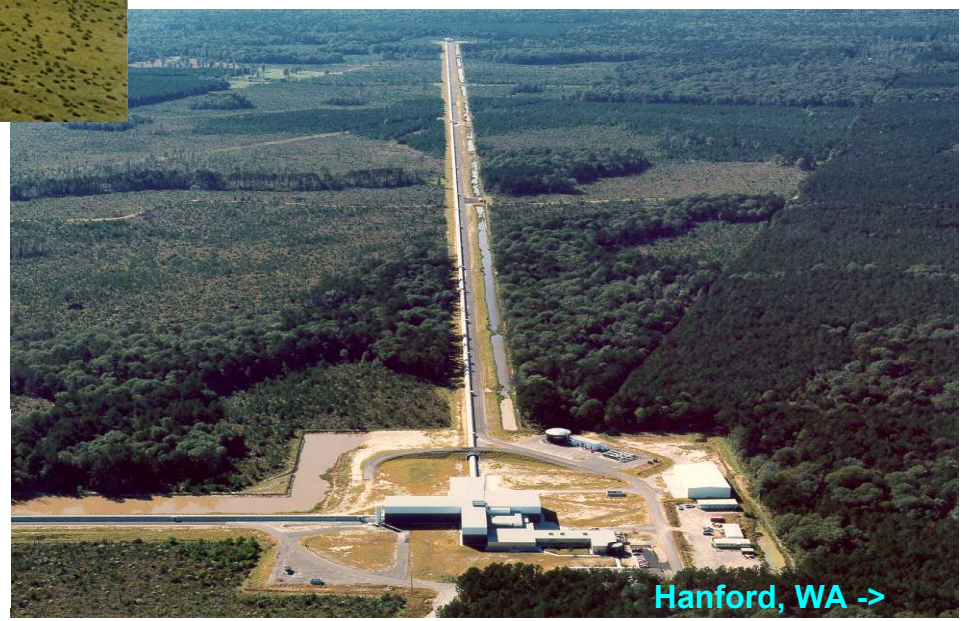
LIGO Observatories



GEODETIC DATA (WGS84)

h: -6.574 m
ϕ: N30°33'46.419531"
λ: W90°46'27.265294"
X arm: S72.2836°W
Y arm: S17.7164°E

Livingston Observatory
Louisiana
One interferometer (4km)



Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

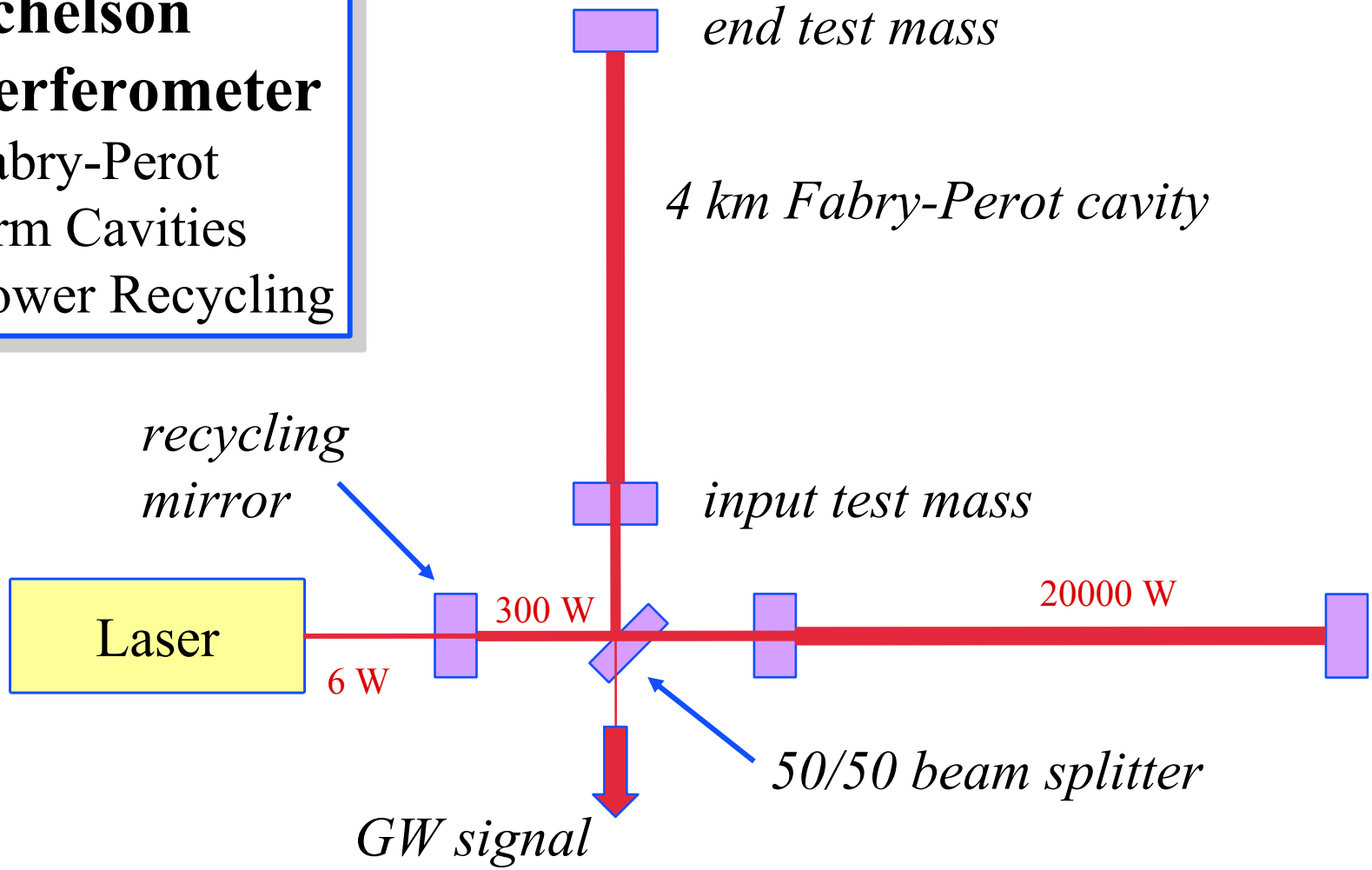
GEODETIC DATA (WGS84)

h: 142.555 m
ϕ: N46°27'18.527841"
λ: W119°24'27.565681"
X arm: N35.9993°W
Y arm: S54.0007°W

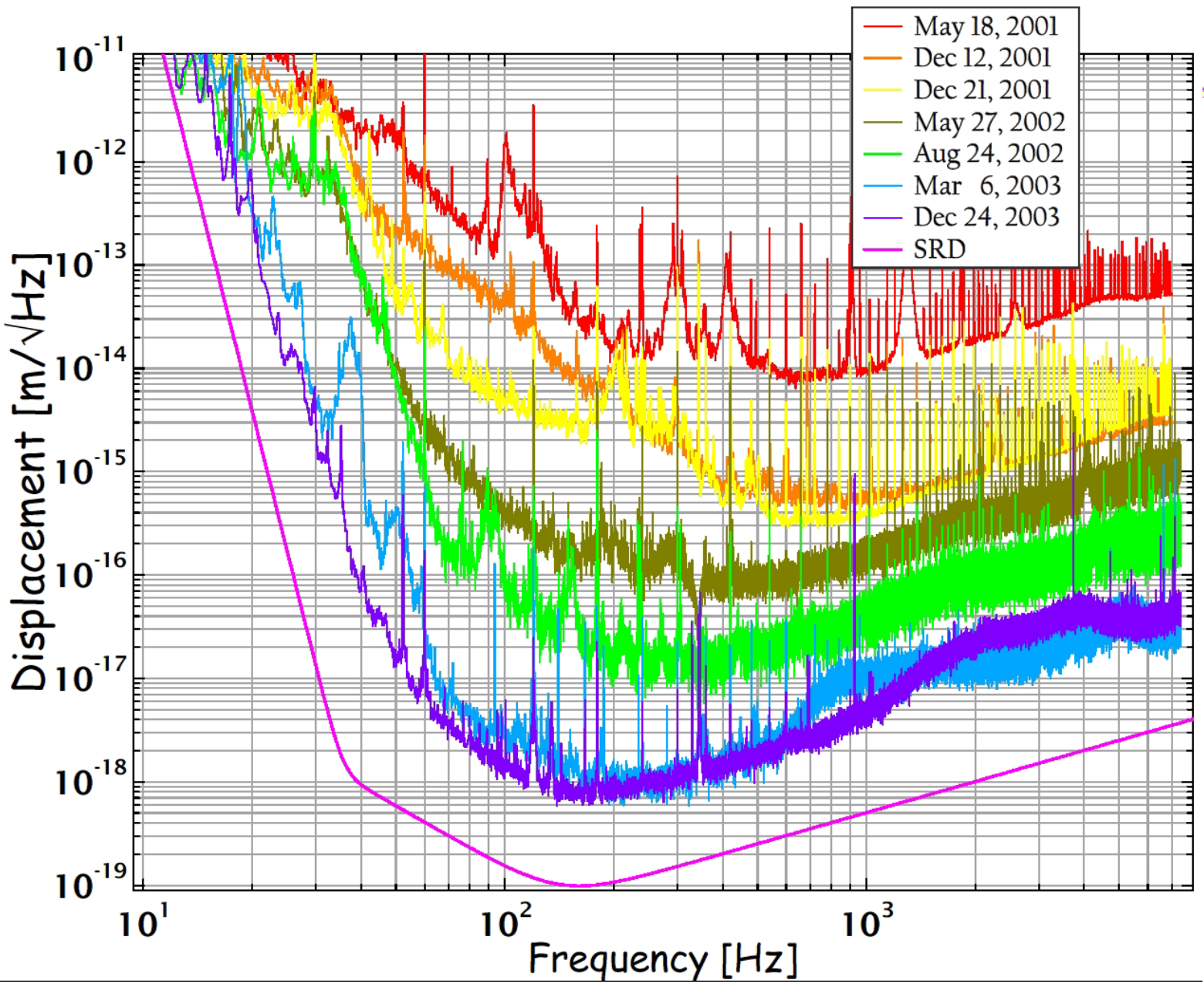
LIGO

LIGO Interferometers

Michelson Interferometer
+ Fabry-Perot Arm Cavities
+ Power Recycling

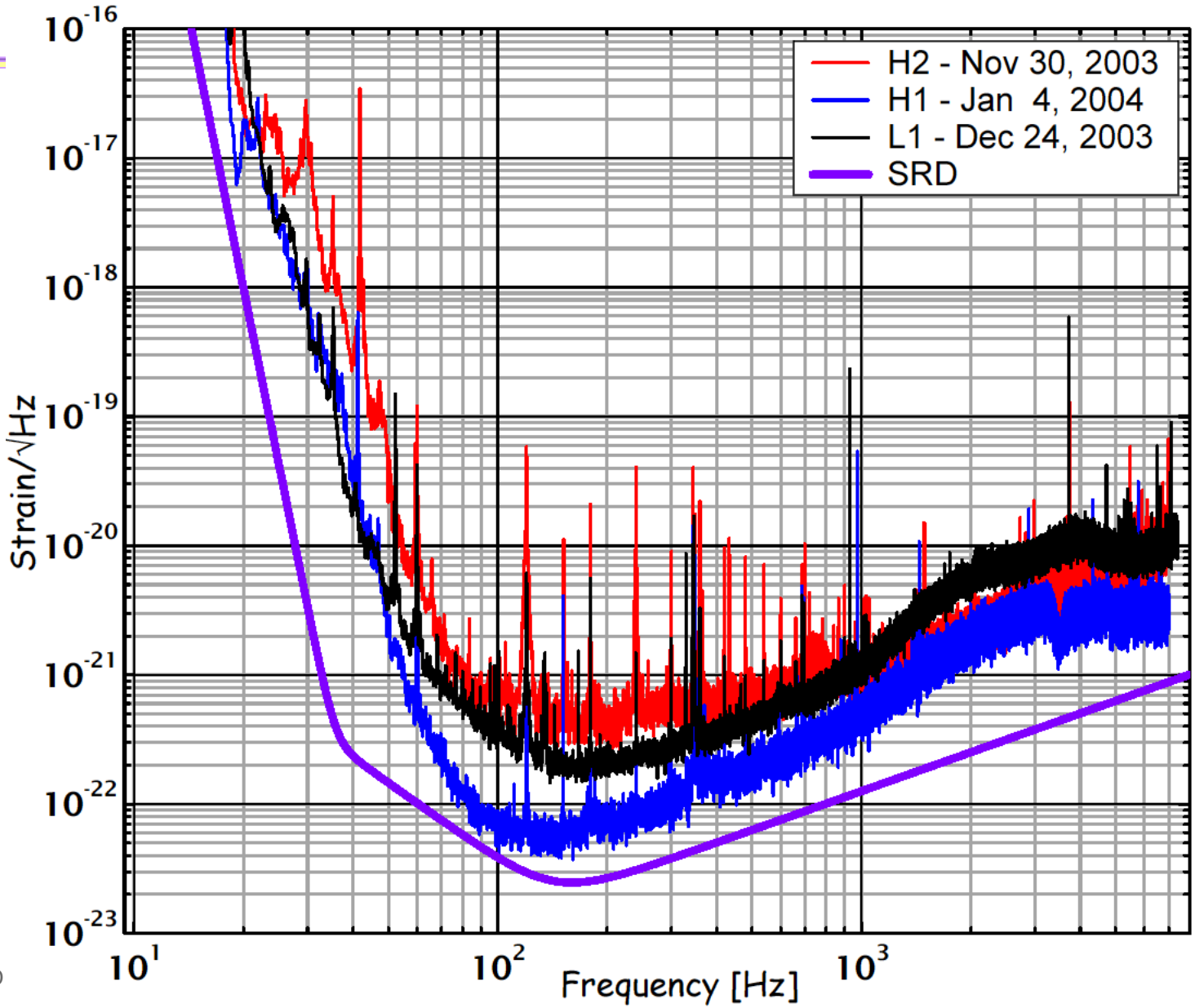


Noise Progression of the Livingston Interferometer



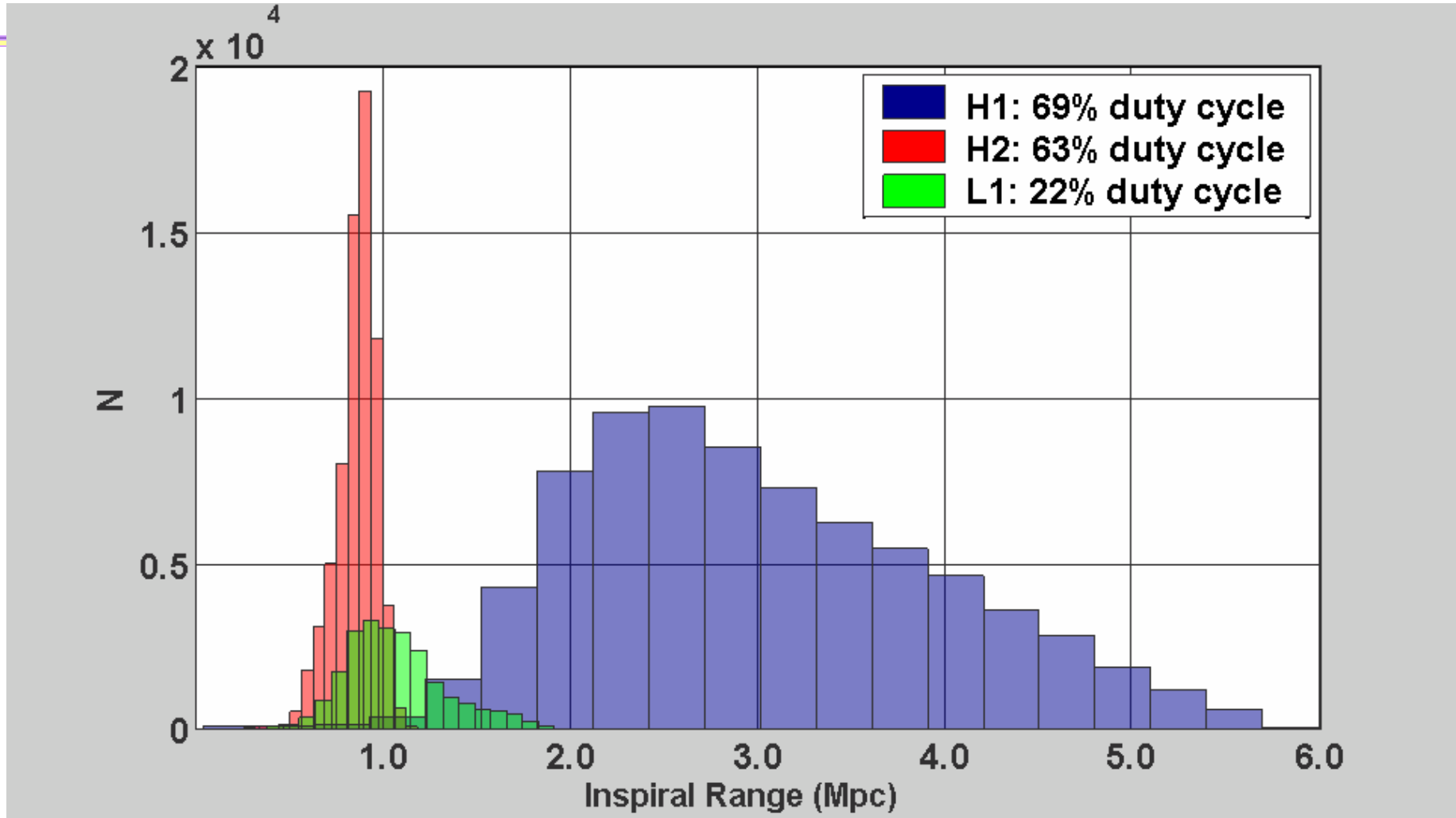
LIGO

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

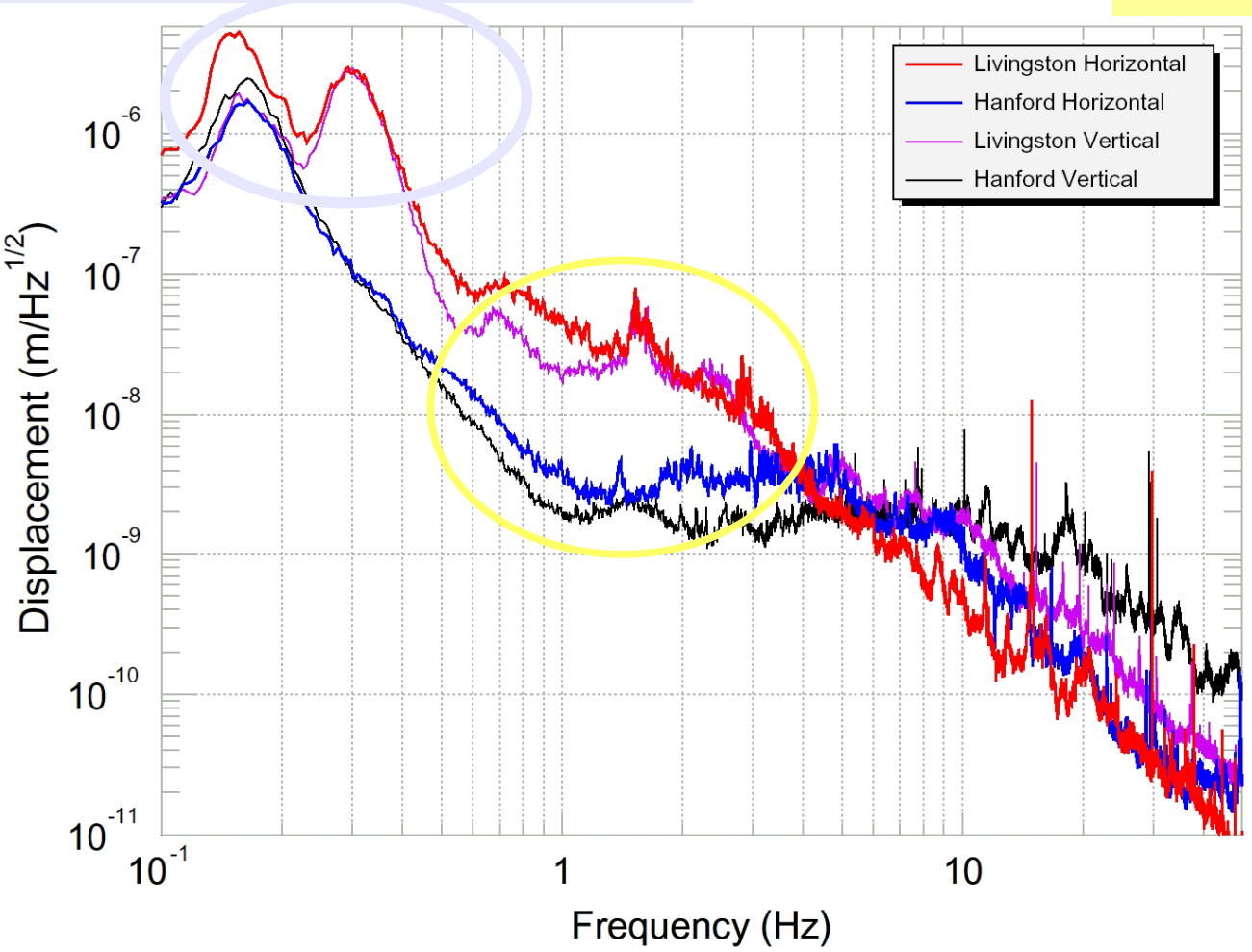
LIGO

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

Seismic Noise

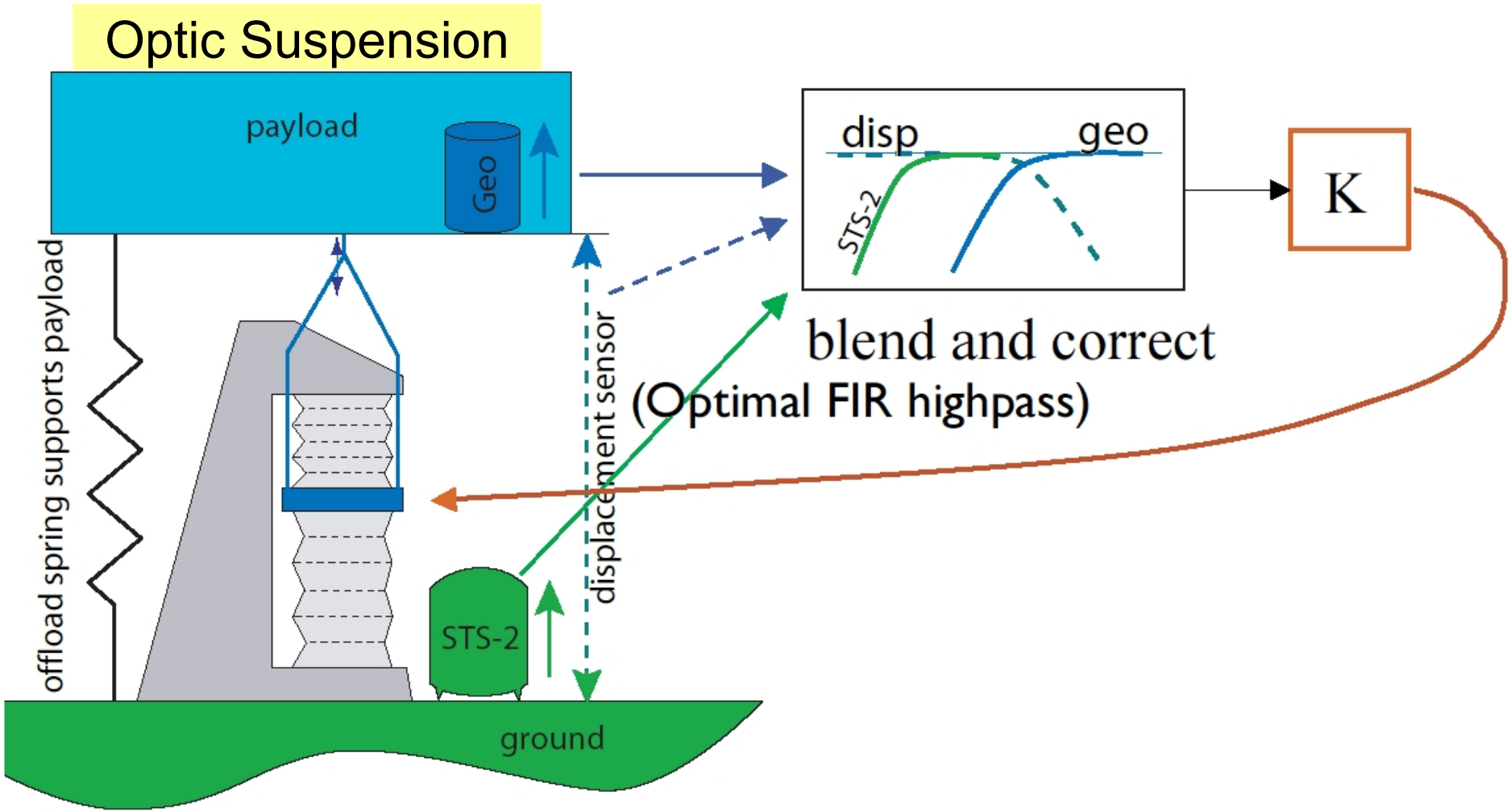
Ocean activity, hurricanes



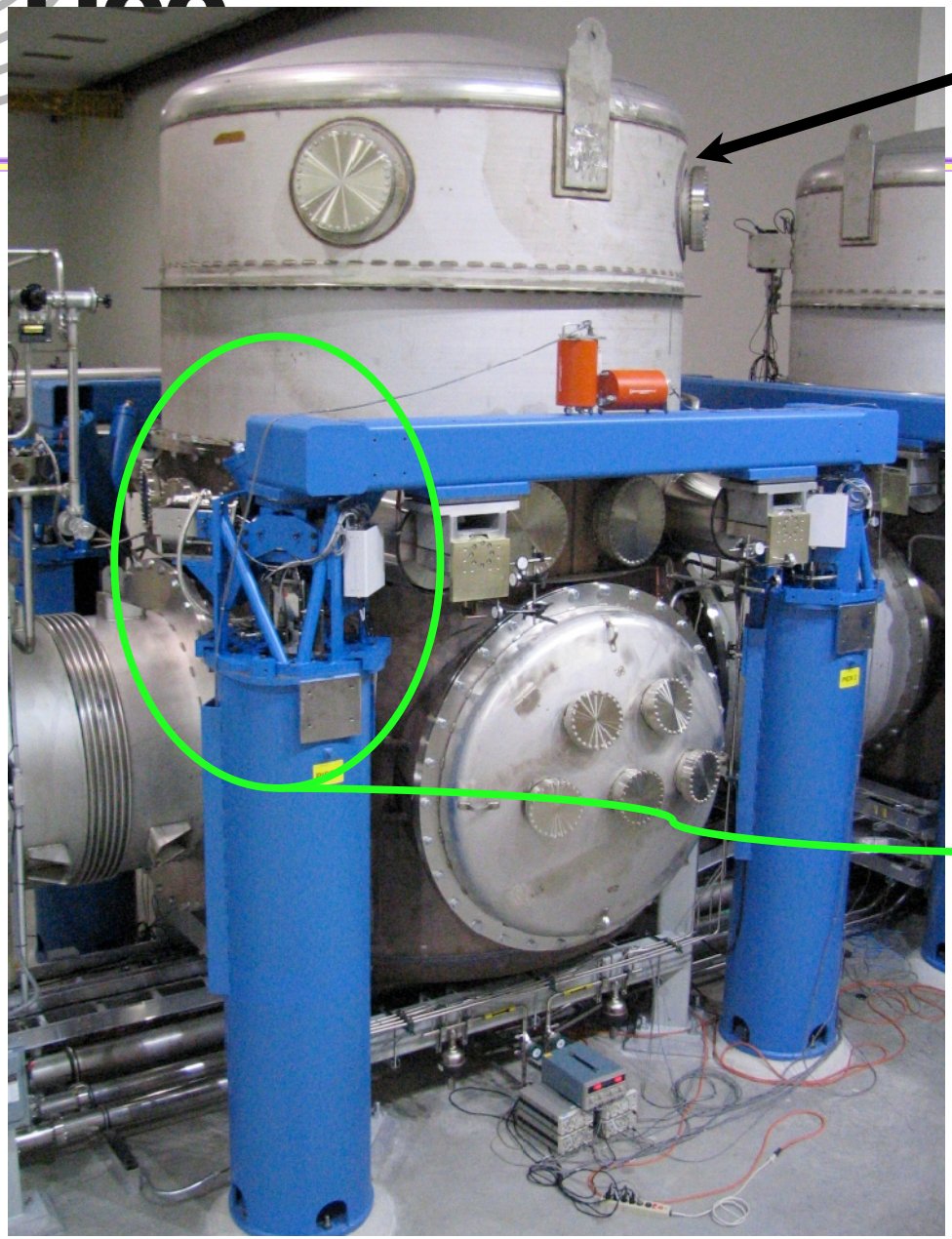
Caused by human activity:
Cars,
Trains,
Trucks,
Logging,
Well Drilling,
Oil Pipeline

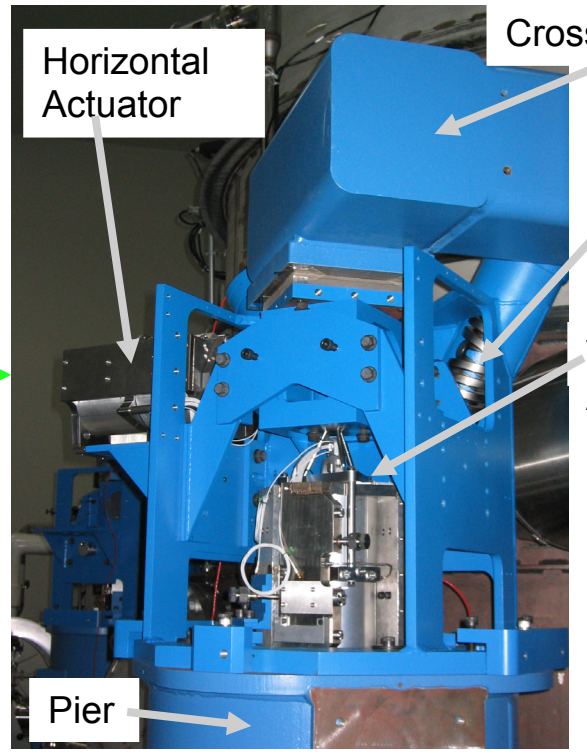
Amplified by internal isolation stack resonances

Active Seismic Isolation



LIGO

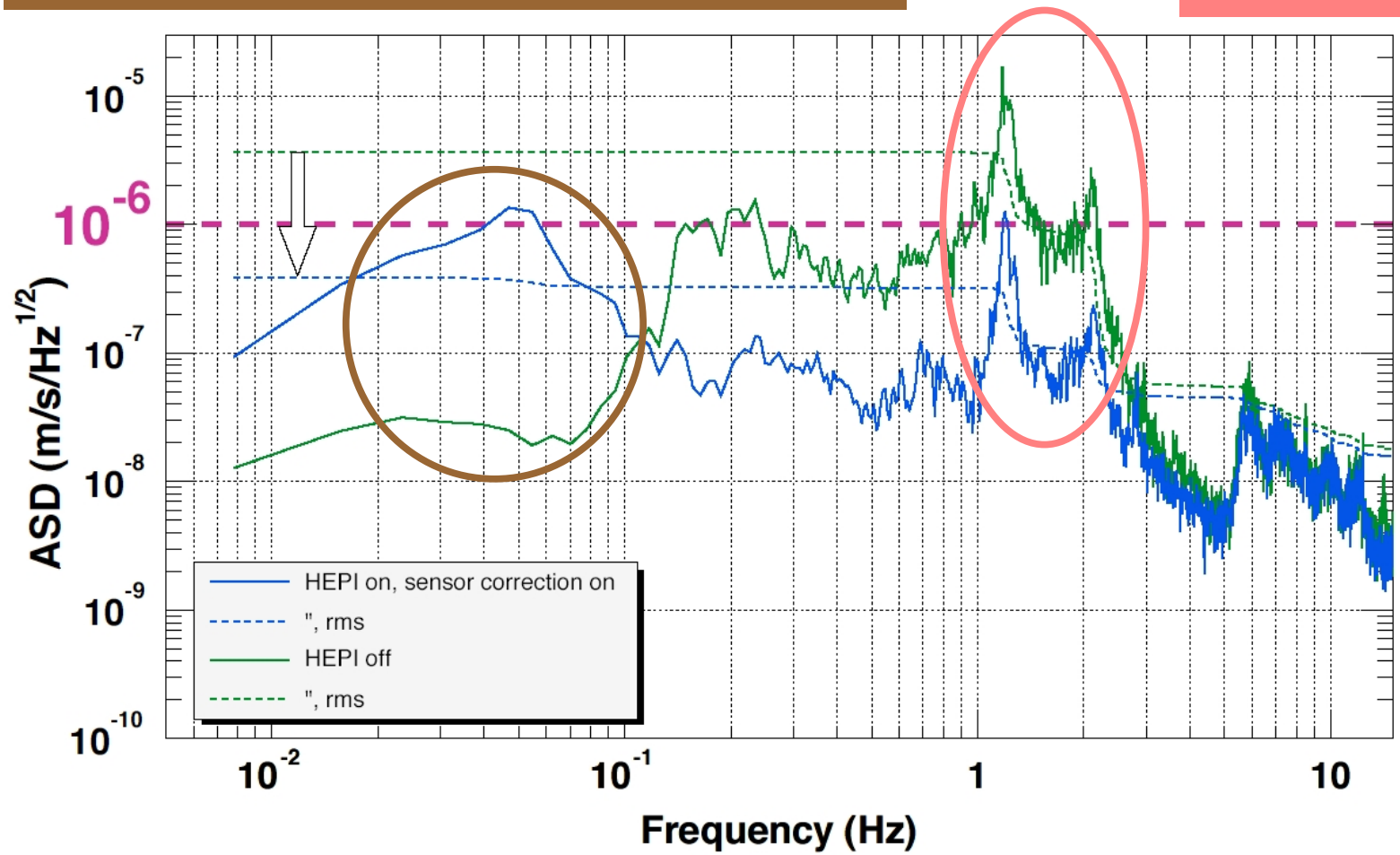

Input Test Mass
Chamber


Horizontal
Actuator
Crossbeam
Helical
Spring
Vertical
Actuator
Pier

Isolation Performance for a single arm cavity

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

10x reduction in the crucial frequency band



LIGO

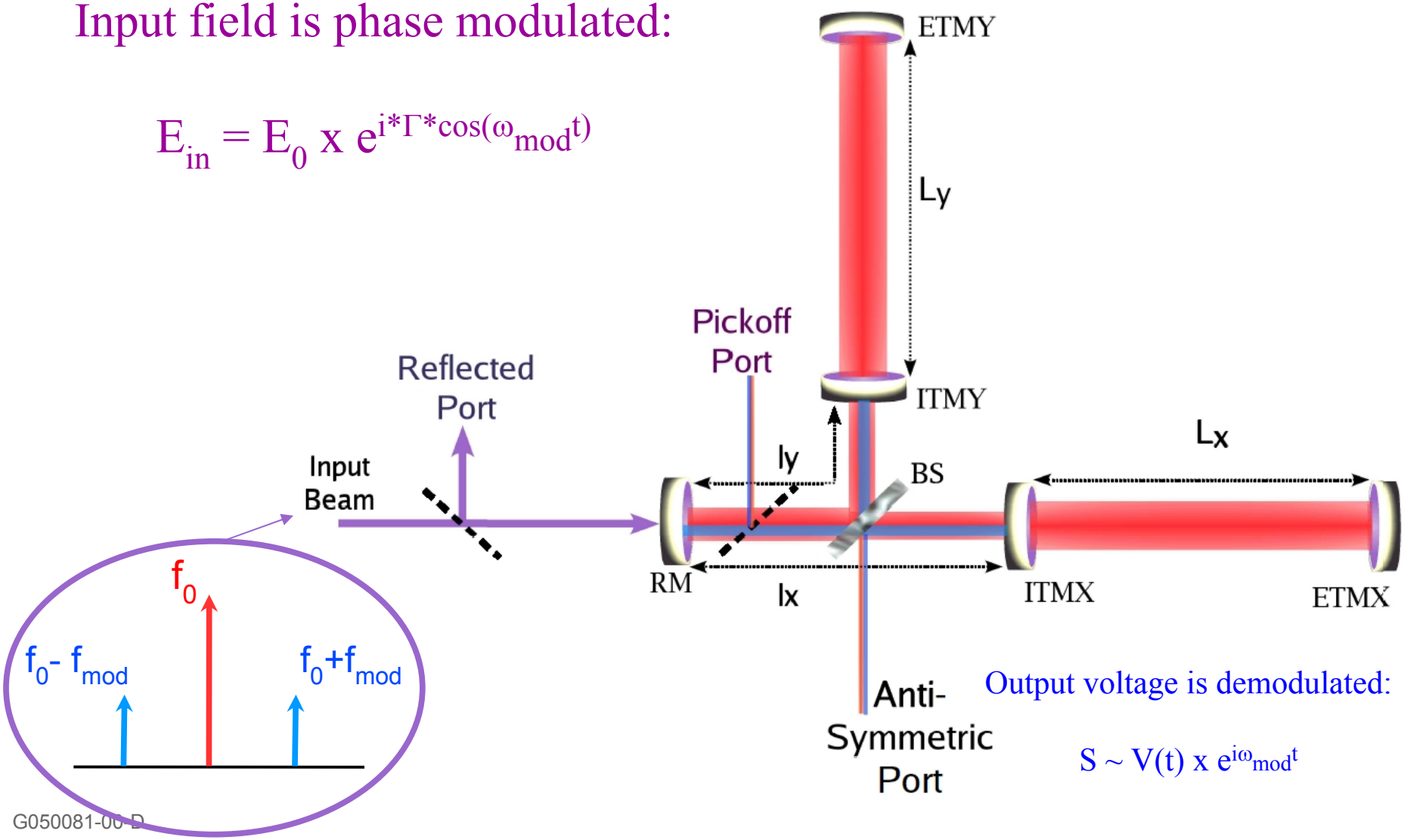
Outline

- Sensitivity & Duty Cycle in the last Science Run
- Louisiana
  - Active Seismic Isolation
  - 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:

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



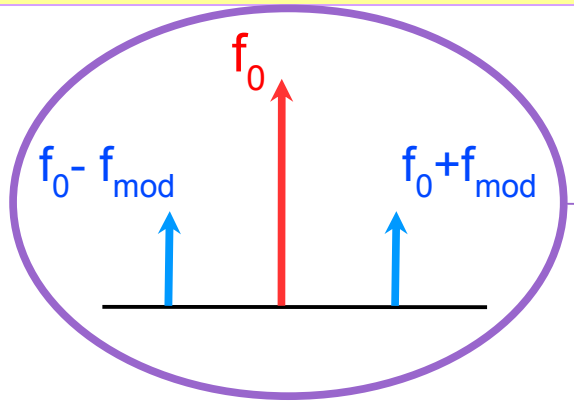
Output voltage is demodulated:

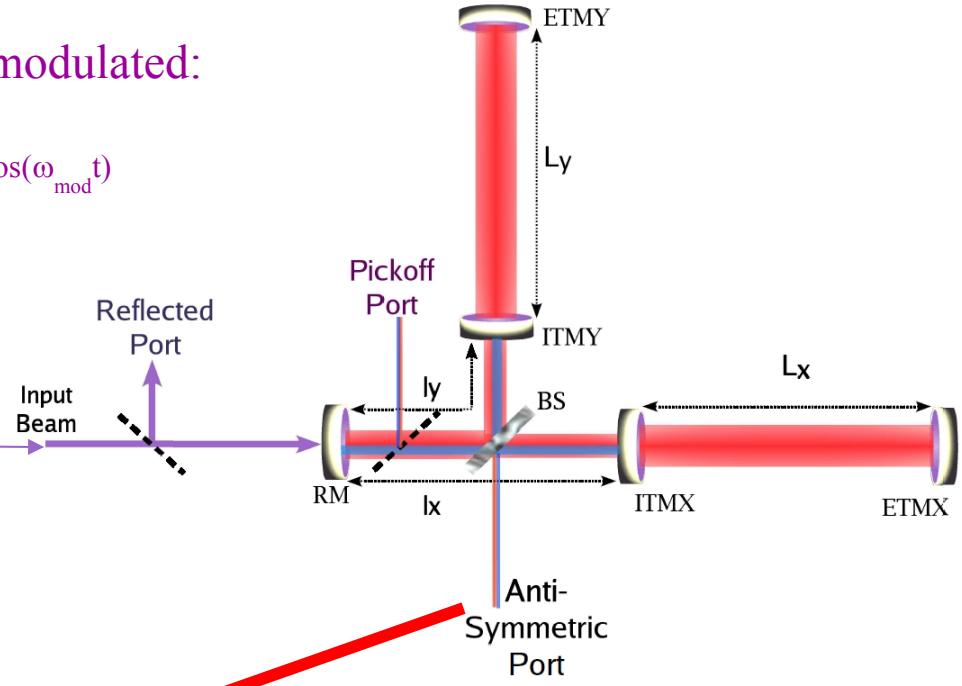
$S \sim V(t) \times e^{i\omega_{mod}t}$

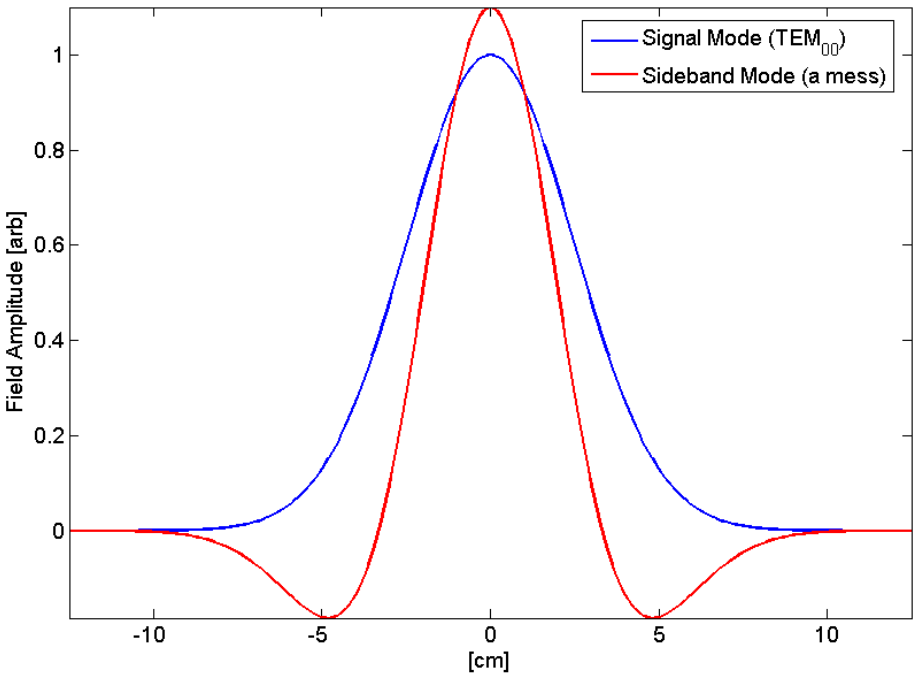
LIGO

Input field is phase modulated:

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







Output Signal, AS_Q proportional to field overlap

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

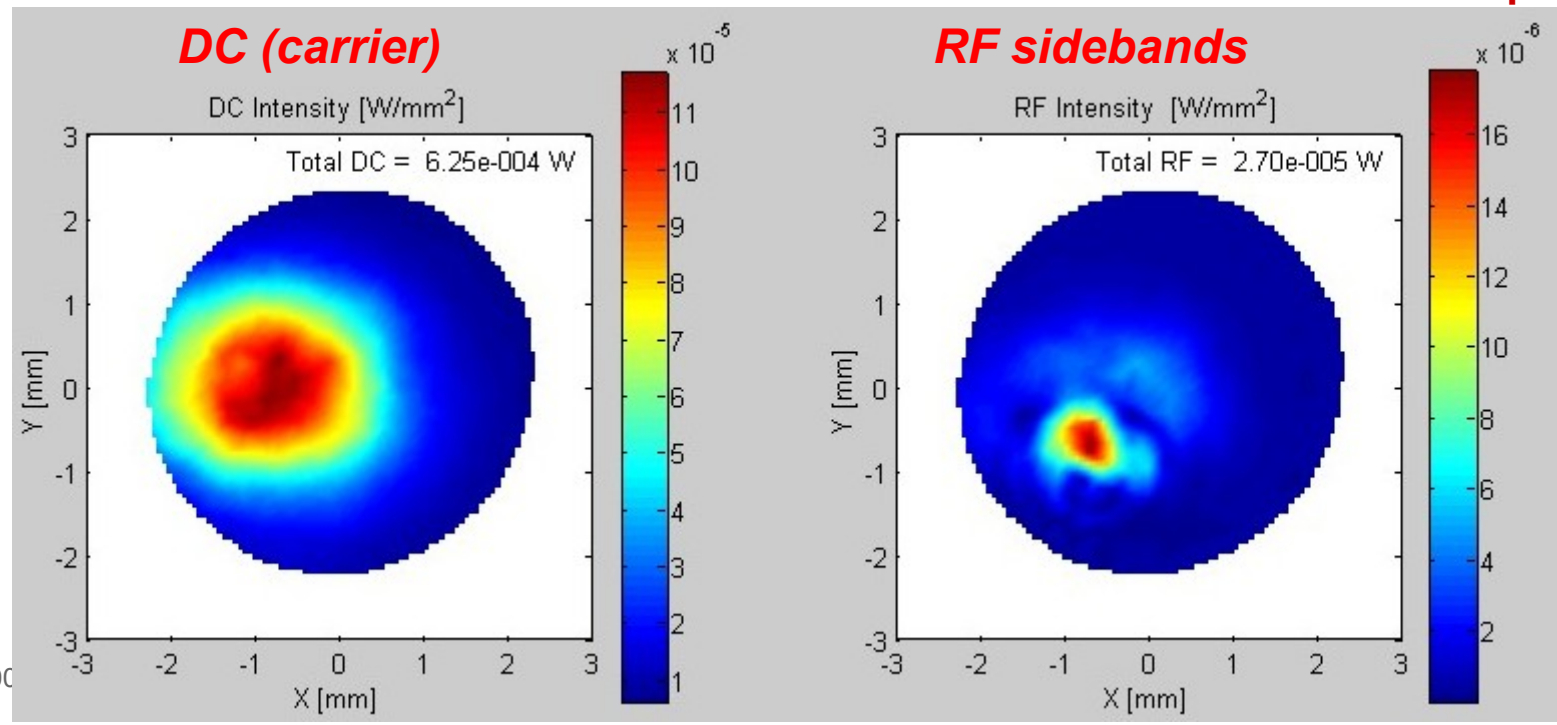
Shot Noise doesn't care about overlap

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

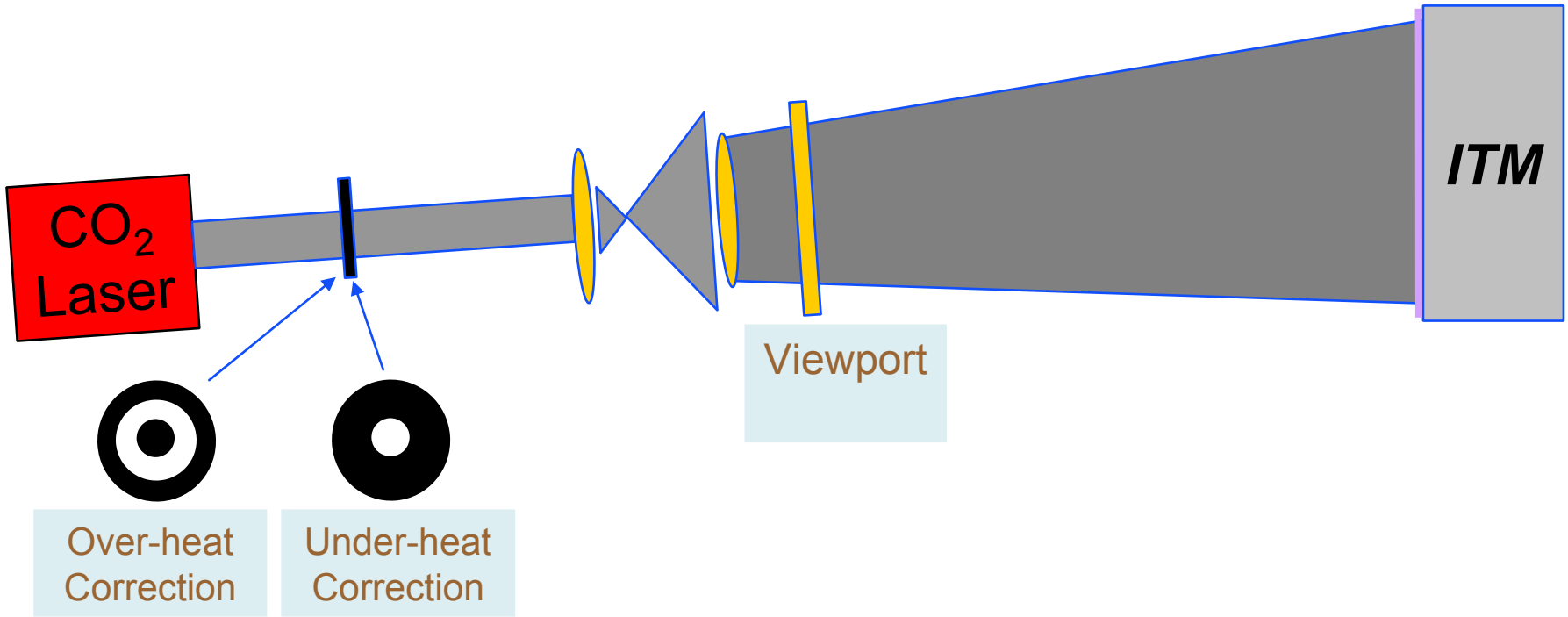
Recycling Cavity Degeneracy

- Full 'Frontal modulation' scheme depends on efficient coupling
  - 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
  - Input to Dark Port efficiency: ~6%
  - incorrect/insufficient thermal lens makes $g_1 \cdot g_2 > 1$ (unstable resonator)

⇒Bad mode overlap!

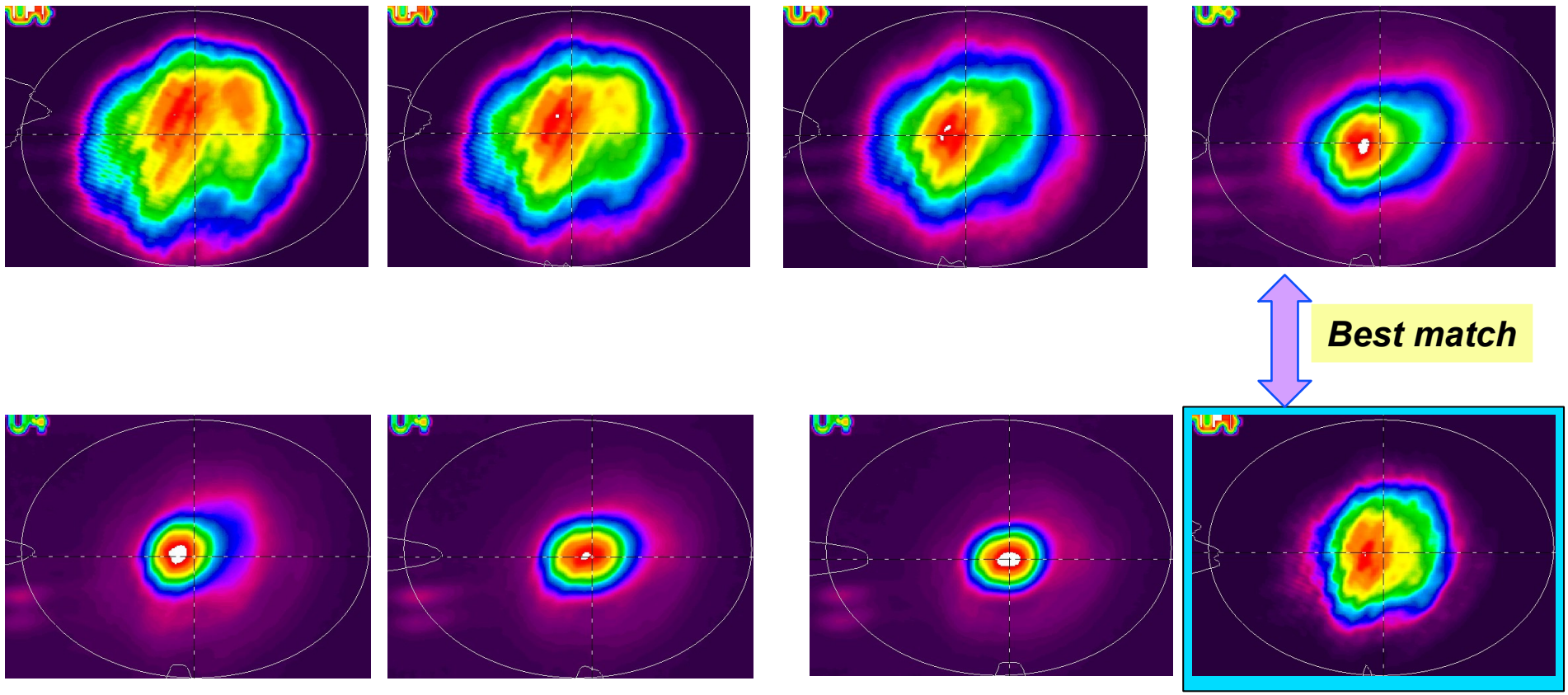


Thermal Compensation



- 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

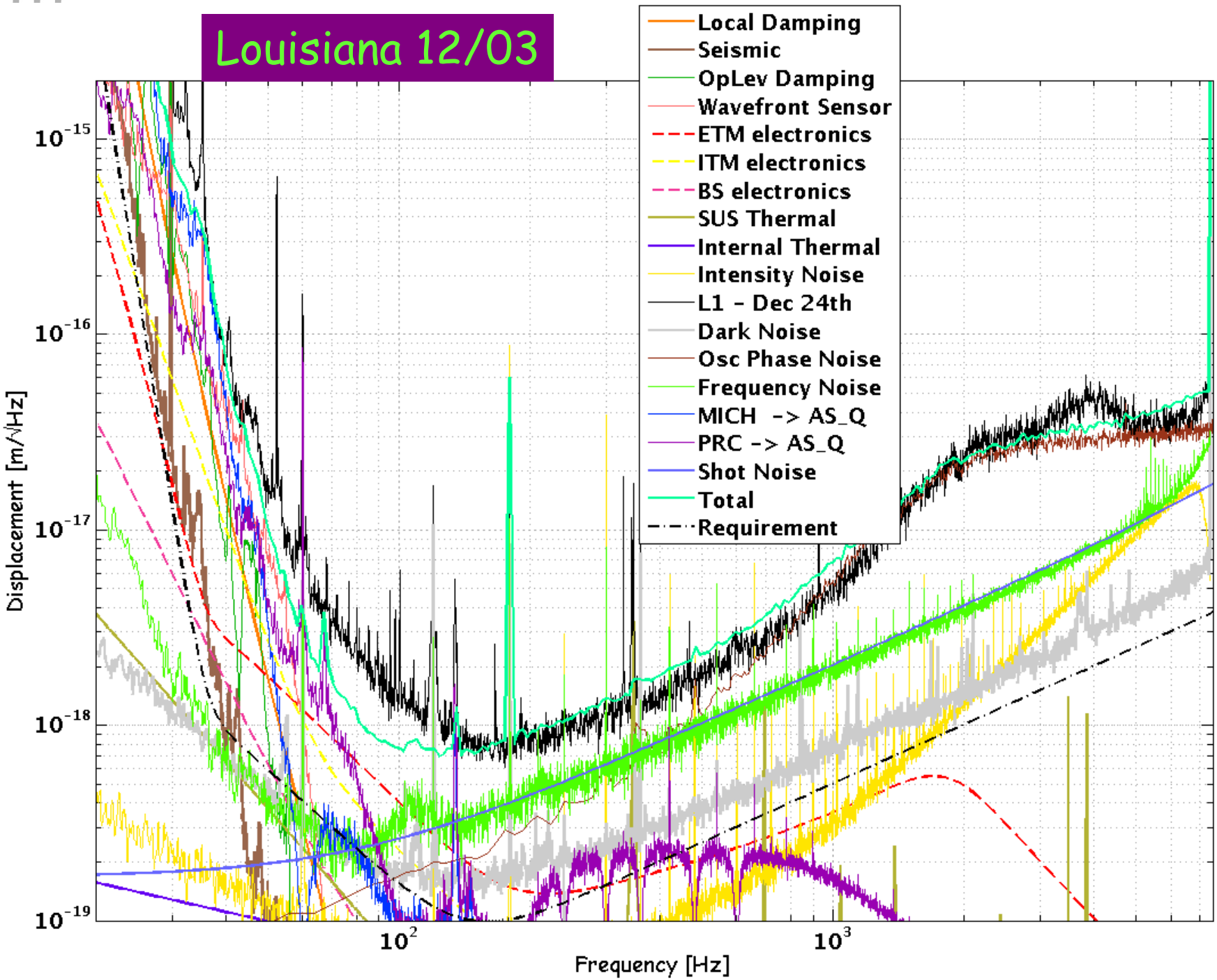


LIGO

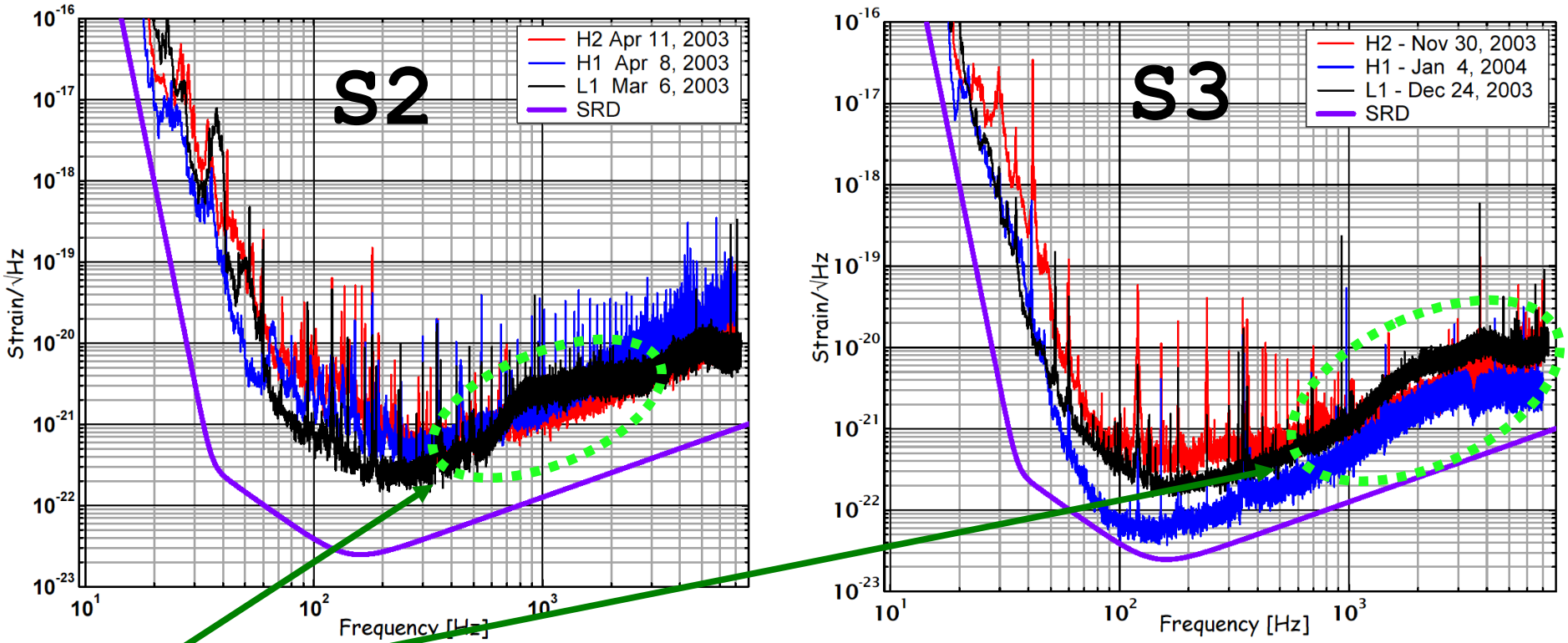
Outline

- 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

Louisiana 12/03



Mysterious ~kHz noise bumps

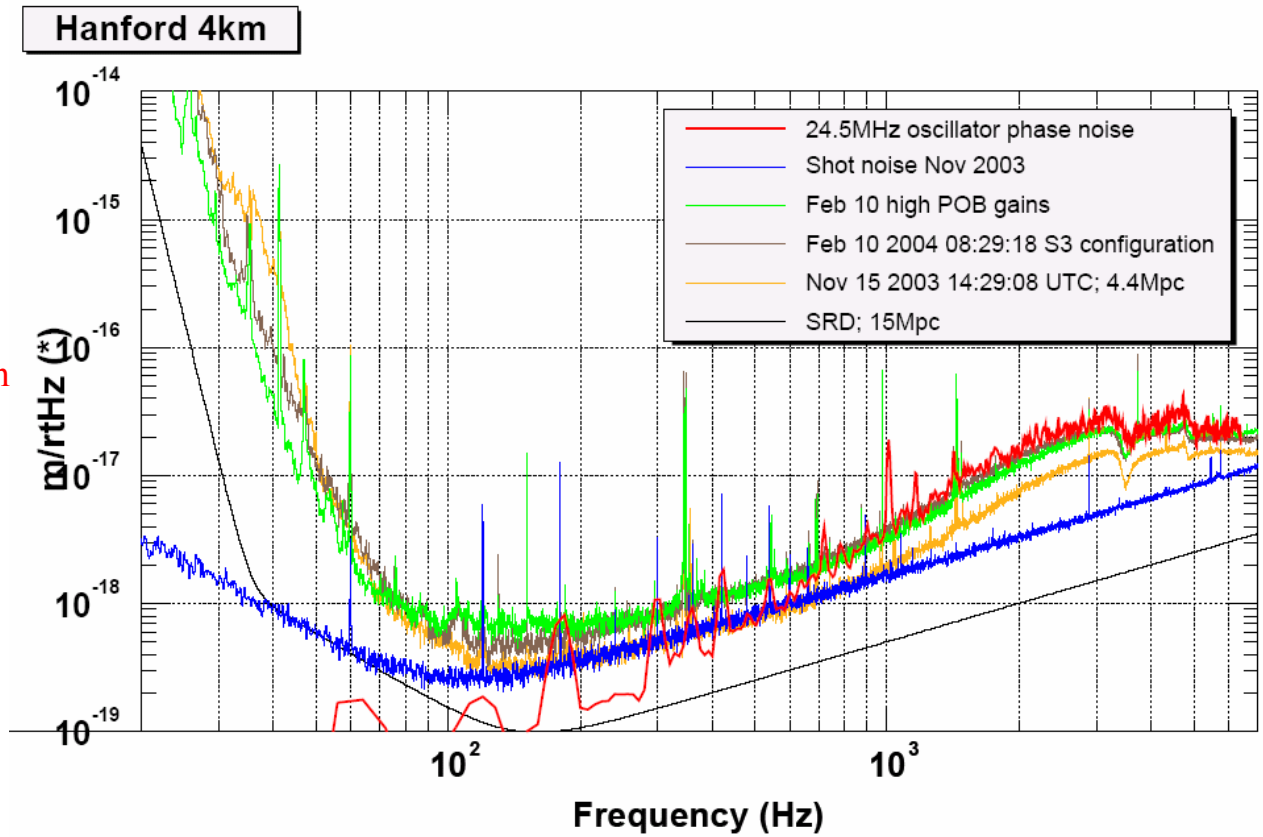


- *Present in noise curves since early '03*
- *Does not scale with laser power*

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



LIGO

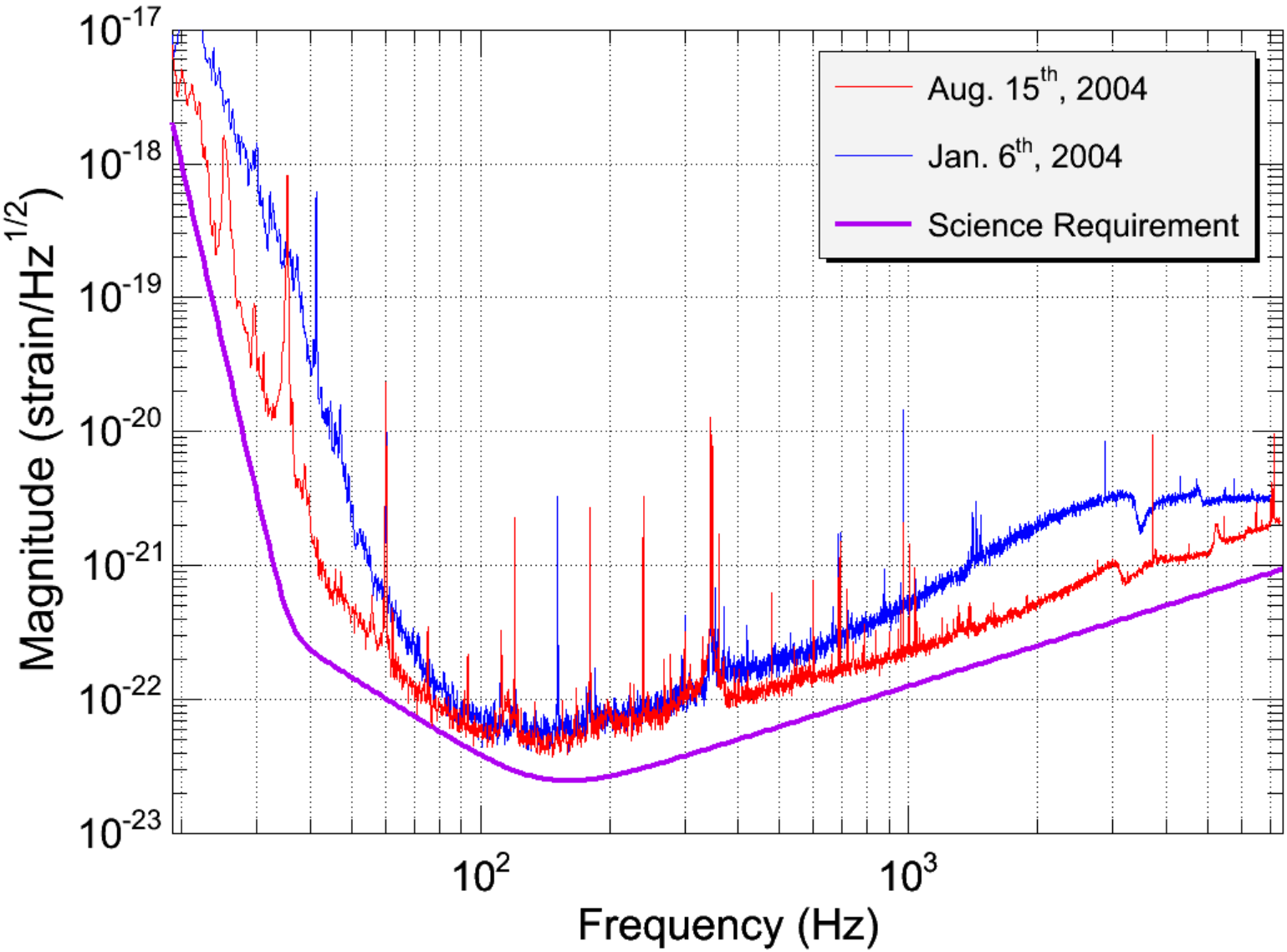
Noise Reduction

- 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...

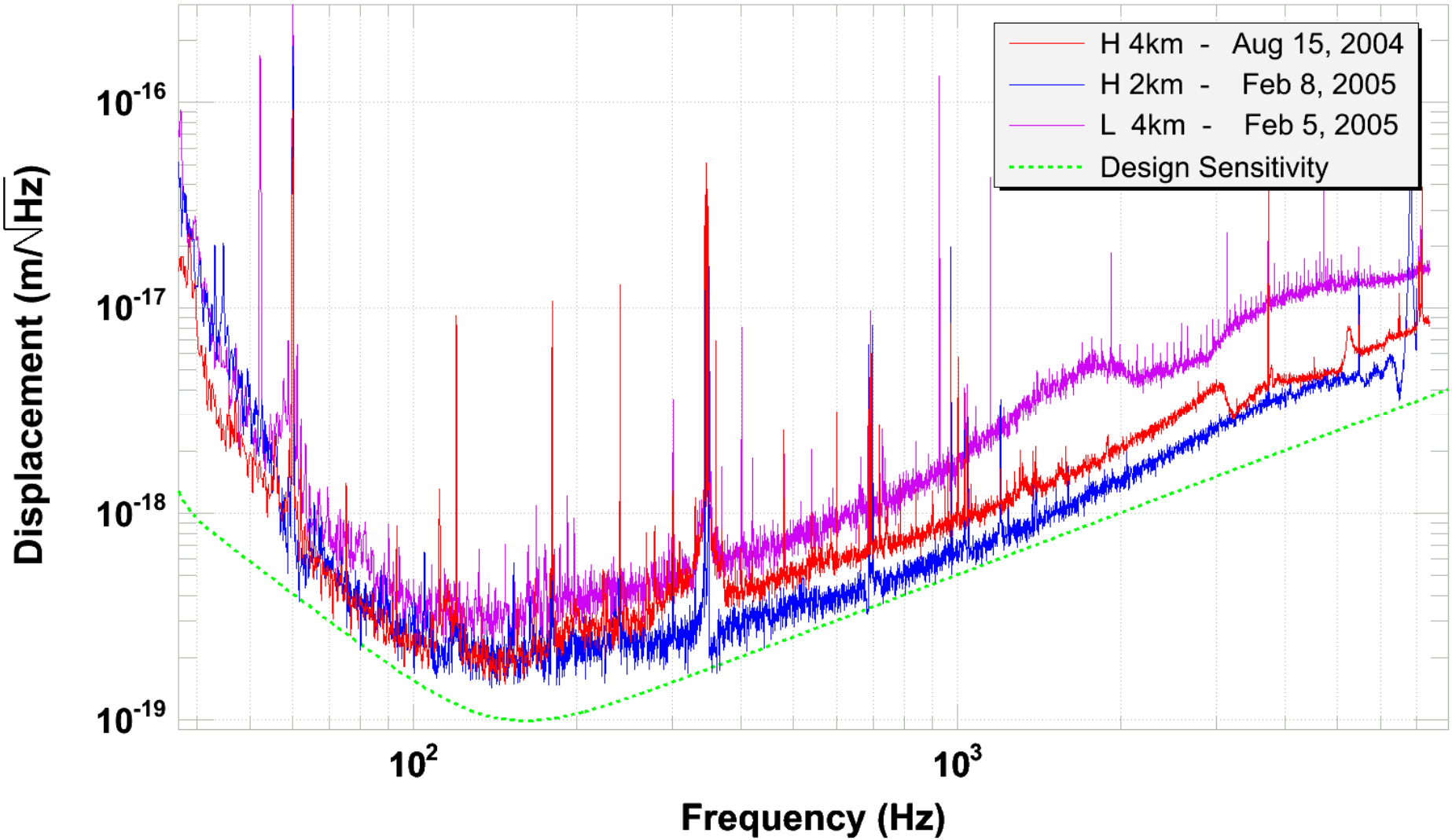
LIGO

Good Sensitivity Improvements



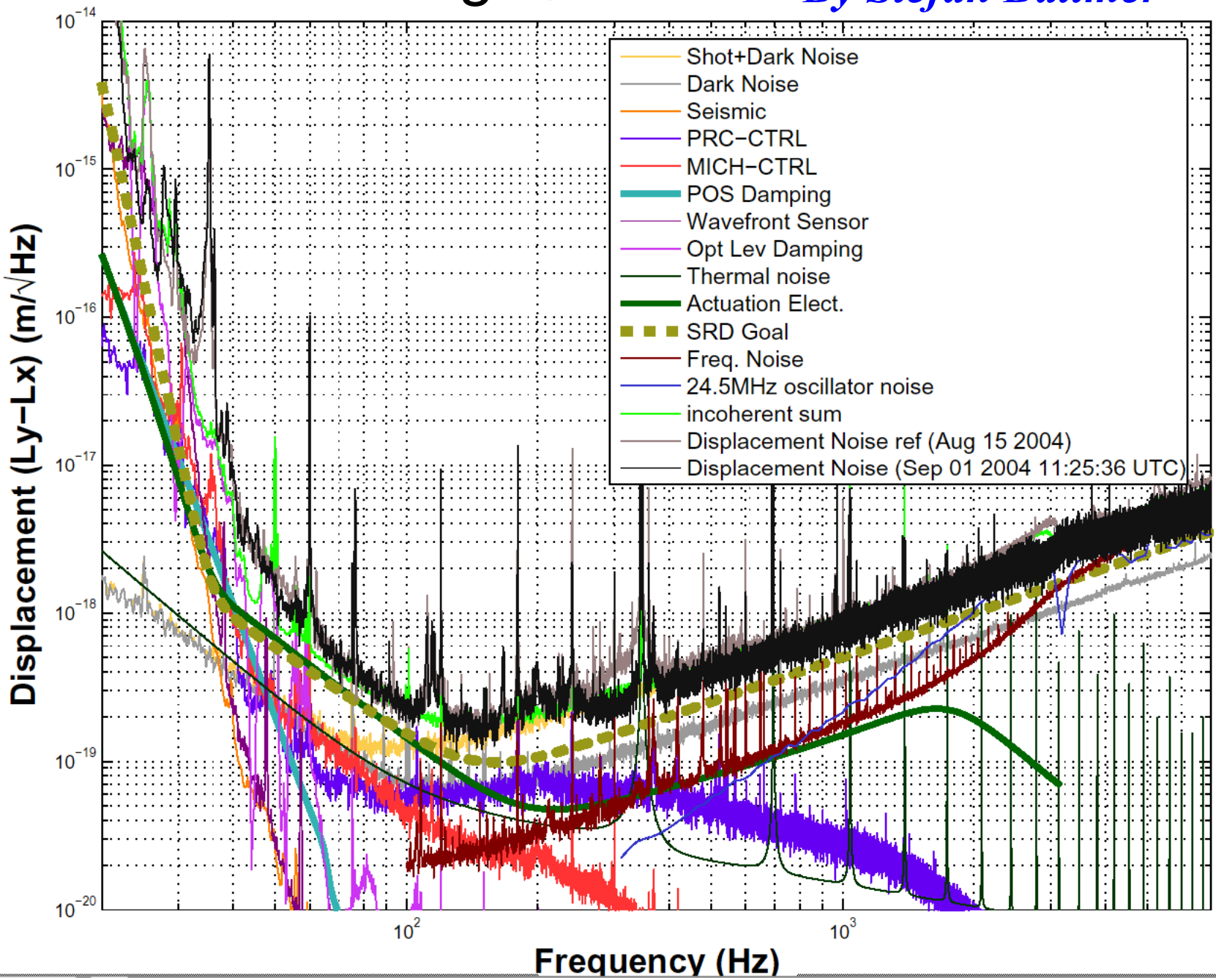
LIGO

Latest Engineering Run (E12)



Noise Budget

By Stefan Ballmer



LIGO

Outline

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

Post-S4 Steps

	Next ***6 months***
L 4k	Low Phase Noise Crystal Oscillator Increase Laser Power to 10 W Wideband Angular Controls (like in GEO)
H 4k	Investigate Excess Absorption Increase Laser Power to 10 W Wideband Angular Controls
H 2k	❑ Higher Laser Power

LIGO

The End

- All interferometers can now run **all day and night**
- All interferometers have all lengths and angles under control
  => **repeatable, stable operation**
- All interferometers within 3x of design