Calibrating and Improving the Sensitivity of the LIGO Detectors

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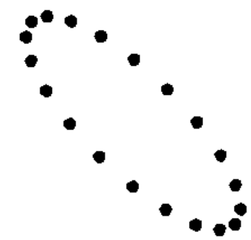
Ph. D. Thesis Defense, Louisiana State University

September 8th 2010

- Introduction
- The Laser Interferometer Gravitational Wave Observatory
- Calibration of the LIGO Detectors
- Advanced LIGO
- Prototype Seismic Isolation System
- Conclusions

Gravitational Waves and Astrophysical Sources

- General relativity predicts the existence of gravitational waves
- Produce quadrupolar strain h on space-time
- Astrophysical sources typically divided into 4 categories:



Short Duration | *Long Duration*

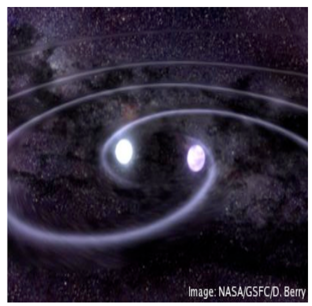
Modeled

Compact Binary Coalescences

$$h_{CBC}^{1.4-1.4}(15\,\text{Mpc}) \approx 10^{-21}$$

$$f_{CBC}^{1.4-1.4} \approx 100\ \text{Hz}$$

$$R_{CBC}^{1.4-1.4} \approx 100\ \text{Mpc}^{-3}\,\text{Myr}^{-1}$$

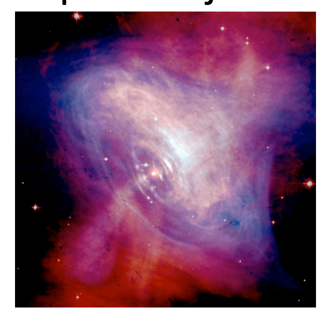


J Abadie *et al* 2010 *Class. Quantum Grav.* **27** 173001

Non-Spherically Rotating Compact Objects

$$h_{Pulsar} \approx 10^{-27}\ \text{-}\ 10^{-24}$$

$$f_{CW} \approx 2 f_{rot}$$



L. Bildsten 1998 *ApJ* **501** L89

Unmodeled

Bursts from Supernova and other Unmodeled Sources

$$h_{CC\ SNe} \approx 10^{-23}\ \text{-}\ 10^{-20}$$

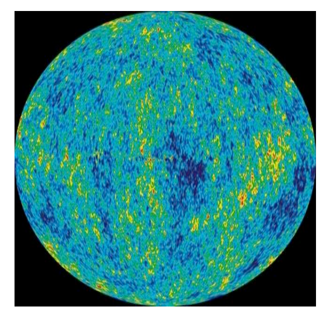
$$f_{CC\ SNe} \approx 1000\ \text{Hz}$$

C. D. Ott *et al* 2004 *ApJ* **600** 834

Stochastic Background

$$h(\Omega = 10^{-8}) \approx 10^{-24}$$

$$\text{for } f_{Stoch} \approx 50-150\ \text{Hz}$$



B. Allen 1996 *arXiv:gr- qc/9604033v3*

Basic Observation of Gravitational Waves

- Can detect strain using Michelson interferometer

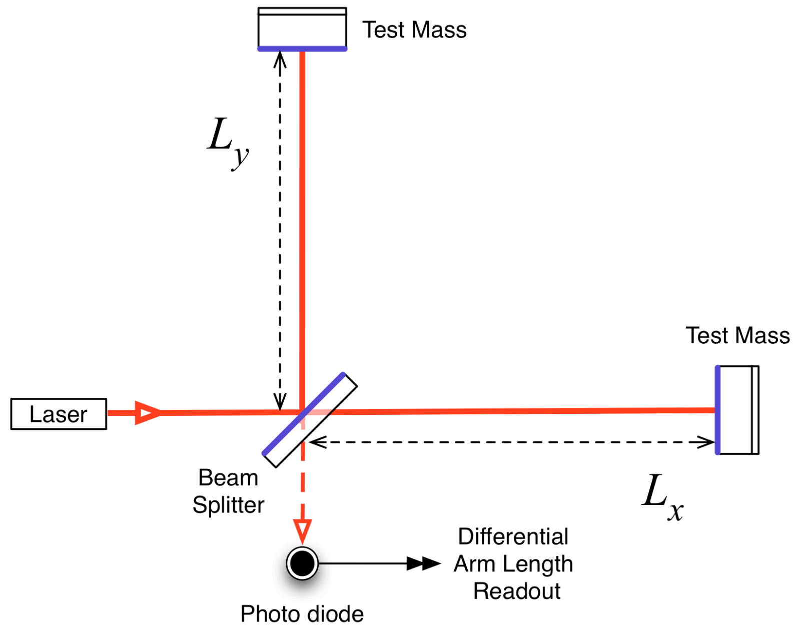
- Differential changes in arm length measure strain

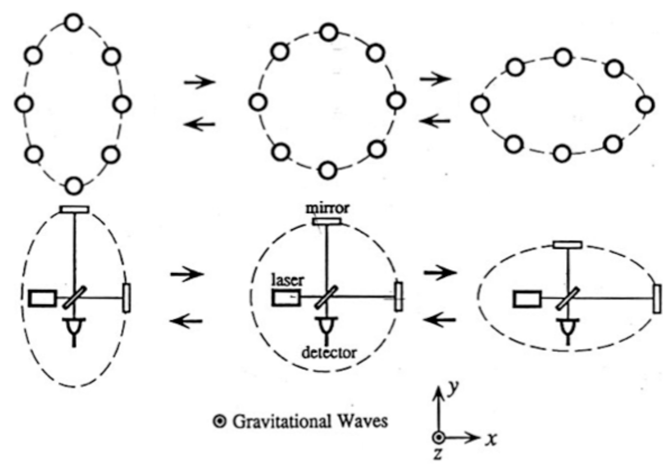
$$\Delta L = L_X - L_Y = h\,L$$

- Suspended Mirrors act as inertial particles or “test masses”

- But even if Michelson arms are 1 km long,

$$\Delta L = h_{CBC}^{1.4-1.4}\ L_{km} = 10^{-18}\,m$$





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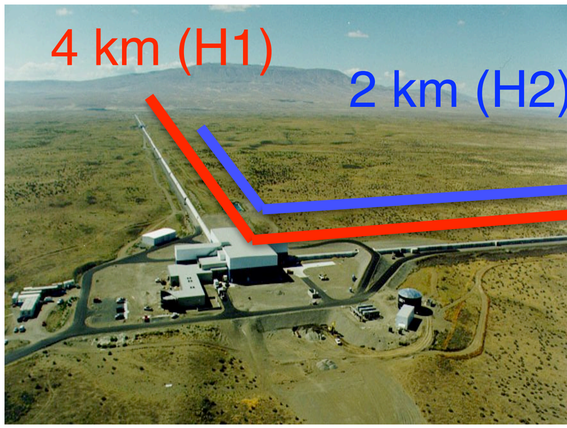
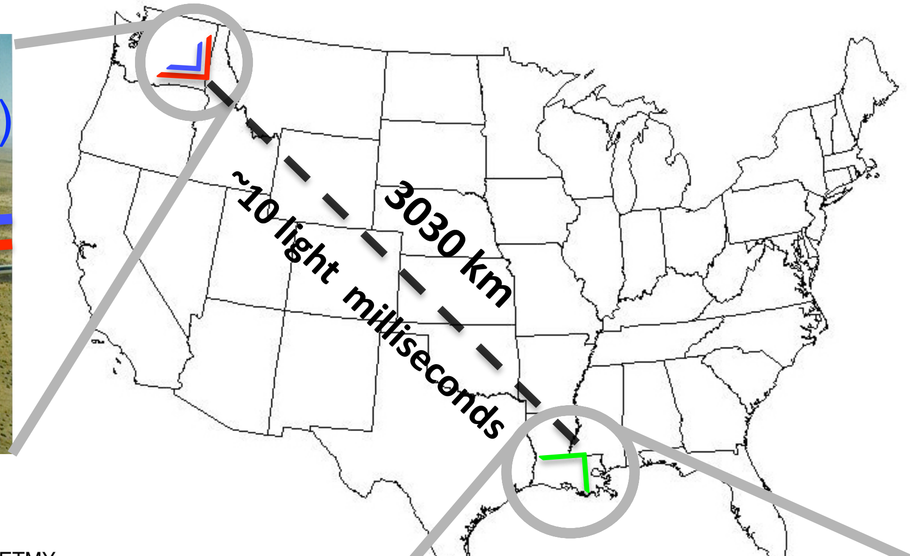
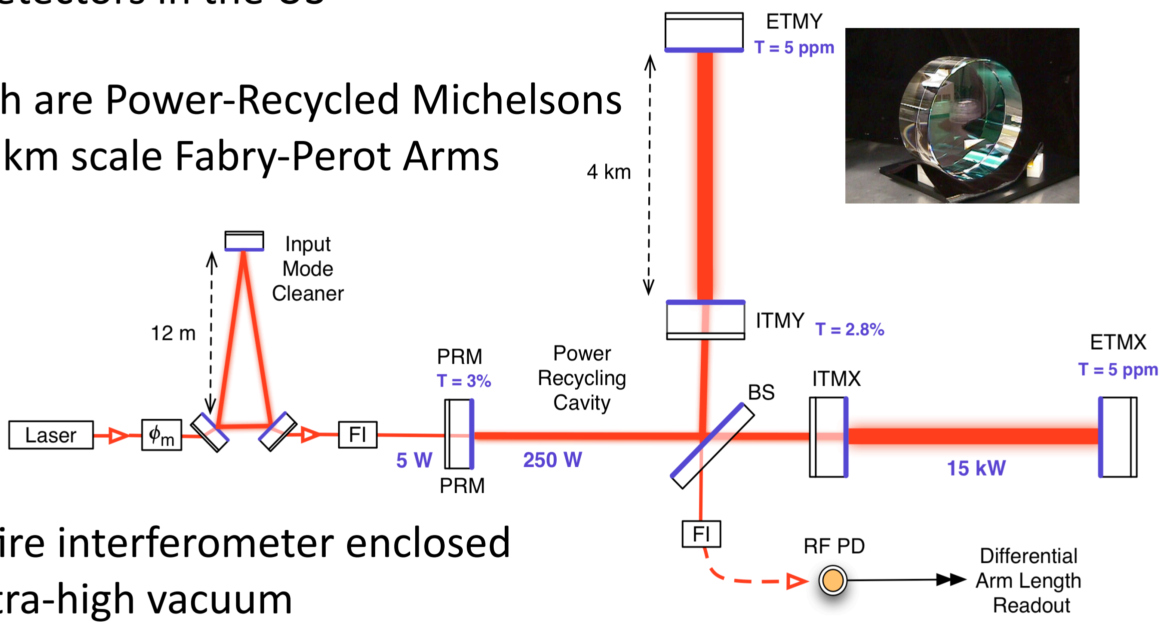
The Laser Interferometer Gravitational Wave Observatory
The Detectors





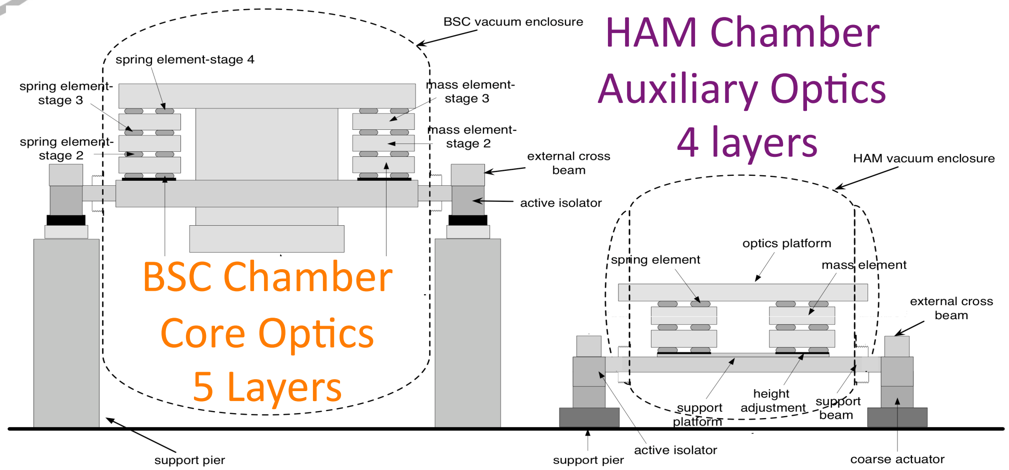
- 3 detectors in the US

- Each are Power-Recycled Michelsons with km scale Fabry-Perot Arms

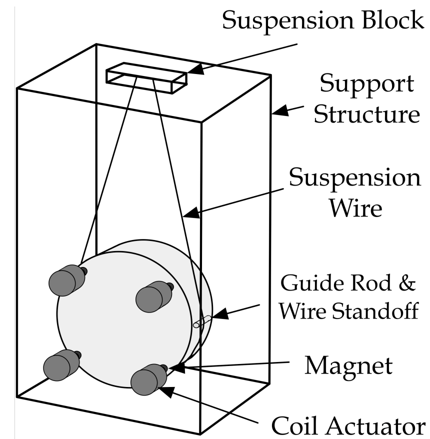


- Entire interferometer enclosed in ultra-high vacuum

The LIGO Detectors
Seismic Isolation and Control

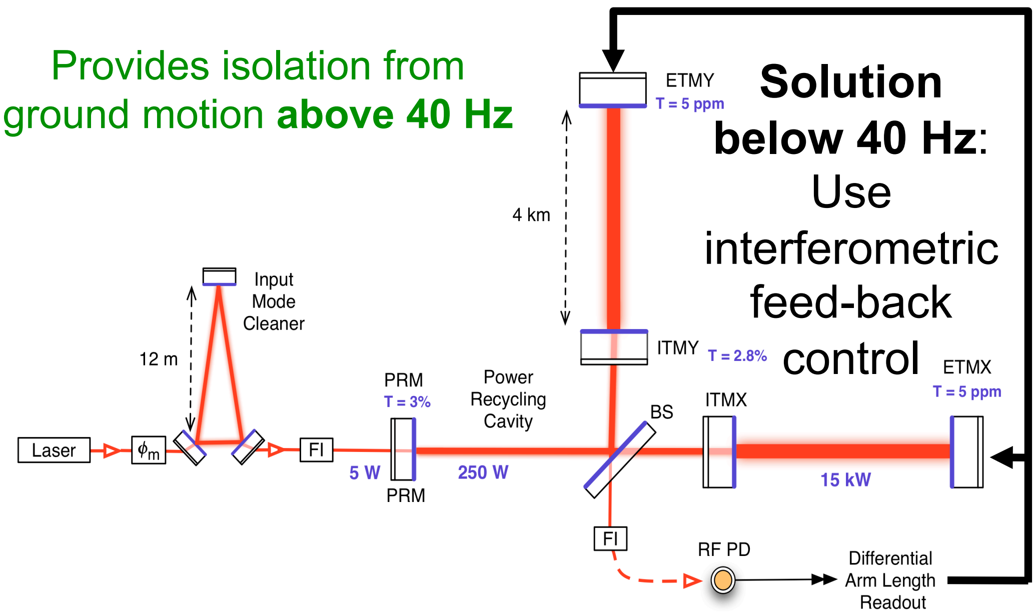


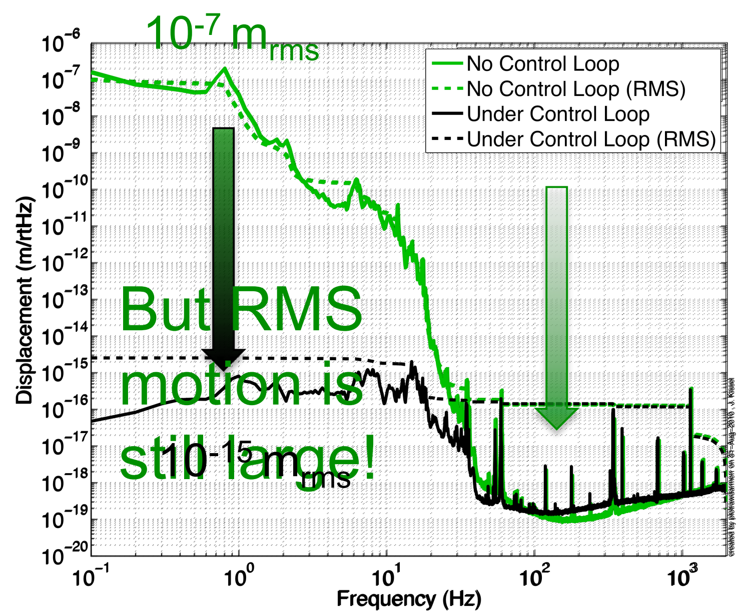
Core Optic Suspension



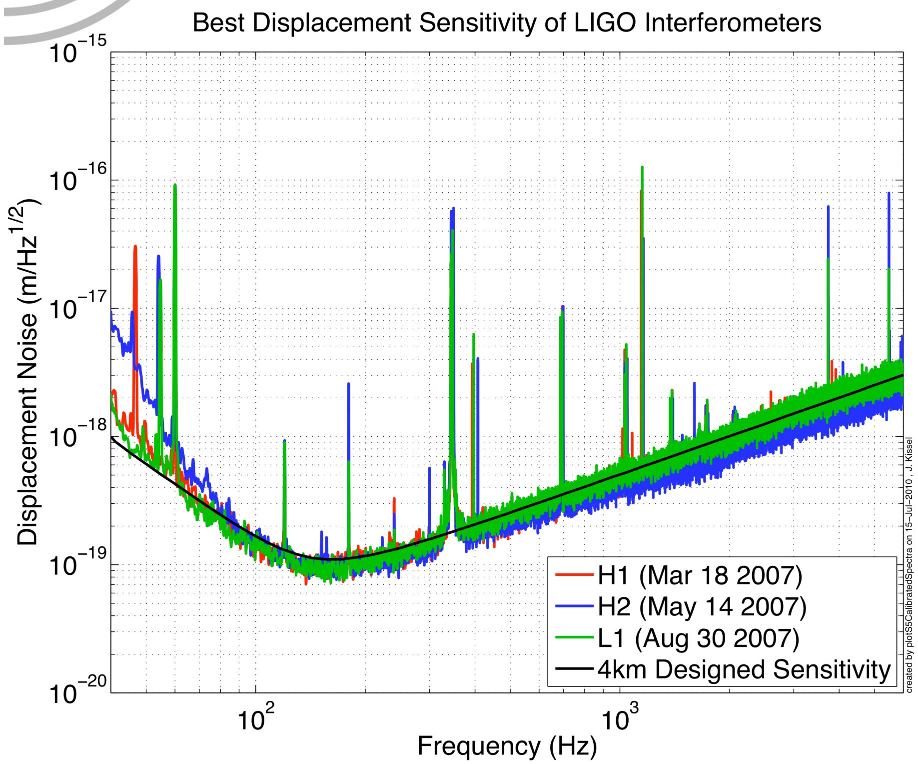
Optics are suspended from cascading layers of passive isolation

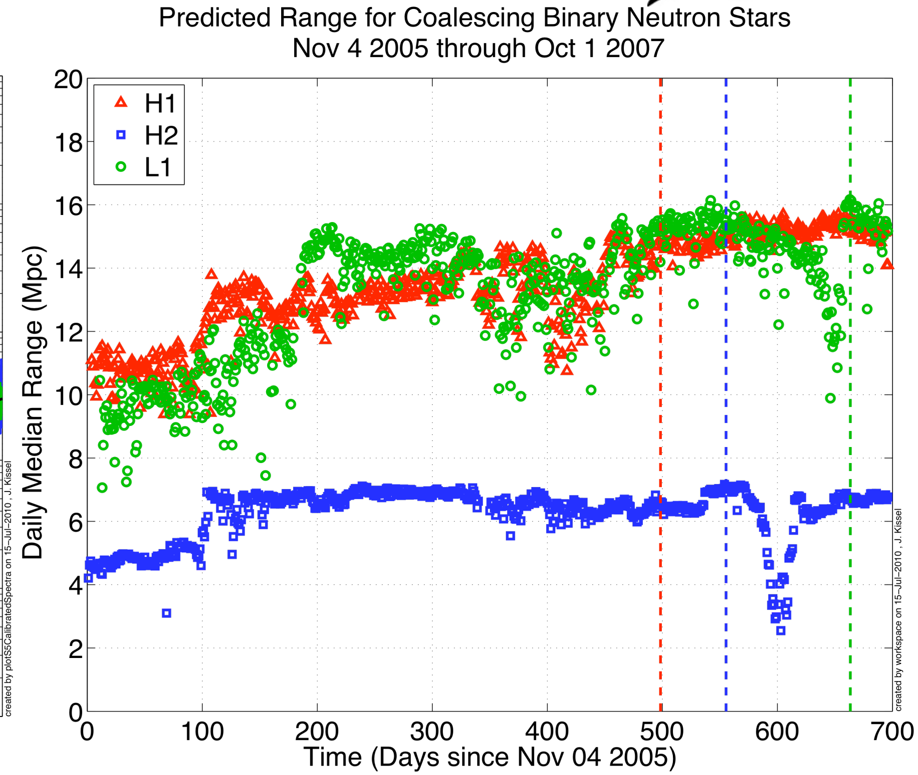
Provides isolation from ground motion **above 40 Hz**





The LIGO Detectors
The Fifth Science Run, S5





- Two year science run, from Nov 2005 to Oct 2007, at or near designed sensitivity with 50% triple-coincidence duty cycle
- No detection, but detection rate was expected to be low: $\dot{N}_{re}^{1.4-1.4} \approx 0.02\ \ \mathrm{yr}^{-1}$
- Measured Displacement noise is ~10^{-19} m/Hz$^{1/2}$ (~10^{-23} in strain/Hz$^{1/2}$) between 100-300 Hz
- How do we know it's 10^{-19} m/rtHz, and with what certainty?

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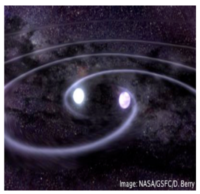
Calibration of the LIGO Interferometers
The Differential Arm Control Loop

Sensing Function



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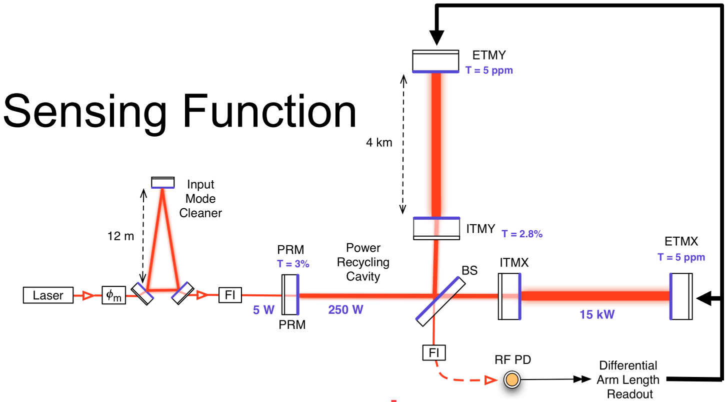
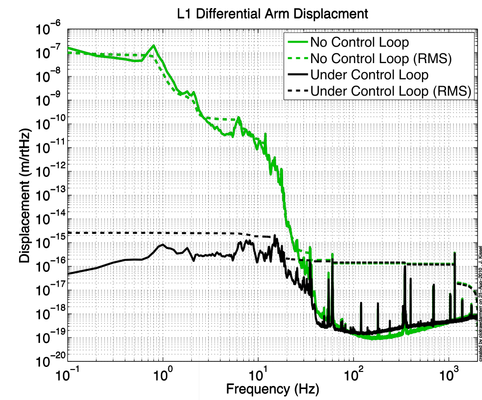
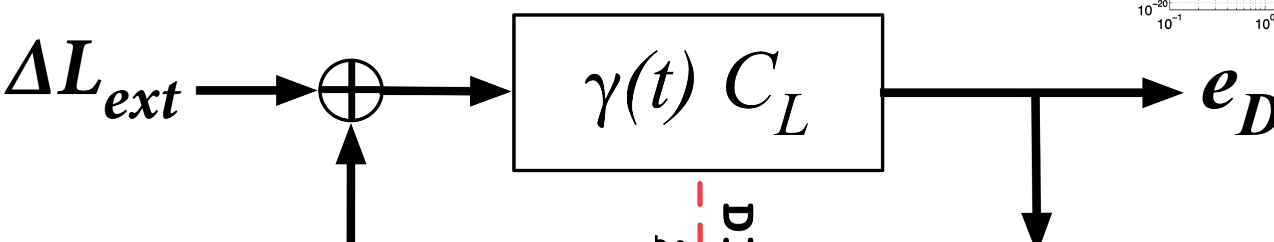
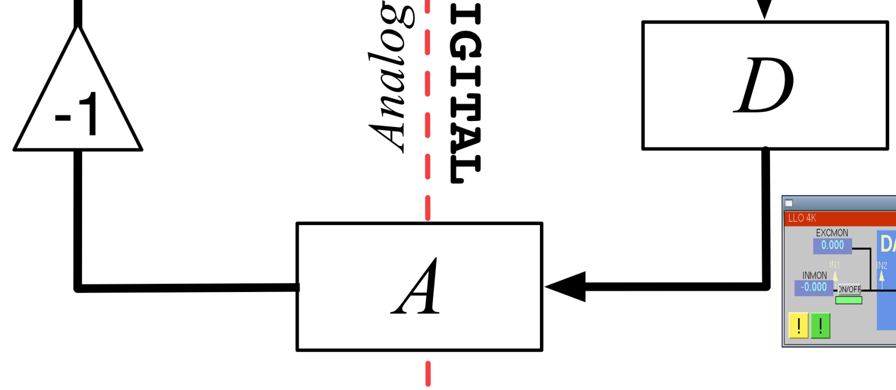
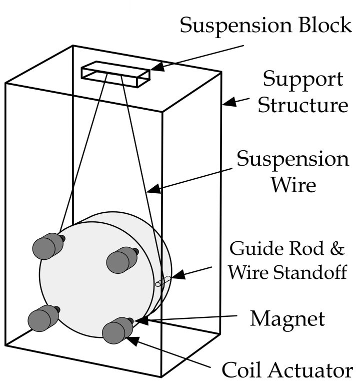




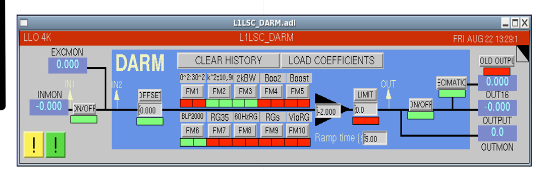






Actuation Function

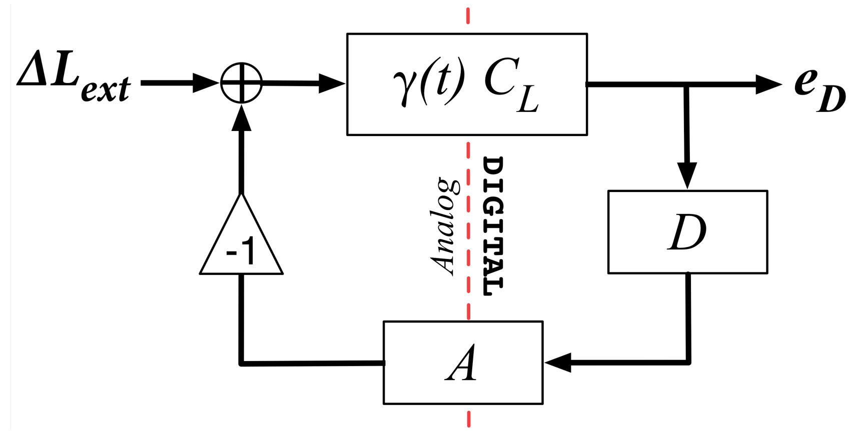
Digital Filters



$$e_D(f) \propto \Delta L_{ext}$$

- Frequency-Domain Model of Control Loop:
  Response Function

$$R_L(f,t) = \frac{1+\gamma(t)G_L(f)}{\gamma(t)C_L(f)}$$



- with the Open Loop Transfer Function

$$G_L(f) = C_L(f)\ D(f)\ A(f)$$

$$\Delta L_{ext} = R_L(f,t)\ e_D(f)$$

- and Sensing Function $C_L(f)$
  - non-linear and immeasurable without closed loop
  - An exact model would need lots of tough-to-measure parameters
  - Frequency dependence can be approximated

⇒ Therefore we* must measure

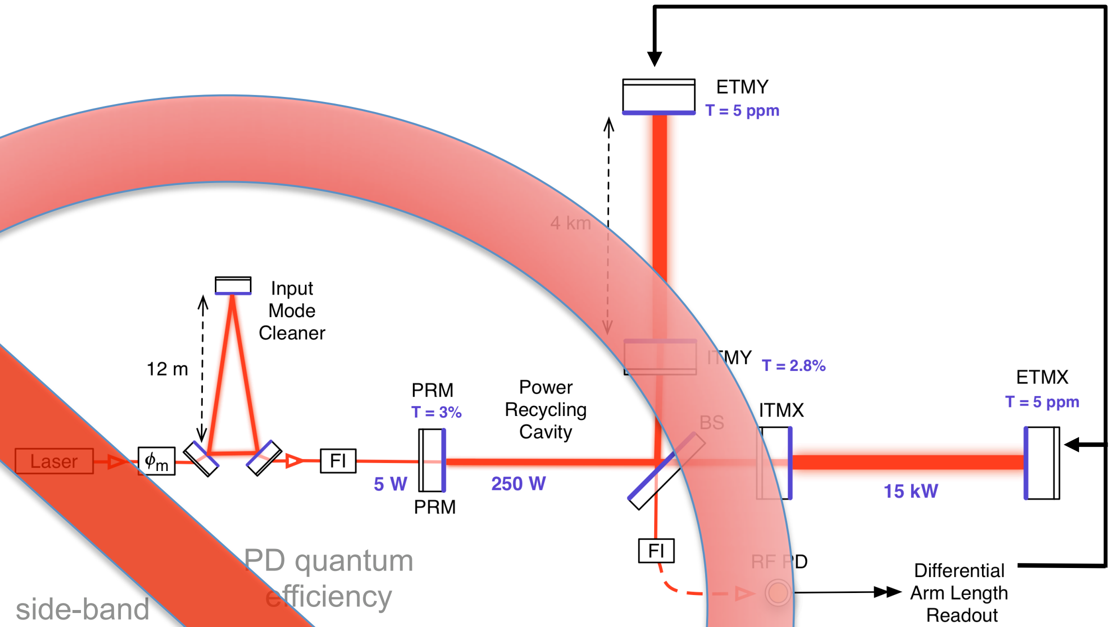
$$A(f),\quad \gamma(t),\quad G_L(f)$$

* we = The Calibration Group: Gaby Gonzalez, Brian O'Reilly, Mike Landry, Rick Savage, Myungkee Sung, Evan Goetz and me!

The Sensing Function Model

• We *could* develop an exact model the sensing function …

• Power-recycled, Fabry-Perot Michelson, using RF modulation locking scheme:



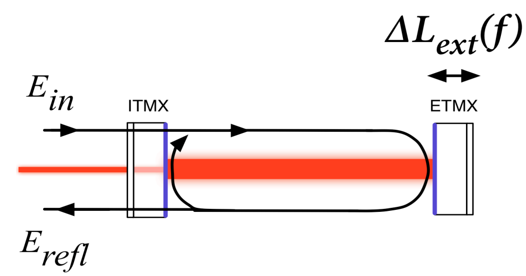
$$\frac{V_{RF\,PD}(f)}{\Delta L_{ext}} = 8\,\frac{2\pi}{\lambda}\,P_{in}\,J_0(\Gamma)J_1(\Gamma)\;g_{rc}\;t_{sb}\;\frac{r_e(1-r_i)^2}{(1-r_i r_e)}\;\eta\,R_{PD}\;\frac{\sin(2\pi f\,\Delta L/c)}{2\pi f\,\Delta L/c}\;\frac{e^{-2\pi i f \Delta L/c}}{1-r_i r_e\;e^{-4\pi i f \Delta L/c}}$$

laser wavelength; modulation strength; side-band transmission; PD quantum efficiency; input power; recycling cavity gain; arm cavity reflectivity; PD circuitry impedance; Messy, nonlinear frequency dependence

• But this would be tough to develop: parameters can have
  • time, thermal, and alignment dependence
  • large uncertainty

The Sensing Function Model

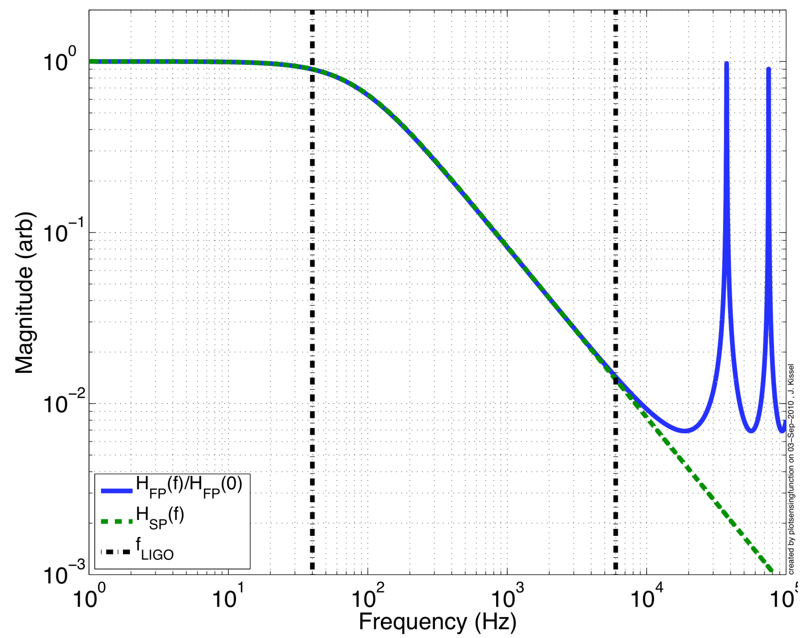
- Fabry Perot cavity's response to changes in length

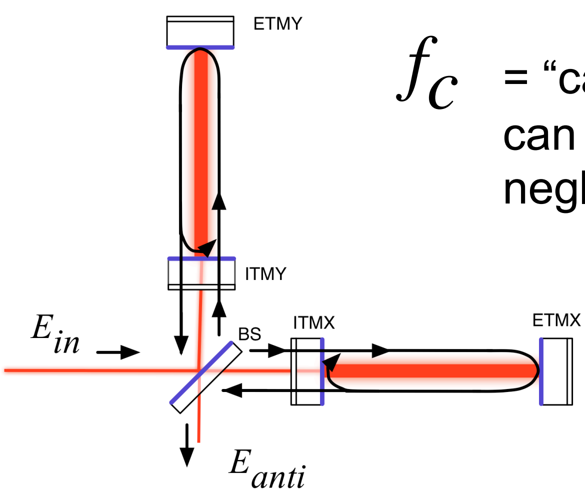


$$H_{FP}(f) \propto \frac{\sin(2\pi f L/c)}{2\pi f L/c} \frac{e^{-2\pi i f L/c}}{1 - r_i r_e \, e^{-4\pi i f L/c}}$$

- BUT when GW wavelengths are much longer than the cavity, we can use single pole approximation:

$$H_{SP}(f) \equiv \frac{H_{FP}(f << 2c/L)}{H_{FP}(0)} \approx \frac{1}{1 + i\,(f/f_c)}$$





f_c = "cavity pole," can be measured to negligible uncertainty

$$C_L(f) \propto [H_{SP}^x(f) + H_{SP}^y(f)] \times [details(f)]$$

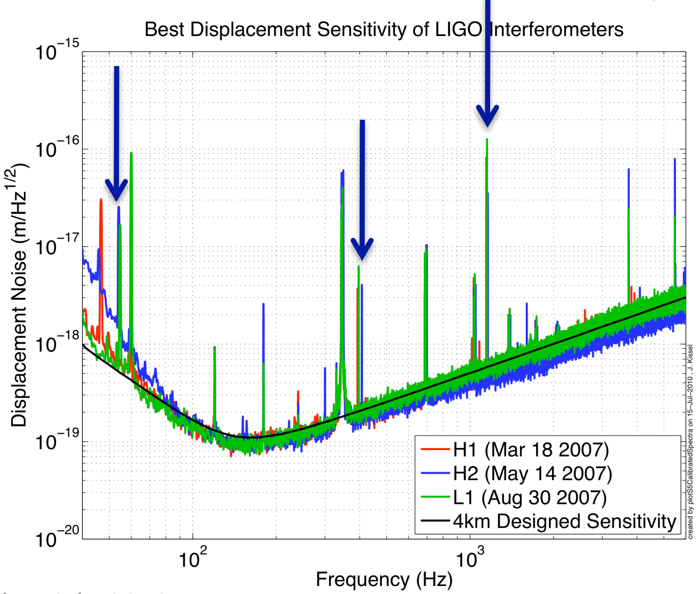
• Absolute scale of sensing function varies slowly ($f << 40$ Hz) with time because of alignment, thermal fluctuations

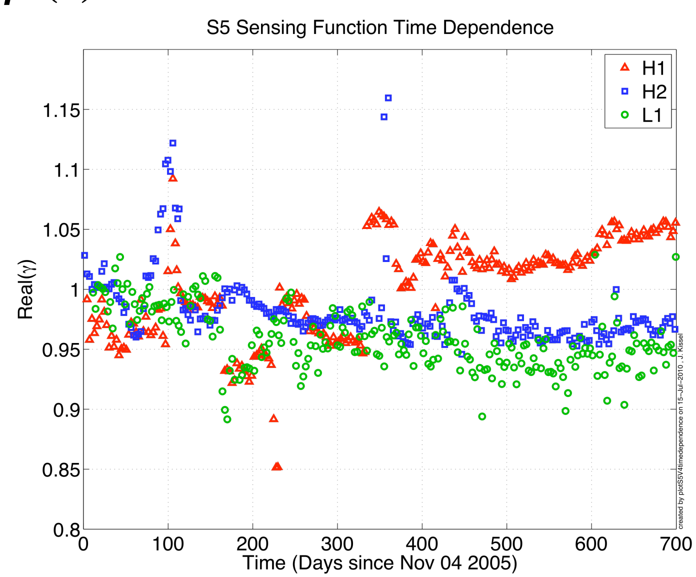
• This time dependence $\alpha(t)$ is measured and compensated digitally with coefficient $\beta(t)$ but not perfect

• Measurement is performed by injecting three sine waves with known amplitude and frequency to coil actuators of one test mass while at full sensitivity

• Residual time dependence is included in response function, as a coefficient close to unity:

$$\gamma(t) = \alpha(t)\beta(t)$$





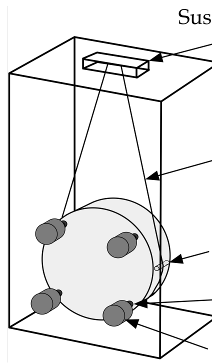
Measuring the Actuation Function

$$A(f) = \xi^x A^x(f) + \xi^y A^y(f)$$

$$A^{x,y}(f) = [K_A^{x,y}\, P^{x,y}(f)] \times [details(f)]$$

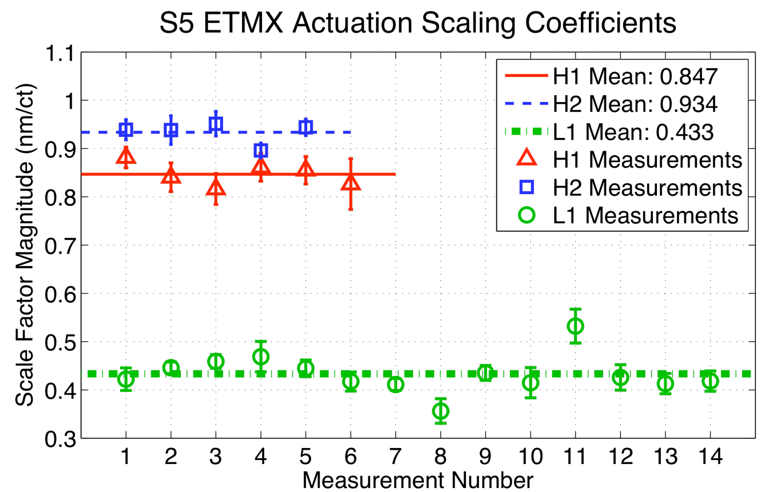
$$P^{x,y}(f) = \frac{f_0^2}{\left(f^2 - \frac{i\omega_0}{Q} f - f_0^2\right)}$$

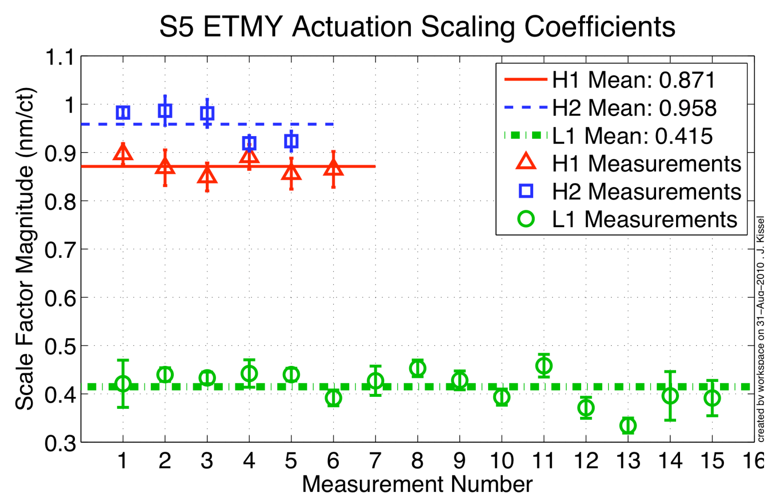
Driven Pendulum Response



$K_A^{x,y}$

- measured with simple configurations of the interferometer
- laser wavelength is fundamental metric
- measured* many times over the science run

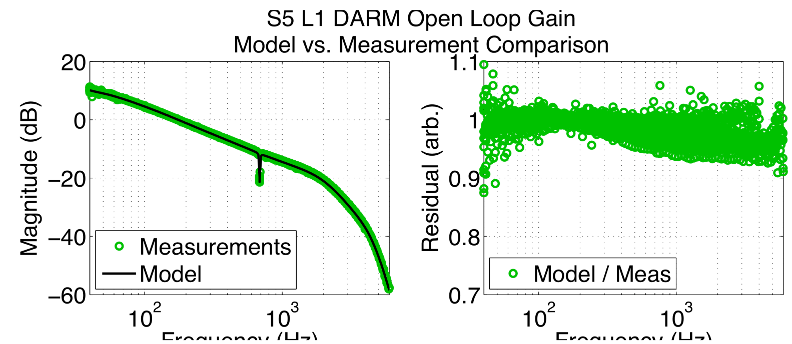




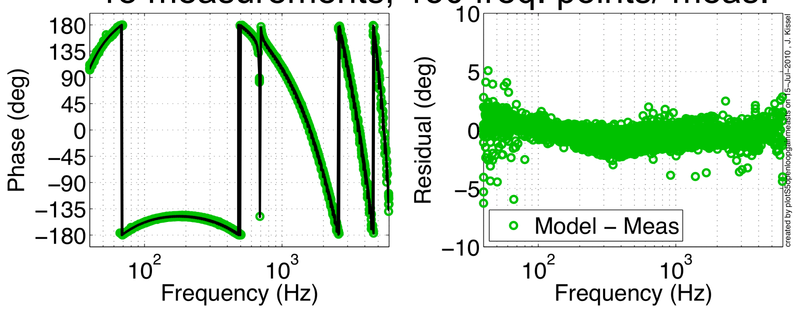
* with compilation and detailed analysis by me

Calibration of the LIGO Interferometers
Open Loop Transfer Function

$$G_L(f) = C_L(f) \quad D(f) \quad A(f)$$

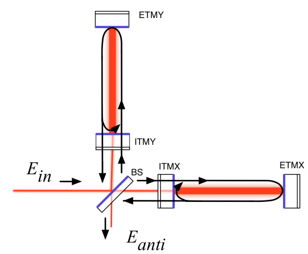


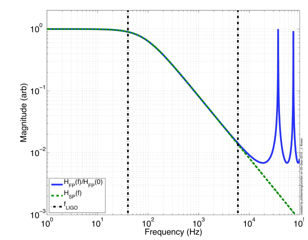
18 measurements, 150 freq. points/ meas.



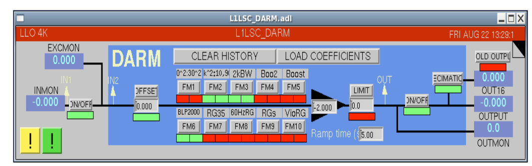
- Digitally excite closed loop, much larger than ΔL_{ext}
- Measured* ~20 / interferometer during the science run
- Remaining absolute scale must be from sensing function (define $\gamma(t) \equiv 1$ during measurement)
- Also confirms model of frequency dependence

$C_L(f)$: frequency dependence modeled

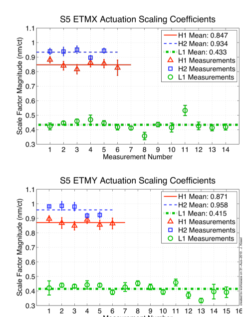


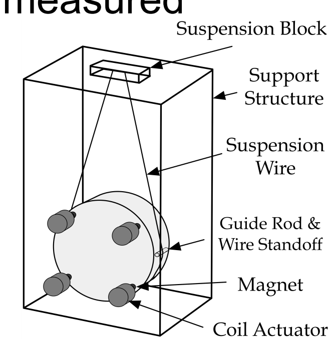


$D(f)$: frequency dependence, absolute scale known

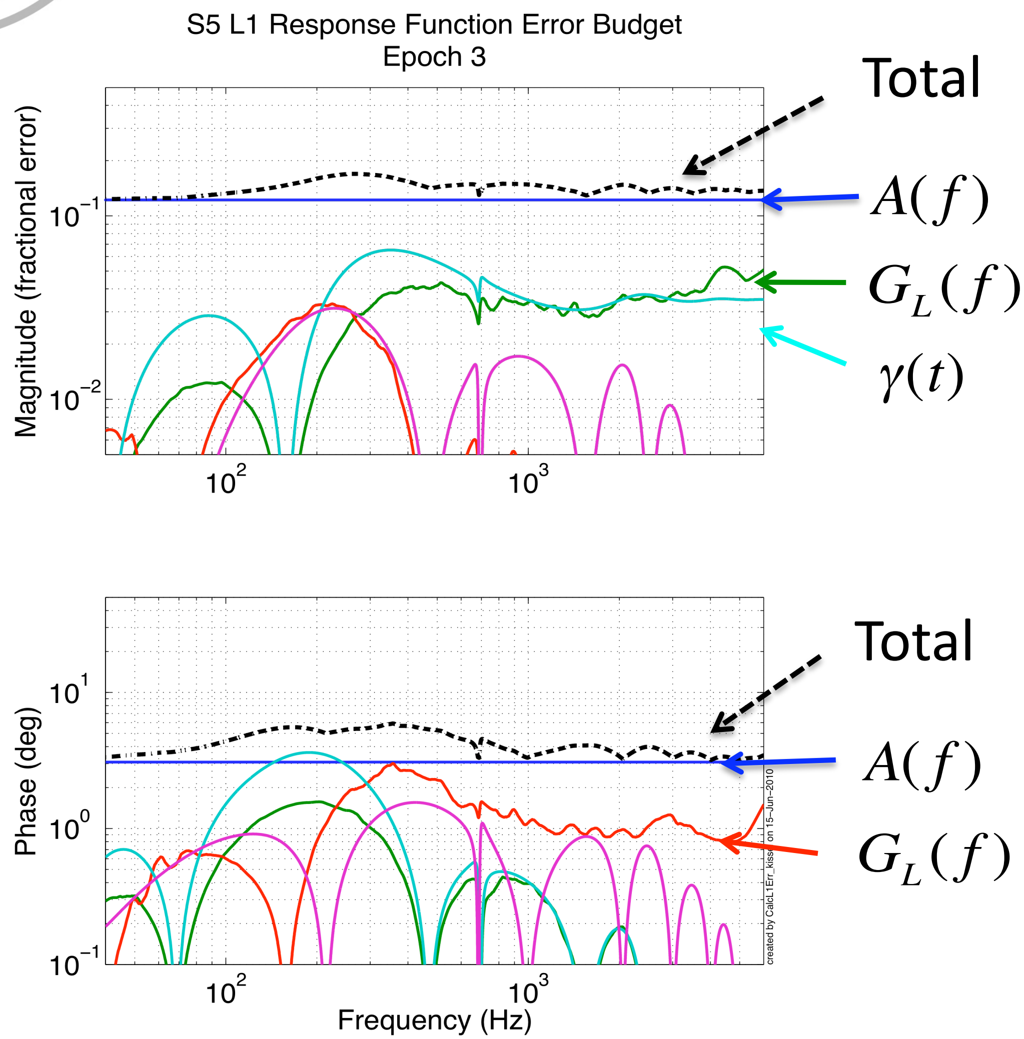


$A(f)$: frequency dependence modeled, absolute scale measured





Calibration of the LIGO Interferometers
Response Function Uncertainty



$$R_L(f,t) = \frac{1+\gamma(t)G_L(f)}{\gamma(t)C_L(f)}$$

- Uncertainty of **< 15% and 5 degrees** over the entire 2 year science run!

- Limited by measurements of the actuation function

⇒ Cannot excite test masses above residual ground motion

Paper: "Calibration of the LIGO gravitational wave detectors in the fifth science run" accepted for publication in Nuclear Instruments and Methods A

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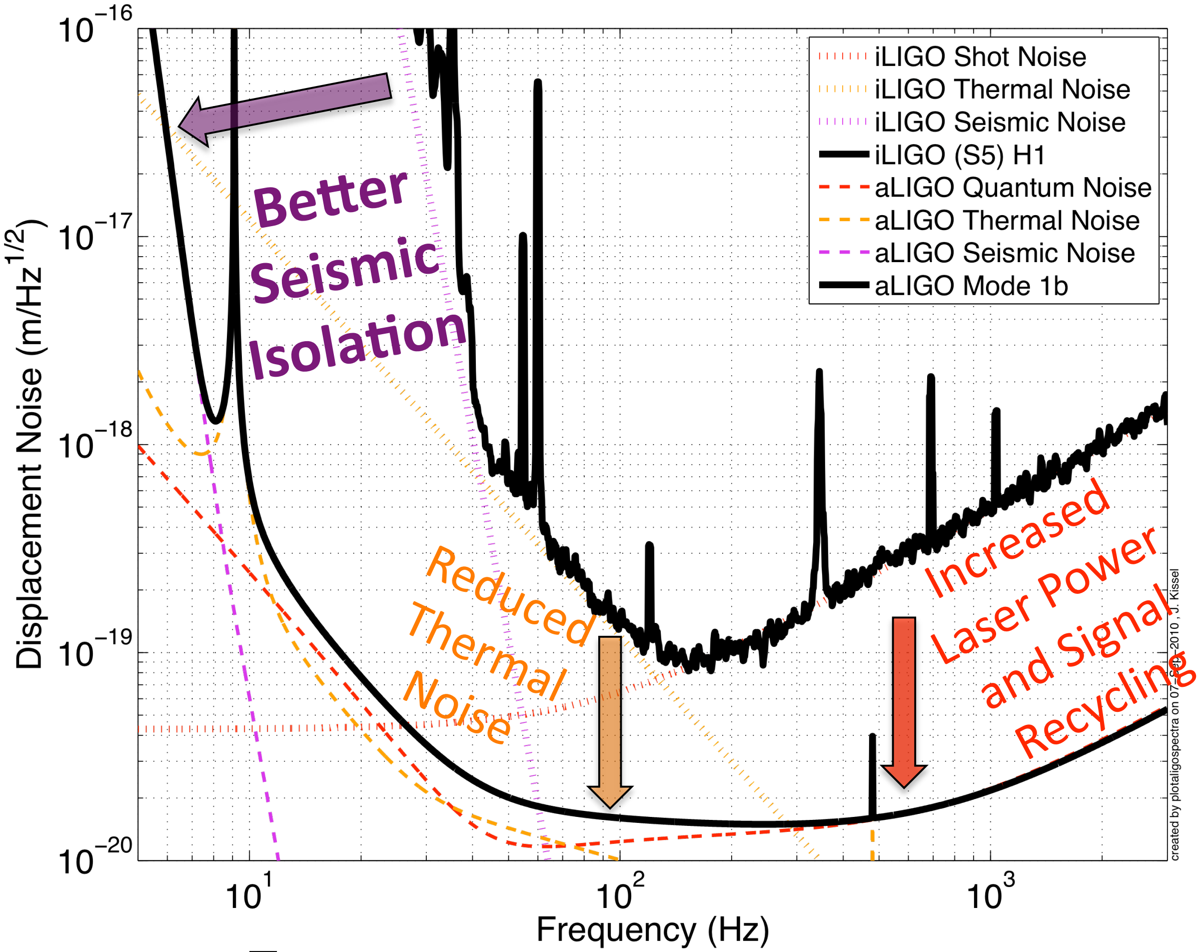
The Advanced LIGO Detectors
Predicted Sensitivity and Timeline

- Major upgrade to all detectors, all internal components replaced
- Three 4km detectors in the same two-site vacuum system
- Designed to be Quantum Noise limited down to 10 Hz
- Predicted Binary Neutron Star Range: **~180 Mpc**
- Detection Rate:

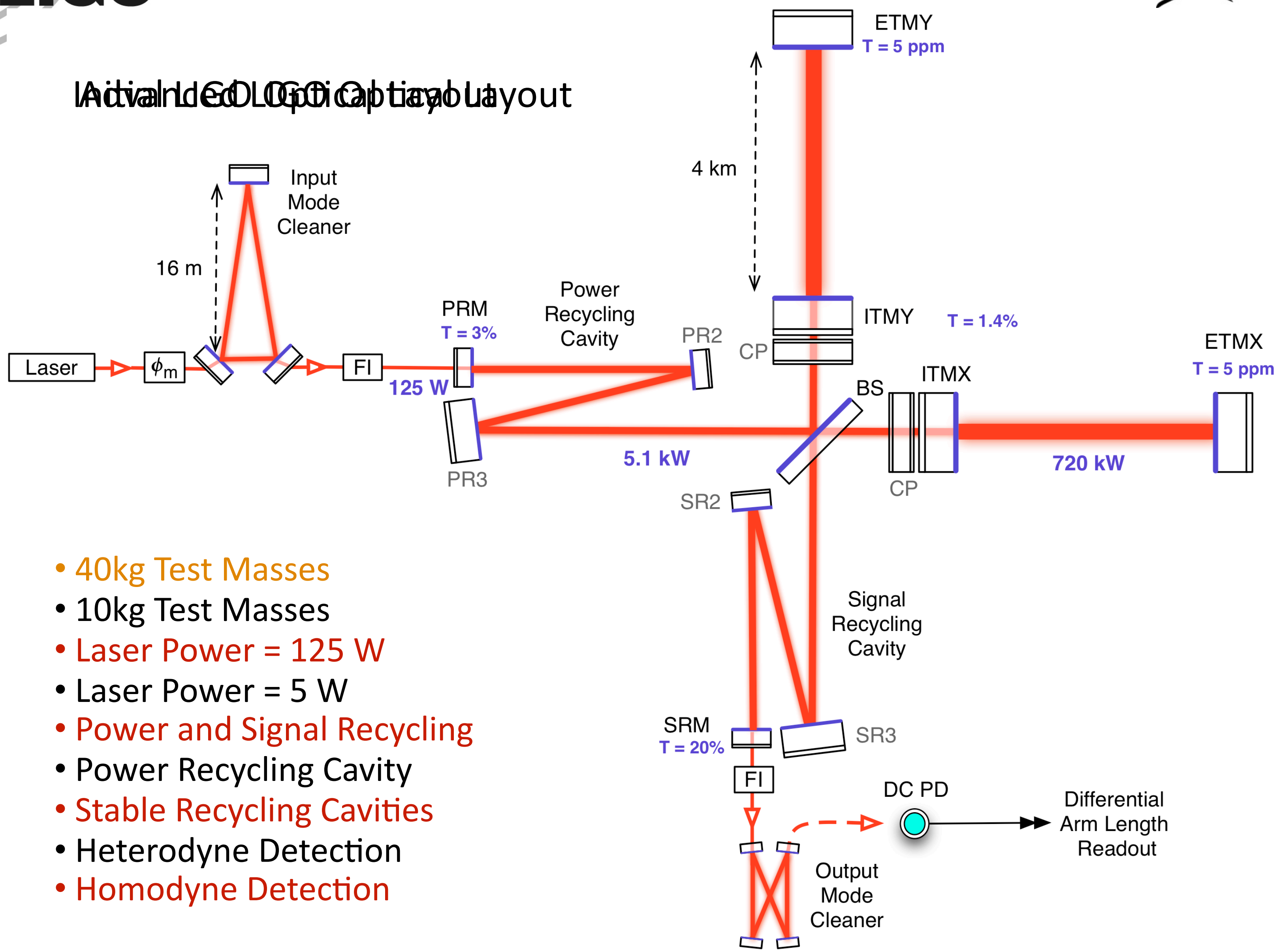
$$\dot{N}_{re}^{1.4-1.4} \approx 40 \ \text{yr}^{-1}$$



	2007	2008	2009	2010	2011	2012	2013	2014	2015
Observing	S5		S6	S6				S7	S7
Upgrading	Enhance!	Enhance!		Advance!	Advance!	Advance!	Advance!		

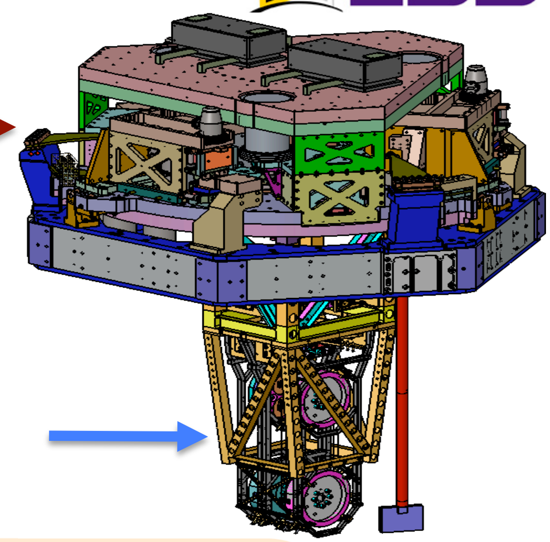
The Advanced LIGO Detectors
Interferometer Comparison

Initial LIGO Optical Layout / Advanced LIGO Optical Layout



- 40kg Test Masses
- 10kg Test Masses
- Laser Power = 125 W
- Laser Power = 5 W
- Power and Signal Recycling
- Power Recycling Cavity
- Stable Recycling Cavities
- Heterodyne Detection
- Homodyne Detection

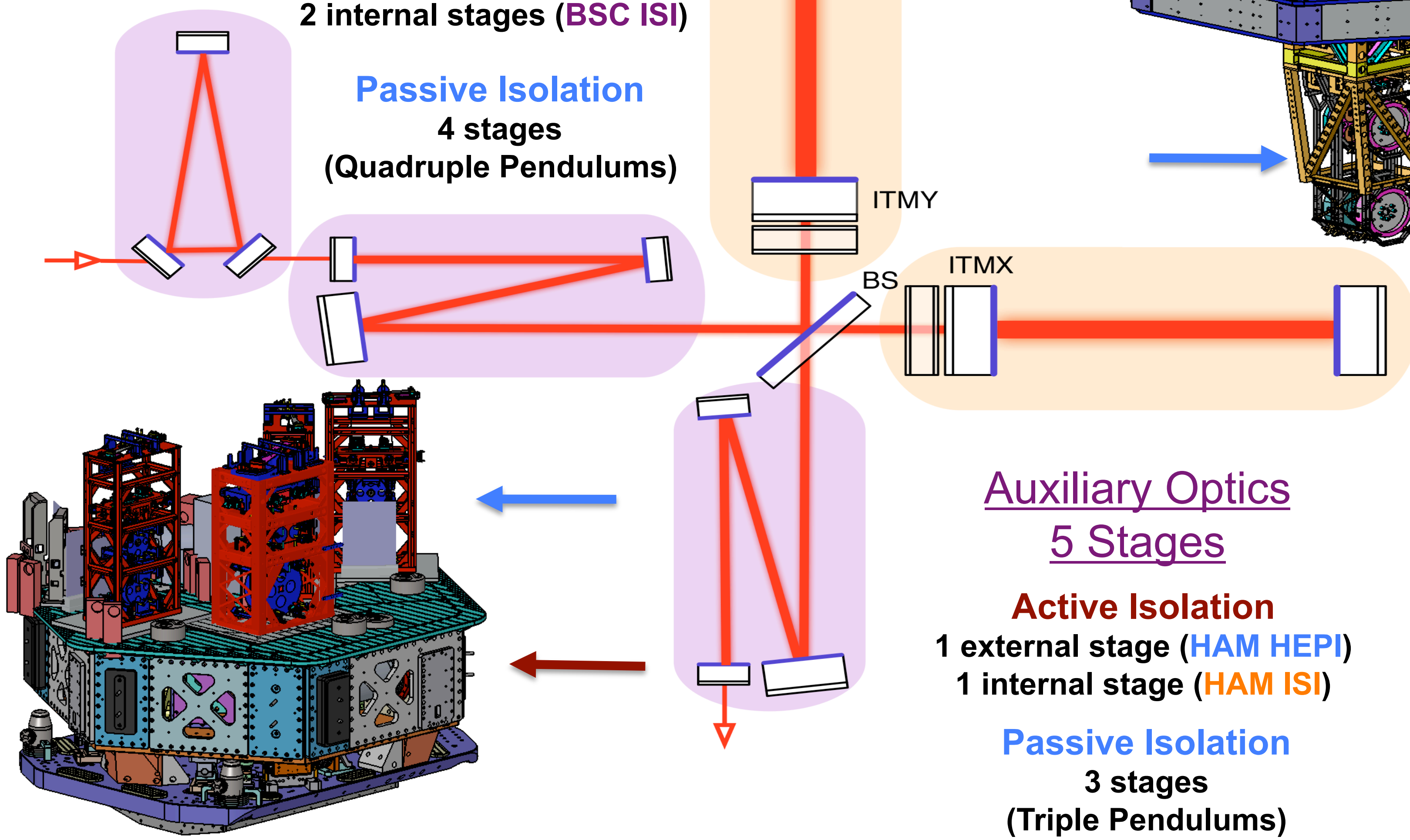
The Advanced LIGO Detectors
Seismic isolation and Suspensions



Core Optics
7 Stages

Active Isolation
1 external stage (BSC HEPI)
2 internal stages (BSC ISI)

Passive Isolation
4 stages
(Quadruple Pendulums)



Auxiliary Optics
5 Stages

Active Isolation
1 external stage (HAM HEPI)
1 internal stage (HAM ISI)

Passive Isolation
3 stages
(Triple Pendulums)

Possible Intermediate Configuration:
- No Signal Recycling
- 25 W Input Power

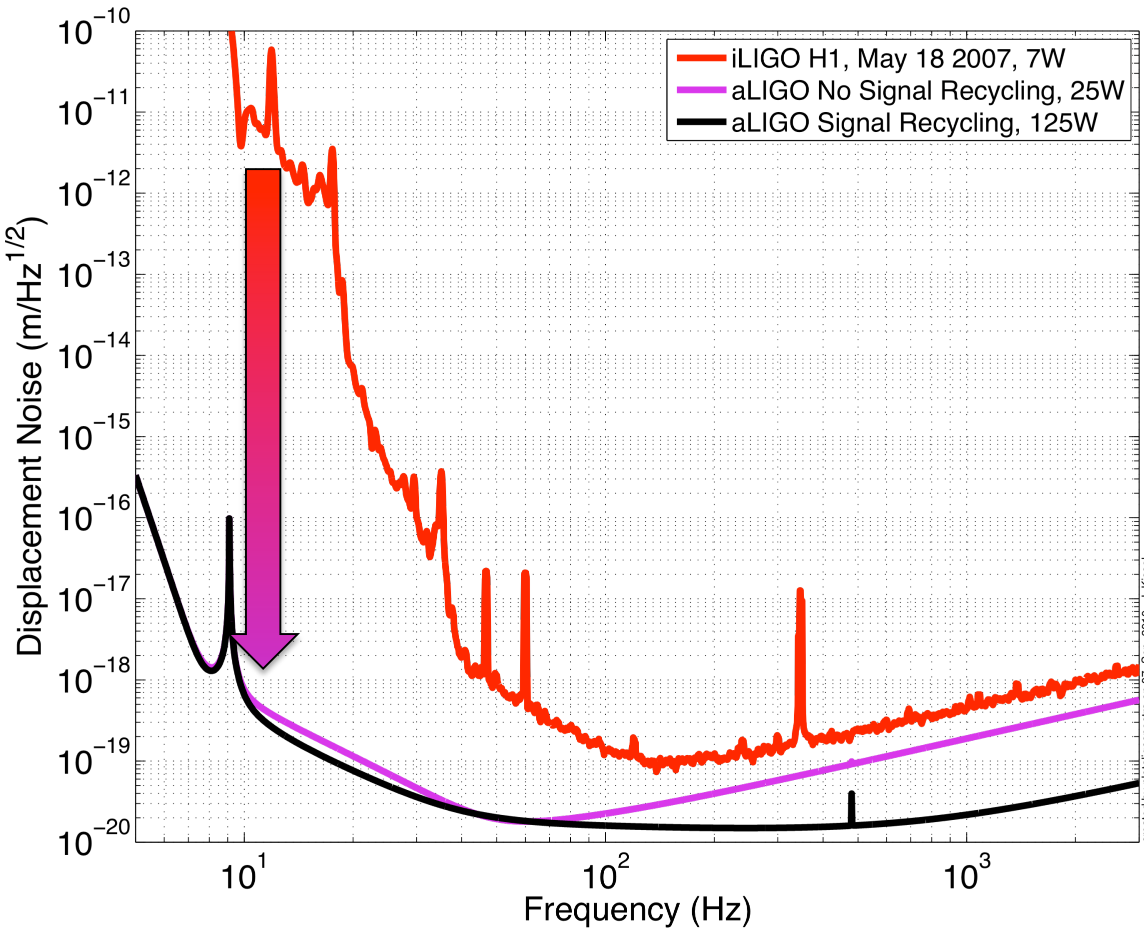
Demonstration of aLIGO suspensions and seismic isolation:

• 7 orders of magnitude less displacement at 10 Hz

⇒ Predicted Binary Neutron Star Range: ~**145 Mpc**

⇒ Event Rate:

$$\dot{N}_{re}^{1.4-1.4} \approx 10 \ \ \mathrm{yr}^{-1}$$



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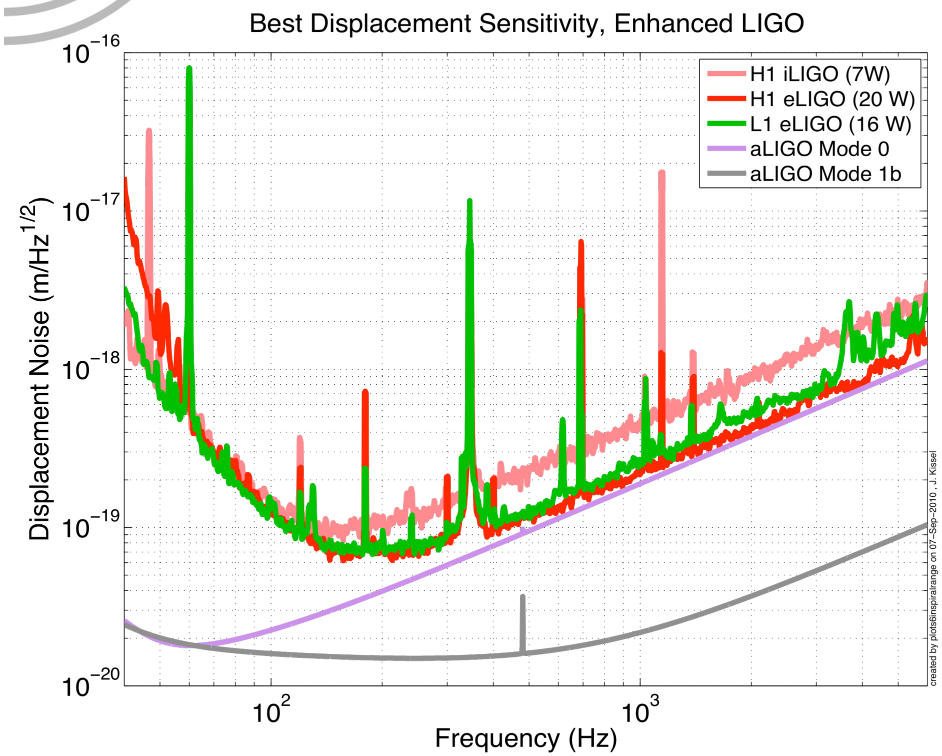
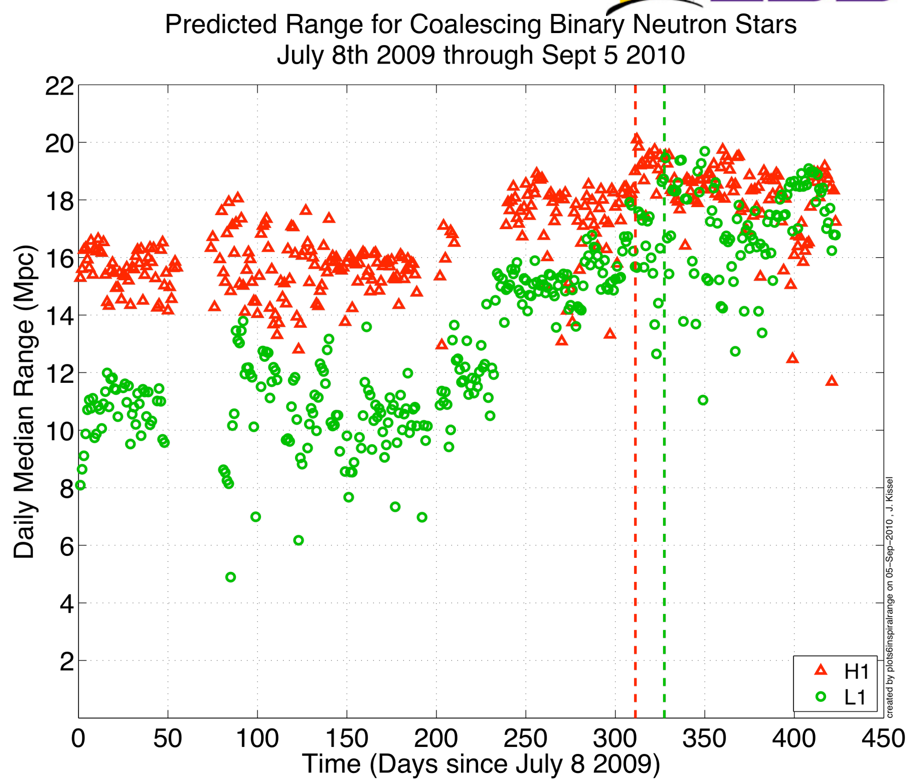
The Enhanced LIGO Detectors
The Sixth Science Run





- Non-invasive upgrade to the S5-era 4 km LIGO detectors, from late 2007 to early 2009
- S6 data run from mid 2009 to mid 2010, typical inspiral range increased by 5 Mpc

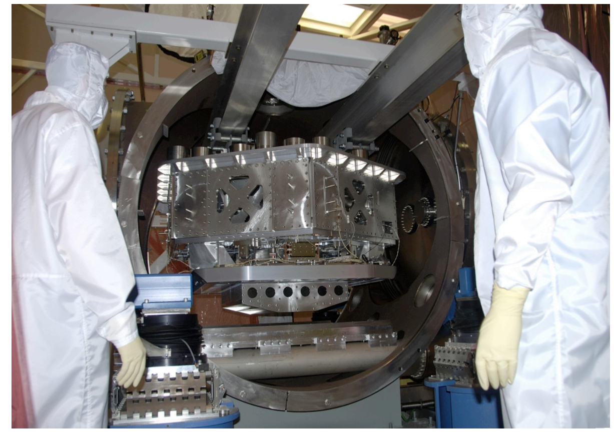
- Upgrades include prototypes of Advanced LIGO Technology
    - Increased laser power from 7 W to 20 W
    - Homodyne detection
    - **Prototype Active Seismic Isolation**

	2007	2008	2009	2010
Observing	S5			S6
Upgrading		Enhance!		

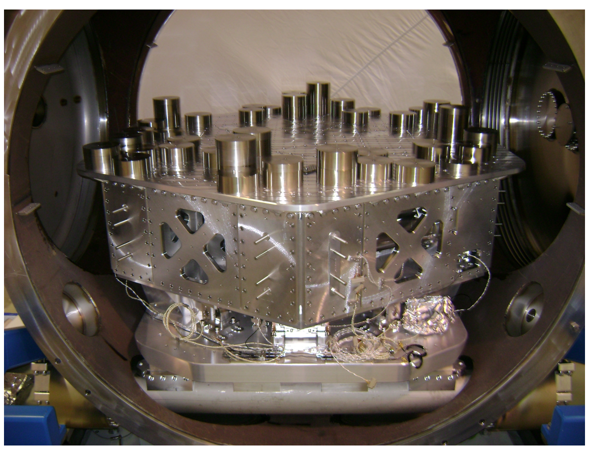
Prototype HAM-ISI Isolation System

- aLIGO prototype for eLIGO upgrade to 4km interferometers, under homodyne readout

- We[@] built and installed both in Winter/Spring of 2008



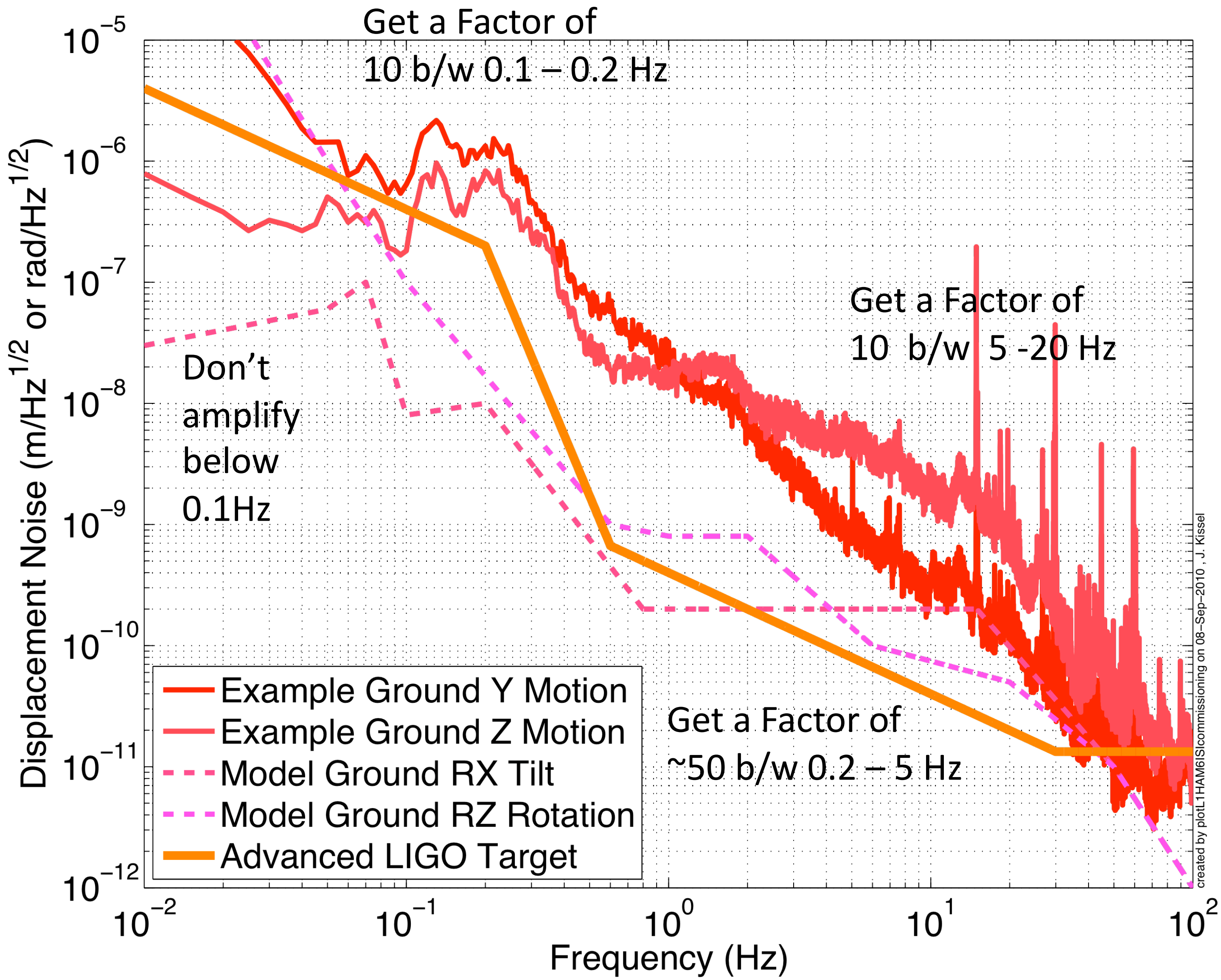
[@] we = Joe Hanson and myself at LLO; Hugh Radkins, Corey Gray and myself at LHO; with lots of help from Brian O'Reilly, Mike Landry, Ken Mason, Andy Stein, Stephany Foley, and Justin Garofoli



- We[t] commissioned the active control system from late 2009 – early 2010

[t] we = Brian Lantz, Rich Mittleman, Corey Gray, lead by me

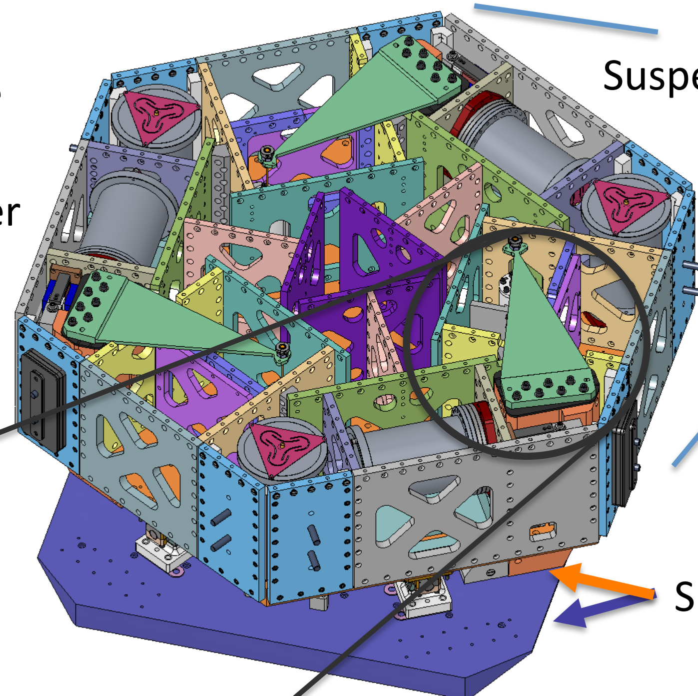
Prototype HAM-ISI Isolation System
Target Performance for Advanced LIGO



Rely on passive isolation above 20 Hz

Prototype HAM-ISI Isolation System
Passive Isolation Components

- Suspended stage is a rigid, light structure
- Platform is suspended via three cantilever blade springs attached to wire flexures
- Suspension acts as a pendulum, which filters seismic noise above resonances

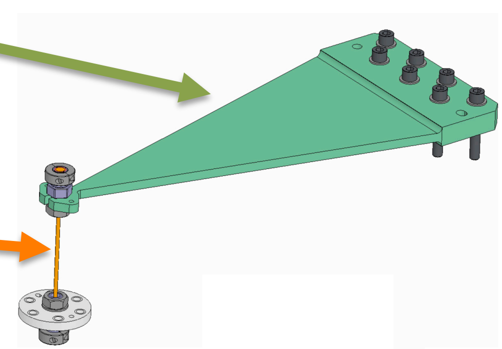


Suspended Stage

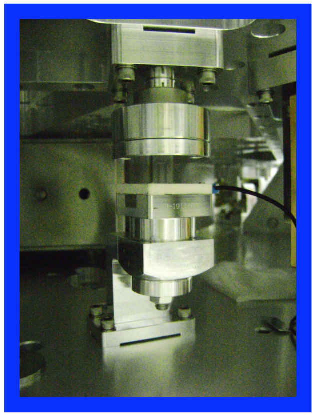
Support Stage

Blade Spring

Wire Flexure



Prototype HAM-ISI Isolation System
Active Isolation Components

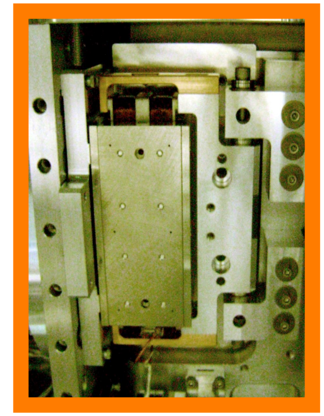


Displacement Sensors

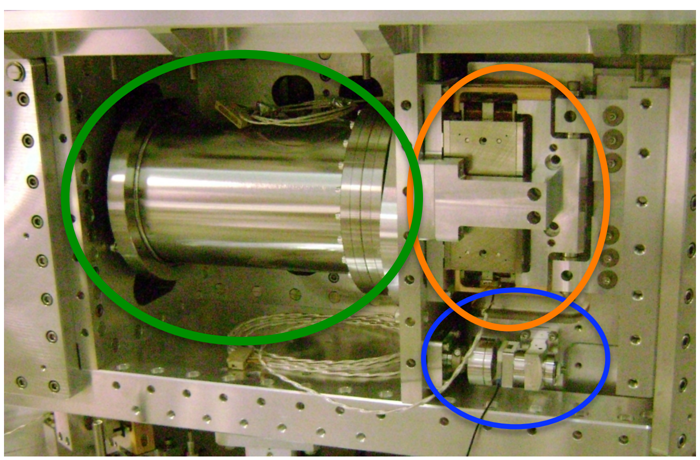
Inertial Sensors

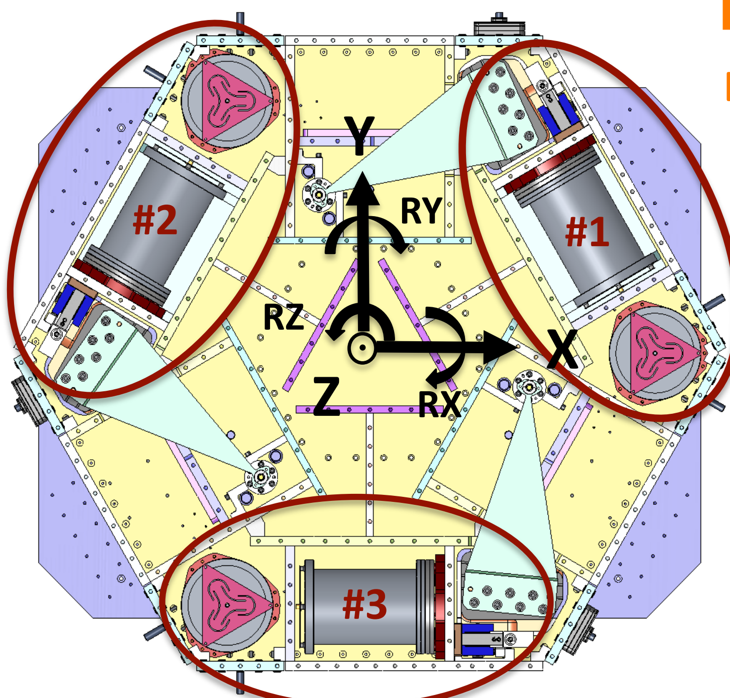
Ground Sensor

Sense and **control** of **all six** degrees of freedom



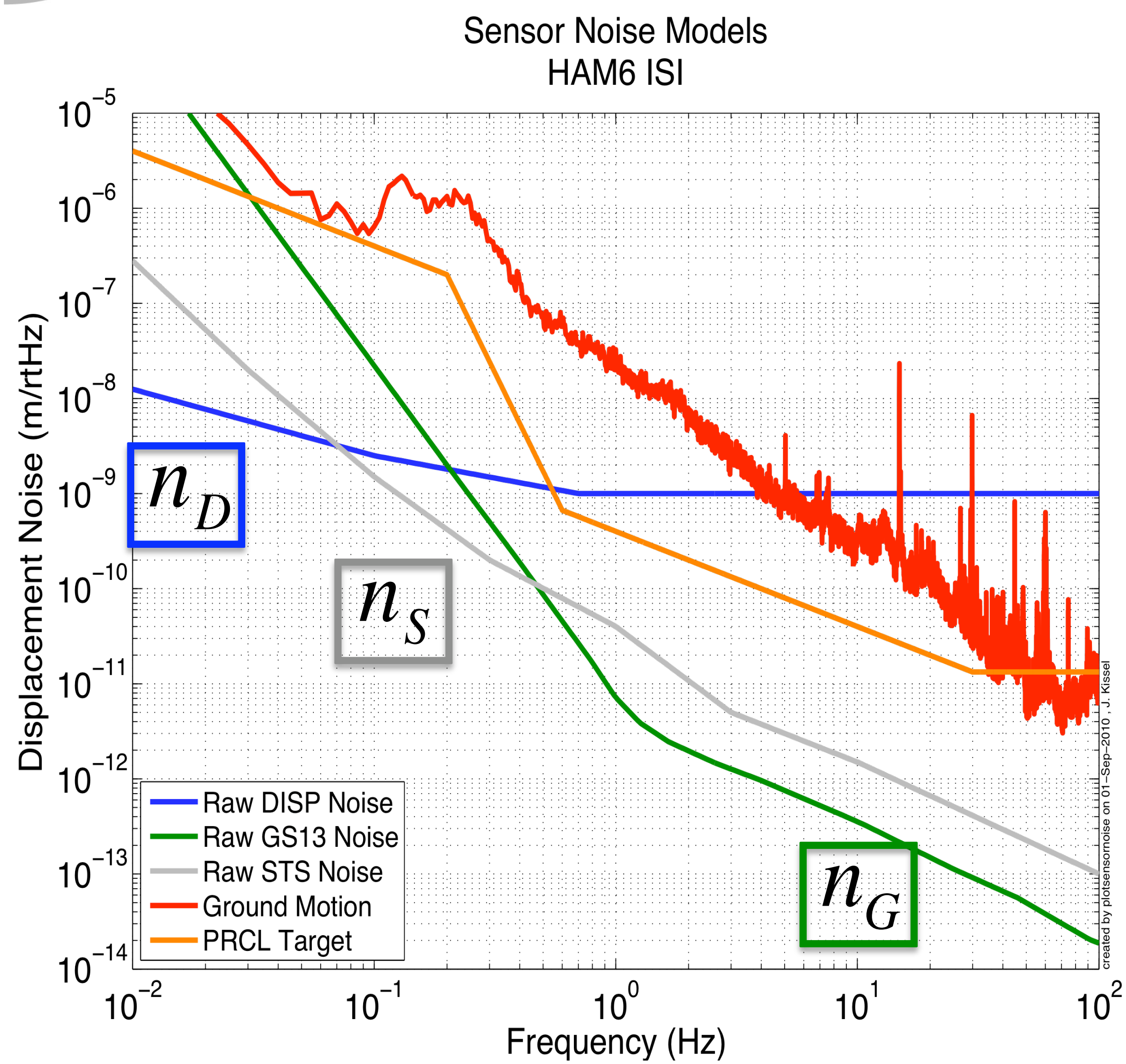
Electromagnetic Actuators





On-board sensors co-located with actuators

Prototype HAM-ISI Isolation System
Active Control Loop Noise Sources



- Displacement Sensors
noisy at high frequency (> 0.5 Hz)

- Inertial Sensors
noisy at low frequency (< 0.5 Hz)

- Solution:
BLEND THEIR SIGNALS!

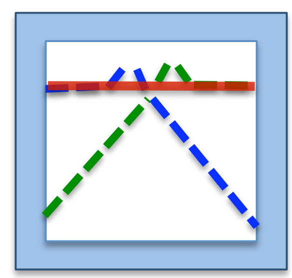
Low-pass the displacement sensors

+

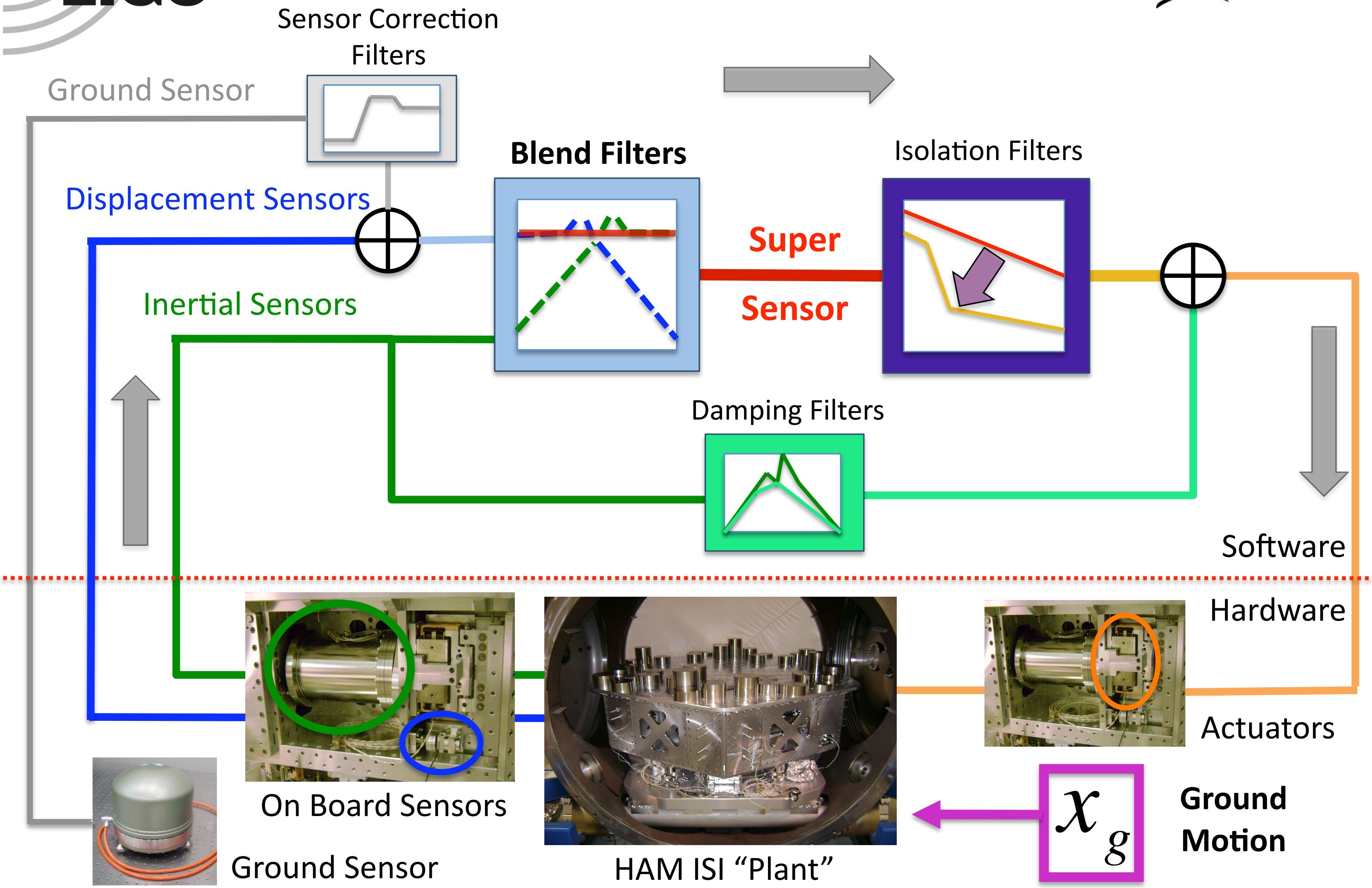
High-pass the inertial sensors

=

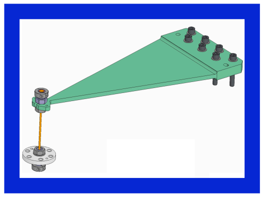
Super sensor!

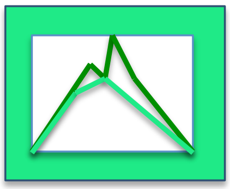


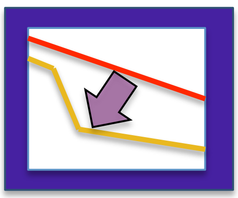
Prototype HAM-ISI Isolation System
Active Control Loop Design

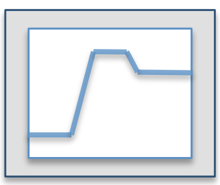


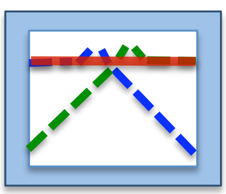
Prototype HAM-ISI Isolation System
Active Control Loop Commissioning

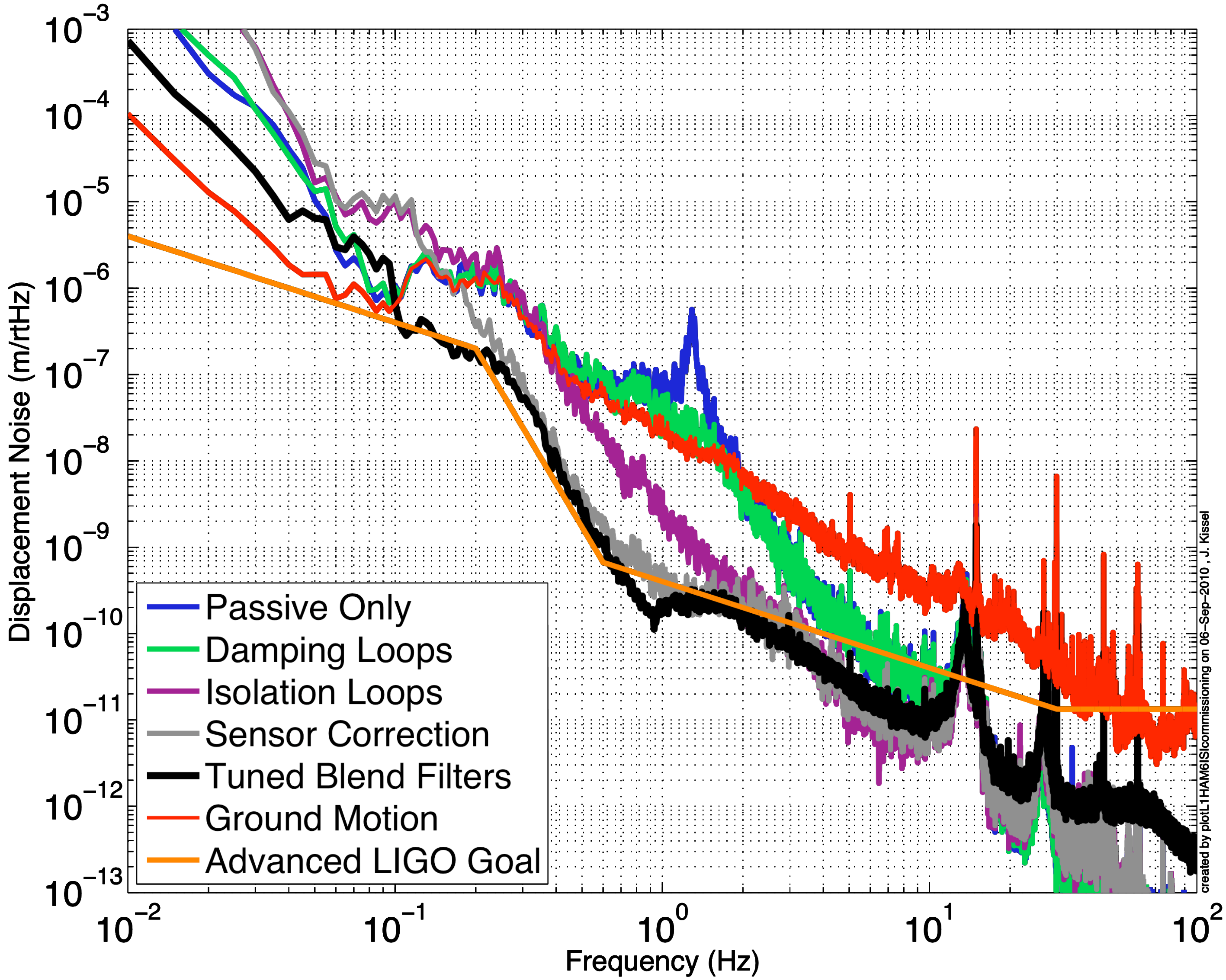




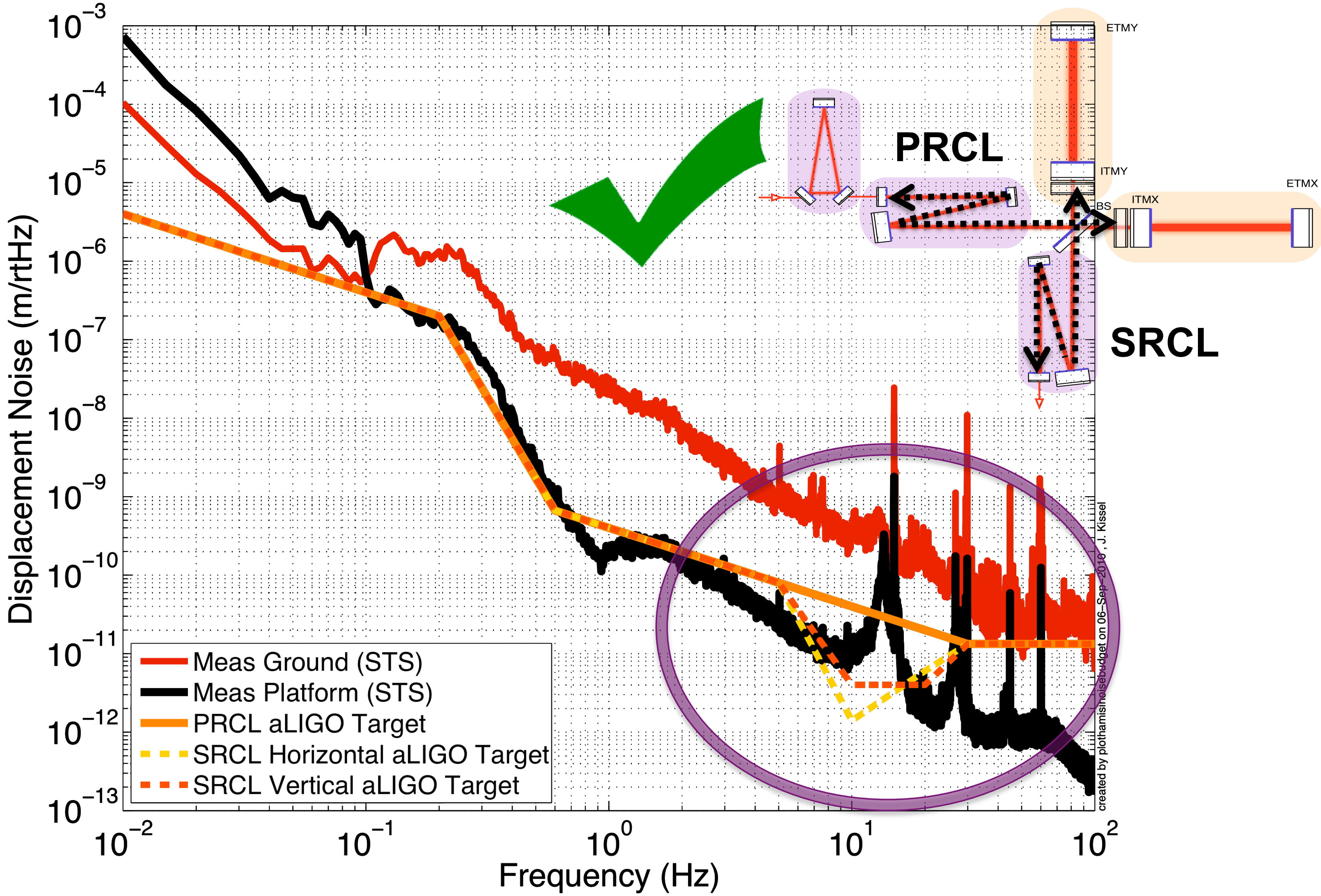




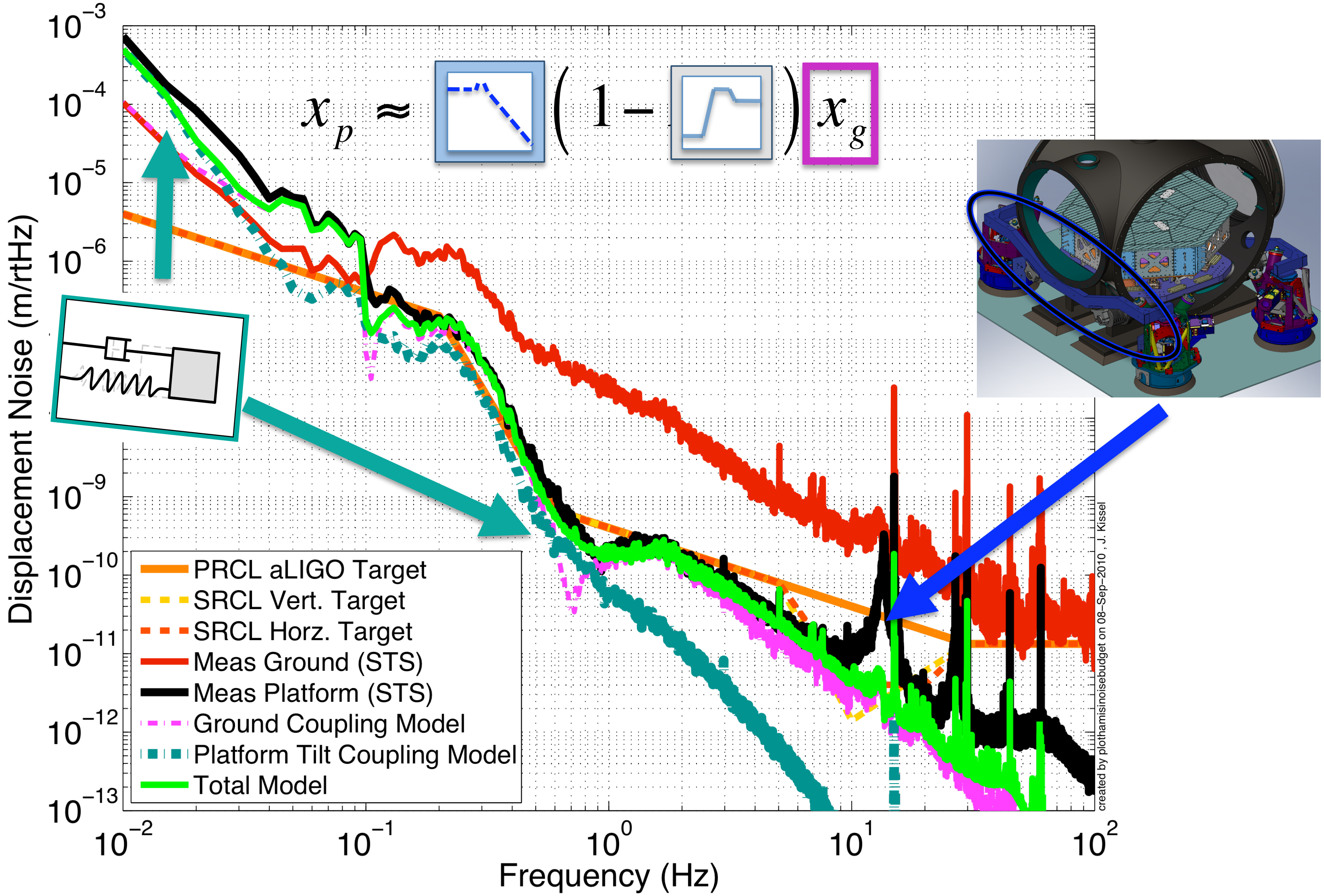




Prototype HAM-ISI Isolation System Performance Results



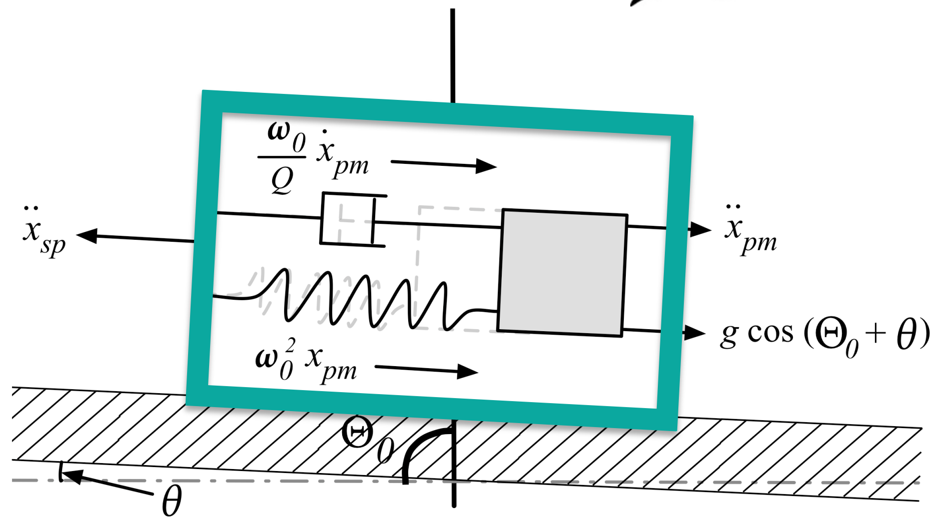
Prototype HAM-ISI Isolation System
Understanding the Results



Prototype HAM-ISI Isolation System
The Future - Tilt Horizontal Coupling

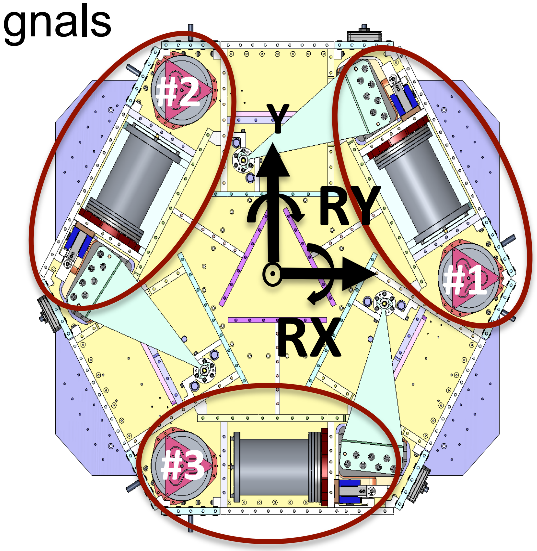
• Fundamental property of a horizontal inertial sensor

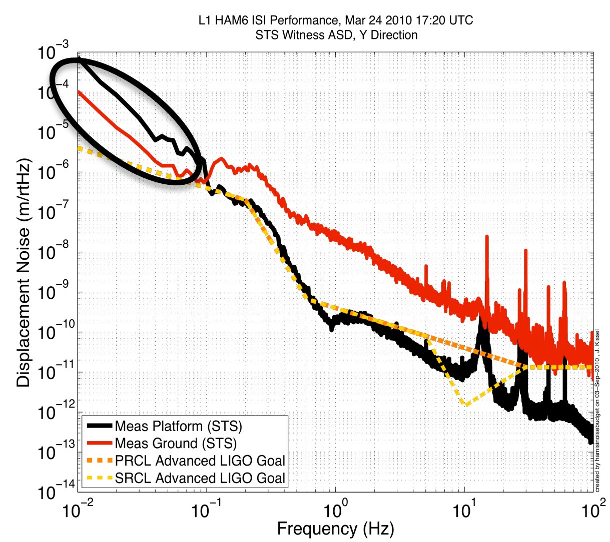
$$x_{pm}^{(h)} \propto \left(x_{sp}^{(h)} - \frac{g}{\omega^2}\theta \right)$$



• Effect dominant at low frequency (< 0.5 Hz)

• HAM-ISI uses differential signals dominated by sensor noise





Possible **Mitigations**:
• Blend Filter tuning

• Tilt Sensor

• Interferometry

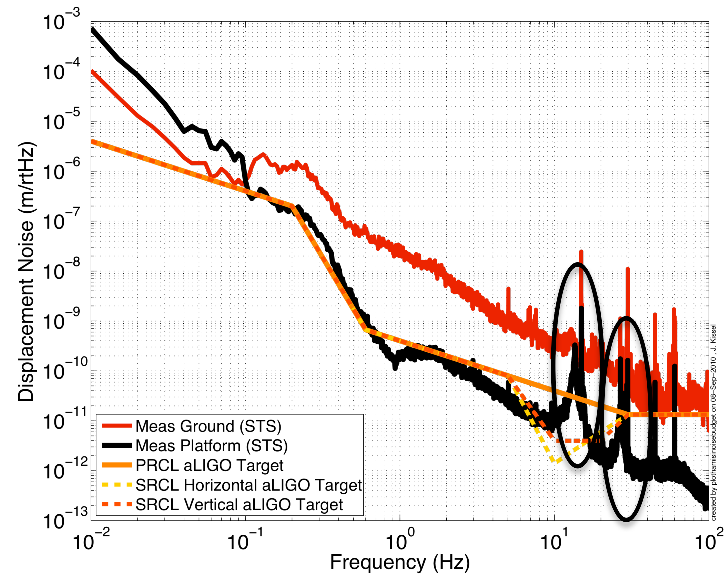
Prototype HAM-ISI Isolation System
The Future – Support Structure Resonances

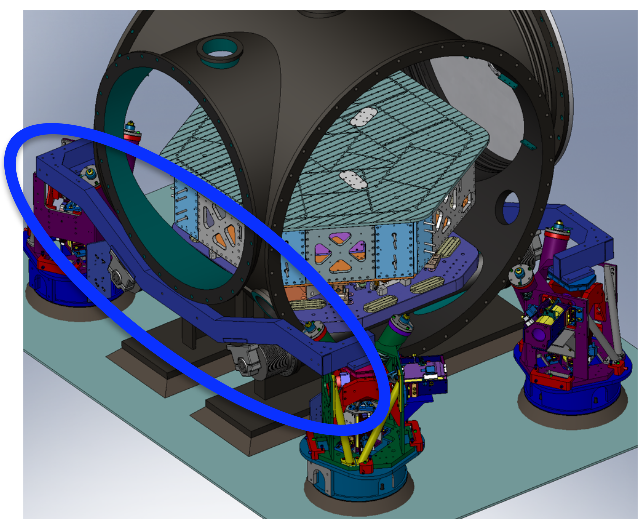
Mitigation:
Stiffer support structure, add *external* pre-isolation!

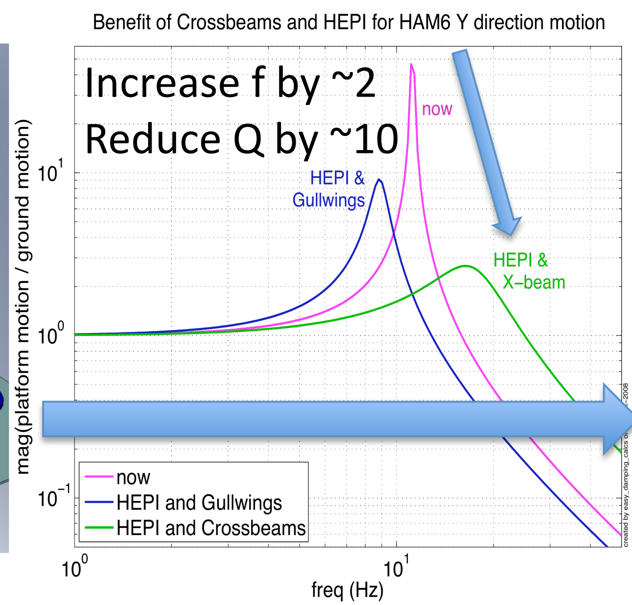
Gullwings → Crossbeams

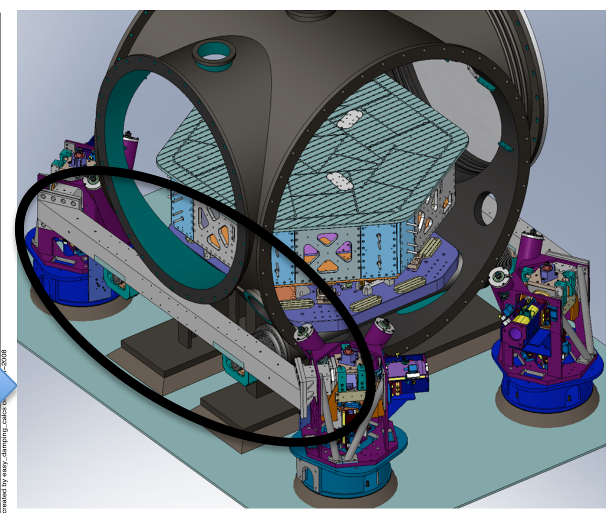
- Support structure has been redesigned for aLIGO

- Hydraulic External Pre-Isolation will be installed under redesigned crossbeams



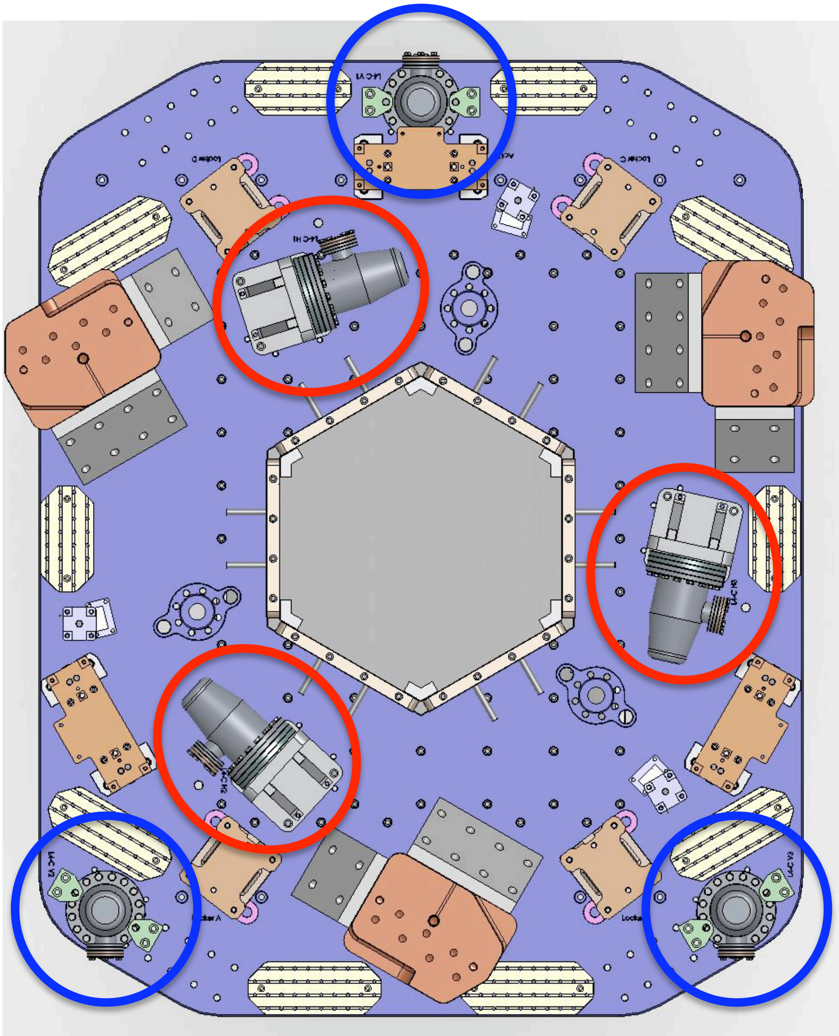


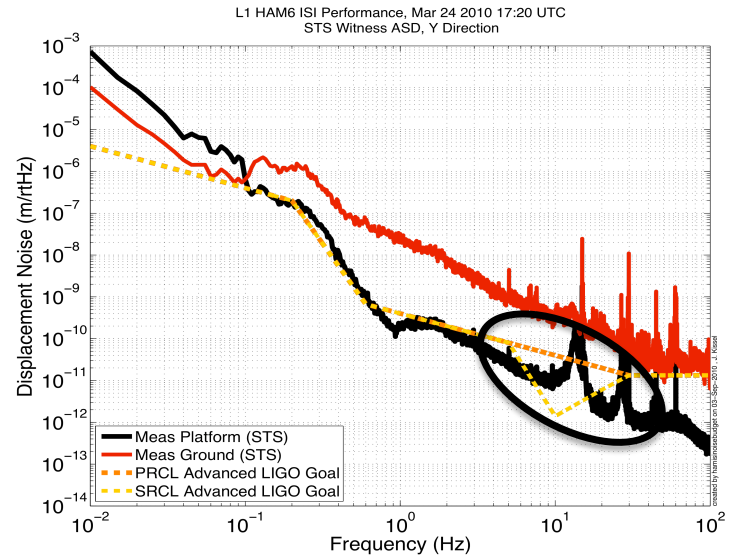




Prototype HAM-ISI Isolation System

The Future – Signal Recycling Cavity Performance





- SRCL chambers need performance *a factor of 10-100 more* between 5 and 20 Hz

Mitigation: More Feed-forward!

- 6 additional inertial sensors that feed-forward from support stage to suspended stage (Three Horizontal, Three Vertical)

- Prototyping fall/winter of 2010

Conclusions

- In S5, the LIGO interferometers measured displacement of **10^{-19} m/rtHz** for **two years**, no discovery, but lots of results
- Results depend on calibration, which is accurate to **within 15% and 5 degrees** in most sensitive region for S5 *(Paper written by me accepted for publication)*
- Accuracy limited by residual seismic noise in measurements of model components
- Advanced LIGO will improve sensitivity by factor of ten or more, using **impressive seismic isolation systems**
- Prototypes for Advanced LIGO HAM-ISI **meet or beat target performance** at most frequencies *(Active control system commissioning lead by me)*
- Limitations to performance are **understood**, mitigation techniques planned for production units
- Many more hurdles to jump, but payoff is **astronomical**! $\dot{N}_{re} \approx 40 \ \ \text{yr}^{-1}$

Thanks!

Gaby

- Seismic Team:

Brian Lantz, Brian O'Reilly, Rich Mittleman, Fabrice Matichard, Andy Stein, Joe Hanson, Corey Gray, Hugh Radkins, Justin Garofoli

- Calibration Group:

Gaby Gonzalez, Brian O'Reilly, Keita Kawabe, Mike Landry, Rick Savage, Myungkee Sung, Evan Goetz, Justin Garofoli