Improving the Sensitivity of Gravitational Wave Interferometers

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IPAM GWAWS IV
Big Data in Multi-Messenger Astrophysics
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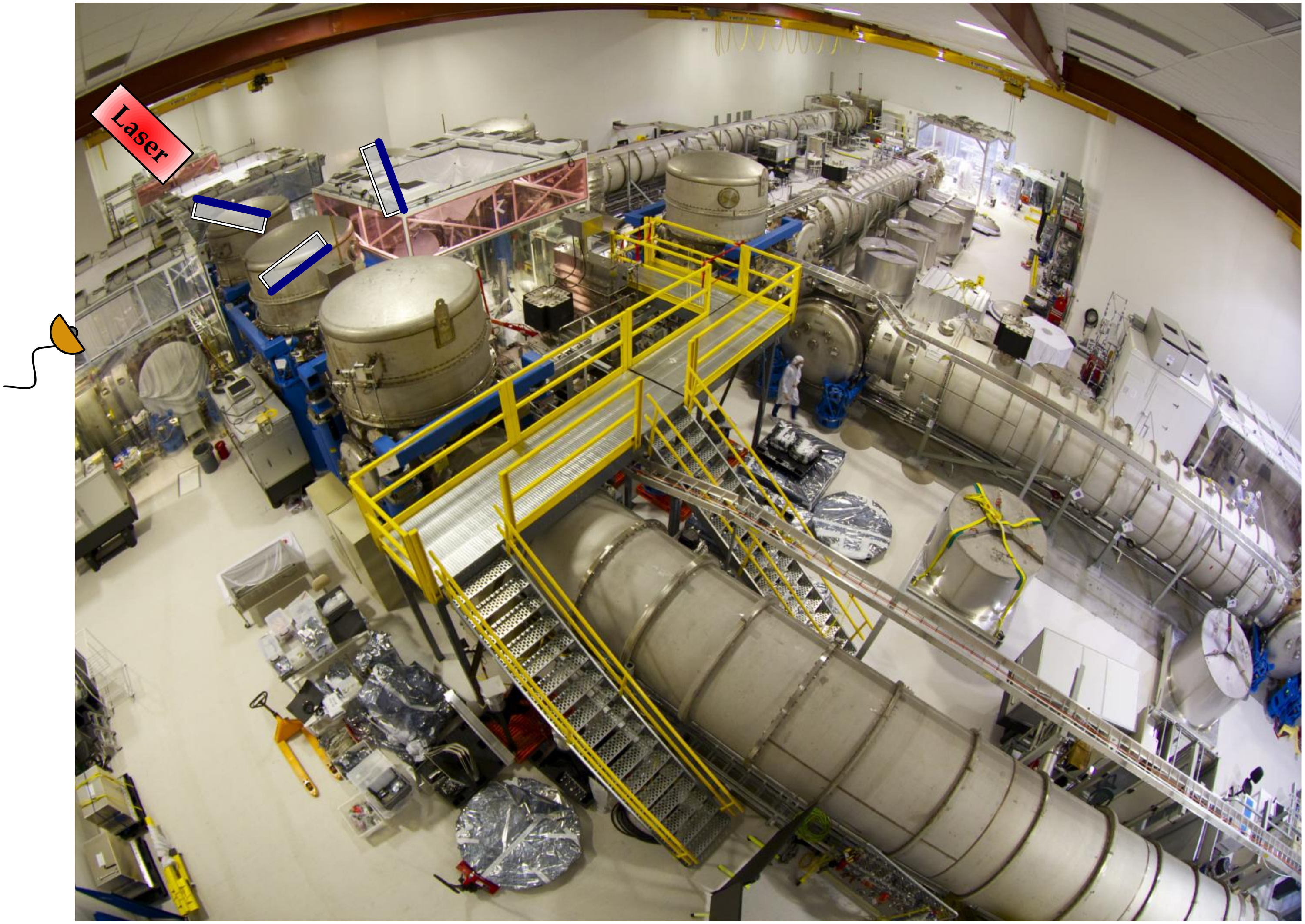
Perspective of an Instrumentalist

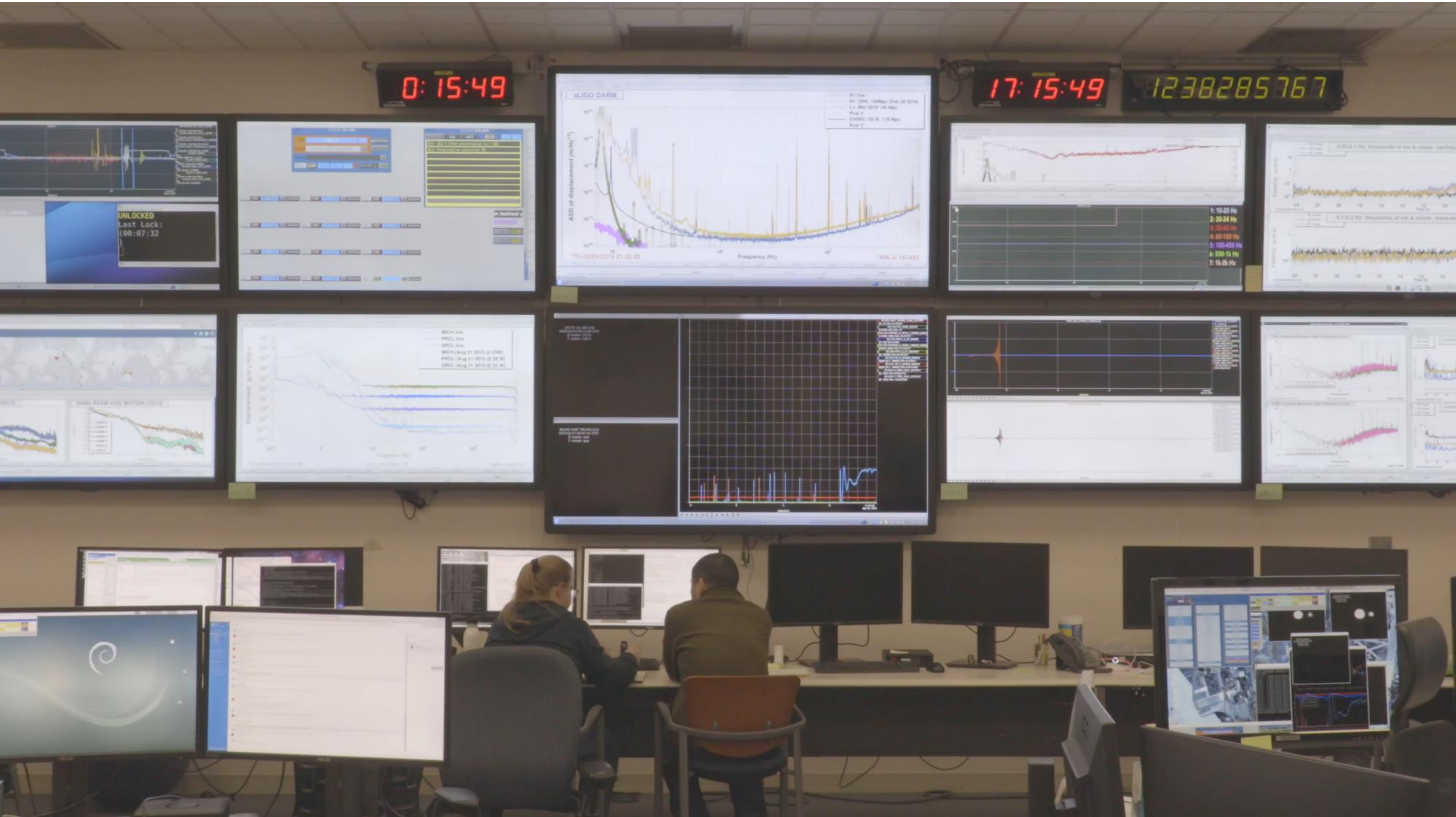
The gravitational wave data must come from somewhere

Lots of opportunity to apply Big Data techniques to improve the detectors

Instrument Hall



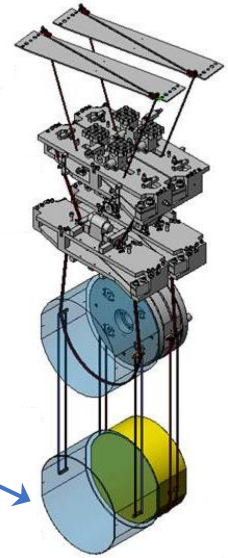
Many Varieties of Data



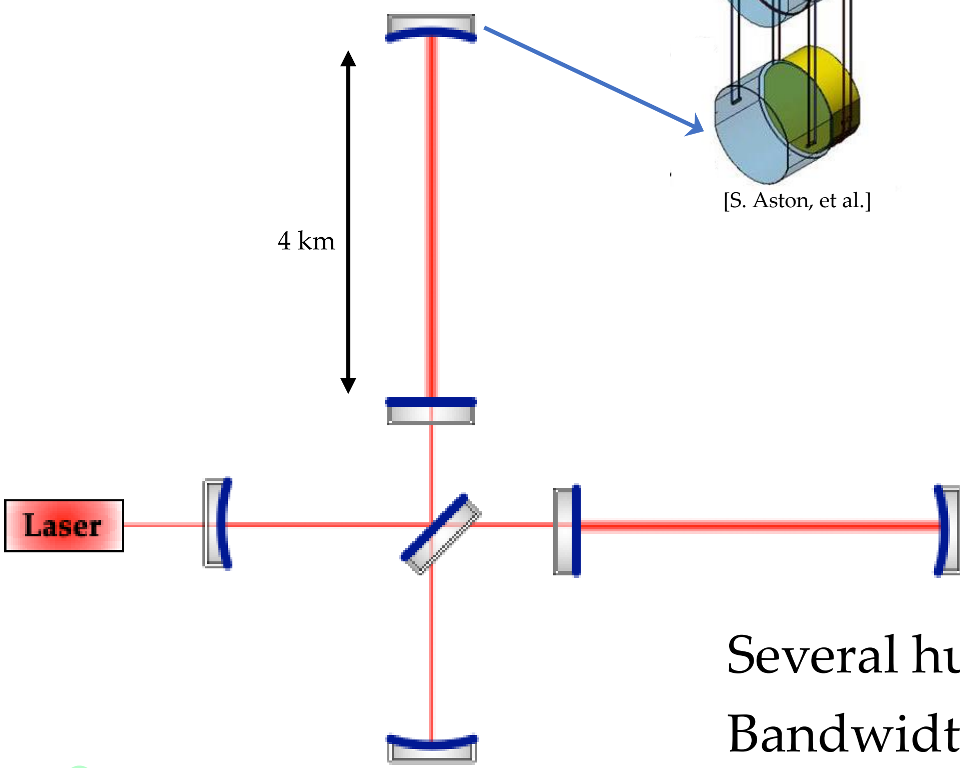
Movie by Kai Staats

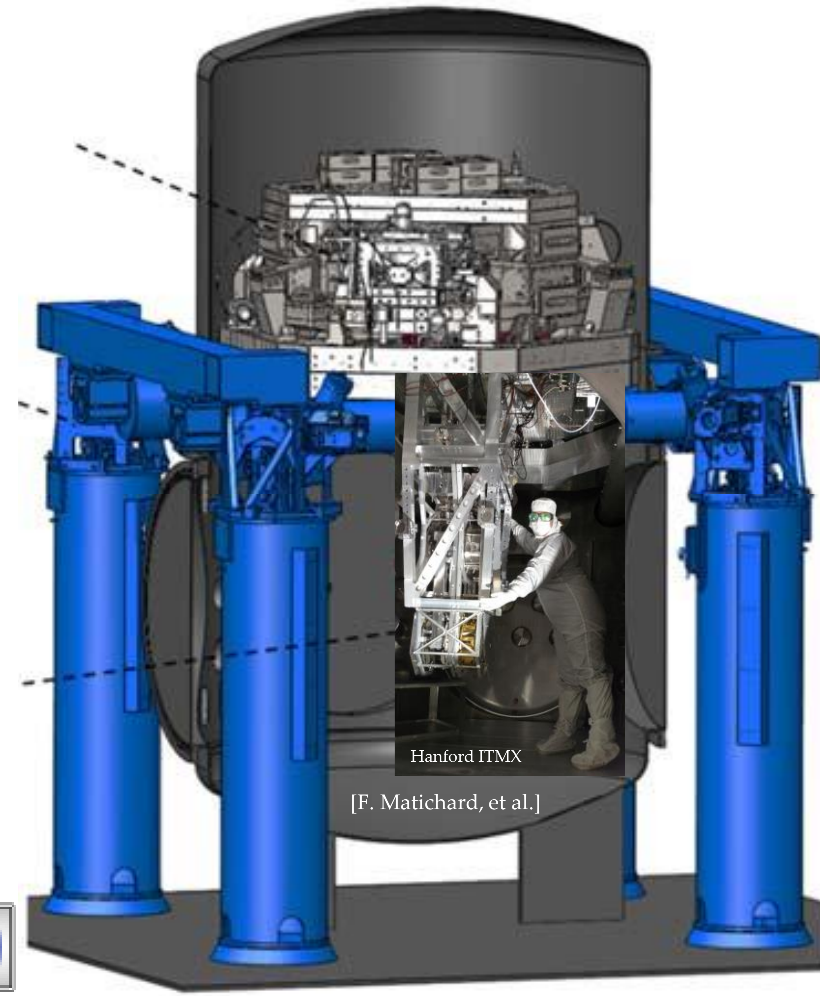
What Do We Control?

- Distances between mirrors
- Angles of mirrors
- Laser frequency
- Laser intensity



[S. Aston, et al.]



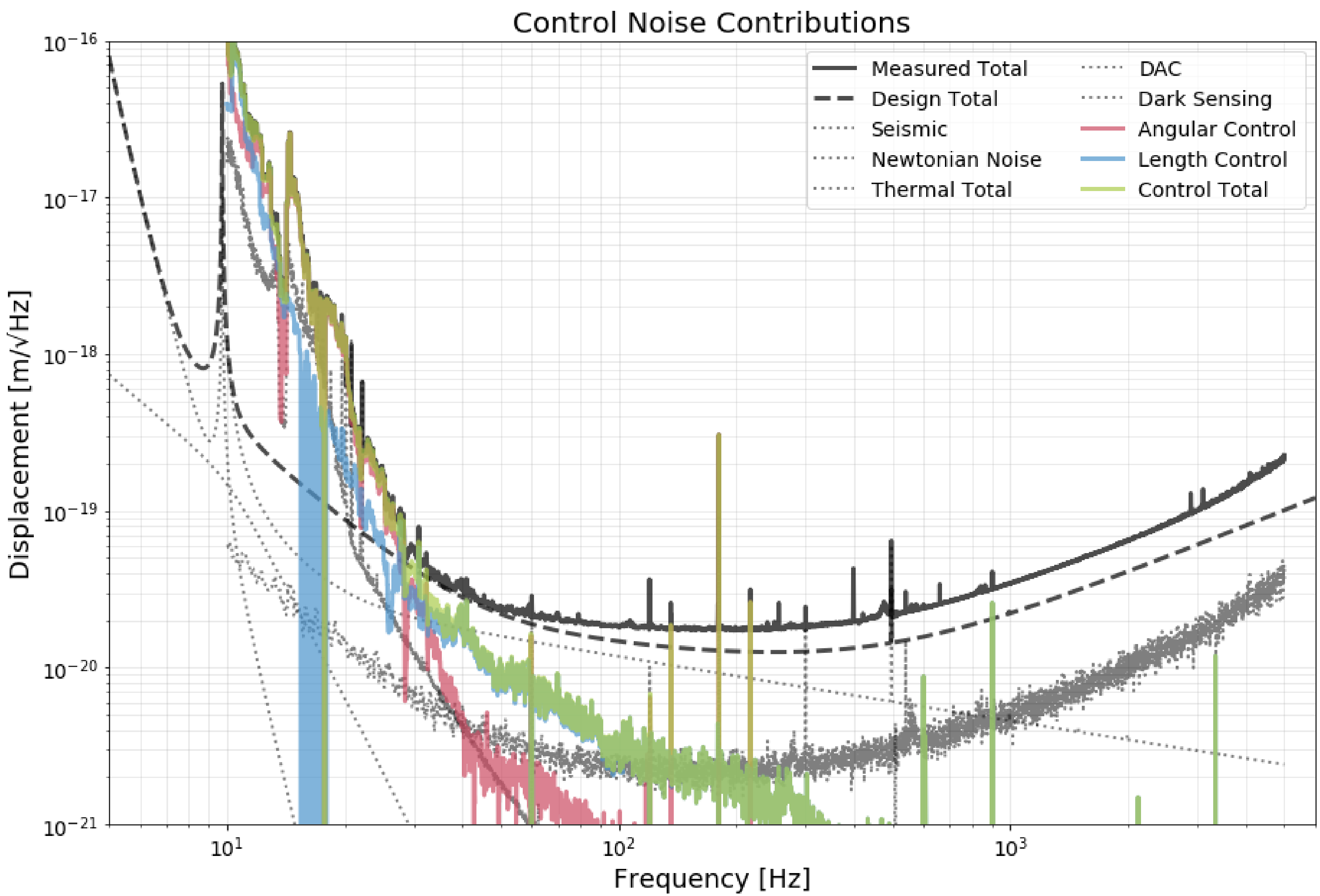


[F. Matichard, et al.]

Several hundred simultaneous control loops

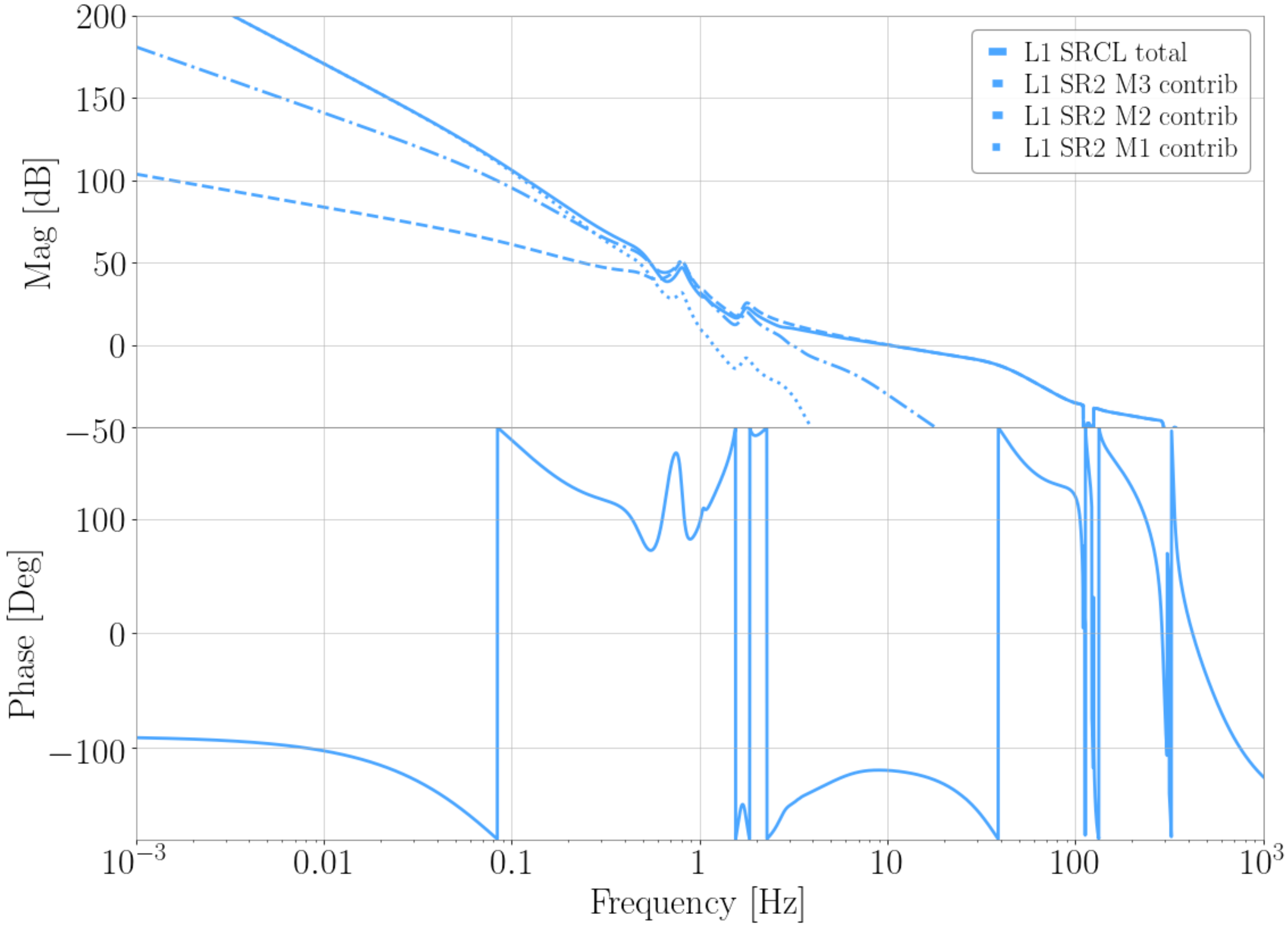
Bandwidths range from mHz to 750 kHz

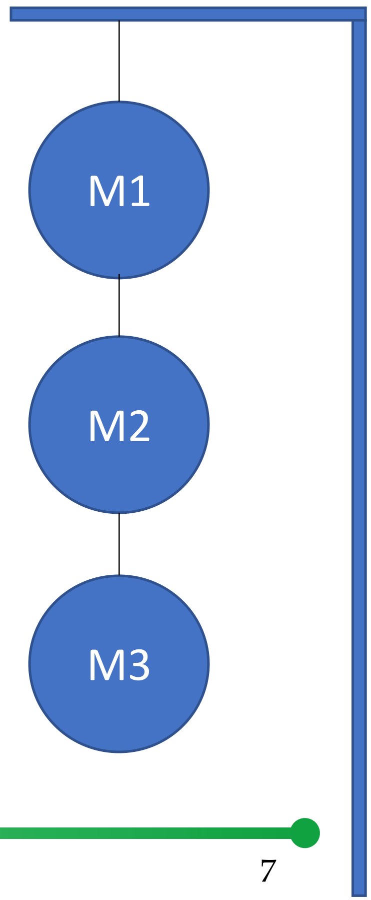
Noise Limits Due To Controls



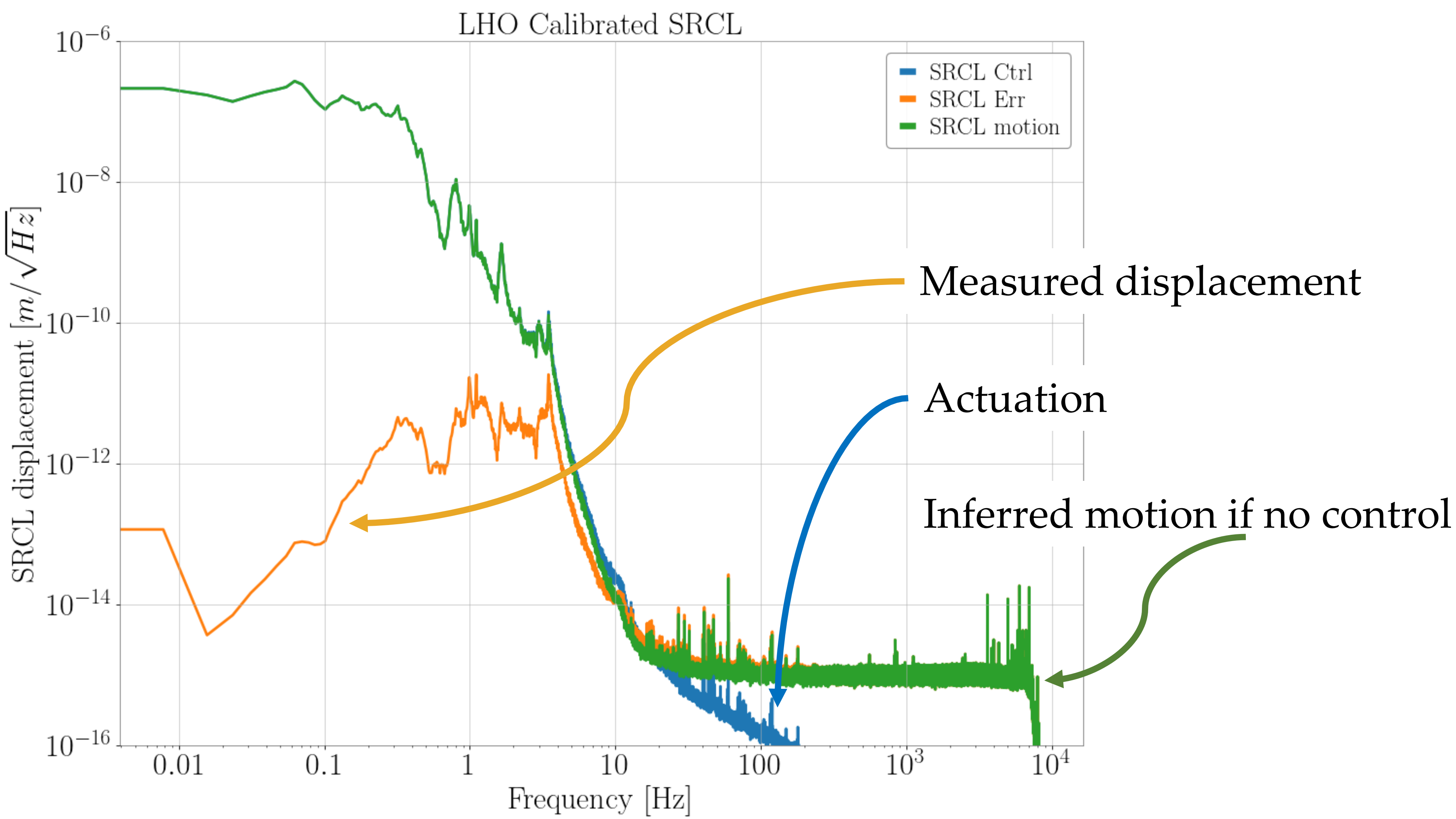
LIGO Length Control of Suspensions

How should we push on a mirror, to maintain cavity resonance?





Length Displacement



Criteria for Control System

Reduce motion, including root-mean-square of residual motion

Minimize control contribution to other loops' residual motion

- Lower unity gain frequencies for auxiliary loops is generally preferred

Hold system in the linear regime

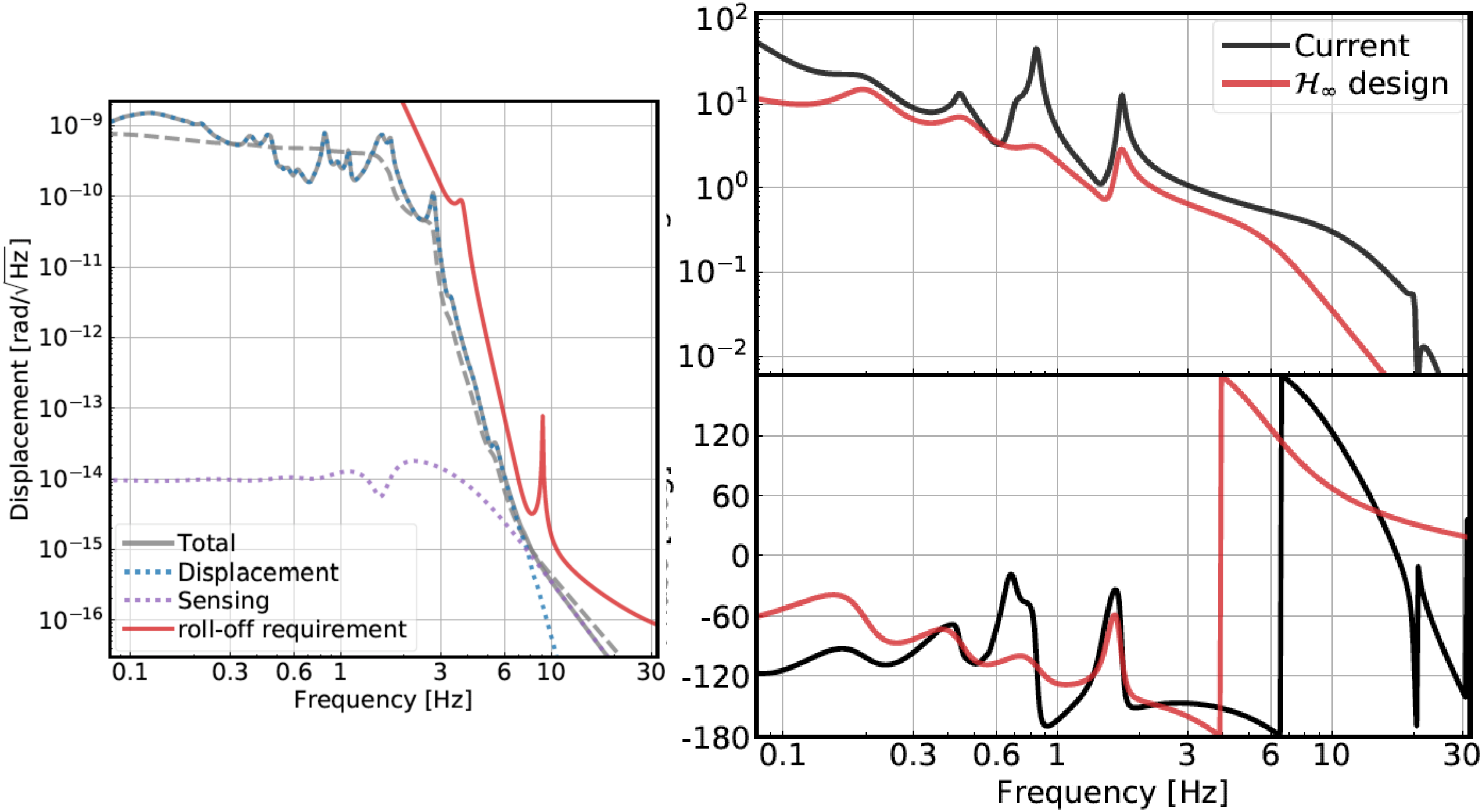
- Do not saturate actuators

Robust against changes in mechanical plant and changes in input disturbances

- Often cannot tolerate the solutions from "optimal controls" methods due to their limited stability margins

Must be causal, to implement in the realtime online system

Automating Loop Design



Hang Yu, PhD Thesis, MIT 2019

Playground Problems

https://github.com/rxa254/LIGO-Controls-Problems

Information for "challenge problems" on github (provided by Prof. Rana Adhikari), for folks to get started trying new methods on LIGO-like problems

Interesting problem: combining the single-suspension damping loop design along with 'global' controls design, eg. how does single-suspension control affect control of cavity-axis motion?

LIGO Newtonian Gravitational Force

Along arm cavity axis:

$$\delta\vec{a}_{\mathrm{NN}} = \frac{\delta\vec{F}}{m} = G\rho_0\int \mathrm{dS}\,\frac{\xi_{\mathrm{vert}}}{r^2}\hat{r}$$

Acceleration due to Newtonian Noise

Gravitational Constant

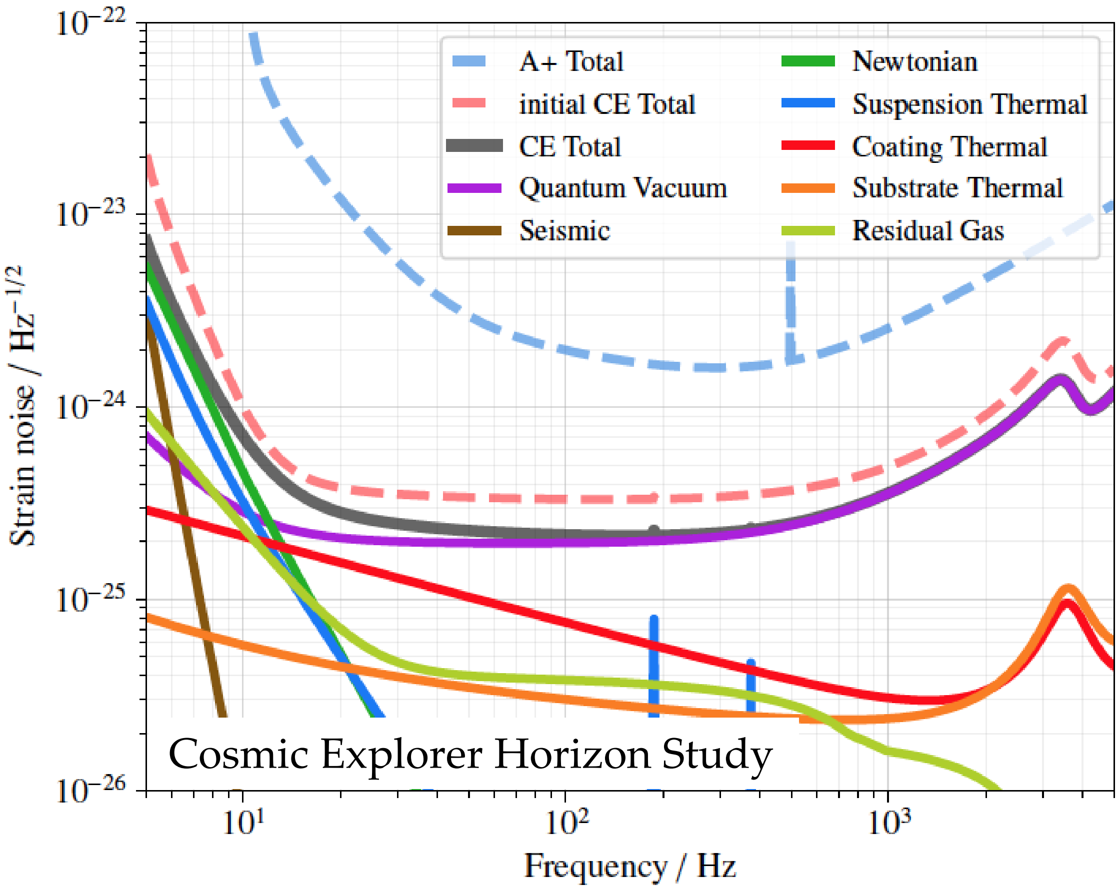
Density of ground

Displacement of ground

Distance between ground and mirror

Integrate over all ground near mirror

Low Frequency Noise Limiter



Future generations of ground-based detectors depend on reduction of Newtonian gravitational noise

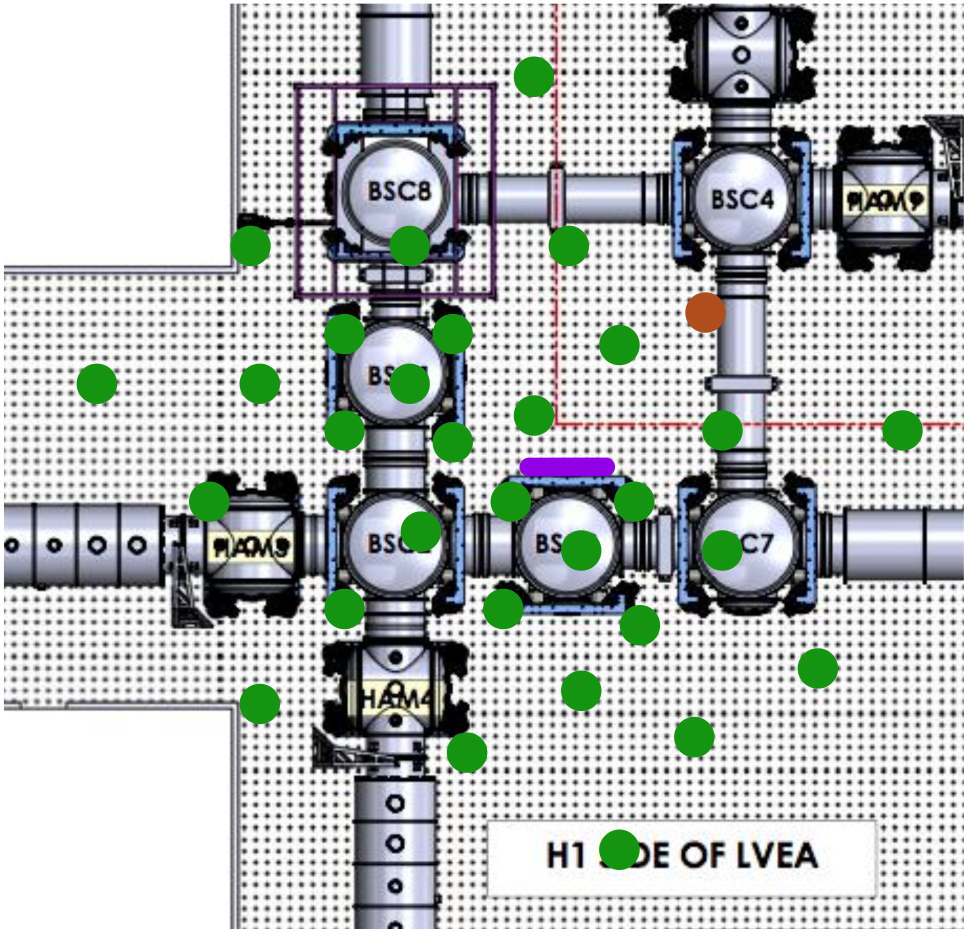
10x surface wave seismic

3x body wave seismic

Not yet requiring reduction of other sources of Newtonian noise

Difficult to 'engineer away', likely must subtract in post-processing

Newtonian Noise Array

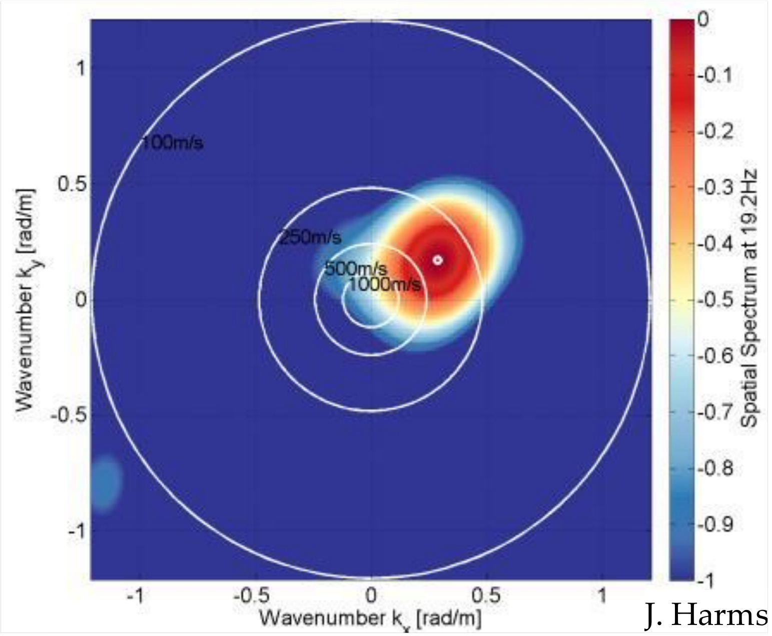


Installed throughout O2

- 30 single-axis seismic sensors
- 1 tiltmeter
- 1 three-axis seismic sensor

h(t) not sensitive enough (yet!) at low frequencies to directly measure Newtonian noise

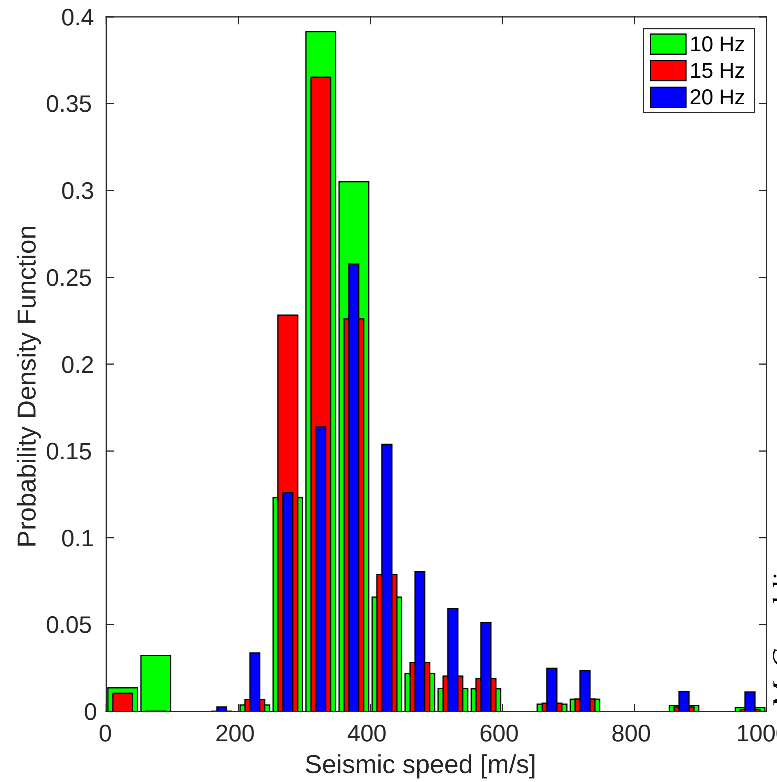
Determining Seismic Speeds



J. Harms

Wavenumber maps can be generated for any given frequency at some time

Extract direction and speed of seismic waves travelling through the array



M. Coughlin

Understanding current sites helps indicate size and type of arrays needed for future detectors

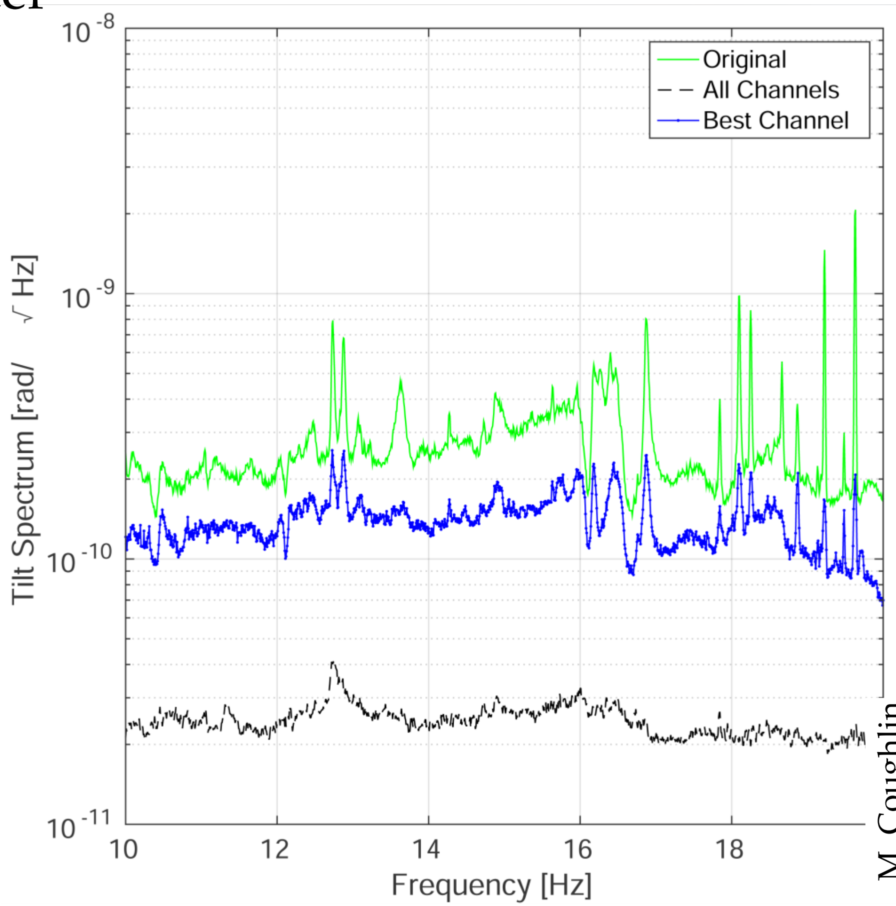
Subtraction Test

Use beam rotation sensor as proxy for Newtonian noise

Using Wiener filters, subtract seismometer data from tiltmeter to determine approximately how well we should be able to subtract Newtonian noise

Achieve factors of 10 subtraction

Still need to directly measure and show that we can subtract true Newtonian noise from a gravitational wave data stream

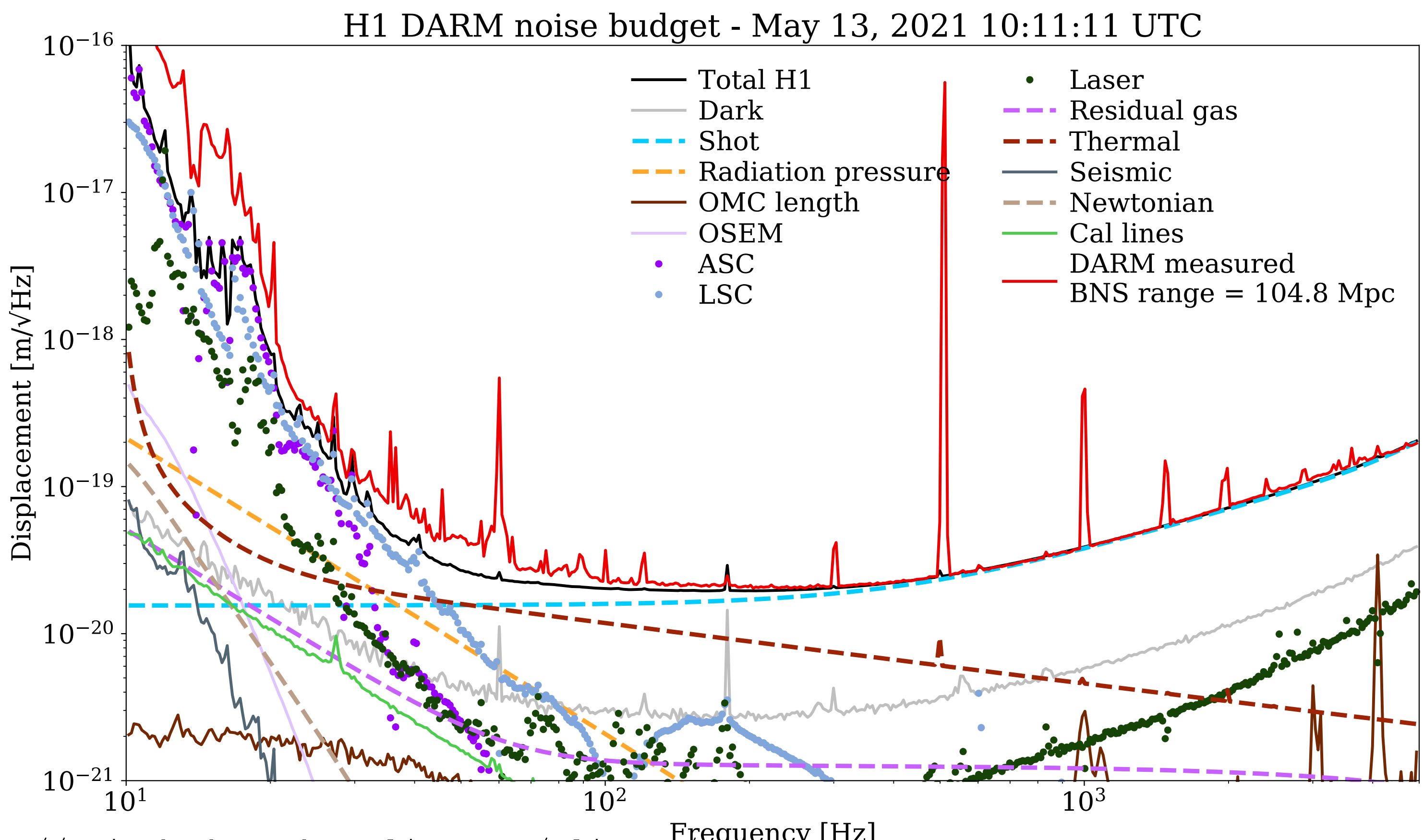


M. Coughlin, et al., CQG 33:24 (2016)

M. Coughlin, et al., PRL 121, 221104 (2018)

Lots of Data, of Many Kinds

It takes a lot of data from a wide variety of sources to produce the single gravitational wave strain data stream



From `https://noisebudget.docs.ligo.org/aligoNB/`