Lessons from Commissioning Advanced LIGO

Jenne Driggers, for the LIGO Commissioning Team
LIGO Hanford Observatory
California Institute of Technology

GWADW, Elba
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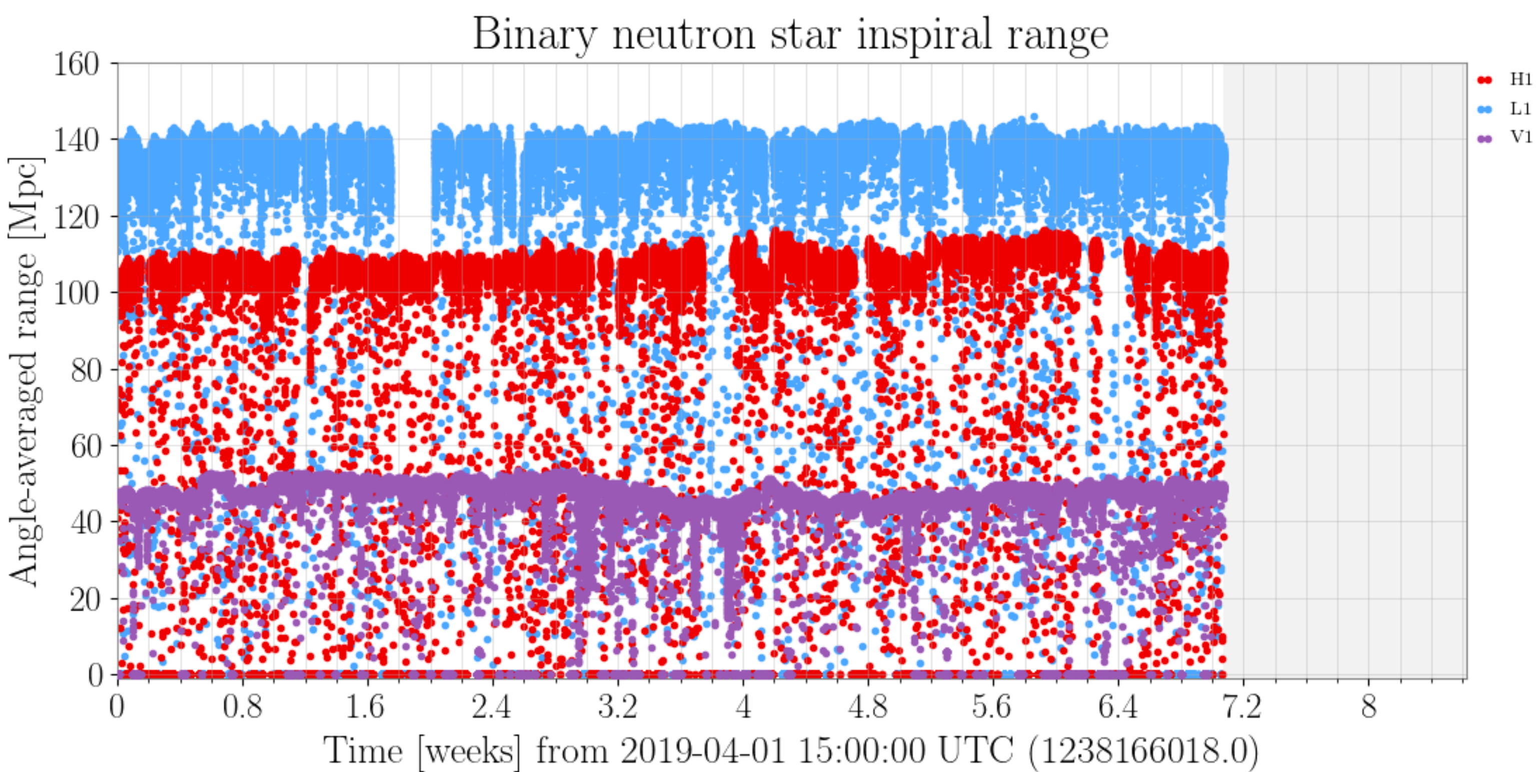
Status of LIGO

O3 a great success so far

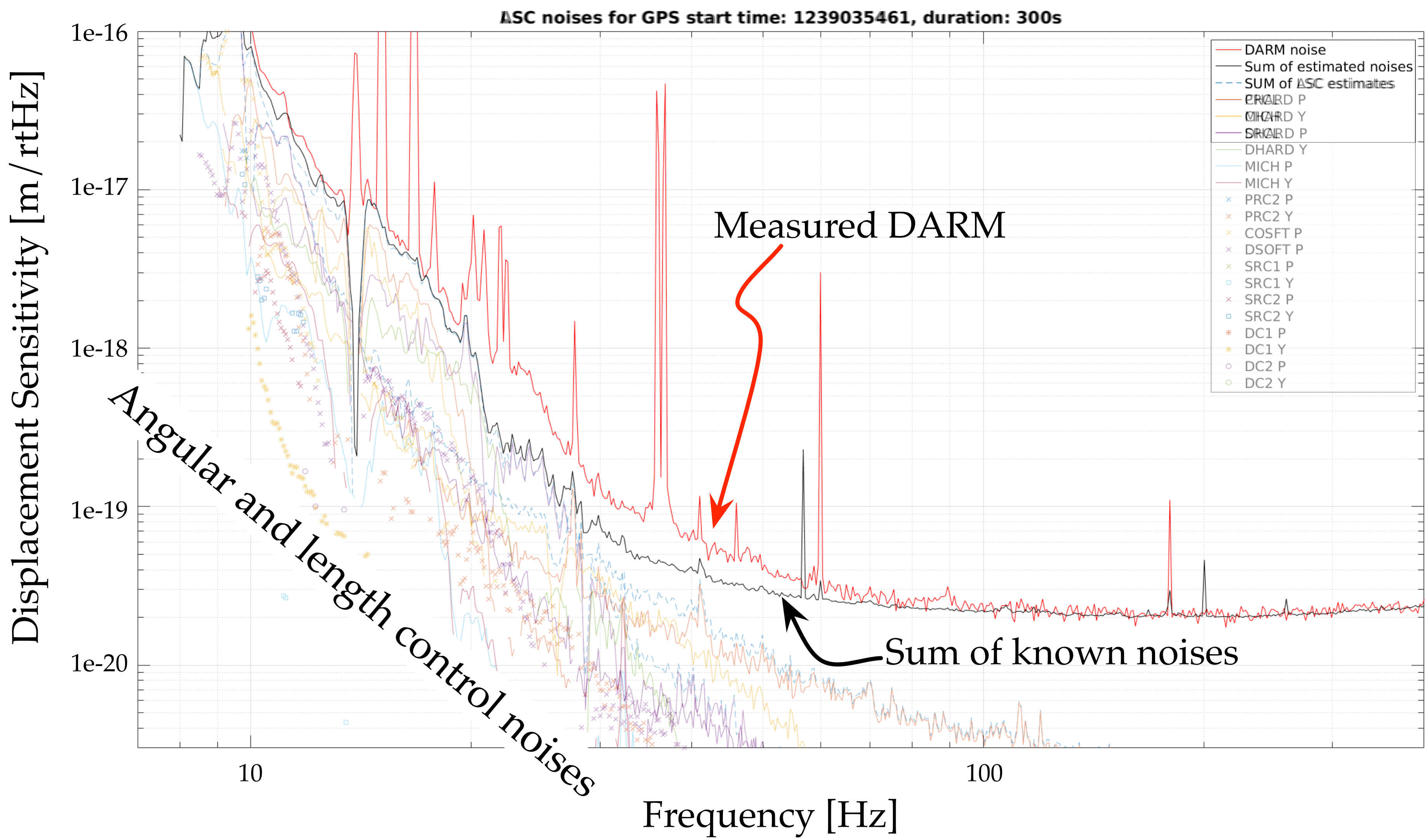
Hanford: 185 kW circulating power, 2 dB squeezing

Livingston: 225 kW circulating power, 3 dB squeezing

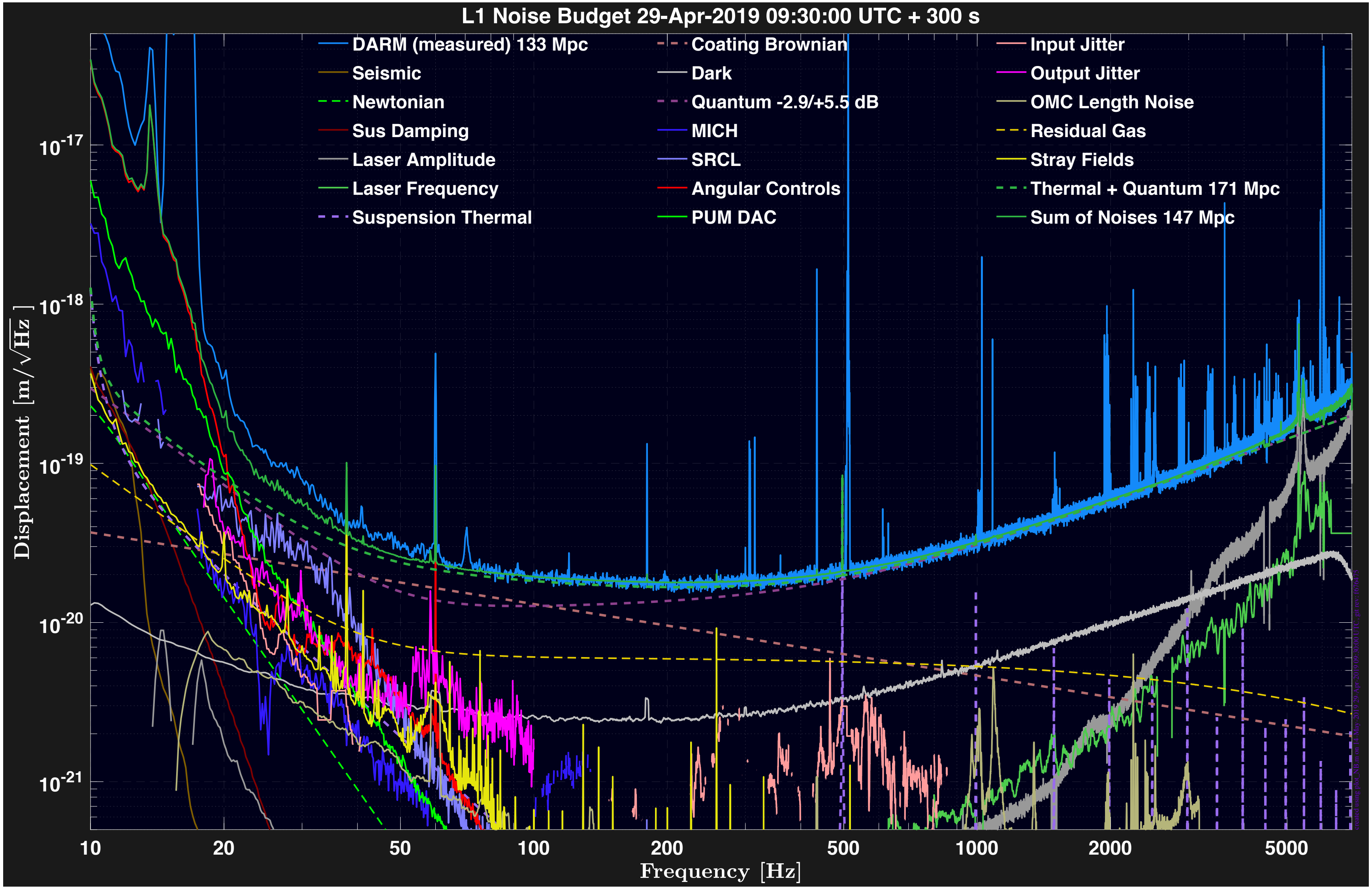
Taking ~6 hours per week for sensitivity or other improvements



Hanford Noise Budget



Livingston Noise Budget



Low Frequency is Difficult

Empirically, it's easier to match noise budget expectations at high frequencies

Control noise from loops matters at low frequency, less so at high frequencies

Scattered light is tricky, and matters at low frequency

Many noise sources are known, but others are still considered 'mystery noise'

Every measurement takes time, which is in conflict with wanting to have high duty cycle observation time

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We should still strive for low frequency detectors, but recognize that they will always be extremely challenging

High Power is Difficult

Non-uniform absorption matter more with more circulating power

- Steer away from point absorbers
- Other non-uniform absorption harder to avoid

Significantly affecting the recycling gains of RF sidebands, as well as carrier

- Makes control more difficult
- Thermalization takes time, and thermal tuning takes lots of time

Excited for future improvements in thermal compensation

Damping parametric instabilities has been very helpful

Facilities and Time

Balancing time of upgrades (and maintenance) against observing

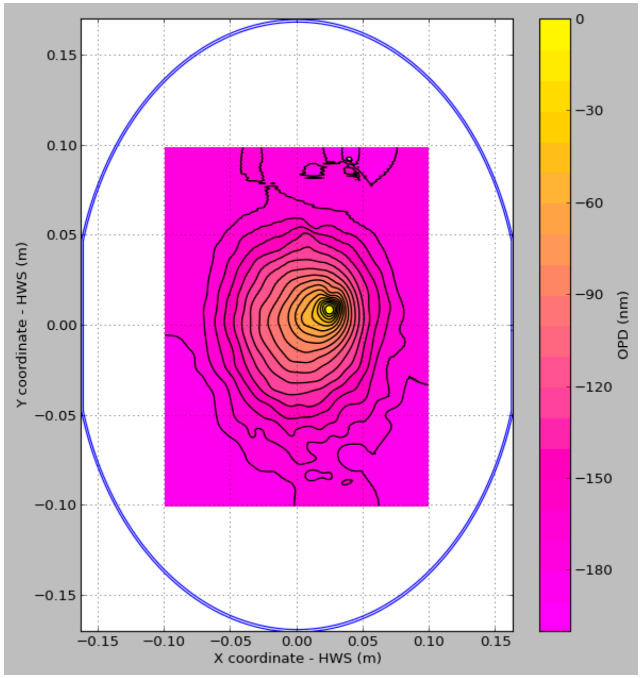
- Reducing pump down (and cool down) time will be very useful
- Hosting many interferometers in a single facility will be challenging
  - Difficult to perform hardware upgrades on one interferometer while operating another

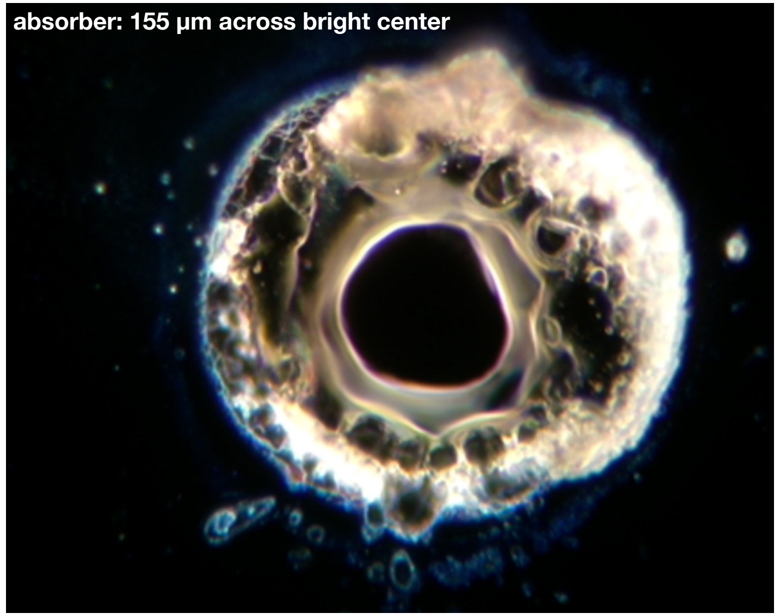
Many measurements take a long time

- Low frequency measurements with high precision
- Thermal state changes require thermalization
- Must balance observation time against potential sensitivity improvements

Absorbers on Optics

Wavefront distortion of beam on mirrors





5 of 8 test masses replaced in LIGO

- Still have non-uniform absorption

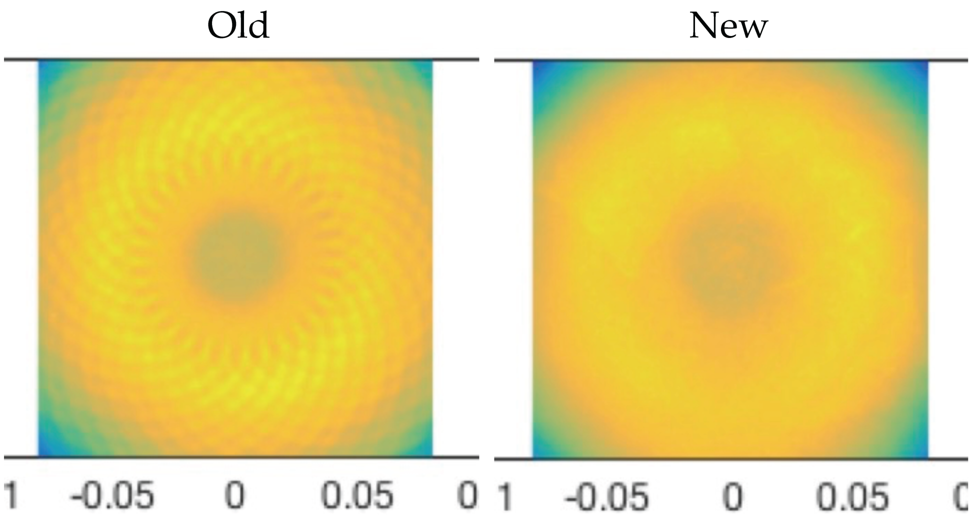
Limits recycling gain of carrier, sidebands

- Circulating power
- Control error signals
- Coupling in laser jitter noise

Scattered Light

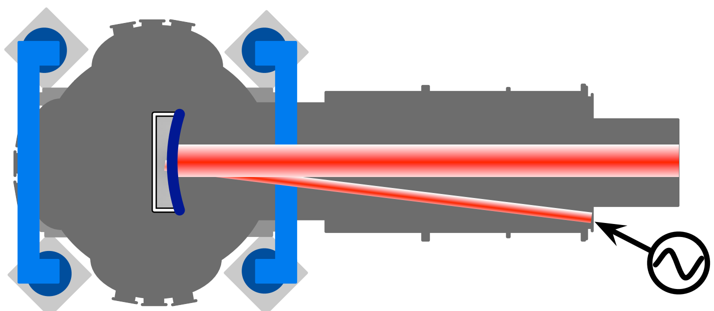
Hard to identify, and model

Nonlinear coupling to gravitational wave readout

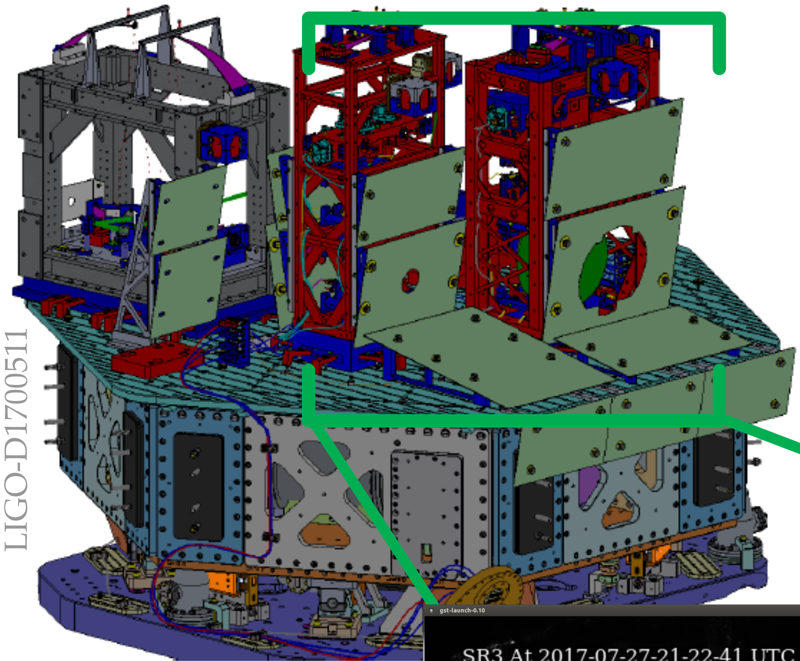


LIGO end mirrors replaced to reduce light scattered from cavity

One of the biggest things we can do for future detectors: Install low frequency shakers on vacuum enclosure to help identify coupling sites for baffling



Scattered Light



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Many baffles added before O3

- Scattering seems better, but it's certainly not gone
- Avoid reflective surfaces everywhere practicable

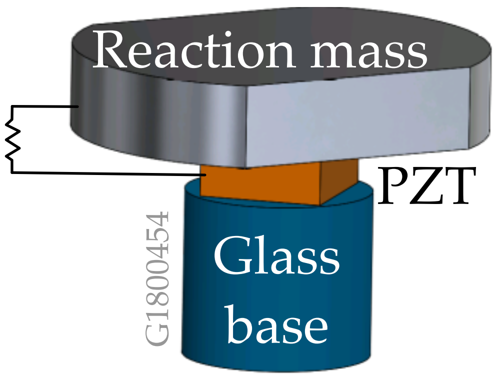
Camera looking at optics

LLO alog 36459

Opto-Mechanical Instabilities

Acoustic modes of mirrors overlap with optical modes of cavity

Passively damp modes

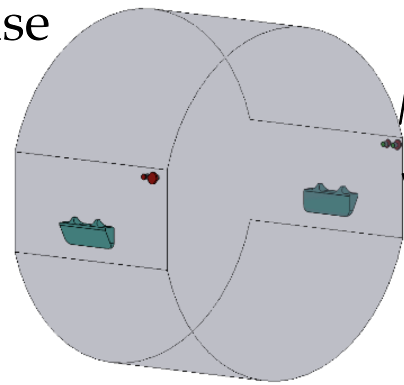


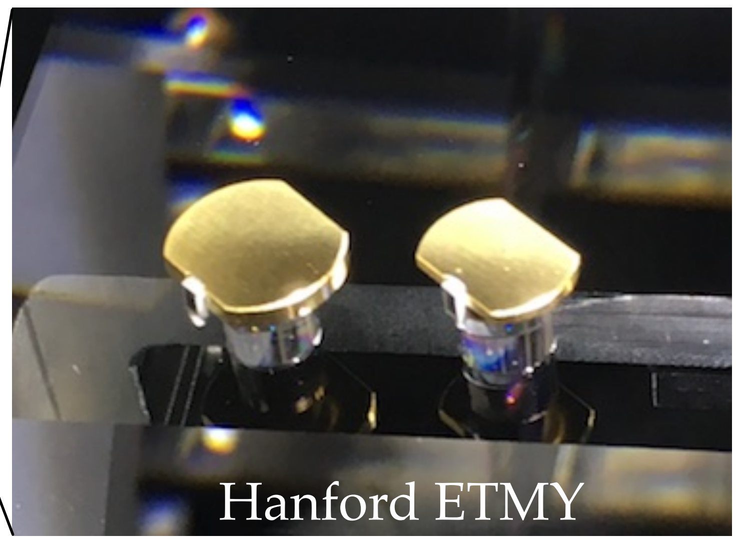
Reaction plate moves, causes PZT to create voltage

Electrical energy converted by the plate is dissipated through a resistor

Negligible thermal noise increase

Successful; must be installed in any future high power detectors





LHO alog 41231

Lowering Q of Suspension Modes

Bounce-Roll dampers installed for quad suspensions

Bounce-Roll dampers designed for other LIGO suspensions

Violin mode dampers under development

On the one hand, there are thermal noise consequences

On the other hand, with the modes causing high lines, we are already losing sensitivity due to upconversion

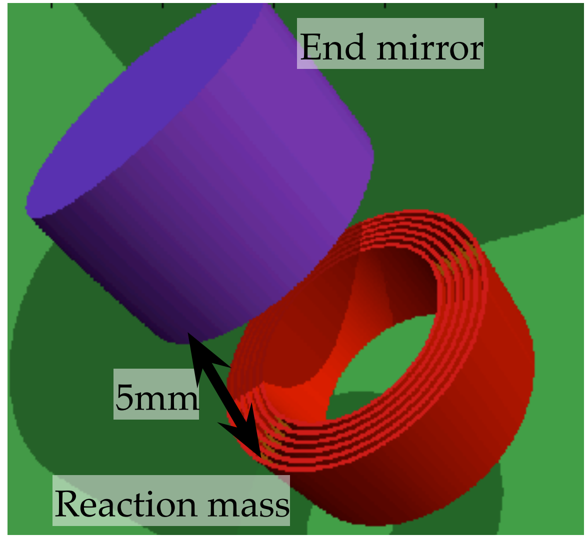
If the modes get rung up very high, we lose livetime to damping

Residual Gas Noise

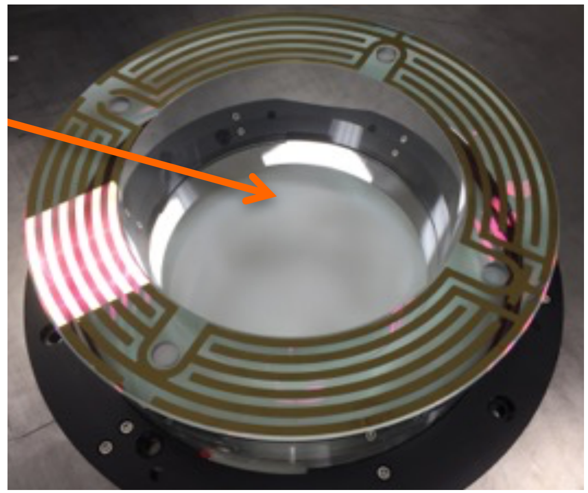
Small gap between end mirrors and actuation reaction masses

Molecules bounce between mirror and reaction mass

LIGO has removed the material from the center of the reaction masses



Upgrades and maintenance on vacuum system to be at lower pressure



Overall reduction in damping forces by factor of 2.5

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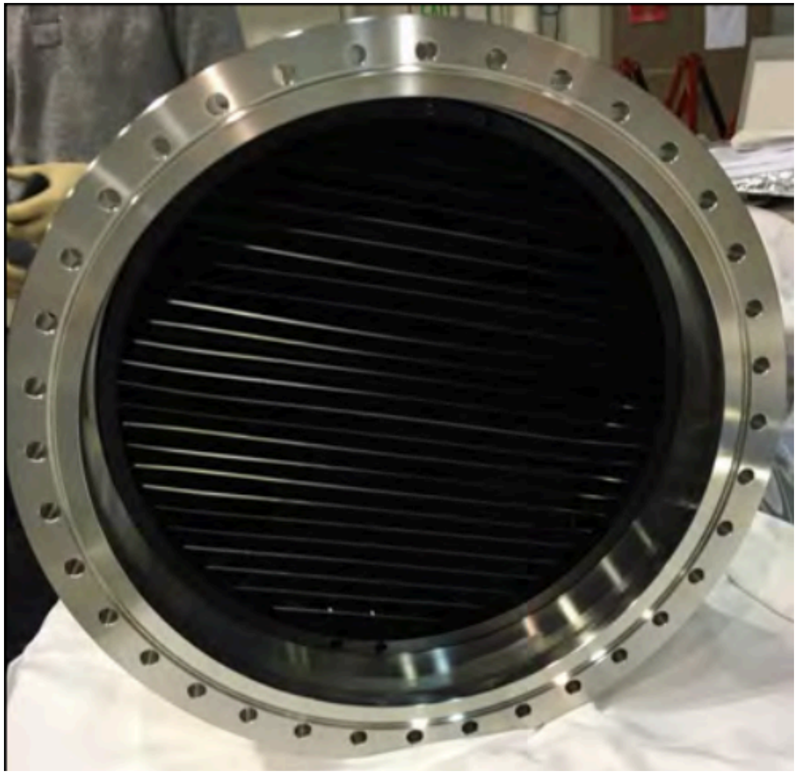
Charge and Electric Fields

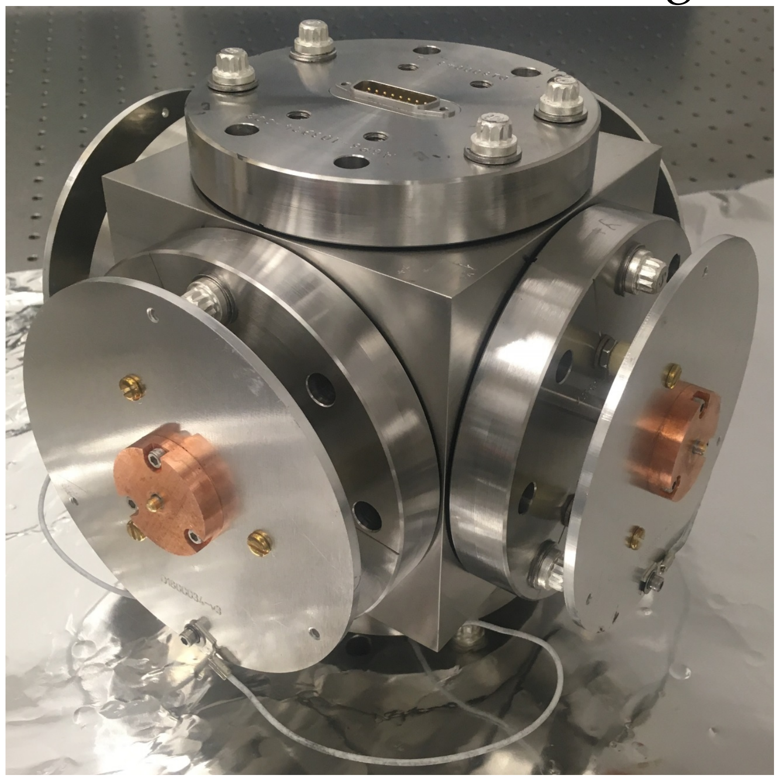


Discharge optics via gentle flow of ions (positive and negative)

Prevent ion vacuum pumps from directly "seeing" the optics at LIGO

Avoid optics hitting safety stops during earthquakes

Electric field meter for monitoring fields



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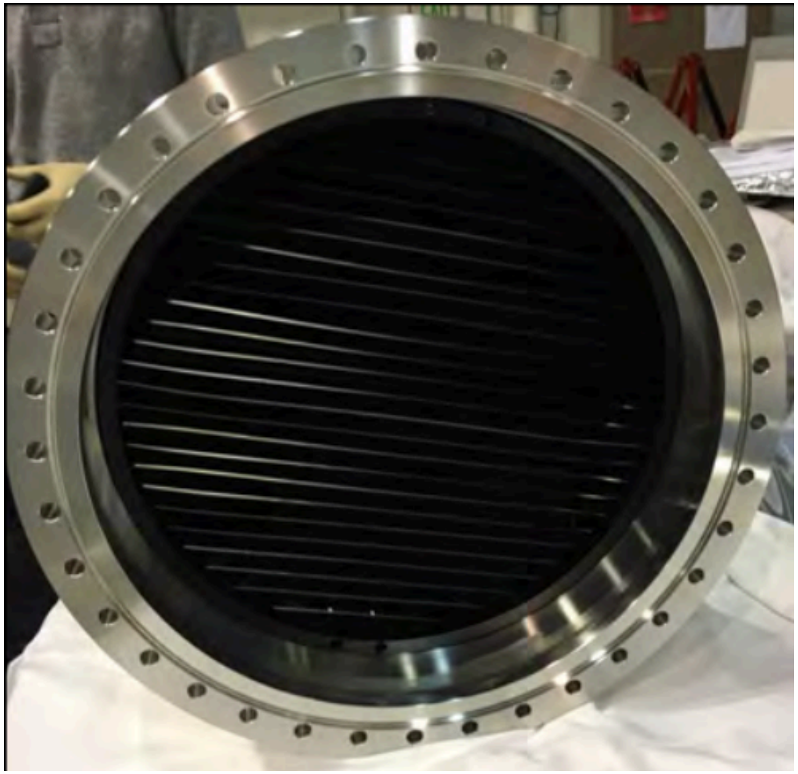

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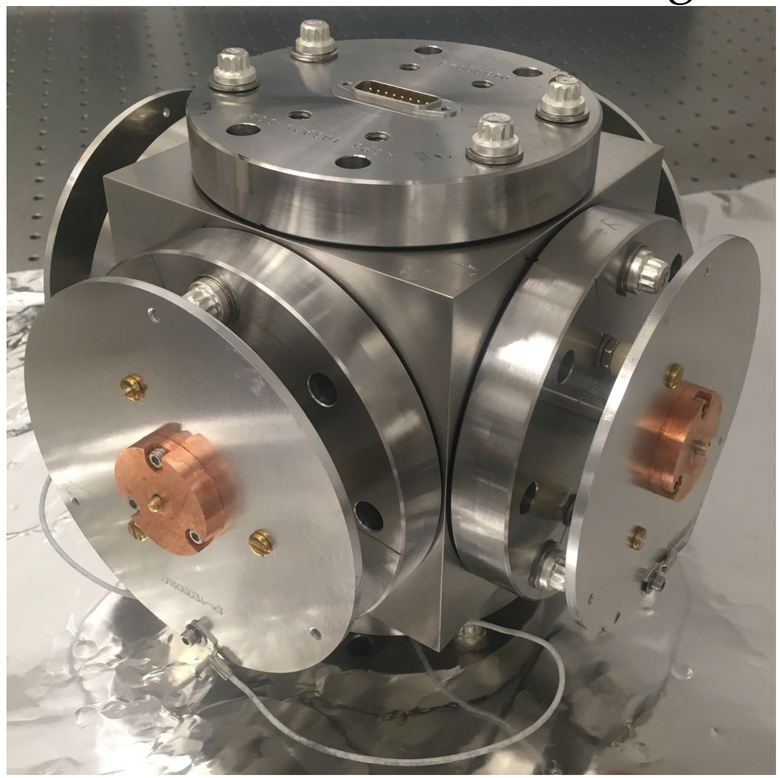

LIGO-G1800293

Discharge optics via gentle flow of ions (positive and negative)

This effect, as well as gas damping, argue strongly in favor of a photon actuator for the final mirror stages

Electrical Grounding and Isolation

Need to be mindful of electrical connections when constructing facility

- Avoid ground loops, both in vacuum, at electronics racks, and at vacuum flanges

Plan for many, many magnetometers at electronics racks for identification of lines in DARM

- Looking for cyclic currents that are coupling to DARM
- Otherwise, monitor current in every wire - infeasible
- Example: LEDs on electronics boxes flashed at the same time, created comb in DARM

Install large wall-mounted magnetic injection coils for feedforward cancellation, including Schumann resonances

Seismic Sensors Everywhere

Reducing motion of platforms is very important; but also ensure that every table has witness sensors

See S. Cooper's talk Wed for exciting new sensor candidates

See S. Biscan's talk Wed for seismic platform noise budgets

Shorter term, consider replacing all coarse CPS (capacitive position sensors) with fine CPS on LIGO seismic platforms

Concluding Thoughts

There have been many lessons learned - we need to compile them and incorporate them into the design of future facilities and interferometers

Some of my favorites:

- Reducing the RMS motion of the optics will help address many issues
- Avoid reflective surfaces everywhere practicable
- Must be able to tune the thermal state of all mirrors in a non-axisymmetric way

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- Avoid reflective surfaces everywhere practicable
- Must be able to tune the thermal state of all mirrors in a non-axisymmetric way

There will always be things that we cannot anticipate

- Best thing we can do for these is to provide many witness sensors, and many diagnostic tools