Advanced LIGO Detectors in O3

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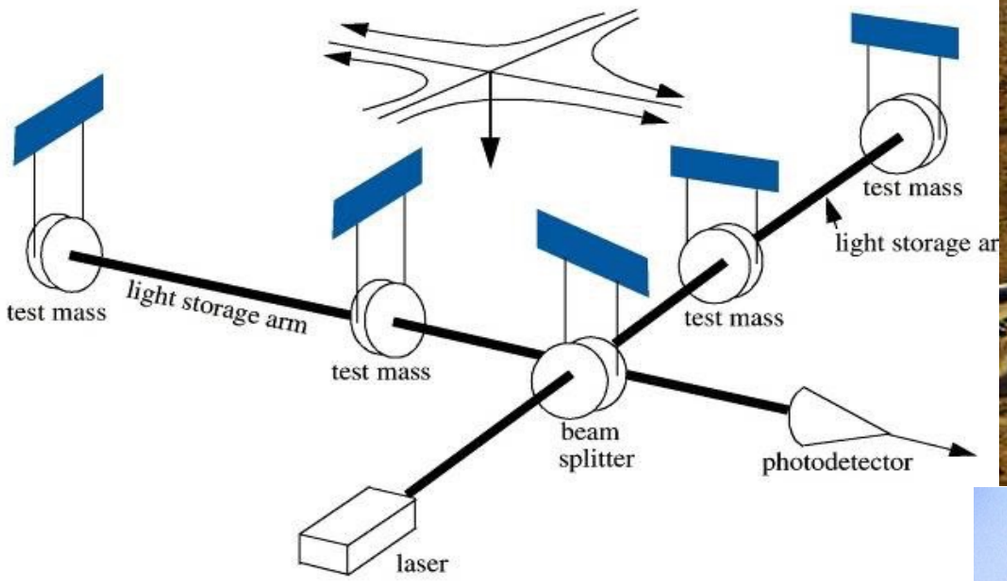
for the LIGO Instrument Team

GR22/Amaldi13
10 July 2019

LIGO-G1900455



- O1/O2 were very successful…but we want more!

Third Observing Run (O3)

- 19 month commissioning break after O2
- Triple detector network: LIGO Hanford (LHO), LIGO Livingston (LLO), and Virgo
- Began 1 April 2019, run for ~1 year (O2 was 9 months)
- Observing full time w/ Tuesday maintenance and ~6 hrs/ week of commissioning
- Most sensitive run yet!

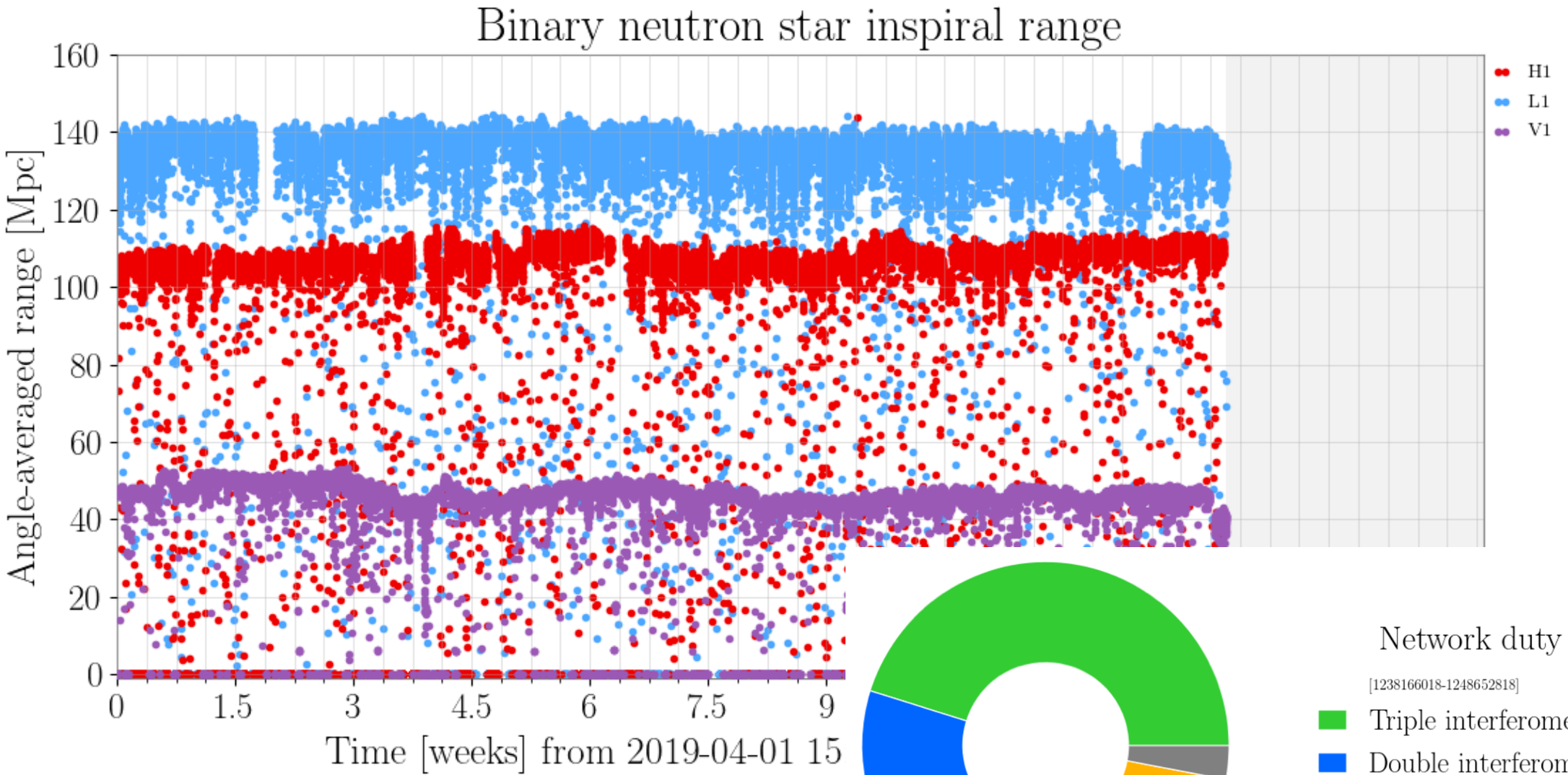
First run with public alerts

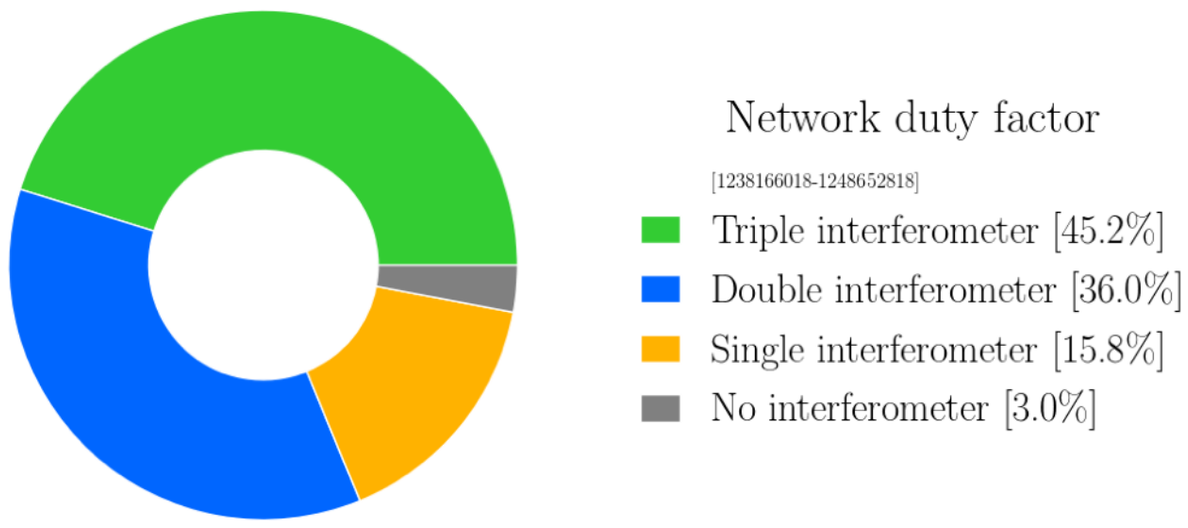
UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created (UTC)
S190701ah	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC

https://gracedb.ligo.org/latest/

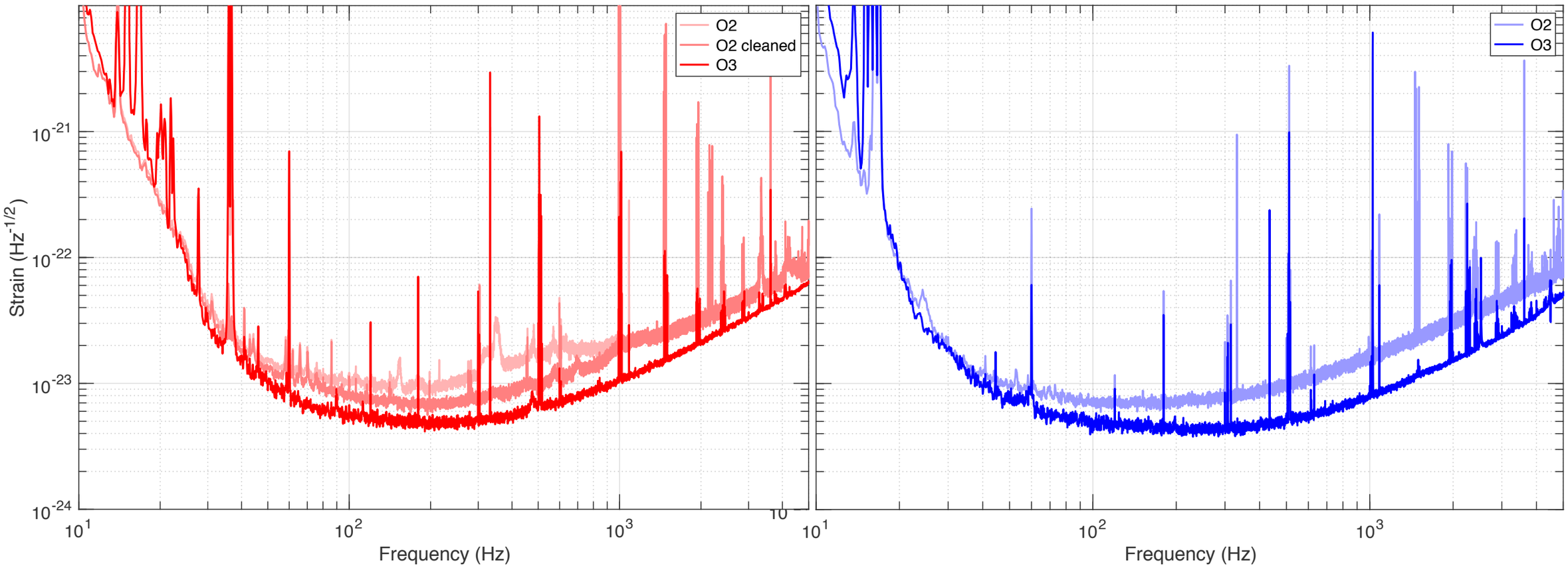
- ~~16~~ ~~17~~ 18 GW candidates in O3 so far
- Compared to 11 confirmed events from O1/O2

O3: Most Sensitive Run Yet





O2/O3 Comparison



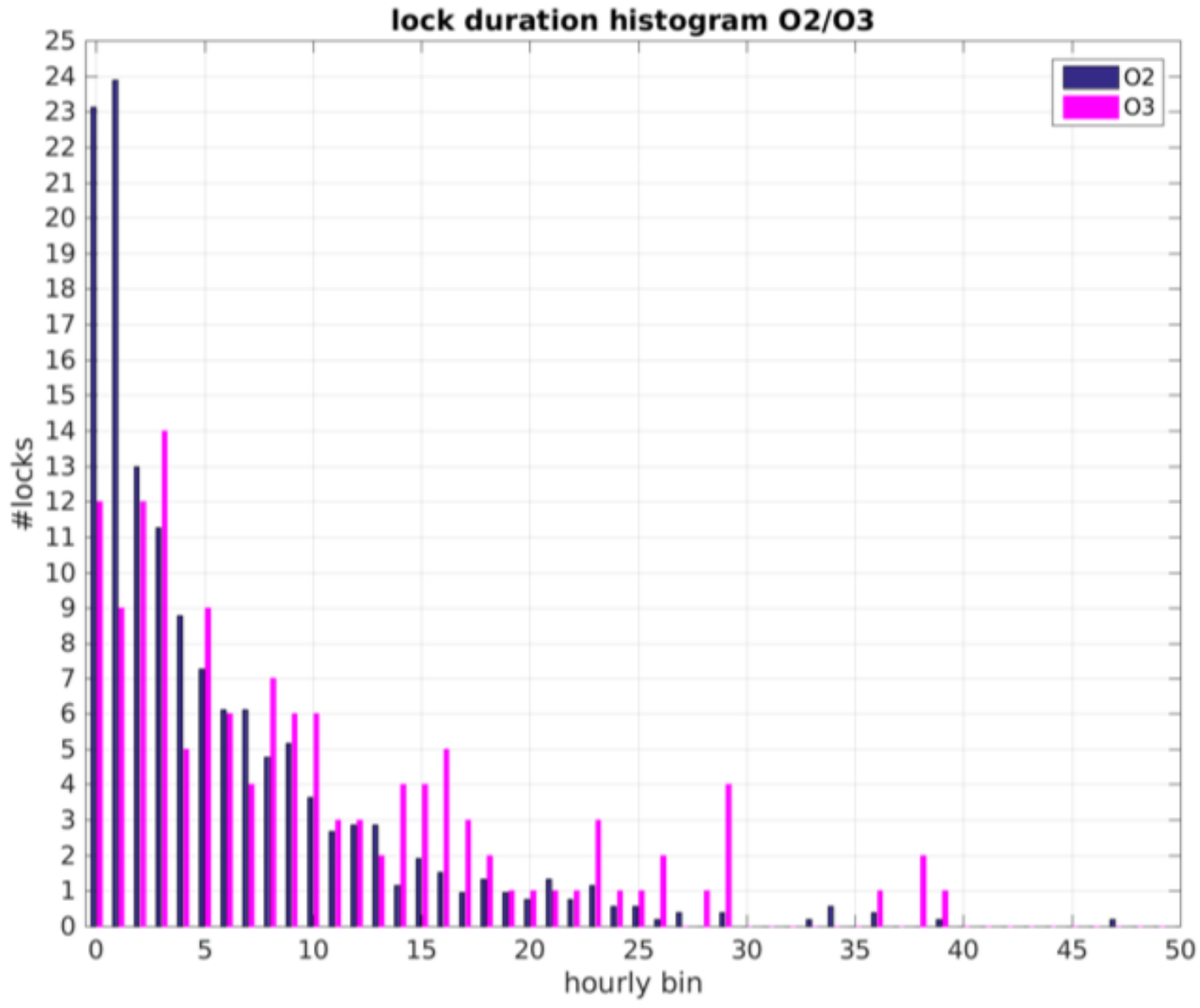
O3 (O2)	Hanford	Livingston
Input Power [W]	37 (30)	46 (25)
Intracavity Power [kW]	190 (120)	230 (100)
BNS Range, 1.4 M_{solar} [Mpc]	110 (65‡)	140 (100)
BBH Range, 30 M_{solar} [Mpc]	800	1100
Duty Cycle	70% (62%*)	74% (61%*)

‡82 after cleaning

*Includes planned engineering break

Improved reliability

- Total O2 lock losses = 717/240 days ~ 3/day
- Total O3 lock losses = 137/74 days < 2/day
- Record 101 hr lock

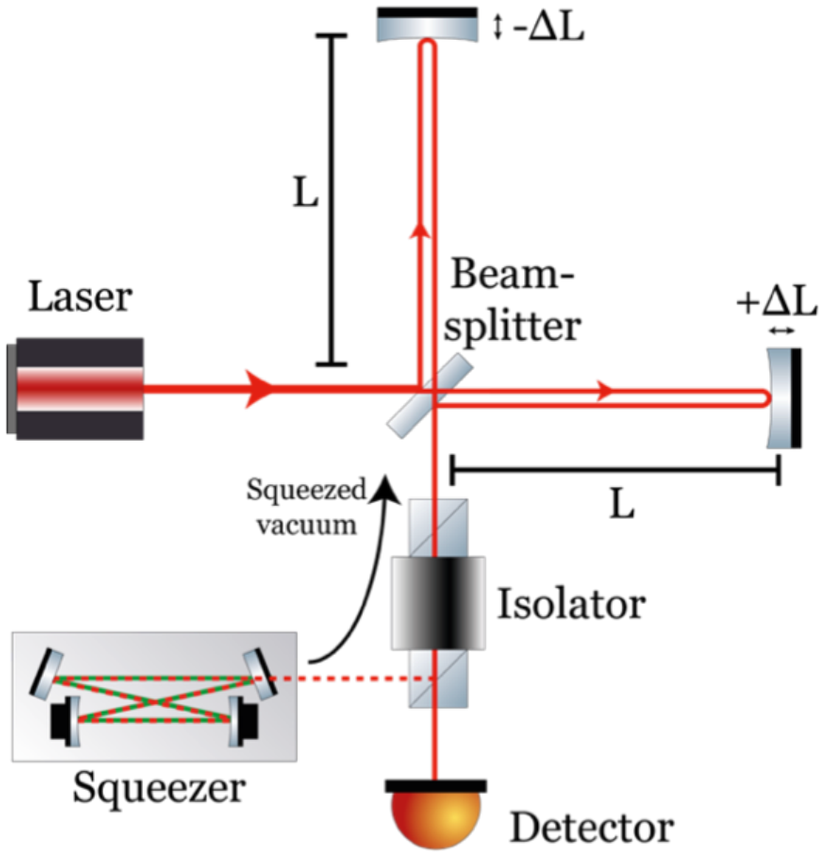


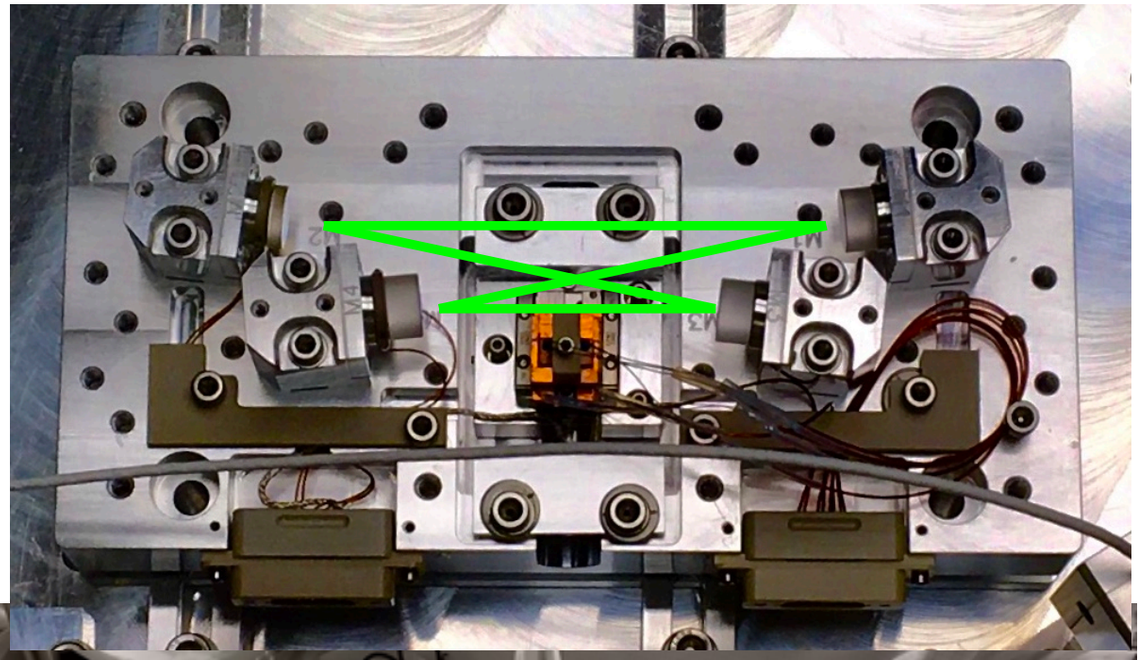
G1901122-v3

How did we get here?

In-vacuum Squeezer

- Injection of squeezed vacuum reduces shot noise





Squeezer Performance

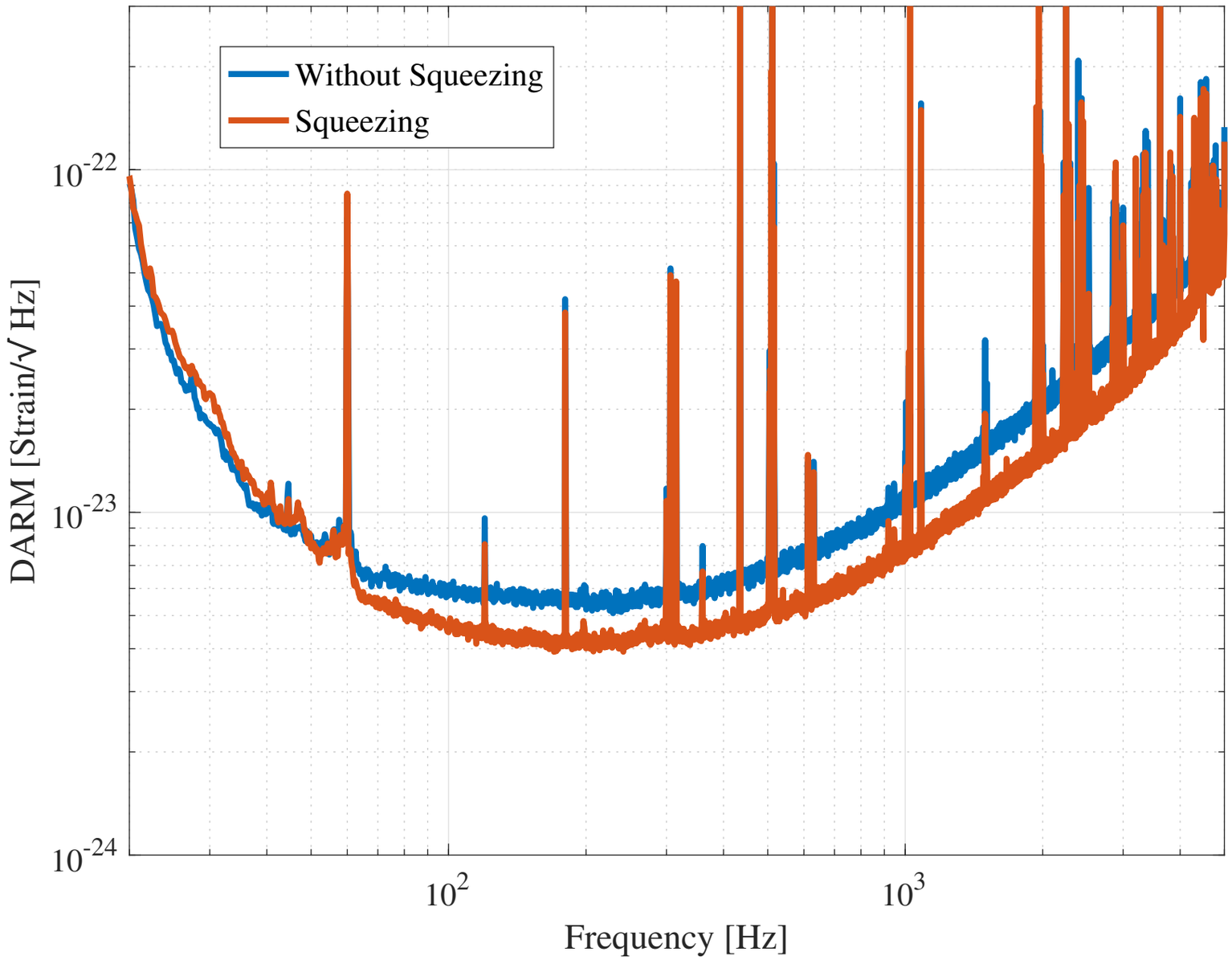
LLO
3.2 dB (5.5 dB anti-sqz)
⇒ 17 Mpc increase in

BNS range

LHO
2.2 dB (4.4 dB anti-sqz)
⇒ 14.5 Mpc increase in

BNS range

- No degradation in sensitivity
- Limited by excess loss
  - Known ~20%, measured ~40%



LLO log 45069

Squeezer Performance

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3.2 dB (5.5 dB anti-sqz)
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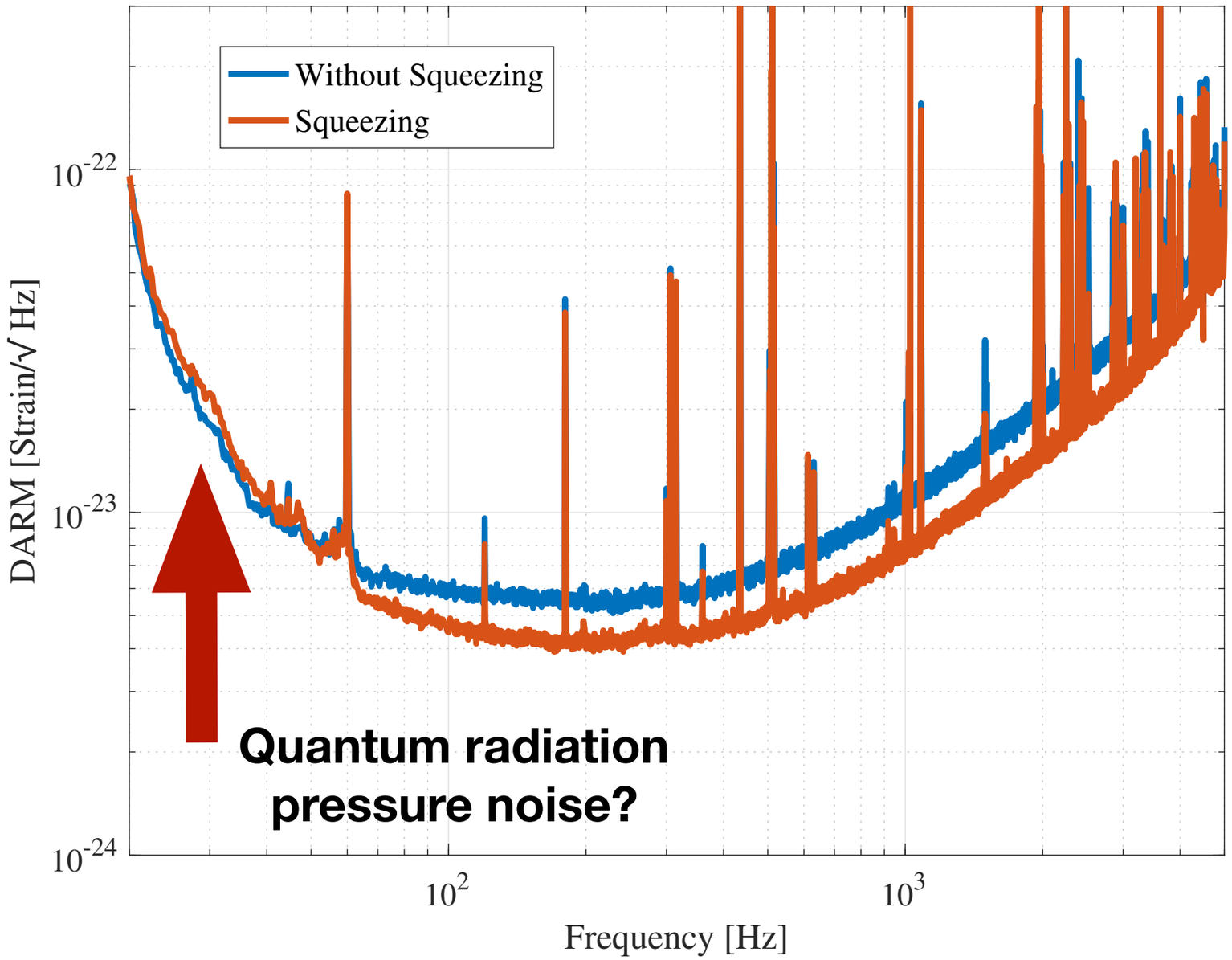
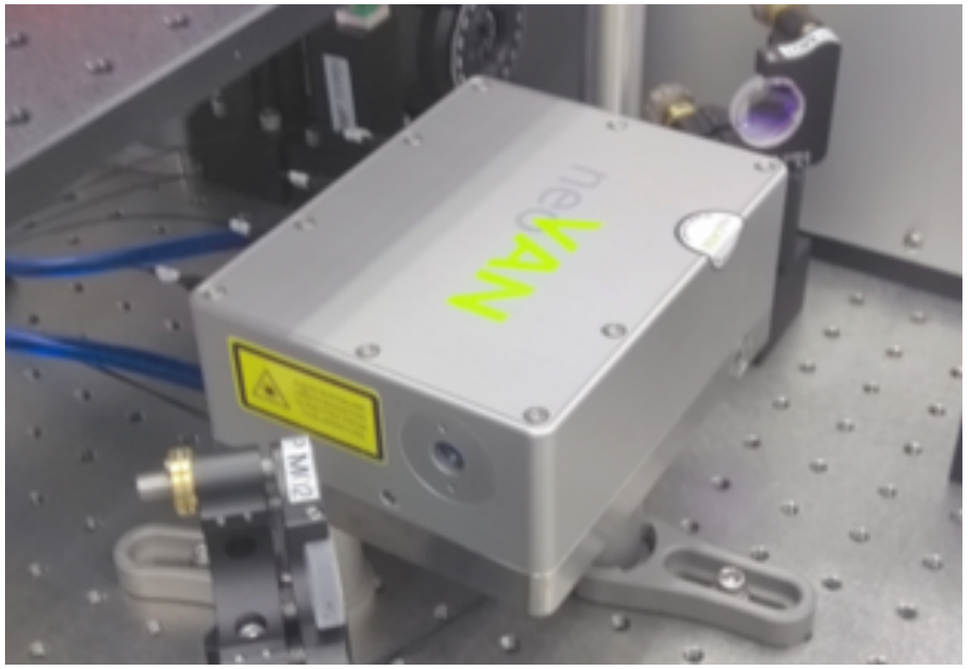


LLO log 45069

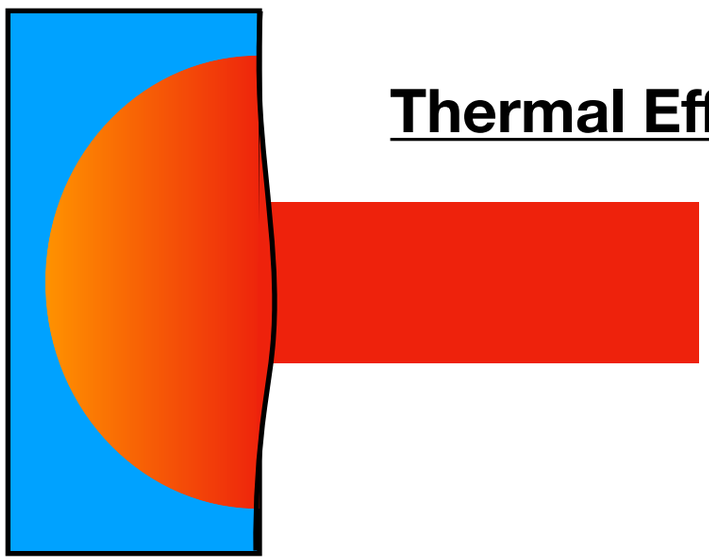
Squeezer Reliability

- Fully automated
- Active angular control
- Duty cycle >98% (1 April – 17 May)

Increasing Power

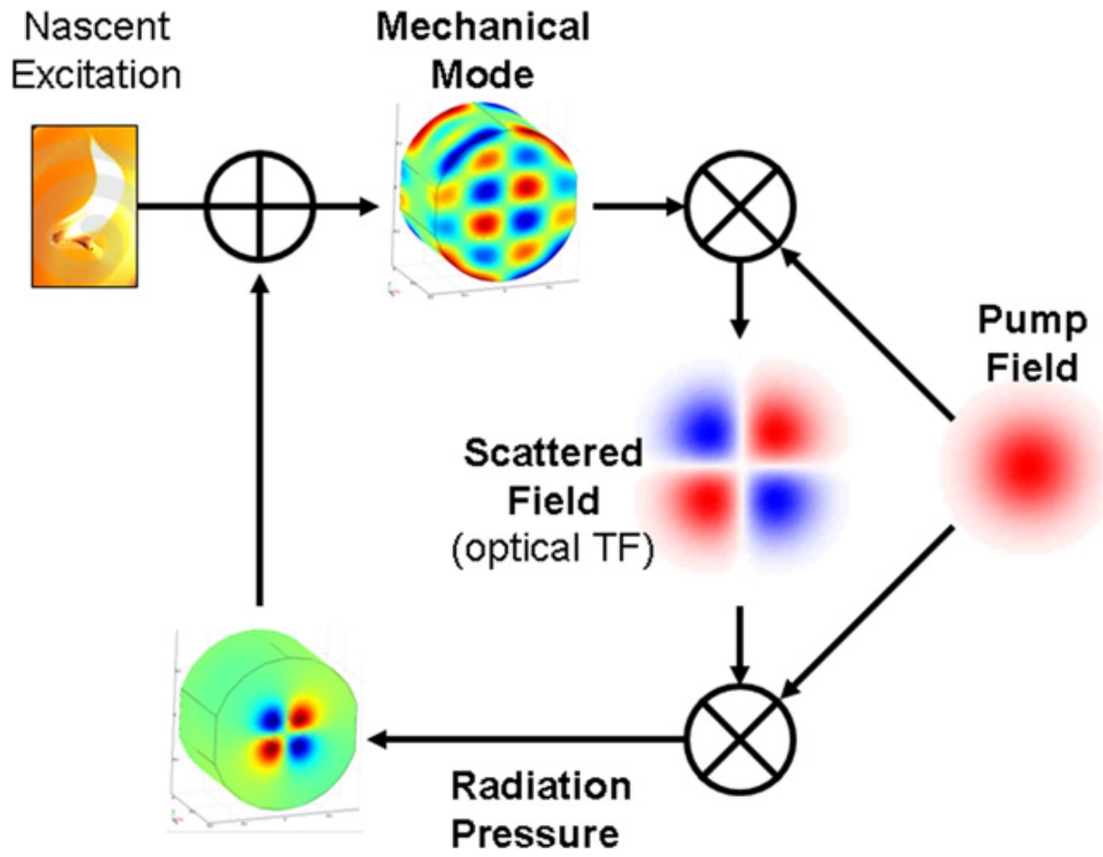


High-Power Sources

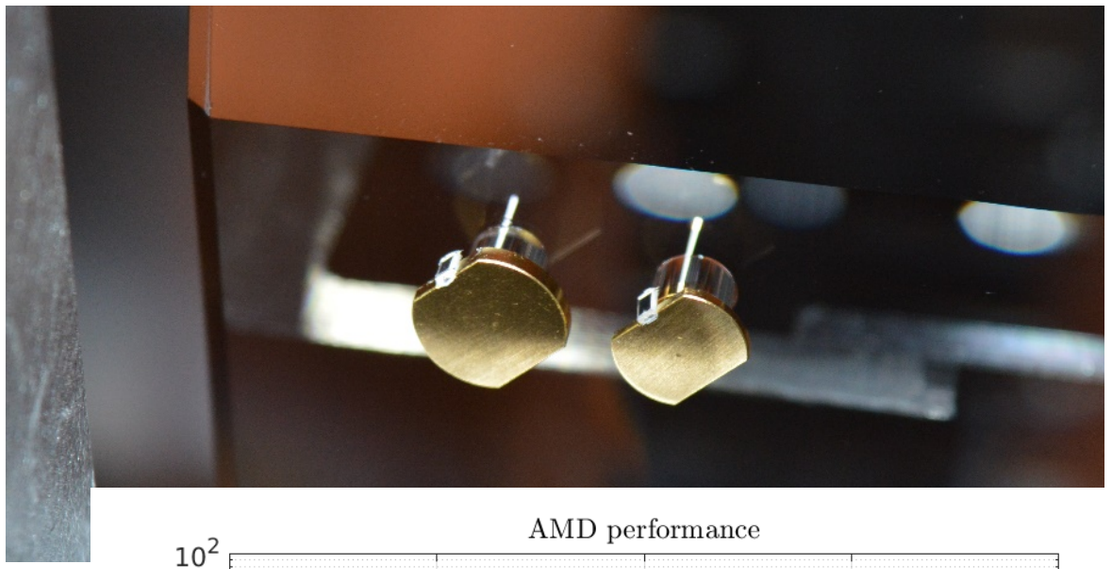


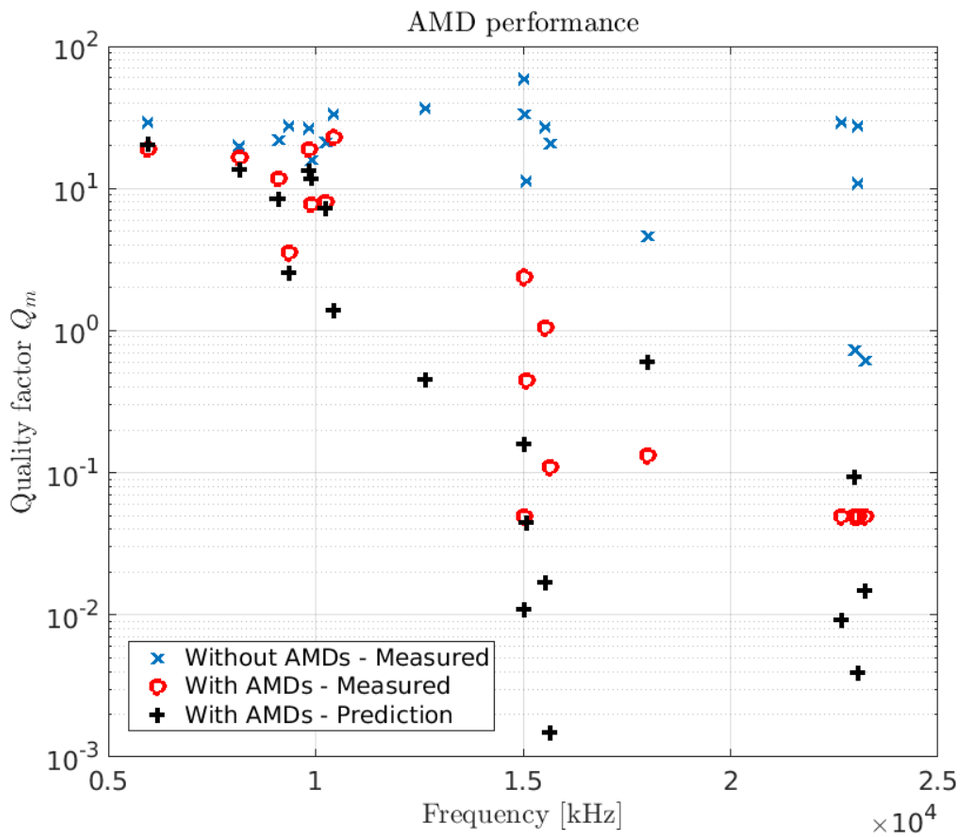
Thermal Effects

Parametric Instabilities

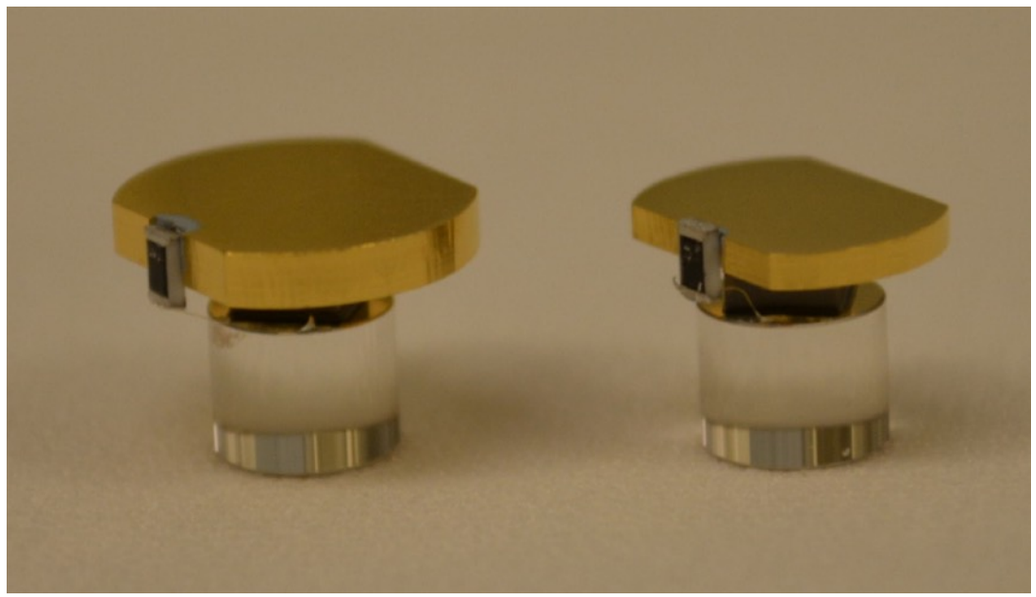


Acoustic Mode Dampers (AMDs)



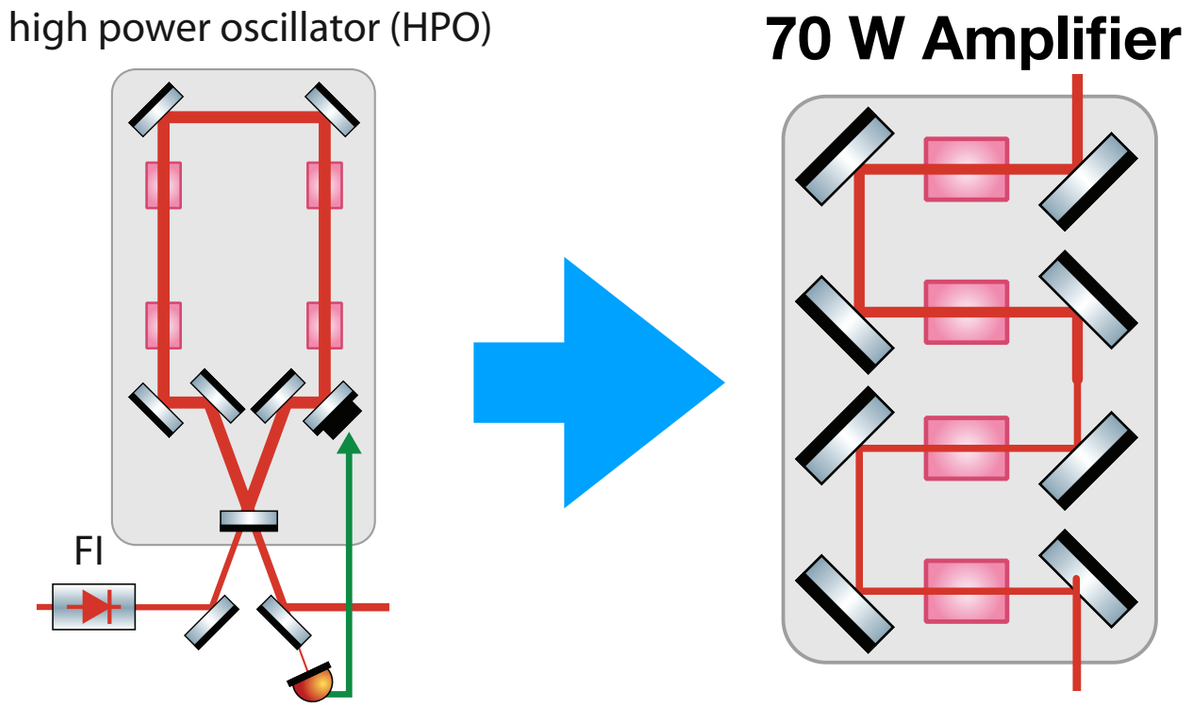


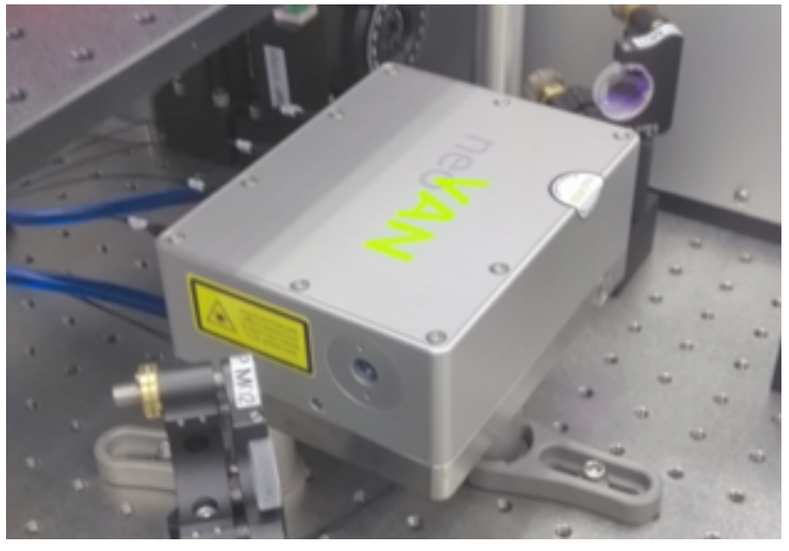
- Tuned to damp test mass mechanical body modes
- Installed on all test masses
- Successfully suppress parametric instabilities!
- Negligible increase to thermal noise



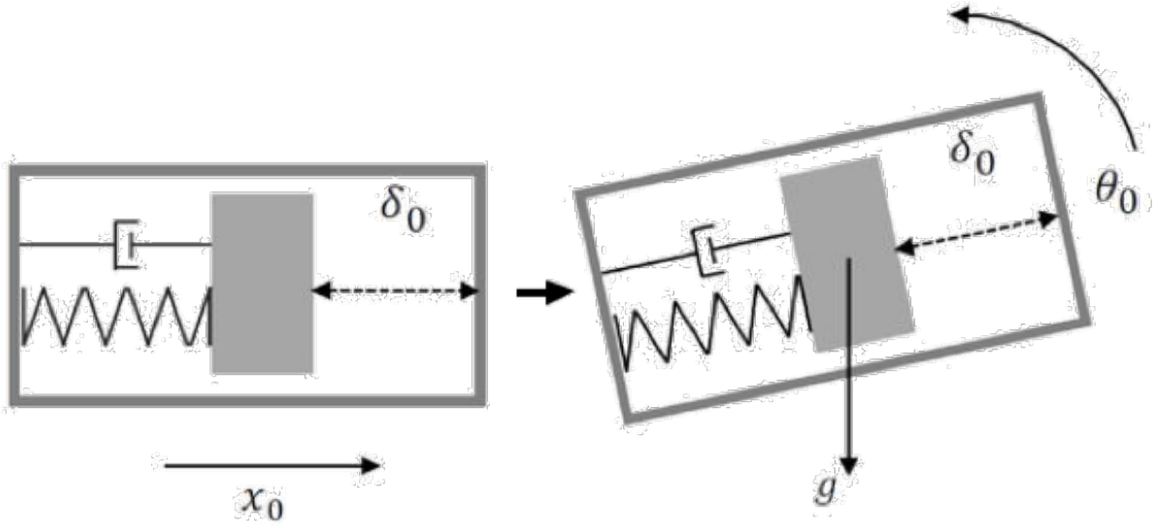
New Pre-stabilized Laser

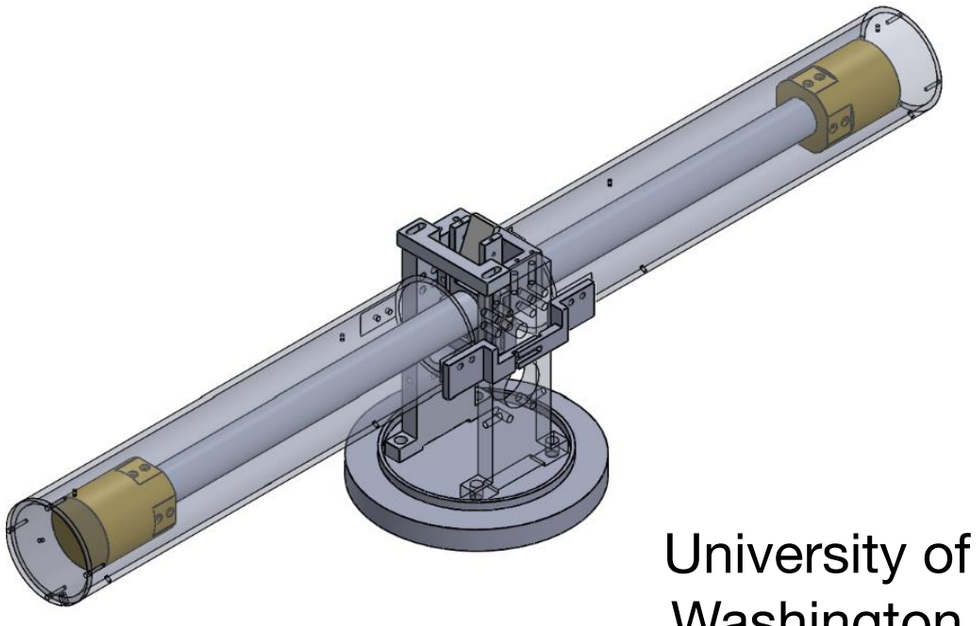
- Replace high-power oscillator with 70 W amplifier (neoLASE neoVAN-4S)
- Lower water flow for improved jitter
- ~50 W available to interferometer





Beam Rotation Sensor

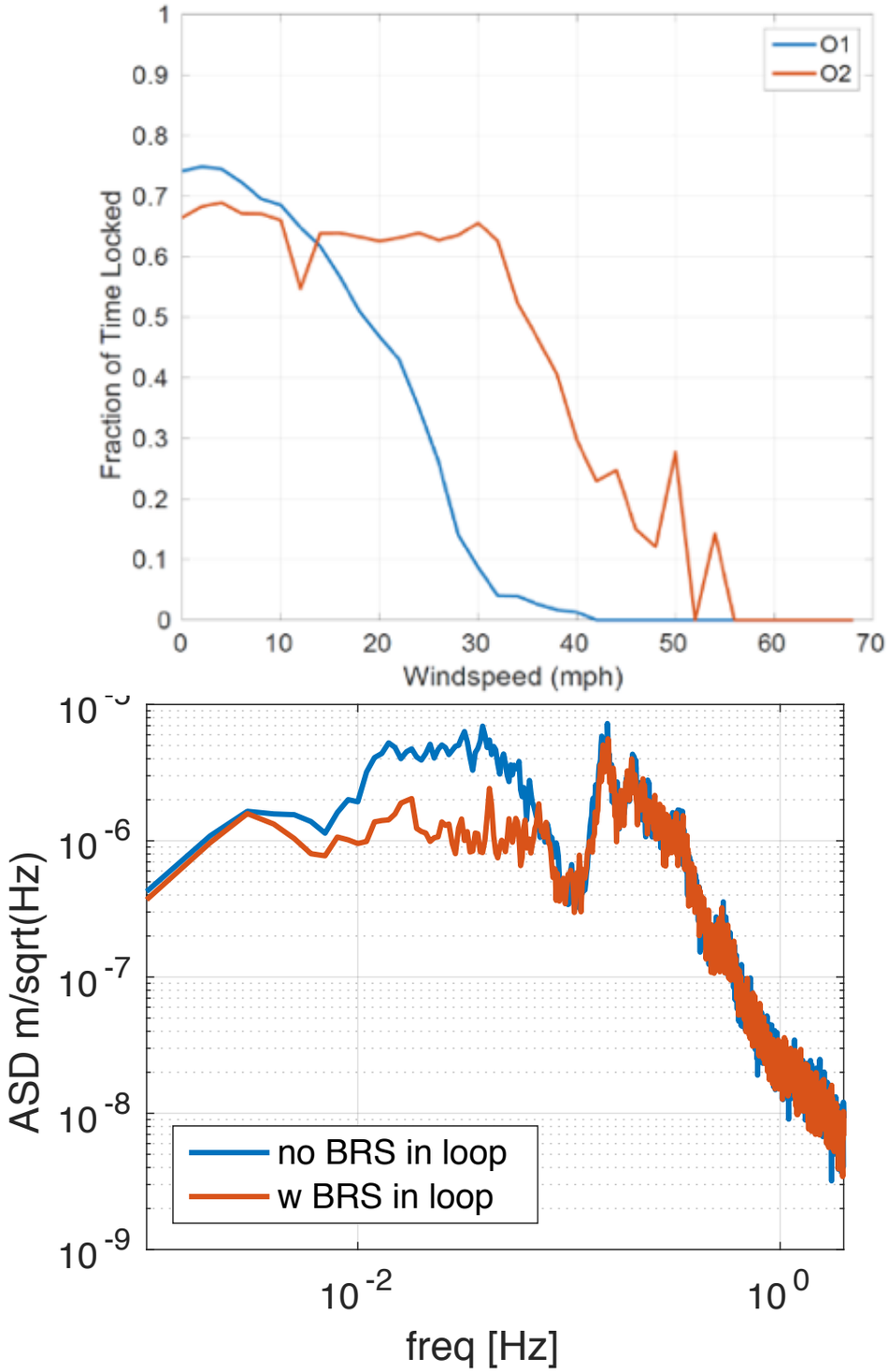




University of Washington

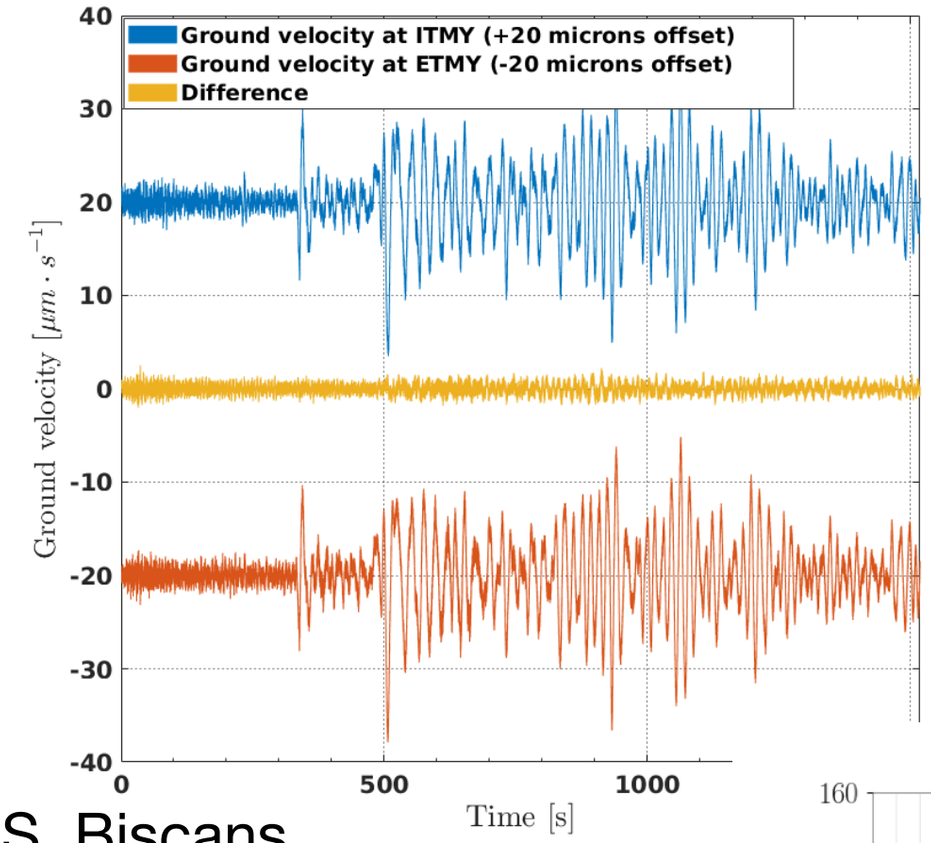
- Idea: remove tilt coupling to seismometer signals
- 1-m long beam
- 4.5 kg-mass
- Cu-Be flexures
- Resonance ~3-8 mHz
- Autocollimator readout

Beam Rotation Sensor



- Installed at LHO prior to O2, now also at LLO
- Improvement of ~3x at LLO and improves locking in windy conditions

Earthquake Resilience

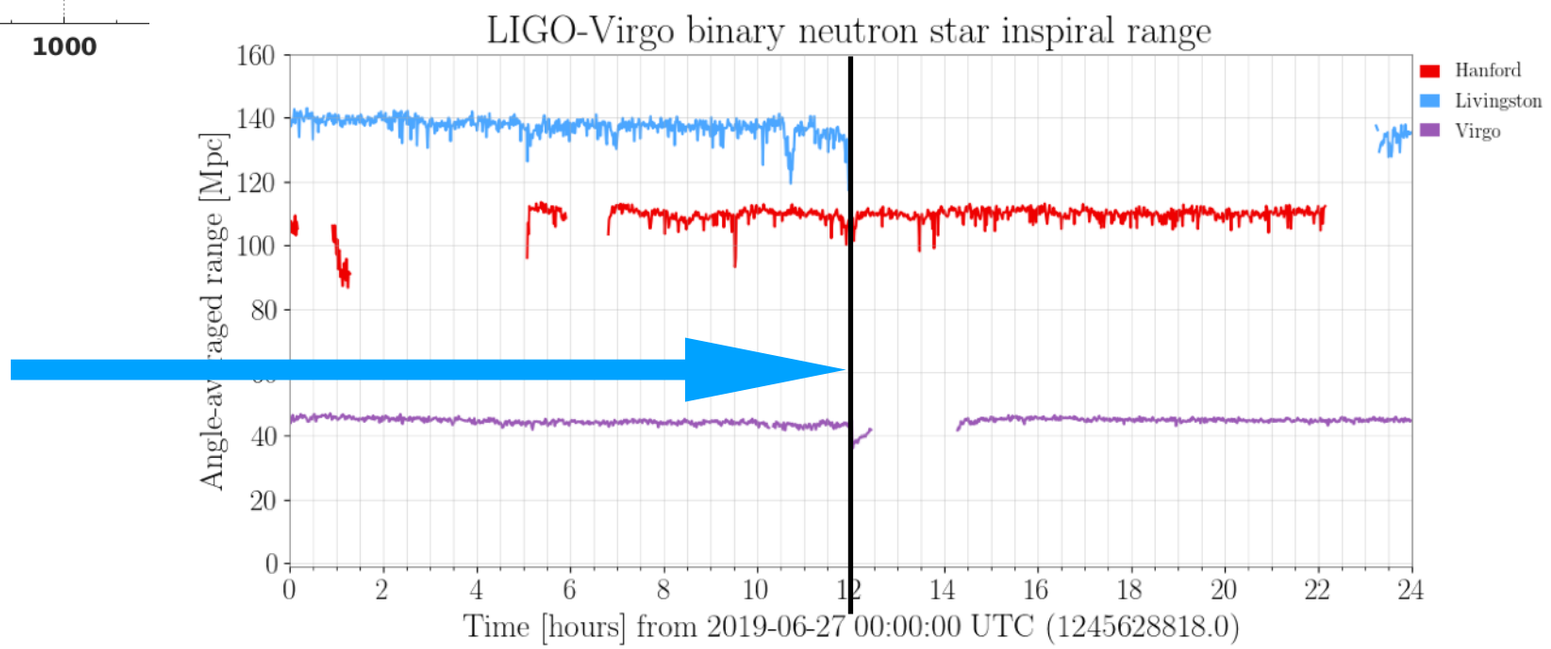


S. Biscans

- Idea: only isolate differentially during earthquake
- To be implemented at LLO
- Improves duty cycle

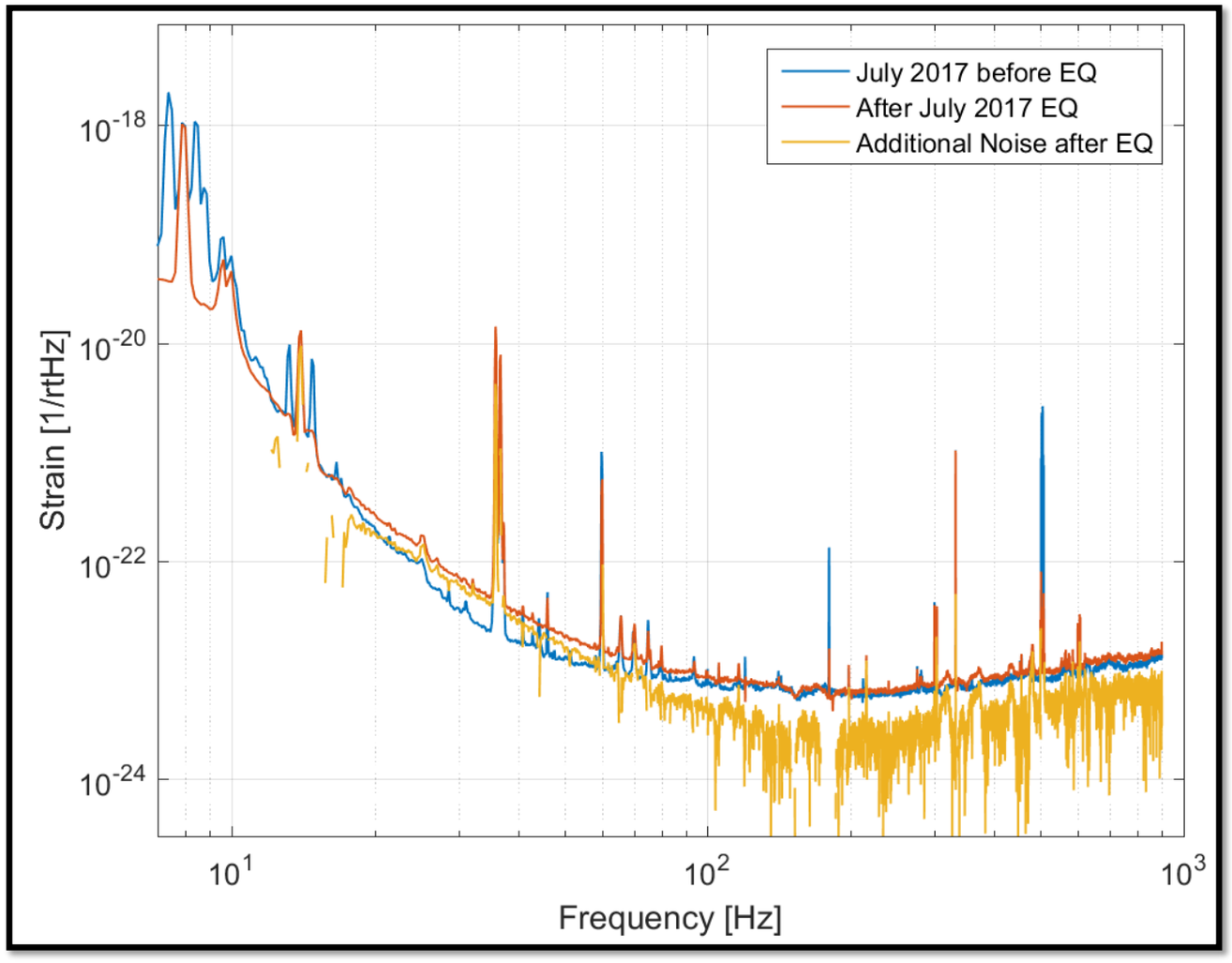
M 6.3 earthquake near New Zealand

LHO log 50236

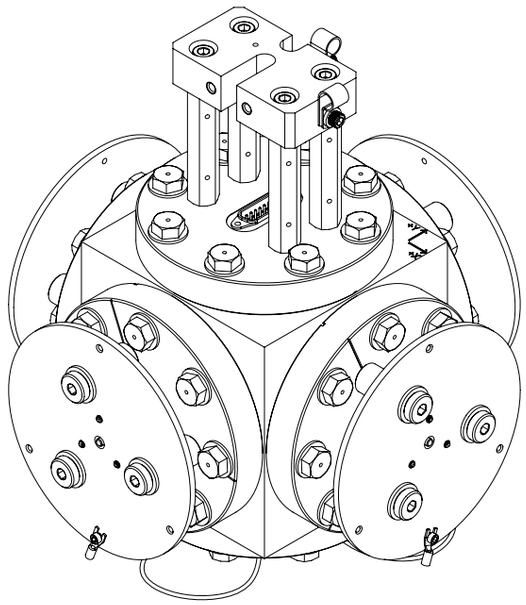


Stray Electric Fields and Optic Charge in O2

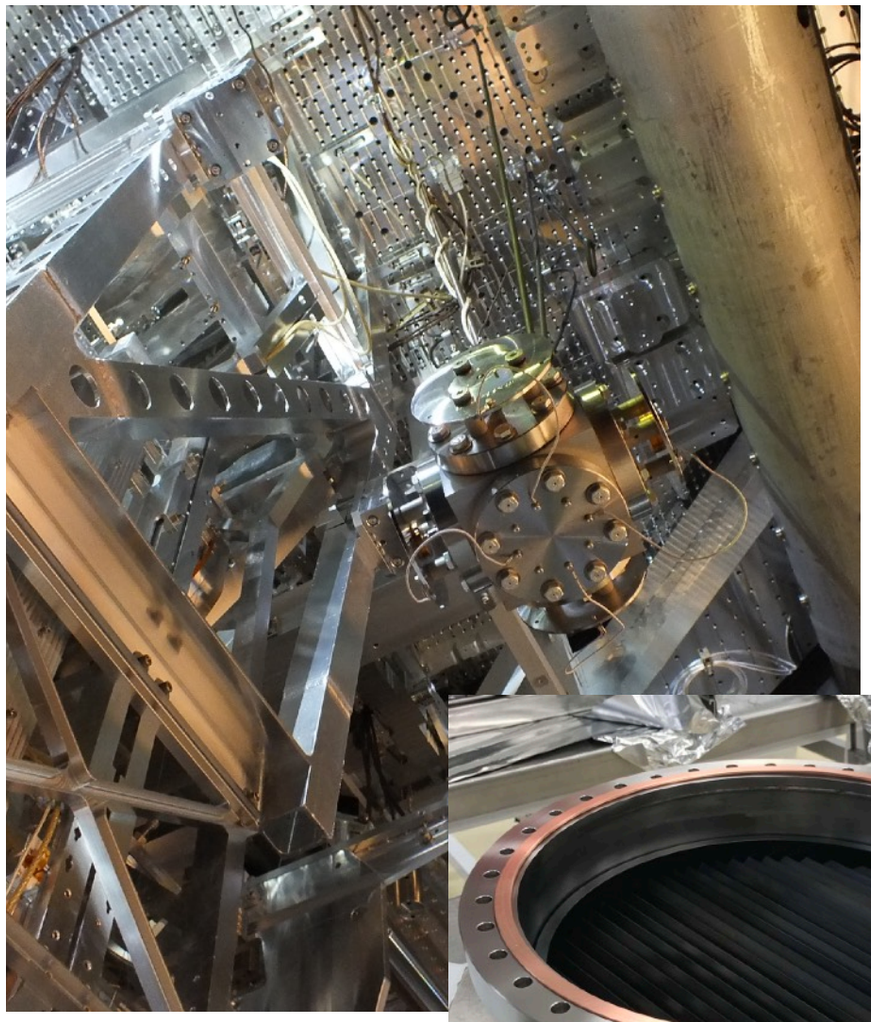
- Increase in noise after Montana EQ July 2017
  - Noise largely disappeared after optic discharge
- Additional excess noise in certain actuator configurations
- <u>Suggests optic charge and/or stray E fields</u>



Stray Electric Fields and Charge

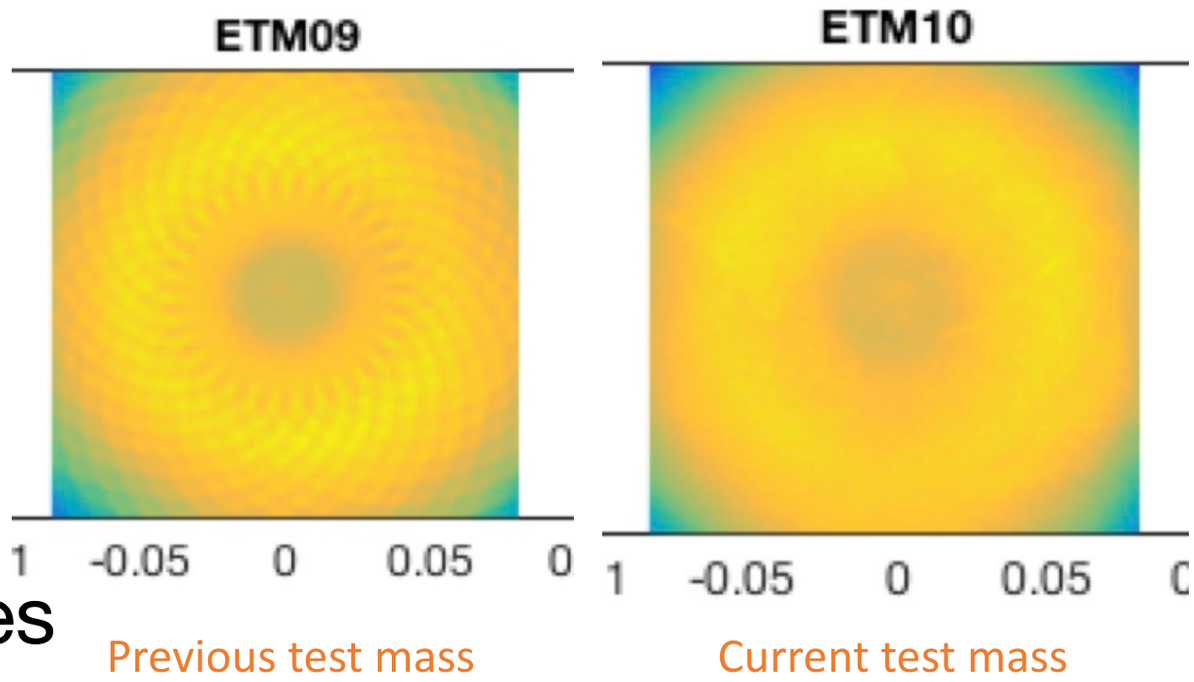


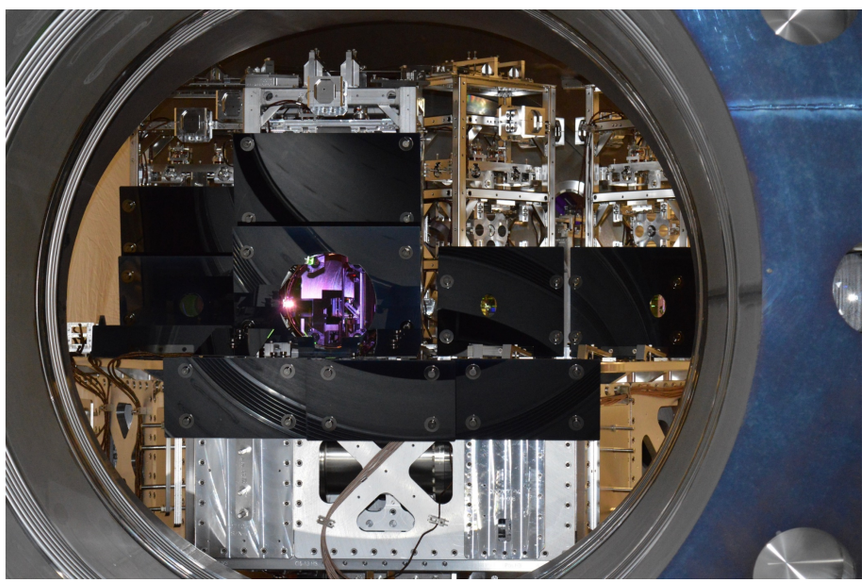
- Installed electric field meter in chamber to monitor fluctuating electric fields
- Viewport injections suggest large-scale E Fields >100x below current sensitivity
- Additional tests to understand and mitigate local E fields
- Chevron baffles installed on ion pumps

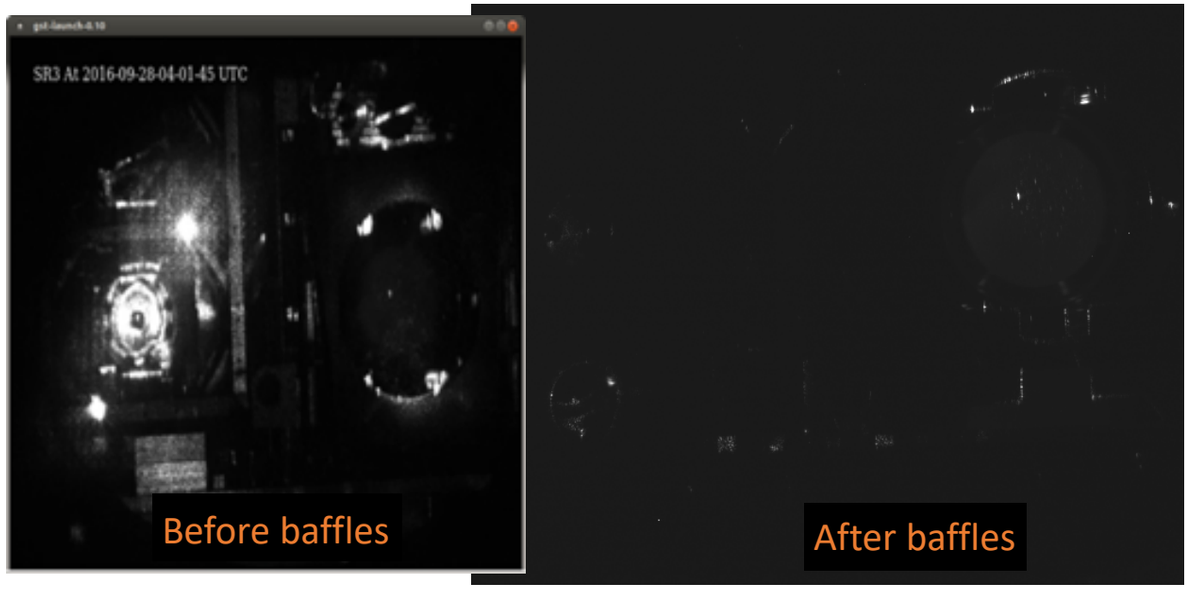


Scattered Light Mitigation

- End masses replaced
  - Decreased scatter loss
  - ~10% increase in power buildup
- Installation of additional baffles

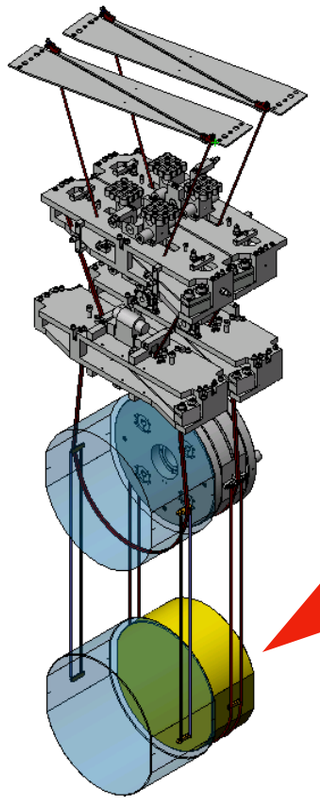






Other improvements

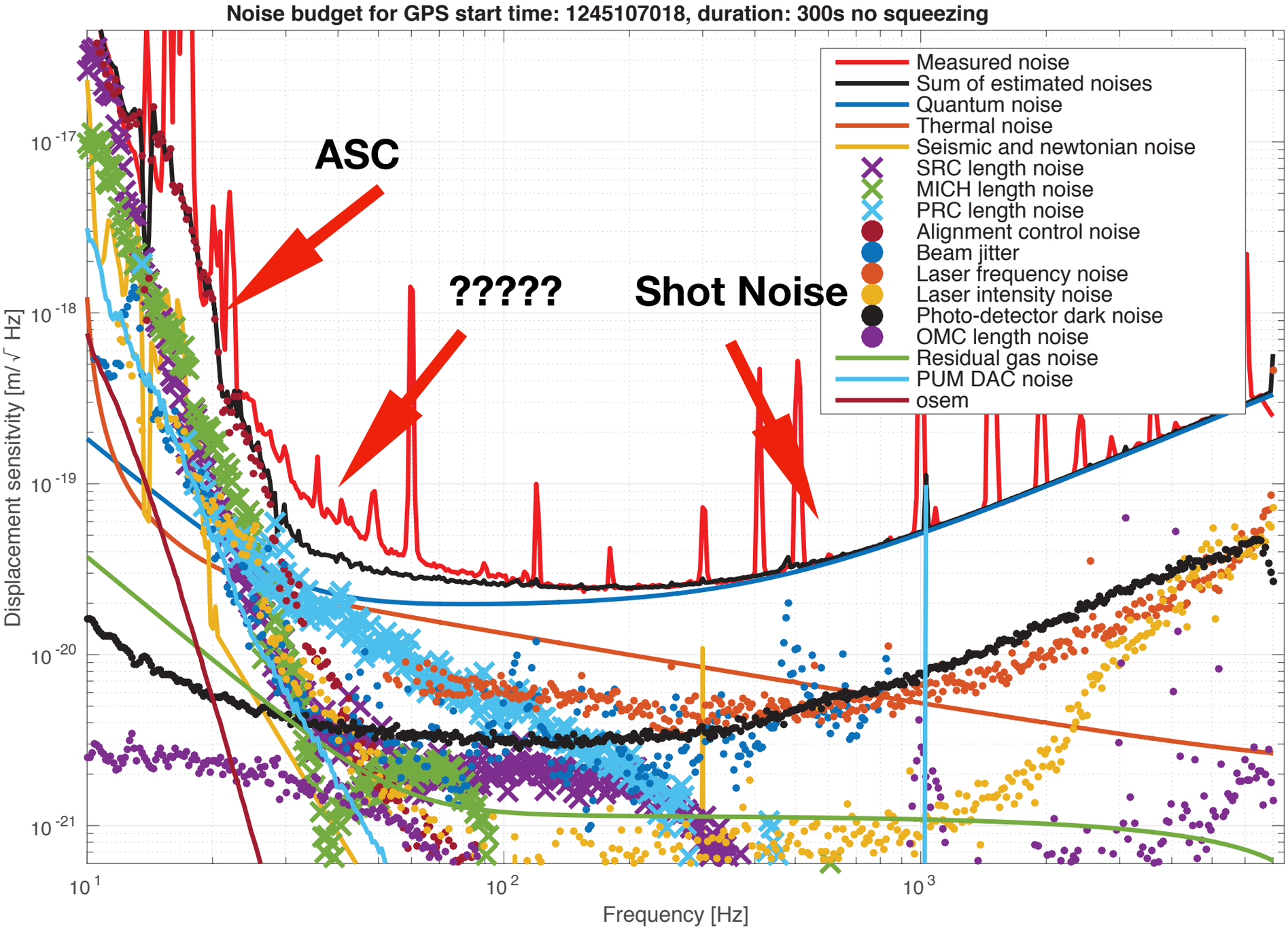
- New annular reaction masses to reduce squeezed film damping
- Signal recycling angular control scheme
- New signal recycling mirror (T 37%->33%) and holder (thermal noise)
- Reduced vibration on primary laser table
- Improved actuator filtering to improve resistance to fast transients
- Tweaks to angular control loops



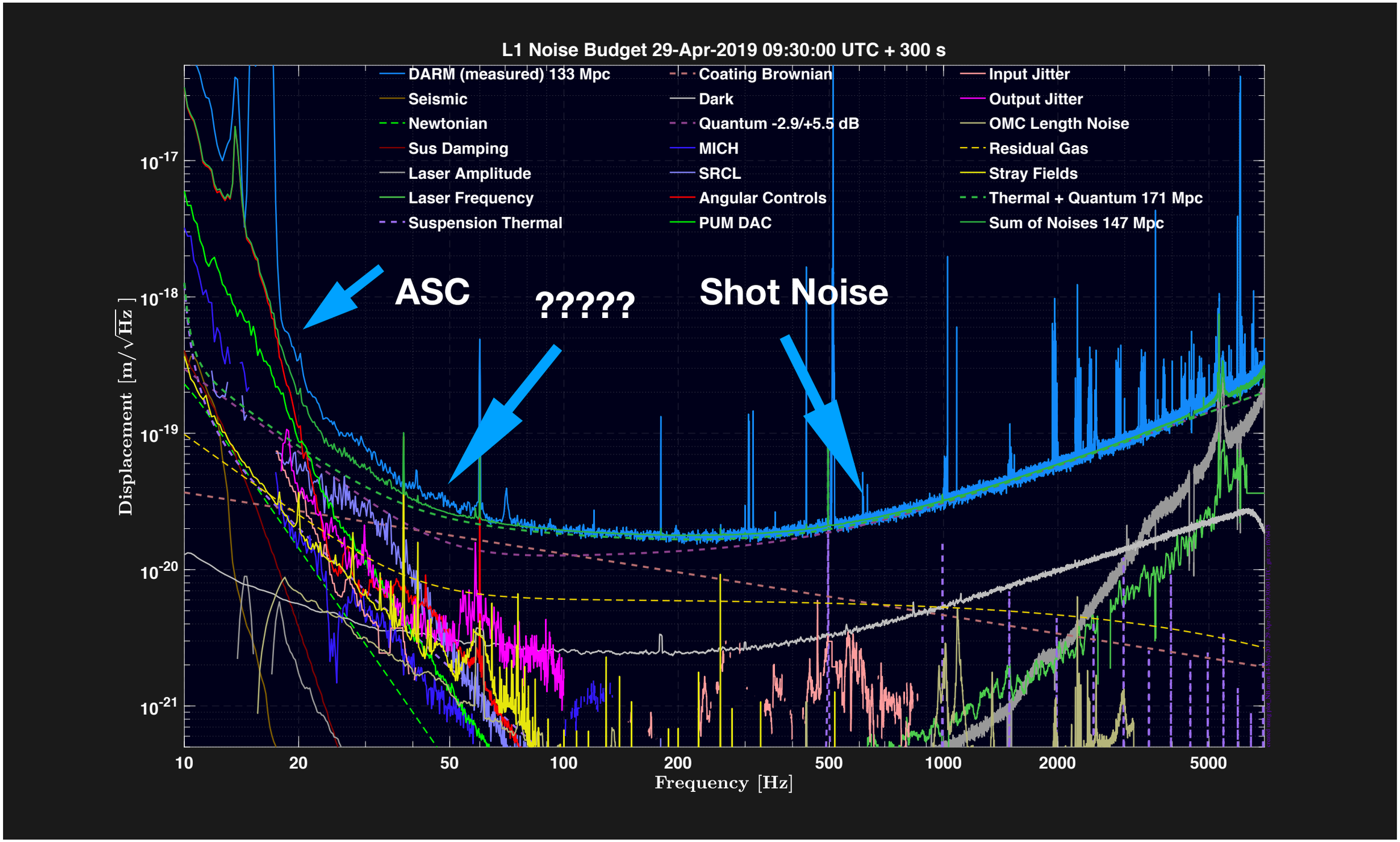
J. Romie

Where else can we improve?

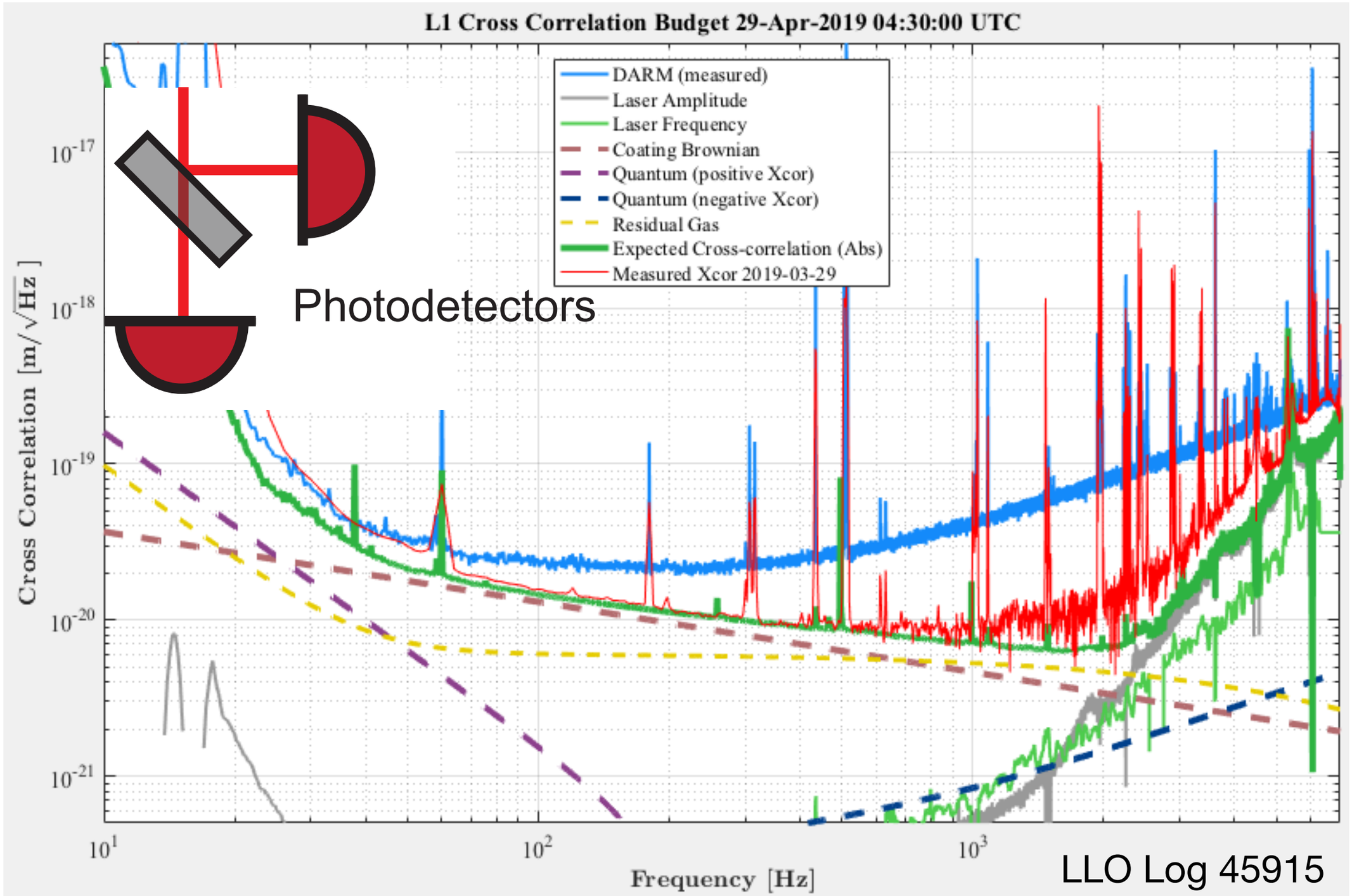
LHO Noise Budget



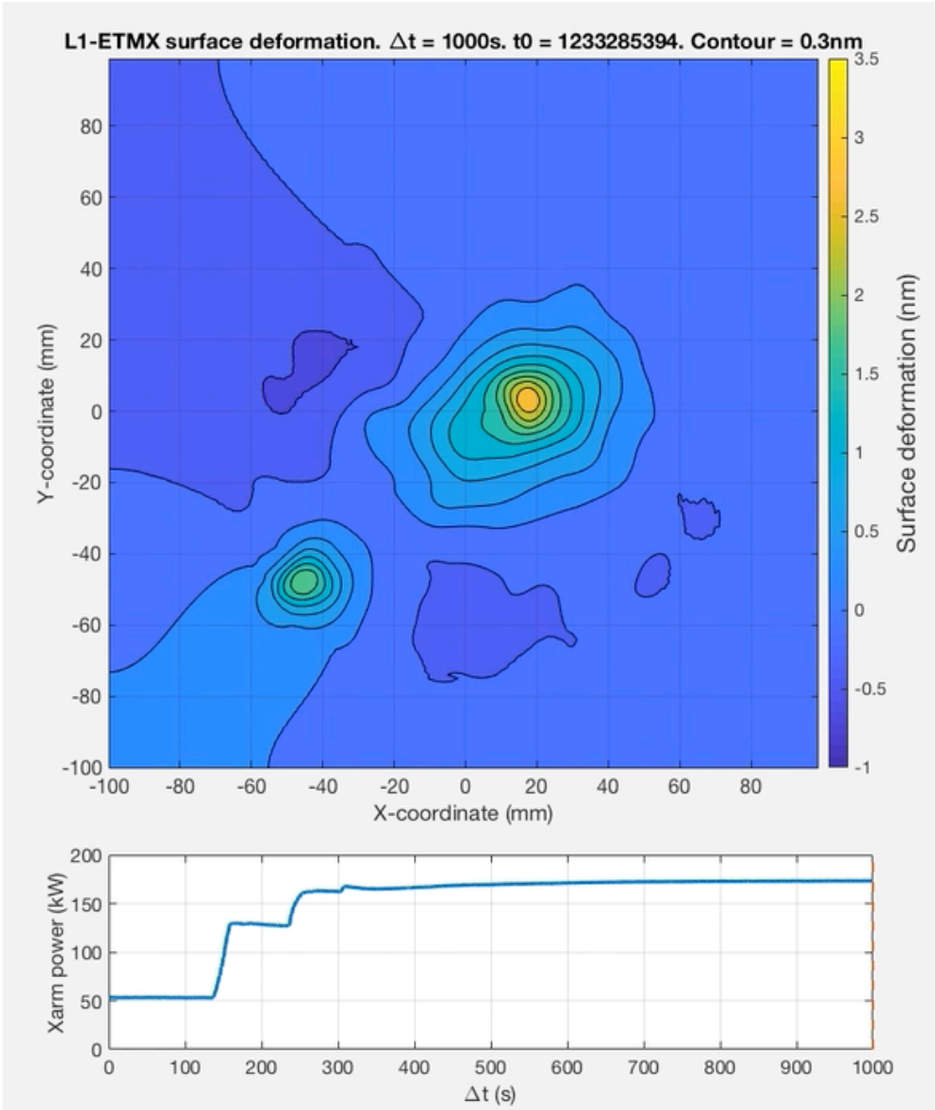
LLO Noise Budget



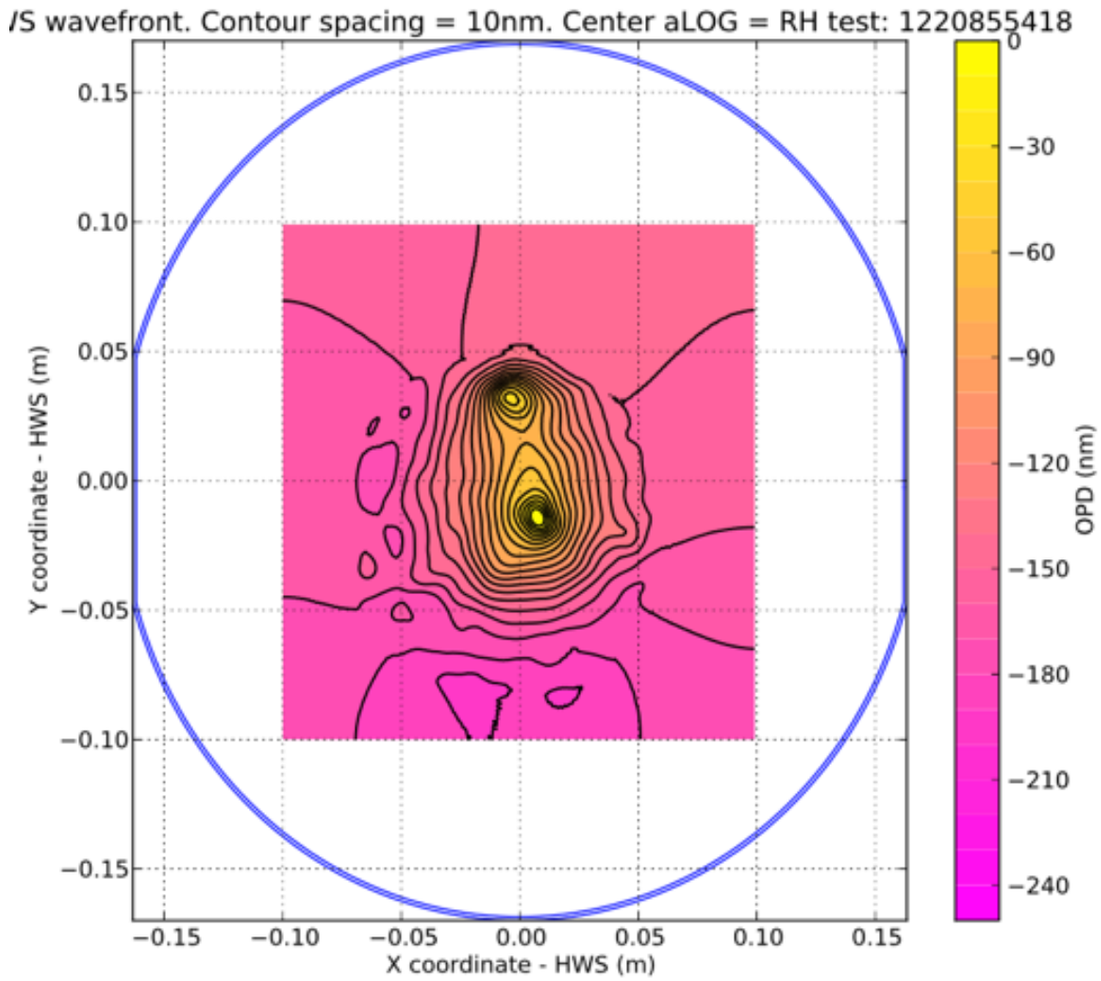
Looking below shot noise



Point Absorbers on Coating

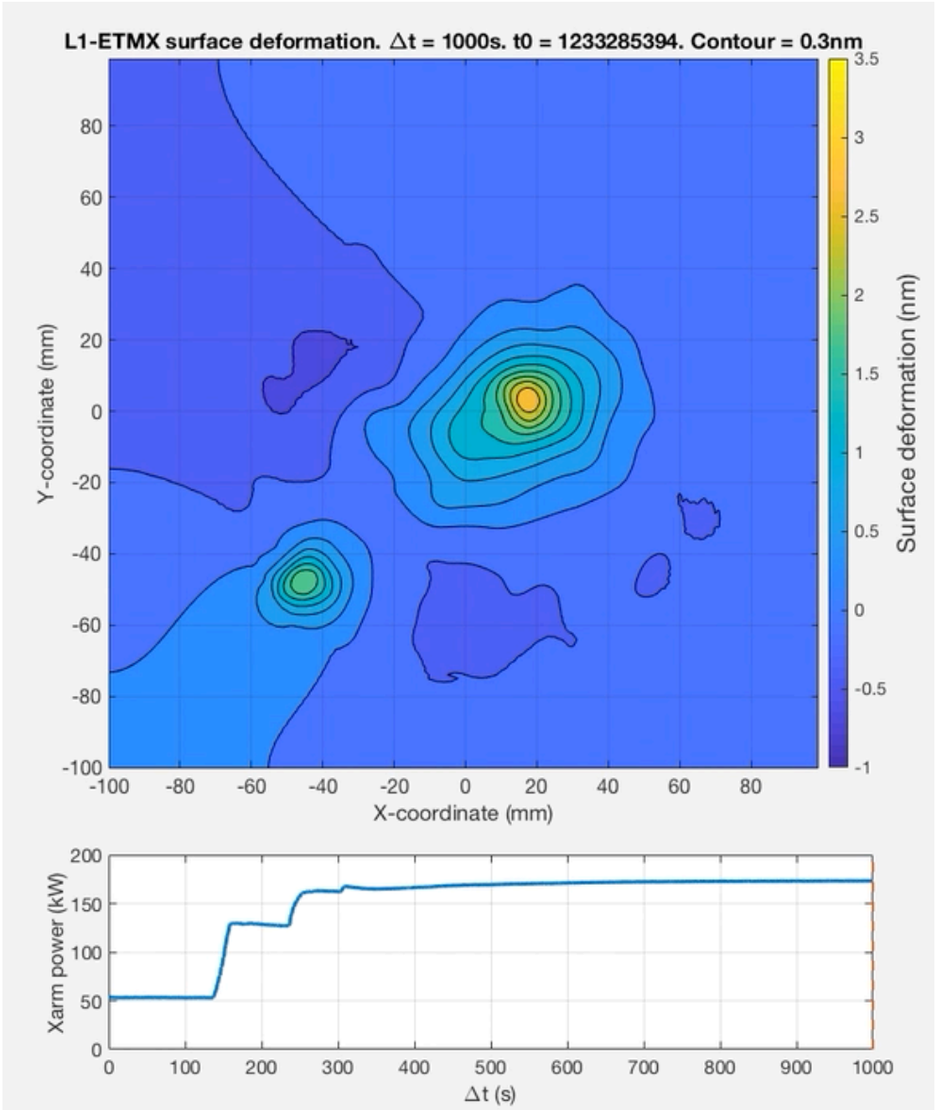


LLO ETMX

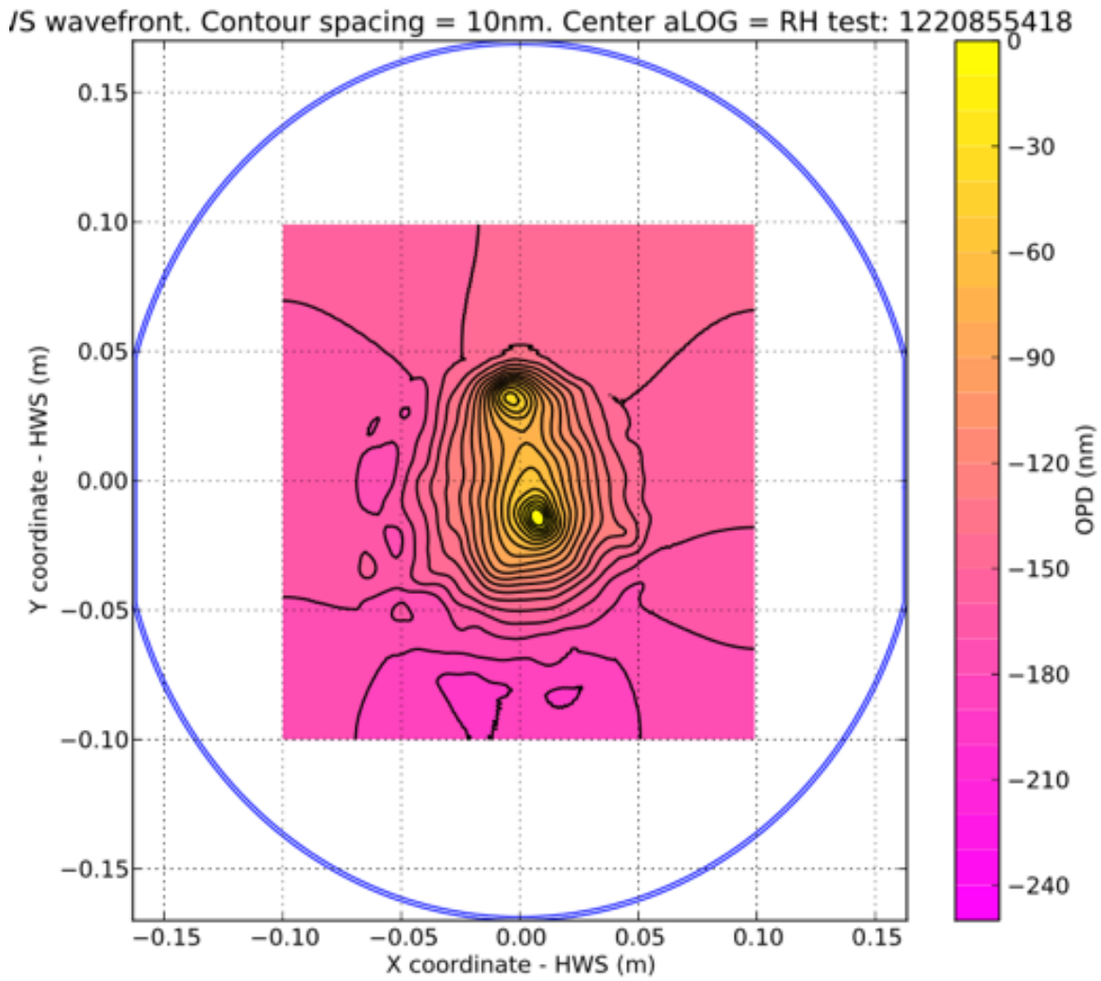


LHO ITMY

Point Absorbers on Coating



LLO ETMX

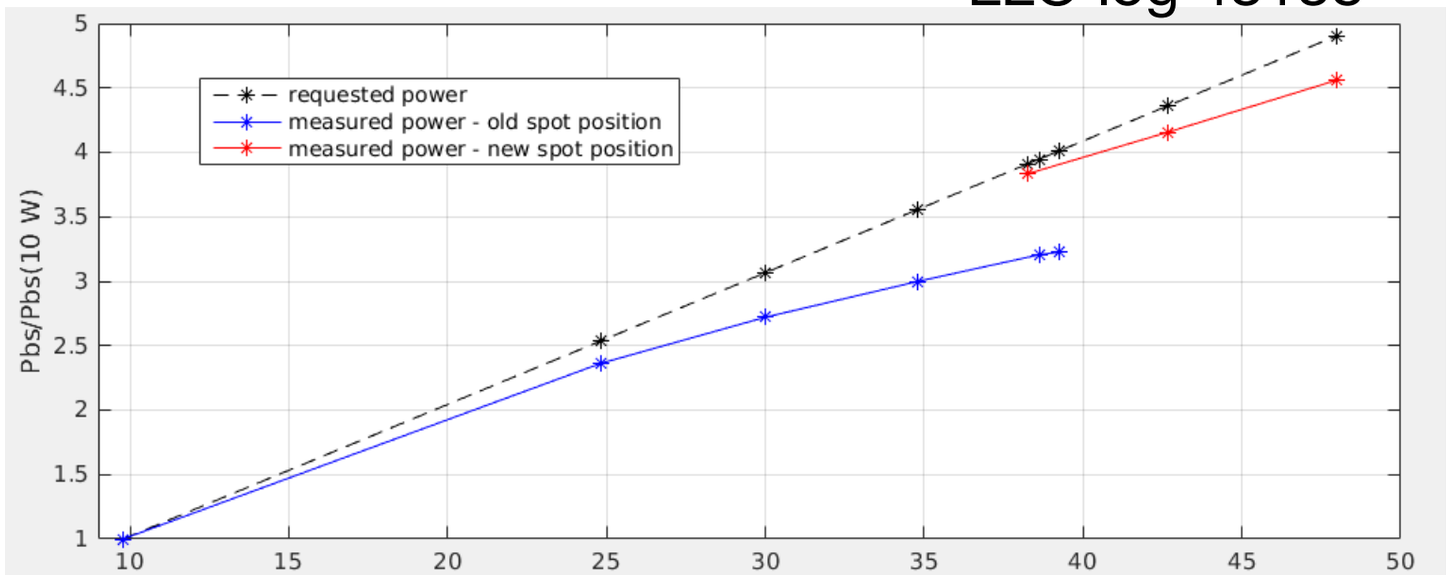


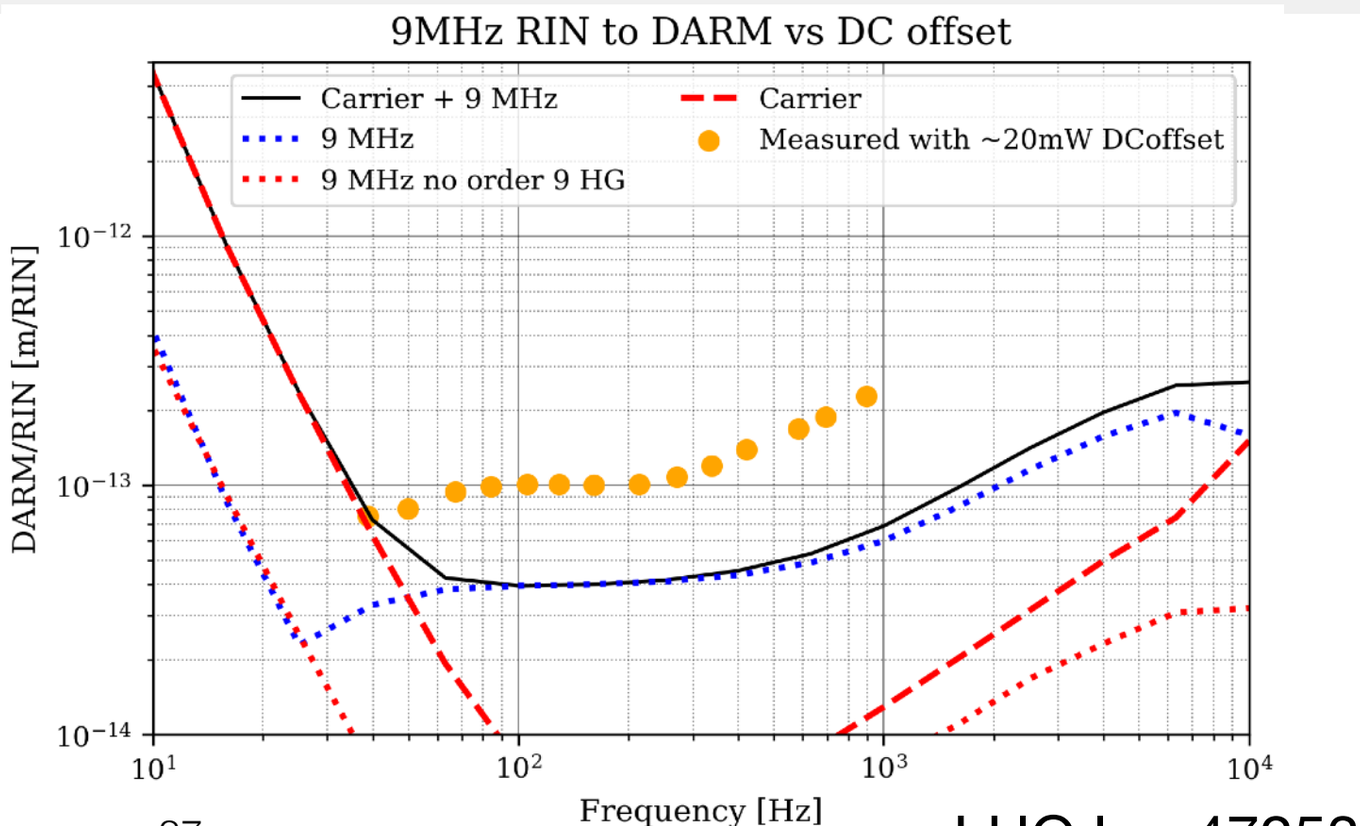
LHO ITMY

Point Absorbers

- Limit power buildup
  - Can’t correct with ring heaters
- Negatively affects angular control signals
- Couples in jitter noise
- May be responsible for increased intensity noise coupling via scatter
- Can’t correct with thermal compensation

LLO log 43138

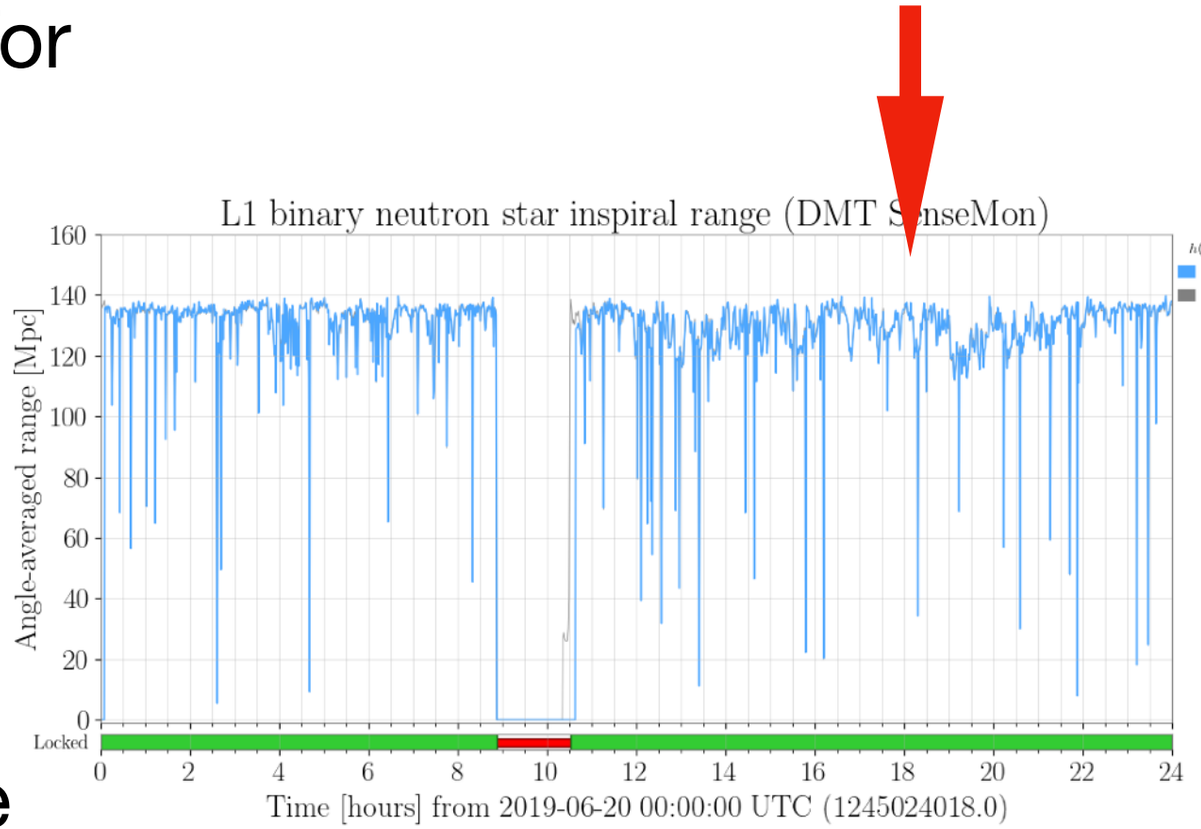




LHO log 47253

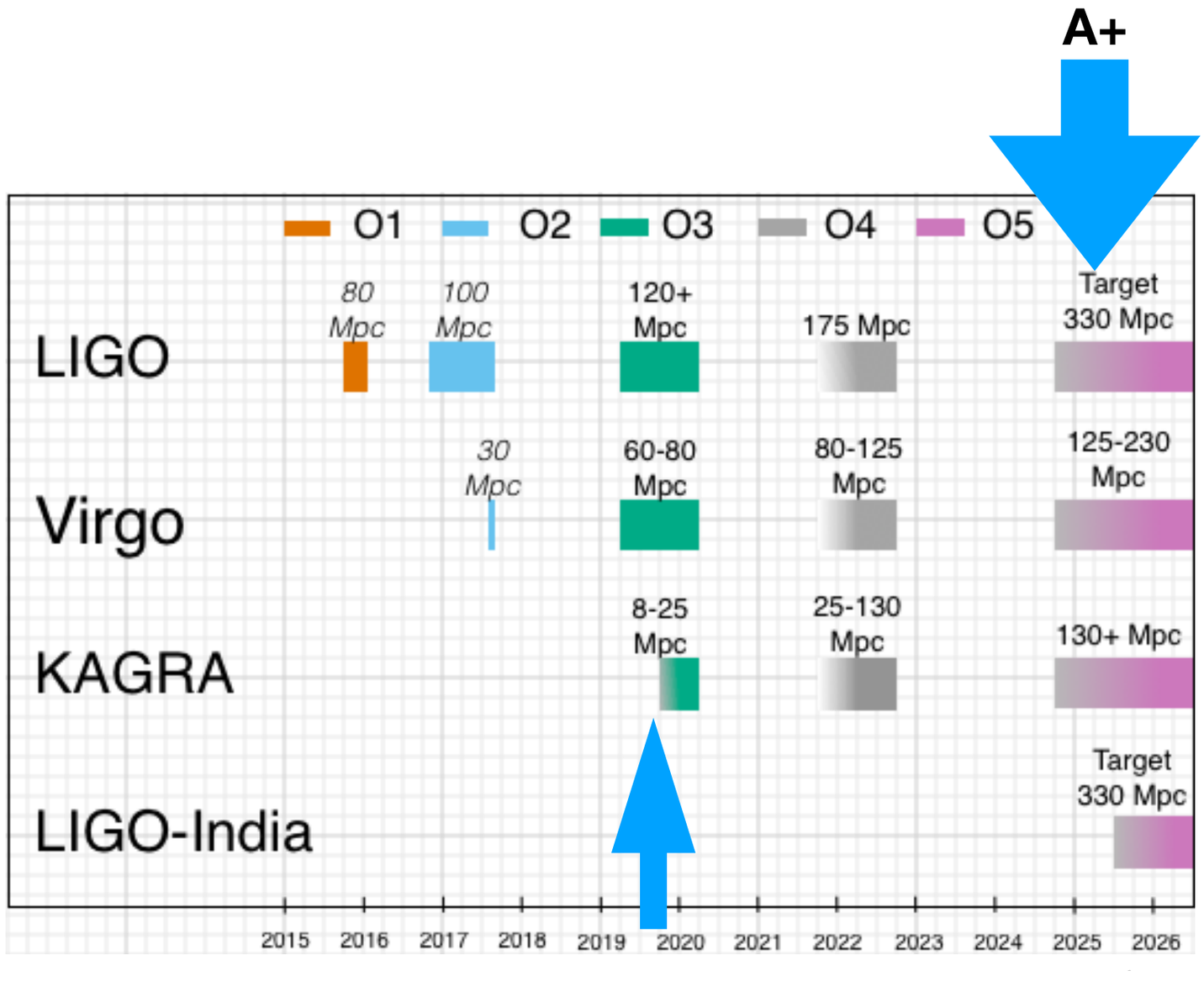
Open Questions

- Point absorbers
  - How can we compensate for them?
  - How can we detect and/or remove these before installation?
- Scattering + anthropogenic noise @ LLO
- Low-frequency mystery noise
- LLO X arm pressure increase



Schedule

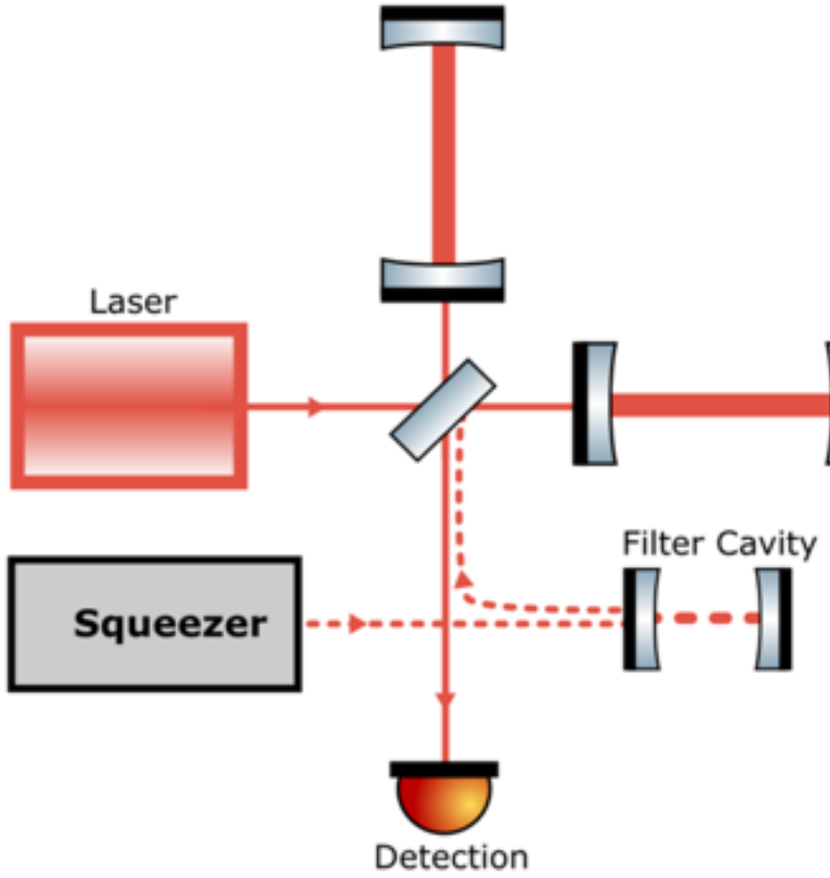
- KAGRA join end of 2019
- One month commissioning break in October 2019
- Run ends ~1 May 2020
- Prep for O4/A+

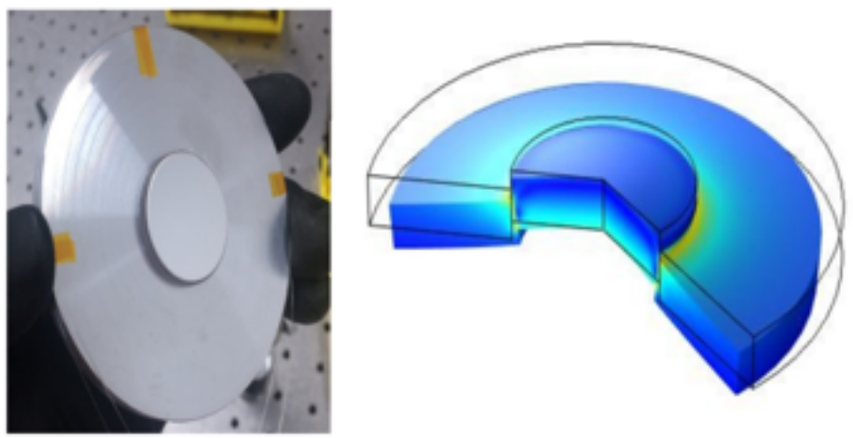


You are HERE P1200087-v50

Next Steps

- More squeezing:
  - Understand excess loss
  - Increase squeezing level (more green power, OPO finesse)
  - Low-loss Faraday isolator
    - ★See D. Tanner poster
  - Adaptive mode-matching to IFO
- Frequency-dependent squeezing
- More scatter mitigation
- Increased power
- Swap test masses?



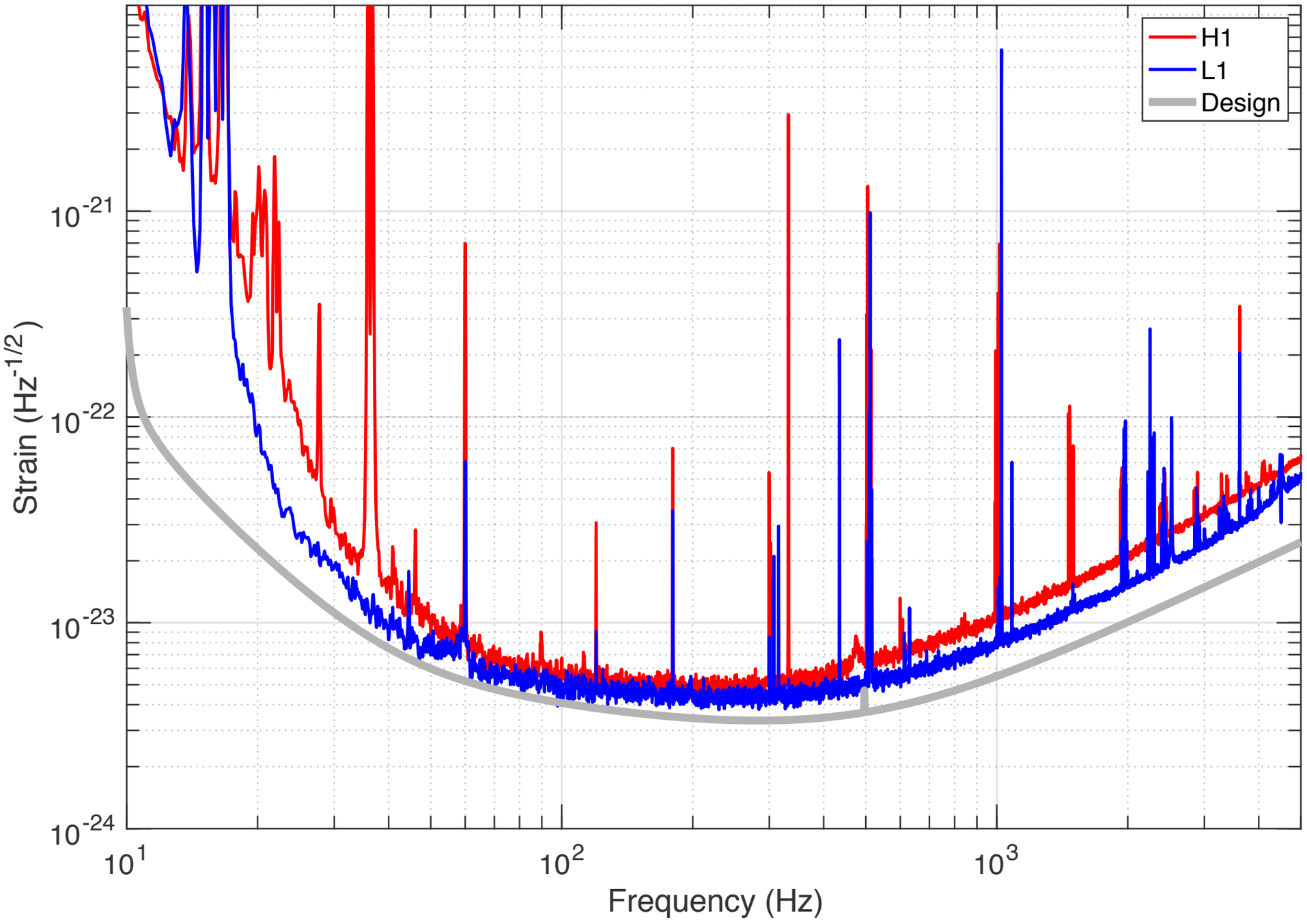


Thermal Deformable Mirror (CIT/Adelaide)

Questions?

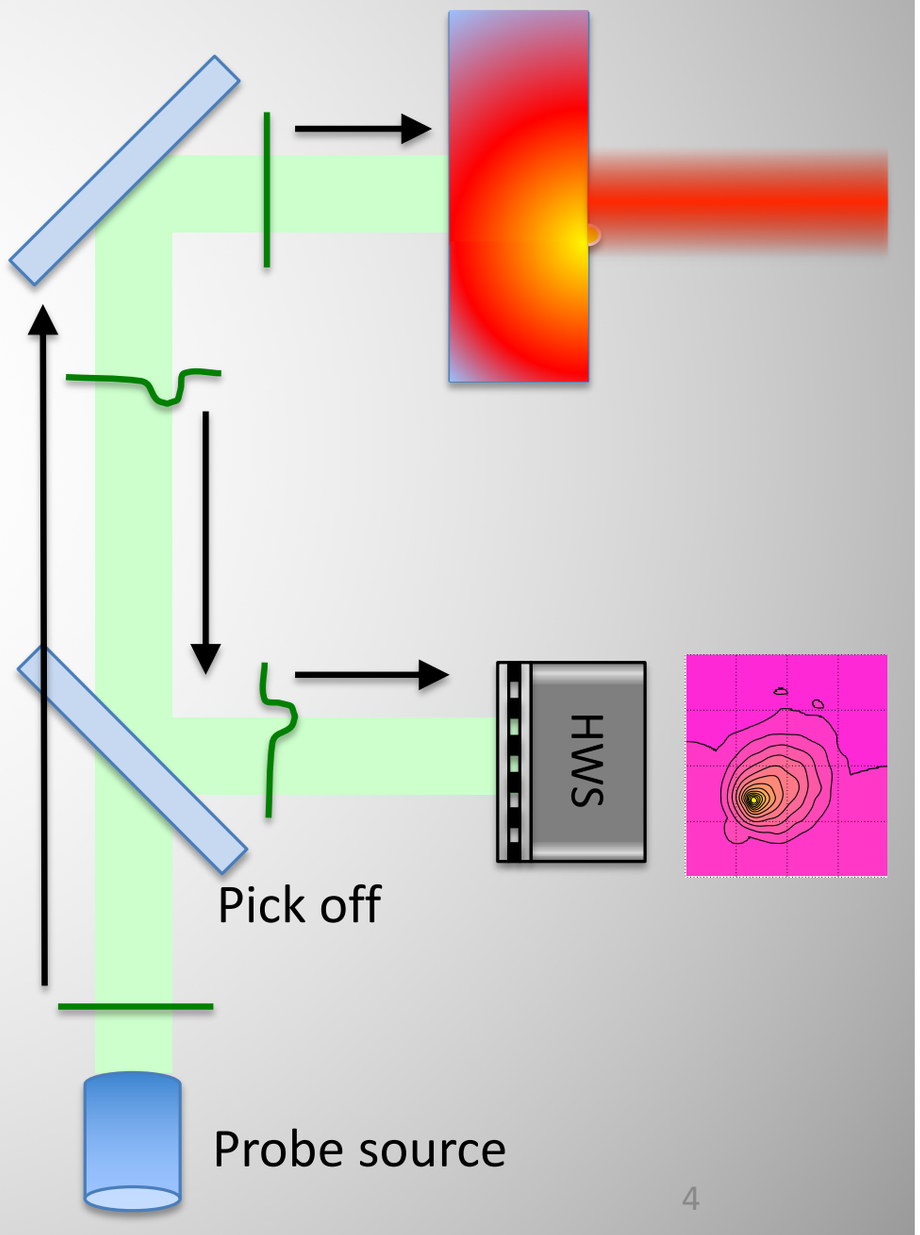
Extras

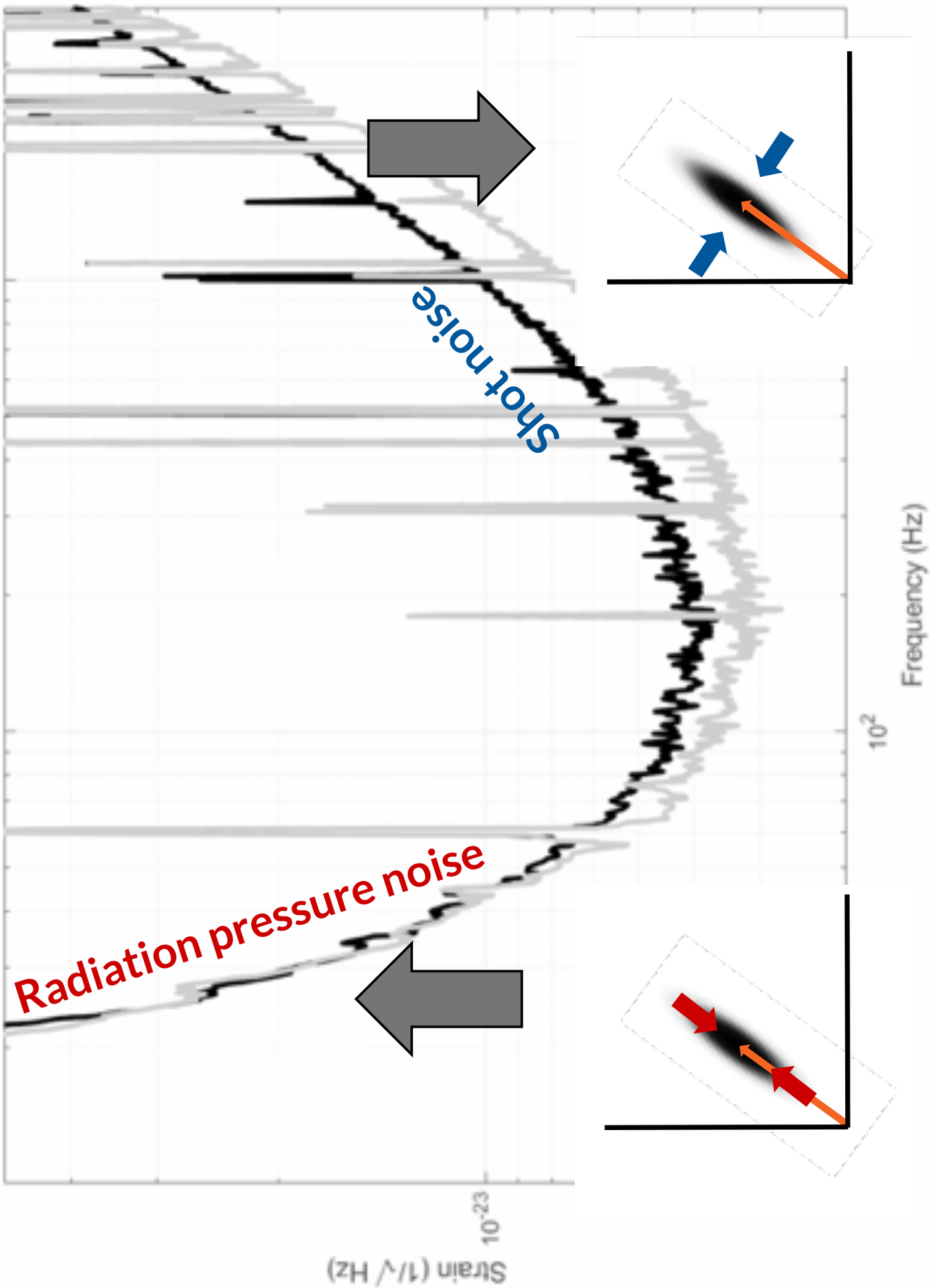
H1/L1 Sensitivity



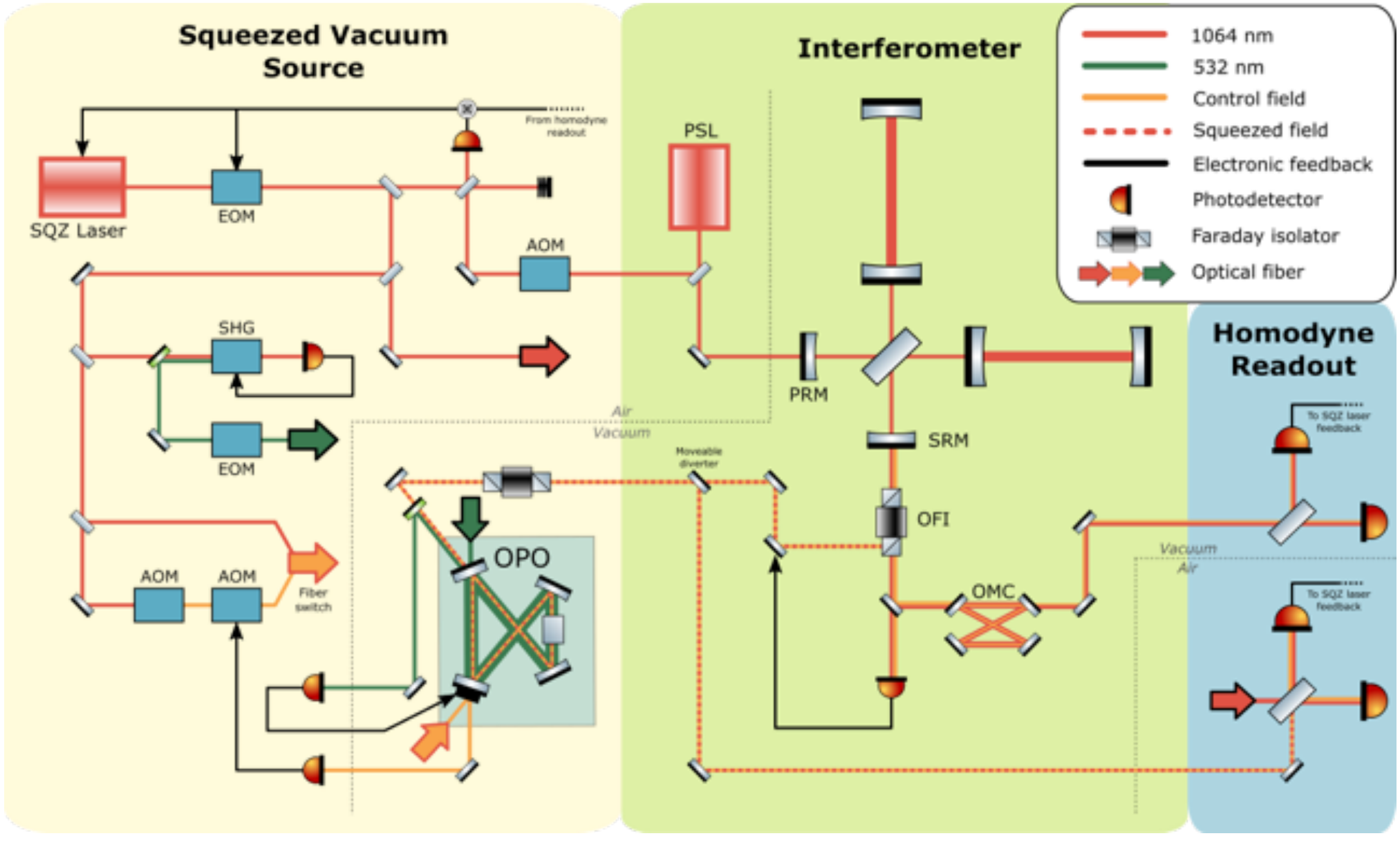
Seen with Hartmann sensors

- Probe beam interrogates test masses
- Measures 2D map of refractive index variation
- Optical Path Distortion:
  - Substrate thermal lens (TL)
  - Surface deformation (SD)
  - TL ≈ 13.5 × SD
  - $OPD_{HWS} = 2\ (TL + n \times SD)$

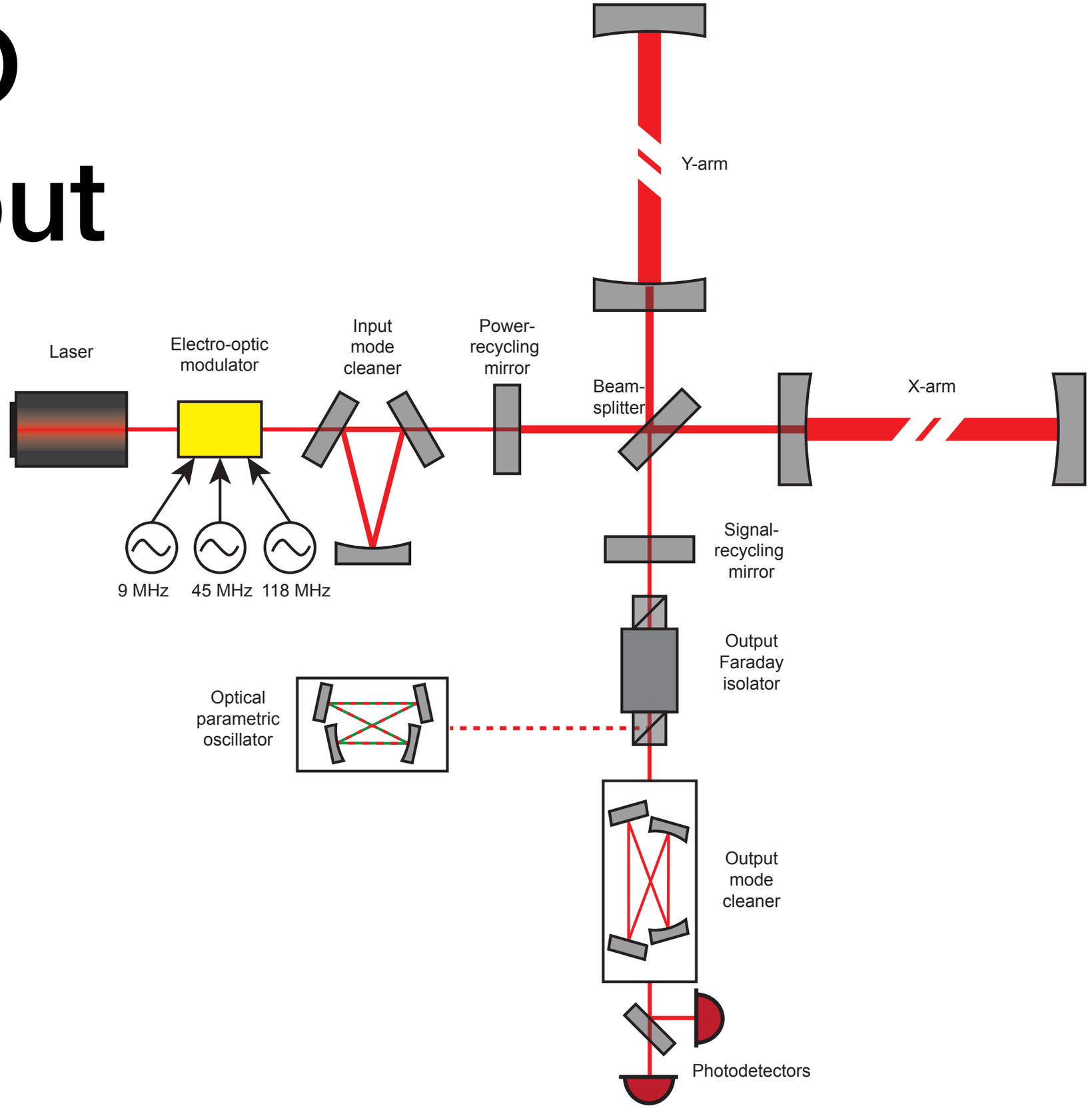



Shot noise
Radiation pressure noise
Strain (1/√ Hz)
10^-23
10^2
Frequency (Hz)

Squeezer Control

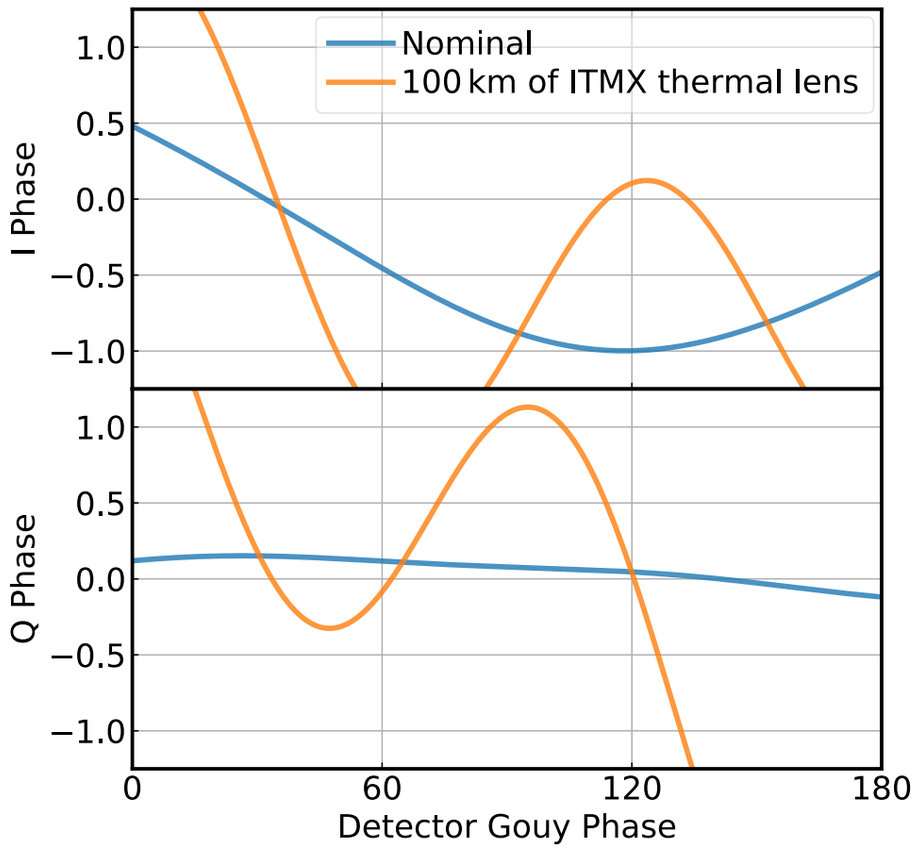


IFO Layout

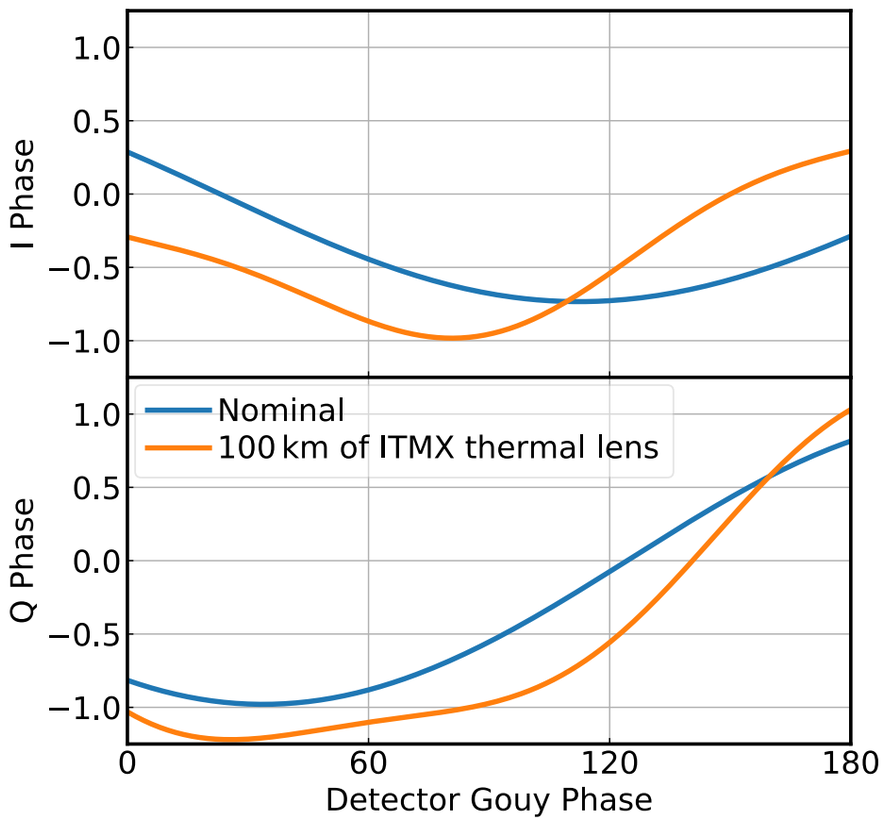

Y-arm
Laser
Electro-optic modulator
Input mode cleaner
Power-recycling mirror
Beam-splitter
X-arm
9 MHz
45 MHz
118 MHz
Signal-recycling mirror
Output Faraday isolator
Optical parametric oscillator
Output mode cleaner
Photodetectors

SRC ASC

Old (36 MHz)

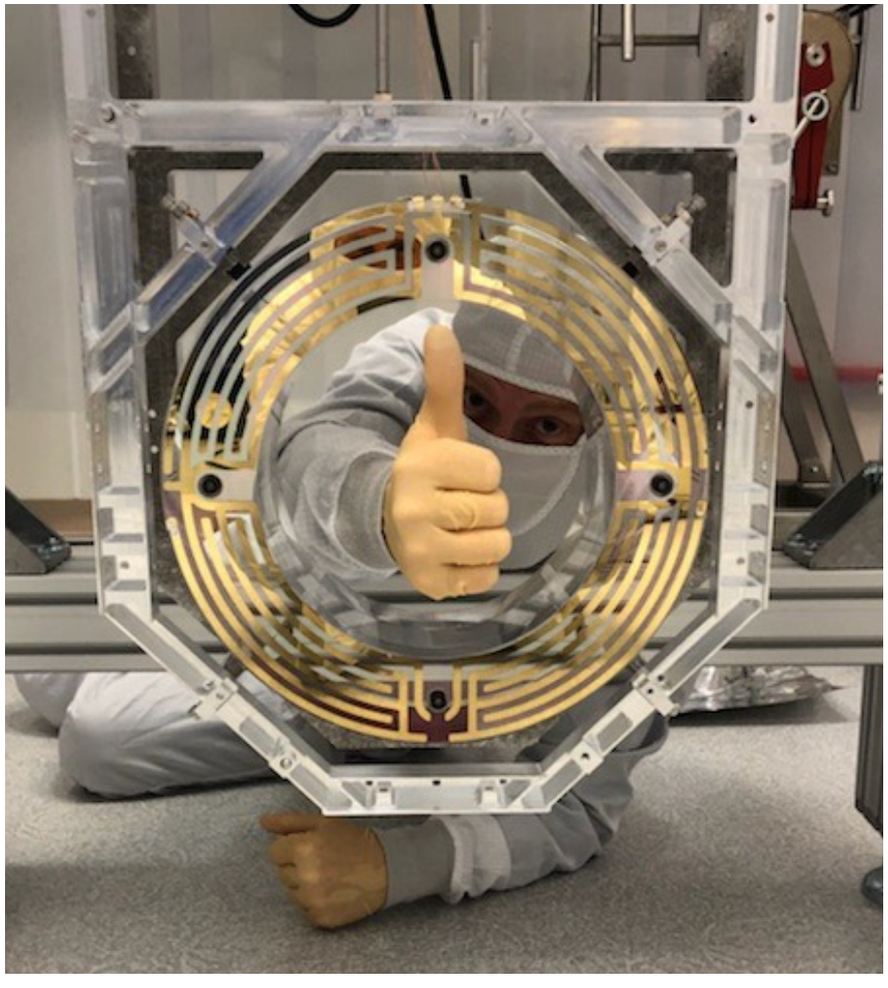


New (118-36 = 72 MHz)

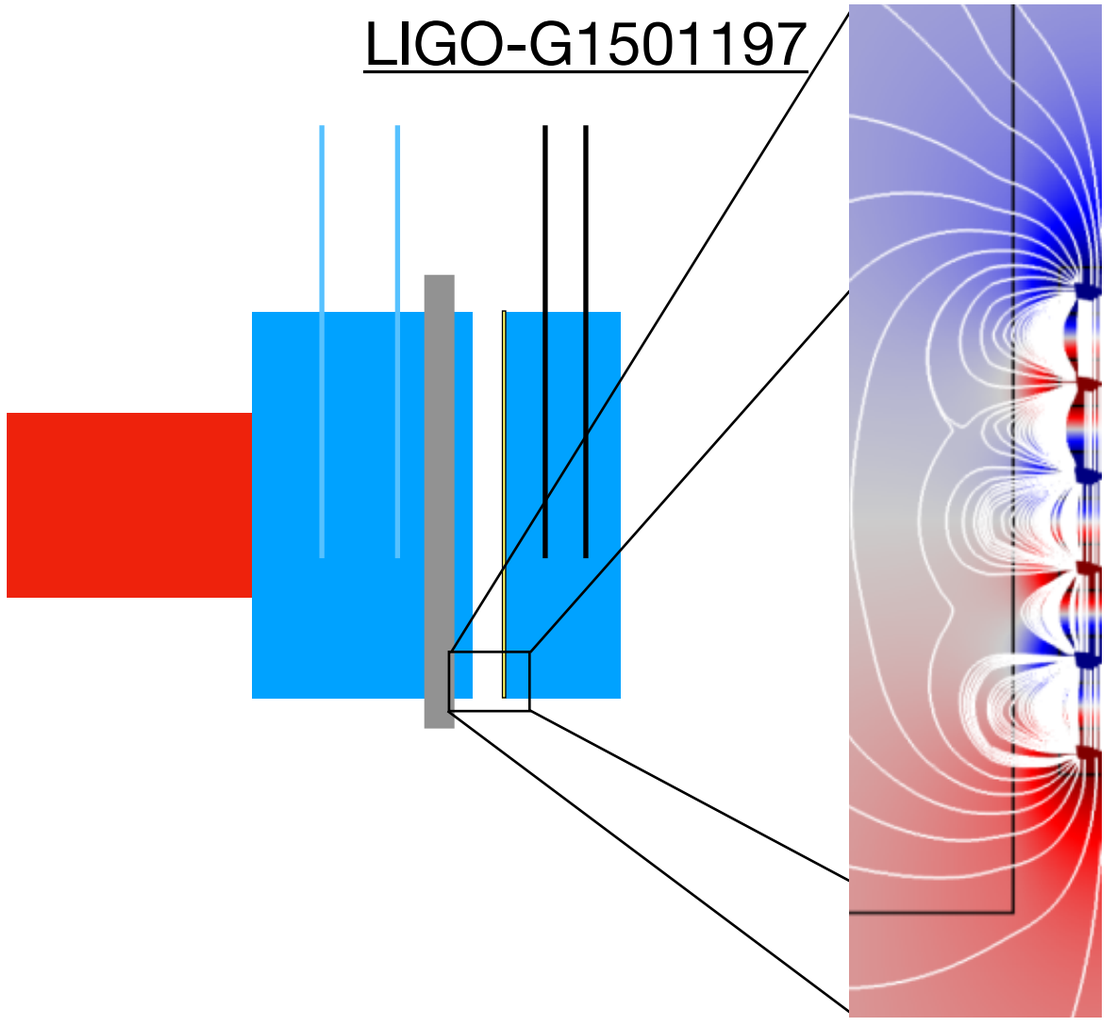


Credit: Hang Yu

Electrostatic Drive (ESD)

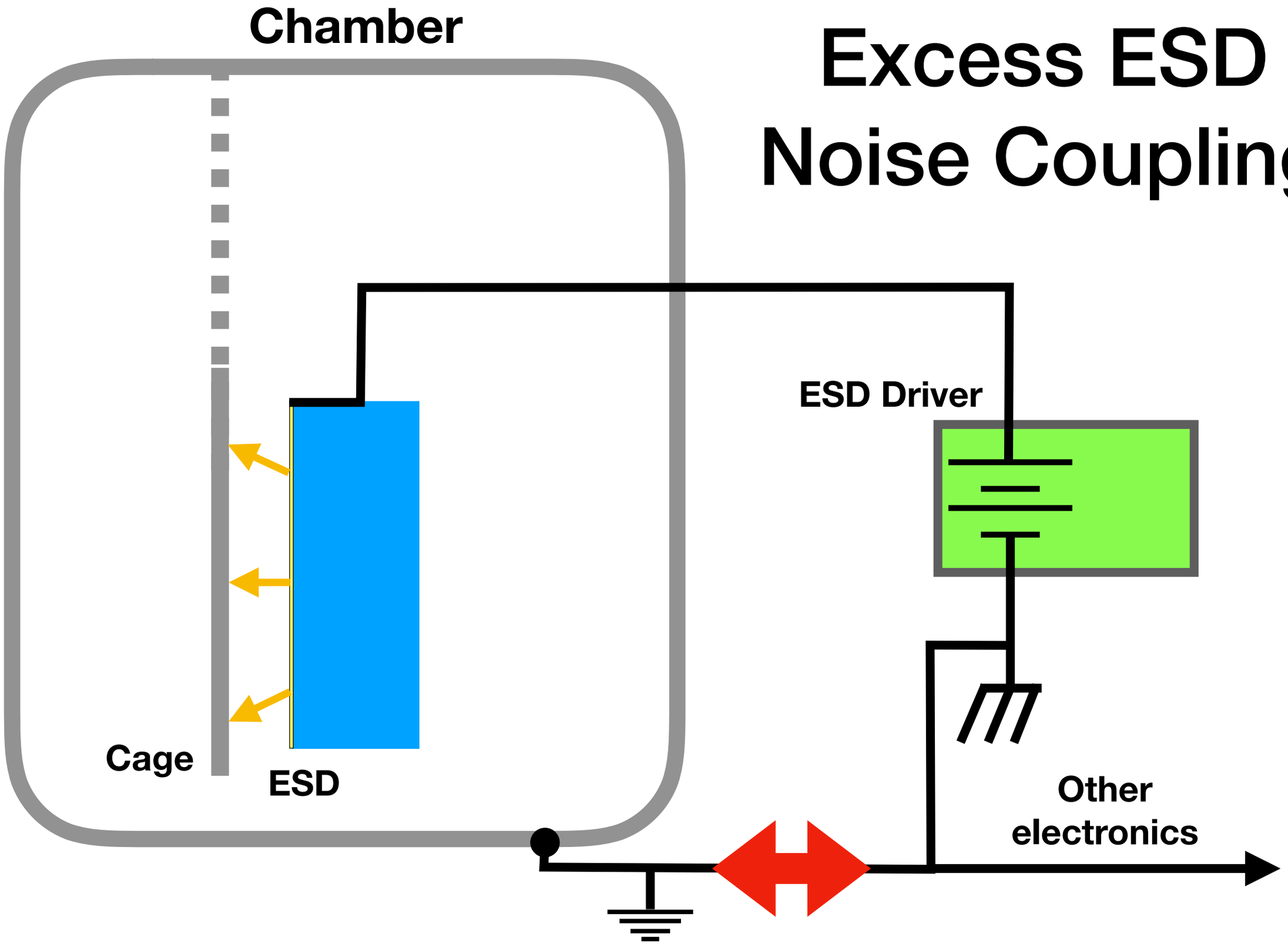


J. Romie



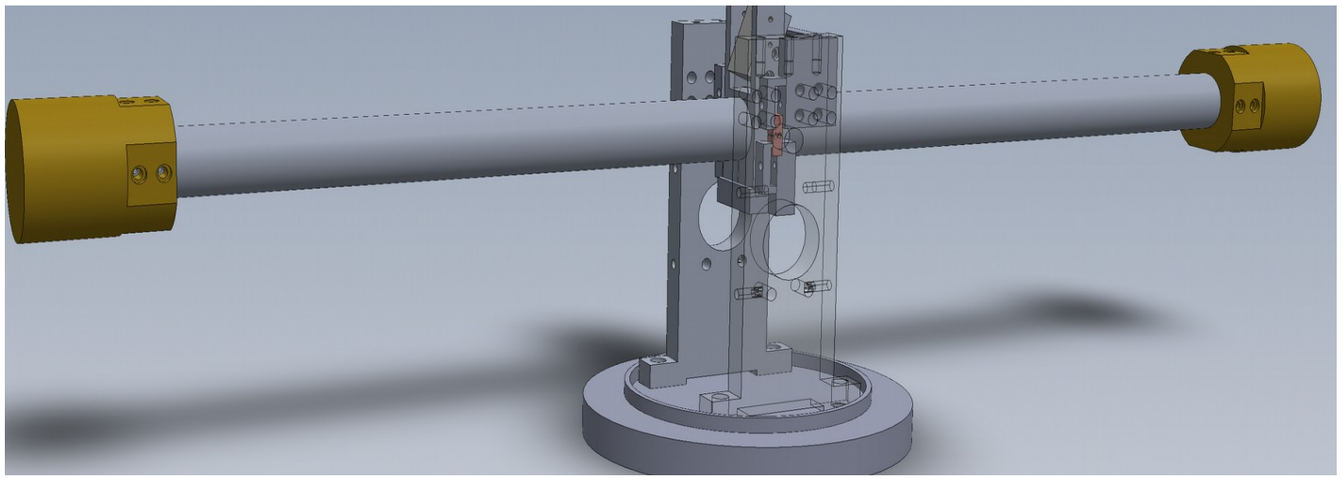
$$F = A(V_{bias} - \delta V_{sig})^2$$
$$= A(V_{bias}^2 + \delta V_{sig}^2 - 2V_{bias}\delta V_{sig})$$

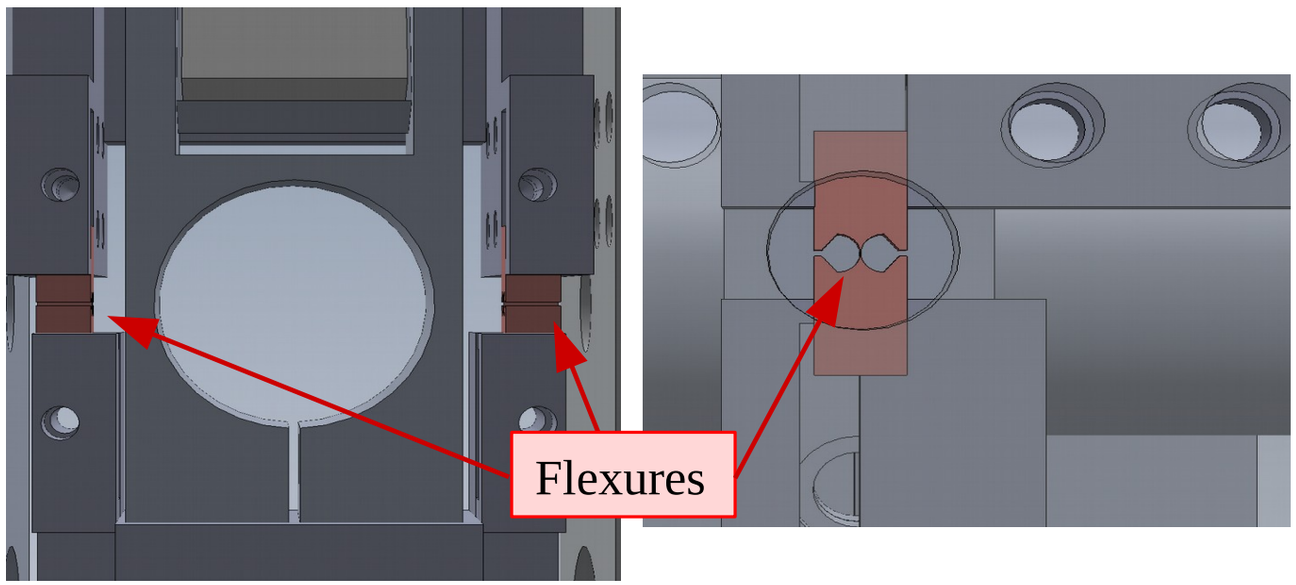
Excess ESD Noise Coupling



Beam Rotation Sensor

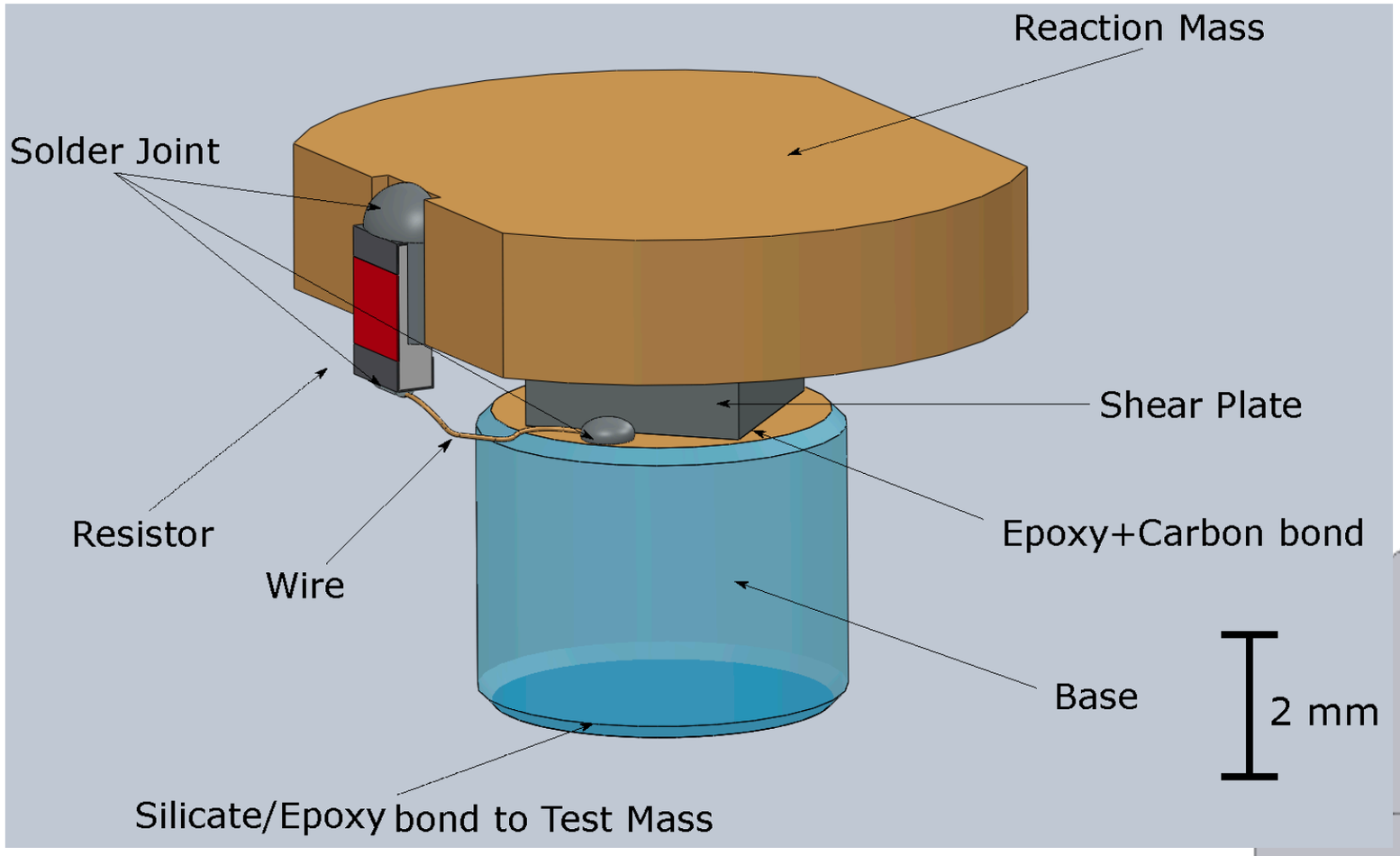
- Same concept as a seismometer but with rotations
- 1-m long beam hung from 10-15 µm-thick flexures with 3-8 mHz resonance
- Angle between casing and beam readout by autocollimator

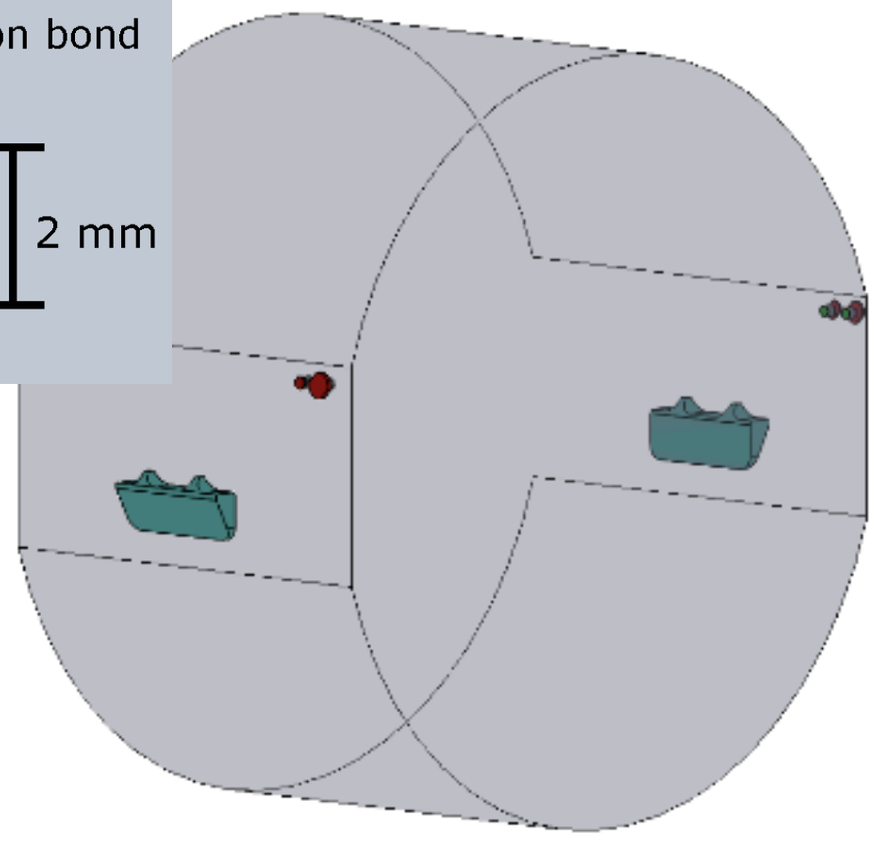




G1901195

AMD Details





G1800454