

Noise Couplings in LIGO

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IUCAA Detector
Characterization Workshop
Dec 2025
Pune, India

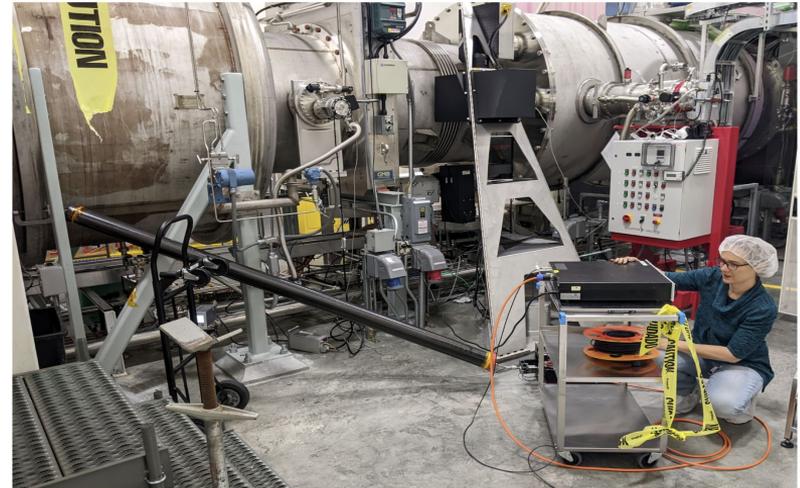
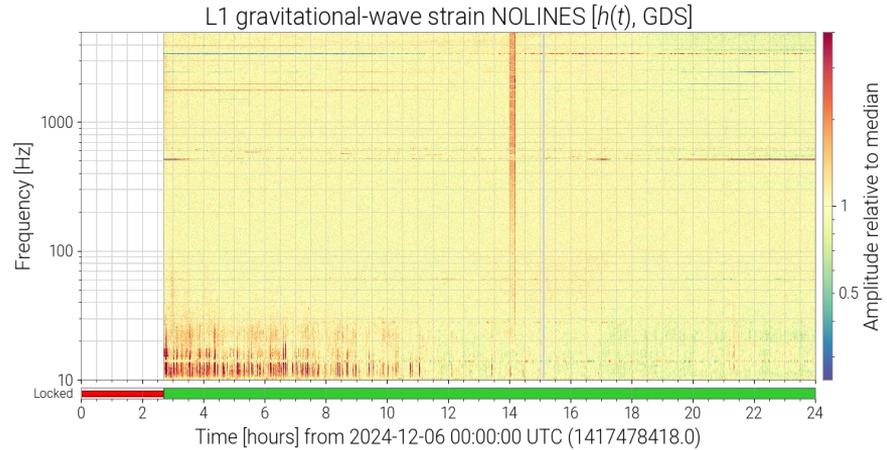
Overview

- Introduction
- Transient Noise
- Scattered Light Noise
- Slow Scattering reduction in LIGO O3
- Fast Scattering reduction in LIGO O3
- Slow Scatter in LIGO O4
- Summary

Detector Characterization

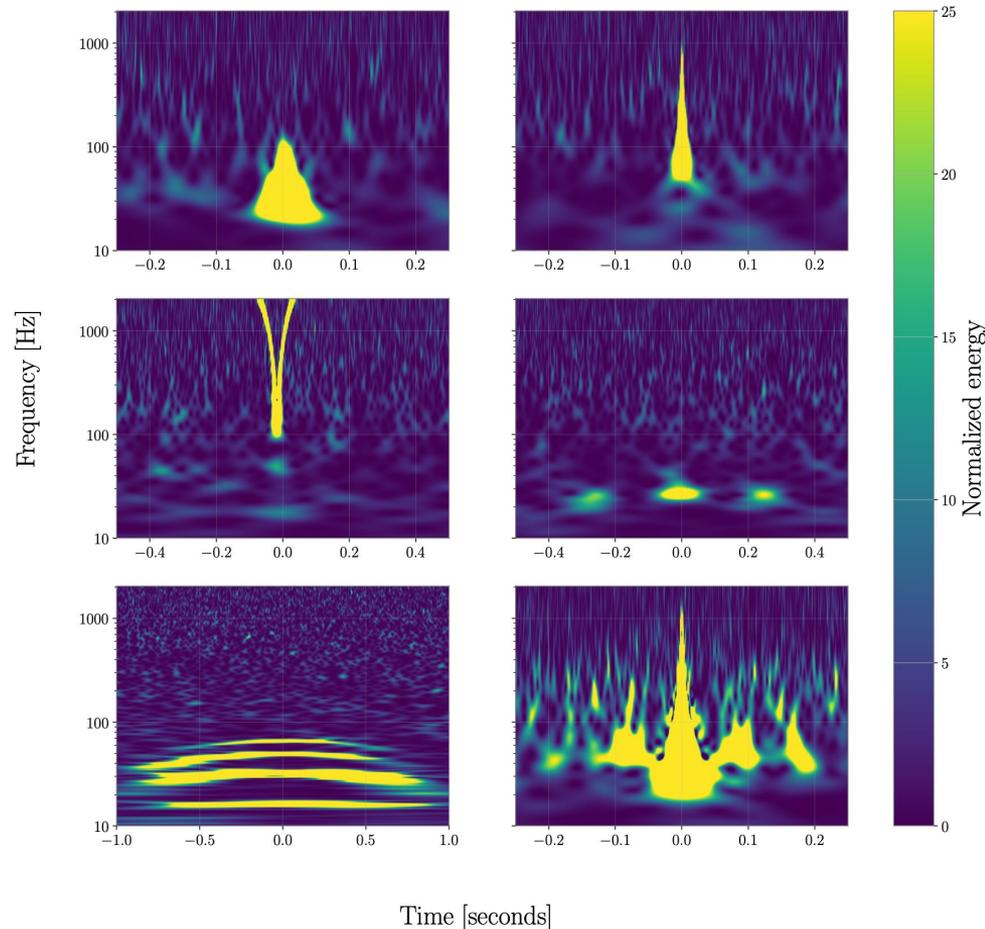
- Monitor the status of detector : Instrumental and data quality investigations
- Hardware Injections: To check the safety of auxiliary channels
- Physical Environment Monitoring: injection tests and noise coupling calculations
- Event Validation: Check data quality around the events (Francesco, Dishari)
- Summary pages: maintenance and development (Evan)
- Detchar Tools: maintenance and development (Joe A)

LIGO detector characterization in the first half of fourth Observing run. S Soni et al 2025 *Class. Quantum Grav.* **42** 085016



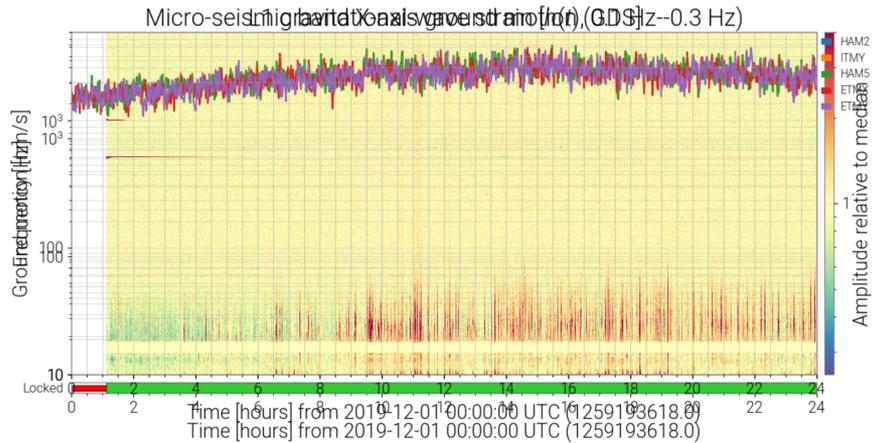
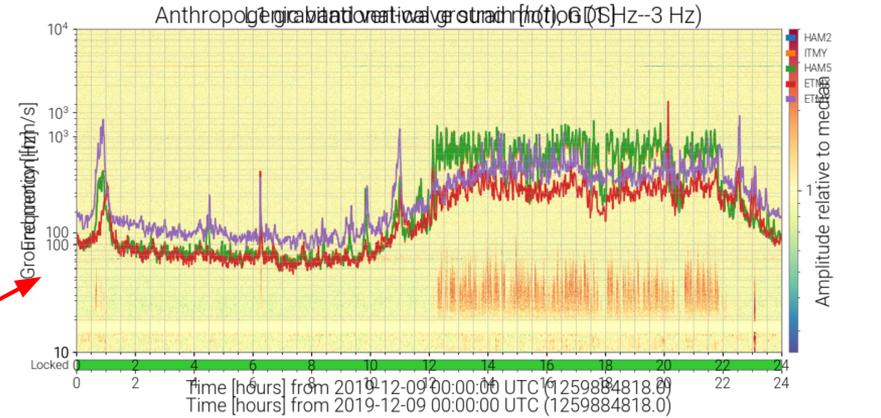
Transient noise

- Short duration excess power
- Environmental or instrumental coupling
- Mess up with the real events, parameter estimation, create false alerts
- Originate in detector hardware
- Investigate using detchar tools, injections, on/off tests etc



Transient noise in O3

- Scattered light due to ground motion was the most common source of noise in O3 at LLO and LHO
- Fast Scatter due to anthropogenic ground motion
- Slow Scatter due to microseismic motion

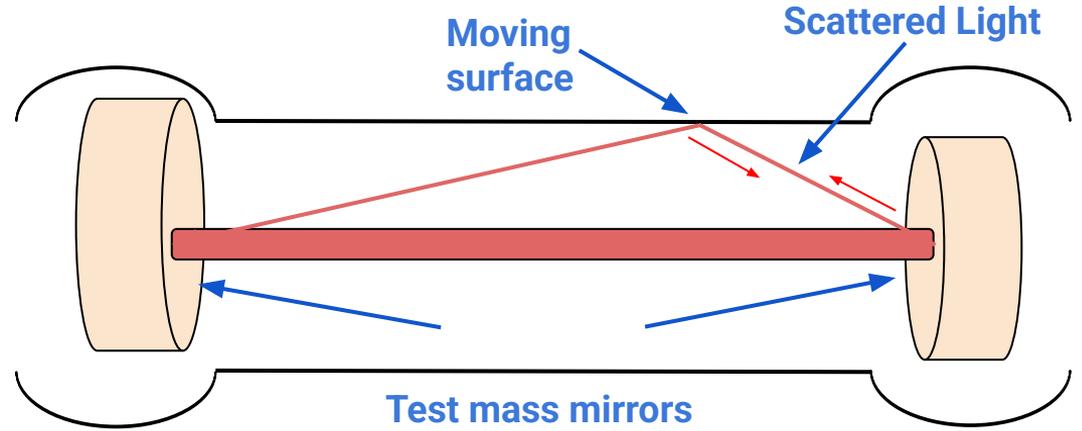


Stray light noise

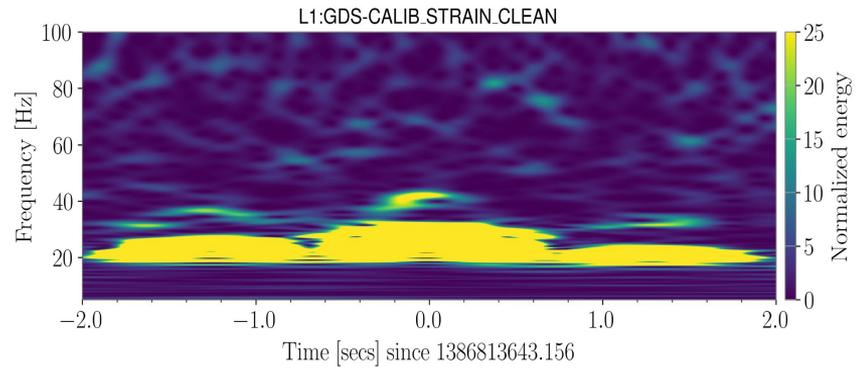
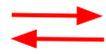
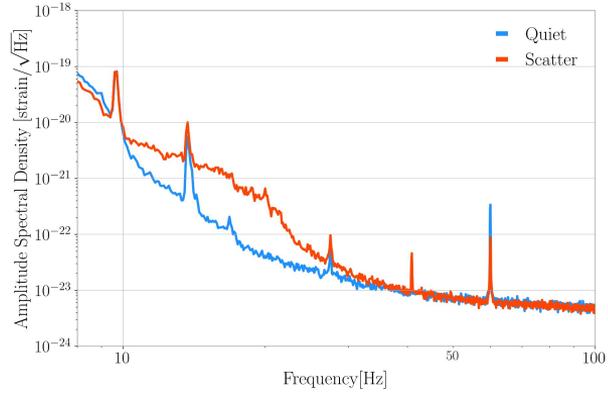
Stray light Motion

$$h_{sc} = A \frac{\lambda}{8\pi L} \sin(\delta\phi_{sc}(t))$$

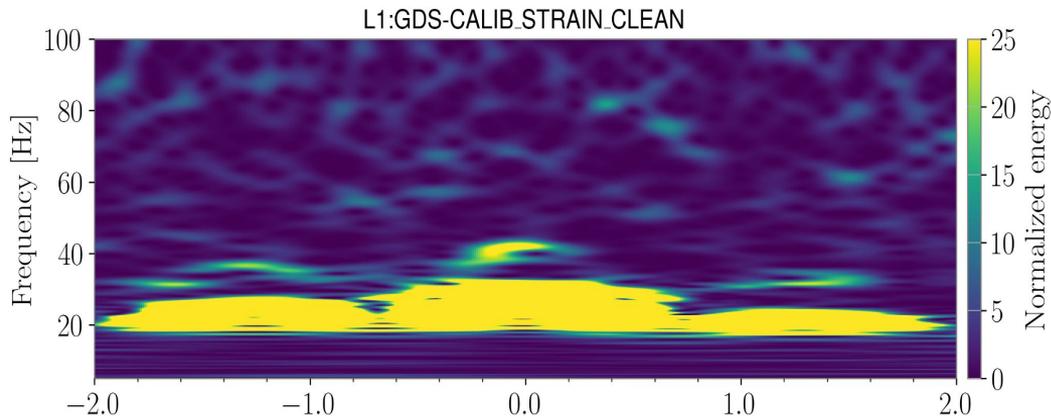
$$\delta\phi_{sc}(t) = \frac{4\pi}{\lambda} x_{sc}(t)$$



If motion ~ wavelength, we get upconversion



Stray light noise mitigation



Stray light amplitude

Motion

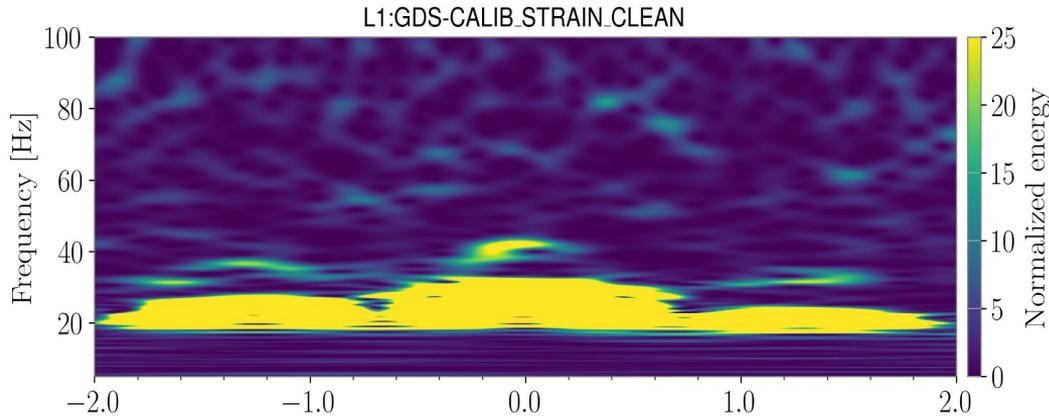
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$$\delta\phi_{sc}(t) = \frac{4\pi}{\lambda} x_{sc}(t)$$

$$f_{fringe} = \left| \frac{2v_{scatter}}{\lambda} \right|$$

- What environmental conditions led to this noise?
- Which moving optic or optics is injecting the noise?
- At what frequency and how much is this optic moving?
- How much stray light this optic needs to create this noise?

Stray light noise mitigation



Stray light amplitude

Motion

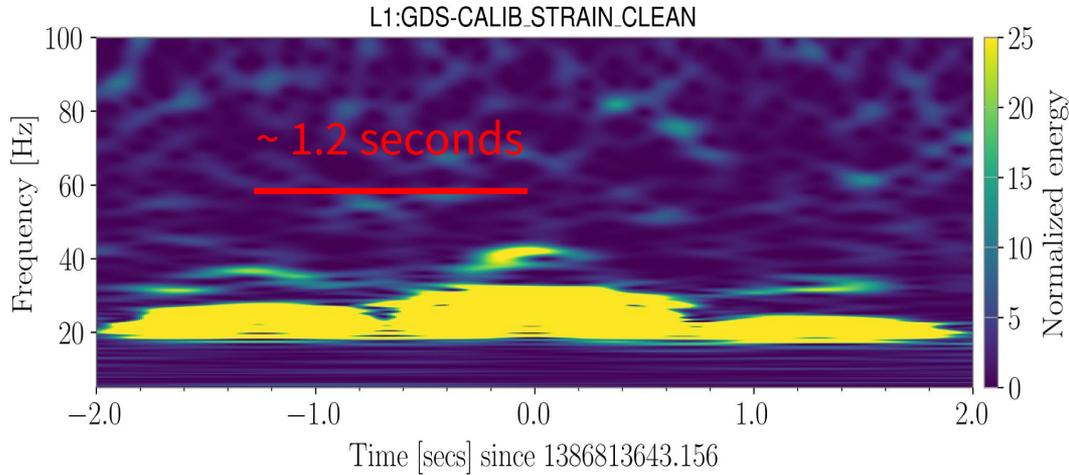
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Motion of the scattering surface



Separation between the consecutive arches, tells us the frequency with which the scattering surface is moving.

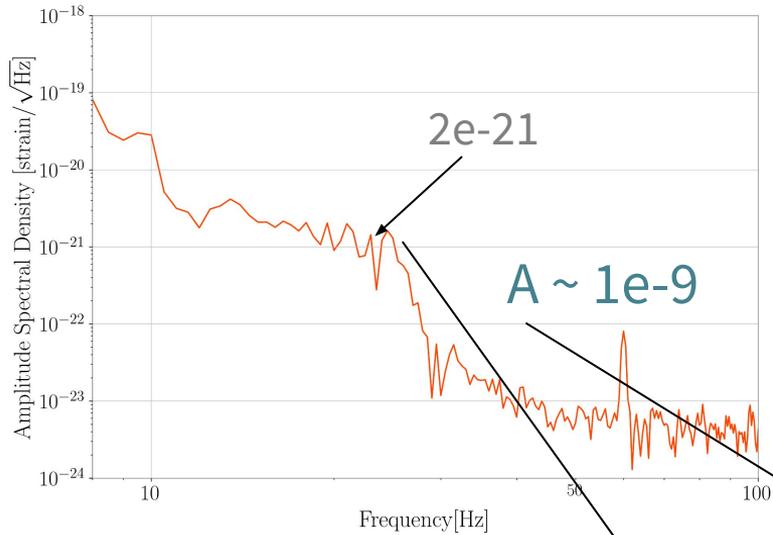
Peak to peak separation: 1.2 secs
Frequency: $1/(2.4) \sim 0.42$ Hz

↓
Frequency of scattering surface

So now we can ask, what surface could be moving or have a resonance around this frequency.

Spectrograms tell us the motion of the scattering surface.

Light amplitude on the optic



How much stray light is required to create the noise?

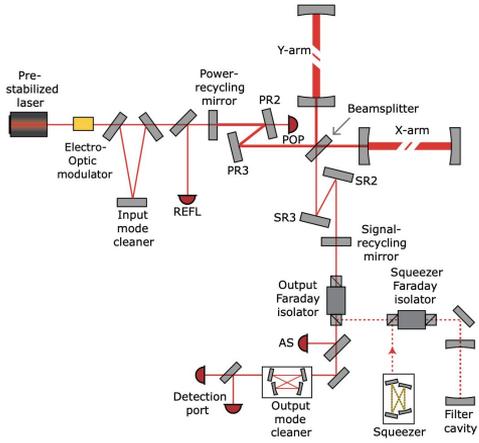
Where can we get this much stray light?

If we know the motion, we can find **A**

$$h_{ph}(f) = A \frac{\lambda}{8\pi L} \mathcal{F} [\sin \delta\phi(t)]$$

Noise spectrum tells us the light on the scattering surface.

Once we know motion and light amp, narrows down the list of suspects



Multiple Sources of Noise

Noise studies:
Detchar Group

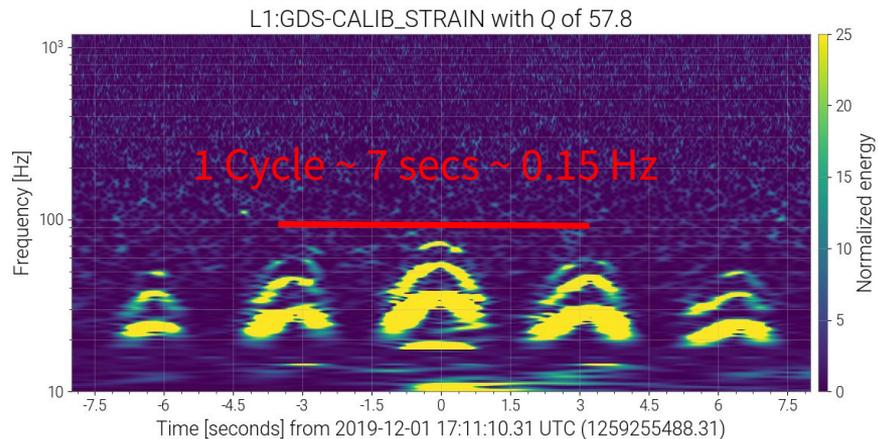
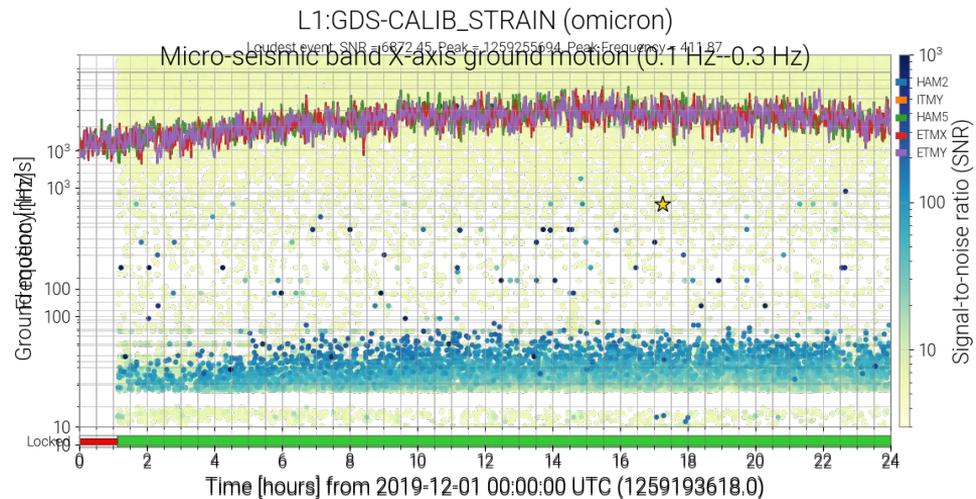
Stray light:
Motion and
light
amplitude

Transient noise:
short duration
bursts of power

Slow Scatter mitigation in O3

Slow Scatter in O3

- How bad: Slow Scatter was the most frequent source of transient noise in O3
- Slow Scatter: 23% and 47% of all transient noise at LLO and LHO respectively
- Conditions: Microseismic motion (0.1-0.3 Hz) + Earthquakes (0.03-0.1 Hz)
- Frequency of scatterer: ~ 0.15 Hz
- Gravitational wave band impacted: 10 - 120 Hz, multiple harmonics



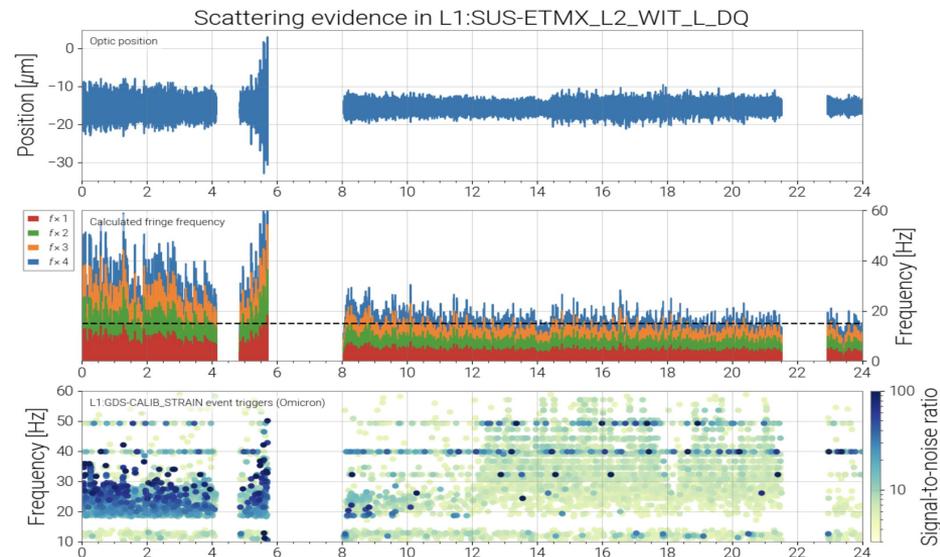
Where's the source?

- OSEMs (Optical Sensor and Electromagnetic Actuators) are present throughout the detector
- They measure relative distance fluctuations between optics

$$f_{fringe} = \left| \frac{2v_{scatter}}{\lambda} \right|$$

Differential Arm Cavity (DARM) **control drive** to keep detector on resonance

L2 Stage OSEM record distance changes between Reaction chain and Main chain

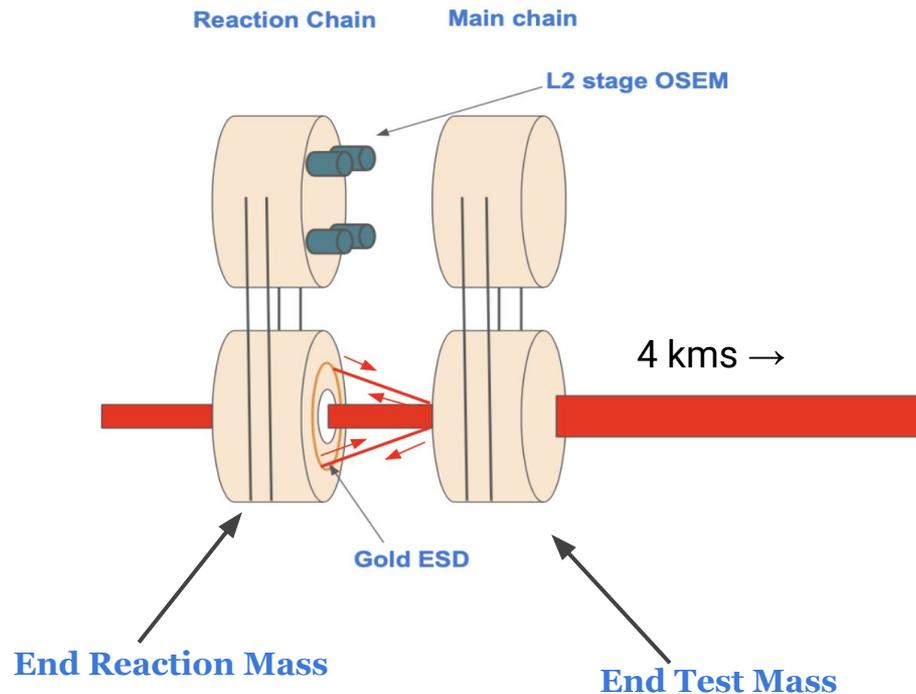


Where's the source?

- OSEMs (Optical Sensor and Electromagnetic Actuators) are present throughout the detector
- They measure relative distance fluctuations between optics
- Noise correlated with increased motion sensed by penultimate mirror OSEM

Differential Arm Cavity (DARM) **control drive** to keep detector on resonance

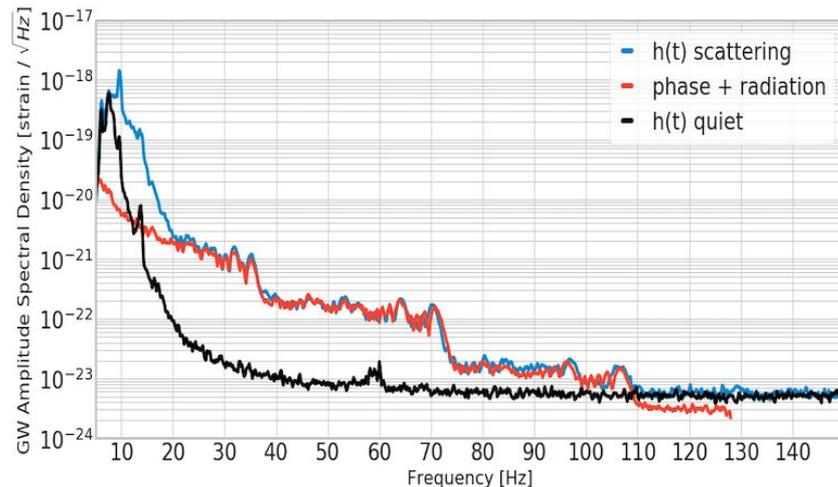
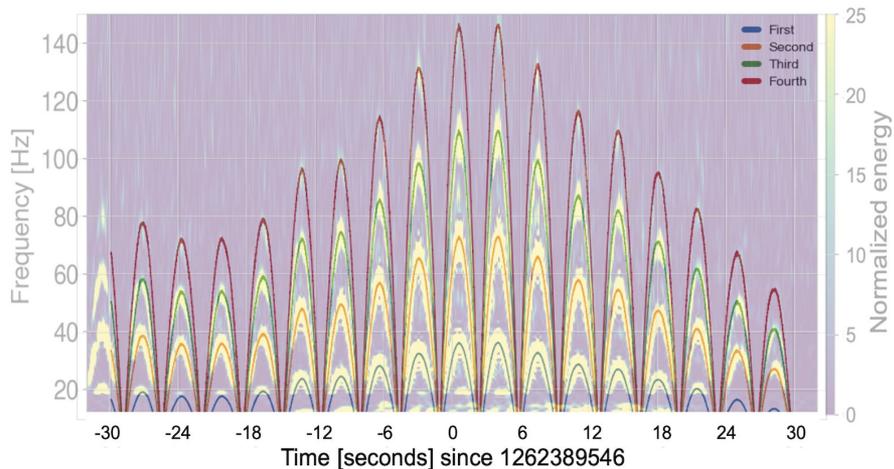
L2 Stage OSEM record distance changes between Reaction chain and Main chain



A fraction of light hits the Gold Electrostatic Drive, reflects back and joins the main beam after ETM transmission

Scattering arches in GW $h(t)$ channel

L2 Stage OSEM and Scattering



$$h_{ph}(f) = A \frac{\lambda}{8\pi L} \mathcal{F} [\sin \delta\phi(t)]$$

- Once you know the motion, you can model the noise and find the light amplitude needed to create noise
- In O3, the stray light amplitude is about $1e-9$

Reduction in Slow Scatter after Reaction Chain tracking

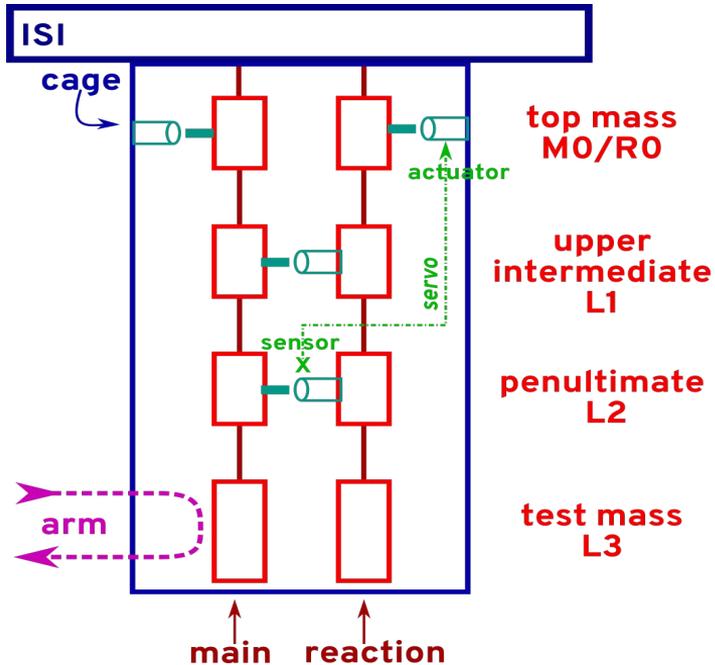


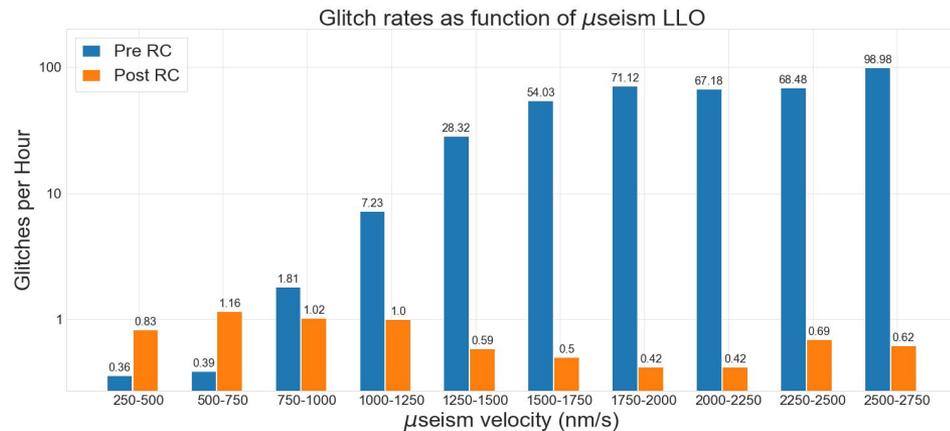
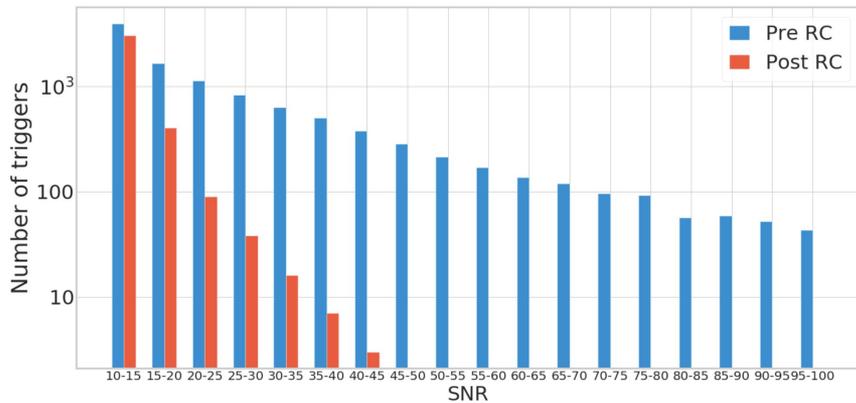
Figure credit: Anamaria Effler

- Source of noise: motion between the reaction chain and the main chain
- This motion was rerouted from L2 stage to R0 stage
- Reducing velocity reduces the frequency at which noise appears and at low frequencies, this stray light noise is masked by the seismic noise.

Reducing scattered light in LIGO's third observing run (*Soni et al 2021 Class. Quantum Grav.* 38 025016)

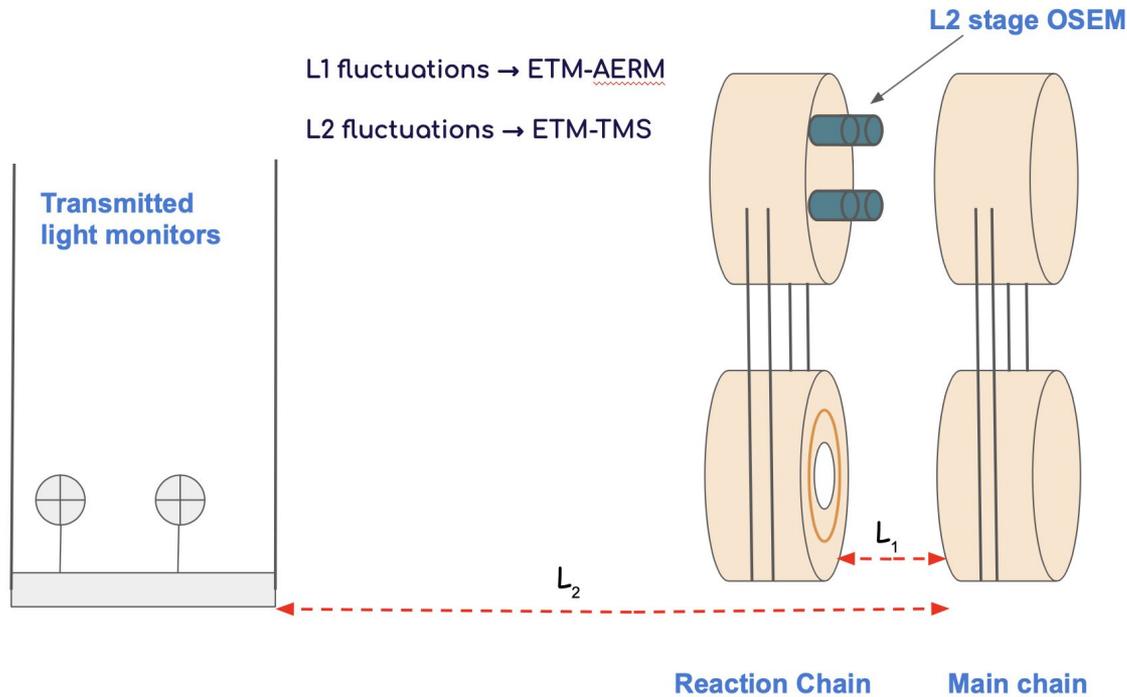
Reduction in Slow Scatter after Reaction Chain tracking

- Reduction in the rate of slow scattering by a factor of ~ 100 for similar levels of ground motion
- No more high SNR slow scatter in the data
- Avg fraction of false alerts in O3b reduced from 0.55 to 0.21



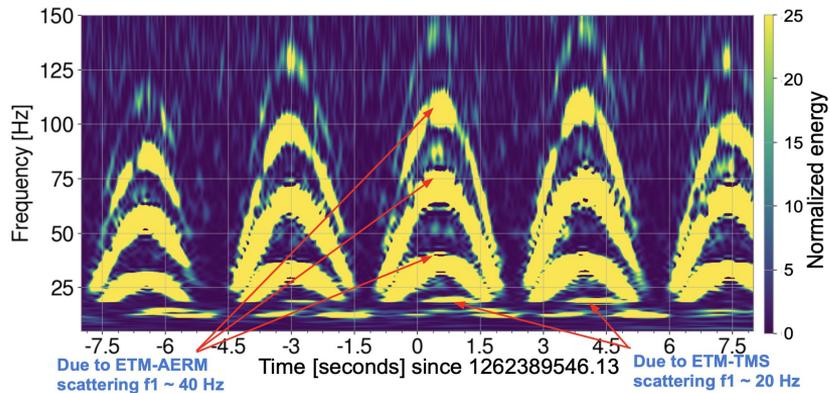
Reducing scattered light in LIGO's third observing run (*Soni et al 2021 Class. Quantum Grav.* 38 025016)

End Test Mass-Transmission Motor System Scattering

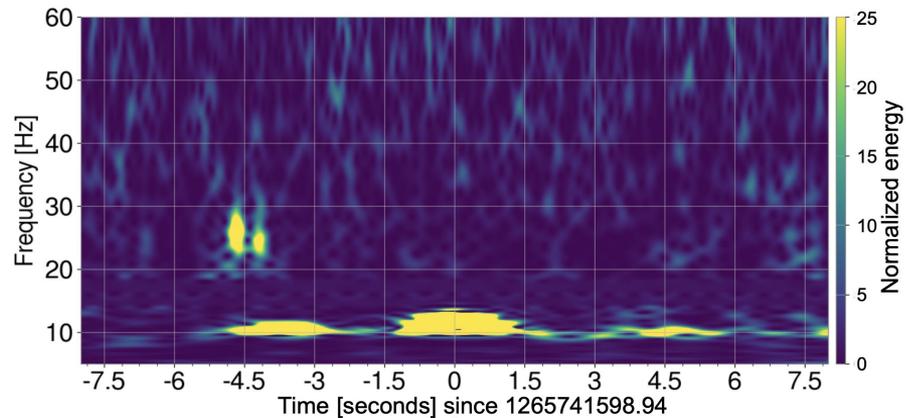


- A small fraction of light is received by the Photodiodes located behind the End test mass mirrors.
- Some of that light gets reflected back to the test mass mirror and joins the main beam
- The noise depends on the relative motion between the test mass and the TMS.
- The noise shows up as arches in $h(t)$ as well as the transmon channels

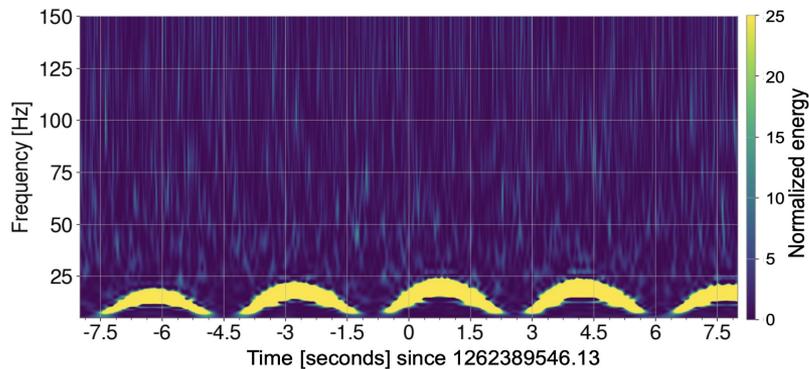
$$v_2 = \frac{v_1}{2} \quad f_2 = \frac{f_1}{2} \quad f_{max} = \frac{2nv}{\lambda}$$



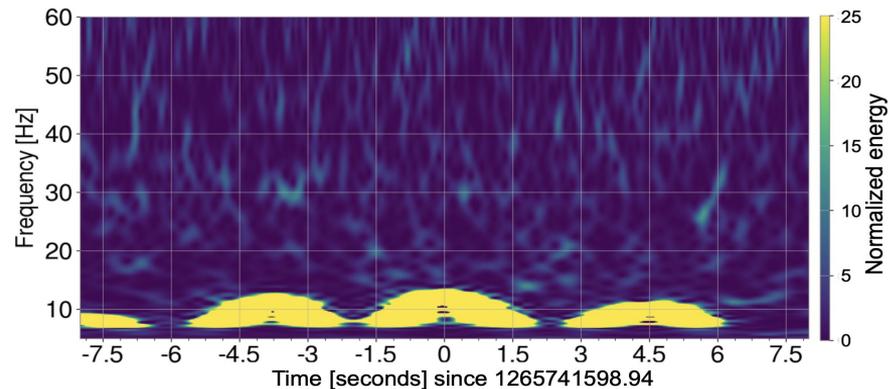
Pre RC $h(t)$



Post RC $h(t)$



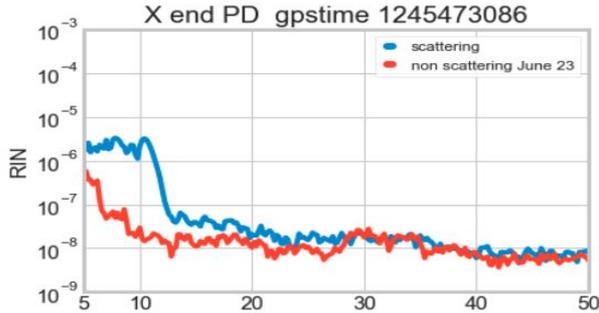
Pre RC Transmon PD



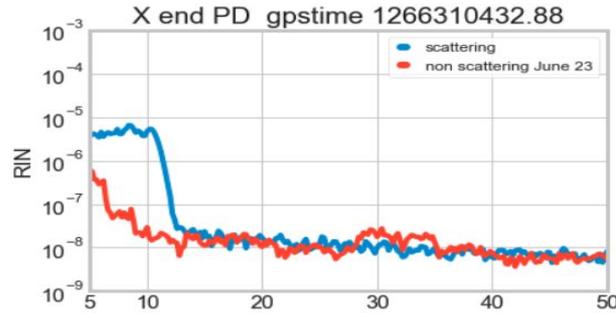
Post RC Transmon PD

Pre RC and Post RC tracking Comparison

Pre RC tracking

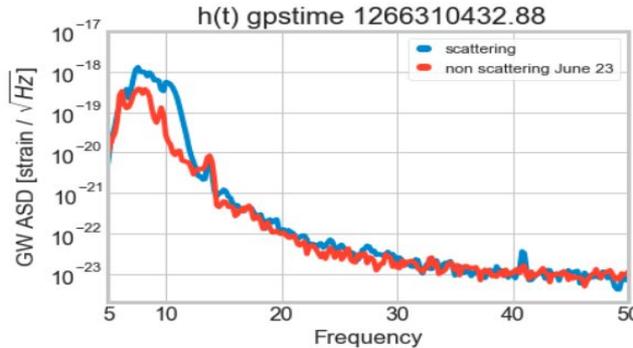
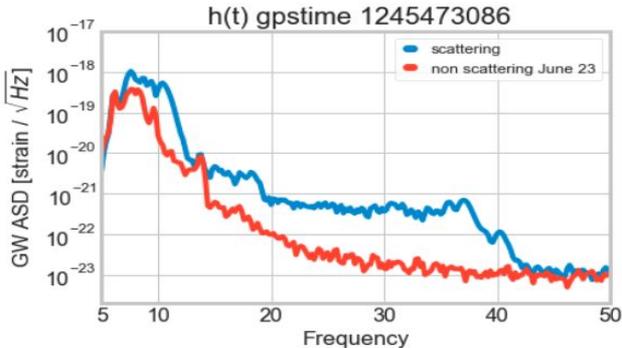


Post RC tracking



Pre RC tracking
Shelf at f Hz in TMS \rightarrow
Shelf at $f, 2f, 4f$ Hz and so
on in $h(t)$

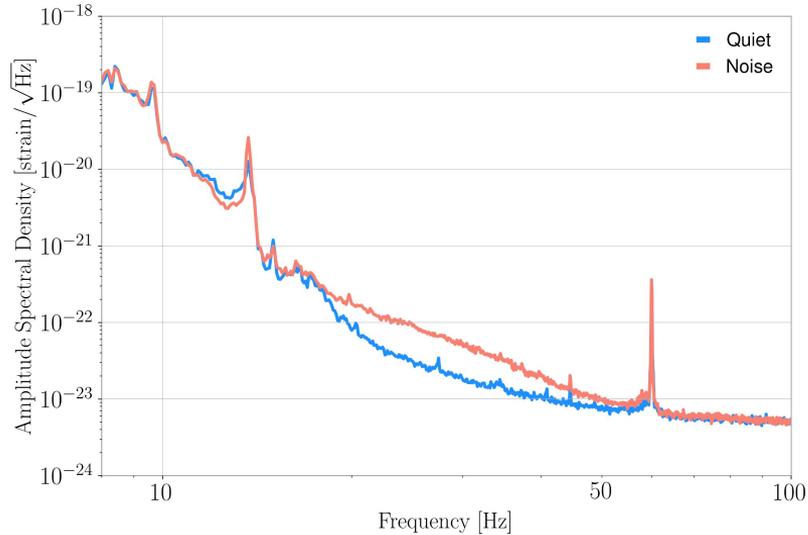
Post RC tracking
Shelf at f Hz in TMS \rightarrow
Shelf at f Hz in $h(t)$



Splitting the control drive between X and Y end reduced this noise in O4.

Reducing Fast Scatter at LIGO Livingston

Fast Scatter at LIGO Livingston in O3 Apr 2019 - Mar 2020



So first step is identification of transient noise in the data

Second is noise modeling

And third is noise reduction

What we knew

- Increased noise mostly between 10 Hz and 50 Hz
- During high anthropogenic (1-3 Hz) ground motion caused by human activities, logging, trains, trucks

What we didn't know

- What is the morphology?
- Are there sub-populations or multiple types of the transients?
- If Scatter: what is the frequency of the moving surface?
- How much light is reflected by the moving surface?
- What is the source of the noise?

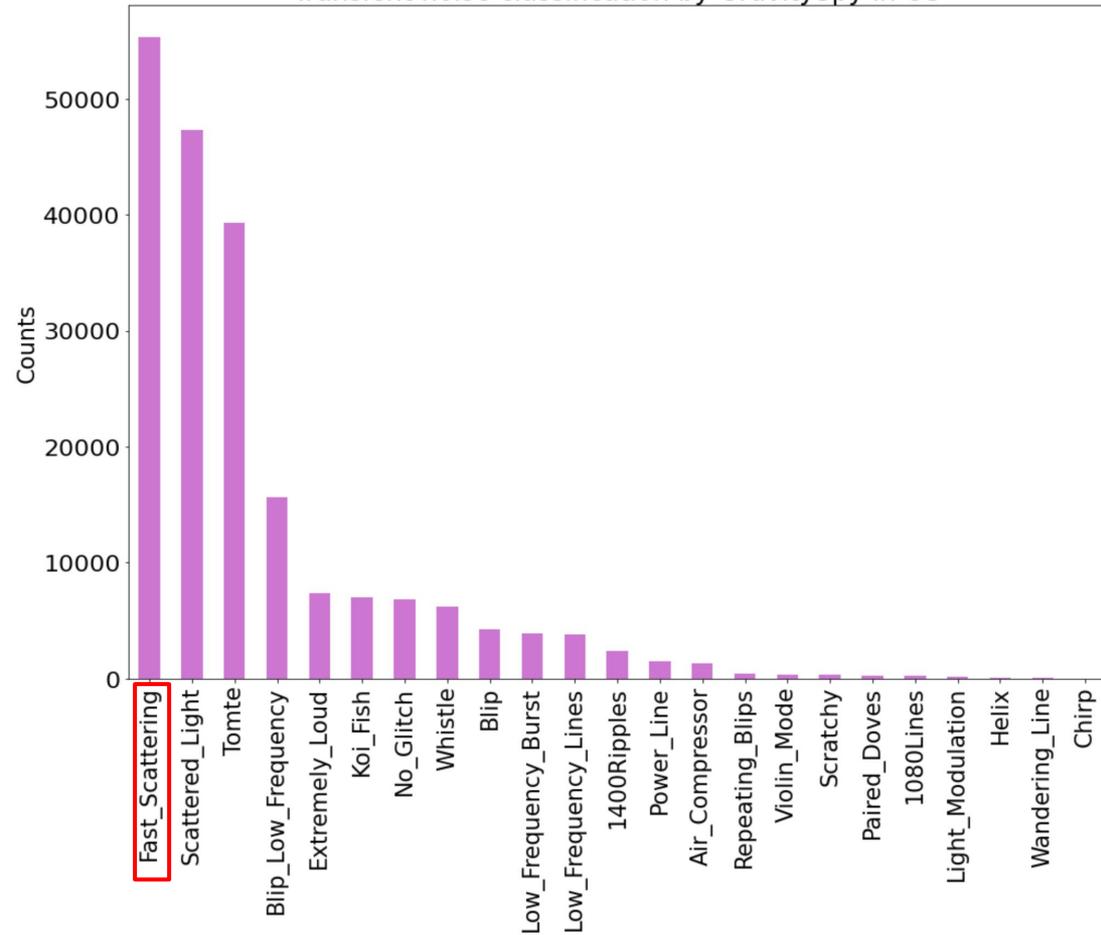
Retraining GravitySpy

GravitySpy: ML based tool to classify transient noise into different categories based on their morphology in time-frequency plane.

Retrained GravitySpy to identify Fast Scatter transients in the data and then Reclassified the whole O3 dataset

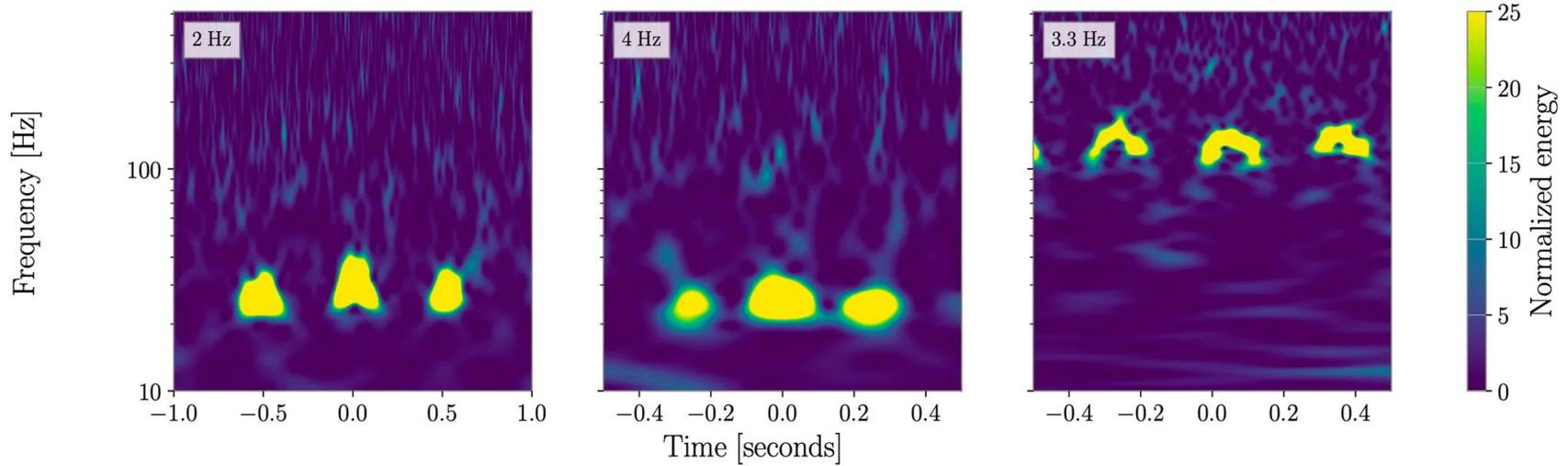
Reclassification showed that Fast Scatter is the most frequent source of transients at LLO in O3

Transient noise classification by GravitySpy in O3



Fast Scatter morphology

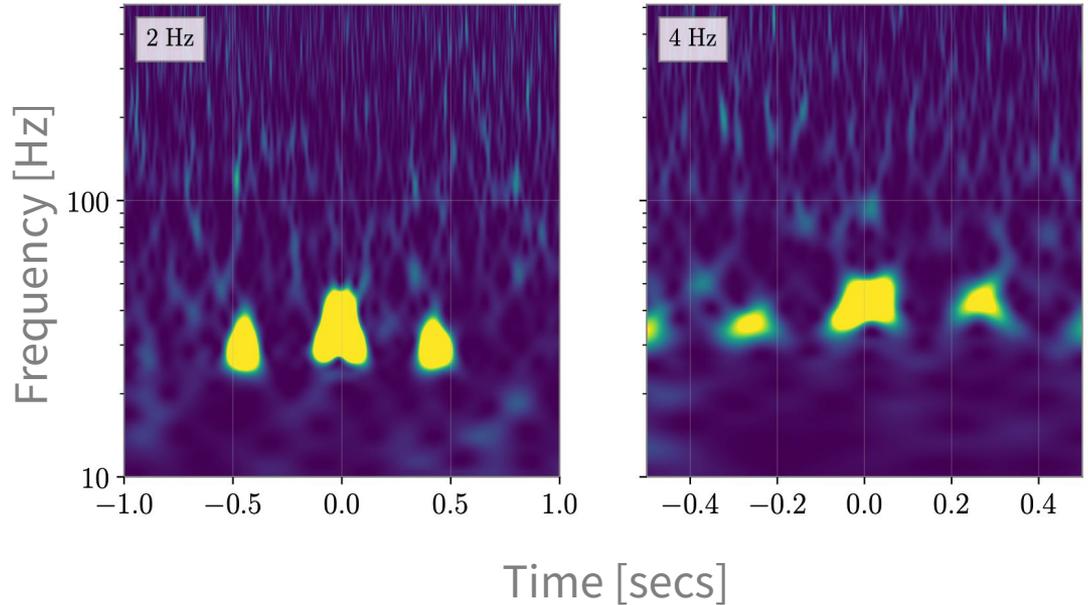
- ML assisted noise identification → Two major population (2 and 4 Hz) of fast scatter in the data



2 Hz and 4 Hz during O3, 3.3 Hz in the Post O3 data

2 Hz and 4 Hz Fast Scatter

- Mainly two populations of Fast Scatter 2 Hz and 4 Hz
- 2 Hz is dominant during high anthropogenic + microseism
- 4 Hz is dominant during high anthropogenic
- Are there two different sources?
- Seismic noise modeling to better understand the noise



Anthropogenic: Mostly 1 - 3 Hz, caused by human activities

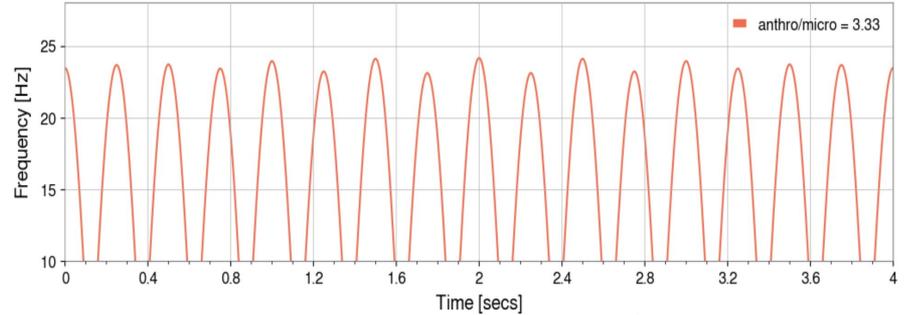
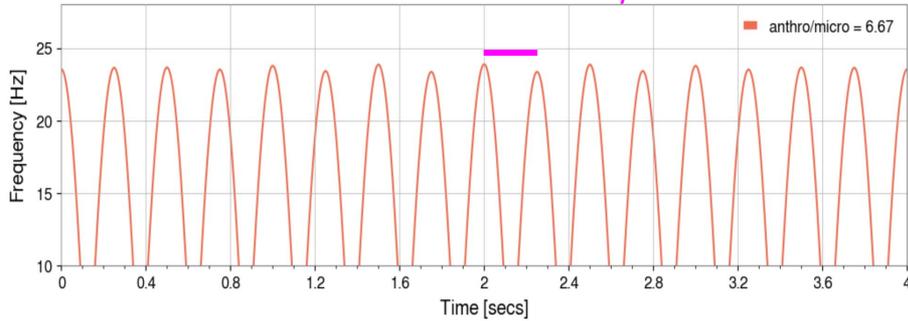
Microseism: Mostly 0.1 - 0.3 Hz, caused by ocean storms

Adding increasing amount of microseismic motion at 0.15 Hz to anthropogenic motion at 2 Hz

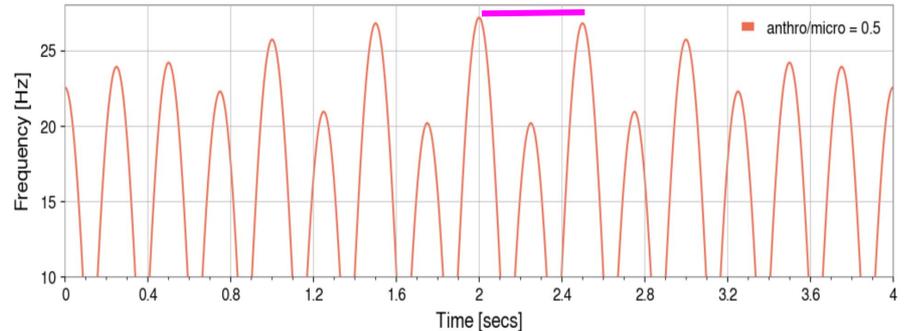
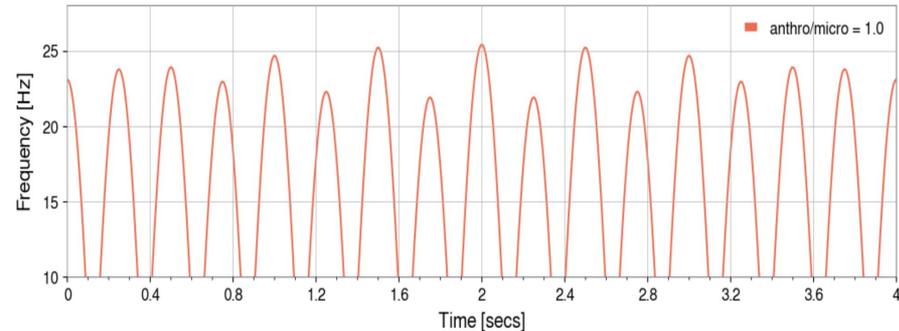
$$h_{sc} = \frac{A\lambda}{4\pi L} \sin\left(\frac{4\pi}{\lambda} x_{sc}\right) \leftarrow \text{motion}$$

$$h_{sc} = \frac{A\lambda}{4\pi L} \sin\left(\frac{4\pi}{\lambda} [x_{anthro} + x_{micro}]\right)$$

0.25 secs / 4 Hz



0.5 secs / 2 Hz



As the anthro/micro ratio decreases, the dominant arch separation goes from 0.25 seconds to 0.5 seconds

Anthropogenic + Microseism Model of Fast Scatter

Fast Scatter Model:

Fast Scattering in DARM is due to a combination of anthropogenic and microseism (or EQ band) motion.

Depending on the relative strength of ground motion in these two different bands, we get 4 Hz or 2 Hz Fast Scatter from this **2 Hz motion**

$$h_{sc} = \frac{A\lambda}{4\pi L} \sin\left(\frac{4\pi}{\lambda} x_{sc}\right)$$

$$h_{sc} = \frac{A\lambda}{4\pi L} \sin\left(\frac{4\pi}{\lambda} [x_{anthro} + x_{micro}]\right)$$

2 Hz motion + low microseism

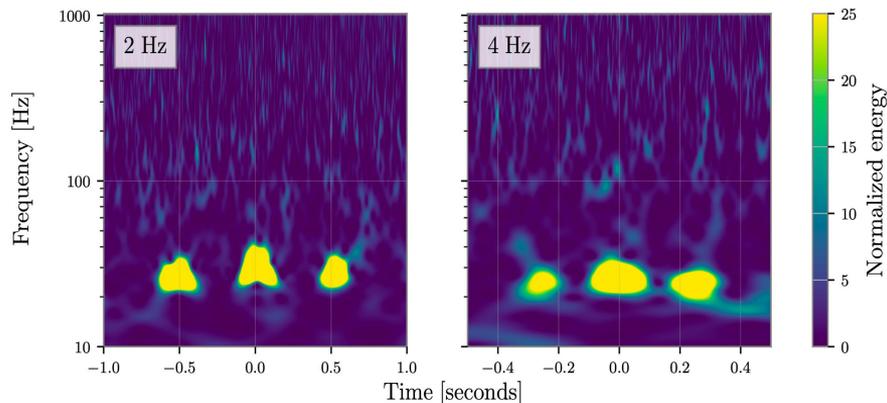


4 Hz
Fast Scatter

2 Hz motion + high microseism



2 Hz
Fast Scatter

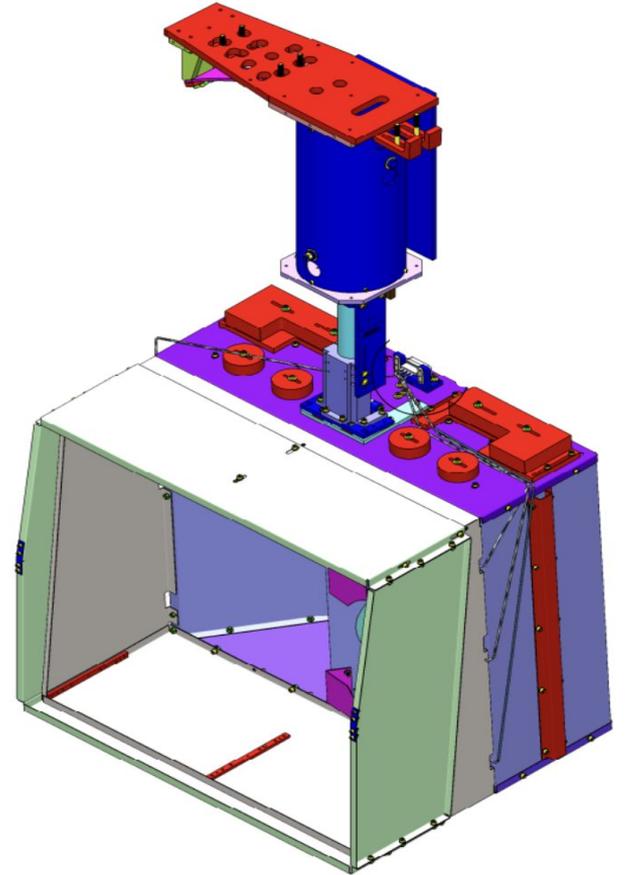


There is one source for both 2 and 4 Hz Fast Scatter

Now, we are looking for a surface with a resonance ~ 2 Hz

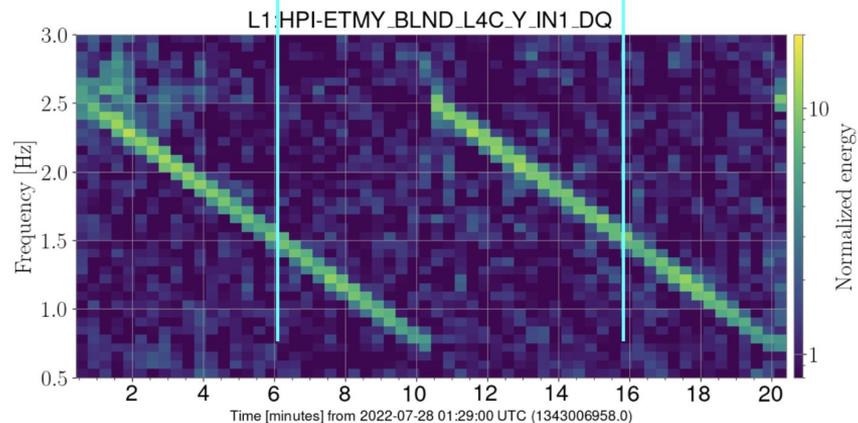
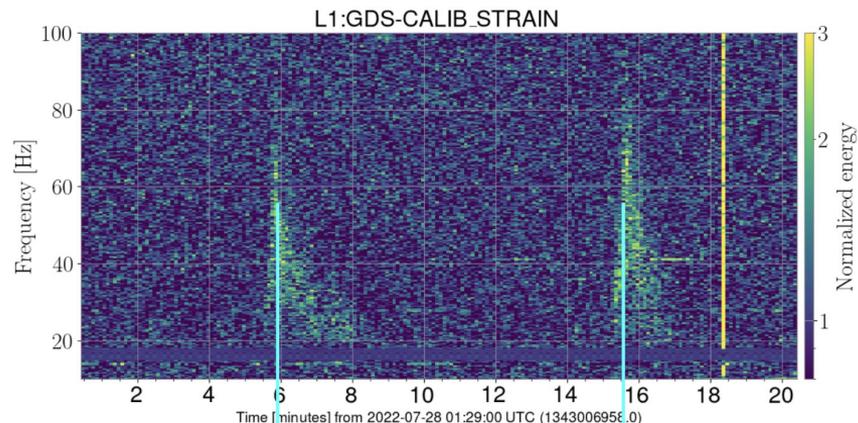
Arm Cavity Baffle Resonances

- Arm Cavity Baffle is located in front of all the 4 test masses.
- Sweep injections revealed the presence of resonance near 1.6 Hz in Arm Cavity Baffles!!
- Resonance moved from ~2 Hz in O3 to ~ 1.6 Hz Post O3
- These resonances were fixed during O3-O4 break
- This led to near elimination of the upconverted Fast Scatter noise at LLO in the band 10 - 50 Hz!

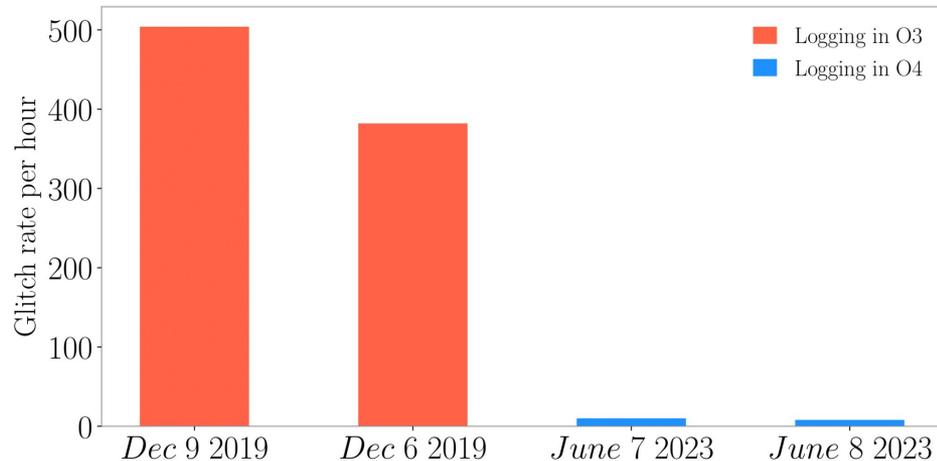
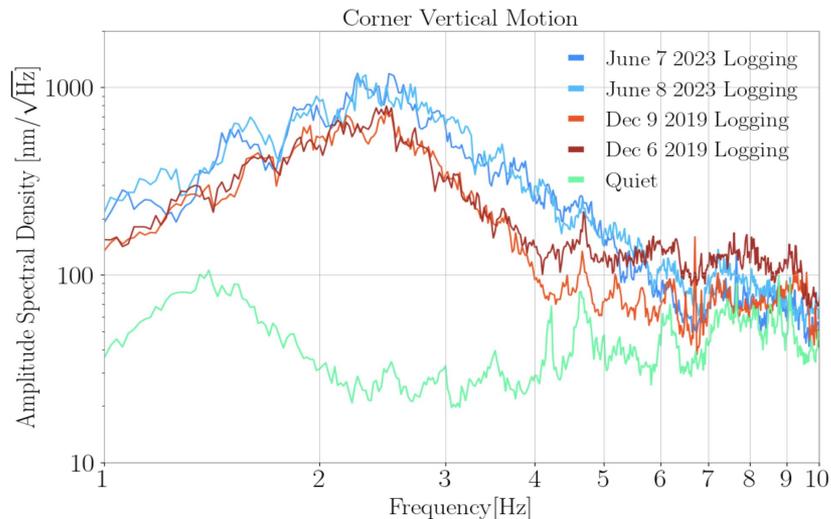


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Noise reduction in O4



alog [65494](#)

Modeling and Reduction of high frequency scatter at LIGO Livingston Soni et al 2024 *Class. Quantum Grav.* 41

135015

Comments related to this report

anamaria.effler@LIGO.ORG - 16:39, Friday 09 June 2023 (65498)

What Sidd doesn't explicitly say here is that

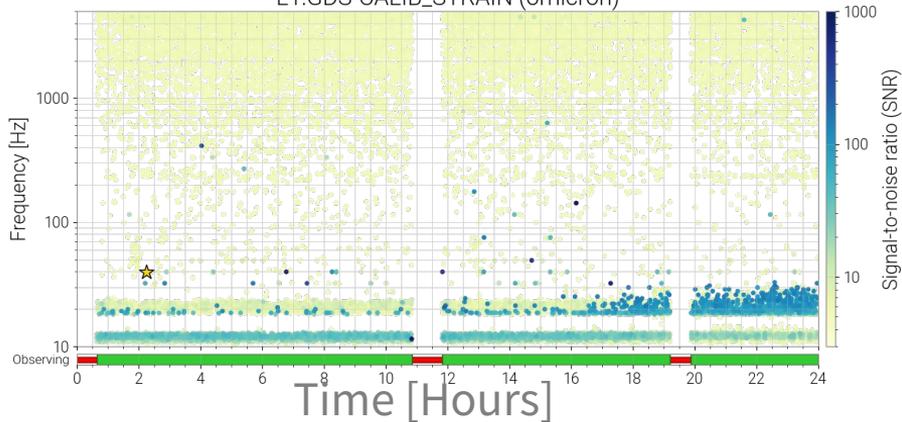
WE. GOT. RID. OF. ALL. THIS. NOISE. COUPLING.



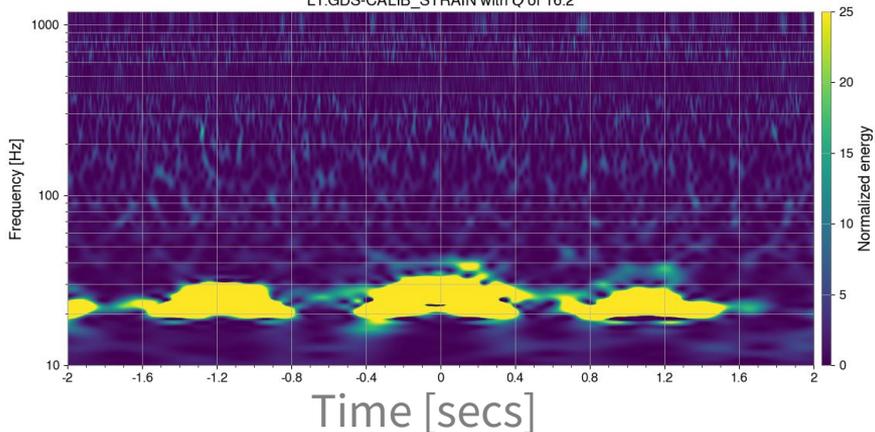
image credit: Jane

Loudest event: SNR = 2903.83, Peak = 1386728111, Peak Frequency = 39.79

L1:GDS-CALIB_STRAIN (omicron)



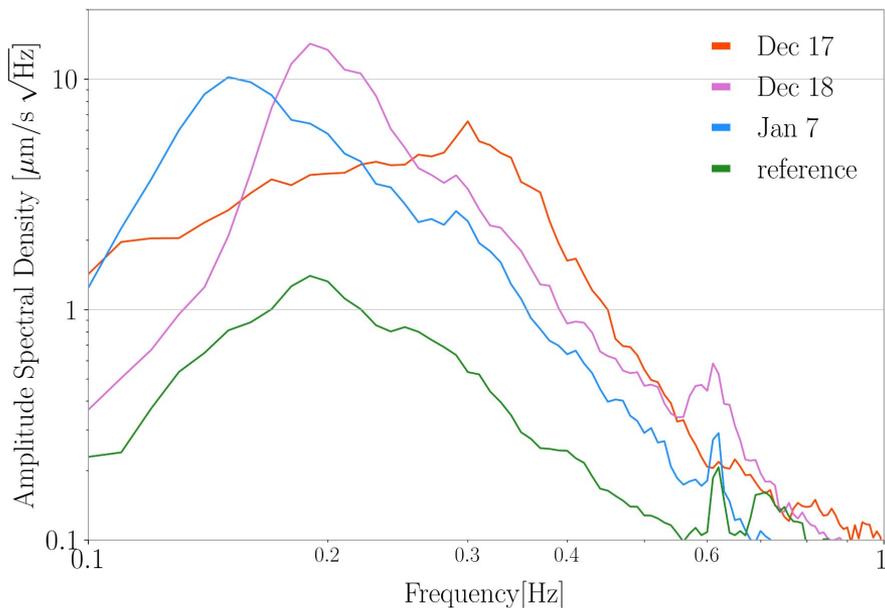
L1:GDS-CALIB_STRAIN with Q of 16.2



O4: Slow Scatter
makes a come back!

Ground motion

Ground motion at End X



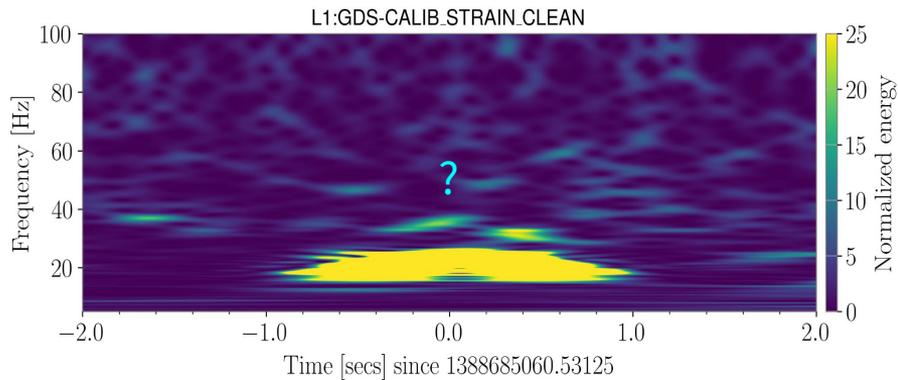
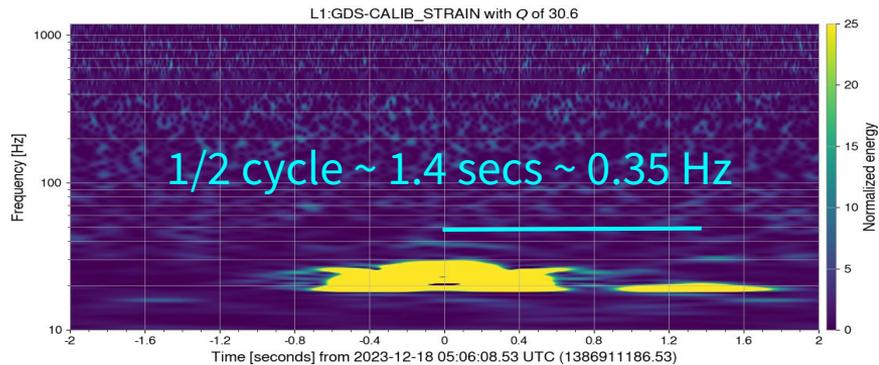
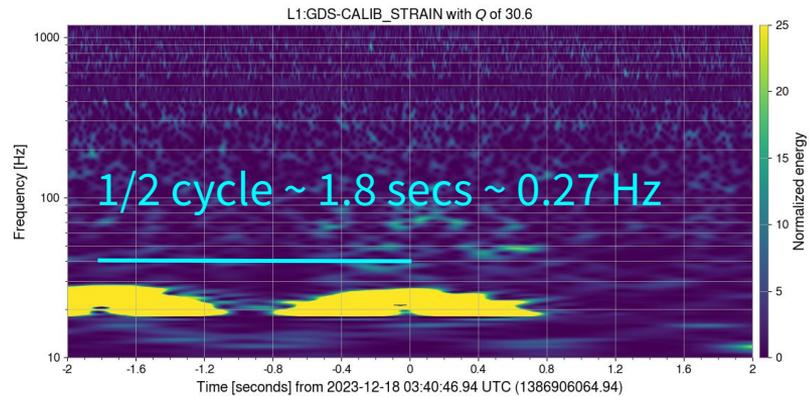
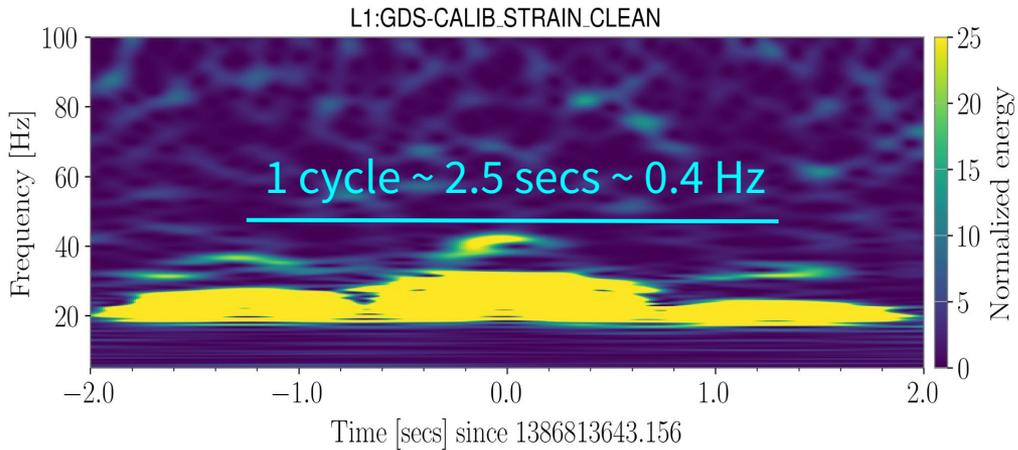
Ground motion band responsible for noise?

Usually motion close to one particular frequency (resonance) creates noise, not what we observe in O4a.

Dec 17 and 18 had very similar rate of scatter noise. Comparatively, the rate (lower) and morphology of transients on Jan 7 was different.

Depending on where the resonance is, we should have noise only for 1 (at most 2) of these 3 days. So where's the resonance?

Frequency of the moving surface



Motion and light on the surface

How much is the scattering surface moving?

Depends on the frequencies. To create a shelf at 25 Hz:

$$f_{fringe} = \left| \frac{2v_{scatter}}{\lambda} \right|$$

At 0.25 Hz, $d = 25\lambda / (2\pi \cdot 0.25) = 17 \mu\text{m}$

At 0.3 Hz, $d = 25\lambda / (2\pi \cdot 0.3) = 14 \mu\text{m}$

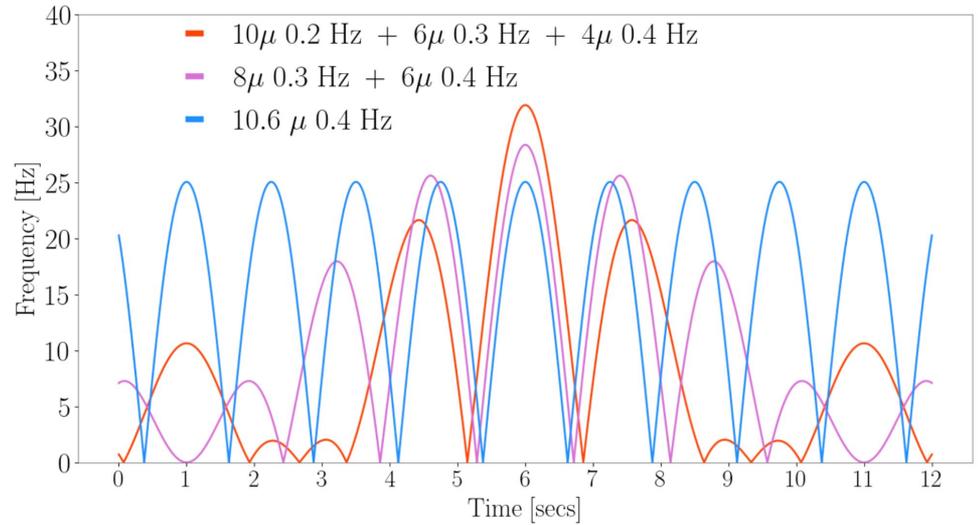
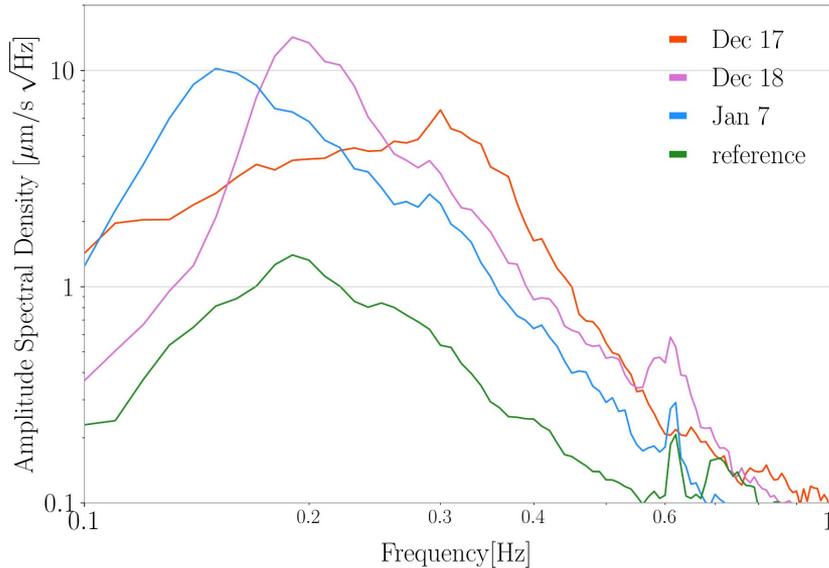
At 0.4 Hz, $d = 25\lambda / (2\pi \cdot 0.4) = 10.6 \mu\text{m}$

This is a lot of motion!

Where can we get this much motion at these frequencies?

The total motion is the sum of motion at all the frequencies → we need comparatively less motion at each frequency

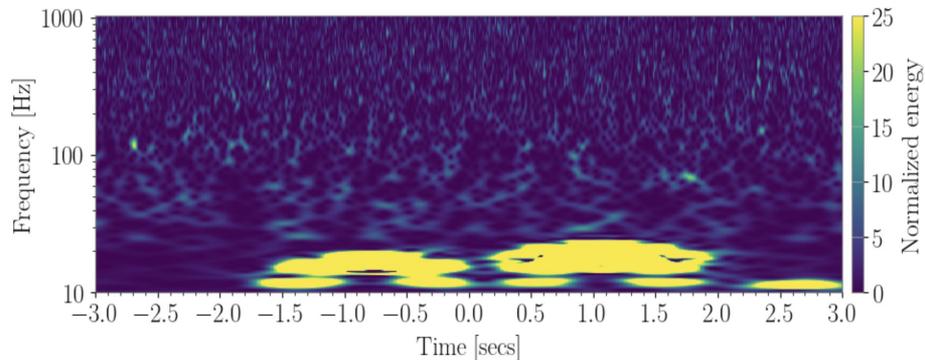
Ground motion at End X



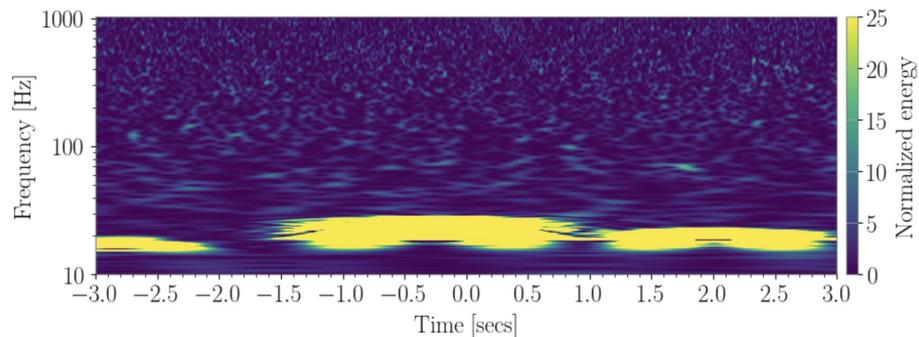
This is the ideal case, seismic waves at different frequencies won't combine this coherently

- We use the ground motion in 0.1-0.5 Hz to see if it can create noise above the DARM sensitivity
- It does but we need a factor of 2 more motion (which is not hard to obtain)

Phase noise from ground motion

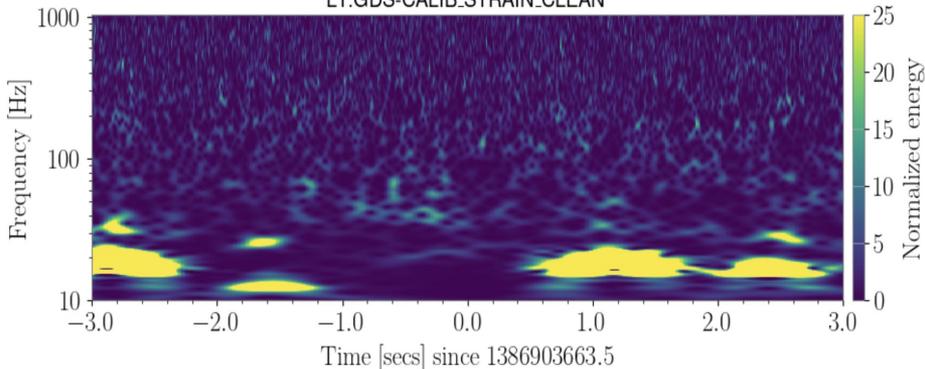


Phase noise from ground motion



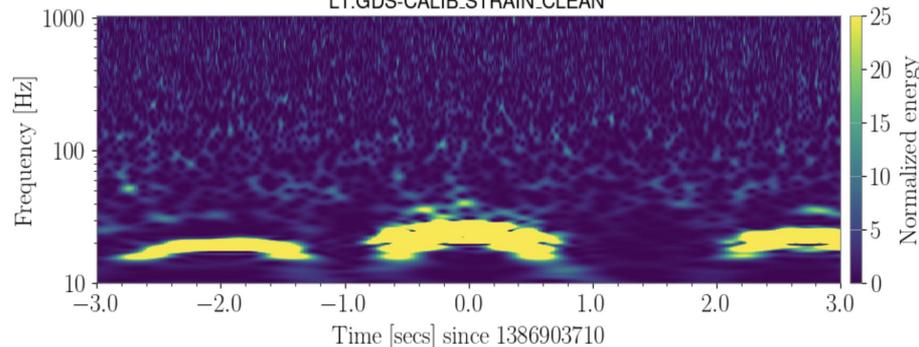
Actual noise in DARM

L1:GDS-CALIB_STRAIN_CLEAN



Actual noise in DARM

L1:GDS-CALIB_STRAIN_CLEAN



O4 Slow Scatter Summary

- Resurgence of Slow Scatter in O4 at LLO
- Does not have a unique frequency
- After the recent commissioning work earlier this year, we have noticed evidence of reduced Slow Scatter (collecting more evidence)
- Debasmita (LSU) is leading the effort on this work

Summary

- Multiple sources of noise impact LIGO detectors sensitivity: some are harder to eliminate than others
- Ground motion induced scatter transient noise remains our biggest challenge
- Lots of work done in the area of scatter noise modeling since O3
- Improved monitoring of motion with more OSEMs will help

Thank You!
Questions?