Reduction and Identification of Scattered Light noise at LIGO

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Detchar Award Talk
LIGO Seminar
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Overview

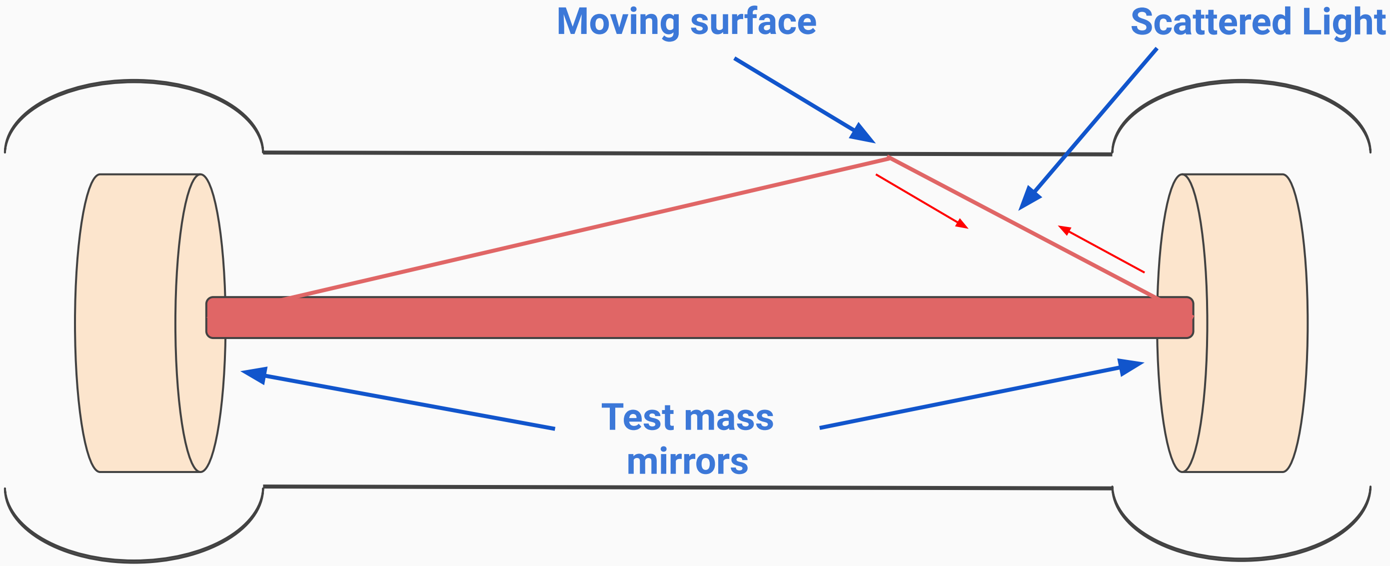
- Scattered Light Noise
- Slow Scattering in LIGO detectors
- Reaction Chain Tracking
- GravitySpy Retraining and Reclassification
- Impact of Retraining

Light scattering

$$\phi_{sc} = \frac{4\pi}{\lambda}(x_0 + \delta x_{sc}(t))$$

$$h_{sc} = K.sin(\phi_{sc}(t))$$

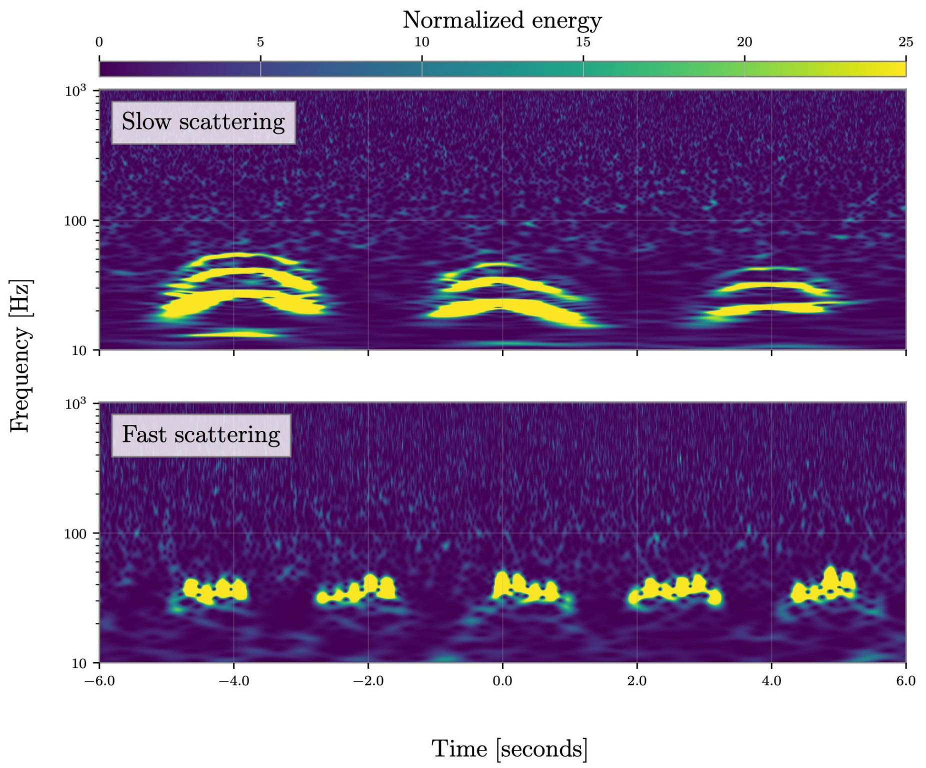
$$f_{max} = \frac{2v}{\lambda}$$



[David J Ottaway, Peter Fritschel, and Samuel J. Waldman]

[T Accadia et al]

Scattering arches in h(t)



Glitch	Count	Percent
Scattered_Light	58739	71.4%
Extremely_Loud	5604	6.8%
Koi_Fish	3710	4.5%
Blip	3410	4.1%
Blip_Low_Frequency	1928	2.3%
Low_Frequency_Burst	1885	2.3%

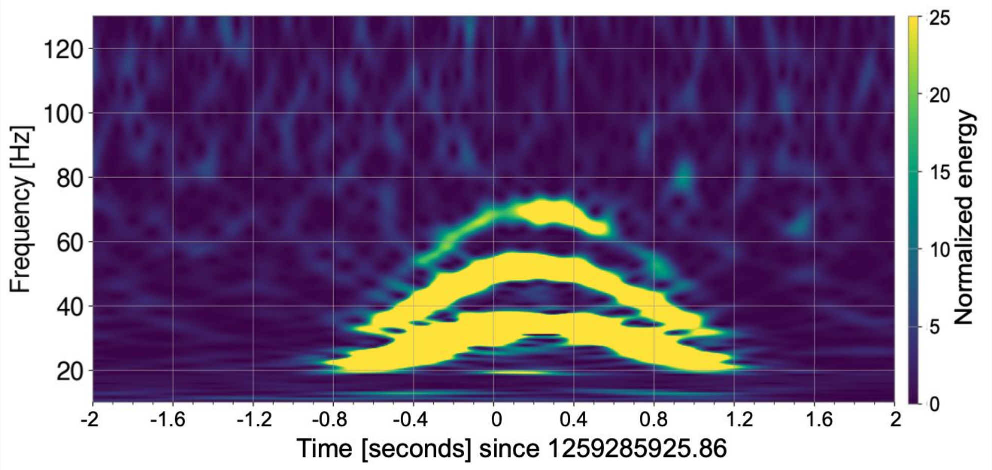
H1 GravitySpy O3b

Glitch	Count	Percent
Scattered_Light	44682	32.4%
Fast_Scattering	36918	26.8%
Tomte	22361	16.2%
Blip_Low_Frequency	8728	6.3%
Whistle	5381	3.9%
Extremely_Loud	3461	2.5%

L1 GravitySpy O3b

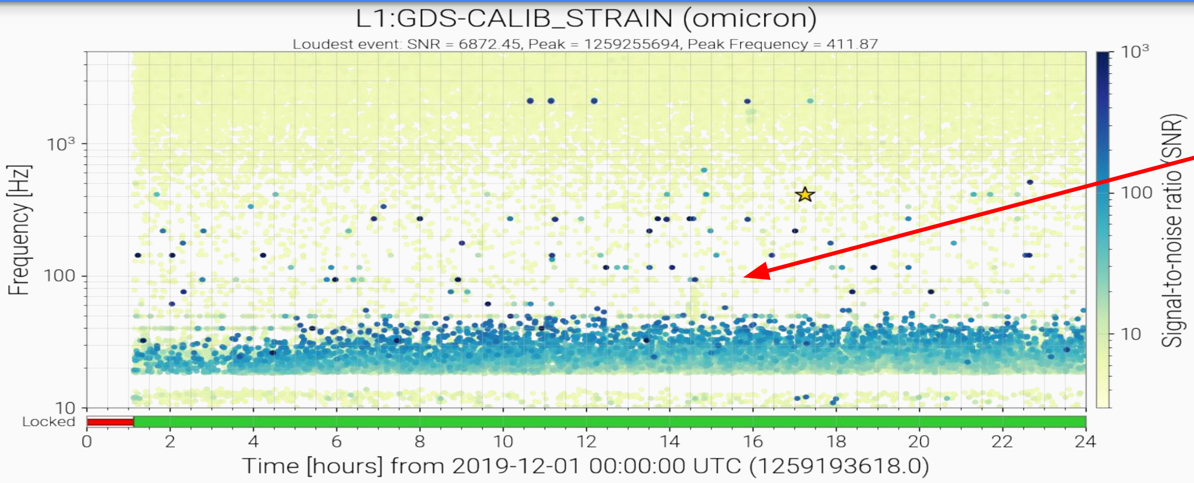
Slow Scattering in LIGO detectors

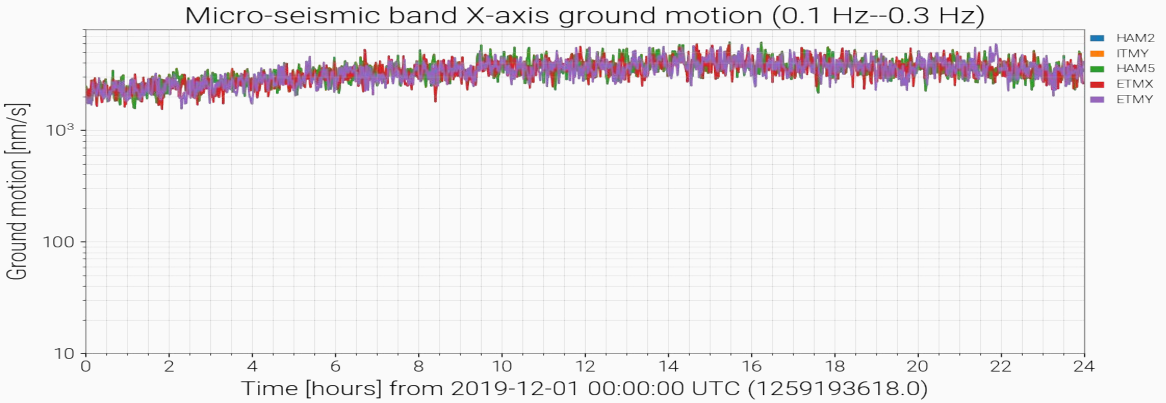
Slow Scattering arches



- Multiple scattering arches due to multiple reflection
- High microseism (0.1 Hz - 0.3 Hz), Earthquakes (0.03 Hz - 0.1 Hz)
- Noise in the band 10 Hz - 120 Hz
- The overall O3 rate of Slow Scattering 7.85/hr and 9.8/hr at LLO and LHO respectively
- During O3b, this rate is 15.5/hr at LLO, and 18.8/hr at LHO because of high microseism in winter
- Two separate couplings found during O3

Microseismic Ground motion and Slow Scattering



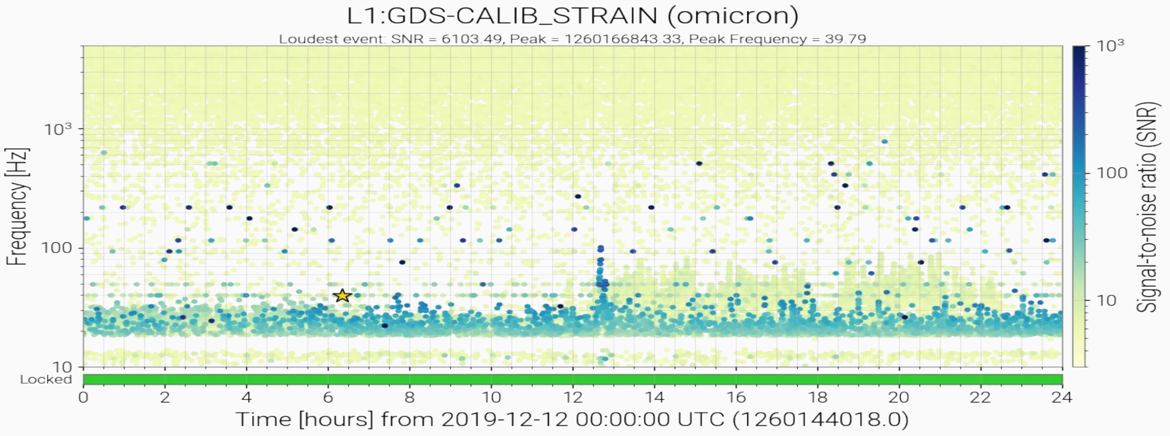


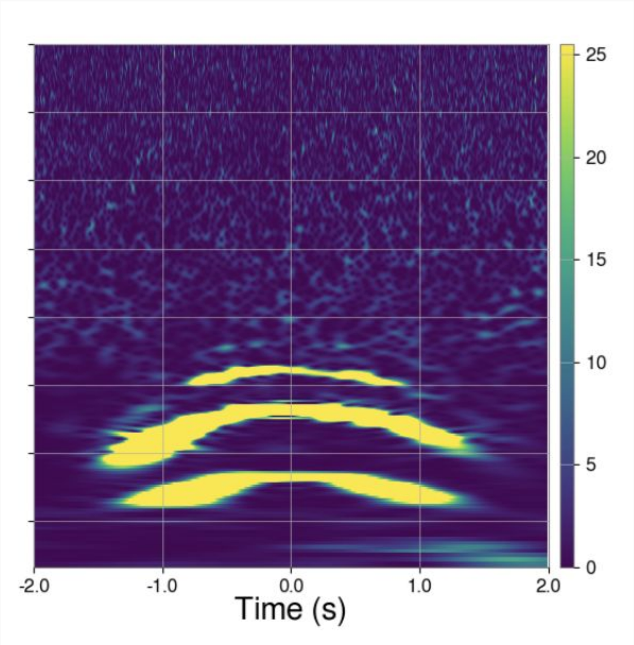
79% of these are Slow Scattering

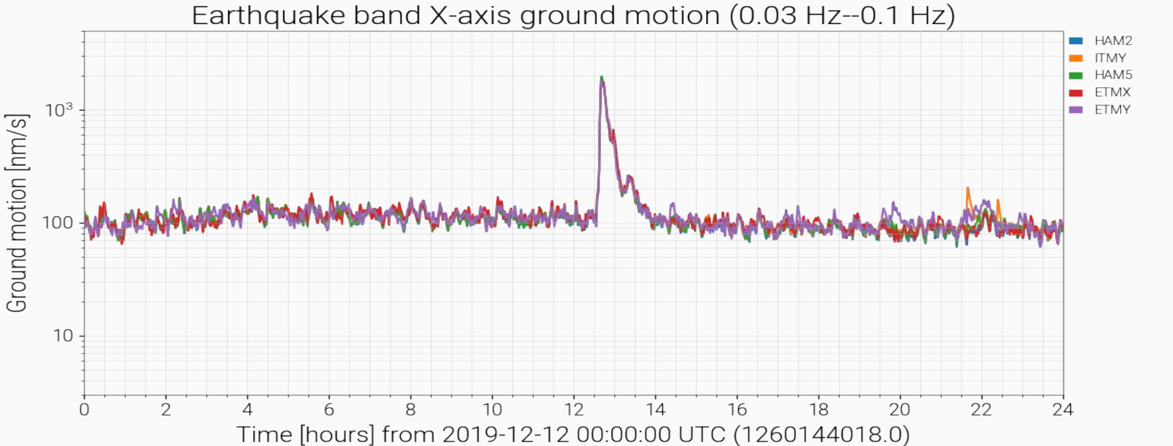
Days with high microseism and high rate of Slow Scattering at LLO

[Dec 13], [Dec 22], [Jan 6]

Earthquakes, microseism and Slow Scattering

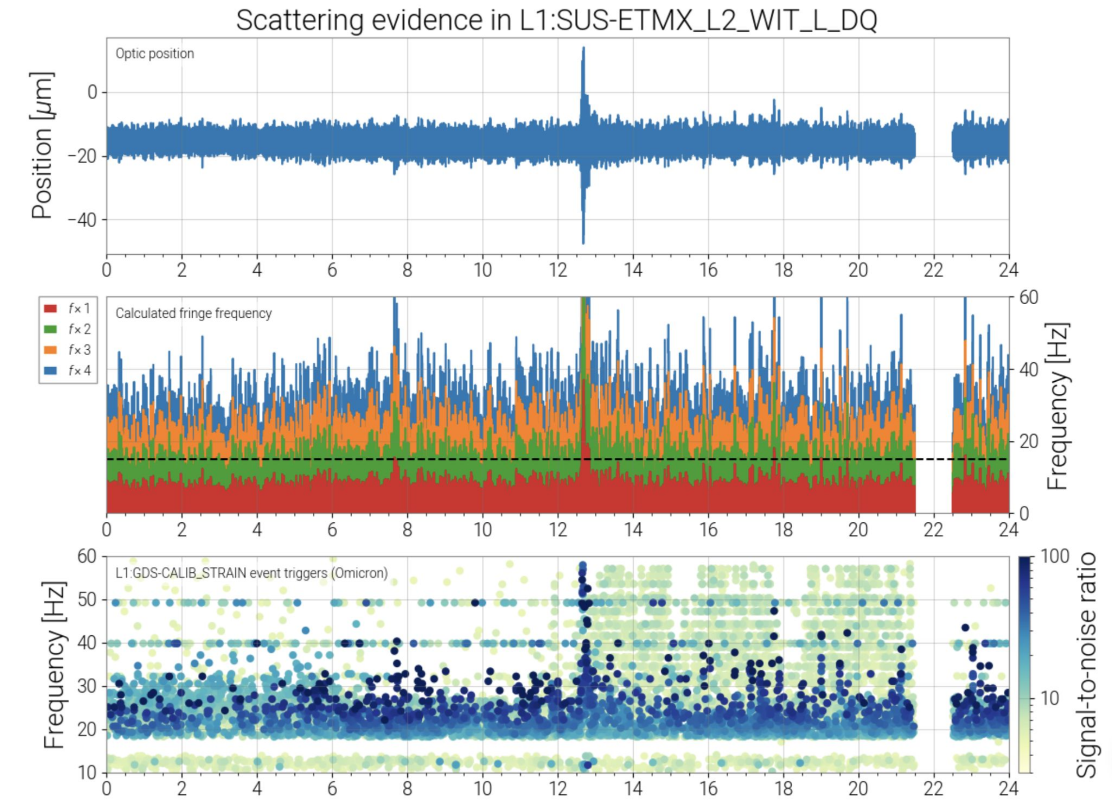


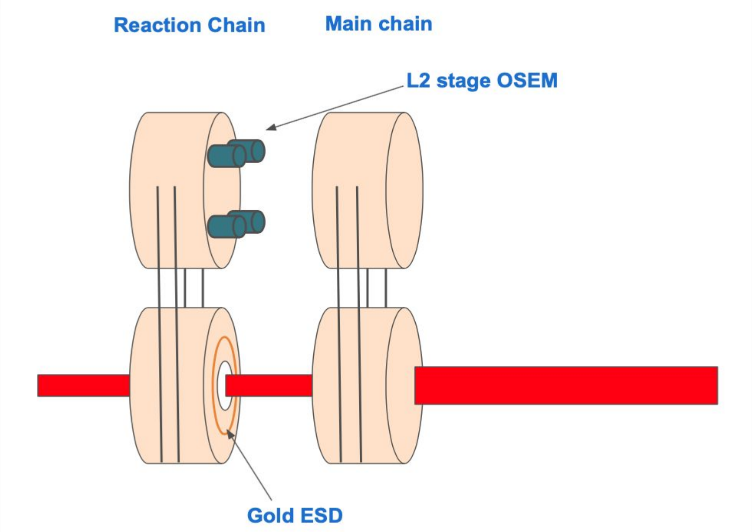




Dec 12

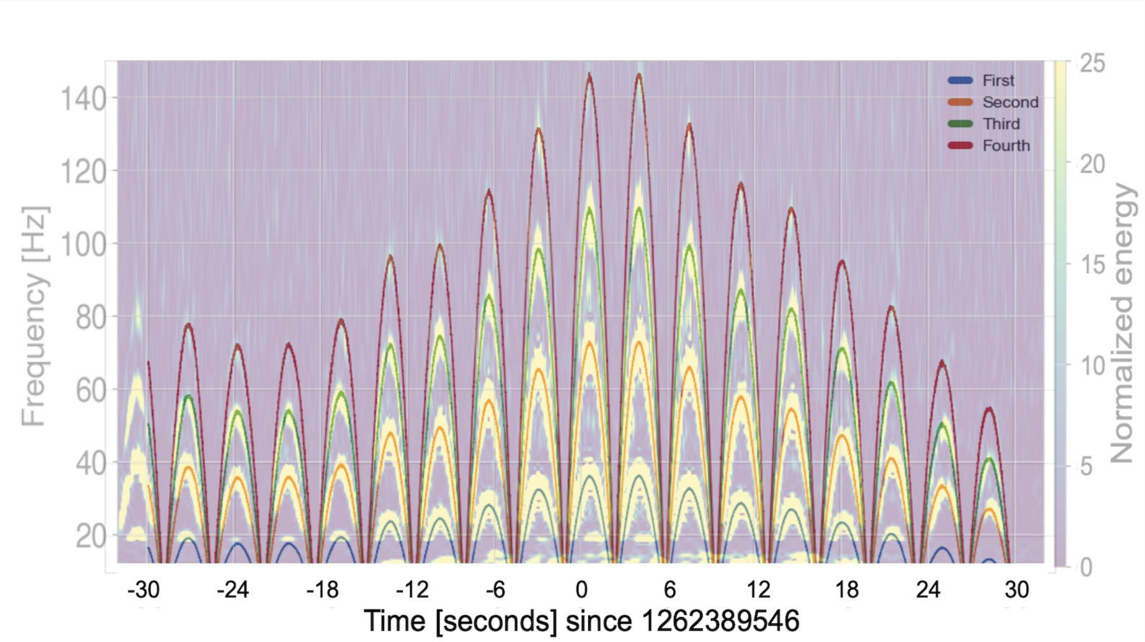
L2 Stage OSEM





$$f_{max} = \frac{2nv}{\lambda}$$

L2 OSEM and Slow Scattering



- If relative displacement is larger than the wavelength

$$\delta x_{sc}(t) > \lambda$$

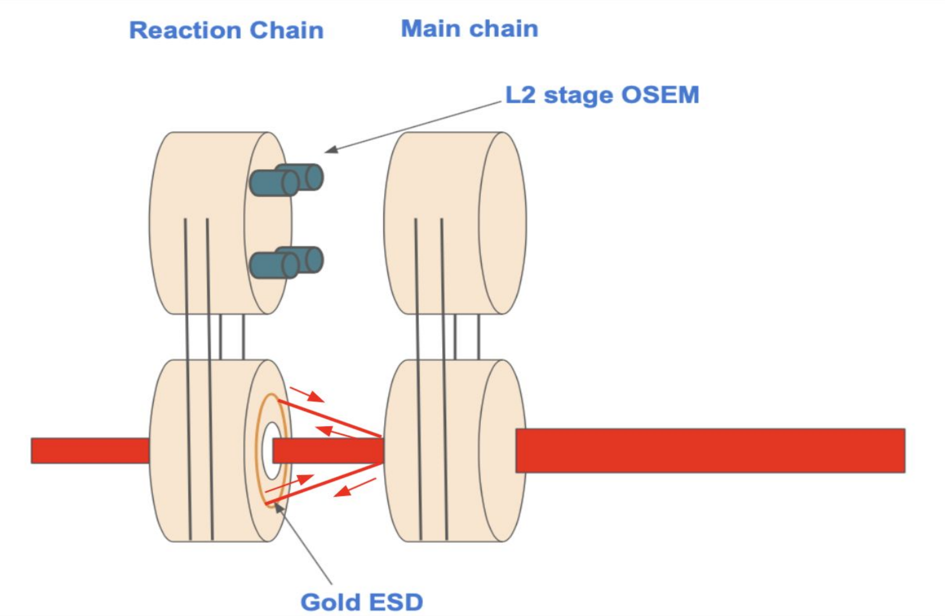
- Noise is upconverted to higher frequencies and appears as arches

$$h_{ph}(t) = K \sin\left(\frac{4\pi \delta x_{sc}(t)}{\lambda}\right)$$

- Fringe frequency motion

$$f_{max} = \frac{2nv}{\lambda}$$

ETM-AERM scattering

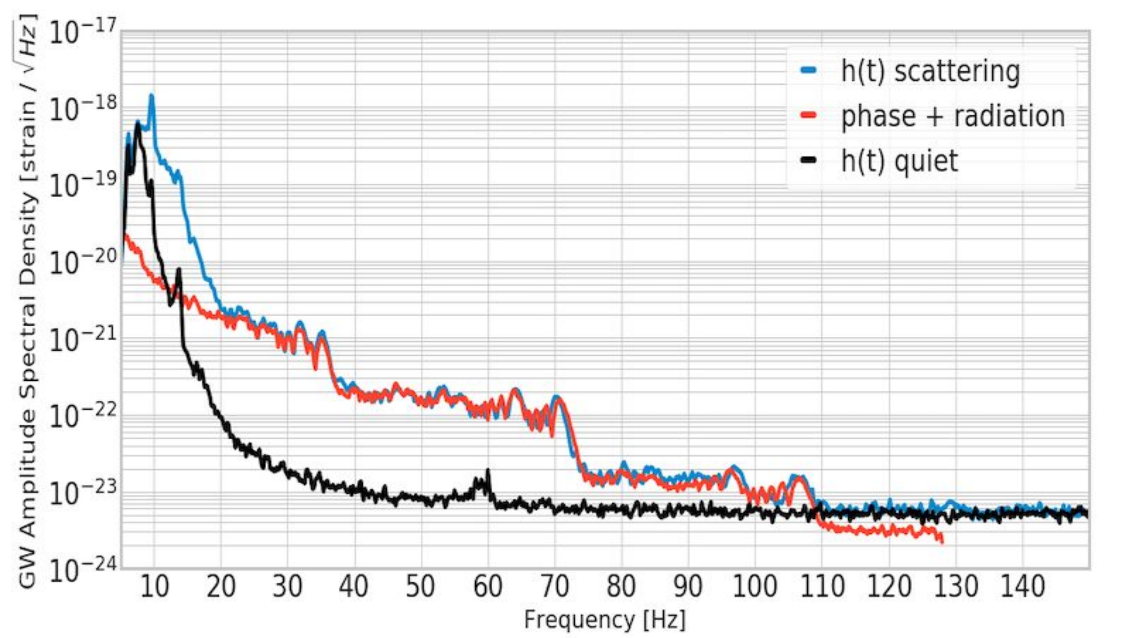


- DARM control drive applied in between the chains creates relative motion between them
- A fraction of light hits the Gold ESD, reflects back and joins the main beam after ETM transmission
- Scattering arches in h(t)

Robert's alog [54298]

Hiro's document [DCC]

h(t) noise spectrum

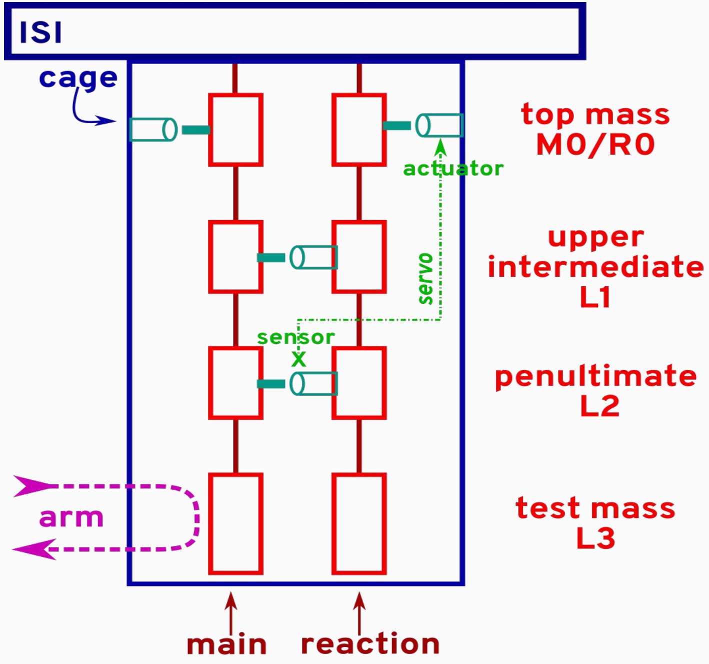


- Arches in spectrogram appears as scattering shelves in the h(t) spectra

$$h_{ph}(f) = \frac{\lambda T_{end}\sqrt{f_r}}{8\pi L}\mathcal{F}[\sin[\frac{4\pi}{\lambda}\delta x_{sc}(t)]] \qquad h_{rad}(f) = T_{end}\sqrt{f_r}\frac{2\Gamma P}{Mc}\frac{2}{\Omega^2 - \omega^2}\mathcal{F}[\cos[\frac{4\pi}{\lambda}\delta x_{sc}(t)]]$$

$\mathcal{F}$ → Fourier transform

Reaction Chain Tracking



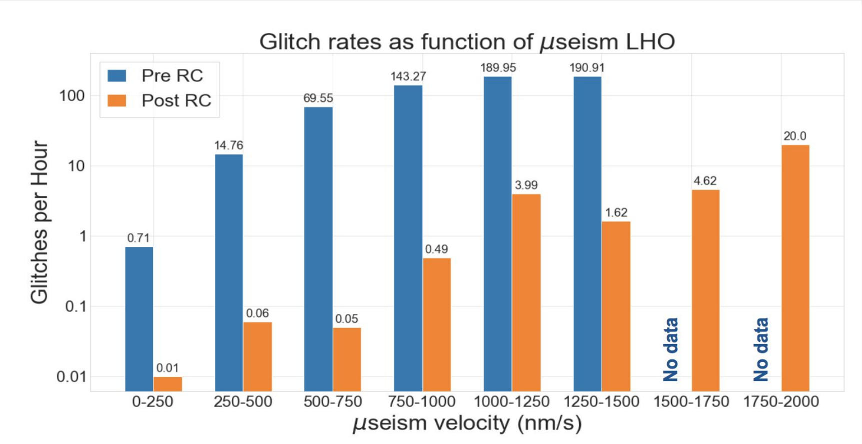
- Noise is due to the relative motion between the chains
- Take the motion from L2 stage and feed it to R0 stage.
- This reduces the relative motion and the peak frequency of the arches

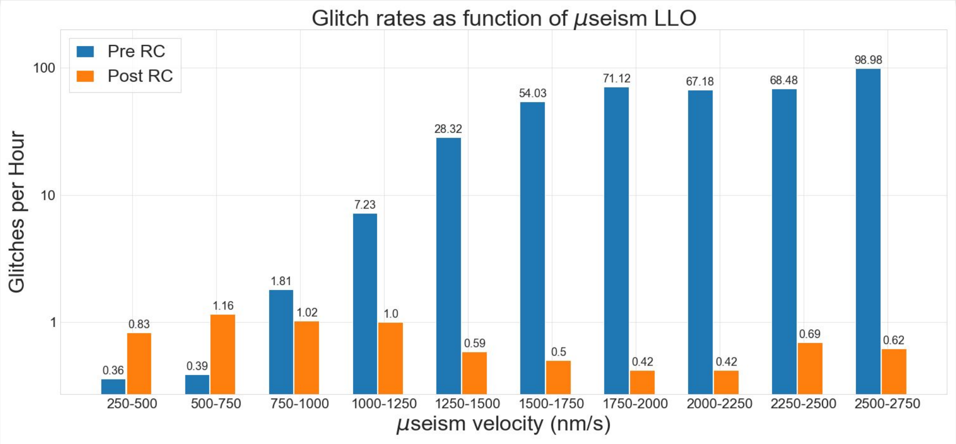
$$f_{max} = \frac{2nv}{\lambda}$$

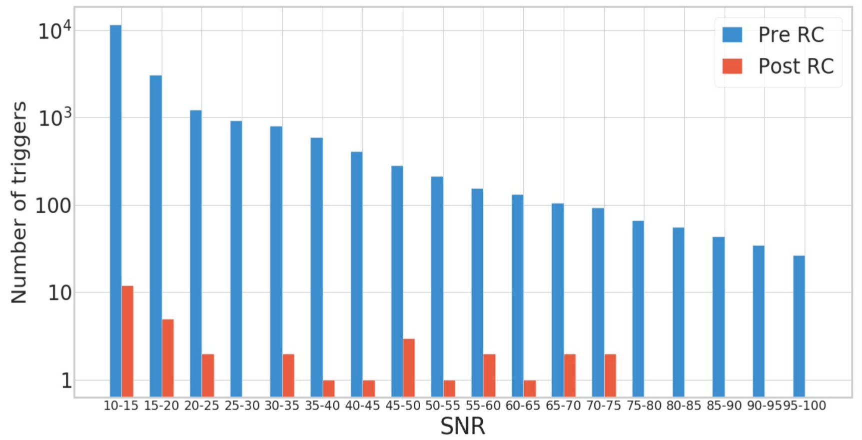
RC tracking alogs 50851, 54506

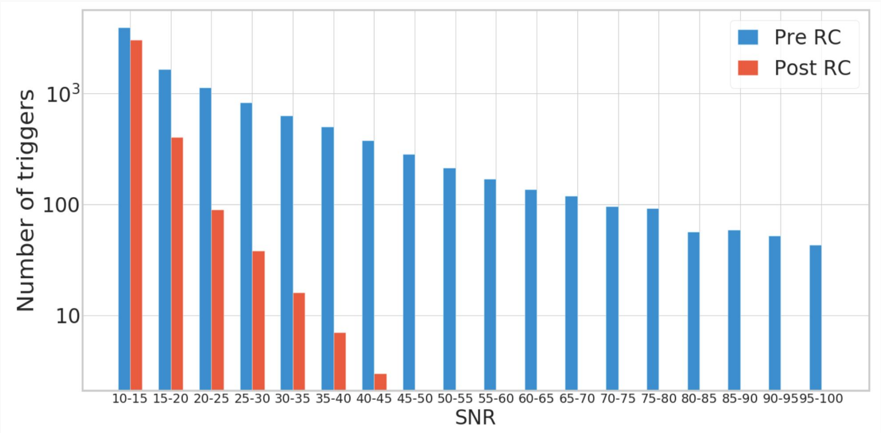
Reducing Scattered Light in LIGO's Third Observing Run. S Soni et al link

RC tracking impact on Rate and SNR

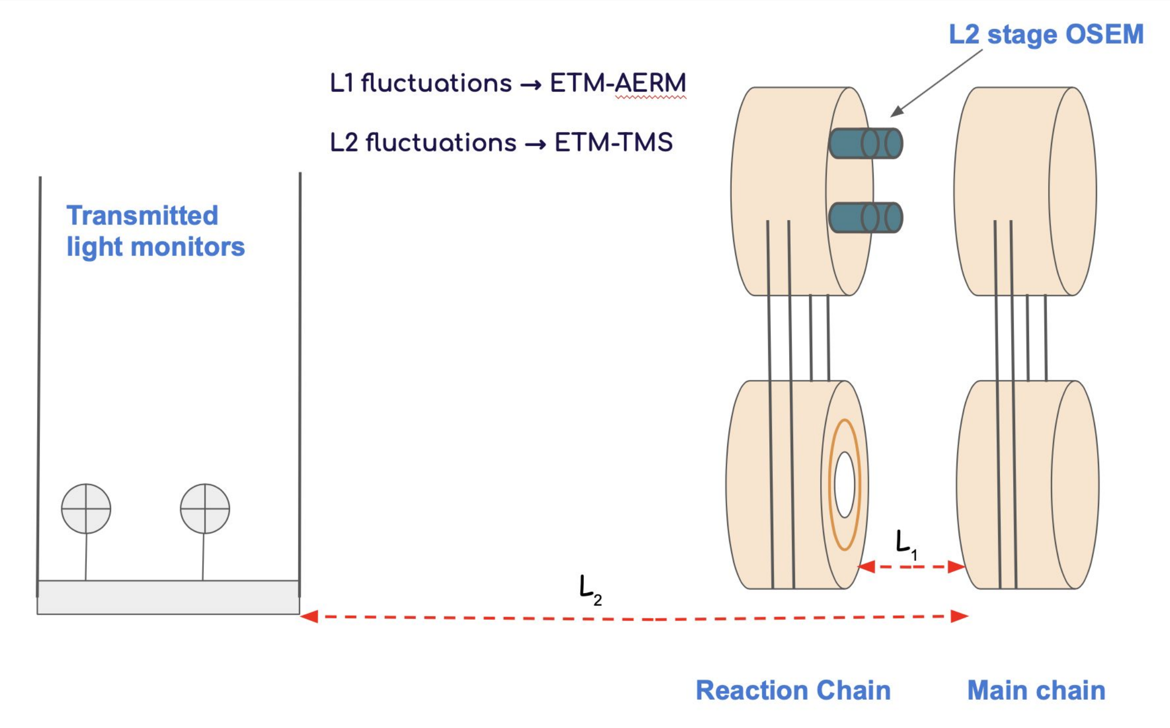








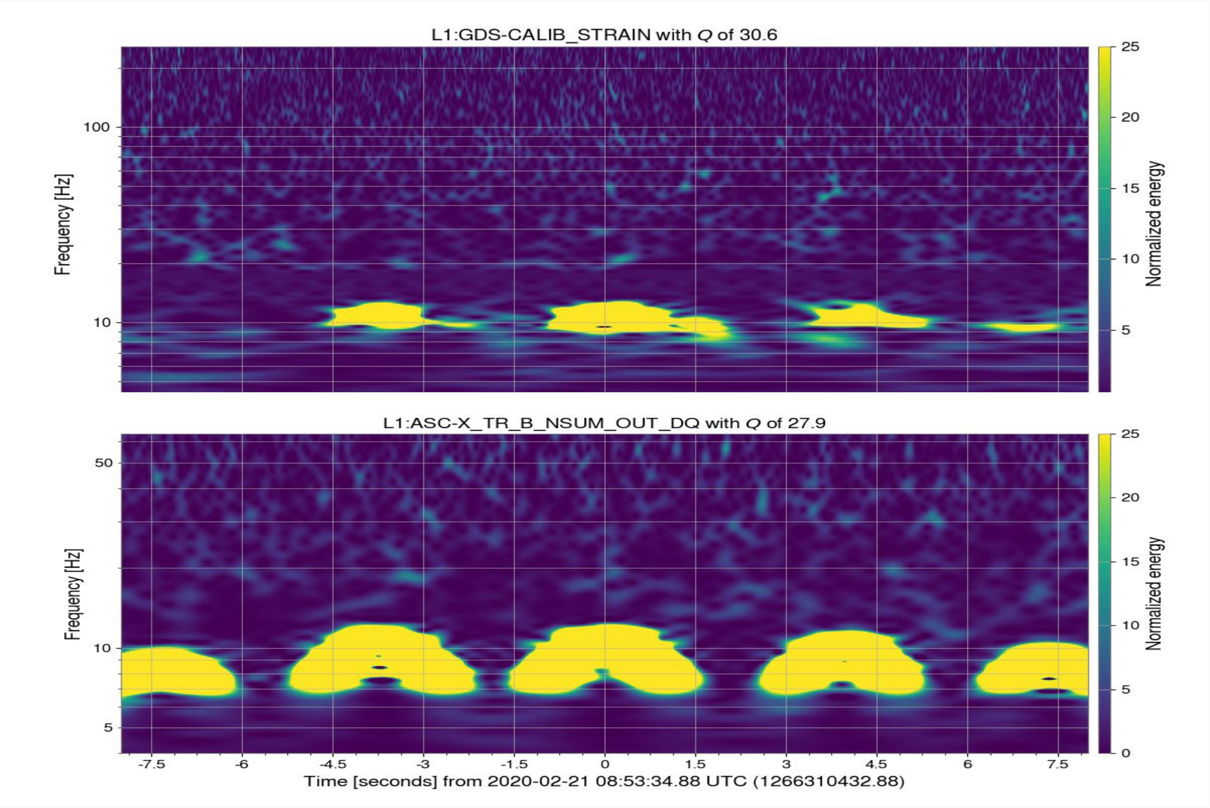
End Test Mass-Transmission Motor System Scattering



- 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

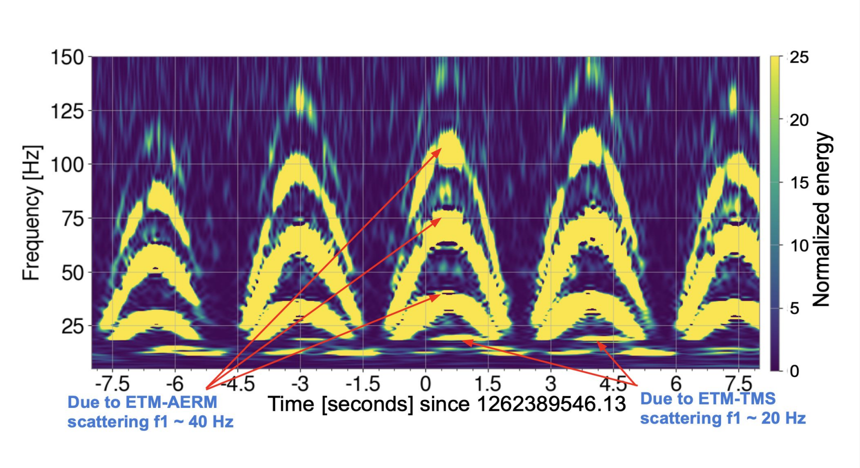
$$v_2 = \frac{v_2}{2}, \quad f_2 = \frac{f_1}{2} \qquad f_{max} = \frac{2nv}{\lambda}$$

Scattering arches in Transmons

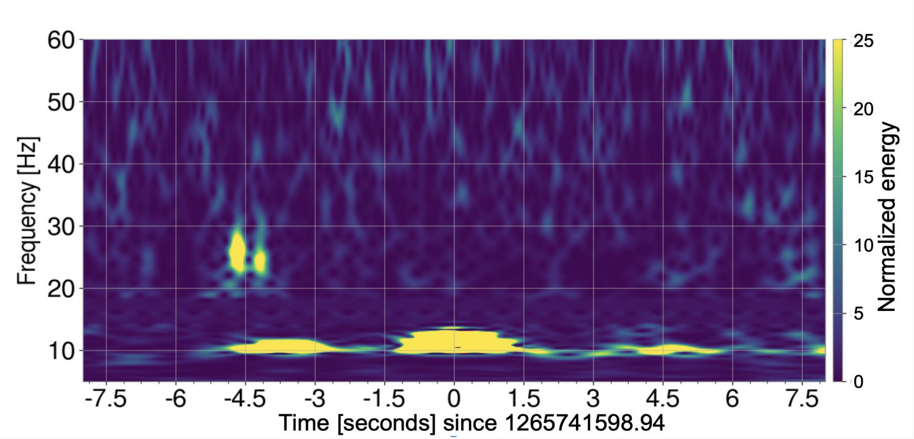


- Scattering arches in TMS Photo-diodes at the same frequency as h(t)
- Hveto correlations between h(t) and TMS PD channels
- Added TMS PD's on Scattering summary page
- Tests confirmed noise in DARM and TMS
- TMS tracking before O4

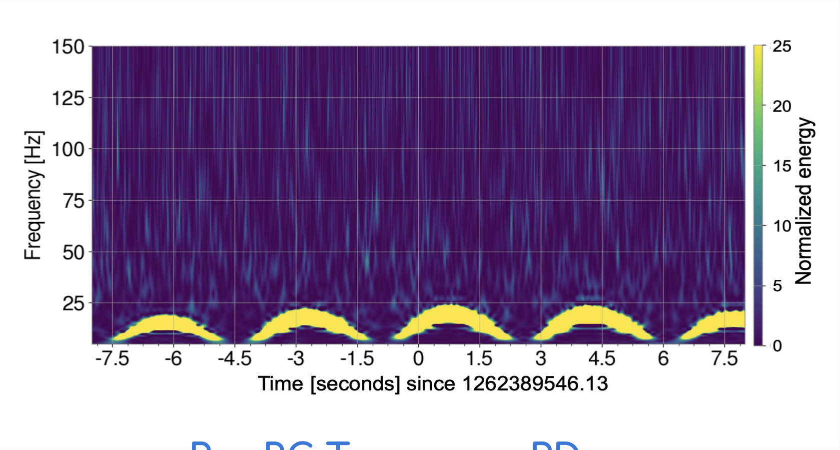
alogs [52204](), [52118]()



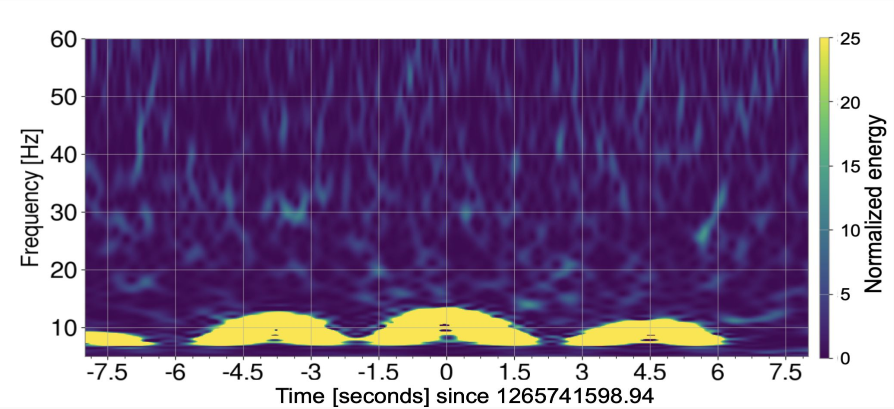
Pre RC h(t)



Post RC h(t)



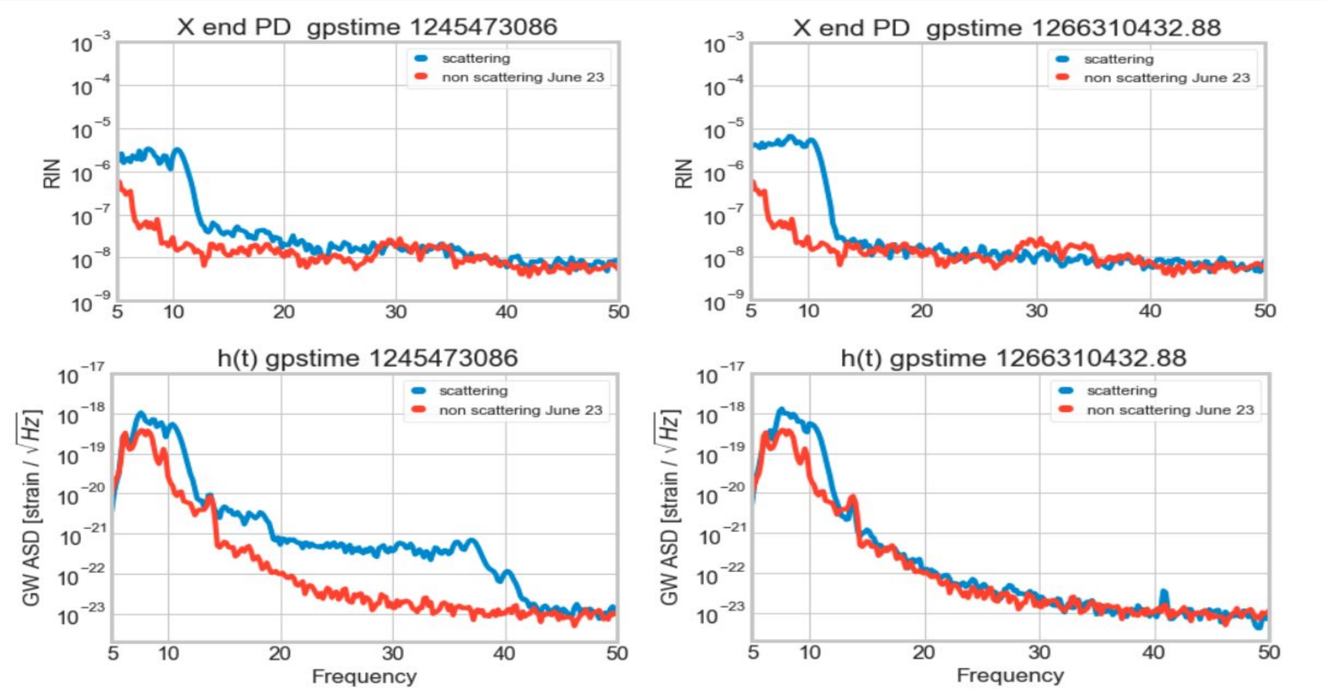
Pre RC Transmon PD



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 → Shelf at f, 2f, 4f Hz and so on in h(t)

Post RC tracking
Shelf at f Hz in TMS → Shelf at f Hz in h(t)

Summary

- RC Tracking implemented in Jan 2020 reduced the rate of Slow scattering due to ETM-AERM noise coupling
- TMS tracking system to be implemented before the start of O4
- Reducing Scattered Light in the Third Observing Run of LIGO. S Soni et al paper link
- Hiro's Technical document DCC
- RC Tracking alogs 54298, 50851, 51594, 51613, 53499
- TMS noise alogs 52071, 52118, 52204, 52224

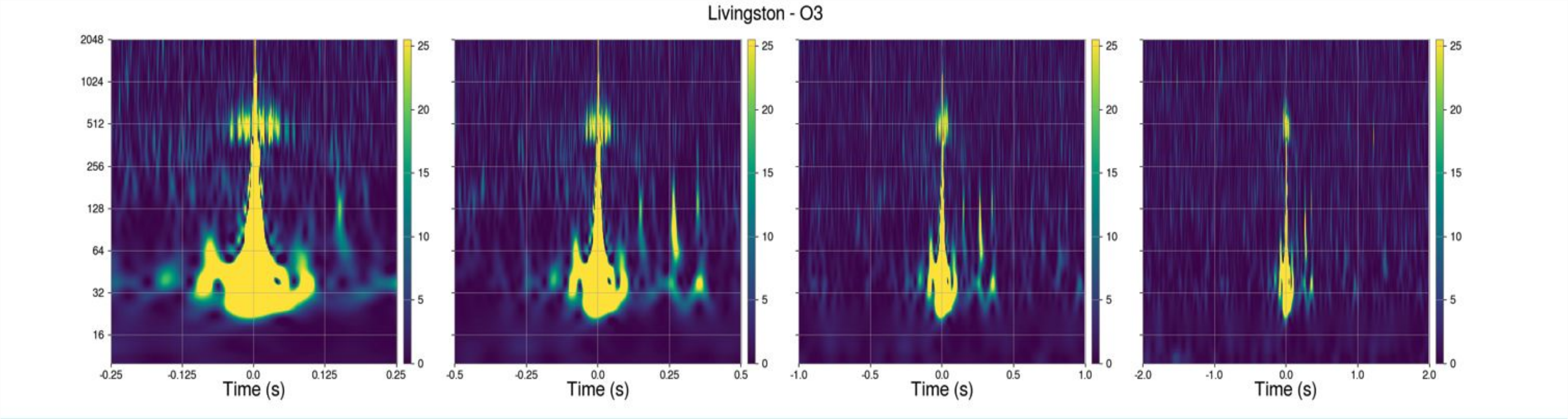
GravitySpy Retraining and Reclassification

What is GravitySpy?

- It is an image recognition algorithm based on convolutional neural networks (CNN)
- Classifies transient noise at LIGO in 23 classes/labels
- https://ldvw.ligo.caltech.edu/ldvw/gspySearch web interface of GravitySpy
- Download the data in csv format for further analysis
- GravitySpy paper
- GravitySpy guide DCC

Training set

- The algorithm is trained on time-frequency spectrograms of noise transients
- For each event, the training set contains 4 images of 0.5, 1, 2 and 4 secs.



- These 4 images are then concatenated to form a single image used for training.

Model details

- Number of layers: 5 + 1
  - 4 CNN, 1 fully connected layer + softmax output layer.
- The output of softmax layer is:

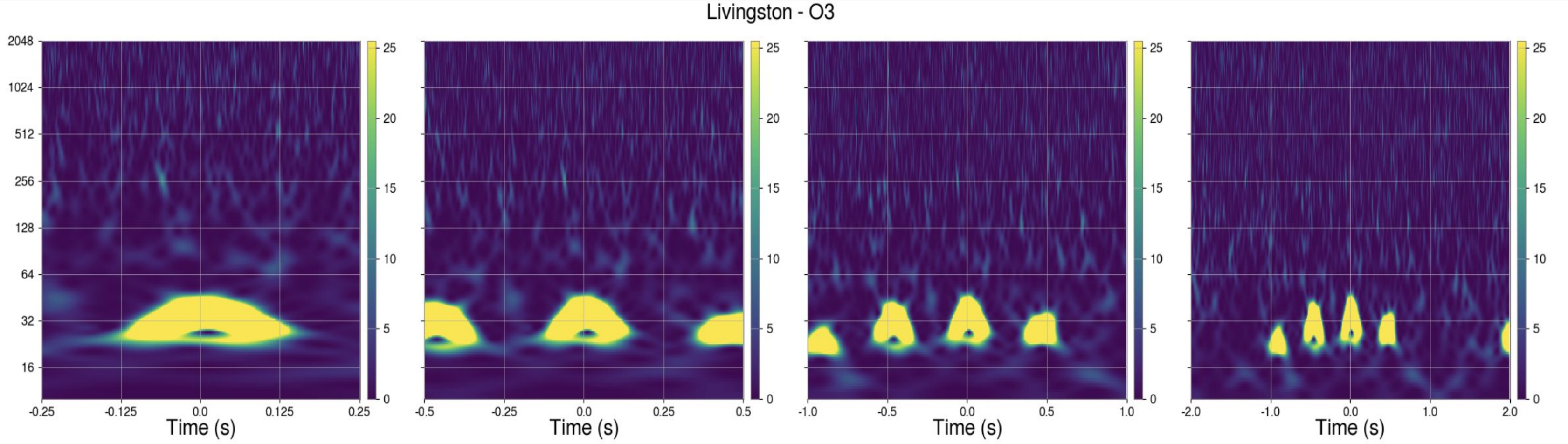
$$o_c^i = \frac{e^{w_c^T x}}{\sum_{c=1}^{C} e^{w_c^T x}}$$ for ith image, c = 1 to C, the number of classes

- Loss function : Cross entropy

$$-\sum_{i=1}^{N}\sum_{c=1}^{C} y_c^i \log o_c^i$$

y^i denotes the binary label for sample i.

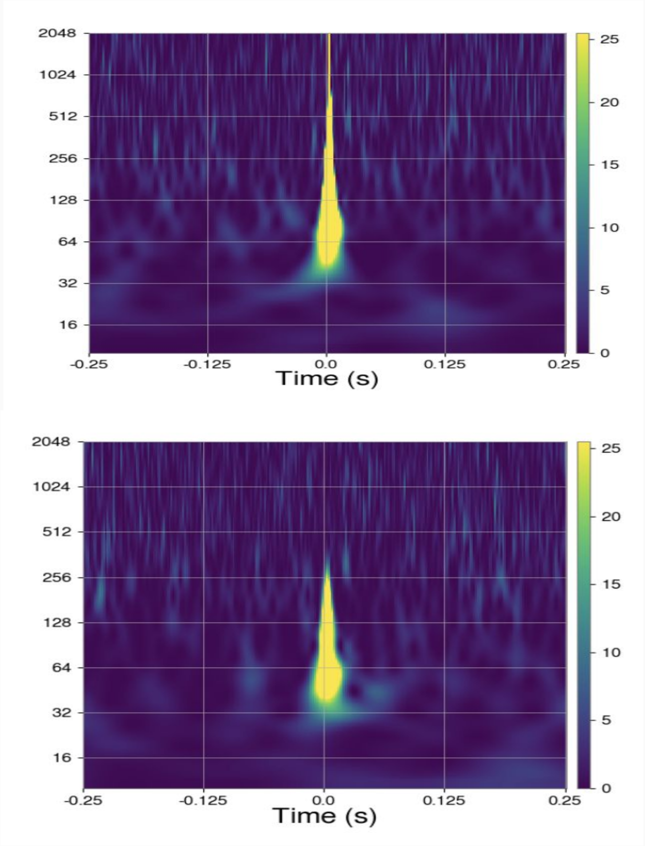
Fast scattering



Short duration fast scattering arches

- A new transient noise noticed in O3
- Strong correlation with ground motion in microseism (0.1 Hz - 0.3 Hz) and anthropogenic (1 Hz - 6 Hz) band
- Not recognized by GravitySpy, was classified as Slow Scattering or None of the Above

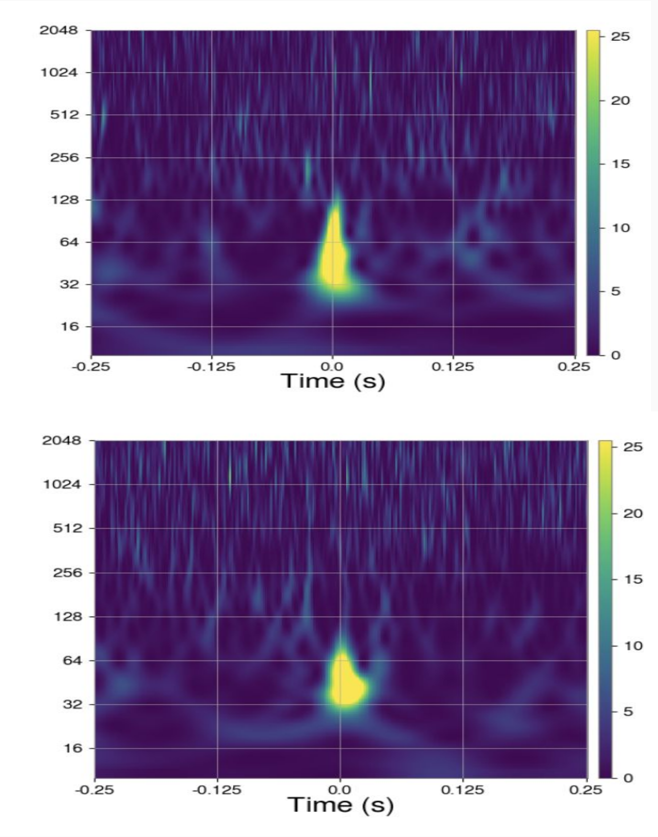
Blips and Low frequency blips



Blips

All four triggers assigned as Blips with confidence above 0.95 by the current GravitySpy model

They may have different origins due to different bandwidth



Low frequency blips

Training set

- Total 23 classes
- Addition of two new classes
  - Fast scattering
  - Low frequency blips

- Removed None of the above glitch category

```
df_fastblip2['Label'].value_counts()
```

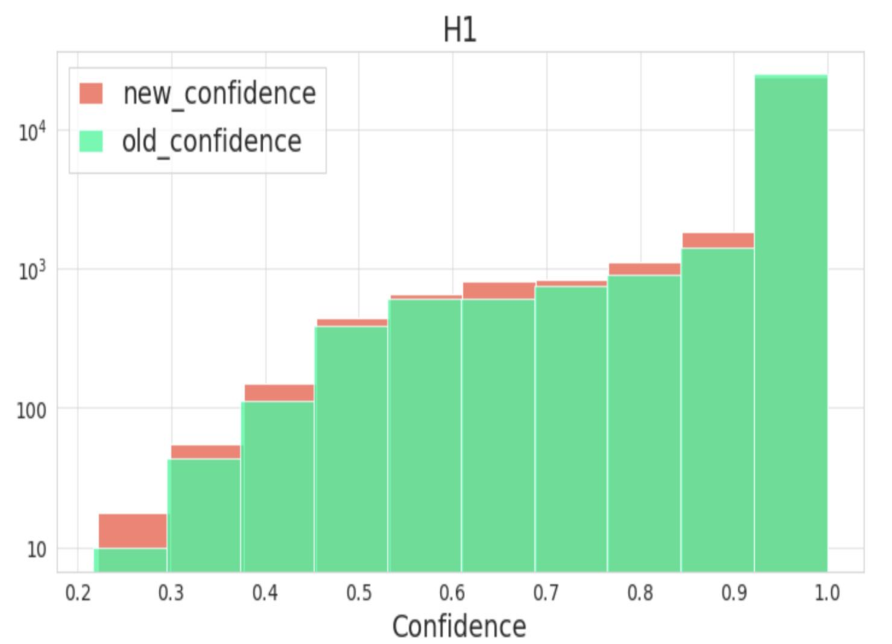
```
Blip                    1821
Koi_Fish                 706
Tomte                    703
Blip_Low_Frequency       630
Low_Frequency_Burst      621
Scattered_Light          593
Light_Modulation         512
Power_Line               449
Low_Frequency_Lines      447
Extremely_Loud           447
Violin_Mode              412
Fast_Scattering          400
Scratchy                 337
1080Lines                327
Whistle                  299
Helix                    279
Repeating_Blips          263
No_Glitch                117
1400Ripples               81
Chirp                     60
Air_Compressor            58
Wandering_Line            42
Paired_Doves              27
Name: Label, dtype: int64
```

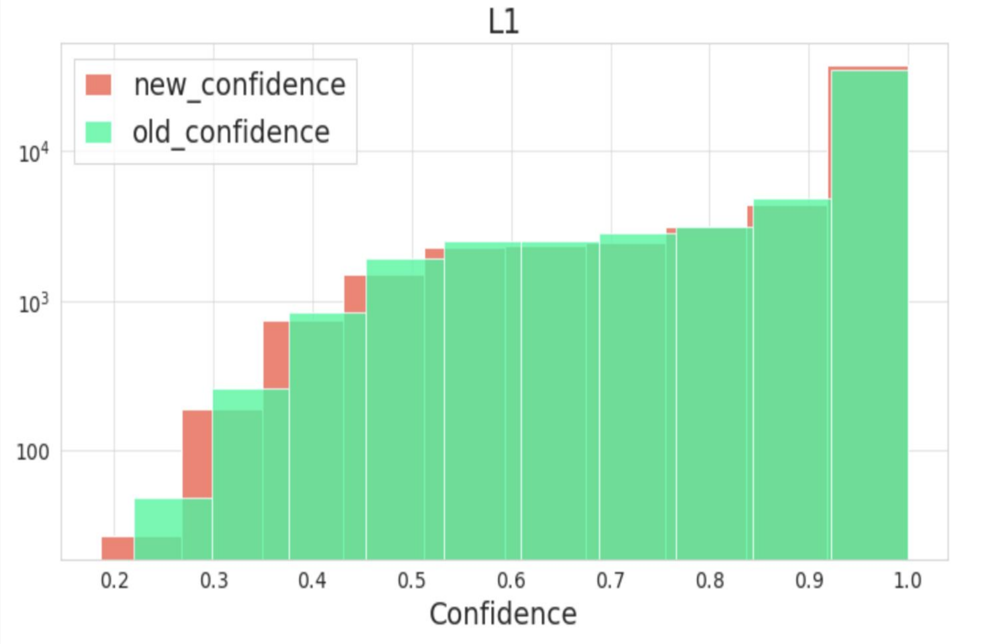
Training set

Testing on O3 sample

- Confirmed the new model is recognizing Fast Scattering and Low Frequency Blips
- Classified 20% of the O3 gravity spy triggers at L1 and H1 with the new model
- Some of the questions we can ask are:
  - Is there a big change in confidence assigned to the triggers by the new model?
  - What percentage of triggers are labelled with a different classification?
  - For triggers assigned a different class, what is the distribution of new labels?
  - Does the change make sense?

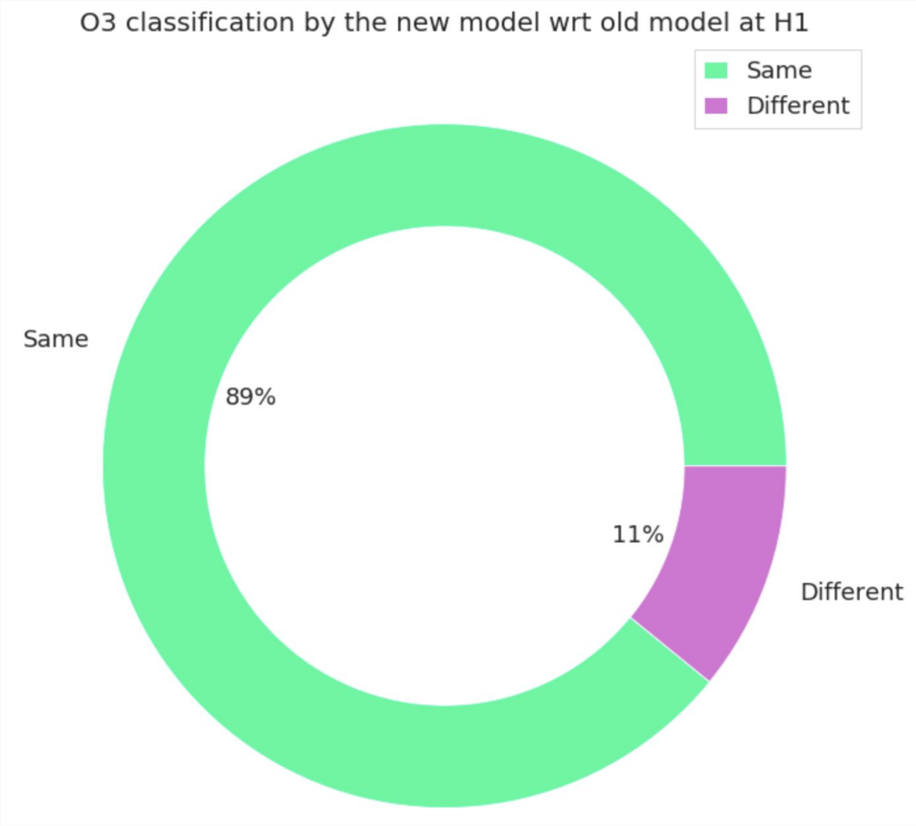
Confidence comparison

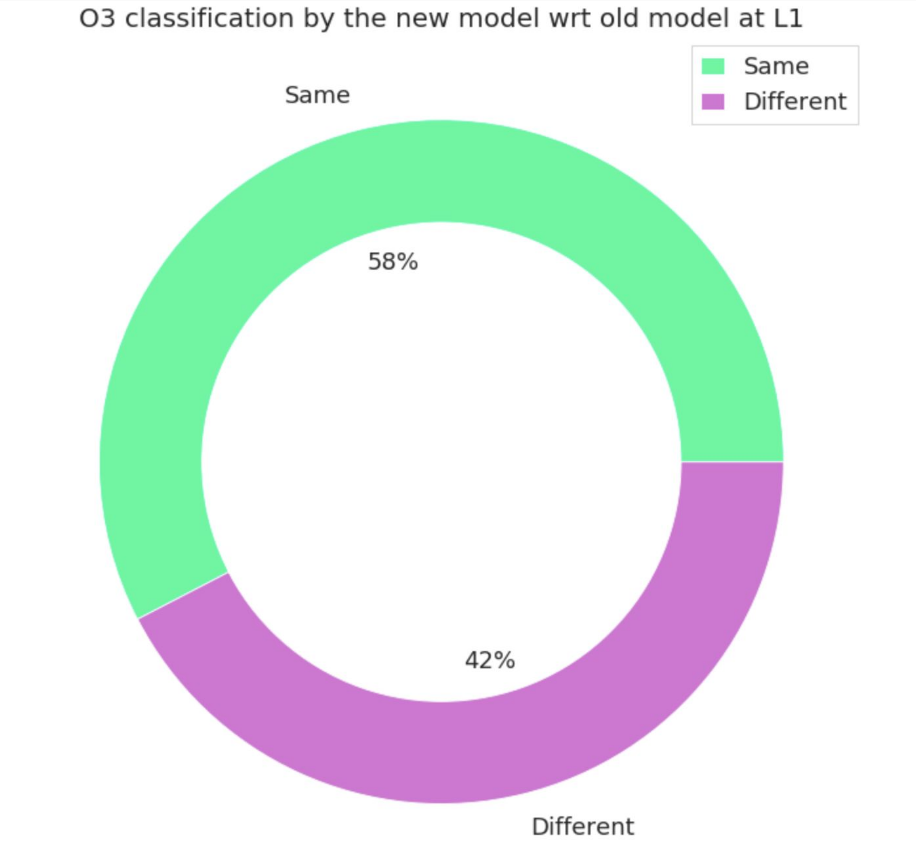




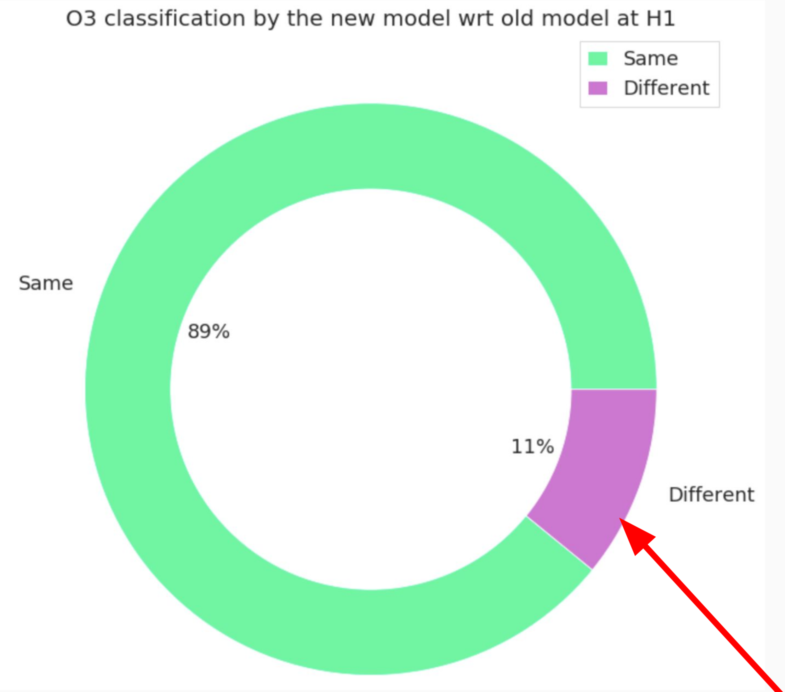
Change in confidence assigned to the glitches is minimal

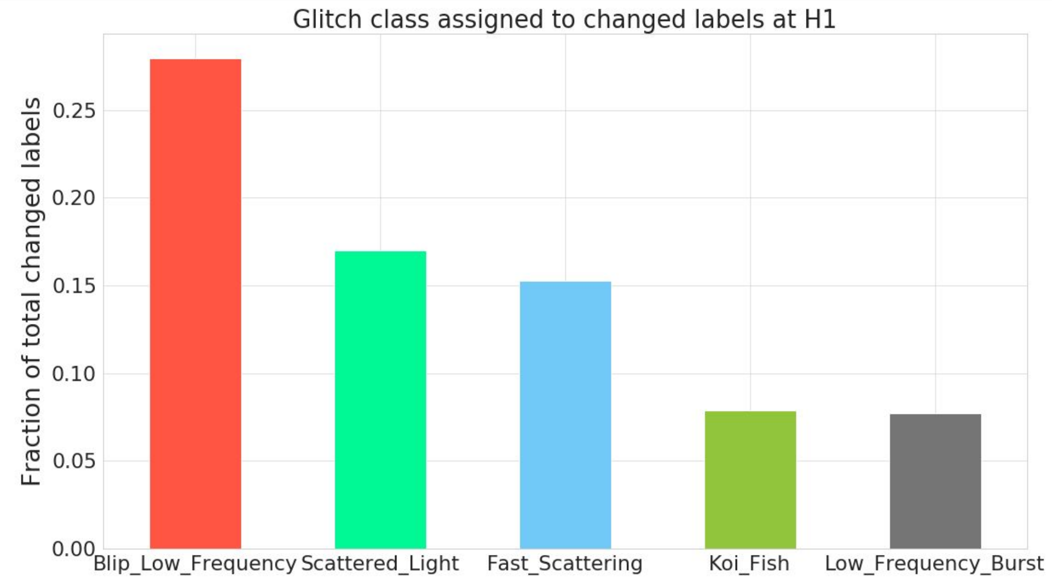
Change in class labels





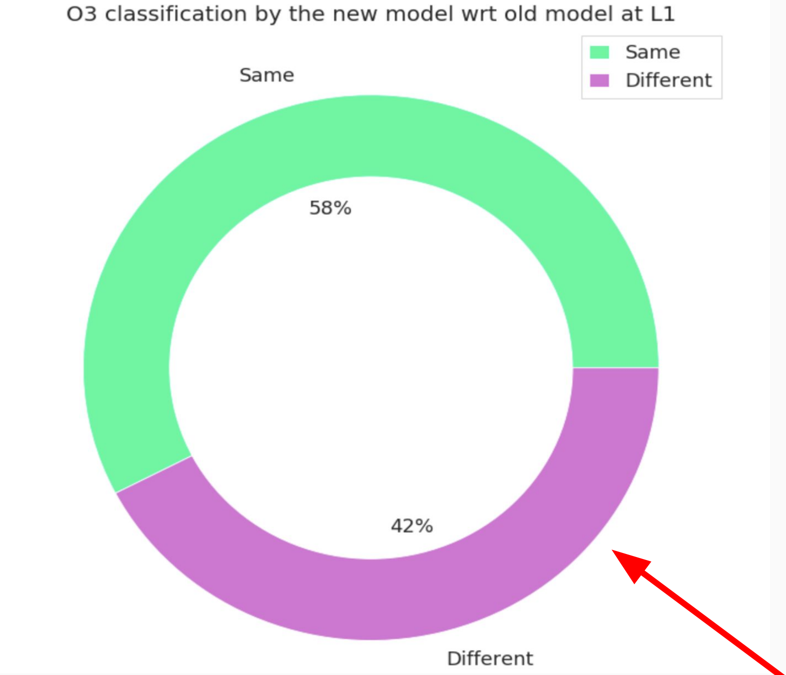
Distribution of new labels at H1

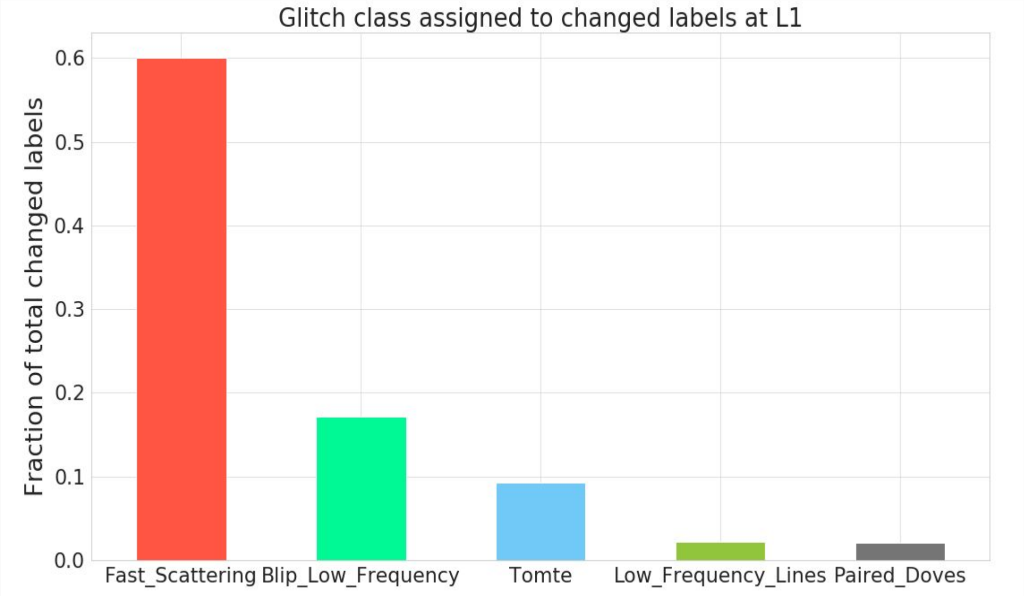




Glitch class assigned to these triggers

Distribution of new labels at L1





Glitch class assigned to these triggers

Old classification to new

- New model to identify
  - Fast scattering
  - Low frequency blips

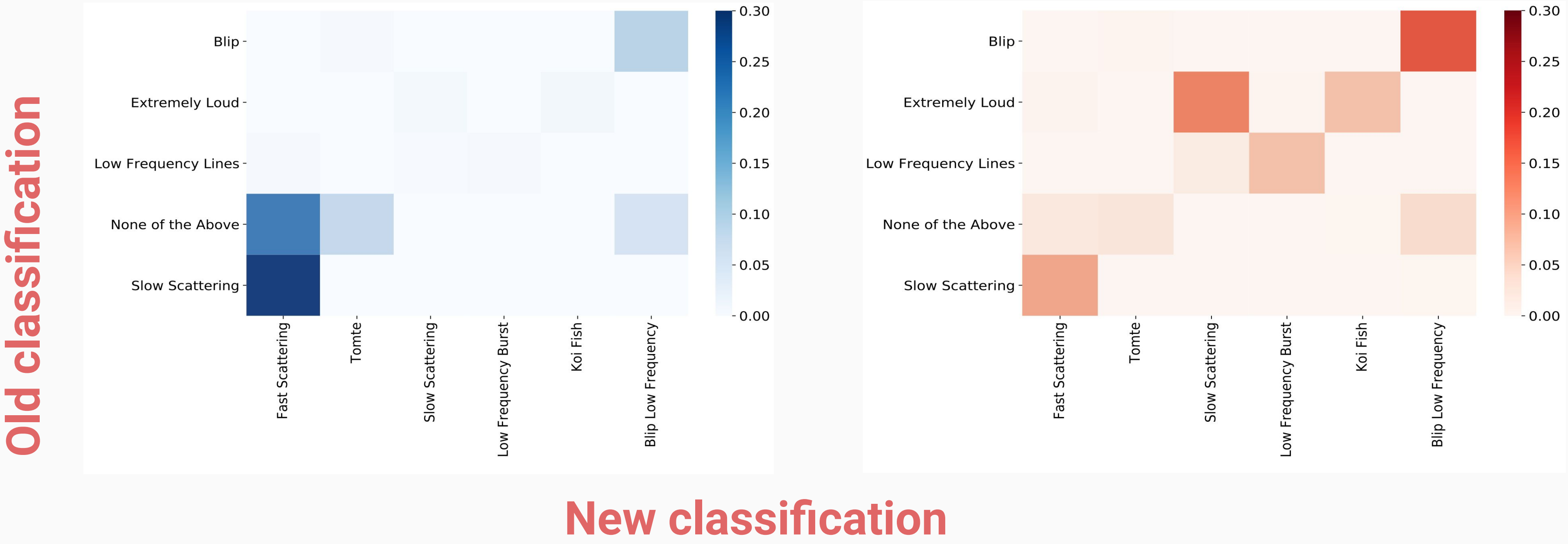
- It should not affect other classes

Heatmap on next slide

- We consider those glitches that are assigned a different glitch class by the new model

- For each old label we look at the distribution of new labels assigned

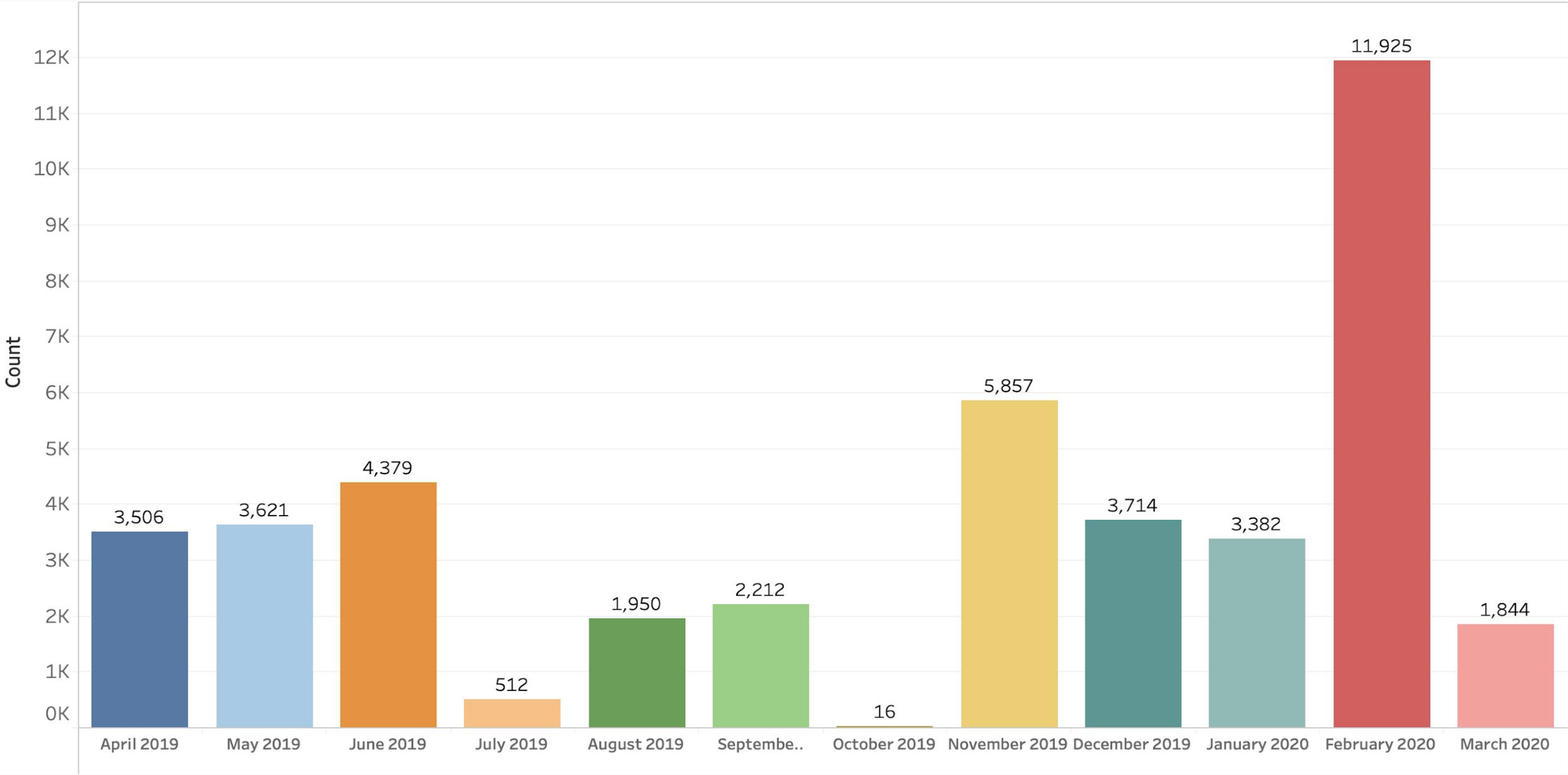
H1 old to new



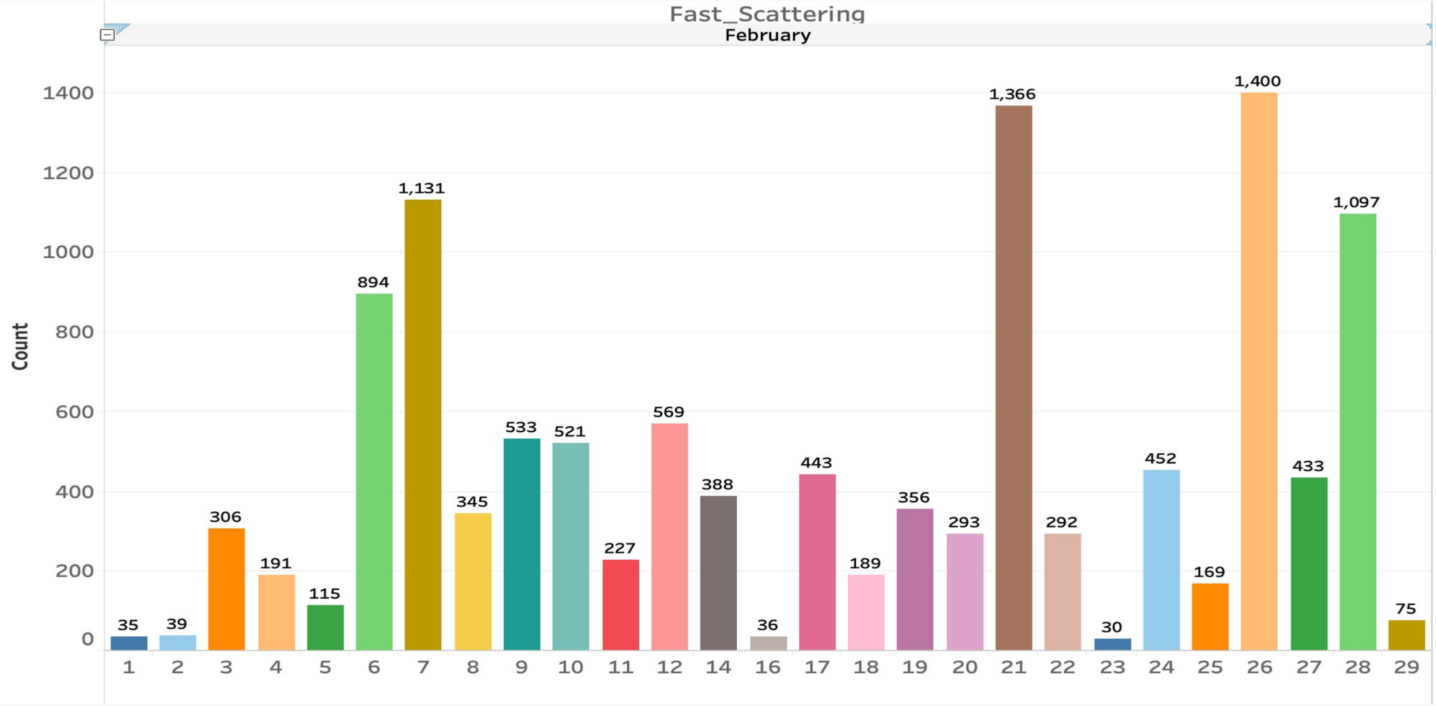
- Slow Scattering and None of the above → Fast Scattering
- No unexpected change in labels
- A fraction of Extremely_Loud triggers classified as Scattering at H1.
- Omega scans show those triggers are indeed scattered light noise.

Impact of Reclassification

Fast Scattering in O3

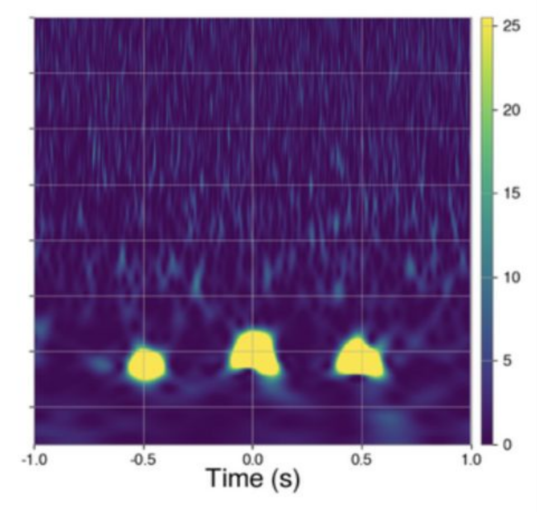


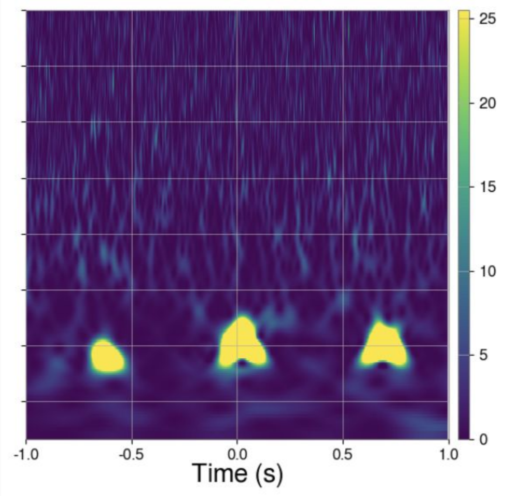
Fast Scattering in Feb 2020

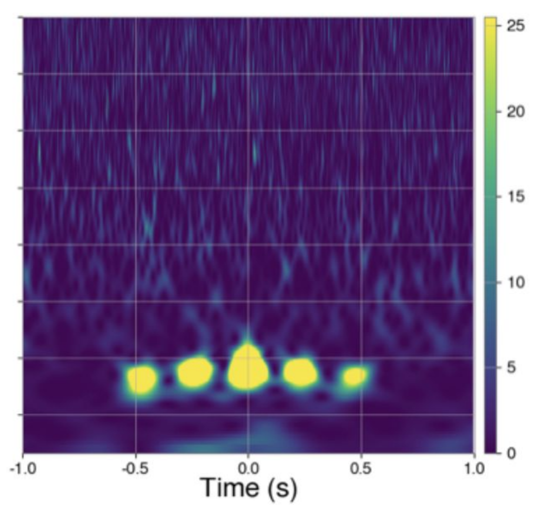


Fast scattering triggers in Feb 2020 at LLO, identified by GravitySpy with confidence above 0.9

Types of Fast scatter







Non 4 Hz fast scatter

- Correlates with ground motion in the microseism band
- Dominant type of scatter on Feb 6, Feb 14, Feb 21 at LLO

LVC talk [DCC]

4 Hz fast scatter

- Correlates with motion in anthropogenic band (1 Hz - 6 Hz) band
- Trains near the Y end at LLO, thunderstorms near the site, delivery trucks shake the ground

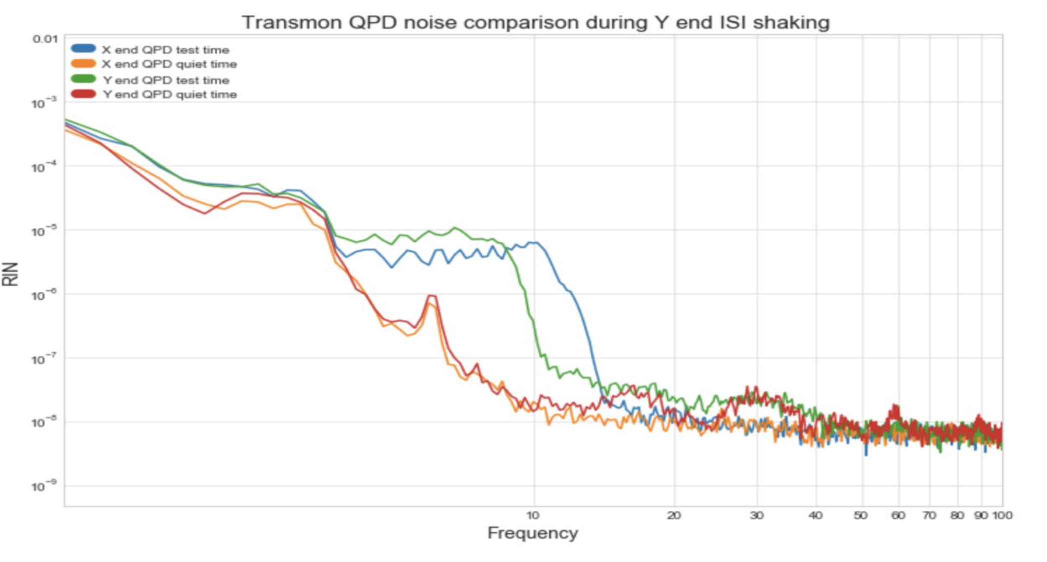
Summary

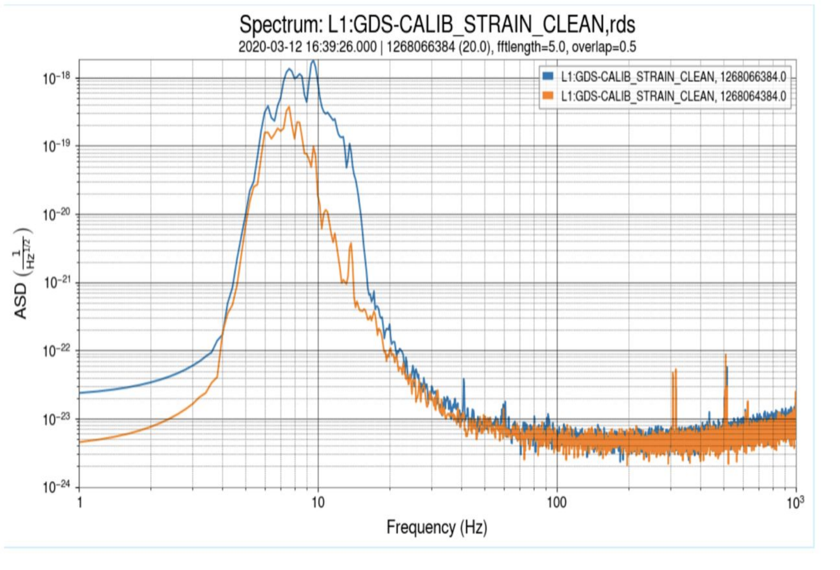
- Retrained GravitySpy to identify Fast Scattering and Low frequency Blips
- Reclassified the O3 data with the new model
- Improved characterization of Fast Scattering
- GravitySpy paper draft at DCC
- LVC talk on Fast Scattering DCC
- GravitySpy guide DCC

Thank You!
Questions?

Extra Slides

ISI shaking test





- Test confirmed noise in DARM and TMS
- TMS tracking before O4
- alogs 52204, 52118

```
[11]:  Blip                     1821
       Koi_Fish                  706
       Low_Frequency_Burst       621
       Light_Modulation          512
       Power_Line                449
       Extremely_Loud            447
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       Air_Compressor             58
       Wandering_Line             42
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       Name: true_label, dtype: int64
```

Old training set

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1400Ripples              81
Chirp                    60
Air_Compressor           58
Wandering_Line           42
Paired_Doves             27
Name: Label, dtype: int64
```

New training set

Testing on Fast scattering and Low frequency Blips

- Randomly sample 100 triggers currently classified as **Scattering** at L1 by GravitySpy between June, 1, 2019 and June, 30, 2019, with q between 8 and 14

- The new model classified all of them as **Fast Scattering**

- Random visual inspection of the omega scans of these 100 triggers to confirm correct classification

- These scans are stored here

Fast_Scattering

- Randomly sampled 79 triggers currently classified as **Blip** at L1 by GravitySpy between Feb, 1, 2020 and Mar, 1, 2020 with peak frequency between 10 and 50 Hz

- The new model classified 78 of these as **Blip_Low_Frequency** and 1 as **Tomte**

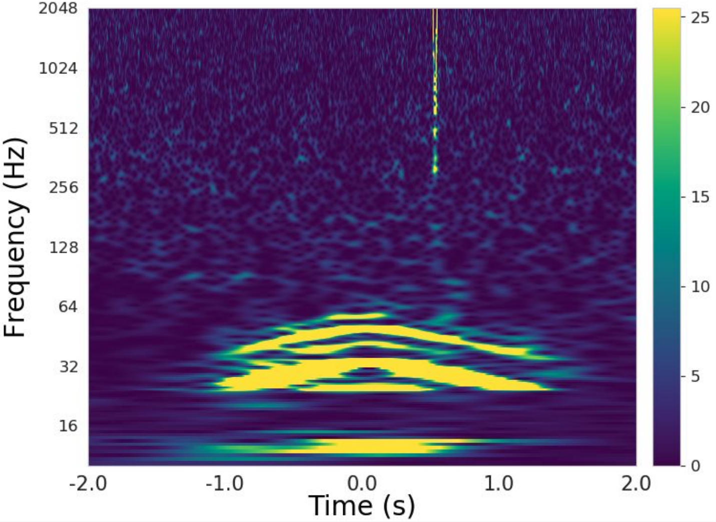
- Visually inspected the scans

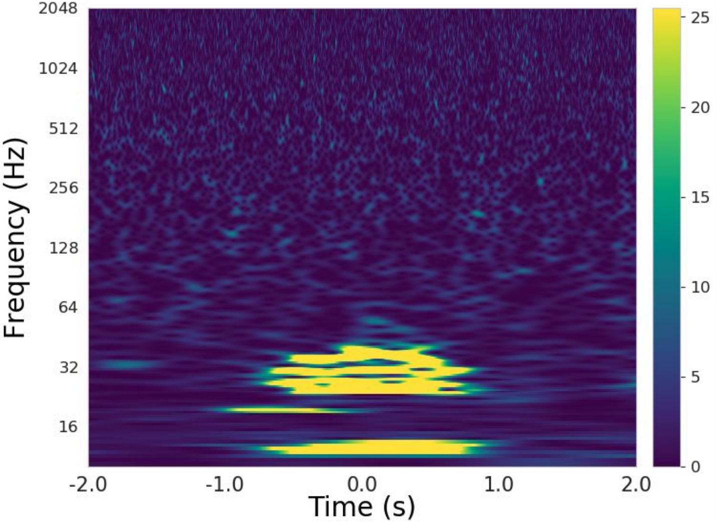
- These scans are stored here

Blip_Low_Frequency

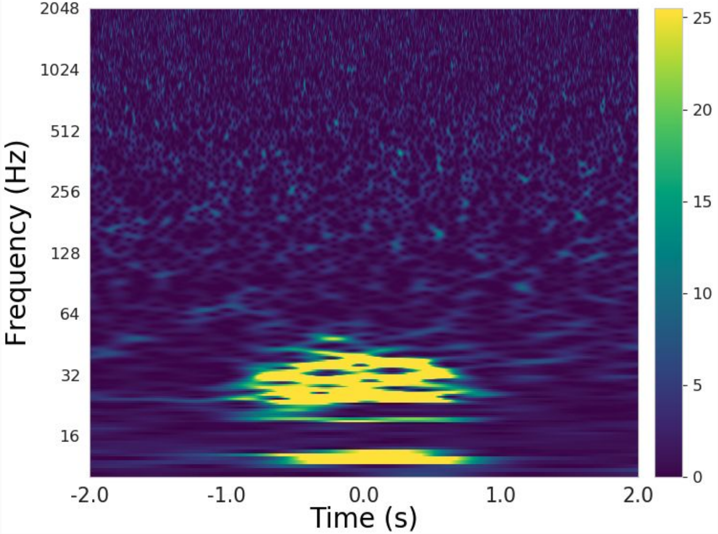
Training set

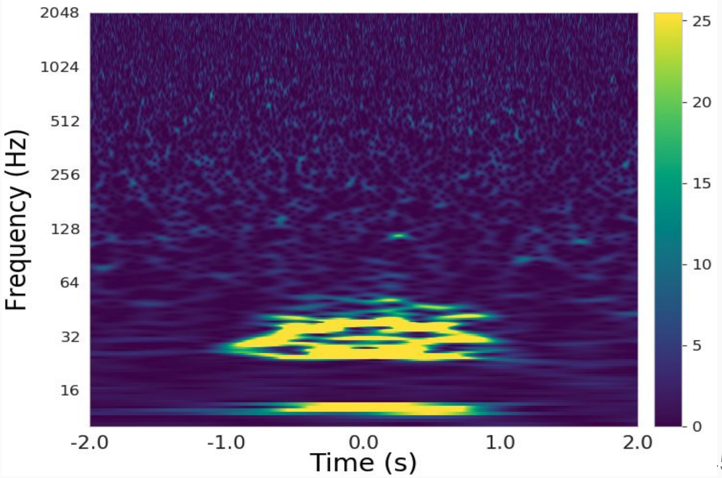
- All training images taken from O3 classification are with confidence above 0.95
- For fast scattering, 400 triggers currently classified as scattering with Q-value between 8 and 14
- For low frequency blips, 630 Blips with peak frequency between 10 and 50 Hz
- 150 slow scattering (Scattered_Light) images
- 300 Tomte
- Removed None_of_the_Above
- Valid acc: 0.988, Training acc: 0.999

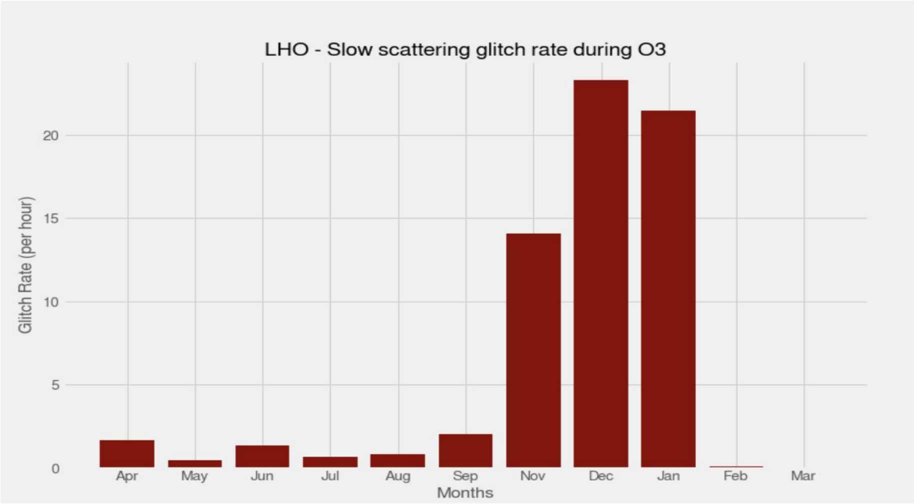


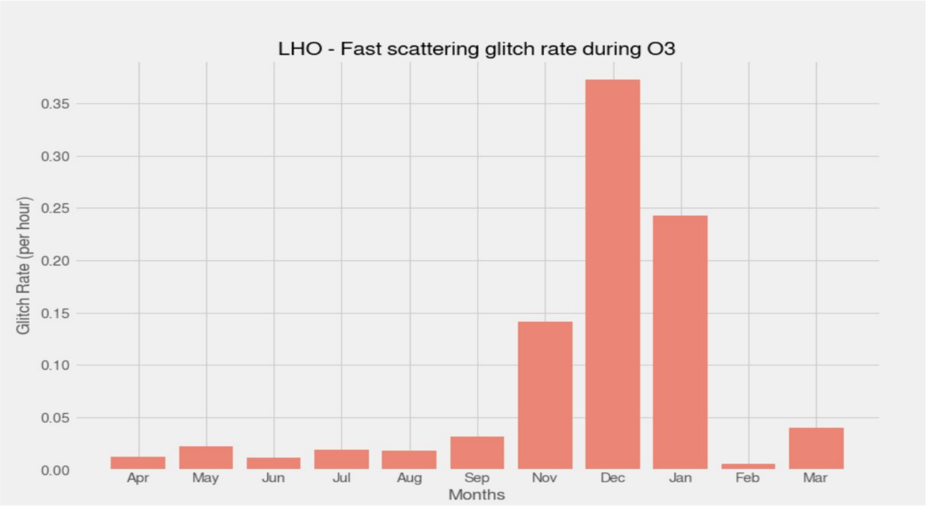


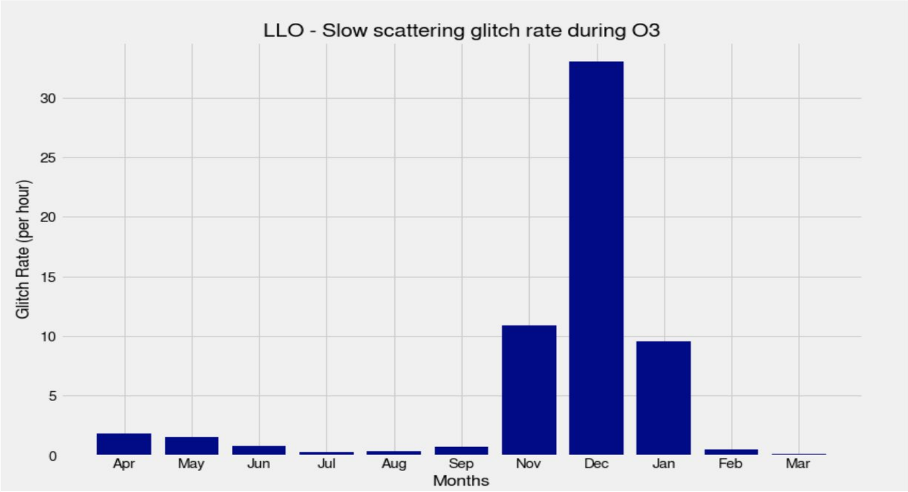
Scattered_Light triggers wrongly classified as Extremely_Loud by the older model

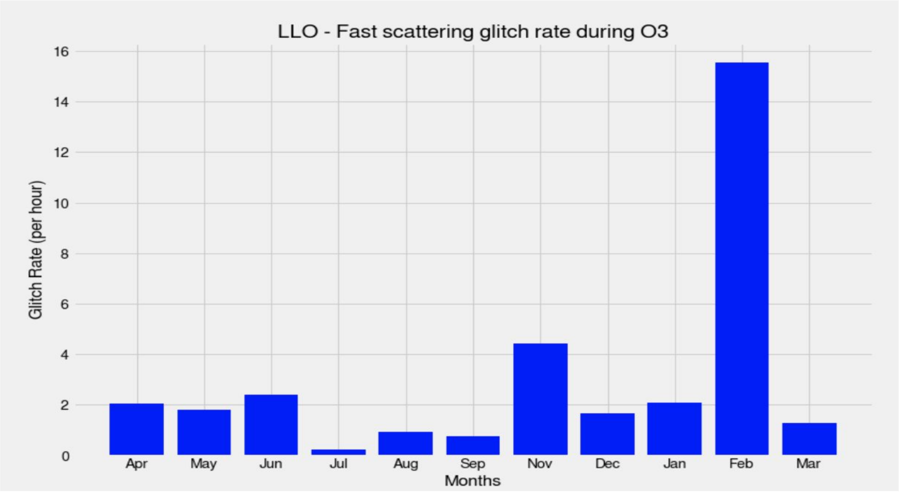





LHO - Slow scattering glitch rate during O3
Glitch Rate (per hour)
0
5
10
15
20
Apr
May
Jun
Jul
Aug
Sep
Nov
Dec
Jan
Feb
Mar
Months


LHO - Fast scattering glitch rate during O3
Glitch Rate (per hour)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Apr
May
Jun
Jul
Aug
Sep
Nov
Dec
Jan
Feb
Mar
Months

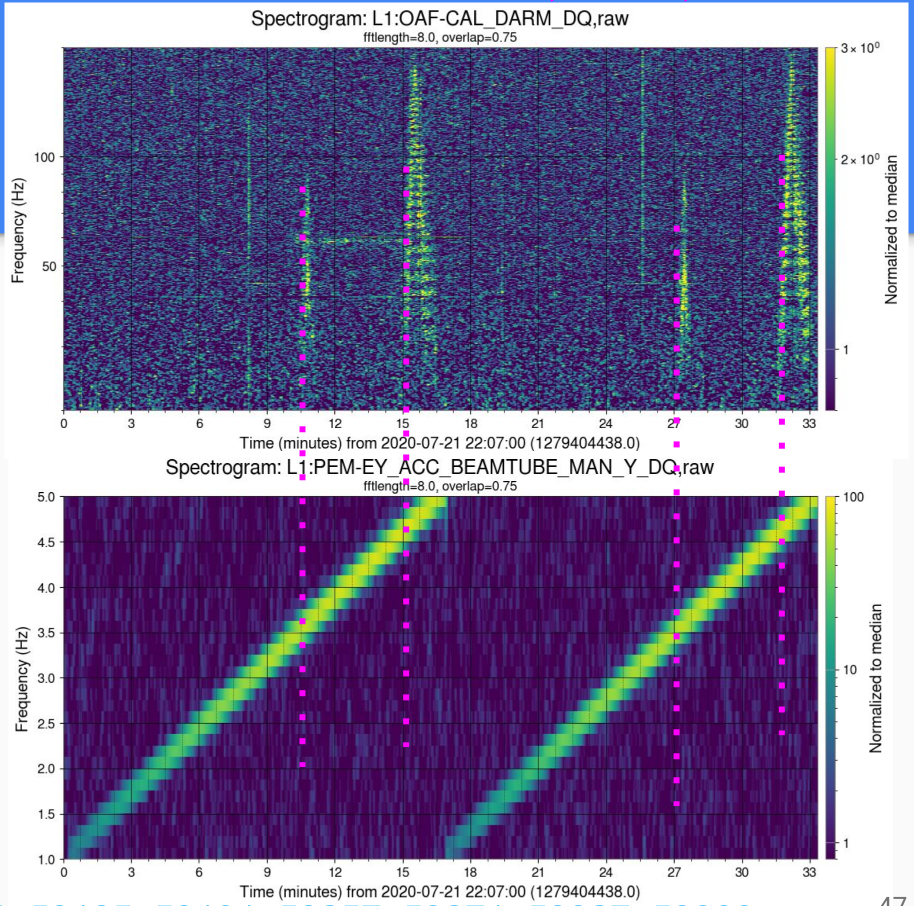

LLO - Slow scattering glitch rate during O3
Glitch Rate (per hour)
0
5
10
15
20
25
30
Apr
May
Jun
Jul
Aug
Sep
Nov
Dec
Jan
Feb
Mar
Months


LLO - Fast scattering glitch rate during O3
Glitch Rate (per hour)
0
2
4
6
8
10
12
14
16
Apr
May
Jun
Jul
Aug
Sep
Nov
Dec
Jan
Feb
Mar
Months

Cryo Baffle Resonances

EX has 4.10 Hz, Q~2000
Corner (ITMY) has 3.825 and 4.191, Q~ 70, 2000

EY has 3.49 and 4.62 Hz, Q~140, 440



During the EY vent at L1, we plan to damp the cryo baffle, and retest.
If successful, propagate to all stations including H1

alogs: 53364, 53025, 53057, 53062, 53077, 53131, 53166, 53185, 53191, 53257, 53271, 53327, 53309

Noise in TMS PD’s