Investigation of the scattered light noise in KAGRA interferometer

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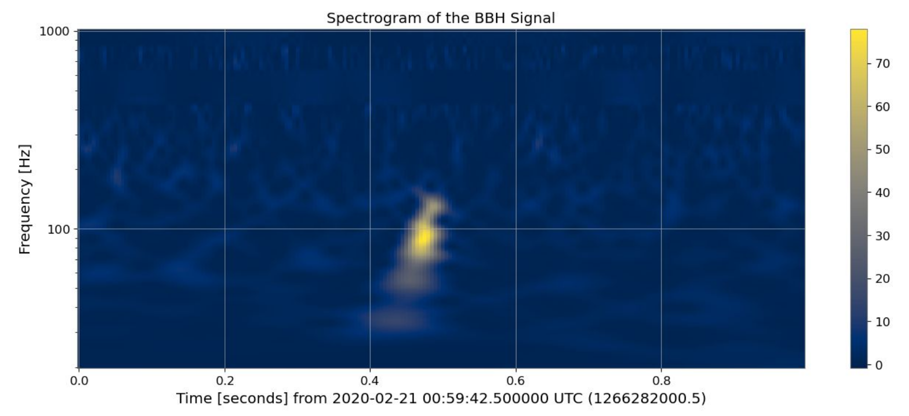
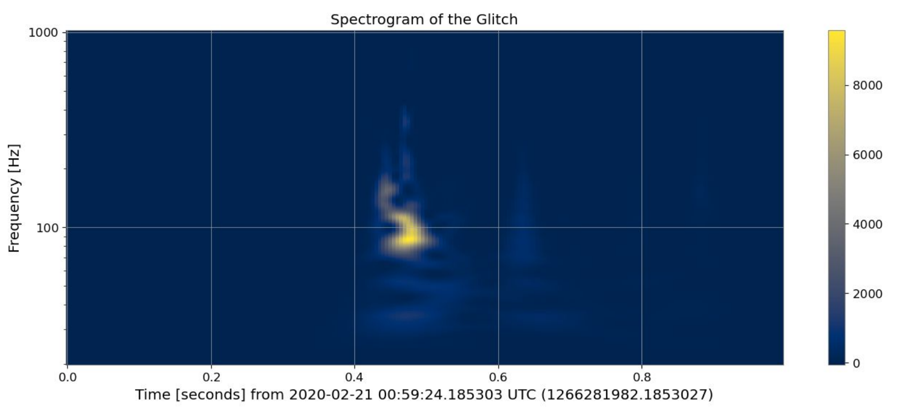
KAGRA

Introduction & Motivation

Transient & Non-gaussian noise - Glitches



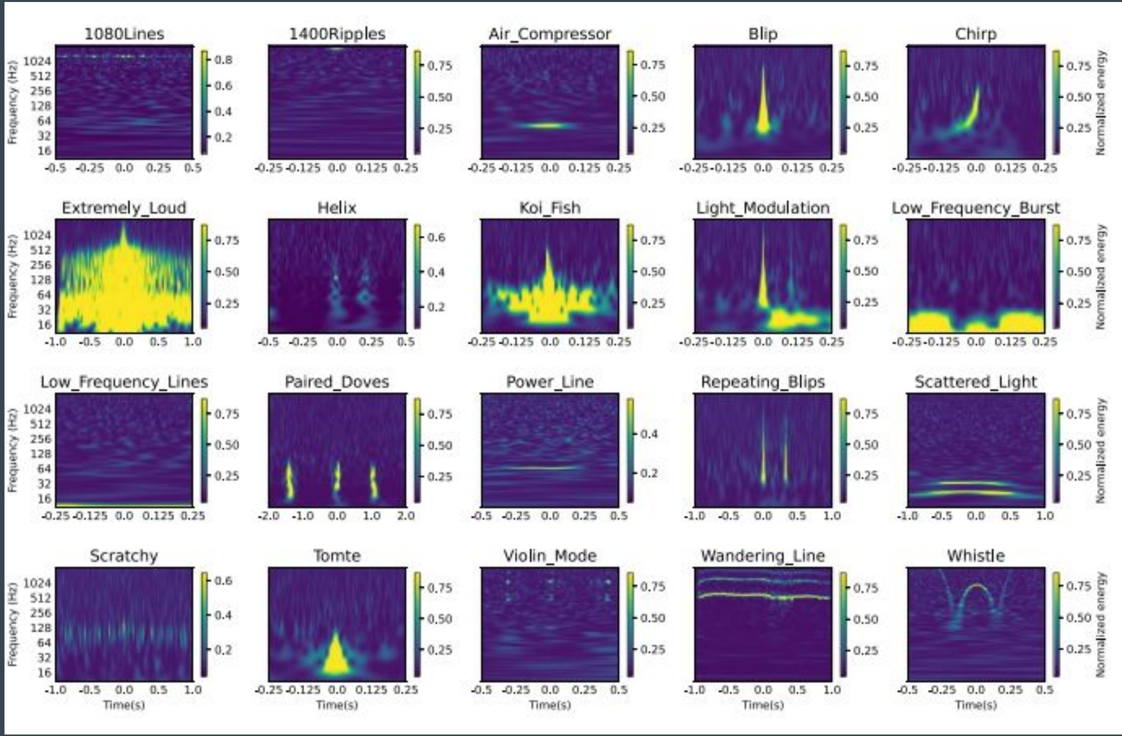
Gravitational wave signal in LIGO-Hanford



Glitch in LIGO-Hanford

Introduction & Motivation

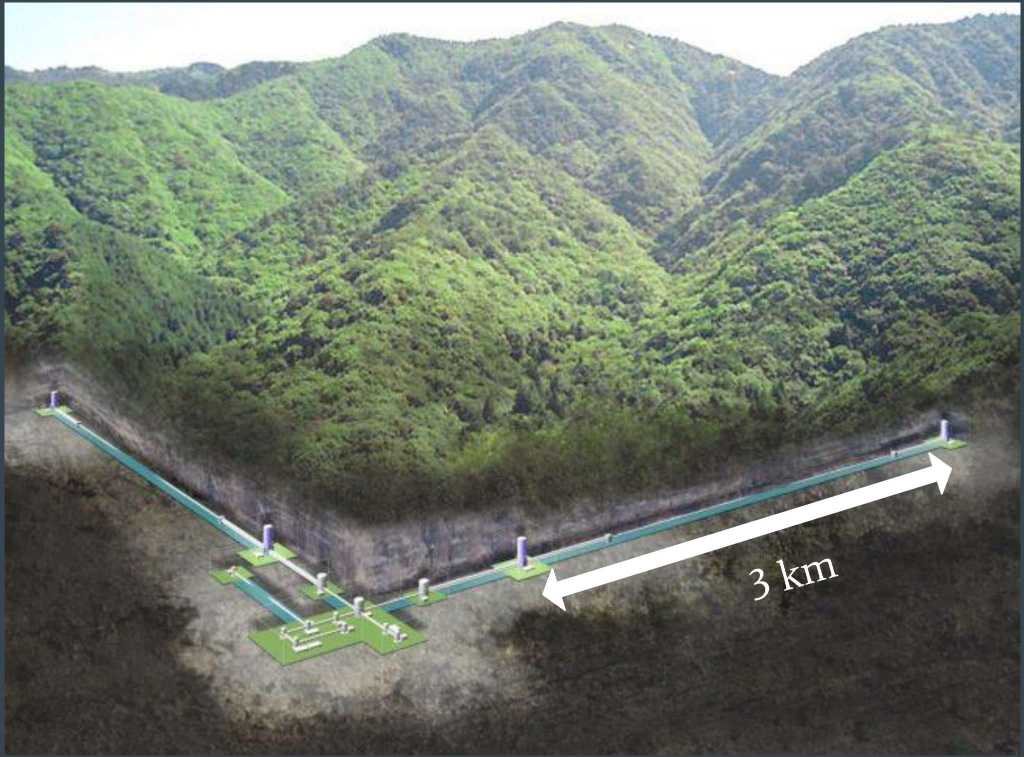
Different kinds of Glitches in LIGO O3 run



Class. Quantum Grav. 40 (2023) 195018 (23pp)

Introduction & Motivation – KAGRA

KAGRA: Large-scale Cryogenic Gravitational Wave Telescope



Location:

- Gifu prefecture, Japan
- Underground: small seismic motion

Cryogenic:

- 20 K: reduce the thermal noise
- Sapphire mirror

Interferometer:

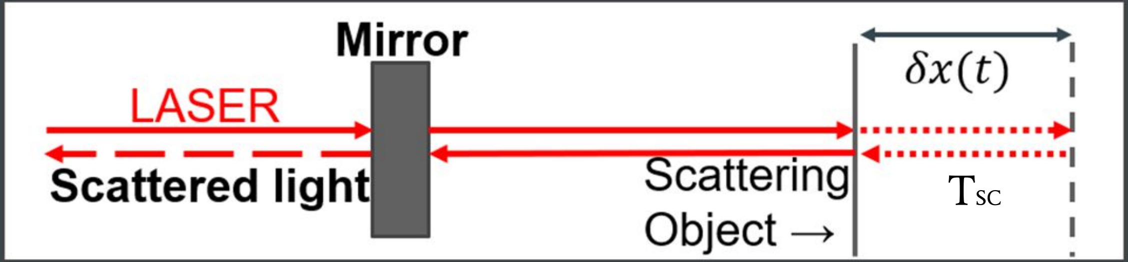
- Michelson
- Fabry-Perot: 3 km cavity

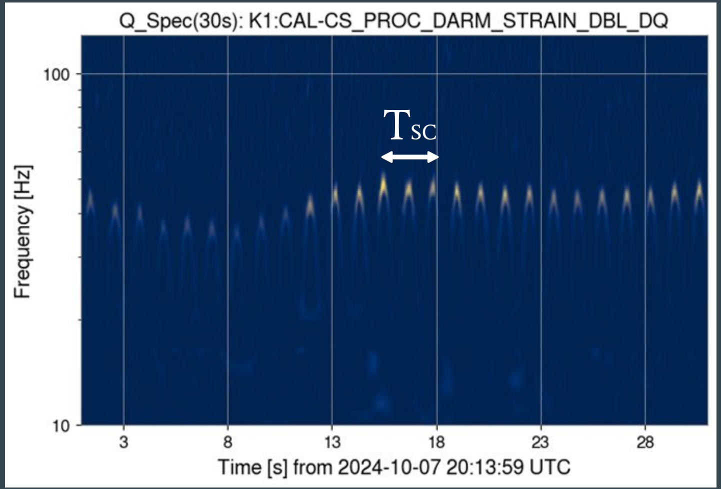
Introduction & Motivation – Scattered light noise in KAGRA

Scattered light noise in interferometers

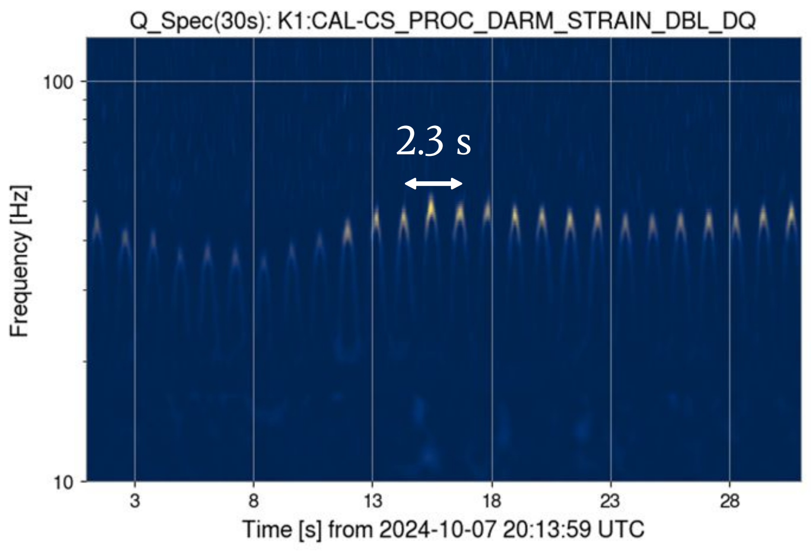
- The recoupling of diffused light from scattering objects.
- Sequence of arch-shapes in time-frequency map. e.g. Q-spectrogram.
- The model of scattering light noise in time domain[1] is $h_{sc}(t) = G \sin\left(\frac{4\pi}{\lambda}\left(x_0 + \delta x_{sc}(t)\right)\right)$
- Time variation of frequency $f_{\text{arch}}(t) = \left|2\frac{\delta\dot{x}_{sc}}{\lambda}\right| = \left|2\frac{v_{sc}(t)}{\lambda}\right|$

[1] M Wąs et al 2021 Class. Quantum Grav. 38 075020





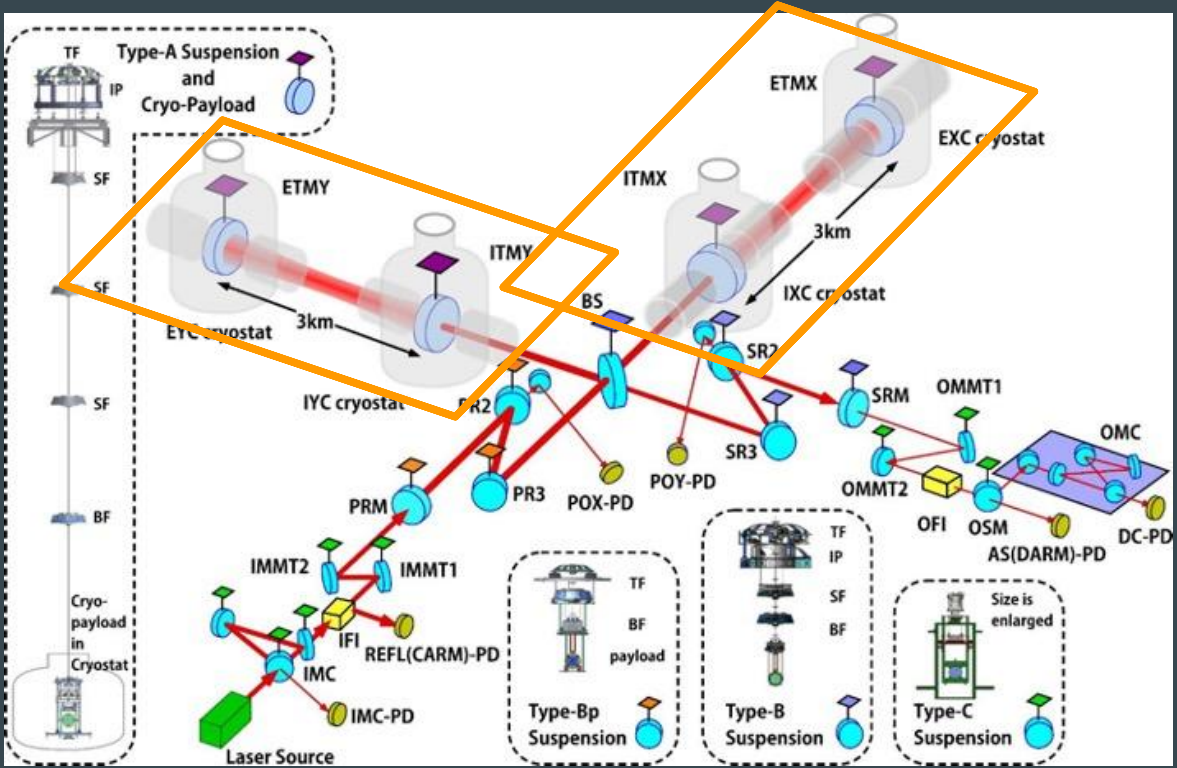
Introduction & Motivation – Scattered light noise in KAGRA



In KAGRA:

- Being seen in the strain signal from O4a run (2023.5.23 ~ 2023.6.21)
- Sensitivity contamination of 30 ~ 100 Hz
- Locally periodic occurring in T_{sc} = 2.3 s or f_{sc} = 0.43 Hz
  → movement of scattering objects
- Type-Bp suspension resonant frequency: 0.42 Hz

Introduction & Motivation – Scattered light noise in KAGRA



DARM (orange)

- Differential arm length
- Readout of GW signal
- Michelson + Fabry-Perot interferometer

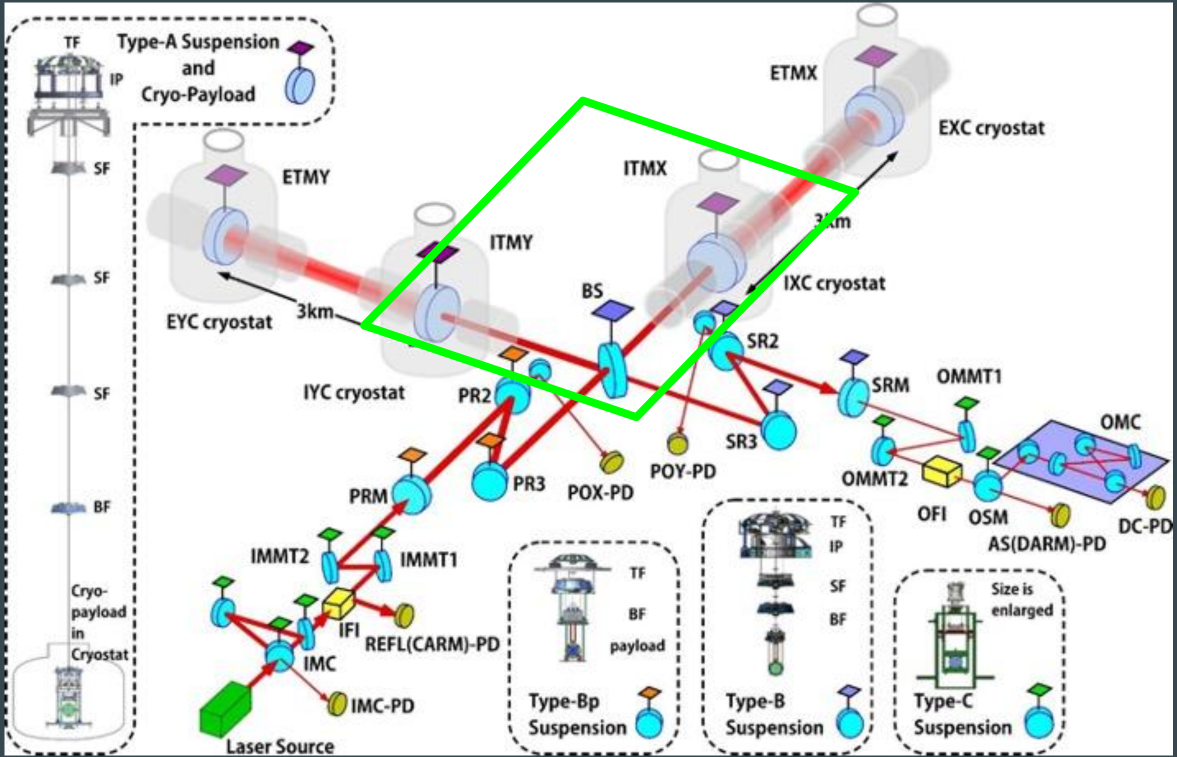
MICH

- Michelson interferometer
- BS / ITMX / ITMY

PRCL

- Power recycling
- PRM / PR2 / PR3
- Type-Bp suspension (0.42Hz)

Introduction & Motivation – Scattered light noise in KAGRA

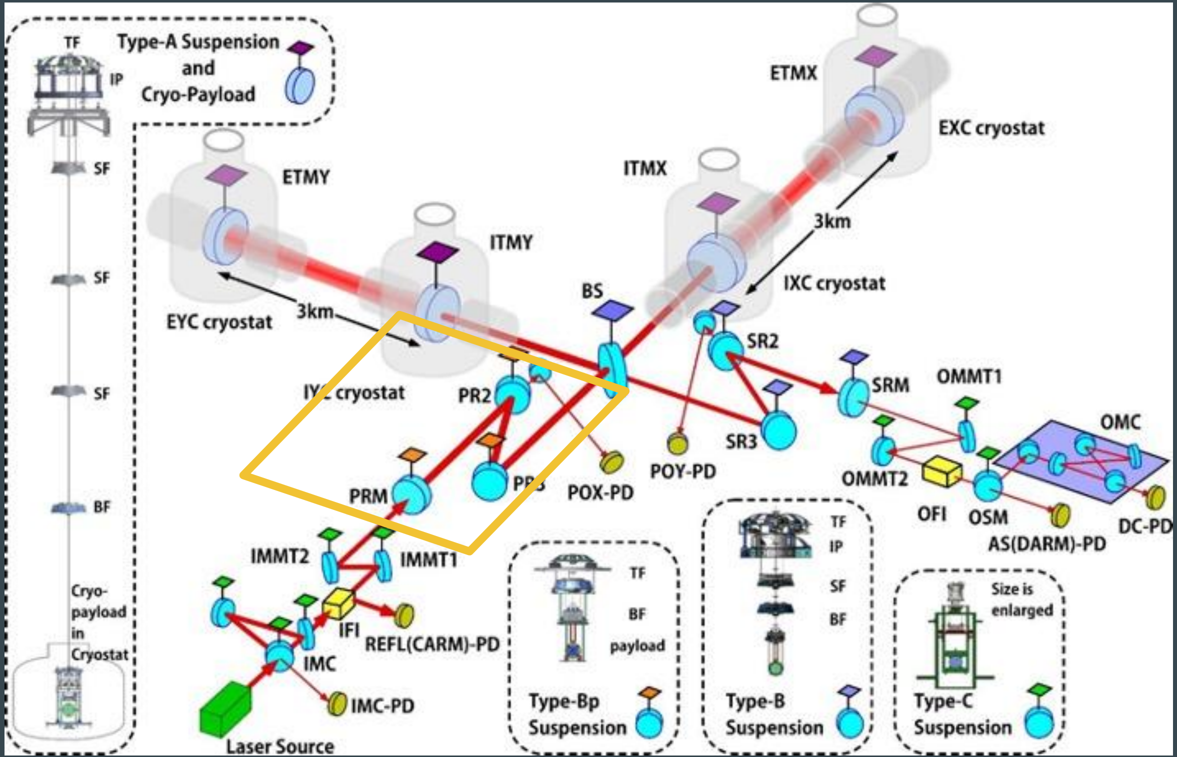


DARM
- Differential arm length
- Readout of GW signal
- Michelson + Fabry-Perot interferometer

MICH (green)
- Michelson interferometer
- BS / ITMX / ITMY

PRCL
- Power recycling
- PRM / PR2 / PR3
- Type-Bp suspension (0.42Hz)

Introduction & Motivation – Scattered light noise in KAGRA



DARM

- Differential arm length
- Readout of GW signal
- Michelson + Fabry-Perot interferometer

MICH

- Michelson interferometer
- BS / ITMX / ITMY

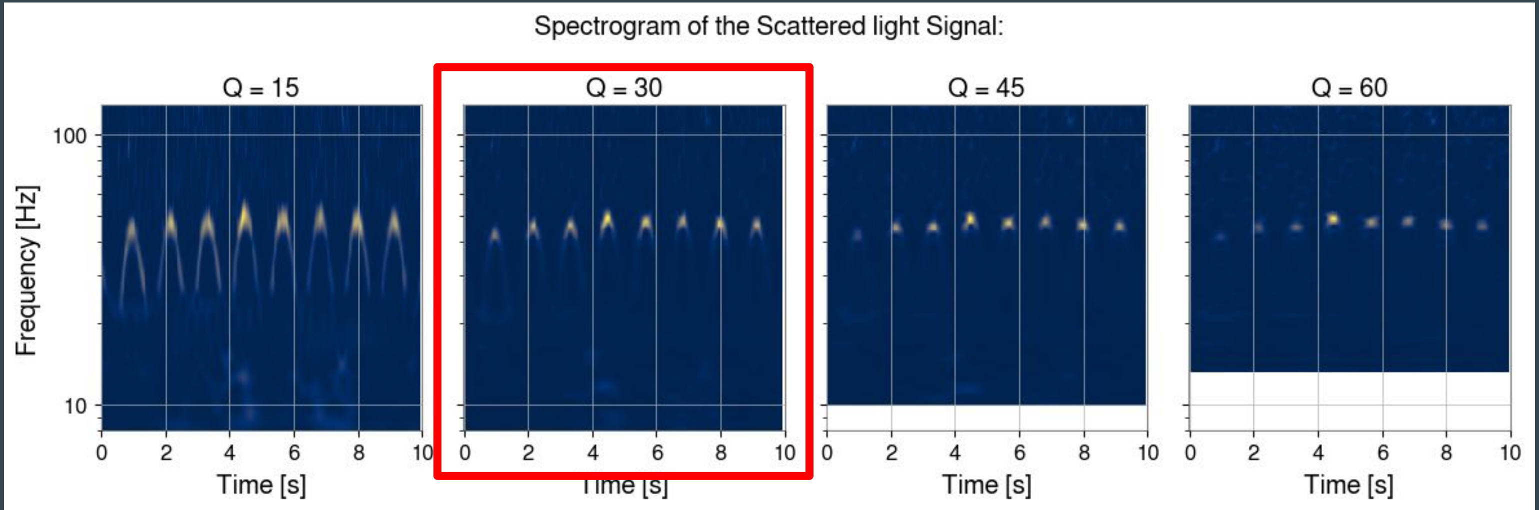
PRCL (yellow)

- Power recycling
- PRM / PR2 / PR3
- Type-Bp suspension (0.42Hz)

Method – Q-transform & Q-Spectrogram

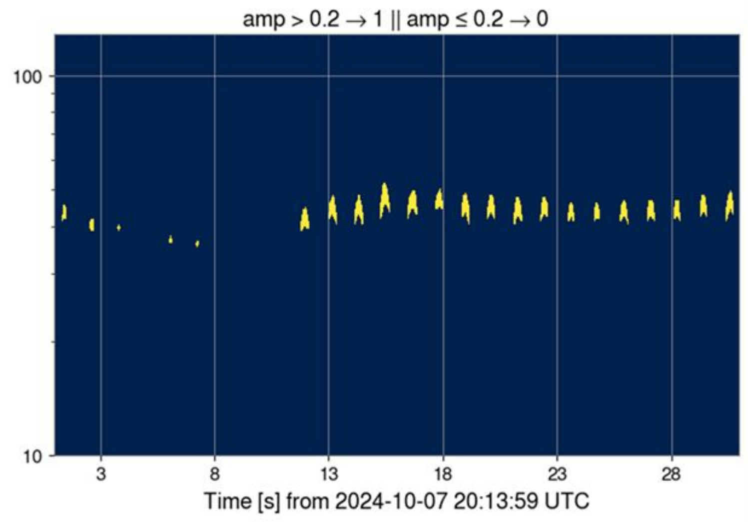
Trade-off of resolution (δf or δt, tile size in spectrogram)

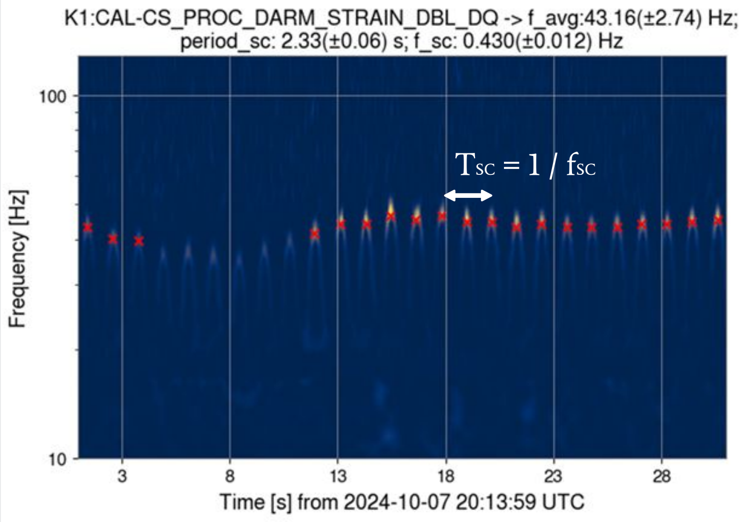
- Fourier transform: $\delta f \to 0$; $\delta t \to \infty$
- FFT spectrogram: $\delta f \to 1 / dt$ (window length); $\delta t \to dt \Rightarrow$ fixed resolution
- Constant Q-transform: $\delta f \to f / Q$; $\delta t \to Q / f \Rightarrow$ **Flexible resolution**



Method – Labeling: More Accurate Occurrence Frequency

Prepare 30 s Q-spectrograms → Normalization → Binary amplitude by a threshold → Labeling the arches → Longest consecutive arch-sequence → Scattering light noise frequency





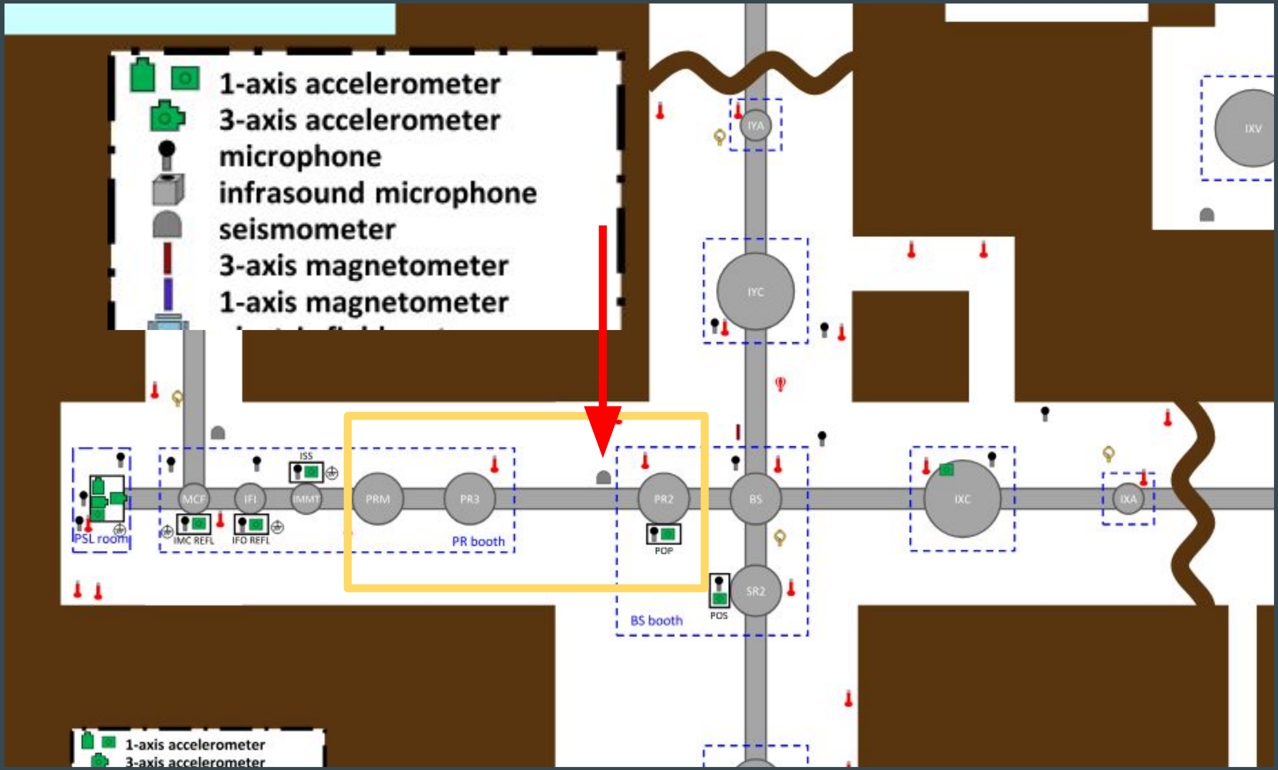
Output:

- T_{SC}, σ_t
- f_{SC}, σ_f

Constraints to the Scattered light (SL):

- $\sigma_t < 0.3$ s
- $0.3 < f_{SC} < 0.5$ Hz

Method – Seismic motion



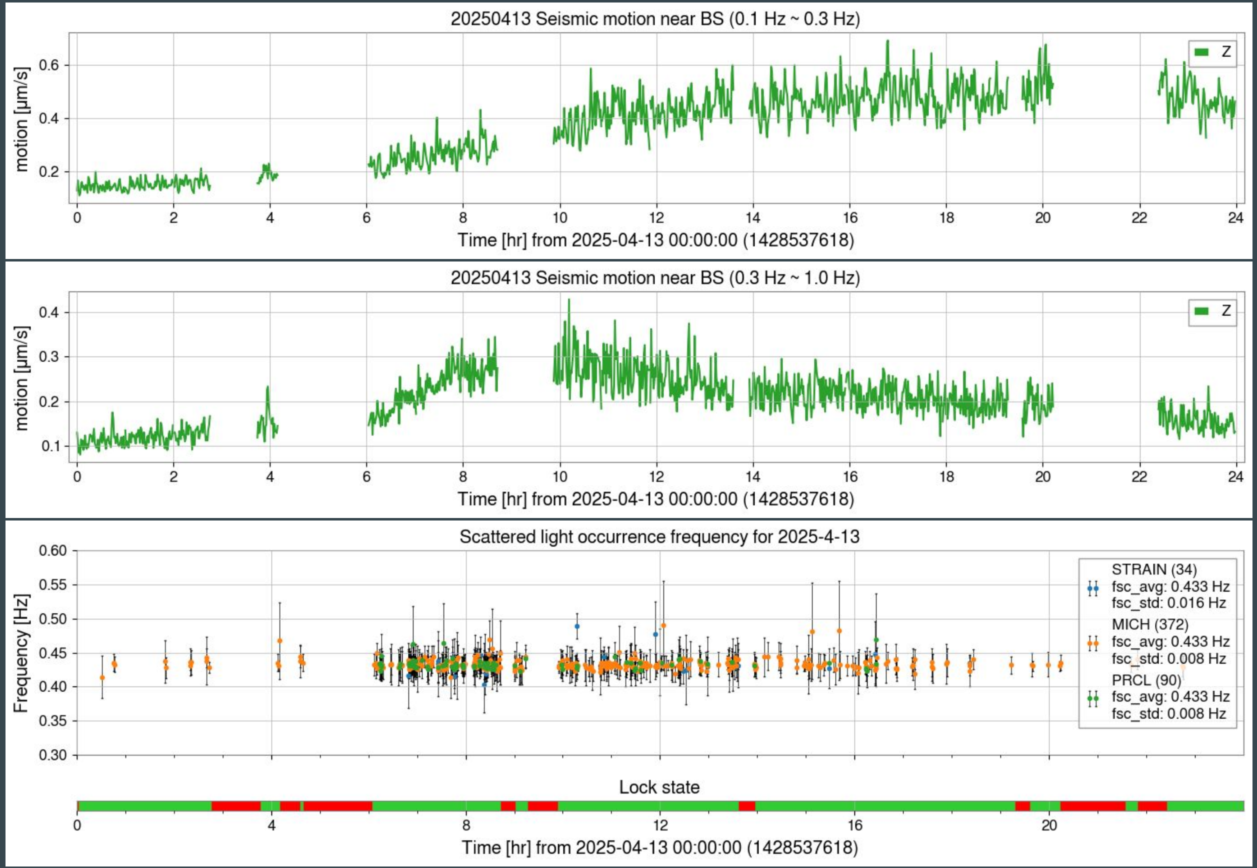
Red arrow: Seismometer

Yellow box:
Mirrors with type-Bp suspension

Type-Bp suspension:

- Resonant frequency: 0.42 Hz
- PRM/2/3 → PRCL
- Close to MICH

Results – Seismic motion



Focused bands:

0.1 ~ 0.3 Hz:

- Oceanic microseismic: 0.2 Hz

0.3 ~ 1 Hz:

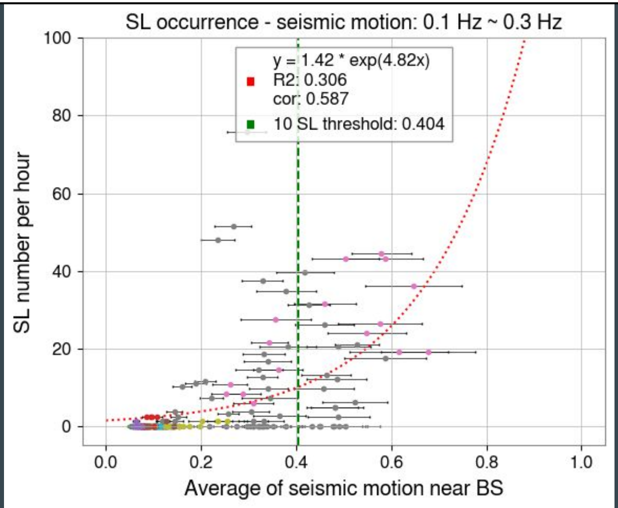
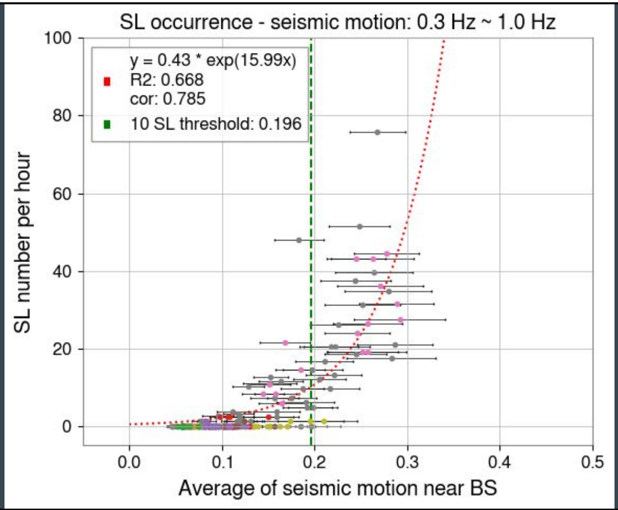
- Type-Bp suspension: 0.42 Hz
- Occurrence frequency: 0.433 Hz

SL occurrence frequency

- STRAIN(34): 0.433(±0.016) Hz
- MICH(372): 0.433(±0.008) Hz
- PRCL(90): 0.433(±0.008) Hz

Results – Scattered light occurrence v.s. Seismic Motion

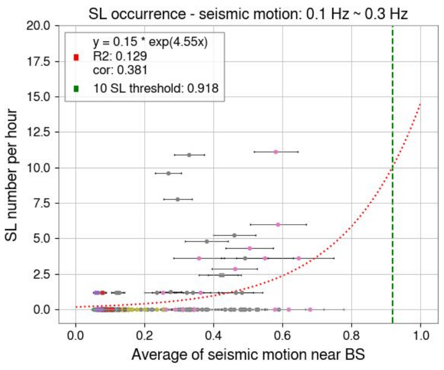
MICH (Data collected from 2025 April)

0.1 ~ 0.3 Hz	0.3 ~ 1 Hz
	
R^2 = 0.306 (exp) = 0.345 (linear) Pearson correlation: 0.587	R^2 = 0.668 (exp) = 0.616 (linear) Pearson correlation: **0.785 → Highly correlated**

Results – Scattered light occurrence v.s. Seismic Motion

DARM (Data collected from 2025 April)

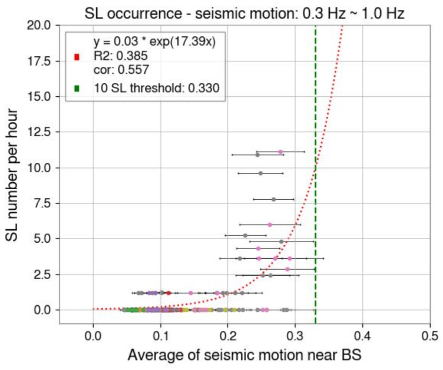
0.1 ~ 0.3 Hz



R^2 = 0.129 (exp)
= 0.145 (linear)

Pearson Correlation: 0.381

0.3 ~ 1 Hz

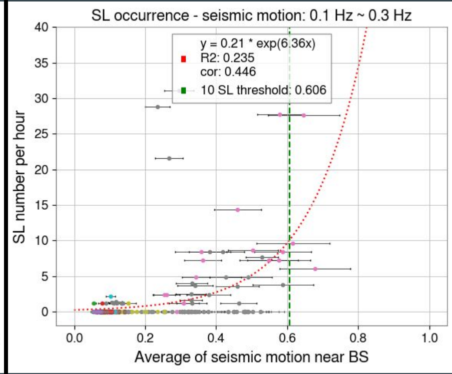


R^2 = 0.385 (exp)
= 0.311 (linear)

Pearson Correlation: 0.557

PRCL (Data collected from 2025 April)

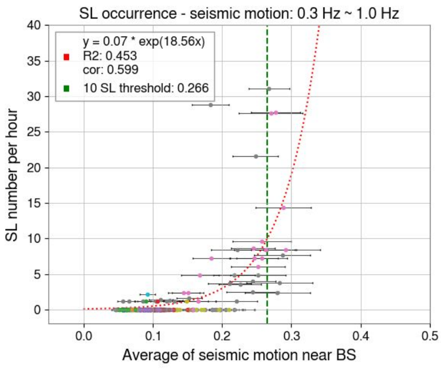
0.1 ~ 0.3 Hz



R^2 = 0.235 (exp)
= 0.199 (linear)

Pearson Correlation: 0.446

0.3 ~ 1 Hz

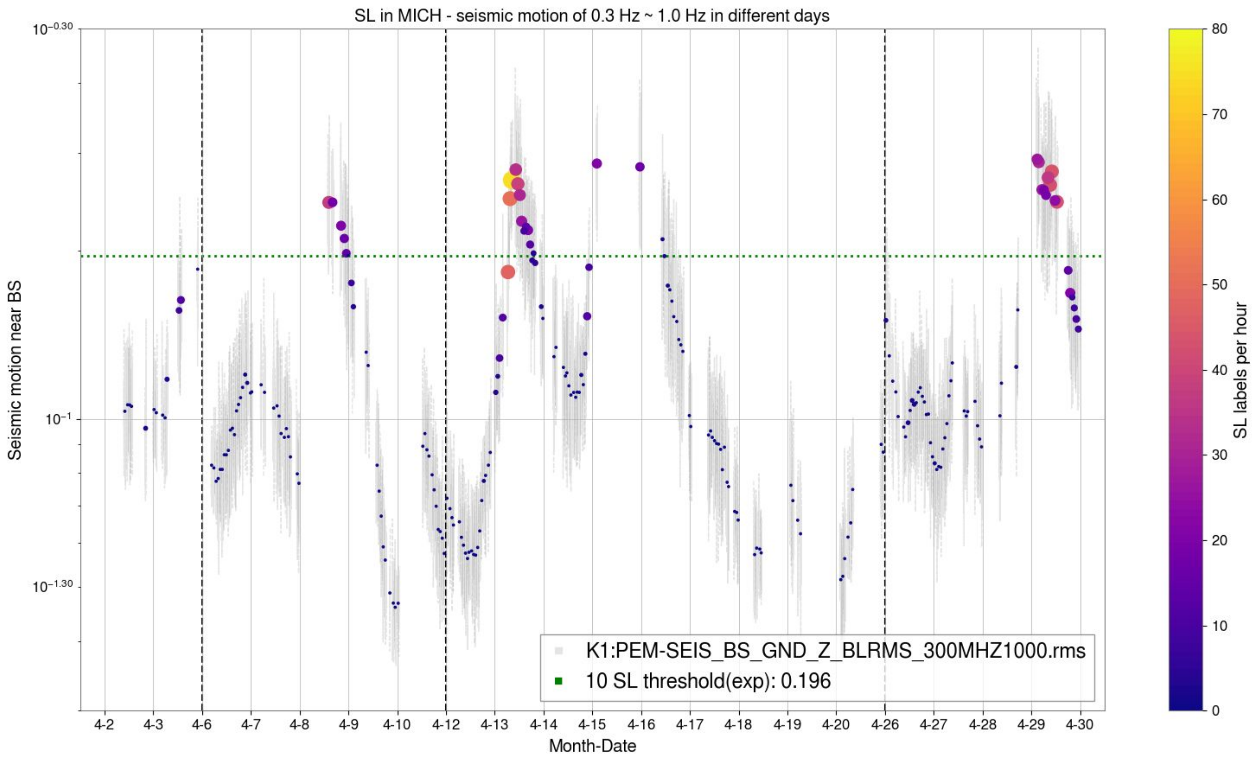


R^2 = 0.453 (exp)
= 0.359 (linear)

Pearson Correlation: 0.599

SL in MICH vs. 0.3~1 Hz seis: R^2 = 0.668 (exp); Cor: 0.785

Results – Daily Monitoring of Scattered Light



SL in MICH - Seismic motion for 2025 April

Example:

MICH, 2025, April

Results:

- **Positive correlation** between scattered light occurrence and seismic motion
- MICH found most scattered light noises
- 10 SL threshold: 0.196 μm/s

Conclusion & Future work

1. The theoretical model of scattered light noise worked to model the scattered light noise in KAGRA. $f_{\mathrm{arch}}(t) = \left|2\frac{\delta \dot{x}_{sc}}{\lambda}\right| = \left|2\frac{v_{sc}(t)}{\lambda}\right|.$
2. Scattered light noise can be seen in DRAM / MICH / PRCL.
3. A method is developed to label scattered light noise and compute its feature.
4. We observed positive correlation between seismic motion and Scattered light noise occurrence.
5. In the future, we hope to identify the source of scattered light noise and mitigate its effect to the sensitivity of KAGRA.

Appendix

Q-transform

Constant Q-transform:

$$X(t,f,Q) = \int_{-\infty}^{\infty} x(\tau)w(\tau - t,f,Q)e^{-i2\pi f\tau}d\tau$$

,where $w(\tau - t,f,Q) = \frac{W_g}{\sigma_t\sqrt{2\pi}}\exp\left(-\frac{1}{2\sigma_t^2}(\tau - t)^2\right);\ \sigma_t^2 = \frac{Q^2}{8\pi^2 f^2}$