Investigations of Binary Neutron Star Inspiral Range Oscillations at LIGO Livingston

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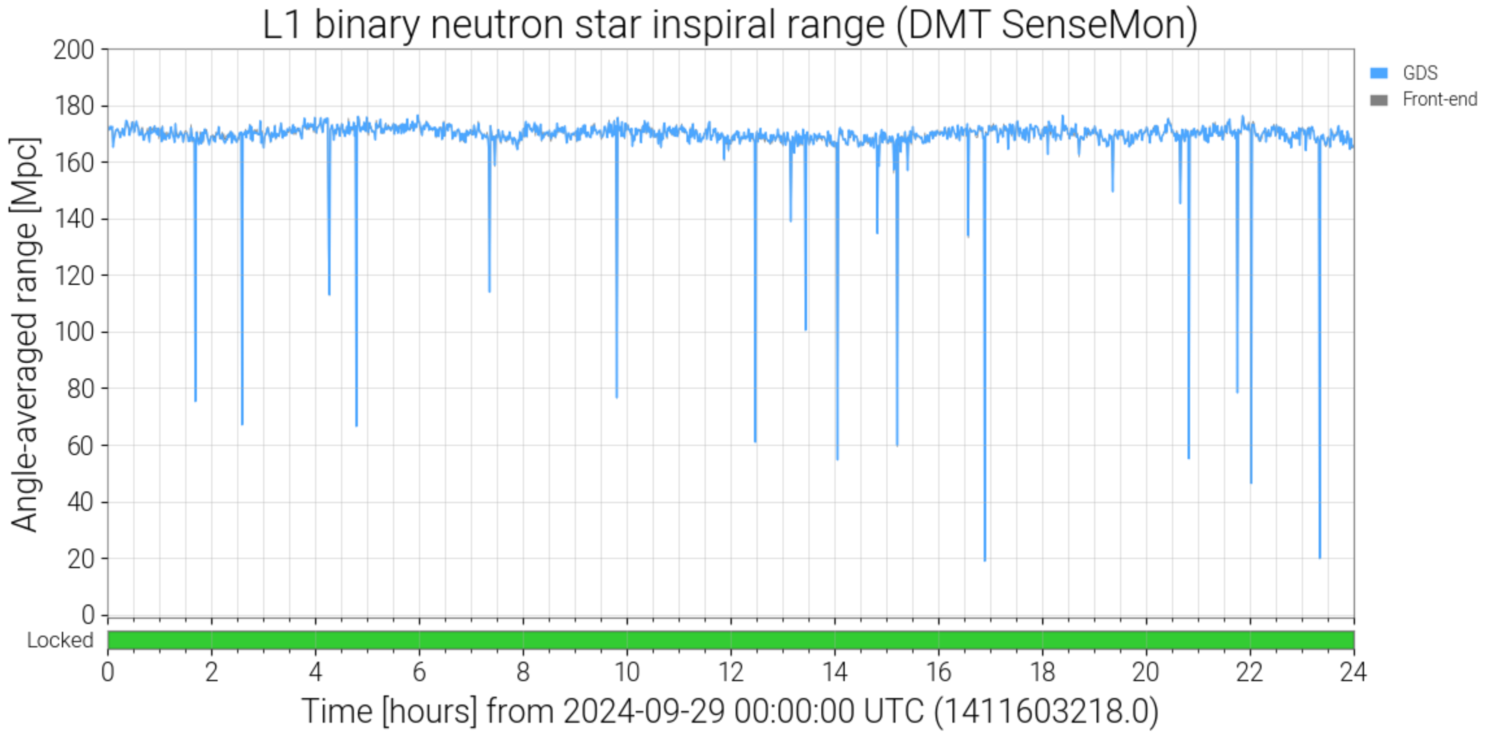
LIGO SURF 2025

Minnesota State University Moorhead

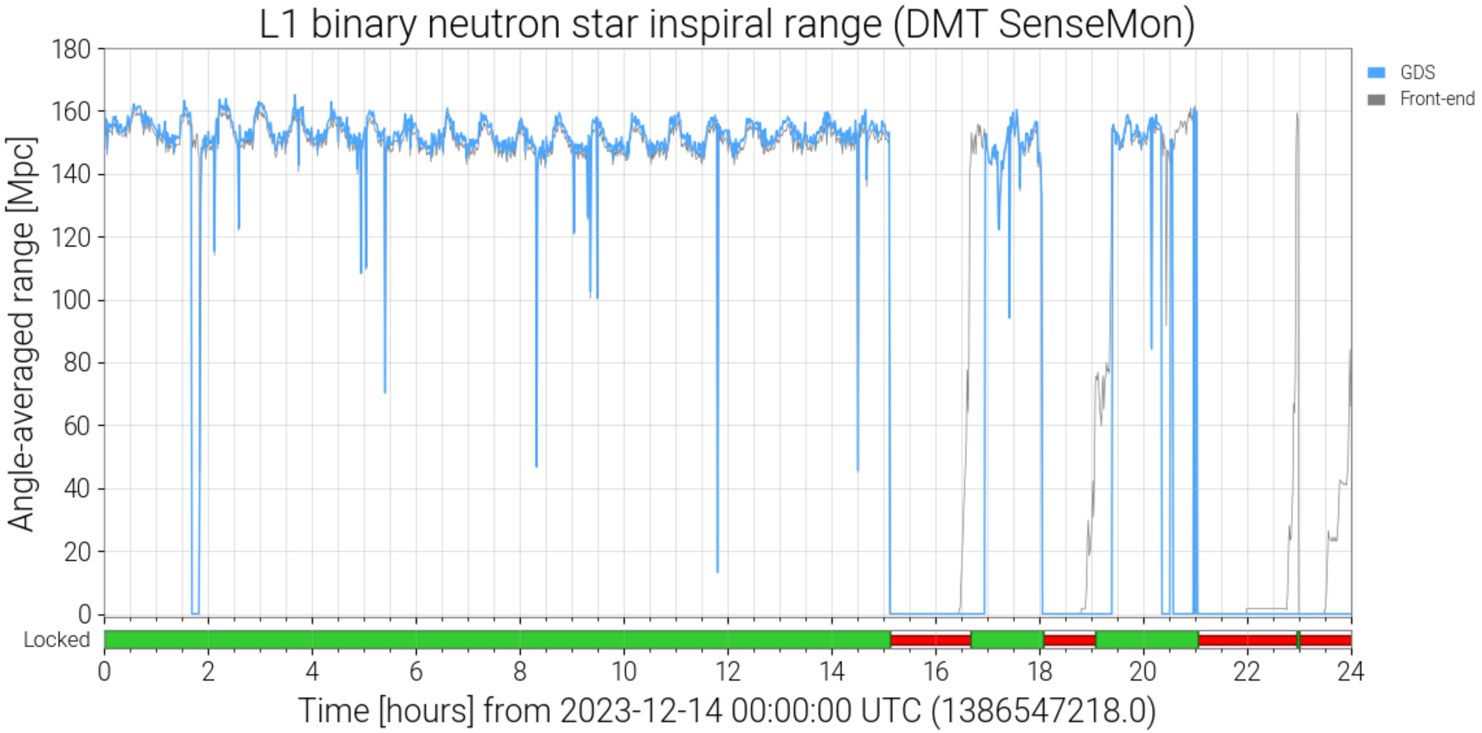
BNS Range

- Binary Neutron Star Inspiral Range (BNS) is a metric used to monitor detector sensitivity
- BNS range: the distance to which we can measure a binary neutron star inspiral of 1.4 $M_\odot$ each with a signal-to-noise ratio of 8



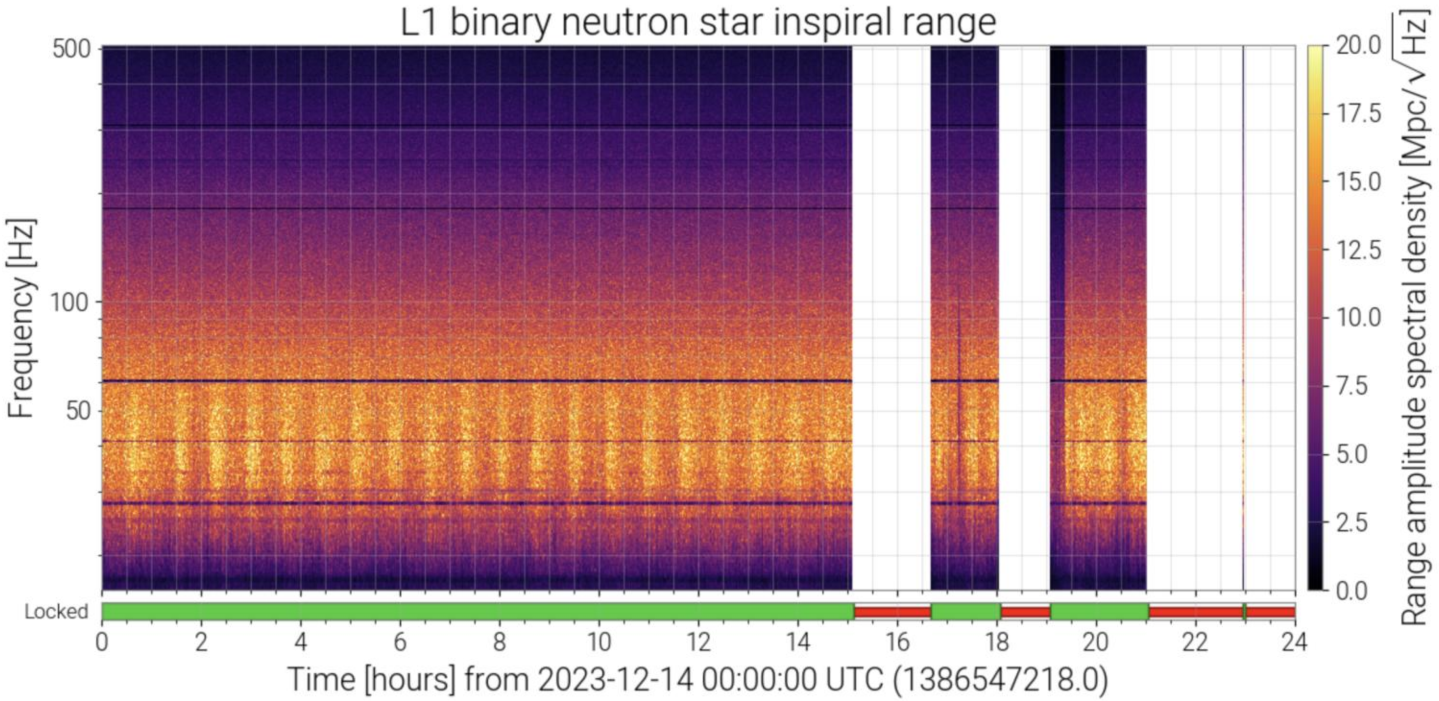
BNS Range Oscillations

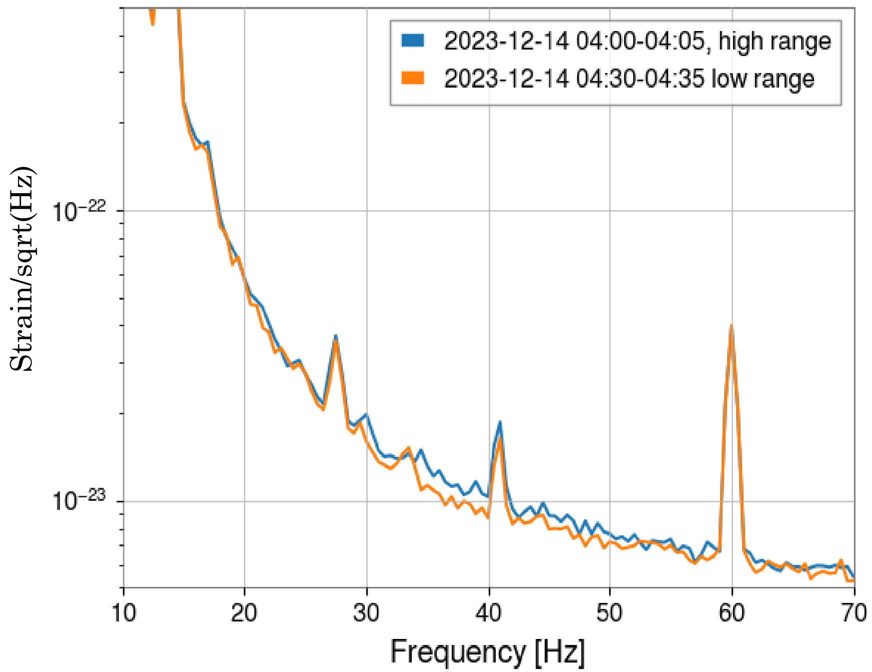
- Recurring oscillations that happen at random in O4
- Roughly 30-minute period
- Changes of 5-15 megaparsecs



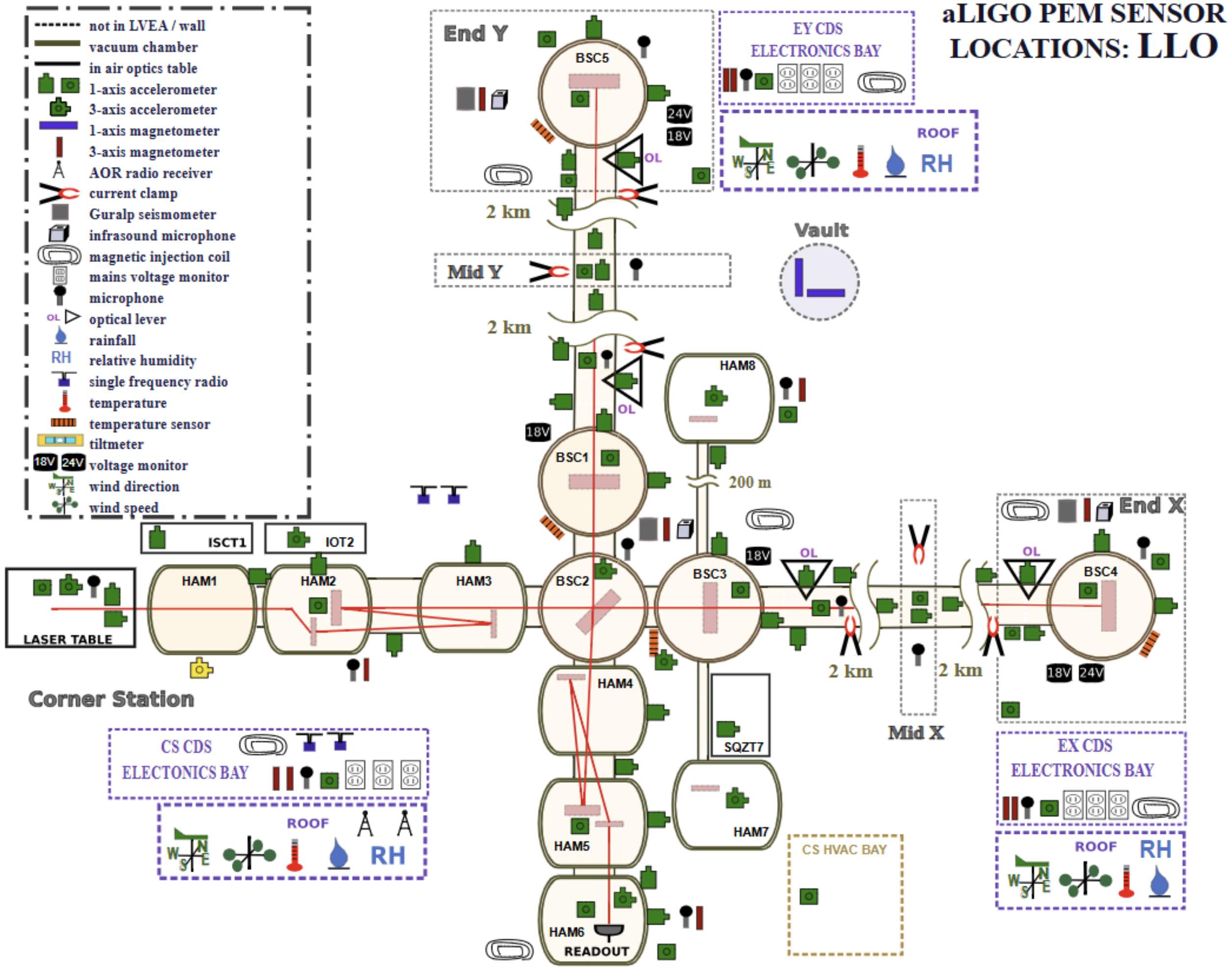
BNS Range Oscillations

- Noise seen in the 30-50 Hz range
- This noise effects the sensitivity at which we can detect higher mass binary black holes





Detector Characterization



- Responsible for identifying and mitigating noise sources in detector
- LIGO is complicated and large, potential for noise everywhere
- Many sensor types throughout LIGO facilities

Auxiliary Channels Subsystems

- **FMC**: “Facility Management and Control”
- **PEM**: “Physical Environment Monitoring”
- **SUS**: “Suspension”
- **HPI**: “Hydraulic External Pre-Isolator”
- **ISI**: “Internal Seismic Isolation”
- **ALS**: “Arm Length Stabilization”

Objective

Identify the source and the coupling mechanism of the oscillations in the BNS range

- Many auxiliary channels exhibiting ~30 minute oscillatory behavior
- Oscillations have been occurring since the start of O4
- Cross-correlation with a time lag between band-limited RMS (BLRMS) of the gravitational wave strain data, and BLRMS of auxiliary channel data to identify potential couplings
  - Do specific auxiliary channels lead the strain?
- Examined 19 days of 04 so far in the End-X station
  - Roughly 150 channels per day

Cross-Correlation

- Cross-correlation: a data analysis technique that calculates how similar a signal is to another
  - Sliding two time series together at different lags to see what fits best and when

$$\rho[k] = \frac{\sum_t (y_t - \bar{y})(a_{t-k} - \bar{a})}{\sqrt{\sum_t (y_t - \bar{y})^2}\sqrt{\sum_t (a_t - \bar{a})^2}}$$

Cross correlation

Pearson style normalization = [-1,1]

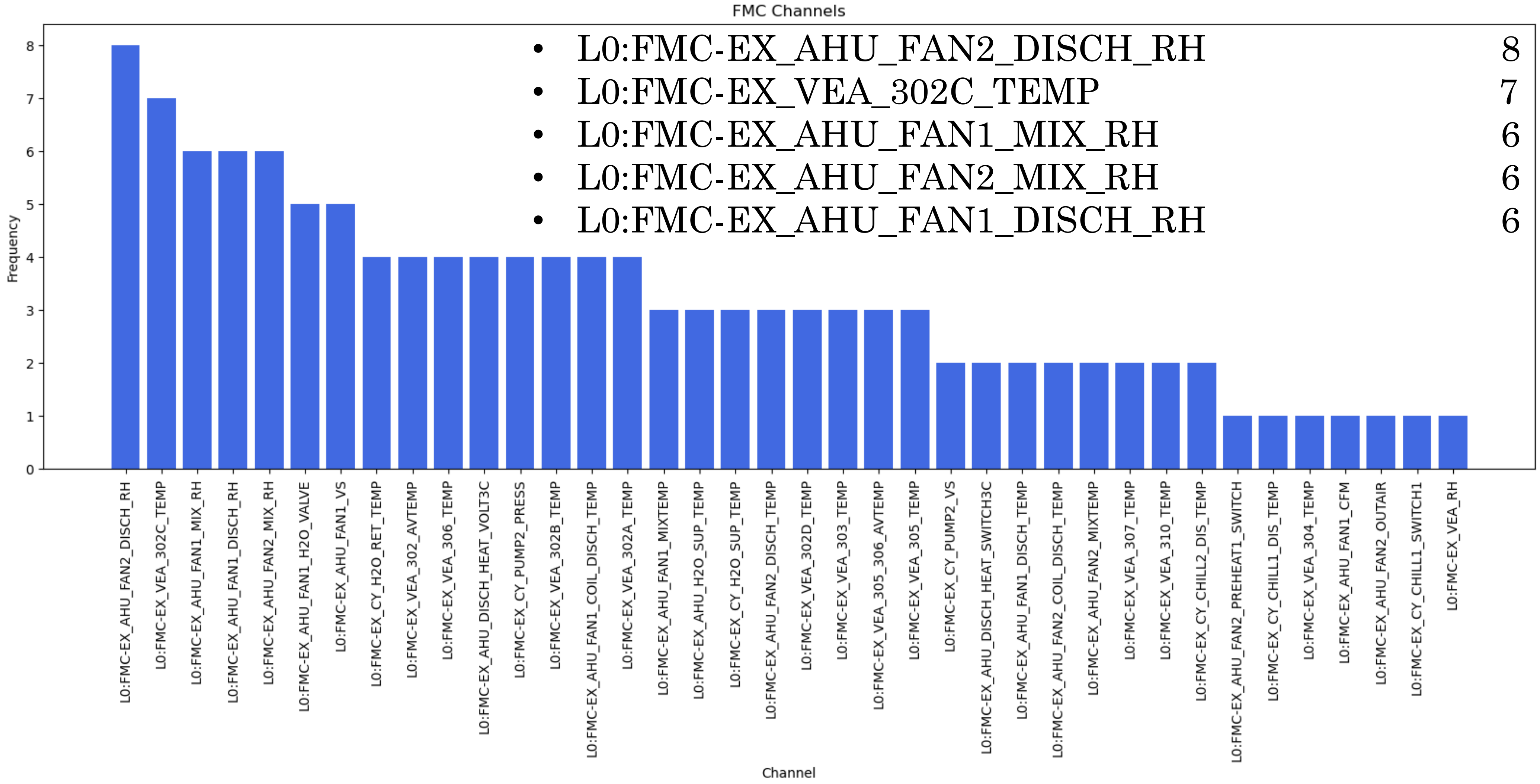
- y = 30-50 Hz strain data BLRMS, a = 30-50 Hz auxiliary data BLRMS, k = lags

- Pearson style normalization: correlations comparable across channels/days

- Looking for auxiliary channels that precede everything else
  - Negative time-lag

Selection criteria: between lags -1s and -1800s with a correlation of 0.3 or greater

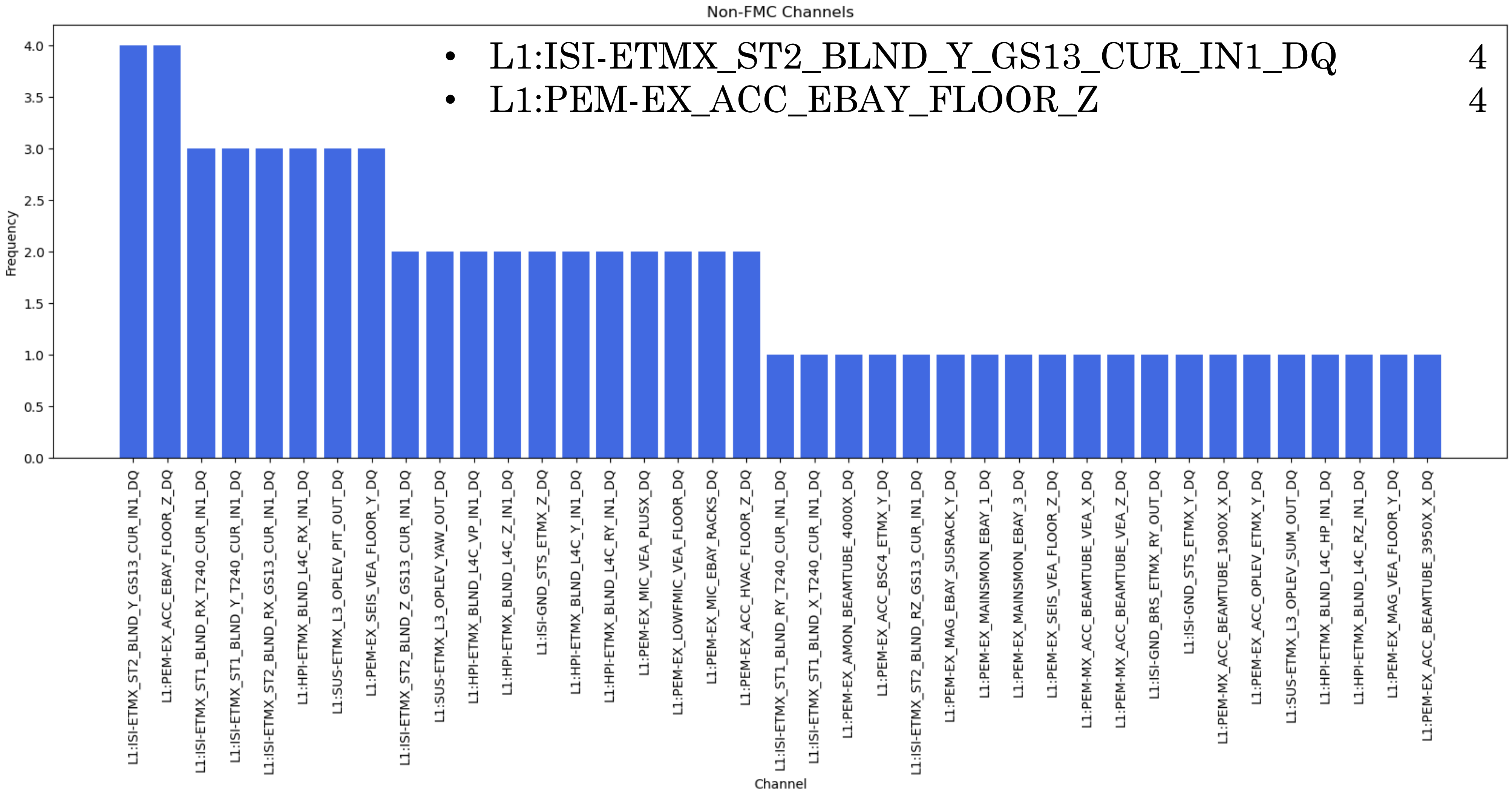
Results: FMC



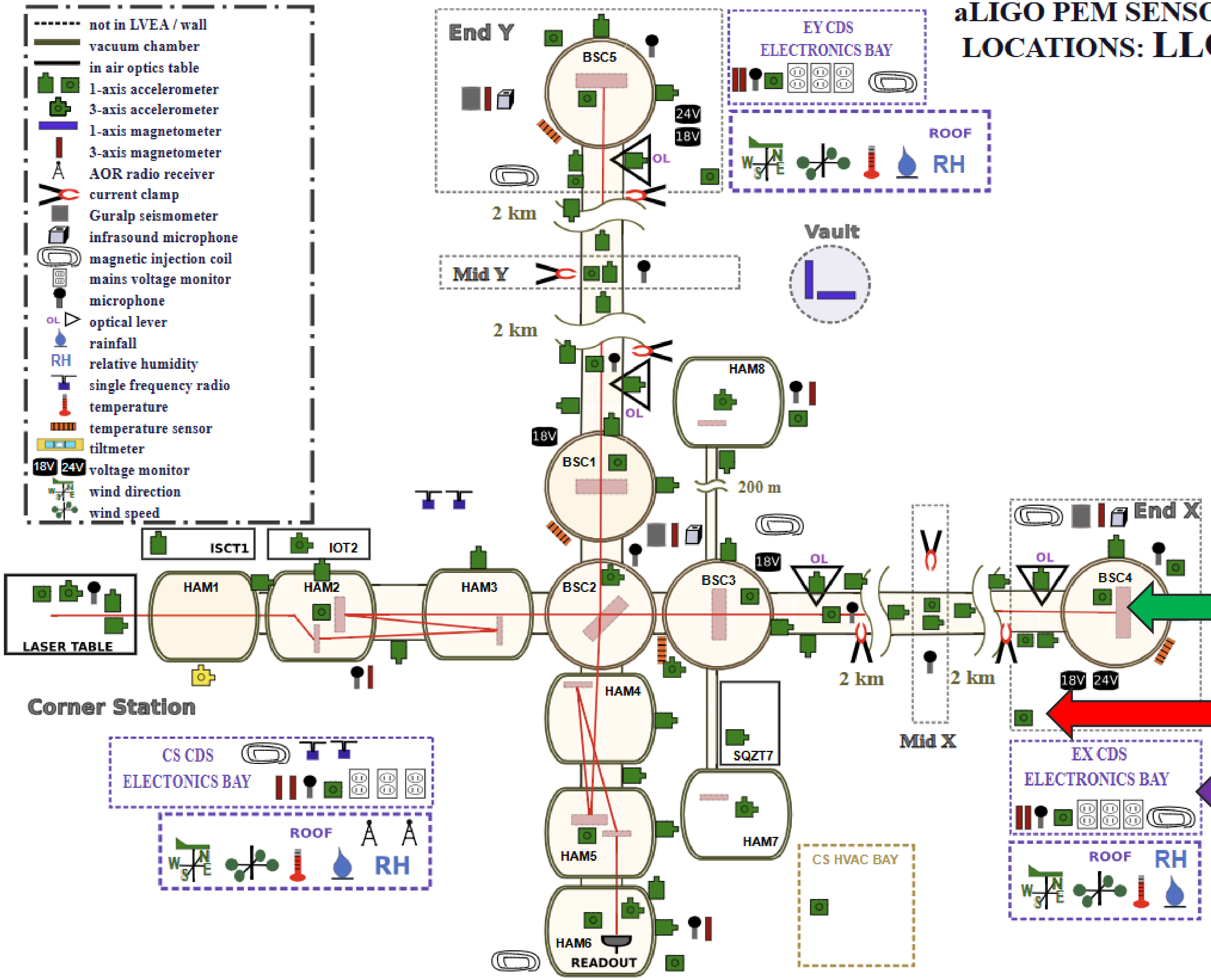
- L0:FMC-EX_AHU_FAN2_DISCH_RH 8
- L0:FMC-EX_VEA_302C_TEMP 7
- L0:FMC-EX_AHU_FAN1_MIX_RH 6
- L0:FMC-EX_AHU_FAN2_MIX_RH 6
- L0:FMC-EX_AHU_FAN1_DISCH_RH 6

Results: PEM/SUS/ISI/HPI/ALS

- L1:ISI-ETMX_ST2_BLND_Y_GS13_CUR_IN1_DQ 4
- L1:PEM-EX_ACC_EBAY_FLOOR_Z 4

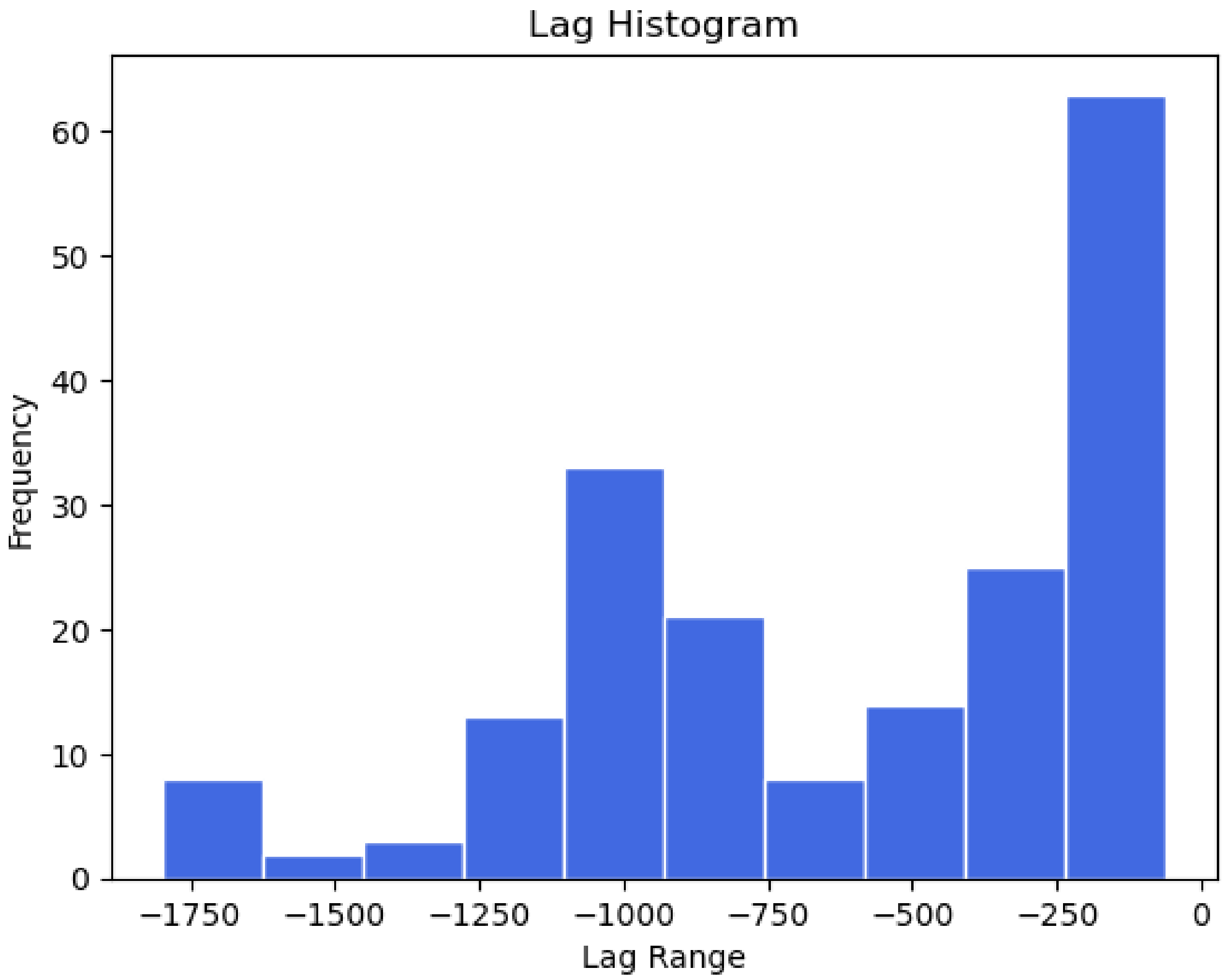


aLIGO PEM SENSOR LOCATIONS: LLO



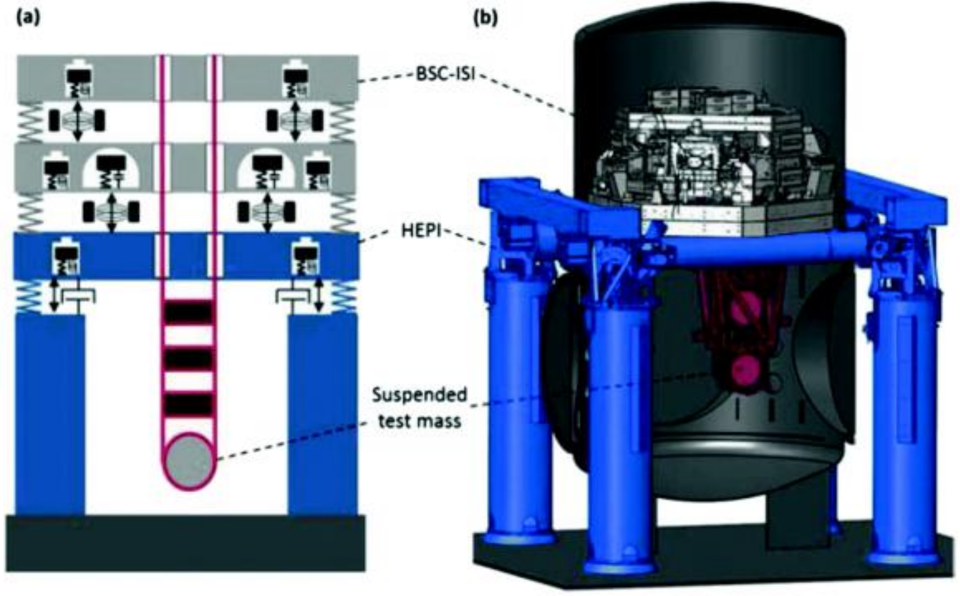
- Electronics bay
- ISI seismometer
- HVAC

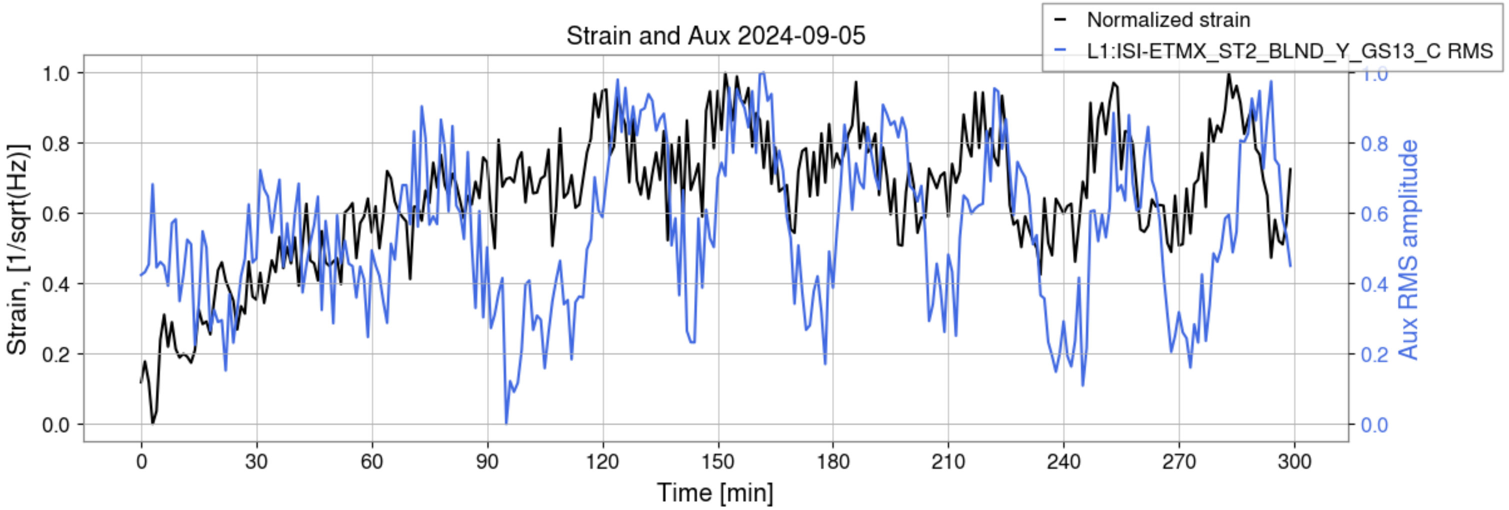
Histogram of Time-Lags



- Peak around -250 seconds is on the scale of seconds to a few minutes, possibly indicating a quick response from the BNS range
- Bump around -1000s (15 min), which is roughly half of our 30-minute period

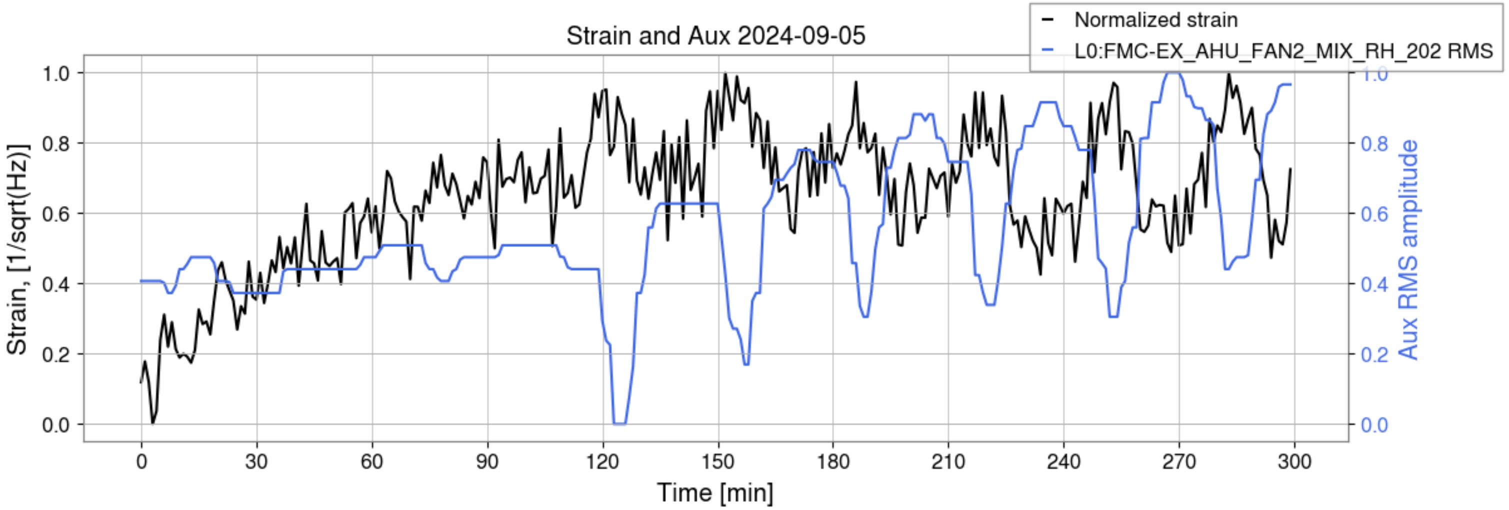
ISI Coupling with FMC





End-X test mass: Seismometer on second stage ISI (no lag)

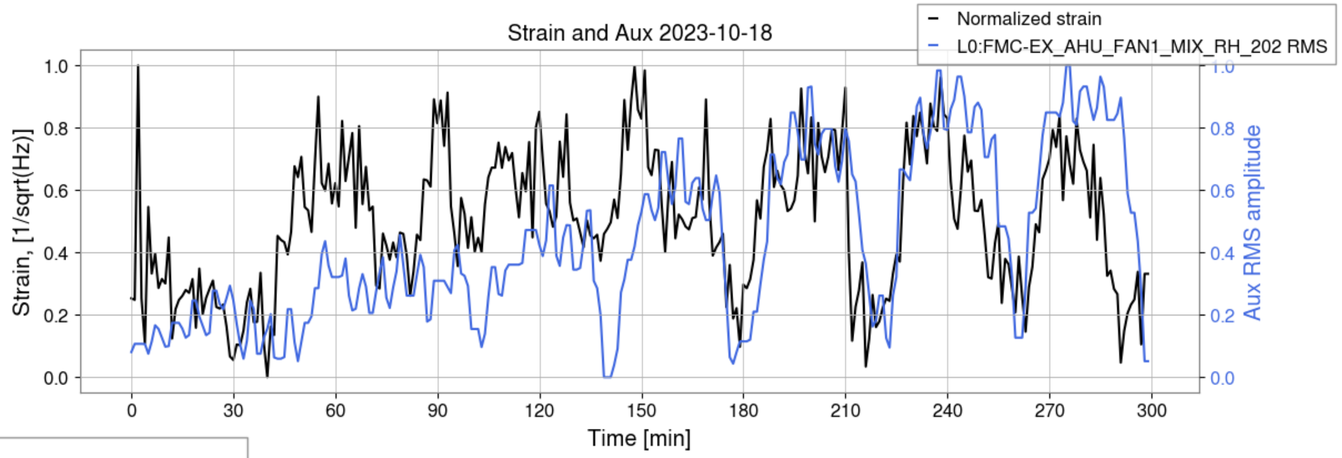
- optimum lag of -300 seconds



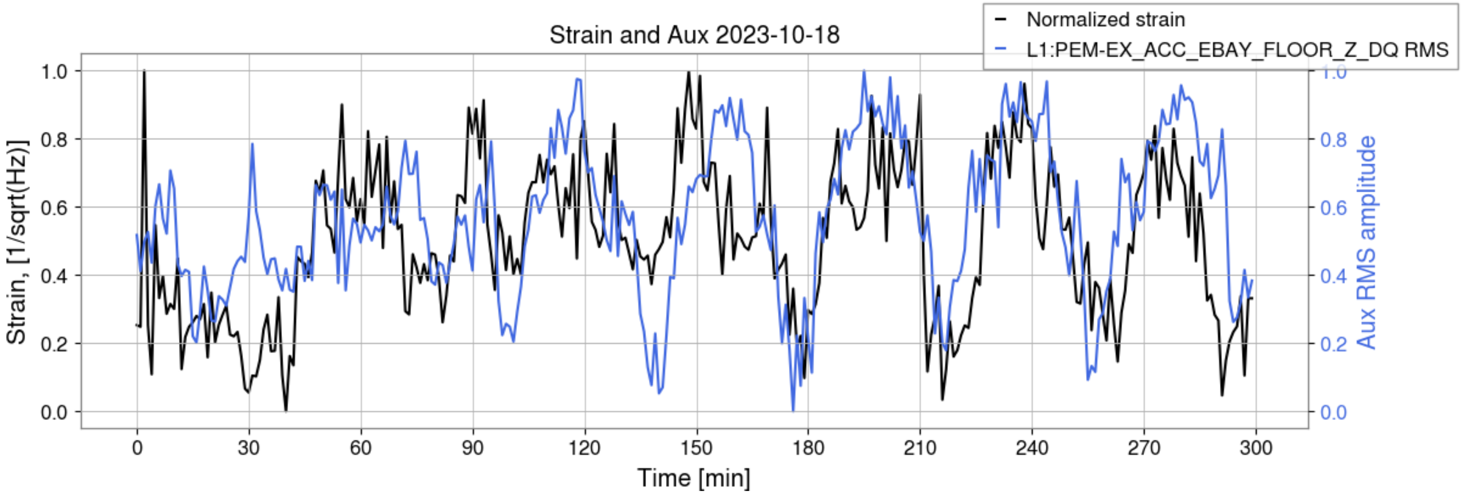
Relative humidity sensor (no lag)

- optimum lag of -300 seconds

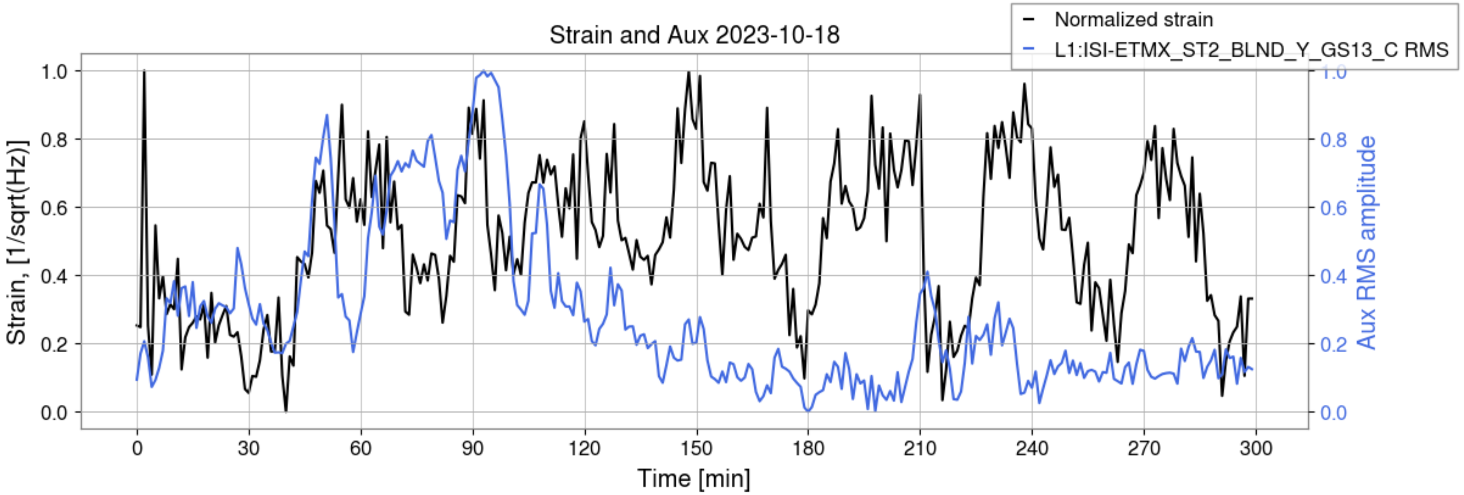
More Coupling Mechanisms?



Relative humidity sensor



Electronics bay accelerometer has a negative lag of -120 seconds



Same ISI seismometer as before not observing the noise

Conclusions

- FMC channels (temperature and relative humidity sensors) most frequently have the highest correlation with negative lag of all sensor types
  - Humidity cycling in the AHU may be a driver
- Suspect multiple coupling mechanisms with FMC as PEM and ISI channels are not oscillating every day the BNS oscillations are present
  - FMC w/ ISI: temperature and/or humidity fluctuations are somehow propagating into the vacuum
  - FMC w/ PEM: possible airflow or structural vibrations originating from the electronics bay or HVAC

Future Steps

- Comprehensively cross-correlate auxiliary channels at other stations (corner station and End-Y)
- Develop some method to track how the amplitude of the oscillations in the auxiliary channels change over time
- Follow-up with the LIGO Livingston commissioners for potential temperature related tests

Acknowledgements

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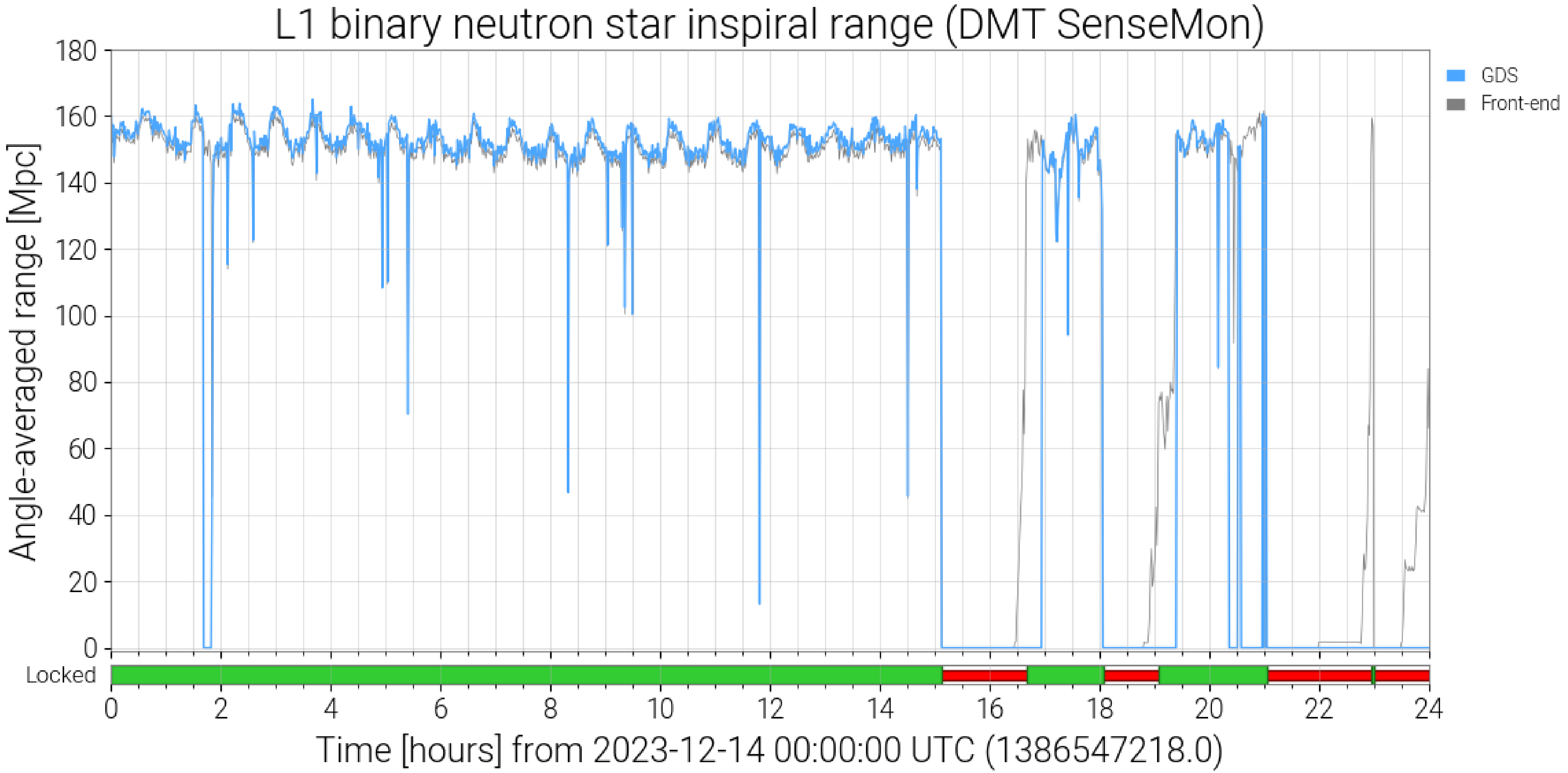
I would like to thank my mentor, Jane Glanzer, for her guidance on this project and my first foray into detector characterization.

NSF

LIGO

Caltech

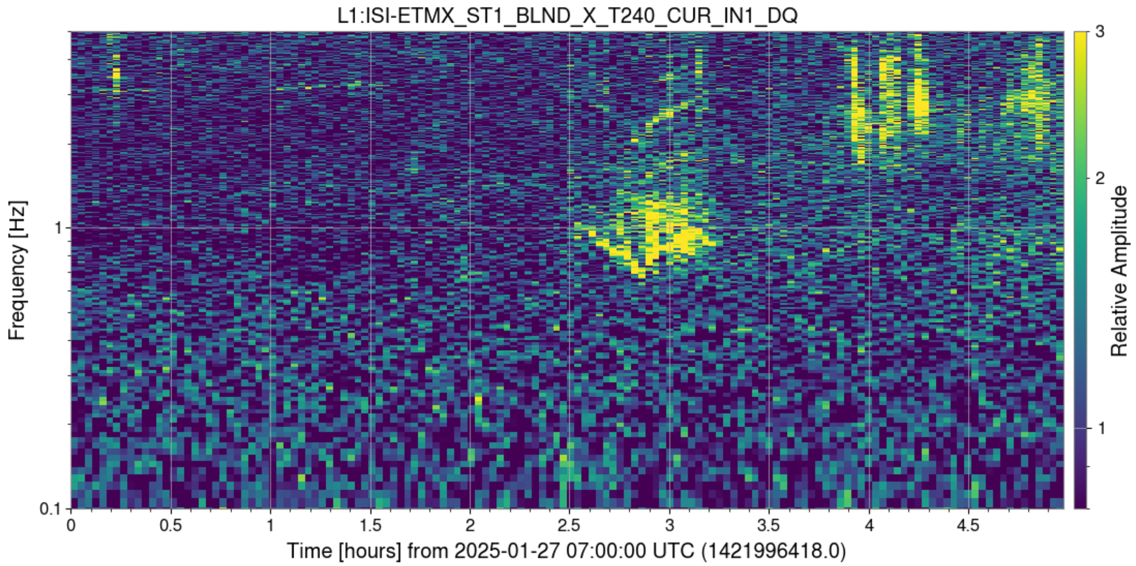
Questions?

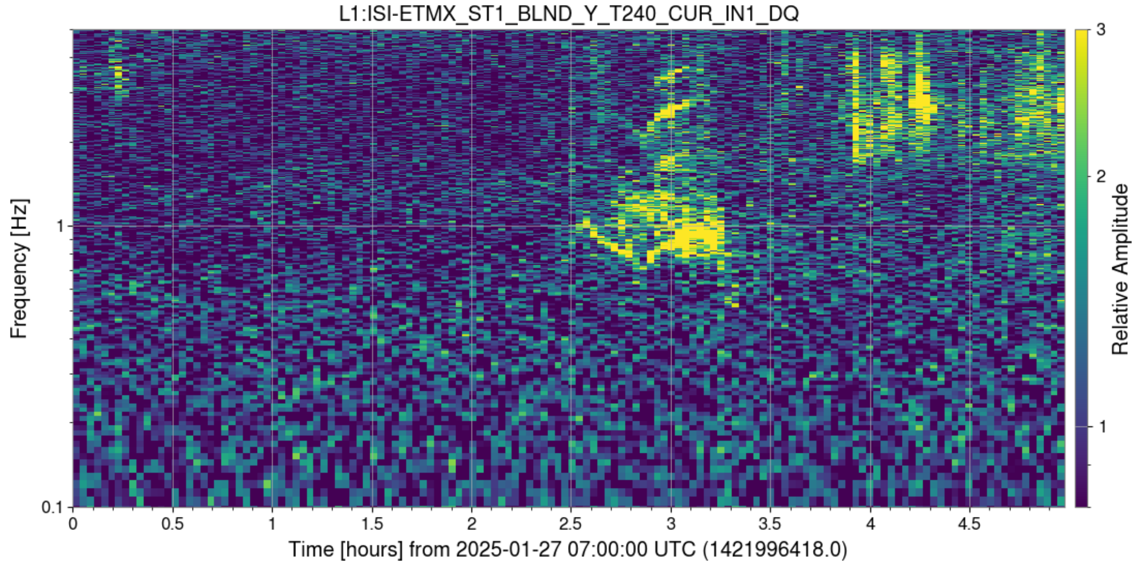


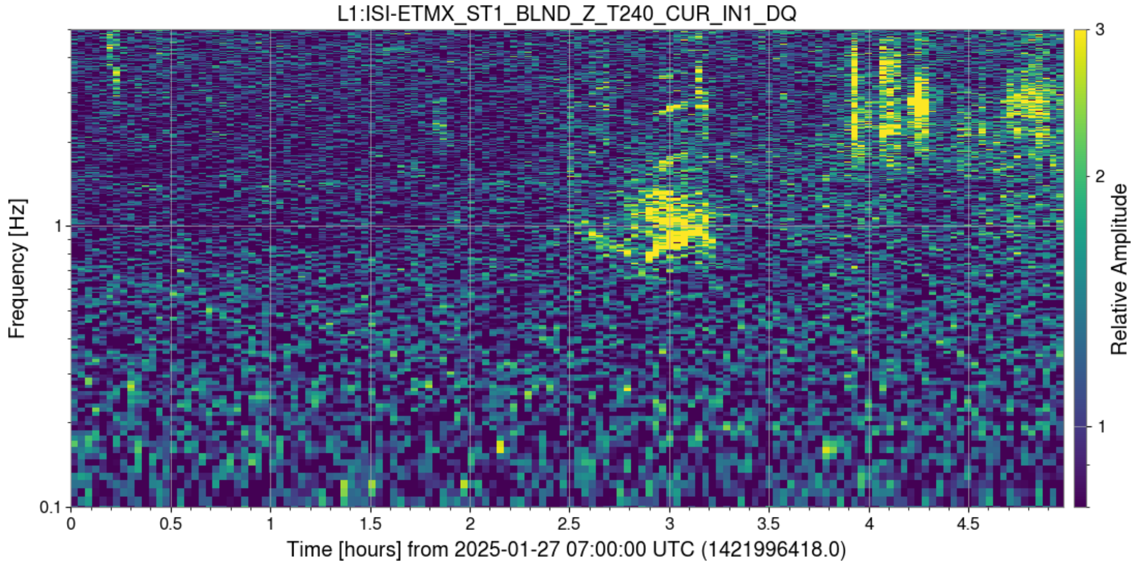
L1 binary neutron star inspiral range (DMT SenseMon)
GDS
Front-end
Angle-averaged range [Mpc]
180
160
140
120
100
80
60
40
20
0
Locked
0
2
4
6
8
10
12
14
16
18
20
22
24
Time [hours] from 2023-12-14 00:00:00 UTC (1386547218.0)

Low Frequencies

- Explored low frequency behavior in 0.1-0.25 Hz range because motion at low frequencies has the possibility to up convert into higher frequencies
- No substantial evidence of low frequency, periodic noise







Second stage ISI →

HPI →