Enhancing CUORE Data Quality with Denoising Techniques

Kenneth J. Vetter
on behalf of the CUORE Collaboration

Department of Physics, University of California, Berkeley, CA 94720, USA
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

kenneth_vetter@berkeley.edu

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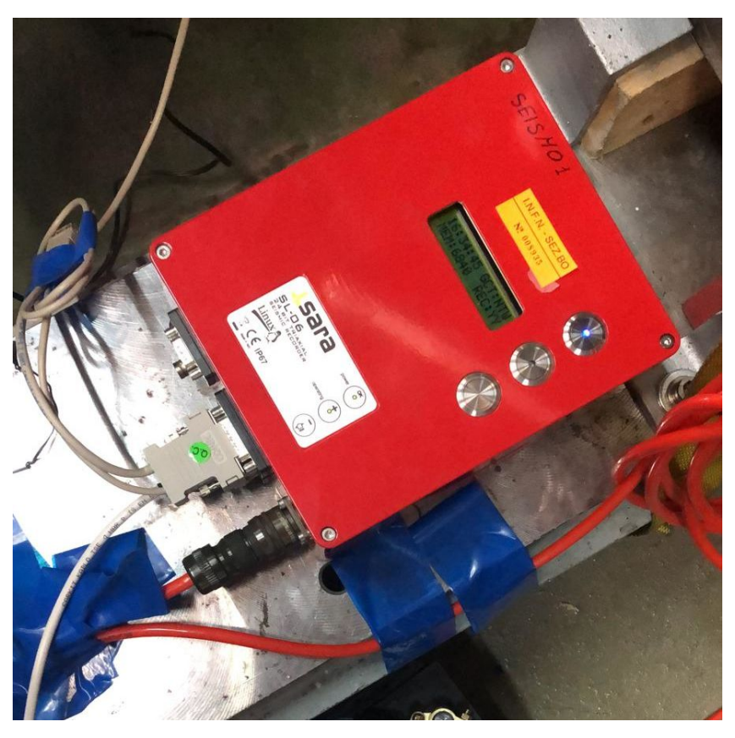
Abstract

The Cryogenic Underground Observatory for Rare Events (CUORE) experiment, located at the Gran Sasso National Laboratory (LNGS) in Italy, is an ongoing search for neutrinoless double beta ($0\nu\beta\beta$) decay. Previous work has shown that the quality of CUORE data can be enhanced through noise decorrelation algorithms utilizing auxiliary devices such as microphones, accelerometers, and seismometers. Here, we showcase the application of these algorithms in improving CUORE's data quality, including enhancing detector baseline resolution, thus enabling lower thresholds and improved coincidence tagging. Additionally, we outline the anticipated benefits of noise decorrelation on ongoing and future CUORE datasets, leveraging an expanded array of auxiliary devices including antennas and additional accelerometers.

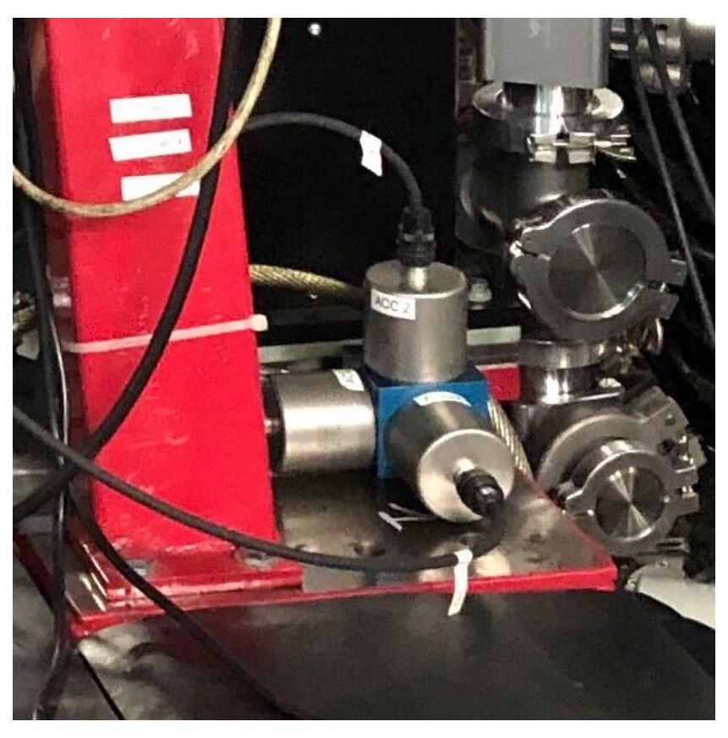
Auxiliary Devices Used in CUORE

To measure vibrational and electrical noise, we install several devices around the CUORE cryostat. All of these devices operate at room temperature and are read out to the CUORE DAQ system. They are digitized simultaneously with the CUORE detector channels at a sampling frequency of 1 kHz.



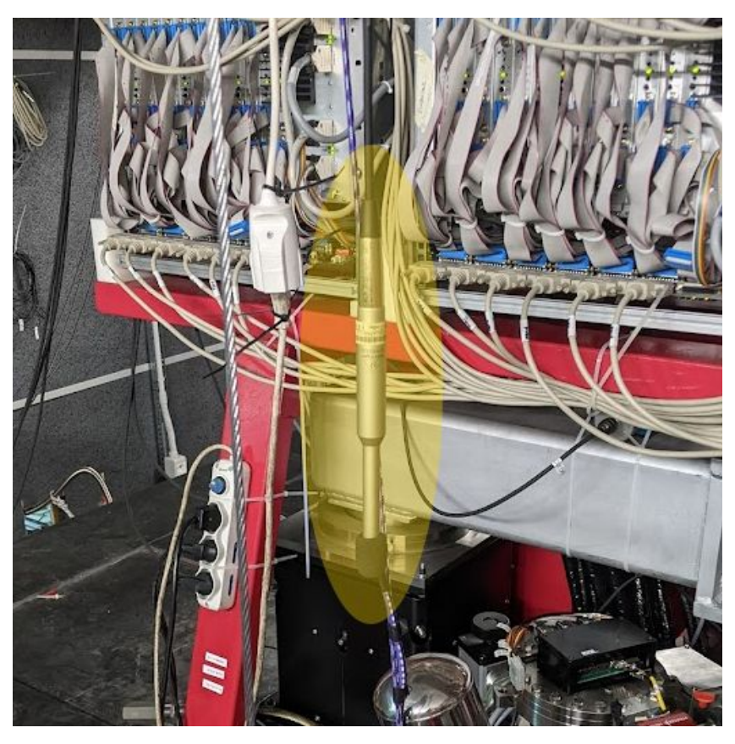
Seismometers:

- Sensitive to frequencies between 0.1 and 50 Hz, covering the most important part of the CUORE detector signal band
- Measures signals from structural resonances, microseisms, and sea storm activity in the Tyrrhenian and Adriatic Seas



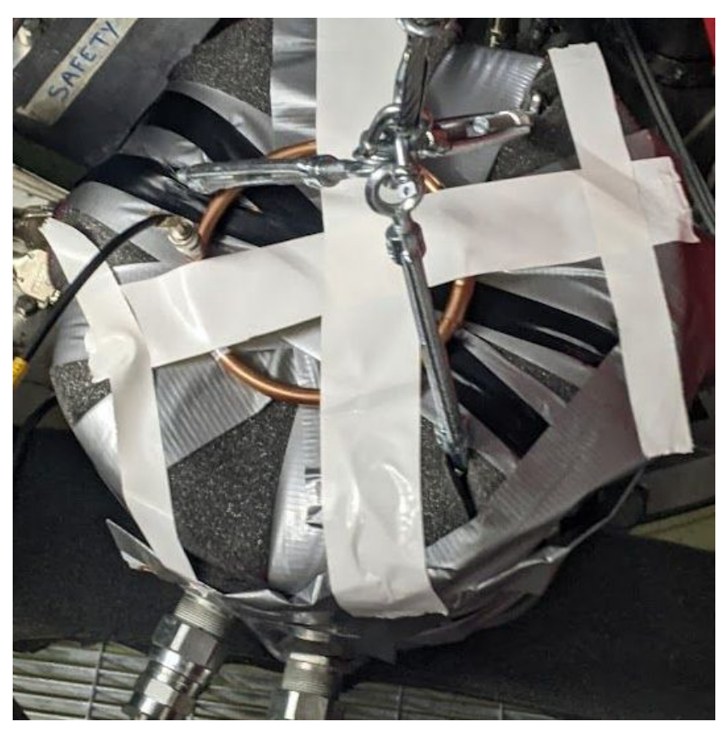
Accelerometers:

- Sensitive to frequencies between 1 and 200 Hz, which covers almost all of the CUORE detector signal band
- Measure the noise from pulse tubes extremely well



Microphones:

- Four microphones installed around the faraday cage
- Sensitive to frequencies from 20 Hz to 2 kHz
- Still useful for monitoring noise conditions in the Faraday cage and identifying noise transients



Antennas:

- Measure electrical noise with high sensitivity without needing amplification
- Most prominent electrical noise occurs at 50 Hz and harmonics, falling mostly outside the CUORE signal band

Overview of the Algorithm

Make a matrix of spectral densities of the aux devices at each frequency:

$$G_{ij} = \langle X_i^*[f]\, X_j[f] \rangle$$

Make a vector of cross-spectral densities between the detector and aux devices:

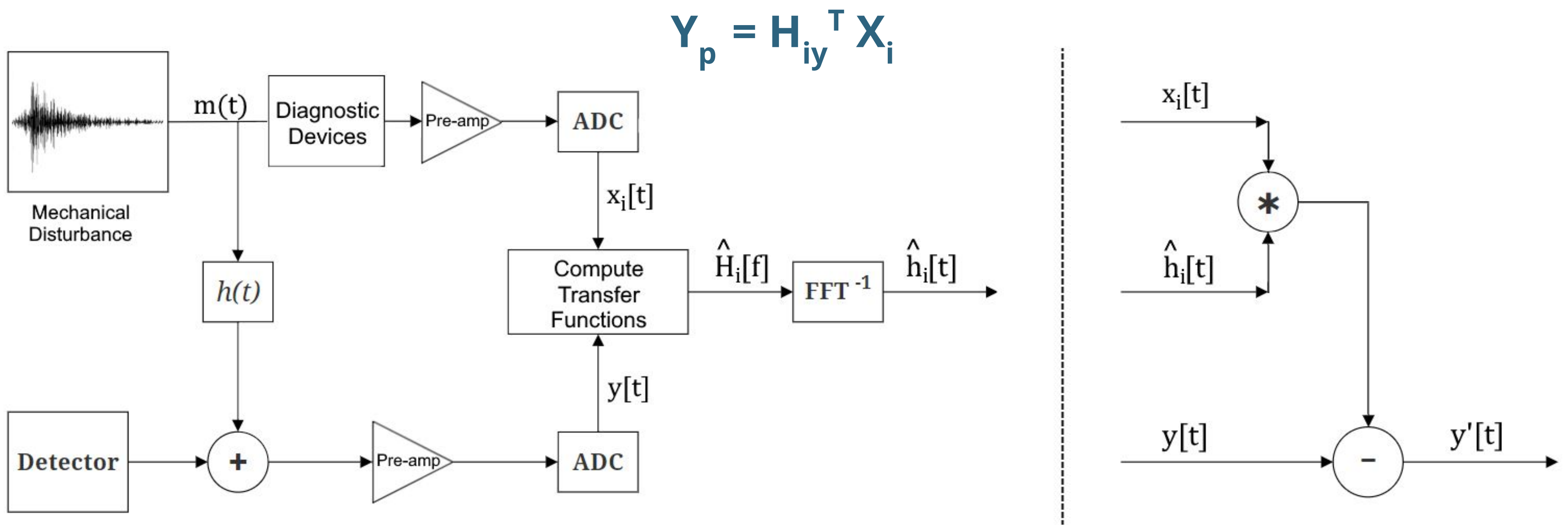
$$G_{iy} = \langle X_i^*[f]\, Y[f] \rangle$$

Calculate the transfer function by inverting the aux spectral density matrix:

$$H_{iy} = G_{ij}^{-1} G_{jy}$$

Predict the noise by filtering the aux device signals with the transfer function:

$$Y_p = H_{iy}^{T} X_i$$



Acknowledgements

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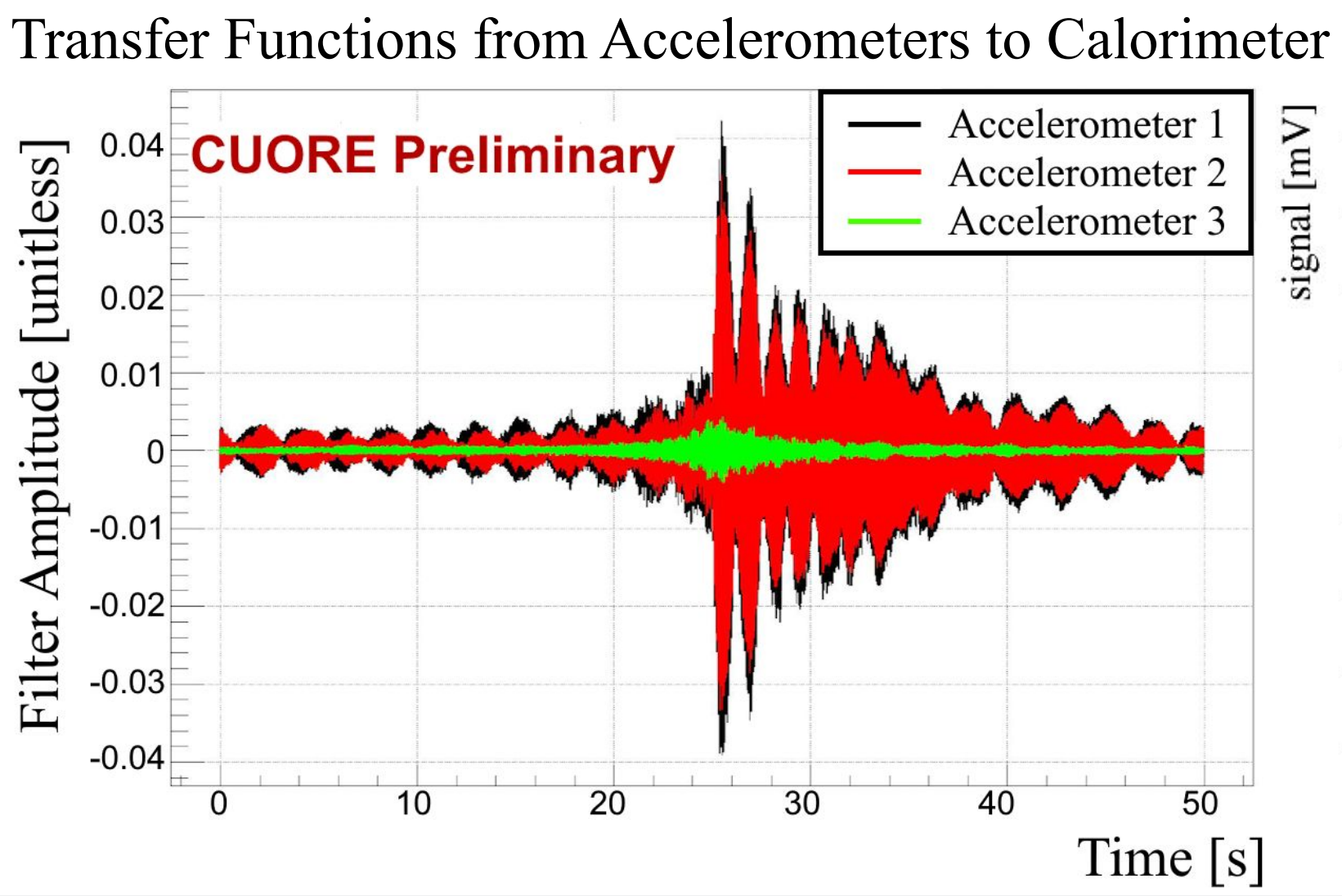
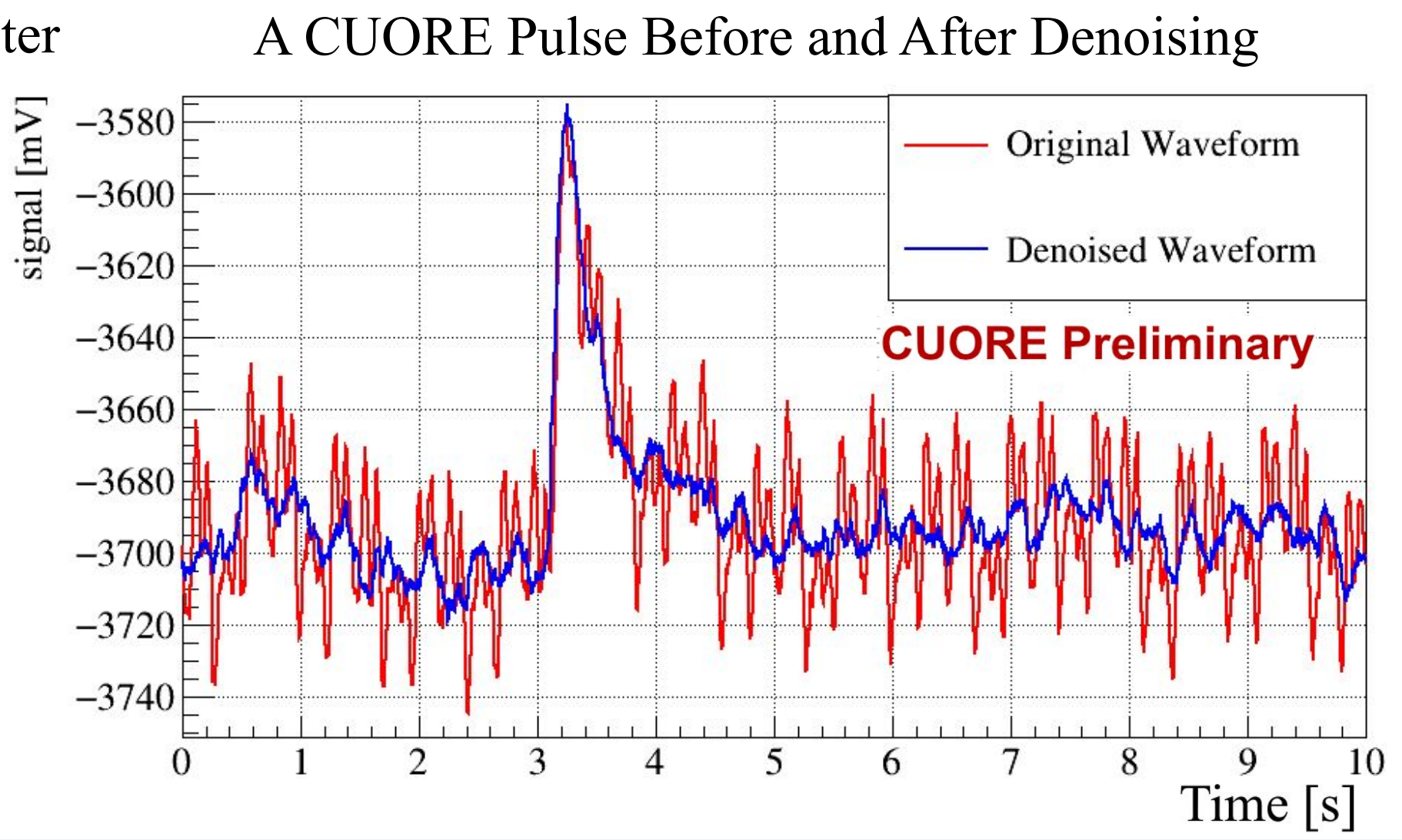
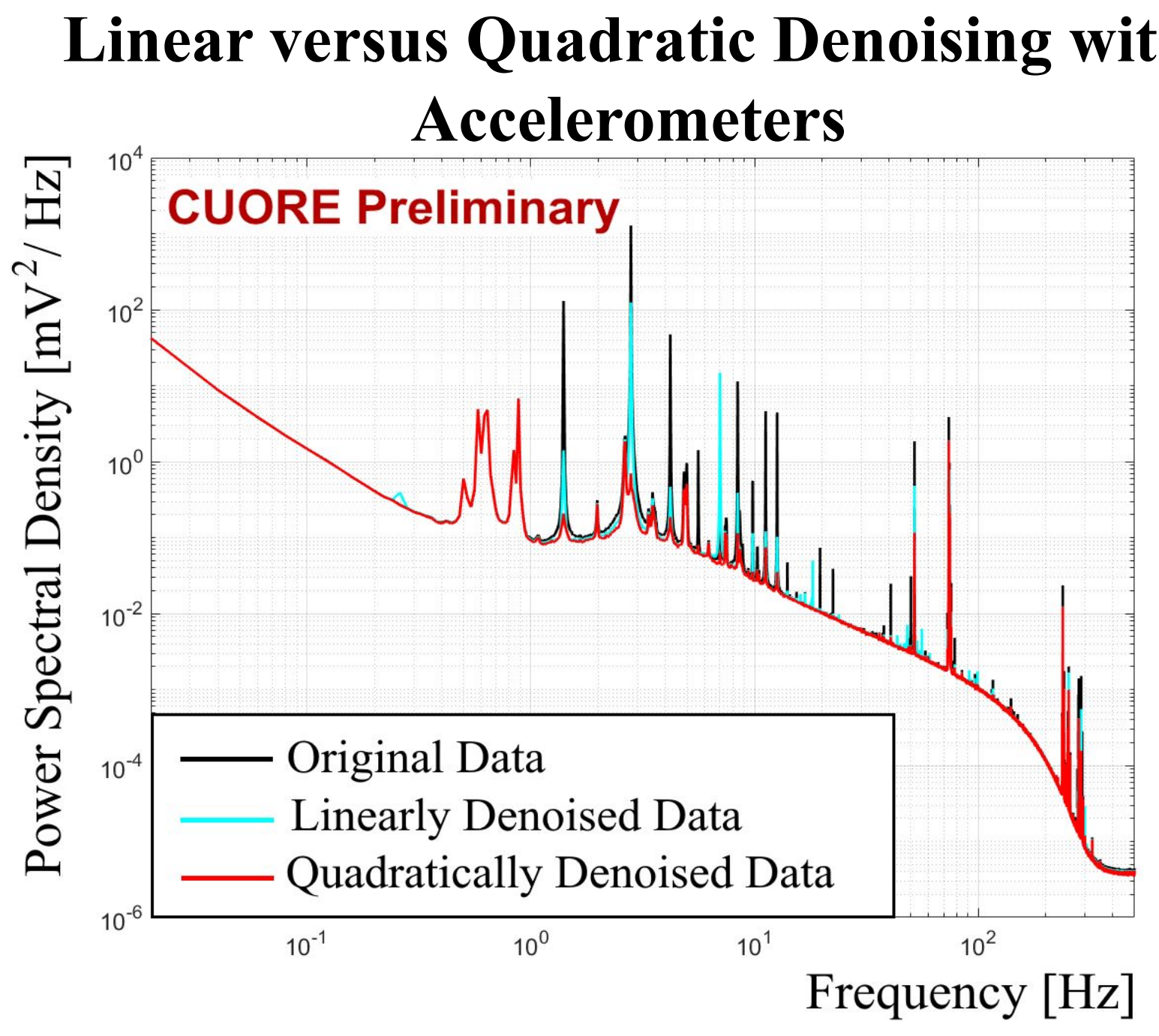
Outputs of the Algorithm

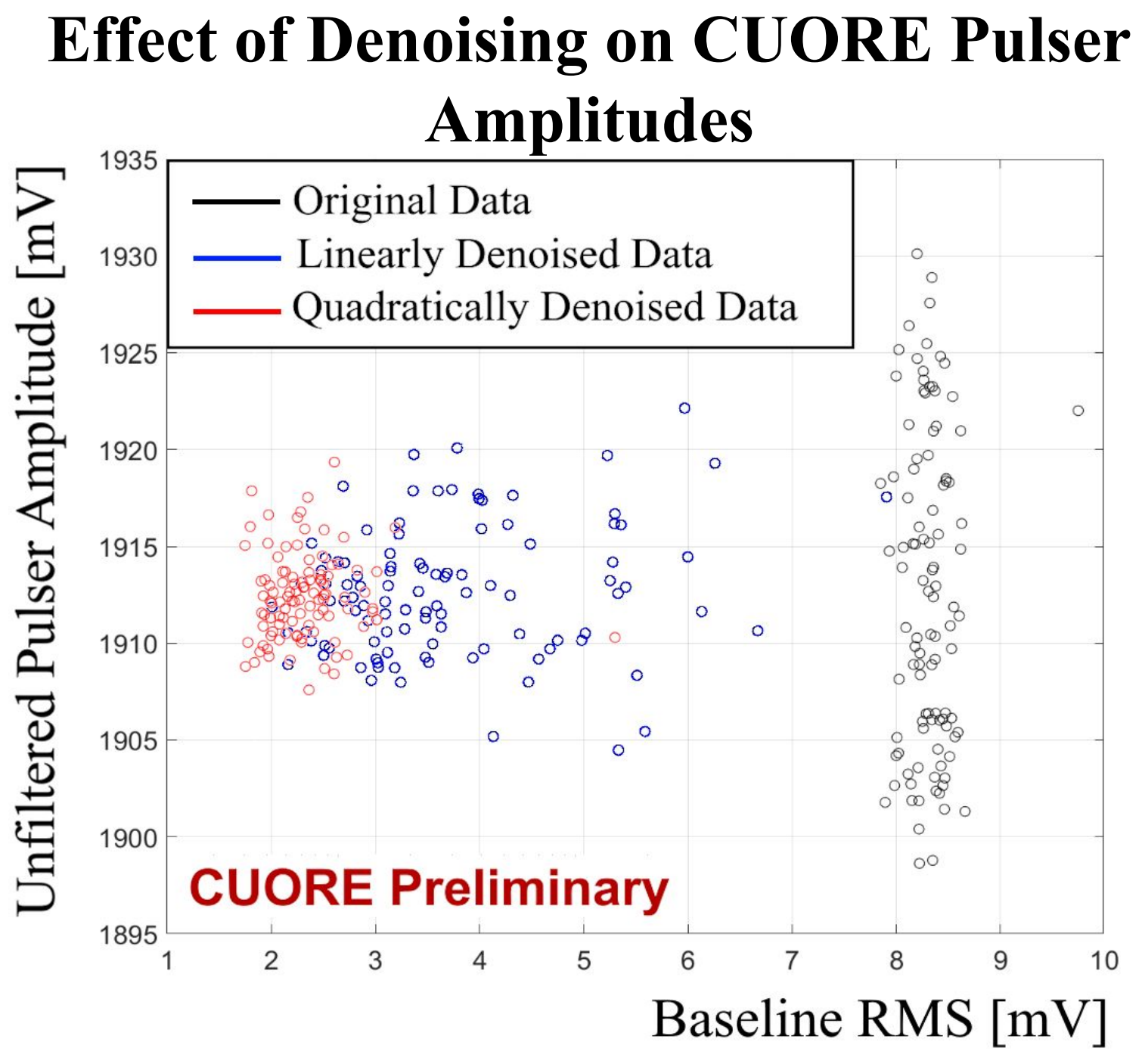

Transfer Functions from Accelerometers to Calorimeter

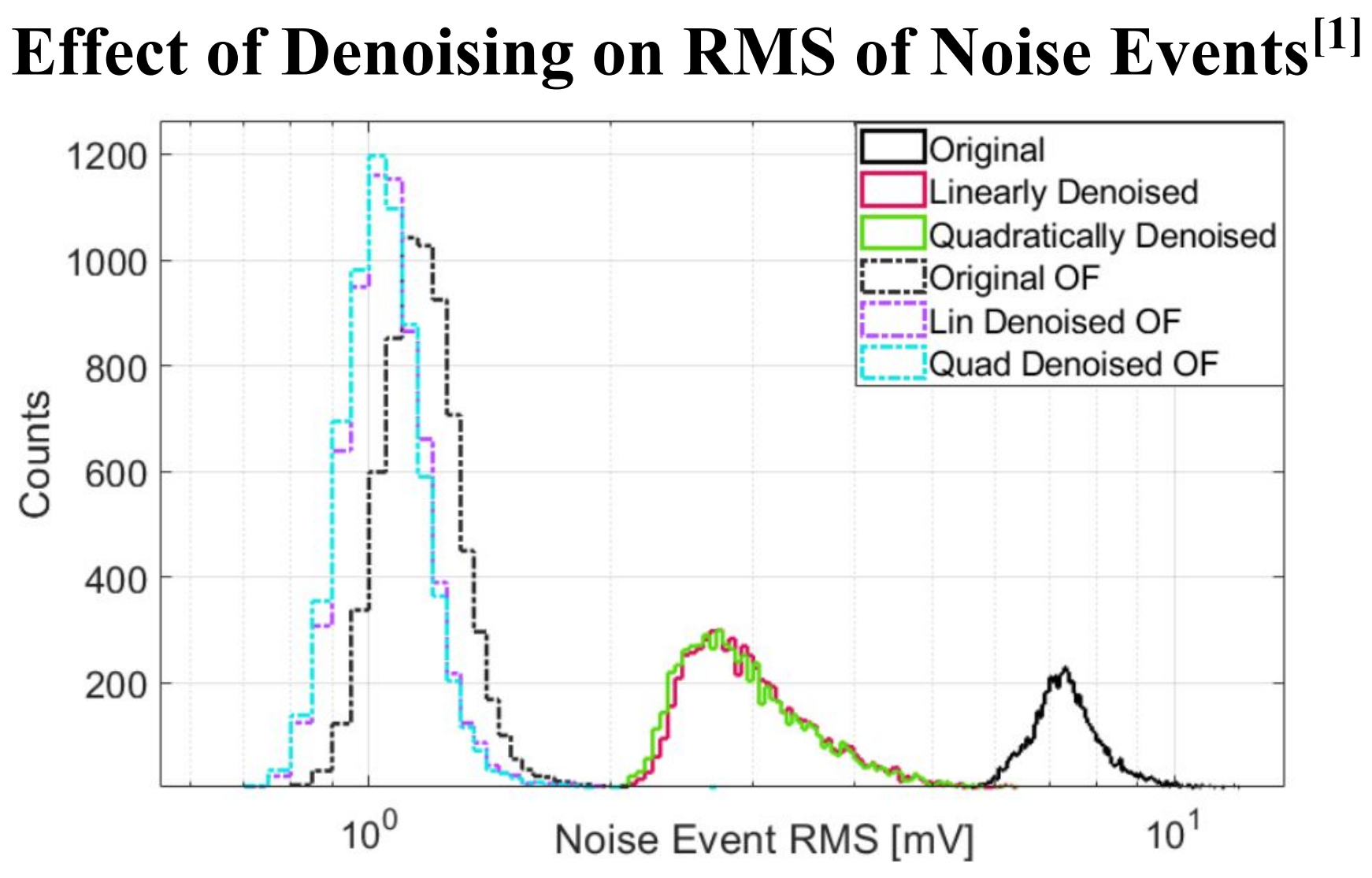

A CUORE Pulse Before and After Denoising

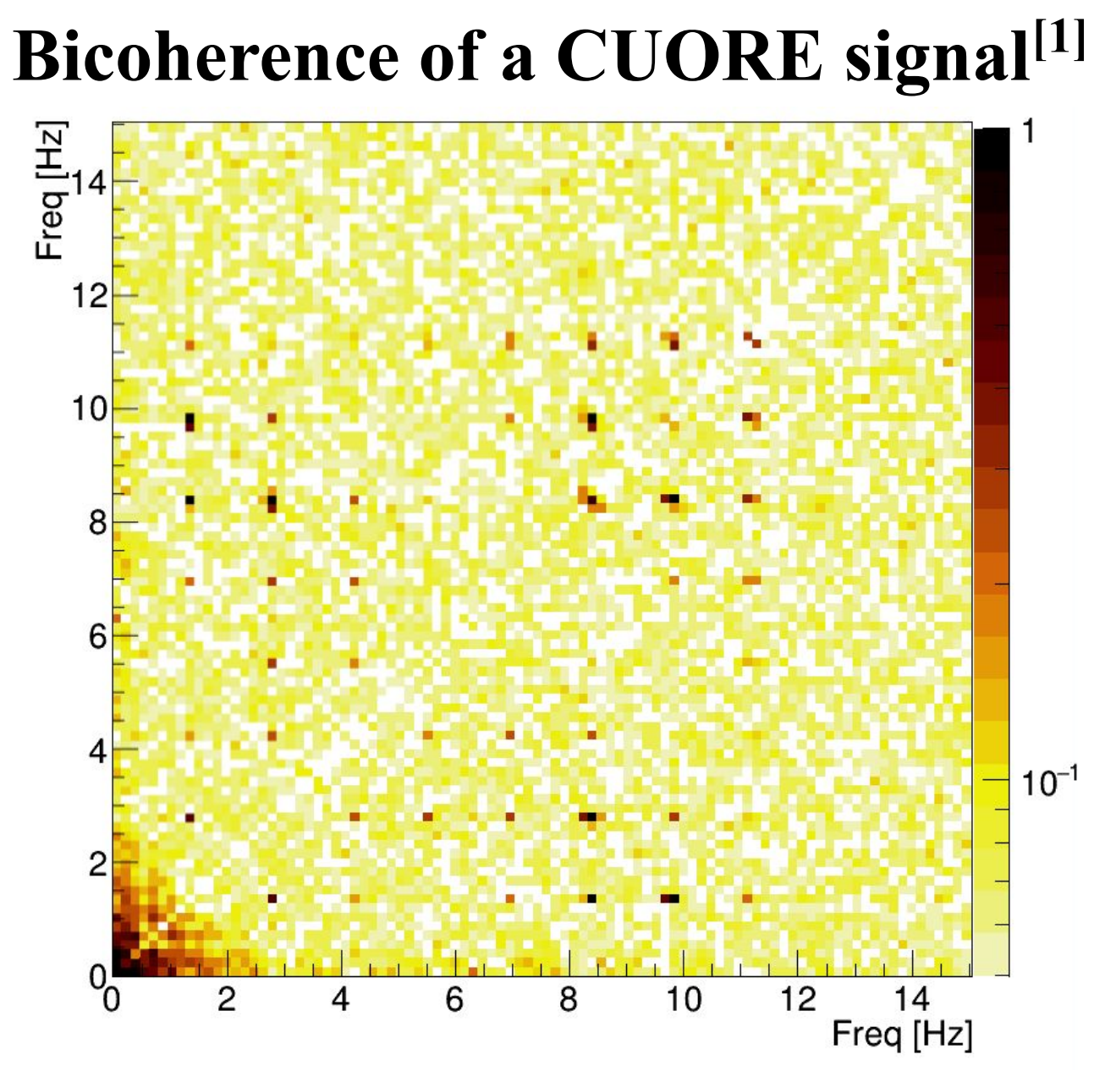
Nonlinear Extension of the Algorithm

The response of a thermal detector should be the same regardless of the directionality of the signal, thus the thermal response to bipolar vibration signals should have a unipolar thermal component along with a bipolar capacitive pickup term. We use the squares of the auxiliary devices as proxies for the thermal response, and we include them as additional auxiliary signals in our model.


Linear versus Quadratic Denoising with Accelerometers


Effect of Denoising on CUORE Pulser Amplitudes

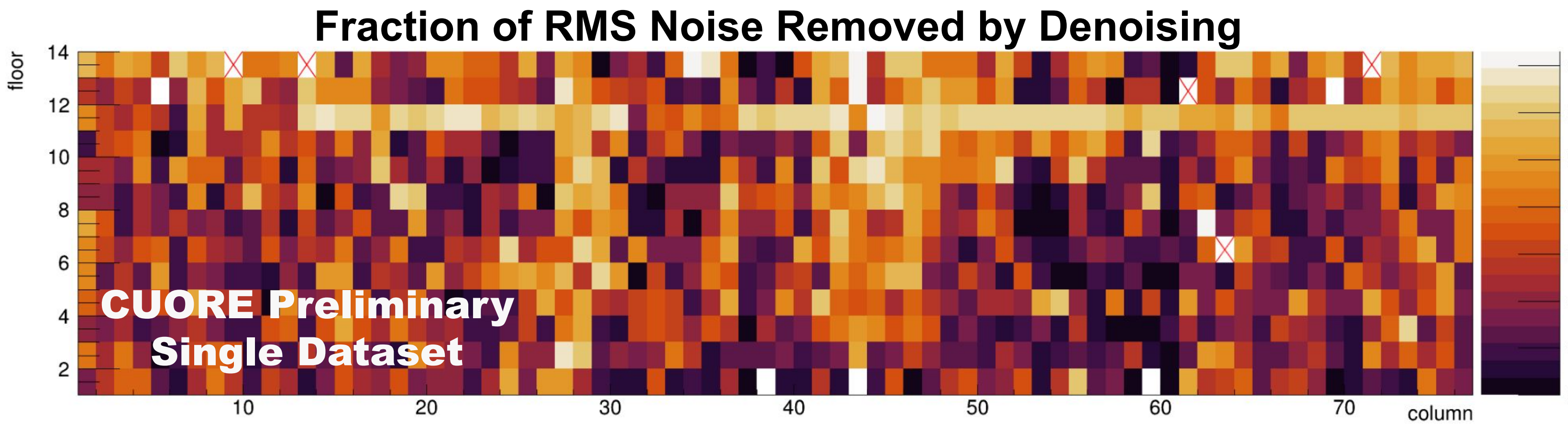

Effect of Denoising on RMS of Noise Events[1]


Bicoherence of a CUORE signal[1]

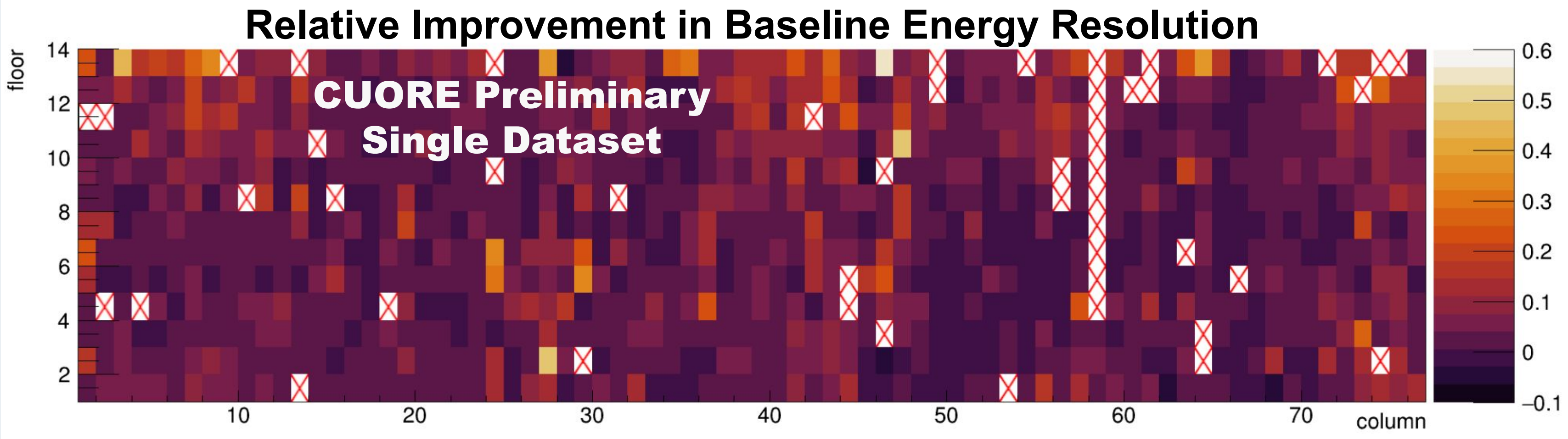
[1] K. J. Vetter et al. Improving the performance of cryogenic calorimeters with nonlinear multivariate noise cancellation algorithms. Eur. Phys. J. C 84, 243 (2024). https://doi.org/10.1140/epjc/s10052-024-12595-y

Effects of the Algorithm on the Entire CUORE Detector

Using a single dataset of CUORE data, we compare different quantities related to the noise of the detector before and after denoising. For this particular dataset, we decorrelate the noise against the accelerometer signals and their squares.


Fraction of RMS Noise Removed by Denoising

The total noise RMS of all CUORE detectors is reduced by **39.6%.** The median reduction in noise for across all channels is **25.8%**. There is clearly a geometric dependence on the reduction of noise: channels on the 11th floor demonstrate a greater reduction in noise due to the higher relative presence of correlated noise.


Relative Improvement in Baseline Energy Resolution

After applying the optimal filter and calibrating each channel, we find an average improvement in the baseline energy resolution of **4.5%**. In the context of searching for $0\nu\beta\beta$ decay, this in turn gives an equivalent reduction in threshold, allowing for betting coincidence tagging and background rejection.

Future Work

In the future, we hope to develop a more robust model of the thermal response to vibrations in the CUORE detectors. Adaptive algorithms may also further reduce noise due to transient effects such as earthquakes. Noise decorrelation algorithms like these will also be essential to future experiments such as CUPID.