# NON-LINEAR NOISE SUBTRACTION FOR LOW FREQUENCY

Final Presentation for LIGO SURF 2021
August 19, 2021

Student: Yuka Lin

Mentor: Dr. Gabriele Vajente

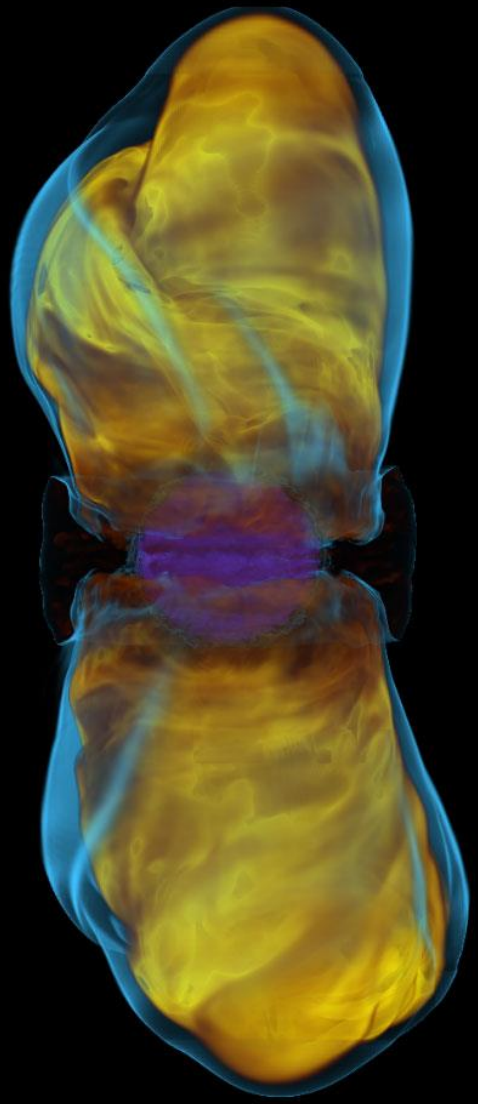
# OUTLINE

- Motivation
- NonSENS Algorithm
- Results
- Questions

# MOTIVATION

# CORE-COLLAPSE SUPERNOVAE

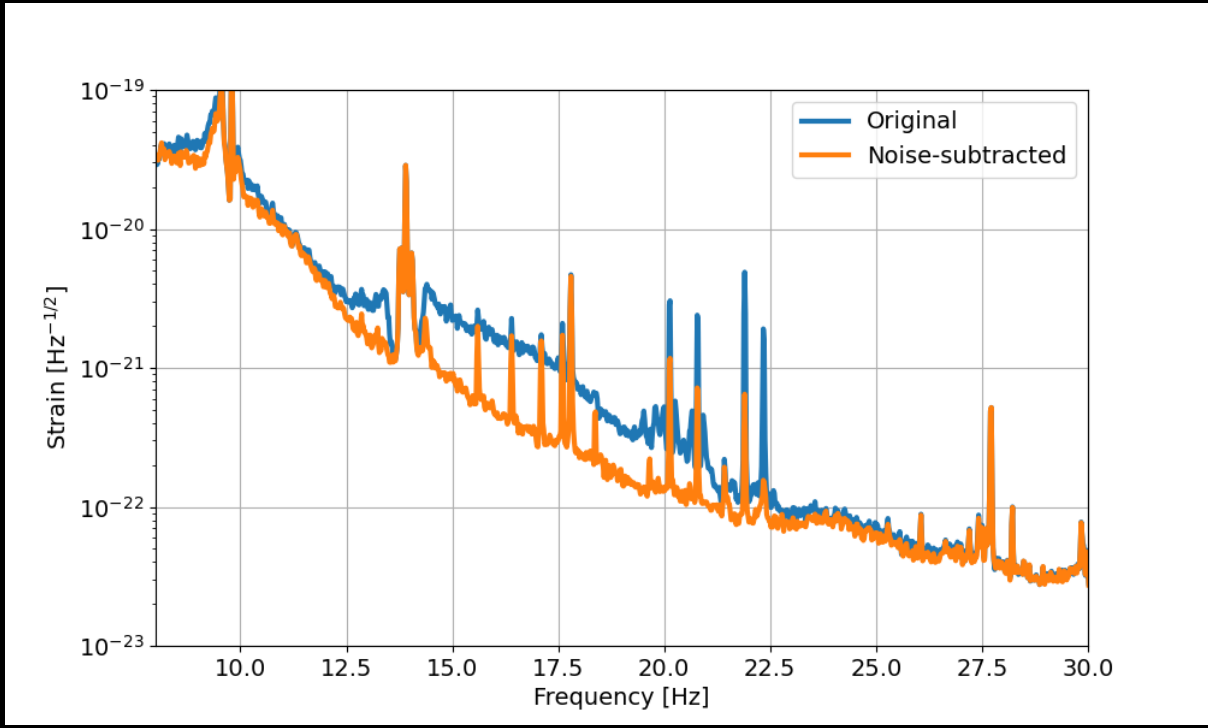
- when a massive star reaches the end of its lifespan and experiences rapid collapse
- in an event such as a galactic supernova, a fraction of the GW memory might be able to be detected above the noise floor
  - GW "*memory*" is permanent deformation of spacetime in the LOW FREQUENCY range of the signal
- GW memory emission of CCSN's can peak below ~10 Hz
  - has the center frequency around 2Hz but it has tails that survive up to 40Hz and that can be above the current LIGO noise for a galactic SN



# NONSENS ALGORITHM

- **Non**-**S**tationary **E**stimation of **N**oise **S**ubtraction
- Original application of the algorithm used for subtraction in frequency ranges *over* 10 Hz
- Now we want to modify the algorithm to perform similar noise reductions *under* 10 Hz

**Project Goal: reduce the noise in the range where the GW memory is relevant for a CCSN**




https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=57423

# NONSENS ALGORITHM

# NONSENS ALGORITHM

- Was created to reduce the noise that are coupled non-linearly and non-stationary in a strain signal
  - Noise "couples" or leak into main signal; limits sensitivity of detectors
  - Noise coupling – physical process of adding some noise sources to the GW output

Linear — Non-linear

$$\boldsymbol{h(t) = h_{GW} + \underbrace{H[s(t)]}_{\text{Linear}} + \underbrace{\sum_{i=1}^{N} \alpha_i [x_i(t) s(t)]}_{\text{Non-linear}} + \varepsilon_F}$$

$h_{GW}$ = Gravitational Waves signal

$\alpha_i$ = non-linear noise coupling

$H$ = linear noise coupling

$s(t)$ = "fast" noise witness

$x_i(t)$ = "slow" modulation noise witness

# WHAT IS THE NON-LINEAR SUBTRACTION?

- In the **linear and stationary** subtraction, the noise that is witnessed by some auxiliary channel will couple to the strain

$$\boldsymbol{\varepsilon_L} = \int_0^\infty h(\tau)s(t-\tau)d\tau = \boldsymbol{H[s(t)]}$$

- In the **non-stationary** case, the coupling is modulated **(**In other words, the effects of the noise in the strain contains non-stationary characteristics)

$$\boldsymbol{\varepsilon_{NL}} = \sum_{i=1}^{N} \int_0^\infty \boldsymbol{\alpha_i}(\tau)\boldsymbol{n_i}(t-\tau)d\tau = \sum_{i=1}^{N} \boldsymbol{\alpha_i[x_i(t)s(t)]}$$

Where:
$n_i(t) = x_i(t)s(t)$

# AUXILIARY CHANNELS

**Auxiliary channel** – time series data recorded by the detector; monitors detector behavior and environment

- $s(t)$, fast noise witnesses contains content in the higher frequency band (1-10 Hz)
- $x_i(t)$ , slow modulation witness contains content in the lower frequency band (below 1 Hz)

# SUBTRACTION

- The modulated signals are coupled with the non-stationary transfer function $\alpha_i$
- Then:

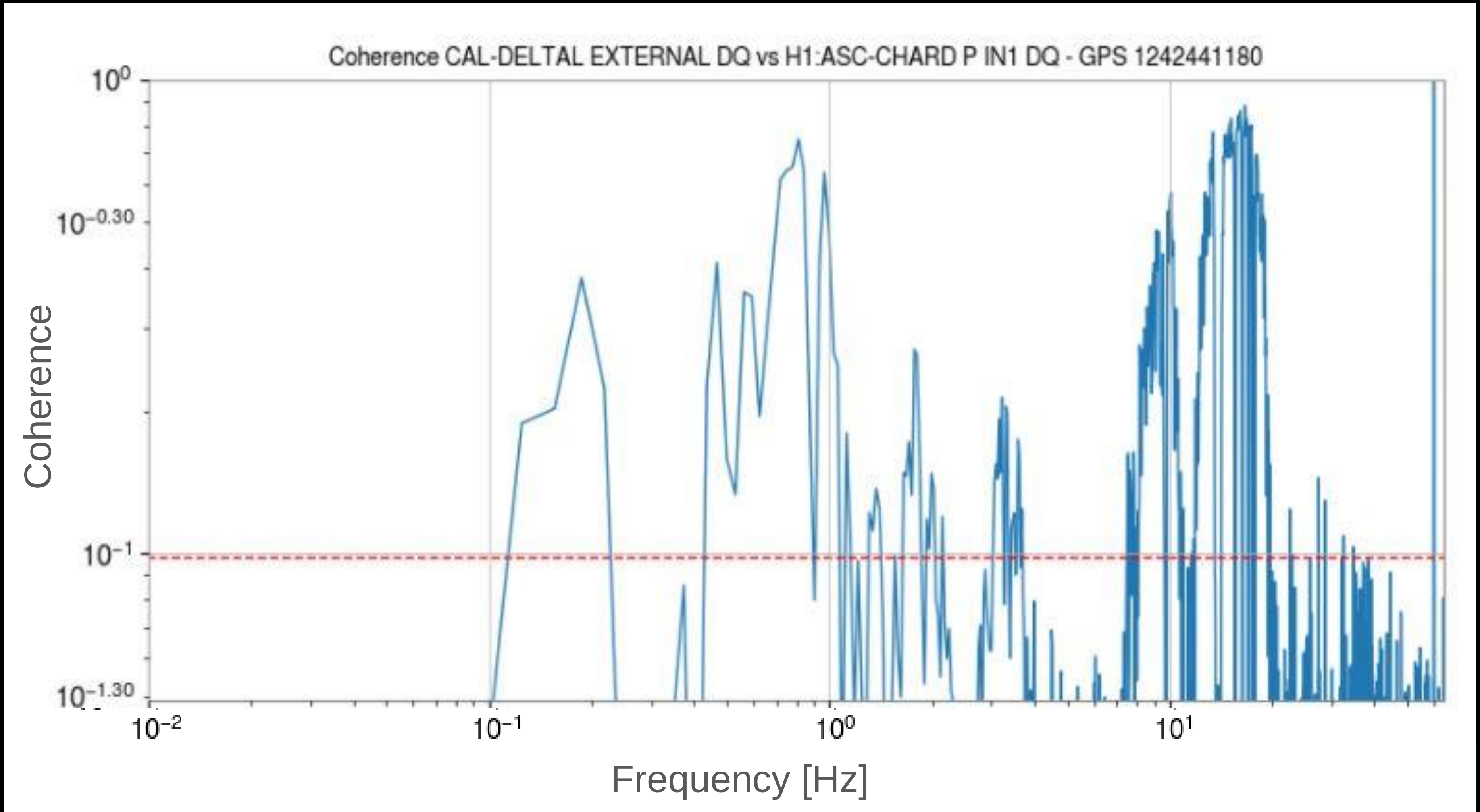
$$h_{sub}(t) = h(t) - sum\ of\ modulated\ signals$$

- Purpose of algorithm is to find the best parameters that will reduce the maximum amount of noise from the target strain as possible; the algorithm then will perform a prediction of the most optimal subtraction possible

# RESULTS

# RESULTS:

Step 1) Linear Coherence:




https://ldas-jobs.ligo.caltech.edu/~gabriele.vajente/bruco_lf_2021_06_22/

**Linear coherence** describes the correlation between the two signals in the frequency domain.

# RESULTS:

Step 2) Picking fast noise witness channels that perform the best linear subtraction

| Best Noise Witness Channels: |
|---|
| ASC-DSOFT_P_IN1_DQ |
| ASC-DHARD_P_IN1_DQ |
| ASC-X_TR_B_PIT_OUT_DQ |
| ASC-X_TR_B_YAW_OUT_DQ |
| ASC-X_TR_A_PIT_OUT_DQ |
| ASC-X_TR_A_YAW_OUT_DQ |
| SUS-SRM_M3_ISCINF_L_IN1_DQ |
| SUS-SRM_M3_ISCINF_P_IN1_DQ |
| SUS-SRM_M3_ISCINF_Y_IN1_DQ |
| SUS-SRM_M3_WIT_P_DQ |
| SUS-SRM_M3_WIT_Y_DQ |
| SUS-SRM_M3_WIT_L_DQ |
| SUS-ZM2_M1_VOLTMON_UL_OUT_DQ |
| SUS-ZM2_M1_VOLTMON_LL_OUT_DQ |
| SUS-ZM2_M1_VOLTMON_LR_OUT_DQ |

Some naming convention for channels:

**<u>Subsystems:</u>**
**ASC** - Alignment Sensing and Control
**SUS** – Suspension

**<u>Mirror Identifiers:</u>**
**SRM** – Signal Recycling Mirrors
**ZM2** – 2nd Squeezer Mirror
**M1, M3** – Suspension levels

**<u>Signal Identifiers:</u>**
**DSOFT** – differential control arms (soft)
**DHARD** – different control arms (hard)
**X_TR** – transmission to X arm

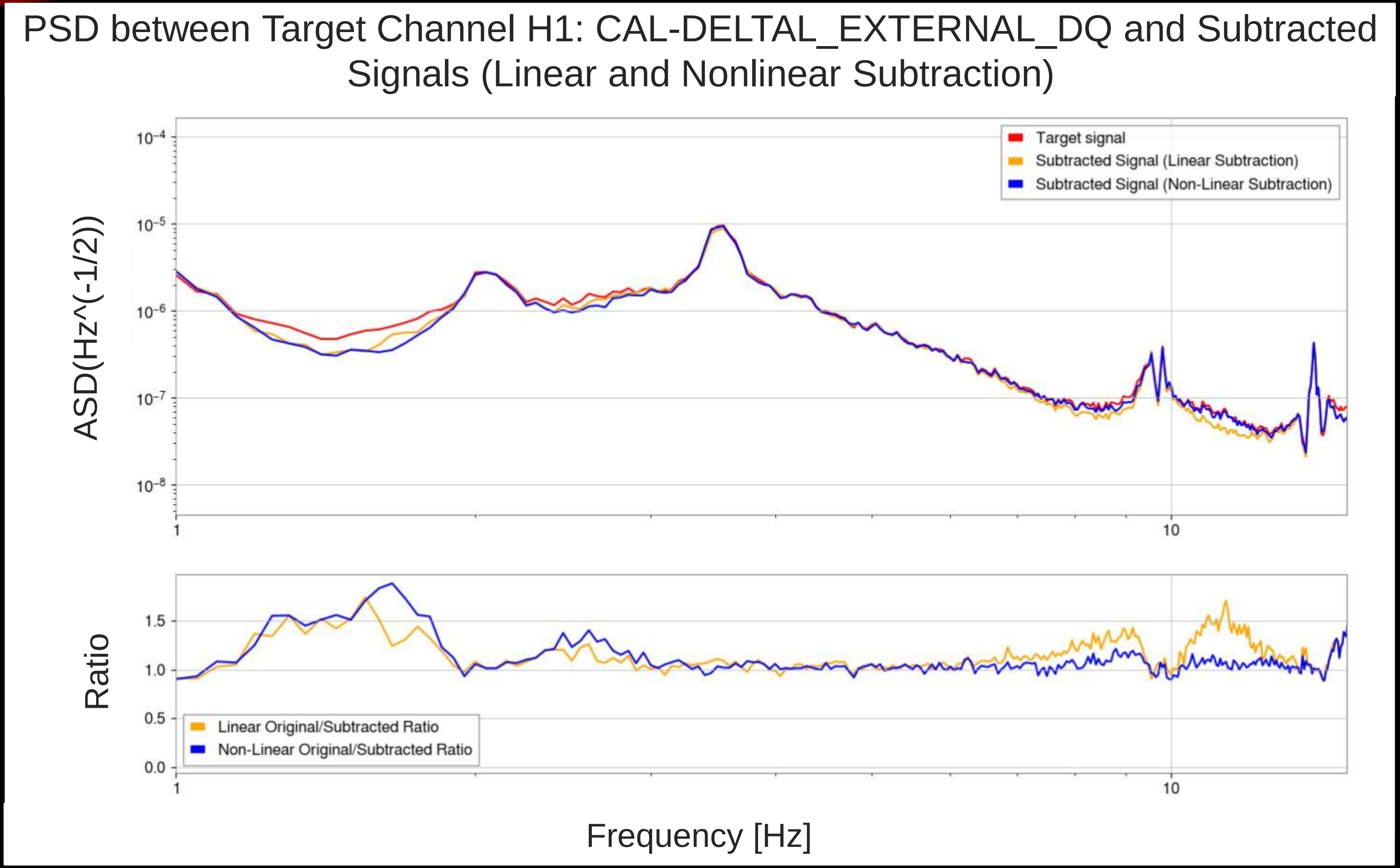
# RESULTS:

Step 3) Try non-stationary subtraction by adding "slow" modulation channels.

| Modulation Witness Channels: |
|---|
| ASC-INP1_P_INMON |
| ASC-INP1_Y_INMON |
| ASC-MICH_P_INMON |
| ASC-MICH_Y_INMON |
| ASC-PRC1_P_INMON |
| ASC-PRC1_Y_INMON |
| ASC-PRC2_P_INMON |
| ASC-PRC2_Y_INMON |
| ASC-SRC1_P_INMON |
| ASC-SRC1_Y_INMON |
| ASC-SRC2_P_INMON |
| ASC-SRC2_Y_INMON |
| ASC-DHARD_P_INMON |
| ASC-DHARD_Y_INMON |
| ASC-CHARD_P_INMON |
| ASC-CHARD_Y_INMON |
| ASC-DSOFT_P_INMON |
| ASC-DSOFT_Y_INMON |
| ASC-CSOFT_P_INMON |
| ASC-CSOFT_Y_INMON |

# RESULTS:

Time Domain Subtraction Plot:




*algorithm doesn't always converge; no guarantee you will get an optimal solution

# IS THIS RESULT GOOD?

- Original plan was to run algorithm through all of the O3 data
  - Takes a lot of time/computation
  - Goal is to do more subtraction in order to be able to be effective for study at lower frequency range
  - more possible channels relevant to the noise sources in the low frequency range should be assessed – mainly only the SUS and ASC channels were found in this project
- Continuation of project ☺

# ACKNOWLEDGEMENTS

A special thanks to:

***Dr. Gabriele Vajente*** *(mentor)*

*LIGO Summer Undergraduate Research Fellowship*

*Research Experiences for Undergraduates (REU) Program of the National Science Foundation*

Thank you for listening!

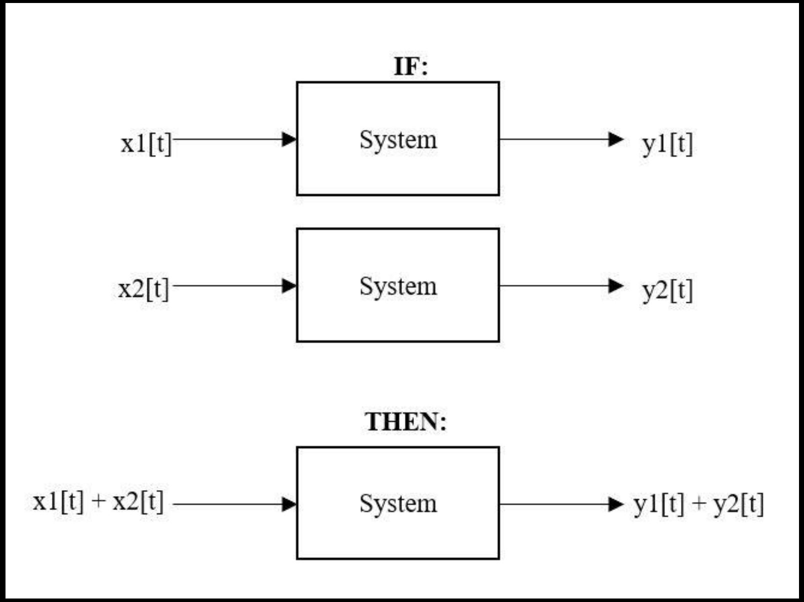
Any Questions?

Contact:
liny10@my.erau.edu

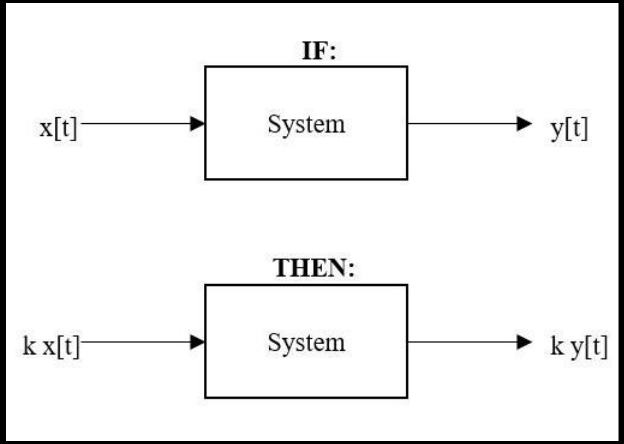
# LINEAR/NONLINEAR SYSTEM

System – process in which an output signal is produced as a result of the response to an input signal

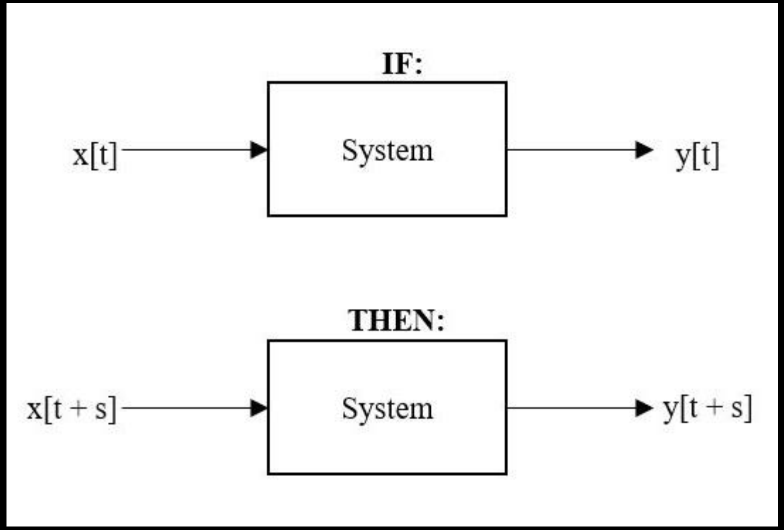
Additivity




Homogeneity




Shift Invariance




LINEAR AND TIME INVARIANT SYSTEM

# LINEAR AND TIME INVARIANT SYSTEM

$$x(t) = k_1 x(t - t_1) + k_2 x(t - t_2) + \cdots + k_i x(t - t_i)$$

Properties:

Additivity

Homogeneity

Shift Invariance

$$x(t) = \sum_{i=1}^{N} k_i x(t - t_i)$$

$$x(t) = \int_0^\infty k(\tau)\delta(t - \tau)d\tau = (k * h)(t)$$

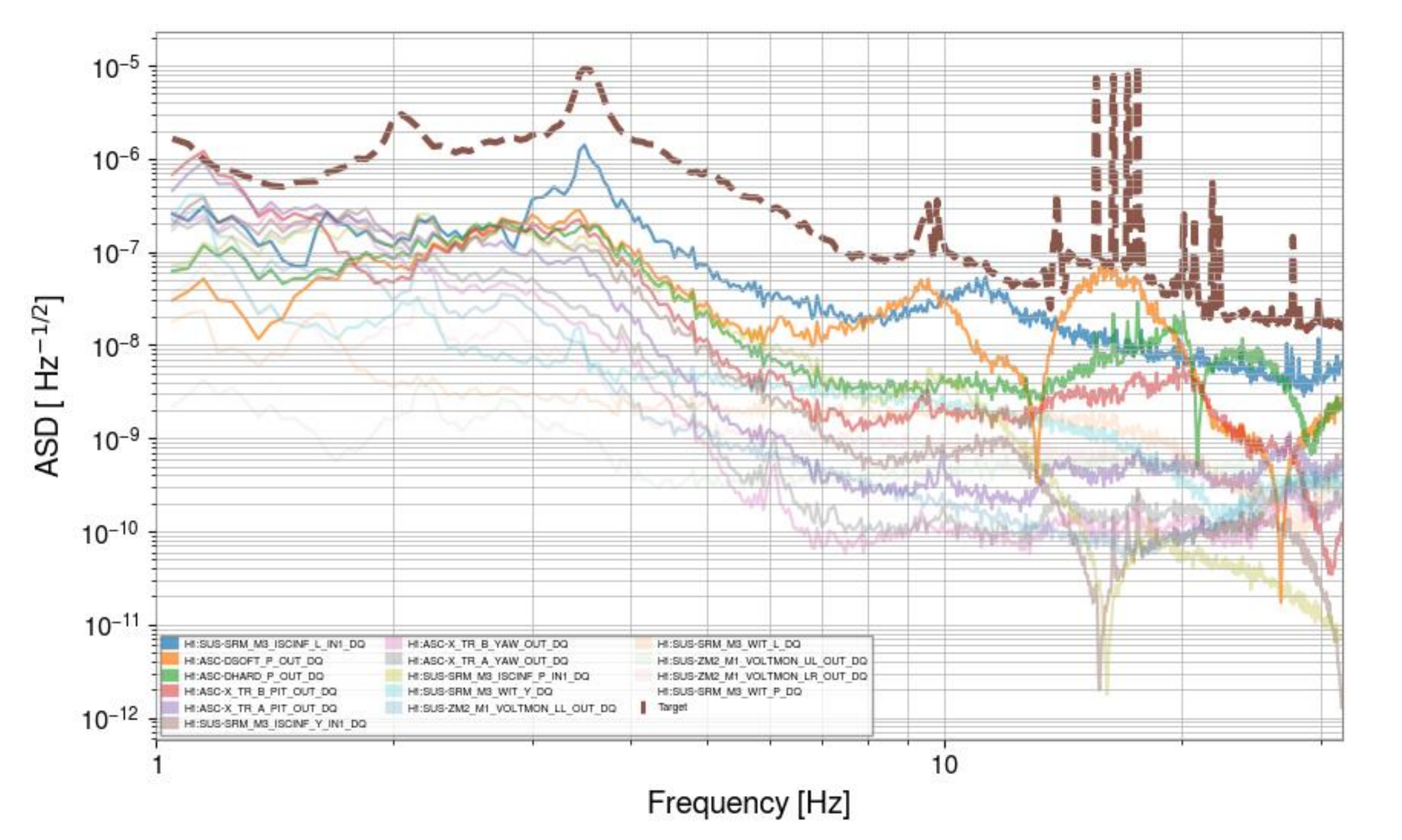
# "TARGET" STRAIN CHANNEL (SUPPLEMENTAL)

$$h(t)$$

- The **target** channel is the channel that we want to subtract the noise from
- For this project, utilize: **CAL-DELTAL_EXTERNAL_DQ**
  - produces the calibrated strain signals that are corrected below 10 Hz
  - Advantage: the only channel currently that contains calibrated strain below 10 Hz.
  - Disadvantage: less accuracy than the GDS-CALIB_STRAIN channel, which was the target channel that was originally used for subtracting noise between 10 and 30 Hz

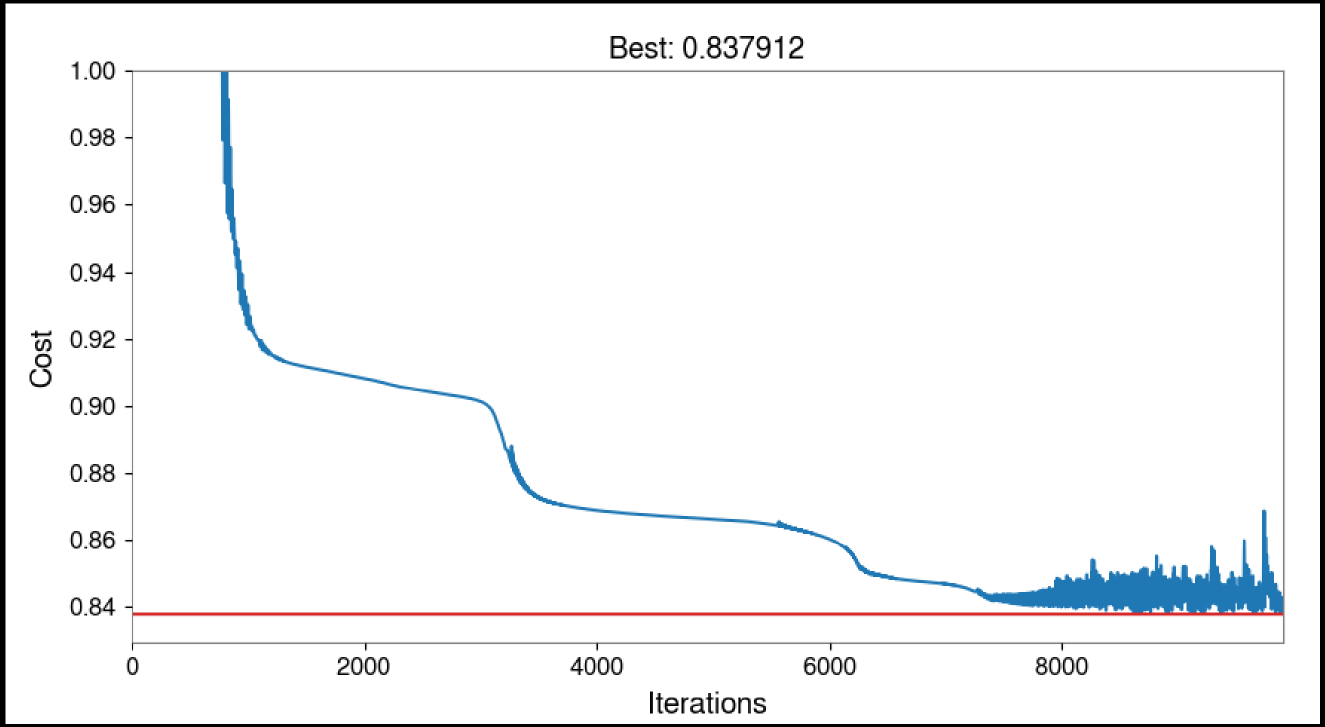
# (SUPPLEMENTAL) RESULTS:

Contribution plot:



# (SUPPLEMENTAL) RESULTS:

Cost Function:




- Optimized parameter is the minimum value that is calculated by the cost function
- Algorithm doesn't always converge

# (SUPPLEMENTAL) MODULATED SIGNALS

$$\begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \end{bmatrix} \times \begin{bmatrix} s_1(t) \\ s_2(t) \\ s_3(t) \\ s_4(t) \\ s_5(t) \end{bmatrix} = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ \\ x_1(t) \cdot s_1(t) \\ x_1(t) \cdot s_2(t) \\ x_1(t) \cdot s_3(t) \\ x_1(t) \cdot s_4(t) \\ \\ x_2(t) \cdot s_1(t) \\ x_2(t) \cdot s_2(t) \\ \dots \\ \dots \\ \dots \\ x_4(t) \cdot s_5(t) \end{bmatrix}$$

Noise Witnesses signals

Modulation Witnesses signals

Total Modulated signals