LIGO-T2300145

sga46@cornell.edu

LIGO SURF

NOISE ANALYSIS FOR THE FROSTI ADAPTIVE OPTIC

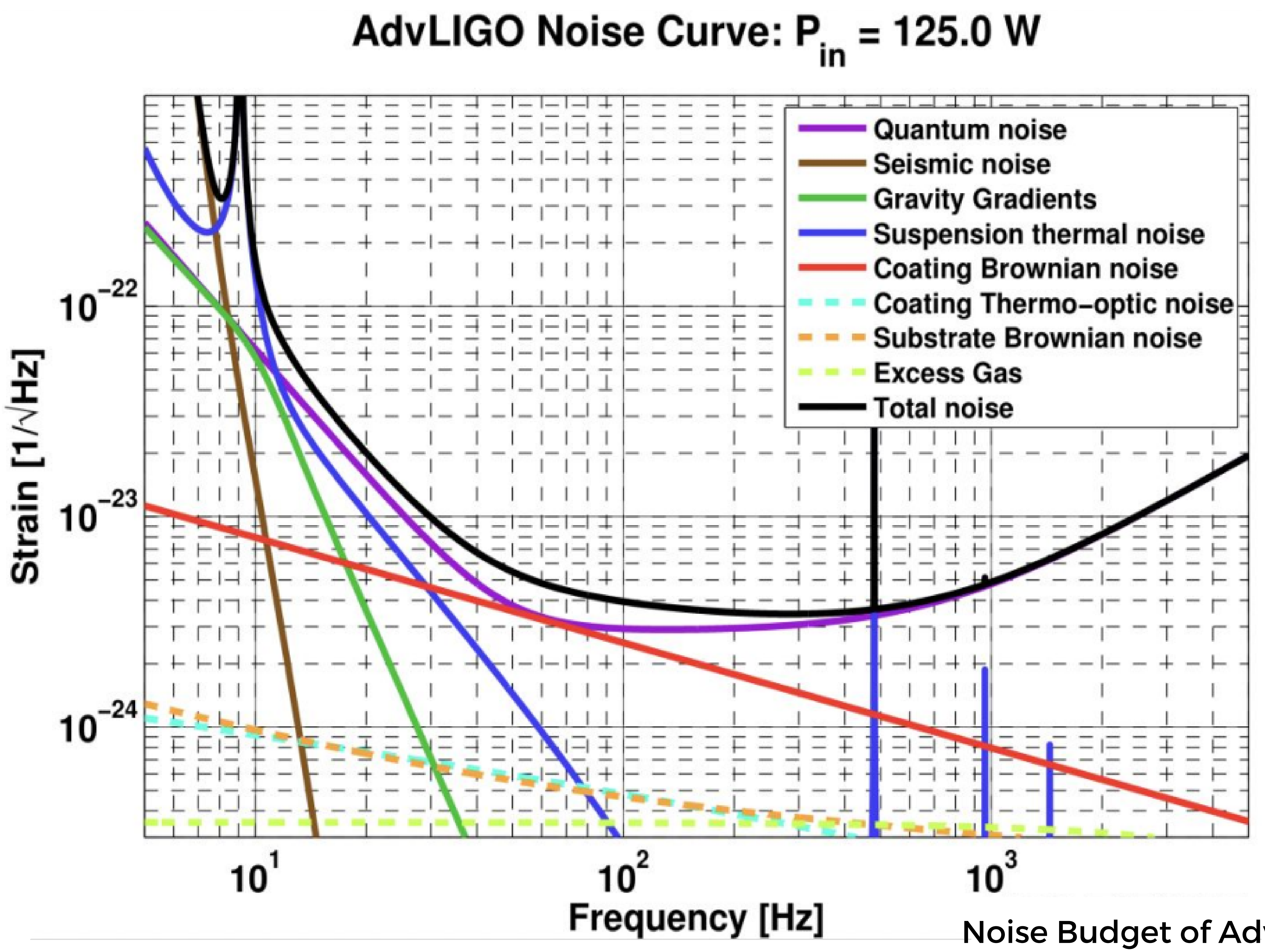
Sophia Arnold, Cornell University
Mentors: Jonathan Richardson and Tyler Rosauer, UC Riverside

Presentation Outline

1. Motivation
2. Proposed Solution: FroSTI
3. Intensity Noise GUI Development
4. Applying the GUI
5. Project Synthesis

1) MOTIVATION
FUTURE IMPROVEMENTS TO LIGO

Motivation
Higher laser power



Noise Budget of AdvLIGO
(Hild 2017, G1200598)

[Answer]

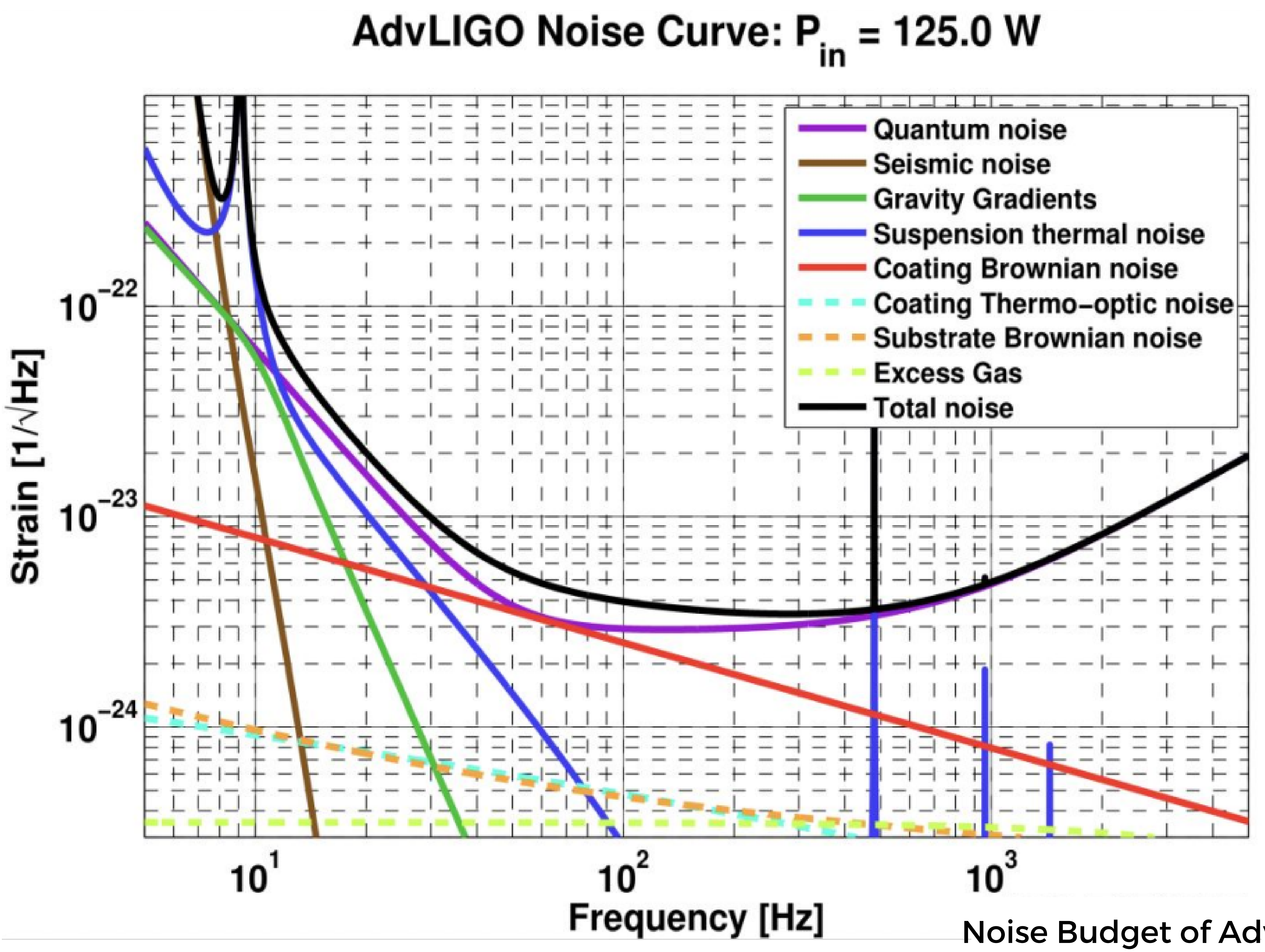
Notice:

At **frequencies** higher than **100Hz**, **quantum noise dominates** the **total noise**!

Lowering the **photon shot noise** will lower **quantum noise**.

The amplitude of the spectral density of **shot noise** decreases with $\frac{1}{\sqrt{N}}$
where N = number of photons.

Motivation
Higher laser power



Noise Budget of AdvLIGO
(Hild 2017, G1200598)

Answer

Notice:

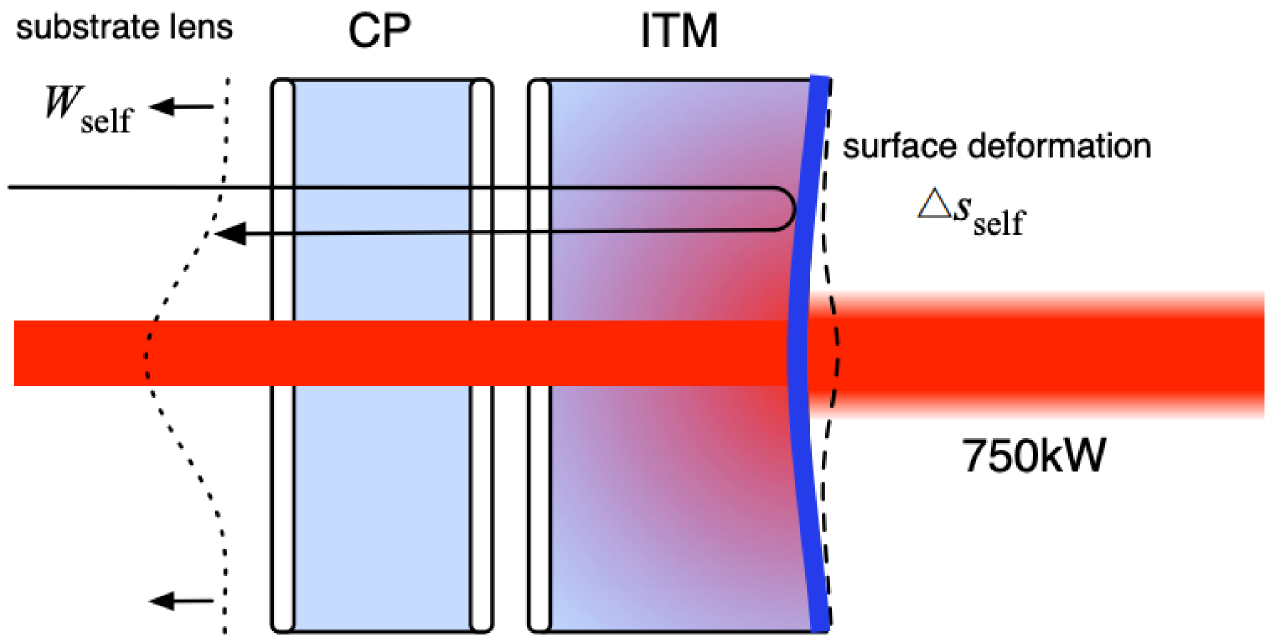
At **frequencies** higher than **100Hz**, **quantum noise dominates** the **total noise**!

Lowering the **photon shot noise** will lower **quantum noise**.

The amplitude of the spectral density of **shot noise** decreases with $\frac{1}{\sqrt{N}}$ where N = number of photons.

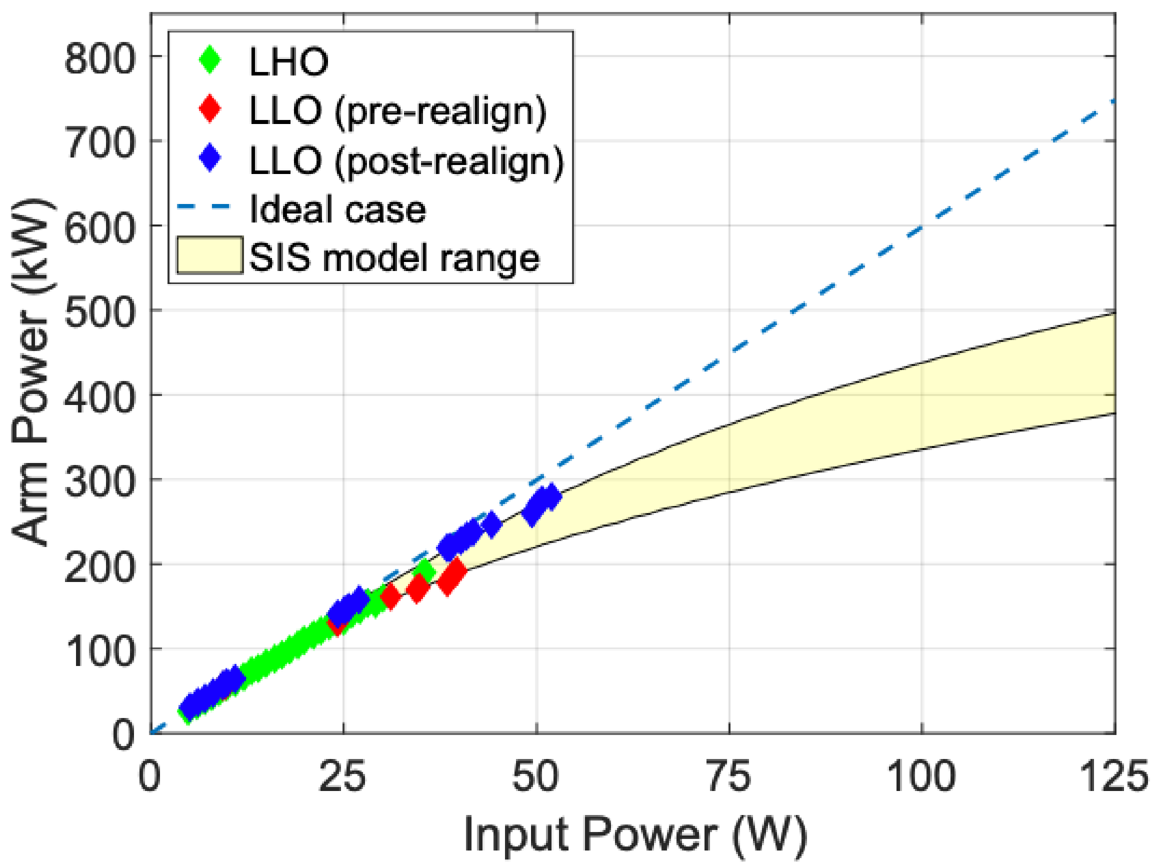
Solution: Higher laser power!

Motivation
Higher laser power and the associated costs



Thermal deformation of lens (Brooks, arXiv:1608.02934 [physics.ins-det])

aLIGo ideal vs. actual arm power vs. input power circa O3 (Brooks et al., P1900287)

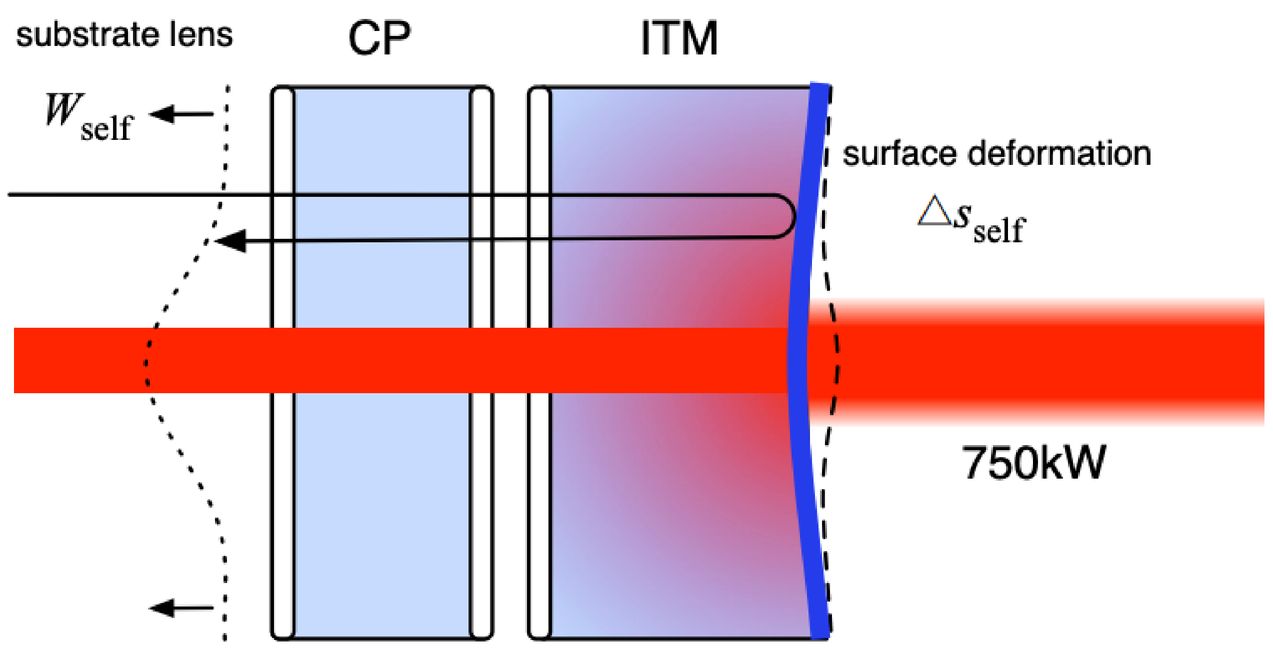


The **Thermal Compensation System (TCS)** is not equipped for higher laser power.

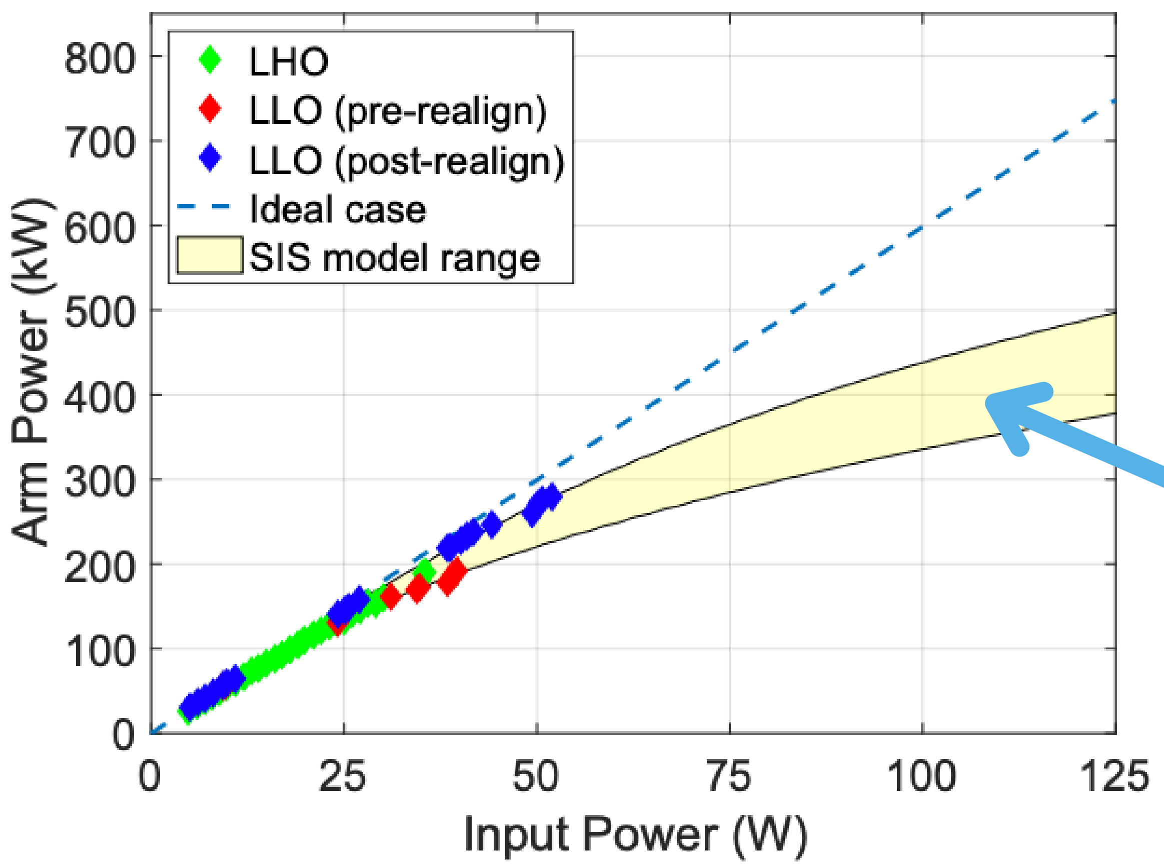
Worse effects from **uniform absorption**. **TCS augments** the problem.

Larger effects from point absorbers. **TCS** is **still not able to compensate**.

Motivation
Higher laser power and the associated costs



Thermal deformation of lens (Brooks, arXiv:1608.02934 [physics.ins-det])



aLIGo ideal vs. actual arm power vs. input power circa O3 (Brooks et al., P1900287)

The **Thermal Compensation System (TCS)** is not equipped for higher laser power.

Worse effects from **uniform absorption**. **TCS augments** the problem.

Larger effects from point absorbers. **TCS** is **still not able to compensate**.

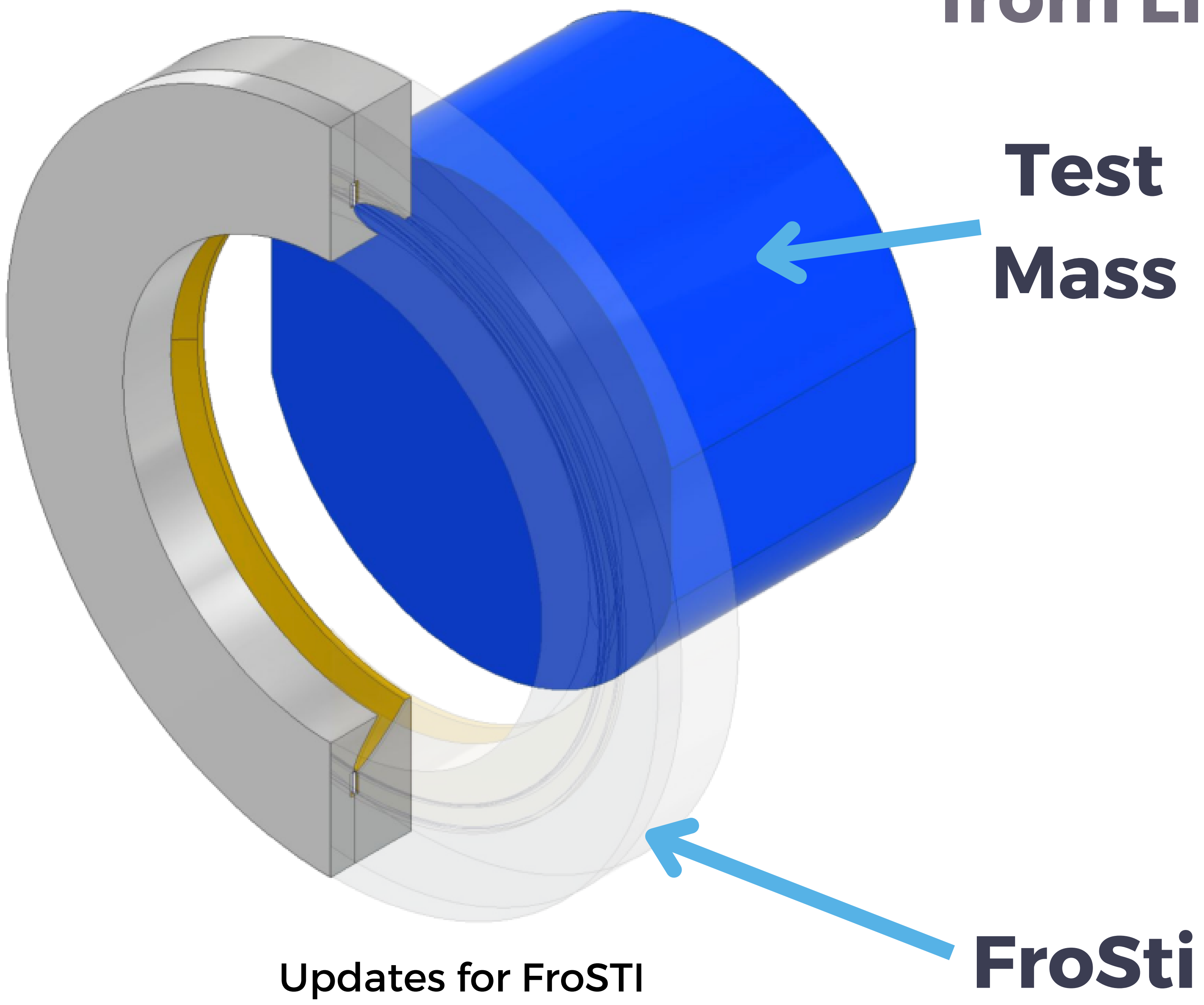
Predicted losses due to point absorbers

2) PROPOSED SOLUTION: FROSTI

ELIMINATING TEST MASS LOSSES

Front Surface Type Irradiator (FroSTI)
Richardson lab

A next generation, annular ring heater, designed to combat power losses from LIGO's test masses



Updates for FroSTI
(Richardson 2022, G2200399)

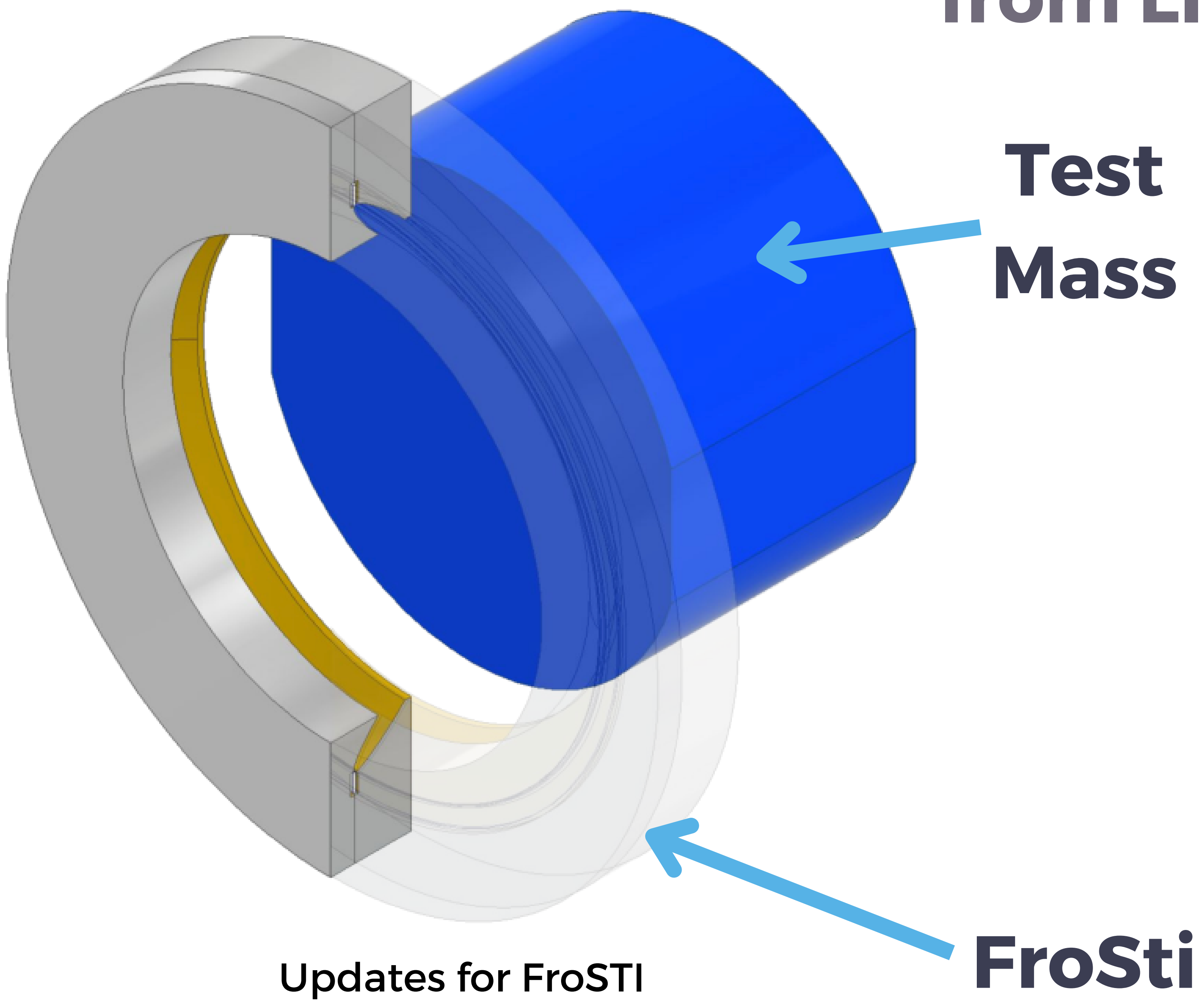
Purpose:

Correct problems posed by both thermal deformity of test masses, and point absorbers by:

Creating precise wavefront control technology that reduces power loss.

Front Surface Type Irradiator (FroSTI)
Richardson lab

A next generation, annular ring heater, designed to combat power losses from LIGO's test masses



Updates for FroSTI
(Richardson 2022, G2200399)

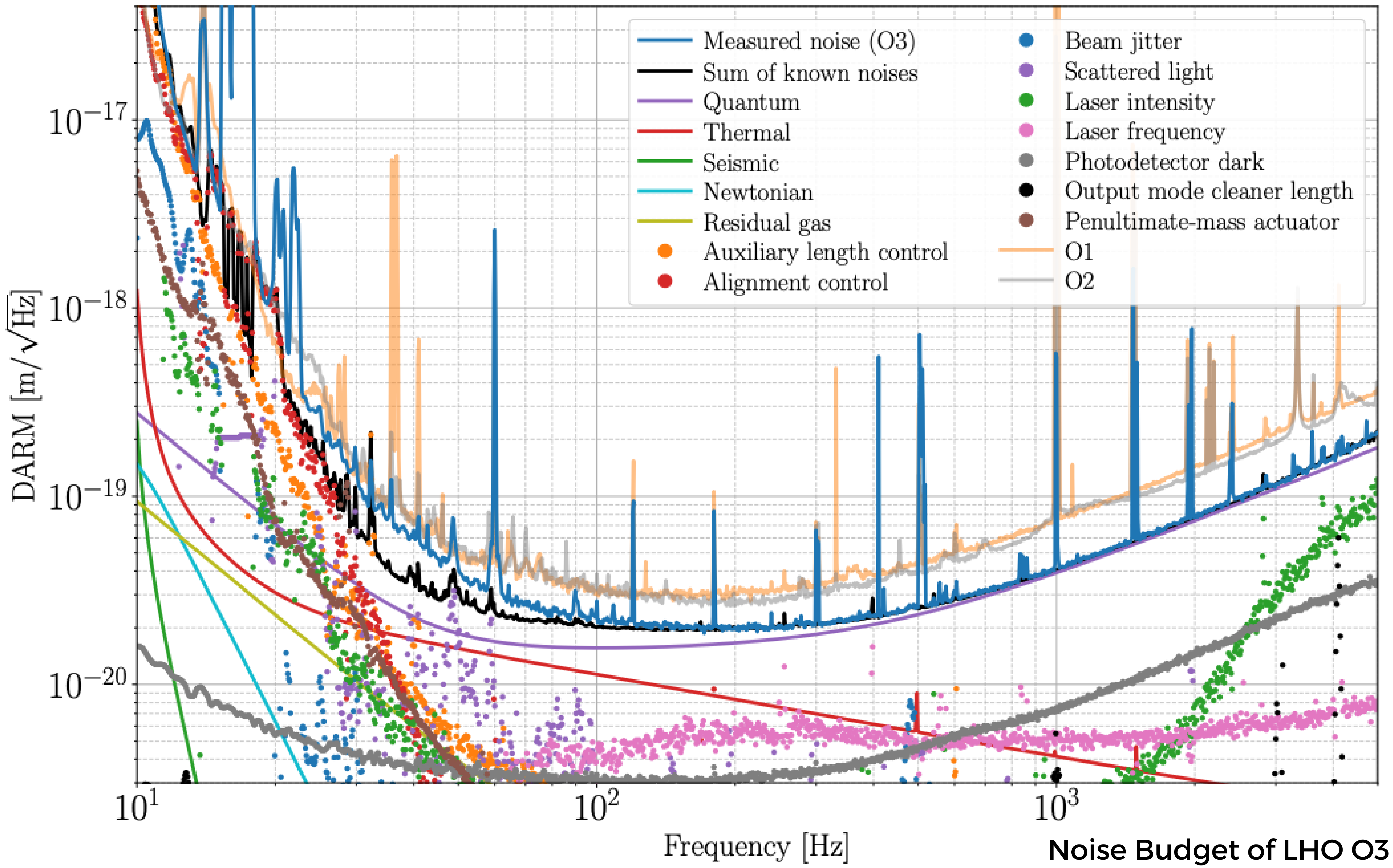
Purpose:

Correct problems posed by both thermal deformity of test masses, and point absorbers by:

Creating precise wavefront control technology that reduces power loss.

Still needs to be experimentally tested

Proposed Solution: FroSTI
Installing FroSTI in LIGO

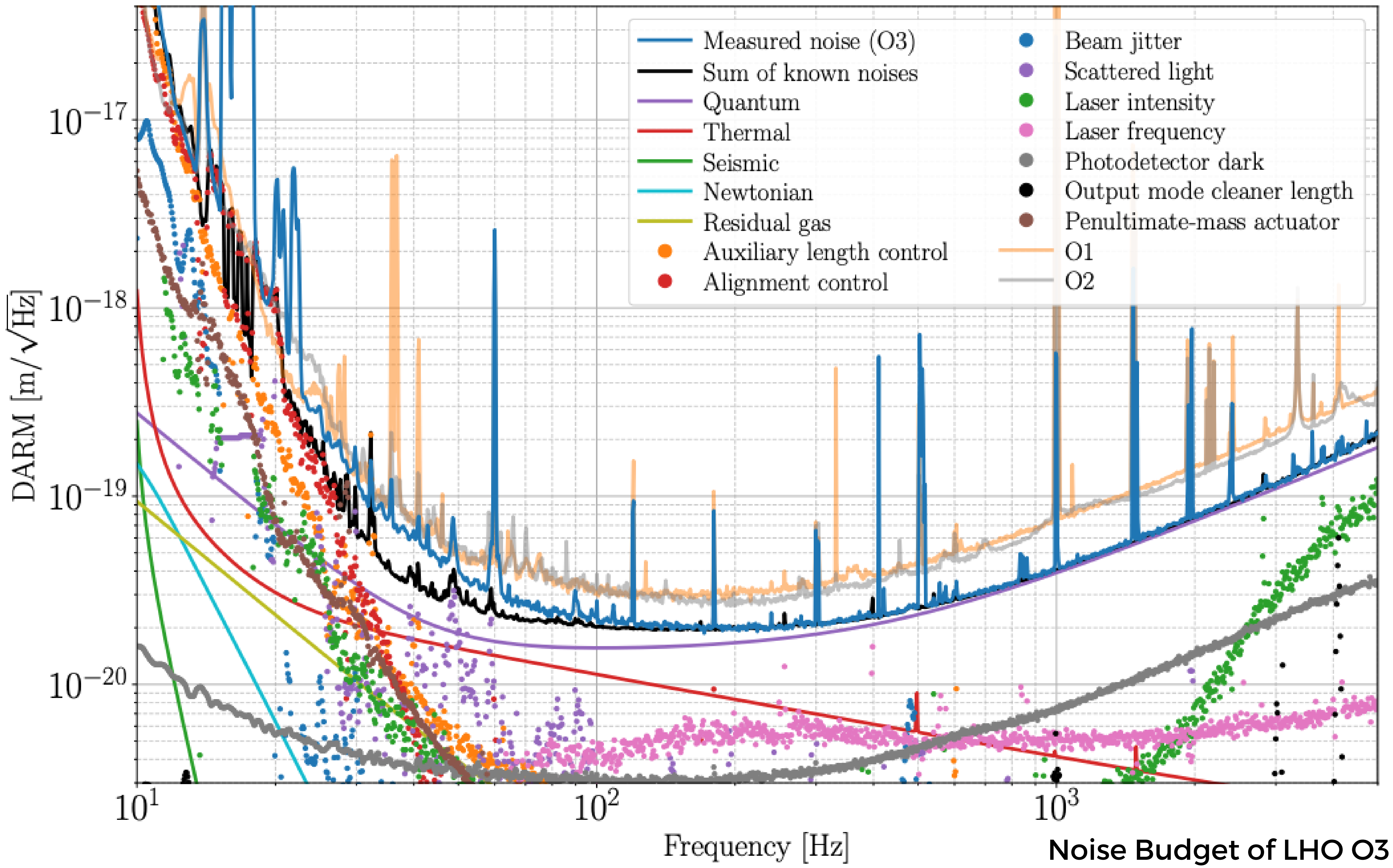


Noise Budget of LHO O3
(G. L. Mansell 2020, P2000122-v)

The Challenge

Noise in FroSTI's heating elements must be **100x less** than the **quantum noise of a photodetector**!

Proposed Solution: FroSTI
Installing FroSTI in LIGO



Noise Budget of LHO O3
(G. L. Mansell 2020, P2000122-v)

The Challenge

Noise in FroSTI's heating elements must be **100x less** than the **quantum noise of a photodetector**!

How can we measure noise on this scale?

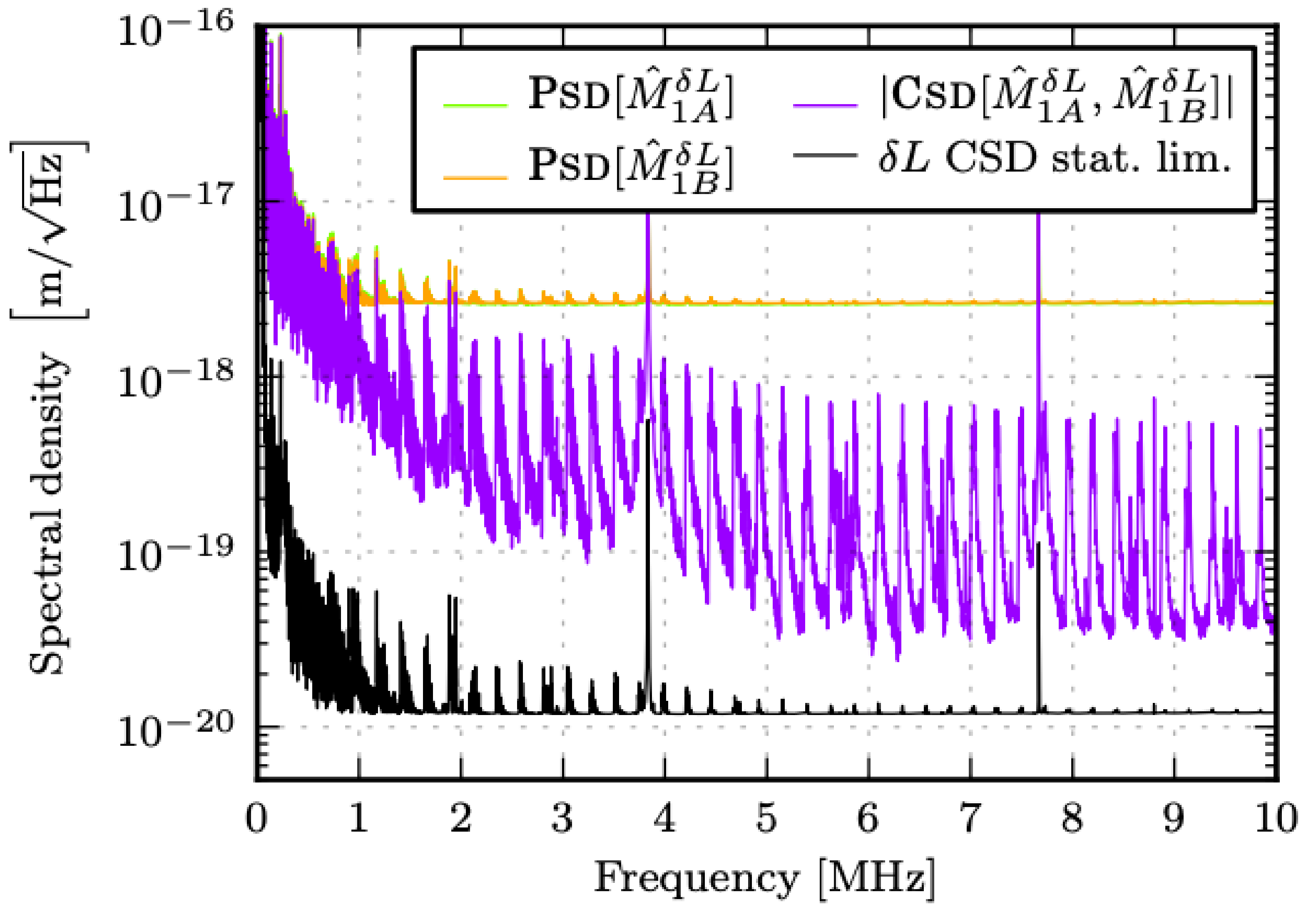
Proposed Solution: FroSTI
Installing FroSTI in LIGO

The Solution:

Use the **Power Spectral Density (PSD)** and **Cross Spectral Density (CSD)**.

Use the **rolling time average** of these values computed from a **continuous signal** to find noise **below LIGO's desired threshold**.

Fermilab Holometer Paper



Thermal noise of one interferometer. The Holometer: An Instrument to Probe Planckian Quantum Geometry (Chou: arXiv:1611.08265 [physics.ins-det])

Proposed Solution: FroSTI
SURF Project Objectives

My Goals:

Create a program which will **dynamically** find the **intensity noise performance** of FroSTI's heating elements.

Plot both the **CSD amplitude and phase** for **real-time noise analysis** of the heating elements.

The Red Pitaya

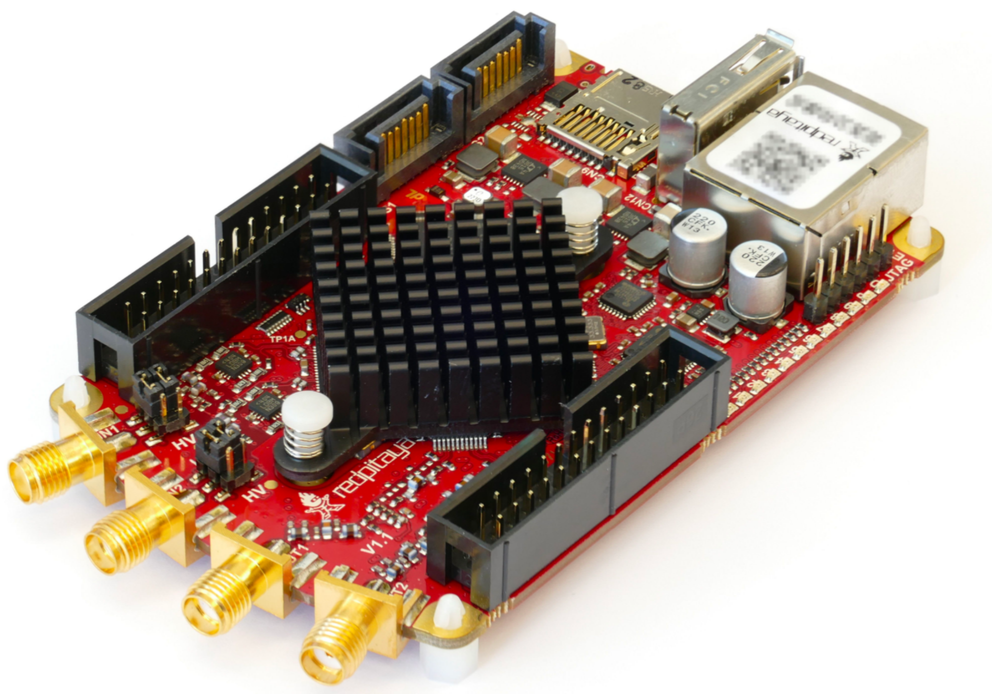
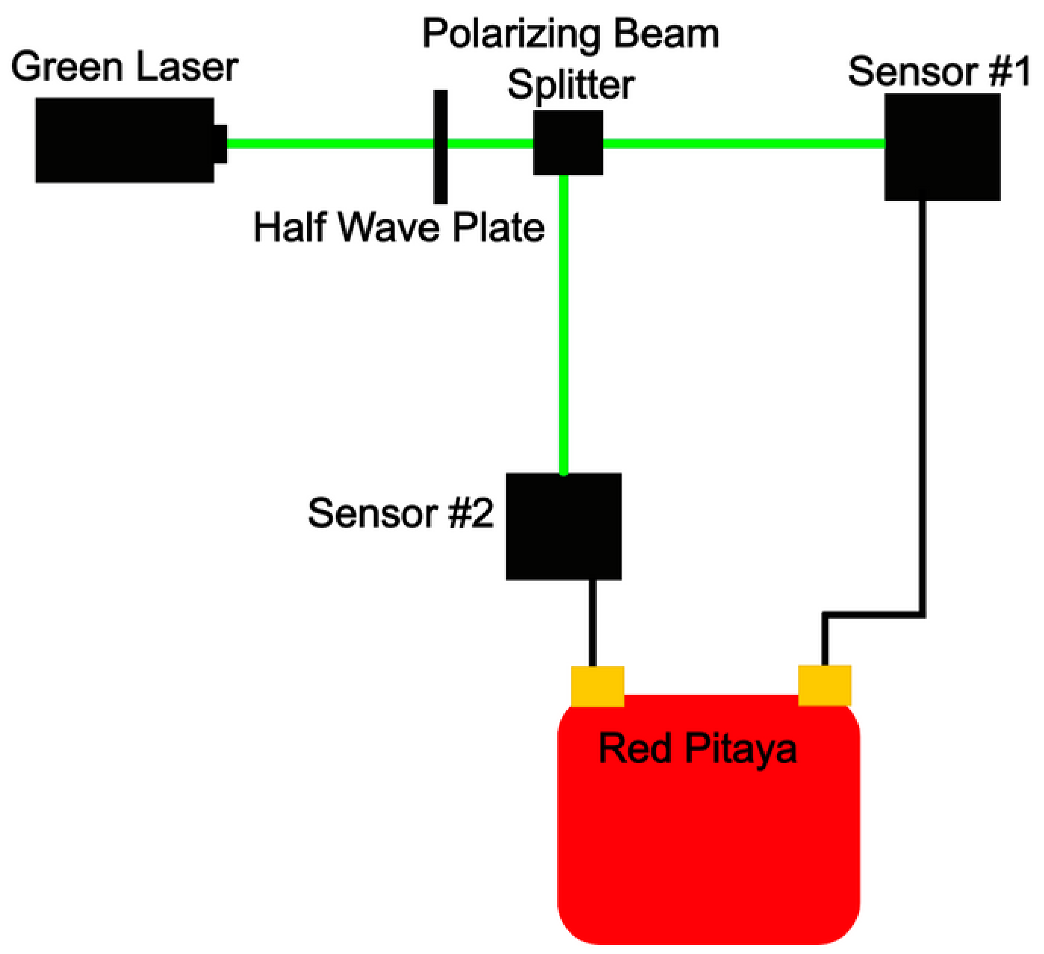


Image of a Red Pitaya (Image from: https://redpitaya.com/product/stemlab-125-14/)



Proposed Solution: FroSTI
SURF Project Objectives

My Goals:

Create a program which will **dynamically** find the **intensity noise performance** of FroSTI's heating elements.

Plot both the **CSD amplitude and phase** for **real-time noise analysis** of the heating elements.

The Red Pitaya

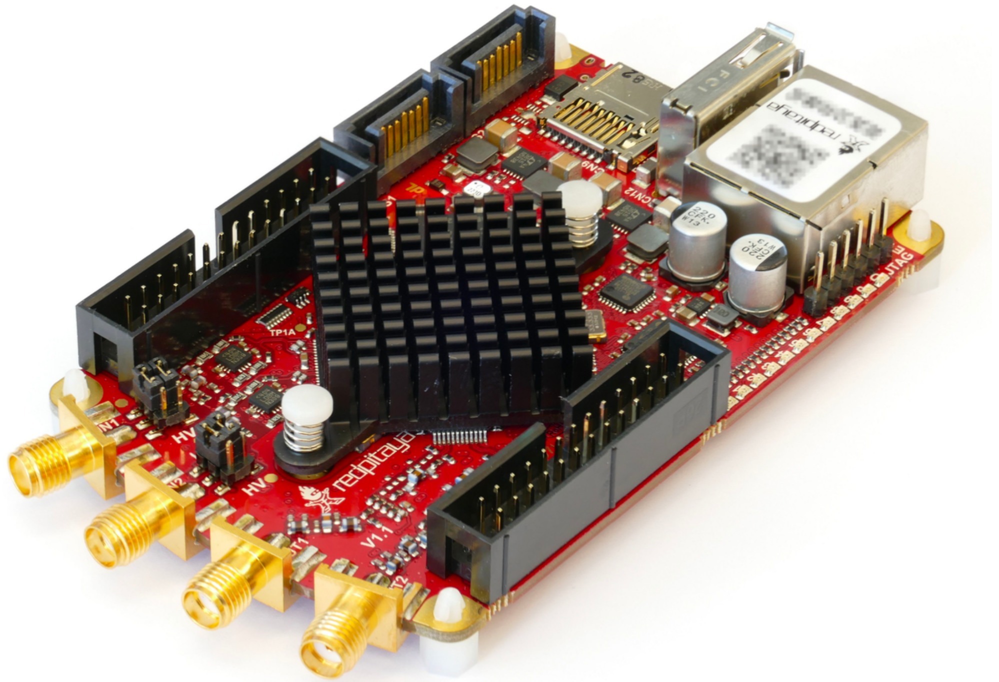
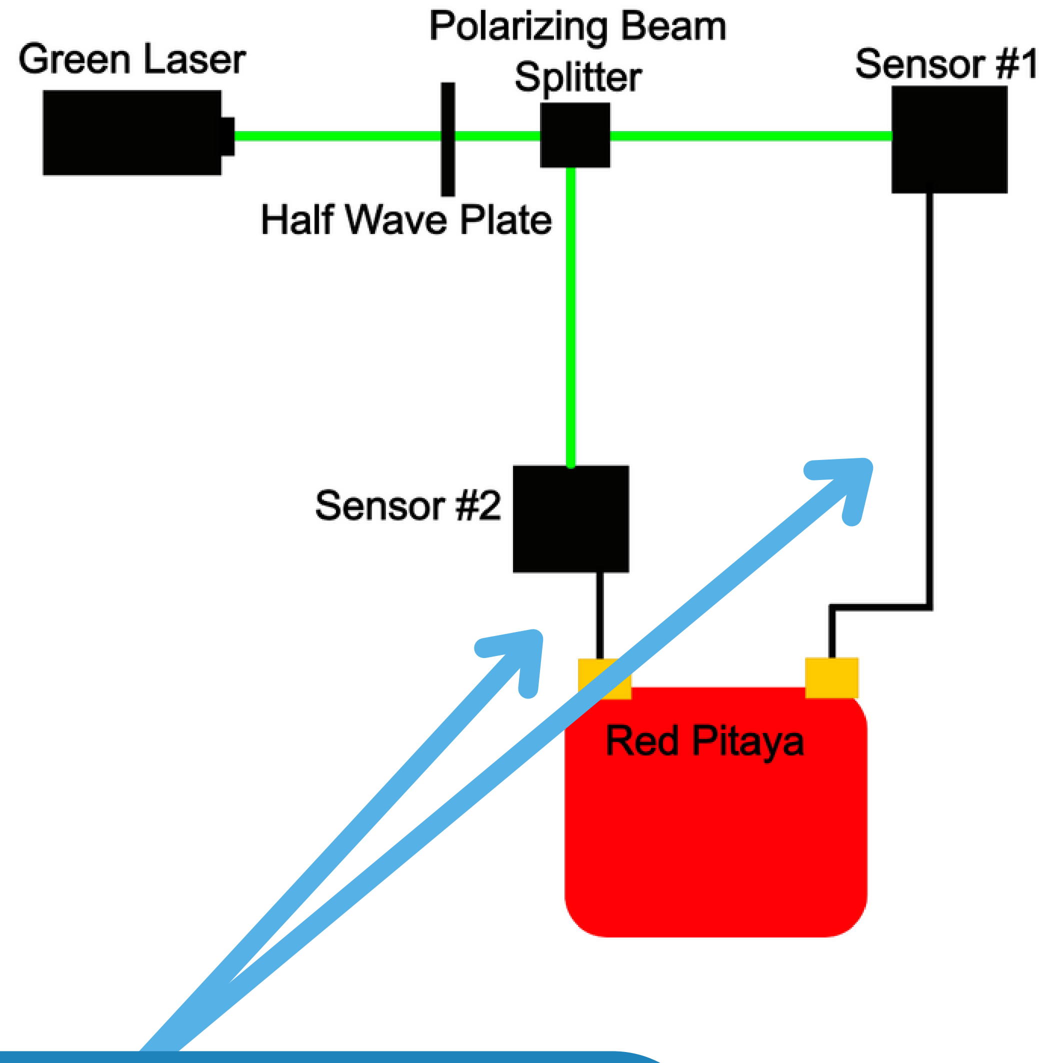


Image of a Red Pitaya
(Image from: https://redpitaya.com/product/stemlab-125-14/)

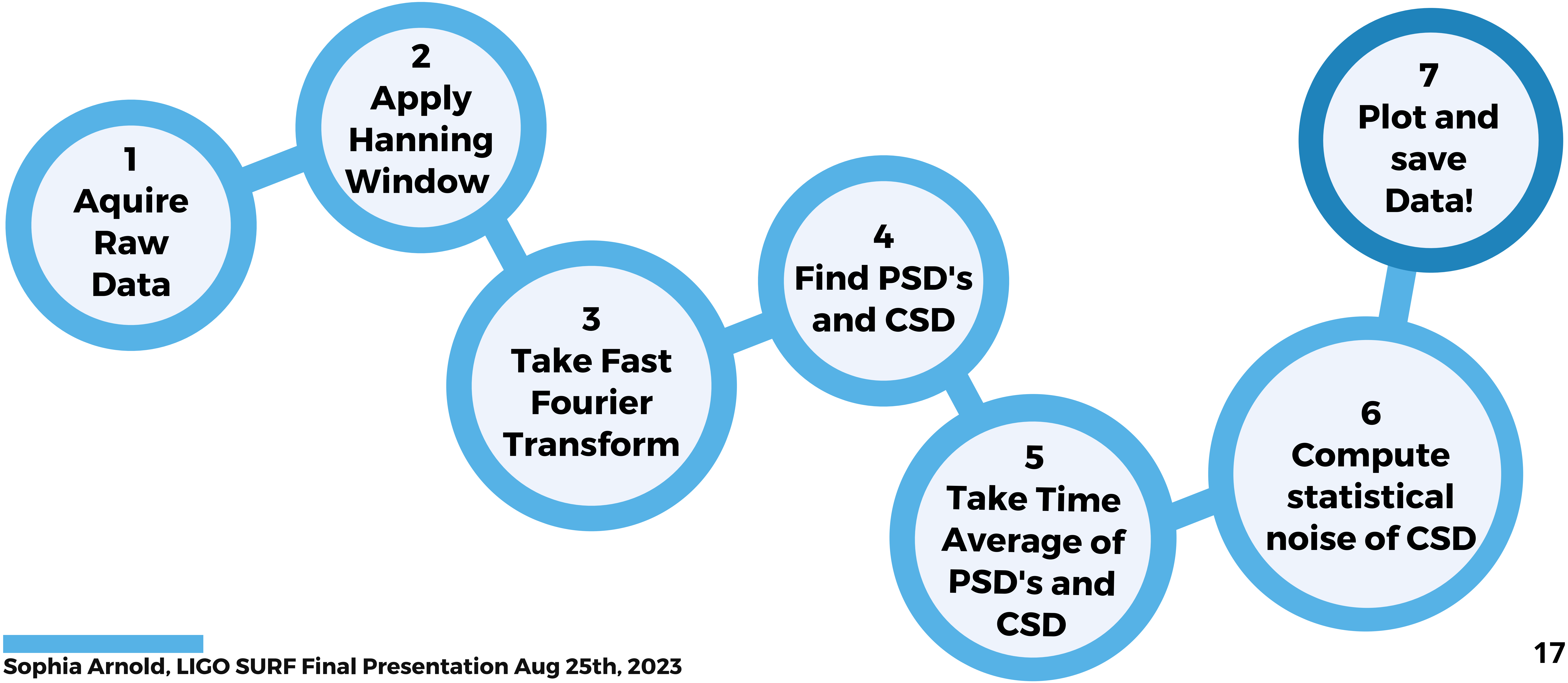


In our experiment, cables connecting sensors to Red Pitaya were the same length

3) INTENSITY NOISE GUI DEVELOPMENT

A WAY TO MEASURE INTRINSIC ELECTRICAL NOISE

Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI



Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI

1
Aquire Raw Data

To acquire the **raw data**, we needed to communicate with the **Red Pitaya**.

Communicating with the **Red Pitaya** was the **primary cause** of the **issues** I faced when developing this GUI.

7
Plot and save Data!

Transform

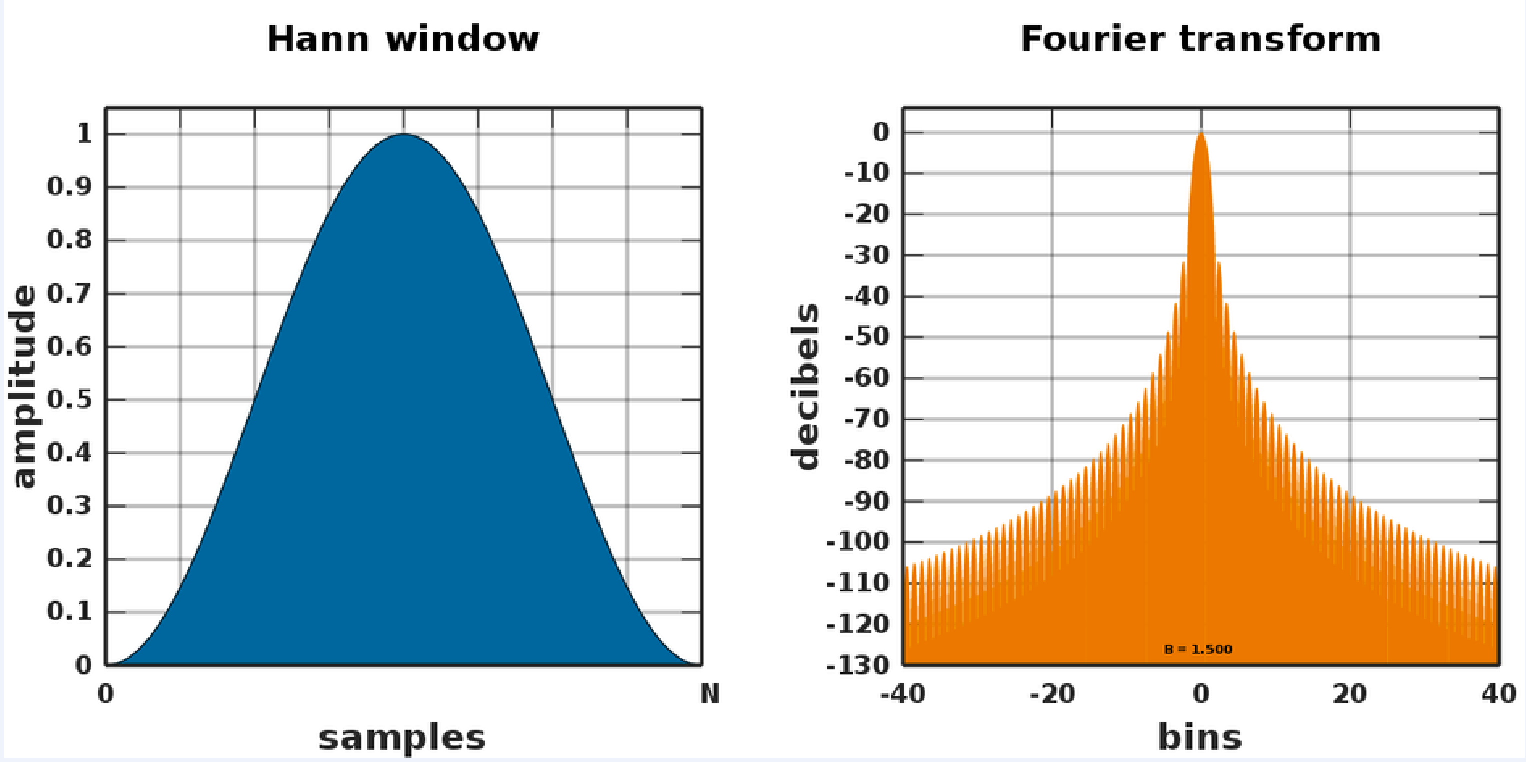
5
Take Time Average of PSD's and CSD

6
Compute statistical noise of CSD

Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI

1 Aquire Raw Data

2 Apply Hanning Window



Hann Window in Time (left) and Frequency (right) domains
(image from: https://en.wikipedia.org/wiki/Hann_function)

The **Hann window** is a **filter** which is can be applied to samples **prior** to performing an **FFT** to **clean** the FFT process up, and **prevent spillage** of signals into **unwanted frequency bins**.

Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI

1 Aquire Raw Data

2 Apply Hanning Window

3 Take Fast Fourier Transform

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi kn/N}$$

Equation for Fast Fourier Transform
(Image from: https://speech.zone/forums/topic/explaining-dft-formula/)

Fast Fourier Transform: A process which takes a **finite list** of **time-series data**, and transforms it into the **frequency domain**.

Useful for: **Signal Processing** and **noise signal identification**.

CSD

Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI

PSD: Power Spectral Density

The distribution of the power received from a signal over the frequency range computed from an FFT.

$$\mathrm{PSD}\left[\widehat{\mathrm{M}}_1^{\mathrm{ex}}; f, t\right] = \mathrm{H}_1^{\mathrm{A}}(f,t) \cdot \overline{\mathrm{H}_1^{\mathrm{A}}(f,t)}$$

4
Find PSD's and CSD

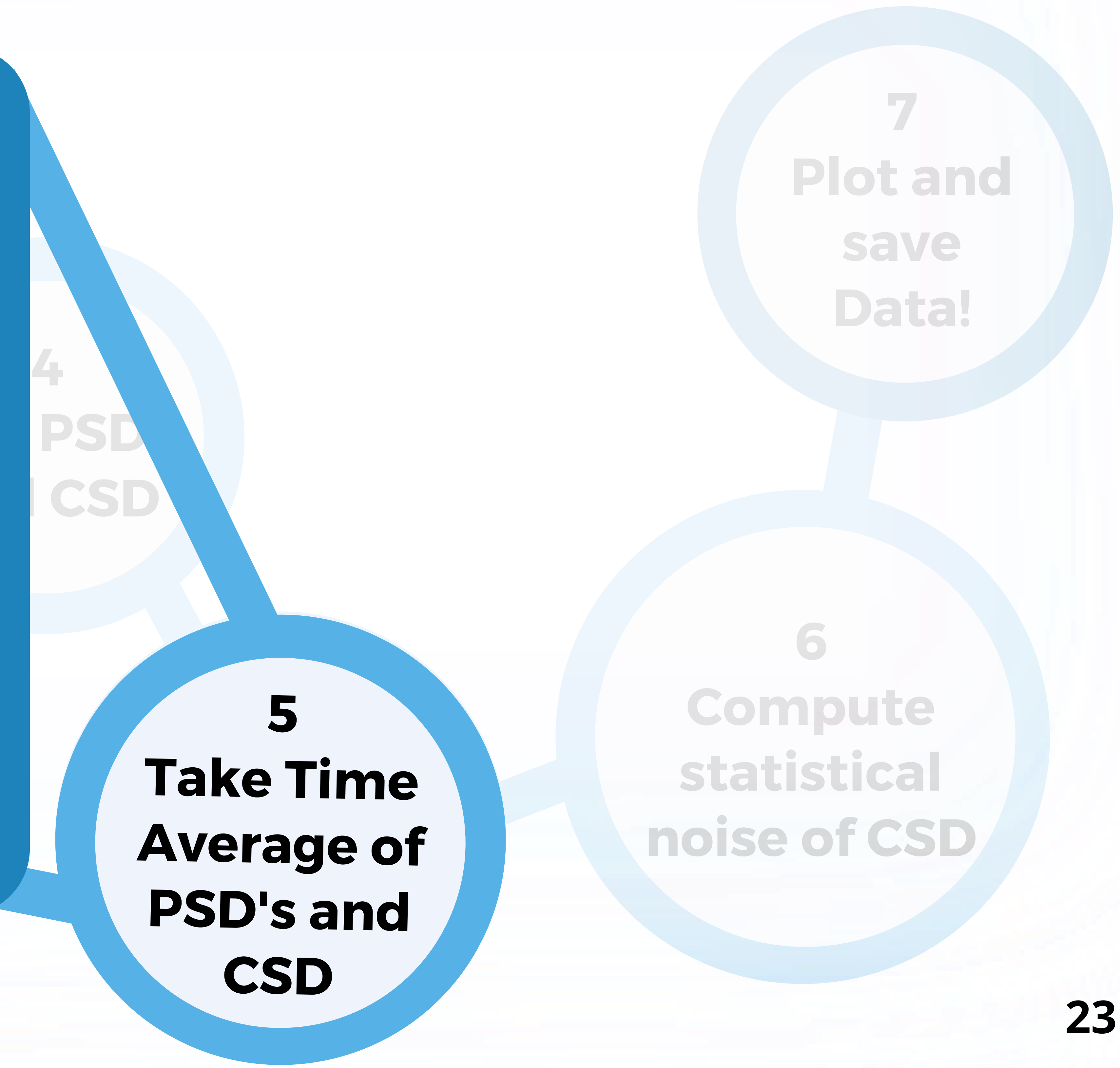
CSD: Cross Spectral Density

The distribution of power for two signals over the frequency range.

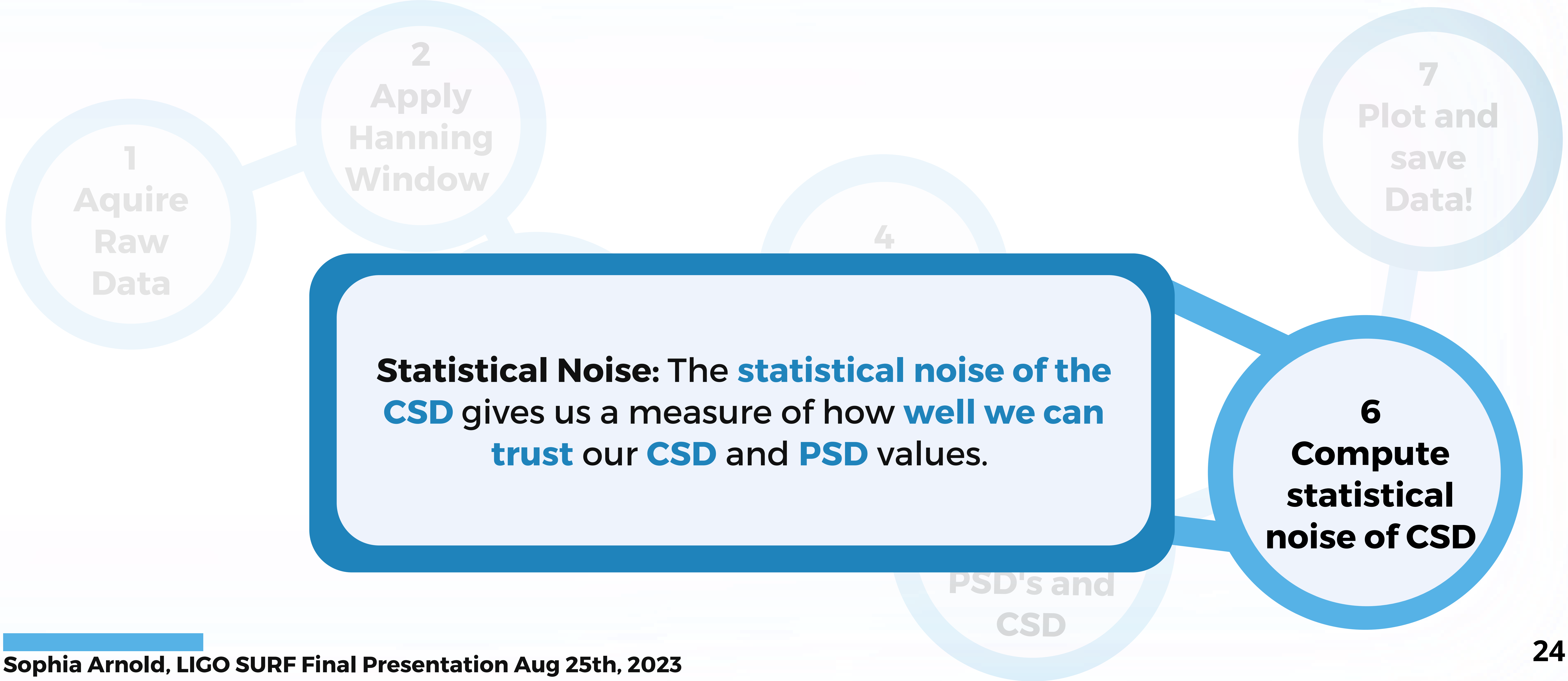
$$\mathrm{CSD}\left[\widehat{\mathrm{M}}_1^{\mathrm{ex}}, \widehat{\mathrm{M}}_2^{\mathrm{ex}}; f, t\right] = \mathrm{H}_1^{\mathrm{A}}(f,t) \cdot \overline{\mathrm{H}_2^{\mathrm{A}}(f,t)}$$

Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI

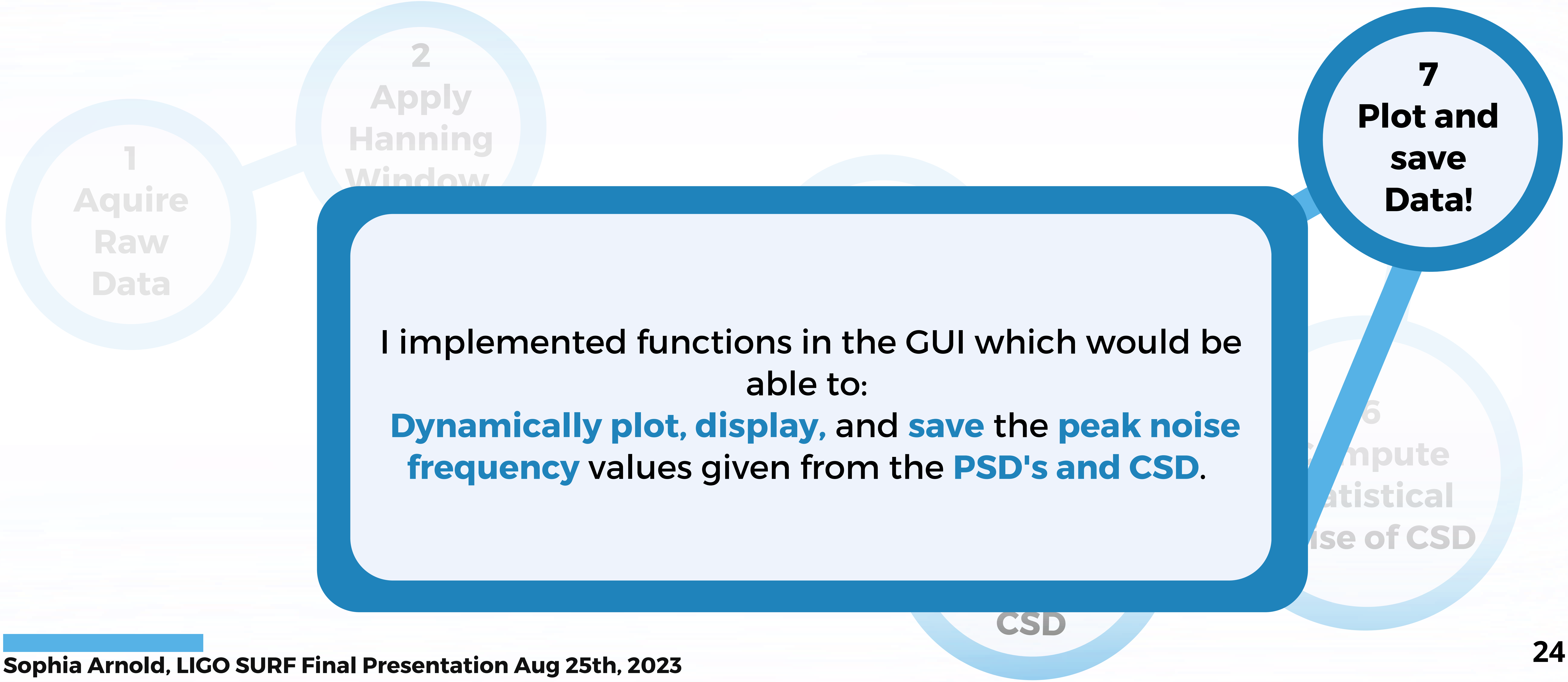
In order to achieve **sensitivity levels** at the detection limit needed to confirm we can **install FroSTI in LIGO**, we must average our **PSD and CSD** values through time.



Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI

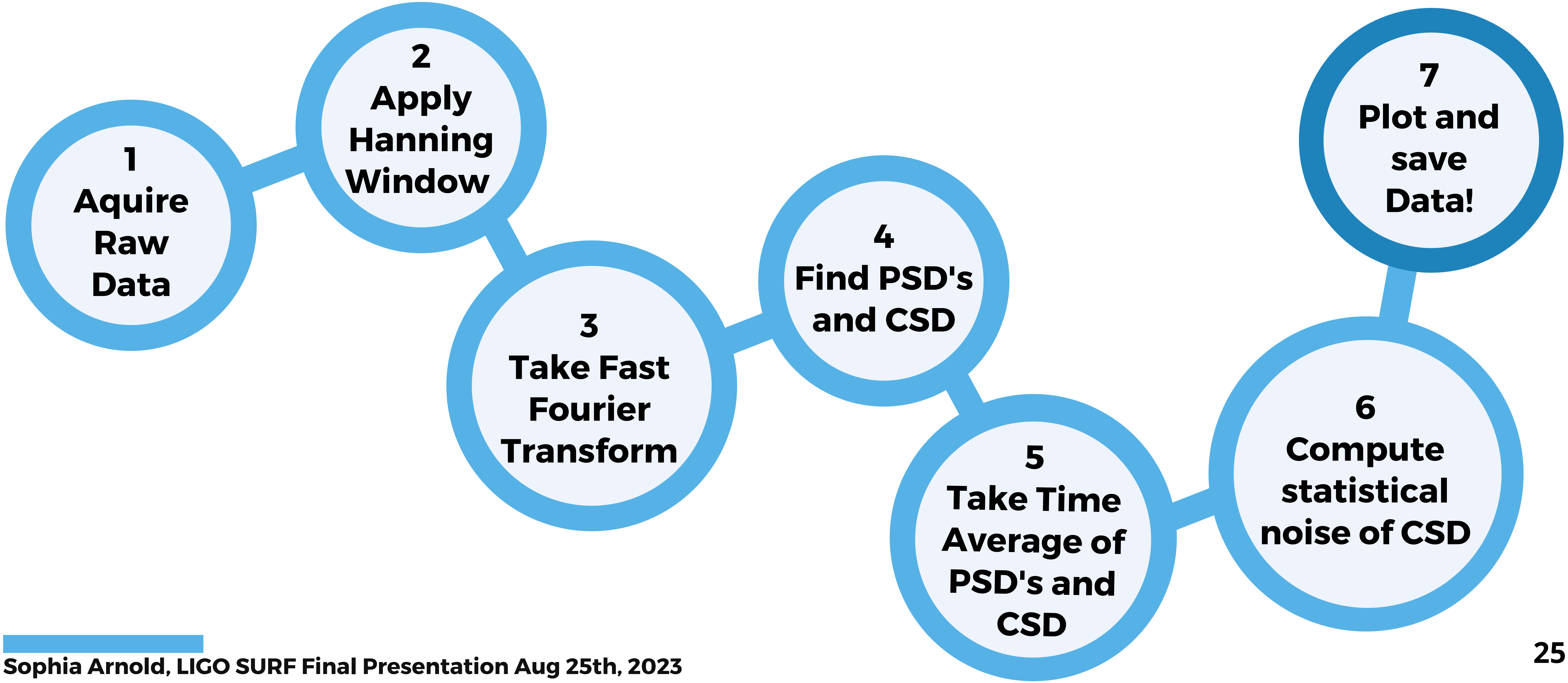


Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI



I implemented functions in the GUI which would be able to:
Dynamically plot, display, and **save** the **peak noise frequency** values given from the **PSD's and CSD**.

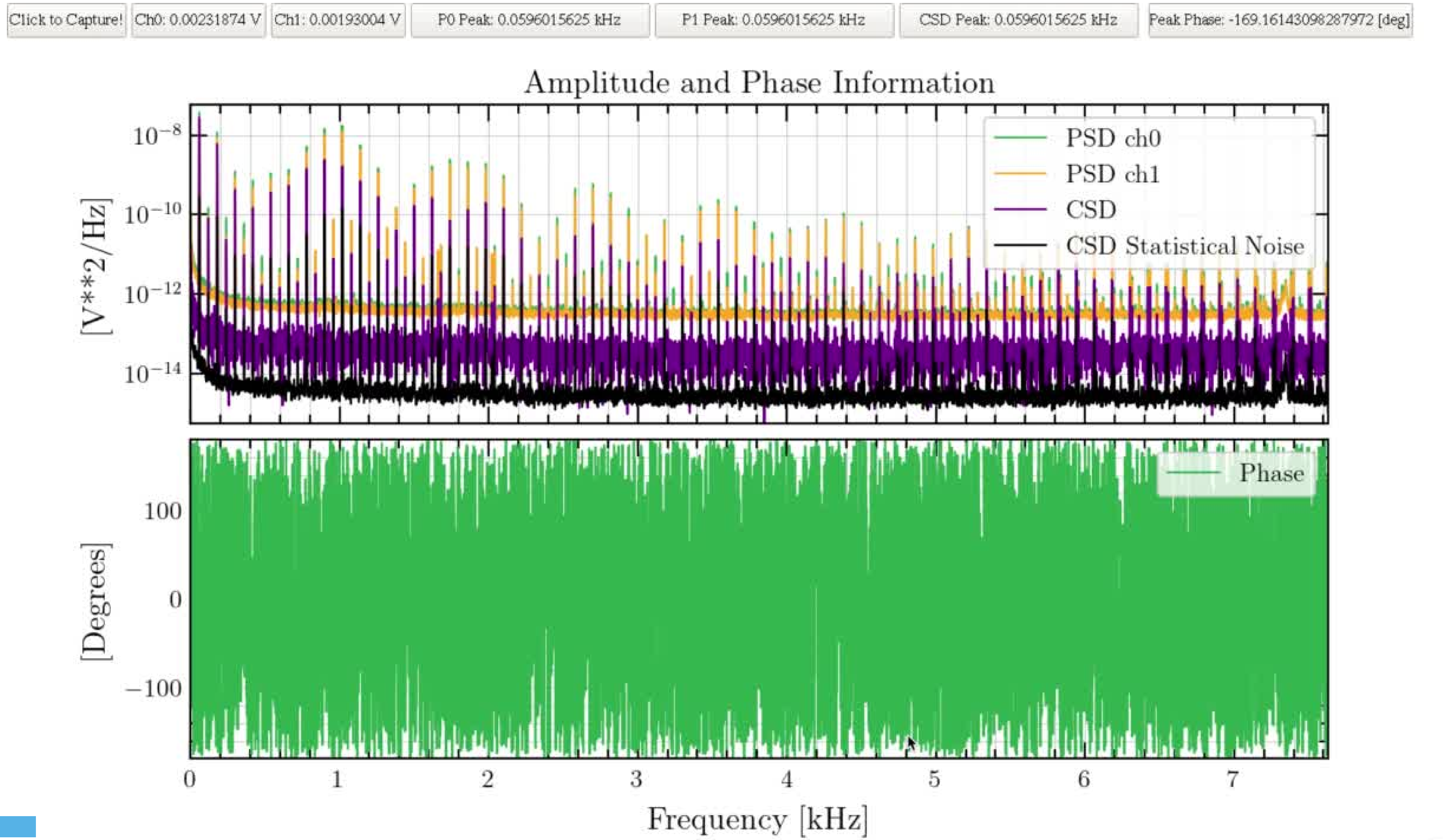
Intensity Noise GUI Development
Pipeline for Intensity Noise Calculation GUI



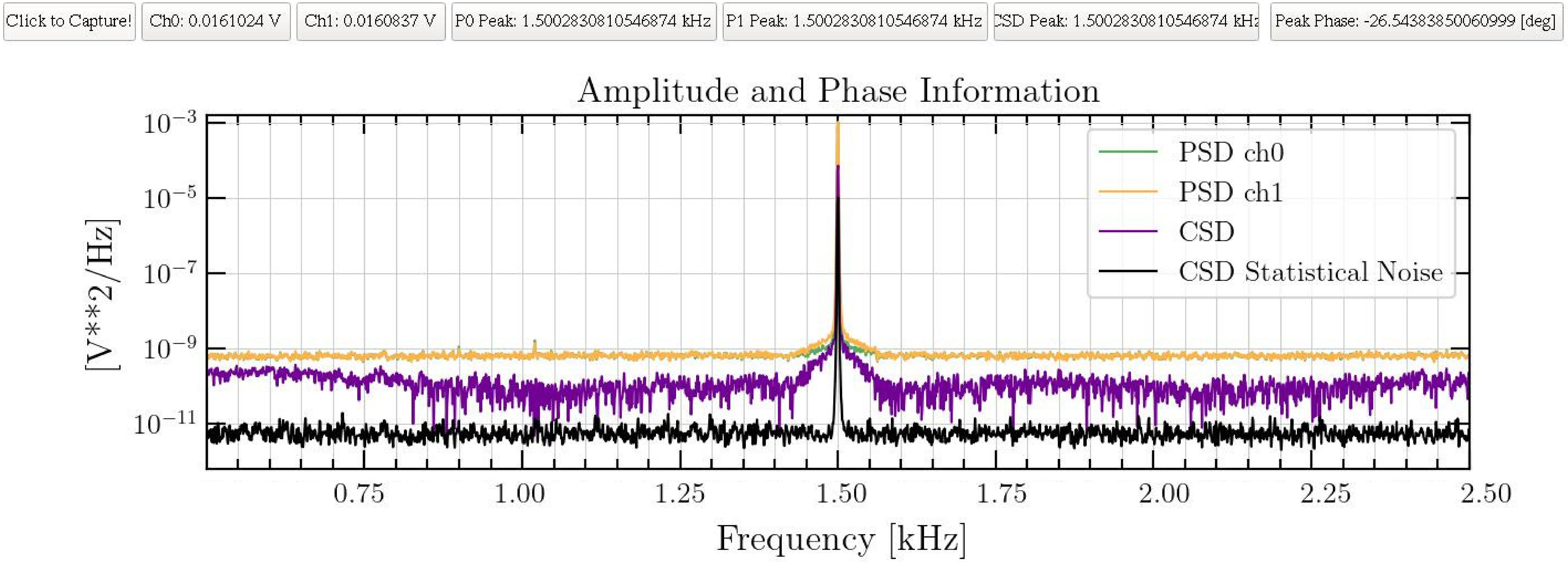
4) APPLYING THE GUI

PERFORMANCE AND ACCURACY TESTS

Applying the GUI
Final GUI Interface



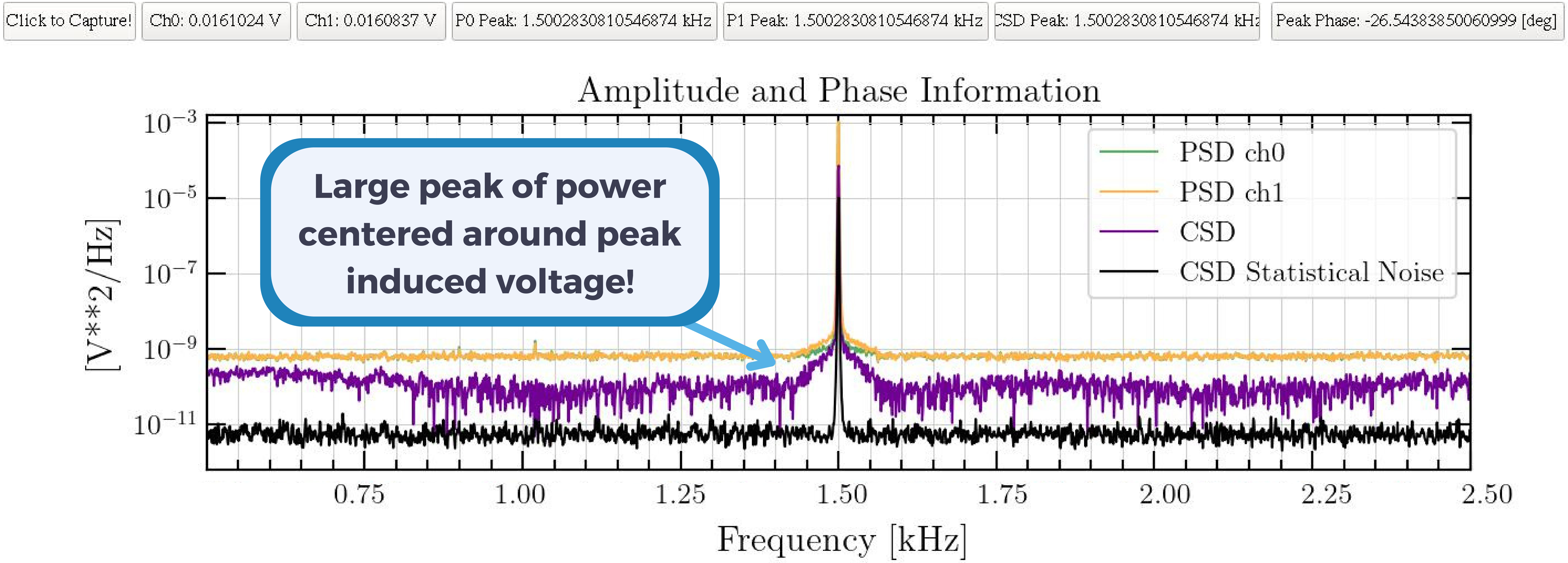
Applying the GUI
Function Generator Tests: Noise and Long Duration



Expected Voltage: 15mV

Expected Frequency: 1.5kHz

Applying the GUI
Function Generator Tests: Noise and Long Duration



Expected Voltage: 15mV

Expected Frequency: 1.5kHz

5) PROJECT SYNTHESIS

THE CULMINATION OF MY WORK

Results and Summary
Where will this GUI be applied?

This **GUI** will be used to test the **heater elements** of FroSTI, but it has the **potential for many other applications**!

This is a **universal program** which can be **updated** and used to find **electrical noise** in any **electrical system**!

ACKNOWLEDGEMENTS

Thank you **Tyler**, **Dr. Richarsdon**, and all students and faculty who have supported me throughout this program!

Additionally, thank you to the **NSF**, **UC Riverside**, the **LIGO Laboratory**, and the **Caltech SURF Program** for an incredible experience and opportunity!

Use my GUI for your own work at: GitHub Link

My email for any inquiries: **sga46@cornell.edu**

THANK YOU!

LIGO Caltech UCR NSF