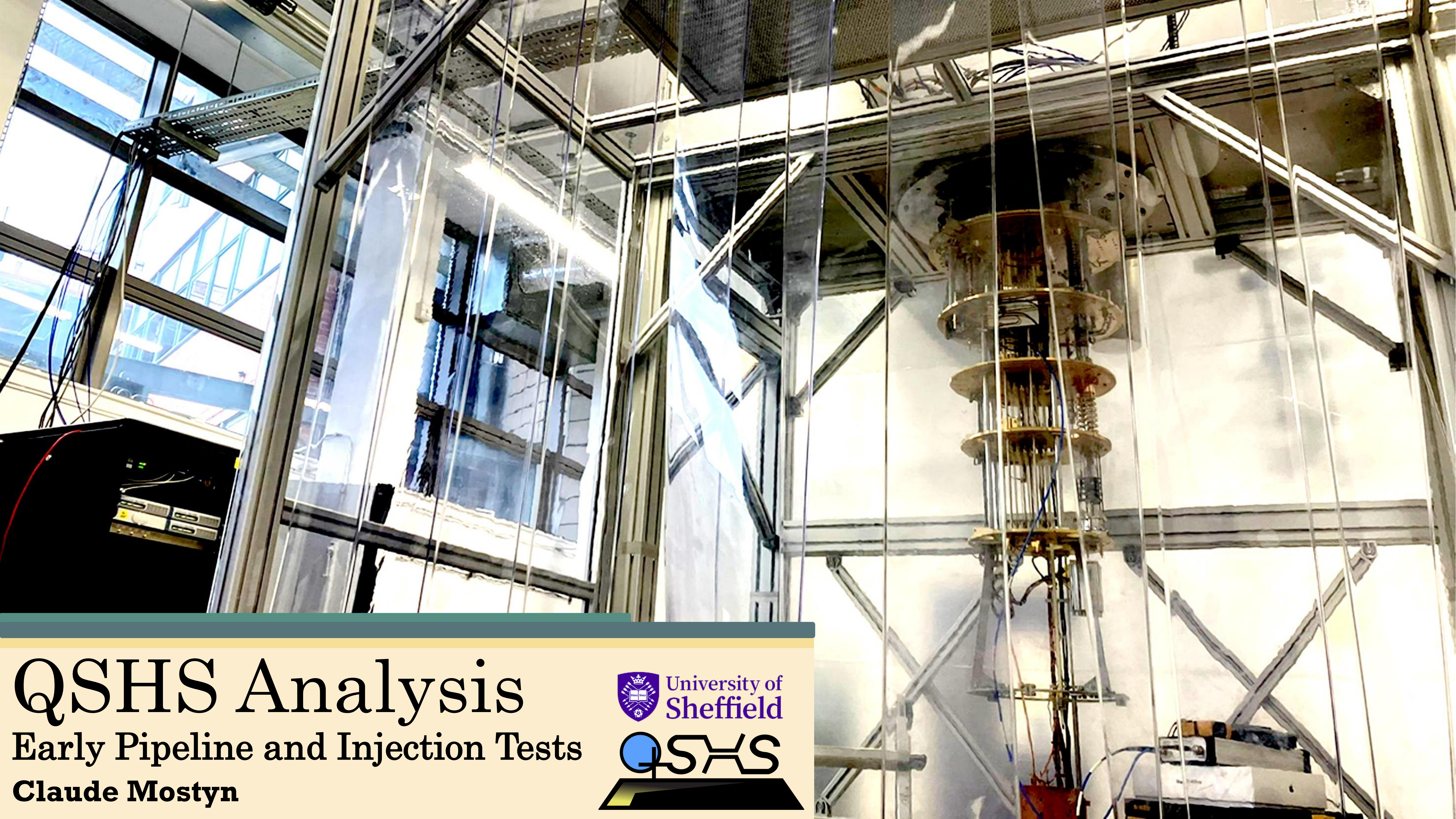

QSHS Analysis

Early Pipeline and Injection Tests

Claude Mostyn

University of Sheffield

QSHS

The Overall Procedure

Individual Spectra

1 Data Cuts and Drift Correction

Remove Poor Data and Correct for Overall Systematic Drift

2 Baseline Removal

Raw Spectra Processing, Remove Receiver Electronics Baseline to Produce Gaussian Spectra (in the Absence of a Signal)

Claude Mostyn

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Combined Spectra

3 Spectra Combination

Combine Individual Spectra on a Single RF Frequency Axis, While Maximising SNR

4 Making the Grand Spectrum

Rebin Combined Spectra to Improve SNR , Produce the Axion-Search Spectrum

5 Identify Rescan Candidates

Identify a Reasonably Sized List of High Deviation Candidate Frequencies for Rescanning

QSHS First Analysis Tests

Claude Mostyn

The Overall Procedure

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Rescan Analysis

• Rescan Data Taking

6 Rescan Analysis

Similar to Initial Analysis Chain, Some Changes if New Data is Combined with Earlier Passes

7 Setting Exclusion Limit

Calculate Coupling Corresponding to 90% Candidate Detection Rate, Using SNR Estimates from Analysis and Monte Carlo Injected Signals

7' Further Candidate Analysis

Individually Interrogate Remaining Candidates For Axion Possibility

QSHS First Analysis Tests

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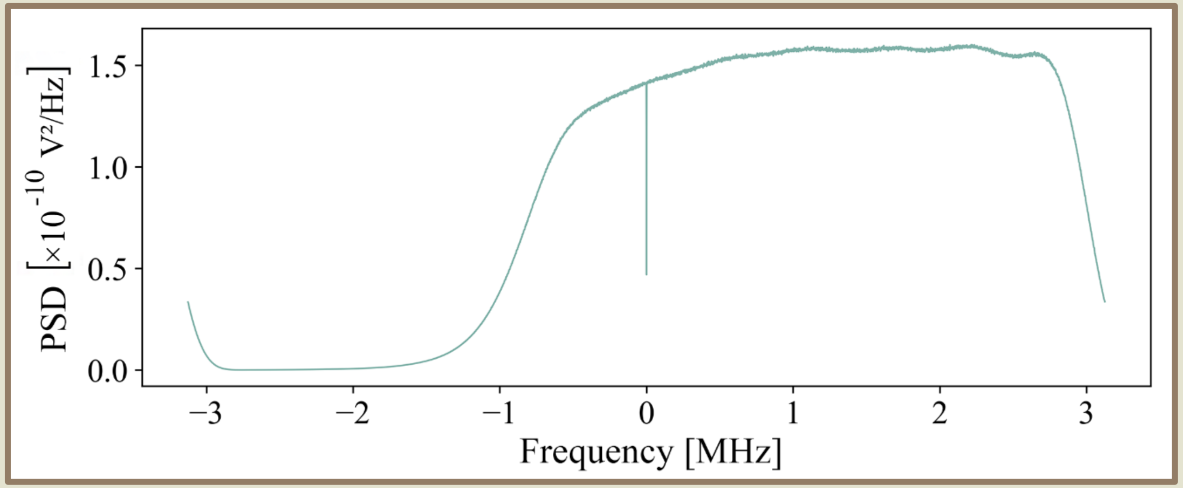
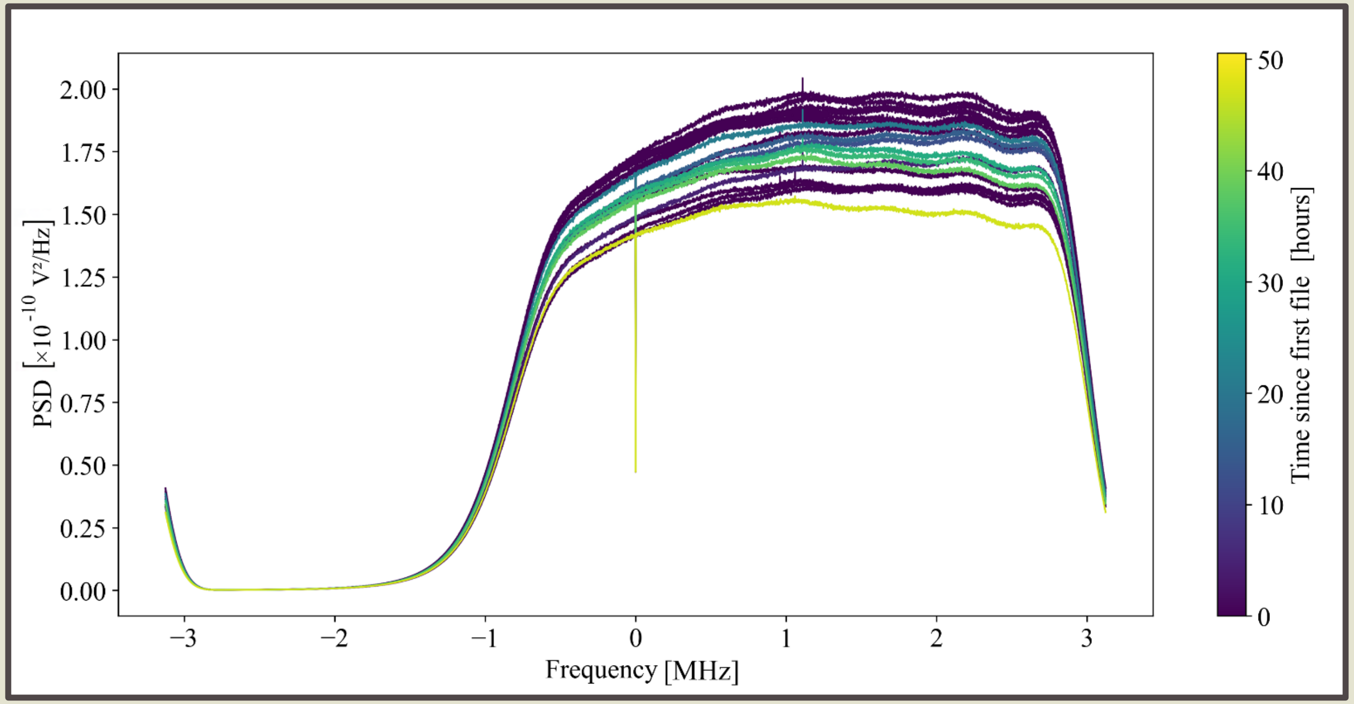
0 The Data Set

- The data is a series of power spectral densities after double heterodyne and Welch average
- Local oscillator tracks cavity resonance 20.5 MHz (hardware heterodyne), then digital uses LO 19.5 MHz - f_0 at 1 MHz
- Tuning range between 75 and 130°, TM_{010} 4.25 to 5.4 GHz, step ≈0.3× the cavity FWHM
- No antenna coupling/reflection measurements this run – both antenna undercoupled
- 100 sec integration times, long cable before first amplification at 4K plate
- Signal line gain ≈130 dB



Single Raw PSD



PSDs throughout run

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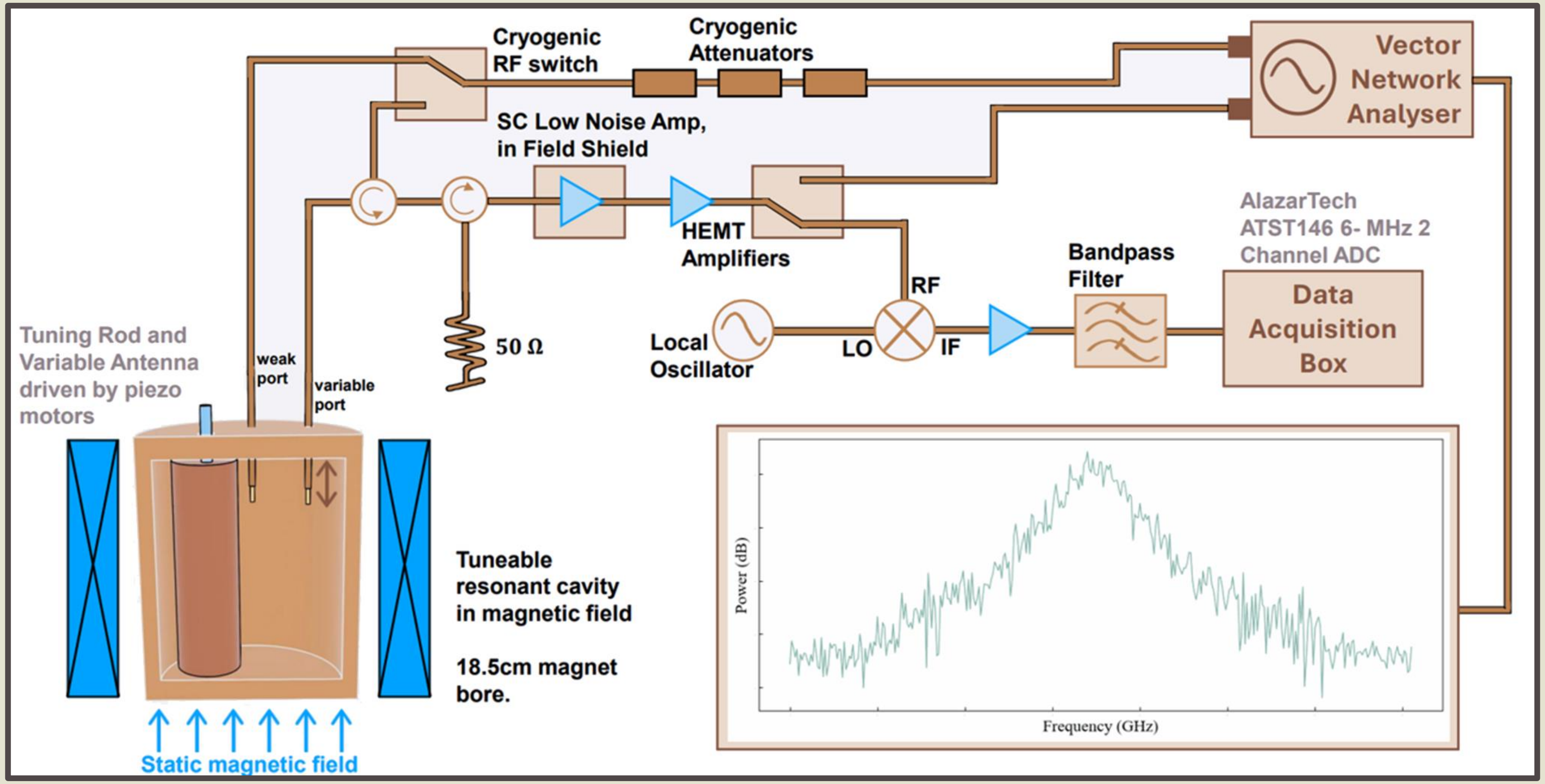
Claude Mostyn

QSHS First Analysis Tests

0 The Data Set

- Testing early hardware and software injection retrieval
- CW hardware injections (single frequency) at -10/-20 dBm through ≈120 attenuation, signal $\approx 10^{-16}/10^{-17}$W at cavity
- Hardware injection frequency tracked tuning rod, so we tune through multiple signals
- Software "axion like" signals can be injected at random frequency into the raw PSDs before analysis - Maxwell–Boltzmann lineshape (Δf ≈ 3 kHz at 4.5 GHz)
- 100 random software injections per tested power used as first test



Receiver chain, Not fully implemented

Hardware injections are

$\approx 10^7 \times$ **KSVZ**

No 1st-stage amp · 100 s integration · undercoupled antenna

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0 The Data Set

- Testing early hardware and software injection retrieval
- CW hardware injections (single frequency) at -10/-20 dBm through ≈120 attenuation, signal ≈ $10^{-16}/10^{-17}$ At cavity
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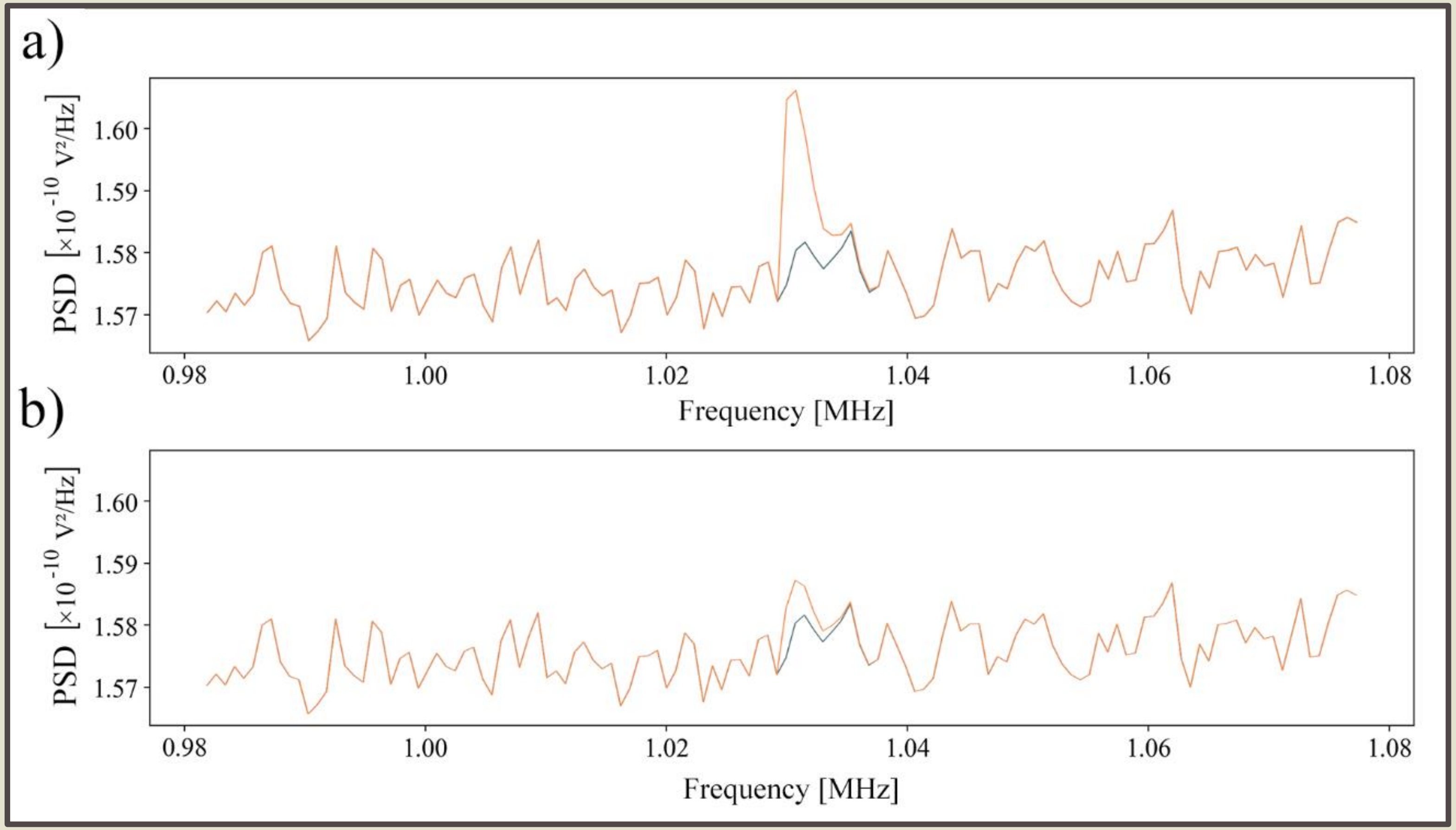

Software injected signal examples,
a) peak amplitude =3×10^{-12} V^2/Hz**, b) 0.8**$\times$ 10^{-12} V^2/Hz**,**

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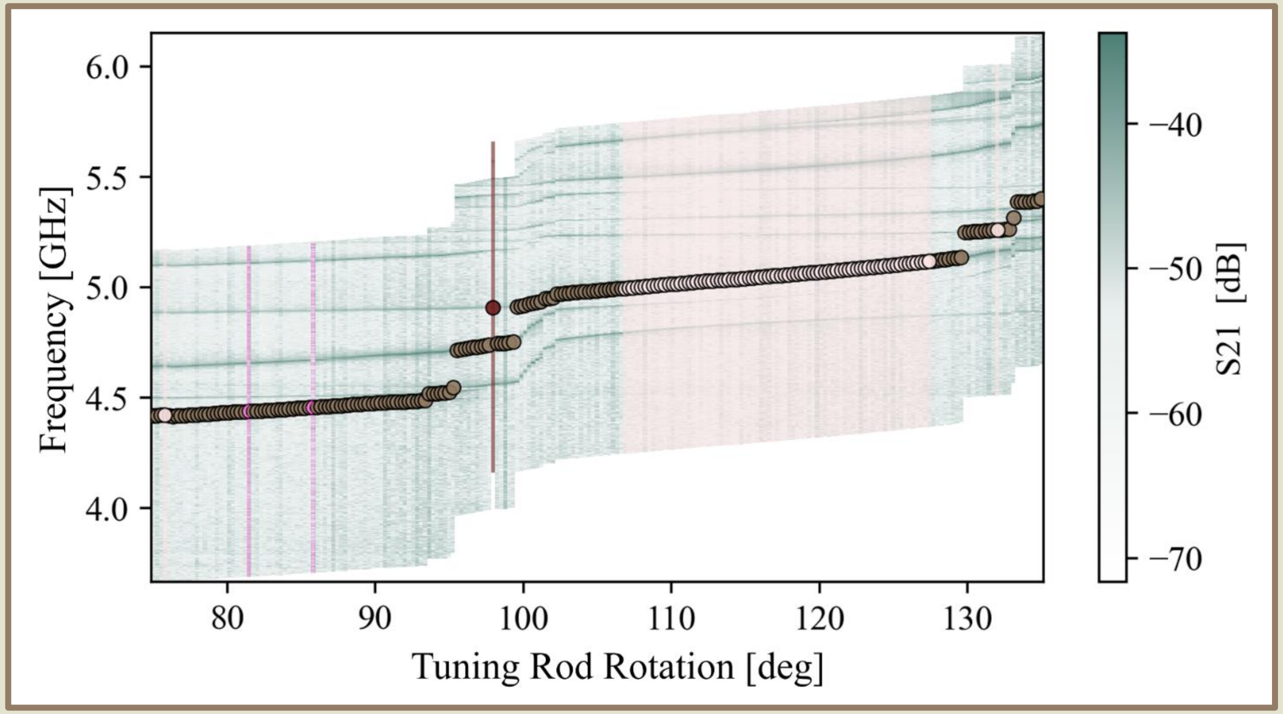
1 Data Cuts + Cropping

- Predominant data loss was digitiser failure for first run, fixed by second run
- IF band cropped to −0.3 to +2.3 MHz (centered on 1 MHz resonance bin)
- DC zero gets averaged out
- **Mode crossings retained:** too frequent at QSHS high range frequencies to cut; effects handled during analysis and candidate recovery instead
- **Gain-profile flatness cuts and frequency drift cuts not implemented for this short test run — both standard in ADMX/HAYSTAC**



Mode map coloured by reason for data cut, -10dBm RUn

- Good Data
- Digitiser Failure
- Mode Tracking Failure
- Switching Failure

Cut	No. Spectra Lost
Digitiser Failure	532
$0.05\text{K} < T_{cav} < 0.2\text{K}$	0
$0.3\text{ MHz} < \text{FWHM}_{cav} < 2\text{ MHz}$	17
Mode tracking failure	1

Data Lost over full CW injection test run

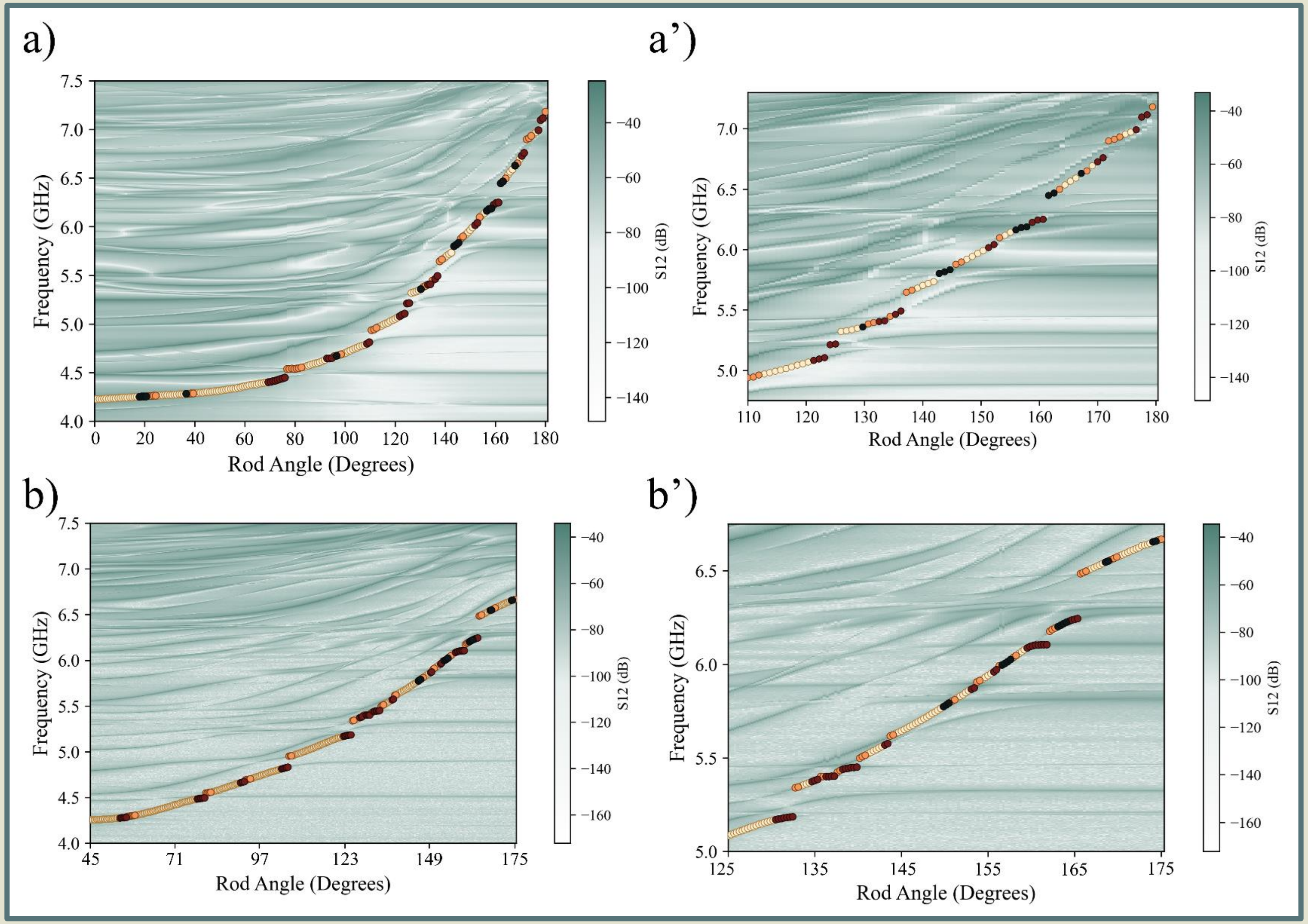
QSHS First Analysis Tests

University of Sheffield

Claude Mostyn

1 Data Cuts + Cropping

- **Mode crossings retained:** too frequent at QSHS high range frequencies to cut; effects handled during analysis and candidate recovery instead
- QSHS cavity from simulations:
- Approximately 60% is clear tuning state (well-separated from other mode)
- 40% sees some amount of form factor degradation, with ≈22% seeing a >10% relative form factor drop



Clear tuning, high form factor

Mode crossing, reduced form factor

Post mode crossing, recovering form factor

Full experimental QSHS mode maps at RT (top) and LT (bottom) Zoomed of high angle on right

QSHS First Analysis Tests

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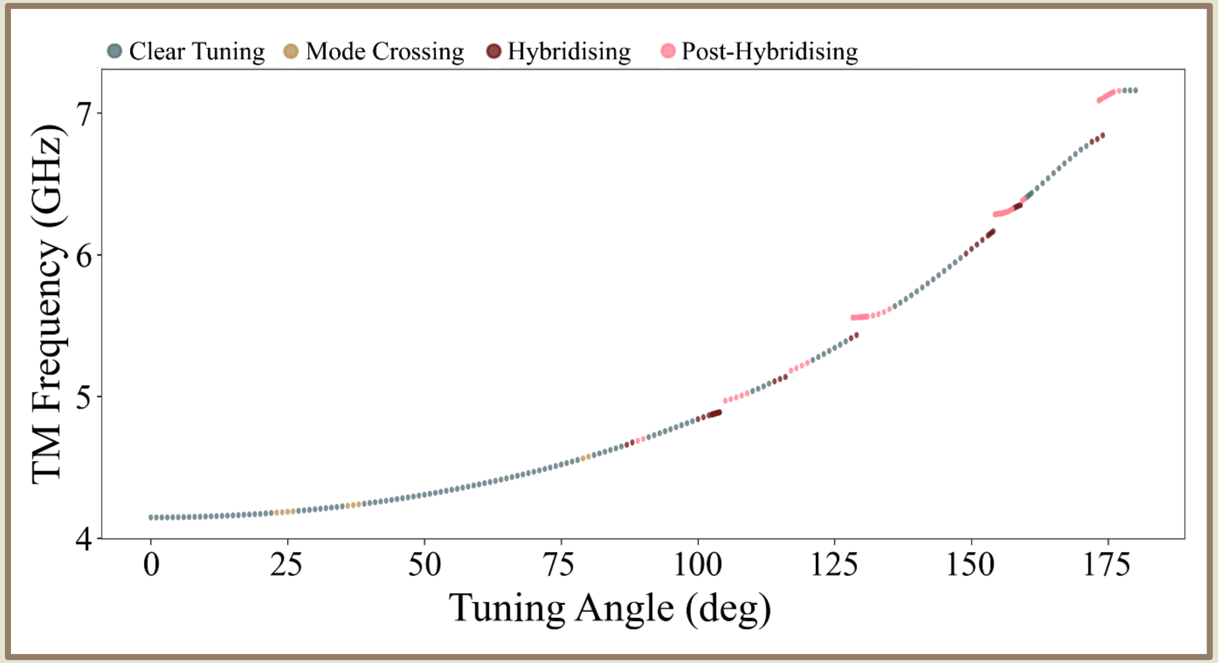
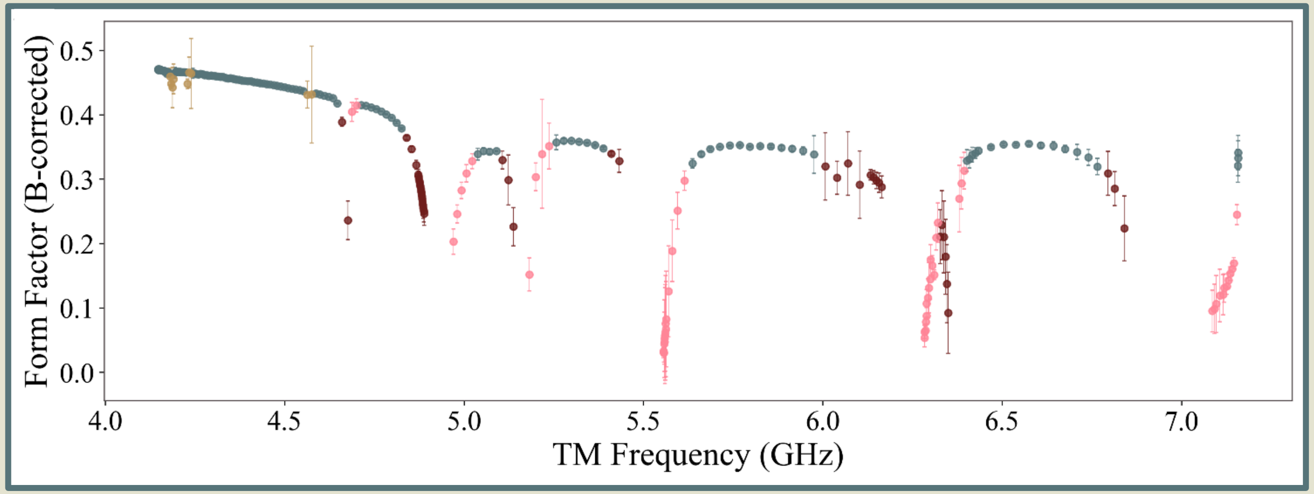


Simulated (ANSYS HFSS) mode map, coloured by mode crossings



Simulated form factor by frequency, Coloured by mode crossings

QSHS First Analysis Tests

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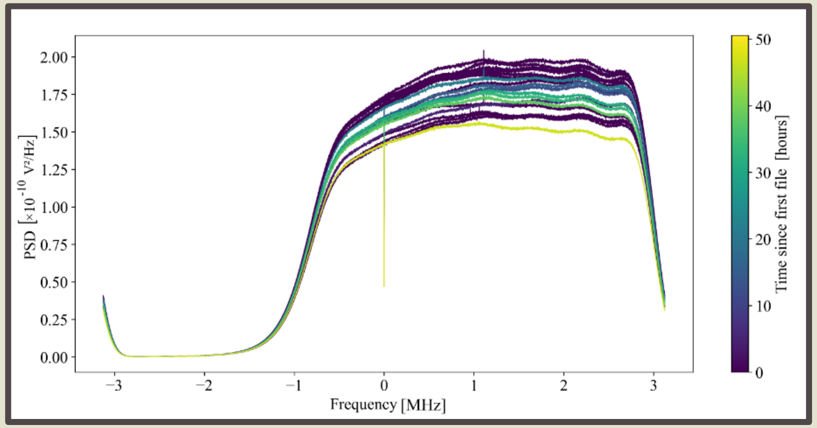
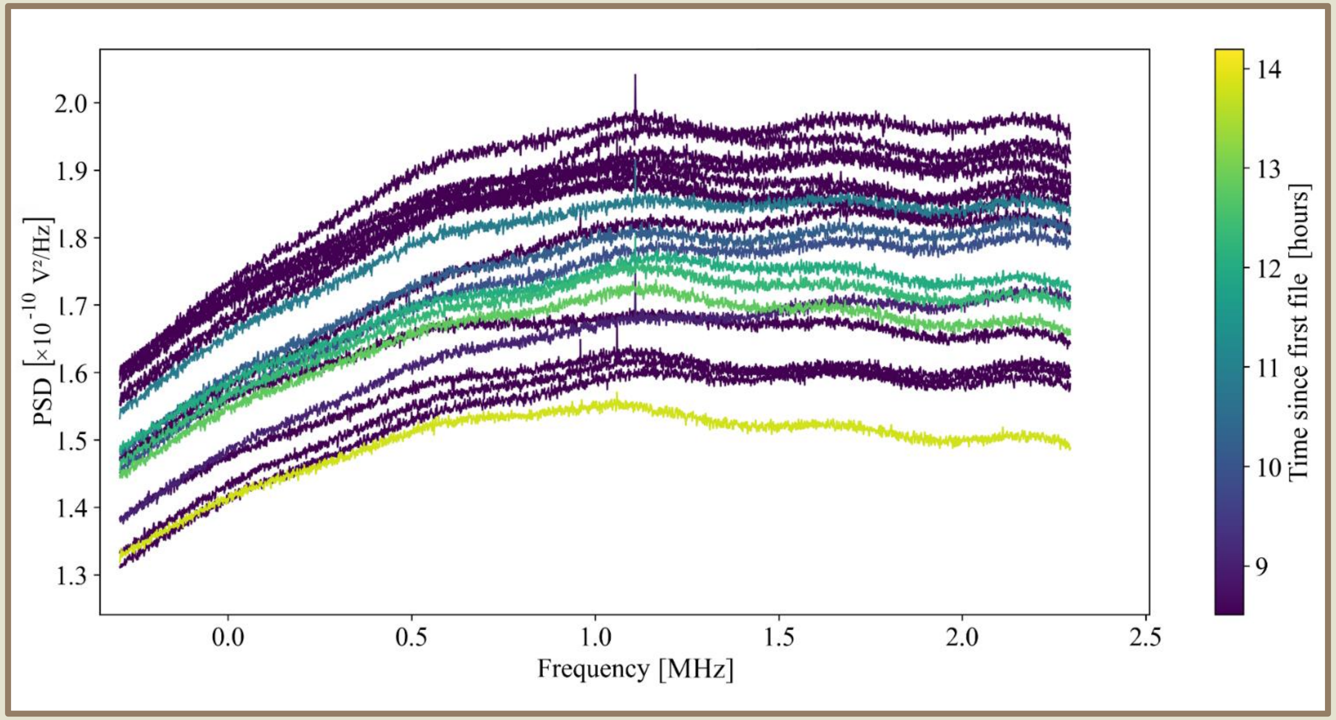


Full PSDs, across -10dBm tests



Cropped PSDs, across -10dBm tests

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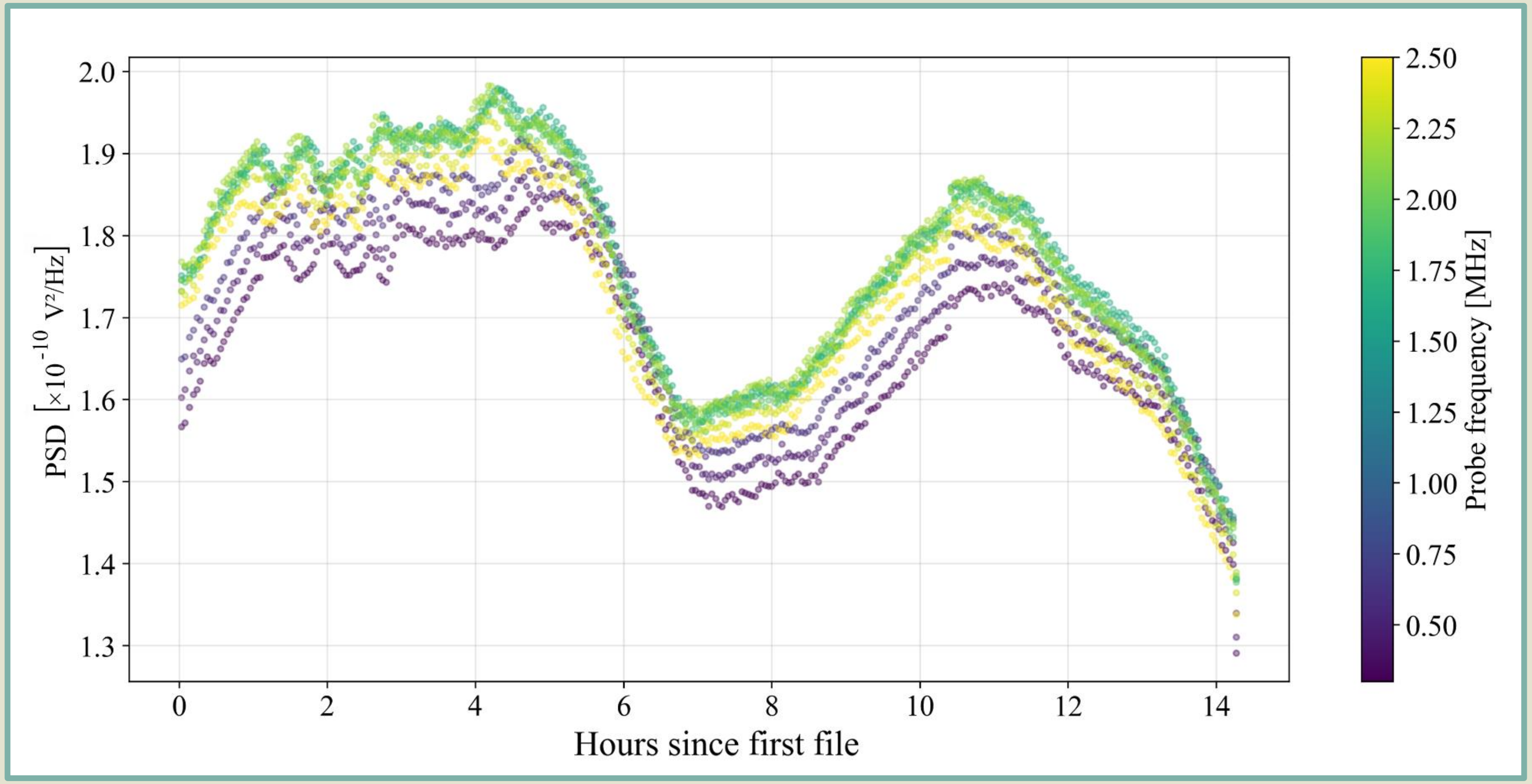
1 Gain Drift

- **Temporal drift: <0.2% of mean PSD.** Slight negative correlation with room temperature (RT amplifier)
- **Frequency-dependent drift dominates** — primarily receiver electronics; consistent with hotload across different cools → calibration feasible
- **Q-dependent component:** near mode crossings, falling cavity Q causes additional PSD amplitude decrease
- **Current correction:** global median shift per PSD. Final model: data-driven hotload calibration (deferred to when full receiver chain installed)



Time dependence (~ frequency dependence) of PSD amplitude by IF frequency bin

QSHS First Analysis Tests

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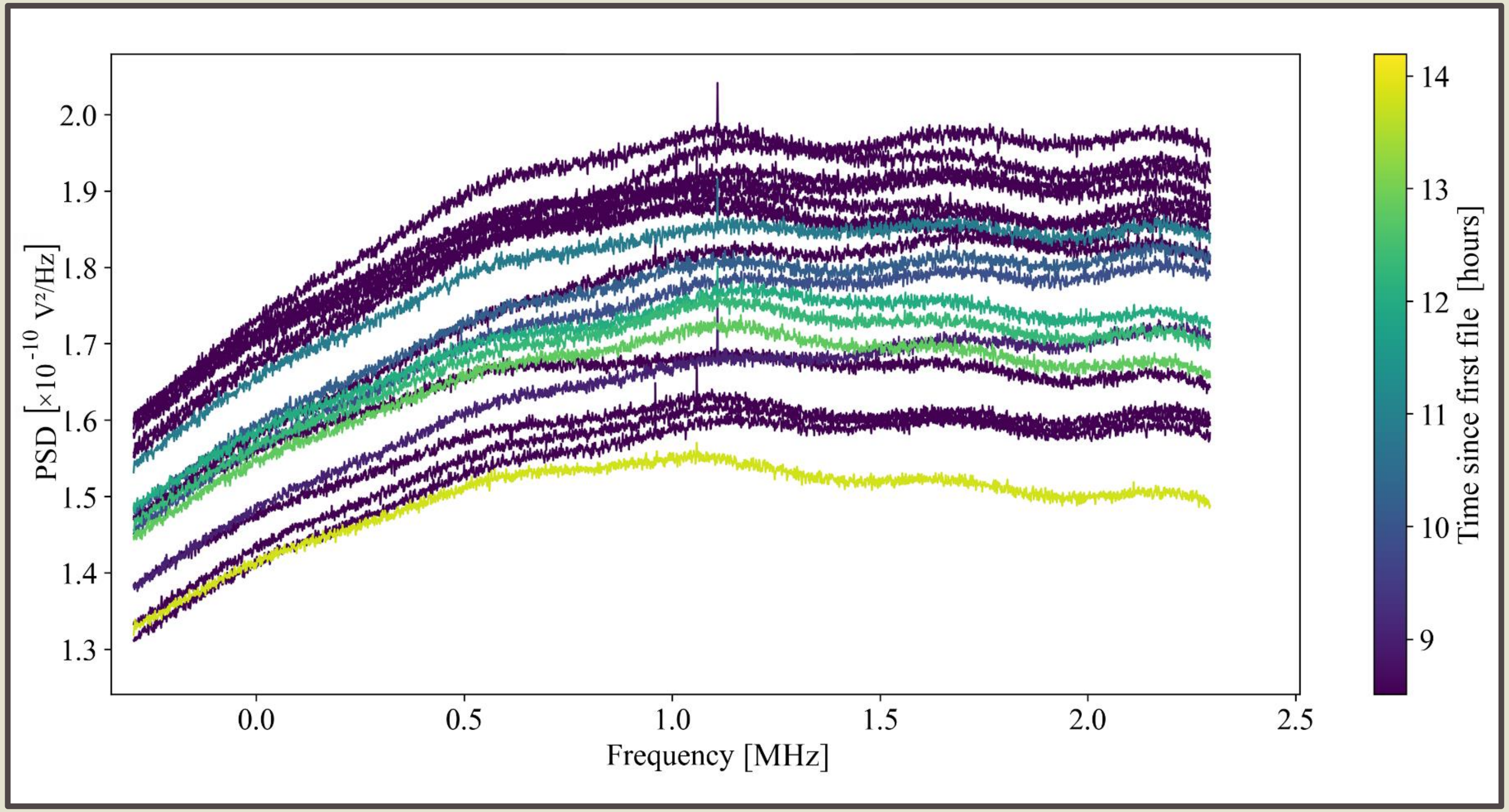
2 Baseline Removal

- **Goal:** remove receiver electronics baseline per PSD without reducing axion-scale SNR; produce Gaussian residuals. Target: Gaussian to ~4.5σ

- **Warm baseline:** first pass fits a single baseline to multiple PSDs to handle small scale structure without fitting out candidates

- **Cold baseline:** second per-spectra fit pass to remove fast-moving with tuning angle broader frequency scale structure



Cropped PSDs, across -10dBm tests

QSHS First Analysis Tests

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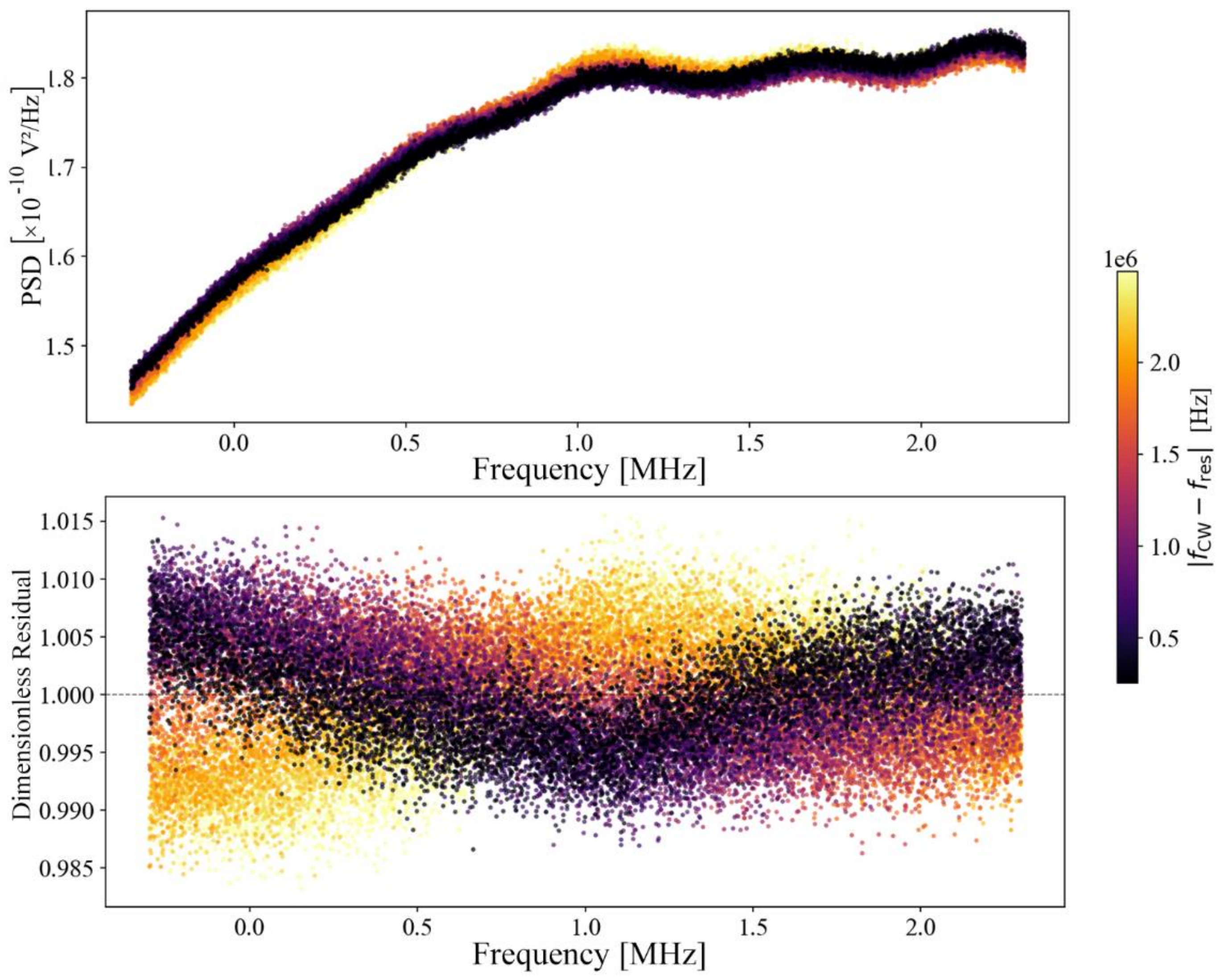
2 Warm Baseline

- HAYSTAC-like method
- Group PSDs by time intervals (30 minutes here) and produce a single averaged spectra
- Perform a Savitsky Golay (window 251, order 2 vs. PSD length 3408) fit
- Mask IF bins in individual PSDs >4.5σ from fit, repeat with new average PSD over 3 iterations



Example PSD group, before and after first pass baseline removal

QSHS First Analysis Tests

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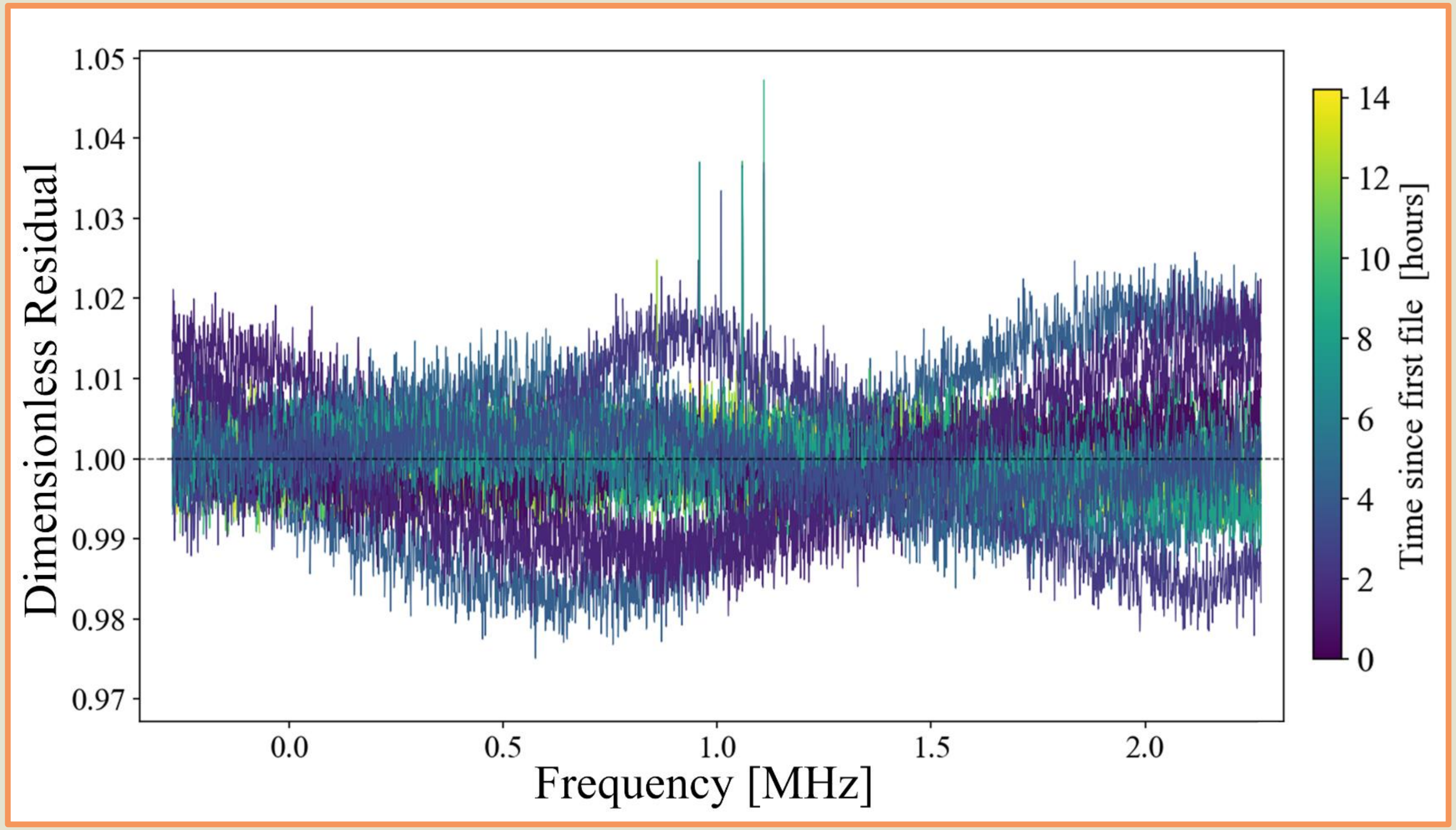

PSDs post first pass/cold baseline removal, across -10dBm tests

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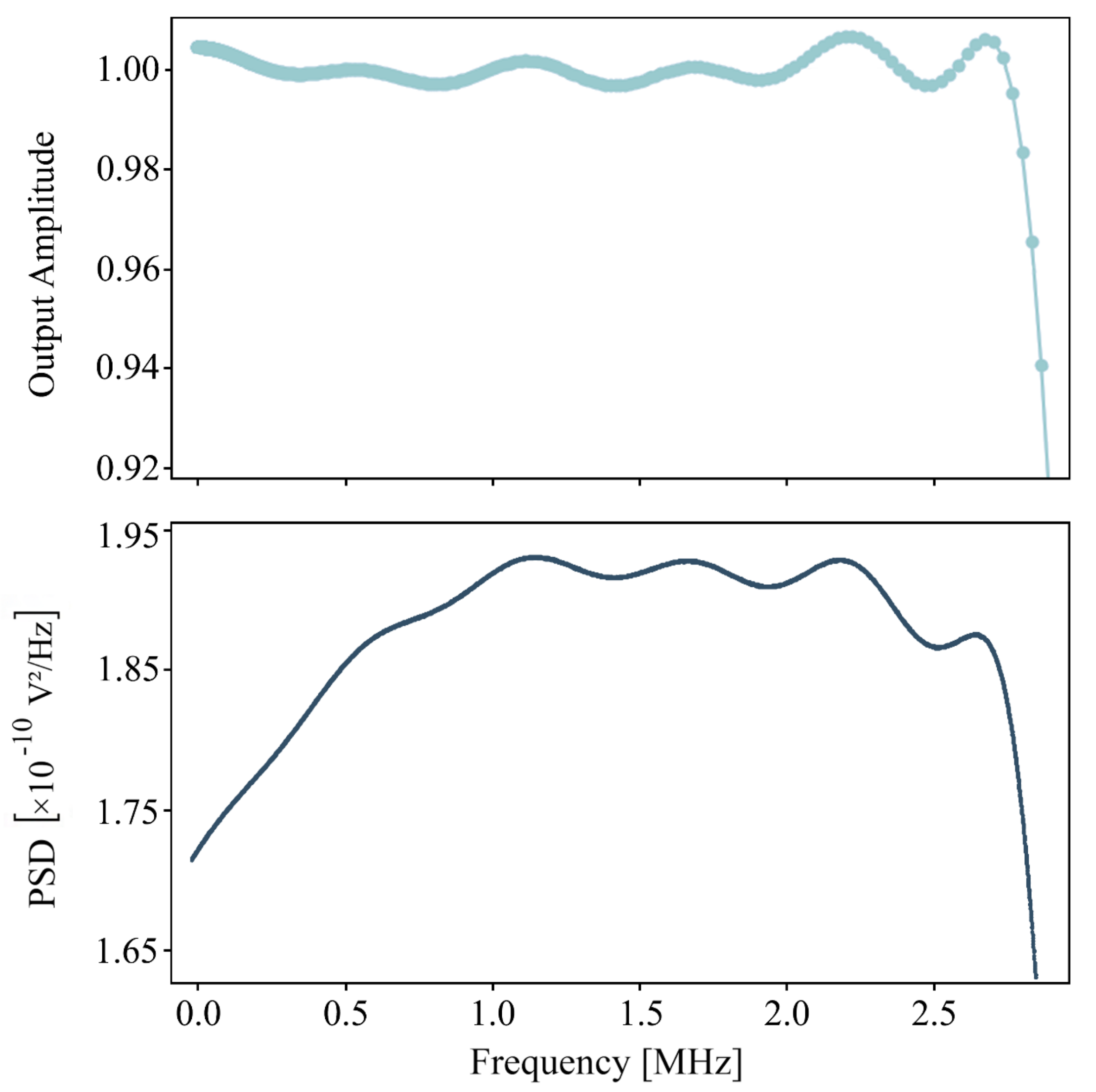
2 Warm Baseline

- Alternative hotload measurement or direct calibration
- FIR1 (default ×8 decimation filter) introduces passband ripple that is baked into the power spectra once produced
- FIR4 planned for next run
- Overall shape of gain passband tracks hotload spectra
- Could either implement a full hotload baseline spectra across tuning range, or develop a specific calibration model



FIR filter transfer function (top) and example PSD, peak structures align

QSHS First Analysis Tests

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2 Baseline Removal

- Alternative hotload measurement or direct calibration
- FIR1 (default ×8 decimation filter) introduces passband ripple that is baked into the power spectra once produced
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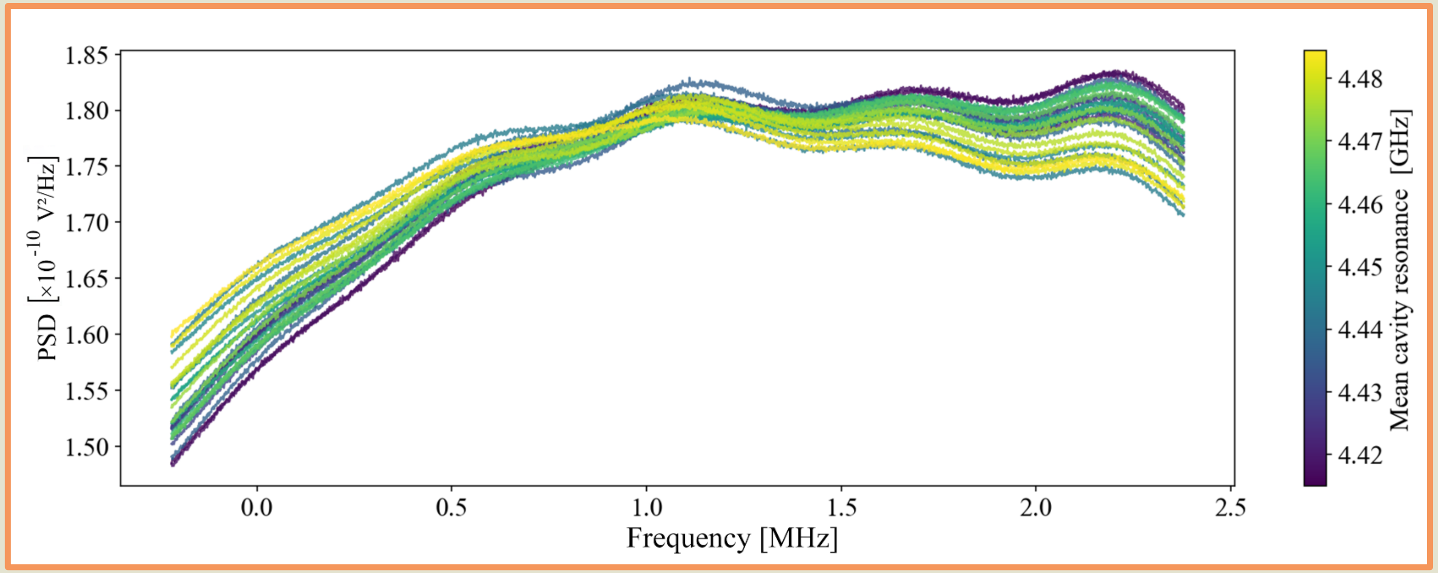
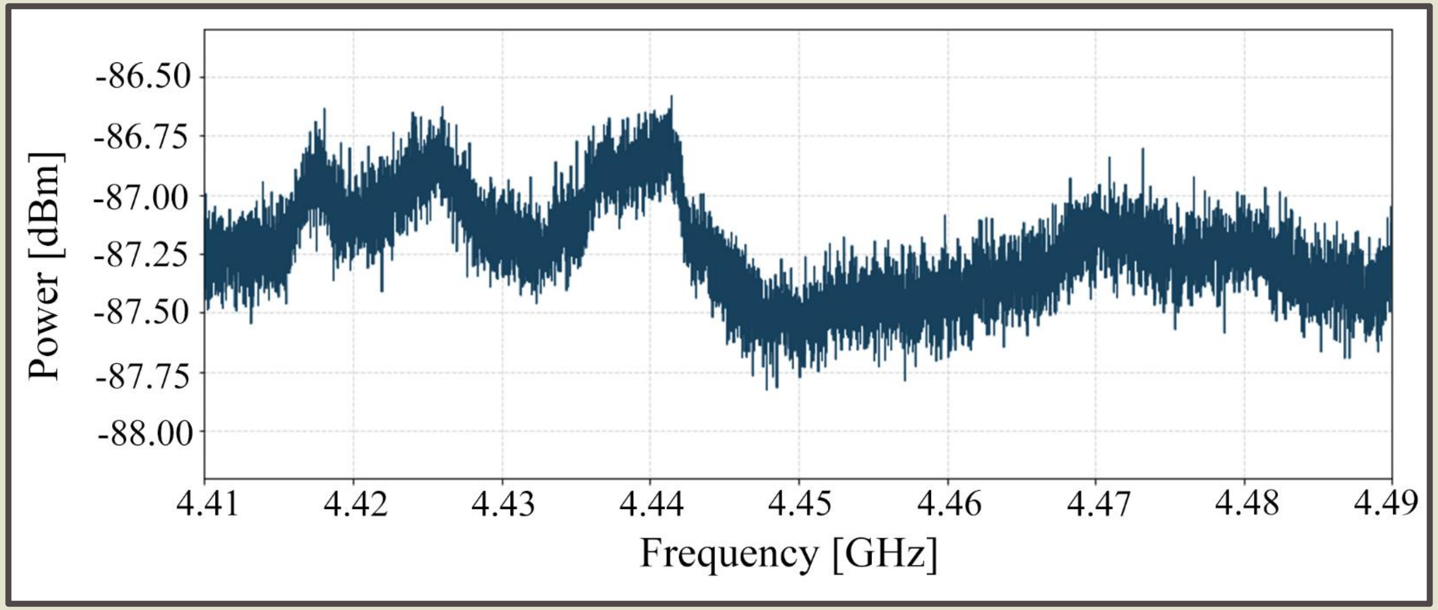


All group averages from cold baseline pass



Hotload spectra from previous cool, peaks match the "tilt" seen in PSD groups

QSHS First Analysis Tests

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2 Baseline Removal - Cold

- **Four post-warm categories:** slow curves (a)/ cavity peaks (b) / cavity troughs (c) / S-shaped (d)

- Using per-spectra fit of form

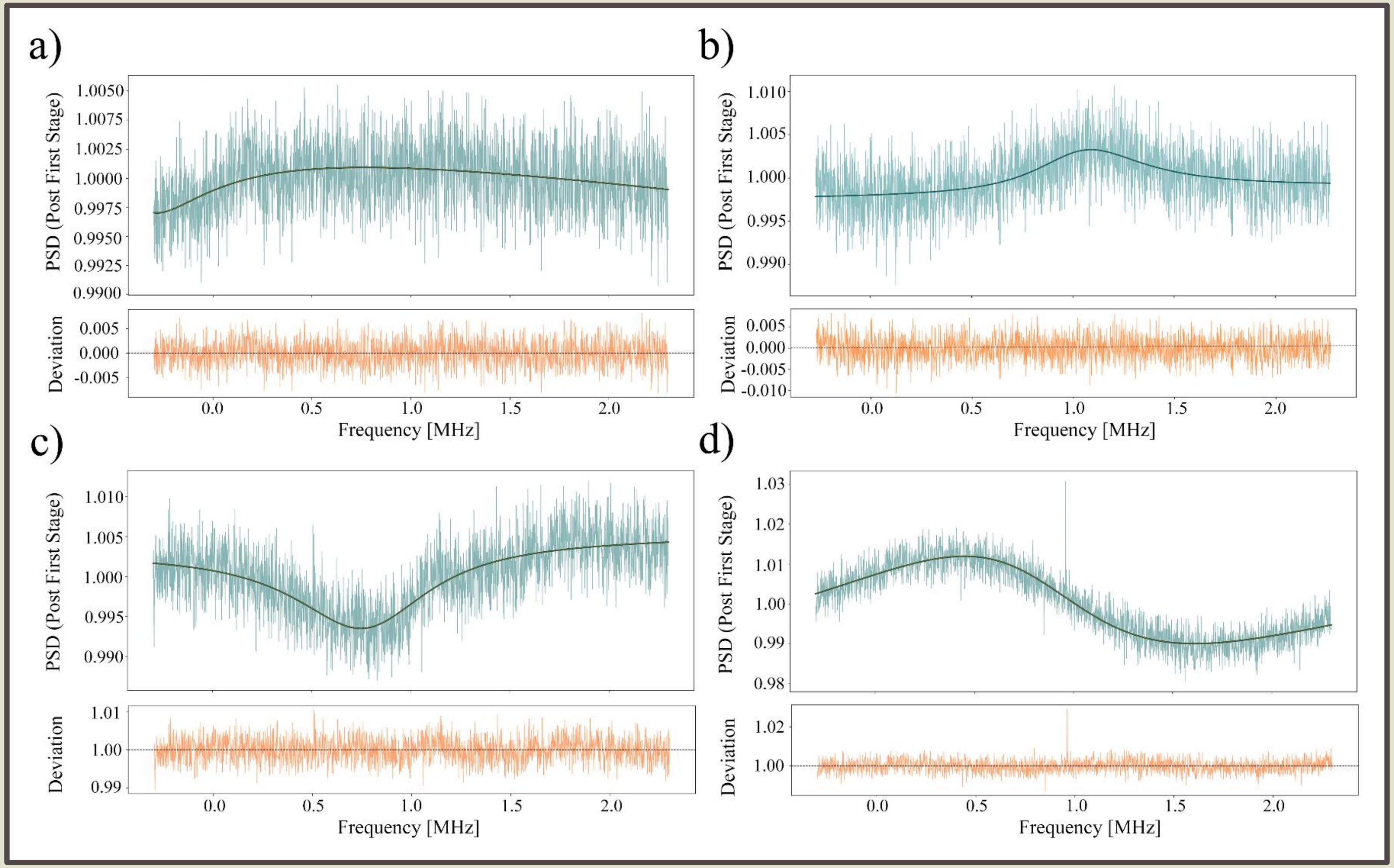
$$1 + \frac{(A-1) + \alpha_{\mathrm{asym}} x}{1 + x^2}$$

With

$$x = \frac{2(f - f_0)}{\mathrm{FWHM}_{\mathrm{cav}}}$$

- Converges for all spectra, slightly underfits some sharp frequency structure (for ≈3% of spectra)

- Structure likely from standing waves in 0.8 m superconducting cable



Example individual PSD spectra and fits

QSHS First Analysis Tests

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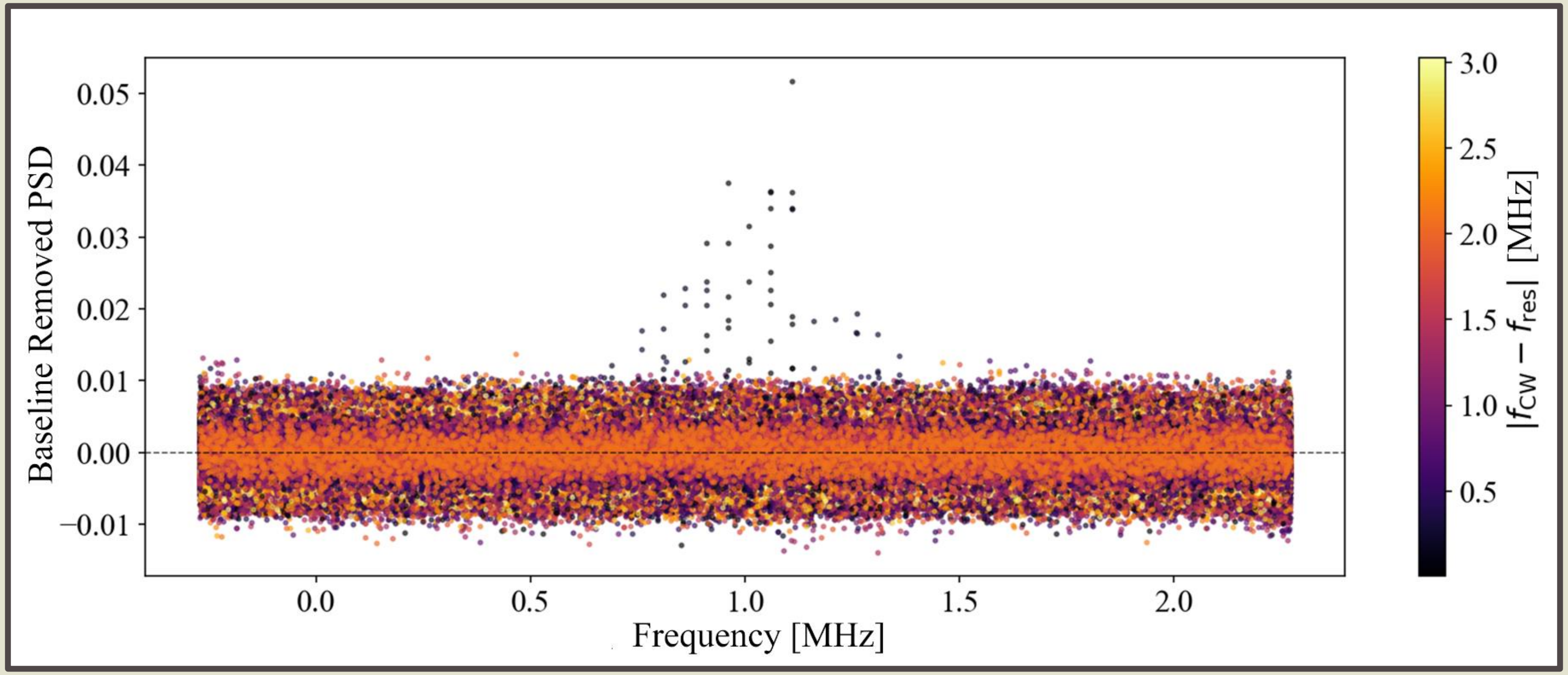
2 Baseline Removal - Cold

- PSDs reasonably flat post-baseline removal
- SNR retention: 0.92 ± 0.06 (for high power CW injections)
- Signal bins kept as single high σ counts
- Gaussian to $\approx 3\sigma$
- No systematic IF interference bins identified (outside cavity resonance region) — noise predominantly stochastic



All PSDs from -10 dBm run post baseline removal

QSHS First Analysis Tests

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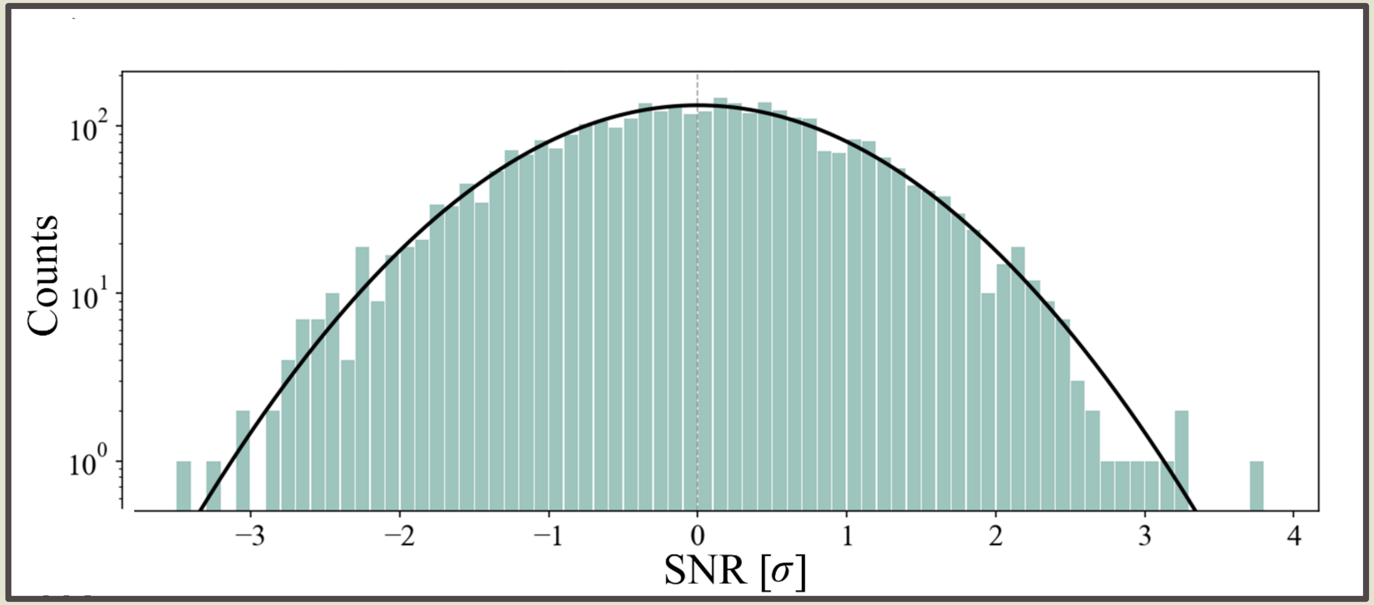
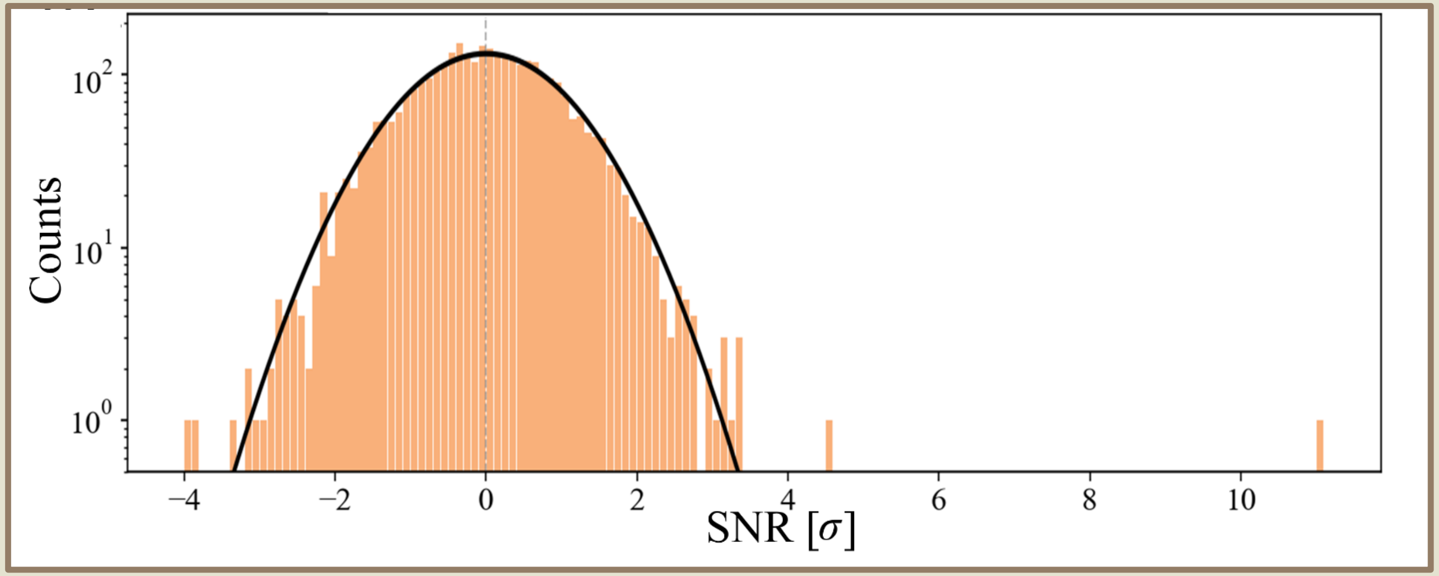


Histogram for a single PSD post baseline removal, CW injection maximally detuned from cavity resonance



CW injection maximally on cavity resonance

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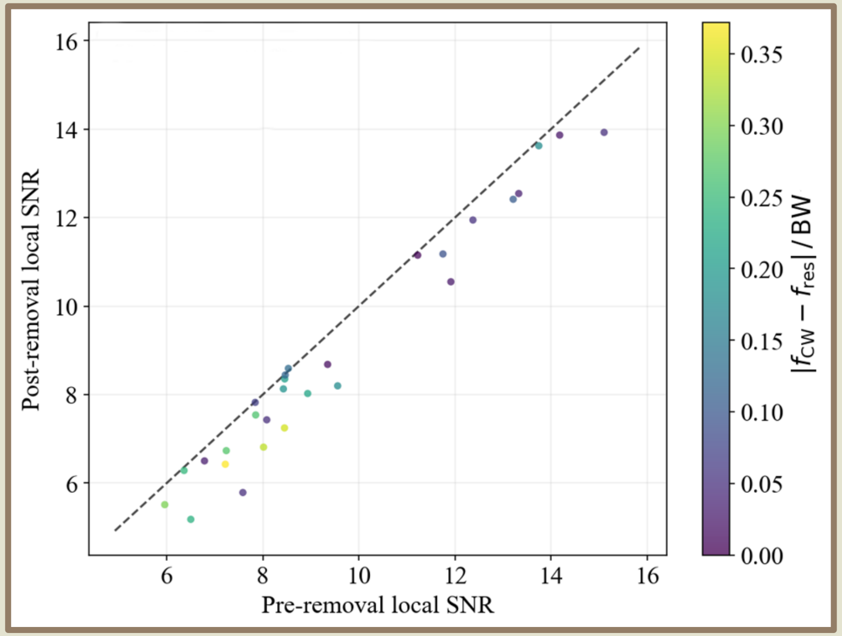

-10 dBm CW injection signal heights before and after baseline removal, dashed line shows ideal no reduction

Coloured by minimum detuning of signal from resonance

Comparison of different baseline methods and resulting signal SNR reduction

Single pass causes excess candidate

SNR Degradation vs Baseline Removal Method

Fit Method	SG Window	Warm Fit Time Window [min]	No. of Candidates	Mean S.N.R. Reduction
Two Pass	251	30	28	0.93 ± 0.06
Two Pass	551	60	28	0.92 ± 0.07
Two Pass	251	60	29	0.91 ± 0.07
Two Pass	551	30	28	0.93 ± 0.06
Single Pass SG	501	N.A.	33	0.84 ± 0.05
Single Pass SG (3 Iterations)	501	N.A.	30	0.94 ± 0.05

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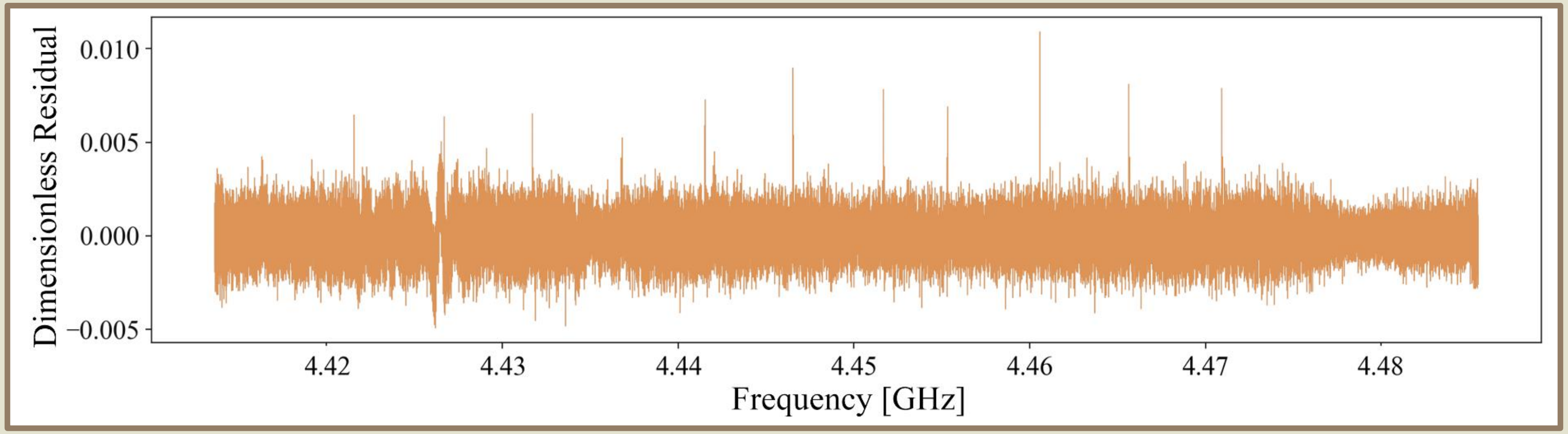
3 Spectra Combination

- RF mapping assumes constant conversion based on fixed 20.5 MHz offset of local oscillator
- Lorentzian weights used as

$$w_{ik} = \frac{h_{ik}}{\sigma_i^2}$$

- For h the normalised Lorentzian transfer function, evaluated at each bin k, and σ the per-spectrum (i) overall stan. dev.
- Total integration time per frequency bin =100 secs × contributing spectra (between 5 and 25 across range, dependent on cavity FWHM)
- IF drift not monitored, no weighting based on system noise temperature, form factor, Q etc.



Combined Spectrum, for clear tuning region of -10dBm injection tests

QSHS First Analysis Tests

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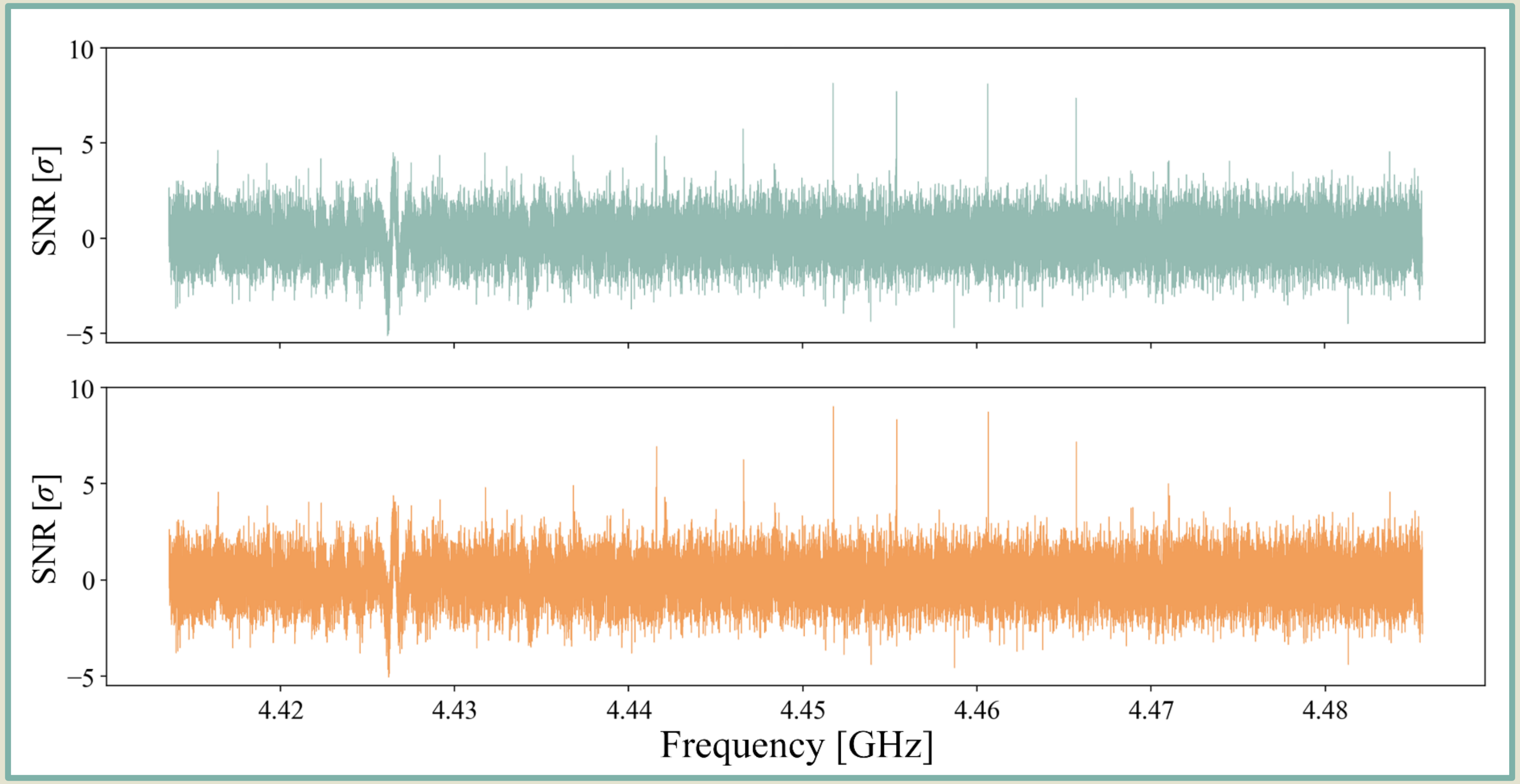
4 Grand Spectrum Rebins

- Combined spectrum bin width 763 Hz – to grand axion linewidth 2390 Hz
- 0.5 overlap fraction to reduce misalignment suppression of signals
- Lineshape weighting found to have no notable effect on recovery of signals (either CW or software) at these power levels
- **Final conversion to $g_{a\gamma\gamma}$ not yet done.** Requires corrections for bin-bin correlations from baseline removal, any SNR suppression factors, bin-overlap DOF reduction, T_{sys} calibration per grand bin etc.



Grand spectrum with inverse variance weighting only (top, blue), and with inverse variance and lineshape weighting (bottom, orange)

QSHS First Analysis Tests

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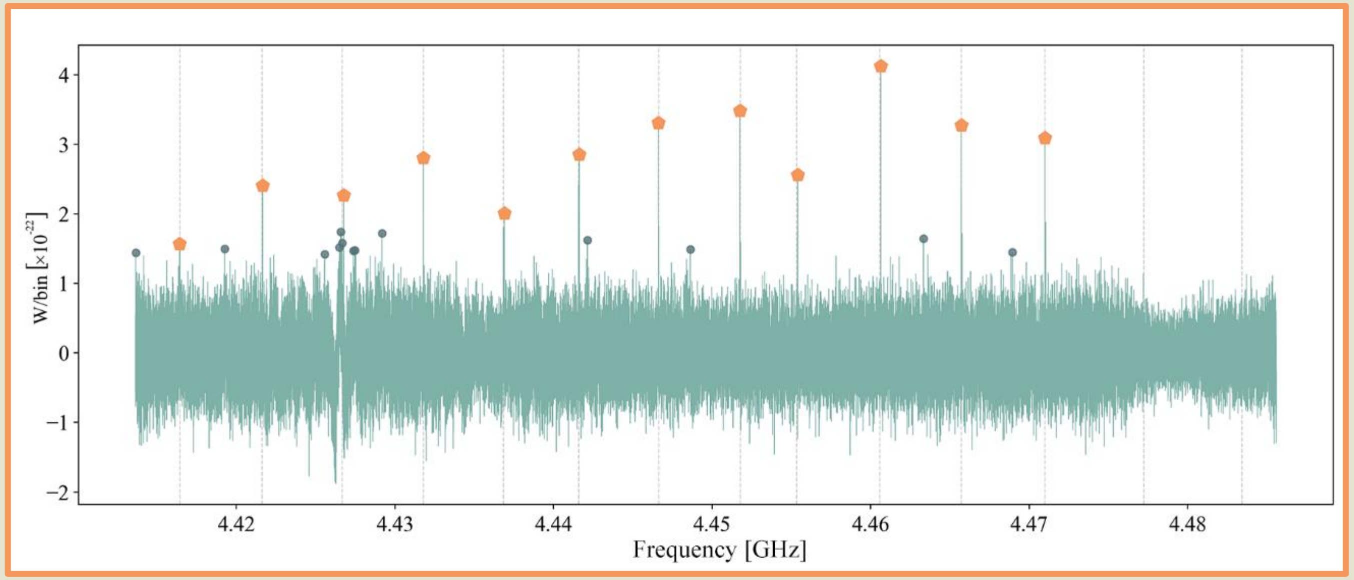
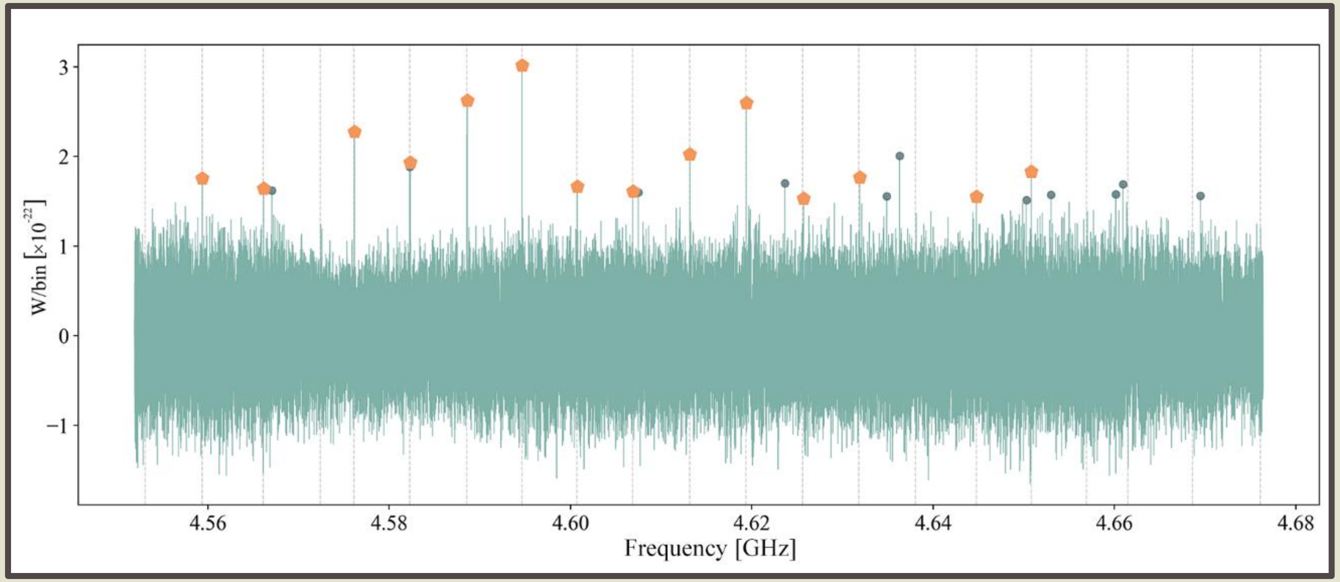
5 Candidates - Hardware

- **Rolling σ cut:** flag highest-σ bin, mask neighbours, lower threshold, flag all beating threshold, repeat.
- **12/14 Candidates returned in first 25,** 85% recovery at 0.35 candidates/MHz for -10 dBm tests, 108 candidates needed to return all CW injections
- **Frequency detuning: 0.03 ± 0.04 MHz,** zero within error; positive bias in higher detuning cases consistent with a systematic in IF→RF conversion (LO or cavity drift)
- **Candidate clustering:** residual baseline non-Gaussianity from standing waves in SC



Combined spectrum and top 25 candidates for -10 dBm clear region



Combined spectrum and top 25 candidates for -20 dBm higher frequency clear region

QSHS First Analysis Tests

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5 Candidates - Hardware

- **Rolling σ cut:** flag highest-σ bin, mask neighbours, lower threshold, flag all beating threshold, repeat.
- **12/14 Candidates returned in first 25,** 85% recovery at 0.35 candidates/MHz for -10 dBm tests, 108 candidates needed to return all CW injections
- **Frequency detuning: 0.03 ± 0.04 MHz,** zero within error; positive bias in higher detuning cases consistent with a systematic in IF→RF conversion (LO or cavity drift)
- **Candidate clustering:** residual baseline non-Gaussianity from standing waves in SC

CW Recovery with Grand Spectrum Weighting Method

Grand Bin Weighting	CW Power [dBm]	Frequency Range [GHz]	No. Candidates to Return All CW	CW Within Top 25
Combined Spectrum	−10	4.415 – 4.493	108	12/14
Combined Spectrum	−20	4.415 – 4.493	508	2/13
Combined Spectrum	−20	4.55 – 4.68	433	14/21
Inverse variance only	−10	4.415 – 4.493	292	12/14
Inverse variance only	−20	4.415 – 4.493	234	3/13
Inverse variance only	−20	4.55 – 4.68	354	14/21
Inverse variance and Lineshape	−10	4.415 – 4.493	299	12/14
Inverse variance and Lineshape	−20	4.415 – 4.493	268	3/13
Inverse variance and Lineshape	−20	4.55 – 4.68	401	10/21

Table 1.8: The number of candidates flagged before all injected CW signals are recovered and the number of CW signals identified within 25 candidates, for the combined spectrum and for grand spectra weighted only by inverse variance and weighted by both inverse variance and MBBD lineshape.

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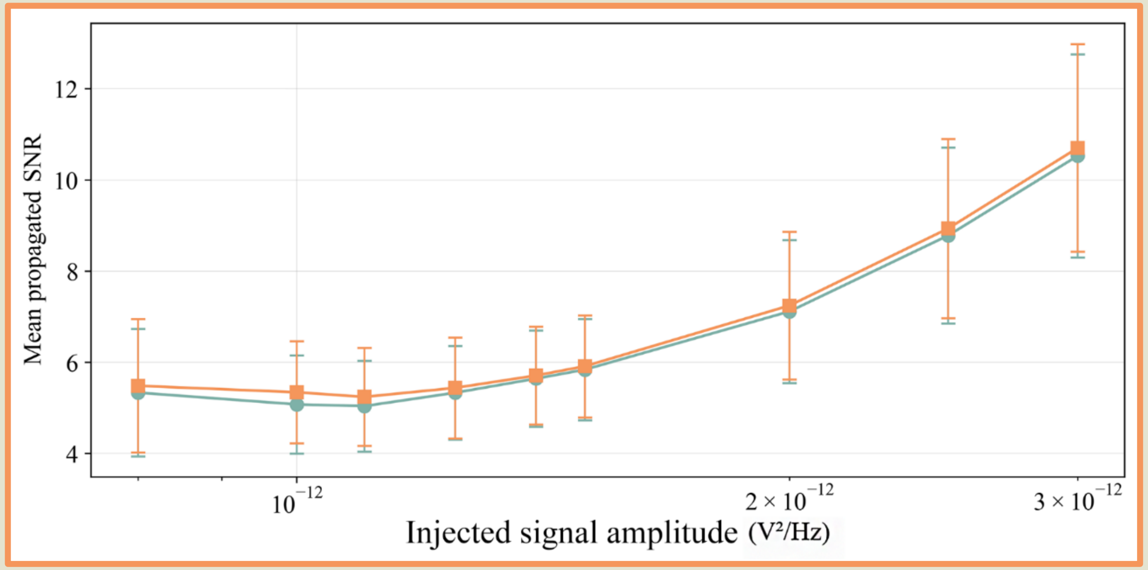
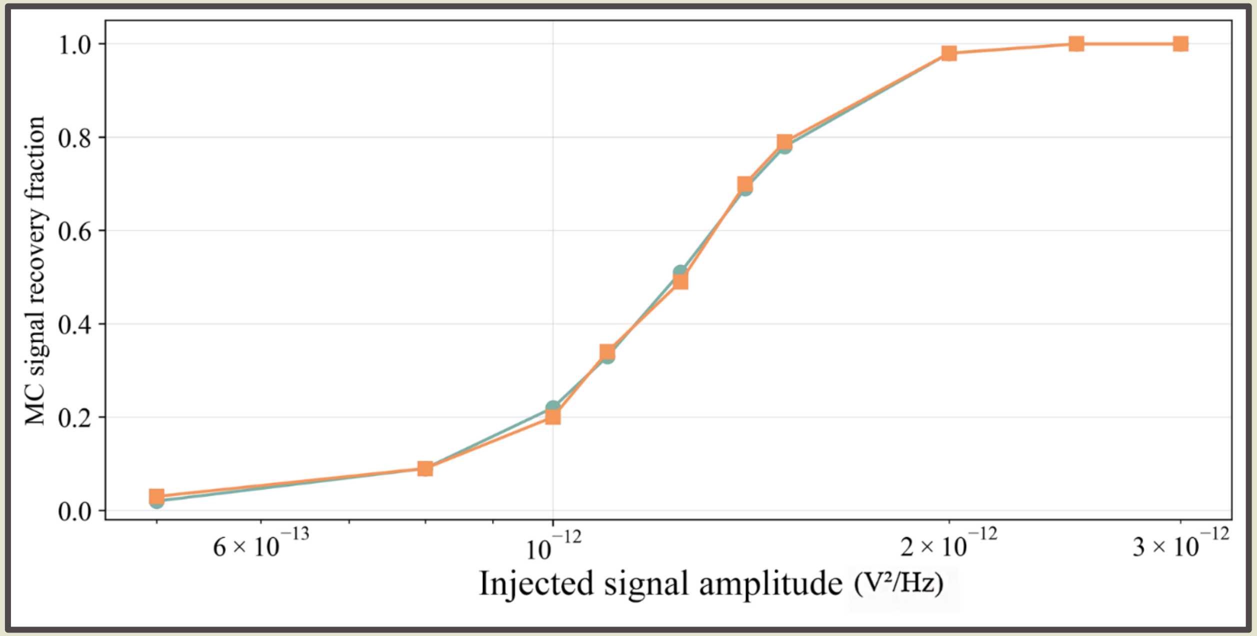
5 Candidates, Software

- 90% recovery threshold: peak injected power ≈ $2 \times 10^{-12} V^2/Hz \rightarrow \approx 1.5 \times 10^{-21}$ W at cavity accounting for ≈130 dB gain and bin width 763 Hz. ≈ 150 × KSVZ*.
- Using only 100 MC injections here, propagated σ needs calibrating with hardware injection tests



Software injection recovered σ vs injected peak amplitude



Software injection recovery fraction vs injected peak amplitude

*- estimate based on uncertain gain

QSHS First Analysis Tests

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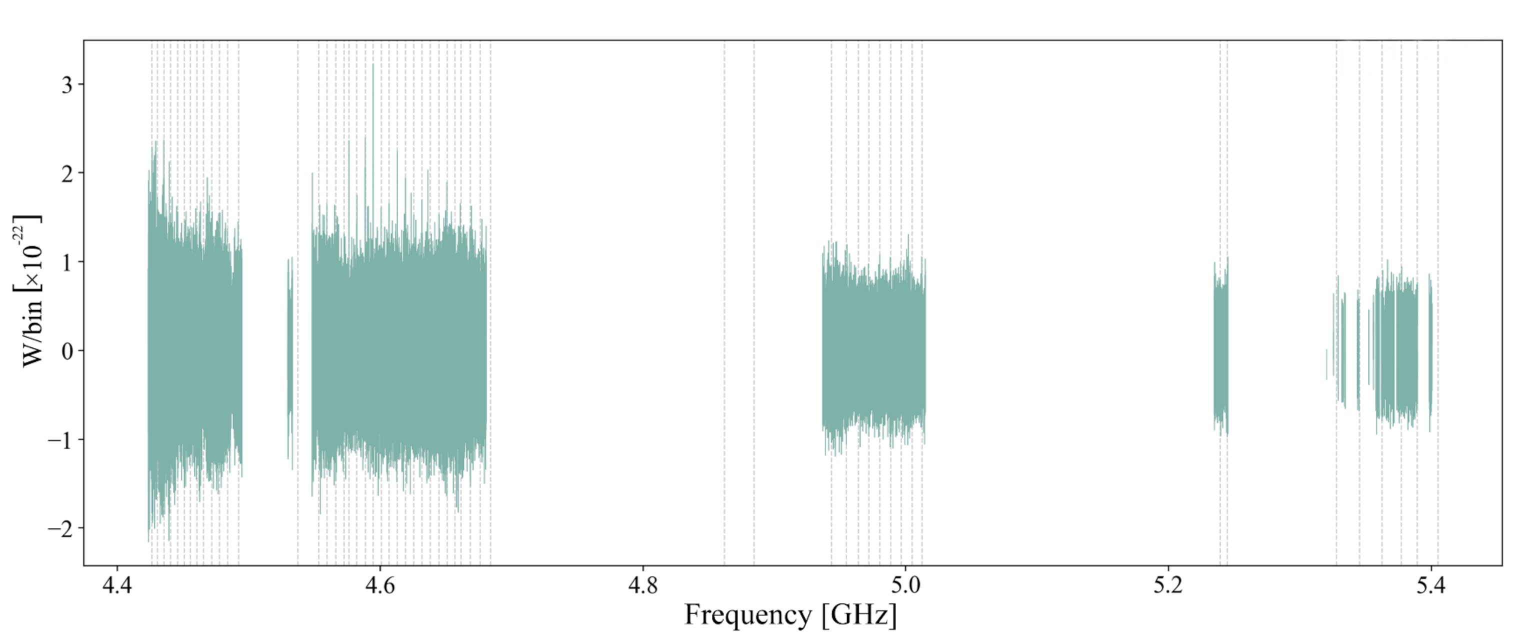
Full Runs and Range

- CW signal bins visible across most of accessible range; amplitude decreases toward higher frequencies (undercoupled static antenna + mode crossings)
- Large frequency discontinuities in tuning range obvious and cause regions of low spectra coverage
- Thermal settling after large rod movements: ≈30 min to 1 hr cooldown required (relevant for rescan jumps)



Full combined spectrum, -20dBm run

CW injected signals recovered in top 50 using different search methods
Out of 35 total for -10 dBm run and out of 55 total for -20 dBm run

CW Signal Recovery by Search Method

Search Method	CW Power [dBm]	Recovered in Top 50
Global σ	−10	16
Time-based rolling window	−10	17
Frequency-based rolling window	−10	18
Global σ	−20	15
Time-based rolling window	−20	20
Frequency-based rolling window	−20	20

QSHS First Analysis Tests

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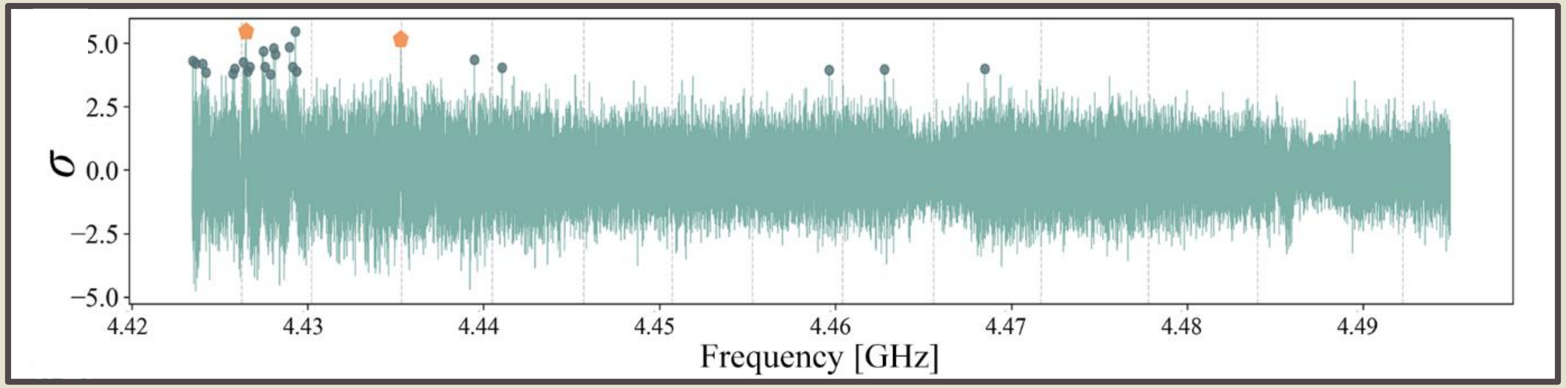
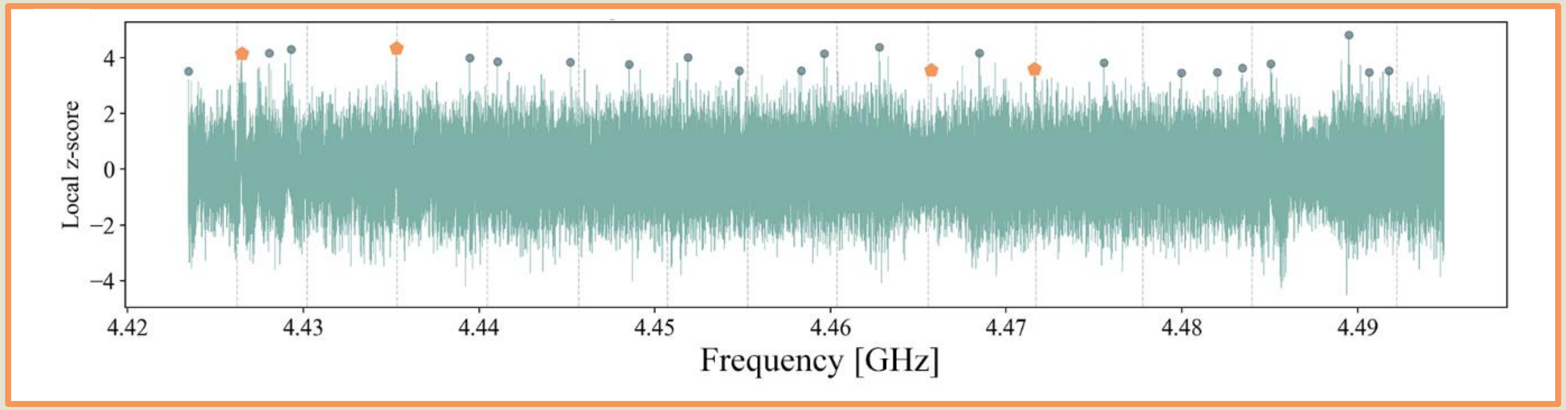
5 Candidate Recovery

- Regular mode crossings create localised noise elevations — global σ cut clusters in these regions, need to either cut mode crossings (loses a lot of range for QSHS cavity) or use a local score
- Rolling z-score (window ≈5 cavity linewidths ≈3.5 MHz) ranking each bin by deviation from local mean rather than global spectrum gives significantly improved results
- 108 → 28 candidates needed to recover all -10 dBm injections in the no-mode-crossing region

Top 25 candidates for -20dBm combined spectrum, using rolling σ cut





Top 25 candidates for -20dBm combined spectrum, using rolling local z-score cut

QSHS First Analysis Tests

Data Cuts & Drift
- Final data cut metrics need deciding.

Baseline Removal
- 1st-stage amp + adjustable antenna should reduce fast varying small-scale structure/standing waves
- Potentially develop direct calibration (FIR filter + hotload), or full hotload measurement for cold pass

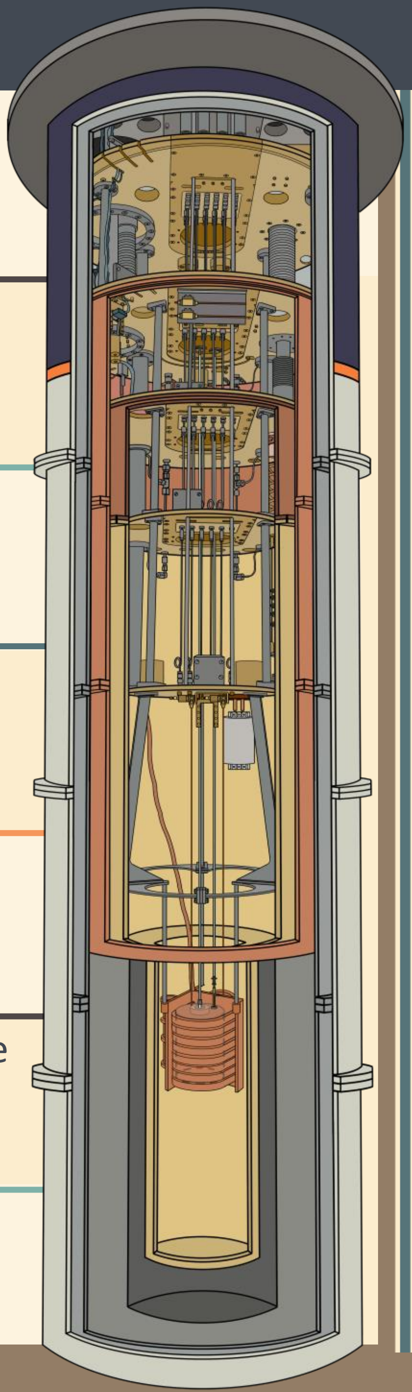
Spectra Combination
- May want to use more sophisticated weighting (considering form factor, system noise temperature measurements, etc.)

Grand Spectrum
- Statistics corrections (bin-bin correlations, SNR suppression factor, bin-overlap DOF, etc.)

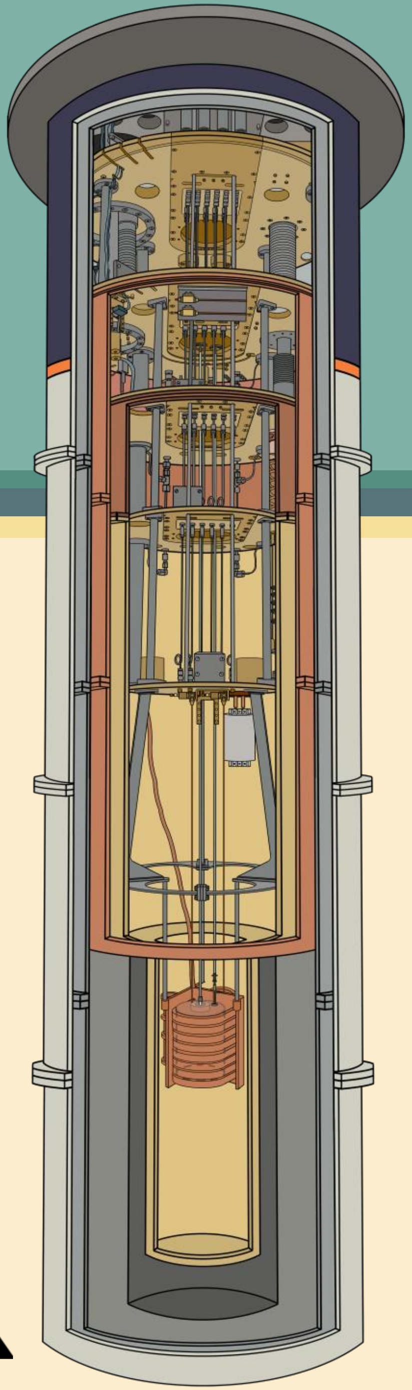
Candidate Recovery
- Final re-binning/search metric method needs to be decided
- Target sensitivity or candidate number needs to be set

Exclusion Limits
- **Conversion to $g_{a\gamma\gamma}$** - will require full noise temperature measurements and potentially full hardware injection campaign, improved lineshape hardware injection methods underway
- Overall exclusion limit setting logic/final injection test suite needs deciding

Rescan Analysis
- Altered analysis if combining original and rescan data sets



Thank You!



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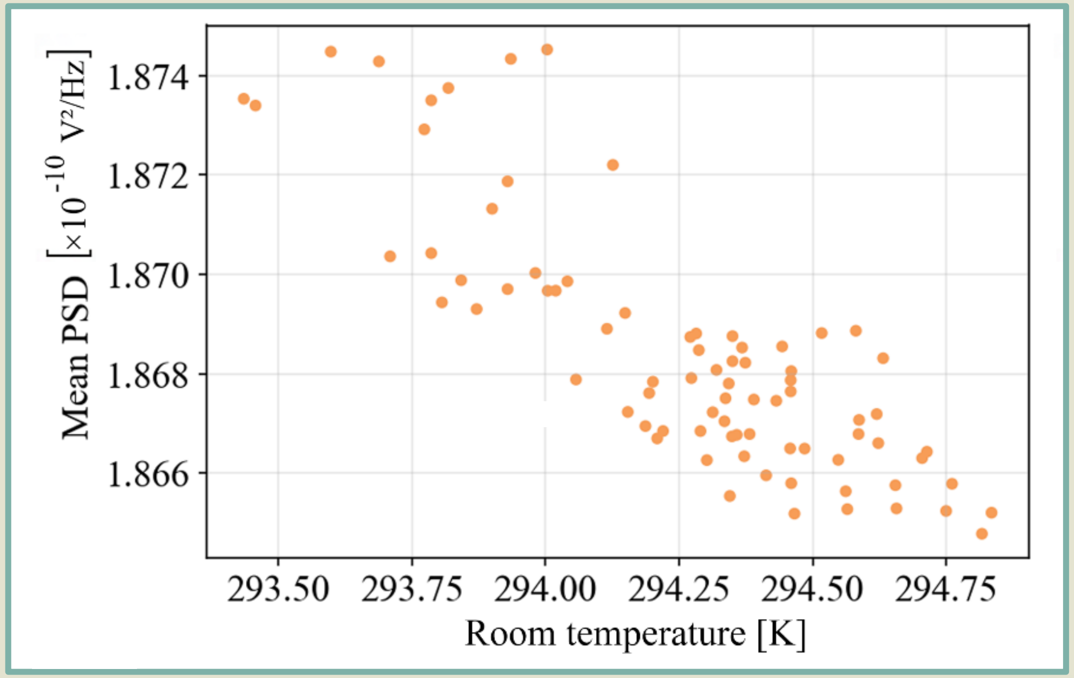
QSHS First Analysis Tests

Claude Mostyn

1 Gain Drift

- **Temporal drift: <0.2% of mean PSD.** Slight negative correlation with room temperature (RT amplifier)
- **Frequency-dependent drift dominates** — primarily receiver electronics; consistent with hotload across different cools → calibration feasible
- **Q-dependent component:** near mode crossings, falling cavity Q causes additional PSD amplitude decrease
- **Current correction:** global median shift per PSD. Final model: data-driven hotload calibration (deferred to when full receiver chain installed)



Temperature dependence of PSD mean

QSHS First Analysis Tests

Claude Mostyn

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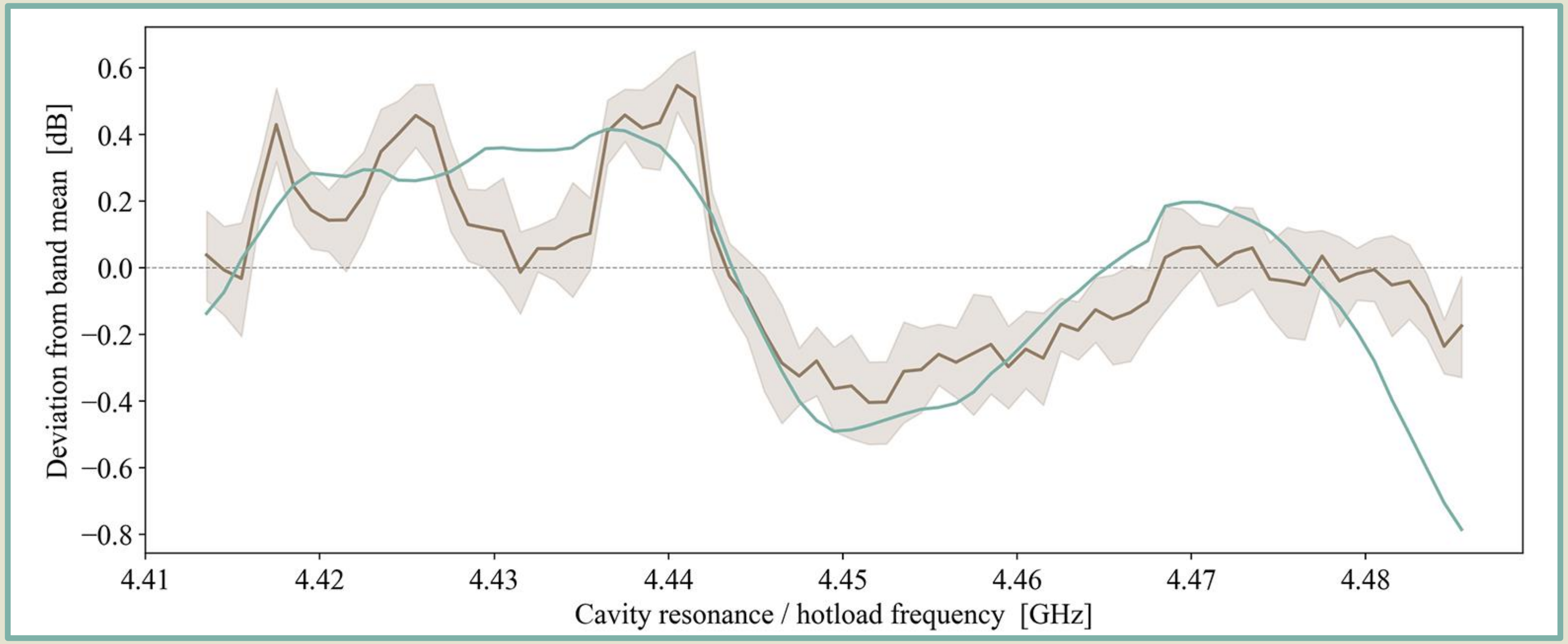

Hotload spectrum (brown, noise in light brown) tracks PSD mean amplitude (blue), using hotload scaling factor (extra amplifier added)

QSHS
University of Sheffield

QSHS First Analysis Tests

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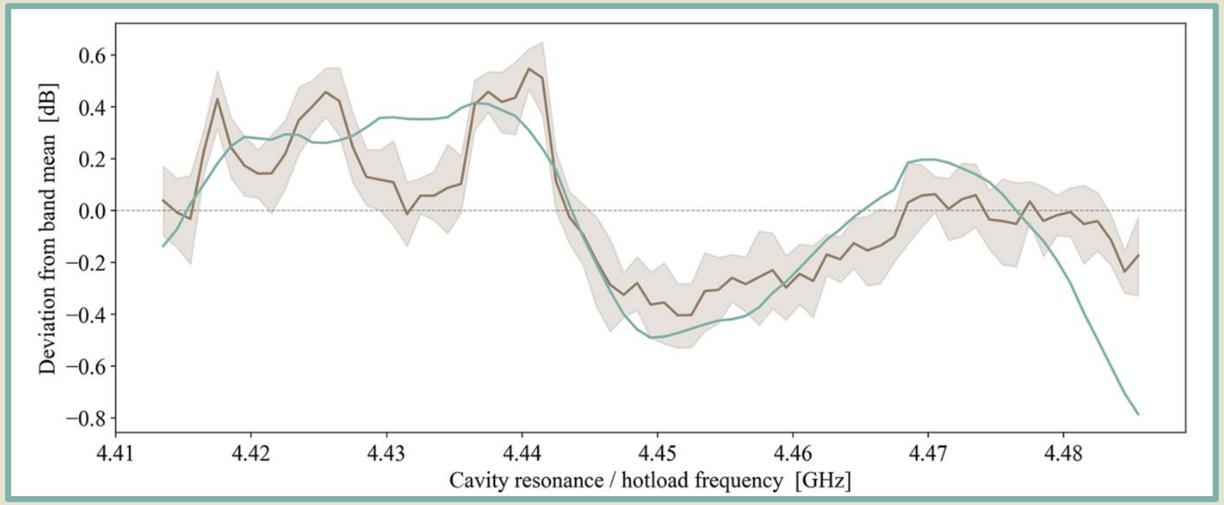
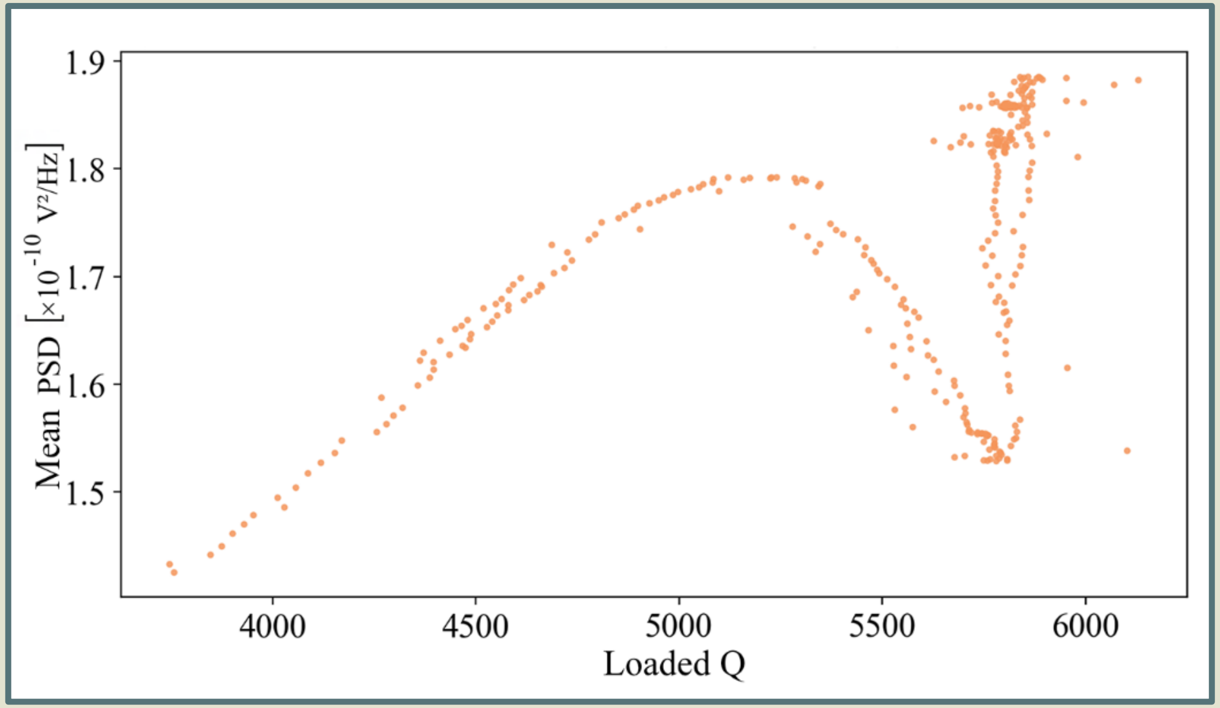


Hotload spectrum tracks PSD mean amplitude



PSD mean amplitude becomes approximately linear in Q where $A < 5000$