LHO End of O4 PEM Coupling Measurements

Samantha Callos, Genevieve Connolly, Robert Schofield, Ryan Short, Carlos Campos

Quick Overview

- What are PEM coupling and injections?
- How are coupling functions calculated?
- Vibrational coupling results
- Magnetic coupling results
- Summary & future projects

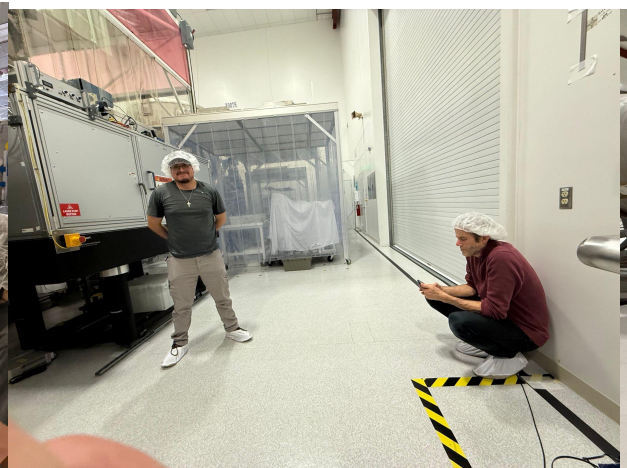
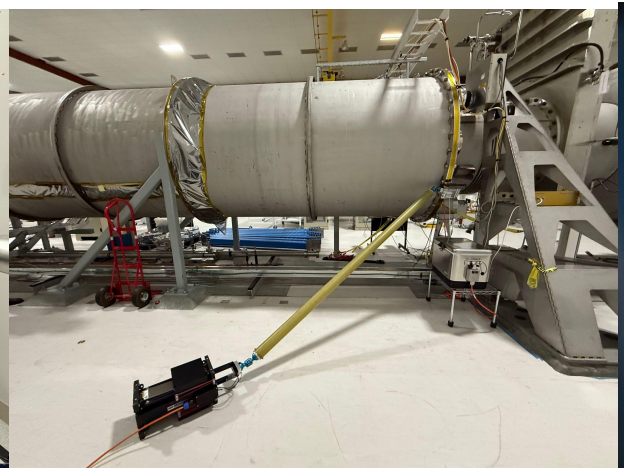
PEM Coupling & Injections

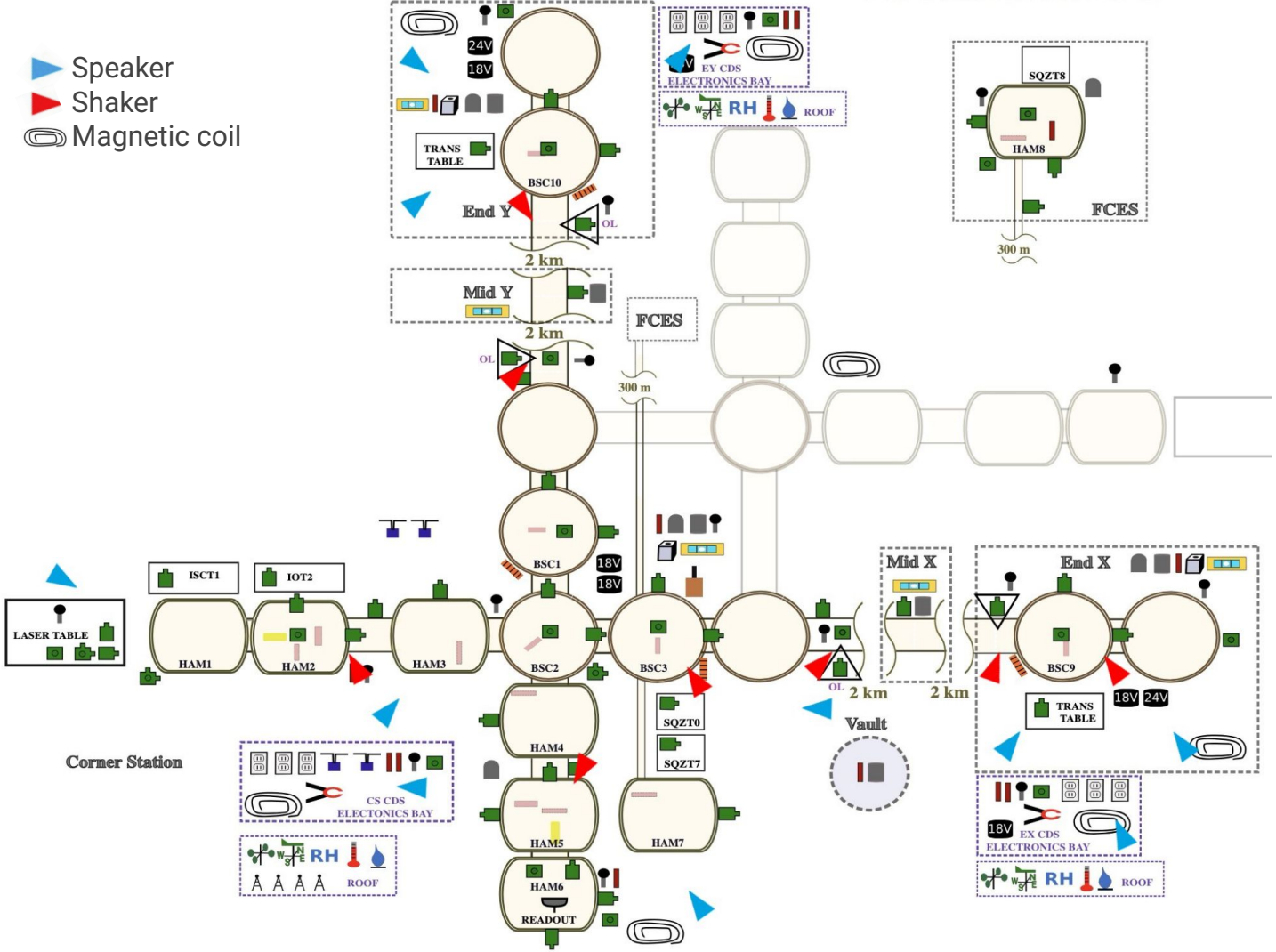
- Coupling quantifies how environmental noise picked up by PEM sensors is likely to be seen in DARM
- Injections: make noise using a shaker, speaker, magnetic coil, etc and compare sensor response to DARM response
- We did vibrational & magnetic injections at the end of November after we ended the run
- Instrumentation changed → needed to do a full set of injections

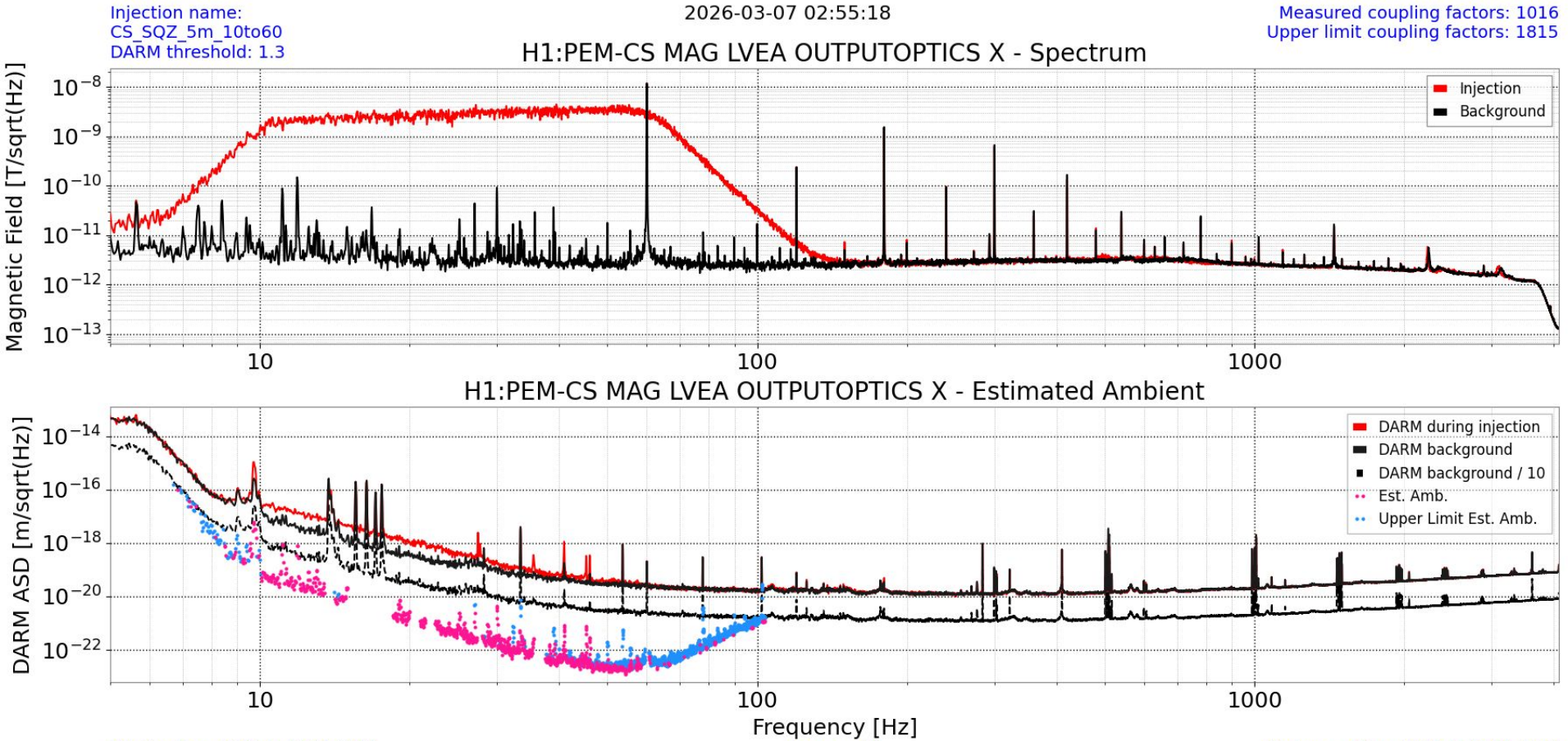
November 2025		Frequencies (Hz)	CS	EX	EY
Vibrational	Shaker	3 to 10 10 to 20 20 to 40	HAM5 X Reduction Flange BSC3 MC Tube Y Reduction Flange	BSC9 Manifold	Reduction Flange
	Acoustic	40 to 100 100 to 1000 1000 to 4000	X Manifold EBAY Far Output Input Optics PSL	EBAY Mech Door Near Door	EBAY Mech Door Near Door
Magnetic		10 to 60 60 to 100 100 to 200 200 to 600 600 to 1000 1000 to 2500 2500 to 4000	Vertex Wall Coil CER Wall Coil SQZ Bay Wall Coil	VEA Wall Coil EBAY Wall Coil	VEA Wall Coil EBAY Wall Coil

May 2023		Frequencies (Hz)	CS	EX	EY
Vibrational	Shaker	5 to 10 10 to 20 20 to 40	HAM6 X Reduction Flange BSC3 HAM2 Y Reduction Flange	BSC9 Manifold	Manifold BSC10
	Acoustic	40 to 100 100 to 1000 1000 to 4000	X Manifold EBAY Far Output Input Optics PSL**	EBAY Mech Door* Near Door*	EBAY* Mech Door* Near Door*
Magnetic		10 to 100 100 to 1000 1000 to 4000	Vertex Wall Coil CER Wall Coil SQZ Bay Wall Coil	VEA Wall Coil EBAY Wall Coil	VEA Wall Coil EBAY Wall Coil

*40-60, 60-100, 100-1000, 1000-4000 Hz
**40-90, 90-1000, 1000-4000 Hz



Speaker
Shaker
Magnetic coil
24V
18V
TRANS TABLE
BSC10
End Y
OL
2 km
Mid Y
2 km
OL
EY CDS ELECTRONICS BAY
RH
ROOF
SQZT8
HAM8
FCES
300 m
FCES
300 m
BSC1
18V
18V
ISCT1
IOT2
LASER TABLE
HAM1
HAM2
HAM3
BSC2
BSC3
SQZT0
SQZT7
HAM4
HAM5
HAM7
HAM6
READOUT
Corner Station
CS CDS ELECTONICS BAY
RH
ROOF
OL
2 km
Vault
Mid X
2 km
End X
BSC9
TRANS TABLE
18V
24V
18V
EX CDS ELECTRONICS BAY
RH
ROOF


Injection name:
CS_SQZ_5m_10to60
DARM threshold: 1.3
2026-03-07 02:55:18
Measured coupling factors: 1016
Upper limit coupling factors: 1815
H1:PEM-CS MAG LVEA OUTPUTOPTICS X - Spectrum
Magnetic Field [T/sqrt(Hz)]
Injection
Background
H1:PEM-CS MAG LVEA OUTPUTOPTICS X - Estimated Ambient
DARM ASD [m/sqrt(Hz)]
DARM during injection
DARM background
DARM background / 10
Est. Amb.
Upper Limit Est. Amb.
Frequency [Hz]
Injection Time: 2025-11-25 04:26:03
(1448079981)
Averages: 17
Bin width: 0.030 Hz
Background Time: 2025-11-25 03:05:58
(1448075176)

What are coupling functions?

- Y_{inj} is DARM ASD during injection
- Y_{bkg} is DARM ASD during background
- X_{inj} is sensor ASD during injection
- X_{bkg} is sensor ASD during background
- Estimated ambient: $CF(f) * X_{bkg}(f)$

- Composite: take CF value for the loudest injection in the sensor at each frequency bin
- Sitewide: take the highest CF value at each frequency bin across all channels (measured values take precedence over upper limits)

Measured value: if X_{inj}/X_{bkg} > sensor threshold AND Y_{inj}/Y_{bkg} > DARM threshold

$$CF(f) = \sqrt{\frac{Y_{inj}^2(f) - Y_{bkg}^2(f)}{X_{inj}^2(f) - X_{bkg}^2(f)}}$$

Upper limit value: if X_{inj}/X_{bkg} > sensor threshold BUT Y_{inj}/Y_{bkg} < DARM threshold

$$CF(f) = \frac{Y_{bkg}(f)}{\sqrt{X_{inj}^2(f) - X_{bkg}^2(f)}}$$

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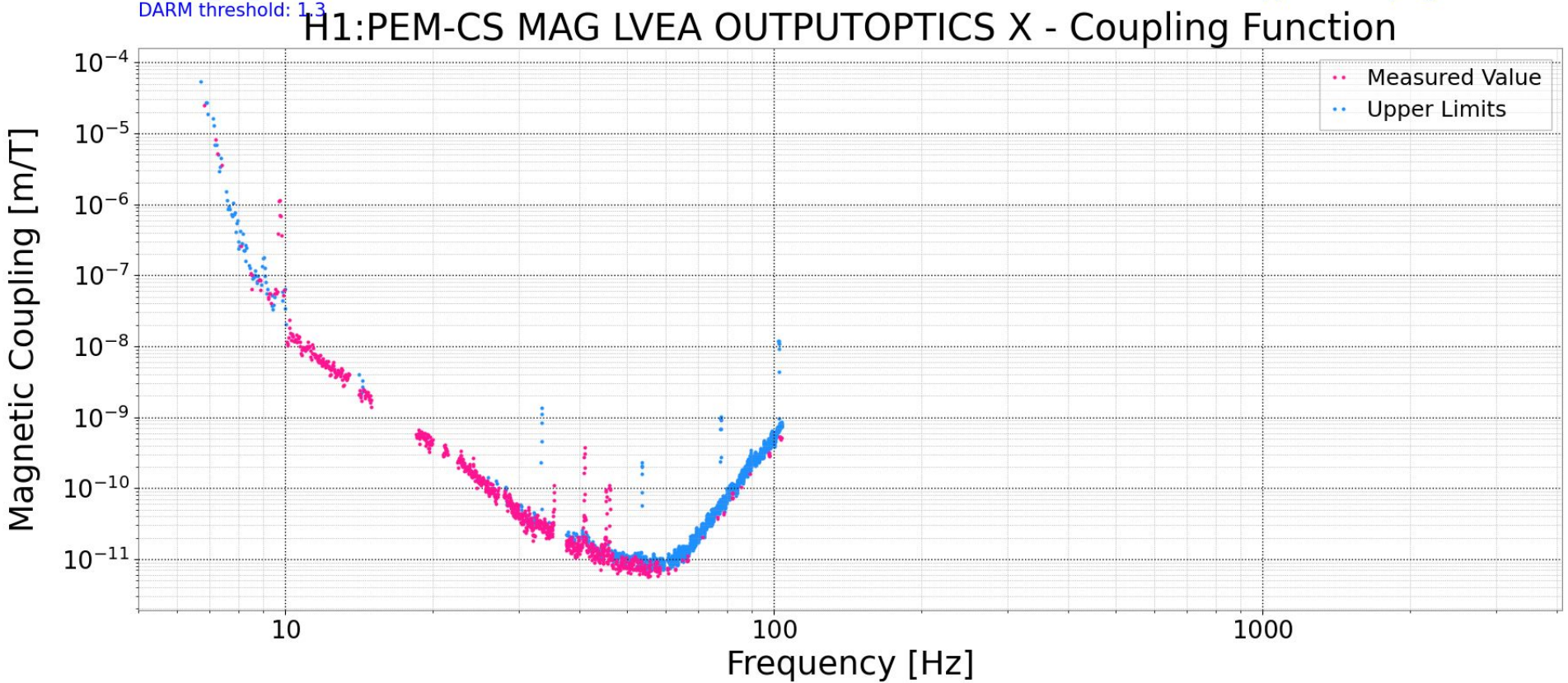

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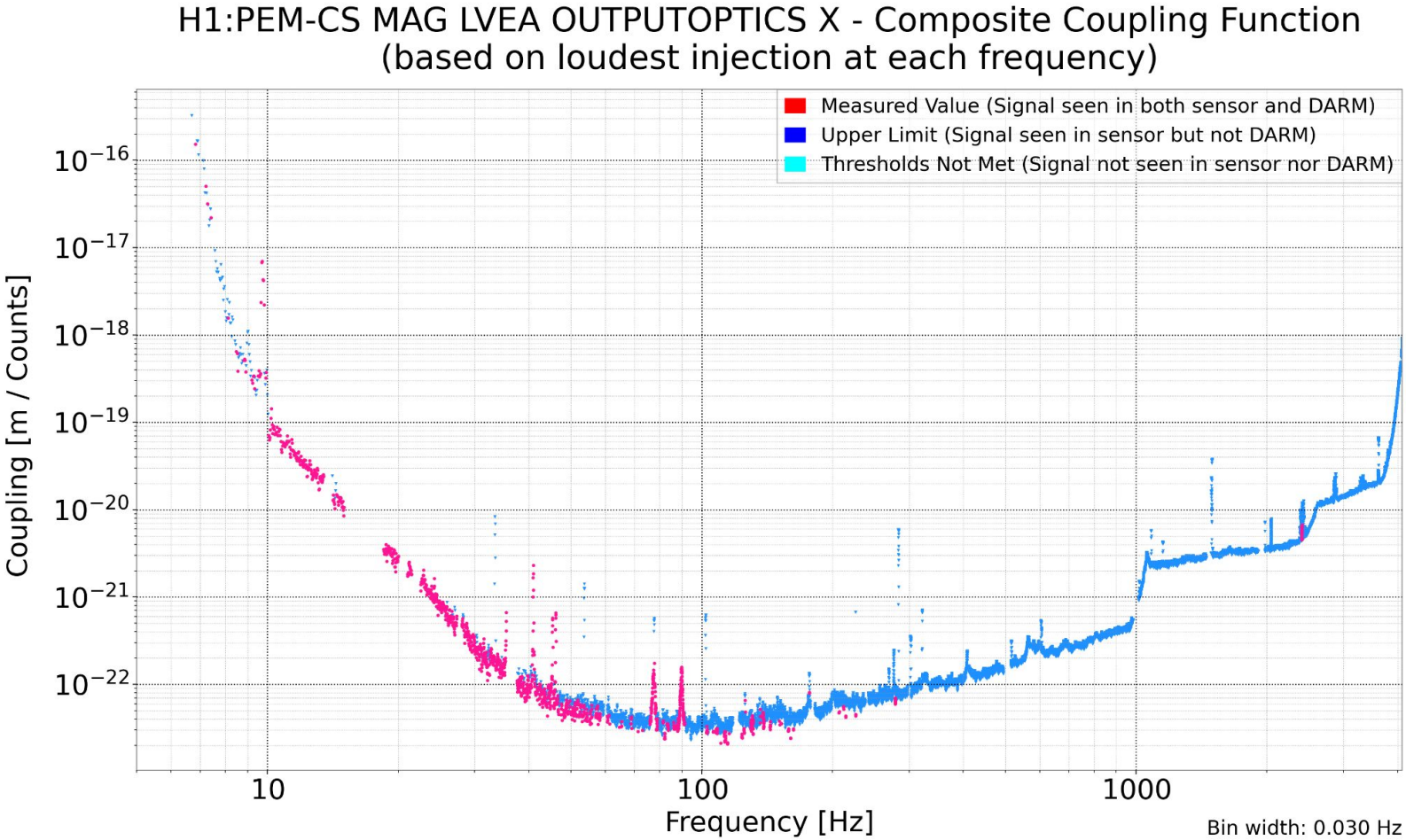
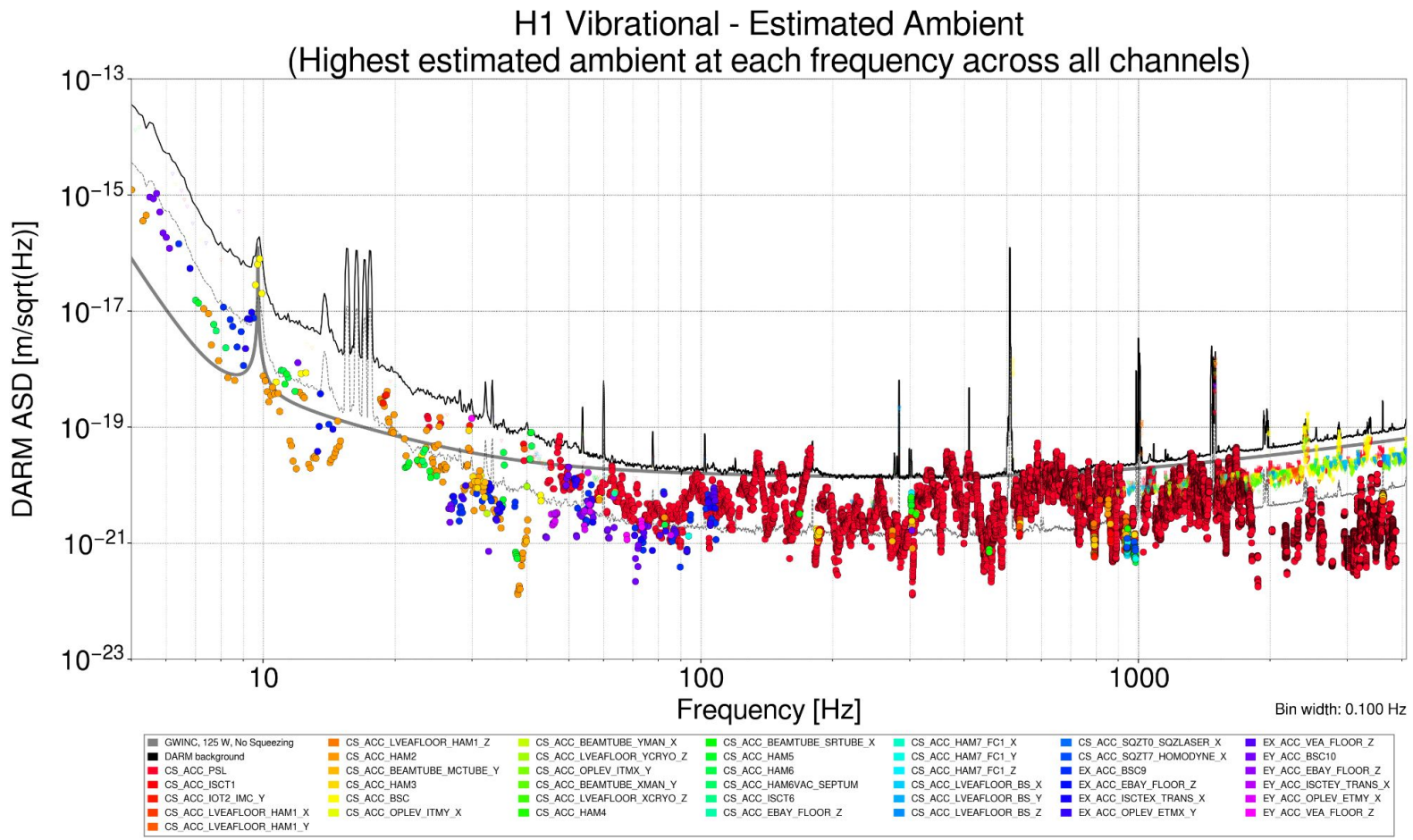

H1:PEM-CS MAG LVEA OUTPUTOPTICS X - Composite Coupling Function
(based on loudest injection at each frequency)
Measured Value (Signal seen in both sensor and DARM)
Upper Limit (Signal seen in sensor but not DARM)
Thresholds Not Met (Signal not seen in sensor nor DARM)
Coupling [m / Counts]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10
100
1000
Frequency [Hz]
Bin width: 0.030 Hz

Vibrational Injections

2023 ACC PEM Injs



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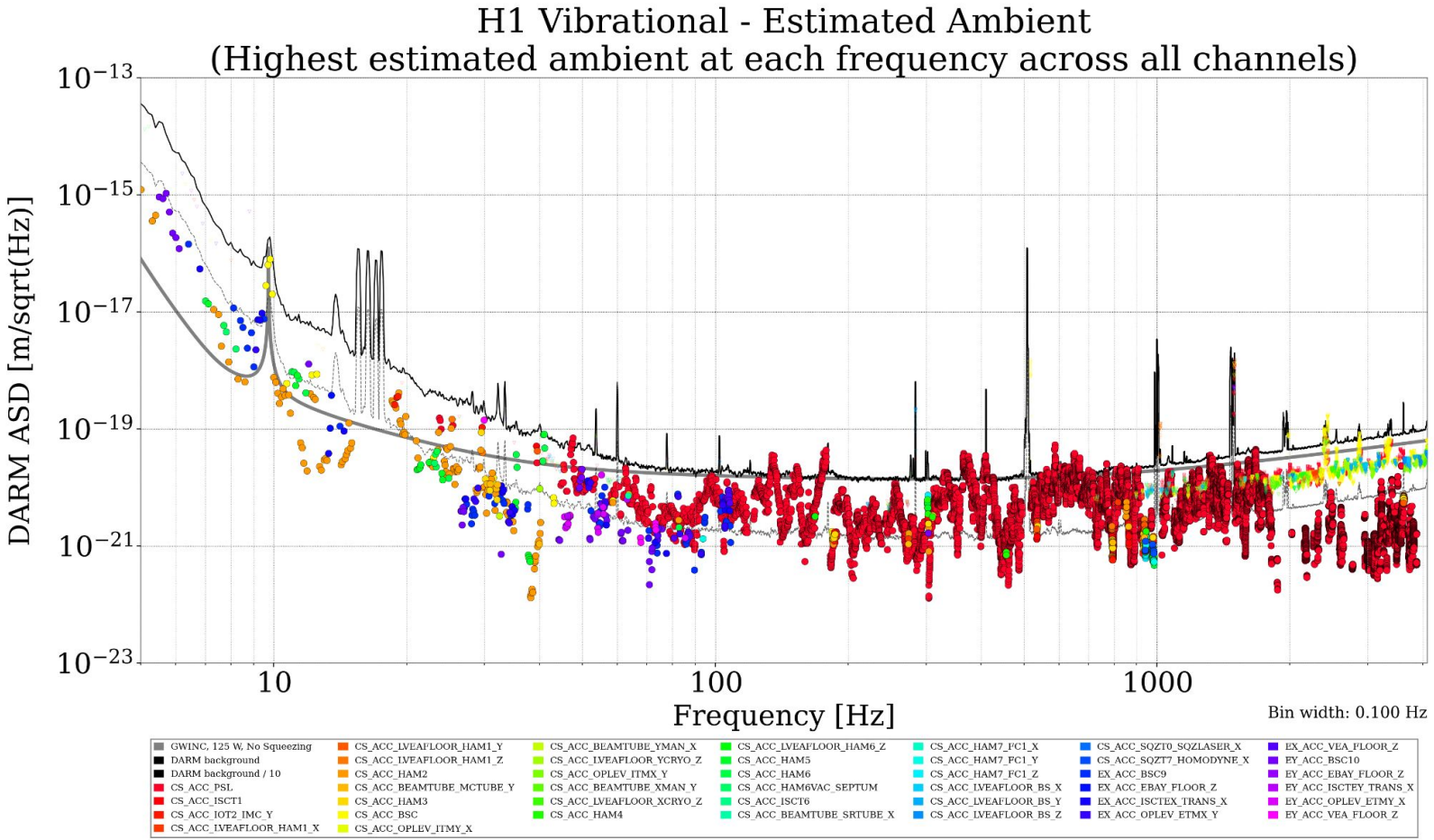

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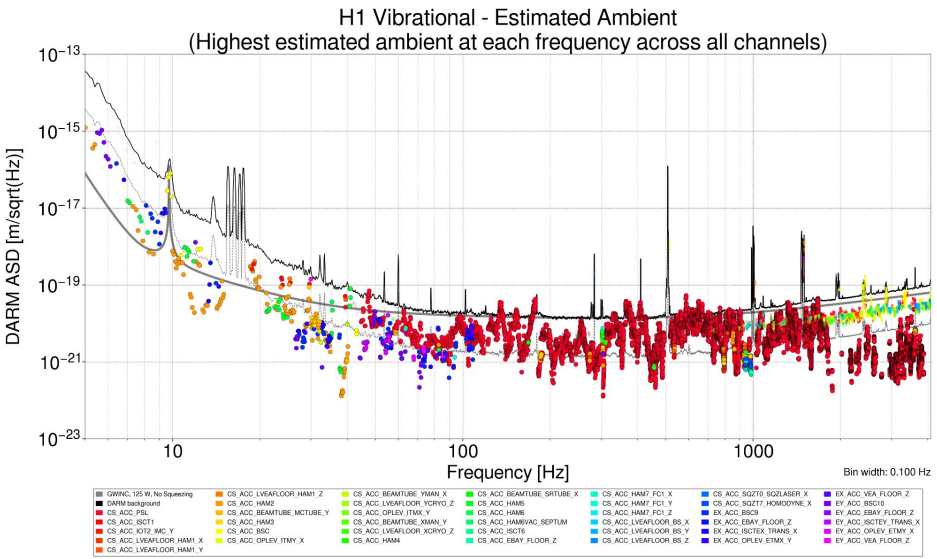
Less END X coupling points (upper limits) at low and mid-high tens frequencies

Jitter (tiny bit worse)



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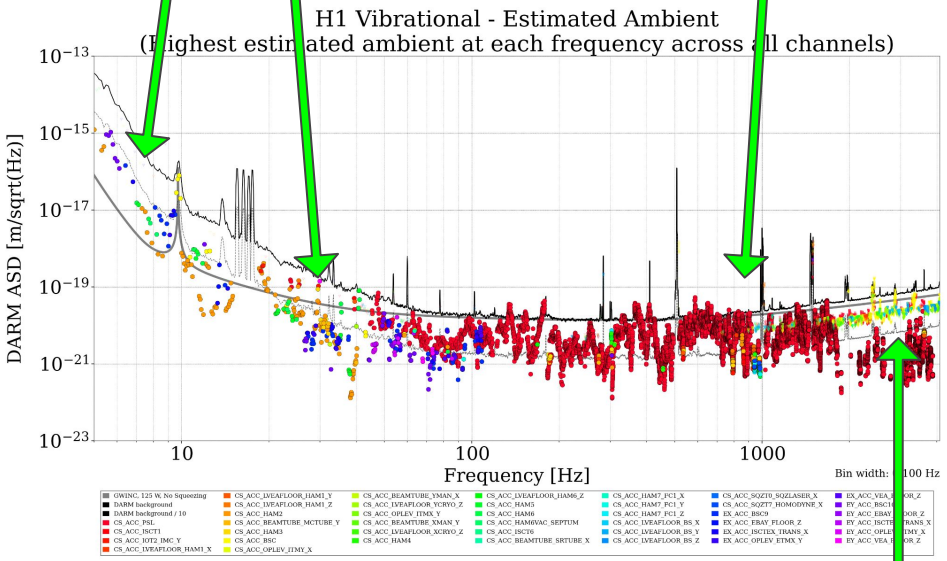

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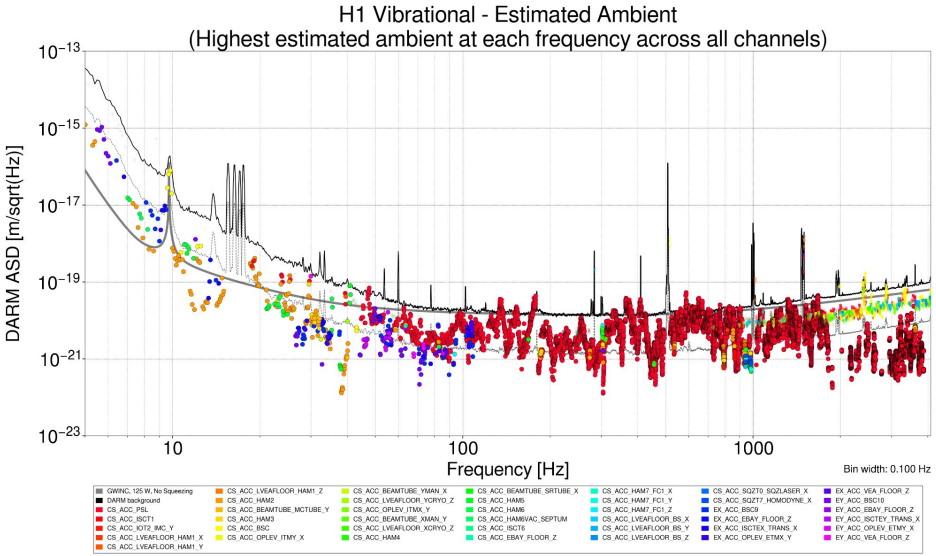
2025

Hitting fewer upper limits then 2023



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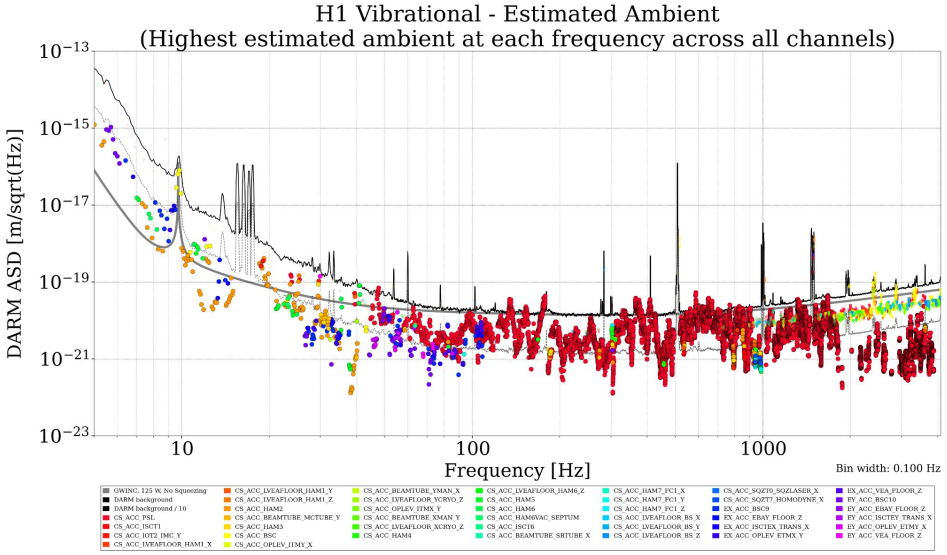

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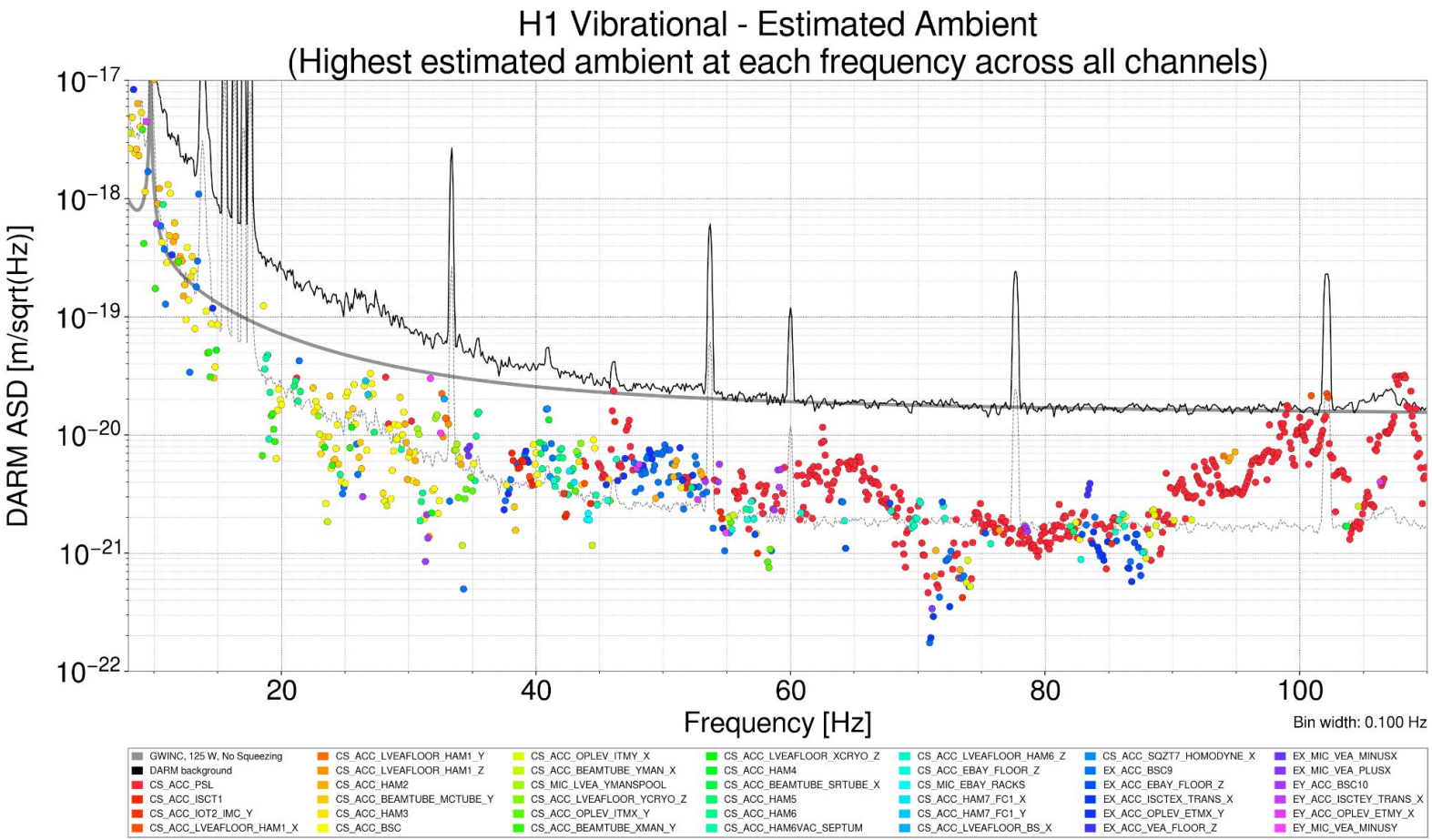

2025

(8 - 110 Hz)

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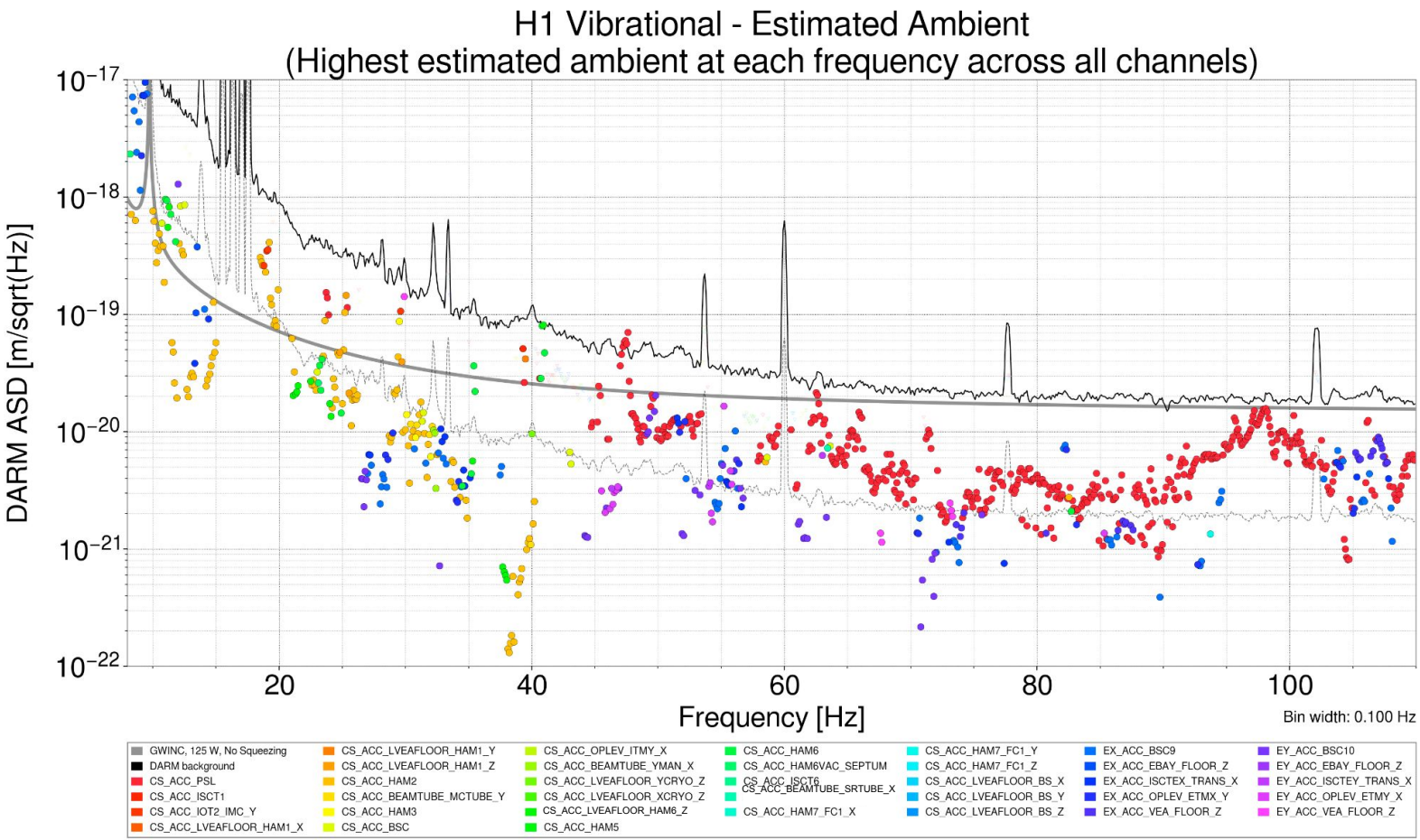

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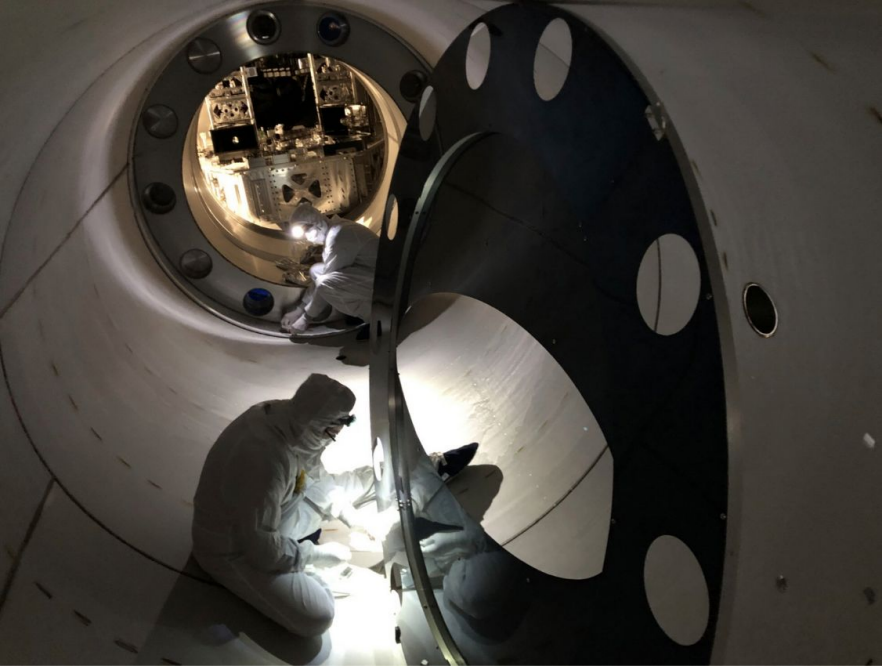


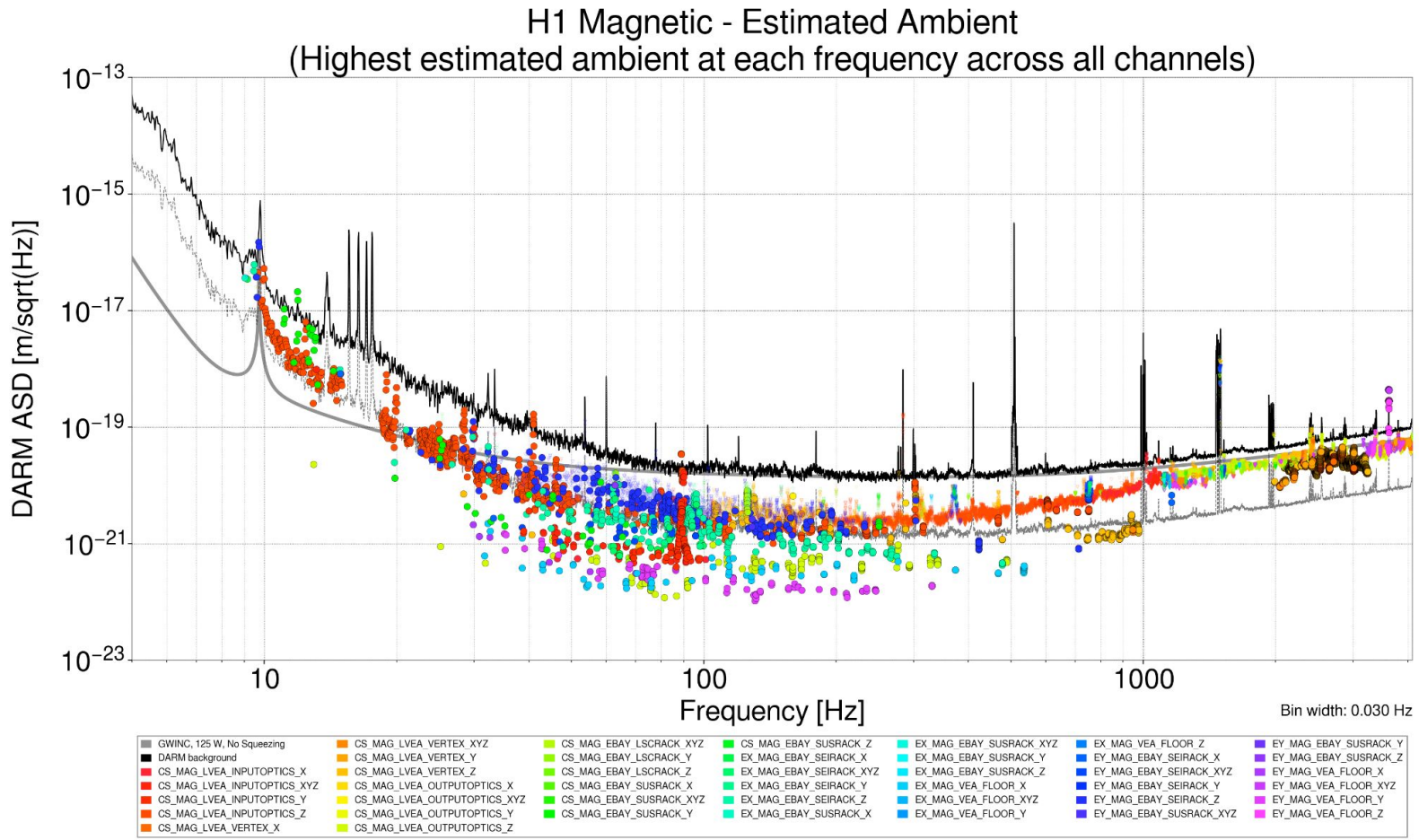
Vibration Summary

- Low frequency coupling improved by damping at EX cryo baffle and CS MC baffle adjustments
- Upper limits improved due to more background sampling
- Jitter looks a little worse but some of it is subtracted out. In IR1 we will have a jitter attenuation cavity.
- Overall as we get more sensitive and mitigate linear noise, we find more nonlinear noise.

Alogs:

76969: EX cryo baffle
75654: MC tube
75637: MC tube

Magnetic Injections



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2023 MAG PEM Injs

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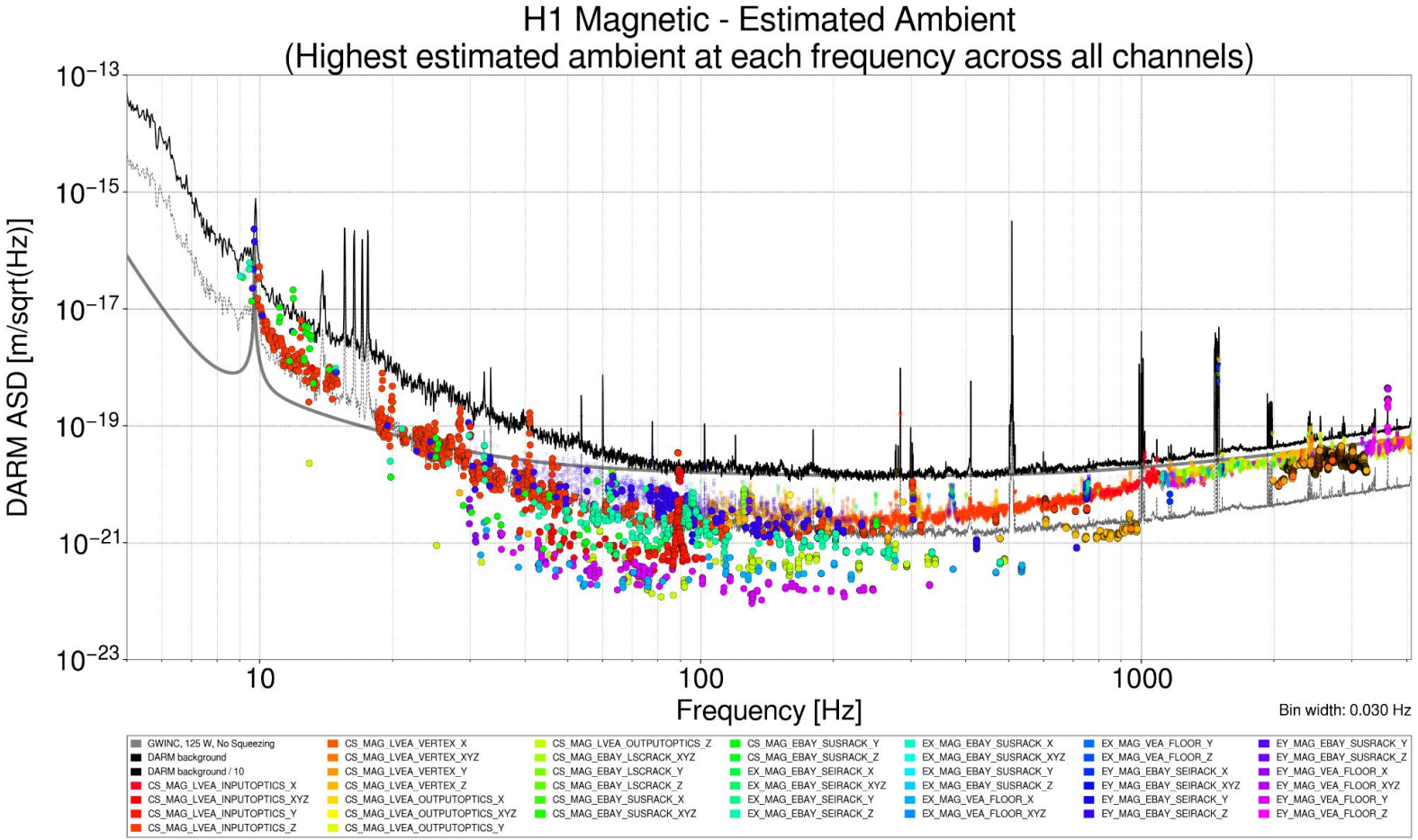

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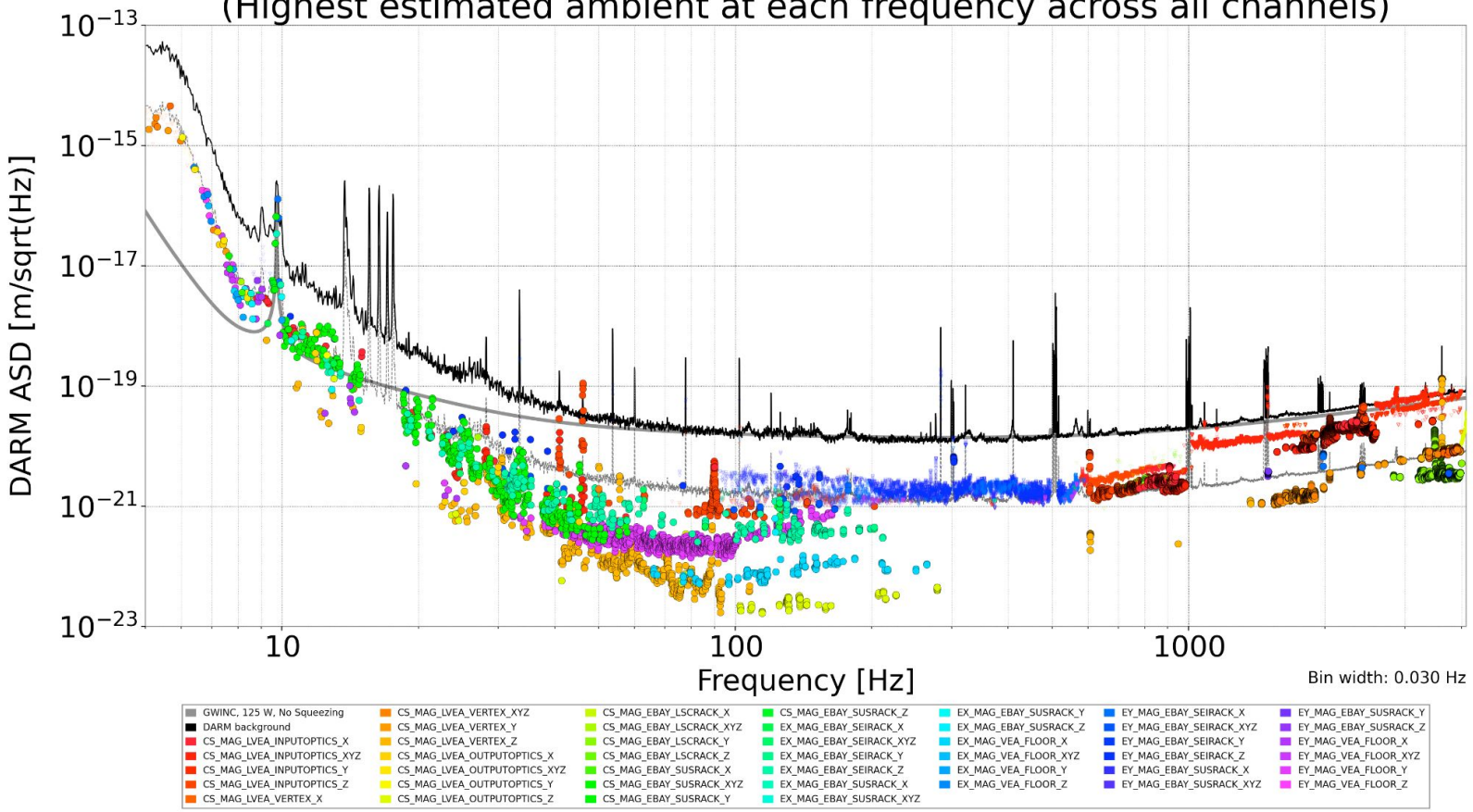

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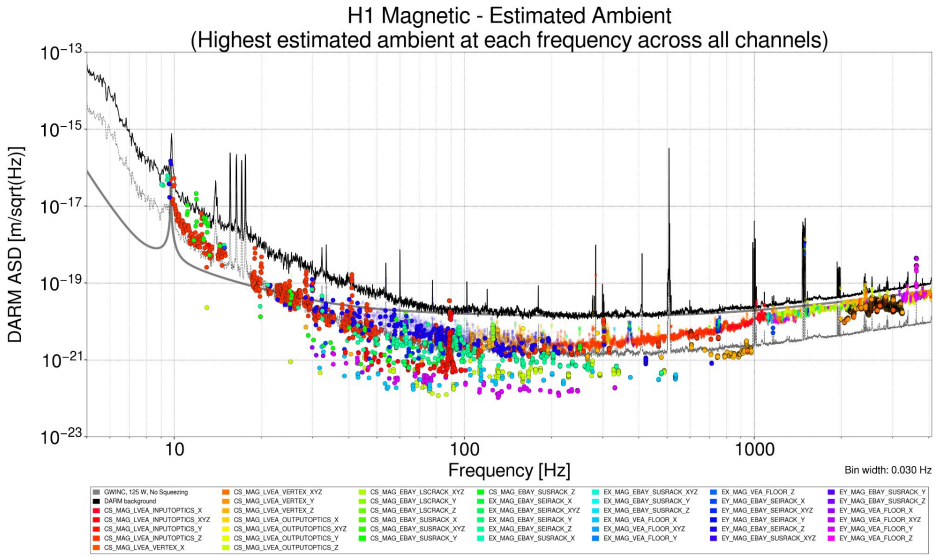

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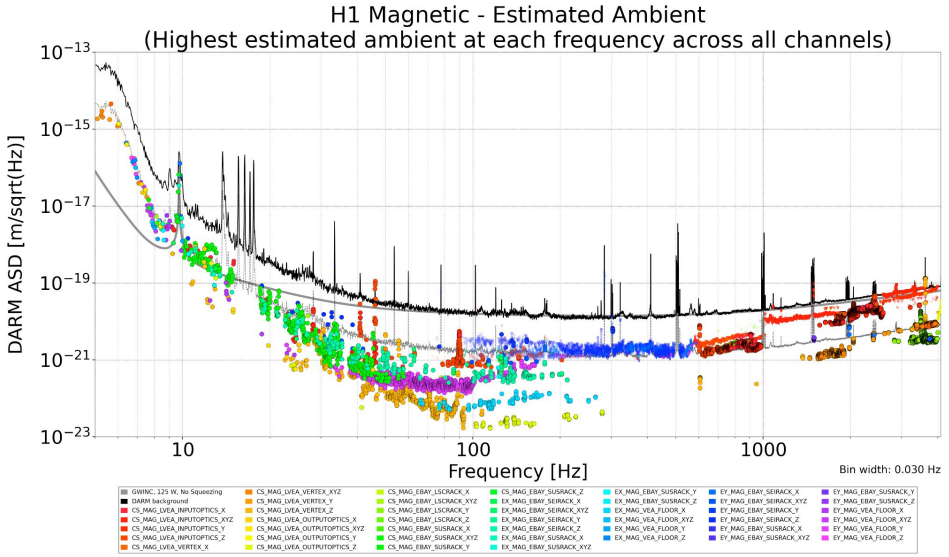

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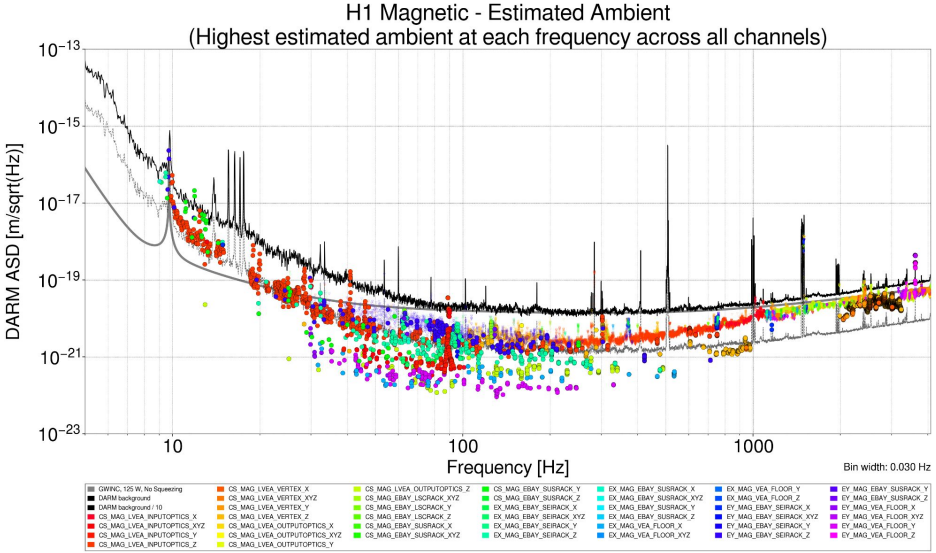

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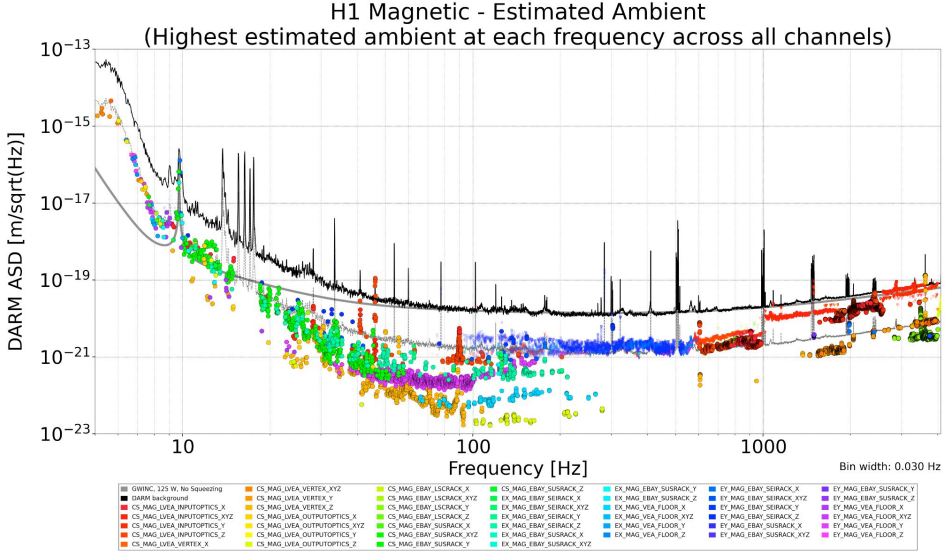

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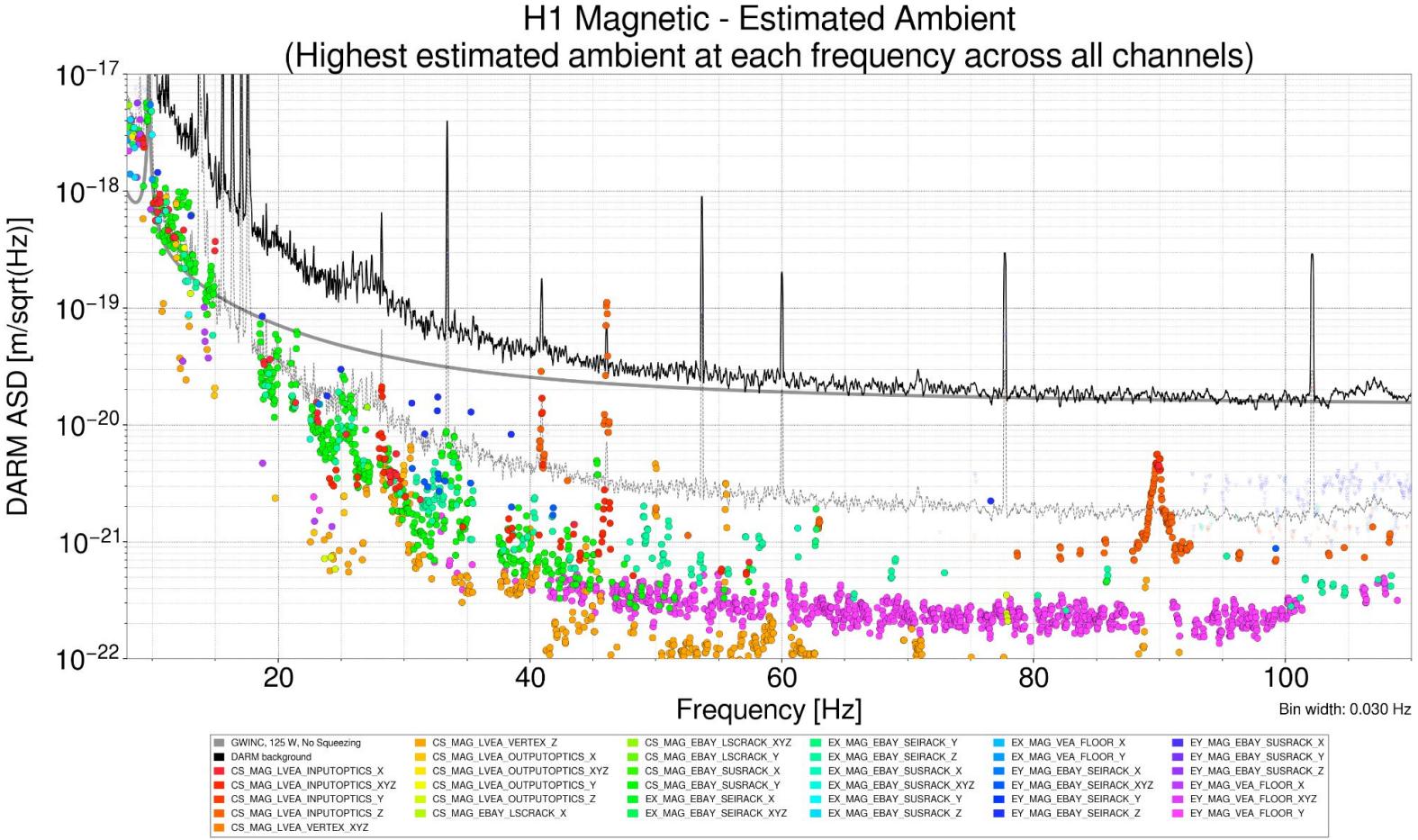

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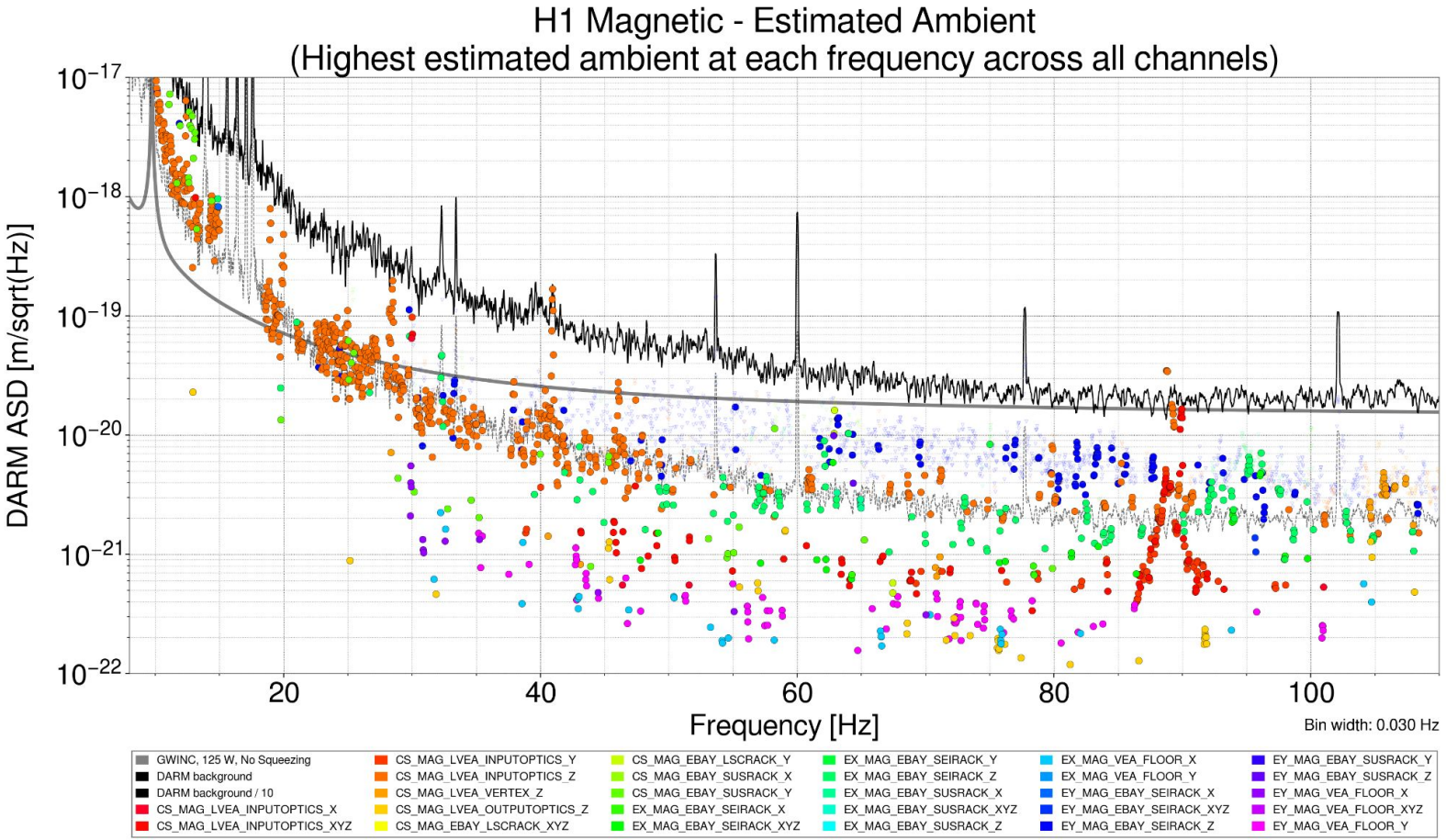

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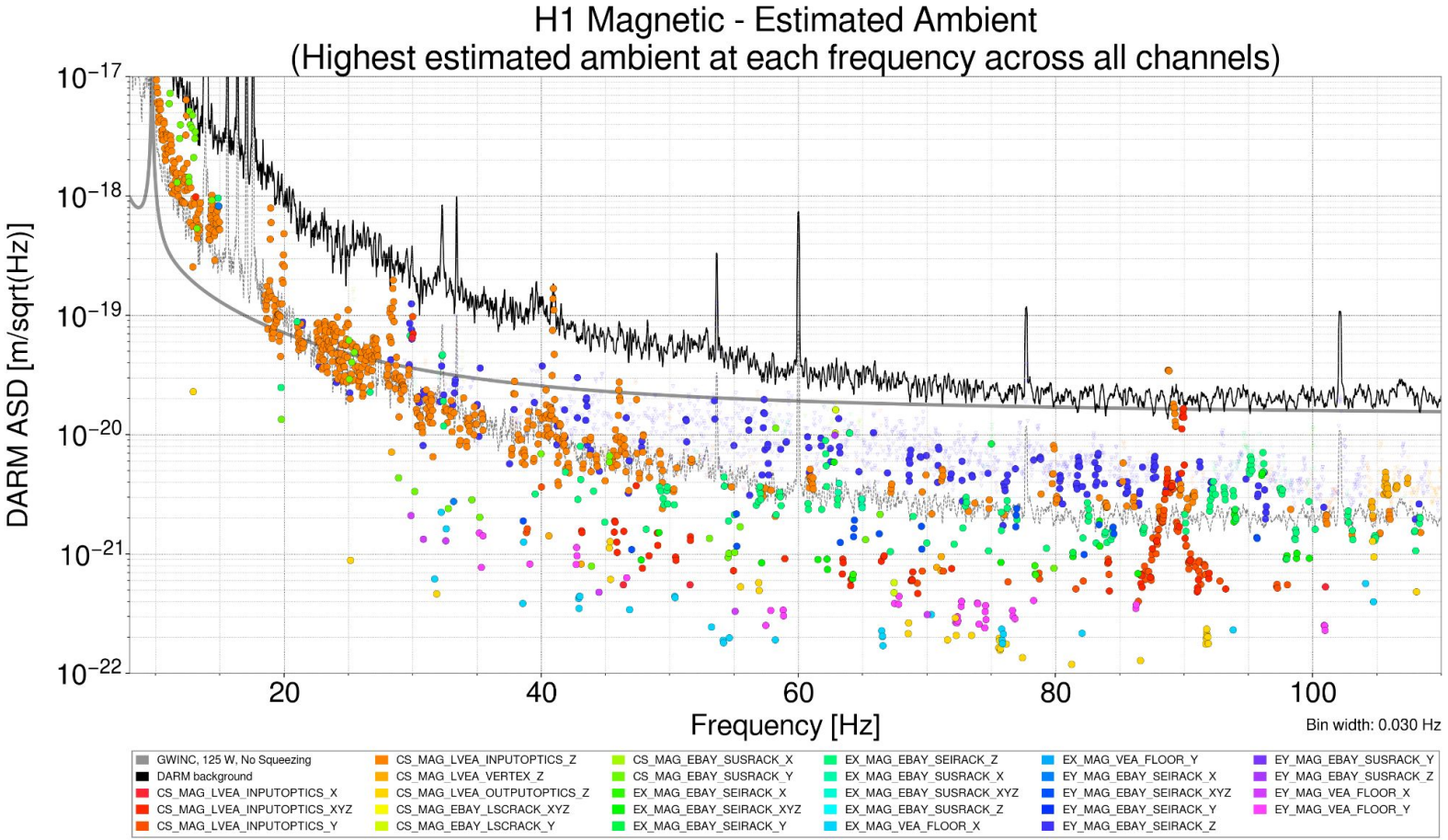

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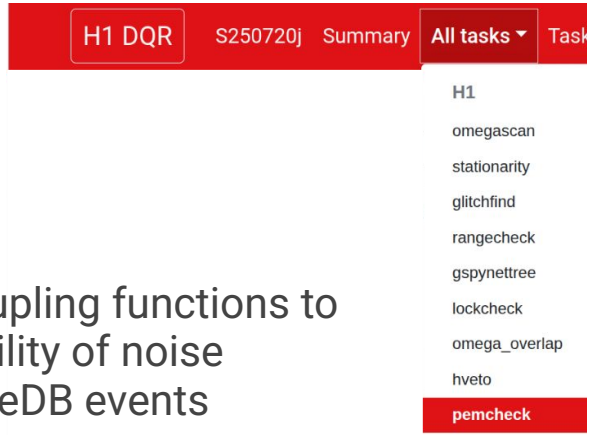
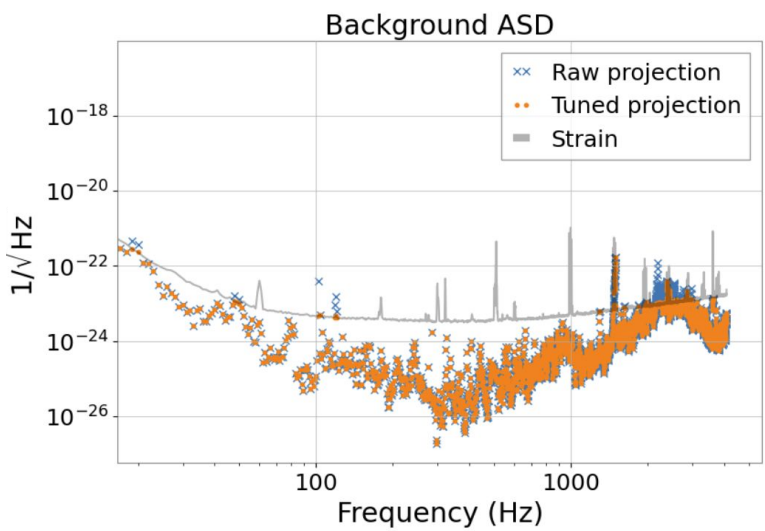
Magnetic Summary

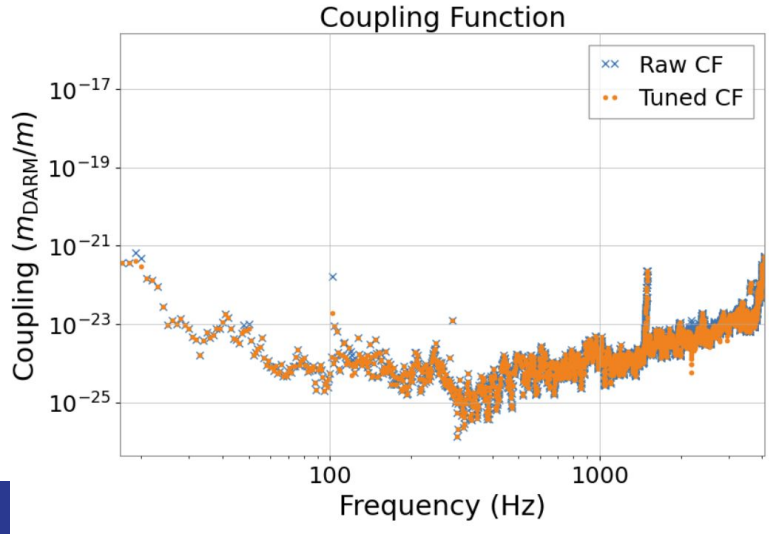
- Testing new automated magnetic injection system
- Injected at more frequency bands
  - broader bands results in more upper limits because the threshold for hitting an upper limit is lower
- Injected closer to saturation to lower the upper limits
- The amount of coupling remains roughly the same
- Future MAG injections: Bring back single line and comb injections to look deeper/beyond upper limits

PEMCheck



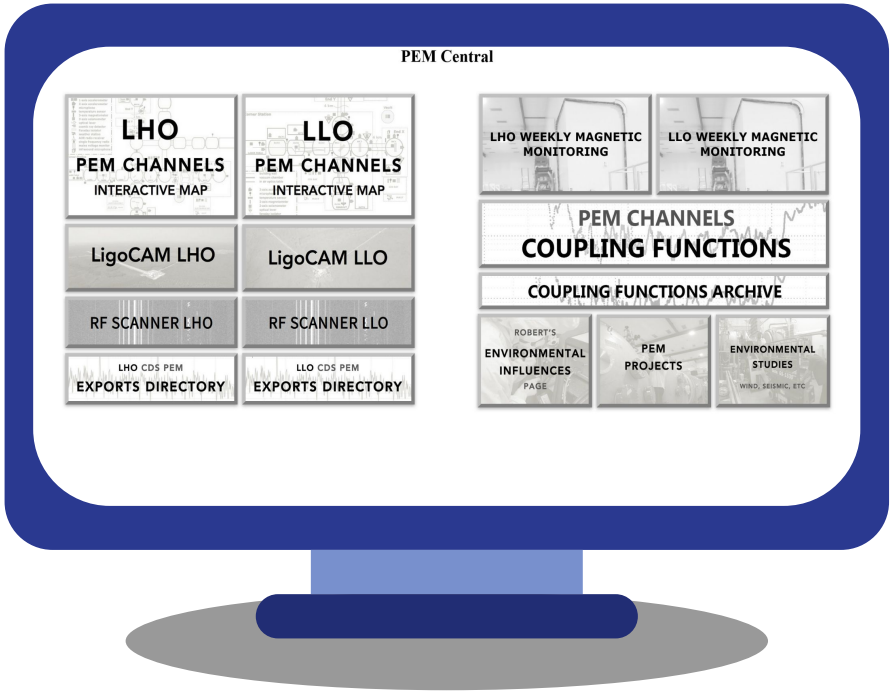
- DQR app
- PEMCheck uses coupling functions to evaluate the probability of noise contributing to GraceDB events
- “Raw” coupling function: what we just talked about
- “Tuned” coupling function: recalculated from sensor and DARM ASDs at the time of the event
- Raw & tuned CFs should be aligned. If not, there may have been noise at the time of the event.



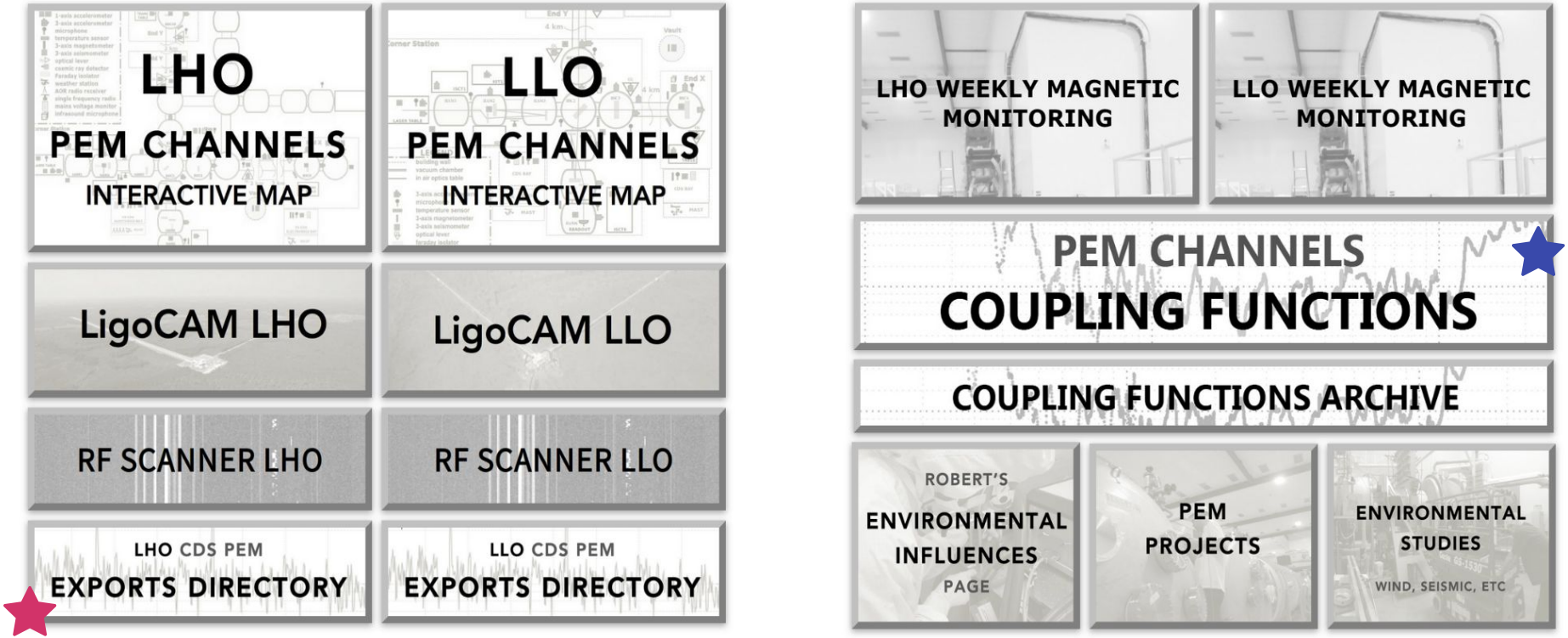


Where can I find the injection data?

The PEM website!
pem.ligo.org



PEM Central



Exports directory → 2025EndofO4PEMinjections

Coupling Functions → Additional resources → O4 git repo

Overall Summary

- Hardware improvements → improvement in coupling (i.e. there is less coupling)
- Upper limits improved by injecting closer to saturation
- Compared to 2023, we have roughly the same amount (magnetic) or less (vibrational) coupling
- Additionally
  - Livingston also did an injection set, analysis ongoing

Questions: scallos@uoregon.edu, gconnoll@uoregon.edu

DCC: https://dcc.ligo.org/LIGO-G2600768