Full Results from HAYSTAC's Phase II Operation with a Squeezed-State Receiver

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on behalf of the HAYSTAC Collaboration

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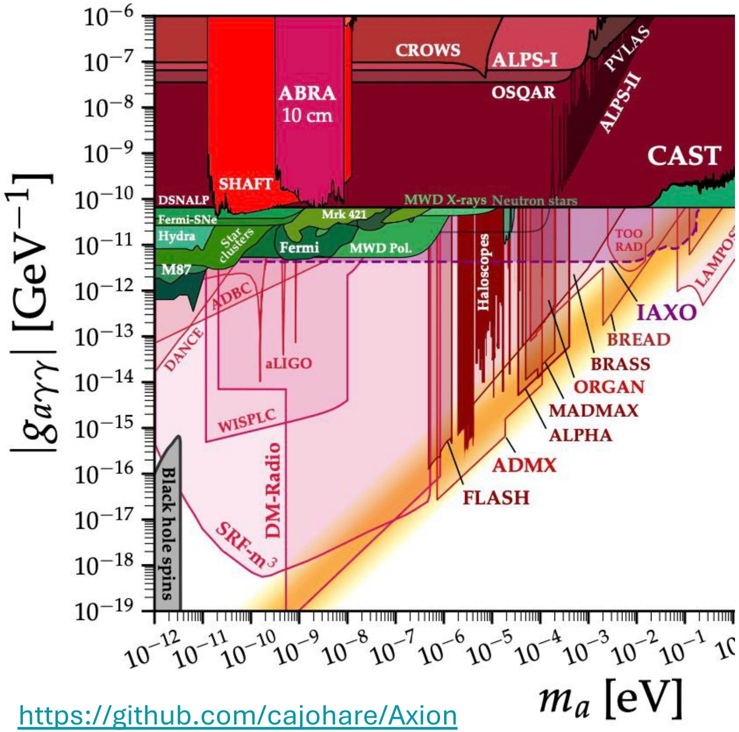
HAYSTAC

Axions as Dark Matter Candidates

- Discovery would solve the strong CP problem + dark matter



https://github.com/cajohare/AxionLimits

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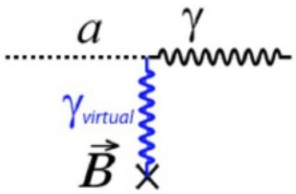
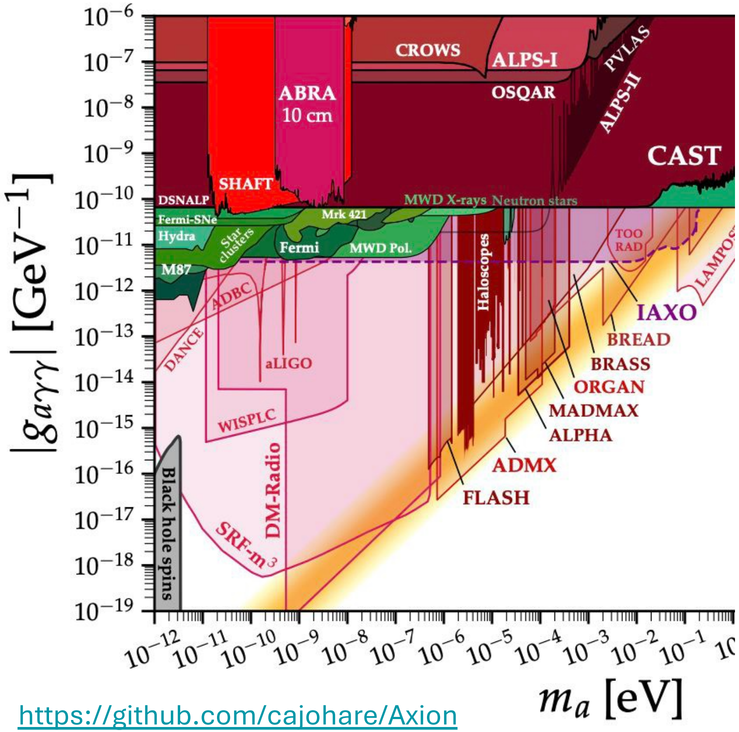
- Primakoff effect:

$$\mathcal{L} \supset g_{a\gamma\gamma} a(\boldsymbol{E} \cdot \boldsymbol{B})$$





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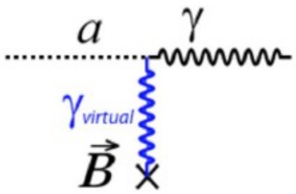
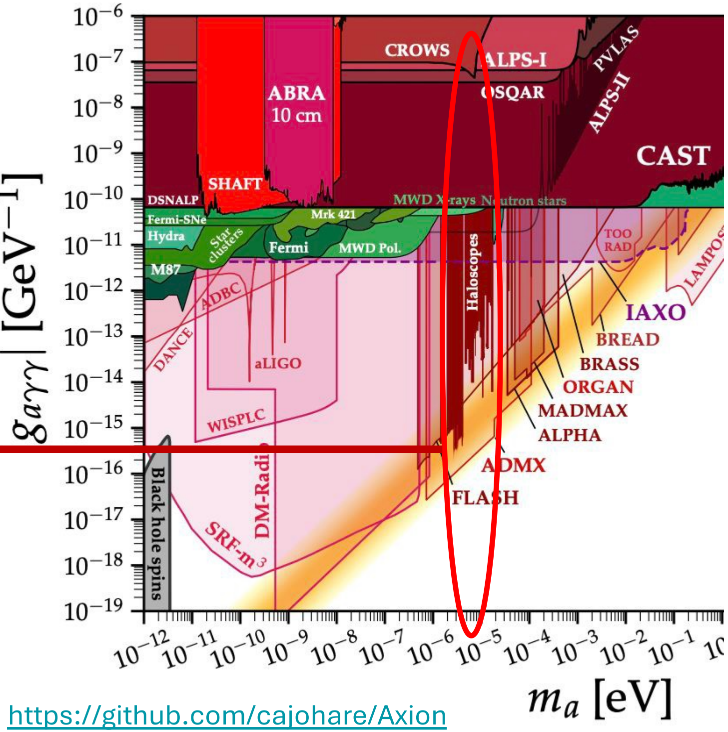
- HAYSTAC target:

  >15 μeV





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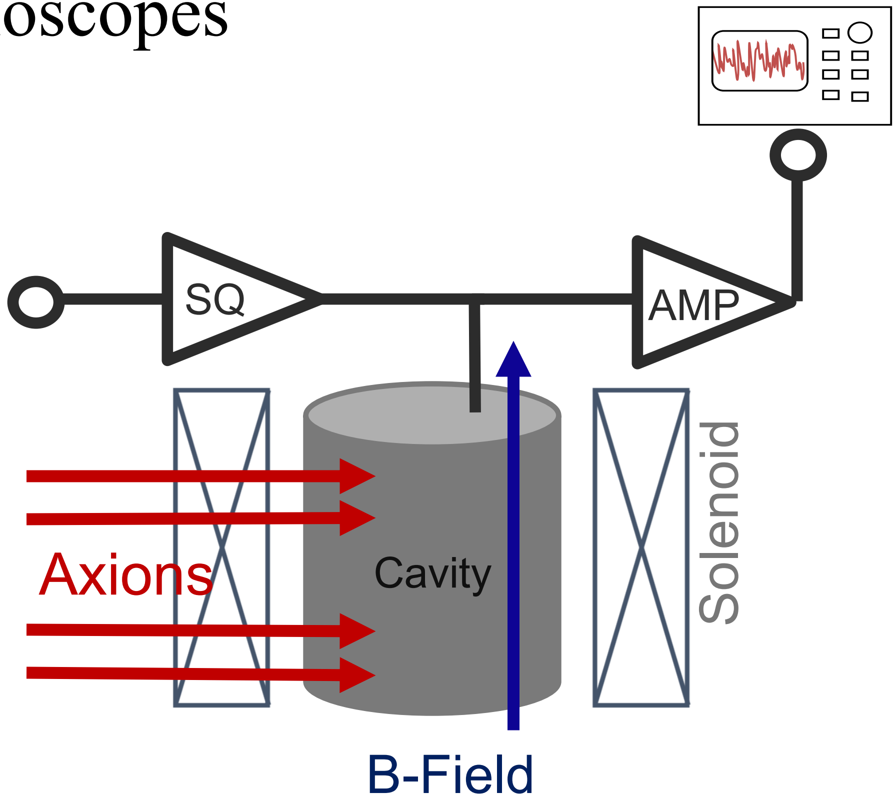
Searching for axions with Haloscopes

- Scan rate is the main FOM:

$$\frac{d\nu}{dt} \propto \frac{\eta Q B^4 V^2 C^2}{N^2}$$



Searching for axions with Haloscopes

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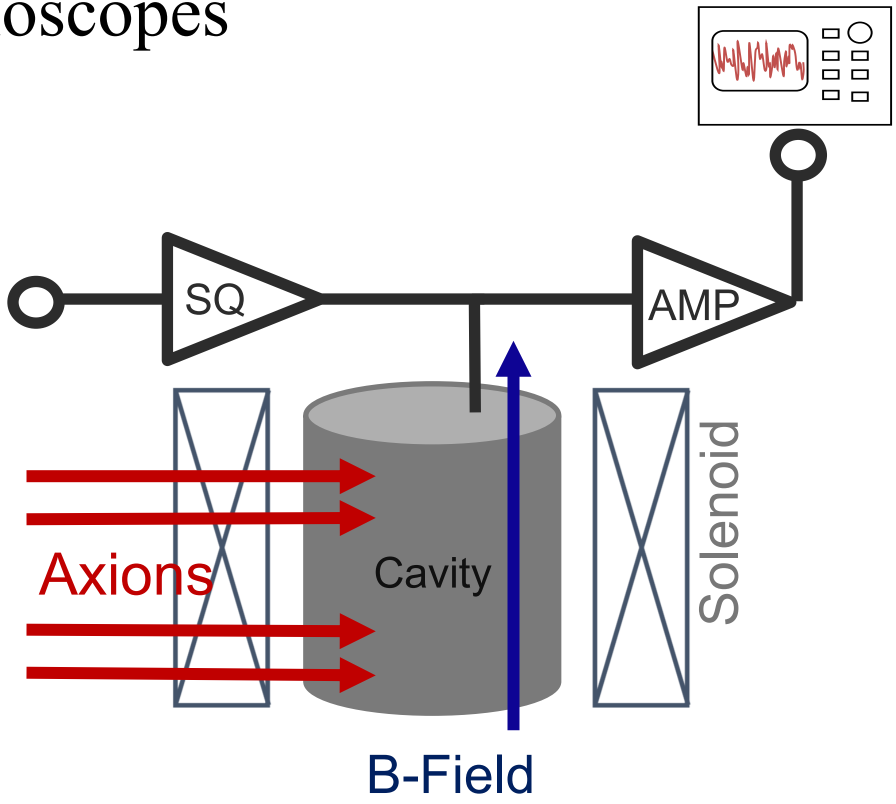
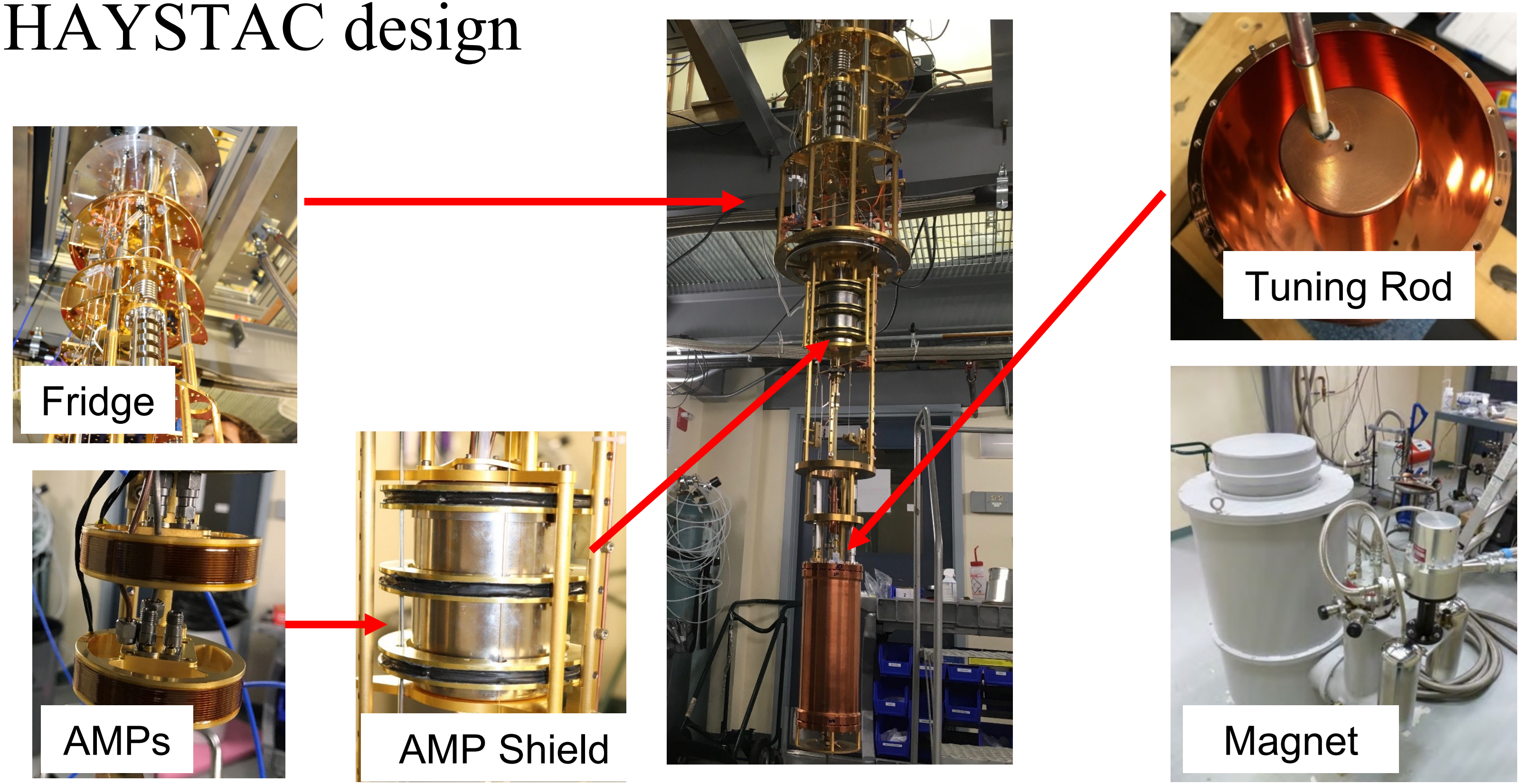
$$\frac{d\nu}{dt} \propto \frac{\eta Q B^4 V^2 C^2}{N^2}$$

- Magnetic Filed (B) ~ 8T
- High Q Cavity ~ 50000
- Volume (V) ~ 1.5L
- Tunable ~ 4-5GHz
- Low Noise Amplifiers (N)
- Cryogenic ~ 60mK



HAYSTAC design



Signal power

- Axion presence is determined by measurements of the cavity field,

$$\hat{H} = \frac{h\nu_c}{2}(\hat{X}^2 + \hat{Y}^2)$$

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- Antenna couples to the cavity to extract power from the field

$$P_{ax} = \left(\frac{g_\gamma^2 \alpha^2}{\pi^2 f_a^2} \frac{\rho_a}{m_a}\right) B_0^2 V C Q_L \frac{\beta}{1+\beta} \frac{1}{1 + (2\delta_\nu / \Delta\nu_c)^2}$$

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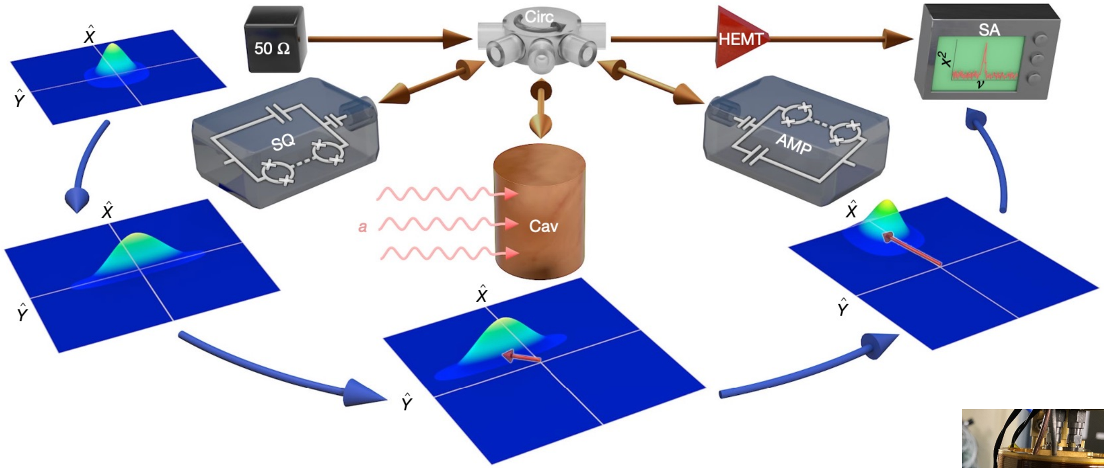
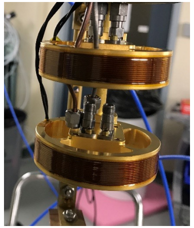
$$\sim 10^{-24}\ \mathrm{W}$$

- Extremely small signal!
  - Quantum noise becomes important

Quantum Enhancement: what makes HAYSTAC unique

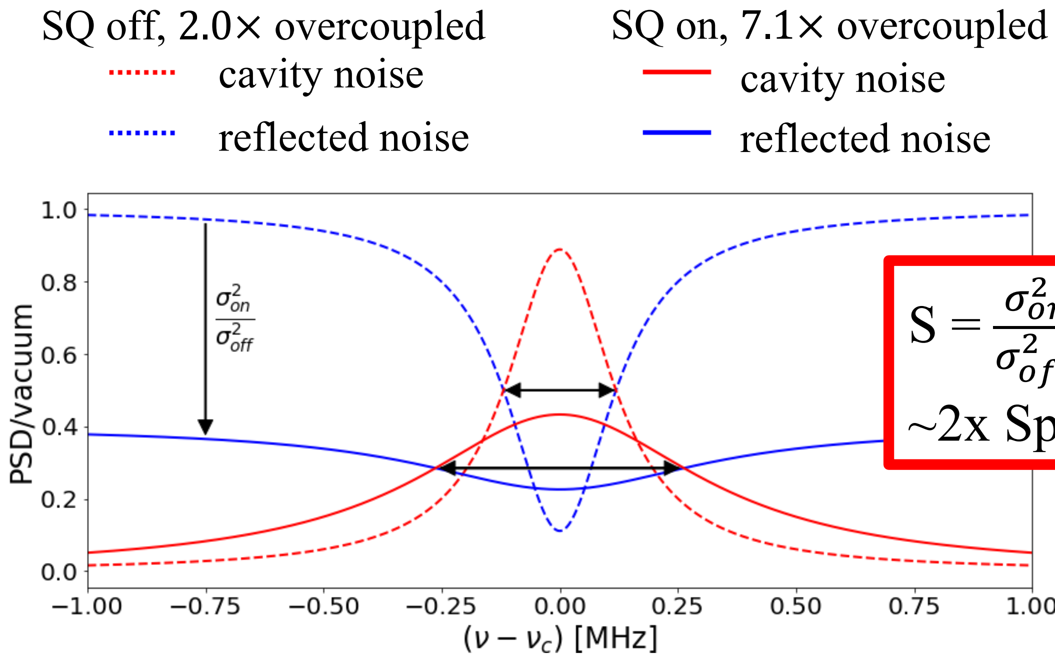
- Phase Insensitive Amps
  - Quantum Limited Noise
- Squeezed State Receiver
- Overcoupled Antenna
  - Larger Sensitive Bandwidth





Nature 590, 238 (2021)

Quantum Enhancement



$$S = \frac{\sigma^2_{on}}{\sigma^2_{off}} = 4.0dB$$

~2x Speed

Phase I
Single JPA in Phase-Insensitive Mode

Phase II
Squeezed State Receiver

2012-2014
Initial
Design/Construction

2014-2016
Initial
Commissioning

Aug 2016-May 2017
Upgrades
(Tuning + Thermal)

2017-2019
Rebuild/Upgrade
(SSR)

April 2020-July 2021
Upgrades
(JPAs + DAQ)

2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

Data Runs

Jan-Aug 2016
Phase I, Run 1

May 2017-July 2017
Phase I, Run 2

Sep 2019-April 2020
Phase IIa

July 2021–Nov 2021
Phase IIb

Sept 2022- Mar 2023
Phase IIc

Sept 2023-May 2024
Phase IId

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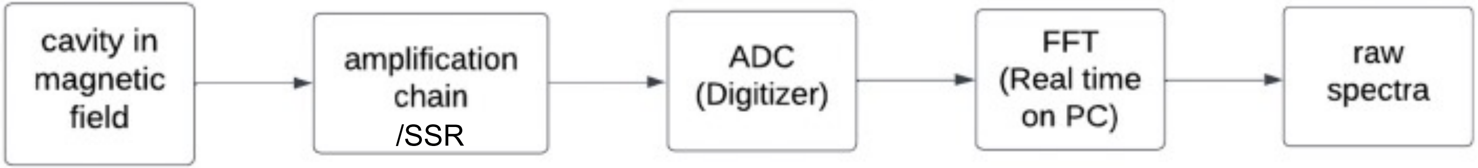
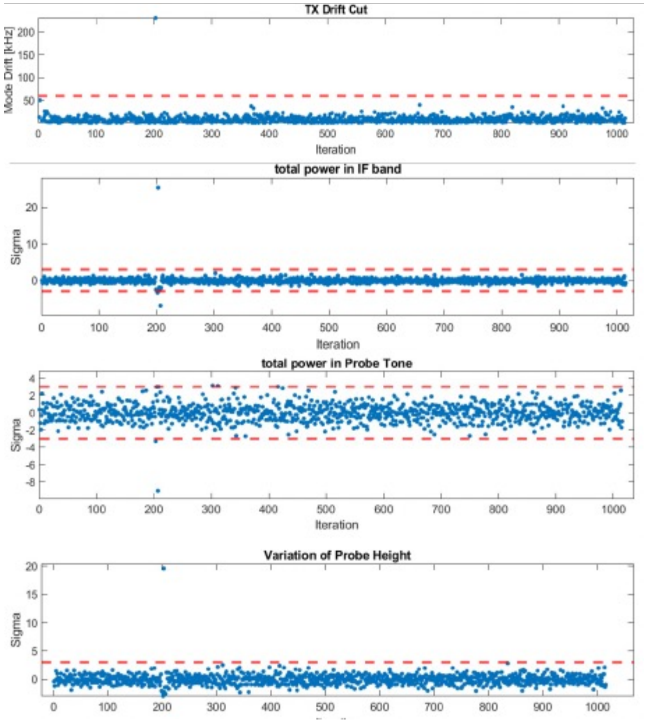
Analysis Overview: data acquisition



$$\Delta\nu_b = 1/10\text{ms} = 100\text{Hz}$$

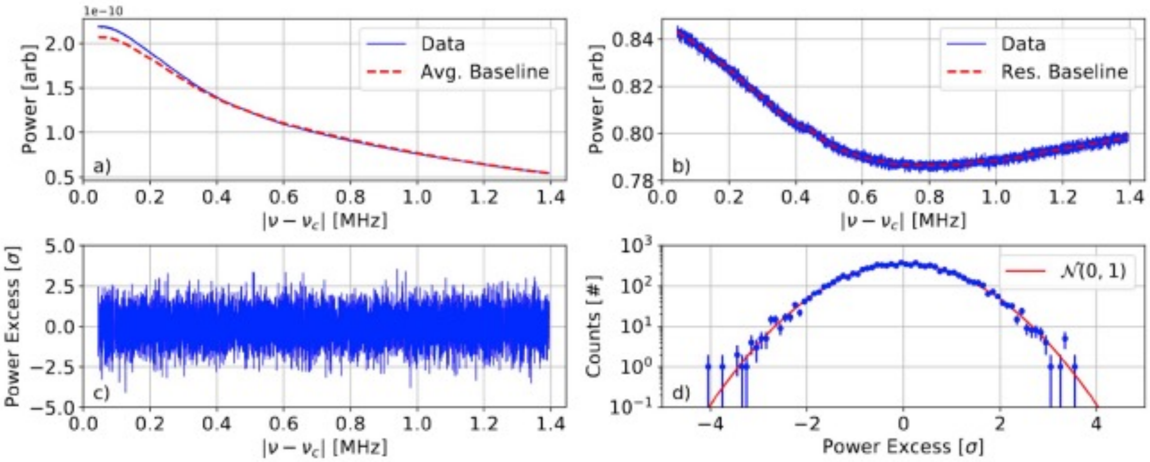
Analysis Overview: process individual spectra (1)

- Data quality cuts: remove compromised spectra
    - Total spectrum power
    - Probe tone height
    - Probe tone power
    - Cavity drift
    - Others
- About 1% of the data is cut



Analysis Overview: baseline removal (2)

- Shape of the raw spectra:
  - Cavity (Lorentzian) + amplifiers + bandpass filters
- Remove the spectrum baseline (SG filter), so only the fluctuations (noise + signal) remains



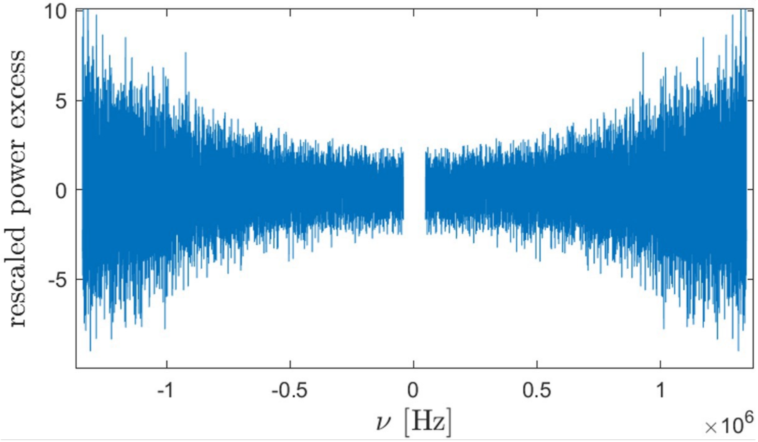
M. Jewell, et al. doi:10.1103/PhysRevD.107.072007

Analysis Overview: rescale spectra (3)

- Scale all spectra before combining
  - axion would yield same mean power excess in any bin (1 in the presence of a single KSVZ axion, 0 otherwise)
- Scaling factor is the inverse SNR:

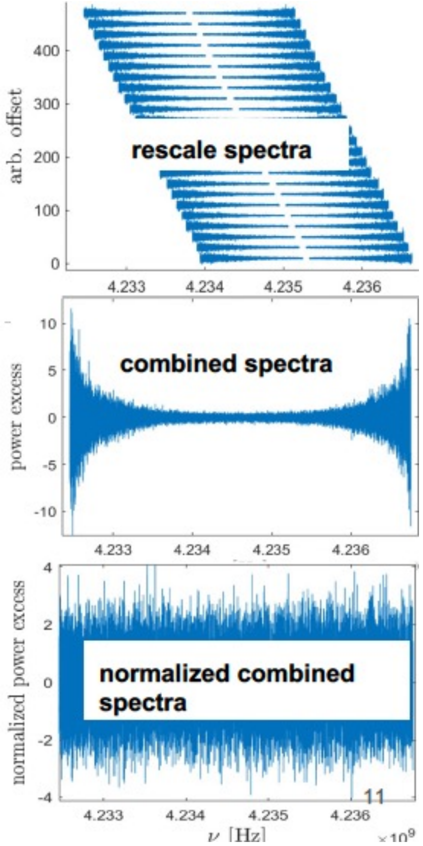
$$f = \frac{h\nu N_{\mathrm{sys}} \Delta\nu_b}{P_{\mathrm{ksvz}}}$$

- Takes into account:
  - cavity detuning
  - system noise differences



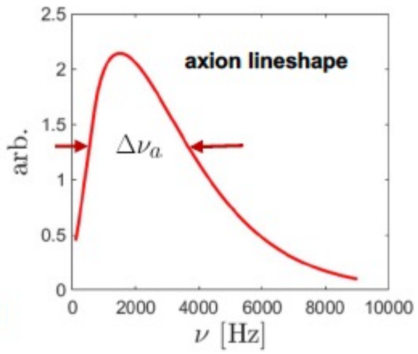
Analysis Overview: combine spectra (4)

- Add contribution of each spectrum to the power at each frequency
- Combine spectra **vertically** through **maximum likelihood (ML) weighting**
  - Maximizes the SNR
- Output: combined spectra
  - Gaussian distributed with mean = 1 in presence of an axion, and 0 in its absence
  - Normalize so that std = 1



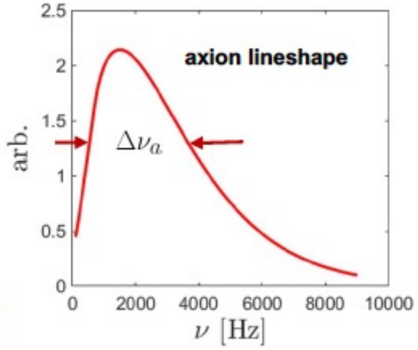
Analysis Overview: combine spectra (5)

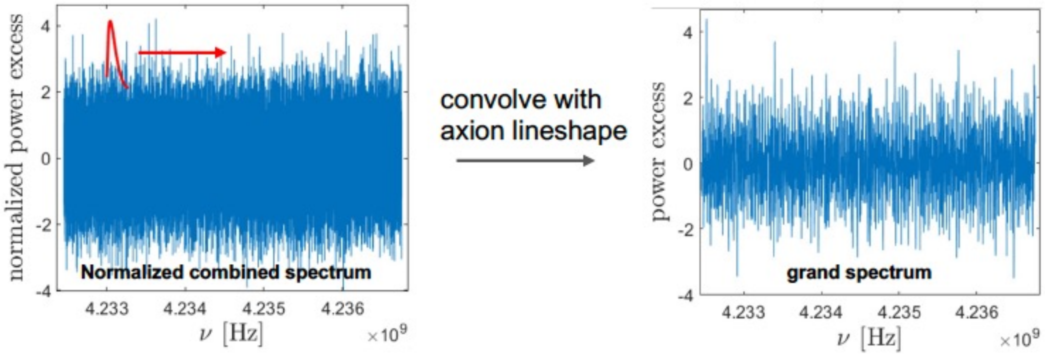
- Axion linewidth > frequency resolution
  - Axion signal would be divided across multiple bins
  - Expect **correlation** among the bins
  - Correlation encoded in **axion lineshape (AL)**



Analysis Overview: combine spectra (5)

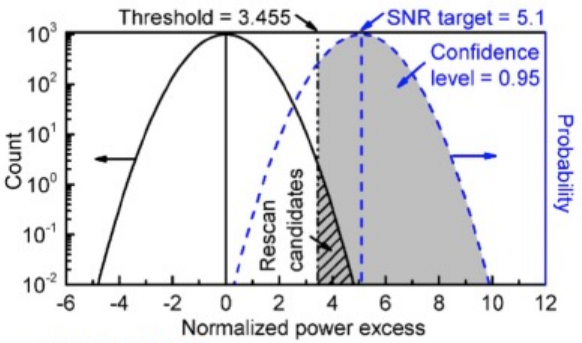
- Axion linewidth > frequency resolution
  - Axion signal would be divided across multiple bins
  - Expect **correlation** among the bins
  - Correlation encoded in **axion lineshape (AL)**
- Summed horizontally taking into account Maxwellian AL
  - Output is the grand spectrum

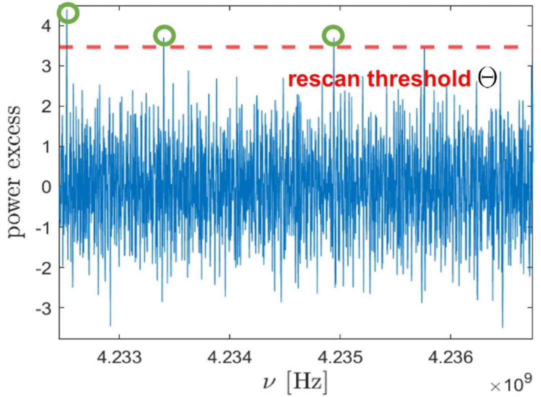




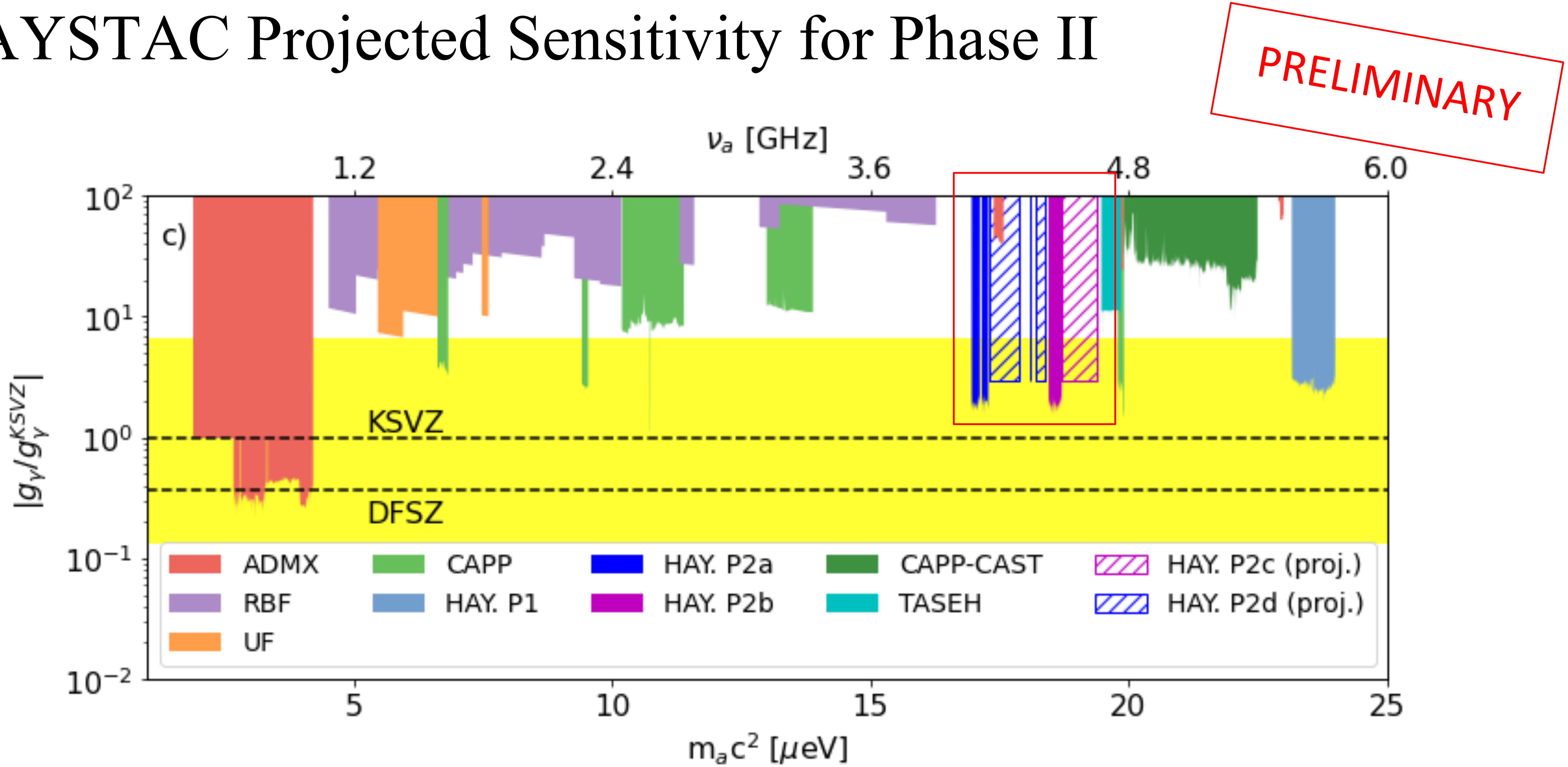
Get Rescans and Axion Exclusion

- Axion candidates are identified by setting a threshold of 3.468 σ
  - 95% confidence level for a single scan in Frequentist framework
- Perform rescan on these candidates
- 60 axion candidates for Phase IIc and 96 for IId





HAYSTAC Projected Sensitivity for Phase II

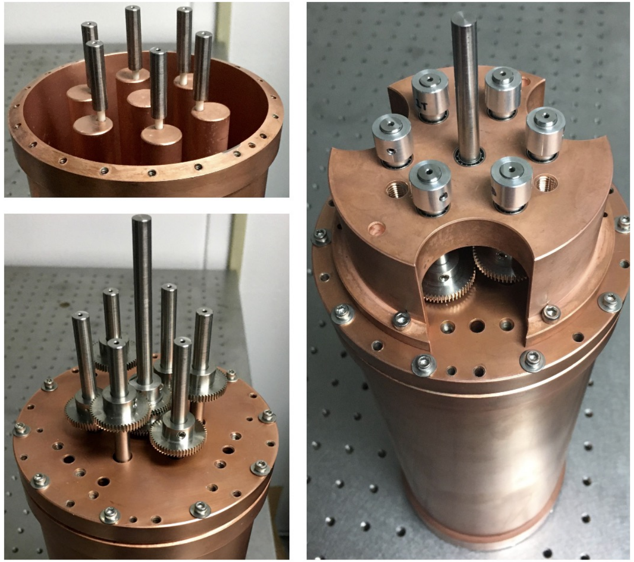


Phase II summary

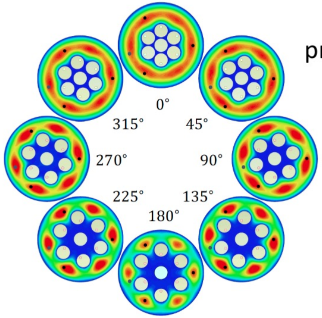
- 551 MHz covered
- 414 MHz of previously unexplored space:
  - 18.685-19.467 μeV in Phase IIc
  - 17.279-18.453 μeV in Phase IId (excluding mode crossings at 17.899-18.081 and 18.135-18.176 μeV)
  - g_γ^{KSVZ} exclusion in progress
- Noise below quantum limit with SSR with robust operation over a wide range

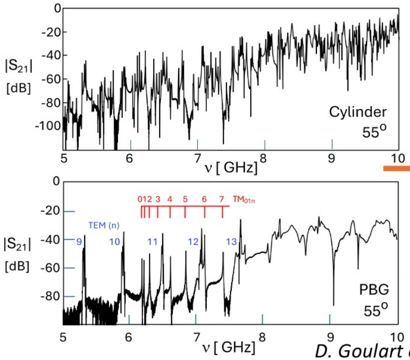
Future work: 7-rod cavity

Symmetric lattice cavity for 6-10 GHz range, tuned by changing the lattice constant; symmetry maximizes Figure-of-Merit

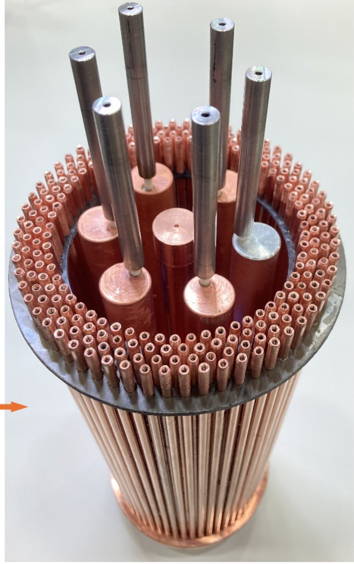


M. Simanovskaia et al., Rev. Sci. Instr. 92, 033305 (2021)





Tunable symmetric lattice resonator with PBG for TE mode suppression; proof of concept for ALPHA 10-20 GHz resonator



D. Goulart et al., paper in preparation (2024)

Huge thanks to our collaborators!

Wright Laboratory

JILA
CU Boulder and NIST

LUX ET VERITAS

JOHNS HOPKINS
UNIVERSITY

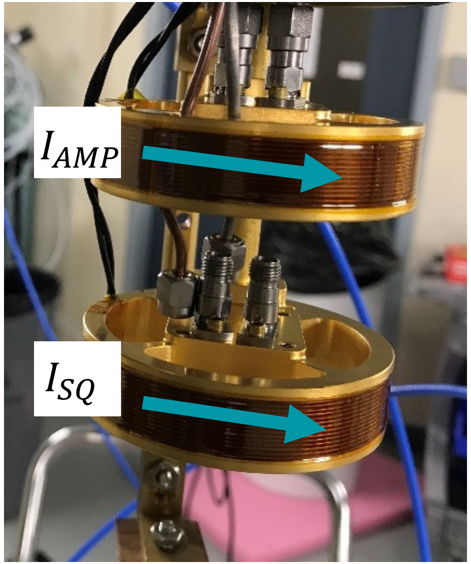
HEISING-SIMONS
FOUNDATION

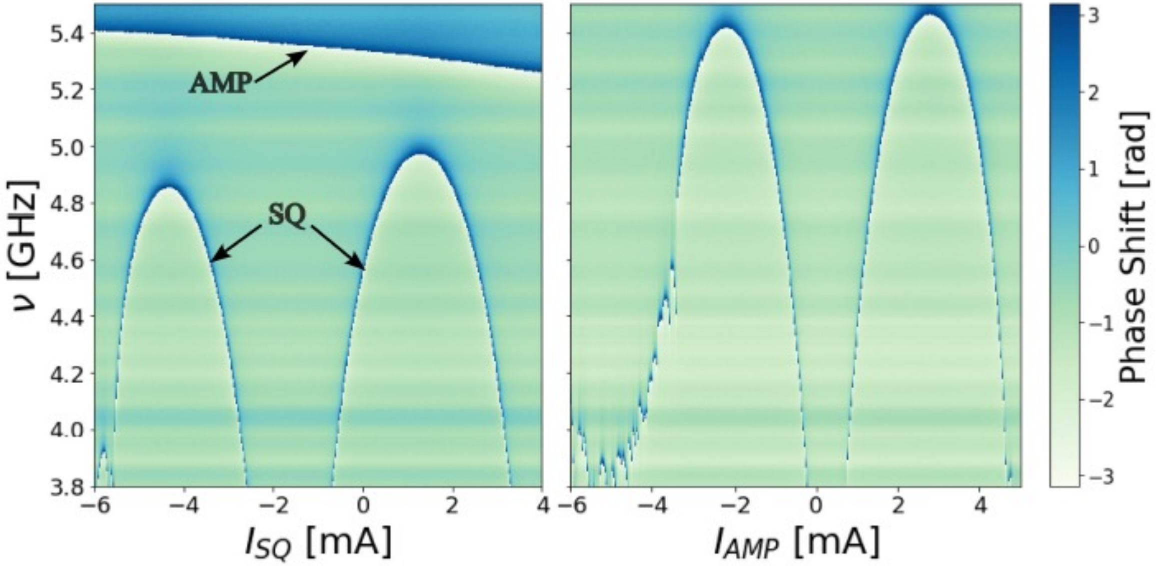
NSF

Extra slides

Quantum enhancement: Squeezed State Receiver

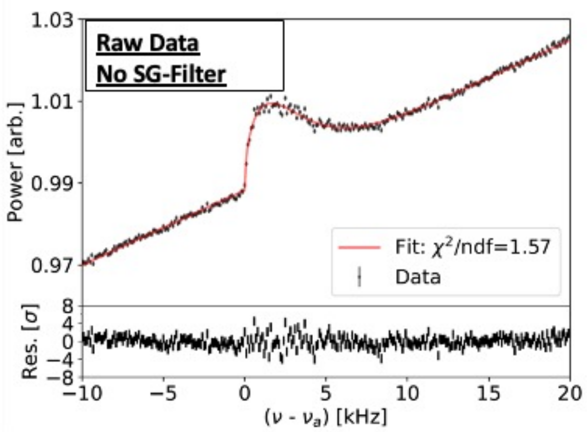
- 2 JPAs in tandem can beat the quantum limit

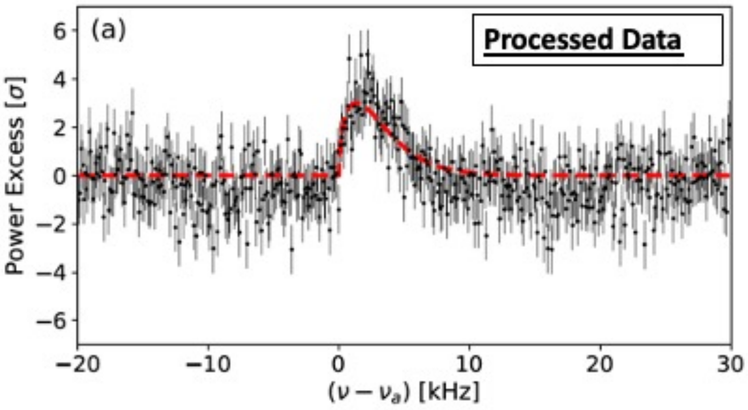




Realistic Signal Injection

- Started "salting" our data using a mode-hopping technique (*Rev.Sci.Instrum.* 94 (2023) 5, 054712)
- Injected 6 total signals between PIIc/PIId
  - Not truly "blind" but used to confirm things are working





Get Rescans and Axion Exclusion

Frequentist

If rescan did not persist, we can publish exclusion.

The exclusion is encoded in the SNR.

$$P_{\mathrm{ax}} \propto g_\gamma^2 \longrightarrow G \sim \sqrt{\frac{P_{\mathrm{ax}}}{P_{\mathrm{ksvz}}}} \sim \sqrt{\frac{\mathrm{SNR}_t}{\mathrm{SNR}_{\mathrm{ksvz}}}}$$

$$g_\gamma = G g_\gamma^{\mathrm{ksvz}}$$

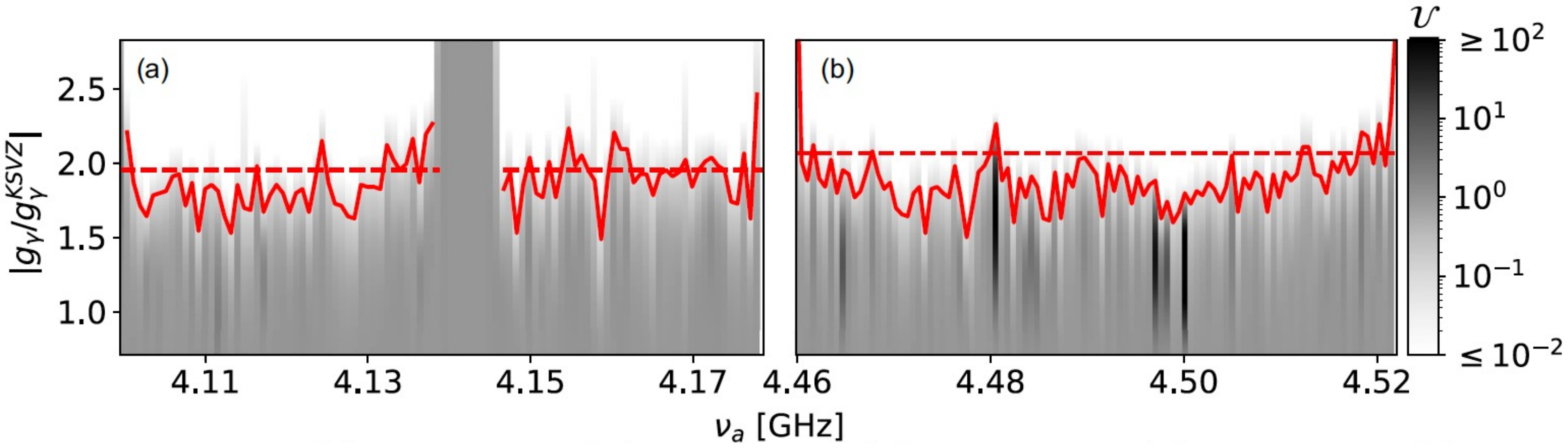
Bayesian

Gives a probability interpretation of the scans, taking into account how big the power excess is.

Answers the question given the power excess, what is the likelihood that an axion has been measured at this frequency?

$$P(\mathcal{A}_i|\delta_i) = \frac{P(\delta_i|\mathcal{A}_i)P(\mathcal{A}_i)}{P(\delta_i)}$$

Phase IIa and IIb Results



Axion exclusions showing the two-dimensional prior update U in grayscale for (a) Phase IIa and (b) Phase IIb. This includes the 10% prior update contour (solid red) as well as the 90% aggregate exclusion (dashed red)

HAYSTAC Results

- So far we have **4 major Result papers**
    - Phase I, Run 1: First Axion search with Quantum limited Noise
      Phys. Rev. Lett. 118, 061302 (2017)
    - Phase I, Run 1+2: Improved Search
      Phys. Rev. D 97, 092001 (2018)
    - Phase IIa: First Search Below the SQL
      Nature 590, 238 (2021)
    - Phase IIa+b: Detailed overview of SSR Search
      Phys. Rev. D 107, 072007 (2023)