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

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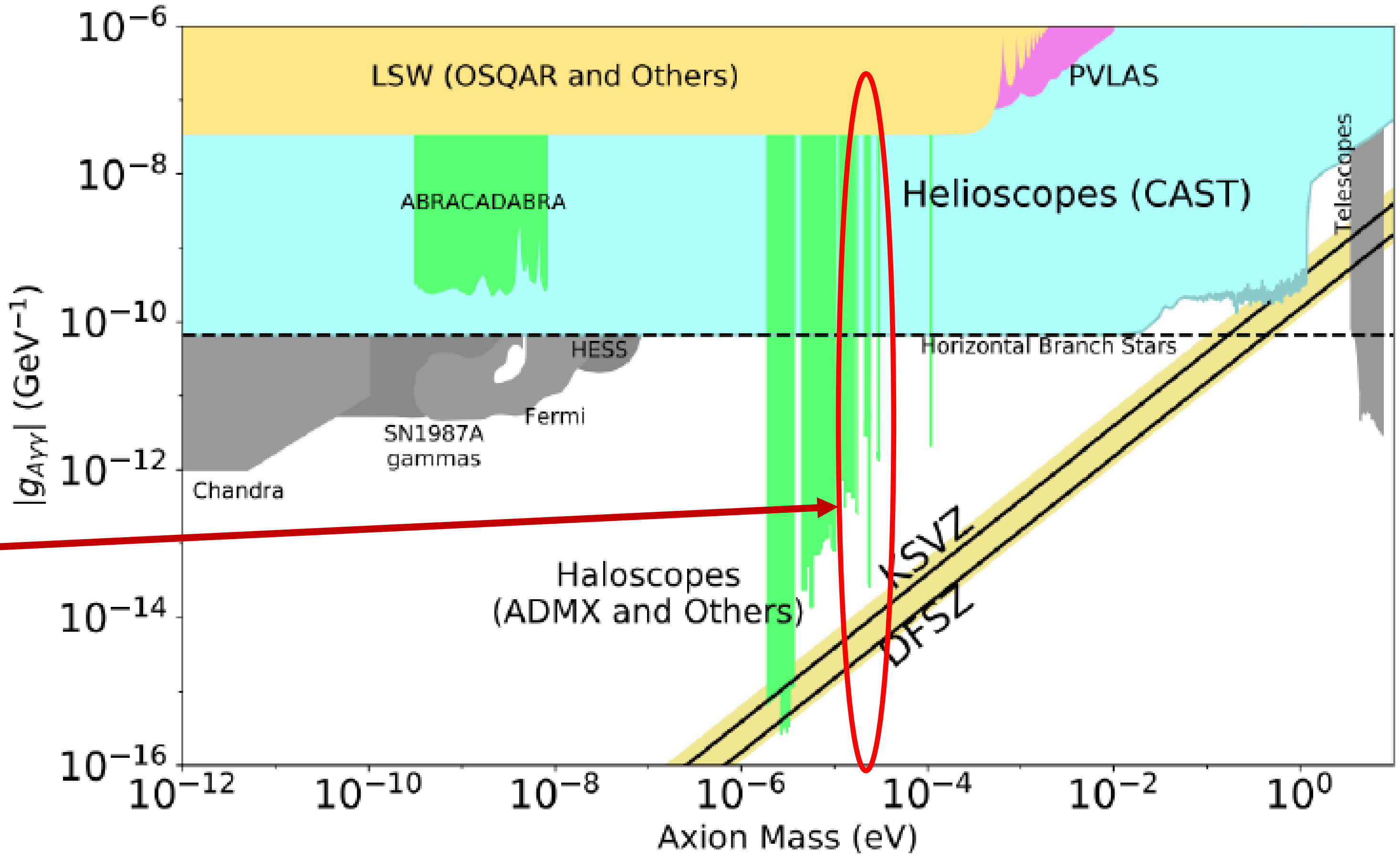
Yale University

UCLA Dark Matter, April 2023

Axions as Dark Matter

- Solve CP Problem + Dark Matter
  - Axion mass/coupling is unknown
- Post inflation models
  - $m_a > 10$ μeV [1,2]
- HAYSTAC target
  - ~20 μeV



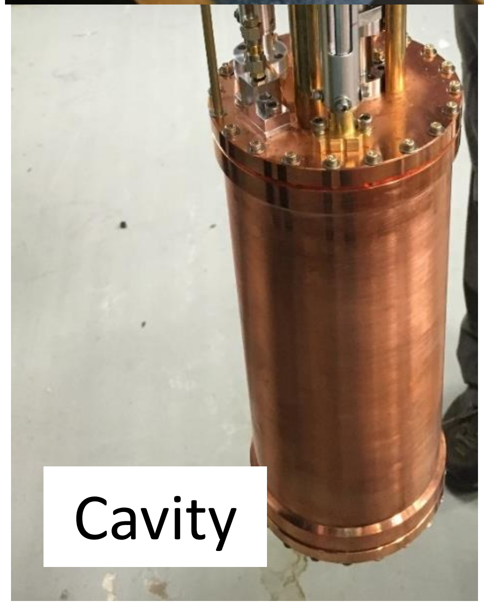
Review of Particle Physics 2020, A. Ringwald, L.J. Rosenberg and G. Rybka

[1] E. Berkowitz, M. I. Bucho, and E. Rinaldi. Phys. Rev. D, 92 034507, 2015
[2] S. Borsanyi, Z. Fodor, J. Guenther, et al. Nature, 539 69, 2016

HAloscope at Yale Sensitive To Axion CDM

- Located at Yale's Wright Lab
- Copper Microwave Cavity
  - V: 1.5L
  - ν_c: 3.6-5.8GHz
  - Q: ~45k
- 8T Superconducting Solenoid
- Dilution Fridge ~60mK
- Josephson Parametric Amplifier (JPA)

$$\frac{d\nu}{dt} \propto \frac{\eta Q B^4 V^2 C^2}{N^2} \longrightarrow \frac{d\nu}{dt} \propto \nu^{-\frac{14}{3}}$$

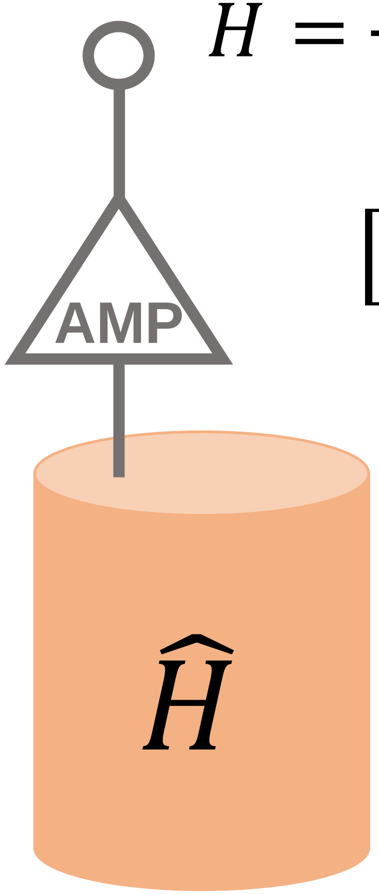


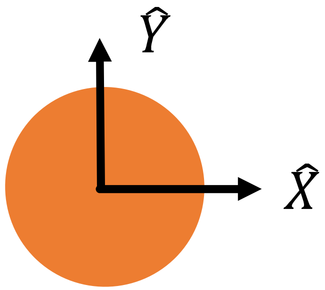
Josephson Parametric Amplifier (JPA)

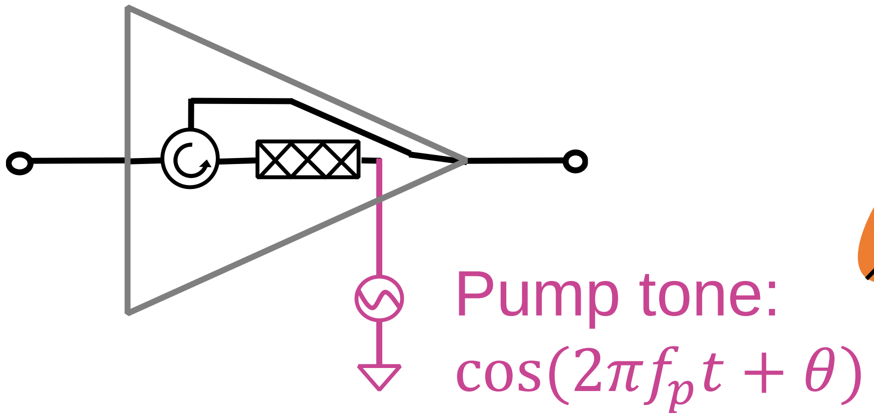
- Phase Sensitive Amplifier
- Can operate in Phase Insensitive Mode
  - Near Quantum limited amplifiers
- Phase sensitive mode can produce “Squeezed” States

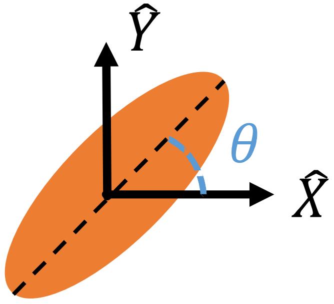
$$\hat{H} = \frac{h\nu_c}{2}(\hat{X}^2 + \hat{Y}^2)$$

$$[\hat{X}, \hat{Y}] = \frac{i}{2}$$

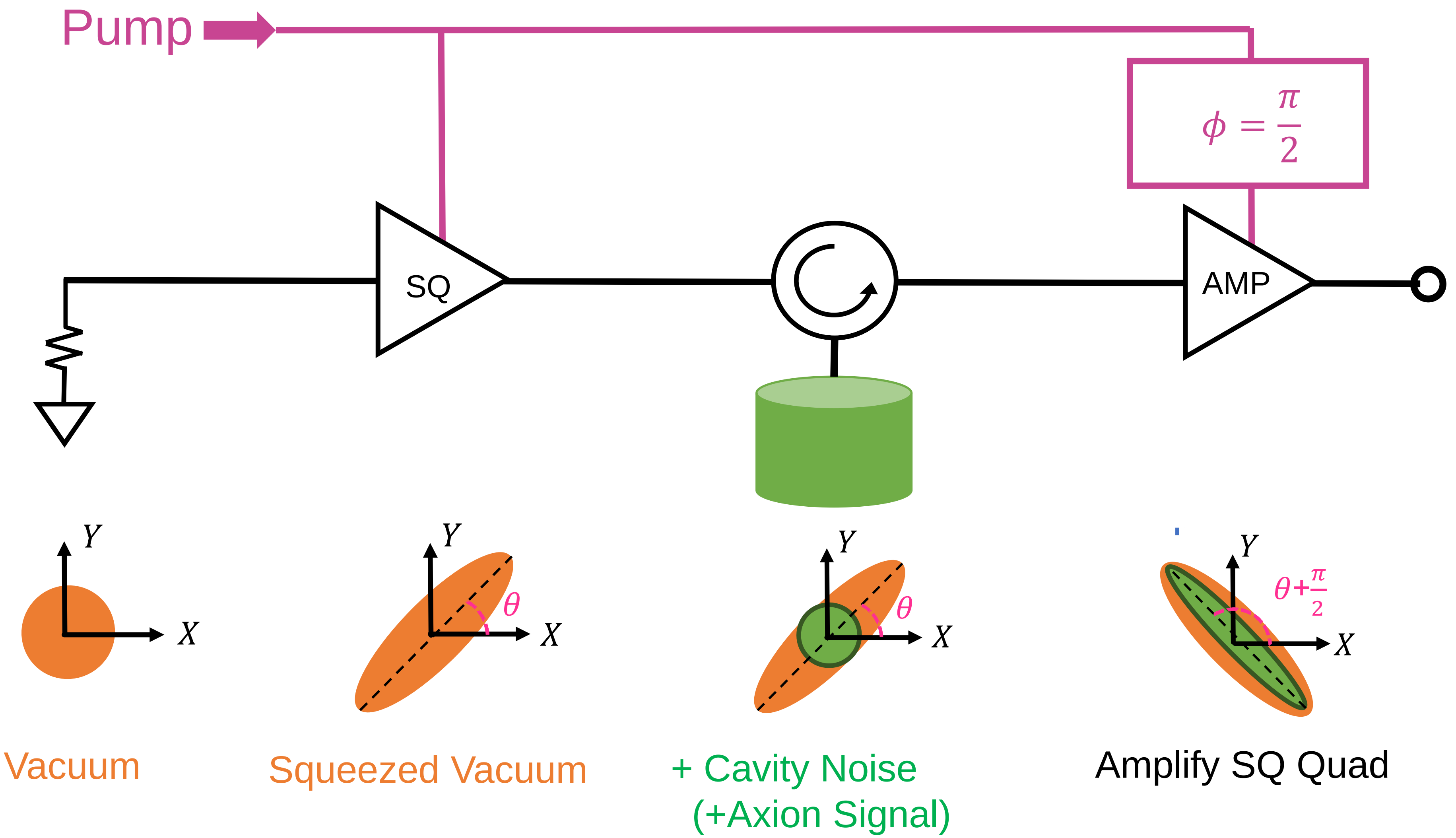




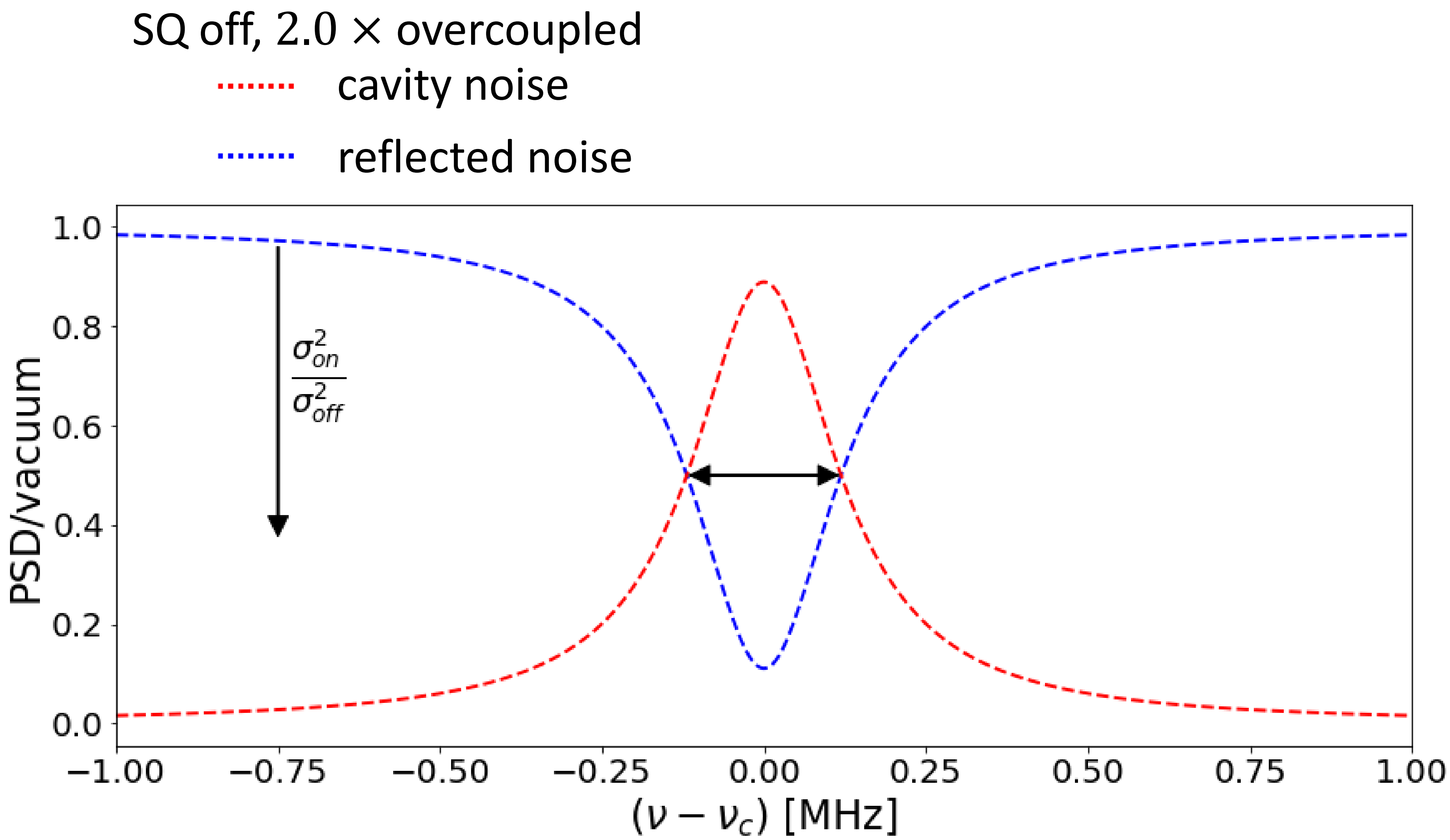




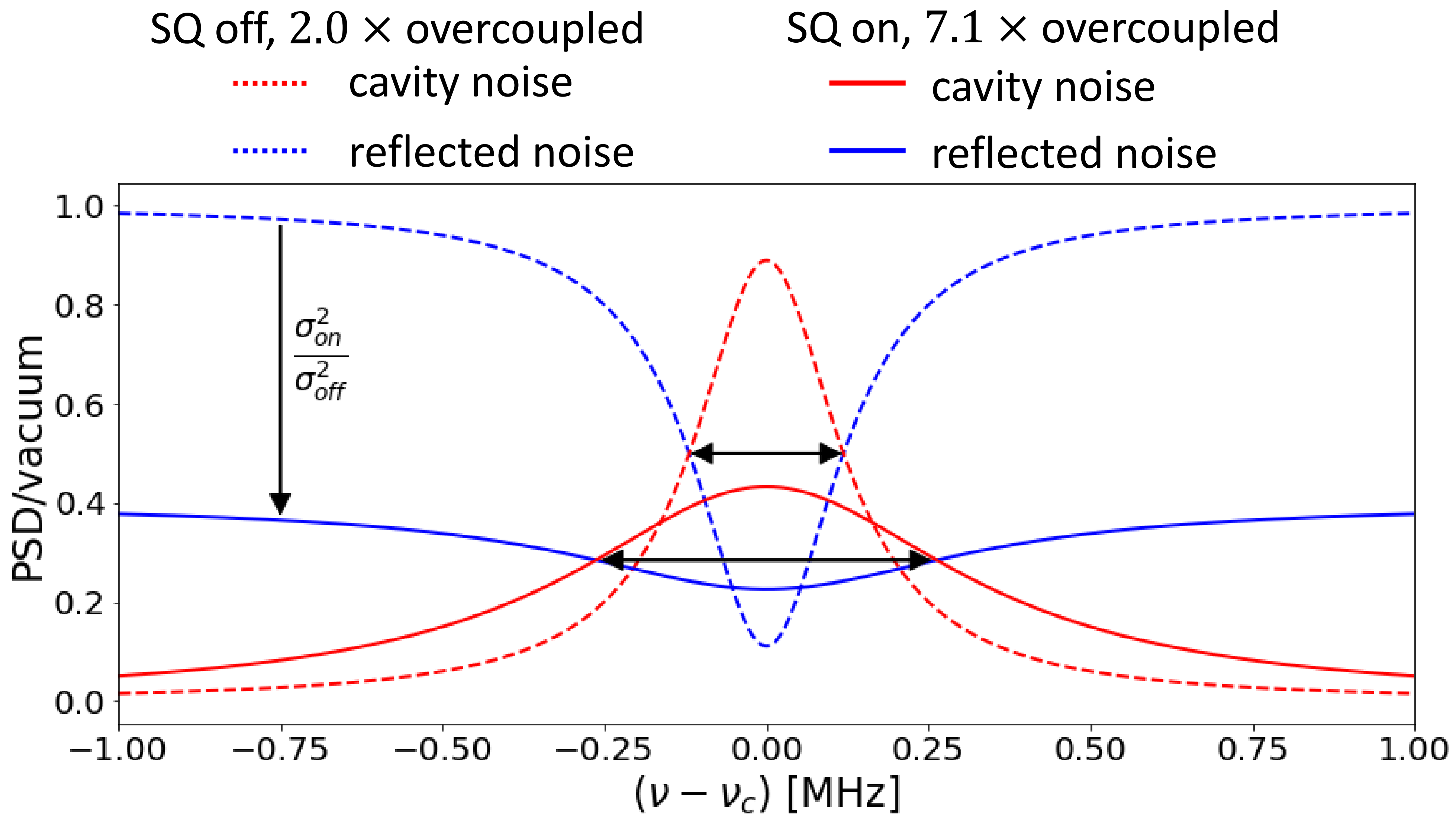
Squeezed State Receiver (SSR)



Bandwidth Enhancement



Bandwidth Enhancement

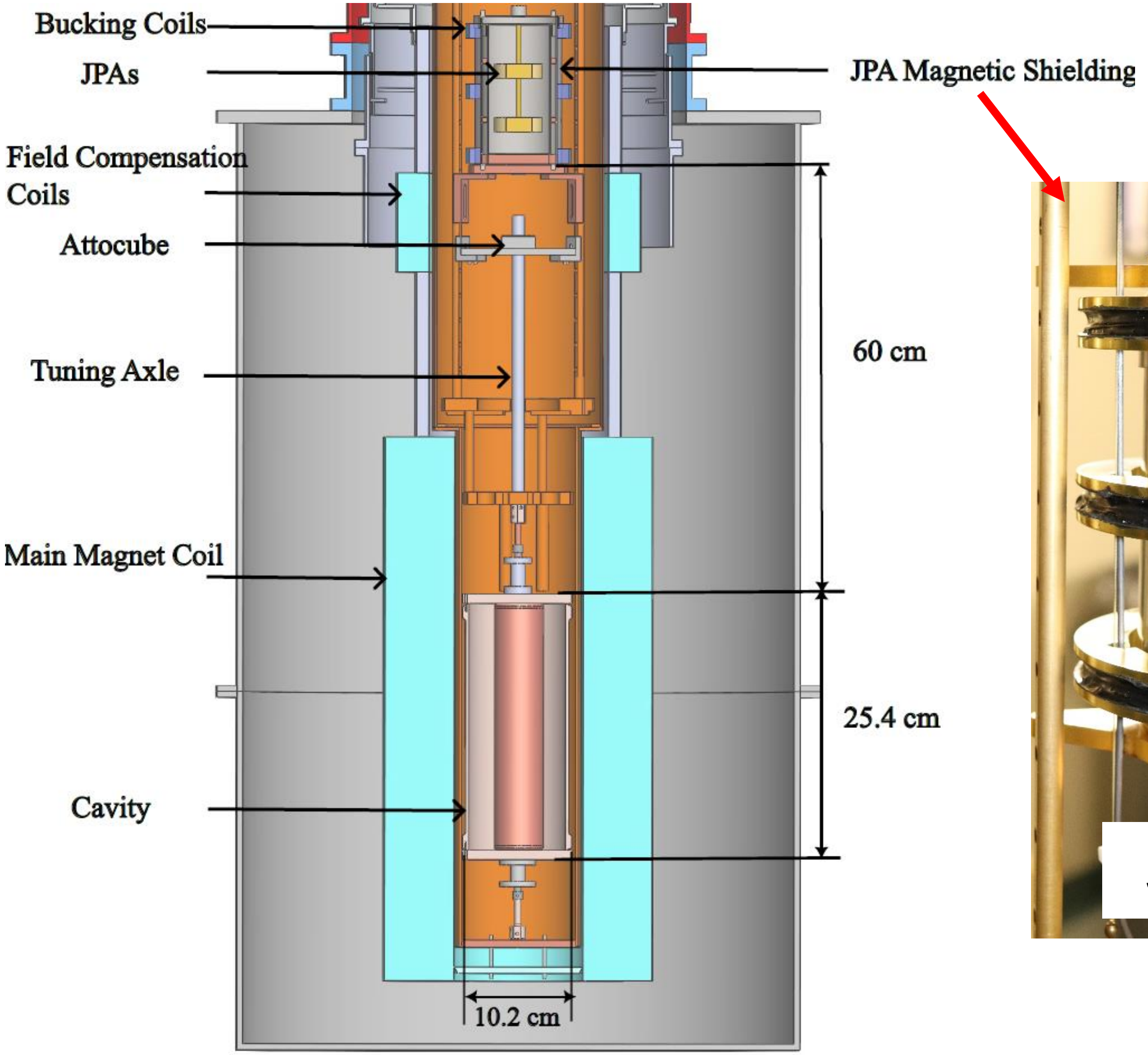


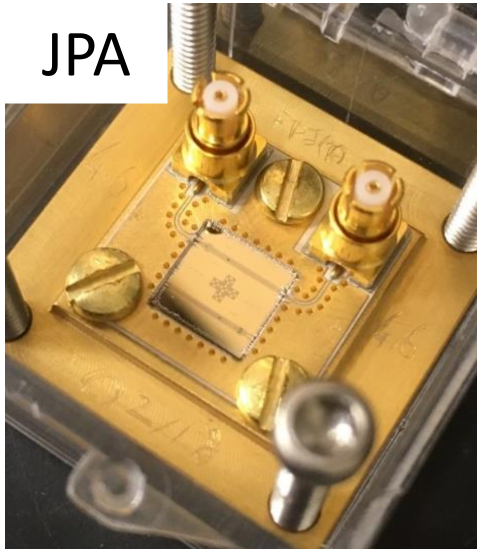
HAYSTAC Timeline

- Operating since 2016
- Two Phases
  - **Phase I:** Single JPA, Phase-Insensitive Measurement
  - **Phase II:** Two JPAs, Phase-Sensitive Measurement

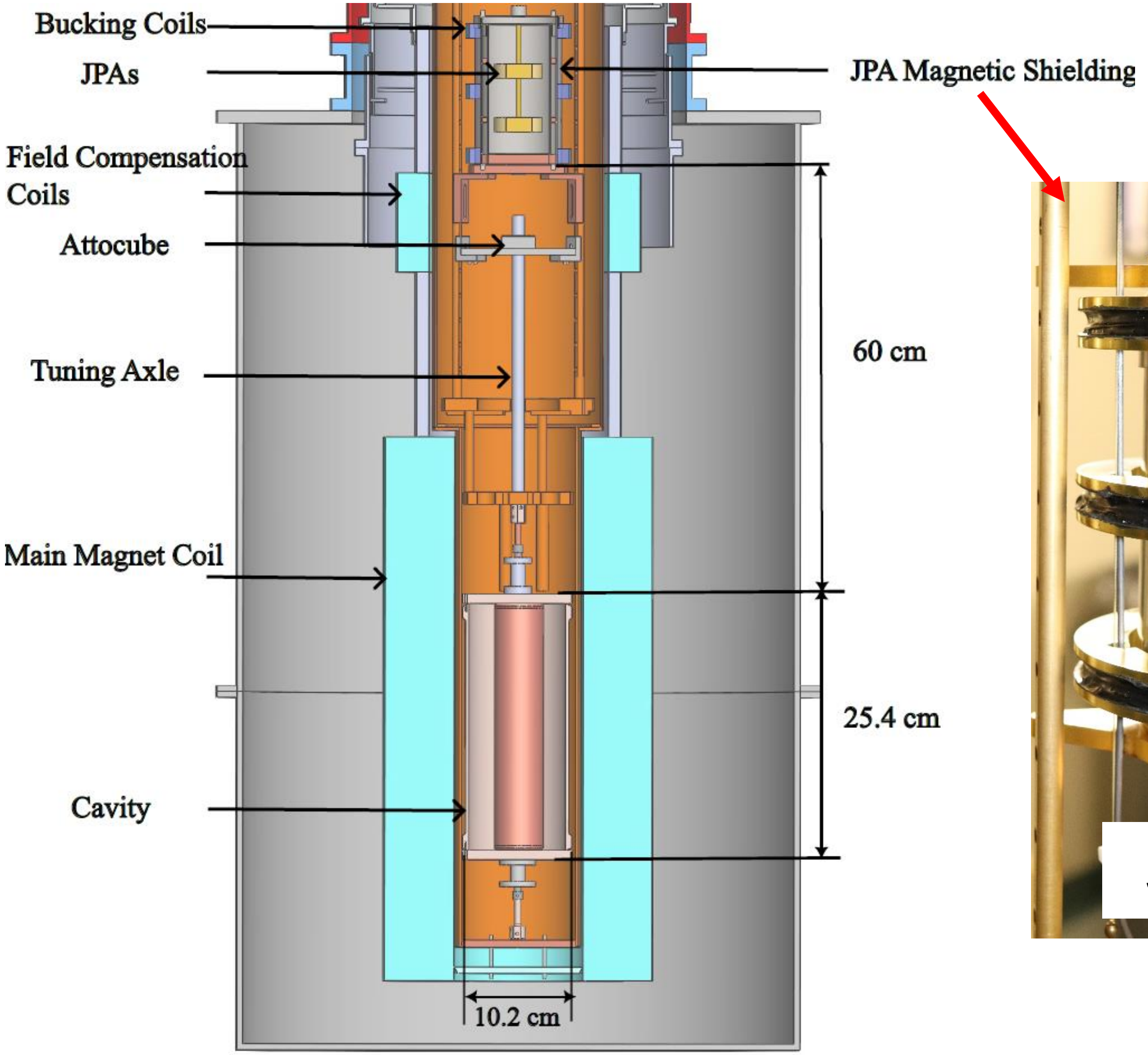
Name	Amplifier	Dates	Freq. Range	Sensitivity	Publication
Phase I	Phase Insensitive	Jan. 2016 – Jan. 2017	5.6–5.8 GHz	$2.70\times \lvert g_\gamma^{KSVZ}\rvert$	*Phys. Rev. D* 97 (2018)
Phase II a	Phase Sensitive	Sept. 2019 – April 2020	4.100-4.140 GHz, 4.145-4.178 GHz	$1.95\times \lvert g_\gamma^{KSVZ}\rvert$	*Nature* 590 (2021)
Phase II b	Phase Sensitive	July 2021 – Nov. 2021	4.459–4.523 GHz	$2.06 \times \lvert g_\gamma^{KSVZ}\rvert$	*arXiv:2301.09721 (2023)*

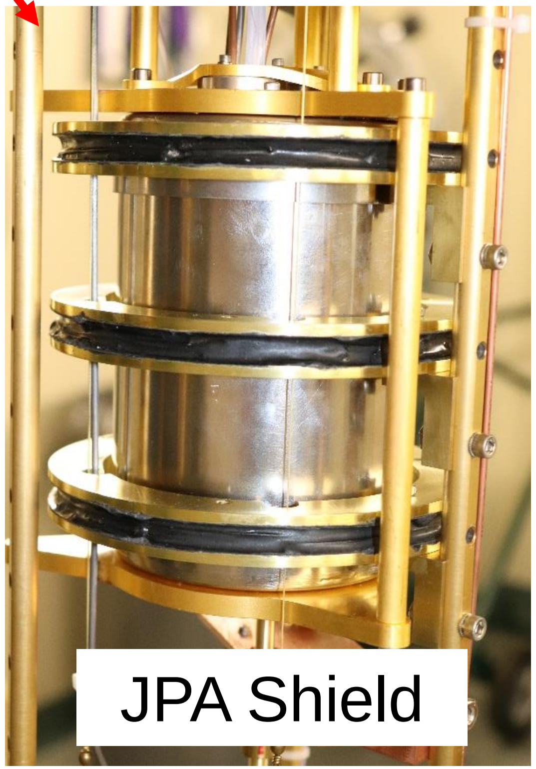
JPAs in HAYSTAC

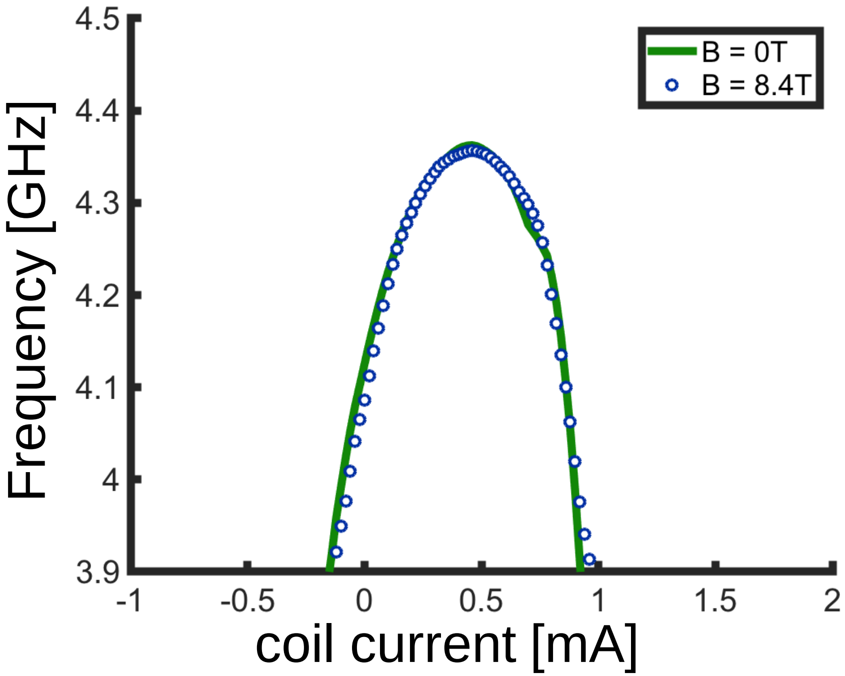




JPAs in HAYSTAC

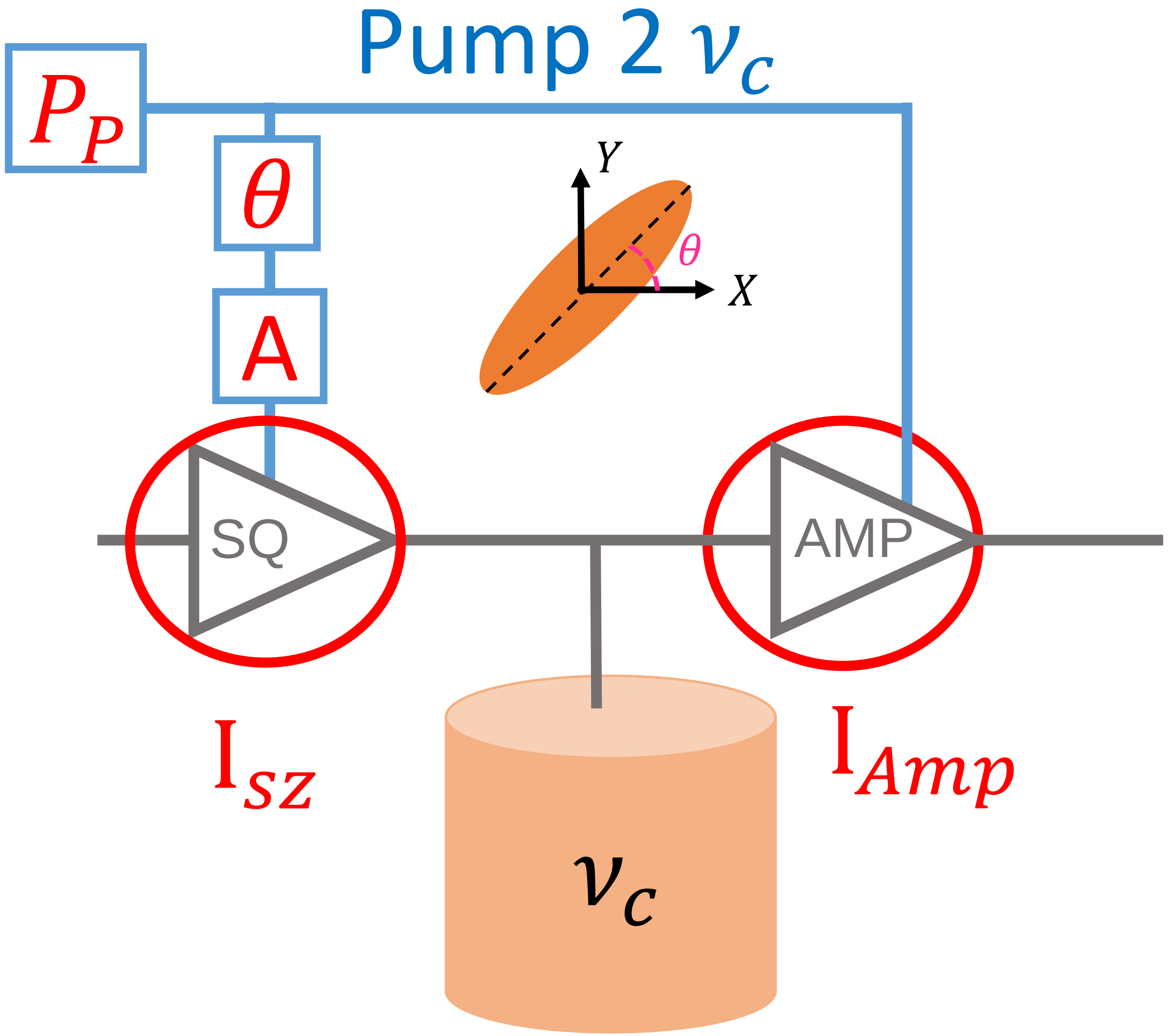






Tuning with SSR

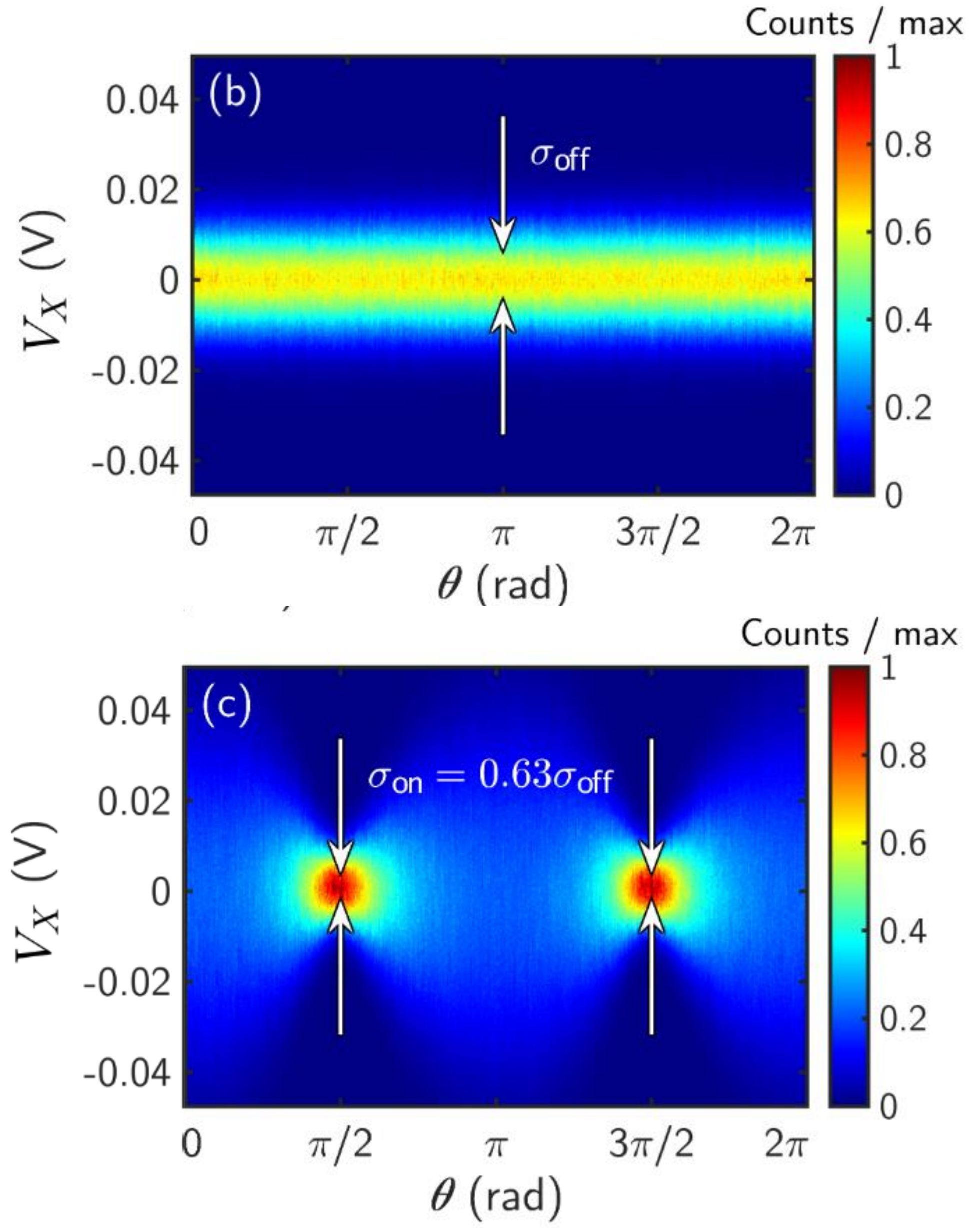
- Five parameter optimization
- JPAs tuned to match Cavity Resonance
  - I_{sz}: Squeezer Flux Bias
  - I_{AMP}: Amplifier Flux Bias
- Amplifiers share same Pump Source
  - P_P: Amplifier Gain
  - A: Squeezer Gain
  - θ: Phase difference



Phase II Timeline

	Days [#]	Spectra [#]	Freq. [MHz]
Phase-IIa	105	861	73
Phase-IIa (rescans)	53	508	”
Phase-IIb	51	791	64
Phase-IIb (rescans)	48	799	”

- Phase IIa (Sept 2019 – April 2020):
  - First Quantum enhanced axion search
  - **Scan rate enhanced by ~2x**
  - *K.M. Backes et al., Nature 590 (2021)*
- Phase IIb (July 2021 – Nov 2021):
  - Upgraded search at higher frequency with SSR
  - *arXiv:2301.09721 (2023, Accepted to PRD)*

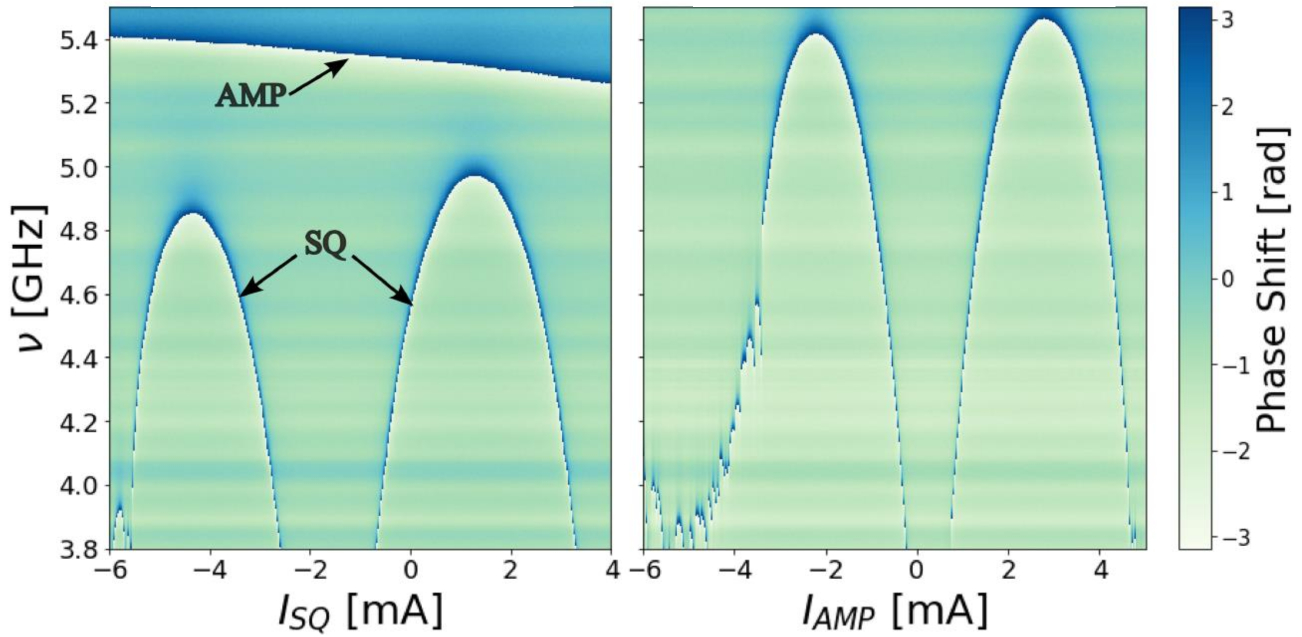


Improvements for Phase IIb

Higher Frequency JPAs

New pair of JPAs to extend frequency above 4.2GHz

SQZ JPA **AMP JPA**

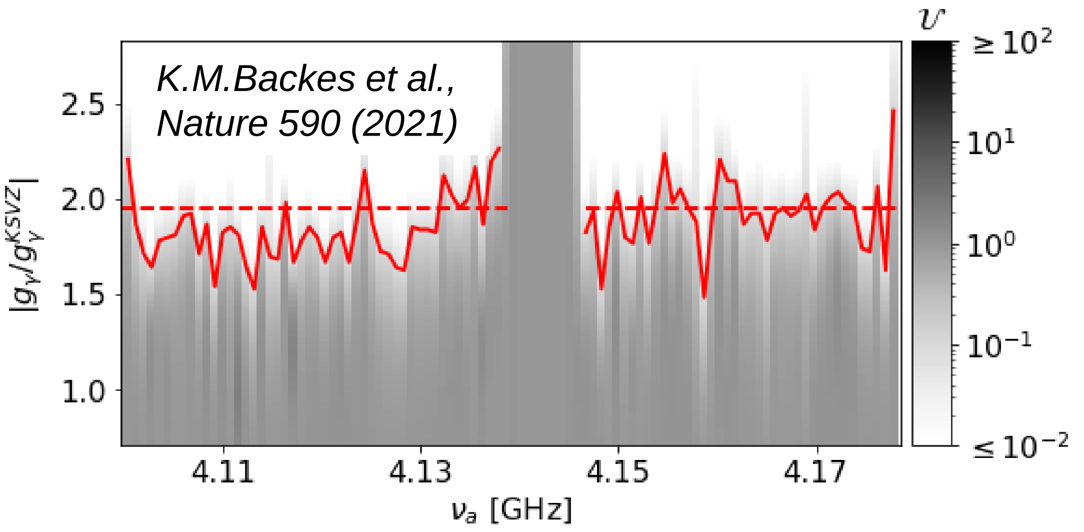


Reduced DAQ Deadtime

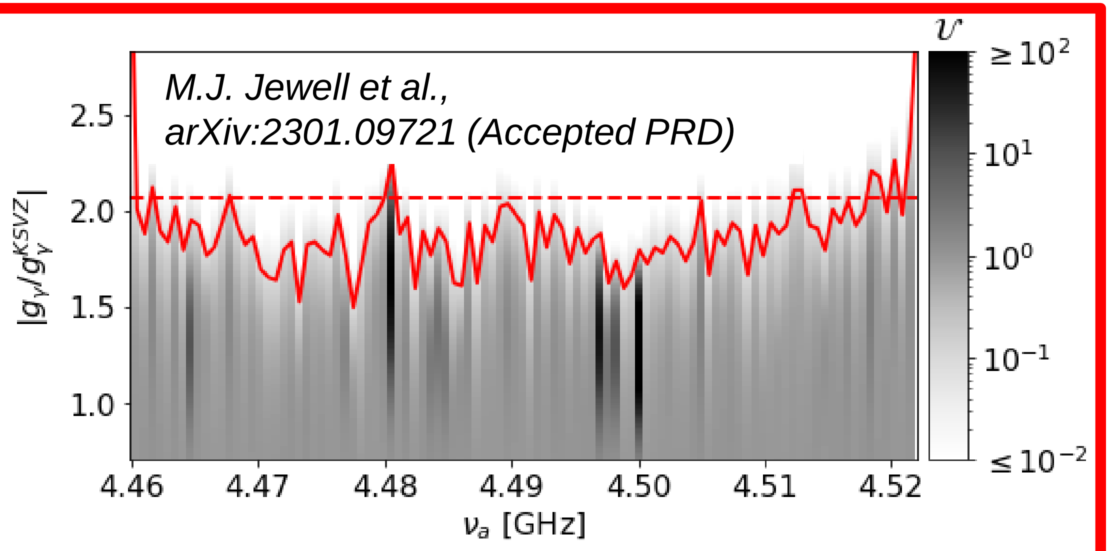
Improved DAQ routine to reduce deadtime from in-situ processing (1.6x speed up)

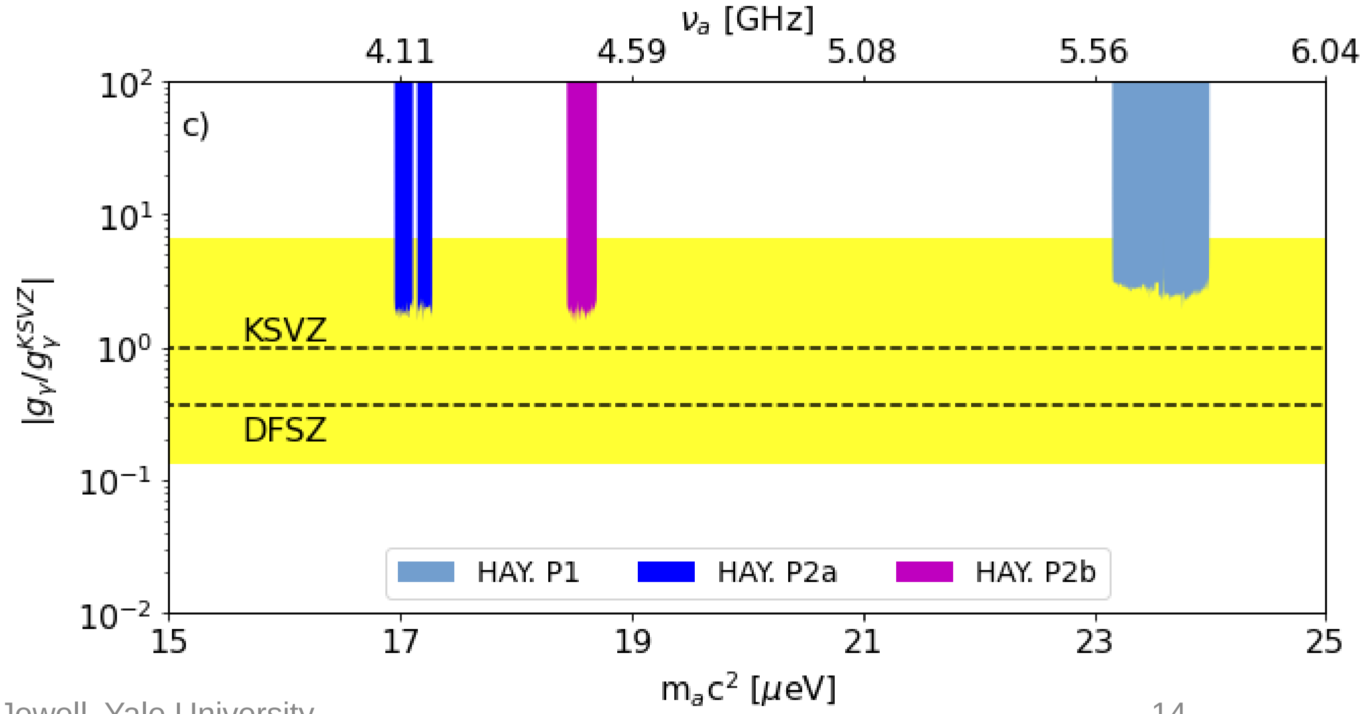
	Fractional Time [%]	
	Phase IIa	Phase IIb
DAQ	40	10
Tuning	12	8
Livetime	48	82

Results From HAYSTAC Phase II

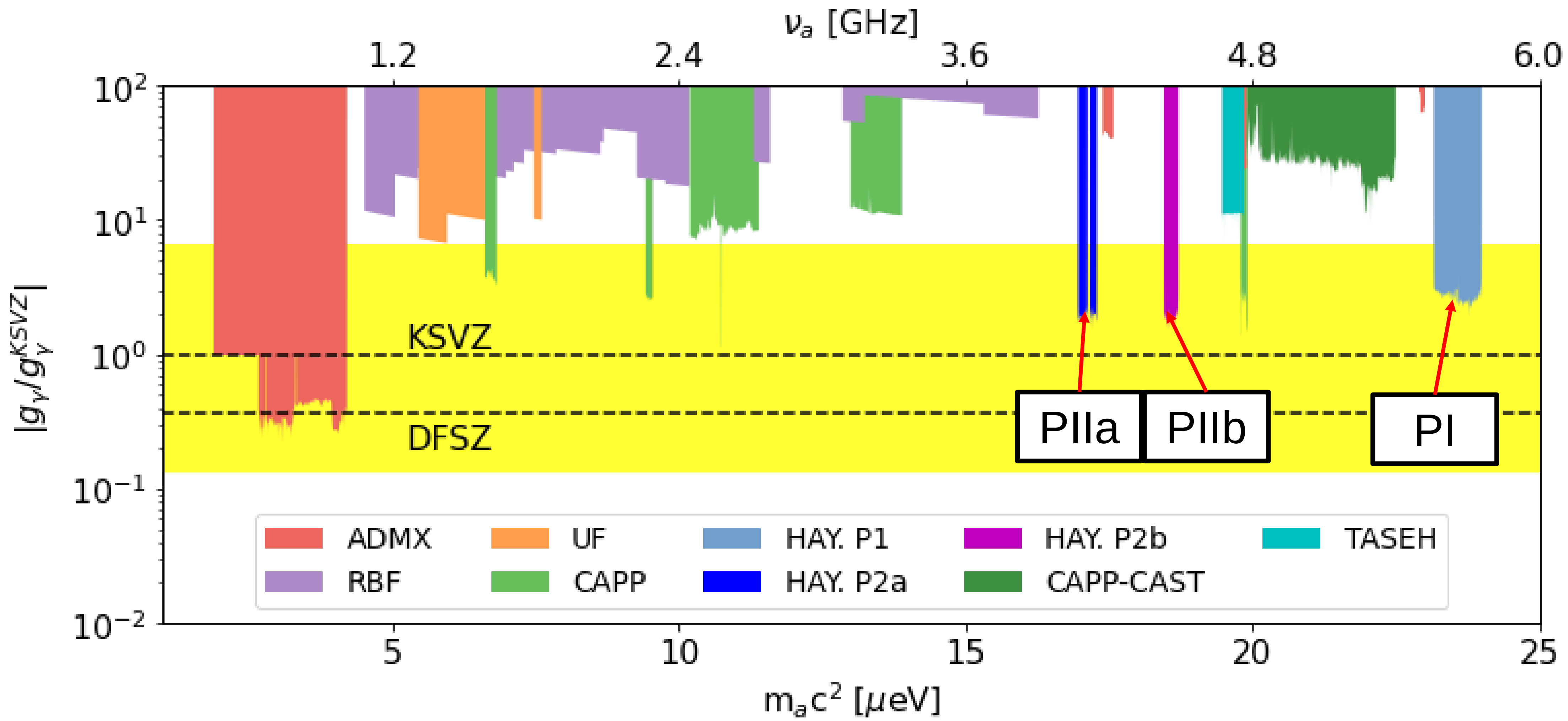


- No statistically significant signals in Phase II
  - 137MHz of scanned parameter space
- Exclude couplings at 90% CL using Bayesian Analysis
  - Phase IIa: $1.95\times\left|g_\gamma^{KSVZ}\right|$
  - Phase IIb: $2.06\times\left|g_\gamma^{KSVZ}\right|$





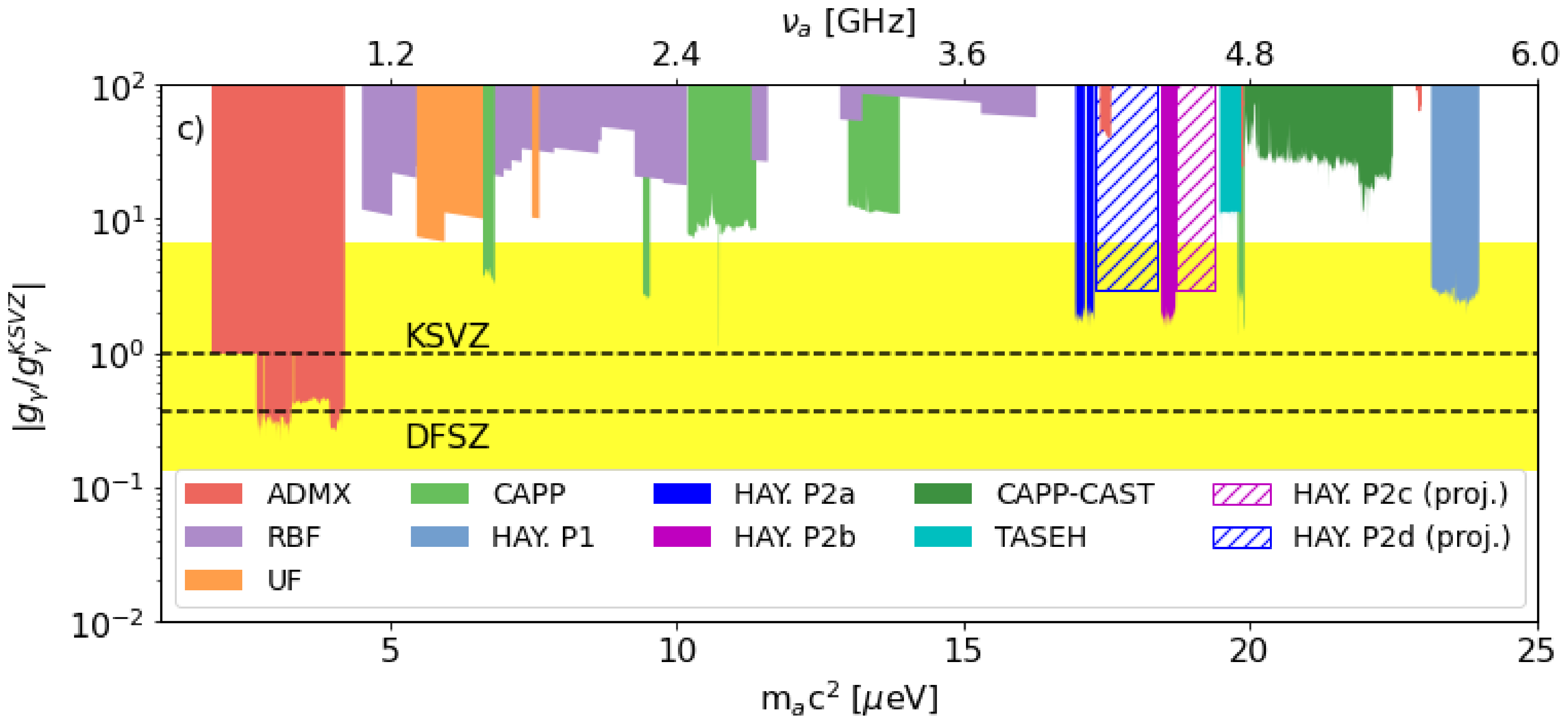
Results From HAYSTAC



arXiv:2301.09721(Accepted to PRD)

Continued Phase II Operation

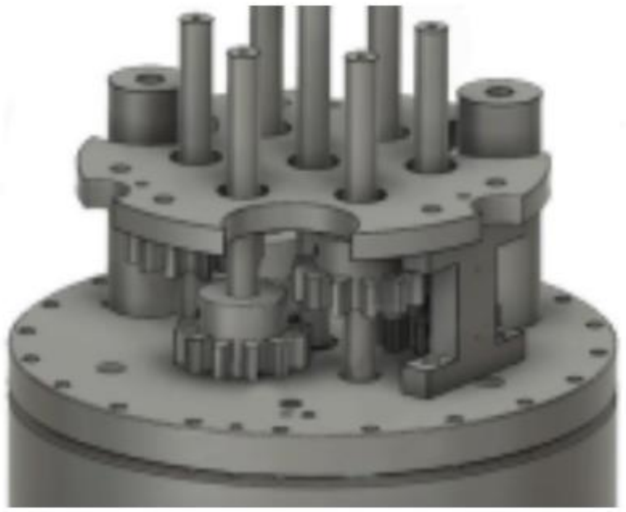
- Using the same cavity/JPAs there are still ~450MHz between 4.2 – 4.7GHz to be searched



Beyond Phase II

7-Rod Cavity

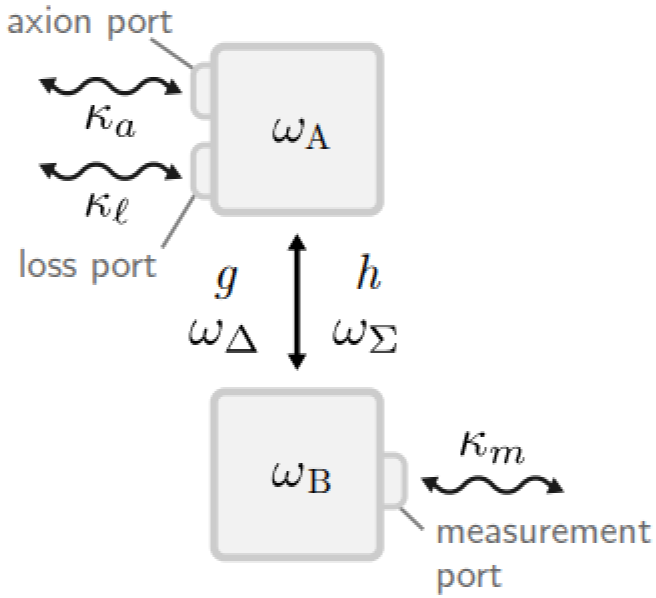
Repurpose cavity for higher frequency (~7GHz)



[M. Simanovskaia et al, Rev. Sci.Instrum. (2021)](#)

CEASFIRE

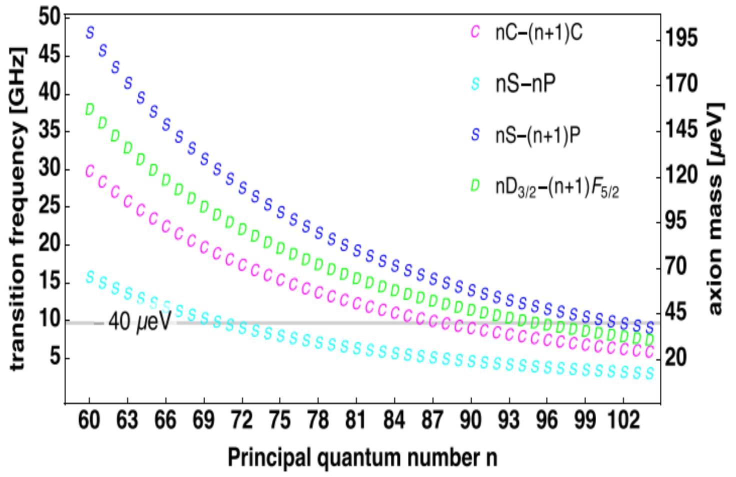
Improve the level of squeezing with entangled states



[K. Wurtz et al, PRX Quant. 2 (2021)](#)

Single Photon Counting

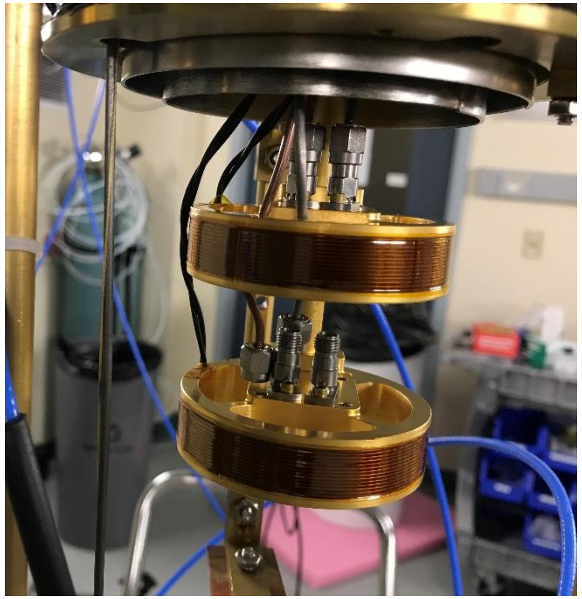
Use Rydberg atoms as single photon counters for >10GHz

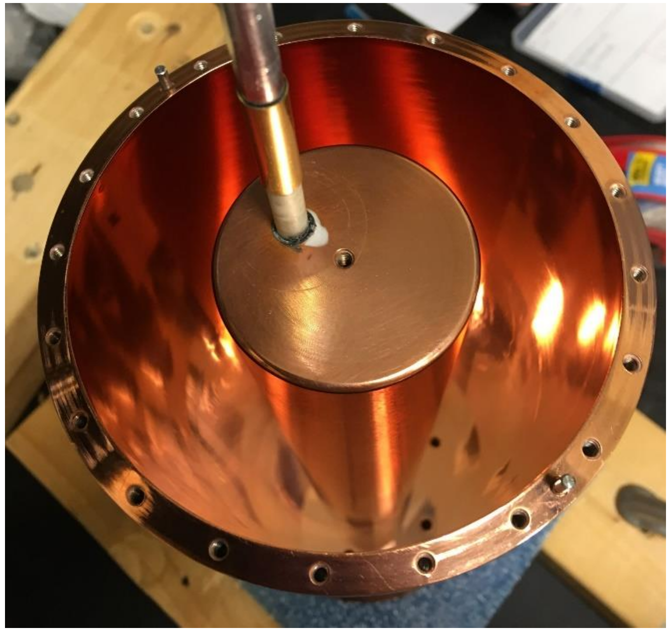


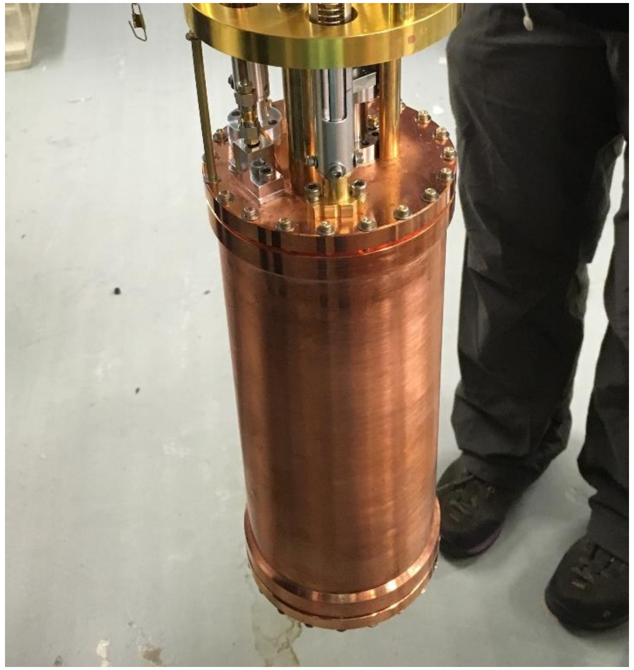
[Y. Zhu et al, Phys. Rev. A (2021)](#)

Conclusion

- HAYSTAC is continuing to search for axions with m_a > 10 μeV
- Completed two runs with Squeezed State Receiver
  - Covering 137MHz between 4.10GHz and 4.52GHz
  - Achieving sensitivity ~2 × $|g_\gamma^{KSVZ}|$
- Continuing search with current setup + developing new ideas to search at higher frequency

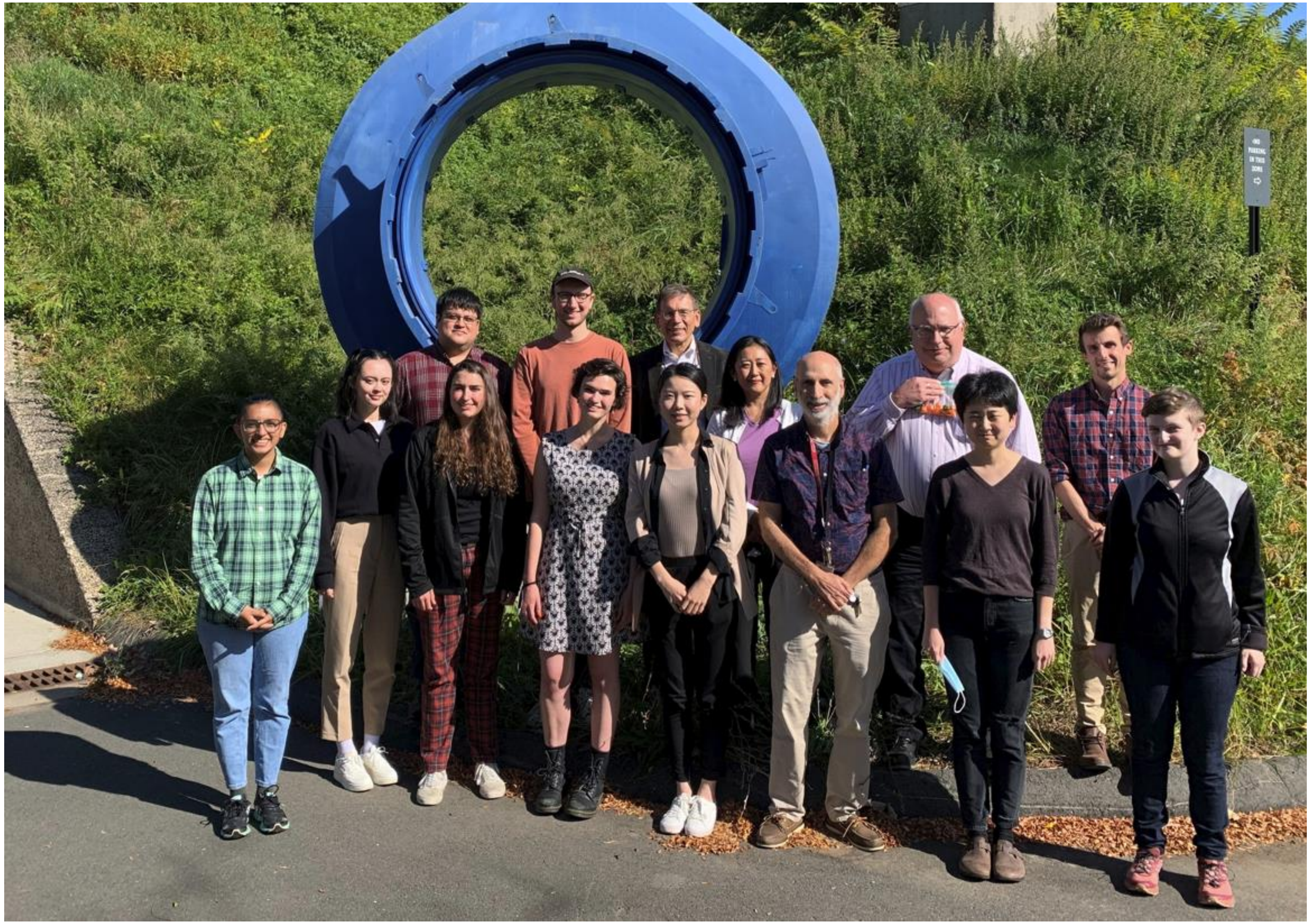






Haystac

Thanks



Wright Laboratory

JILA
CU Boulder and NIST

LUX ET VERITAS

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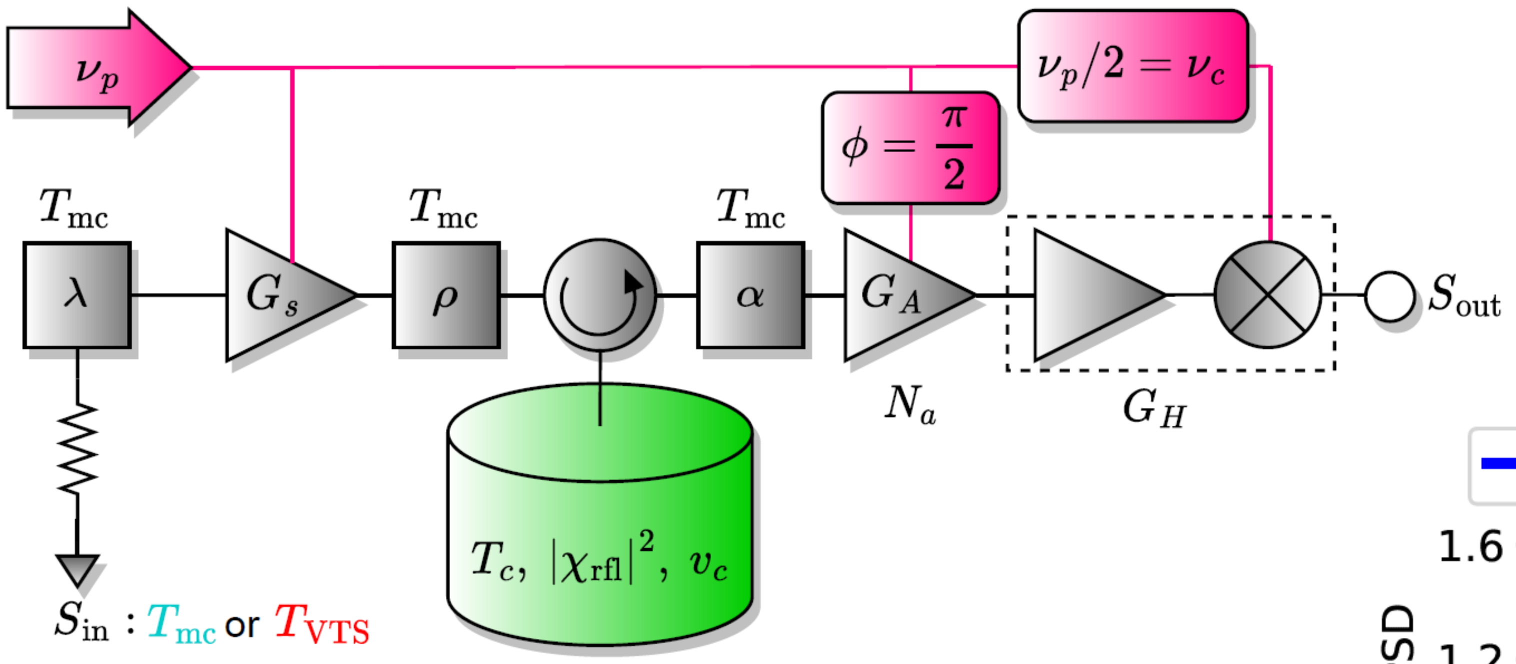
THE UNIVERSITY OF CALIFORNIA BERKELEY 1868

HEISING-SIMONS FOUNDATION

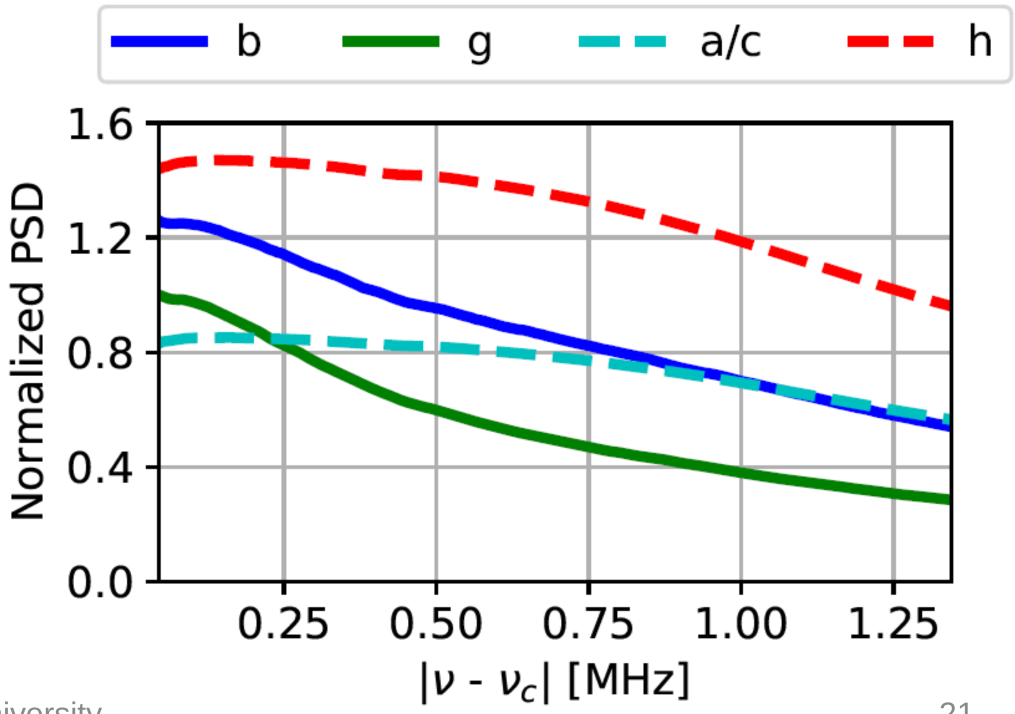
NSF

Backups

Detector Calibration

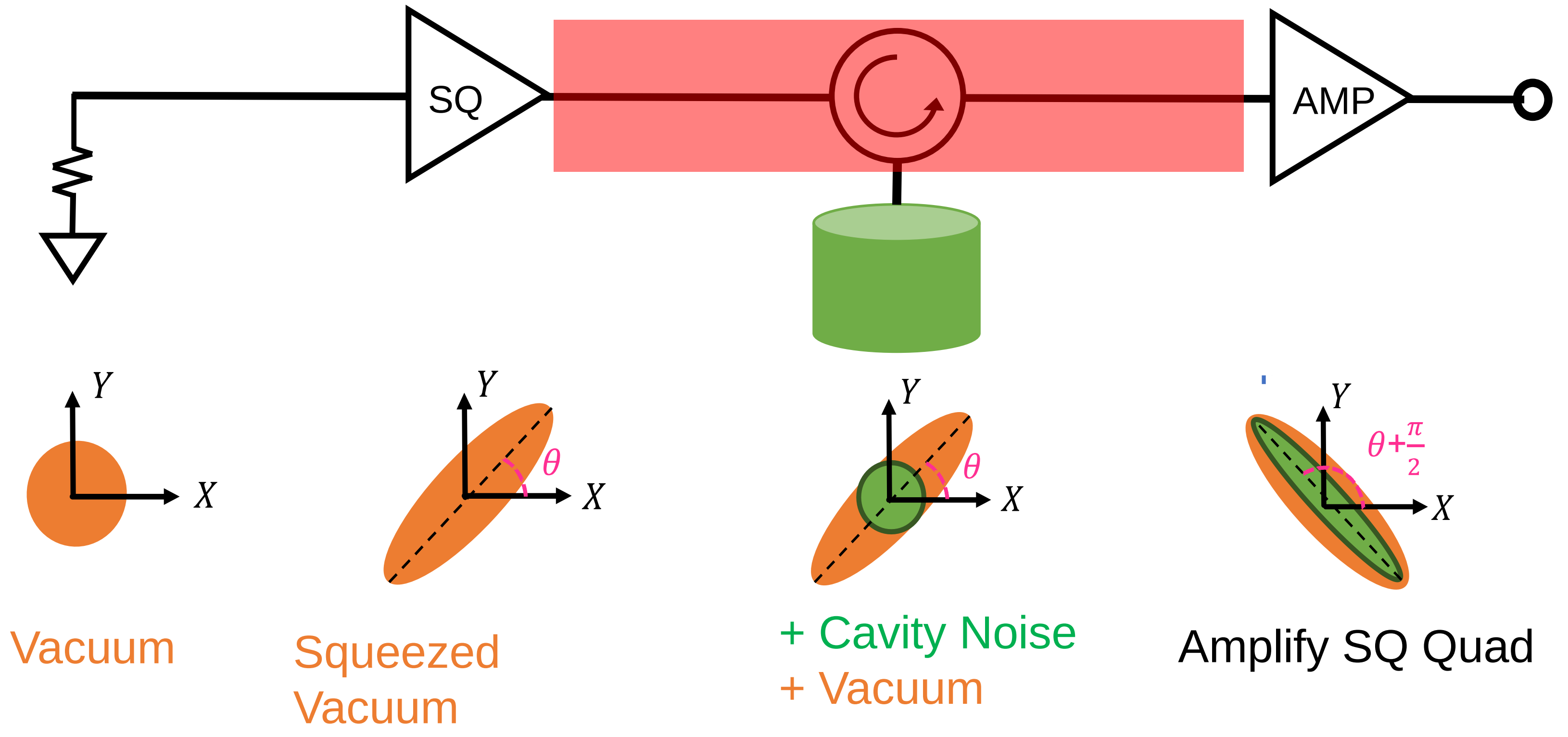


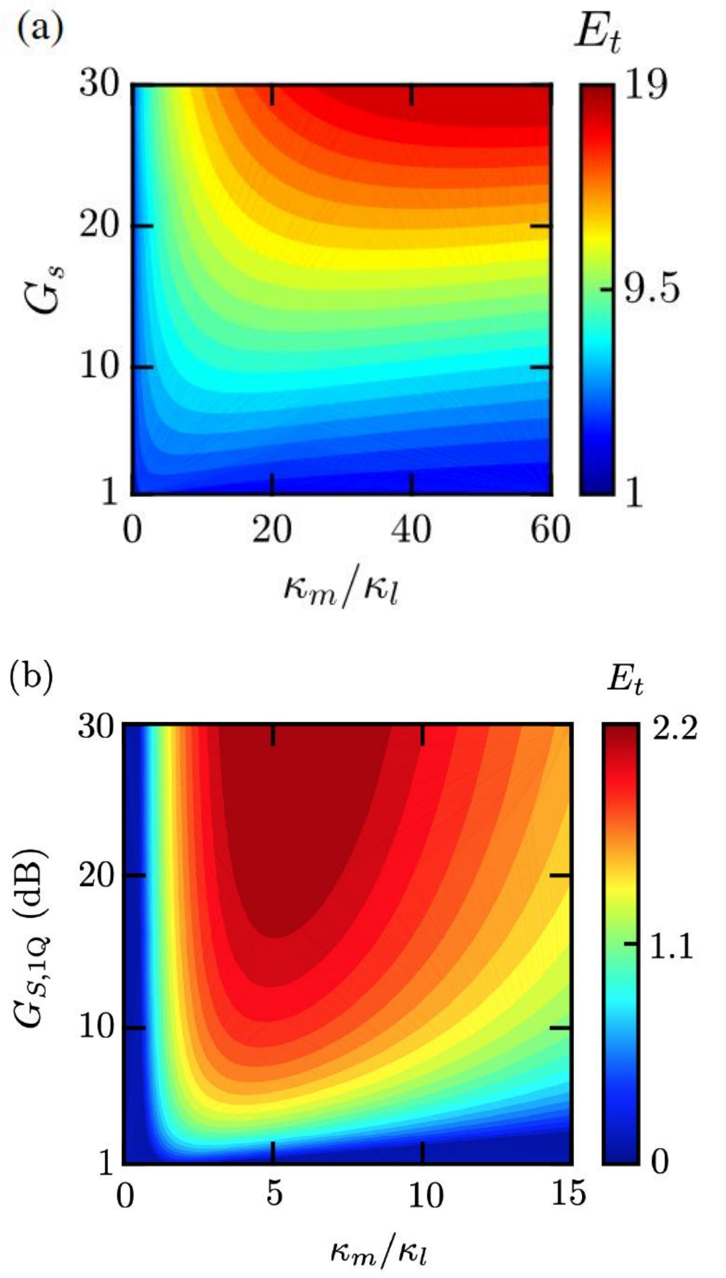
Calib ID	SQZ	$(\nu_p/2 - \nu_c)$	Load Temp.	τ_{cal}	G_A
g	ON	0 MHz	$T_{\rm mc}$	10 s	G_A^g
b	OFF	0 MHz	$T_{\rm mc}$	10 s	
a	OFF	-3 MHz	$T_{\rm mc}$	10 s	G_A^c
cold(c)	OFF	-3 MHz	$T_{\rm mc}$	900 s	
hot(h)	OFF	-3 MHz	$T_{\rm VTS}$	900 s	G_A^h



Limiting Factor

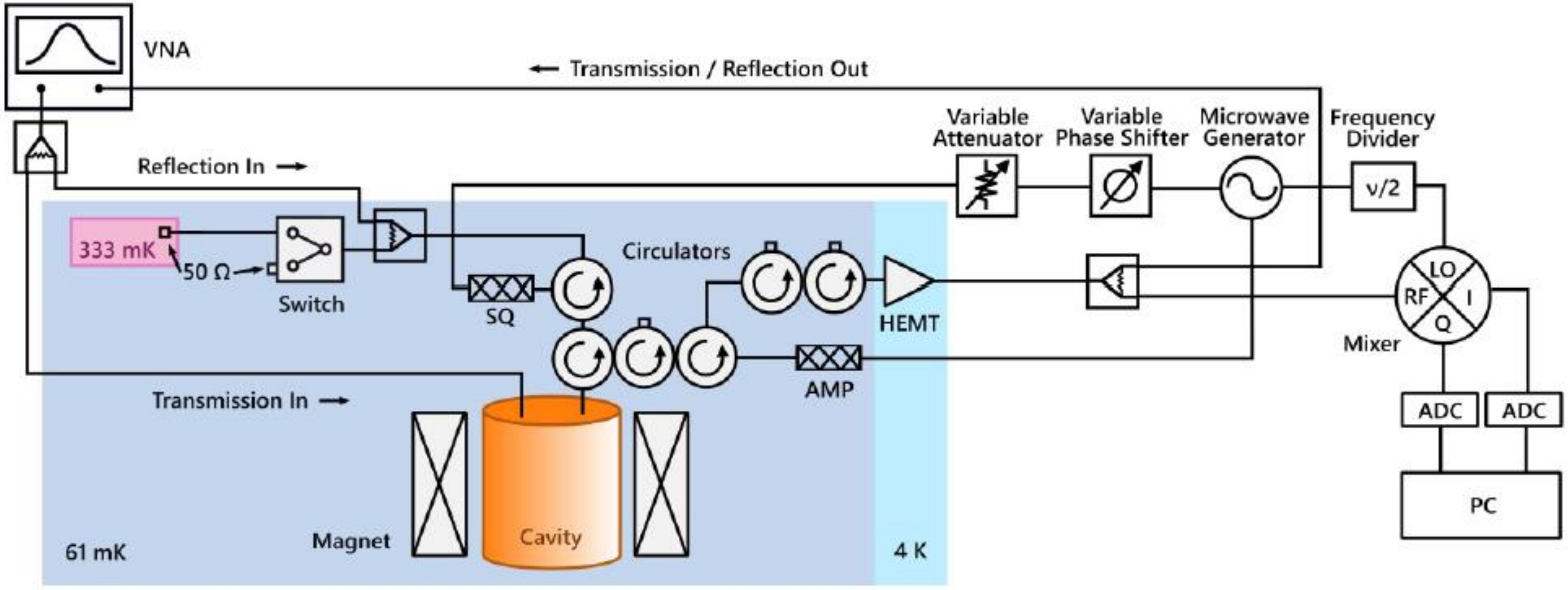
- SSR is limited by loss between two JPAs
  - Loss is dominated by triple junction circulator
  - 4dB of Squeezing is roughly best we can do currently





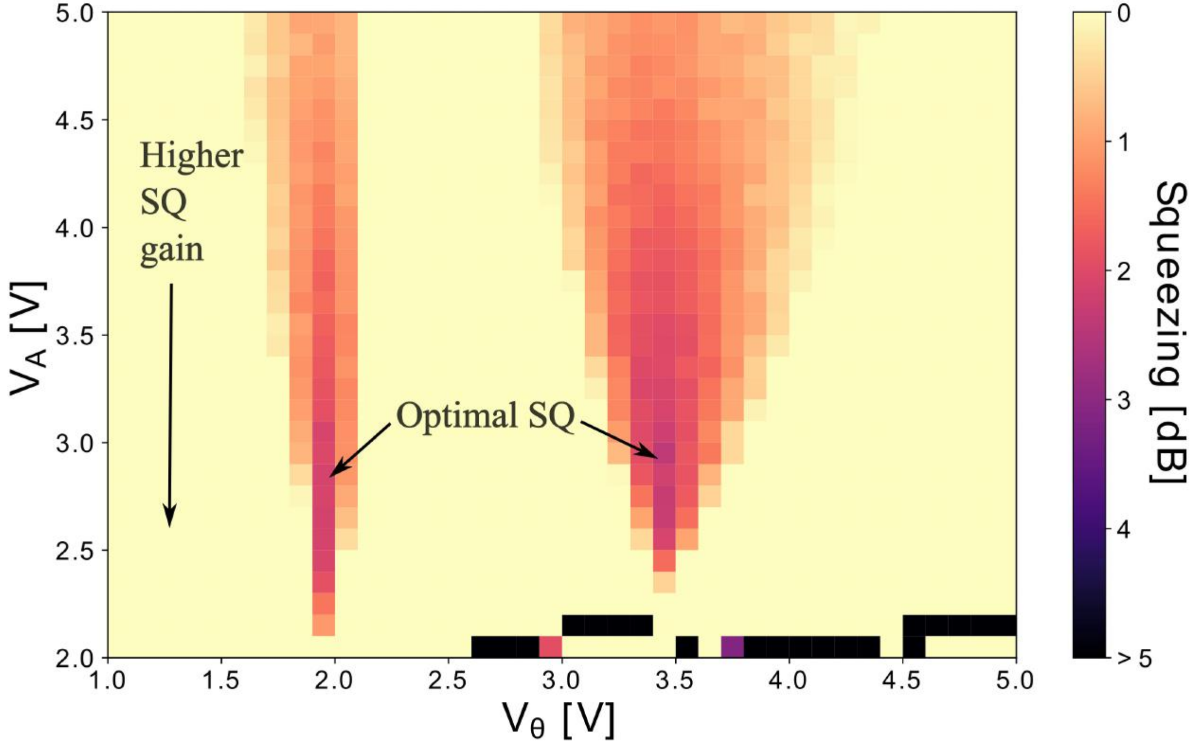
M. Malnou et al., Phys. Rev. X 9, 021023 (2019)

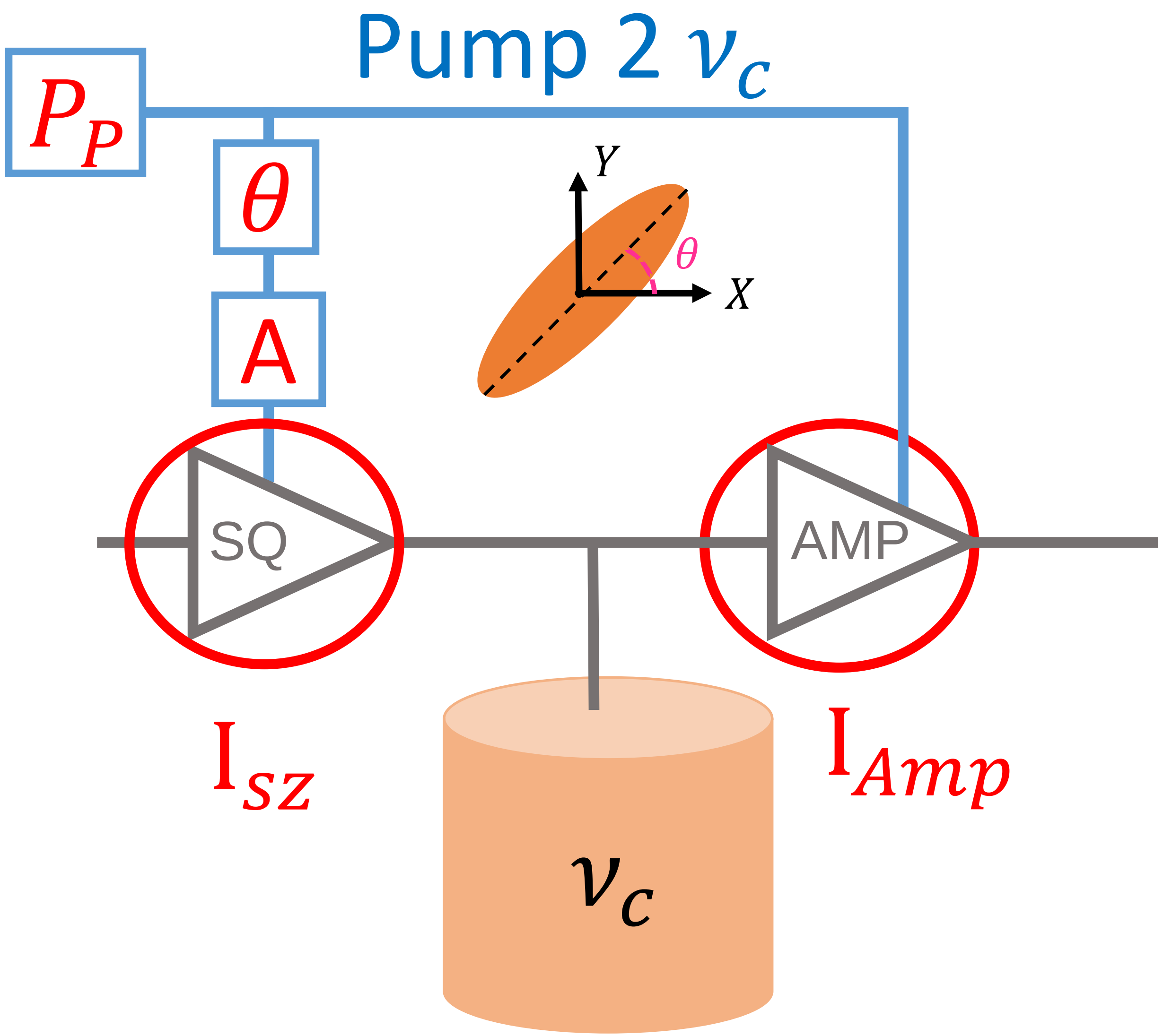
System Diagram



Tuning with SSR

- Five parameter optimization



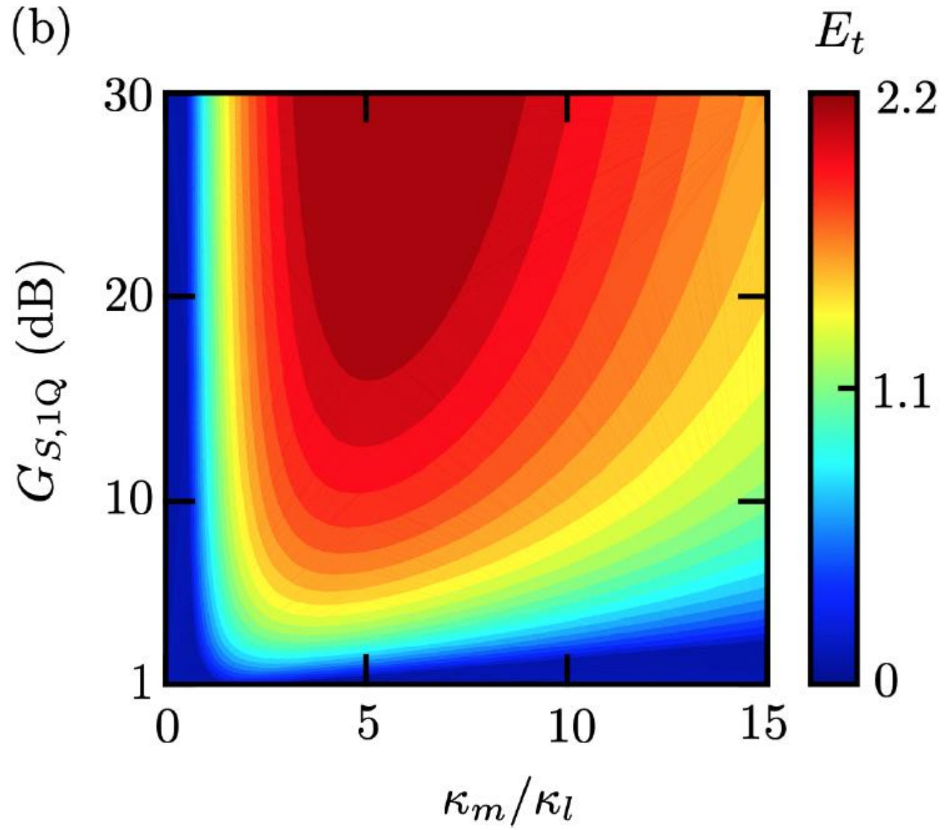


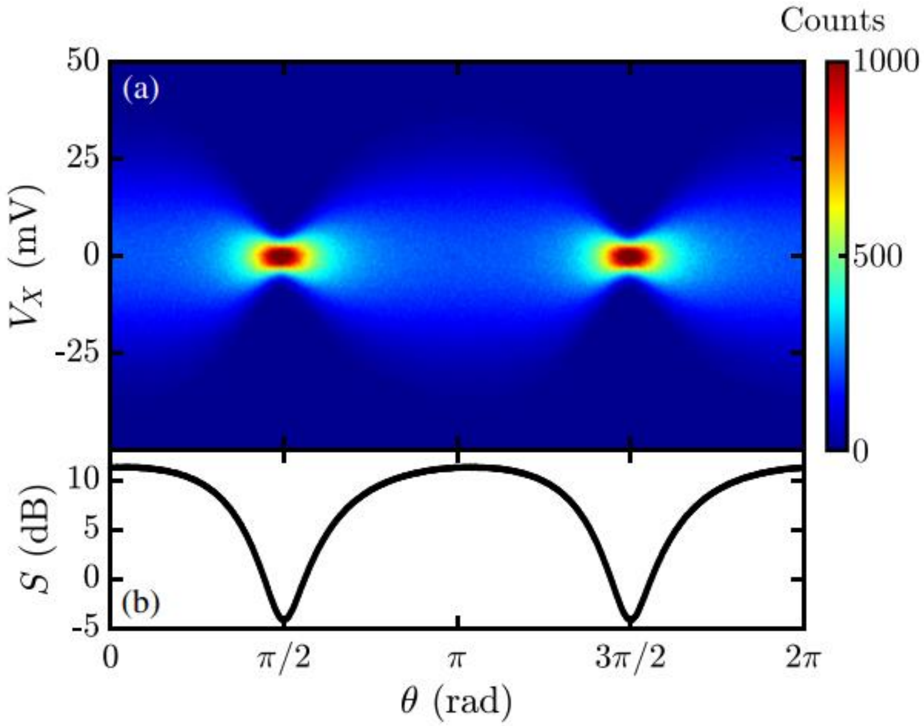
First Demonstration

- Demonstration by Colorado Group
- SSR speed up for "Fake" Axion signal

S = $\frac{\sigma_{on}^2}{\sigma_{off}^2} = 4.5dB$

2.1x Speed





M. Malnou et al., Phys. Rev. X 9, 021023 (2019)

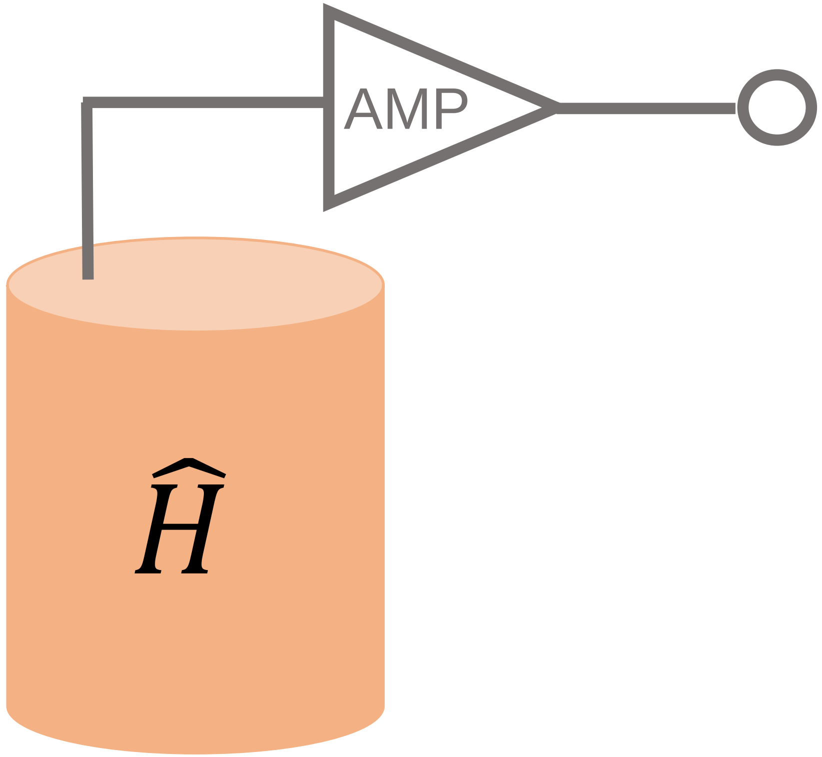
Quantum Limit for Haloscopes

Cavity Hamiltonian: $\hat{H} = \frac{h\nu_c}{2}(\hat{X}^2 + \hat{Y}^2)$ $\quad [\hat{X}, \hat{Y}] = \frac{i}{2}$

Vacuum Fluctuations: $N_v \geq \frac{1}{2} h\nu_c$

Linear Amplifier: $N_A \geq \frac{1}{2} h\nu_c$

Total SQL: $N_{total} \geq h\nu_c$

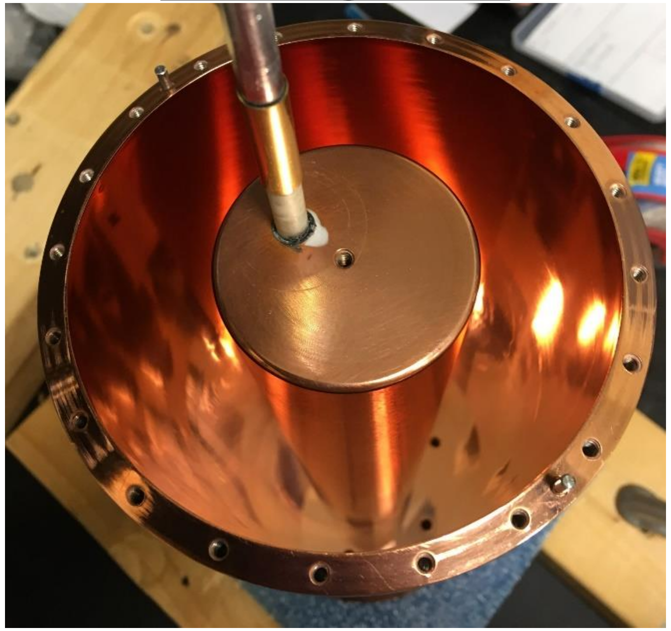


C. M. Caves. Phys. Rev. D, 26 1817-1839, (1982)
H. A. Haus and J. A. Mullen. Phys. Rev., 128 2407-2413, Dec 1962.

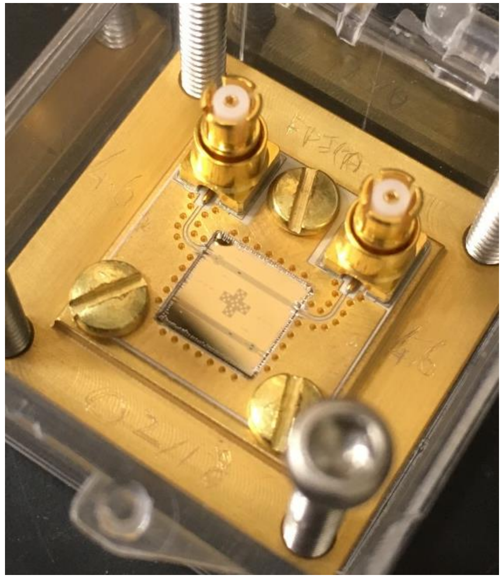
Haloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM

Cavity

Tuning Rod



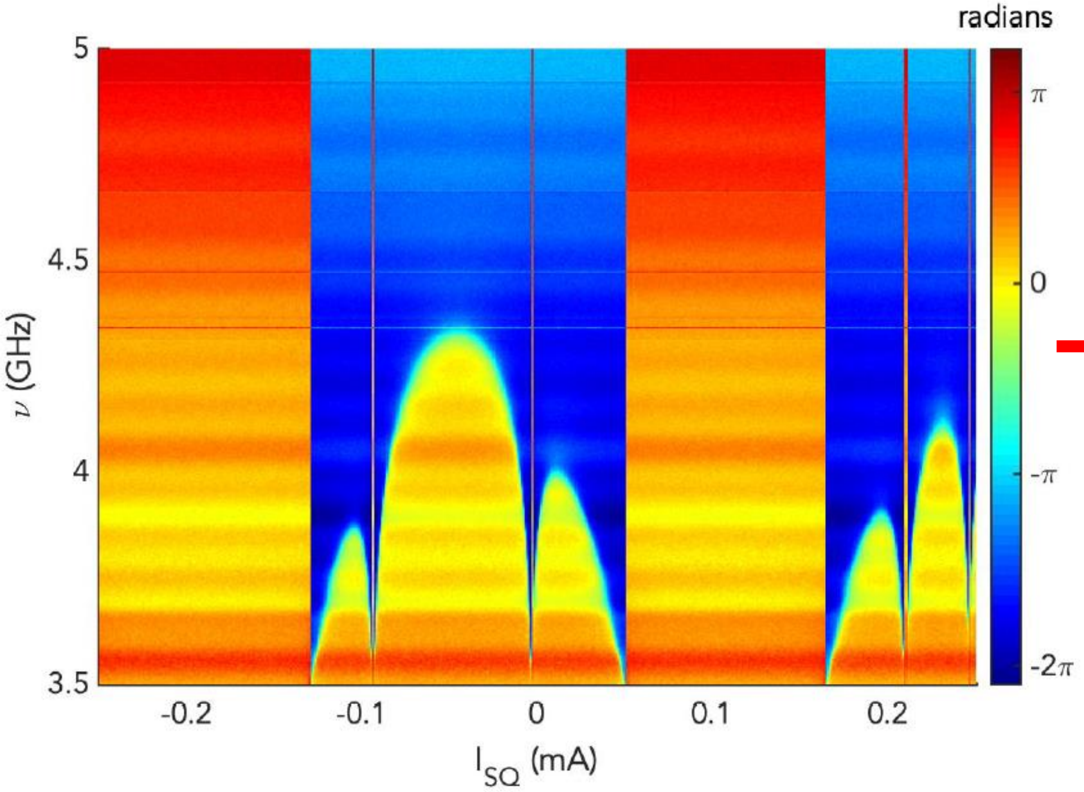
JPA

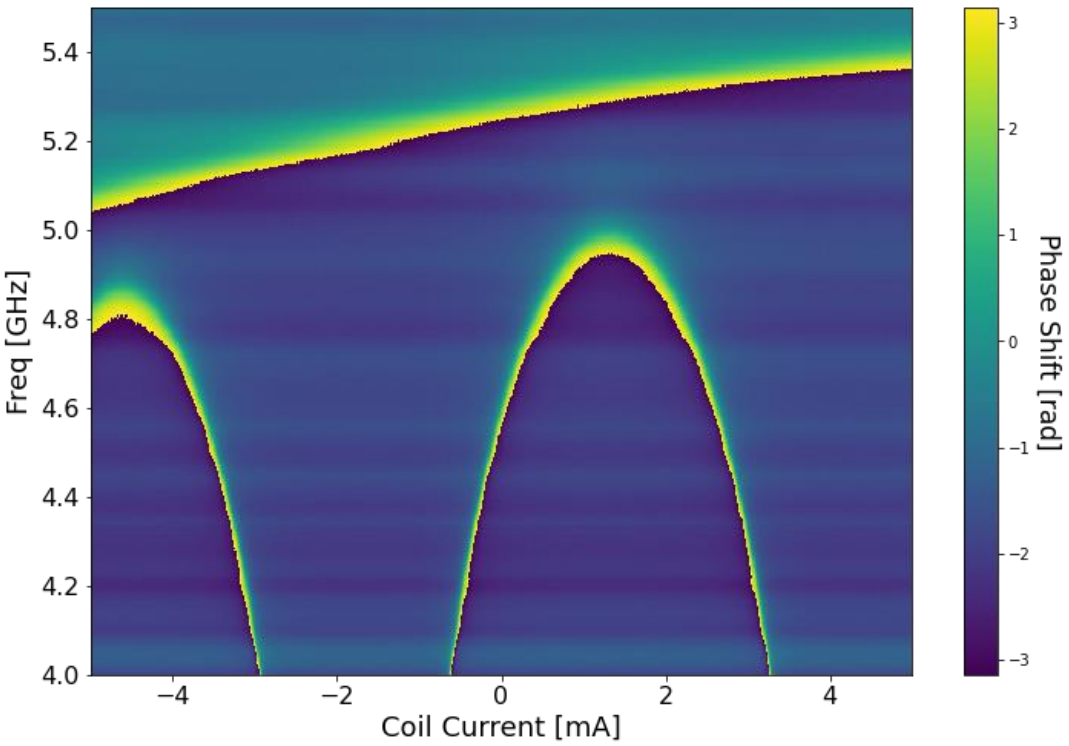


JPA Shield

Extending Beyond 4.2GHz

- Previous search limited by JPA Range
  - Max Frequency ~4.2GHz
- New JPAs designed to extend to 4.6-4.7GHz



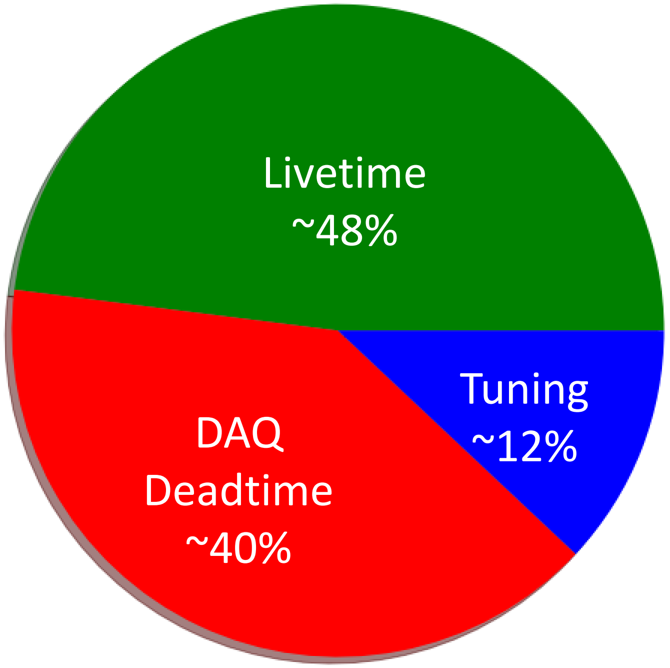


Improved Livetime

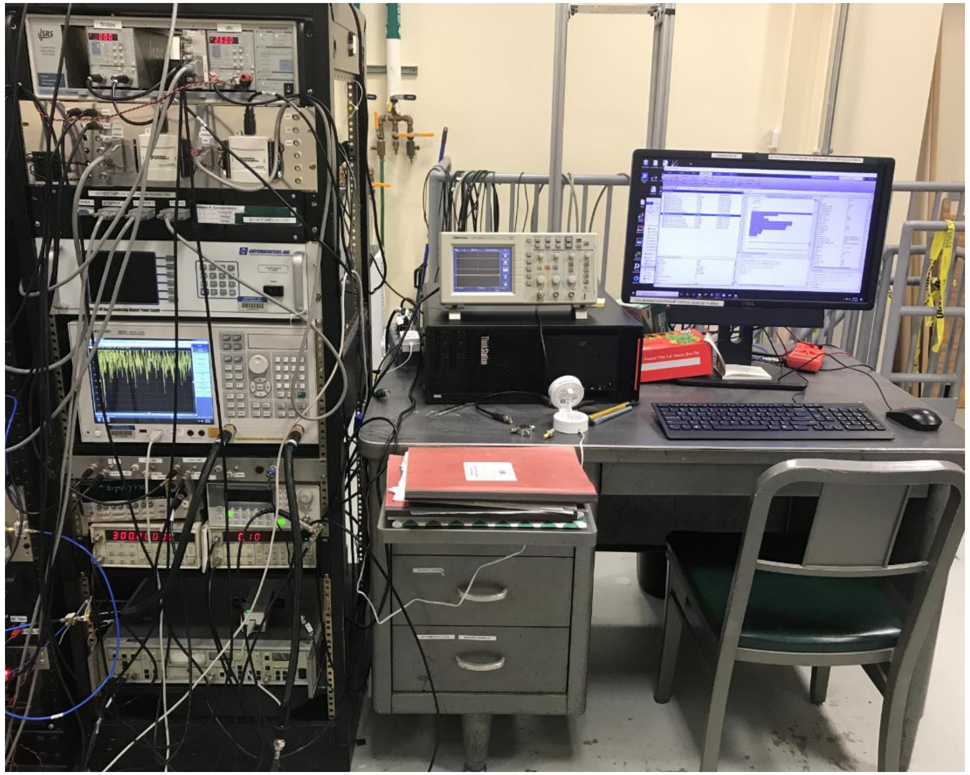
- Ideally always recording cavity field

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

- Phase IIa operation ~48% livetime



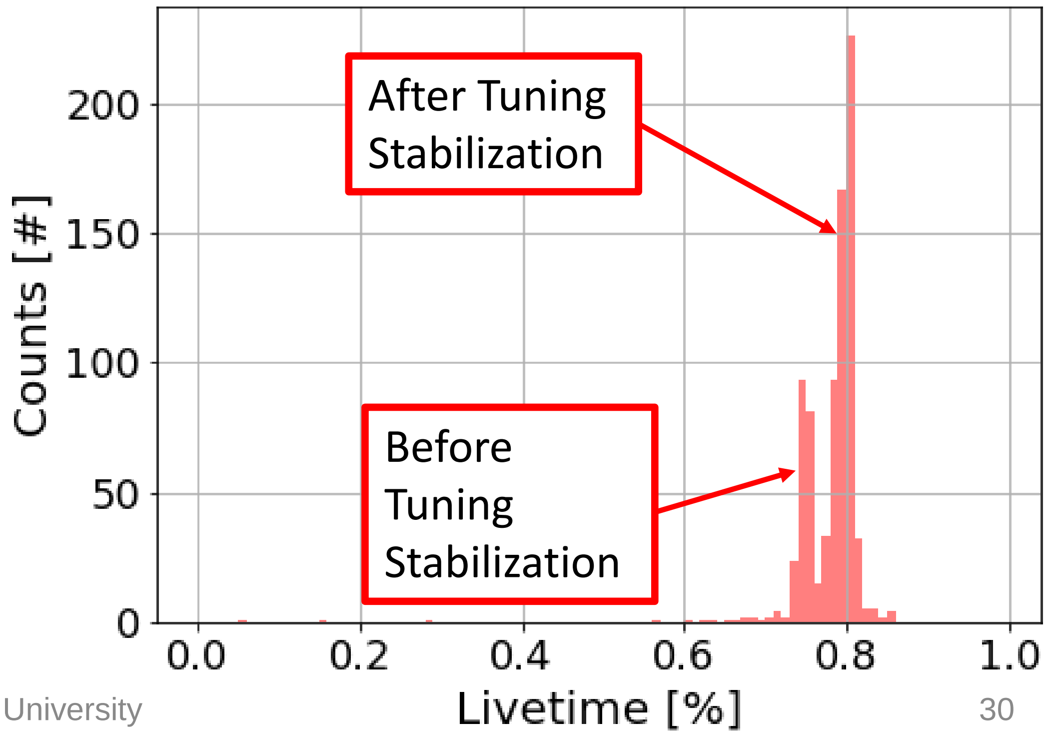
- 1hr of data @ 10 MS/s
- ~100GB per tuning
- >100TB for Phase IIa



Improving Livetime

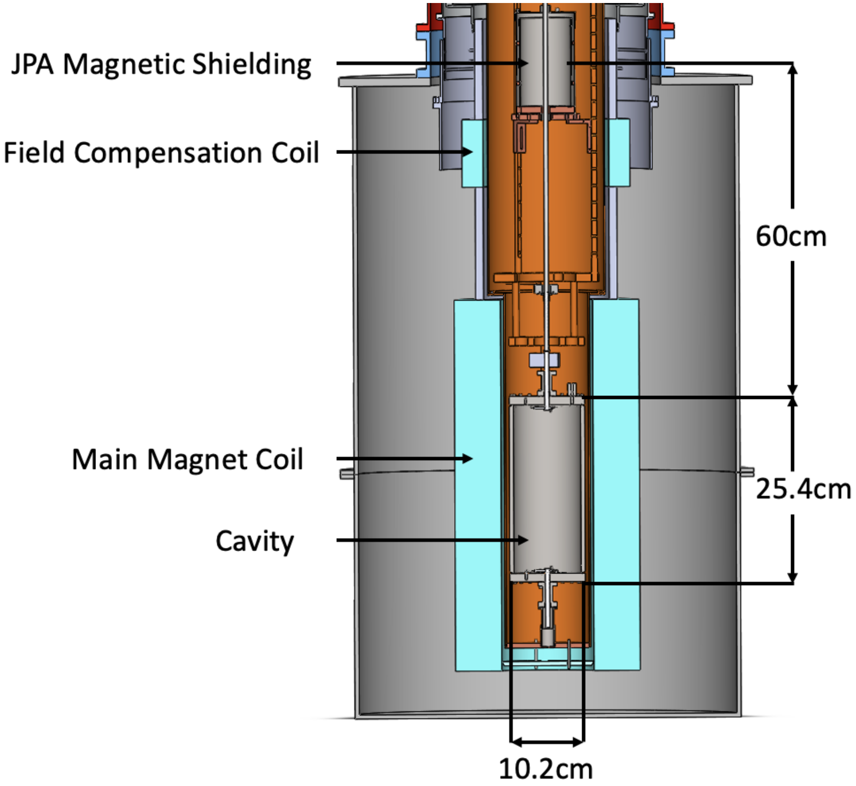
- DAQ Deadtime
  - Parallelization of FFT
  - Optimization of Data Transfer
- Tuning Stabilization
  - Reinstalled cavity has less mode drift after tuning
  - Better rod alignment
- Phase IIb achieved 78% average livetime
  - 82% after tuning improvement

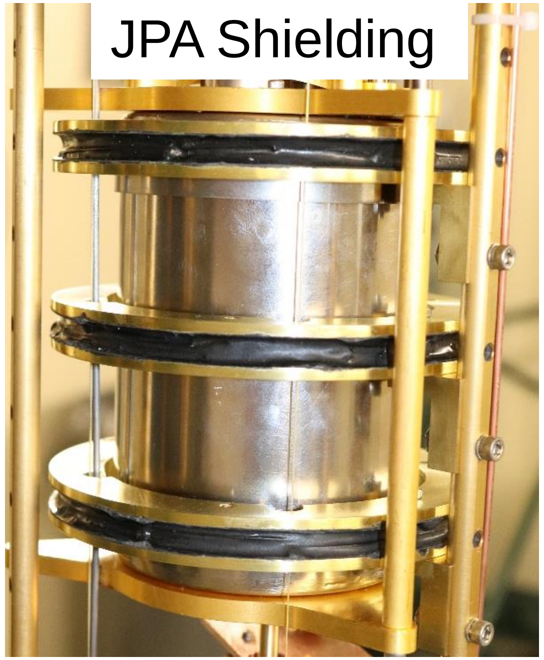
	Fractional Time [%]	
	Phase IIa	Phase IIb
DAQ	40	10
Tuning	12	8
Livetime	48	82

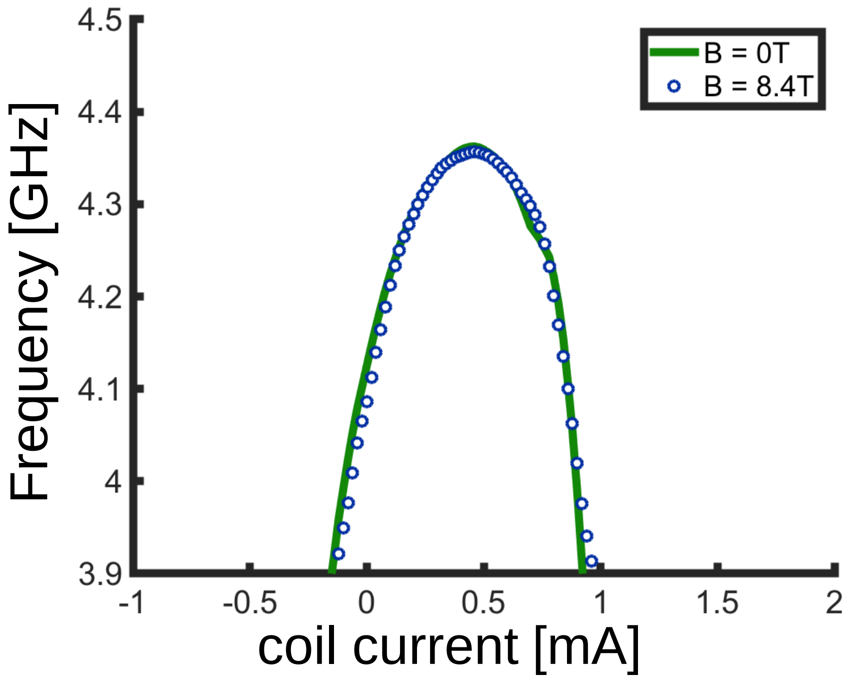


Operating JPAs Near Magnet

- JPAs are extremely sensitive to stray B-Fields
  - << 1 flux quantum (~2G)







Single Photon Detection

- Ultimate goal of “Squeezing” is Single Photon Detection
  - Lose Spectral Information
  - Only shot noise limited
  - Payoff >~10GHz (*S. K. Lamoreaux et al., Phys. Rev. D 88, 035020 (2013)*)