Updated Results from HAYSTAC's Quantum-Enhanced Search for Dark Matter Axions

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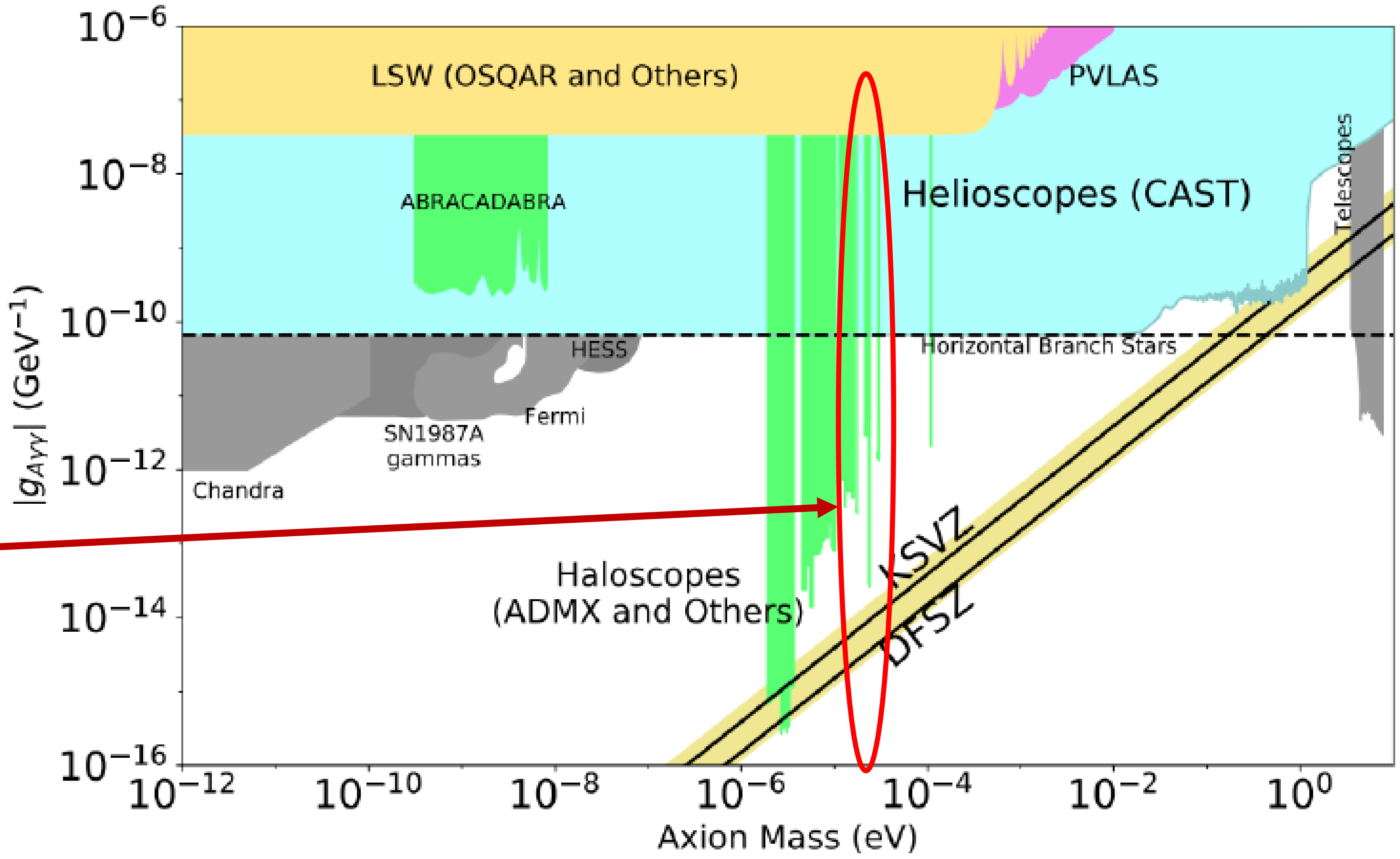
Yale University

17th Patras Workshop, August 2022

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
  - 16-20 μeV



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

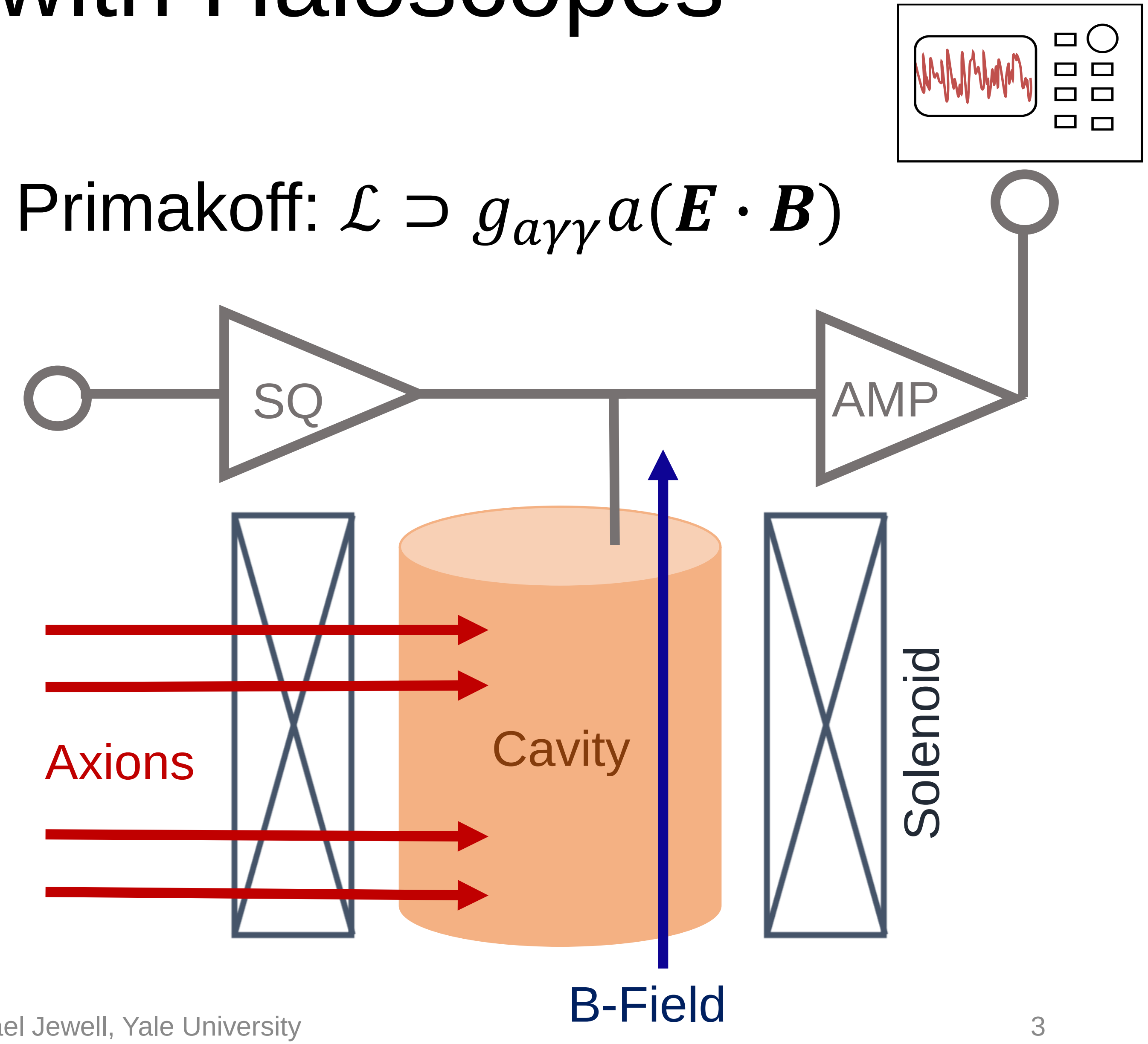
[1] E. Berkowitz, M. I. Bucho, and E. Rinaldi. Phys. Rev. D, 92 034507, 2015
[2] S. Borsanyi, Z. Fodor, J. Guenther, et al. Nature, 539 69, 2016

Searching with Haloscopes

- Magnetic Filed (B)
- High Q Resonant Cavity (Q)
- Large Volume (V)
- Tunable Frequency (ν)
- Low Noise Amplifiers (N)
- Cryogenic (N)
- Figure of Merit (Scan Rate):

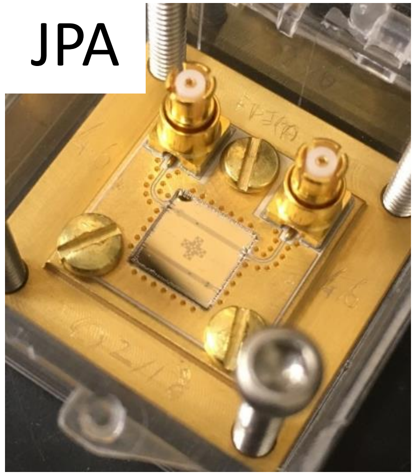
$$\frac{d\nu}{dt} \propto \frac{\eta Q B^4 V^2 C^2}{\boxed{N^2}}, \quad \frac{d\nu}{dt} \propto \nu^{-\frac{14}{3}}$$

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



HAYSTAC Detector

- Located at Yale's Wright Lab
- Copper Microwave Cavity
  - Q: ~45k
  - V: 1.5L
  - ν_c: 4-6GHz
- 8T Superconducting Solenoid
- Dilution Fridge 61mK
- **<u>Josephson Parametric Amplifier (JPA)</u>**



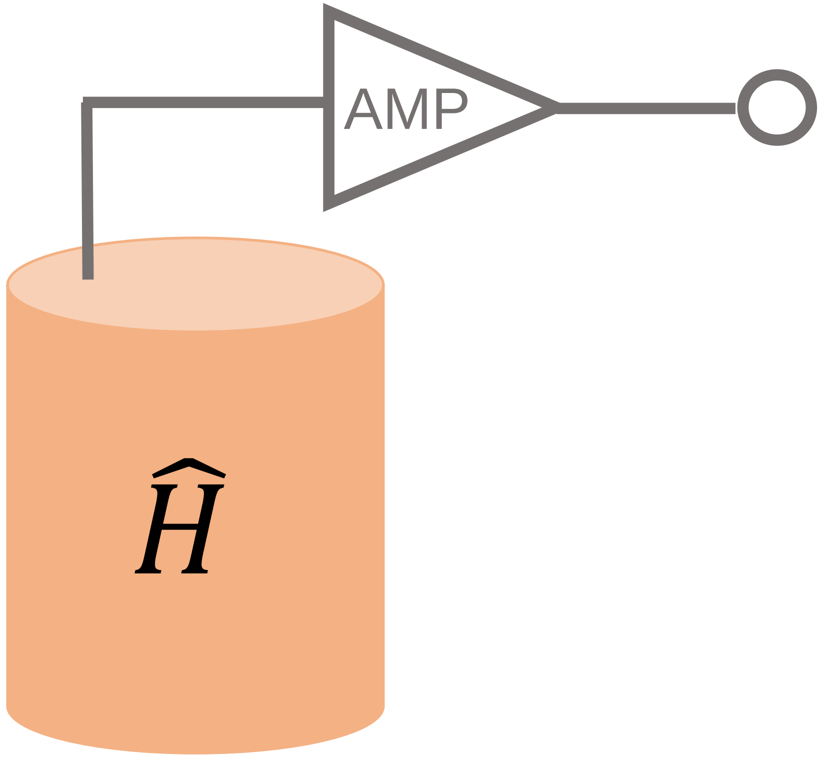
Quantum Limit for Haloscopes

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

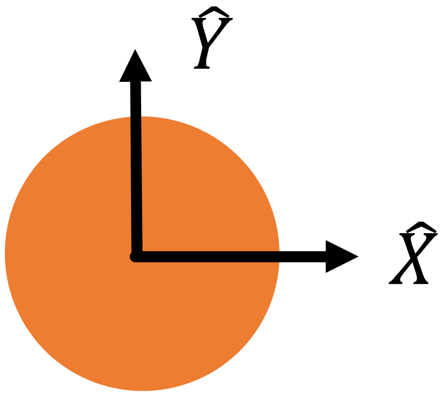


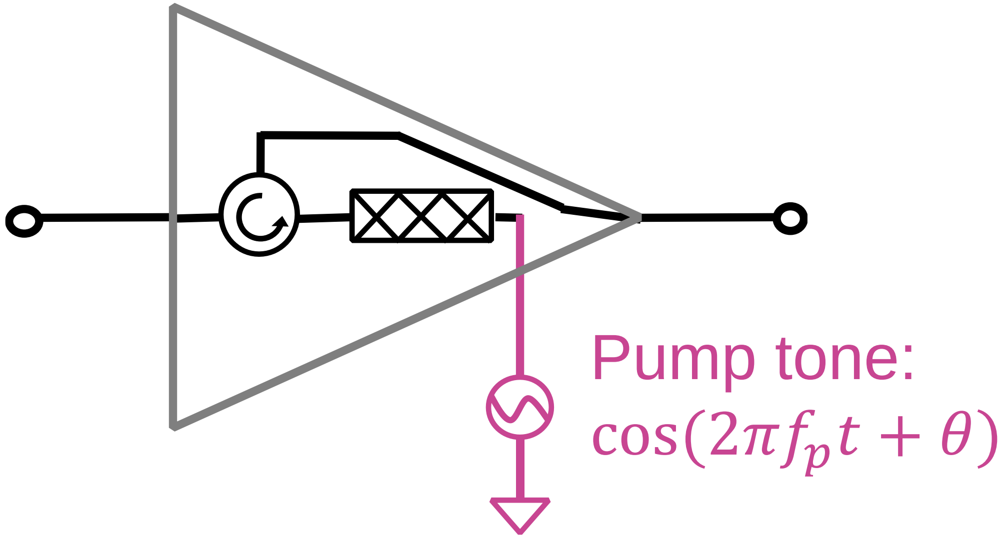
C. M. Caves. Phys. Rev. D, 26 1817-1839, (1982)

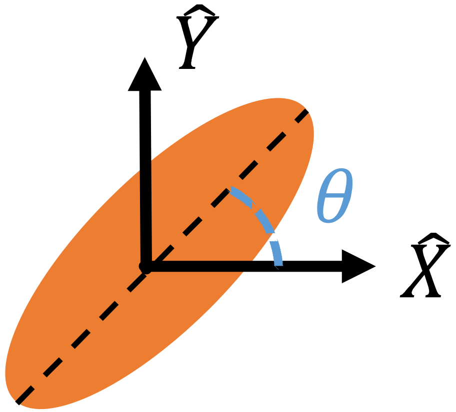
H. A. Haus and J. A. Mullen. Phys. Rev., 128 2407-2413, Dec 1962.

Benefit of JPA

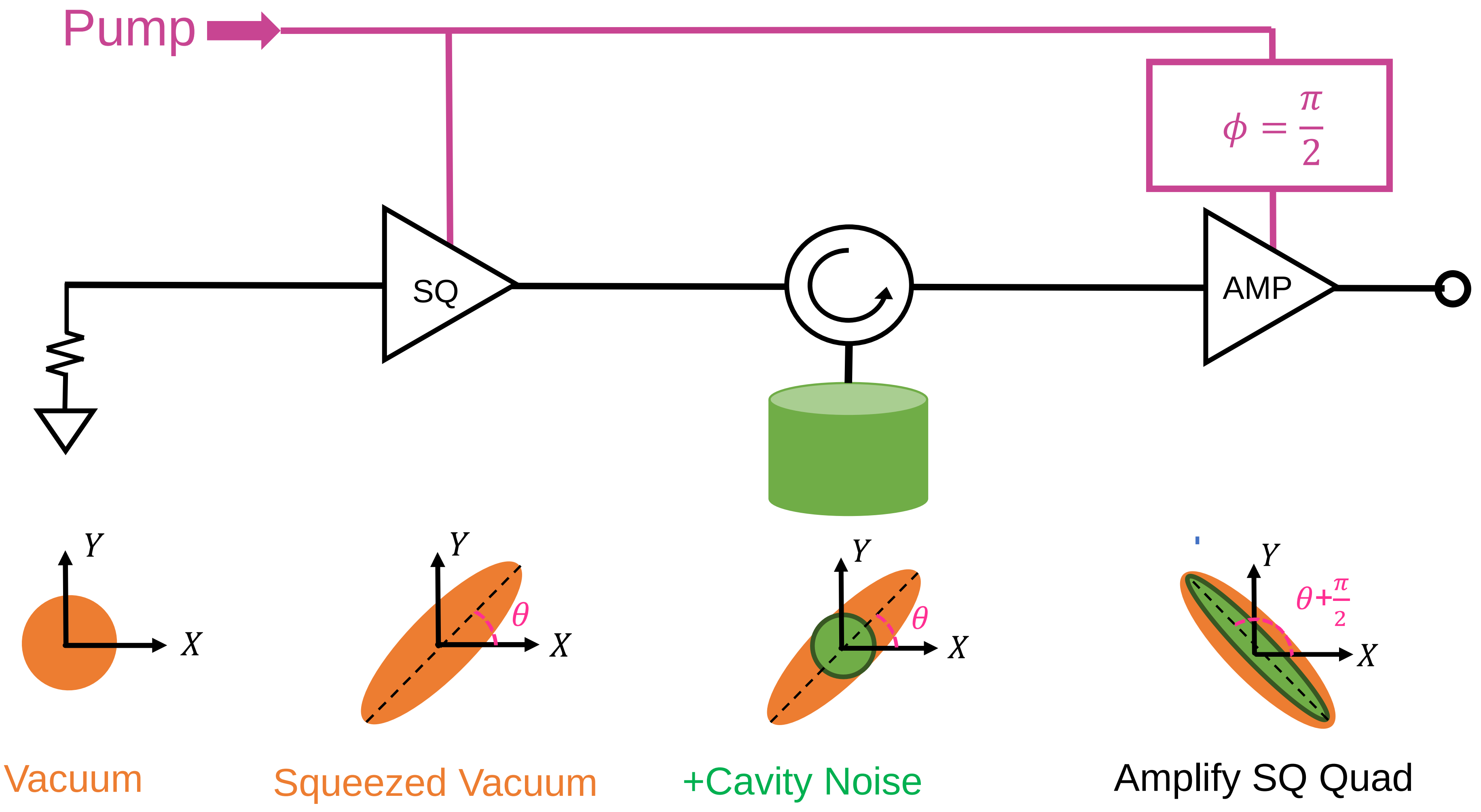
- JPAs achieve near SQL when Phase-Insensitive
- JPAs are Phase-Sensitive Amplifiers
- Each Phase alone is not limited by SQL
- Can produce “Squeezed” States
  - Dump all uncertainty/noise into a single quadrature



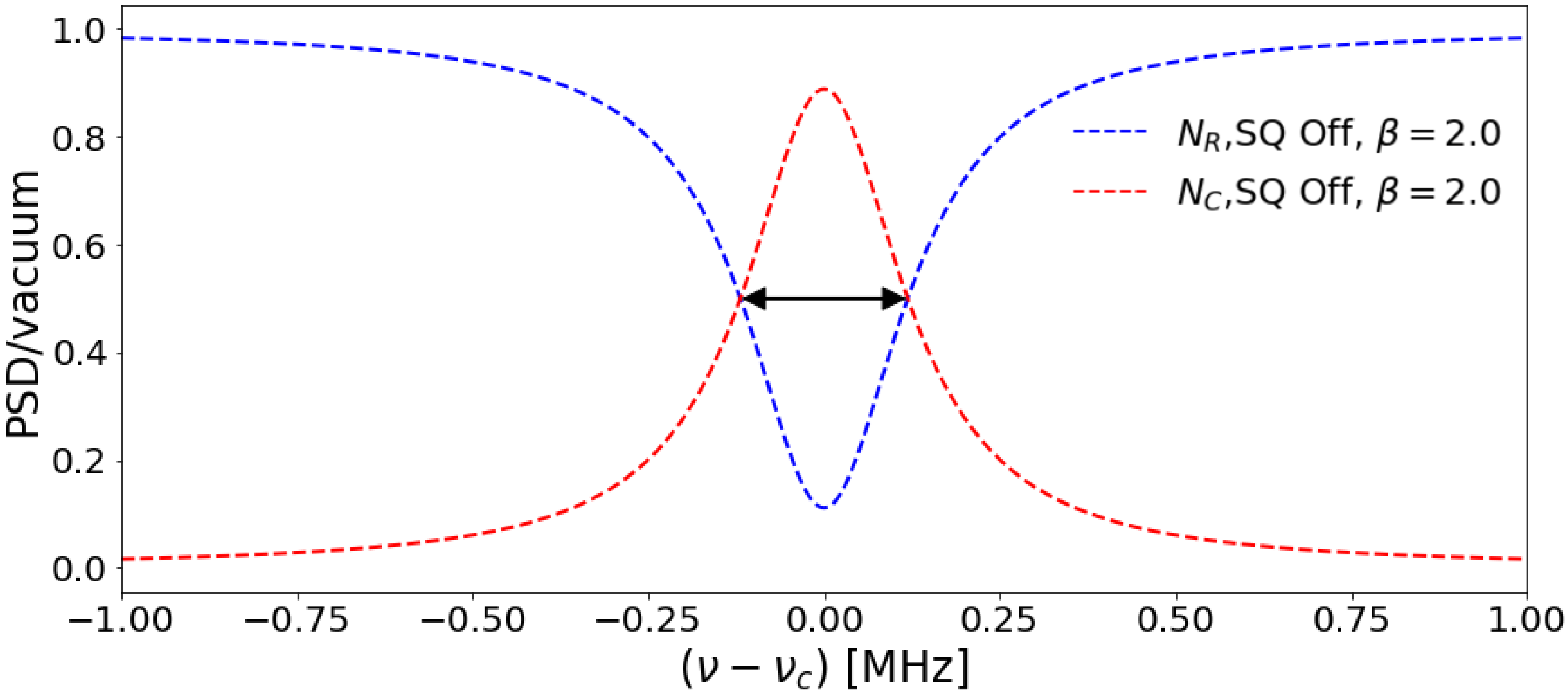




Squeezed State Receiver



Bandwidth Enhancement



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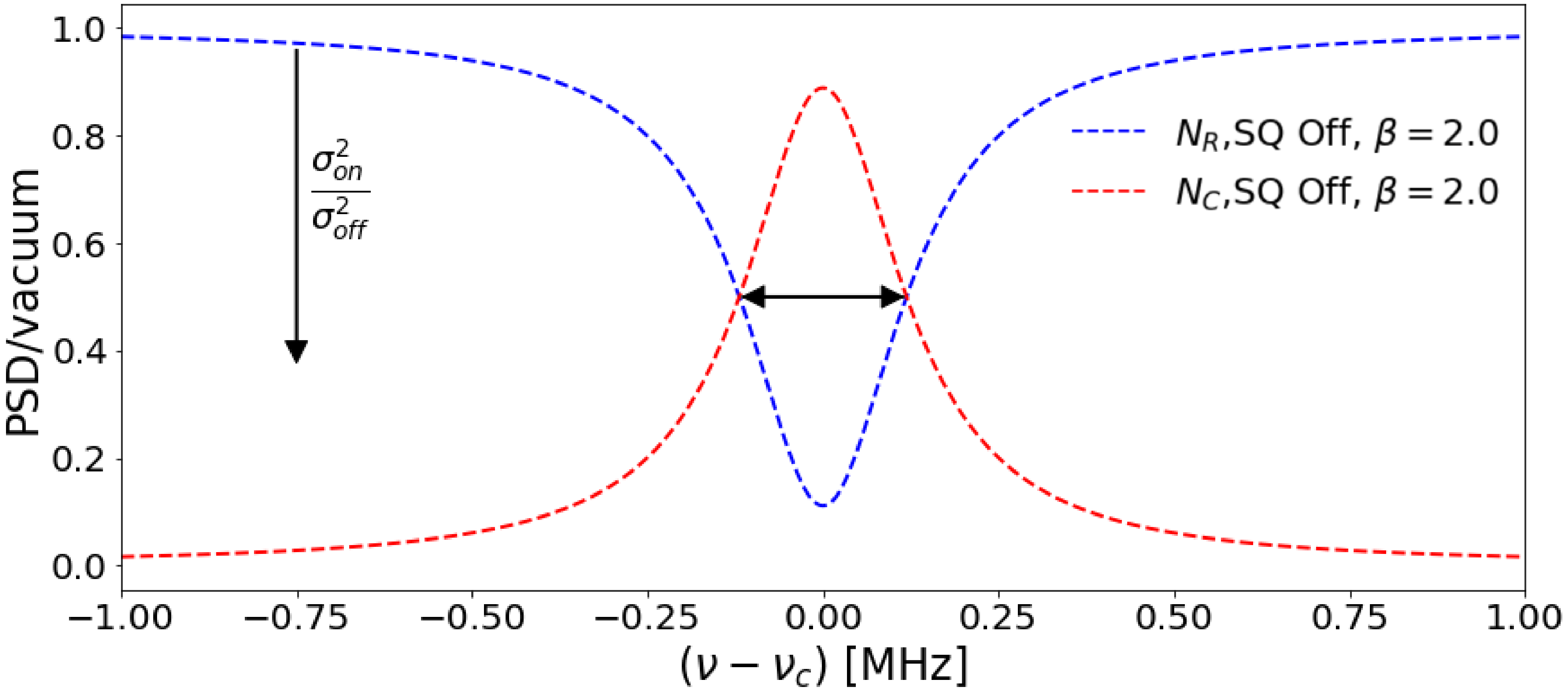

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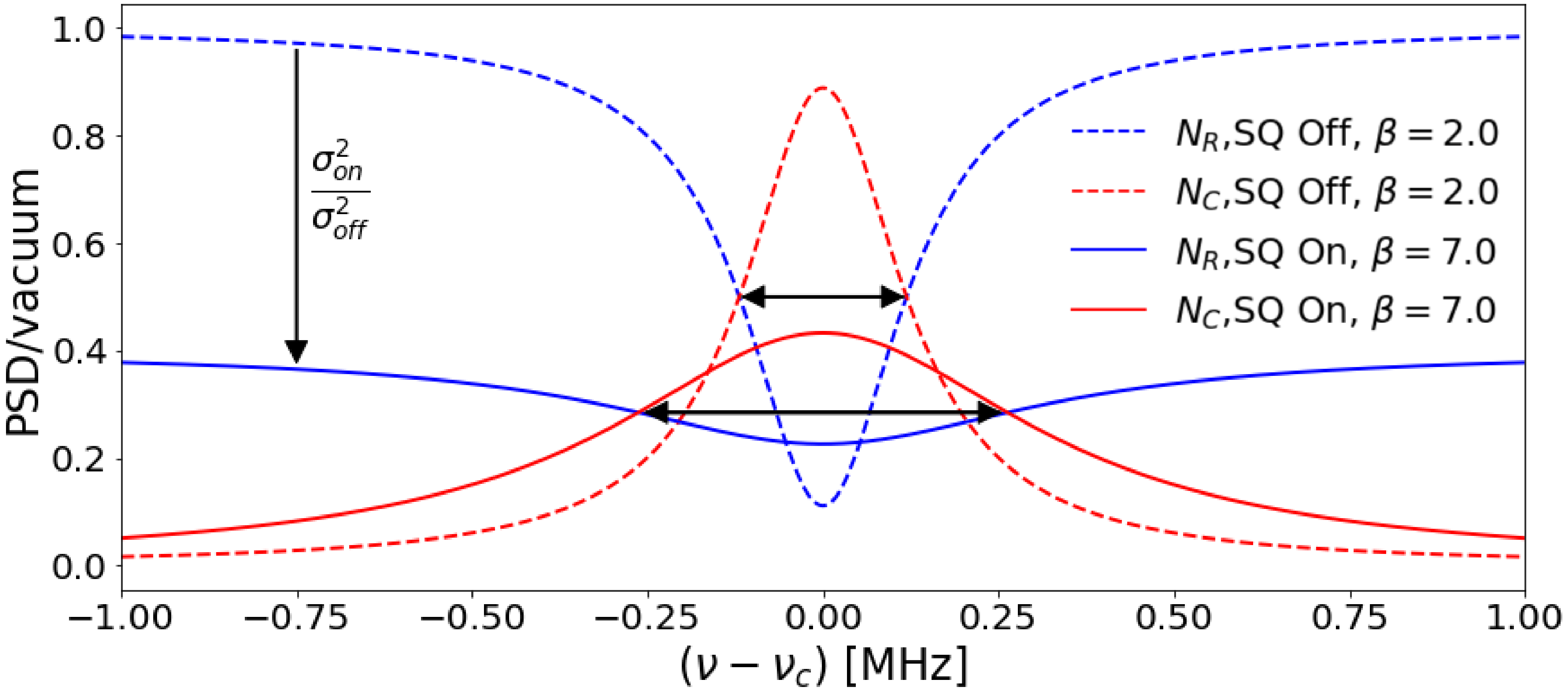
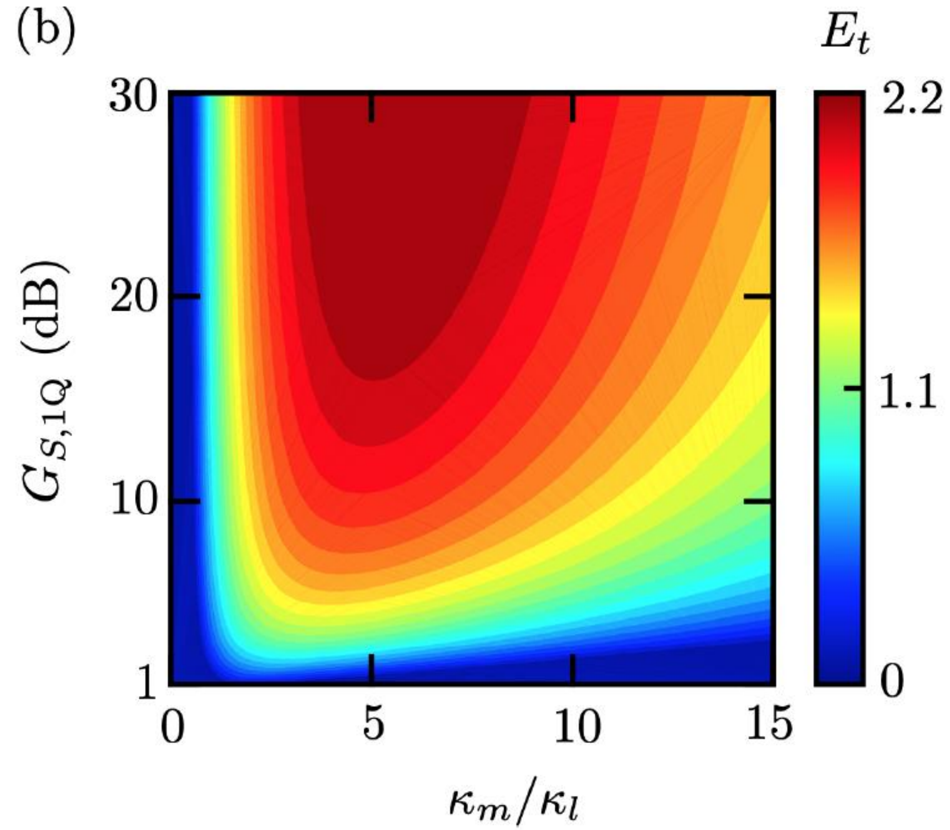


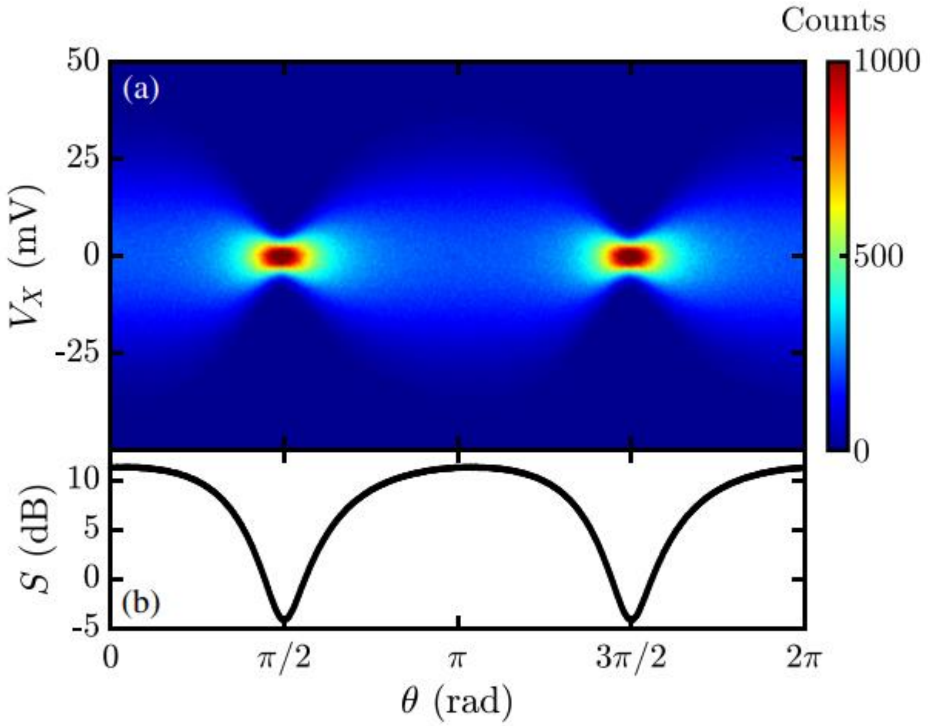
First Demonstration

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

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

2.1x Speed

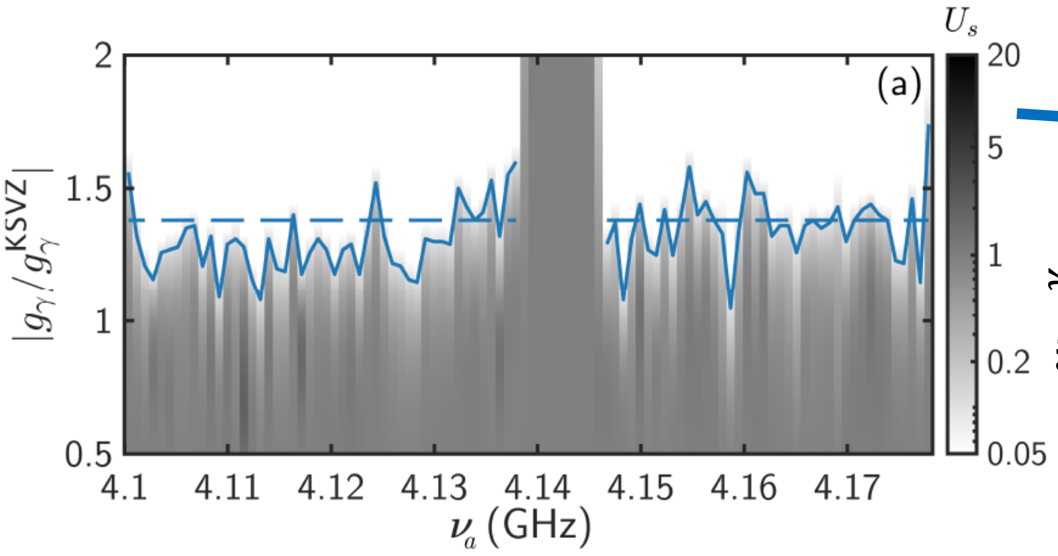


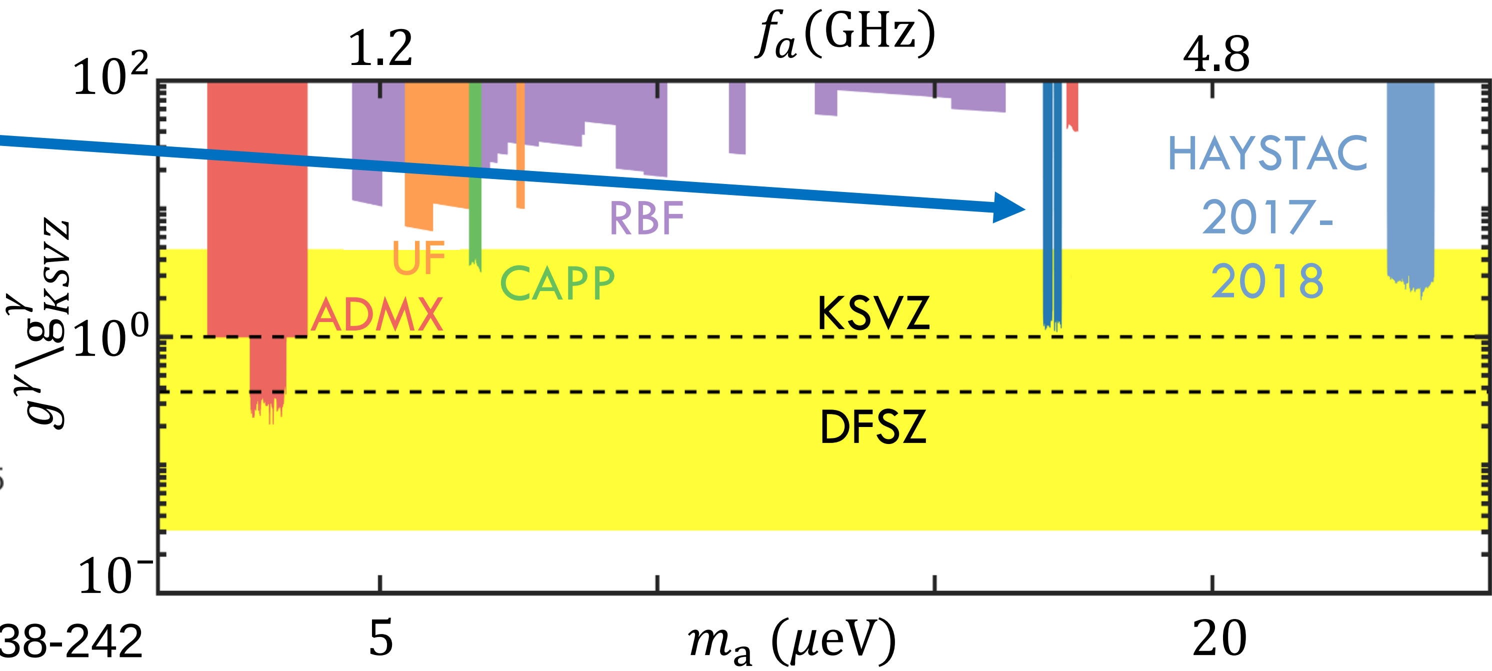


M. Malnou et al., Phys. Rev. X 9, 021023 (2019)

First Results with Squeezing

- Enhancement from Squeezing
  - ~4 dB of Squeezing
  - Speed up of ~2x
- Axion Exclusion
  - Scanned ~73MHz of parameter space
  - Achieved sensitivity to g_γ=1.38g_γ^{KSVZ}





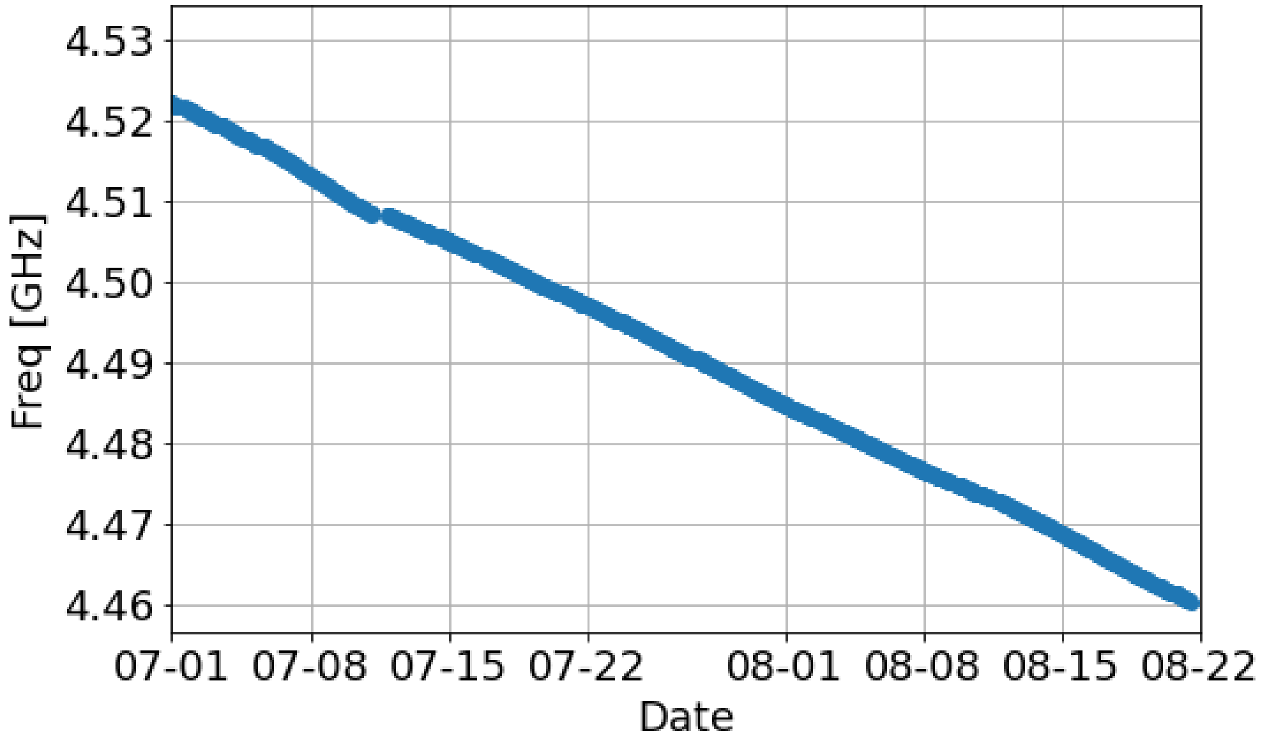
K.M. Backes et al. , Nature 590 (2021) 7845, 238-242

Additional Data Taking

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

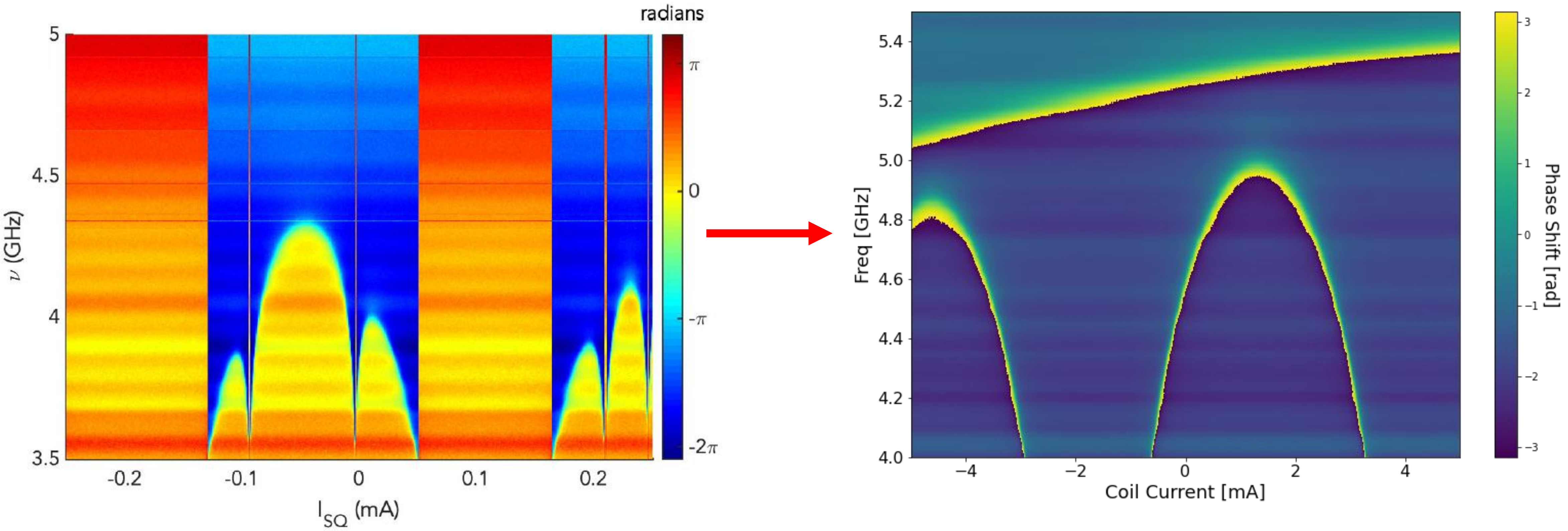
- Recently completed 2nd data taking campaign
  - **Analysis still preliminary**
- Main Changes/Improvements
  - New JPAs → Higher Frequency
  - Modified DAQ → Improved Livetime
  - Realigned Tuning Rod → Less Mode Drift

Preliminary



Extending Beyond 4.2GHz

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

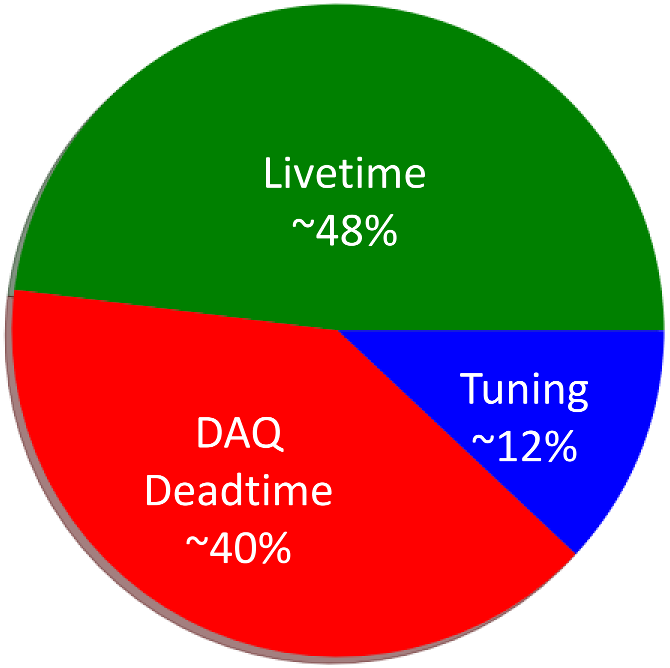


Improved Livetime

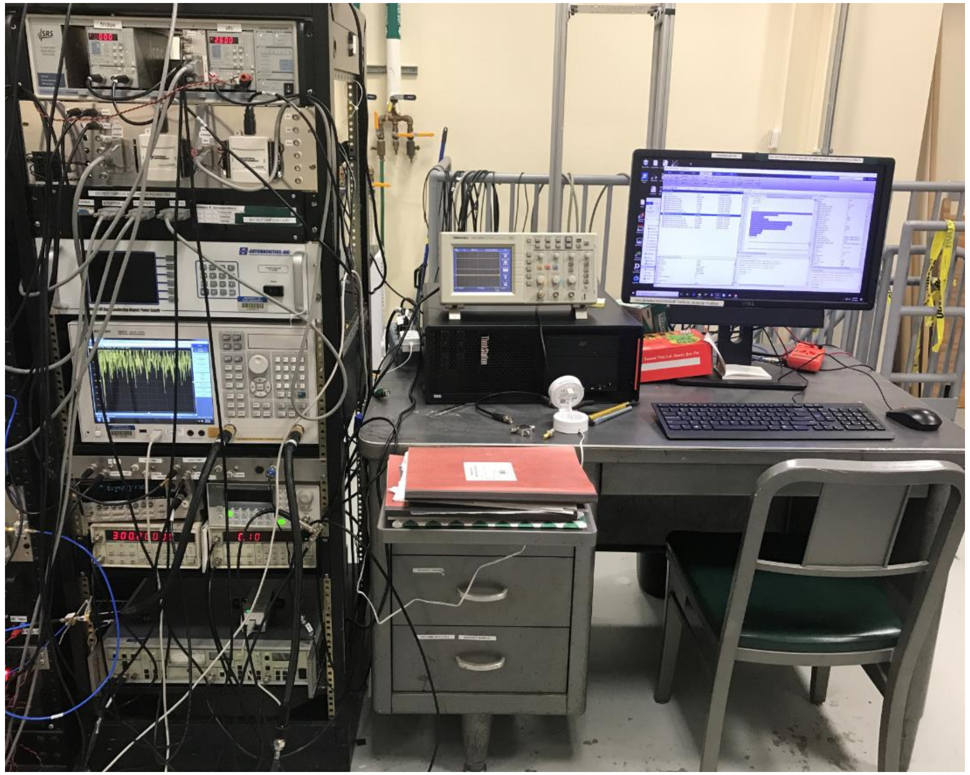
- Ideally always recording cavity field

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

- Phase IIa operation ~48% livetime



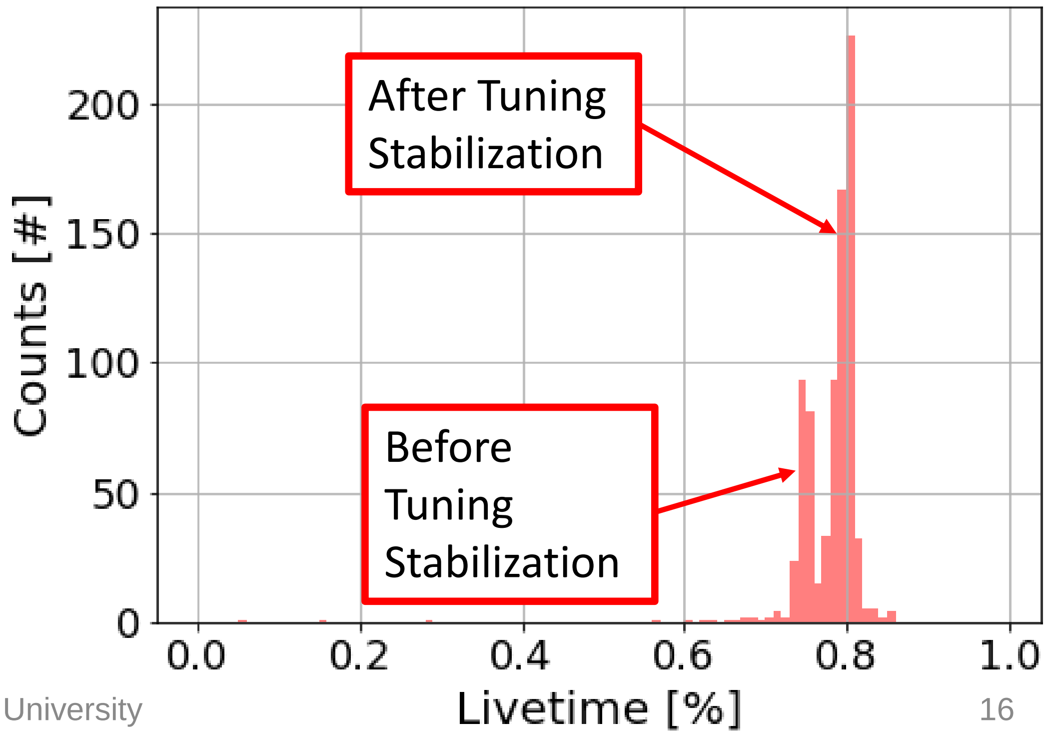
- 1hr of data @ 10 MS/s
- ~100GB per tuning
- >100TB for Phase IIa



Improving Livetime

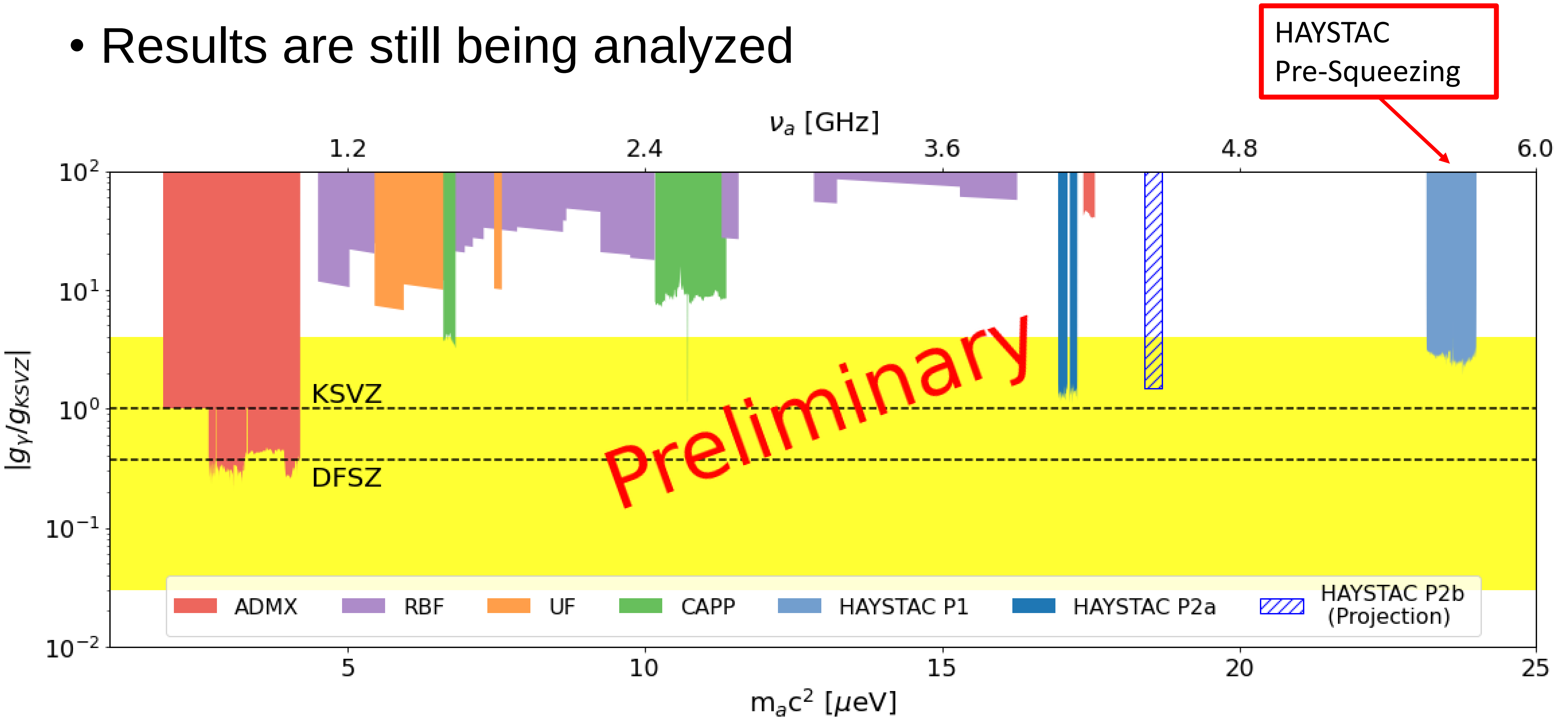
- DAQ Deadtime
  - Parallelization of FFT
  - Optimization of Data Transfer
- Tuning Stabilization
  - Reinstalled cavity has less mode drift after tuning
  - Better rod alignment
- Phase IIb achieved 78% average livetime
  - 82% after tuning improvement

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



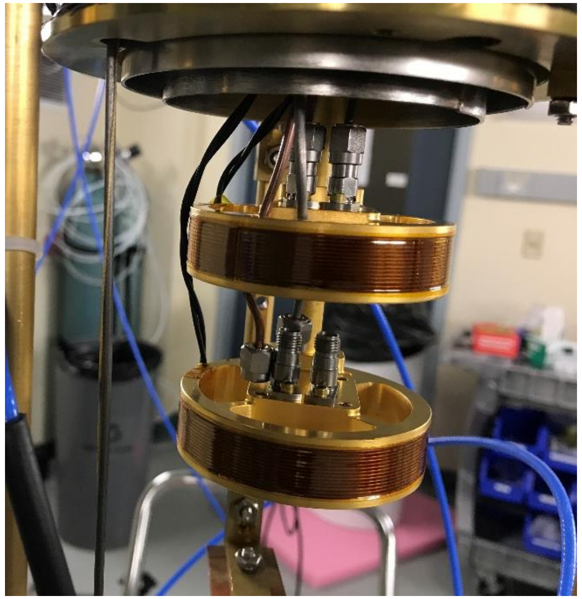
Projected Sensitivity

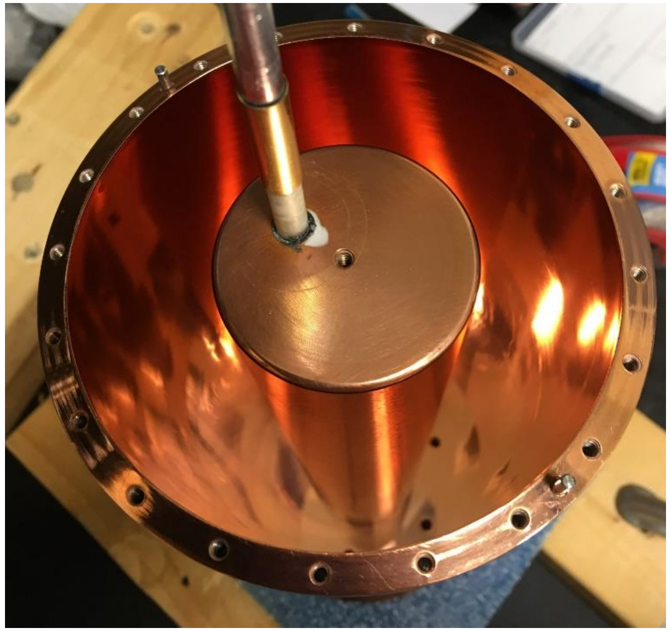
- Results are still being analyzed

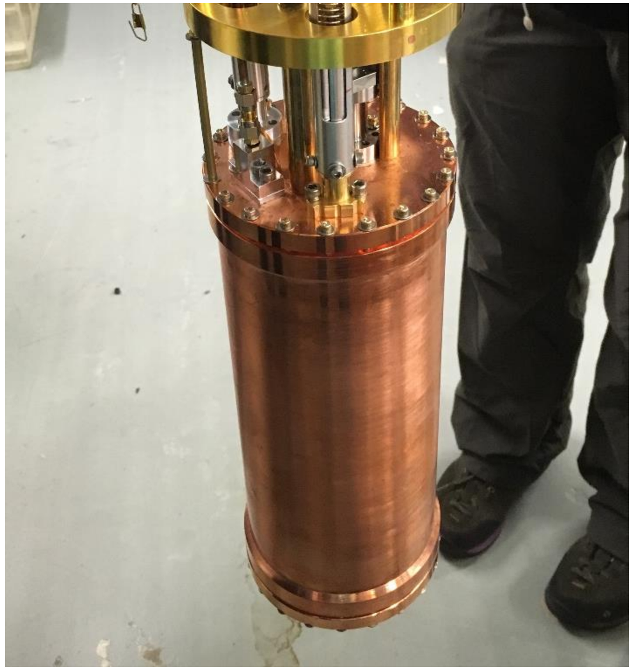


Conclusion

- HAYSTAC is continuing to search for axions with m_a > 10 μeV
- Second Data taking Phase with the SSR
  - Searched another 62 MHz of parameter space
  - New JPAs → Extend search to 4.5GHz
  - Improvement livetime to ~78% → ~1.6x scan rate enhancement

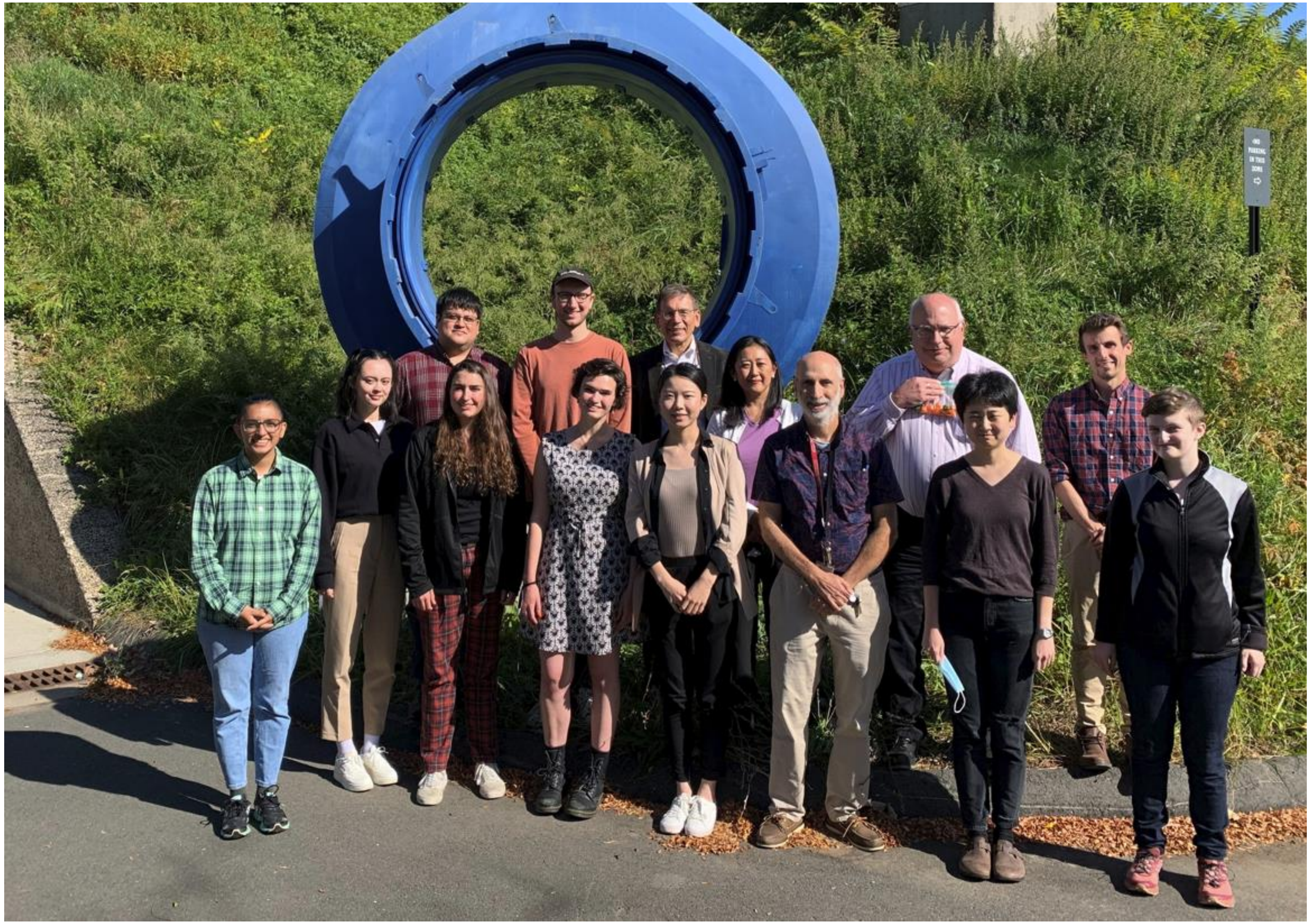






Haystac

Thanks



Wright Laboratory

JILA
CU Boulder and NIST

LUX ET VERITAS

JOHNS HOPKINS
UNIVERSITY

THE UNIVERSITY OF CALIFORNIA BERKELEY
LET THERE BE LIGHT
1868

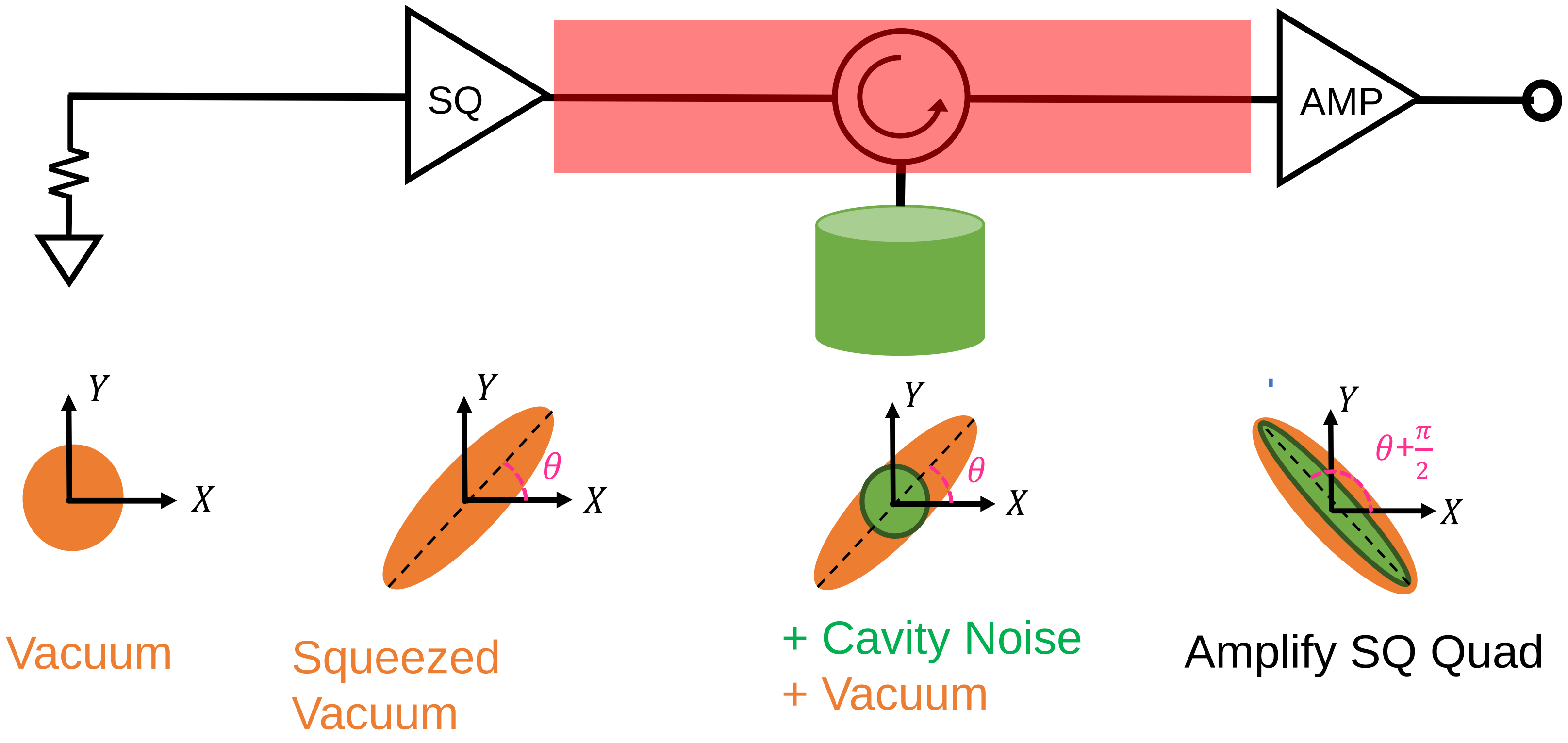
HEISING-SIMONS
FOUNDATION

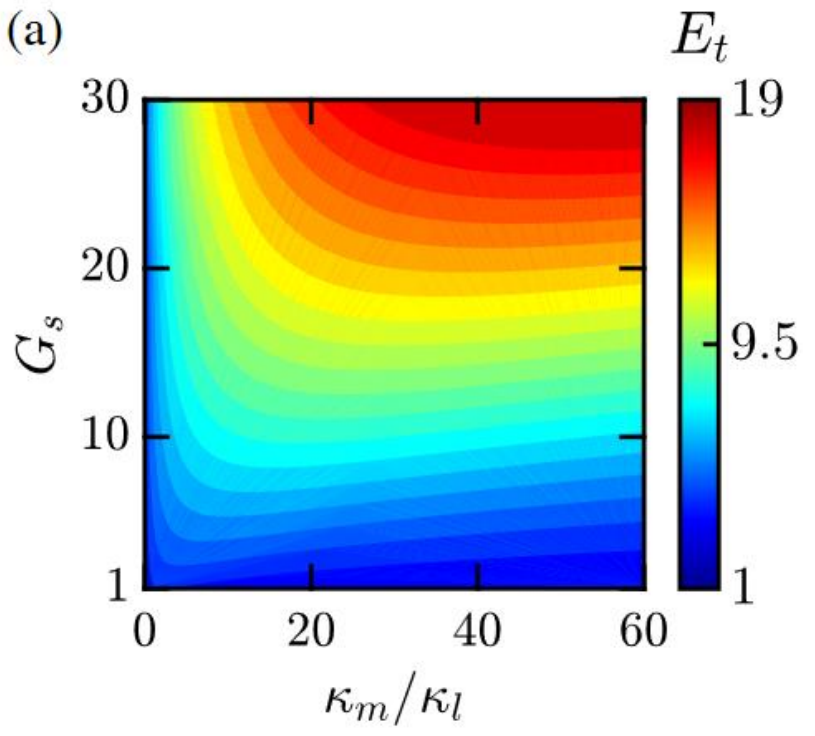
NSF

Backups

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

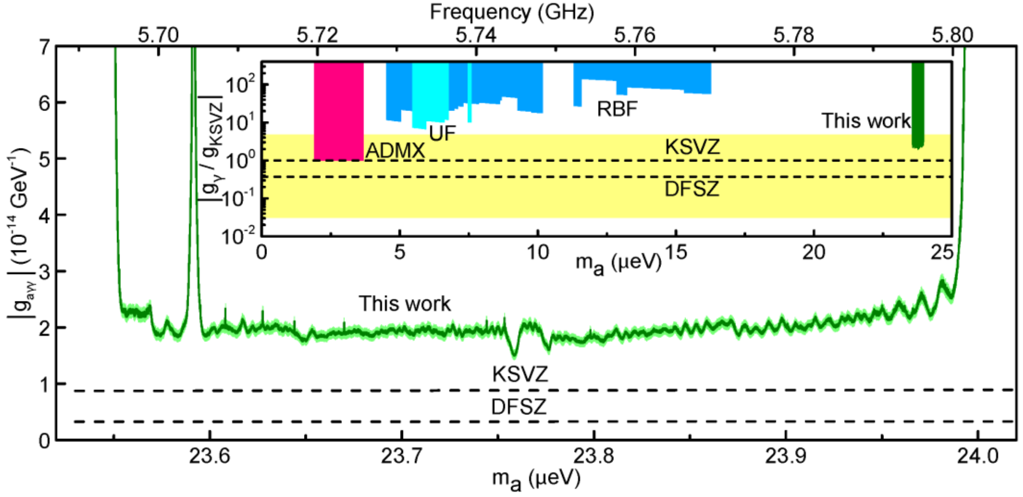


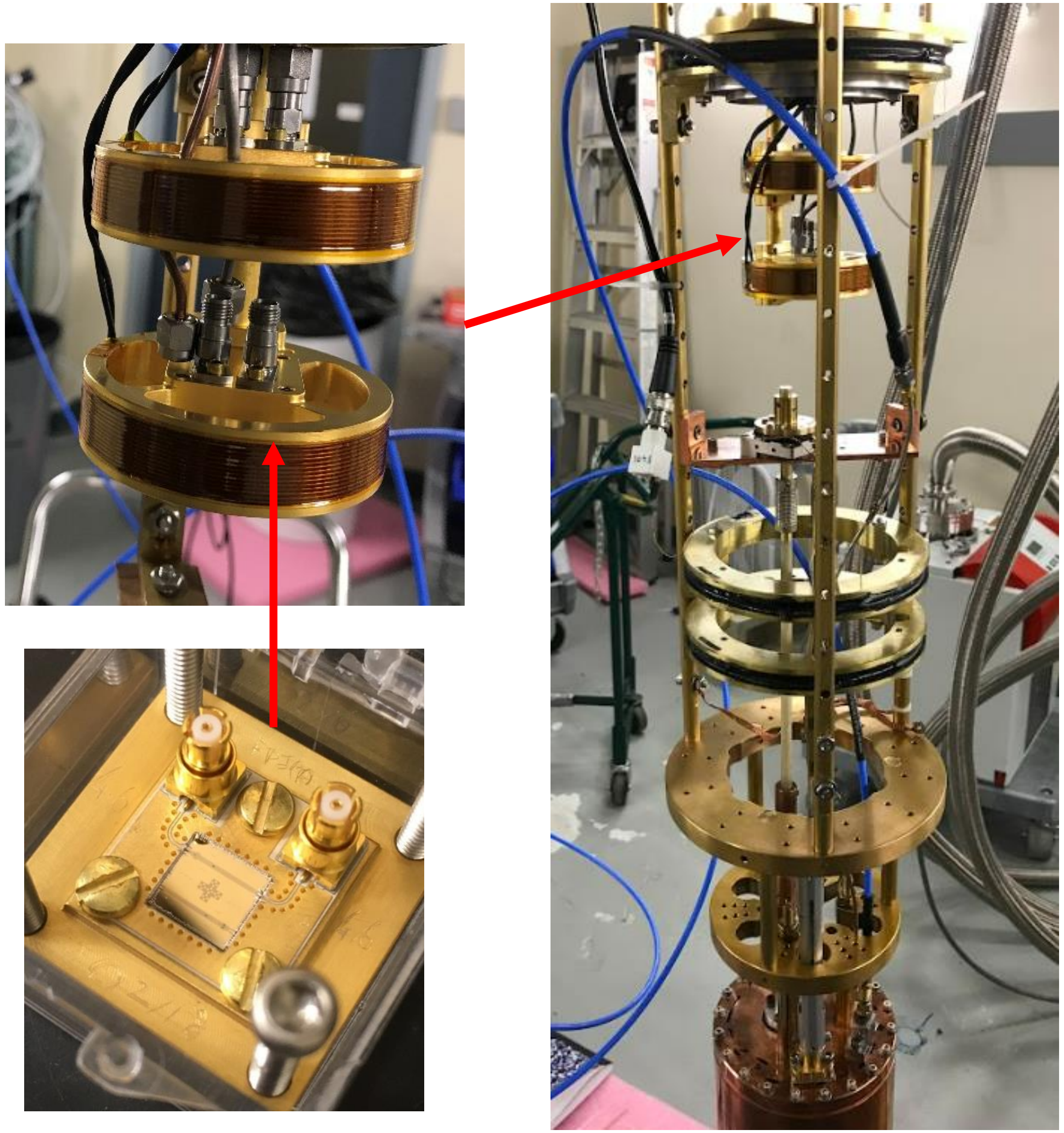


M. Malnou et al., Phys. Rev. X 9, 021023 (2019)

Installing SSR in HAYSTAC

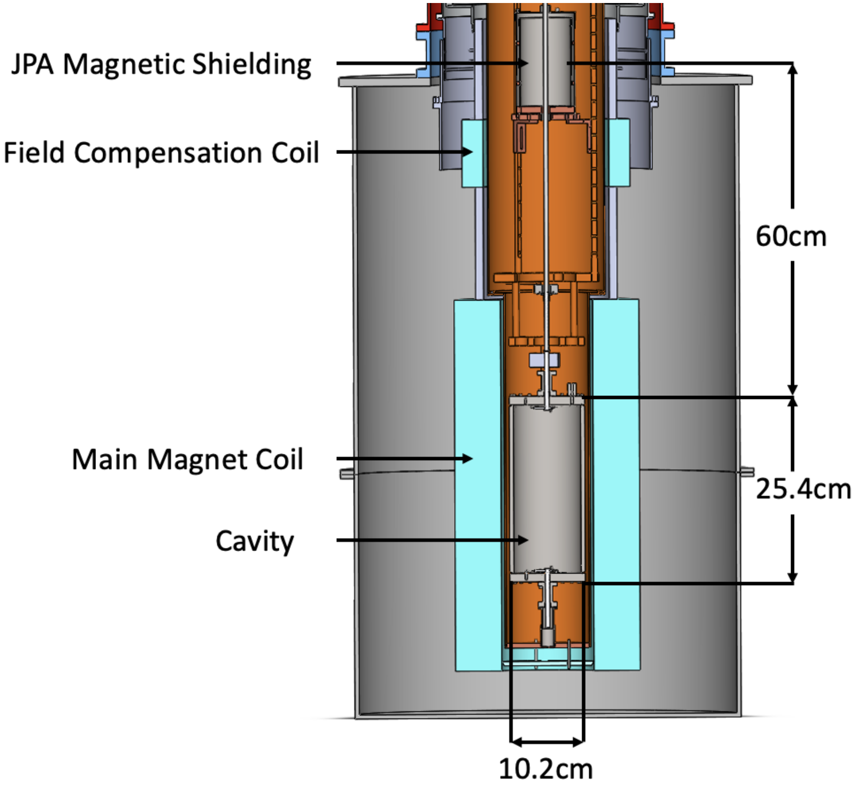
- Phase-I (2012-2018)
  - Single Phase-Insensitive JPA
  - Scanned 5.6-5.8GHz
  - *Phys. Rev. D* 97 (2018) 9, 092001
- SSR installed into HAYSTAC in 2018

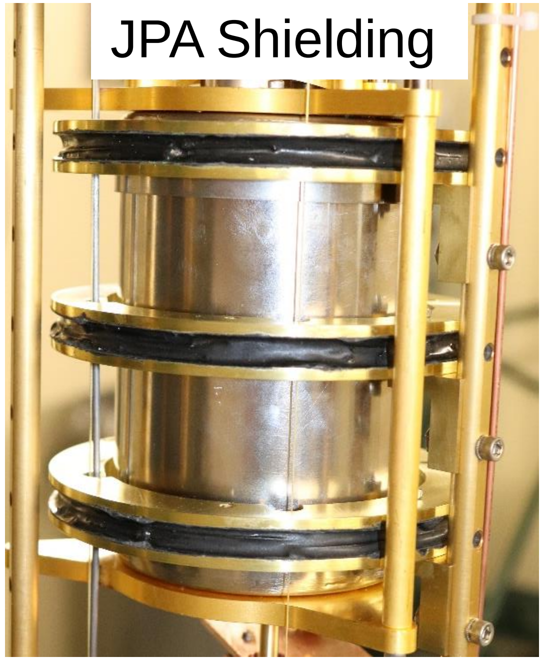


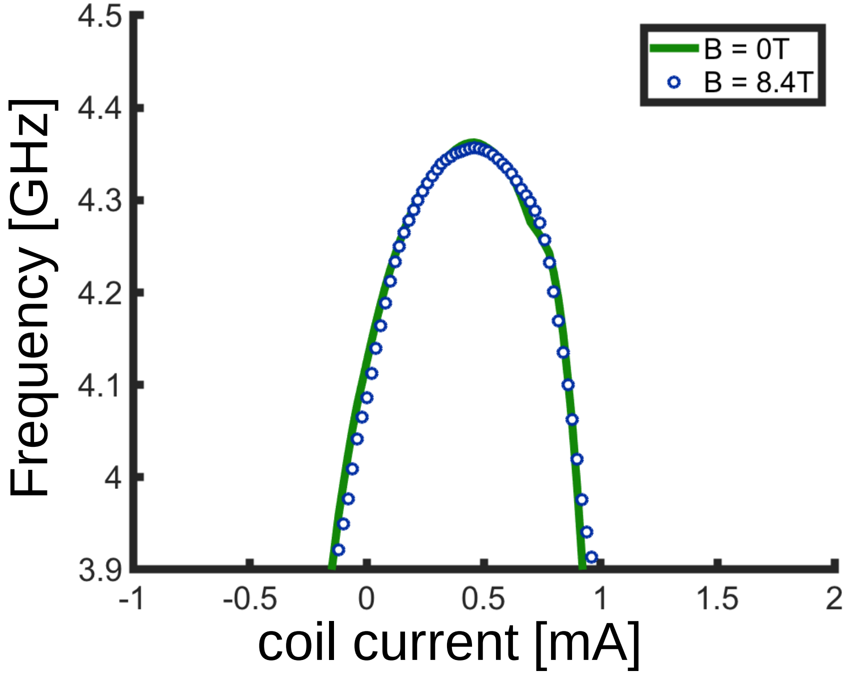


Operating JPAs Near Magnet

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

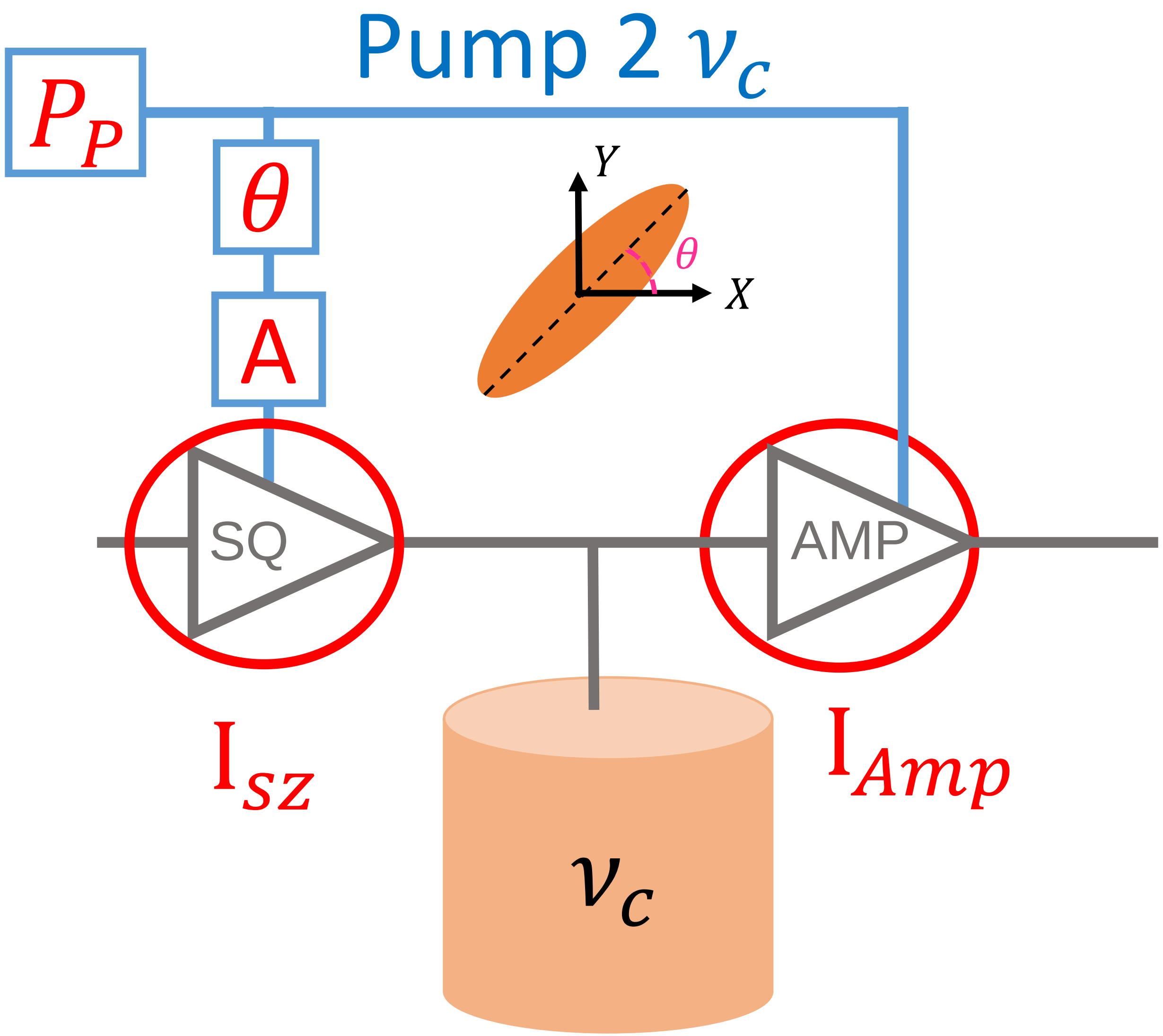






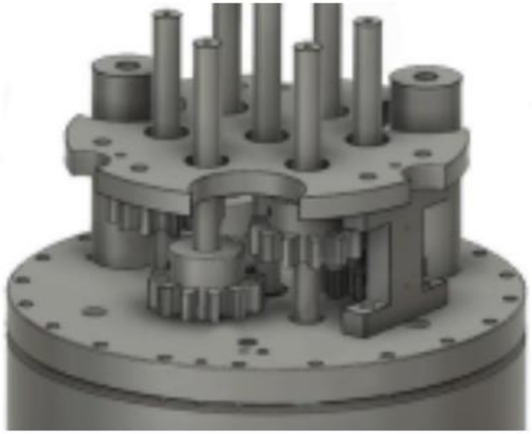
Tuning with SSR

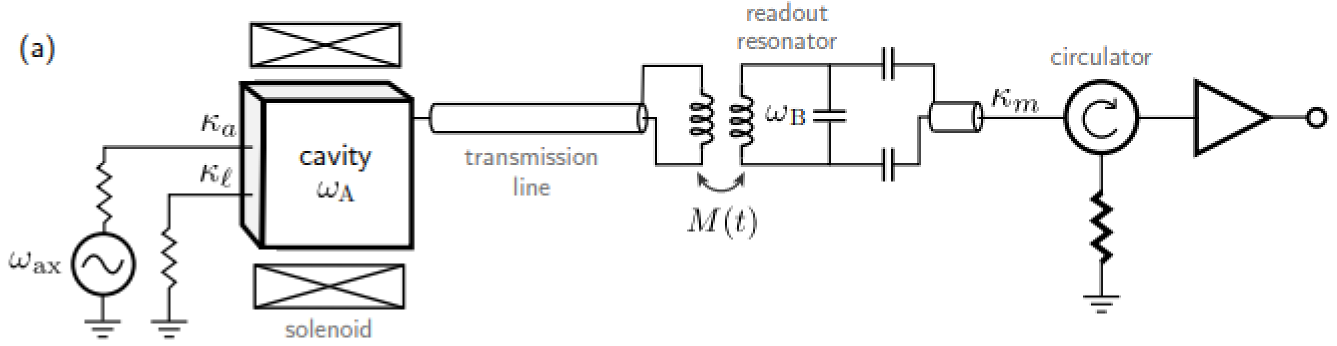
- Five parameter optimization
- JPAs tuned to match Cavity Resonance
  - I_{sz}: Squeezer Flux Bias
  - I_{AMP}: Amplifier Flux Bias
- Amplifiers share same Pump Source
  - P_P: Amplifier Gain
  - A: Squeezer Gain
  - θ: Phase difference

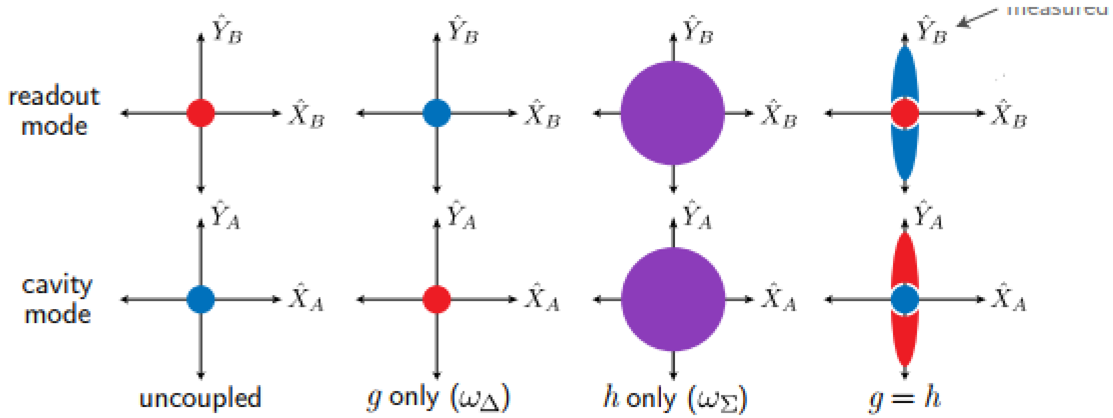


What's Next…

- Further enhancement with Squeezing
  - **State Swapping (CEASEFIRE):** Squeezing before loss
    (*K. Wurtz et al, PRX Quantum 2 (2021) 4, 040350*)
- Current setup tops out around ~6GHz
  - Limited by Cavity Range
  - **Multi-Rod Cavity:** Same cavity but 5-7GHz
    (*M. Simanovskaia et al, Rev. Sci.Instrum.* 92 (2021) 3, 033305)

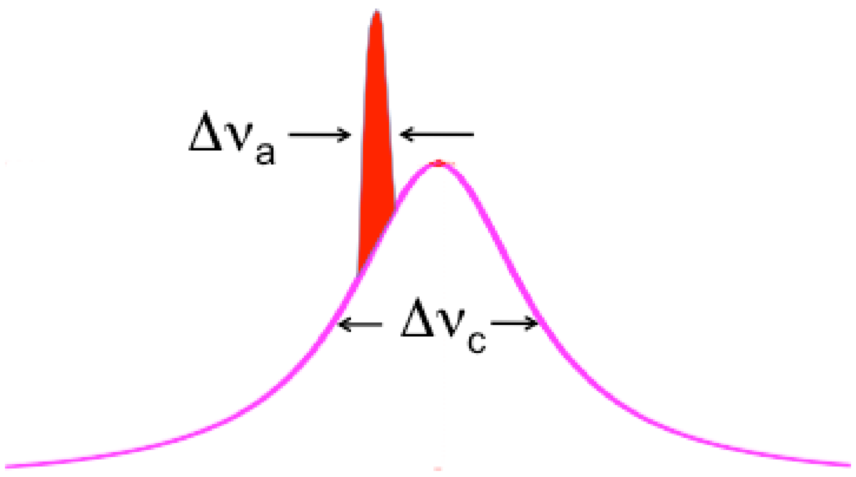


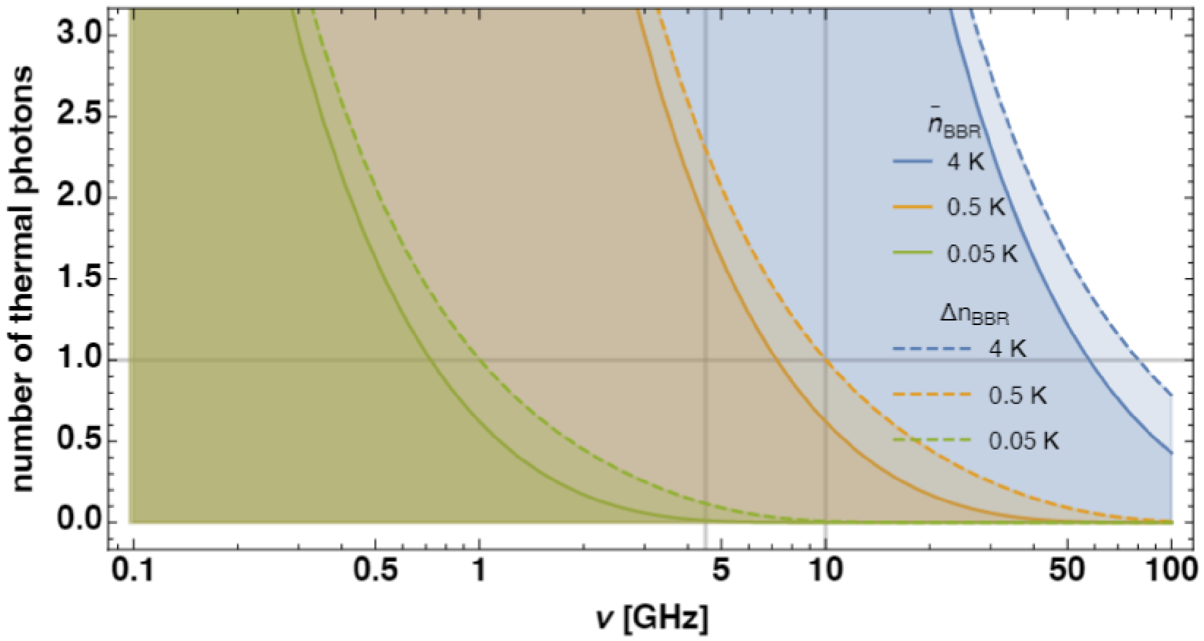




Single Photon Detection

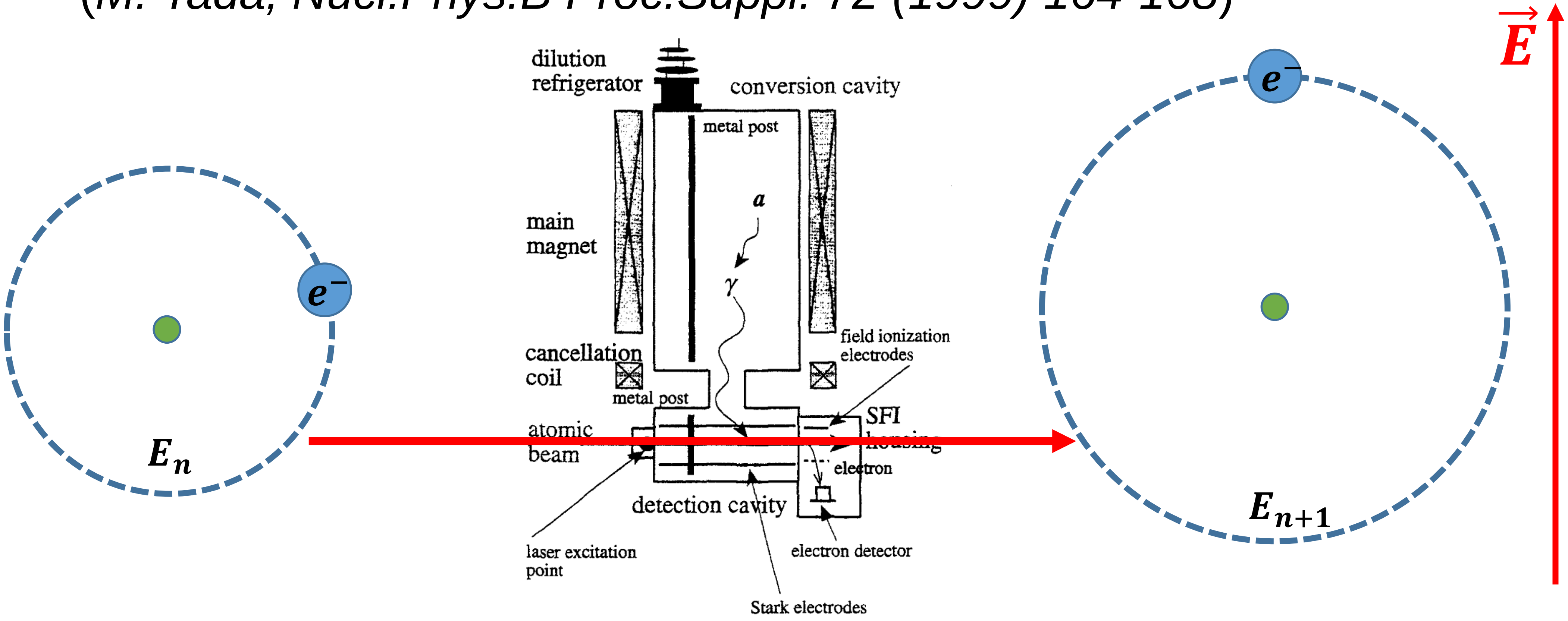
- Ultimate goal of “Squeezing” is Single Photon Detection
  - Lose Spectral Information
  - Only shot noise limited
  - Payoff >~10GHz (*S. K. Lamoreaux et al., Phys. Rev. D 88, 035020 (2013)*)





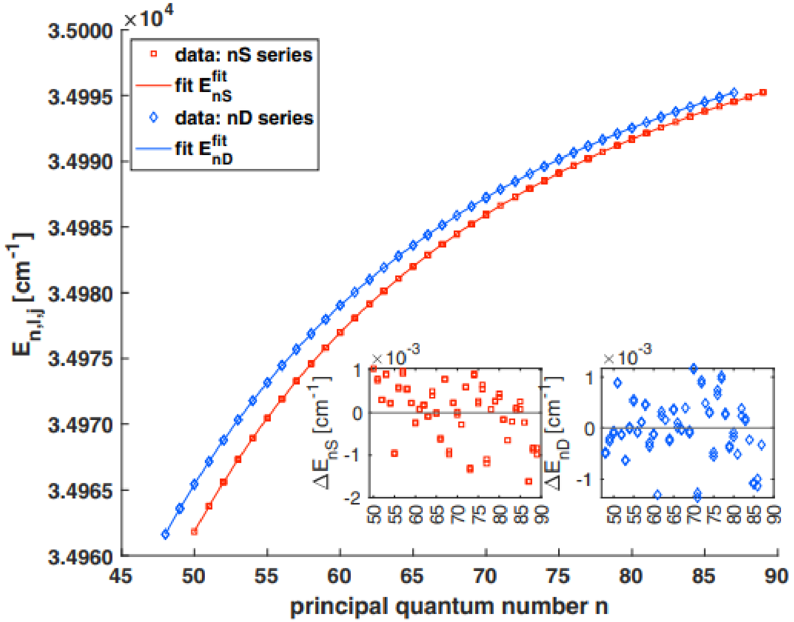
Rydberg Atoms

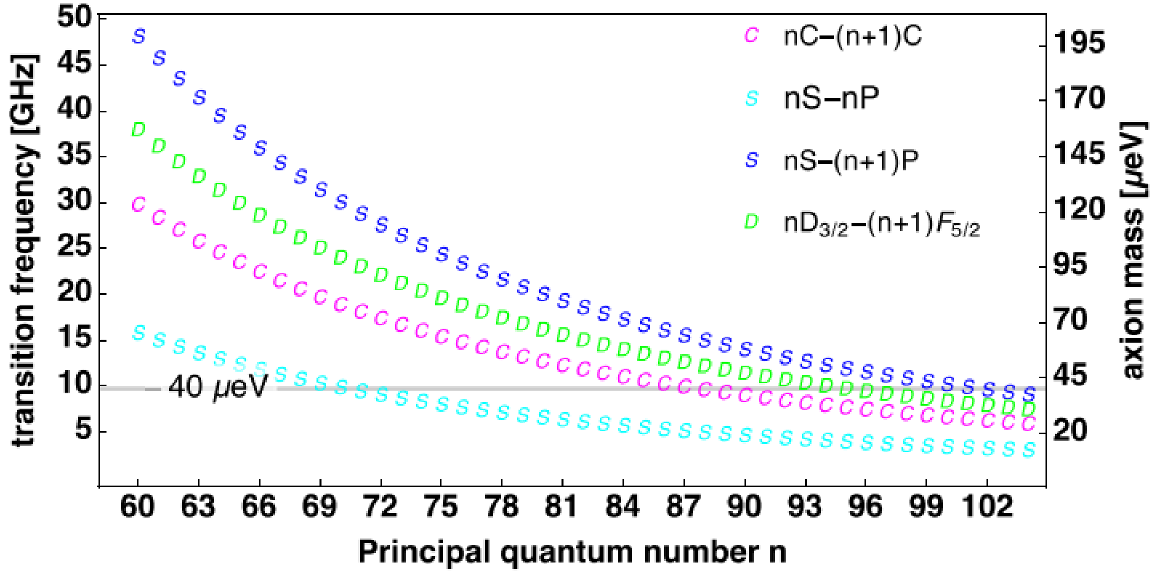
- Rydberg Atoms have transition frequencies >10GHz
  - First proposed by CARRACK
    (*M. Tada, Nucl.Phys.B Proc.Suppl. 72 (1999) 164-168*)



Rydberg Atoms at Yale (RAY)

- ^{39}K Rydberg Atoms
  - Demonstrated production of Rydberg states n=60-90
- Transition Frequencies give access to >10GHz

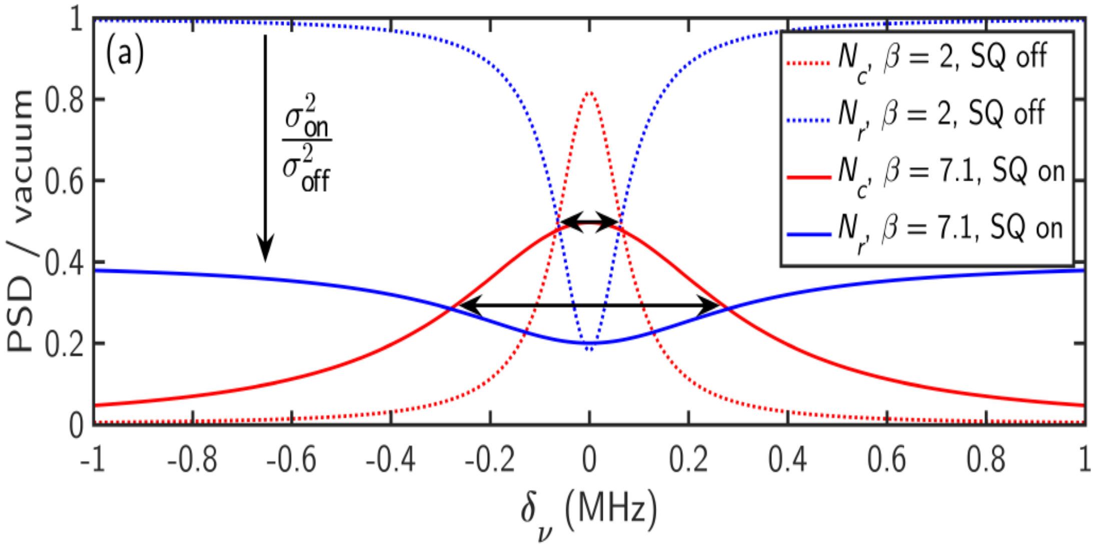


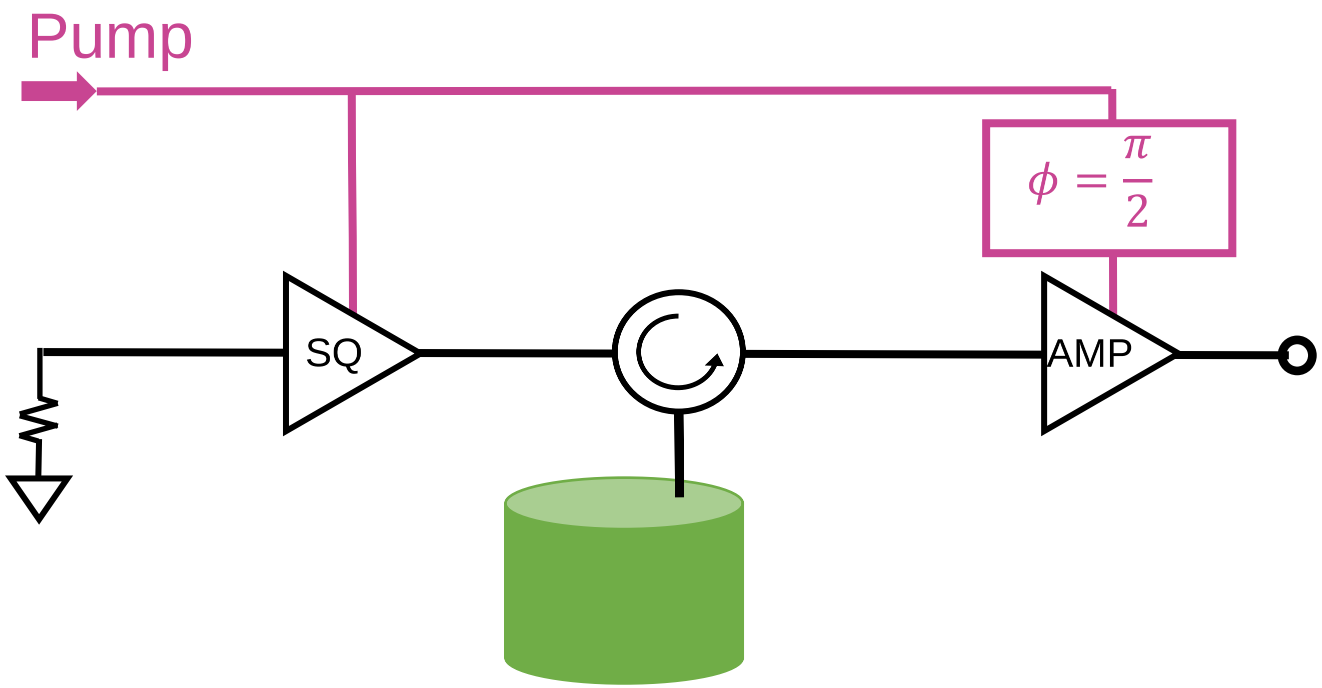


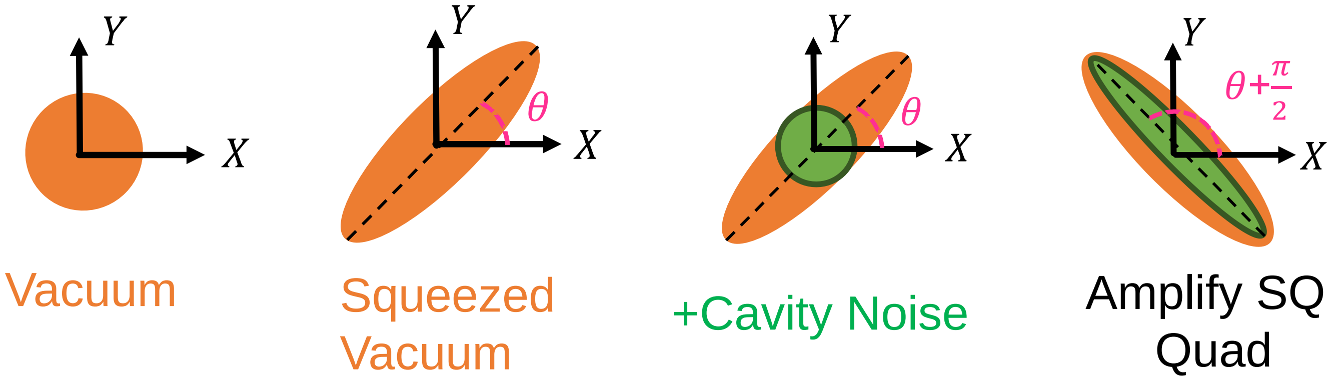
Y. Zhu et al, Phys. Rev. A 105, 042808

Quantum Enhancement

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



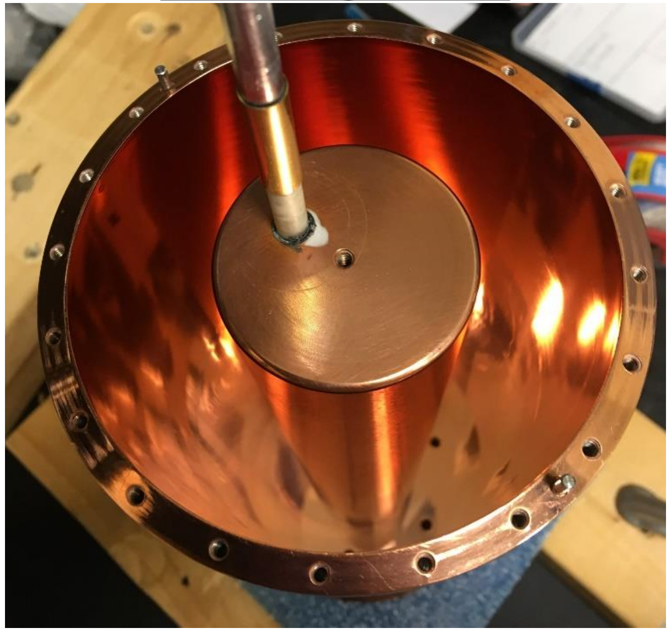




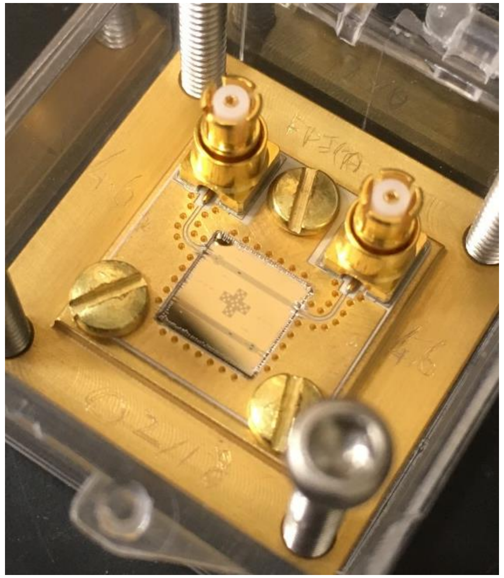
Haloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM

Cavity

Tuning Rod

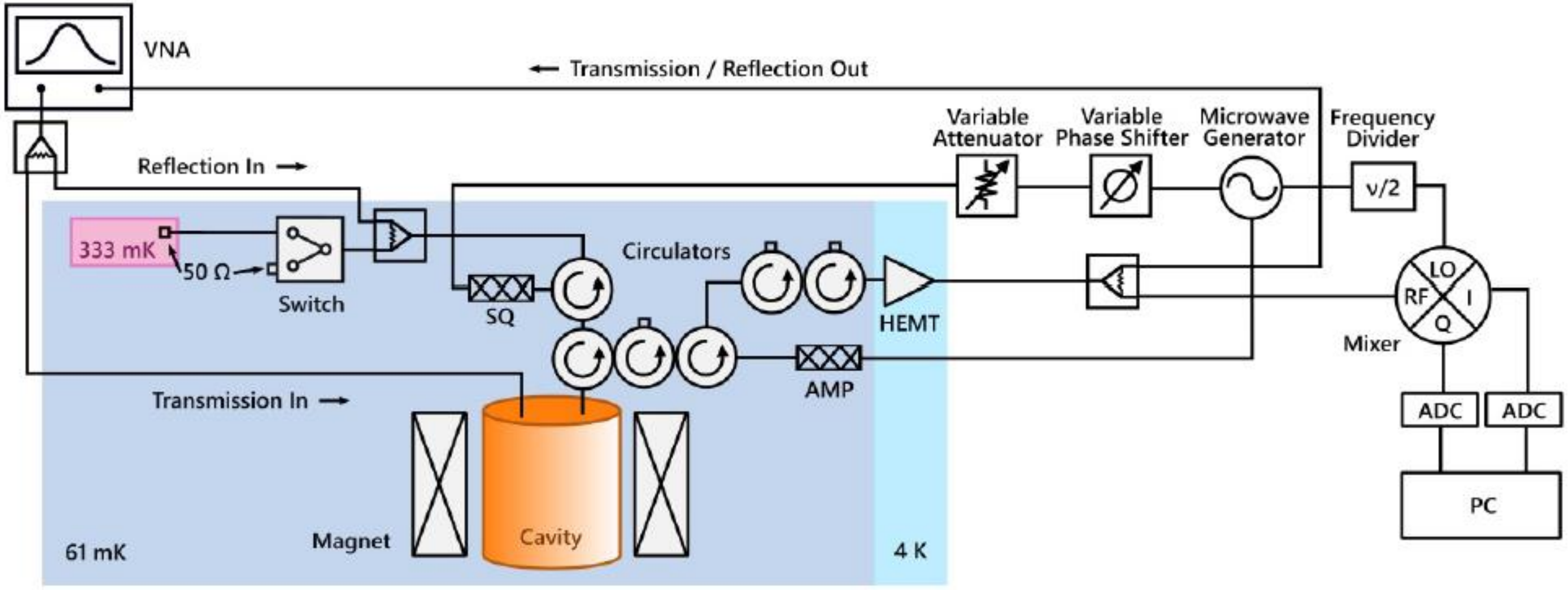


JPA



JPA Shield

System Diagram



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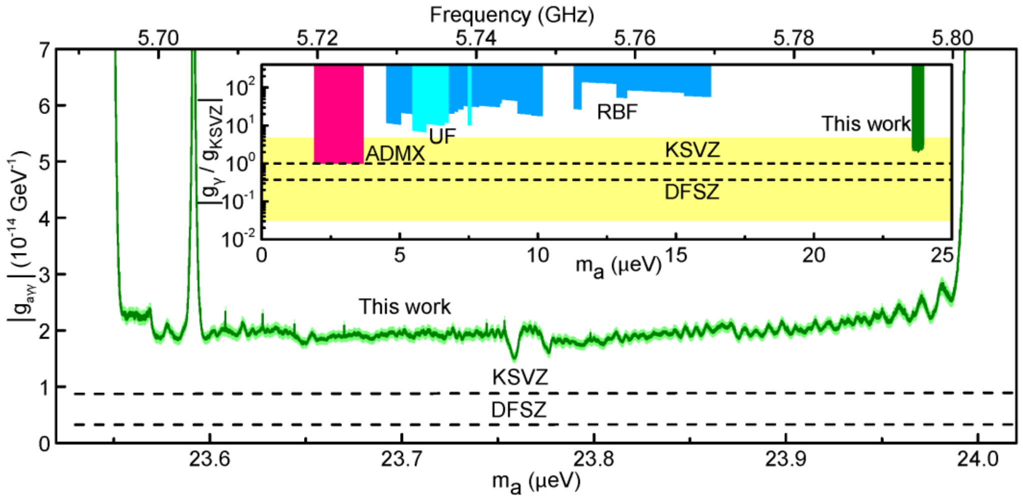

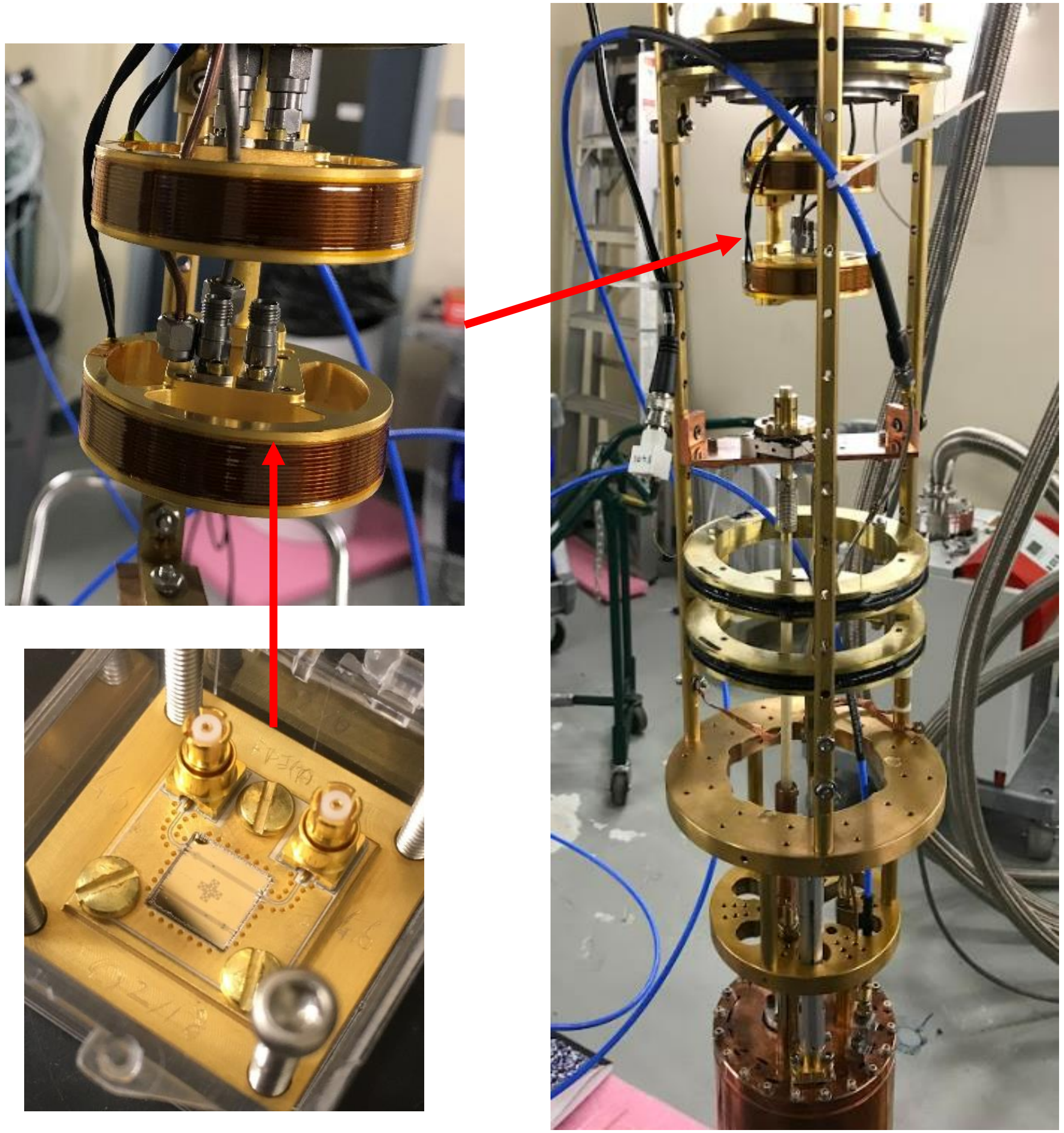

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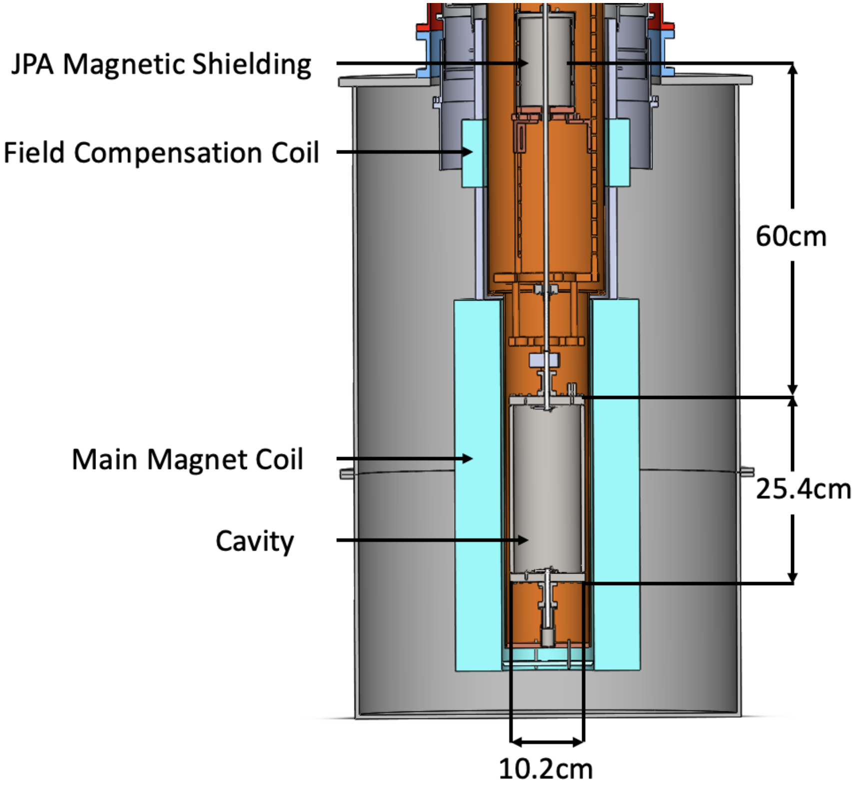

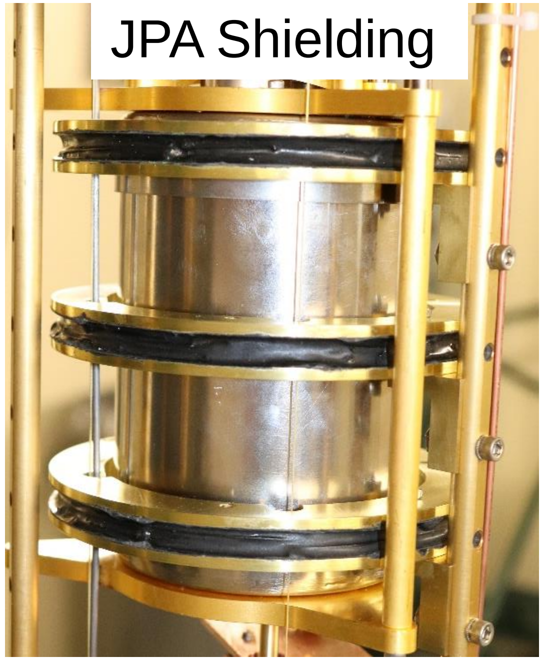

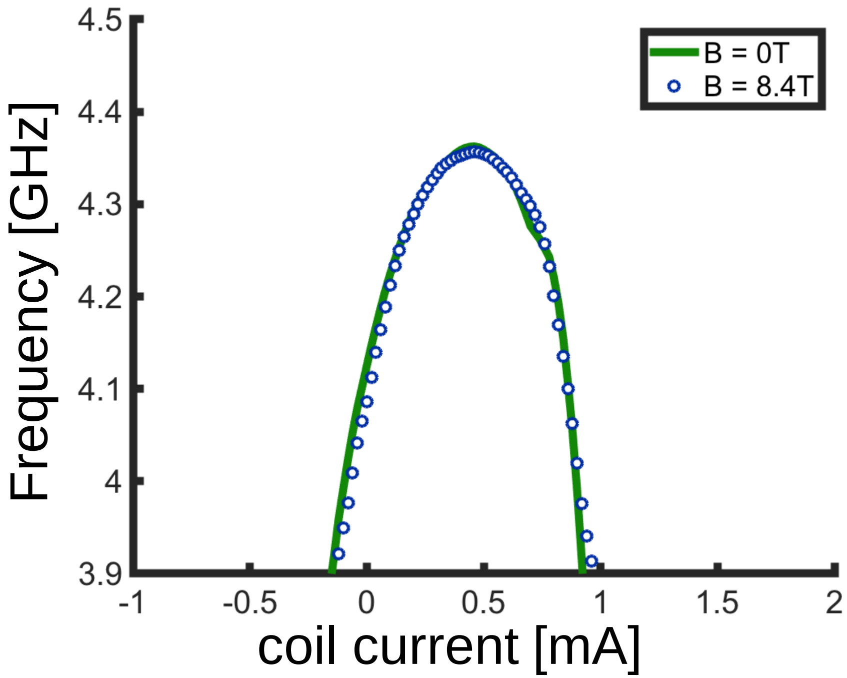

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