HAYSTAC: The Haloscope at Yale Sensitive to Axion CDM

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IQ PITT PACC Workshop

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Today

- Moving to higher frequencies in axion haloscopes
- The HAYSTAC experiment: A quantum-enhanced search for axion dark matter
- Next steps

The Haloscope Technique

- Magnetic Field (8T)
- High Q-Cavity (~50k)
- Tunable Frequency (~5 GHz)
- Low Noise Amplifier
- Cryogenic (100 mK)

$P_a \sim 10^{-24}$ Watts

$k_B T_N \sim 10^{-21}$ Watts

$$SNR = \frac{P_a}{k_B T_N}\sqrt{\frac{\tau}{\Delta \upsilon}}$$

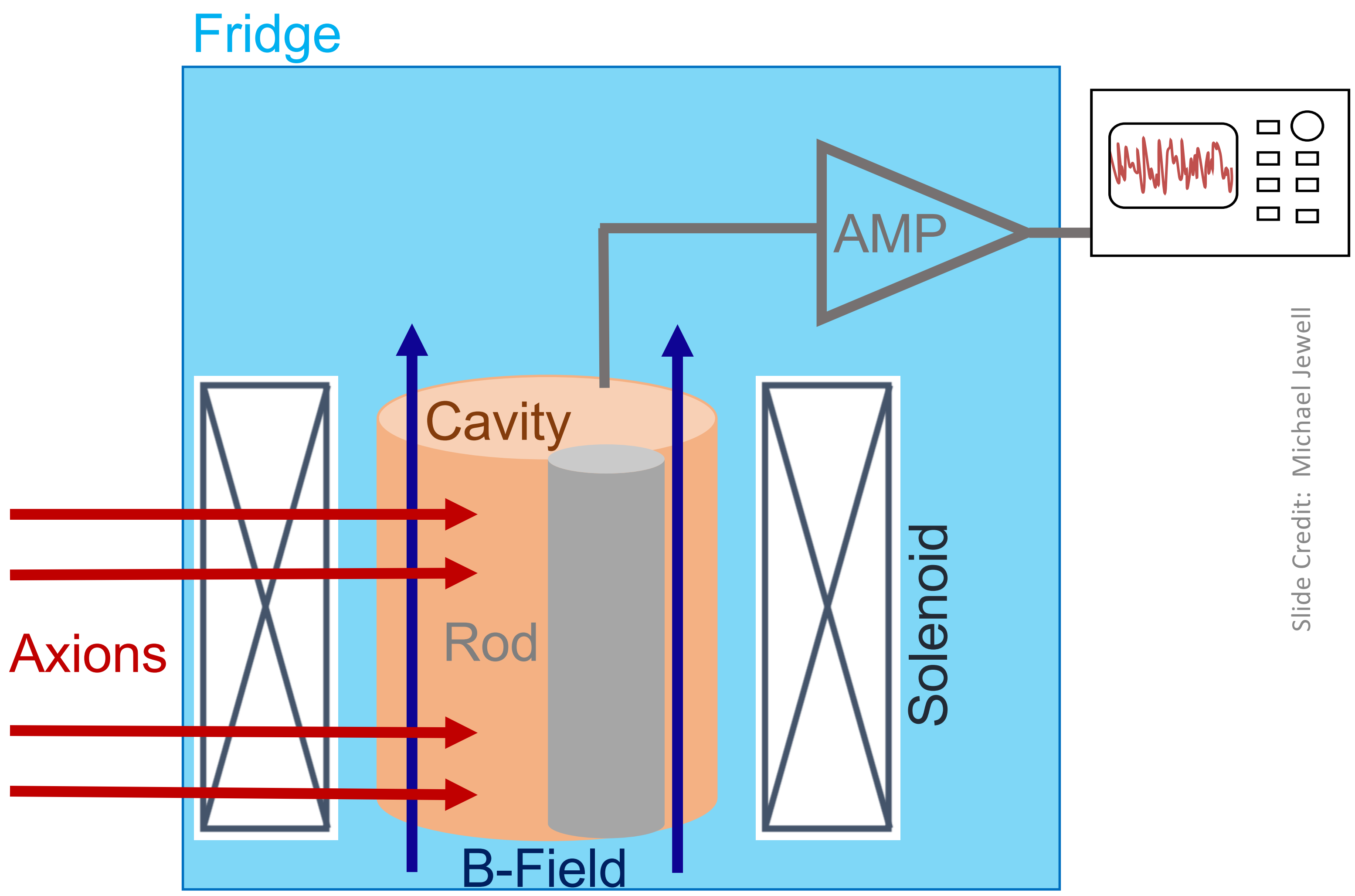
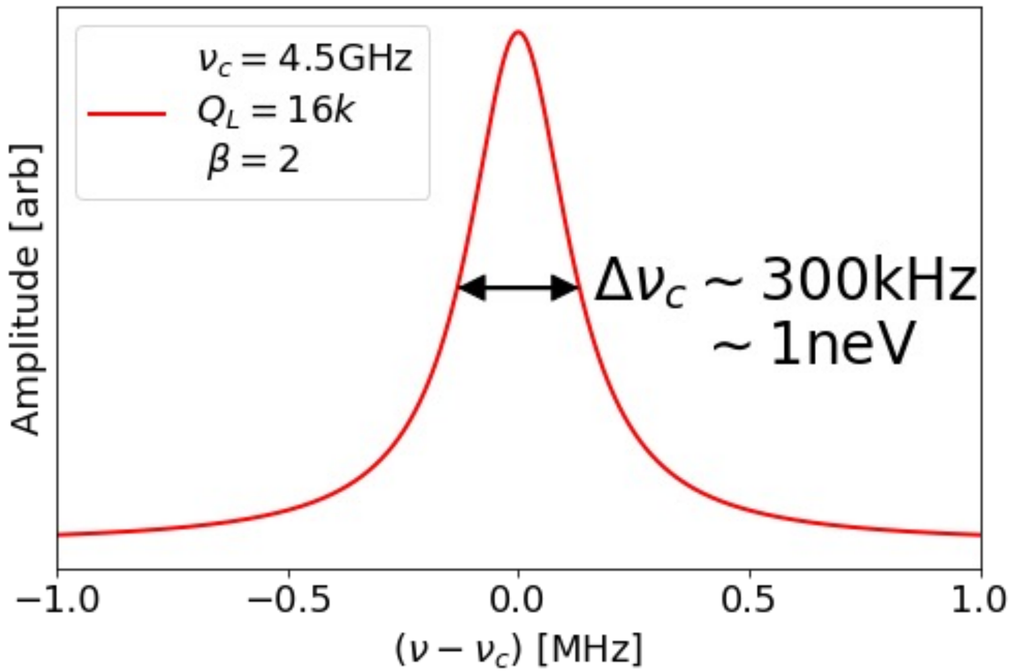
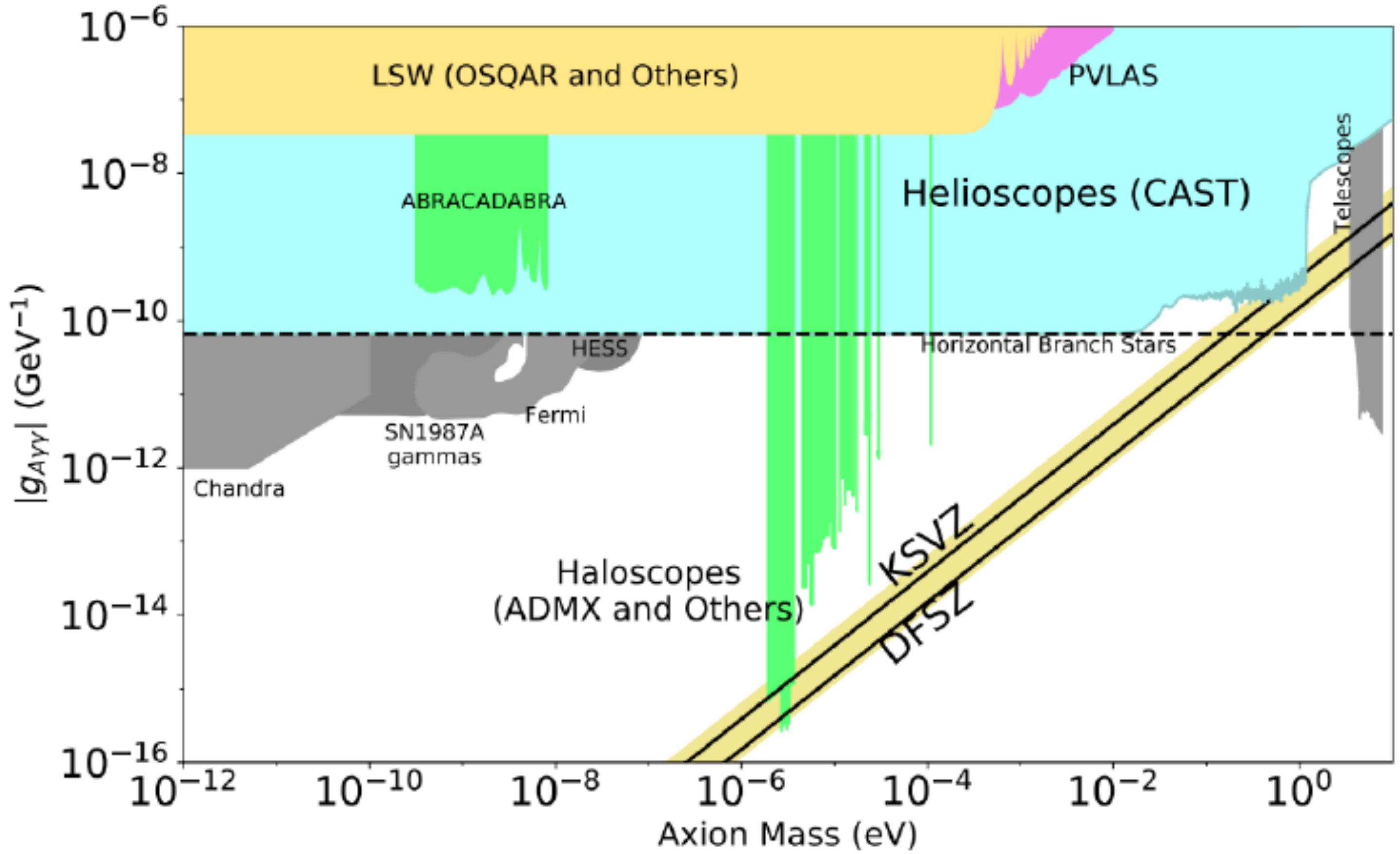


Figure of Merit



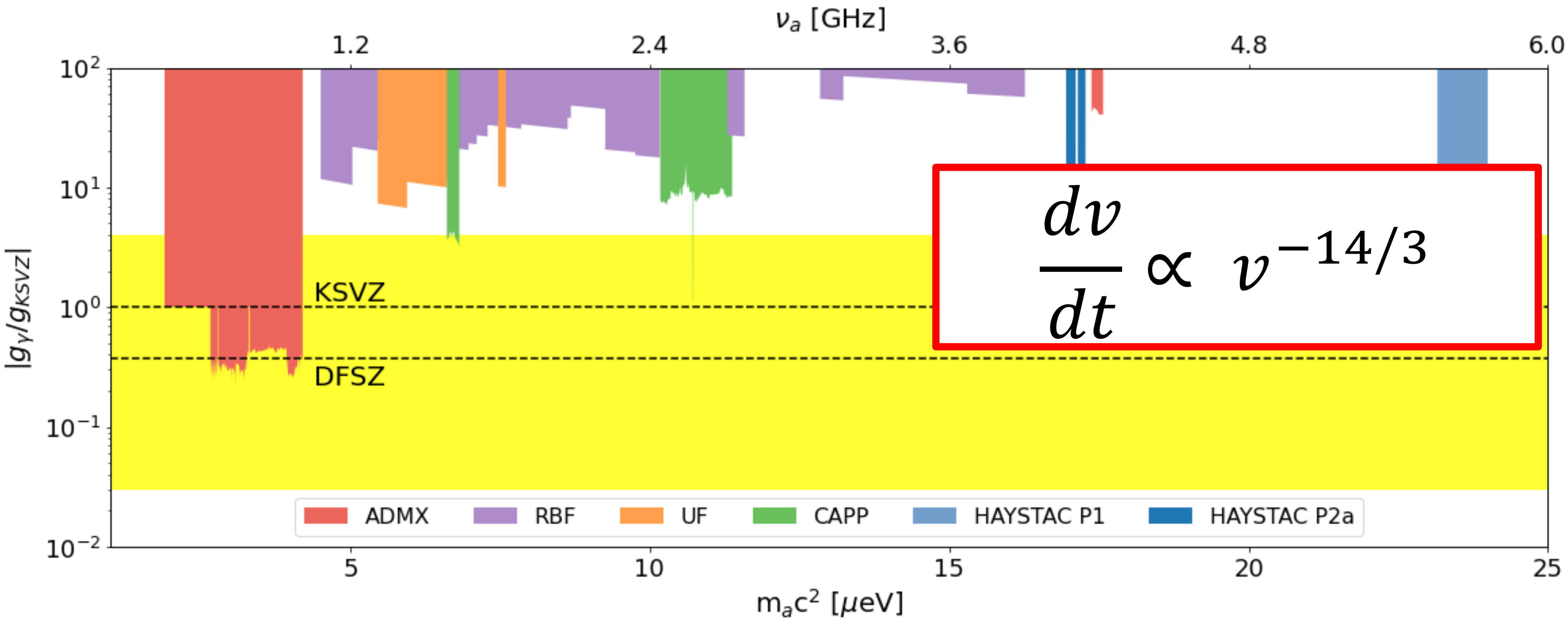
$$\frac{dv}{dt} \propto g_{\gamma}^{4} \frac{B^4 Q V^2}{T_N^2}$$



I. G. Irastorza and J. Redondo, Progress in Particle and Nuclear Physics, vol. 102, pp. 89–159, 2018.

Slide Credit: Michael Jewell

Haloscope Landscape



$$\frac{d\nu}{dt} \propto \nu^{-14/3}$$

Slide Credit: Michael Jewell

Solutions for High Frequencies

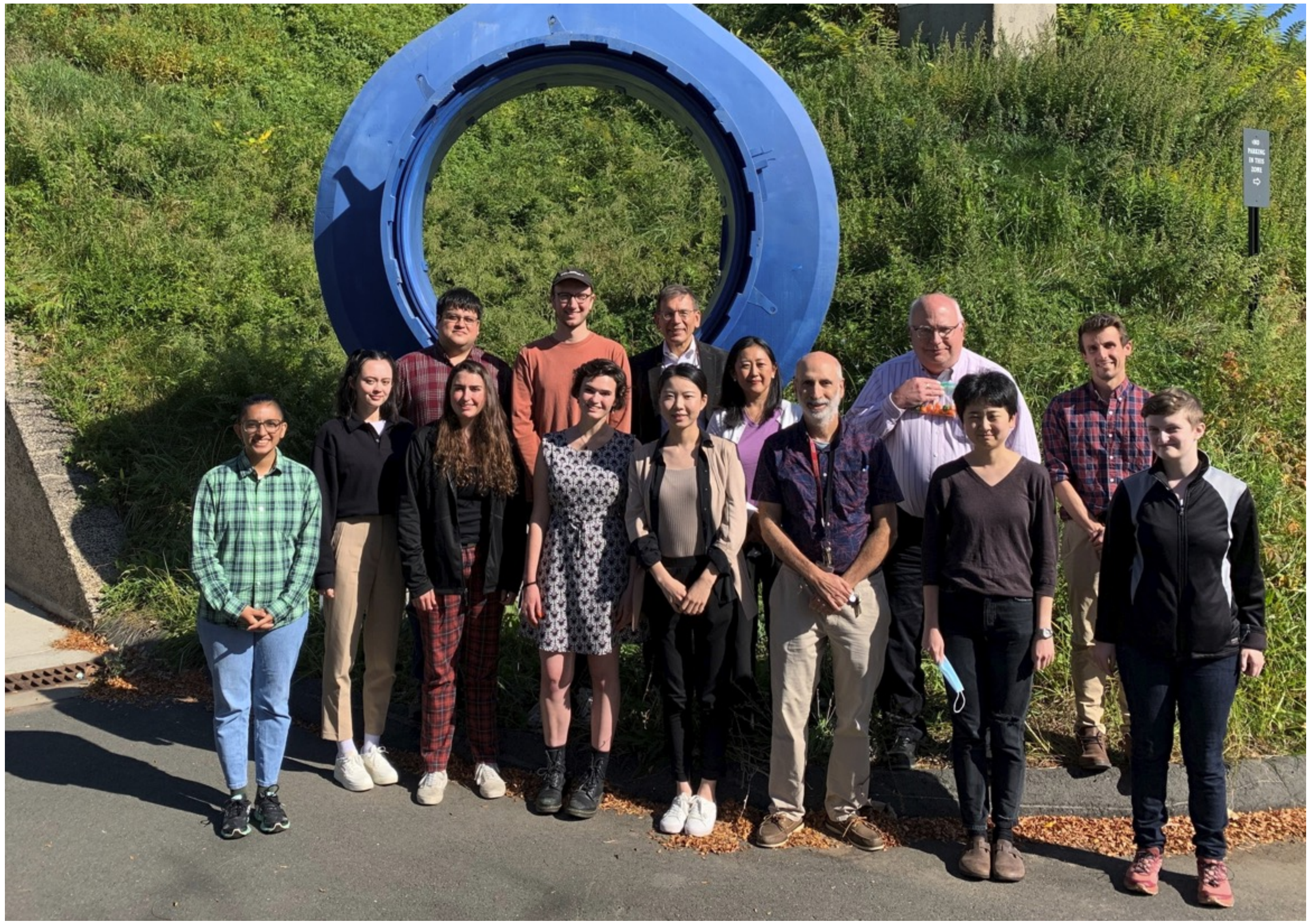
- Volume: Scales inversely with frequency
  - Higher order modes (less conversion power)
- Q: Resistive loses in cavity walls
  - Superconducting Cavities (hard with B-Field)
- B-Field: Largest payoff ... but $$$
  - B~9T close to current limit for reasonable price

$$\frac{d\nu}{dt} \propto \nu^{-14/3}$$

$$\frac{d\nu}{dt} \propto \frac{\cancel{B^4}\,\cancel{QV^2}}{T_N^2}$$

Slide Credit: Michael Jewell

The HAYSTAC Collaboration



JILA
CU Boulder and NIST

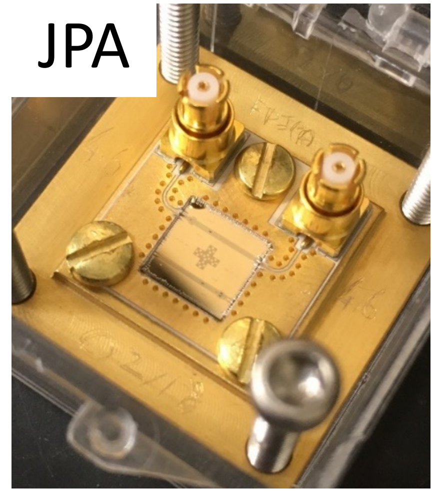
JOHNS HOPKINS
UNIVERSITY

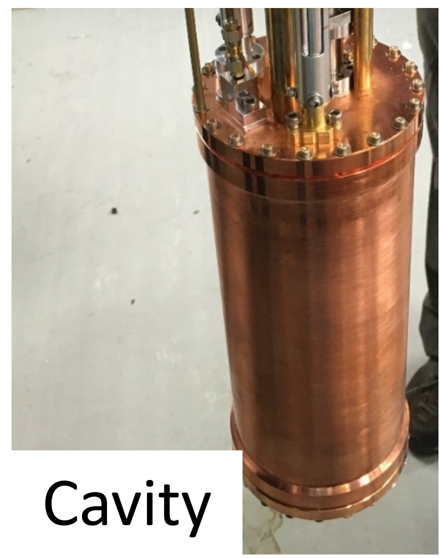
Wright
Laboratory

The HAYSTAC Experiment

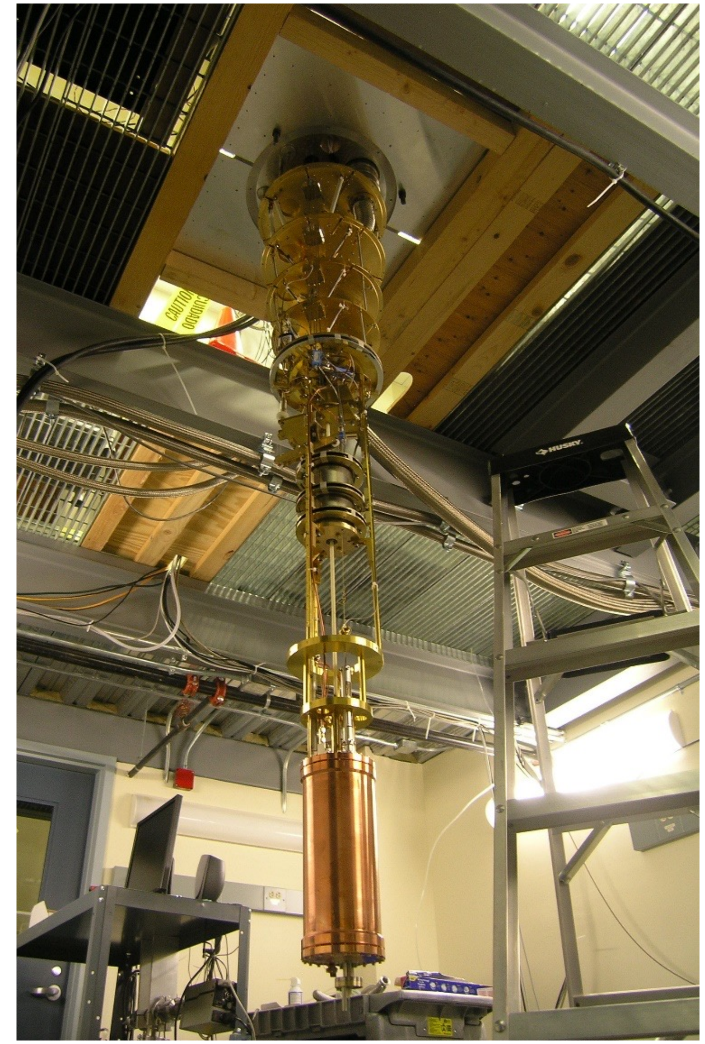
- Yale Wright Laboratory
- Copper Microwave Cavity
  - Q: ~45k
  - V: 1.5L
  - ν_c: 4-6GHz
- 8T Superconducting Solenoid
- Dilution Fridge 61mK
- Josephson Parametric Amplifier **<u>(JPA)</u>**

JPA





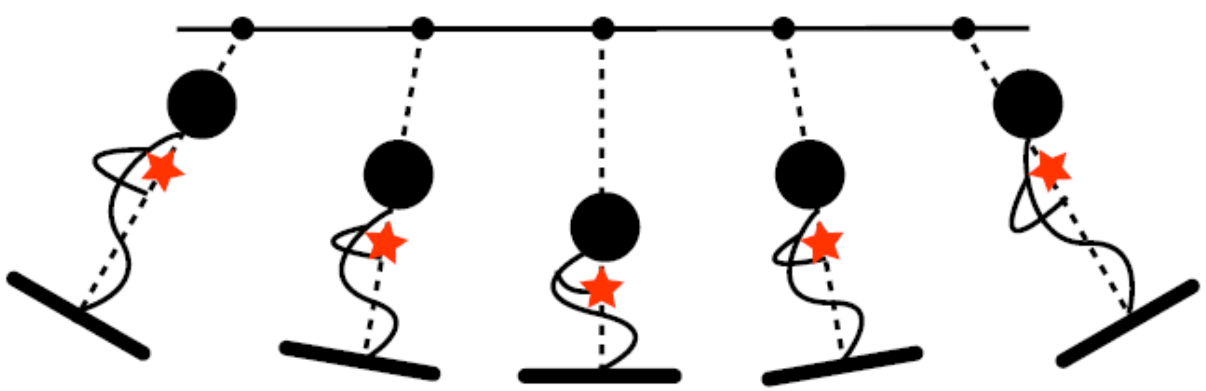
Cavity



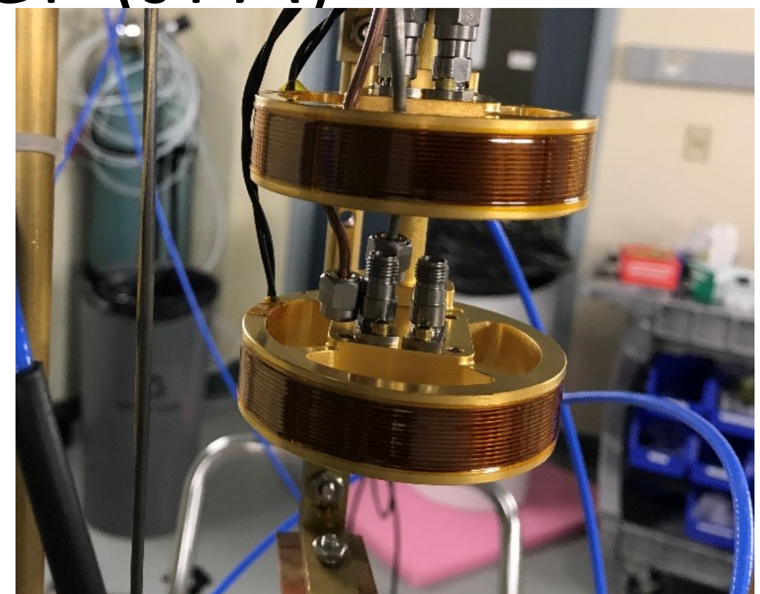
Slide Credit: Michael Jewell

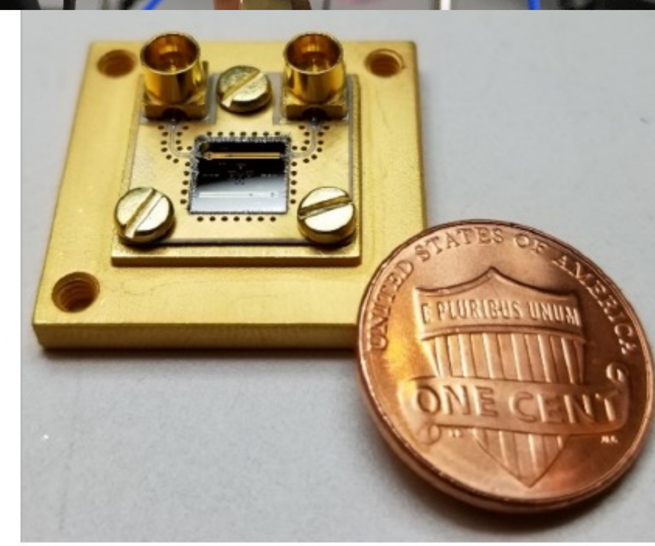
Josephson Parametric Amplifier (JPA)

- Tunable LC Resonator
  - Flux tuning
- Parametric Gain
  - Non-Linear Inductance from SQUIDs
- Modulation at twice resonant frequency
- Near Quantum Limited Noise



P.D. Nation, Rev.Mod.Phys. 84 (2012)





Slide Credit: Michael Jewell

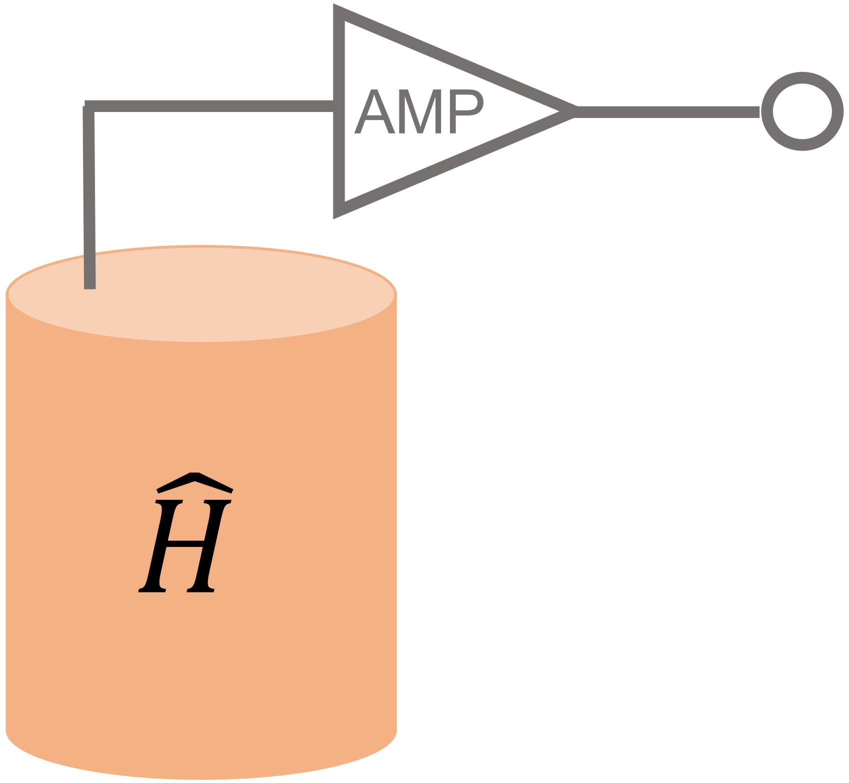
The Standard Quantum Limit for Haloscopes

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

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

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

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



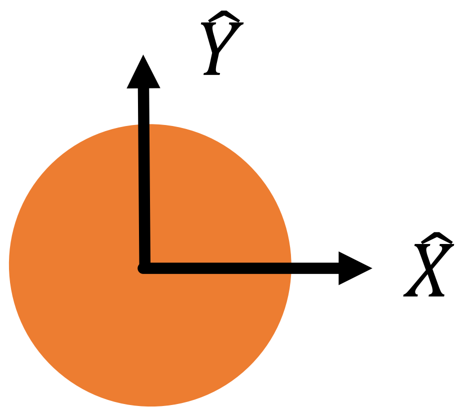
Slide Credit: Michael Jewell

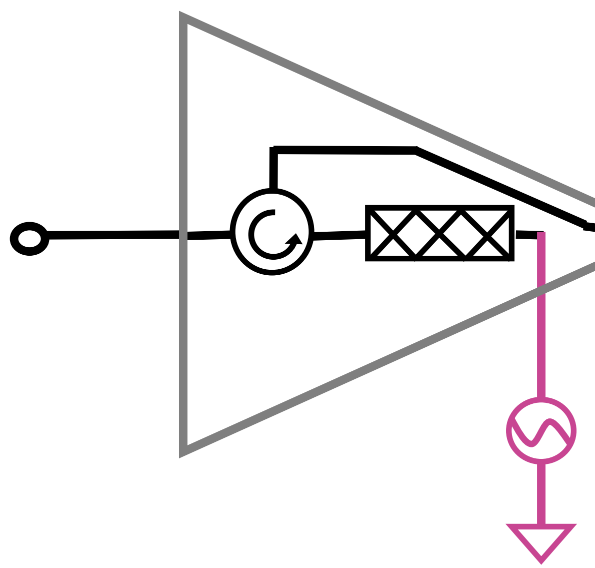
C. M. Caves. Phys. Rev. D, 26 1817-1839, (1982)

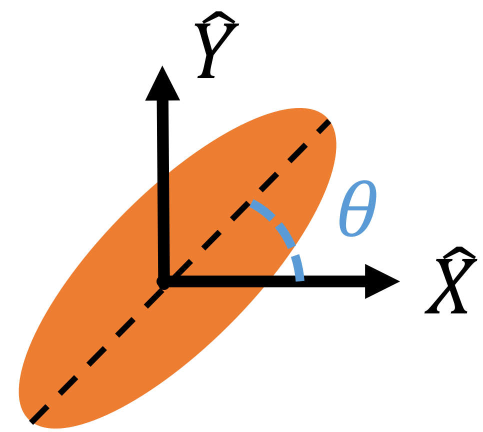
H. A. Haus and J. A. Mullen. Phys. Rev., 128 2407-2413, Dec 1962.

Benefits of JPAs

- 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







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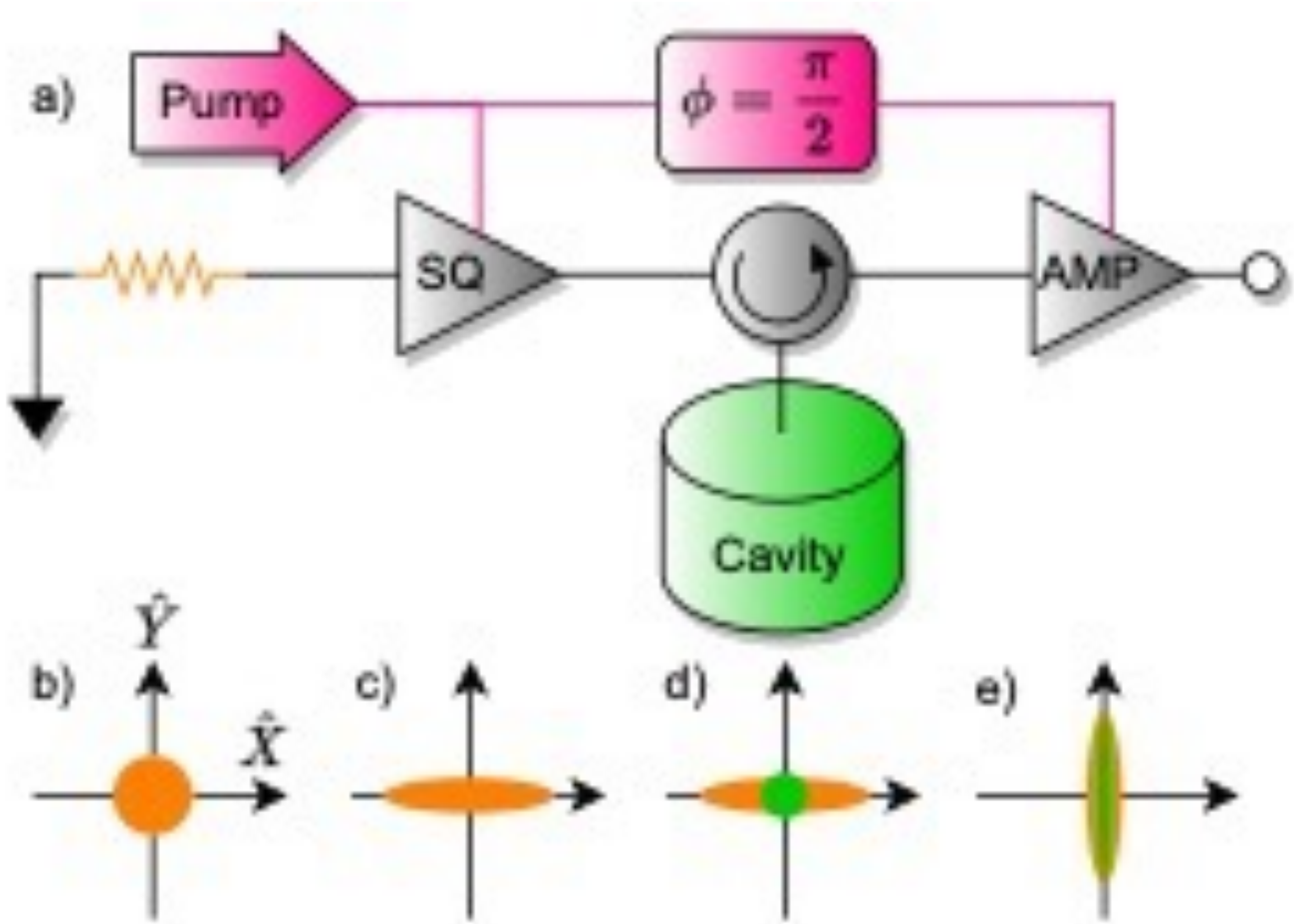
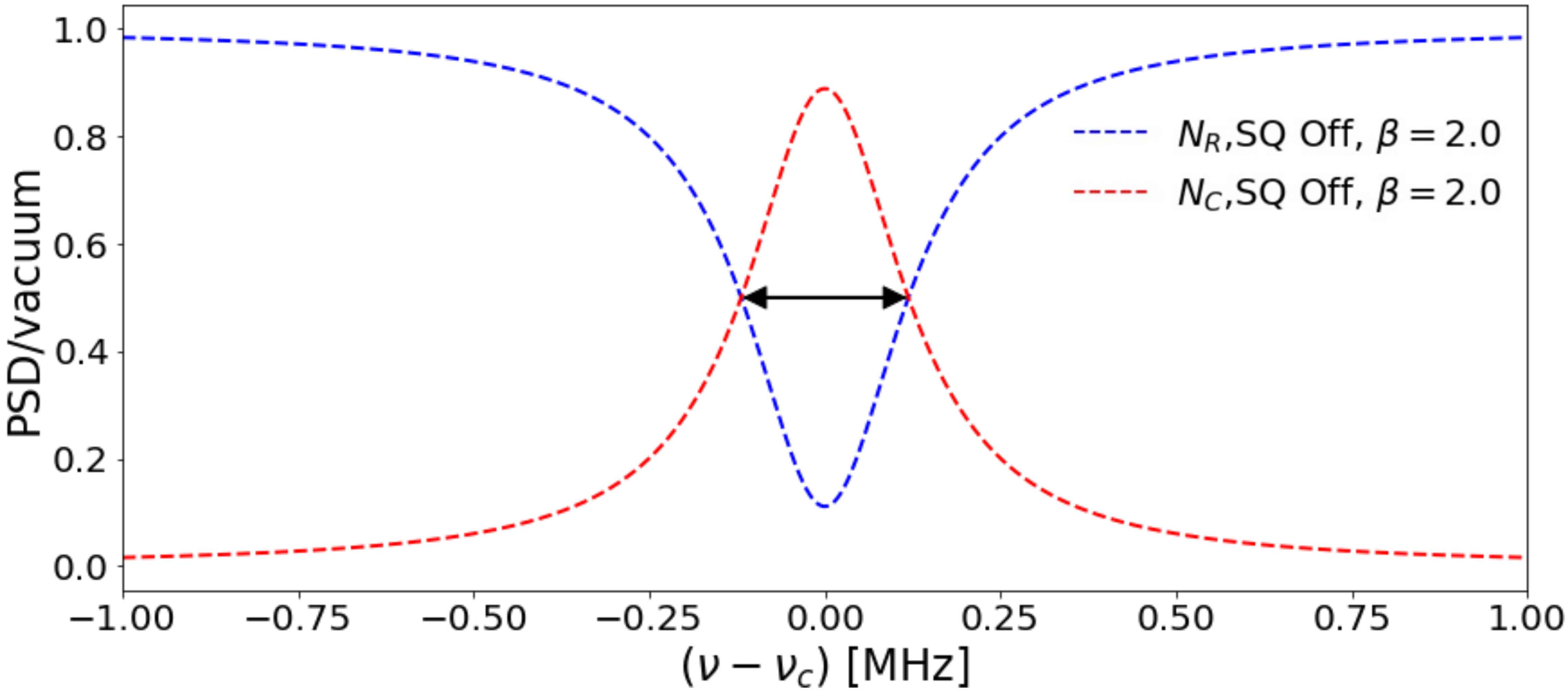
Squeezed State Receiver Model



https://arxiv.org/abs/2301.09721
(Accepted to PRD)

Bandwidth Enhancement



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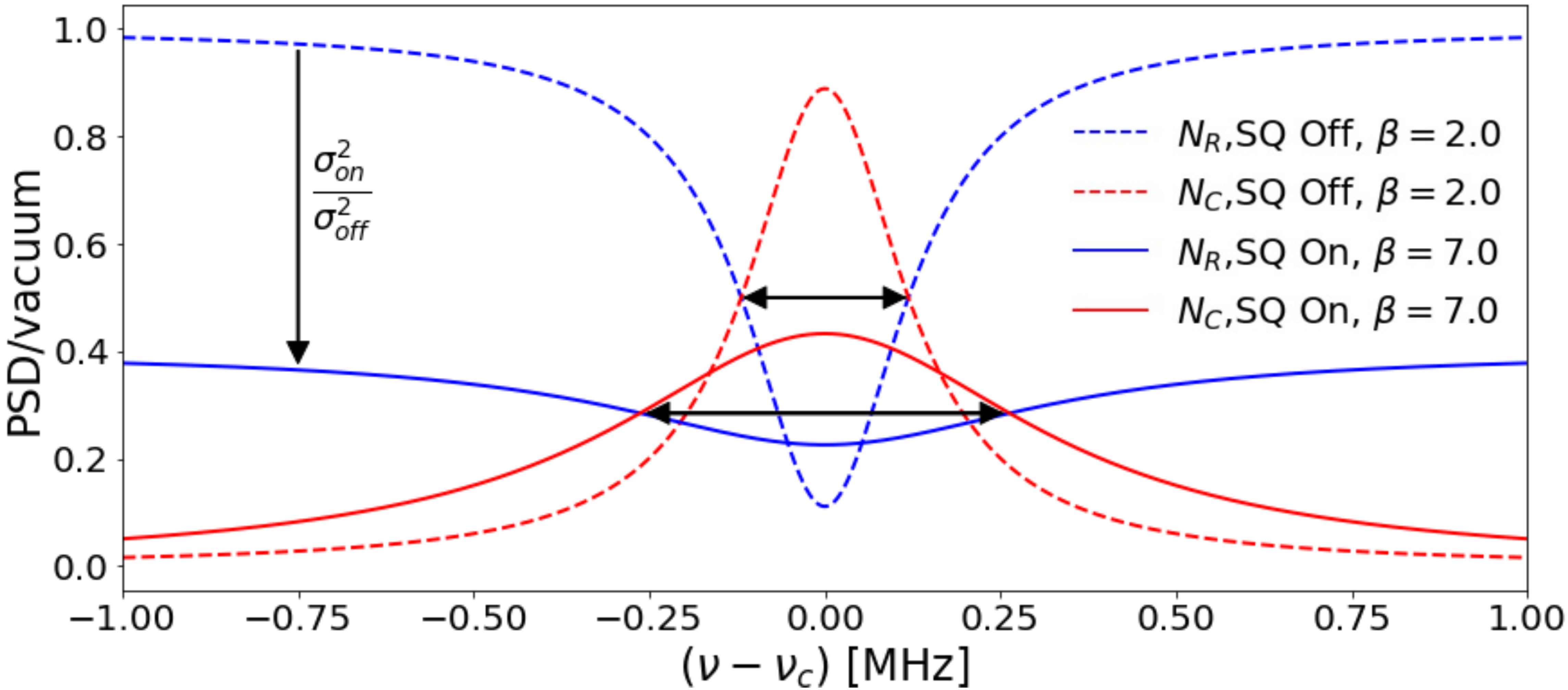
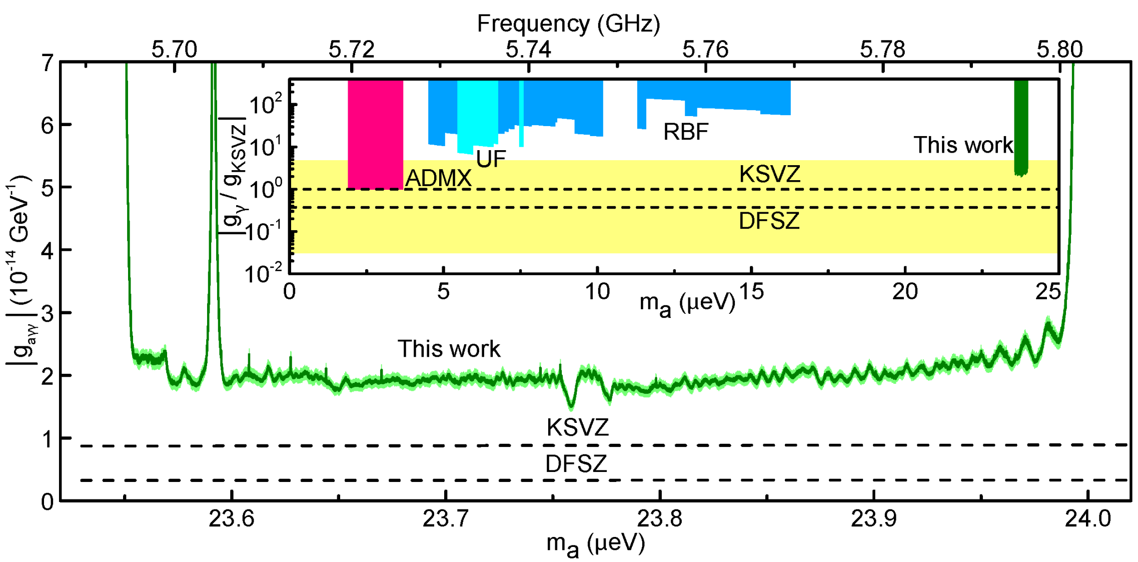
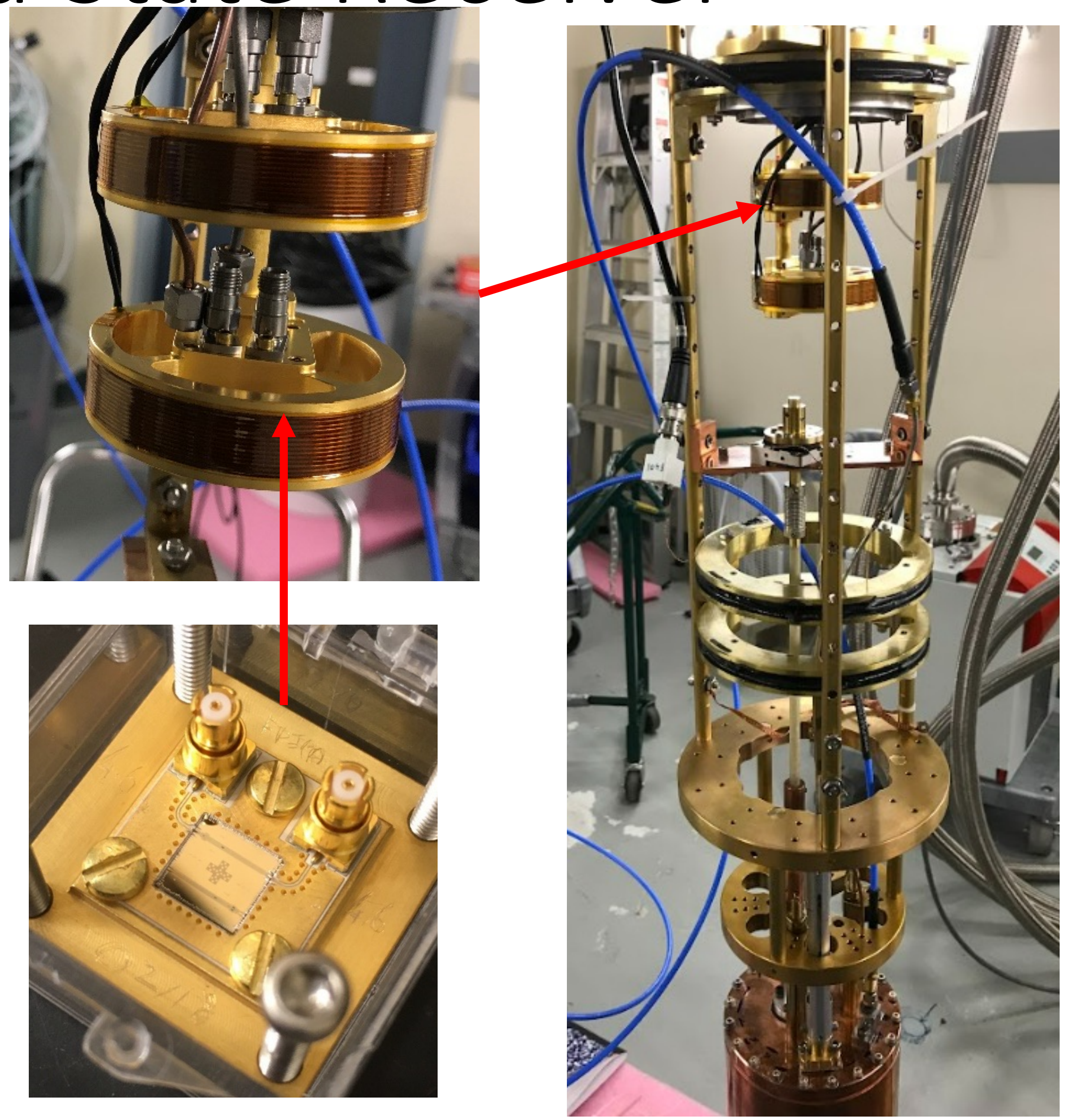


Slide Credit: Michael Jewell

Installing the Squeezed State Receiver

- 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

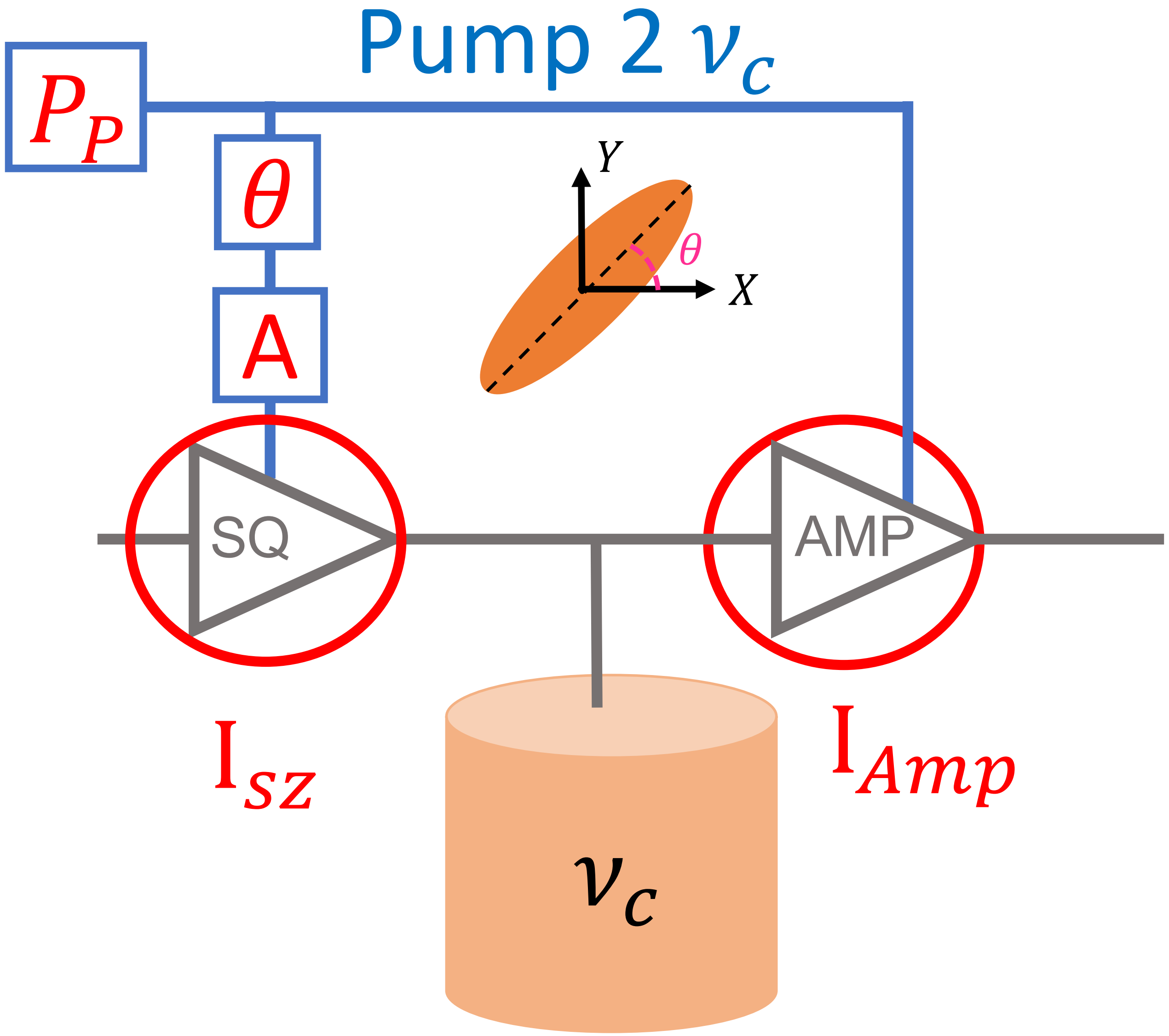




Slide Credit: Michael Jewell

Tuning the 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



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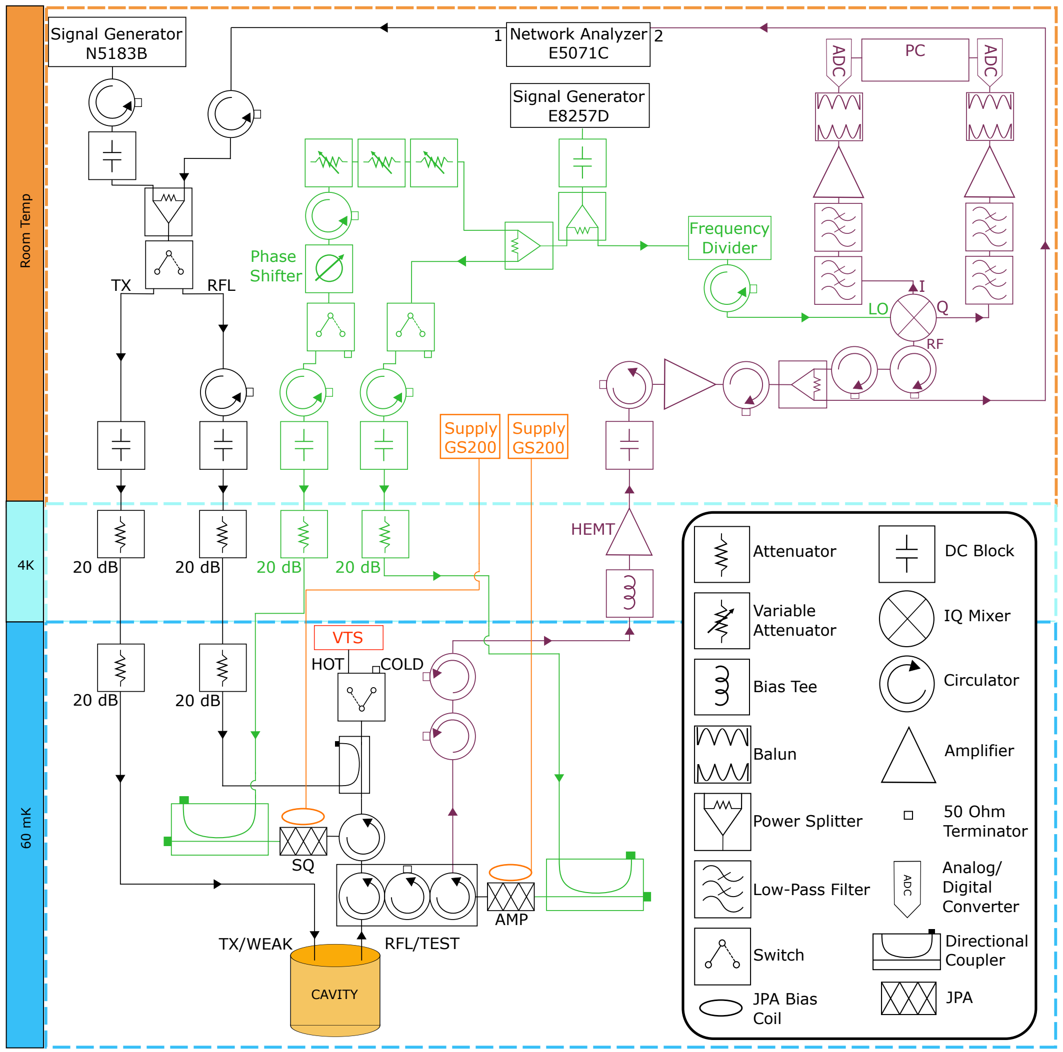
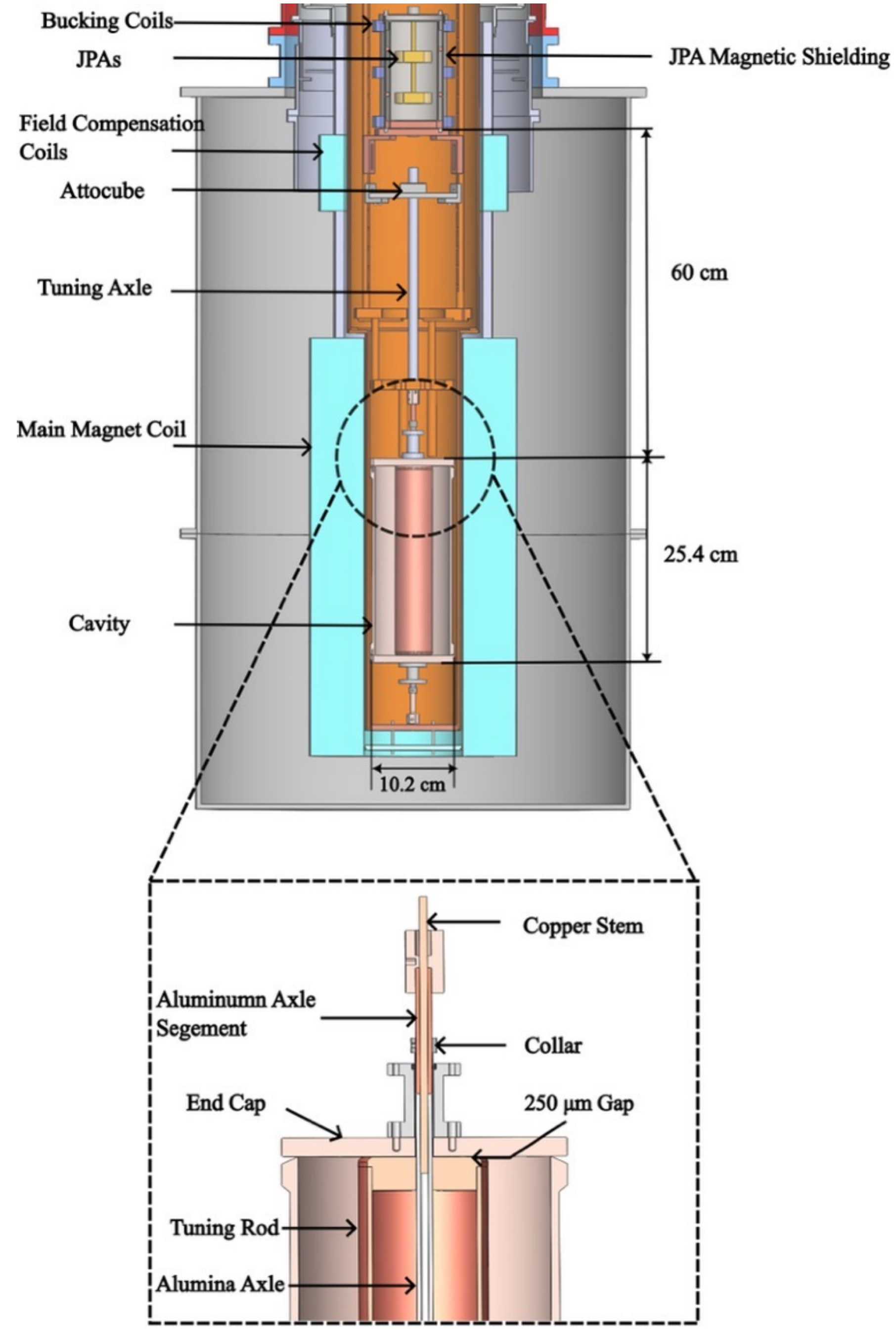
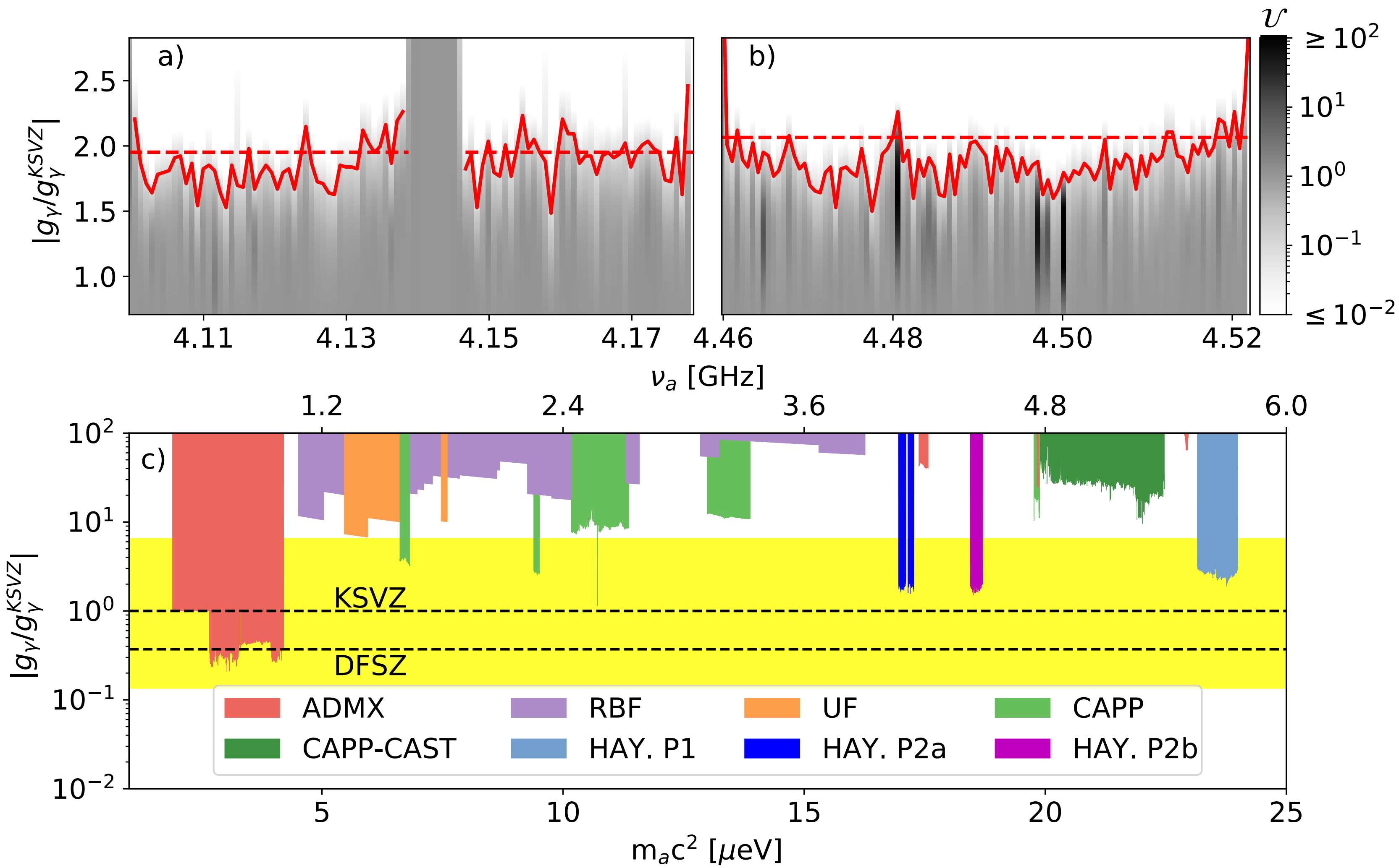
HAYSTAC Experimental Layout





https://arxiv.org/abs/2301.09721

HAYSTAC Results

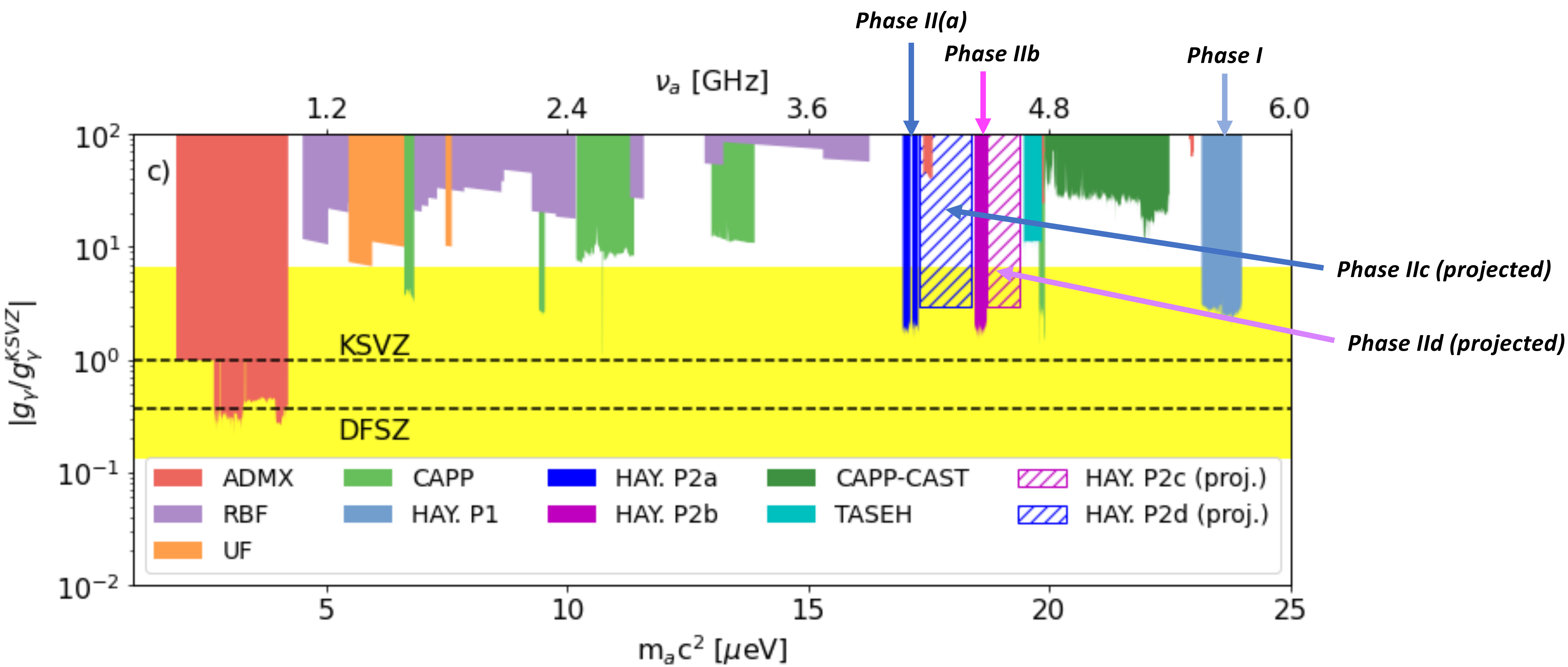


Nature **volume 590**, pages 238–242 (2021), https://arxiv.org/abs/2301.09721 (2023)

HAYSTAC Timeline

	Exp. Config	Mass	Frequency	Period	Publications
Phase I	JPA	23.15-24.0 $\mu eV/c^2$	5.6-5.8 GHz	Jan 2016-July 2017	Phys. Rev. D 97, 092001 (2018)
Phase IIa	SSR	16.96-17.2 $\mu eV/c^2$	4.100-4.140 GHz	Sept 2019-Apr 2020	*Nature* **590**, 238–242 (2021)
Phase IIb	SSR	18.44-18.71 $\mu eV/c^2$	4.459-4.523 GHz	July 2021-Nov 2021	Accepted to PRD arXiv:2301.09721
Phase IIc	SSR	19.44-18.61 $\mu eV/c^2$	4.7-4.5 GHz	July 2022-November 2022; finalizing rescans	Analysis pending
Phase IId	SSR	18.4-17.36 $\mu eV/c^2$	4.45-4.2 GHz	Upcoming	Upcoming

HAYSTAC Timeline



Conclusions

- Axions are a compelling target for HEP searches, and new technologies have enabled new approaches.
- The μeV region of the mass range covers parameter space interesting for post-inflationary QCD axions. HAYSTAC has the sensitivity to efficiently probe that mass region to couplings relevant for QCD.
- Part of the technology that makes this possible in HAYSTAC is the squeezed state receiver developed by collaborators at CU Boulder/JILA. The use of squeezed state receivers in HAYSTAC is the continuation of a long tradition of the development and deployment of new technology driven by searches in fundamental physics.
- New results from HAYSTAC accepted for publication, and preparations for the next run phase are in progress

Acknowledgements: Many of the slides in this talk are from a seminar given by Mike Jewell (Yale University) at the Harvard LPPC seminar in 2022. Thanks Mike!