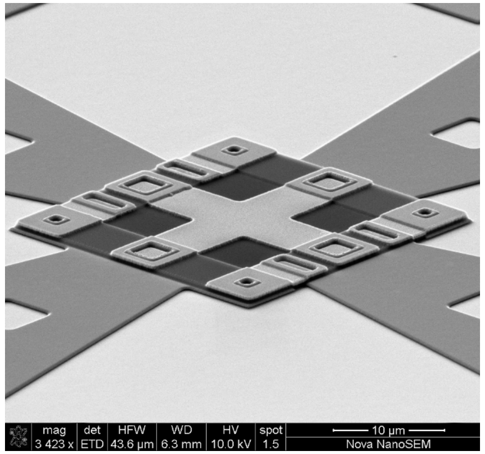
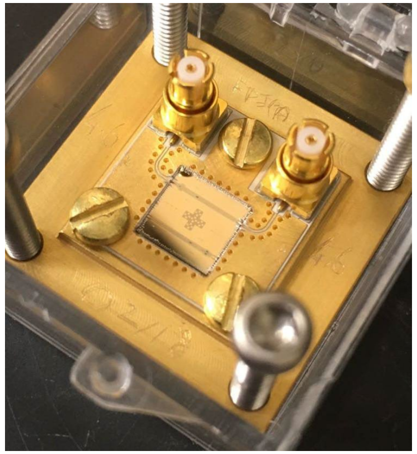
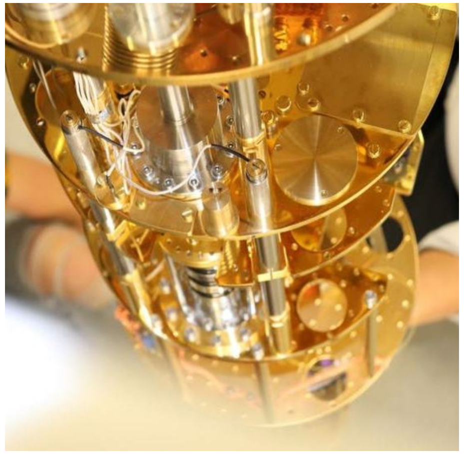
The dark side of quantum enhanced sensing



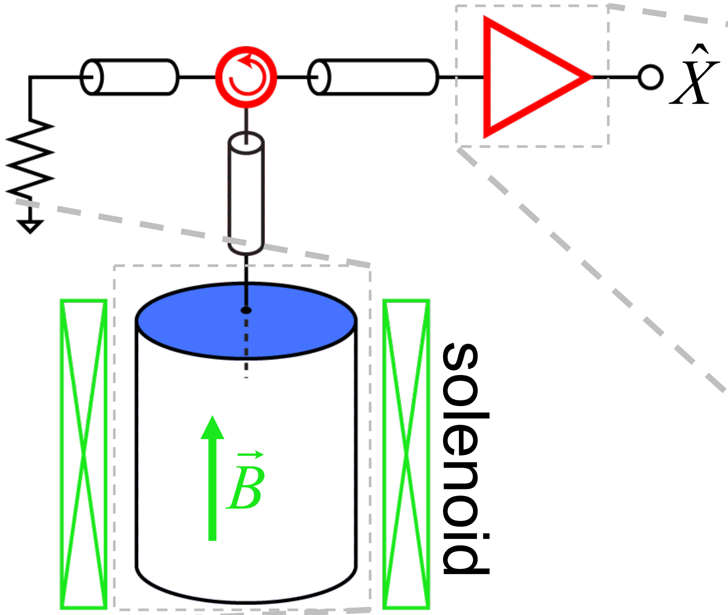

Konrad W. Lehnert
YCIU talk
New Haven CT, May 30th, 2025

Scan cavity to search for resonant axion to photon conversion

1 L volume

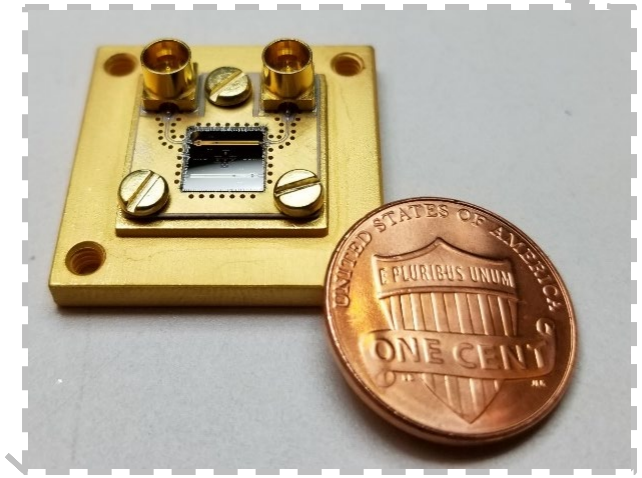
$Q = 10^4$

$\omega_{\text{cav}} \sim 2\pi \times 5\ \text{GHz}$



tunable cavity

$$T \approx \frac{\hbar\omega_{\text{cav}}}{k_B}$$

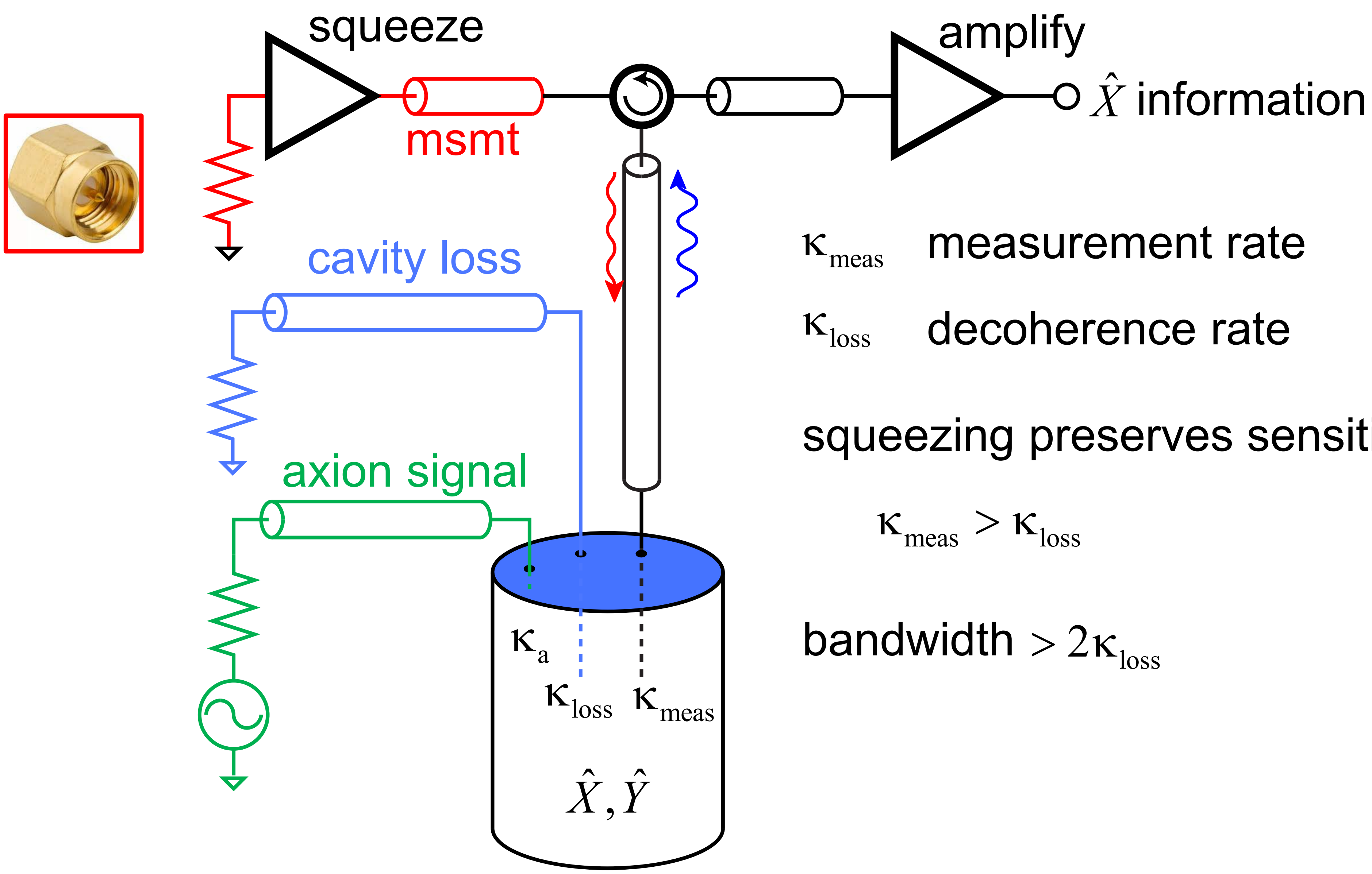


Josephson parametric amplifier (JPA)

measure $\hat{X}$ noiselessly

haloscope (Sikivie 1983) at the quantum limit (HAYSTAC 2017)

Squeezed state receiver reduces measurement backaction



κ_{meas} measurement rate

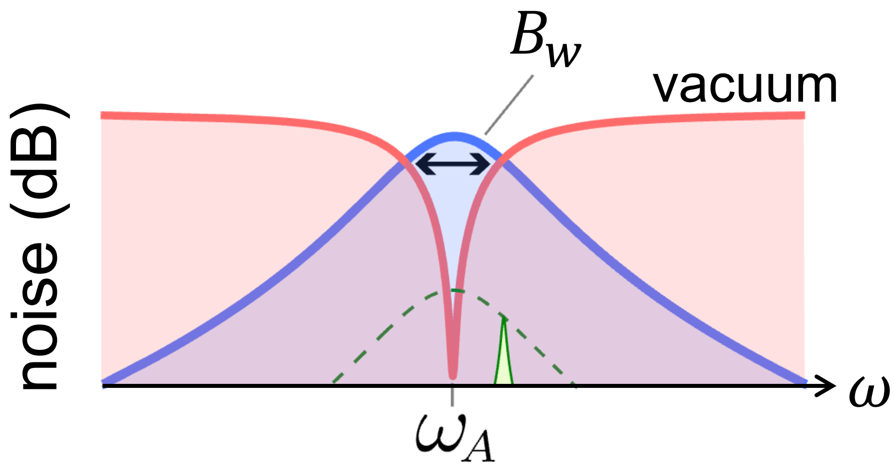
κ_{loss} decoherence rate

squeezing preserves sensitivity with

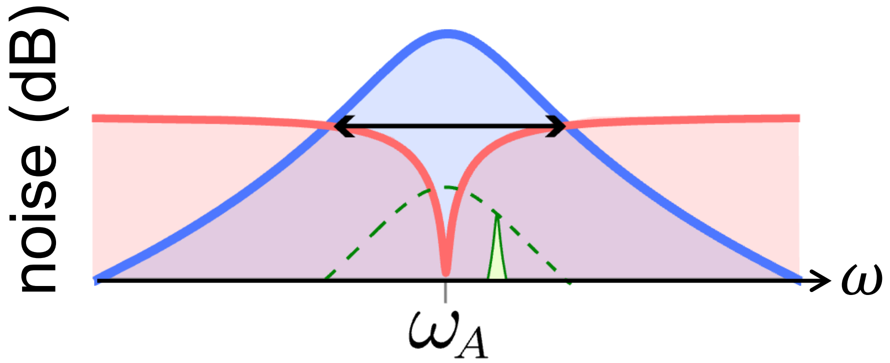
$$\kappa_{meas} > \kappa_{loss}$$

bandwidth $> 2\kappa_{loss}$

Squeezing increases bandwidth of maximum sensitivity



standard quantum limit

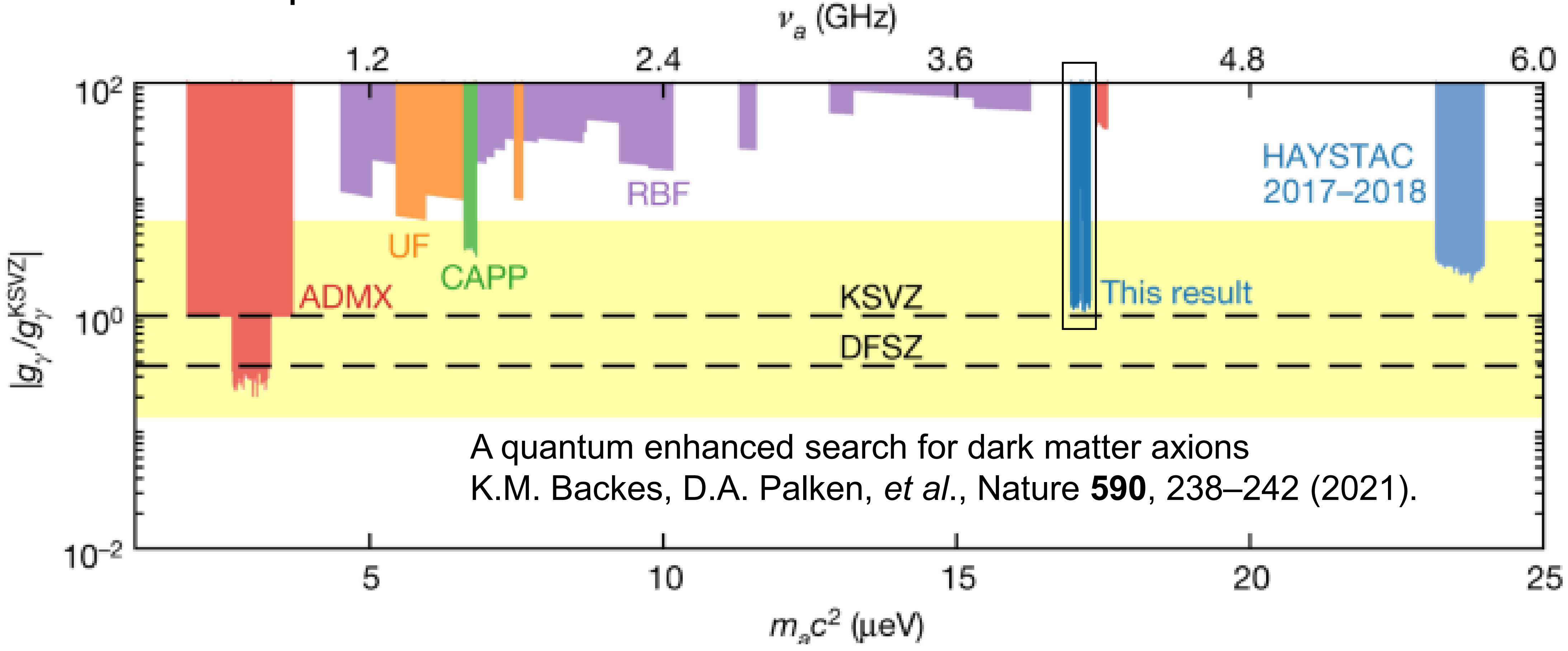


$\boxed{\times\, 2}$

squeezing

Quantum enhanced sensing is now routine in HAYSTAC

double the quantum limited scan rate

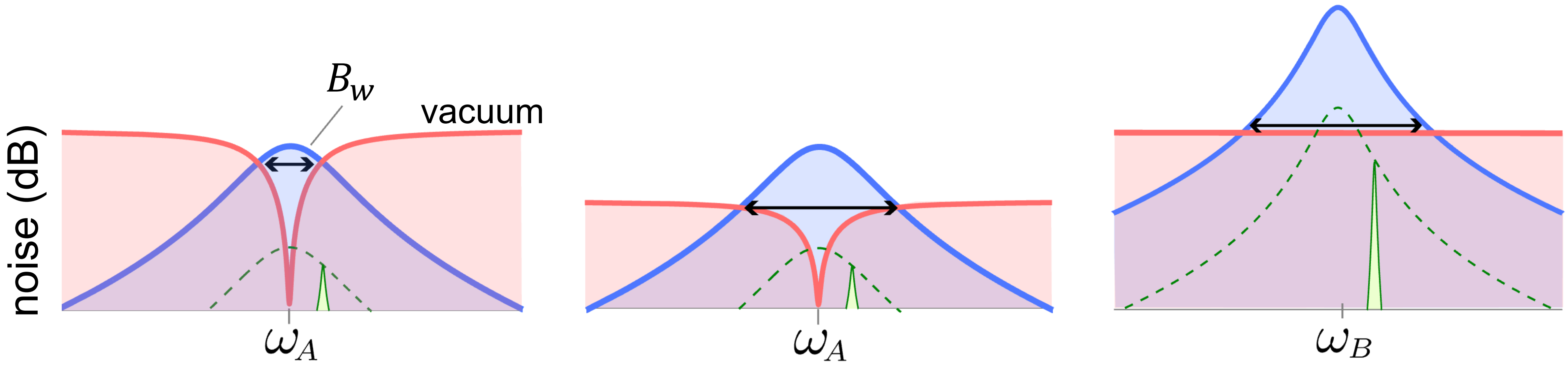


A quantum enhanced search for dark matter axions
K.M. Backes, D.A. Palken, *et al.*, Nature **590**, 238–242 (2021).

M. J. Jewell *et al.* (HAYSTAC Collaboration)
Phys. Rev. D **107**, 072007 (2023).

Can we do better than 2?

Amplify signal before encountering measurement port noise



standard quantum limit

$\times\ 2$

squeezing
HAYSTAC apparatus

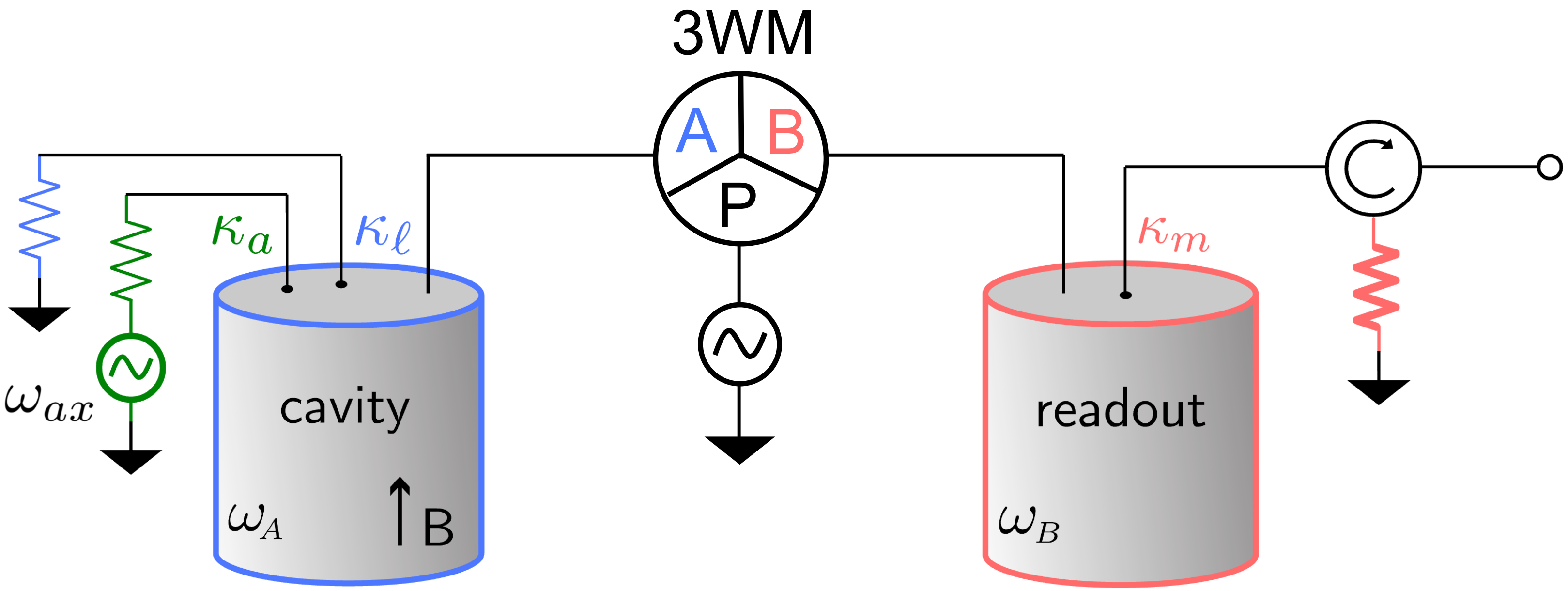
$\times\ 8.2$

cavity entanglement
“CEASEFIRE” Demo

Y. Jiang, E.P. Ruddy, K.O. Quinlan, M. Malnou, N.E. Frattini, KWL, *PRX Quantum* **4**, 020302 (2023)

K. Wurtz, Benjamin Brubaker, Y. Jiang, E. Ruddy, Daniel Palken, KWL, PRX Quantum **2**, 040350 (2021)

Dynamically couple axion cavity and readout mode by 3-wave mixing

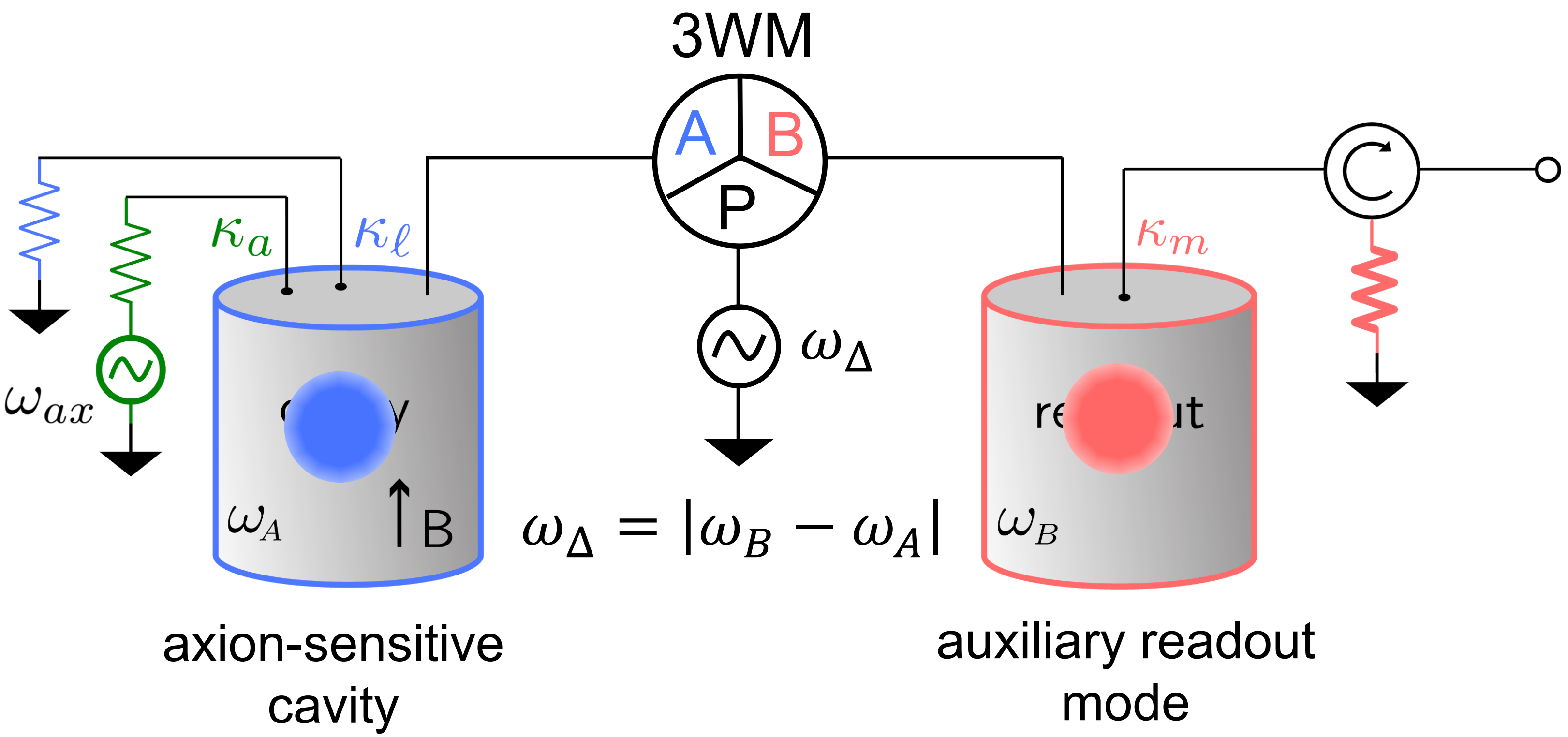


axion-sensitive cavity

auxiliary readout mode

$$\hat{\mathrm{H}}_{3\mathrm{WM}} \propto \left(\hat{A} + \hat{A}^\dagger\right)\left(\hat{B} + \hat{B}^\dagger\right)\left(\hat{P} + \hat{P}^\dagger\right)$$

State swapping (C) interaction swaps states between two modes

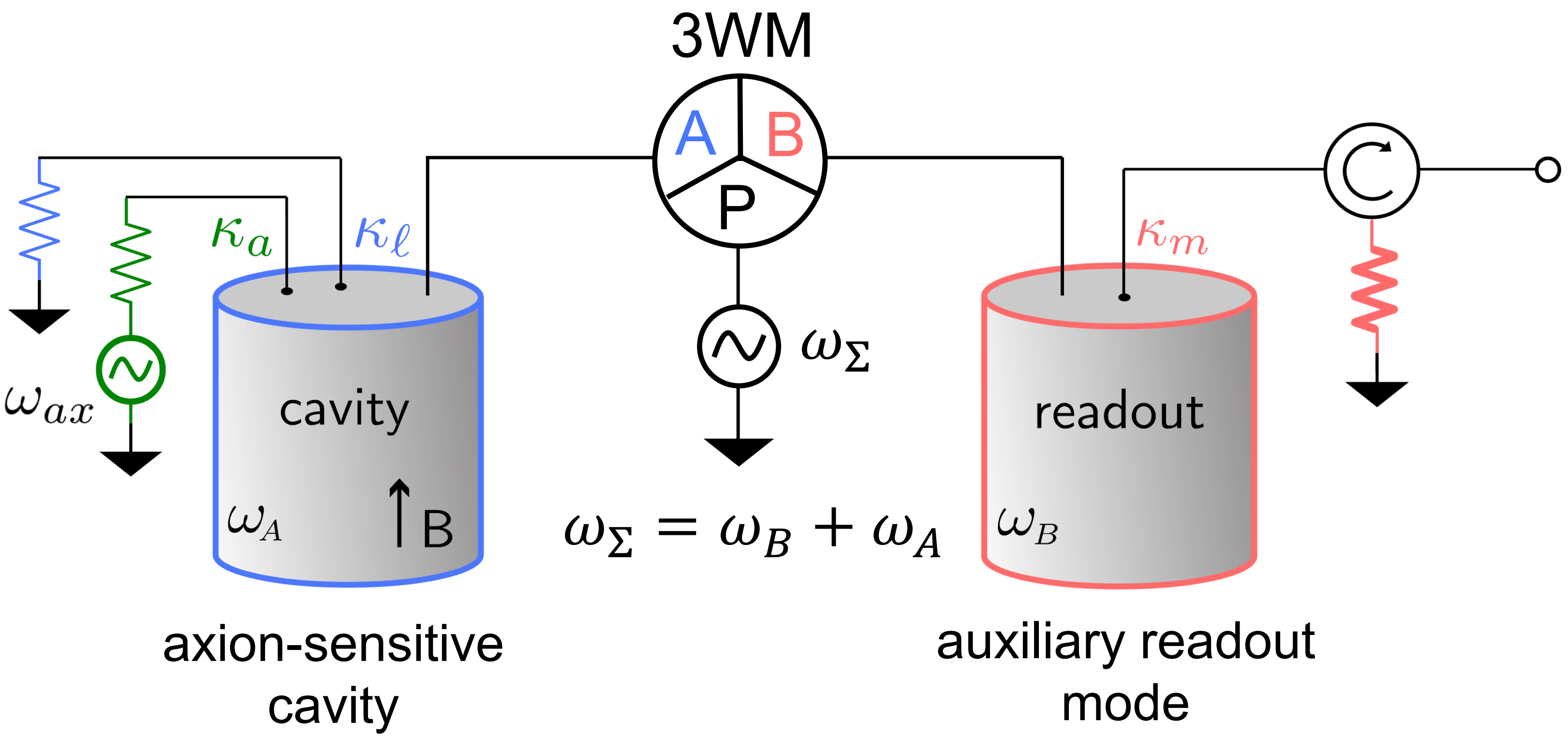


$$\hat{\mathrm{H}}_{3\mathrm{WM}} \propto \left(\hat{A} + \hat{A}^\dagger\right)\left(\hat{B} + \hat{B}^\dagger\right)\left(\hat{P} + \hat{P}^\dagger\right)$$

$$\hat{P} \rightarrow g_C e^{-i\omega_\Delta t} + \text{c.c.} \quad \boxed{\rightarrow g_C\left(\hat{A}\hat{B}^\dagger + \hat{A}^\dagger\hat{B}\right)}$$

state-swapping

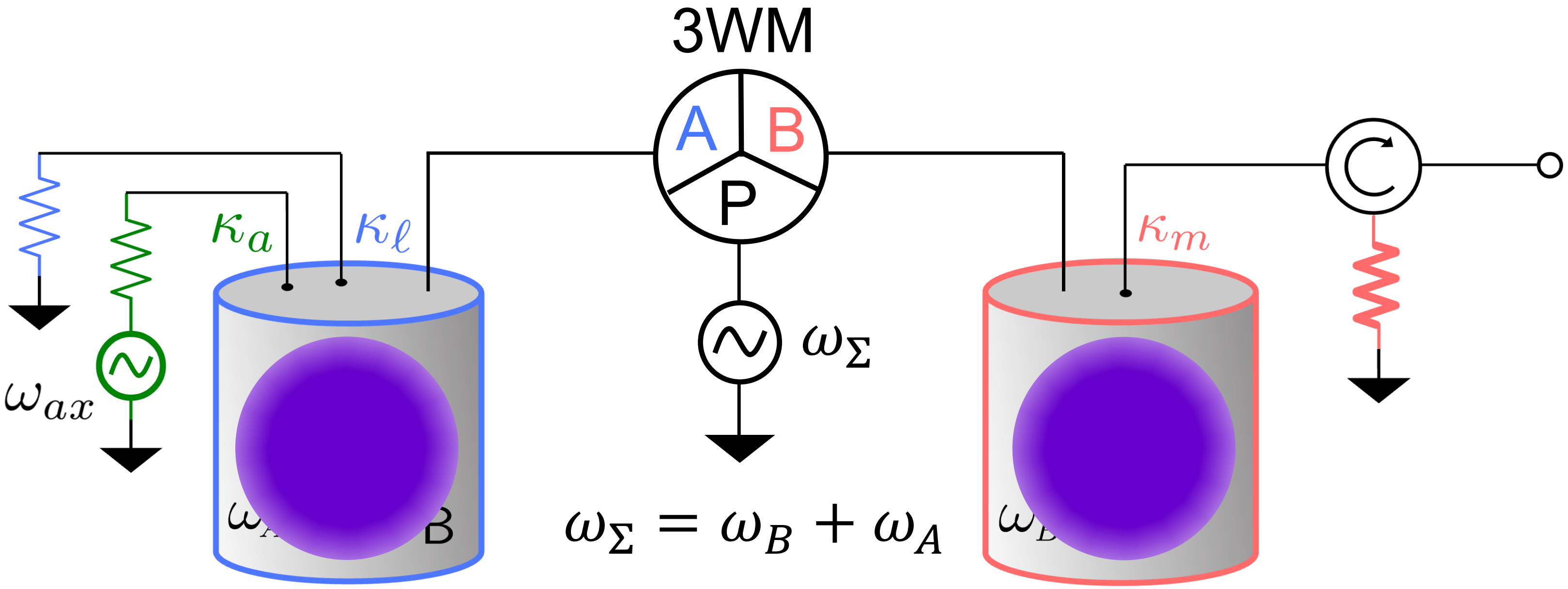
Two-mode squeezing (G) induces amplification and entanglement



$$\widehat{\mathrm{H}}_{3\mathrm{WM}} \propto (\hat{A} + \hat{A}^\dagger)(\hat{B} + \hat{B}^\dagger)(\hat{P} + \hat{P}^\dagger)$$

$\hat{P} \to g_G e^{-i\omega_\Sigma t}$ + c.c. $\boxed{\to g_G\left(\hat{A}^\dagger \hat{B}^\dagger + \hat{A}\hat{B}\right)}$ two-mode squeezing

Two-mode squeezing (G) induces amplification and entanglement



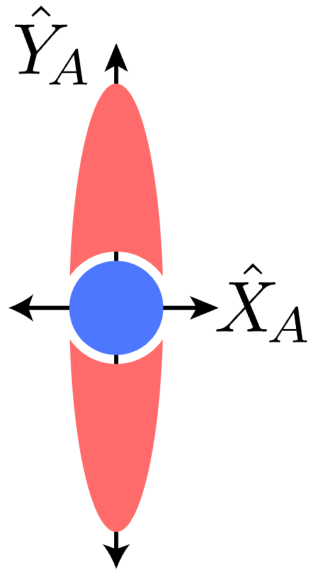
axion-sensitive cavity

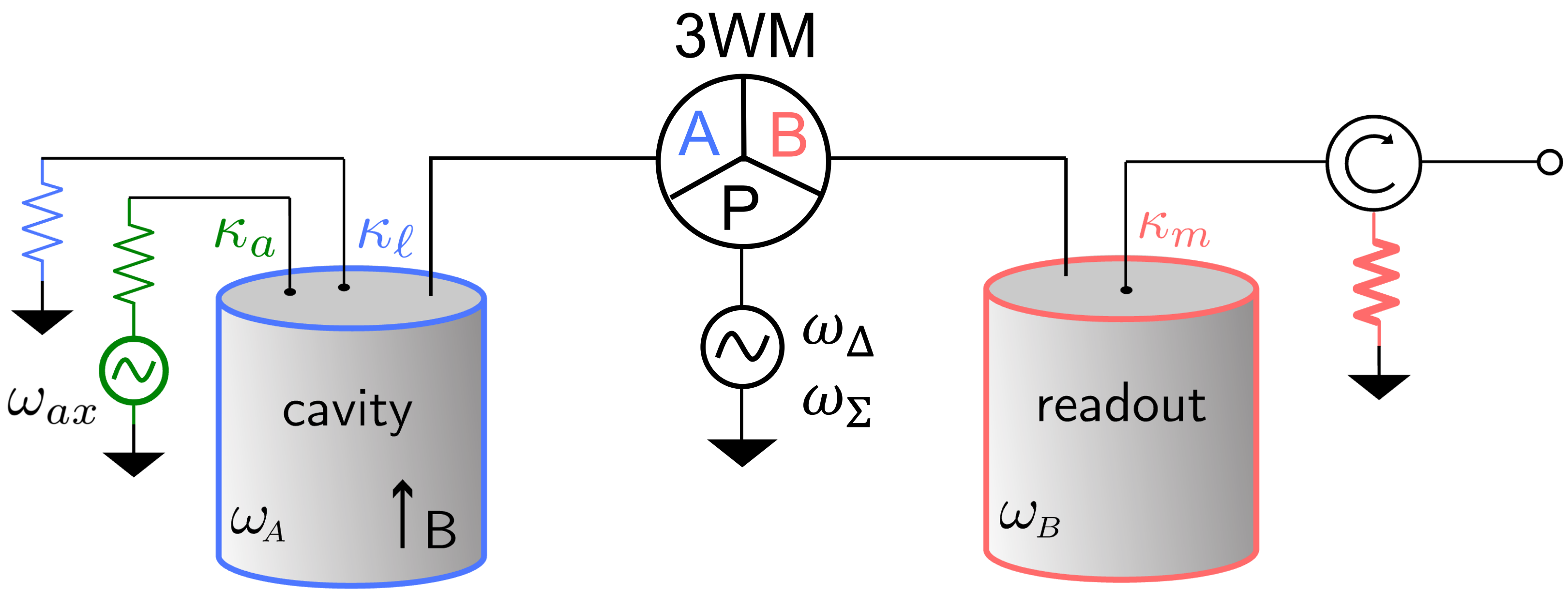
auxiliary readout mode

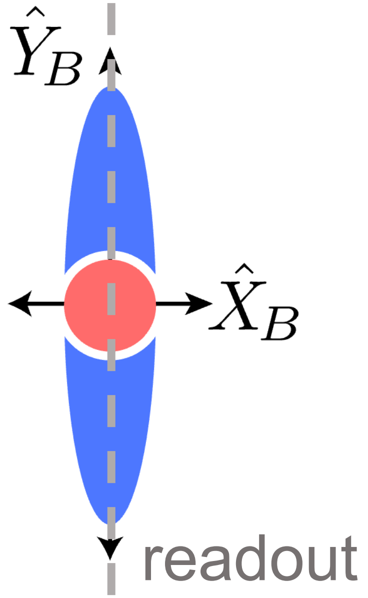
$$\hat{\mathrm{H}}_{3\mathrm{WM}} \propto \left(\hat{A} + \hat{A}^\dagger\right)\left(\hat{B} + \hat{B}^\dagger\right)\left(\hat{P} + \hat{P}^\dagger\right)$$

$$\hat{P} \rightarrow g_G e^{-i\omega_\Sigma t} + \text{c.c.} \quad \boxed{\rightarrow g_G\left(\hat{A}^\dagger \hat{B}^\dagger + \hat{A}\hat{B}\right)}$$ two-mode squeezing

Quantum non-demolition interaction yields bandwidth increase

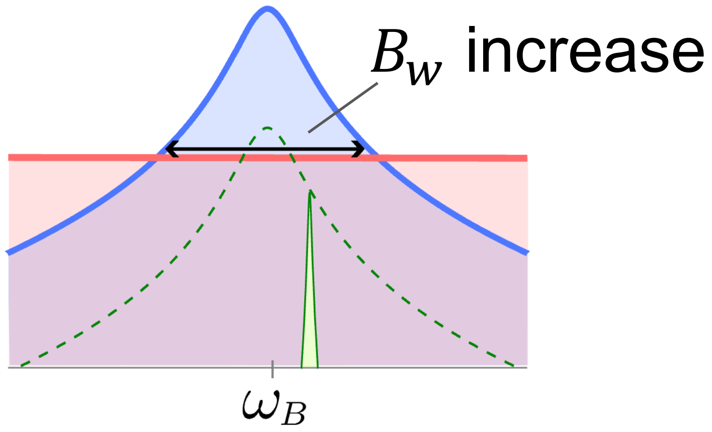






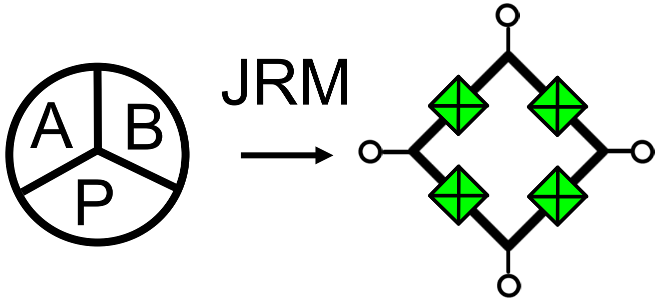
$$\hat{H}_{3WM} = g_C \hat{A}\hat{B}^\dagger + g_G \hat{A}^\dagger \hat{B}^\dagger + \text{c.c.} \quad \boxed{\xrightarrow{\text{QND}} \; 2g\hat{X}_A\hat{X}_B}$$

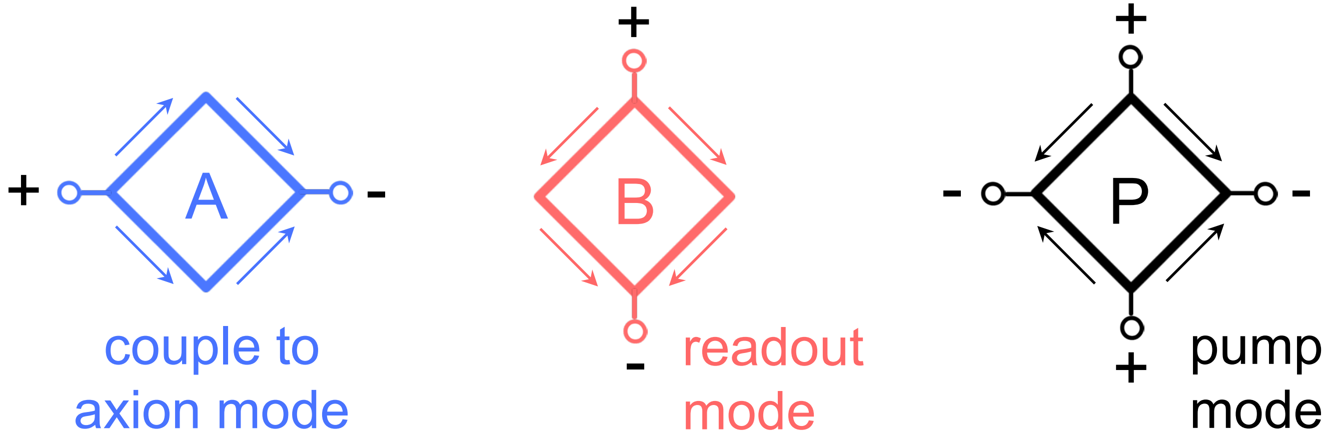
$d\hat{Y}_B/dt = -2g\hat{X}_A$	$d\hat{X}_A/dt = 0$
amplification	QND

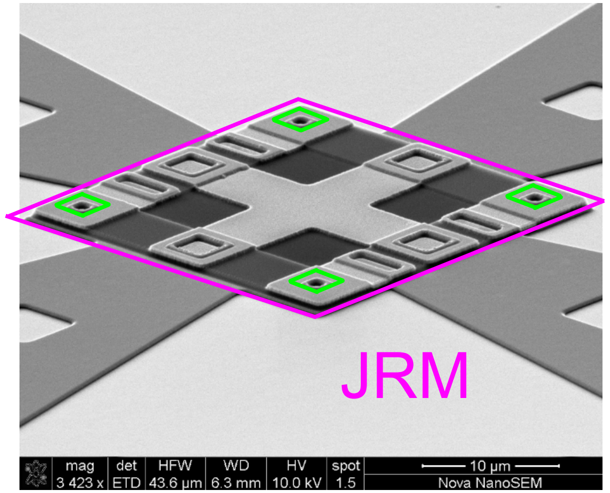


Metelmann, A. and Clerk, A.A., *Physical Review X* 5.2 (2015): 021025. Chien, T-C., et al. *Physical Review A* 101.4 (2020): 042336.

Josephson Ring Modulator for realizing 3-wave mixing



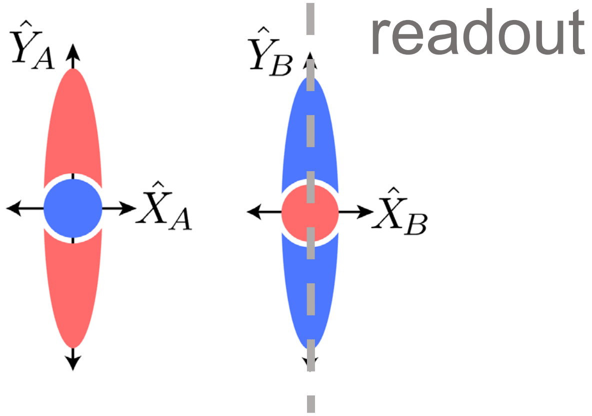




$$\hat{\mathrm{H}}_{\mathrm{JRM}} = \lambda(\hat{P} + \hat{P}^{\dagger})(\hat{A} + \hat{A}^{\dagger})(\hat{B} + \hat{B}^{\dagger})$$

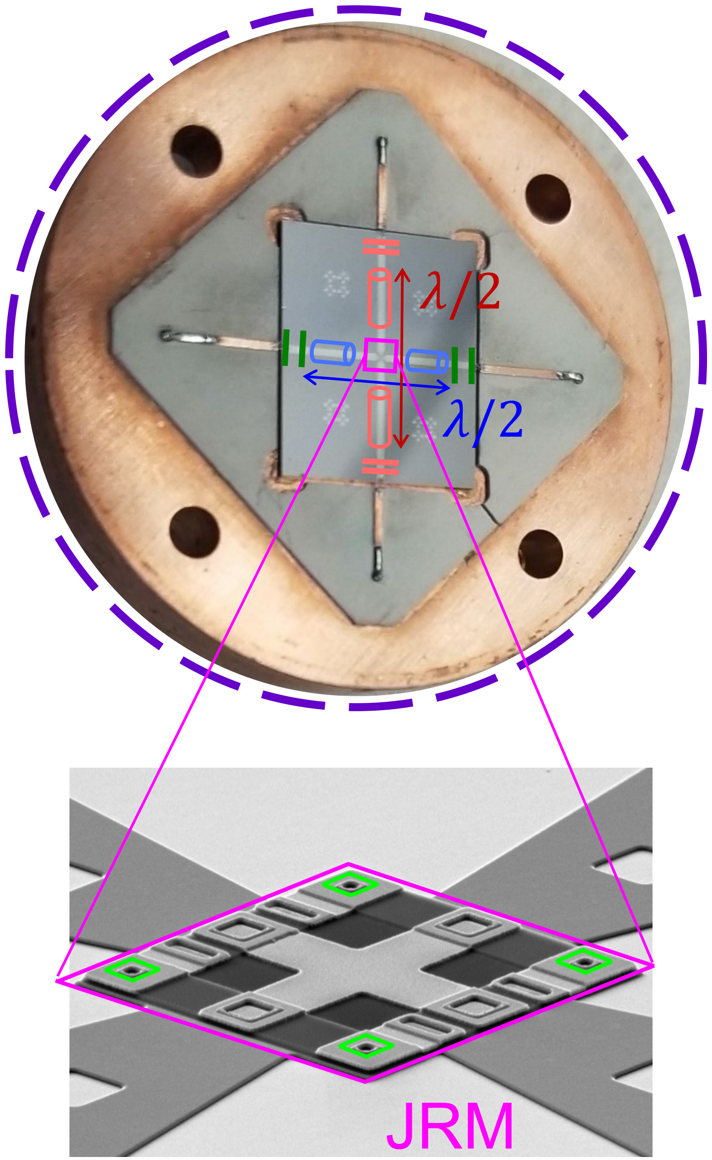
$$\Big\downarrow \; \omega_{\Delta,\Sigma}$$

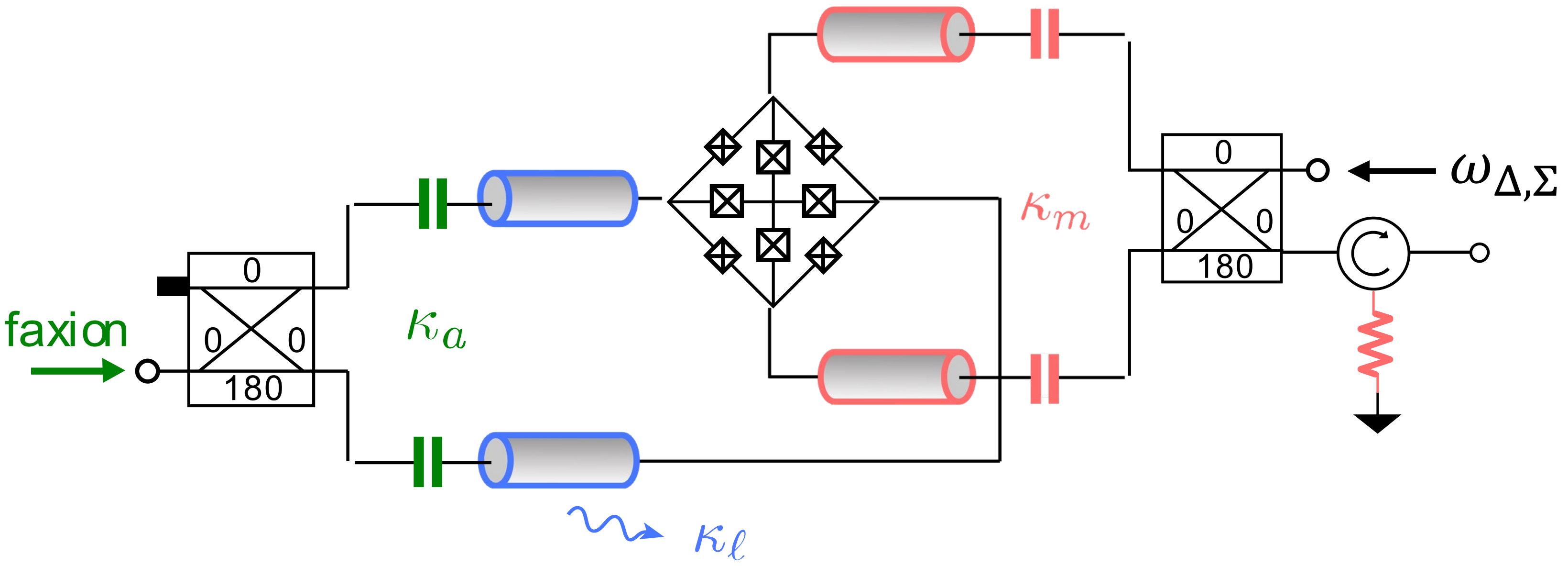
$$\hat{\mathrm{H}}_{\mathrm{QND}} = 2g\hat{X}_A\hat{X}_B$$

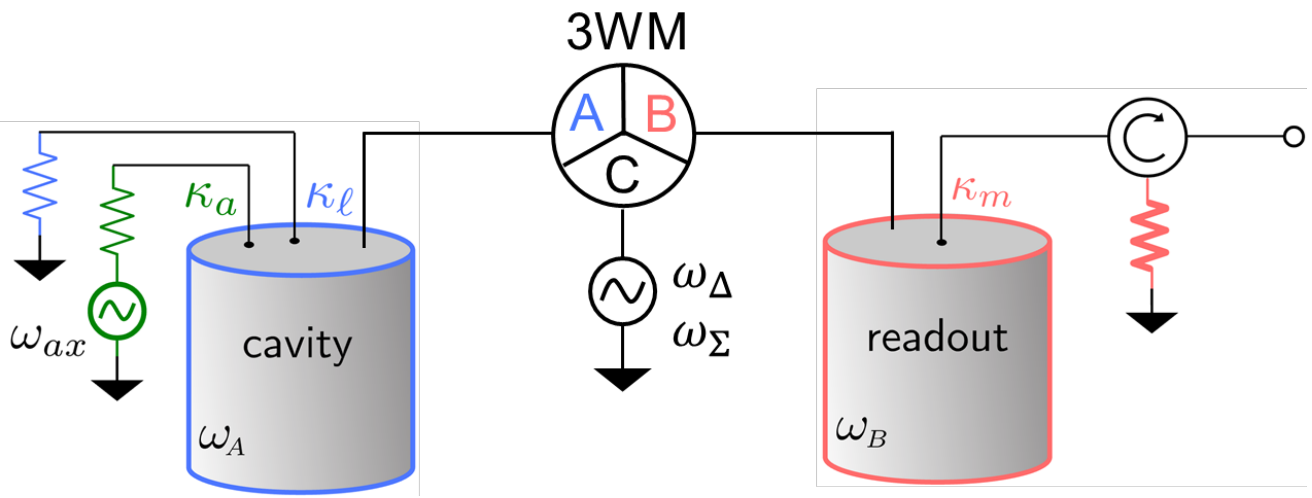


Bergeal, N., et al. *Nature Physics* 6.4 (2010).

Josephson parametric converter for prototype demonstration





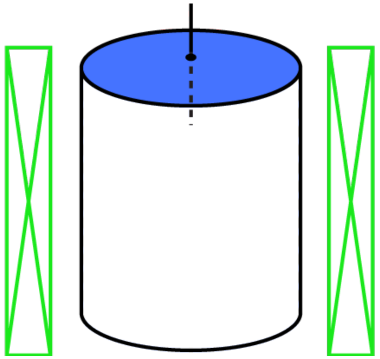


implementation

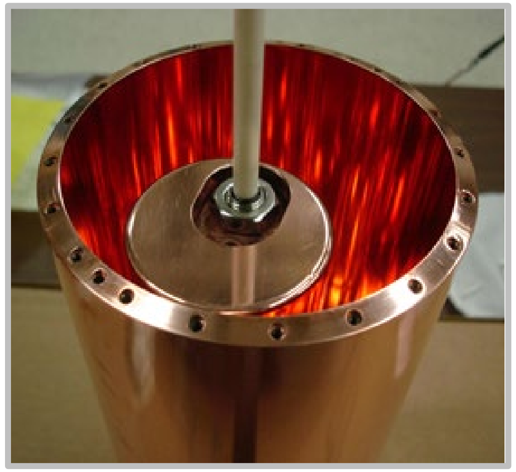
Engineering constraints of the axion cavity

resides in large magnetic field

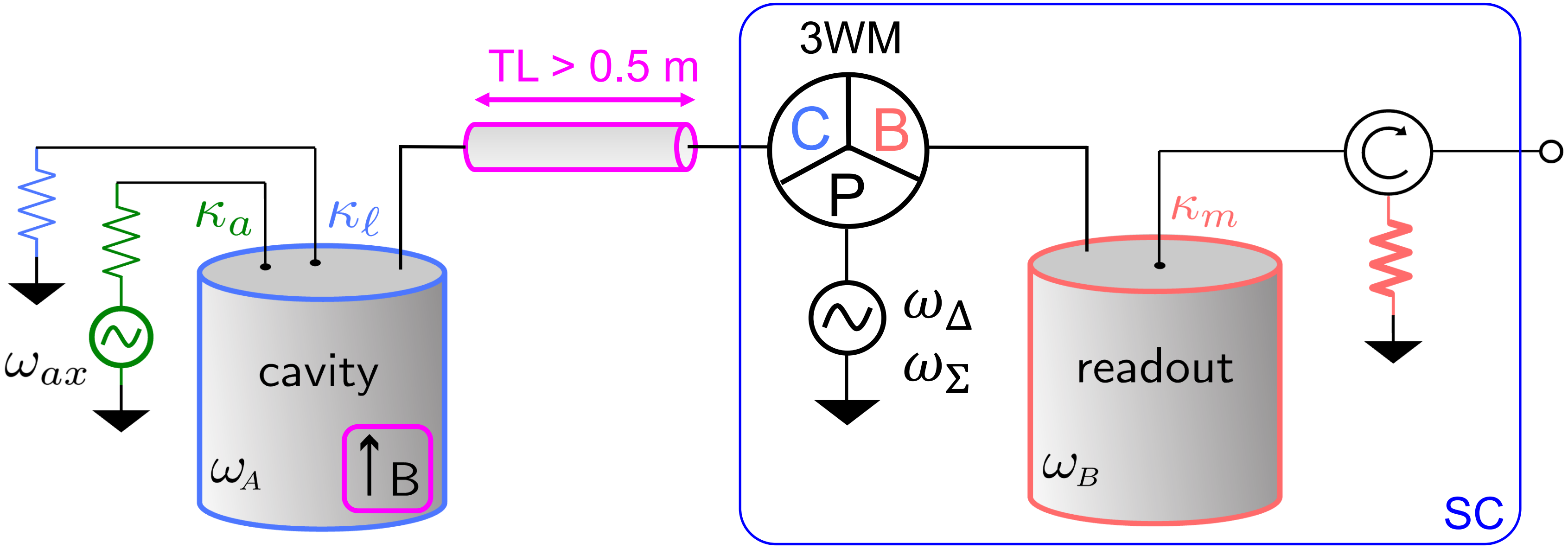
quantum electric circuits must be remote



has tunable resonance frequency and coupling



Long, lossy cable separates axion cavity from JRM circuit

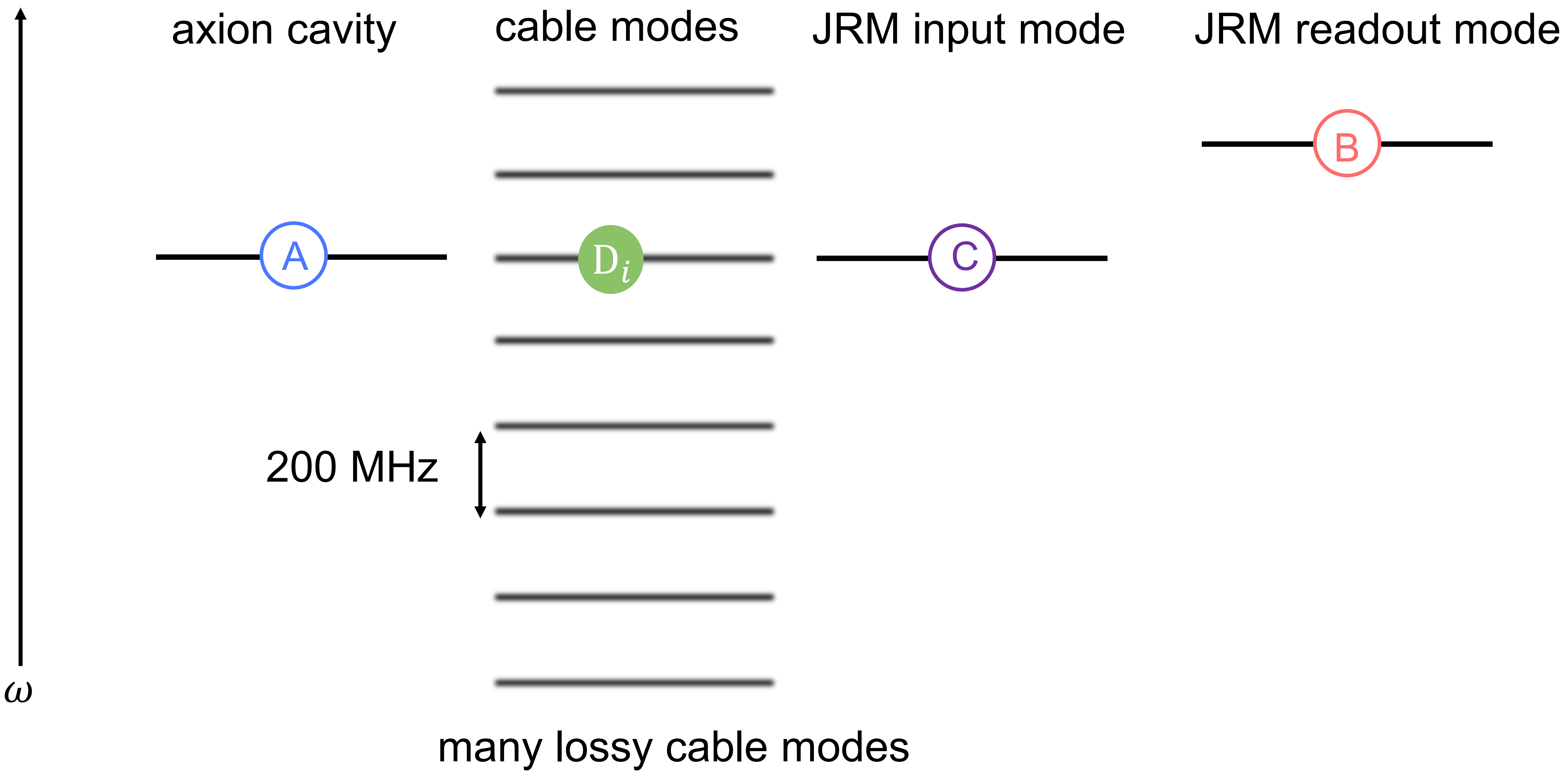


superconducting cable partially in large B-field

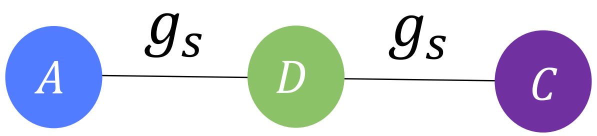
$$Q_{\text{cable}} \approx 2500$$

cable-mode frequency spacing: 200 MHz

Couple axion cavity to JRM through a dark state



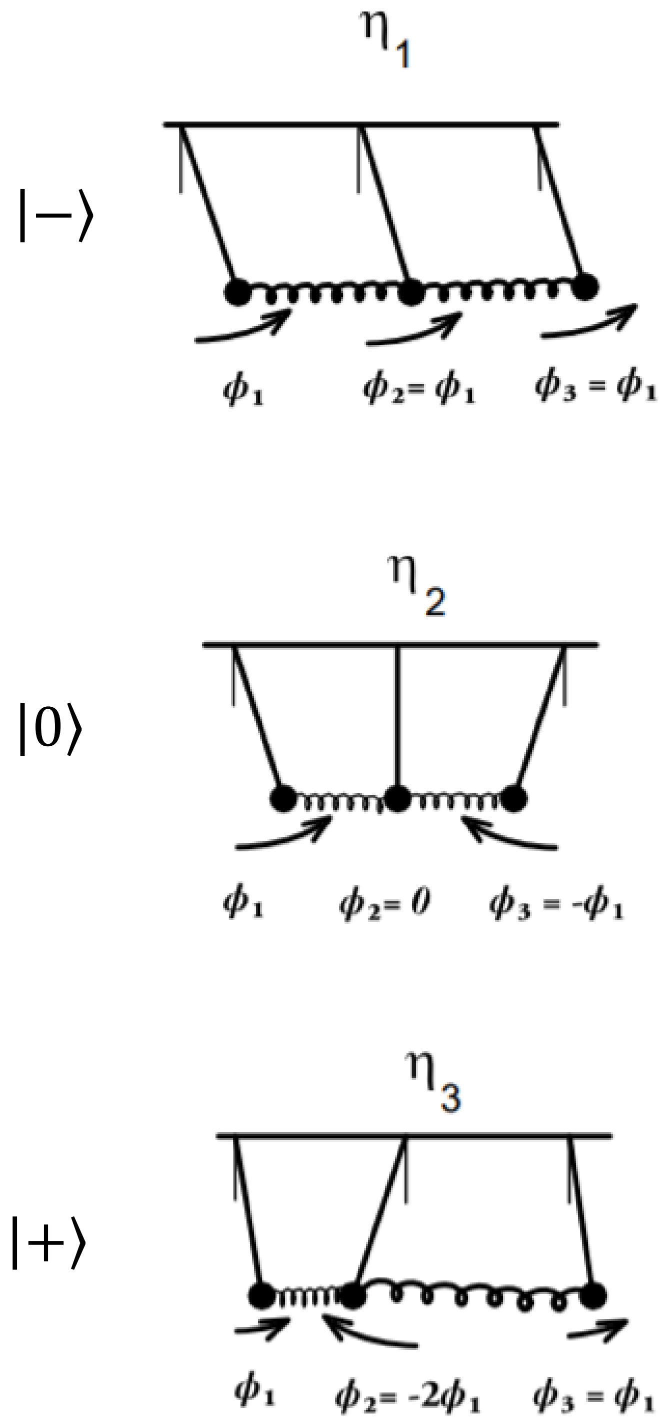
Dark state mediated coupling



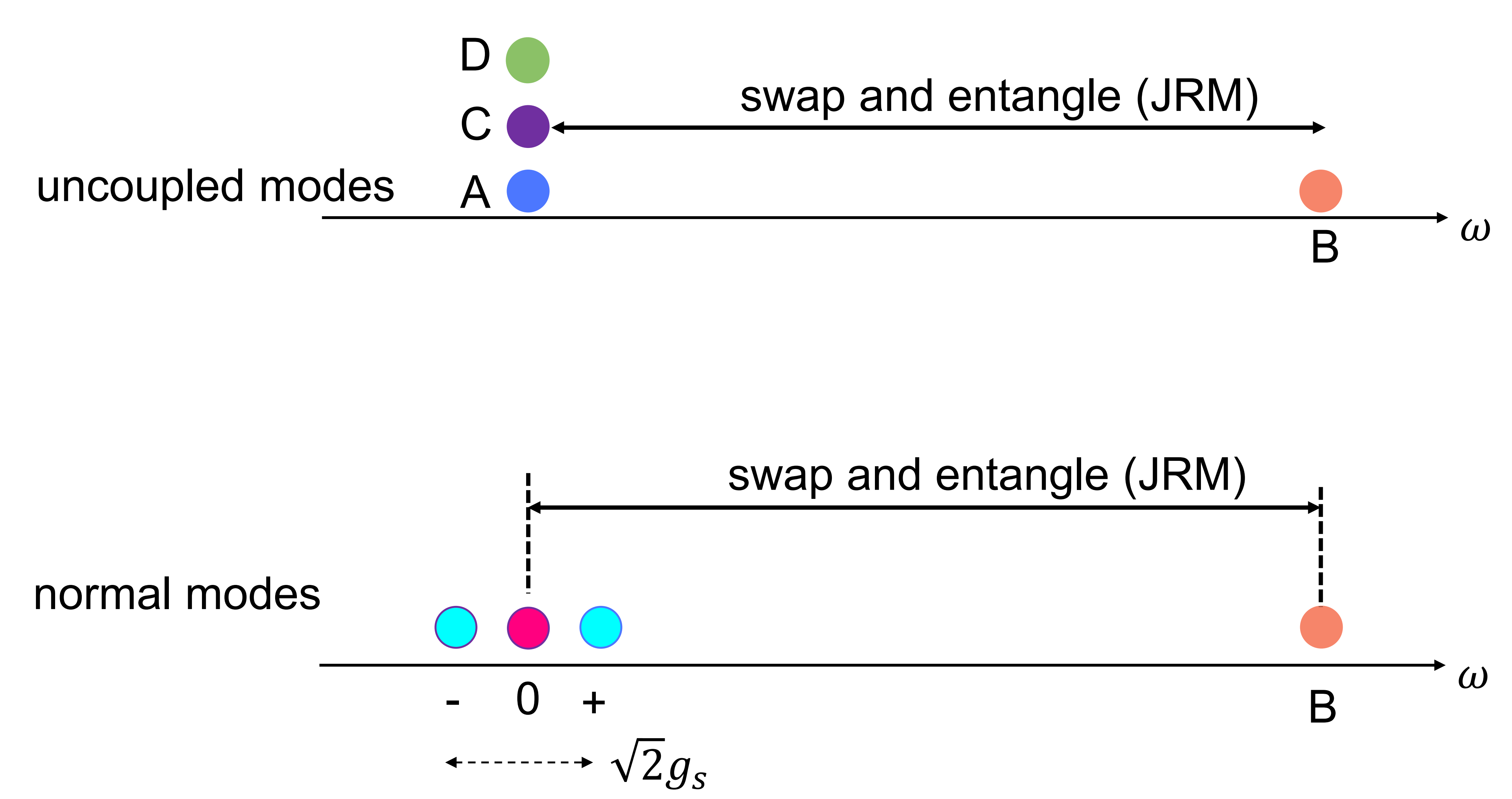
$$\hat{\mathrm{H}}_{\mathrm{int}} = \begin{pmatrix} \omega_A & g_s & 0 \\ g_s & \omega_D - i\kappa_D/2 & g_s \\ 0 & g_s & \omega_C \end{pmatrix} \qquad \omega_A = \omega_D = \omega_C$$

$$\boxed{|0\rangle = \frac{1}{\sqrt{2}}(|A\rangle - |C\rangle)}$$ “dark” state

$$|\pm\rangle = \frac{1}{2}\left(|A\rangle \pm \sqrt{2}|D\rangle + |C\rangle\right)$$

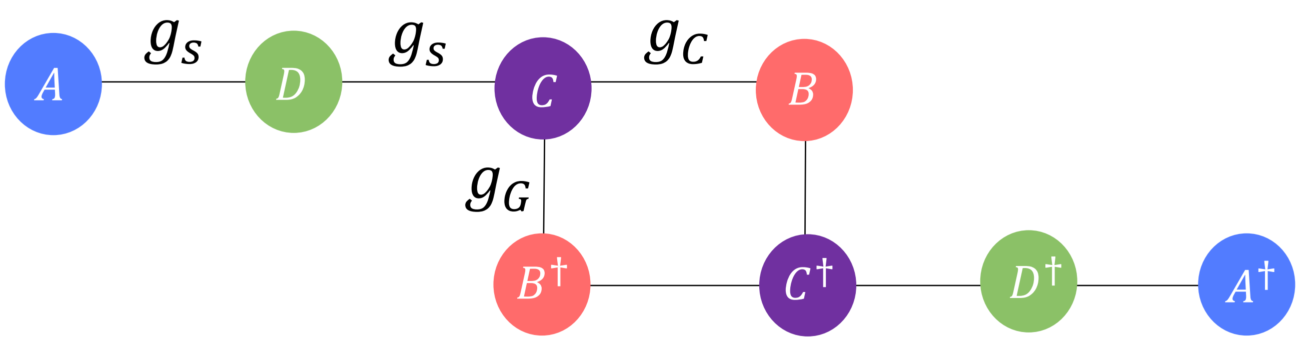


Remote entanglement via dark state transfer

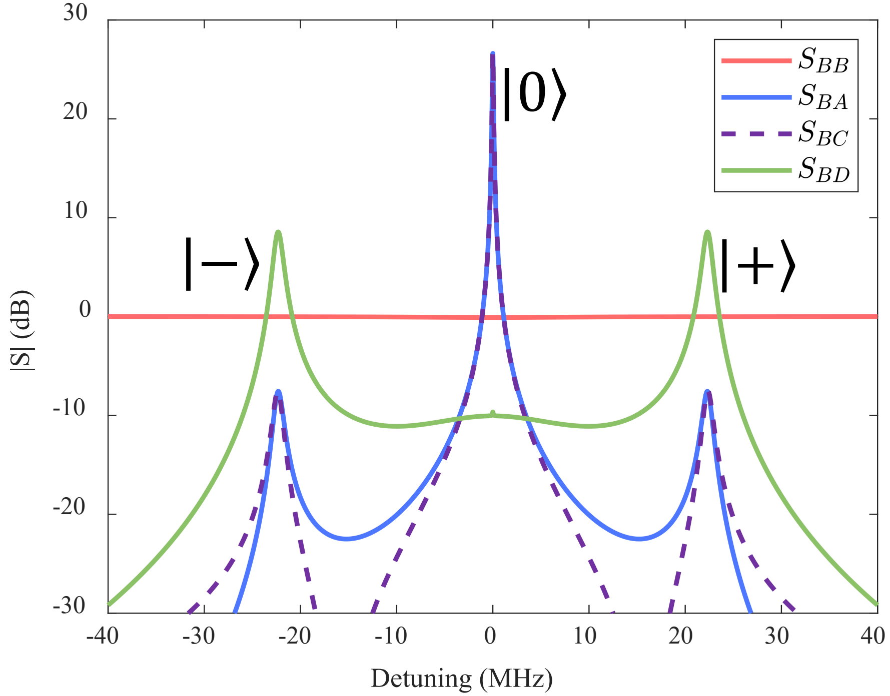


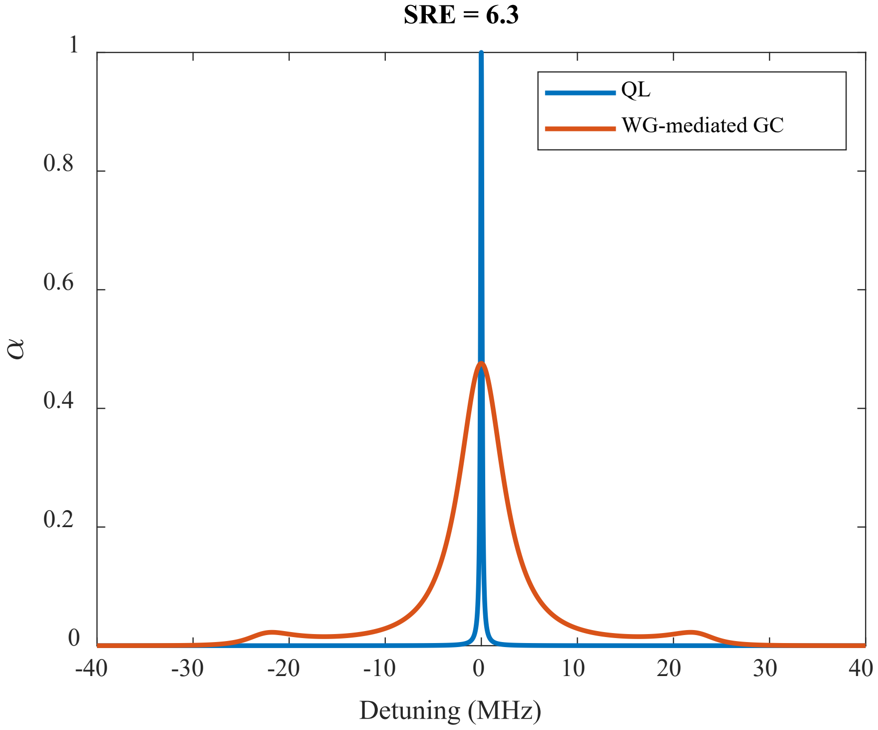
Balance cable coupling to axion cavity and chip mode

$$\hat{\mathrm{H}}_{\mathrm{int}} = g_s \hat{A}\hat{D}^\dagger + g_s \hat{C}\hat{D}^\dagger + g_C \hat{C}\hat{B}^\dagger + g_G \hat{C}^\dagger \hat{B}^\dagger + \mathrm{h.c.}$$



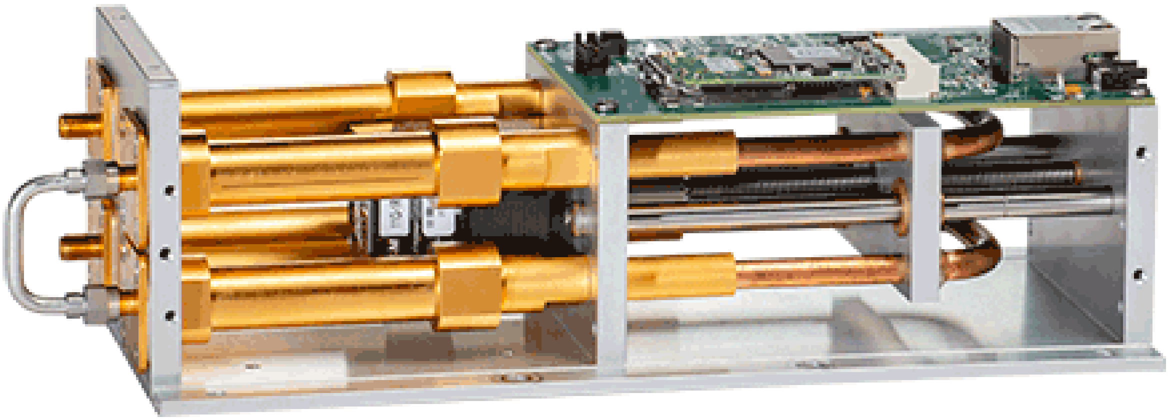
$$\kappa_D = 2\pi \times 2\ \mathrm{MHz}$$
$$\kappa_A = \kappa_C = 2\pi \times 100\ \mathrm{kHz}$$
$$g_s = g_C = g_G = 2\pi \times 15\ \mathrm{MHz}$$





Tune transmission line into resonance with cavity

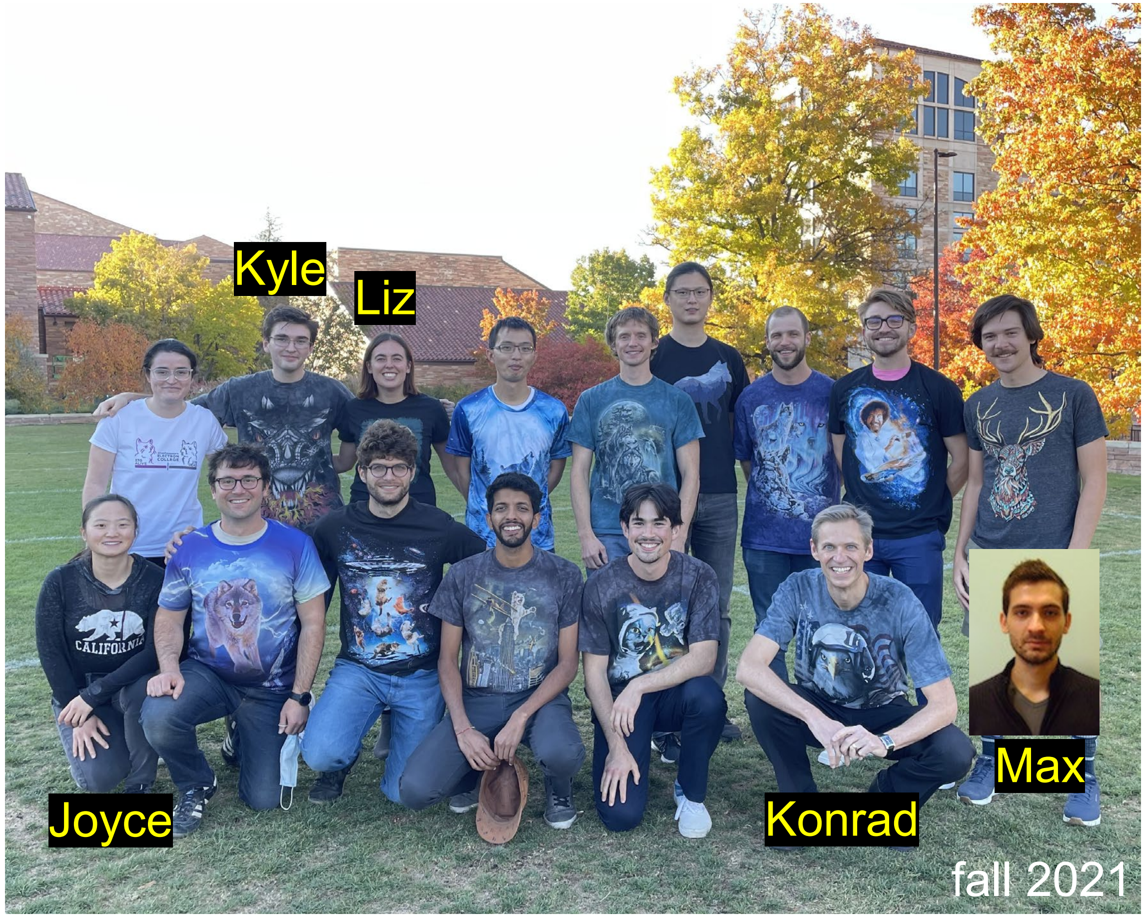
What complexity is added by the quantum engineer?



microwave trombone: Colby instruments

an additional tunable element…

Acknowledgements



JILA pfc
Fermilab
NSF
Q-SEnSE
U.S. DEPARTMENT OF ENERGY | Office of Science

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Nick Frattini
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HAYSTAC collaborators

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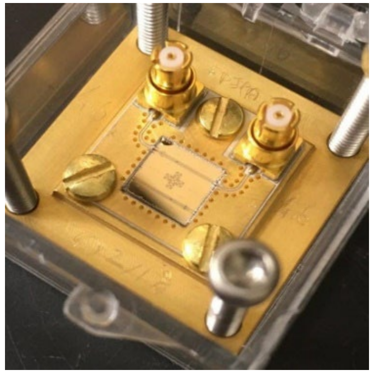
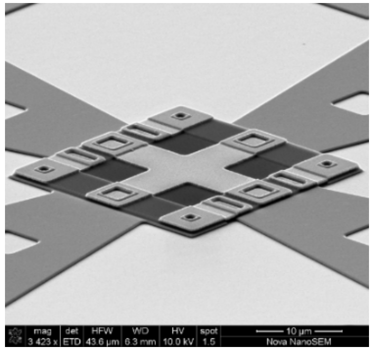
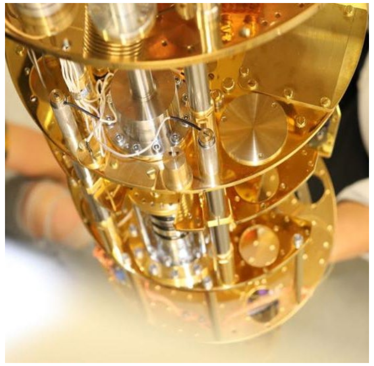
Berkeley
Johns Hopkins







The **H**aloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**DM

HAYSTAC