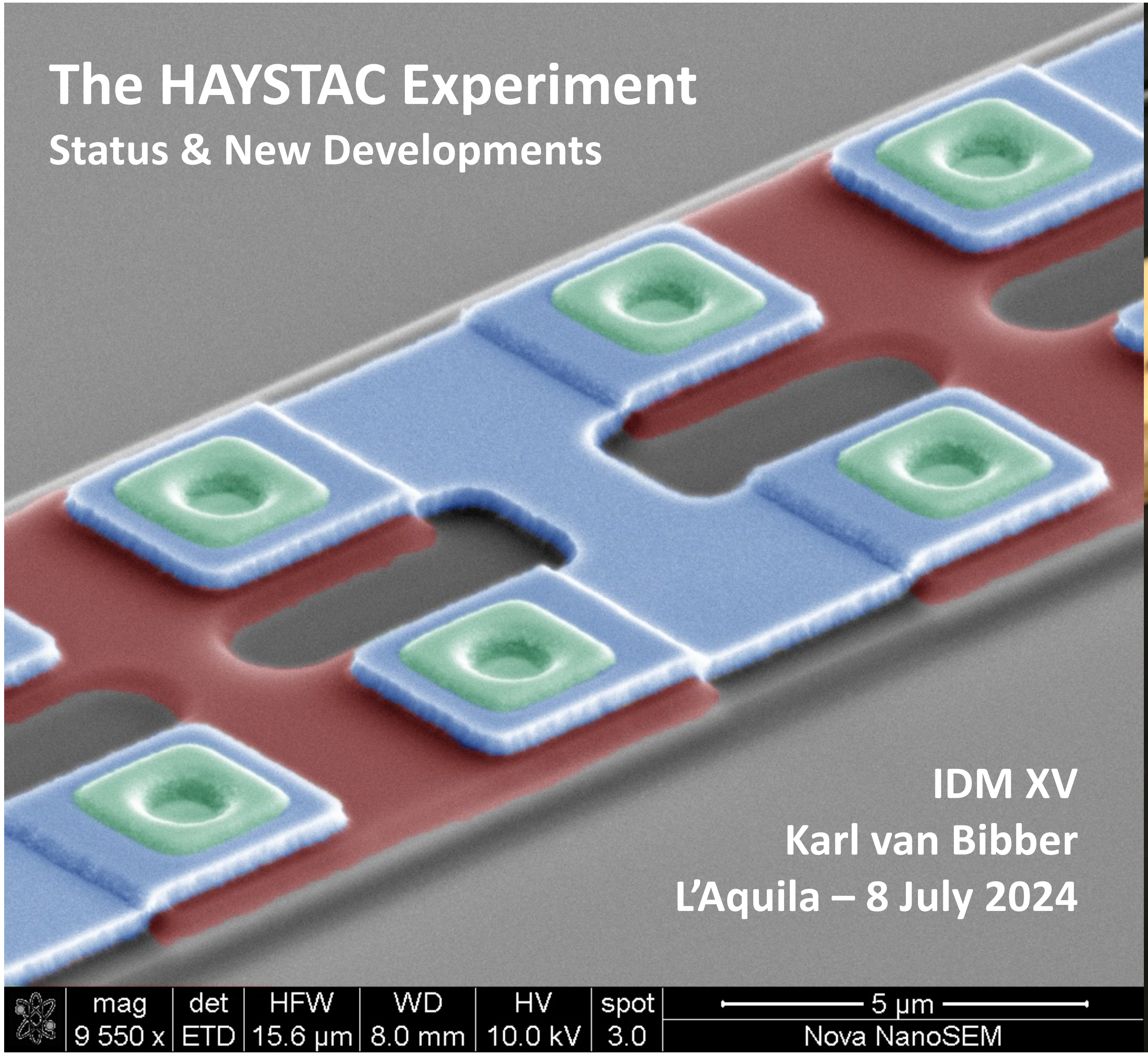
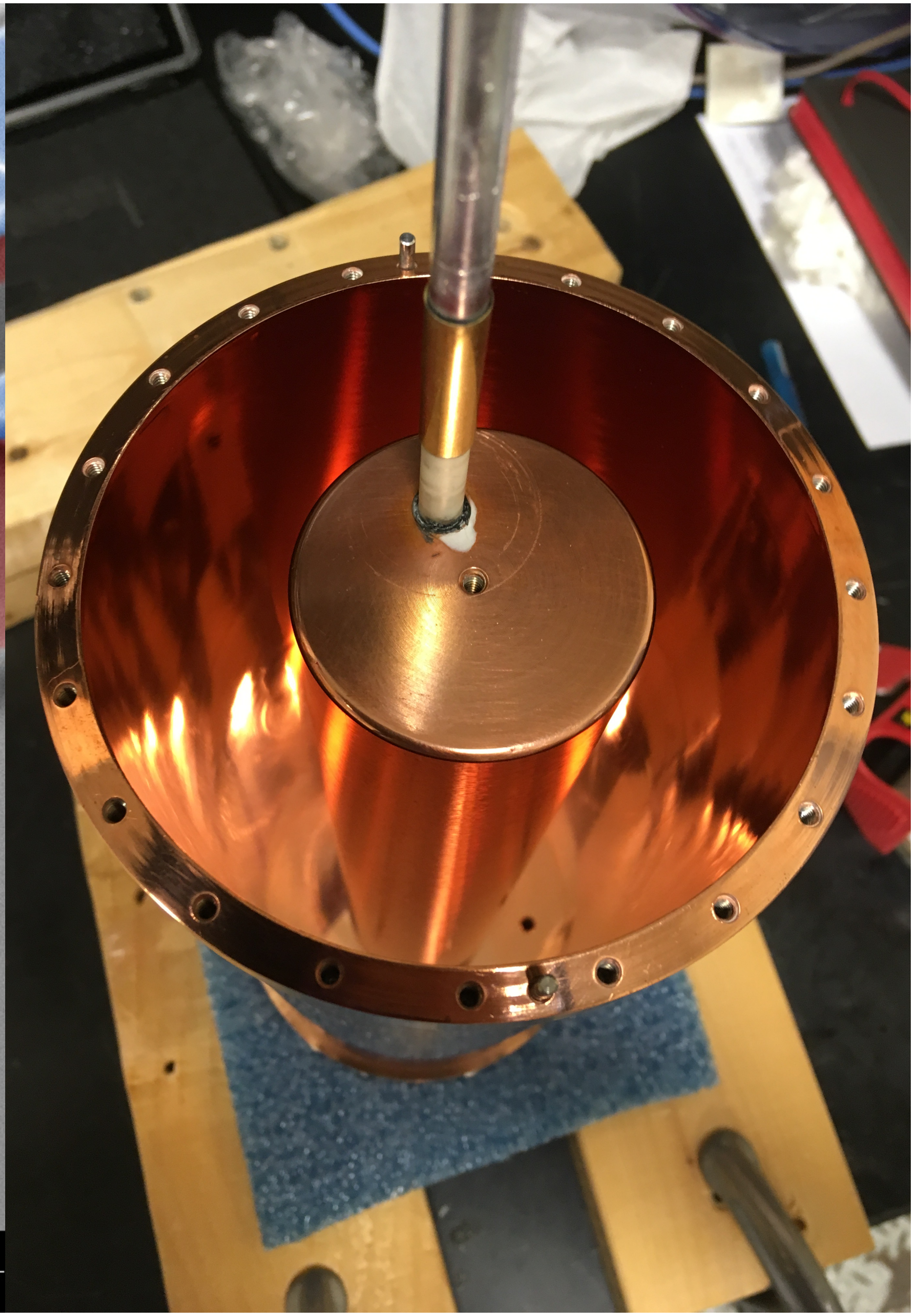
The HAYSTAC Experiment

Status & New Developments





IDM XV
Karl van Bibber
L'Aquila – 8 July 2024

THE UNIVERSITY OF CALIFORNIA · BERKELEY · 1868
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Wright Laboratory

אורים ותמים
LUX ET VERITAS

JILA
CU Boulder and NIST

JOHNS HOPKINS
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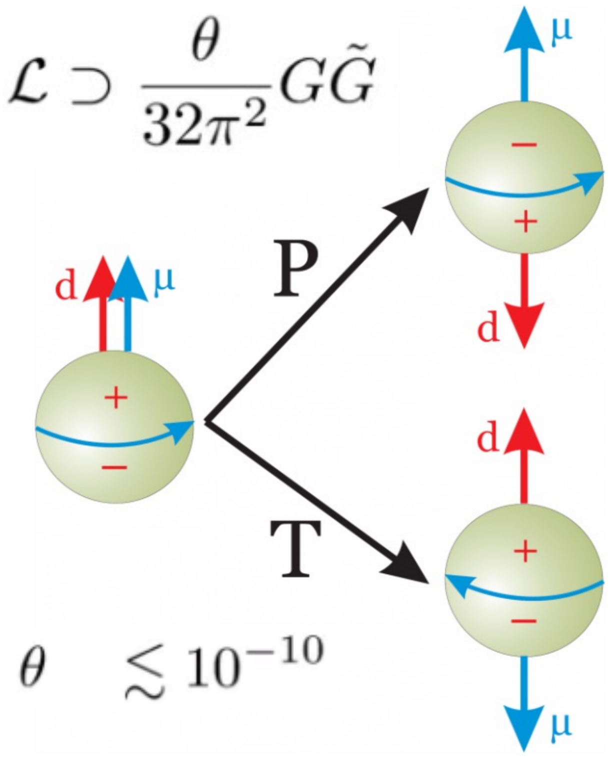
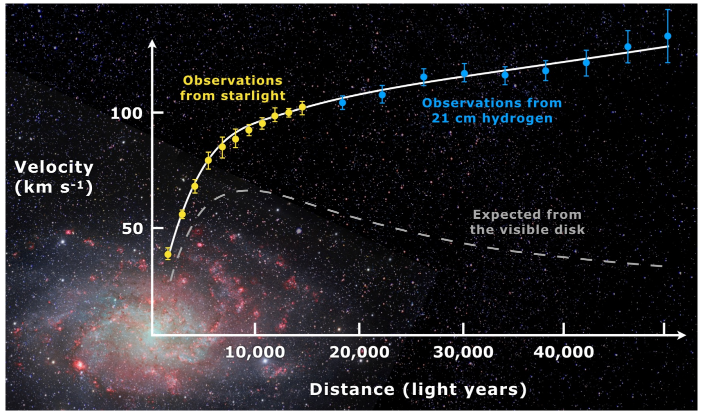
NSF

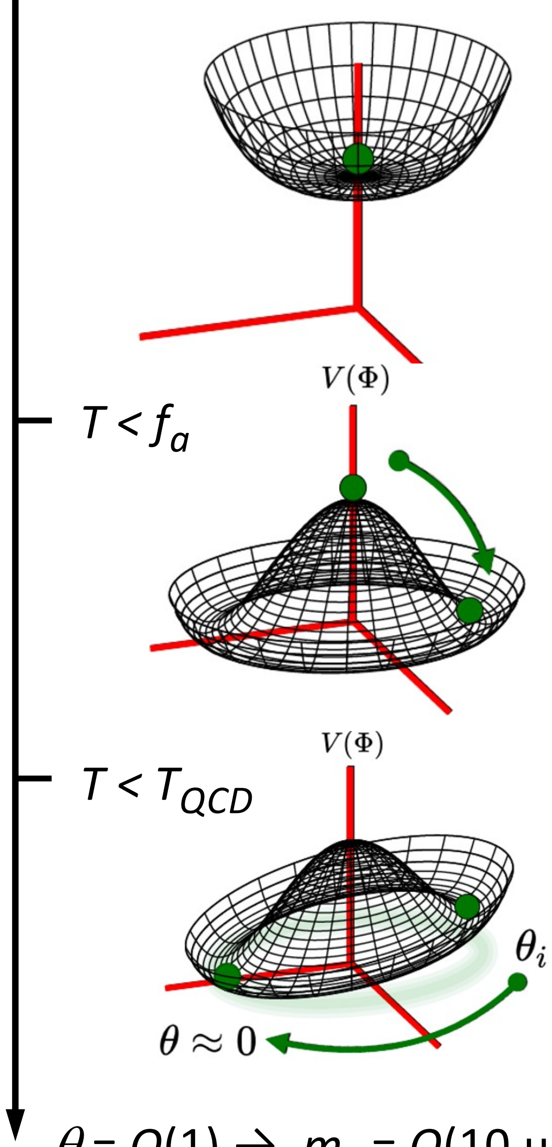
$$\mathcal{L} \supset \frac{\theta}{32\pi^2} G\tilde{G}$$



$$\theta \lesssim 10^{-10}$$



Peccei-Quinn
Weinberg-Wilczek



$T < f_a$

$T < T_{QCD}$

θ_i

$\theta \approx 0$

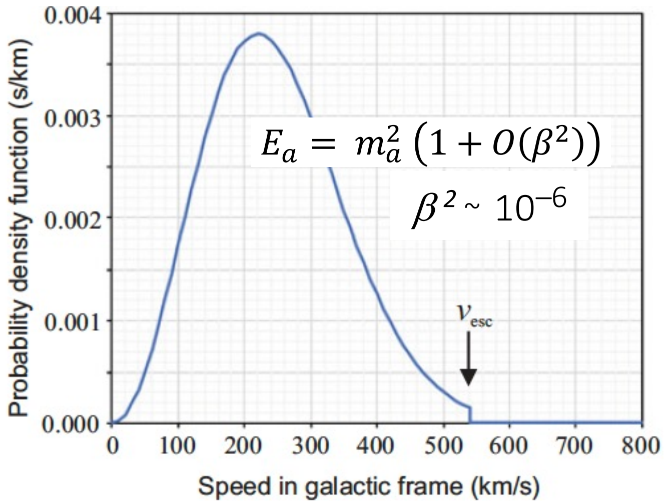
$\theta = O(1) \rightarrow \; m_a = O(10\ \mu\text{eV})$
to saturate the dark matter

The axion

$m_a\, ,\, g_{aii} \propto f_a^{-1} \quad \therefore \quad g_{aii} \propto m_a$

$10^{-12}\ \text{eV} < m_a < 60\ \text{meV}$

The axion as halo dark matter



$E_a = m_a^2\,(1 + O(\beta^2))$

$\beta^2 \sim 10^{-6}$

For $m_a \sim 10\ \mu eV$

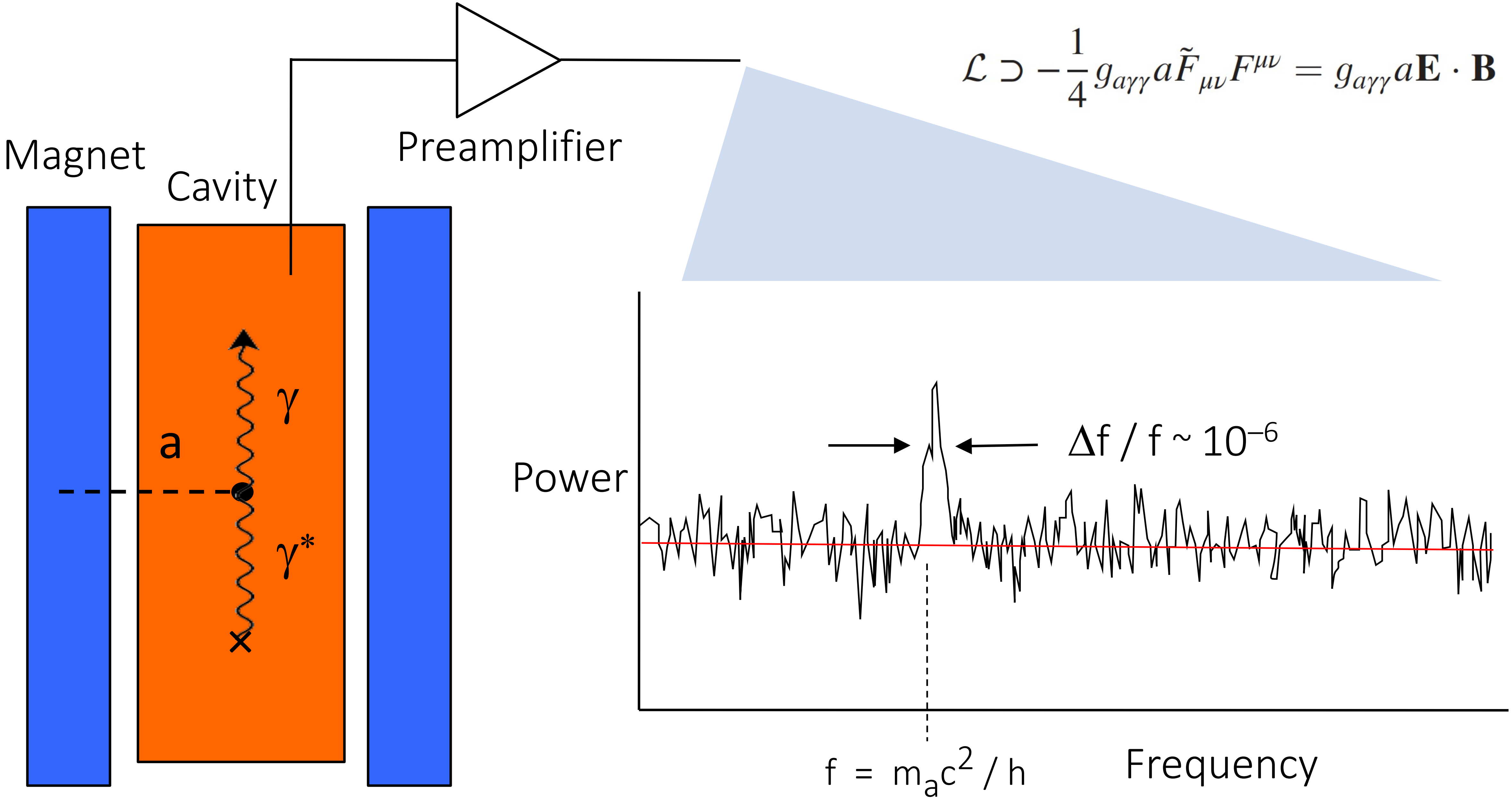
- $\rho_a \sim 10^{14}\ \text{cm}^{-3}$
- $\lambda_{deB} \sim 100\ \text{m}$

> *This is wavelike dark matter,*
> *treat as a classical field!*

The Microwave Cavity Dark Matter Experiment

P. Sikivie, Phys. Rev. Lett. 51 (1983) 1415

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a \tilde{F}_{\mu\nu} F^{\mu\nu} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$



Magnet

Cavity

Preamplifier

Power

$\Delta f / f \sim 10^{-6}$

$f = m_a c^2 / h$

Frequency

Conversion power, scan rate

Signal power

$$P_0 = 1.7\times10^{-21}\mathrm{W}\left(\frac{V}{0.2\mathrm{m}^3}\right)\left(\frac{B_0}{7.6T}\right)^2 \times C_{\mathrm{lmn}}\left(\frac{g_\gamma}{0.97}\right)^2\left(\frac{\rho_{\mathrm{a}}}{7.5\times10^{-25}\mathrm{g/cm^3}}\right) \times\left(\frac{f}{700\ \mathrm{MHz}}\right)\left(\frac{Q_{\mathrm{L}}}{90000}\right)\frac{\beta}{(1+\beta)}\frac{1}{1+(2Q_{\mathrm{L}}\delta f/f_0)^2}$$

Q_L =	$Q_0/(1+\beta)$	Loaded Q-value; β coupling
δf =	$f - f_0$	Offset from central
C_{lmn}		Cavity form factor

Scanning rate

$$\frac{\mathrm{d}f}{\mathrm{d}t}\approx\frac{15\mathrm{GHz}}{\mathrm{year}}\left(\frac{V}{0.2\mathrm{m}^3}\right)^2\left(\frac{B_0}{7.6T}\right)^4 \times C_{010}^2\left(\frac{g_\gamma}{0.97}\right)^4\left(\frac{\rho_{\mathrm{a}}}{7.5\times10^{-25}\mathrm{g/cm^3}}\right)^2 \times\left(\frac{f}{700\ \mathrm{MHz}}\right)^2\left(\frac{Q_L}{90000}\right)\frac{\beta^2}{(1+\beta)^2}\left(\frac{5}{\mathrm{SNR}}\right)^2 \times\left(\frac{3K}{T_{\mathrm{S}}}\right)^2\left(\frac{f_{\mathrm{step}}}{\Delta f}\right)\sum_{n=-m}^{m}\frac{1}{(1+((2nf_{\mathrm{step}}/\Delta f))^2)^2}$$

Δf	Cavity bandwidth
f_{step}	Frequency tuning steps
n	Overlapping tuning steps

Form factor & Quality Factor

$$C_{\mathrm{lmn}} = \frac{\left(\int_V \boldsymbol{B}(\boldsymbol{x})\cdot\boldsymbol{E}_{lmn}(\boldsymbol{x})\,\mathrm{d}^3\boldsymbol{x}\right)^2}{B_0{}^2 V\int_V \varepsilon_{\mathrm{r}}(\boldsymbol{x})\boldsymbol{E}_{lmn}(\boldsymbol{x})^2\,\mathrm{d}^3\boldsymbol{x}}$$

$$Q = O\frac{(Volume)}{(Surface\ Area)\cdot(Skin\ Depth)}$$

System noise temperature, Figure-of-merit

System Noise Temperature

Dicke radiometer equation:

$$SNR = \frac{P}{k_B T_{SYS}} \sqrt{\frac{t}{\Delta\nu_a}}$$

$$k_B T_{SYS} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} \right) + k_B T_A$$

T	Physical temperature
T_A	Amplifier noise temperature
t	Integration time

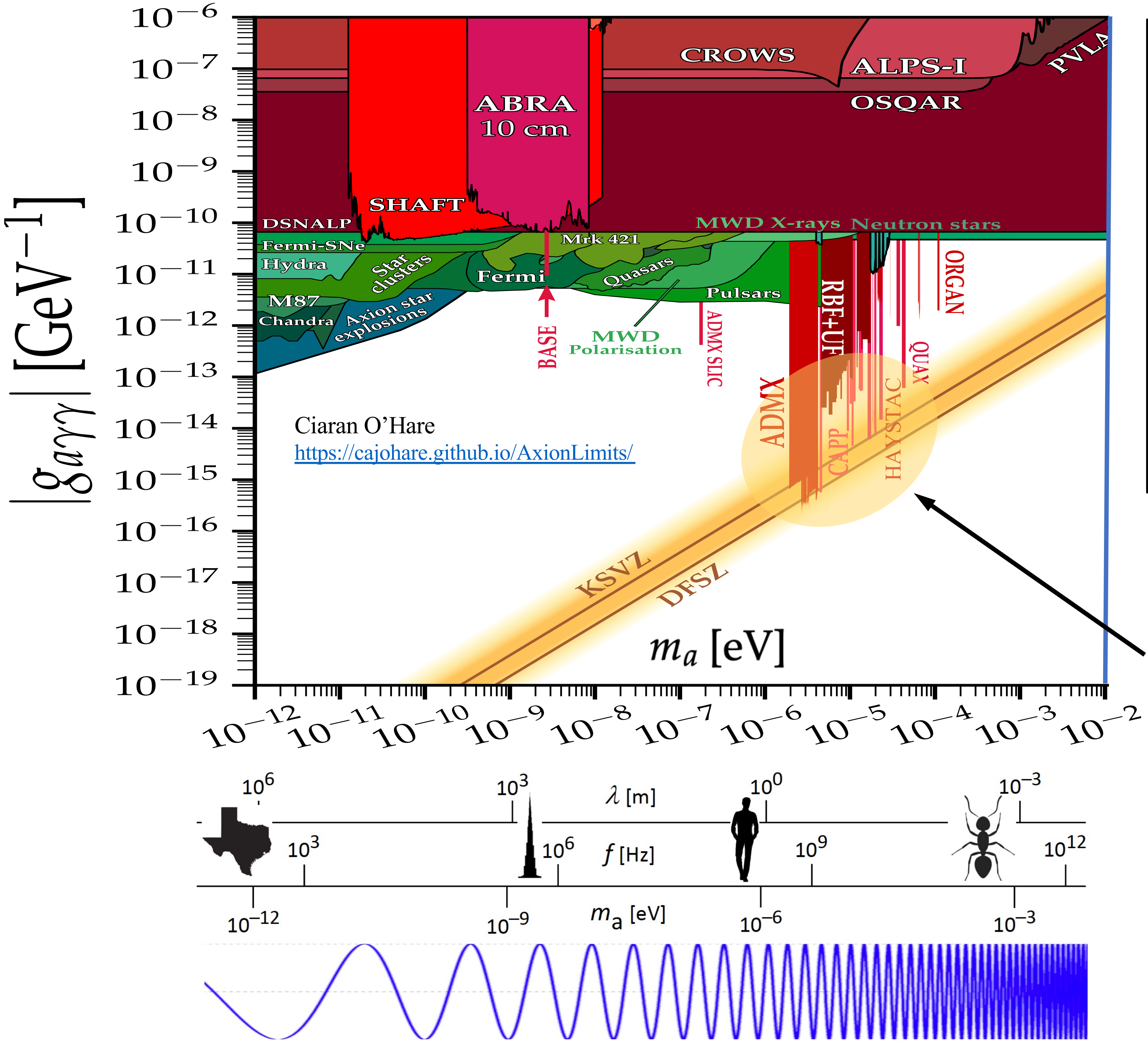
The Standard Quantum Limit for Linear Amplifiers

$$T_A > T_{SQL}$$

where

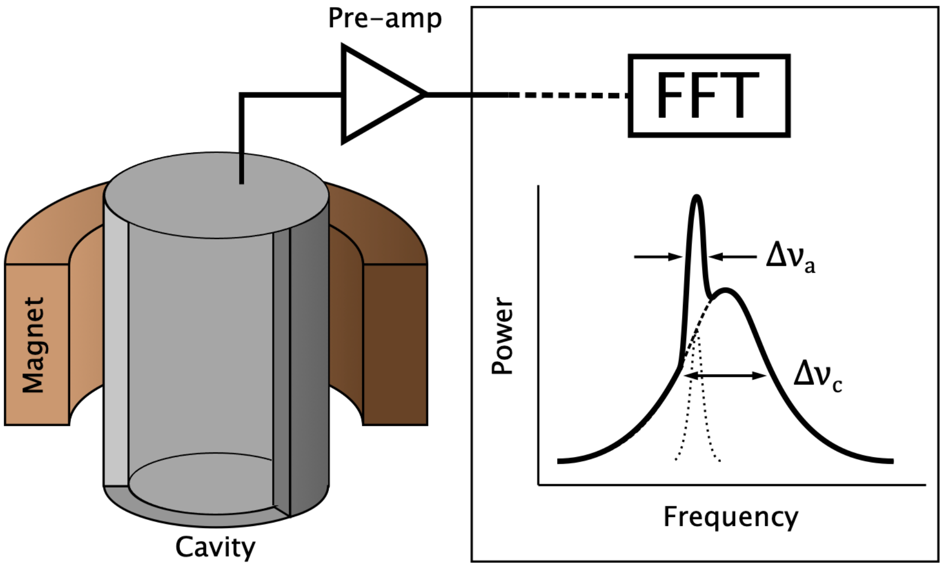
$$k_B\, T_{SQL} = h\,\nu$$

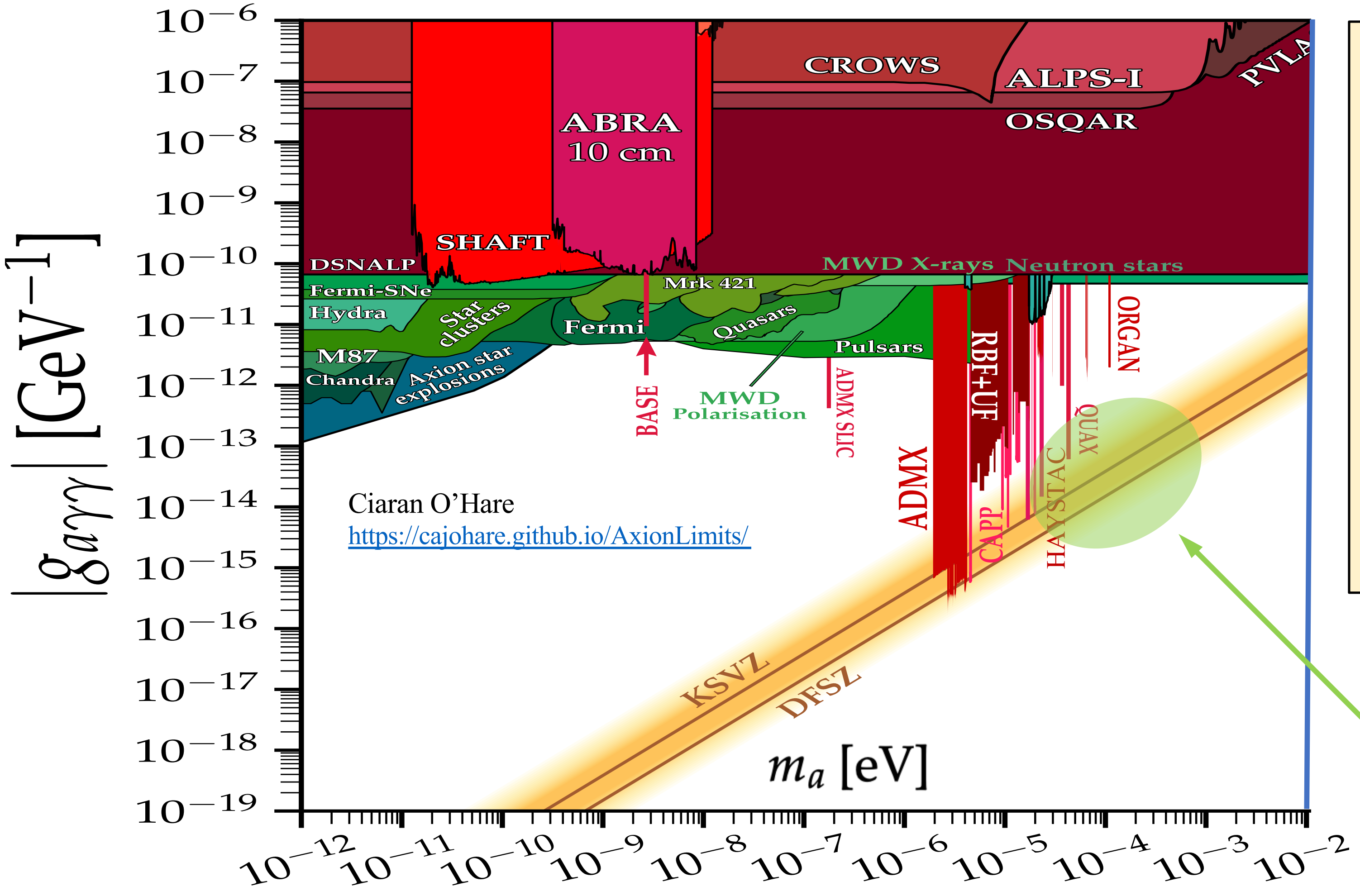
$$FOM \propto \frac{B^4 V^2 C^2 Q}{T_{SYS}}$$



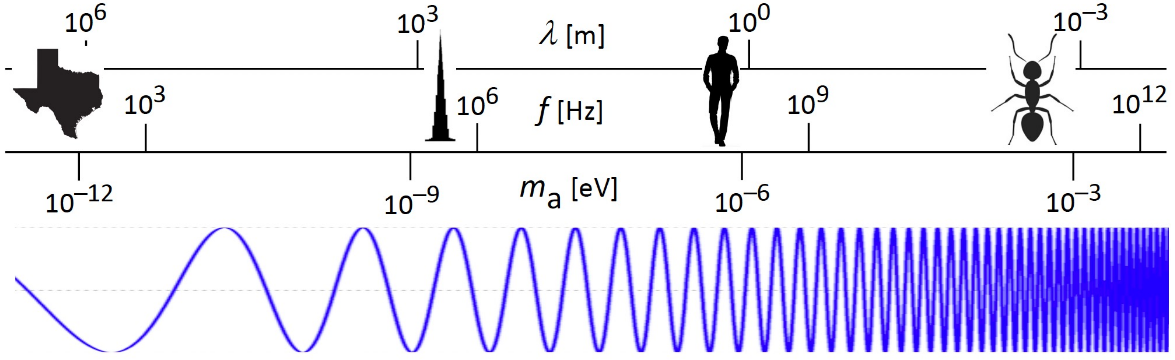
Vacuum Realignment

- $m_a \sim O(10\ \mu\mathrm{eV})$
- $\nu \sim O(\mathrm{GHz})$
- $d \sim \lambda_C \sim O(0.1\text{-}1\ \mathrm{m})$
- microwave cavities



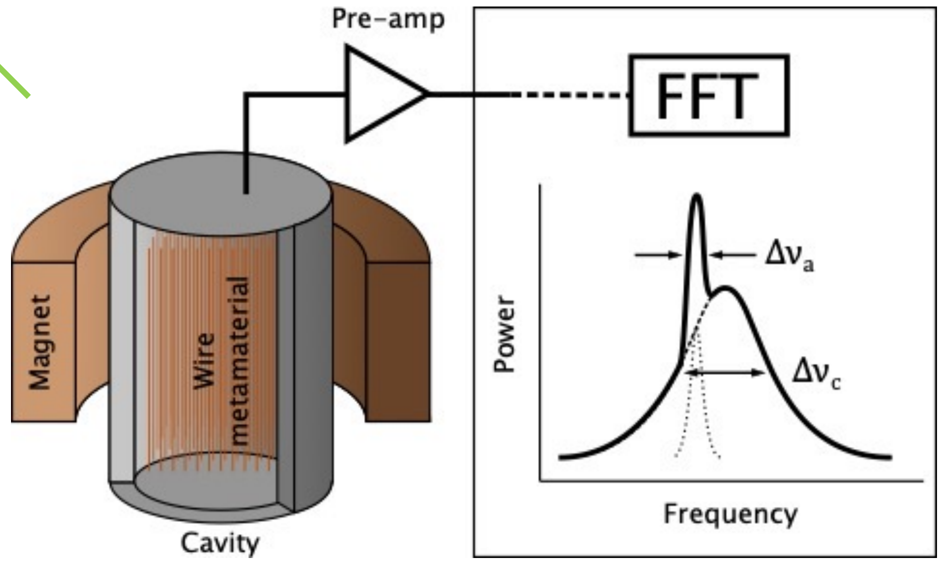


Ciaran O’Hare
https://cajohare.github.io/AxionLimits/



Post-Inflation Axion

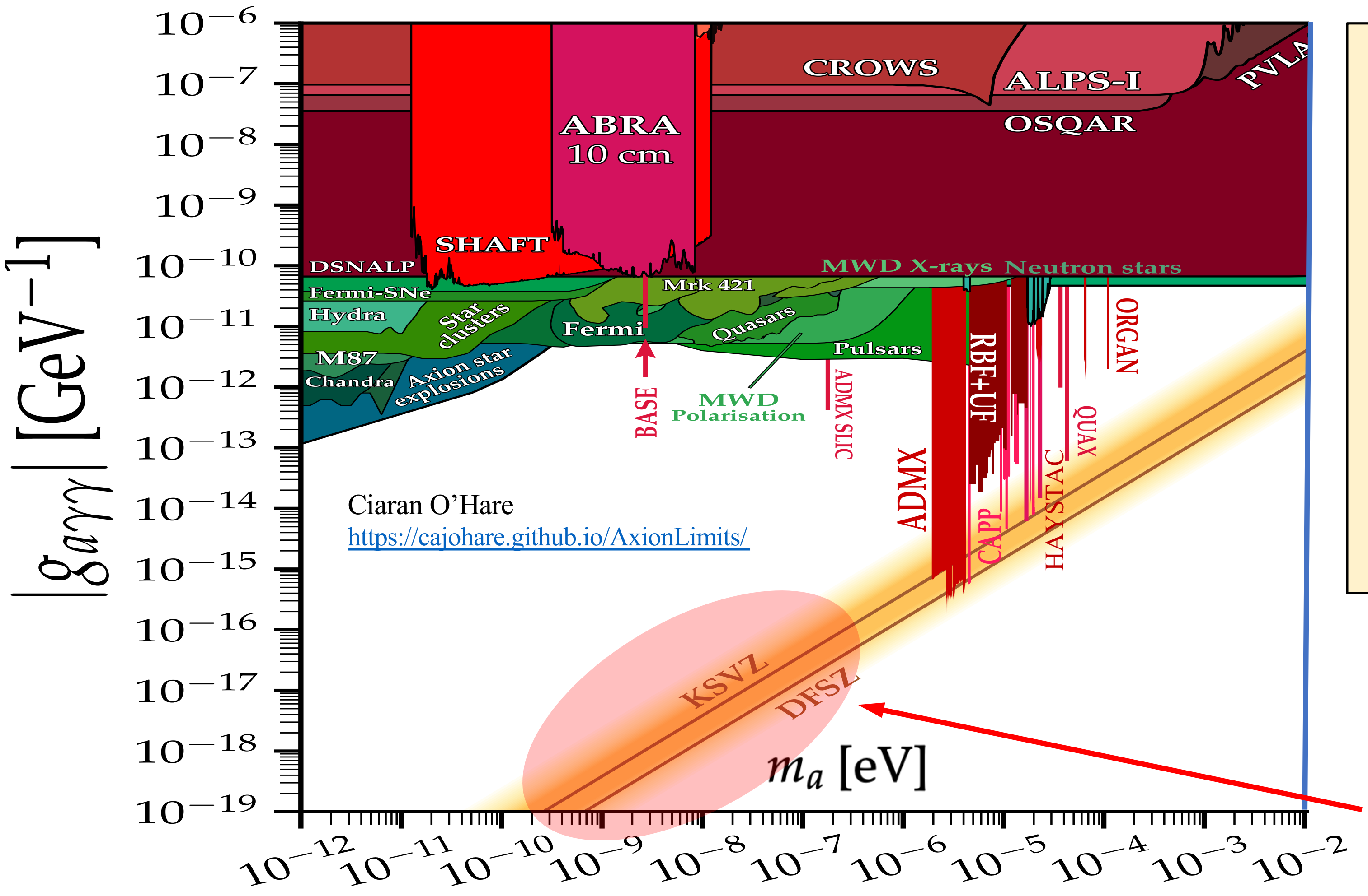
- ➢ $m_a \sim O(100\ \mu\text{eV})$
- ➢ $\nu \sim O(10\text{-}100\ \text{GHz})$
- ➢ $\lambda_C = h/m_a c \leq O(\text{cm})$
- ➢ e.g. metamaterials



See H. Jackson, A. Gallo Rosso

GUT-scale Axions

- $m_a \sim\ O(\text{neV})$
- $\nu\ \sim\ O(\text{kHz-MHz})$
- $\lambda_C = h/m_a c \sim O(\text{km})$
- lumped-element circuit



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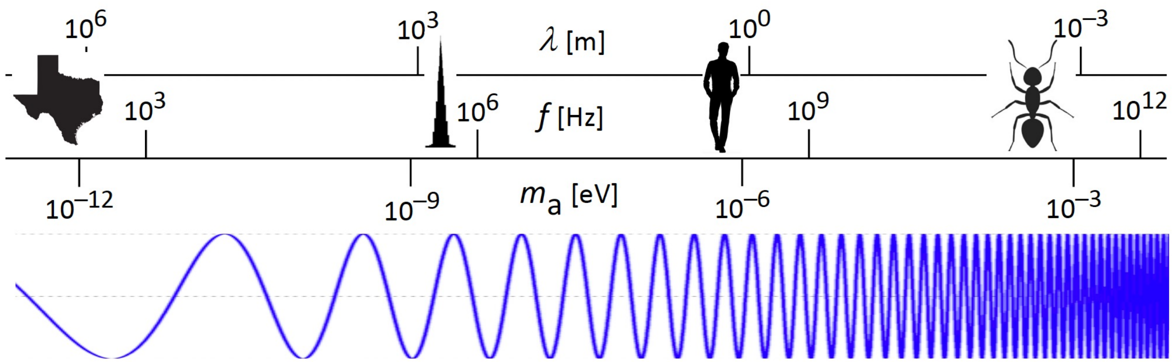
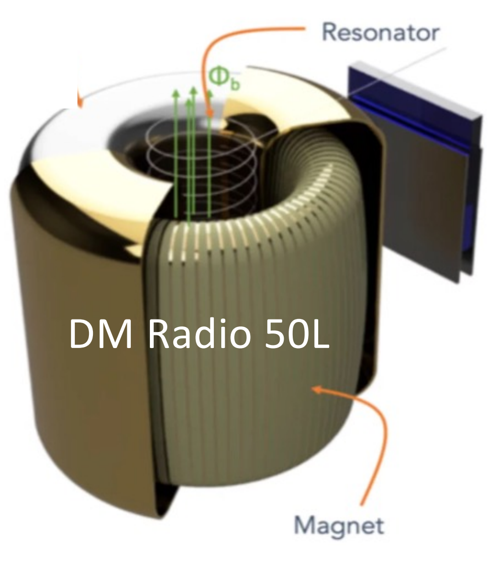
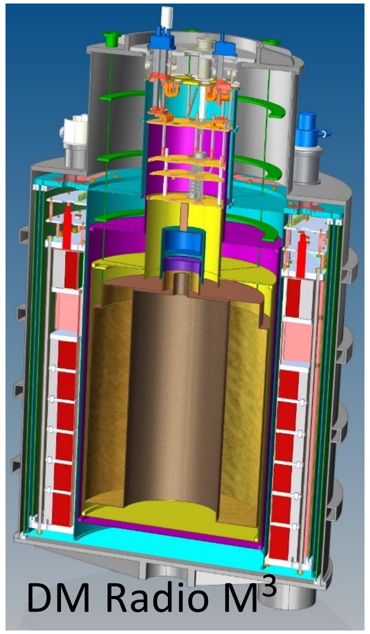


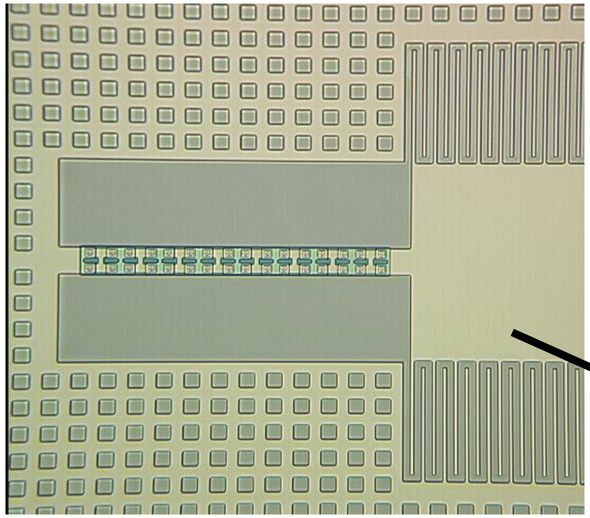


See A. Droster

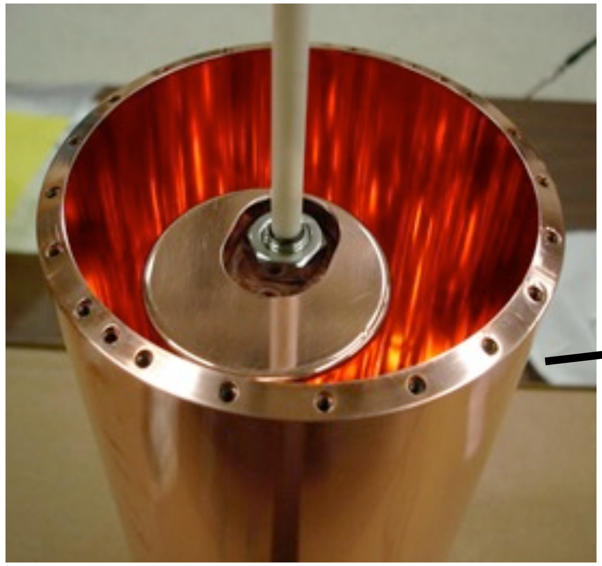


HAYSTAC – Pathfinder & Technology Testbed toward Post-Inflation Axion

JPA-based Squeezed-State Receiver



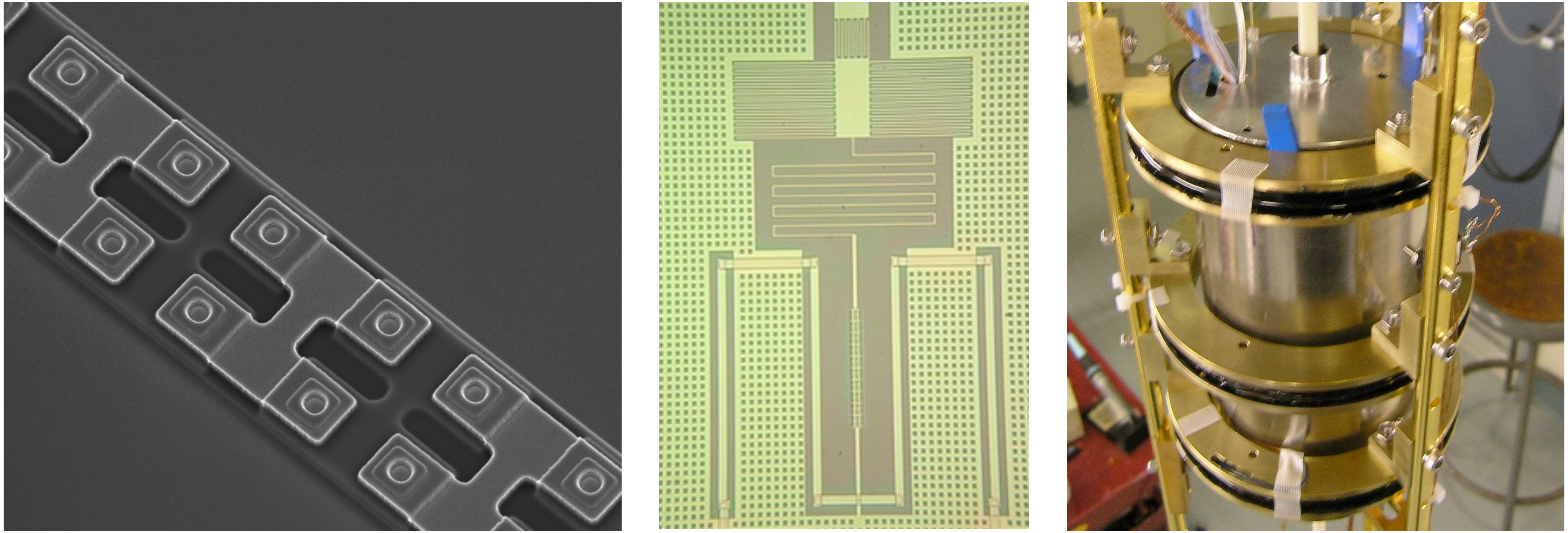
Microwave Cavity (copper)



^{3}He/^{4}He Dilution Refrigerator

9.4 Tesla, 10 Liter Magnet

HAYSTAC Phase I – single Josephson Parametric Amplifier (JPA)

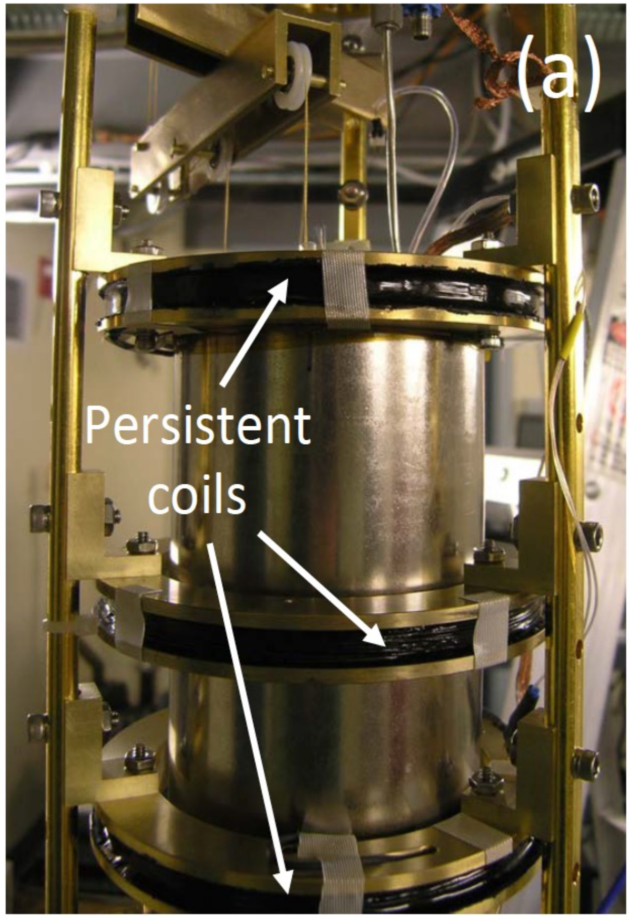


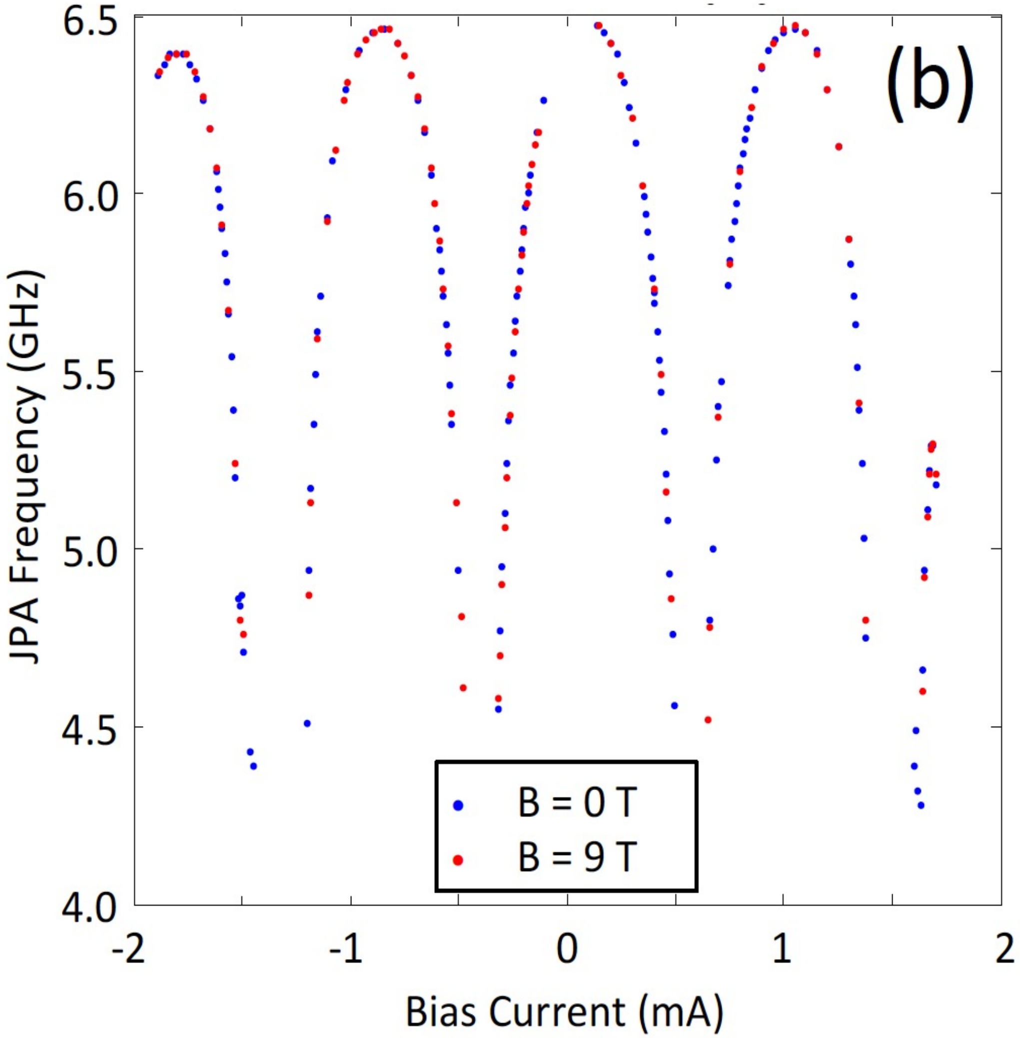
Operated at T_{SYS} ~ (2-3) x T_{SQL} at 6 GHz

The major challenge – magnetic shielding of the JPA

"Defense in depth"

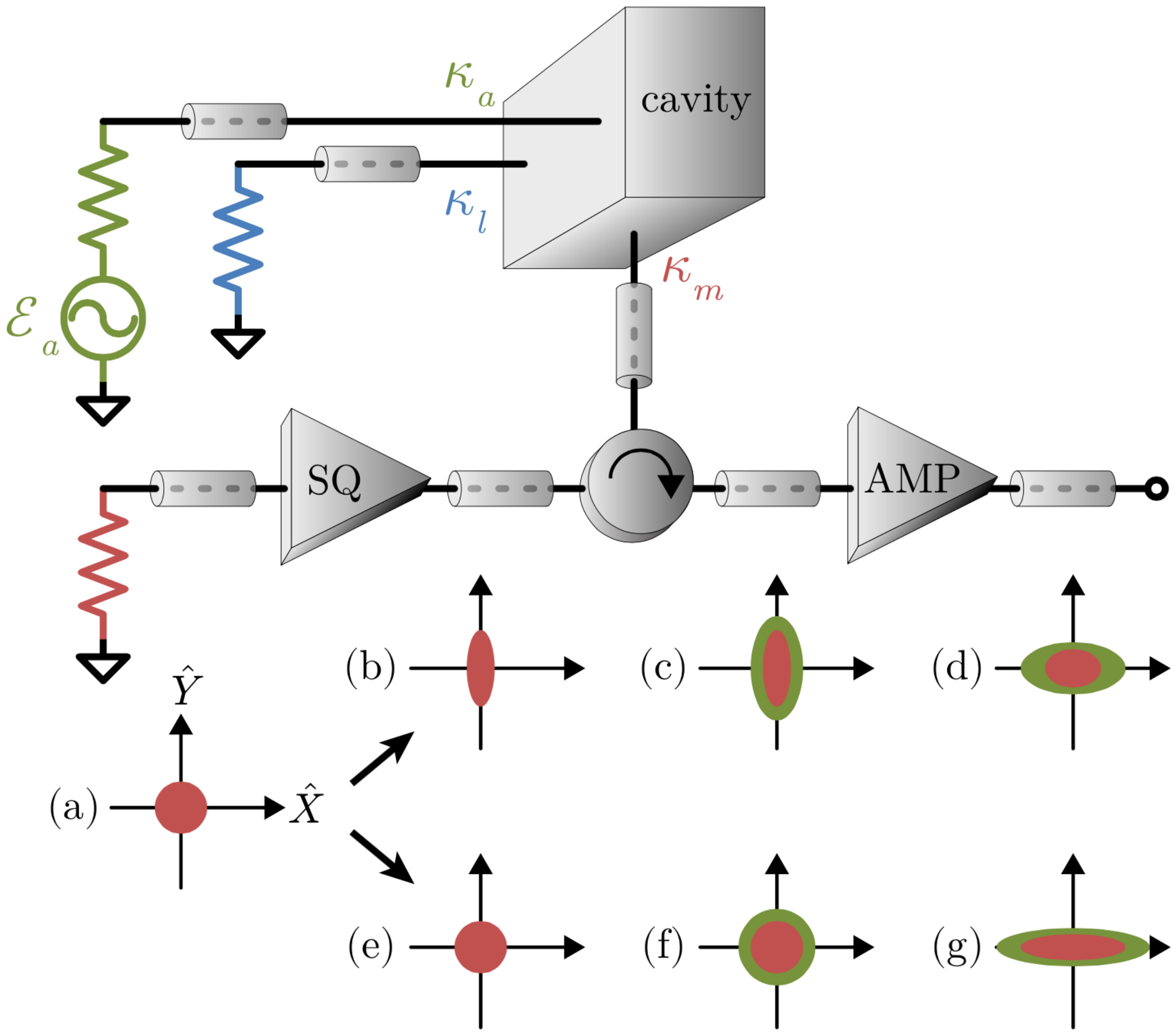
- Active bucking coil
- Persistent coils (4)
- Cryoperm (2 layers)
- S'con lead sheet
- S'con aluminum sheet

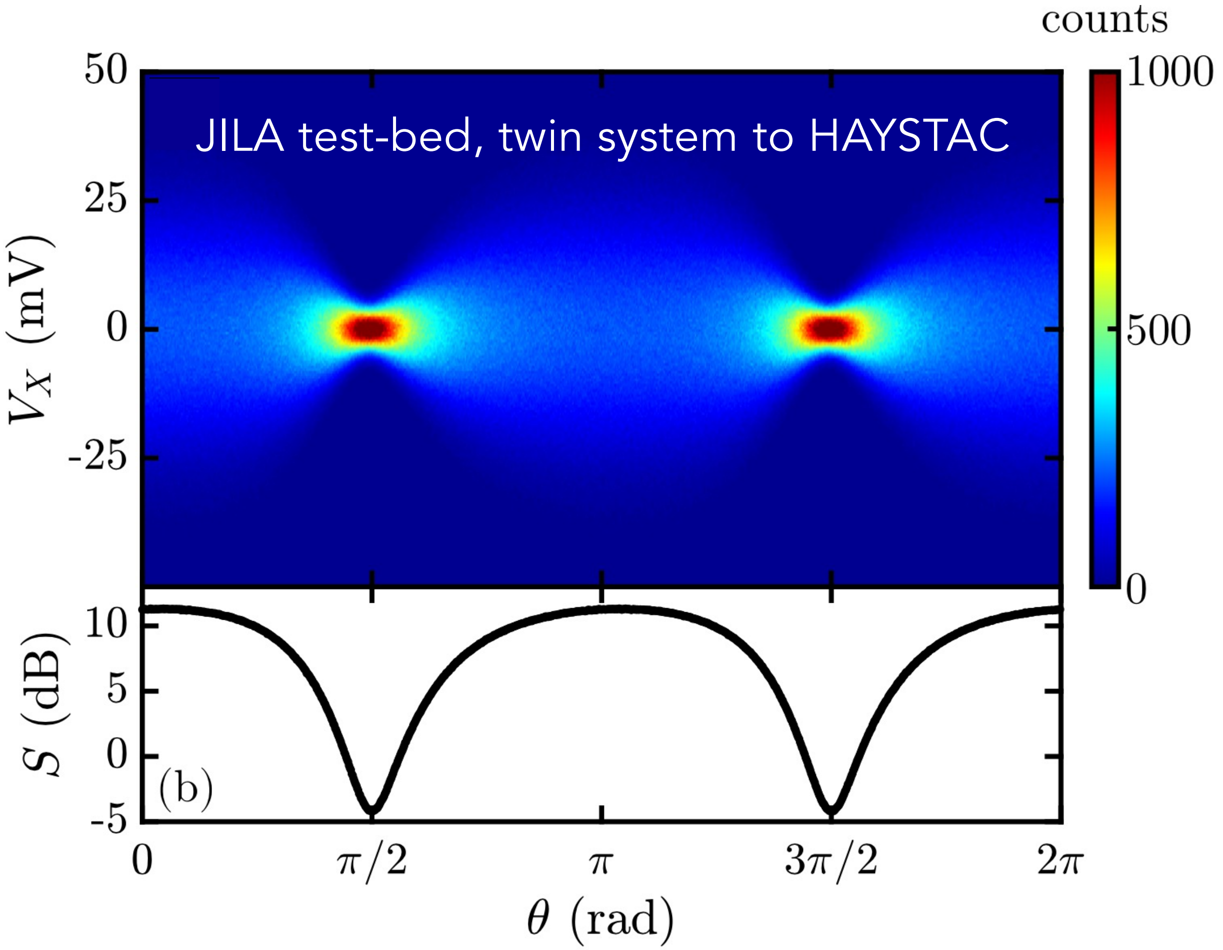




Remnant field at JPA ultimately reduced to < 0.01 flux quantum

HAYSTAC Phase II – Squeezed State Receiver (M. Malnou *et al.*, Phys. Rev. X 9 (2019) 021023)

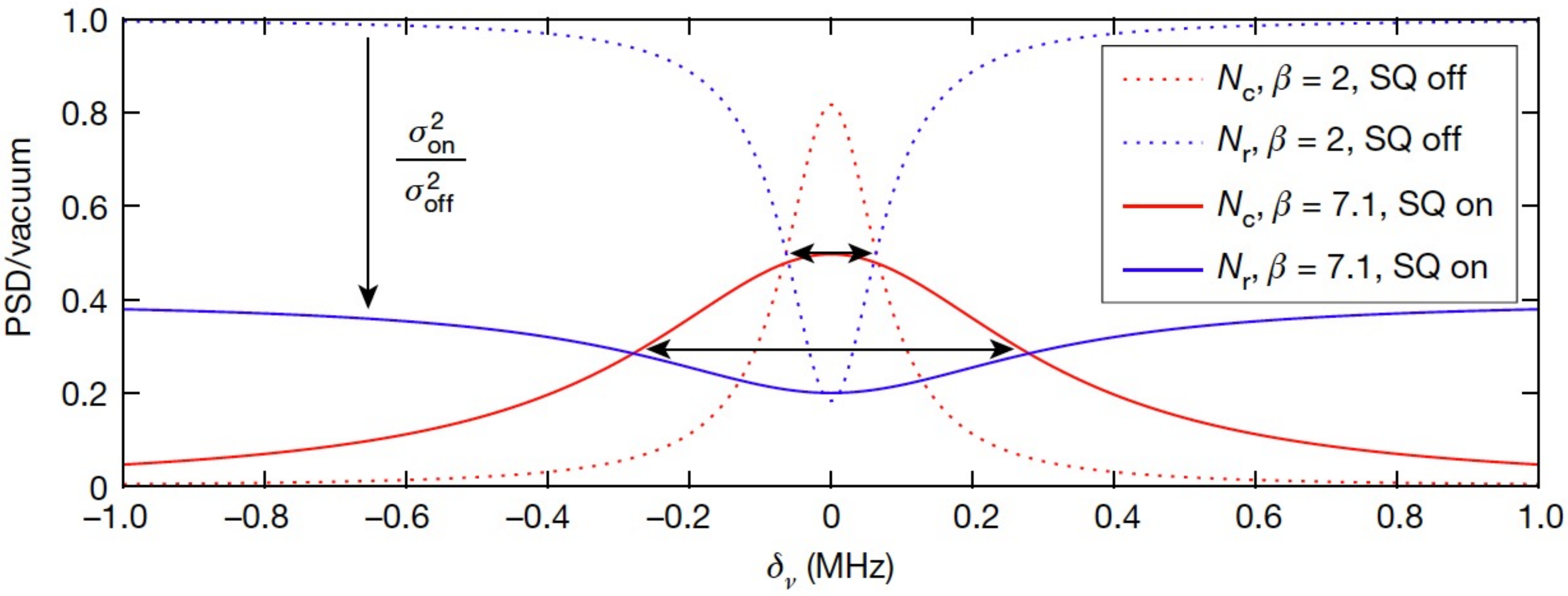




JILA test-bed, twin system to HAYSTAC

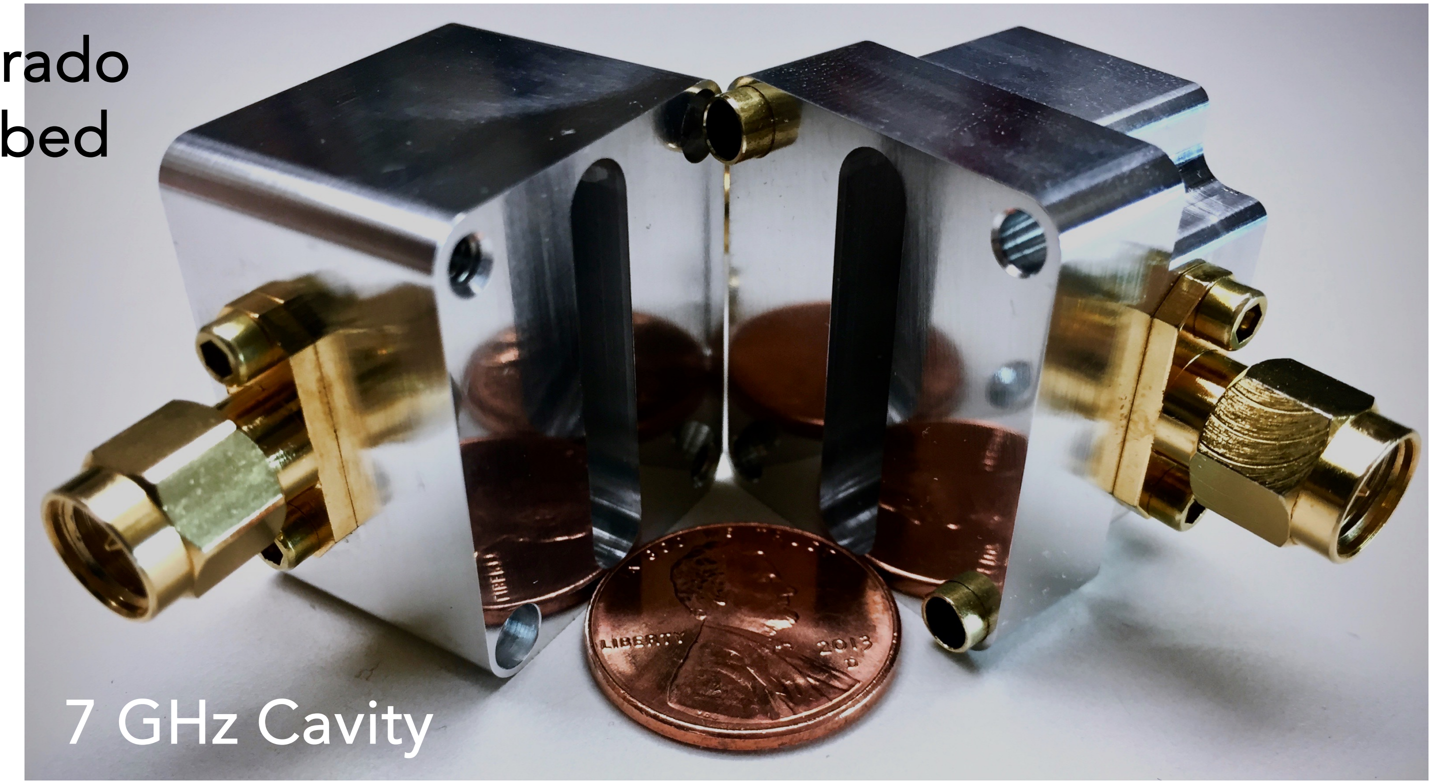
Squeezing and amplifying in the same quadrature yielded –4.5 ± 0.1 dB, as predicted by modeling

Squeezing in detail

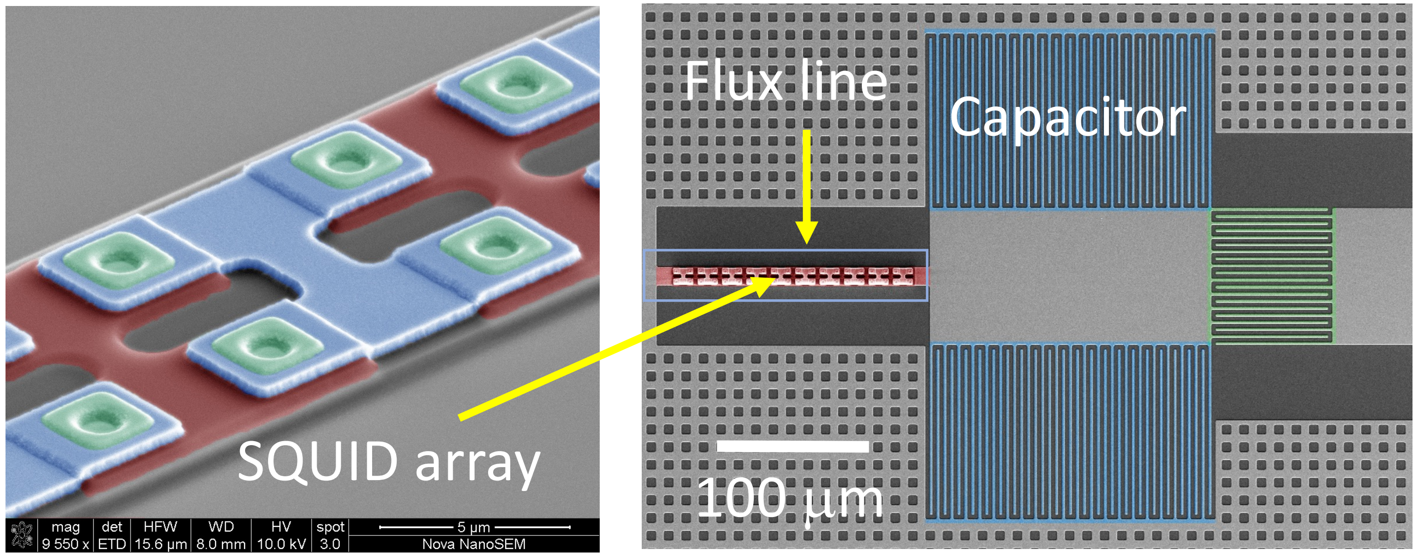


Overcoupling is essential to the acceleration

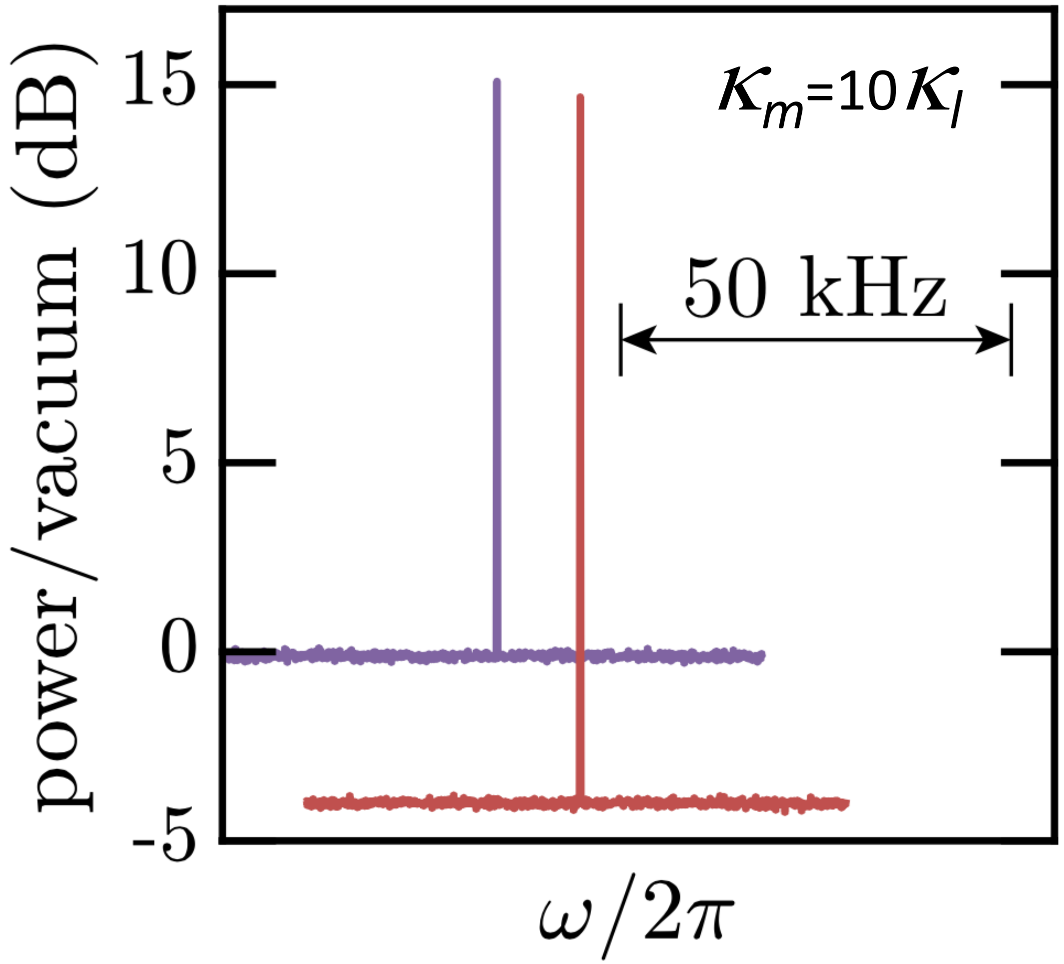
JILA/Colorado
SSR Test-bed

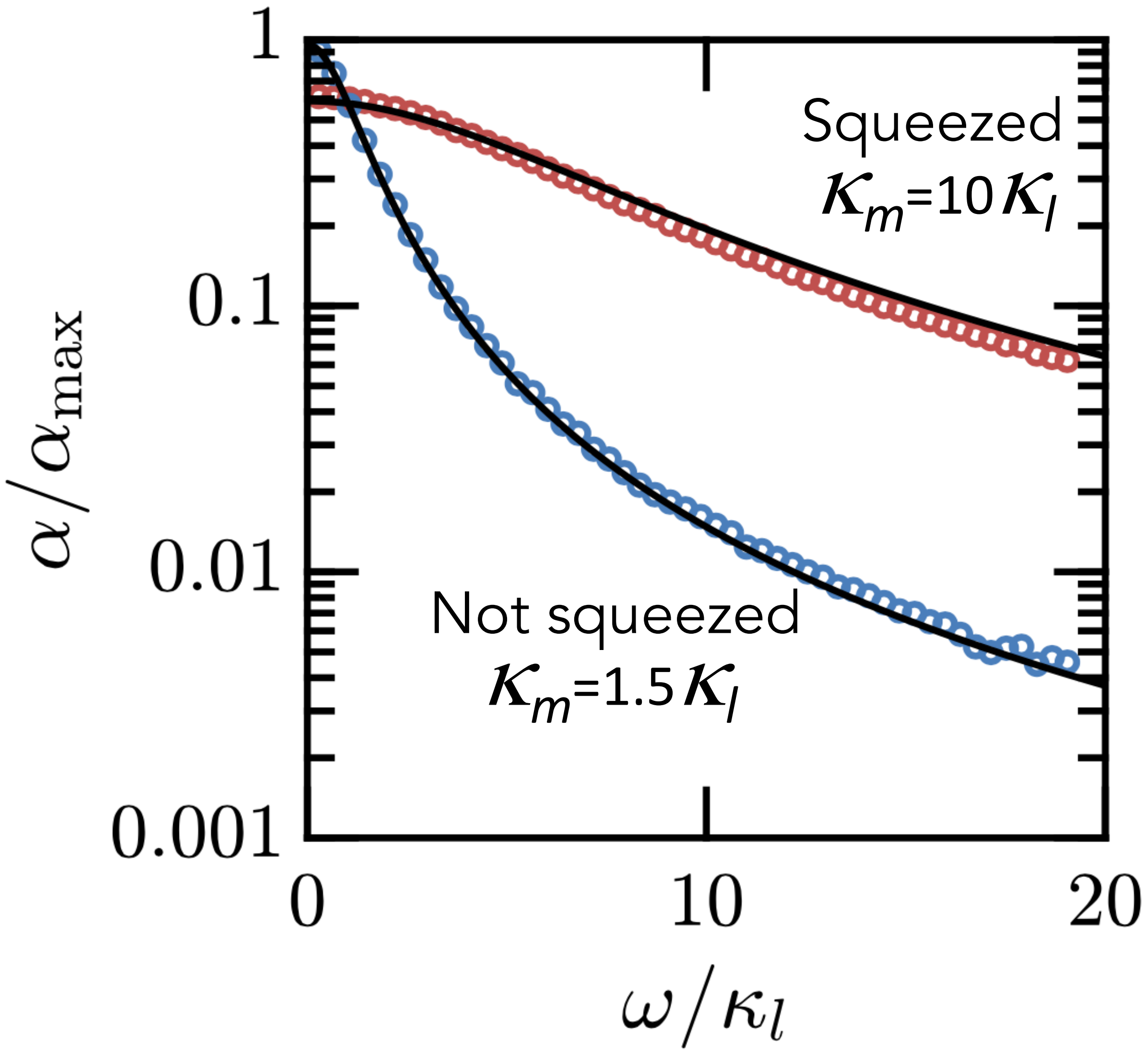


7 GHz Cavity



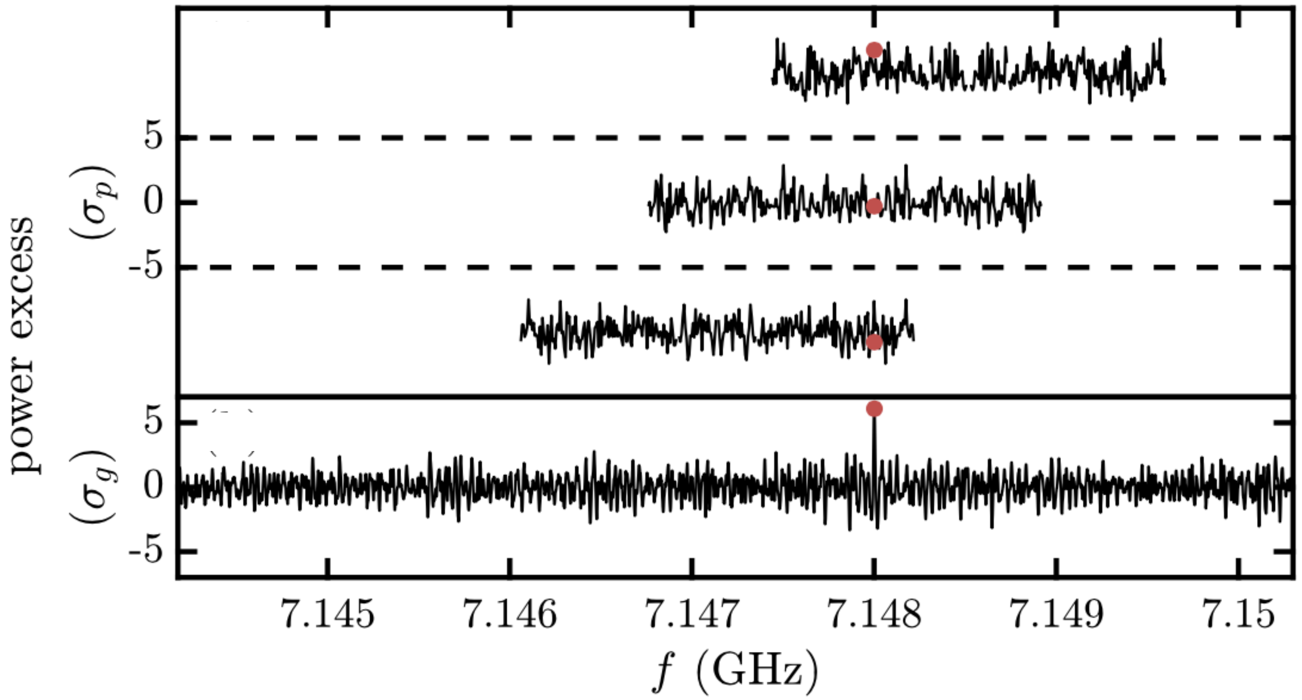
Squeezing implies uniformly higher S/N over a wider bandwidth

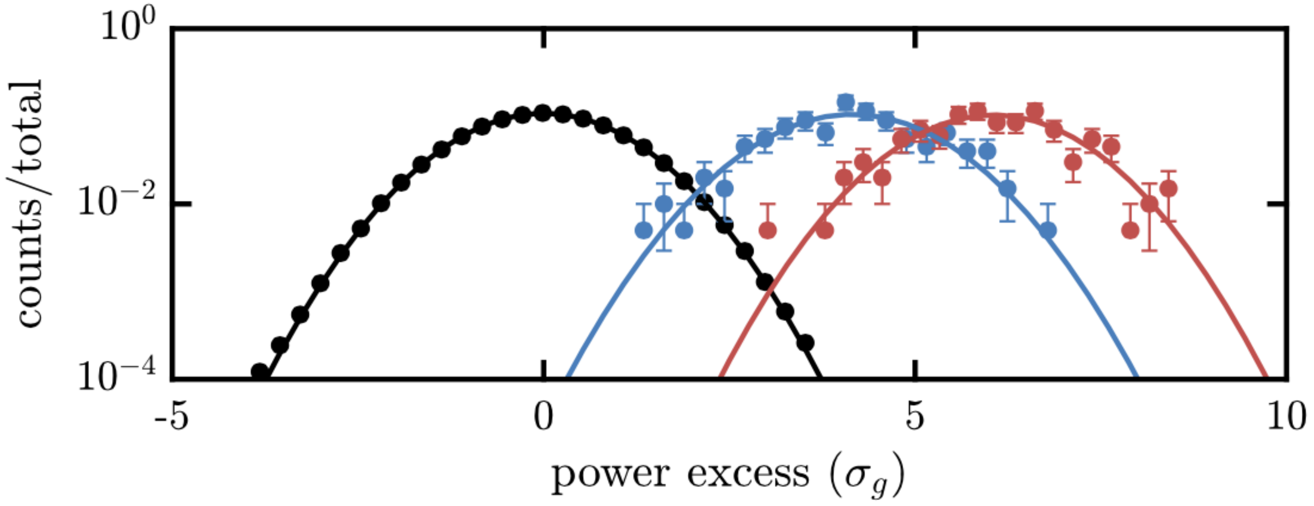




The scan rate with squeezing optimizes at large overcoupling of the cavity, thus higher BW

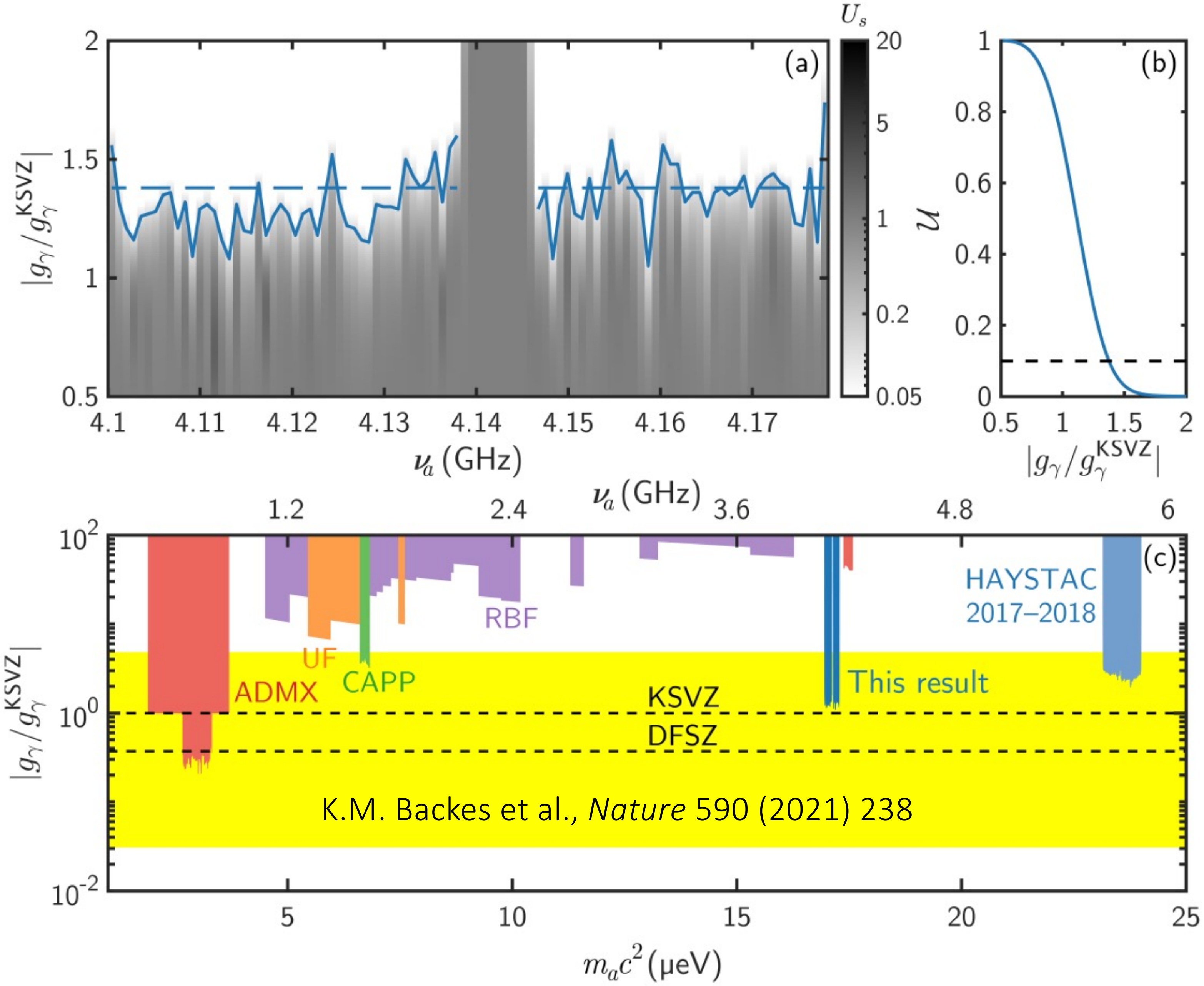
Factor of 2.1 speedup in testbed; HAYSTAC achieved 1.9 *in situ* data taking





- ☐ Mock axion search done at JILA testbed
- ☐ Synthetic signal injected into the system of unknown frequency
- ☐ Search protocol repeated 200 times for each configuration
- ☐ Results are μ_s = 6.05 ± 0.07 (with squeezing), μ_s = 4.15 ± 0.07 (w/o), leading to 2.12 ± 0.08 speedup
- ☐ HAYSTAC Phase II Run 1 achieved ~ x2 speedup from SSR, x3 speedup overall

HAYSTAC Phase II Run 1: First quantum-enhanced dark matter experiment; reaches 1.38 x KSVZ

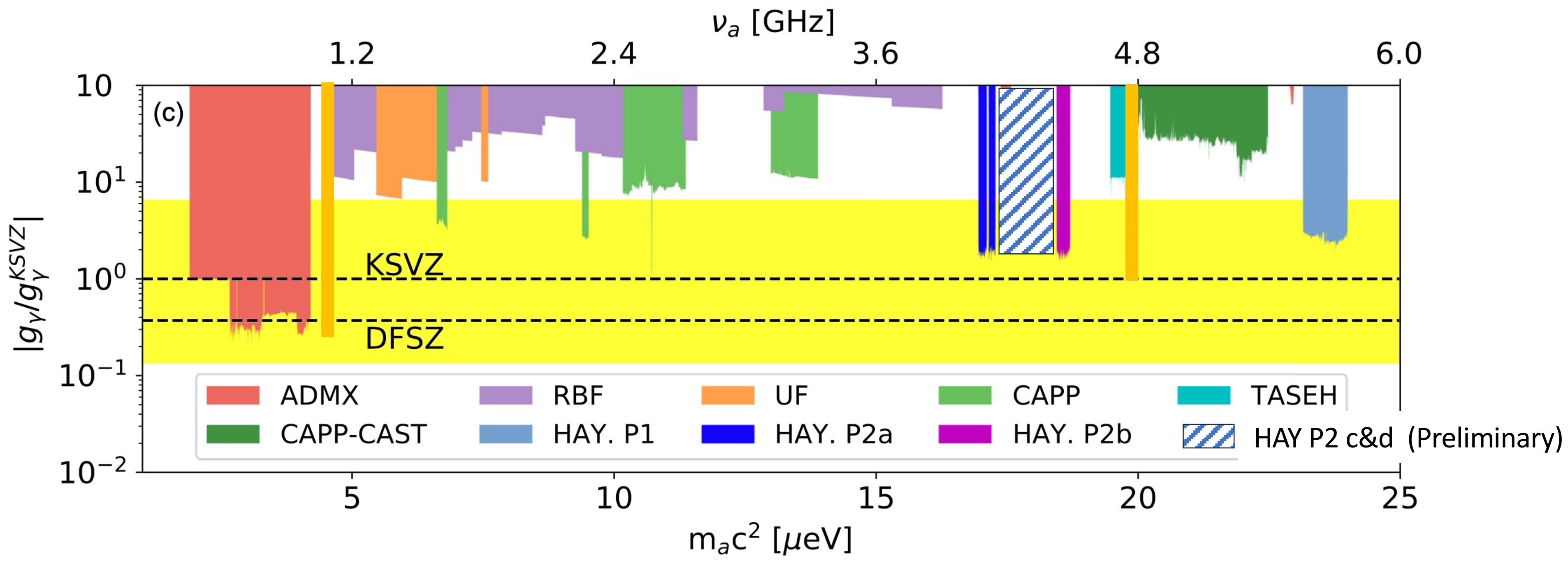


K.M. Backes et al., *Nature* 590 (2021) 238

- SSR reduced run time by ½
- Analysis incorporated new Bayesian analysis method
  (Palken et al., PRD 101 (2020) 123011)
- Sensitivity at 1.38 x KSVZ

HAYSTAC data (2016 –)

Name	**Amplifier**	**Dates**	**Freq. Range**	**Sensitivity**	**Publication**
Phase I	Phase Insensitive	Jan. 2016 – Jan. 2017	5.6–5.8 GHz	$2.70\times\lvert g_\gamma^{KSVZ}\rvert$	*PRL 107 (2017)* *PRD* 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)
b		July 2021 – Nov. 2021	4.459–4.523 GHz	$2.06\ \times\lvert g_\gamma^{KSVZ}\rvert$	*Phys. Rev, D 107 (2023)*
Phase II c, d	Phase Sens.	2023-24	4.178-4.779 GHz	$\sim 2.7\ \times\lvert g_\gamma^{KSVZ}\rvert$	*Preliminary*



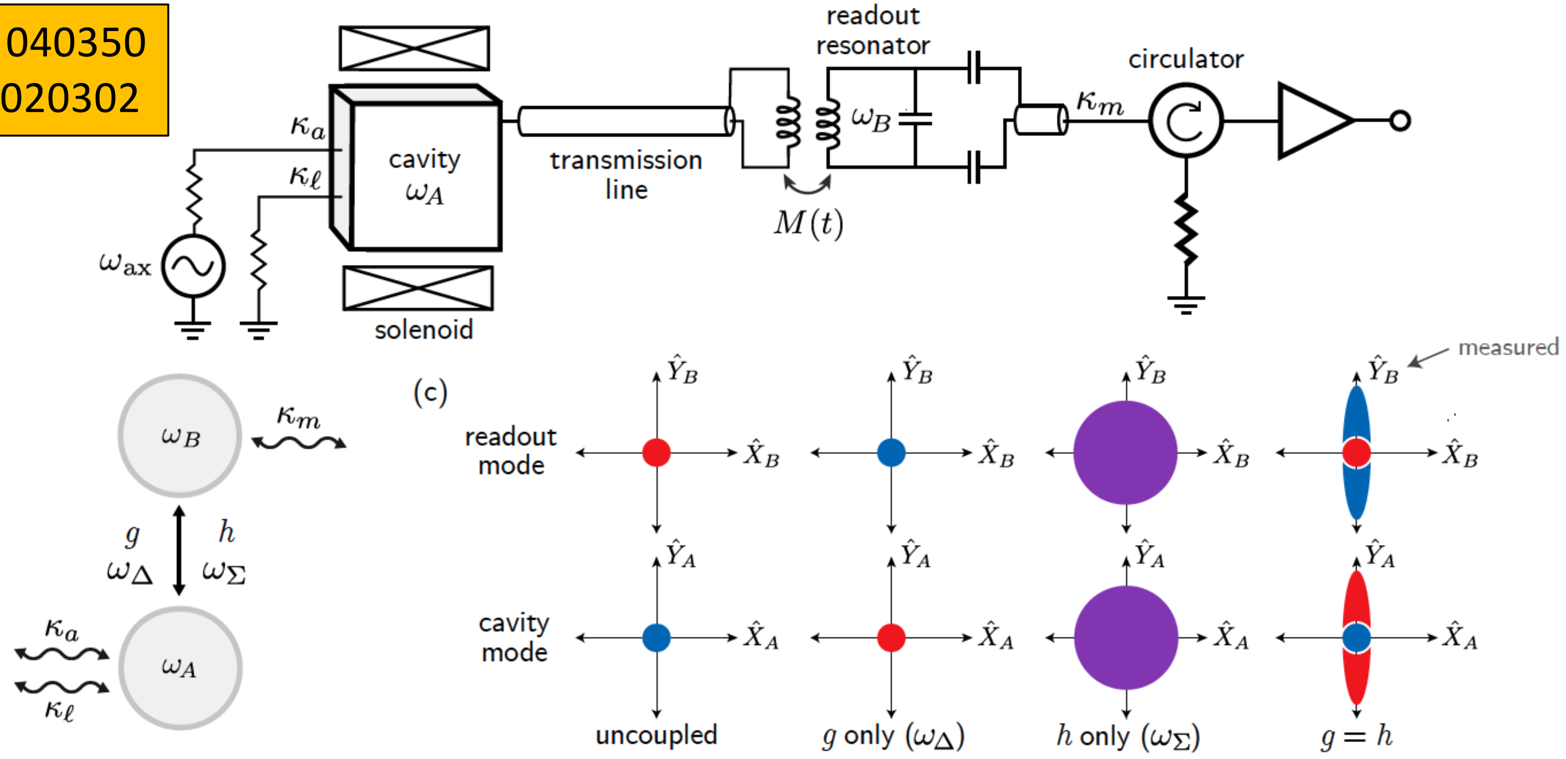
Phase III: CEASEFIRE – Cavity Entanglement and State Exchange for Improved Readout Efficiency

K. Wurtz *et al.*, PRX Quantum 2 (2021) 040350
Y. Jiang *et al.*, PRX Quantum 4 (2023) 020302

Following the same pattern of prototype-experiment twins

To deploy in HAYSTAC 2025

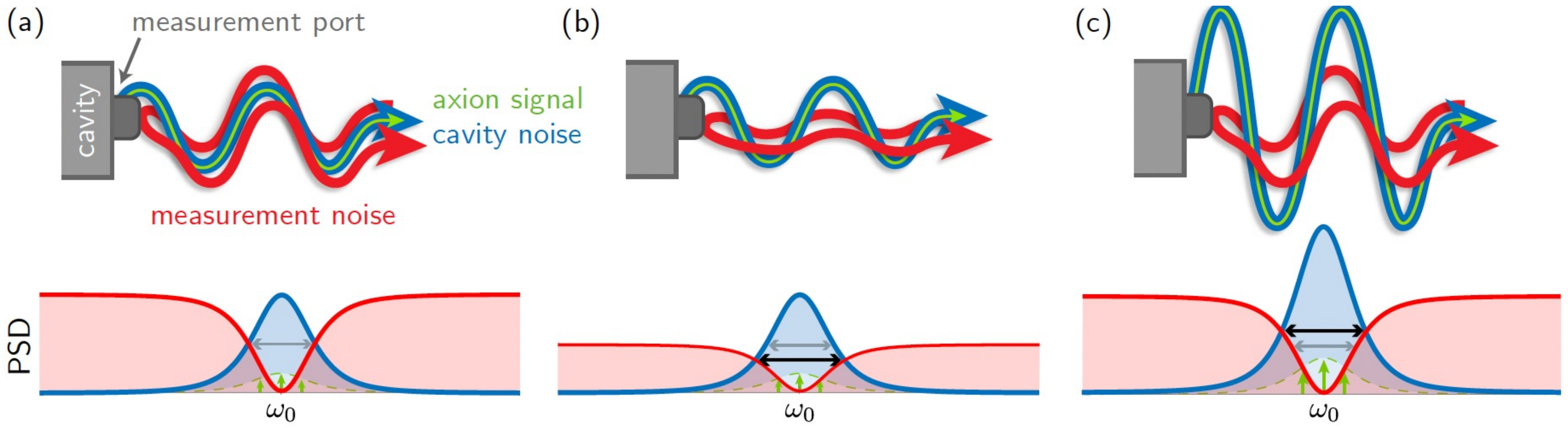
Projected ×8 scan speedup



(a) Linear amplifier

(b) Squeezing

(c) Squeezing with state exchange



Crossover point between Linear Amplifiers etc. and Single Quantum Detection

There is a frequency range above which photon counting will be more sensitive and the advantage will grow with frequency, roughly 10 GHz. See:

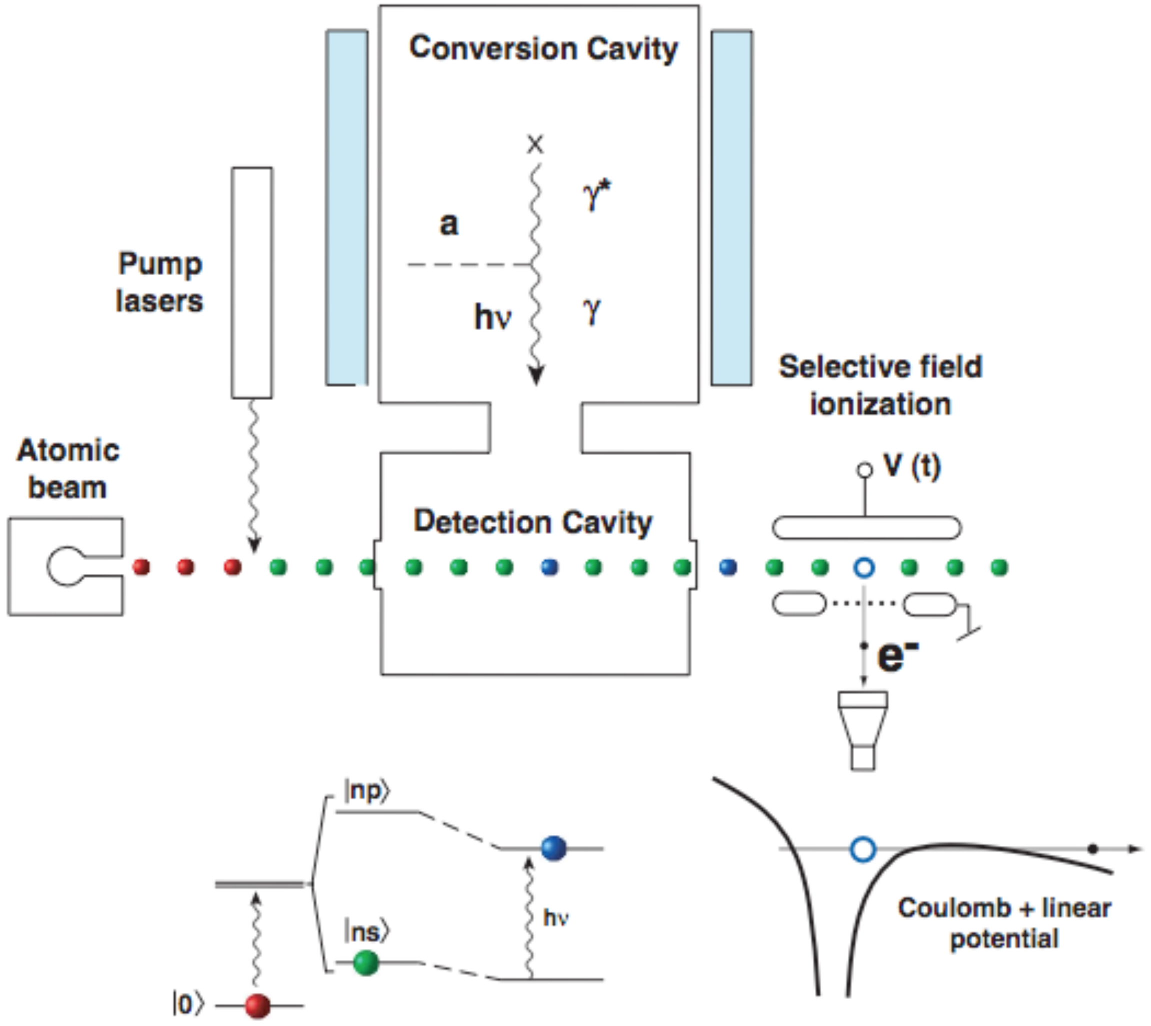
S.K. Lamoreaux *et al.*, Phys. Rev. D 88 (2013) 035020

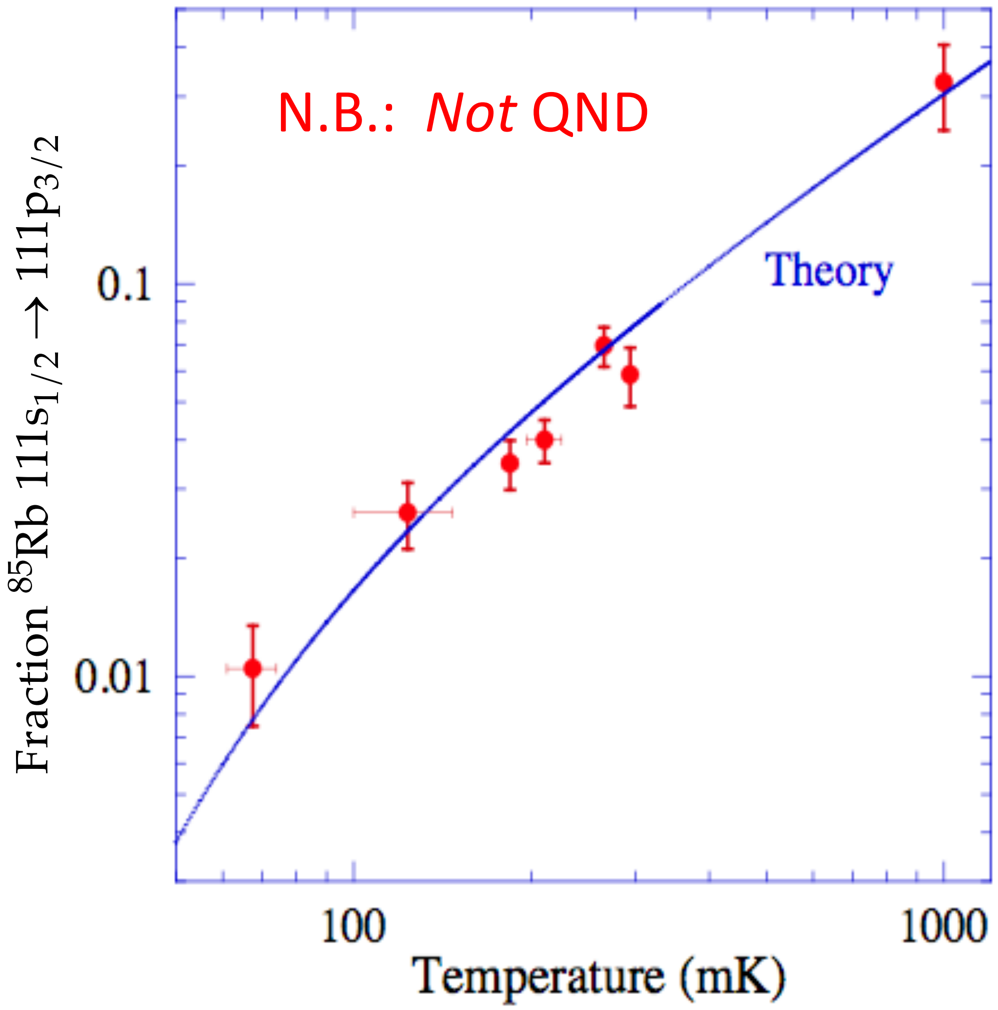
E. Graham *et al.*, Phys. Rev. D 109 (2024) 032009

Challenges with single-quantum detection will be in implementing it into an axion haloscope, i.e. efficient coupling to the conversion chamber, tunability, and dark counts above expectation.

RAY (Rydberg At Yale) aims to deliver a single-quantum detector for HAYSTAC

The CARRACK (Kyoto) Rydberg-atom Single Photon Detector (S. Matsuki *et al.*)

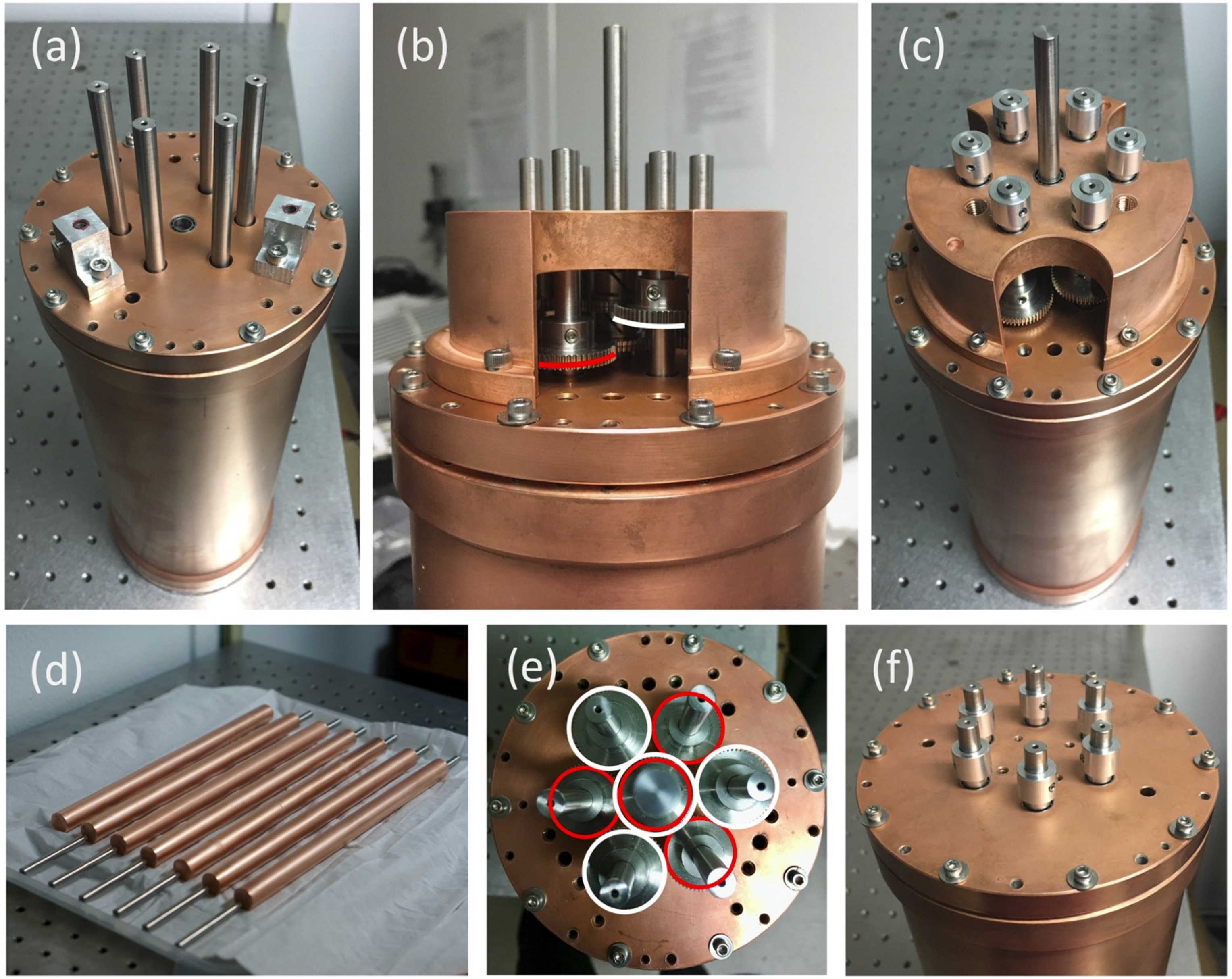




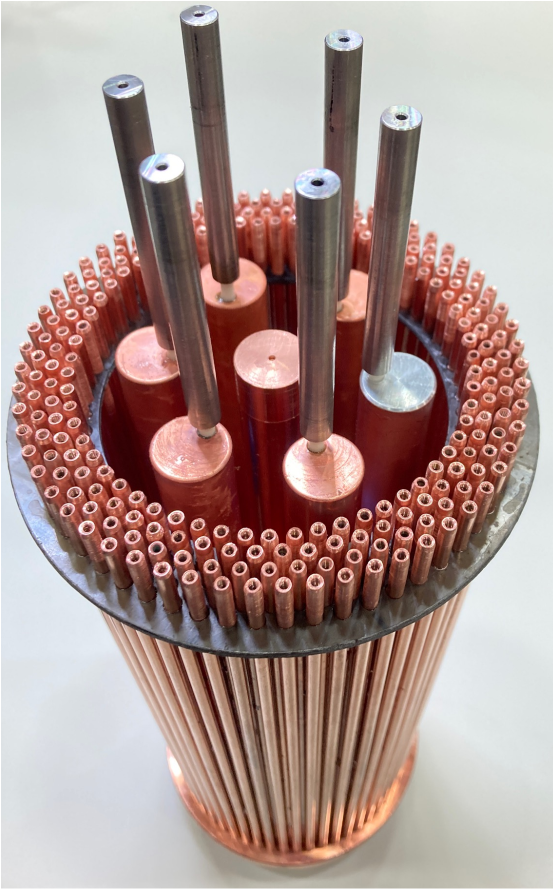
N.B.: *Not* QND

Tada *et al. Phys. Lett. A* 349:488 (2006) demonstrated a receiver a factor ~2 below SQL at 2.527 GHz (~120 mK).
DFSZ exclusion at ~10 μeV presented at conference (Matsuki, 1997), but never published in a refereed journal.
RAY: See Y. Zhu et al, Phys. Rev. A (2021), E. Graham *et al.*, Phys. Rev. D 109 (2024) 032009

HAYSTAC Phase IIIa – Lattice-type cavity *M. Simanovskaia et al., Rev. Sci. Instr. 92, 033305 (2021)*



(left) 7-rod cavity, tuned by varying the scale factor; (below) with Photonic Band Gap structure for TE mode suppression



Final remarks

- ☐ HAYSTAC has proven to be an effective testbed for new detector and resonator innovations
- ☐ It remains the only spectral dark matter axion experiment that has circumvented the Standard Quantum Limit; a more advanced cavity entanglement and state exchange scheme should produce an order of magnitude speedup in scanning
- ☐ Symmetric lattice & metamaterial designs show promise for higher frequency resonators without loss of volume; Photonic Band Gap structures can eliminate the TE mode forest *(See talk of Heather Jackson)*
- ☐ ALPHA will incorporate these innovations in the search for the post-inflation axion, initially in the 10-20 GHz range *(See talk of Andrea Gallo Rosso)*