Axions as Dark Matter

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12 March 2020

Berkeley Axion Works™

Outline

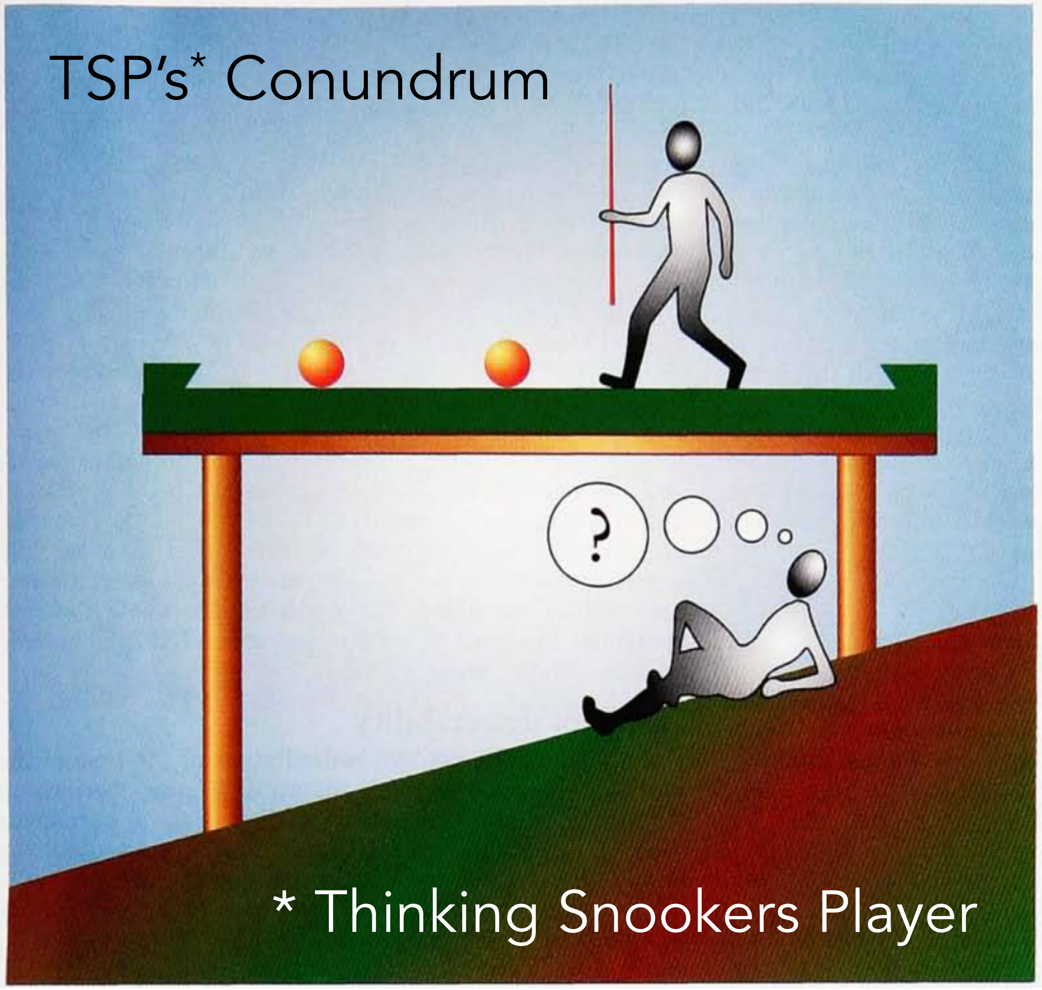
☐ Overview of the Axion and Dark Matter

☐ The Microwave Cavity Search & Variants

☐ The Advent of Quantum Metrology in Dark Matter Searches

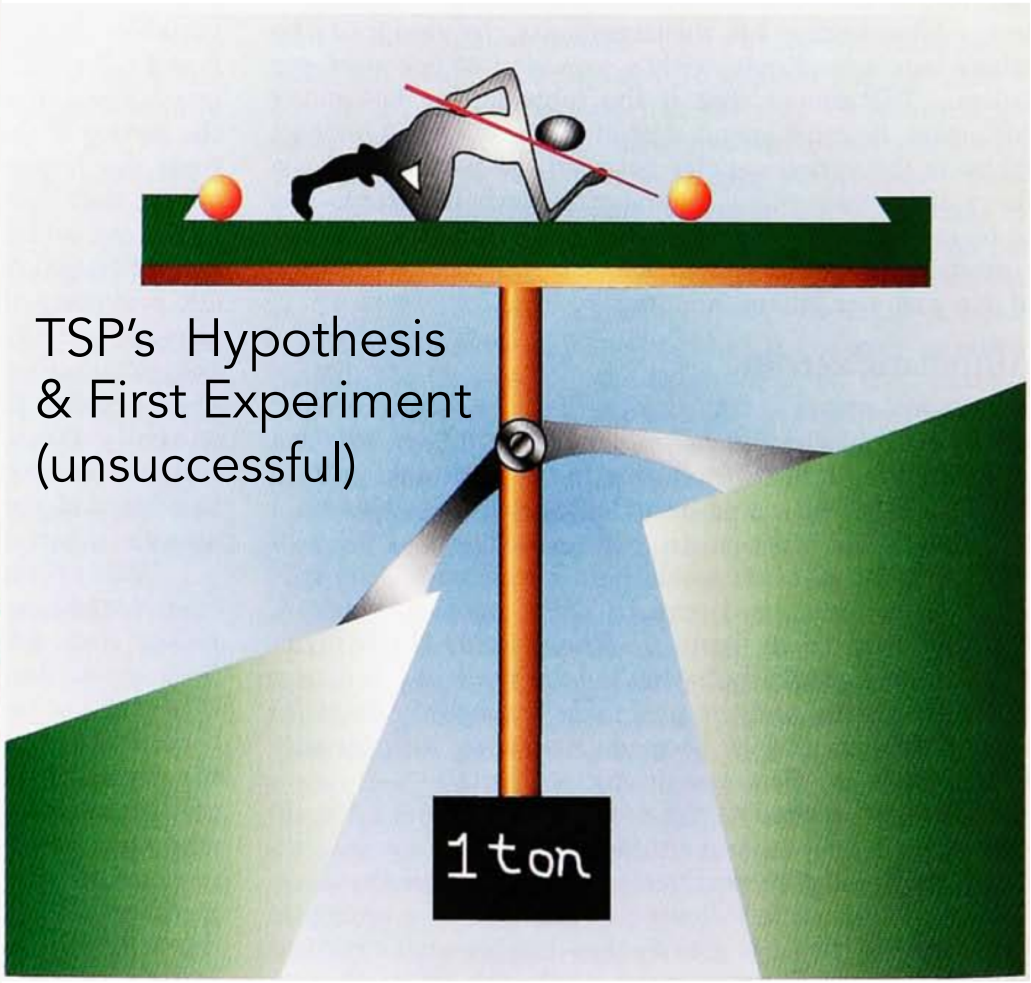
☐ Summary Remarks

"The Pool-Table Analogy for Axion Physics" Pierre Sikivie, *Physics Today* (December 1996)



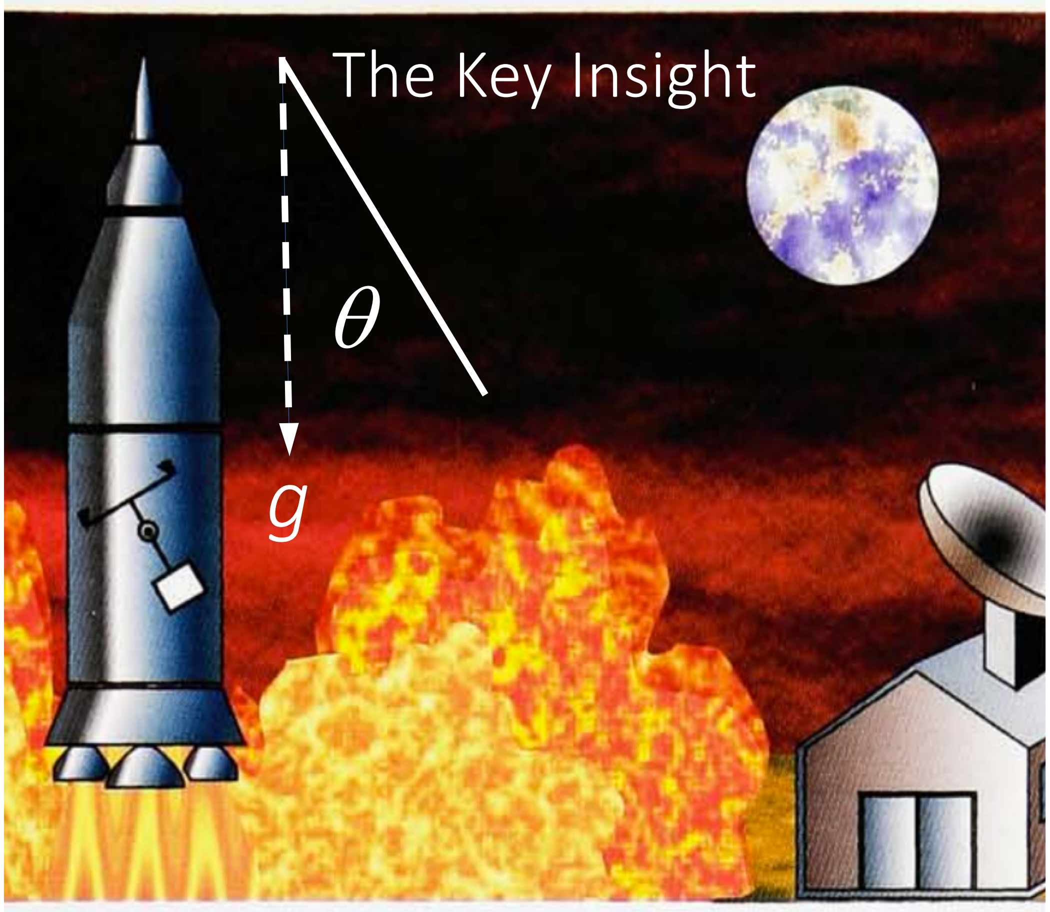
TSP's* Conundrum

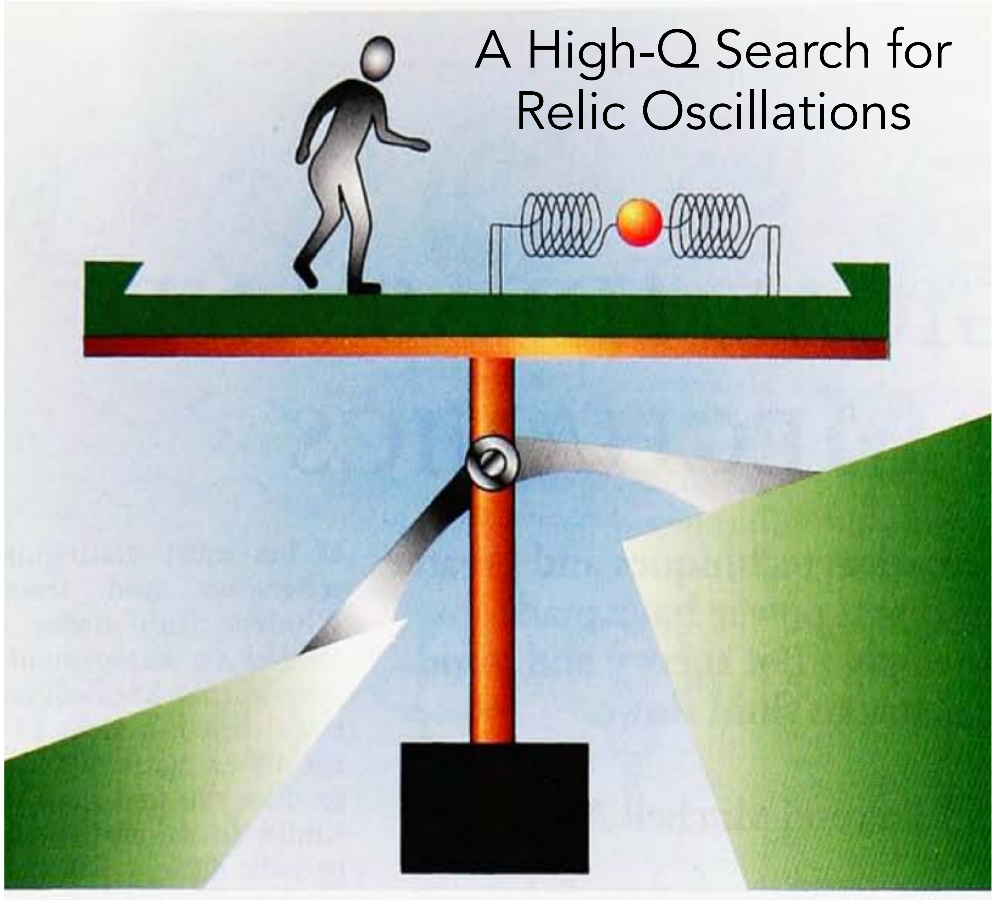
* Thinking Snookers Player



TSP's Hypothesis
& First Experiment
(unsuccessful)

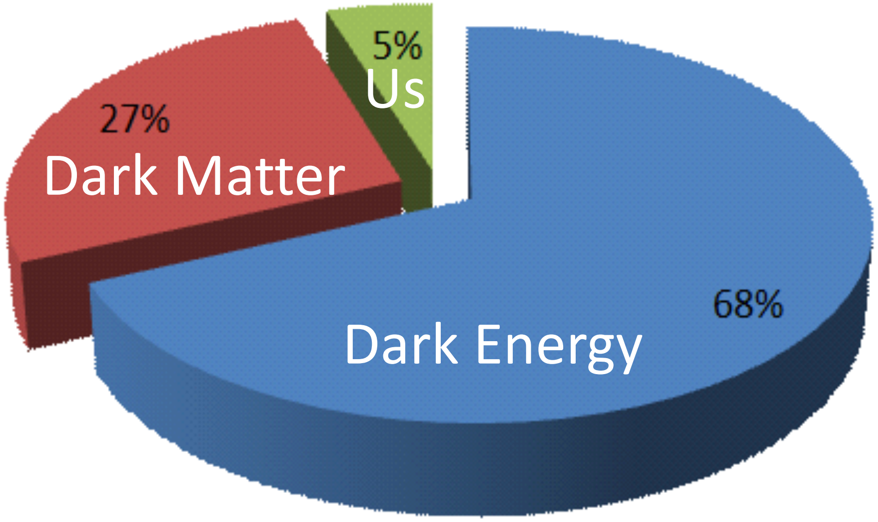
TSP’s breakthrough

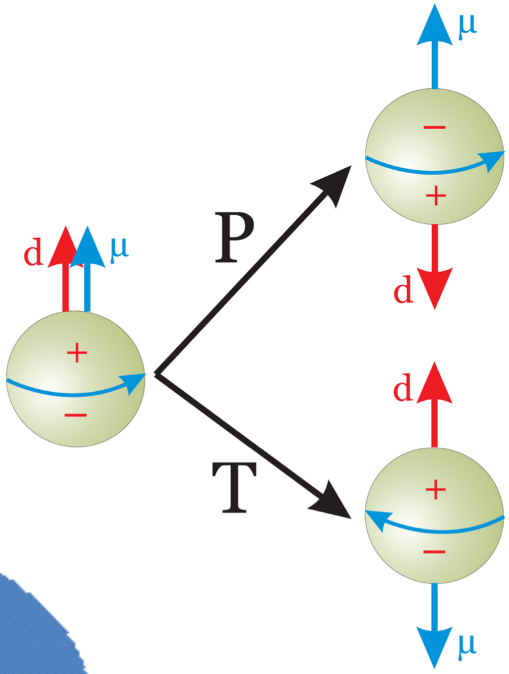

The Key Insight

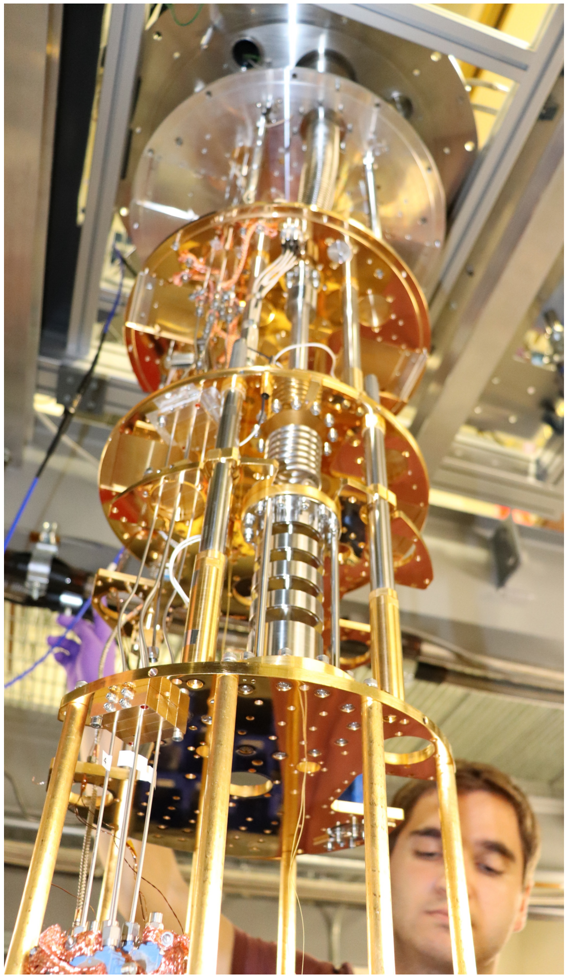

A High-Q Search for Relic Oscillations

The Trifecta

The analogy answers the three questions: What, Why & How



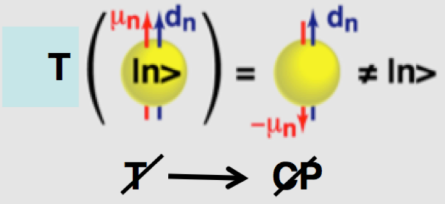




Completing the Pool Table – Axion Connection

The Strong-CP Problem

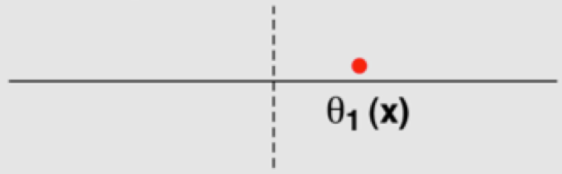
- $\mathcal{L}_{QCD} = ... + \frac{\theta}{32\pi^2} G\tilde{G}$
  - — Explicitly CP-violating
- But neutron e.d.m. $|d_n| < 10^{-25}$ e · cm
  - — $\bar{\theta} < 10^{-10}$
  - — Strong-CP preserving



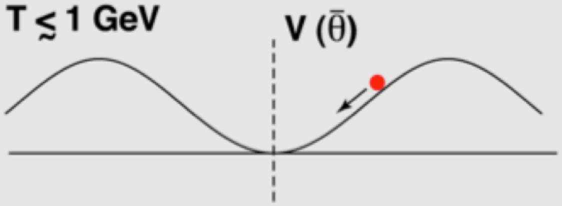
- Why?

Peccei-Quinn / Weinberg-Wilczek

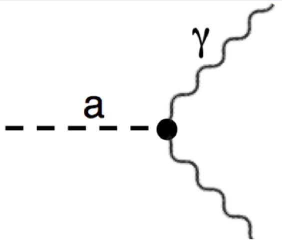
- θ a dynamical variable
- T = f_a spontaneous symmetry breaking



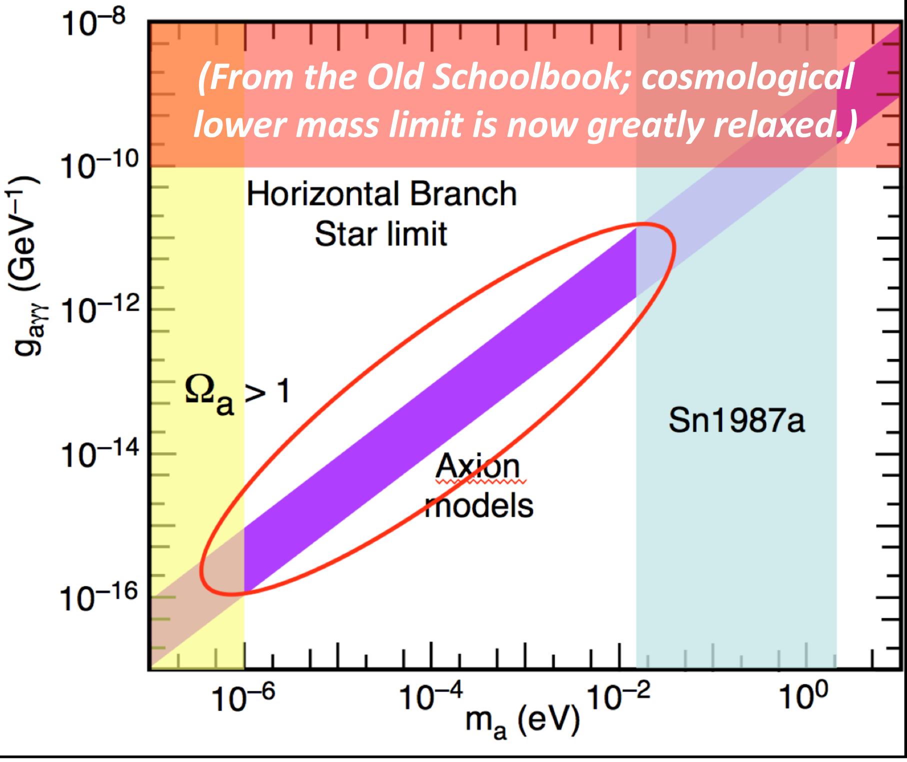
- $T \lesssim 1$ GeV



  - — $\bar{\theta}$ dynamically → 0
  - — Remnant oscillation = Axion

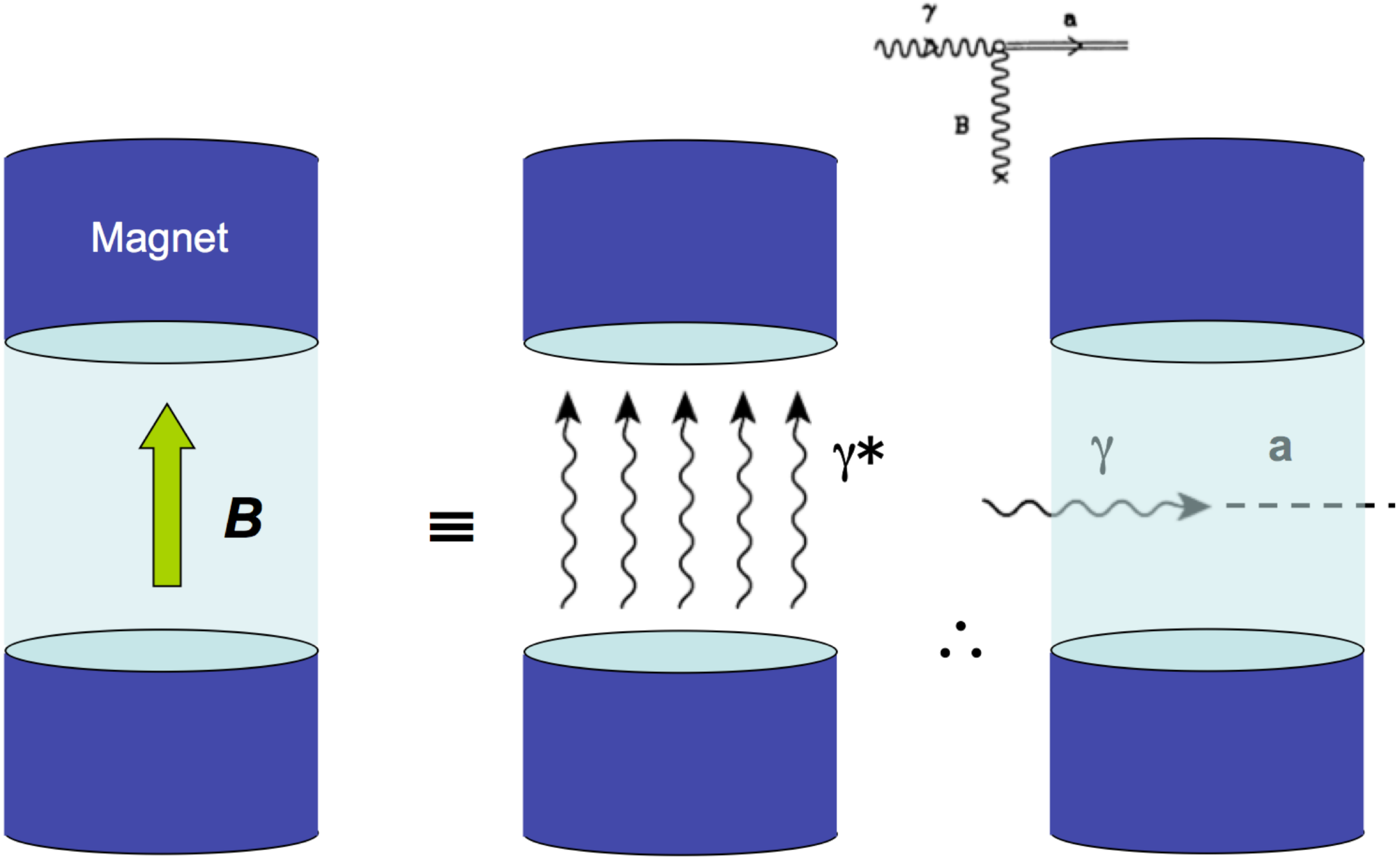


$J^{\pi} = 0^{-}$



(From the Old Schoolbook; cosmological lower mass limit is now greatly relaxed.)

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

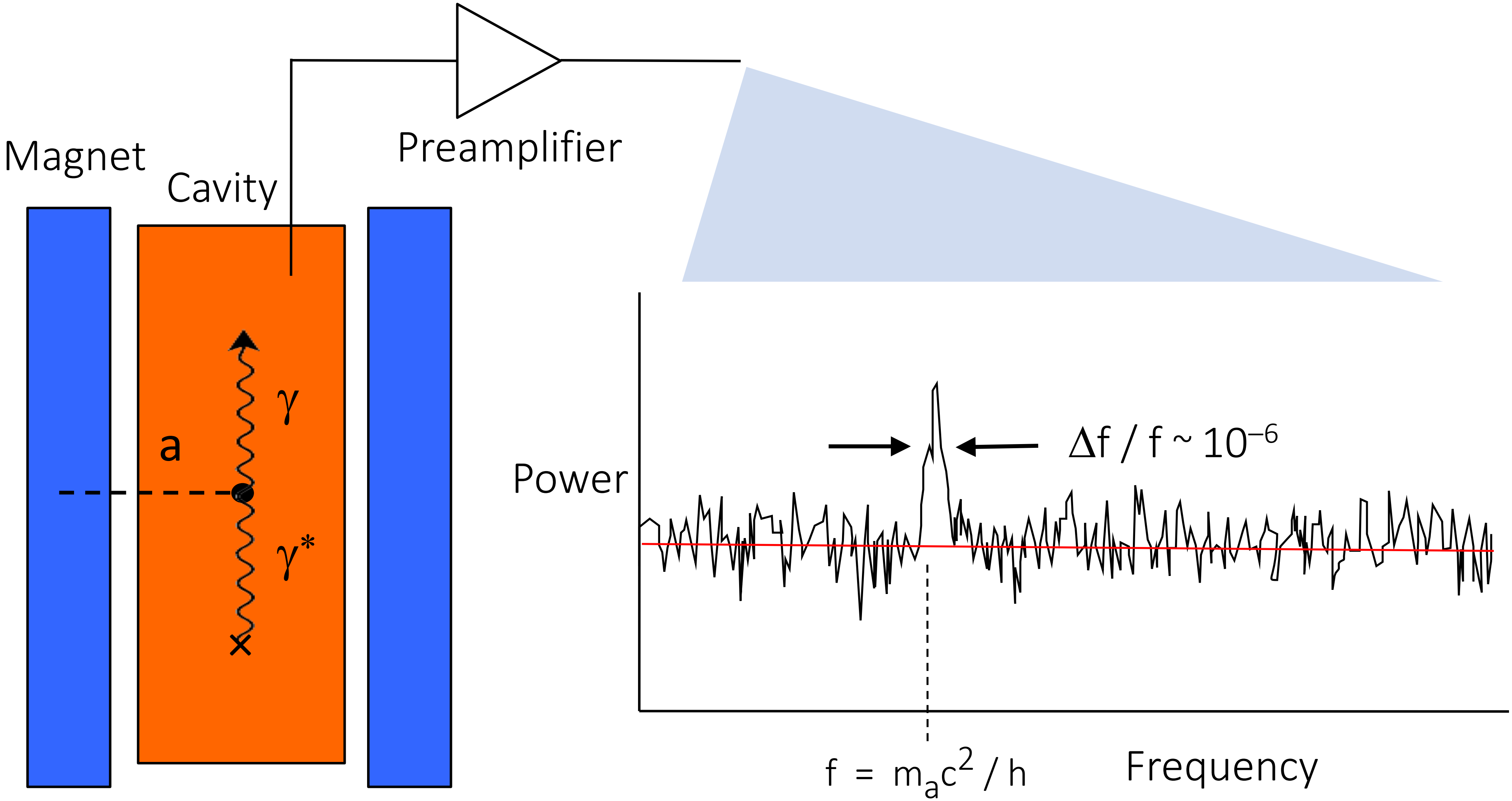


Classical EM field

Sea of virtual photons

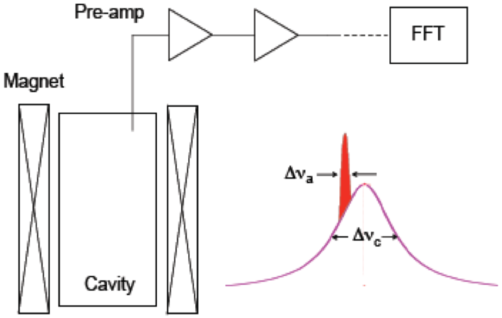
Primakoff Effect

The Microwave Cavity Dark Matter Experiment



Conversion power, Sources of Noise & the Standard Quantum Limit

The Dicke Radiometer Equation dictates the Experimental Strategy



Cavity Bandwidth: $\Delta\nu_c/\nu_c = Q^{-1} \sim 10^{-4}$

Axion Bandwidth: $\Delta\nu_a/\nu_a \sim \beta^2 \sim 10^{-6}$

Conversion Power: $P \sim g^2_{a\gamma\gamma}(\rho_a/m_a)\, B^2 Q_c V C_{nm\ell} \quad \sim 10^{-23}$ watt

Signal to Noise Ratio: $$\mathrm{SNR} = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

System Noise Temperature: $$kT_S = h\nu\left(\frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2}\right) + kT_A$$

Note $T_S \approx T + T_A$, *for* $T >> h\nu$

Linear Amplifiers are subject to the Standard Quantum Limit (SQL)

$$T_N > T_{SQL} \quad \text{where} \quad k_B T_{SQL} = h\nu$$

ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

The SQL can be evaded by

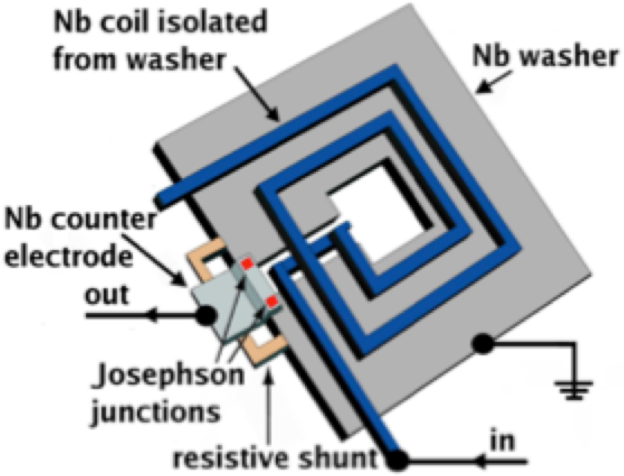
- Squeezed-vacuum state receiver (e.g. GEO, LIGO)
- Single-photon detectors (e.g. qubits, bolometers)

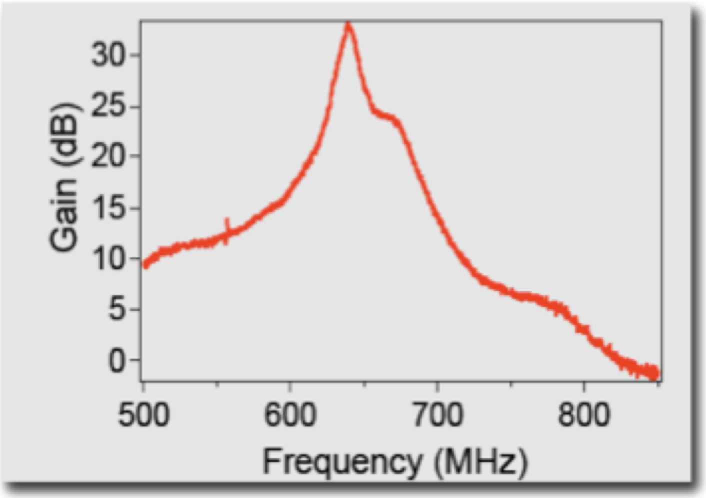
A brief history of (published) haloscopes

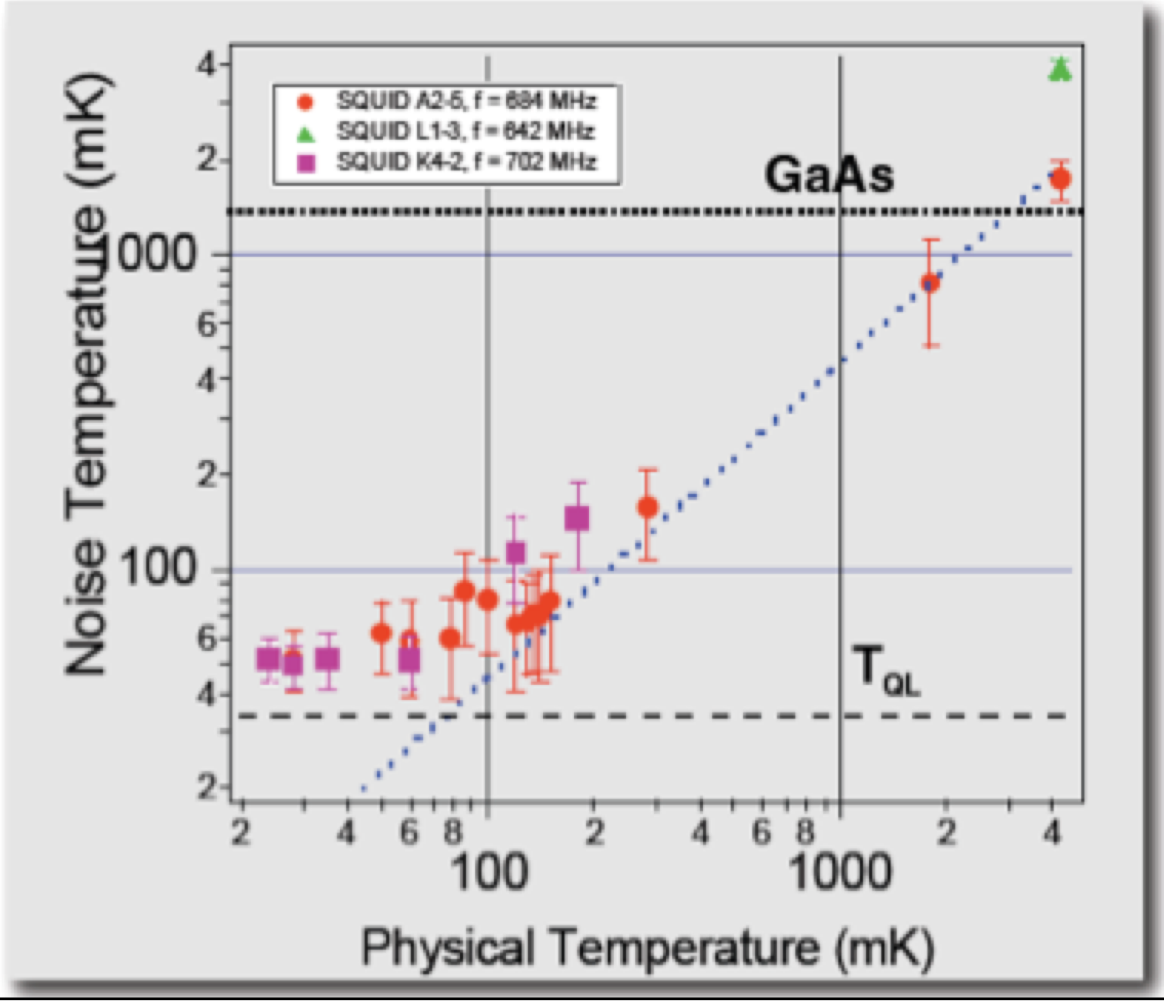
UF / RBF	ADMX @ LLNL	ADMX @ UW	HAYSTAC
1985 – 1990	1995 – 2010	2016 – present	2015 – present
HEMT	HEMT, SQUID	SQUID + dil. fridge	JPA + dil. fridge
f ~ 2.5 GHz	~ 0.5 GHz	~ 0.5 GHz	~ 6 GHz
V ~ 5 L	~ 200 L	~ 150 L	~ 1.5 L
T_{SYS} ~ 5-20 K	~ 3 K	~ 500 mK	< 300 mK *
T_{SYS}/T_{SQL}~100-200	~ 50 – 100	~ 10	< 1 *

* Now with the Squeezed-vacuum State Receiver (SSR)

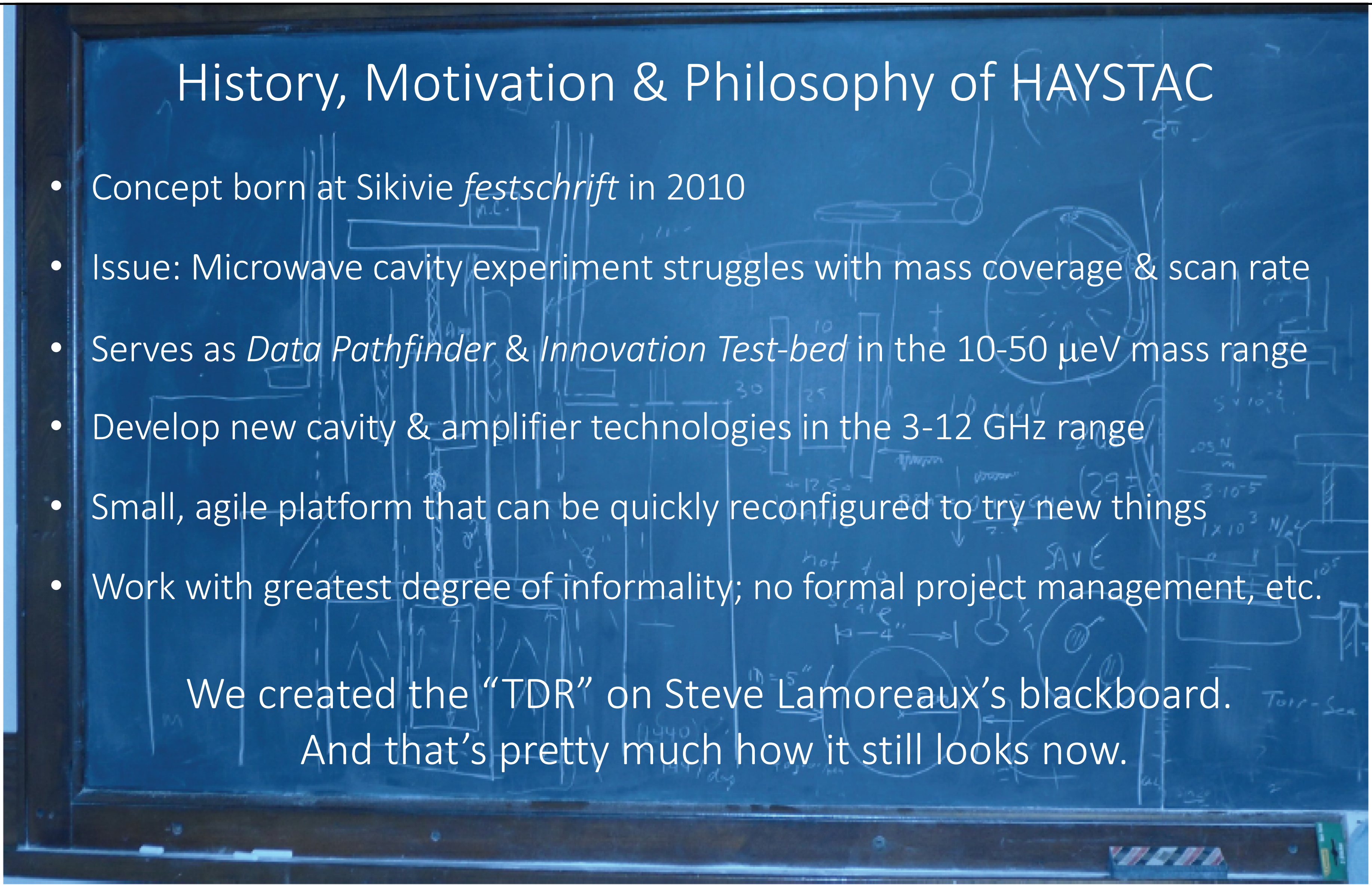
The Microstrip SQUID Amplifier for ADMX *(John Clarke et al., 1998)*







History, Motivation & Philosophy of HAYSTAC

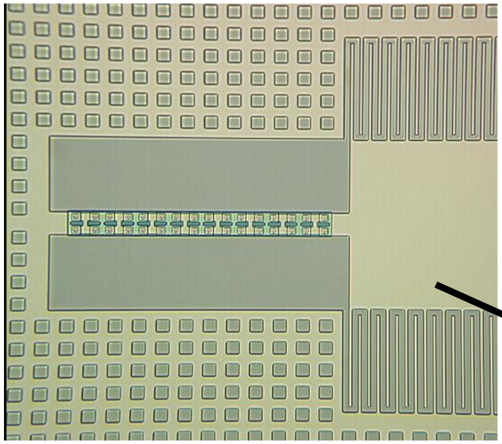


- Concept born at Sikivie *festschrift* in 2010
- Issue: Microwave cavity experiment struggles with mass coverage & scan rate
- Serves as *Data Pathfinder* & *Innovation Test-bed* in the 10-50 μeV mass range
- Develop new cavity & amplifier technologies in the 3-12 GHz range
- Small, agile platform that can be quickly reconfigured to try new things
- Work with greatest degree of informality; no formal project management, etc.

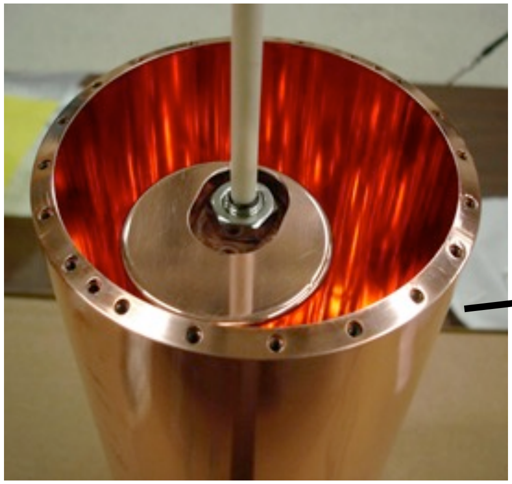
We created the "TDR" on Steve Lamoreaux's blackboard.
And that's pretty much how it still looks now.

HAYSTAC: Data Pathfinder, Innovation Testbed for 2.5-12.5 GHz *(Yale-Colorado-Berkeley)*

Josephson Parametric Amplifier



Microwave Cavity (copper)



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

9.4 Tesla, 10 Liter Magnet

Haloscope At Yale Sensitive To Axion Cold dark matter (HAYSTAC)

Yale University

Kelly Backes, Cady van Assenfeldt, Huajin (Jean) Wang, Gabriel Hoshino, Danielle Speller, Sid Cahn, Reina Maruyama, Steve Lamoreaux

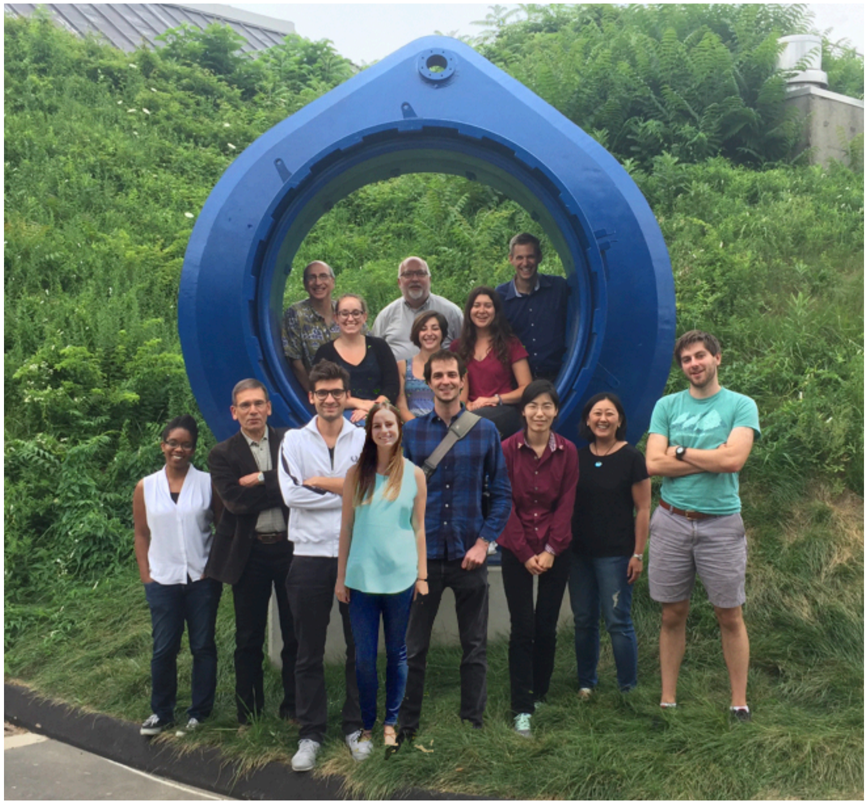
UC Berkeley

Maria Simanovskaia, Samantha Lewis, Alex Droster, Al Kenany, Nicholas Rapidis, Heather Jackson, Mirelys Carcana Barbosa, Alexander Leder, Karl van Bibber

CU Boulder/JILA

Daniel Palken, Kelly Wurtz, Ben Brubaker, Maxime Malnou, Konrad Lehnert

(Current; alumni almost double the roster)

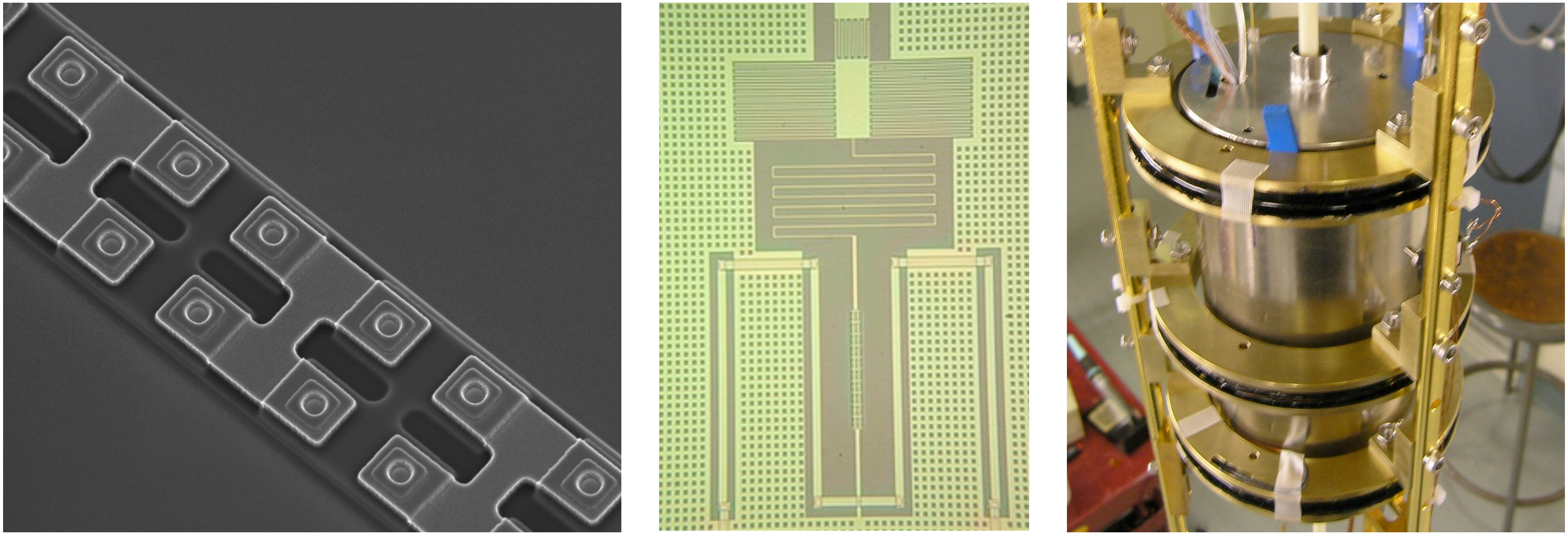


NSF

HEISING - SIMONS FOUNDATION

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

HAYSTAC utilized Josephson Parametric Amplifiers (JPA) from the start

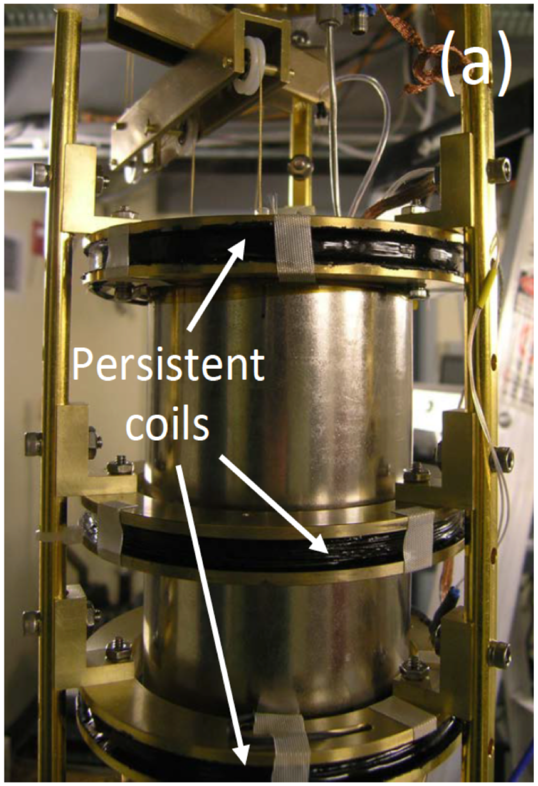


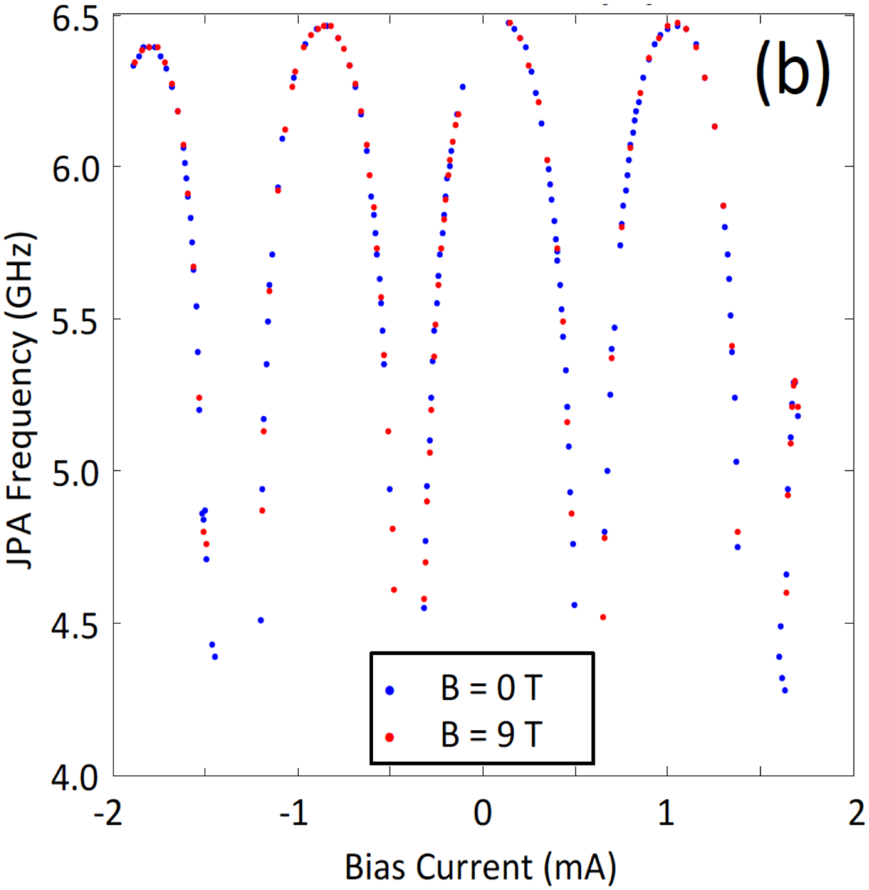
Tunable over 4.4 – 6.5 GHz ; > 20 dB gain ; intrinsically quantum limited

A major challenge – magnetic shielding of the JPA

“Defense in depth”

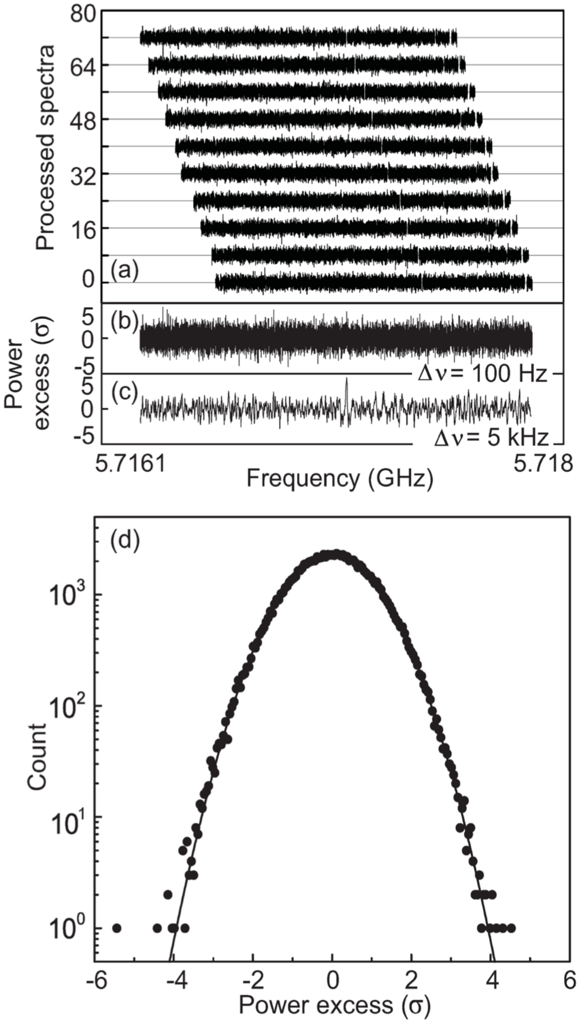
- Active bucking coil
- Persistent coils (4)
- Cryoperm (2 layers)
- S’con lead sheet
- S’con niobium sheet

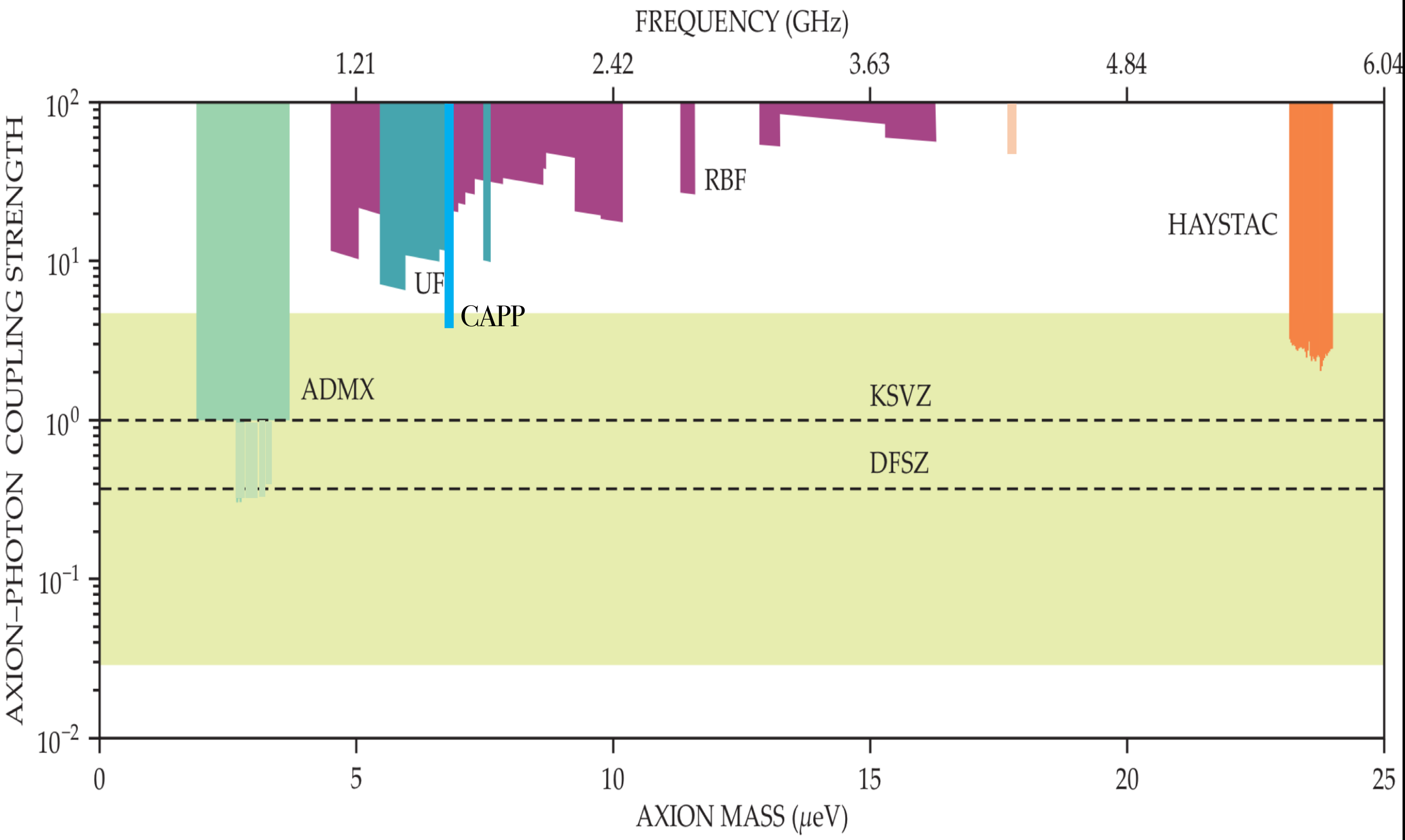




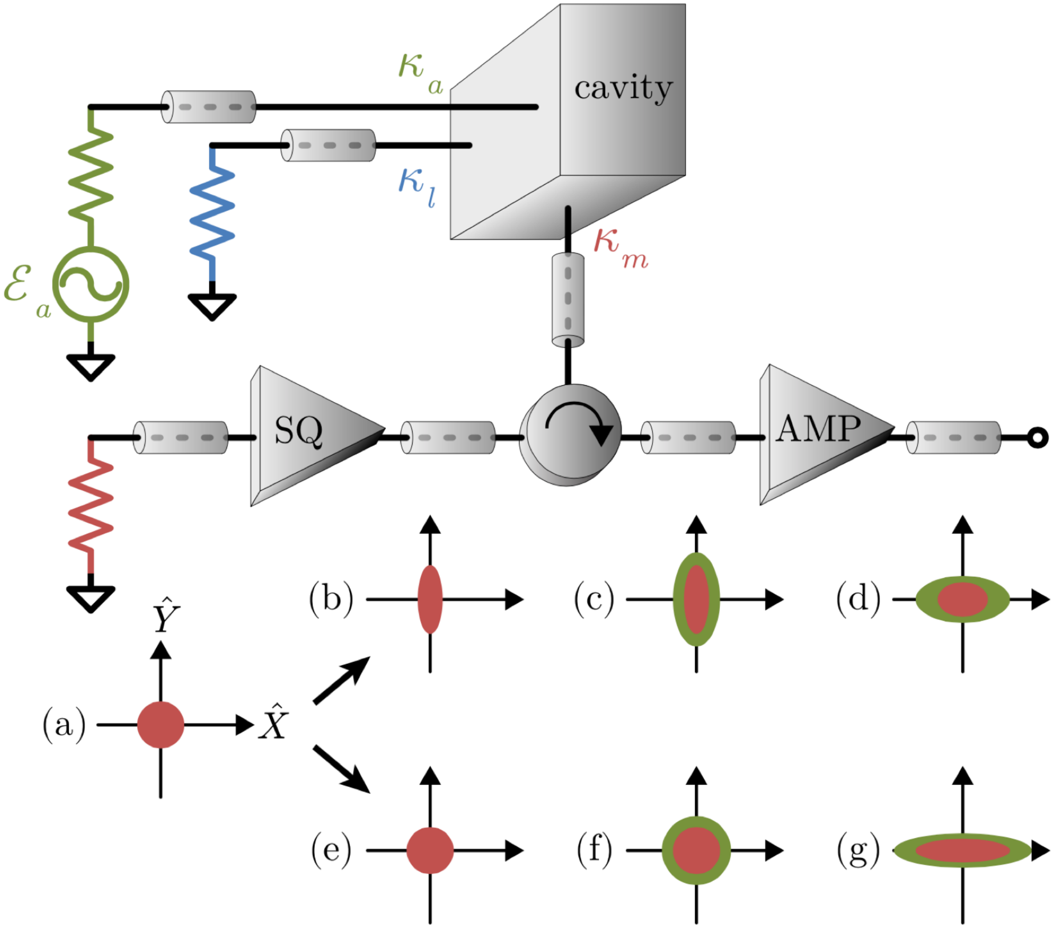
Remnant field at JPA ultimately reduced to < 0.01 flux quantum

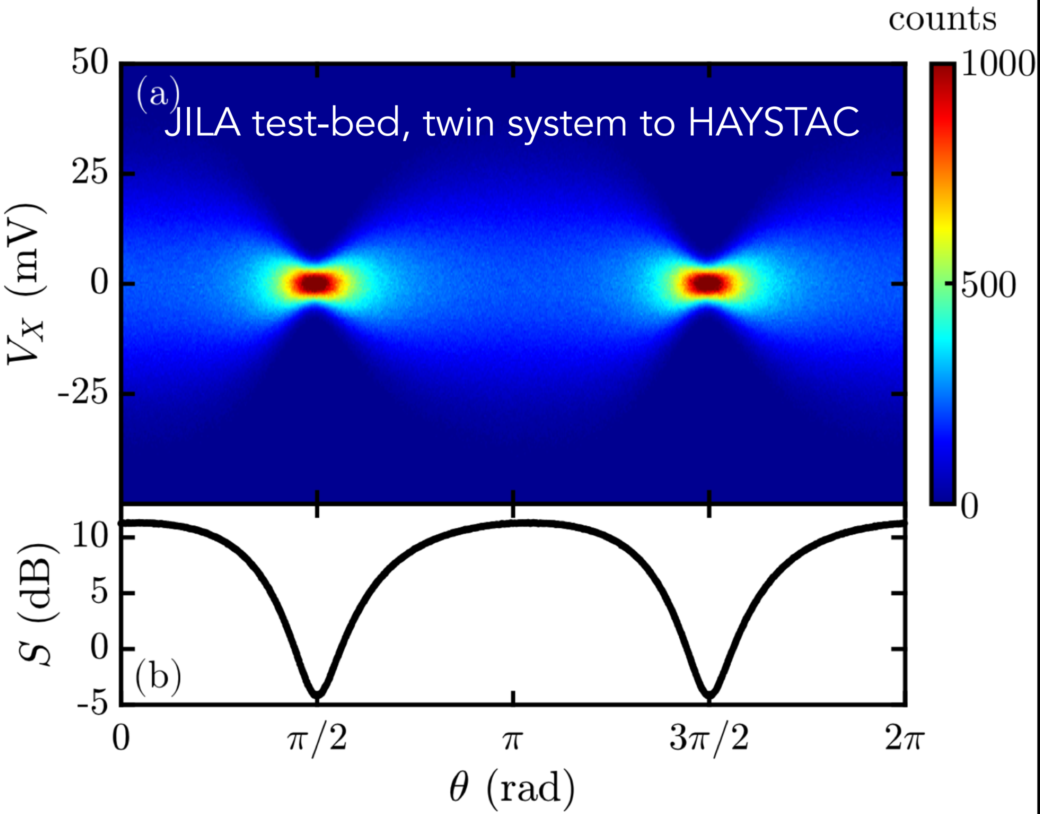
Haloscope mass-coupling exclusion (3/2020)





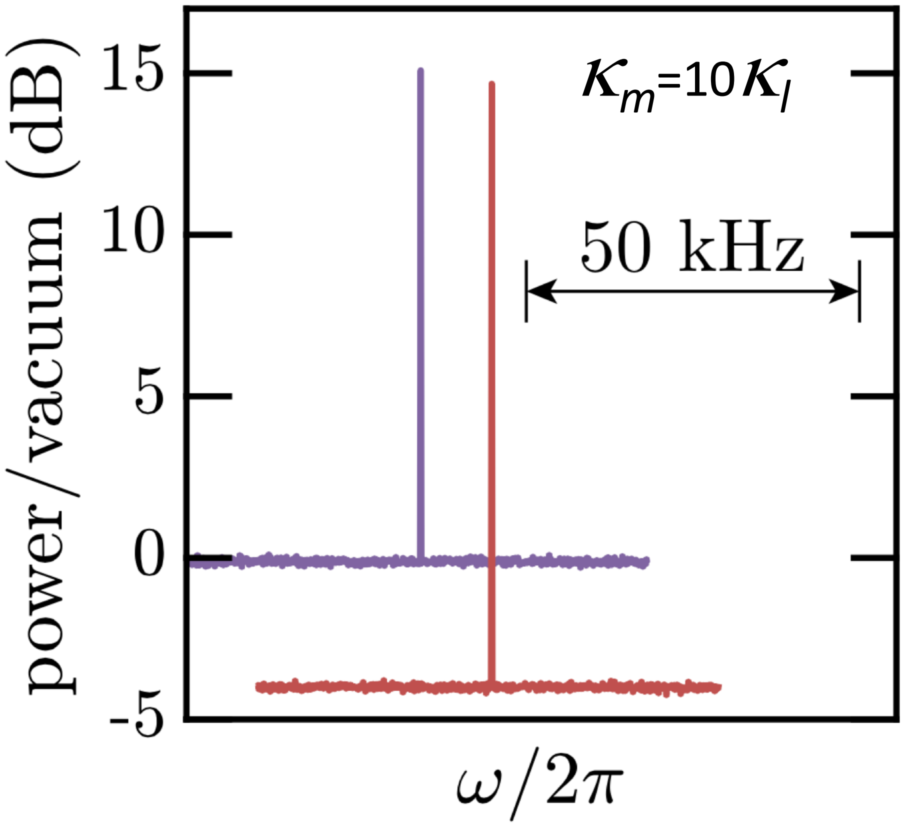
Squeezed states of the vacuum (M. Malnou *et al.*, Phys. Rev. X 9 (2019) 021023; 1809.06470v2)

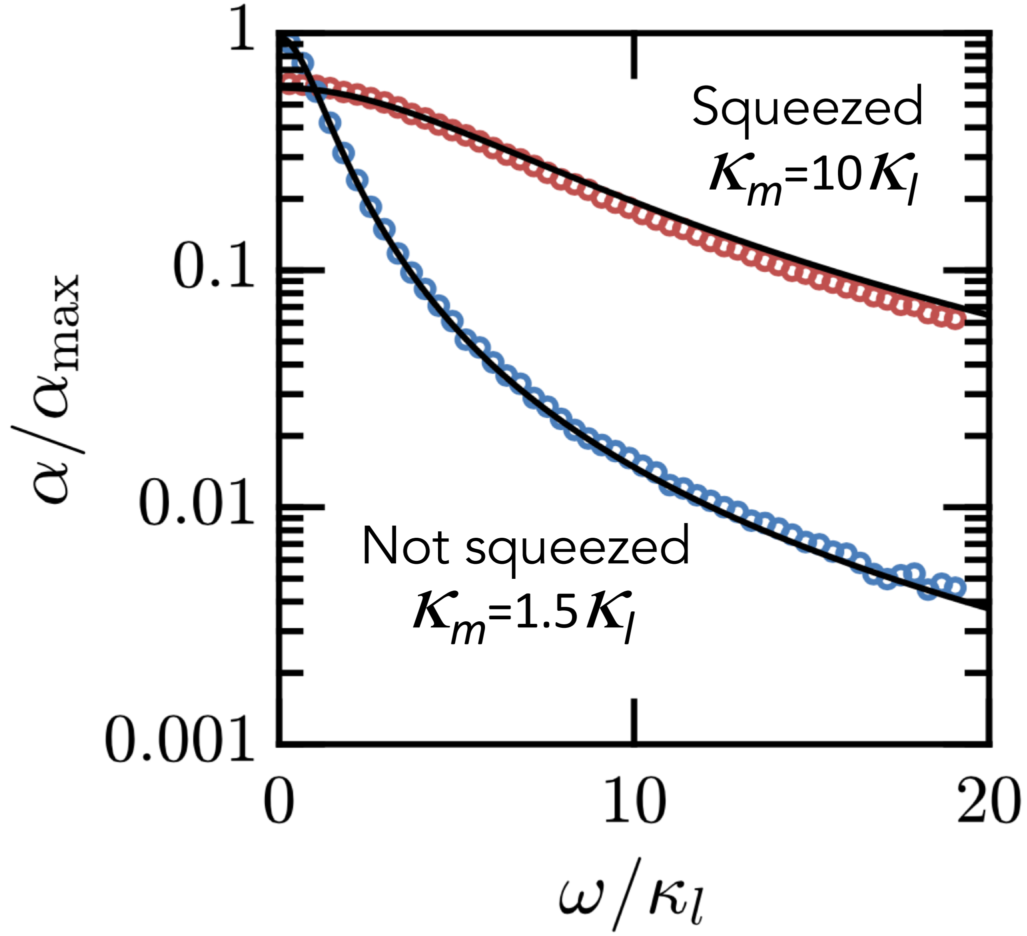



JILA test-bed, twin system to HAYSTAC

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

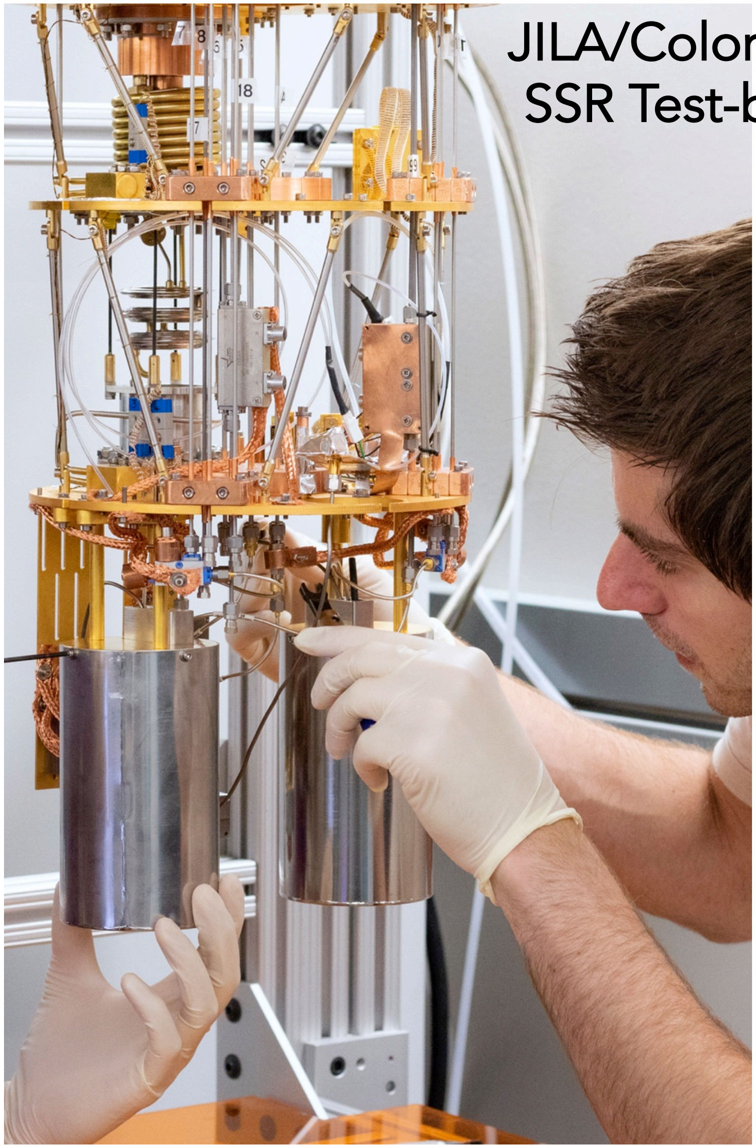
Squeezing implies uniformly higher S/N over a wider bandwidth

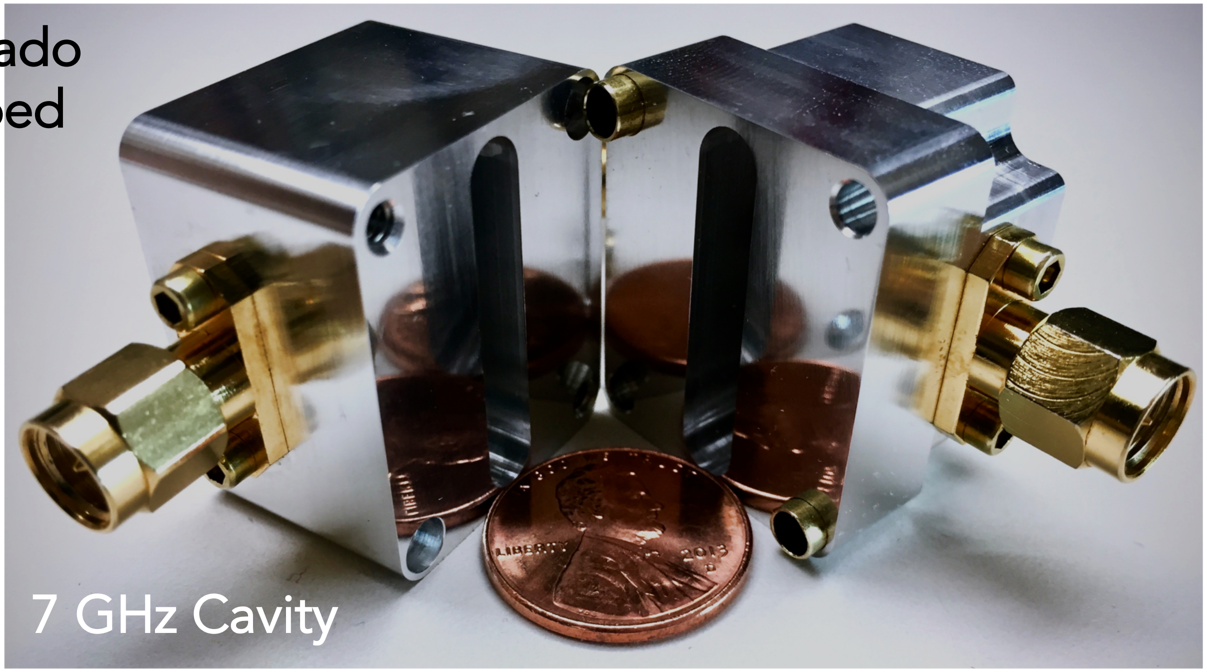


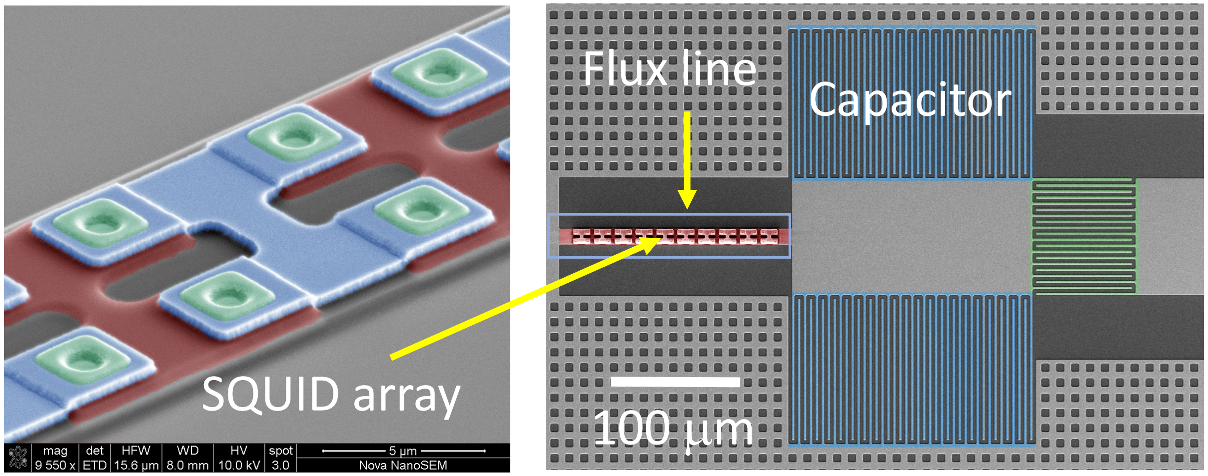


The scan rate with squeezing optimizes at large overcoupling of the cavity, thus higher BW

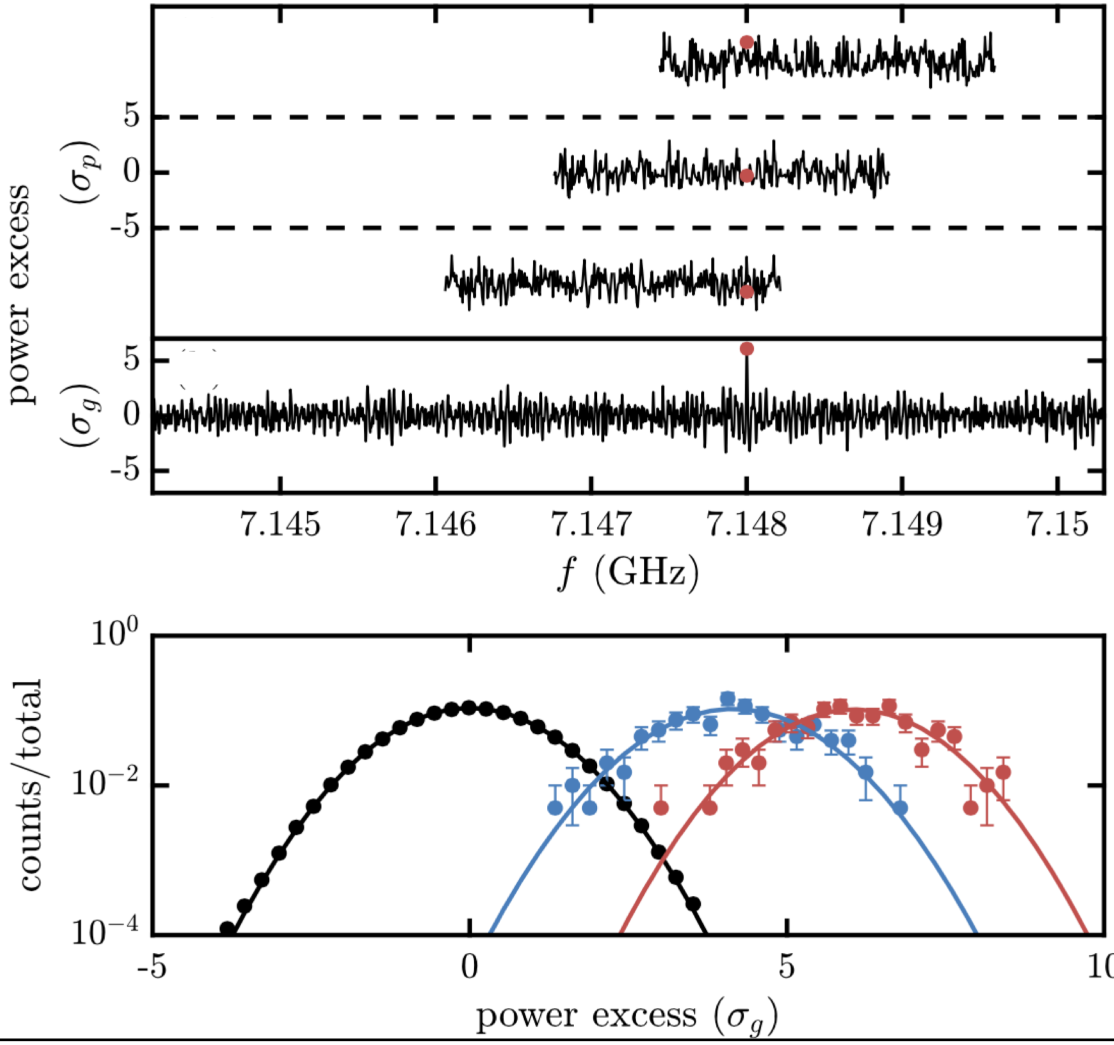
JILA/Colorado SSR Test-bed







Factor of >2 speedup demonstrated; HAYSTAC now running with it



- ☐ Mock axion search conducted on the JILA testbed
- ☐ Synthetic signal injected into the system of unknown frequency
- ☐ Search protocol repeated 200 times for each configuration, data plotted in terms of their standard deviation
- ☐ Results are $\mu_s = 6.05 \pm 0.07$ (with squeezing), $\mu_s = 4.15 \pm 0.07$ (w/o), leading to 2.12 ± 0.08 speedup
- ☐ HAYSTAC is now in data-production with a Squeezed State Receiver
- ☐ JILA working on x10 speedup

We are finishing our first Run with the Squeezed State Receiver

We will finish our first run with the SSR within two weeks. Between improved thermal linkage of the cavity to the dilution refrigerator, and the SSR, the scan rate was improved by x 5-10 over our previous runs.

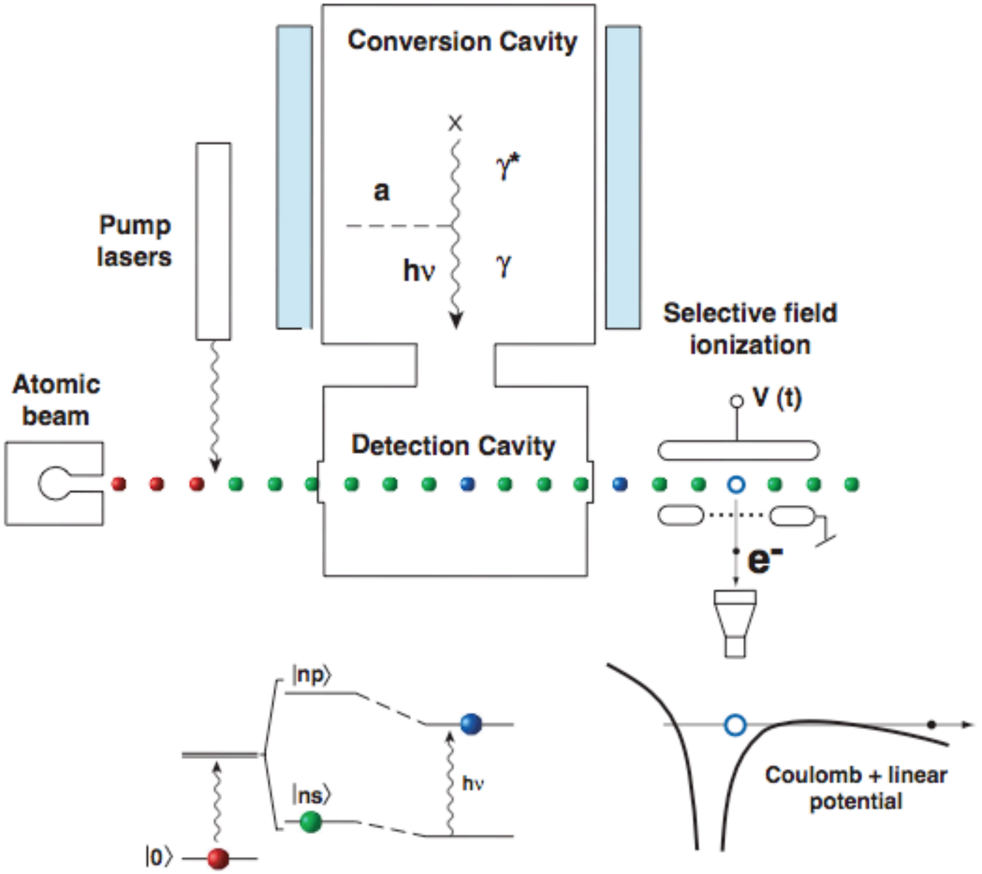
The analysis should be complete and agreed-upon within a month after.

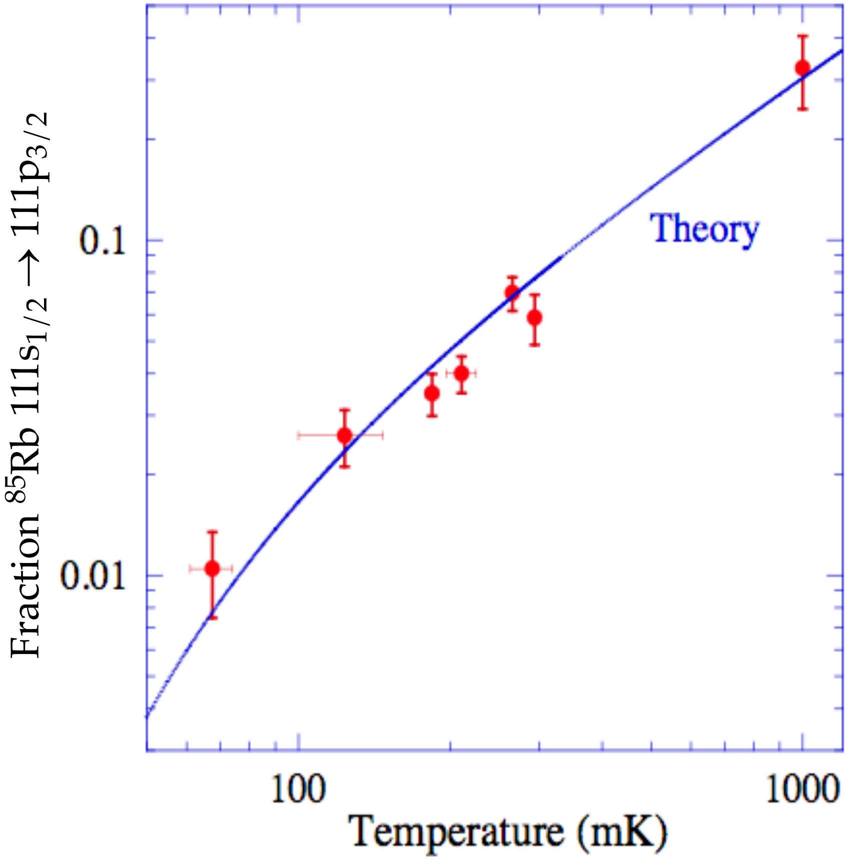
The data will be a relatively small window in the 4-5 GHz range, and is projected to be ~ 1.5 x KSVZ; slightly lower for the Bayesian and slightly higher for the Frequentist analyses.

A new copper-plated aluminum cavity will then be swapped in, with further improved thermal characteristics; this will increase the scan rate by another factor of x2.

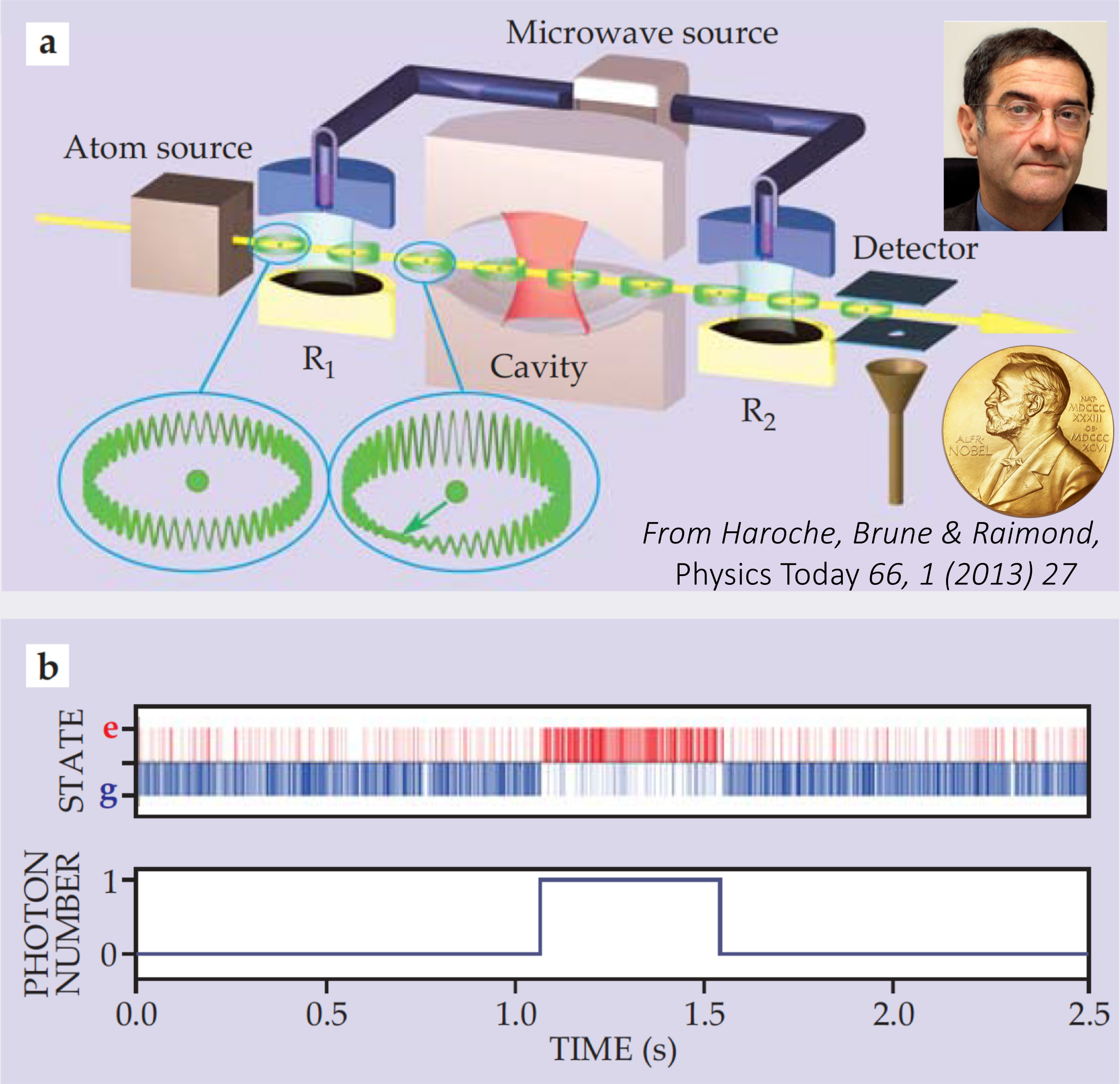
Colorado is developing a SSR of radically new design that should speed up the search by ~ x 10.

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



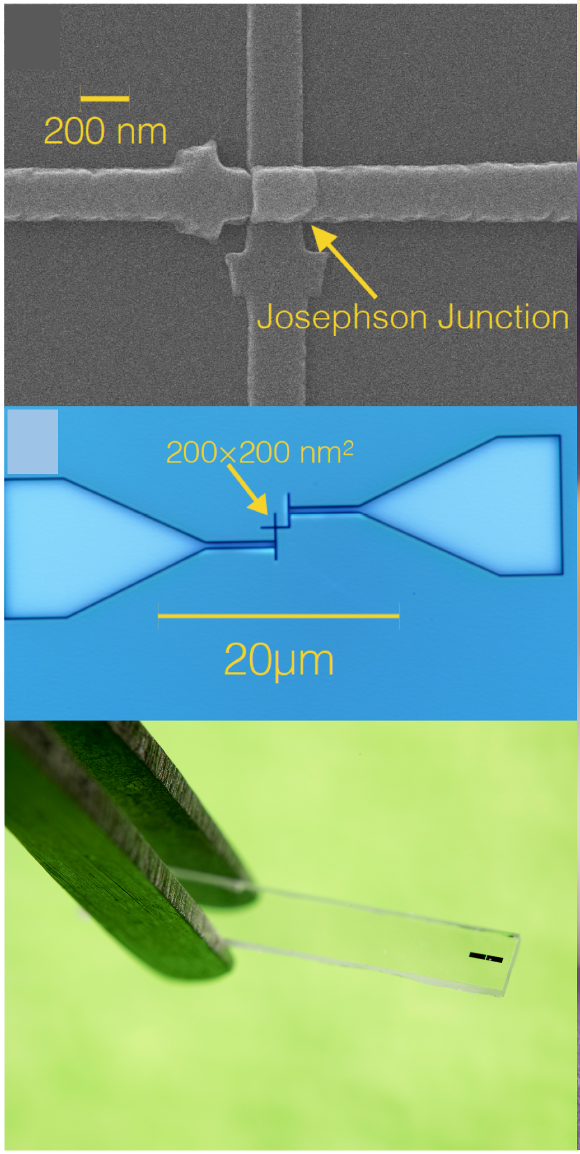


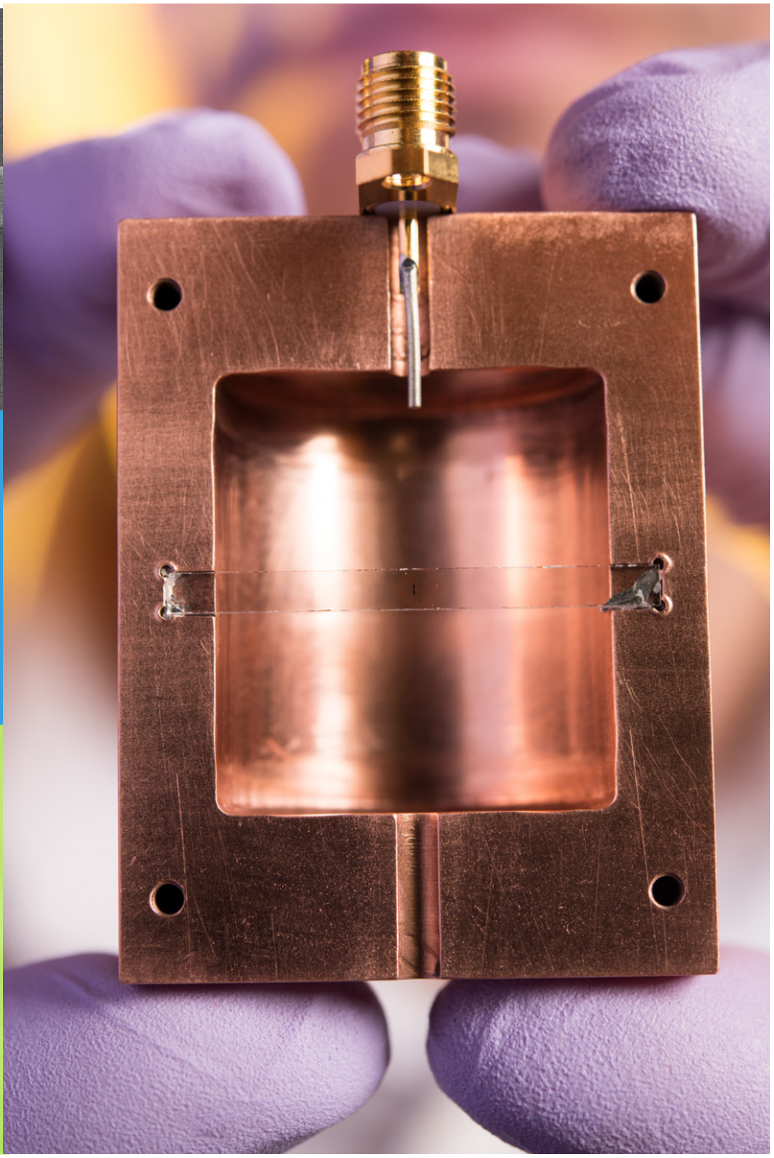
Tada *et al. Phys. Lett. A* 349:488 (2006) demonstrated a receiver a factor ~2 below SQL at 2.527 GHz (~120 mK).
DFSZ exclusion at ~10 μeV presented at conference (Matsuki, 1997), but never published in refereed journal.



From Haroche, Brune & Raimond, Physics Today *66, 1 (2013) 27*

- Serge Haroche’s Quantum Non-Demolition observation of individual photons, based on a Ramsey interferometer.
- A microwave source is tuned close to the n = 50 → 51 (p → s) transition energy, creating a superposition which evolves at the phase difference between the microwave transition frequency, resulting in a large rotating dipole moment.
- An off-resonant photon in the optical cavity perturbs the atomic potential, thus shifting the phase & changing the g, e measurement probabilities at the detector. Individual photons are thus detected without destroying them.
- A R&D program at Yale is ramping up to look at the applicability of Rydberg atom QND as a single-quantum detector for HAYSTAC and beyond (Reina Maruyama).





Superconducting qubit QND measurement of the photon occupation number in the cavity

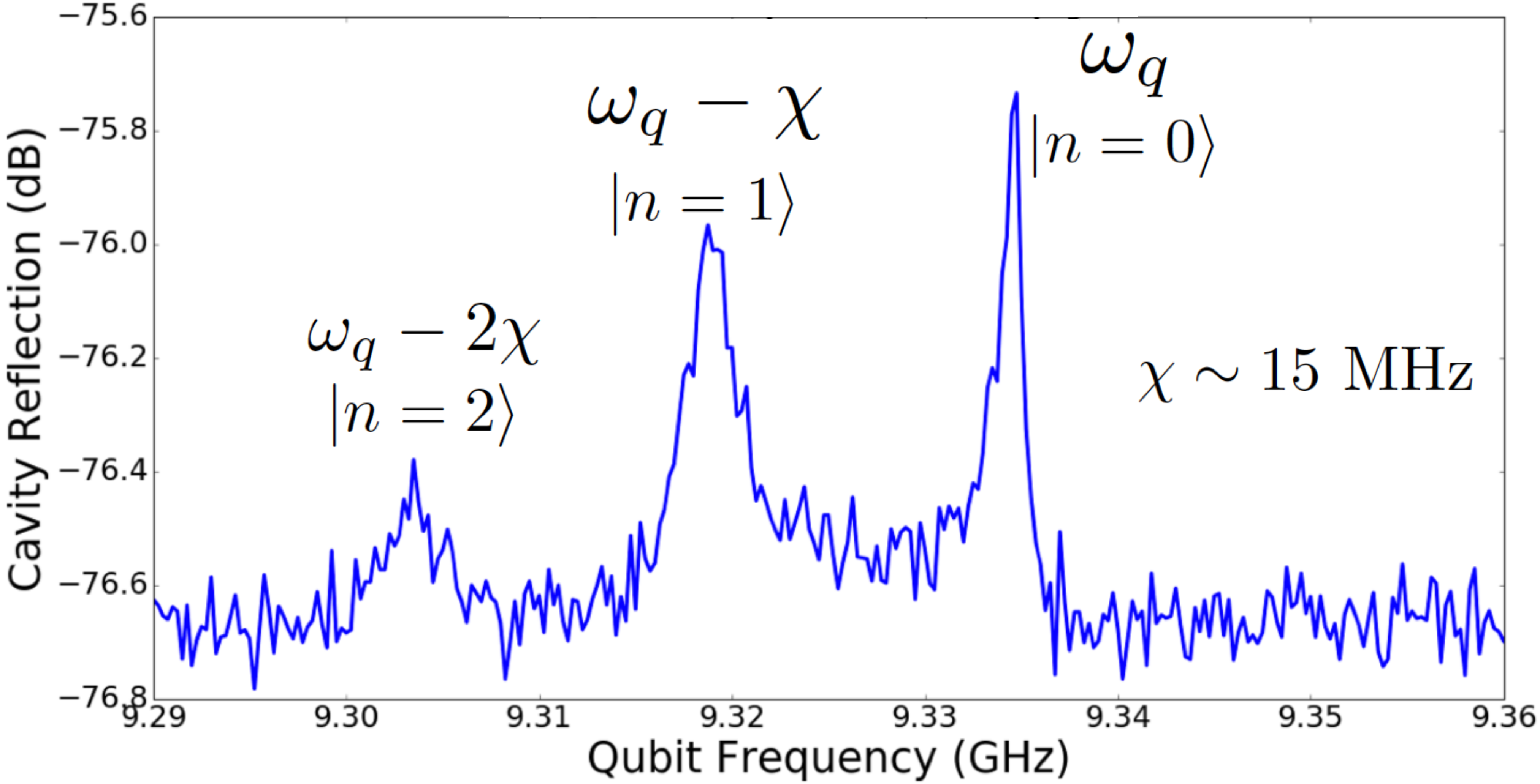
A. Chou, D. Bowring (FNAL)
D. Schuster (Chicago)

Josephson junction is the ‘atom’ with non-linear inductance

The presence of one or more photons in the cavity exercises the anharmonicity of the qubit, shifting its frequency

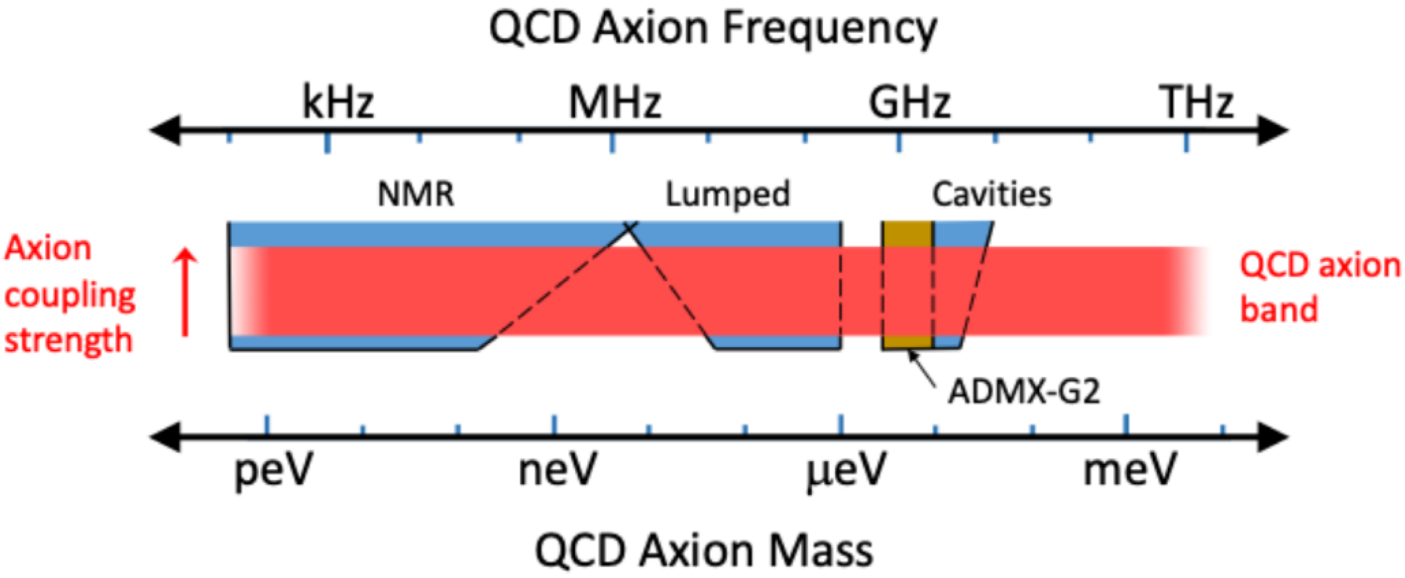
The coupling to the cavity can be improved with a miniature dipole antenna

QND measurement of Poisson-distributed photon occupation in the cavity, with <N> ~ 1



Current theoretical limits permit QCD axions down to 10^{-12} eV or perhaps lower

Covering this entire mass range necessitates an array of detection modalities, i.e.



CASPEr Electric
CASPEr Wind

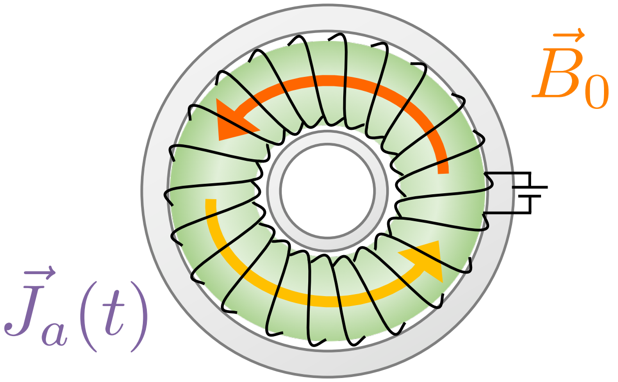
DM Radio
ABRA
LC

ADMX
HAYSTAC
CAPP

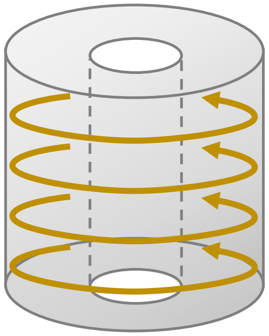
MADMAX
Orpheus

DM Radio/ABRA – A lumped element experiment *(Stanford-SLAC-MIT-Berkeley-UNC-Princeton)*

Top-Down Cross-section



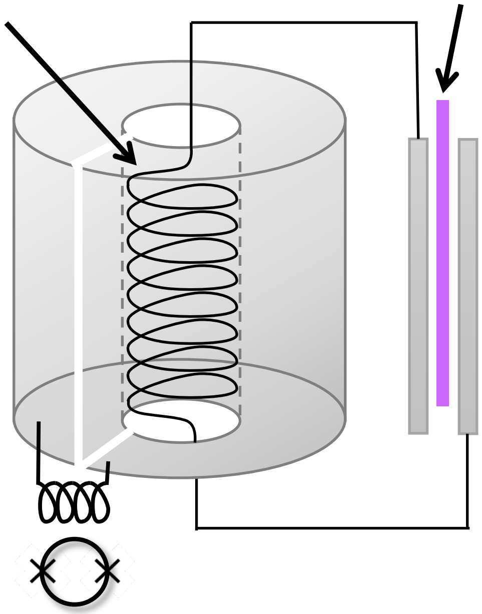
(B_0 toroid *inside* sheath)



Principle of the experiment

Solenoid inductor placed in sheath center hole

Tunable capacitor



Schematic of DM Radio

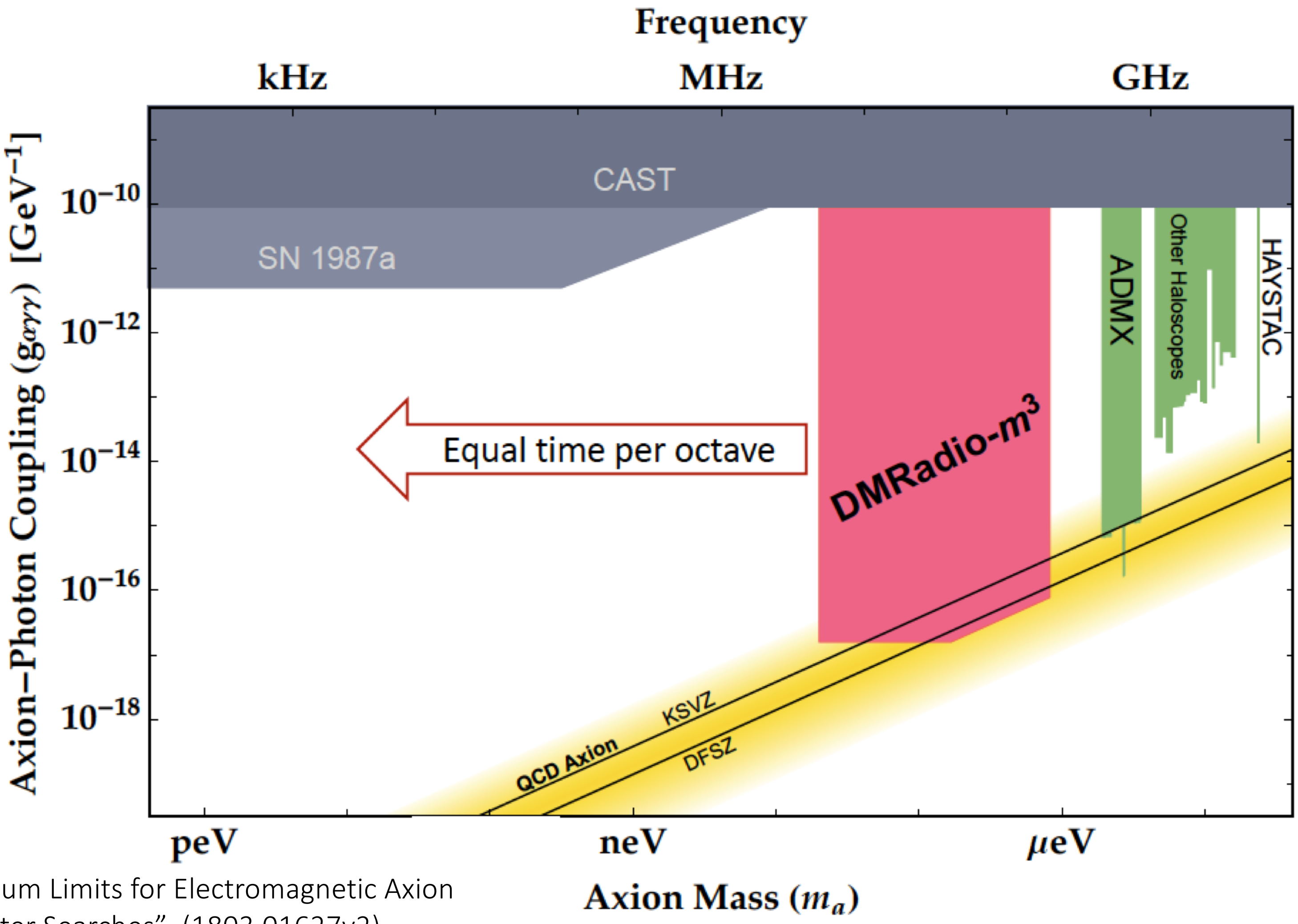
The essential idea is that for DM Radio, the lumped parameter design decouples the resonant frequency from the size of the conversion region, thus allowing the experiment to reach almost arbitrarily low mass

Proposed Science Reach of DM Radio 50 L, and DM Radio Cubic Meter

Cubic Meter Experiment

- 1 m^3 Detection Volume
- 20 mK Temperature
- 4 Tesla Magnetic Field
- 5 MHz– 200 MHz
- dc SQUID with 20× quantum limit
- 3 years of live scan time

- Quantum Acceleration would enable QCD sensitivity at lower mass



See S. Chauduri *et al.*, "Quantum Limits for Electromagnetic Axion and Hidden-Photon Dark Matter Searches" (1803.01627v2)

Summary remarks

❑ Axions (and Light Dark Matter more generally) are finally receiving the attention they merit, and perhaps are now even the most credible dark matter candidates. Our new challenge is a greatly expanded mass range to cover, requiring many approaches.

❑ The sensitivity and scan speed frontiers are yielding ground now, but the major hurdle for axion searches still remains practical concepts for cavities & resonators that satisfy multiple challenging constraints, particularly at higher frequencies.

❑ Much credit is due to the NSF and DOE for their parallel initiatives in quantum sensing and information for High Energy Physics.

❑ HAYSTAC is now operating with a Squeezed State Receiver; to our knowledge along with LIGO, the only cosmology/particle astrophysics data-taking experiments to do so. The next frontier will be single-quantum detection, and experiments are being readied.