HAYSTAC

Haloscope At Yale Sensitive To Axion CDM

Status, Results & Plans

CIPANP 2018
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Outline

I. Preliminaries on the Microwave Cavity Experiment

II. HAYSTAC Technical Description

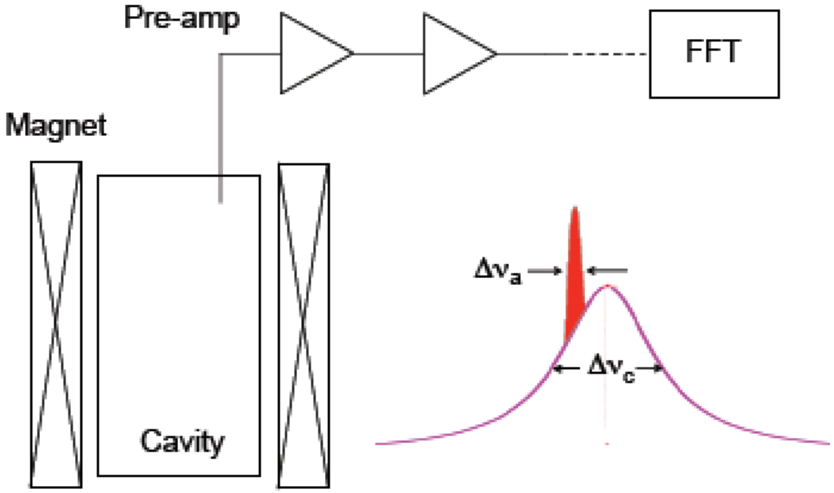
III. Phase I Scientific Results

IV. Phase II Squeezed-Vacuum State Receiver

V. Summary Comments

Principle of experiment, S/N, Detectability

Axion detection – quantitative details



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: $P \sim g_{a\gamma\gamma}^2 (\rho_a / m_a) B^2 Q_c V C_{nm\ell} \sim 10^{-23}$ 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

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

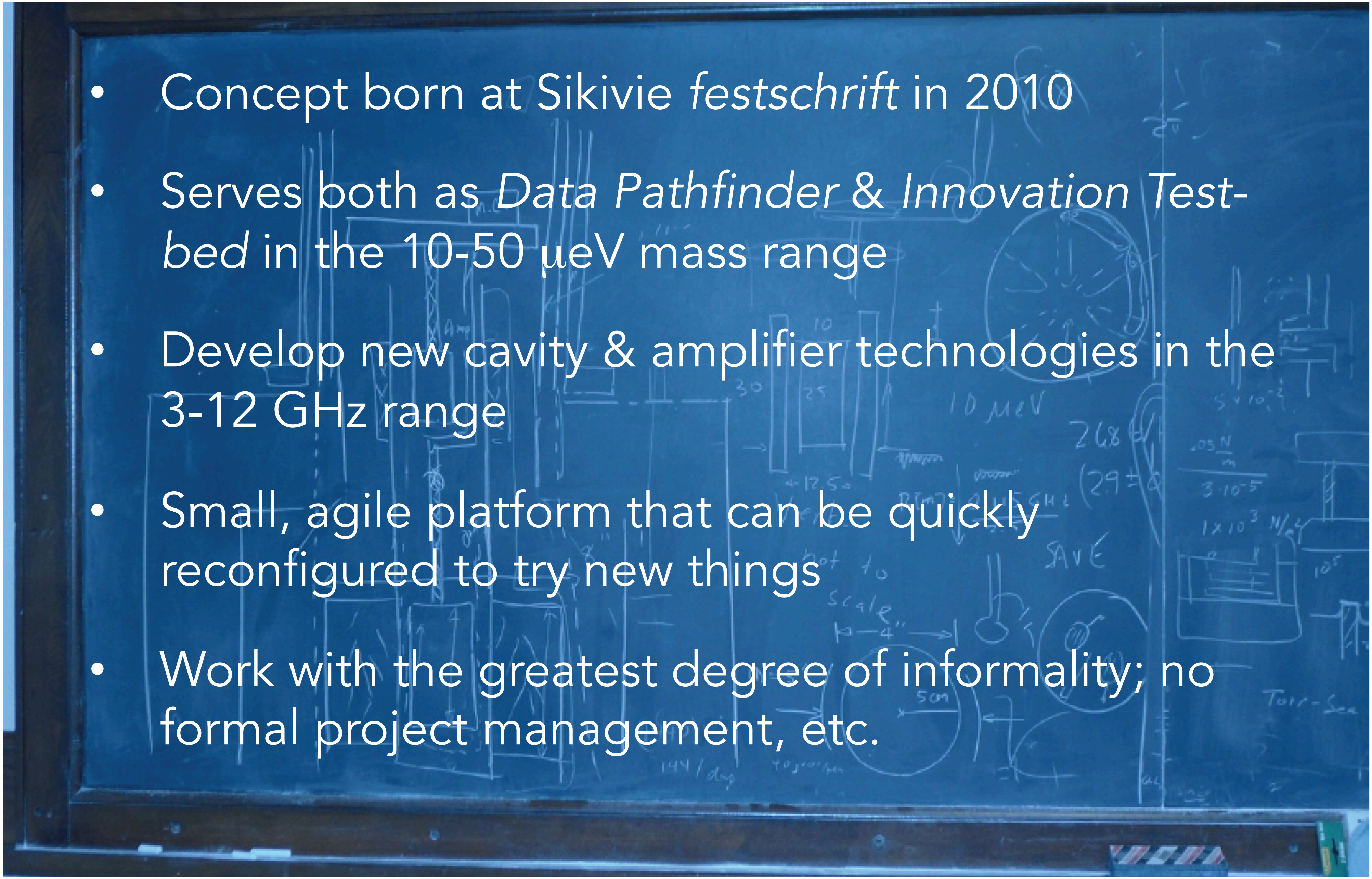
ν [GHz]	m_a [μeV]	T_{SQL} [mK]
0.5	2.1	24
5	20.7	240
20	82.8	960

The SQL can be evaded by

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

HAYSTAC

History, Motivation & Philosophy



- Concept born at Sikivie *festschrift* in 2010
- Serves both 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 the greatest degree of informality; no formal project management, etc.

The Team *(current plus alumni)*

Yale University

Steve Lamoreaux, Reina Maruyama, Yulia Gurevich, Ling Zhong, Danielle Speller, Ben Brubaker, Kelly Backes, Yong Jiang, Sid Cahn

UC Berkeley

Karl van Bibber, Maria Simanovskaia, Samantha Lewis, Alex Droster, Al Kenany, Nicholas Rapidis, Jaben Root, Isabella Urdinaran, Tim Shokair

CU Boulder/JILA

Konrad W. Lehnert, Daniel Palken, William F. Kindel, Maxime Malnou, M.A. Anil

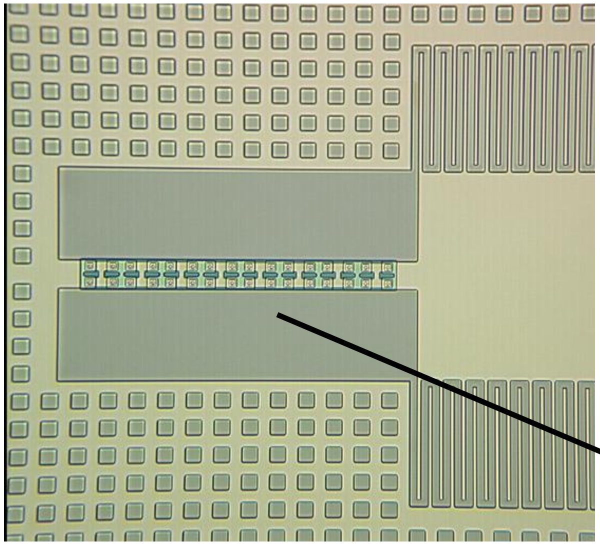
Lawrence Livermore National Lab

Gianpaolo Carosi

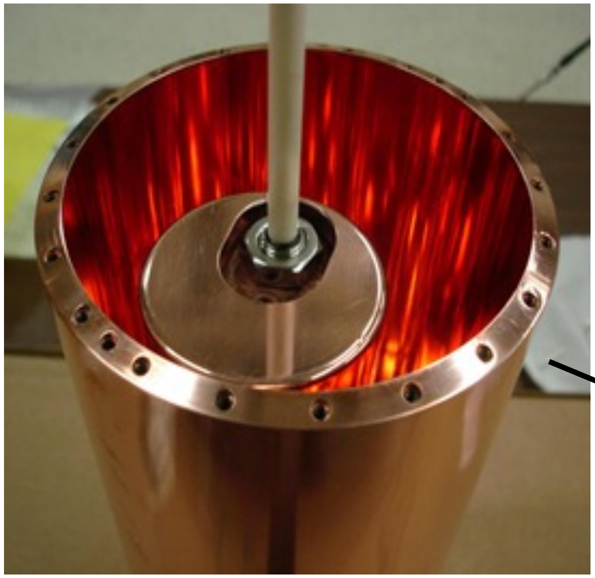
NSF
HSF
HEISING - SIMONS
FOUNDATION
DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

The Hardware

Josephson Parametric Amplifier



Microwave Cavity (copper)

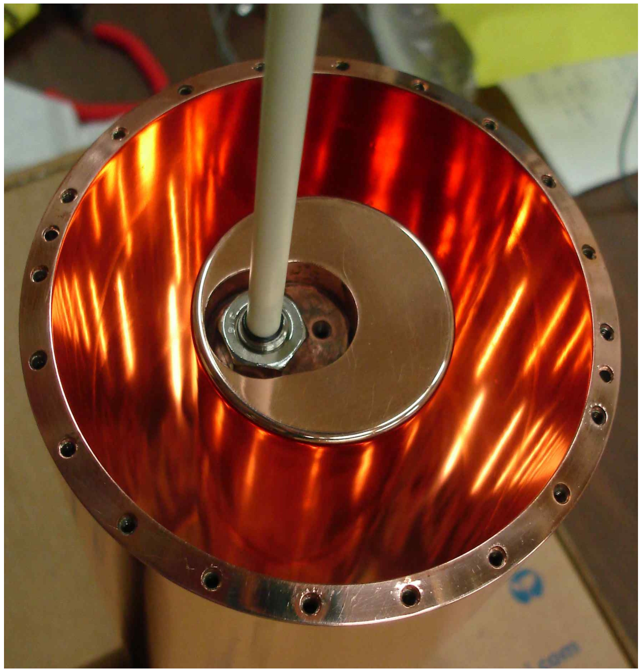


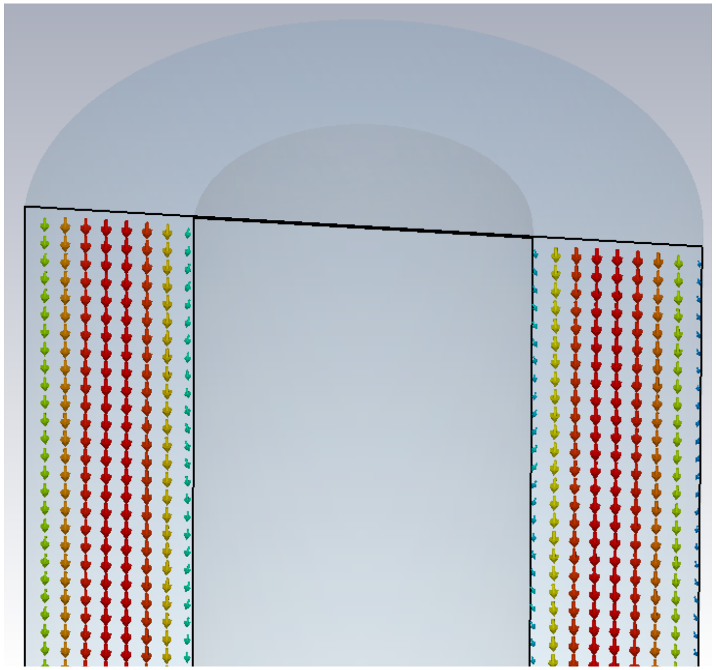
^{3}He/^{4}He Dilution Refrigerator

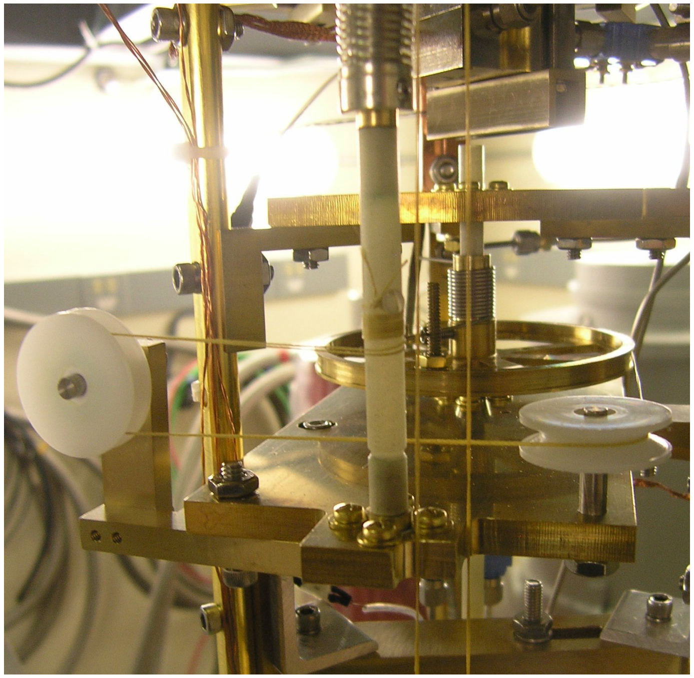
9.4 Tesla, 10 Liter Magnet

Microwave Cavities

- Annular cavity, cam-tuned, annealed Cu on S.S.
- Tunable over 3.6 – 5.8 GHz
- Attocube for rotary motion, stepping motors for linear

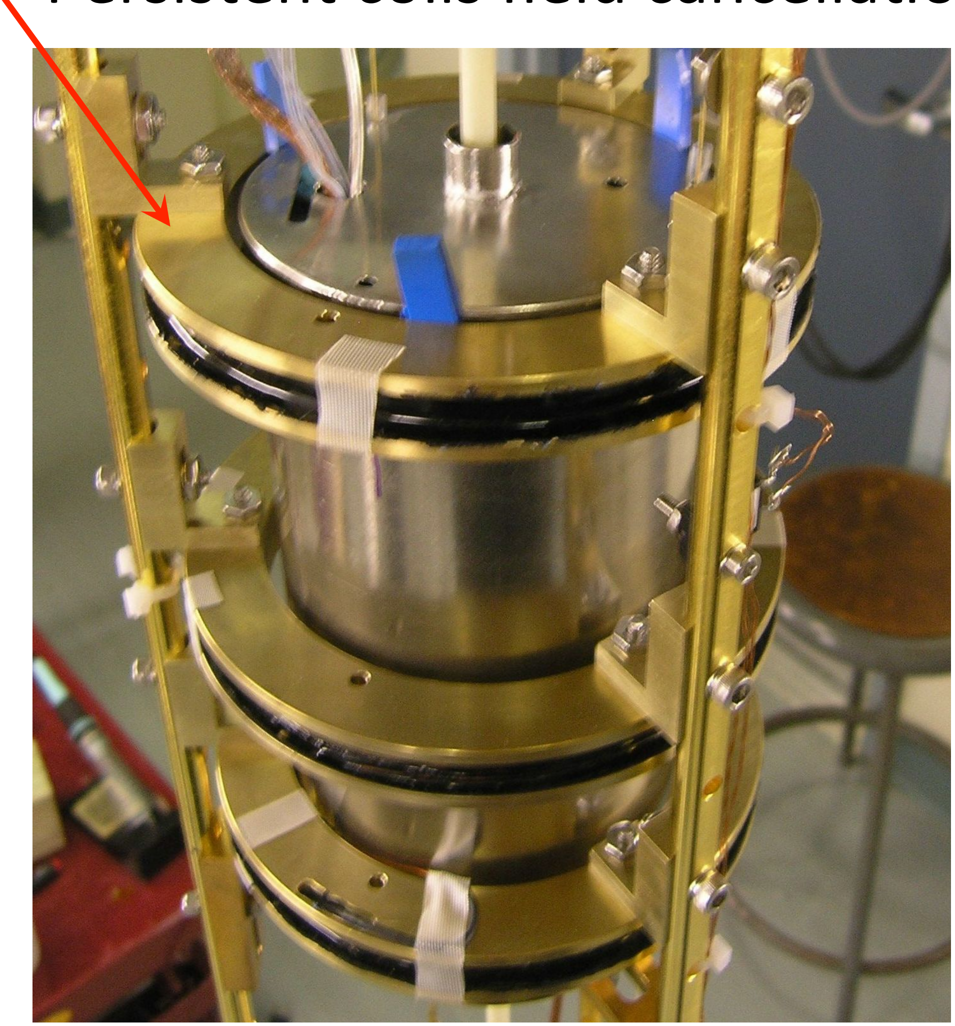


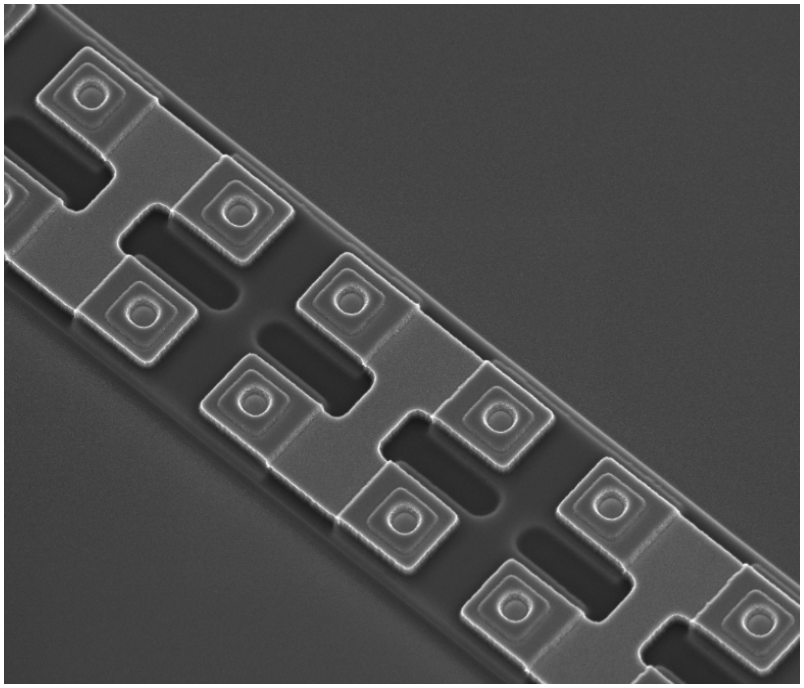


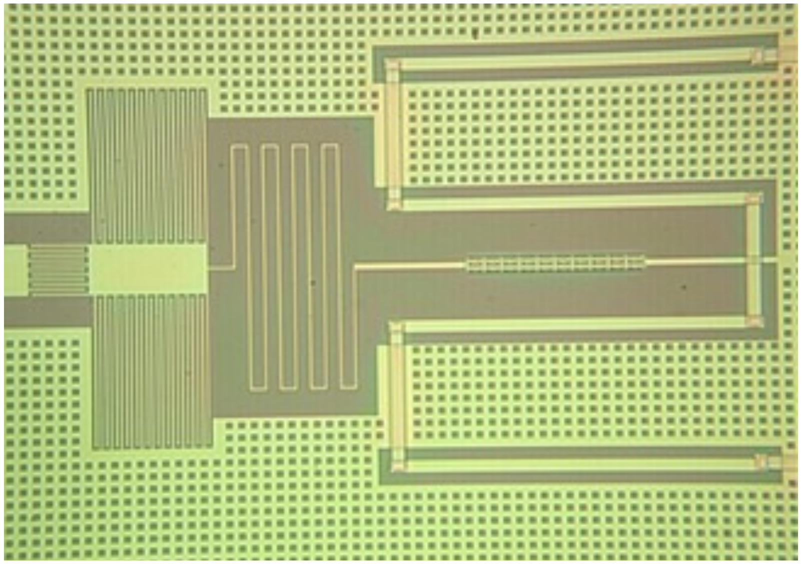


Quantum Limited Josephson Parametric Amplifiers

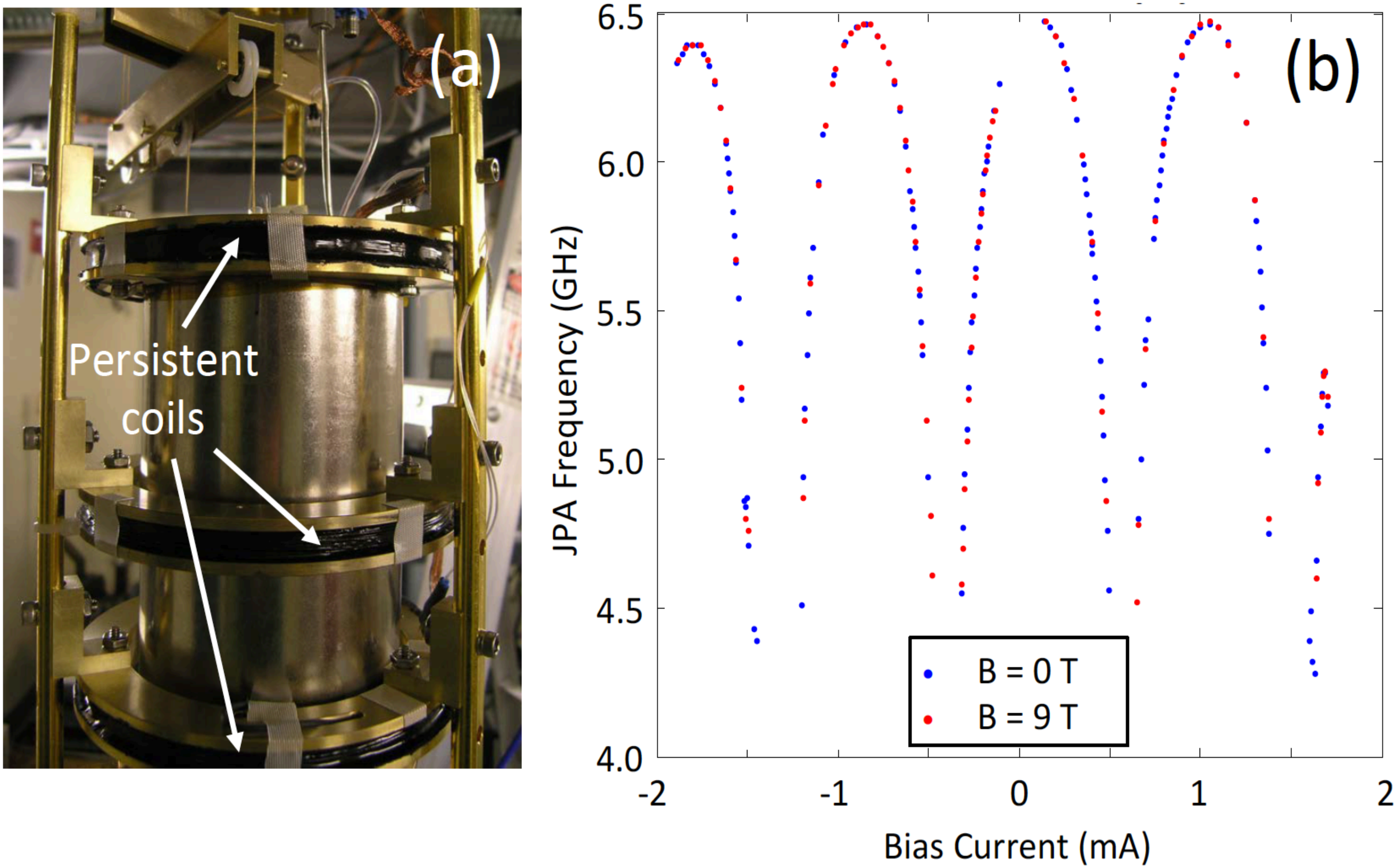
- 20 dB gain, quantum limited
- Tunable over 4.4 – 6.5 GHz
- Persistent coils field cancellation



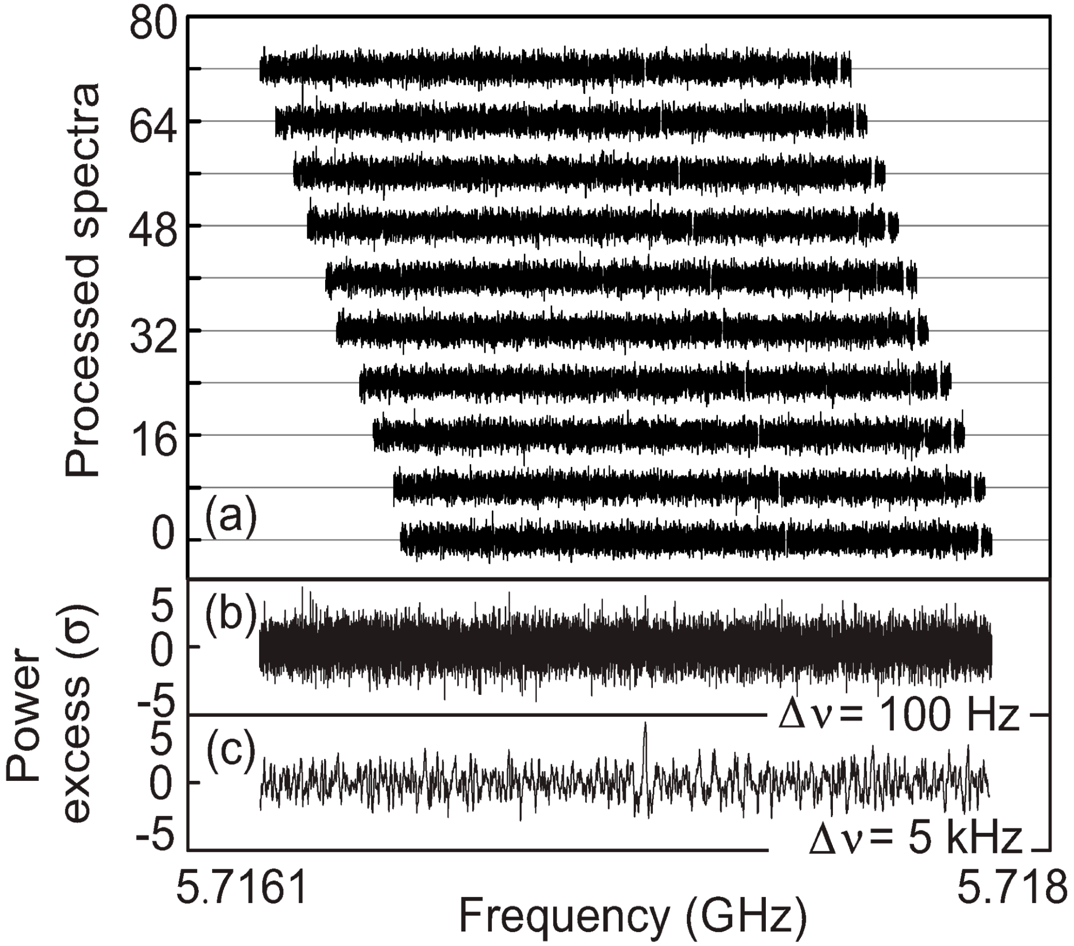


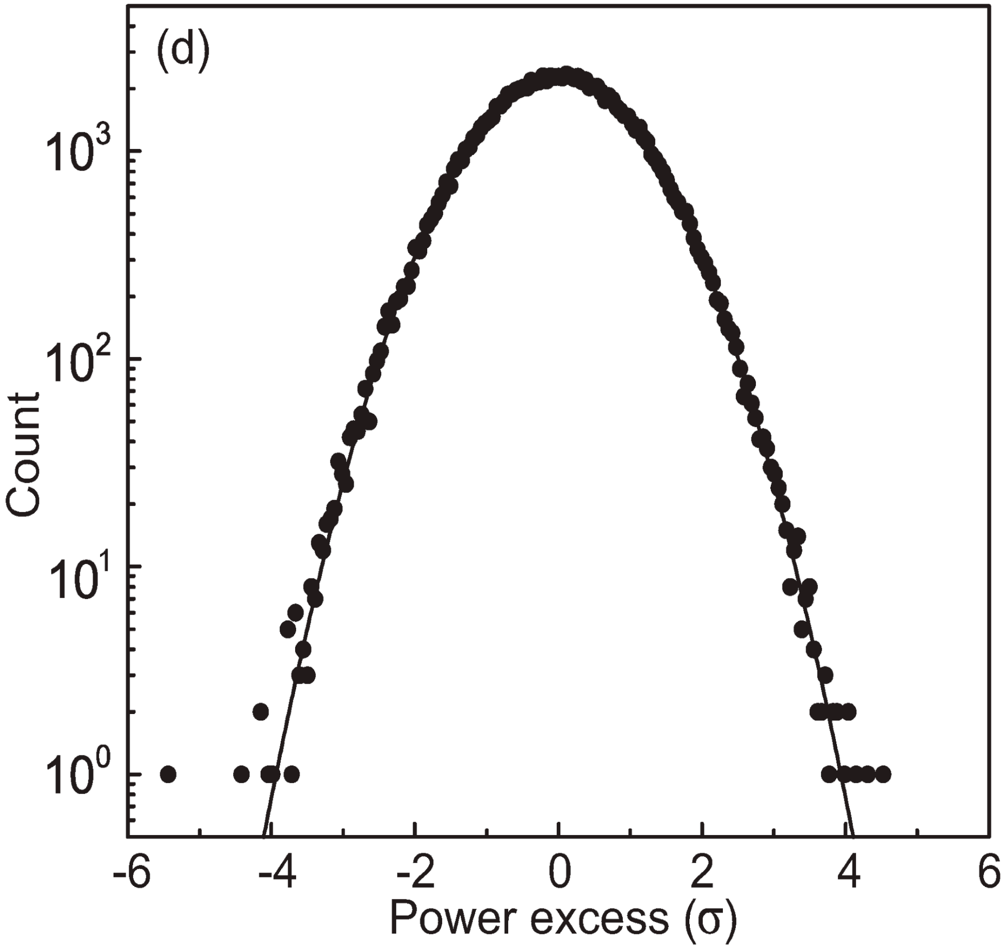


A major challenge – magnetic shielding of the JPA



What the data look like





- T_{SYS}~ 3 x T_{SQL} for first run; 'hot rod' implicated, thermal link improved
- T_{SYS}~ 2 x T_{SQL} for second run recently published

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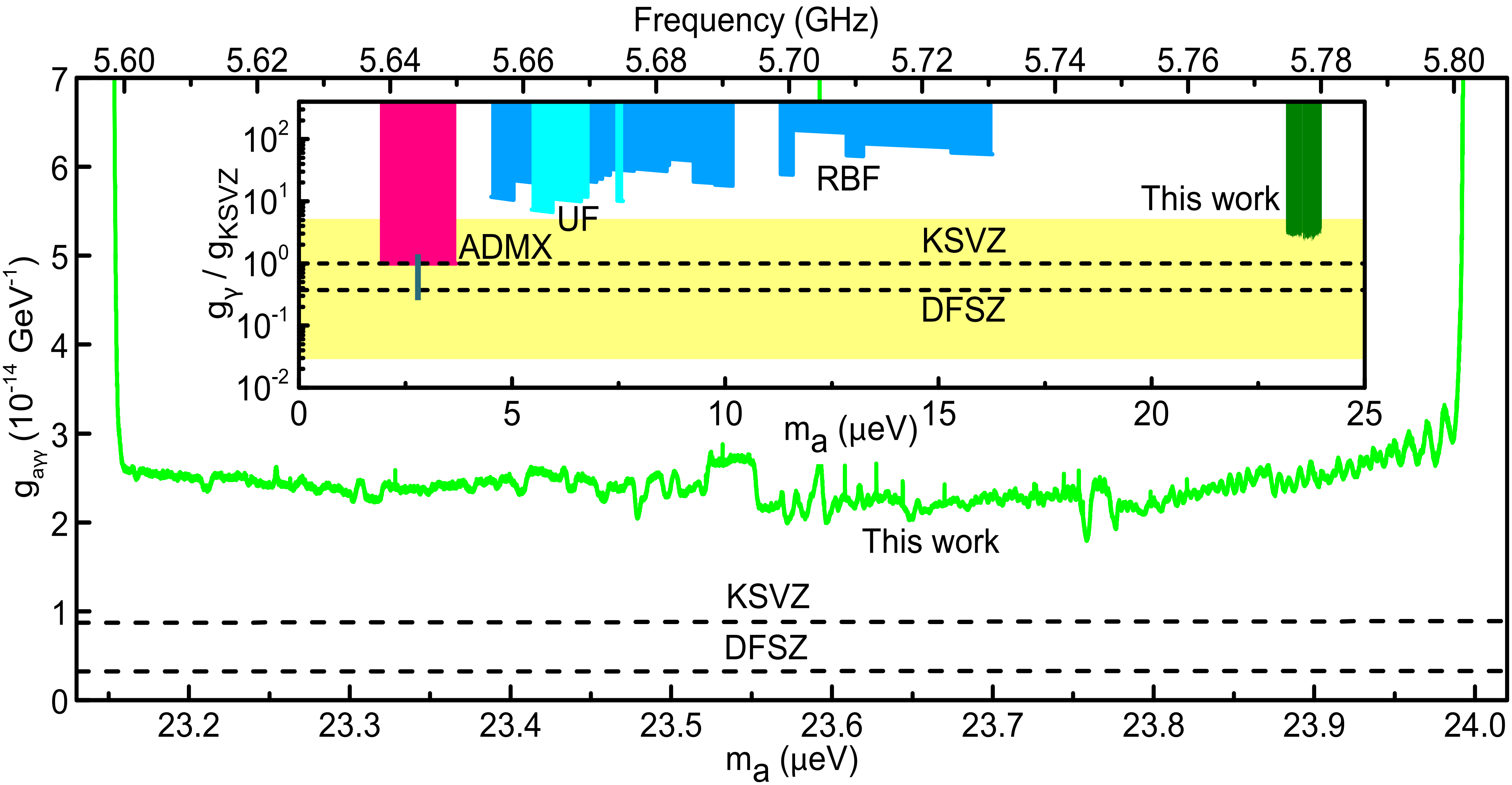
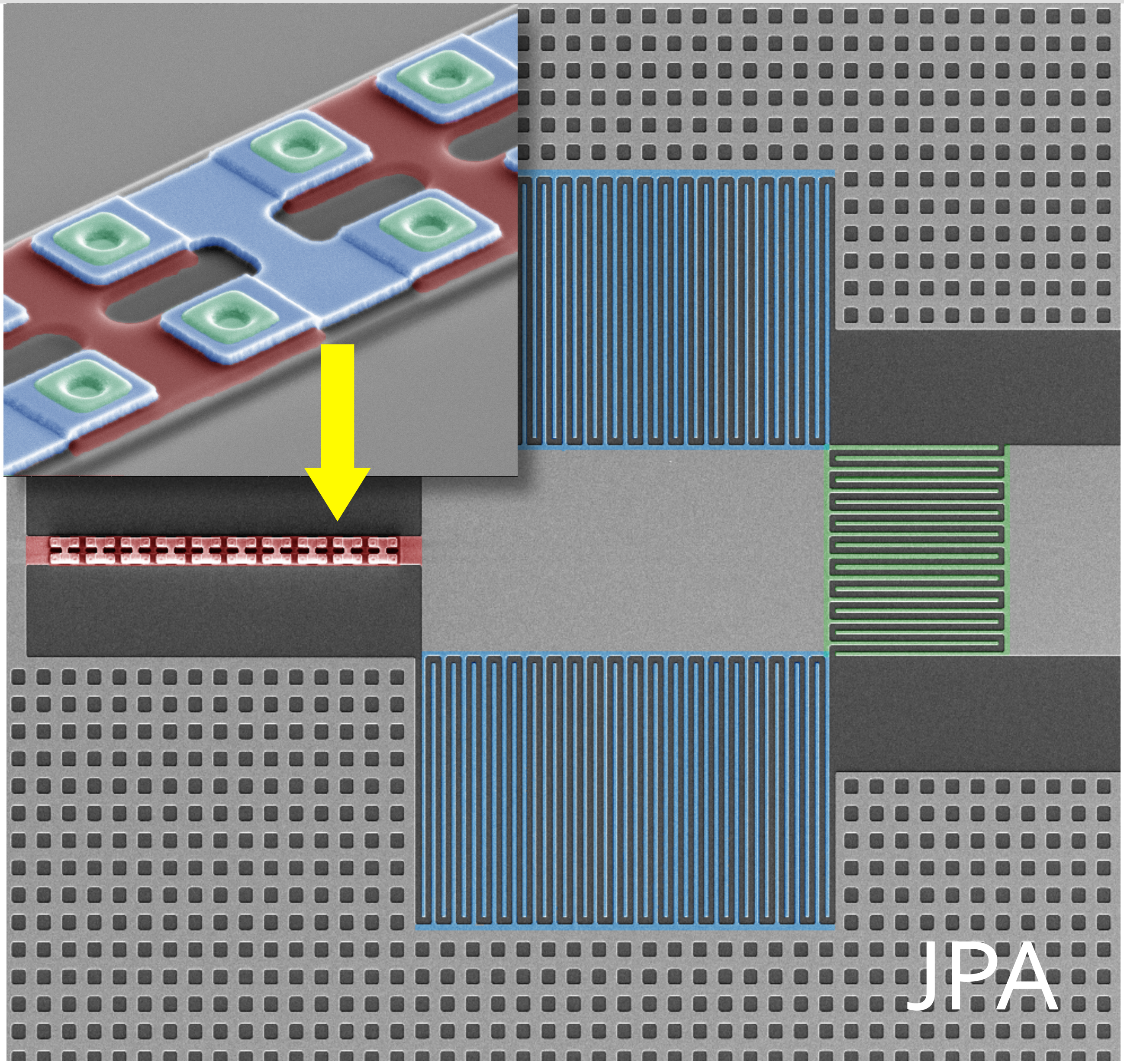
Results from Phase I Operation (2016-17)

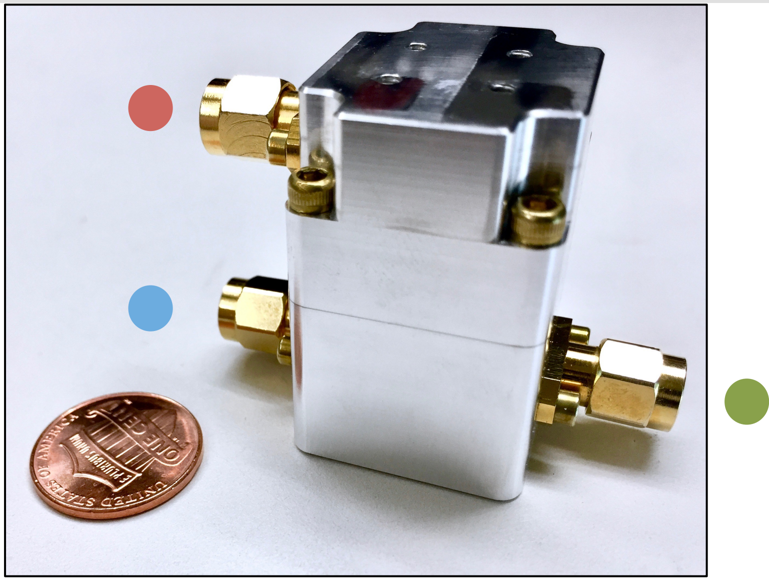


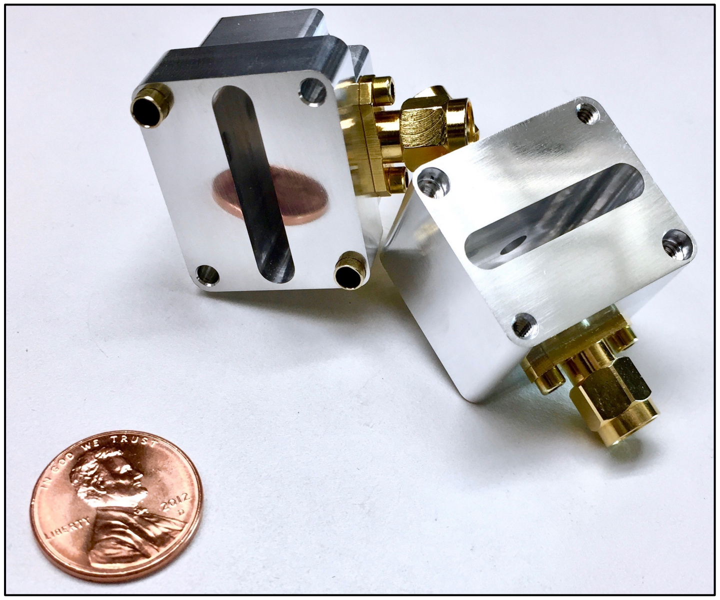
B. Brubaker *et al.*, Phys. Rev. Lett. 118 (2017) 061302

L. Zhong *et al.*, Phys. Rev. D 97 (2018) 092001

Phase II: Squeezing – Circumvent vacuum fluctuations to scan faster





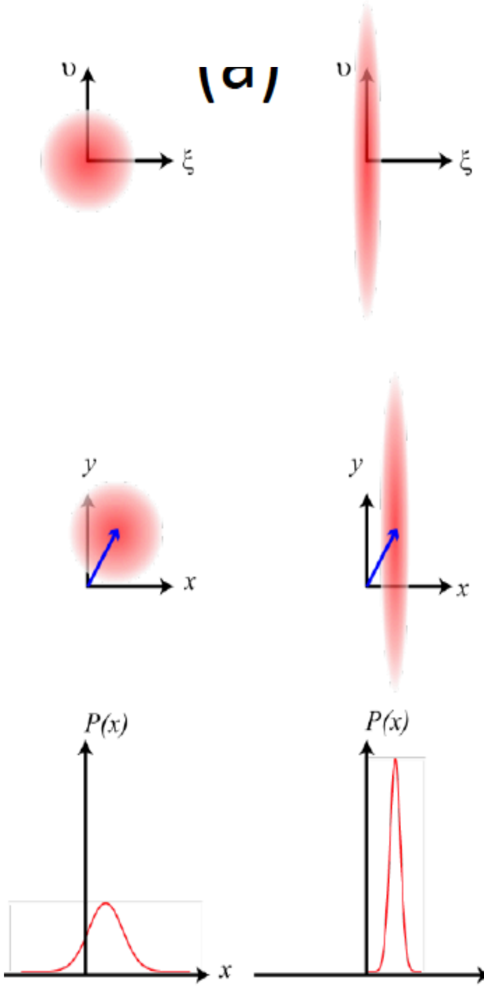


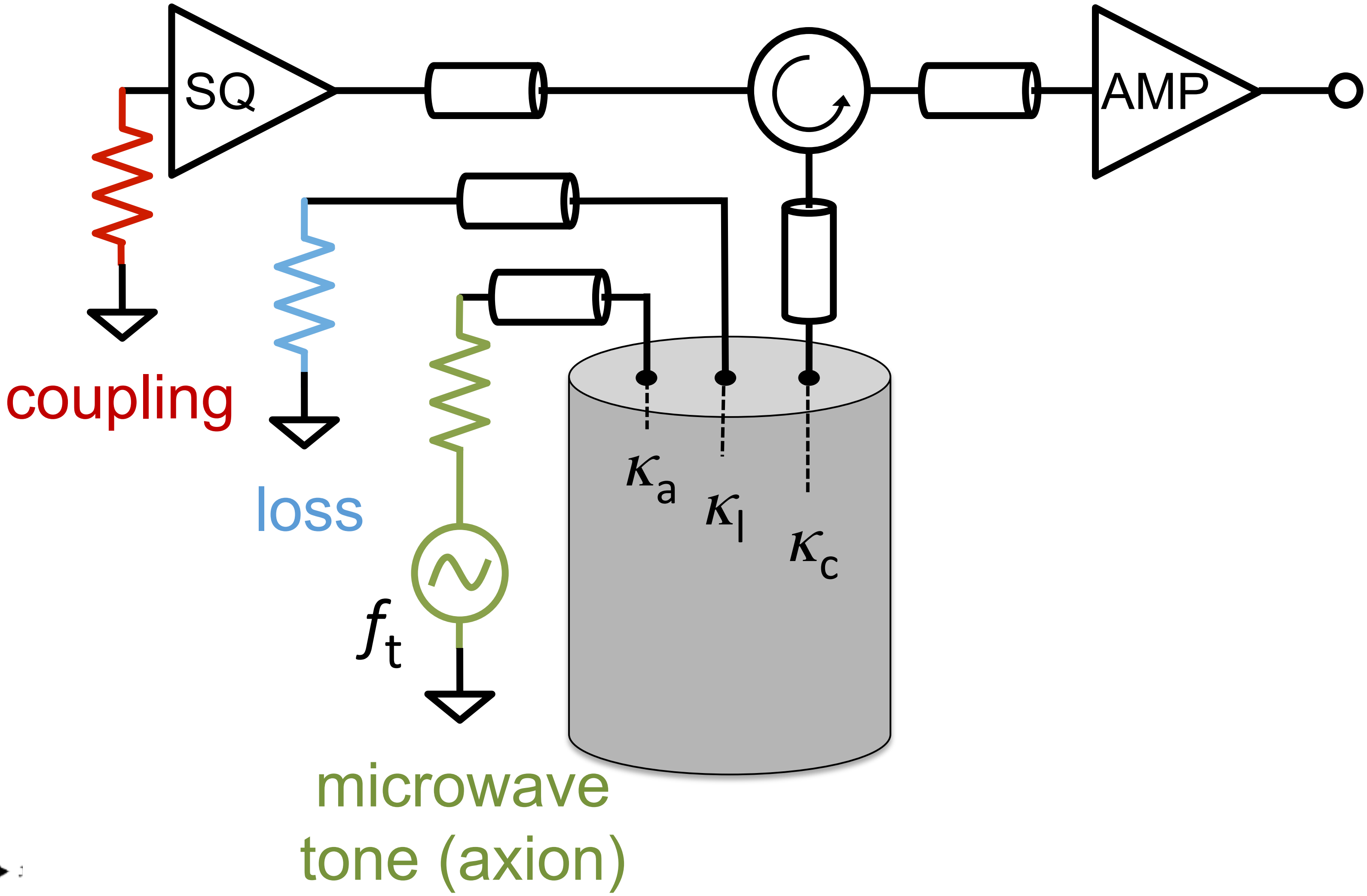
JILA mock haloscope for R&D for squeezing studies with 7 GHz Nb cavity

Actual system to deploy July 2018 in HAYSTAC

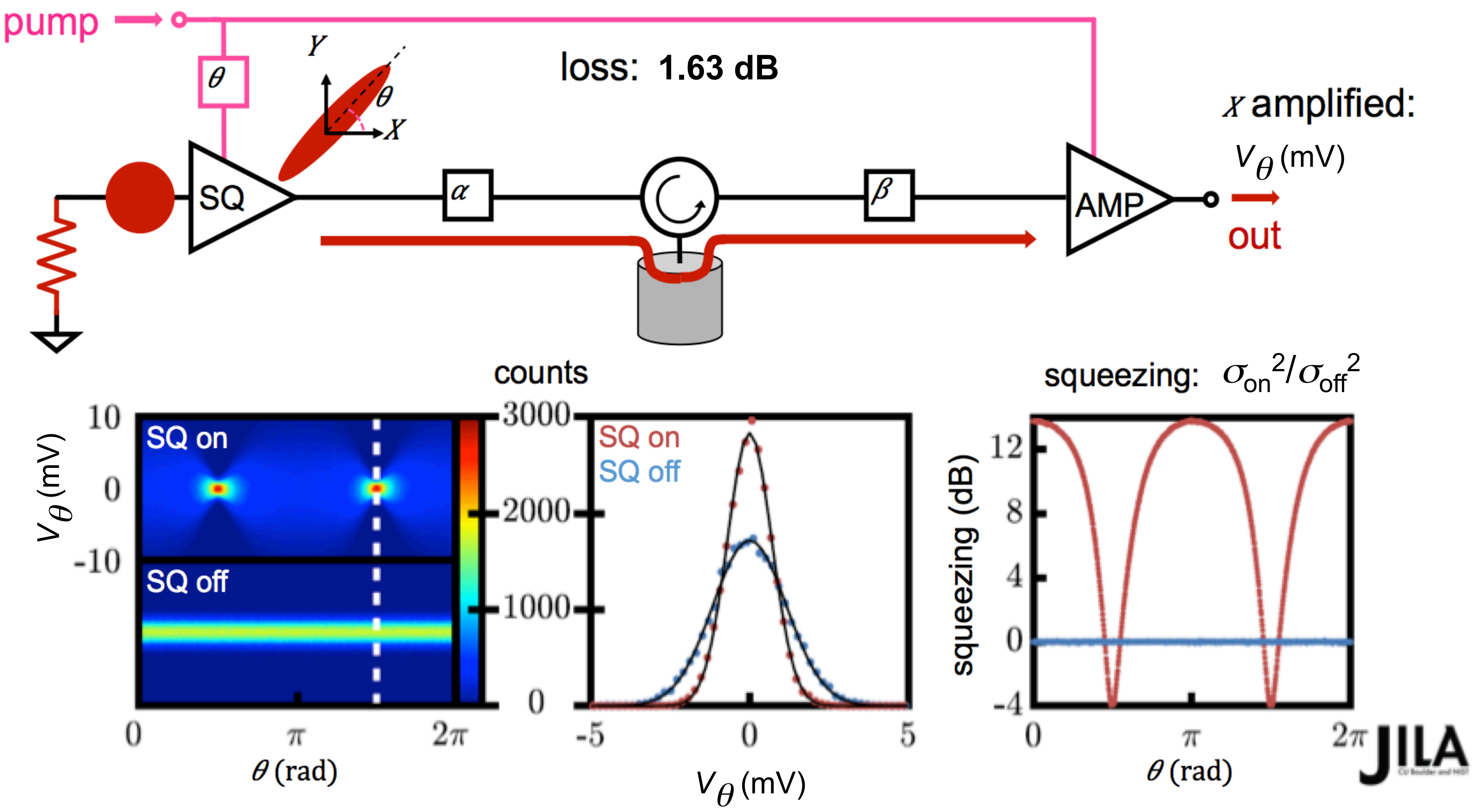
Accelerating dark-matter axion searches with quantum information technology

Zheng *et al.*, arXiv:1607.02529v1





Results from the mock haloscope with squeezing

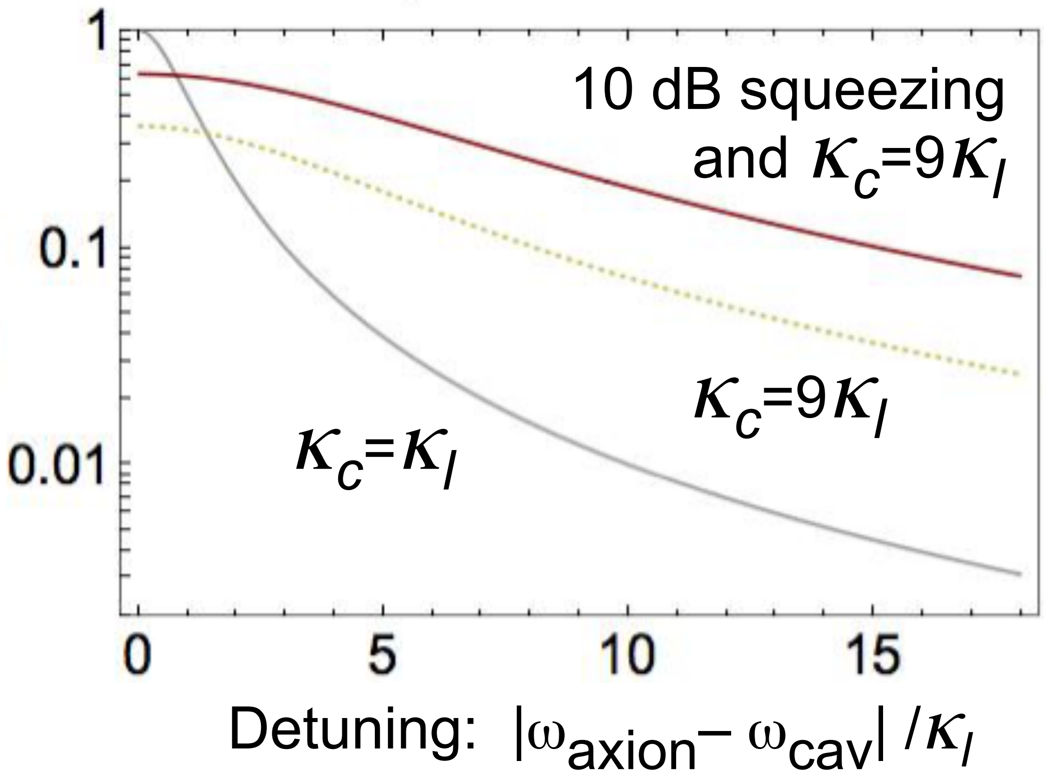


The vacuum variance has been reduced by 4 dB

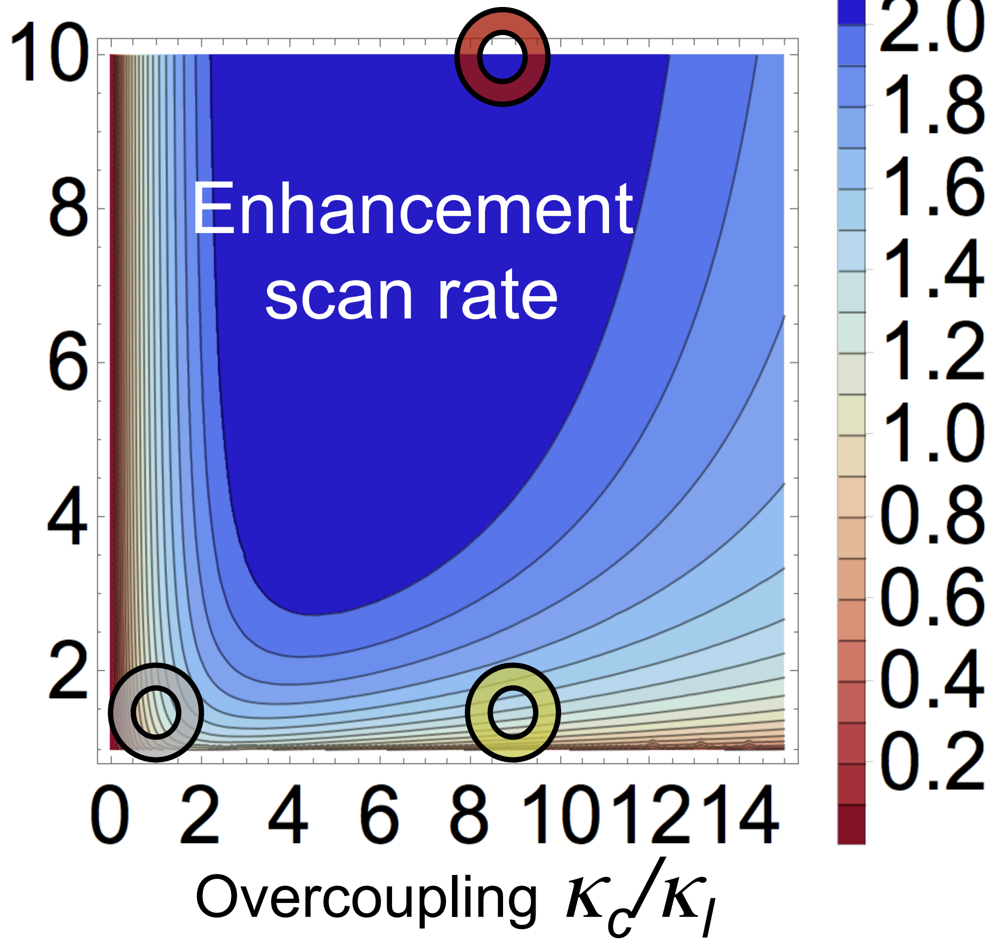
Overcouple & squeeze: search many bare cavity linewidths simultaneously

(These calculations include a realistic 32% power loss)

SNR: P_{axion} / P_{noise}



Squeezing



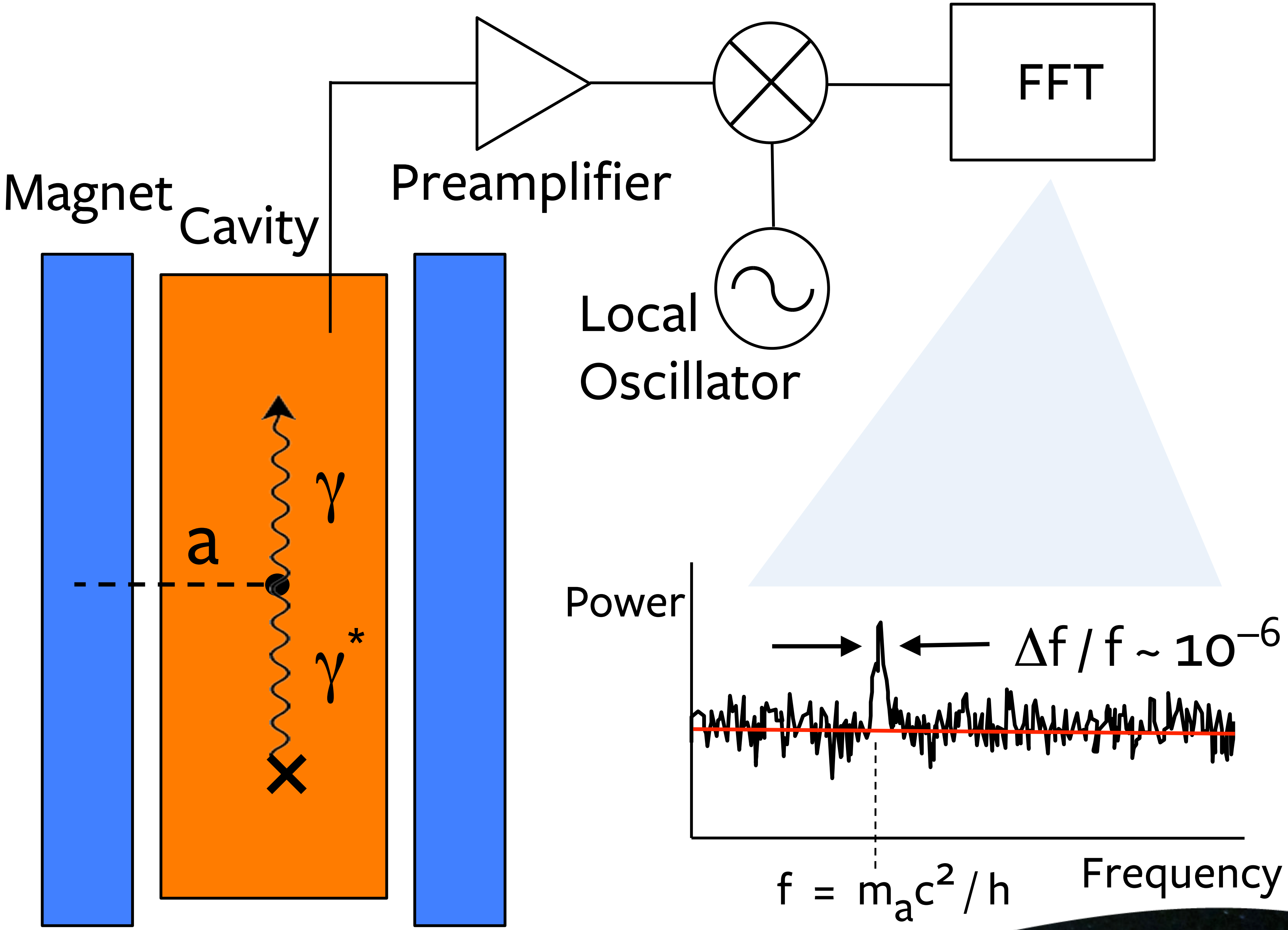
We are projecting an initial ×2.3 speed up for our Phase II run

Summary comments

- After the inaugural squeezed-vacuum state run, we will go to higher frequencies
- A large volume 6 - 12 GHz (25 - 50 μeV) cavity with high quality factor and form factor is being readied for late 2018
- R&D on tunable Photonic Band Gap resonators is ongoing to eliminate the forest of TE modes & thus mode-crossings
- R&D is beginning for single-quantum detection, both qubit- and Rydberg-atom based
- HAYSTAC has proven to be a nimble & effective platform

Backup Slides

The microwave cavity experiment



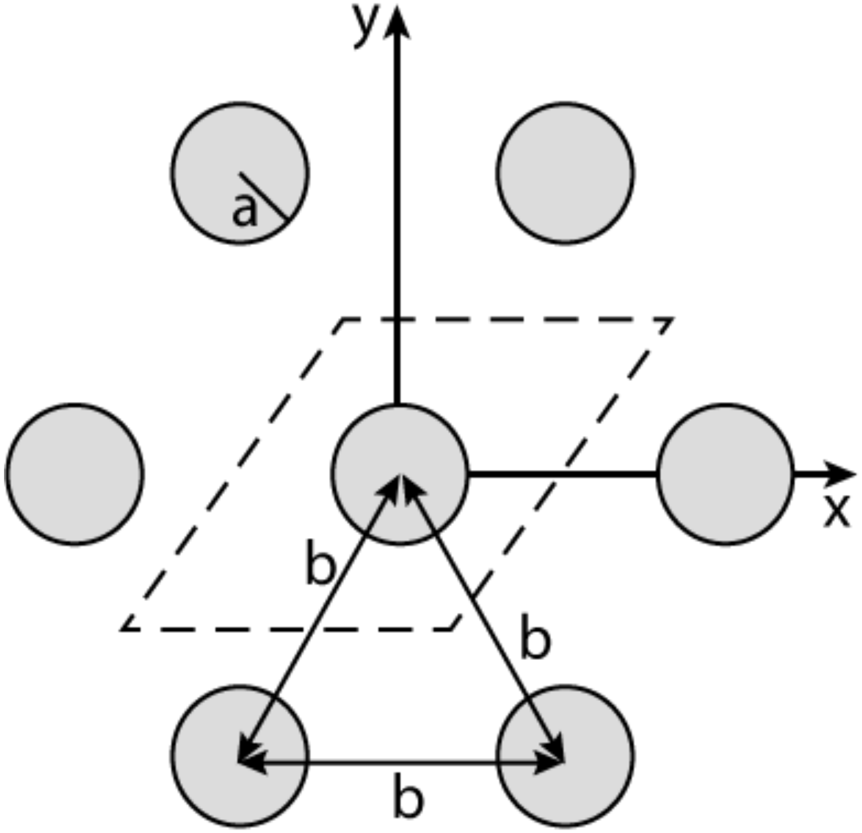
$\Delta f / f \sim 10^{-6}$

$f = m_a c^2 / h$

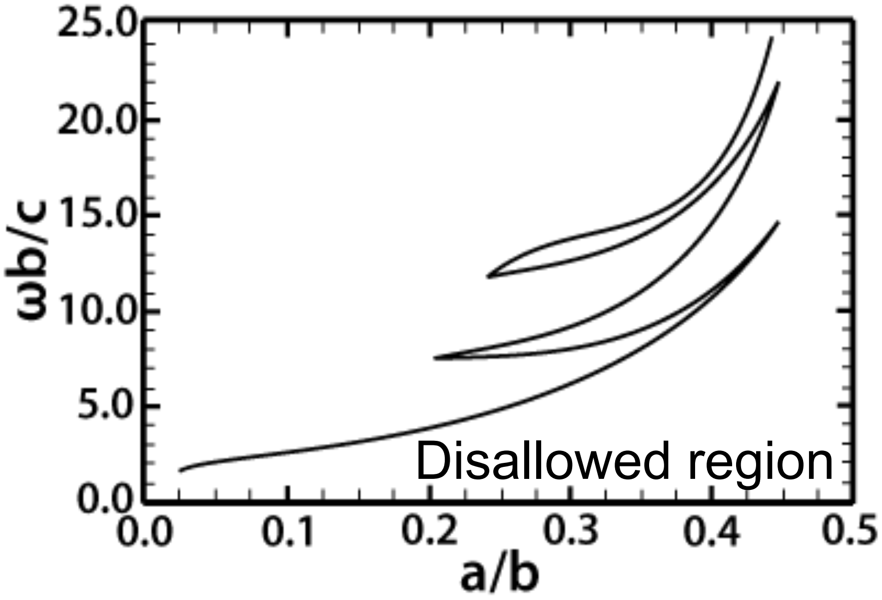
Photonic Band Gap Resonators

Photonic Band Gap Structures

- Periodic lattice of rods
- ‘Band gaps’ of modes which cannot propagate

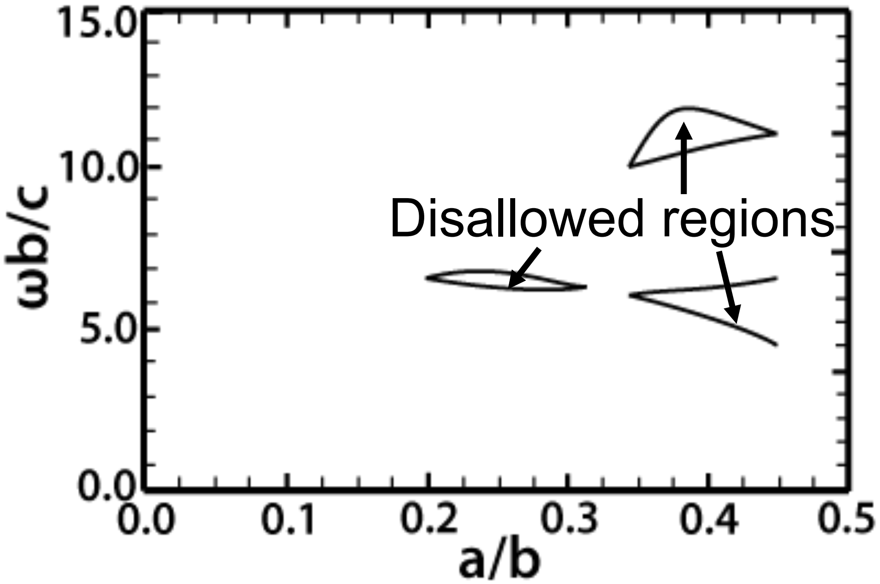


TM modes



Disallowed region

TE modes

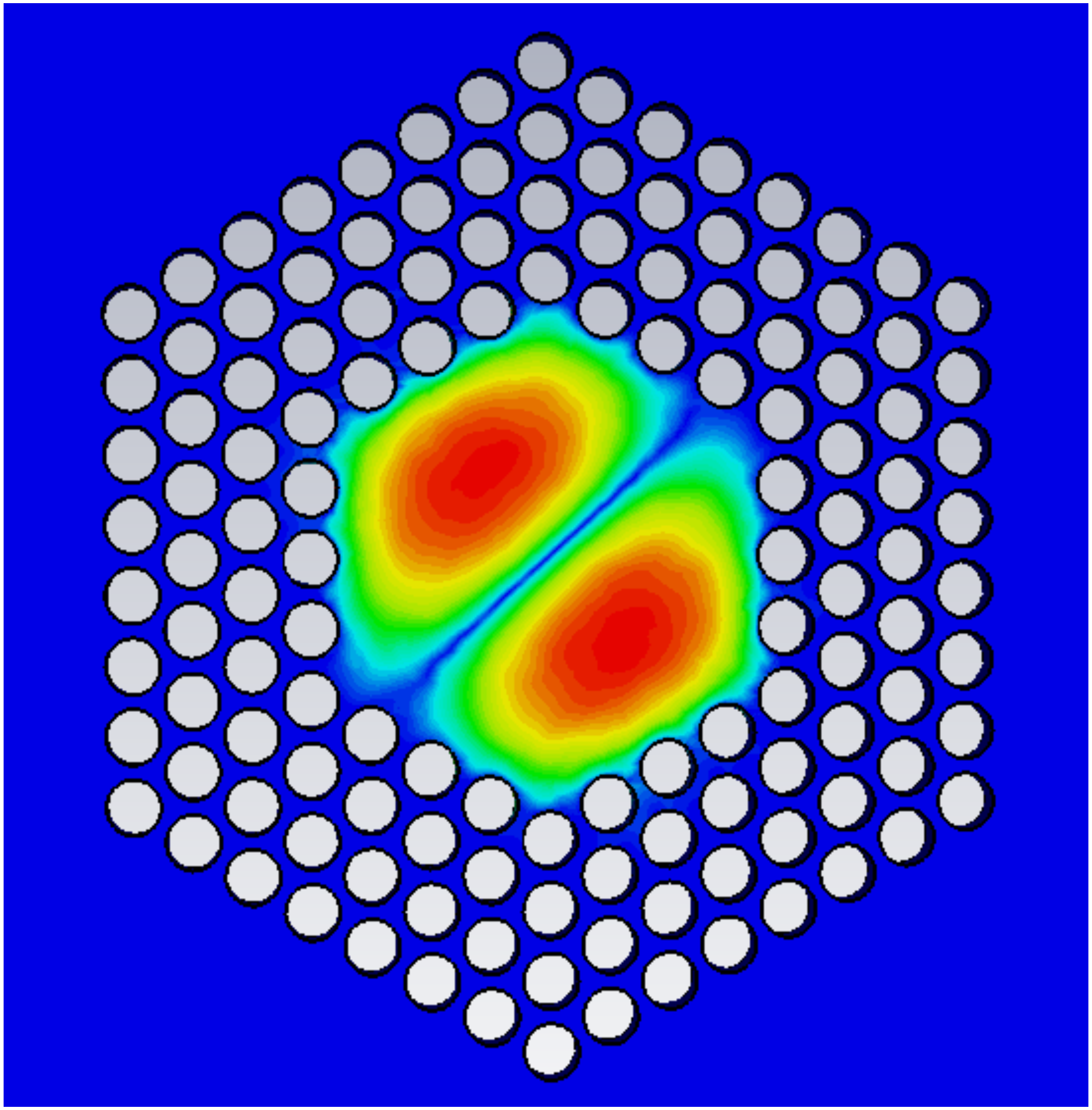


Disallowed regions

Adapted from: Smirnova, et al., *J. Appl. Phys.*, 2002

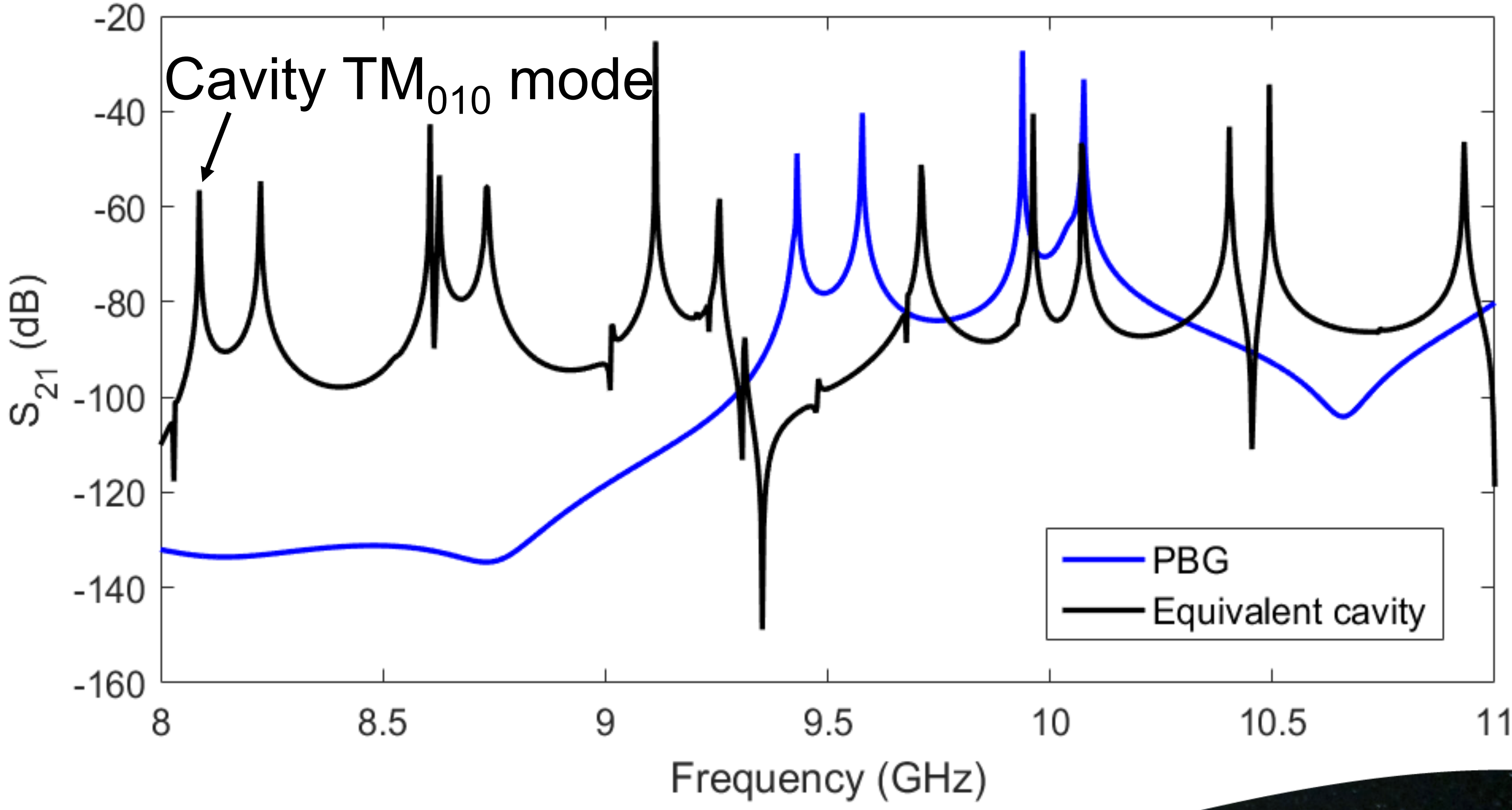
Photonic Band Gap Structures

- Resonator: defect in lattice confines disallowed modes
- All other modes propagate out
- Can have very high Q



Motivation

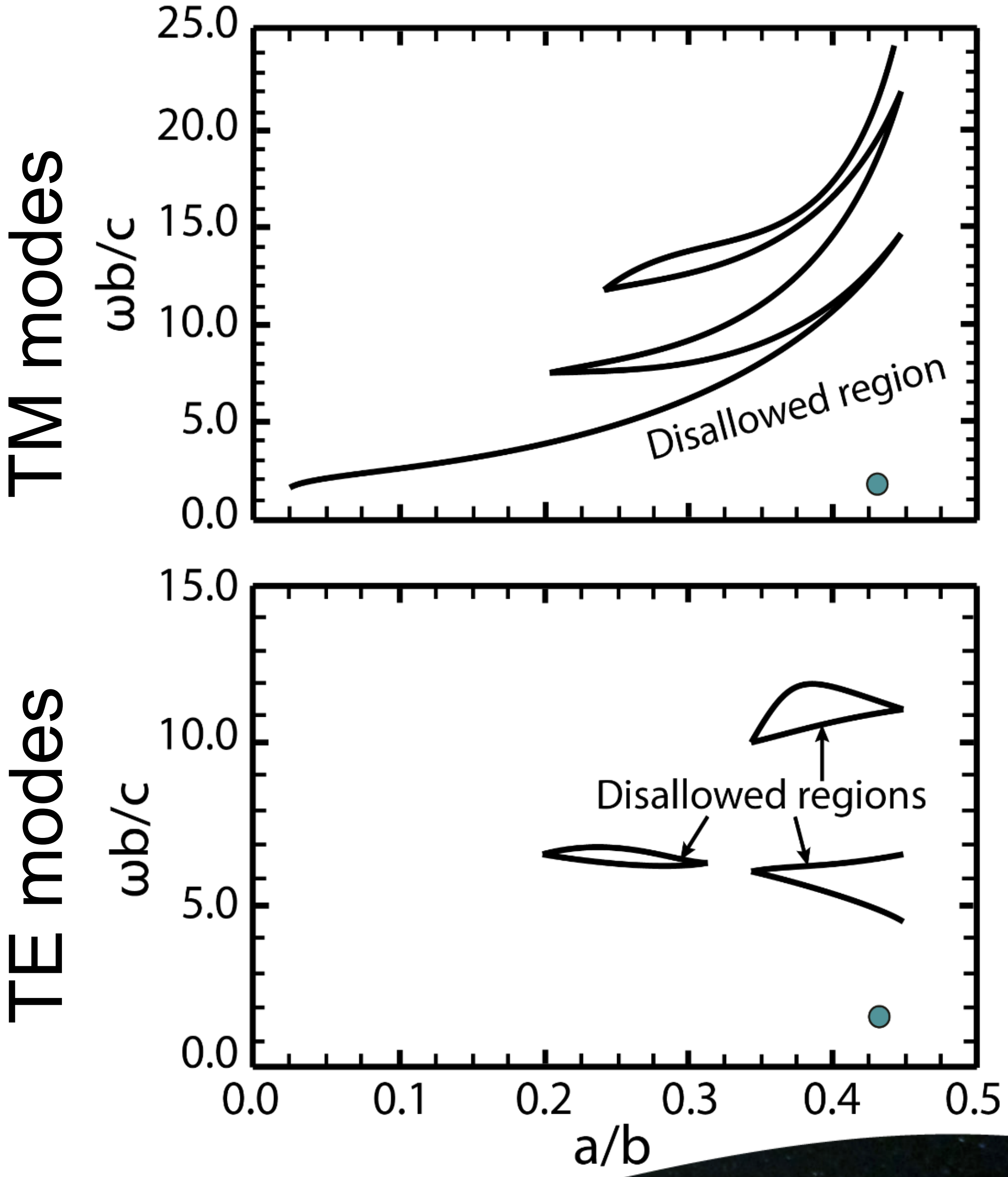
- TE modes don't tune, causing mode crossings
- PBG would confine TM modes while TE modes leak out

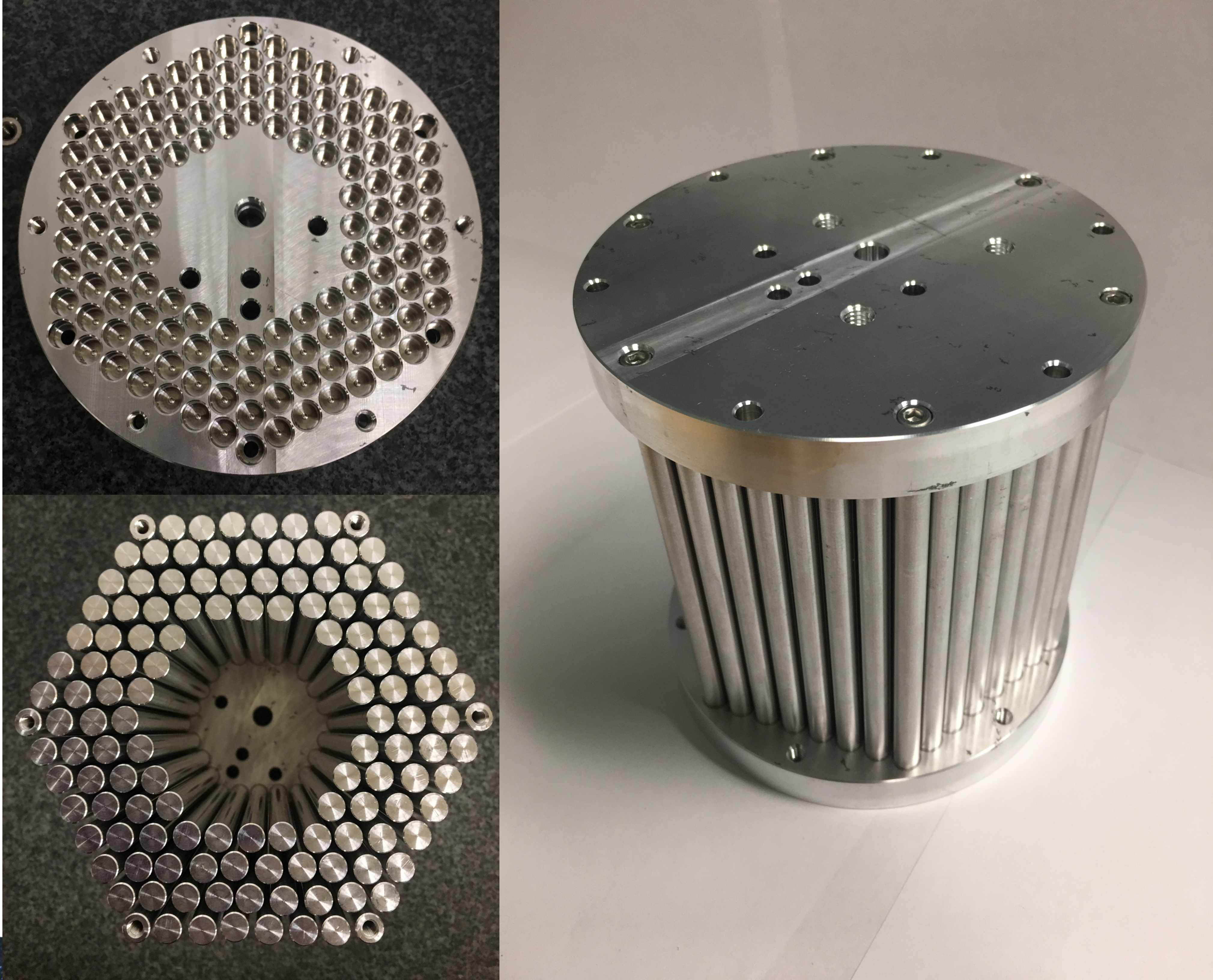


Prototype Design

Lattice parameters

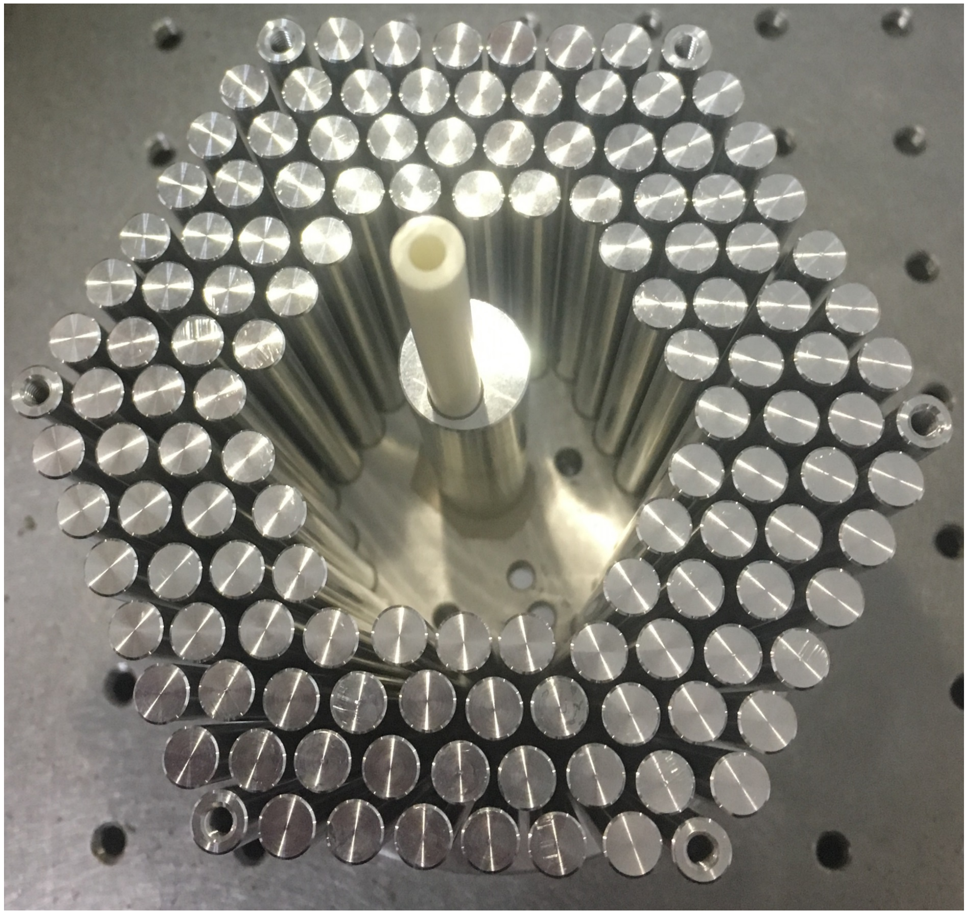
- Made from 7075 aluminum
- 10 cm length
- Quarter inch rods (3.175 mm)
- a/b = 0.43
- With tuning rod, tunes from 7.5 to 9.5 GHz

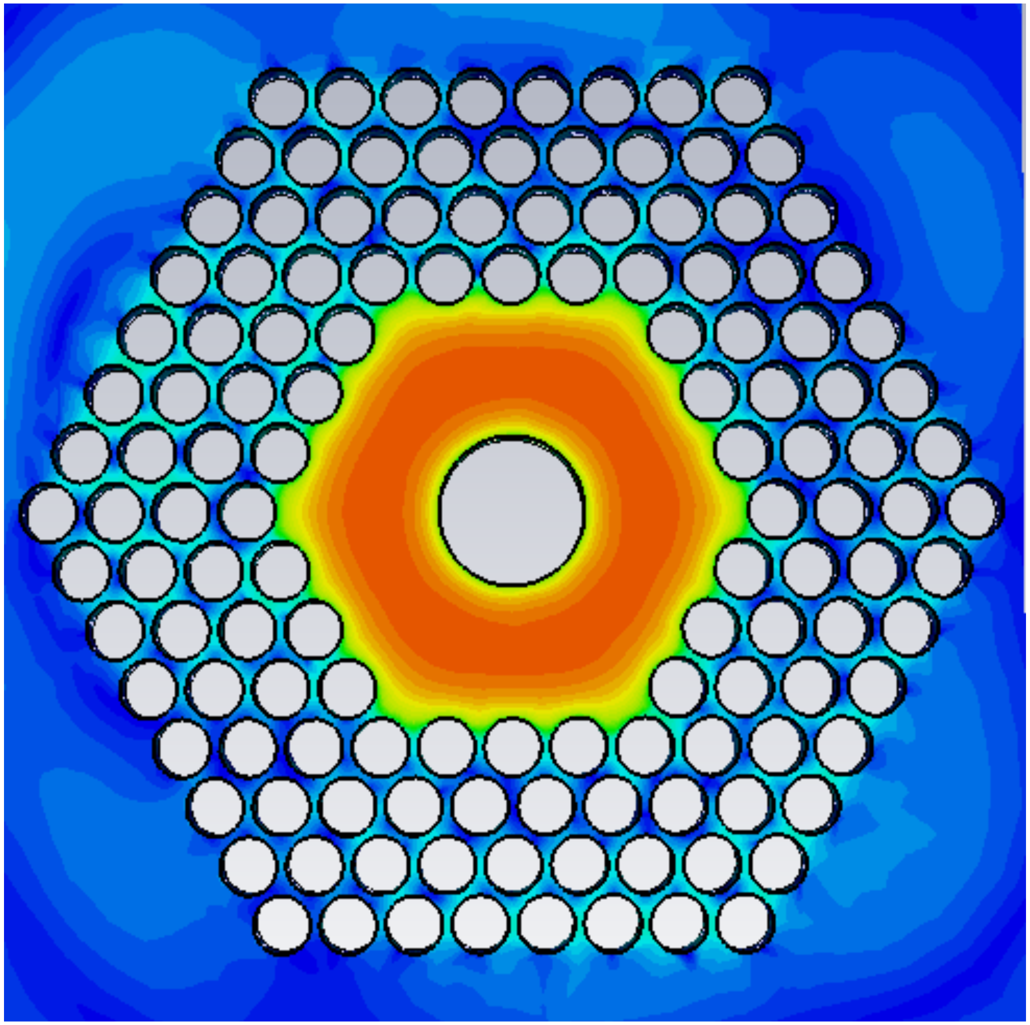




Tuning mechanism

- First test: single off-axis tuning rod
- Alumina axles





Fixed frequency results