Searching for Dark Matter Axions with Resonant Microwave Cavities

Troitsk, Russian Federation
July 24, 2018

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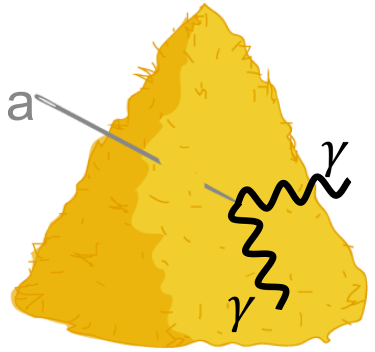

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Outline

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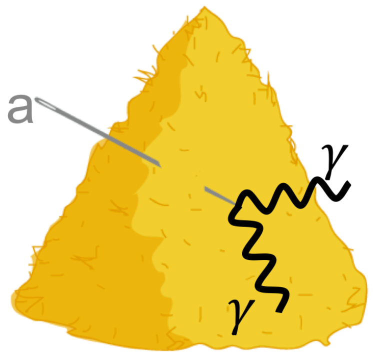
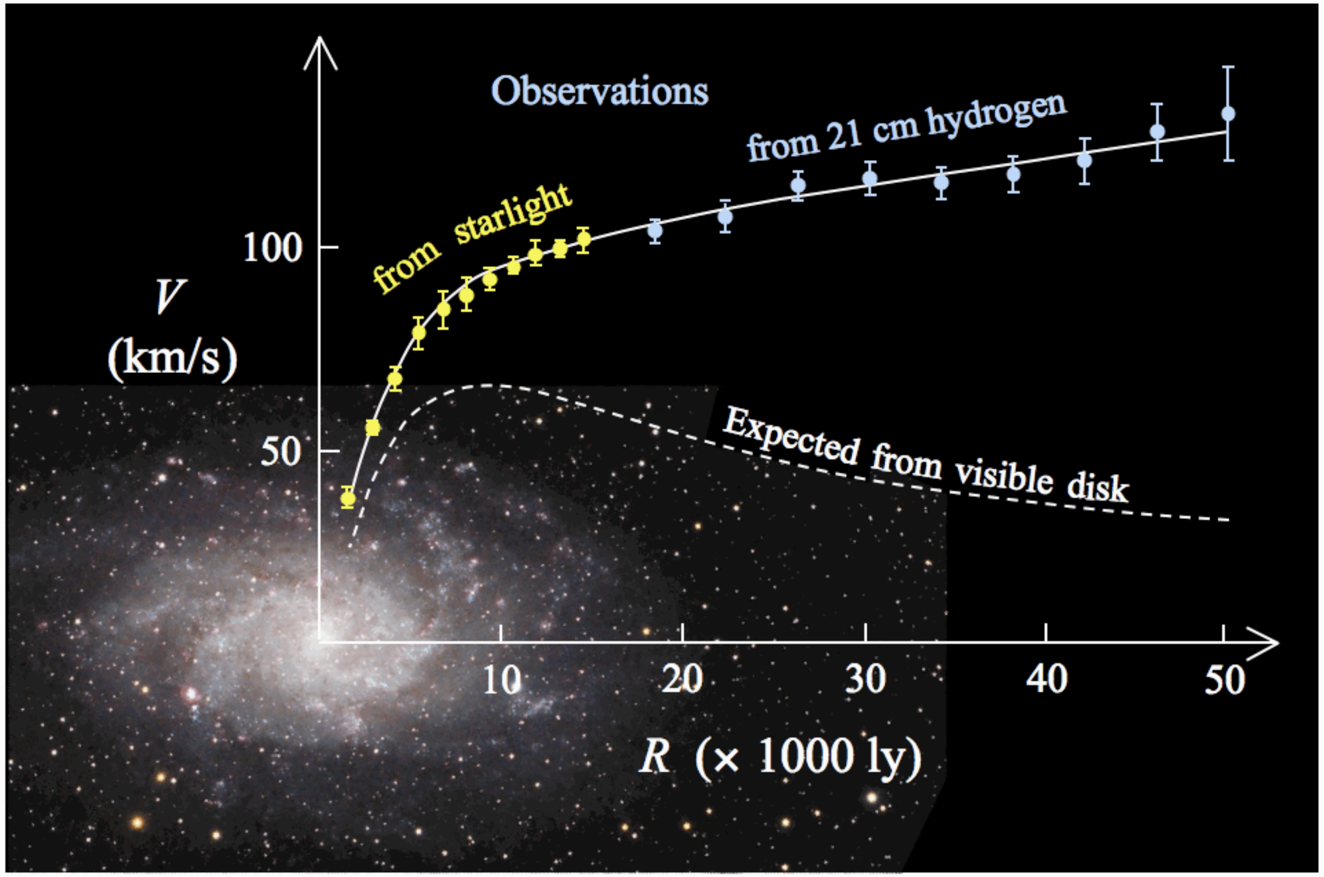
- Background: dark matter, strong charge-parity problem
- Description of axion detection
- Results of phase 1
- Plans for phase 2
- Future directions – research and development (R&D)



Mystery #1: Dark Matter

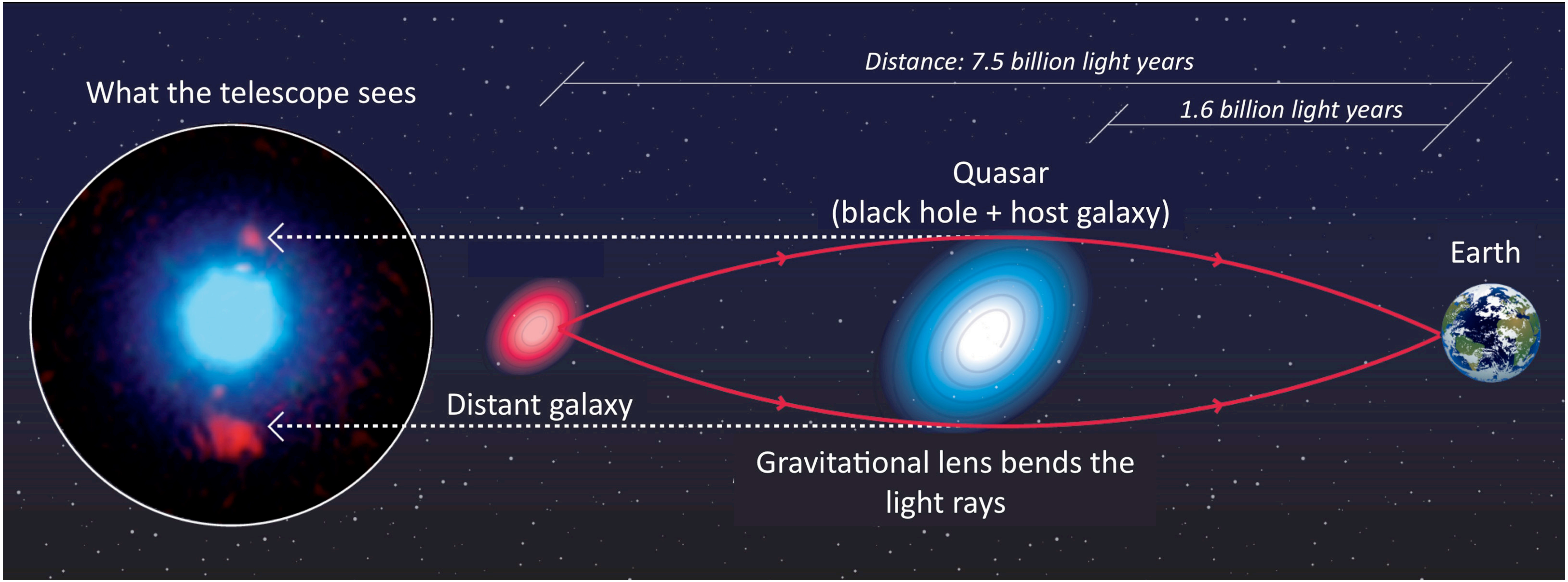
- Galaxy rotation curves



Force on mass m: $F = mv^2/r = GM(r)m/r^2 \implies v = \sqrt{GM(r)/r}$

Mystery #1: Dark Matter

- Gravitational lensing



Mystery #2: Strong CP Problem

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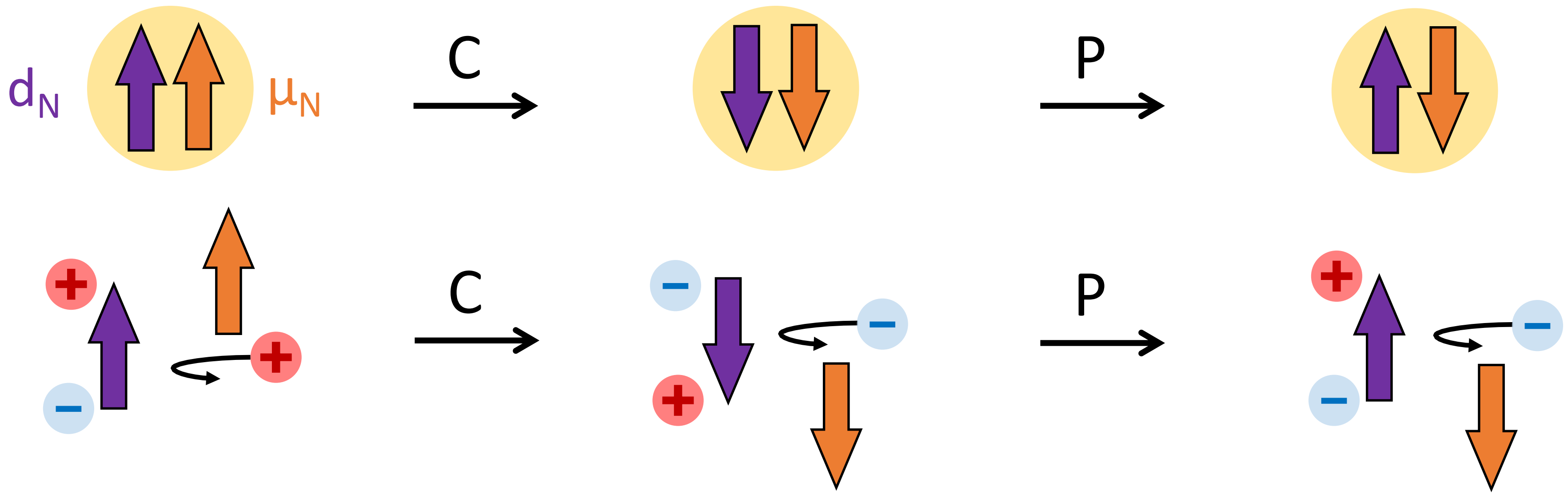
QCD Lagrangian includes a CP-symmetry-violating term $\mathcal{L}_{QCD} = \frac{g^2}{32\pi^2}\ \theta_{QCD}\ F_a^{\mu\nu}\ \tilde{F}_{\mu\nu a} + \cdots$

Standard Model of Particle Physics	Reality
CP symmetry is violated	No CP violation observed
Theory predicts nEDM: $d_N \sim 10^{-16}\ \theta_{QCD}\ e \cdot cm$	Experiments set limit on nEDM: $d_N < 3{\times}10^{-26}\ e \cdot cm$ [1]
$0 \leq \theta_{QCD} \leq 2\pi$	$\theta_{QCD} < 10^{-10}$



[1] J.M. Pendlebury *et al.*, PRD **92**, 092033 (2015).

Solution to the CP Problem

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QCD Lagrangian includes $\mathcal{L}_{QCD} = \frac{g^2}{32\pi^2}\,\theta_{QCD}\,F_a^{\mu\nu}\,\tilde{F}_{\mu\nu a} + \cdots$

Peccei and Quinn proposed dynamic variable $\theta_{QCD} = \frac{a}{f_a}$

Weinberg and Wilczek realized this leads to new pseudoscalar particle

PQWW symmetry breaking $f_a \sim f_{EW} \sim 250\ GeV$ (electroweak scale)

- Axions with $m_a \sim 100\ keV$ ruled out by experiments

Invisible axion $f_a \gg f_{EW}$

- Kim-Shifman-Vainshtein-Zakharov (KSVZ)
- Dine-Fisher-Srednicki-Zhitnisky (DFSZ)
- Great candidate for dark matter!

$$m_a \approx 6\ \mu eV \times \left(\frac{10^{12} GeV}{f_a}\right)$$

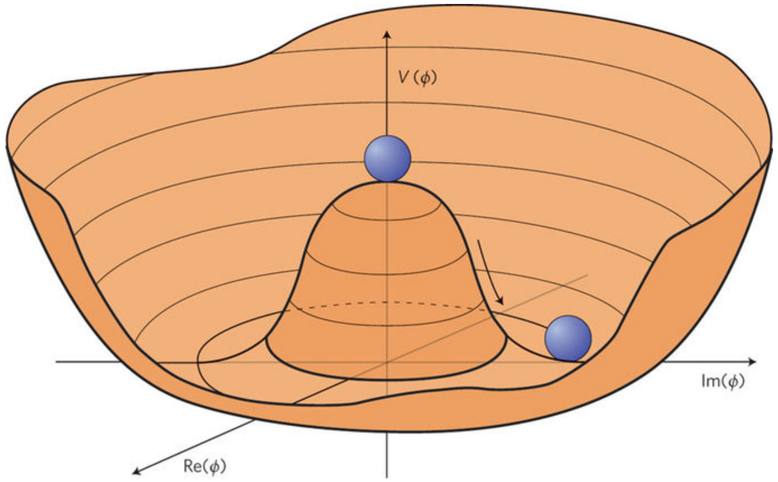


Figure from: L. Alvarez-Gaume and J. Ellis, Nature Phys. **7**, 2 (2011).

Axions will clean up the theoretical mess

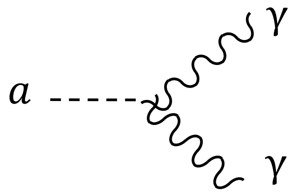
- Dark matter
- Strong CP problem

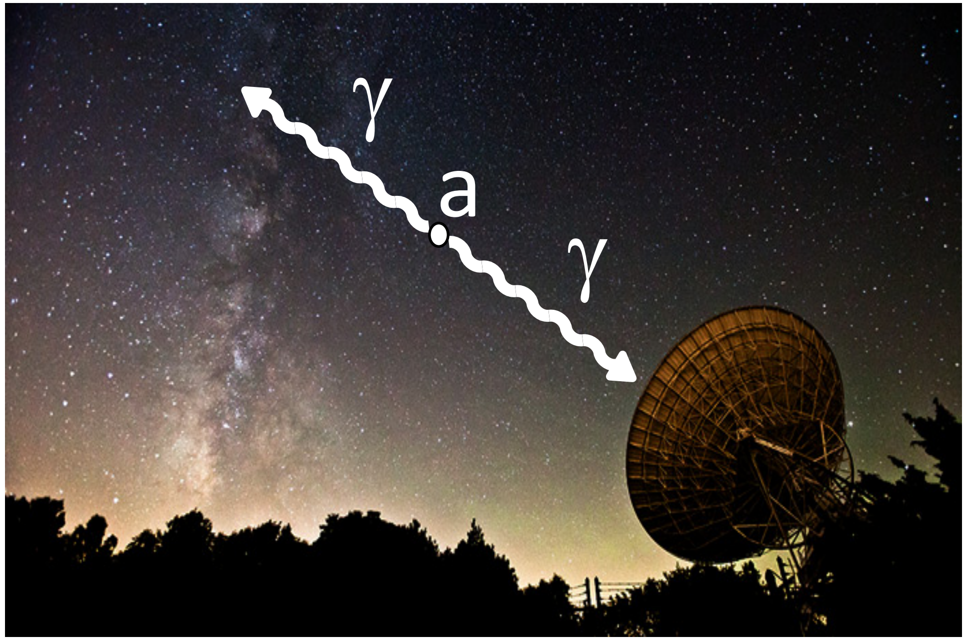
Axion interactions

Axions can interact with nucleons, electrons, photons

Couplings $\propto \frac{1}{f_a}$

Photon coupling





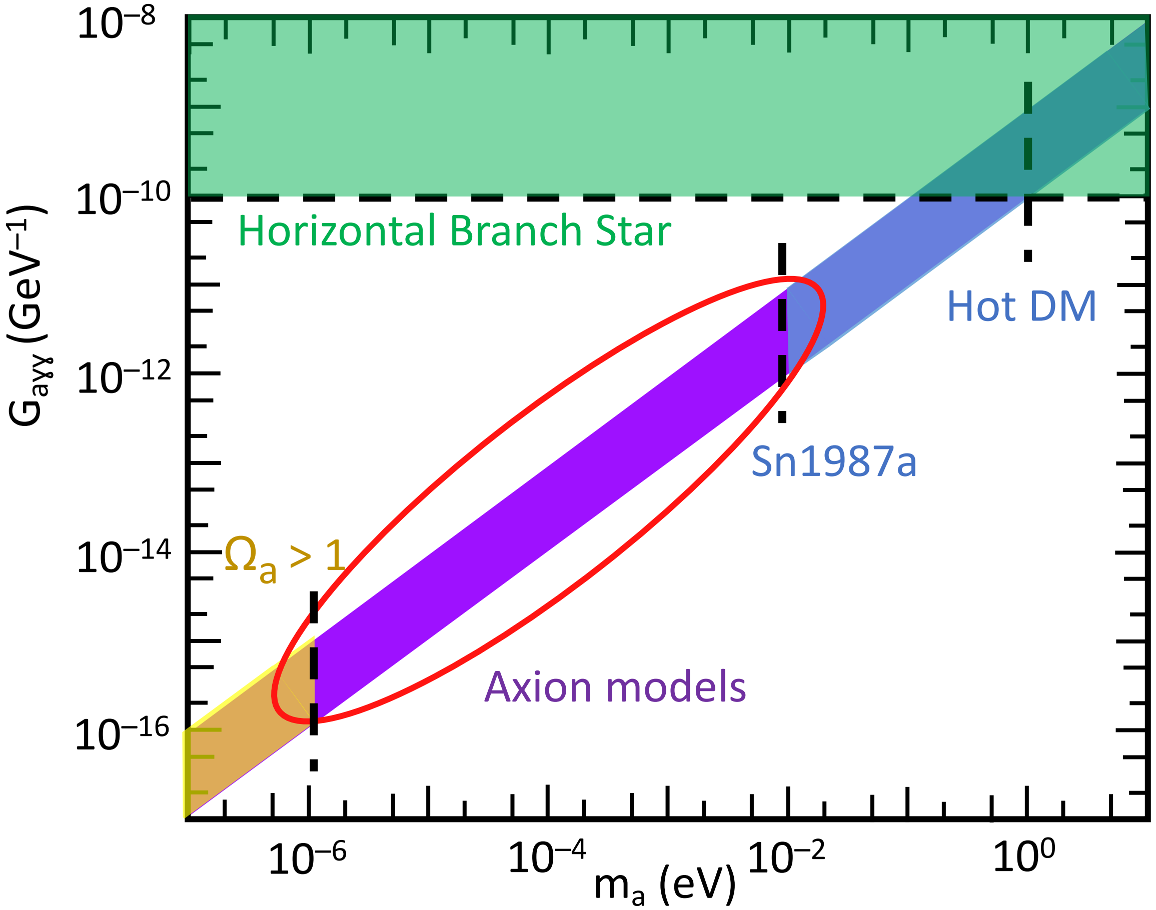
Axion lifetime

$$\tau_{a\rightarrow\gamma\gamma} \sim 10^{47}\ years \left(\frac{1}{g_\gamma}\right)^2 \left(\frac{\mu eV}{m_a}\right)^5$$

Age of universe $\sim 10^{10}\ years$

Pierre Sikivie proposed using resonant cavities to enhance the signal, making the axions possible to detect

Axion parameter space



Light cousin of π^0: $J^{\pi} = 0^-$

Couplings **α** Axion mass

Horizontal branch star

Too much hot dark matter if $m_a > 10^0\ eV$

Axion production quenches neutrino pulse from SN1987a for $10^{-2} < m_a < 10^4\ eV$

Total density **α** $(\text{mass})^{-7/6}$ Too much cold dark matter if $m_a < 10^{-6}\ eV$

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Team HAYSTAC

JILA / CU Boulder
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Daniel Palken
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William F. Kindel

Yale (experiment is here!)
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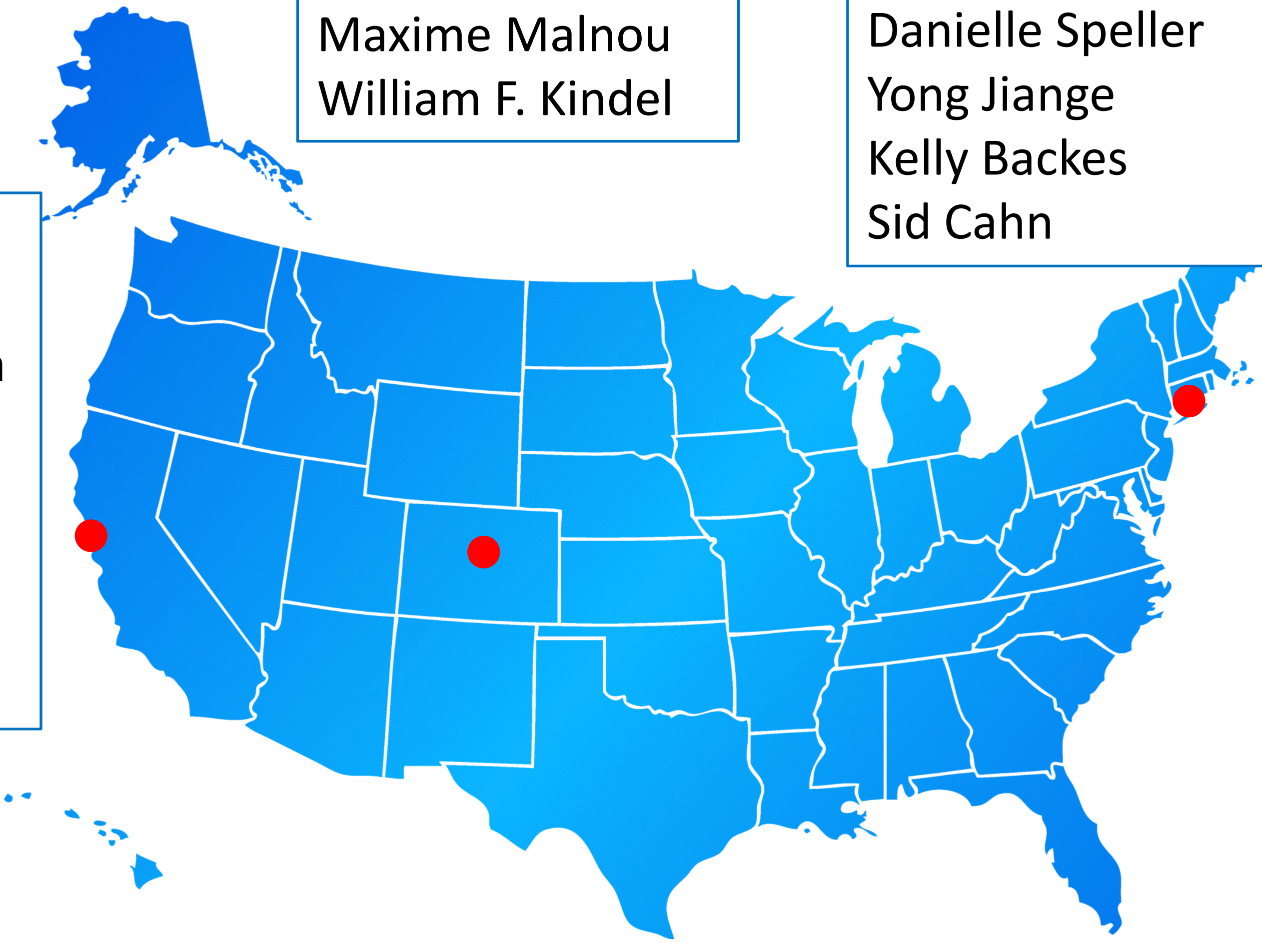
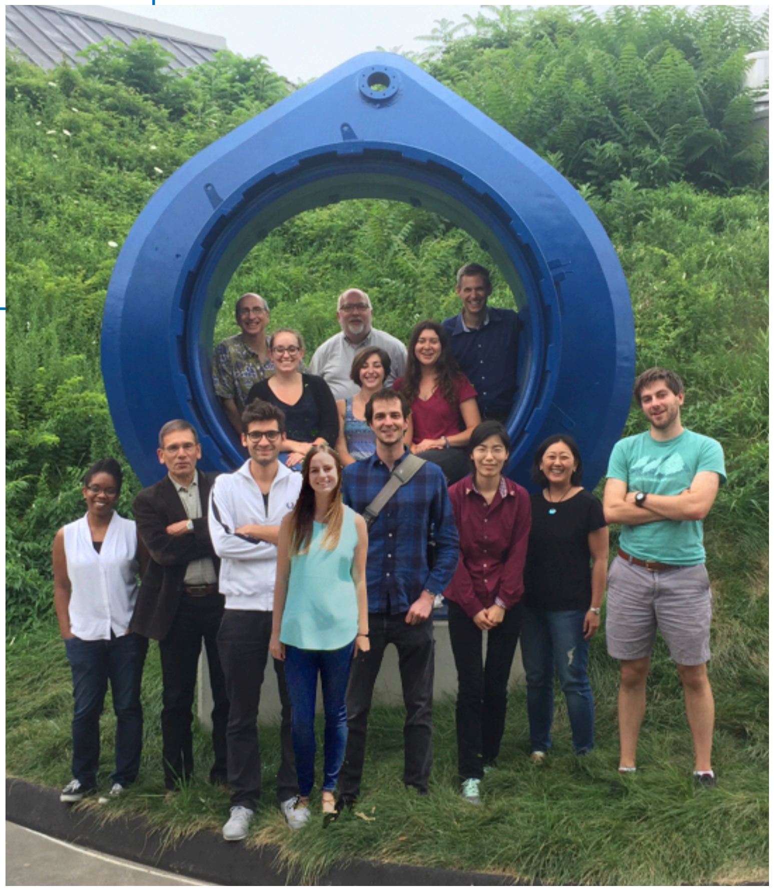
Saad Al Kenany
Isabella Urdinaran
Nicholas Rapidis
Alex Droster





Axion detection - haloscope

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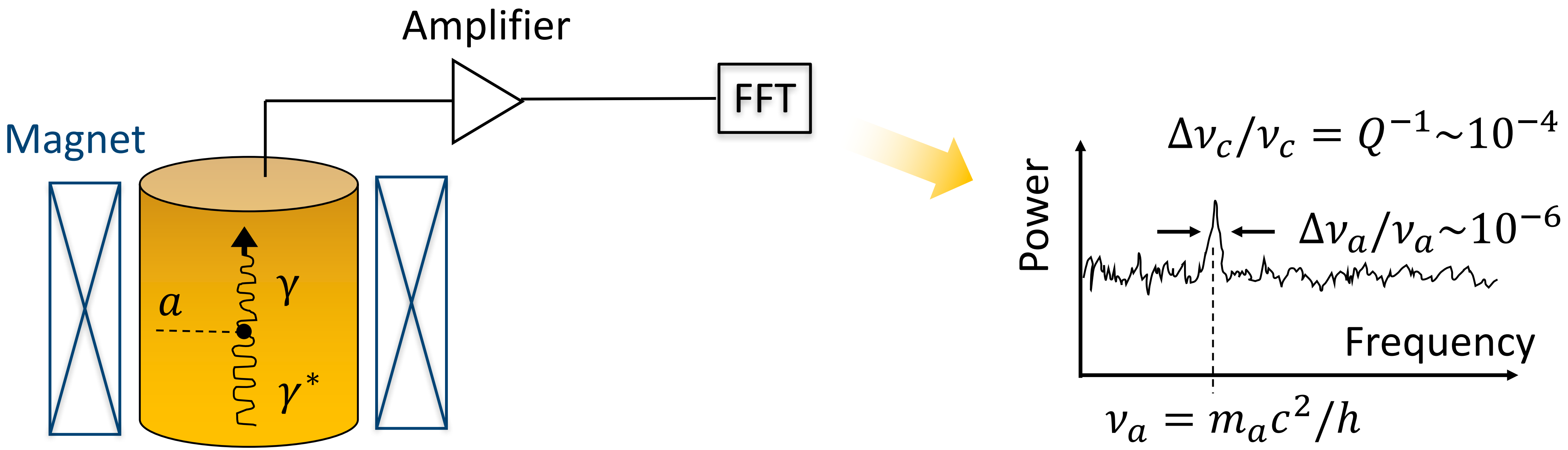

Cavity

$$h\nu = m_a c^2$$

Conversion Power:

$$P \sim 10^{-24}\, W \underbrace{\left(\frac{g_{a\gamma\gamma}}{10^{-24}/\, eV}\right)^2 \left(\frac{\rho_a}{.45\; GeV/cm^3}\right)\left(\frac{10^{-5}\; eV}{m_a}\right)}_{\text{Theory parameters}} \left(\frac{B_{ext}}{9\; T}\right)^2 \left(\frac{Q}{10^4}\right)\left(\frac{V}{1.5\; L}\right)\left(\frac{C_{nml}}{0.5}\right)$$

Axion detection - haloscope

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

SQL: $k_B T_S = h\nu$

Quantum noise

System noise temperature $k_B T_S = h\nu N_{SYS} = h\nu\left(\frac{1}{\exp\left(\frac{h\nu}{k_B T}\right)-1} + \frac{1}{2} + N_A\right)$

Added noise $N_A \geq \frac{1}{2}$

Thermal noise

Scan rate:

$$\frac{d\nu}{dt} \sim 40\ \frac{MHz}{year}\ \frac{\zeta}{.7}\ \frac{Q_L}{10^4}\ \frac{Q_a}{10^6}\left(\left(\frac{g_{a\gamma}}{g_{a\gamma}^{KSVZ}}\right)^2 \frac{\rho_a}{0.45\ GeV/cm^3}\right)^2 \left(\frac{\beta/2}{1+\beta/2}\left(\frac{B_0}{9\ T}\right)^2 \frac{V}{1.5\ L}\ \frac{C_{mnl}}{0.5}\ \frac{2}{N_{SYS}}\right)^2$$

Theory parameters

$\beta = \frac{unloaded\ Q\ (Q_0)}{coupling\ to\ reciever\ (Q_r)}$ and $\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_r}$

ζ: quantifies dead time during data run

History of Haloscopes

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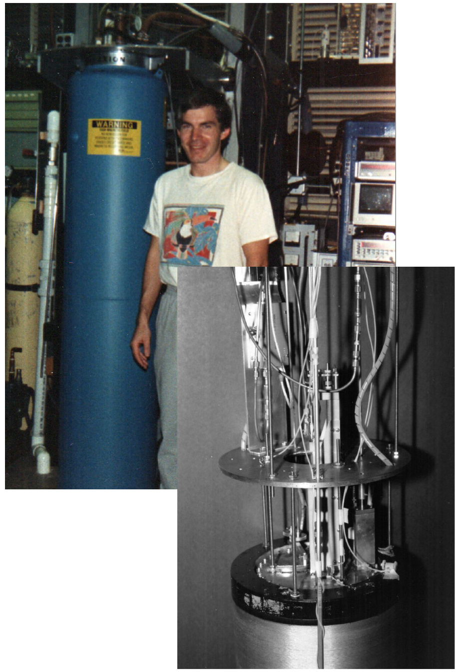
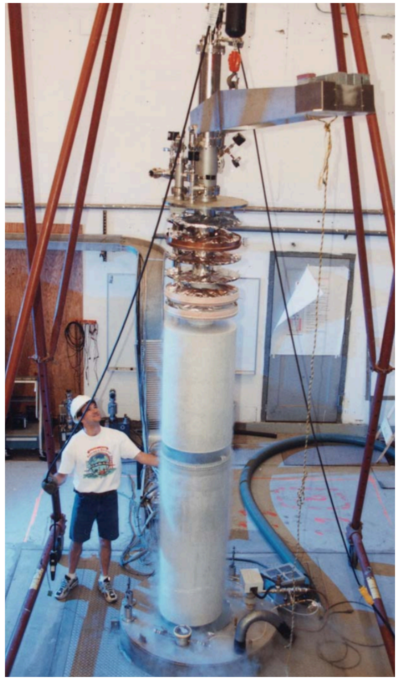
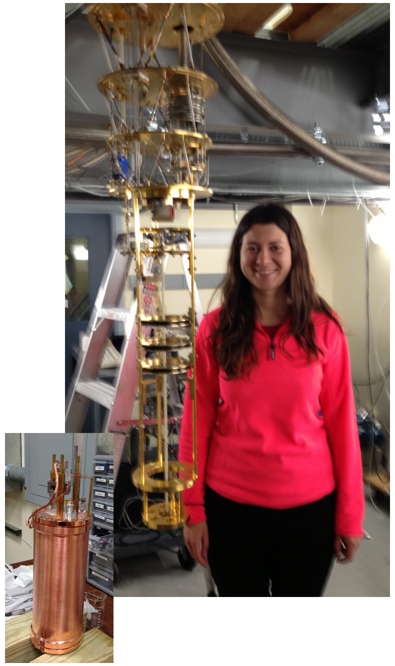


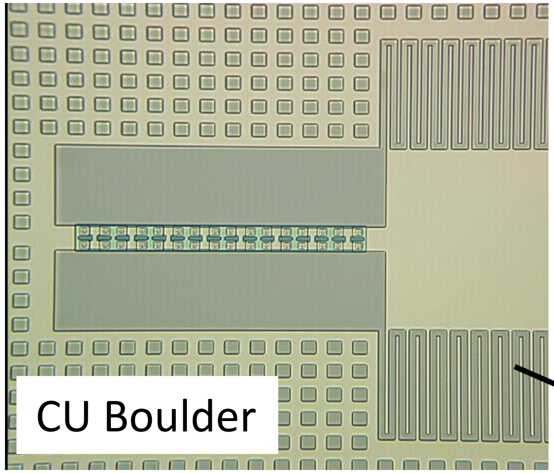




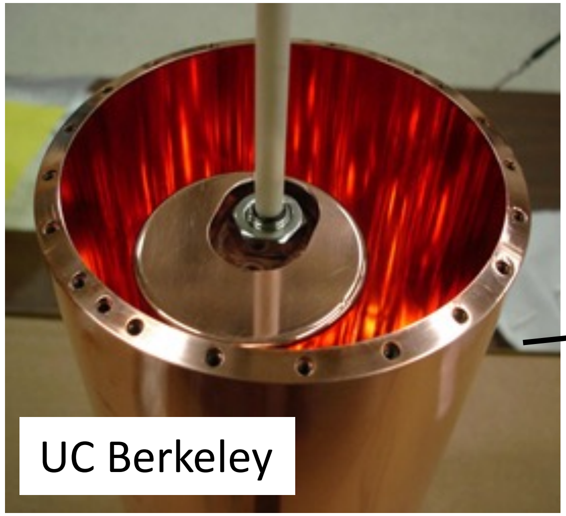
UF / RBF	ADMX @ LLNL	ADMX @ UW	HAYSTAC
1985 – 1990	1995 – 2010	2016 – present	2015 – present
HEMT	HEMT, SQUID	SQUID + dil. fridge	JPA + dil. fridge
$\nu \sim 2.5\ GHz$	$\sim 0.5\ GHz$	$\sim 0.5\ GHz$	$\sim 6\ GHz$
$V \sim 5\ L$	$\sim 200\ L$	$\sim 150\ L$	$\sim 1.5\ L$
$T_{SYS} \sim 5 - 20\ K$	$\sim 3\ K$	$\sim 500\ mK$	$\sim 600\ mK$
$T_{SYS}/T_{SQL} \sim 100 - 200$	$\sim 50 - 100$	~ 10	~ 2

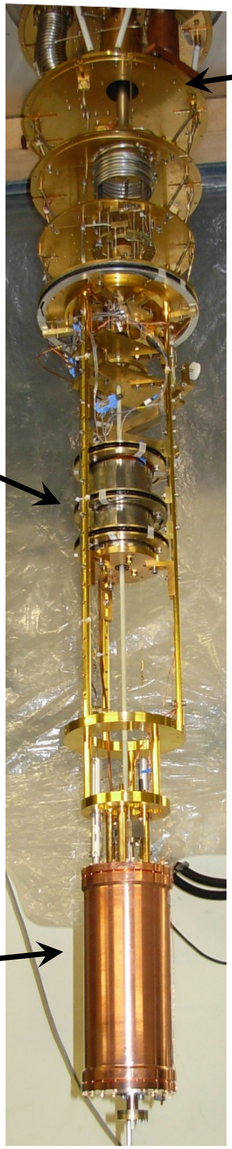
HAYSTAC experiment at Yale

Josephson Parametric Amplifier



Microwave Cavity (copper)



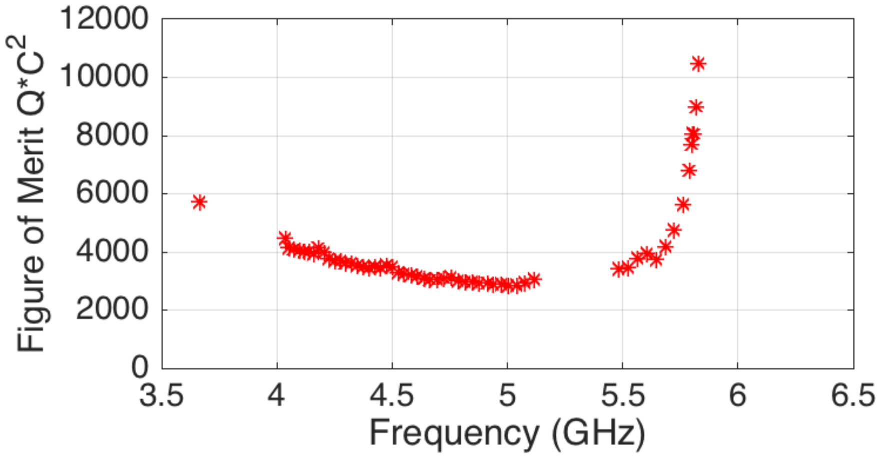


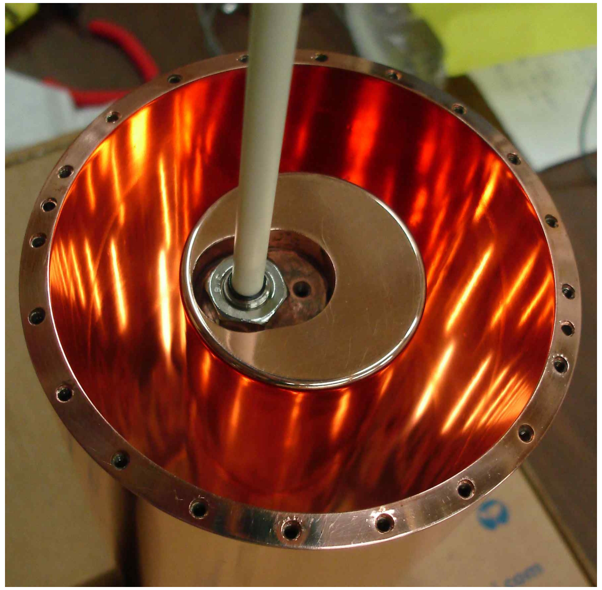
$^3He/^4He$ Dilution Refrigerator

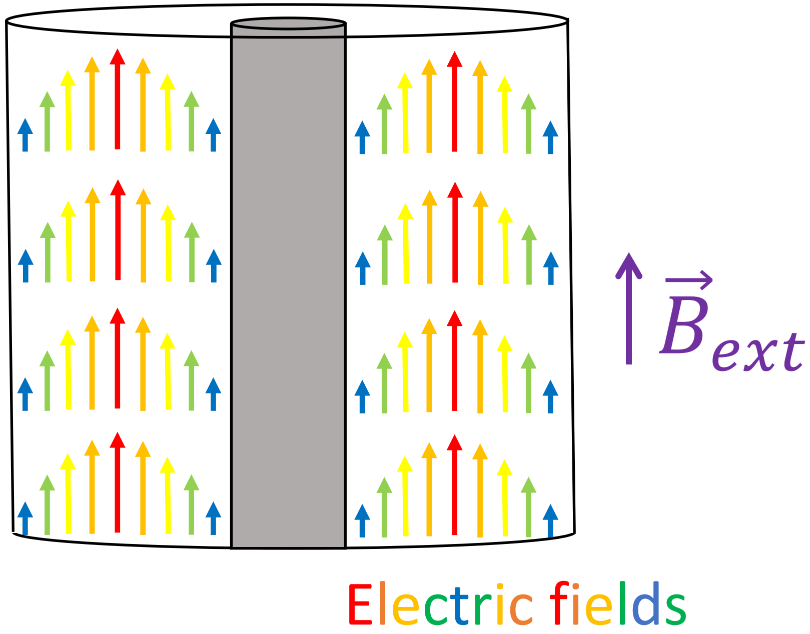
9.4 Tesla, 10 Liter Magnet

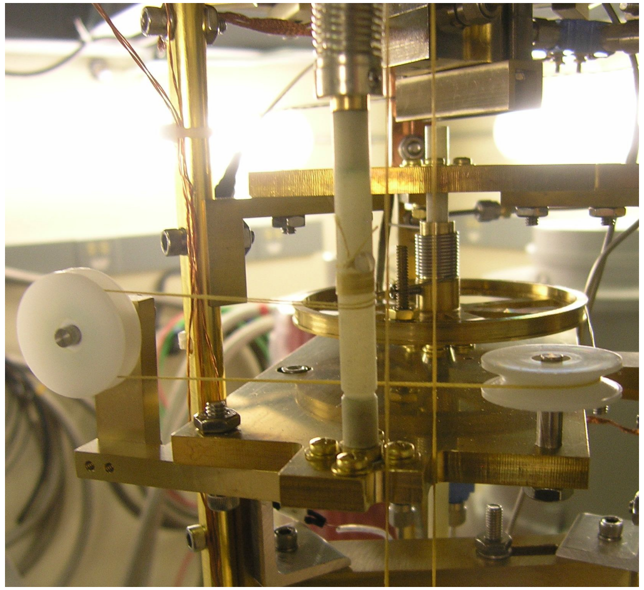
Microwave Cavity

- Cu body with off-axis tuning rod
- Tunable over 3.6 – 5.8 GHz
- Q_C ~ 20,000
- Piezo electric motor used for tuning rod motion









Josephson Parametric Amplifiers

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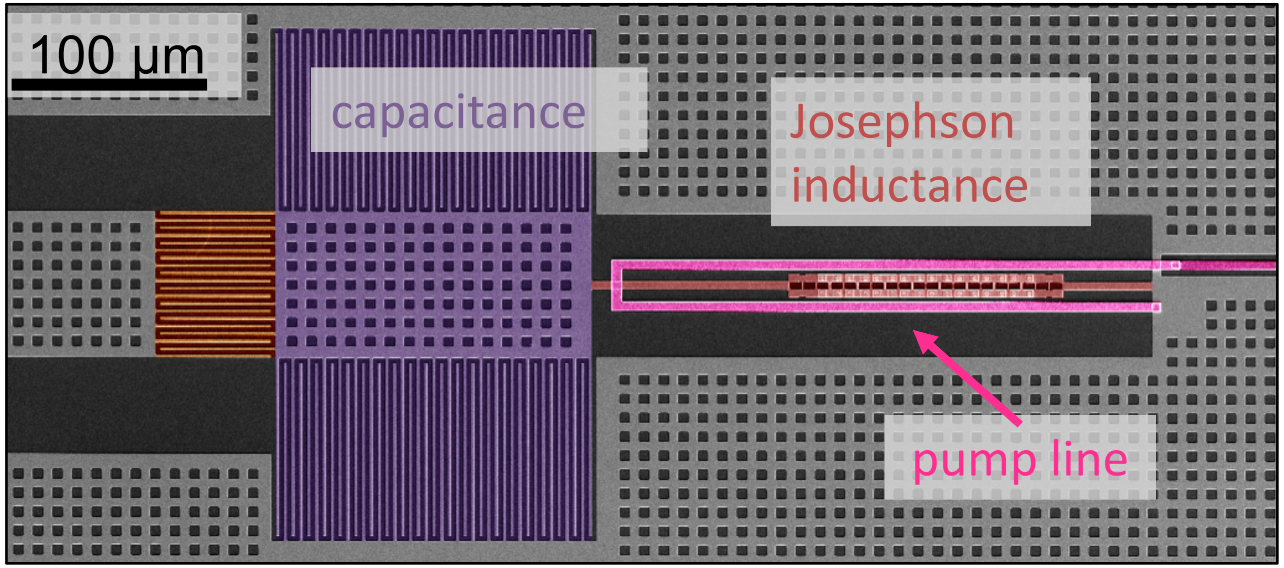
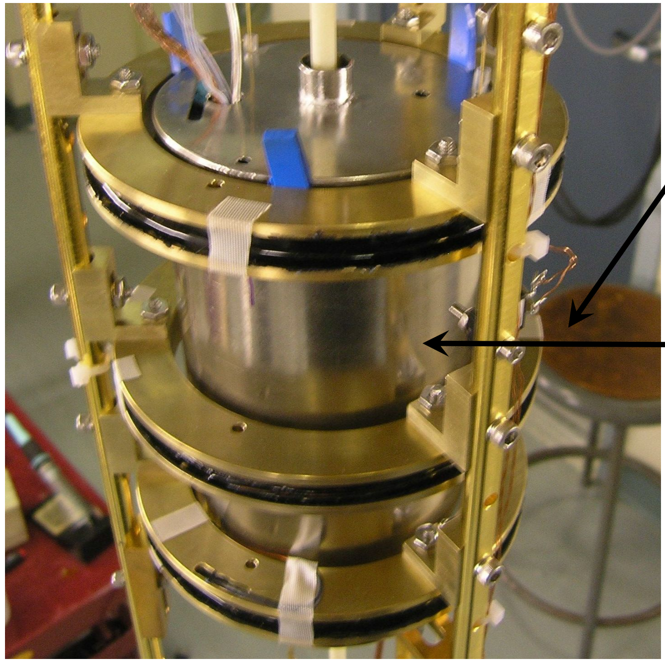
- Composed of SQUIDs
- Tunable
- Require magnetic field-free environment

JPA: tunable LC circuit

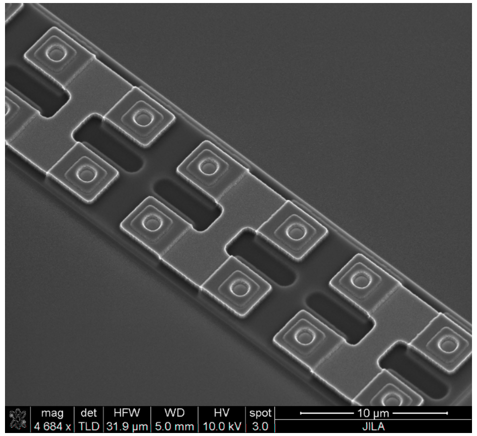


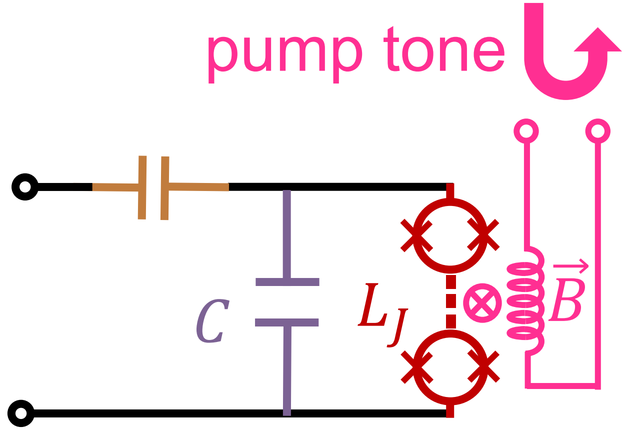


Persistent coils for field cancellation

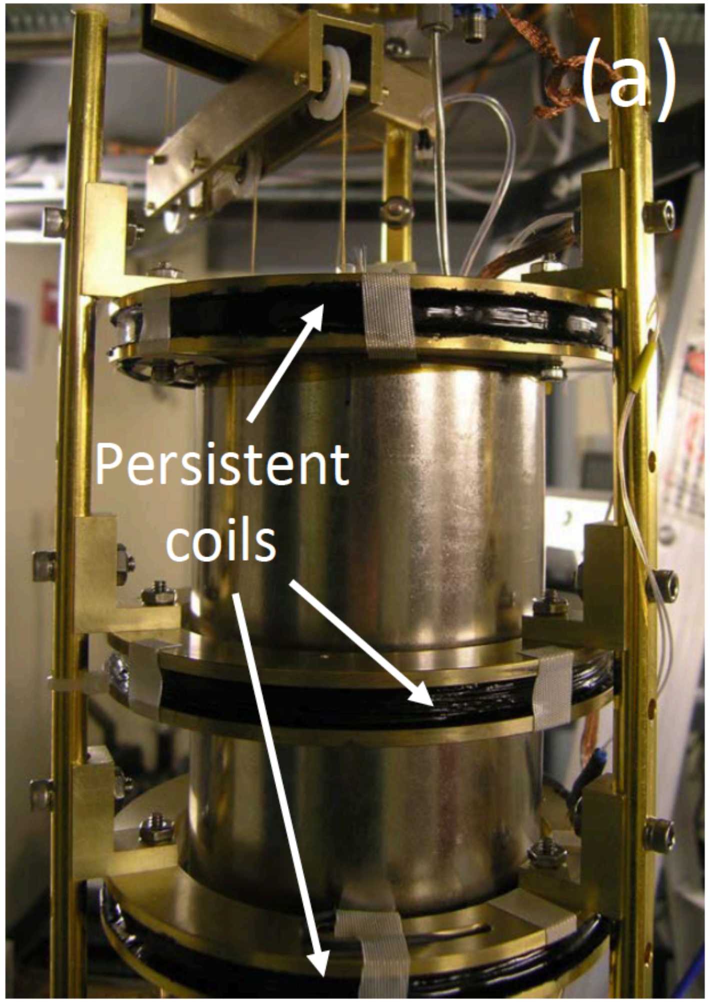
Double wall cryoperm with superconducting Pb foil inside

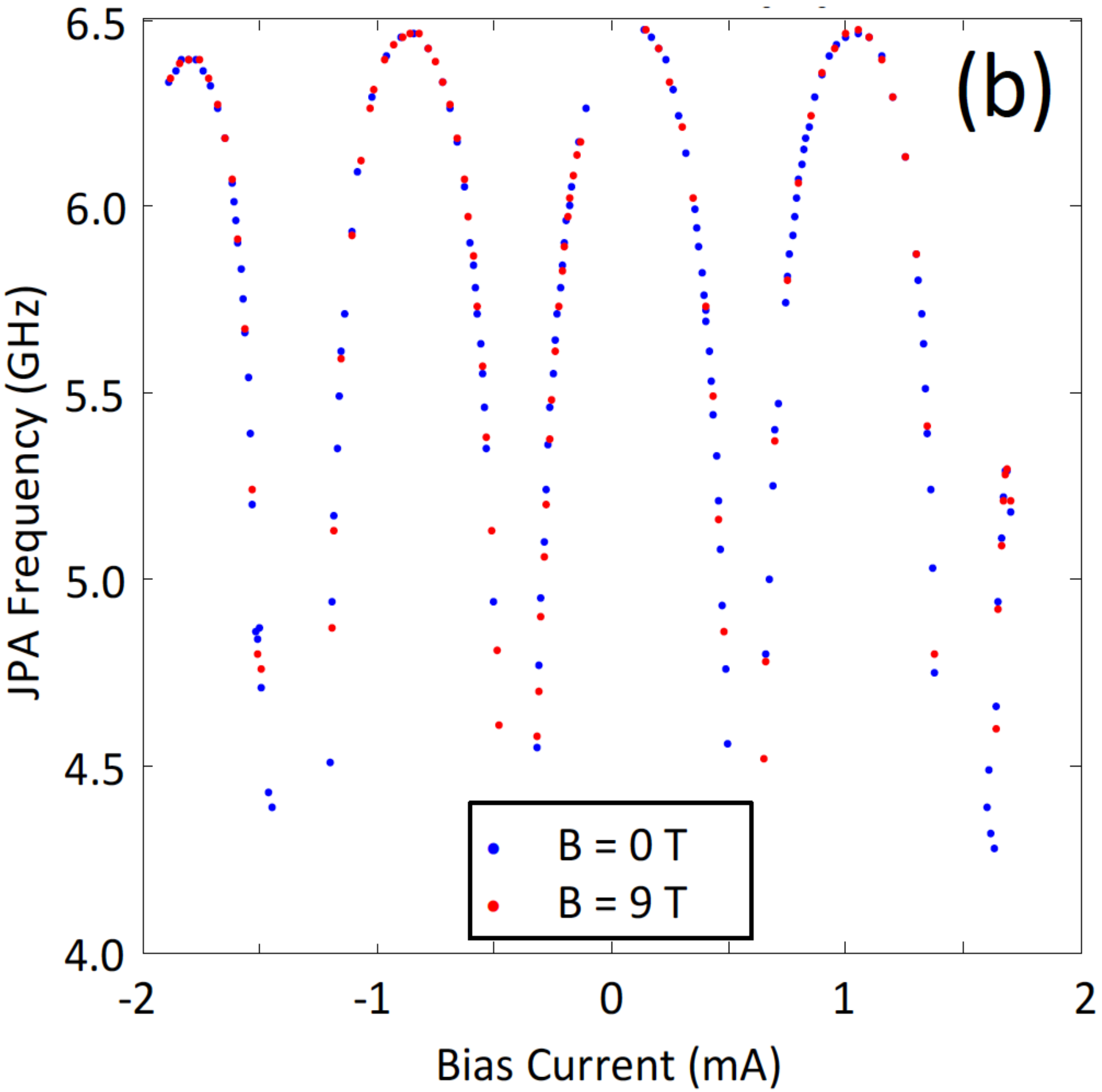
+ magnetic compensation coil





JPA magnetic shielding system efficacy





Field at JPA changes < 0.01 flux quantum as the magnet is ramped.

Project Timeline

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- 2012 — Start of construction
- 2013
- 2014 — Integration
- 2015 — Commissioning run
- 2016 — First data run
- 2017 — Second data run
- 2018 — Phase 1 results published
  - m_a ~ 24.0 μeV
  - T_{SYS} ~ 2 T_{SQL}
  - $g_{a\gamma\gamma}$ ~ 2.7 KSVZ
- 2018 — Start of phase 2

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Data from phase 1

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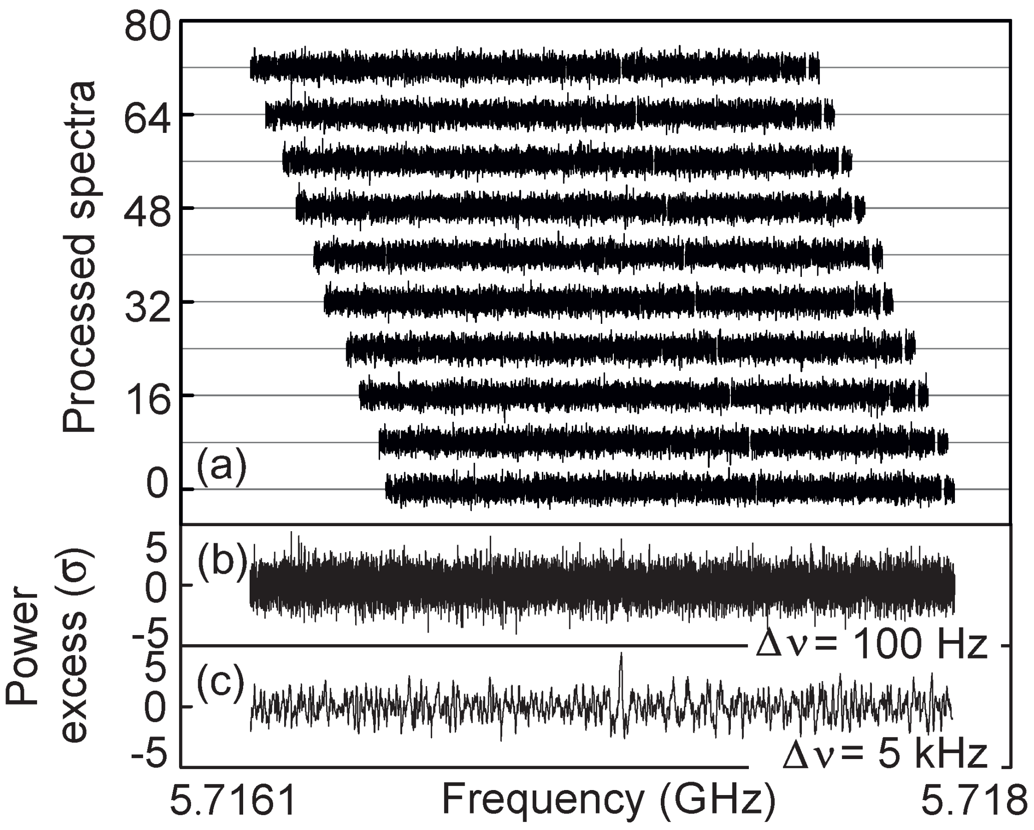
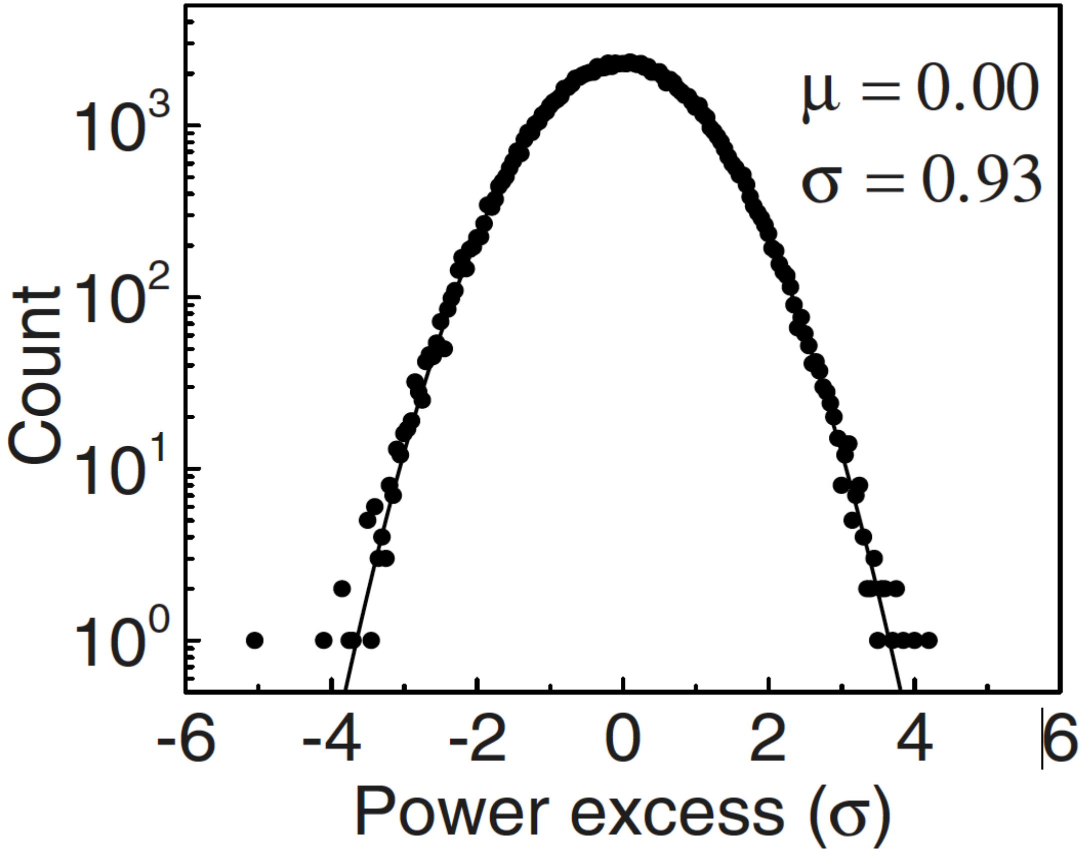
Grand spectrum construction



Power excess histogram



Results from phase 1: no axion yet

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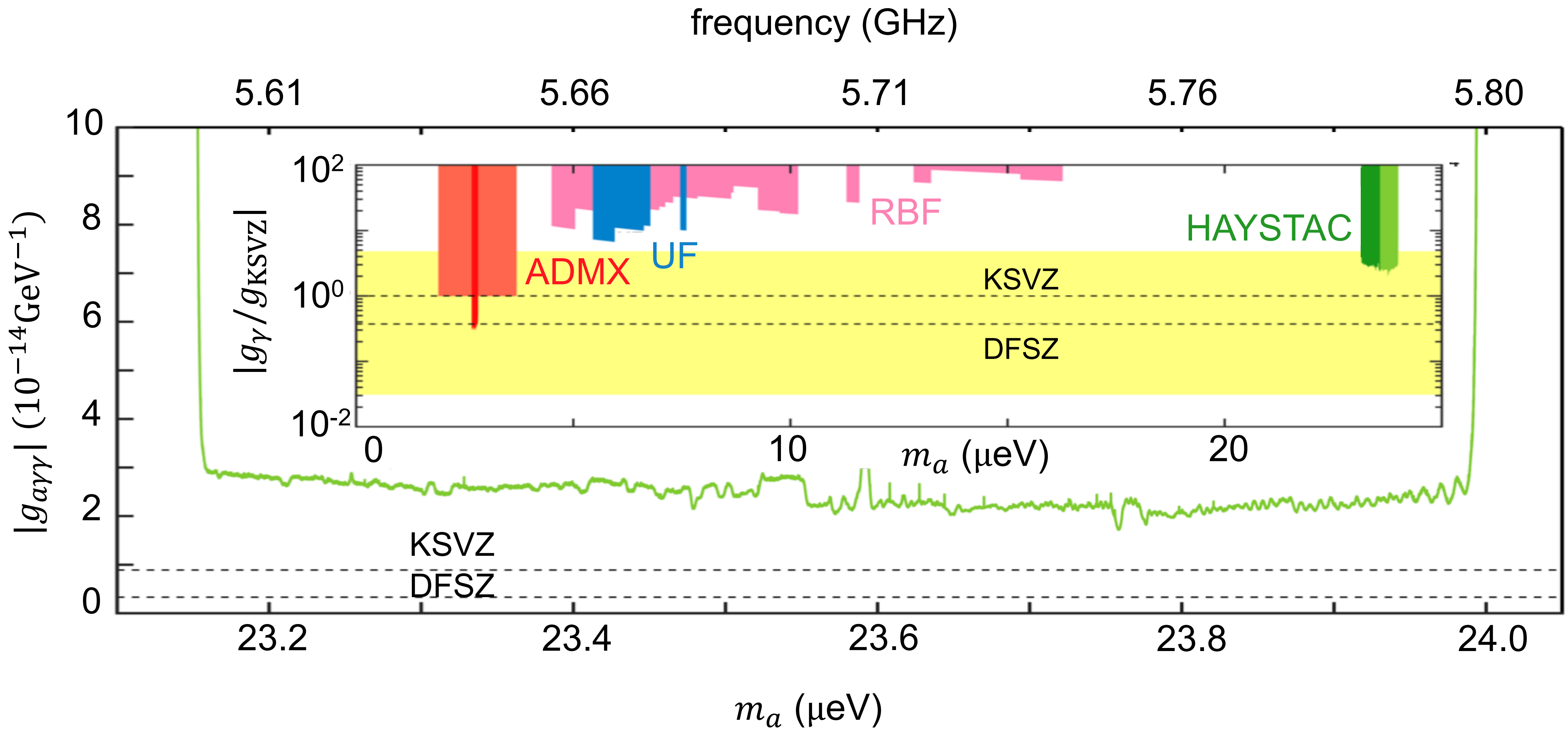

L. Zhong *et al.*, Phys. Rev. D 97 (2018) 092001.

Outline

HAYSTAC

- Background: dark matter, strong charge-parity problem
- Description of our detector
- Results of phase 1
- **Plans for phase 2**
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Phase 2: circumvent SQL

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In Phase 1, we were near-quantum-limited.

Magnet

Scan rate: $\frac{d\nu}{dt} \propto \underbrace{Q\mathrm{V}^2\mathrm{C}_{\mathrm{nml}}^2}_{\text{Cavity}} \overbrace{B^4}^{\text{Magnet}} \underbrace{\frac{1}{N_{SYS}^2}}_{\text{Noise}}$

Cavity

Noise

Squeeze

Quantum noise

System noise temperature: $k_B T_S = h\nu N_{SYS} = h\nu \left(\underbrace{\frac{1}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}}_{\text{Thermal noise}} + \frac{1}{2} + N_A \right)$

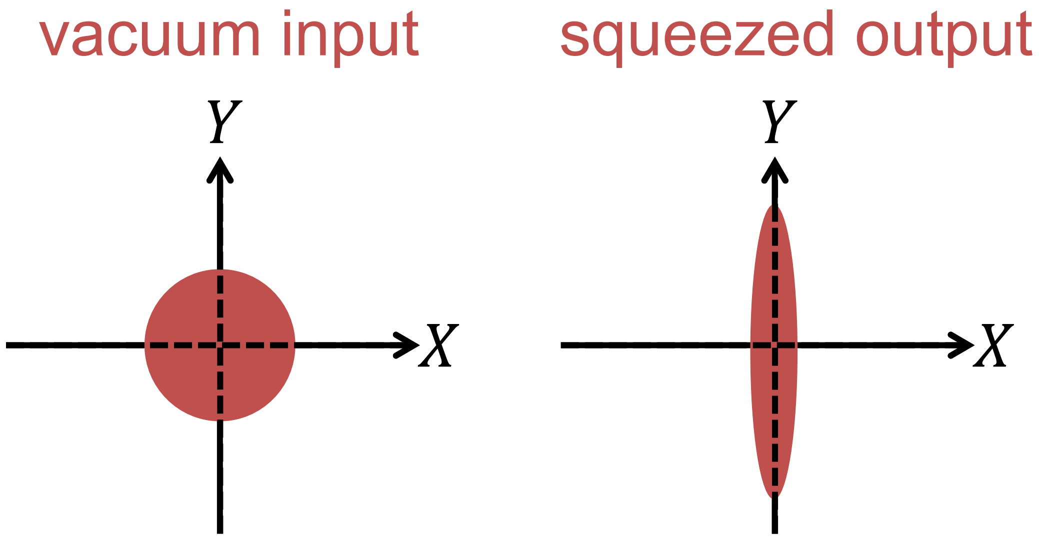
$N_A \geq \frac{1}{2}$

Thermal noise

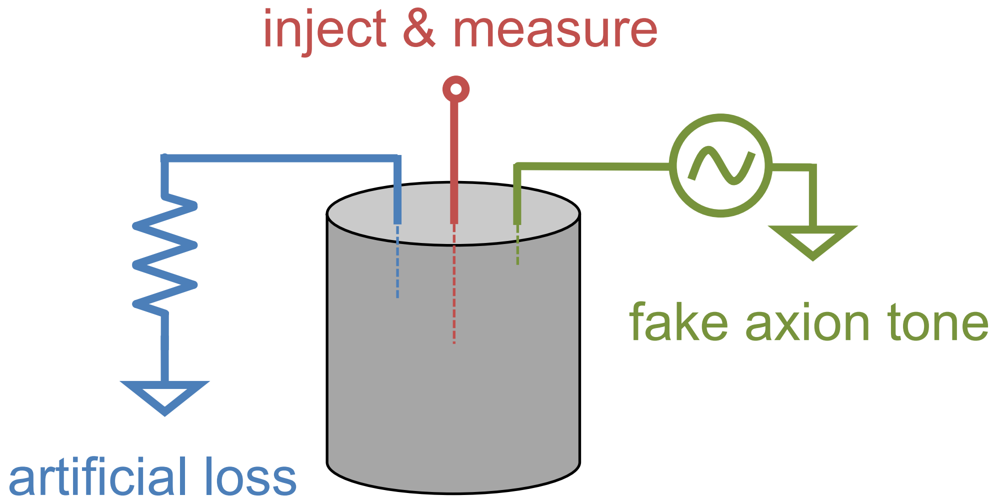
Added noise

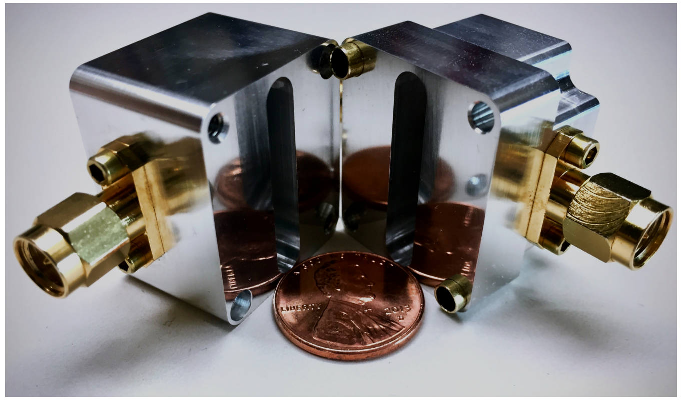
Squeezed-state receiver at JILA / CU Boulder

- Squeeze vacuum fluctuations using JPA
- Decrease variation in one quadrature while increasing variation in the other



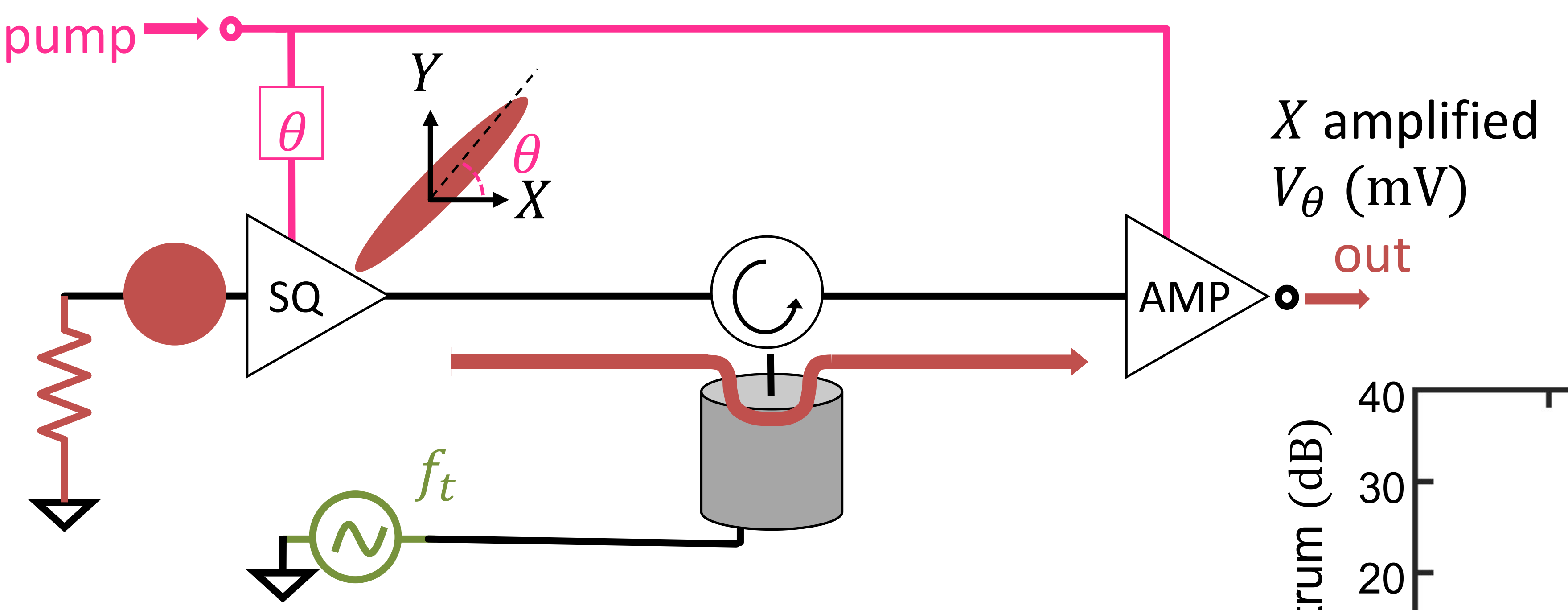
Testing effect of squeezing

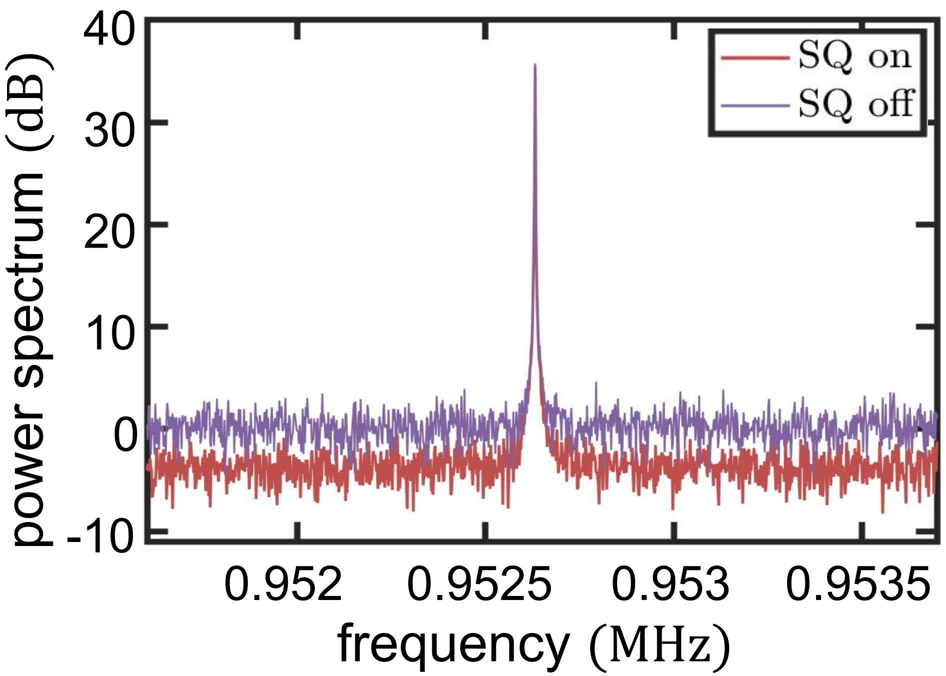




Squeezed-state receiver at JILA / CU Boulder

Mock haloscope to test squeezing





Result: scan rate can be improved by a factor of 2.3

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Moving to higher frequencies

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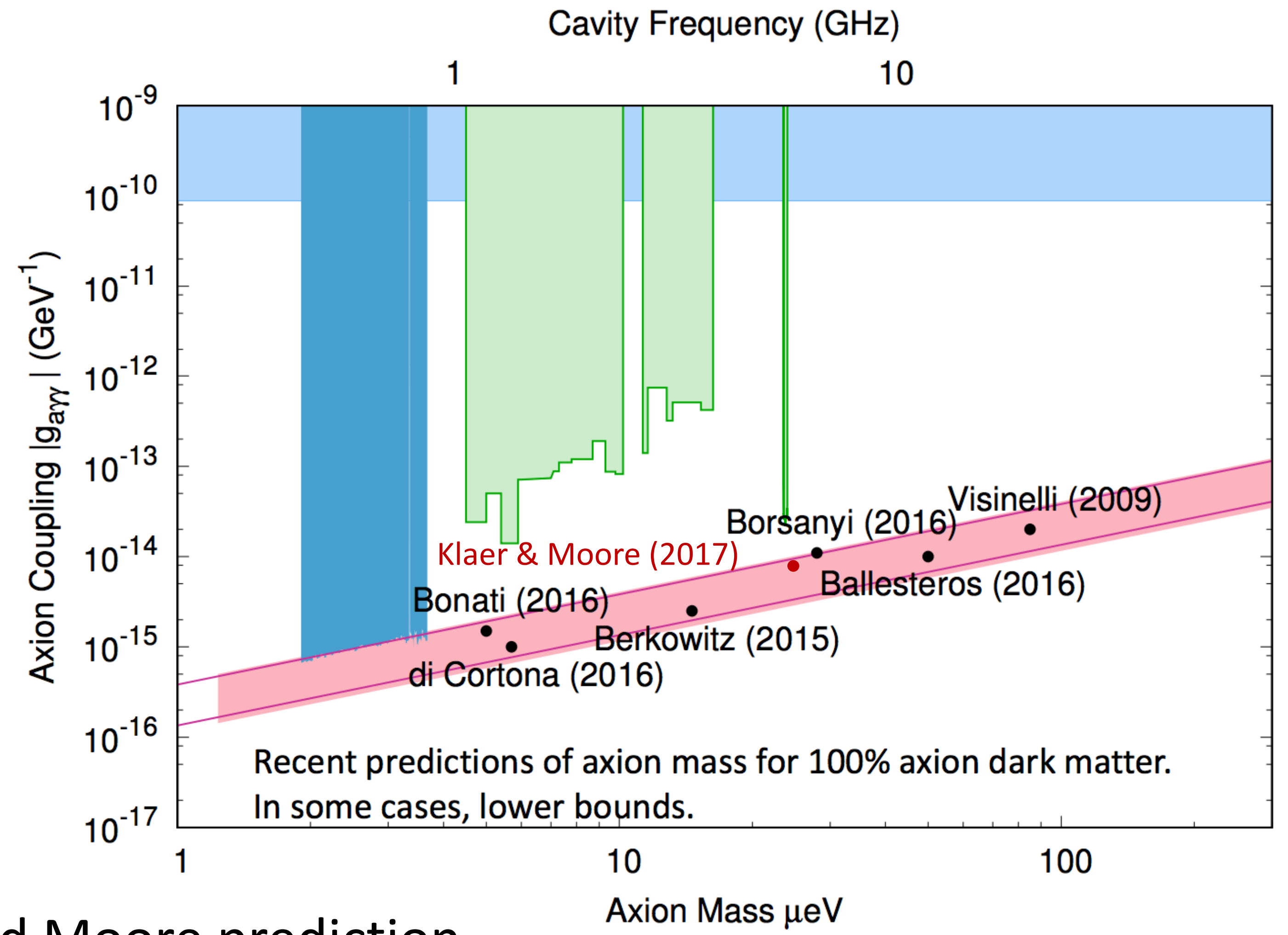
HAYSTAC is well-positioned move up in frequency to test recent theoretical predictions for axion mass

Most comprehensive prediction:
Klaer and Moore (2017)

$$m_a \sim 26.2 \pm 3.4\ \mu eV$$
$$\nu_a \sim 6.3 \pm 0.8\ GHz$$



HAYSTAC's next cavity will test the Klaer and Moore prediction.
If we continue using annular cavities, volume will be too small.
We need to consider other geometries for higher frequencies...

Challenges at higher frequencies

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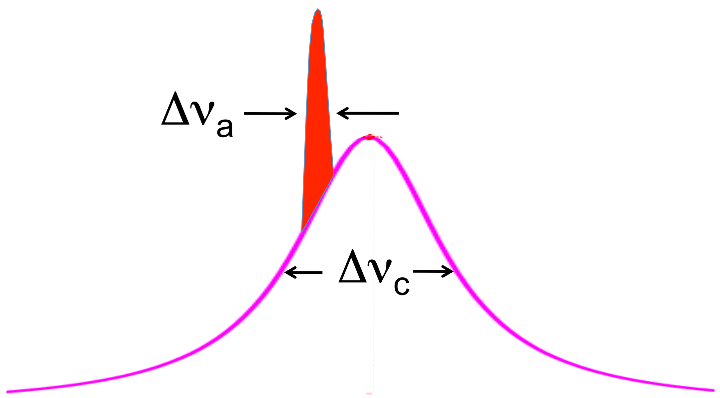
Scan rate: $\frac{d\nu}{dt} \propto \underbrace{Q V^2 C_{nml}^2}_{\text{Cavity}} \overbrace{B^4}^{\text{Magnet}} \underbrace{\frac{1}{N_{SYS}^2}}_{\text{Noise}}$

Cavity R&D:

- Quality factor Q must be kept high
- Cavity volume V decreases at higher frequencies
- Lack of spectral cleanliness hurts form factor C_{nml}



- $Q = min(Q_a, Q_C)$
- $Q_C \sim 10^4 \ll Q_a \sim 10^6 \Rightarrow \Delta\nu_a \ll \Delta\nu_C$

There are two orders of magnitude to gain.

Cavity R&D: increasing Q

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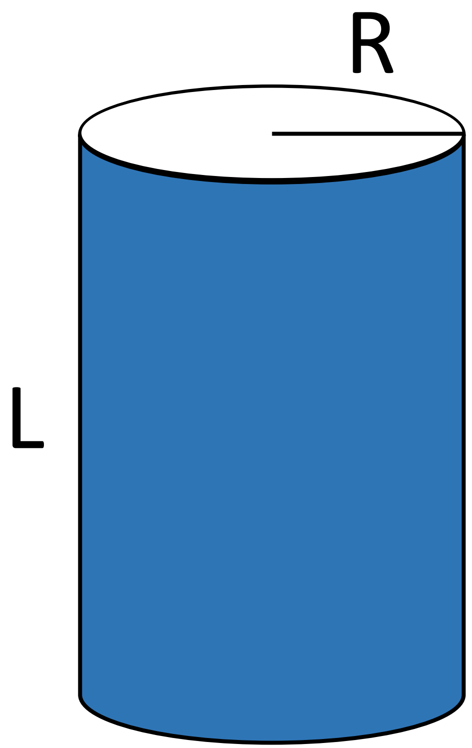
Cu cavity quality factor with superconducting barrel

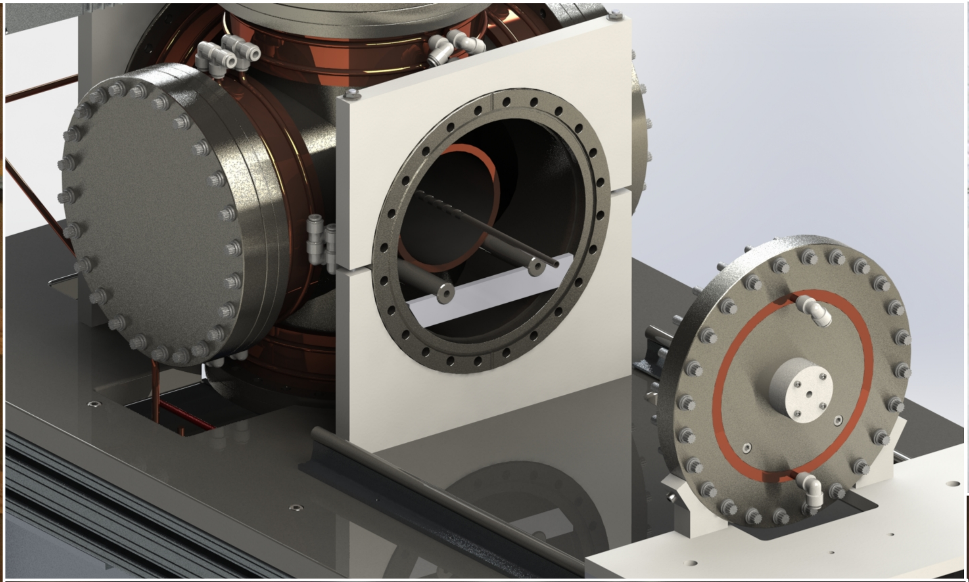
$$Q = \frac{L/R}{1 + \cancel{L/R}} \cdot \frac{R}{\delta}$$ ← skin depth

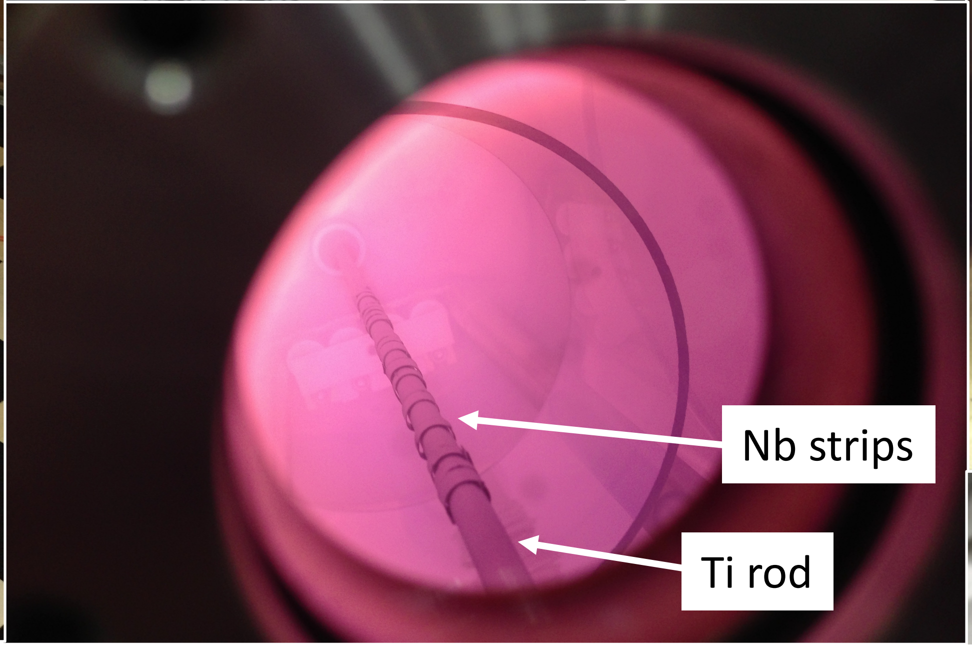
$$Q_{hybrid} = \left(1 + \frac{L}{R}\right) Q_{Cu}$$



For typical ADMX-HF cavity, L/R=5, enhancement factor = 6.

Superconducting thin films





Superconducting thin films

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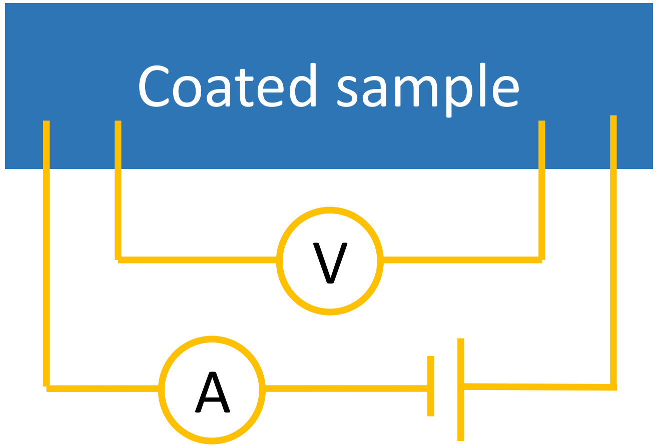
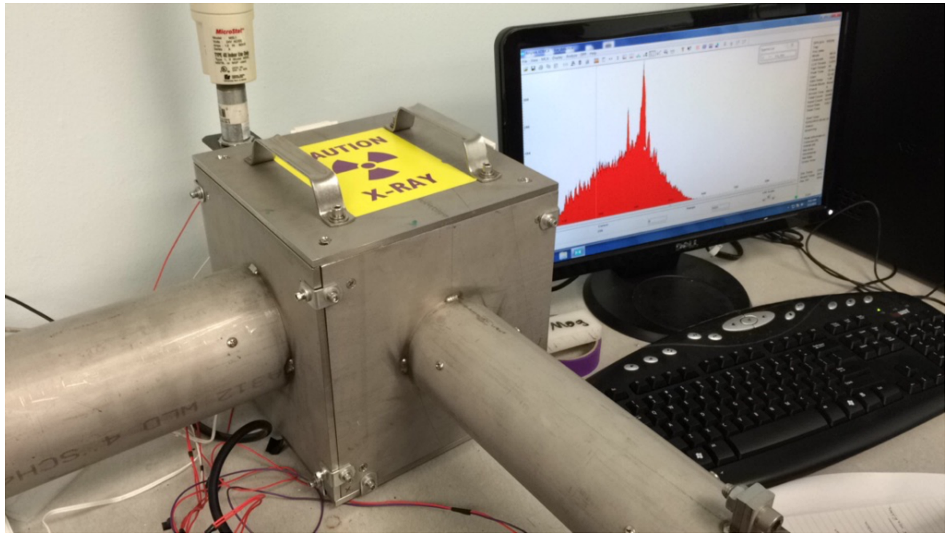
Four wire measurement

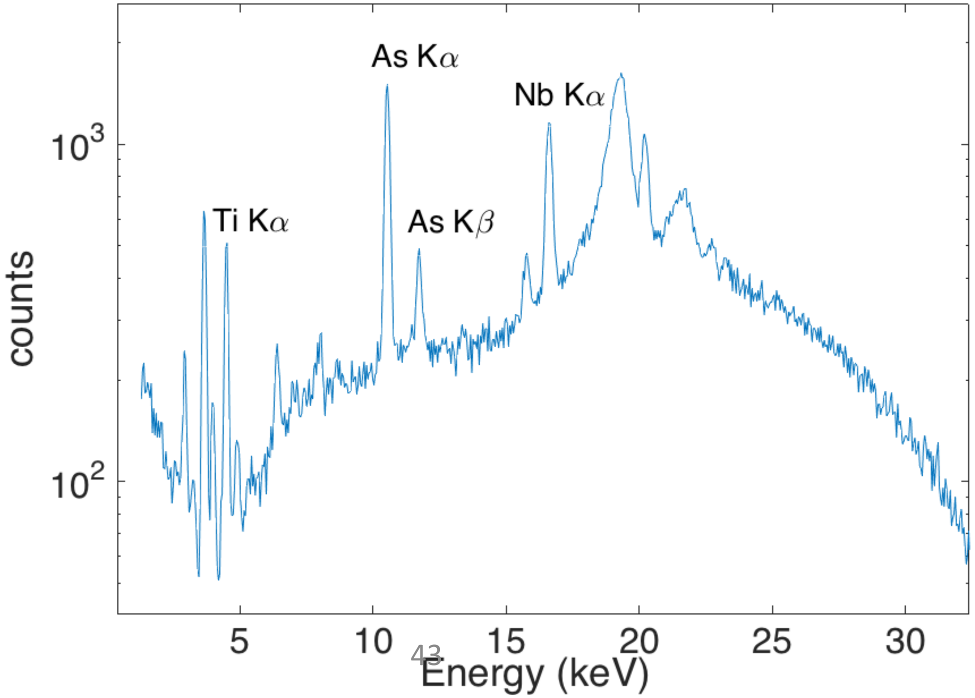
- Measures resistance
- Transition temperature



X-ray fluorescence

- Measures x-rays
- Concentrations of Ti, Nb





Challenges at higher frequencies

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Scan rate: $$\frac{d\nu}{dt} \propto \underbrace{QV^2C_{\mathrm{nml}}^2}_{\text{Cavity}} \overbrace{B^4}^{\text{Magnet}} \underbrace{\frac{1}{N_{SYS}^2}}_{\text{Noise}}$$

Cavity R&D:

- Quality factor Q must be kept high
- Cavity volume V decreases at higher frequencies
- Lack of spectral cleanliness hurts form factor C_{nml}

- For cylindrical cavity of radius R, $\omega_{010} = \frac{2.405}{\sqrt{\mu\epsilon}}\frac{c}{R}$
- ↑ density of TE modes with ↑ cavity length

Changing cavity design could increase V.

Cavity R&D: increasing V and C_{nml}

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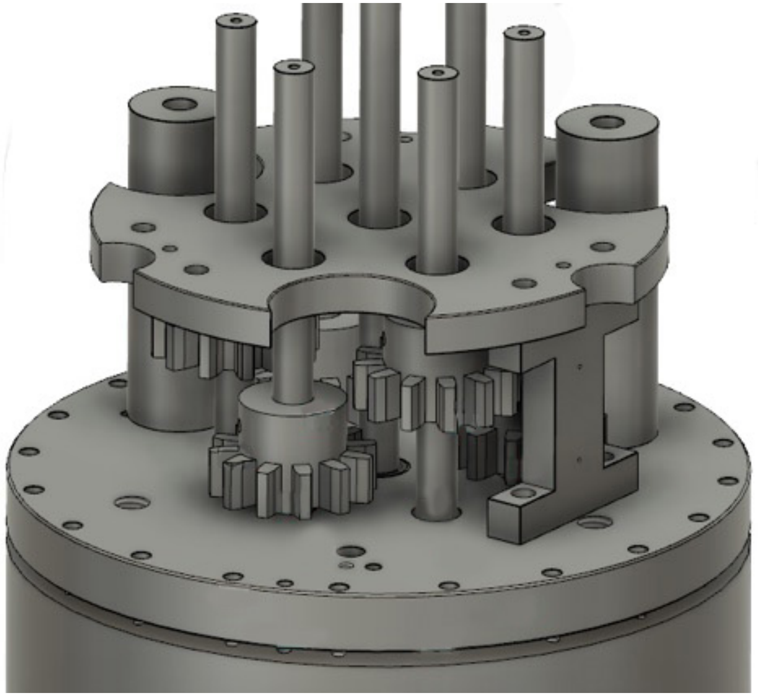
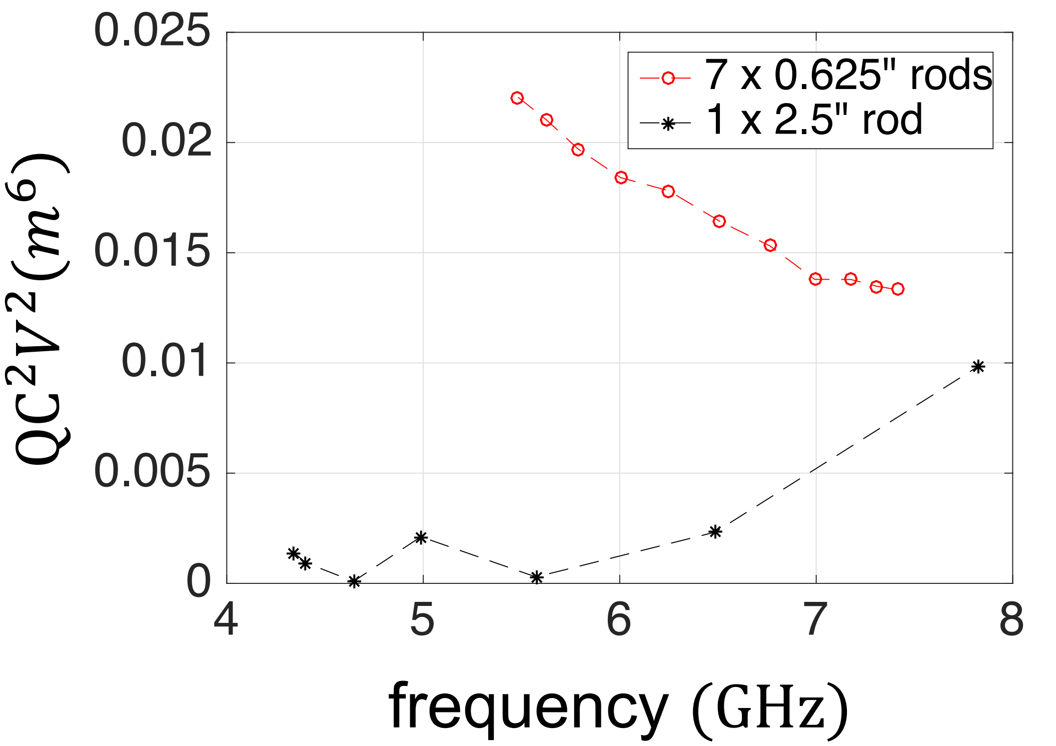
Seven rod cavity can have good form factor and high volume at higher frequencies compared to a single rod cavity

$$C_{nml} = \frac{\left|\int_V dV \vec{E}\cdot\vec{B}_0\right|^2}{B_0^2 V \int_V dV \epsilon \left|\vec{E}\right|^2}$$



Seven rod cavity



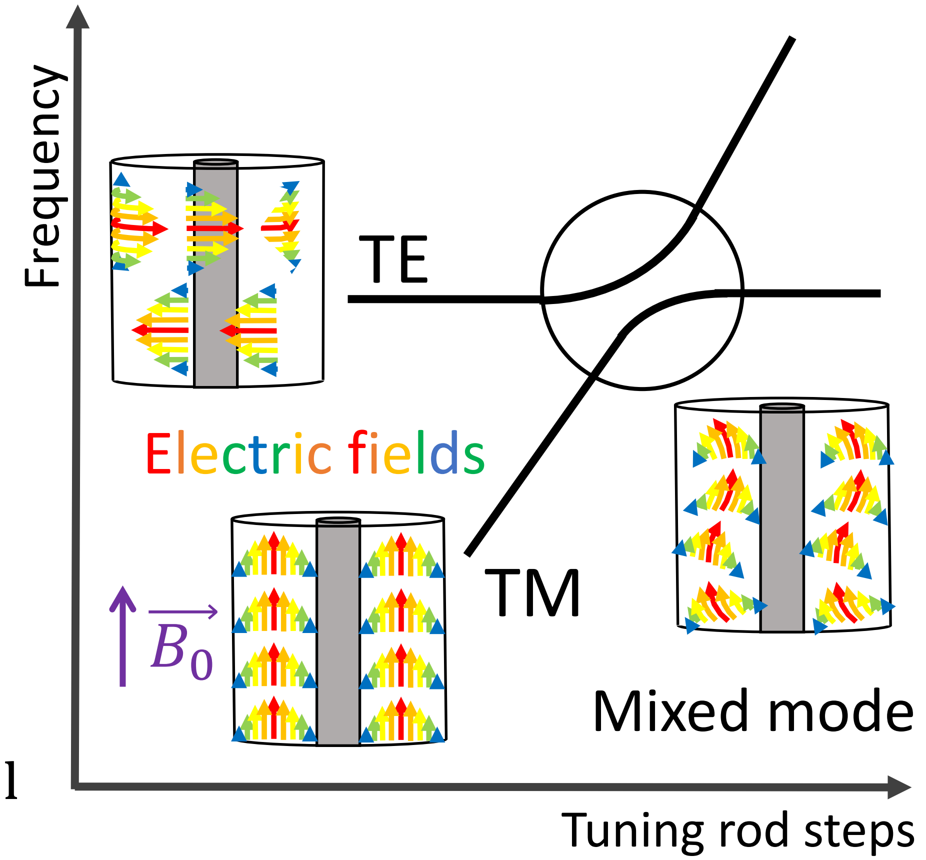
Challenges at higher frequencies

HAYSTAC

Scan rate: $\frac{d\nu}{dt} \propto \underbrace{QV^2C_{\mathrm{nml}}^2}_{\text{Cavity}} \overbrace{B^4}^{\text{Magnet}} \underbrace{\frac{1}{N_{SYS}^2}}_{\text{Noise}}$

Cavity R&D:

- Quality factor Q must be kept high
- Cavity volume V decreases at higher frequencies
- Lack of spectral cleanliness hurts form factor C_{nml}



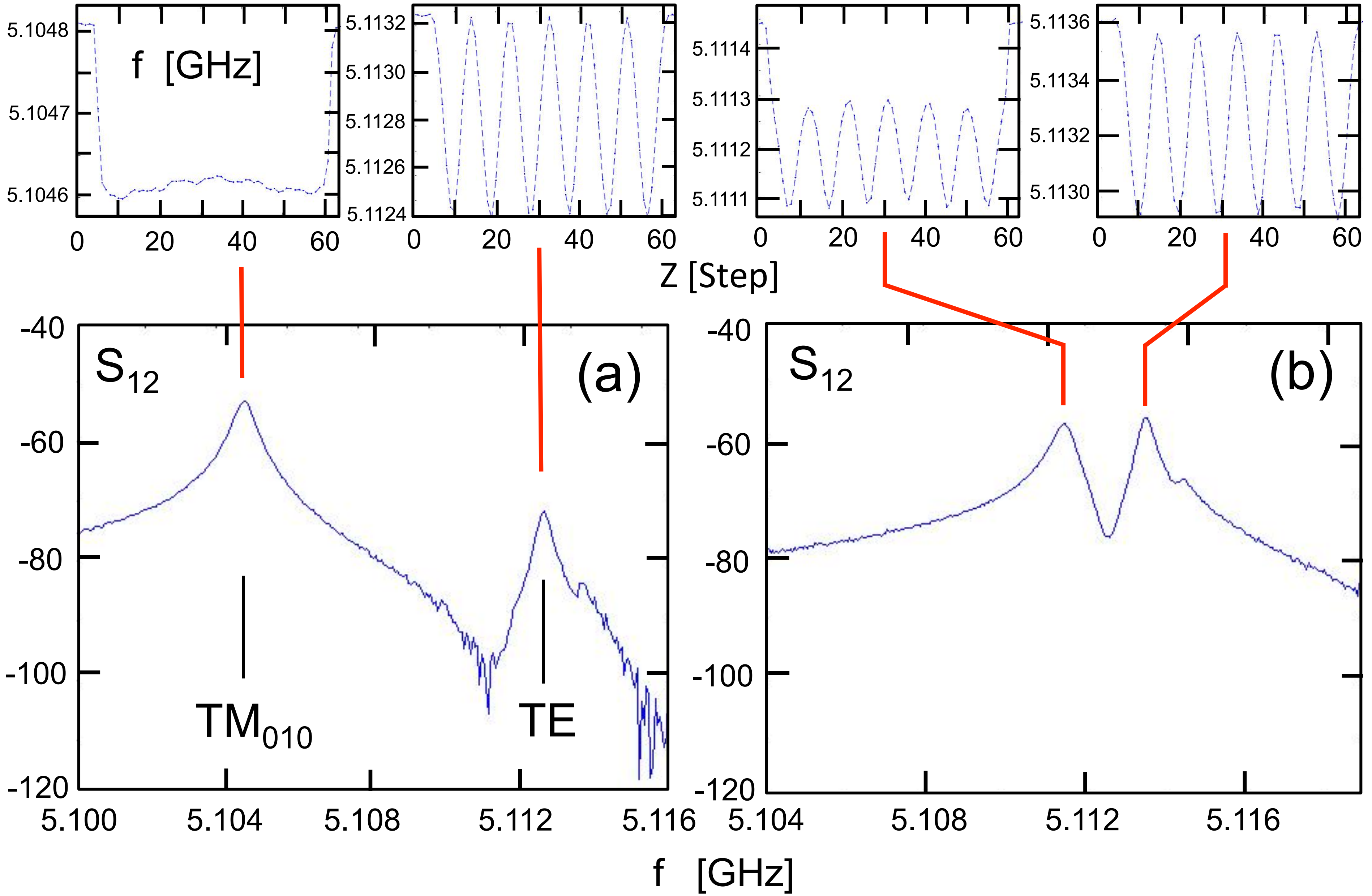
- Modes mix at a mode crossing

$$|state\rangle = \alpha|TM_{010}\rangle + \beta|TE\rangle$$

- Missing frequency steps at mode crossing

Clean spectrum allows for more thorough search.

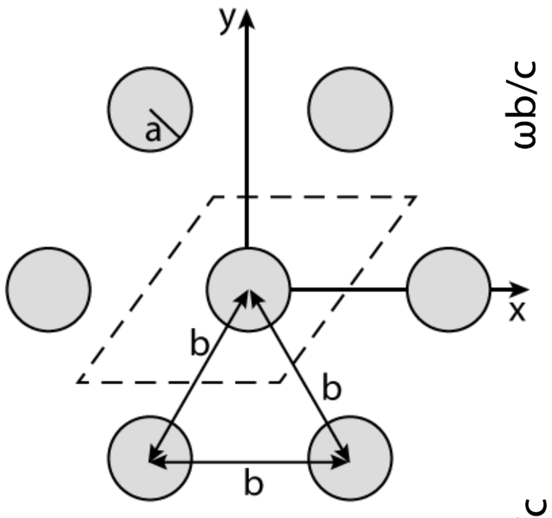
Cavity R&D: Bead-pull characterization HAYSTAC

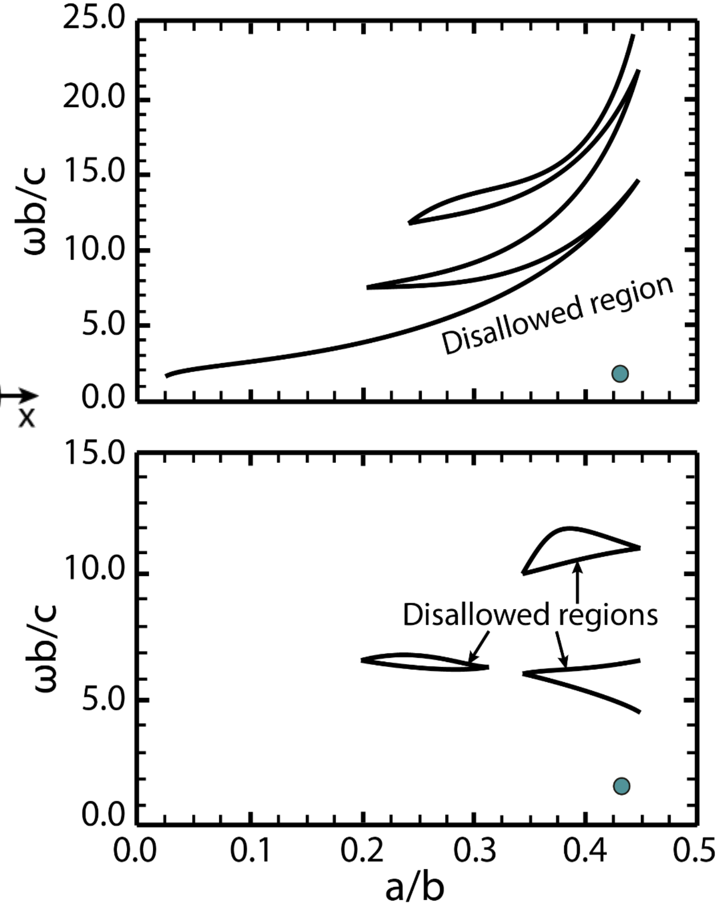


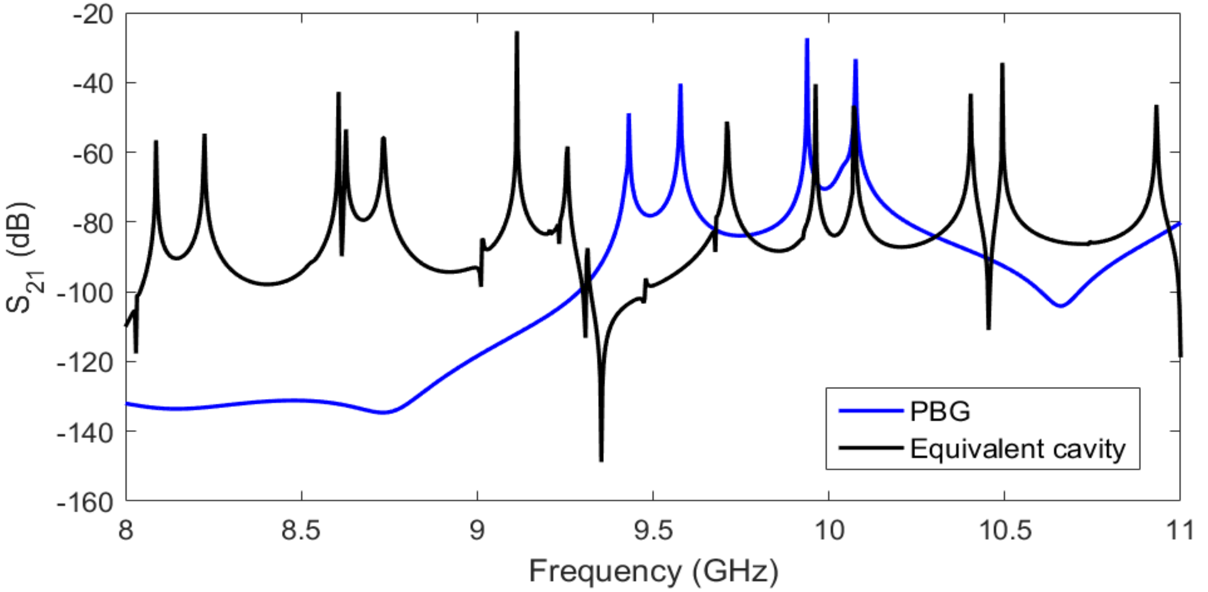
Cavity R&D: photonic band gaps

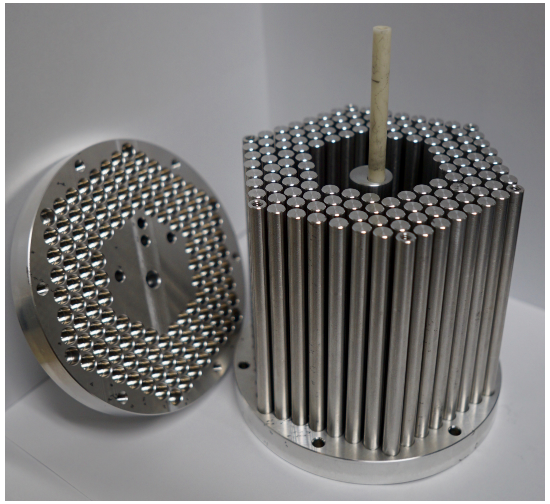
HAYSTAC

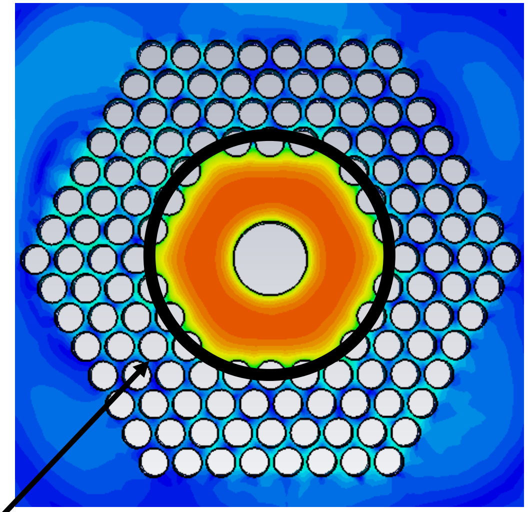
Periodic lattice of rods with defect confines TM modes while TE modes propagate out







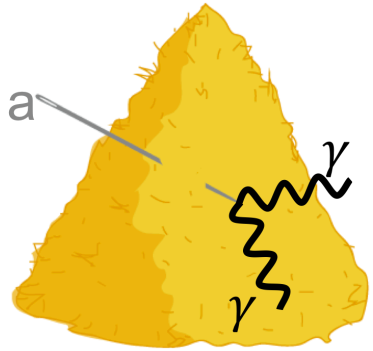




Size of “equivalent” cavity

Summary

- Axions solve the strong CP problem and are a great dark matter candidate
- HAYSTAC completed phase 1, excluding axions around mass 24 μeV with near-quantum-limited sensitivity
- Squeezing using a system of two JPAs can improve scan rate by a factor of 2.3
- HAYSTAC is looking to the future by designing higher-frequency cavities with optimized parameters for improved scan rate



Thank you for listening! Questions?

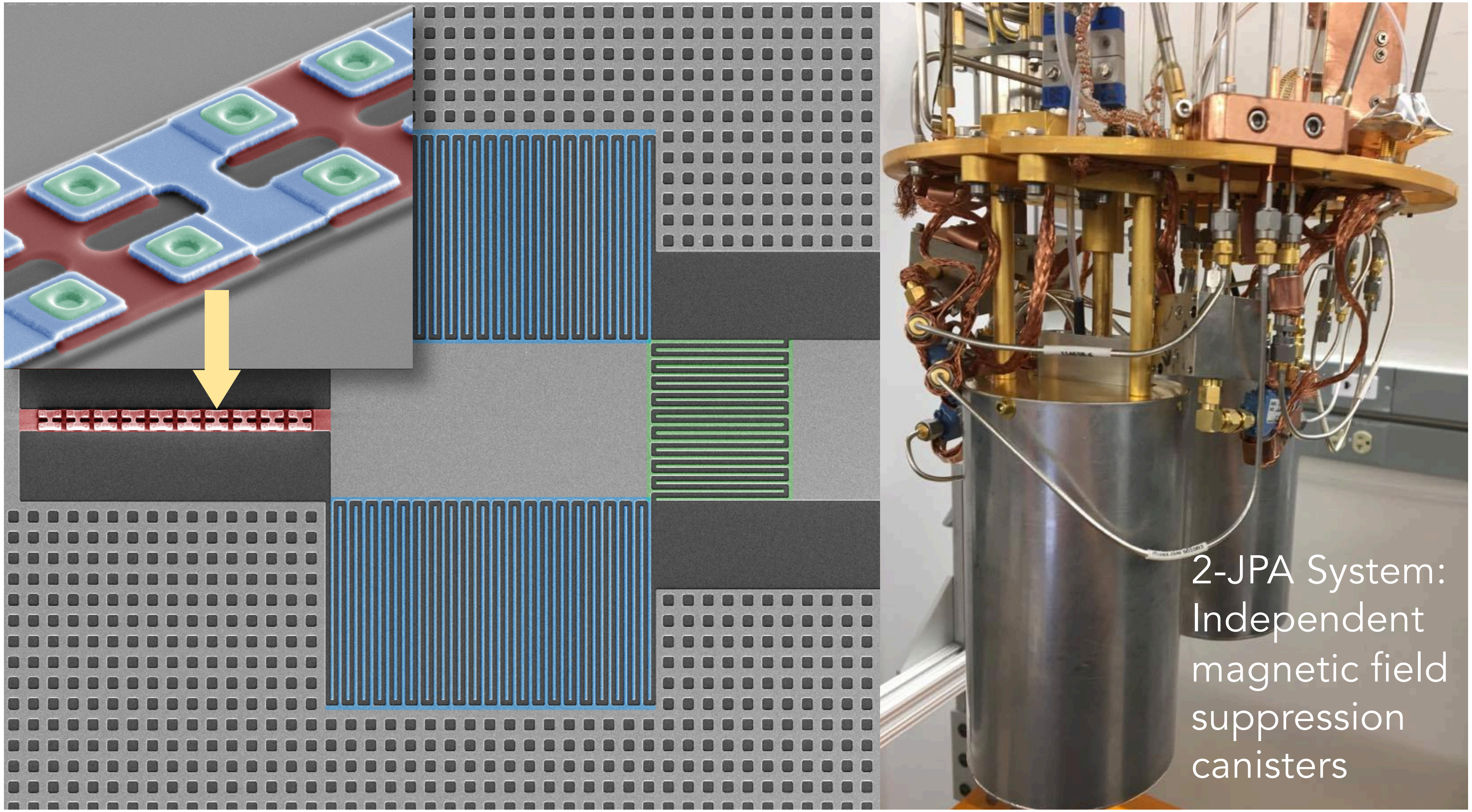
Further information:

- “Results from phase 1 of the HAYSTAC microwave cavity axion experiment,” L. Zhong *et al.*, Phys. Rev. D. (2018) 092001.
- “First results from a microwave cavity at 24 μeV,” B.M. Brubaker *et al.*, Phys. Rev. Lett. 118 (2017) 061302.
- “Design and operational experience of a microwave cavity axion detector for the 20 − 100 μeV Range,” S. Al Kenany *et al.*, Nucl. Instrum. Methods A 854 (2017) 11-24.
- “The HAYSTAC Axion Search Procedure,” B. M. Brubaker *et al.*, Phys. Rev. D 96 (2017) 123008.

Backup slides

HAYSTAC

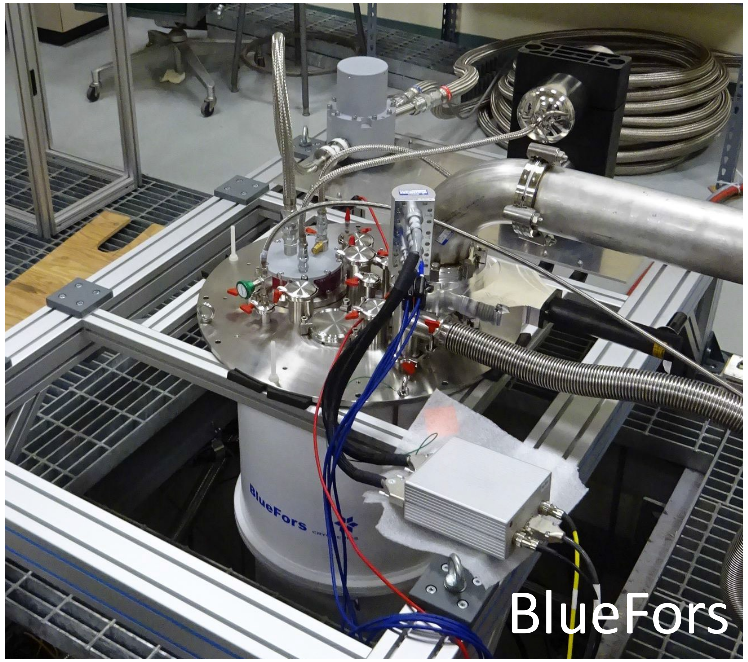
Squeezed-state receiver at JILA / CU Boulder



$T_{SYS} = T_{physical} + T_N$

$T_N \sim ¼ T_{SQL}$ [F. Mallet *et al.*, PRL 106 (2011) 220502]

- ☑ Thermally linked the rod to solve "hot rod" problem
- ☑ Integrated AttoCube piezoelectric rotator to smooth tuning
- ☐ Upgrade to BlueFors dilution refrigerator for reduced vibrations, colder and more stable performance



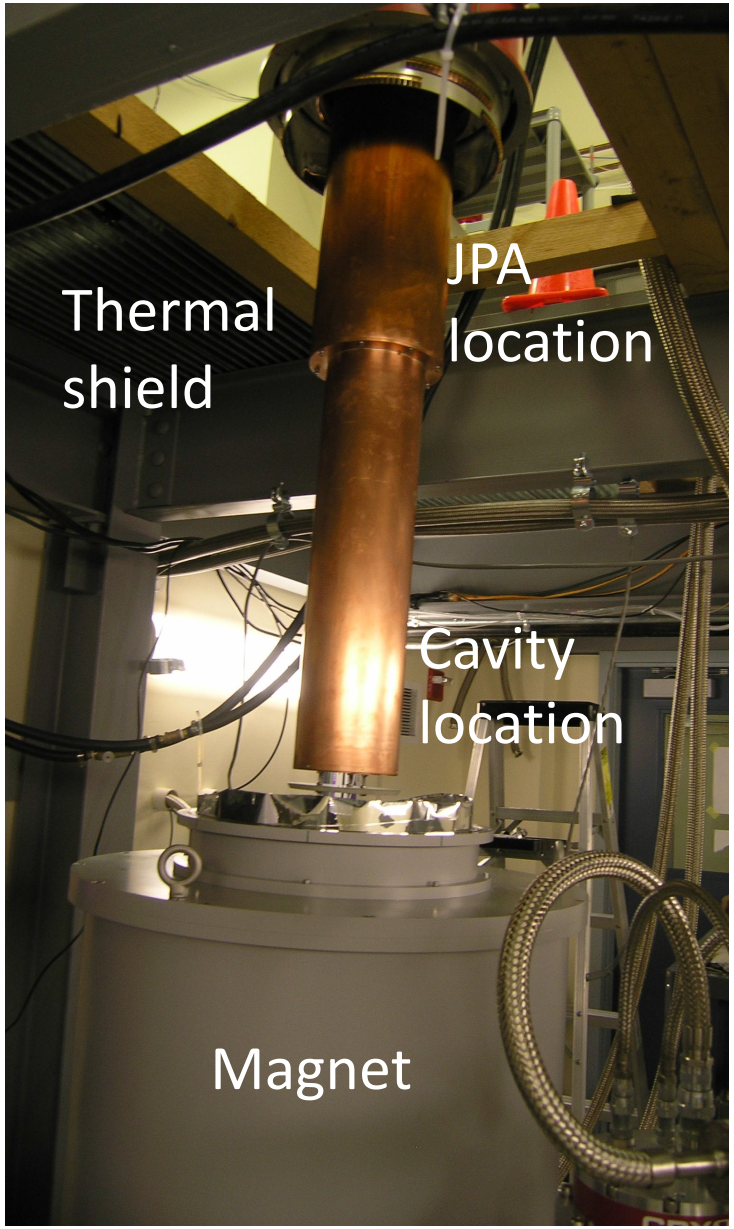
Integration of the Experiment at Yale

Superconducting magnet

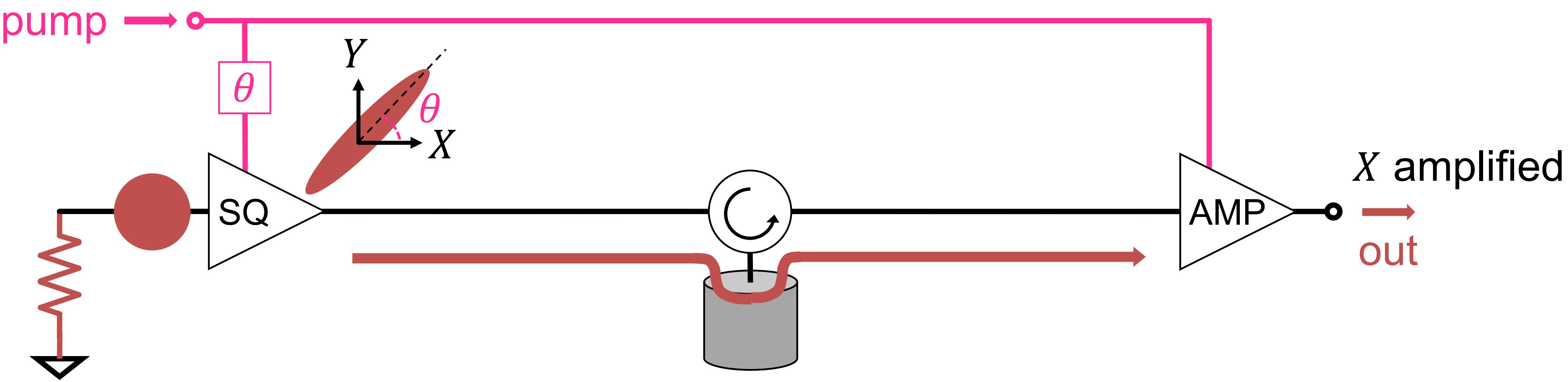
- Made by Cryomagnetics, Inc.
- Maximum field of 9.4 T
- Large bore
- Dry system

Dilution refrigerator

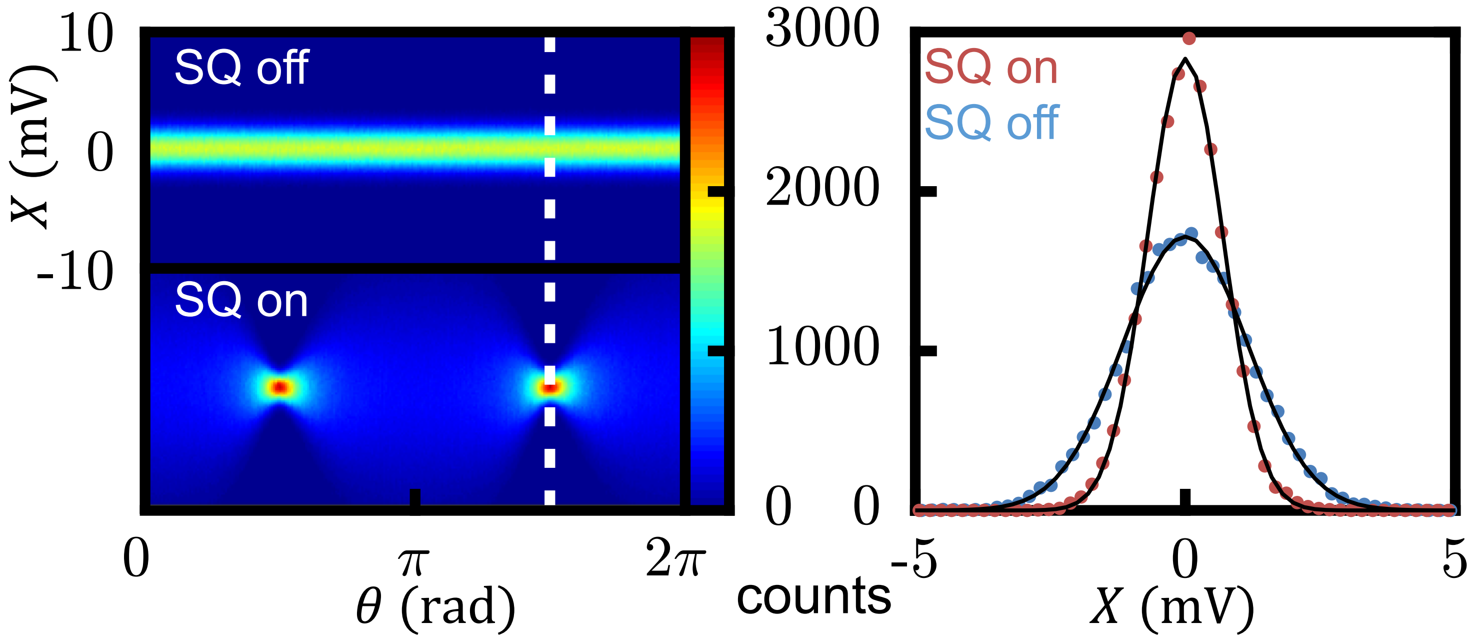
- 25 mK base temperature
- Experiment operates at 100 mK to stabilize the JPA
- Thermal shield contains gantry, JPA, and cavity



We reduce vacuum variance by 4 dB with squeezing



squeezer placed before cavity



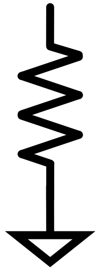
$$\frac{\sigma_{\text{off}}^2}{\sigma_{\text{on}}^2} = 4 \text{ dB}$$

JILA CU Boulder and NIST

SNR measurements demonstrate 2.3× scan rate improvement capability against optimal non-squeezed protocol

signal: 

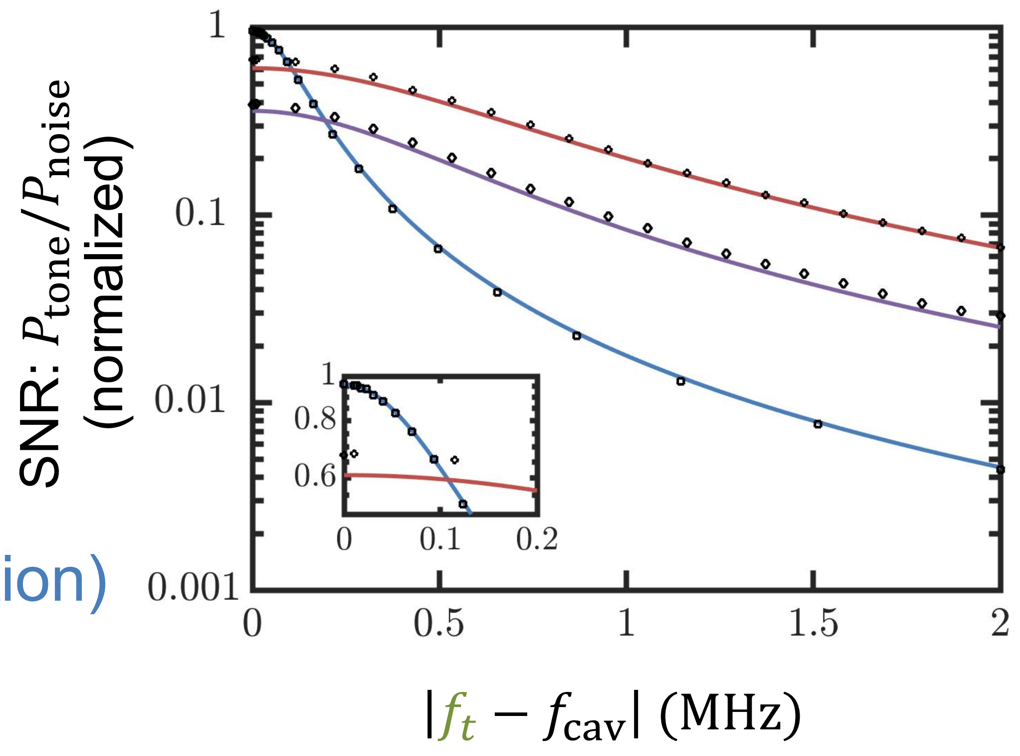
→ microwave tone

noise: 
→ vacuum fluctuations

squeezed

not squeezed

not squeezed
(optimal configuration)

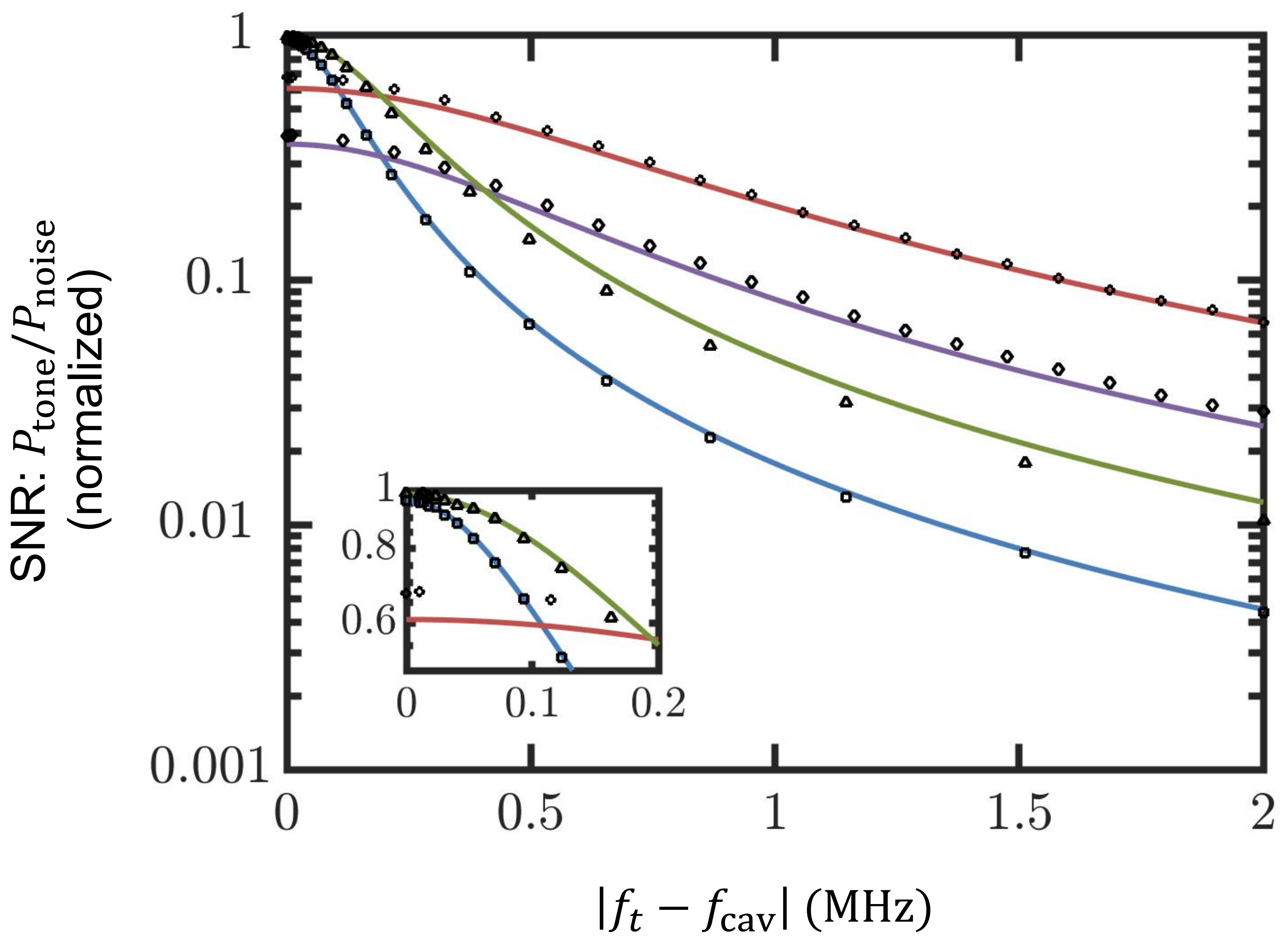


scan rate: $R \propto \int [\mathrm{SNR}(\omega)]^2 d\omega$

$$\frac{R_{\mathrm{SQ}}}{R_{\text{no SQ}}} = 2.3 \pm 0.1$$

JILA CU Boulder and NIST

Scan rate: 4 cases



4 dB squeezed,
9× overcoupled
→ $R = 2.3$

not squeezed,
9× overcoupled
→ $R = 0.7$

4 dB squeezed,
1.5× overcoupled
→ $R = 1.4$

not squeezed,
1.5× overcoupled
→ $R \equiv 1$

JILA CU Boulder and NIST

Mock axion experimental setup