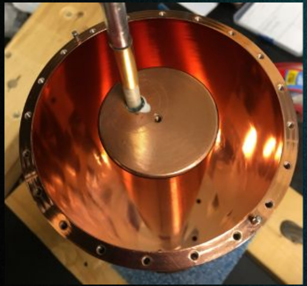
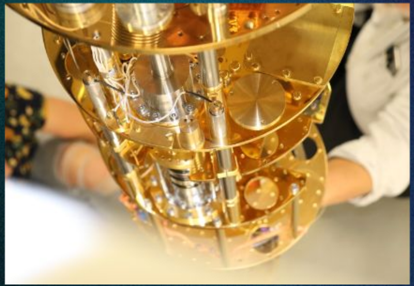
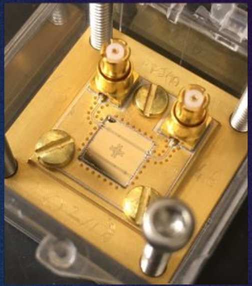
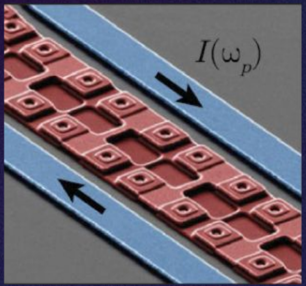
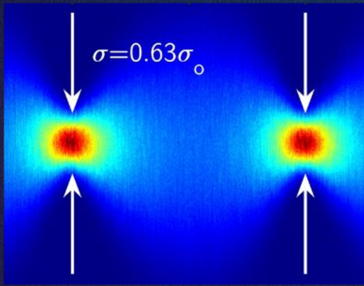
Searching for dark matter axions with HAYSTAC











03.25.25
Recontres de Moriond
La Thuile, Italy

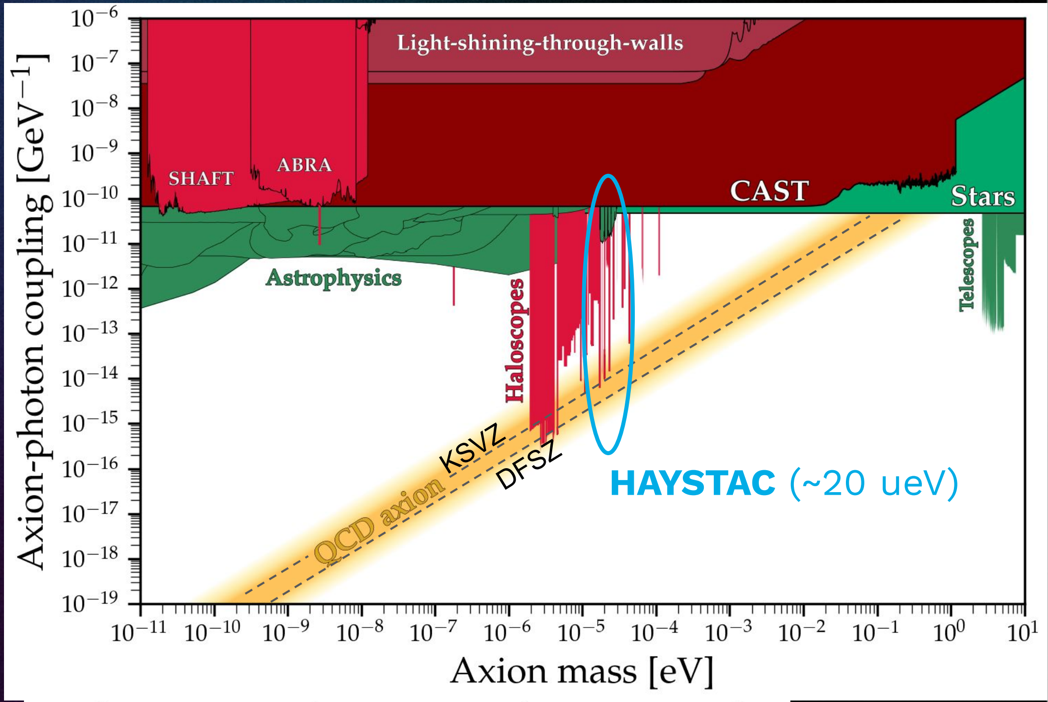
PRESENTATOR: Alex Droster, PhD student
UC Berkeley

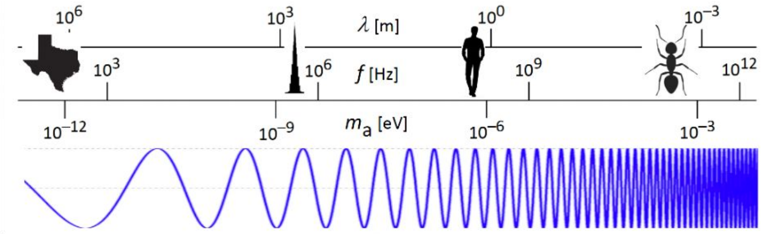
Outline

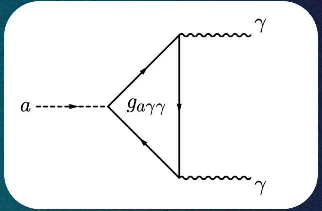
1. Axions as ultralight dark matter
2. The HAYSTAC detector
3. Scan rate enhancement with microwave squeezed states
4. Future of HAYSTAC & ALPHA
5. Final thoughts

Axions as dark matter

- Axions are well-motivated dark matter candidates and could solve the Strong CP problem
    - Created non-thermally in early universe
    - Axion mass/coupling is *a priori* unknown
    - Wavelike: treat as classical field!
- Two photon coupling provides experimental probe
- Post-inflationary model favors $m_a \geq 10$ ueV†







$$\mathcal{L} \sim g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

†Borsanyi, et al. (2016); Klaer & Moore, (2017); Buschmann, et al. (2022)

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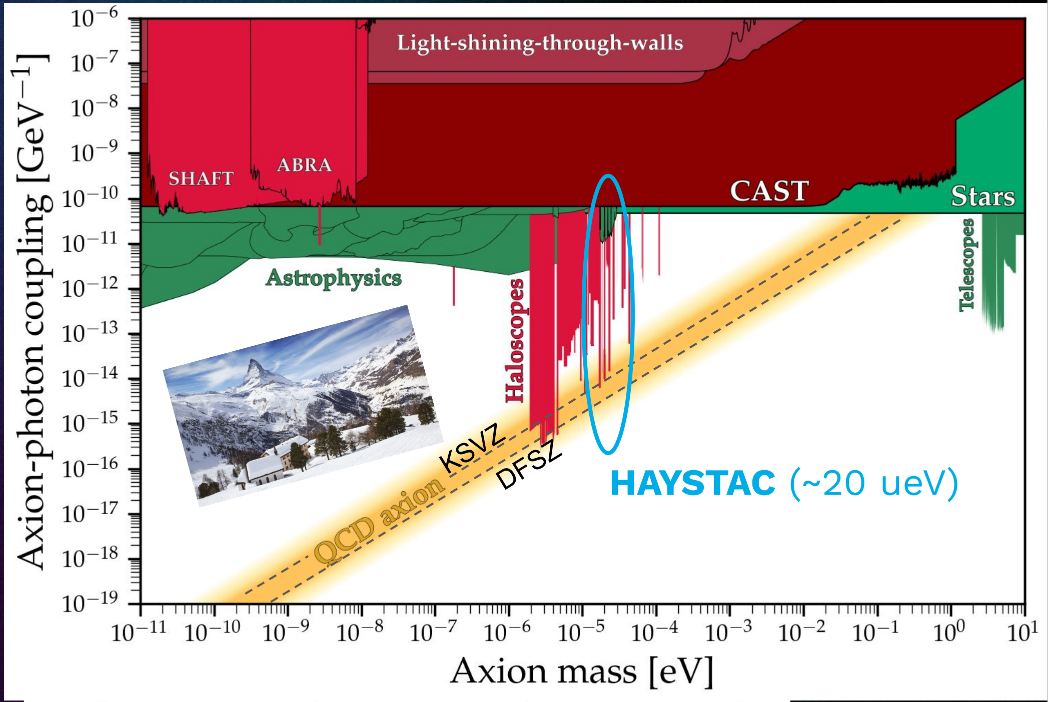

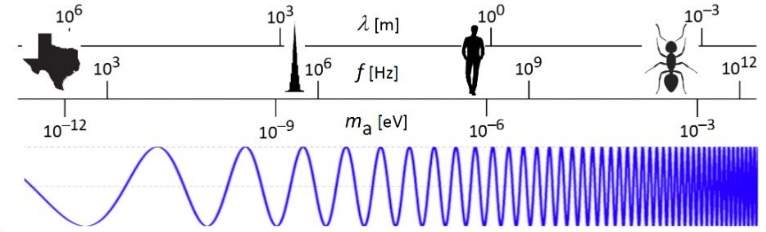

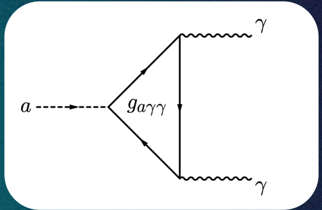

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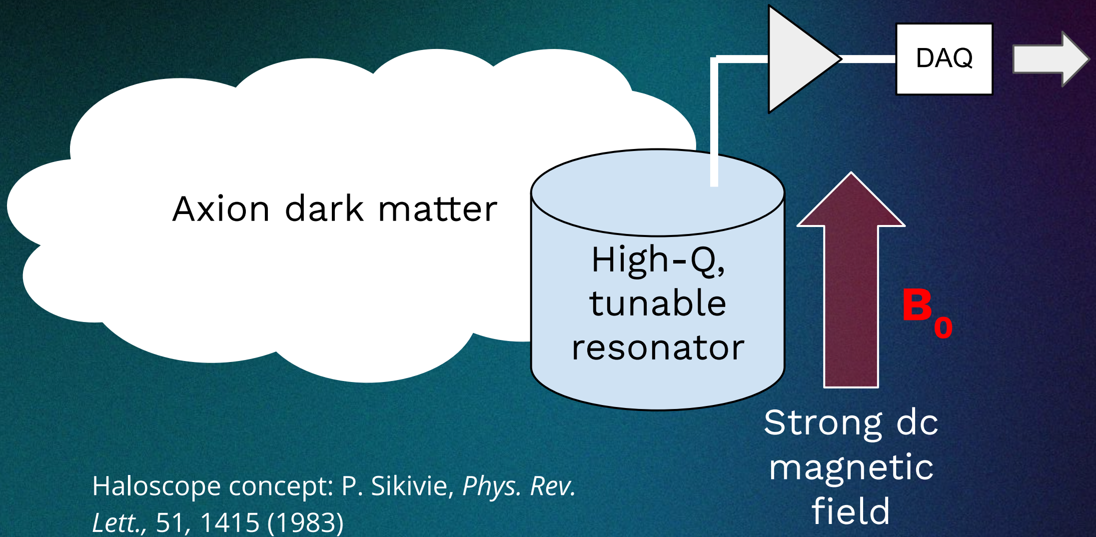
†Borsanyi, et al. (2016); Klaer & Moore, (2017); Buschmann, et al. (2022)

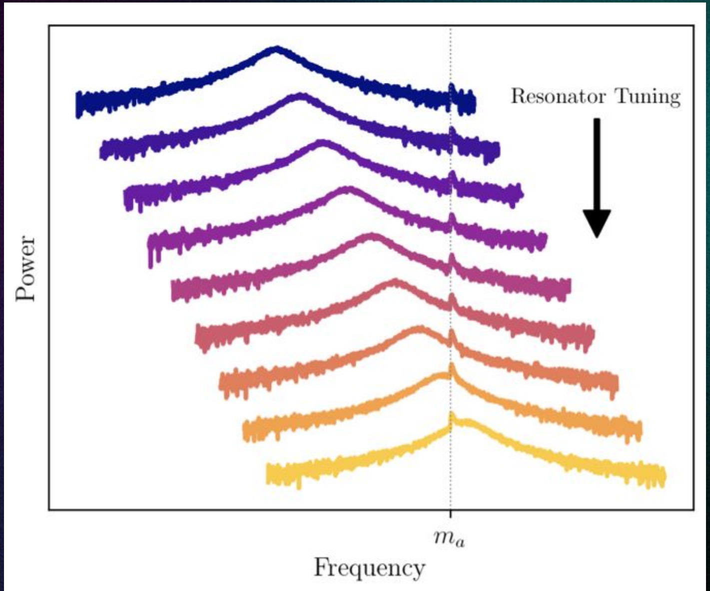
Searching for axions with haloscopes

Expected signal power is very small: 10^{-24} W!

Figure of merit: *scan rate, df/dt*



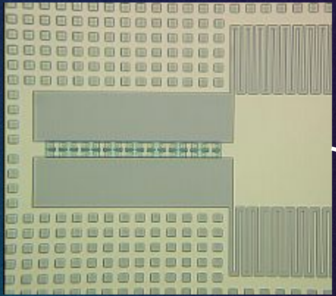
Weak, highly coherent signal tone at unknown frequency



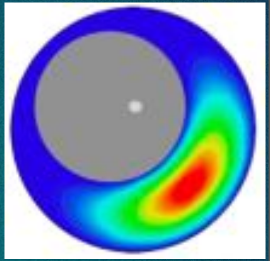
Haloscope concept: P. Sikivie, *Phys. Rev. Lett.*, 51, 1415 (1983)

HAYSTAC: **H**aloscope **A**t **Y**ale **S**ensitive **T**o **A**xion **C**old Dark Matter

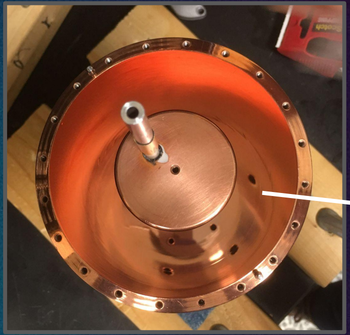
Josephson parametric amplifier (JPA)-based squeezed state receiver



TM$_{010}$ mode E-field



Copper microwave cavity

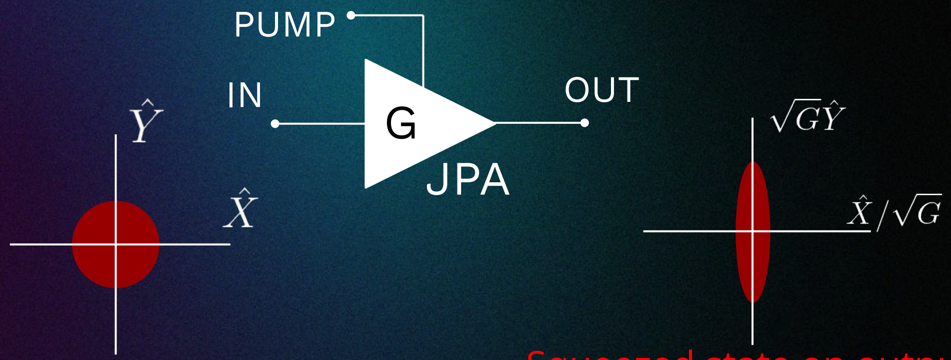


He^3/He^4 dilution refrigerator

9.4 Tesla, 10 L magnet

Josephson parametric amplifiers offer noiseless single-quadrature amplification

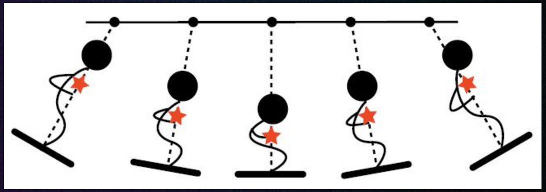
- Any voltage signal can be represented in terms of quadratures, X & Y
- JPAs are *phase sensitive* amplifiers: amplified quadrature depends on phase of pump
- Can produce *squeezed states*



Initial state

Squeezed state on output

Schematic of parametric amplification in classical system



Noise in haloscopes and the Standard Quantum Limit (SQL)

$$N_{sys}(\nu) = \left(\frac{1}{e^{h\nu/k_B T_{sys}} - 1} + \frac{1}{2} + N_A(\nu) \right)$$

Thermal noise

Quantum noise

Amplifier added noise

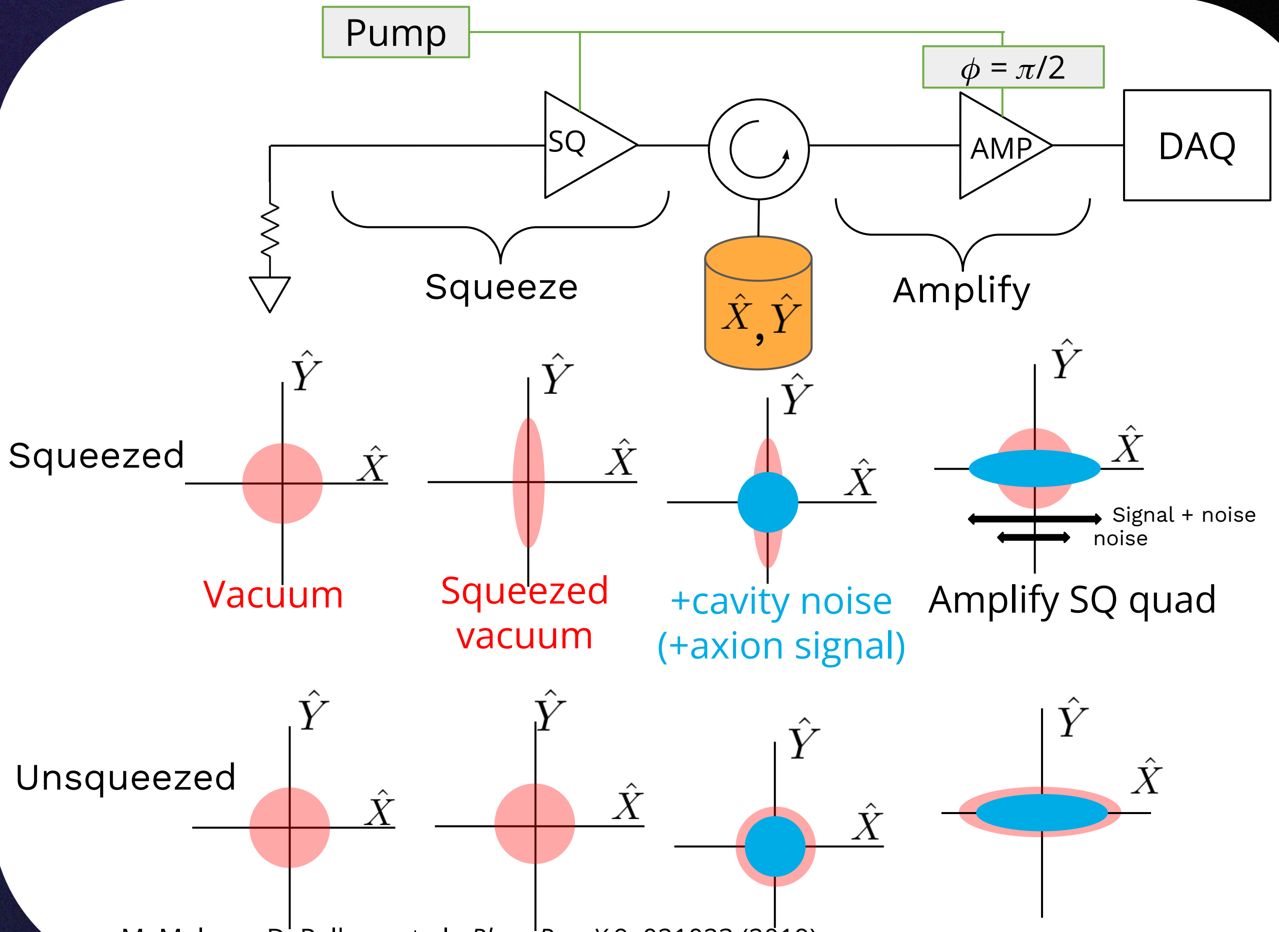
- In the frequency regime of cavity experiments, $h\nu \gg k_B T_{sys}$ and quantum noise dominates over thermal noise
- Both quantum noise and amplifier noise can be reduced with microwave engineering → *reduce noise in one quadrature at the expense of noise in the other quadrature*

Quantum sensing in HAYSTAC Phase II

Two JPAs operating together can beat the SQL

Cavity Hamiltonian:

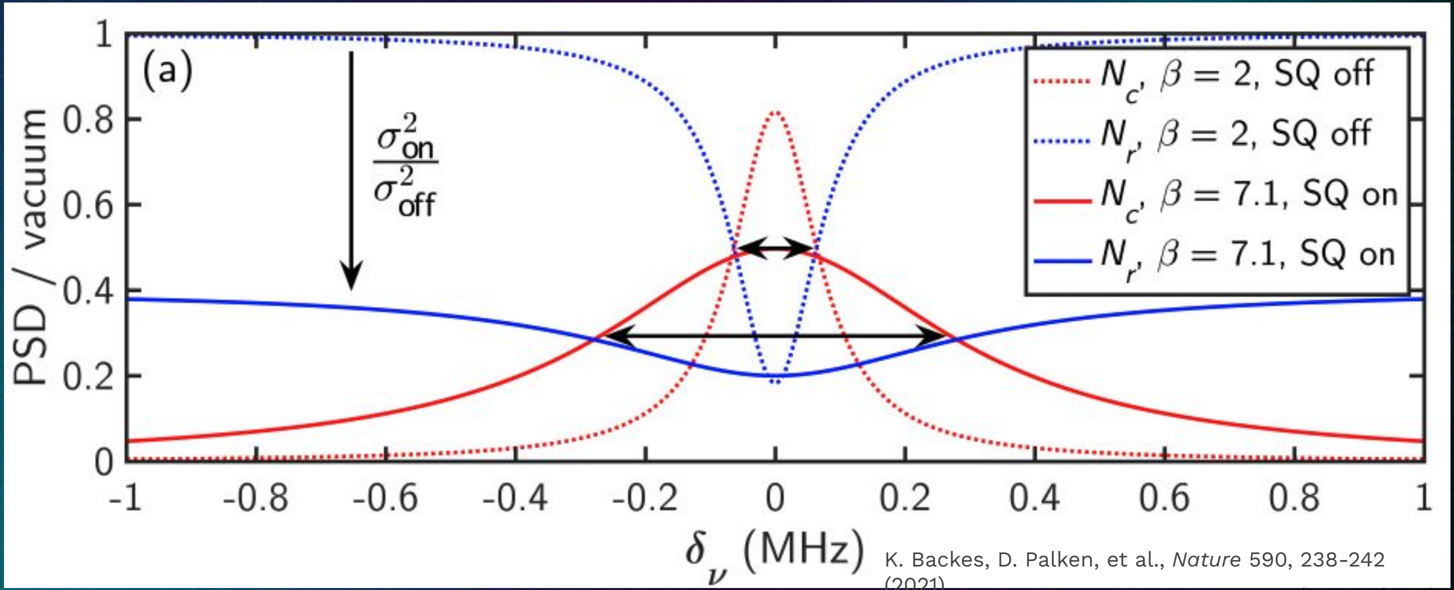
$$\hat{H} = \frac{h\nu_c}{2}(\hat{X}^2 + \hat{Y}^2)$$



M. Malnou, D. Palken, et al., *Phys. Rev. X* 9, 021023 (2019)

Quantum sensing: squeezing in detail

- Squeezing increases bandwidth over which SNR > 1
- Overcoupling to cavity is essential to scan rate enhancement

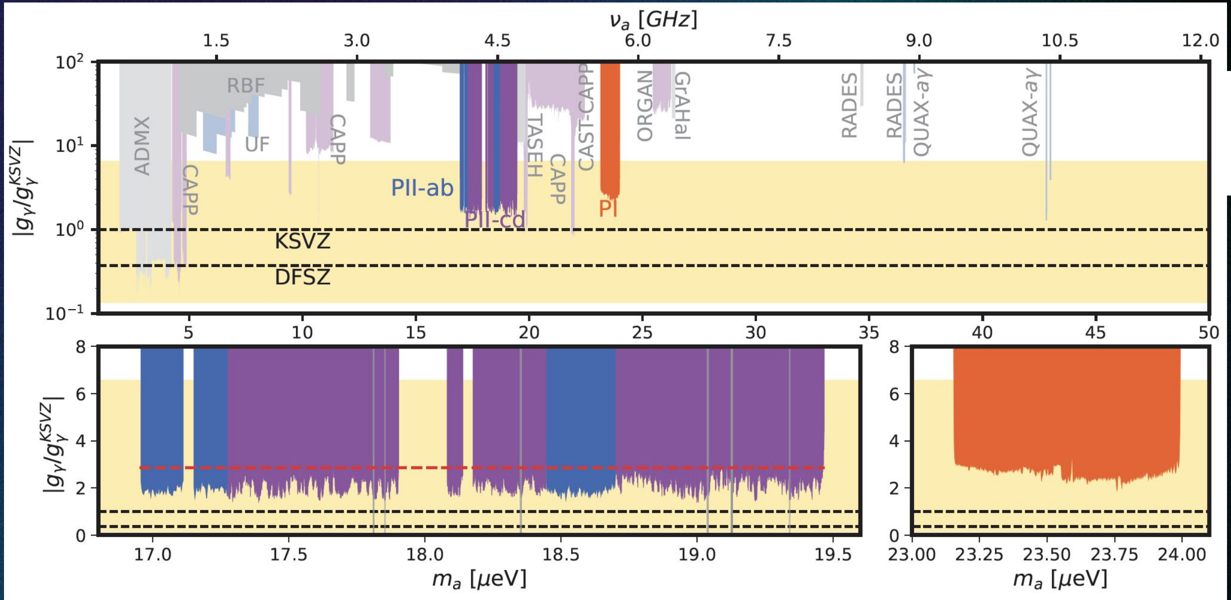


K. Backes, D. Palken, et al., *Nature* 590, 238-242 (2021)

4 dB squeezing

2X scan rate increase

HAYSTAC results so far



New results in **purple**

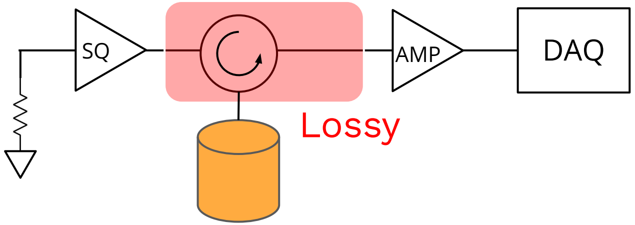
Plot from forthcoming *PRL*

We have 5 major results papers:

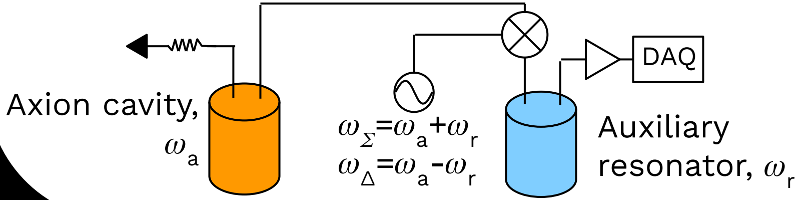
- Phase I, Run 1: First Axion search with Quantum limited Noise, ***Phys. Rev. Lett.* 118, 061302 (2017)**
- Phase I, Run 1+2: Improved Search, ***Phys. Rev. D* 97, 092001 (2018)**
- Phase IIa: First Search Below the SQL, ***Nature* 590, 238 (2021)**
- Phase IIa+b: Detailed Overview of SSR Search, ***Phys. Rev. D* 107, 072007 (2023)**
- Phase IIc+d: Widest Search Using SSR, **arXiv:2409.08998**, **PRL forthcoming**

HAYSTAC upgrades beyond Phase II

Improved Squeezing

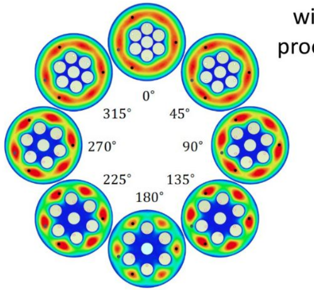


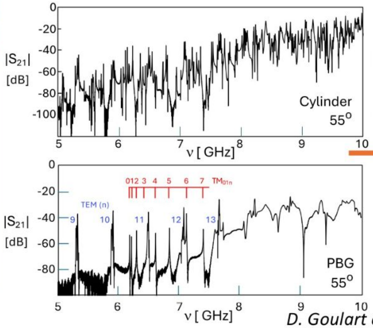
- Squeezing is limited by lossy between two JPAs
- Entangle cavity with auxiliary readout resonator
- Noiselessly amplify one quadrature of cavity state, deposit uncertainty into unmeasured quadrature
- **Projected 6X scan rate enhancement**

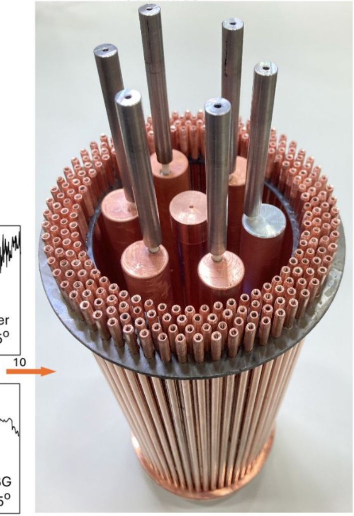


Extending to higher frequencies: multi-rod cavity

Tunable symmetric lattice resonator with PBG for TE mode suppression; proof of concept for ALPHA 10-20 GHz resonator

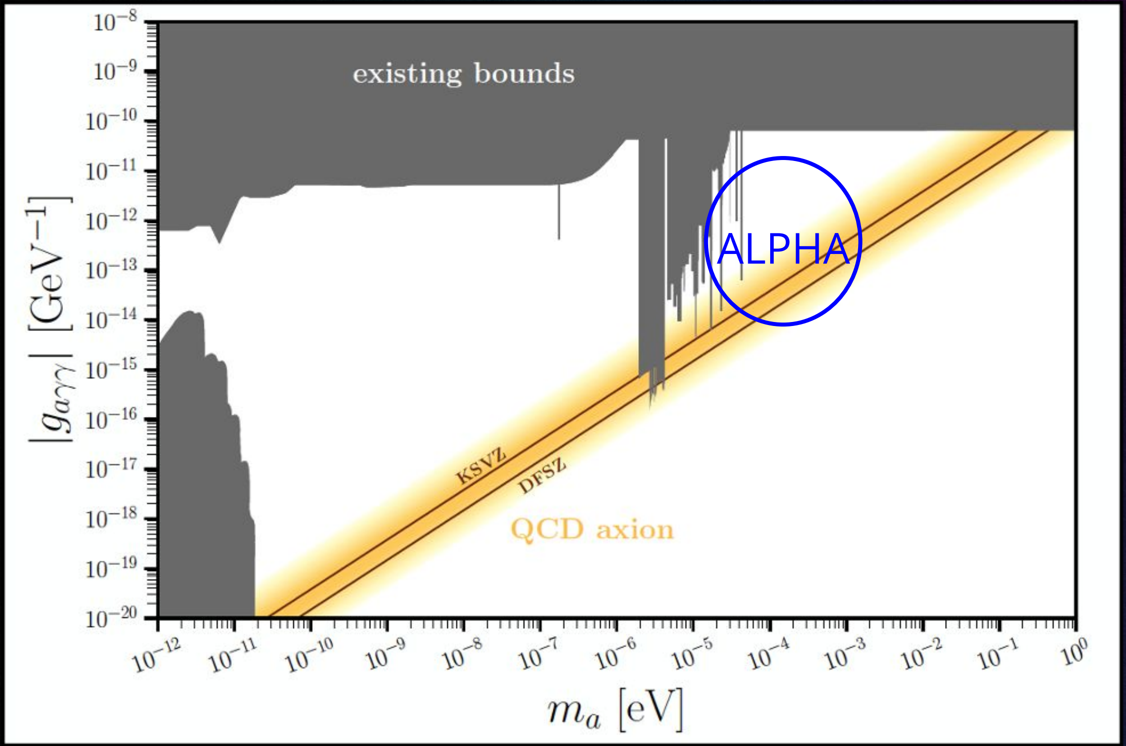




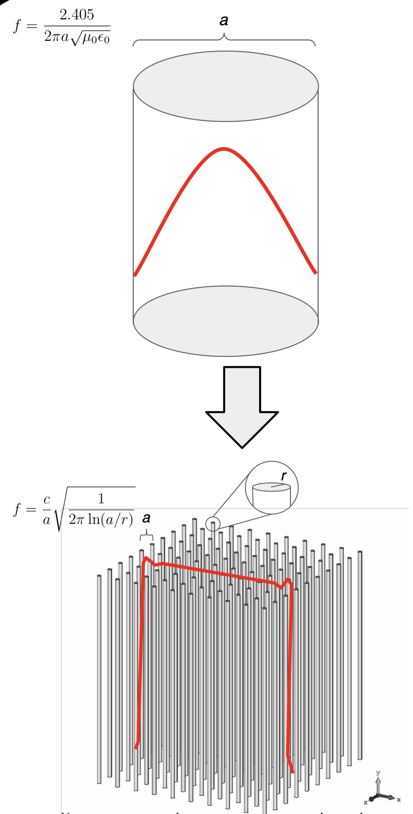


D. Goulart et al., paper in preparation (2024)

Higher end of the parameter space requires advancements in resonator design



- Well-motivated parameter space around m_a~100 ueV (~50 GHz)
- Microwave cavities get prohibitively small
- Metamaterial resonators can probe this region: **ALPHA experiment**



Credit: Jon Gudmunsson, Iceland

Together, Math and Science Foundations Fund 'Tabletop' Physics That Could Transform Our Understanding of the Universe

December 11, 2023

University of California, Berkeley graduate student Heather Jackson performs research on metamaterial resonators to be used in the plasma haloscope search for dark matter axions. AJ Gubser, UC Berkeley

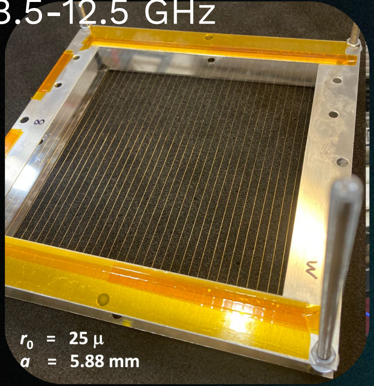
Axion Longitudinal Plasma Haloscope

Yale University
University of California Berkeley
Colorado University
Johns Hopkins University
Massachusetts Institute of Technology
Wellesley College
Arizona State University
Oak Ridge National Laboratory
Stockholm University
Iceland University
ITMO University
Cambridge University

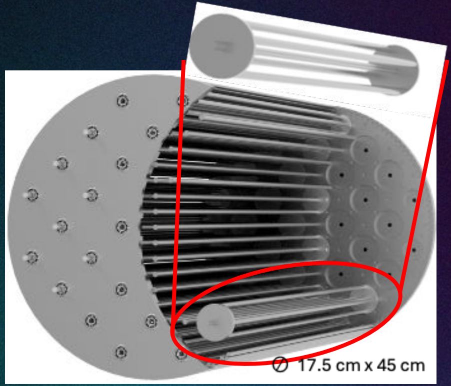
[1] *Host Institution*
[2] *PI Institution*
[3] *Inaugural Spokesperson: Jón Gudmundsson*

Initial idea: M. Lawson, A. Millar, et al. *PRL 123*, 141802 (2019)

Wire array prototype resonator at Berkeley: ~8.5-12.5 GHz

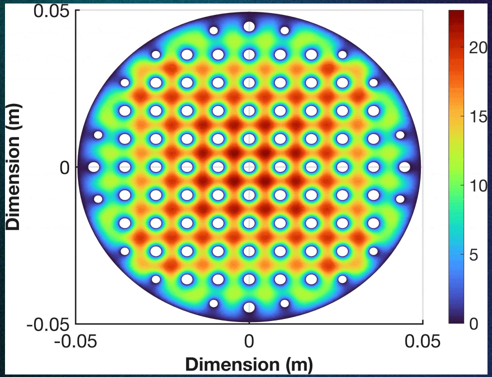


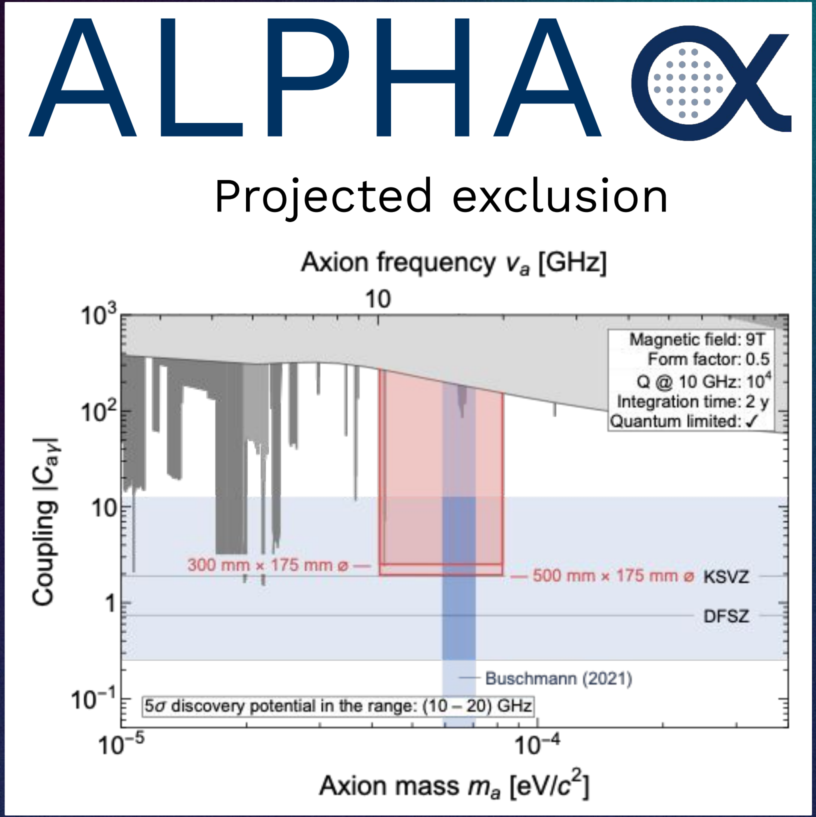
Phase Ia resonator (Berkeley): 11-17 GHz



Stockholm prototype: ~9-12 GHz

Prototype resonator tuning:





Readout at these frequencies presents new challenges: see Aaron Chou's talk later today

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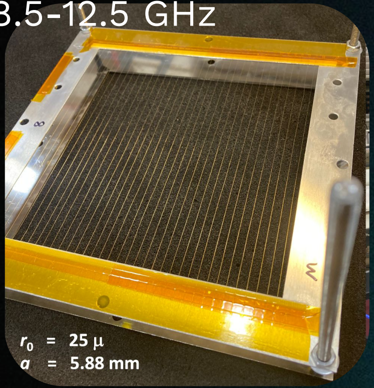

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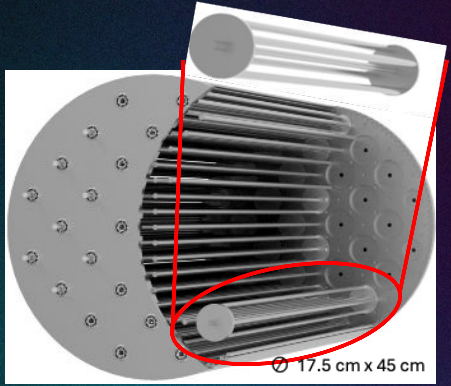

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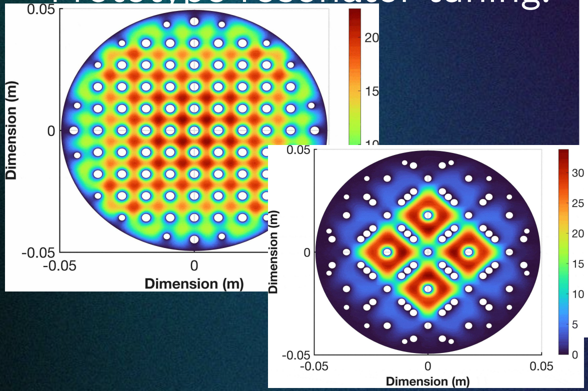
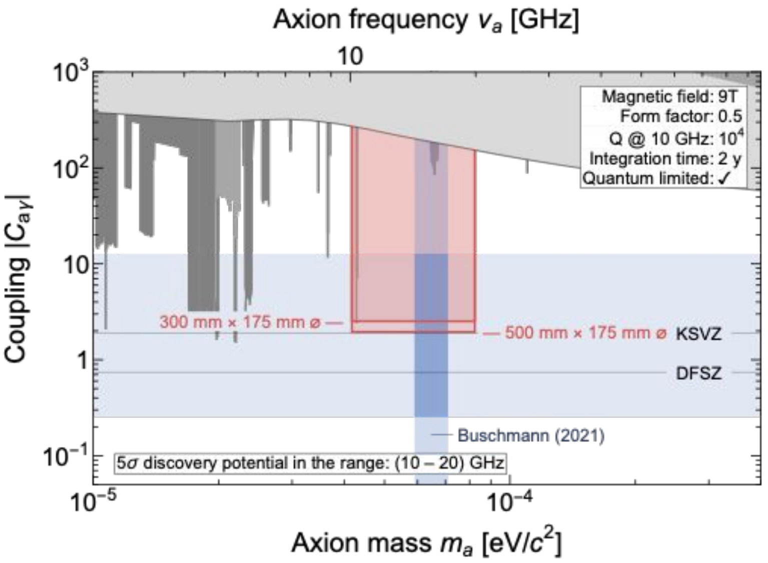


ALPHA

Projected exclusion



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Haystac

ALPHA

Wright Laboratory

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Knut and Alice Wallenberg Foundation

Rymdstyrelsen Swedish National Space Agency

Swedish Research Council

Final thoughts

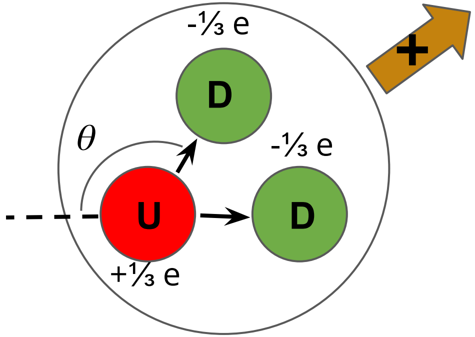
- There is currently an exciting convergence happening between axion theory, axion experiment, and quantum sensing technology, with the possibility of measurement across the full QCD band with breakthrough capability.
- HAYSTAC is an effective testbed for new detector and resonator innovations.
- HAYSTAC is the only axion dark matter experiment that has beaten the Standard Quantum Limit, achieving a **scan rate enhancement of 2X**. A more advanced readout scheme **could achieve 6X**.
- Symmetrical lattice resonators show promise for achieving axion sensitivity at high frequencies; a **7 rod cavity** will be integrated into HAYSTAC later this year. **ALPHA** will incorporate these innovations in a search for the axion at 10-20 GHz.

Extras

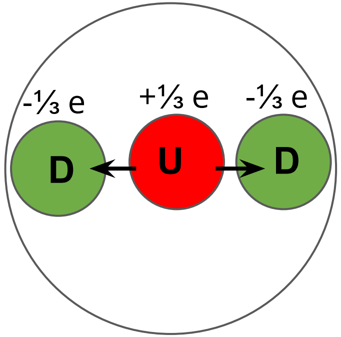
Another problem in physics: Why does QCD seem to preserve CP symmetry?

The neutron has an electric dipole moment many times smaller than expected

Expectation: macroscopic electric dipole moment



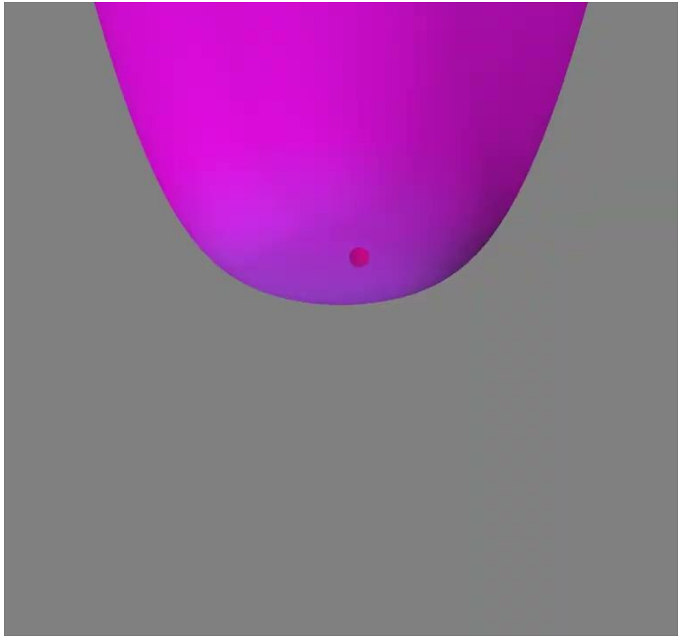
Reality: no dipole moment observed



The neutron, with its constituent quarks and their electric charges shown

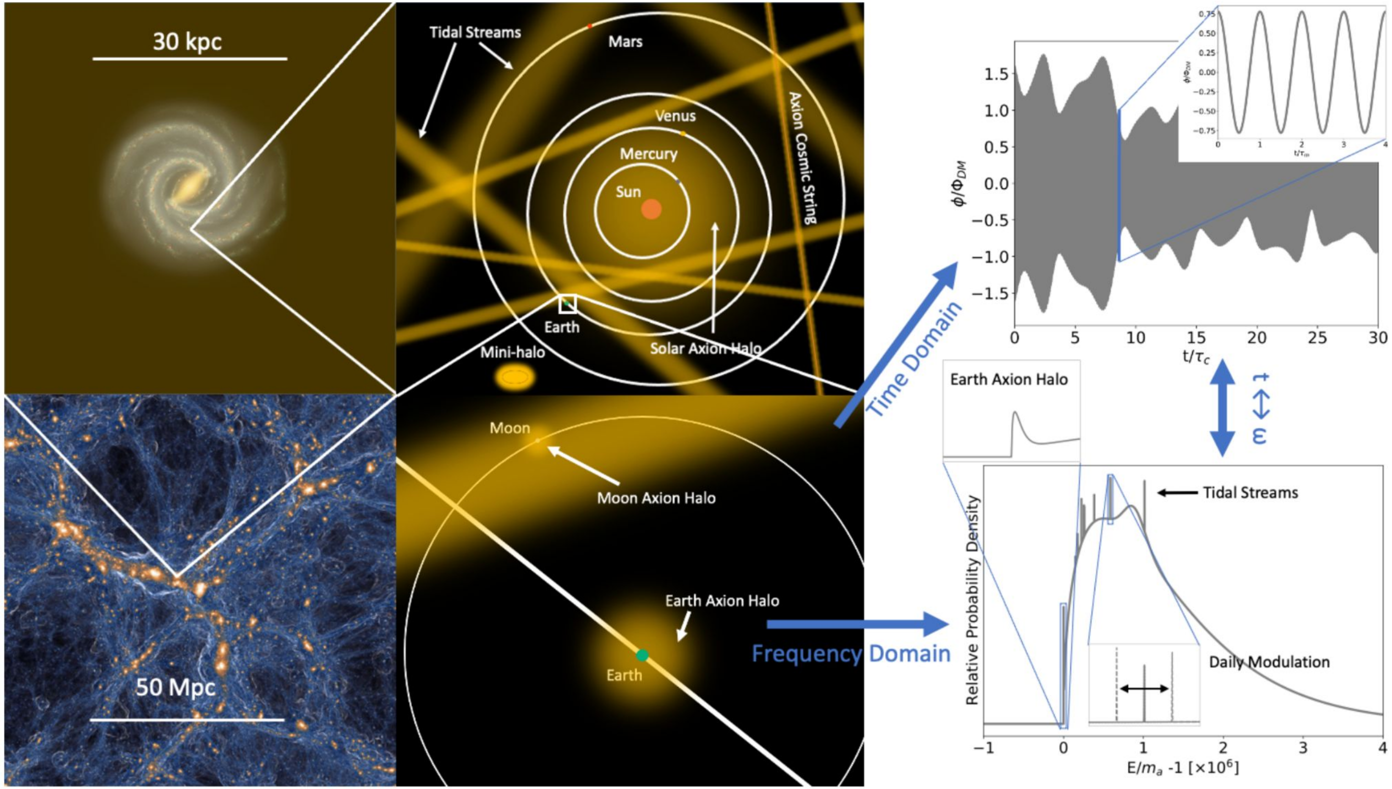
Berkeley

Axion misalignment mechanism



Berkeley

Modern axion cosmic structure



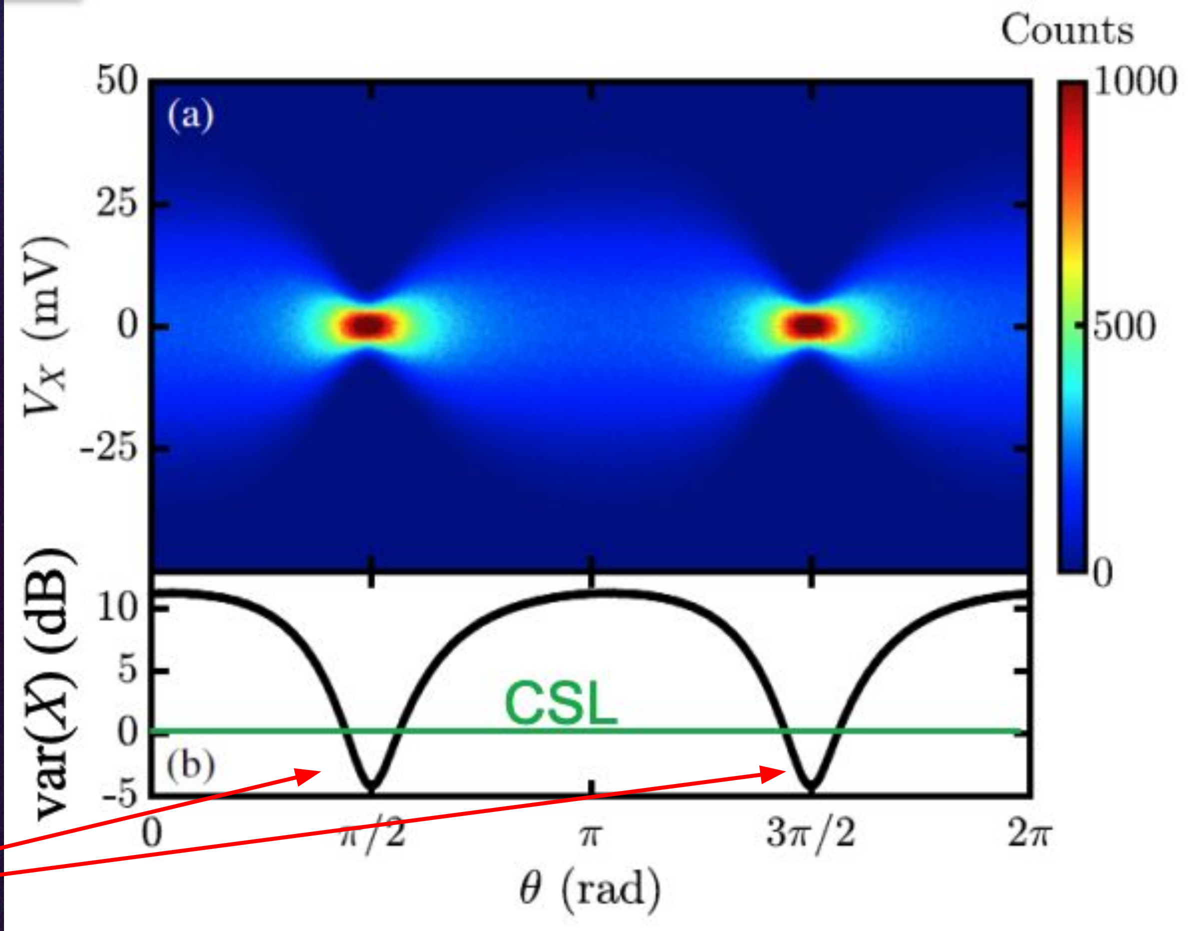
Snowmass 2021 White Paper Axion Dark Matter, arxiv:2203.14923

Berkeley

PQ symmetry, KSVZ & DFSZ

- P&Q proposed a solution to the Strong CP Problem: there exists an additional symmetry of Nature, $U(1)_{PQ}$, which is spontaneously broken by a scalar field σ.
  - σ also gives mass to a quark *q*, similar to how the SM quarks gain mass by EWSB by the Higgs field
  - It makes sense to identify σ with the SM Higgs field but this breaks some things. So instead PQWW assumed there were *two* Higgs doublets (instead of one). This predicts m_a>150 keV which was rapidly ruled out experimentally.
- KSVZ
  - *q* and σ are not SM, σ has its VEV at $\sigma=|f_a|$ and experiences SSB
  - *q* is charged under $U(1)_{PQ}$
  - Phase of σ is the axion
- DFSZ
  - *q* is SM quark, but σ has VEV at $\sigma=|f_a|$ >>200 GeV (EW scale)
  - *q* is charged under $U(1)_{PQ}$
  - Phase of σ is the axion
- Both are families of models, depending on choice of *E/N*

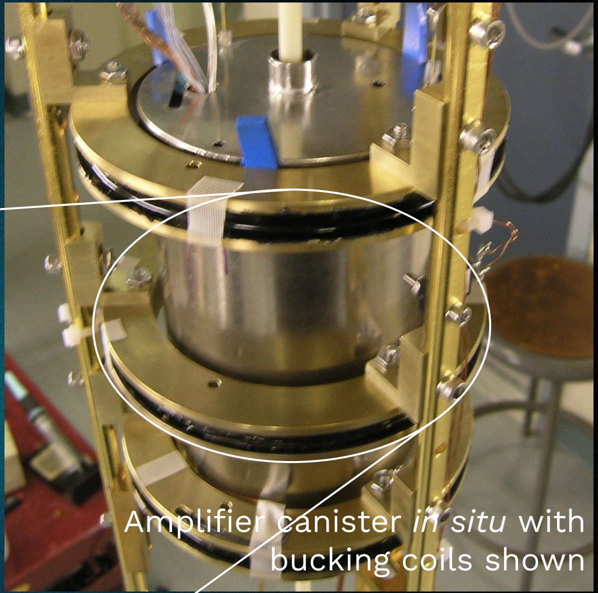
Berkeley



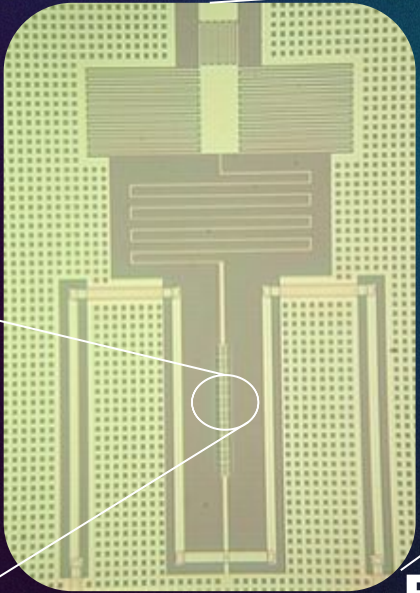
Sub-SQL variance

HAYSTAC Phase I:

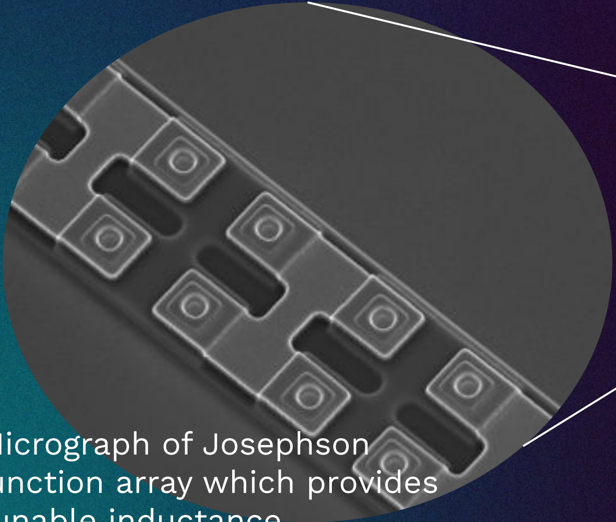
- Single JPA operation to lower system noise
- Near quantum-limited noise: $T_{sys} \sim (2\text{-}3) \times T_{SQL}$ @6GHz



Amplifier canister *in situ* with bucking coils shown



Josephson Parametric Amplifier



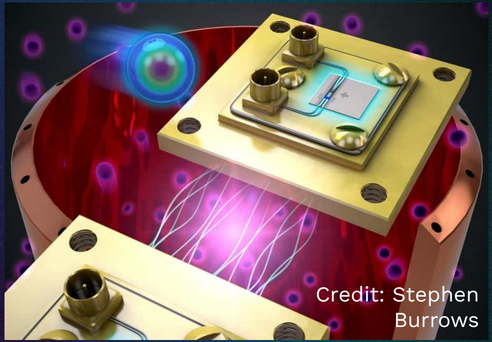
Micrograph of Josephson junction array which provides tunable inductance

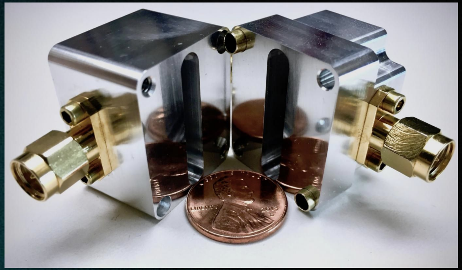
Excluded axions ~24ueV @ $g_{a\gamma\gamma} \sim 2 \times$ KSVZ

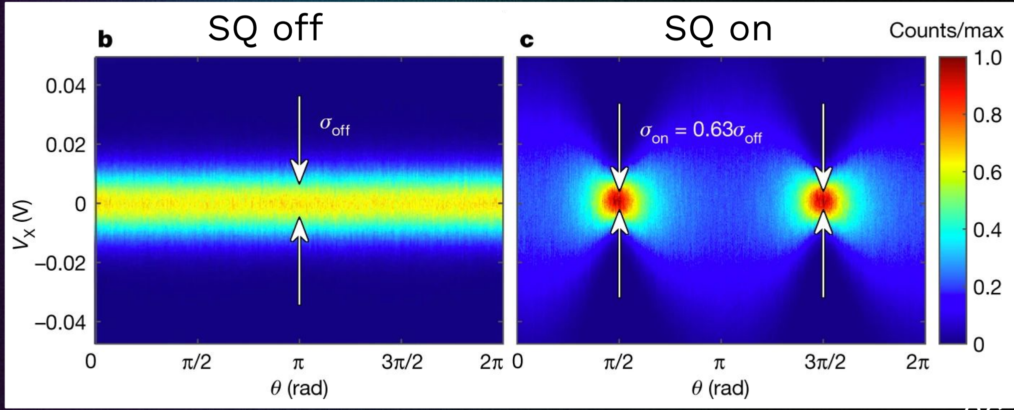
L. Zhong, et al. *PRD* (2018)

HAYSTAC Phase II: key points

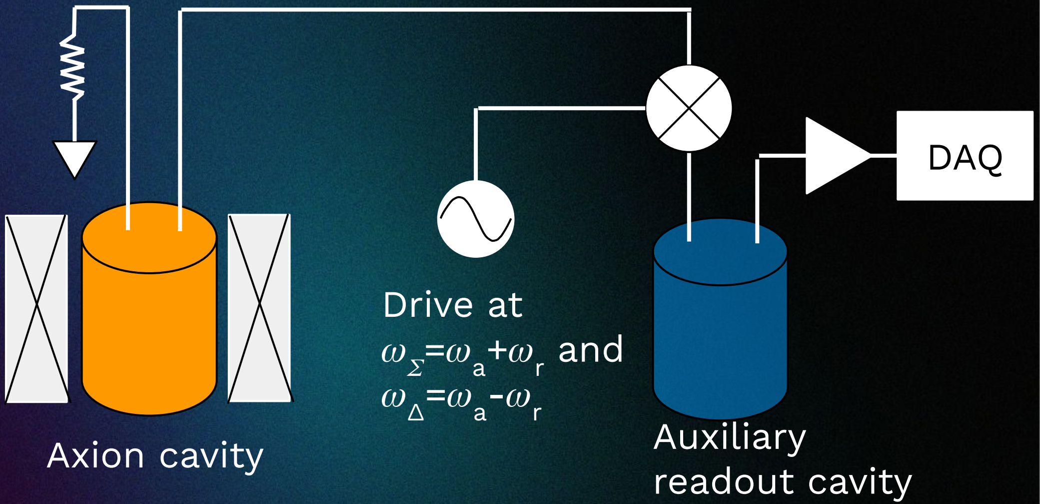
- Dark matter search enhanced by squeezed state operation
- First sub-SQL result in astroparticle physics
- Josephson Parametric Amplifiers create squeezed state + amplify axion signal
- 4 dB noise reduction
- **2X scan rate increase**



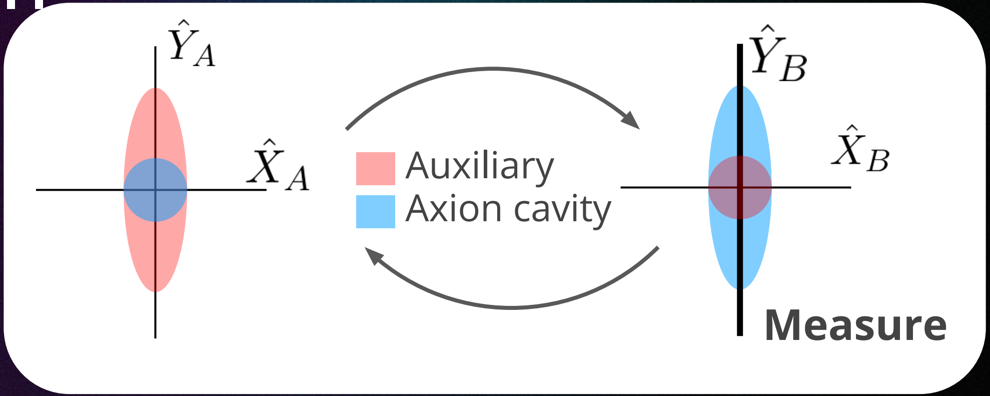




An improved readout scheme: squeezing and state swapping in HAYSTAC Phase III

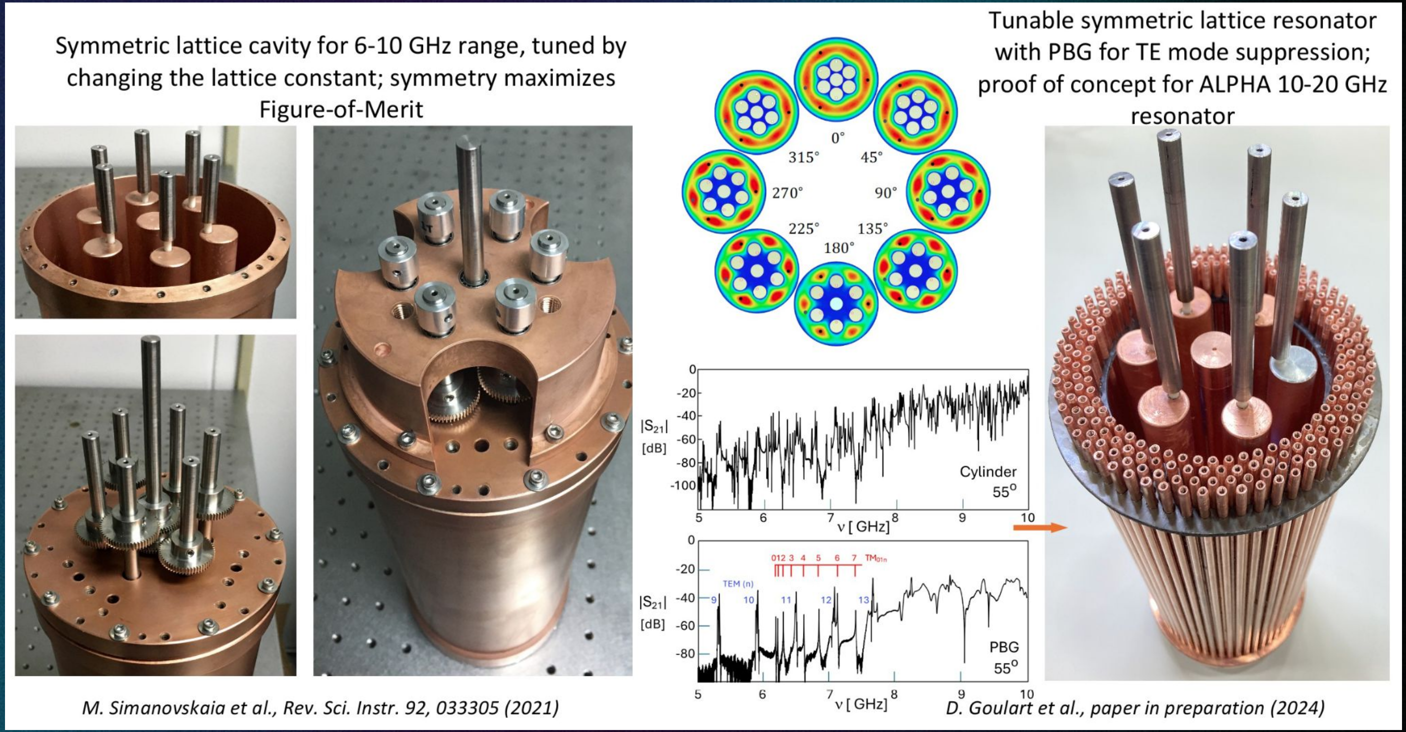


- Squeezing is limited by loss between the two JPAs
- Noiselessly amplify one quadrature of cavity state; deposit uncertainty into unmeasured quadrature
- **~6X scan rate enhancement possible**

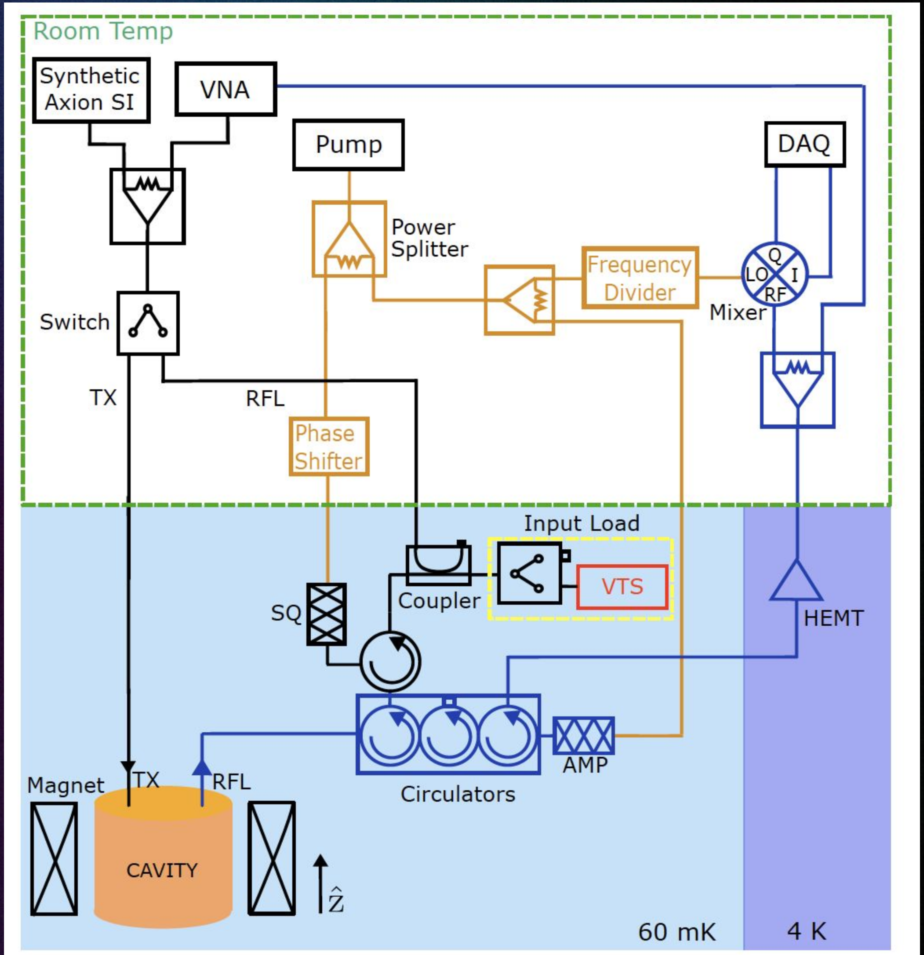


K. Wurtz, et al., *PRX Quantum, 2* 040350 (2021)
Y. Jiang, et al., *PRX Quantum 4* 020302 (2023)

Extending HAYSTAC to higher frequencies: multi-rod cavities



HAYSTAC wiring diagram



Black: inputs + calibration injection
Orange: path of pump tone for SQ and AMP
Blue: readout path

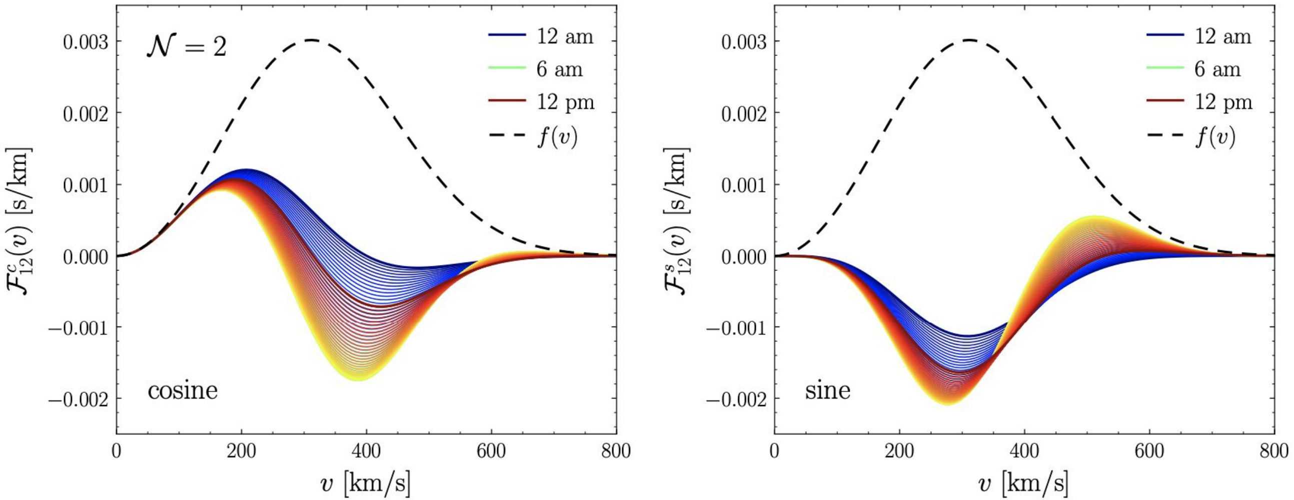
Axion interferometry

- Recent work (J. Foster, et al., *Phys. Rev. D. 103* 076018 (2021)) suggests that two axion haloscopes operating simultaneously within a few axion coherence lengths of each other can uncover details about the dark matter substructure
- We will be able to directly measure vector velocity of the Sun through the galactic halo, cold flows in DM to better than 1°
- Analogous to a global array of radio telescopes

Berkeley

Axion interferometry

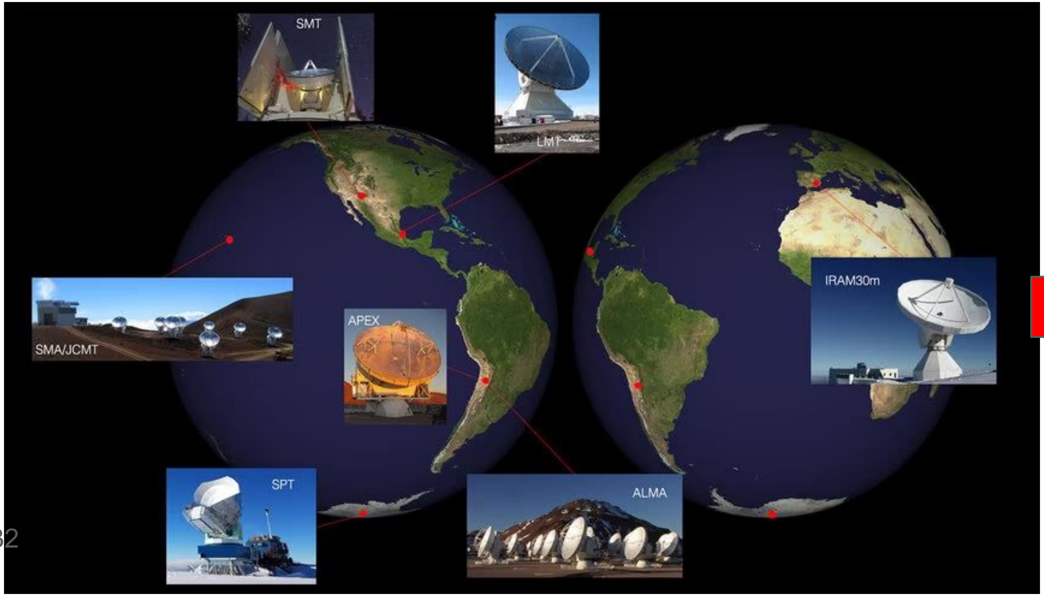
- The example in the J. Foster paper is explicitly based on the HAYSTAC detector
- 10 minutes of data taking with two HAYSTAC-like detectors separated by *d=20 m* ~ $2\lambda_c$ can uncover DM substructure

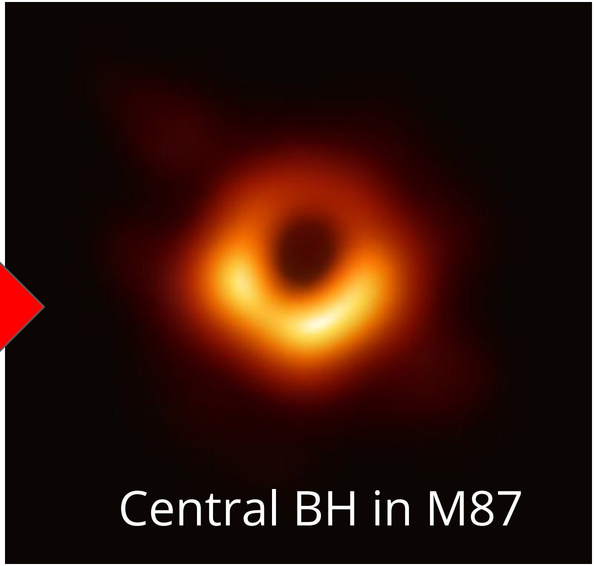


Berkeley

Axion interferometry

- J. Foster papers considers what can be learned from axion haloscopes operating similar to radio telescope arrays
- A recent groundbreaking example from radio astronomy is the Event Horizon Telescope

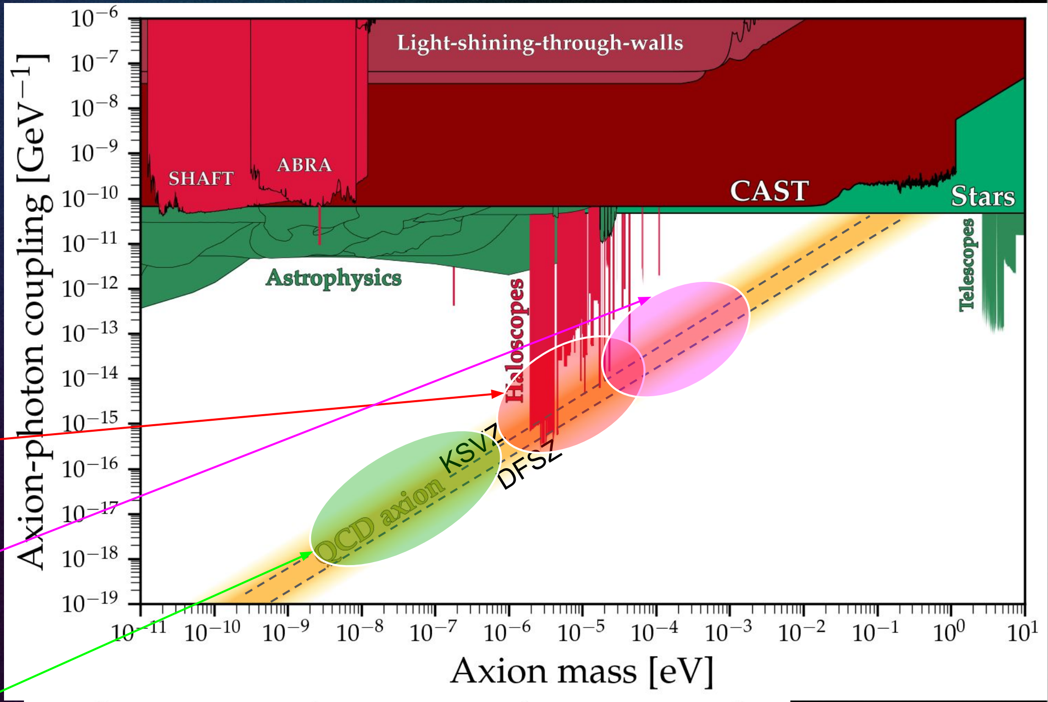


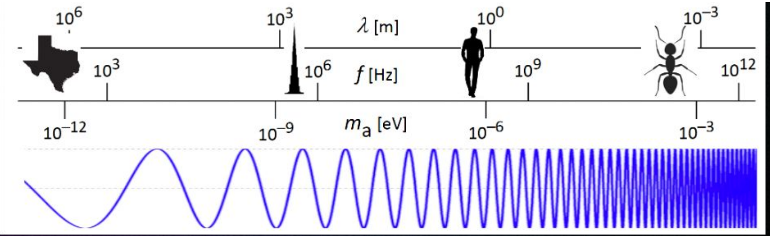


Backup

Axions as dark matter

- Generally three experimental regions:
  - Post-inflationary axion
    - m_a~10 ueV
    - Microwave cavities
  - High mass axions
    - m_a~100 ueV
    - E.g. metamaterials
  - GUT-scale axion
    - m_a~1 neV
    - Lumped element circuit

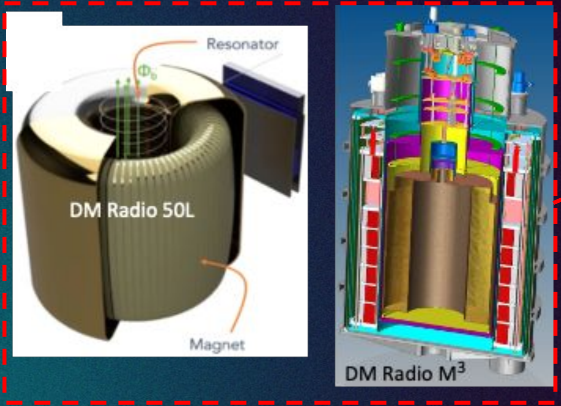


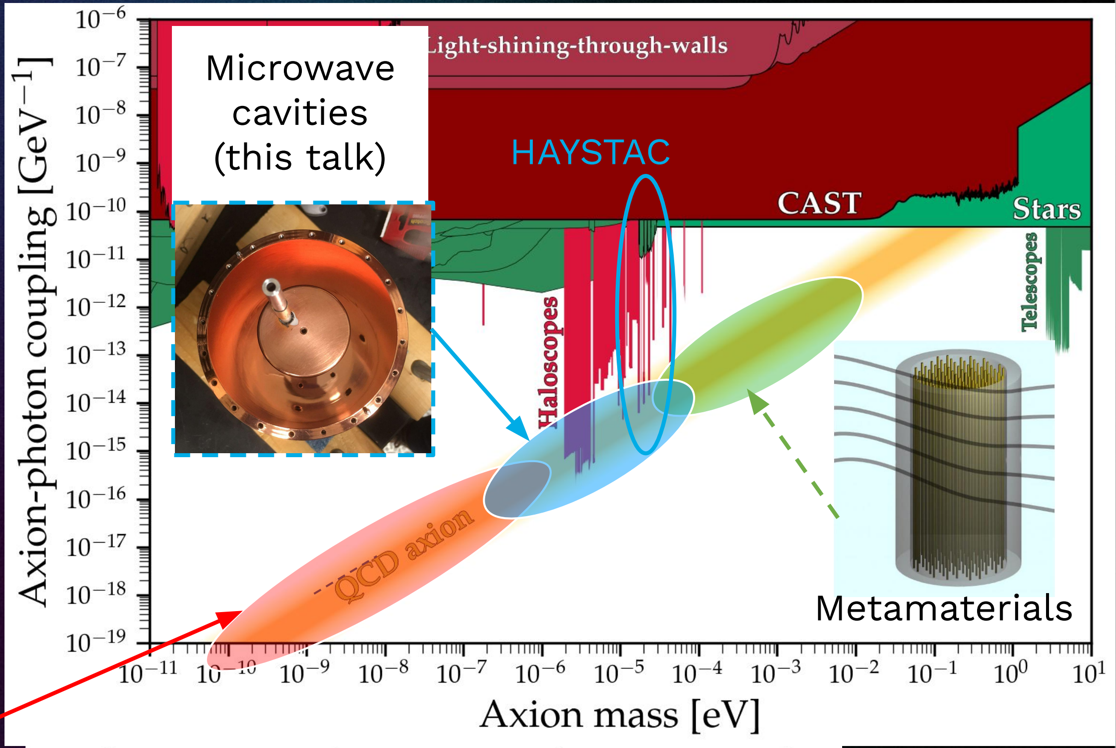


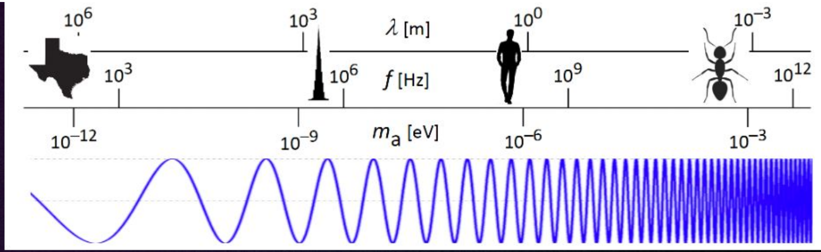
Axions as dark matter

- Probing different axion masses requires different technologies
- **HAYSTAC (this talk)**: 17-24 ueV

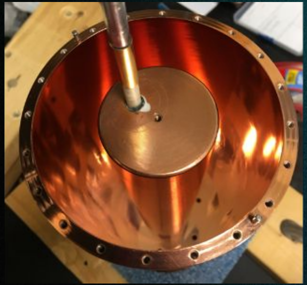
LC oscillators
E.g. DMRadio, ADMX-SLIC...

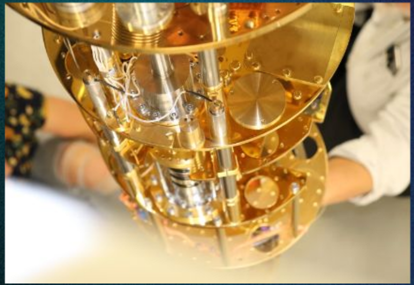


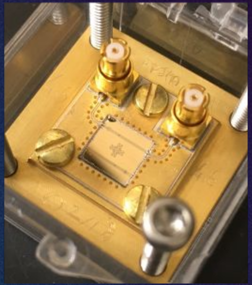


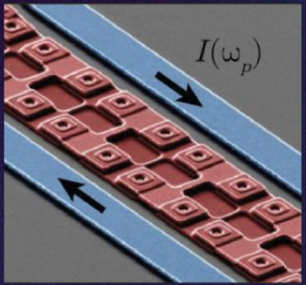


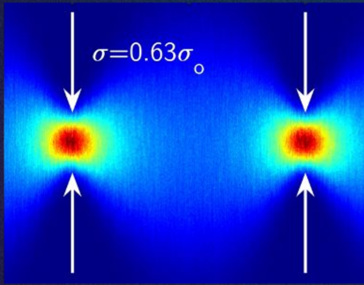
Searching for dark matter axions with HAYSTAC







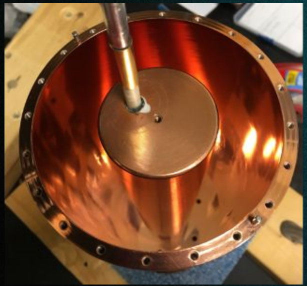


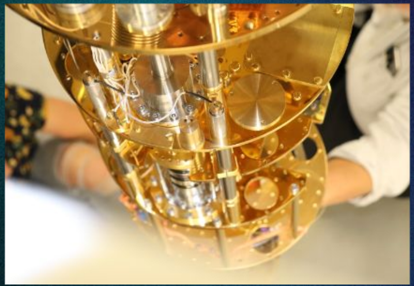


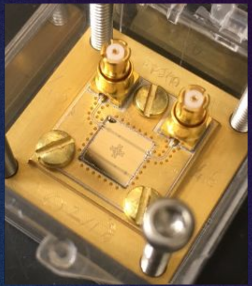
03.25.25
Recontres de Moriond
La Thuile, Italy

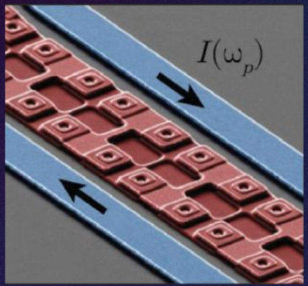
PRESENTATOR: Alex Droster, PhD student
UC Berkeley

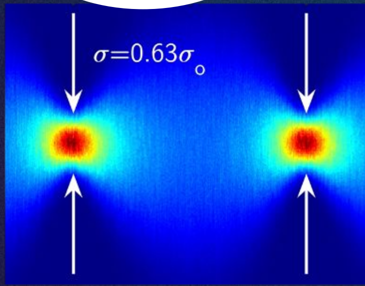
Searching for dark matter axions with HAYSTAC











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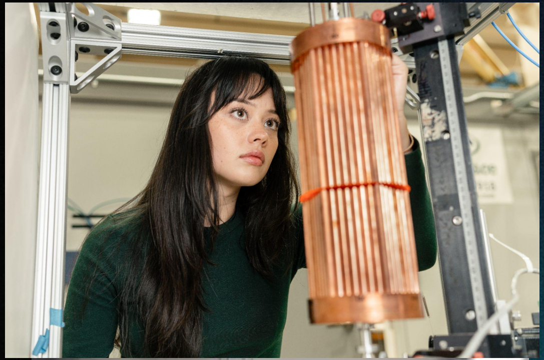
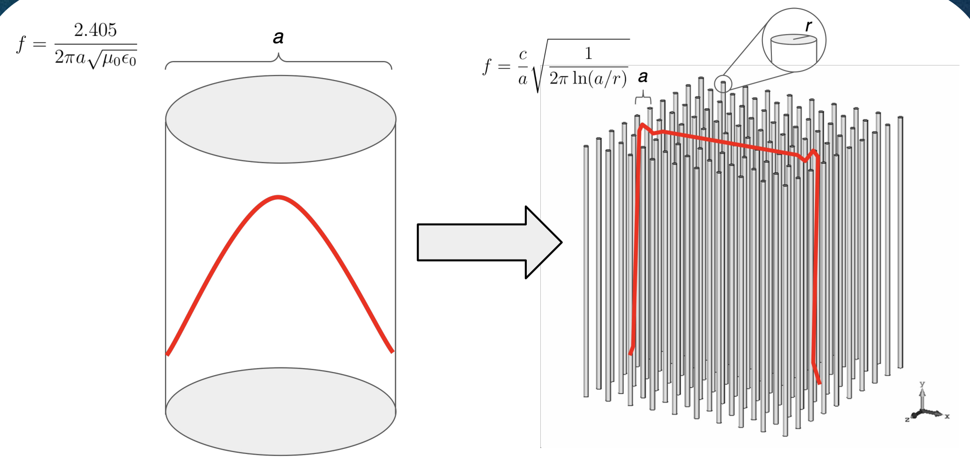
Haystac

ALPHA: **A**xion **L**ongitudinal **P**lasma **Ha**loscope

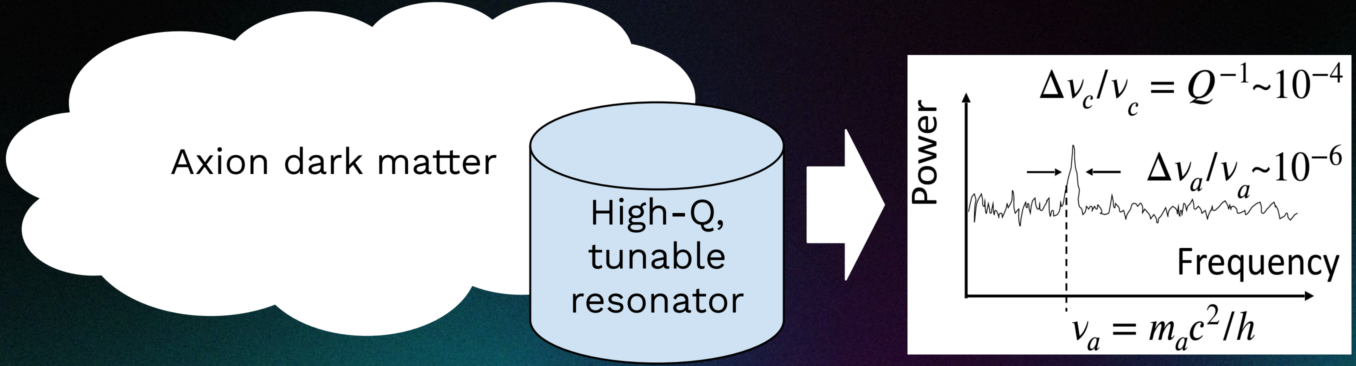


Yale Wright Laboratory



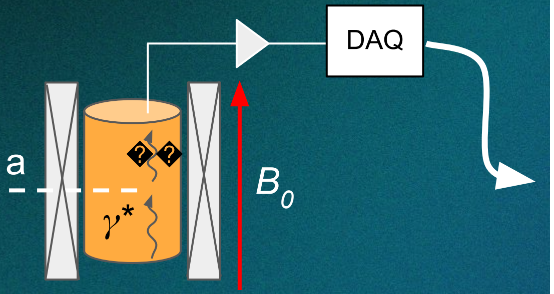
Credit: Jon Gudmunsson

Initial idea: M. Lawson, A. Millar, et al. *PRL 123*, 141802 (2019)



Weak, highly coherent signal tone at unknown frequency

Searching for axions with haloscopes



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

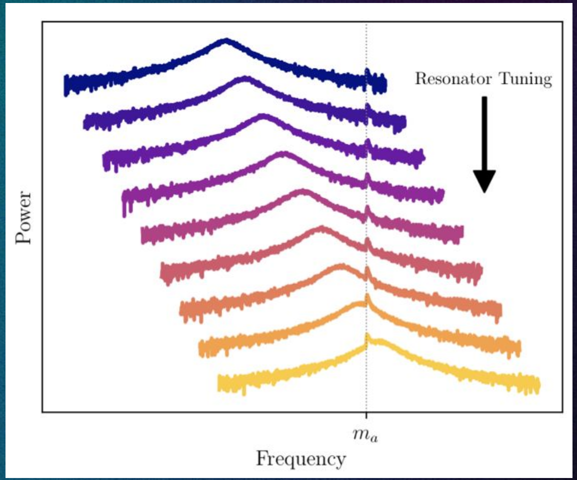
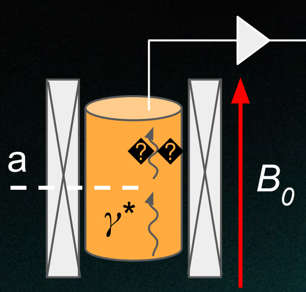


Figure of merit: *scan rate, df/dt*

10,000 years to scan full axion parameter space!

How can we improve this?

Alex Droster



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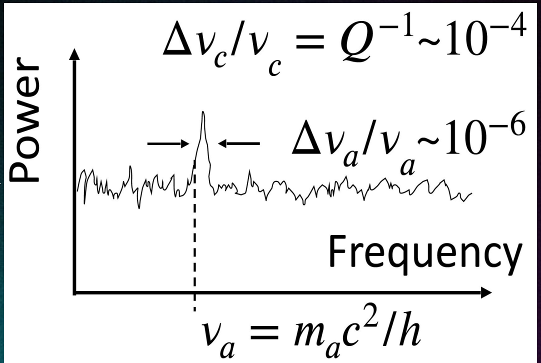
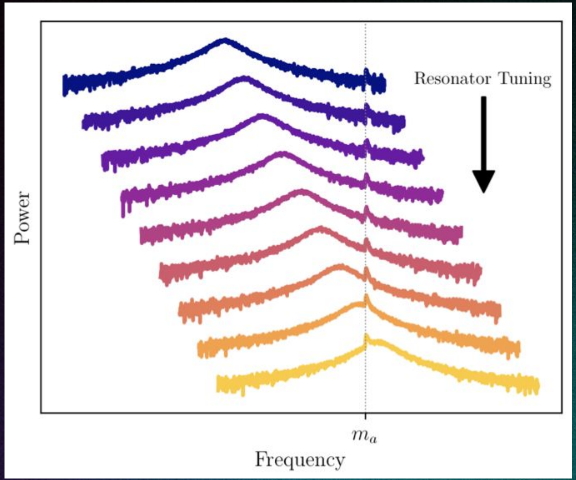




Searching for axions with haloscopes

- Magnet: B_0~9 T
- High cavity Q: ~50,000
- Volume: V~1.5L
- Tunable: 4-6 GHz
- Low noise amplifiers: N_{sys}
- Cryogenic: ~60 mK
- **Expected signal power is very small: 10^{-24} W!**

Figure of merit: *scan rate*

$$R = \frac{d\nu}{dt} \propto Q_L Q_a \left(\frac{g_{a\gamma\gamma}^2 \rho_{DM}}{m_a^2}\right)^2 \left(B_0^2 V C_{mnl} \frac{1}{N_{sys}} \frac{1}{SNR}\right)^2$$

Axion physics — Experimental parameters

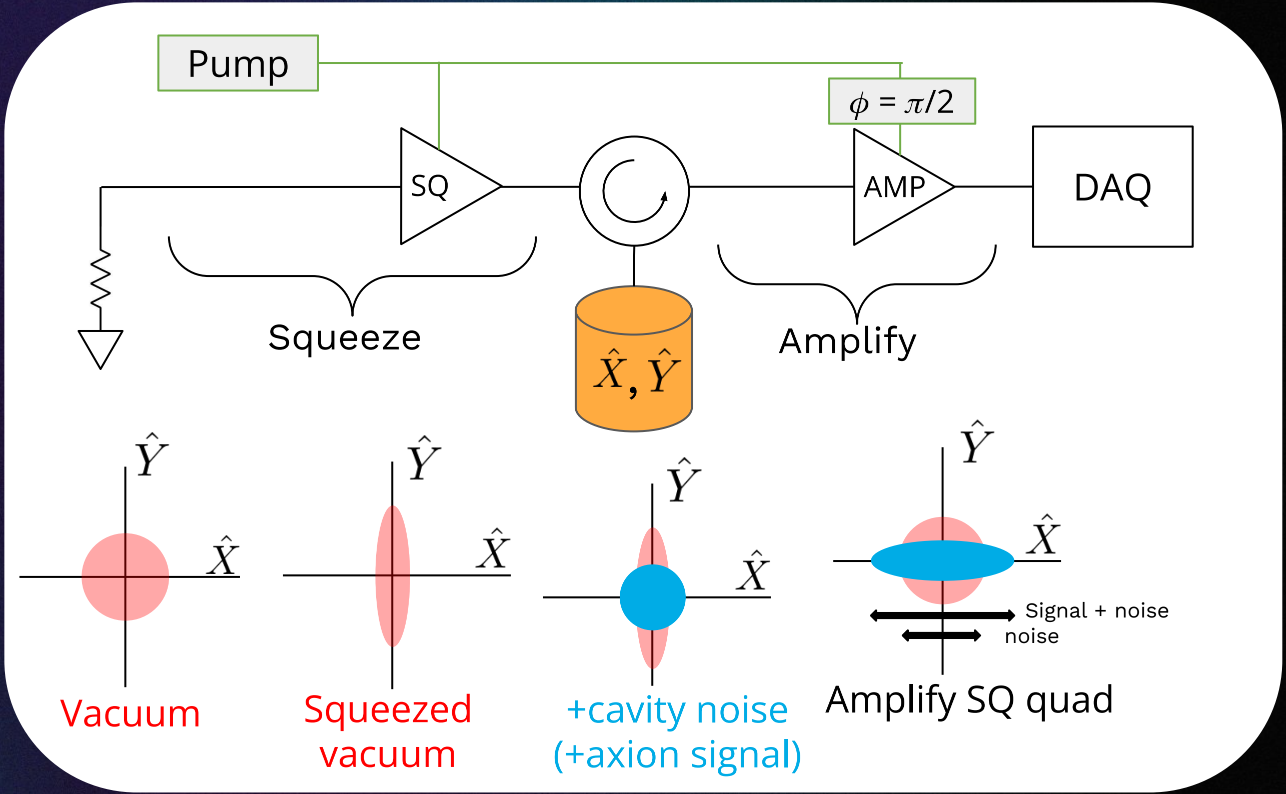
Quantum sensing in HAYSTAC Phase II

Two JPAs operating together can beat the SQL

Cavity Hamiltonian:

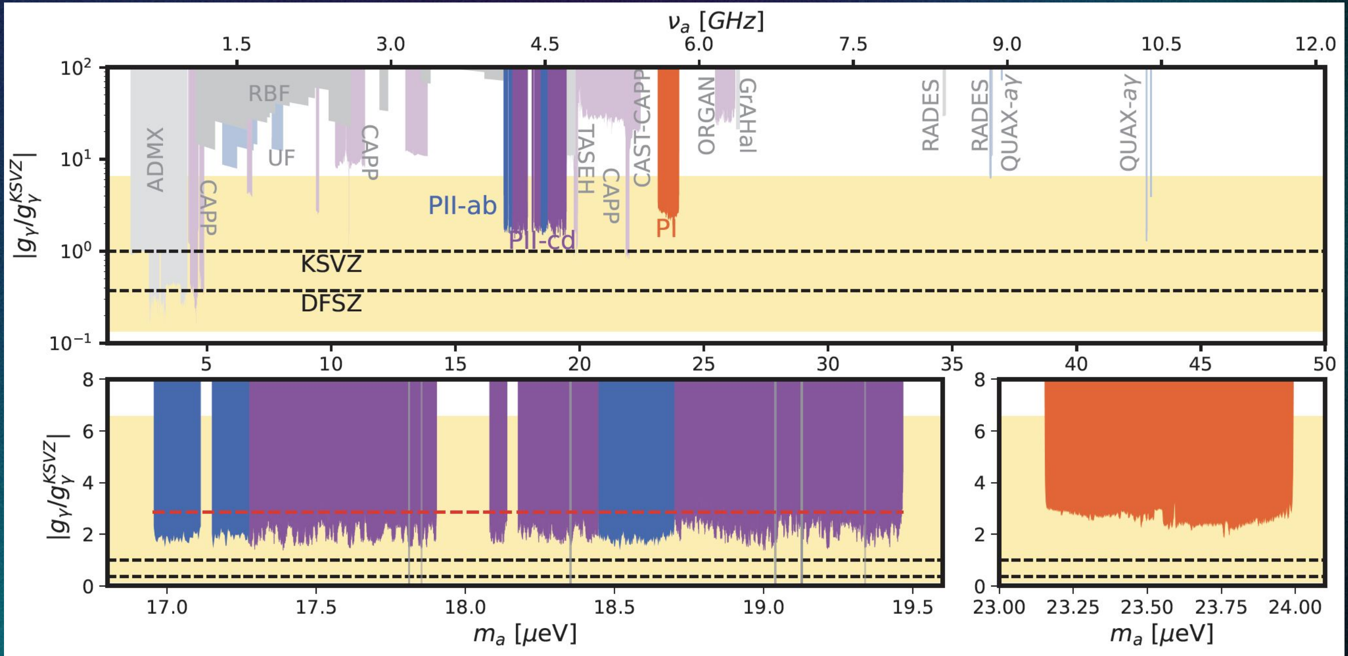
$$\hat{H} = \frac{h\nu_c}{2}(\hat{X}^2 + \hat{Y}^2)$$

$$[\hat{X}, \hat{Y}] = i$$



M. Malnou, D. Palken, et al., *Phys. Rev. X* 9, 021023 (2019)

HAYSTAC results so far



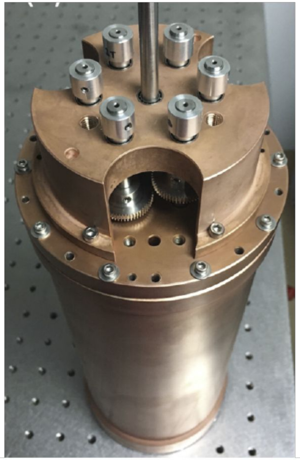
We have 5 major results papers:

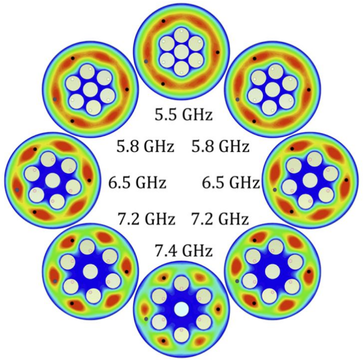
- Phase I, Run 1: First Axion search with Quantum limited Noise, ***Phys. Rev. Lett.* 118, 061302 (2017)**
- Phase I, Run 1+2: Improved Search, ***Phys. Rev. D* 97, 092001 (2018)**
- Phase IIa: First Search Below the SQL, ***Nature* 590, 238 (2021)**
- Phase IIa+b: Detailed Overview of SSR Search, ***Phys. Rev. D* 107, 072007 (2023)**
- Phase IIc+d: Widest Search Using SSR, **PRL forthcoming**

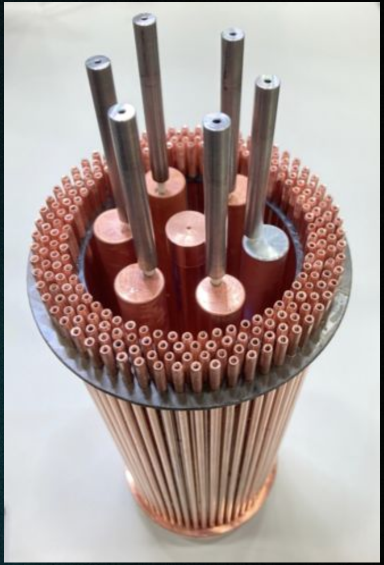
Plot from forthcoming *PRL*

Extending HAYSTAC to higher frequencies: multi-rod cavity, photonic bandgap structures

HAYSTAC Run III







- Jpa details, phase sensitive amplification
- How axion solves CP issue
- TM mode details?
- Quadrature details?