ADMX-VERA: A large volume haloscope for higher axion frequencies

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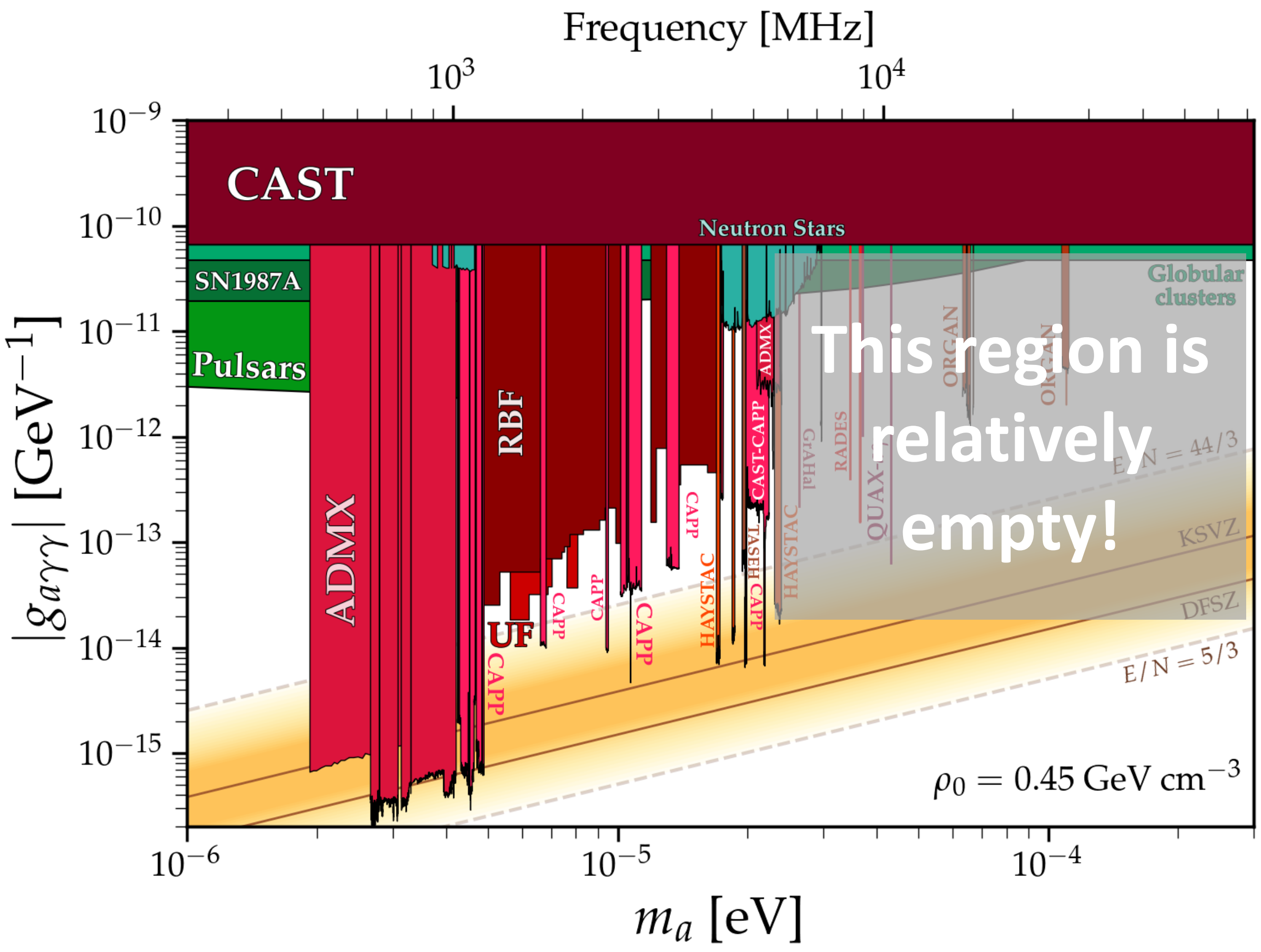
19th PATRAS Workshop on Axions, WIMPs, and WISPs

September 17th, 2024

AXION DARK MATTER EXPERIMENT

Haloscopes for higher frequencies



This region is relatively empty!

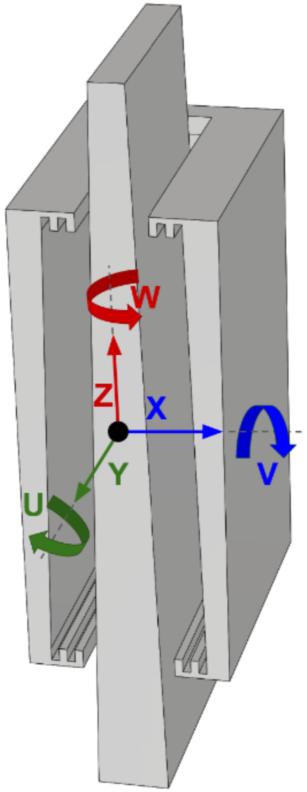
from https://cajohare.github.io/AxionLimits/

$$\frac{d\nu}{dt} \propto B_0^4 \mathbf{V}^{\mathbf{2}} C^2 Q_L T_{\mathrm{sys}}^{-2}\left(\frac{\beta}{1+\beta}\right)^2$$

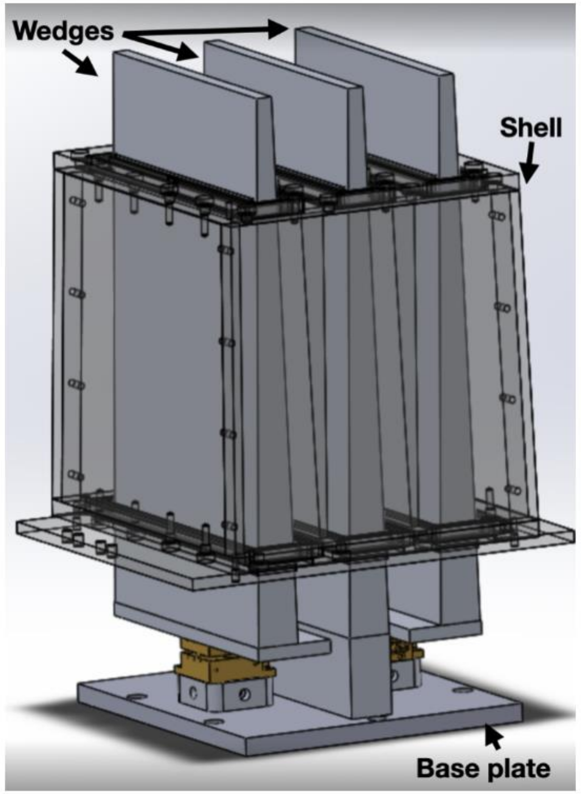
The volume of cylindrical cavities at high frequencies becomes smaller, making QCD-axion-sensitive high-frequency axion searches difficult

ADMX-VERA cavities with high volumes

T. Dyson et al., Phys. Rev. Applied 21, L041002

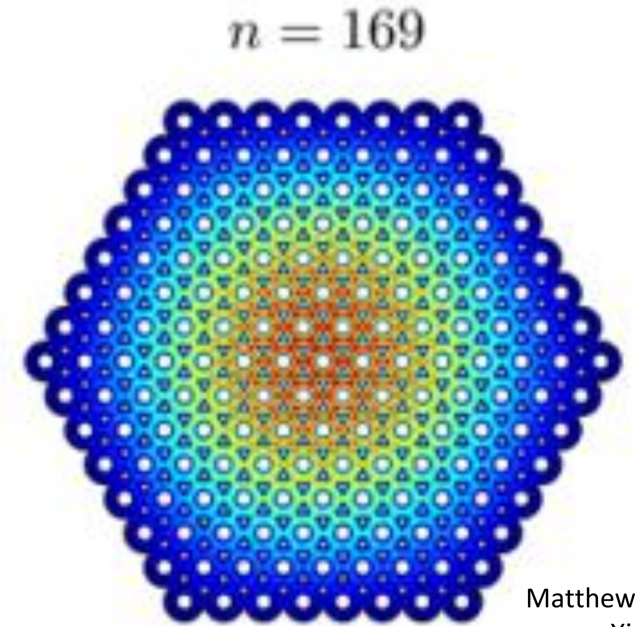


Sephora Ruppert



Single and triple wedge cavity resonant frequencies depend only on the width of the volume space

$$\frac{dv}{dt} \propto B_0^4 \mathbf{V^2} C^2 Q_L T_{sys}^{-2} \left(\frac{\beta}{1+\beta}\right)^2$$

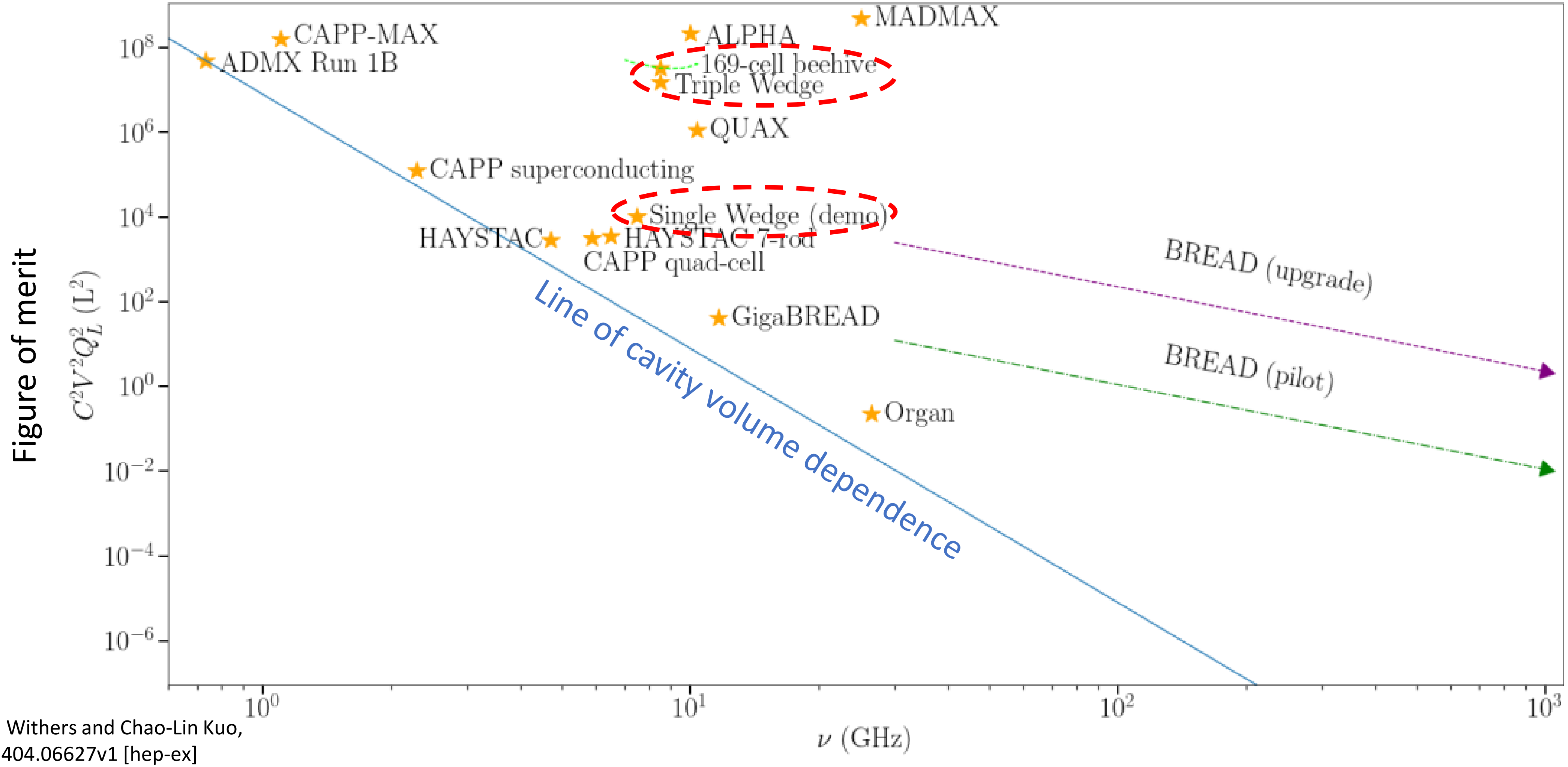


Matthew O. Withers and Chao-Lin Kuo, arXiv:2404.06627v1 [hep-ex]

See Matt's talk for details (yesterday)

Multiple-cell beehive cavity that share the resonant frequency among all cells

Advantages of ADMX-VERA cavities



Matthew O. Withers and Chao-Lin Kuo,
arXiv:2404.06627v1 [hep-ex]

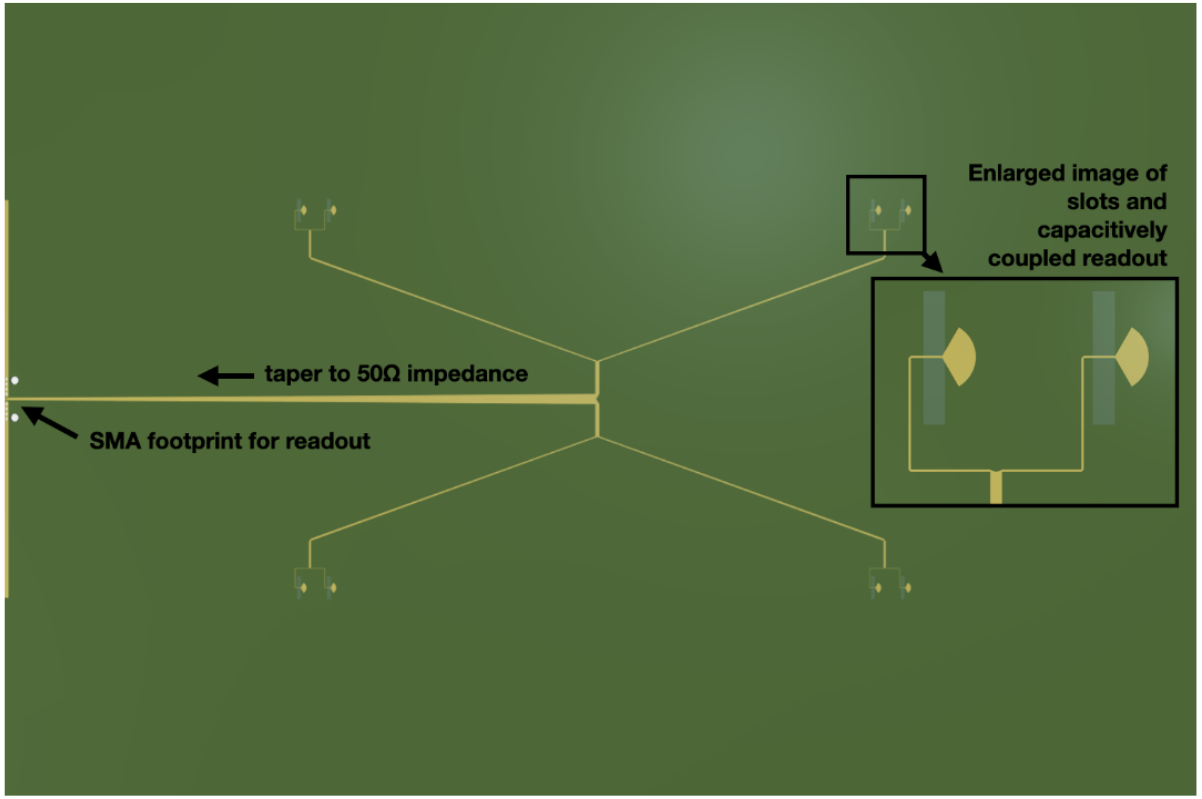
Challenges of the thin shell cavity

- Misalignment in cavity can localize modes and limit wire antenna coupling

$$\frac{dv}{dt} \propto B_0^4 V^2 C^2 Q_L T_{sys}^{-2} \left(\frac{\boldsymbol{\beta}}{\mathbf{1}+\boldsymbol{\beta}}\right)^{\mathbf{2}}$$

Max at $\beta = 2$

- Summing trees can coherently add signals through impedance matching from multiple slot antennas
  - Used in CMB experiments before, and will be the first time to be used in axion haloscope searches



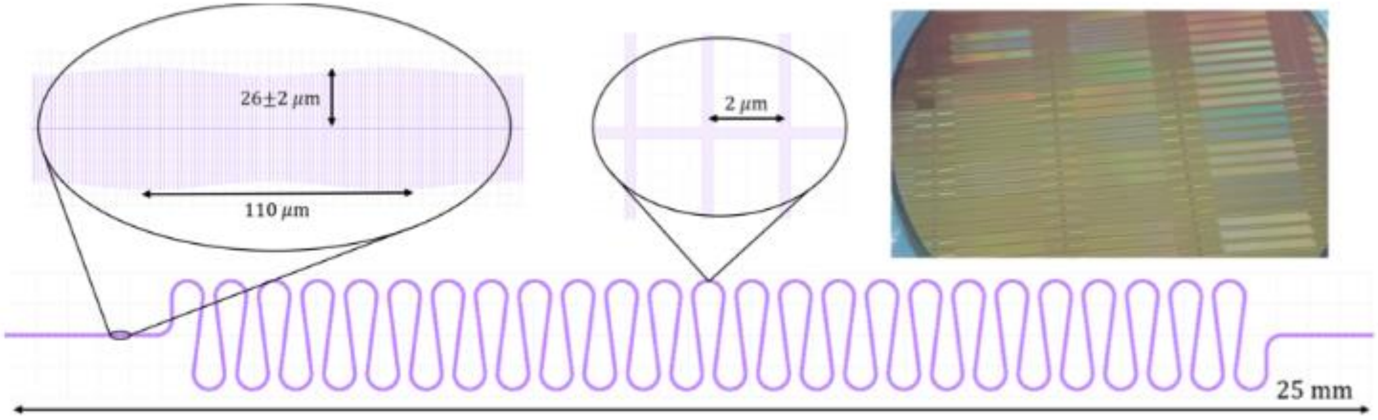
Basic summing tree structure for eight slot antennas

Based on work from Chao-Lin Kuo et al., Millimeter and Submillimeter Detectors and Instrumentation for Astronomy IV, 7020, 415–428. SPIE, (2008)

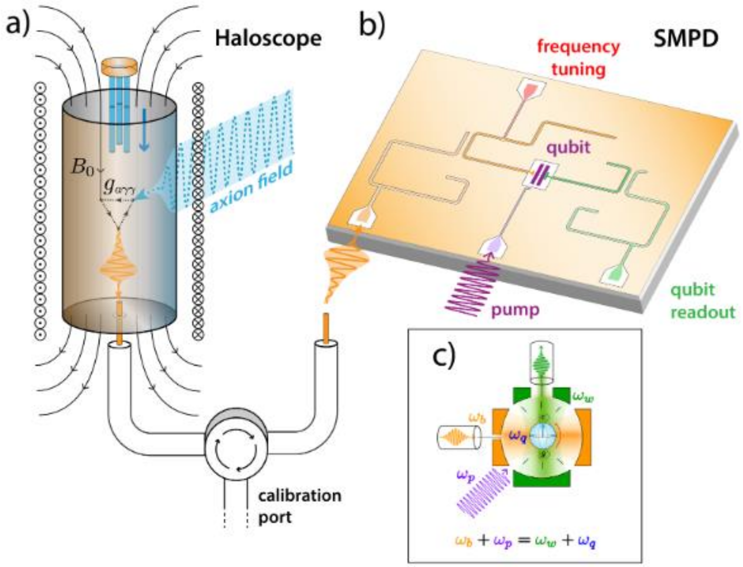
Quantum sensors

- Quantum sensors will be used to decrease noise from the signal

$$\frac{d\nu}{dt} \propto B_0^4 V^2 C^2 Q_L \boldsymbol{T_{\mathrm{sys}}^{-2}} \left(\frac{\beta}{1+\beta}\right)^2$$



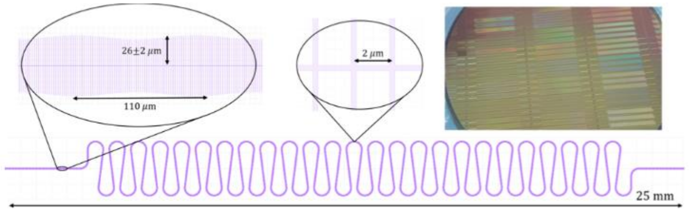
Kinetic inductance travelling-wave parametric amplifiers (KI-TWPAs)

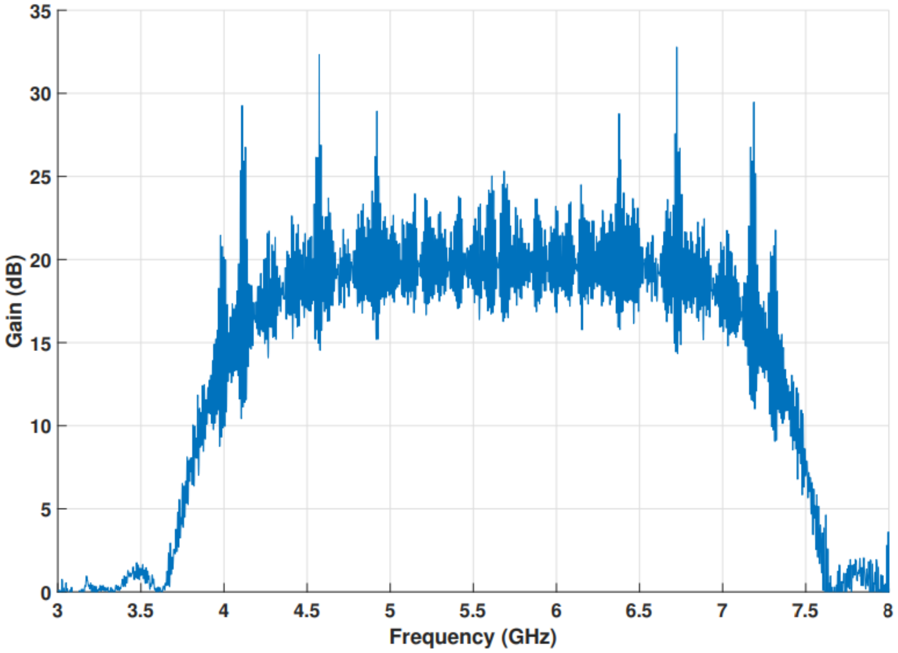


Single microwave photon counting devices (SMPDs)

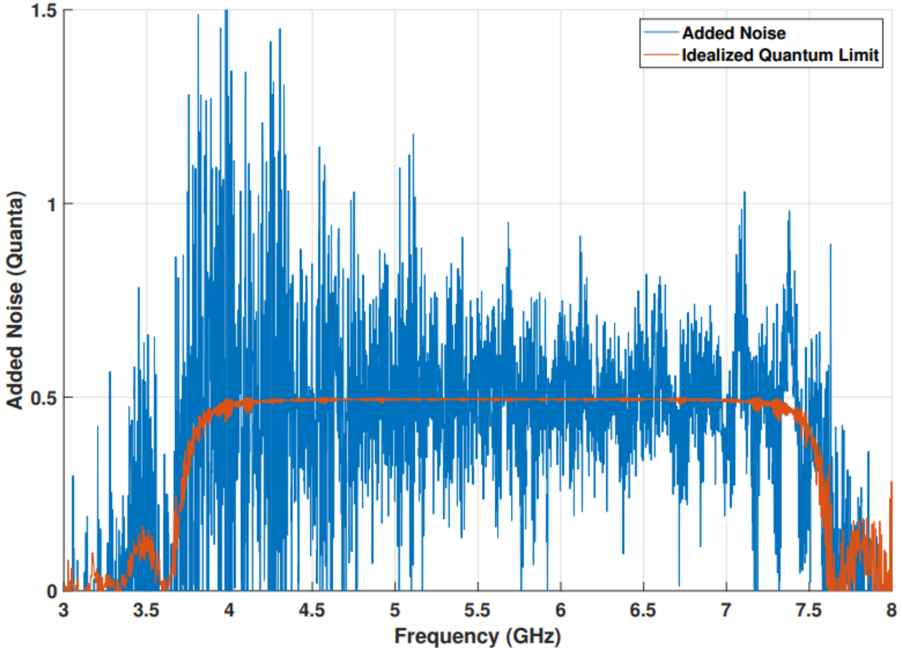
Kinetic inductance travelling-wave parametric amplifiers (KI-TWPAs)

- KI-TWPAs are quantum-limited parametric amplifiers with wide bandwidths using traveling wave periodic structures





High gain, 3 GHz bandwidth

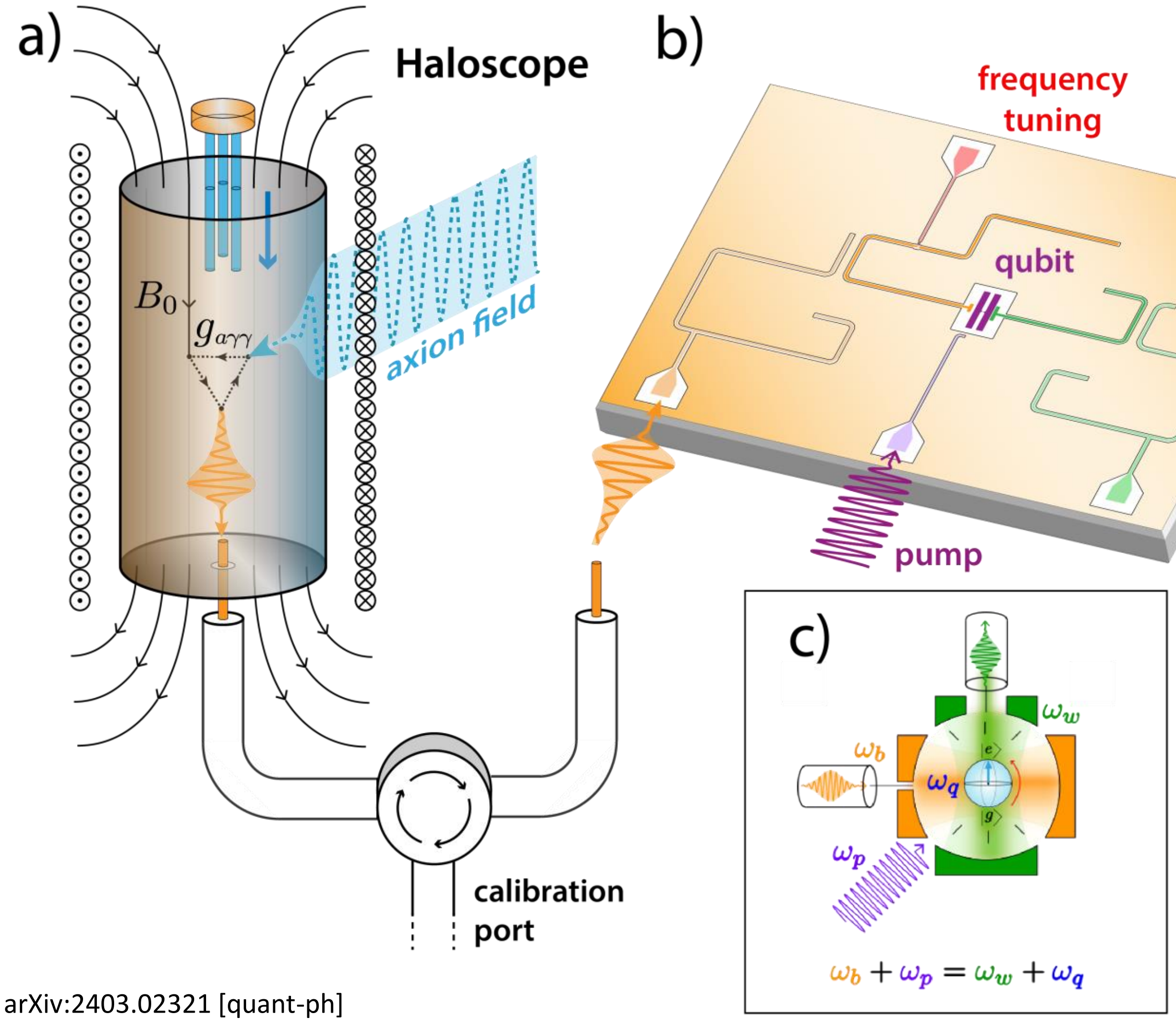


Added amplifier noise (blue) is close to quantum limit (orange)

Klimovich, Nikita Sergeevich (2022) Traveling Wave Parametric Amplifiers and Other Nonlinear Kinetic Inductance Devices. Dissertation (Ph.D.), California Institute of Technology

Single microwave photon counting devices (SMPDs)

- Converted photons in the haloscope excite a superconducting qubit circuit which can be measured as readout
- Frequency is tunable to match target axion frequency
- Advantage over amplifiers at high frequencies and cryogenic temperatures



C. Braggio et al., arXiv:2403.02321 [quant-ph]

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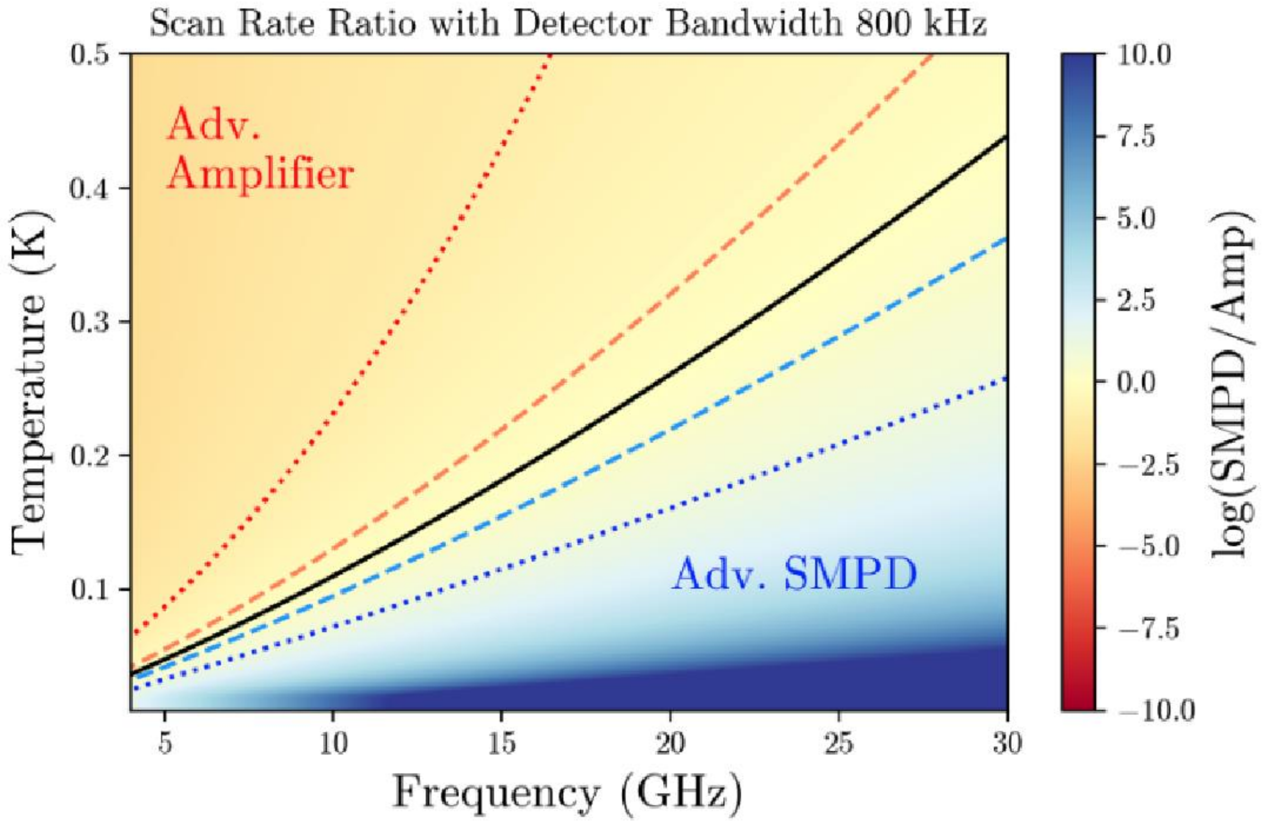
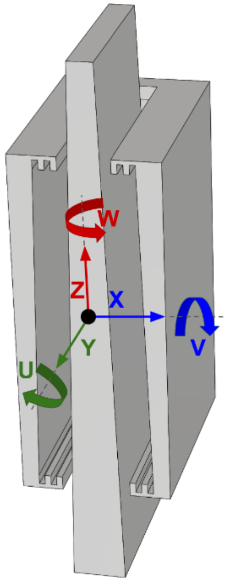
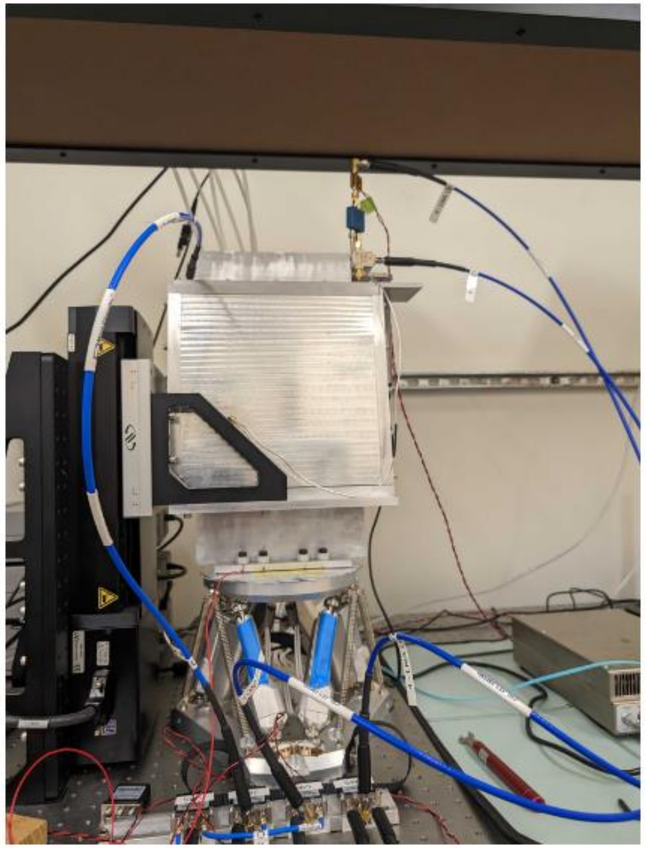


C. Braggio et al., arXiv:2403.02321 [quant-ph]

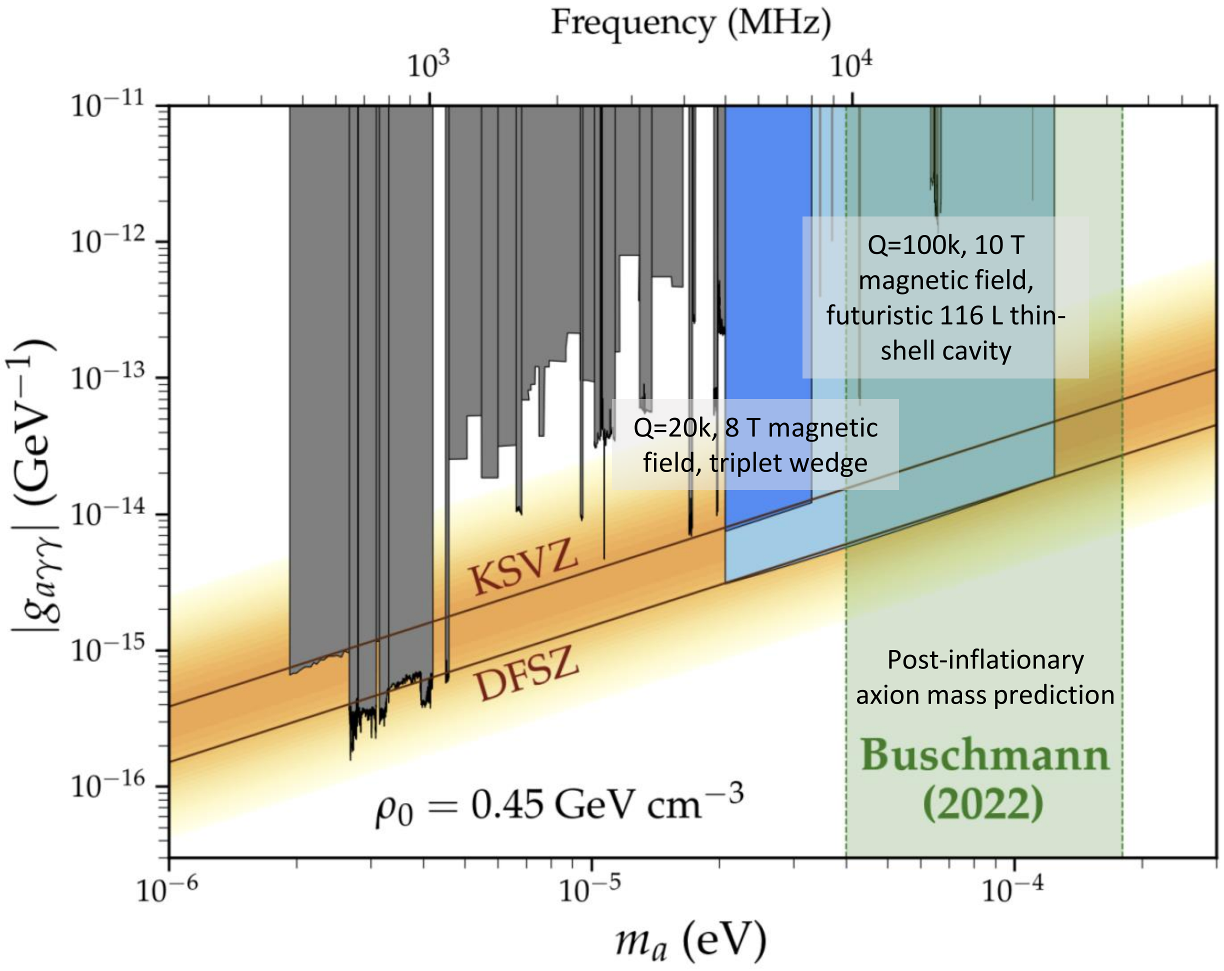
Current progress and discovery potential





Data taken for warm single-wedge cavity dark photon search and now in analysis phase

In progress: cryogenic single-wedge cavity characterization



Q=100k, 10 T magnetic field, futuristic 116 L thin-shell cavity

Q=20k, 8 T magnetic field, triplet wedge

Post-inflationary axion mass prediction

Future axion discovery potential of ADMX-VERA

Summary

- High frequency axion experiments face a small volume problem
- ADMX-VERA has two cavity designs: tunable thin shell cavity and beehive cavity which both increase volume
- Summing trees with slot antennas address low antenna coupling issues
- KI-TWPAs and SMPDs can be used for quantum sensing
- ADMX-VERA is currently using its single wedge cavity for dark photon searches

The ADMX Collaboration

University of Washington 1861

Lawrence Livermore National Laboratory

Berkeley
UNIVERSITY OF CALIFORNIA

The University of Chicago 1890

Fermilab

Pacific Northwest
NATIONAL LABORATORY

Washington University in St. Louis 1853

UF UNIVERSITY of FLORIDA

The University Of Sheffield.

THE UNIVERSITY OF WESTERN AUSTRALIA

ILLINOIS INSTITUTE OF TECHNOLOGY

Los Alamos
NATIONAL LABORATORY
EST. 1943

Axion signal conversion power

- The axion signal conversion power depends on various factors
- $P_{\text{sig}} = \omega_c \frac{U}{Q_L}\left(1 - \frac{1}{1+\beta}\right) = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} \frac{\beta}{1+\beta} \omega_c B_0^2 V \boldsymbol{C} \boldsymbol{Q_L}$

*Assumes $Q_a \gg Q_L$

U: Total energy of a specific mode
$g_{a\gamma\gamma}$: Axion to photon coupling (value varies depending on model)
ρ_a: Axion density in galaxy halos
m_a: Axion mass
β: Cavity coupling parameter (Q_0/Q_r)
ω_c: Cavity resonant frequency
B_0: Average external magnetic field
V: Cavity volume

*Uses natural units and assumes cavity is resonant to axion frequency

C: Form factor, depends on internal electric field of mode and external magnetic field

$$C = \frac{\left|\int_V d^3x \ \vec{E} \cdot \vec{B}\right|^2}{B_0^2 V \int_V d^3x \, \varepsilon_r \left|\vec{E}\right|^2}$$

Q_L: Loaded quality factor, including losses of cavity (Q_0) and receiver (Q_r)

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_r}$$

For an empty cylindrical cavity inside an external B-field in the z-direction, the **TM$_{010}$ mode** has the highest form factor at 0.69