A high quality factor dielectric Fabry-Perot cavity for detecting dark matter axions

Jonathan Gosling

QuEPA

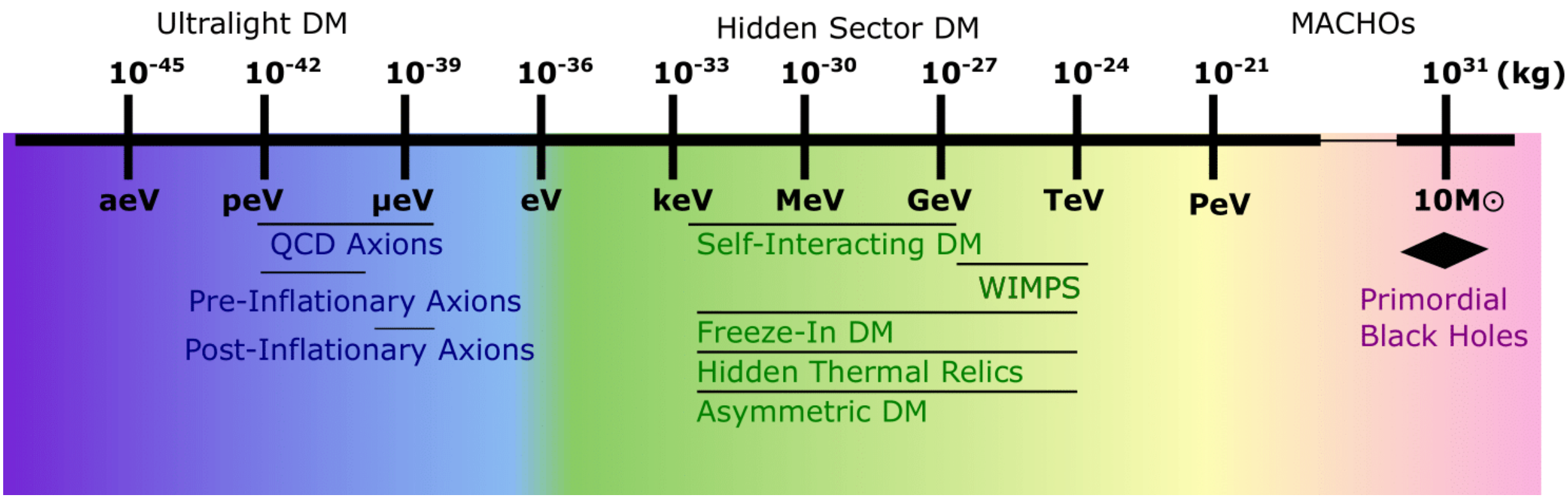
IMPERIAL

THE ROYAL SOCIETY

UKRI Science and Technology Facilities Council

UKRI UK Research and Innovation

Dark matter landscape



E. Killian, et al., AVS Quantum Sci. 6, 030503 (2024)

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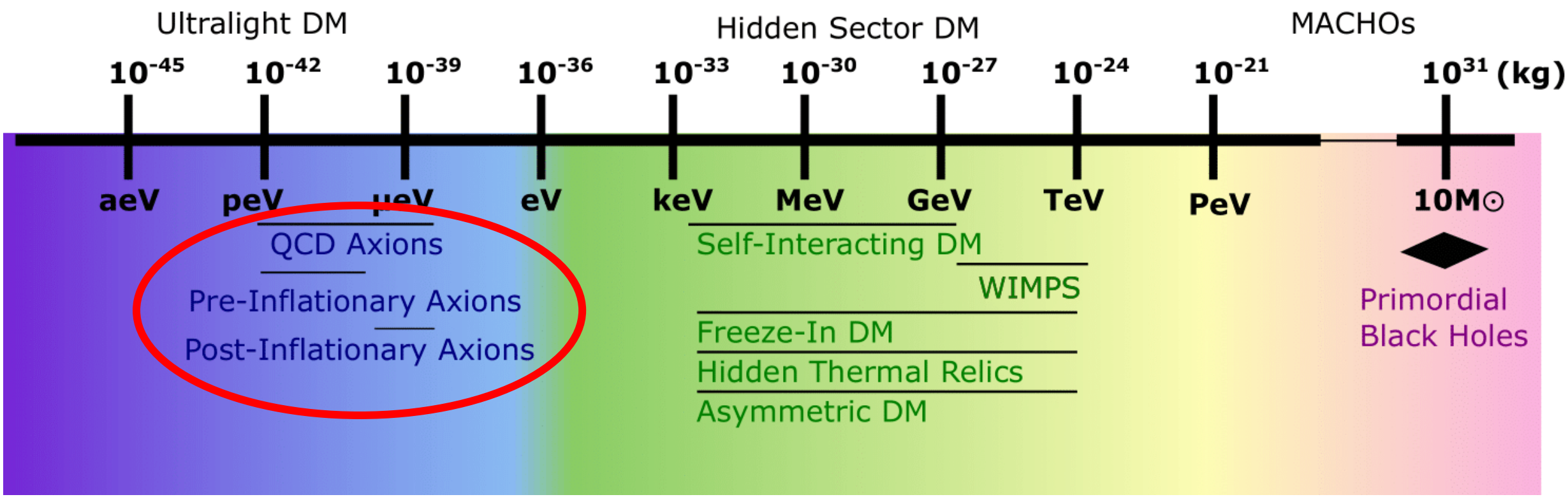
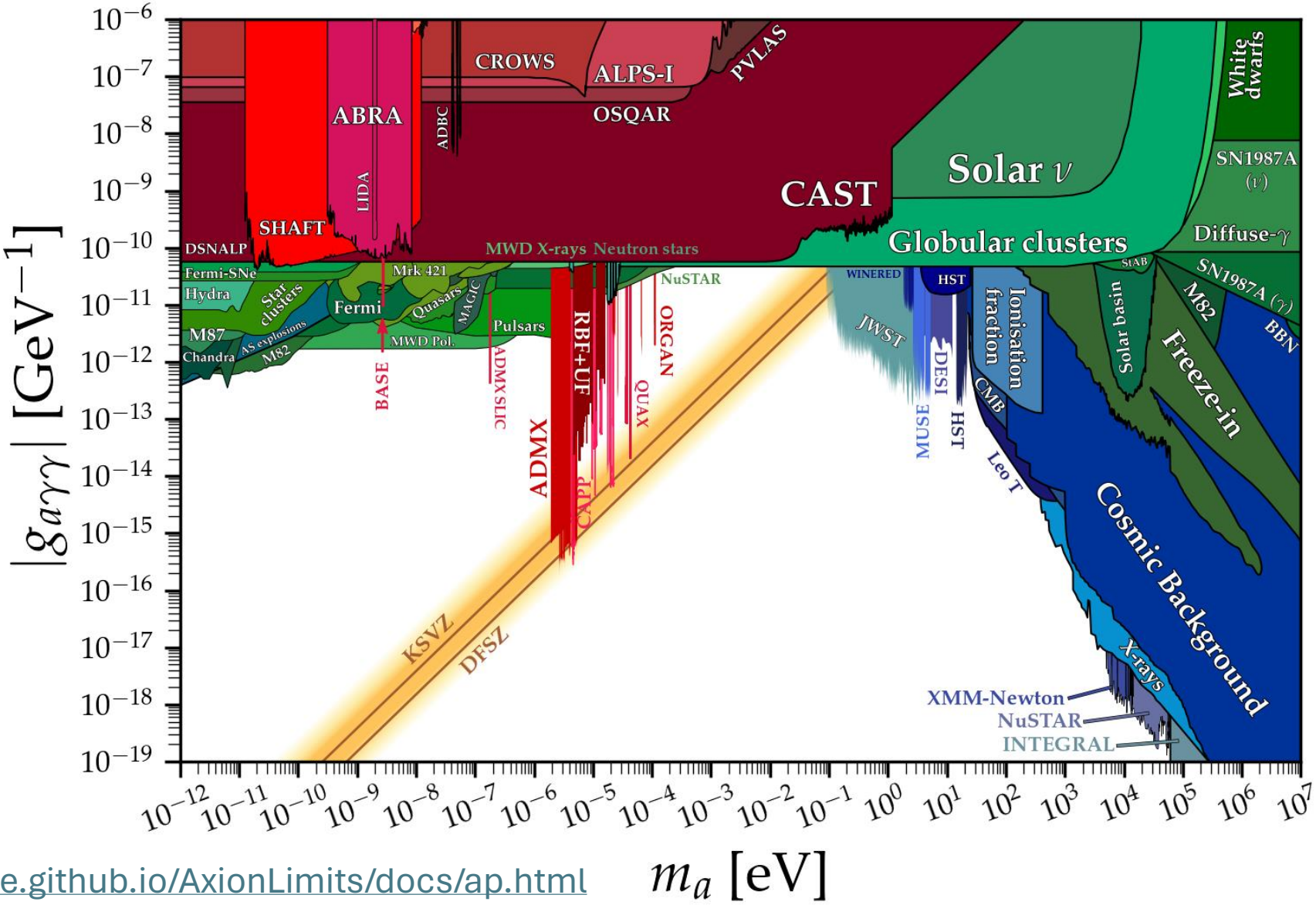


Solves the “strong”-CP problem

E. Killian, et al., AVS Quantum Sci. 6, 030503 (2024)

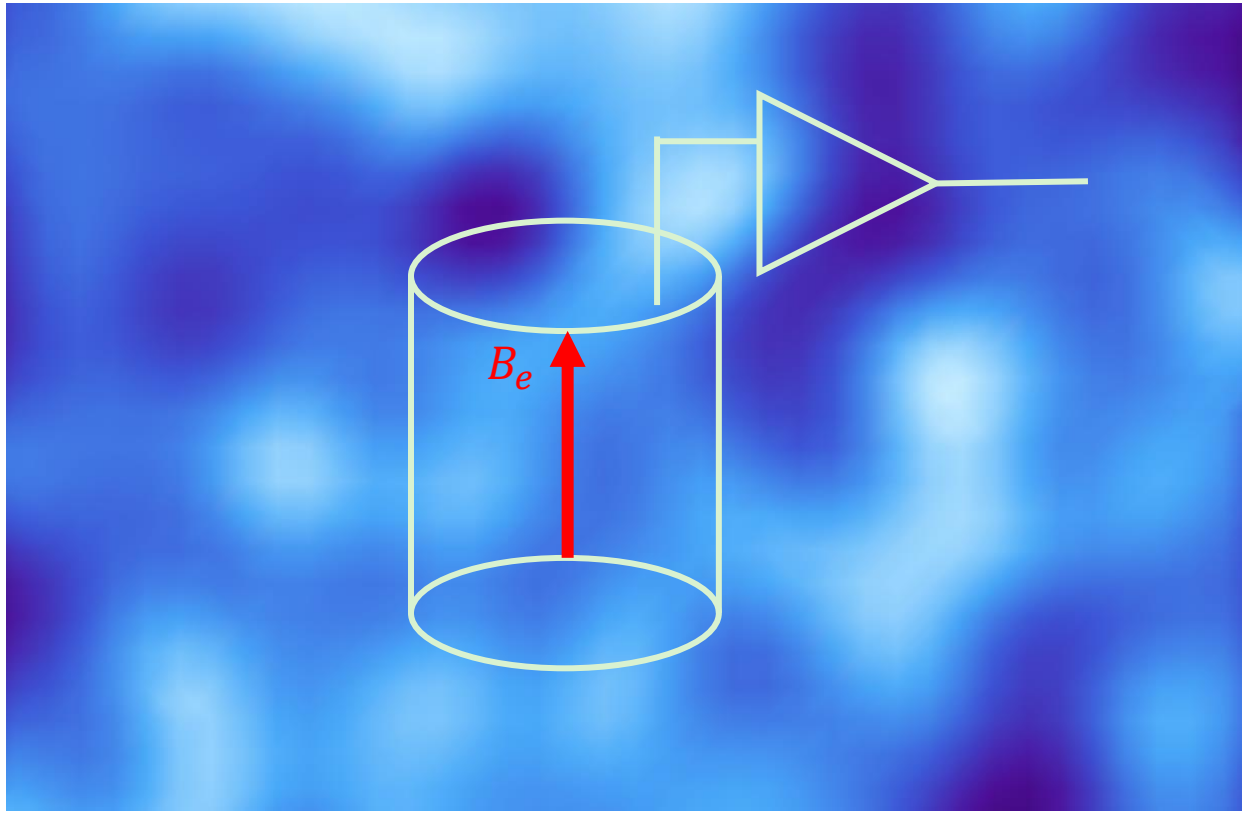
Axion parameter space



Limits from cajohare.github.io/AxionLimits/docs/ap.html

Axion detection with microwave cavities

Cavity placed in an external B_e field:



M. E. Tobar et al., Physics of the Dark Universe **26** (2019)

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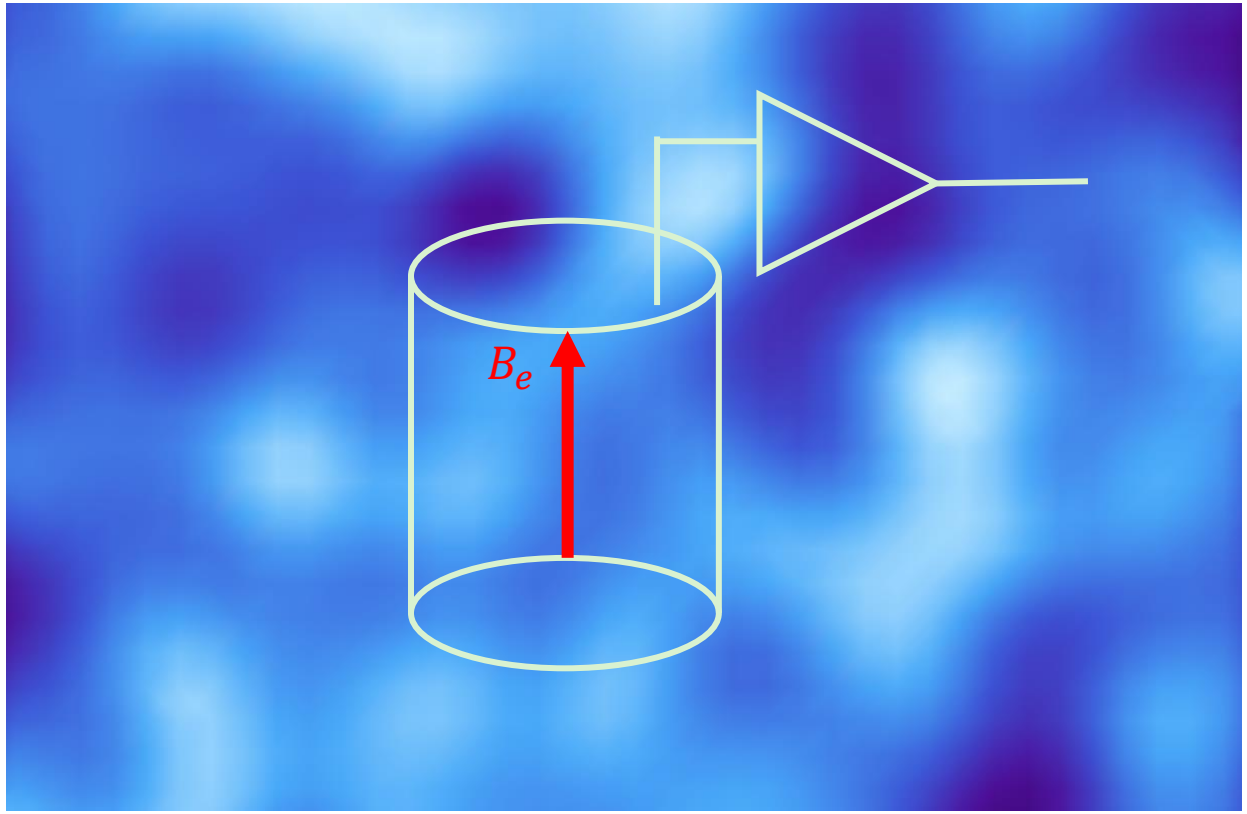

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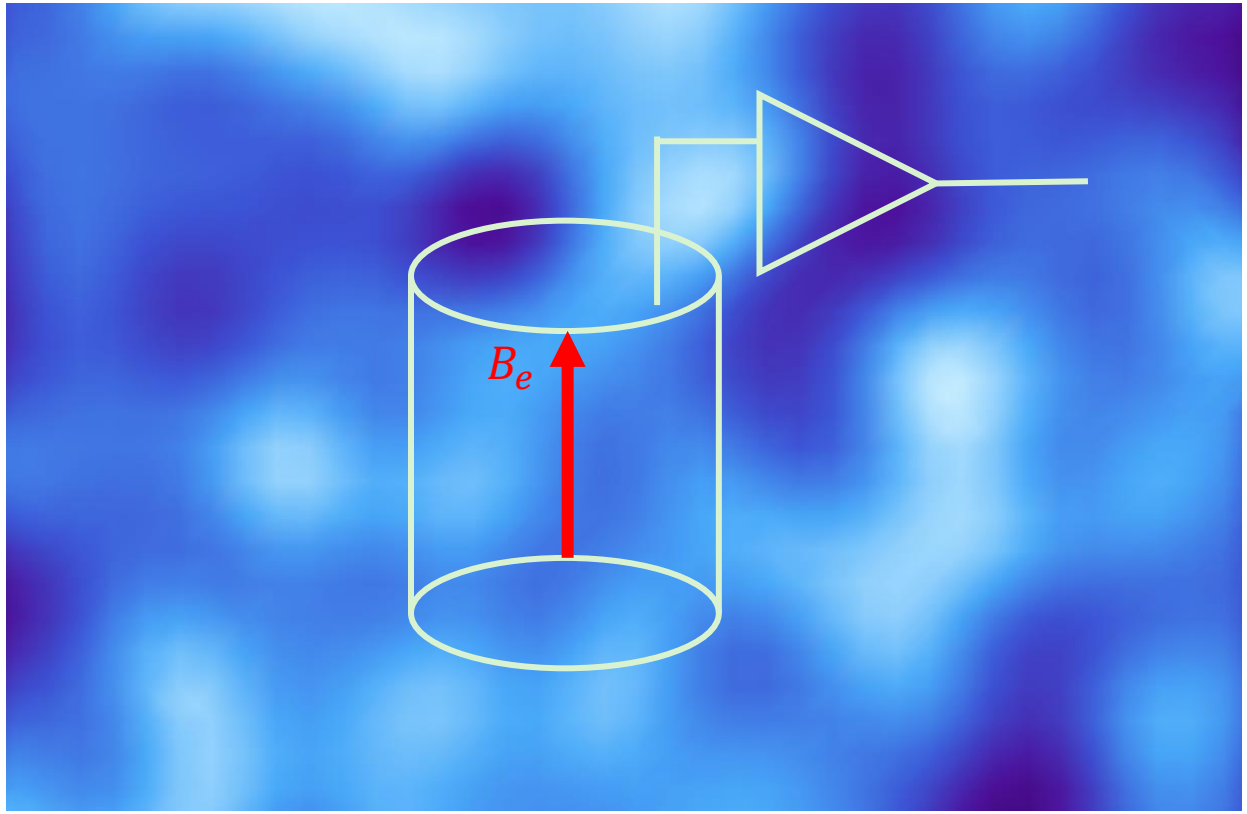

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Rate of photons emitted at optimum cavity coupling is

$$\text{Rate}\,[s^{-1}] \approx 5 \times 10^{-4} C_{a\gamma\gamma}{}^2\, Q\, V_m B^2$$

$$V_m = \frac{|\int E.B_e dV|^2}{\int |E.B_e|^2 dV} \propto \text{Cavity volume}$$

$g_{a\gamma\gamma} \propto C_{a\gamma} m_a$

$(C_{a\gamma} \sim O(1))$

$$Q = \frac{Q_c Q_a}{Q_c + Q_a}$$

Q_c Cavity Q-factor

Q_a Axion Q-factor $\sim 10^6$

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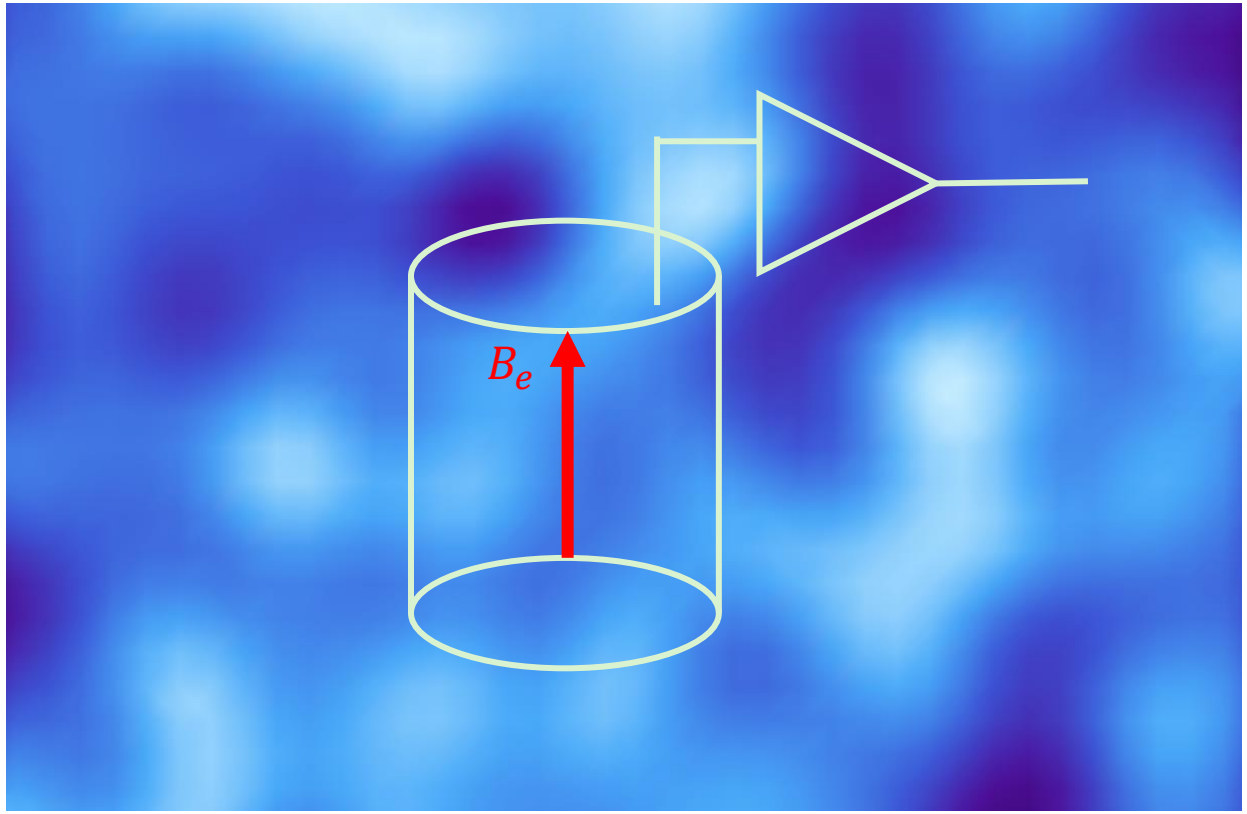

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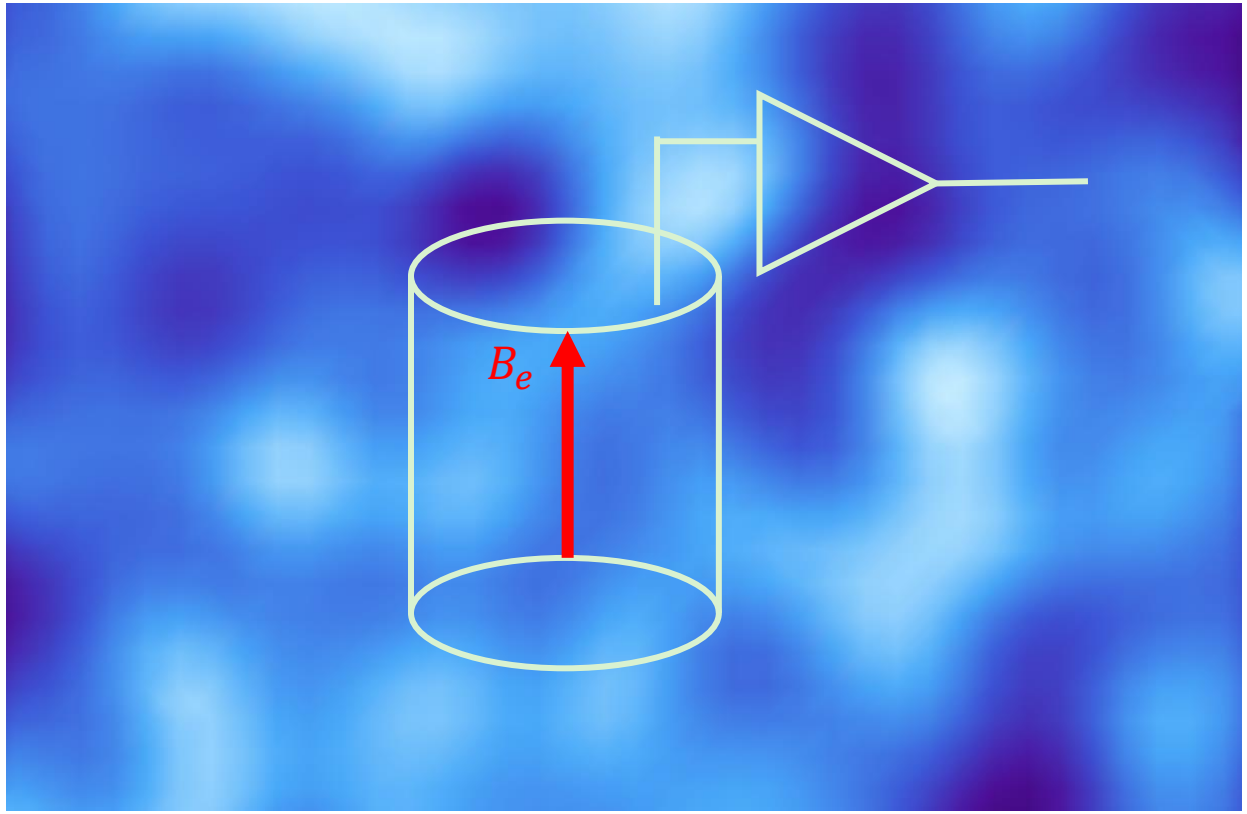

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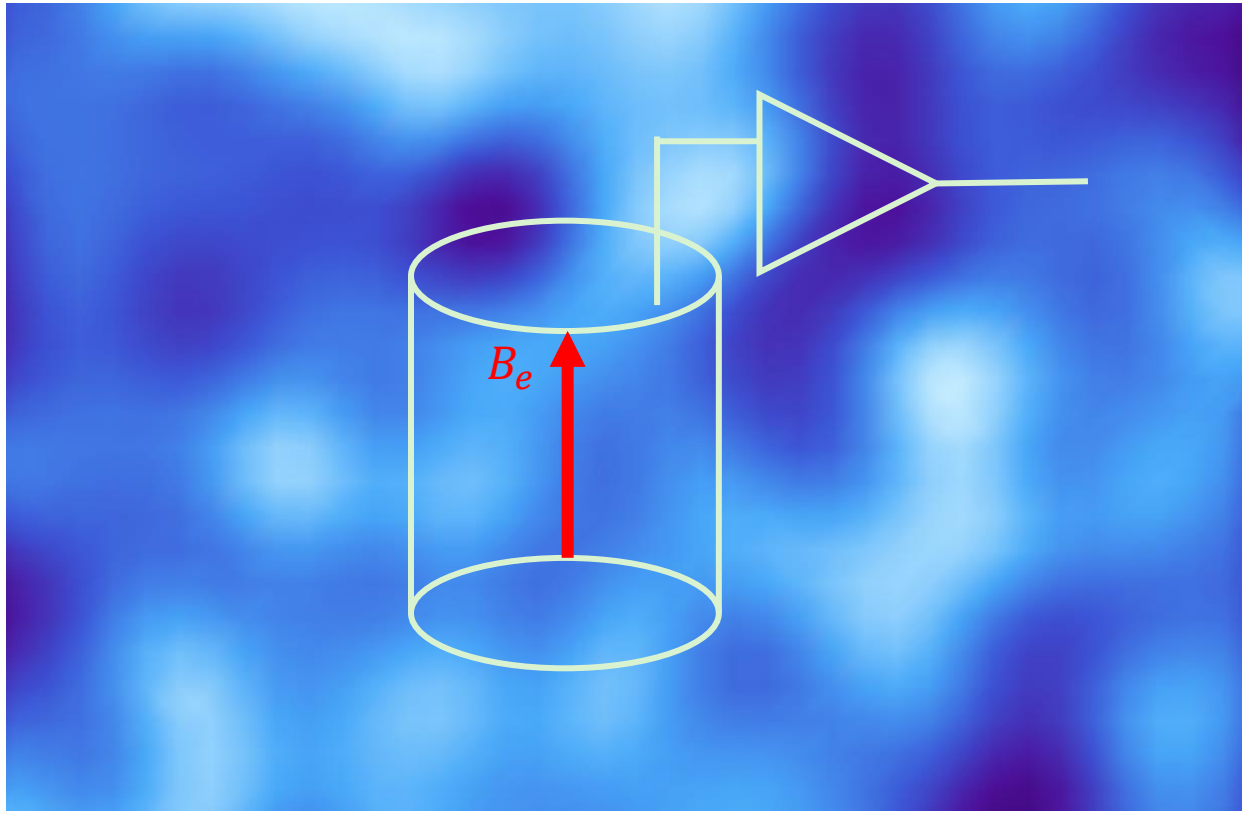

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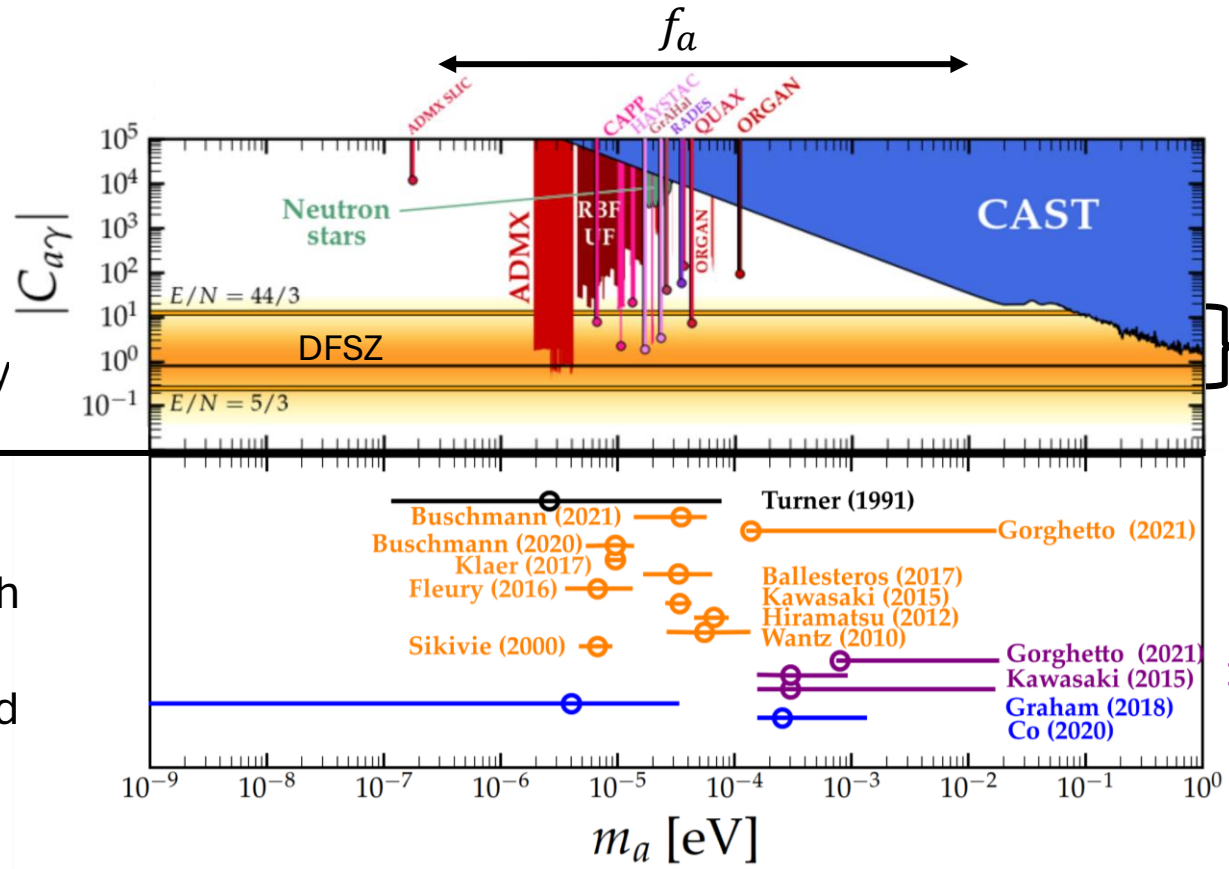
Axion parameter space

Experimental limits on axion masses and $C_{a\gamma}$ from theory



Model predictions

Axion masses consistent with Big Bang cosmology and DM density

Axions formed pre-inflation

Axions formed post-inflation with 1 domain wall

>1 domain wall

Other models

Huge range of viable axion masses to be explored

Top: limits from cajohare.github.io/AxionLimits/docs/ap.html

Bottom: Theory plot adapted from Javier Redondo's talk at TAUP 2021, reproduced with permission

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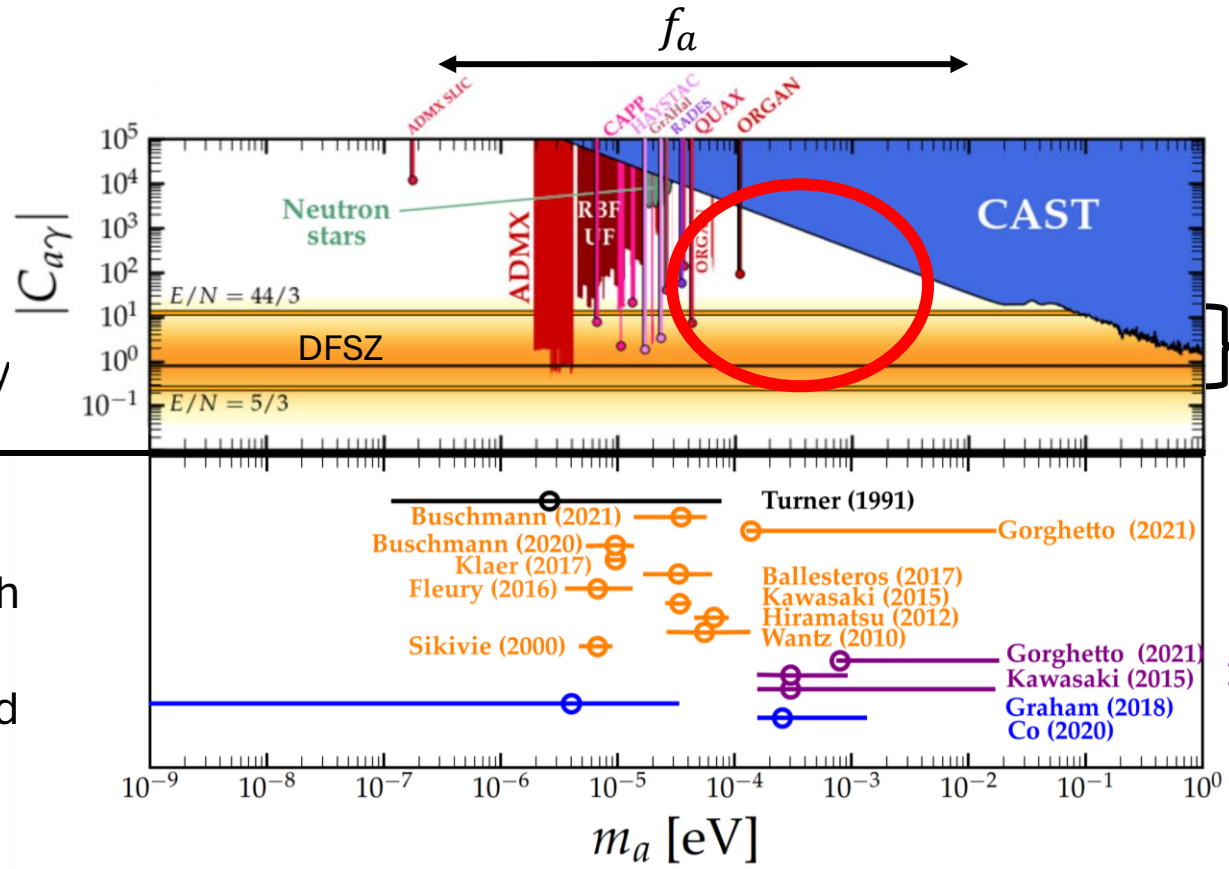

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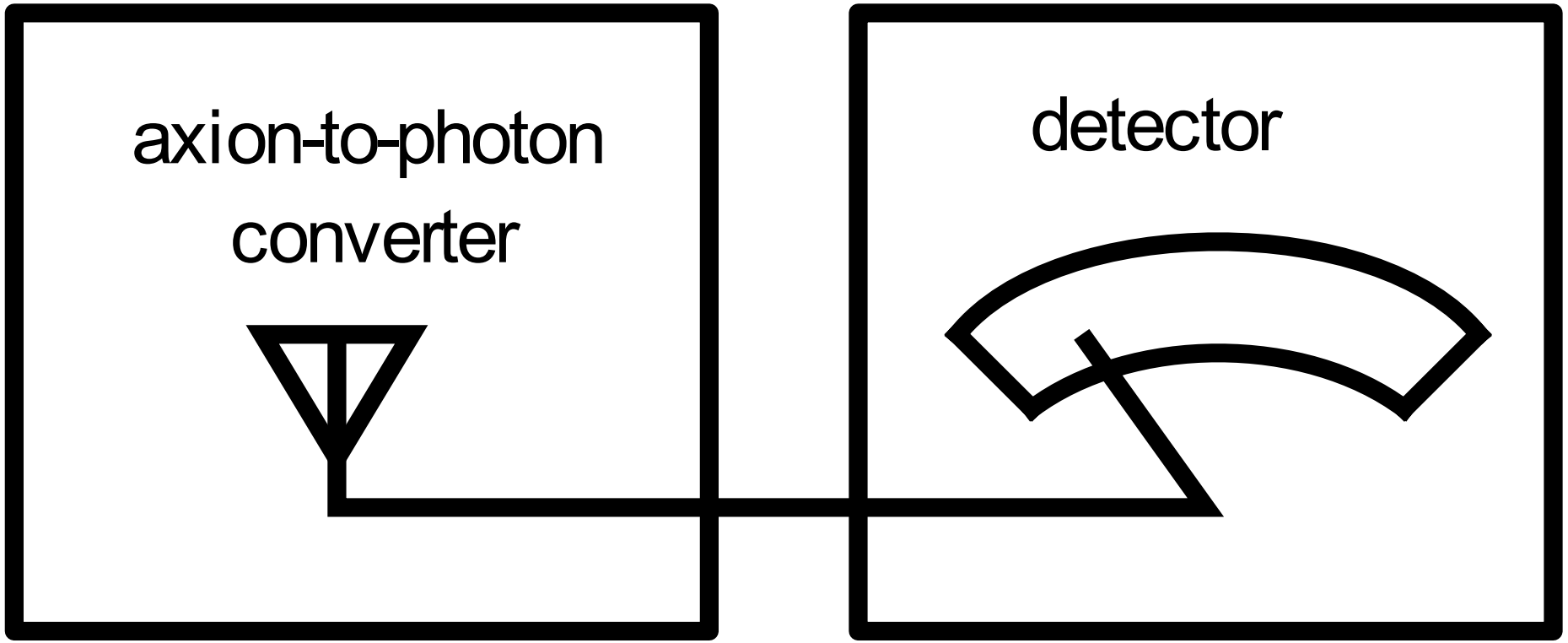

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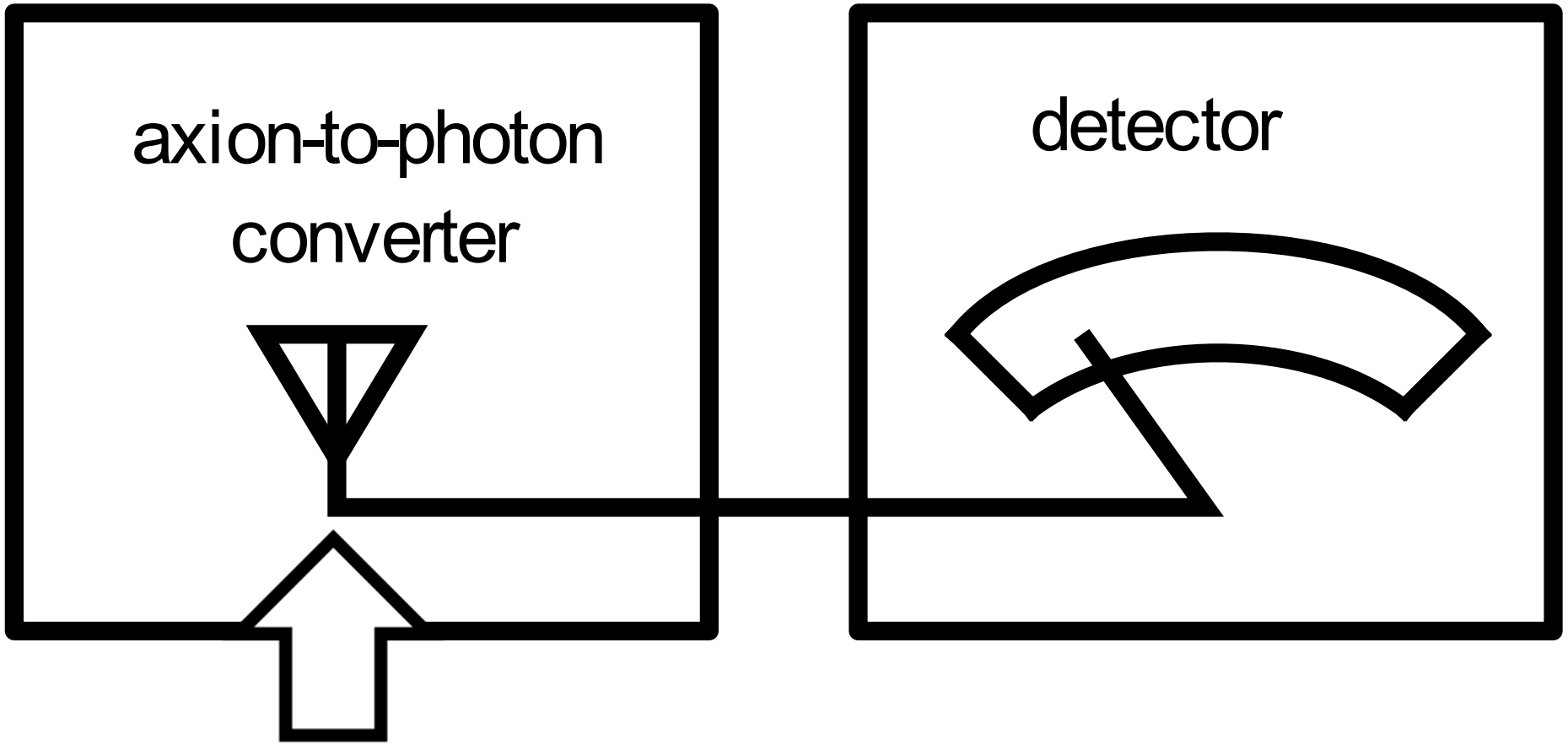

Problem 1:
Decreasing volume
(and Q factor)

Decreasing volume

A cavity haloscope converts $m_a \rightarrow \nu_a = m_a c^2/h$

C. Boutan, et al., Phys. Rev. Lett. **121** (2018)

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Volume factor scales with frequency

$$V_m \propto \frac{1}{{\nu_a}^3}$$

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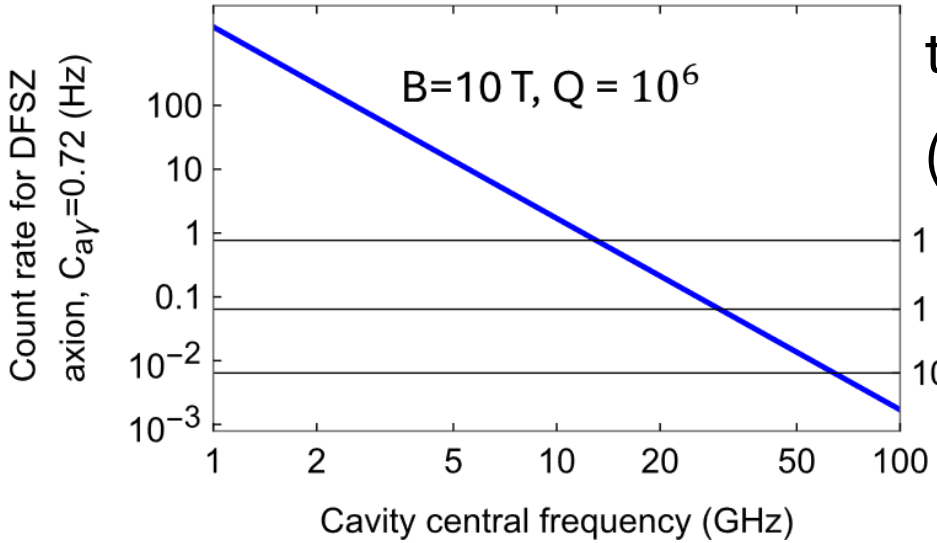
For a cylindrical cavity, DFSZ axion:

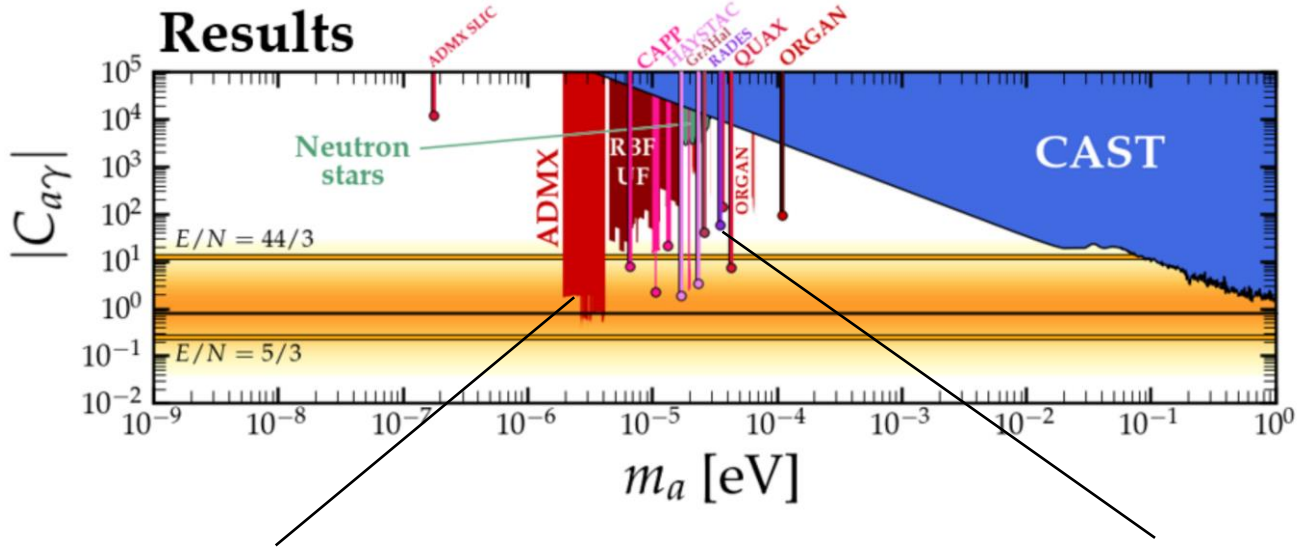


typically, Q $\propto \frac{1}{{\nu_a}^{2/3}}$

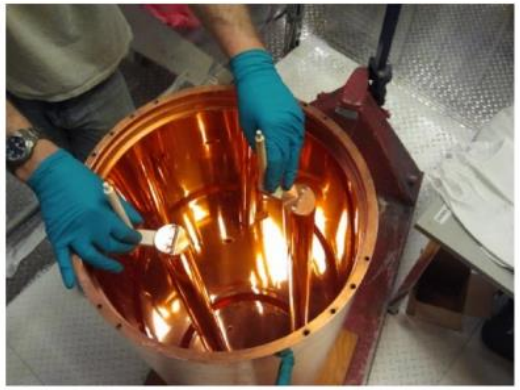
(for copper)

C. Boutan, et al., Phys. Rev. Lett. **121** (2018)

Microwave cavities



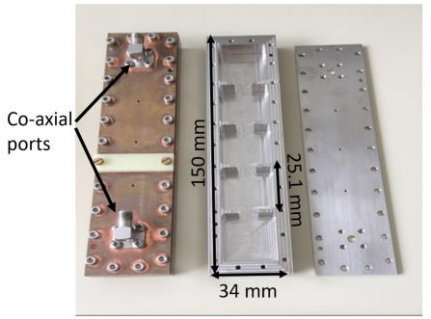
Length ~1 m
Diameter ~0.5 m



ADMX: min frequency ~640 MHz

m_a ↑

Size ↓



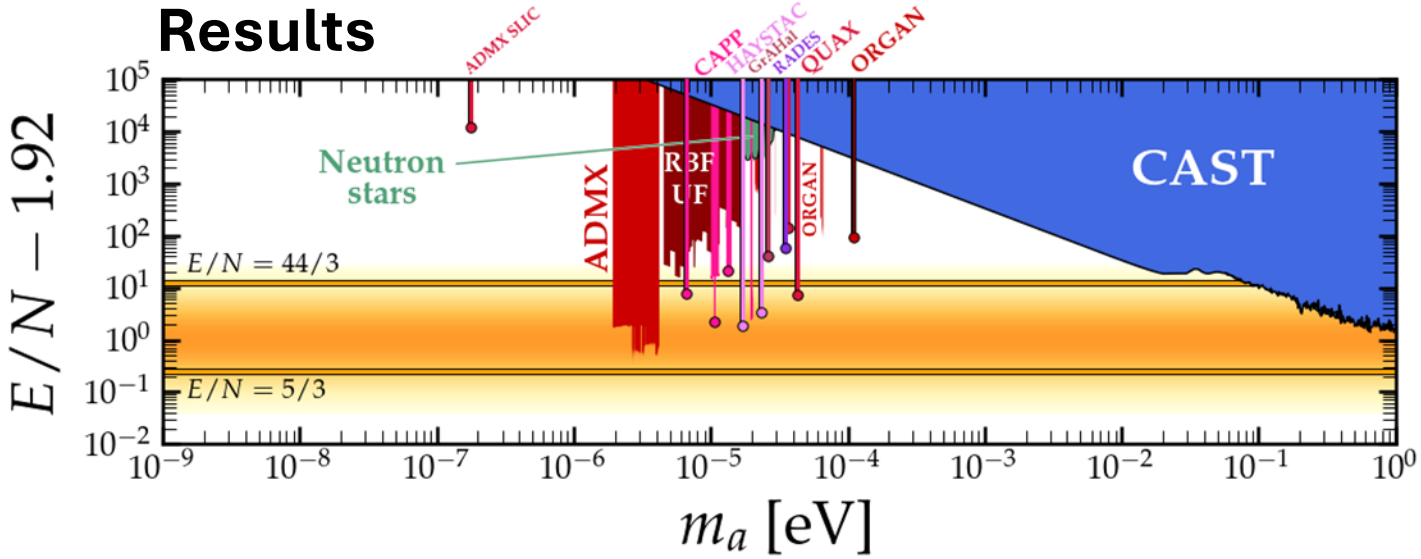
Length ~125 mm
Thickness ~10 mm

RADES: min frequency ~8.4 GHz

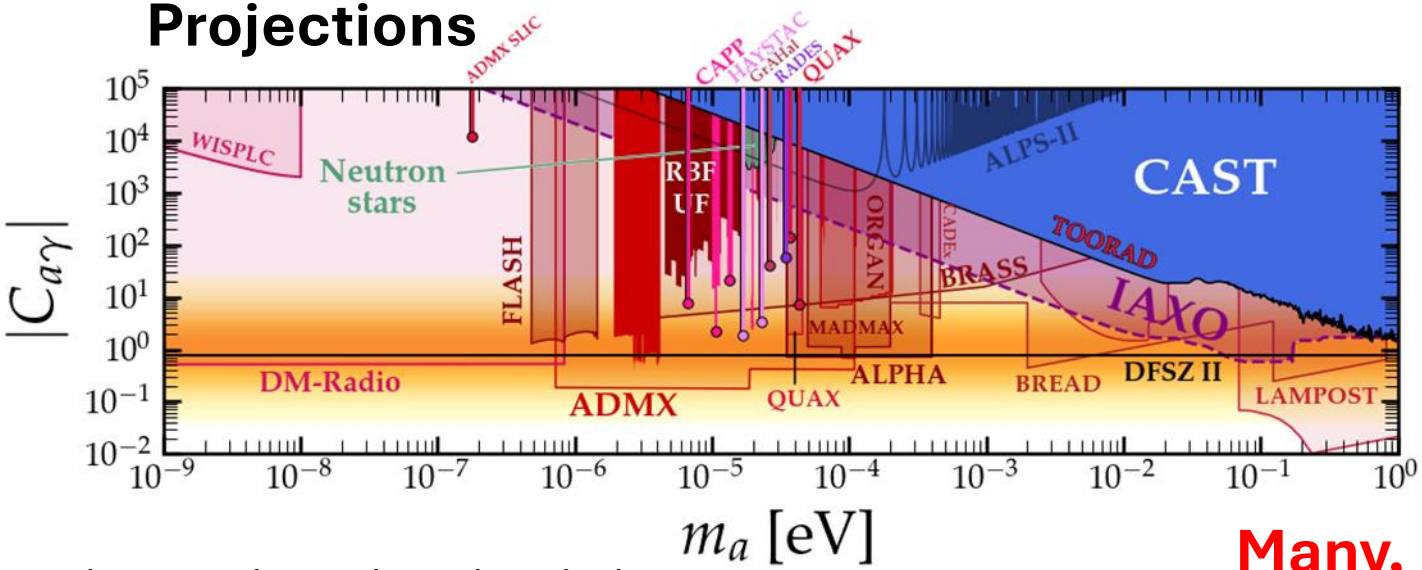
A. Melcón, et al. J. High Energ. Phys. **2021**, 75 (2021)
S. K. Lamoreaux, et al., Phys. Rev. D **88**, 035020 (2013)

Other detection options >30 GHz

Results



Projections



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Dielectric cavities

ORGAN QDM lab (Univ. Western Australia)
Lead by Dr. Michael Tobar

TEM_{00q} Fabry-Perot

ORPHEUS Rybka et al.

Plasma haloscope

ALPHA Frank Wilczek et al.

"Magnetized mirrors"...

BRASS University of Hamburg

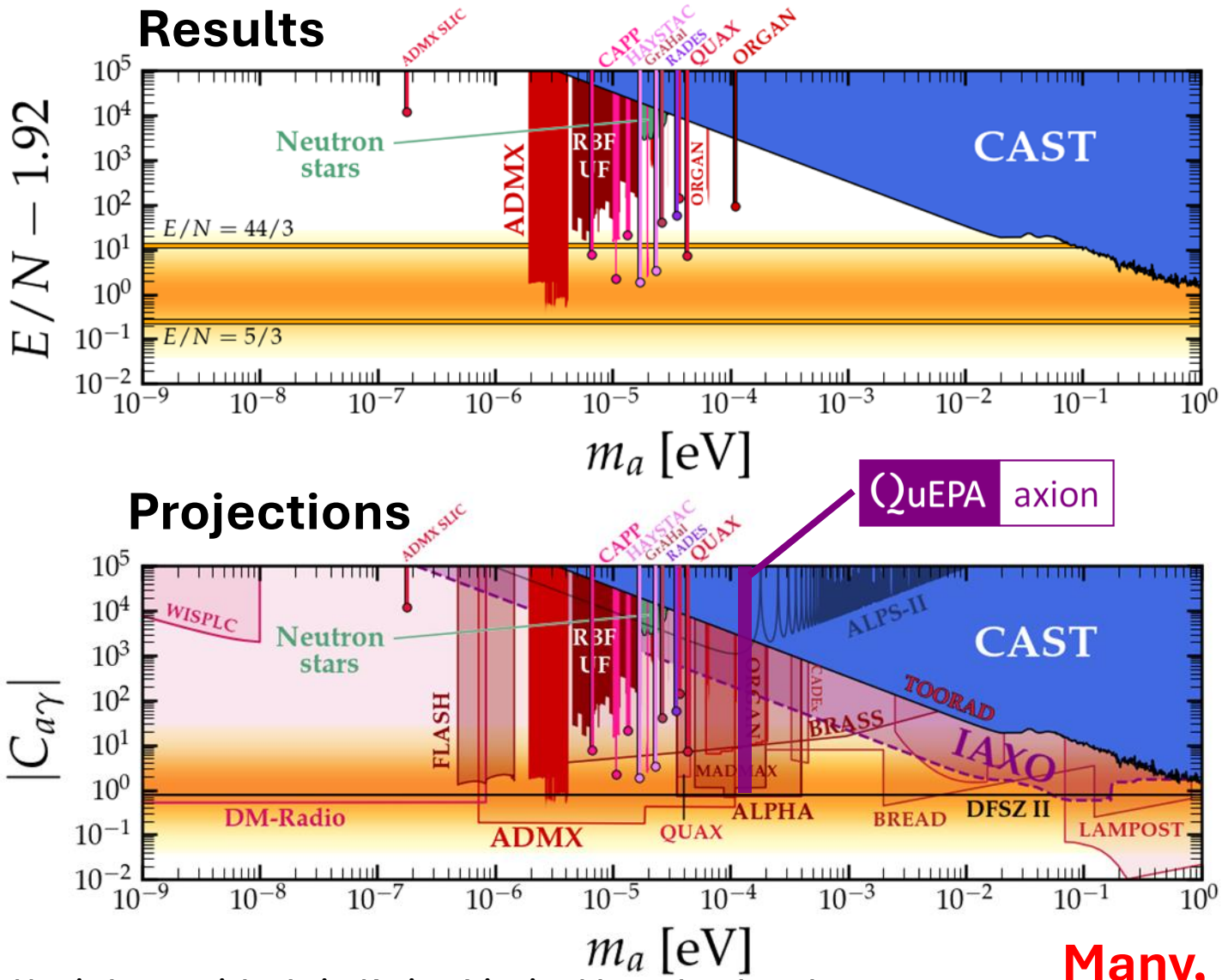
BREAD Cambridge/Fermilab, higher m_a

.. with dielectric boost

MADMAX Big effort at DESY, lower m_a initially

Many, more new ideas between 5-30 GHz

Other detection options >30 GHz



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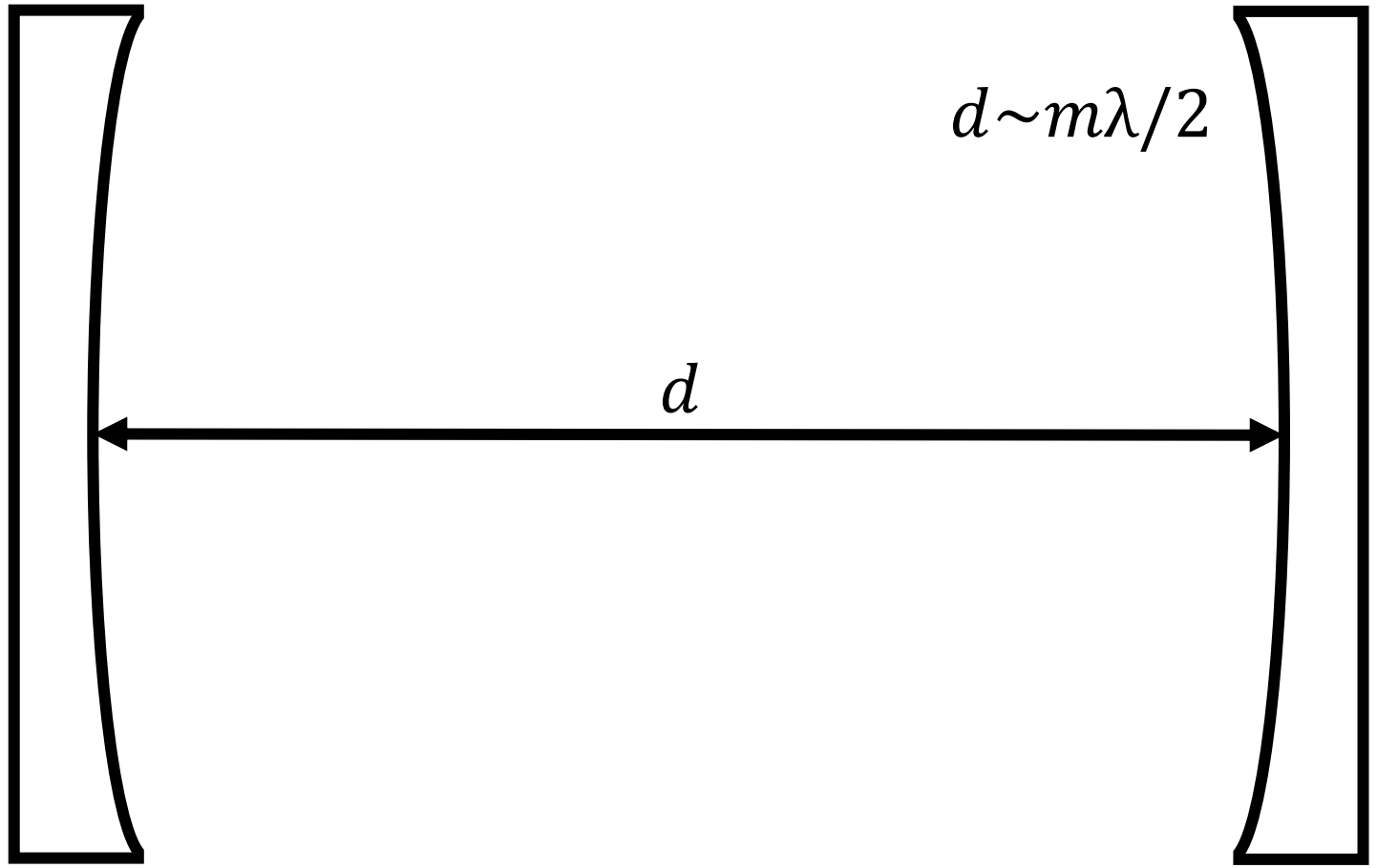

Operating with the fundamental mode

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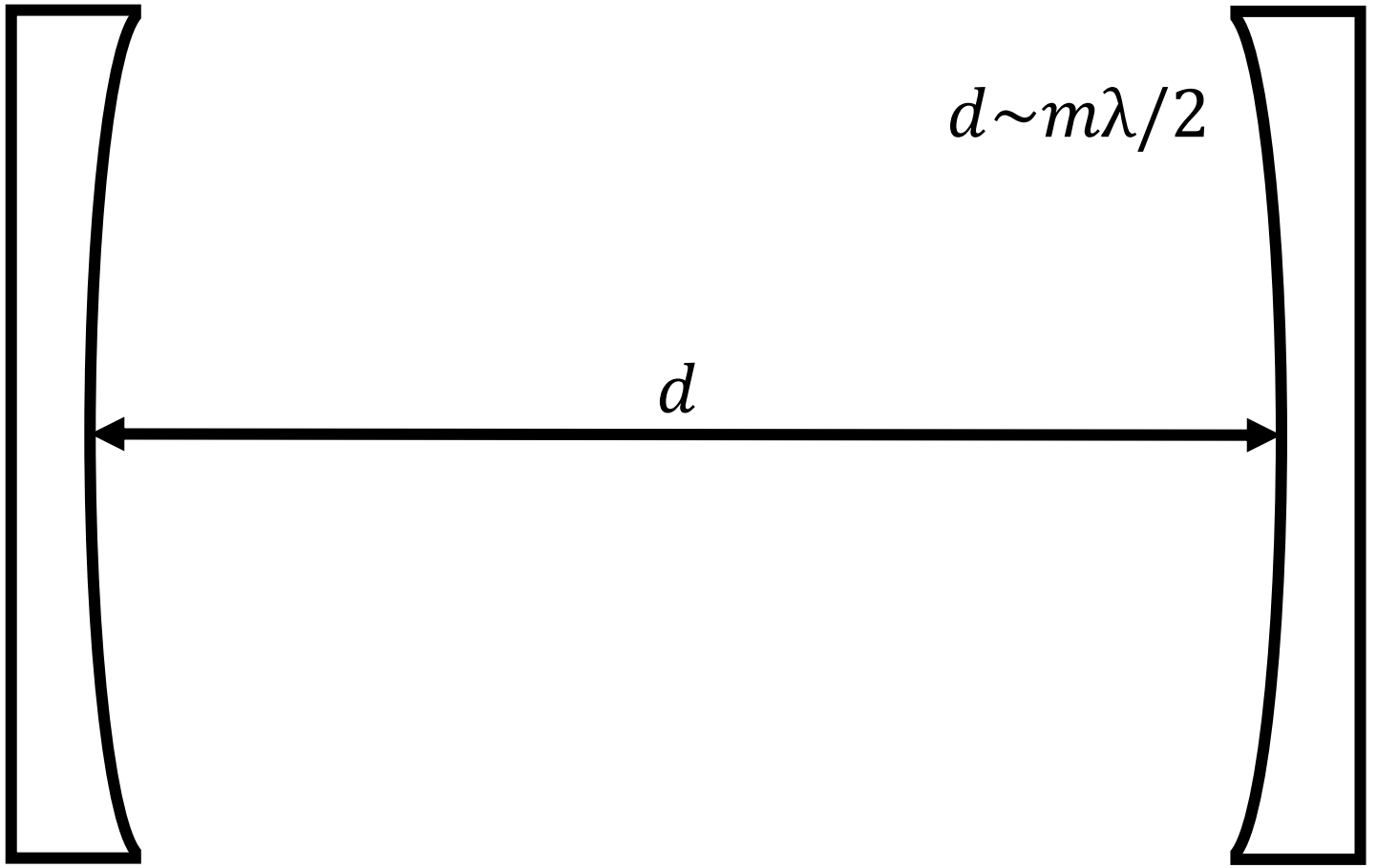

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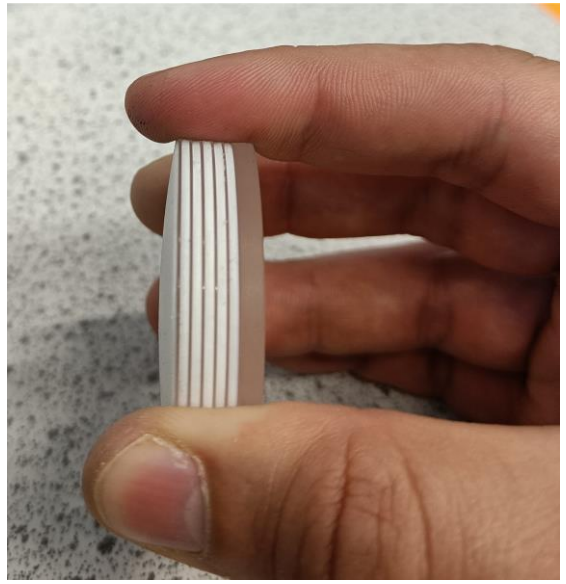

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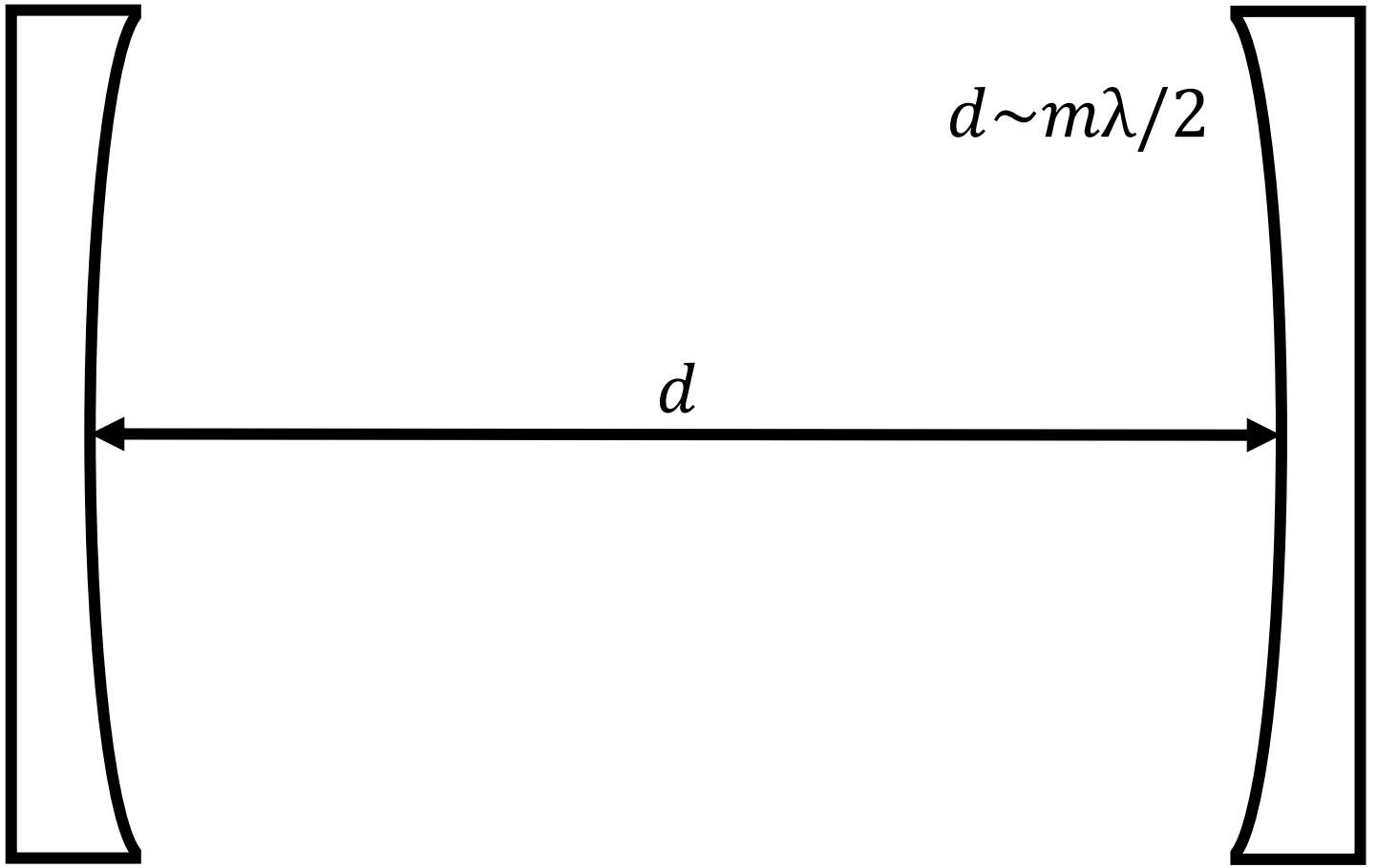

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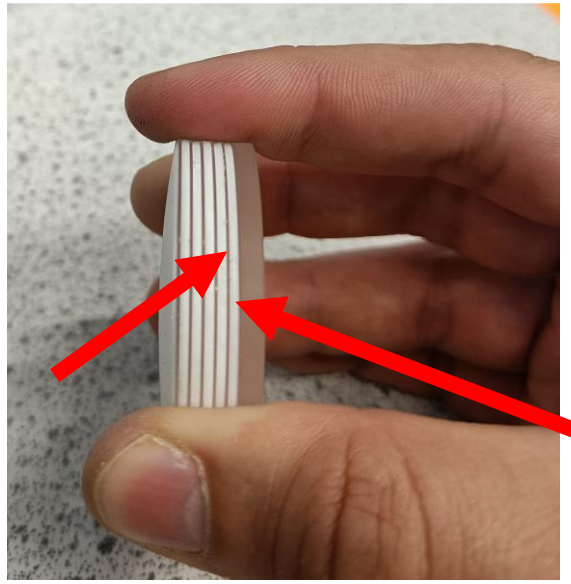

Teflon/ Sapphire stack

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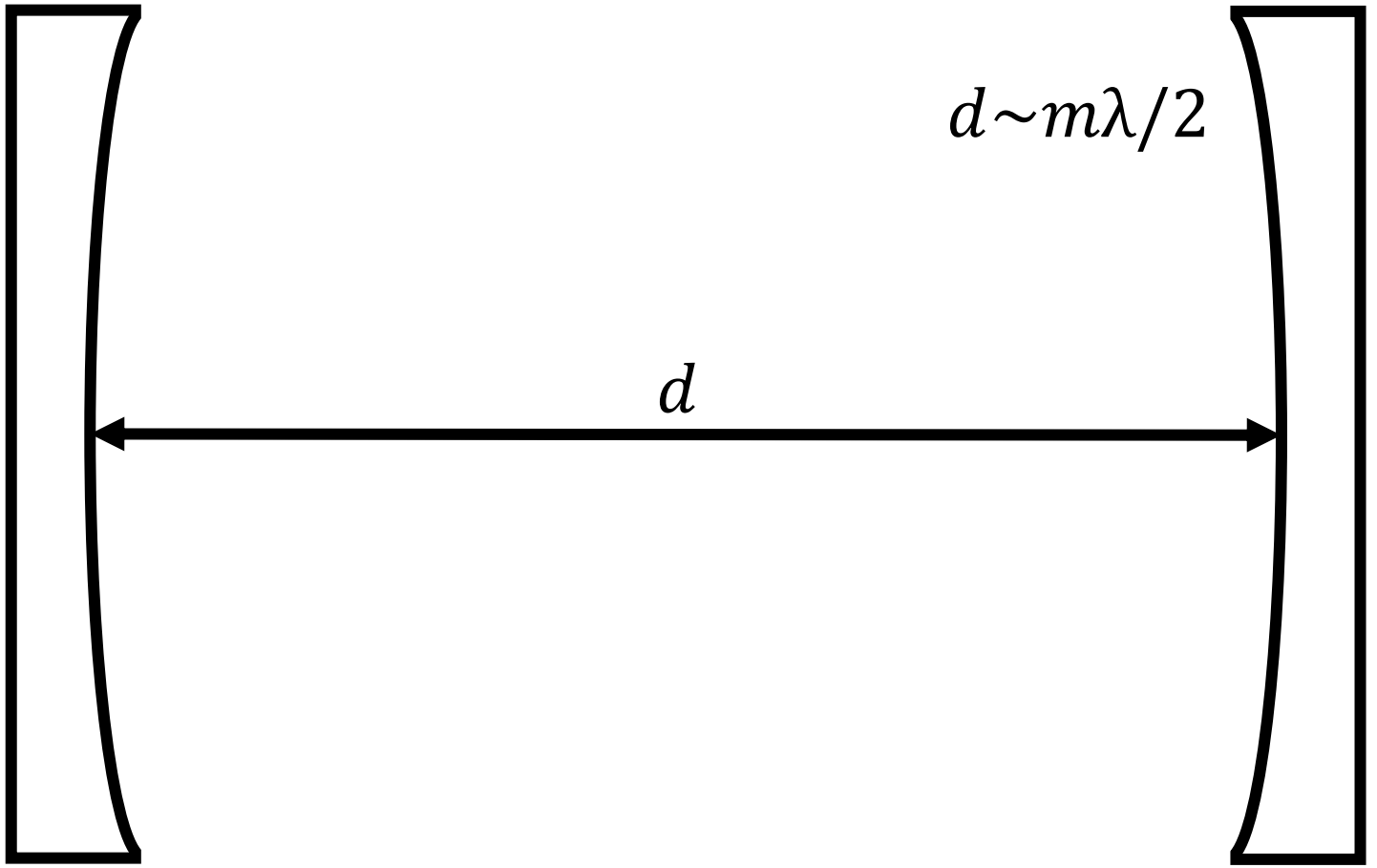
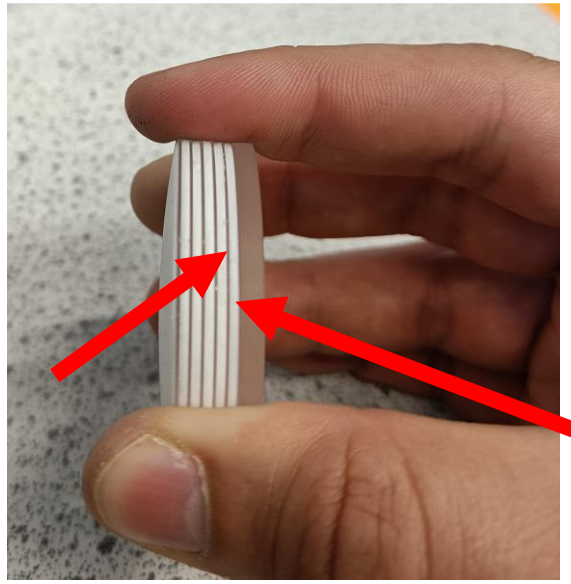


Operating with the fundamental mode

$$n_1 d_1 \sim n_2 d_2 \sim \frac{\lambda}{4}$$



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Why a dielectric Fabry-Perot Cavity?

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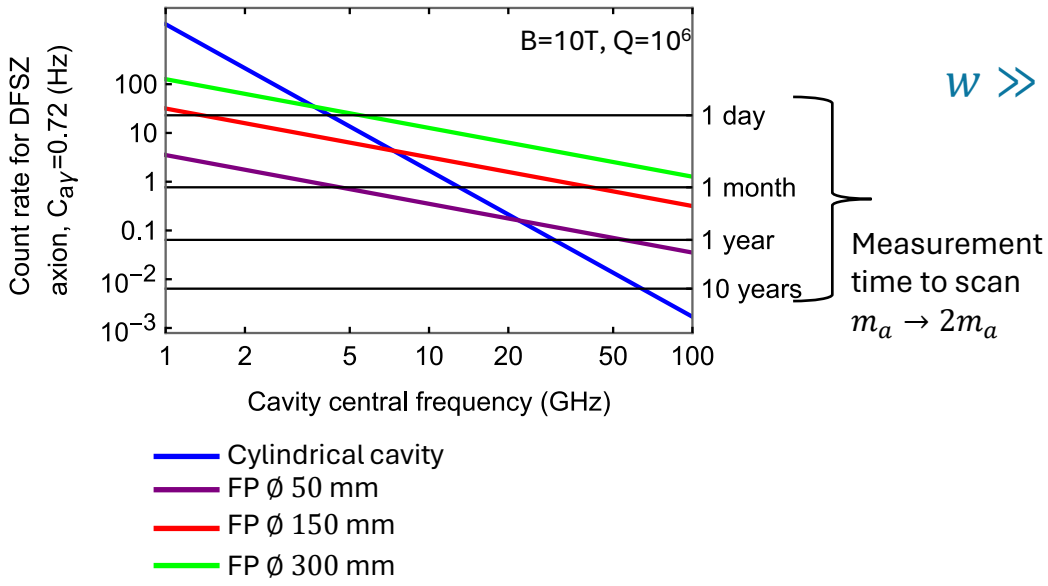
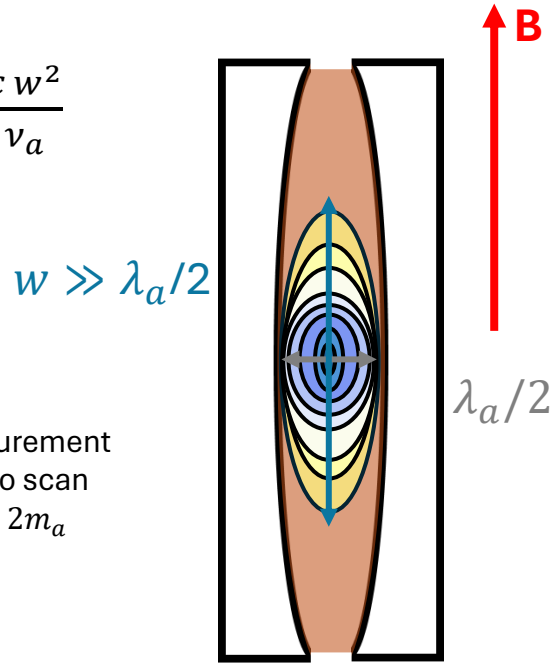
$$\text{Rate}\,[s^{-1}] \approx 5 \times 10^{-4} C_{a\gamma\gamma}{}^2\, Q\, V_m B^2$$

1) Favourable V_m scaling with ν_a

At the optimum design frequency, $V_m = \frac{8}{\pi}\frac{c\,w^2}{\nu_a}$





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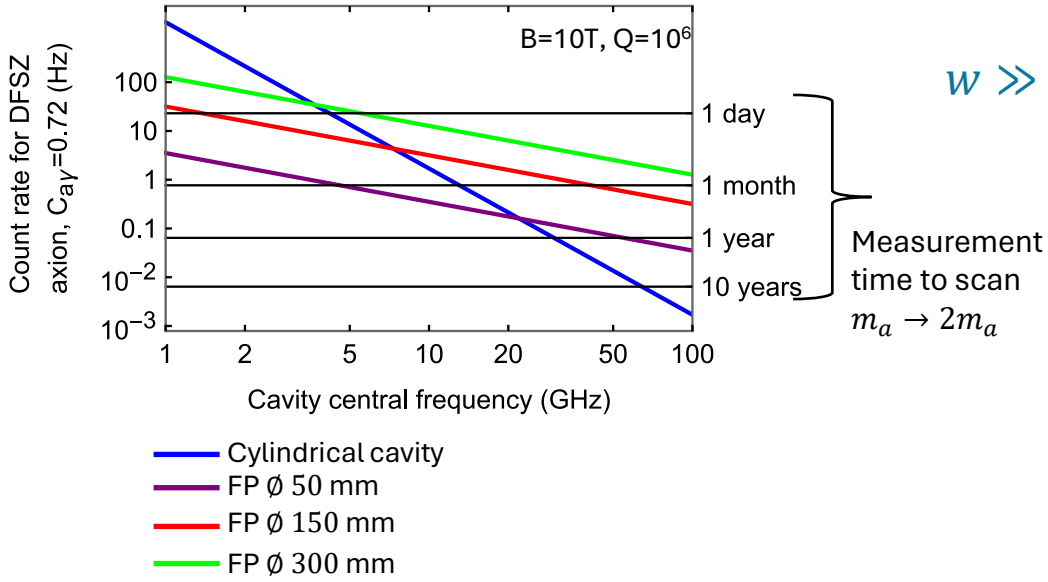
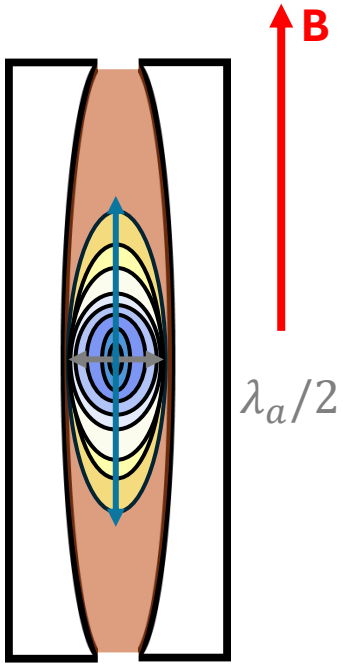
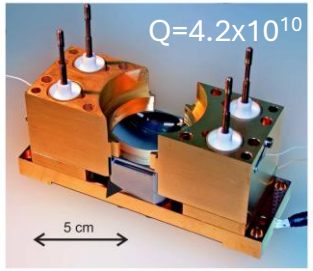


$w \gg \lambda_a/2$



2) High Q possible in this open geometry



S. Kuhr et al., Appl. Phys. Lett. **90**, 164101 (2007)

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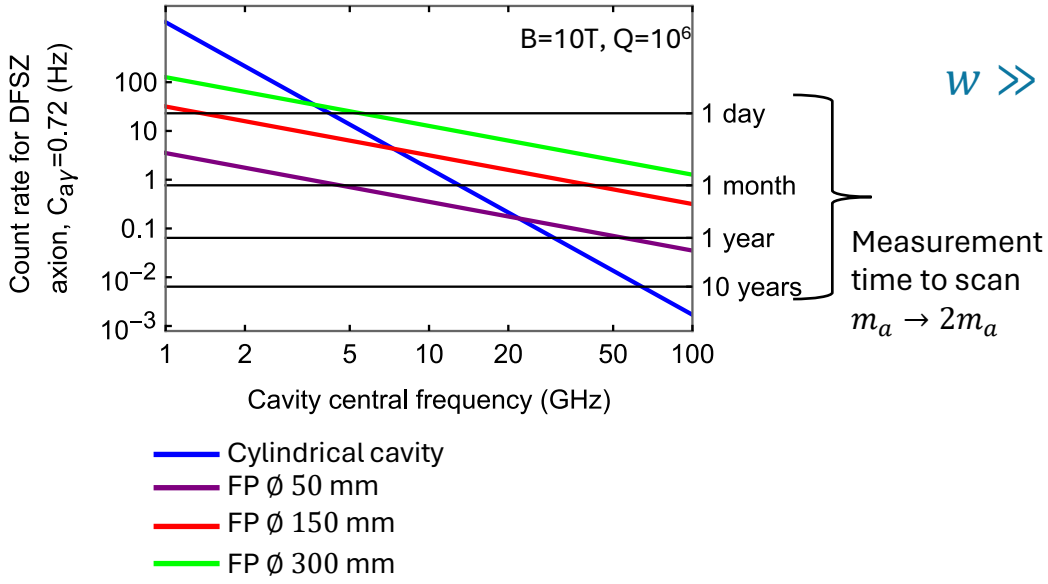

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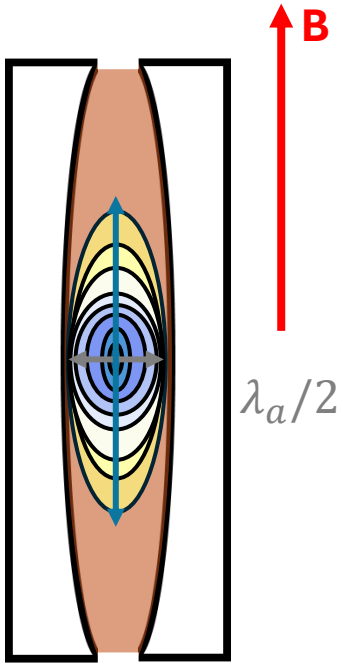

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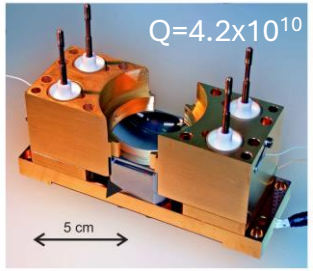

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3) High B-field compatible

Dielectric Bragg mirrors

- All dielectric design – ultralow loss even in high B field
- Large sapphire wafers available: 10-12 inch
- Less likely to crack under differential expansion

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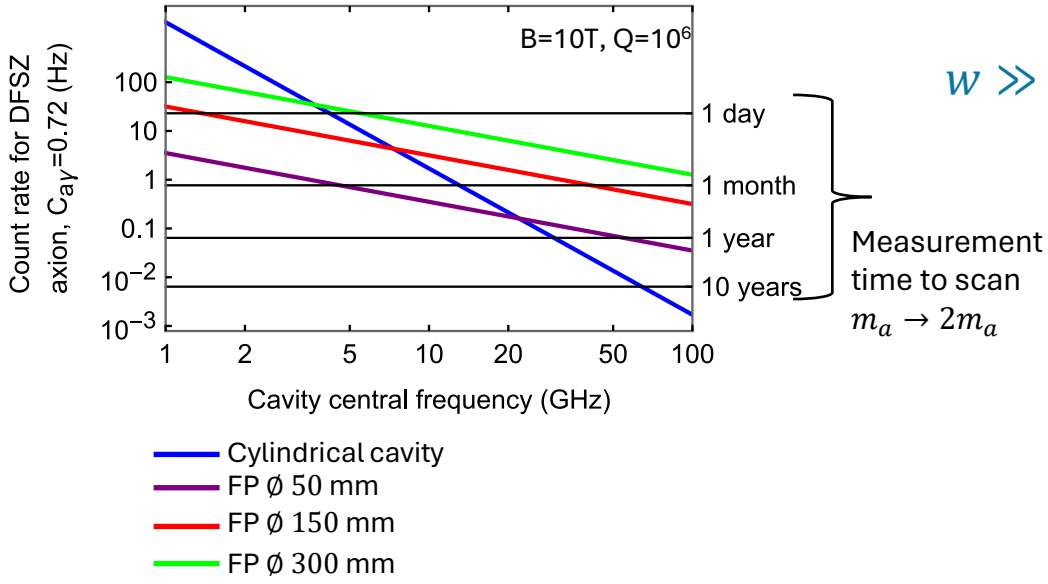
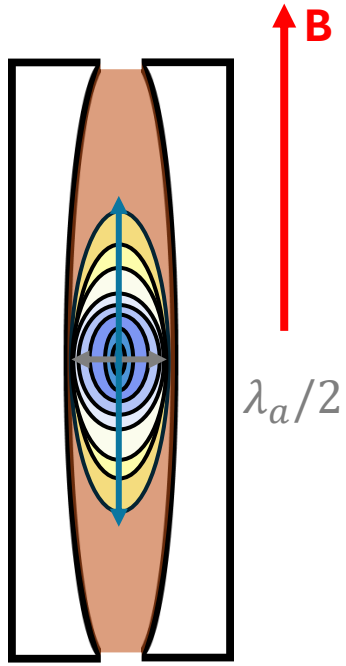
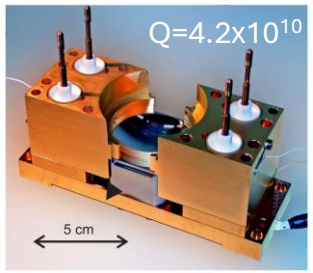
1) Favourable V_m scaling with ν_a

At the optimum design frequency, $V_m = \frac{8}{\pi}\frac{c\,w^2}{\nu_a}$





2) High Q possible in this open geometry



S. Kuhr et al., Appl. Phys. Lett. **90**, 164101 (2007)

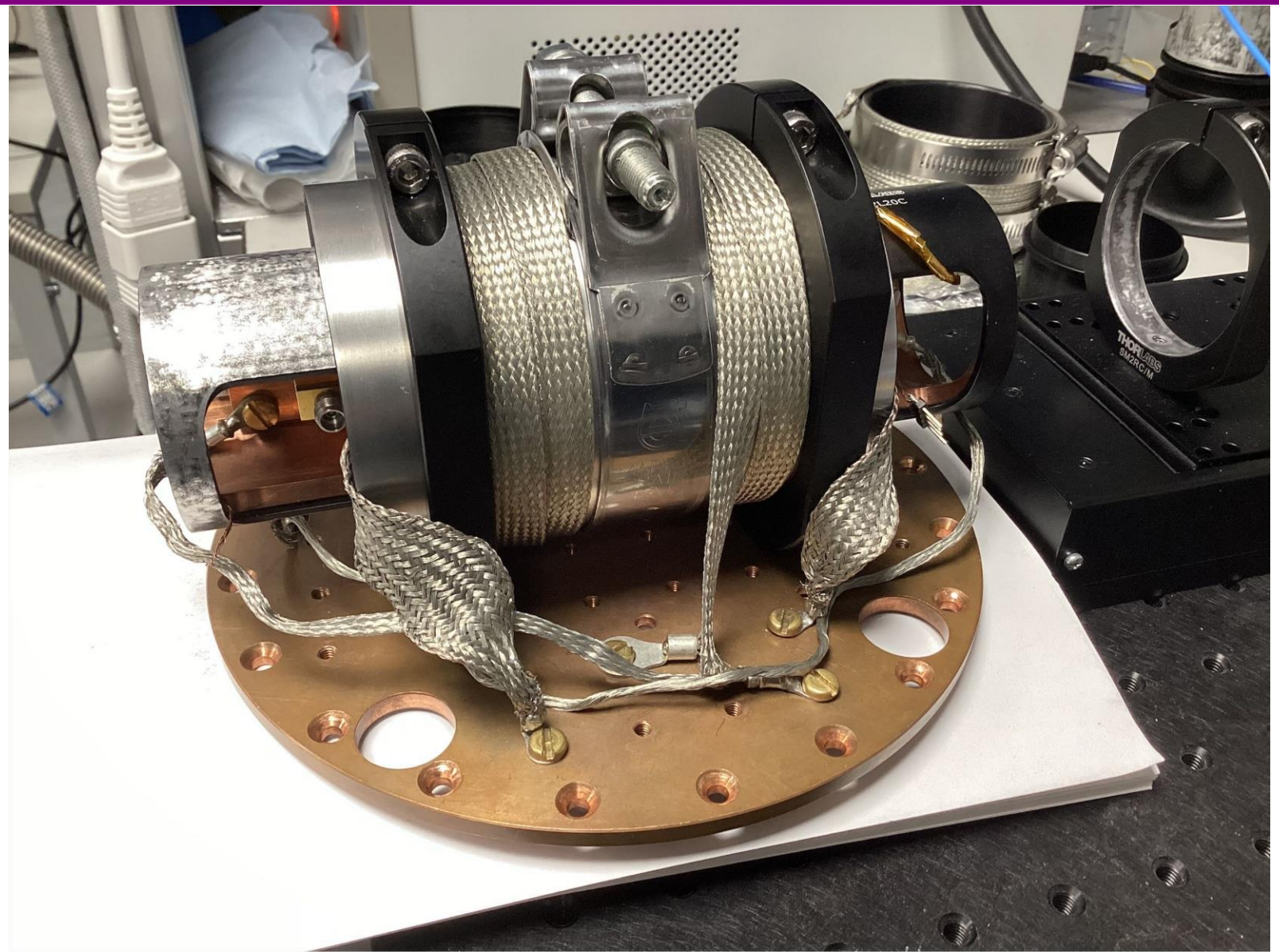
3) High B-field compatible

Dielectric Bragg mirrors

- All dielectric design – ultralow loss even in high B field
- Large sapphire wafers available: 10-12 inch
- Less likely to crack under differential expansion

Other considerations: Frequency adjustment easy, relatively compact, broad tuning range, easy to model, simulate and measure electric fields.

2 inch prototype

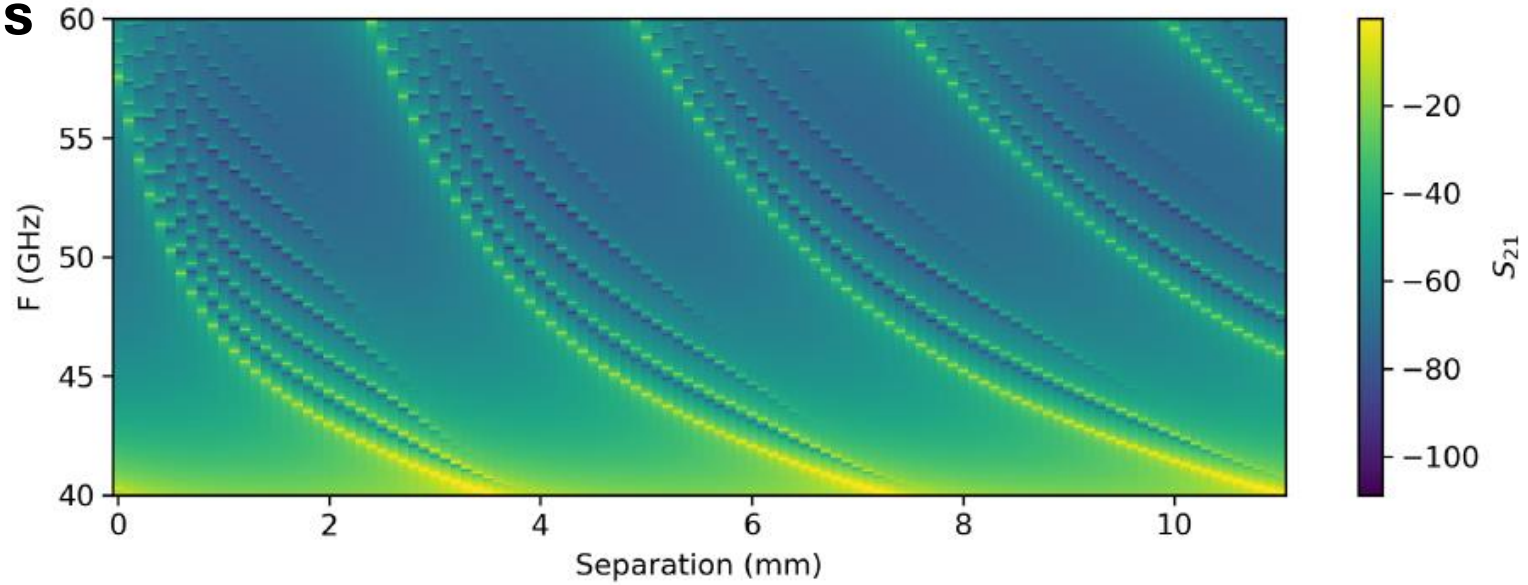


Initial testing at room temperature and 4K.

Characterising cavity

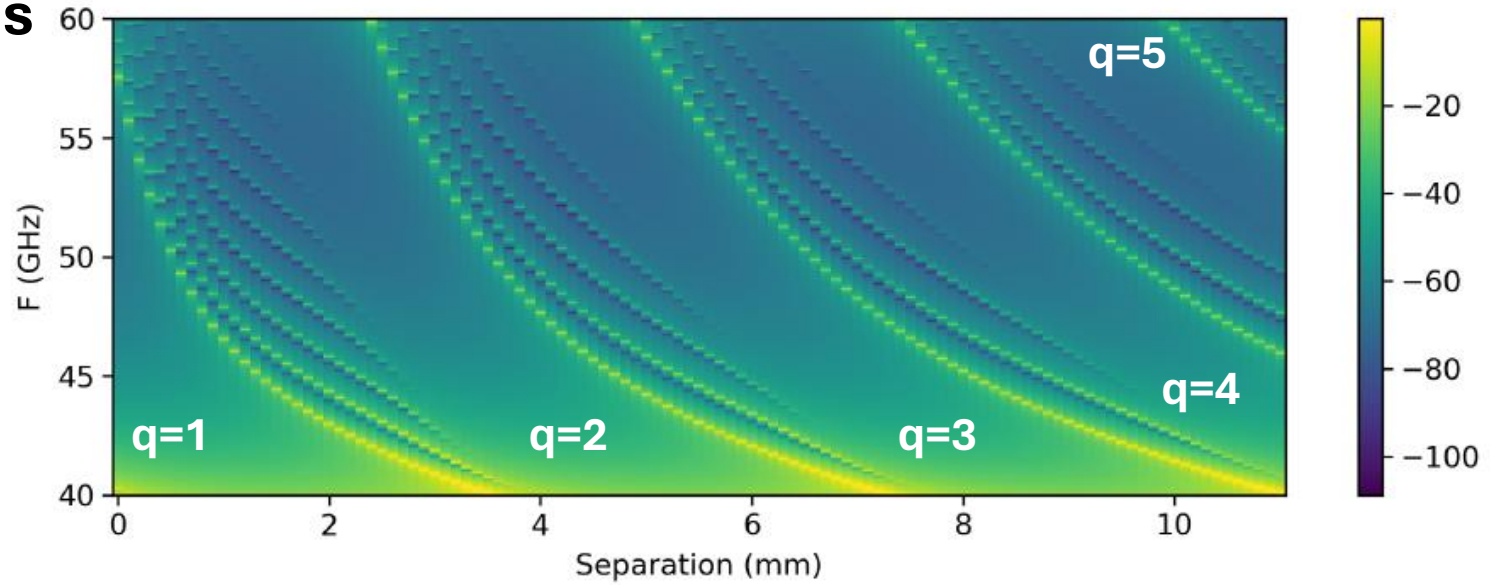
Characterising cavity

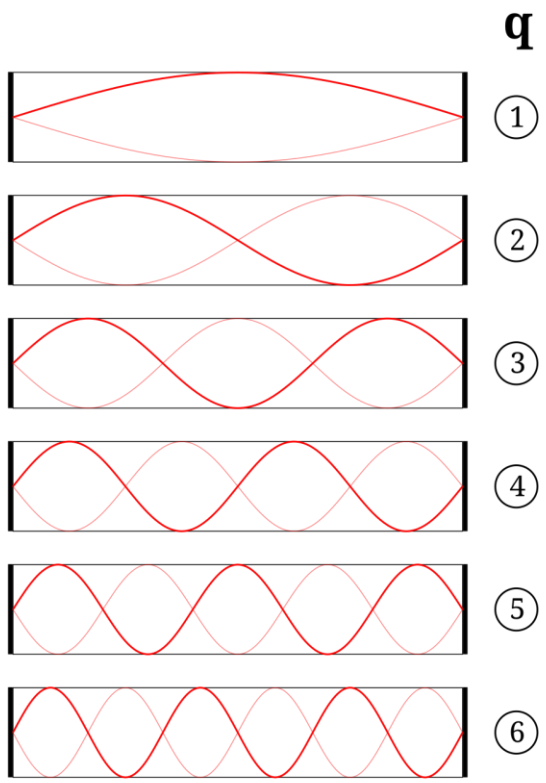
Simulations



Characterising cavity

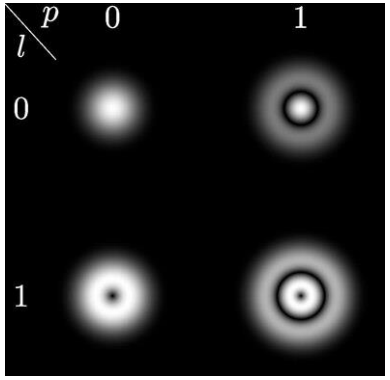
Simulations

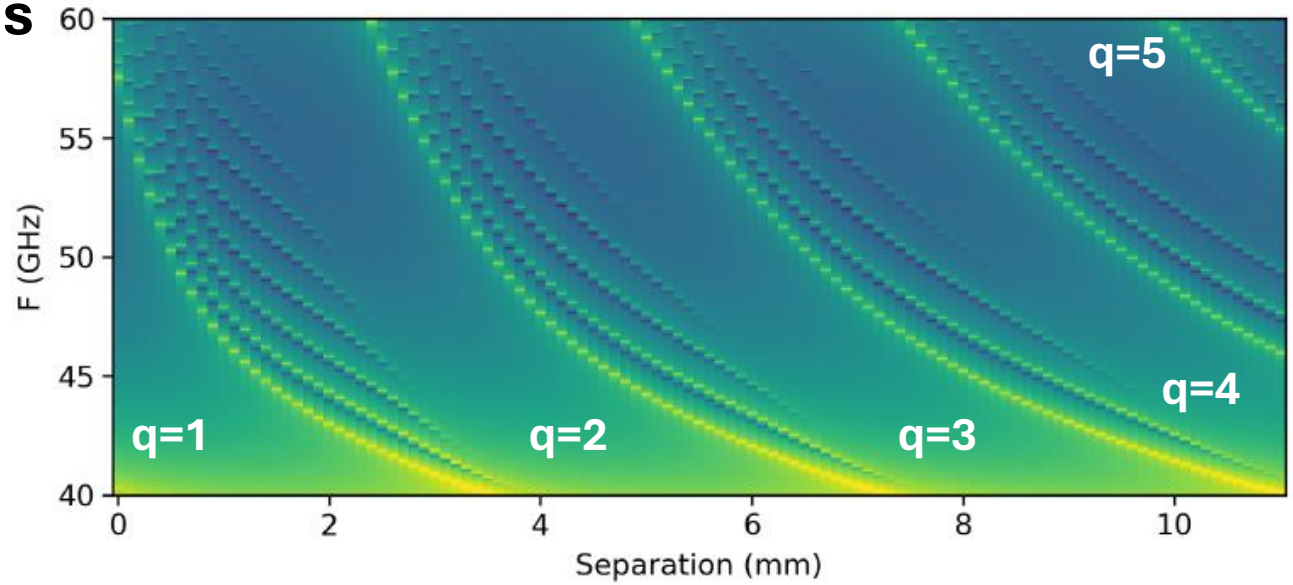


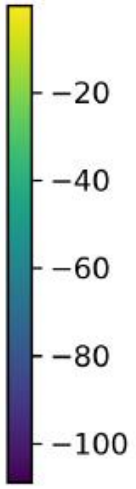


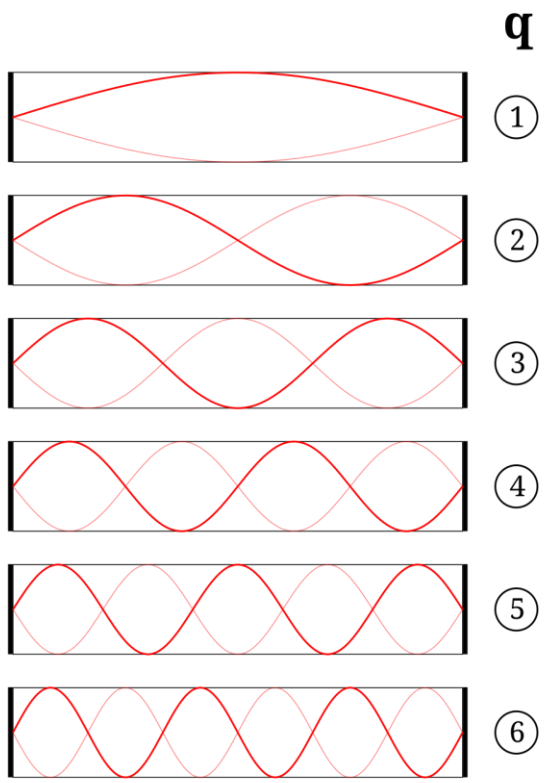
Characterising cavity

Simulations









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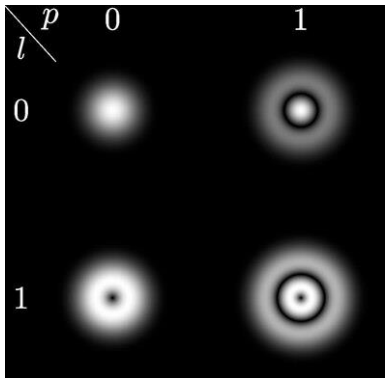
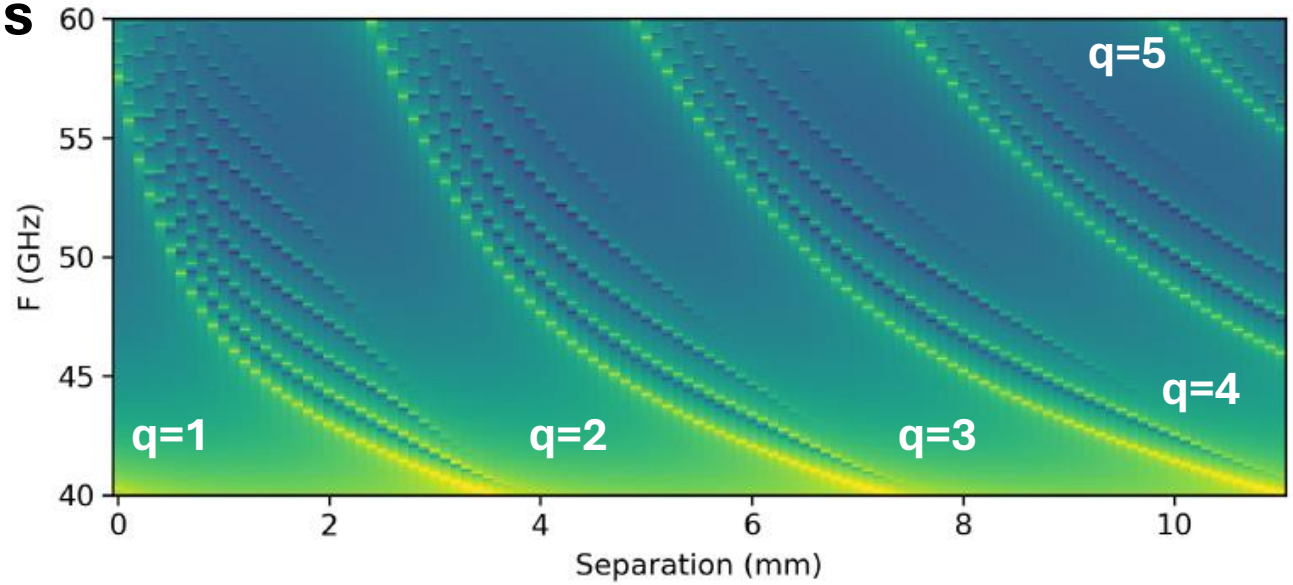
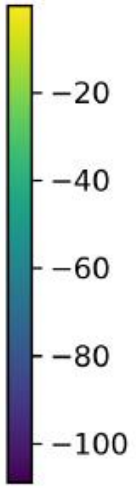
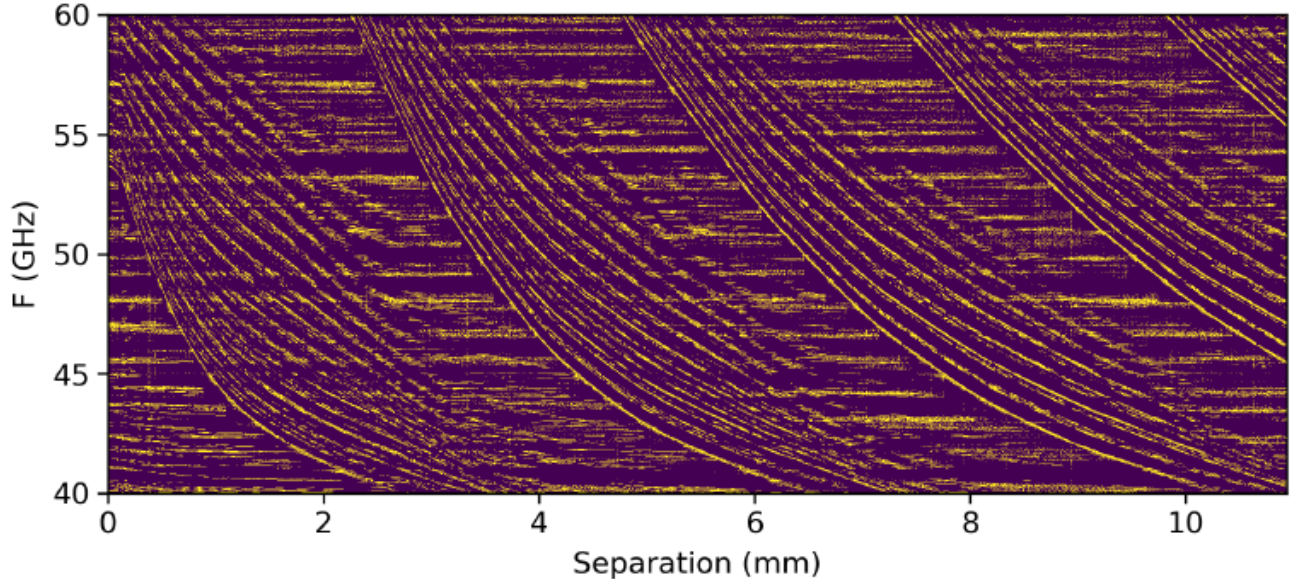
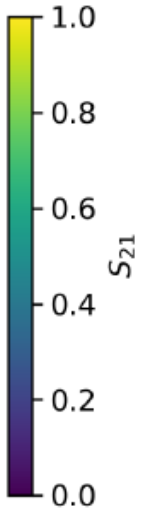


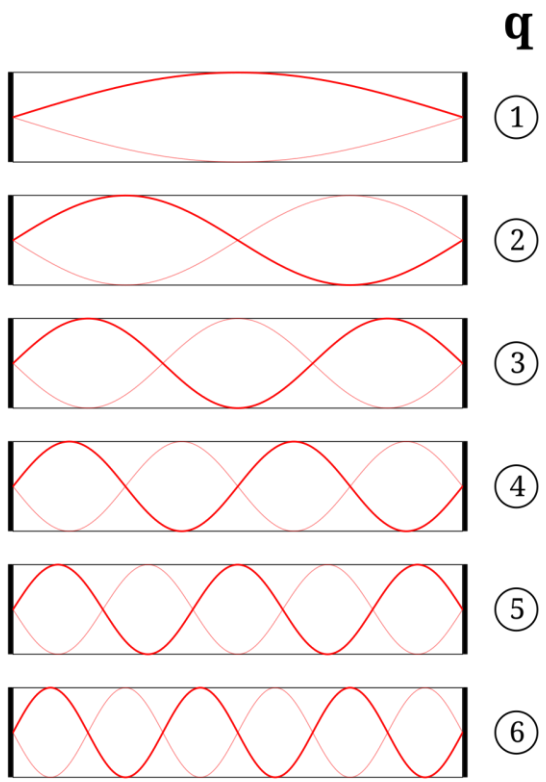




Measured







Measuring Quality factor

$$\text{Rate}\,[s^{-1}] \approx 5\ \times 10^{-4} {C_{a\gamma\gamma}}^2\ Q\ V_m B^2$$

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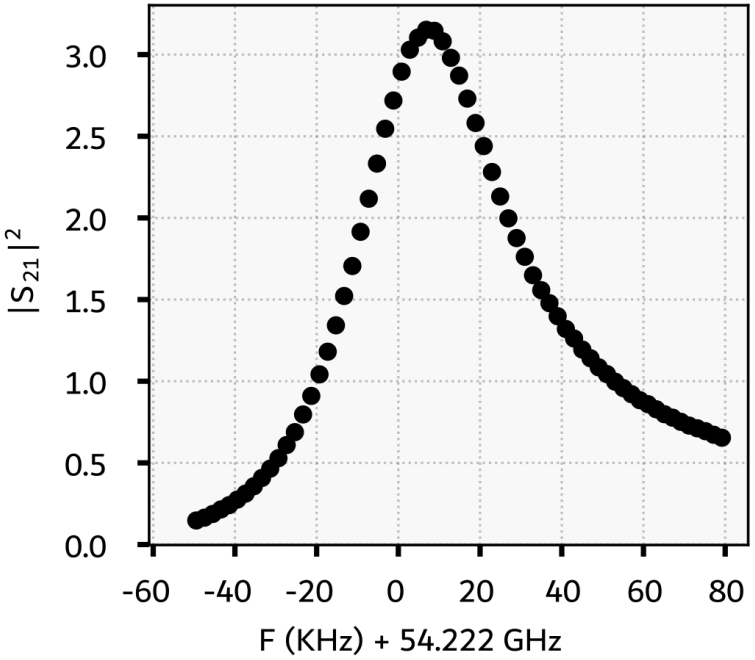

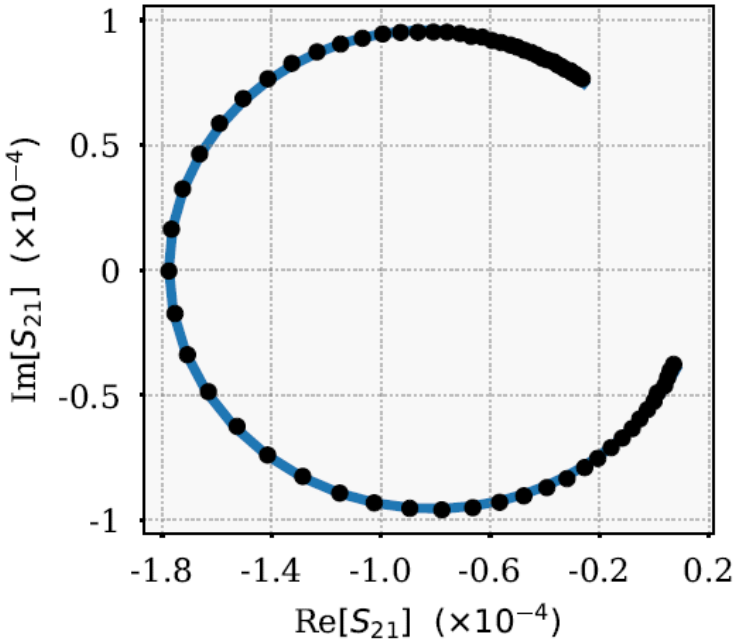

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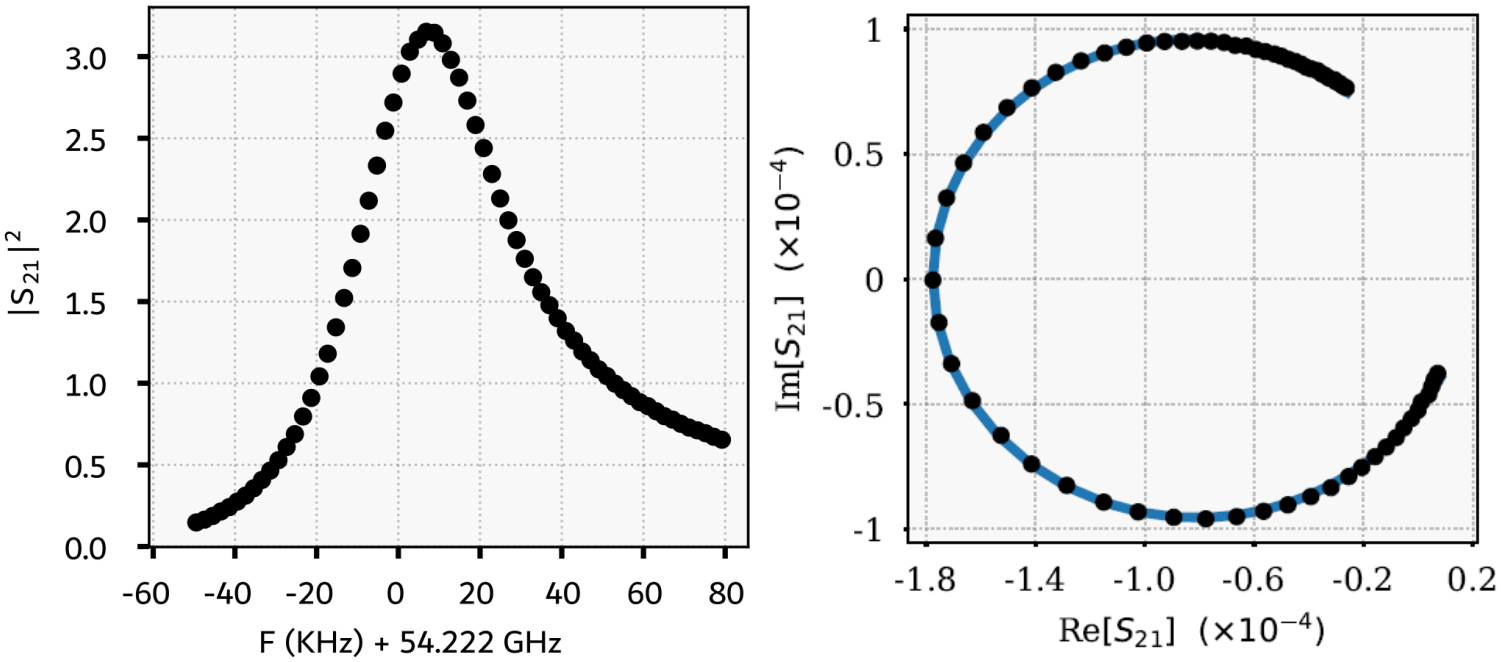
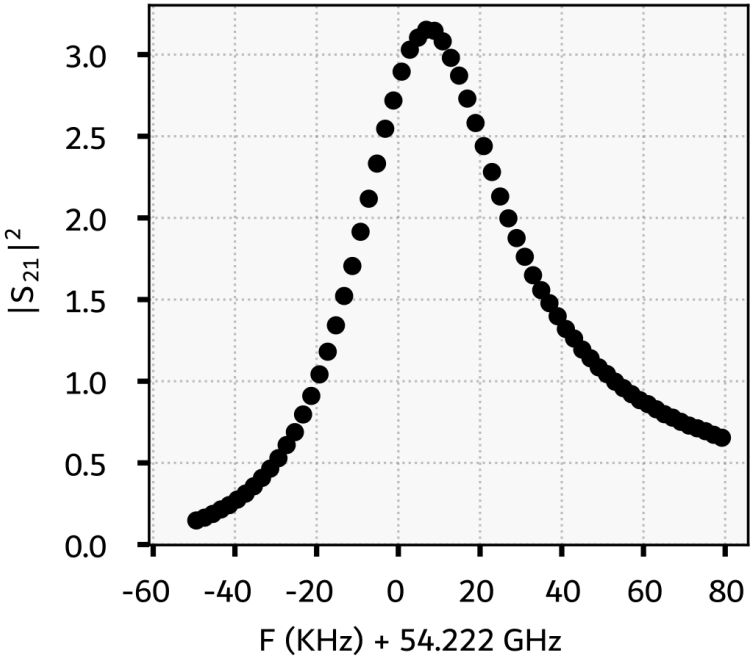
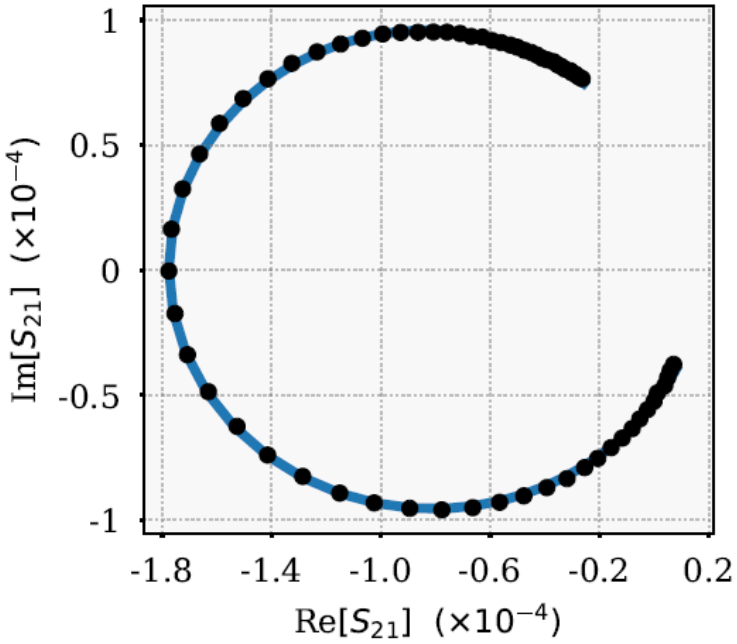


Measured Q factor in excess of 100,000

Measuring Quality factor

$$\text{Rate}\,[s^{-1}] \approx 5 \times 10^{-4} {C_{a\gamma\gamma}}^2\, Q\, V_m B^2$$



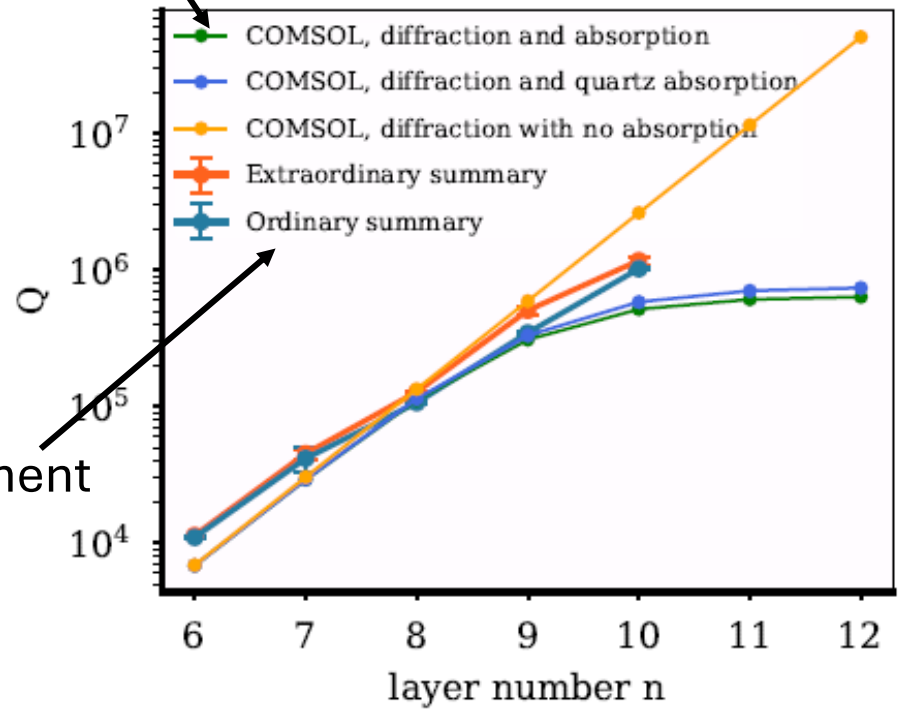


Measured Q factor in excess of 100,000

Simulations

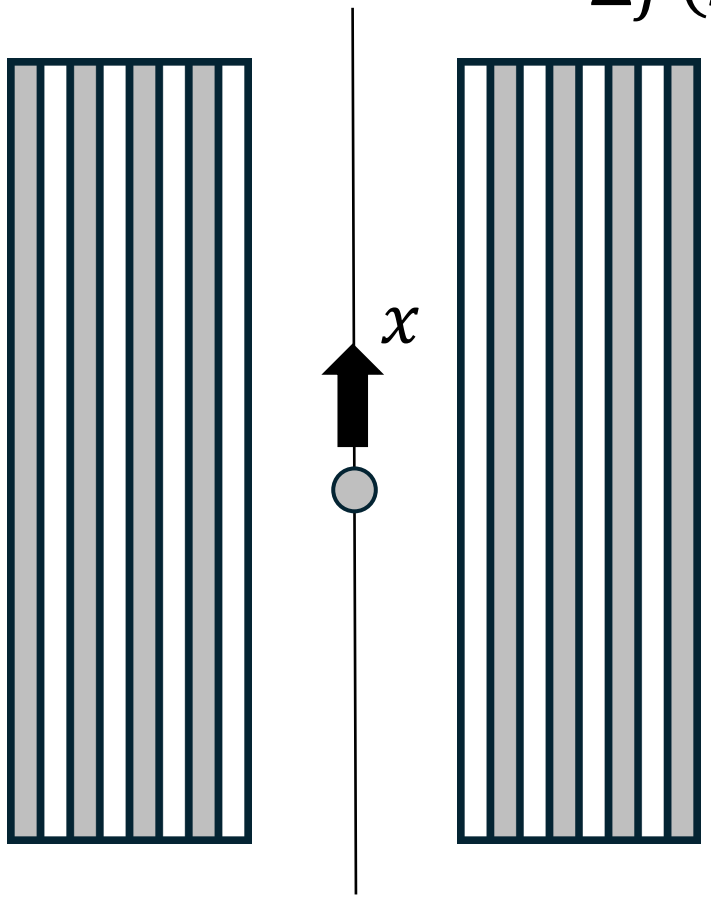
Q factor vs layers in Bragg mirror

Experiment



Cavity Modes

$$\Delta f(x) \propto |E_x(x)|^2$$



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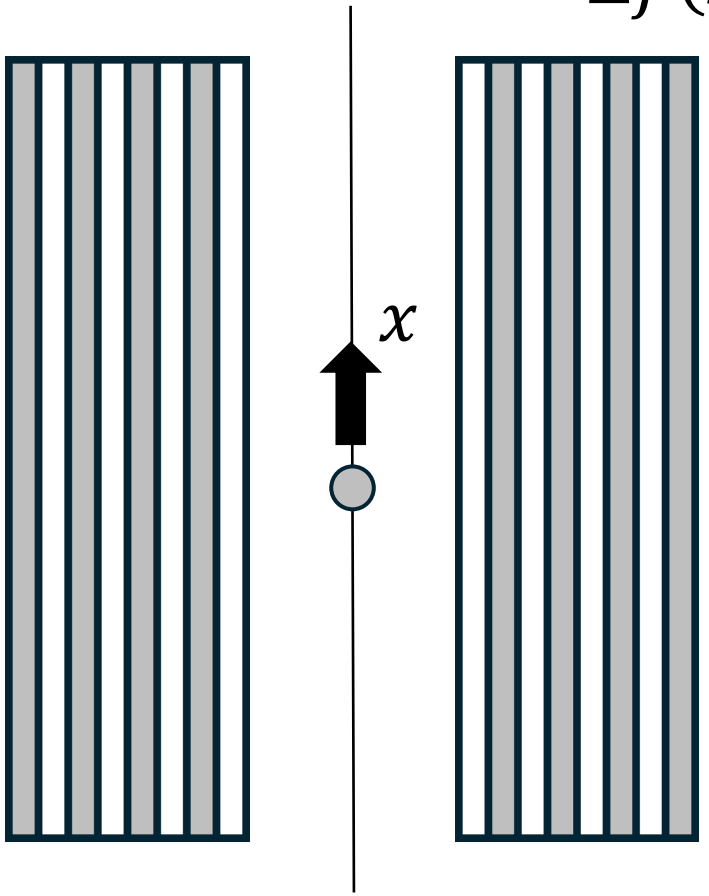
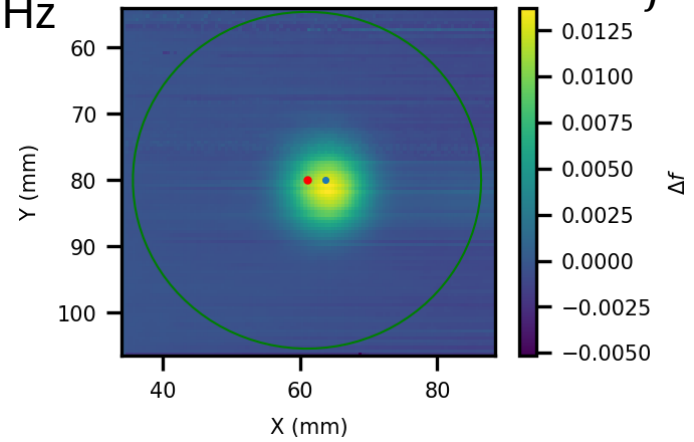
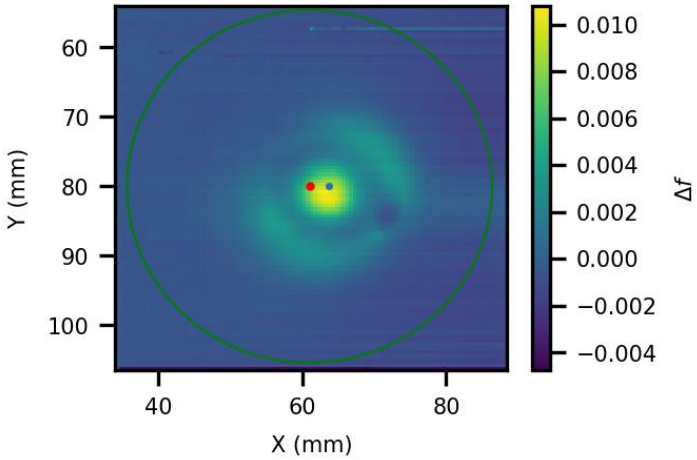


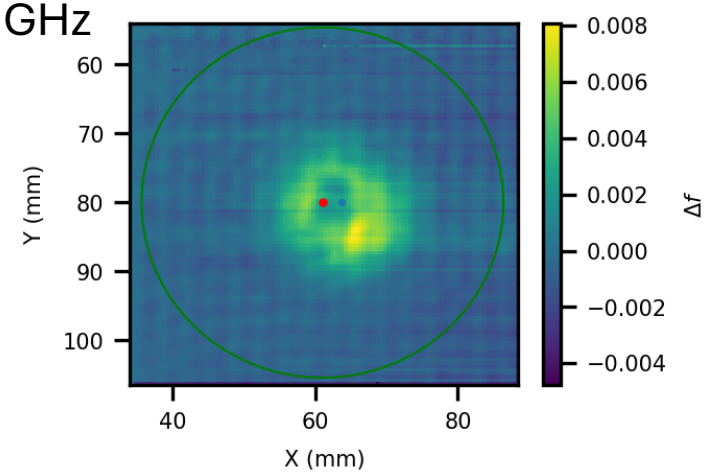
$f \sim 43$ GHz



$f \sim 45$ GHz



$f \sim 44$ GHz



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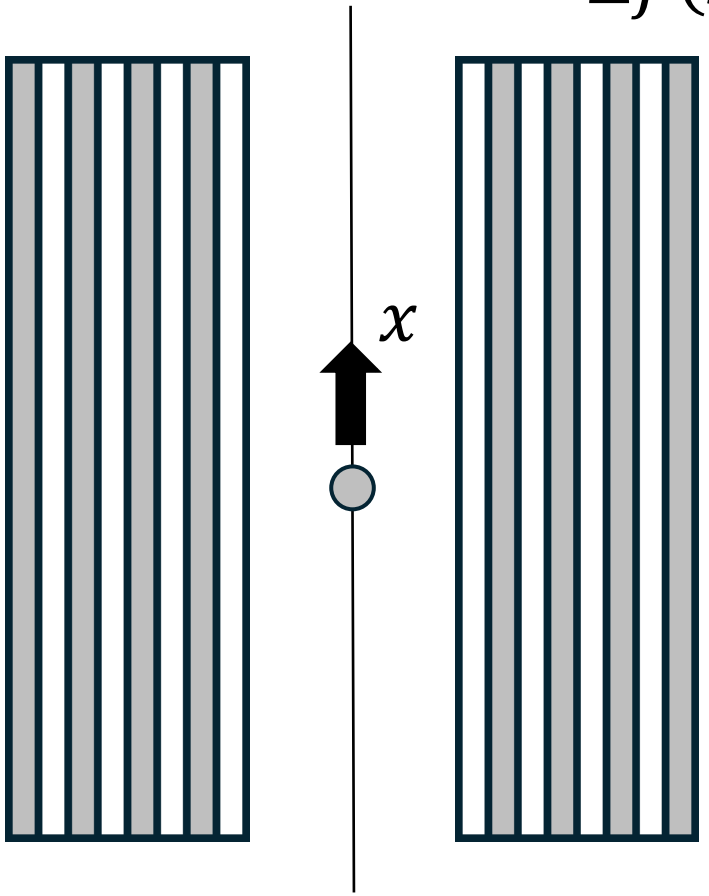

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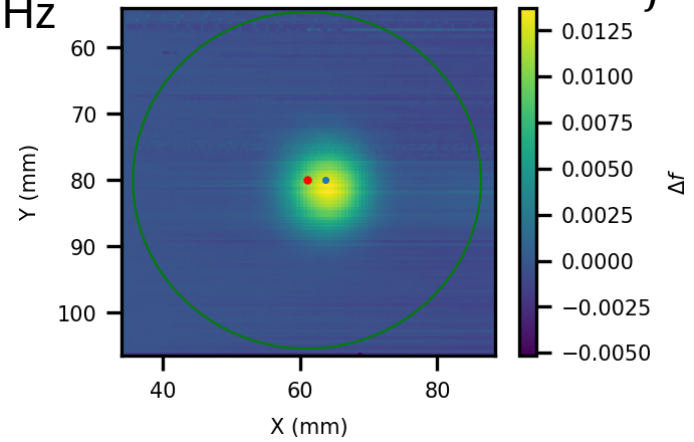

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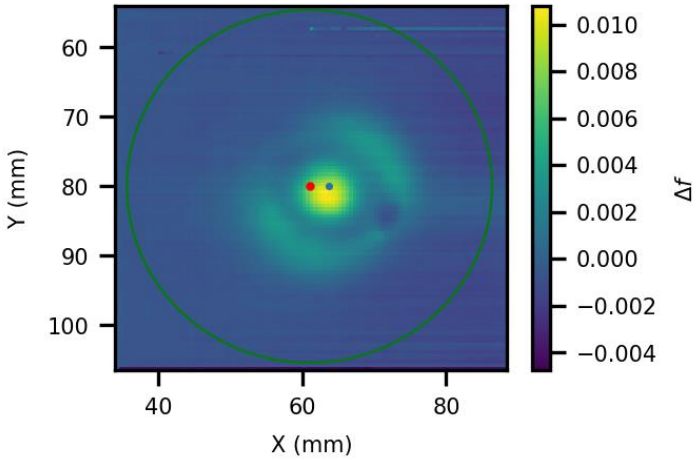

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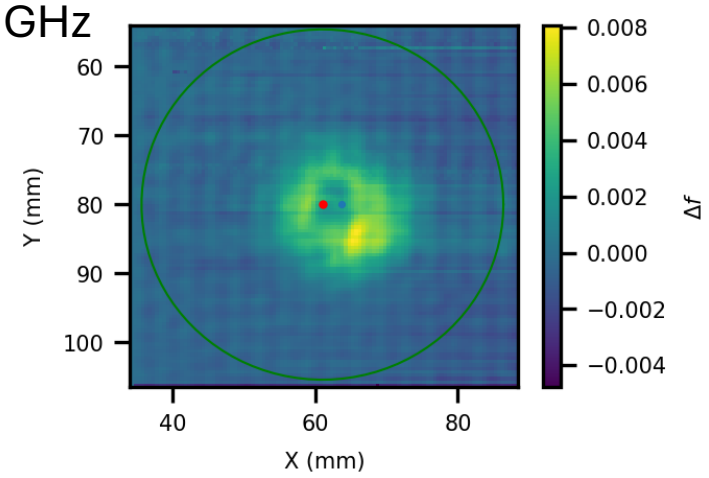
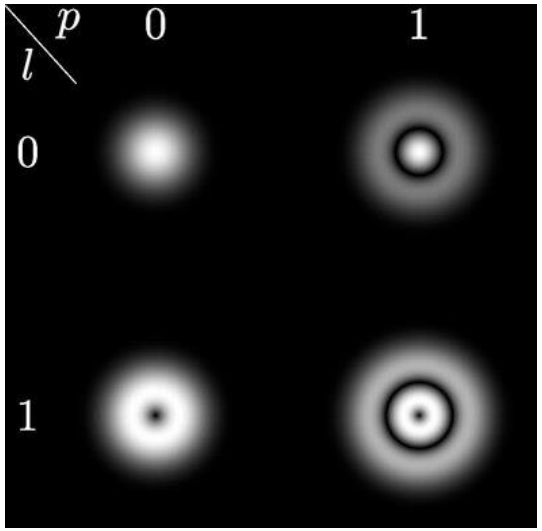
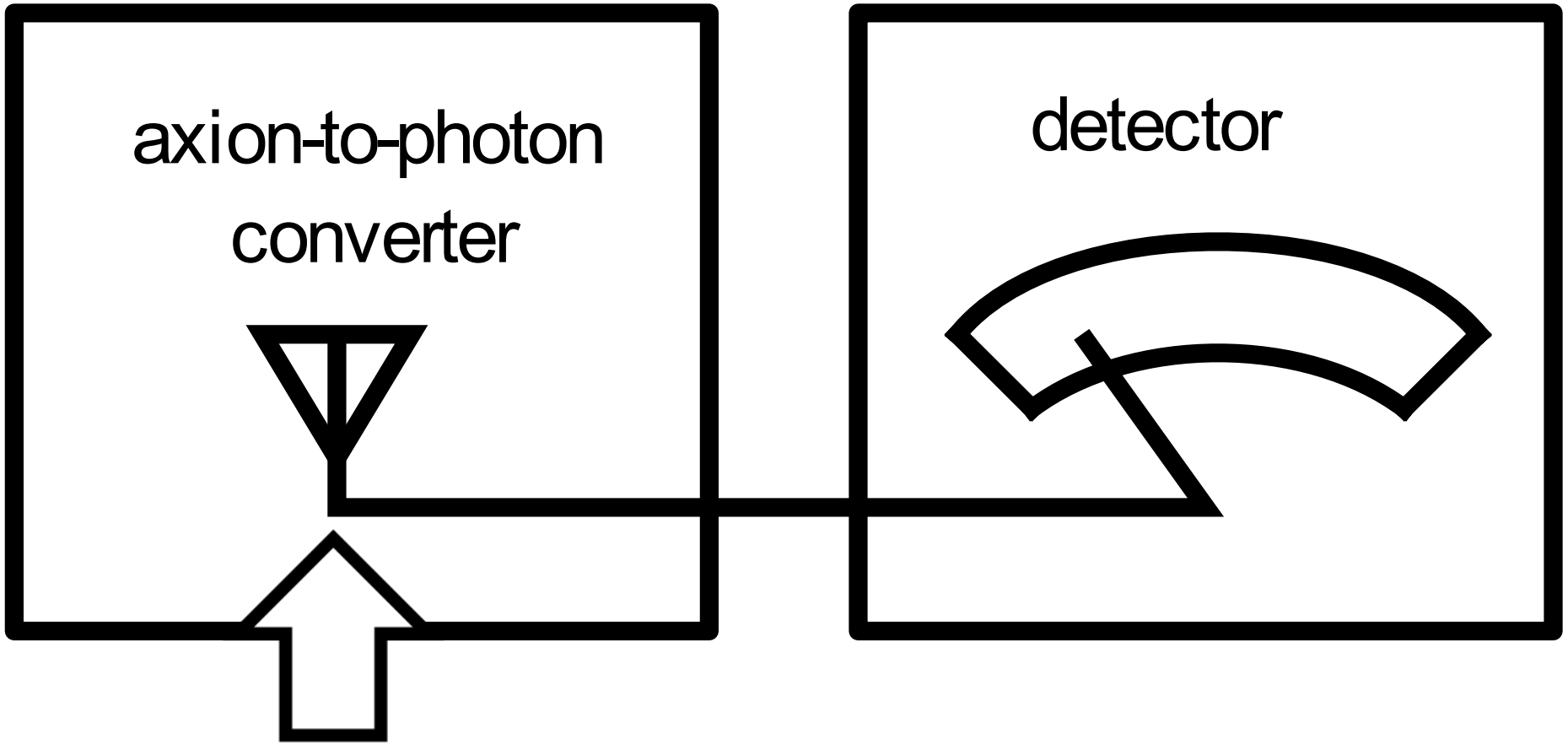


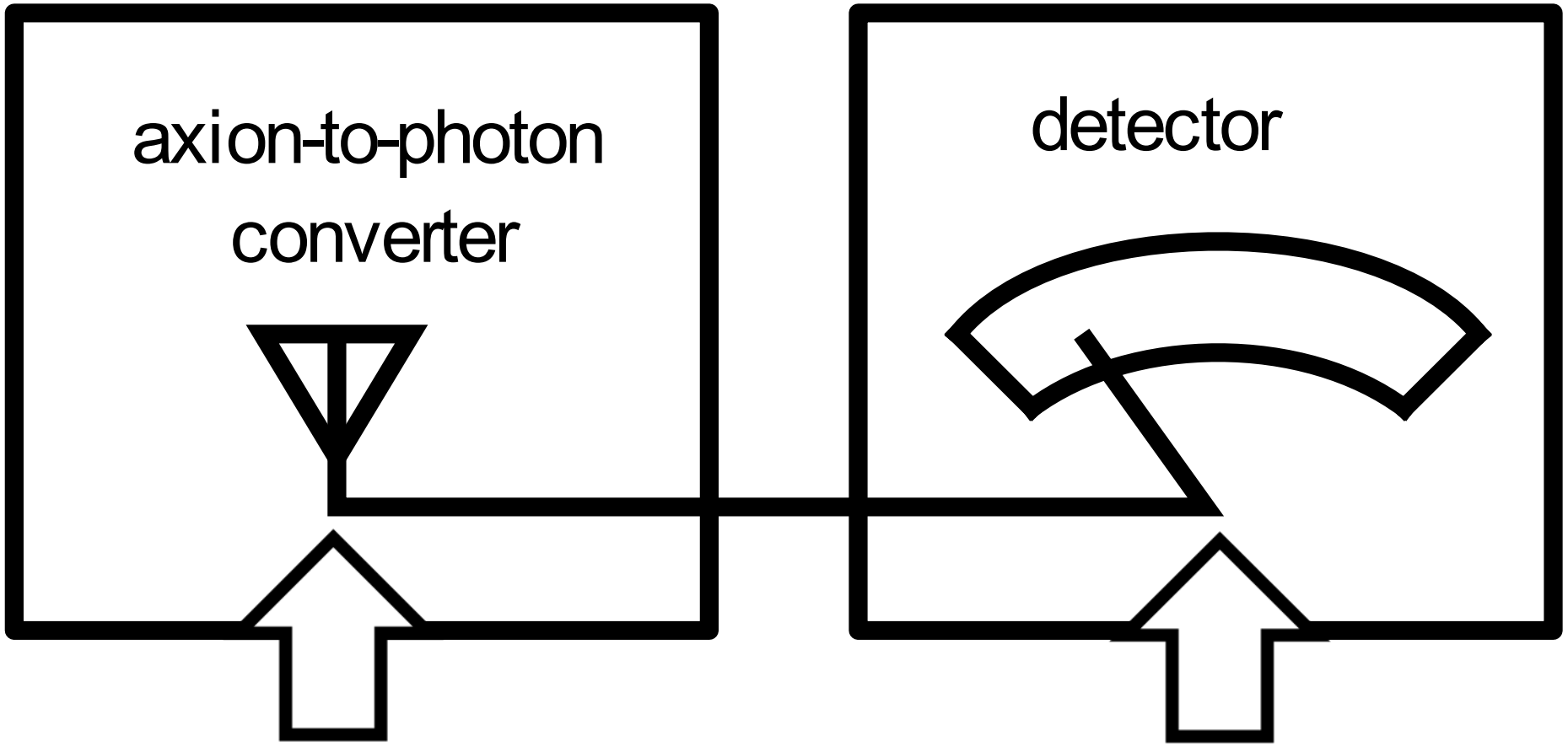


Axion haloscope



Problem 1:
Decreasing volume
(and Q factor)

Axion haloscope

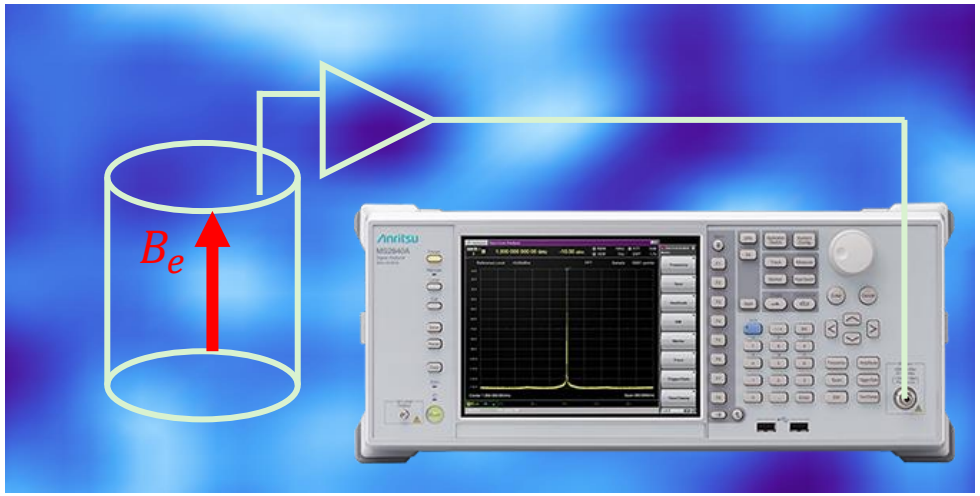


Problem 1:
Decreasing volume
(and Q factor)

Problem 2:
Increasing noise

Increasing noise

Classical readout: linearly amplify signal and use a signal analyzer



$$\text{Noise Power} = h\nu_a(\bar{n} + \frac{1}{2} + \frac{1}{2})\sqrt{\frac{\nu_a}{t\,Q_a}}$$

- Noise from finite temperature
- Zero-point noise from using a normal, Gaussian state of the cavity
- Fundamental quantum amplification noise limit

Standard Quantum Limit (SQL)

S. K. Lamoreaux, et al., Phys. Rev. D **88**, 035020 (2013)

Increasing noise

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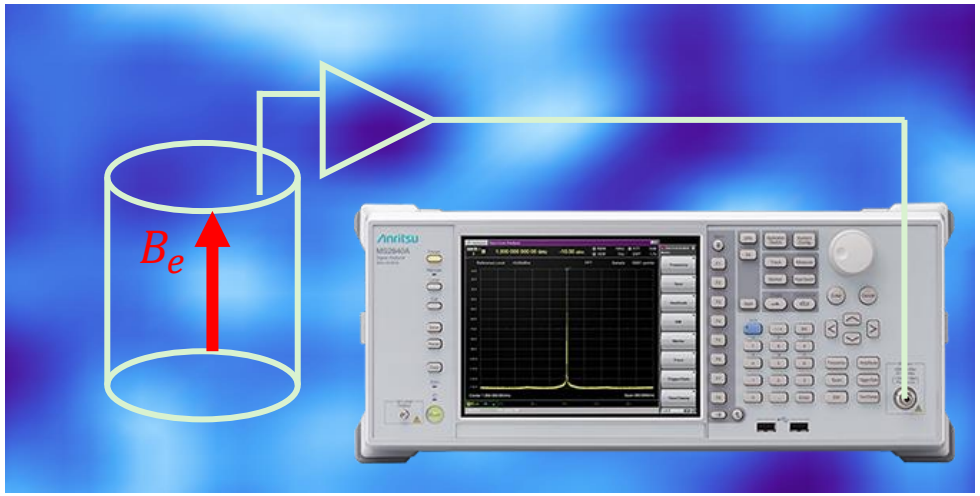

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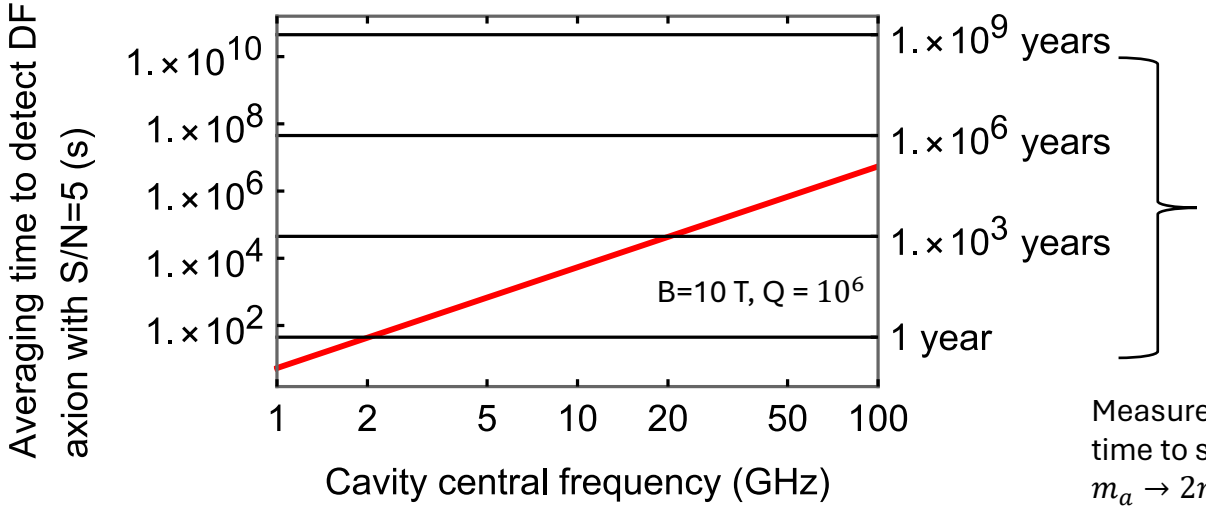
Standard Quantum Limit (SQL)

Cylindrical cavity, DFSZ axion

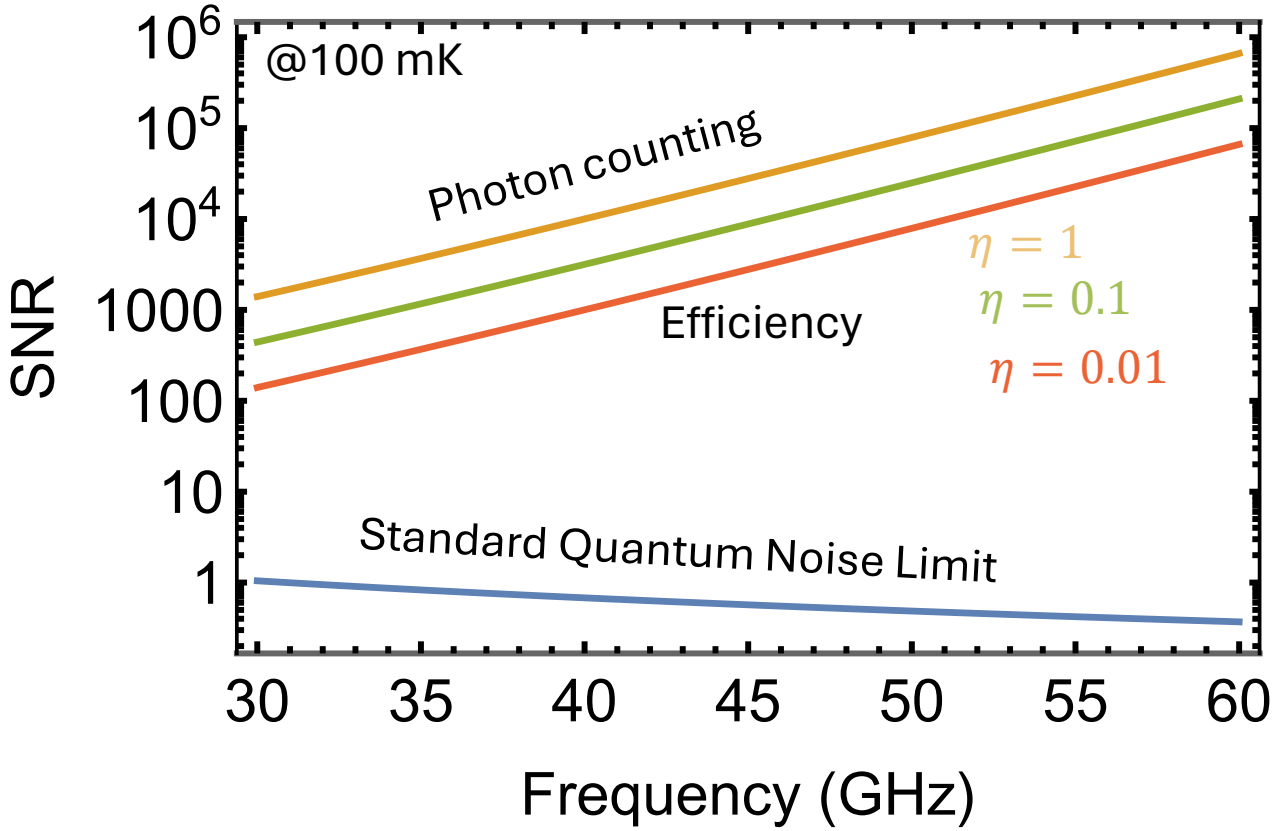
Considering the effect just due to the noise contribution with no decrease in volume



S. K. Lamoreaux, et al., Phys. Rev. D **88**, 035020 (2013)

Photon counting to beat SQL

$$P_{\text{Linear Amp.}} = h\nu_a(\bar{n}+1)\sqrt{\frac{\nu_a}{t\,Q_a}} \quad \text{vs.} \quad P_{\text{photon counting}} = h\nu_a\sqrt{\frac{2\pi\nu_a\eta\bar{n}}{t\,Q_c}}$$



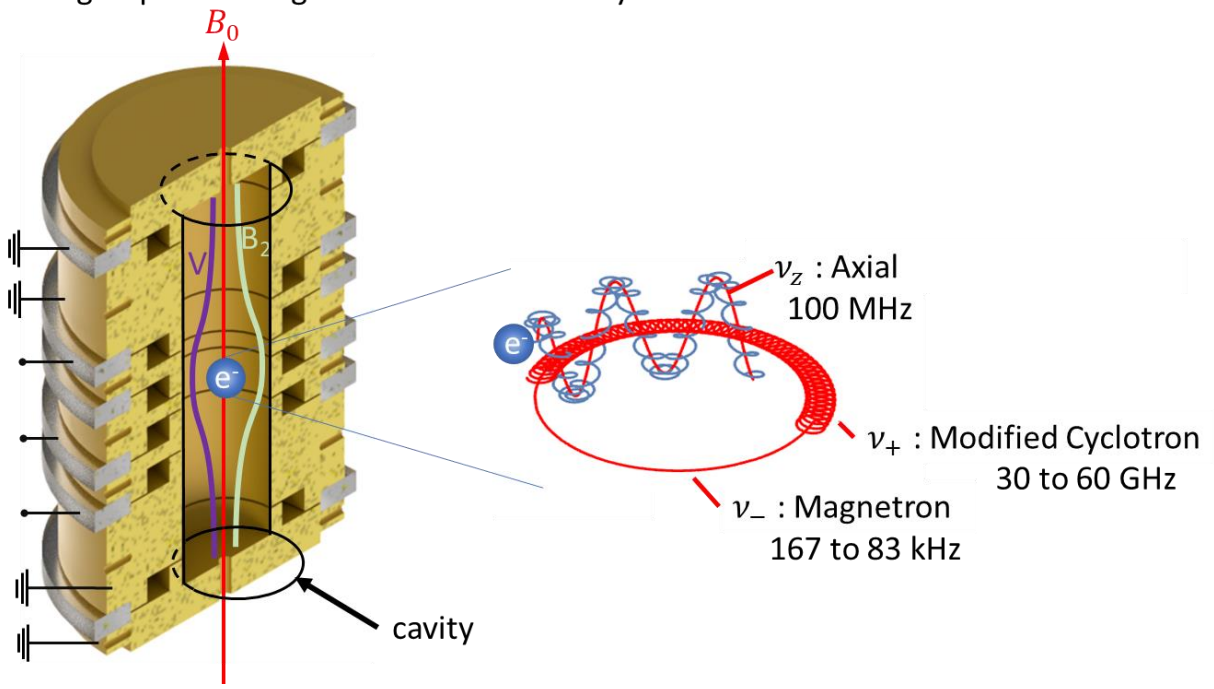
$$\frac{P_{\text{Linear Amp.}}}{P_{\text{photon counting}}} = \sqrt{\frac{Q_c}{2\pi Q_a}}\,e^{h\nu_a/k_BT}$$

for $k_bT/h\nu_a \ll 1$

S. K. Lamoreaux, et al., Phys. Rev. D **88**, 035020 (2013)

Detecting photons with a single trapped electron

A Penning trap with integrated microwave cavity



X. Fan, et al., Photonics, Phys. Rev. D 111, 075022 (2025)
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S. Peil and G. Gabrielse, Phys. Rev. Lett. **83**, 1287 (1999)
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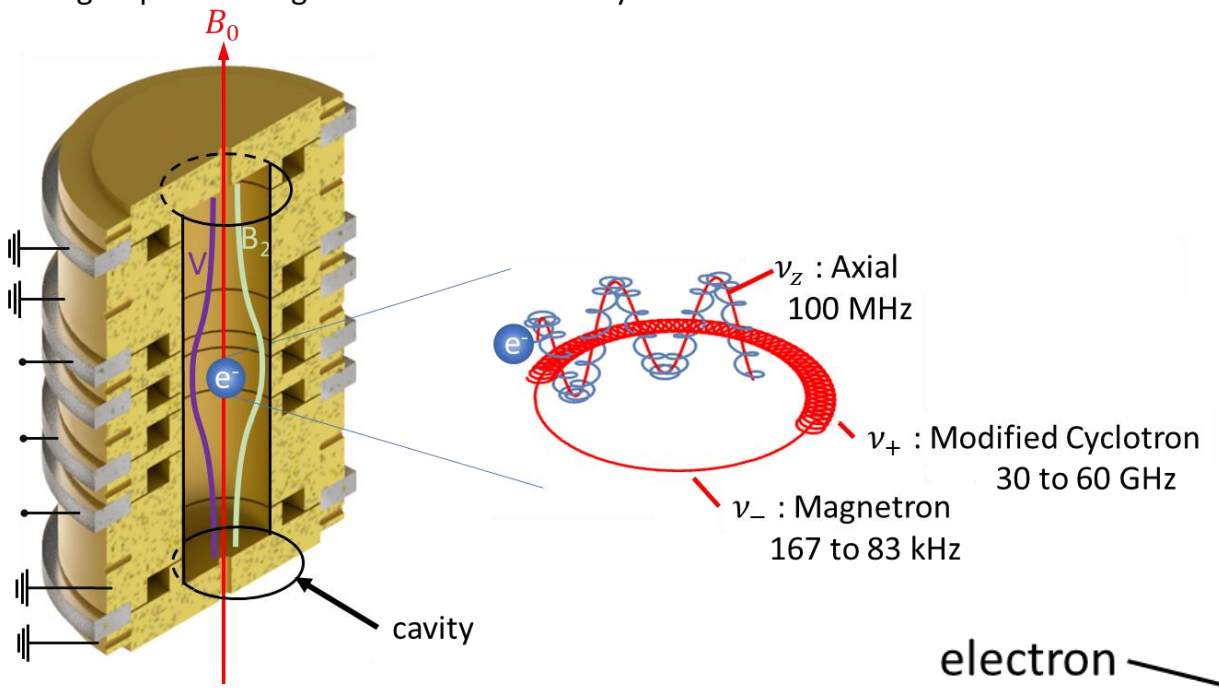

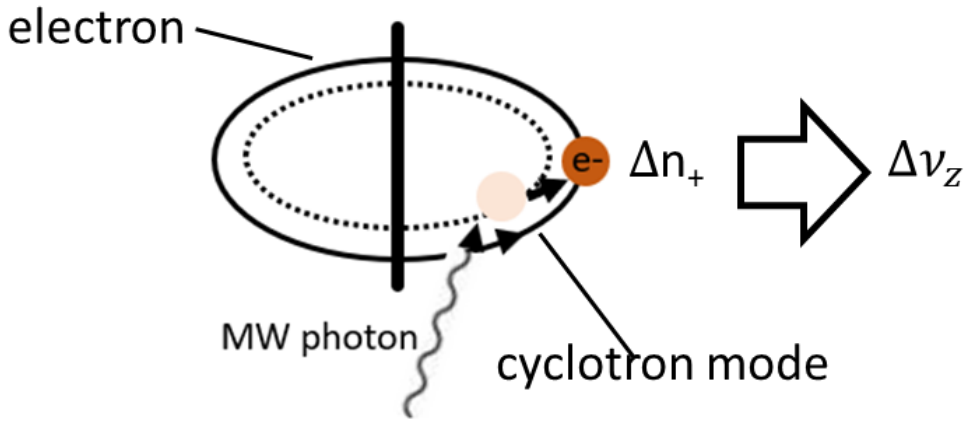

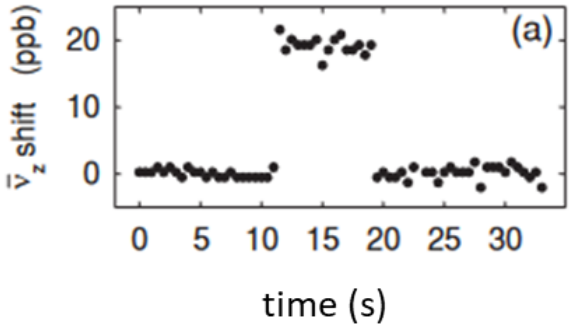

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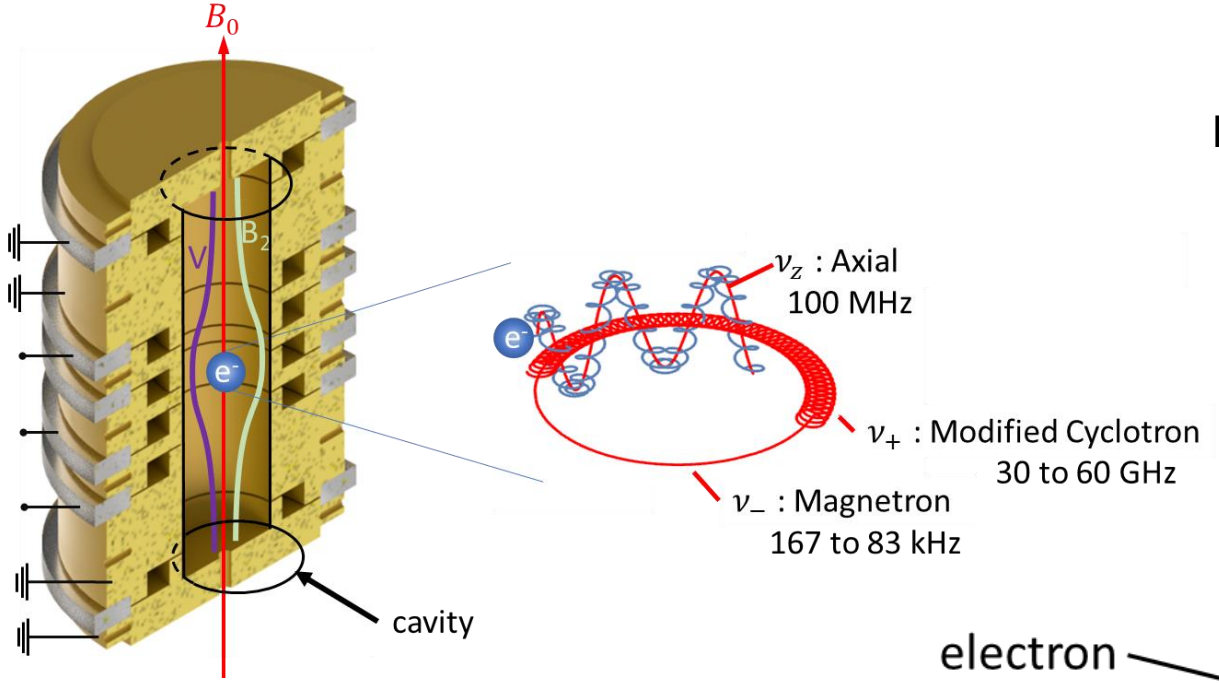
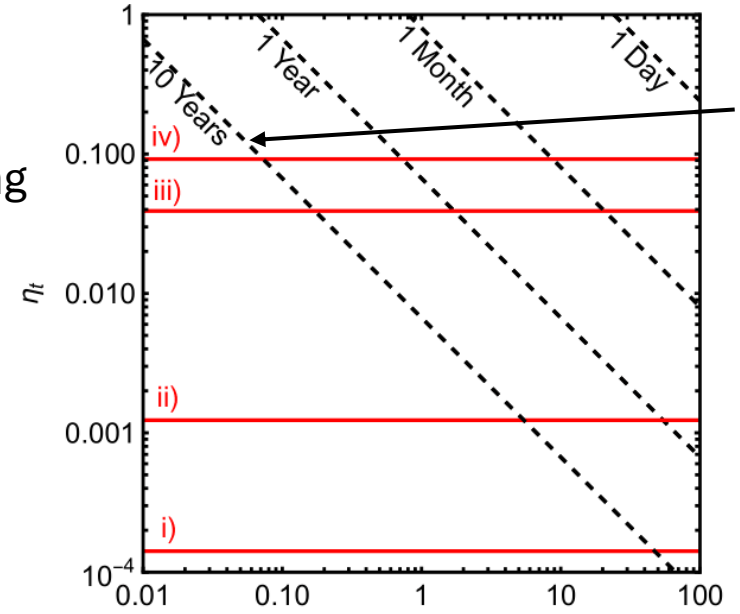
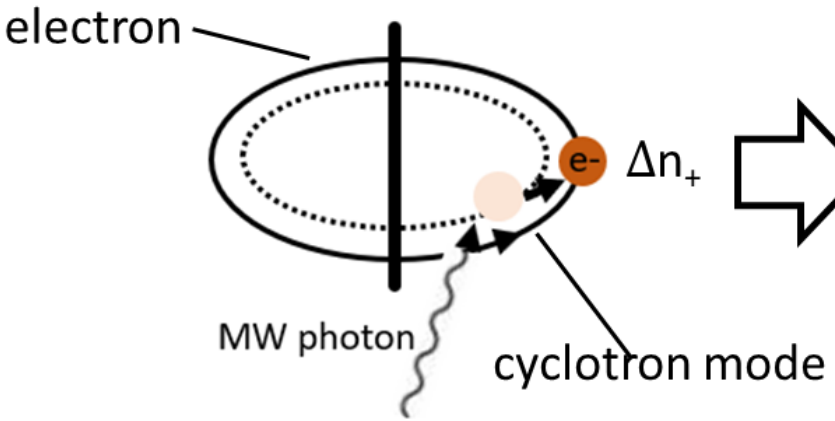


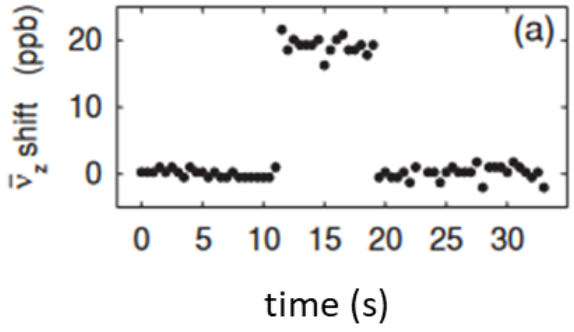
Photon counting efficiency



Photon emission rate



$\Delta\nu_z$



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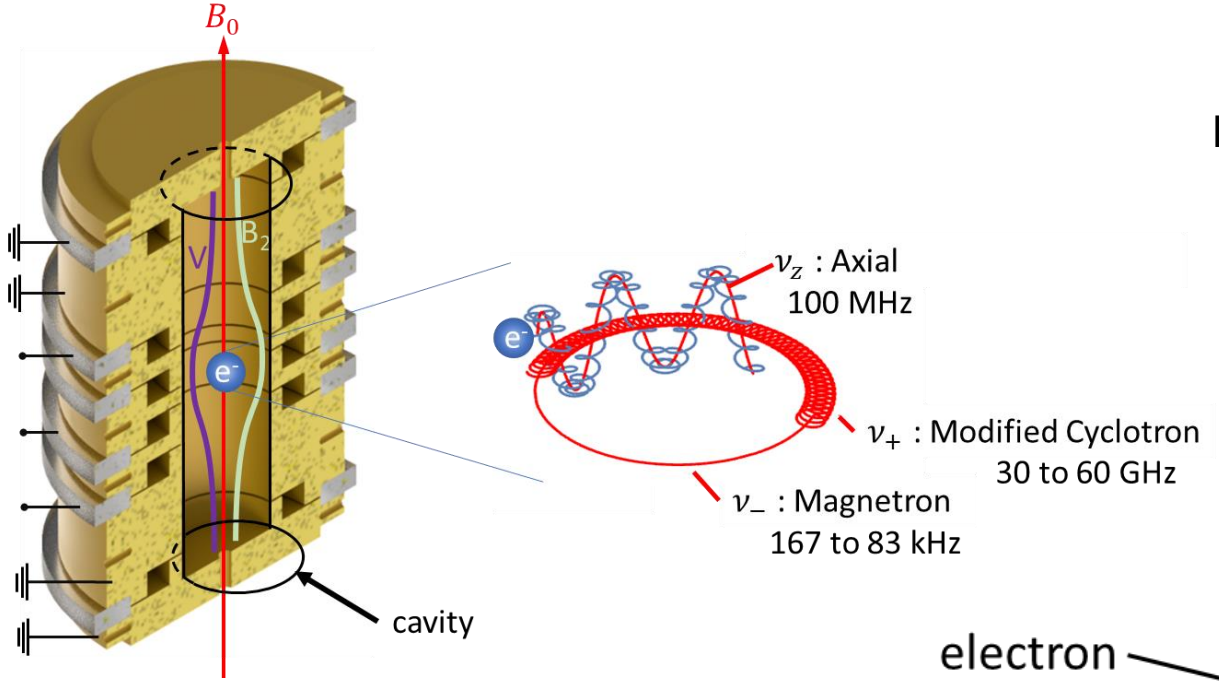
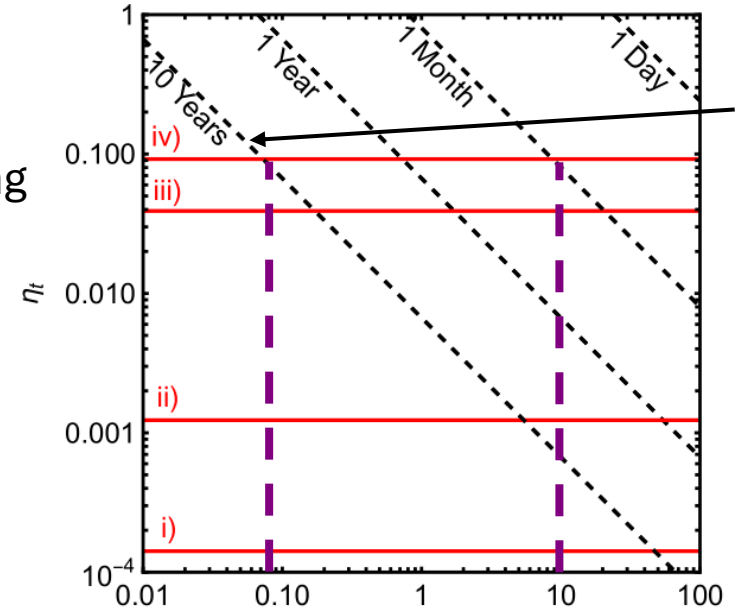
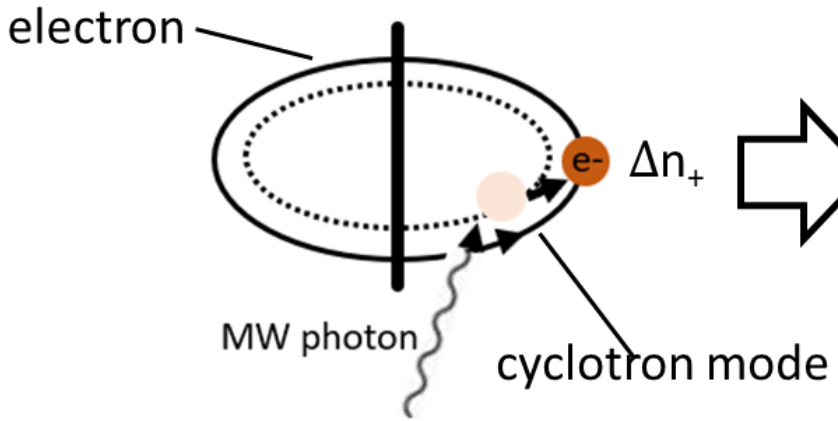


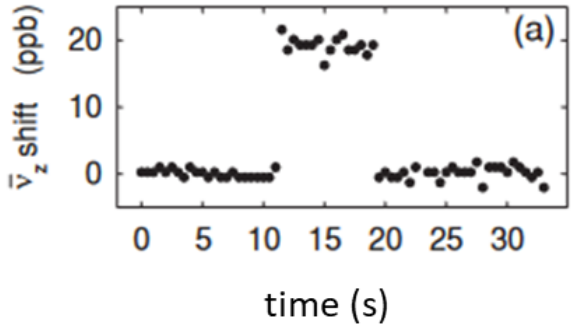
Photon counting efficiency



Time to scan $m_a \rightarrow 2m_a$

Photon emission rate





X. Fan, et al., Photonics, Phys. Rev. D 111, 075022 (2025)
A. Cridland, et al., Photonics, 3(4), 59 (2016)
S. Peil and G. Gabrielse, Phys. Rev. Lett. **83**, 1287 (1999)
D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, PRA **83**, 052122 (2011)

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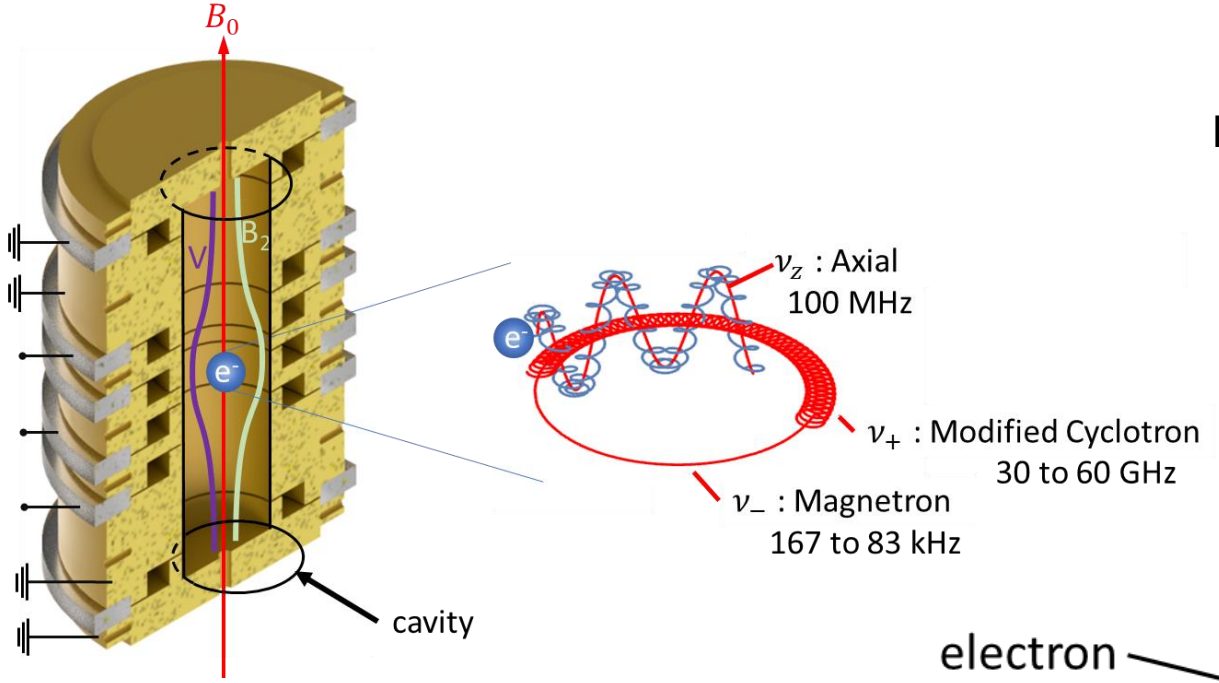

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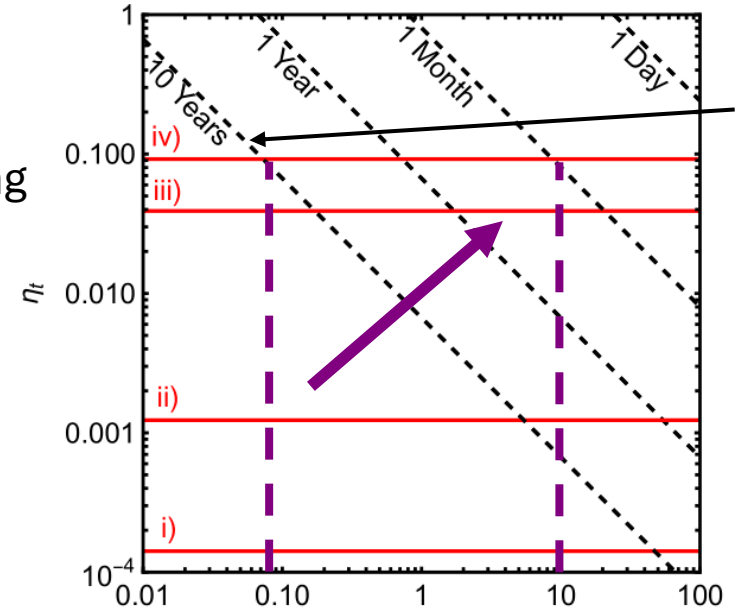

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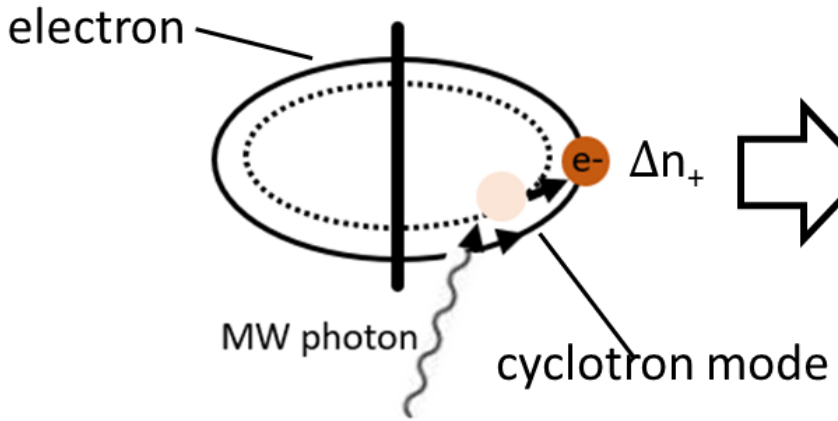
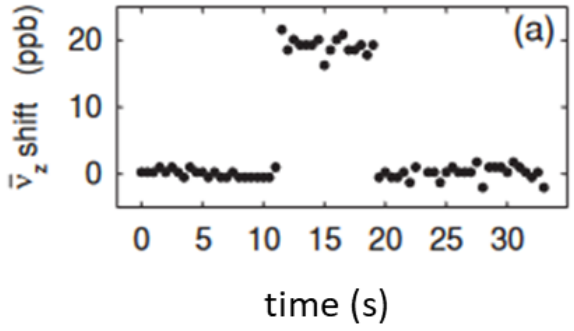


$\Delta\nu_z$



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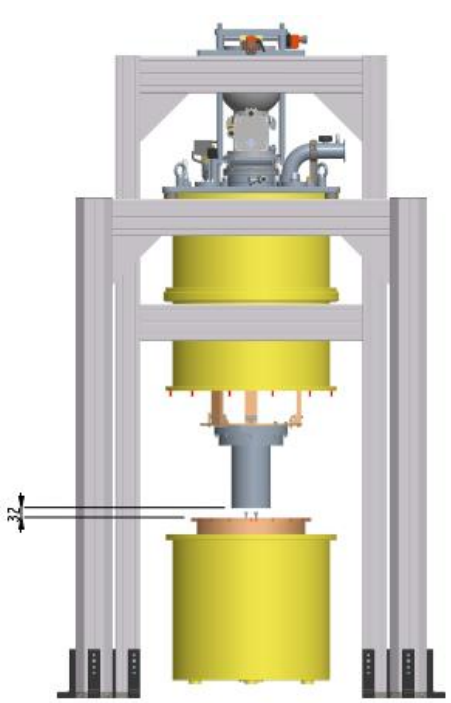
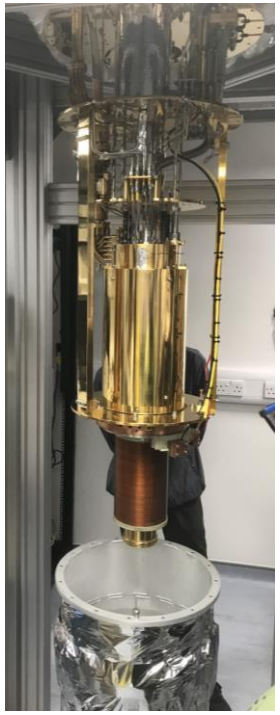
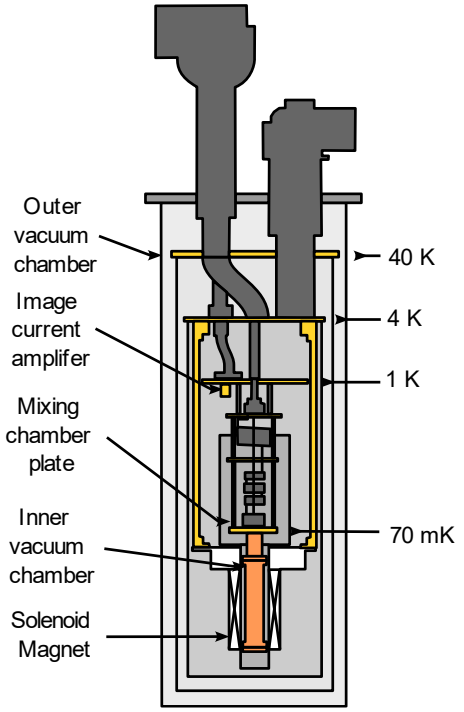
Trapped electrons

Cryo infrastructure

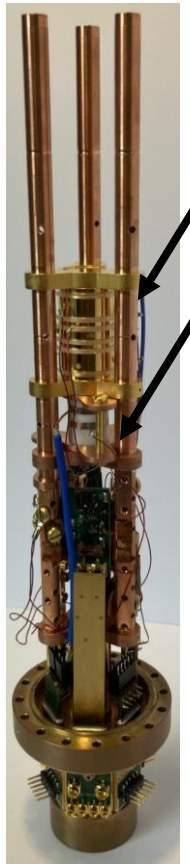


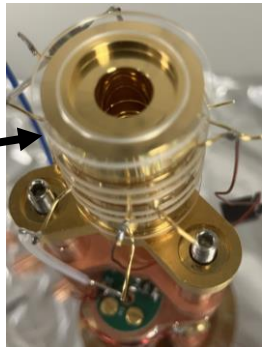


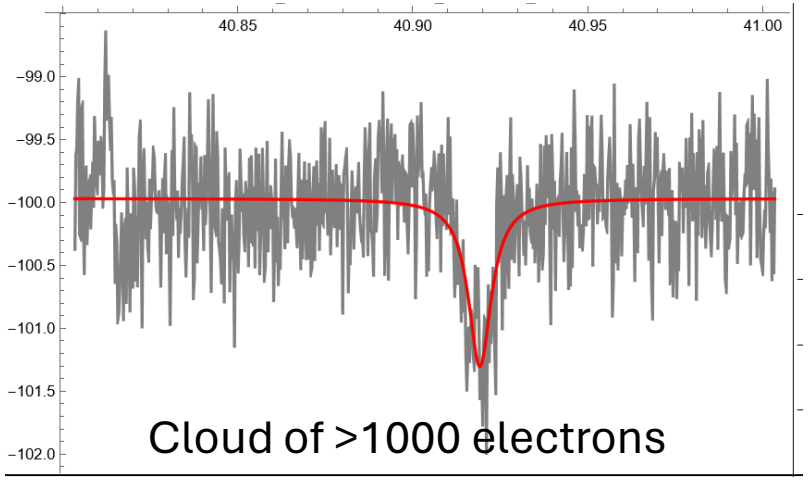


- Dilution fridge installed October 2024
- Base temperature < 50 mK at 2T field
- Vibrations at sample space investigated and found to be acceptable

Penning trap assembly







Next Steps

- Test run with 2 inch Fabry-Perot cavity.
- Reduce number of electrons trapped to a single electron.

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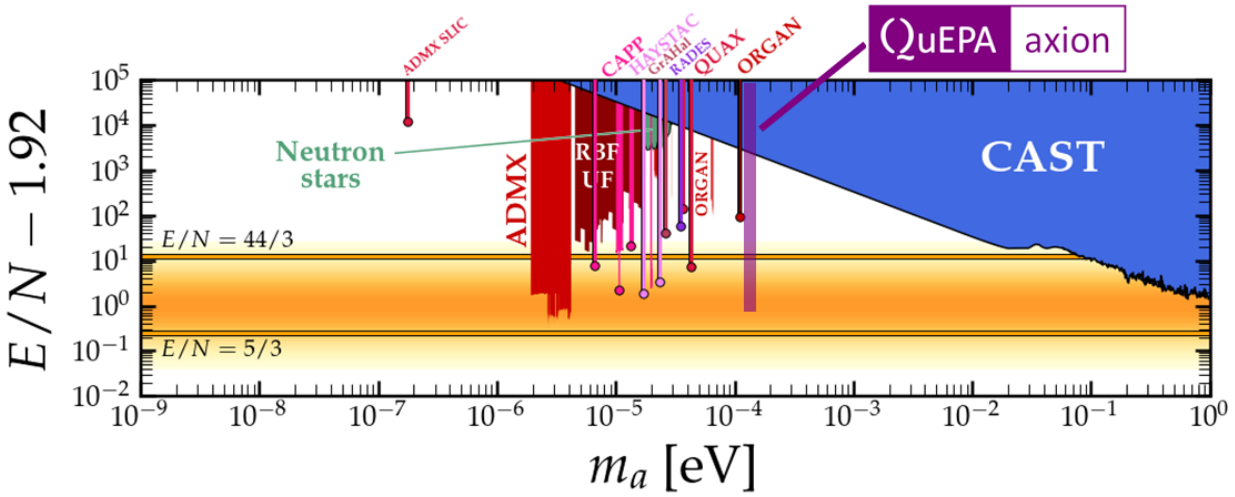
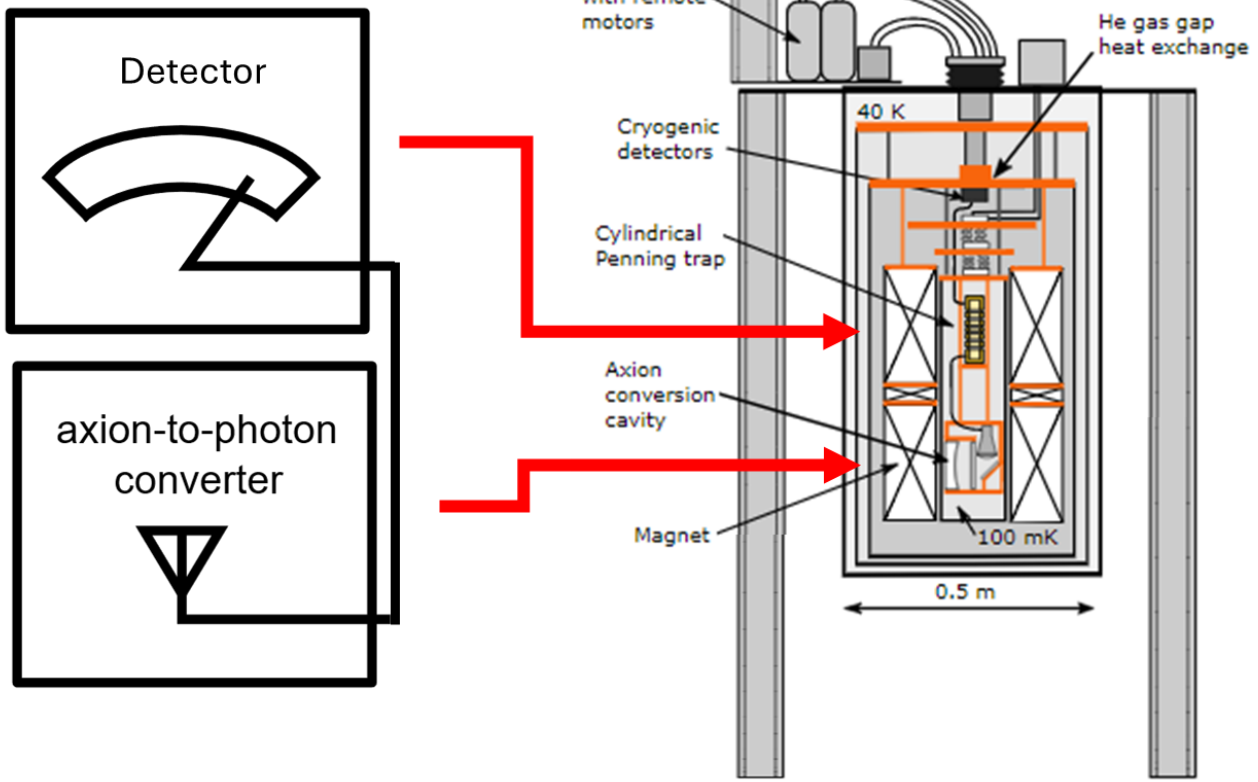


Goal: Search $m_a \sim 125 - 250\ \mu eV$
@ DFSZ sensitivity



Thank you for listening

QuEPA **Qu**antum **E**nhanced **P**article **A**strophysics Team

Richard Thompson

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+ **Mike Tarbutt**

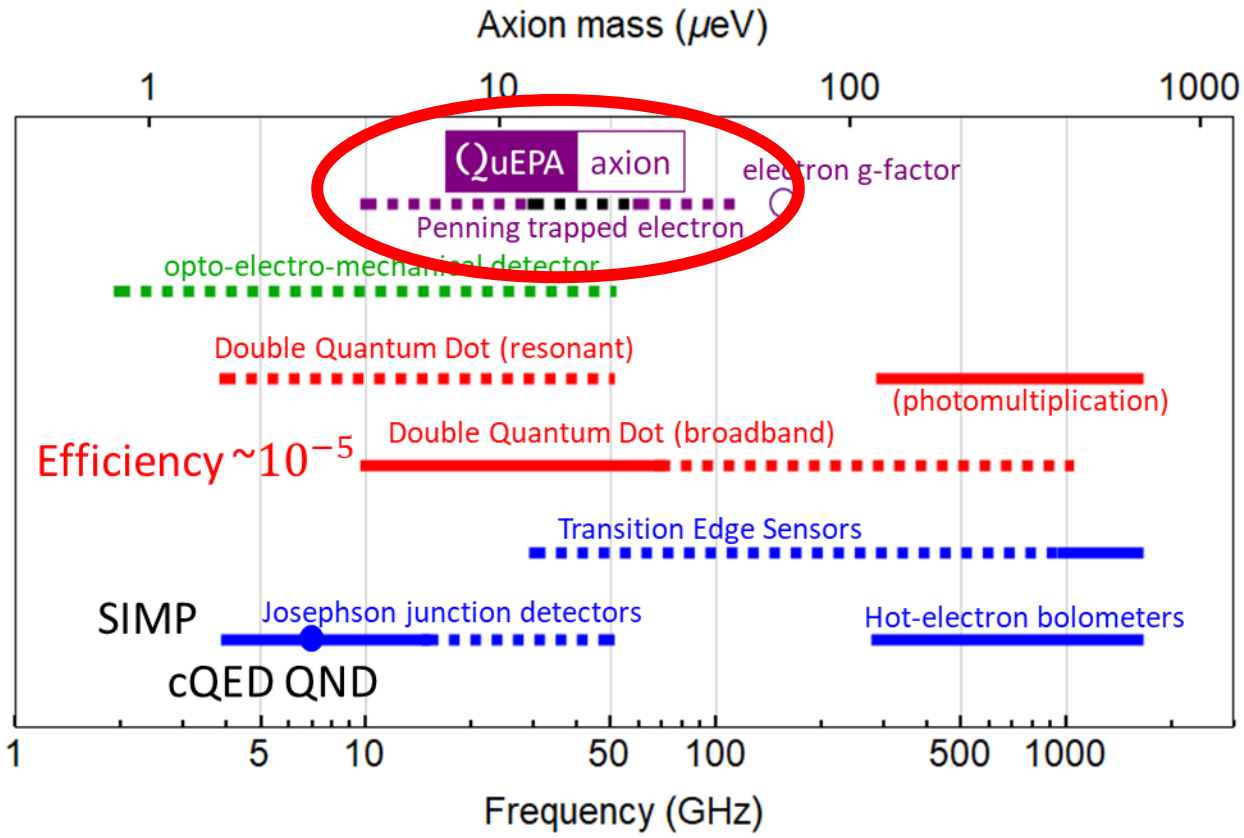
Marios Telemachou &
Mingyao Xu
Maddie Fisher
Horacio Septien-Gonzalez

Toren Dofher Marko Wojtkowiak JAD Shreyak Banhatti

He Zhang Jiacheng Shi

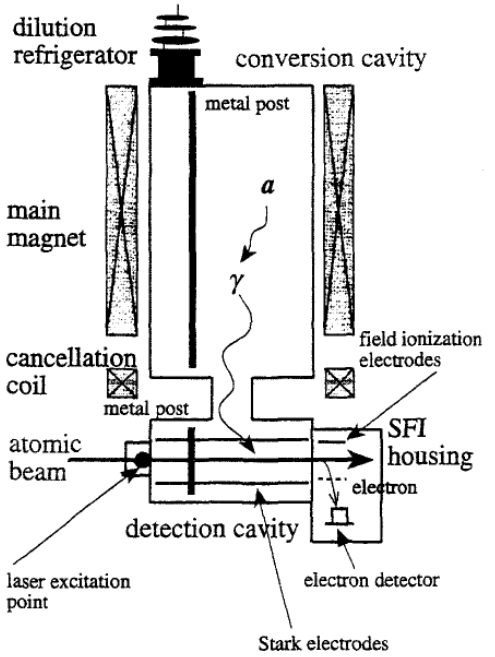
Single photon counters

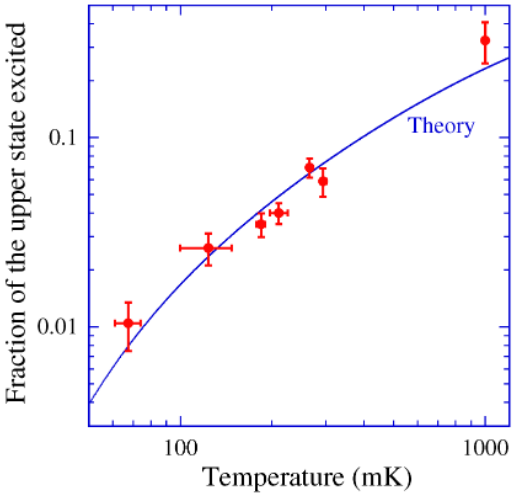
Solid-state devices



Alternative AMO devices

CARRACK I & II Rydberg atoms





Good performance, ultimately effort was not sustained.

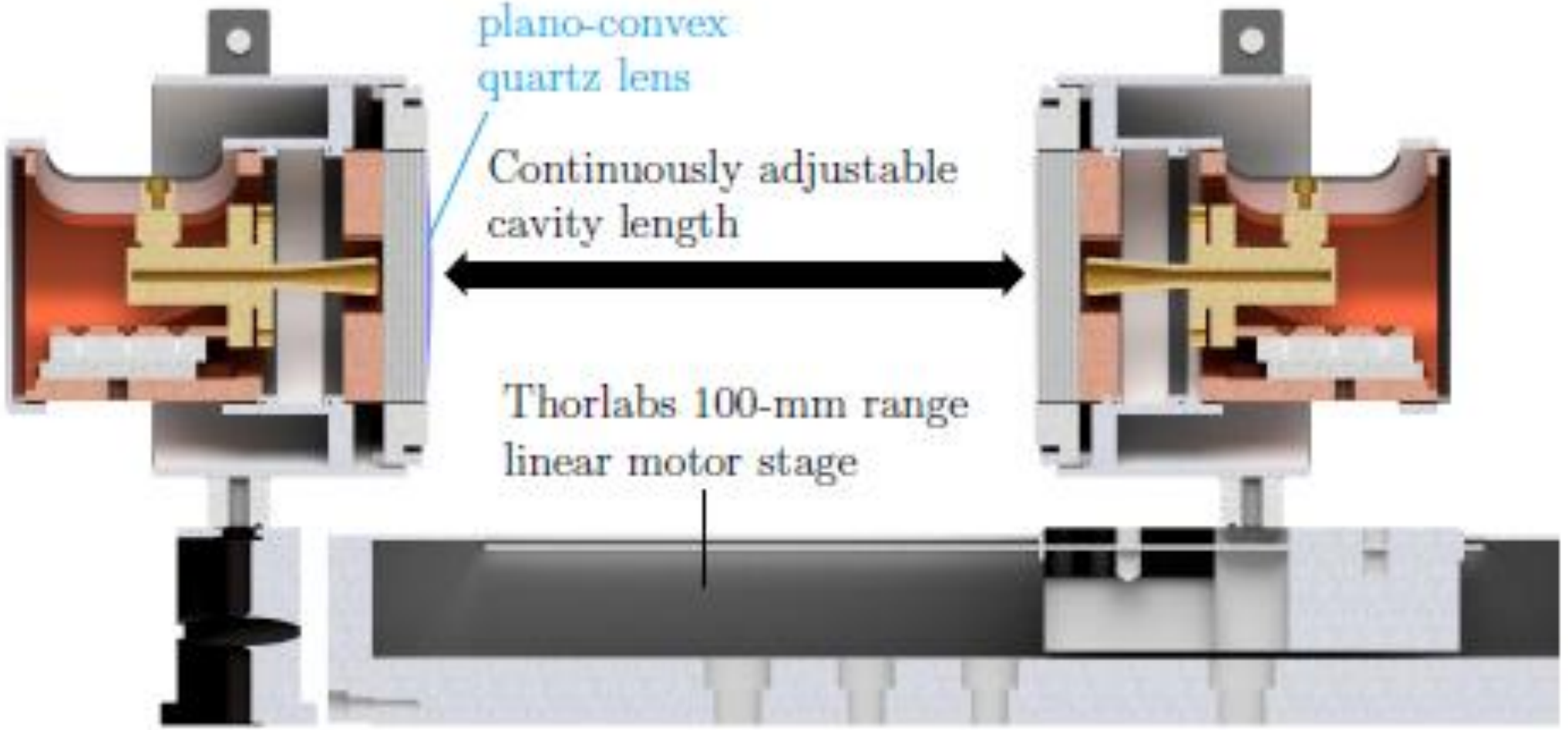
Now Rydberg Axions at Yale (RAY) D. Speller, & S. Ghosh

A. V. Dixit, et al., Phys. Rev. Lett. **126** 141302 (2021)

A. Ghirri et al., Sensors **20(14)**, 4010 (2020)

M. Tada et al., Nuclear Physics B (Proc. Suppl.) **72** 164 (1999)

M. Tada et al., Physics Letters A **349 6** 488 (2006)


plano-convex
quartz lens
Continuously adjustable
cavity length
Thorlabs 100-mm range
linear motor stage