

An axion search using a dielectric Fabry-Perot cavity and trapped electron single photon counter

Jonathan Gosling



IMPERIAL



**UK Research
and Innovation**

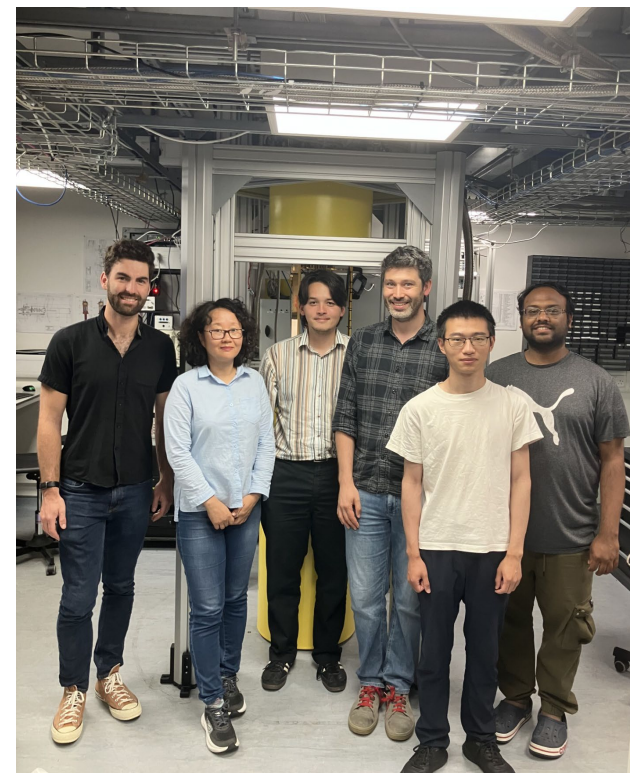
Who we are

Centre for Cold Matter @ Imperial College London



The Centre for Cold Matter uses cold atoms, molecules and ions to test fundamental physics, measure tiny forces, control quantum systems and develop quantum technologies

QuEPA Quantum Enhanced Particle
Astrophysics Team



Richard
Thompson



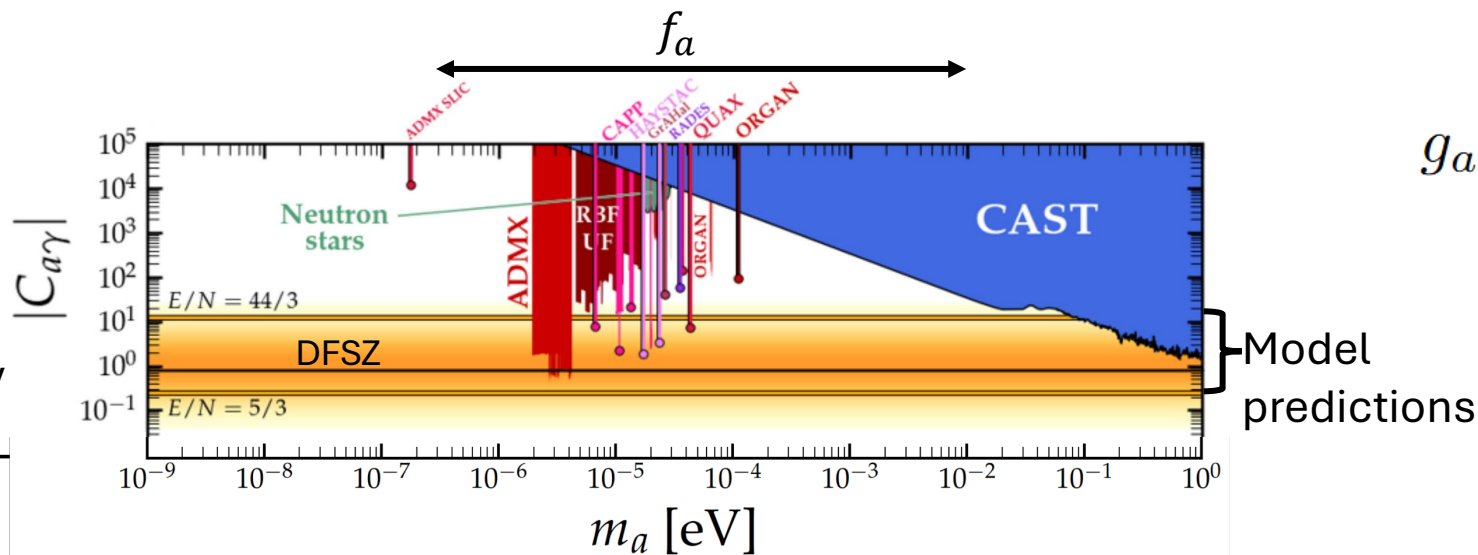
Dr. Kanika

Toren Dofher Marko Wojtkowiak Jack Devlin Shreyak Banhatti
He Zhang Jiacheng Shi

+ **Mike Tarbutt** Marios Telemachou & Mingyao Xu, Maddie Fisher
Horacio Septien-Gonzalez

Axion parameter space

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

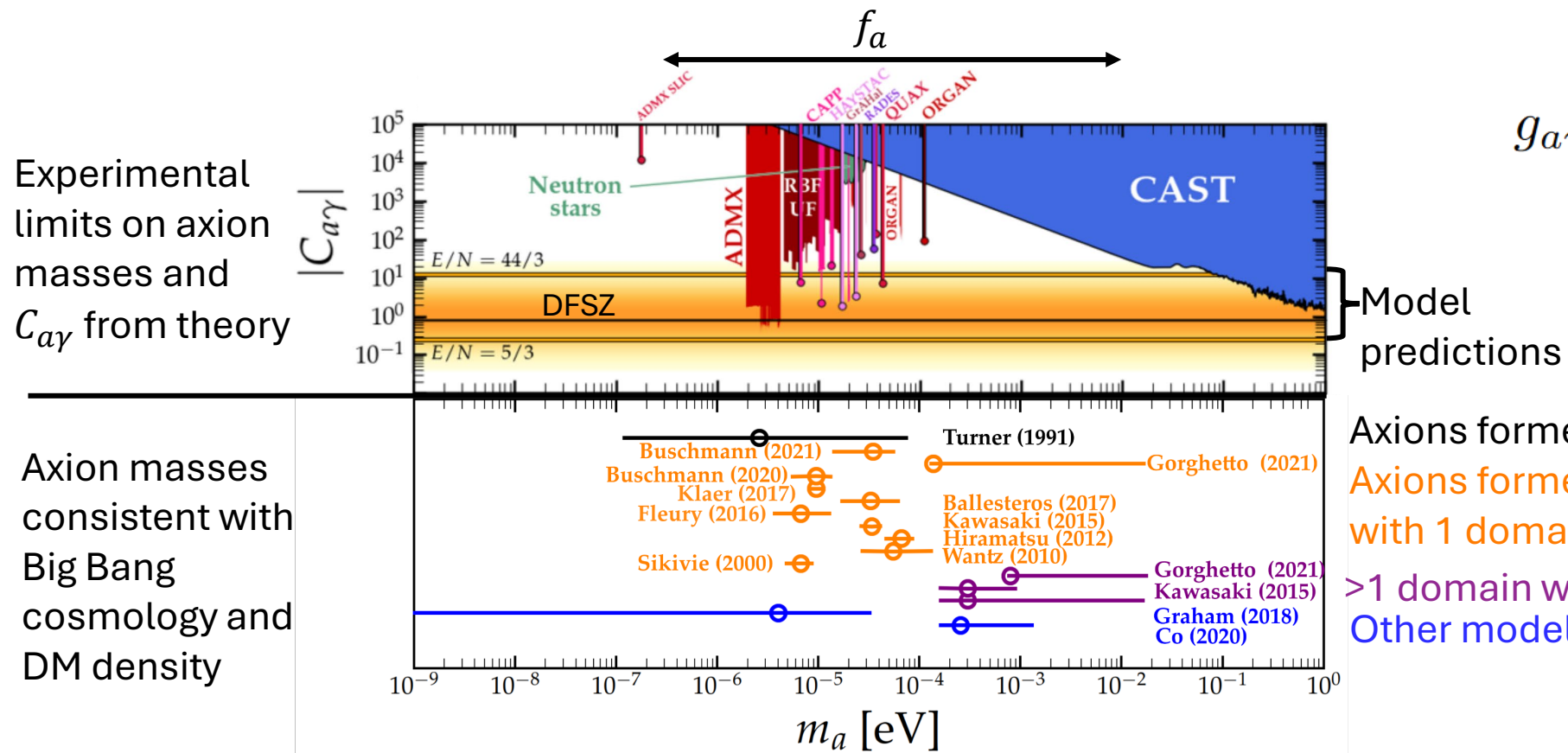


$$g_{a\gamma\gamma} = C_{a\gamma} \frac{\alpha}{2\pi} \frac{m_a}{\sqrt{\chi}}.$$

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

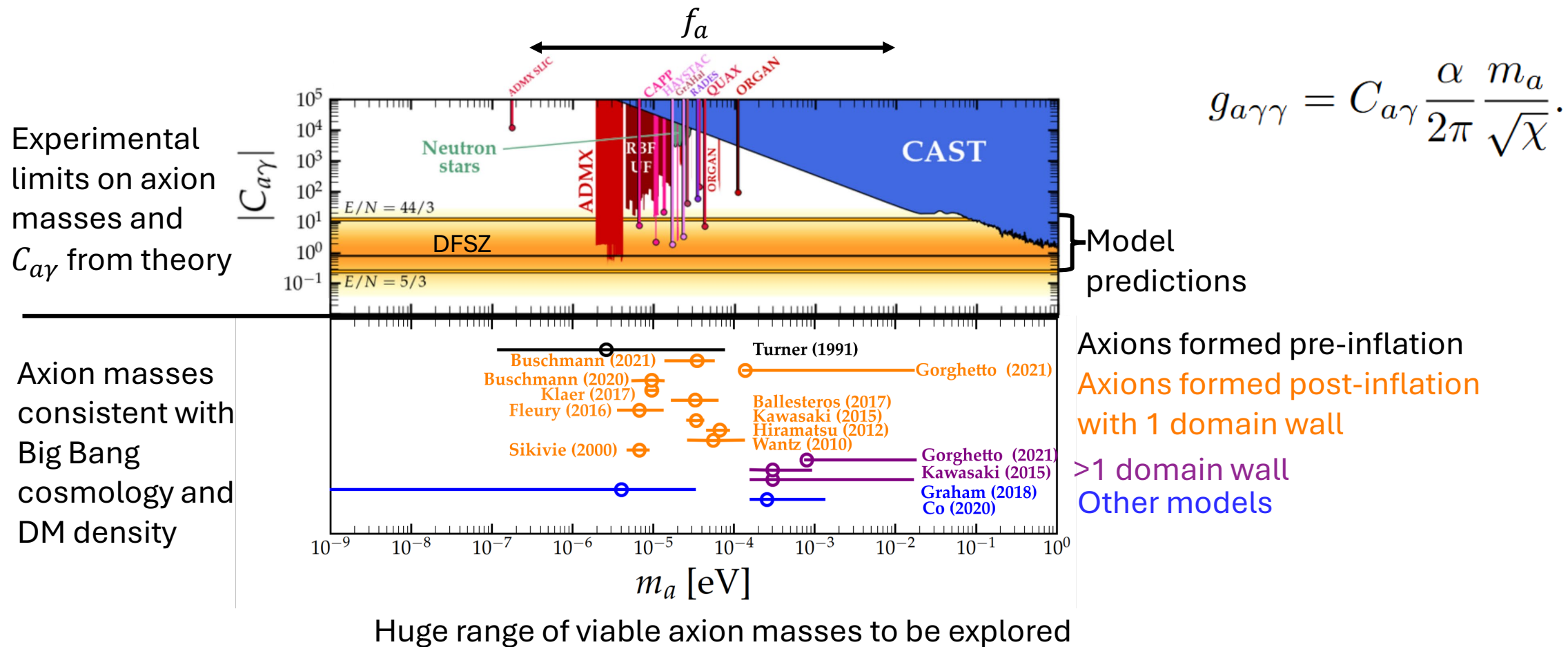
Axion parameter space



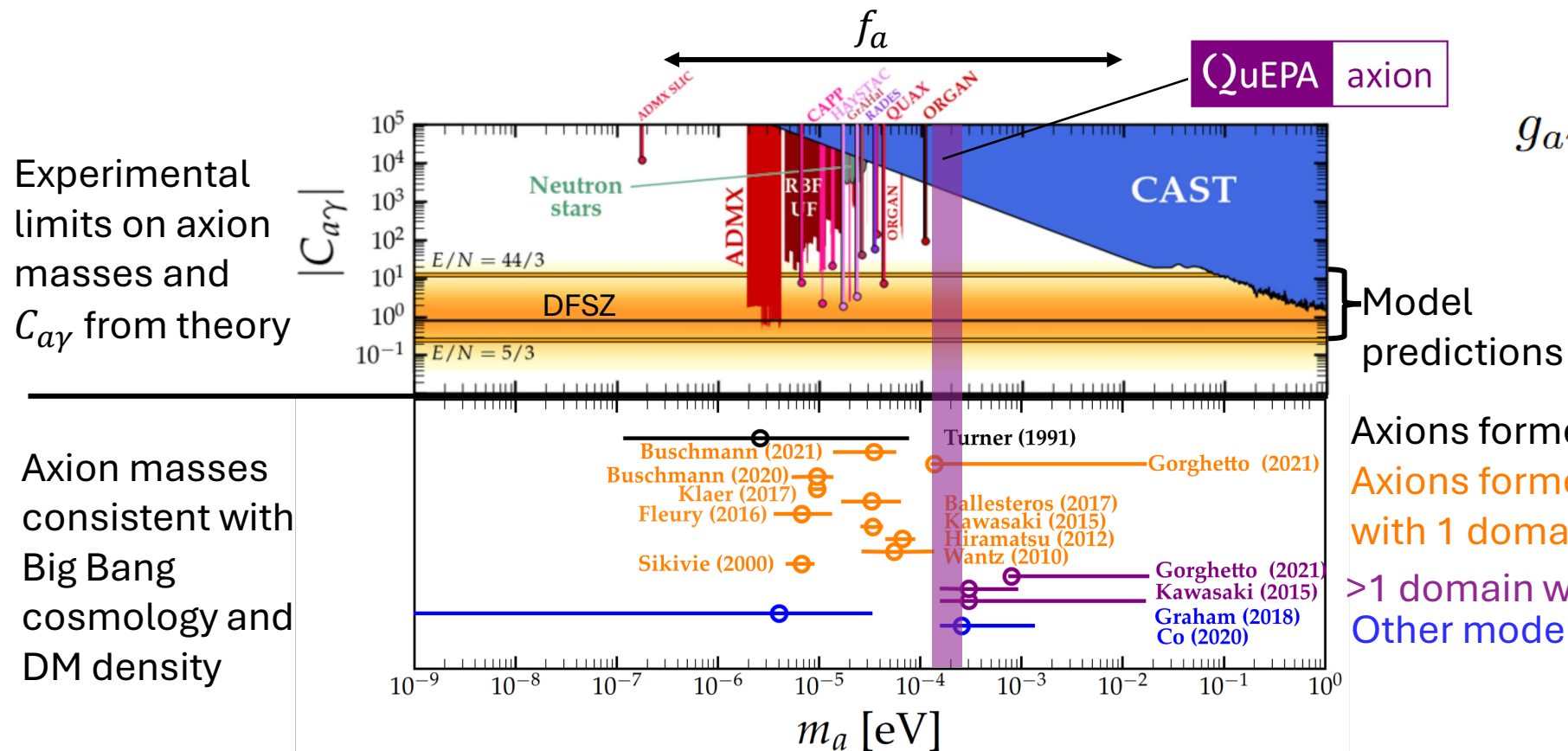
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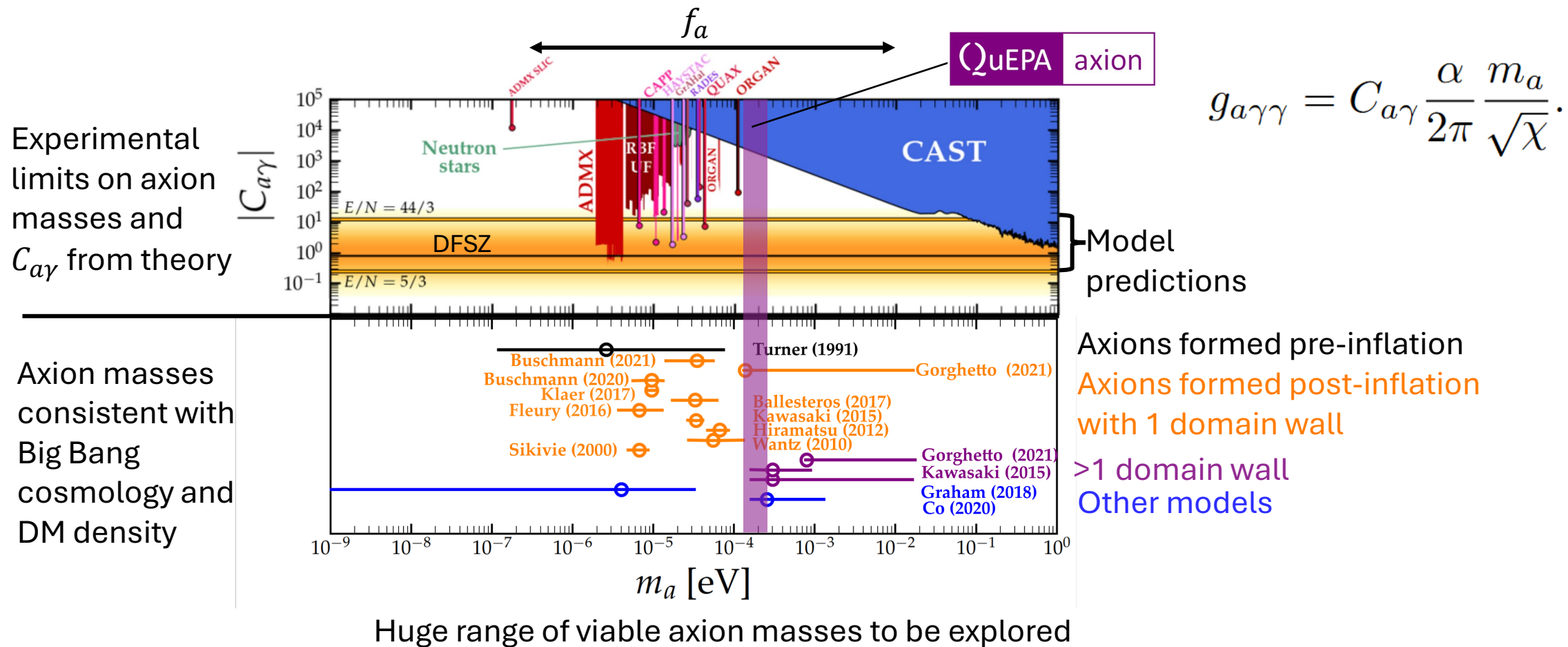


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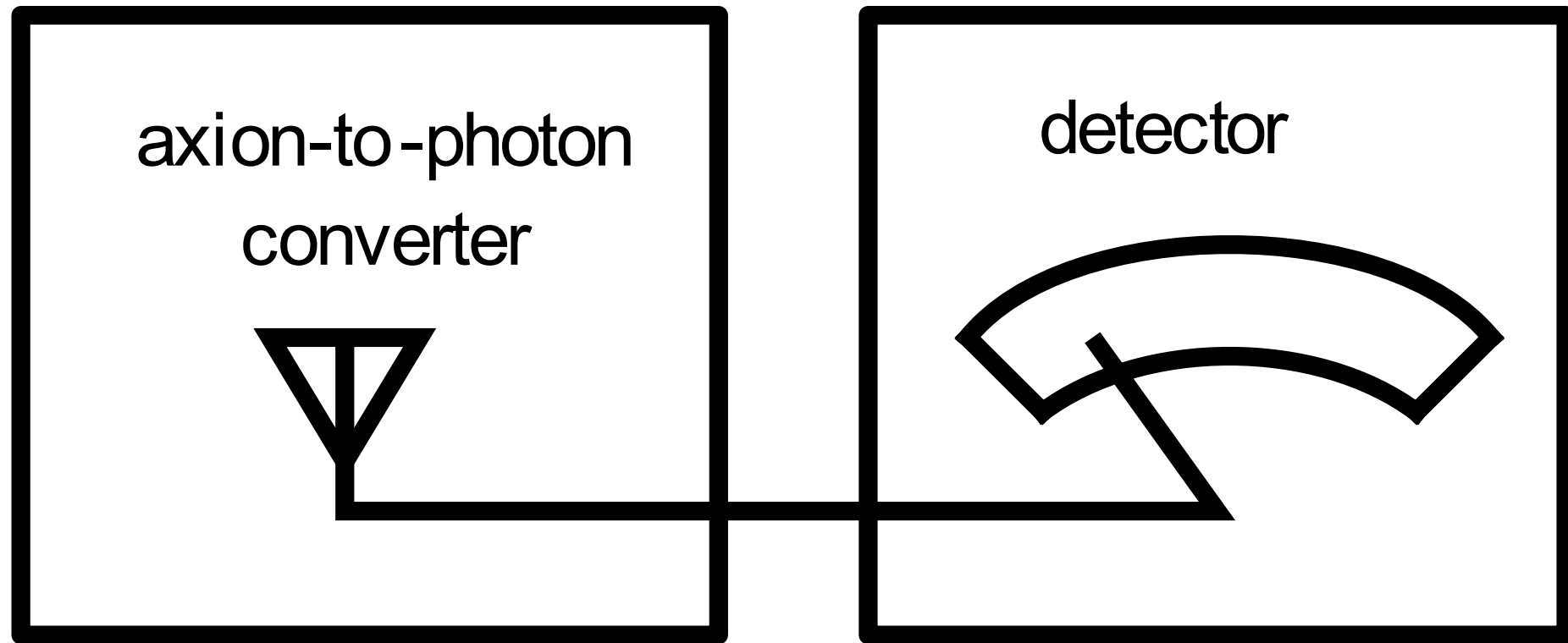


Goal: Search $m_a = 124 - 248 \mu\text{eV}$ @ DFSZ sensitivity

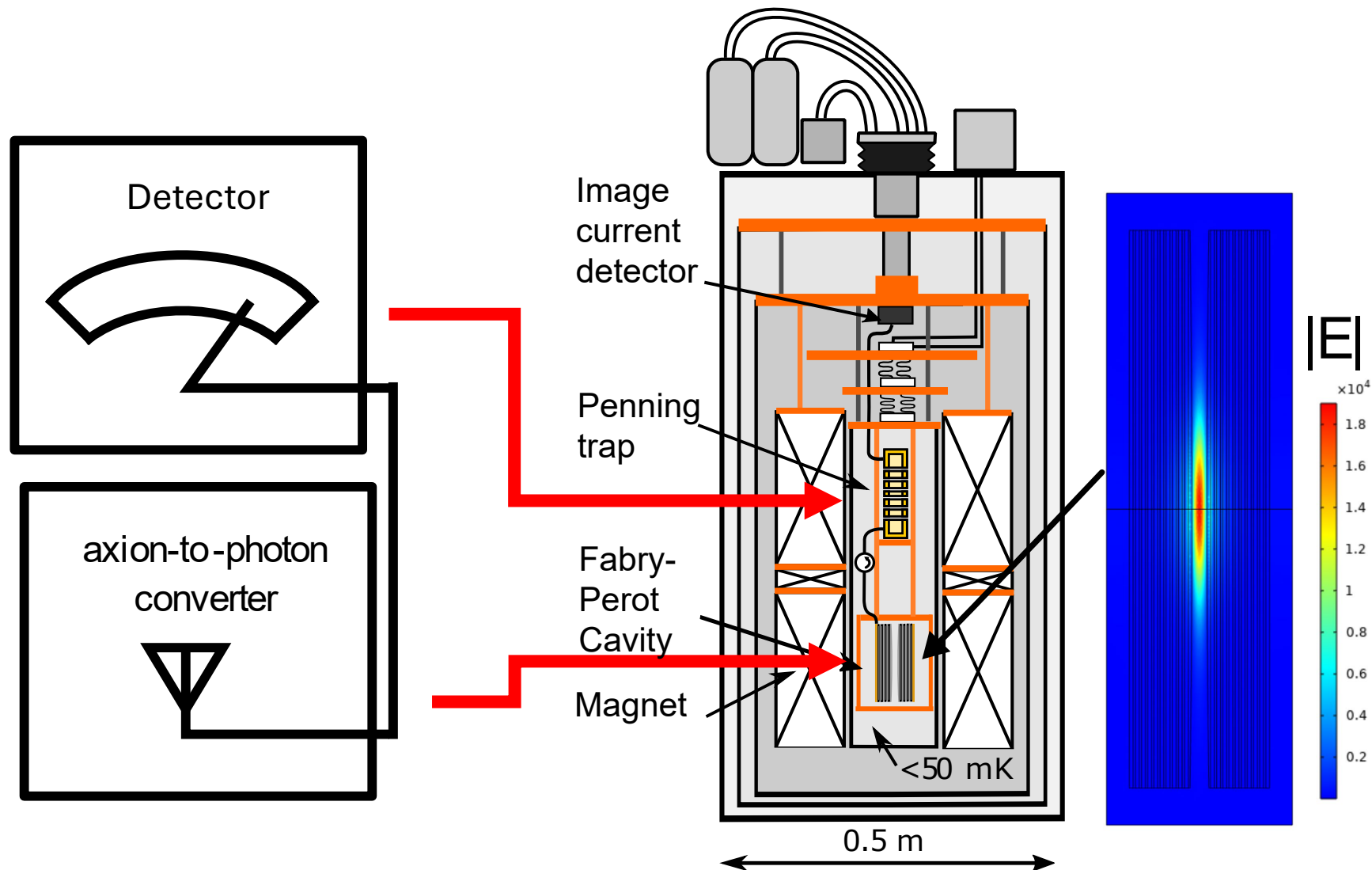
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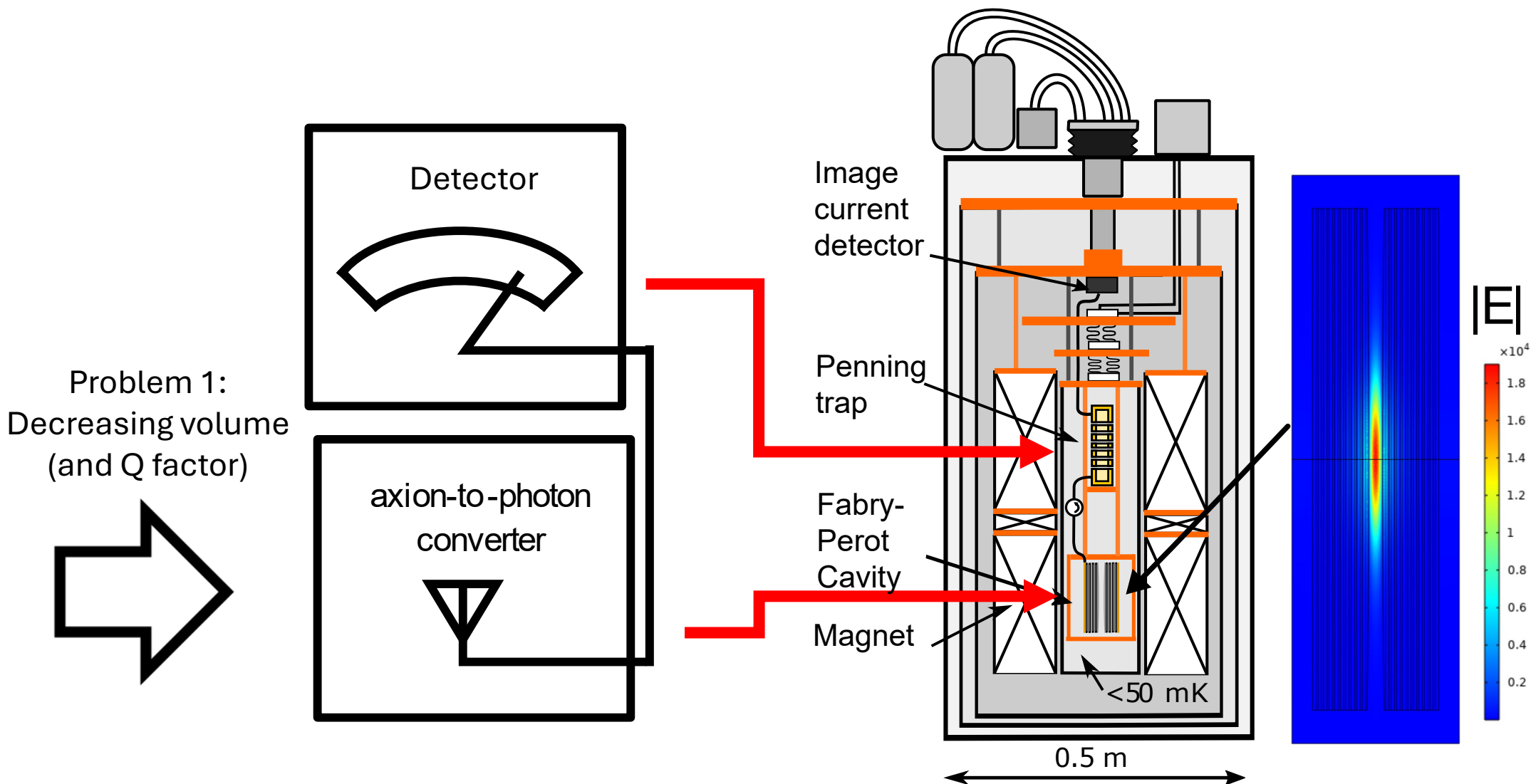
Experimental concept



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Decreasing volume

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

Decreasing volume

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

Q Cavity Q-factor

$$V_m = \frac{|\int E_m \cdot B dV|^2}{B^2 \int \epsilon_r |E_m|^2 dV} \propto \text{Cavity volume}$$

B magnetic field

Decreasing volume

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Volume factor scales with frequency

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

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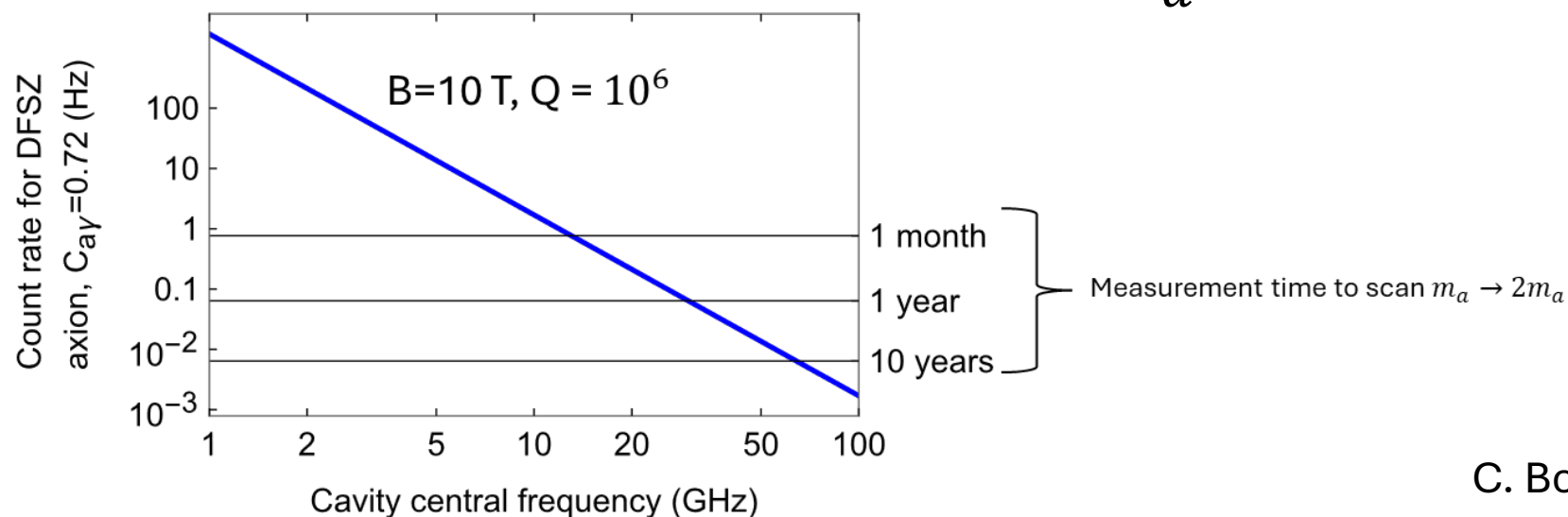
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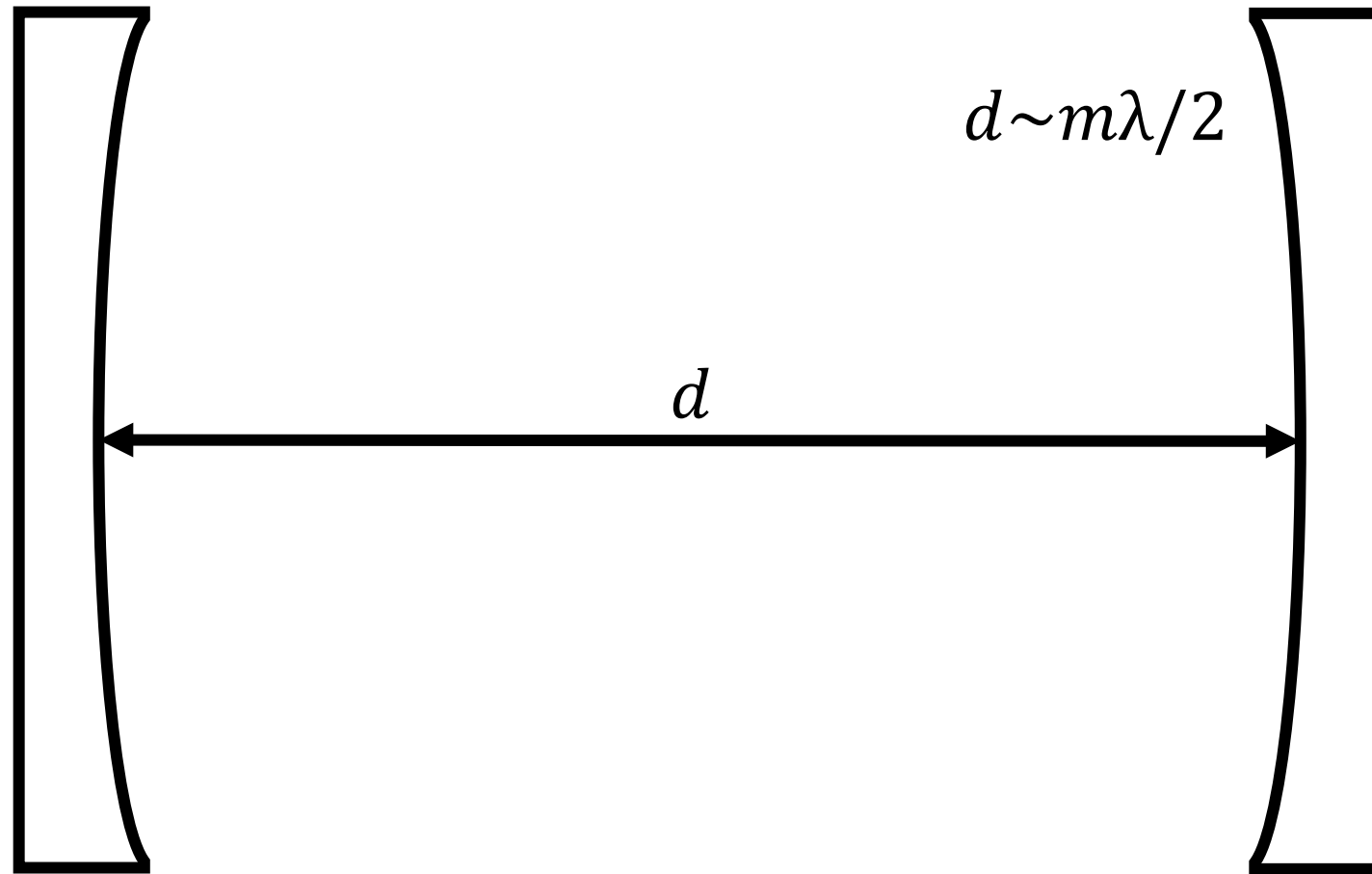
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For a cylindrical cavity, DFSZ axion:

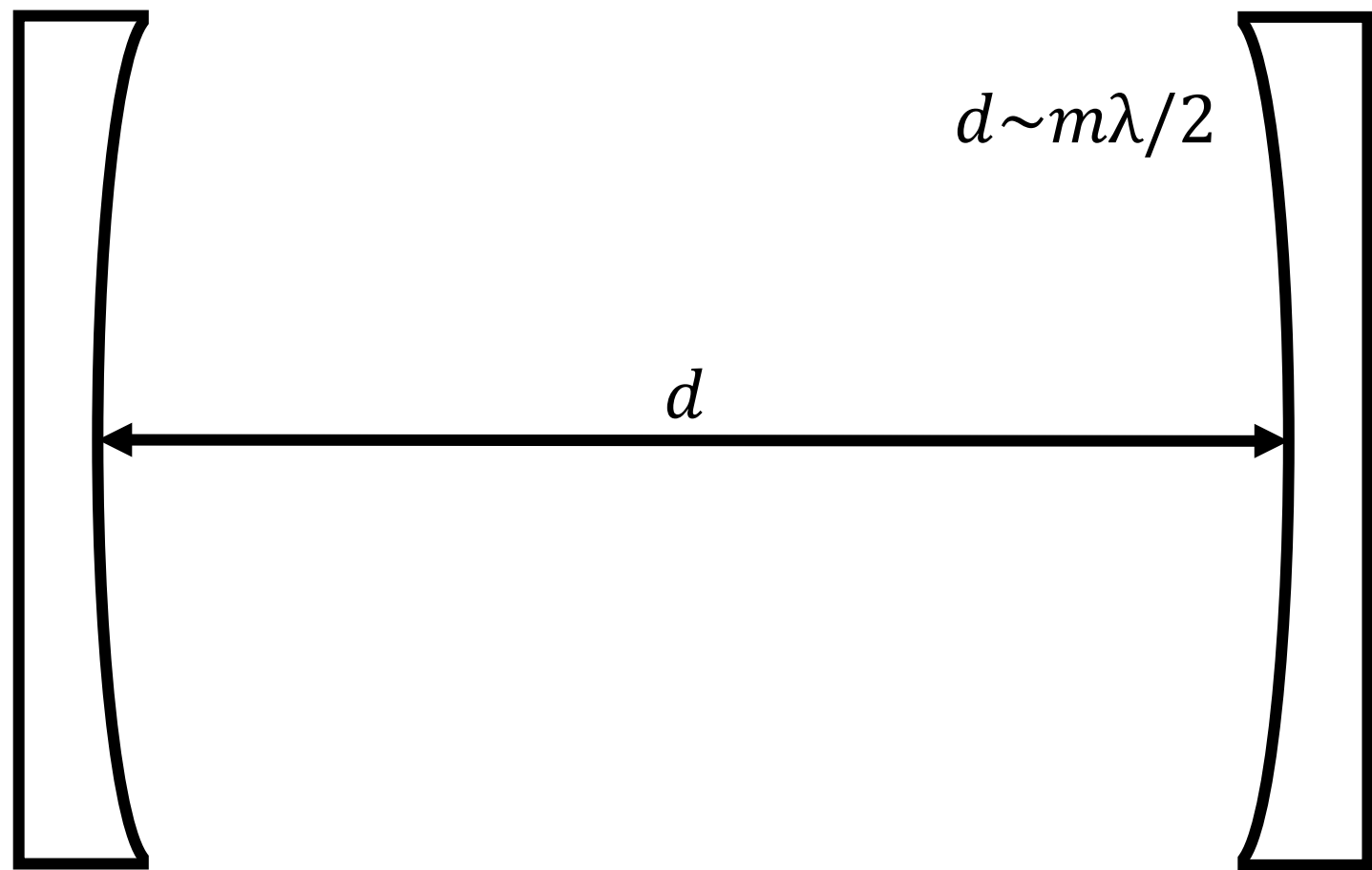


Dielectric Fabry-Perot Cavity

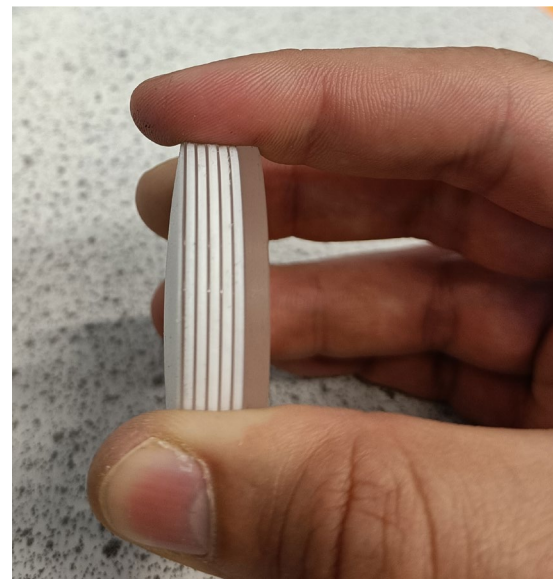


Operating with the
fundamental mode

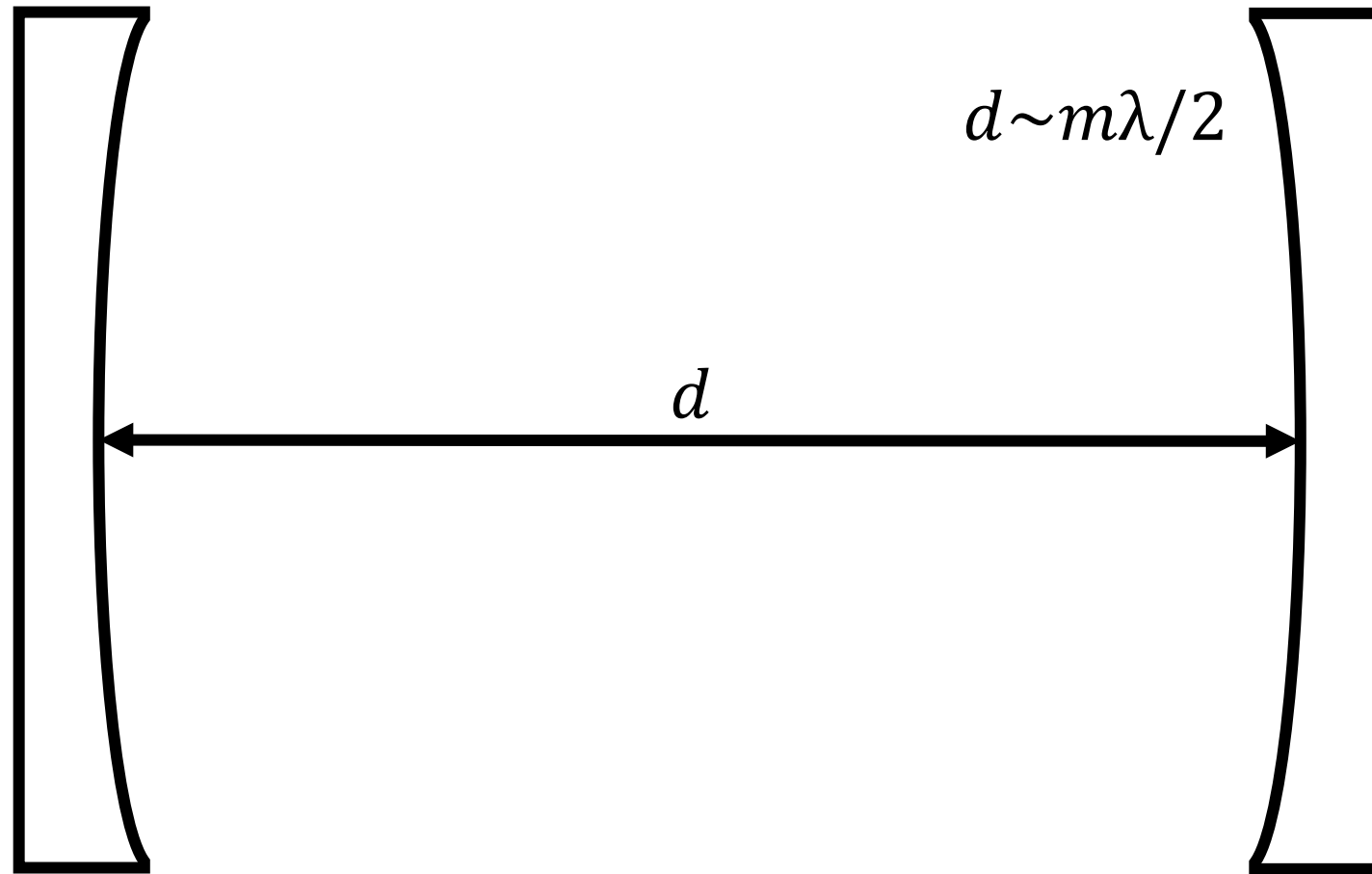
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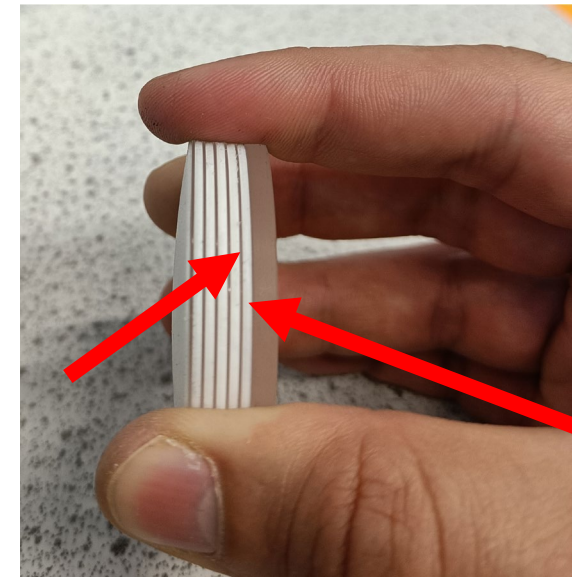
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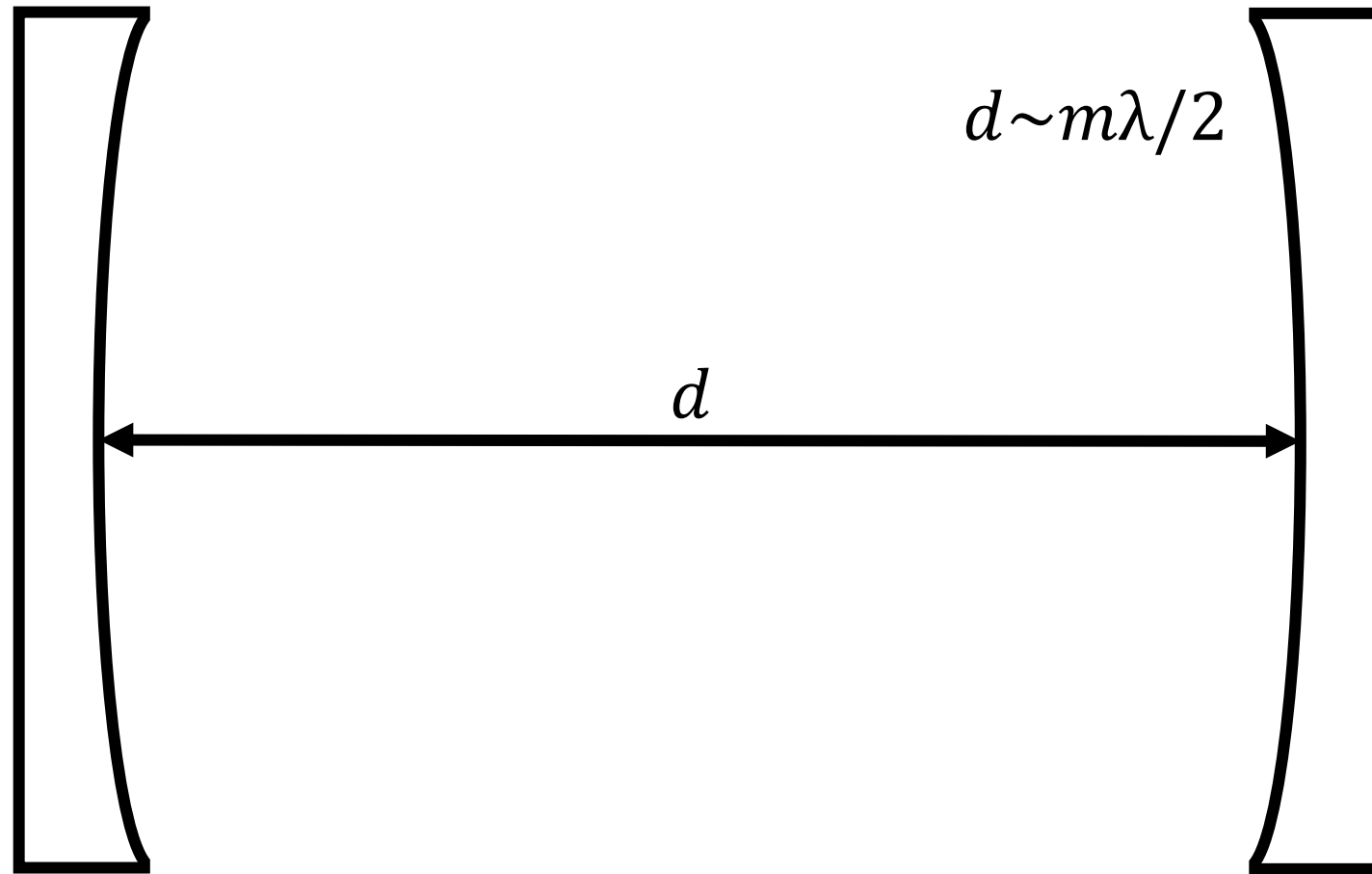


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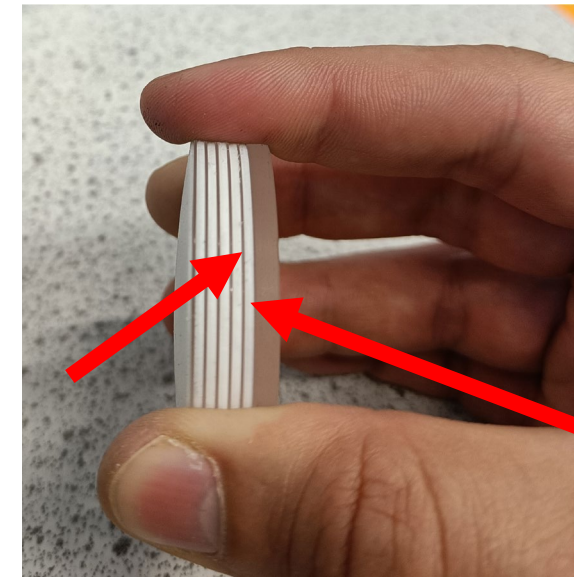
PTFE/
Sapphire
stack

Dielectric Fabry-Perot Cavity



Operating with the
fundamental mode

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



PTFE/
Sapphire
stack

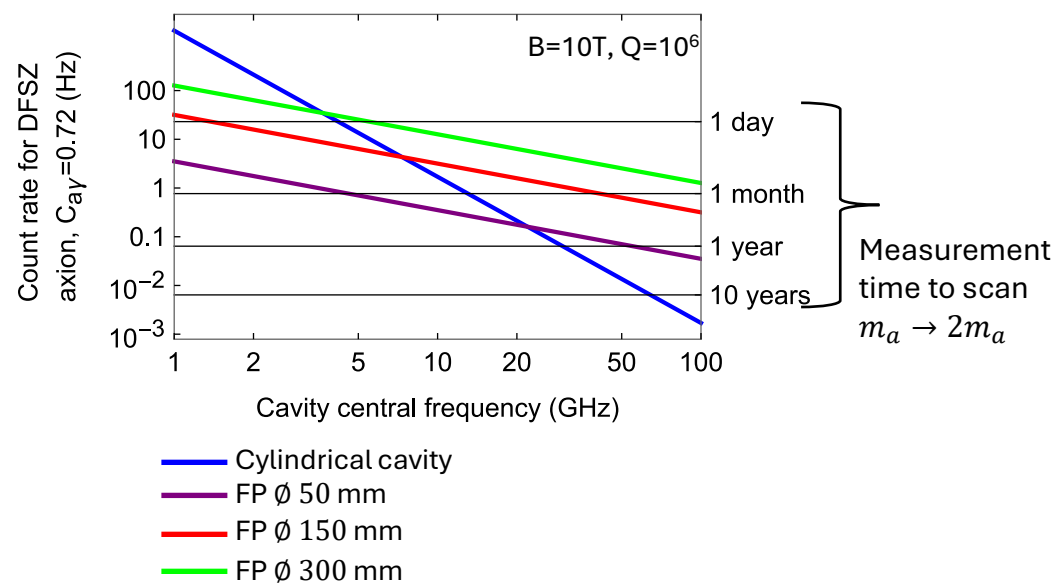
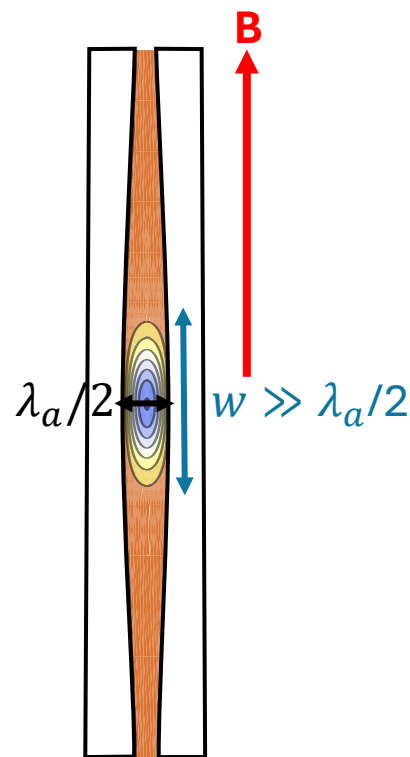
Why a dielectric Fabry-Perot Cavity?

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1) Favourable V_m scaling with ν_a

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

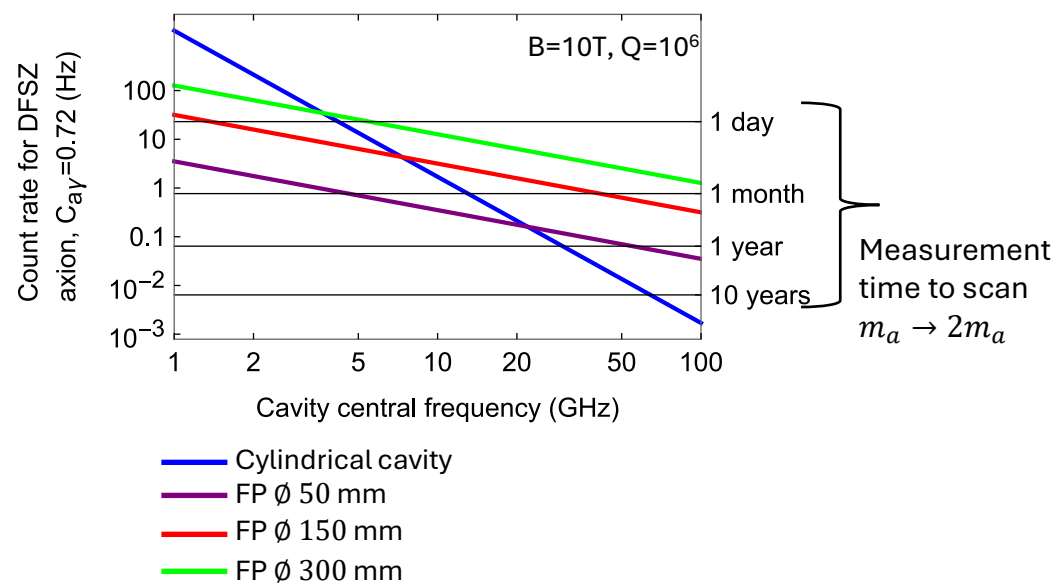
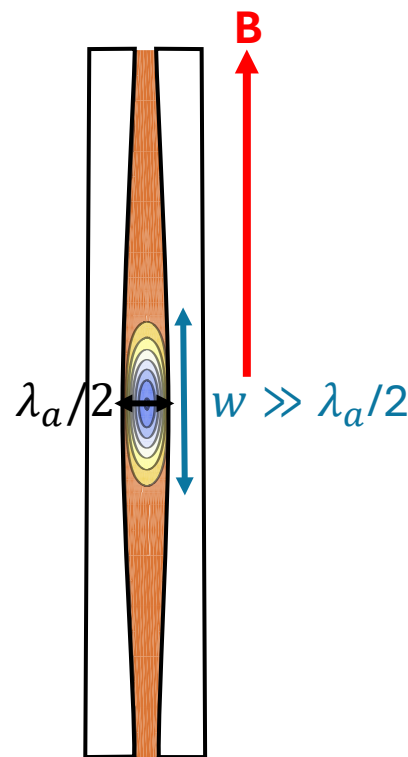


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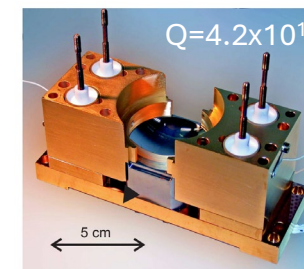
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2) High Q possible in this open geometry



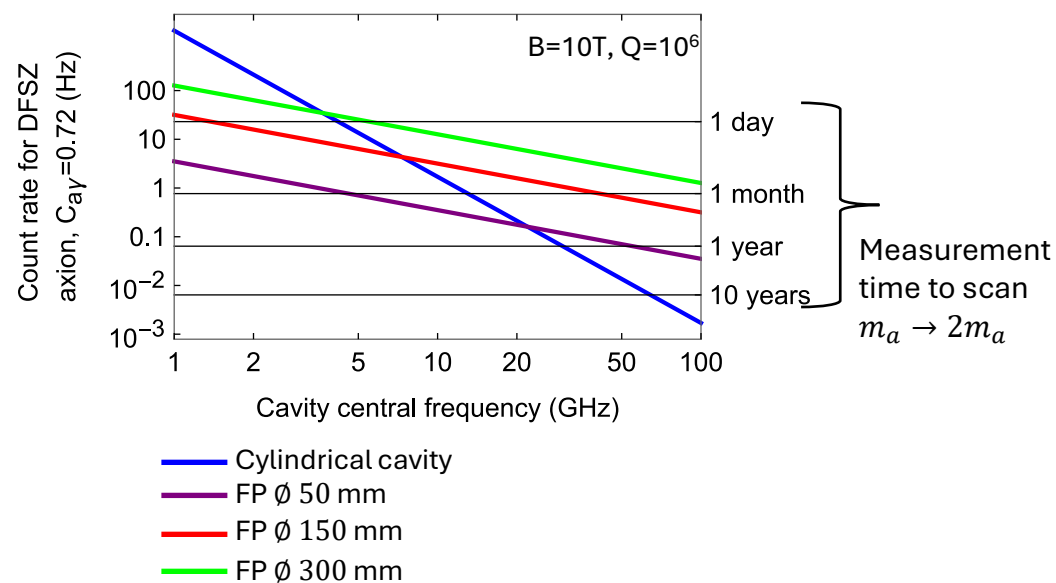
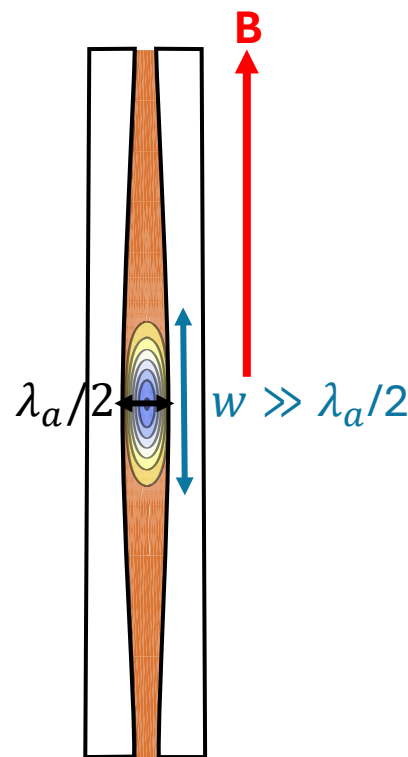
S. Kuhr et al., Appl. Phys. Lett. **90**, 164101 (2007)

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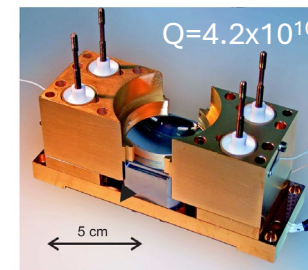
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3) High B-field compatible

Dielectric Bragg mirrors

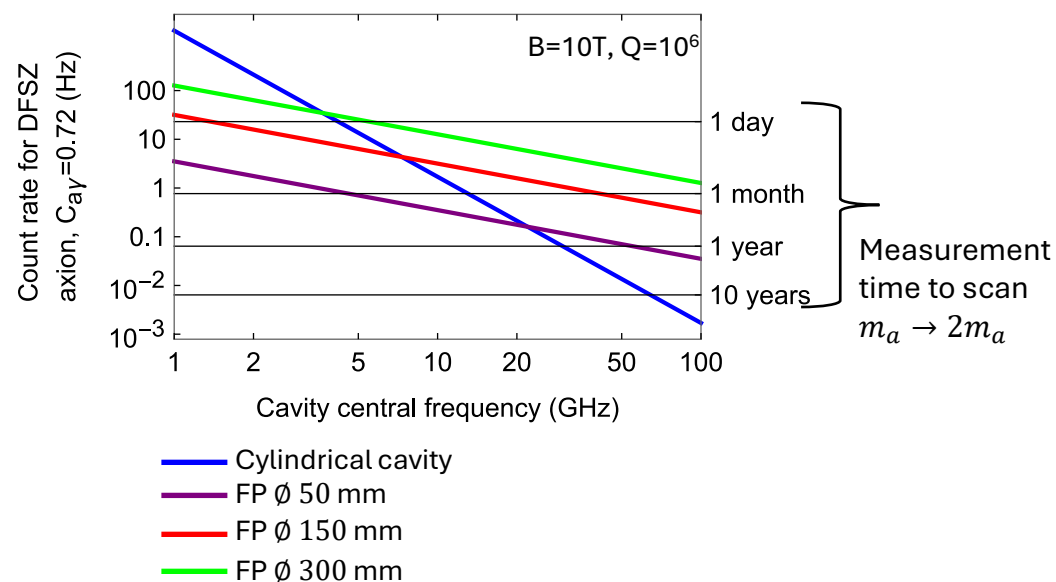
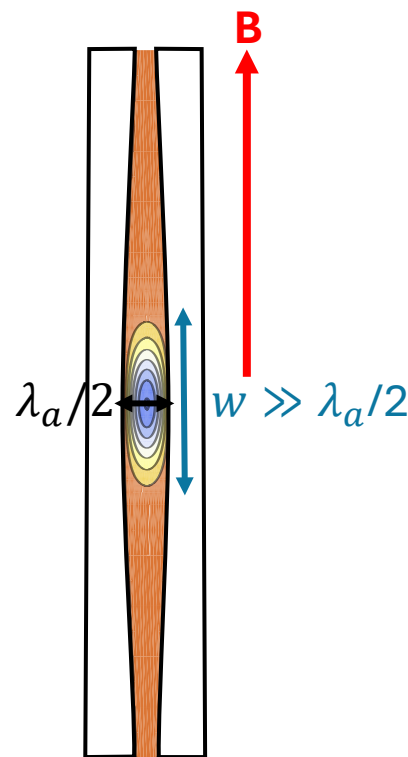
- All dielectric design – ultralow loss even in high B field
 - Large sapphire wafers available: 10-12 inch
 - Less likely to crack under differential expansion
- Microwave Bragg mirrors, $Q > 2.5 \times 10^5$
J. Krupka et al., IEEE trans. ultra. **52** 9 (2005)

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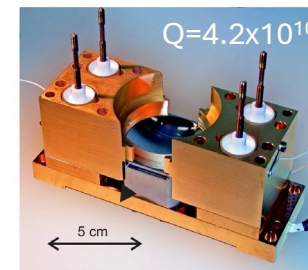
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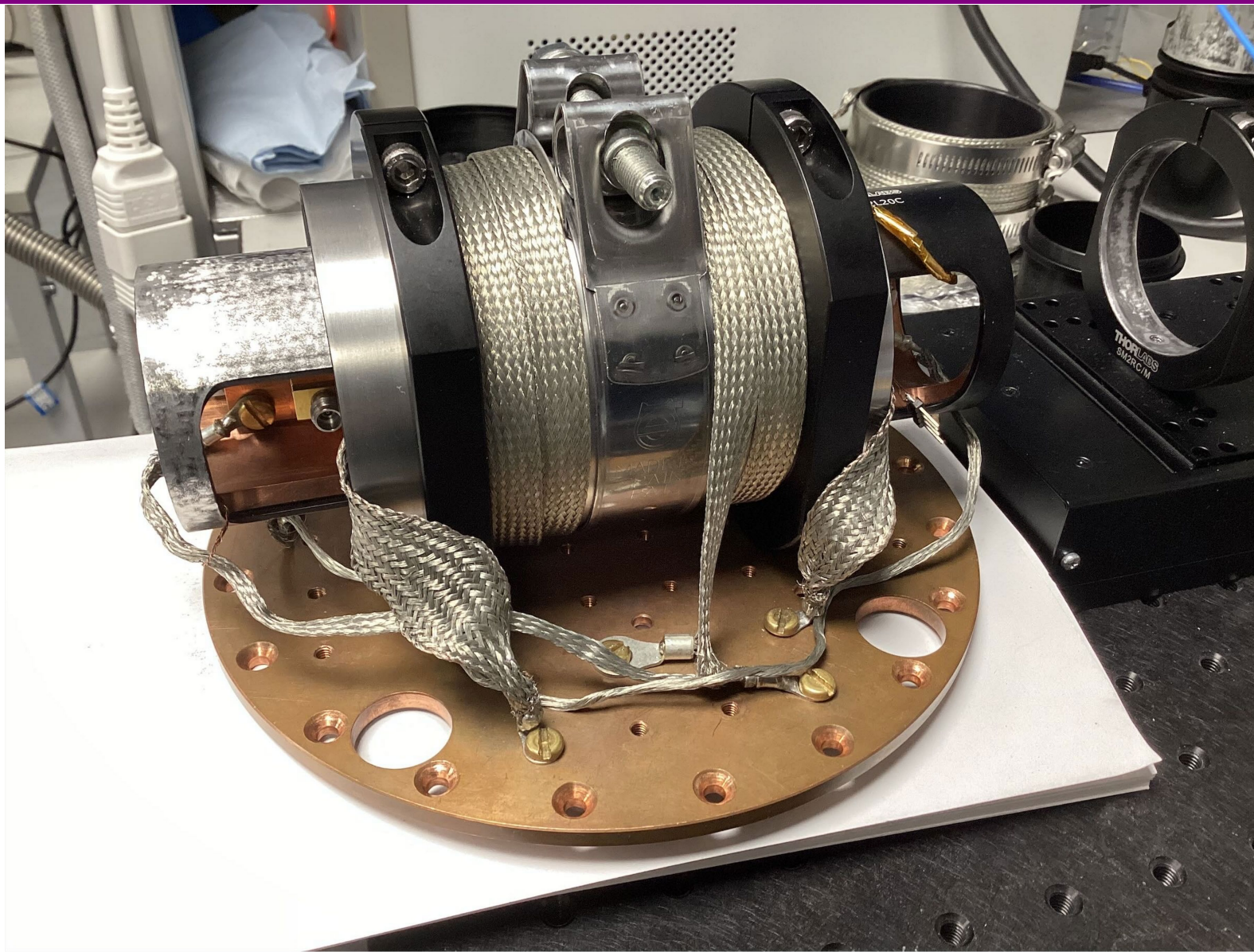
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Dielectric Bragg mirrors

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

2 inch prototype

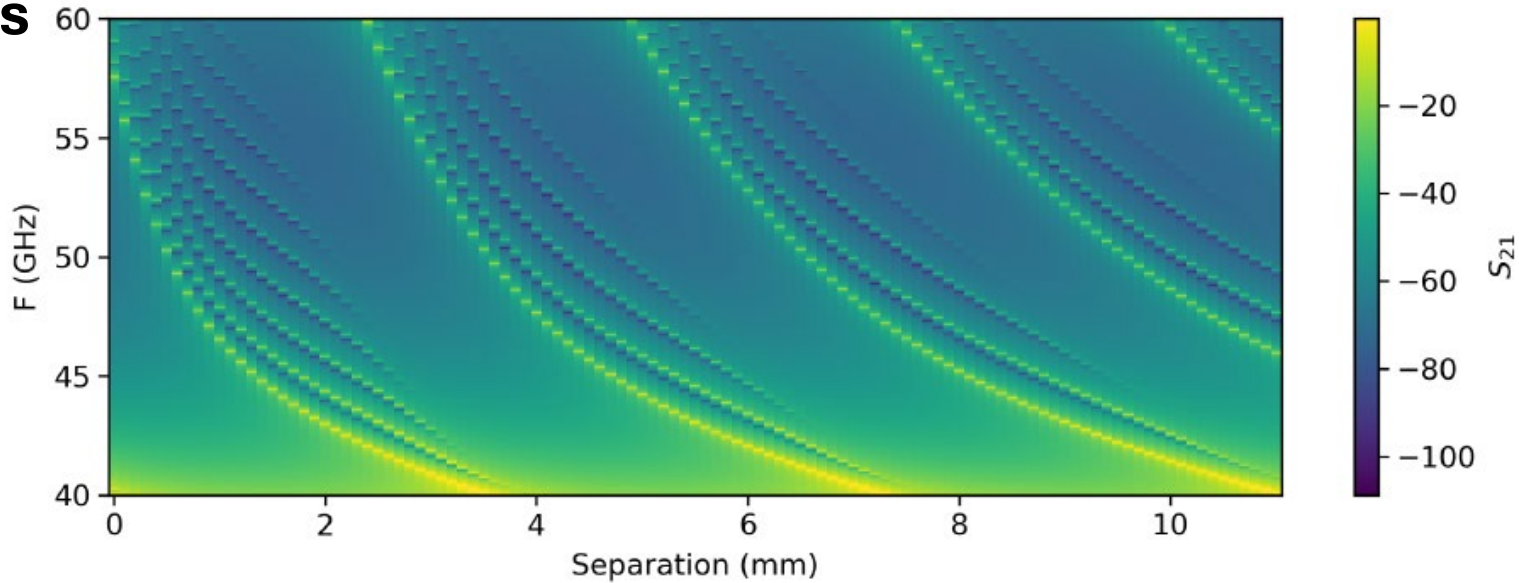


Initial testing at
room temperature
and 4K.

Characterising cavity

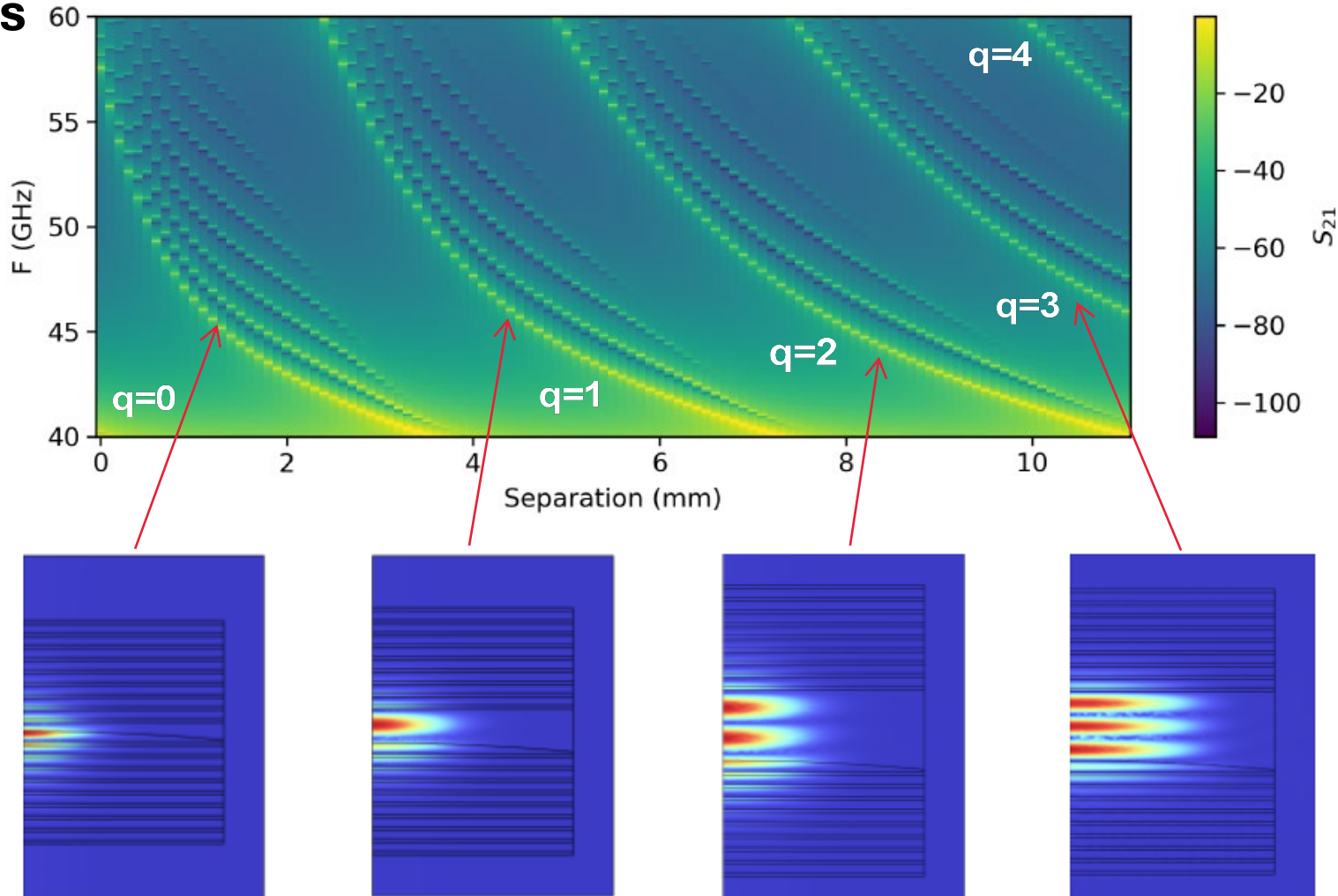
Characterising cavity

Simulations

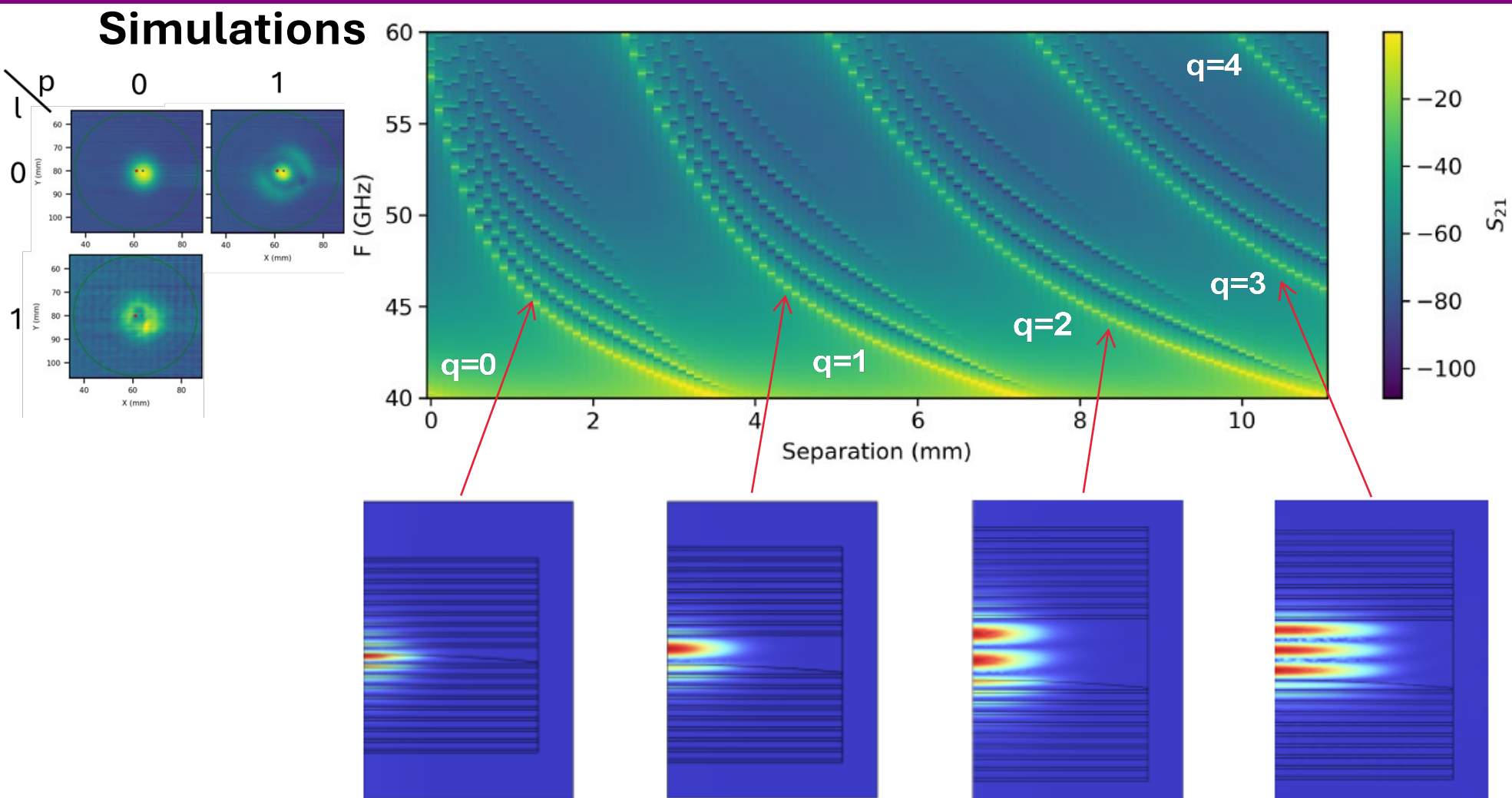


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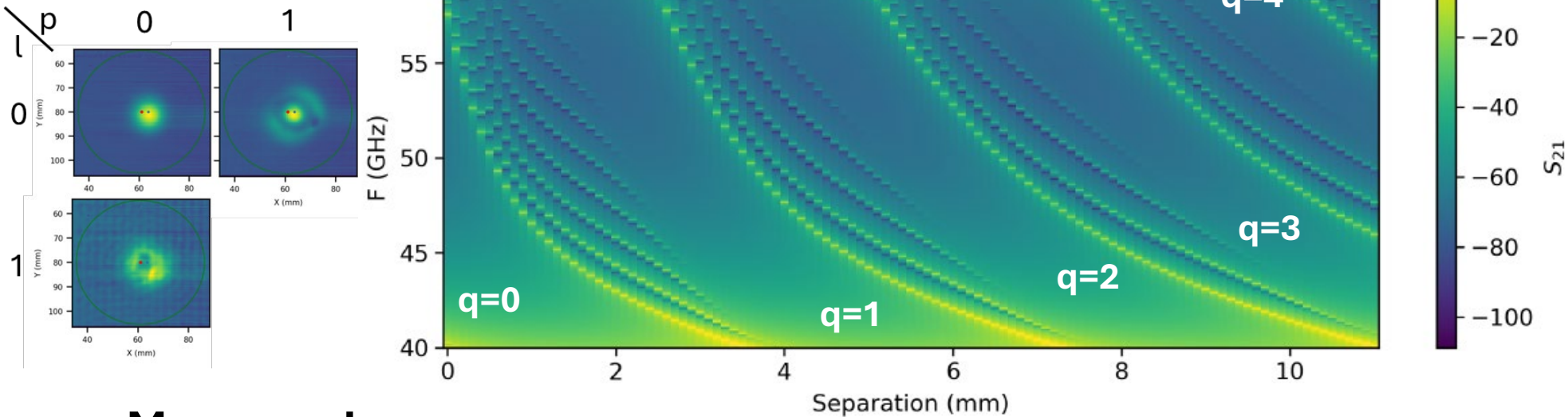


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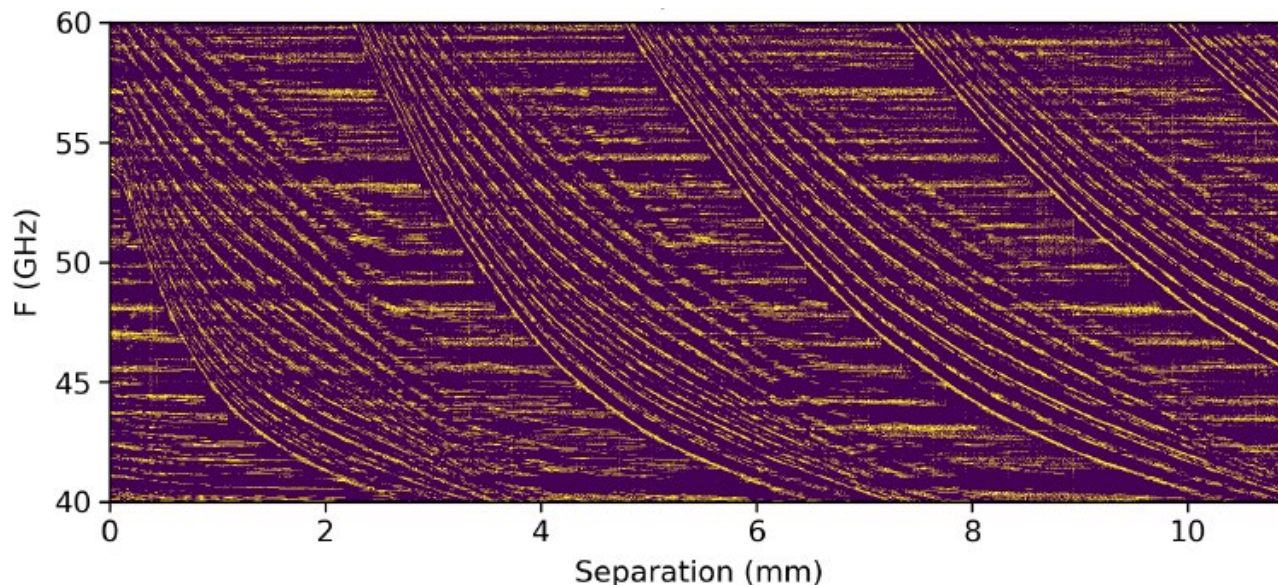


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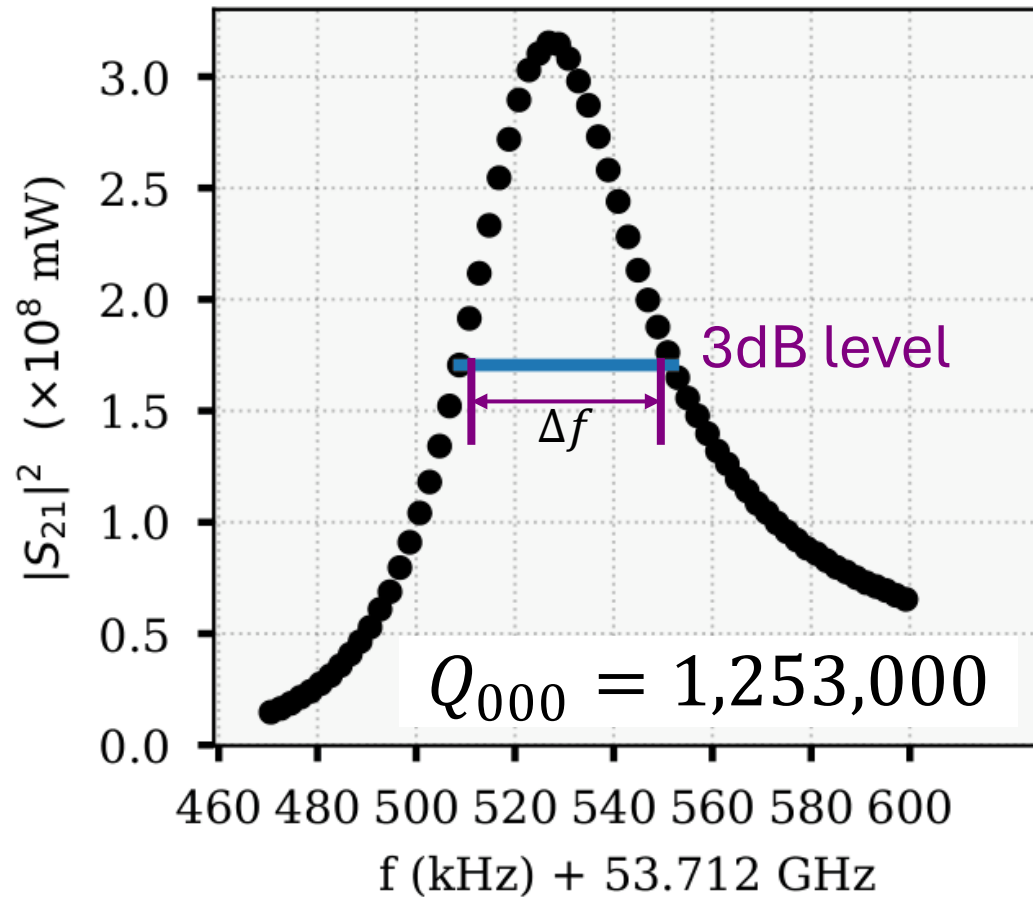
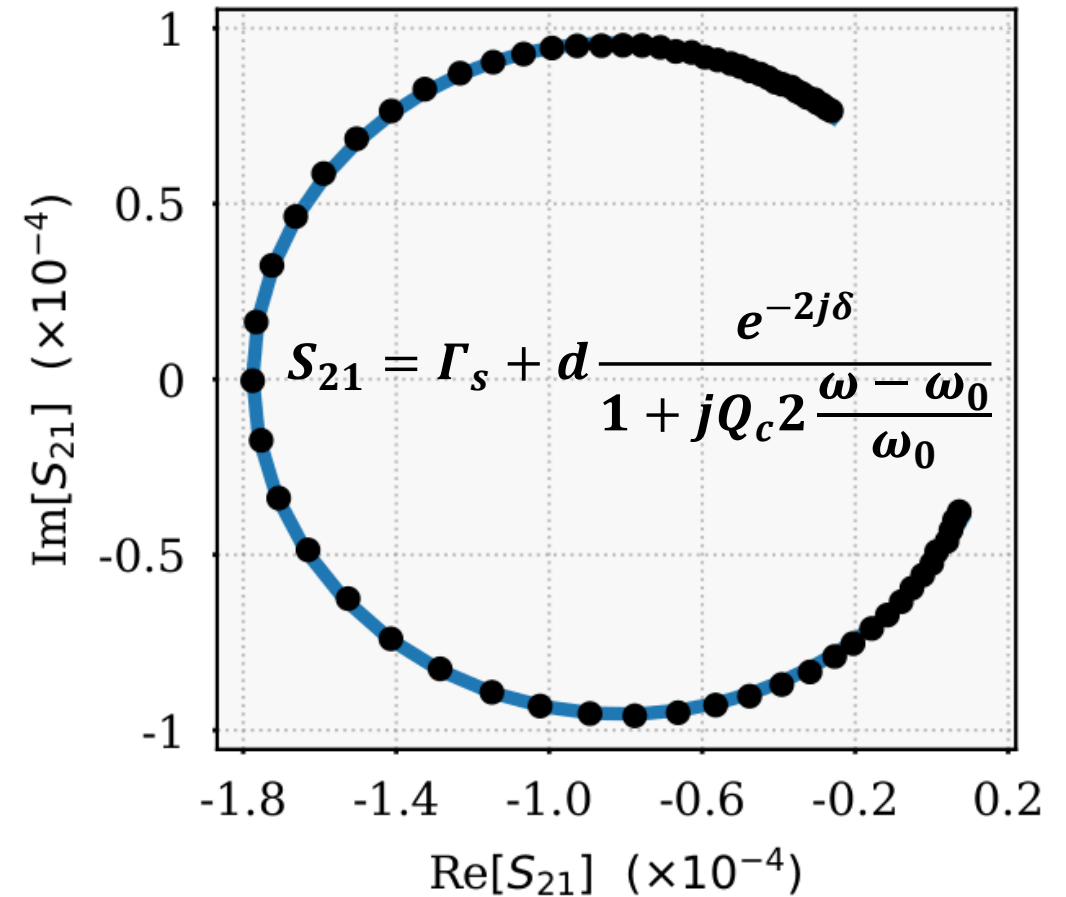


Measured



Measuring Quality factor at 4K

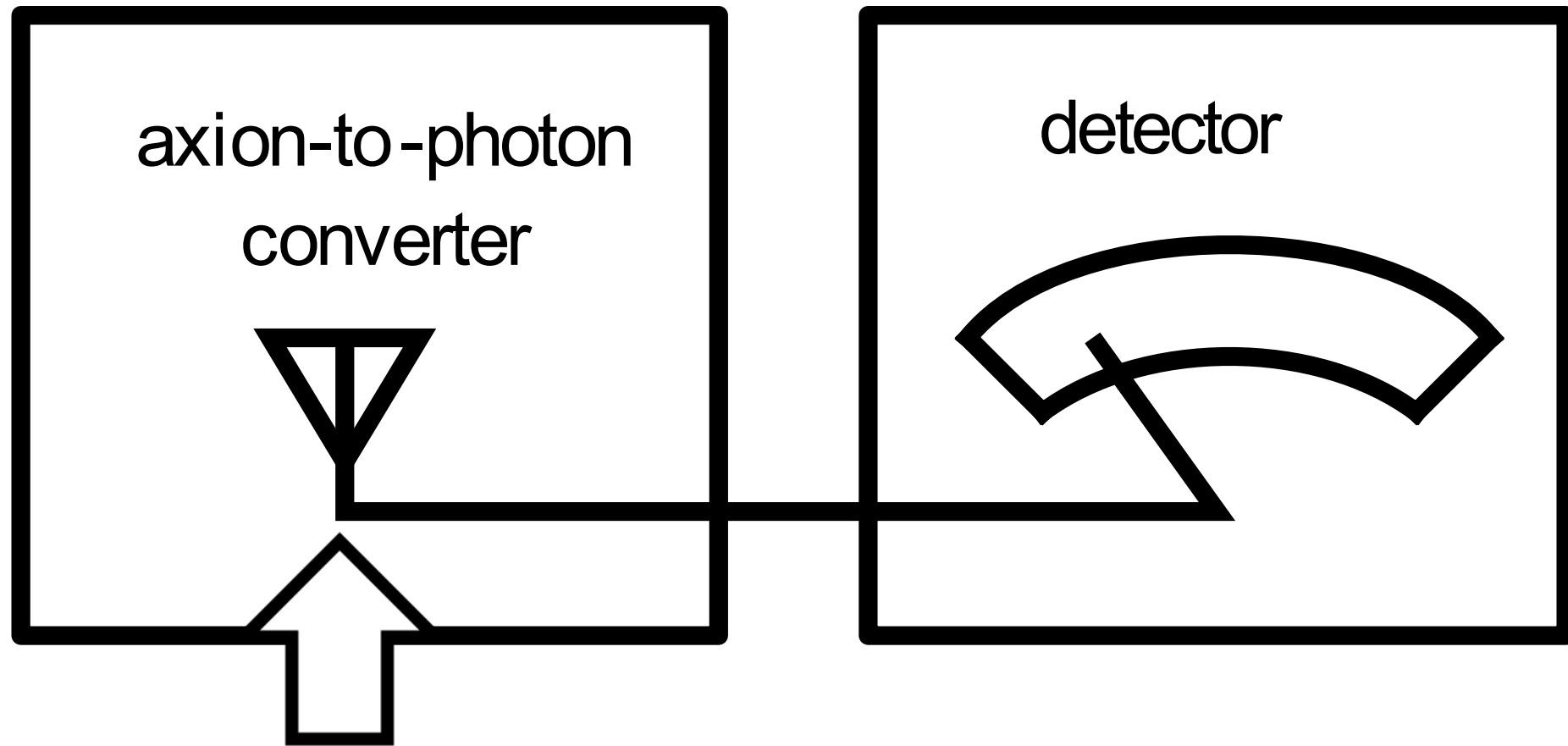
$$\text{Rate [s}^{-1}] \approx 5 \times 10^{-4} C_{a\gamma\gamma}^2 Q V_m B^2$$



Number of PTFE-Sapphire pairs = 10

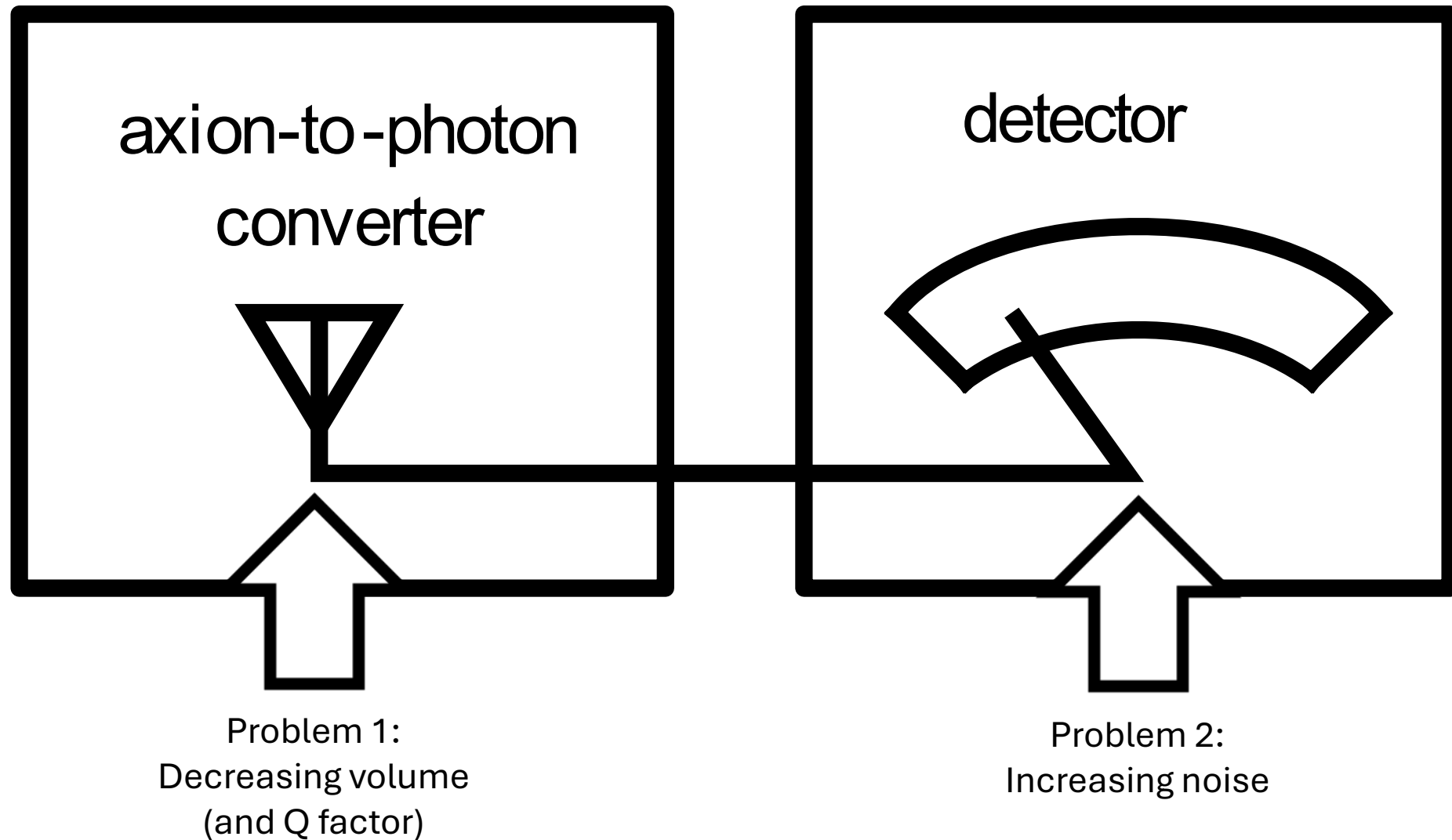
$$Q_{000} = 1,213,000 \pm 8000$$

Axion haloscope



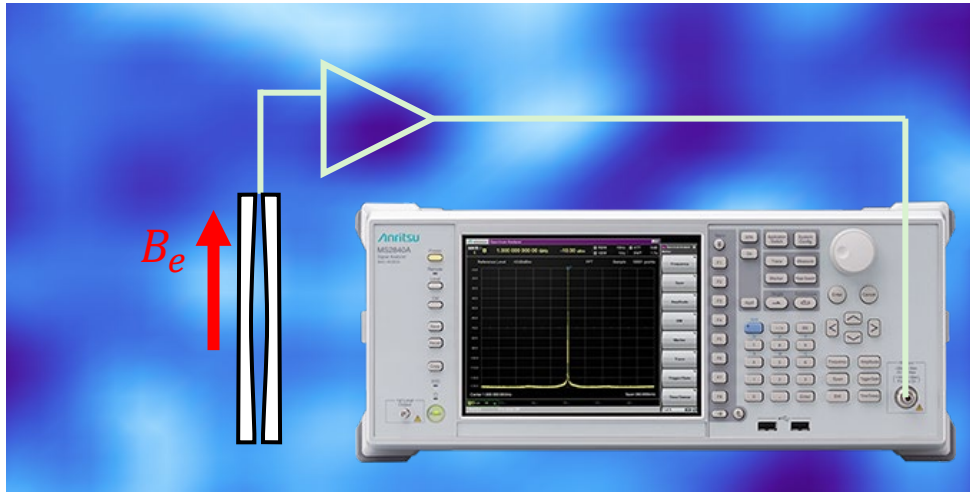
Problem 1:
Decreasing volume
(and Q factor)

Axion haloscope



Increasing noise

Classical readout: linearly amplify signal and use a signal analyzer



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

Noise from finite temperature

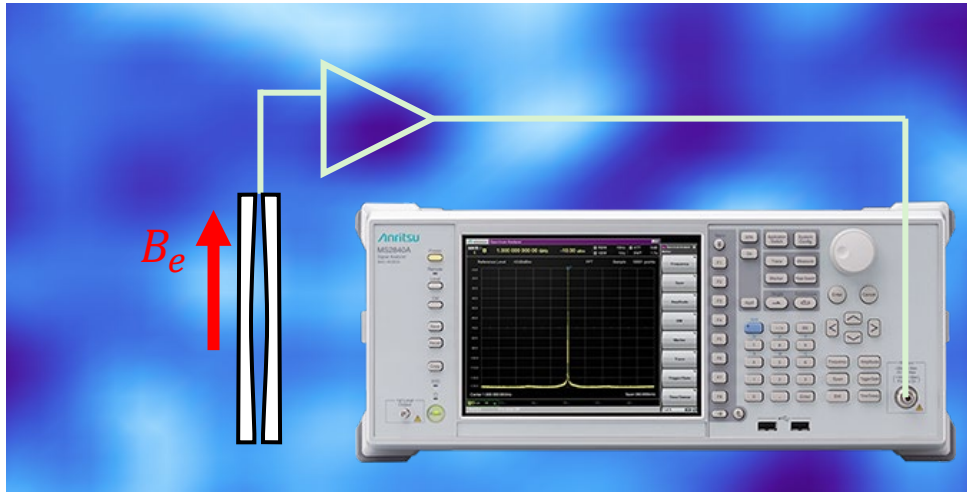
Zero-point noise from using a normal, Gaussian state of the cavity

Fundamental quantum amplification noise, related to zero-point noise of amplifier mode

Standard Quantum Limit (SQL)

Increasing noise

Classical readout: linearly amplify signal and use a signal analyzer



Implications for axion detection

Time to scan for 95% confidence limit

$$m_a = 124 \mu\text{eV} \rightarrow 2m_a = 248 \mu\text{eV}$$

(30 → 60 GHz)

with $Q = 10^6$:

$$t_{\text{scan}} = 8,600 \text{ years} \times \left(\frac{1 \text{ s}^{-1}}{R_a} \right)^2 \left(\frac{1}{\text{Efficiency}} \right)^2$$

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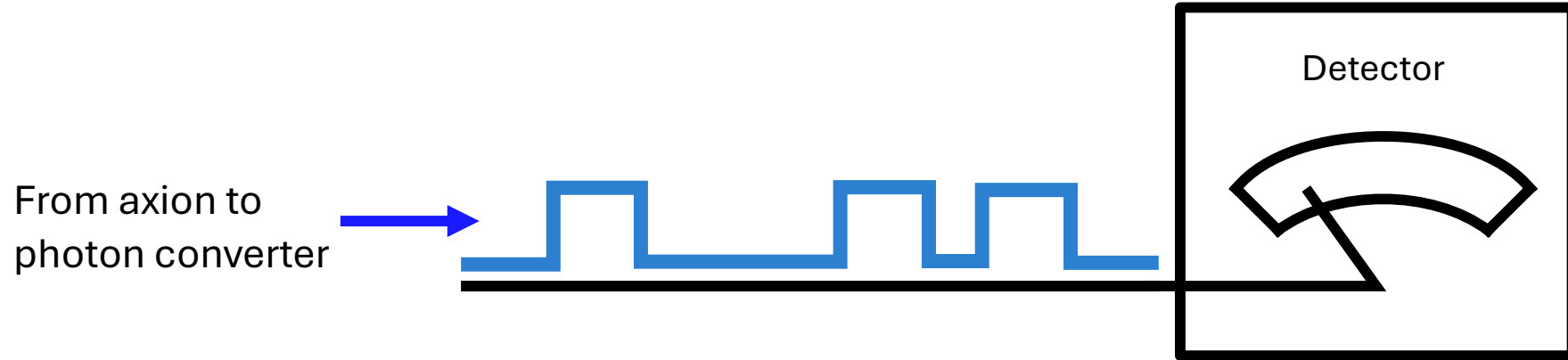
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Photon counting to beat SQL

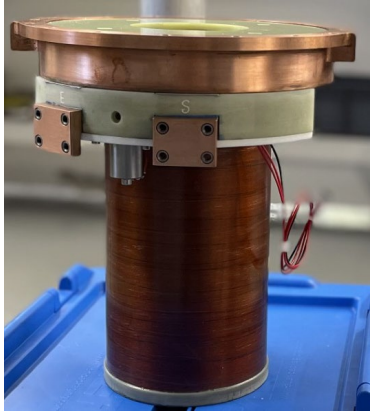
$$P_{\text{Linear Amp.}} = h\nu_a(\bar{n} + 1) \sqrt{\frac{\nu_a}{t Q_a}} \quad \text{vs.} \quad P_{\text{photon counting}} = h\nu_a \sqrt{\frac{2\pi\nu_a\eta\bar{n}}{t Q_c}}$$



Time to scan for 95% confidence limit
 $m_a = 124 \mu\text{eV} \rightarrow 2m_a = 248 \mu\text{eV}$
 (30 $\rightarrow$ 60 GHz) with $Q = 10^6$:

$$t_{\text{scan}} = \text{24 days} \times \left(\frac{1\text{s}^{-1}}{R_a} \right) \left(\frac{1}{\text{Efficiency}} \right)$$

Penning trap

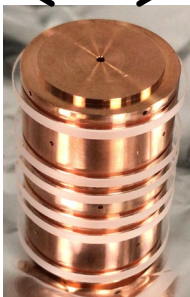


Strong
(~ Tesla)
static
magnetic
field gives
radial
confinement

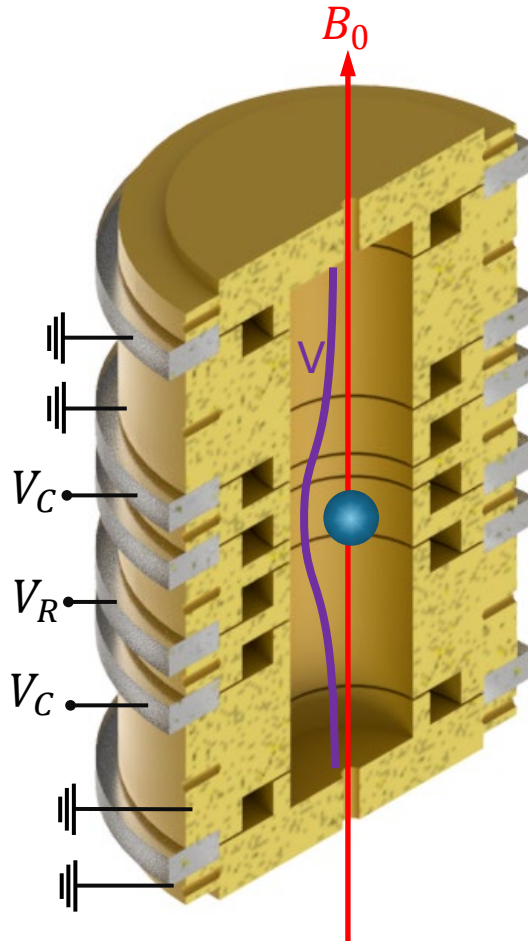
~10 cm

+

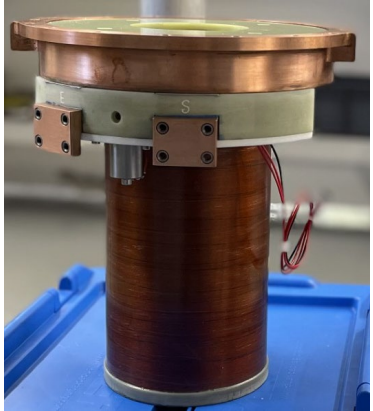
Quadratic
electric
potential gives
axial
confinement



~2 cm



Penning trap



Strong
(~ Tesla)
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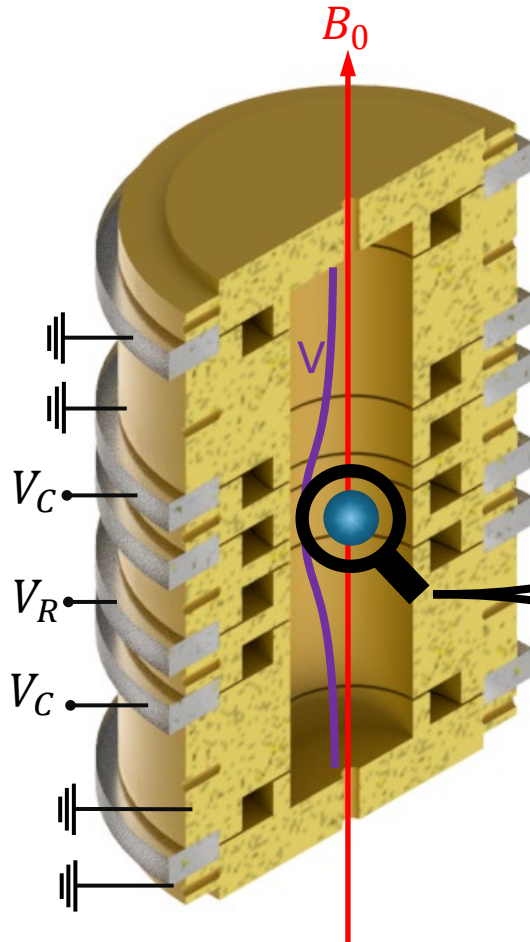
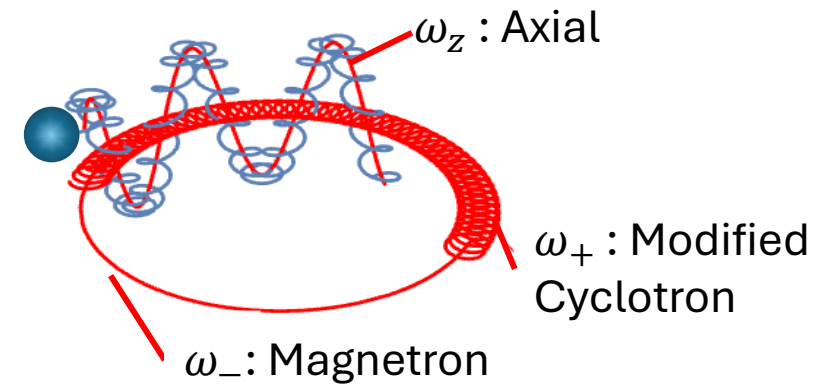
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Penning trap

Modified Cyclotron:

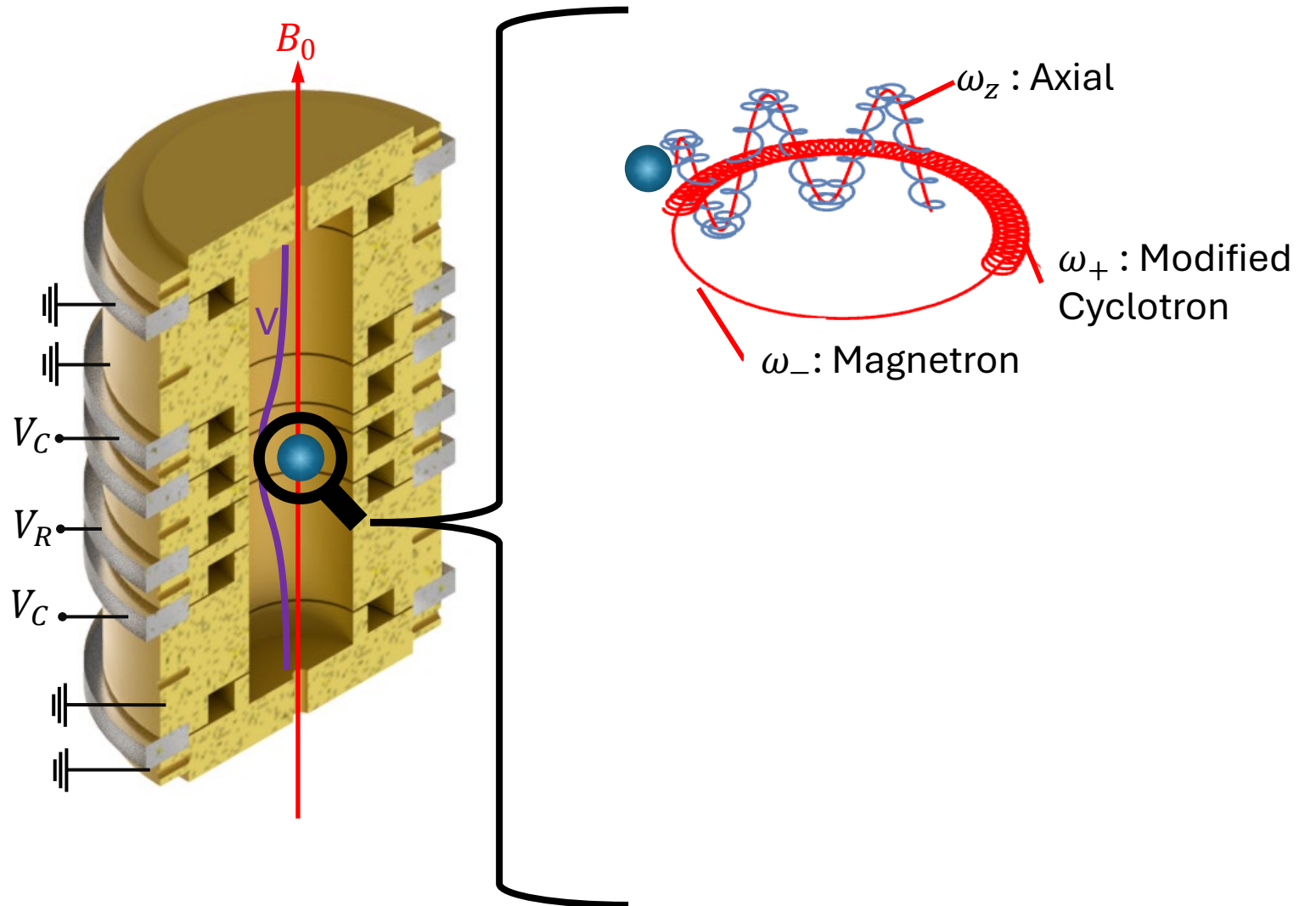
$$\omega_+ \approx 30 - 60 \text{ GHz}$$

Axial:

$$\omega_z \approx 2\pi \times 10 - 100 \text{ MHz}$$

Magnetron:

$$\omega_- \approx 10 - 100 \text{ KHz}$$



Penning trap

Modified Cyclotron:

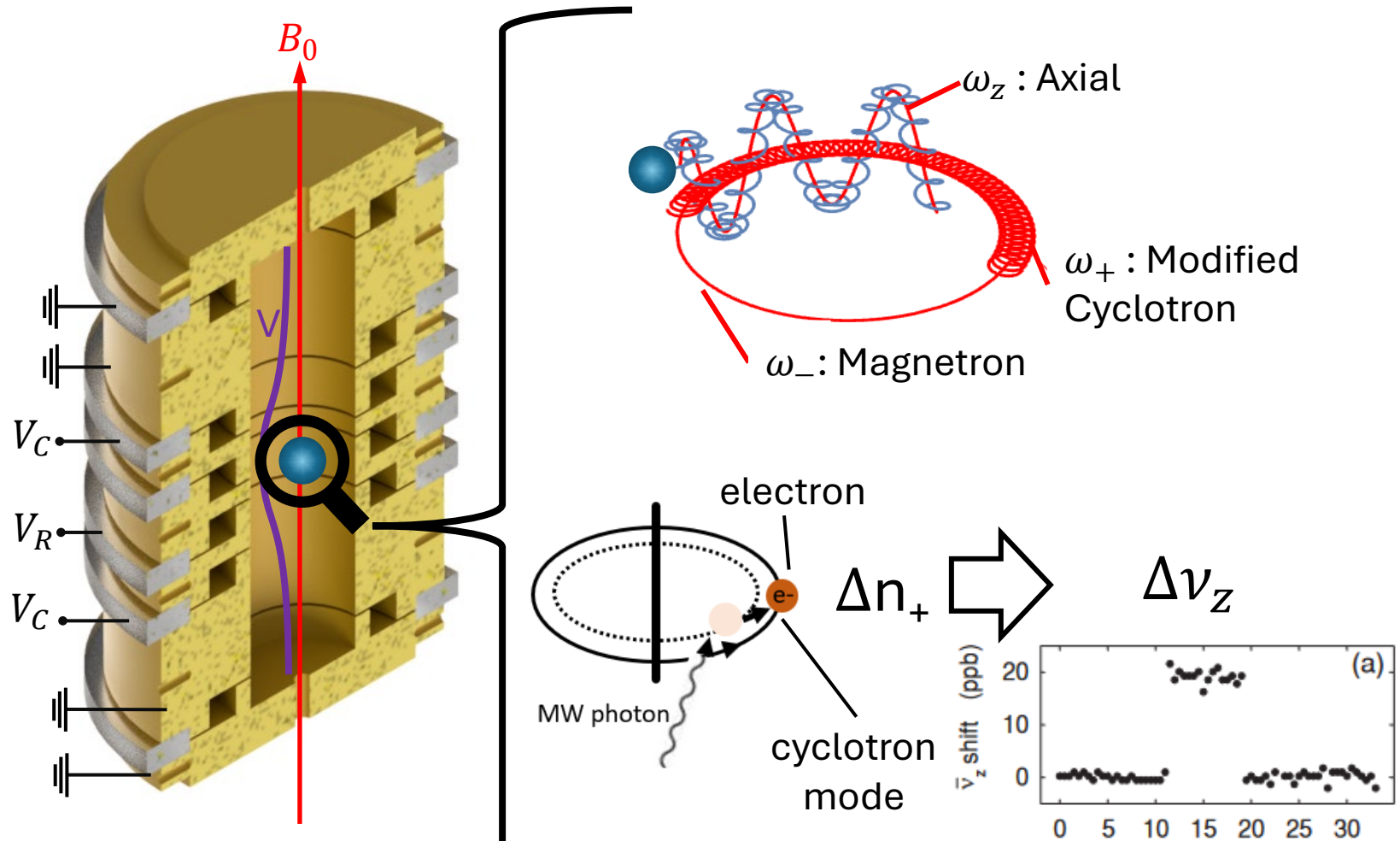
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S. Peil and G. Gabrielse Phys. Rev. Lett. **83**, 1287 (1999)

D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, PRA **83**, 052122 (2011)

Penning trap

Modified Cyclotron:

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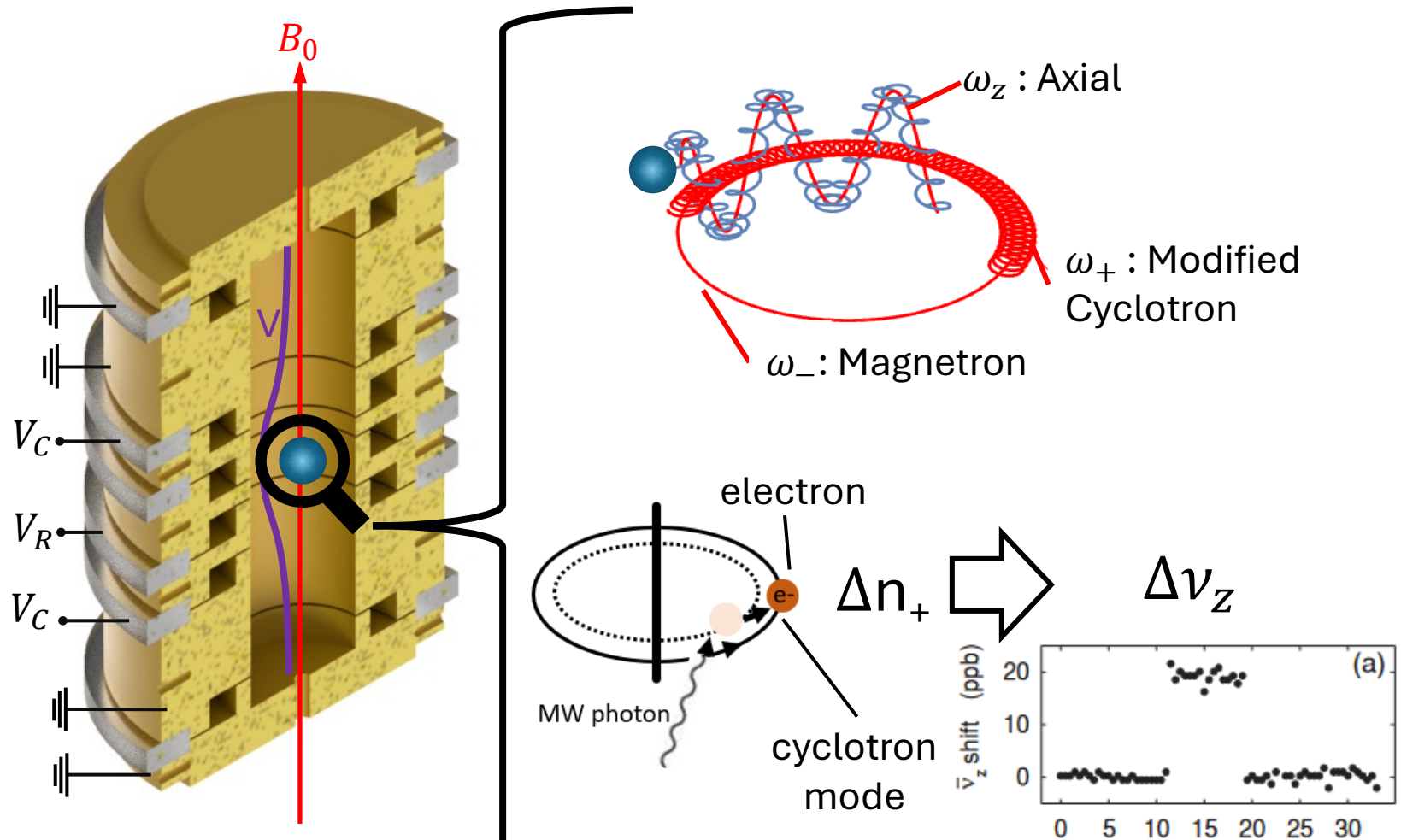
Axial:

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Magnetron:

$$\omega_- \approx 10 - 100 \text{ KHz}$$

Additional magnetic fields introduce a coupling between the Axial and Cyclotron motions.



S. Peil and G. Gabrielse Phys. Rev. Lett. **83**, 1287 (1999)

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Detecting photons with a single trapped electron

Details in J. A. Devlin et al., [arXiv:2601.05472](#)

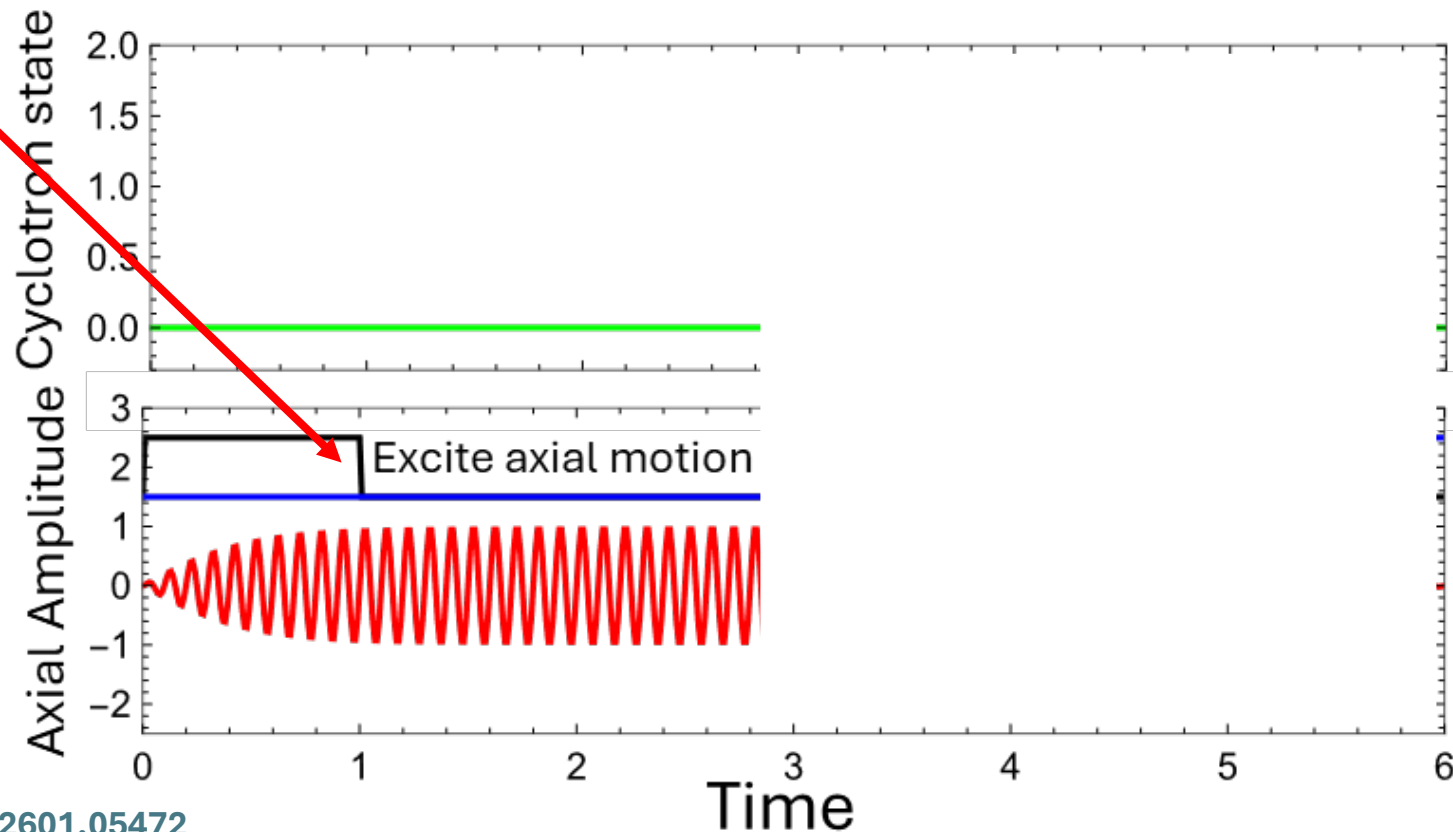
See also similar ideas –

A. Cridland et al., Photonics **3**, 59 (2016).

X. Fan et al., Physical Review D **111**, 075022 (2025).

Detecting photons with a single trapped electron

Step 1: Excite the axial motion



Details in J. A. Devlin et al., [arXiv:2601.05472](https://arxiv.org/abs/2601.05472)

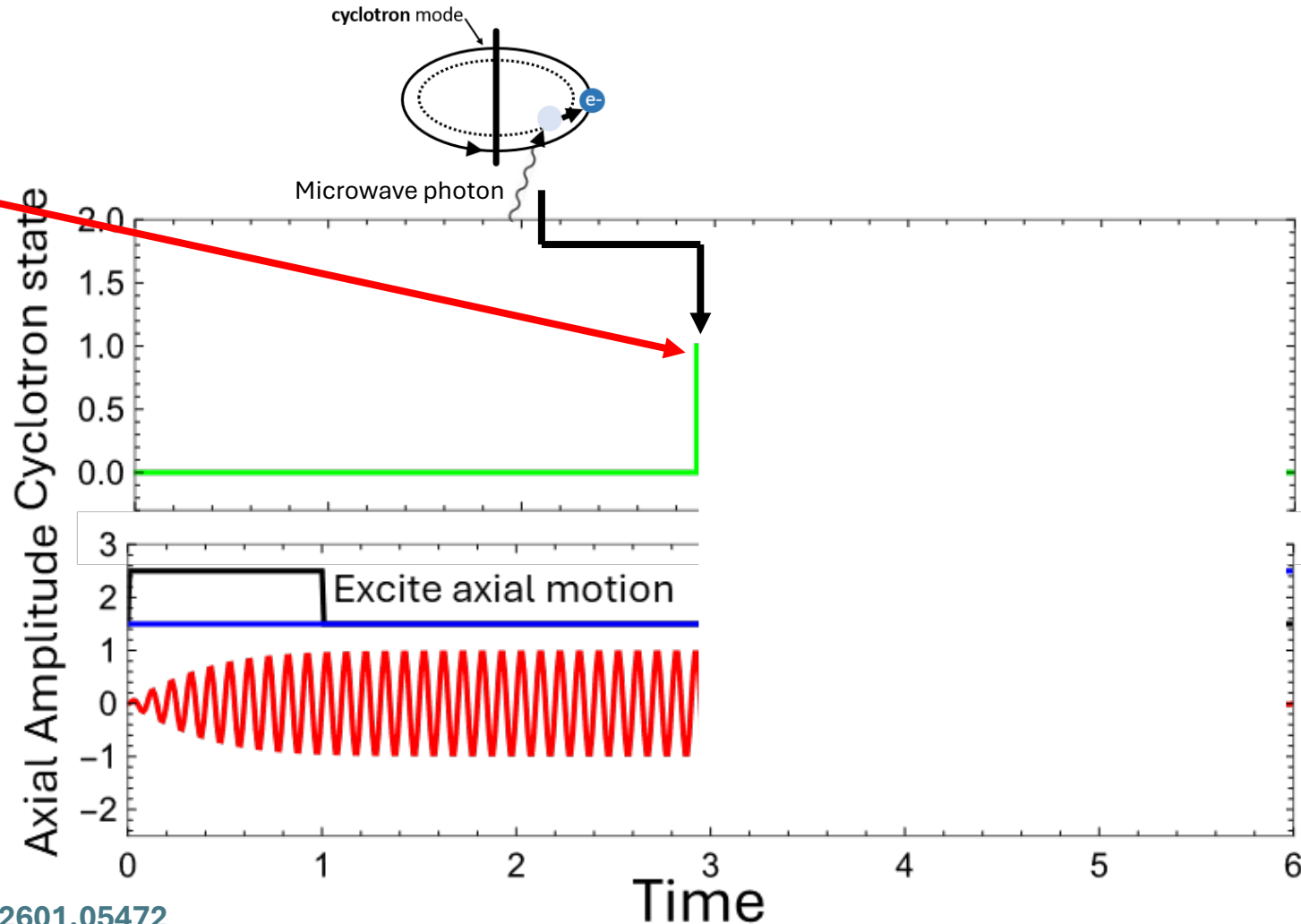
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X. Fan et al., *Physical Review D* **111**, 075022 (2025).

Detecting photons with a single trapped electron

Step 2:
Absorption of
microwave
photon



Details in J. A. Devlin et al., [arXiv:2601.05472](https://arxiv.org/abs/2601.05472)

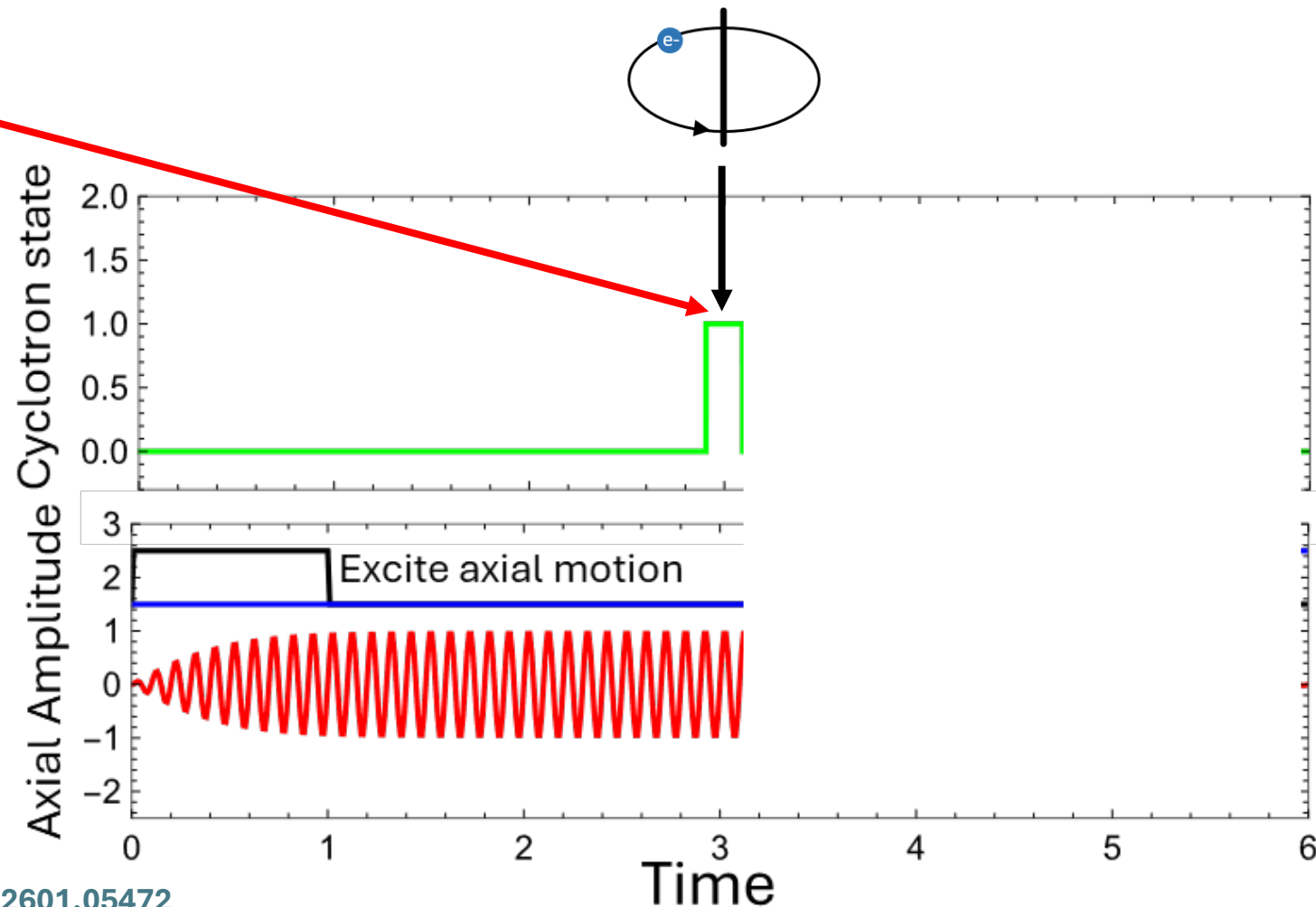
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Detecting photons with a single trapped electron

Step 3: Excited cyclotron state



Details in J. A. Devlin et al., [arXiv:2601.05472](https://arxiv.org/abs/2601.05472)

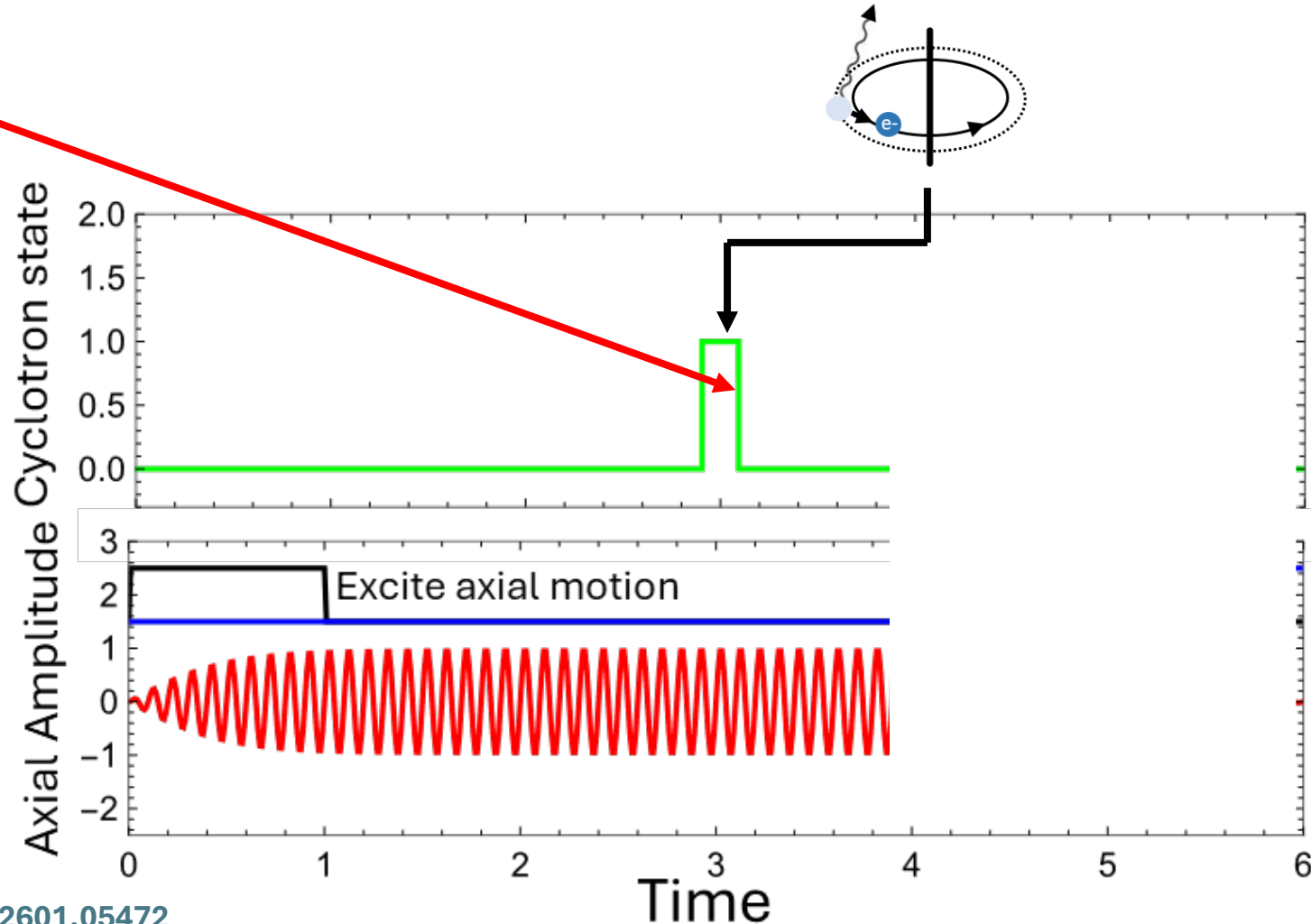
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Detecting photons with a single trapped electron

Step 4: De-excite
cyclotron motion



Details in J. A. Devlin et al., [arXiv:2601.05472](https://arxiv.org/abs/2601.05472)

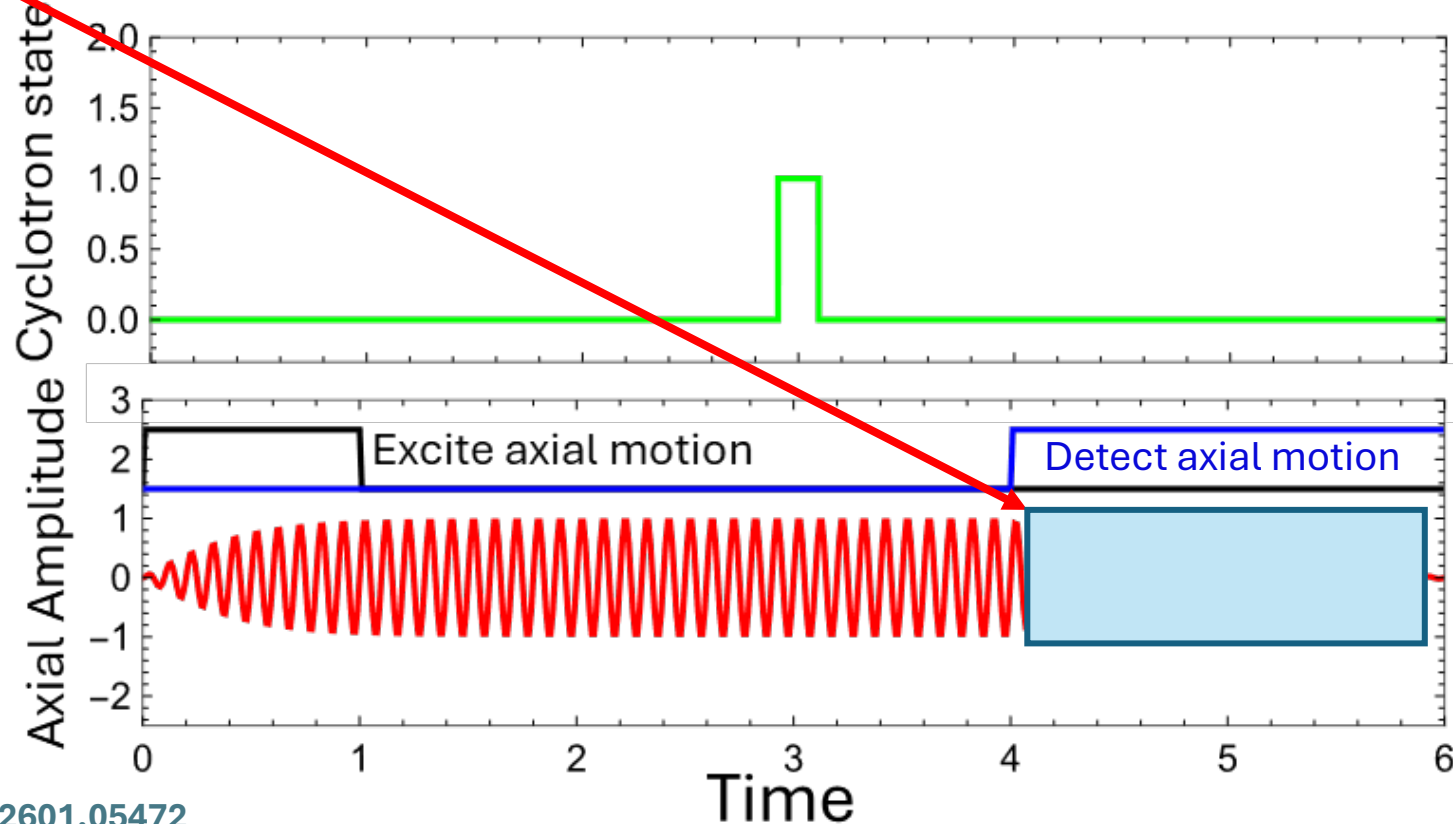
See also similar ideas –

A. Cridland et al., *Photonics* **3**, 59 (2016).

X. Fan et al., *Physical Review D* **111**, 075022 (2025).

Detecting photons with a single trapped electron

Step 5: Detect
axial motion



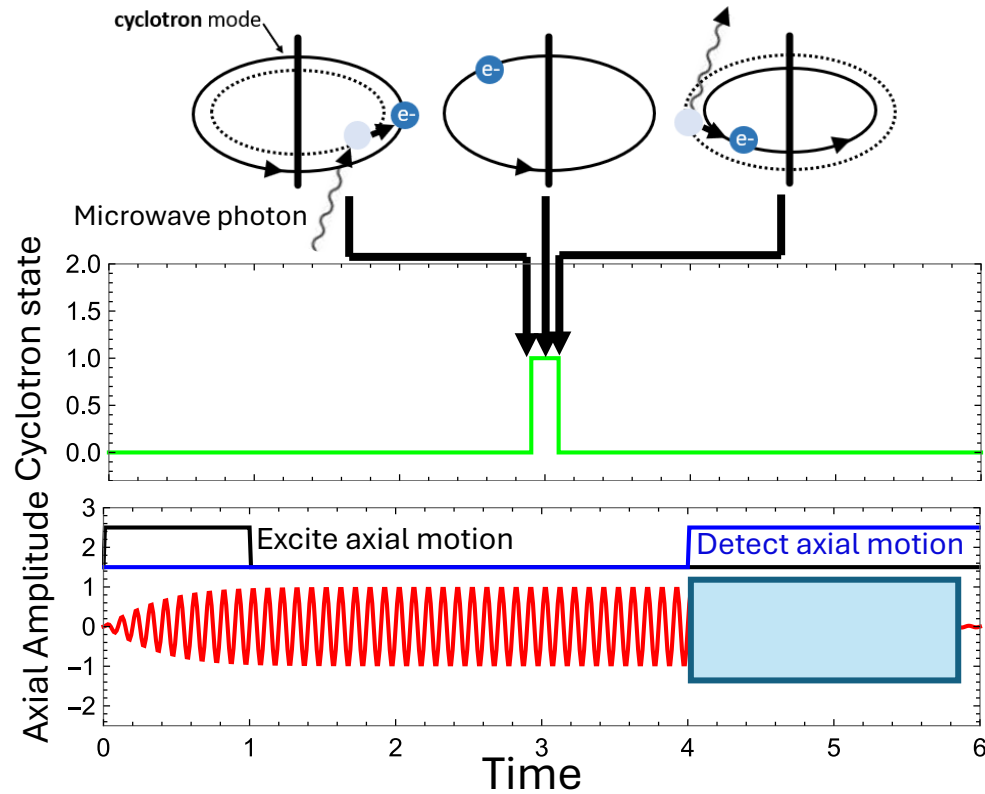
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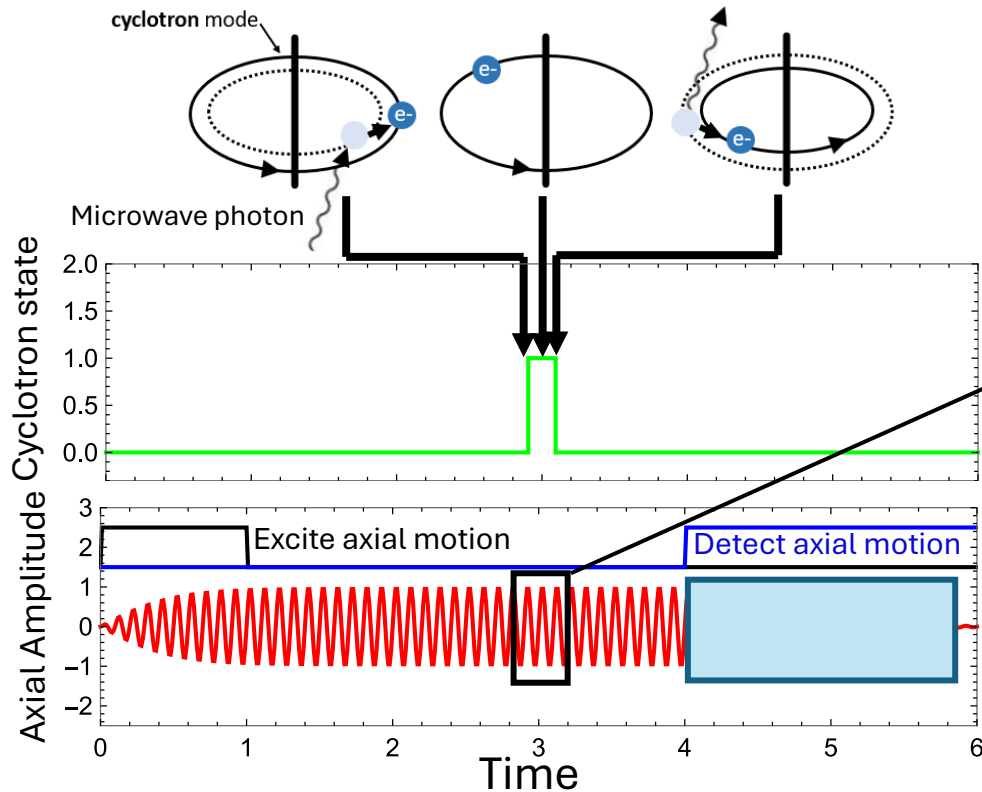
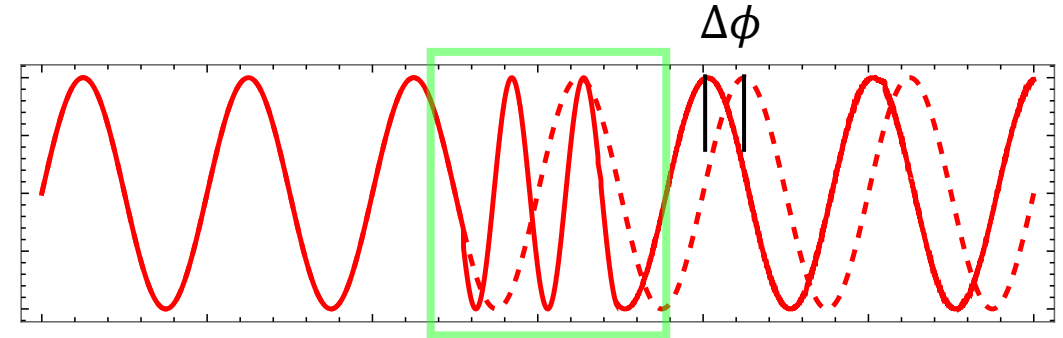
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Detecting photons with a single trapped electron



Microwave absorption causes a detectable phase jump $\Delta\phi$ in the final axial signal

$$\Delta\nu_z = \frac{h\nu_+ B_2}{4\pi^2 m_e \nu_z B_0} \Delta n_+$$

$$\Delta\phi = 2\pi\Delta\nu_z\tau$$

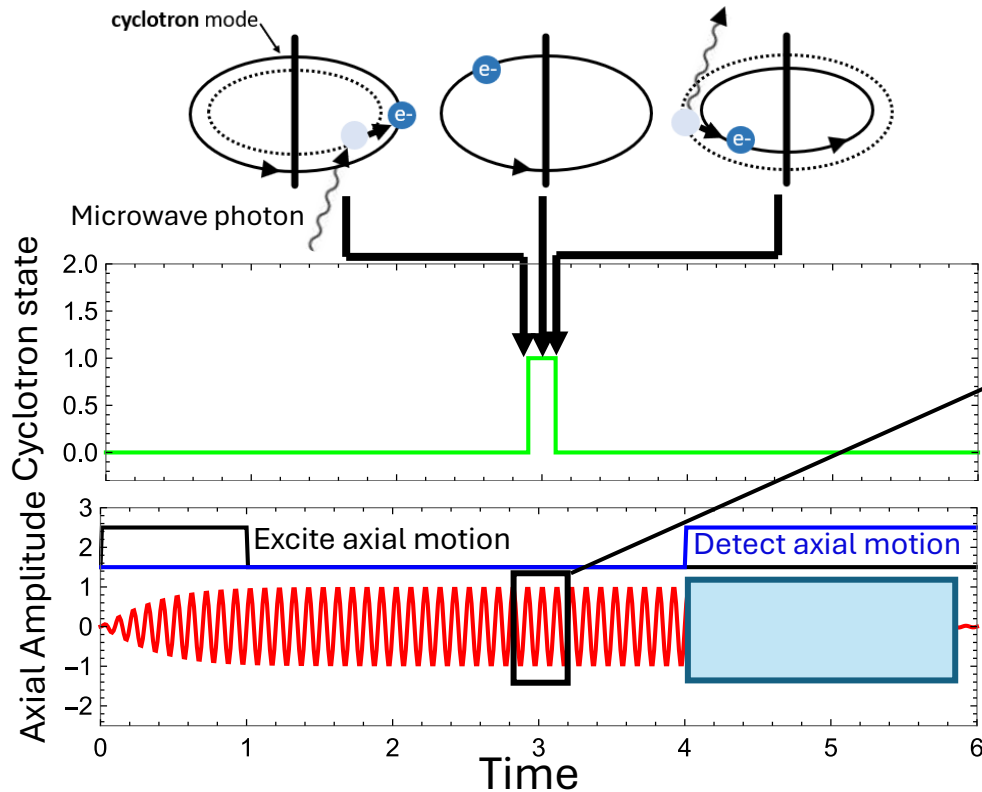
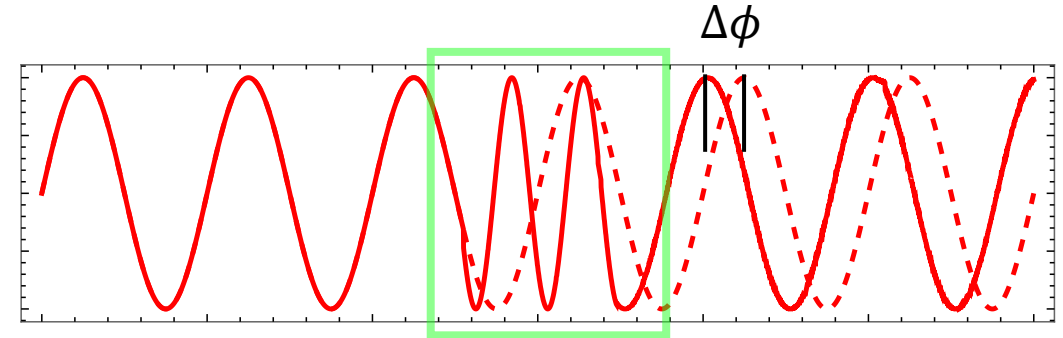
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Detection efficiency: 3-sigma, 7.4%
5-sigma, 3.8%

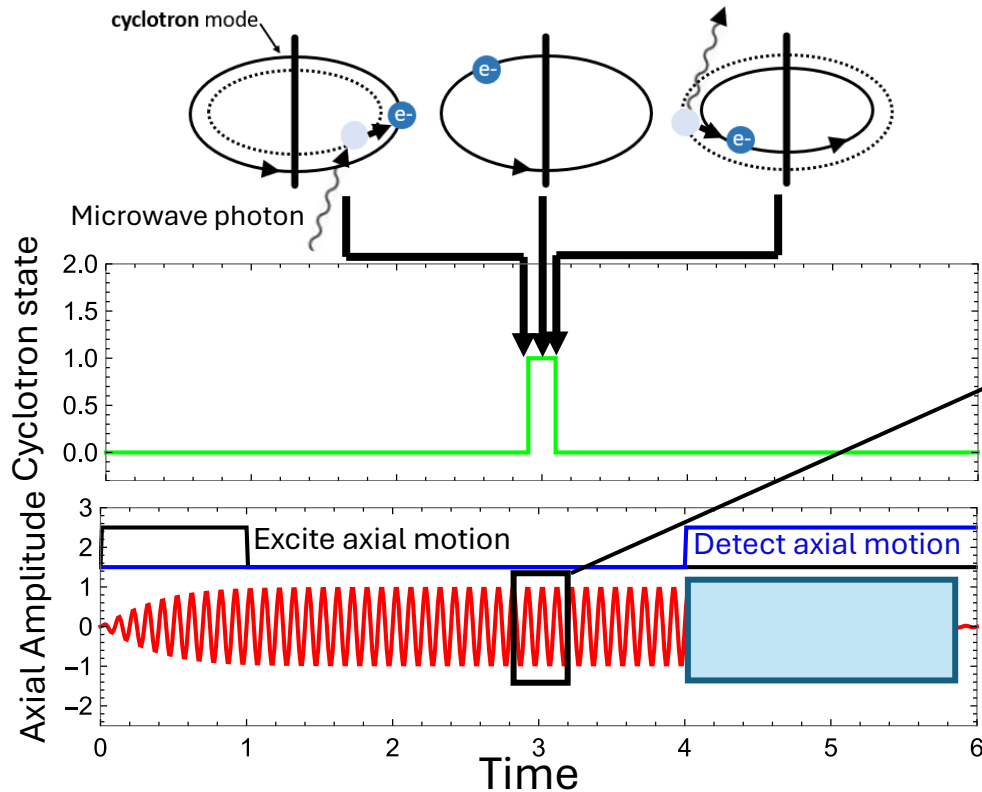
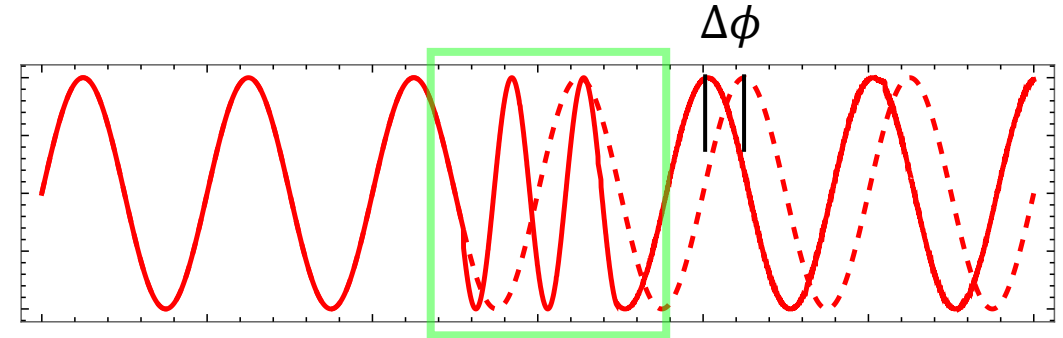
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$$\Delta\phi = 2\pi\Delta\nu_z\tau$$

Detection efficiency: 3-sigma, 7.4%
5-sigma, 3.8%

Exclusion efficiency: 30%

Details in J. A. Devlin et al., [arXiv:2601.05472](https://arxiv.org/abs/2601.05472)

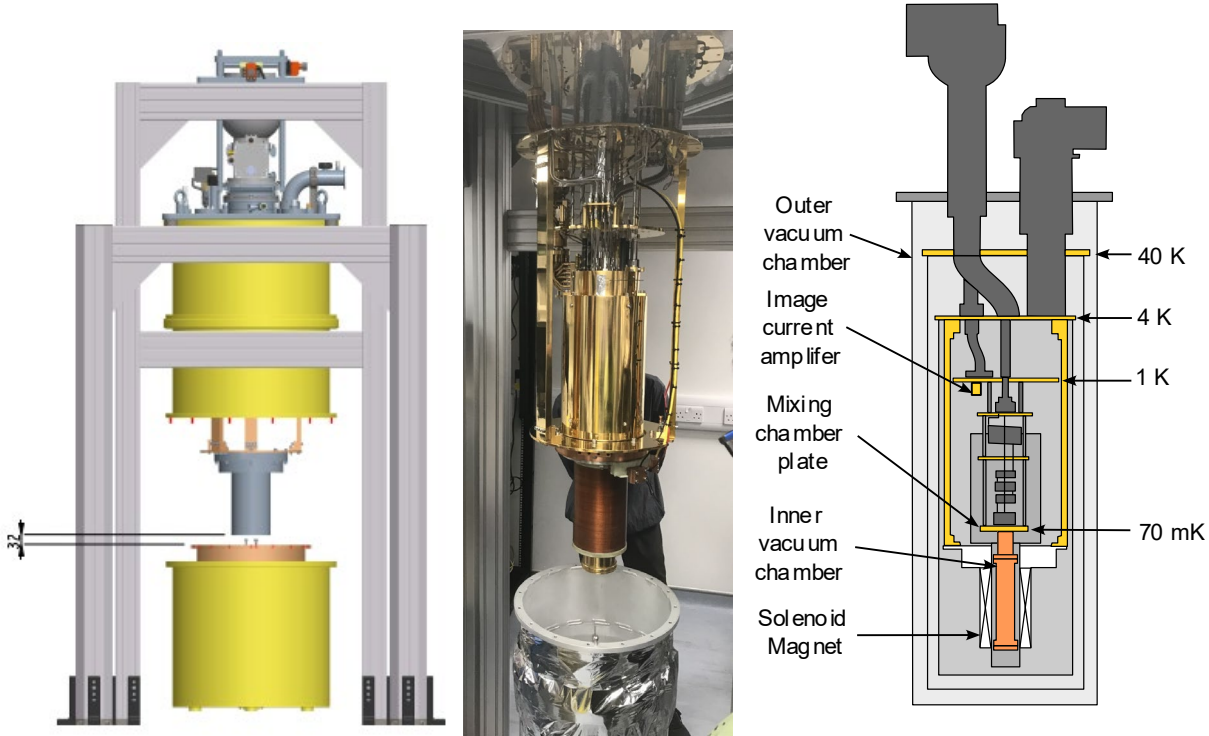
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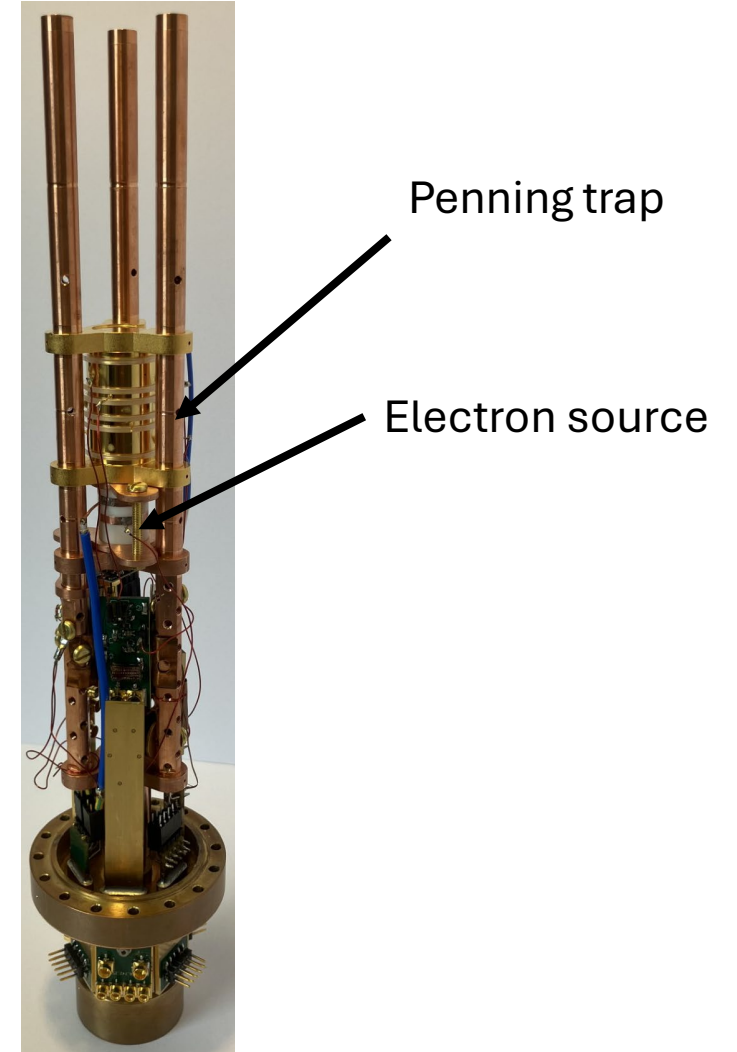
Trapped electrons

Cryo infrastructure



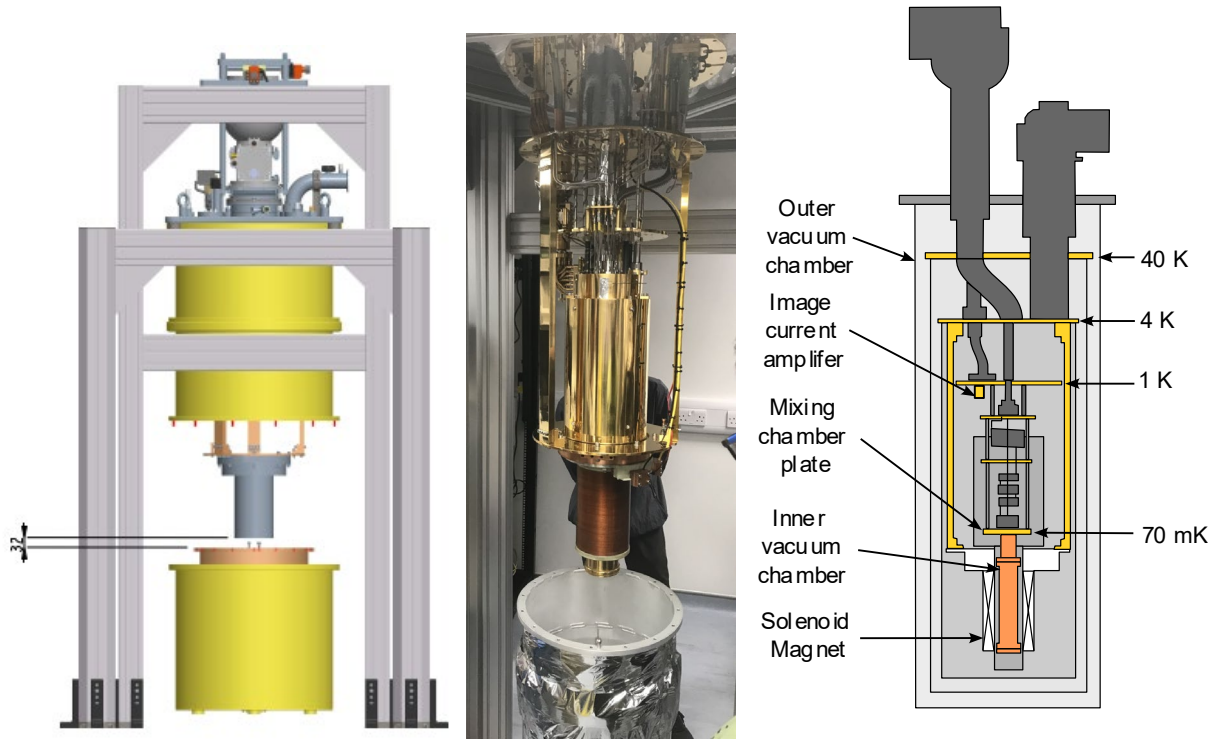
- Dilution fridge installed October 2024
- Base temperature < 50 mK at 2T field
- Vibrations at sample space investigated and found to be acceptable

Penning trap assembly



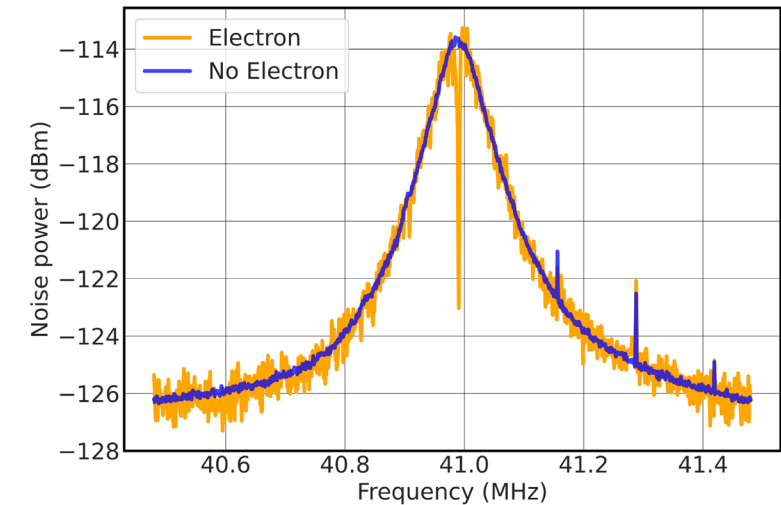
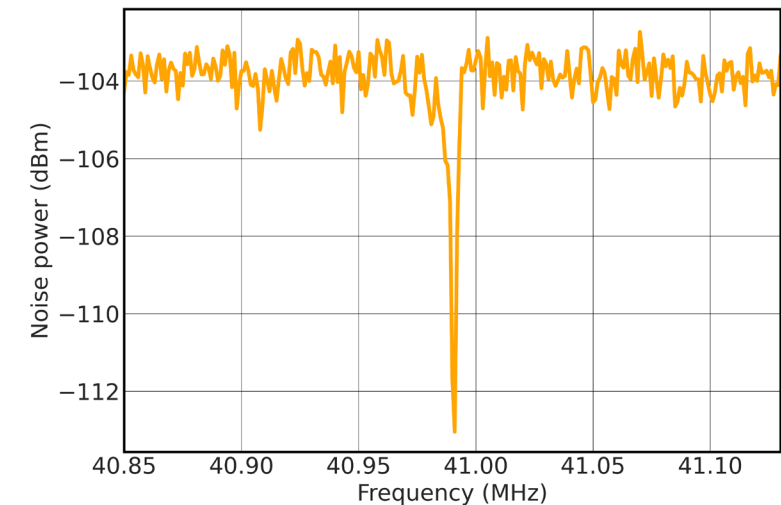
Trapped electrons

Cryo infrastructure



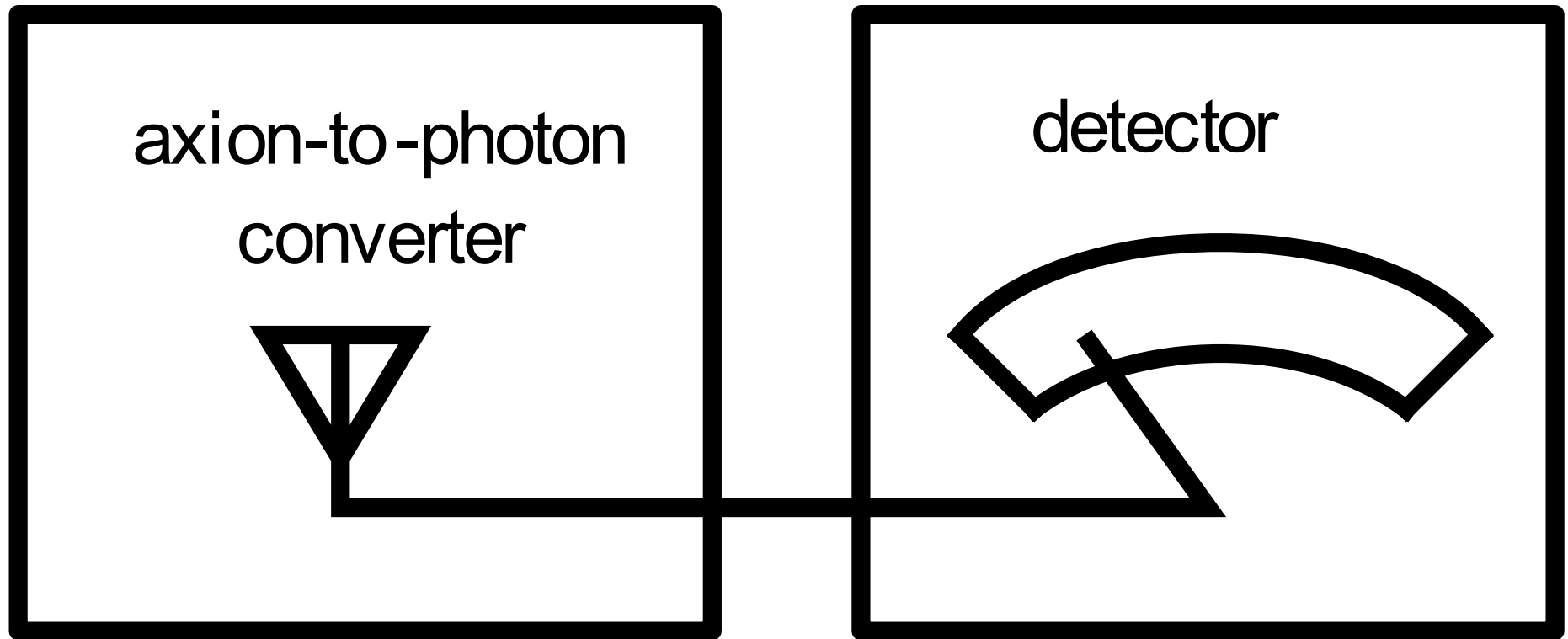
- Dilution fridge installed October 2024
- Base temperature < 50 mK at 2T field
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Up to date images of small cloud of electrons



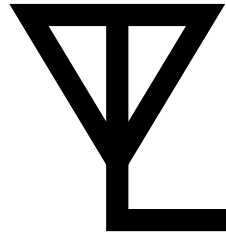
Cloud of 500 electrons

Takeaways



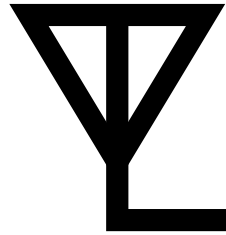
Takeaways

axion-to-photon
converter



Takeaways

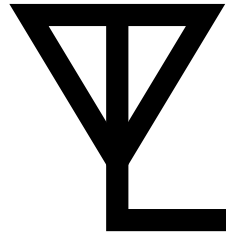
axion-to-photon
converter



- Fabry-Perot cavities has favourable scaling with frequency.

Takeaways

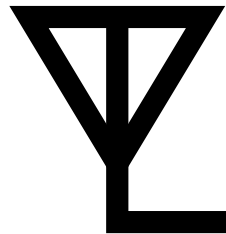
axion-to-photon
converter



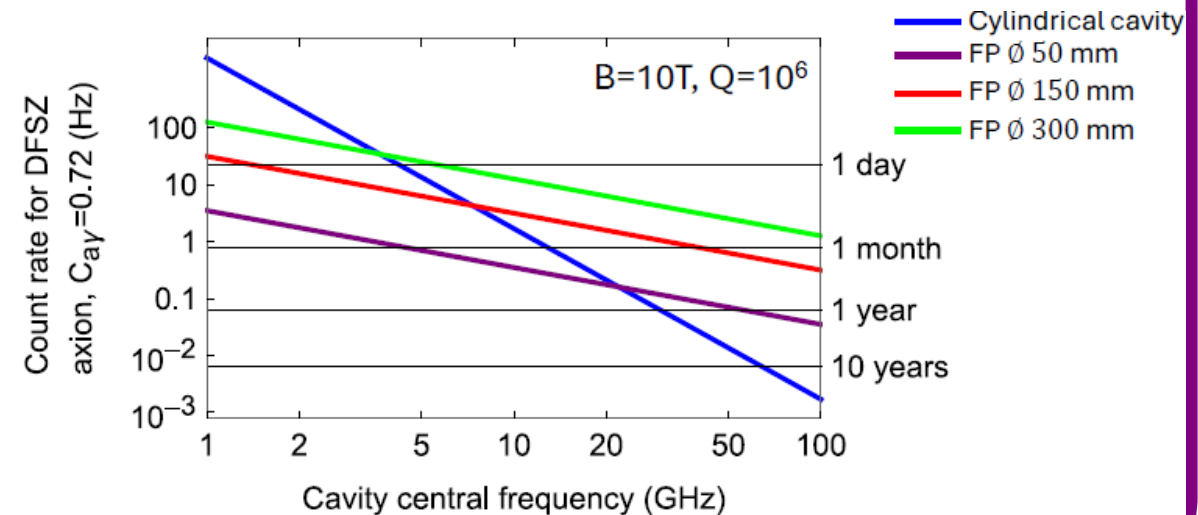
- Fabry-Perot cavities has favourable scaling with frequency.
- High quality factor measured.

Takeaways

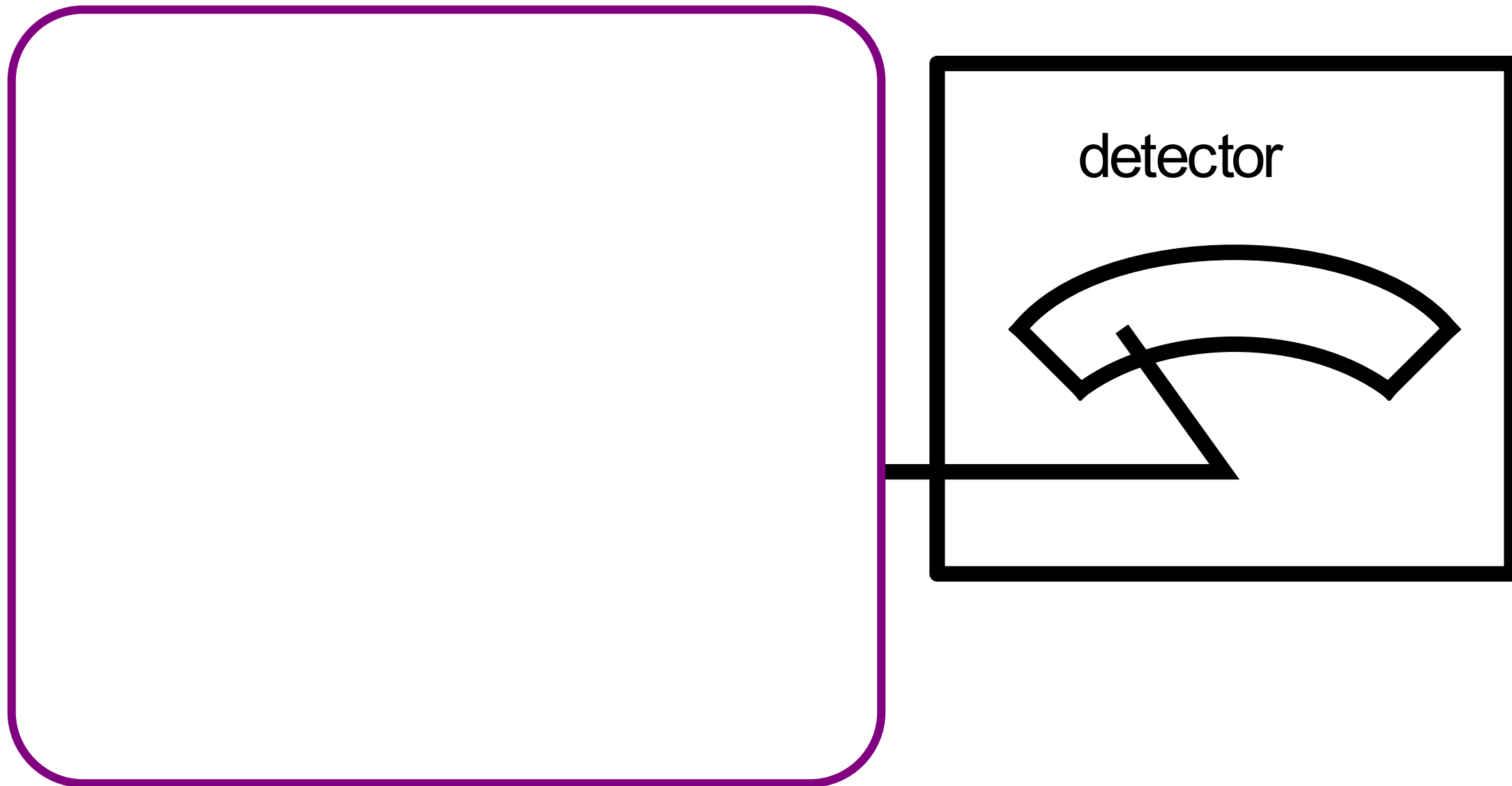
axion-to-photon
converter



- Fabry-Perot cavities has favourable scaling with frequency.
- High quality factor measured.
- Route to high count rates.

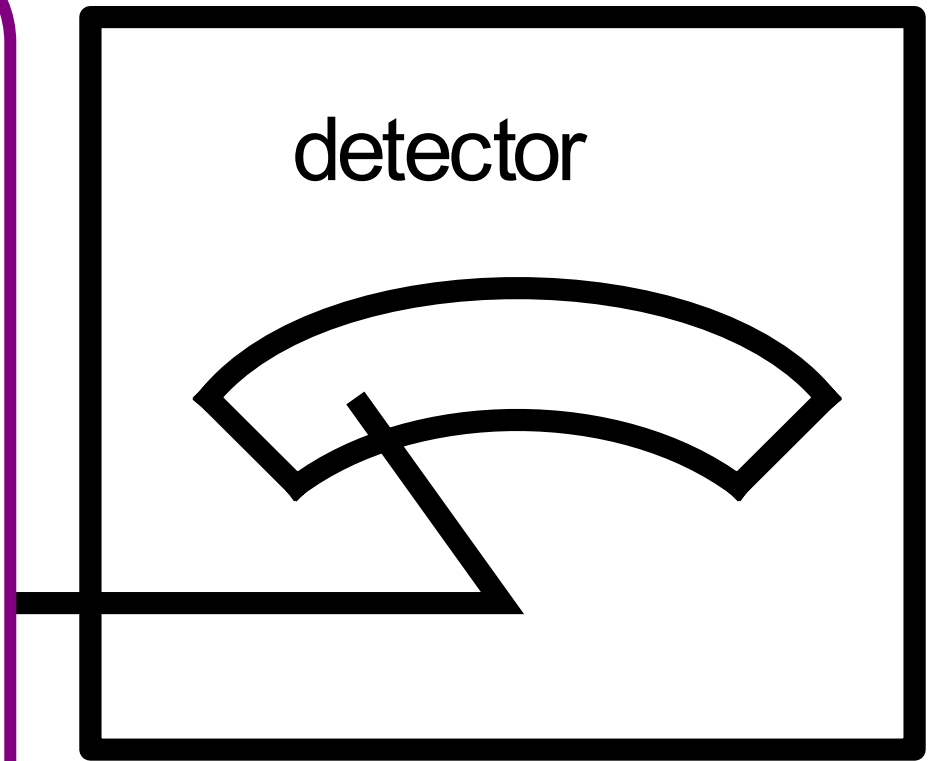


Takeaways



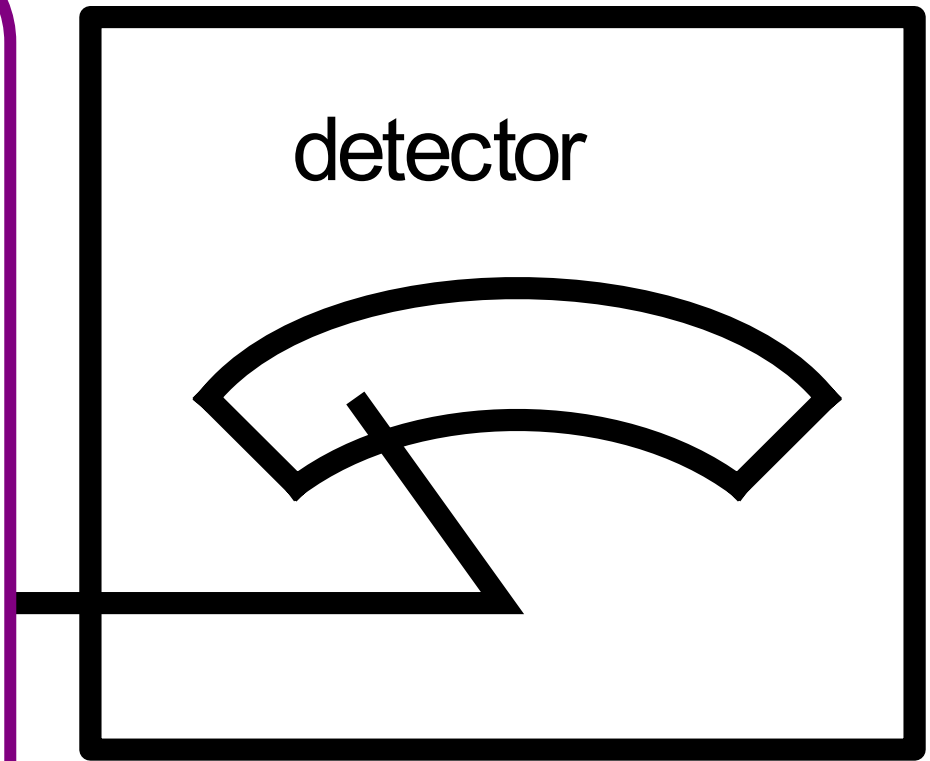
Takeaways

- Single photon counting dramatically speed up high mass axion searches.



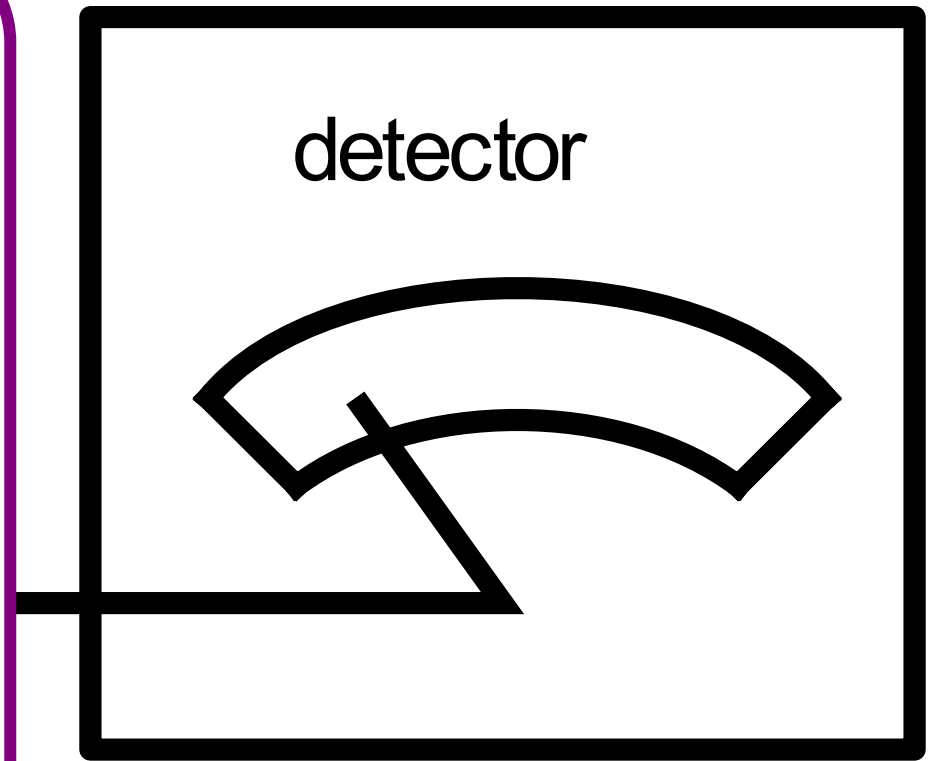
Takeaways

- Single photon counting dramatically speed up high mass axion searches.
- Electrons in a Penning trap can be used as single photon counters.



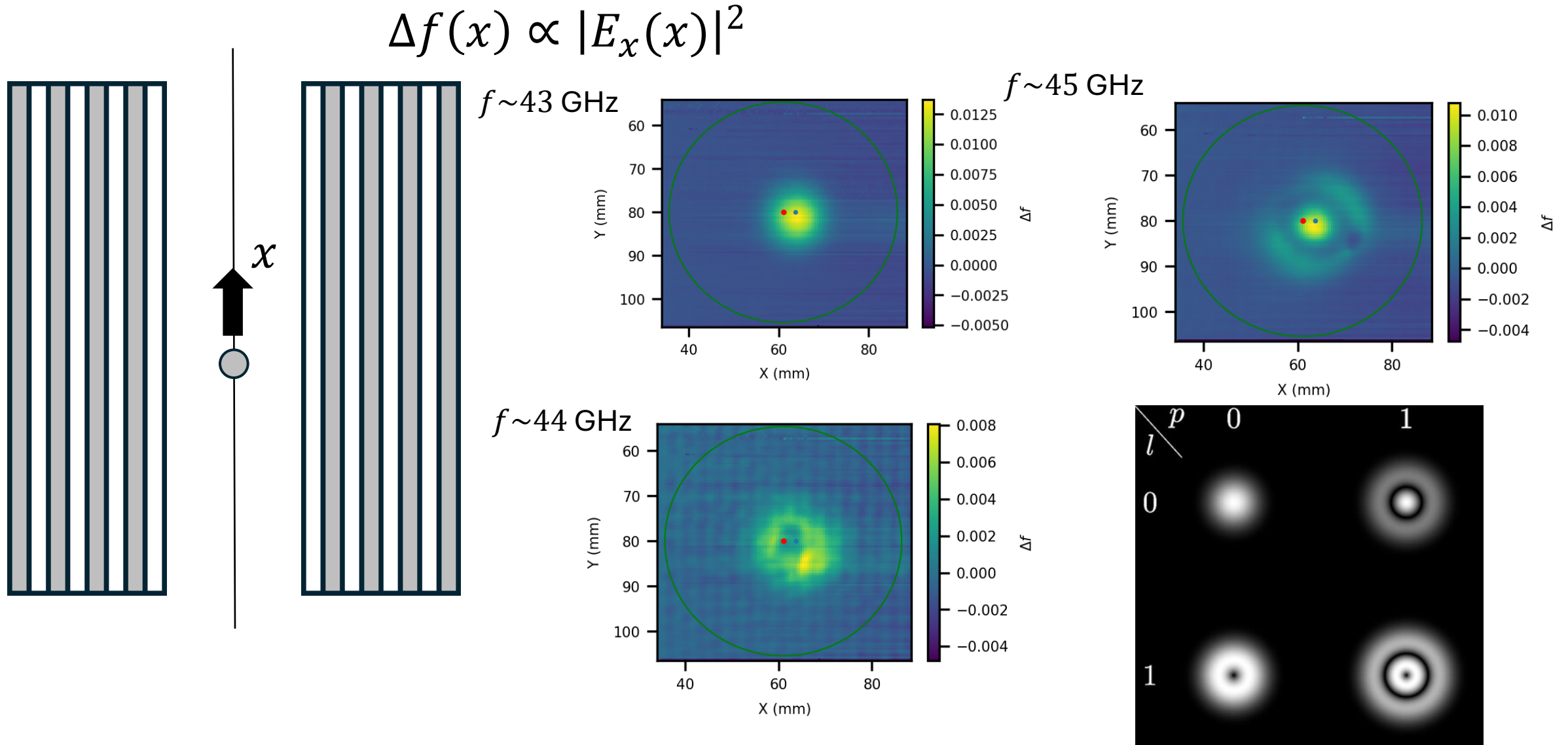
Takeaways

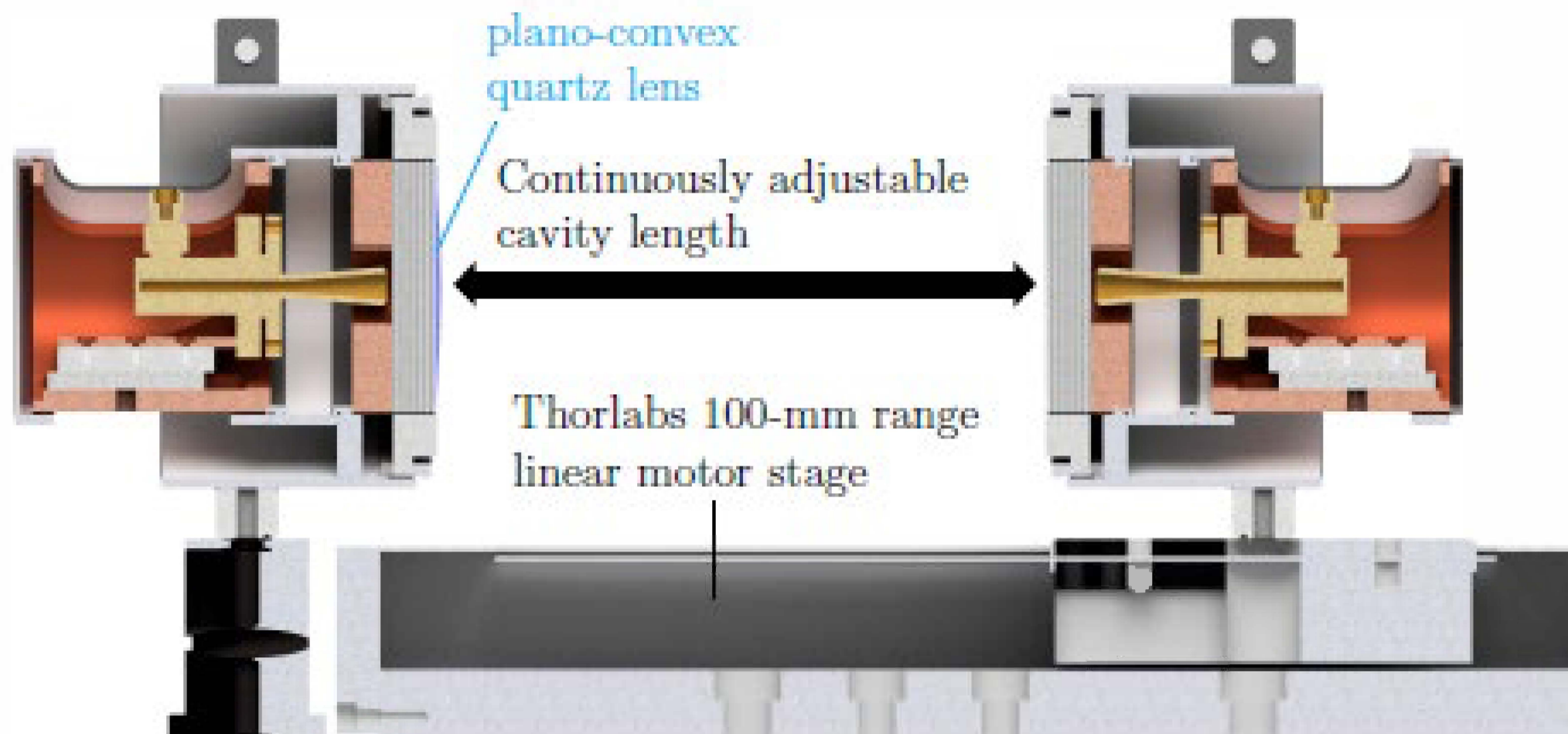
- Single photon counting dramatically speed up high mass axion searches.
- Electrons in a Penning trap can be used as single photon counters.
- Able to load and control small clouds of electrons.



Thank you for listening

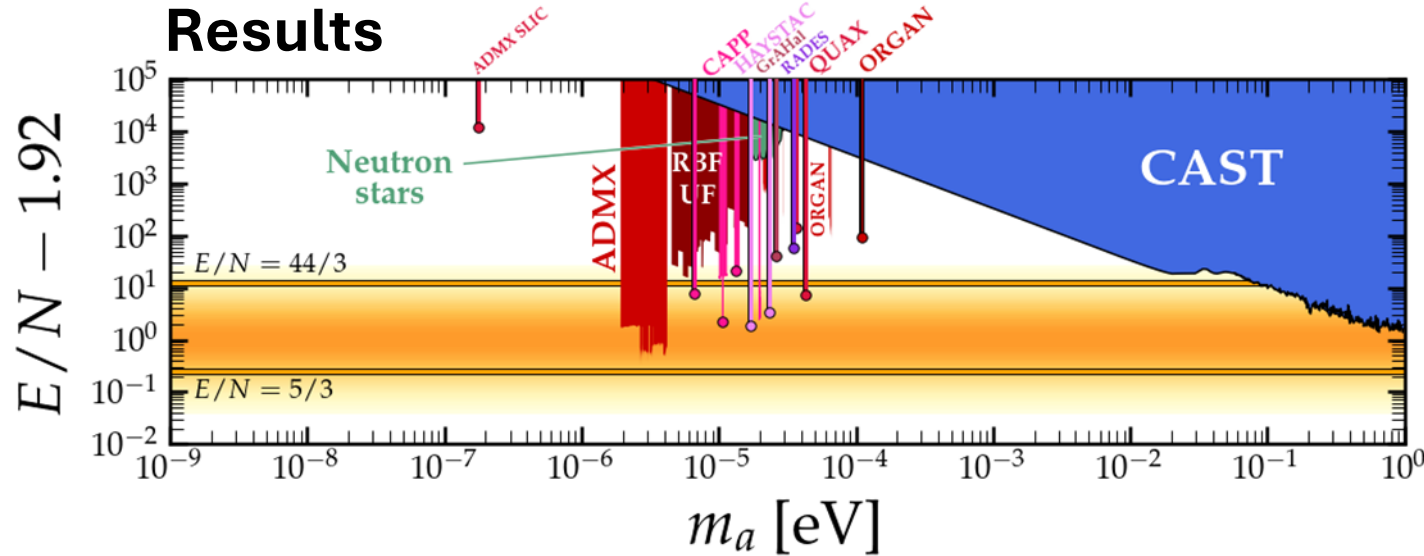
Cavity Modes



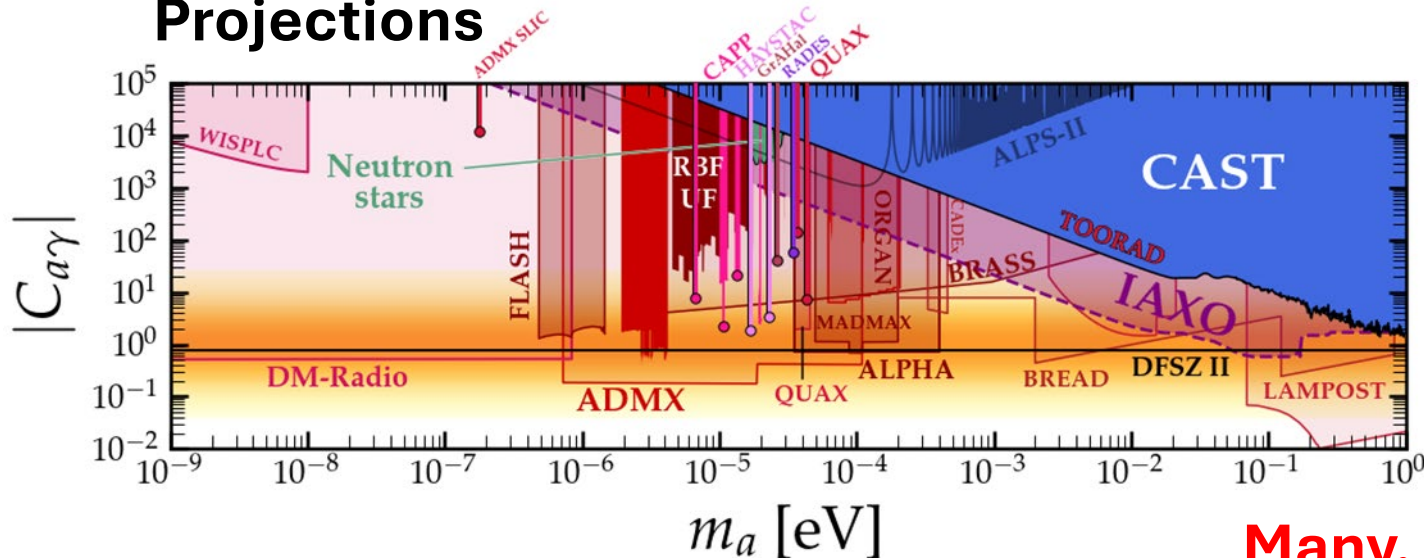


Other detection options >30 GHz

Results



Projections



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

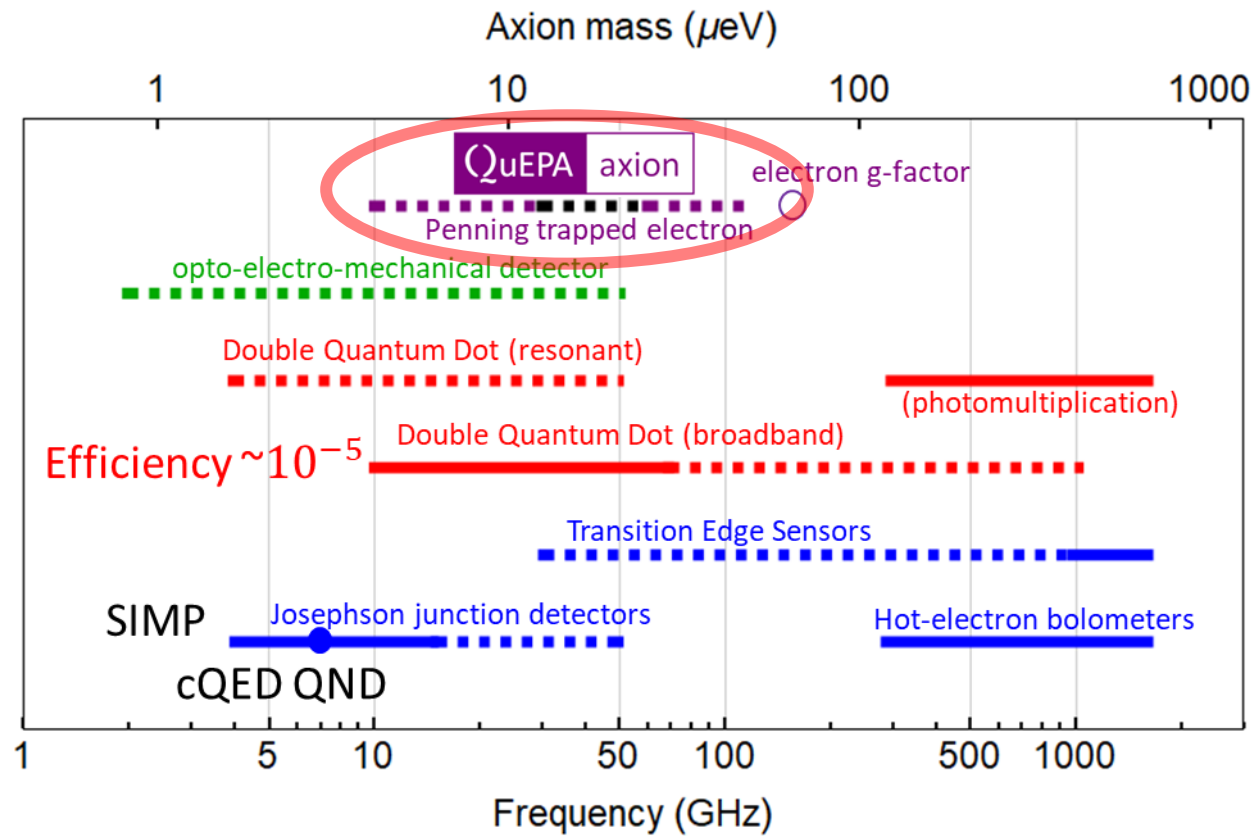
.. with dielectric boost

MADMAX Big effort at DESY, lower m_a initially

Many, more new ideas between 5-30 GHz

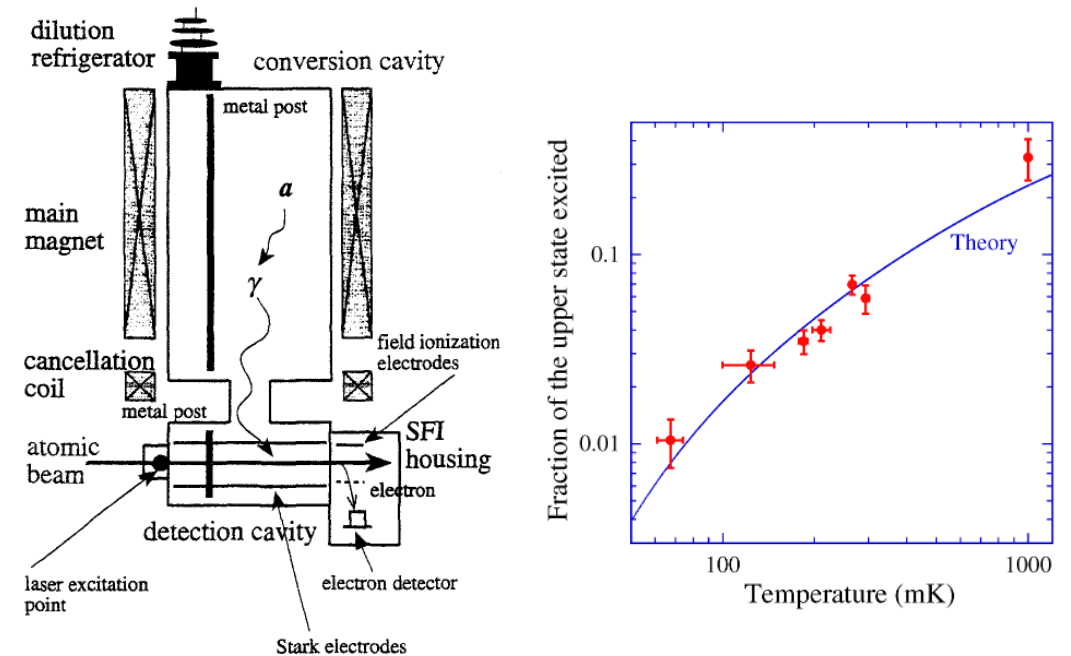
Single photon counters

Solid-state devices



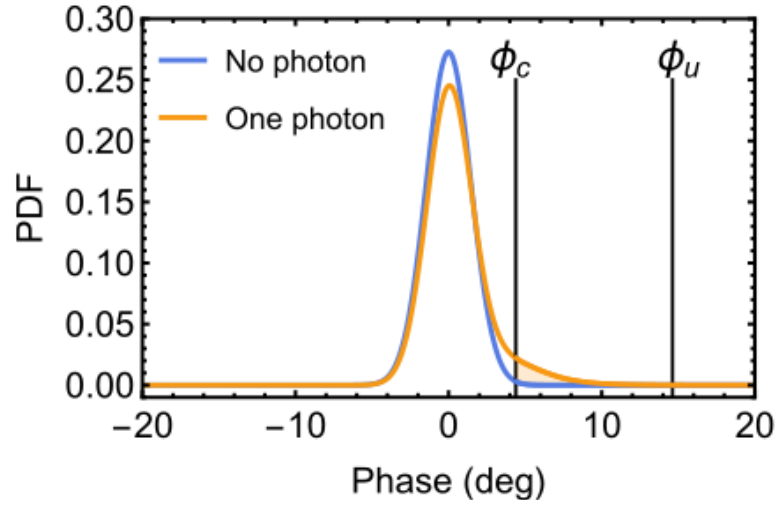
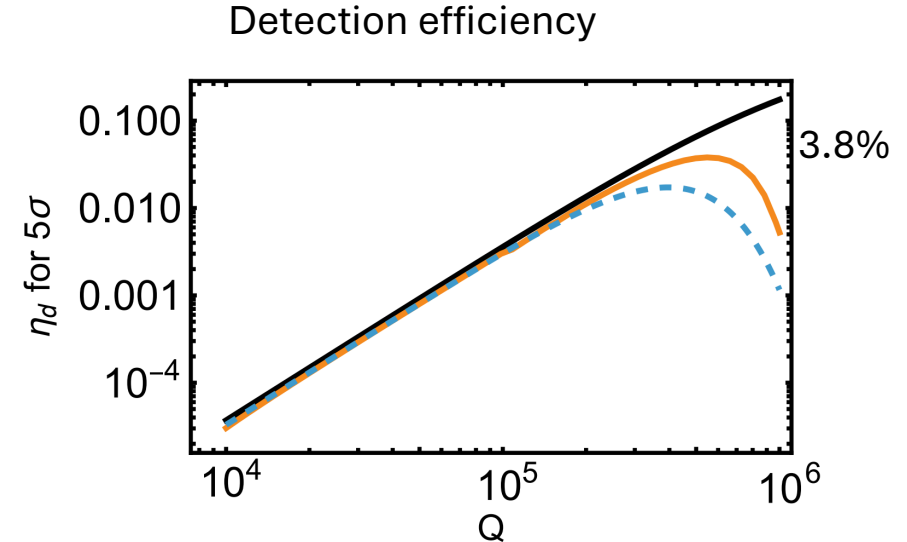
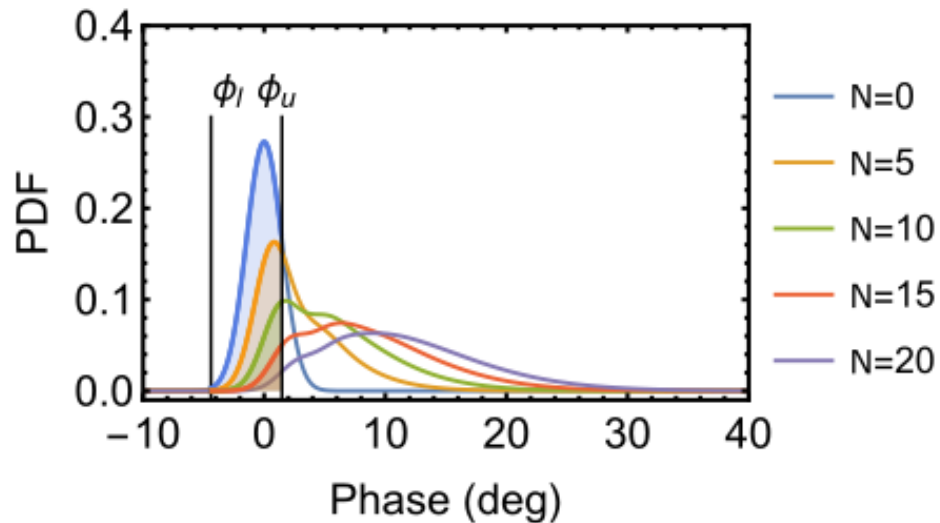
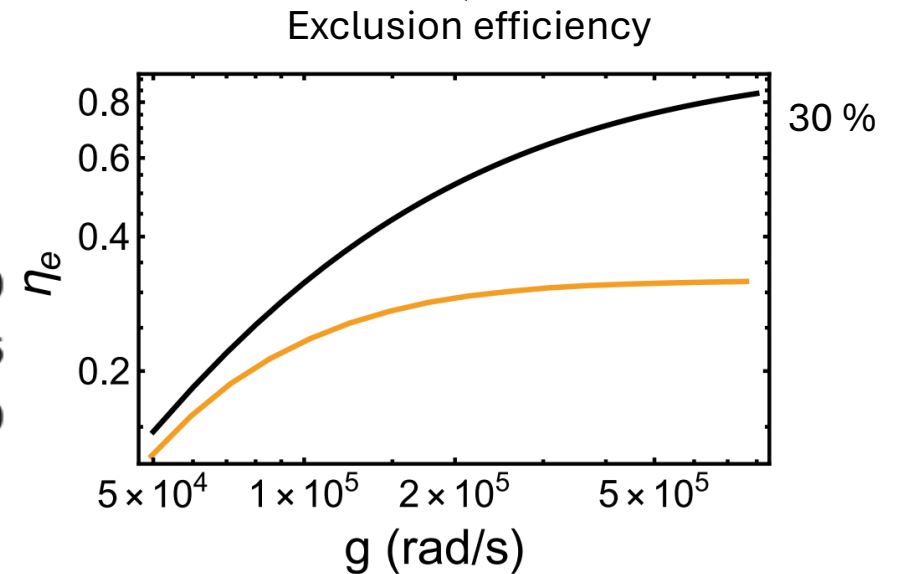
Alternative AMO devices

CARRACK I & II Rydberg atoms



Good performance, ultimately effort was not sustained.
Now Rydberg Axions at Yale (RAY) D. Speller, & S. Ghosh

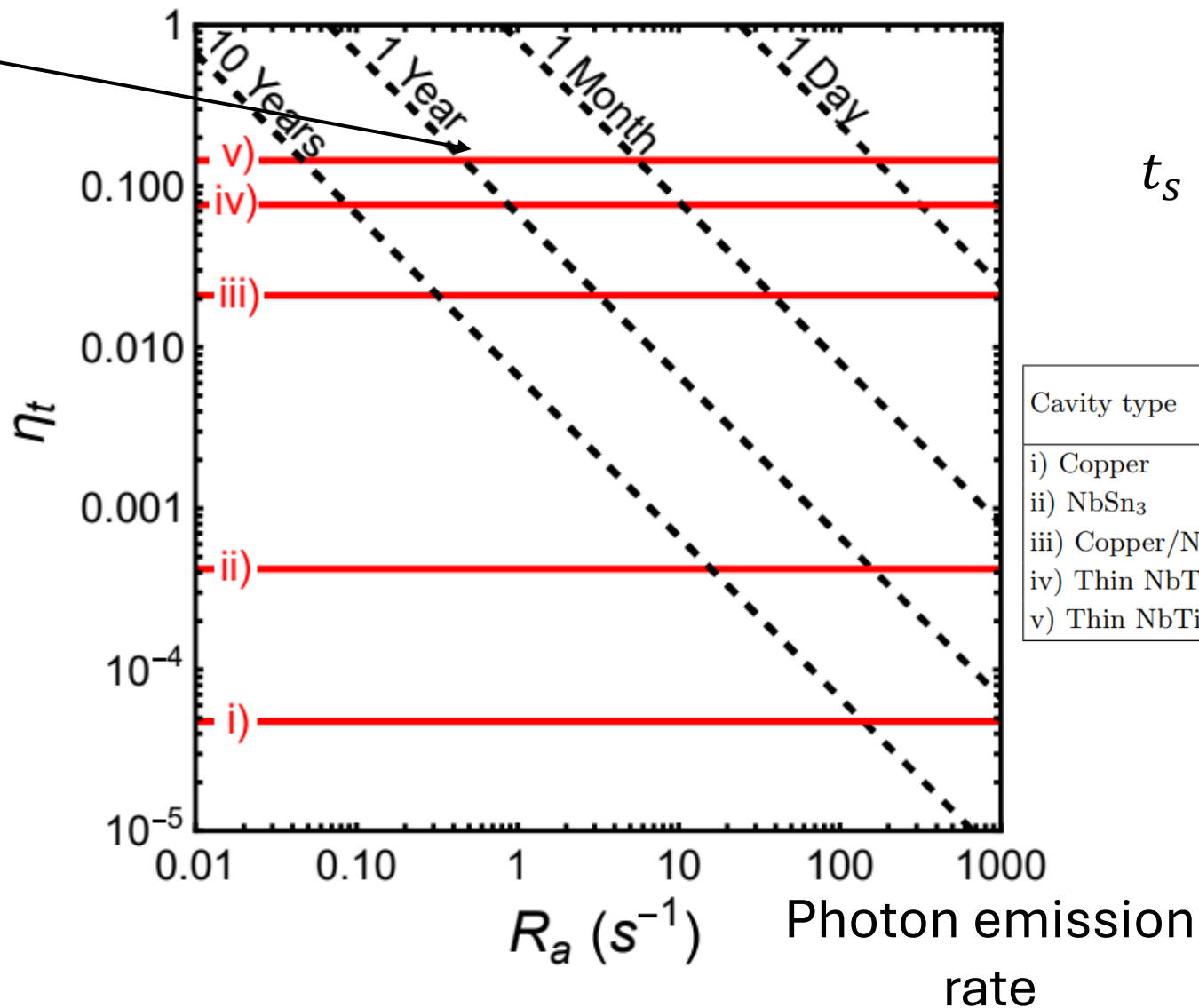
Detection and exclusion efficiency



Projected scan time

Time to scan
 $m_a \rightarrow 2m_a$

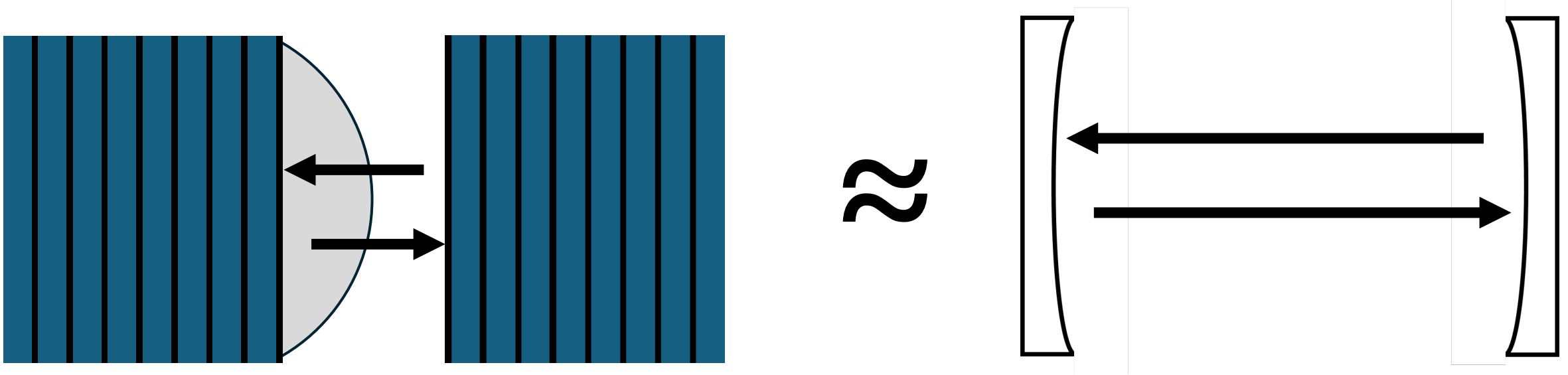
Photon counting
efficiency



$$t_s = \frac{3 \log(2)}{R_a \eta_t \log\left(\frac{1}{Q_a} + 1\right)}$$

Cavity type	Q	g (krad/s)	η_e (%)	Speedup vs. linear amplifier
i) Copper	2×10^4	$2\pi \times 9.1$	0.01	1.4
ii) NbSn ₃	6×10^4	$2\pi \times 9.1$	0.08	13
iii) Copper/NbTi	4×10^5	$2\pi \times 9.1$	4.2	630
iv) Thin NbTi	1×10^6	$2\pi \times 9.1$	15	2300
v) Thin NbTi	1×10^6	$2\pi \times 30$	29	4300

Fabry-Perot Cavity



$$T_{lens} R_{Bragg} T_{lens} = \begin{pmatrix} 1 & 0 \\ -2/f & 1 \end{pmatrix} \approx R_{Mirror} = \begin{pmatrix} 1 & 0 \\ -2/R & 1 \end{pmatrix}$$