# A new search for dark matter axions using quantum technologies

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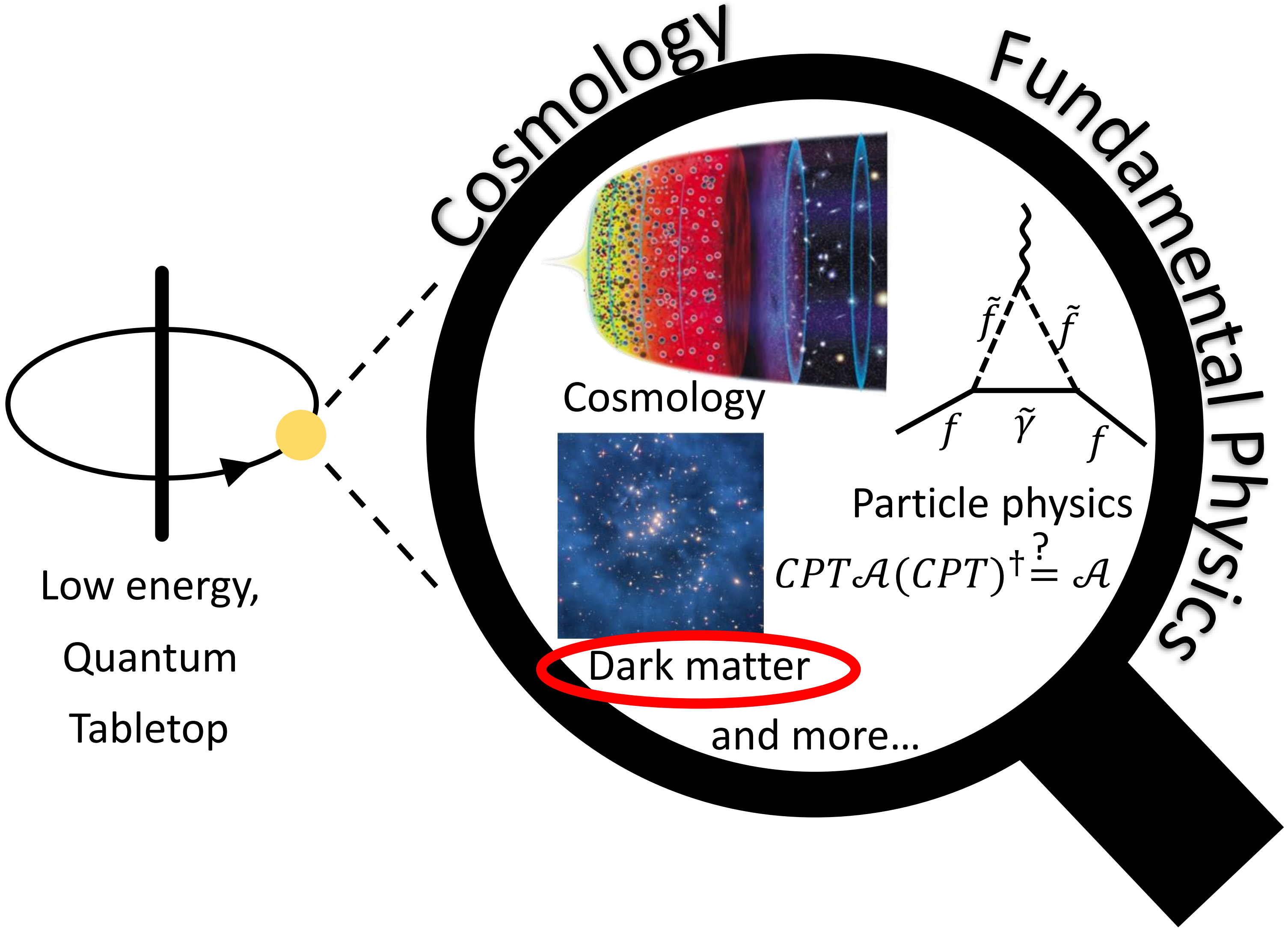
TRIUMF
9/4/2023

# Our Strategy



Low energy,

Quantum

Tabletop

Cosmology

Fundamental Physics

Cosmology

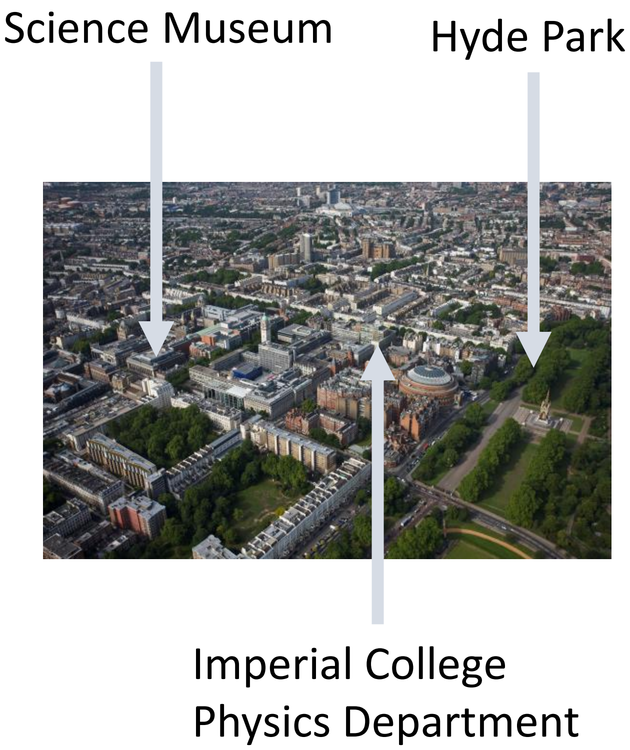
Particle physics

$CPT\mathcal{A}(CPT)^{\dagger} \overset{?}{=} \mathcal{A}$

Dark matter

and more...

# Centre for Cold Matter @ Imperial College



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

Also involved in this work

Ion trapping Group


**Richard Thompson**


**Dr. Kanika**

Marios Telemachou & Mingyao Xu
Maddie Fisher
Horacio Septien-Gonzalez

QuEPA

Quantum Enhanced Particle Astrophysics

# Overview

1. Why QCD axions?
2. Detection techniques
3. Challenges for high $m_a$ haloscopes – and how we plan to solve them
    a) Volume problem
    b) Noise problem
4. Long term goals and other measurements

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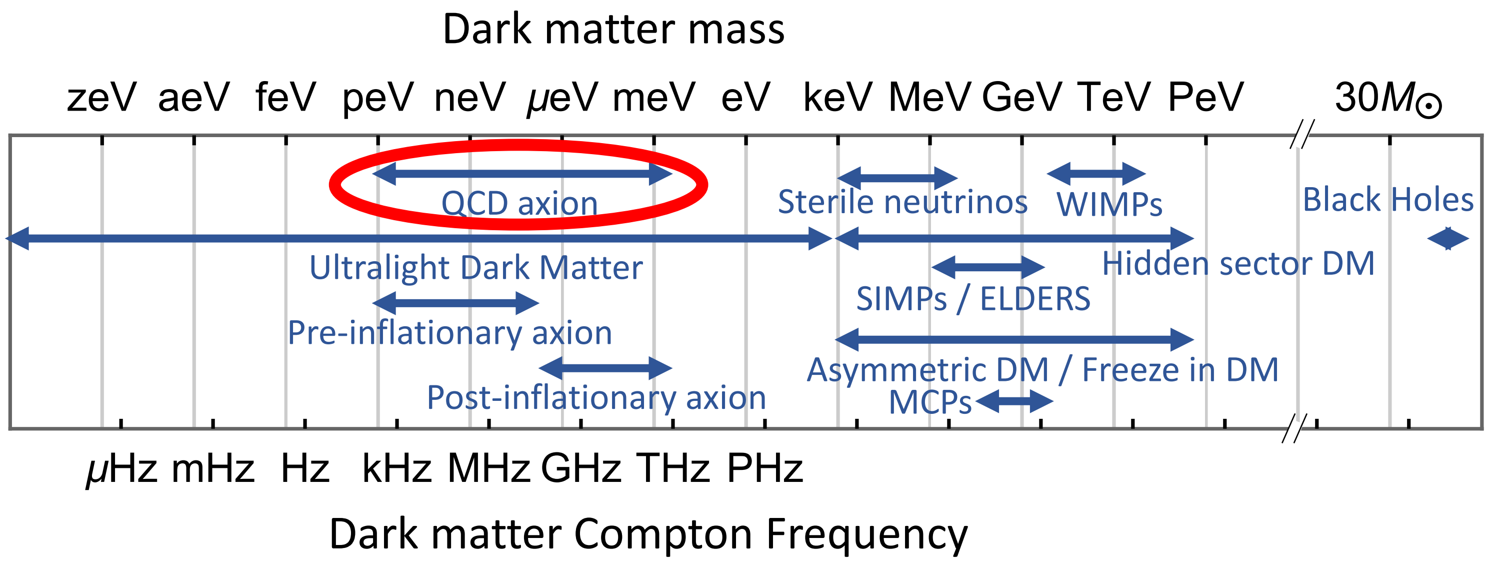
# Many, many dark matter candidates



Not all listed…

Figure adapted from
US Cosmic Visions: New Ideas in Dark Matter 2017 arXiv:1707.04591

# The “strong”-CP problem

There is a QCD term which could break CP symmetry, if $\bar{\theta} \neq 0$ :

$$\mathcal{L}_{\bar{\theta}} = \bar{\theta}\,\frac{g^2}{32\pi^2}\,F_a^{\mu\nu}\,\tilde{F}_{a\mu\nu}$$

The (complex) quark mass matrix

$$\bar{\theta} = \theta - \mathrm{ArgDet}[M]$$

QCD

Electroweak contribution

From neutron EDM $d_n < 1.8 \times 10^{-26}$ e·cm ⟶ $|\bar{\theta}| < 10^{-9}$

no CP violation

Working hypothesis: something is forcing $\bar{\theta} \longrightarrow 0$

The Strong CP Problem and Axions R. D. Peccei, in *Axions* (Springer, Berlin Heidelberg 2008)
C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020)

# The Peccei-Quinn resolution

$\bar{\theta}$ terms relaxed to zero by extra global symmetry with associated particle, the **axion**

Axion: pseudo-scalar, spin-0 boson, with couplings to photons and fermions.

$$\mathcal{L} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Big unknown: $f_a$, an energy scale which determines $m_a$ and (essentially) $g_{a\gamma\gamma}$

$$m_a = 6.3 \mu eV \left(\frac{10^{12}}{f_a}\right)$$

$$g_{a\gamma\gamma} = \frac{1}{f_a} \frac{e^2}{8\pi^2} C_{a\gamma}$$

Model dependent coefficient typically O(1) to O(10)

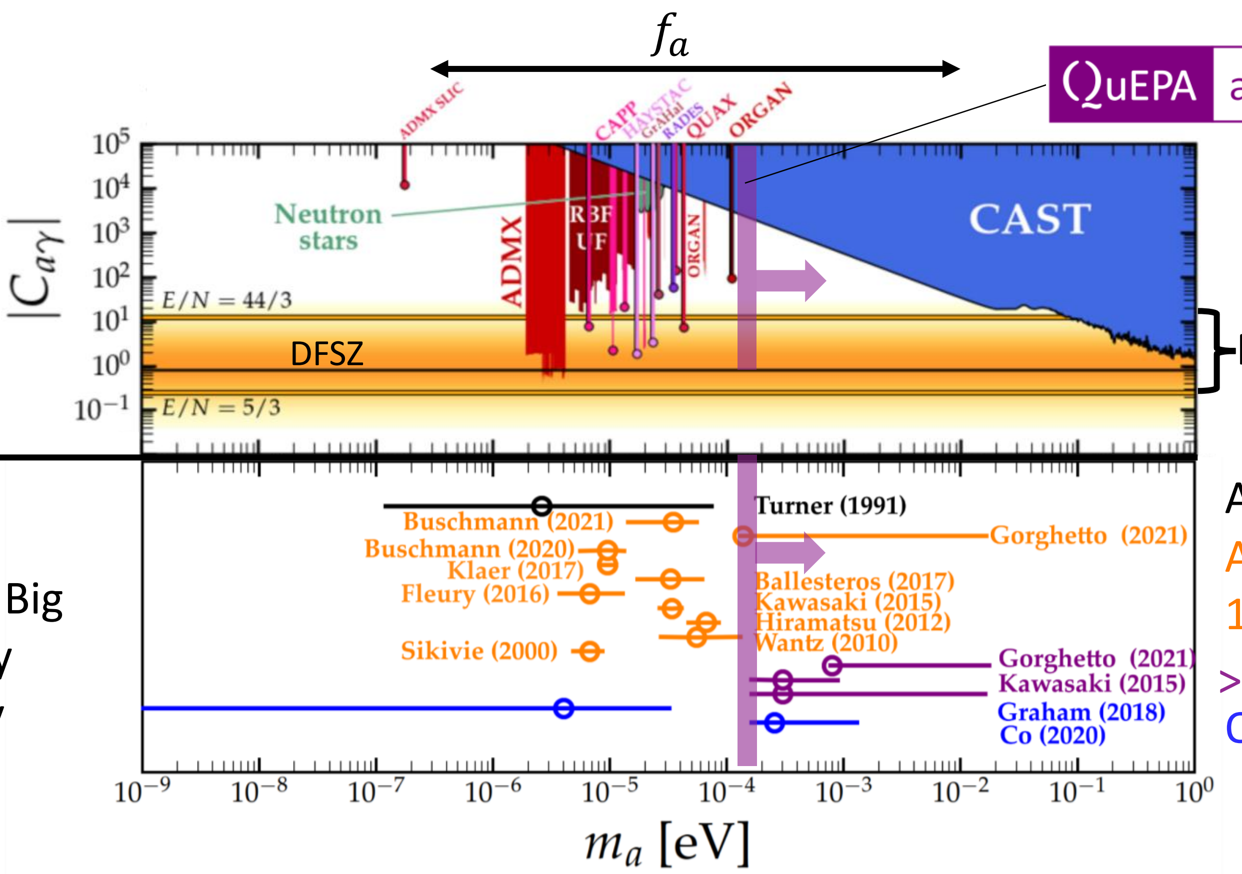
$C_{a\gamma}$=0.74 for DFSZ model
$C_{a\gamma}$=1.92 for KSVZ model

**Any value of $f_a$ solves strong CP problem, but not all values consistent with experiment**

# “invisible” axions as dark matter

QuEPA axion

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

Goal: Search $m_a > 120\ \mu eV$ @ DFSZ sensitivity

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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# How to look for axions from the DM halo

For $m_a = 100\ \mu\mathrm{eV}$ and DM energy density, number of axions in de Broglie volume > $10^{20}$

→ DM halo behaves like new “classical” field

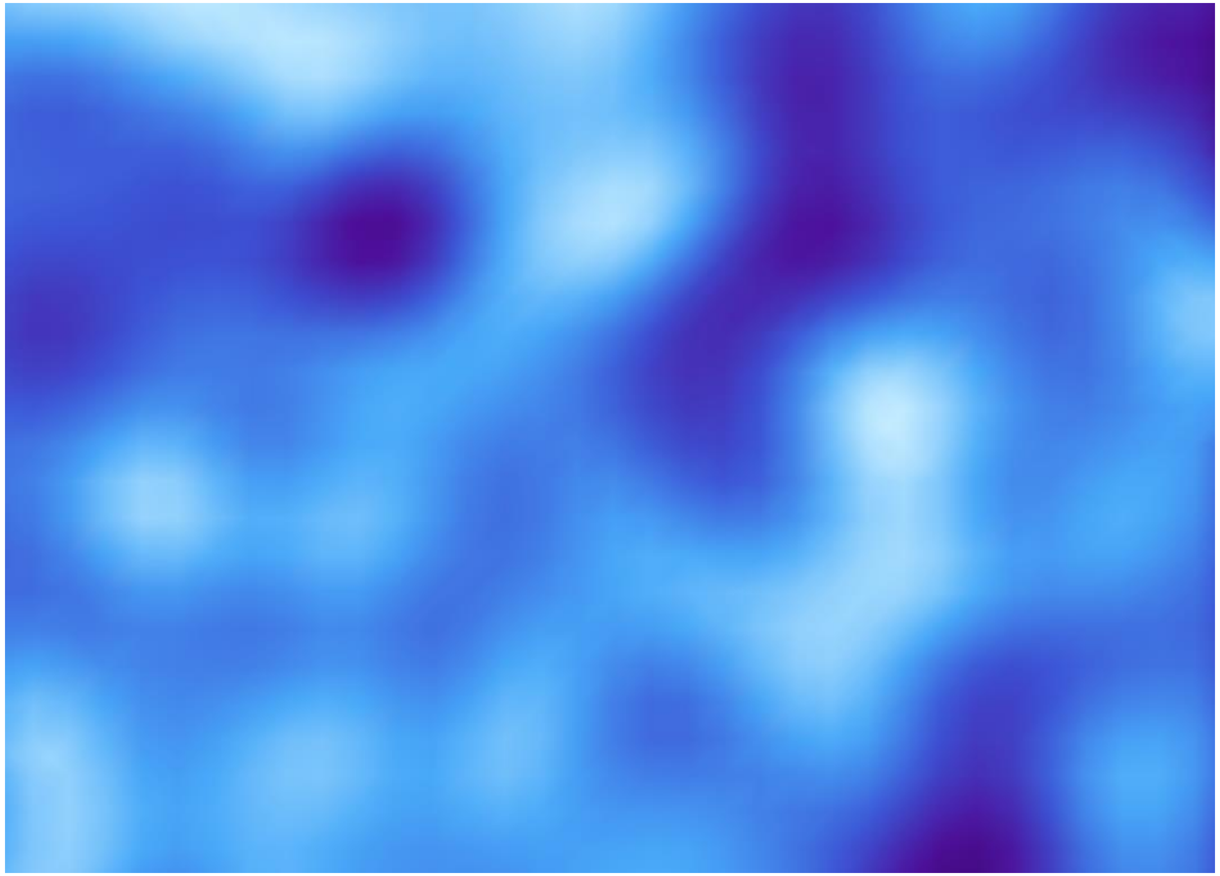
Modifies Maxwell’s Equations:

$$\vec{\nabla}\cdot\vec{D} = \rho_f + \underline{g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\vec{B}\cdot\vec{\nabla}a},$$

$$\vec{\nabla}\times\vec{H} = \vec{J}_f + \frac{\partial\vec{D}}{\partial t} \underline{- g_{a\gamma\gamma}\sqrt{\frac{\epsilon_0}{\mu_0}}\left(\vec{B}\frac{\partial a}{\partial t} + \vec{\nabla}a\times\vec{E}\right)},$$

$$\vec{\nabla}\cdot\vec{B} = 0,$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t},$$

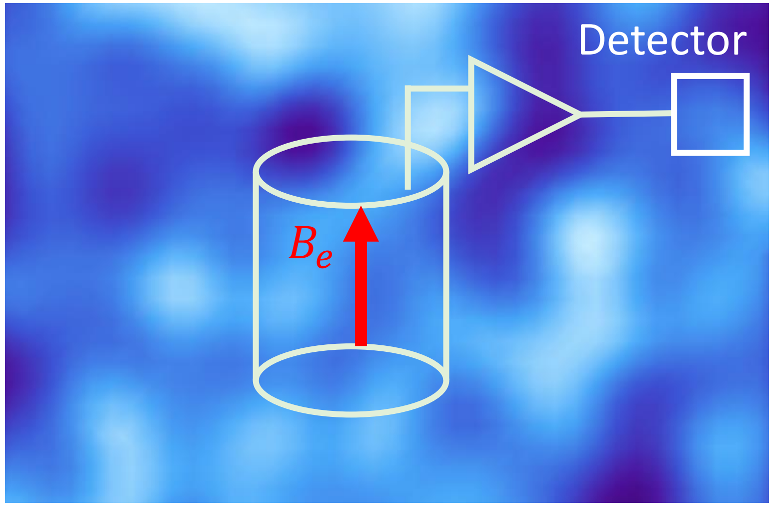


Axion DM halo sources new E and B fields, oscillating at the axion Compton frequency $\omega_a = m_a(c^2+v^2/2)/\hbar$

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

# Signal using a resonant cavity

Imagine some cavity in an external $B_e$ field:



Cavity resonant frequency must be scanned until it matches the unknown axion frequency, then

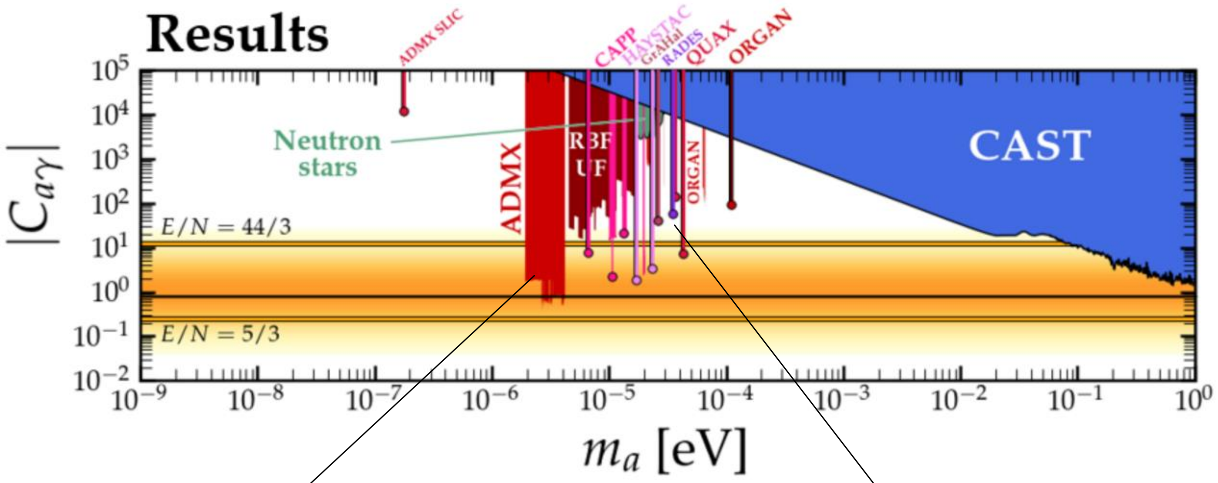
Extracted resonant power at optimum cavity coupling is

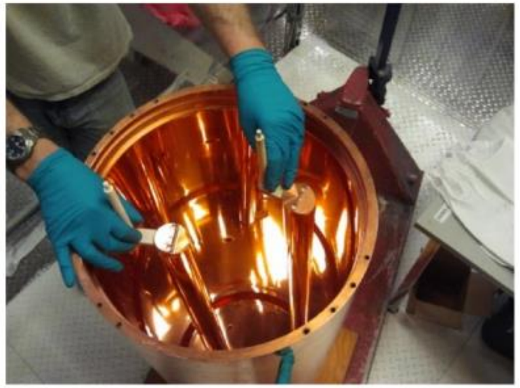
$$\boxed{P = \frac{1}{2} c^2 \epsilon_0 {g_{a\gamma\gamma}}^2 \frac{Q}{\omega} V_m {B_e}^2 \rho_{DM}}$$

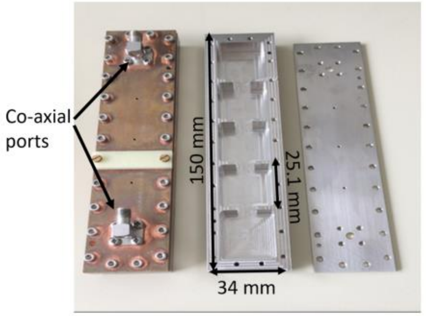
$$V_m = \frac{\left| \int E.B_e dV \right|^2}{\int |E.B_e|^2 dV} \,\tilde{\propto}\, \text{Cavity volume}$$

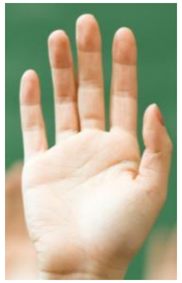
$Q$ : Cavity Q-factor

# How do the cavities look in practice?









ADMX: min frequency ~640 MHz

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)

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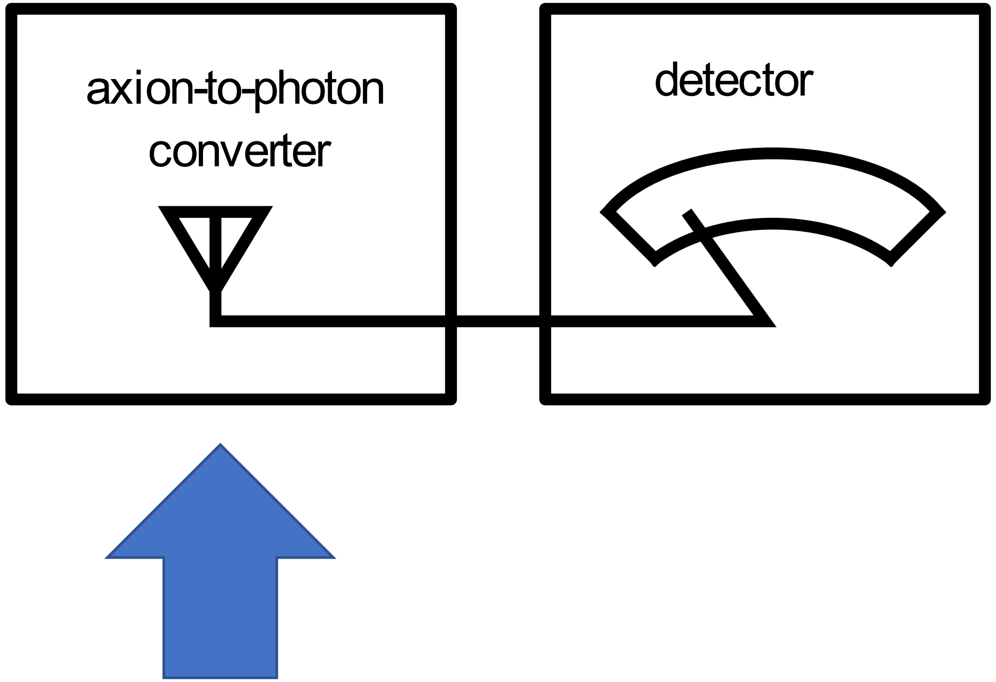
# An axion haloscope



axion-to-photon converter

detector

Problem 1:
Decreasing
volume

# Problem 1: Decreasing volume

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

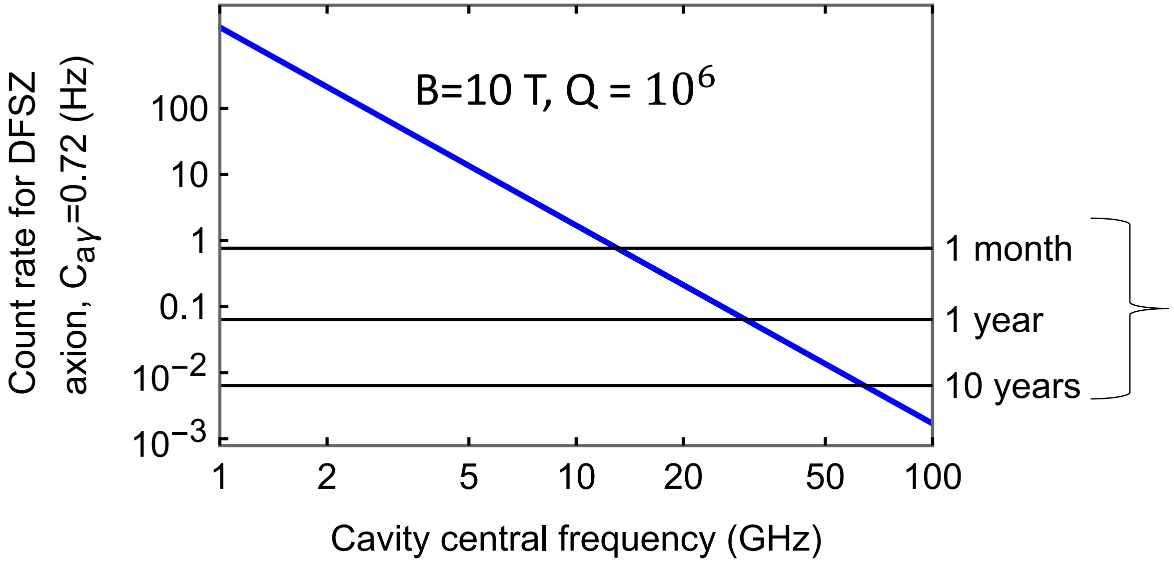
$$P = \frac{1}{2} c^2 \epsilon_0 {g_{a\gamma\gamma}}^2 \frac{Q}{\omega} V_m {B_e}^2 \rho_{DM}$$

$$\text{Rate } [s^{-1}] = 10^{-3} {C_{a\gamma\gamma}}^2 \, Q \, \enclose{circle}{V_m} B^2$$

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

typically, Q ∝ $\frac{1}{{\nu_a}^{2/3}}$ (for copper)

For a cylindrical cavity, DFSZ axion:

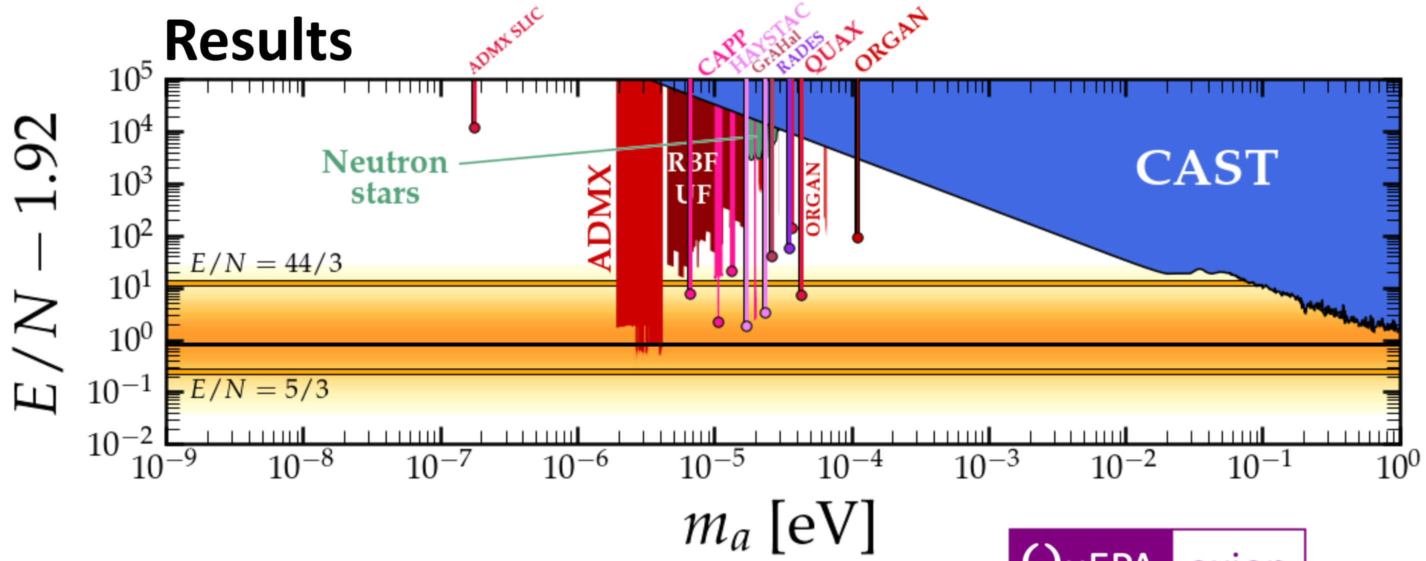


Measurement time to scan $m_a \rightarrow 2m_a$

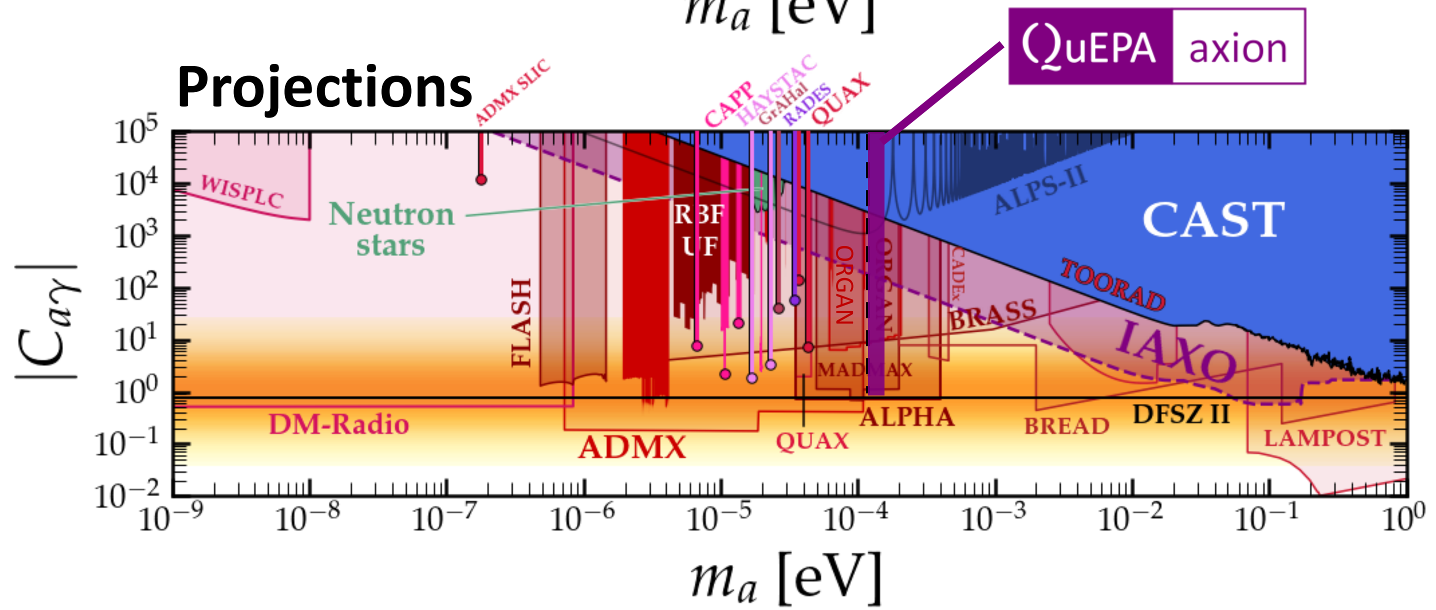
C. Boutan et al., Phys. Rev. Lett. **121** (2018)

# Many creative ideas >30 GHz

**Results**



**Projections**



https://cajohare.github.io/AxionLimits/docs/ap.html

**Dielectric cavities**

| | |
|---|---|
| ORGAN | QDM lab (Univ. Western Australia)<br>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 $m_a$ |

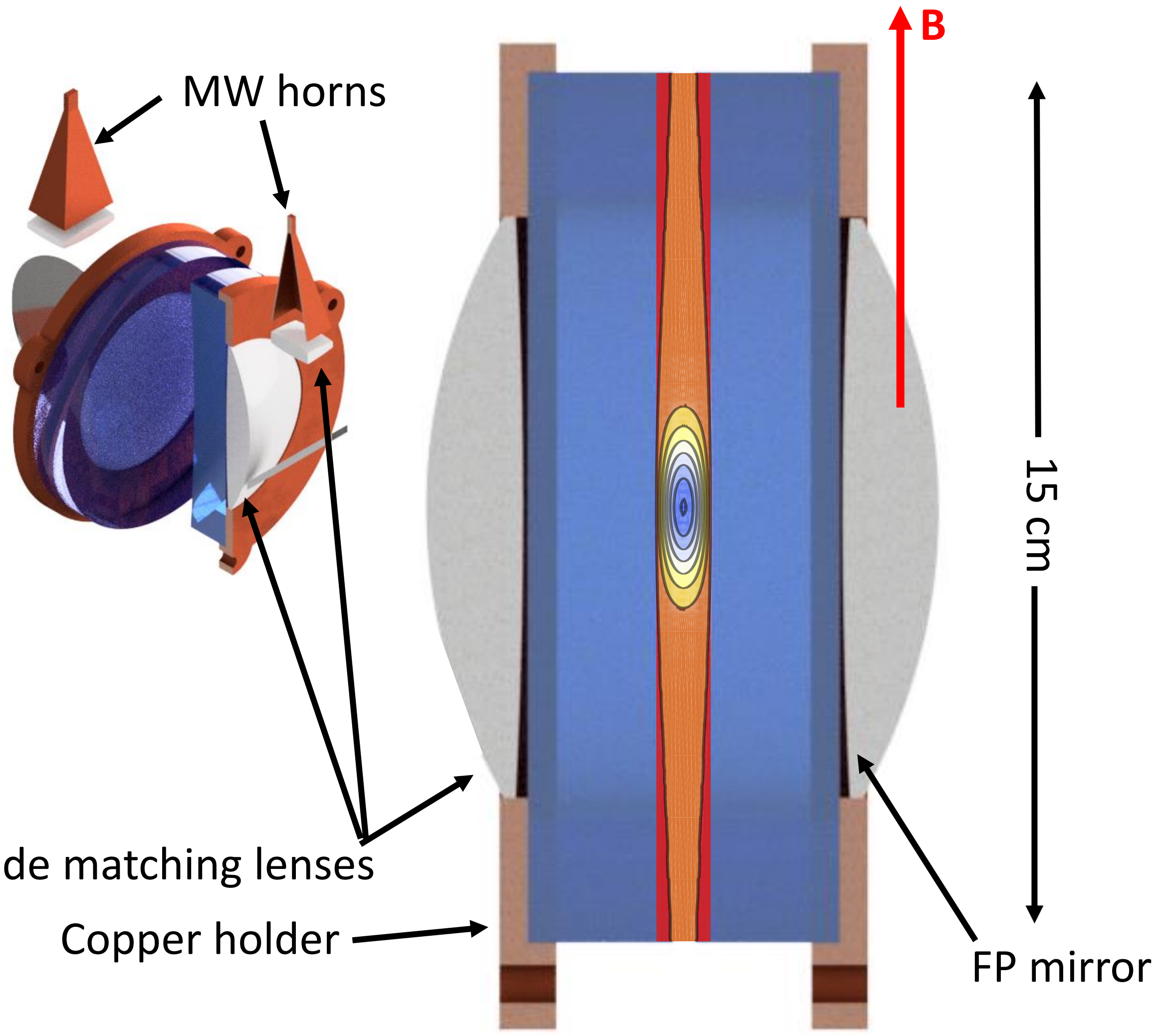
**.. with dielectric boost**

| | |
|---|---|
| MADMAX | Big effort at DESY, lower $m_a$ initially |

**Many, more new ideas between 5-30 GHz**

# Our converter concept

Large mode area Fabry Perot cavity operating in $TEM_{001}$ mode



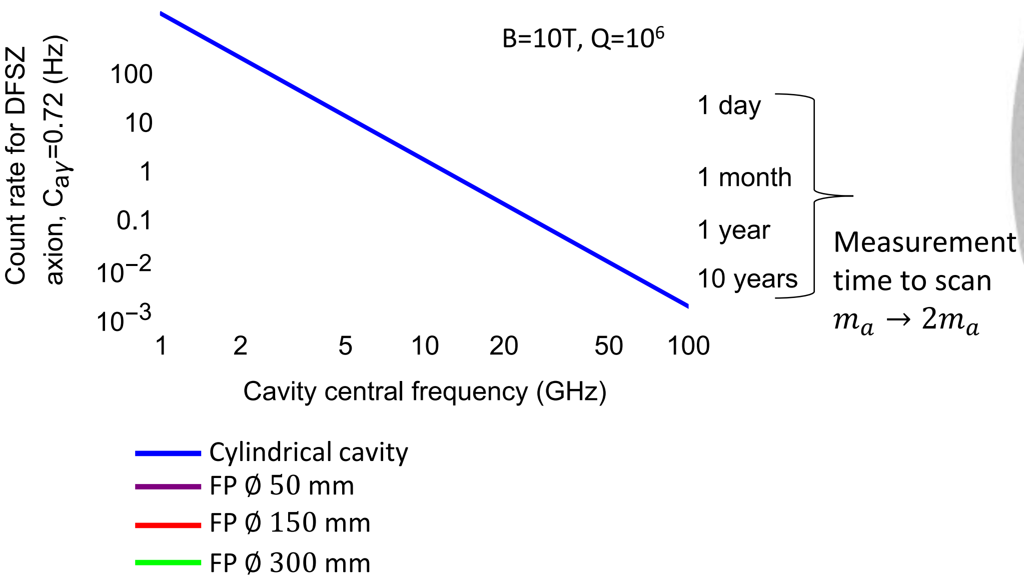
See ORPHEUS for alternative F-P $TEM_{00q}$ concept G. Rybka et al., Phys. Rev. D **91**, 011701 (2015)

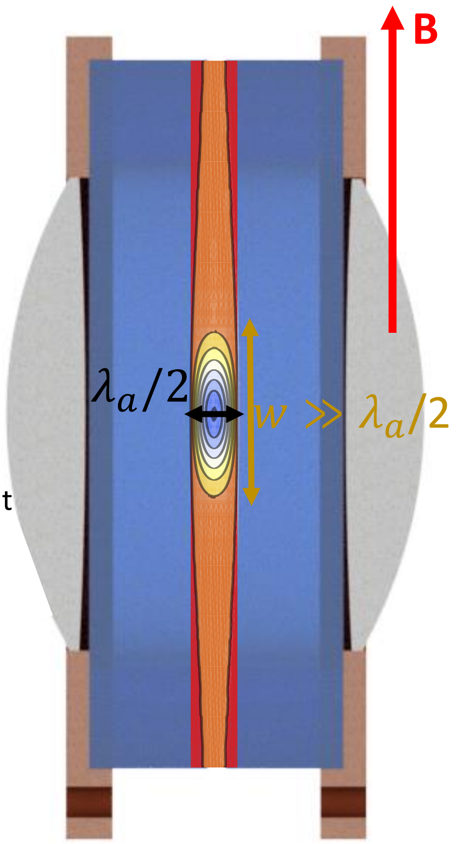
# Why a Fabry Perot?

$$\text{Rate}\,[s^{-1}] = 10^{-3} {C_{a\gamma\gamma}}^2\, V_m Q B^2$$

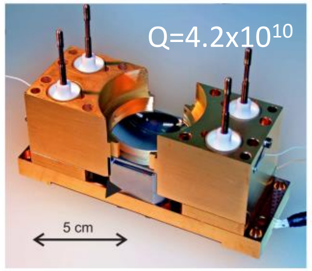
## 1) Favourable $V_m$ scaling with $\nu_a$

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





## 2) High Q possible in this geometry



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

## 3) High B-field compatible

Plan A: Microwave Bragg mirrors, $Q>2.5\times10^5$

J. Krupka et al., IEEE trans. ultra. **52** 9 (2005)

Plan B: B//mirror surface allows

a) High TC YBCO

J. Golm et al., arXiv:2110.01296

b) Sapphire/NbTi multilayer

X. Xi et al., PRL **105**, 257006 (2010)

Other considerations: Frequency adjustment easy, relatively compact, broad tuning range

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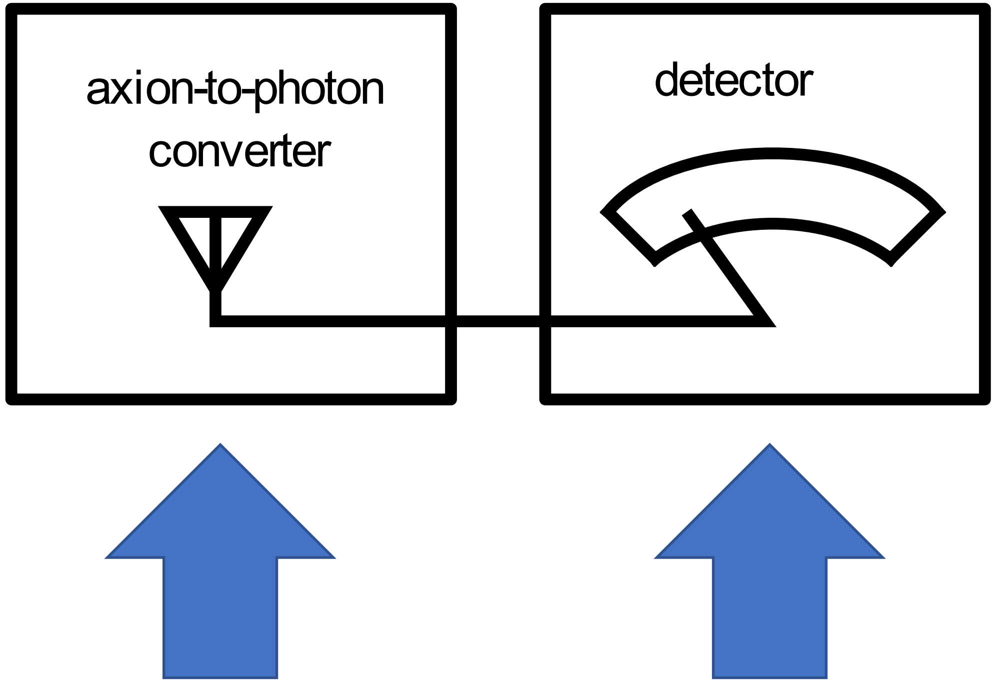


axion-to-photon converter

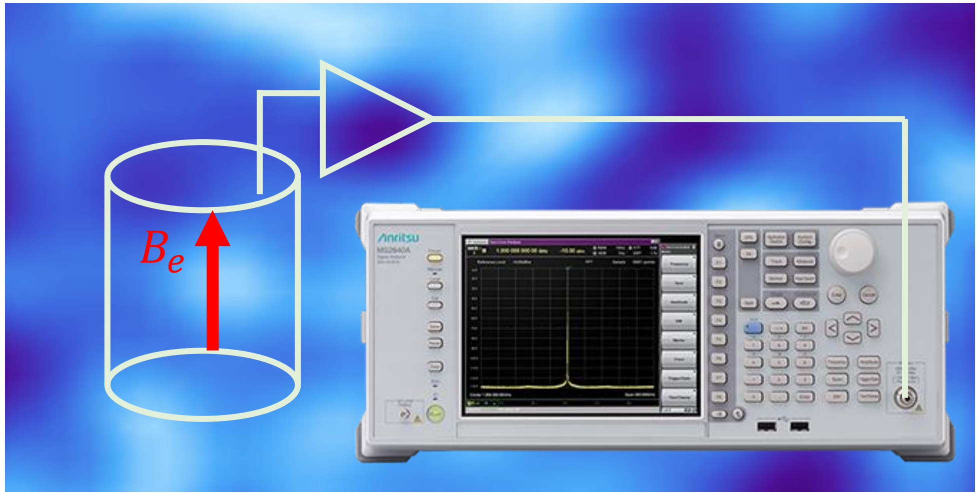
detector

Problem 1:
Decreasing
volume

Problem 2:
Increasing
noise

# Problem 2: Increasing noise

Classical readout: linearly amplify signal and use a signal analyzer



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

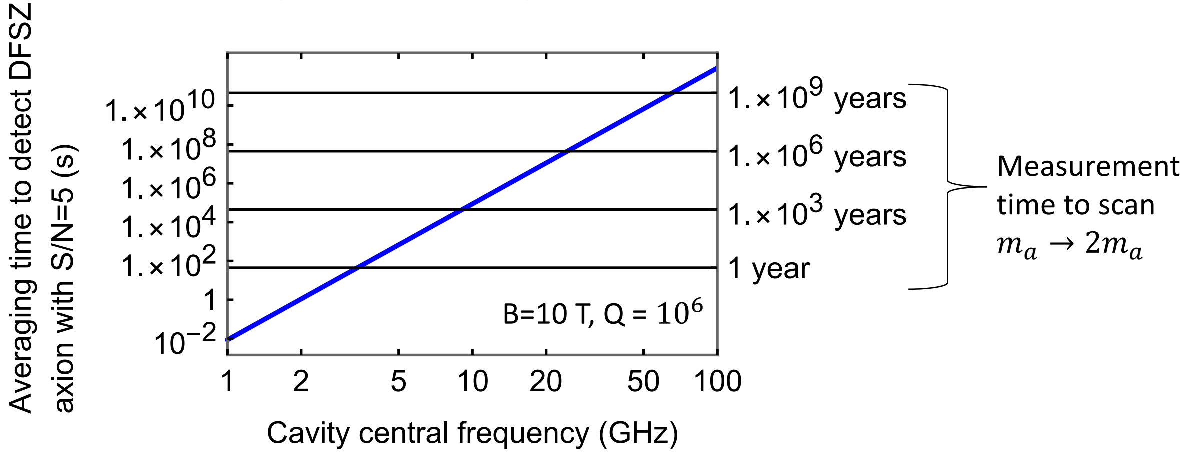
Noise from finite temperature

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

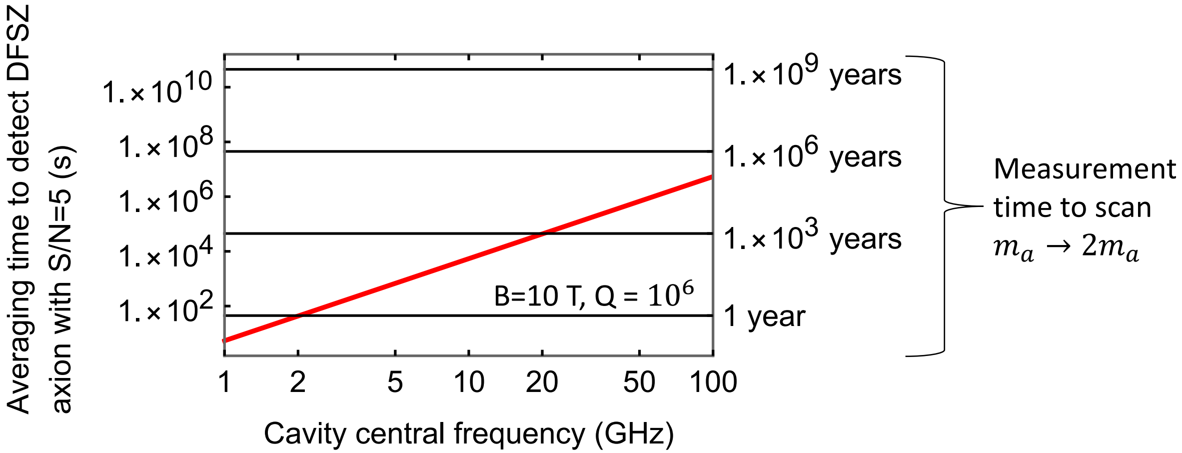
Fundamental quantum amplification noise limit

Standard Quantum Limit (SQL)

For a cylindrical cavity, DFSZ axion



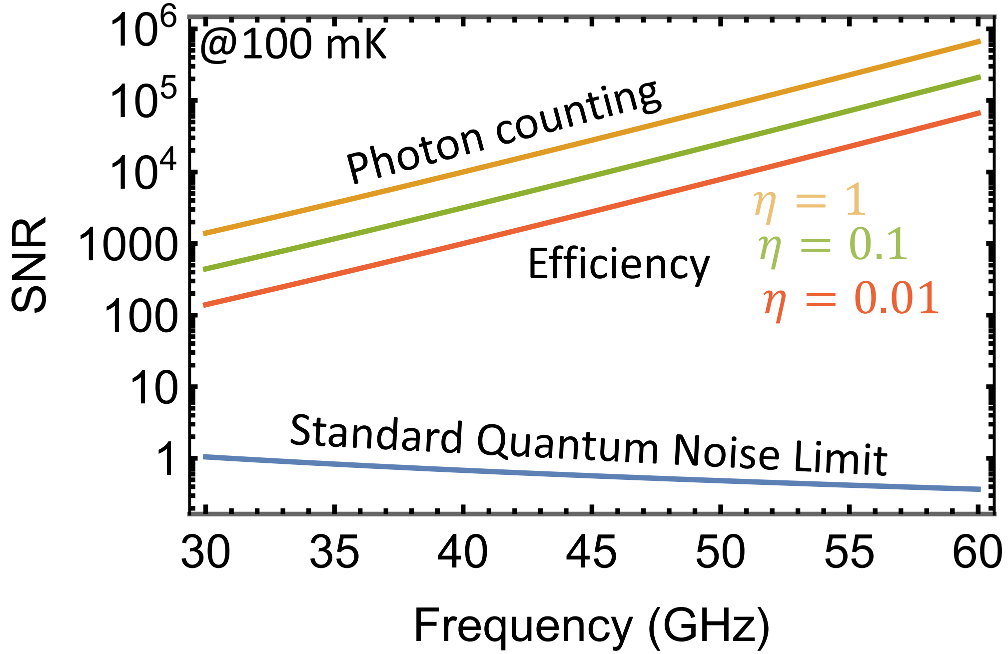
Just the noise contribution, imagine the volume didn't decrease



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

# Solution: Count photons to beat SQL

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

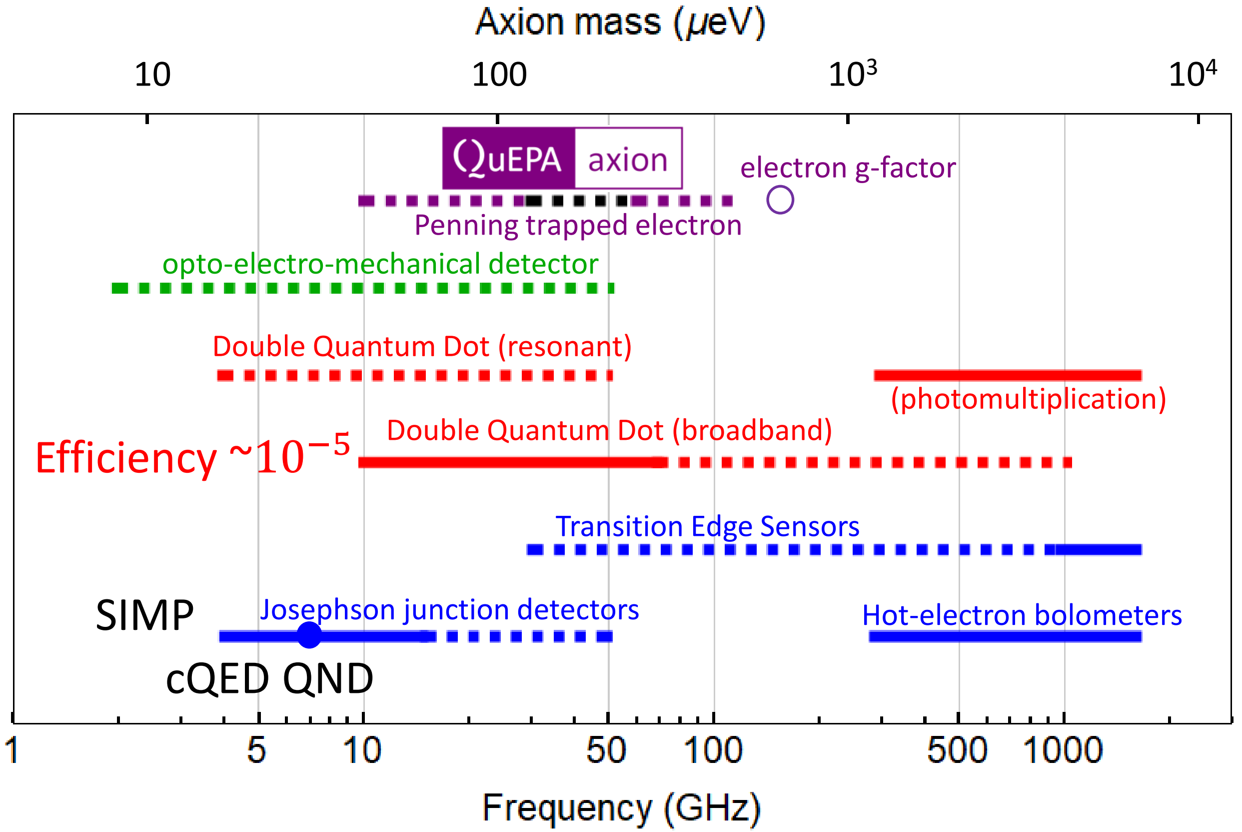


S. K. Lamoreaux, et al., Phys. Rev. D **88**, 035020 (2013)

# Options for single photon counting

## Solid-state devices

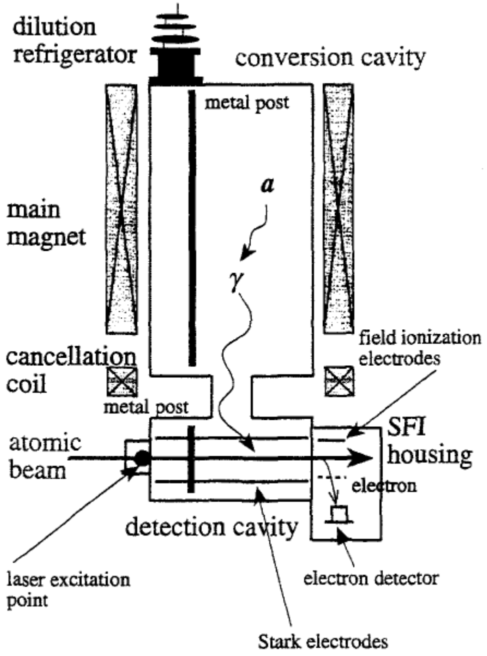
At 100-300 GHz LCKIDs are used for astrophysics
(not single photon sensitivity)

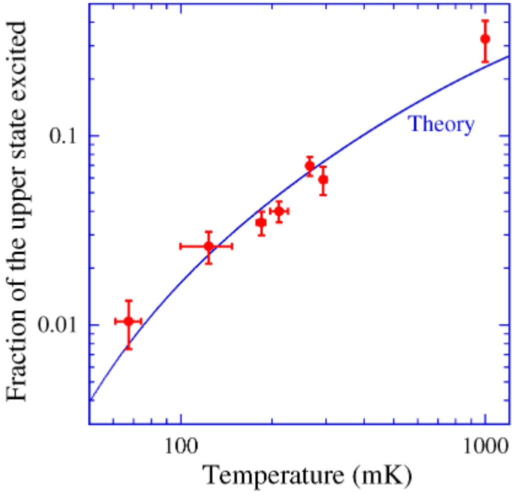


A. V. Dixit, et al., Phys. Rev. Lett. **126** 141302 (2021)
A. Ghirri et al., Sensors **20(14)**, 4010 (2020)

## Alternative AMO devices

### CARRACK I & II Rydberg atoms





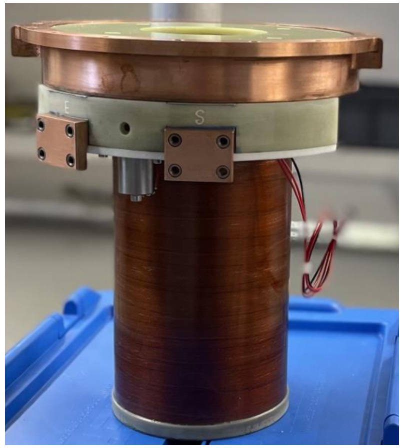
Good performance, ultimately effort was not sustained

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

M. Tada et al., Nuclear Physics B (Proc. Suppl.) **72** 164 (1999)
M. Tada et al., Physics Letters A **349 6** 488 (2006)

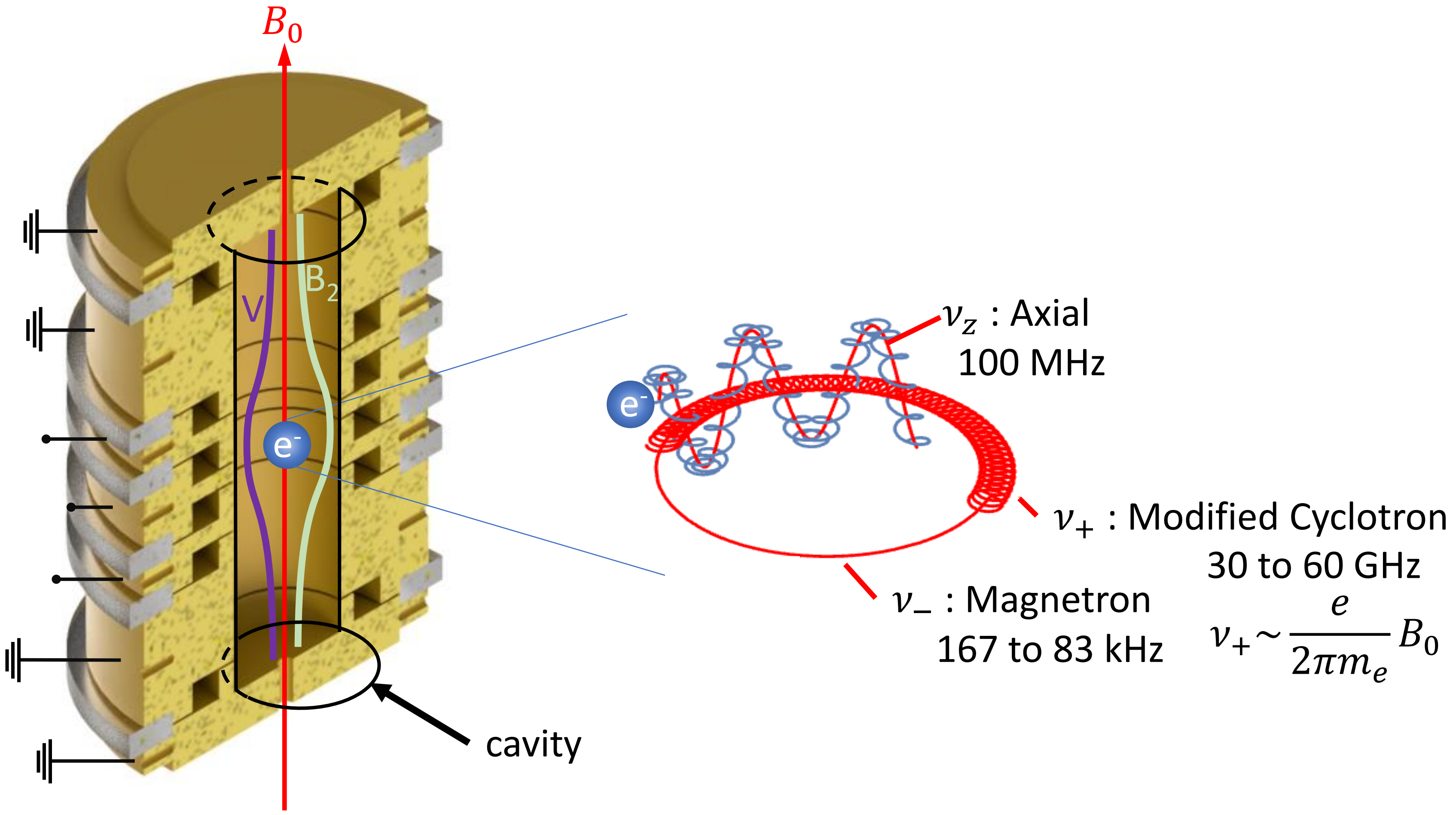
# Enter the Penning trap

1-2 T B field from solenoid



Voltages applied to
ring-shaped electrodes

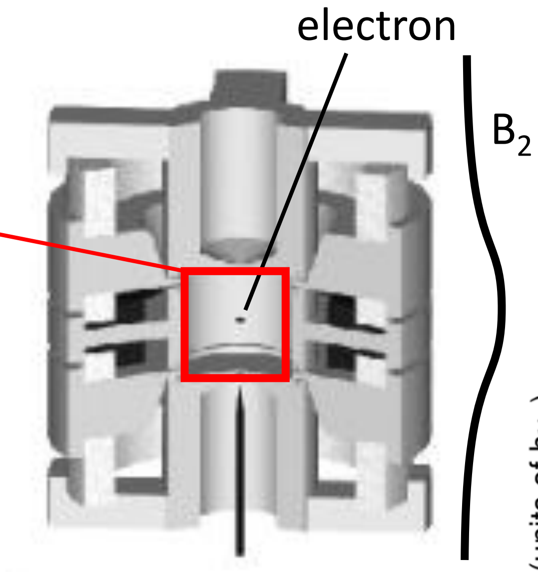
A Penning trap with integrated microwave cavity



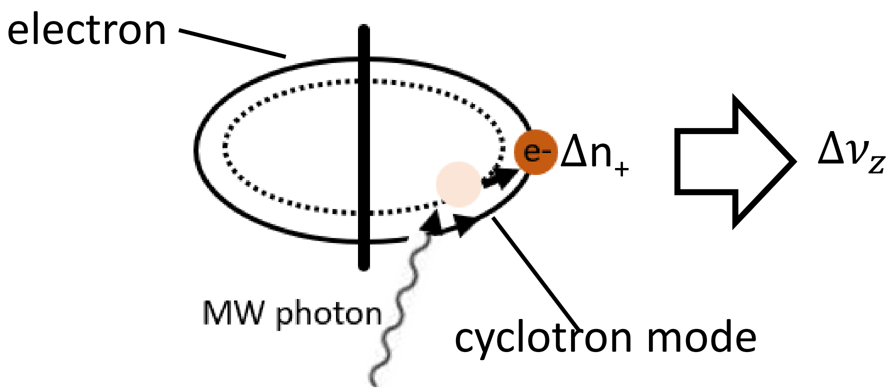
$$\nu_+ \sim \frac{e}{2\pi m_e} B_0$$

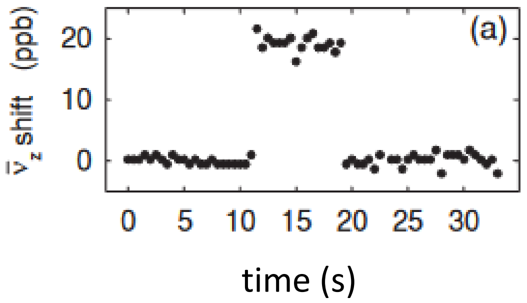
# Detecting photons with a single trapped electron

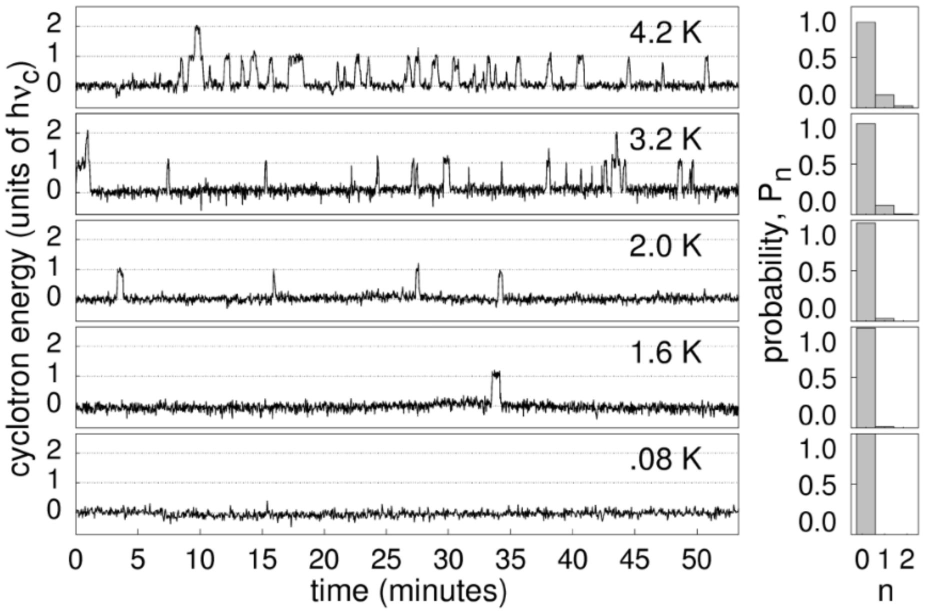
Fixed frequency Cylindrical cavity
far off resonant with cyclotron frequency
Suppresses spontaneous emission



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

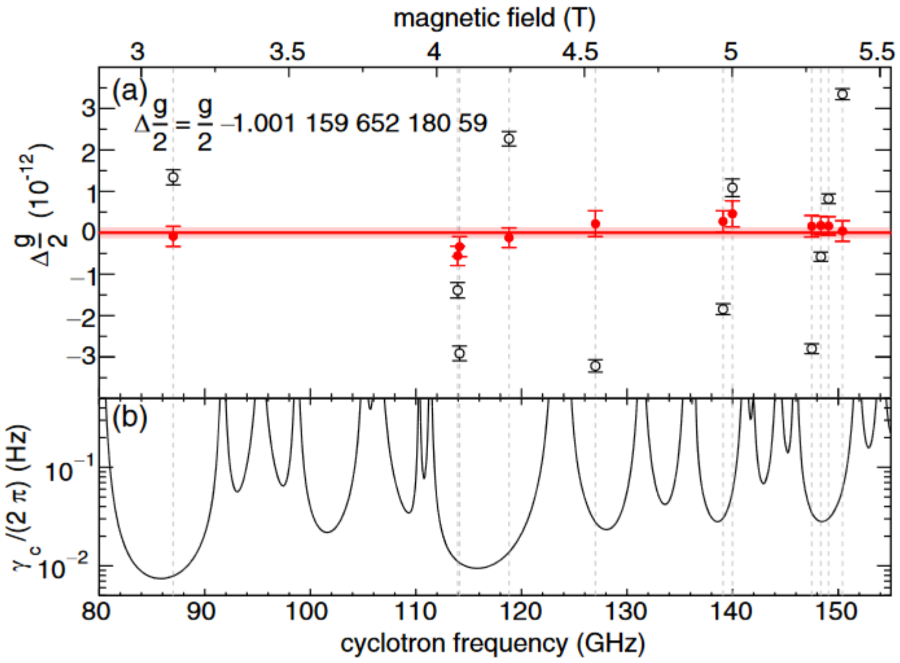






S. Peil and G. Gabrielse Phys. Rev. Lett. **83**, 1287 (1999)
D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, PRA **83**, 052122 (2011)

# Turning this into an efficient, frequency adjustable, photon counter

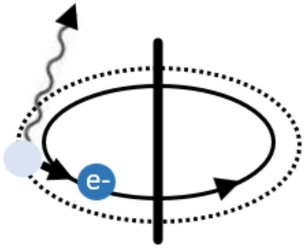


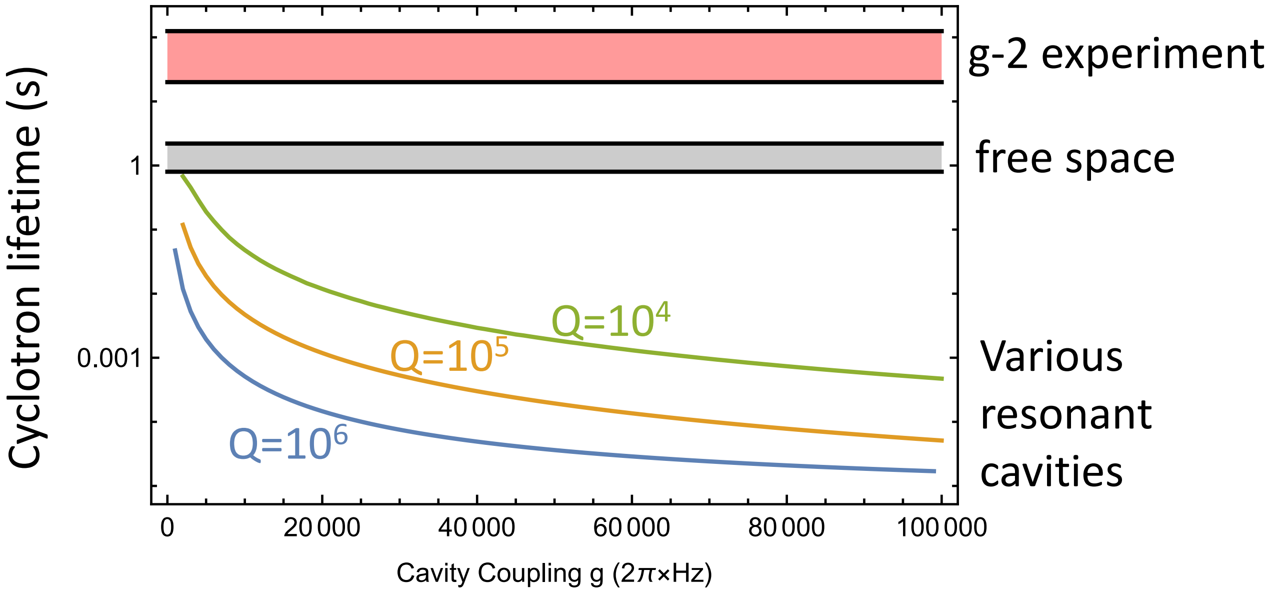
In the electron g-2 measurement, cyclotron frequency deliberately tuned far off resonance to inhibit spontaneous emission.

Can't use this as a single photon counter: far off resonant cavity will reflect almost all incoming photons

X. Fan et al., PRL **130** 071801 (2023)

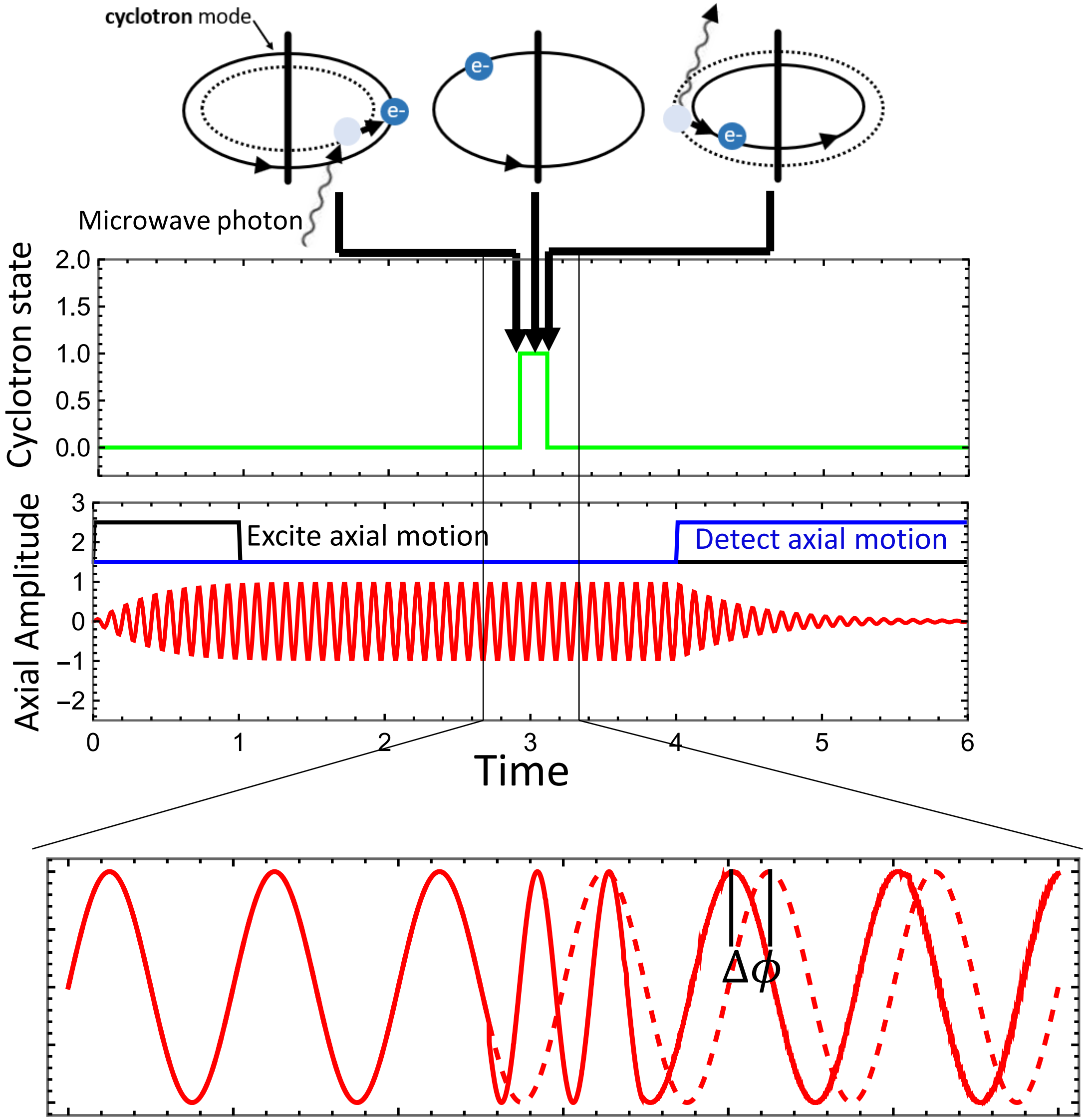
Need to operate on-resonance, but then cyclotron lifetime reduced:





Much faster axial frequency detection method is needed

# Fast phase sensitive detection



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

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

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

$\langle t\rangle$ = cyclotron lifetime

E. A. Cornell et al., PRA **41** 312 (1990)
S. Stahl et al., J. Phy. B **38** 297 (2005)

# Absorption efficiency and detection probability

The photon-electron interaction can be treated with simple Cavity QED model for coupled harmonic oscillators

$$H = H_0 + H_{int}$$

$$H_0 = \hbar\omega_+\left(b^\dagger b + \tfrac{1}{2}\right) + \hbar\omega\left(a^\dagger a + \tfrac{1}{2}\right)$$

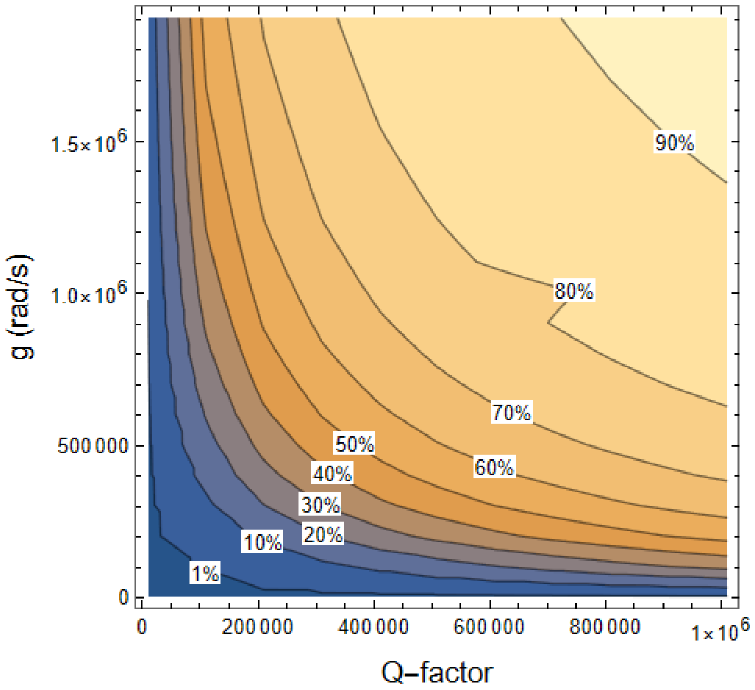
$$H_{int} = \hbar g\left(ab^\dagger + a^\dagger b\right)$$

$$g = e\sqrt{\frac{1}{2\epsilon_0 m_e \tilde{V}}}$$

$$\tilde{V} = \frac{\int |E|^2\, dV}{|E(0,0)|^2}$$

$$\dot{\rho} = -\frac{i}{\hbar}[H_{int}, \rho] + \frac{\omega_+}{Q}\mathcal{L}[\rho]$$

Absorption probability



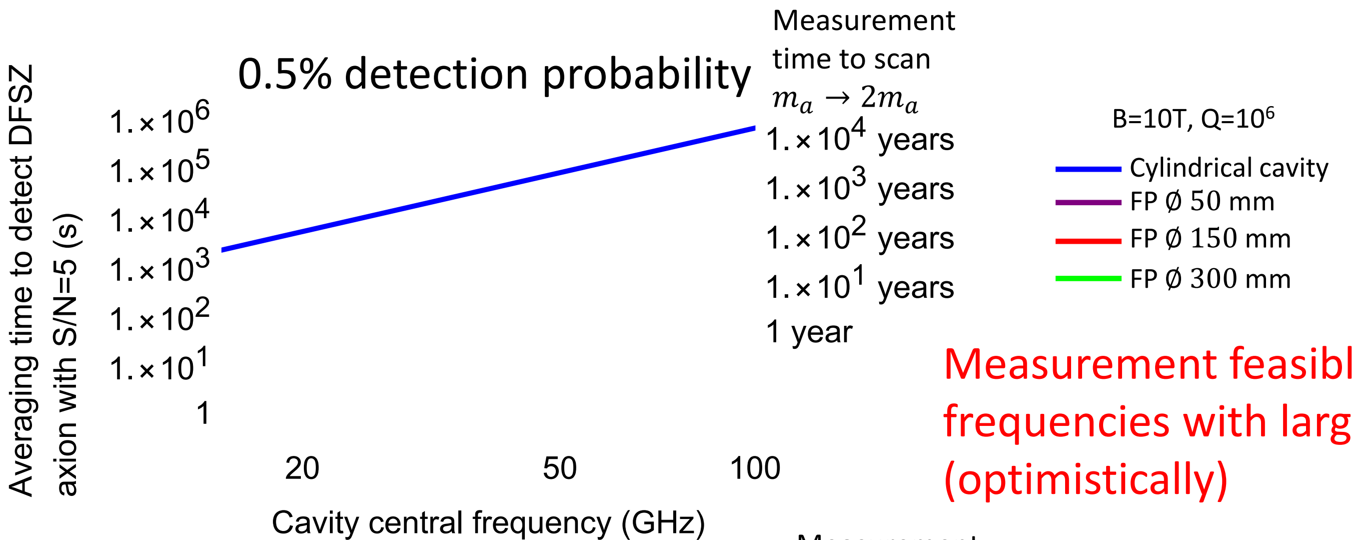
Short term aim:
Q=100,000 at 30 GHz
$g = 2\pi \times 11{,}000$ Hz

Cyclotron lifetime: 1 ms
B2 = 82,000 T/$m^2$

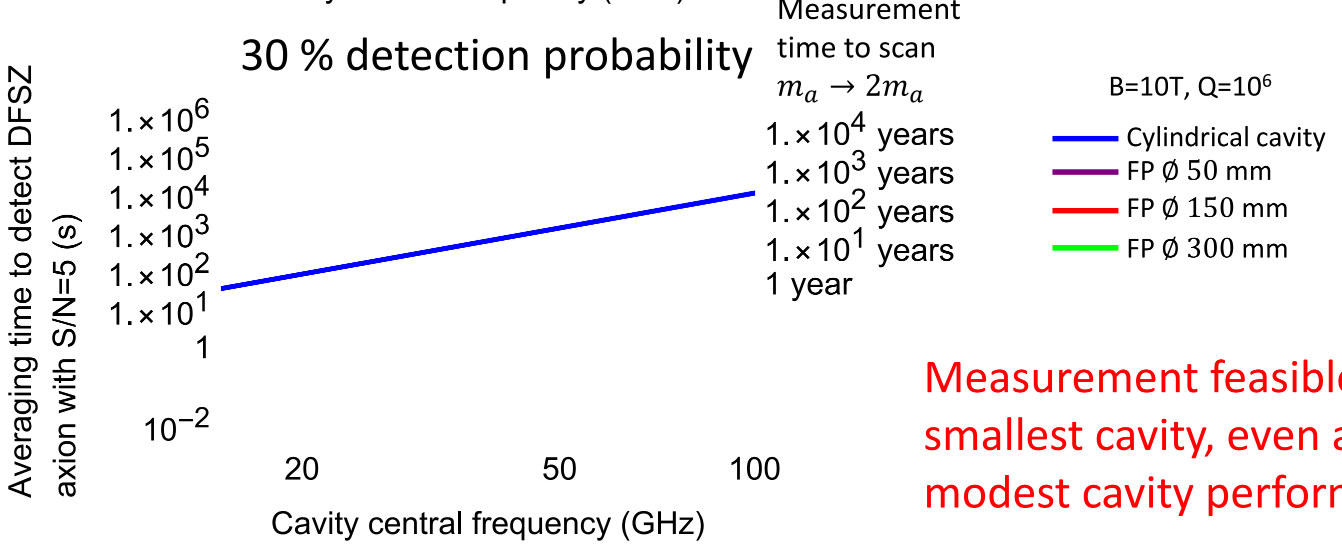
Overall detection efficiency ~0.5%

Longer term aim:
Increase Q to $10^6$
Work with small clouds of particles
B2>500,000 T/$m^2$
Overall detection efficiency >30%

# Even modest detection efficiencies are useful



Measurement feasible at lower frequencies with largest cavity (optimistically)



Measurement feasible with smallest cavity, even at more modest cavity performance

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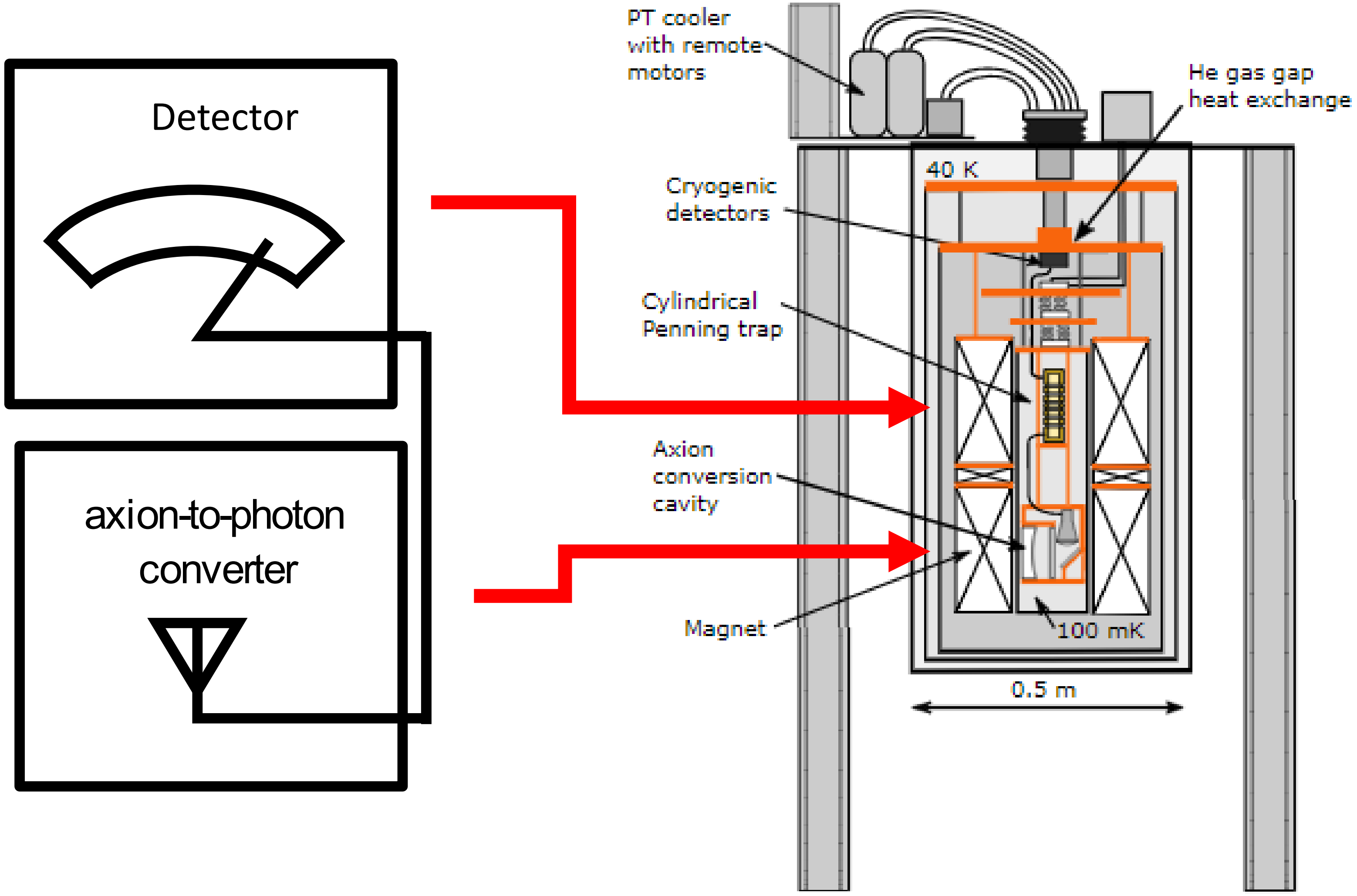
1. Why QCD axions?
2. Detection techniques
3. Challenges for high $m_a$ haloscopes – and how we plan to solve them
    a) Volume problem
    b) Noise problem
4. Long term goals and other measurements

# The eventual experiment



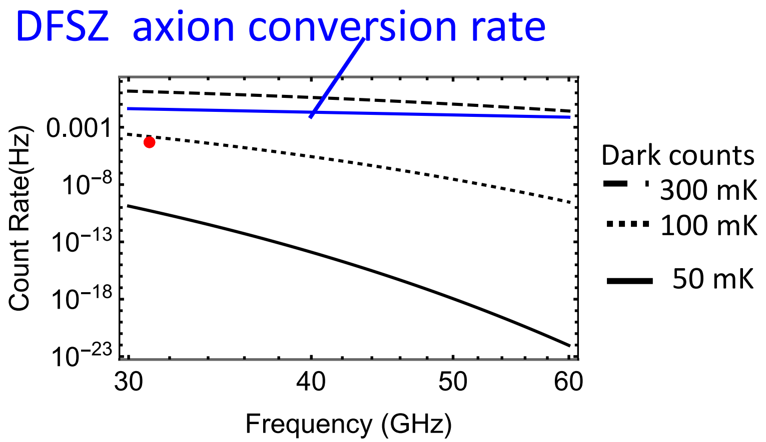
# Some long term numbers

## Axion production cavity assumptions

| Parameter | Value | Why? |
|---|---|---|
| Q | 250,000 | Calculated Bragg mirror |
| B | 7 T | Modest large bore Nb-Ti magnet field |
| Mirror diameter | 15 cm | Standard semiconductor substrate size |
| Mirror radius of curvature | 1 m | $g_{max} = 0.9975$<br>$w_{max} = 1.5$ cm = d/10<br>$\Delta f_{\mathrm{min}} \frac{Q}{f} = 4 * 10^3$ |
| In-coupling losses | 50 % | Modest mode mismatch |

## Photon counting assumption

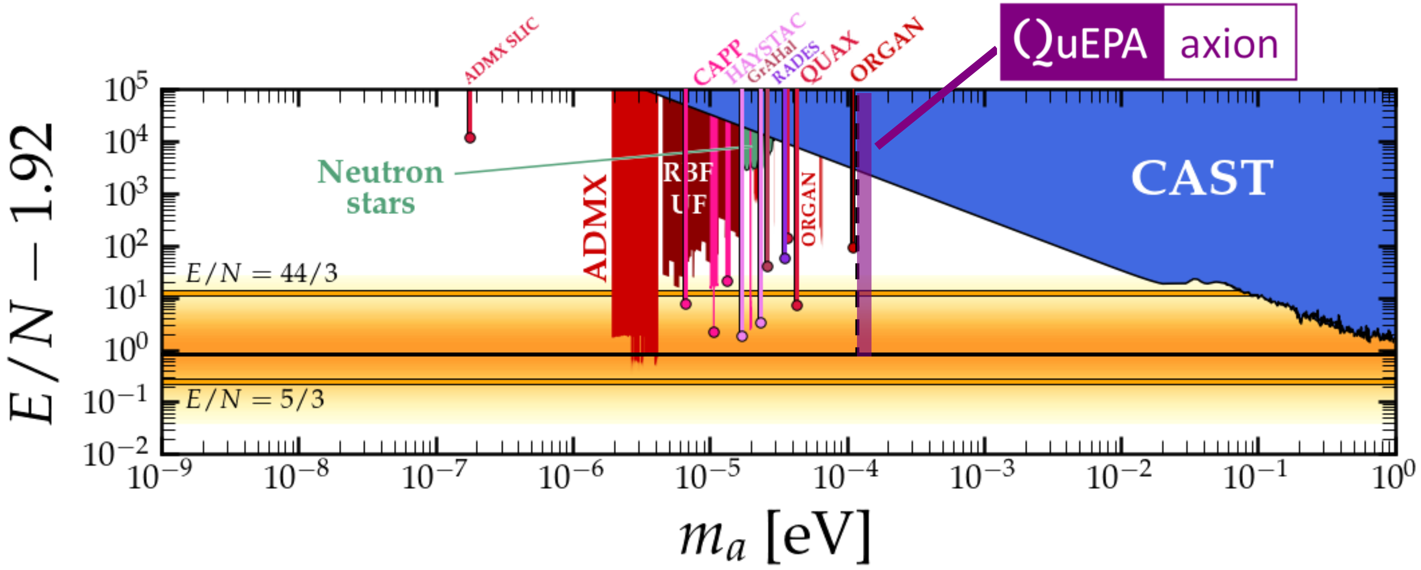
| Parameter | Value | Why? |
|---|---|---|
| Q | 10^6 | Cavity limits |
| Missed fraction | 5 % | < 1 ppm axial stability |


DFSZ axion conversion rate

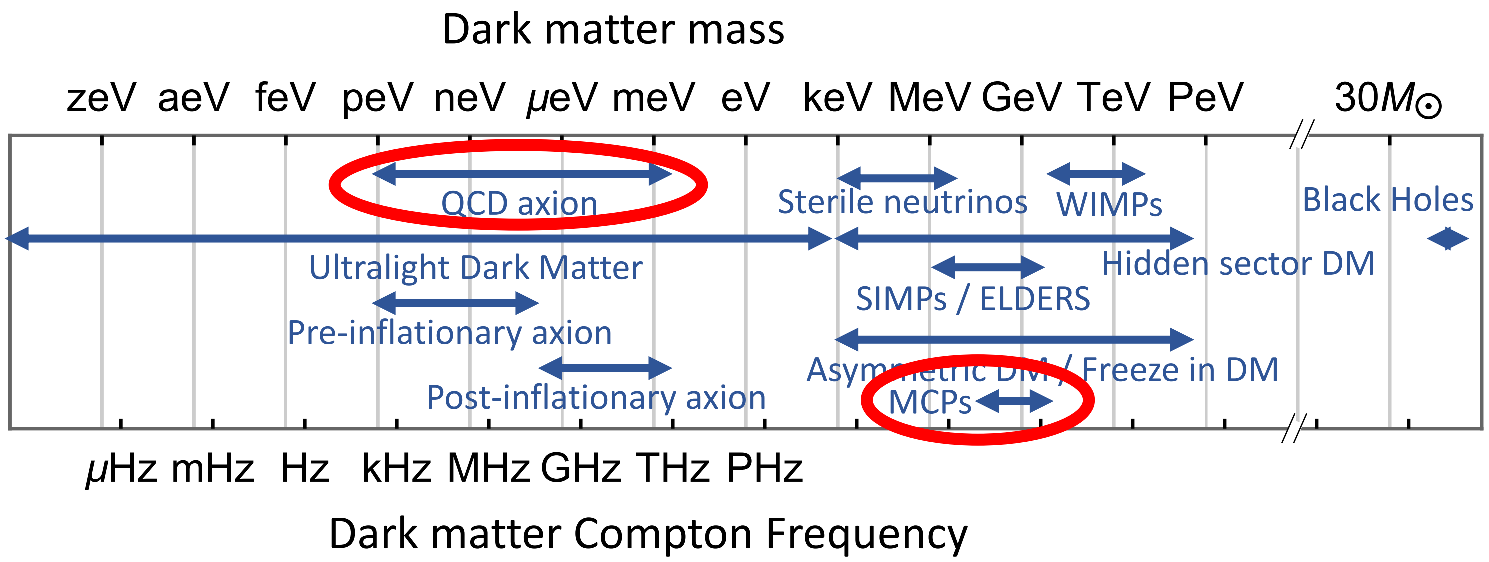
Goal

$m_a = 120 \leftrightarrow 160\ \mu eV$

@ DFSZ sensitivity with about 5 years scanning time



# Many, many dark matter candidates

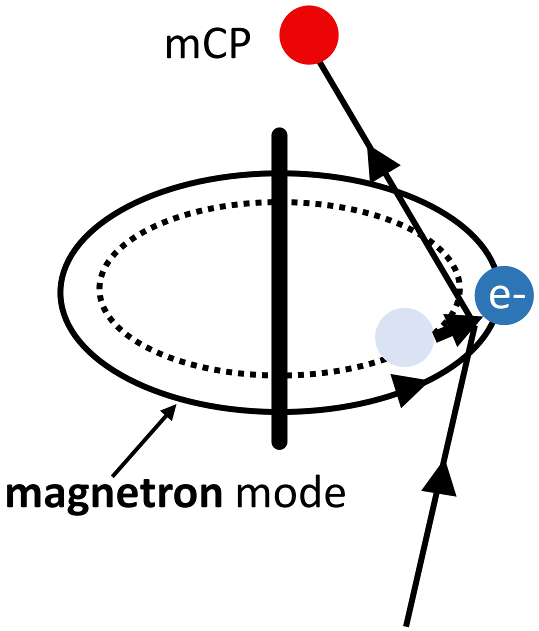


Not all listed…

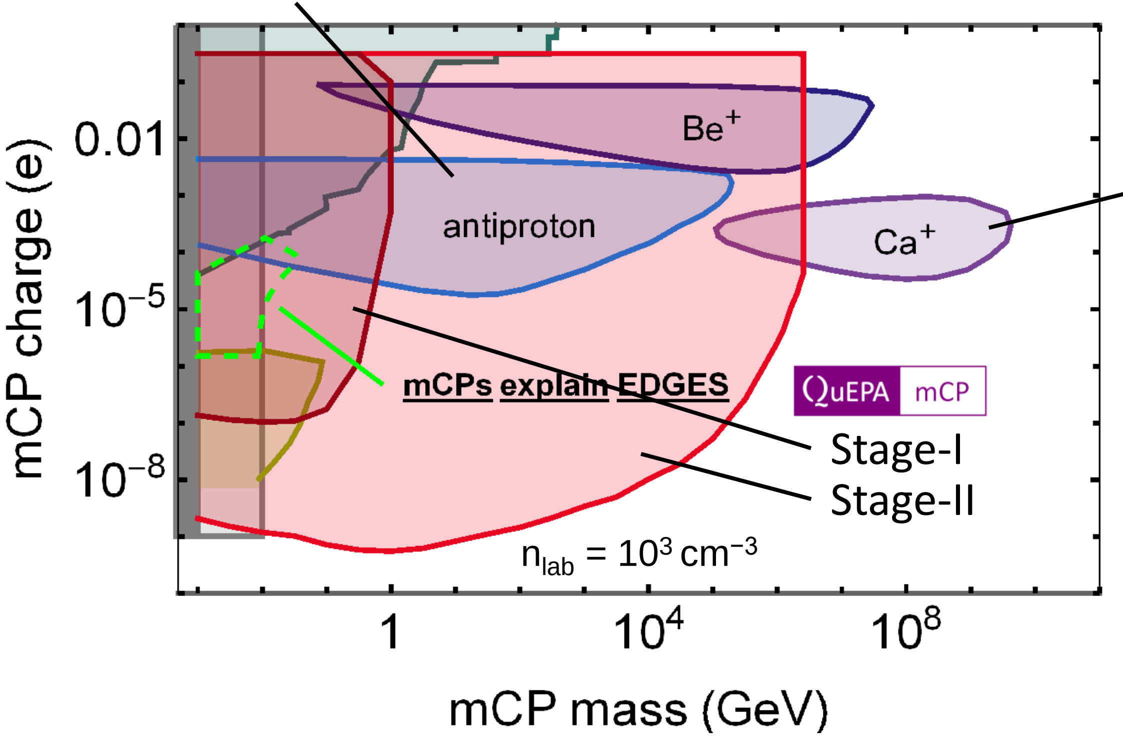
Figure adapted from
US Cosmic Visions: New Ideas in Dark Matter 2017 arXiv:1707.04591

# Other applications – millicharged particles

Look for collisions between millicharged particles (mCPs) and electrons that change the magnetron mode



Ultralow heating rates in Penning traps
M. J. Borchert, et al., PRL **122**, 043201 (2019).



Imperial College London

Stage-I: magnetron heating, cyclotron coupling
Stage-II: cyclotron-magnetron coupling to resolve lower heating rates

D. Budker et al., PRX QUANTUM **3**, 010330 (2022)

D. Carney et al., Phys. Rev. Lett. **127**, 6 (2022)

# Thank you listening

Any Questions?

Also involved in
this work

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