A new search for dark matter axions using quantum technologies

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Imperial College London

DMUK meeting
22/9/2022

QuEPA Imperial College London THE ROYAL SOCIETY UKRI Science and Technology Facilities Council

Who we are

QuEPA **Q**uantum **E**nhanced **P**article **A**strophysics

QuEPA axion — Axion search in the EHF band

QuEPA mCP — Millicharged particle search

} In preparation

Project started 1/9/2022

Local Team

Jack Devlin

PI

David Pitman

Mechanical Engineer

Richard Thompson

Penning trap expert

Norbert Klein

Microwave expert

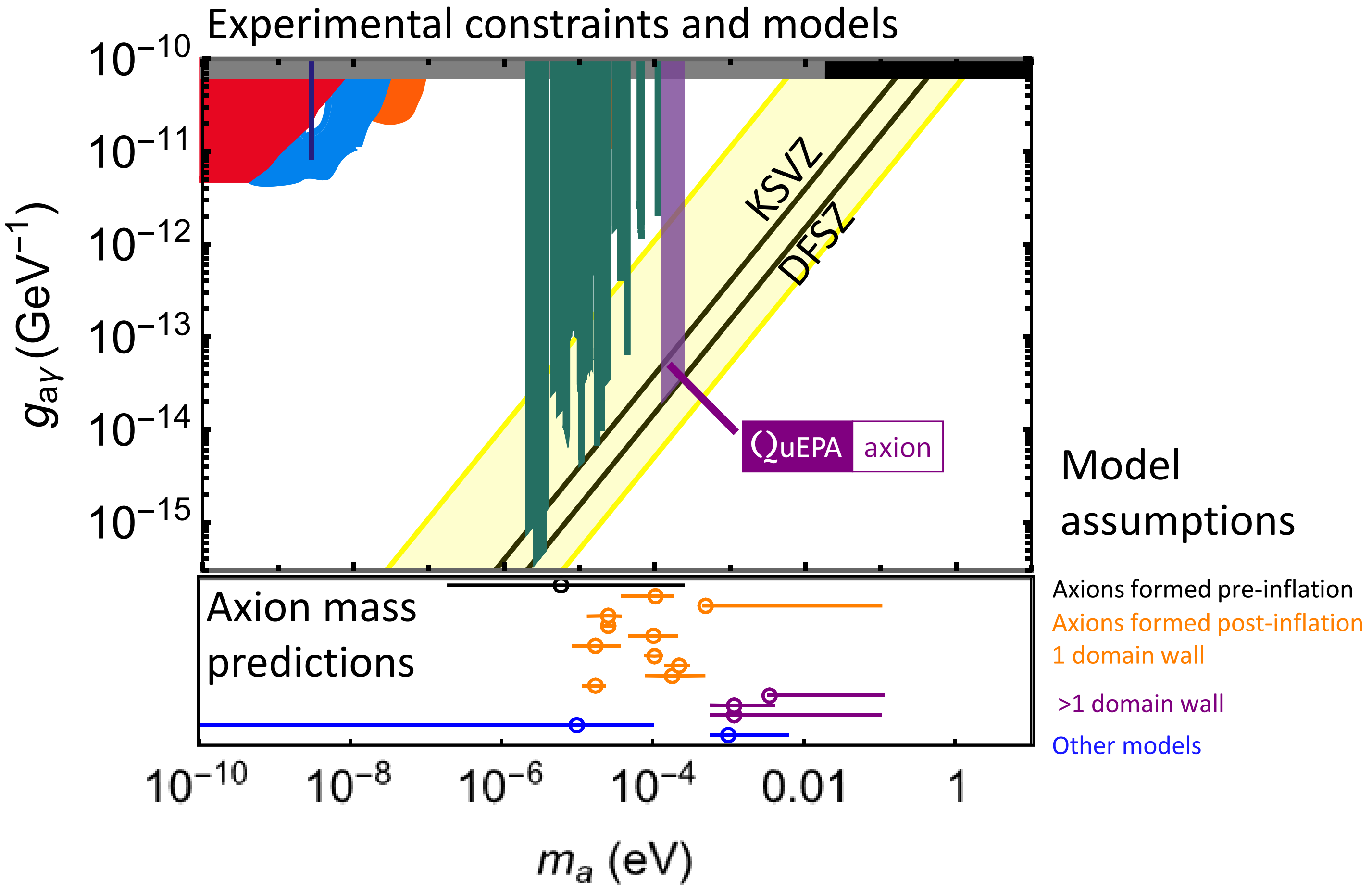
Support

Mike Tarbutt

Quantum Science and Fundamental Physics

Imperial College London

Overview



Use tools of AMO physics to search for axions

Medium term

$m_a = 120 \leftrightarrow 240\ \mu eV$

@ DFSZ sensitivity

Figure adapted from:
G. Irastorza and J. Redondo, Prog. Part. Nucl. Phys. **102**, 89 (2018).
Additions from https://cajohare.github.io

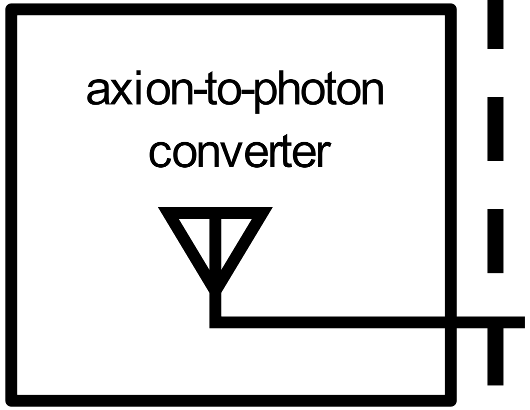
An axion haloscope

Converter $m_a \rightarrow \nu_a = m_a c^2/h$

$$P_{out} = \frac{\hbar \rho_{DM} {g_{a\gamma\gamma}}^2}{c^3 \mu_0 m_a} \times B^2 V_m Q$$

<u>Desirable</u>

- High volume factor
- Q-factor up to Q_a =10^6
- High B field compatible
- Easy to adjust frequency
- Broad tuning range
- Feasible

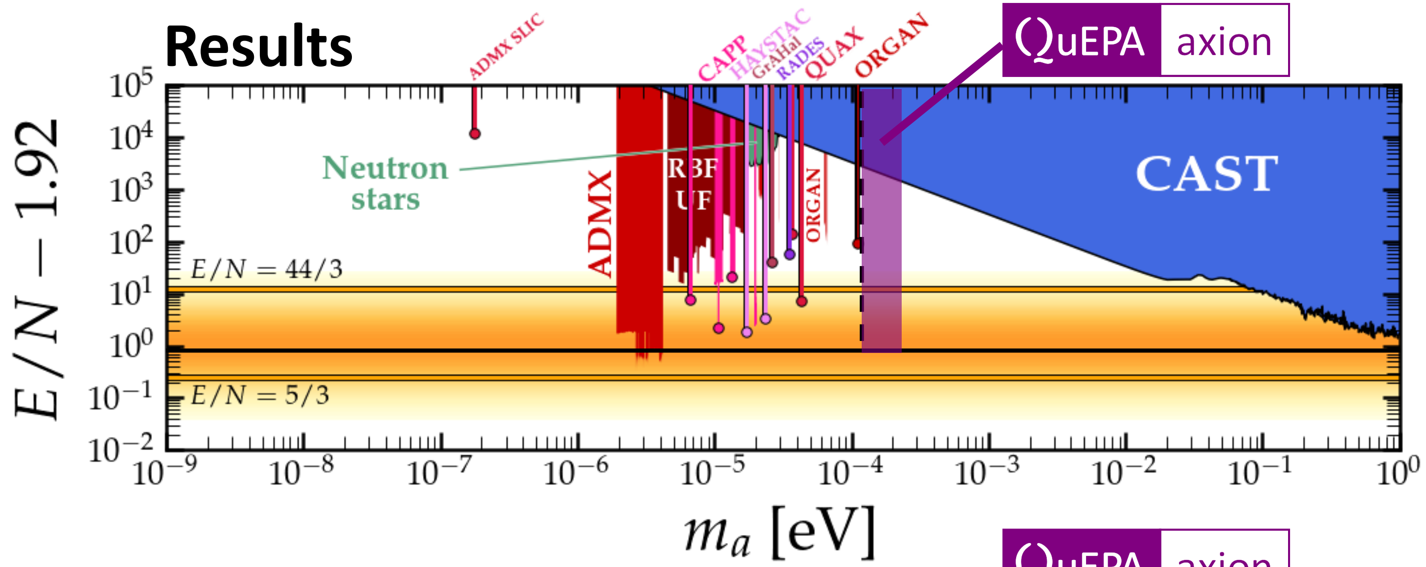


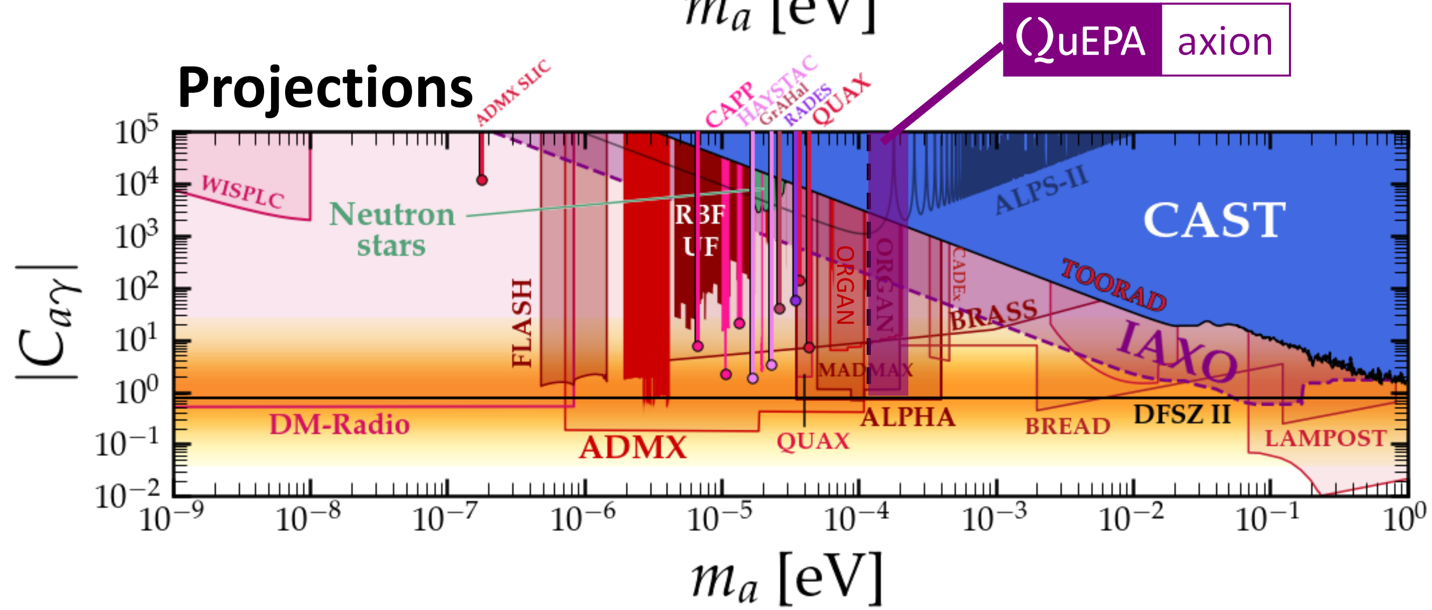
<u>Why hard at higher masses/frequencies?</u>

Typically $V_m \propto \frac{1}{{\nu_a}^3}$, Q $\propto \frac{1}{{\nu_a}^{2/3}}$ (for copper)

G. Rybka et al., Phys. Rev. D **91**, 011701 (2015)

Other axion-photon converter efforts above 30 GHz





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

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

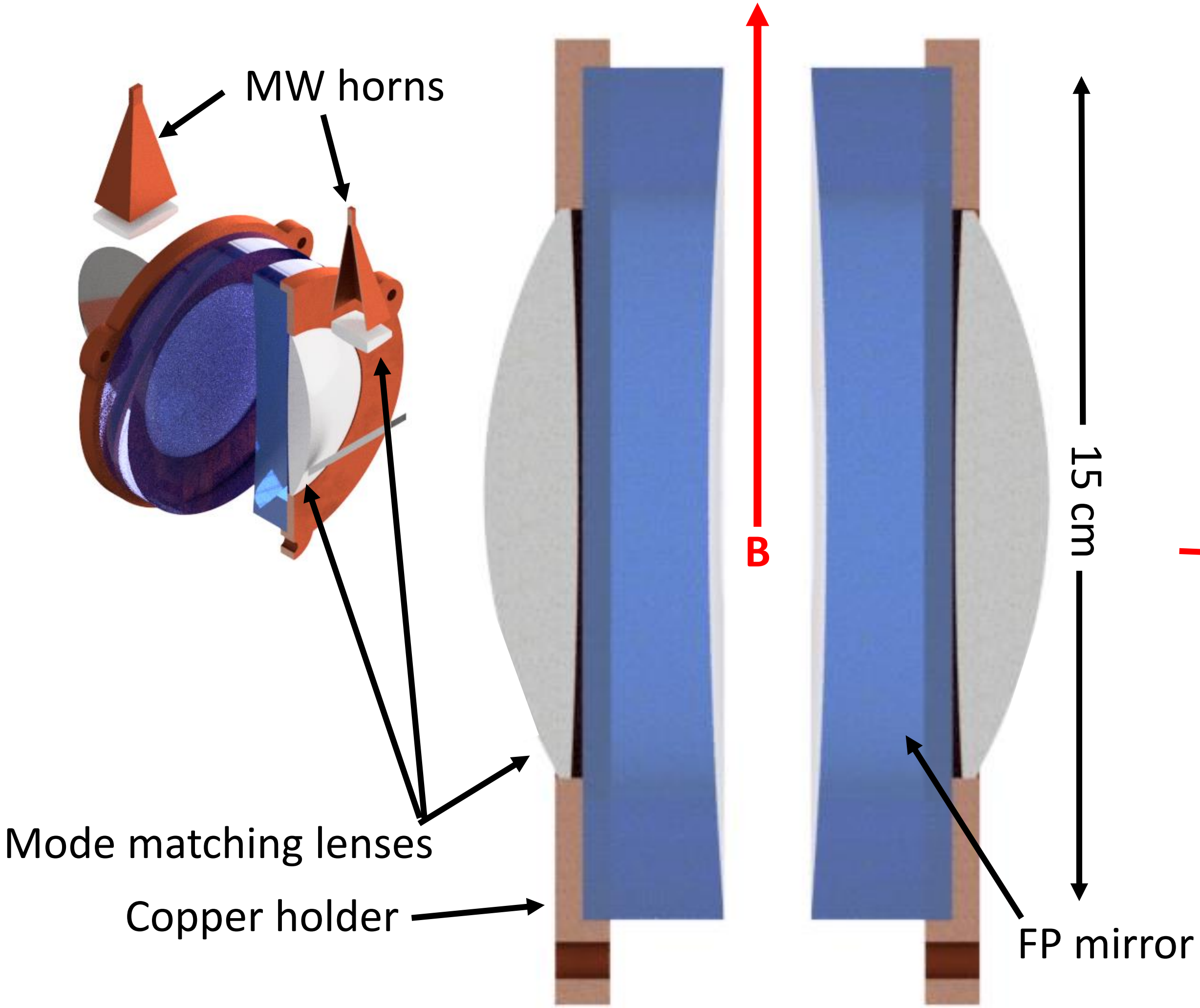
.. with dielectric boost

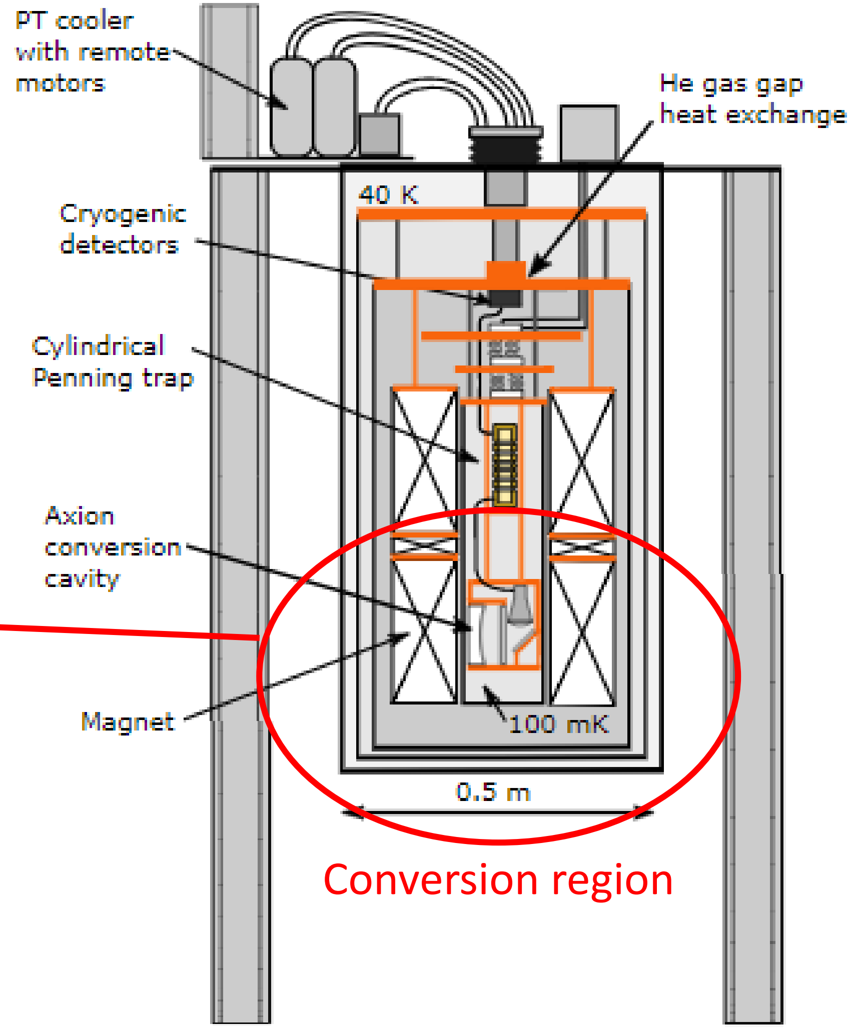
MADMAX Big effort at DESY, lower m_a initially

Many more new ideas between 5-30 GHz

Our converter concept

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



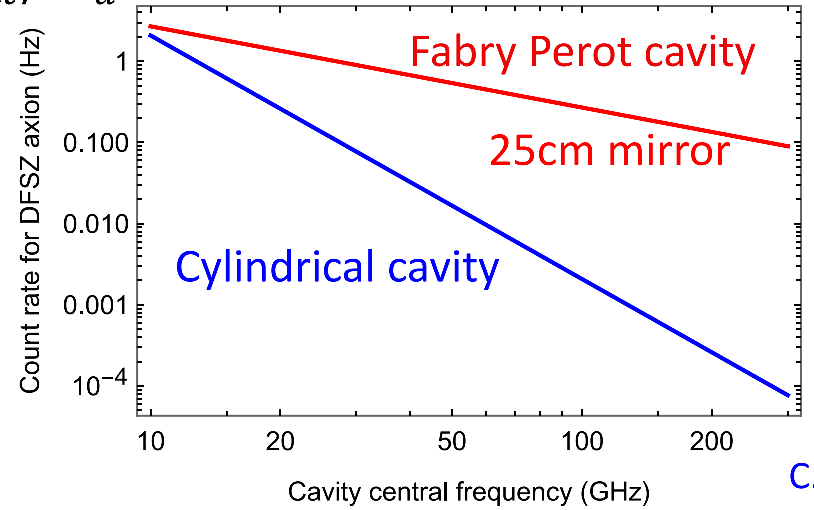


See ORPHEUS for alternative F-P TEM_{00q} concept G. Rybka et al., Phys. Rev. D **91**, 011701 (2015)

Performance

R= $P_{out}/h\nu_a$

Geometry V_m boost



At design frequency

$$R_{FP}=K C_{a\gamma} w^2 \frac{\pi\ c}{16\ \nu_a} Q B^2$$

$$R_{CC}=K C_{a\gamma} 0.69 \times 1.8 * \frac{c^3}{{\nu_a}^3} Q B^2$$

Crossover at ~10 GHz

B=10, Q=10^6 for both

C. Boutan et al., Phys. Rev. Lett. **121** 261302 (2018)

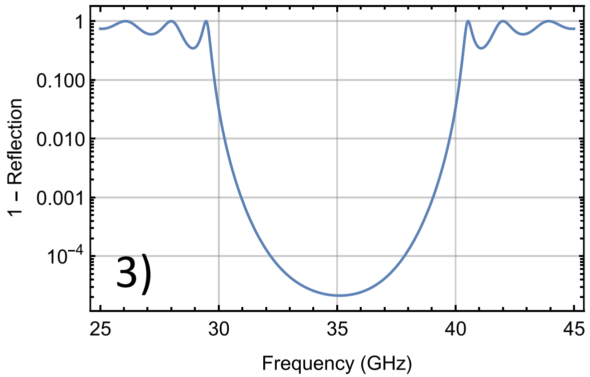
Desirable

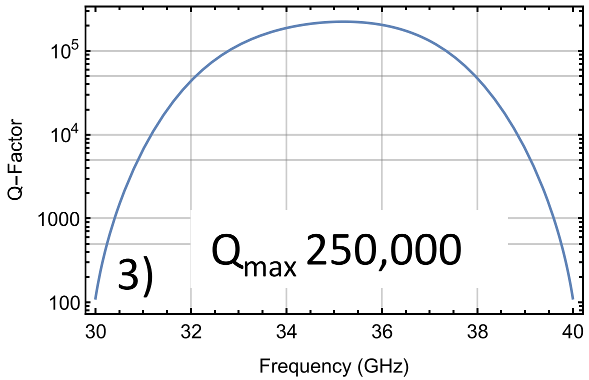
- High volume factor ✓
- Q-factor up to Q_a =10^6 ✓
- High B field compatible ✓
- Easy to adjust frequency ✓
- Broad tuning range ✓
- Feasible ✓

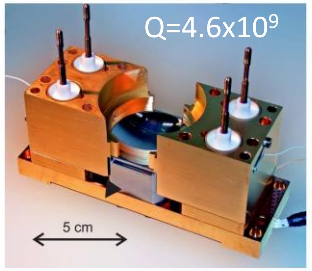
15-25 cm diameter, realistic B-fields

Options for coatings:

1) High TC YBCO **see** J. Golm et al., arXiv:2110.01296
2) Sapphire/NbTi multilayer **see** Xiaoxiang Xi et al., Phys. Rev. Lett. **105**, 257006 (2010)
3) Sapphire/quartz Bragg mirror





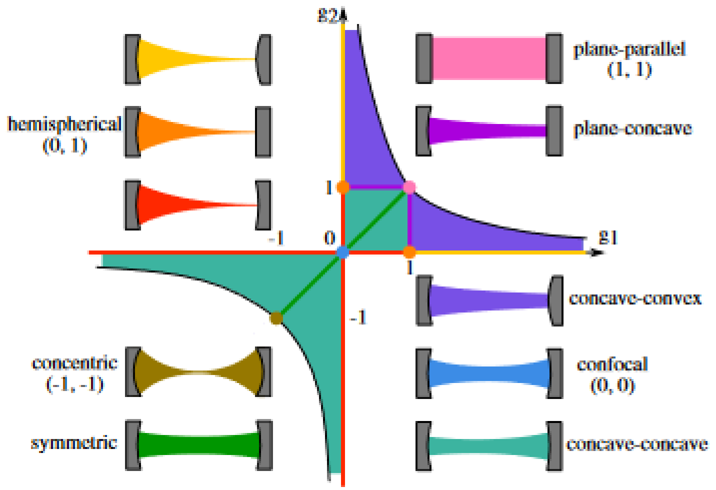


S. Kuhr et al., Appl. Phys. Lett. **90**, 164101 (2007)

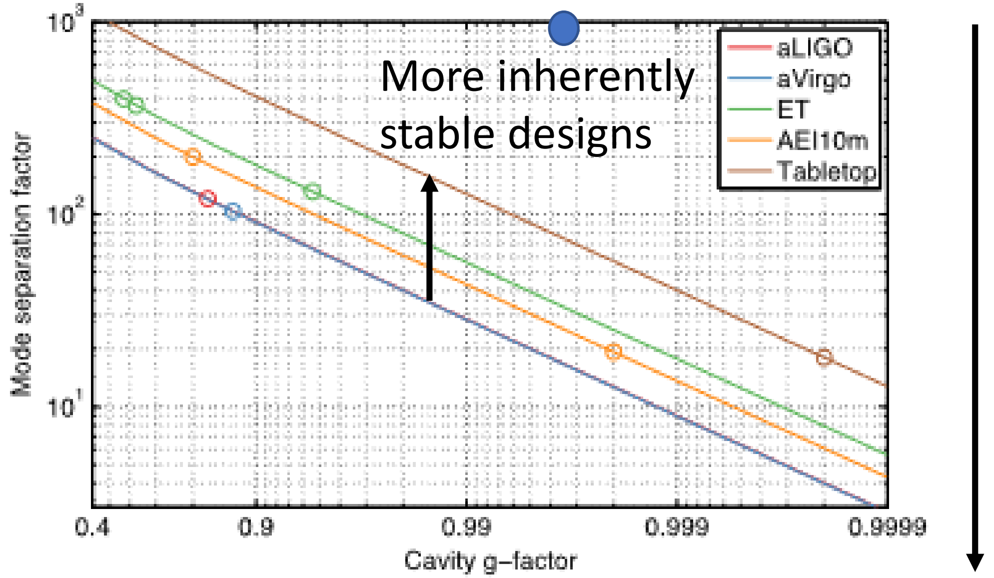
Research program

R&D program:

1) Which coating technology is best?
2) Test mirror construction techniques
3) How close to the instability limit can we reach?



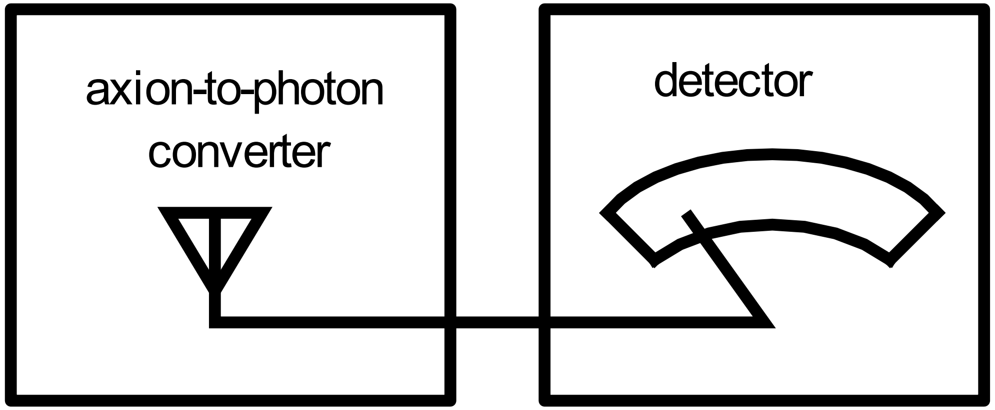
$$\delta = \frac{\Delta f_n}{\mathrm{FWHM}/2}$$



More unstable,
Harder to operate

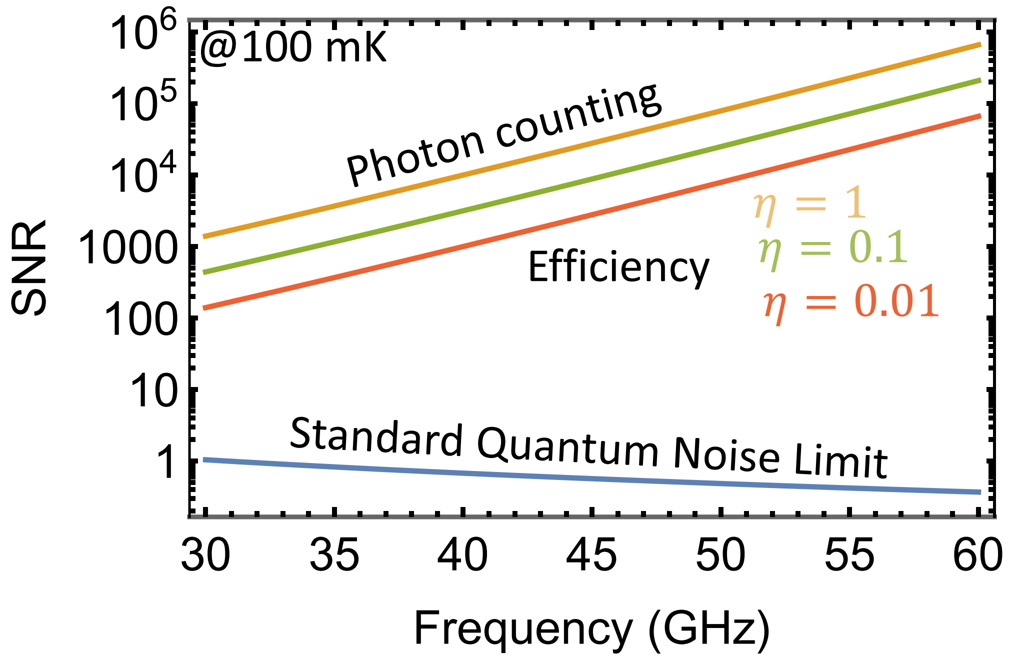
Roughly where this cavity will sit

H. Wang Phys. Rev. D **97** 022001 (2018)


axion-to-photon
converter
detector

Making a better detector

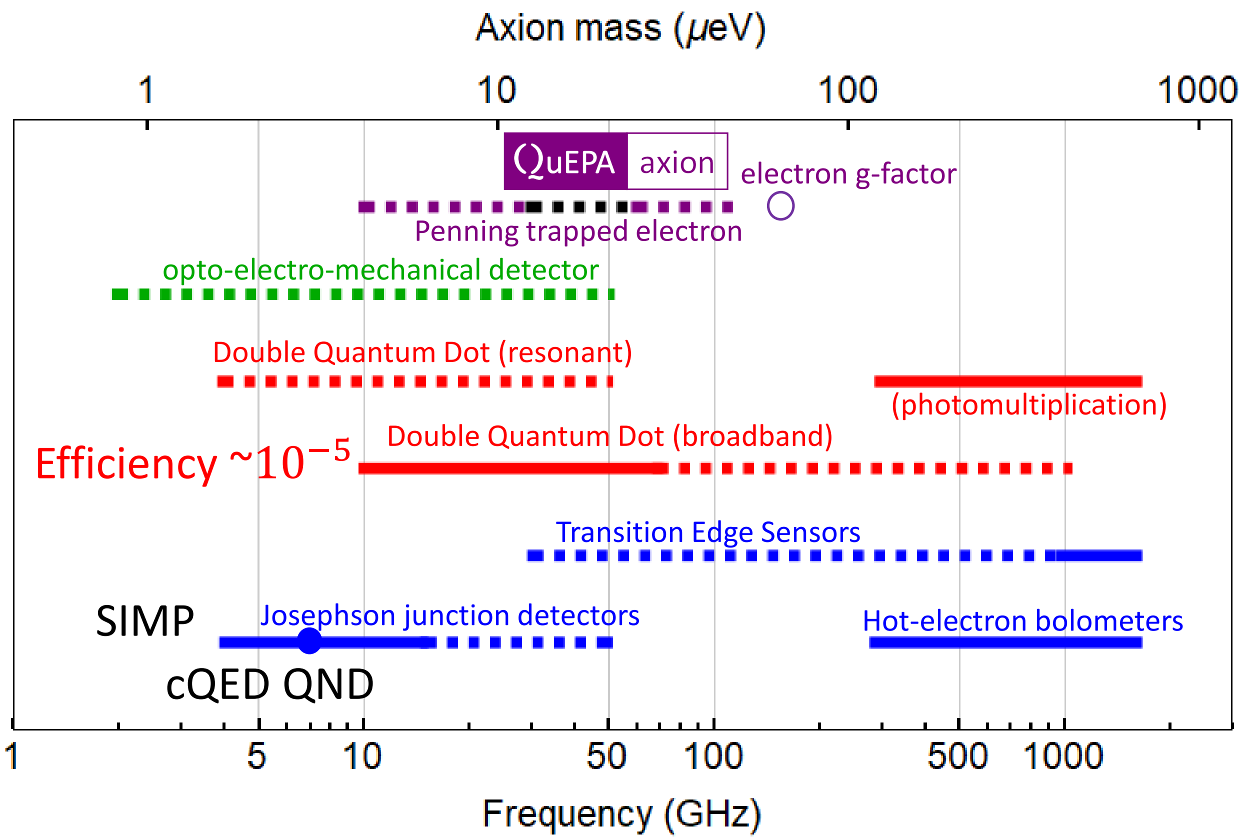
$$P_{count\ noise} = h\nu_a \sqrt{\frac{2\pi\nu_a\eta\bar{n}}{t\ Q_a}}$$



$$P_{SQL\ noise} = h\nu_a(\bar{n}+1)\sqrt{\frac{\nu_a}{t\ Q_a}}$$

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

What technology to use?



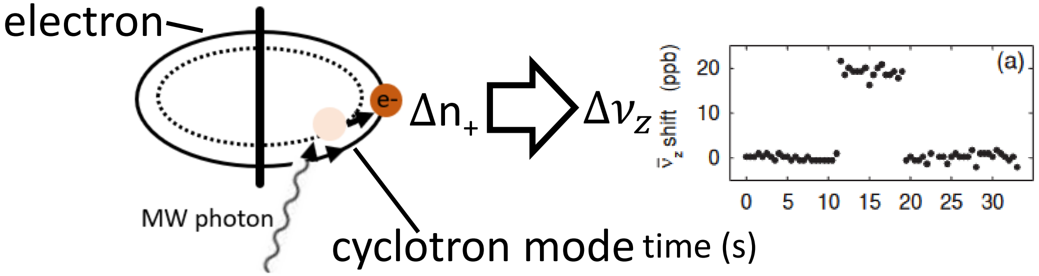
A. Ghirri et al., Sensors **20(14)**, 4010 (2020)

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

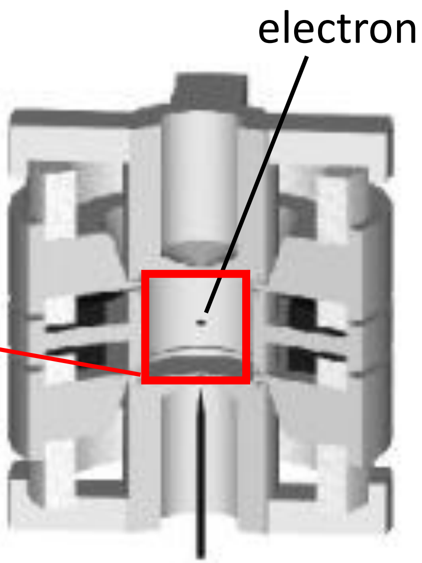
AMO Quantum technology for Single Photon Counting

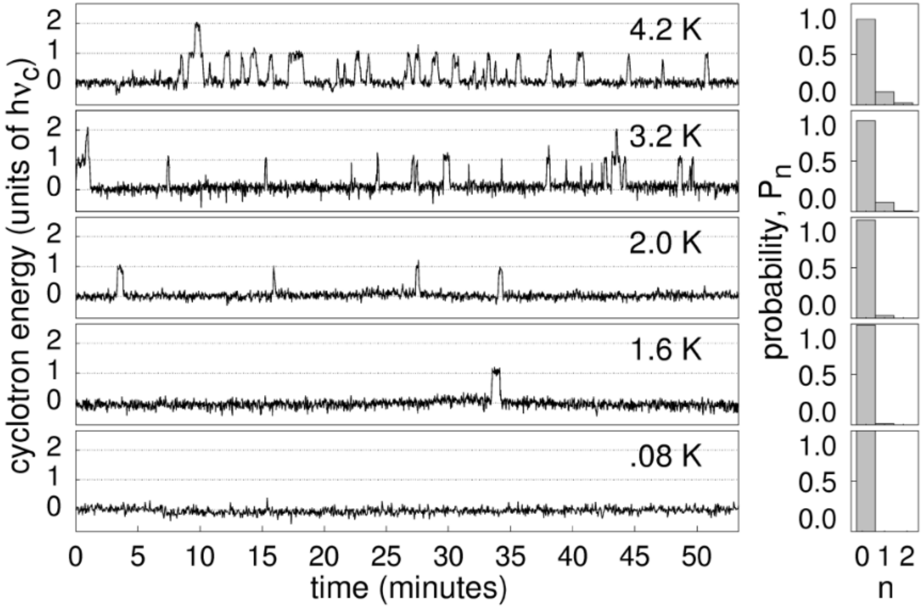
An old idea: CARRACK I & II Rydberg atoms

Counting photons with a single trapped electron



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



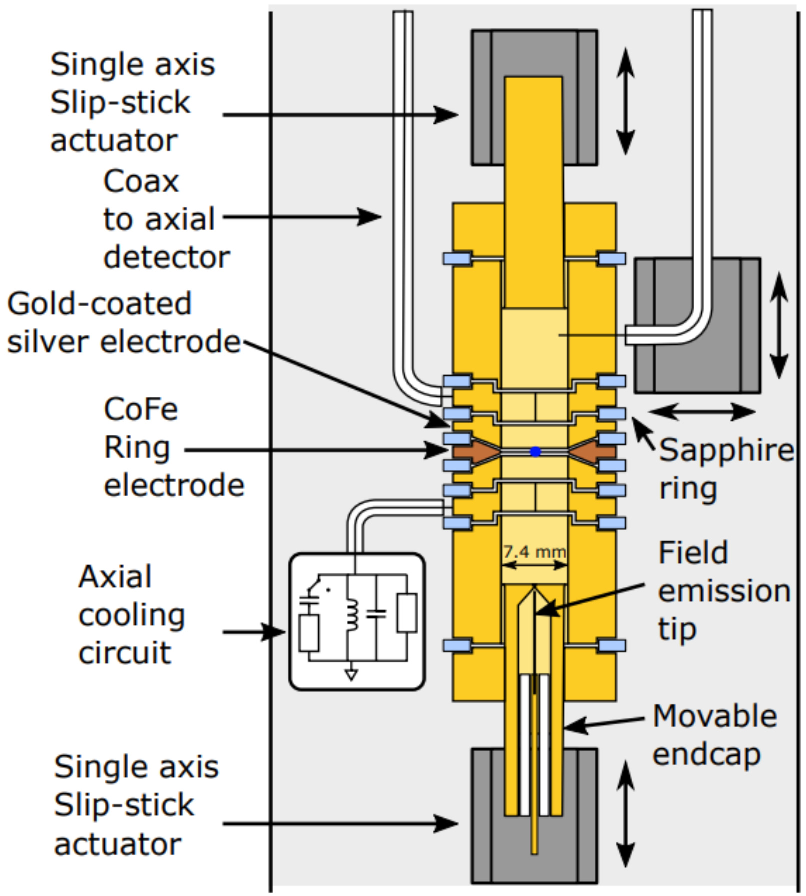


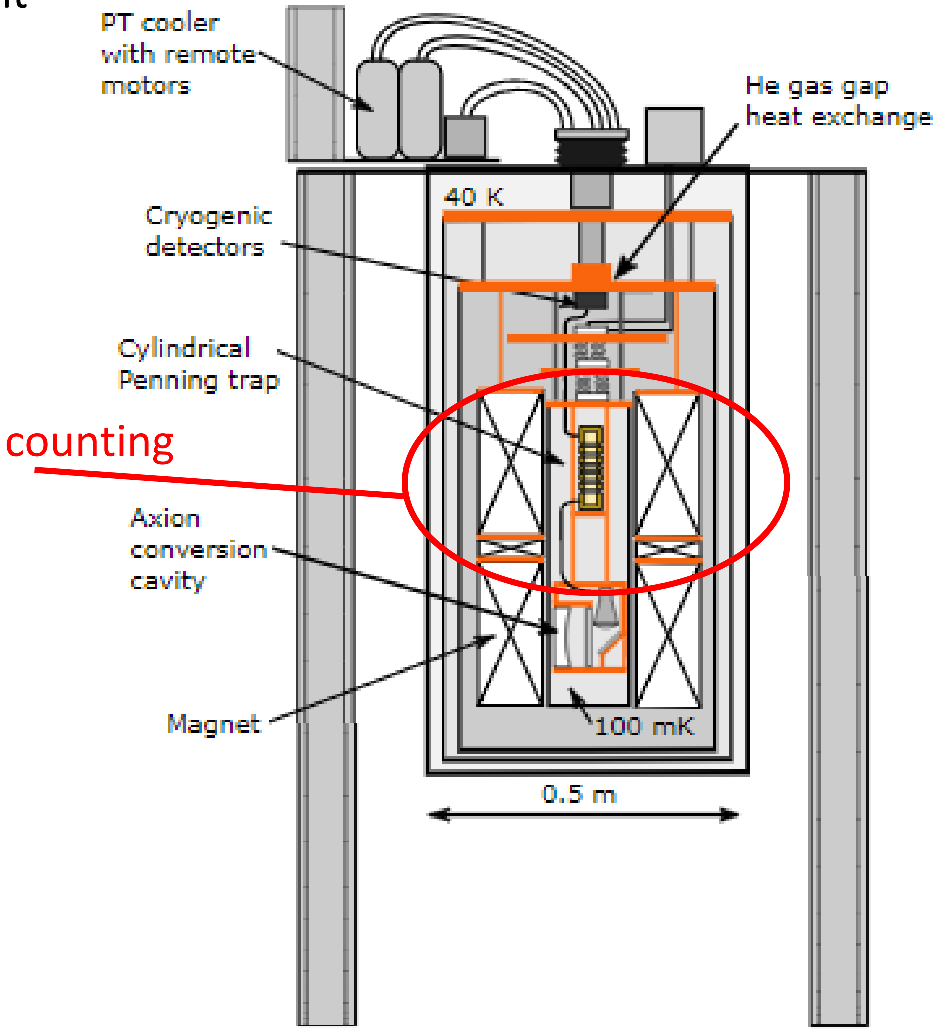
M. Tada et al., Nuclear Physics B (Proc. Suppl.) **72** 164 (1999)
M. Tada et al., Physics Letters A **349 6** 488 (2006)

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

Our approach

Moving endcaps allows TE_{11x} modes to be matched to cyclotron frequency for efficient detection





R&D goals

- Application of frequency measurement techniques compatible with on resonant cavity
- Medium-Q (25,000) cavity.

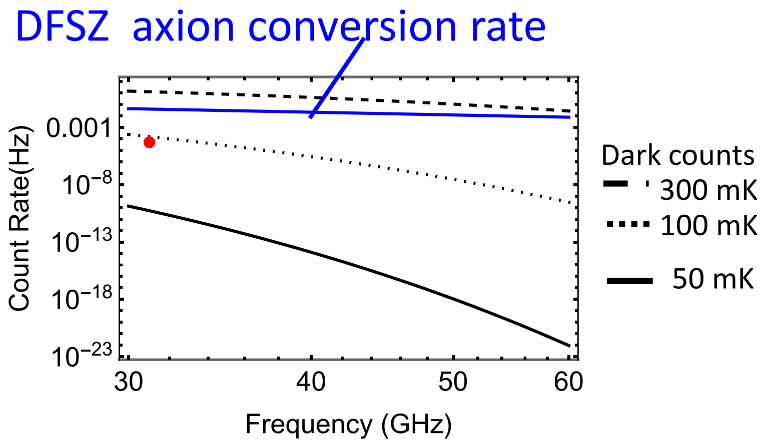
Some realistic numbers

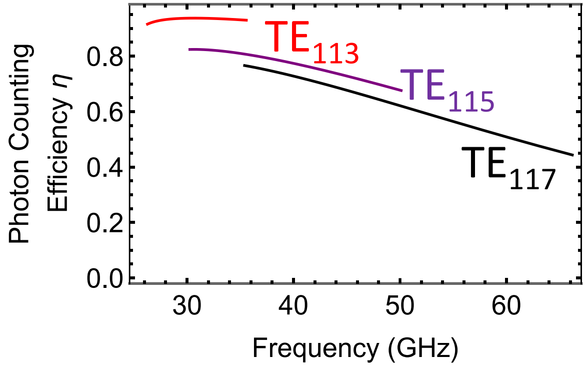
Axion production cavity assumptions

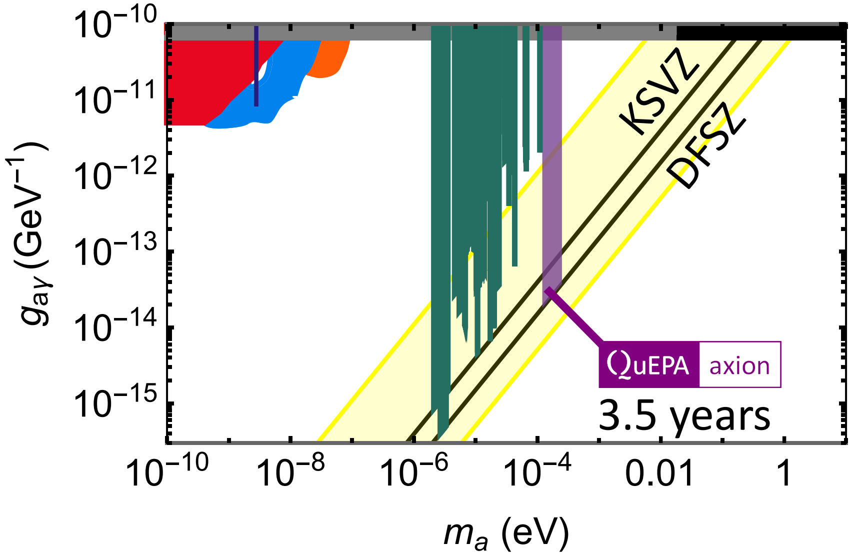
Parameter	Value	Why?
Q	250,000	Calculated Bragg mirror
B	7 T	Modest large bore Nb-Ti magnet field
Mirror diameter	15 cm	Standard semiconductor substrate size
Mirror radius of curvature	1 m	g_{max}= 0.9975 w_{max}= 1.5 cm = d/10 $\Delta f_{min} \frac{Q}{f} = 4 * 10^3$
In-coupling losses	50 %	Modest mode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

Photon counting assumption

Parameter	Value	Why?
Q	25,000	Cavity wavemeter/electron g-factor
Missed fraction	5 %	< 1 ppm axial stability

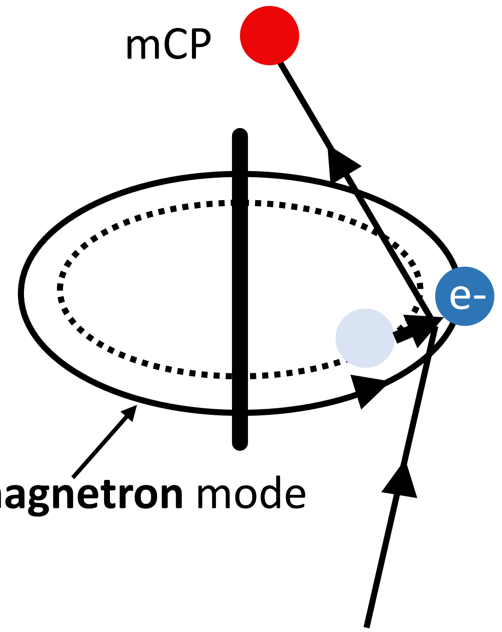




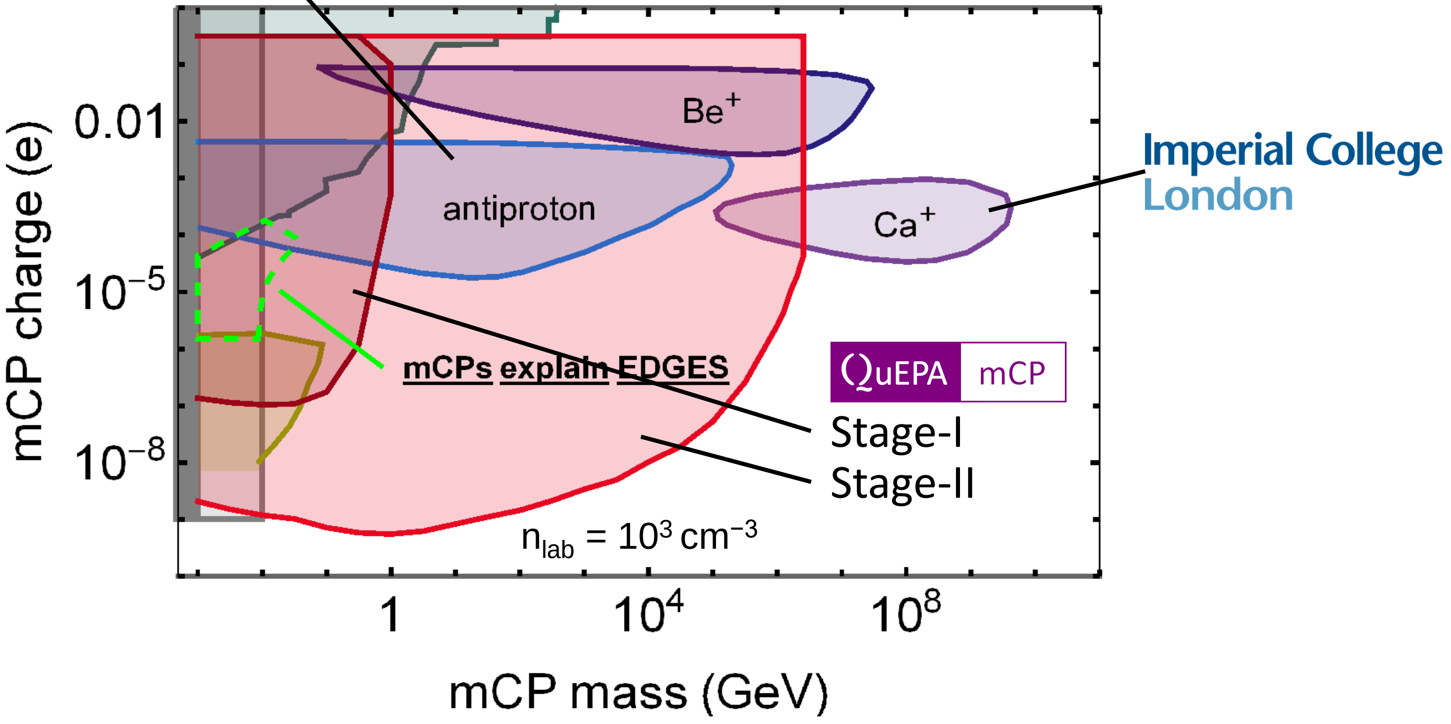


Other applications – millicharged particles

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



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



D. Budker et al., PRX QUANTUM **3**, 010330 (2022)   D. Carney et al., Phys. Rev. Lett. **127**, 6 (2022)

Status and short-term goals

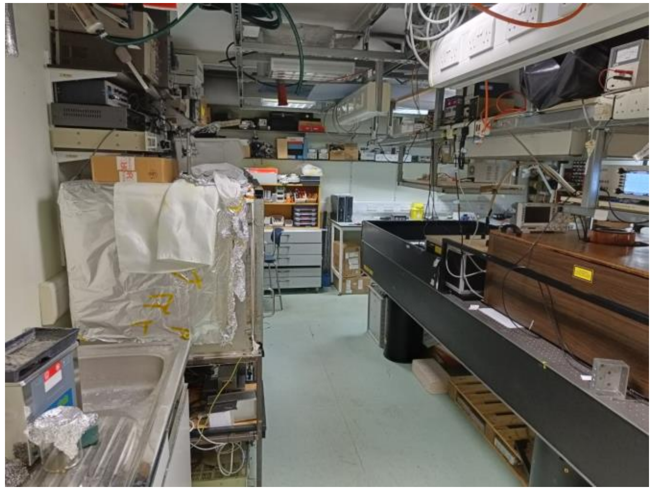
Project started 1/9/2022

THE ROYAL SOCIETY

£125 k for developing Fabry Perot cavity
+ 5-year University Research Fellowship for JAD

Imperial College London

40 m^2 lab space in Ion Trapping Group
Use of facilities in Dept. of Engineering
Equipment sharing with Centre for Cold Matter



UKRI Science and Technology Facilities Council

£500k fEC "Developing Quantum Technologies for Fundamental Physics" call for cryocooler (300 mK) + magnet and personnel

2-year R&D goals

Fabry-Perot cavity

- Cavity coating
- Construct cryogenic test cavity

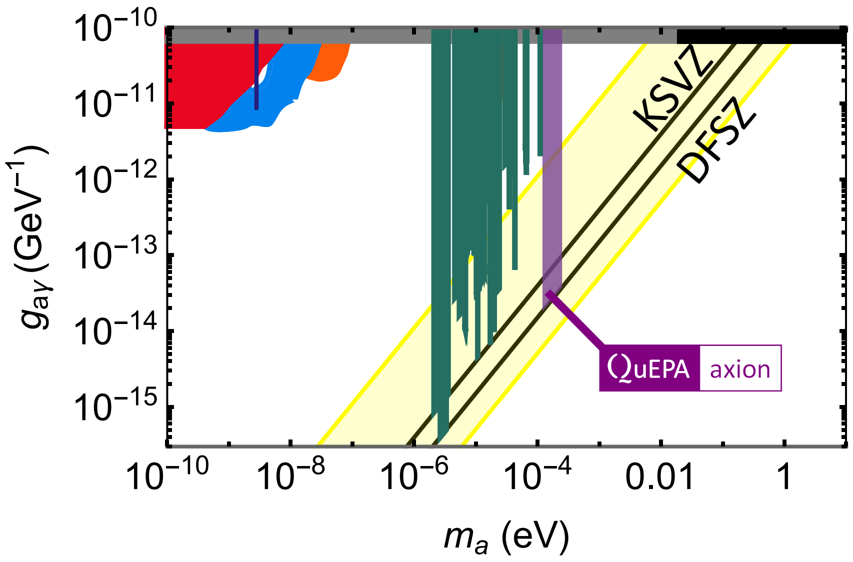
Penning trap

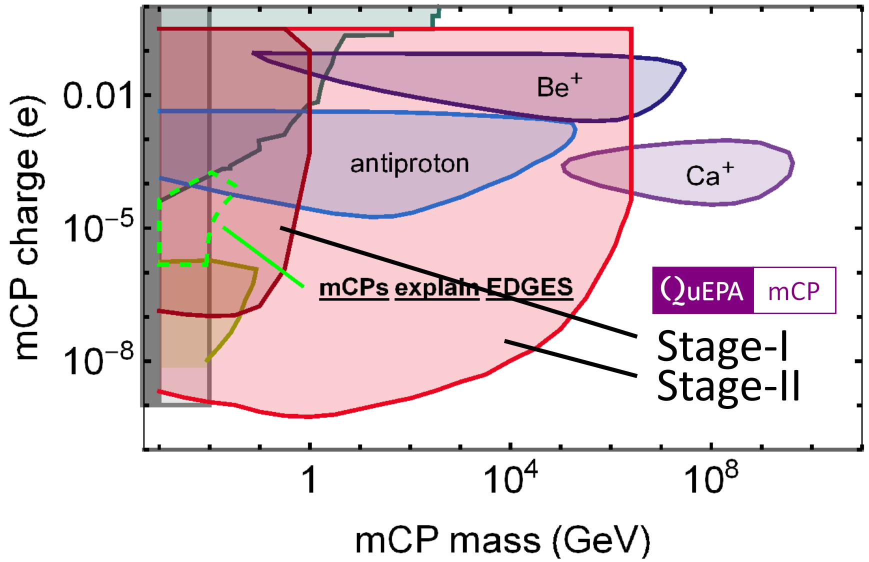
- Construct trap
- Trap and detect single electrons
- Measure magnetron heating rate
- Demonstrate principle of photon counting

2-year physics goal

→ mCP search

Thank you for listening





The local team

Jack Devlin

PI

David Pitman

Mechanical Engineer

Richard Thompson

Penning trap expert

Norbert Klein

Microwave expert

Support

Mike Tarbutt

Quantum Science and Fundamental Physics

We're recruiting: https://www.imperial.ac.uk/ion-trapping/positions/ 1 PhD

UKRI Science and Technology Facilities Council

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