Electron Trap as a Dark Matter Detector

Samuel Wong
June 6, 2024
PLANCK2024

2208.06519 and 2406.XXXXX:
Xing Fan, Gerald Gabrielse, Peter W. Graham, Roni Harnik, Thomas G. Myers, Harikrishnan Ramani, Benedict A. D. Sukra, Samuel S. Y. Wong, and Yawen Xiao

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Wavelike Dark Matter

- Local density $\rho_{DM} = 0.3\ \frac{\mathrm{GeV}}{\mathrm{cm}^3}$, but mass unknown
- If $m \ll 1\ \mathrm{eV}$: bosonic, non-relativistic, classical wave
- **Axion**:
  - Pseudo-scalar
  - QCD axion – strong CP

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} m_a a^2$$

- **Dark Photon**:
  - Dark U(1), simplest extension of SM

$$\mathcal{L} \supset -\frac{1}{4}\left({F'}_{\mu\nu}{F'}^{\mu\nu} - 2\epsilon F_{\mu\nu}{F'}^{\mu\nu}\right) + \frac{1}{2} m_{A'} {A'}_{\mu} {A'}^{\mu}$$

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ultimate target

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Phenomenology

- Dark photon generates weak, harmonic electric fields

$$E \sim \epsilon\sqrt{2\rho_{DM}}\cos(m_{A'}t)$$

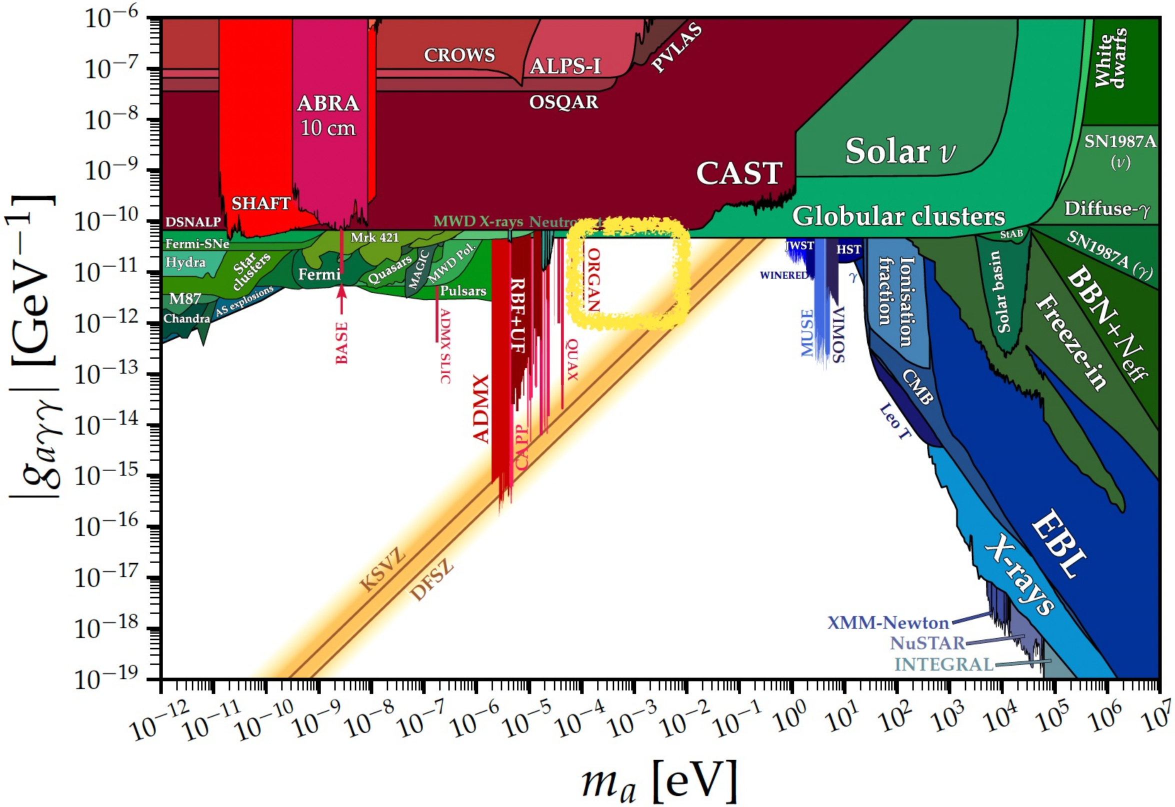
$$\uparrow$$

$$m_{A'} + \frac{1}{2}m_{A'}v^2 + \ldots$$

- Axion needs a background magnetic field

$$\vec{E} \sim g_{a\gamma\gamma}\frac{\sqrt{2\rho_{DM}}}{m_a}\vec{B}_{ext}\cos(m_a t)$$

Axion Parameter Space



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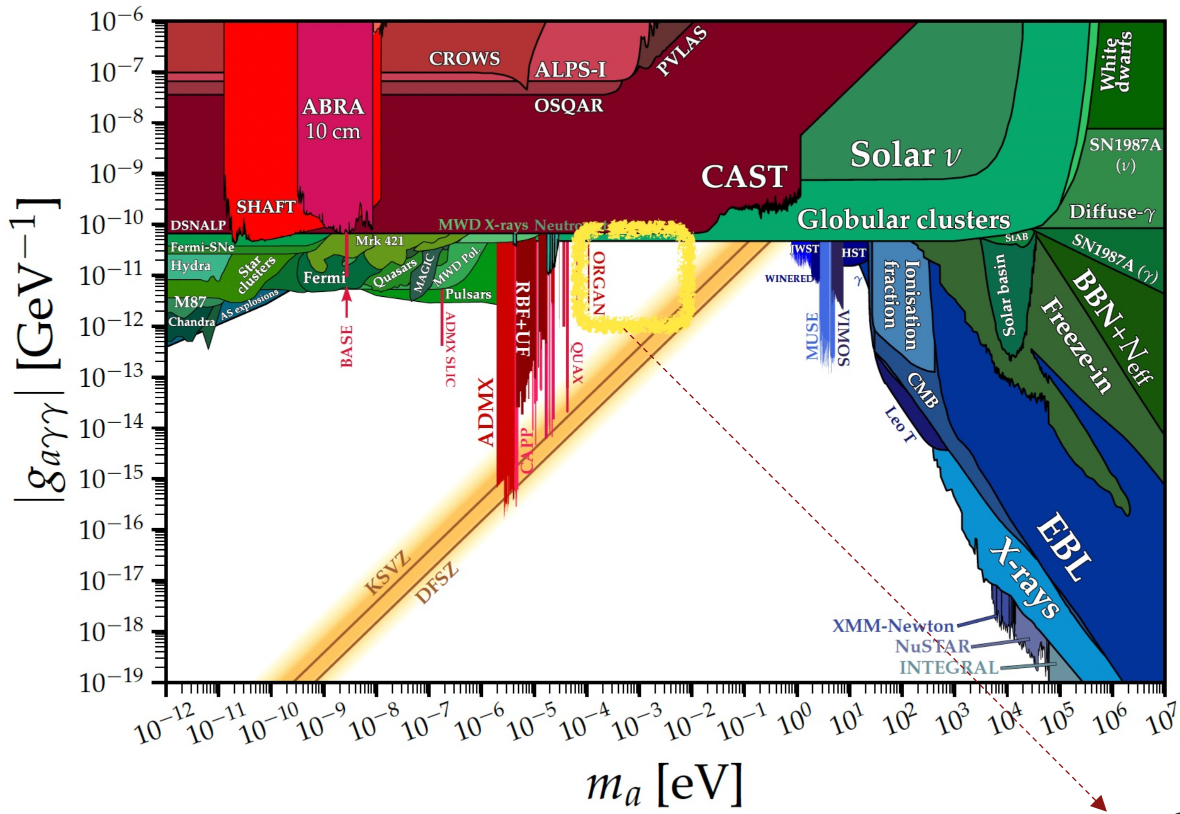
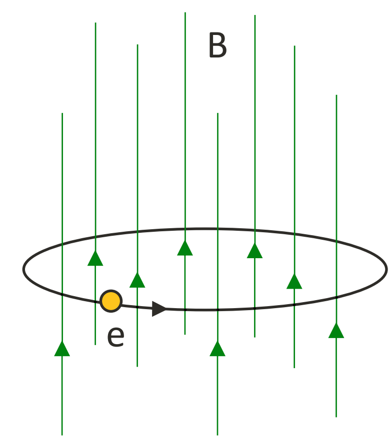
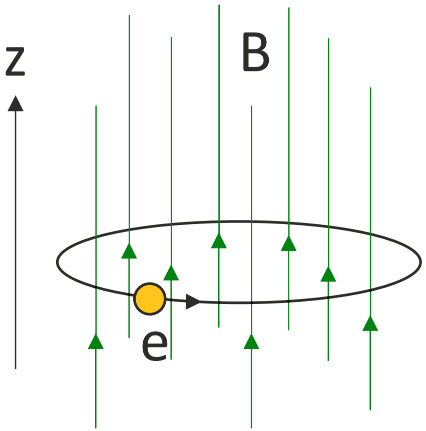




electron cyclotron motion

$$\omega_c = \frac{eB}{m_e} = 0.6\ \mathrm{meV}\ (150\ \mathrm{GHz})$$

Electron Penning Trap



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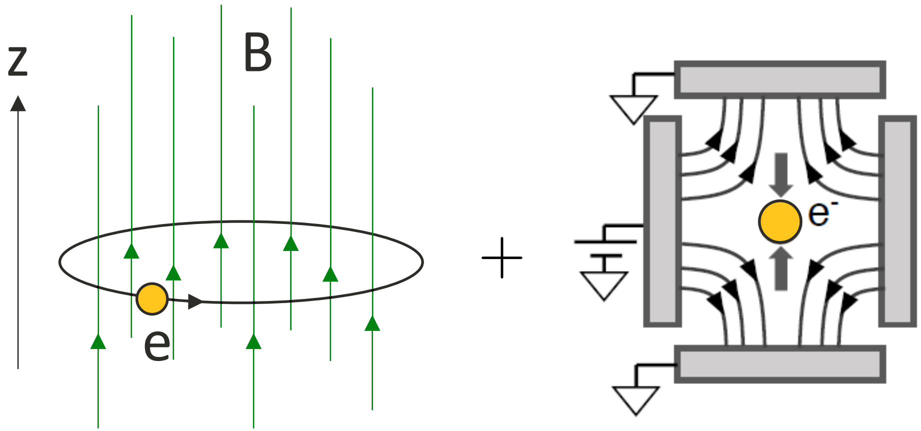

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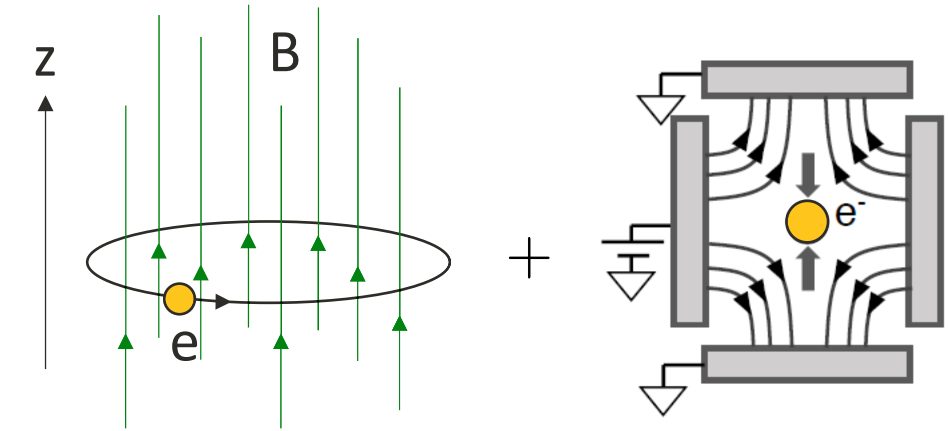

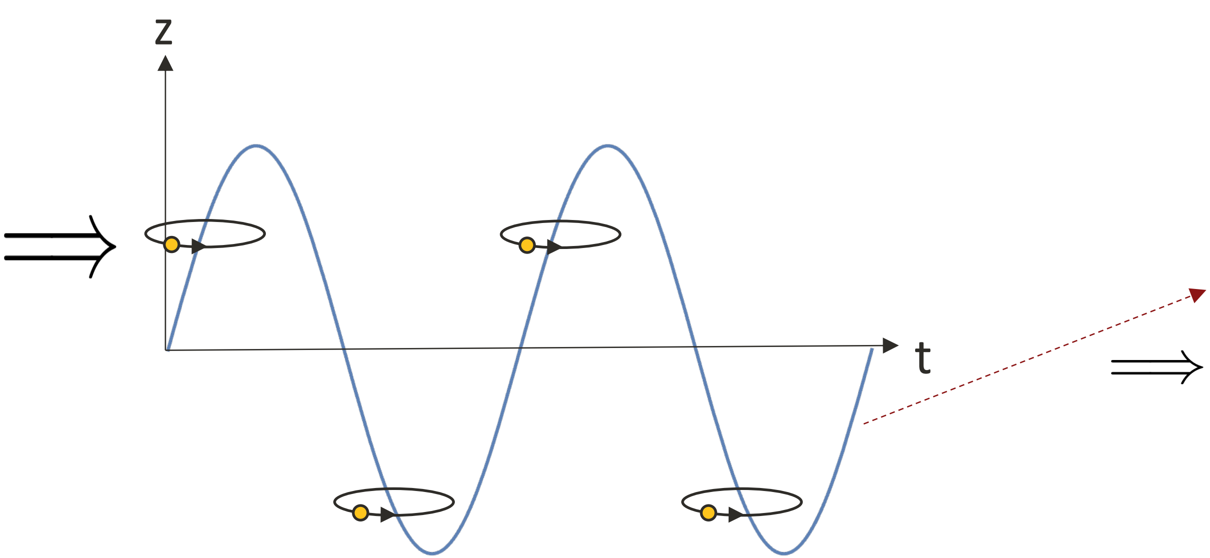

axial oscillation

$\Longrightarrow$ classical image current

$\omega_z \sim 100$ MHz

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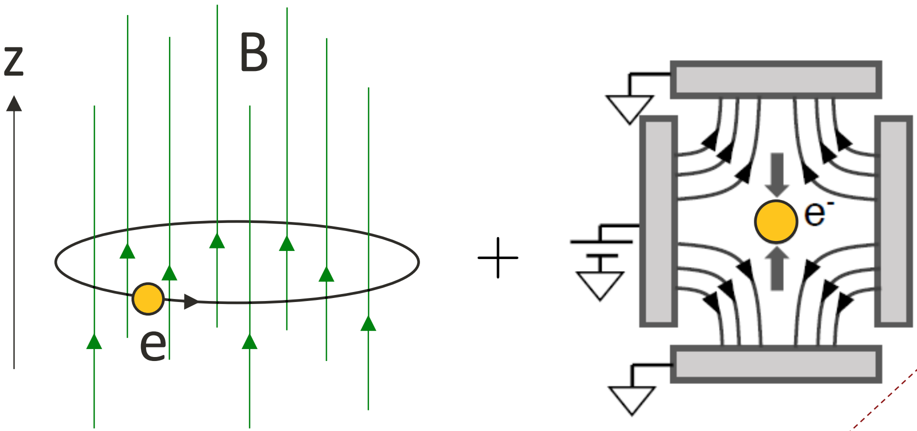
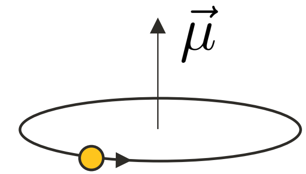
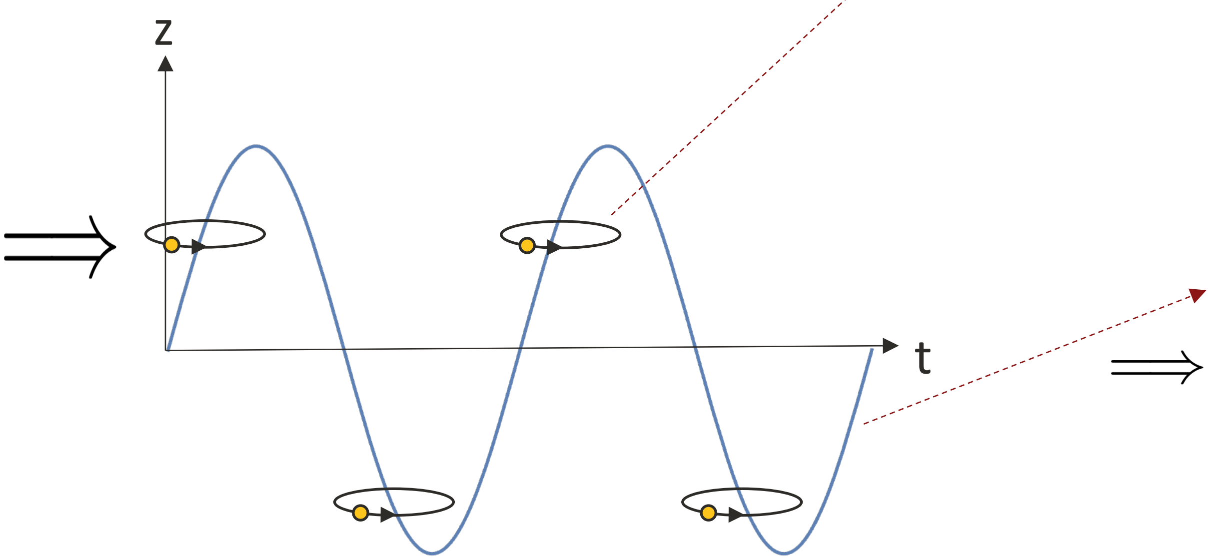


cyclotron motion





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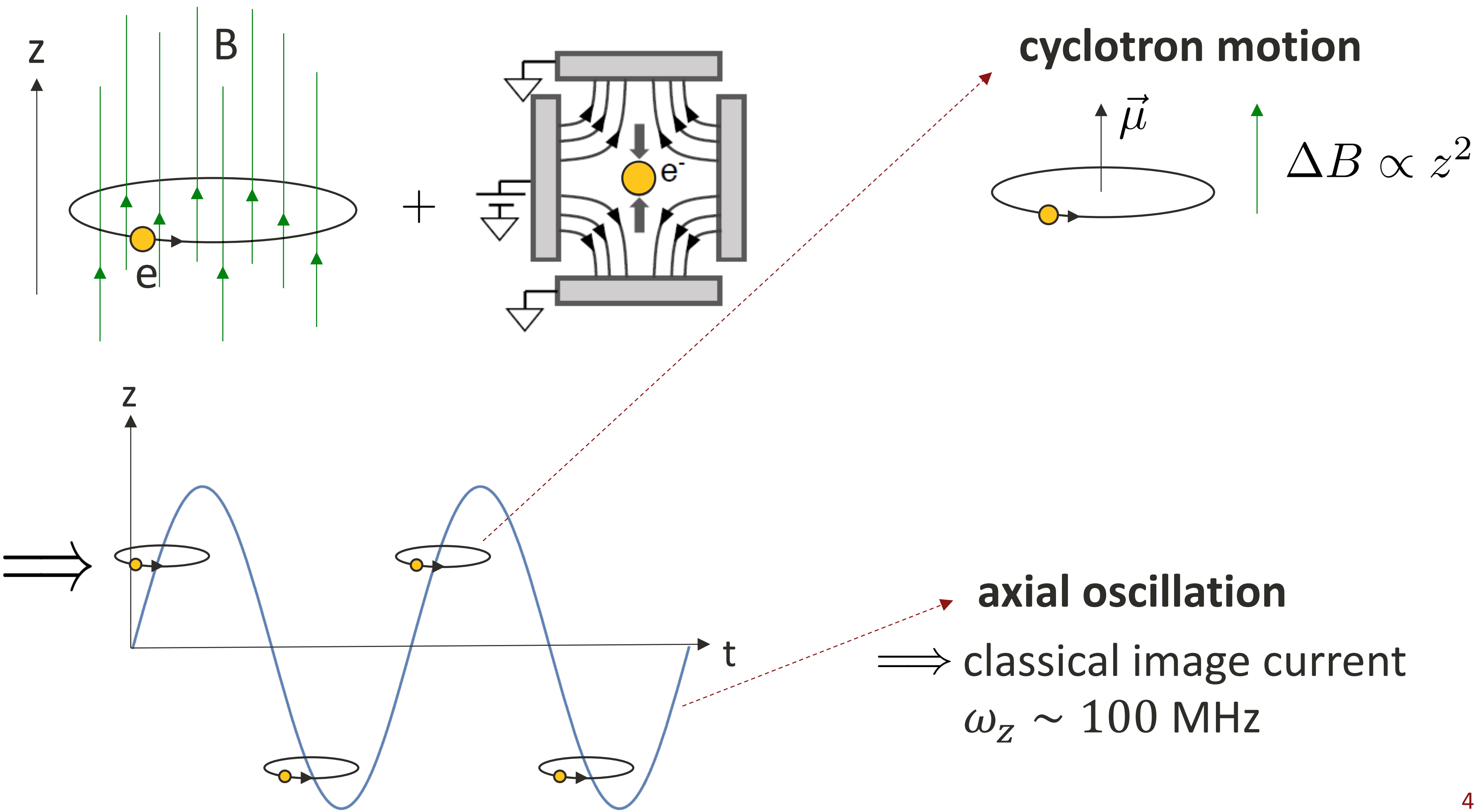

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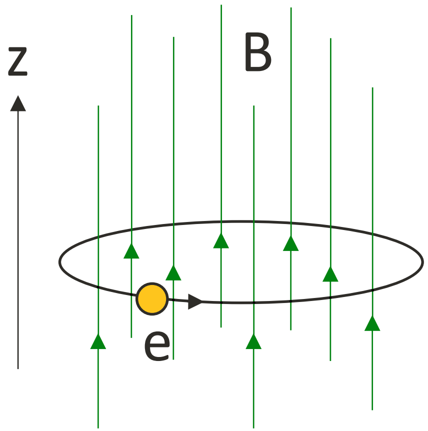
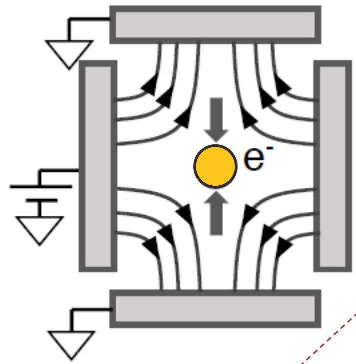


+



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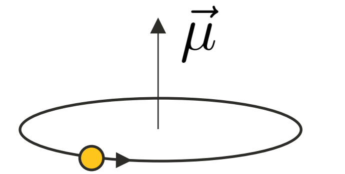
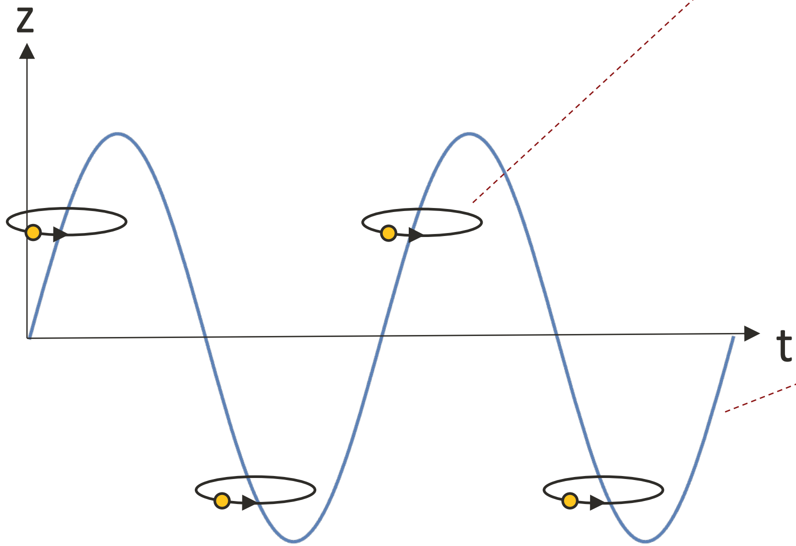


$\Delta B \propto z^2$

$\Longrightarrow$ quantized axial frequency shifts

$$\omega_z \to \omega_z + n_c\delta$$

$\Longrightarrow$



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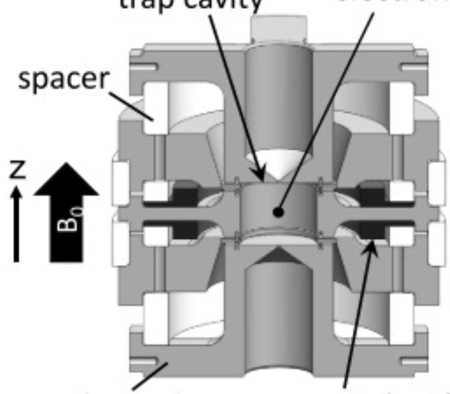
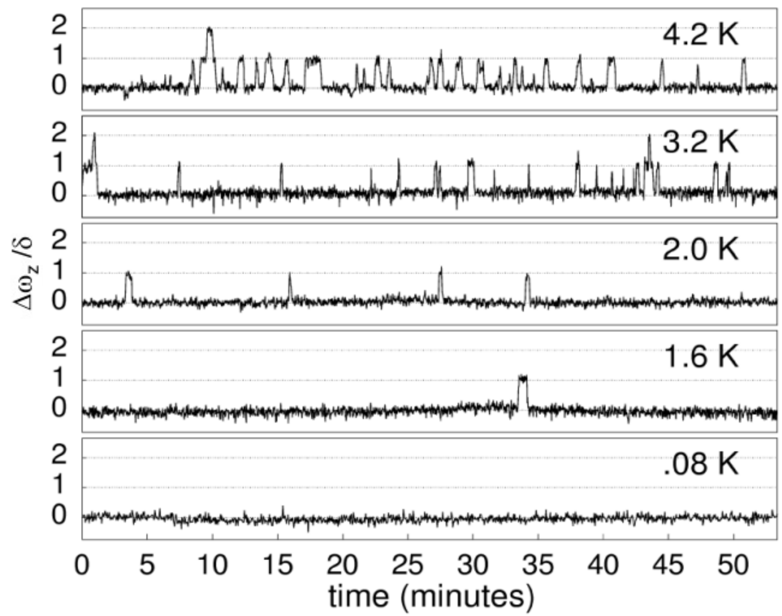
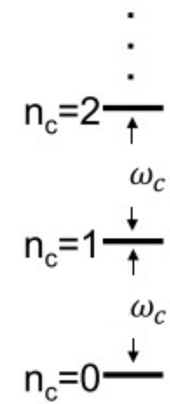


ω_c	20-200 GHz
ω_z	~100 MHz
T_{wall}	0.05 K = 6 GHz



[S. Peil and G. Gabrielse, *Phys.Rev.Lett.* 83 (1999) 7]



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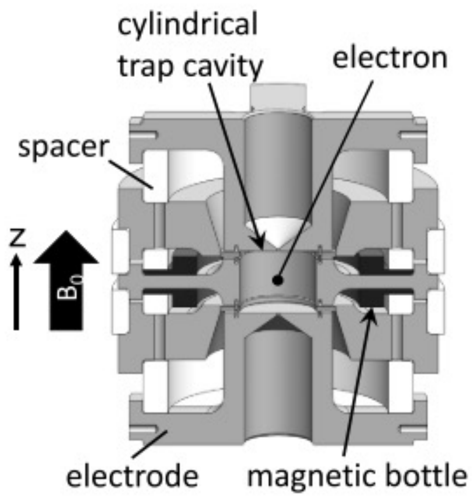

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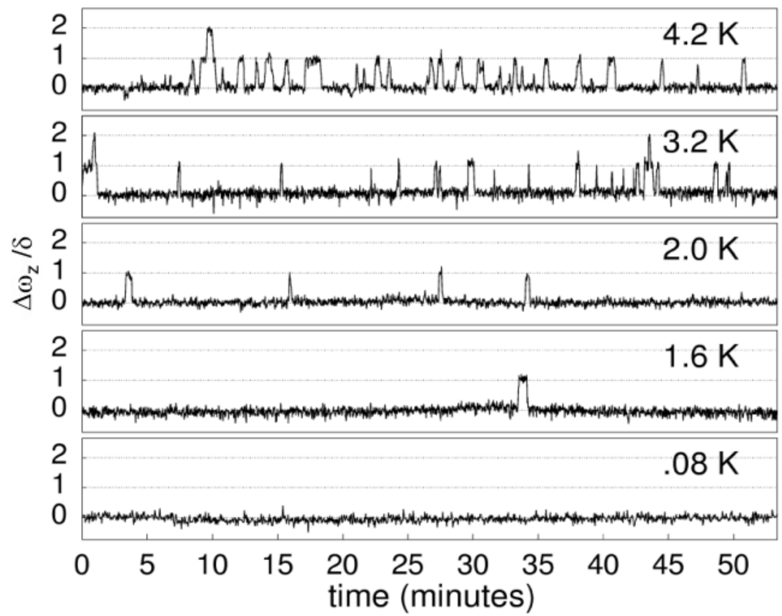

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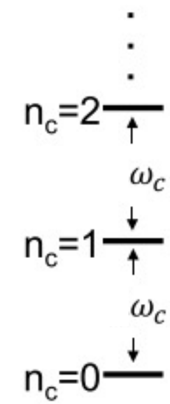
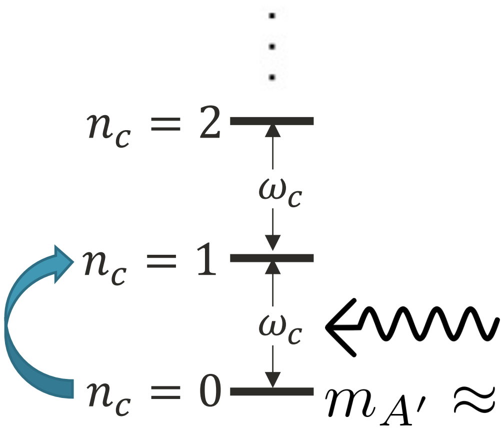


$$\omega_z \to \omega_z + n_c\delta$$

proof-of-principle measurement: background-free over 7.4 days !

Resonant Detection of Dark Photon



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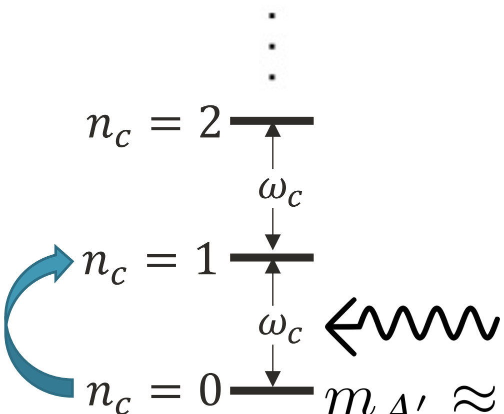

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Scan B-field (0.1 – 2 meV)

thermal background

B = 20 Tesla

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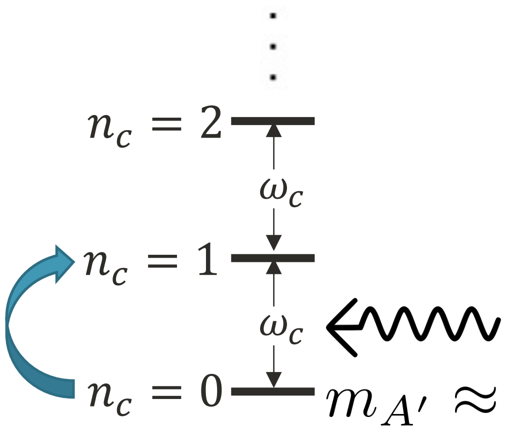

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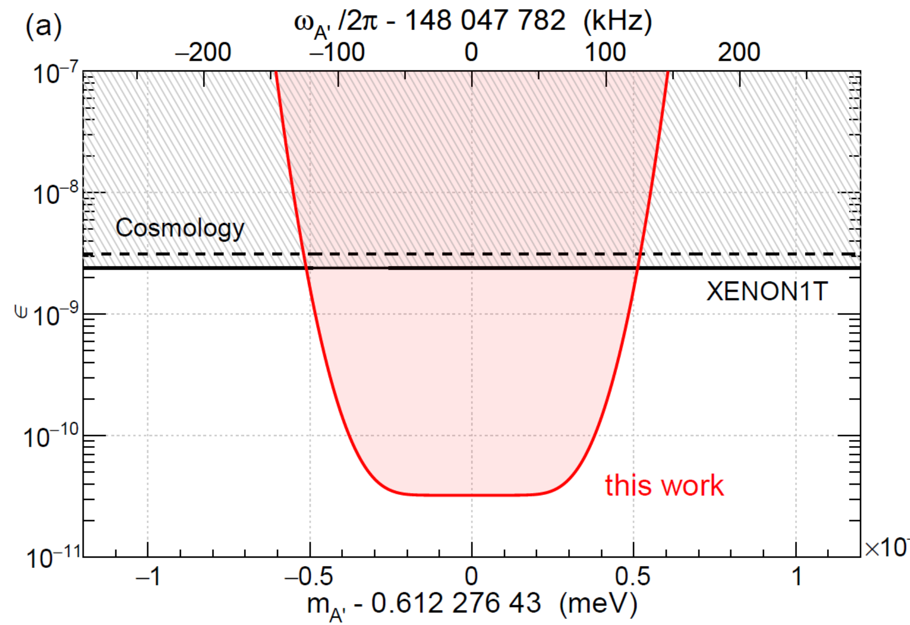

[2208.06519]
Published in PRL

How to Improve?

- Only dark photon so far.
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2. effects of cavity

1. excited states

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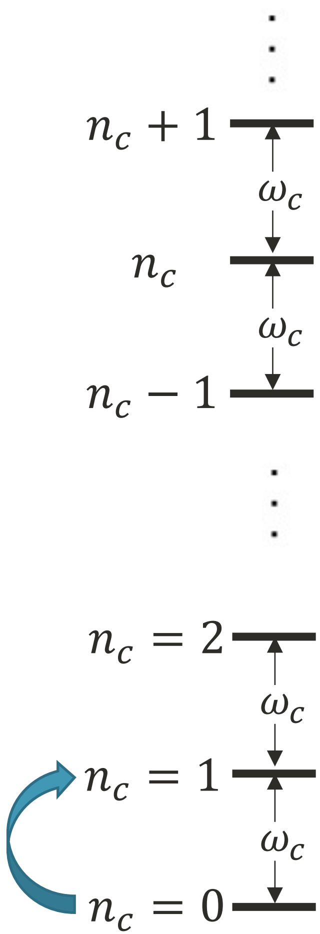

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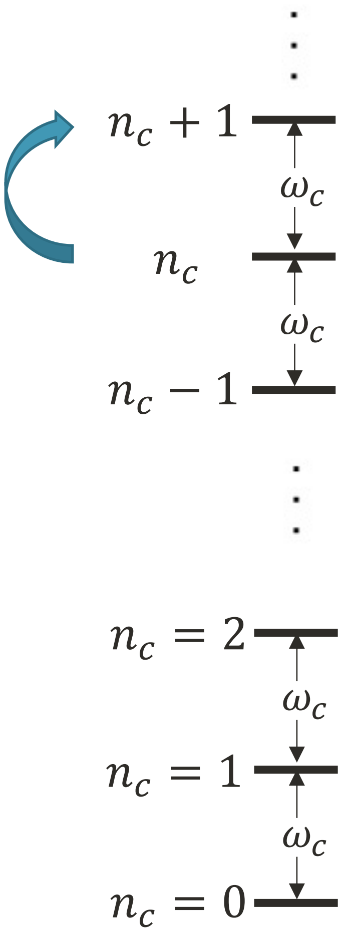

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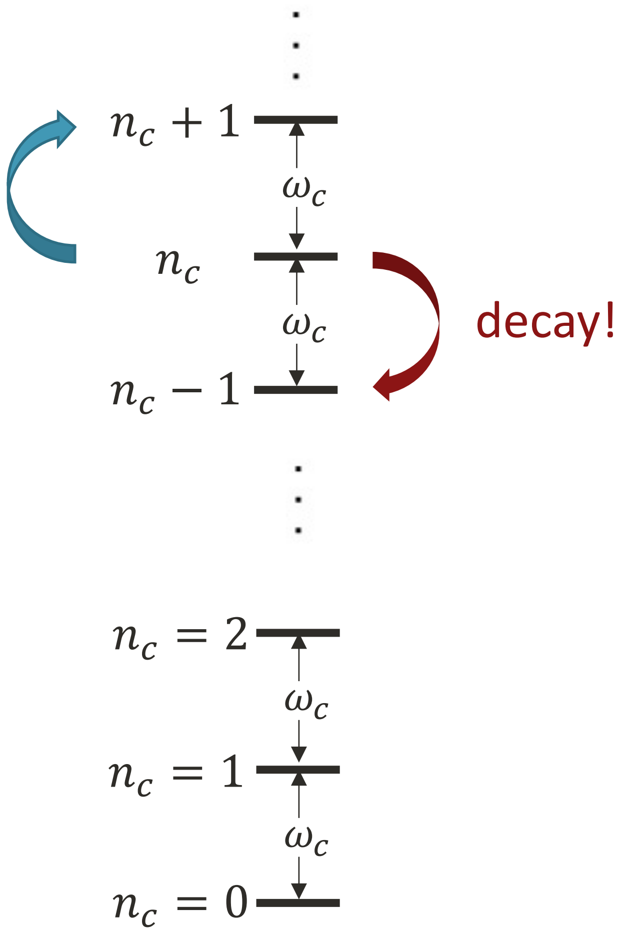

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$$\tau_c \approx \frac{1}{n_c} 3\ s$$

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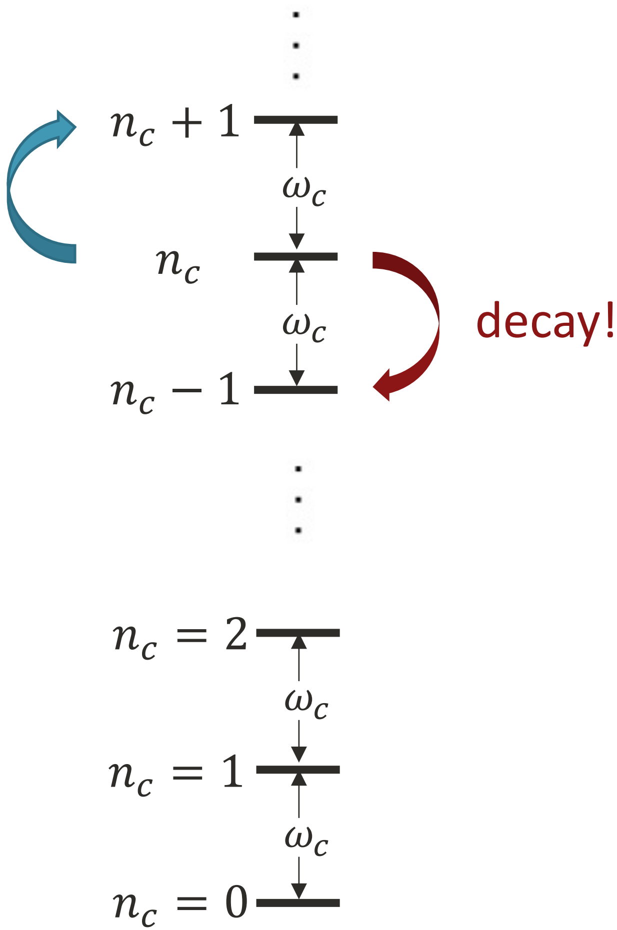

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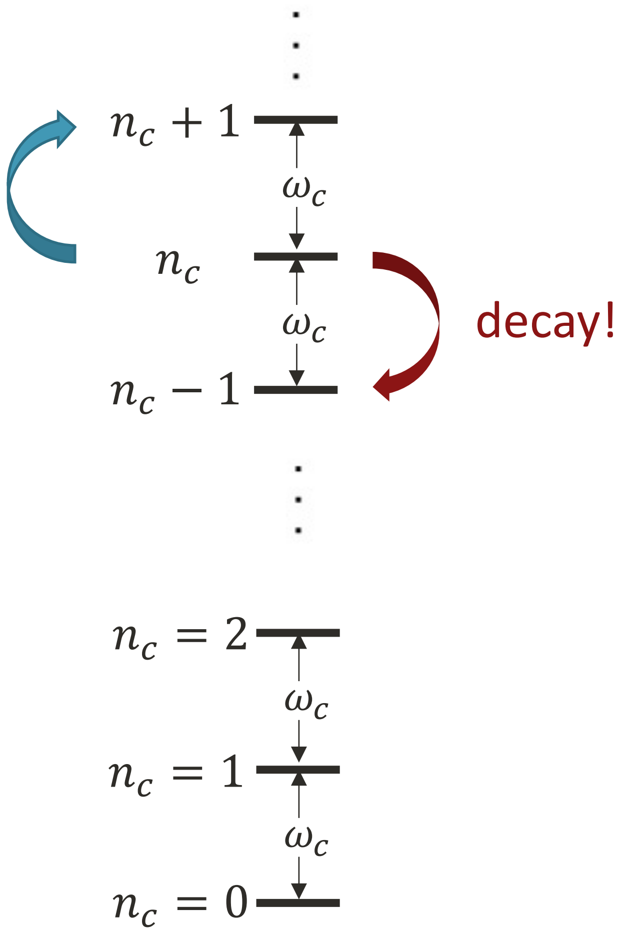

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- Theoretical minimum:

$$t_{ave} \approx 3 \times 10^{-5} s$$

$$\Longrightarrow \boxed{n_c \approx 10^5}$$

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2. effects of cavity (κ^2)

1. excited states (n_c)

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$$\kappa^2 = \left(\frac{E_{cavity}}{E_{free}}\right)^2$$

BREAD

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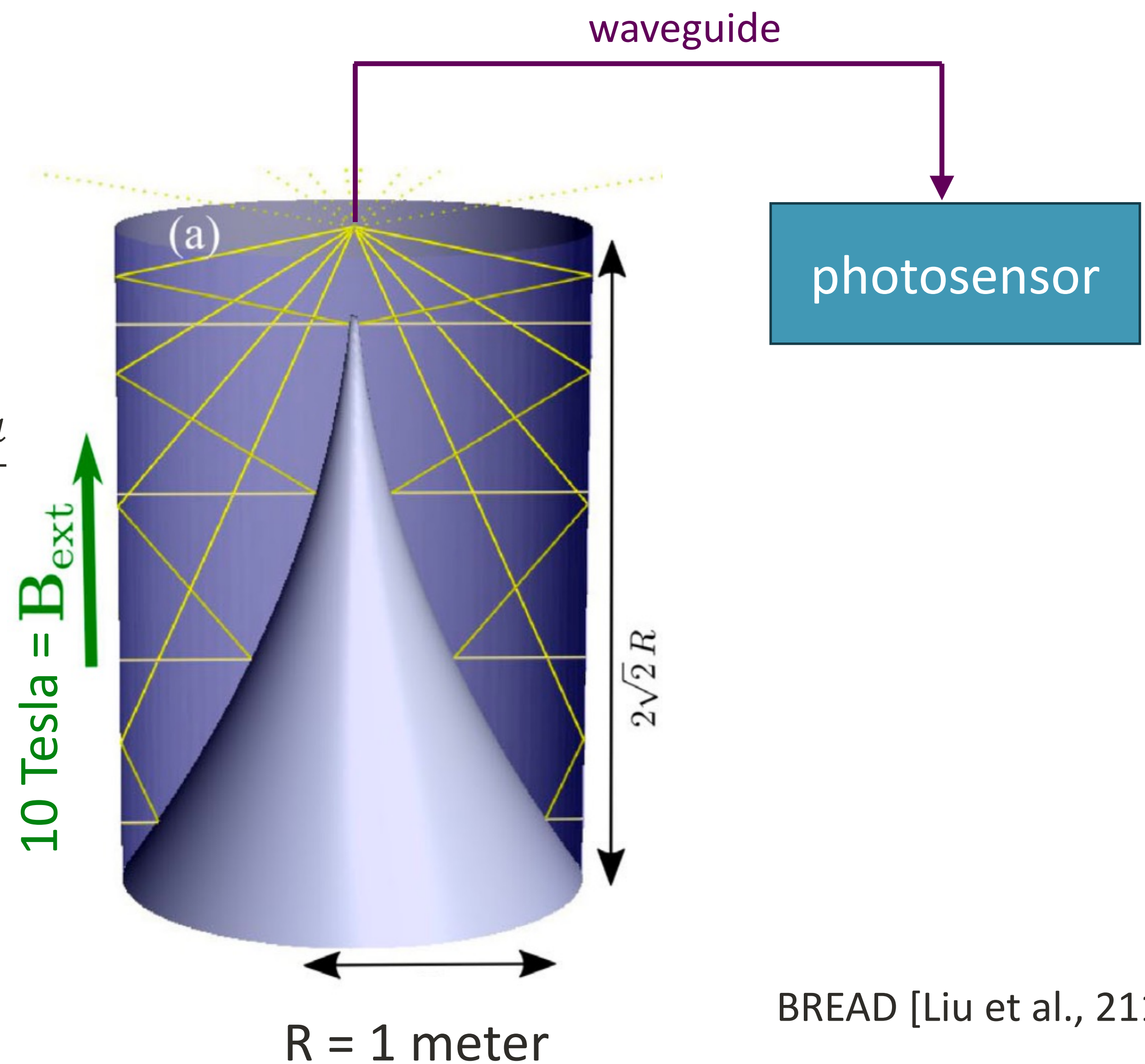
$$= \frac{surface\ area}{m_a^{-2}}$$

$$\approx 10^6$$



BREAD [Liu et al., 2111.12103]

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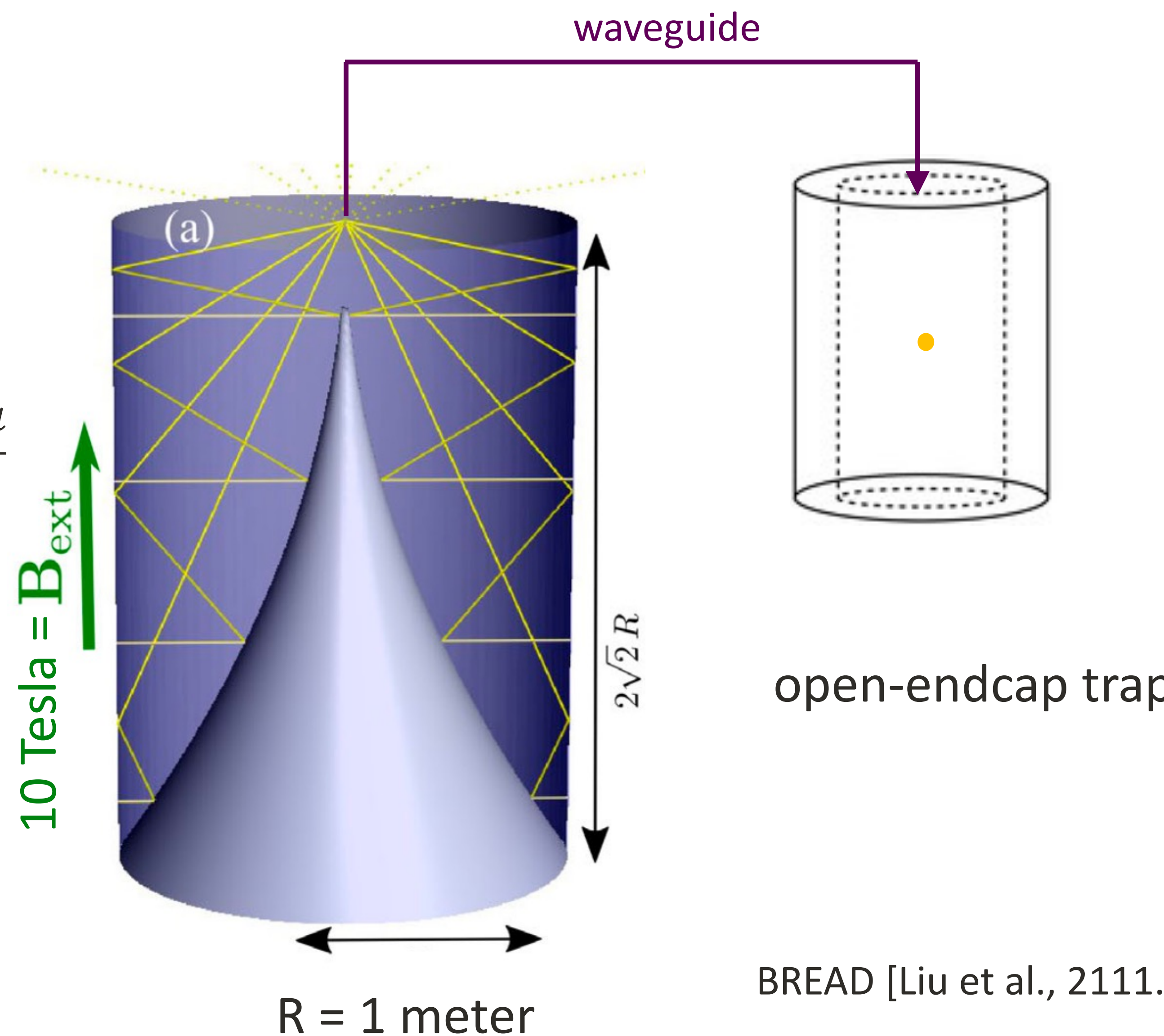

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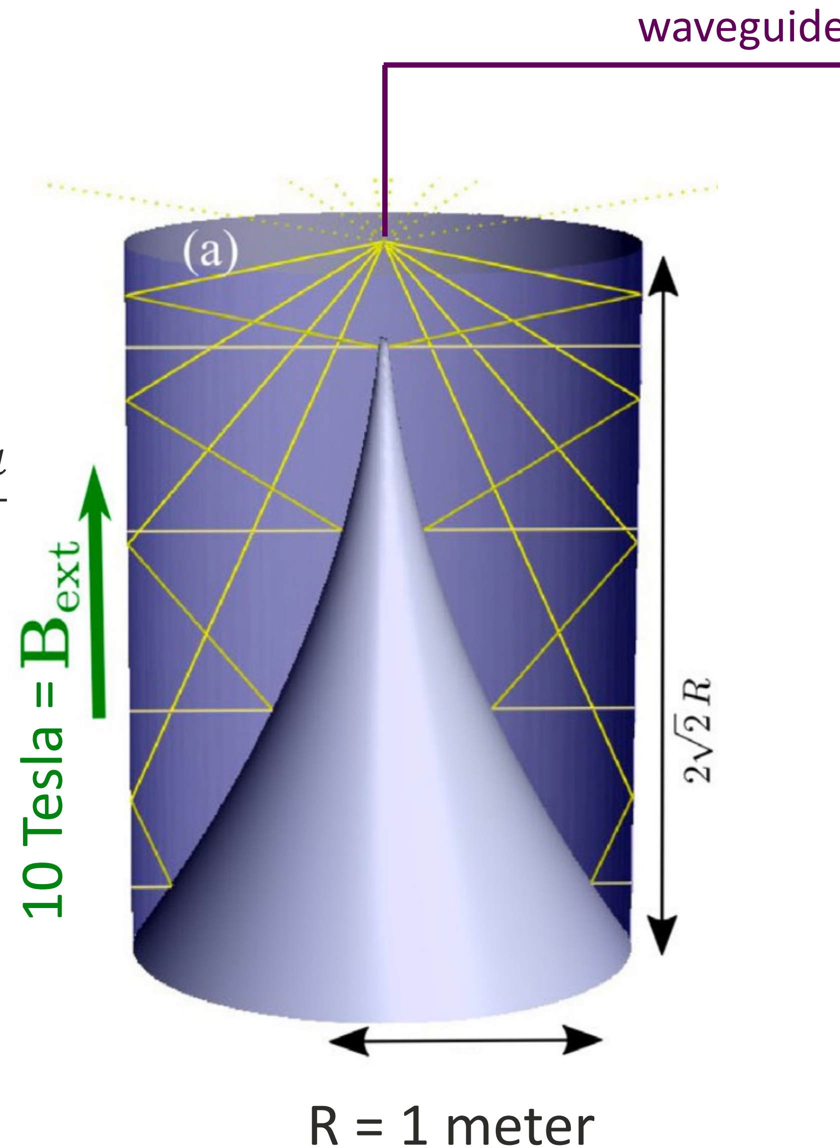
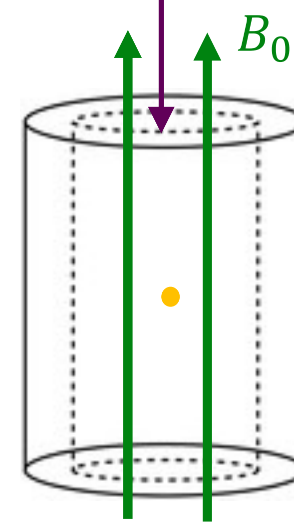
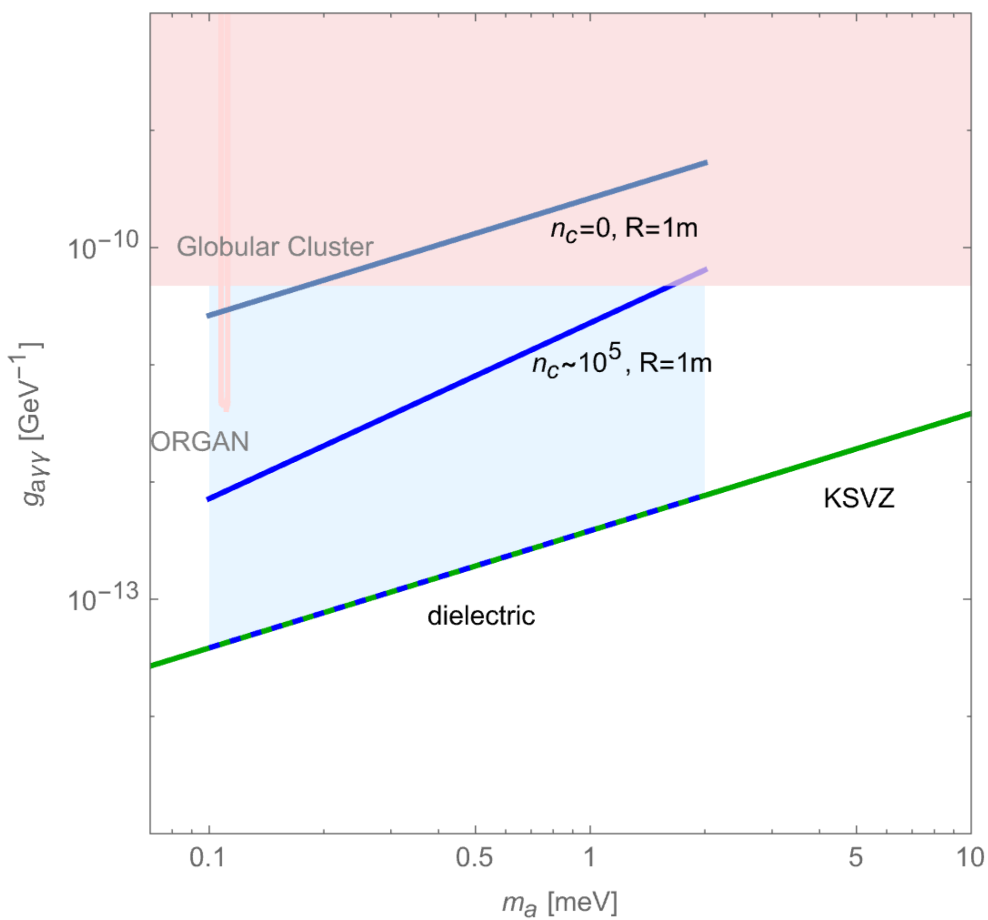




open-endcap trap

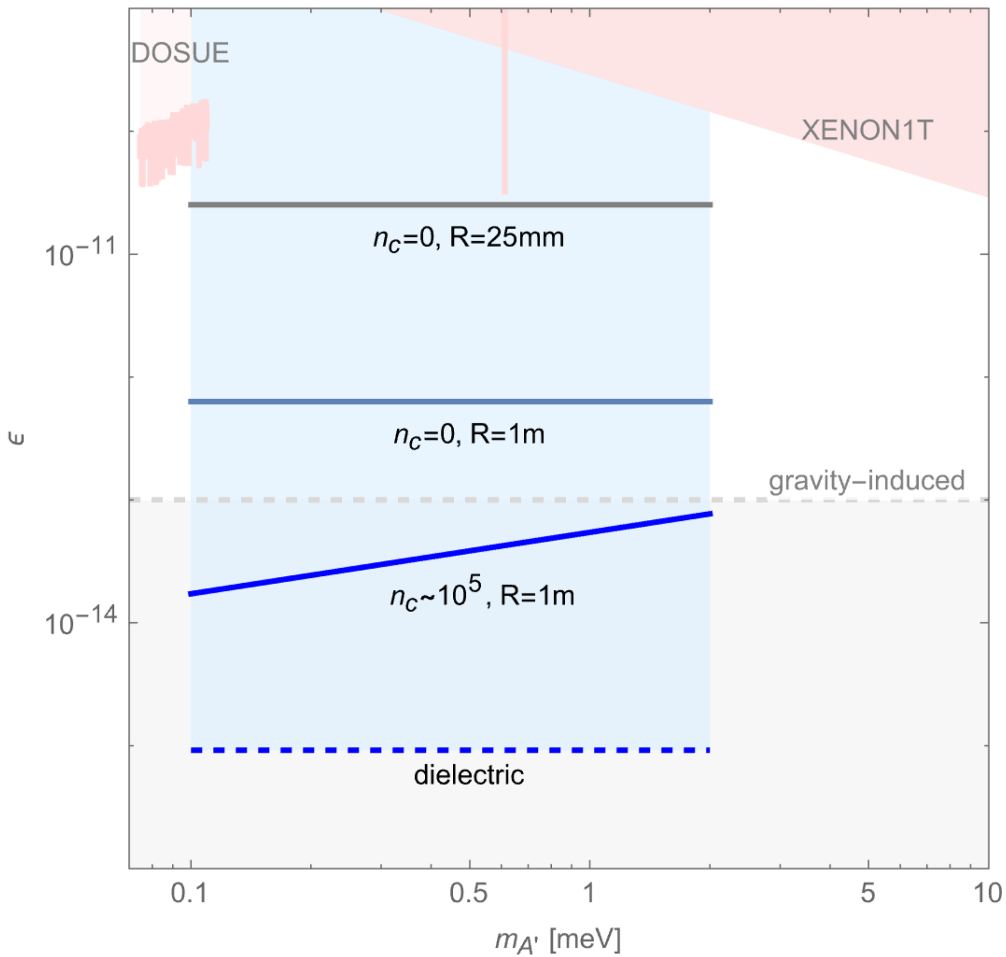
BREAD [Liu et al., 2111.12103]

Axion Projection



1000 days per decade

Dark Photon Projection



1000 days per decade

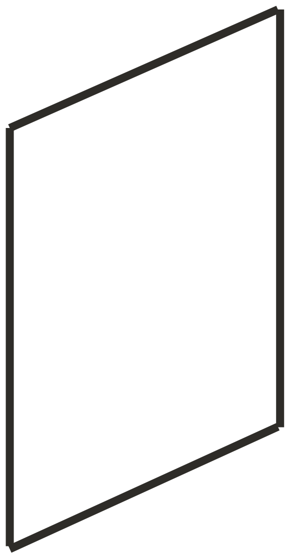
Thank You

Back Up Slides

Hamiltonian

- $H_0 = \omega_c \left(n_c + \frac{1}{2}\right) + \omega_z \left(n_z + \frac{1}{2}\right)$
- $H' = \delta \left(n_c + \frac{1}{2}\right)\left(n_z + \frac{1}{2}\right)$
- $[H_0, H'] = 0$

Effects of Cavity



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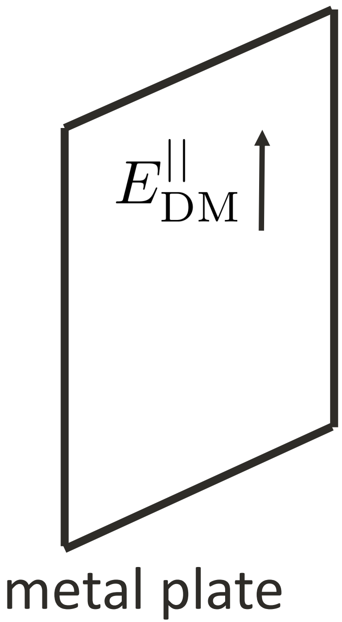

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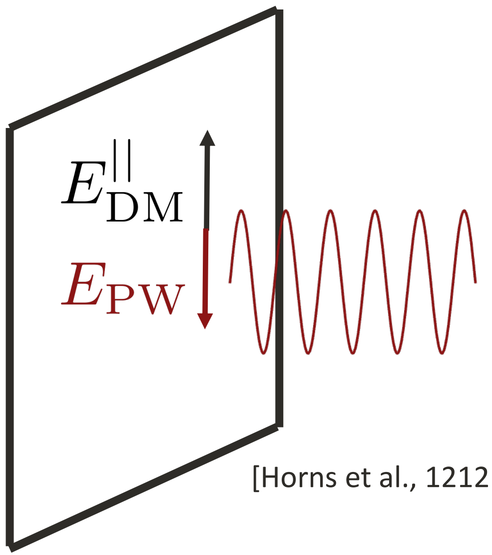
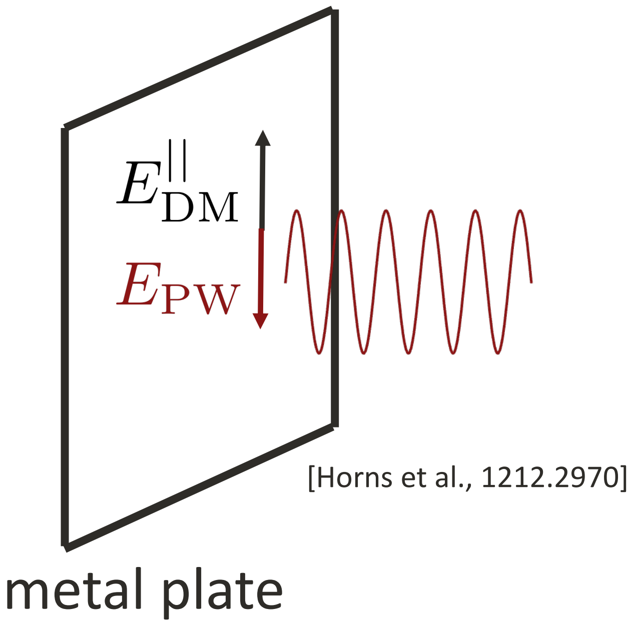
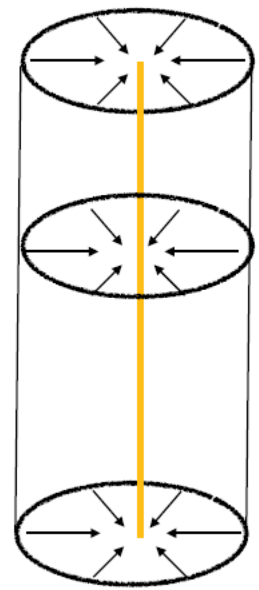


[Horns et al., 1212.2970]

metal plate

Focusing





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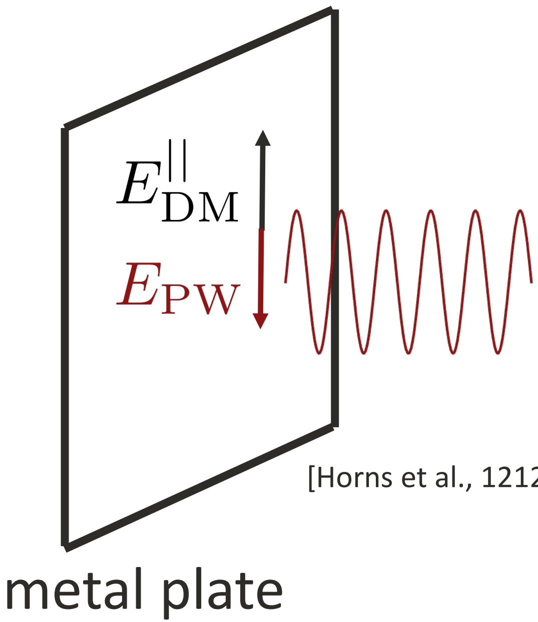

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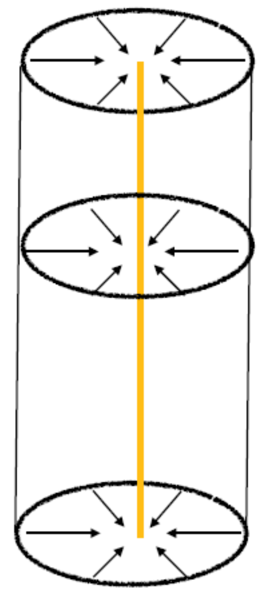

$$\kappa = \frac{E_{\mathrm{cavity}}(0)}{E_{\mathrm{free}}(0)} \qquad \kappa^2 \approx \frac{R}{m_{A'}^{-1}}$$

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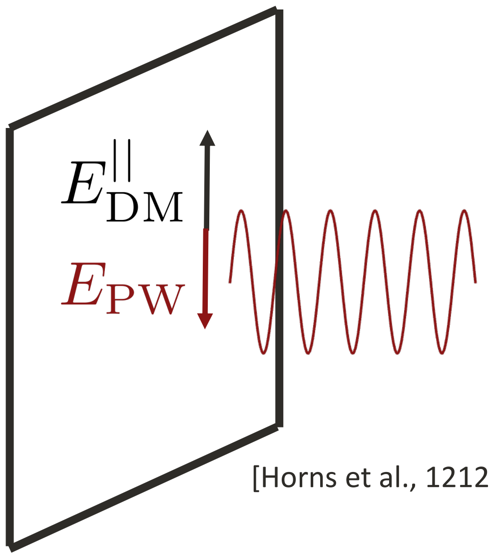

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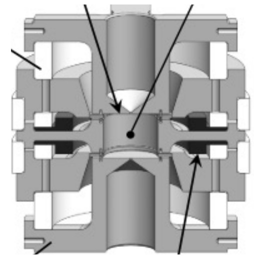

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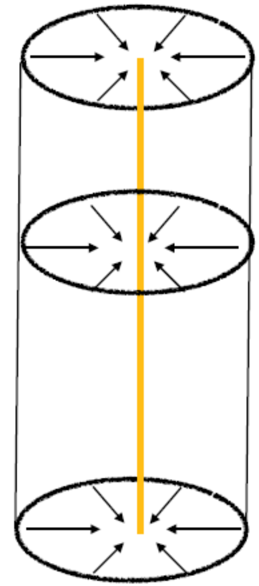

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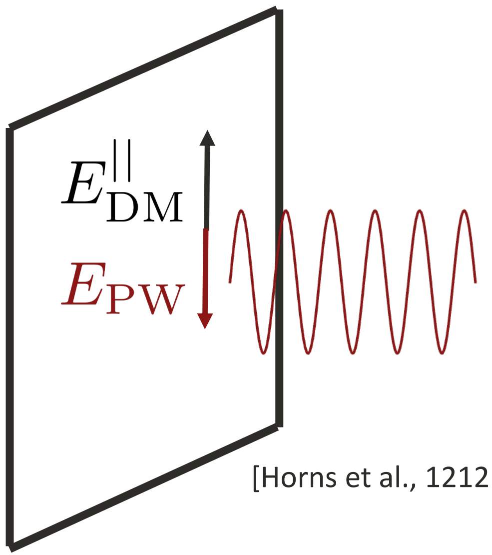

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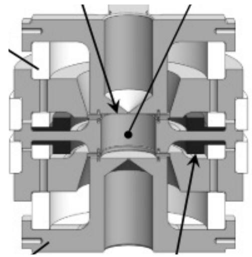

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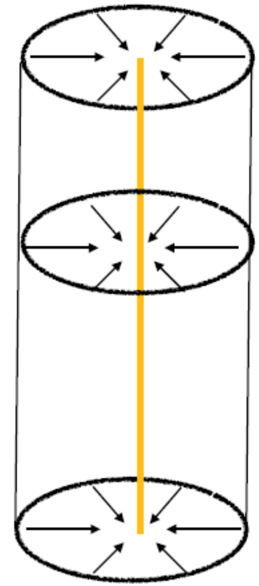

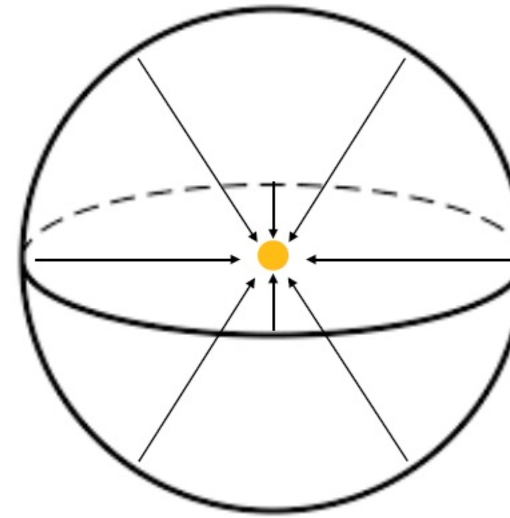

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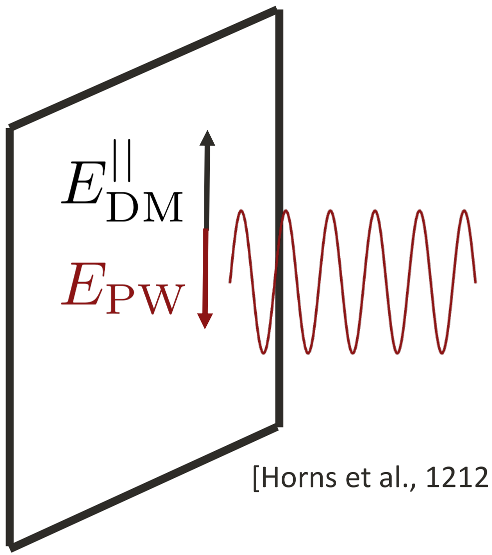
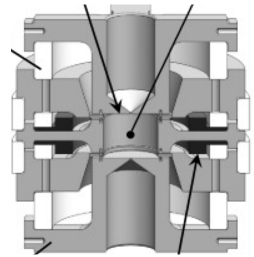
$$\kappa^2 \approx \left(\frac{R}{m_{A'}^{-1}}\right)^2$$

Focusing



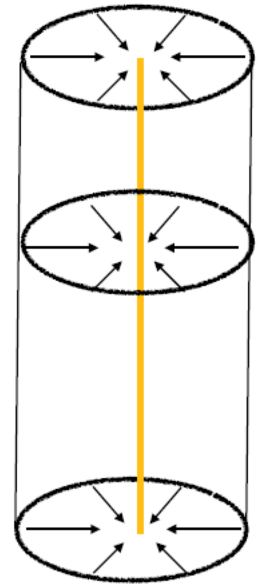
metal plate



[Horns et al., 1212.2970]

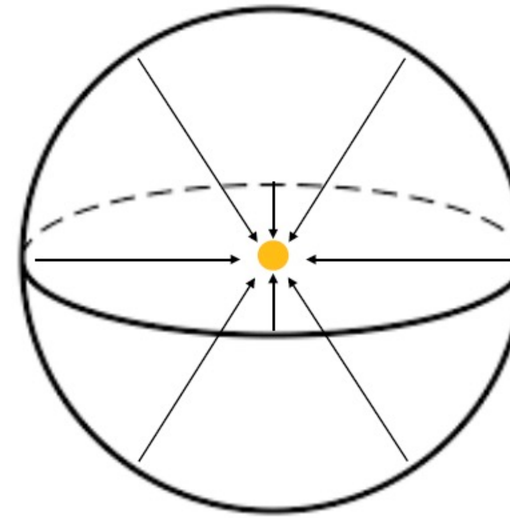
$$\kappa = \frac{E_{\mathrm{cavity}}(0)}{E_{\mathrm{free}}(0)}$$

$\kappa^2 \approx 2.4$



$$\kappa^2 \approx \frac{R}{m_{A'}^{-1}}$$

$\kappa^2 \approx 1600$



$$\kappa^2 \approx \left(\frac{R}{m_{A'}^{-1}}\right)^2$$

How to Improve?

- Only dark photon so far.
- For axion, scanning hurts magnetic field: $\omega_c = \frac{eB}{m_e}$
- Cyclotron transition rate:

$$\Gamma_c \propto \kappa^2 (n_c + 1) \epsilon^2 \rho_{DM} \times N_l^2$$

2. effects of cavity (κ^2)

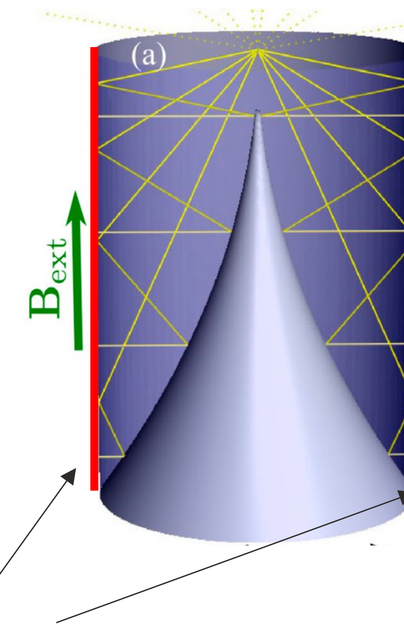
1. excited states (n_c)

3. dielectric conversion enhancement (N_l^2)

enhancement in detection (1 and 2)

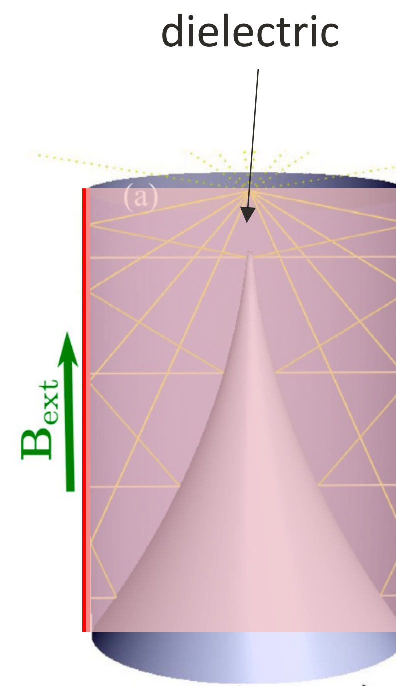
Dielectric Conversion Enhancement

- So far, only a thin layer of metal is converting axion



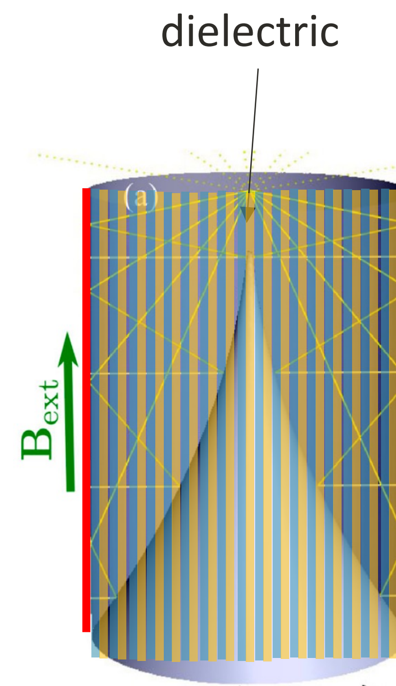
Dielectric Conversion Enhancement

- So far, only a thin layer of metal is converting axion
- What if the entire volume is filled with converting material?
- Needs to be transparent to photons: dielectric!



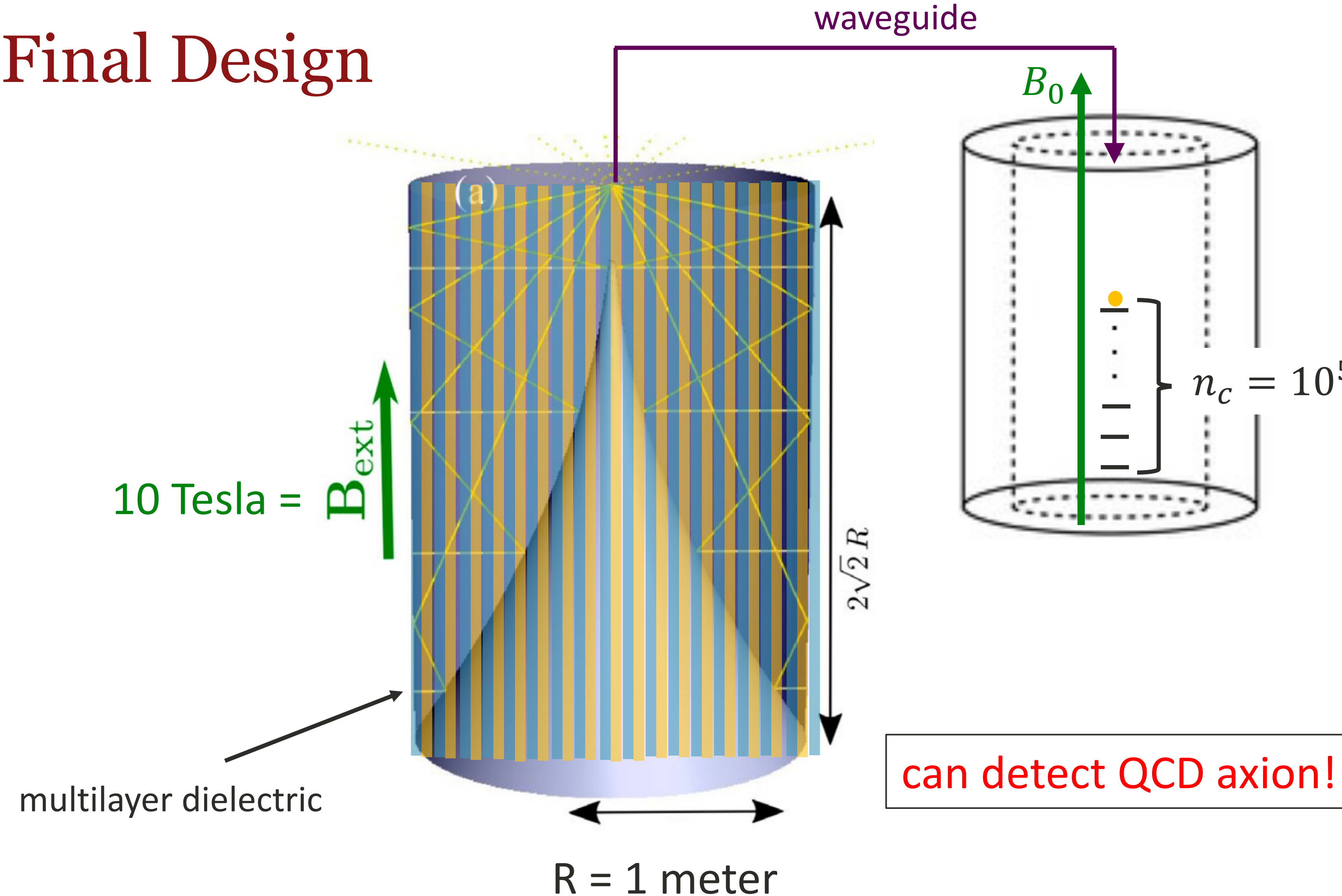
Dielectric Conversion Enhancement

- So far, only a thin layer of metal is converting axion
- What if the entire volume is filled with converting material?
- Needs to be transparent to photons: dielectric!
- Layers of dielectrics of alternating indices of refraction
- Resonance conversion to axion if thickness ≈ axion wavelength
- Limited by size of cavity and how often we switch dielectrics to scan frequency (once a month)



Baryakhtar et. al [1803.11455]

Final Design



can detect QCD axion!