Electron Trap as an Axion Dark Matter Detector

Samuel Wong

July 10, 2024

IDM2024, L'Aquila, Italy

2208.06519 and 2407.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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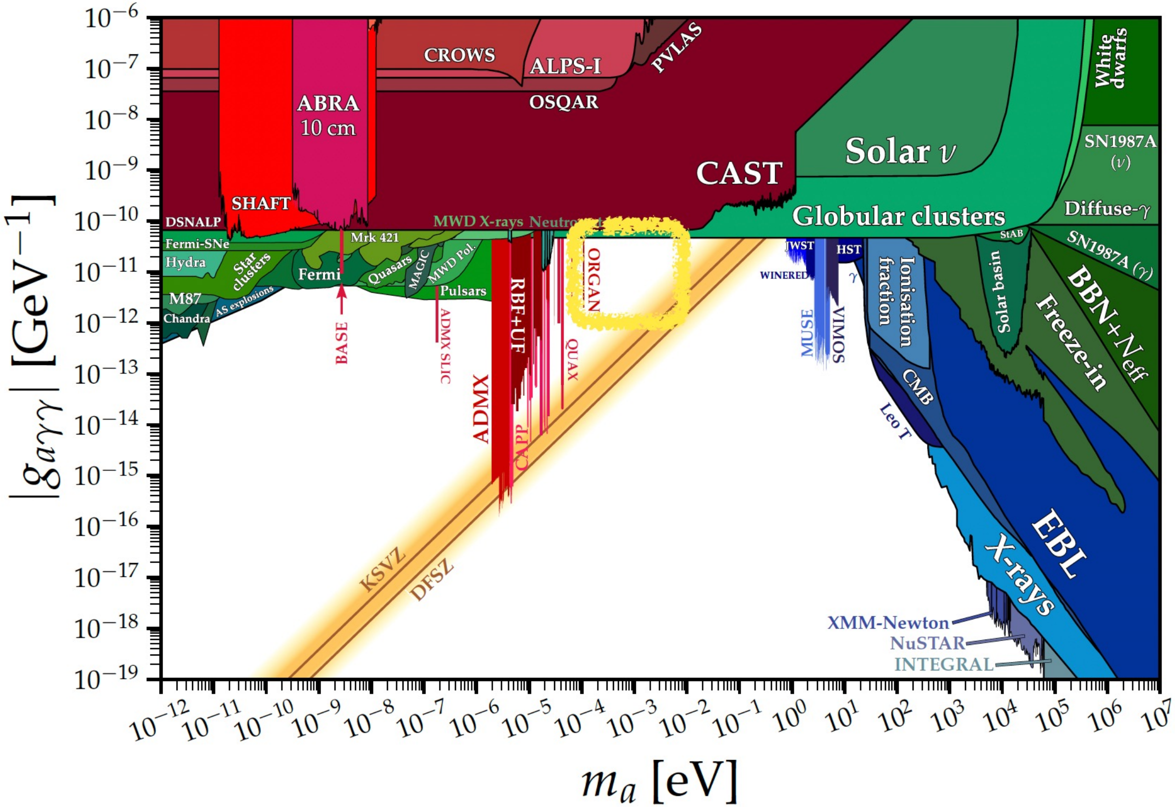
Axion Parameter Space



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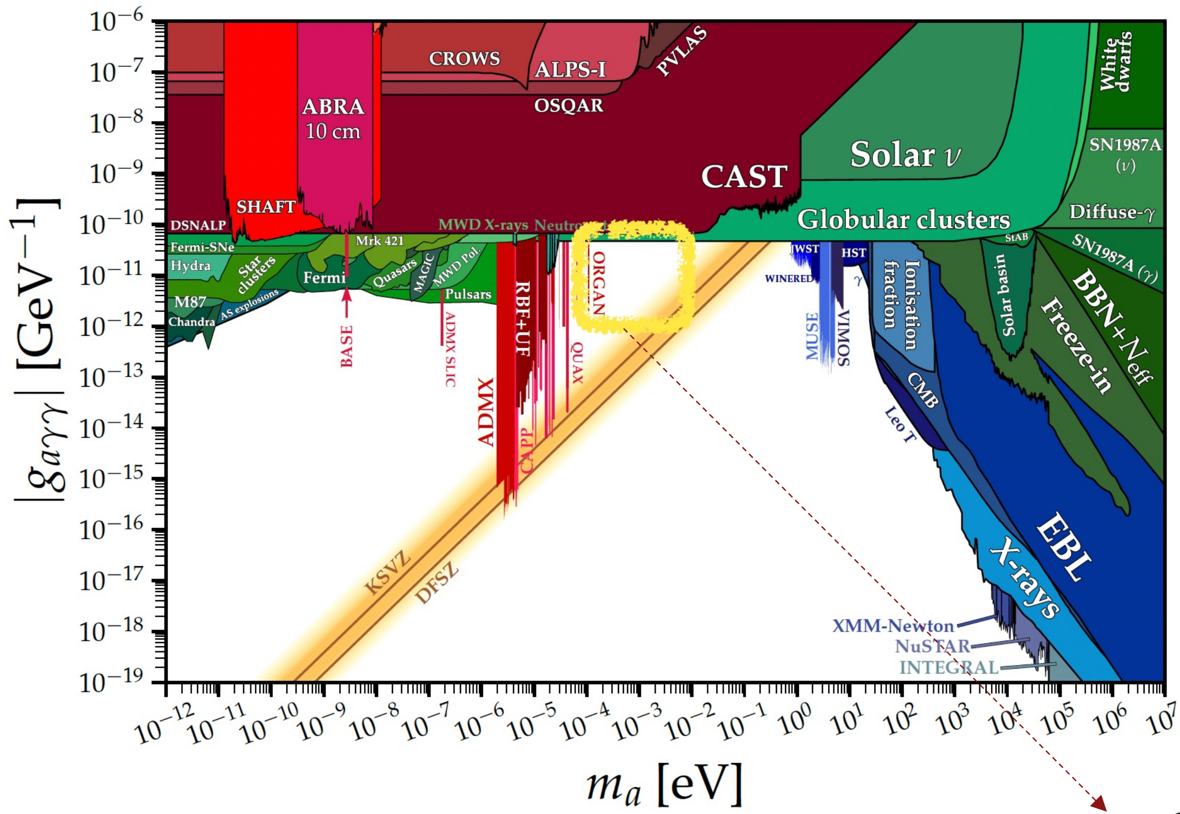
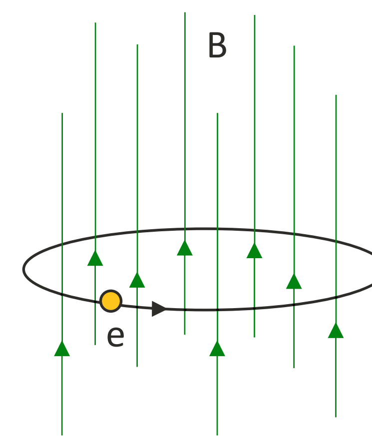
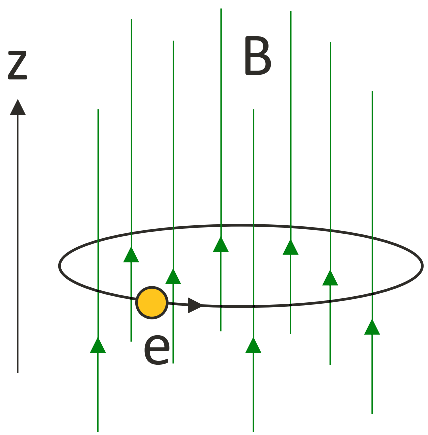




electron cyclotron motion

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

Electron Penning Trap



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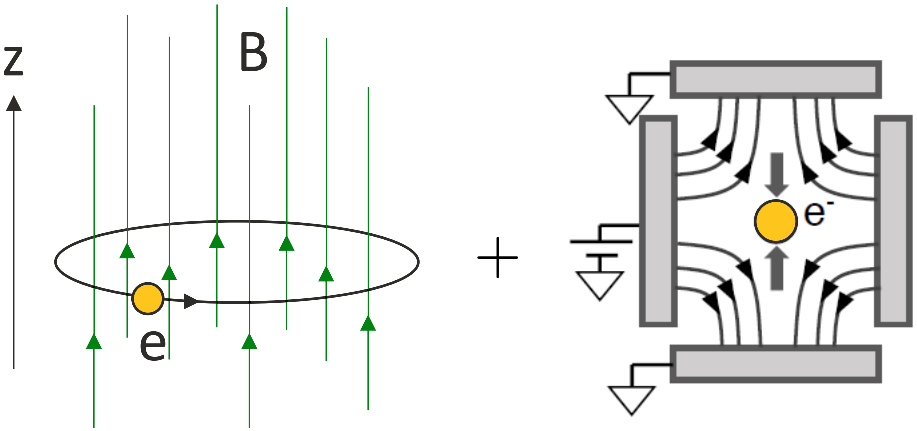

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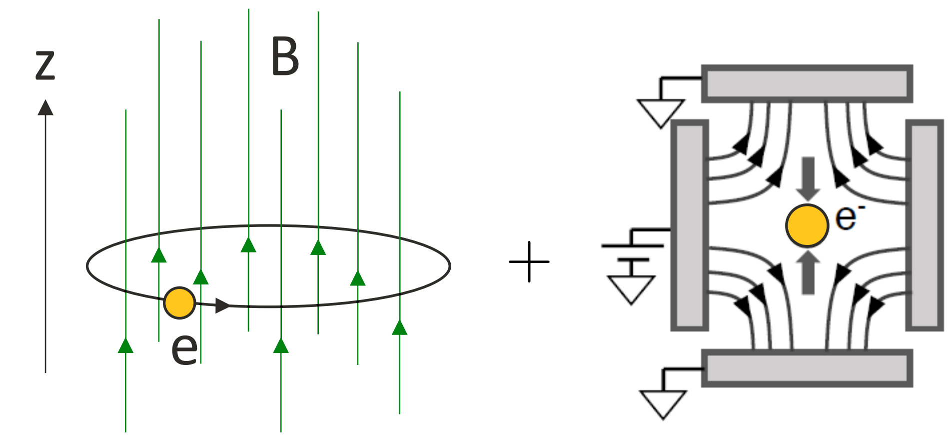

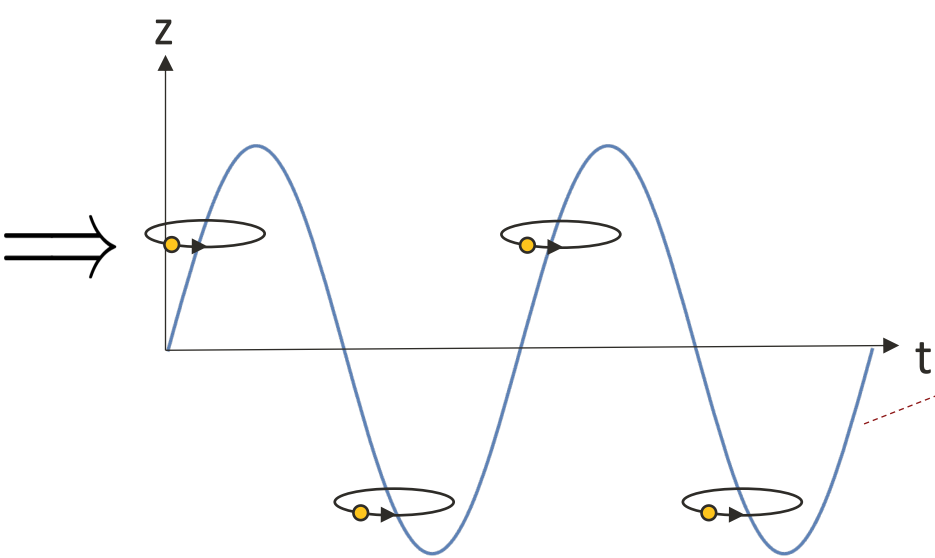

axial oscillation

⟹ classical image current

$\omega_z \sim 100$ MHz

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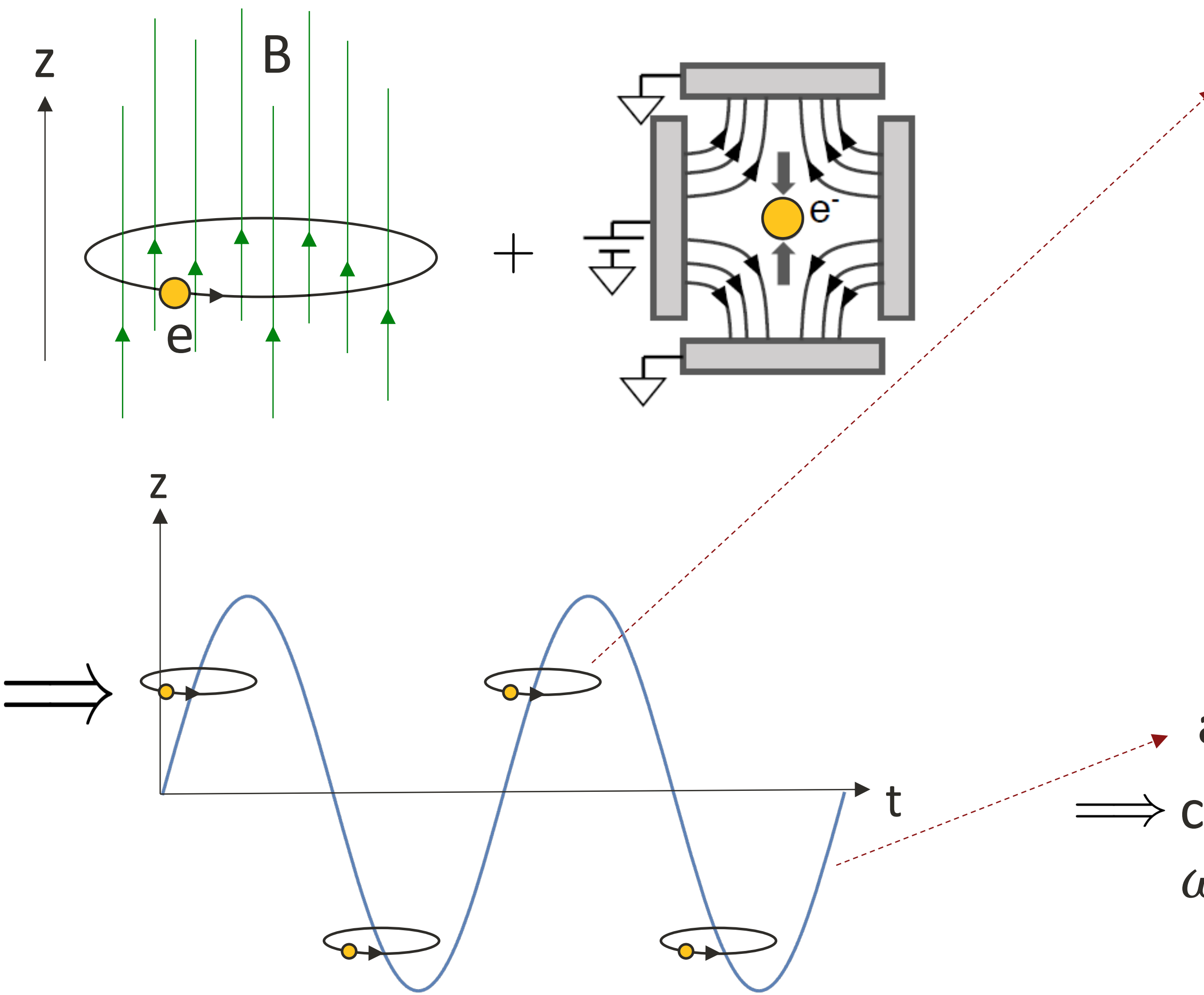
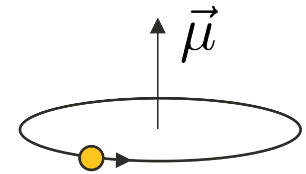


cyclotron motion



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$\Longrightarrow$ classical image current

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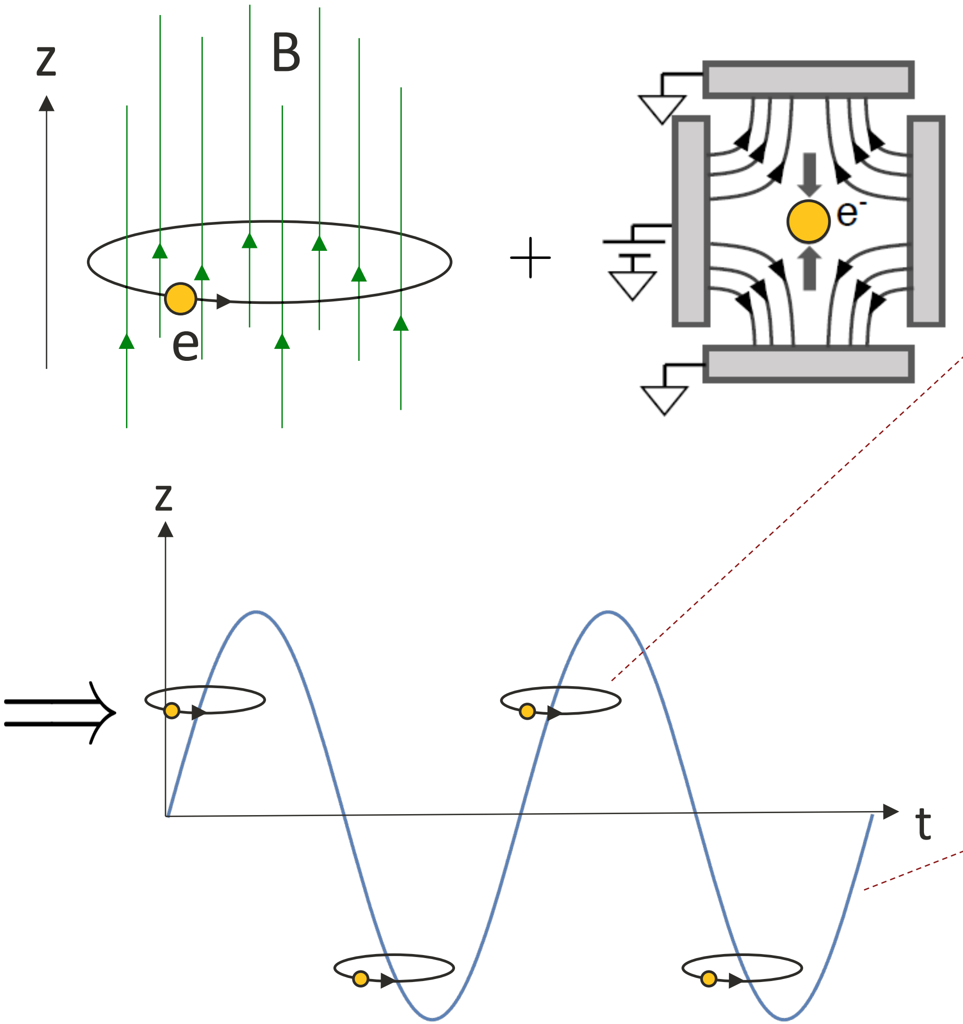

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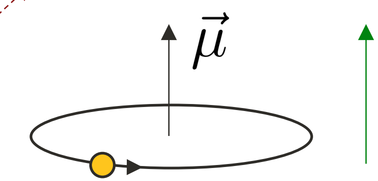

$\Delta B \propto z^2$

axial oscillation

$\Longrightarrow$ classical image current

$\omega_z \sim 100$ MHz

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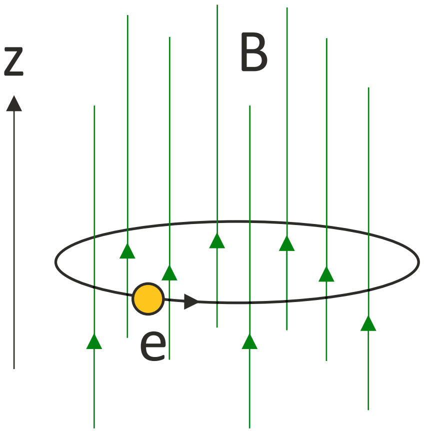

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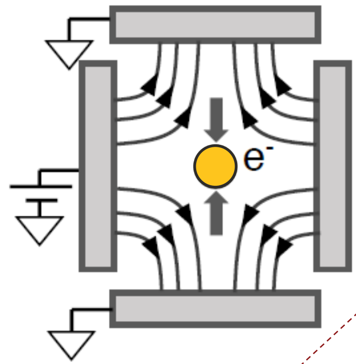

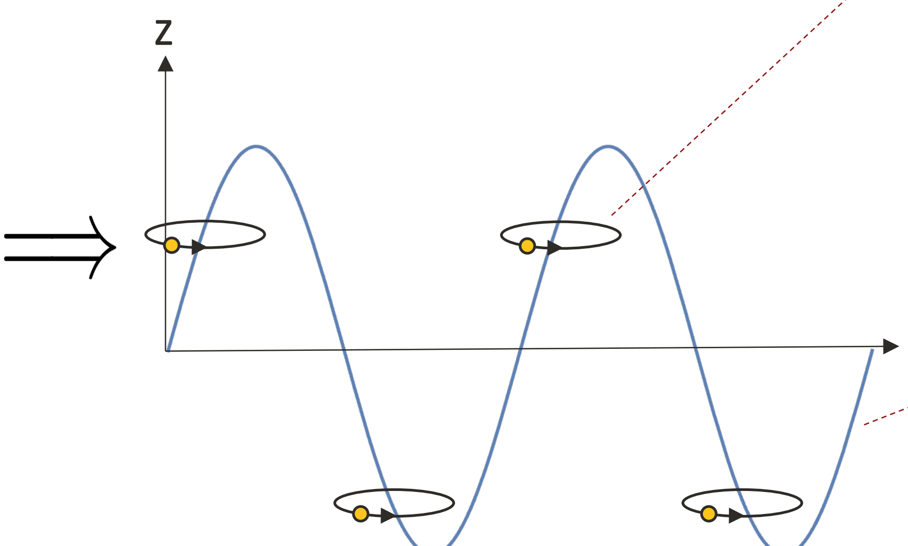

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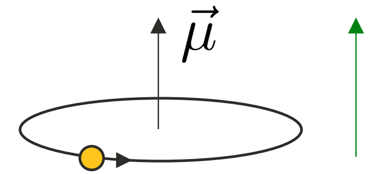


$\Delta B \propto z^2$

$\Longrightarrow$ quantized axial frequency shifts

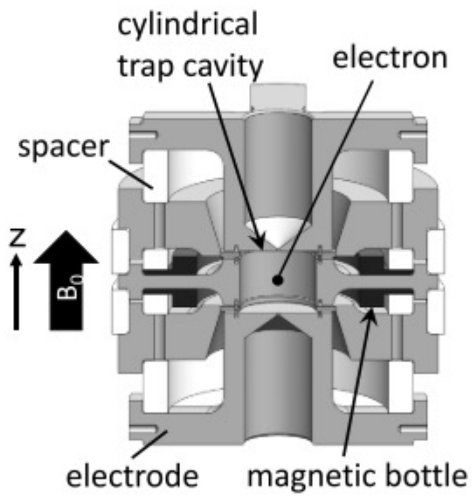
$$\omega_z \to \omega_z + n_c\delta$$

axial oscillation

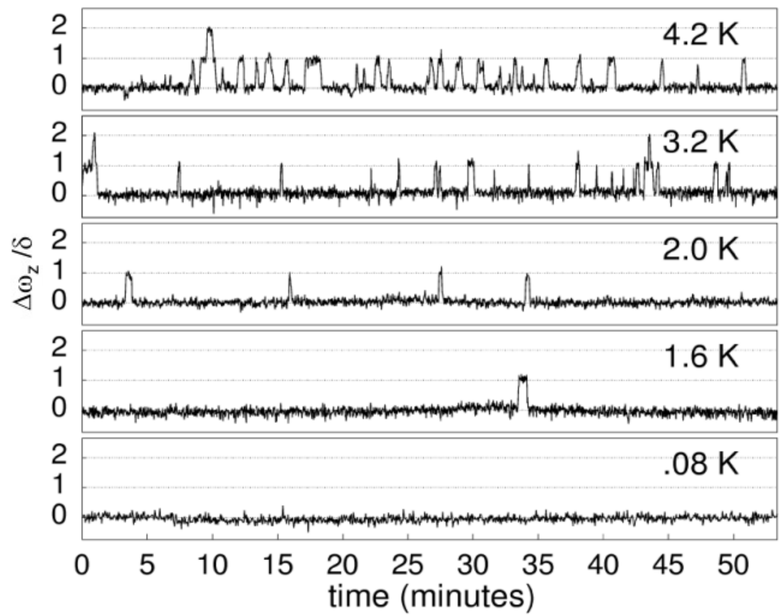
$\Longrightarrow$ classical image current

$\omega_z \sim$ 100 MHz

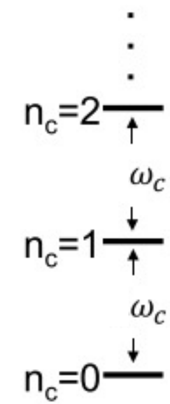
Electron Penning Trap



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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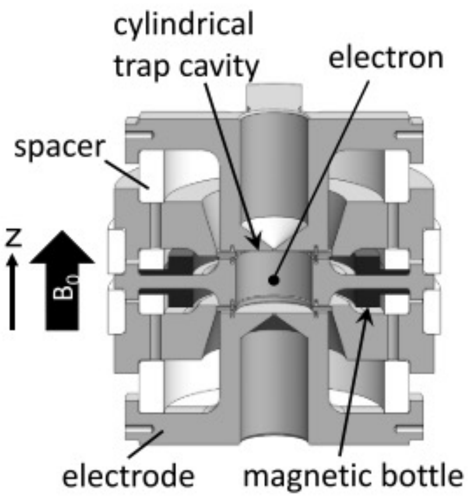

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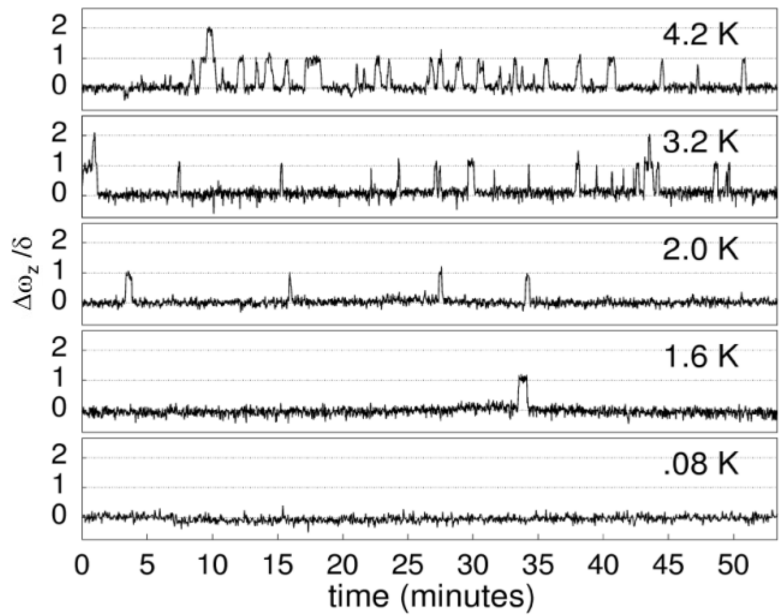

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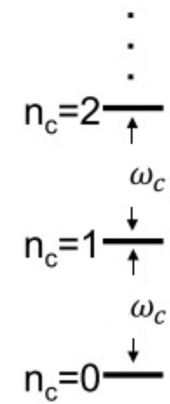
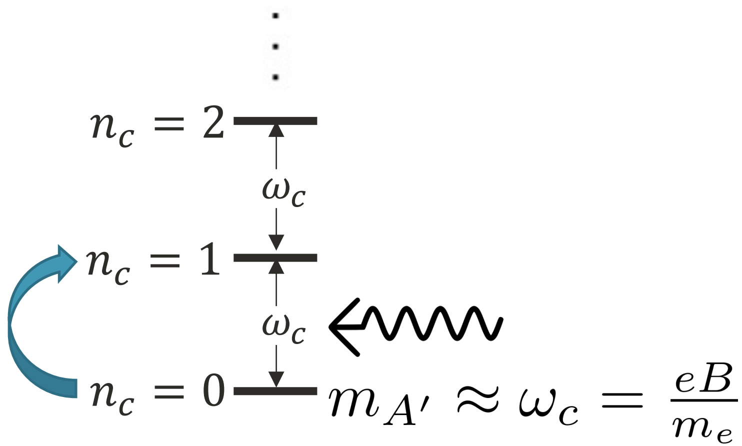


$$\omega_z \to \omega_z + n_c\delta$$

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

Resonant Detection of Dark Photon



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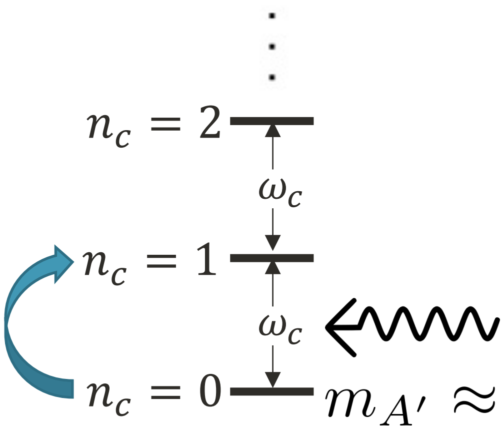

$$m_{A'} \approx \omega_c = \frac{eB}{m_e}$$

Scan B-field (0.1 – 2 meV)

thermal background

B = 20 Tesla

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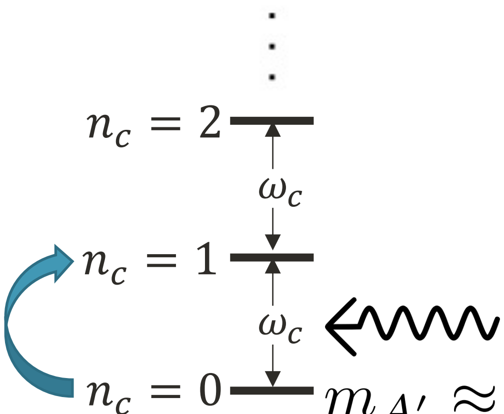

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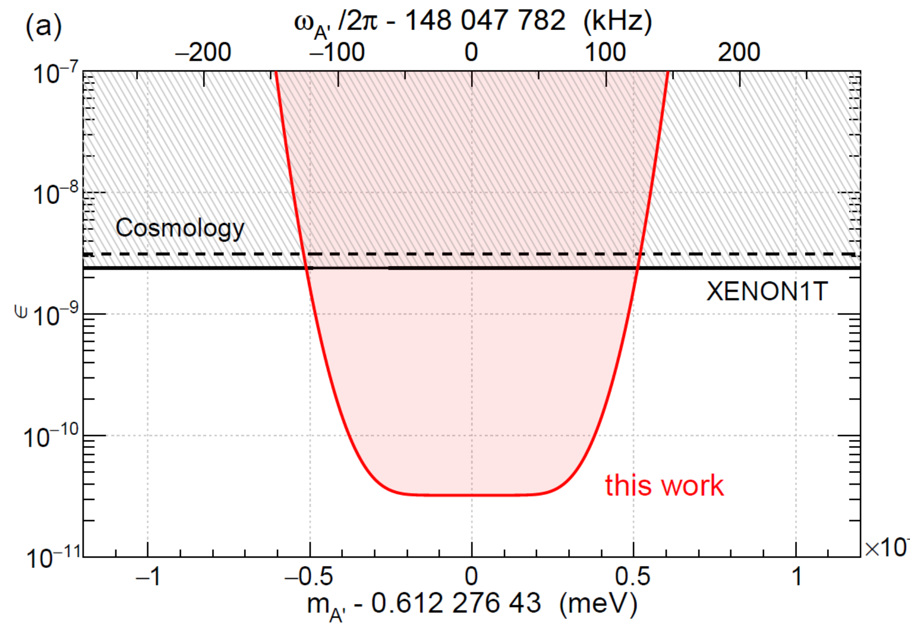

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[2208.06519]
Published in PRL

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2. effects of cavity (κ^2)

1. excited states (n_c)

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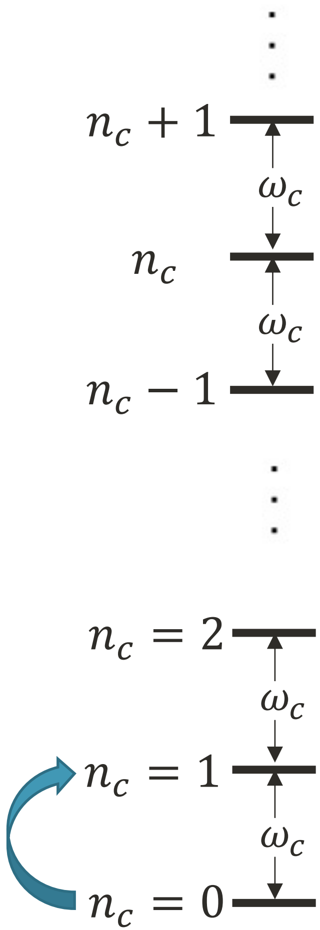
Highly Excited State



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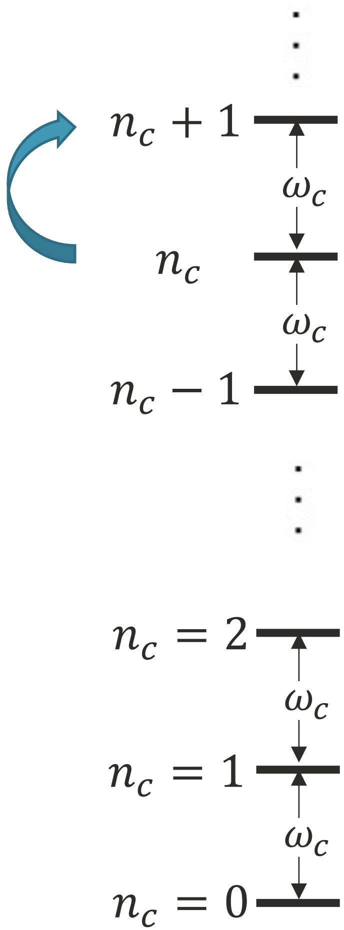

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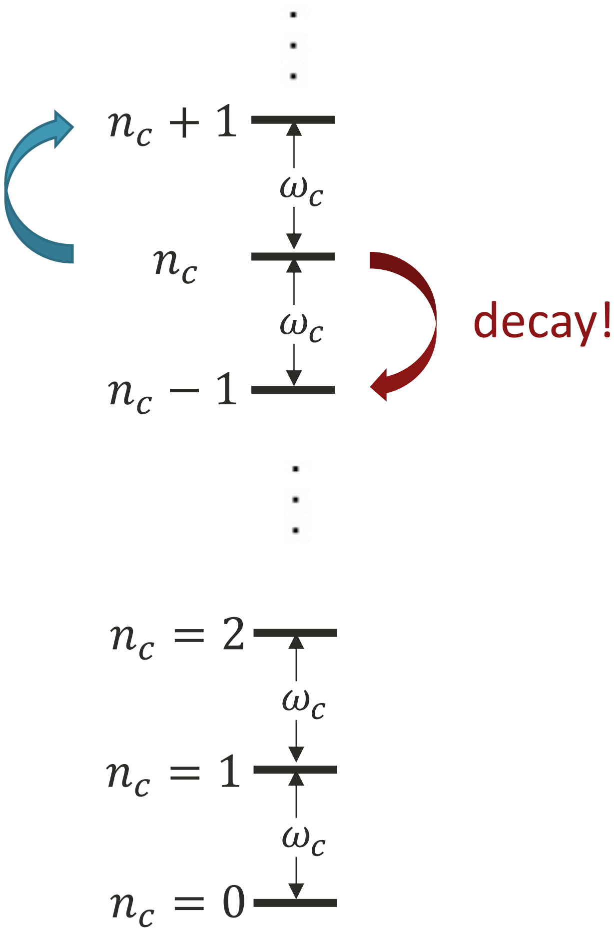

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$$\tau_c \approx \frac{1}{n_c} 3\ s$$

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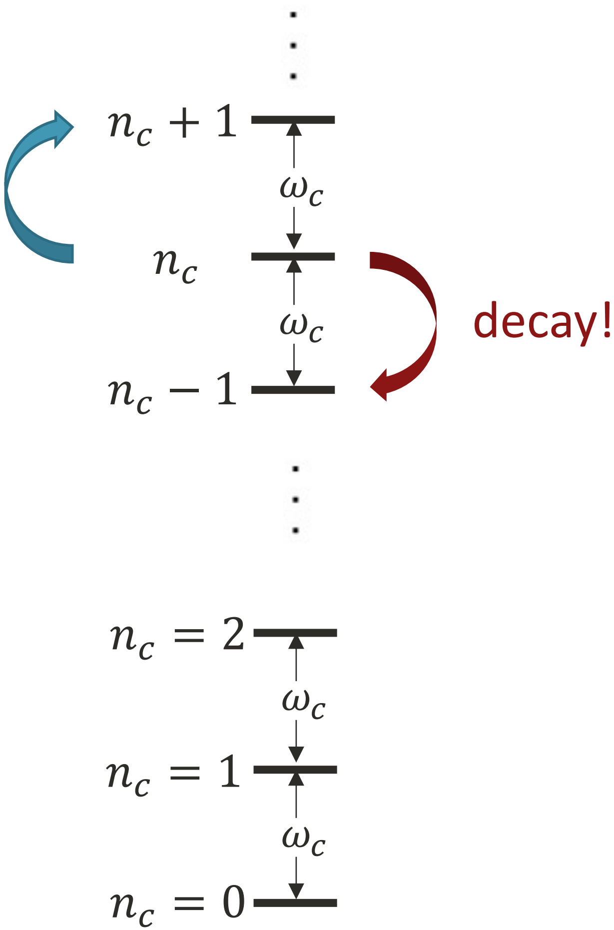

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- "State of the arts":

$$t_{ave} \approx 2\ s$$

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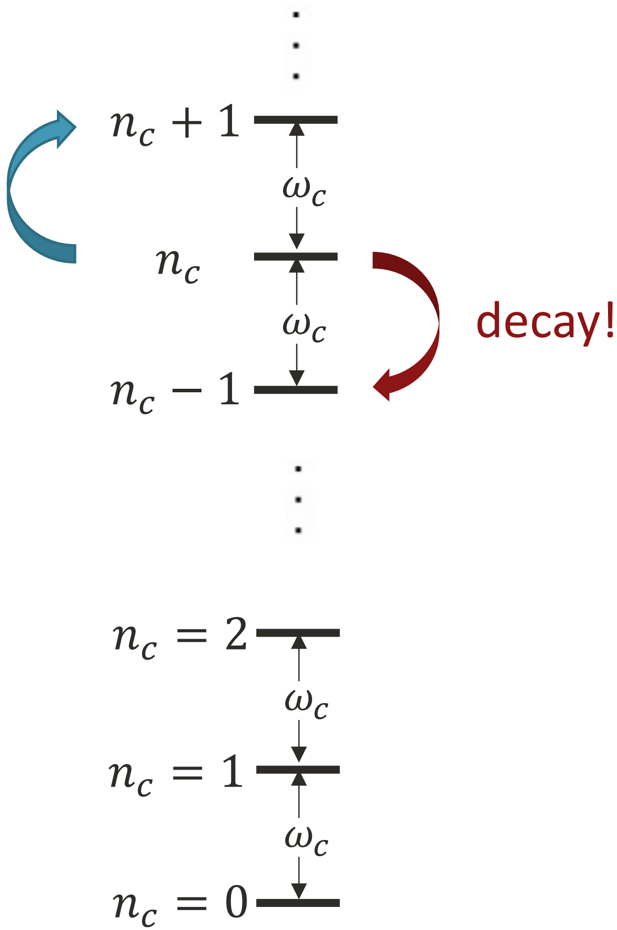

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- Theoretical minimum:

$$t_{ave} \approx 3 \times 10^{-6} s$$

$$\Longrightarrow \boxed{n_c \approx 10^6}$$

Experimental Parameters

- Lowering averaging time by 10^6 is difficult!

parameter	symbol	optimal	lower limit	upper limit
external magnetic field	B_{ext}	10 T	N/A	BREAD experiment
cavity size	R	1 m	BREAD experiment	
perturbation magnetic field	$\tilde{B}_2$	0.27 T	N/A	maximum magnetic field
bottle size	R_{bot}	0.5 mm	fabrication technique	N/A
magnetic field gradient	B_2	1.08×10^6 T/m^2	$B_2 = \frac{\tilde{B}_2}{R_{\text{bot}}^2}$	
axial amplitude	$z_{\max}$	0.2 mm	N/A	R_{bot} (diffraction & B_2 anharmonicity)
trap radius and height	R_{trap}	0.5 mm	axial anharmonicty	R_{bot}
trap height	d	1.02 mm	$d = 2.0478 R_{\text{trap}}$ (axial anharmonicity [100])	
static trapping potential	V_0	4 mV	trapping in axial direction	power supply
axial frequency	$\frac{\omega_z}{2\pi}$	9.8 MHz	$\omega_z = \sqrt{\frac{4eV_0}{m_e(R_{\text{trap}}^2 + \frac{1}{2}d^2)}}$	
axial frequency shift	$\frac{\delta}{2\pi}$	56.9 kHz	$\delta = \frac{eB_2}{m_e^2 \omega_z}$	
signal formation time	t_{signal}	2.8×10^{-6} s	$t_{\text{signal}} = \frac{1}{\delta}$	
detector quality factor	Q_{det}	2.9×10^4	$Q_{\text{det}} \leqslant 2.8 \times 10^5 \left(\frac{1\text{ MHz}}{\omega_z/2\pi}\right)$	
quality factor efficiency	q	0.0061	$q = \frac{Q_{\text{det,eff}}}{Q_{\text{det}}}$	
detector damping rate	$\frac{\gamma_{\text{det}}}{2\pi}$	56.2 kHz	$\gamma_{\text{det}} = \frac{\omega_z}{Q_{\text{det,eff}}}$	
detection time	t_{det}	2.8×10^{-6} s	$t_{\text{det}} = \frac{1}{\gamma_{\text{det}}}$	
circuit capacitance	C	7.43×10^{-12} F	material property	N/A
circuit inductance	L	3.54×10^{-5} H	satisfying $\frac{1}{\sqrt{LC}} = \omega_z$	
circuit effective resistance	R_{eff}	380kΩ	$R_{\text{eff}} = q \times \frac{Q_{\text{det}}}{C} \frac{1}{\omega_z}$	
image charge parameter	d_1	0.9	depends on the aspect ratio $\frac{d}{R_{\text{trap}}}$ [100]	
axial damping rate	$\frac{\gamma_z}{2\pi}$	1.4 kHz	$\gamma_z = \frac{1}{m_e}\left(\frac{ed_1}{d}\right)^2 R_{\text{eff}}$	
circuit temperature	T_R	0.01K	cryogenic technology	N/A
axial energy	E_z	0.43 meV	$E_z = \frac{1}{2} m_e \omega_z^2 z_{\max}^2$	
signal to noise ratio	SNR	5	background	N/A
SNR time	t_{SNR}	2.87×10^{-6} s	$t_{\text{SNR}} = \frac{\text{SNR}^2 T_R}{2E_z \gamma_z}$	
averaging time	t_{ave}	2.87×10^{-6} s	$\max(t_{\text{signal}}, t_{\text{det}}, t_{\text{SNR}})$	τ_c
cyclotron lifetime	τ_c	$2.87 \times 10^{-6}\text{ s}\left(\frac{1.2 \times 10^6}{n_c}\right)\left(\frac{0.1\text{ meV}}{\omega_c}\right)^2$	$\tau_c = \frac{1}{n_c} \frac{3m_e}{4\alpha\omega_c^2}$	
cyclotron number	n_c	$1.2 \times 10^6 \left(\frac{0.1\text{ meV}}{\omega_c}\right)^2$	N/A	
cyclotron linewidth	$\Delta\omega_c$	5×10^{-3} meV	$\Delta\omega_c = \omega_c \frac{B_2}{B_0} z_{\max}^2 + \frac{1}{\tau_c}$	
cyclotron quality factor	Q_c	$20 \sim 200$	$Q_c = \frac{\omega_c}{\Delta\omega_c}$	
total detecting time	t_{total}	1000 days	N/A	N/A
detecting time per frequancy bin	t_{obs}	5.5 days	$t_{\text{obs}} = t_{\text{total}} \frac{\Delta\omega_c}{m_{A',\max} - m_{A',\min}}$	

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2. effects of cavity

1. excited states

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

BREAD

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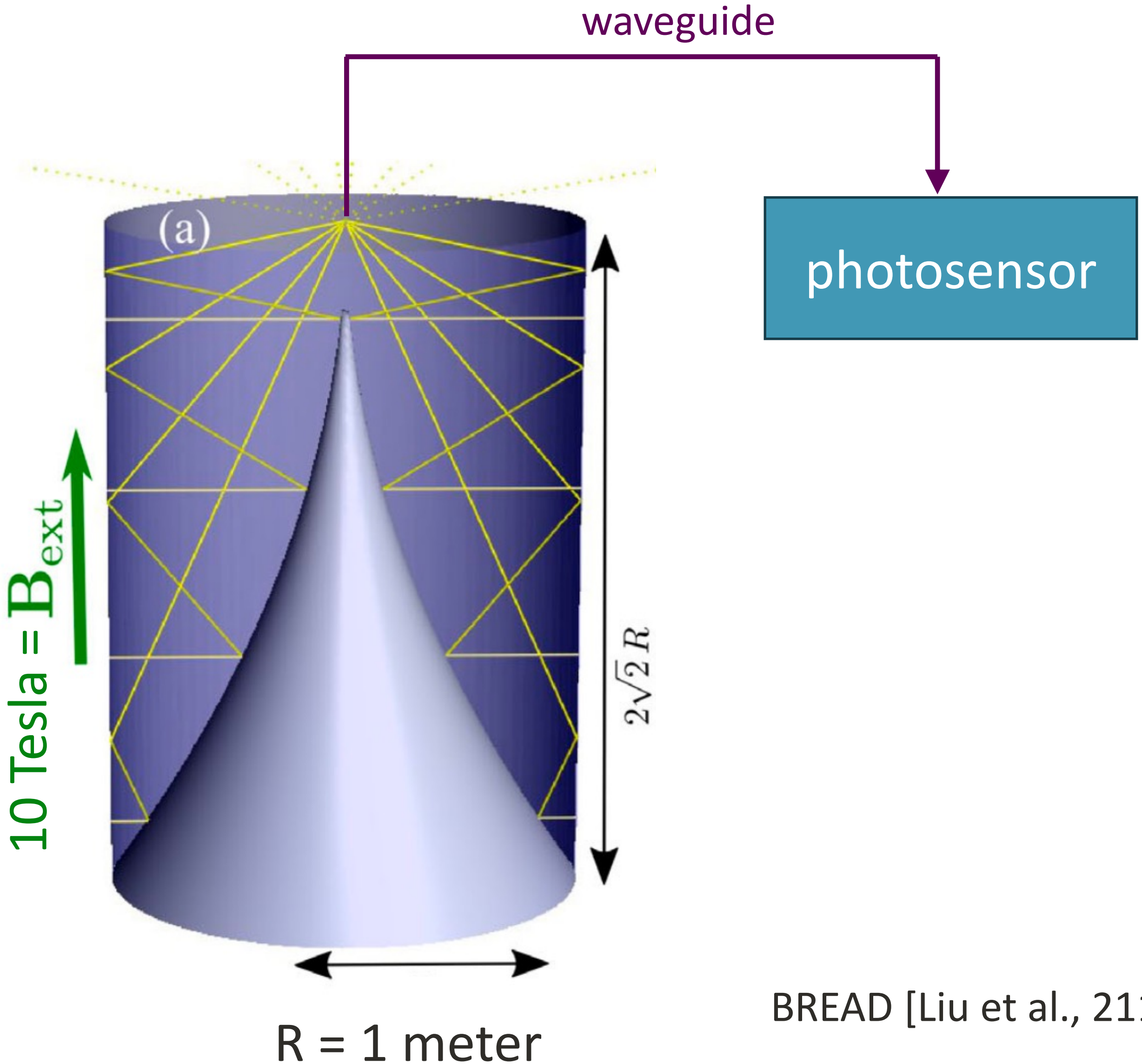
$$= \frac{surface\ area}{m_a^{-2}}$$

$$\approx 10^6$$



BREAD [Liu et al., 2111.12103]

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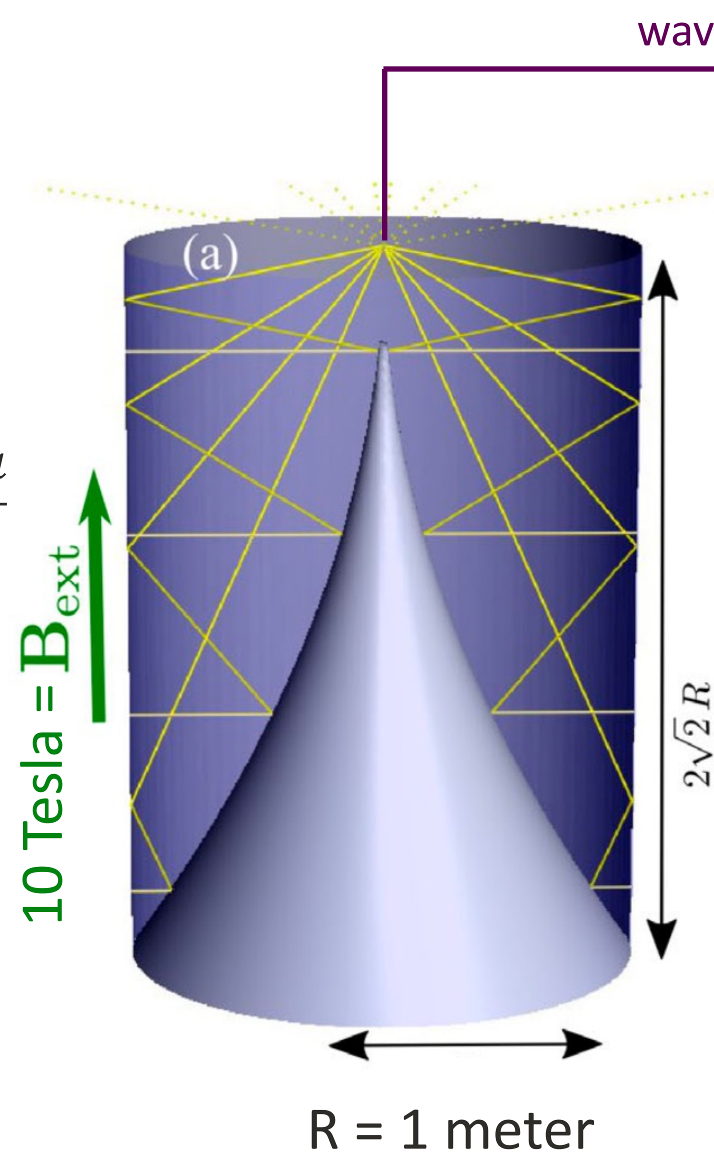

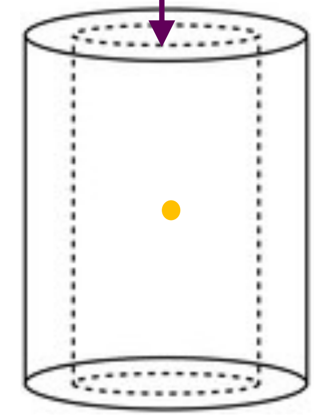

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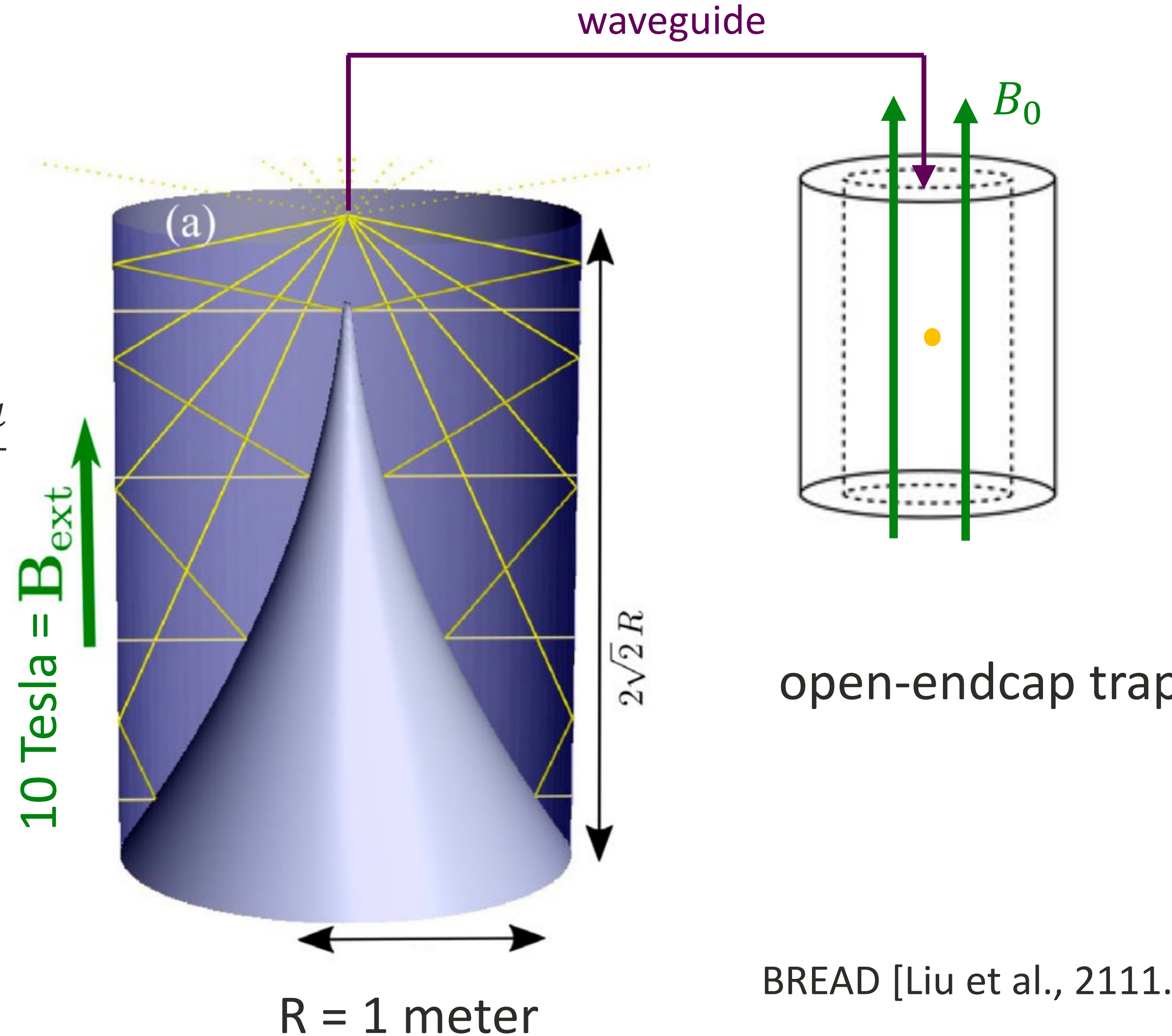

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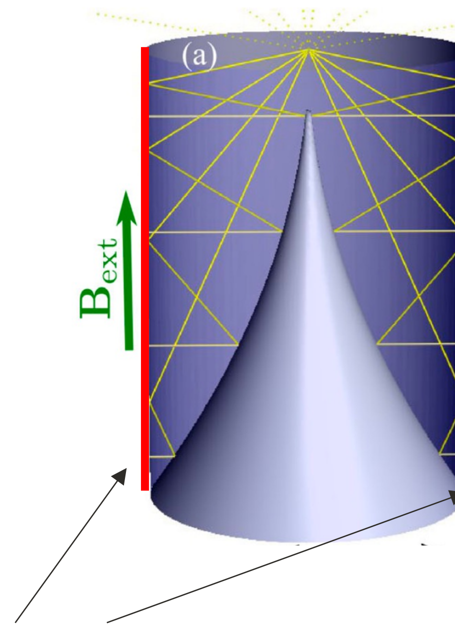
3. dielectric conversion enhancement

enhancement in detection

Dielectric Conversion Enhancement

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



converting metal

Dielectric Conversion Enhancement

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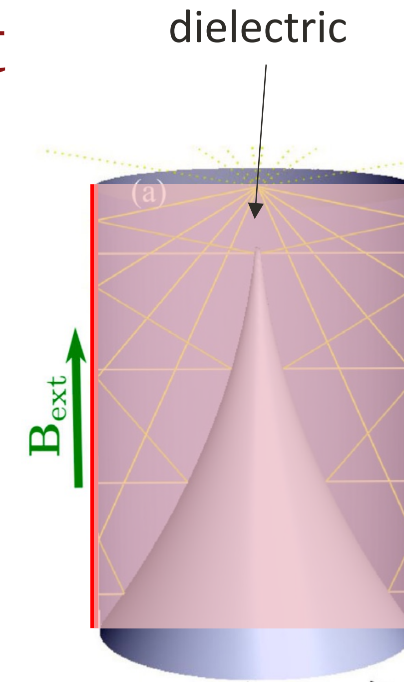
- What if the entire volume is filled with converting material?
- Needs to be transparent to photons: dielectric!



Dielectric Conversion Enhancement

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- What if the entire volume is filled with converting material?
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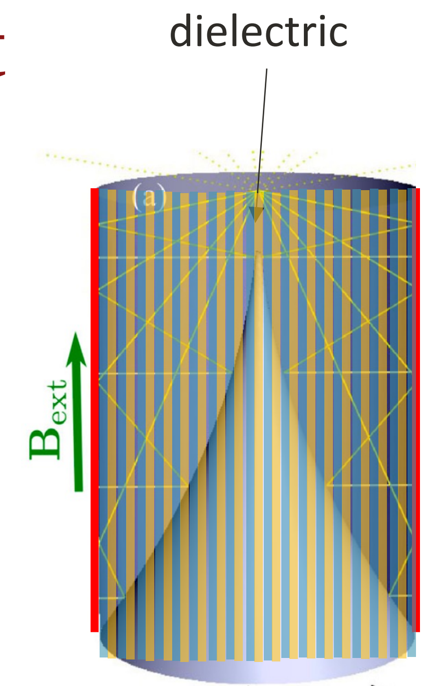
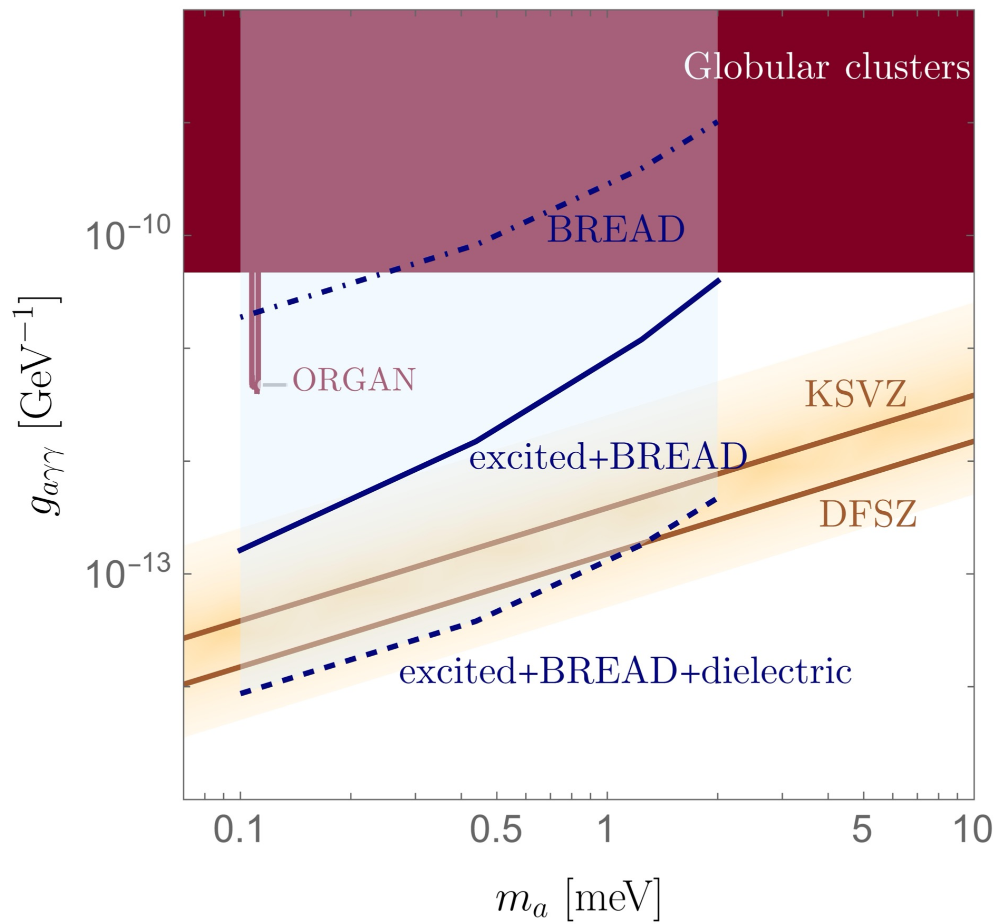
- Layers of dielectrics of alternating indices of refraction
- Resonance conversion to axion if thickness ≈ axion wavelength
- Limited by size of cavity and how often we switch dielectrics to scan frequency (once a month)



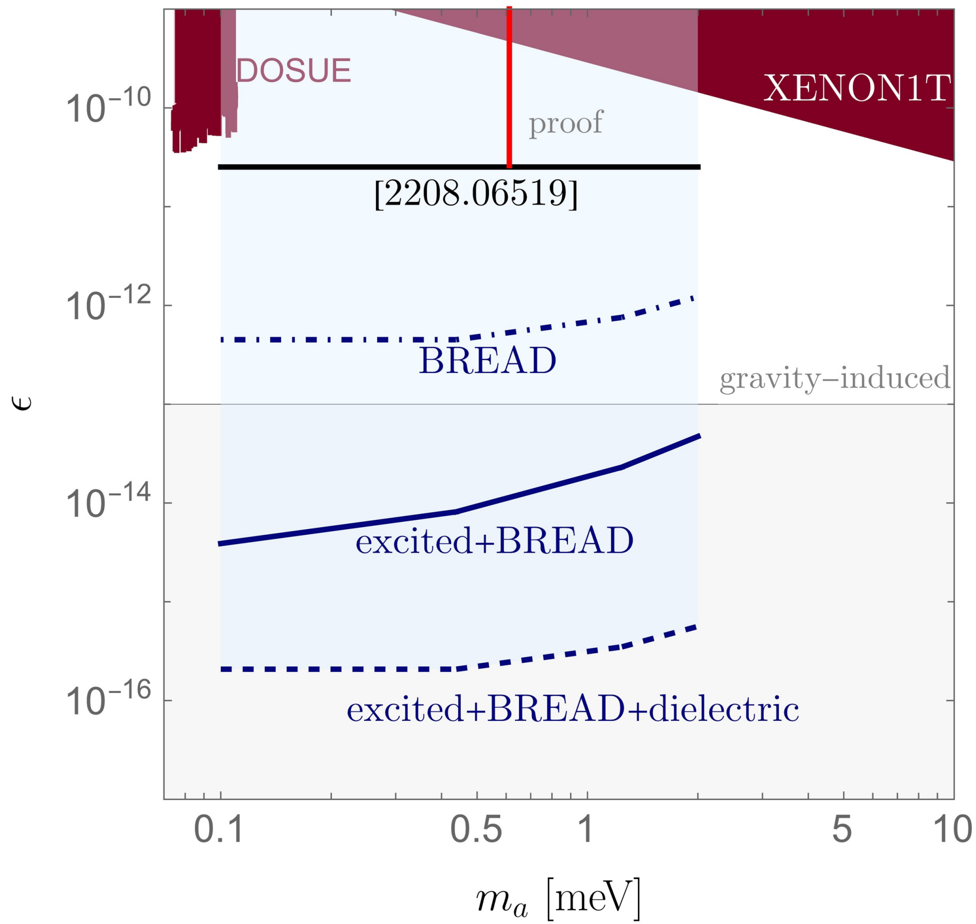
Baryakhtar et. al [1803.11455]

Axion Projection



1000 days per decade

Dark Photon Projection



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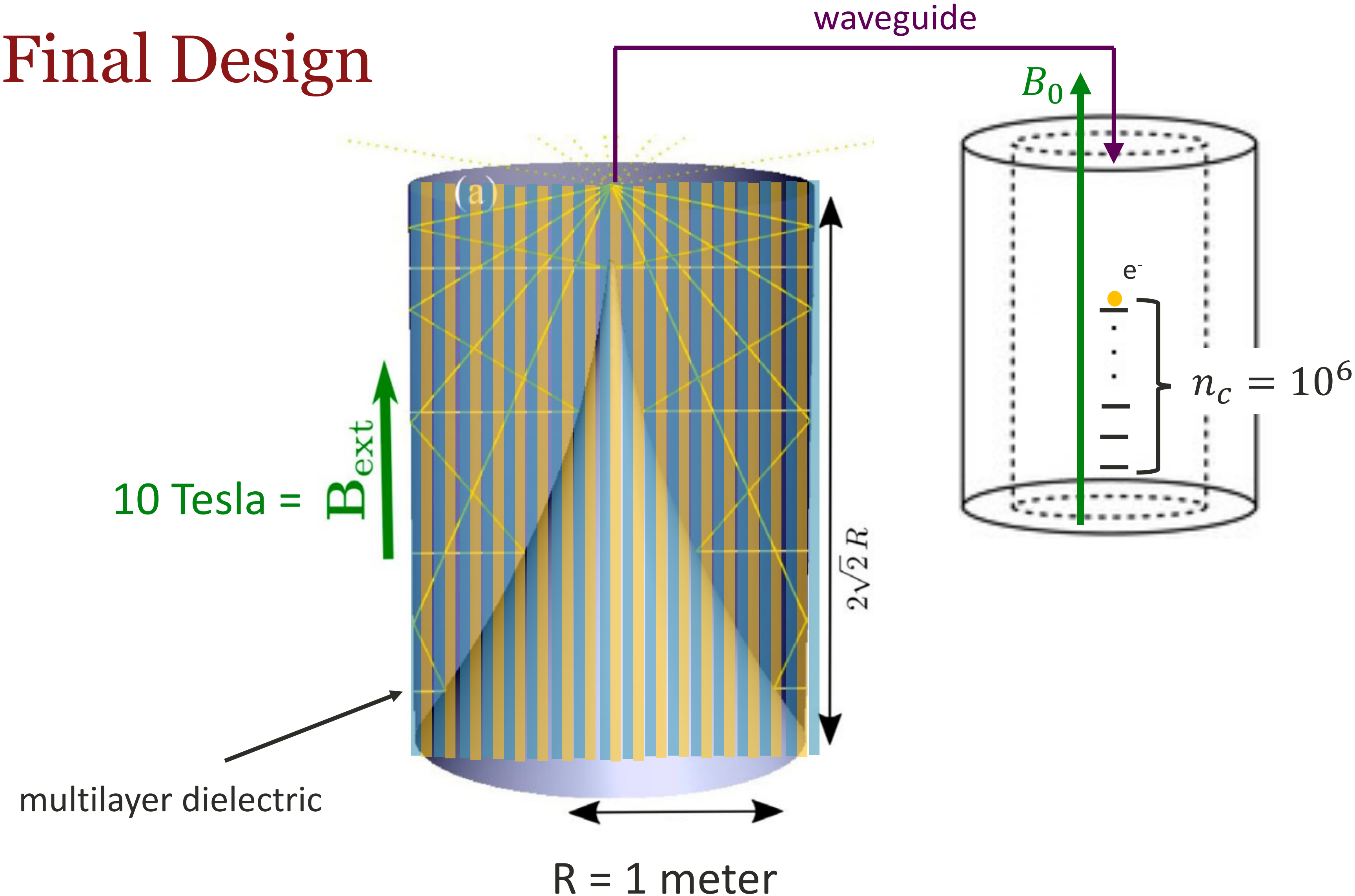
Final Design



Thank You

Back Up Slides

Hamiltonian

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