Electron Trap as a meV Axion and Dark-Photon Dark Matter Detector

Yawen Xiao

Aug 26, 2024

TeVPA 2024

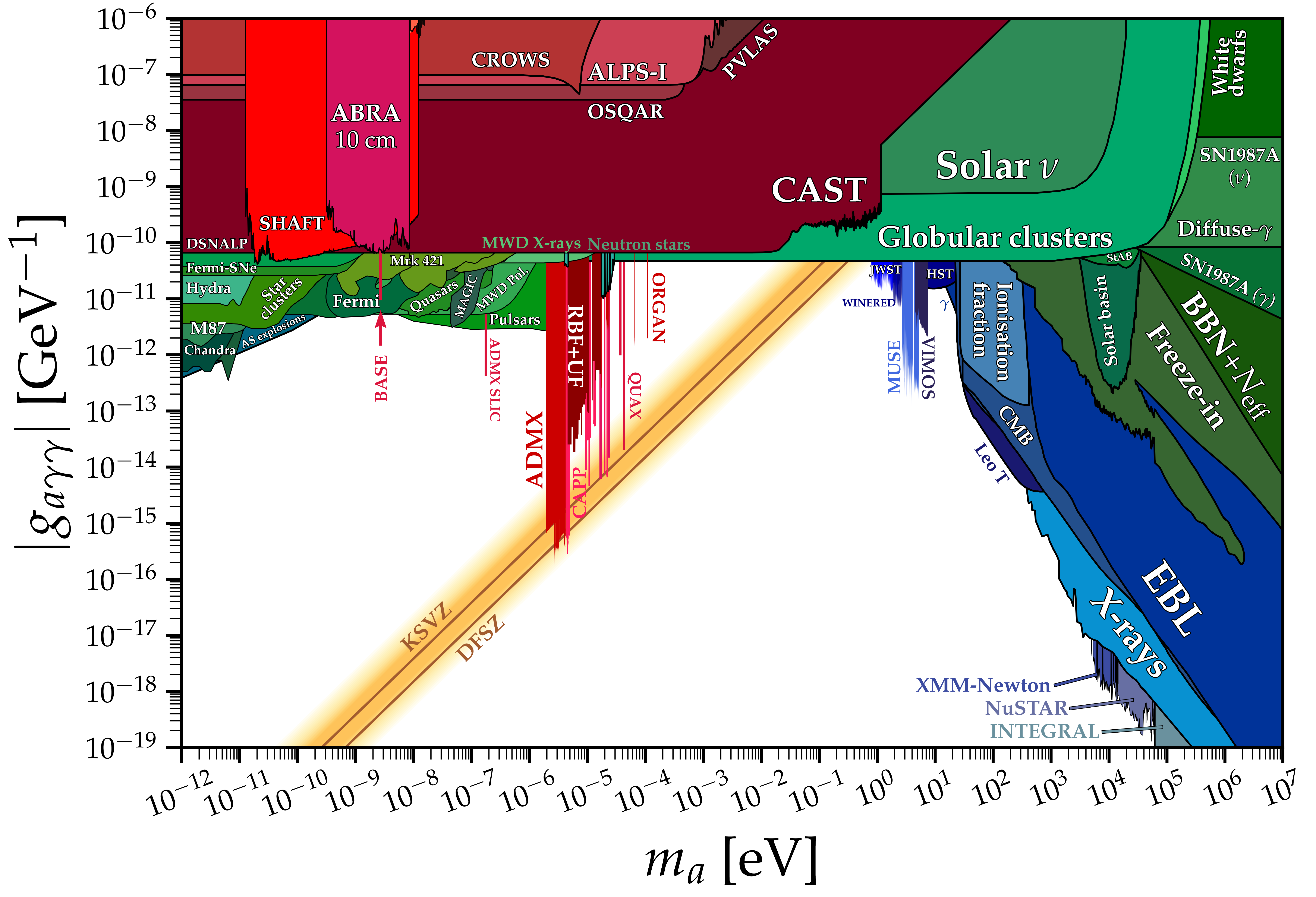
2208.06519: Xing Fan, Gerald Gabrielse, Peter W. Graham, Roni Harnik, Thomas G. Myers, Harikrishnan Ramani, Benedict A. D. Sukra, Samuel S. Y. Wong, and Yawen Xiao

2409.xxxxx: Xing Fan, Gerald Gabrielse, Peter W. Graham, Harikrishnan Ramani, Samuel S. Y. Wong, and Yawen Xiao

Axions

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

- Pseudo scalar
- Strong CP problem: QCD Axion
- Dark Matter Candidate



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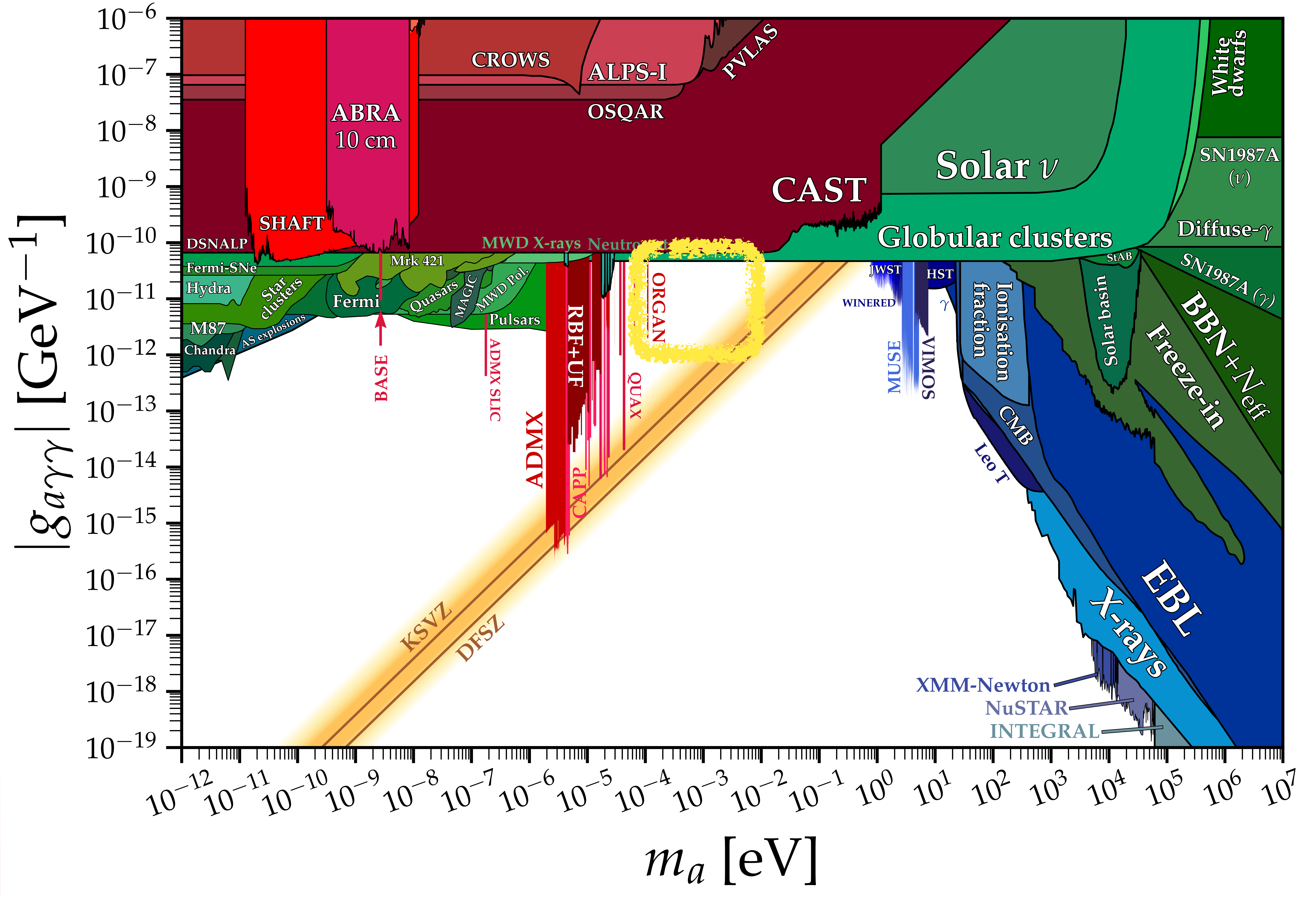
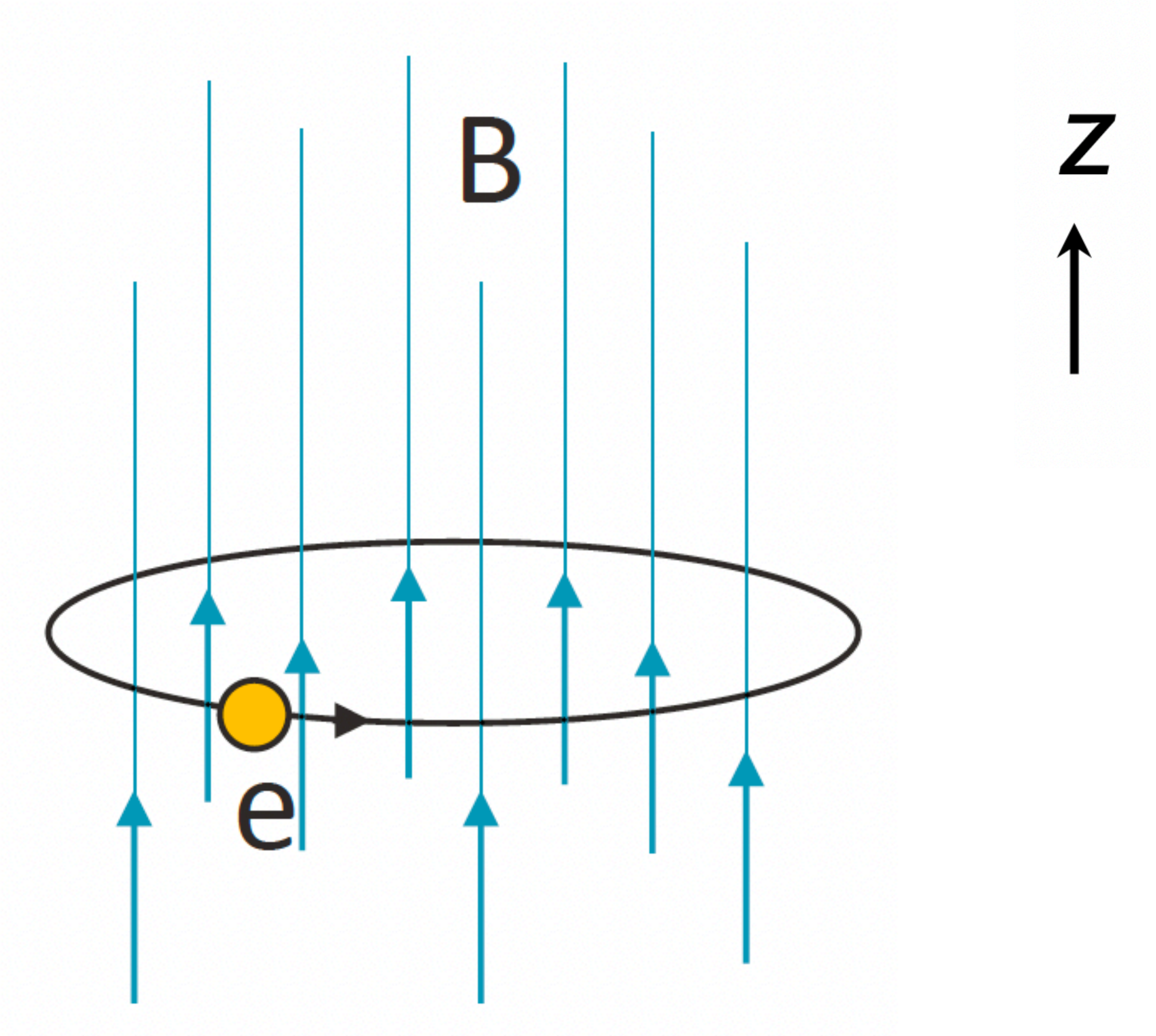
- meV ~ wavelike DM



Electron Penning trap



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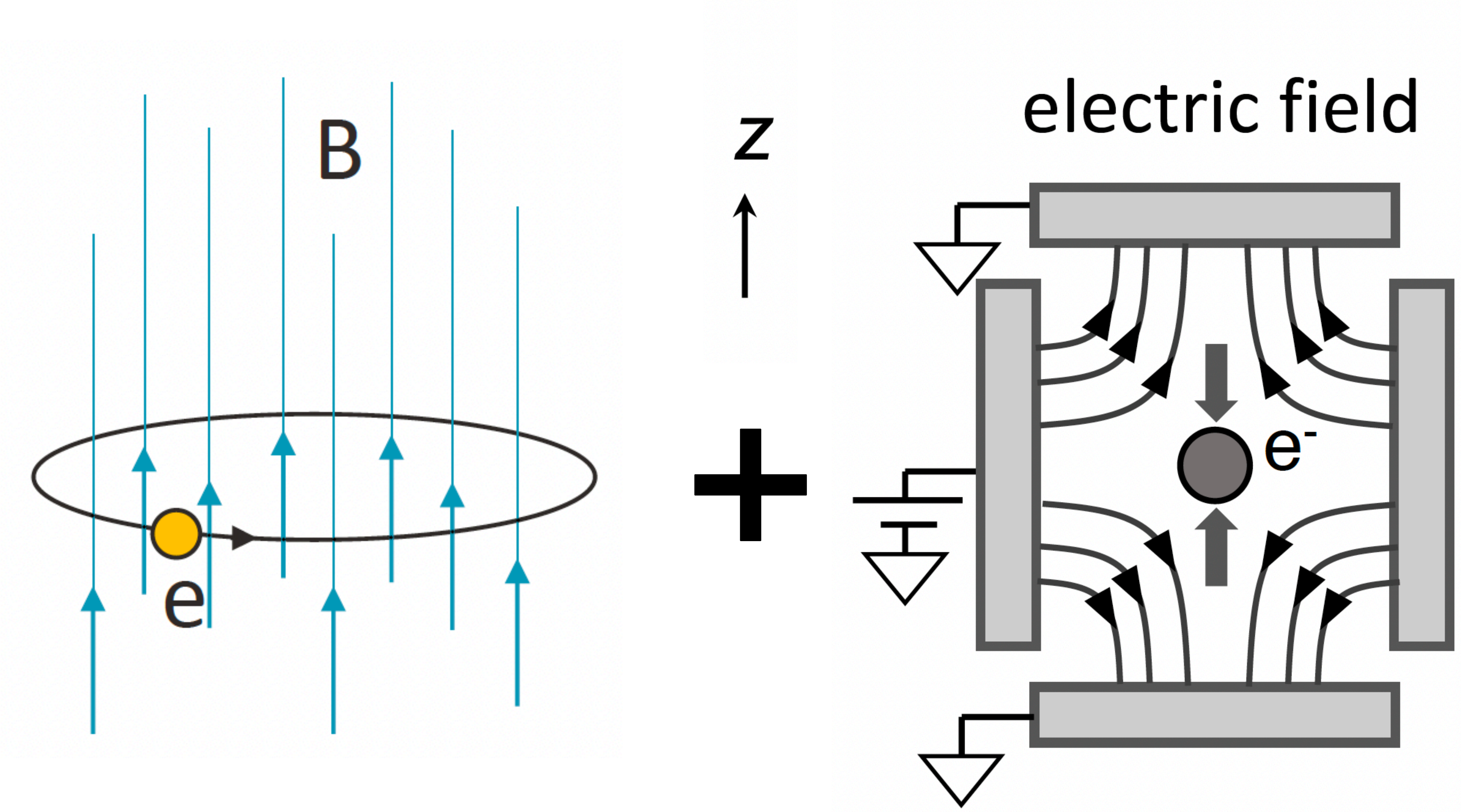

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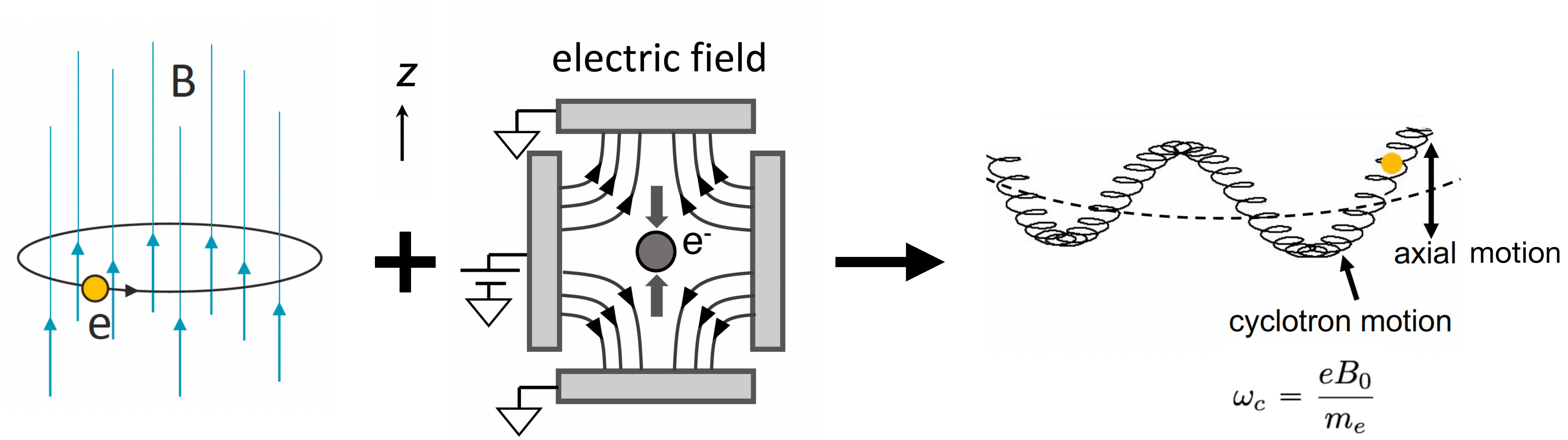
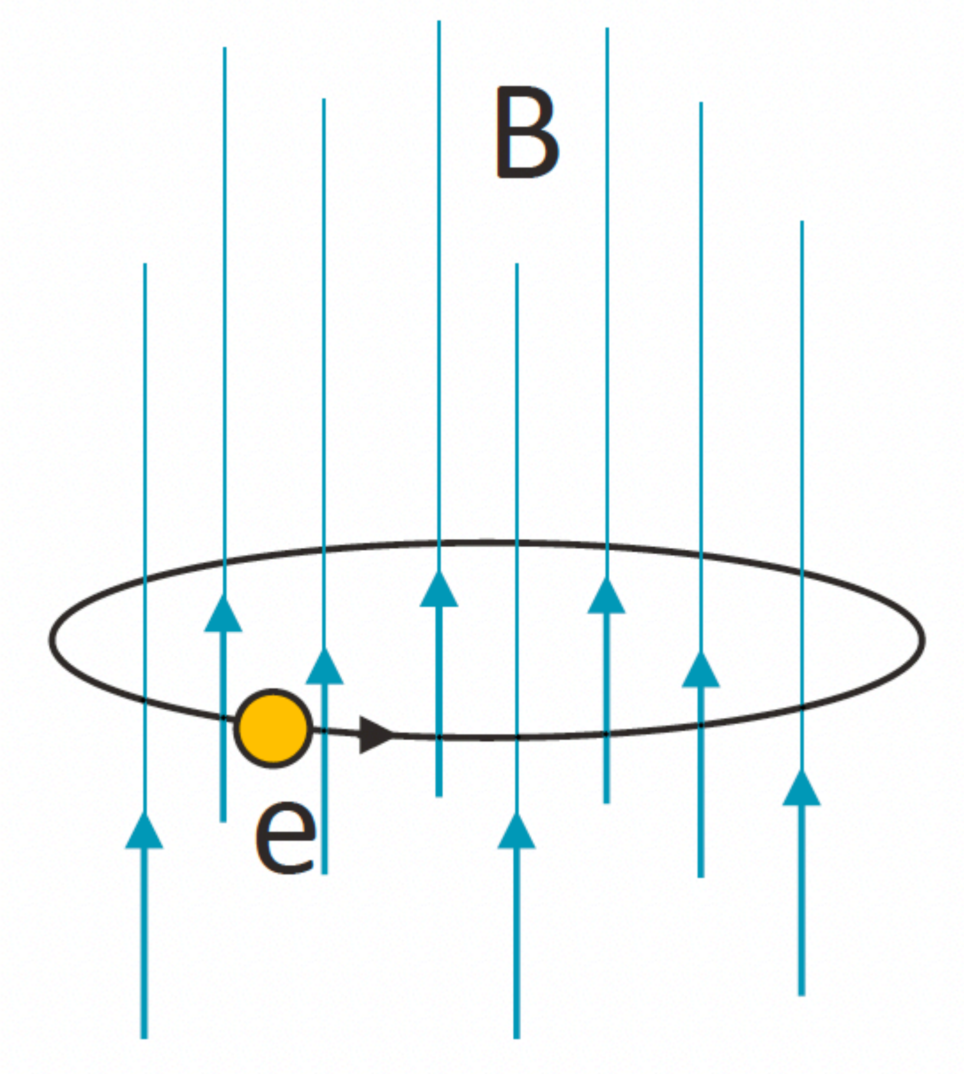
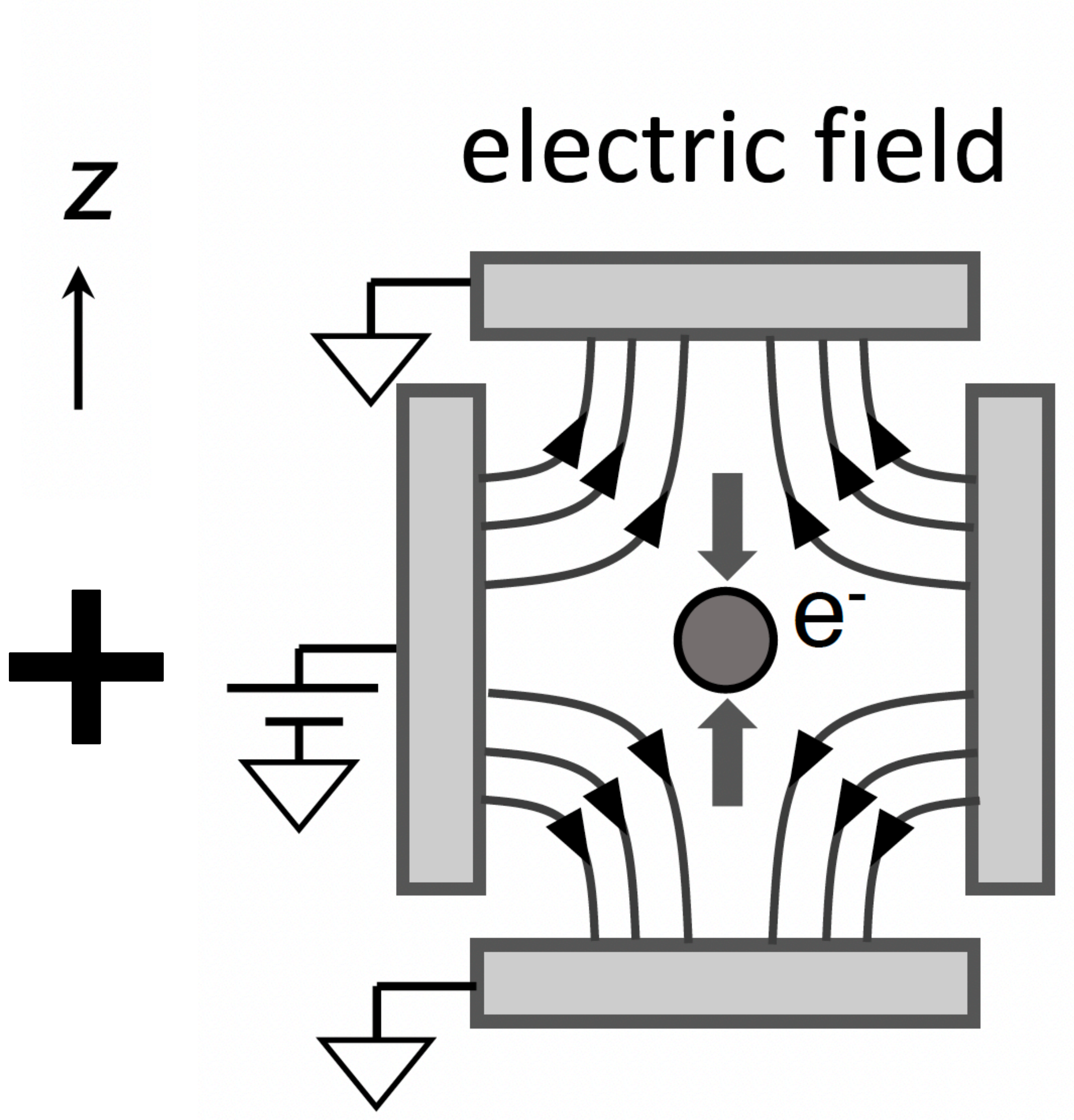
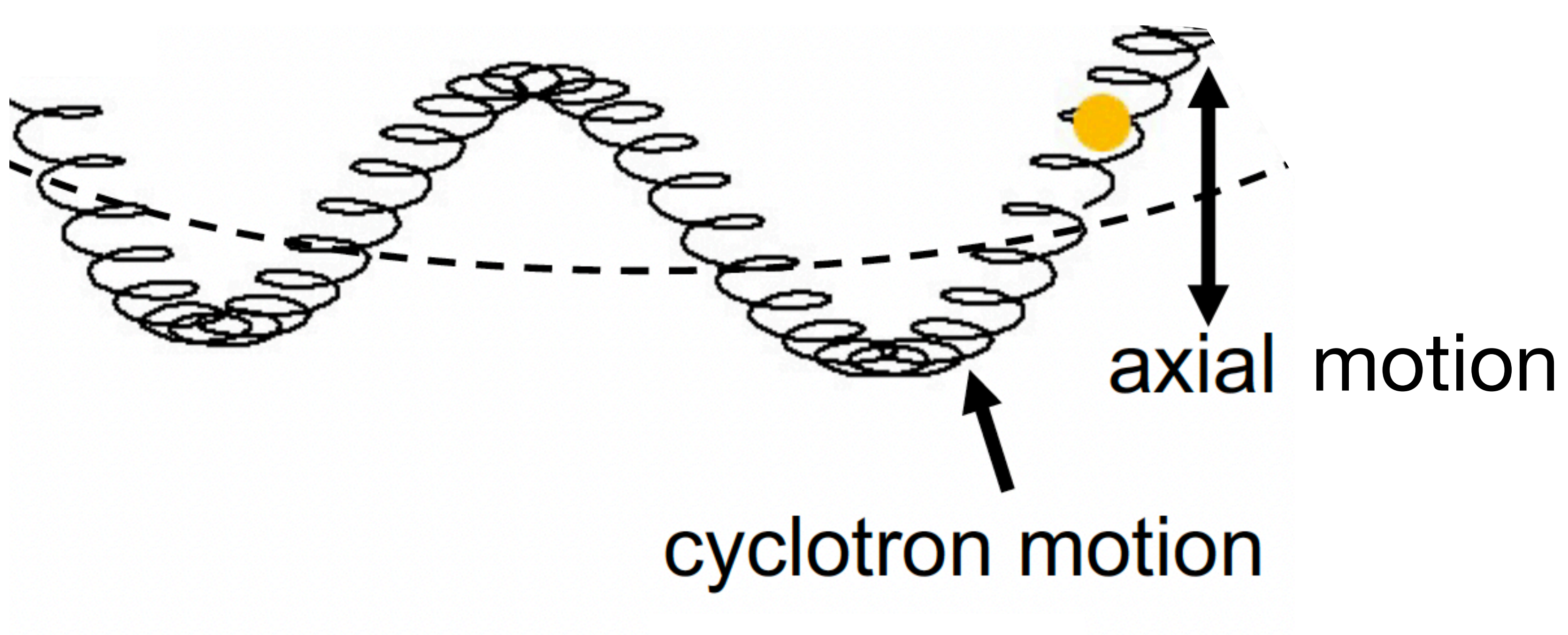


$$\omega_c = \frac{eB_0}{m_e}$$

Electron Penning trap







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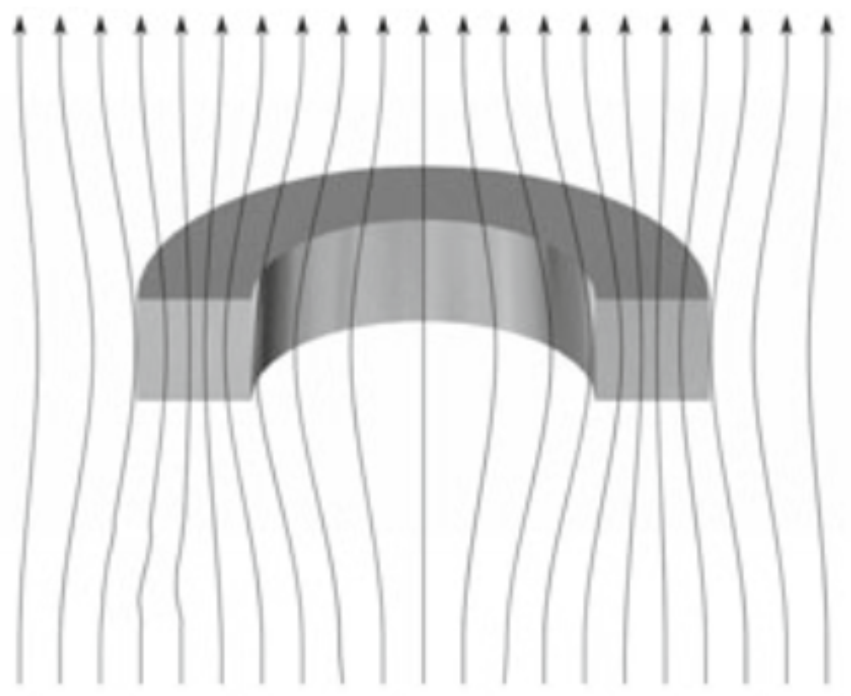
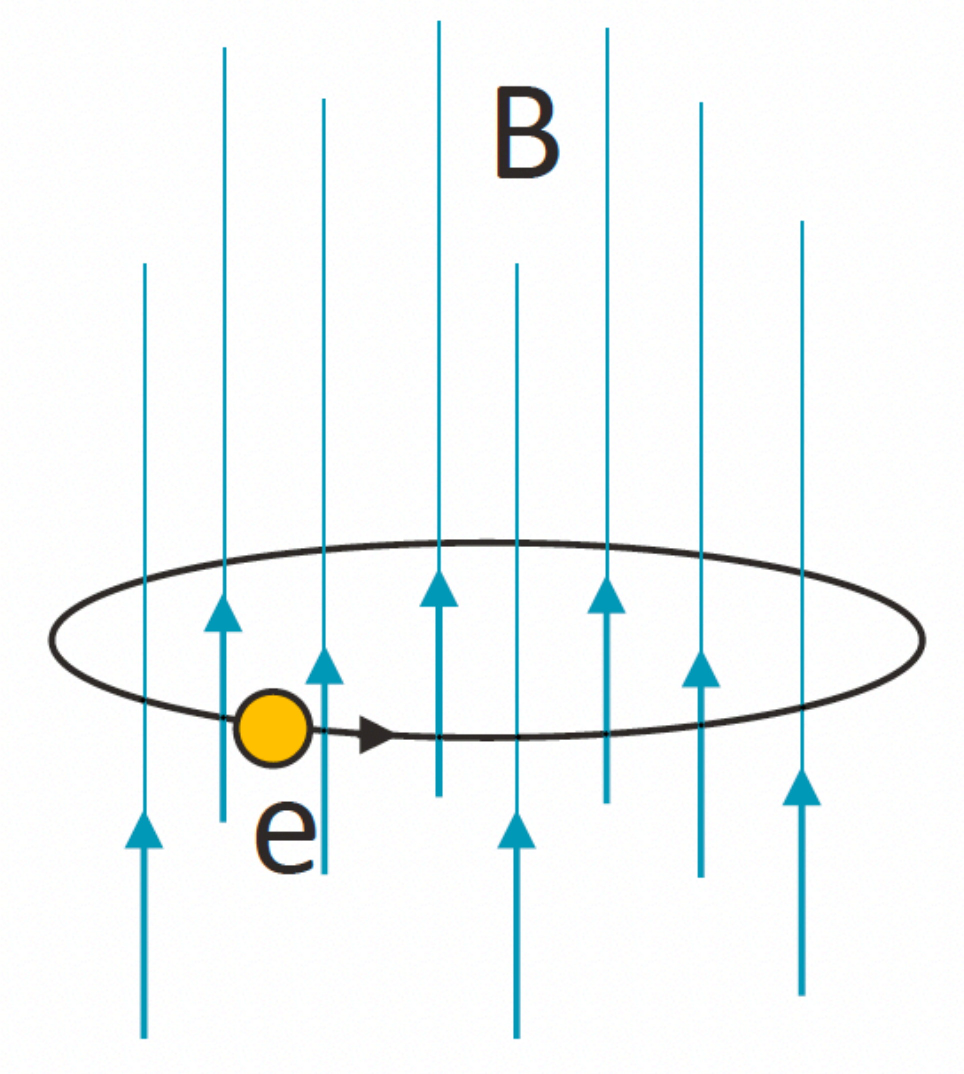


$$\Delta B \propto z^2$$

monitor the cyclotron state by quantizing axial shift

Electron Penning trap



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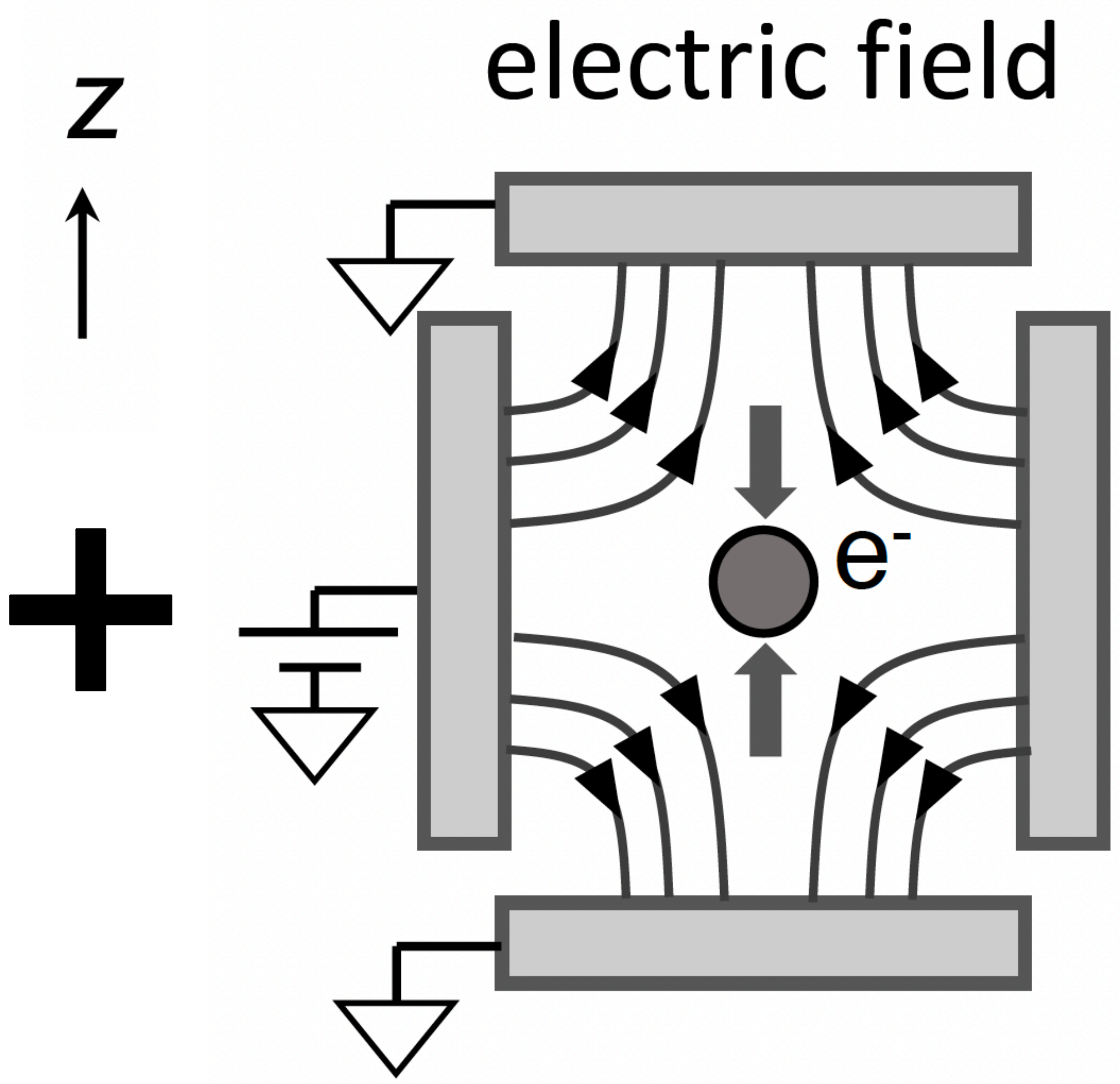

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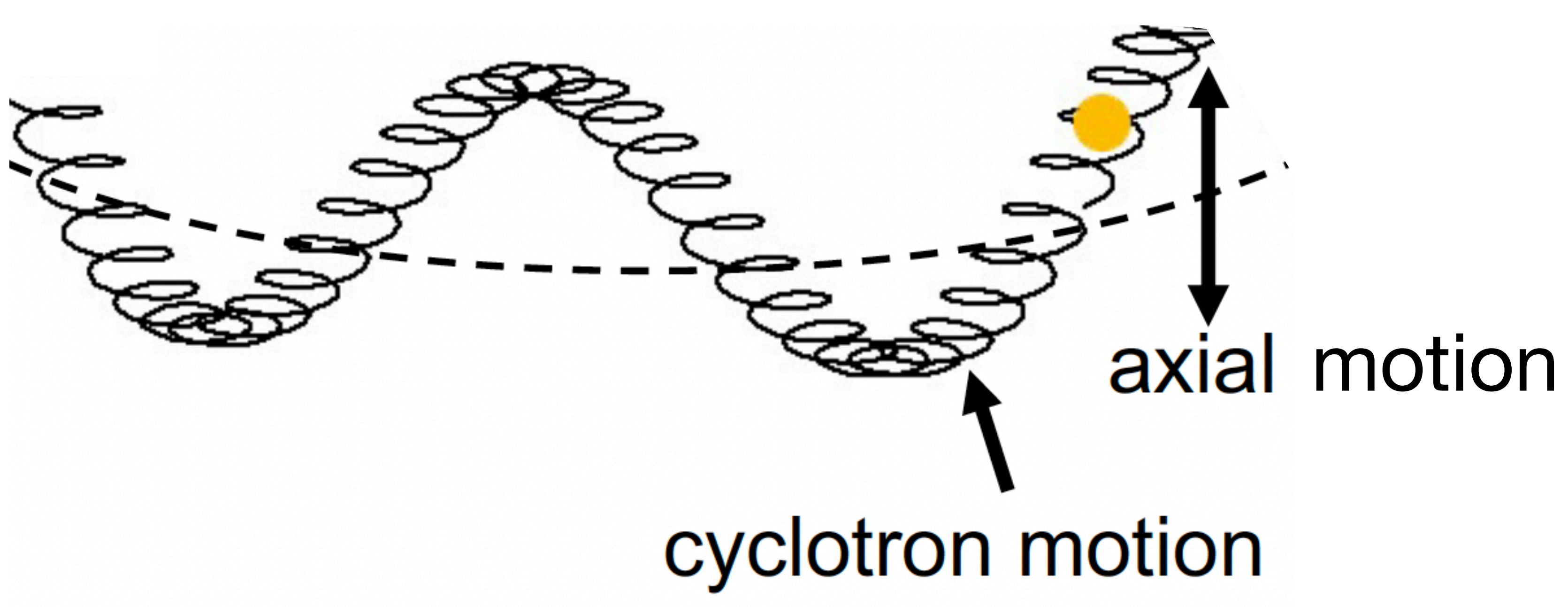

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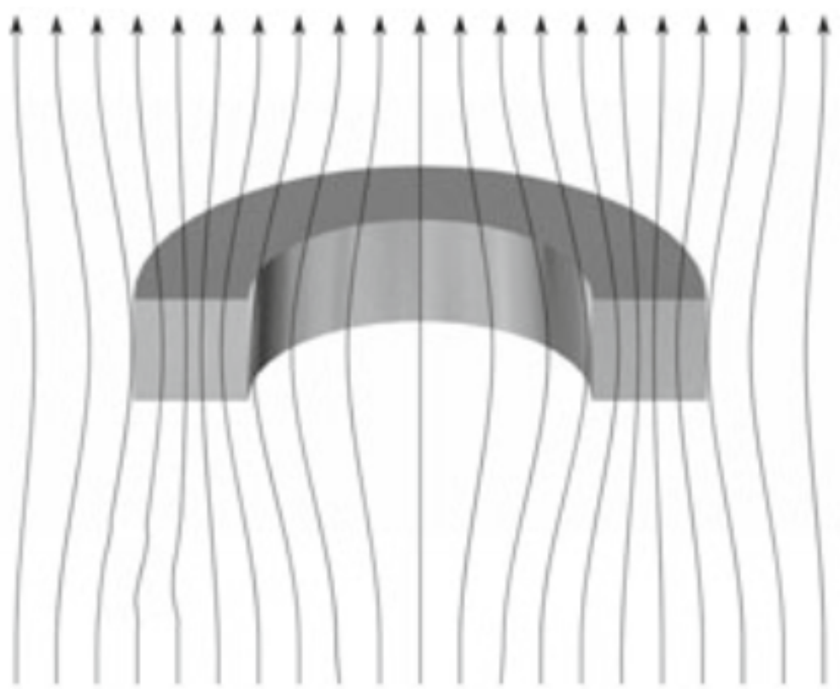
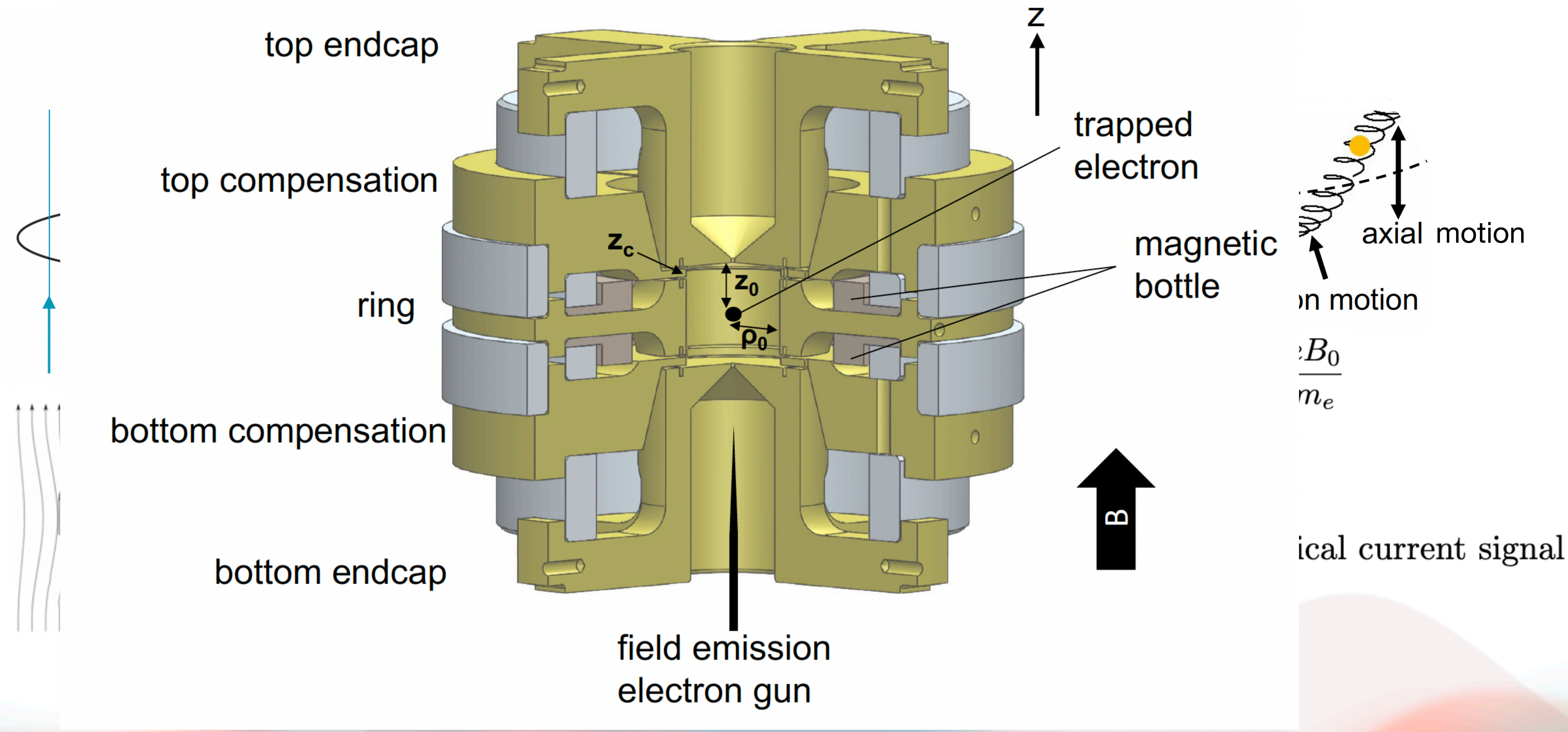


$$\Delta B \propto z^2$$

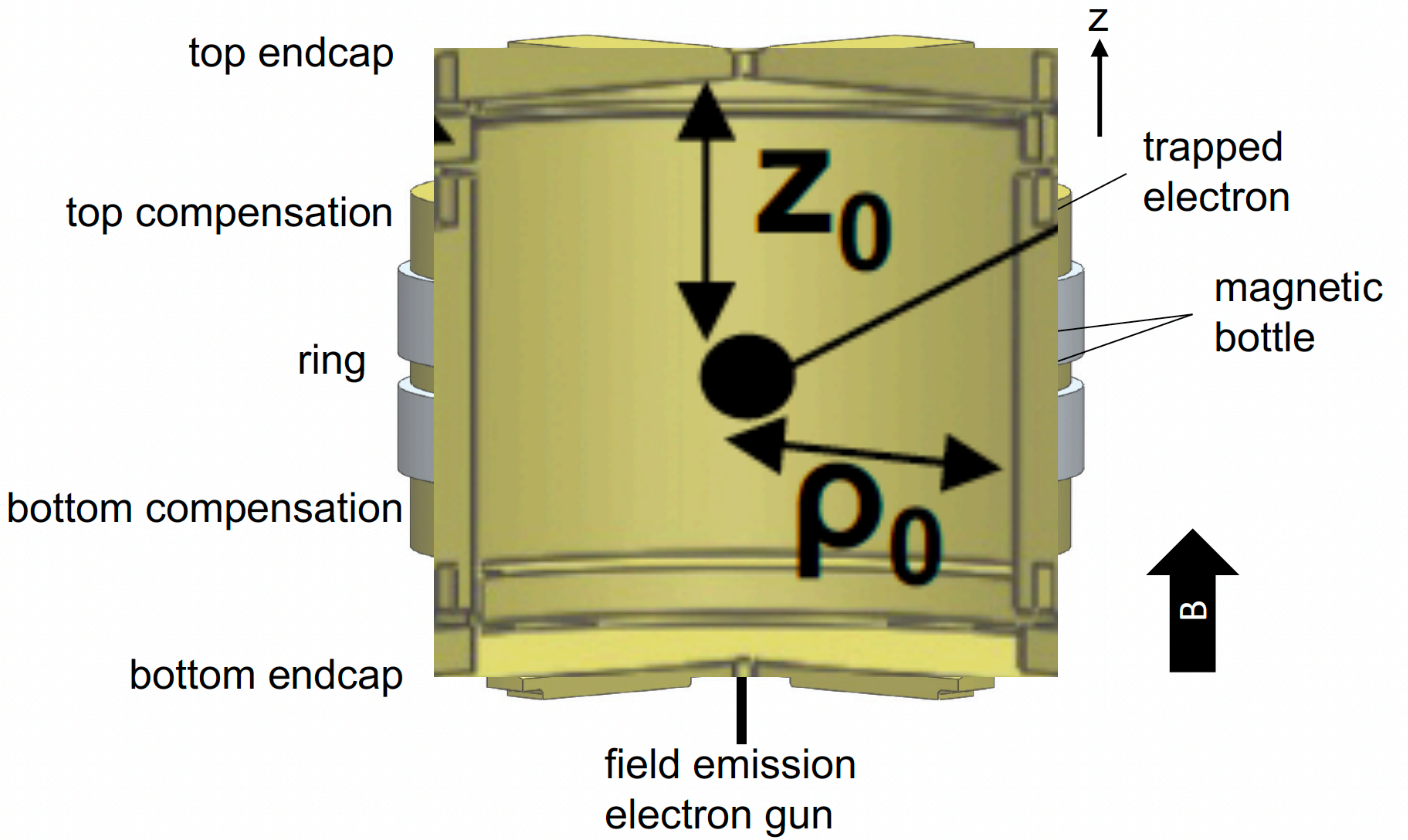
monitor the cyclotron state by quantizing axial shift

jump in cyclotron mode $\Rightarrow \omega_z$ shift $\Rightarrow \dot{z} \Rightarrow$ classical current signal

Electron Penning trap



Interaction with Dark Matter



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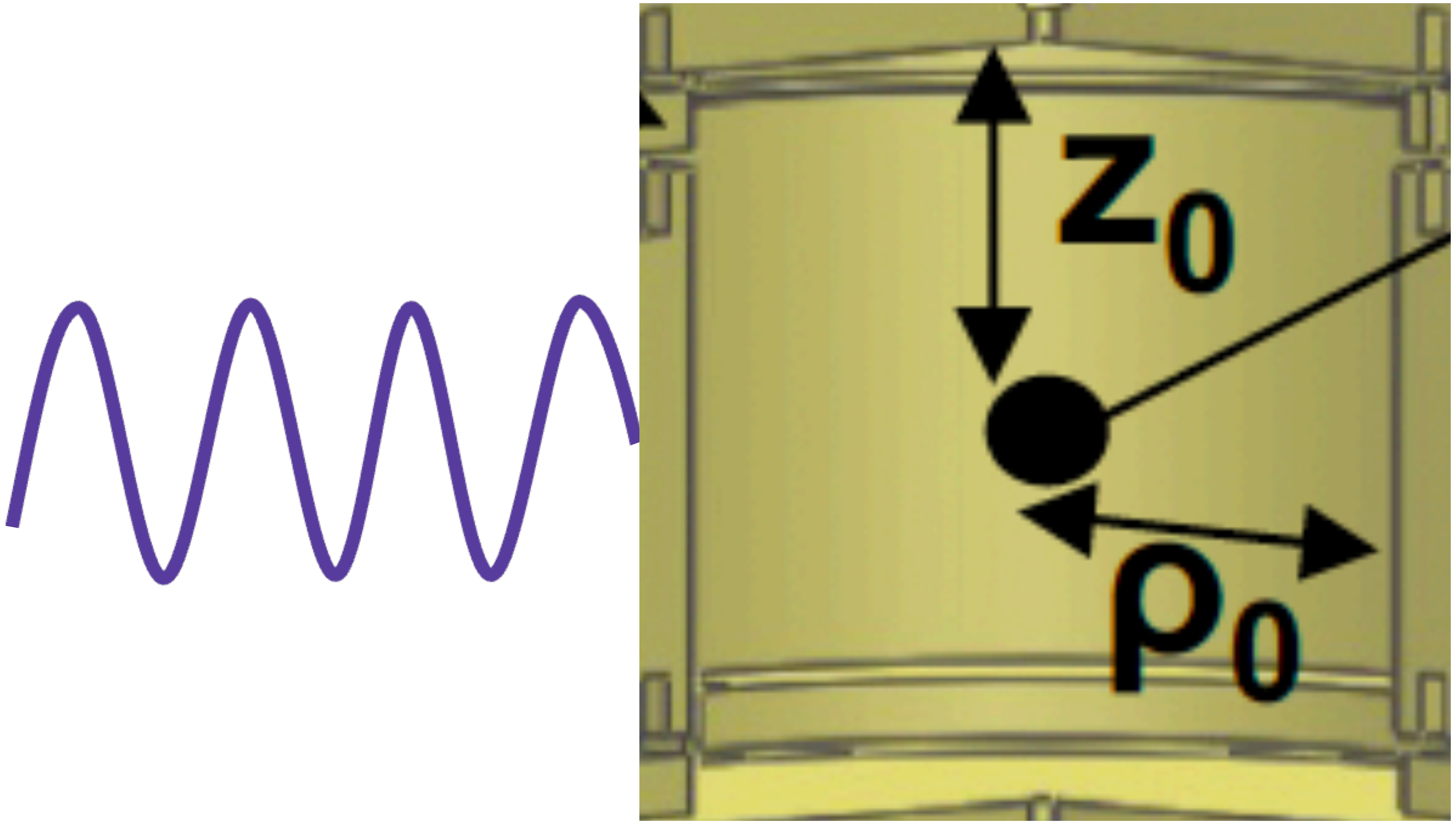

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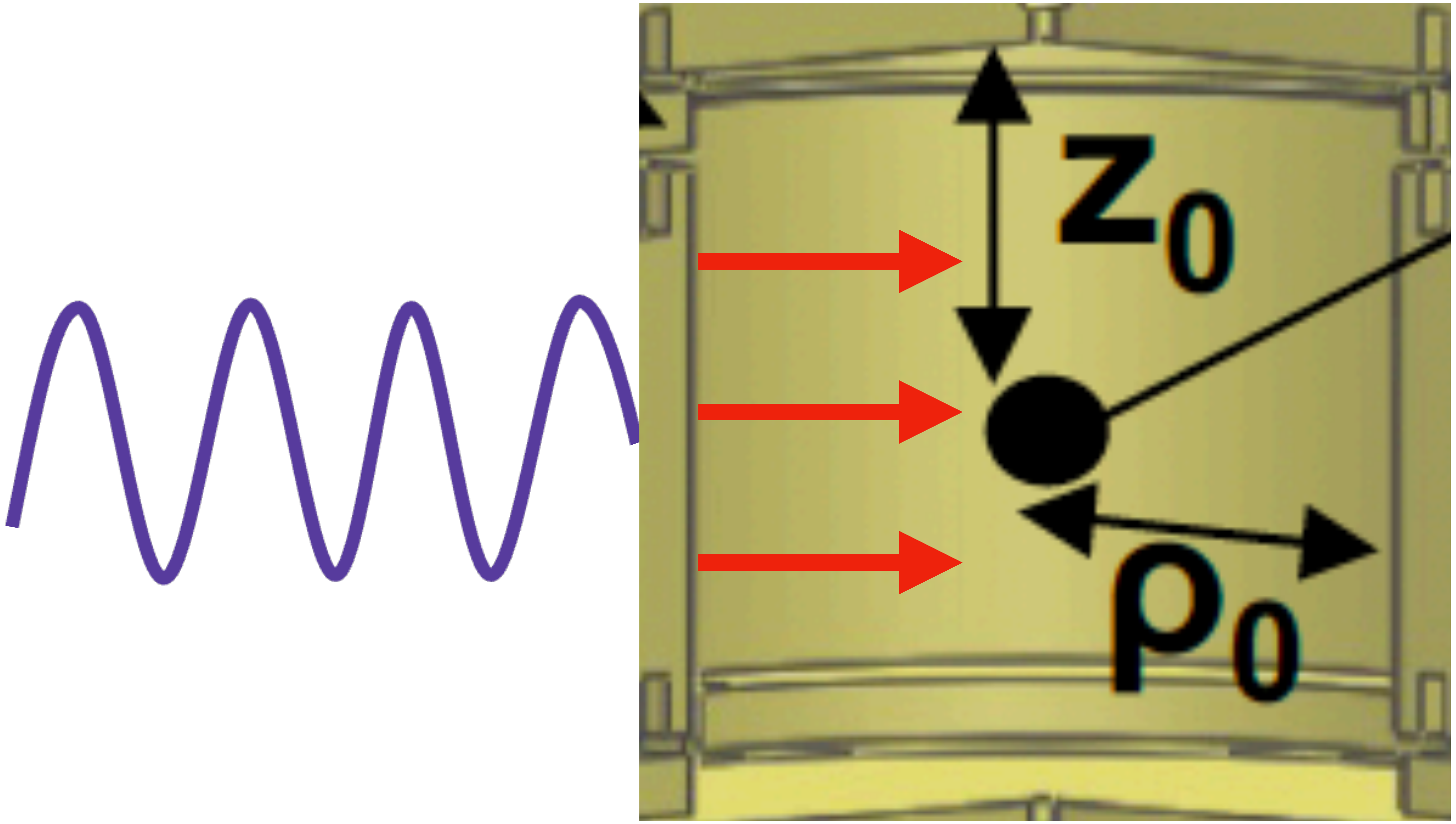
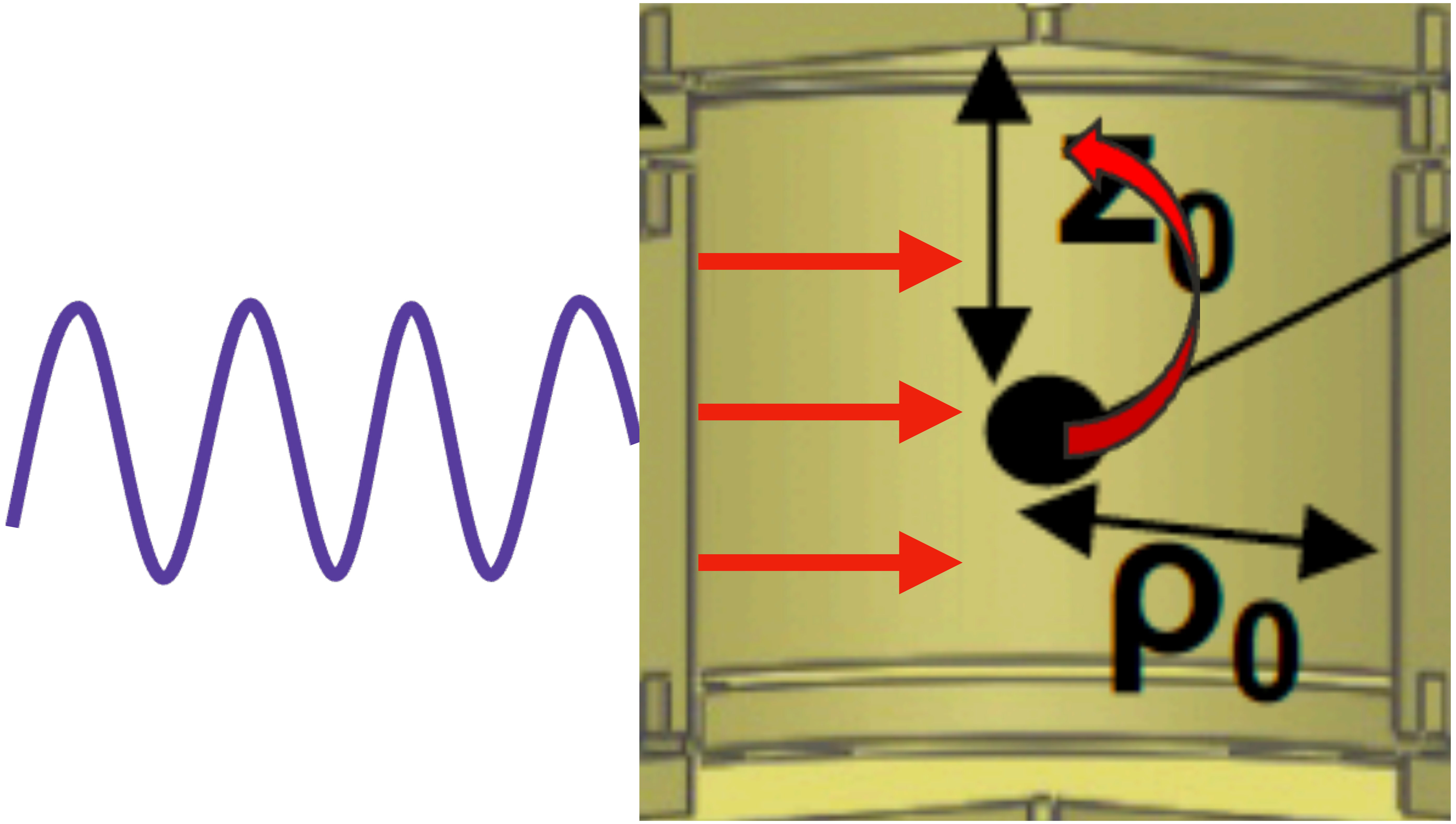


Dark matter will generate photons from the wall!

Interaction with Dark Matter



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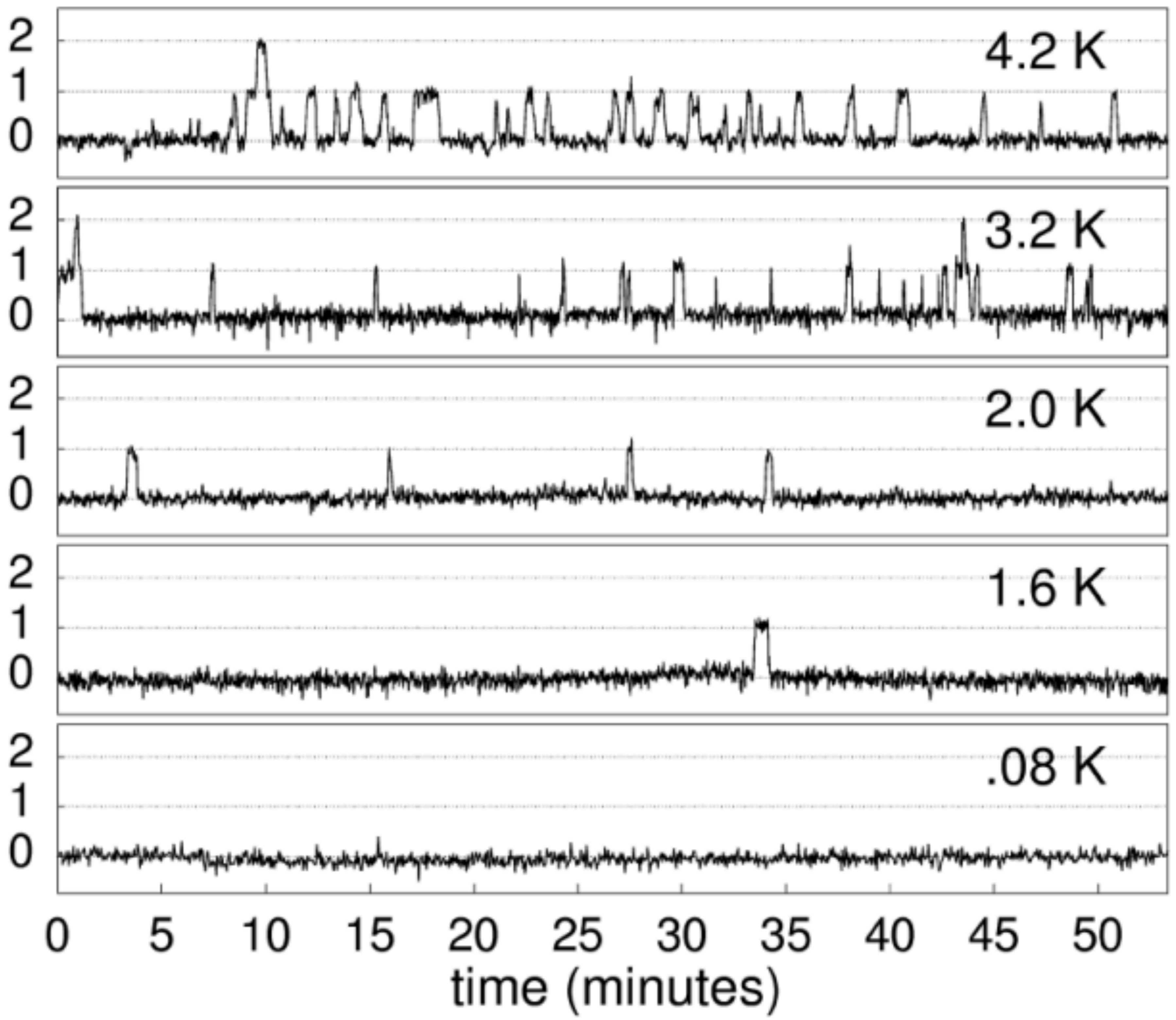
Background-free Detection

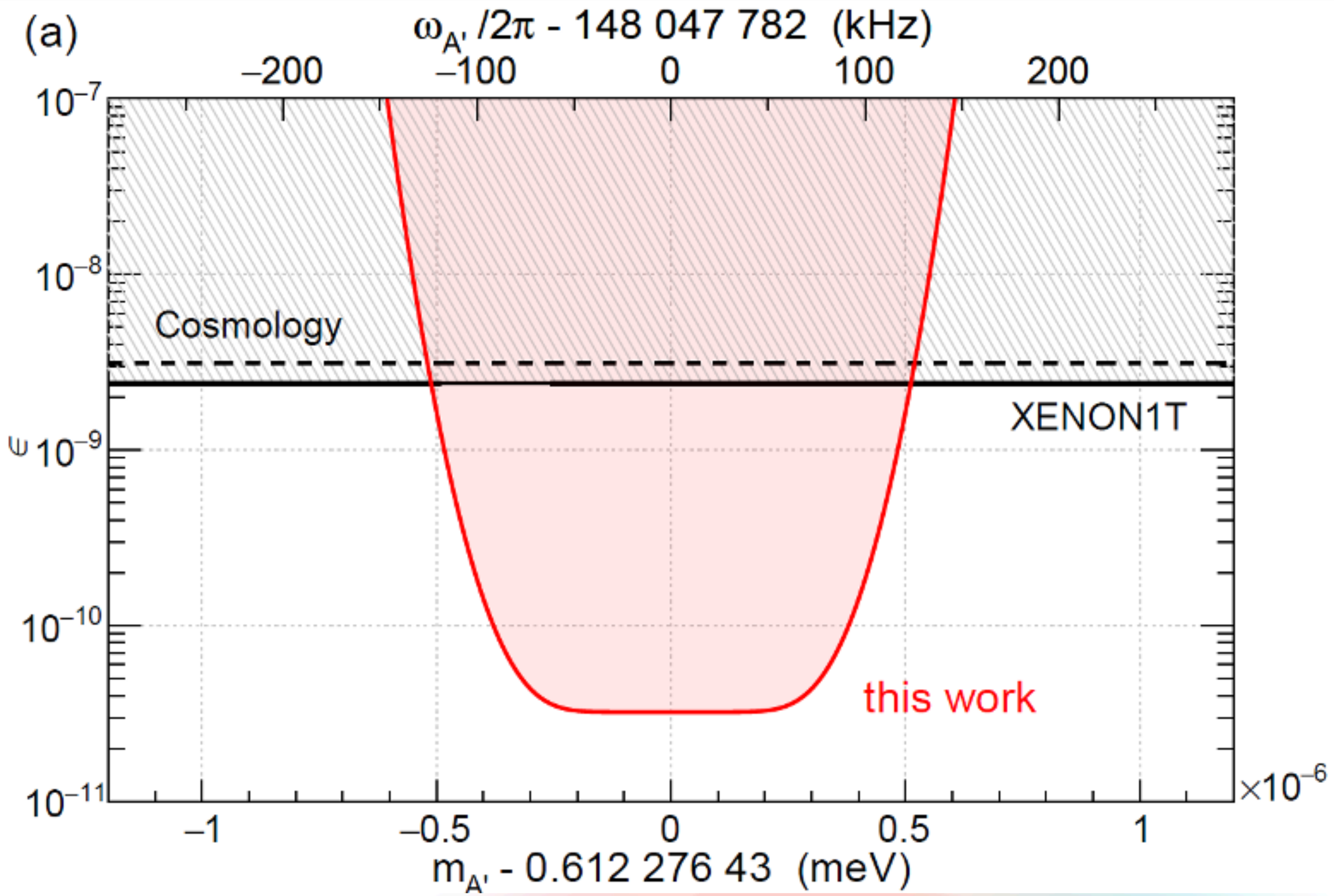


[S. Peiland G. Gabrielse, Phys.Rev.Lett.83(1999)7]

- Quantization of states
- One single jump is detectable
- Noise reduced at low T

Proof-of-principle experiment: Background-free over 7.4 days!

Proof-of-Principle Experiment



DPDM:

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

Proof-of-principle experiment: Background-free over 7.4 days!

From DPDM to Axion:

- Scanning hurts magnetic field: a strong external magnetic field
- Separate the generation and detection process: Open Trap

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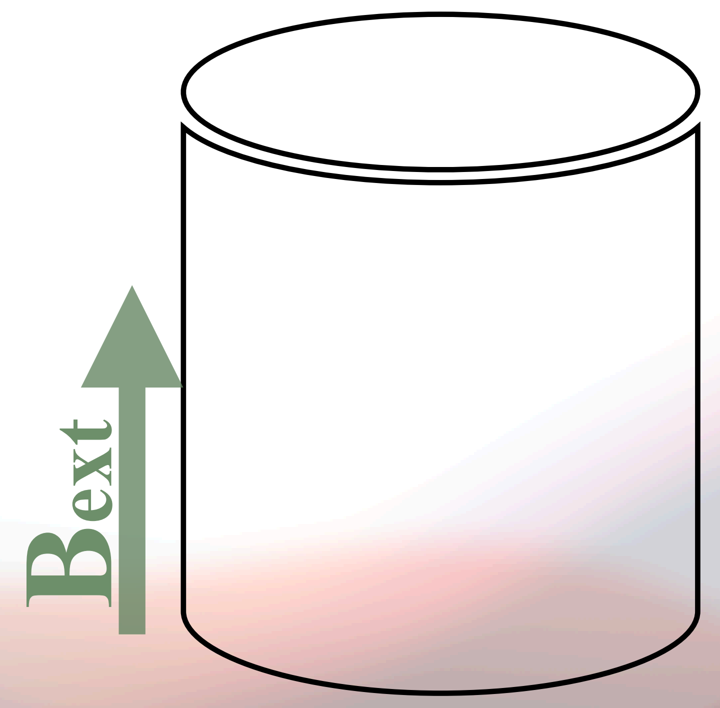
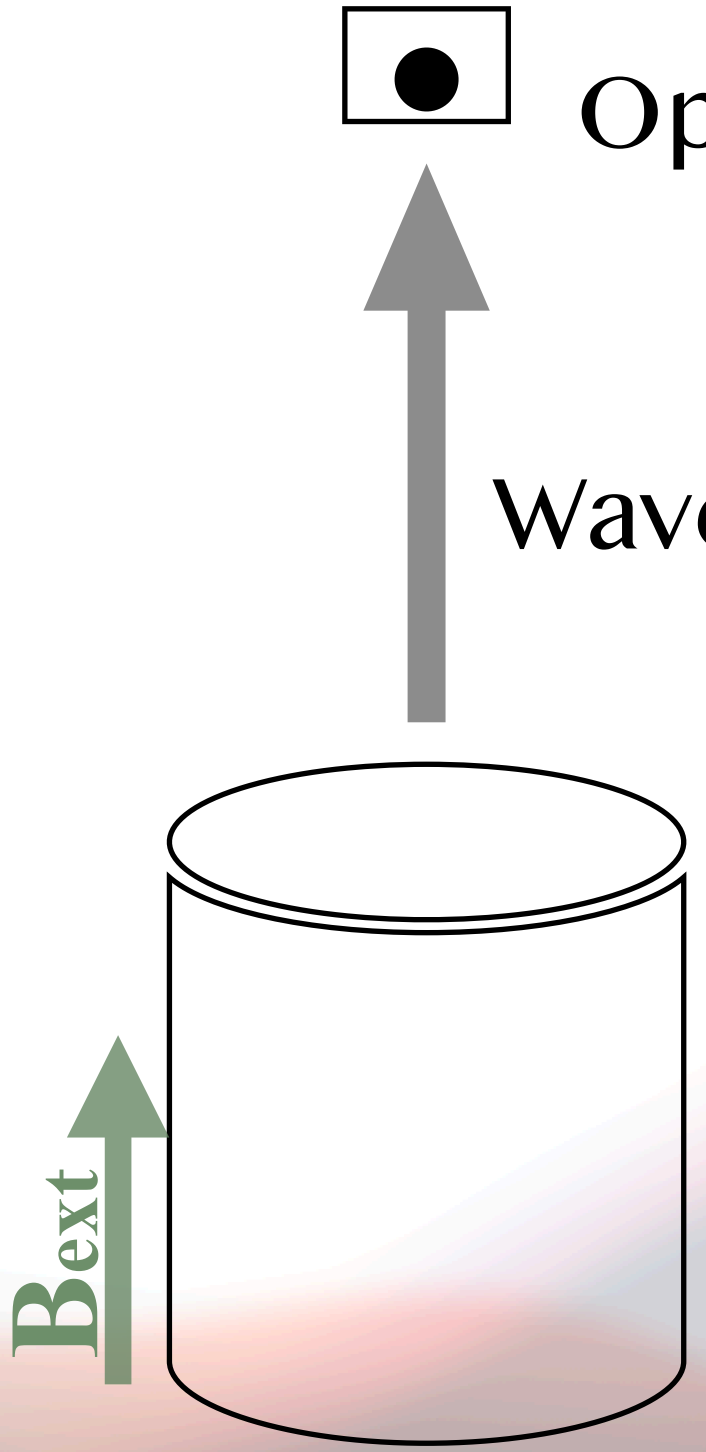


Cavity with strong magnetic field: generating Axions

From DPDM to Axion:

- Scanning hurts magnetic field: a strong external magnetic field
- Separate the generation and detection process: Open Trap



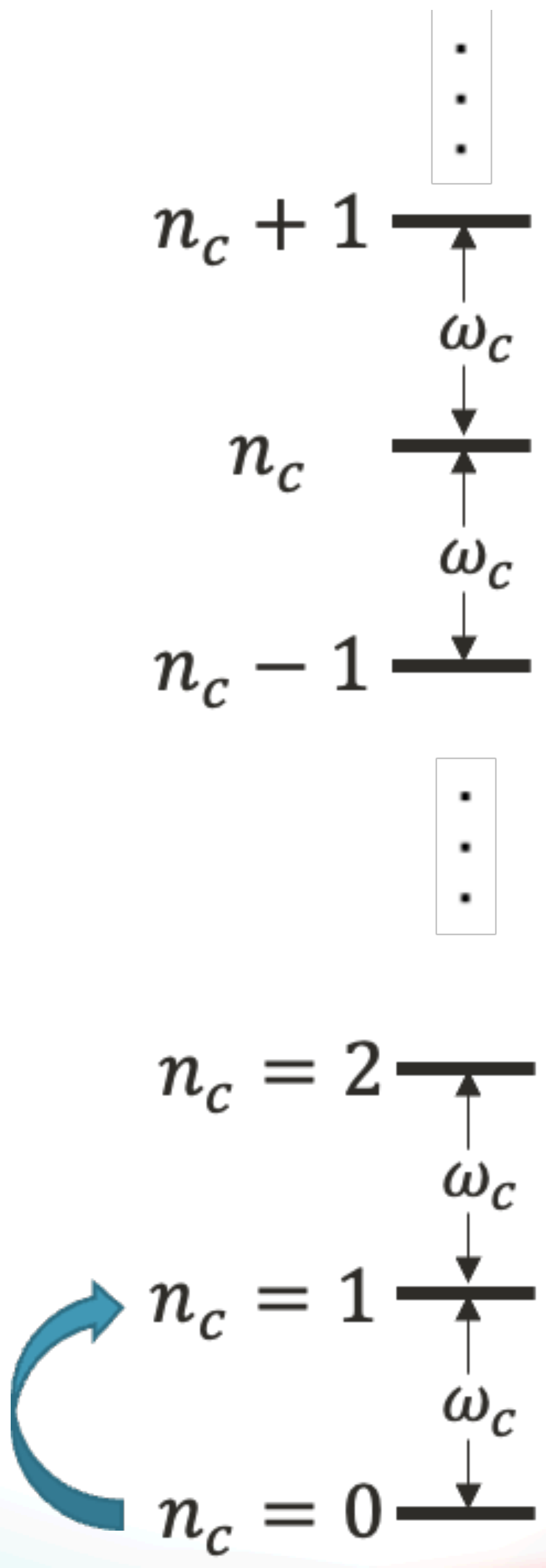
Open trap

Waveguide: transport all generated photons to the trap

Cavity with strong magnetic field: generating Axions

$\Gamma_c \propto (n_c + 1)$

Highly Excited State n_c



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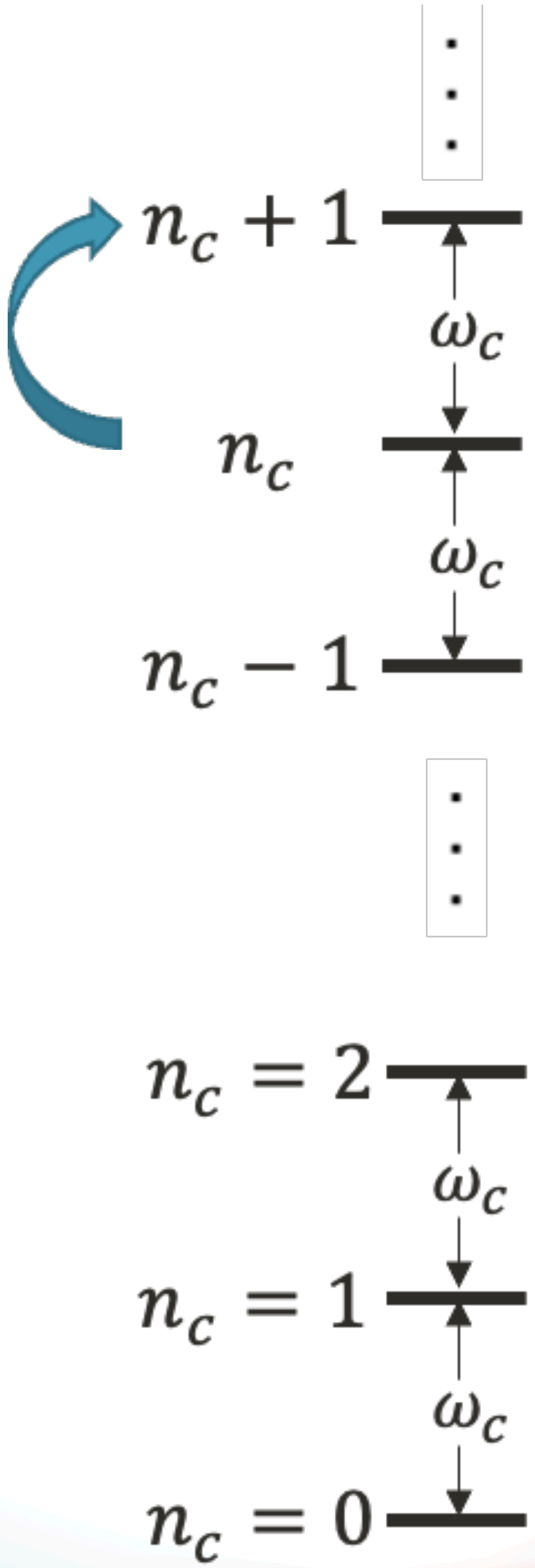

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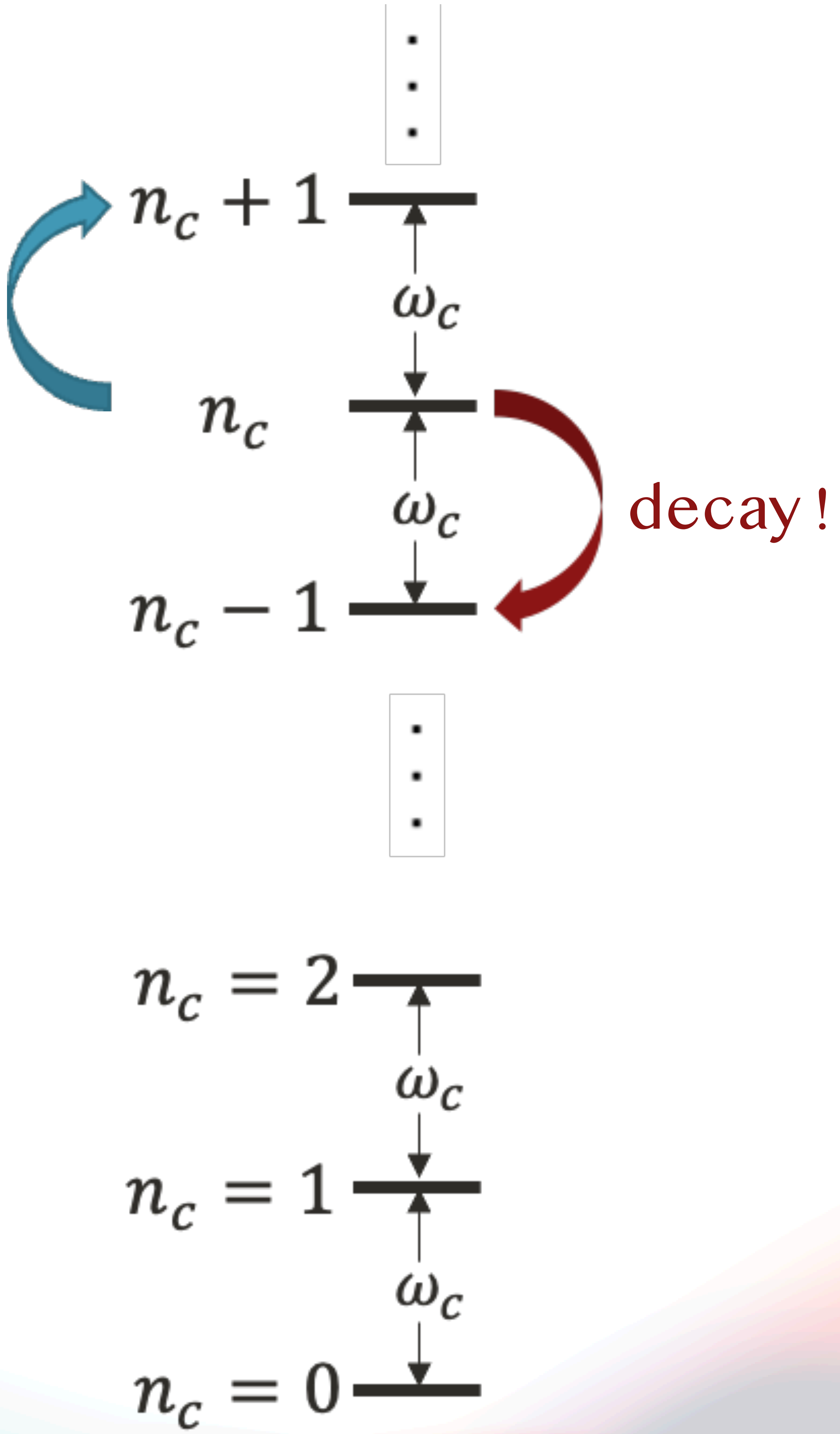

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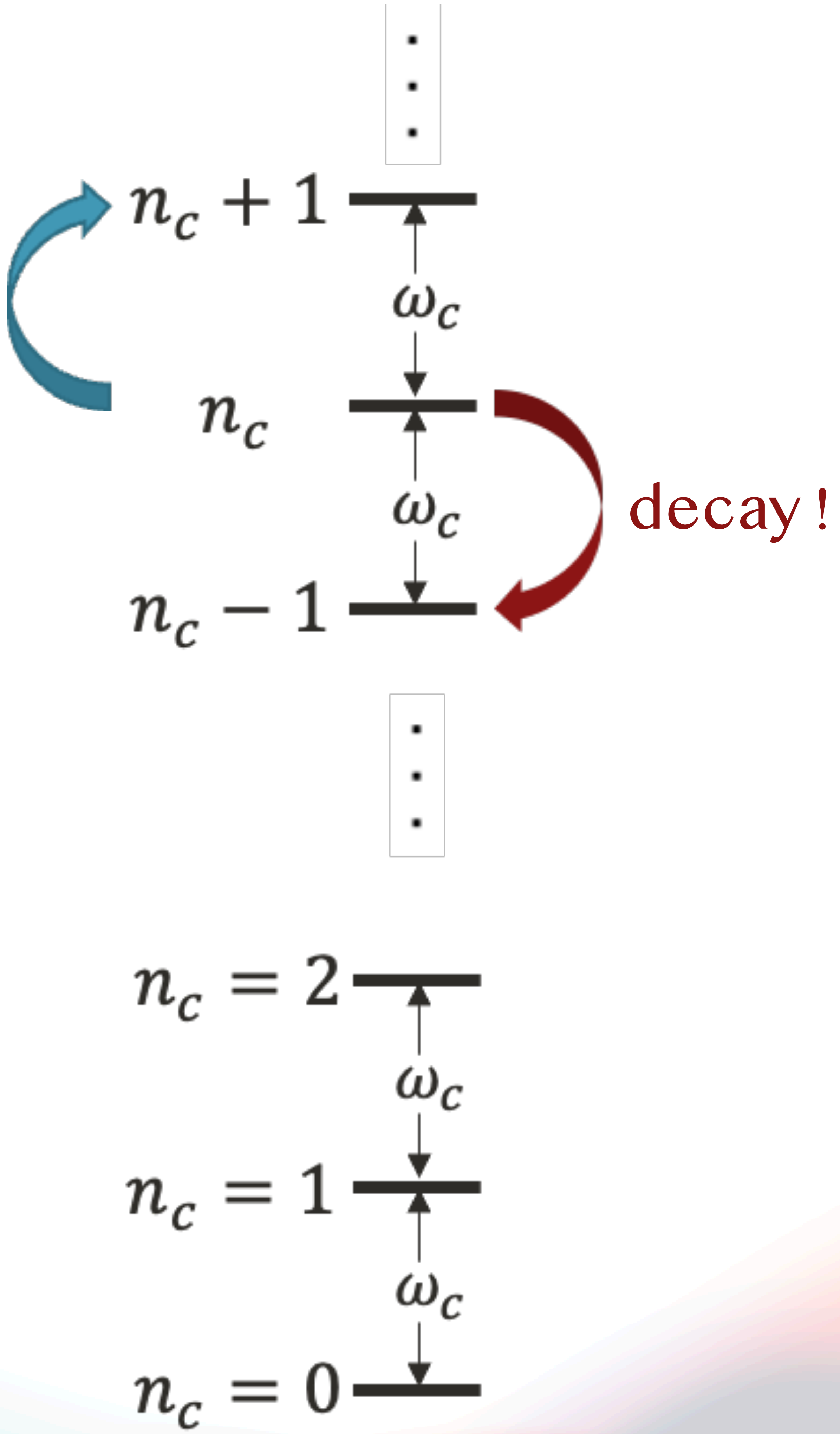

When the Transition Rate increases,

the Decay Rate also increase

Cyclotron lifetime:

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

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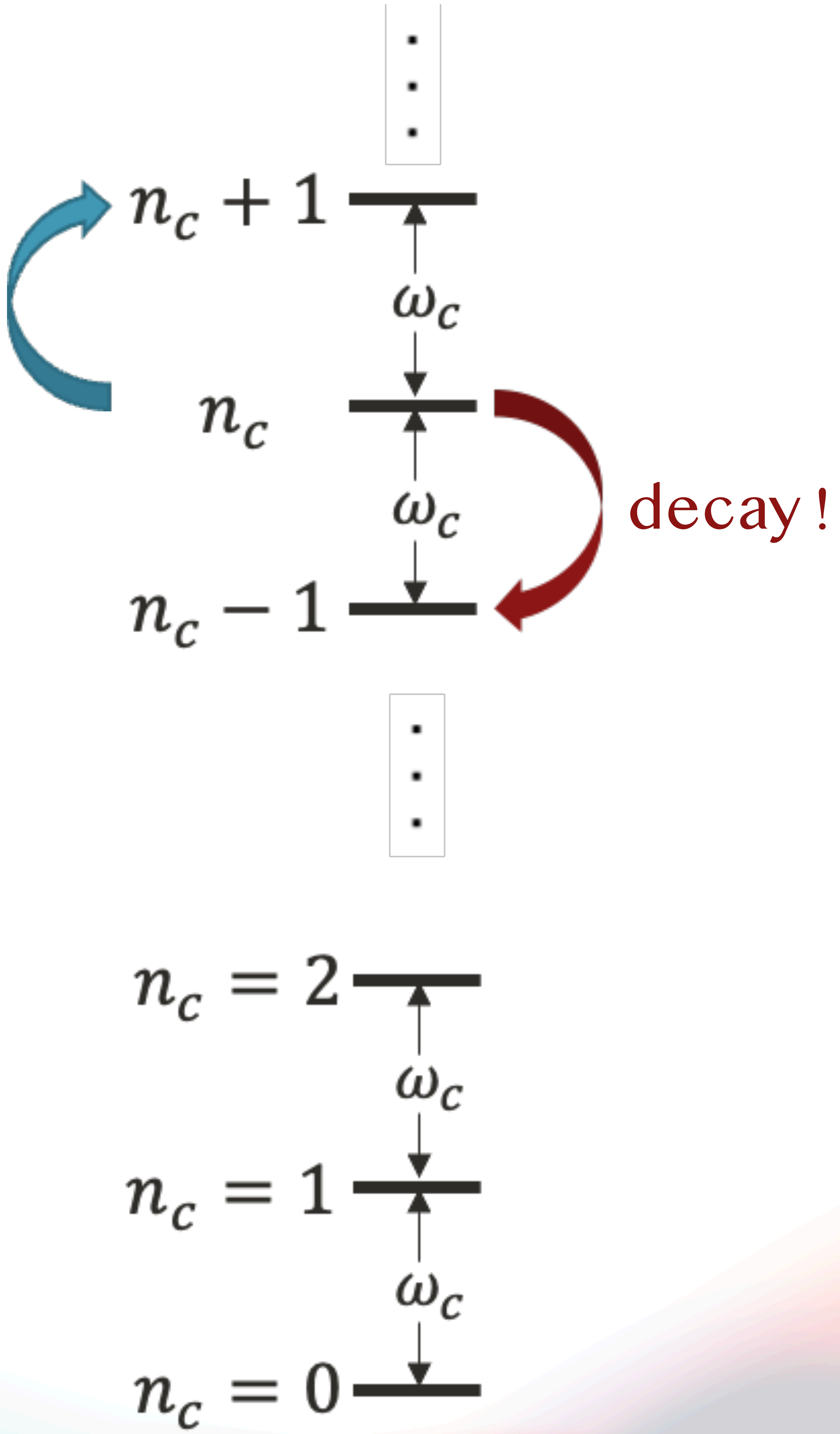

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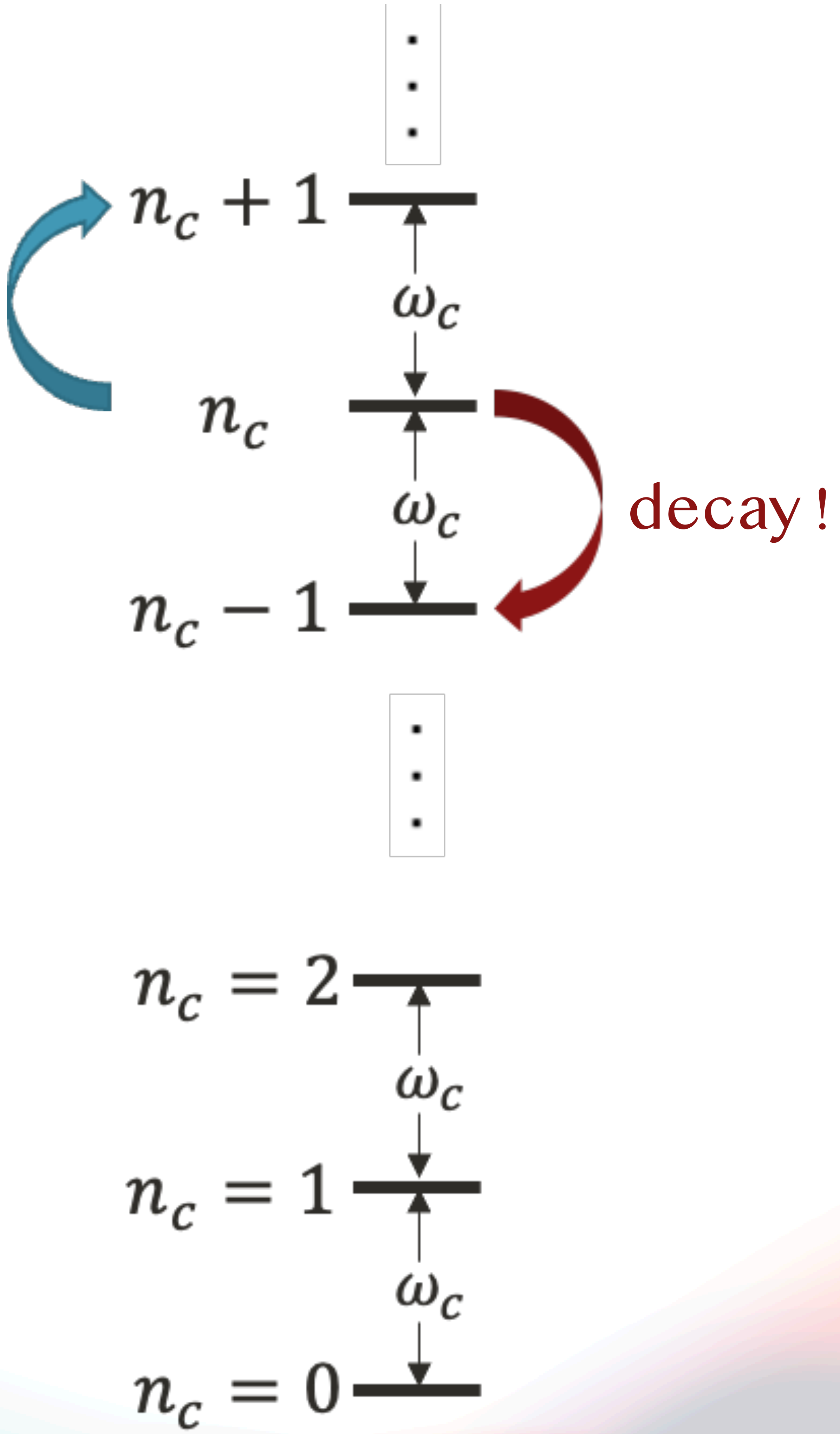

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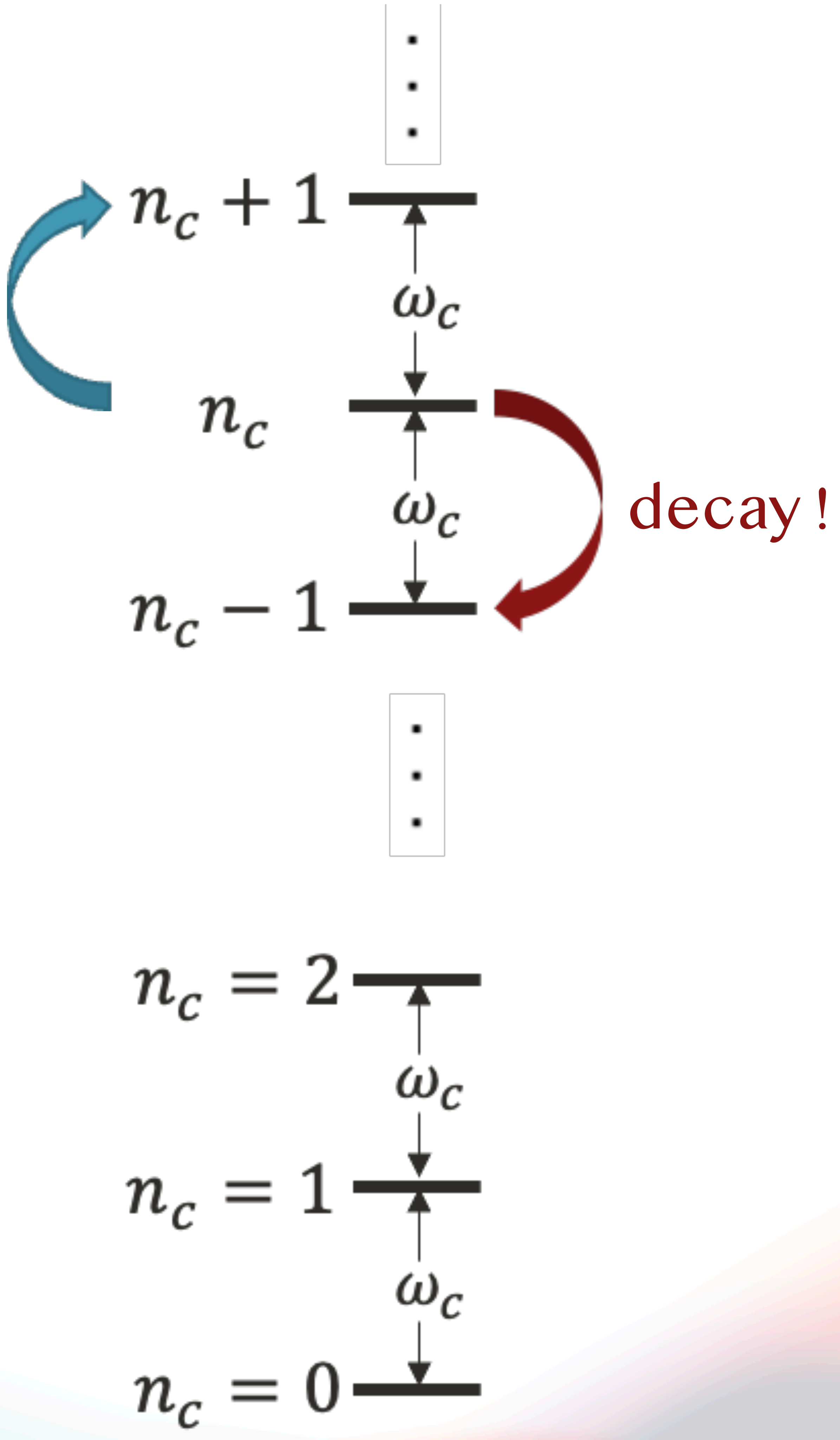

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Time Limit

$n_c \approx 10^6$!

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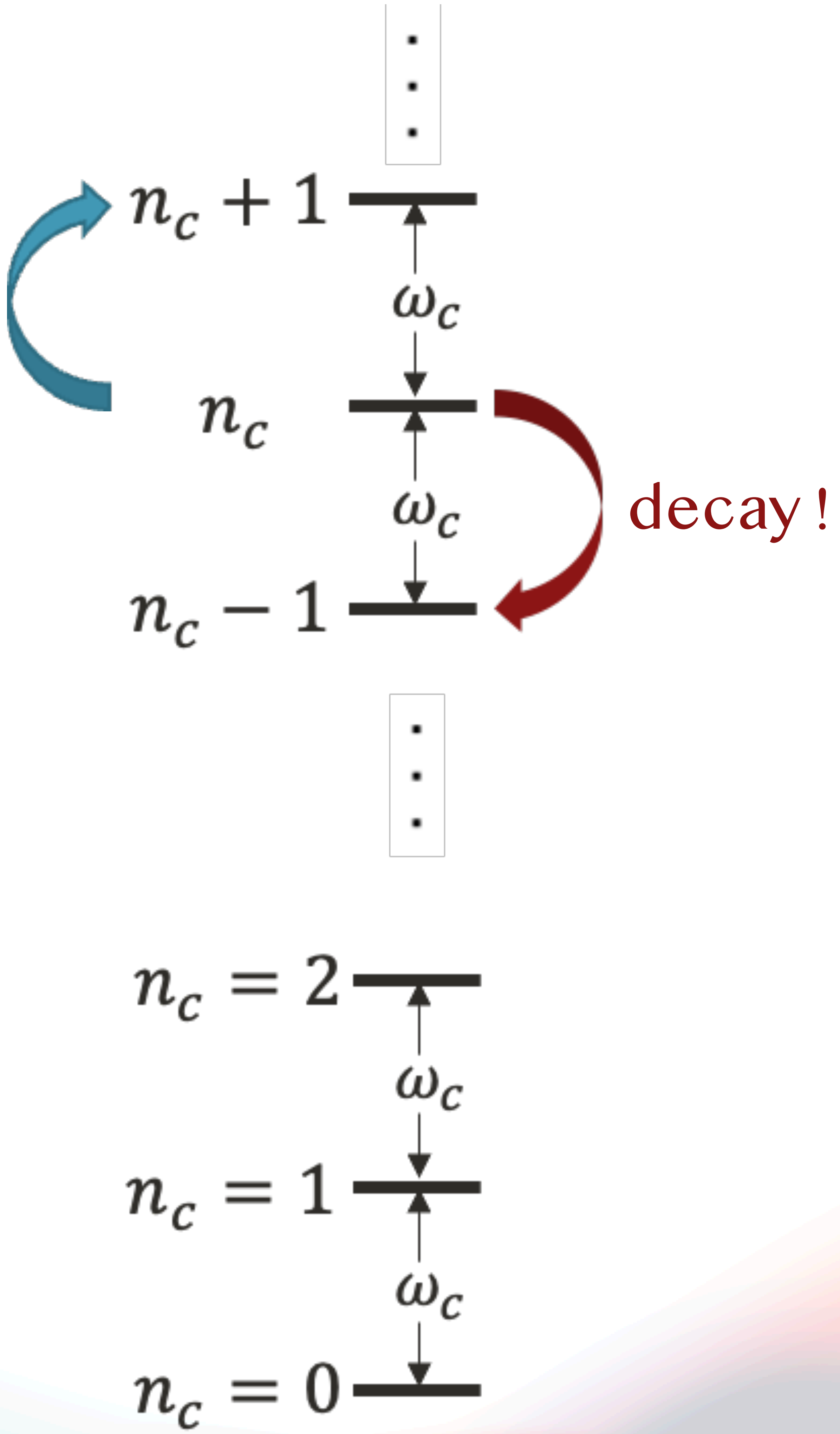
Highly Excited State n_c



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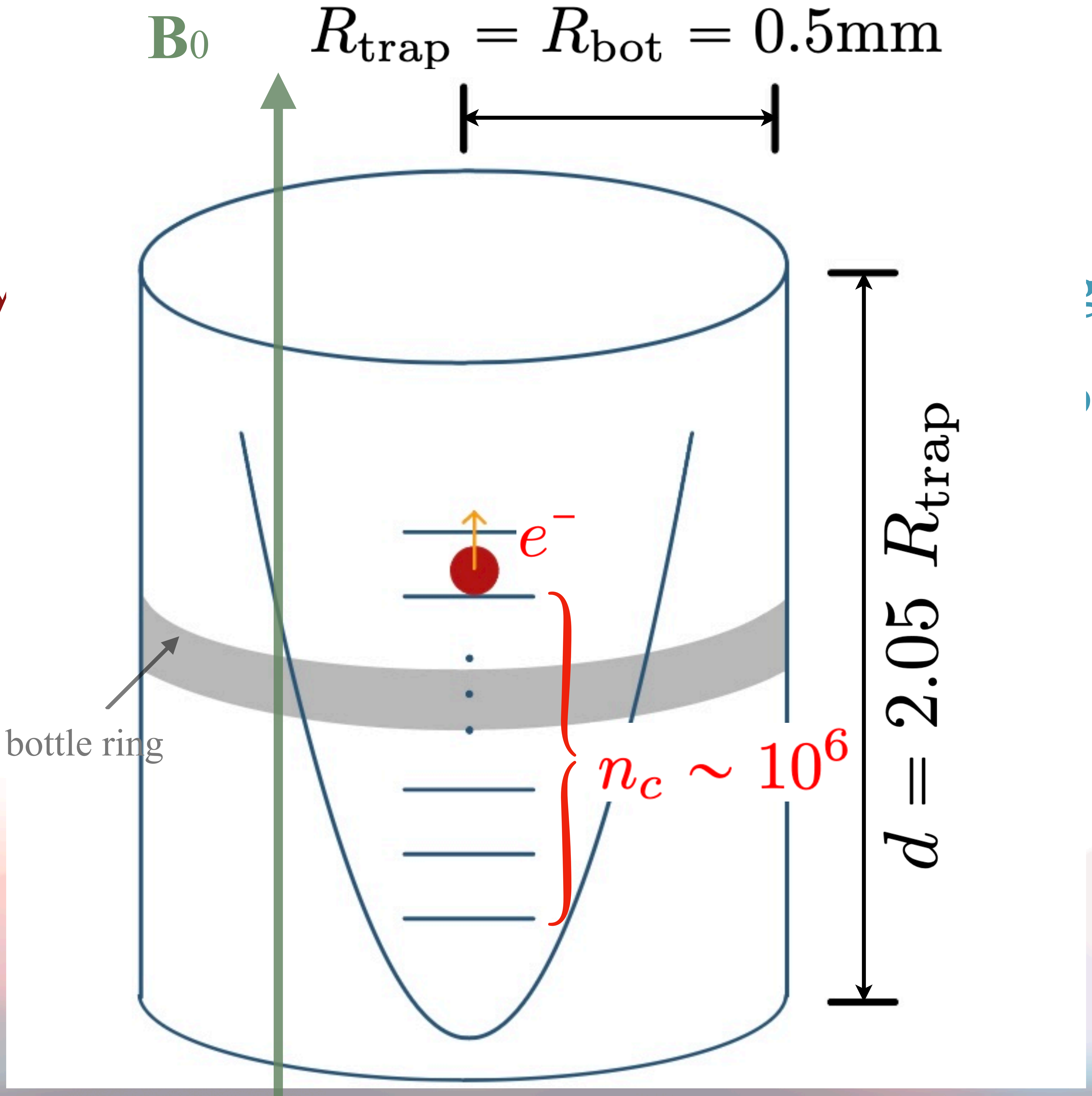

:

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Focusing–Effect of Cavity

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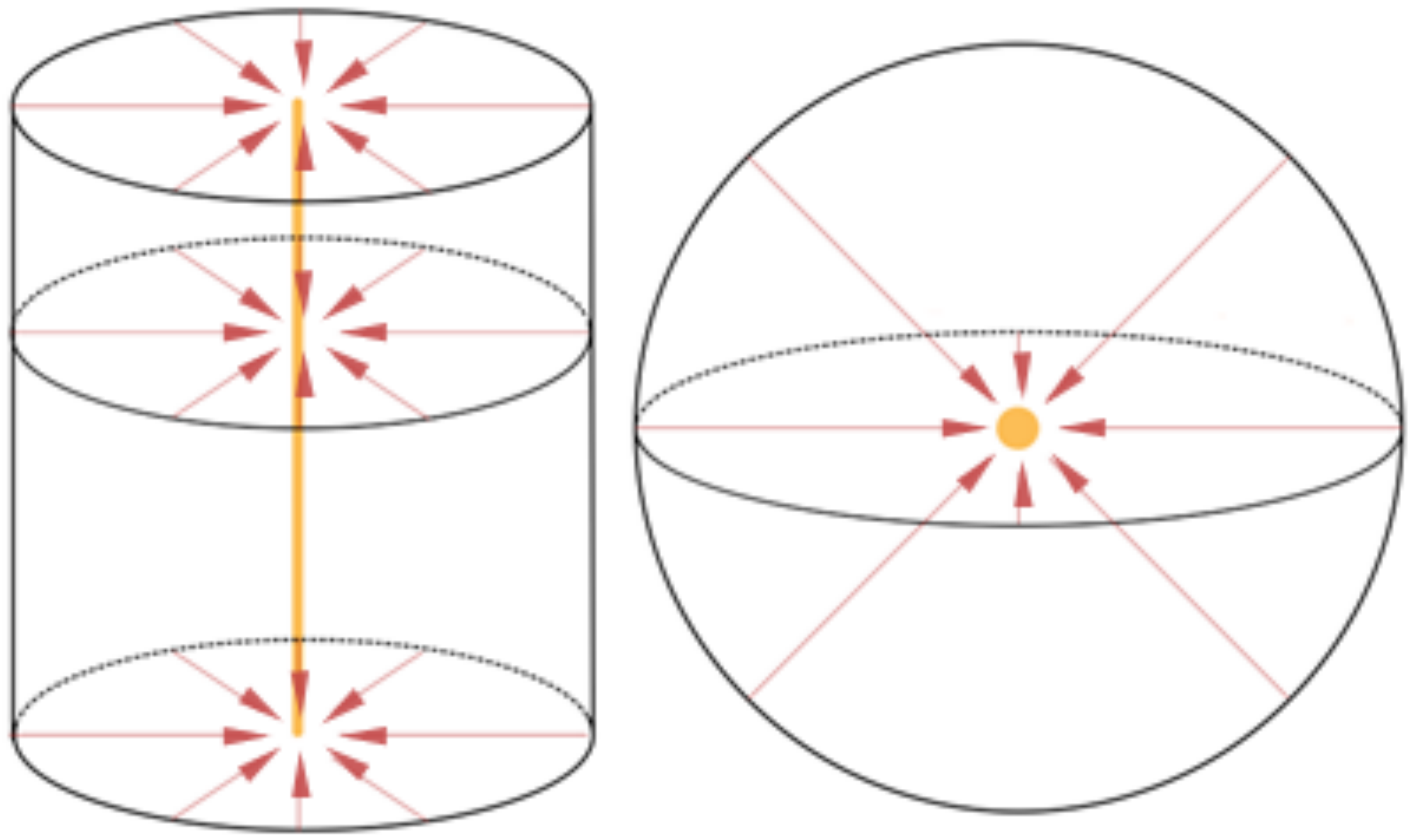
$$\Gamma_{c,\text{cavity}} = \kappa^2 \Gamma_{c,\text{free}}$$



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

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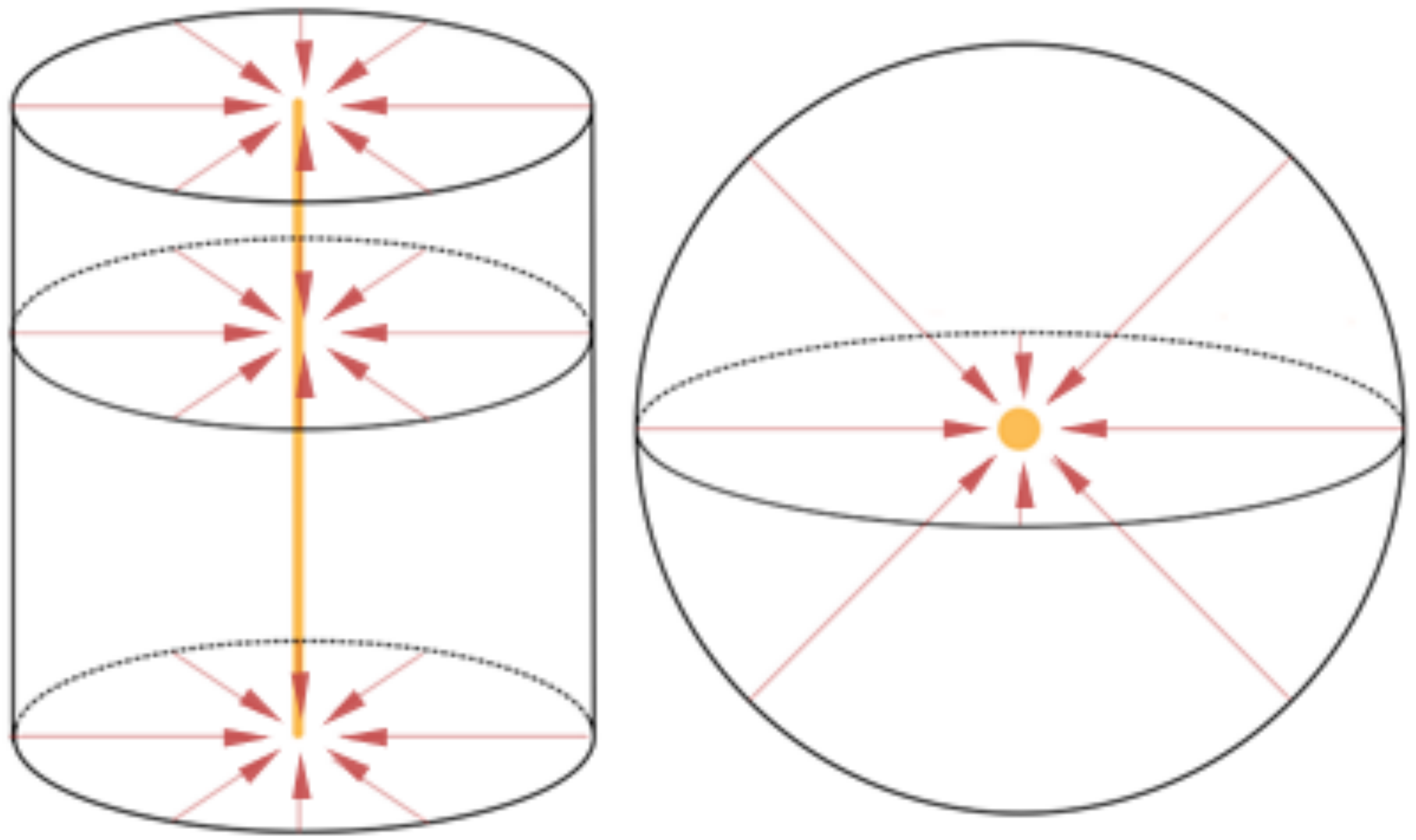

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Dark matter drives light to be emitted from the walls;

The right cavity geometery can focus this into the center

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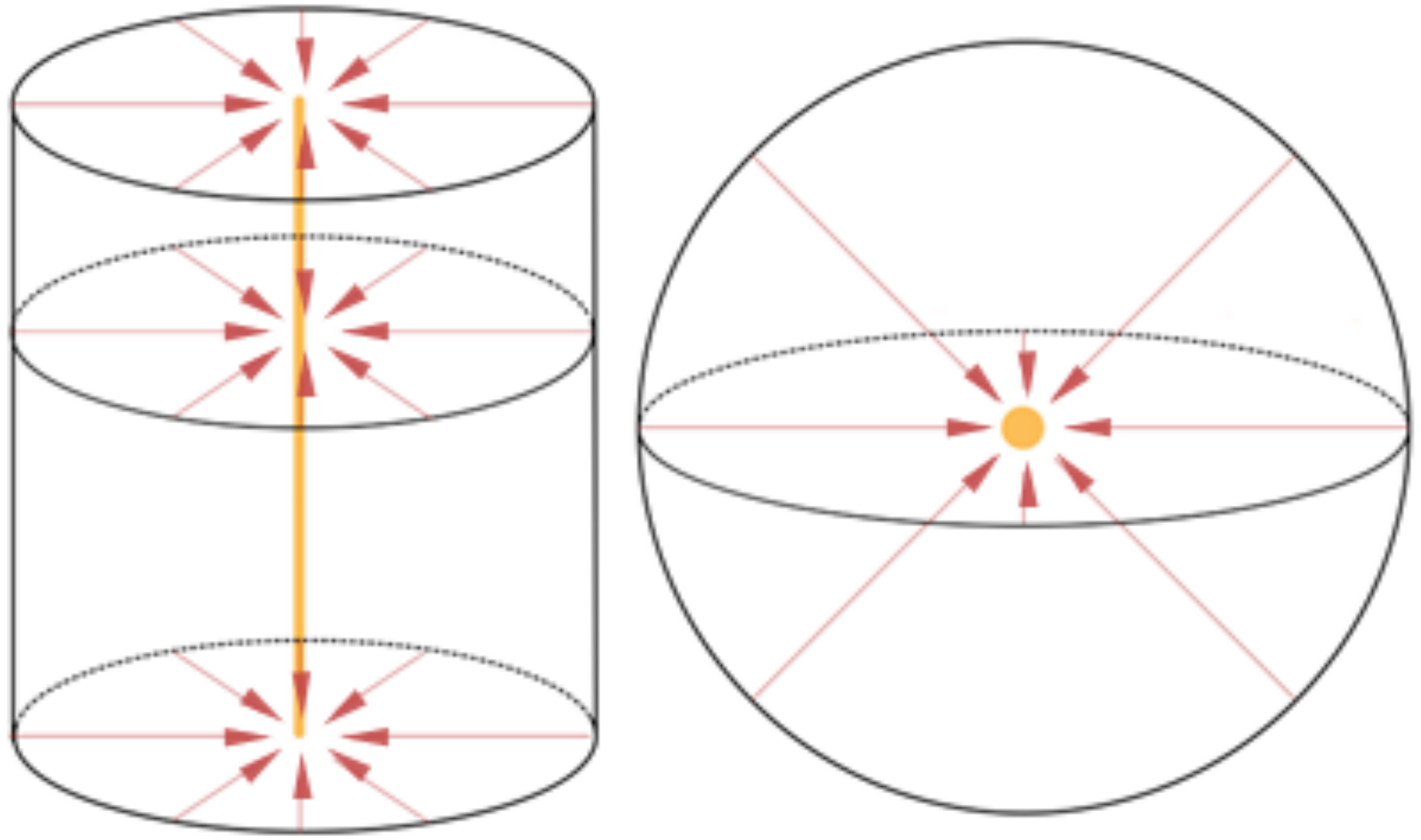

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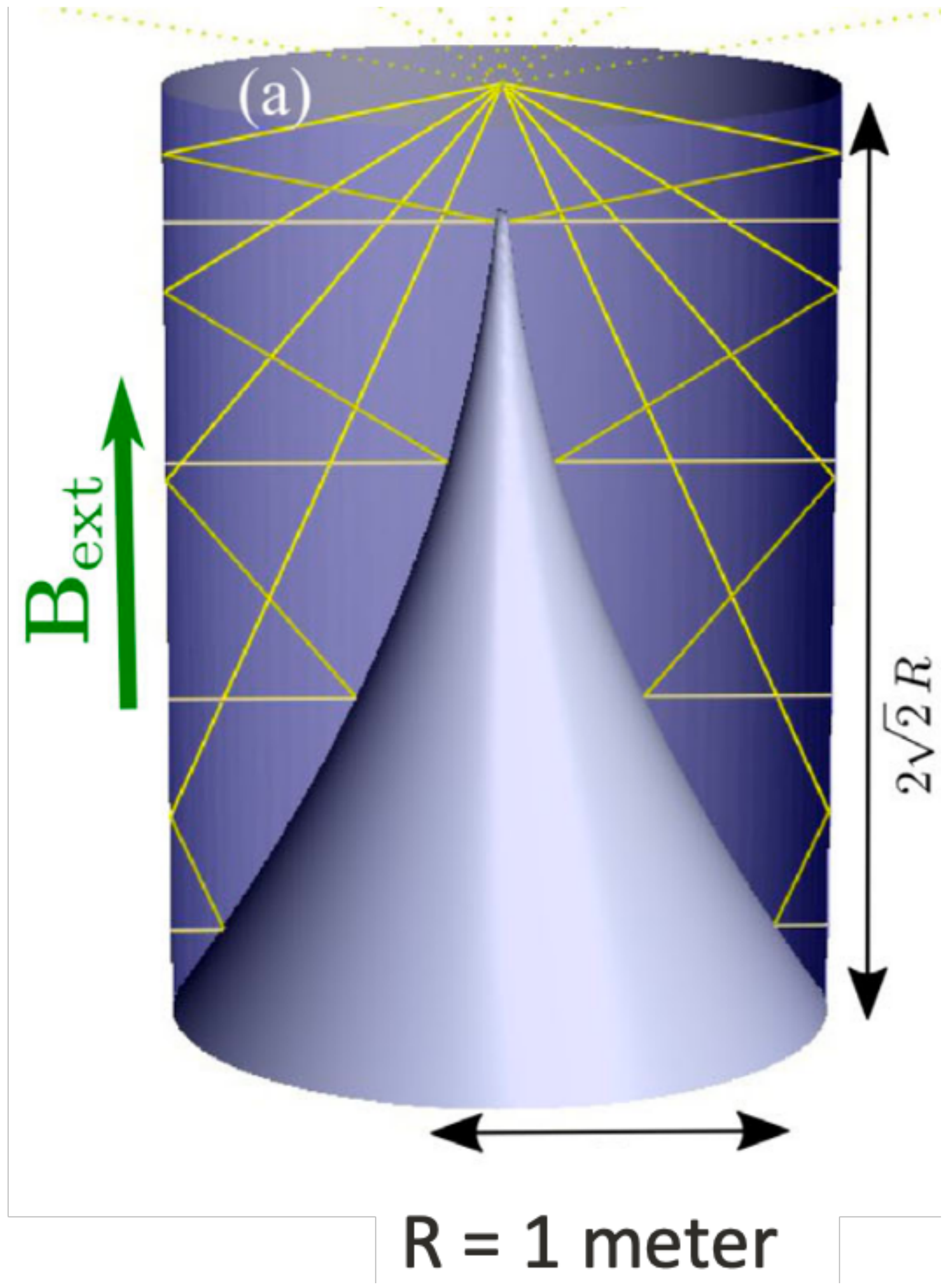

[Liu et al., 2111.12103]

Dark matter drives light to be emitted form the walls;
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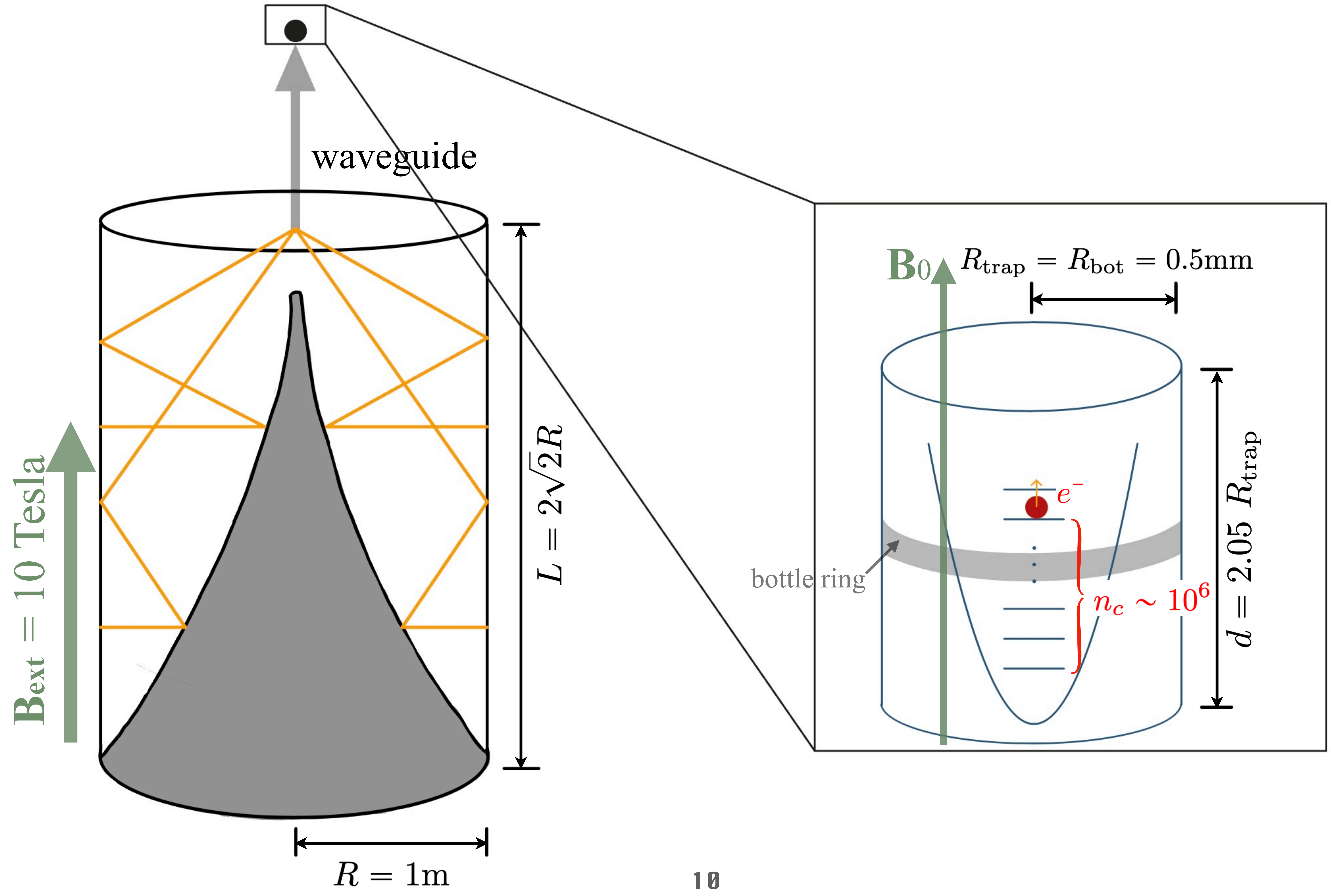
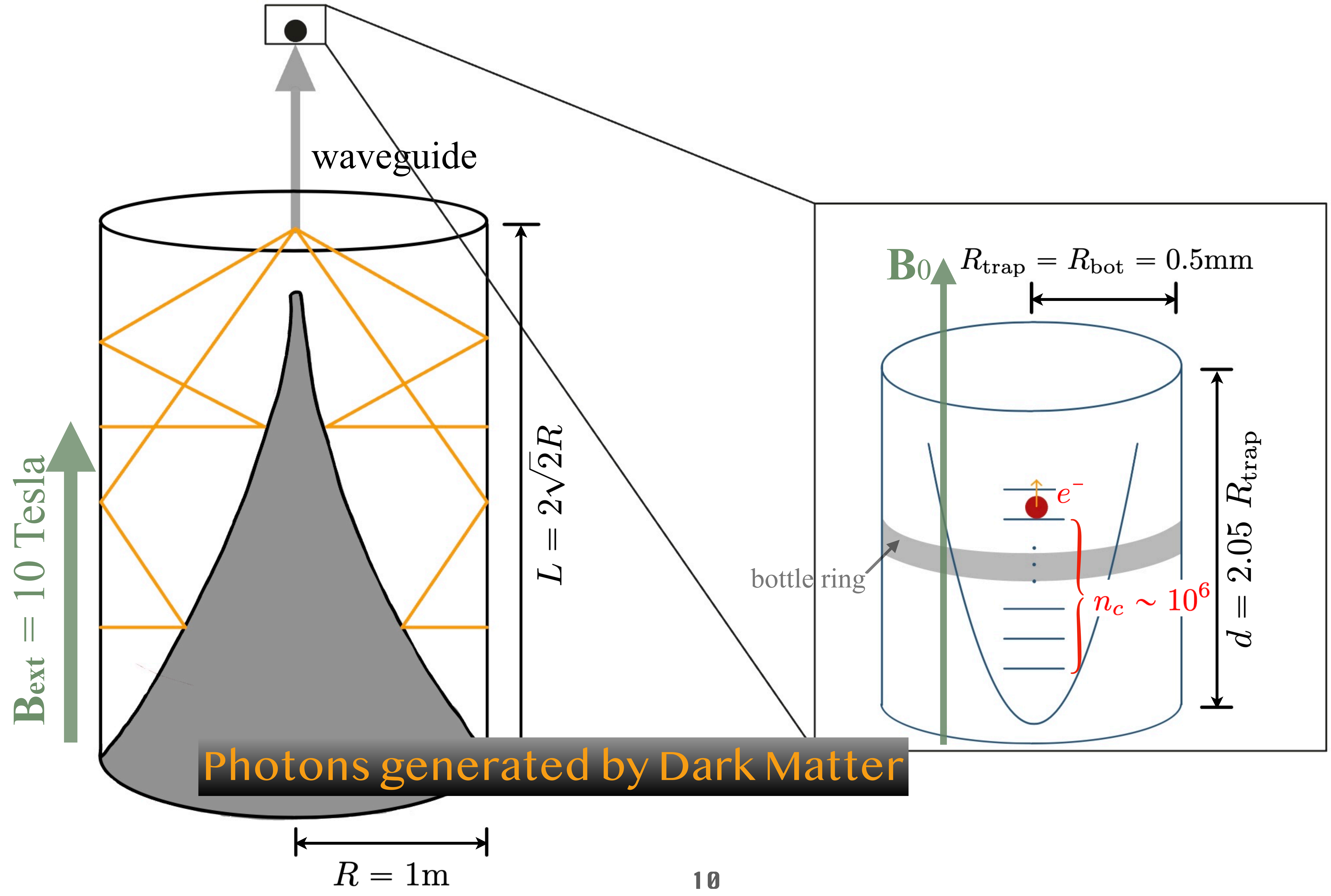
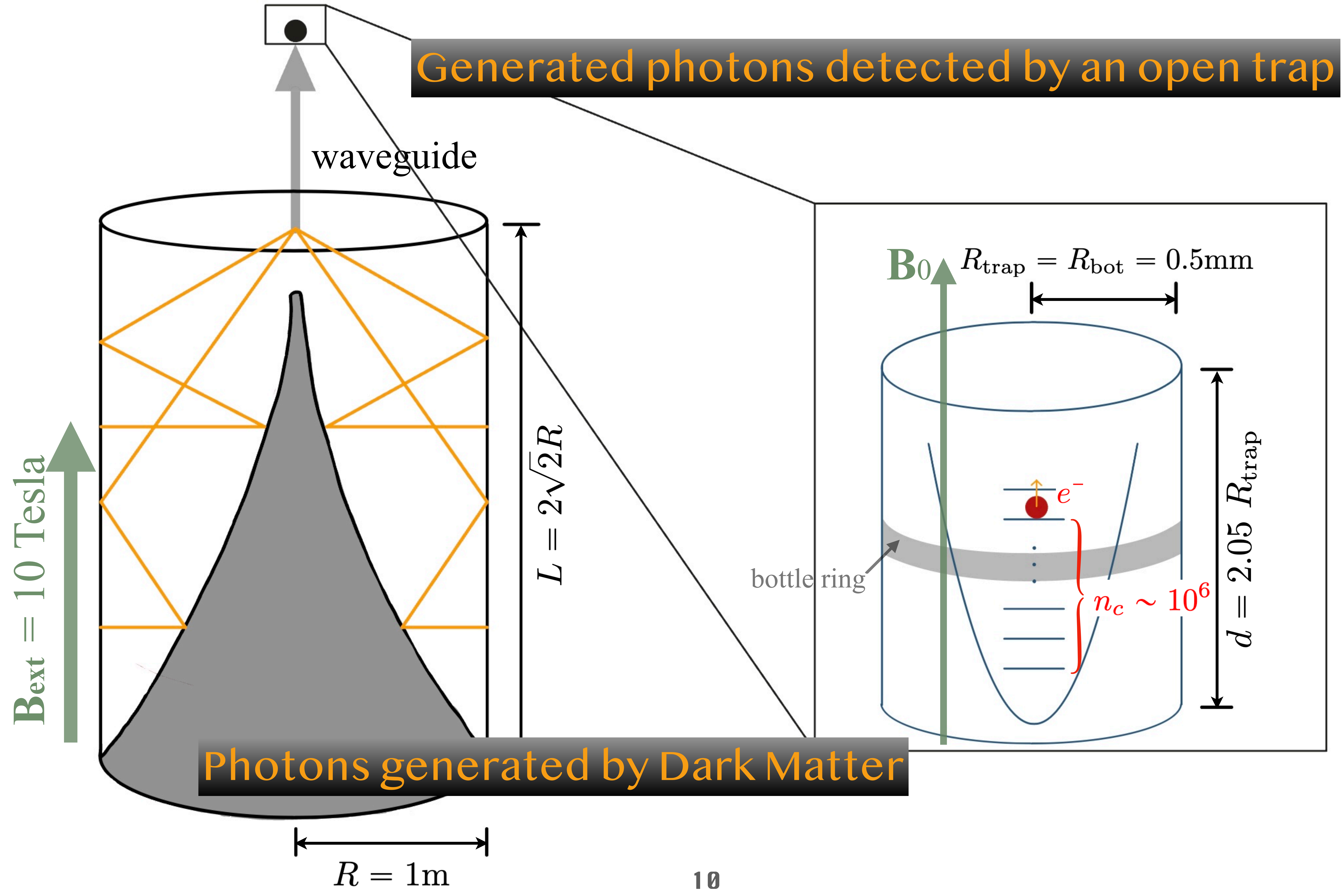
BREAD:
A Nicer Design with the same idea



waveguide
$B_{ext} = 10$ Tesla
$L = 2\sqrt{2}R$
$R = 1$m
B_0
$R_{trap} = R_{bot} = 0.5$mm
e^-
bottle ring
$n_c \sim 10^6$
$d = 2.05\ R_{trap}$



Photons generated by Dark Matter



Generated photons detected by an open trap
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$B_{ext} = 10$ Tesla
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$R = 1\text{m}$
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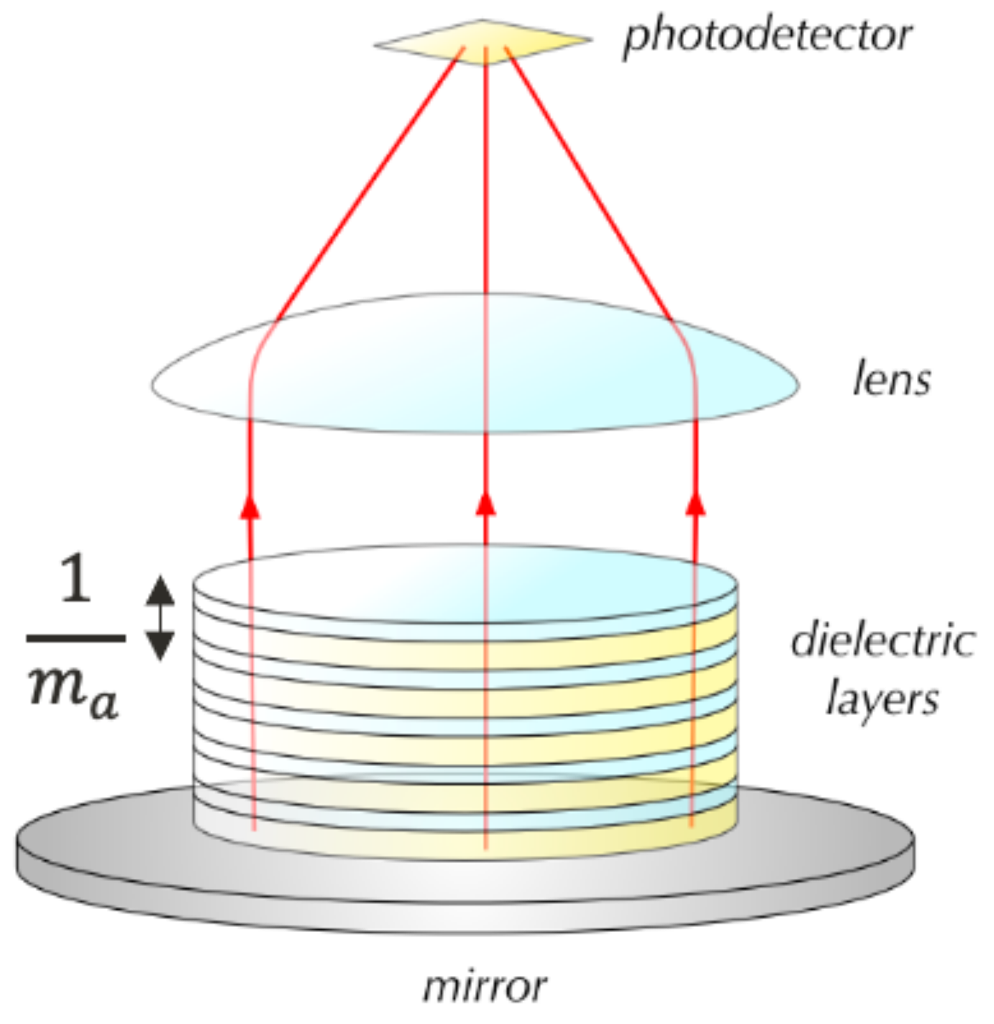
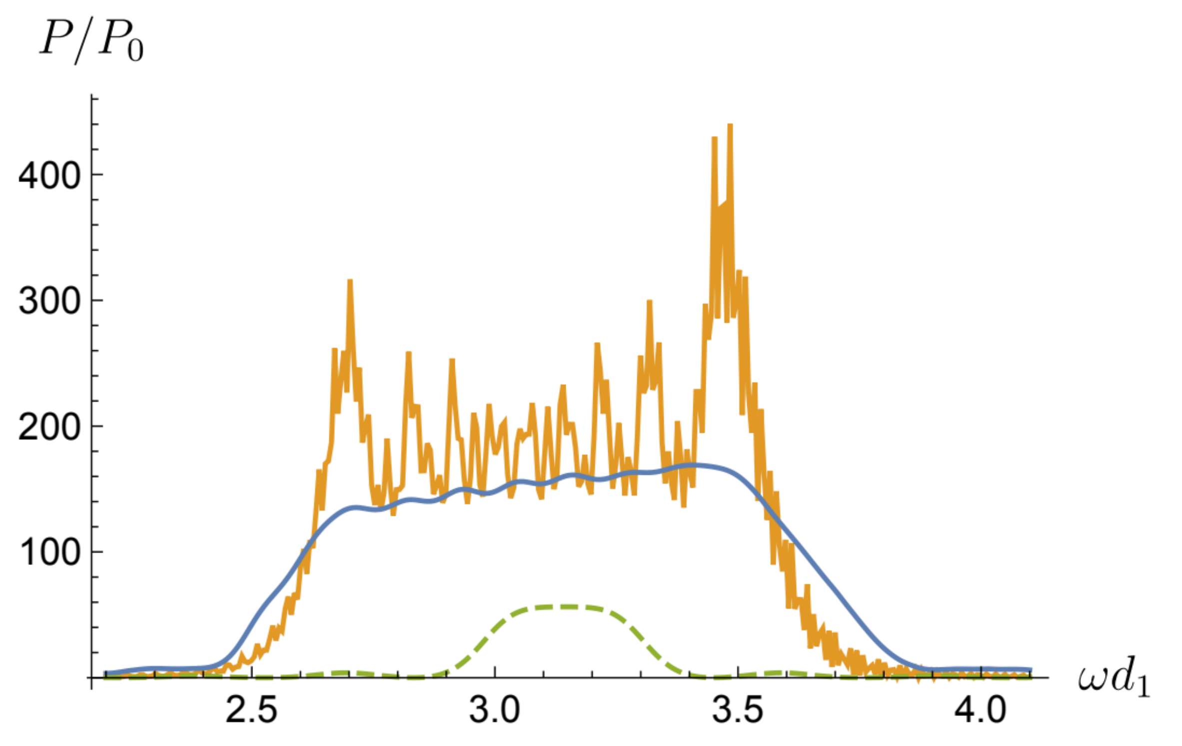
Dielectric Layers



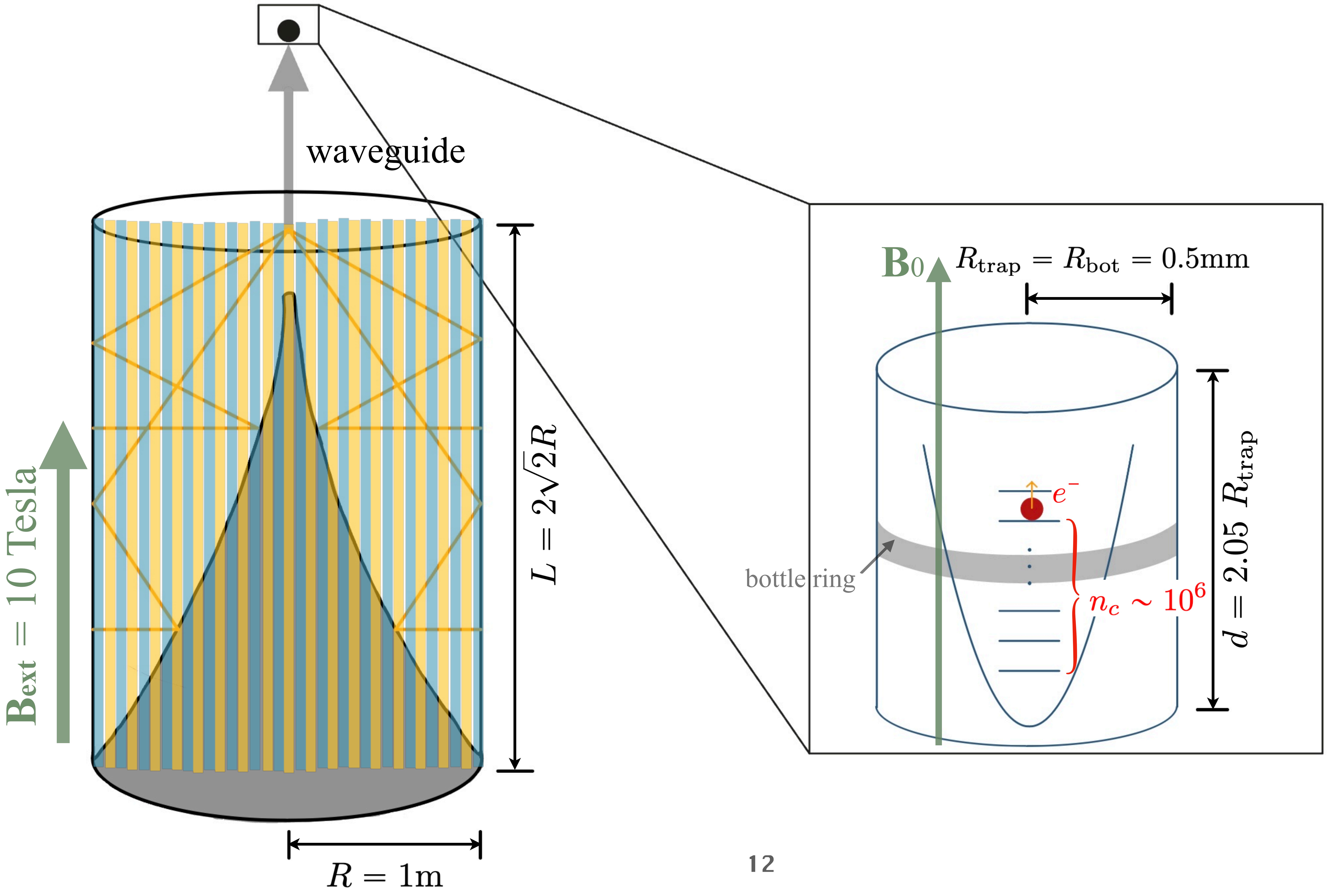


Baryakhtar et. al [1803.11455]

Each layer iteslf will contribute to the focusing effect

- N_l **layers** with the same thickness in one stack: λ_DM = thickness got enhanced by resonance
- N_s **stacks** with different thicknesses: broader frequency range
- Limited the size of the BREAD cavity $N_l \times N_s < R/d$
- **1 switch/month**

$$\Gamma_c = \Gamma_c \times N_l^2$$



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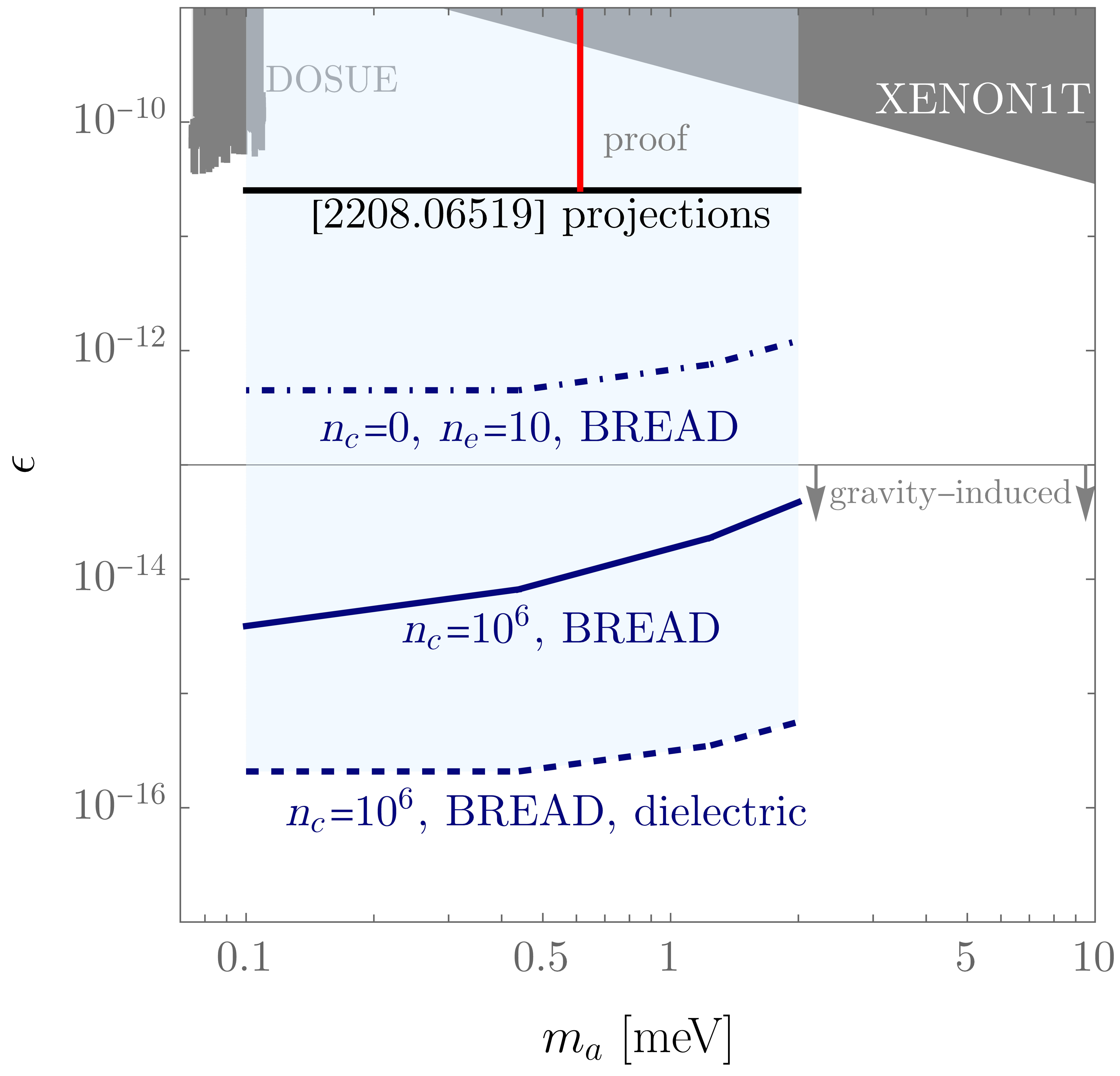
bottle ring
$n_c \sim 10^6$
$d = 2.05\ R_{\text{trap}}$

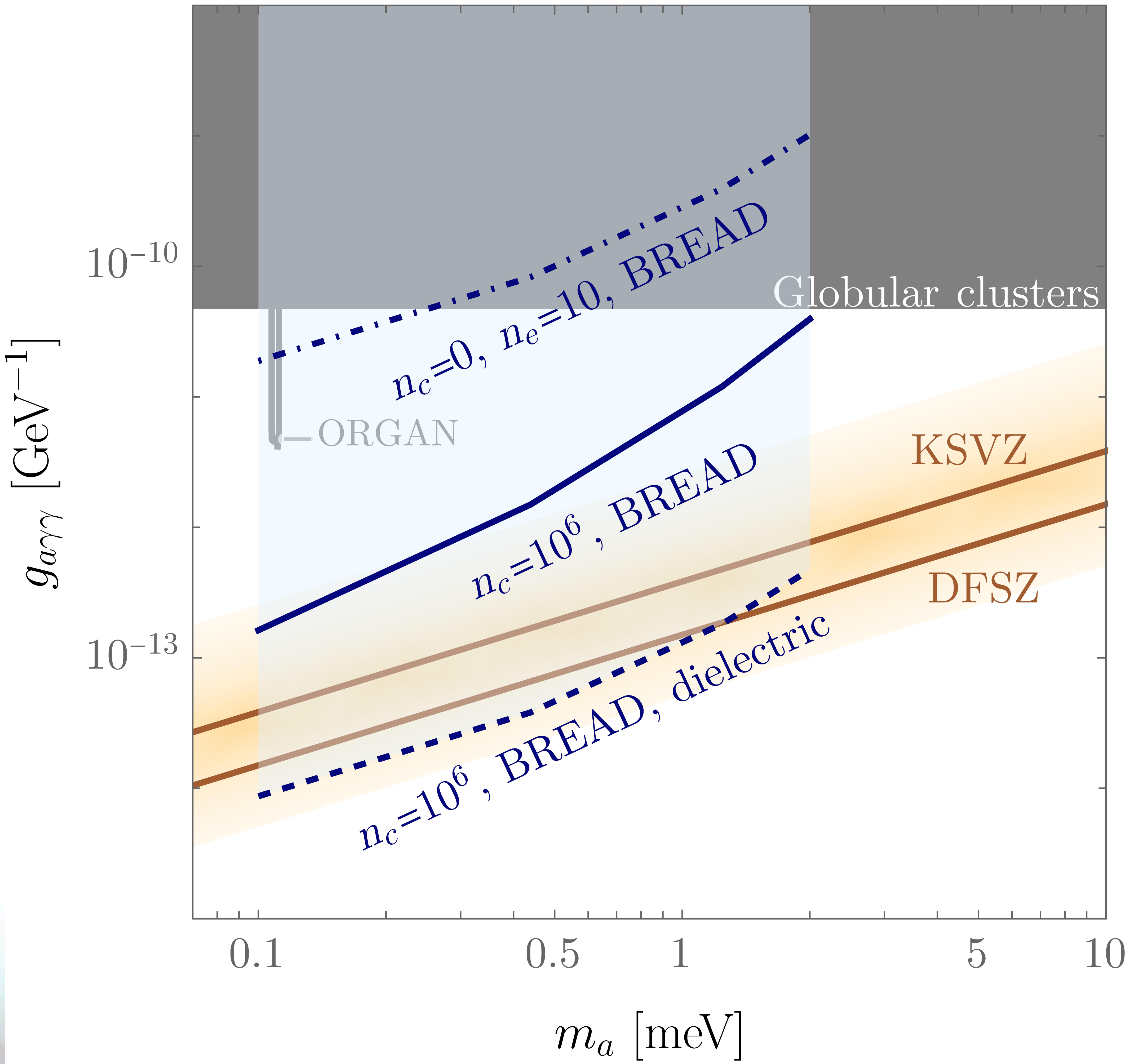
Conclusion

- Using Electron Trap as a Dark Matter Detector
- Background-free Over 7.4 Days
- Detect both Axion and DPDM
- Increase the Result by Optimizing Parameters

Projection



DPDM



Axions

Thank You

Questions?

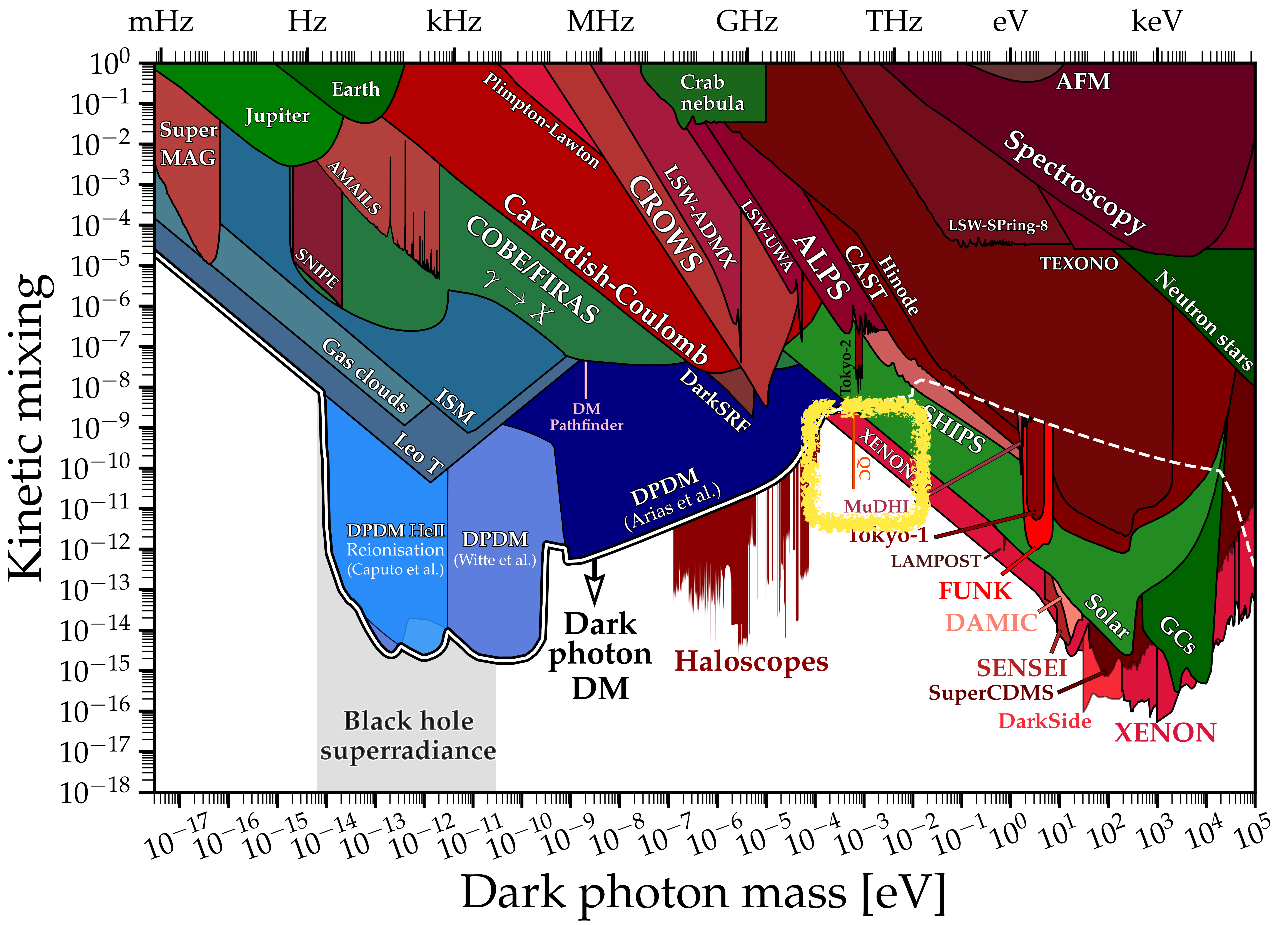
Backup

Stanford

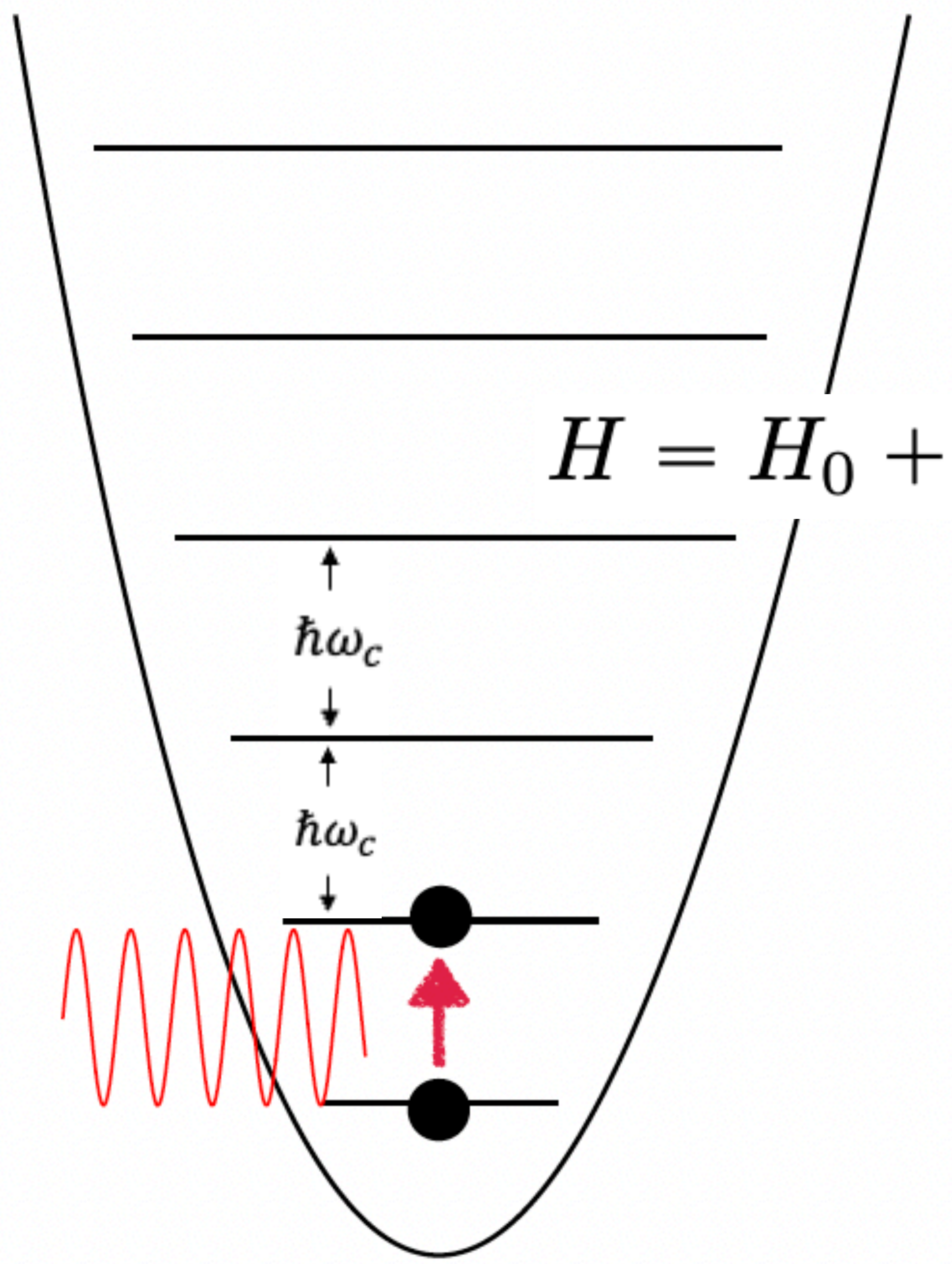
Dark Photon Dark Matter

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \boxed{\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu$$

- Dark U(1)
- Massive vector
- Kinetic mixing
- Dark Photon Dark Matter



Resonance & Selection Rule



$$H = H_0 + H_{\text{int}} \Rightarrow \begin{cases} \text{Axions: } \Gamma_{c,\text{free}} \propto g_{a\gamma\gamma}^2 B_{\text{ext}}^2 \dfrac{\rho_{\text{DM}}}{\Delta\omega_a} \\ \text{DPDM: } \Gamma_{c,\text{free}} \propto \epsilon^2 \dfrac{\rho_{\text{DM}}}{\Delta\omega_{A'}} \end{cases}$$

The transition rate is enhanced by

the dark matter width $\Delta\omega_{A'} \approx \frac{1}{2} m_{A'} v^2$

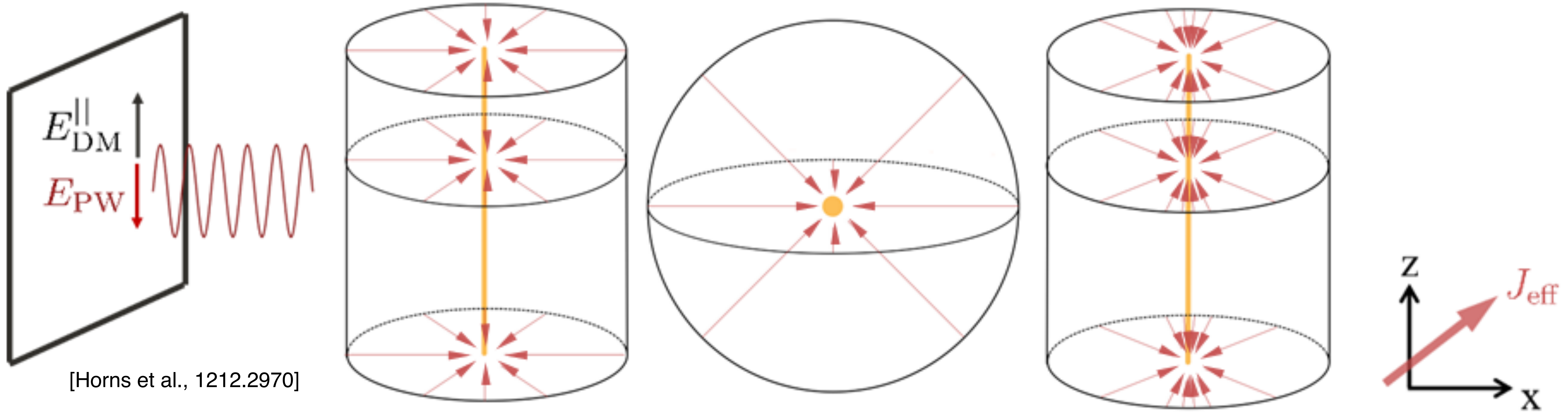
Selection Rule: only one jump at a time.

Due to the small coupling with dark matter

First-order perturbation theory applied

Focusing–Effect of Cavity

$$\Gamma_{c,\text{cavity}} = \kappa^2 \Gamma_{c,\text{free}}$$

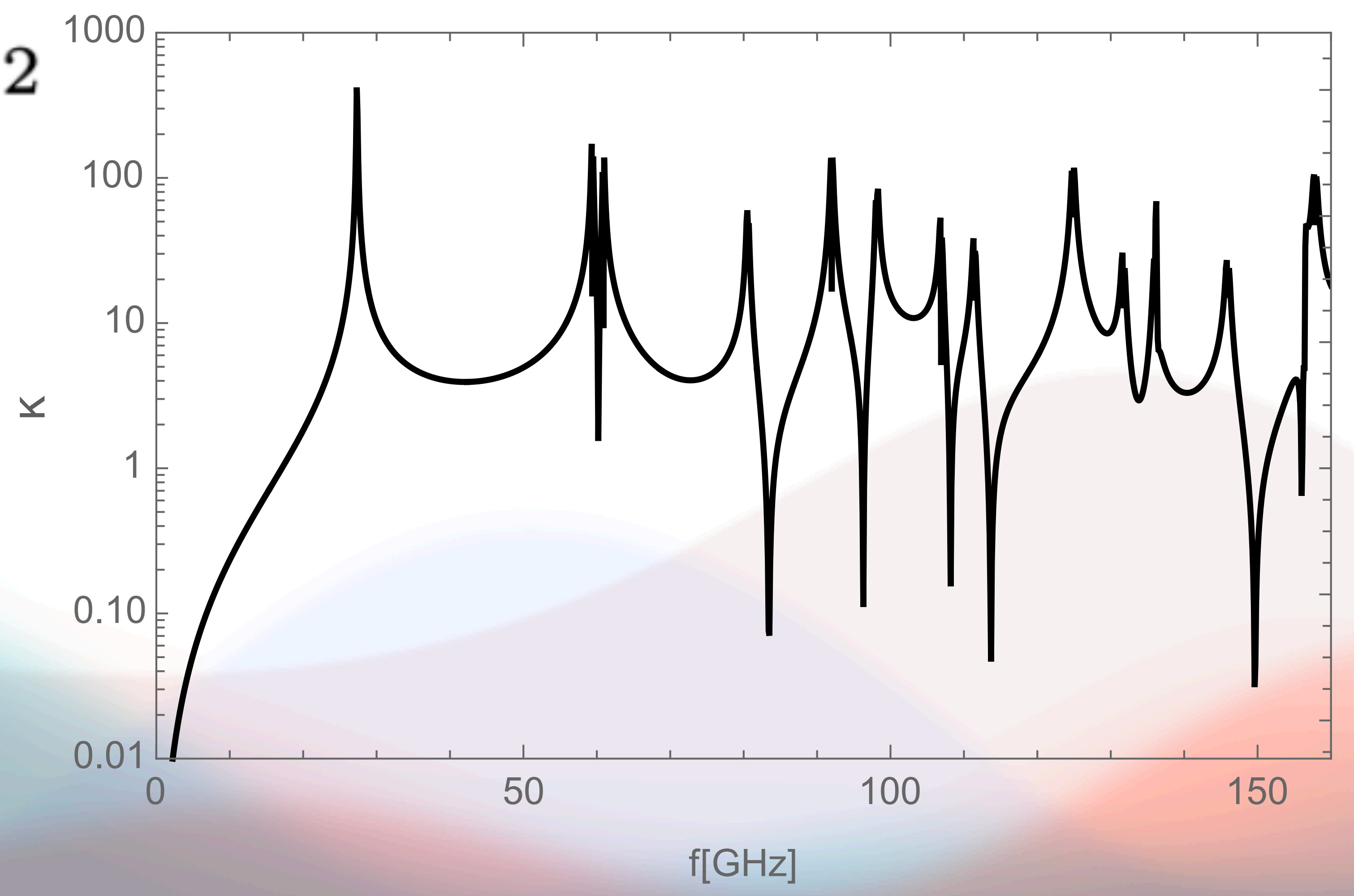


[Horns et al., 1212.2970]

$$E_{||}^{\text{Dark}} = \epsilon\sqrt{2\rho_{\text{DM}}}\cos\omega t$$

$$E_{||}^{\text{pw}} = -\,\epsilon\sqrt{2\rho_{\text{DM}}}\cos\left(\omega t \pm kx\right)$$

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



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