Axionic and Phonon Polaritons for Axion Dark Matter Detection

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Joint IQ Initiative & PITT PACC Workshop: Axions, Funamentals and Synthetic, University of Pittsburgh
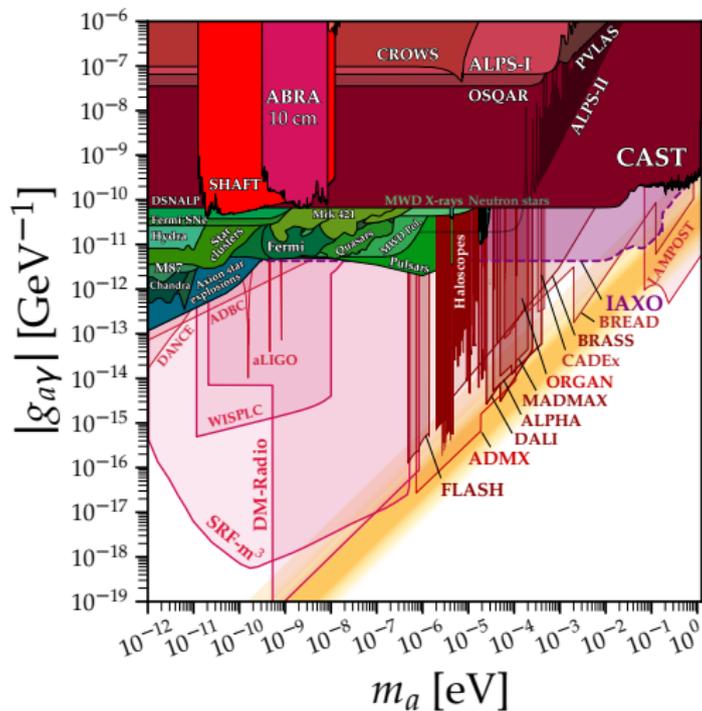
based on

[**JSE**, D.J.E. Marsh, A.J. Millar, et al. 21]**,** [D. J. E. Marsh, K.C. Fong, E. Lentz, L. Smejkal, M. Ali, 18] [D.J.E. Marsh, J.I. McDonald, A.J. Millar, **JSE** 22]
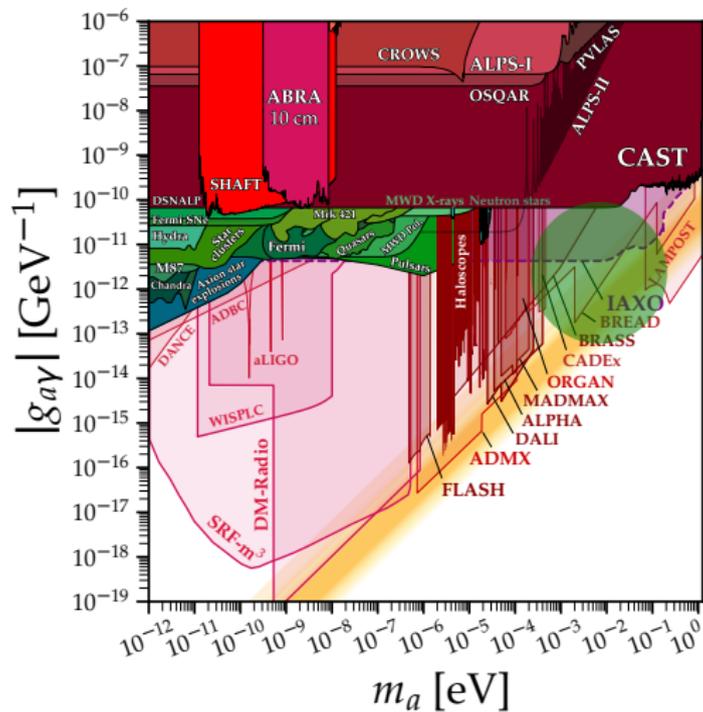
04/06/23

Constraints on Dark Matter axions

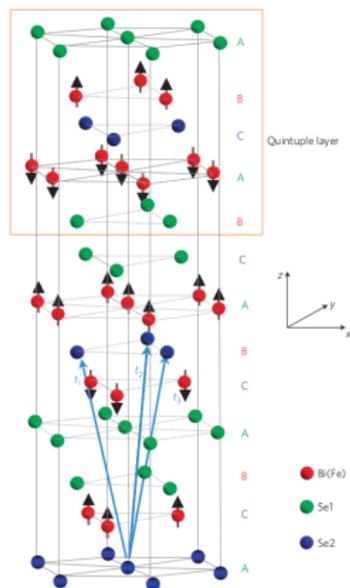adapted from [cajohare.github.io/AxionLimits/]

Constraints on Dark Matter axions

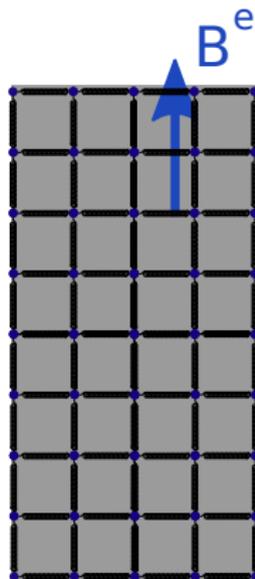adapted from [cajohare.github.io/AxionLimits/]

Axion DM Detection with
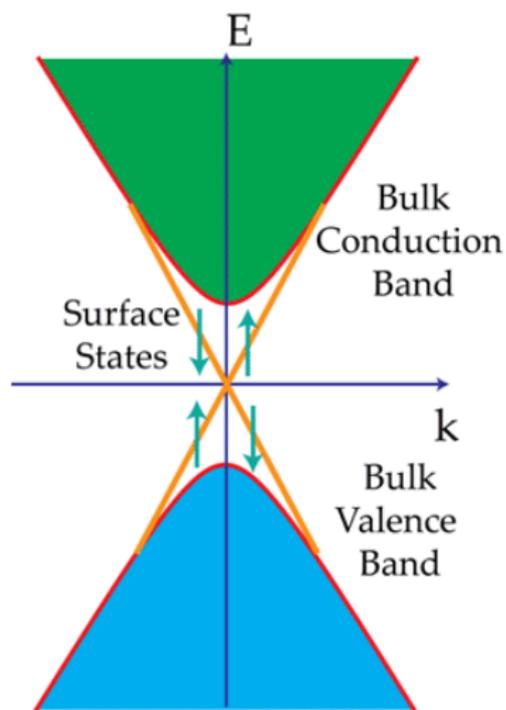
Axion quasiparticles

[Li, Wang, Qi, Zhang 10]

Phonons

Axion Quasiparticles (AQs)

Axion Quasiparticles (AQs)

arise in materials with $\mathcal{L} \supset \delta\Theta \boldsymbol{E} \cdot \boldsymbol{B}$

Topological insulator in a nutshell

[hoffman.physics.harvard]

- Topological insulator is insulating in the bulk and conducting on the surface
- Physical realization for example: Bi_2Te_3 or Bi_2Se_3

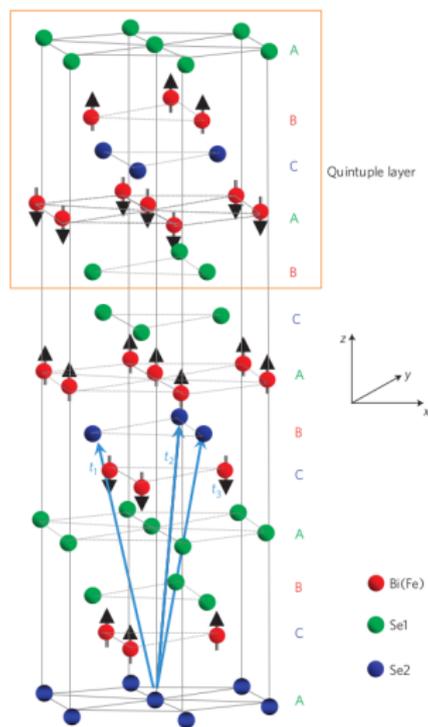# Effective description of topological insulator

- Topological insulator

$$S_{TI} = \int d^3x dt (\epsilon E^2 - \frac{1}{\mu} B^2) + \underbrace{\frac{\theta}{2\pi} \frac{\alpha}{2\pi} \int d^3x dt \boldsymbol{E} \cdot \boldsymbol{B}}_{S_\theta}$$

- θ is periodic in 2π

$$\theta \boldsymbol{E} \cdot \boldsymbol{B} \xrightarrow{T} -\theta \boldsymbol{E} \cdot \boldsymbol{B} \xrightarrow{\theta \text{ periodic}} (-\theta + 2\pi) \boldsymbol{E} \cdot \boldsymbol{B} \xRightarrow{\text{T inv.}} \theta = \pi$$

- Time reversal invariant insulator $\theta = 0, \pi$ ($\theta = 0$ normal insulator, $\theta = \pi$ topological insulator)
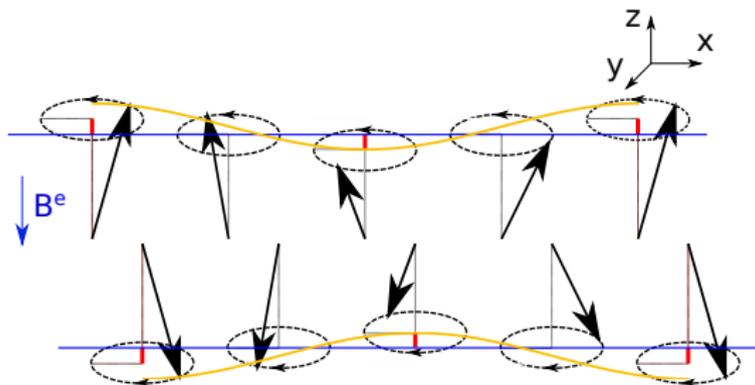- Most topological insulators have *T* symmetry.

Dynamical Axion field in Topological Magnetic Insulator

[Li, Wang, Qi, Zhang 10]

- Add P or T breaking terms $\Rightarrow \theta$ deviates form $0, \pi$, realization in antiferromagnetic phase
- Antiferromagnetic phase has spin wave excitations (Magnons) which behave as a dynamical axion field
- Suggested material: $(Bi_{1-x}Fe_x)_2Se_3$

Dynamical AQs in antiferromagnets

Néel vector $\boldsymbol{M}^- = \frac{1}{2}\left(\langle\boldsymbol{S}_A\rangle - \langle\boldsymbol{S}_B\rangle\right)$

> AQ is longitudinal spin wave
>
> $$\delta\Theta(\boldsymbol{x}, t) = \delta M_z^-(\boldsymbol{x}, t)$$
> $$\mathcal{L} \supset \frac{\alpha}{4\pi^2}\delta\Theta\boldsymbol{E}\cdot\boldsymbol{B}$$

[Li, Wang, Qi, Zhang 10], [Afflek 89]

Other suggested material candidates

- $Mn_2Bi_2Te_5$ [Cao, Han, et al. 21]
- Weyl semimetal [J. Gooth, B. Bradlyn et al. 19]
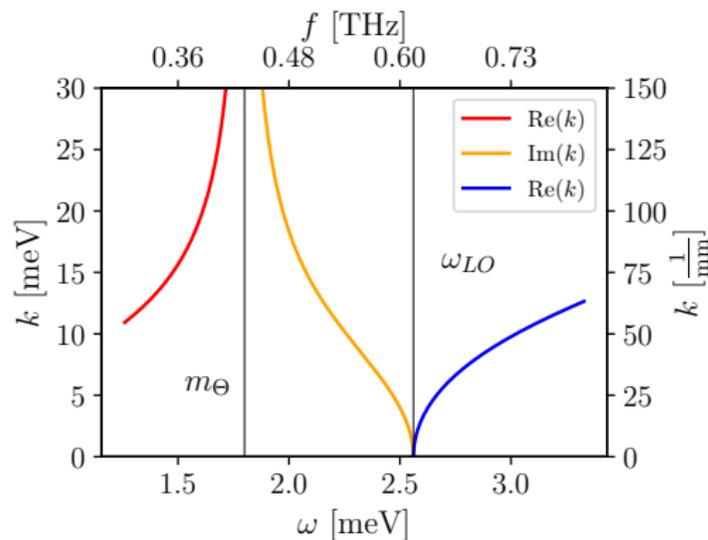- topological paramagnetic insulator [Wang, Lian, Zhang, 16]

Detecting Axion Quasiparticles

$$\nabla \cdot \boldsymbol{D} = -\frac{\alpha}{\pi} \nabla \Theta \cdot \boldsymbol{B}^e,$$

$$\nabla \times \boldsymbol{H} - \partial_t \boldsymbol{D} = \frac{\alpha}{\pi} \boldsymbol{B}^e \partial_t \Theta,$$

$$\partial_t^2 \delta\Theta + m_\Theta^2 \delta\Theta = \frac{1}{f_\Theta^2} \frac{\alpha}{\pi} \boldsymbol{E} \cdot \boldsymbol{B}^e.$$

with $\boldsymbol{D} = n^2 \boldsymbol{E}$, $\boldsymbol{H} = \boldsymbol{B}$ and $\Theta \equiv \delta\Theta + \Theta^0$

Axion polariton dispersion relation

Mixing of AQ with photons $\Rightarrow$ axion polariton (collective mode is coupled linearly to photons)

$$k^2 = n_\Theta^2 \omega^2$$

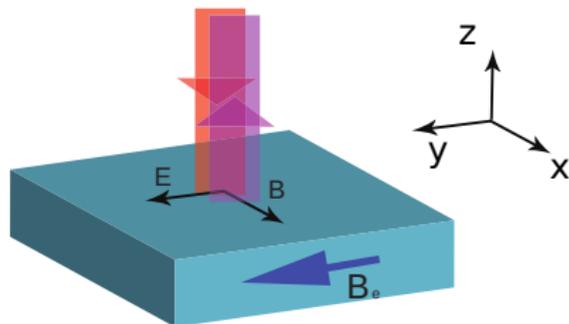$$n_\Theta^2 = n^2 \left[\frac{b^2}{m_\Theta^2 - \omega^2} + 1 \right]$$

$$m_\Theta = 2\,\text{meV}$$

$$\omega_{\text{LO}} = \sqrt{m_\Theta^2 + b^2}$$

$$b = \frac{\alpha}{\pi\sqrt{2}} \frac{B^e}{n f_\Theta} = 1.6\,\text{meV} \left(\frac{25}{n^2} \right)^{1/2} \left(\frac{B^e}{2\,\text{T}} \right) \left(\frac{70\,\text{eV}}{f_\Theta} \right).$$

Detecting Axion Quasiparticles

THz time domain spectroscopy

[Li, Wang, Qi, Zhang 10]

In the medium:

$$E(z) = C_+ e^{i\omega n_\theta z} + C_- e^{-i\omega n_\theta z}$$
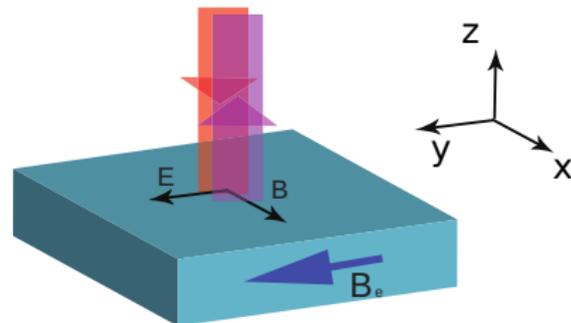$$\delta\Theta(z) = D_+ e^{i\omega n_\theta z} + D_- e^{-i\omega n_\theta z}$$

Boundary conditions:

$$\hat{\boldsymbol{e}}_z \cdot (\boldsymbol{D}_{\text{vac}} - \boldsymbol{D}_{\text{mat}}) = 0,$$
$$\hat{\boldsymbol{e}}_z \times (\boldsymbol{H}_{\text{vac}} - \boldsymbol{H}_{\text{mat}}) = 0.$$

Detecting Axion Quasiparticles

THz time domain spectroscopy

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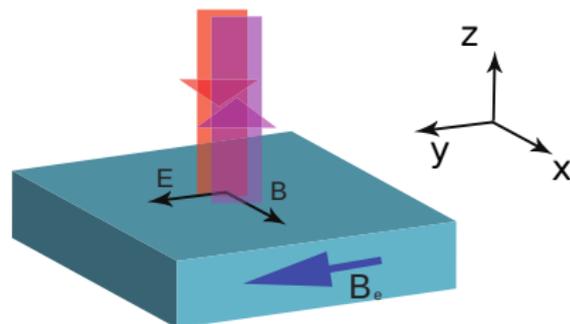
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Short aside:

$$\nabla \cdot \boldsymbol{D} = -\frac{\alpha}{\pi} \nabla\Theta \cdot \boldsymbol{B},$$
$$\nabla \times \boldsymbol{H} - \partial_t \boldsymbol{D} = \frac{\alpha}{\pi} (\boldsymbol{B}\partial_t\Theta - \boldsymbol{E} \times \nabla\Theta),$$

THz time domain spectroscopy

[Li, Wang, Qi, Zhang 10]

In the medium:

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$$\delta\Theta(z) = D_+ e^{i\omega n_\theta z} + D_- e^{-i\omega n_\theta z}$$
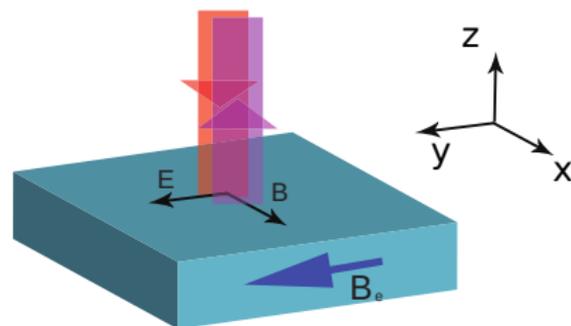
Boundary conditions:

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Short aside:

$$\nabla \cdot \boldsymbol{D}_\Theta = 0$$
$$\nabla \times \boldsymbol{H}_\Theta - \partial_t \boldsymbol{D}_\Theta = 0,$$

Detecting Axion Quasiparticles

THz time domain spectroscopy

[Li, Wang, Qi, Zhang 10]

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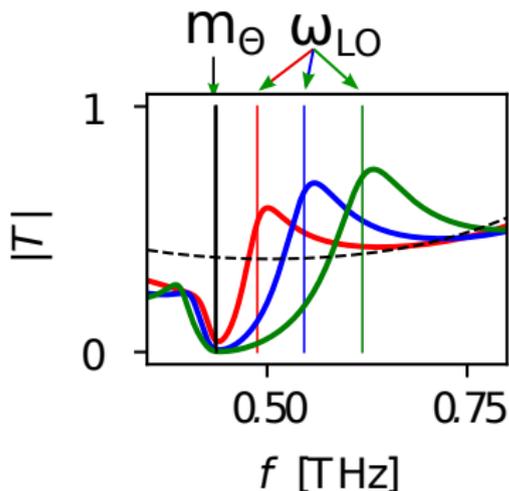
Boundary conditions:

$$\hat{\boldsymbol{e}}_z \cdot (\boldsymbol{D}_{\text{vac}} - \boldsymbol{D}_{\text{mat}}) = 0,$$
$$\hat{\boldsymbol{e}}_z \times (\boldsymbol{H}_{\text{vac}} - \boldsymbol{H}_{\text{mat}}) = 0.$$

Short aside:

$$\boldsymbol{n} \cdot (\boldsymbol{D}_{\Theta,\text{vac}} - \boldsymbol{D}_{\Theta,\text{mat}}) = 0$$
$$\boldsymbol{n} \times (\boldsymbol{H}_{\Theta,\text{vac}} - \boldsymbol{H}_{\Theta,\text{mat}}) = 0$$

where $\boldsymbol{D}_\Theta = \boldsymbol{D} + \frac{\alpha}{\pi}\Theta\boldsymbol{B}$, $\boldsymbol{H}_\Theta = \boldsymbol{H} - \frac{\alpha}{\pi}\Theta\boldsymbol{E}$.

Transmission spectra

$B_e = 1.0$ T $B_e = 1.5$ T $B_e = 2.0$ T   - - - - $\delta\Theta = 0$

m_Θ ω_{LO}

$$n_\Theta^2 = n^2 \left[1 + \frac{b^2}{m_\Theta^2 - \omega^2 - i\Gamma_m\omega} + i\frac{\Gamma_\rho}{\omega} \right]$$

$d = 0.03$ mm

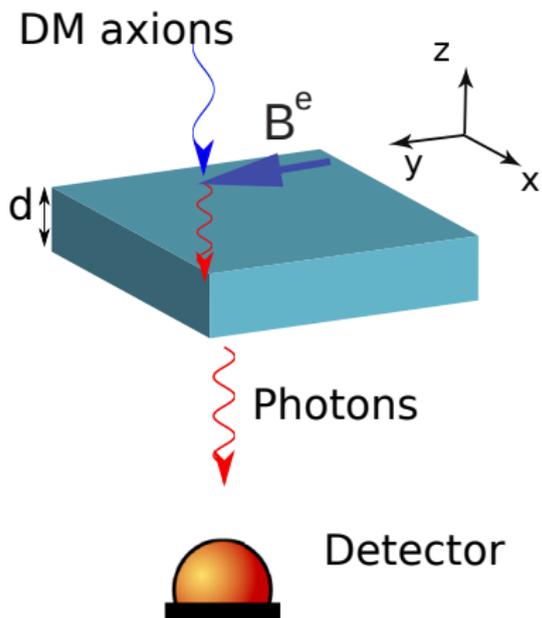Magnon losses: $\Gamma_m = 10^{-1}$

Photon losses: $\Gamma_\rho = 10^{-1}$

(artificial large losses to make effect clearer.)

[Bayrakci et al. 06]

$$T = \frac{2in_\Theta}{(n_\Theta^2 + 1)\sin\Delta + 2in_\Theta\cos\Delta} + \mathcal{O}\left(\left(\frac{\alpha}{\pi}\Theta^0\right)^2\right)$$
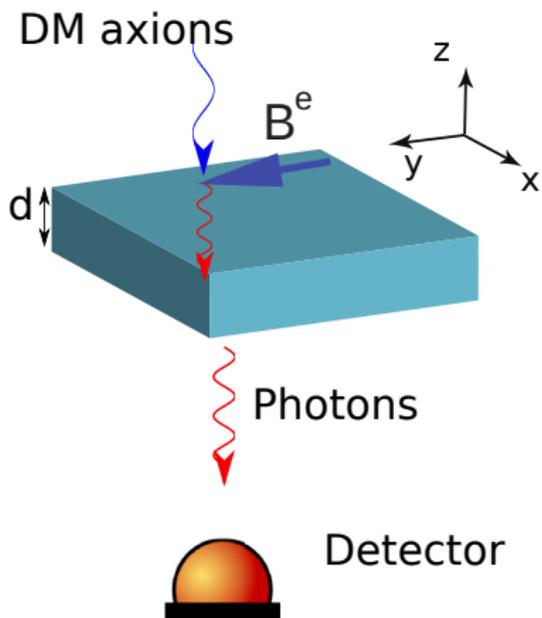
with $\Delta = dk_\Theta$

Axion dark matter detection with AQs

DM axions

B^e

z

y   x

d

Photons

Detector

Surface Area $A = (20\,\text{cm})^2$

TOORAD (Topological
Resonant Axion Detection)

DM axions

B^e

z

y   x

d

Photons

Detector

Surface Area $A = (20\,\text{cm})^2$

TOORAD (Topological Resonant Axion Detection)

$$\nabla \cdot \boldsymbol{D} = -\frac{\alpha}{\pi}\nabla\Theta \cdot \boldsymbol{B}^e$$
$$-g_{a\gamma}\nabla a \cdot \boldsymbol{B}^e,$$
$$\nabla \times \boldsymbol{H} - \partial_t \boldsymbol{D} = \frac{\alpha}{\pi}\boldsymbol{B}^e\partial_t\Theta$$
$$+g_{a\gamma}\boldsymbol{B}^e\partial_t a,$$
$$\nabla \cdot \boldsymbol{B} = 0,$$
$$\nabla \times \boldsymbol{E} + \partial_t \boldsymbol{B} = 0,$$
$$\partial_t^2\delta\Theta + m_\Theta^2\delta\Theta = \frac{1}{f_\Theta^2}\frac{\alpha}{\pi}\boldsymbol{E}\cdot\boldsymbol{B}^e,$$
$$(\partial_t^2 - \nabla^2 + m_a^2)a = g_{a\gamma}\boldsymbol{E}\cdot\boldsymbol{B}^e.$$

Effective description: axion induced E-field excites material with effective refraction index n_Θ

$$\partial_z^2 E(z) + \omega^2 n_\Theta^2(\omega)E(z) = -\omega^2 E_a$$
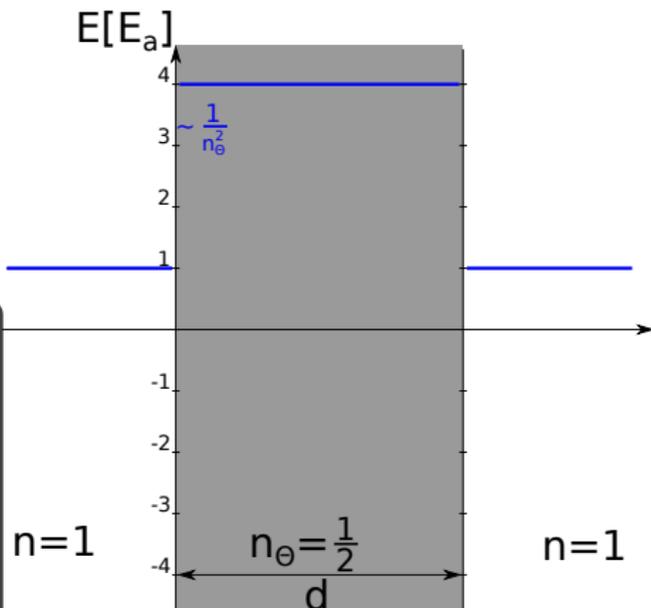
Physical understanding

Resonance condition:

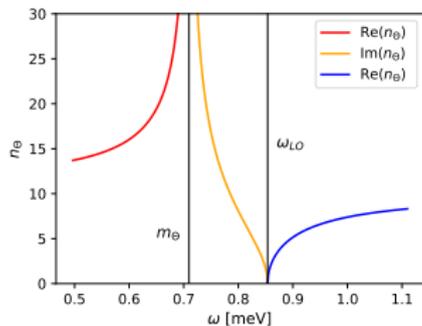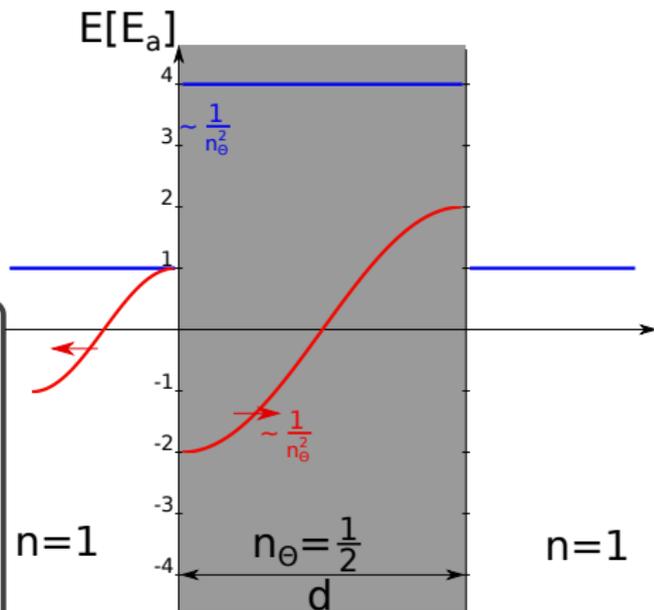$$\pi = n_\Theta(\omega_{\text{res}})\omega_{\text{res}}d$$
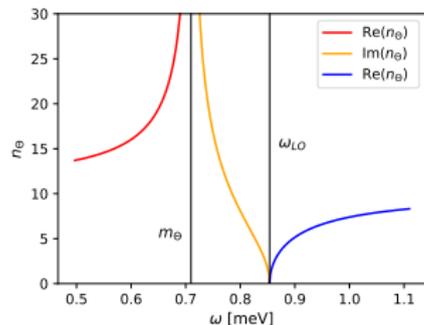
$$n_\Theta(\omega) = n\left[\frac{b^2}{m_\Theta^2 - \omega^2} + 1\right]^{\frac{1}{2}}$$

$$b \sim \text{ext. B-field}$$

Principle similar to dielectric haloscopes. Matching E and B-fields at interfaces.
Similarities to Fabry-Perot cavity.

Physical understanding

Resonance condition:

$$\pi = n_\Theta(\omega_{\mathrm{res}})\omega_{\mathrm{res}}d$$

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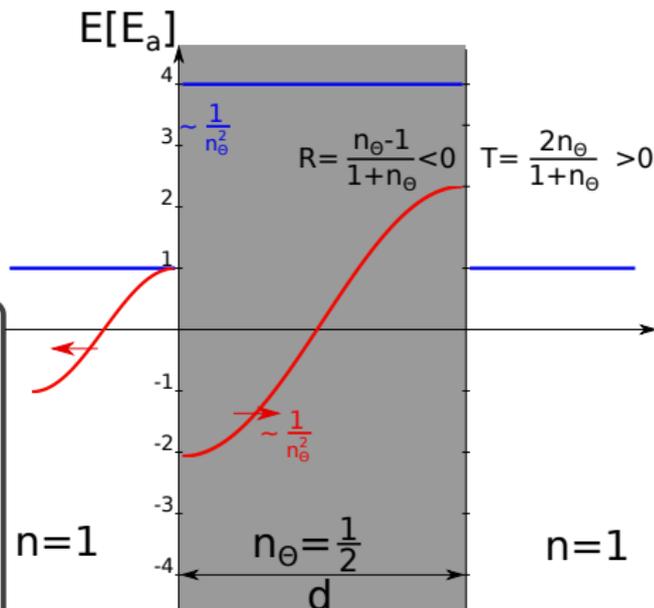Similarities to Fabry-Perot cavity.

Physical understanding

Resonance condition:

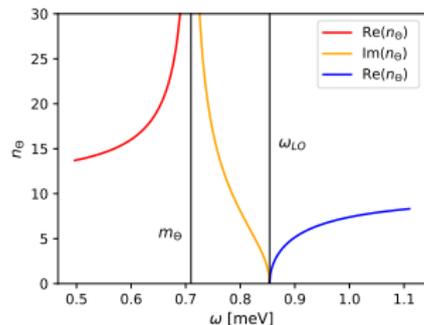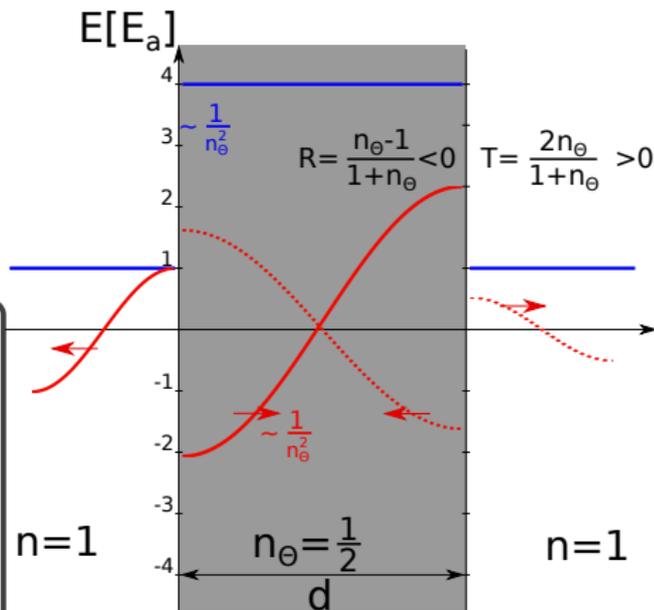$$\pi = n_\Theta(\omega_{\text{res}})\omega_{\text{res}}d$$

$$n_\Theta(\omega) = n\left[\frac{b^2}{m_\Theta^2 - \omega^2} + 1\right]^{\frac{1}{2}}$$

$$b \sim \text{ext. B-field}$$

$E[E_a]$

$R = \dfrac{n_\Theta - 1}{1 + n_\Theta} < 0 \qquad T = \dfrac{2n_\Theta}{1 + n_\Theta} > 0$

$\sim \dfrac{1}{n_\Theta^2}$

$\sim \dfrac{1}{n_\Theta^2}$

n=1

$n_\Theta = \dfrac{1}{2}$

d

n=1

Principle similar to dielectric haloscopes. Matching *E* and *B*-fields at interfaces.
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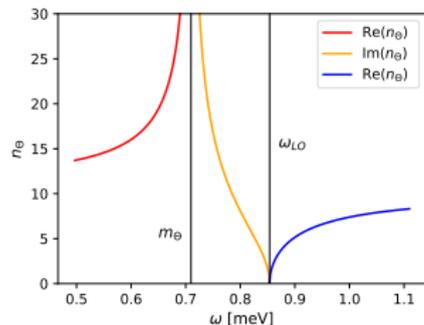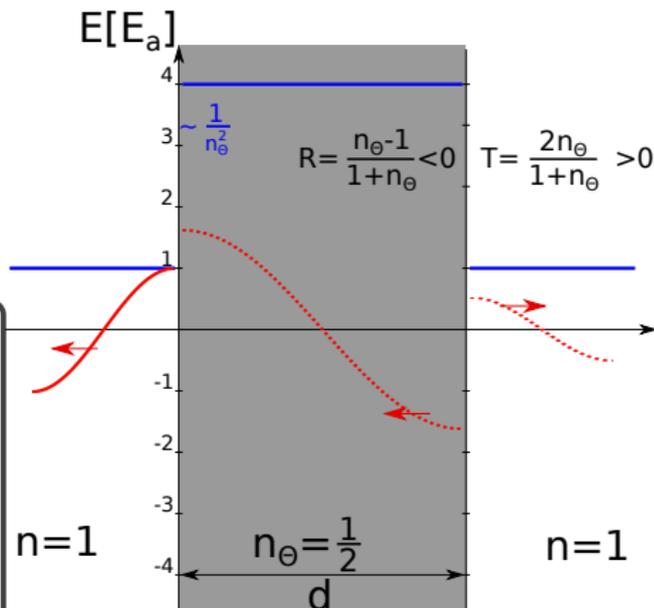$$\pi = n_\Theta(\omega_{\text{res}})\omega_{\text{res}}d$$

$$n_\Theta(\omega) = n\left[\frac{b^2}{m_\Theta^2 - \omega^2} + 1\right]^{\frac{1}{2}}$$

$$b \sim \text{ext. B-field}$$

In the figure: $E[E_a]$

$R = \frac{n_\Theta - 1}{1 + n_\Theta} < 0$ $T = \frac{2n_\Theta}{1 + n_\Theta} > 0$

$\sim \frac{1}{n_\Theta^2}$

$\sim \frac{1}{n_\Theta^2}$

n=1 $n_\Theta = \frac{1}{2}$ n=1

d

Principle similar to dielectric haloscopes. Matching *E* and *B*-fields at interfaces.
Similarities to Fabry-Perot cavity.

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Resonance condition:

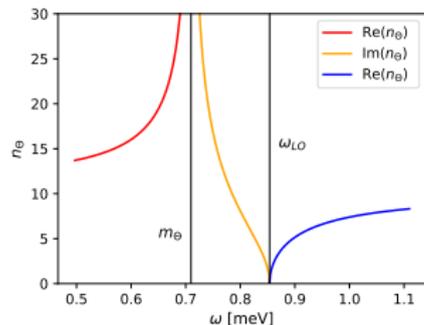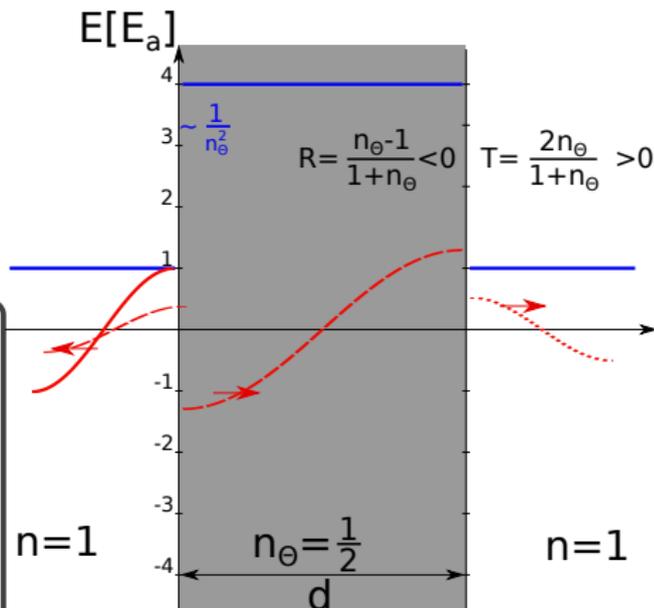$$\pi = n_\Theta(\omega_{\text{res}})\omega_{\text{res}}d$$

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Principle similar to dielectric haloscopes. Matching E and B-fields at interfaces.
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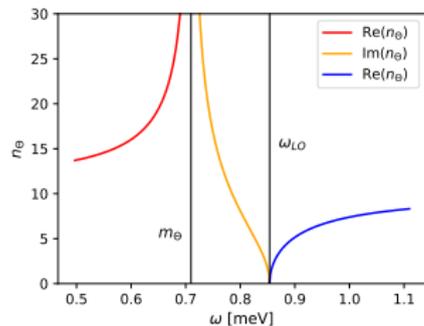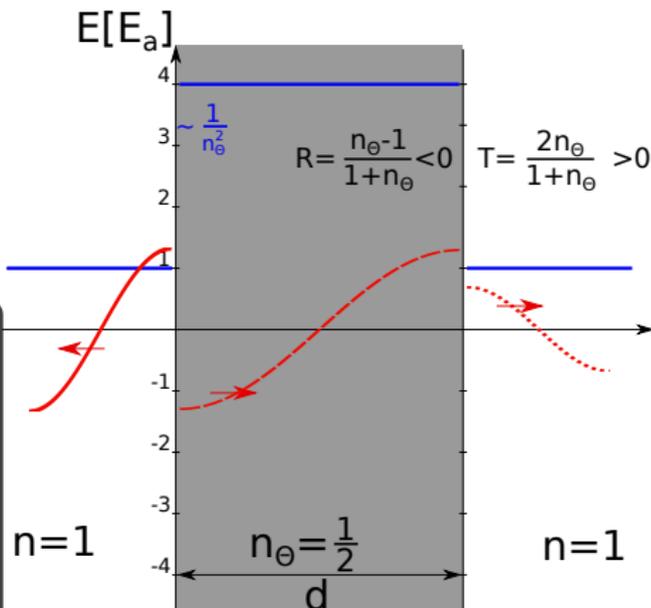$$\pi = n_\Theta(\omega_{\text{res}})\omega_{\text{res}}d$$
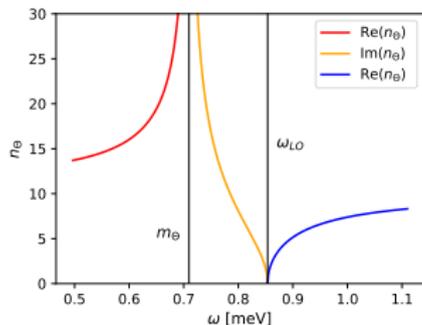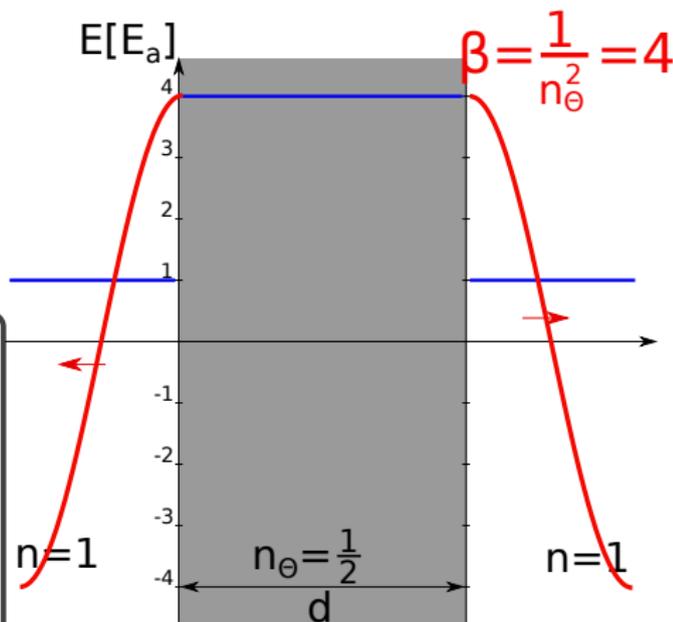
$$n_\Theta(\omega) = n\left[\frac{b^2}{m_\Theta^2 - \omega^2} + 1\right]^{\frac{1}{2}}$$

$$b \sim \text{ext. B-field}$$

Principle similar to dielectric haloscopes. Matching E and B-fields at interfaces.
Similarities to Fabry-Perot cavity.

Physical understanding

Resonance condition:

$$\pi = n_\Theta(\omega_{\mathrm{res}})\omega_{\mathrm{res}}d$$

$$n_\Theta(\omega) = n\left[\frac{b^2}{m_\Theta^2 - \omega^2} + 1\right]^{\frac{1}{2}}$$

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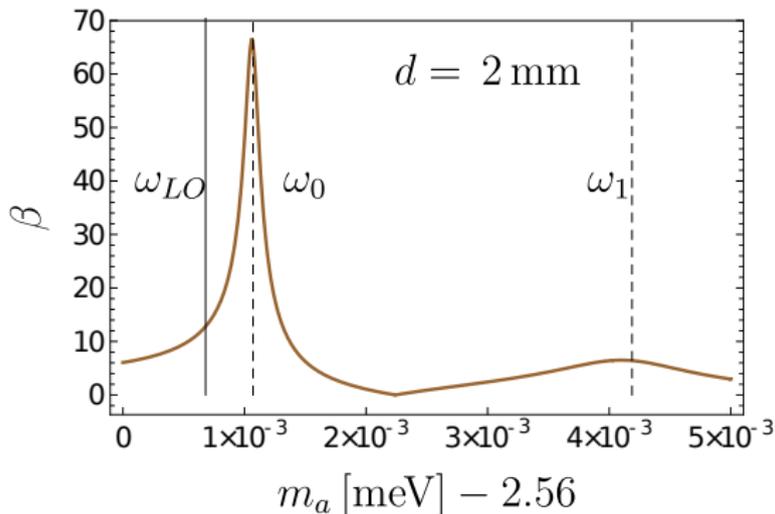
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$$n_\Theta(\omega) = n\left[\frac{b^2}{m_\Theta^2 - \omega^2} + 1\right]^{\frac{1}{2}}$$

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Principle similar to dielectric haloscopes. Matching E and B-fields at interfaces. Similarities to Fabry-Perot cavity.

$d = 2\,\text{mm}$

External *B*-field fixed in figure. Changing it shifts resonance peaks
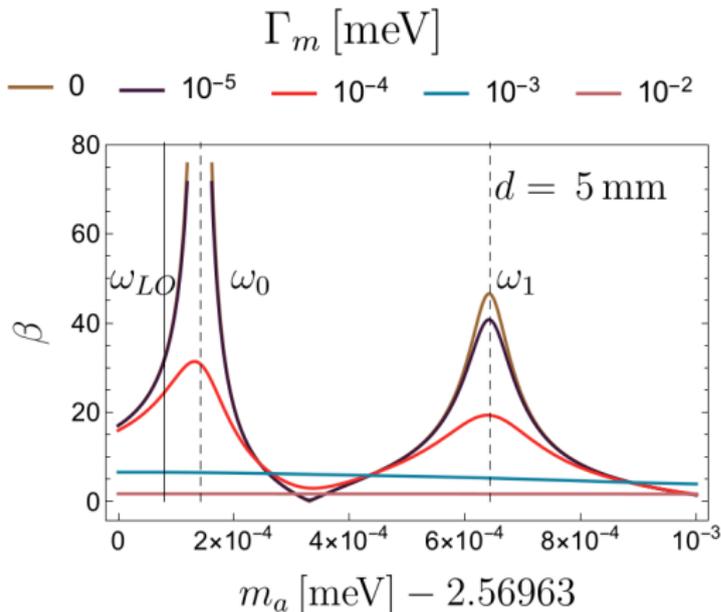$\Rightarrow$ scan different axion masses.

$$\beta = \frac{E_{\text{out}}}{E_a}$$

$$\beta = \frac{\sin(\Delta/2)\,(1 - n_\Theta^2)}{n_\Theta\,(n_\Theta \sin(\Delta/2) + i \cos(\Delta/2))}$$

Resonance condition:

$$\Delta = \Delta_j = n_\Theta(\omega_j)\omega_j d = (2j+1)\pi,\; j \in \mathbb{N}_0$$
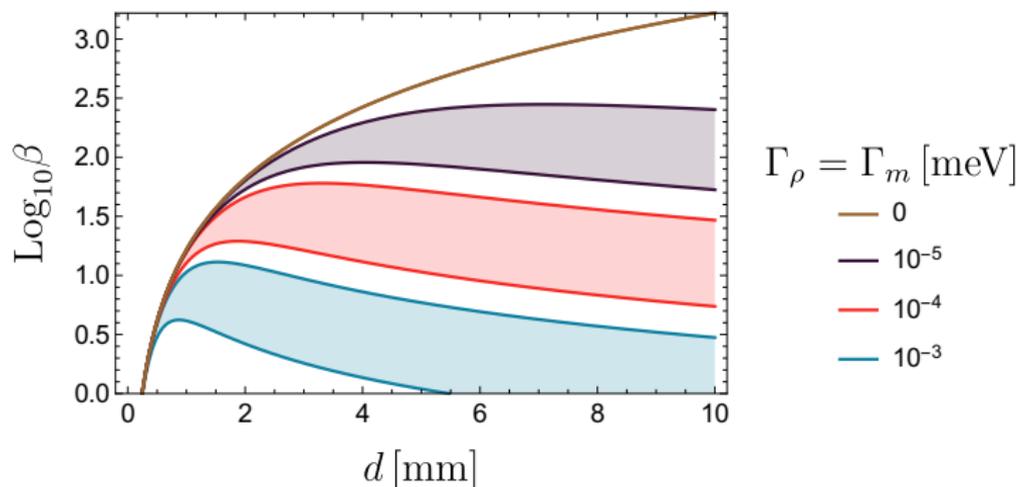
Including losses

$$n_{\Theta}^2 = n^2 \left[1 + \frac{b^2}{m_{\Theta}^2 - \omega^2 - i\Gamma_m\omega} + i\frac{\Gamma_\rho}{\omega} \right]$$

$$\gamma_j = \frac{4b^2 \Delta_j^2}{n^2 \omega_{\mathrm{LO}}^4 d^3} + \left(\Gamma_m + \frac{b^2}{\omega_{\mathrm{LO}}^2} \Gamma_\rho \right)$$

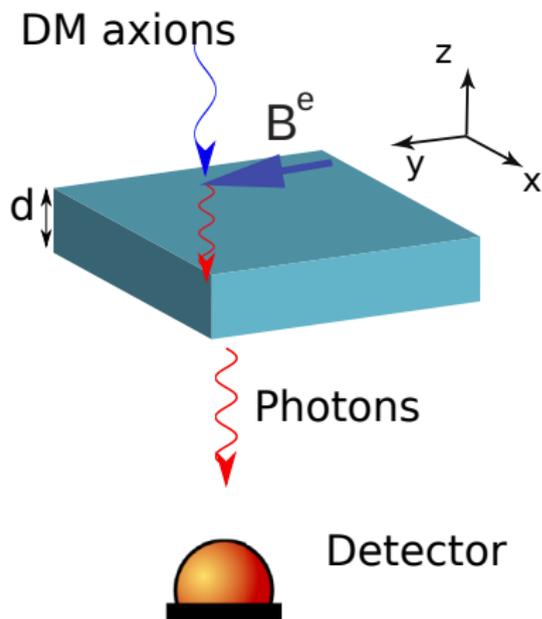$$\beta(\omega_j) = \frac{4b^2}{n^2 \omega_{\mathrm{LO}}^2 d \gamma_j}$$

Optimal thickness

Bands indicate changing refractive index *n*.

$$d_{\mathrm{opt}} = \frac{2}{\omega_{\mathrm{LO}}} \left(\frac{\Delta_j}{n} \right)^{\frac{2}{3}} \left(\frac{1}{\frac{\Gamma_\rho}{\omega_{\mathrm{LO}}} + \frac{\Gamma_m \omega_{\mathrm{LO}}}{b^2}} \right)^{\frac{1}{3}}.$$

Single photon detection

DM axions

B^e

d

Photons

Detector

Number of signal events per time

$$\lambda_s = \eta \frac{|E_a|^2}{2\omega} \beta^2 A$$

η photon counting efficiency, A surface area,
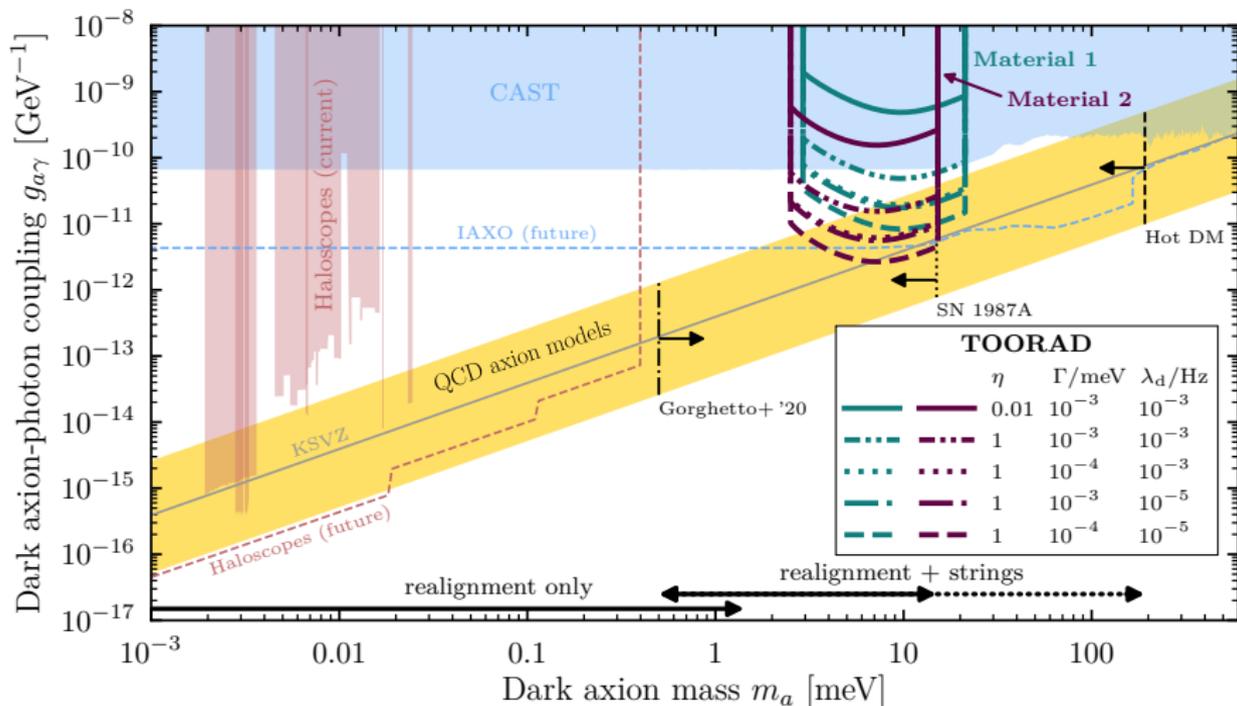$E_0 = g_{a\gamma} B^e \frac{\sqrt{2\rho_a}}{m_a}$

Single photon counting

$$\lambda_s < \frac{1}{\tau} + 2\sqrt{\frac{\lambda_d}{\tau}}$$

[Bityukov,Krasnikov, 98]
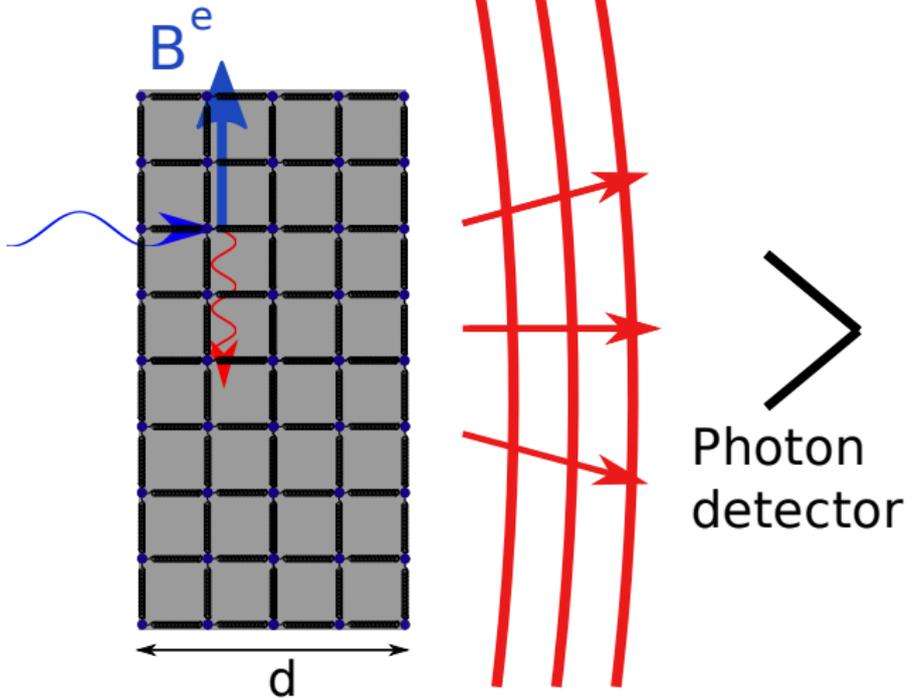λ_d dark count rate, τ measurement time.

Material 1: $Bi_{1-x}Fe_xSe_3$, Material 2: $Mn_2Bi_2Te_5$

values fo the detector parameters: [Fong and Schwab 12], [Hocberg et al. 19]

Axion DM detection with phonon polaritons

First proposed in [A. Mitridate, T. Trickle, Z. Zhang, K.M. Zurek, 20]. Here phenomenological description with Maxwell's eqs. and single photon readout.
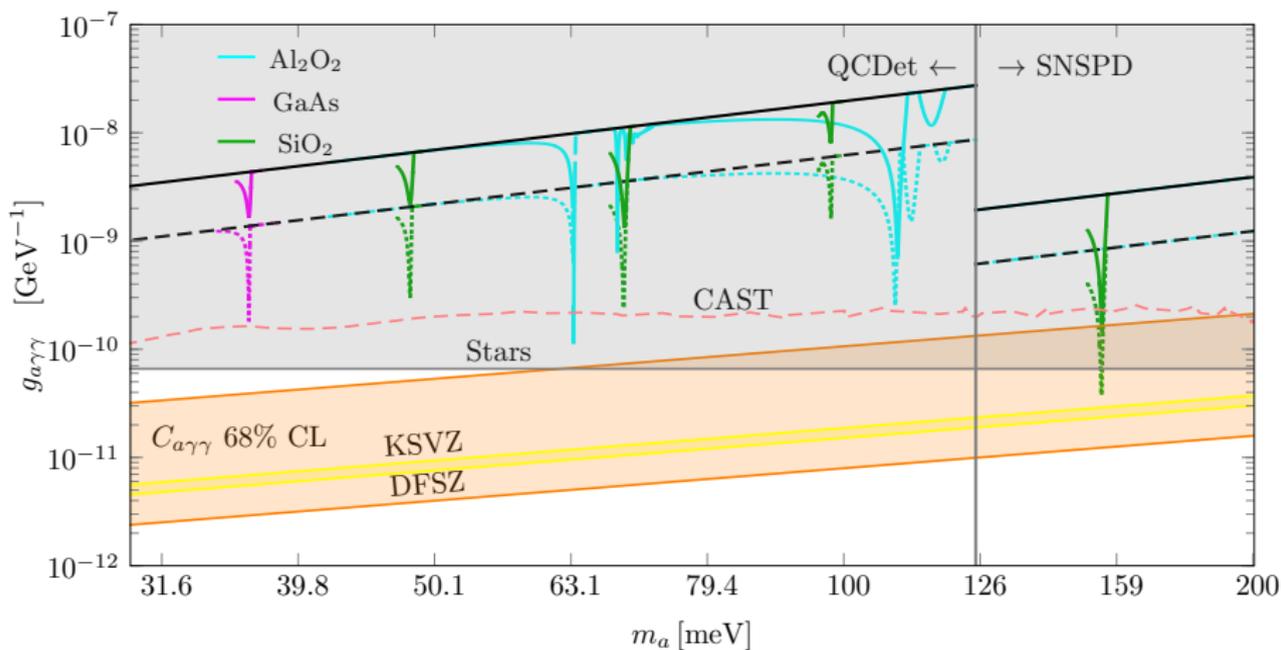
B^e

Photon
detector

d

Effective description

$$n^2(\omega) = \epsilon_\infty \left(1 + \frac{\omega_{\text{pl}}^2/\epsilon_\infty}{\omega_{\text{TO}}^2 - \omega^2 - i\omega\Gamma} + i\frac{\Gamma_\rho}{\omega} \right) \, .$$

compare to

$$n_\Theta^2 = n^2 \left[1 + \frac{b^2}{m_\Theta^2 - \omega^2 - i\Gamma_m\omega} + i\frac{\Gamma_\rho}{\omega} \right]$$

black: dish antenna, integration time one month per resonance, $A = (0.1\text{m})^2$, more optimistic dashed (100 ties better dark count rate) and losses dominated by impurities.

Conclusions

- AQ are expected in condensed matter systems
- Detection and characterization of AQ with THz transmission spectroscopy
- DM axion detection with AQs in well motivated meV axion mass range
- Effective description for AQs can be applied to phonon polaritons too.
- Effective description suited for description of finite volume effects and losses. Close connection to measurements

Thank you for your attention