

Detecting Axion Dark Matter with Phonons and Magnons

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PITT IQ Initiative: Axions, Fundamental and Synthetic – April 7th, 2023



University of
Pittsburgh

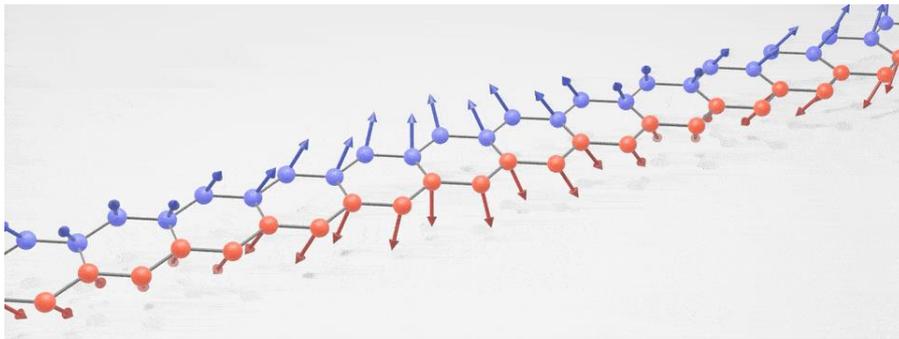
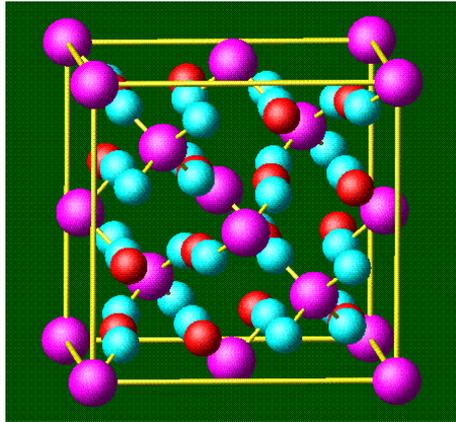
Outline

- Phonons and magnons for dark matter direct detection
- Axion absorption on **phonons**
- Axion absorption on **magnons**

What are phonons and magnons?

Words: Collective motion of ions and spins, respectively

Pictures:



Equations:

$$\hat{H} = \sum_{lj} \frac{\mathbf{p}_{lj}^2}{2m_j} + \frac{1}{2} \sum_{l'j'j''} \mathbf{u}_{lj} \cdot \mathbf{V}_{l'j'j''} \cdot \mathbf{u}_{l'j'}$$

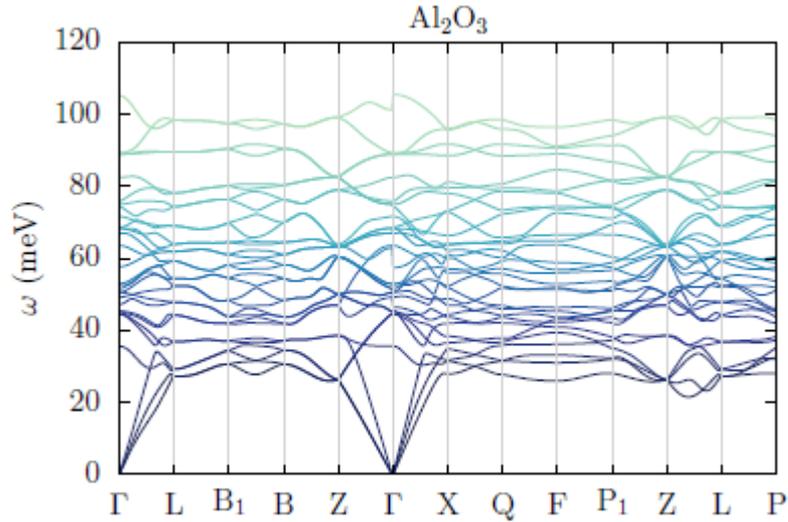
$$\mathbf{u}_{lj} = \sum_{\nu=1}^{3n} \sum_{\mathbf{k}} \frac{1}{\sqrt{2Nm_j\omega_{\nu,\mathbf{k}}}} (\hat{a}_{\nu,\mathbf{k}} + \hat{a}_{\nu,-\mathbf{k}}^\dagger) e^{i\mathbf{k}\cdot\mathbf{x}_{lj}^0} \boldsymbol{\epsilon}_{\nu,\mathbf{k},j}$$

$$\hat{H} = \sum_{l'j'j''} \mathbf{S}_{lj} \cdot \mathbf{J}_{l'j'j''} \cdot \mathbf{S}_{l'j'} + \mu_B \mathbf{B} \cdot \sum_{lj} g_j \mathbf{S}_{lj}$$

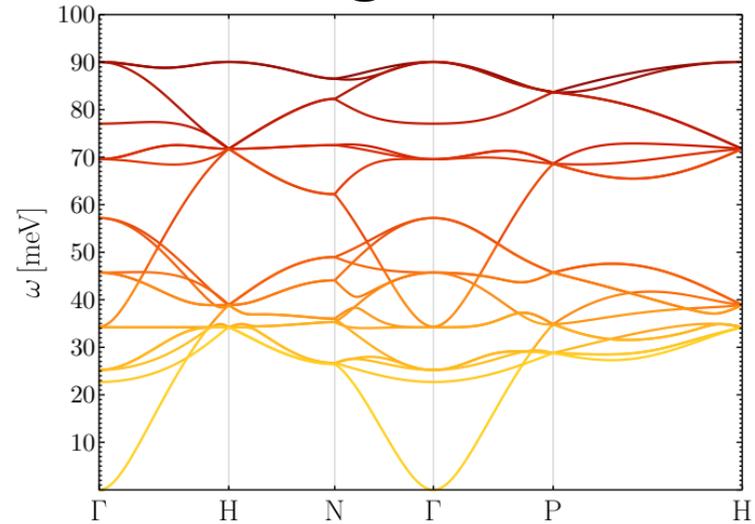
$$\mathbf{S}_{nj} = \sqrt{\frac{S_j}{2}} (\bar{\mathbf{u}}_j b_{nj} + \mathbf{u}_j b_{nj}^\dagger) + \mathbf{v}_j (S_j - b_{nj}^\dagger b_{nj})$$

What are phonons and magnons?

Phonons

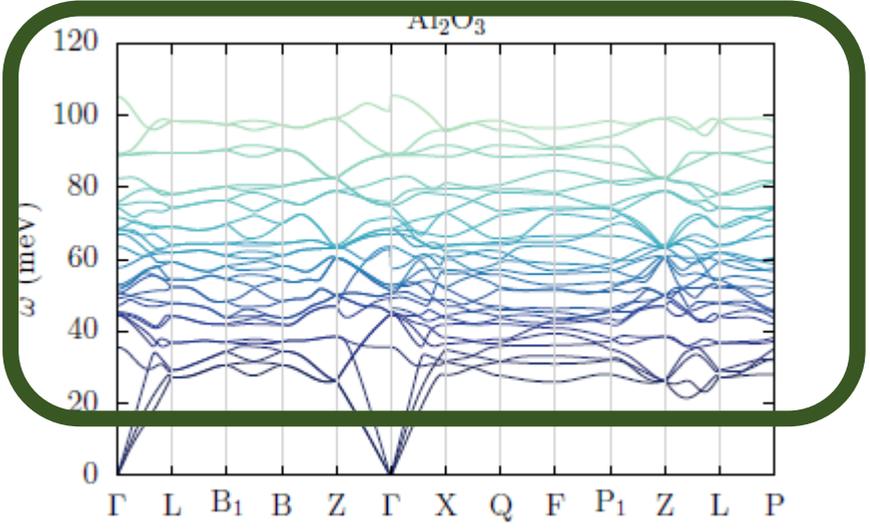


Magnons

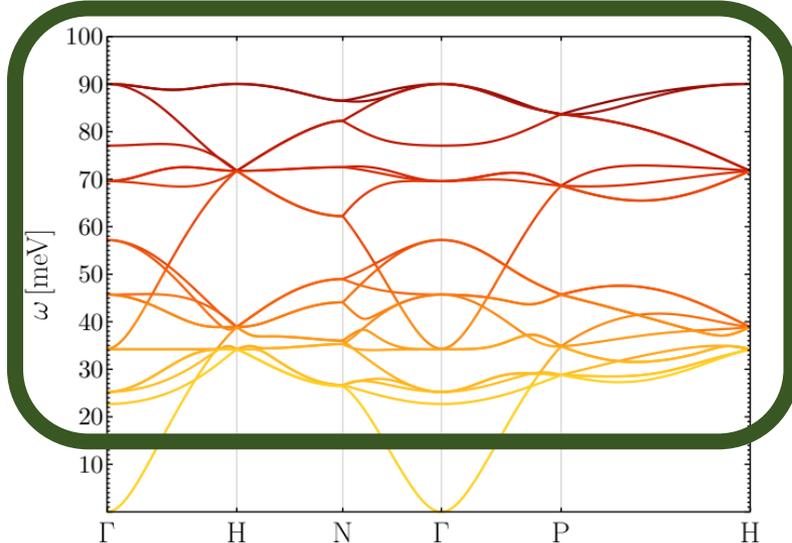


Why are they useful for detection of DM?

Phonons



Magnons



Kinematics

Absorption

$$m_{\text{DM}}^{\text{min}} \sim \omega$$

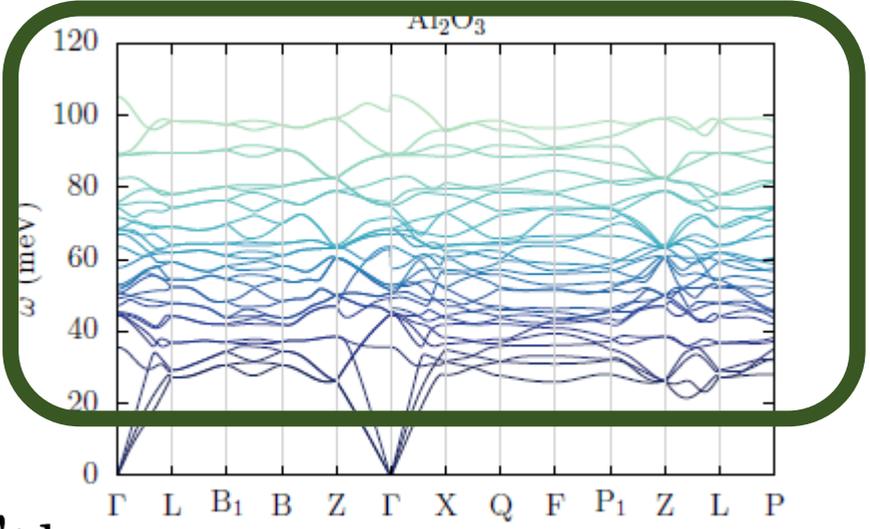
Scattering

$$m_{\text{DM}}^{\text{min}} \sim \frac{\omega}{v_{\text{DM}}^2}$$

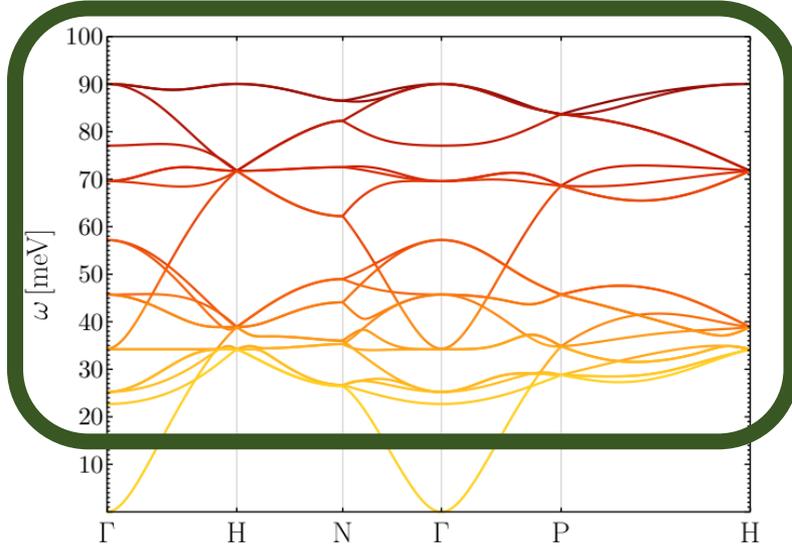
Lower energy excitations allow searching for lower mass DM

Why are they useful for detection of DM?

Phonons



Magnons



ω_{th}

keV

eV

meV

Electronic ionization

- XENON
- DarkSide

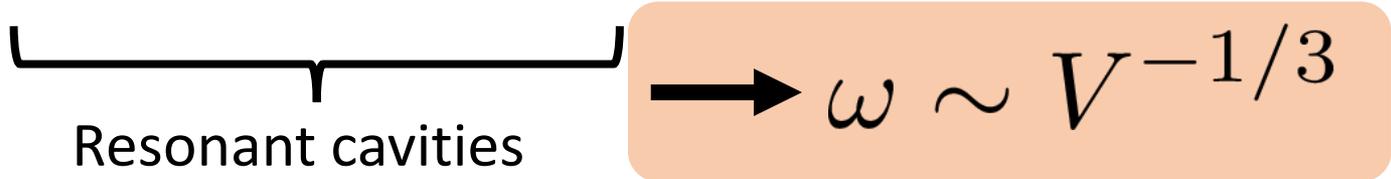
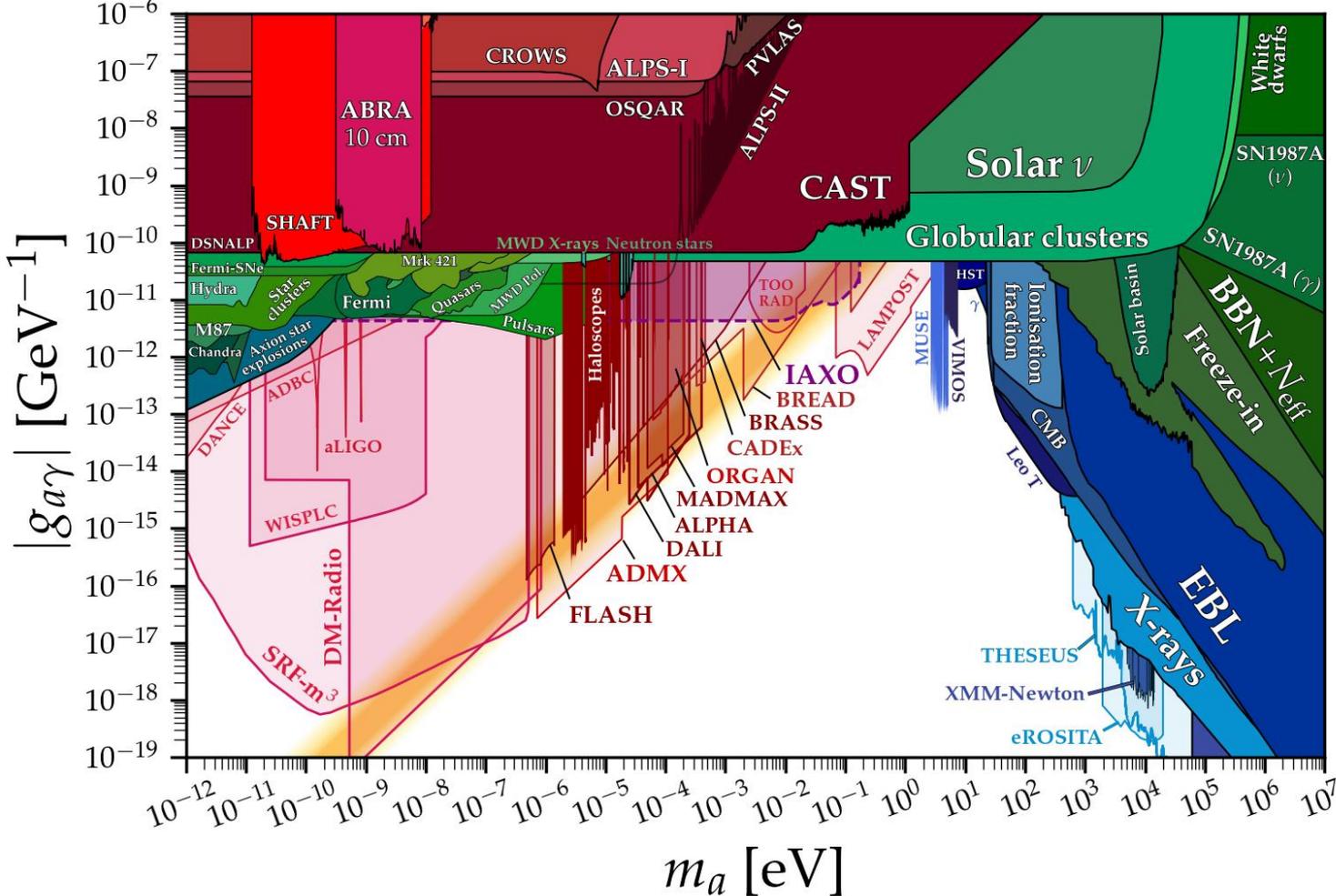
Electronic excitations

- DAMIC
- SENSEI
- SuperCDMS
- Edelweiss
- CDEX

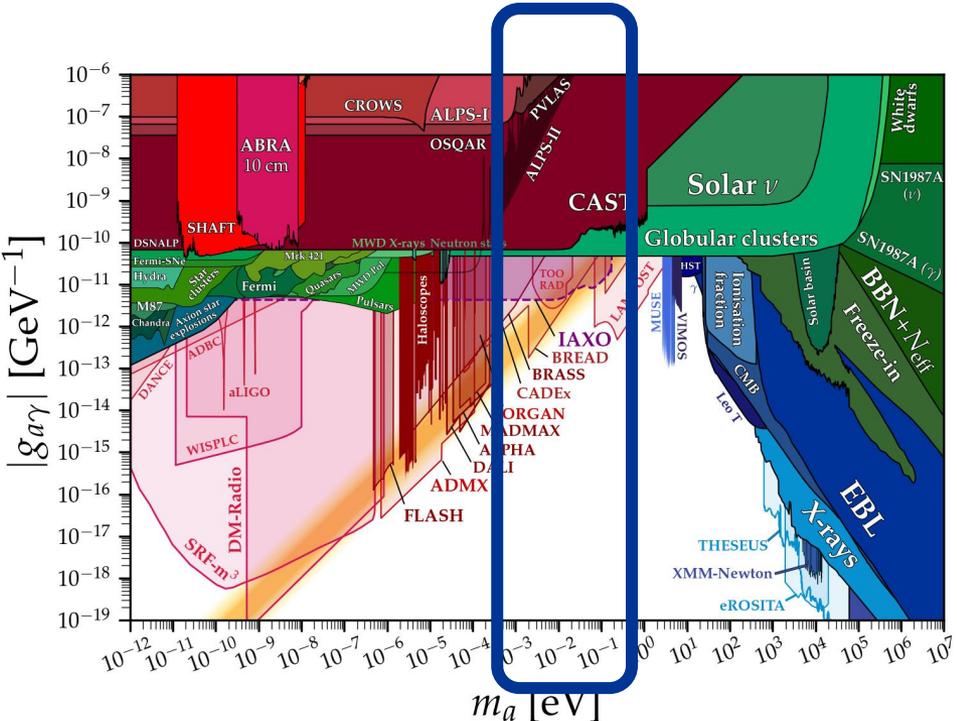
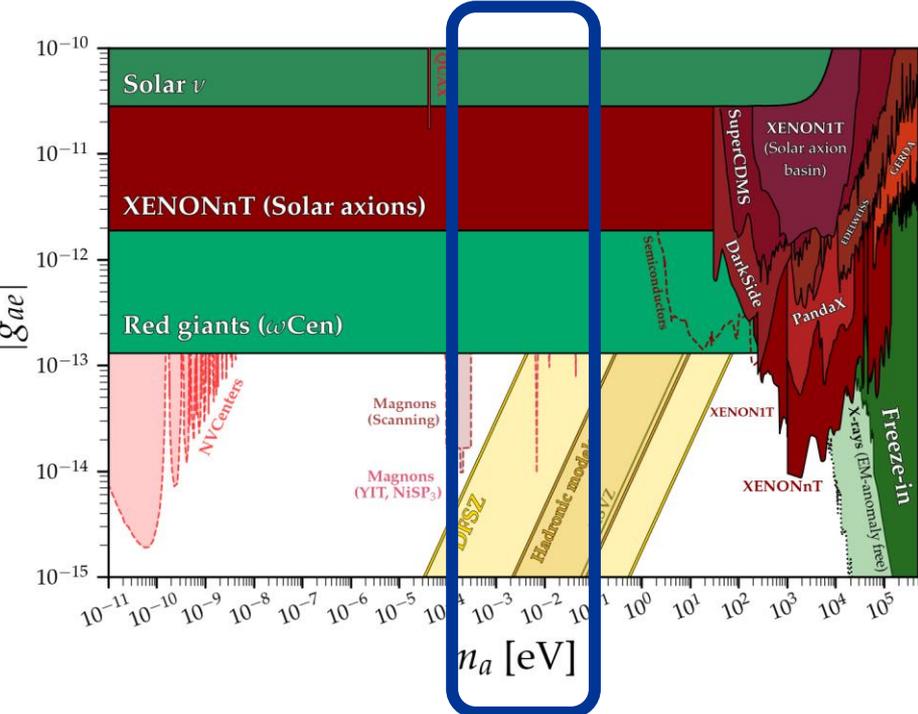
Collective Excitations

- Phonons
- Magnons
- Axion quasiparticles
- ???

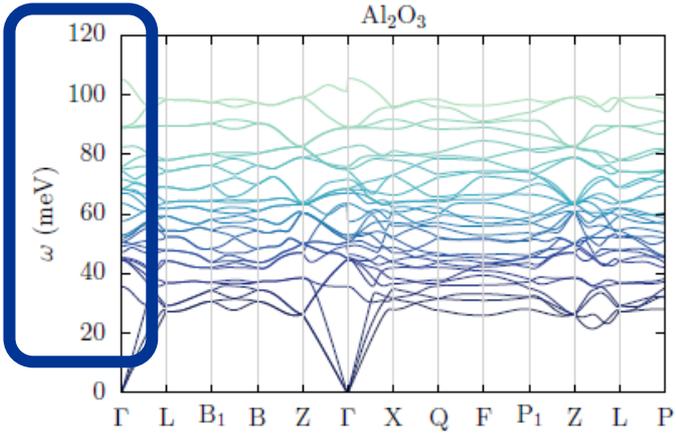
Why are they useful for detection of axions?



Why are they useful for detection of axions?



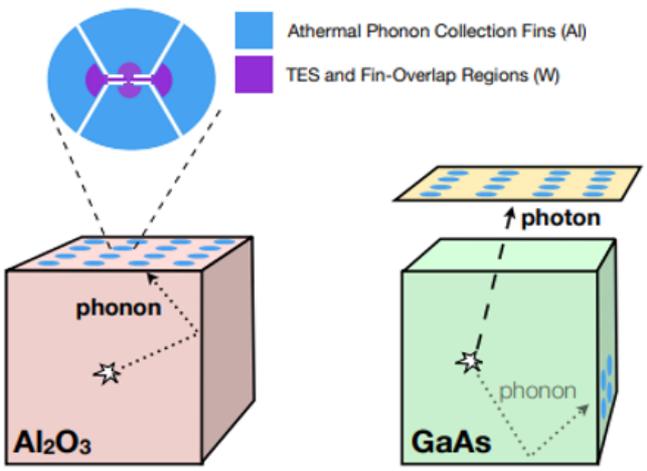
$$\omega \approx V^{-1/3}$$



Current Experimental Efforts

Snowmass2021 - Letter of Interest

The TESSERACT Dark Matter Project



QUAX (QUArere Axion eXperiment)

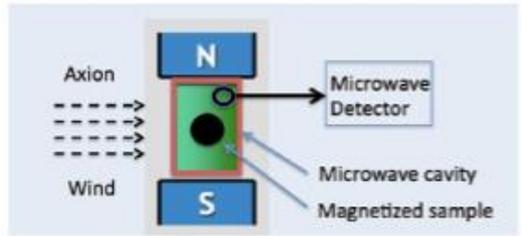
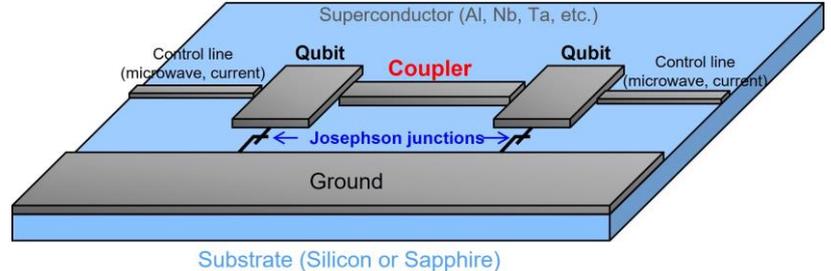


Fig. 1. Principle scheme of the axion haloscope.

- Need non-cavity readout mechanism



Other proposal (photon readout): [\[2209.12909\] Axion detection with phonon-polaritons revisited \(arxiv.org\)](https://arxiv.org/abs/2209.12909)

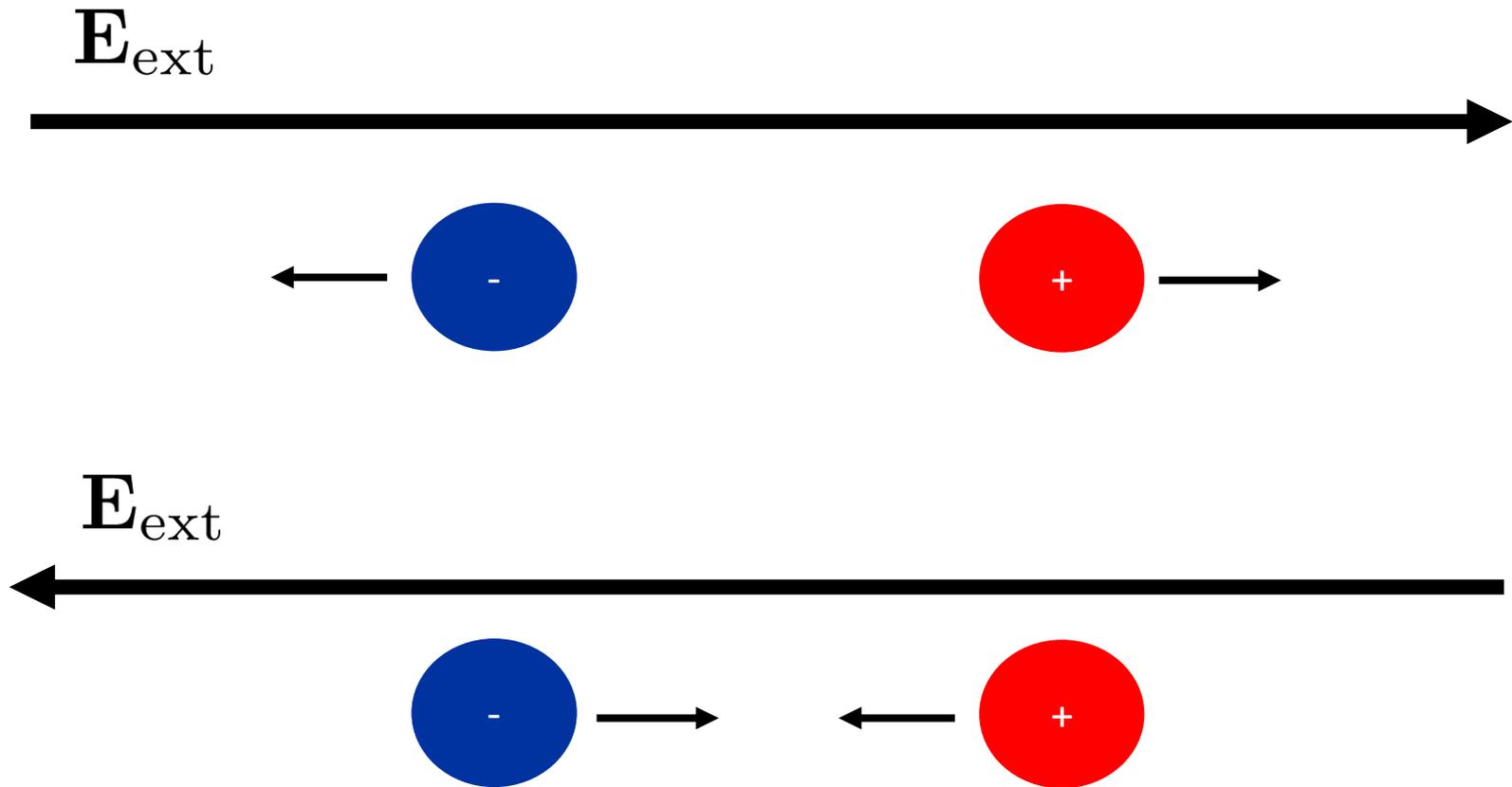
Outline

- Phonons and magnons for dark matter detection
- Axion absorption on **phonons**
- Axion absorption on **magnons**

The Idea

External electric field creates phonons by shaking dipoles

$$\delta H \sim \mathbf{E}_{\text{ext}} \cdot \mathbf{u}$$



The Idea

External electric field creates phonons by shaking dipoles

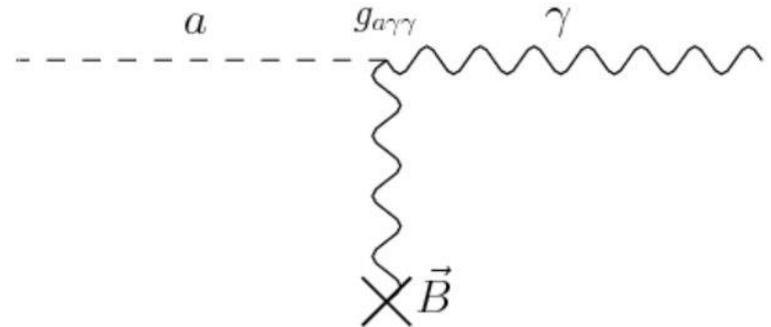
$$\delta H \sim \mathbf{E}_{\text{ext}} \cdot \mathbf{u}$$

In a background magnetic field, axion generates an electric field

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$-g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}_0$$

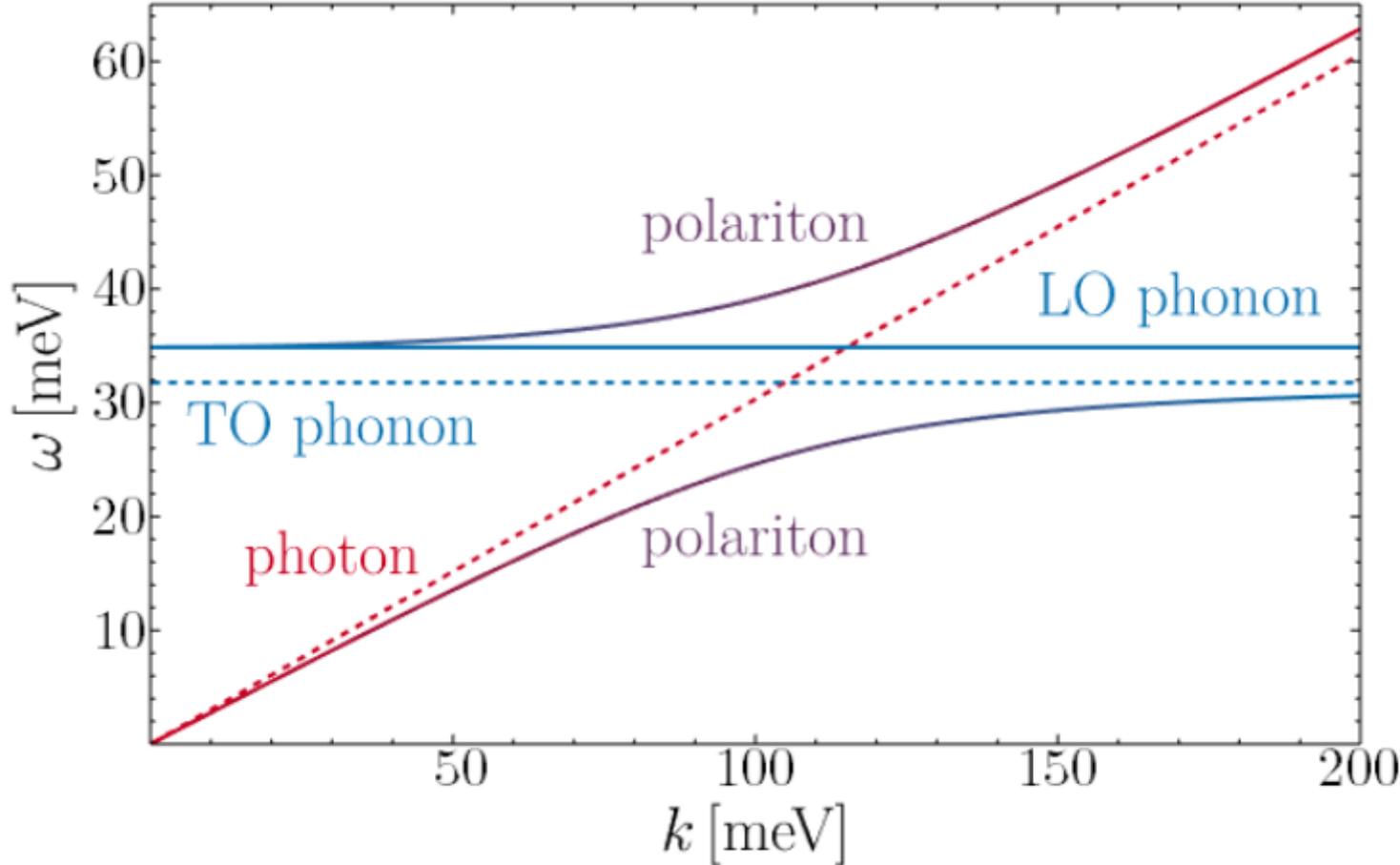
$$\delta H \sim \mathbf{E}_a \cdot \mathbf{u}$$



Axion converts to electric field, which then causes the dipoles to oscillate.

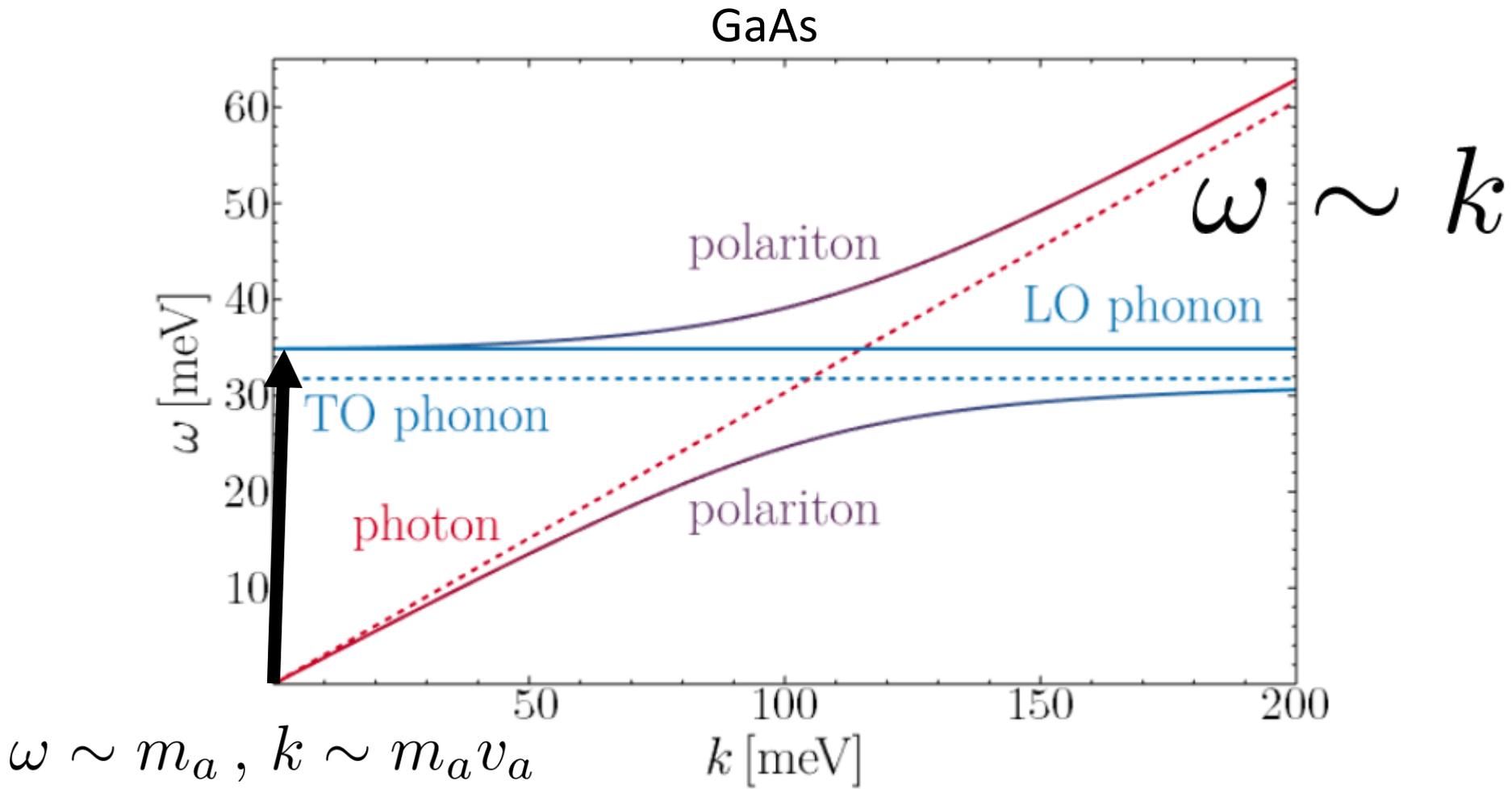
Phonons vs. Phonon-Polaritons

GaAs



$$\hat{H}^0 = \hat{H}_{\text{phonon}}^0 + \hat{H}_{\text{photon}}^0 + \hat{H}_{\text{mix}}^0 \longrightarrow \hat{H}_{\text{phonon-polariton}}^0$$

Phonons vs. Phonon-Polaritons



Single Phonon Absorption Rate: Simple

To compute the absorption rate, just use Fermi's Golden rule

$$\Gamma_{I \rightarrow F} = 2\pi |\langle F | \delta \hat{H} | I \rangle|^2 \delta(\omega - (\omega_F - \omega_I))$$

Single Phonon Absorption Rate

$$\begin{aligned}\delta\hat{H} &= -e \sum_{lj} \mathbf{E}_a \cdot \mathbf{Z}_j^* \cdot \mathbf{u}_{lj} = eg_{a\gamma\gamma} a_0 \sum_{lj} e^{i\mathbf{p} \cdot \mathbf{x}_{lj}^0} \mathbf{B}_0 \cdot \epsilon_\infty^{-1} \cdot \mathbf{Z}_j^* \cdot \mathbf{u}_{lj} \\ &\equiv \sum_{lj} e^{i\mathbf{p} \cdot \mathbf{x}_{lj}^0} \mathbf{f}_j \cdot \mathbf{u}_{lj}\end{aligned}$$

$$\mathbf{f}_j = \frac{1}{\sqrt{2}} g_{a\gamma\gamma} \frac{e\sqrt{\rho_a}}{m_a} \mathbf{B} \cdot \epsilon_\infty^{-1} \cdot \mathbf{Z}_j^*$$

$$R = \frac{2\omega}{m_{\text{cell}}} \sum_{\nu} \frac{\omega'_{\nu} \gamma_{\nu}}{(\omega^2 - \omega'_{\nu}{}^2)^2 + (\omega \gamma_{\nu})^2} \left| \sum_j \sum_{\mu} \frac{1}{\sqrt{m_j \omega_{\mu}}} \mathbf{f}_j \cdot \epsilon_{\nu,j}^* (\mathbf{U}_{\mu\nu}^* + \mathbf{V}_{\mu\nu}) \right|^2$$

Axion -> single phonon-polariton absorption rate per target exposure

Single Phonon Absorption Rate

$$\begin{aligned}\delta\hat{H} &= -e \sum_{lj} \mathbf{E}_a \cdot \mathbf{Z}_j^* \cdot \mathbf{u}_{lj} = eg_{a\gamma\gamma} a_0 \sum_{lj} e^{i\mathbf{p} \cdot \mathbf{x}_{lj}^0} \mathbf{B}_0 \cdot \epsilon_\infty^{-1} \cdot \mathbf{Z}_j^* \cdot \mathbf{u}_{lj} \\ &\equiv \sum_{lj} e^{i\mathbf{p} \cdot \mathbf{x}_{lj}^0} \mathbf{f}_j \cdot \mathbf{u}_{lj}\end{aligned}$$

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Polariton/phonon eigensystem – compute from first principles

$$+ \frac{1}{2} \sum_{l'j'} \mathbf{u}_{lj} \cdot \mathbf{V}_{ll'jj'} \cdot \mathbf{u}_{l'j'}$$

DFT \longrightarrow **Phonopy** is an open source package for phonon calculations at harmonic and quasi-harmonic levels.

Single Phonon Absorption Rate

$$\begin{aligned}\delta\hat{H} &= -e \sum_{lj} \mathbf{E}_a \cdot \mathbf{Z}_j^* \cdot \mathbf{u}_{lj} = eg_{a\gamma\gamma} a_0 \sum_{lj} e^{i\mathbf{p} \cdot \mathbf{x}_{lj}^0} \mathbf{B}_0 \cdot \epsilon_\infty^{-1} \cdot \mathbf{Z}_j^* \cdot \mathbf{u}_{lj} \\ &\equiv \sum_{lj} e^{i\mathbf{p} \cdot \mathbf{x}_{lj}^0} \mathbf{f}_j \cdot \mathbf{u}_{lj}\end{aligned}$$

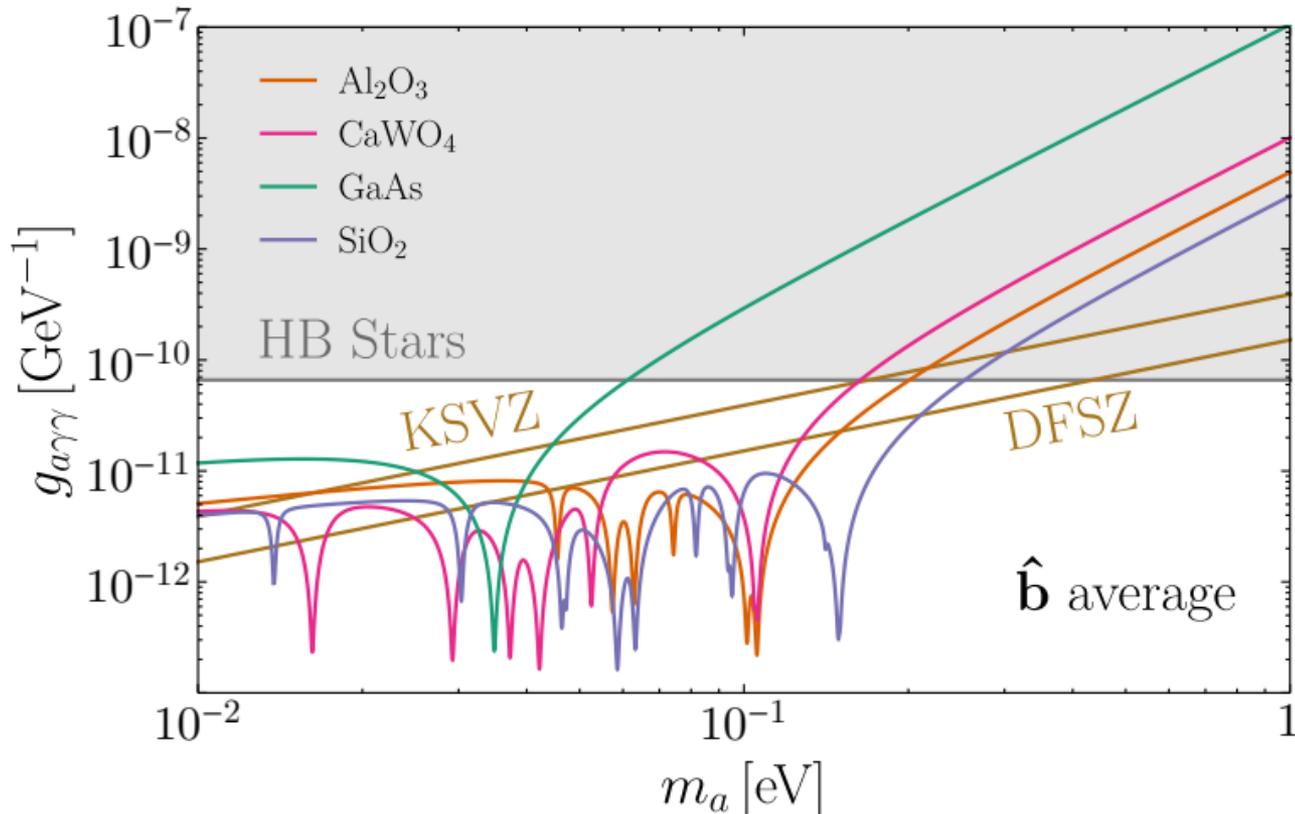
$$\mathbf{f}_j = \frac{1}{\sqrt{2}} g_{a\gamma\gamma} \frac{e\sqrt{\rho_a}}{m_a} \mathbf{B} \cdot \epsilon_\infty^{-1} \cdot \mathbf{Z}_j^*$$

$$R = \frac{2\omega}{m_{\text{cell}}} \sum_{\nu} \frac{\omega'_\nu \gamma_\nu}{(\omega^2 - \omega'^2_\nu)^2 + (\omega \gamma_\nu)^2} \left| \sum_j \sum_\mu \frac{1}{\sqrt{m_j \omega_\mu}} \mathbf{f}_j \cdot \epsilon_{\nu,j}^* (\mathbf{U}_{\mu\nu}^* + \mathbf{V}_{\mu\nu}) \right|^2$$

Polariton width - $\gamma \sim 1/\tau$

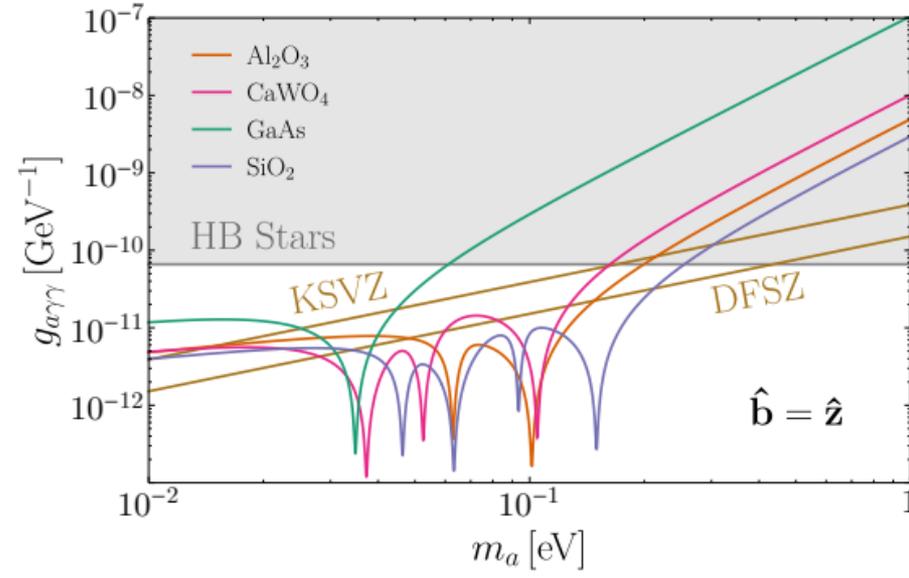
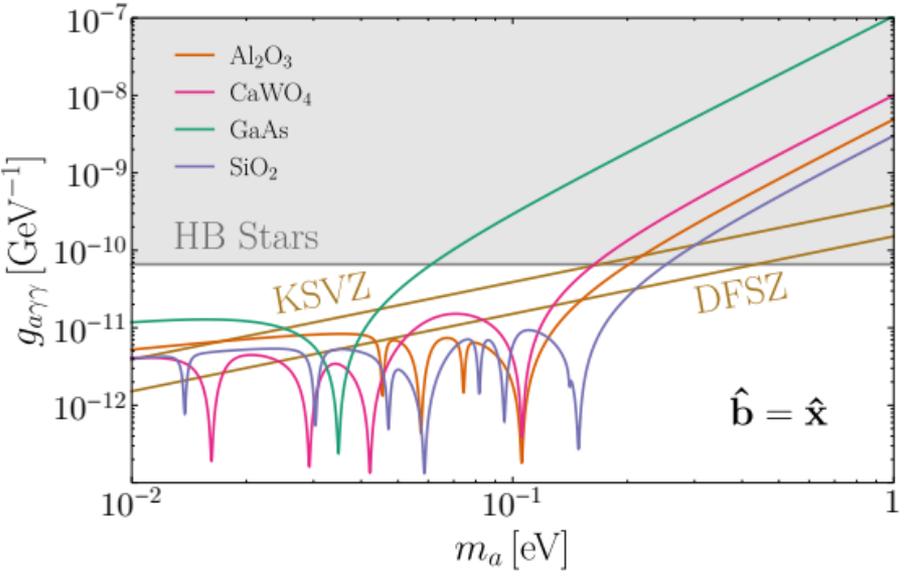
DFT \longrightarrow **Phonopy** is an open source package for phonon calculations at harmonic and quasi-harmonic levels.

Projected Reach



- Averaged over external B field directions
- kilogram-year exposure, no backgrounds
- $\gamma/\omega = 10^{-2}$

Projected Reach: B field variation



- **Specific** external B field directions
- Different resonances appear for different directions
- $\gamma/\omega = 10^{-2}$
- **Useful for background mitigation**

Outline

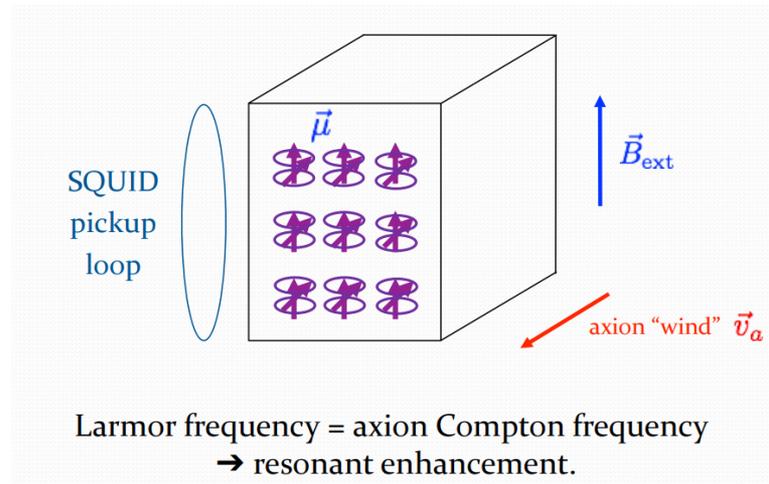
- Phonons and magnons for dark matter detection
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The Idea

$$\mathcal{L} \supset \frac{g_{aee}}{2m_e} (\partial_\mu a) \bar{e} \gamma^\mu \gamma^5 e \longrightarrow -\frac{g_{aee}}{2m_e} \nabla a \cdot \mathbf{S}_e$$

a ----- ~~X~~ ===== magnon

CASPER Wind – but with electrons, no external B field



Single Magnon Absorption Rate

$$\delta \hat{H} = -\frac{g_{aee}}{m_e} \nabla a \cdot \sum_{lj} (g_j - 1) \mathbf{S}_{lj} = -\frac{g_{aee}}{m_e} (i m_a \mathbf{v}_a) \frac{a_0}{2} \cdot \sum_{lj} (g_j - 1) \mathbf{S}_{lj} e^{i\mathbf{p} \cdot \mathbf{x}_{lj}^0}$$

$$\mathbf{f}_j = -\frac{i}{\sqrt{2}} g_{aee} (g_j - 1) \frac{\sqrt{\rho_a}}{m_e} \mathbf{v}_a$$

$$R = \frac{2\omega}{m_{\text{cell}}} \sum_{\nu} \frac{\omega_{\nu} \gamma_{\nu}}{(\omega^2 - \omega_{\nu})^2 + (\omega \gamma_{\nu})^2} \left| \sum_j \sqrt{S_j} \mathbf{f}_j \cdot (\mathbf{U}_{j\nu}^* \mathbf{r}_j + \mathbf{V}_{j\nu} \mathbf{r}_j^*) \right|^2$$

“Magnon polarization vectors” – computed from first principles

$$\sum_{l'l''} \mathbf{S}_{lj} \cdot \mathbf{J}^{l'l''} \cdot \mathbf{S}_{l''j'}$$

Great! What About YIG?



The saga of YIG: Spectra, thermodynamics, interaction and relaxation of magnons in a complex magnet

Vladimir Cherepanov ^{*1 a}, Igor Kolokolov ^b, Victor L'vov ^{*1 c}

Resonant cavity
 ω_c, τ_c, V_c

Microwave magnetic field

**YIG sphere
(Ferrimagnet)**
 $\omega_L = \gamma B_0, \tau_2, V_s$

Used In QUAX

Compute the rate and...

$$R = 0 \text{ ???}$$

Problem: Selection Rules

Selection rules limit which magnon modes can be excited

$$\hat{H} = \hat{H}_0 + \delta\hat{H}$$

$$\Gamma \propto |\langle F | \delta\hat{H} | I \rangle|^2$$

if $[\hat{H}_0, \delta\hat{H}] = 0 \longrightarrow (E_F - E_I) \langle F | \delta\hat{H} | I \rangle = 0$

if $E_F \neq E_I$ then $\Gamma = 0$

Problem: Selection Rules

$$\hat{H}_0 \propto \mathbf{S}_1 \cdot \mathbf{S}_2 \quad \text{Simple, isotropic exchange interactions}$$

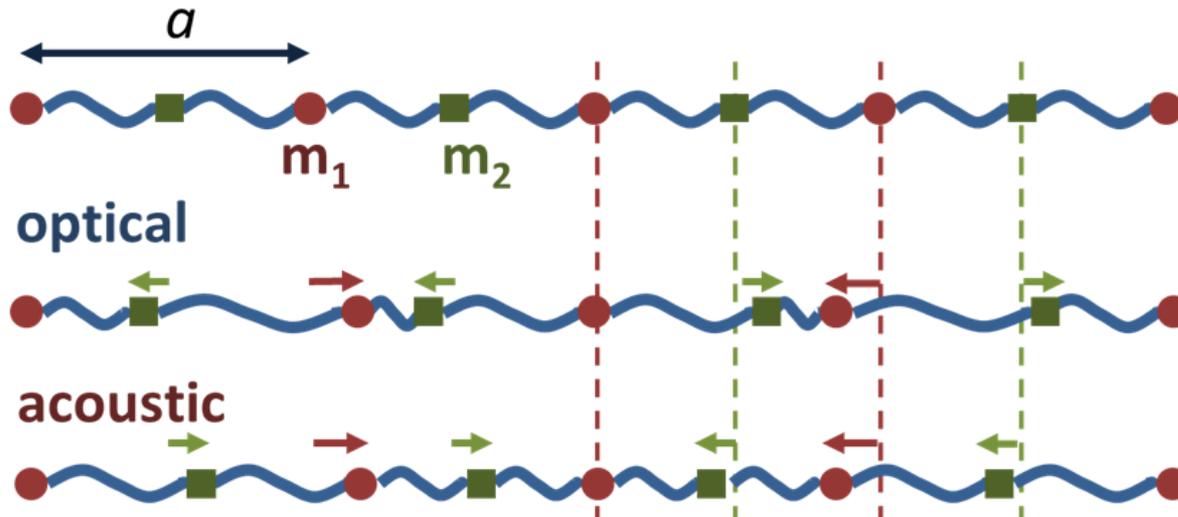
$$\delta\hat{H} \propto \sum_{i=1}^2 \mathbf{S}_i \quad \text{Axion coupling to net spin}$$

$$\begin{aligned} [\hat{H}_0, \delta H] &\propto [S_1^j, S_1^i] S_2^j + S_1^j [S_2^j, S_2^i] \\ &\propto \epsilon^{jik} S_1^k S_2^j + \epsilon^{jik} S_1^j S_2^k \\ &= 0 \end{aligned}$$

No absorption on magnons in simple magnets!

Selection Rules: Intuition

Similar (“coupling to mass”) effect for phonons



Couple to all masses equally \rightarrow no out-of-phase (optical) response!

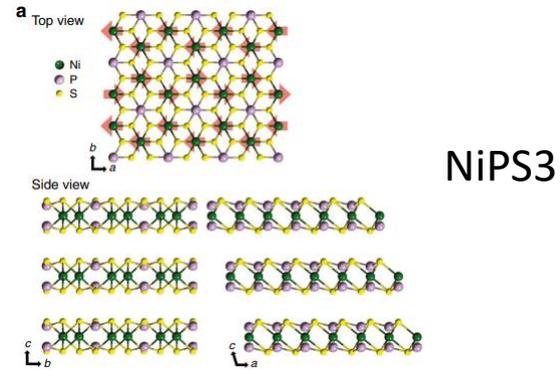
Three Ways Around Selection Rules

1) External Magnetic Field

$$\hat{H}_0 \supset \mu_B \mathbf{B} \cdot \sum_{\ell j} \mathbf{S}_{\ell j} \quad \omega_L = 2\mu_B B = 0.12 \text{ meV} \left(\frac{B}{\text{T}} \right)$$

2) Anisotropic Exchange Interactions

$$\hat{H}_0 \supset \sum_{\ell \ell' j j'} \mathbf{S}_{\ell j} \cdot \mathbf{J}_{\ell \ell' j j'} \cdot \mathbf{S}_{\ell' j'}$$

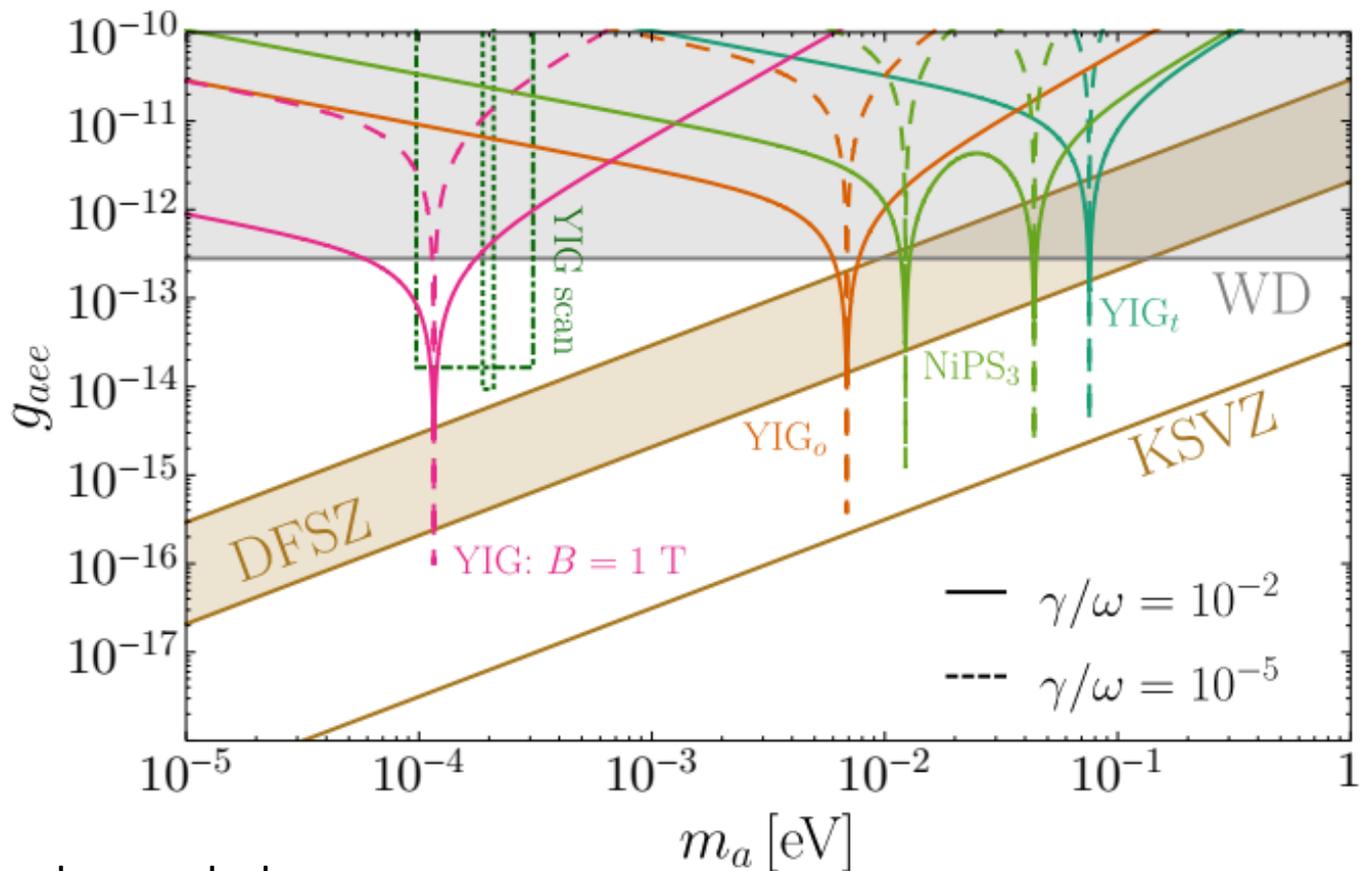


[Suppression of magnetic ordering in XXZ-type antiferromagnetic monolayer NiPS3 | Nature Communications](#)

3) Non-degenerate Lande g factors

$$\delta \hat{H} \propto \sum_{\ell j} (g_j - 1) \mathbf{S}_{\ell j} \quad g_j = \frac{3}{2} + \frac{1}{2} \frac{s_j(s_j + 1) - \ell_j(\ell_j + 1)}{S_j(S_j + 1)}$$

Projected Reach



- No backgrounds, kg-yr exposure
- YIG – external B, YIG_o/t – nondegenerate g factor, NiPS3 – anisotropic exchange int.
- “YIG scan” - [\[2001.10666\] Detecting Light Boson Dark Matter through Conversion into Magnon \(arxiv.org\)](https://arxiv.org/abs/2001.10666)

Summary

Process	Fundamental interaction	Effective coupling in Eq. (4)
Axion + B field \rightarrow phonon	$a\mathbf{E} \cdot \mathbf{B}$	$\mathbf{f}_j = \frac{1}{\sqrt{2}} g_{a\gamma\gamma} \frac{e\sqrt{\rho_a}}{m_a} \mathbf{B} \cdot \boldsymbol{\epsilon}_\infty^{-1} \cdot \mathbf{Z}_j^*$
Axion \rightarrow magnon	$\nabla a \cdot \mathbf{s}_e$	$\mathbf{f}_j = -\frac{i}{\sqrt{2}} g_{aee} (g_j - 1) \frac{\sqrt{\rho_a}}{m_e} \mathbf{v}_a$

- Collective excitations are an exciting new frontier in direct detection of light dark matter
- Phonon and magnon excitations are complementary probes of axions for notoriously difficult axion masses

Questions:

- Paths forward for single magnon readout?
- General EFT framework for absorption on collective excitations?

Thank you!

Detecting Axions with Electrons

