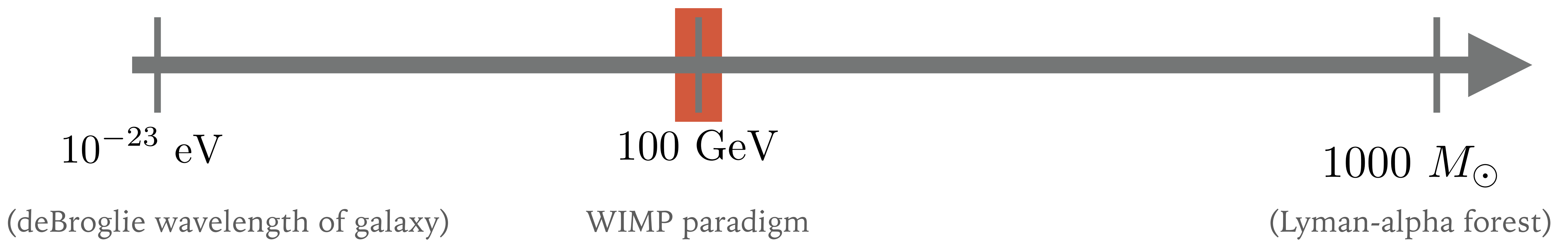
DARK MATTER DIRECT DETECTION WITH PHONONS AND MAGNONS

Based on work with Hochberg, Lin, Knapen, Mitridate, Zhang, Trickle, Griffin

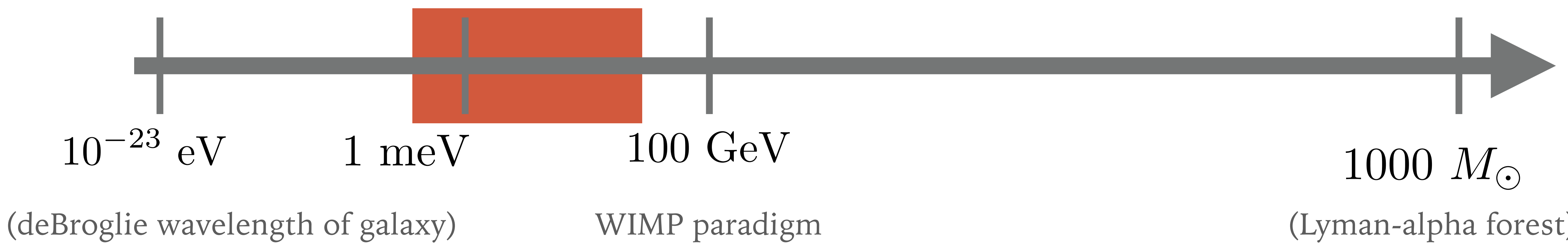
Kathryn M. Zurek

THE DARK MATTER PANORAMA



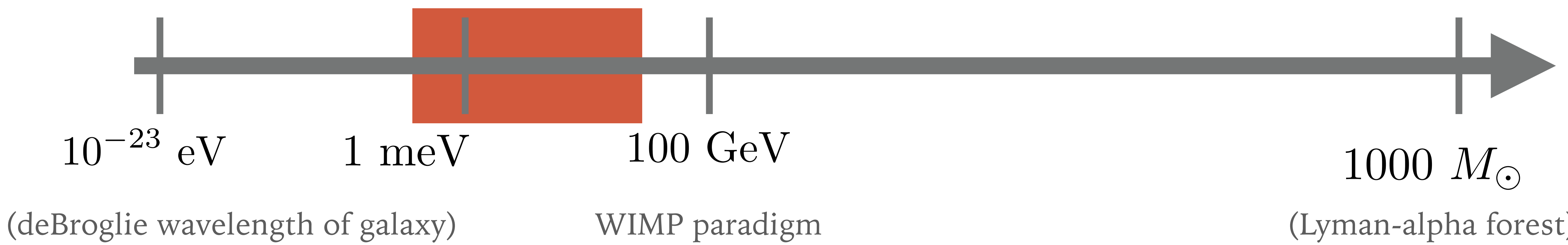
- From an observational standpoint, a wide range of dark matter masses are consistent with data.
- Focused on WIMP largely from arguments based on EFT

THE DARK MATTER PANORAMA

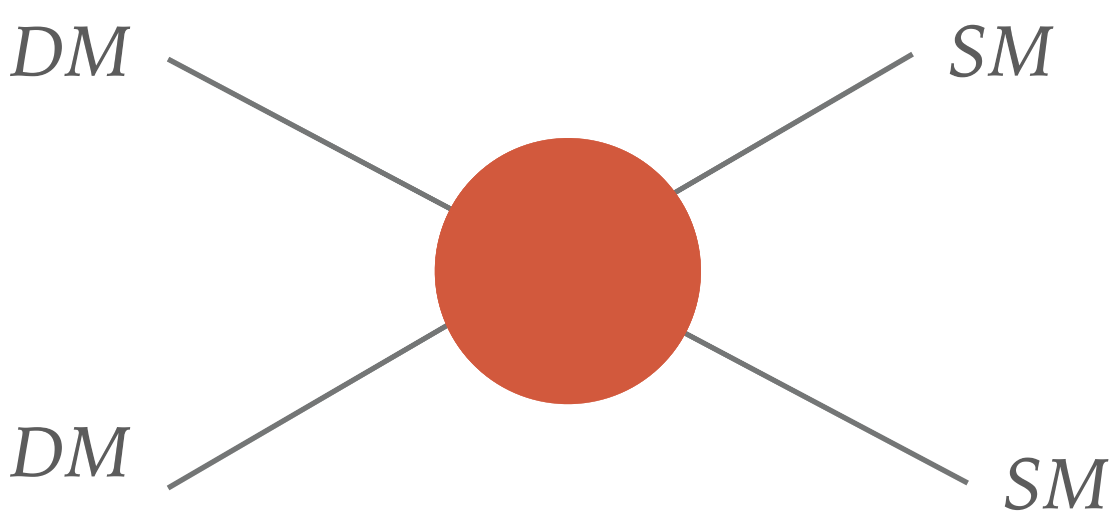


- From an observational standpoint, a wide range of dark matter masses are consistent with data.
- Our discussion will focus on extending the window of observability by 12 OOM in mass utilizing collective excitations in materials
- Why look there?

THE DARK MATTER PANORAMA



- Similar argument as to WIMP based on EFT reasoning
- Dark matter abundance is related to SM interactions

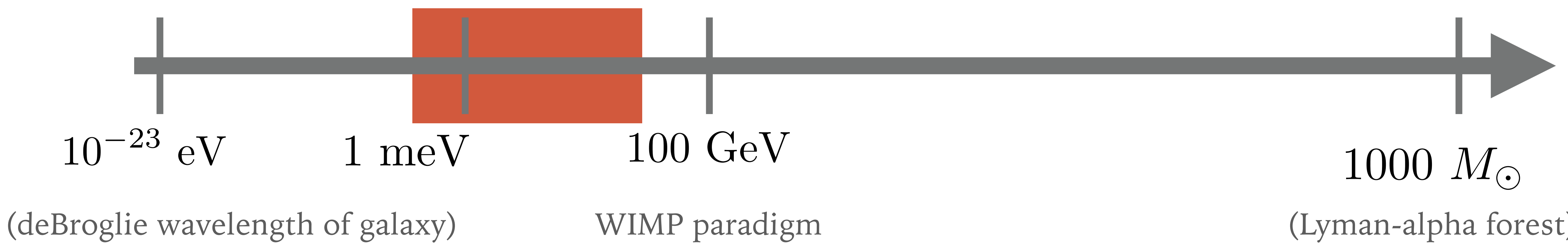


$$n_{DM}\langle\sigma v\rangle \simeq H(T_{\rm fo})$$

$$\rho_{DM} = \rho_{obs}$$

$$\langle\sigma v\rangle \simeq 3\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

THE DARK MATTER PANORAMA



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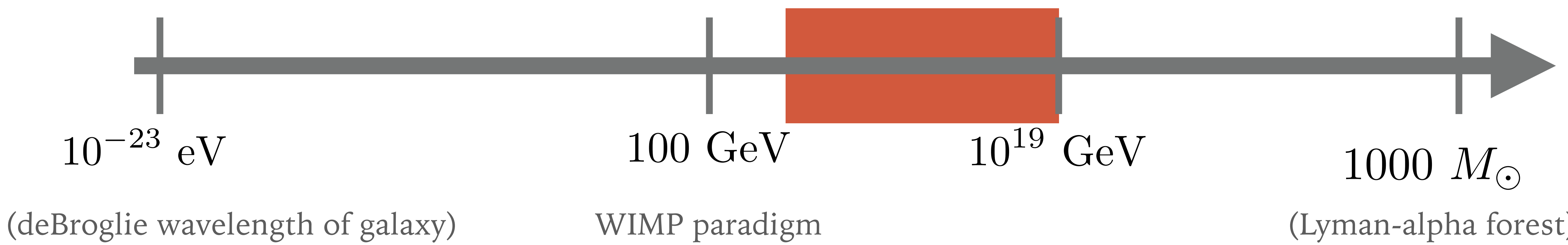
- Dark matter abundance is related to SM interactions

$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4}\frac{c}{3} \simeq 10^{-24}\frac{\mathrm{cm}^3}{\mathrm{s}}\left(\frac{100\ \mathrm{GeV}}{M}\right)^2$$

THE DARK MATTER PANORAMA



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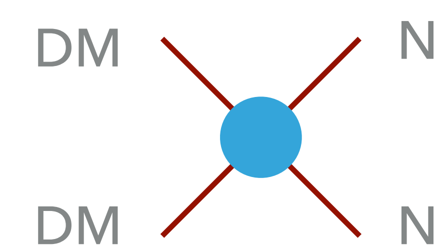
- Heavier dark matter: setting relic abundance through interactions with Standard Model is challenging (NB: exceptions)
- At heavier masses, detection through Standard Model interactions is (generally) not motivated by abundance

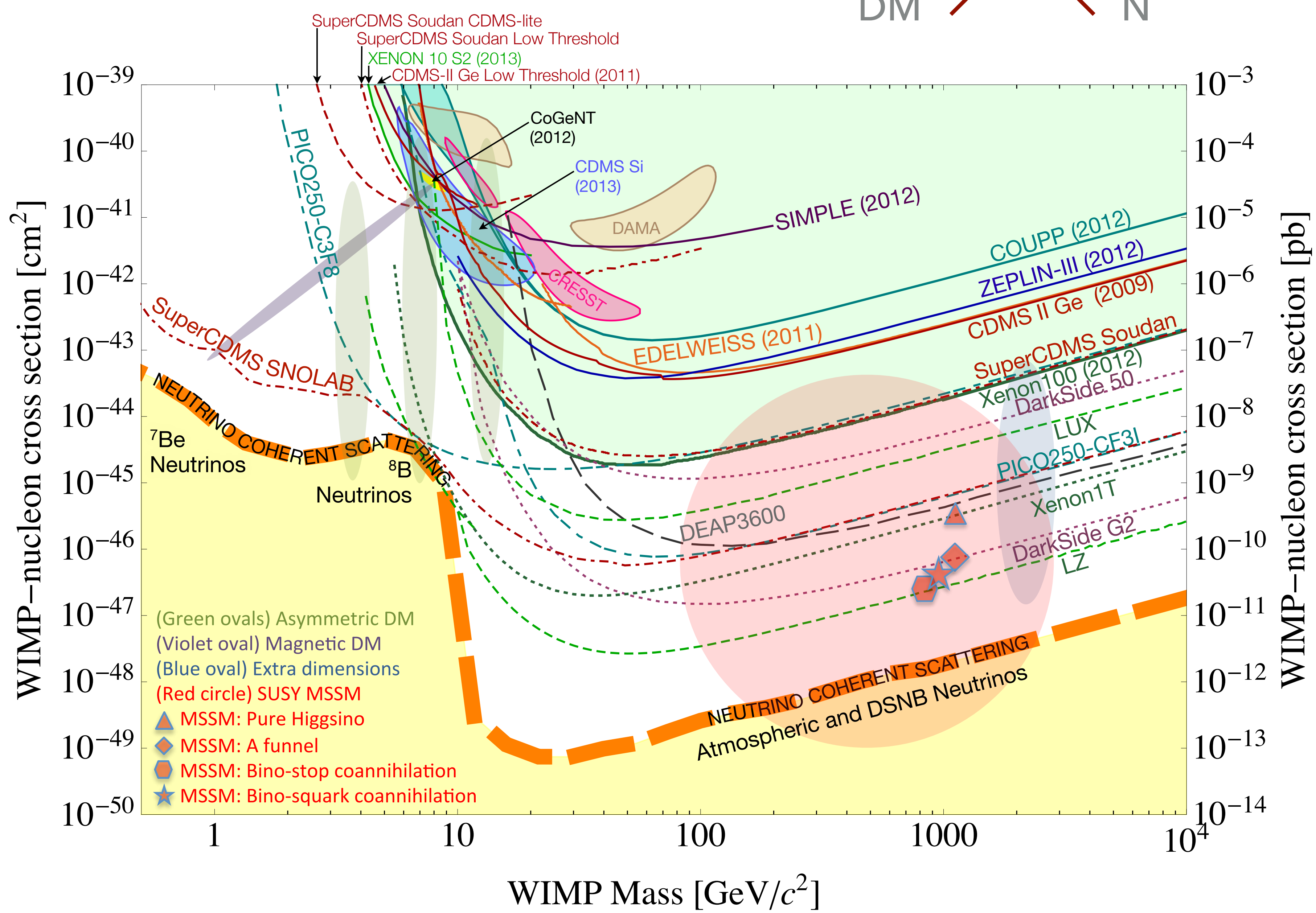
DETECTABLE INTERACTION RATES

- Direct detection searches accordingly focused on weak scale

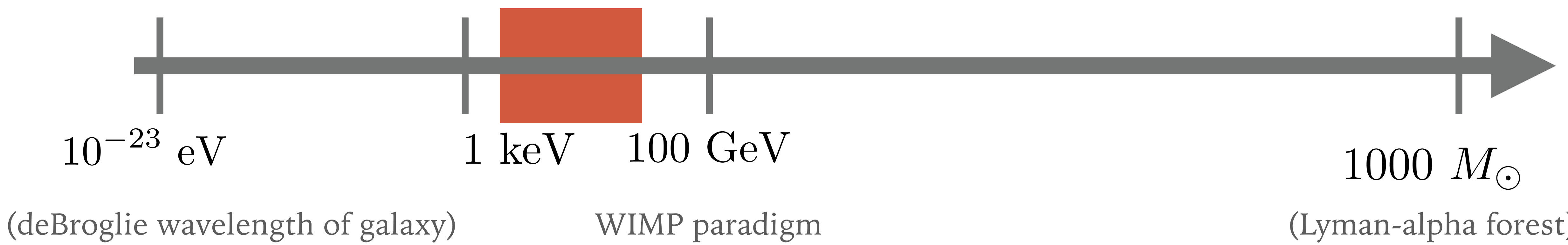


Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



DARK MATTER DETECTION: A FULL COURT PRESS

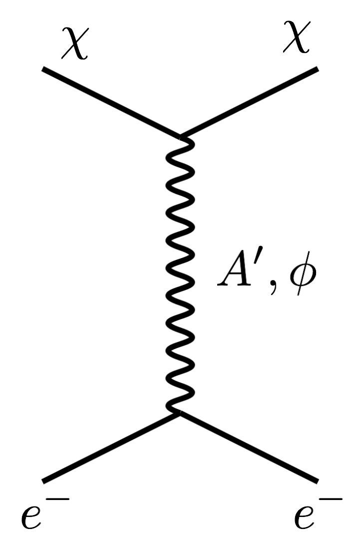


- Abundance may still be set by (thermal) population from SM sector

$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \frac{c}{3} \simeq 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \left(\frac{100\ \mathrm{GeV}}{M} \right)^2$$

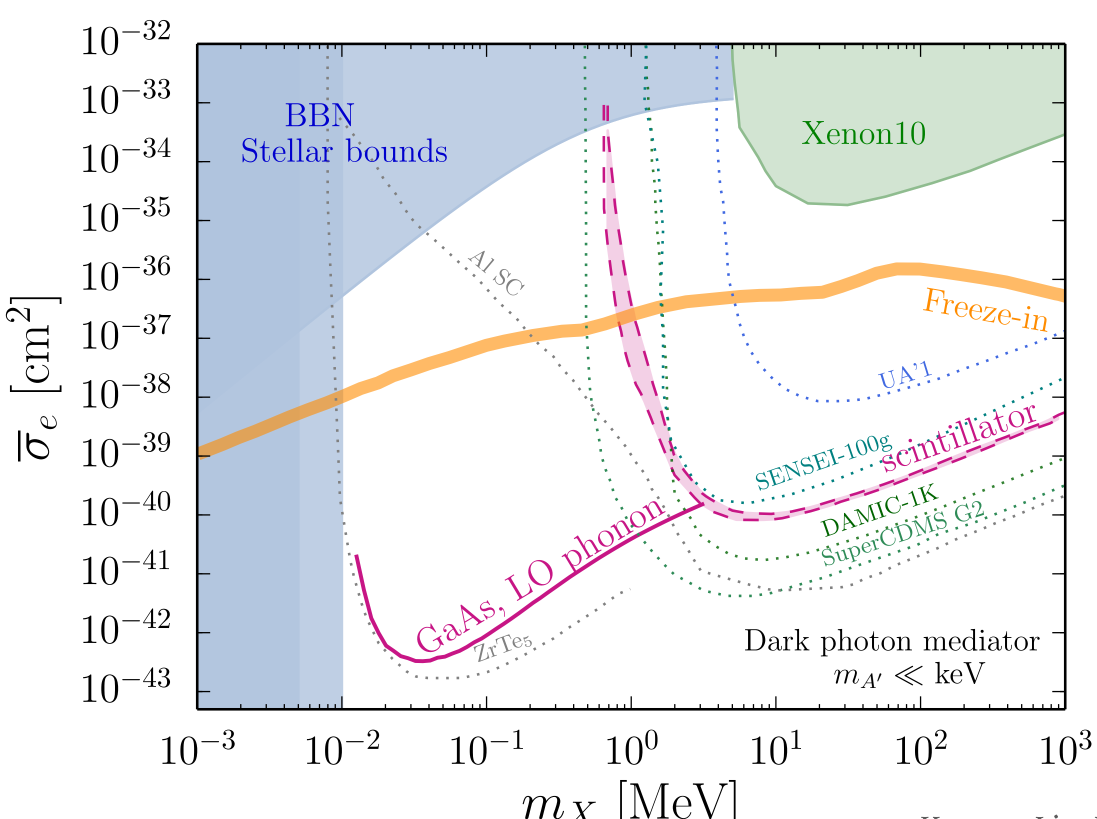
CROSSING SYMMETRY

- Utilize DM Abundance and crossing symmetry as guide for interaction rates

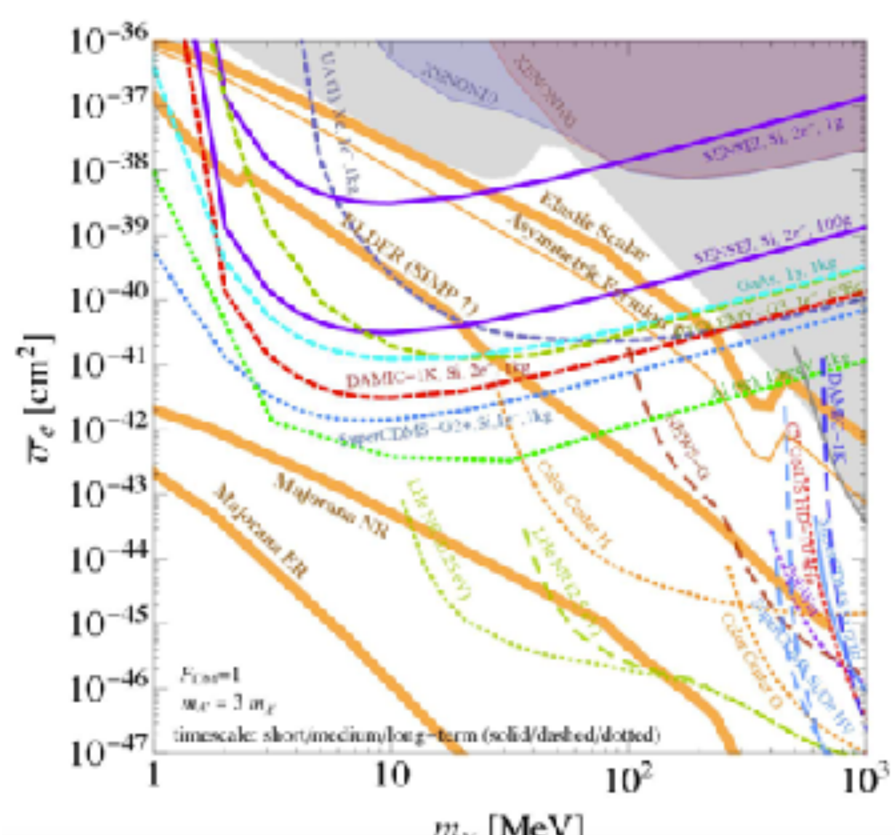


Freeze-in

Asymmetric Dark Matter

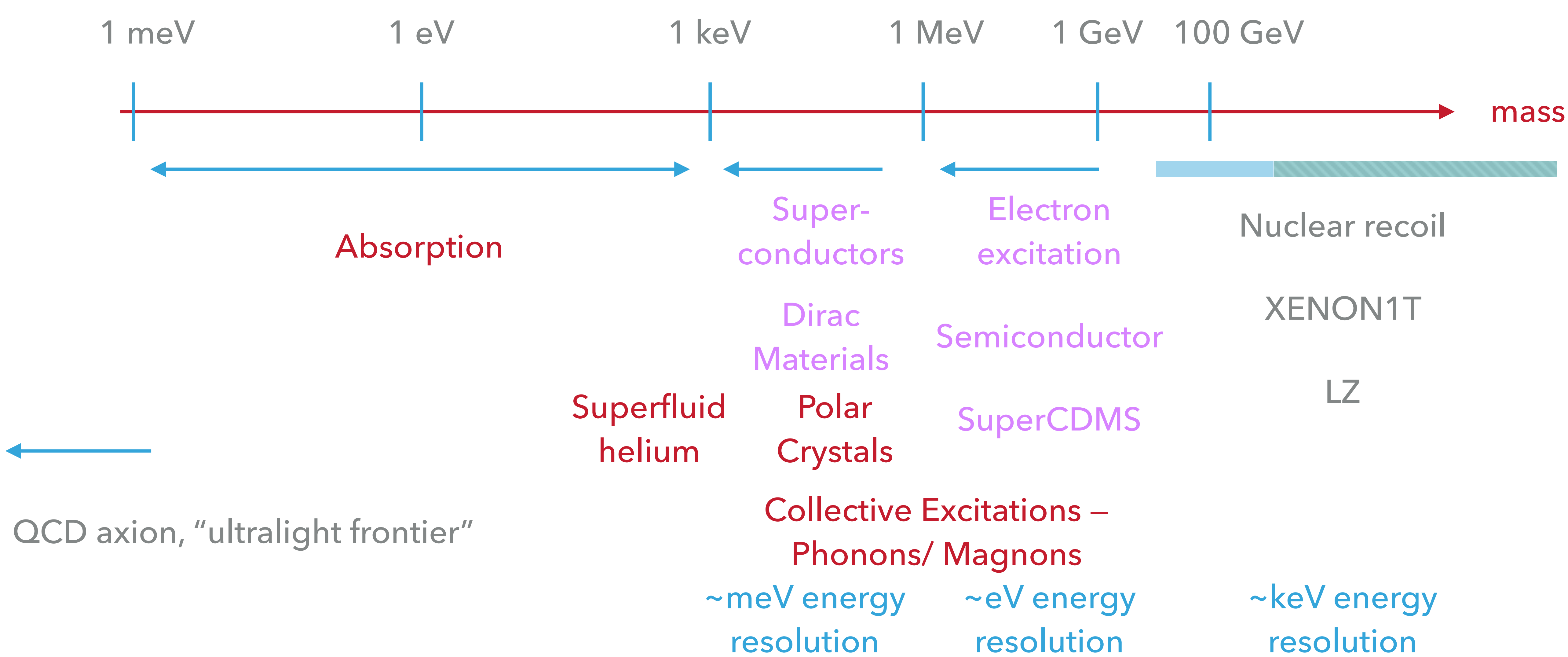


Knapen, Lin, Pyle KZ 1712.06598



US Cosmic Visions 1707.04591

COLLECTIVE PHENOMENA IN MATERIALS

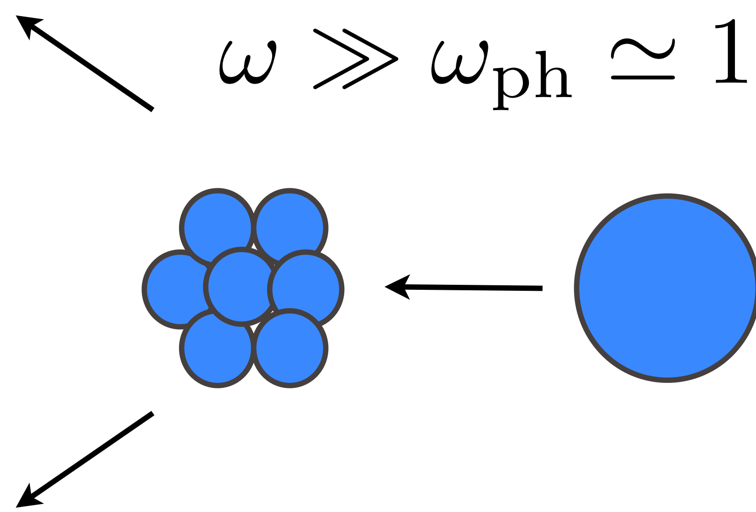


BEYOND BILLIARD BALL SCATTERING

- Nuclear recoil-based direct detection

$$\omega \gg \omega_{\rm ph} \simeq 100 \text{ meV}$$

$q, \; E_D$



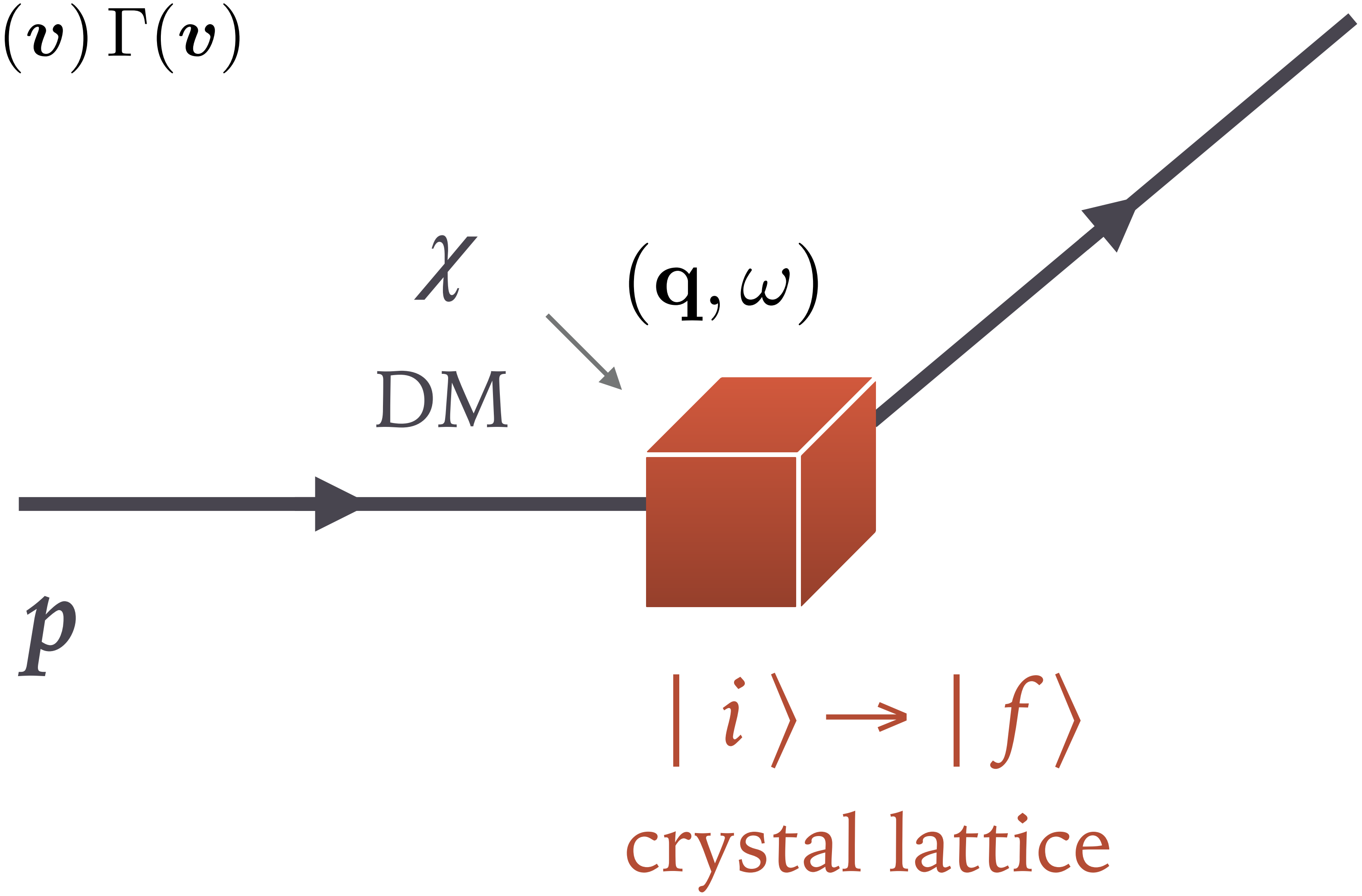
$v \sim 10^{-3} c$

$$E_D = \frac{q^2}{2 m_N} \qquad\qquad q_{\rm max} = 2 m_X v$$

- Nuclei, at least for high enough energy deposition, can typically be treated as free, and their kinematics is classical $\omega \gg \omega_{\rm ph} \simeq 100 \text{ meV}$

LOOKING BEYOND BILLIARD BALLS

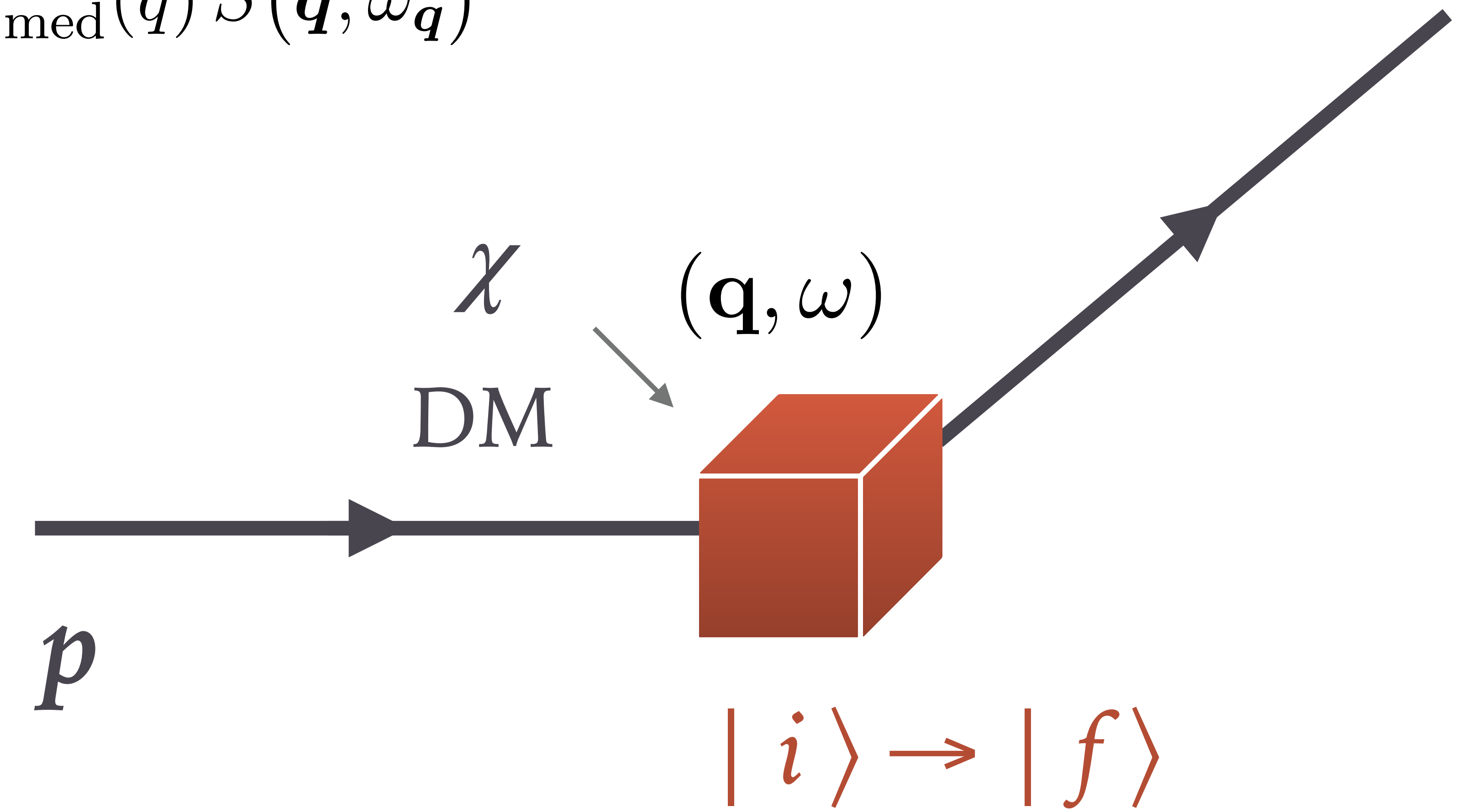
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int d^3v\, f_\chi(\boldsymbol{v})\,\Gamma(\boldsymbol{v})$$



For summary of theoretical formalism, including nuclear recoils, electrons, collective excitations, see 1910.08092

LOOKING BEYOND BILLIARD BALLS

$$\Gamma(\boldsymbol{v}) = \frac{\pi \overline{\sigma}}{\mu^2} \int \frac{d^3 q}{(2\pi)^3} \, \mathcal{F}^2_{\rm med}(q) \, S\big(\boldsymbol{q}, \omega_{\boldsymbol{q}}\big)$$



Dynamic Structure Factor

$$S(\boldsymbol{q}, \omega) \equiv \frac{1}{V} \sum_f \left| \langle f | \mathcal{F}_T(\boldsymbol{q}) | i \rangle \right|^2 2\pi \delta\big(E_f - E_i - \omega\big)$$

For summary of theoretical formalism, including nuclear recoils, electrons, collective excitations, see 1910.08092

Electrons

Lighter and less free

LIGHTER TARGETS FOR LIGHTER DARK MATTER — ELECTRONS

$$E_D = \frac{q^2}{2m_e} \qquad q_{\max} = 2m_X v$$

- In insulators, like xenon

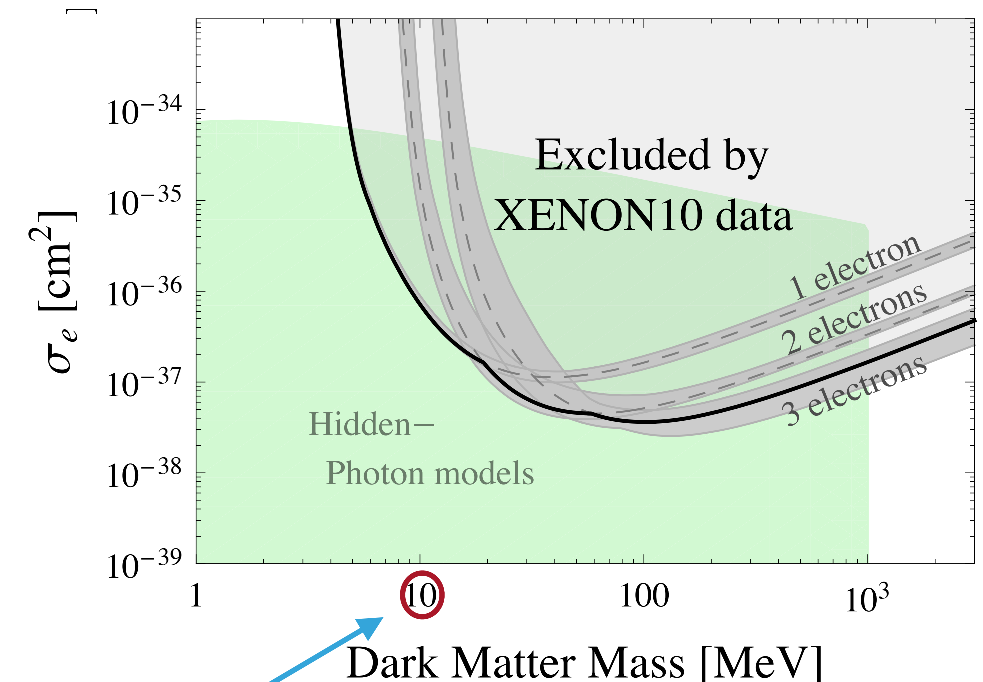
Tightly bound; ionize for signal

Gap = DM Kinetic Energy

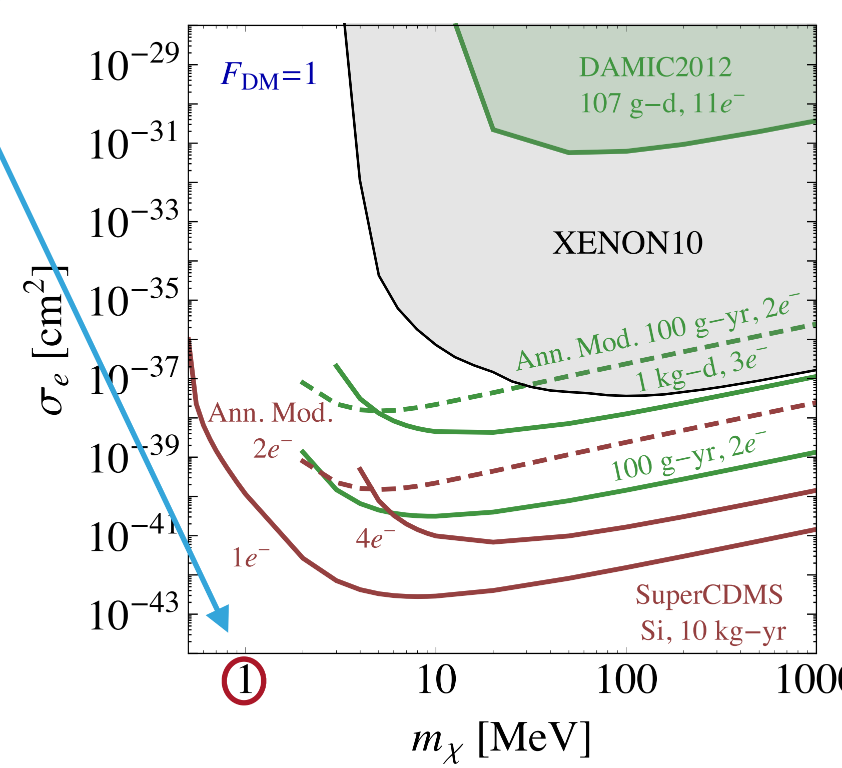
- In semi-conductors, like Ge, Si

Excite electron to conduction band

P. Sorensen et al 1206.2644

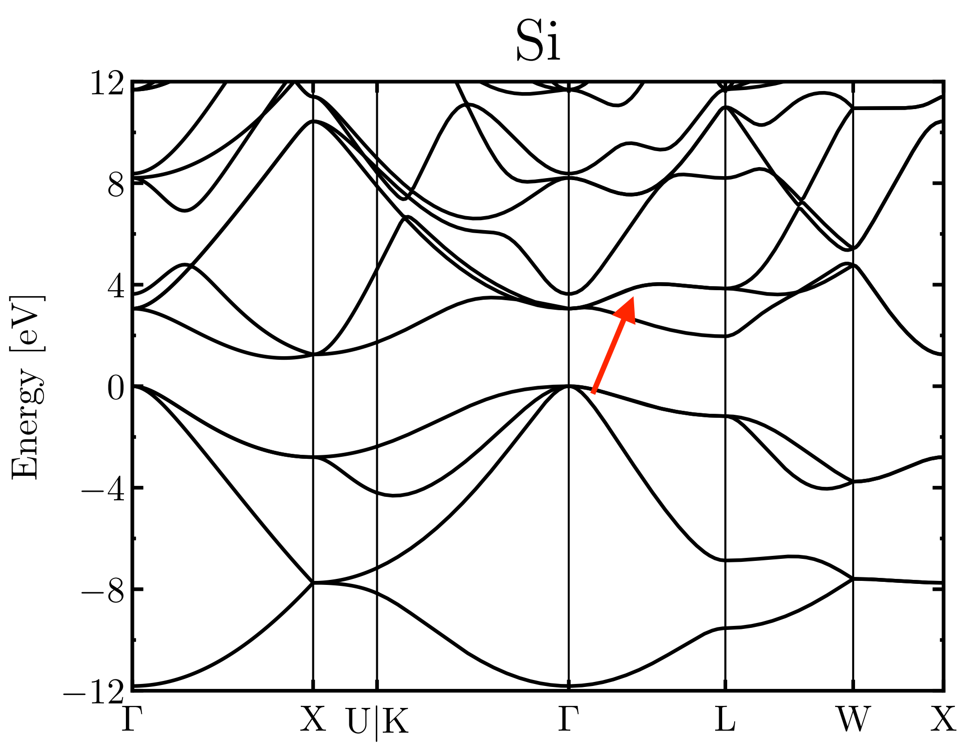


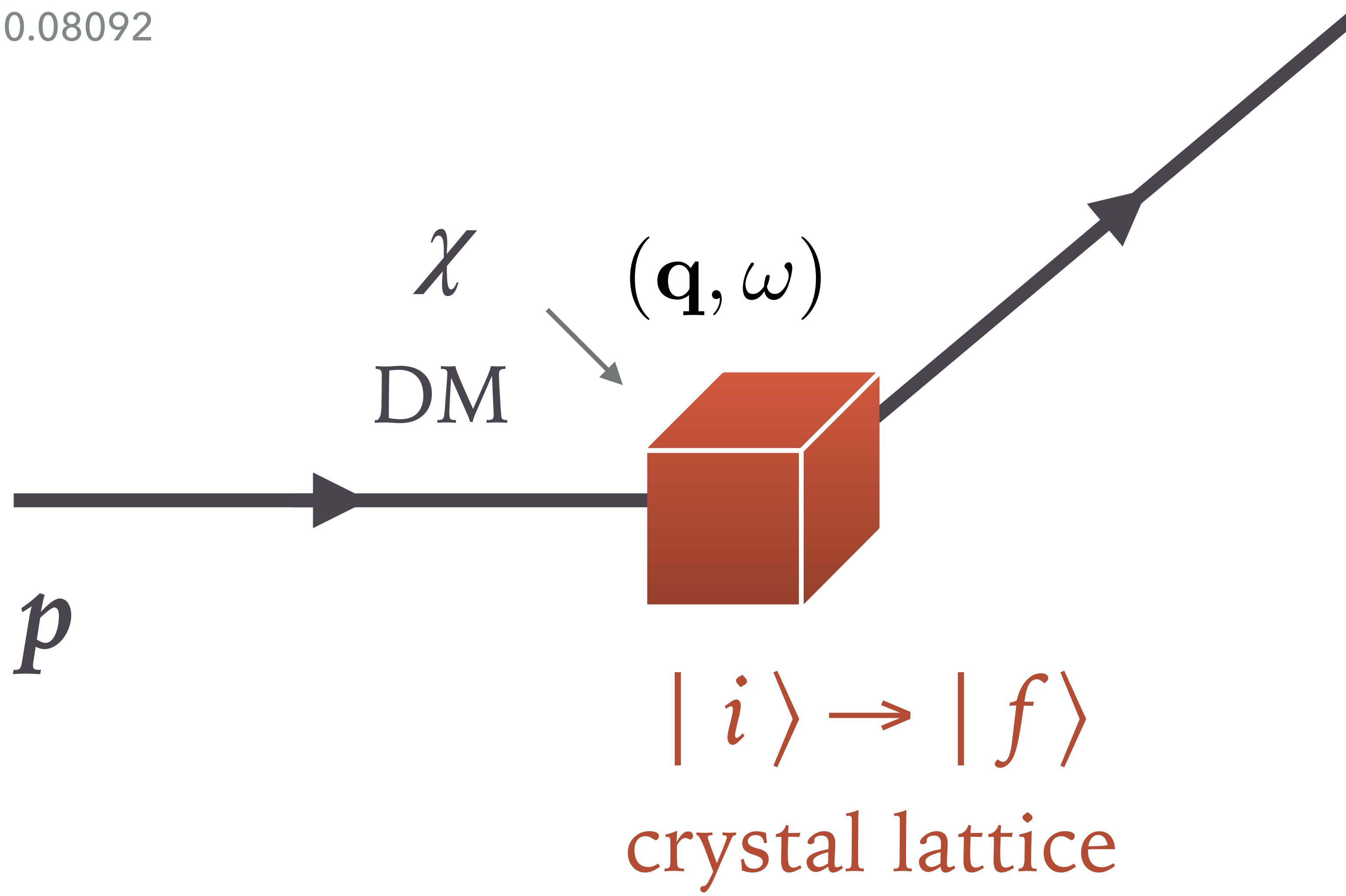
Essig et al 1509.01598



EXCITATION OF ELECTRONIC STATES BY DARK MATTER

For summary of theoretical formalism, see 1910.08092





$$\Gamma_{i,s,\sigma\to f,s',\sigma'}(\mathbf{v}) = \frac{2\pi}{16V m_e^2 m_\chi^2} \int \frac{d^3q}{(2\pi)^3}\, \delta(E_{f,s'} - E_{i,s} - \omega_{\mathbf{q}}) \times \left| \int \frac{d^3k}{(2\pi)^3}\, \mathcal{M}_{\sigma' s' \sigma s}(\mathbf{p}-\mathbf{q}, \mathbf{k}+\mathbf{q}, \mathbf{p}, \mathbf{k})\, \widetilde{\psi}_f^*(\mathbf{k}+\mathbf{q}) \widetilde{\psi}_i(\mathbf{k}) \right|^2$$

DM-ELECTRON DETECTION RATE CALCULATOR

- Codes are publicly available — see 2105.05253
- exceed-dm.caltech.edu
- **EXtended Calcuation of Electronic Excitation for Direct detection of Dark Matter**
- Contains repository for rate calculator
- Only code to include all-electron wavefunctions for silicon and germanium (allows reconstruction of higher momentum components of valence states), as well as core states
- Manual coming soon

Phonons

Power of Collective Excitations

EXCITING COLLECTIVE MODES

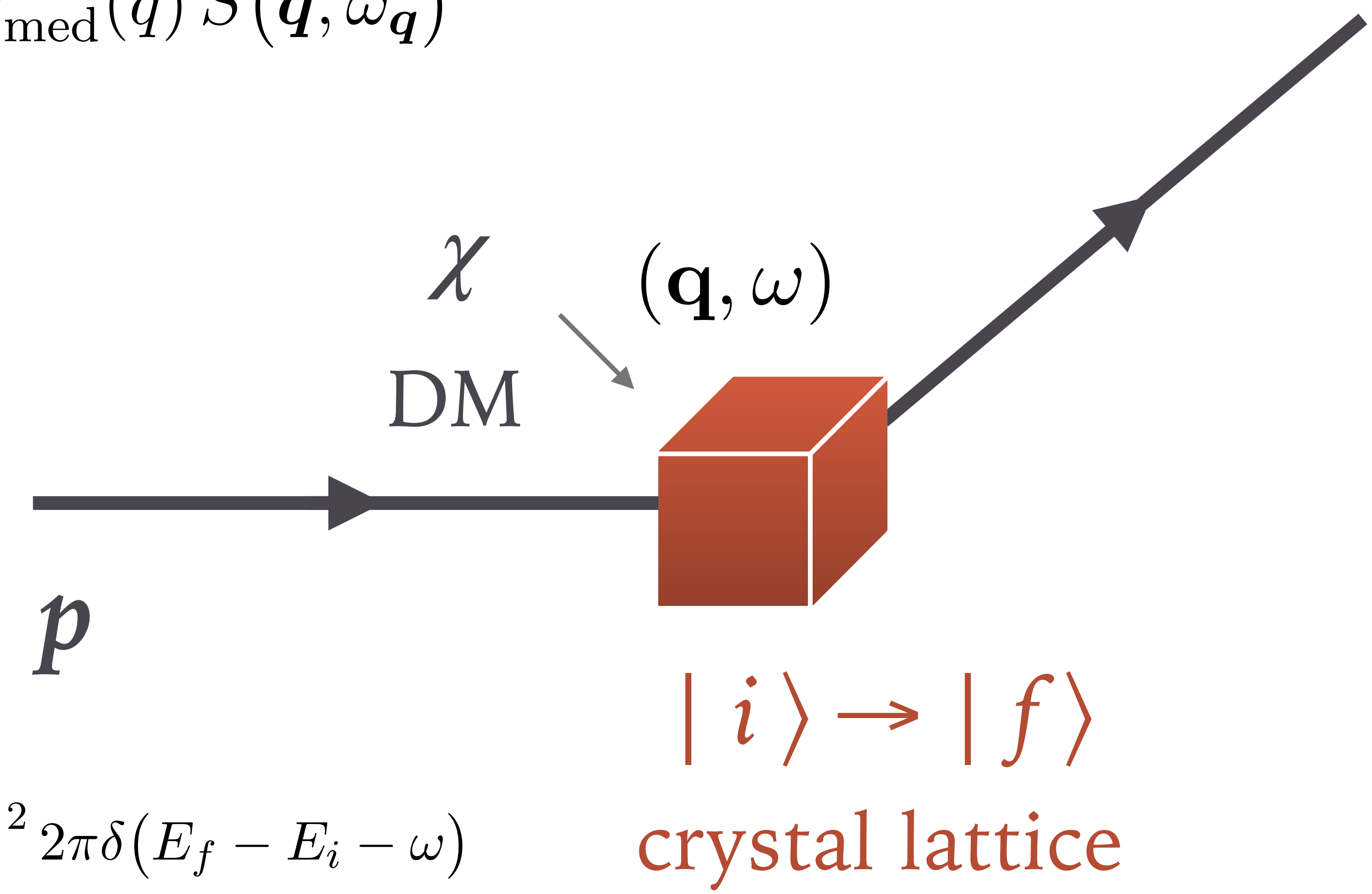
- Once momentum transfer drops below an keV, deBroglie wavelength is longer than the inter particle spacing in typical materials
- Therefore, relevant d.o.f. in target are no longer individual nuclei or ions
- Must coarse grain to describe DM coupling to “collective excitations”
- Collective excitations = phonon modes, spin waves (magnons)
- Can be applied to just about any material
- Details depend on
  - 1) *nature of collective modes in target material*
  - 2) *nature of DM couplings to target*

Schutz, KZ 1604.08206, Hochberg, Lin, KZ 1604.06800, Knapen, Lin, KZ 1611.06228, Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

LOOKING BEYOND BILLIARD BALLS

$$\Gamma(\boldsymbol{v}) = \frac{\pi\overline{\sigma}}{\mu^2}\int \frac{d^3q}{(2\pi)^3}\,\mathcal{F}^2_{\rm med}(q)\,S\big(\boldsymbol{q},\omega_{\boldsymbol{q}}\big)$$

Tabulates the (lattice) potential the incoming DM sees — which in turn depends on the collective modes in the material

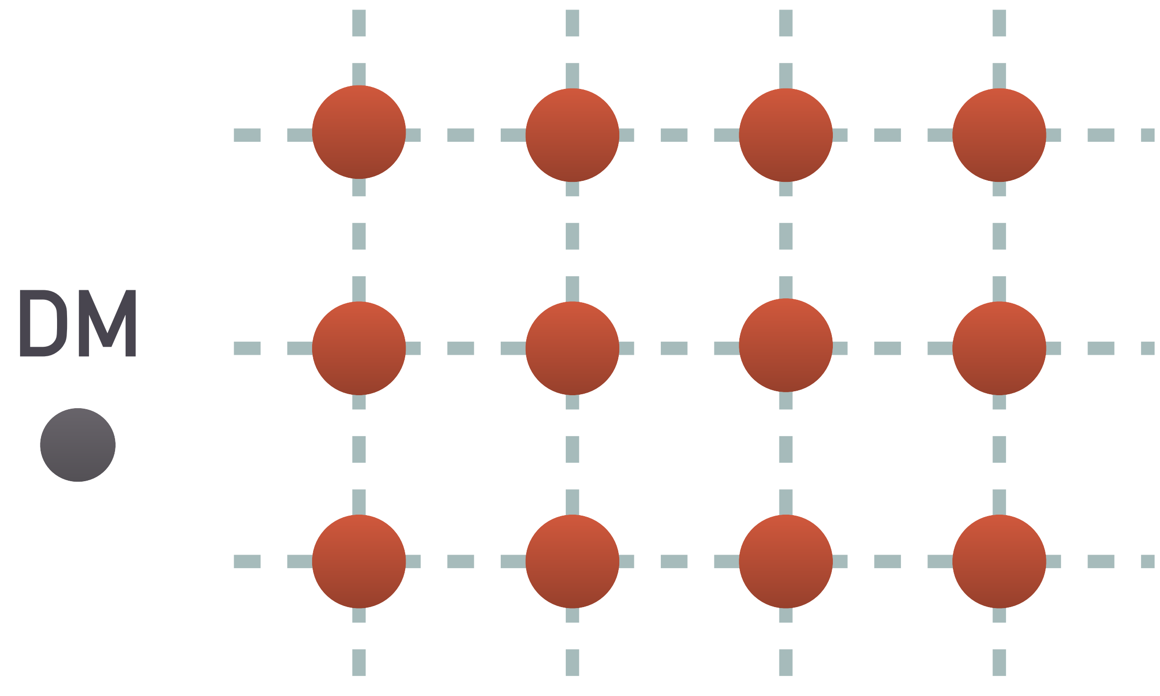


$$S(\boldsymbol{q},\omega) \equiv \frac{1}{V}\sum_f \big|\langle f|\mathcal{F}_T(\boldsymbol{q})|i\rangle\big|^2\, 2\pi\delta\big(E_f - E_i - \omega\big)$$

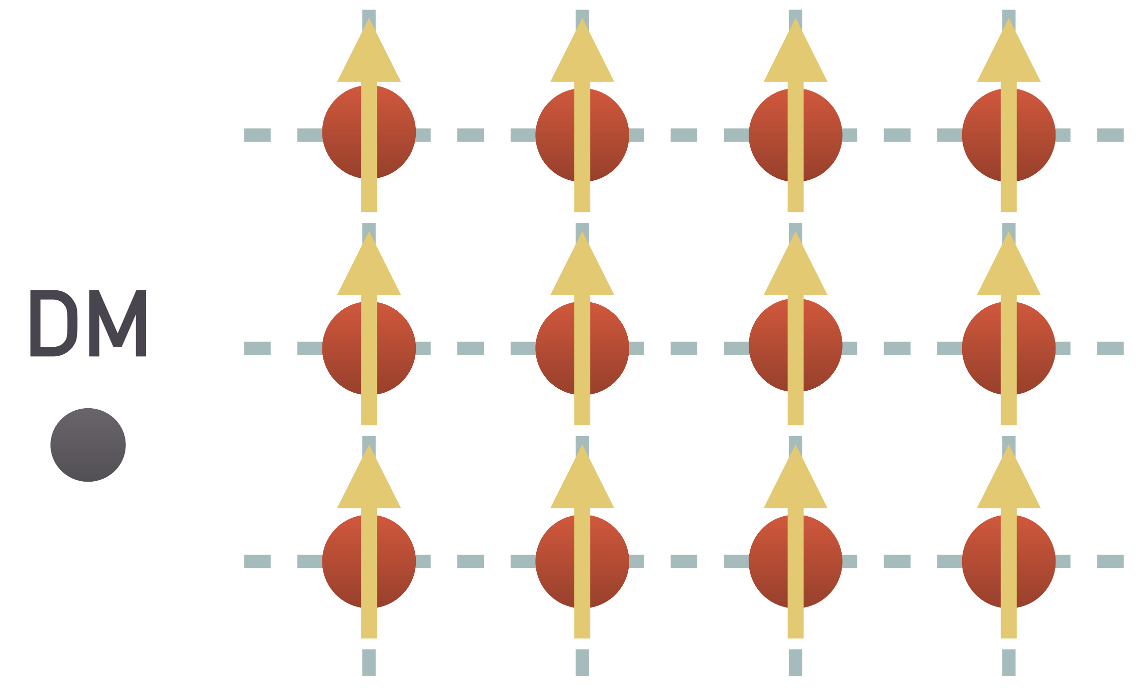
For summary of theoretical formalism, including nuclear recoils, electrons, collective excitations, see 1910.08092

LATTICE DEGREES OF FREEDOM

- Will focus on crystals that have lattice d.o.f.



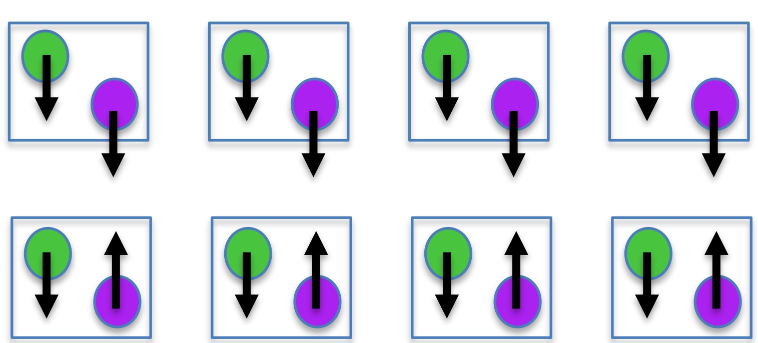
Phonons



Magnons

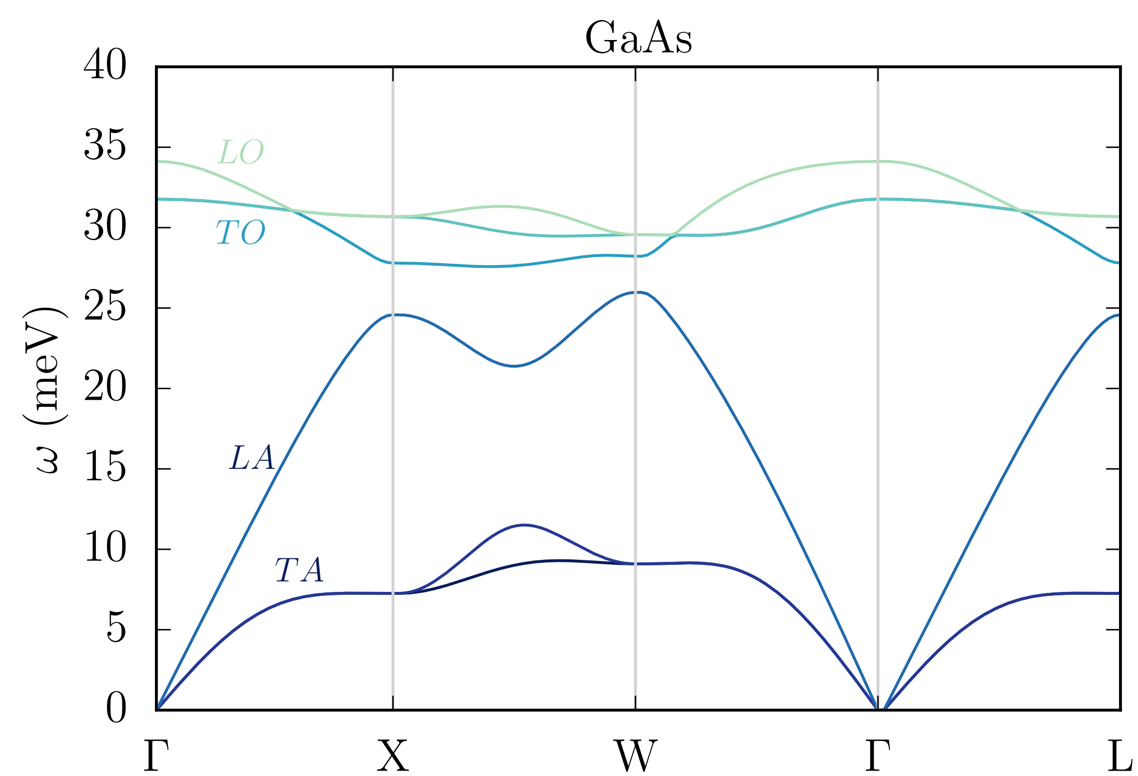
Acoustic

Optical

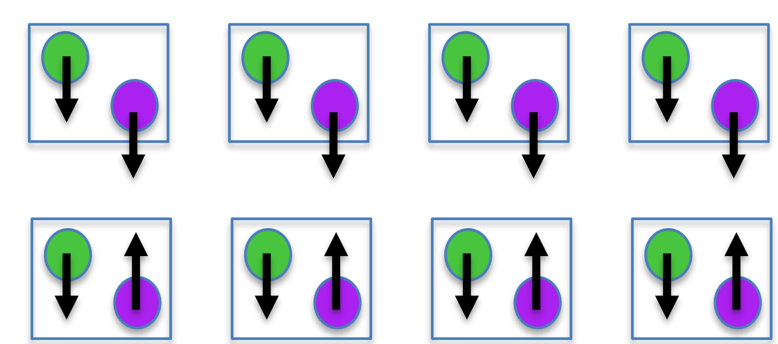


NATURE OF COLLECTIVE OSCILLATIONS OF IONS — PHONONS

- Number of collective modes: 3 x number of ions in unit cell
- 3 of those modes describe in phase oscillation — acoustic phonons — and have a translation symmetry implying gapless dispersion
- The remaining modes are gapped



Momentum transfer

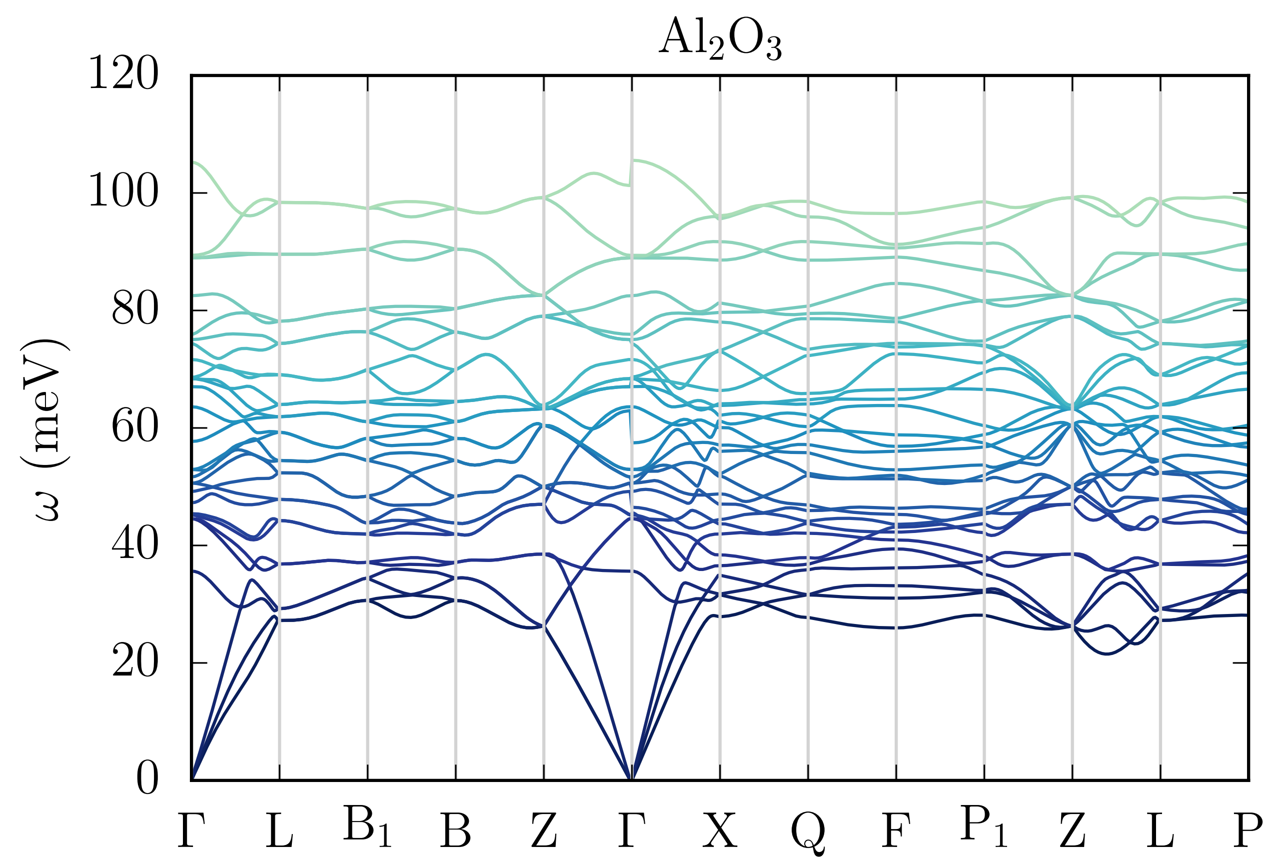


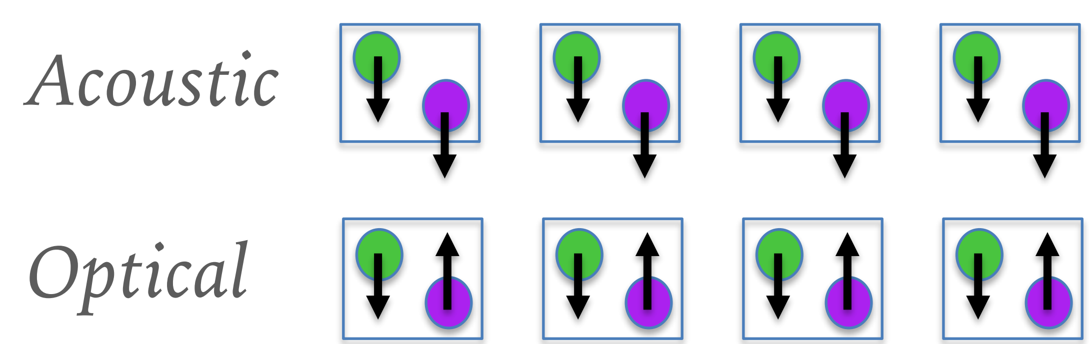
Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

NATURE OF COLLECTIVE OSCILLATIONS OF IONS — PHONONS

- Some materials have an abundance of these modes
- When these gapped modes result from oscillations of more than one type of ion, it sets up an oscillating dipole: Polar Materials
- This oscillating dipole allows to compute an effective interaction and compute the dynamic structure factor

Sapphire





Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

KINEMATICS OF COLLECTIVE MODES

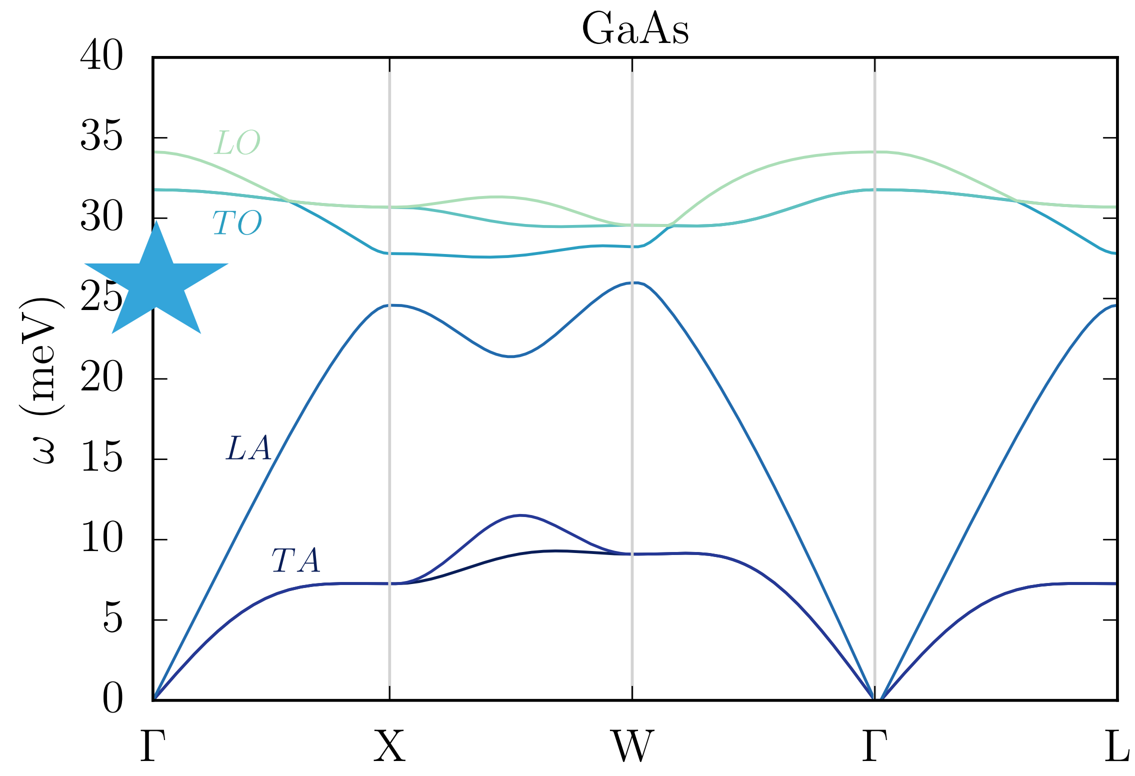
- Each phonon mode is a resonance. The DM needs to be well matched kinematically to the modes to excite large response

$$E_D \sim v_X q$$

vs

$$E_D \sim c_s q$$

$$c_s \ll v_X$$

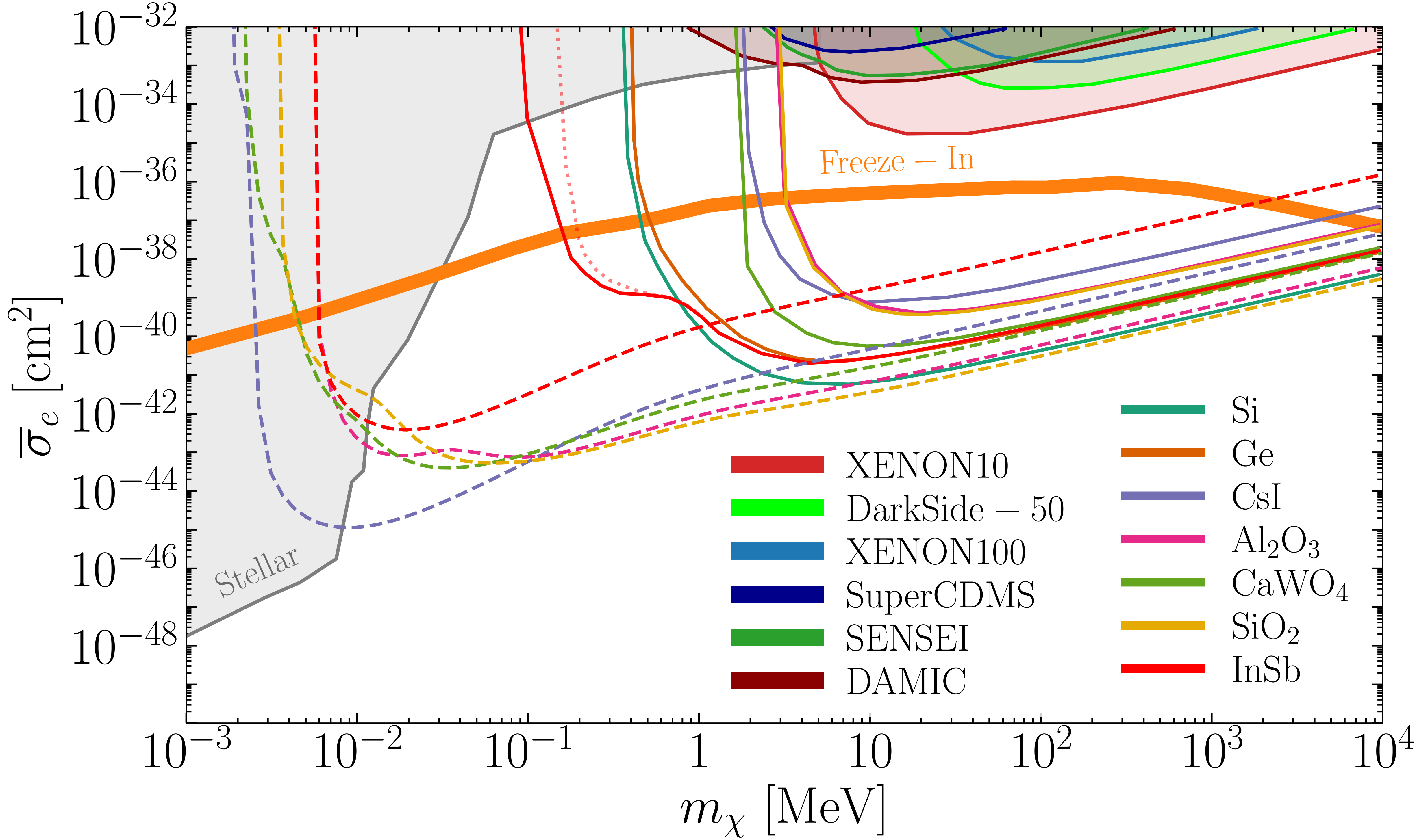


- Better coupling to gapped modes

Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

OPTICAL PHONONS IN POLAR MATERIALS

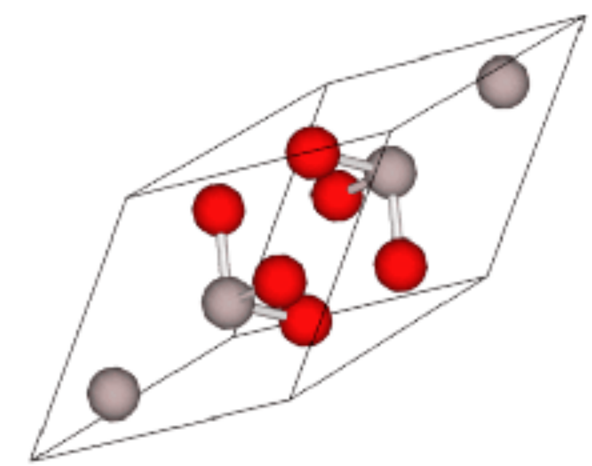
Griffin, Inzani, Trickle, Zhang, KZ, 1910.10716

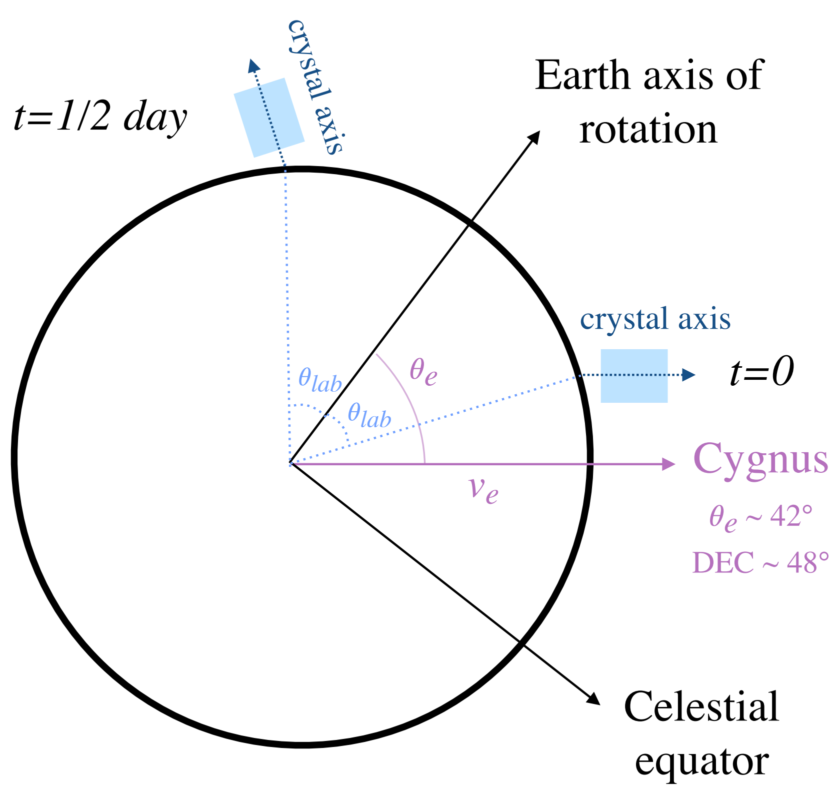


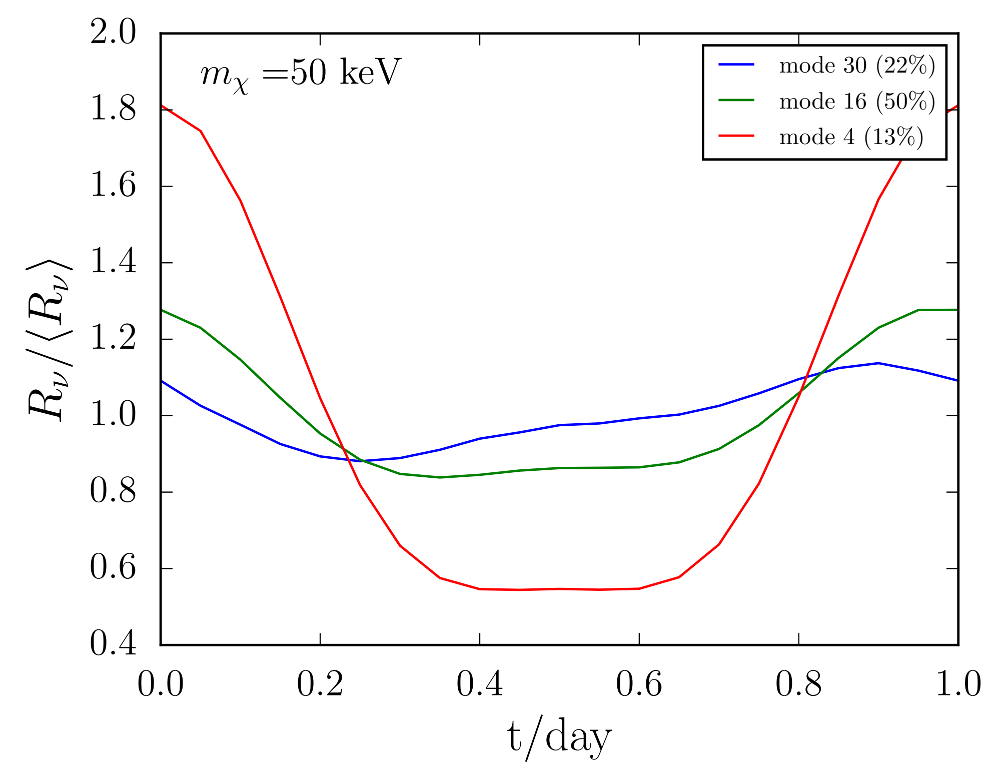
DIRECTIONALITY IN ANISOTROPIC MATERIALS!

Griffin, Knapen, Lin, KZ 1807.10291
Coskuner, Trickle, Zhang, KZ 2102.09567

- Crystal Lattice is not Isotropic
- Especially pronounced in certain materials, like sapphire







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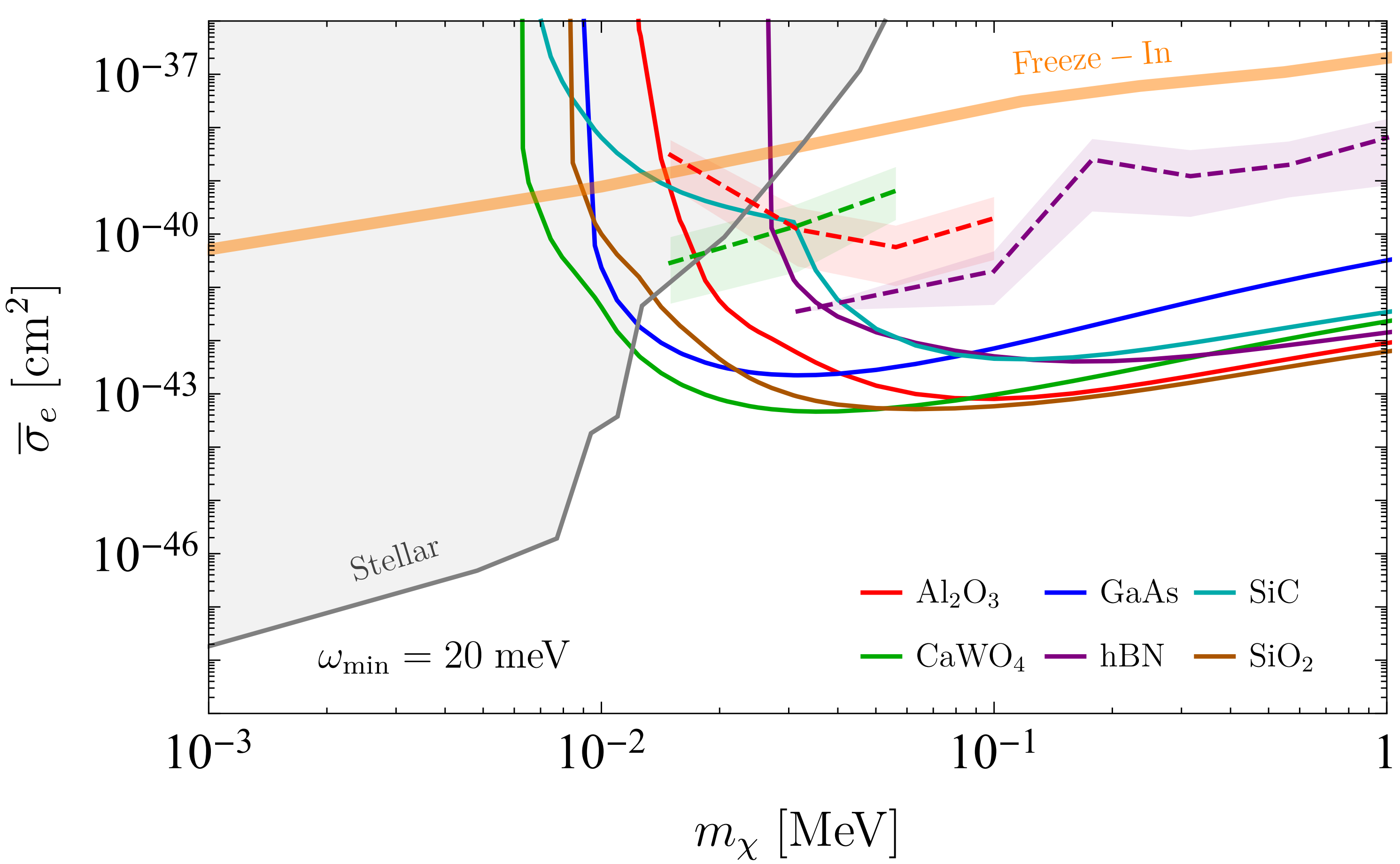


DM – COLLECTIVE MODE EFT

See Trickle, Zhang, KZ 2009.13534

Trickle, Zhang, KZ, Griffin, Inzani 1910.08092

Griffin, Inzani, Trickle, Zhang, KZ 1910.10716

- Match relativistic ops onto non-relativistic ops

  (Trivial for SI interactions)

- Match NR ops onto lattice d.o.f.

  (Provided by Frohlich Hamiltonian or dynamic structure factor computed)

- Compute DM excitation rates

  (Straightforward once one understands the (inelastic) kinematics of the system)

DM – COLLECTIVE MODE EFT

See Trickle, Zhang, KZ 2009.13534

Lagrangian Term	Coupling Type	(Effective) Current $\to$ NR Limit
$g_S \phi \bar{\psi}\psi$	Scalar	$J_S = \bar{\psi}\psi \to \mathbb{1}$
$g_P \phi \bar{\psi} i\gamma^5 \psi$	Pseudoscalar	$J_P = \bar{\psi} i\gamma^5\psi \to -\frac{i\boldsymbol{q}}{m_\psi}\cdot \boldsymbol{S}_\psi$
$g_V V_\mu \bar{\psi}\gamma^\mu\psi$	Vector	$J_V^\mu = \bar{\psi}\gamma^\mu\psi \to \left(\mathbb{1},\ \frac{\boldsymbol{K}}{2m_\psi} - \frac{i\boldsymbol{q}}{m_\psi}\times \boldsymbol{S}_\psi\right)$
$g_A V_\mu \bar{\psi}\gamma^\mu\gamma^5\psi$	Axial vector	$J_A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi \to \left(\frac{\boldsymbol{K}}{m_\psi}\cdot \boldsymbol{S}_\psi\ ,\ 2\boldsymbol{S}_\psi\right)$
$\frac{g_\text{edm}}{4m_\psi} V_{\mu\nu}\bar{\psi}\sigma^{\mu\nu} i\gamma^5\psi$	Electric dipole	$J_\text{edm}^\mu = \frac{1}{2m_\psi}\partial_\nu\left(\bar{\psi}\sigma^{\mu\nu}i\gamma^5\psi\right) \to \left(-\frac{i\boldsymbol{q}}{m_\psi}\cdot\boldsymbol{S}_\psi\ ,\ \frac{i\omega}{m_\psi}\boldsymbol{S}_\psi + \frac{i\boldsymbol{q}}{m_\psi}\times\left(\frac{\boldsymbol{K}}{2m_\psi}\times\boldsymbol{S}_\psi\right)\right)$
$\frac{g_\text{mdm}}{4m_\psi} V_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi$	Magnetic dipole	$J_\text{mdm}^\mu = \frac{1}{2m_\psi}\partial_\nu\left(\bar{\psi}\sigma^{\mu\nu}\psi\right) \to \left(\frac{i\boldsymbol{q}}{m_\psi}\cdot\left(\frac{\boldsymbol{K}}{2m_\psi}\times\boldsymbol{S}_\psi\right) - \frac{\boldsymbol{q}^2}{4m_\psi^2}\ ,\ -\frac{i\boldsymbol{q}}{m_\psi}\times\boldsymbol{S}_\psi\right)$
$\frac{g_\text{ana}}{4m_\psi^2}(\partial^\nu V_{\mu\nu})\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right)$	Anapole	$J_\text{ana}^\mu = -\frac{1}{4m_\psi^2}(g^{\mu\nu}\partial^2 - \partial^\mu\partial^\nu)\left(\bar{\psi}\gamma_\nu\gamma^5\psi\right) \to -\frac{\boldsymbol{q}^2}{4m_\psi^2}J_A^\mu + \left(\frac{\boldsymbol{q}}{m_\psi}\cdot\boldsymbol{S}_\psi\right)\frac{q^\mu}{2m_\psi}$
$\frac{g_{V2}}{4m_\psi^2}(\partial^\nu V_{\mu\nu})\left(\bar{\psi}\gamma^\mu\psi\right)$	Vector ($\mathcal{O}(q^2)$)	$J_{V2}^\mu = -\frac{1}{4m_\psi^2}\partial^2\left(\bar{\psi}\gamma^\mu\psi\right) \to -\frac{\boldsymbol{q}^2}{4m_\psi^2}J_V^\mu$

DM – COLLECTIVE MODE EFT

See Trickle, Zhang, KZ 2009.13534

Model		**UV Lagrangian**	**NR EFT**	**Responses**
Standard SI		$\phi\left(g_\chi J_{S,\chi} + g_\psi J_{S,\psi}\right)$ or $V_\mu\left(g_\chi J^\mu_{V,\chi} - g_\psi J^\mu_{V,\psi}\right)$	$c_1^{(\psi)} = \frac{g_\chi g_\psi^{\text{eff}}}{\boldsymbol{q}^2 + m_{\phi,V}^2}$	N
Standard SD [a]		$V_\mu\left(g_\chi J^\mu_{A,\chi} + g_\psi J^\mu_{A,\psi}\right)$	$c_4^{(\psi)} = \frac{4 g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$	S
Other scalar mediators	P × S	$\phi\left(g_\chi J_{P,\chi} + g_\psi J_{S,\psi}\right)$	$c_{11}^{(\psi)} = \frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi^{\text{eff}}}{\boldsymbol{q}^2 + m_\phi^2}$	N
	S × P	$\phi\left(g_\chi J_{S,\chi} + g_\psi J_{P,\psi}\right)$	$c_{10}^{(\psi)} = -\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_\phi^2}$	S
	P × P	$\phi\left(g_\chi J_{P,\chi} + g_\psi J_{P,\psi}\right)$	$c_6^{(\psi)} = \frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_\phi^2}$	S
Multipole DM models	Electric dipole	$V_\mu\Big(g_\chi J^\mu_{\text{edm},\chi} + g_\psi\big(J^\mu_{V,\psi} + \delta\tilde{\mu}_\psi J^\mu_{\text{mdm},\psi}\big)\Big)$	$c_{11}^{(\psi)} = -\frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi^{\text{eff}}}{\boldsymbol{q}^2 + m_V^2}$	N
	Magnetic dipole	$V_\mu\Big(g_\chi J^\mu_{\text{mdm},\chi} + g_\psi\big(J^\mu_{V,\psi} + \delta\tilde{\mu}_\psi J^\mu_{\text{mdm},\psi}\big)\Big)$	$c_1^{(\psi)} = \frac{\boldsymbol{q}^2}{4m_\chi^2} \frac{g_\chi g_\psi^{\text{eff}}}{\boldsymbol{q}^2 + m_V^2}$ $c_4^{(\psi)} = \tilde{\mu}_\psi \frac{\boldsymbol{q}^2}{m_\chi m_\psi} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_{5a}^{(\psi)} = \frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi^{\text{eff}}}{\boldsymbol{q}^2 + m_V^2}$ $c_{5b}^{(\psi)} = \frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_6^{(\psi)} = -\tilde{\mu}_\psi \frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$	$N,\ S,\ L$
	Anapole	$V_\mu\Big(g_\chi J^\mu_{\text{ana},\chi} + g_\psi\big(J^\mu_{V,\psi} + \delta\tilde{\mu}_\psi J^\mu_{\text{mdm},\psi}\big)\Big)$	$c_{8a}^{(\psi)} = \frac{\boldsymbol{q}^2}{2m_\chi^2} \frac{g_\chi g_\psi^{\text{eff}}}{\boldsymbol{q}^2 + m_V^2}$ $c_{8b}^{(\psi)} = \frac{\boldsymbol{q}^2}{2m_\chi^2} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_9^{(\psi)} = -\tilde{\mu}_\psi \frac{\boldsymbol{q}^2}{2m_\chi^2} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$	$N,\ S,\ L$
$(\boldsymbol{L} \cdot \boldsymbol{S})$-interacting		$V_\mu\big(g_\chi J^\mu_{V,\chi} + g_\psi(J^\mu_{\text{mdm},\psi} + \kappa J^\mu_{V2,\psi})\big)$	$c_1^{(\psi)} = (1+\kappa) \frac{\boldsymbol{q}^2}{4m_\psi^2} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_{3a}^{(\psi)} = c_{3b}^{(\psi)} = \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_4^{(\psi)} = \frac{\boldsymbol{q}^2}{m_\chi m_\psi} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_6^{(\psi)} = -\frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$	$N, S,\ L \otimes S$

“

Magnons

Access to Spin-Dependent Interactions

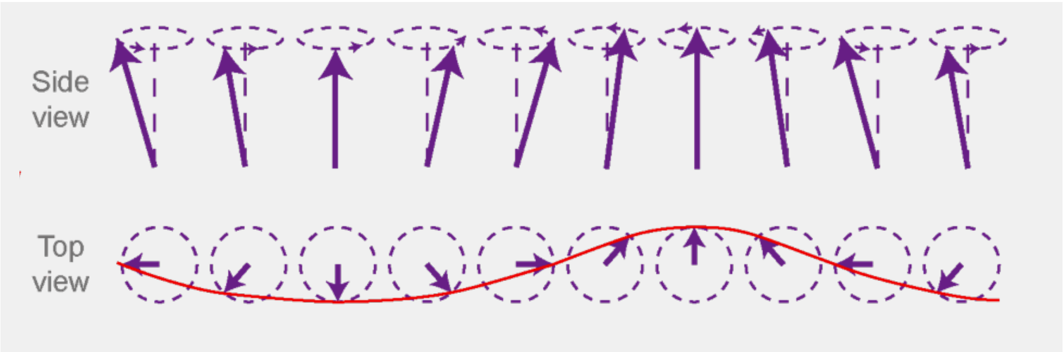
SPIN-DEPENDENT INTERACTIONS

Trickle, Zhang, KZ 1905.13744

- Some types of particle interactions have dominant interactions with spin

Magnetic dipole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi} \bar{\chi} \sigma^{\mu\nu} \chi \, V_{\mu\nu} + g_e \bar{e} \gamma^\mu e \, V_\mu$
Anapole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi^2} \bar{\chi} \gamma^\mu \gamma^5 \chi \, \partial^\nu V_{\mu\nu} + g_e \bar{e} \gamma^\mu e \, V_\mu$

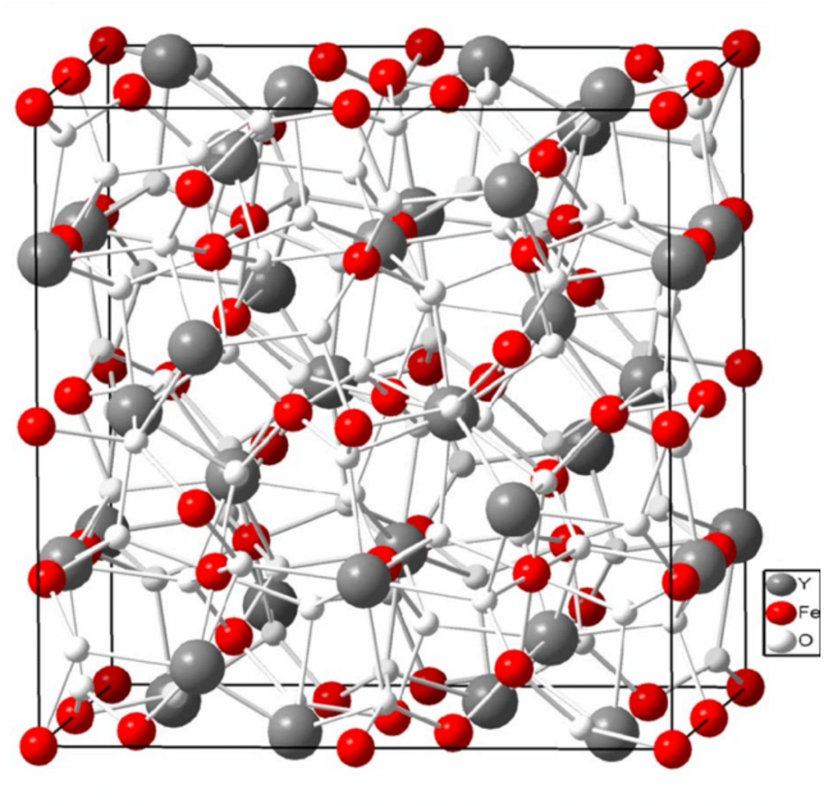
- Collective (electron) spin-waves = magnons
- Magnetically ordered materials (ferro- or ferri-magnets)

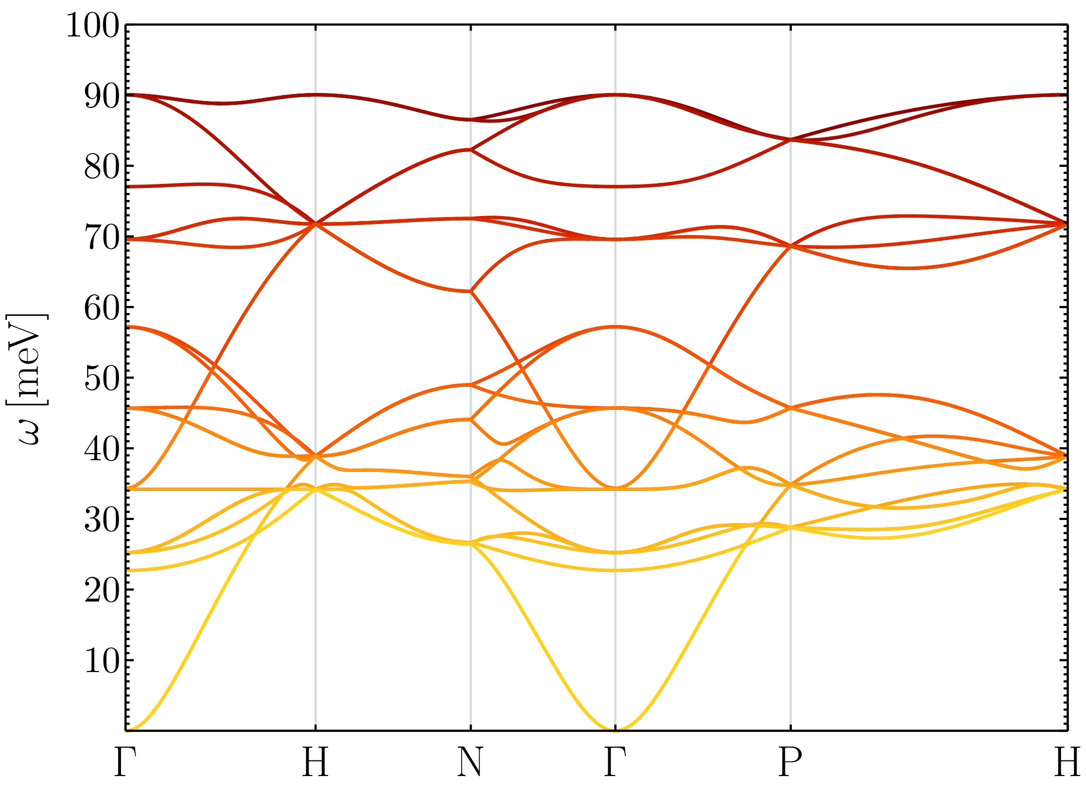


SPIN-DEPENDENT INTERACTIONS

Trickle, Zhang, KZ 1905.13744

- Classic example: YIG (Y3Fe5O12)
- 20 magnetic ions in the unit cell —> 20 magnon branches





MAGNON COLLECTIVE EXCITATIONS

See Trickle, Zhang, KZ 2009.13534
Trickle, Zhang, KZ 1905.13744

- Magnons are sensitive to spin-dependent couplings

$$\mathcal{L} = -\sum_{\alpha=1}^{3} \hat{\mathcal{O}}_\chi^\alpha(\boldsymbol{q}) \hat{S}_e^\alpha$$

Interaction Type	NR Operators	Crystal Response
Coupling to *charge*, $\boldsymbol{v}_\psi$*-independent*	$\mathcal{O}_1^{(\psi)} = \mathbb{1}$ $\mathcal{O}_{5a}^{(\psi)} = \boldsymbol{S}_\chi \cdot \left(\frac{i\boldsymbol{q}}{m_\psi} \times \boldsymbol{v}_\chi\right)$ $\mathcal{O}_{8a}^{(\psi)} = \boldsymbol{S}_\chi \cdot \boldsymbol{v}_\chi$ $\mathcal{O}_{11}^{(\psi)} = \boldsymbol{S}_\chi \cdot \frac{i\boldsymbol{q}}{m_\psi}$	N
Coupling to *spin*, $\boldsymbol{v}_\psi$*-independent*	$\mathcal{O}_{3a}^{(\psi)} = \boldsymbol{S}_\psi \cdot \left(\frac{i\boldsymbol{q}}{m_\psi} \times \boldsymbol{v}_\chi\right)$ $\mathcal{O}_4^{(\psi)} = \boldsymbol{S}_\chi \cdot \boldsymbol{S}_\psi$ $\mathcal{O}_6^{(\psi)} = \left(\boldsymbol{S}_\chi \cdot \frac{\boldsymbol{q}}{m_\psi}\right)\left(\boldsymbol{S}_\psi \cdot \frac{\boldsymbol{q}}{m_\psi}\right)$ $\mathcal{O}_{7a}^{(\psi)} = \boldsymbol{S}_\psi \cdot \boldsymbol{v}_\chi$ $\mathcal{O}_9^{(\psi)} = \boldsymbol{S}_\chi \cdot \left(\boldsymbol{S}_\psi \times \frac{i\boldsymbol{q}}{m_\psi}\right)$ $\mathcal{O}_{10}^{(\psi)} = \boldsymbol{S}_\psi \cdot \frac{i\boldsymbol{q}}{m_\psi}$ $\mathcal{O}_{12a}^{(\psi)} = \boldsymbol{S}_\chi \cdot \left(\boldsymbol{S}_\psi \times \boldsymbol{v}_\chi\right)$ $\mathcal{O}_{13a}^{(\psi)} = \left(\boldsymbol{S}_\chi \cdot \boldsymbol{v}_\chi\right)\left(\boldsymbol{S}_\psi \cdot \frac{i\boldsymbol{q}}{m_\psi}\right)$ $\mathcal{O}_{14a}^{(\psi)} = \left(\boldsymbol{S}_\psi \cdot \boldsymbol{v}_\chi\right)\left(\boldsymbol{S}_\chi \cdot \frac{i\boldsymbol{q}}{m_\psi}\right)$ $\mathcal{O}_{15a}^{(\psi)} = \left(\boldsymbol{S}_\chi \cdot \left(\frac{i\boldsymbol{q}}{m_\psi} \times \boldsymbol{v}_\chi\right)\right)\left(\boldsymbol{S}_\psi \cdot \frac{i\boldsymbol{q}}{m_\psi}\right)$	S

MAGNON COLLECTIVE EXCITATIONS

Trickle, Zhang, KZ 1905.13744

- Magnons are sensitive to spin-dependent couplings

$$\mathcal{L} = -\sum_{\alpha=1}^{3} \hat{\mathcal{O}}_\chi^\alpha(\boldsymbol{q})\hat{S}_e^\alpha$$

- Need to work out how coupling to spin excites individual magnon modes
- Need magnetic material to have non-zero spin expectation value over unit cell
- Expand in Holstein-Primakoff bosons, diagonalize Hamiltonian

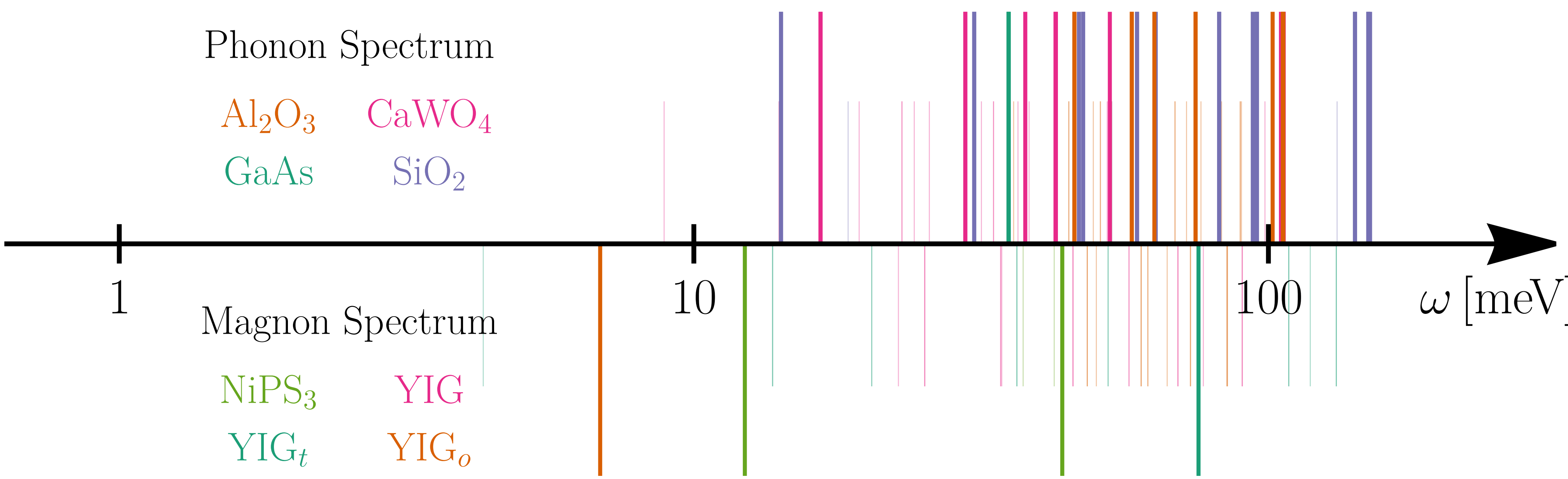
$$\mathcal{M}_{\nu,\boldsymbol{k}}^{s_i s_f}(\boldsymbol{q}) = \delta_{\boldsymbol{q},\boldsymbol{k}+\boldsymbol{G}} \frac{1}{\sqrt{N\Omega}} \sum_{\alpha=1}^{3} \langle s_f | \hat{\mathcal{O}}_\chi^\alpha(\boldsymbol{q}) | s_i \rangle \, \epsilon_{\nu,\boldsymbol{k},\boldsymbol{G}}^\alpha$$

Spin -> Collective mode

ABSORPTION OF BOSONIC DARK MATTER

Trickle, Zhang, KZ 2005.10256

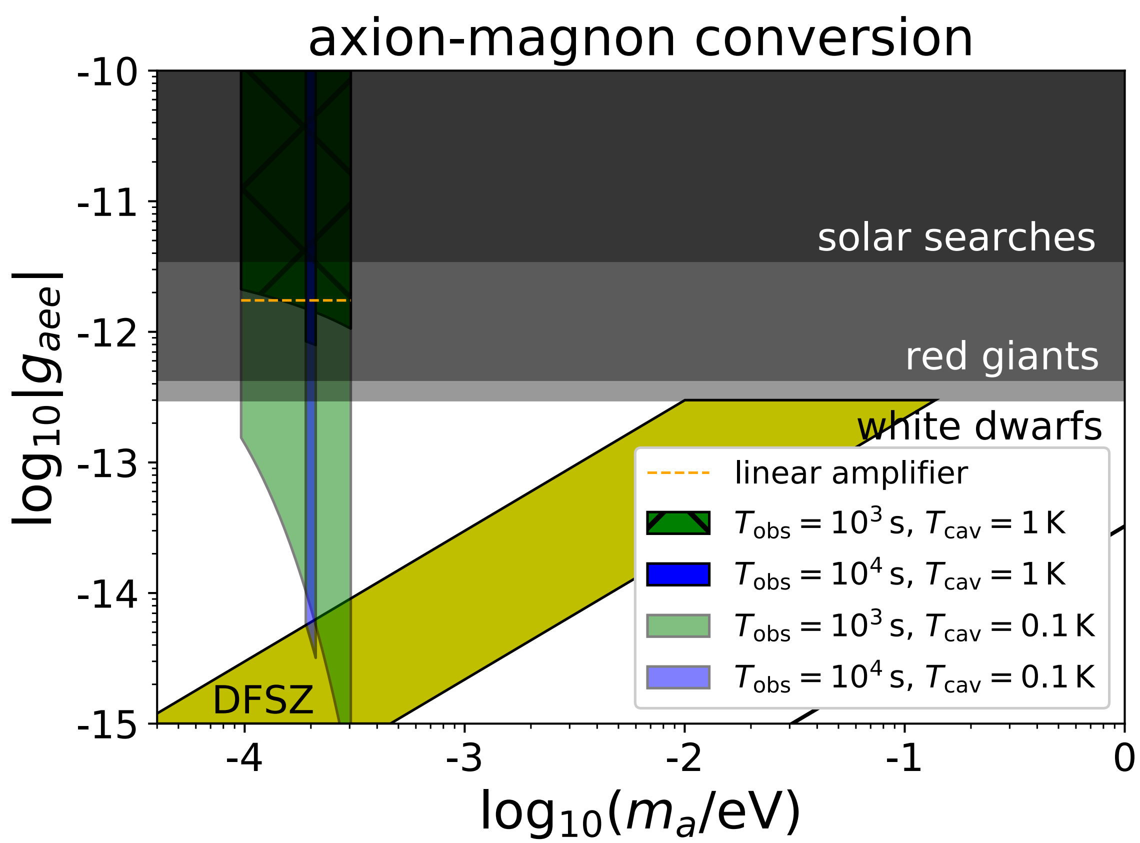
- Rather than depositing kinetic energy, entire mass energy can be absorbed.
- How about 1-100 meV mass axions?



Process	Fundamental interaction	Effective coupling in Eq. (4)	Rate formula
Axion + B field → phonon	$a\boldsymbol{E}\cdot\boldsymbol{B}$	$\boldsymbol{f}_j = \frac{1}{\sqrt{2}} g_{a\gamma\gamma} \frac{e\sqrt{\rho_a}}{m_a} \boldsymbol{B}\cdot\boldsymbol{\varepsilon}_\infty^{-1}\cdot\boldsymbol{Z}_j^*$	Eq. (18)
Axion → magnon	$\nabla a\cdot\boldsymbol{s}_e$	$\boldsymbol{f}_j = -\frac{i}{\sqrt{2}} g_{aee}(g_j-1)\frac{\sqrt{\rho_a}}{m_e}\boldsymbol{v}_a$	Eq. (27)

AXIONS AND QUAX

- We calculate *single* magnon excitation
- Agree with classical calculation in the relevant limit

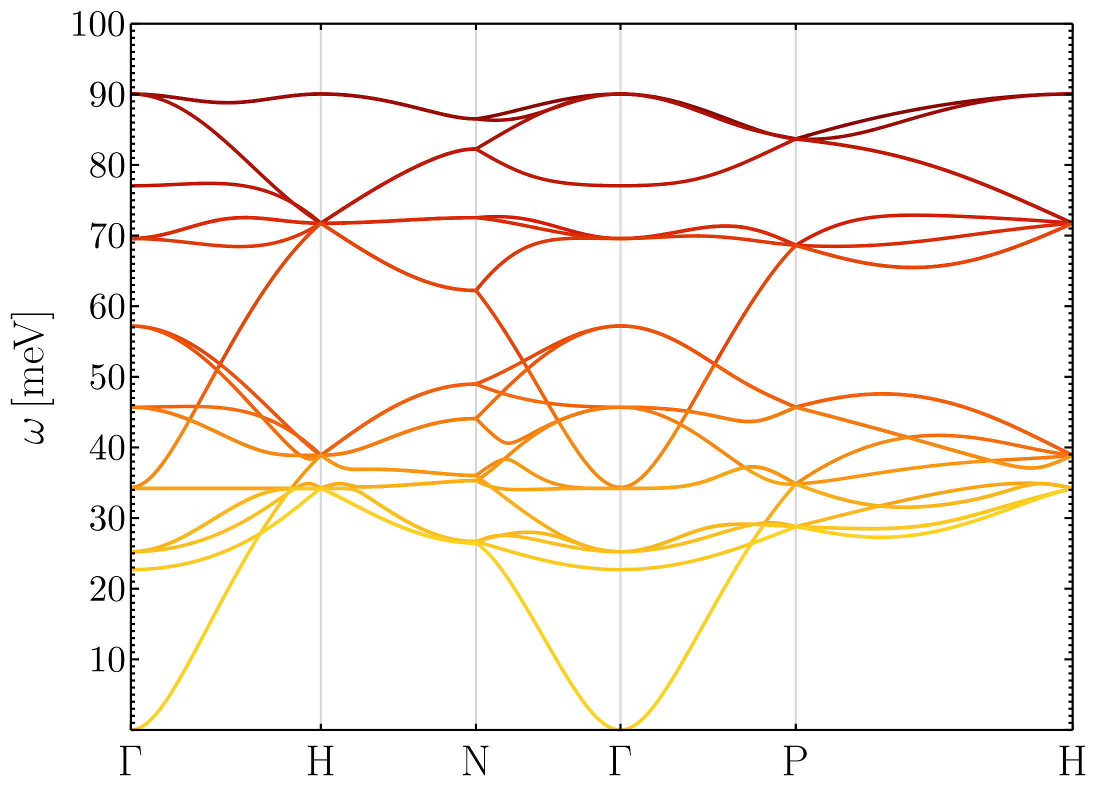


Chigusa, Moroi, Nakayama 2001.10666

- QUAX based on this idea   Barbieri, Cerdonio, Fiorentini, Vitale '89
  Barbieri, Braggio et al 1606.02201
- Requires lifting gapless magnon with external B-field

AXIONS AND QUAX

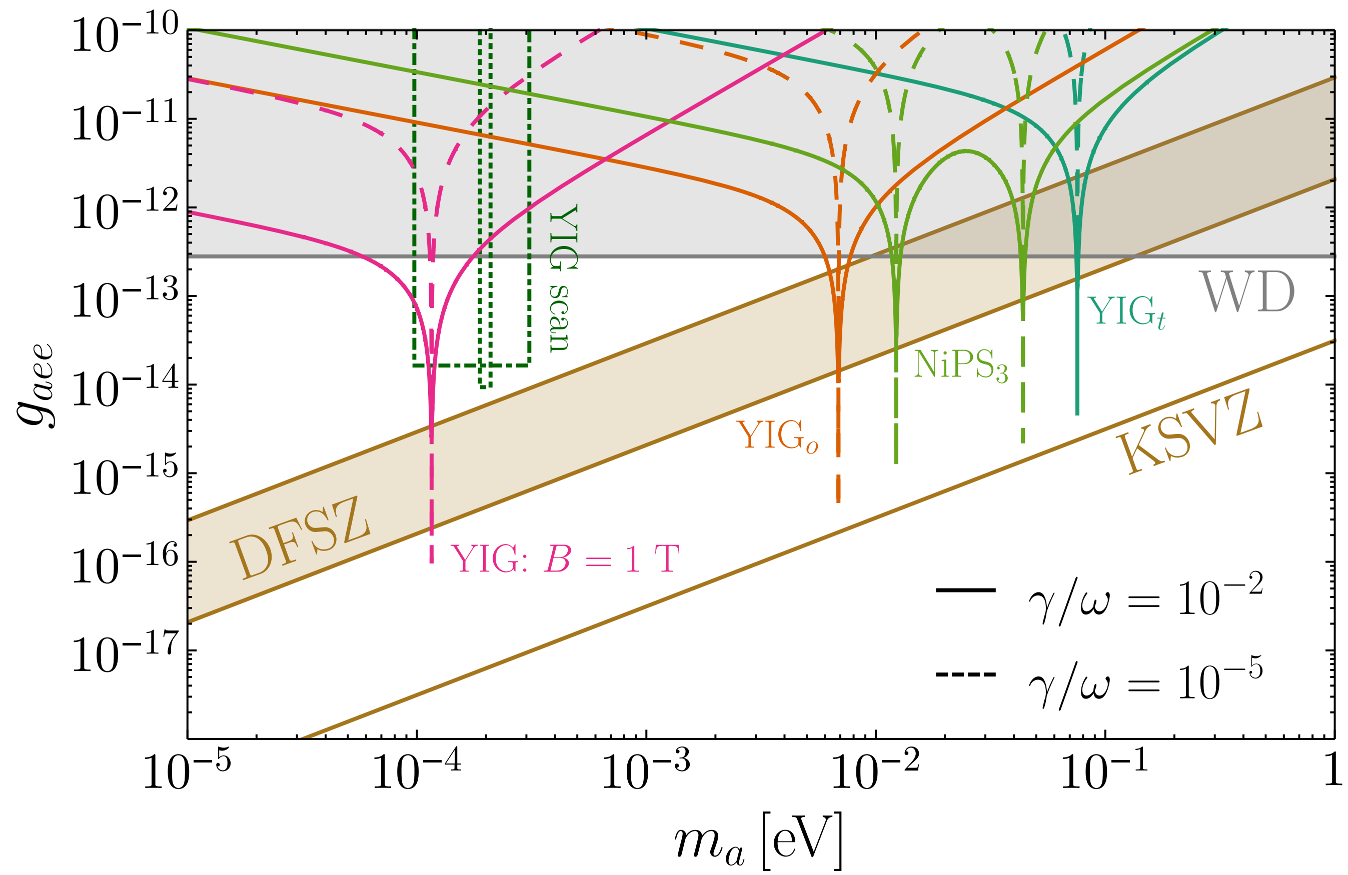
- We calculate *single* magnon excitation
- Agree with classical calculation in the relevant limit



- QUAX based on this idea, dating from ‘80s
- Requires lifting gapless magnon with external B-field

AXION DETECTION WITH SINGLE MAGNON

Trickle, Zhang, KZ 2005.10256



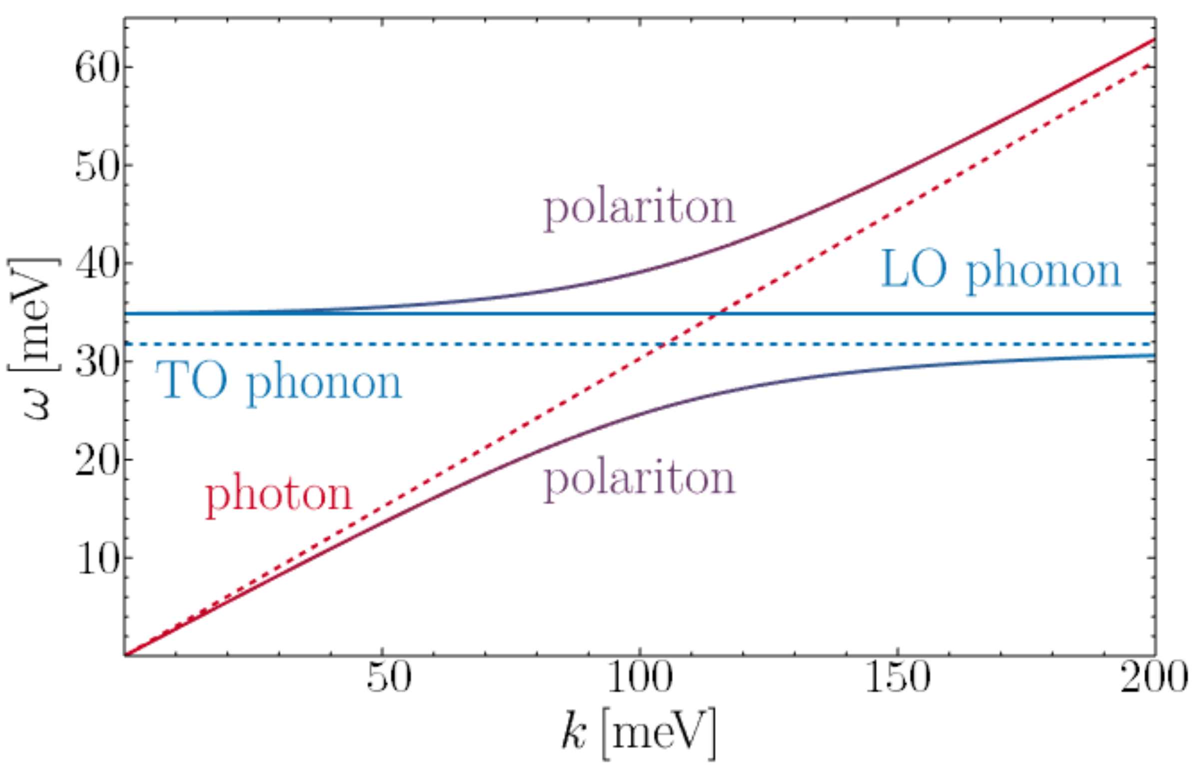
- There are other ways to lift the gapless mode
- Material anisotropy, non-degenerate g-factor. *toy-models* show good reach

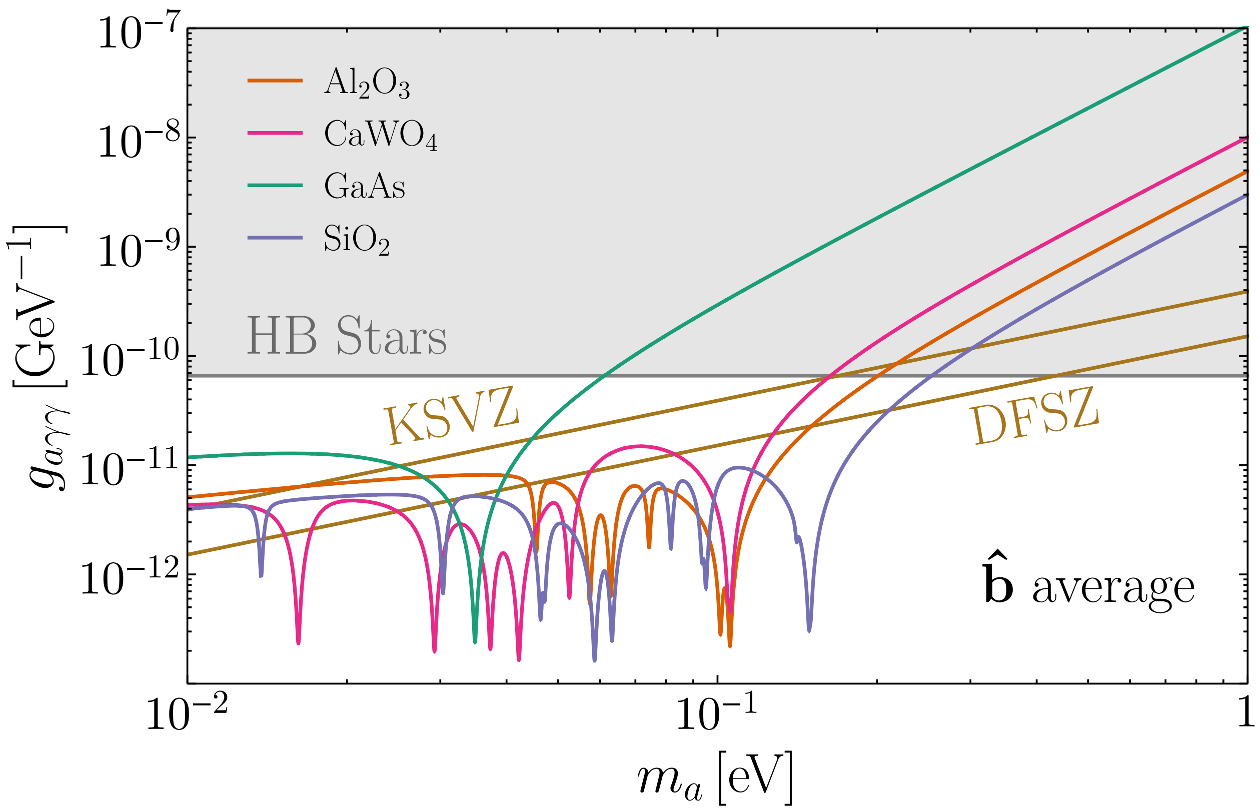
$$2\boldsymbol{s}_{lj} + \boldsymbol{\ell}_{lj} = g_j \boldsymbol{S}_{lj}$$

ABSORPTION OF BOSONIC DARK MATTER

Trickle, Zhang, KZ 2005.10256

- Phonon-polaritons also couple to the axion!



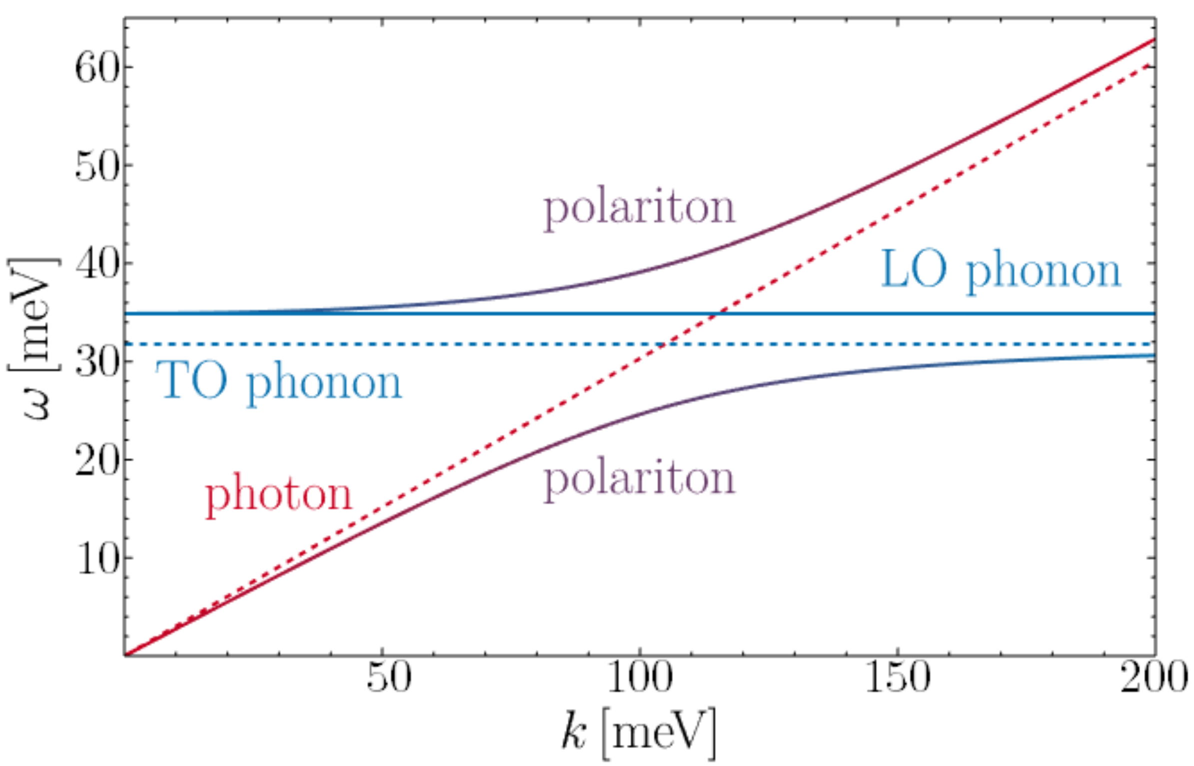


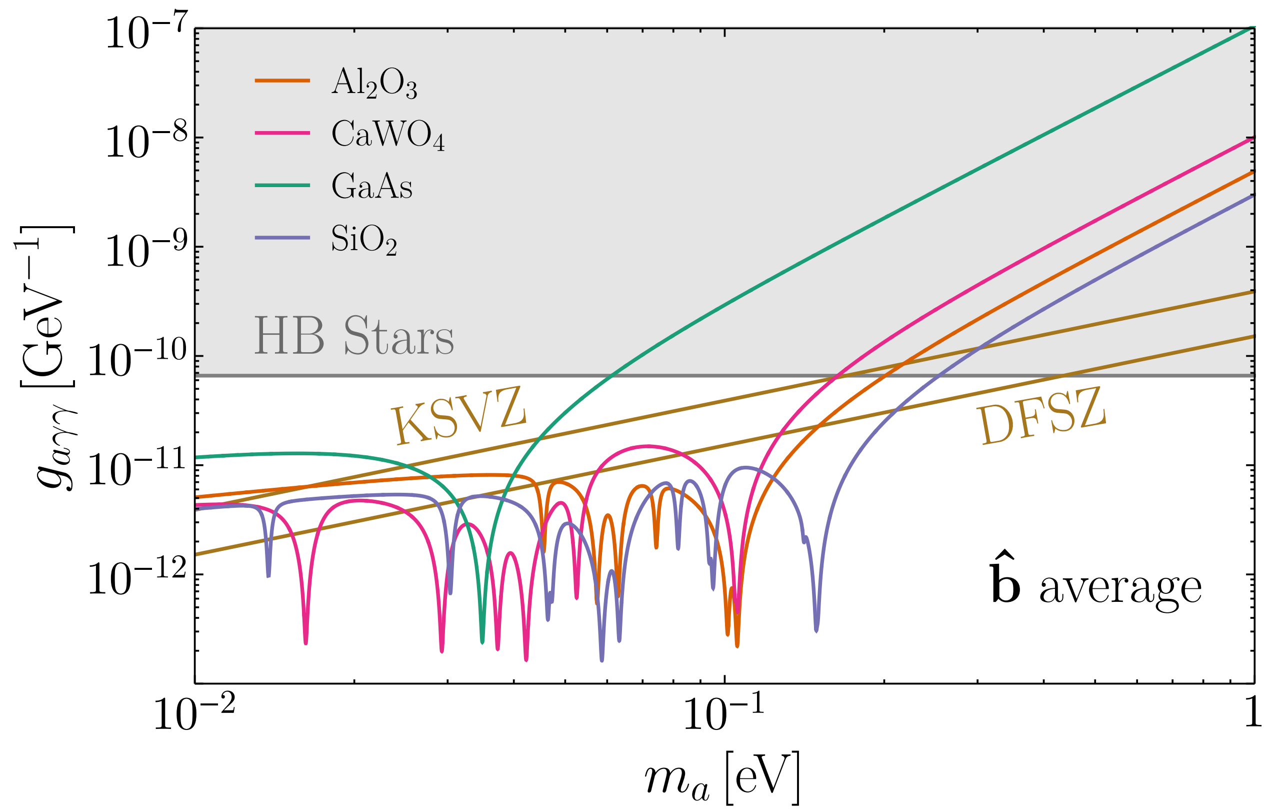
Process	Fundamental interaction	Effective coupling in Eq. (4)	Rate formula
Axion + B field → phonon	$a\boldsymbol{E}\cdot\boldsymbol{B}$	$\boldsymbol{f}_j = \frac{1}{\sqrt{2}}\, g_{a\gamma\gamma}\,\frac{e\sqrt{\rho_a}}{m_a}\,\boldsymbol{B}\cdot\boldsymbol{\varepsilon}_\infty^{-1}\cdot\boldsymbol{Z}_j^*$	Eq. (18)
Axion → magnon	$\nabla a\cdot\boldsymbol{s}_e$	$\boldsymbol{f}_j = -\frac{i}{\sqrt{2}}\, g_{aee}\,(g_j-1)\,\frac{\sqrt{\rho_a}}{m_e}\,\boldsymbol{v}_a$	Eq. (27)

ABSORPTION OF BOSONIC DARK MATTER

Trickle, Zhang, KZ 2005.10256

- The challenge here is single phonon detection in external B-field





Process	Fundamental interaction	Effective coupling in Eq. (4)	Rate formula
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SPIN-DEPENDENT VS SPIN-INDEPENDENT

Gresham, KZ 1401.3739

See Trickle, Zhang, KZ 2009.13534

- UV Complete theories tend to give rise to both spin-independent and spin-dependent interactions

Multipole DM models	Electric dipole	$V_\mu\left(g_\chi J^\mu_{\mathrm{edm},\chi} + g_\psi\left(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{\mathrm{mdm},\psi}\right)\right)$	$c_{11}^{(\psi)} = -\frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$	N
	Magnetic dipole	$V_\mu\left(g_\chi J^\mu_{\mathrm{mdm},\chi} + g_\psi\left(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{\mathrm{mdm},\psi}\right)\right)$	$c_1^{(\psi)} = \frac{\boldsymbol{q}^2}{4m_\chi^2}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_4^{(\psi)} = \widetilde{\mu}_\psi^{\mathrm{eff}}\frac{\boldsymbol{q}^2}{m_\chi m_\psi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_5^{(\psi)} = \frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_6^{(\psi)} = -\widetilde{\mu}_\psi^{\mathrm{eff}}\frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$	$N,\ S,\ L$
	Anapole	$V_\mu\left(g_\chi J^\mu_{\mathrm{ana},\chi} + g_\psi\left(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{\mathrm{mdm},\psi}\right)\right)$	$c_8^{(\psi)} = \frac{\boldsymbol{q}^2}{2m_\chi^2}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_9^{(\psi)} = -\widetilde{\mu}_\psi^{\mathrm{eff}}\frac{\boldsymbol{q}^2}{2m_\chi^2}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$	$N,\ S,\ L$

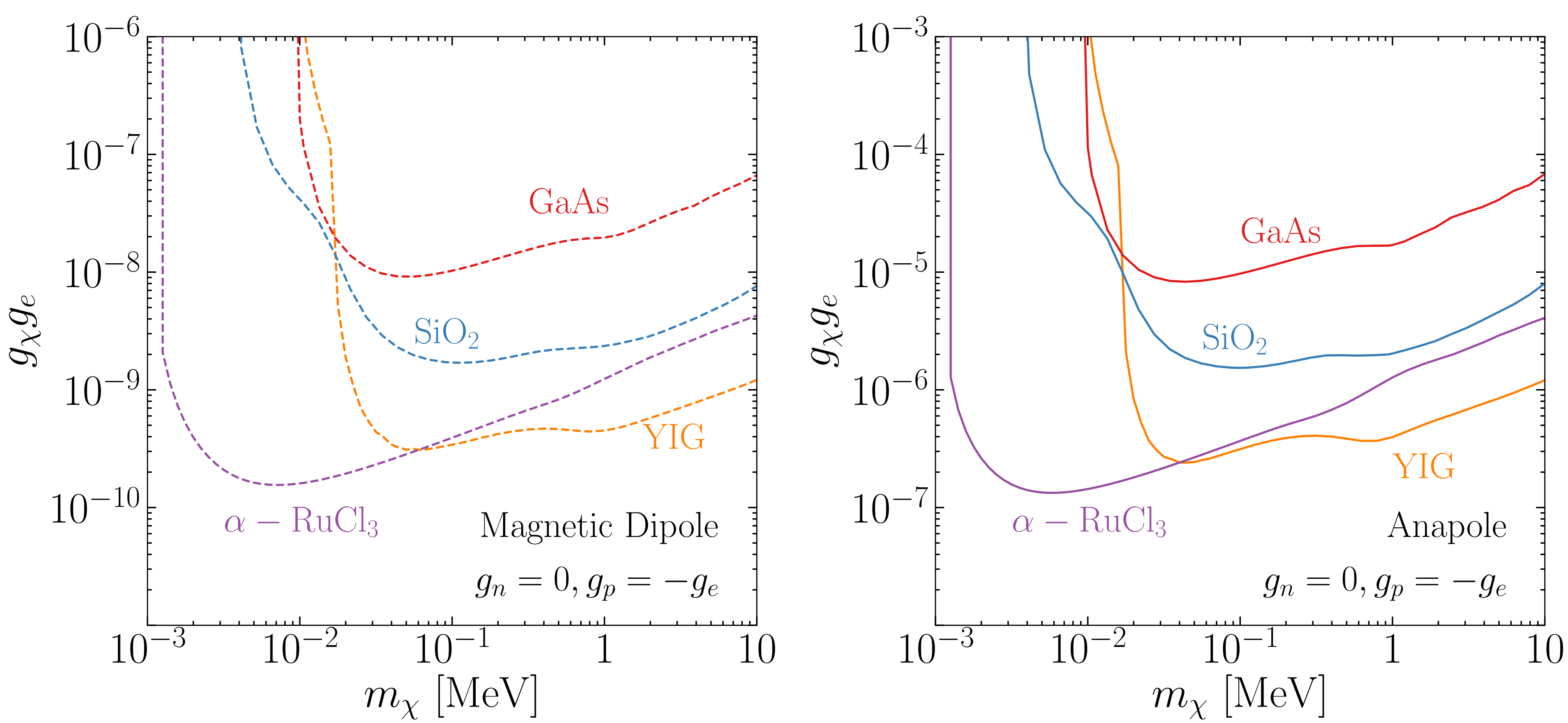
All have N response, probed by phonons

- Exception is pseudoscalar coupling on SM side

Other scalar mediators	P × S	$\phi\left(g_\chi J_{P,\chi} + g_\psi J_{S,\psi}\right)$	$c_{11}^{(\psi)} = \frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_\phi^2}$	N
	S × P	$\phi\left(g_\chi J_{S,\chi} + g_\psi J_{P,\psi}\right)$	$c_{10}^{(\psi)} = -\frac{g_\chi g_\psi}{\boldsymbol{q}^2+m_\phi^2}$	S
	P × P	$\phi\left(g_\chi J_{P,\chi} + g_\psi J_{P,\psi}\right)$	$c_6^{(\psi)} = \frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi}{\boldsymbol{q}^2+m_\phi^2}$	S

DIPOLE INTERACTIONS — COMPARE SI AND SD REACH

Multipole DM models	Electric dipole	$V_\mu\left(g_\chi J^\mu_{\mathrm{edm},\chi} + g_\psi\left(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{\mathrm{mdm},\psi}\right)\right)$	$c_{11}^{(\psi)} = -\frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$	N
	Magnetic dipole	$V_\mu\left(g_\chi J^\mu_{\mathrm{mdm},\chi} + g_\psi\left(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{\mathrm{mdm},\psi}\right)\right)$	$c_1^{(\psi)} = \frac{\boldsymbol{q}^2}{4m_\chi^2}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_4^{(\psi)} = \widetilde{\mu}_\psi^{\mathrm{eff}}\frac{\boldsymbol{q}^2}{m_\chi m_\psi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_5^{(\psi)} = \frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_6^{(\psi)} = -\widetilde{\mu}_\psi^{\mathrm{eff}}\frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$	$N,\ S,\ L$
	Anapole	$V_\mu\left(g_\chi J^\mu_{\mathrm{ana},\chi} + g_\psi\left(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{\mathrm{mdm},\psi}\right)\right)$	$c_8^{(\psi)} = \frac{\boldsymbol{q}^2}{2m_\chi^2}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$ $c_9^{(\psi)} = -\widetilde{\mu}_\psi^{\mathrm{eff}}\frac{\boldsymbol{q}^2}{2m_\chi^2}\frac{g_\chi g_\psi^{\mathrm{eff}}}{\boldsymbol{q}^2+m_V^2}$	$N,\ S,\ L$



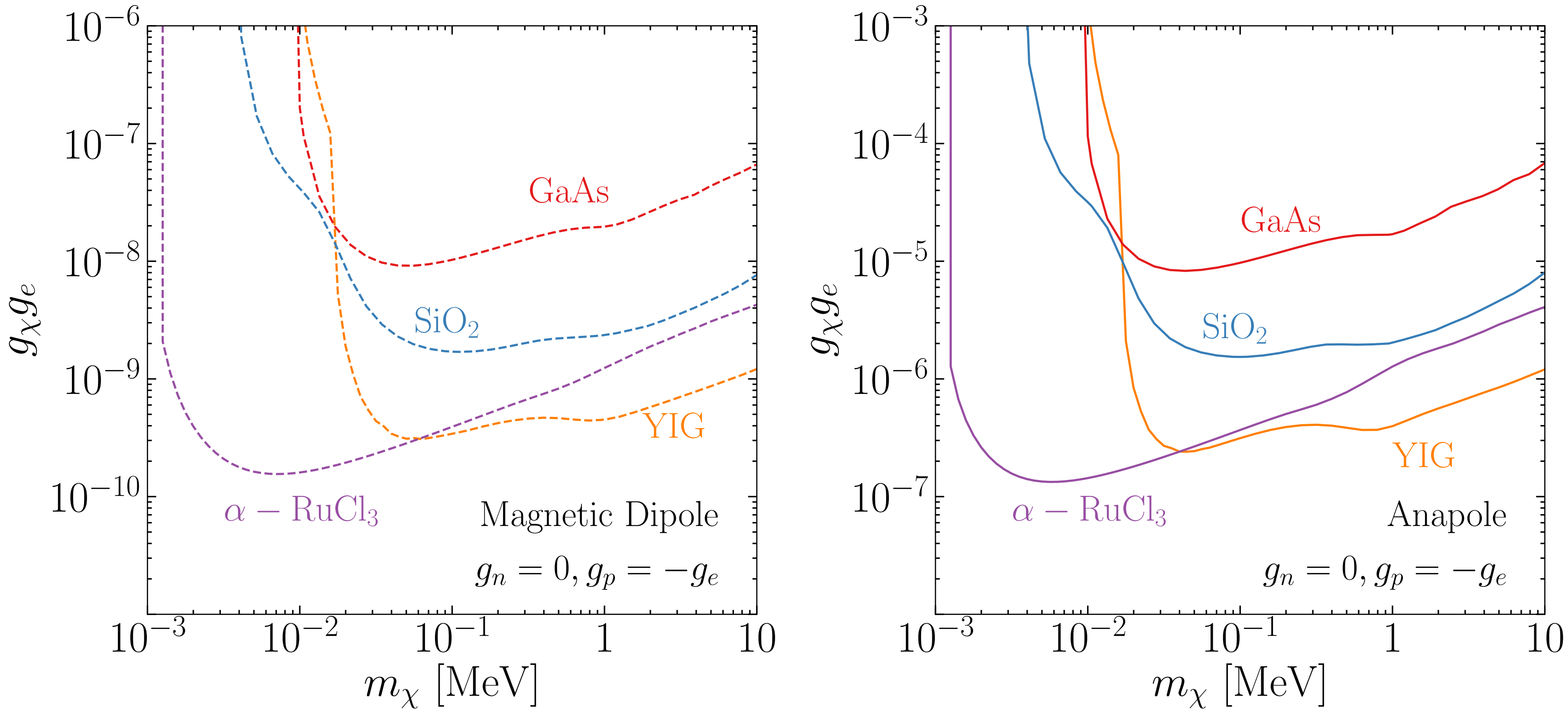
Polar crystals - N response

YIG - S response

Kitaev material - S&L

DIPOLE INTERACTIONS — COMPARE SI AND SD REACH

$$\frac{R^{\text{mdm}}_{\text{phonon}}}{R^{\text{mdm}}_{\text{magnon}}} \sim \frac{R^{\text{ana}}_{\text{phonon}}}{R^{\text{ana}}_{\text{magnon}}} \sim \frac{\mathcal{Q}\, m_{\text{cell}} m_e^2 v^2}{S_{\text{ion}} m_p^2 \cdot 1\,\text{meV}} \sim 10^{-4}\left(\frac{\mathcal{Q}}{1.4\times 10^{-7}}\right)$$



Polar crystals - N response

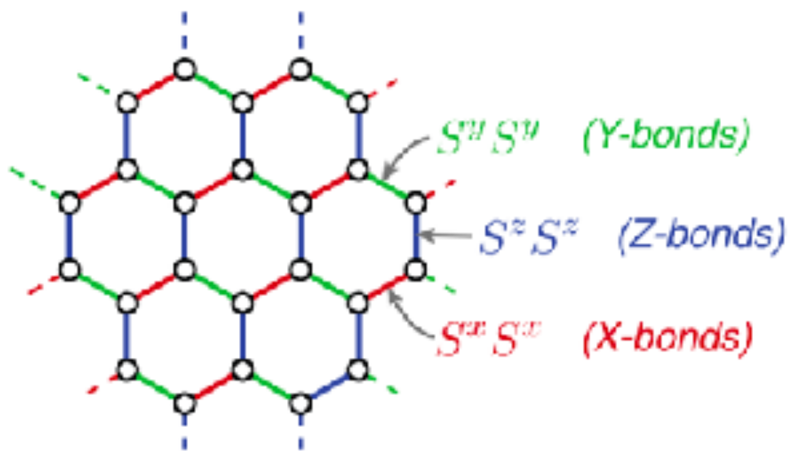
YIG - S response

Kitaev material - S&L

SPIN-ORBIT MATERIALS

See Trickle, Zhang, KZ 2009.13534

- Angular momentum — spin-orbit-entangled Mott insulator
- Effective spins $\lambda_{S,j} = -\frac{1}{3},\ \lambda_{L,j} = -\frac{4}{3}$

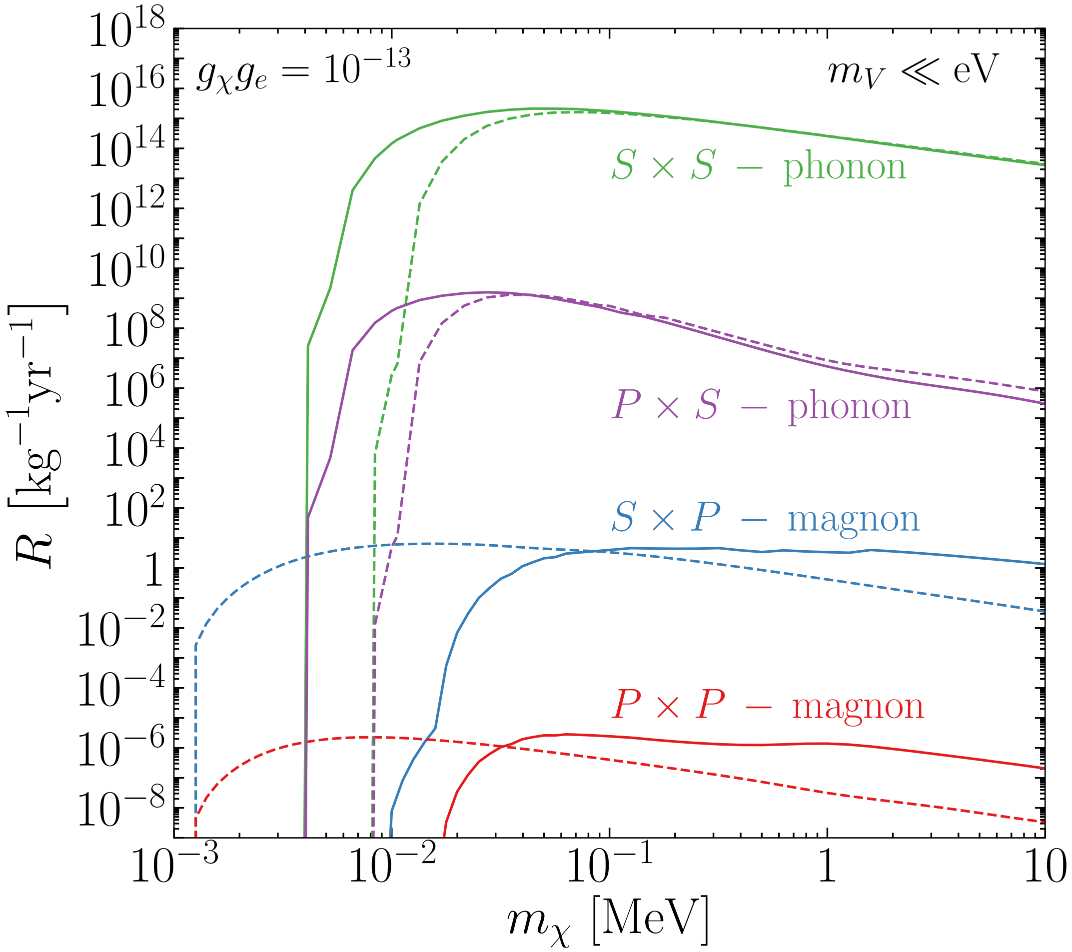


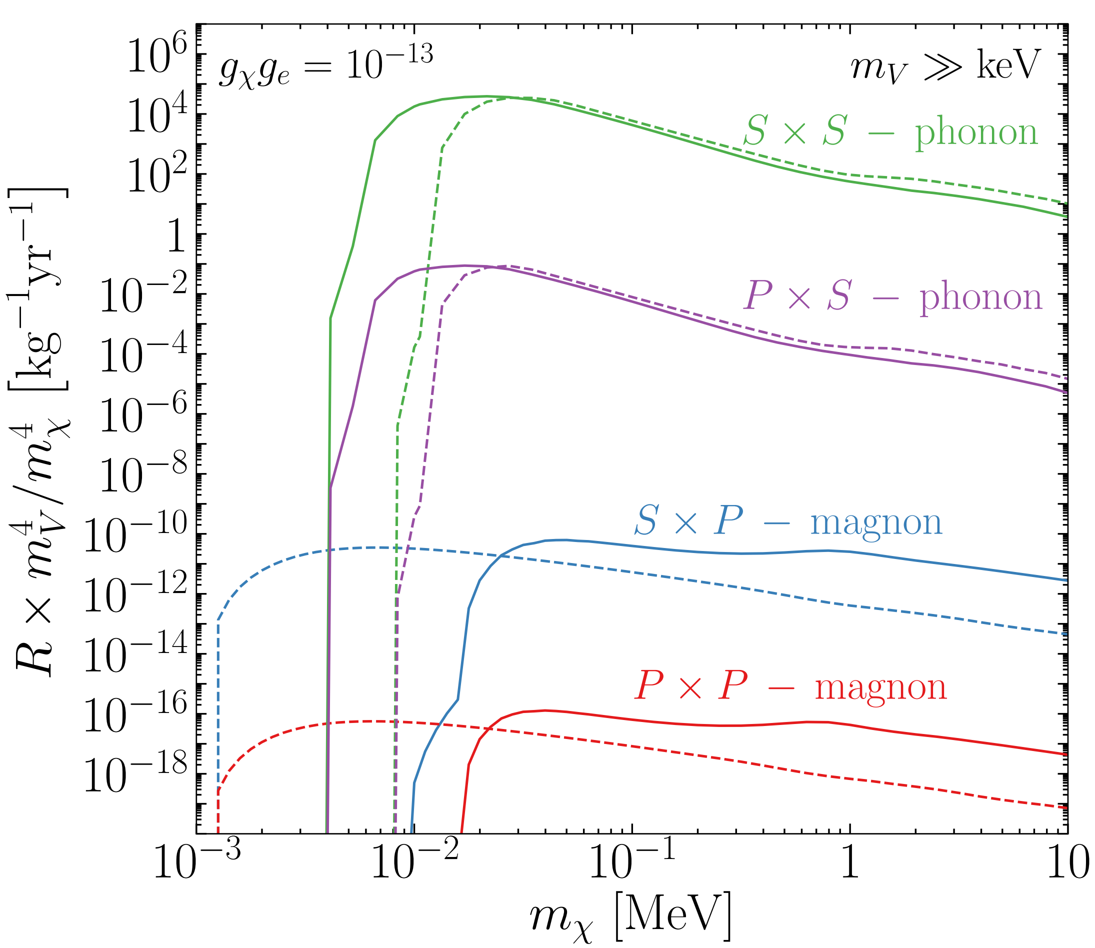
α-$RuCl_3$

- Kitaev material with bond directional coupling, Antiferromagnetic order
- All magnons (4 branches) are gapped
- Theoretical material

PSEUDOSCALAR INTERACTIONS

Other scalar mediators	P × S	$\phi\left(g_\chi J_{P,\chi} + g_\psi J_{S,\psi}\right)$	$c_{11}^{(\psi)} = \frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi^{\text{eff}}}{\boldsymbol{q}^2 + m_\phi^2}$	N
	S × P	$\phi\left(g_\chi J_{S,\chi} + g_\psi J_{P,\psi}\right)$	$c_{10}^{(\psi)} = -\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_\phi^2}$	S
	P × P	$\phi\left(g_\chi J_{P,\chi} + g_\psi J_{P,\psi}\right)$	$c_{6}^{(\psi)} = \frac{m_\psi}{m_\chi} \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_\phi^2}$	S

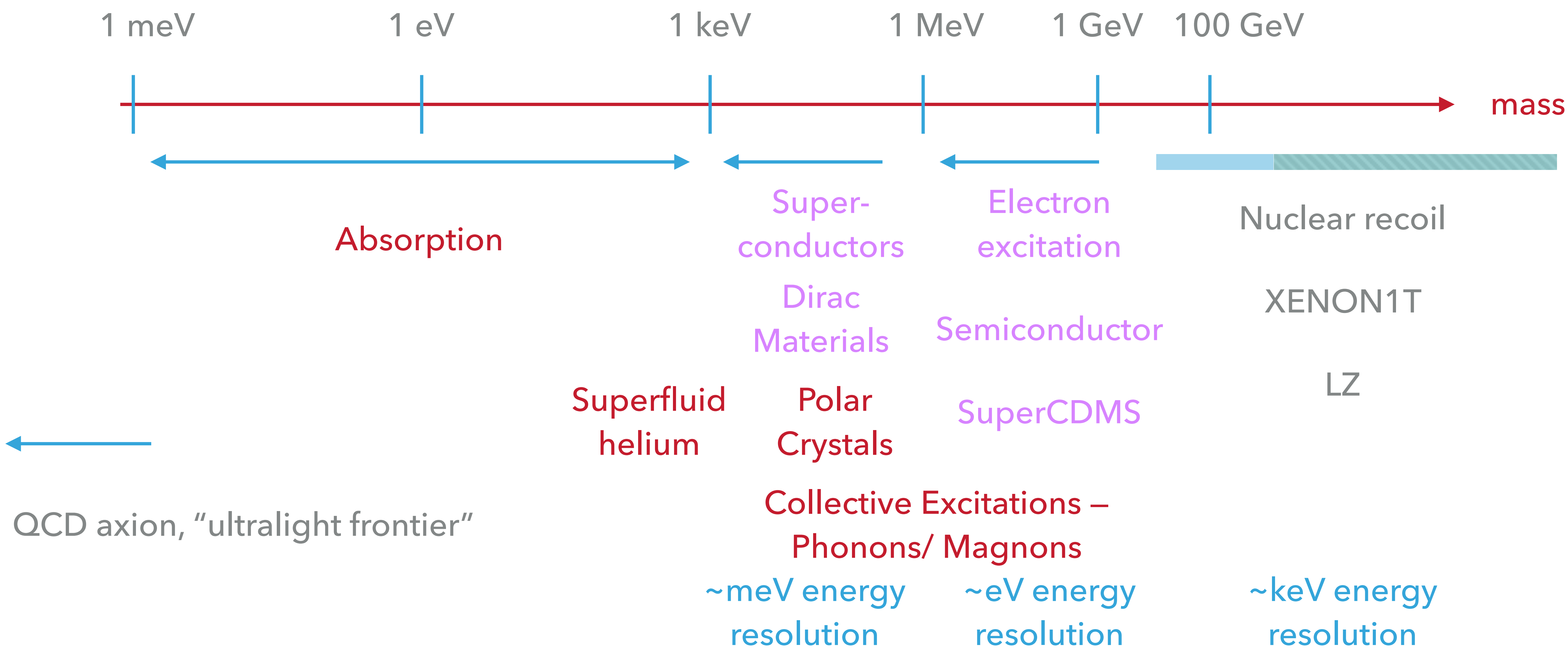




DM-PHONON, DM-ELECTRON DETECTION RATE CALCULATOR

- Codes are publicly available
- **phonodark.caltech.edu, exceed-dm.caltech.edu**
- Code is the work of Tanner Trickle for his thesis
- Accumulates theoretical reach for broad range of interactions (EFT) and materials (26). Also includes daily modulation.
- Accumulates theoretical work starting in 2015 -> 2017 -> 2022 w/Knapen, Lin, Trickle, Zhang

COLLECTIVE PHENOMENA IN MATERIALS



EXPERIMENTAL PROSPECTS

- Sensor to detect phonons coupled to DM "absorber"
- Zero-field read-out of phonons
- Now funded by DoE — TESSERACT (TES with Sub-EV Resolution and Cryogenic Targets)
- For a polar crystal target — Sub-eV Polar Interactions Cryogenic Experiment (SPICE). For superfluid helium, HeRaLD

Snowmass2021 - Letter of Interest

The TESSERACT Dark Matter Project

Thematic Areas:

- IF1 Quantum Sensors
- IF8 Noble Elements
- CF1 Dark Matter: Particle-like
- CF2 Dark Matter: Wavelike

Contact Information:
Dan McKinsey (LBNL and UC Berkeley) [daniel.mckinsey@berkeley.edu]:
TESSERACT Collaboration

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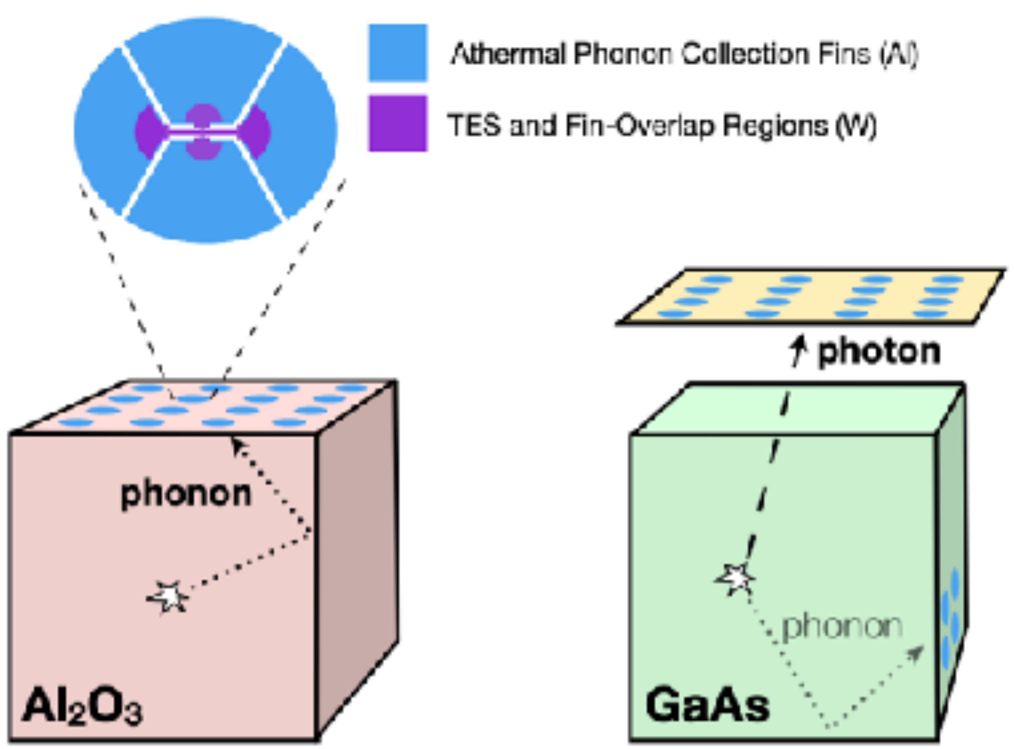

SUMMARY

- Electronic excitation and collective excitations provide a path to detect light DM
- Theory framework for computing DM interaction rates in materials is now well-developed
- New experiments such as TESSERACT/SPICE have broad discovery potential for light DM
- Single magnon detection would offer reach to the QCD axion as well as spin-dependent dark matter, but experimental prospects for *single magnon detection* are unclear. Welcome to discuss ideas!