New ideas in light dark matter direct detection

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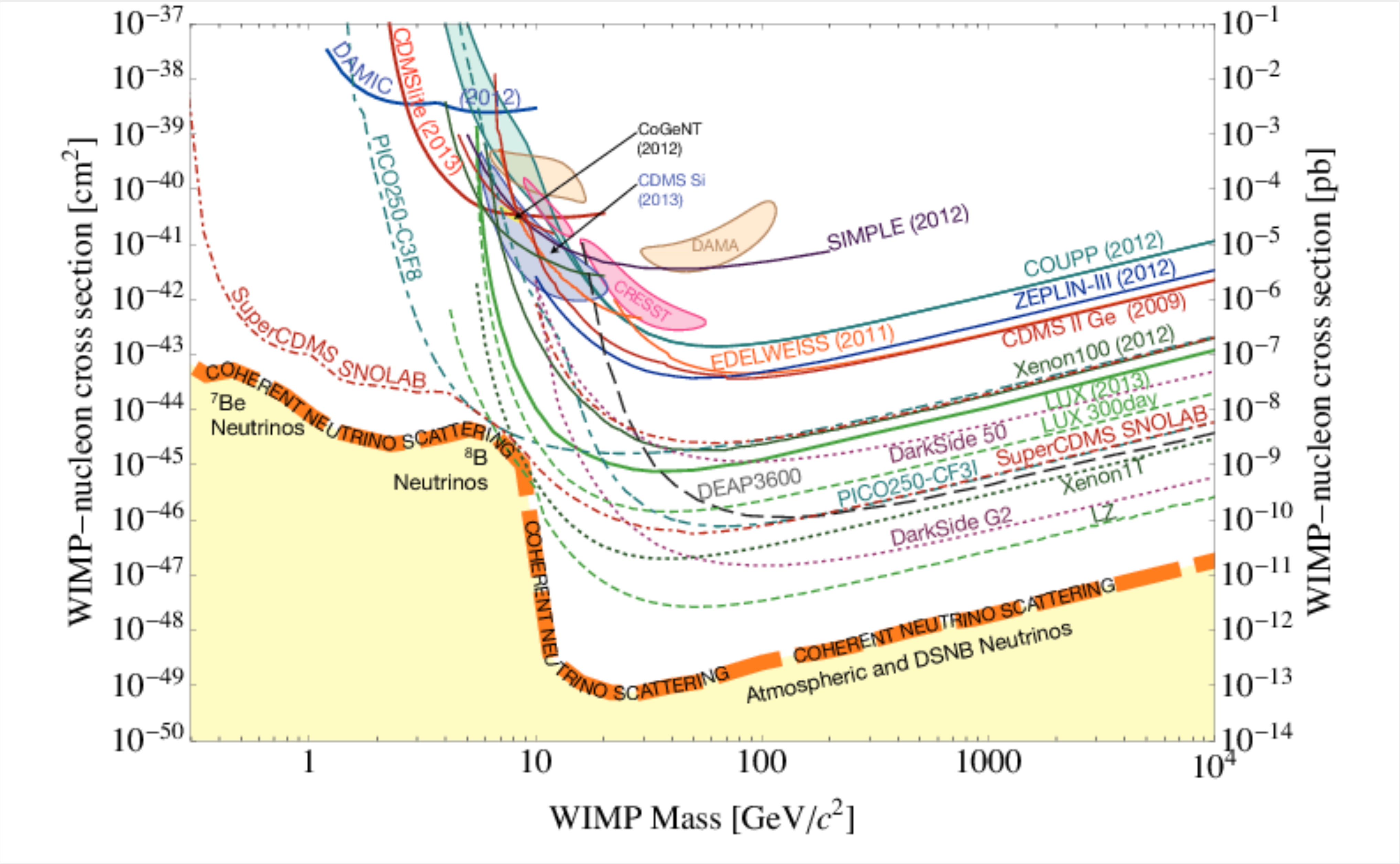
Tanner Trickle, ZZ, Kathryn Zurek, arXiv: 1905.13744.
Tanner Trickle, ZZ, Kathryn Zurek, Katherine Inzani, Sinead Griffin, arXiv: 1910.08092.
Sinead Griffin, Katherine Inzani, Tanner Trickle, ZZ, Kathryn Zurek 1910.10716.

IPMU, Jan. 2020

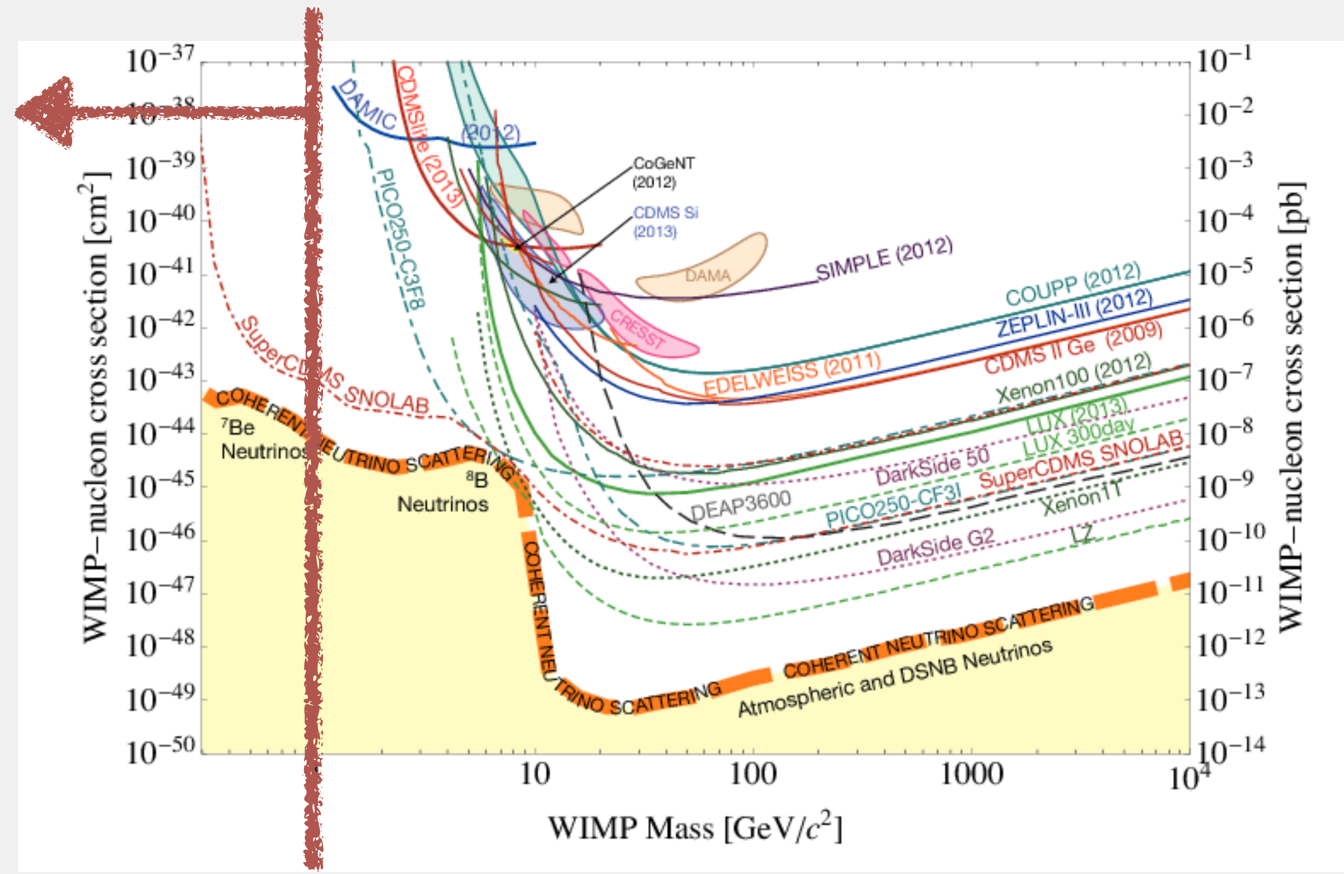
Dark matter direct detection

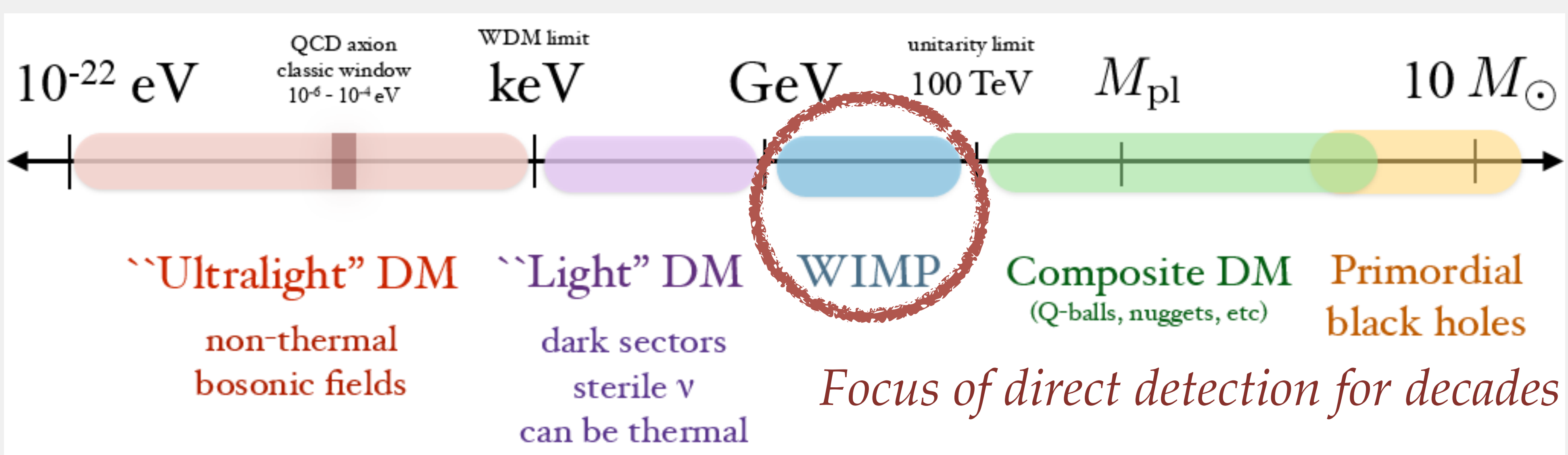


Dark matter direct detection

Many well-motivated theories predict **sub-GeV** dark matter (asymmetric DM, SIMP, etc.).

They are beyond reach of conventional WIMP searches, so we need new ideas.

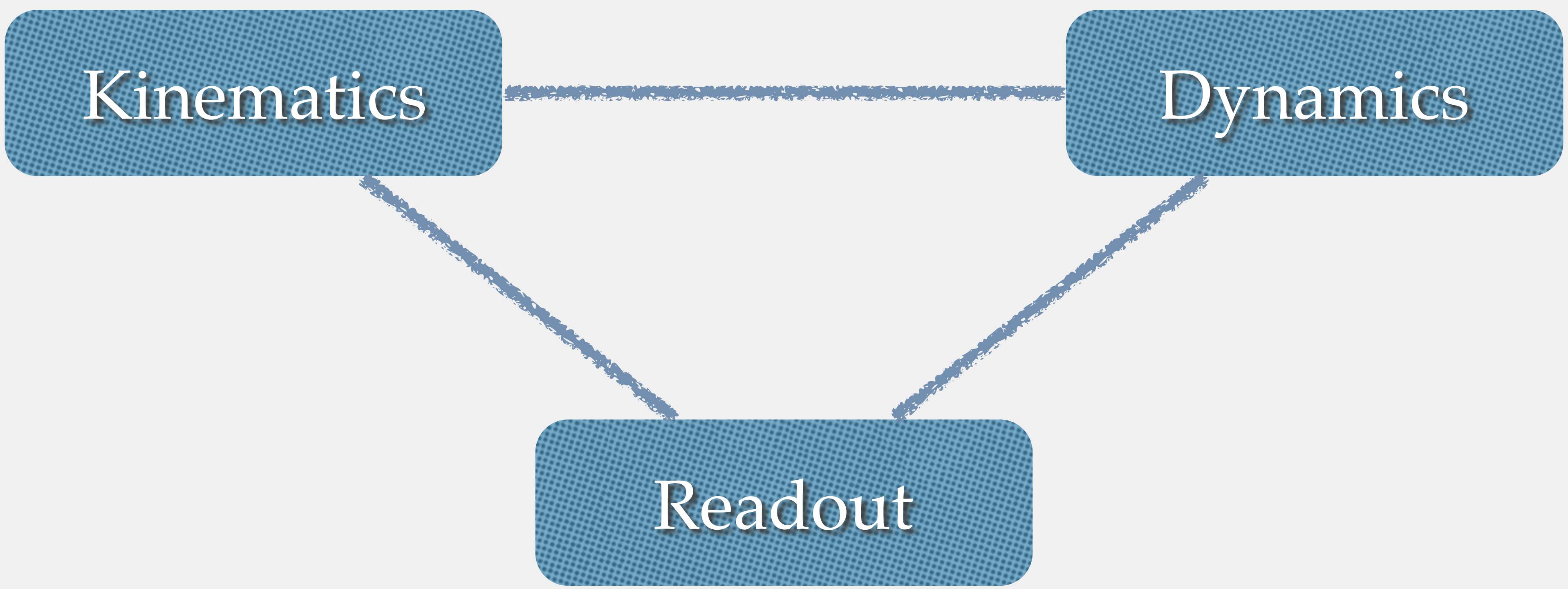




Key words when pursuing new ideas

What kind of excitations can match DM scattering kinematics? (Energy, momentum conservation)

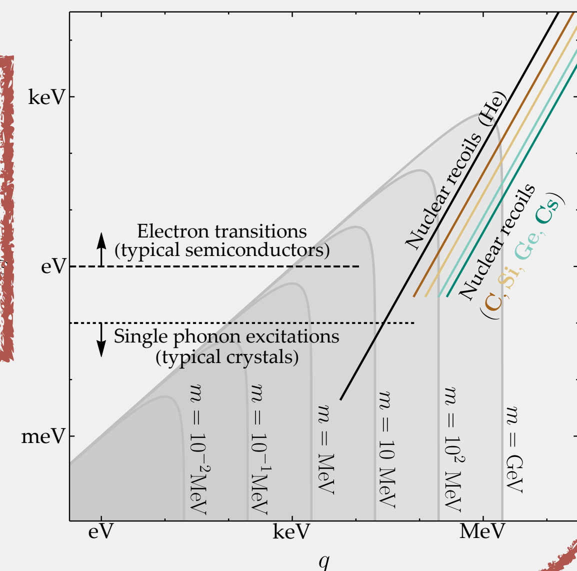
What kind of excitations couple strongly to the DM given a particle physics model?



Is there an experimental scheme to efficiently read out the excitations?

Outline of the talk

Kinematic matching (identify new detection channels, especially in **AMO/CM systems**)



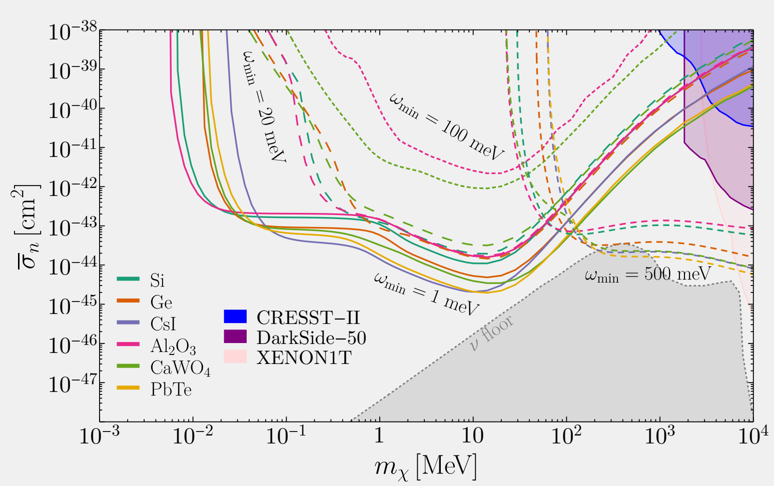
Theoretical framework for multi-channel direct detection (rate calculation from **first principles**)

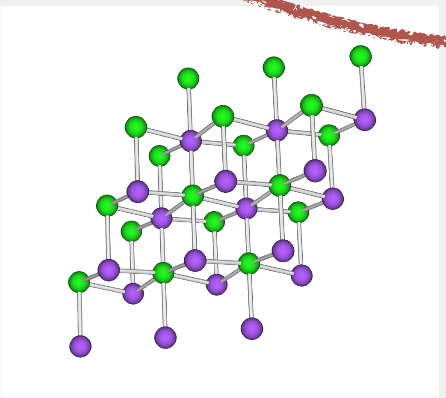
Kinematics

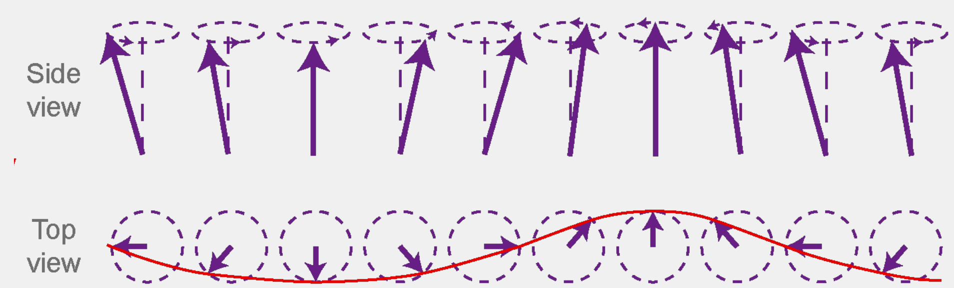
Dynamics

Phonons (spin-independent)
[R&D in progress]

Magnons (spin-dependent)
[new theoretical proposal]

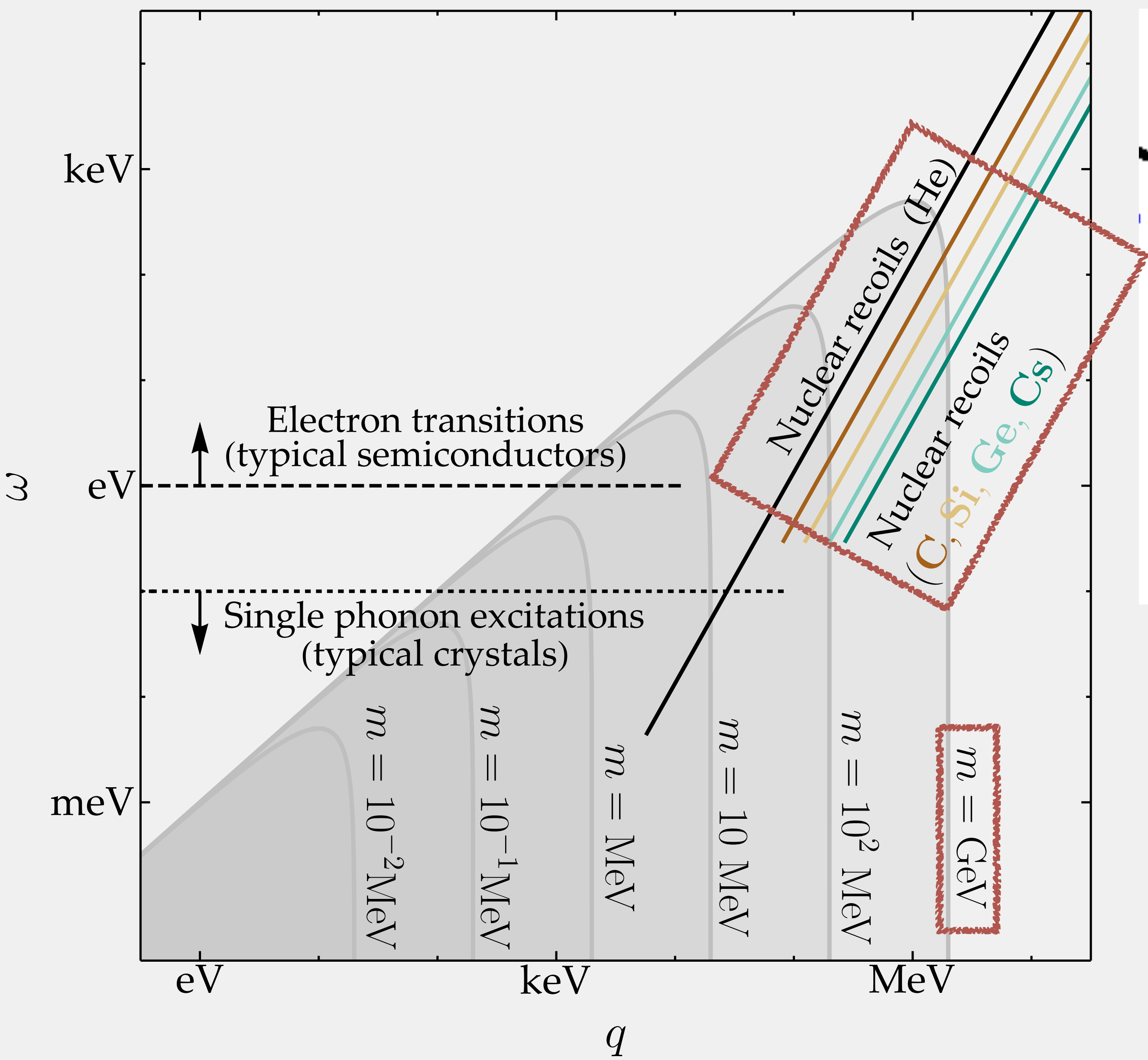


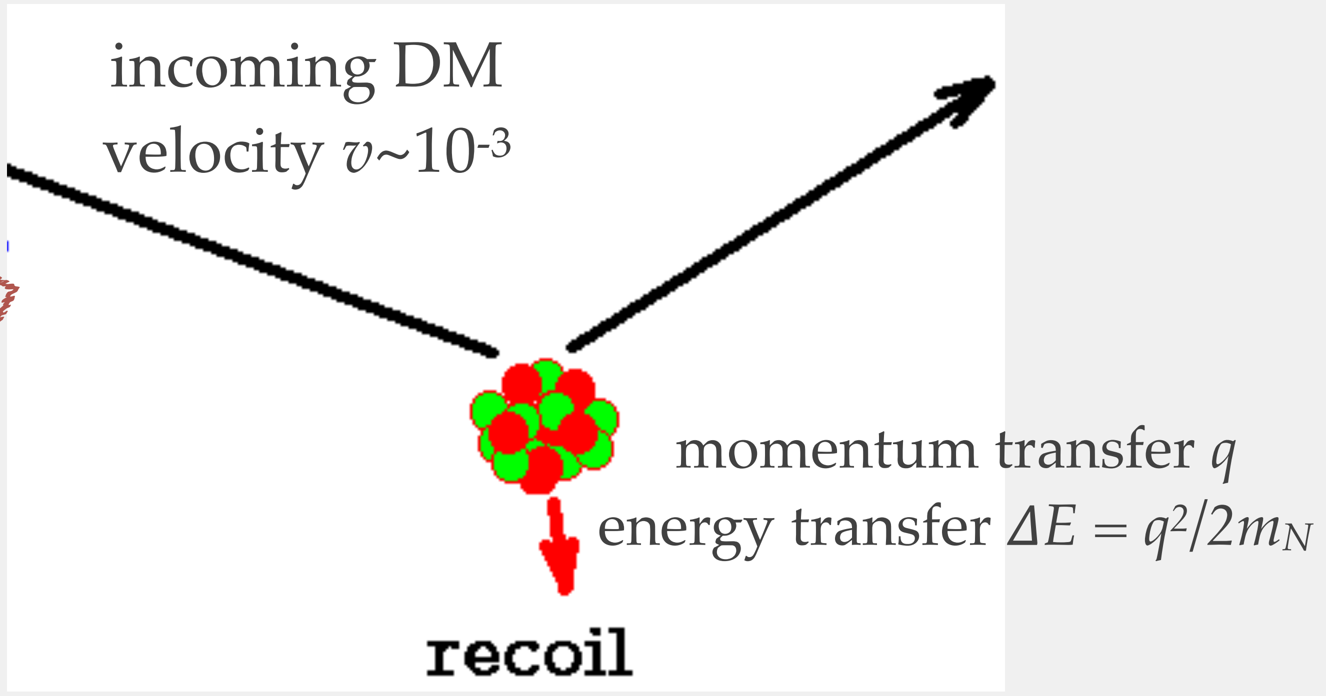




Kinematic matching

$$\Delta E = \frac{1}{2m_\chi}\left((m_\chi v)^2 - (m_\chi \boldsymbol{v} - \boldsymbol{q})^2\right) \leq vq - \frac{q^2}{2m_\chi}$$





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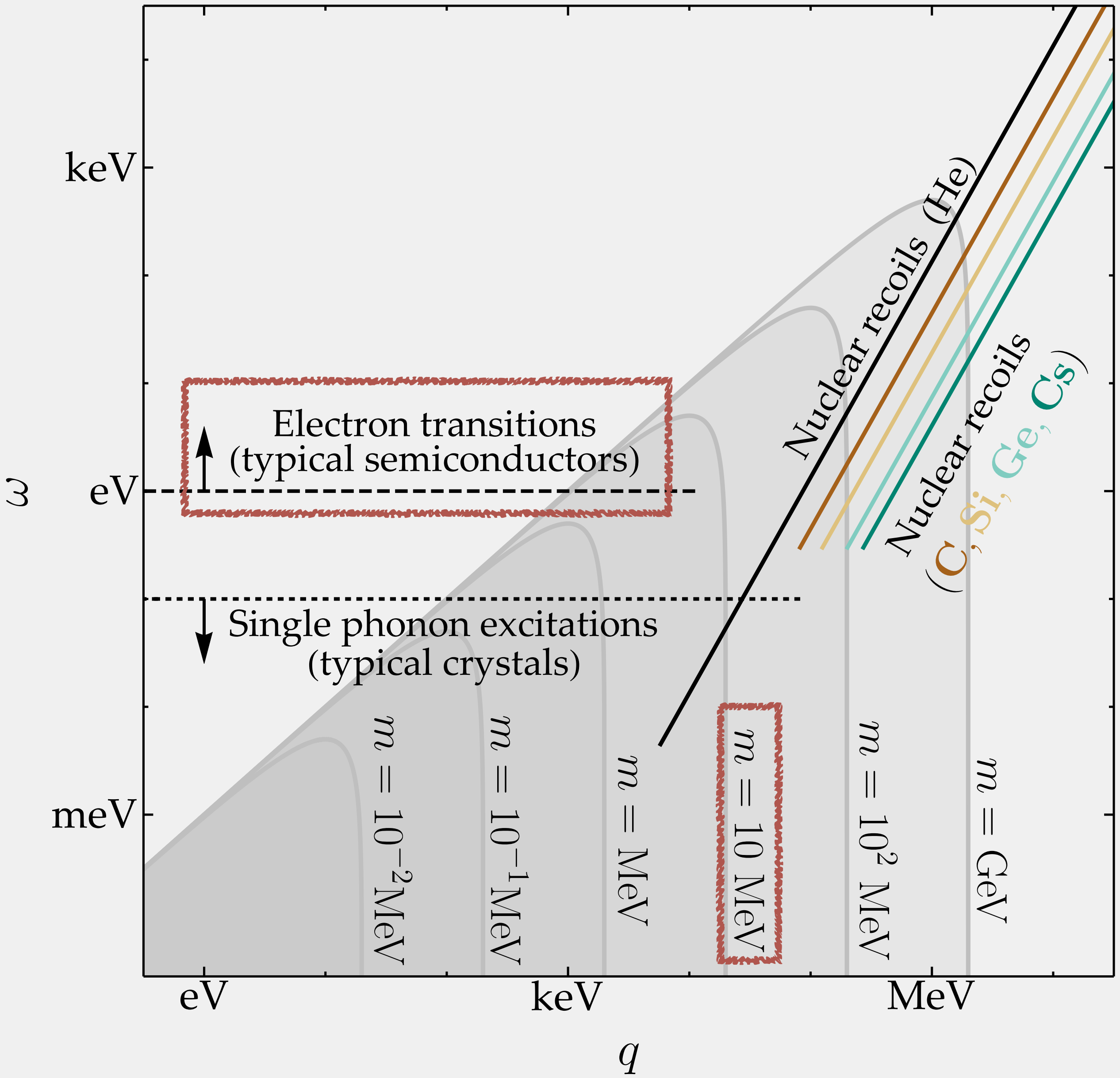
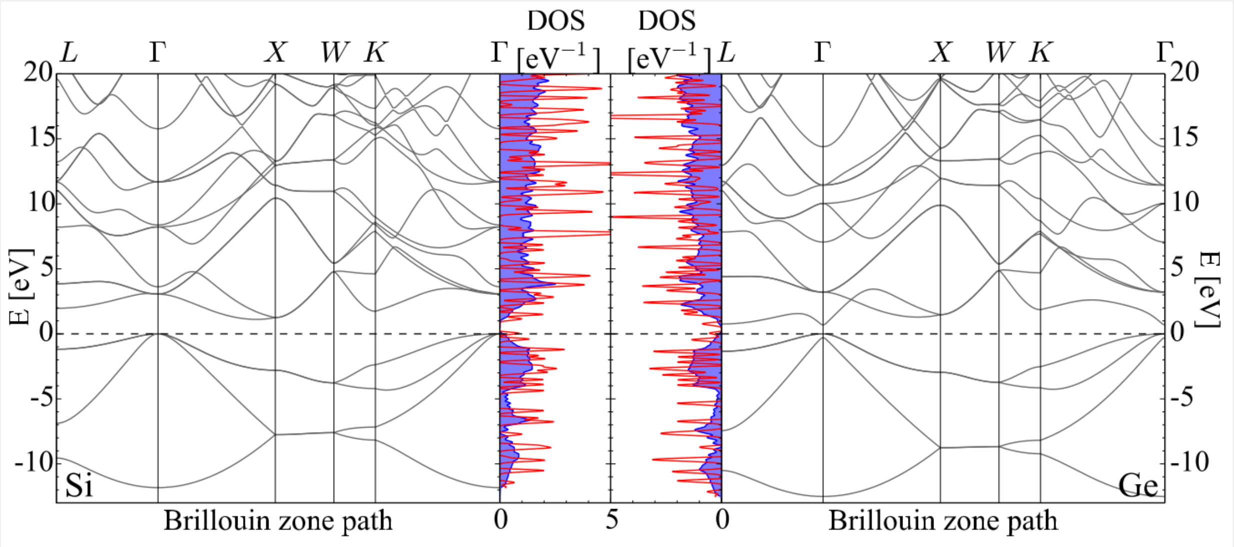


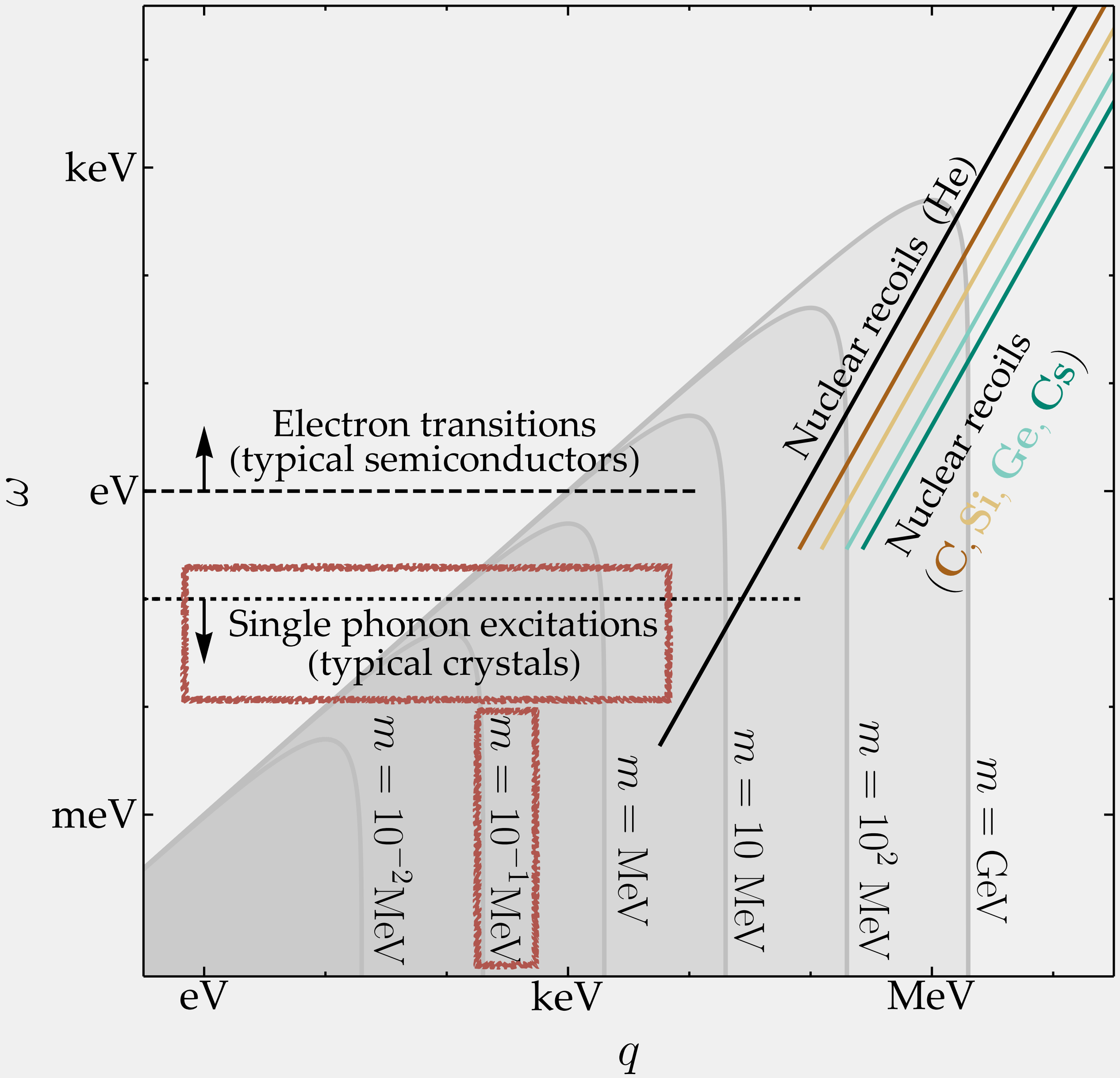
Band gap: O(eV).



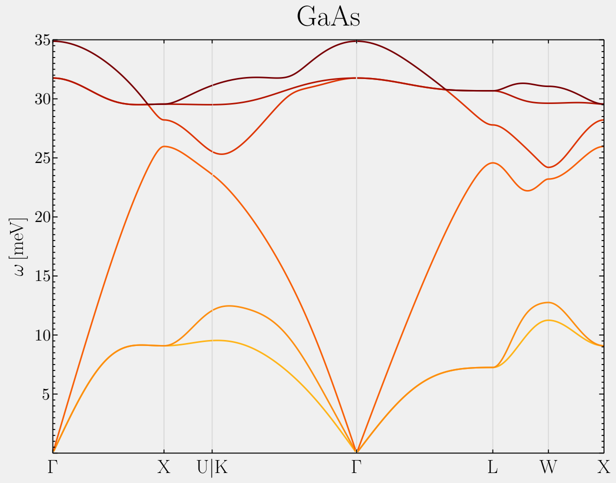
Essig, Mardon, Volansky, 1108.5383.
Graham, Kaplan, Rajendran, Walters, 1203.2531.
Lee, Lisanti, Mishra-Sharma, Safdi, 1508.07361.
Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu, 1509.01598.
Derenzo, Essig, Massari, Soto, Yu, 1607.01009.
Hochberg, Lin, Zurek, 1608.01994.
Bloch, Essig, Tobioka, Volansky, Yu, 1608.02123.
Essig, Volansky, Yu, 1703.00910.
Kurinsky, Yu, Hochberg, Cabrera, 1901.07569.
Emken, Essig, Kouvaris, Sholapurka, 1905.06348.
Griffin, Inzani, Trickle, ZZ, Zurek, 1910.08092, 1910.10716, in prep.

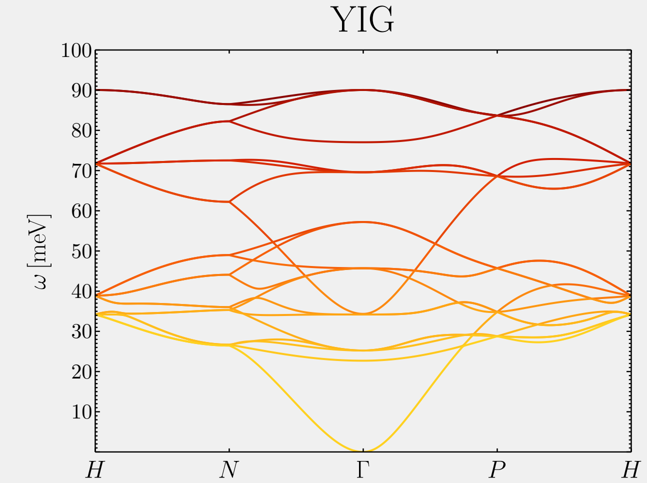
Kinematic matching

$$\Delta E = \frac{1}{2m_\chi}\left((m_\chi v)^2 - (m_\chi \boldsymbol{v} - \boldsymbol{q})^2\right) \leq vq - \frac{q^2}{2m_\chi}$$



Collective excitations, e.g. phonons/magnons in crystals with energies up to O(100meV).





Knapen, Lin, Pyle, Zurek, 1712.06598.
Griffin, Knapen, Lin, Zurek, 1807.10291.
Trickle, ZZ, Zurek, 1905.13744.
Griffin, Inzani, Trickle, ZZ, Zurek, 1910.08092, 1910.10716.
Campbell-Deem, Cox, Knapen, Lin, Melia, 1911.03482.

Kinematic matching

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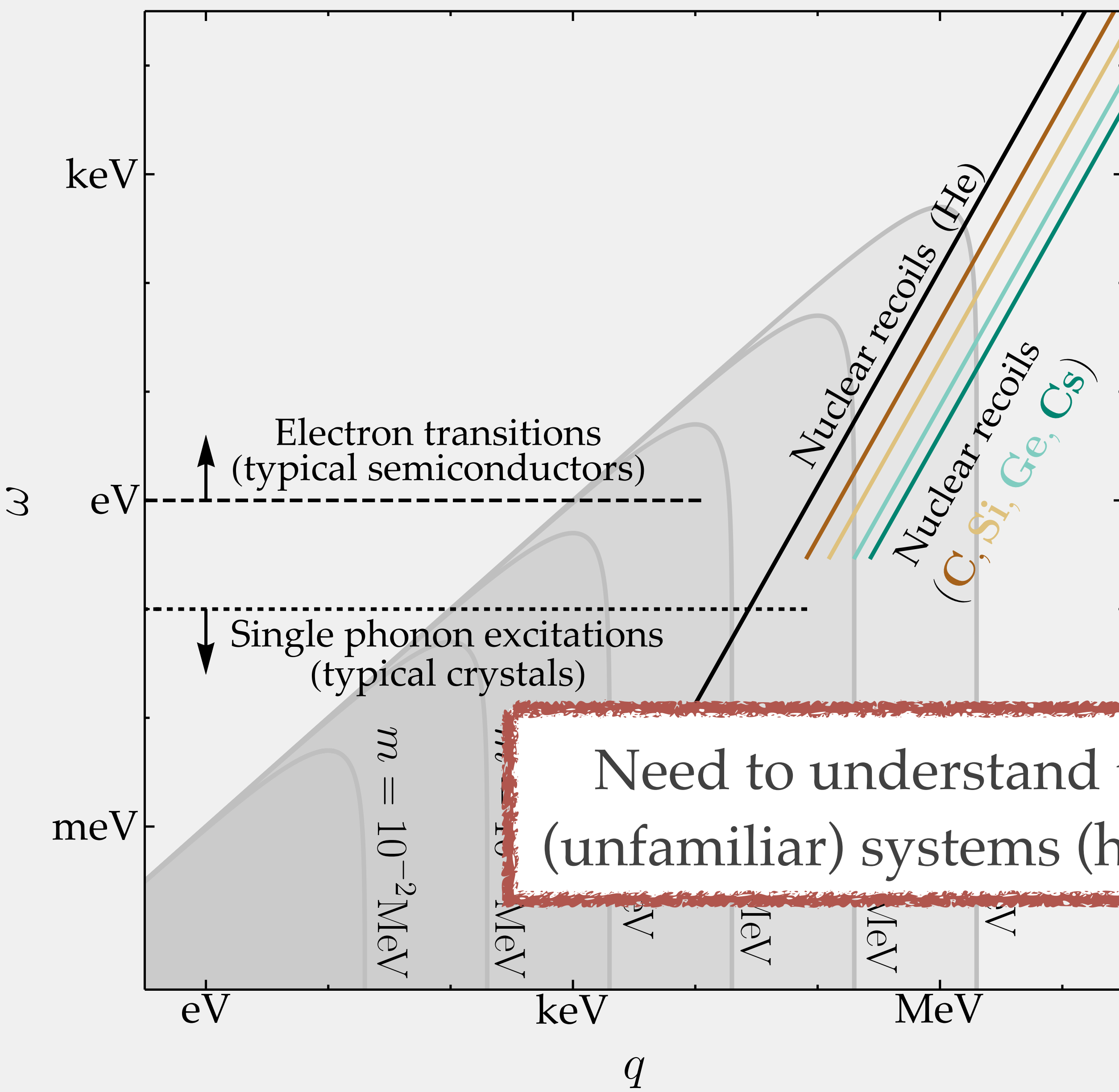


Other ideas at the interface with AMO/condensed matter:

molecules [Essig, Mardon, Slone, Volansky, 1608.02940] [Arvanitaki, Dimopoulos, Van Tilburg, 1709.05354] [Essig, Perez-Rios, Ramani, Slone, 1907.07682]

crystalline defects [Budnik, Chesnovsky, Slone, Volansky, 1705.03016]

graphene [Hochberg, Kahn, Lisanti, Tully, Zurek, 1606.08849]

superconductors [Hochberg, Zhao, Zurek, 1504.07237] [Hochberg, Pyle, Zhao, Zurek, 1512.04533] [Hochberg, Lin, Zurek, 1604.06800]

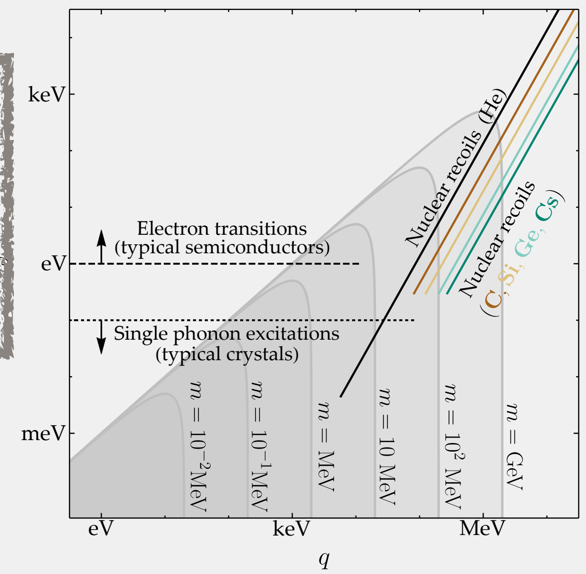
…k, 1604.08206] [Knapen, …a, Esposito, Pelosa, …elosa, 1907.10635]

Need to understand the dynamics of these (unfamiliar) systems (how they couple to DM).

Dirac materials [Hochberg et al, 1708.08929] [Coskuner, Mitridate, Olivares, Zurek, 1909.09170] [Geilhufe, Kahlhoefer, Winkler, 1910.02091]

Outline of the talk

Kinematic matching (identify new detection channels, especially in **AMO/CM systems**)



Theoretical framework for multi-channel direct detection (rate calculation from **first principles**)

Kinematics

Dynamics

Theoretical framework

- Assume spin-independent (SI) interactions.
- For given DM mass and incoming velocity,

$$\Gamma = \int \frac{d^3q}{(2\pi)^3} \, |\mathcal{M}|^2 \, S(\boldsymbol{q}, \omega)\Big|_{\omega = \boldsymbol{q}\cdot\boldsymbol{v} - \frac{q^2}{2m_\chi}}$$

  - $\mathcal{M}$: particle-level $\chi\psi \to \chi\psi$ matrix element (ψ is SM particle).
  - $S(\boldsymbol{q}, \omega)$: **dynamic structure factor** (target response to an energy-momentum transfer).

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

$$\mathcal{F}_T(\boldsymbol{q}) = \frac{f_p(\boldsymbol{q})\, \widetilde{n}_p(-\boldsymbol{q}) + f_n(\boldsymbol{q})\, \widetilde{n}_n(-\boldsymbol{q}) + f_e(\boldsymbol{q})\, \widetilde{n}_e(-\boldsymbol{q})}{f_\psi^0}$$

DM couplings to proton, neutron, electron

Theoretical framework

$$\Gamma = \int \frac{d^3q}{(2\pi)^3} \, |\mathcal{M}|^2 \, S(\boldsymbol{q},\omega)\Big|_{\omega=\boldsymbol{q}\cdot\boldsymbol{v}-\frac{q^2}{2m_\chi}}$$

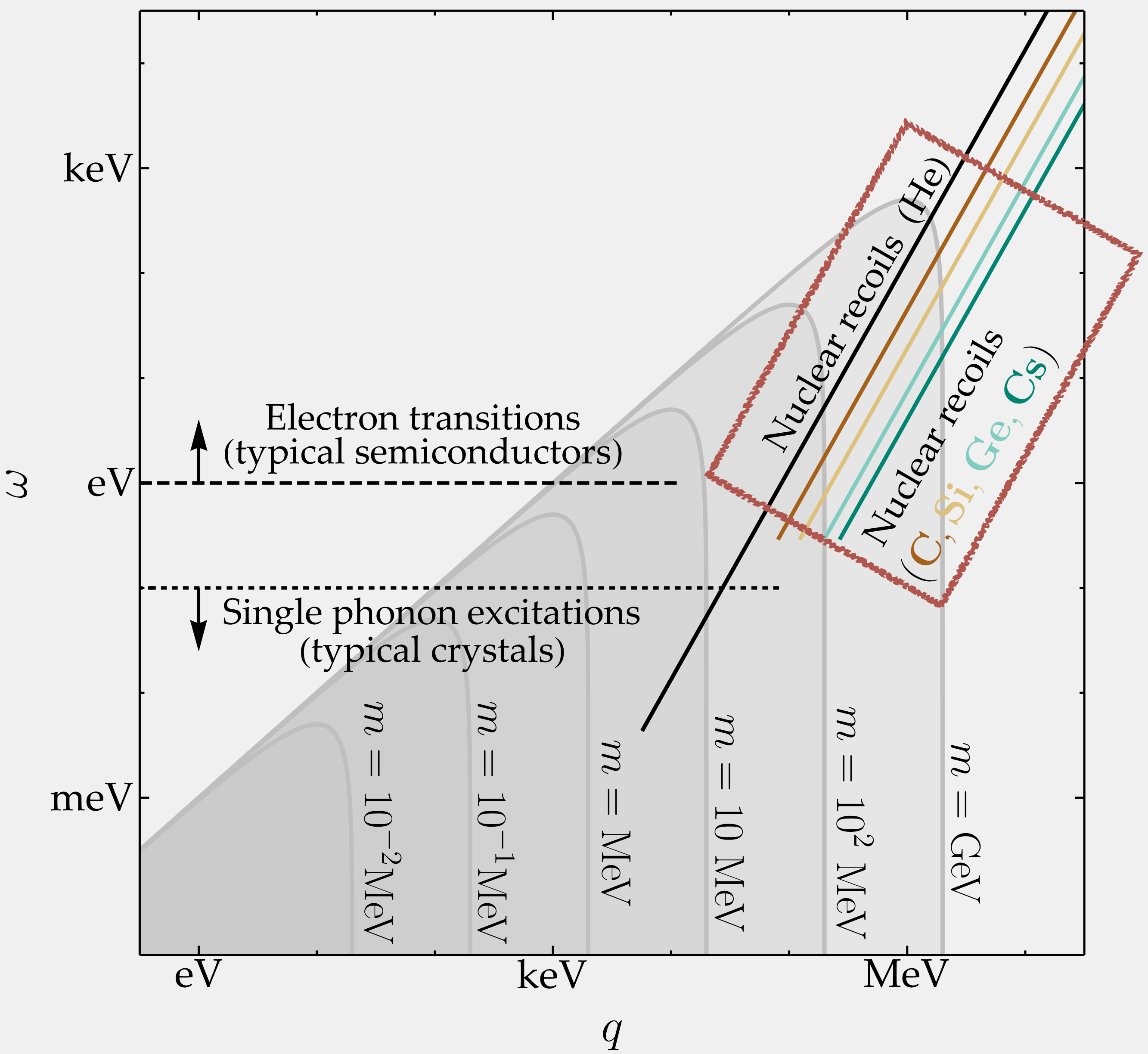
$$S(\boldsymbol{q},\omega) \equiv \frac{1}{V}\sum_f \left|\langle f|\mathcal{F}_T(\boldsymbol{q})|i\rangle\right|^2 2\pi\delta\big(E_f - E_i - \omega\big)$$

$$\mathcal{F}_T(\boldsymbol{q}) = \frac{f_p(\boldsymbol{q})\,\widetilde{n}_p(-\boldsymbol{q}) + f_n(\boldsymbol{q})\,\widetilde{n}_n(-\boldsymbol{q}) + f_e(\boldsymbol{q})\,\widetilde{n}_e(-\boldsymbol{q})}{f_\psi^0}$$

- For any target system, the rate can be calculated from first principles by
  - Identifying accessible final states (low energy d.o.f.).
  - Quantizing number density operators in the appropriate Hilbert space.

Dynamic structure factor

$$\Gamma = \int \frac{d^3q}{(2\pi)^3}\, |\mathcal{M}|^2\, S(\boldsymbol{q},\omega)\Big|_{\omega=\boldsymbol{q}\cdot\boldsymbol{v}-\frac{q^2}{2m_\chi}}$$



- Nuclear recoils:

$$S(\boldsymbol{q},\omega) = 2\pi\,\frac{\rho_T}{m_N}\,\frac{f_N^2}{f_n^2}\,F_N^2\,\delta\Big(\omega-\frac{q^2}{2m_N}\Big)$$

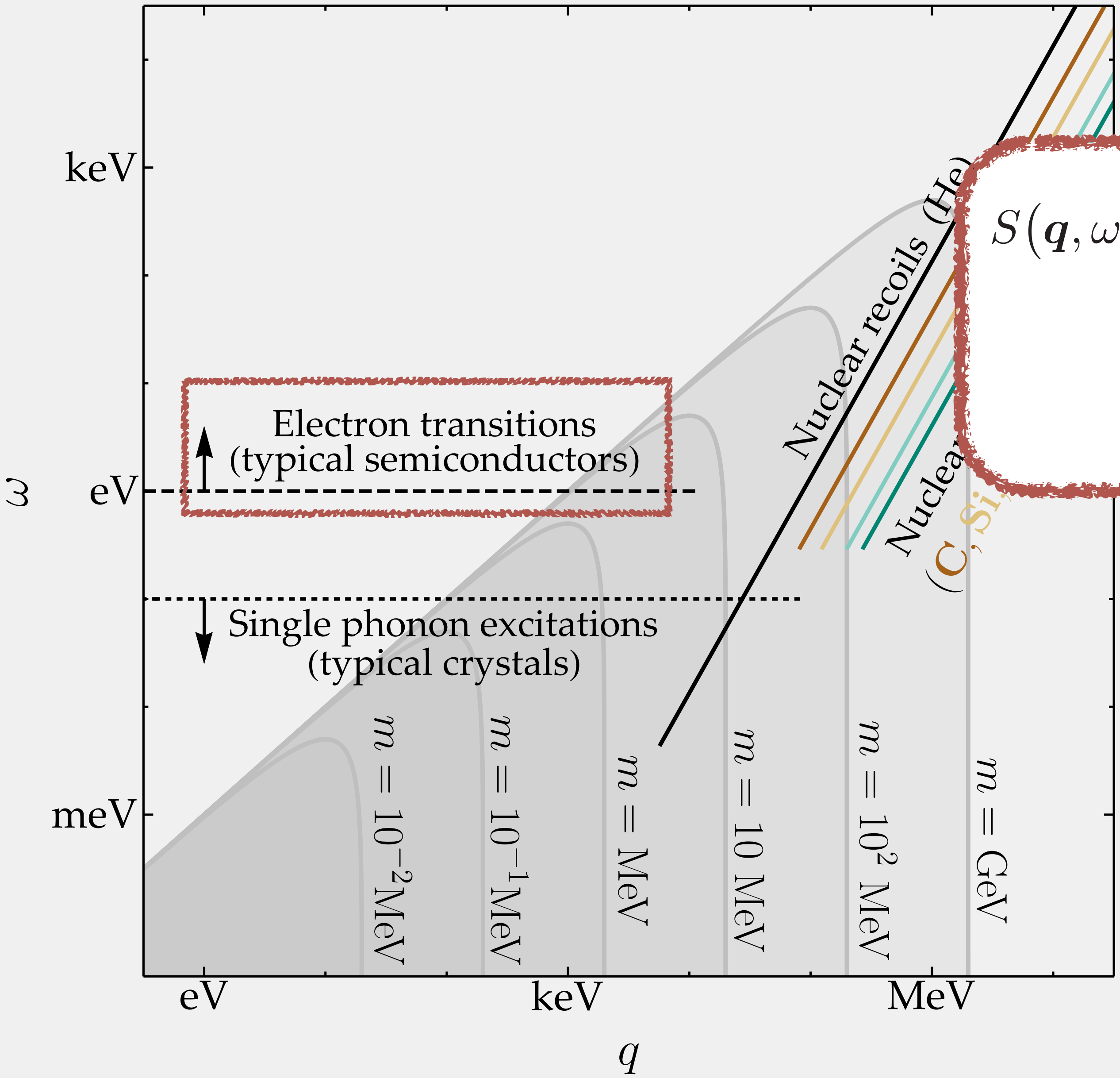
$$f_N \equiv f_p Z + f_n (A-Z)$$

$$F_N = \frac{3\,j_1(qr_n)}{qr_n}\,e^{-(qs)^2/2}$$

$$r_n \simeq 1.14\,A^{1/3}\,\text{fm},\;\; s \simeq 0.9\,\text{fm}$$

Dynamic structure factor

$$\Gamma = \int \frac{d^3q}{(2\pi)^3} \, |\mathcal{M}|^2 \, S(\boldsymbol{q}, \omega)\Big|_{\omega = \boldsymbol{q}\cdot\boldsymbol{v} - \frac{q^2}{2m_\chi}}$$



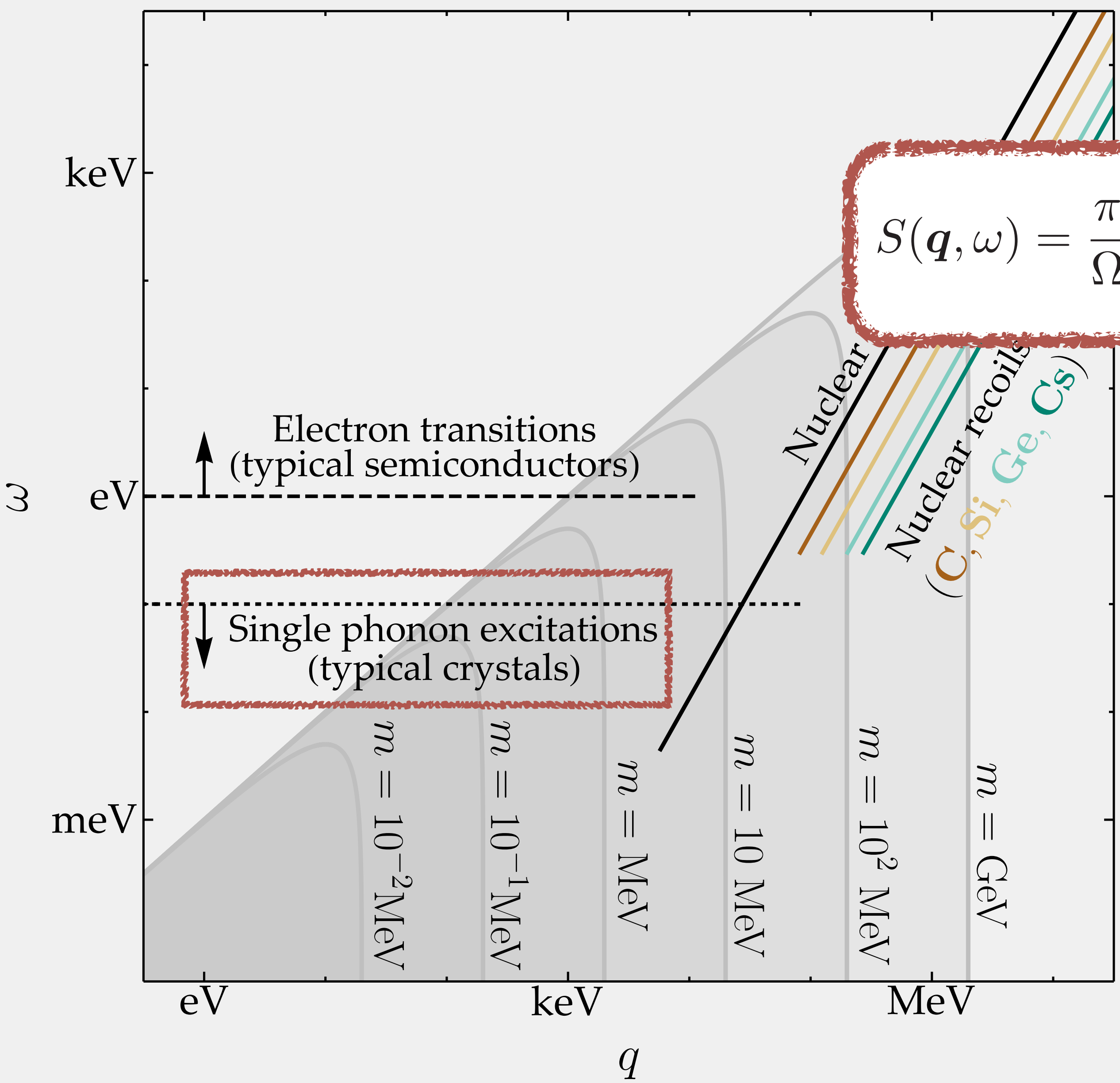
- Electron transitions:

$$S(\boldsymbol{q},\omega) = \frac{2\pi}{V}\left(\frac{f_e}{f_e^0}\right)^2 \sum_{I_1,I_2} \delta(E_{I_2} - E_{I_1} - \omega) \cdot \left| \int \frac{d^3k'}{(2\pi)^3} \frac{d^3k}{(2\pi)^3} (2\pi)^3 \delta^3(\boldsymbol{k}' - \boldsymbol{k} - \boldsymbol{q}) \, \widetilde{\psi}^*_{I_2}(\boldsymbol{k}') \widetilde{\psi}_{I_1}(\boldsymbol{k}) \right|^2$$

  - I_1: occupied state (valence band).
  - I_2: unoccupied state (conduction band).
  - Also applies to meV-gap systems (superconductors, Dirac materials).

Dynamic structure factor

$$\Gamma = \int \frac{d^3q}{(2\pi)^3} \, |\mathcal{M}|^2 \, S(\boldsymbol{q}, \omega)\Big|_{\omega = \boldsymbol{q}\cdot\boldsymbol{v} - \frac{q^2}{2m_\chi}}$$



- Single phonon excitations:

$$S(\boldsymbol{q},\omega) = \frac{\pi}{\Omega}\sum_\nu \frac{1}{\omega_{\nu,\boldsymbol{k}}}\left|\sum_j \frac{e^{-W_j(\boldsymbol{q})}}{\sqrt{m_j}}\, e^{i\boldsymbol{G}\cdot\boldsymbol{x}_j^0}\left(\boldsymbol{Y}_j\cdot\boldsymbol{\epsilon}^*_{\nu,\boldsymbol{k},j}\right)\right|^2 \delta(\omega-\omega_{\nu,\boldsymbol{k}})$$

  - More detail in the next few slides.
  - **Extends** previous results (which rely on mapping specific models that can be onto known CM problems).

Outline of the talk

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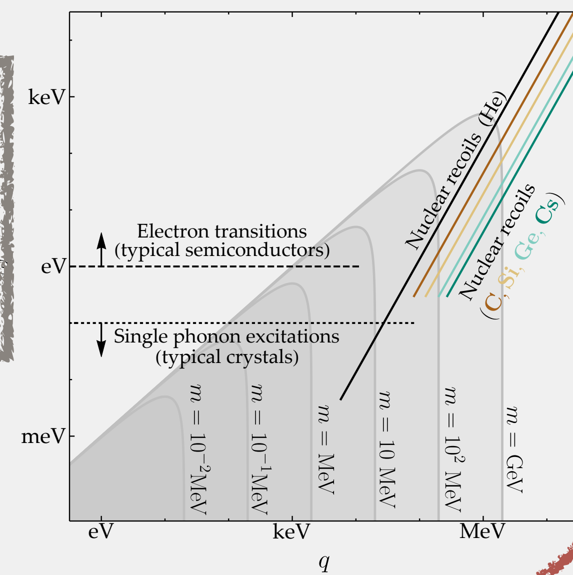
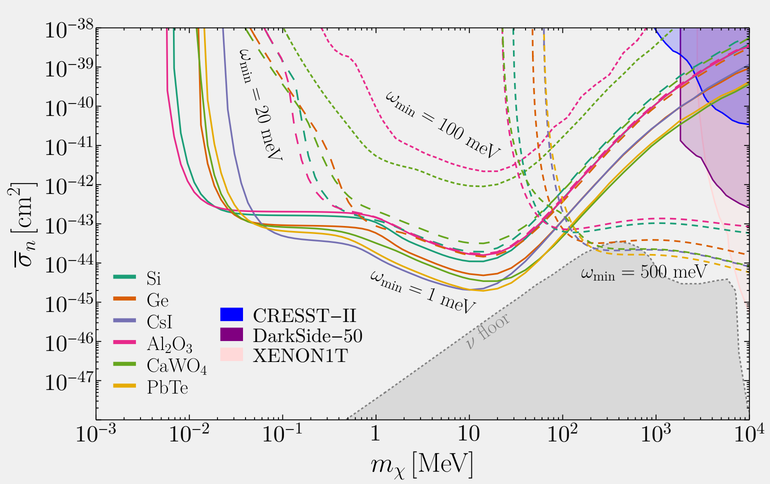


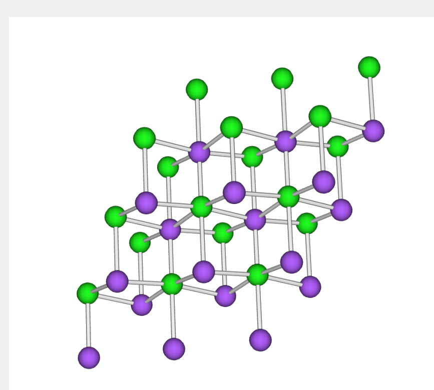
Theoretical framework for multi-channel direct detection (rate calculation from **first principles**)

Kinematics

Dynamics

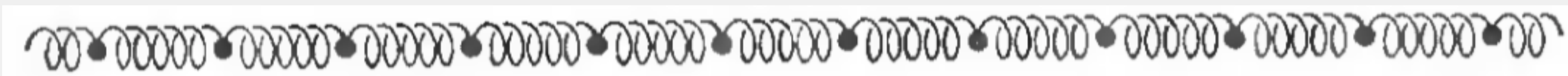
Phonons (spin-independent)
[R&D in progress]





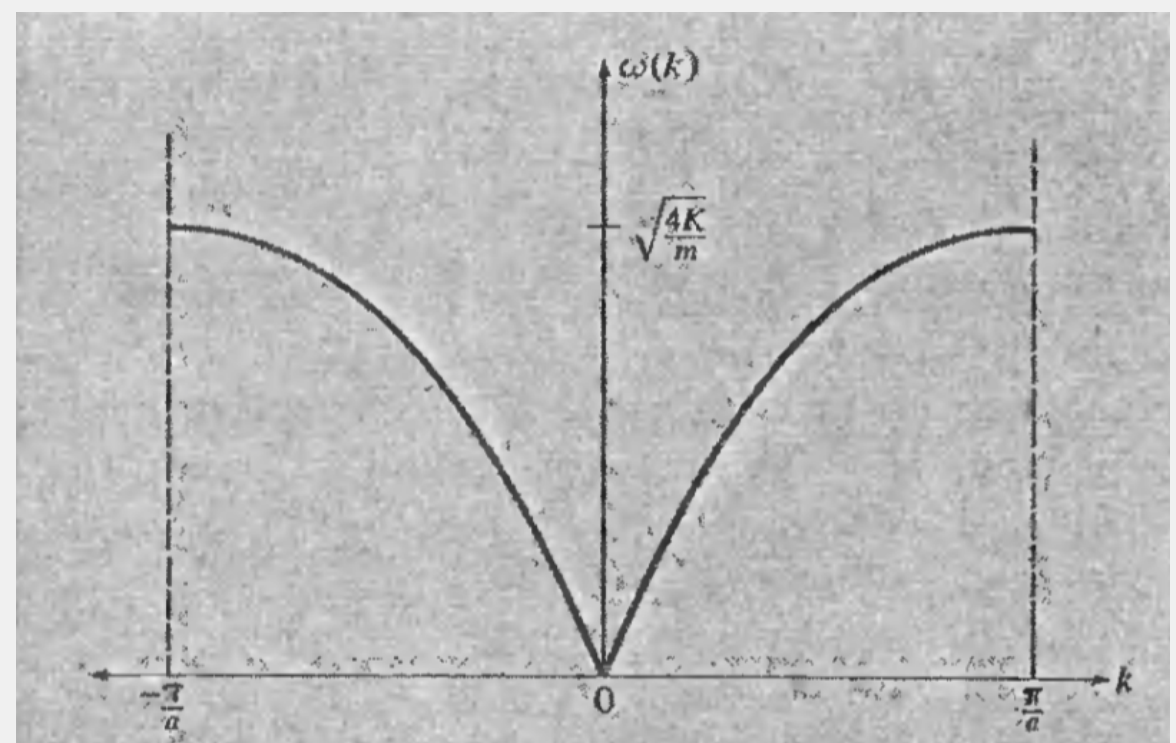
Phonons in crystals

- Consider a 1D lattice:



$$U^{\text{harm}} = \frac{1}{2} K \sum_n [u(na) - u([n+1]a)]^2,$$

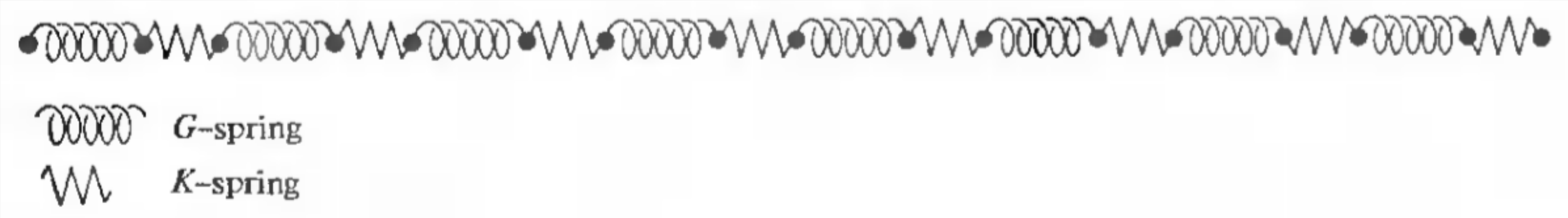
- Diagonalize the Hamiltonian => canonical oscillation modes.
- Quantize => (acoustic) phonons.
  - Quanta of sound waves.
  - Gapless (Goldstone mode of broken translation symmetry).



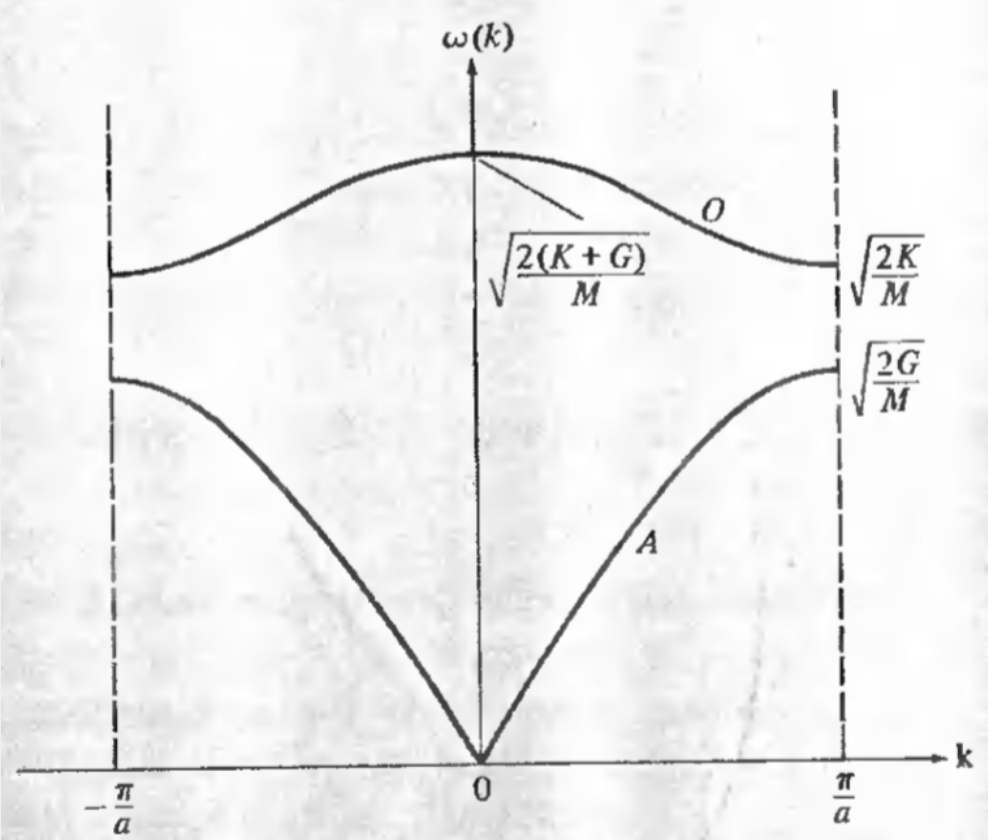
Ashcroft, Mermin, *Solid State Physics*.

Phonons in crystals

- Now suppose there are two inequivalent atoms in the primitive cell:



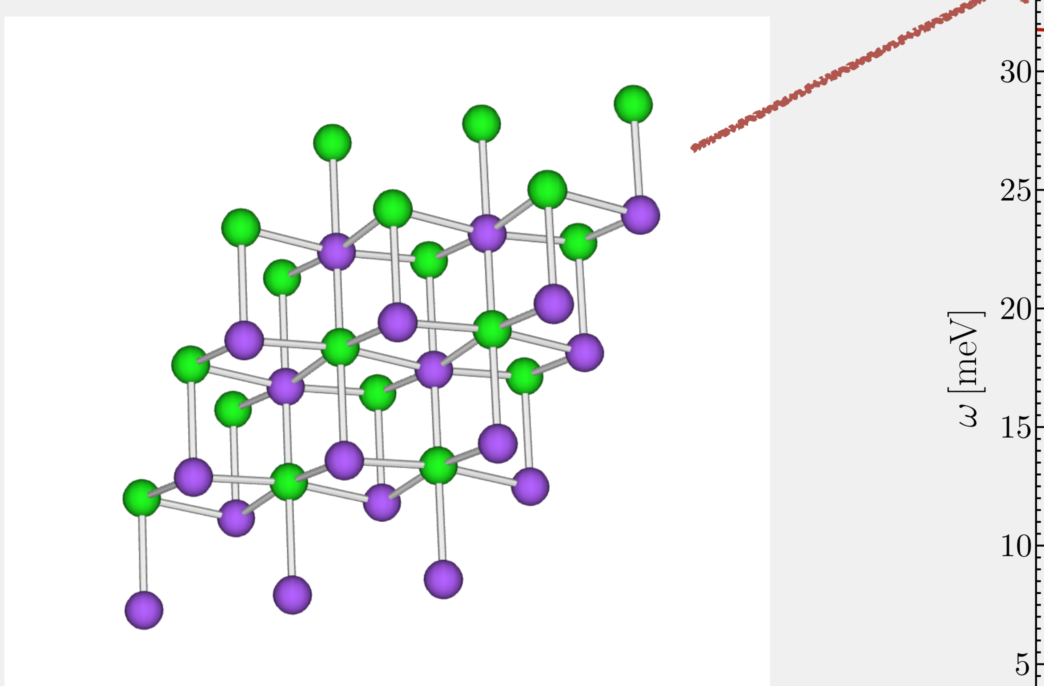
- Two phonon branches:
  - Acoustic phonons (as before).
    - In-phase oscillations, gapless.
  - Optical phonons.
    - Out-of-phase oscillations, gapped.

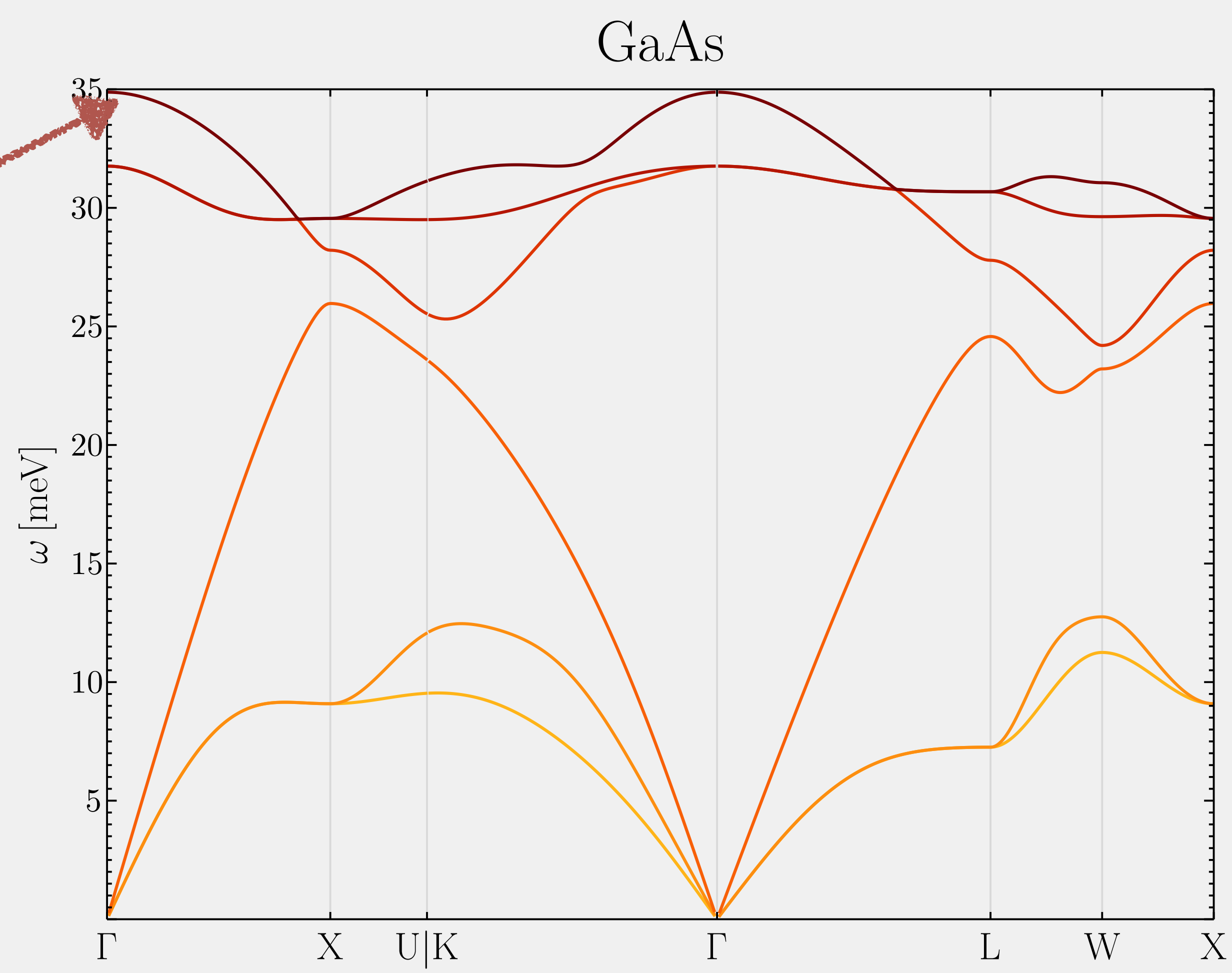


Ashcroft, Mermin, *Solid State Physics*.

Phonons in crystals

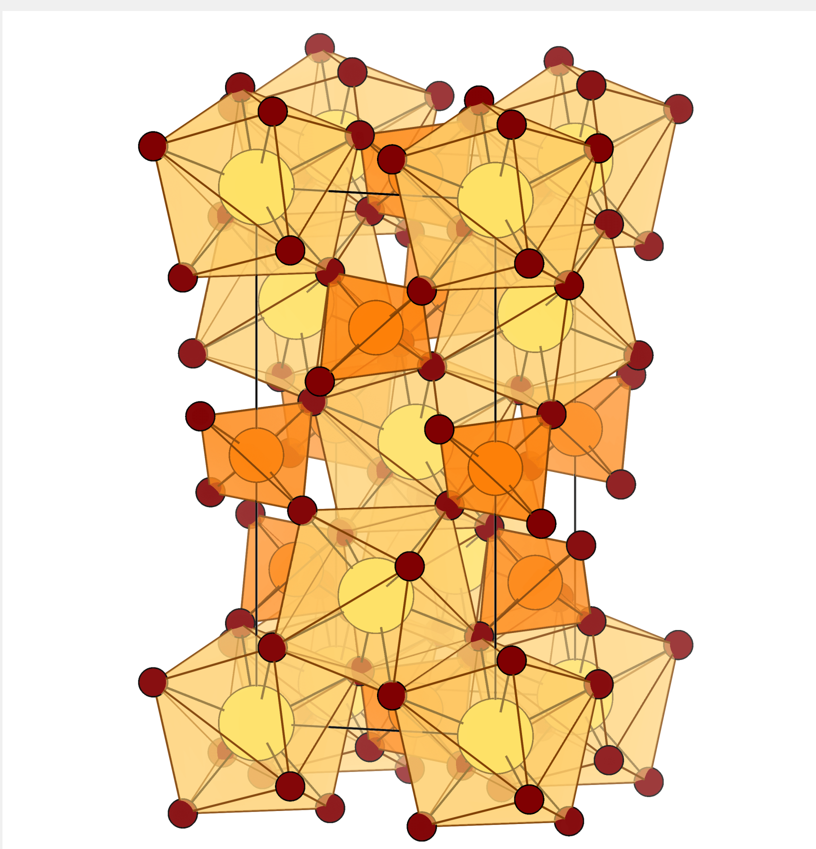
- Analogous in 3D.
  - GaAs: 1 Ga + 1 As per primitive cell => 3 acoustic + 3 optical.

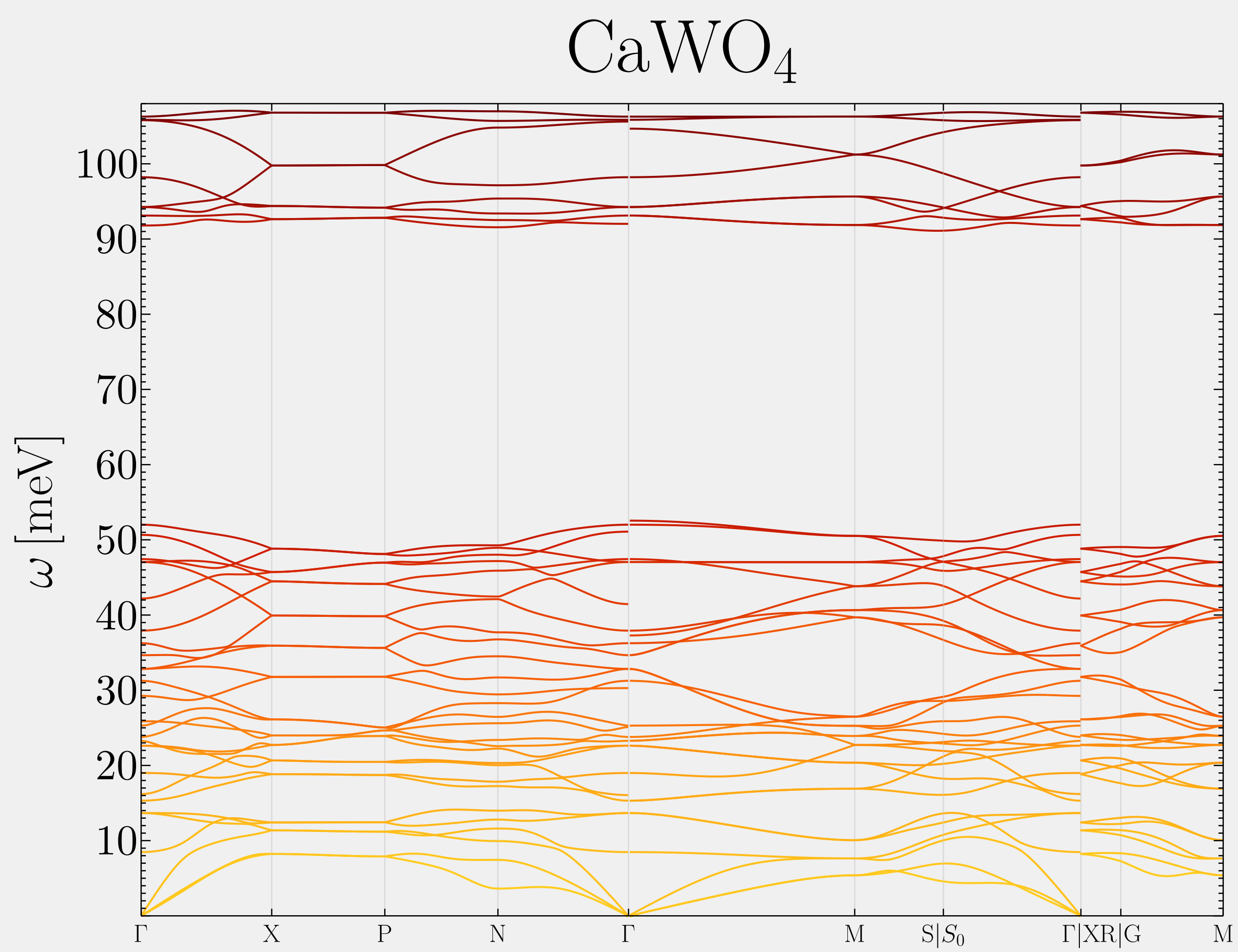




Phonons in crystals

- Analogous in 3D.
  - GaAs: 1 Ga + 1 As per primitive cell => 3 acoustic + 3 optical.
  - $CaWO_4$: 2 Ca +2 W + 8 O per primitive cell => 3 acoustic + 33 optical.





Phonons from DM scattering

- Recall:

$$\Gamma = \int \frac{d^3q}{(2\pi)^3} \, |\mathcal{M}|^2 \, S(\boldsymbol{q}, \omega)\Big|_{\omega = \boldsymbol{q}\cdot\boldsymbol{v} - \frac{q^2}{2m_\chi}}$$

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

- $\mathcal{F}_T(\boldsymbol{q}) = \dfrac{f_p(\boldsymbol{q})\,\widetilde{n}_p(-\boldsymbol{q}) + f_n(\boldsymbol{q})\,\widetilde{n}_n(-\boldsymbol{q}) + f_e(\boldsymbol{q})\,\widetilde{n}_e(-\boldsymbol{q})}{f_\psi^0}$ depends on atom positions.

- Phonons c … ents):

$$S(\boldsymbol{q}, \omega) = \frac{\pi}{\Omega} \sum_\nu \frac{1}{\omega_{\nu,\boldsymbol{k}}} \left| \sum_j \frac{e^{-W_j(\boldsymbol{q})}}{\sqrt{m_j}} \, e^{i\boldsymbol{G}\cdot\boldsymbol{x}_j^0} \big(\boldsymbol{Y}_j \cdot \boldsymbol{\epsilon}^*_{\nu,\boldsymbol{k},j}\big) \right|^2 \delta\big(\omega - \omega_{\nu,\boldsymbol{k}}\big)$$

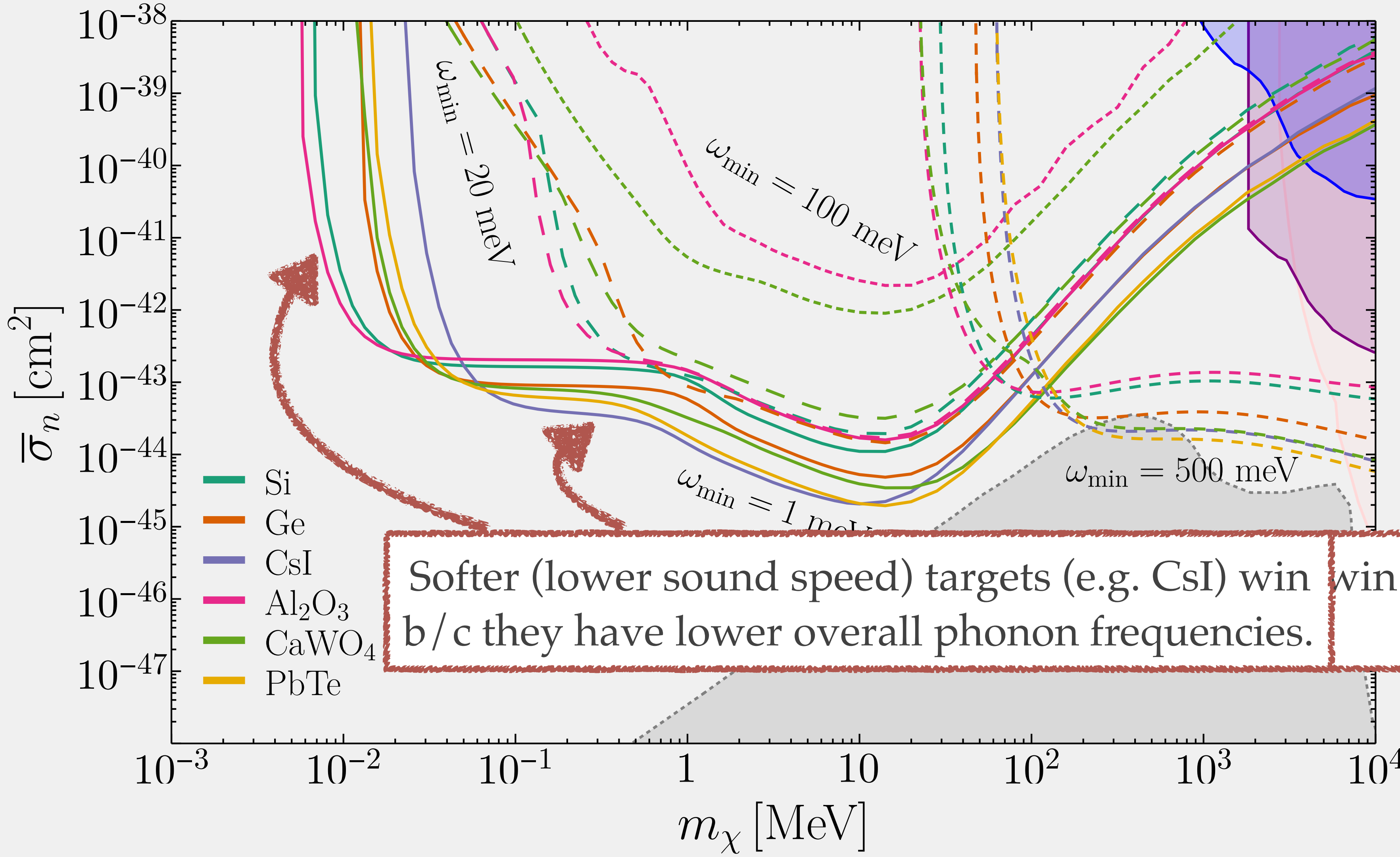
jth atom/ion in the lth primitive cell — phonon creation/annihilation operators

$$\boldsymbol{u}_{lj} = \boldsymbol{x}_{lj} - \boldsymbol{x}_{lj}^0 = \sum_\nu \sum_{\boldsymbol{k}\in 1\mathrm{BZ}} \frac{1}{\sqrt{2Nm_j\omega_{\nu,\boldsymbol{k}}}} \Big(\hat{a}_{\nu,\boldsymbol{k}} \, \boldsymbol{\epsilon}_{\nu,\boldsymbol{k},j} \, e^{i\boldsymbol{k}\cdot\boldsymbol{x}_{lj}^0} + \hat{a}^\dagger_{\nu,\boldsymbol{k}} \, \boldsymbol{\epsilon}^*_{\nu,\boldsymbol{k},j} \, e^{-i\boldsymbol{k}\cdot\boldsymbol{x}_{lj}^0} \Big)$$

equilibrium position — phonon branch — phonon energies — phonon polarization vectors

Acoustic vs. optical phonons

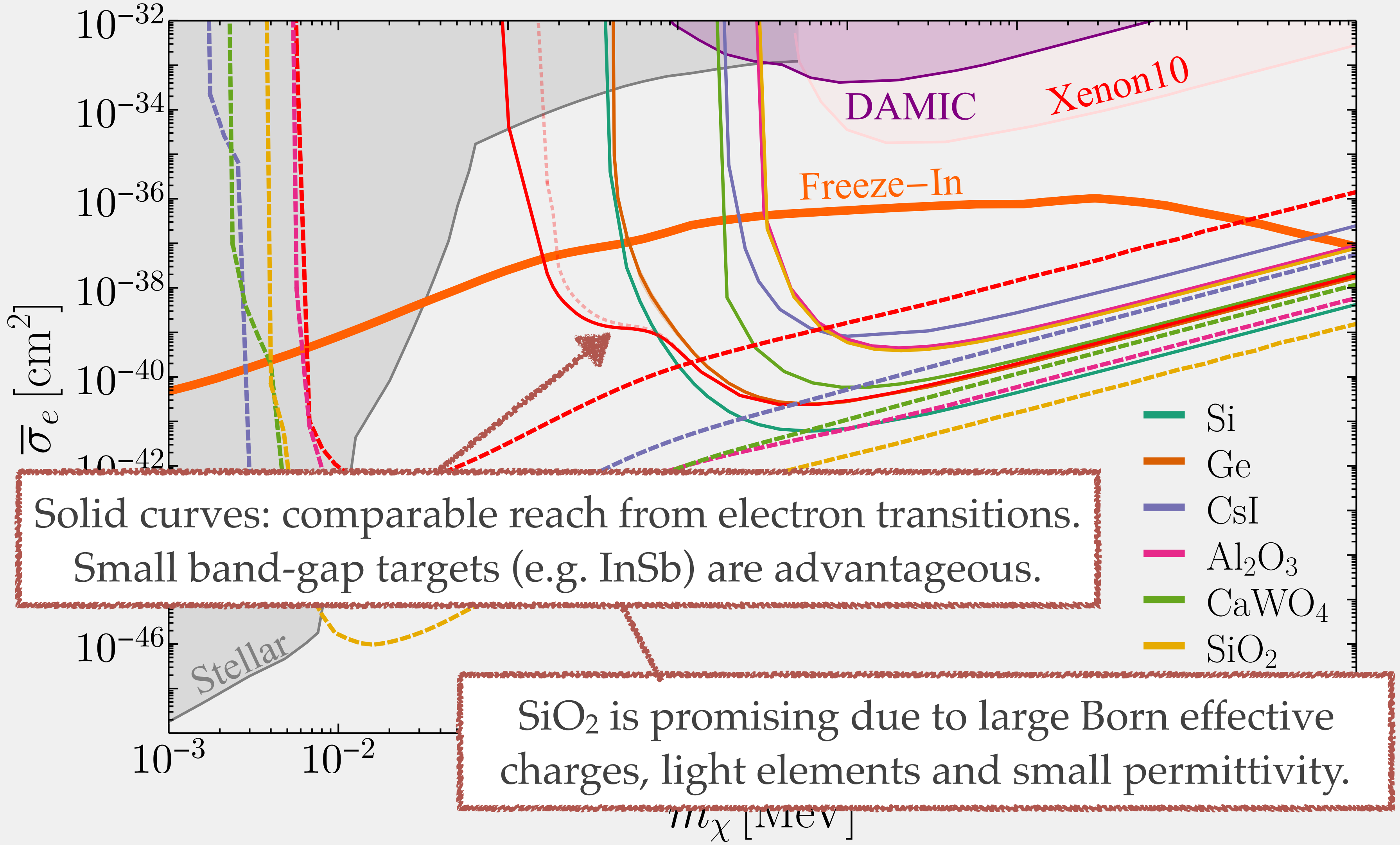
- If DM couples to all atoms/ions with the **same sign** => dominantly excites **acoustic** phonons (in-phase oscillations).
  - Example: coupling to nucleon number via a heavy scalar mediator.



Softer (lower sound speed) targets (e.g. CsI) win b/c they have lower overall phonon frequencies.

Acoustic vs. optical phonons

- If DM couples to different atoms/ions with the **opposite signs** => dominantly excites **optical** phonons (out-of-phase oscillations).
  - Example: coupling to electric charge via a dark photon mediator.



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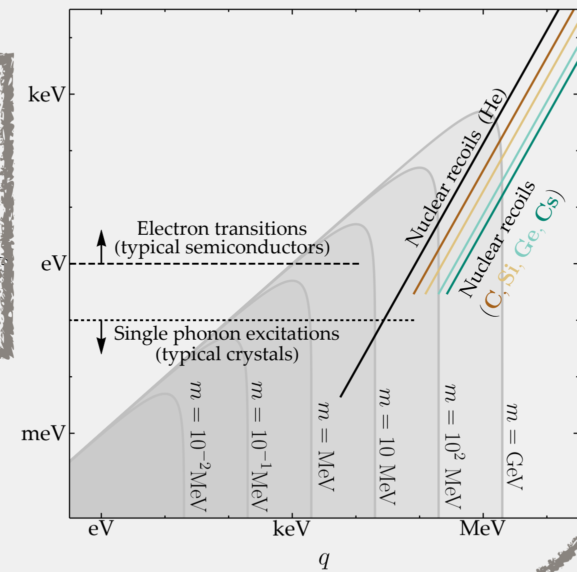

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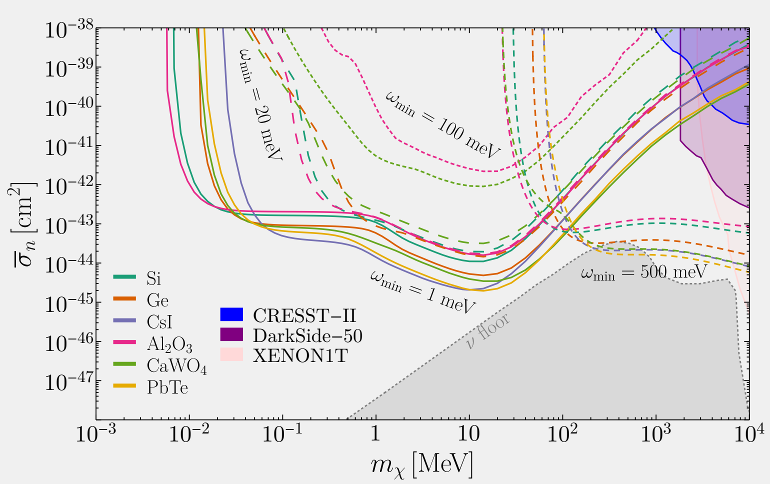
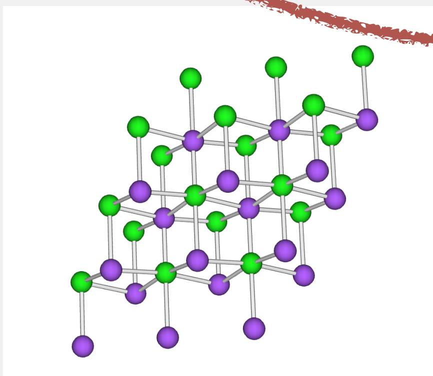
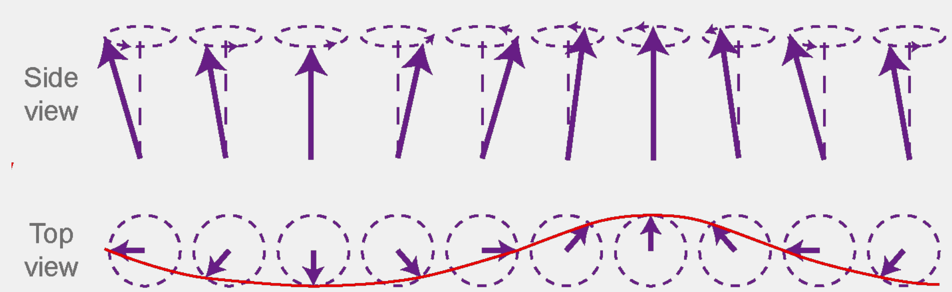
[R&D in progress]

Magnons (spin-dependent)
[new theoretical proposal]







Spin independent (SI) vs. spin dependent (SD)

- In the Standard Model, the neutron is electrically neutral. Its leading interaction with the photon is via a magnetic dipole moment.
- Something similar can happen in the dark sector. The DM may be neutral under the dark photon, but interacts via a multipole moment.

Magnetic dipole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi}\bar{\chi}\sigma^{\mu\nu}\chi\, V_{\mu\nu} + g_e\bar{e}\gamma^\mu e\, V_\mu$	$\hat{\mathcal{O}}_\chi^\alpha = \frac{4g_\chi g_e}{\Lambda_\chi m_e}\left(\delta^{\alpha\beta} - \frac{q^\alpha q^\beta}{q^2}\right)\hat{S}_\chi^\beta$
Anapole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu V_{\mu\nu} + g_e\bar{e}\gamma^\mu e\, V_\mu$	$\hat{\mathcal{O}}_\chi^\alpha = \frac{2g_\chi g_e}{\Lambda_\chi^2 m_e}\epsilon^{\alpha\beta\gamma} i q^\beta \hat{S}_\chi^\gamma$

- In these scenarios, DM couples to the electron **spin** at low energy:

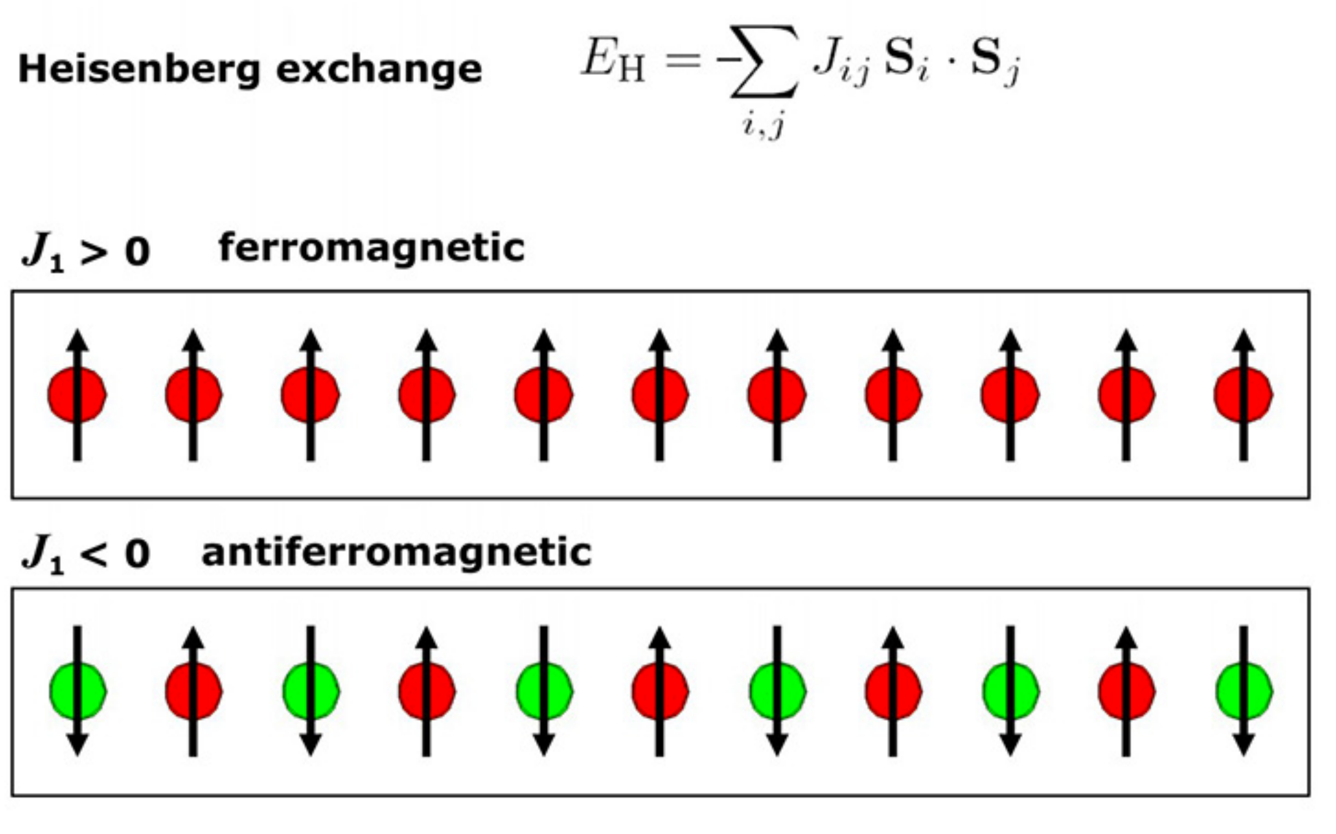
$$\mathcal{L} = -\sum_{\alpha=1}^{3}\hat{\mathcal{O}}_\chi^\alpha(\boldsymbol{q})\hat{S}_e^\alpha$$

- SD interactions can also arise from scalar mediator models.

Pseudo-mediated DM	$\mathcal{L} = g_\chi\bar{\chi}\chi\phi + g_e\bar{e}\, i\gamma^5 e\,\phi$	$\hat{\mathcal{O}}_\chi^\alpha = -\frac{g_\chi g_e}{q^2 m_e} i q^\alpha \mathbb{1}_\chi$

Magnons: what they are and how they couple to DM

- Crystal lattice sites occupied by effective spins (from electrons of magnetic ions.)
- Exchange couplings between neighboring spins => **ordered ground state**.



- Excitations about such a ground state are **magnons**.

Magnons: what they are and how they couple to DM

- Technically, we need to expand the spins in terms of bosonic creation/annihilation operators via the Holstein-Primakoff transformation…

$$S'^{+}_{lj} = \left(2S_j - \hat{a}^\dagger_{lj}\hat{a}_{lj}\right)^{1/2} \hat{a}_{lj}\,, \qquad S'^{-}_{lj} = \hat{a}^\dagger_{lj}\left(2S_j - \hat{a}^\dagger_{lj}\hat{a}_{lj}\right)^{1/2}, \qquad S'^{3}_{lj} = S_j - \hat{a}^\dagger_{lj}\hat{a}_{lj}$$

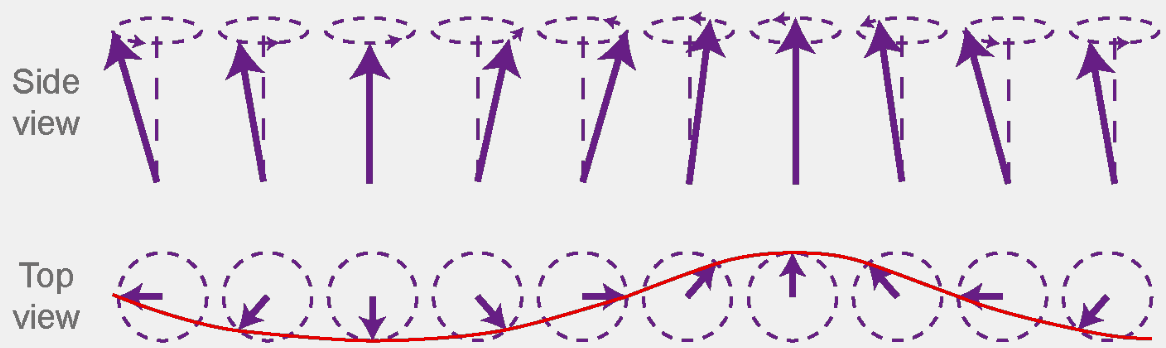
where $S^\alpha_{lj} = \sum_\beta R^{\alpha\beta}_j S'^\beta_{lj}\,, \quad \{\langle S'^1_{lj}\rangle, \langle S'^2_{lj}\rangle, \langle S'^3_{lj}\rangle\} = \{0,\, 0,\, S_j\}$

global coordinates *local coordinates (ground state spin points in +z direction)*

- … and then diagonalize the Hamiltonian via a Bogoliubov transformation…

$$\begin{pmatrix} \hat{a}_{j,\boldsymbol{k}} \\ \hat{a}^\dagger_{j,-\boldsymbol{k}} \end{pmatrix} = \mathrm{T}_{\boldsymbol{k}} \begin{pmatrix} \hat{b}_{\nu,\boldsymbol{k}} \\ \hat{b}^\dagger_{\nu,-\boldsymbol{k}} \end{pmatrix} \qquad \text{where} \quad \mathrm{T}_{\boldsymbol{k}} \begin{pmatrix} \mathbb{1}_n & \mathbb{0}_n \\ \mathbb{0}_n & -\mathbb{1}_n \end{pmatrix} \mathrm{T}^\dagger_{\boldsymbol{k}} = \begin{pmatrix} \mathbb{1}_n & \mathbb{0}_n \\ \mathbb{0}_n & -\mathbb{1}_n \end{pmatrix}$$

$$H = \sum_{\nu=1}^{n} \sum_{\boldsymbol{k}\in 1\mathrm{BZ}} \omega_{\nu,\boldsymbol{k}} \hat{b}^\dagger_{\nu,\boldsymbol{k}} \hat{b}_{\nu,\boldsymbol{k}}$$



canonical magnon modes (quanta of collective precession patterns)

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canonical magnon modes (quanta of collective precession patterns)

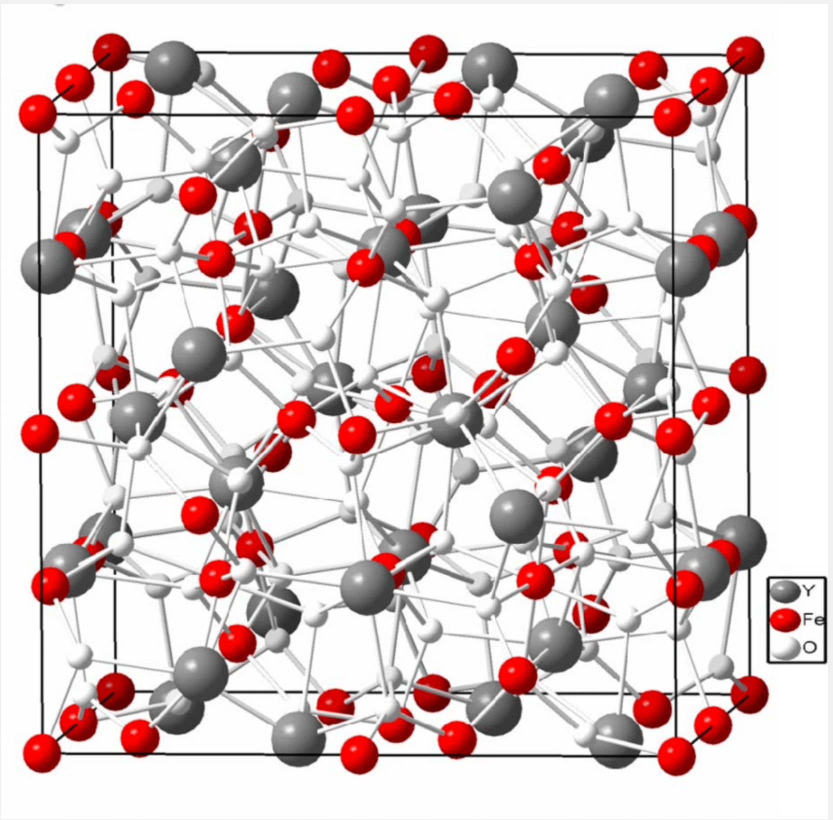
- DM-spin coupling => DM-magnon coupling.

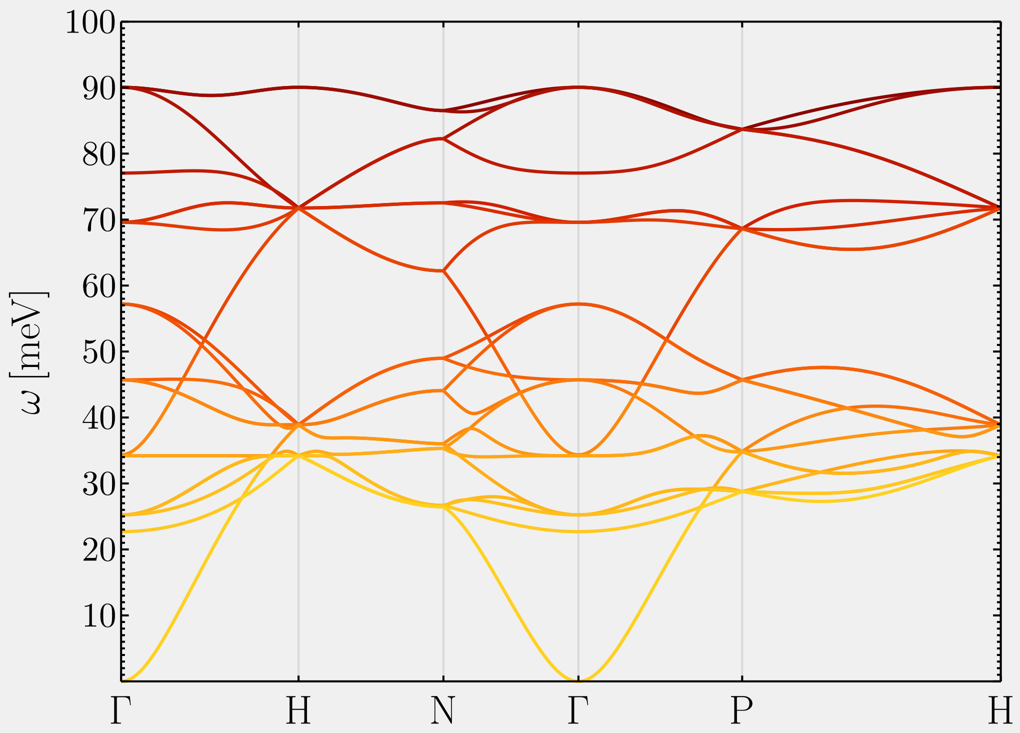
$$\mathcal{L} = -\sum_{\alpha=1}^{3} \hat{\mathcal{O}}^{\alpha}_{\chi}(\boldsymbol{q}) \hat{S}^{\alpha}_{e} \quad \Rightarrow \quad \mathcal{M}^{s_i s_f}_{\nu,\boldsymbol{k}}(\boldsymbol{q}) = \frac{1}{N\Omega} \langle s_f | \hat{\mathcal{O}}^{\alpha}_{\chi}(\boldsymbol{q}) | s_i \rangle \langle \nu, \boldsymbol{k} | \sum_{lj} \hat{S}^{\alpha}_{lj}\, e^{i\boldsymbol{q}\cdot\boldsymbol{x}_{lj}} |0\rangle$$

spin operators create magnons (cf. position operators create phonons)

Projected reach

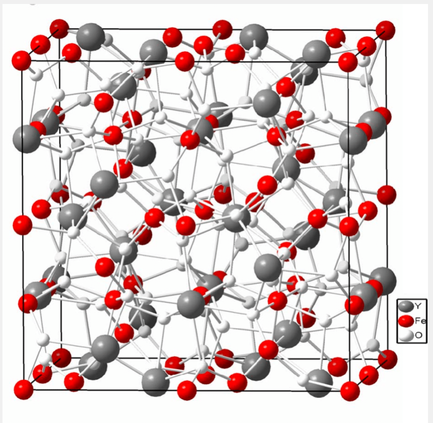
- We consider a **yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$)** target.
  - 20 magnetic ions Fe^{3+} (spin 5/2) in the unit cell => 20 magnon branches.
  - Anti-ferromagnetic exchange couplings. Ground state: 12 up, 8 down.



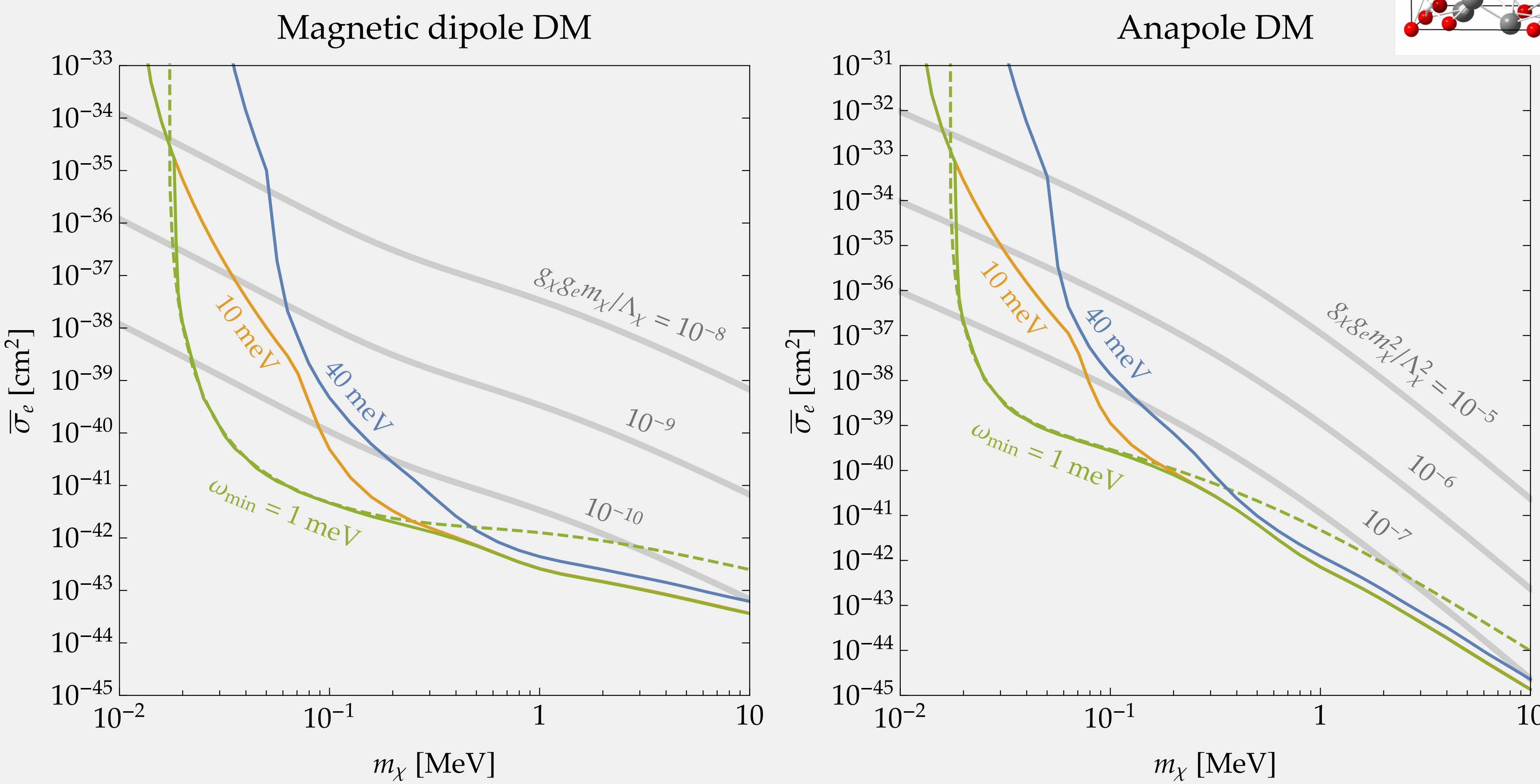


Magnon dispersion calculated by including up to 3rd nearest neighbor exchange couplings taken from: Cherepanov, Kolokolov, L'vov, Physics Reports 229, 81 (1993).

Projected reach



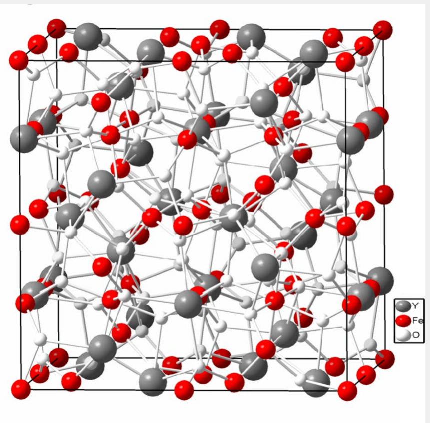
- We consider a **yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$)** target.
- Dark photon mediator (unconstrained by astro/cosmo):

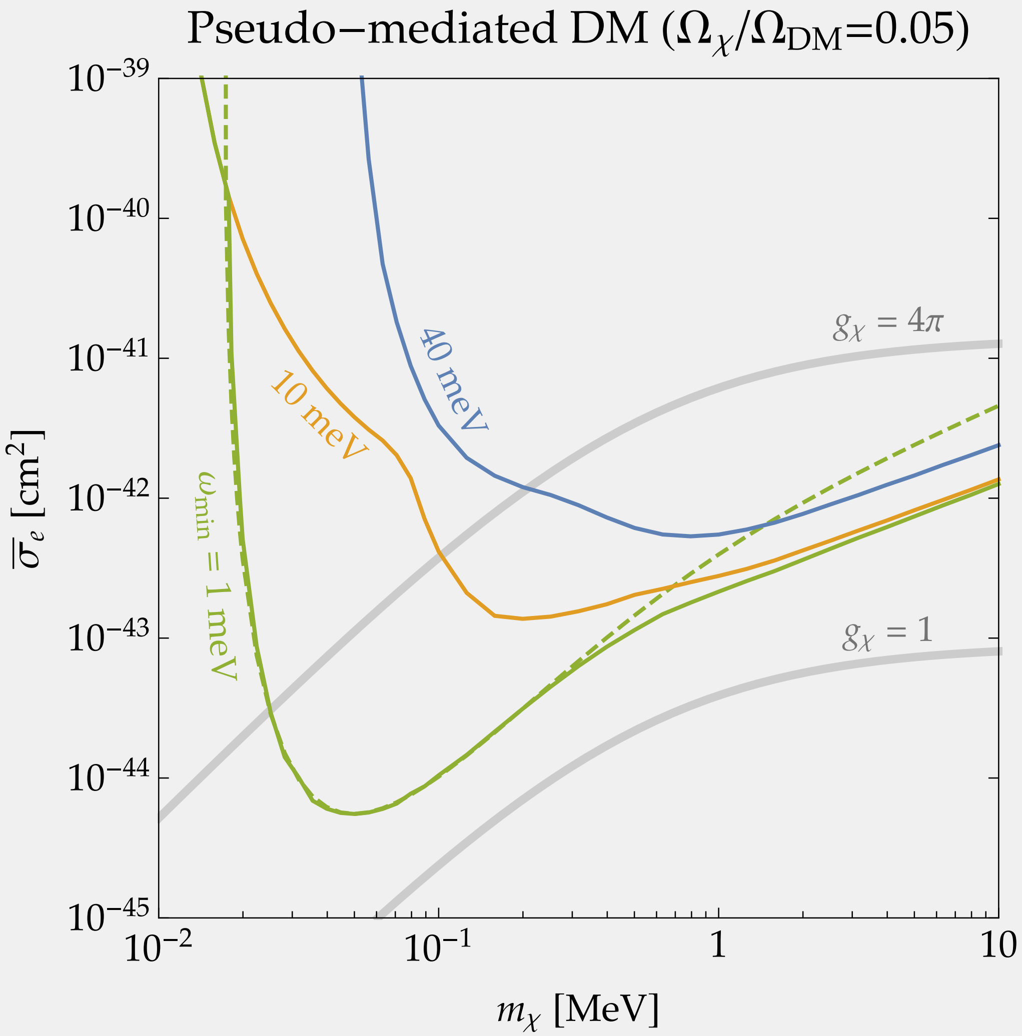


Projection assumes 3 signal events/kg/yr.

Projected reach

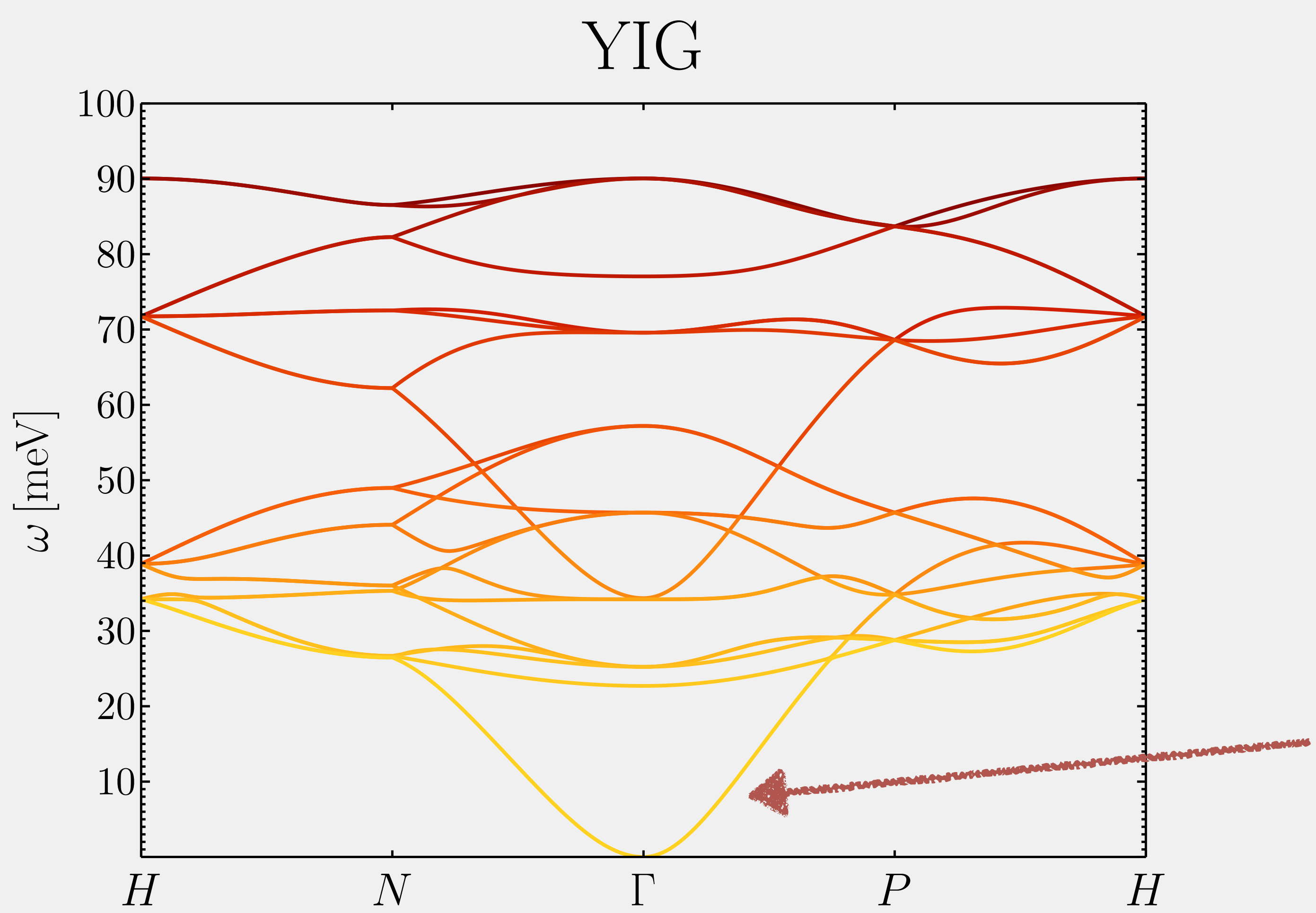
- We consider a **yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$)** target.
- Scalar mediator (impose white dwarf cooling constraint, consider SIDM subcomponent):





Gapless vs. gapped magnons

- YIG has 1 gapless and 19 gapped magnon branches.
- They have different responses to DM scattering.



Gapless magnon branch: Goldstone mode of broken rotation symmetry.

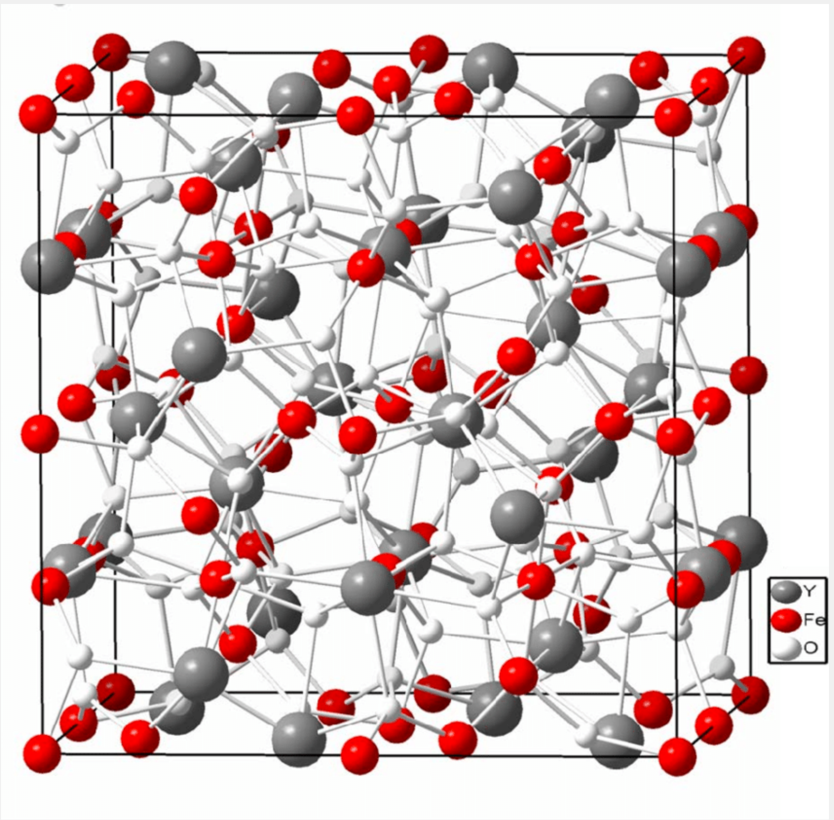
Gapless vs. gapped magnons

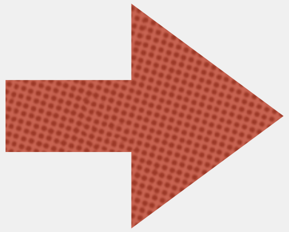
$$\mathcal{L} = -\sum_{\alpha=1}^{3} \hat{\mathcal{O}}_{\chi}^{\alpha}(\boldsymbol{q})\hat{S}_e^{\alpha}$$

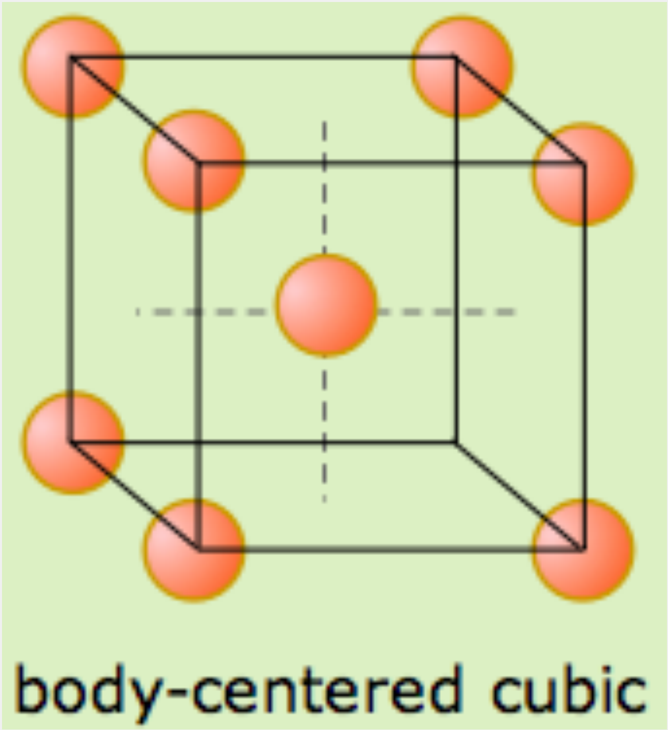
- Consider the limit q -> 0.
- The DM coupling acts like a uniform magnetic field.
- All the spins precess in phase => no change in energy.
- This corresponds to **Goldstone mode** excitation, i.e. only **gapless** magnons can be produced.
- Gapped magnon contributions become significant only for $\boldsymbol{q}$ beyond the first Brillouin zone.

Effective theory of gapless magnons

- Integrate out short-distance degrees of freedom within the unit cell.
- The only low-energy d.o.f. is the spin density: (12-8)x5/2=10 per unit cell.
- Effective theory is a Heisenberg ferromagnet on a bcc lattice, which has only 1 gapless magnon branch.







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

$$\boldsymbol{\epsilon}_{\nu,\boldsymbol{k},\boldsymbol{G}} = \sum_{j=1}^{n} \sqrt{\frac{S_j}{2}} \left(\mathrm{V}_{j\nu,-\boldsymbol{k}} \boldsymbol{r}^*_j + \mathrm{U}^*_{j\nu,\boldsymbol{k}} \boldsymbol{r}_j \right) e^{i\boldsymbol{G}\cdot\boldsymbol{x}_j} \qquad \boldsymbol{\epsilon} = \sqrt{S/2}\,(1, i, 0)$$

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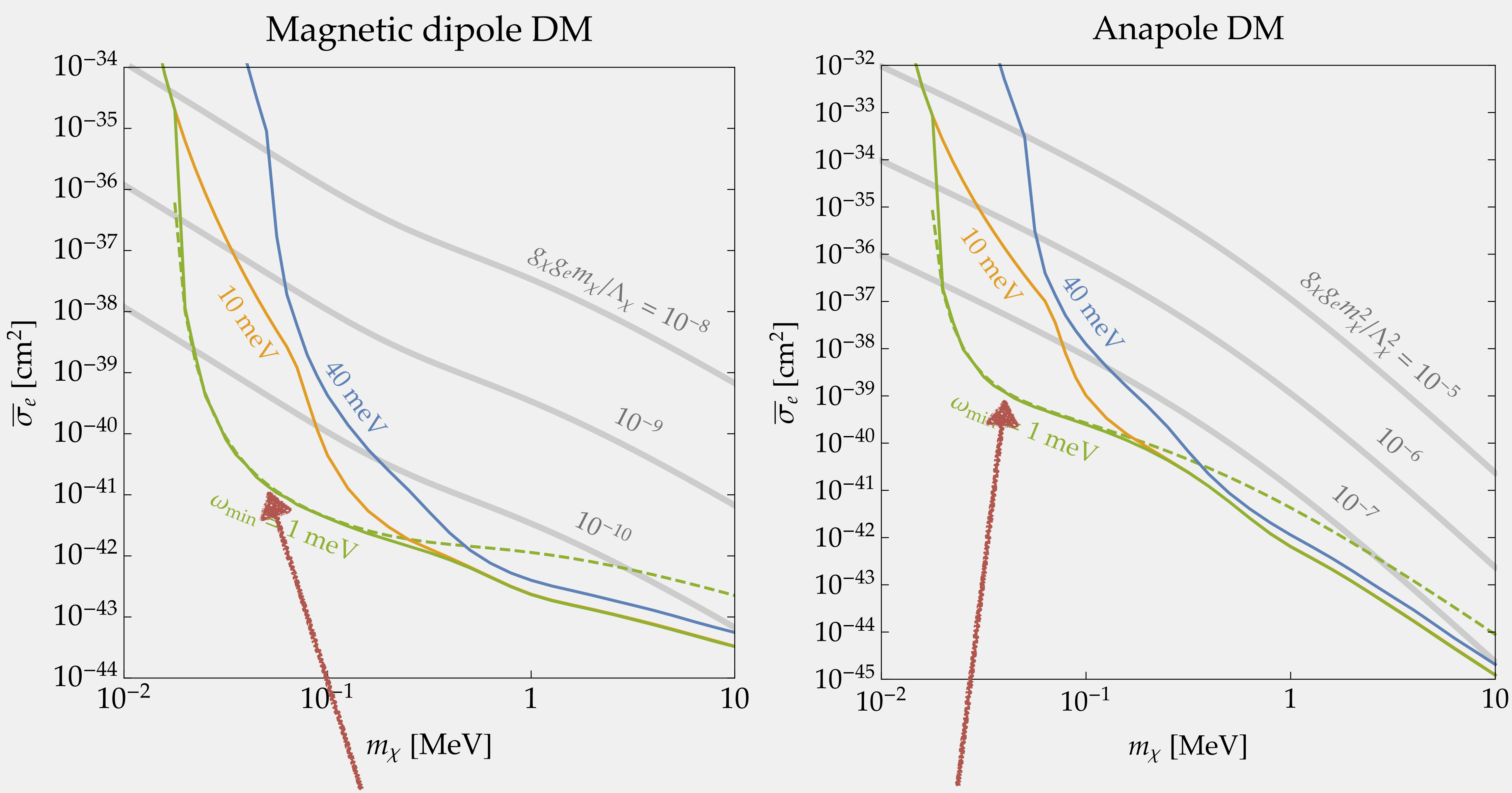
$$R \simeq 3\,(\mathrm{kg{\cdot}yr})^{-1}\left(\frac{n_s}{(4.6\,\text{Å})^{-3}}\right)\left(\frac{4.95\,\mathrm{g/cm^3}}{\rho_T}\right)\left(\frac{0.1\,\mathrm{MeV}}{m_\chi}\right)\int d^3v_\chi\, f(\boldsymbol{v}_\chi)\left(\frac{10^{-3}}{v_\chi}\right)\left(\frac{\hat{R}}{4\times 10^{-27}}\right)$$

$$\hat{R} = \begin{cases} \frac{2g_\chi^2 g_e^2(1+\langle c^2\rangle)}{\Lambda_\chi^2}(q_{\max}^2 - q_{\min}^2) & \text{(magnetic dipole)}\,, \\ \frac{g_\chi^2 g_e^2(1+\langle c^2\rangle)}{4\Lambda_\chi^4}(q_{\max}^4 - q_{\min}^4) & \text{(anapole)}\,, \\ g_\chi^2 g_e^2\langle s^2\rangle \log(q_{\max}/q_{\min}) & \text{(pseudo-mediated)}\,. \end{cases}$$

- $q_{\max} = 2m_\chi v_\chi$, $q_{\min}$ determined by detector threshold.
- Dependence on q follows from effective field theory expectations.

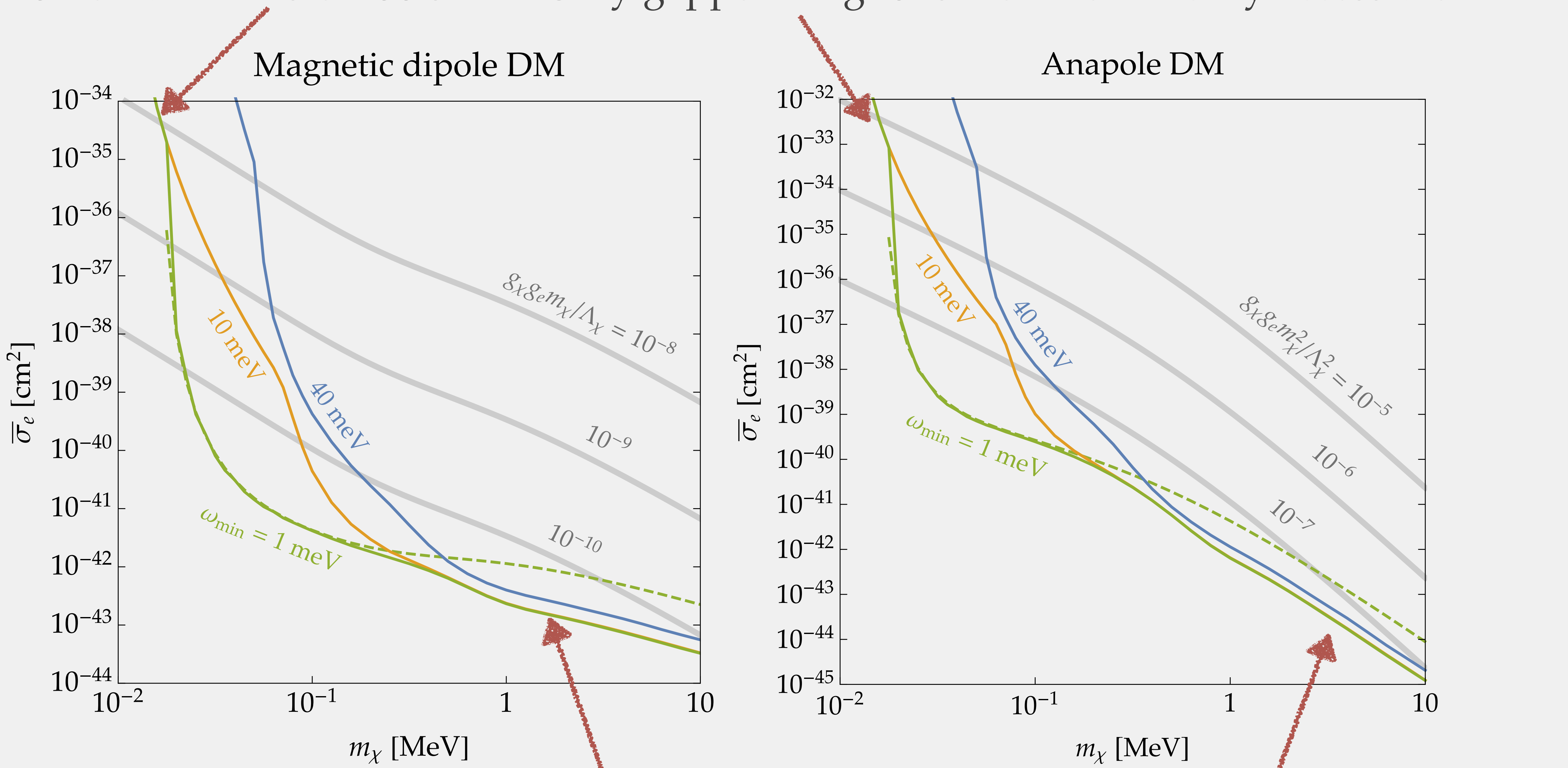
Effective theory vs. full theory



Effective theory calculation (dashed) reproduced full results in the intermediate mass region.

Effective theory vs. full theory

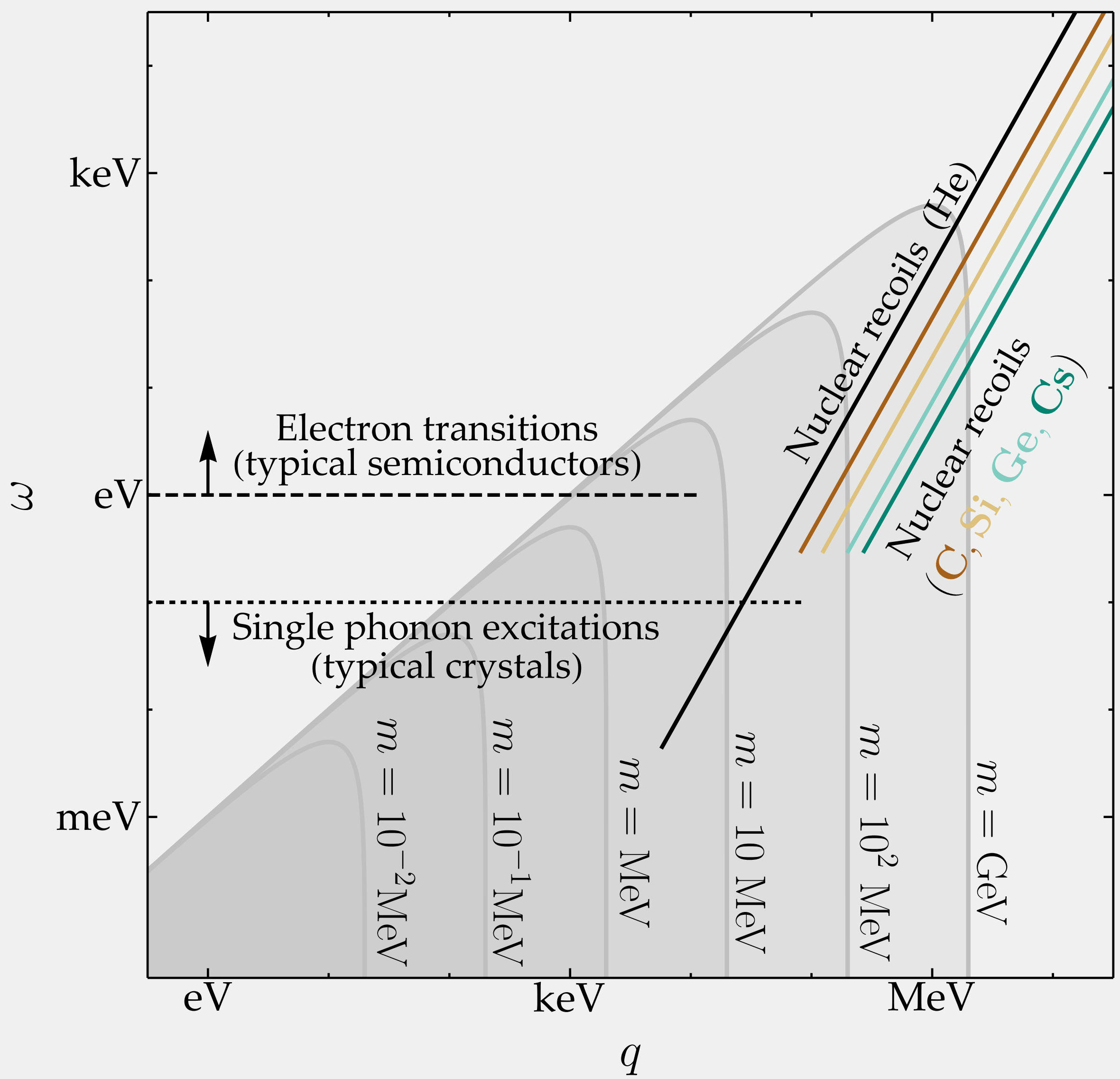
Momentum transfer too small. Only gapped magnons are kinematically accessible.



Momentum transfer beyond the first Brillouin zone. Gapped magnons dominate.

Summary

- New ideas beyond conventional nuclear recoils are needed to detect sub-GeV DM.
- Starting point is to find materials with excitations that match DM kinematics.



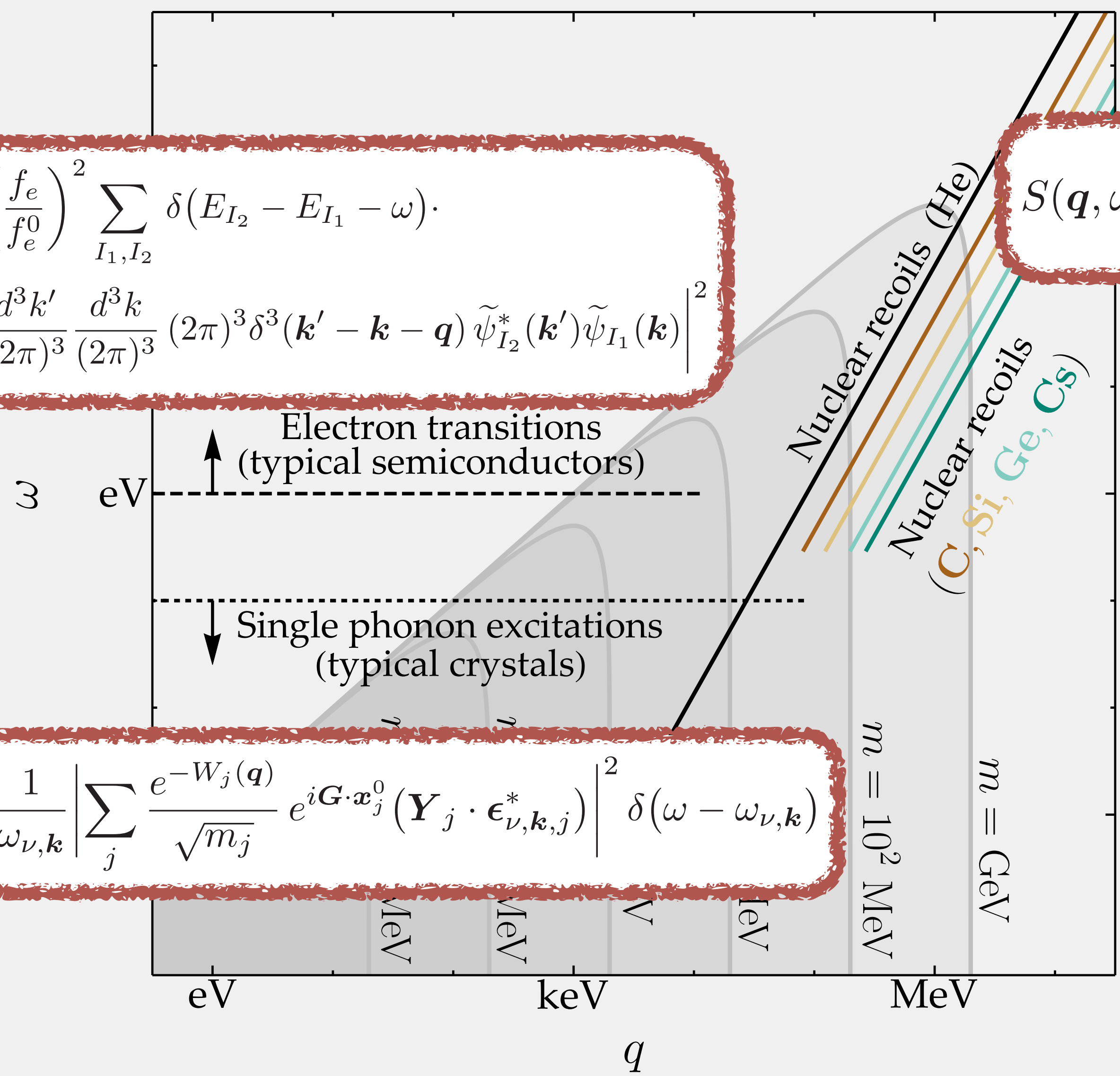
Summary

- Target response is captured by the dynamic structure factor, calculable from first principles.

$$\Gamma = \int \frac{d^3q}{(2\pi)^3}\, |\mathcal{M}|^2\, S(\boldsymbol{q},\omega)\Big|_{\omega=\boldsymbol{q}\cdot\boldsymbol{v}-\frac{q^2}{2m_\chi}}$$

$$S(\boldsymbol{q},\omega) = \frac{2\pi}{V}\left(\frac{f_e}{f_e^0}\right)^2 \sum_{I_1,I_2} \delta(E_{I_2}-E_{I_1}-\omega)\cdot \left|\int \frac{d^3k'}{(2\pi)^3}\frac{d^3k}{(2\pi)^3}(2\pi)^3\delta^3(\boldsymbol{k}'-\boldsymbol{k}-\boldsymbol{q})\,\widetilde{\psi}^*_{I_2}(\boldsymbol{k}')\widetilde{\psi}_{I_1}(\boldsymbol{k})\right|^2$$

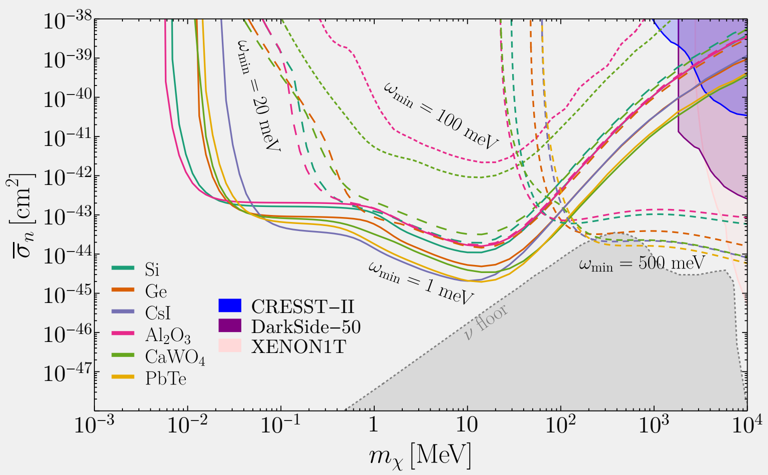
$$S(\boldsymbol{q},\omega) = 2\pi\frac{\rho_T}{m_N}\frac{f_N^2}{f_n^2}F_N^2\,\delta\left(\omega-\frac{q^2}{2m_N}\right)$$

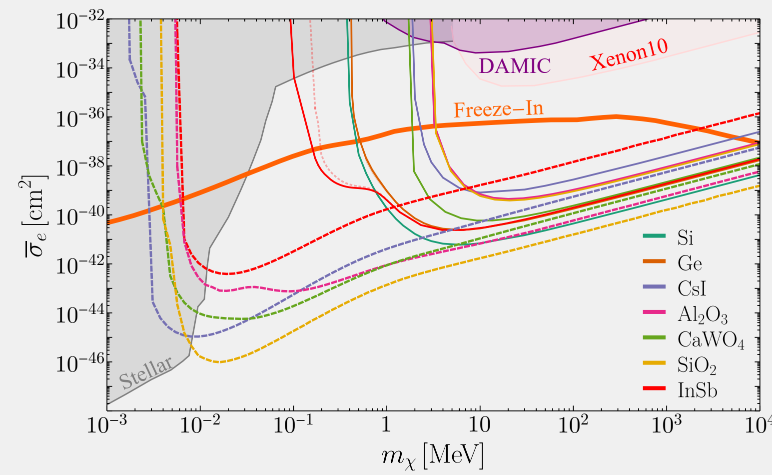


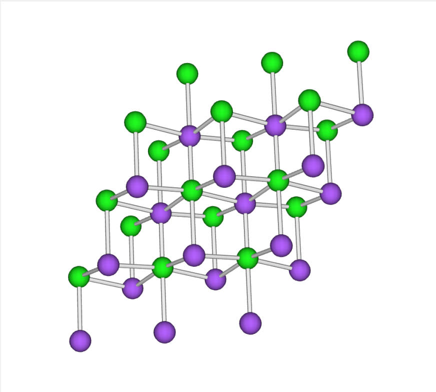
$$S(\boldsymbol{q},\omega) = \frac{\pi}{\Omega}\sum_\nu \frac{1}{\omega_{\nu,\boldsymbol{k}}}\left|\sum_j \frac{e^{-W_j(\boldsymbol{q})}}{\sqrt{m_j}}\,e^{i\boldsymbol{G}\cdot\boldsymbol{x}_j^0}\left(\boldsymbol{Y}_j\cdot\boldsymbol{\epsilon}^*_{\nu,\boldsymbol{k},j}\right)\right|^2\delta(\omega-\omega_{\nu,\boldsymbol{k}})$$

Summary

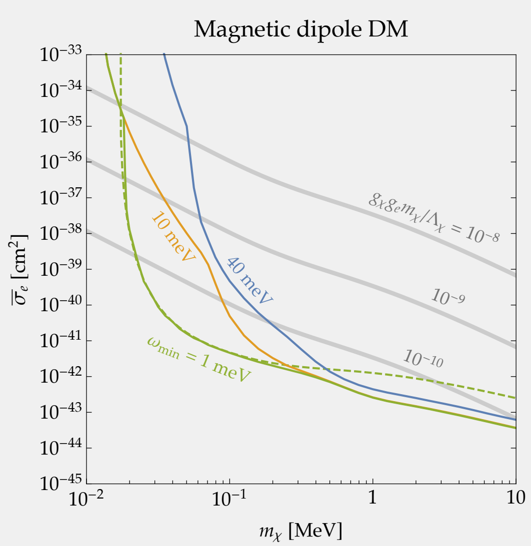
- **Collective excitations** in CM systems offer a promising path forward.
    - Acoustic and optical **phonons** probe different types of SI couplings.

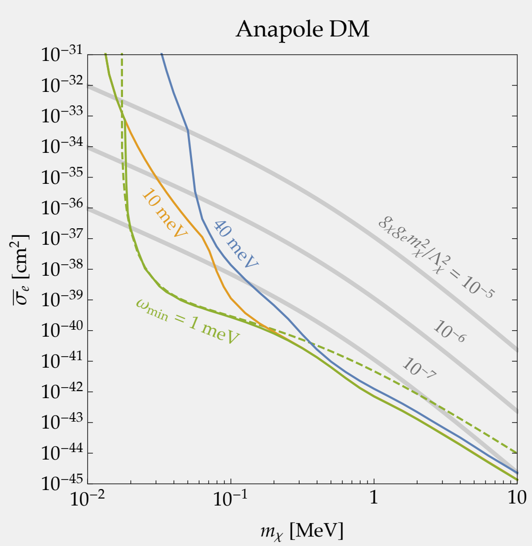


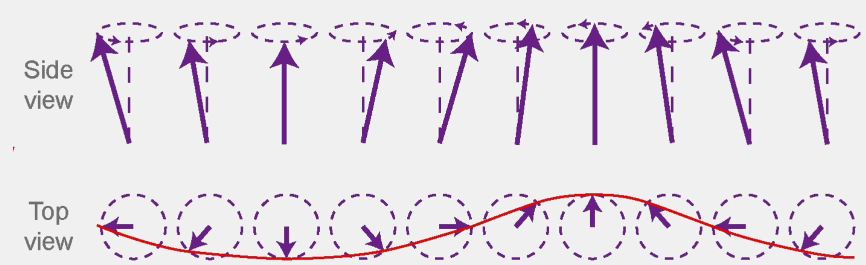




- **Magnons** can probe SD couplings.







The End

Thank you for your attention!

Aside: daily modulation

- The dynamic structure factor $S(\boldsymbol{q}, \omega)$ can be highly anisotropic.
- DM wind comes in from different directions at different times of the day => daily modulation.

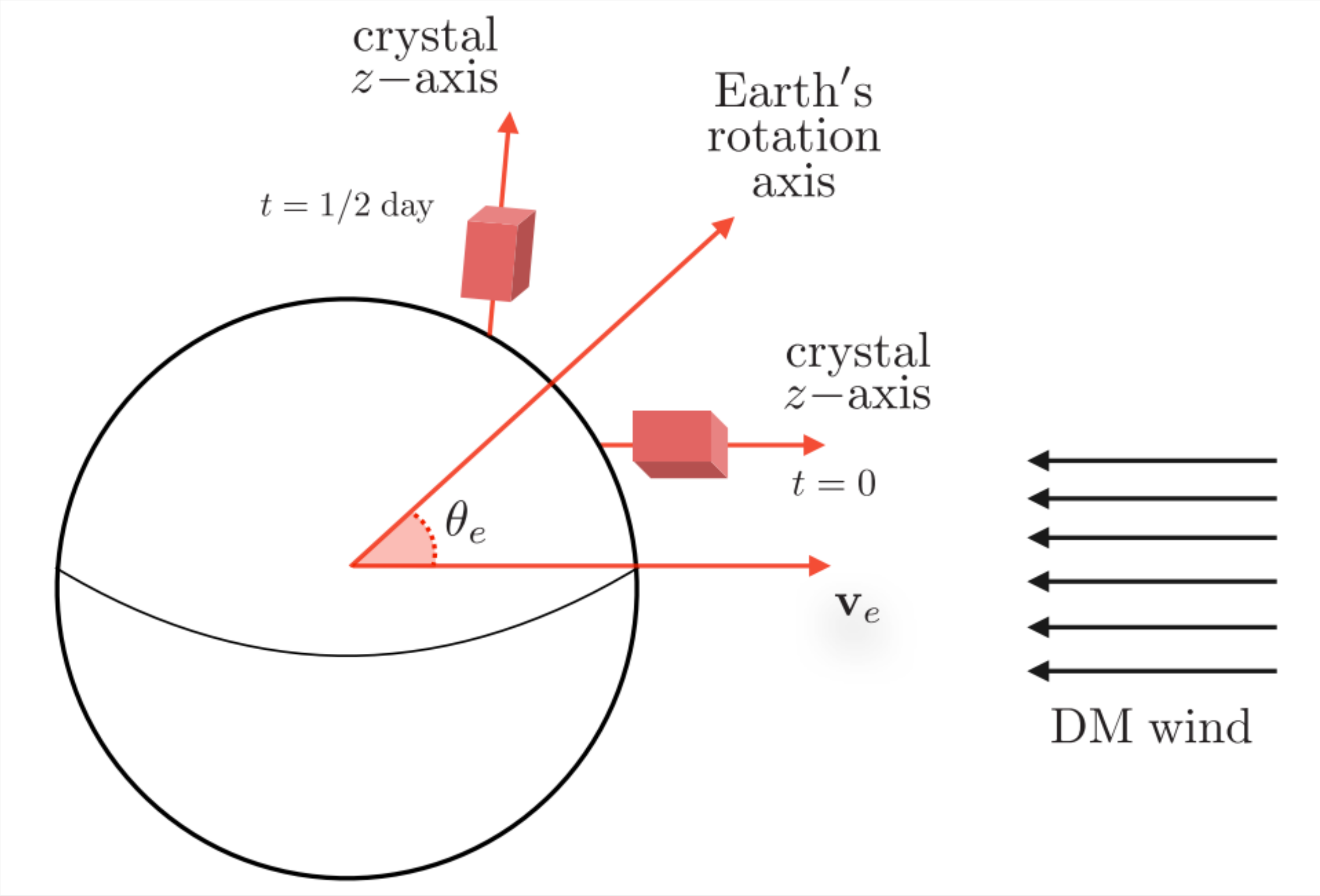


Figure from Coskuner, Mitridate, Olivares, Zurek, 1909.09170.

Aside: daily modulation

- The dynamic structure factor $S(\boldsymbol{q}, \omega)$ can be highly anisotropic.
- O(1) daily modulations in:
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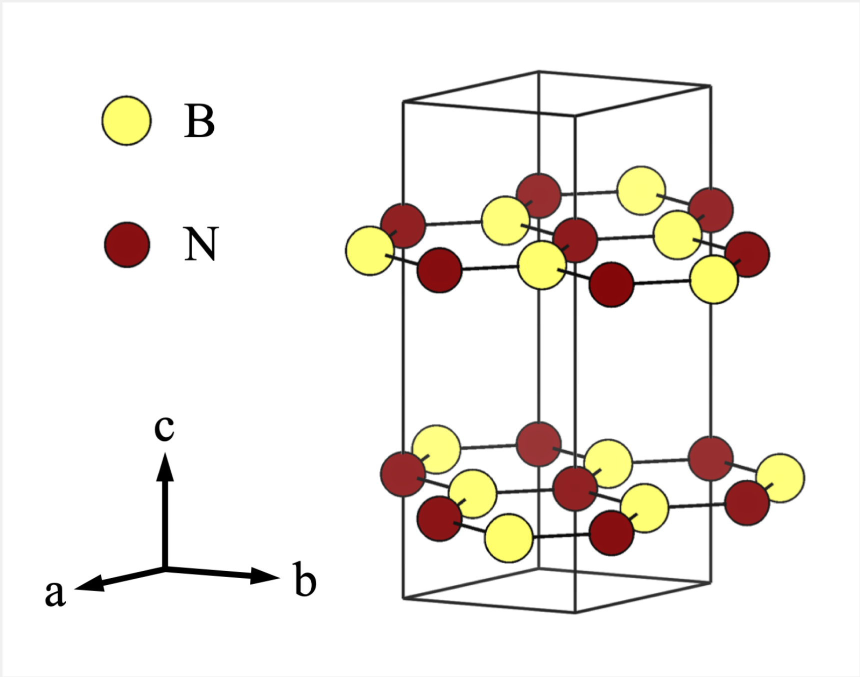

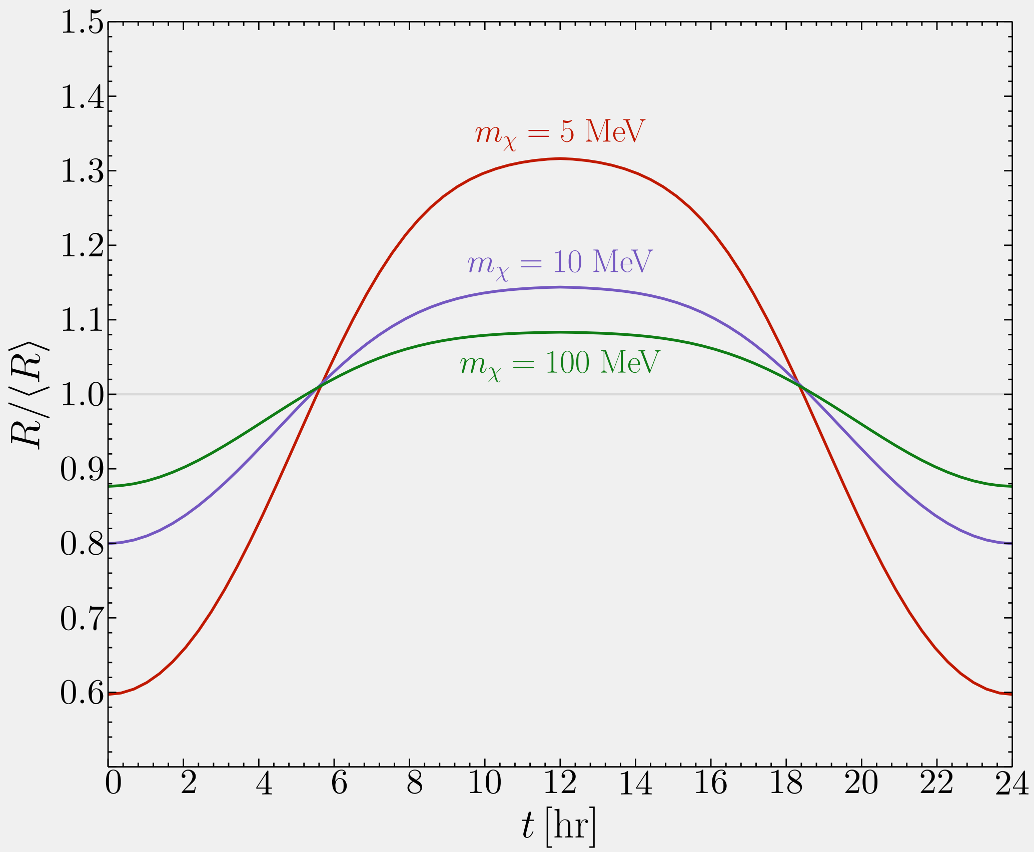

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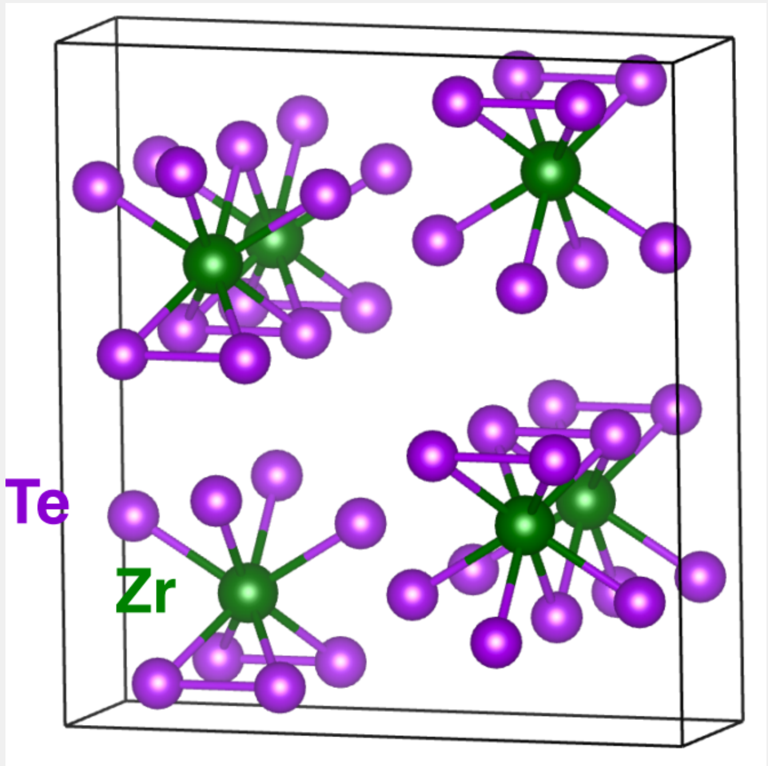

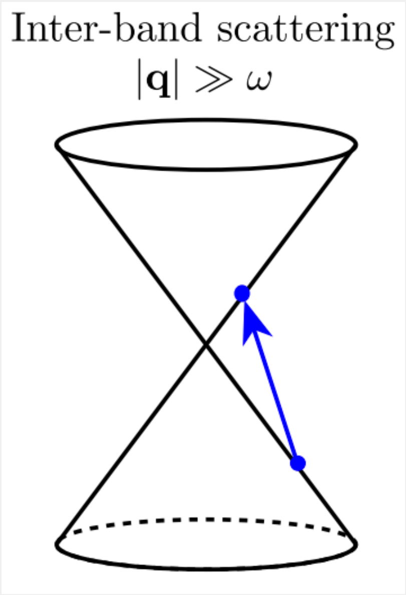

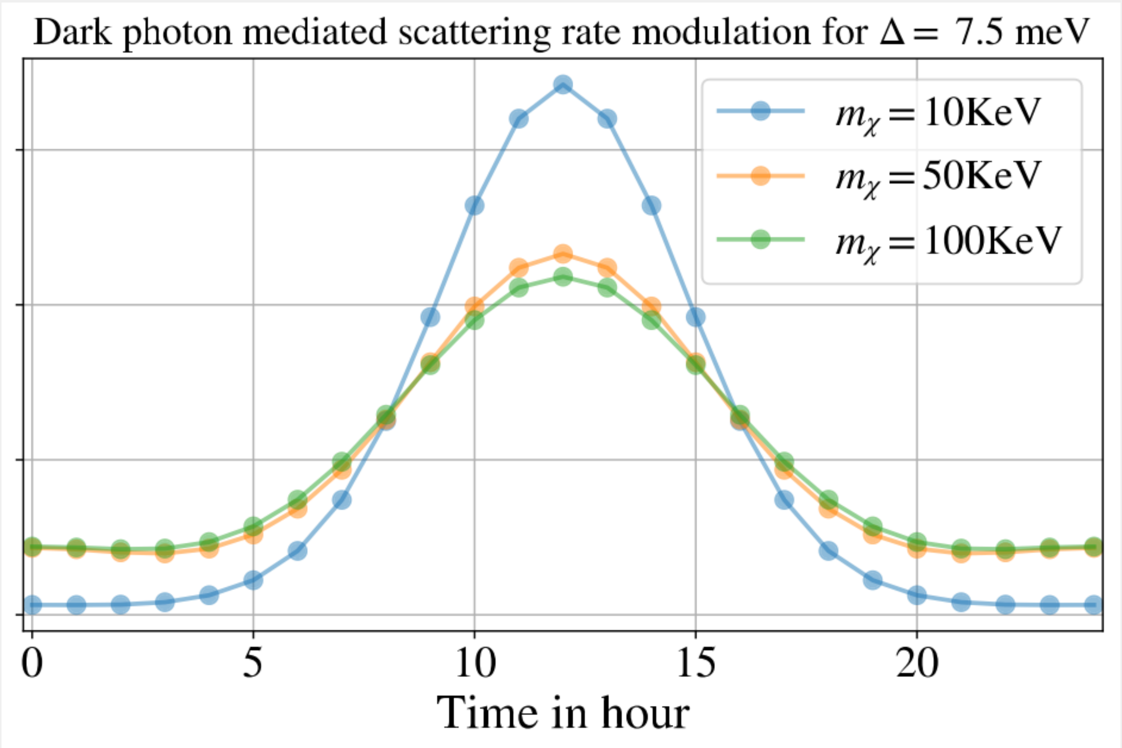

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  - Single phonon excitations in sapphire (Al_2O_3). [Griffin, Knapen, Lin, Zurek, 1807.10291]