Direct detection of light dark matter with magnons

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UC Berkeley

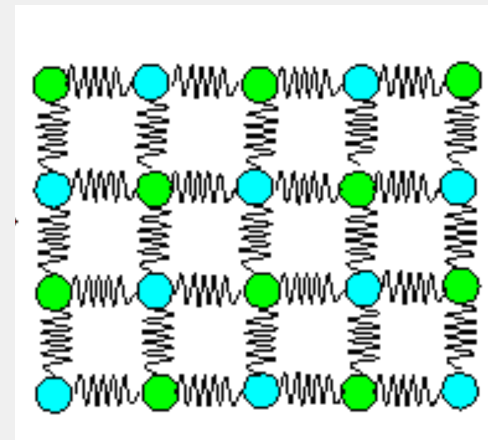
Based on: Tanner Trickle, ZZ, Kathryn Zurek, arXiv: 1905.13744.

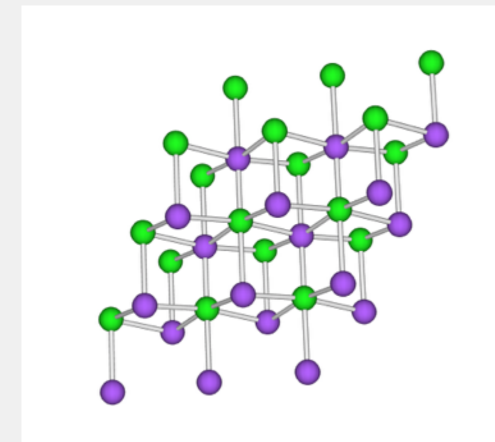
Fermilab / KICP, Jun. 2019

Roadmap

Collective excitations as a path forward for light DM

Kinematic matching in DM direct detection

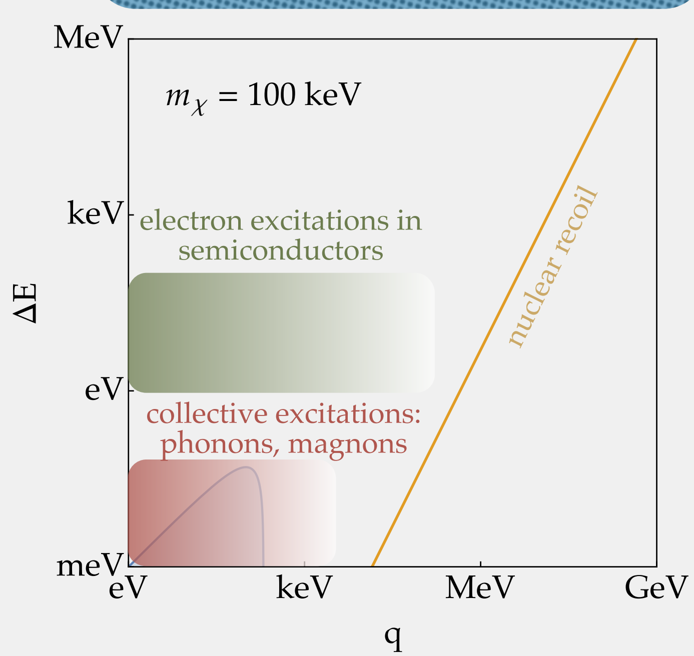




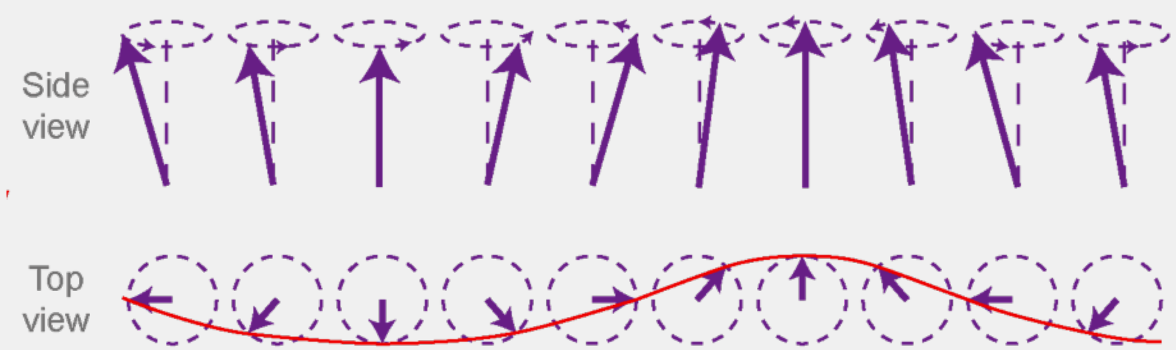
Phonons: detect *spin-independent* interactions

Kinematics

Dynamics

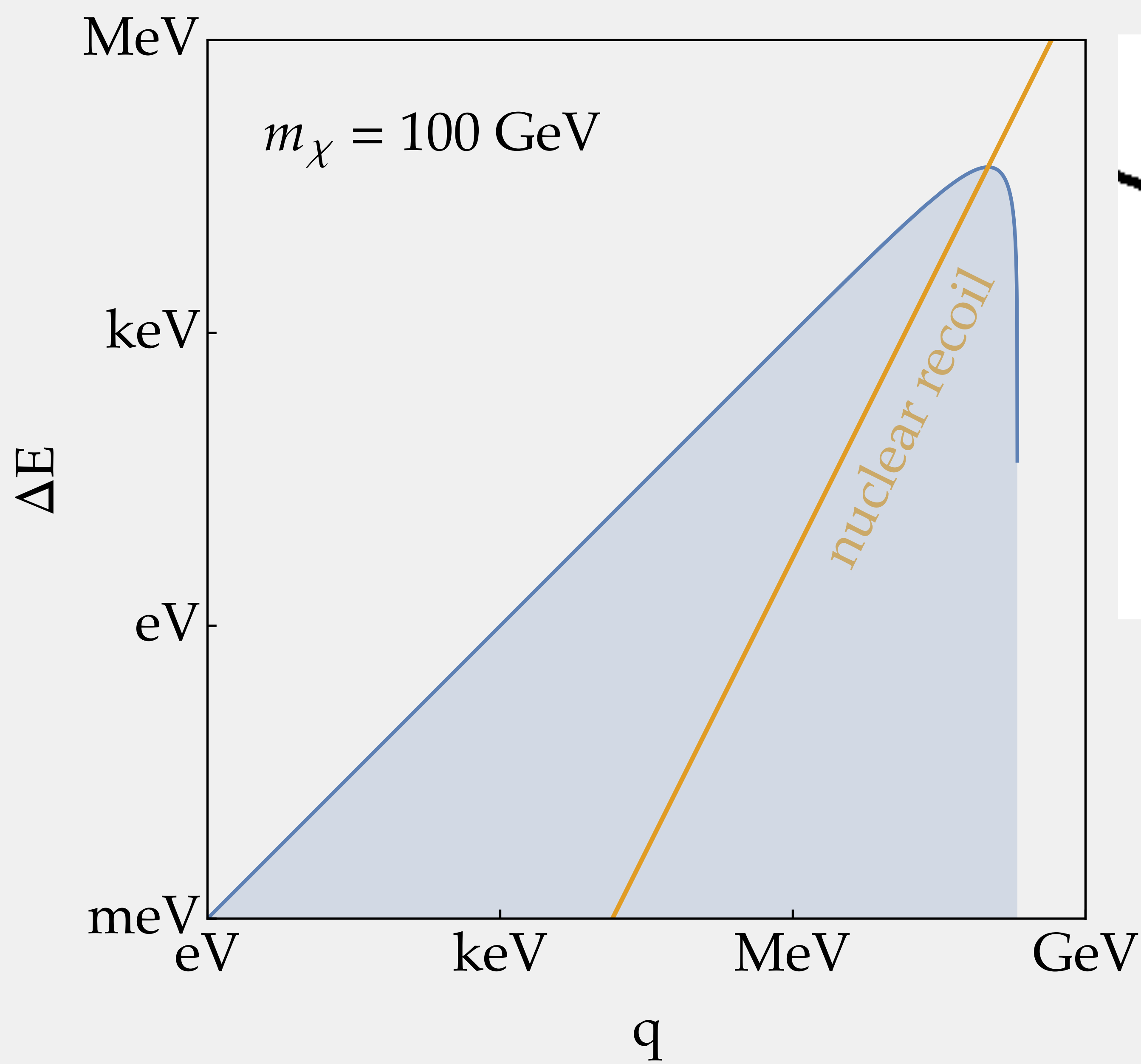


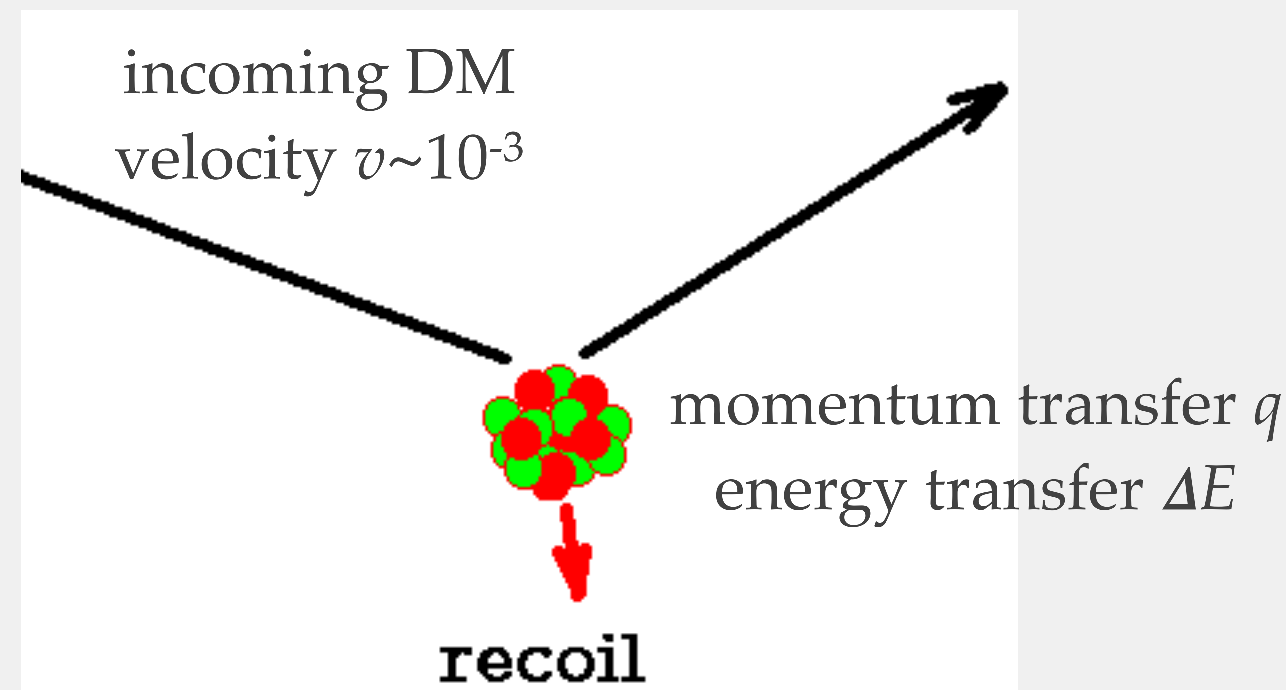
Magnons: detect *spin-dependent* interactions



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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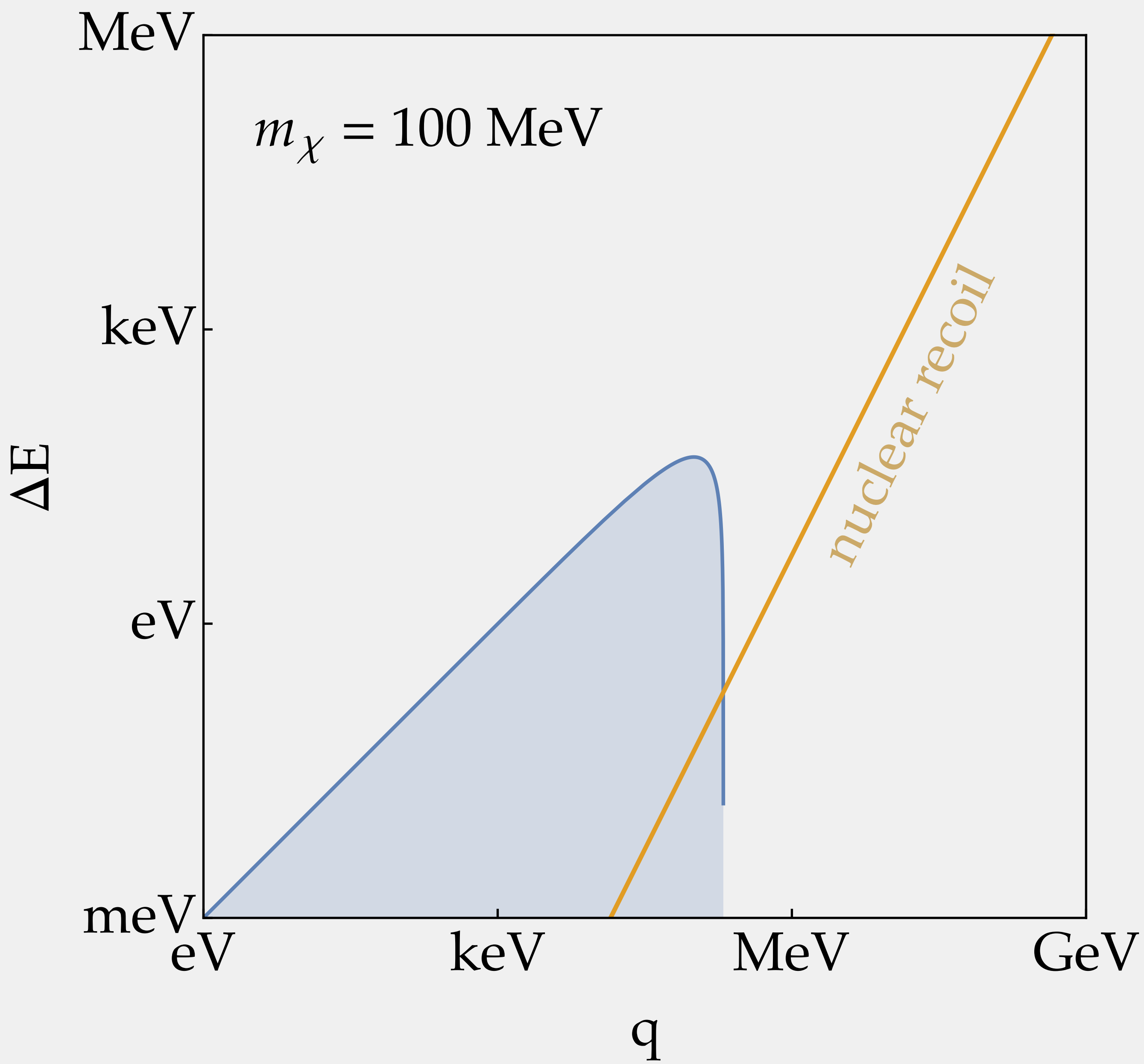

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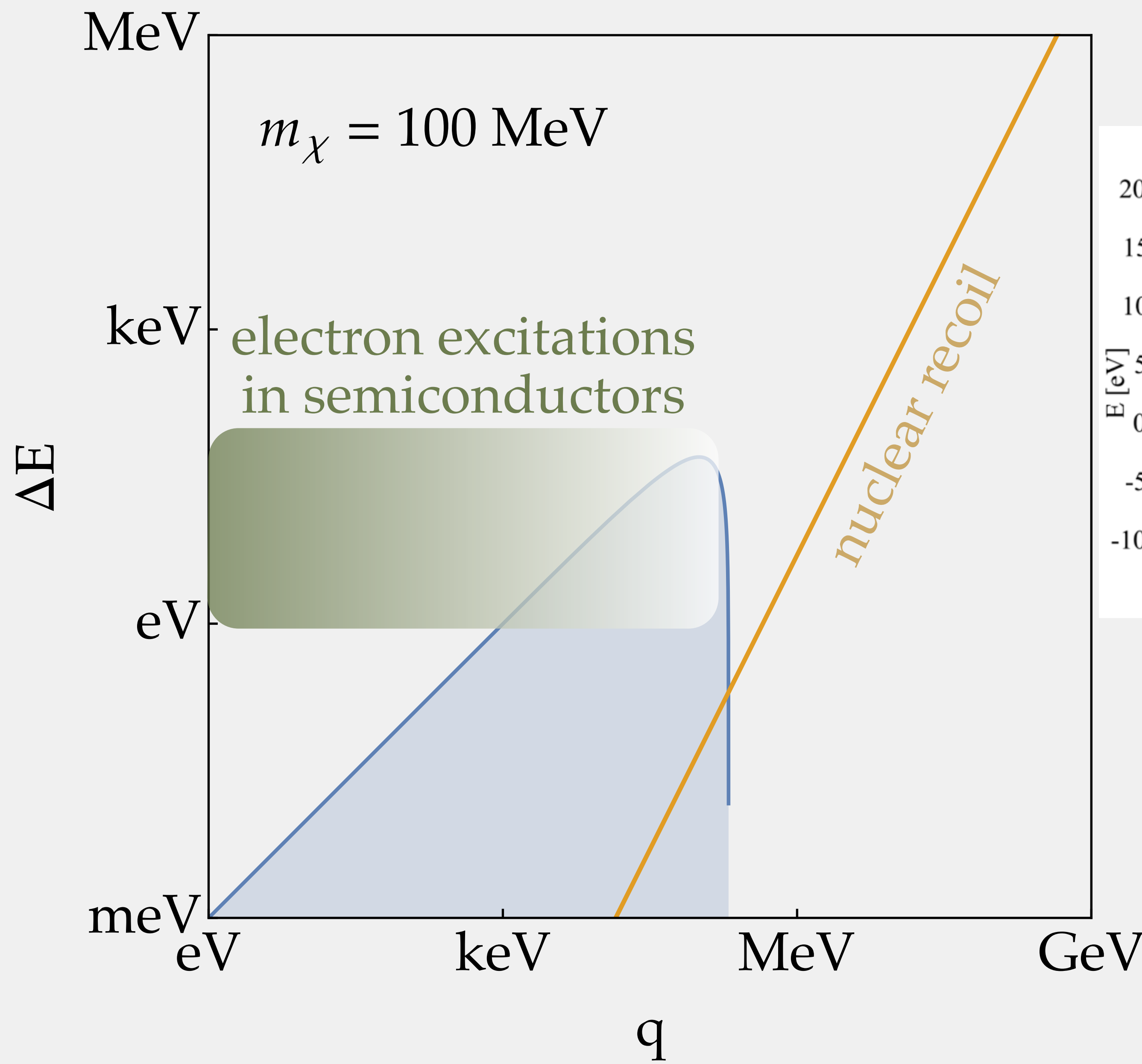
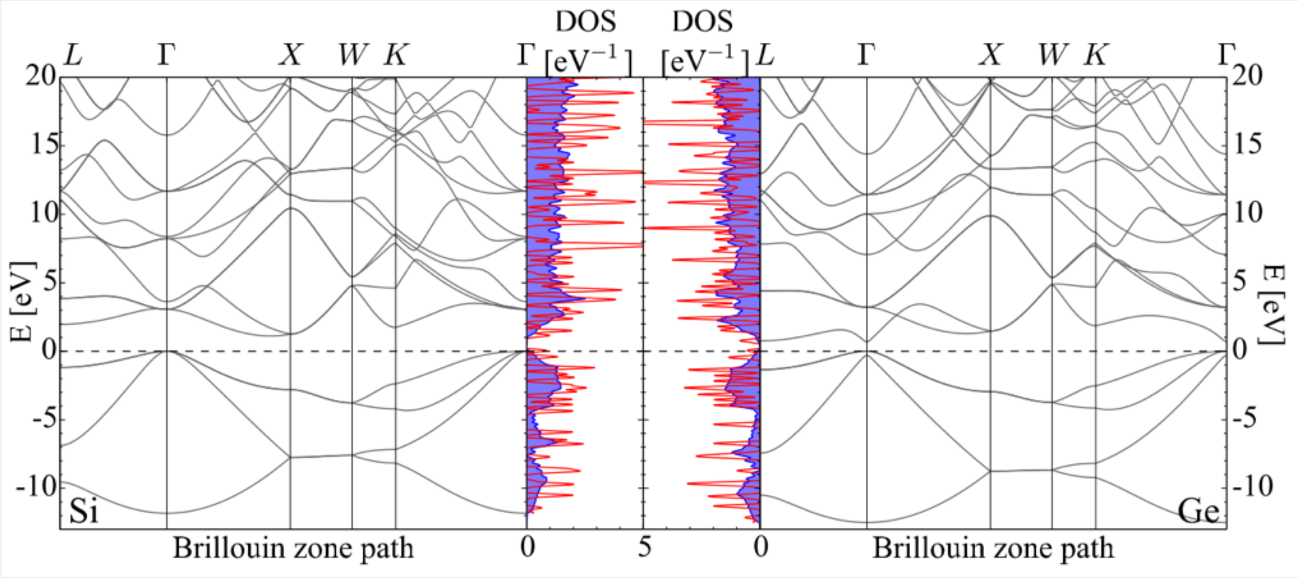


Band gap: O(eV).



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.

See talk by T. Yu.

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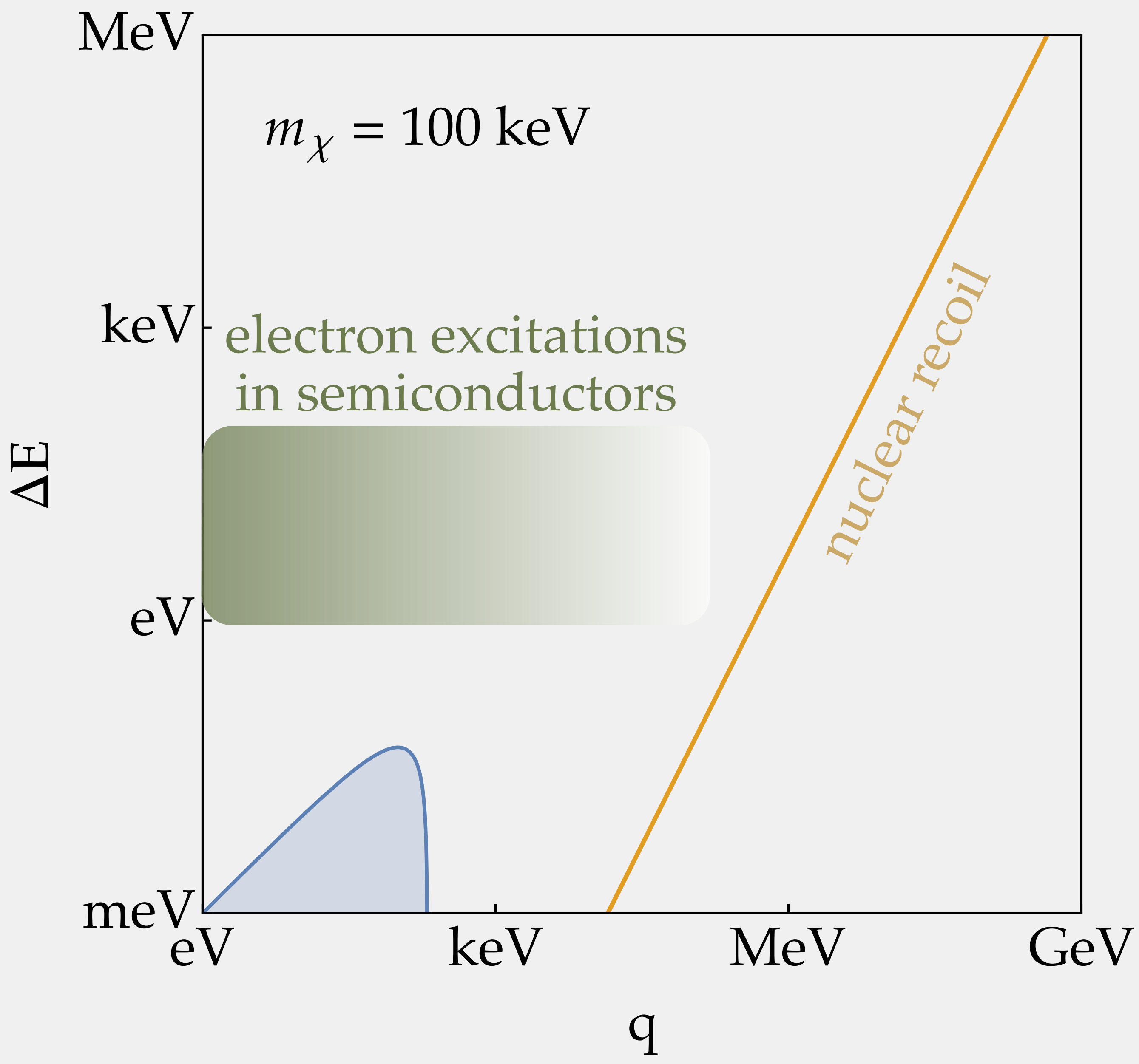

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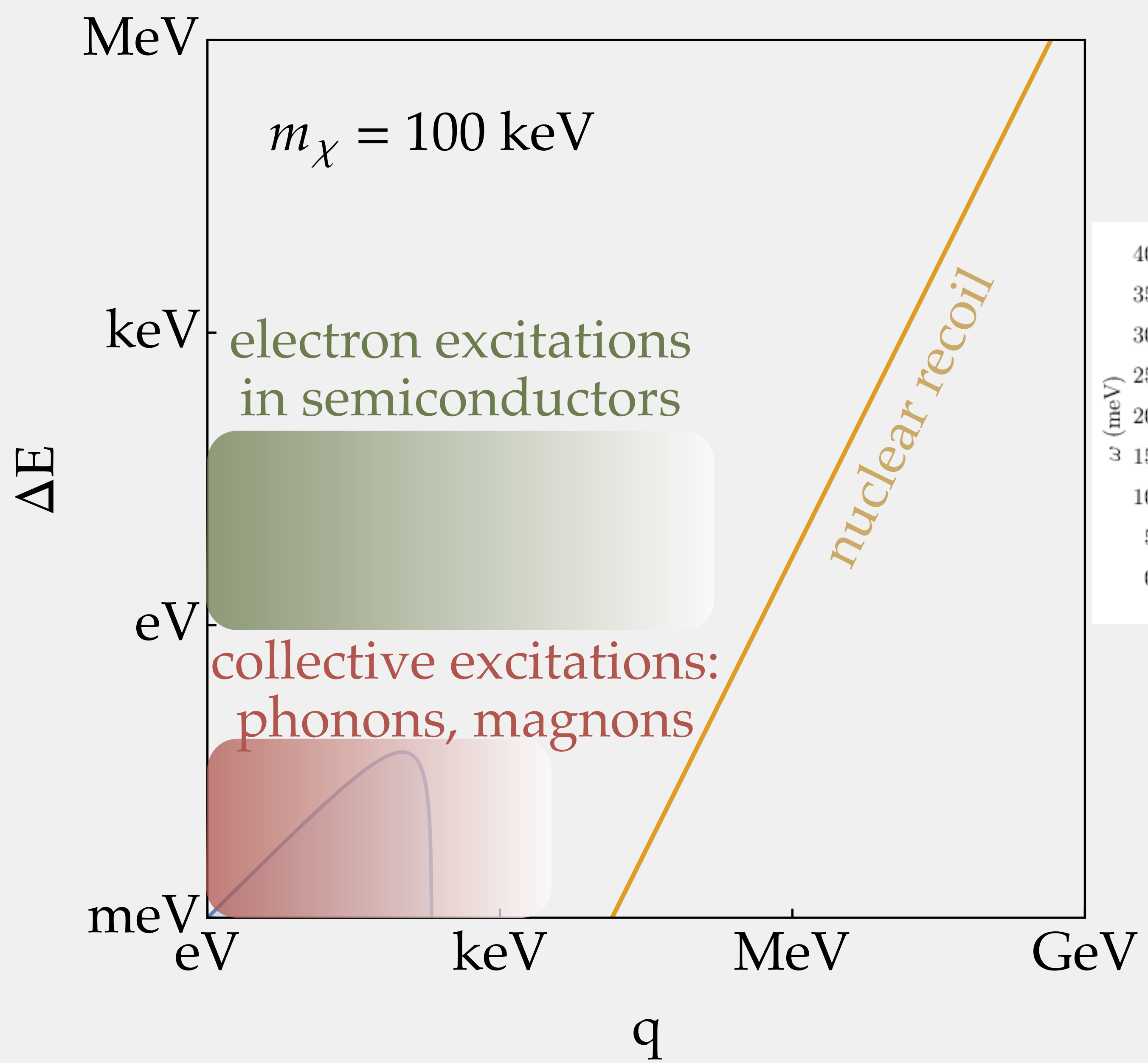
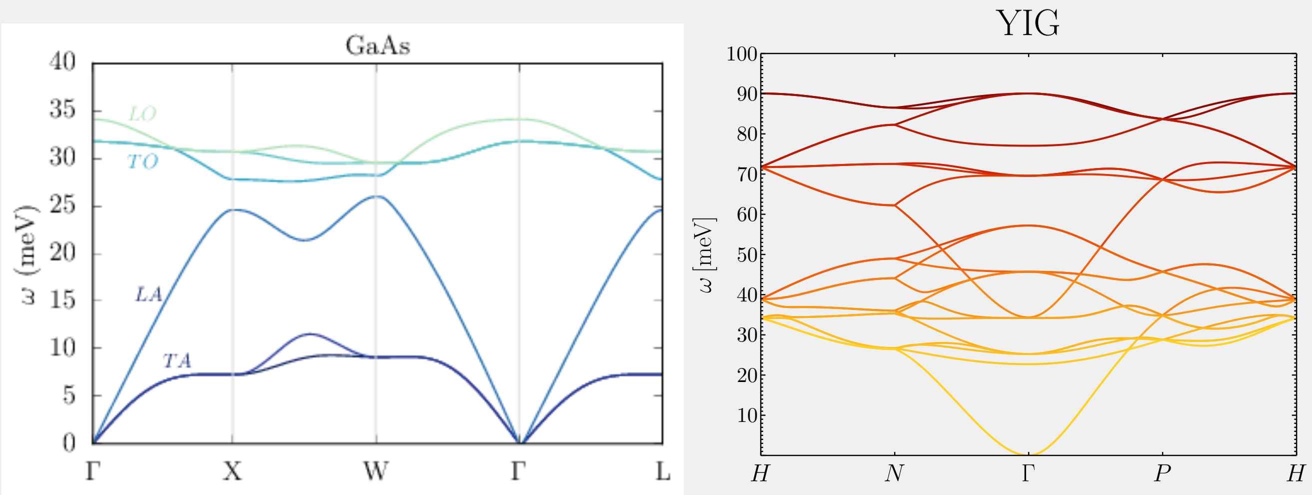


Phonons / magnons in crystals with energies up to O(100meV).

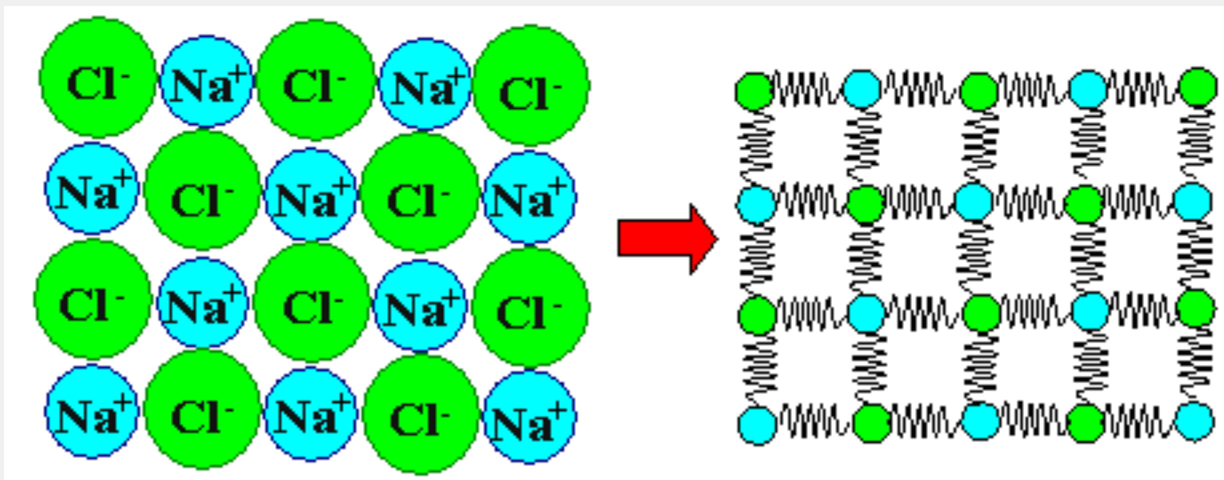


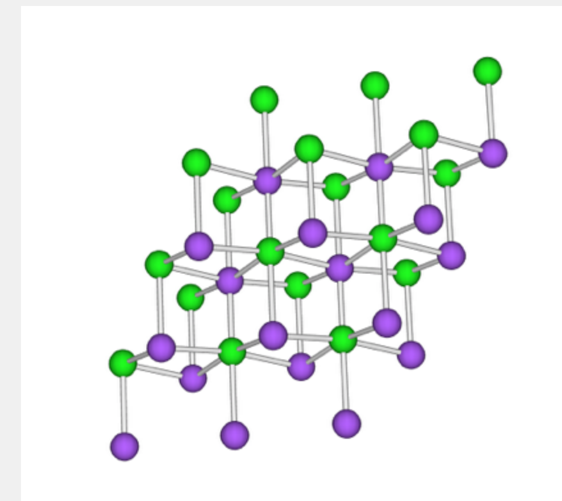
Knapen, Lin, Pyle, Zurek, 1712.06598.
Griffin, Knapen, Lin, Zurek, 1807.10291.
Trickle, ZZ, Zurek, 1905.13744.
Griffin, Inzani, Trickle, ZZ, Zurek, to appear.

See talks by T. Lin, S. Griffin.

Phonons in crystals: a brief recap

See talks by T. Lin, S. Griffin.





- Coupled quantum harmonic oscillators.
- Diagonalize the Hamiltonian => canonical modes — **phonons** (quanta of collective oscillation patterns).

$$\mathbf{u}_{j,\mathbf{l}}(t) = \sum_{\nu}^{3n} \sum_{\mathbf{q}} \sqrt{\frac{1}{2N m_j \omega_{\nu,\mathbf{q}}}} \left(\mathbf{e}_{\nu,j,\mathbf{q}} \hat{a}_{\nu,\mathbf{q}} e^{i\mathbf{q}\cdot(\mathbf{l}+\mathbf{r}_j^0) - i\omega_{\nu,\mathbf{q}} t} + \mathbf{e}^*_{\nu,j,\mathbf{q}} \hat{a}^\dagger_{\nu,\mathbf{q}} e^{-i\mathbf{q}\cdot(\mathbf{l}+\mathbf{r}_j^0) + i\omega_{\nu,\mathbf{q}} t} \right)$$

atom displacements

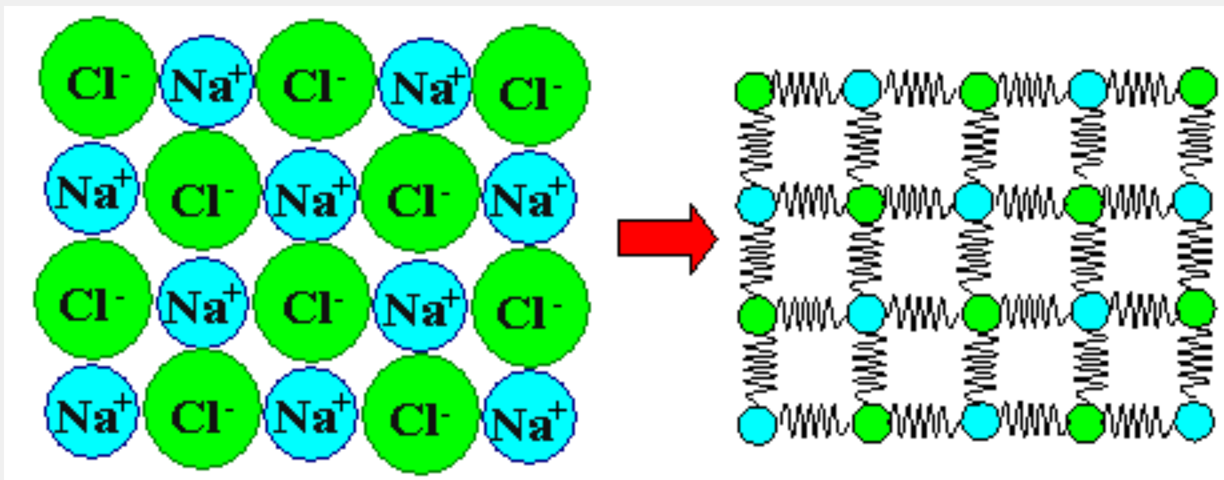
phonon creation/annihilation operators

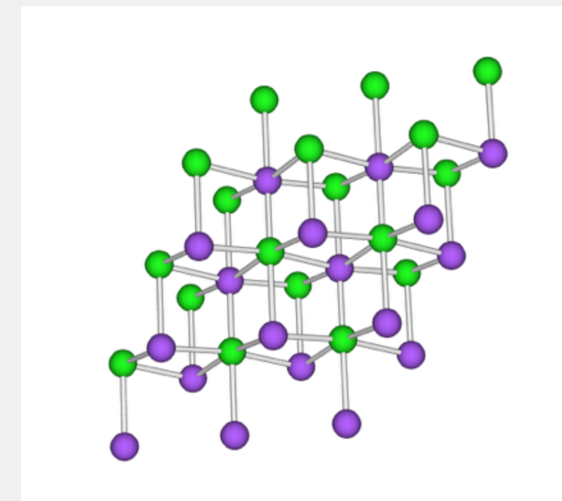
phonon mode labels

phonon polarization vectors

Phonons in crystals: a brief recap

See talks by T. Lin, S. Griffin.



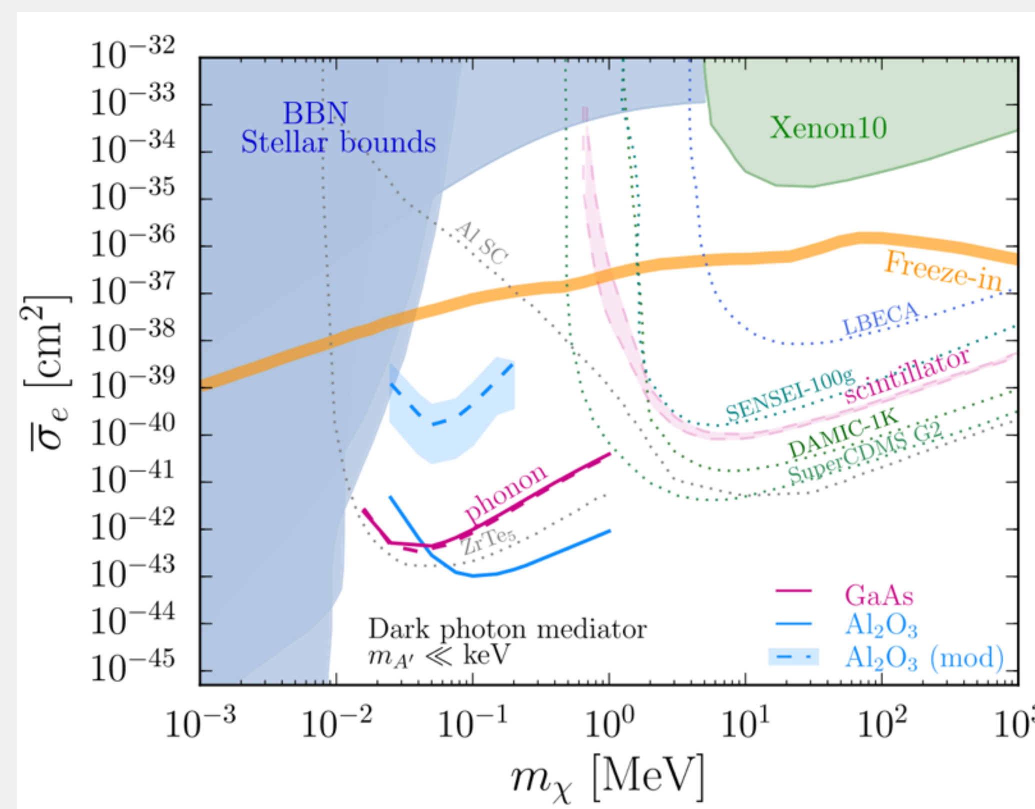


- Single phonon excitation from DM scattering (dark photon mediator case):

phonon mode labels

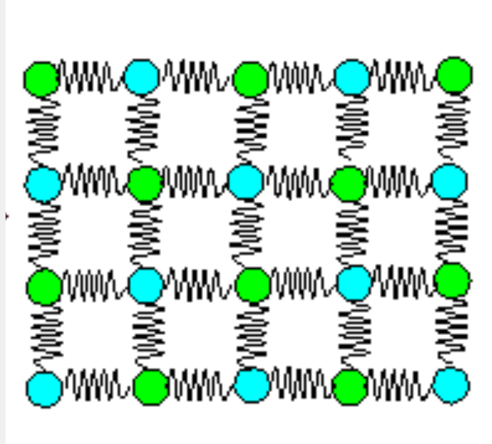
$$\mathcal{M}_{\nu,\boldsymbol{k}}(\boldsymbol{q}) = \frac{1}{N\Omega}\frac{\kappa e g_\chi}{\epsilon_\infty}\frac{1}{q^2}\langle \nu, \boldsymbol{k}| \sum_{l,j} Q_j e^{i\boldsymbol{q}\cdot\boldsymbol{x}_{lj}} |0\rangle$$

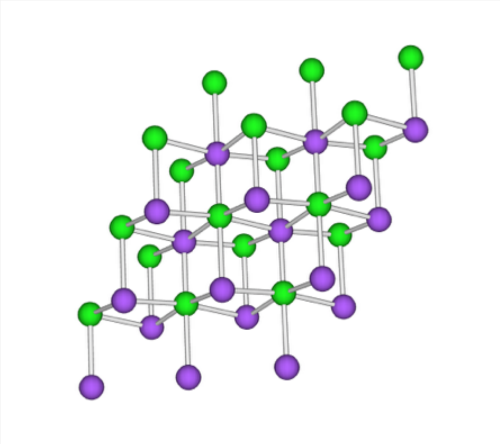
position operators create phonons



Griffin, Knapen, Lin, Zurek, 1807.10291.

Roadmap



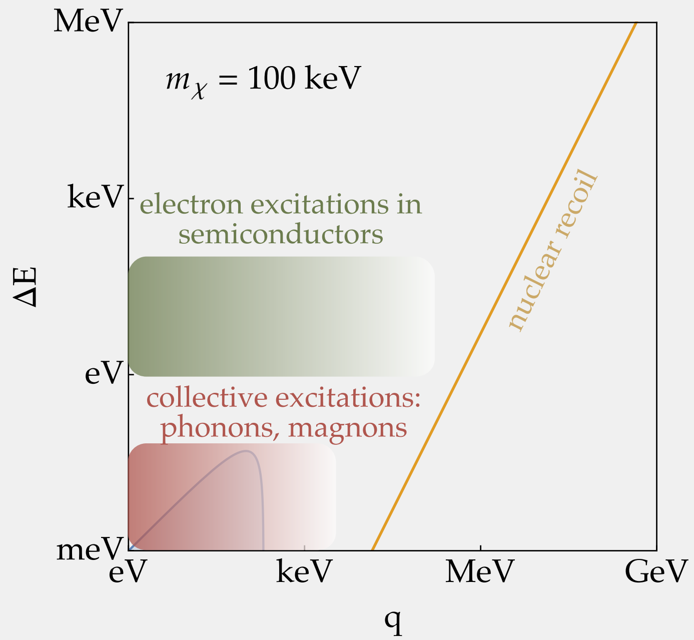


Collective excitations as a path forward for light DM

Kinematic matching in DM direct detection

Phonons: detect *spin-independent* interactions

Kinematics



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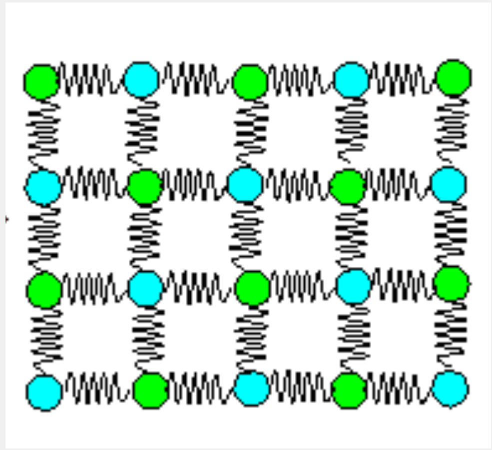

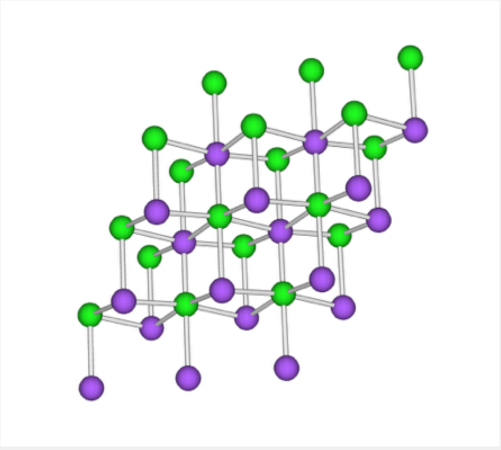

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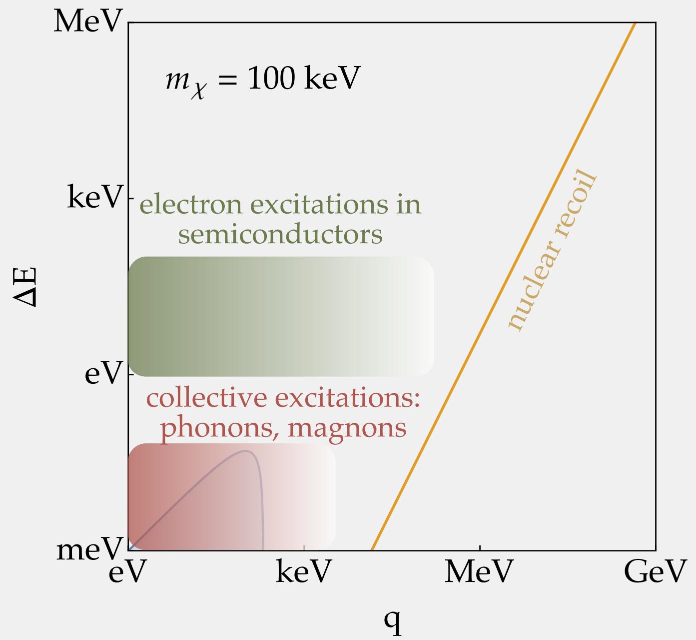
Dynamics



How does the DM couple to Standard Model particles?

DM coupling to electron spin

- 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	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu V_{\mu\nu} + g_e\bar{e}\gamma^\mu e\, V_\mu$	$\hat{\mathcal{O}}_\chi^\alpha = \frac{2g_\chi g_e}{\Lambda_\chi^2 m_e}\epsilon^{\alpha\beta\gamma} i q^\beta \hat{S}_\chi^\gamma$

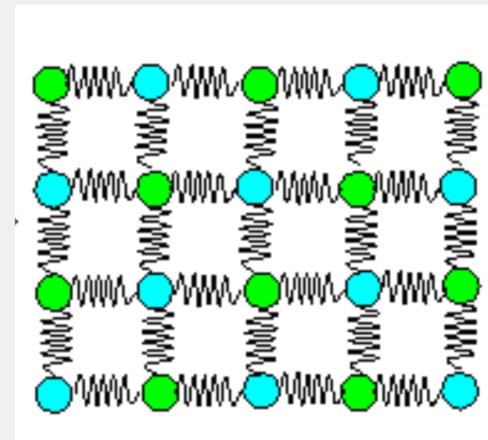
- In these scenarios, DM couples to the electron **spin** at low energy:

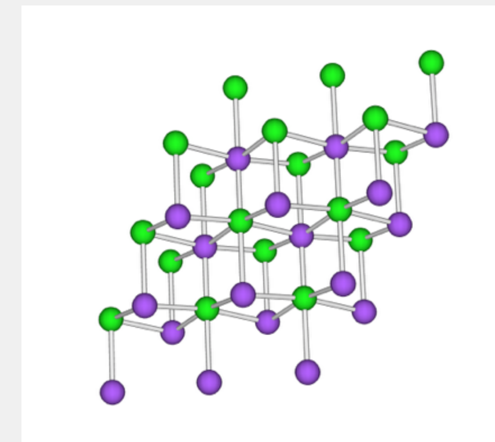
$$\mathcal{L} = -\sum_{\alpha=1}^{3}\hat{\mathcal{O}}_\chi^\alpha(\boldsymbol{q})\hat{S}_e^\alpha$$

- Such couplings can also arise in scalar mediator models.

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

Roadmap

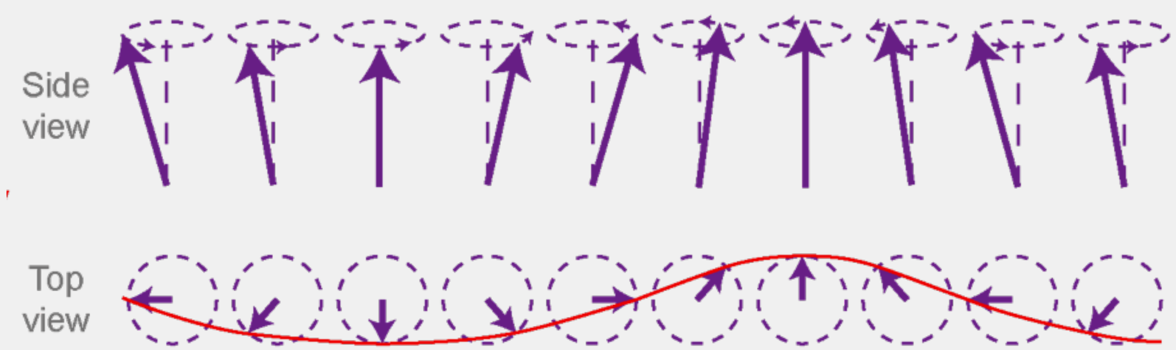




Phonons: detect *spin-independent* interactions

Dynamics

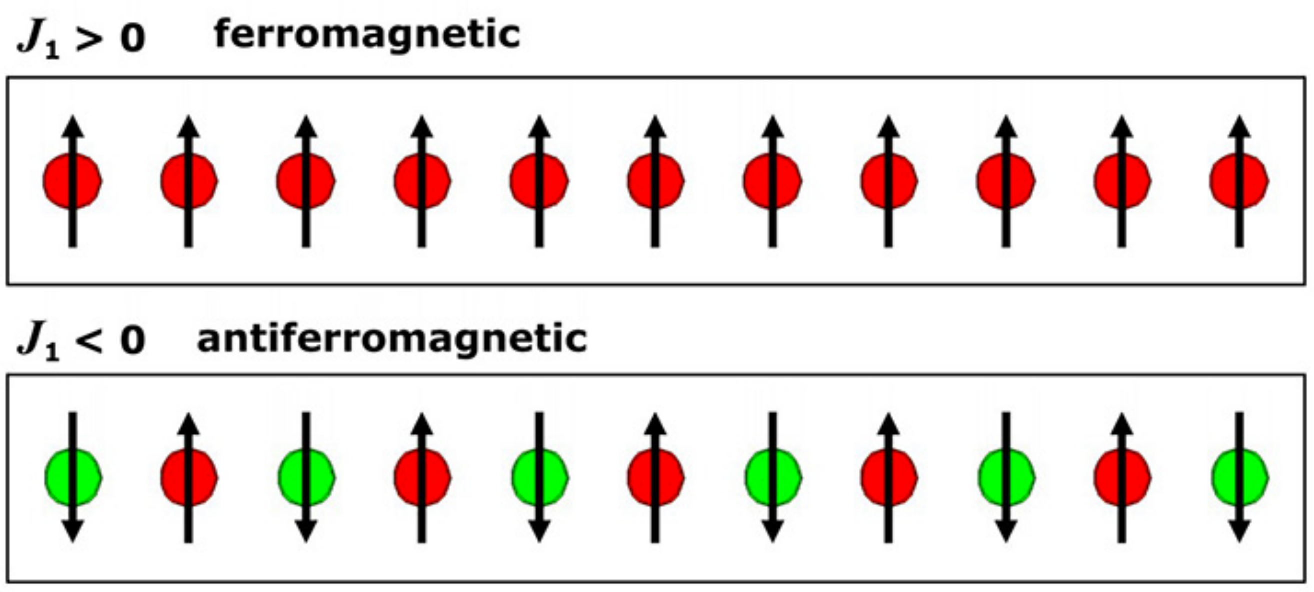
Magnons: detect *spin-dependent* interactions



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**.

Heisenberg exchange $E_{\mathrm{H}} = -\sum_{i,j} J_{ij}\, \mathbf{S}_i \cdot \mathbf{S}_j$



- 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…

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

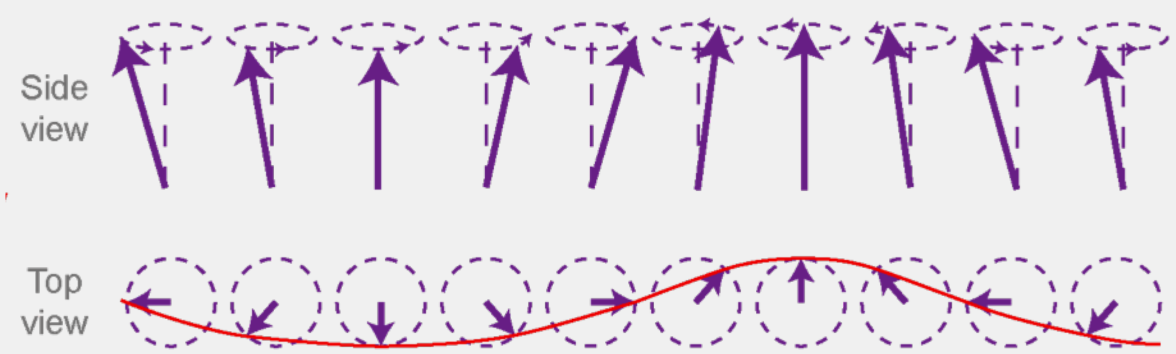
where $$S^\alpha_{lj} = \sum_\beta R^{\alpha\beta}_j S'^\beta_{lj}\,, \qquad \{\langle S'^1_{lj}\rangle, \langle S'^2_{lj}\rangle, \langle S'^3_{lj}\rangle\} = \{0,\, 0,\, S_j\}$$

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

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

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

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



canonical magnon modes
(quanta of collective precession patterns)

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canonical magnon modes (quanta of collective precession patterns)

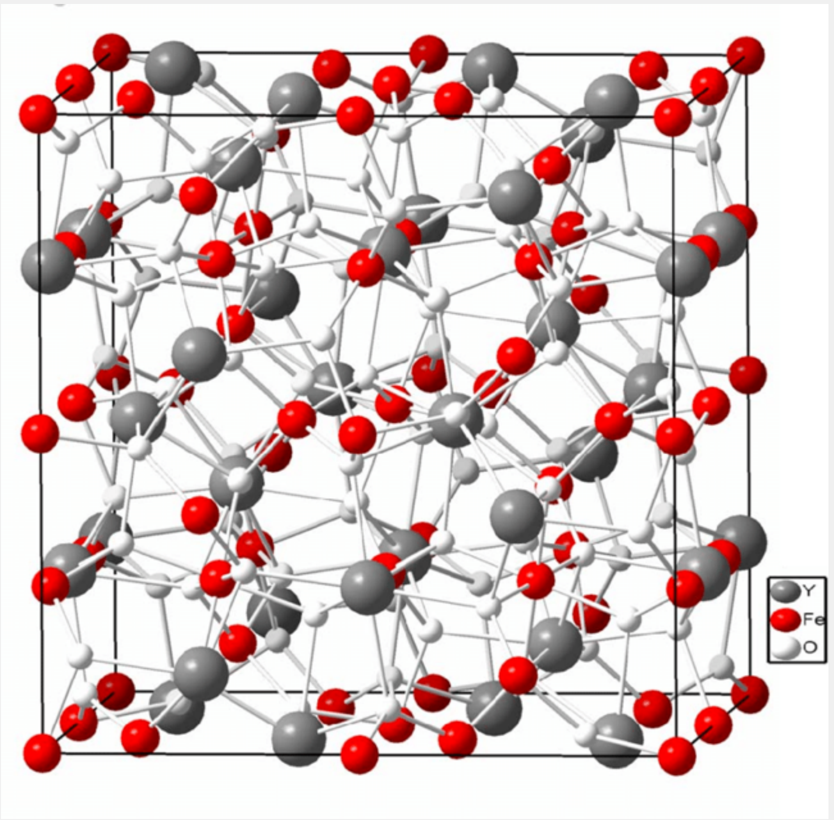
- DM-spin coupling => DM-magnon coupling.

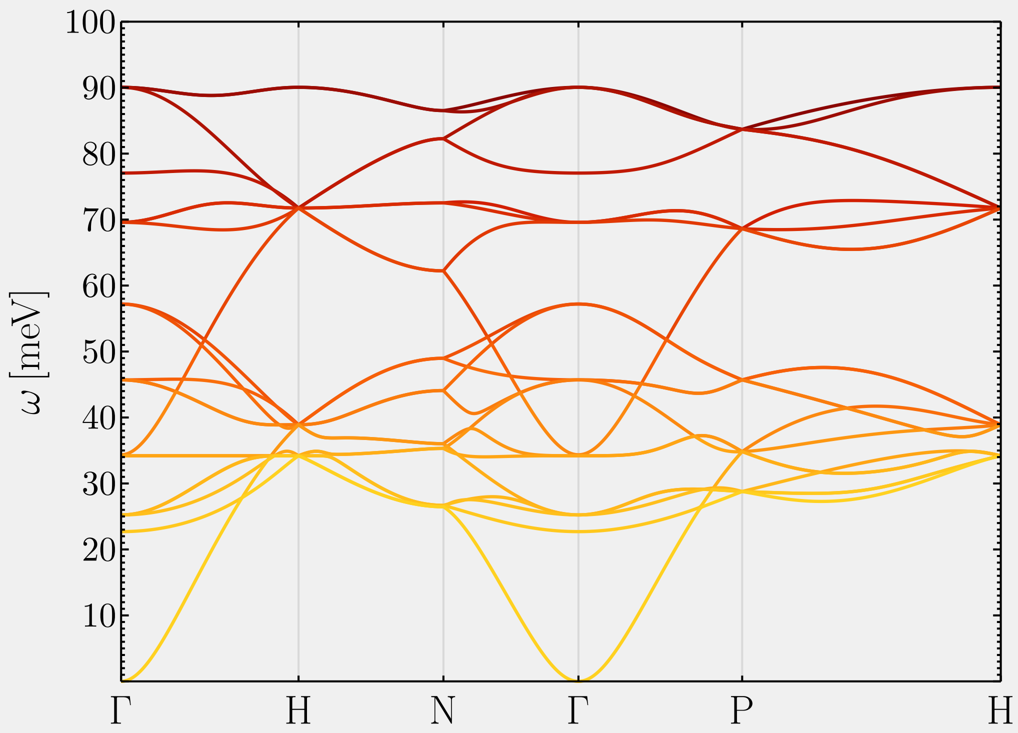
$$\mathcal{L} = -\sum_{\alpha=1}^{3} \hat{\mathcal{O}}^\alpha_\chi(\boldsymbol{q})\hat{S}^\alpha_e \quad \Rightarrow \quad \mathcal{M}^{s_i s_f}_{\nu,\boldsymbol{k}}(\boldsymbol{q}) = \frac{1}{N\Omega}\langle s_f|\hat{\mathcal{O}}^\alpha_\chi(\boldsymbol{q})|s_i\rangle\langle \nu,\boldsymbol{k}|\sum_{lj}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

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.

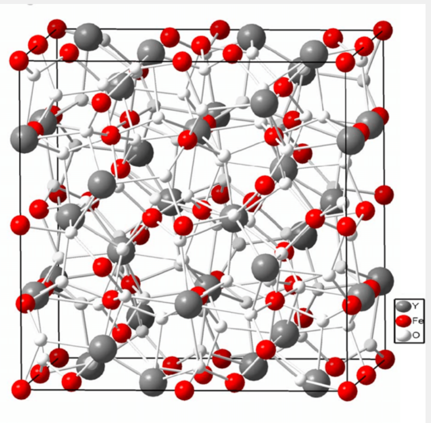


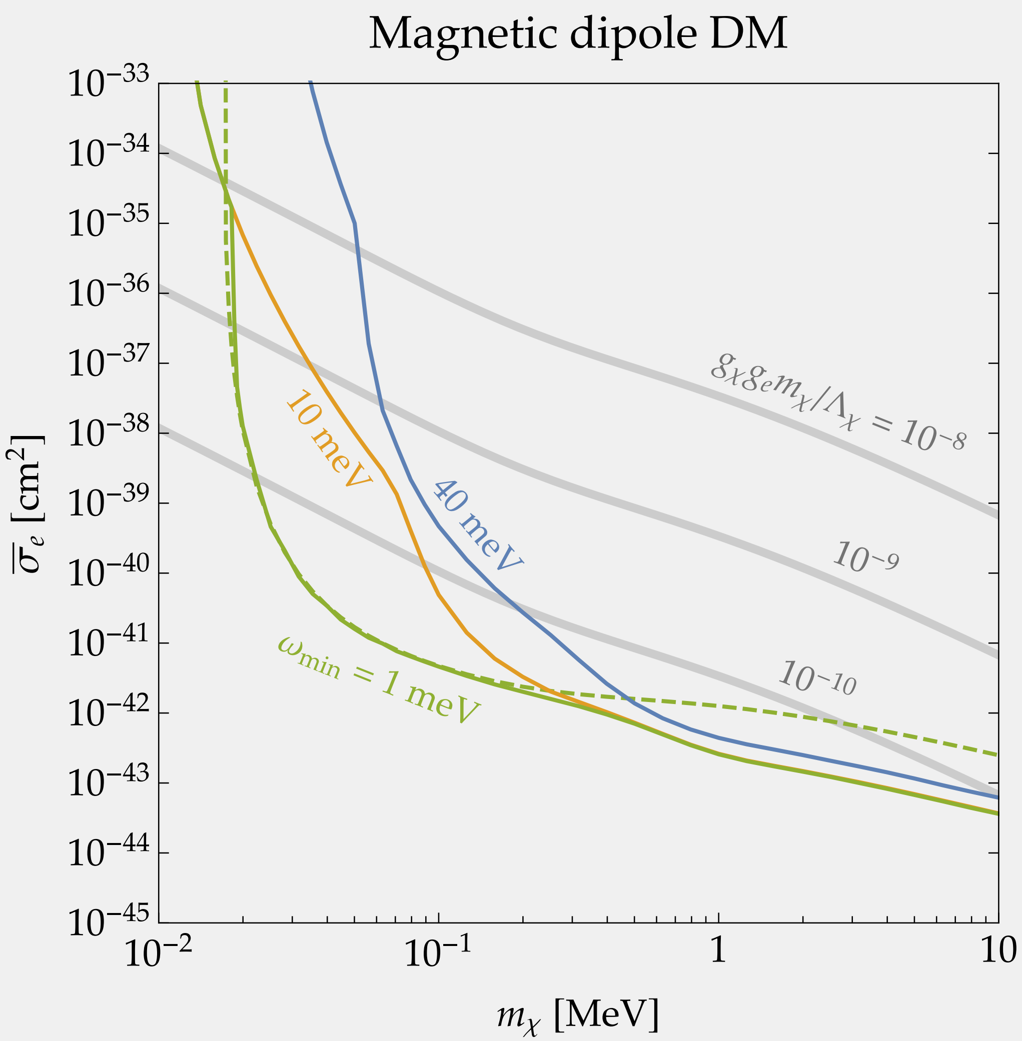


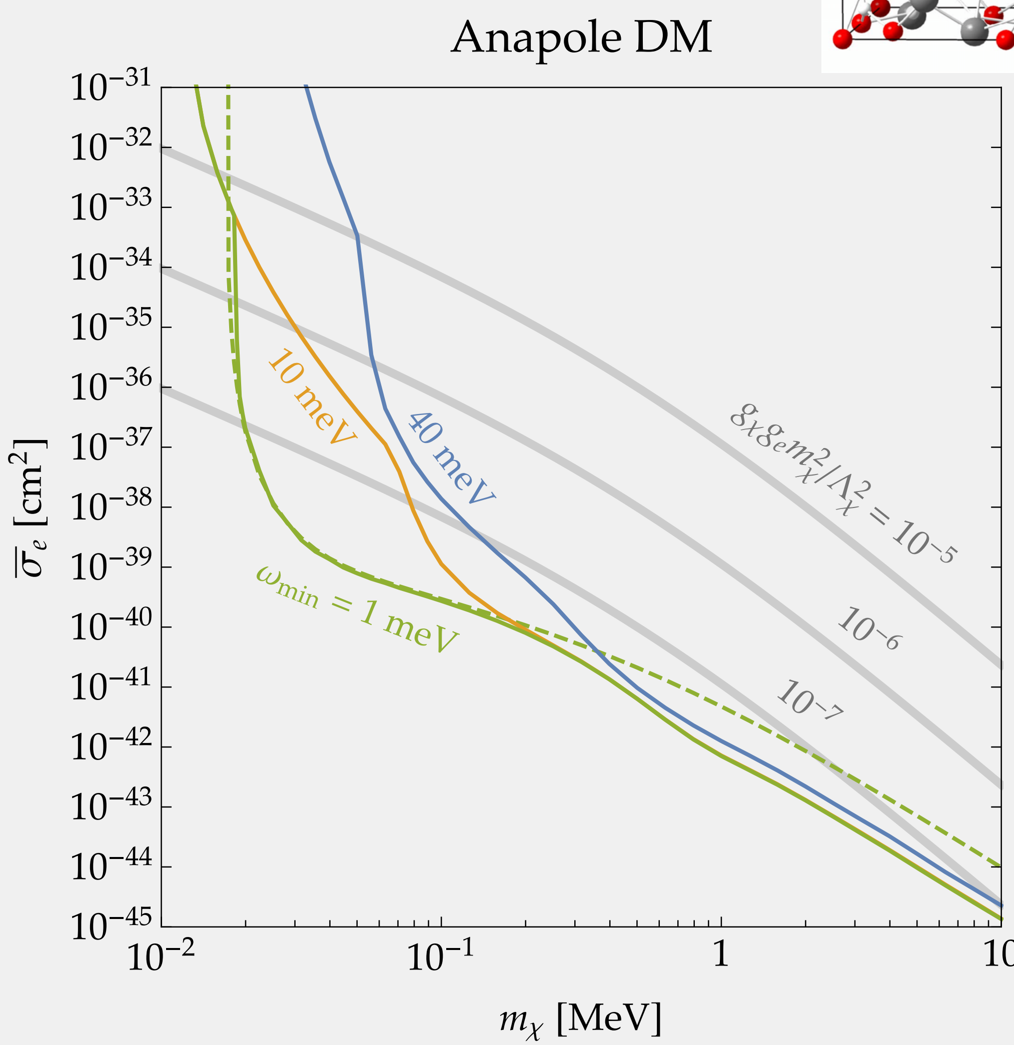
Magnon dispersion calculated by including up to 3rd nearest neighbor exchange couplings taken from: Cherepanov, Kolokolov, L'vov, Physics Reports 229, 81 (1993).

Projected reach

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



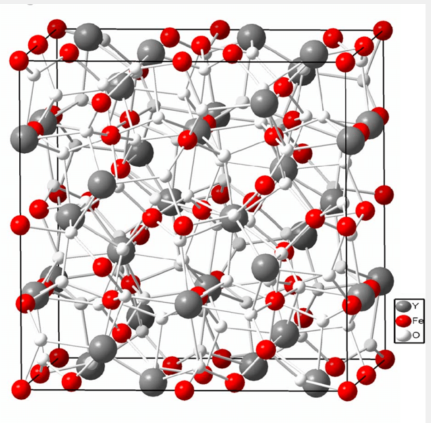


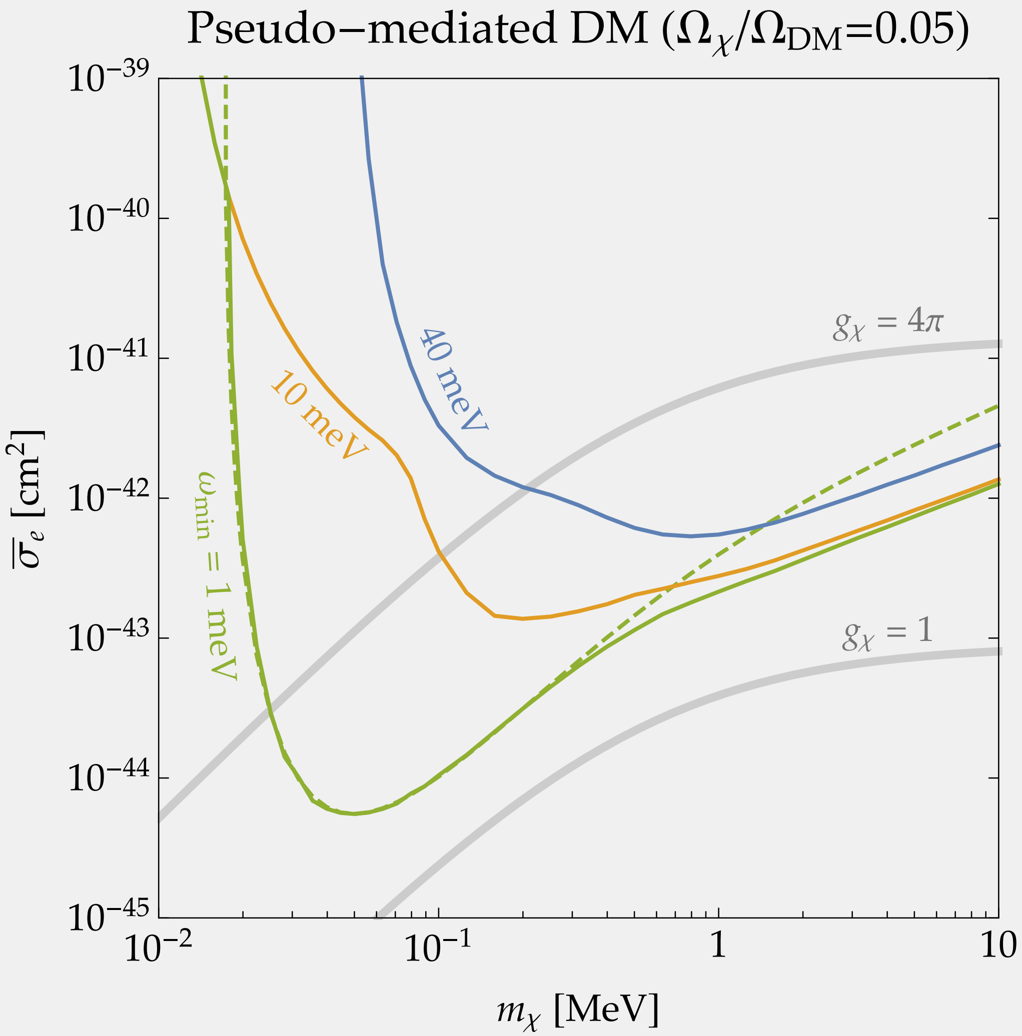


Projection assumes 3 signal events/kg/yr.

Projected reach

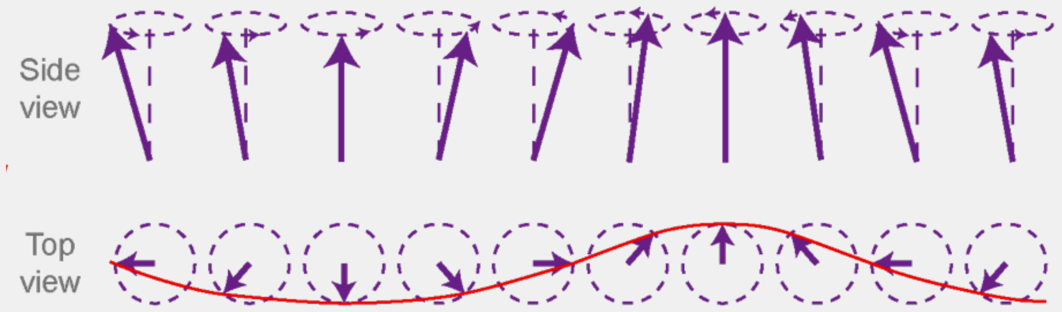
- We consider a **yttrium iron garnet (YIG, $Y_3Fe_5O_{12}$)** target.
- Scalar mediator (impose white dwarf cooling constraint, consider SIDM subcomponent):





Summary

- **Collective excitations** in condensed matter systems offer promising detection paths for light DM due to **kinematic matching**.
- There is also a **dynamics** aspect of direct detection. Different excitations can be sensitive to different DM interactions.
- Previously **phonons** have been demonstrated to have capability of probing interesting DM scenarios with **spin-independent** interactions.
- We have shown that **magnons** (collective spin excitations) can be used to probe **spin-dependent** DM interactions, complementary to phonons.
- Next steps:
  - Detection schemes.
  - DM absorption.
  - Other types of target responses?



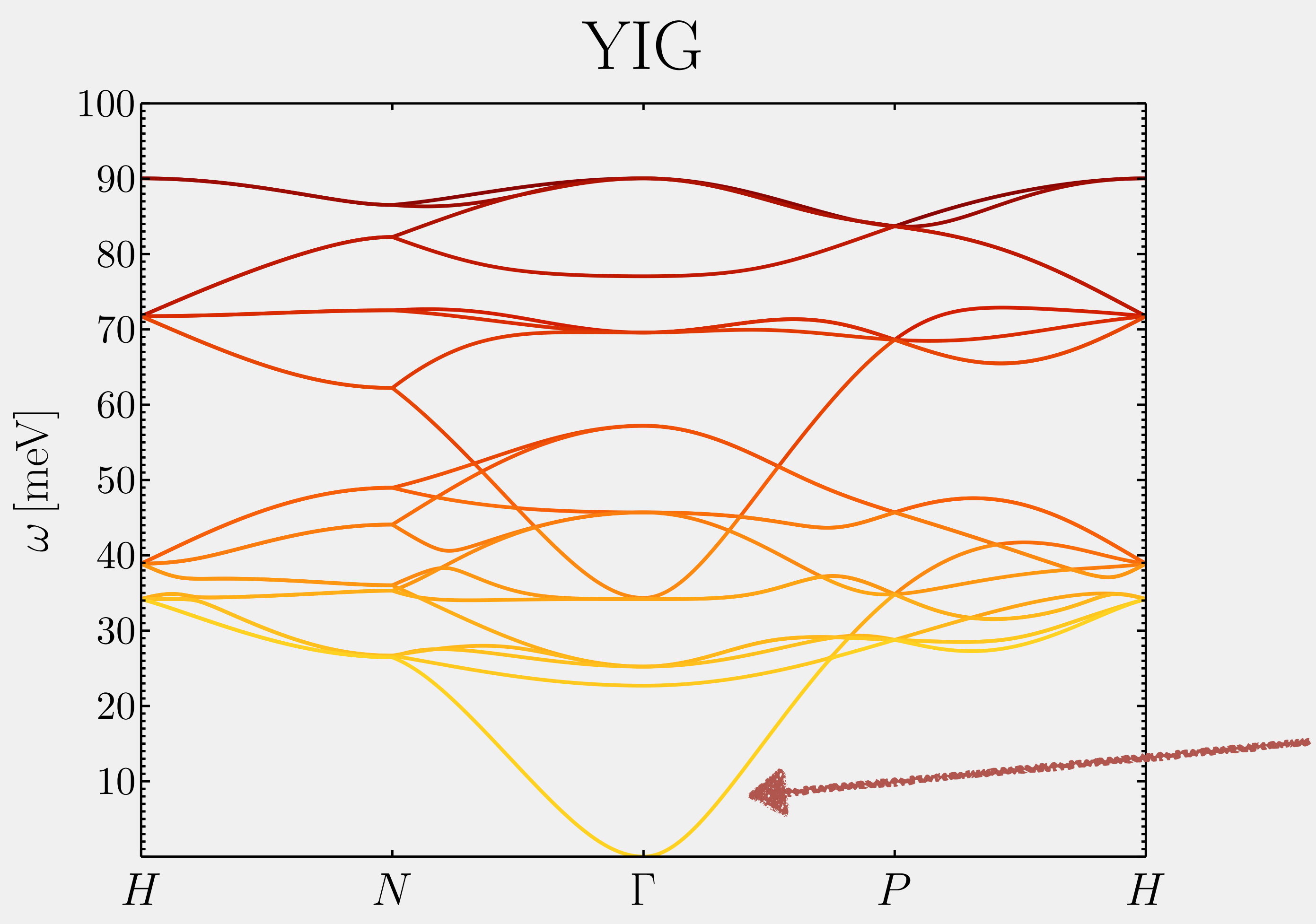
The End

Thank you for your attention!

Back-up slides

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.

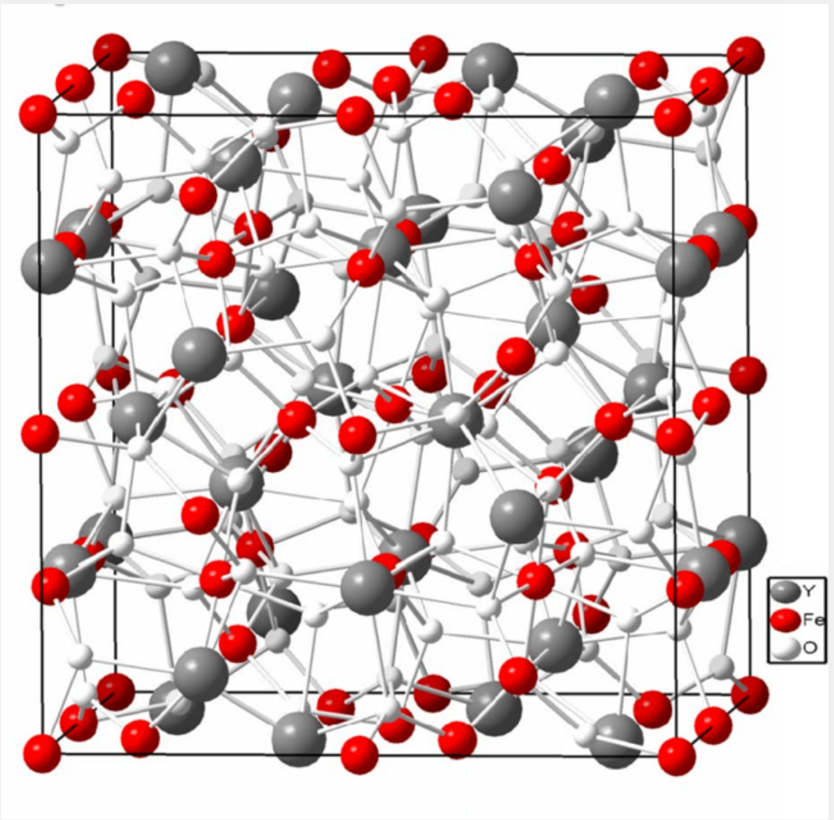
Gapless vs. gapped magnons

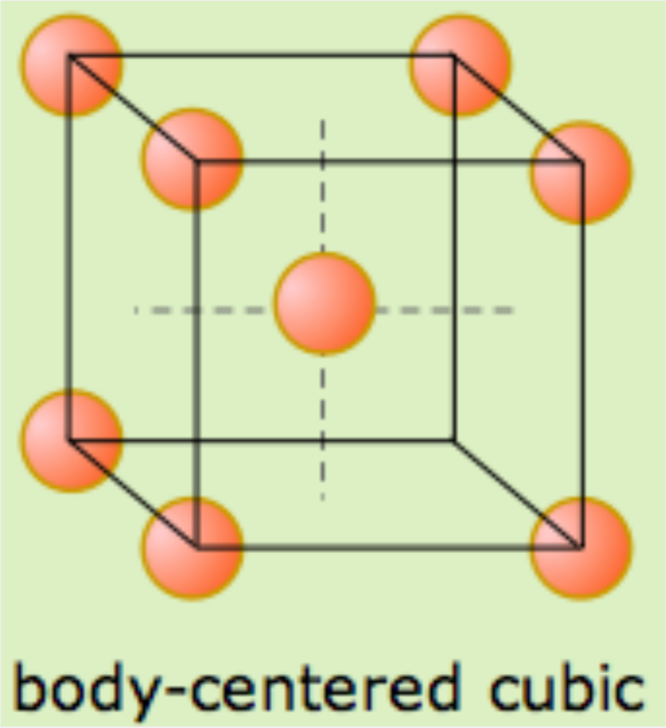
$$\mathcal{L} = -\sum_{\alpha=1}^{3} \hat{\mathcal{O}}_\chi^\alpha(\boldsymbol{q})\hat{S}_e^\alpha$$

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

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

$$\boldsymbol{\epsilon} = \sqrt{S/2}\,(1, i, 0)$$

Effective theory of gapless magnons

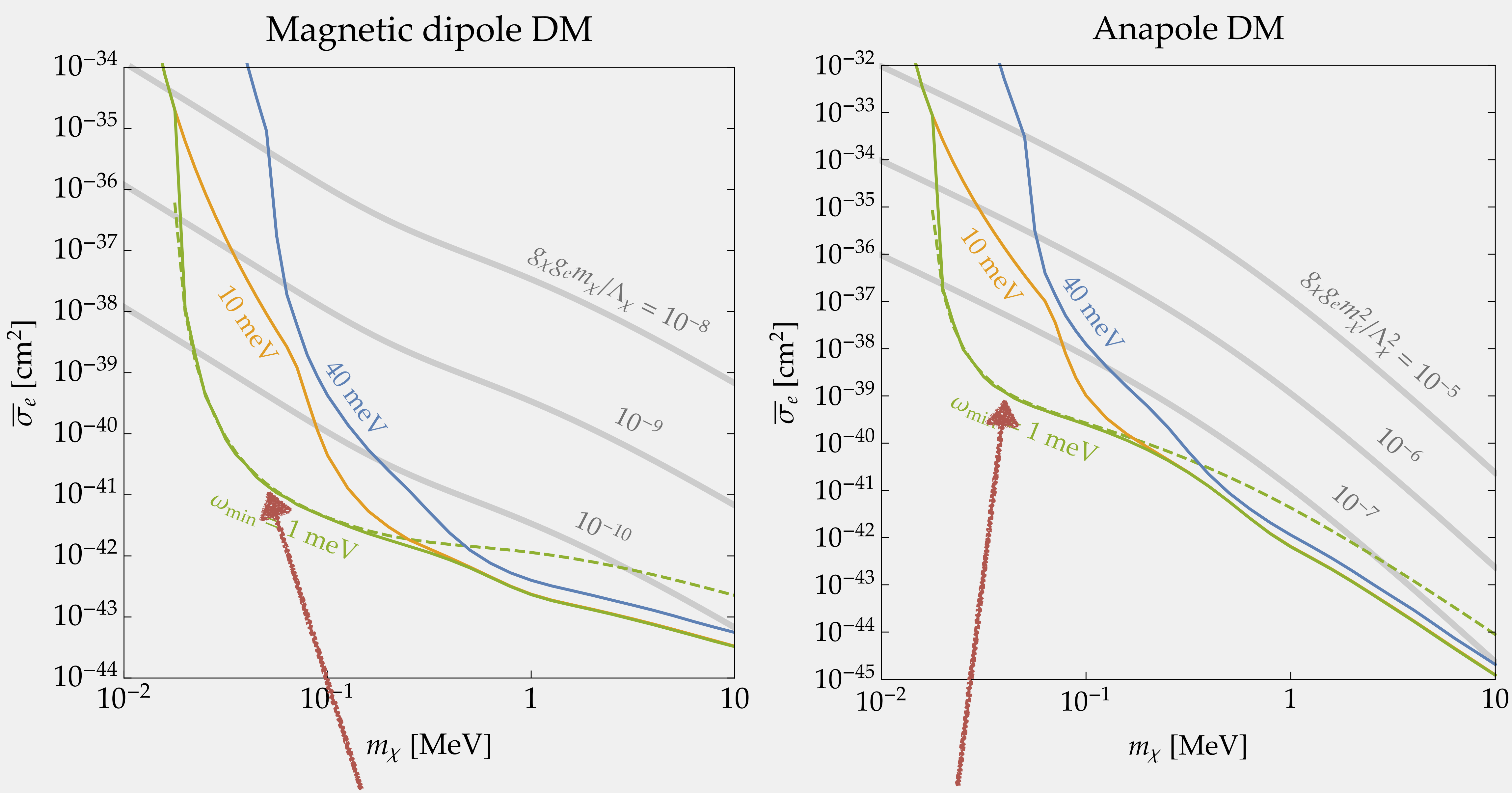
- Integrate out short-distance degrees of freedom within the unit cell.
- The only low-energy d.o.f. is the spin density: (12-8)x5/2=10 per unit cell.
- Effective theory is a Heisenberg ferromagnet on a bcc lattice, which has only 1 gapless magnon branch.

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

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

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

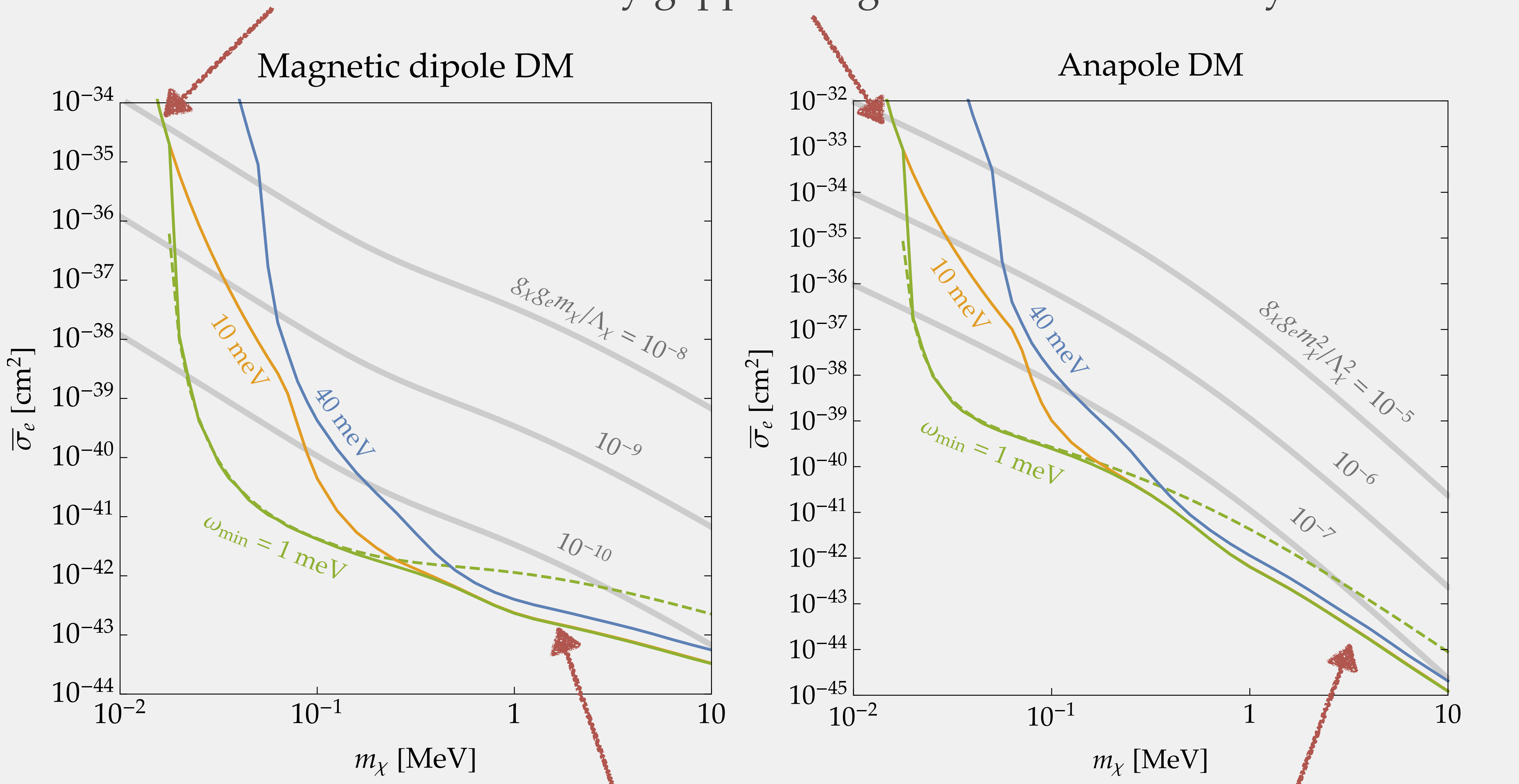
Effective theory vs. full theory



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.