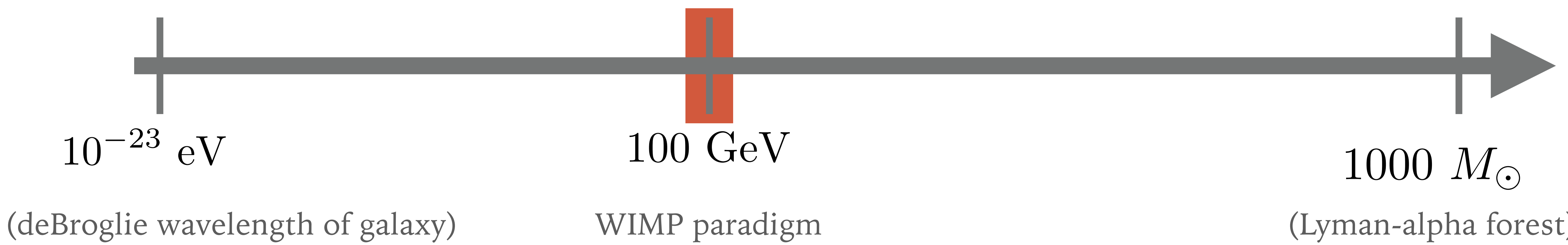
DARK MATTER DIRECT DETECTION: NOVEL PROBES

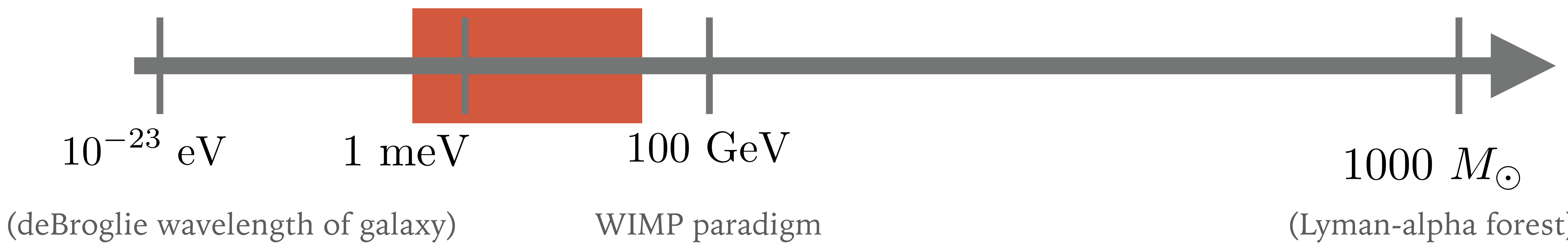
Kathryn M. Zurek

THE DARK MATTER PANORAMA



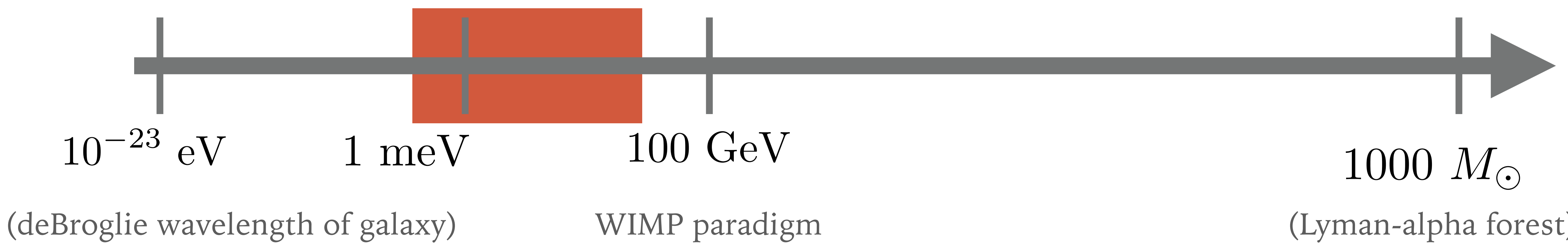
- From an observational standpoint, a wide range of dark matter masses are consistent with data.
- Focused on WIMP largely from arguments based on EFT

THE DARK MATTER PANORAMA

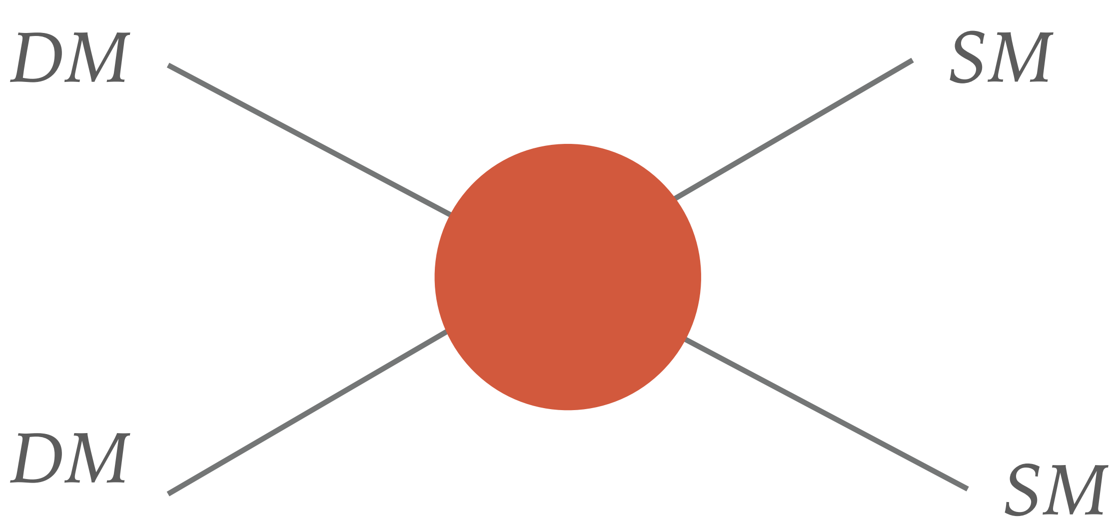


- From an observational standpoint, a wide range of dark matter masses are consistent with data.
- Our discussion will focus on extending the window of observability by 12 OOM in mass utilizing collective excitations in materials
- Why look there?

THE DARK MATTER PANORAMA



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

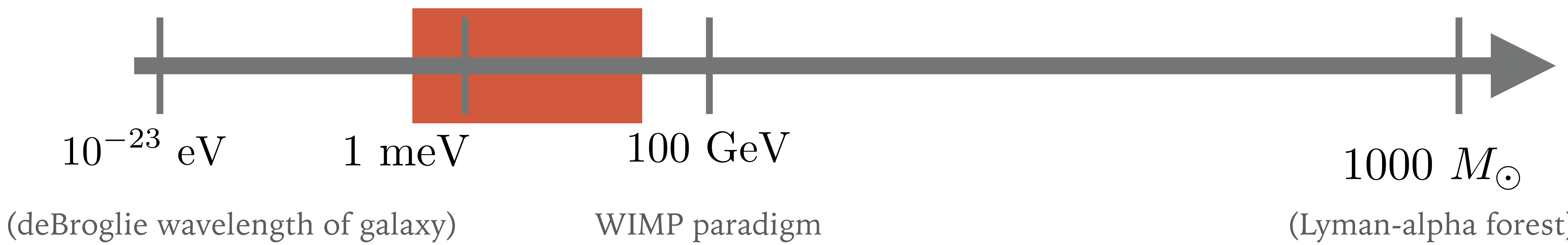


$$n_{DM}\langle \sigma v\rangle \simeq H(T_{\rm fo})$$

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

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

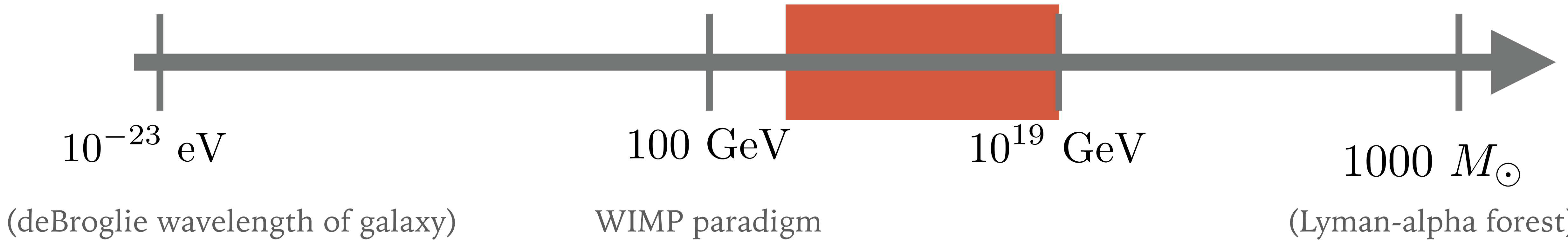
THE DARK MATTER PANORAMA



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

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

THE DARK MATTER PANORAMA

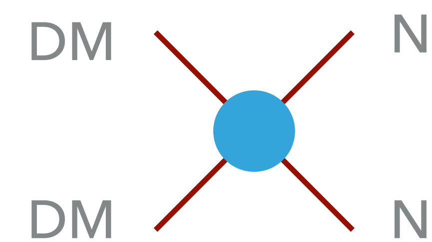


$$\sigma_{wk} v_{fo} \simeq \frac{g_{wk}^4 \mu_{XT}^2}{4\pi m_Z^4} \frac{c}{3} \simeq 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \left(\frac{100 \text{ GeV}}{M} \right)^2$$

- 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

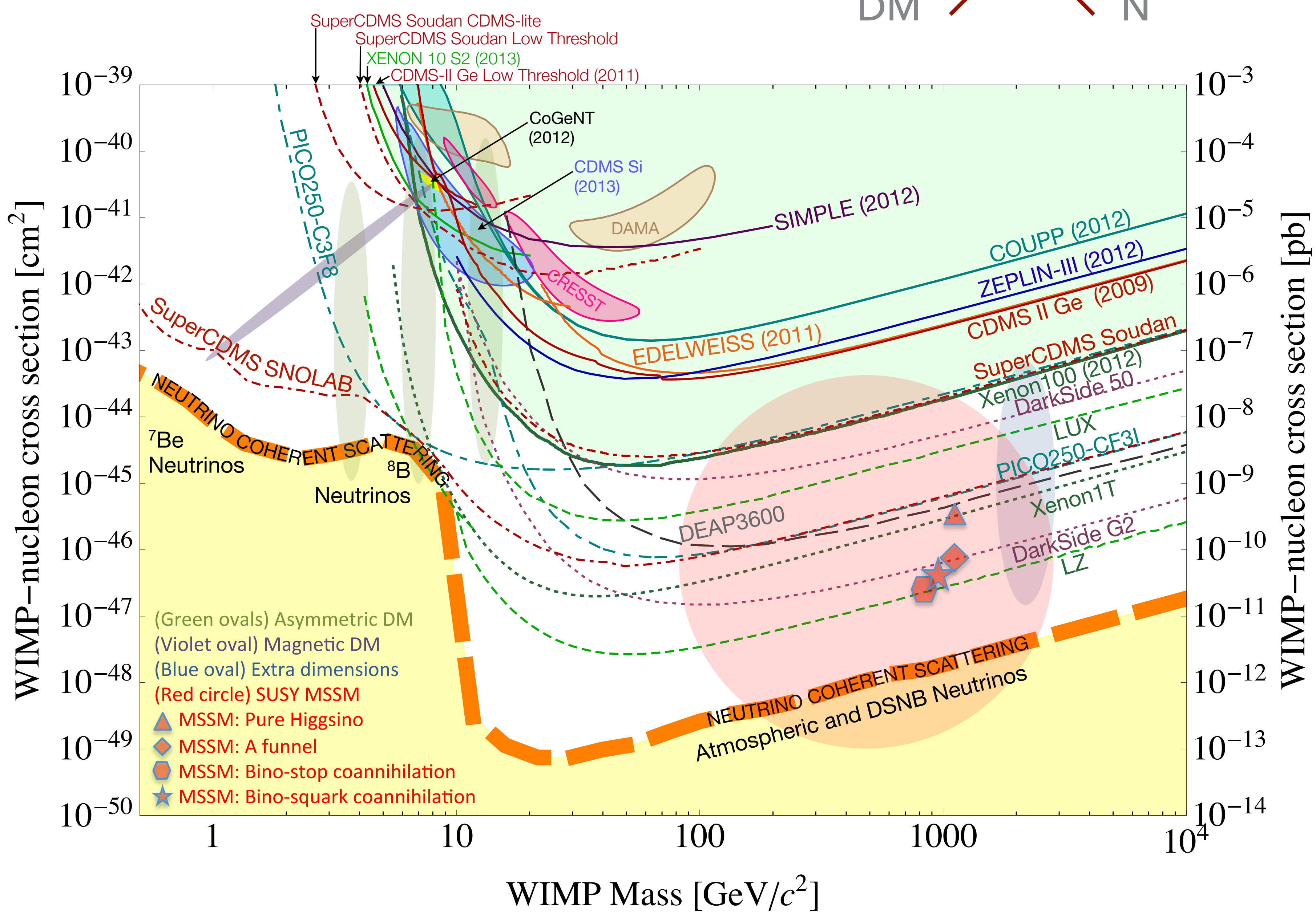
DETECTABLE INTERACTION RATES

- Direct detection searches accordingly focused on weak scale

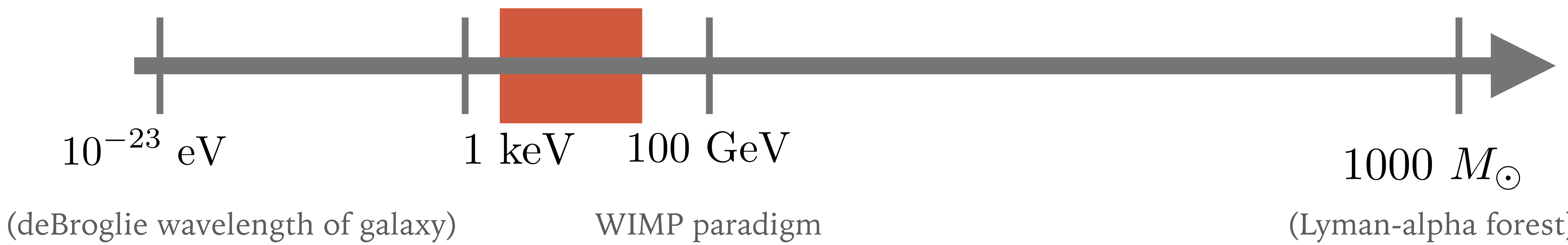


Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



DARK MATTER DETECTION: A FULL COURT PRESS

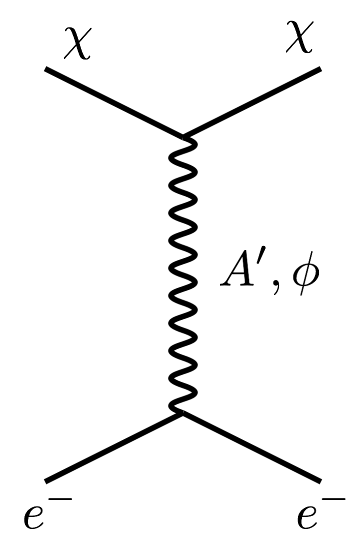


- Abundance may still be set by (thermal) population from SM sector

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

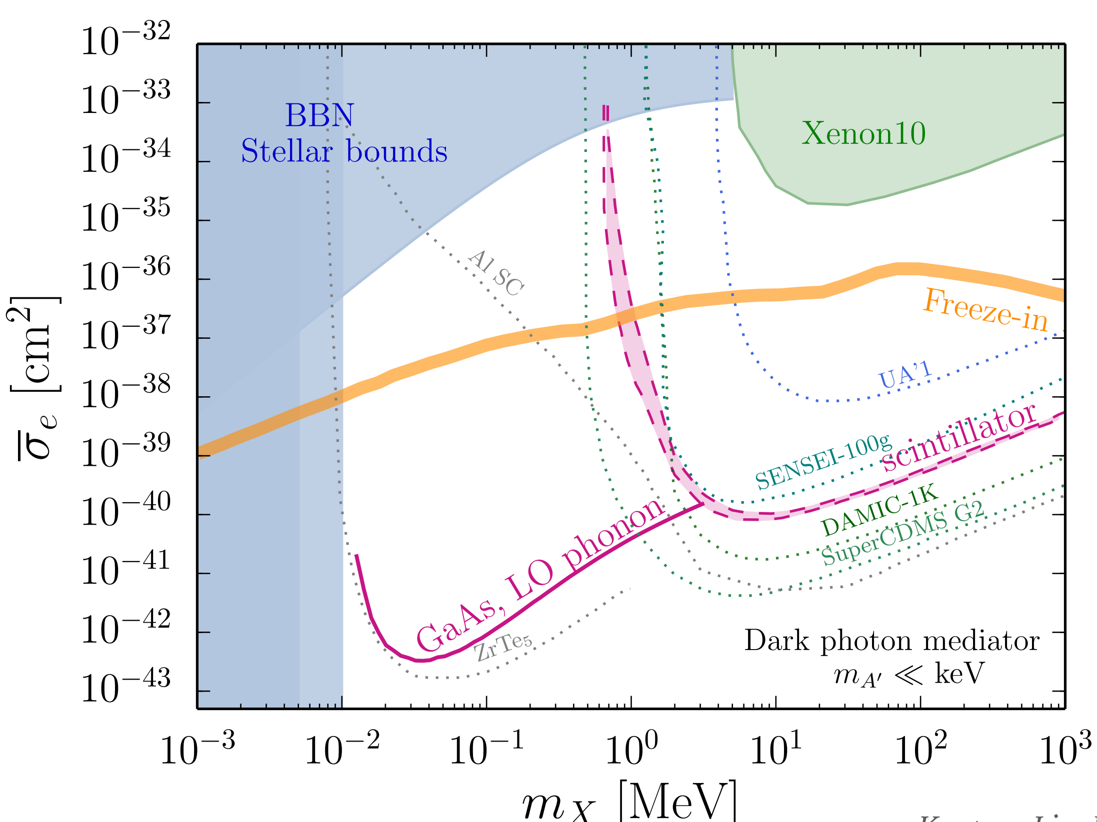
CROSSING SYMMETRY

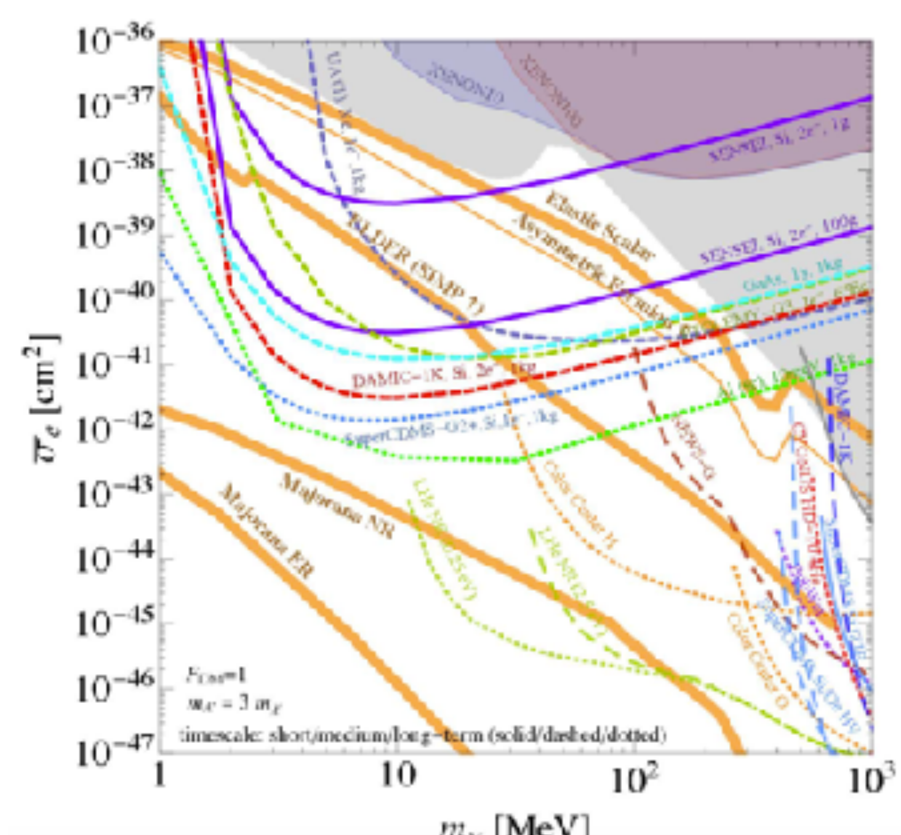
- Utilize DM Abundance and crossing symmetry as guide for interaction rates



Freeze-in

Asymmetric Dark Matter

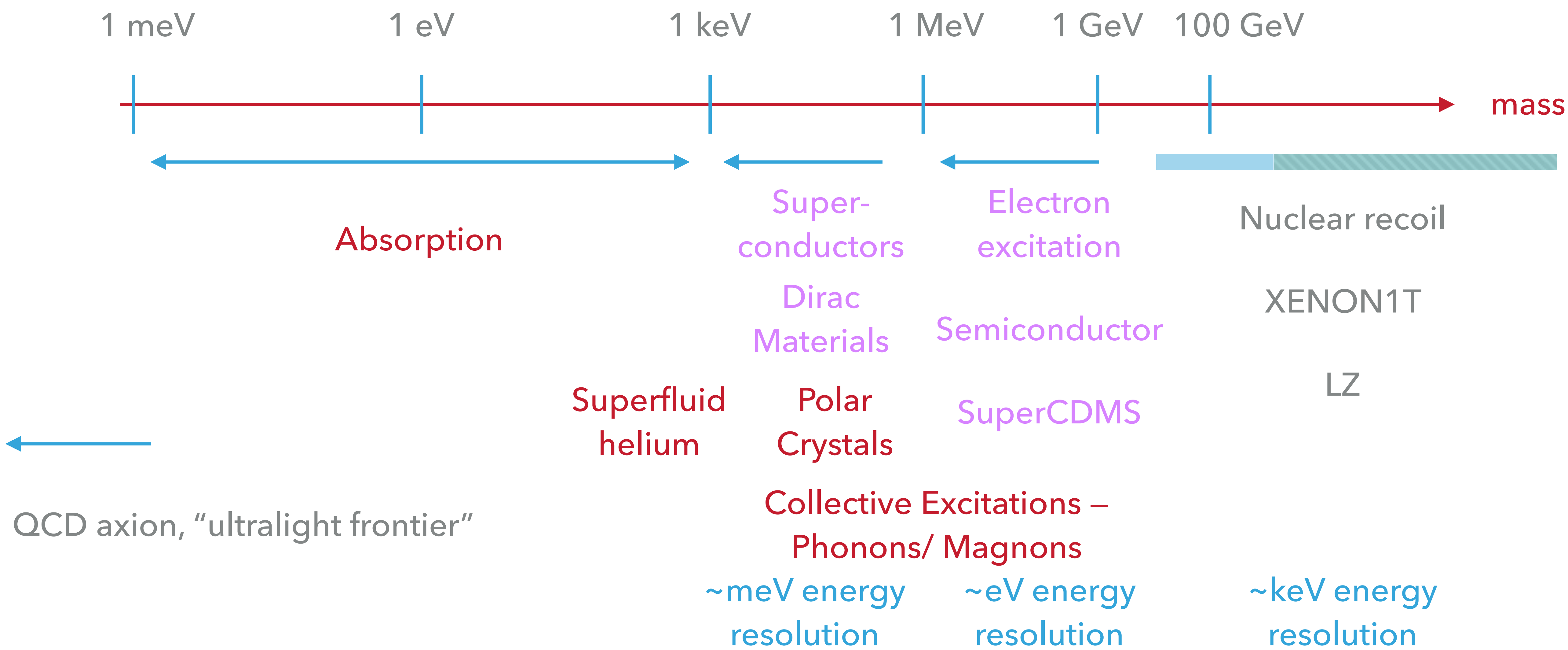




Knapen, Lin, Pyle KZ 1712.06598

US Cosmic Visions 1707.04591

COLLECTIVE PHENOMENA IN MATERIALS

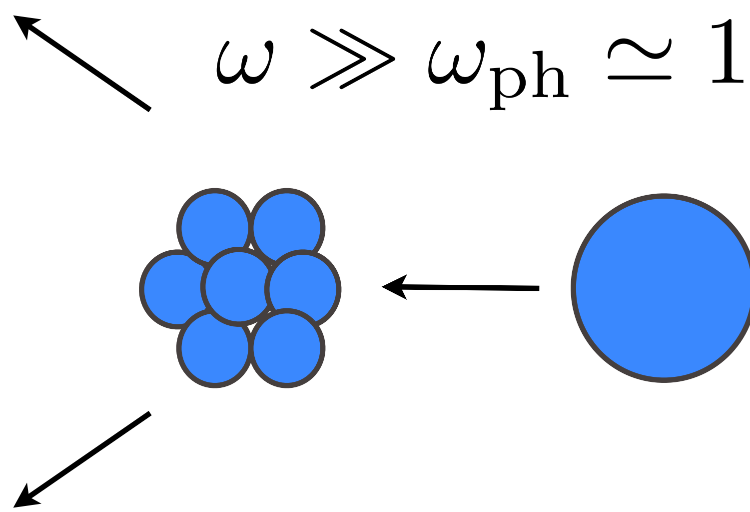


BEYOND BILLIARD BALL SCATTERING

- Nuclear recoil-based direct detection

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

$$q, \;\; E_D$$



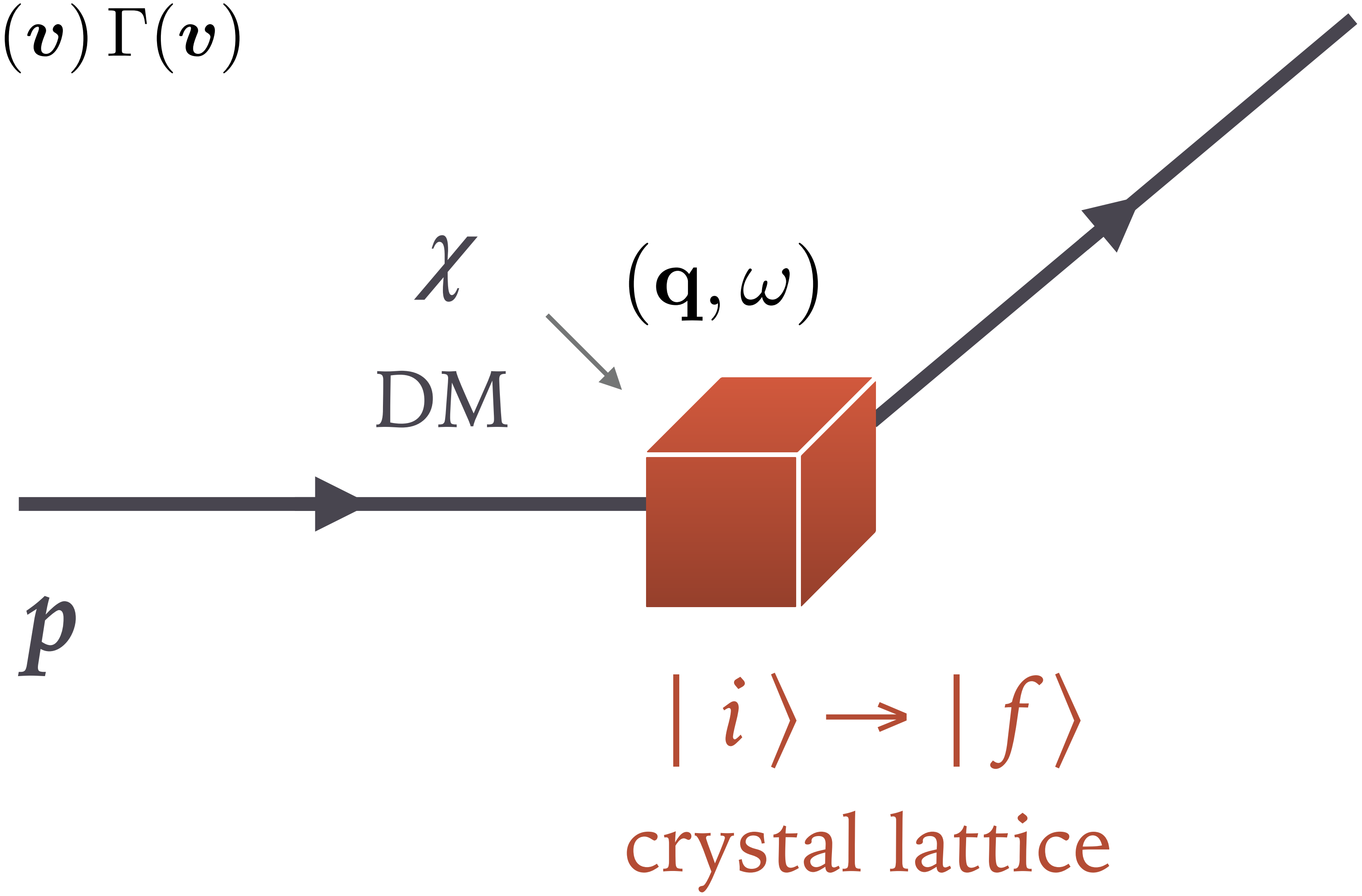
$$v \sim 10^{-3} c$$

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

- 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

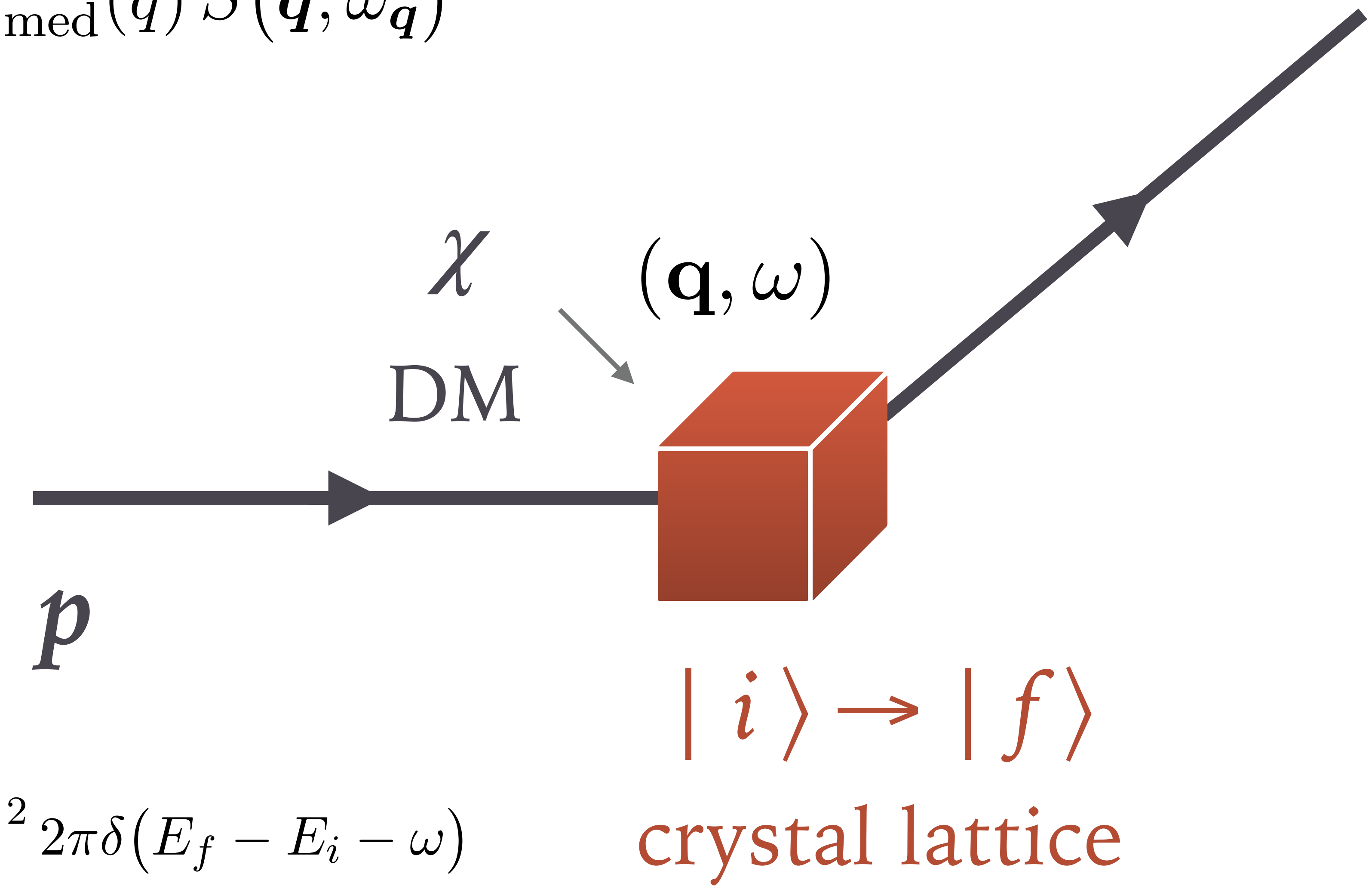
$$R = \frac{1}{\rho_T}\frac{\rho_\chi}{m_\chi}\int d^3v\, f_\chi(\boldsymbol{v})\,\Gamma(\boldsymbol{v})$$



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

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

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

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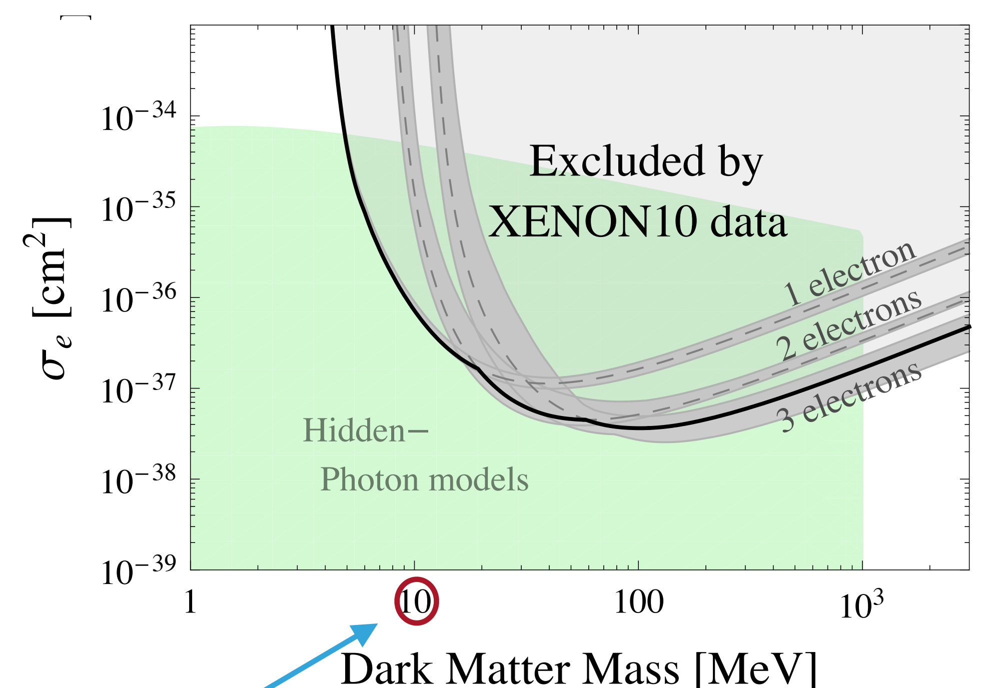
Electrons

Lighter and less free

LIGHTER TARGETS FOR LIGHTER DARK MATTER — ELECTRONS

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

P. Sorensen et al 1206.2644

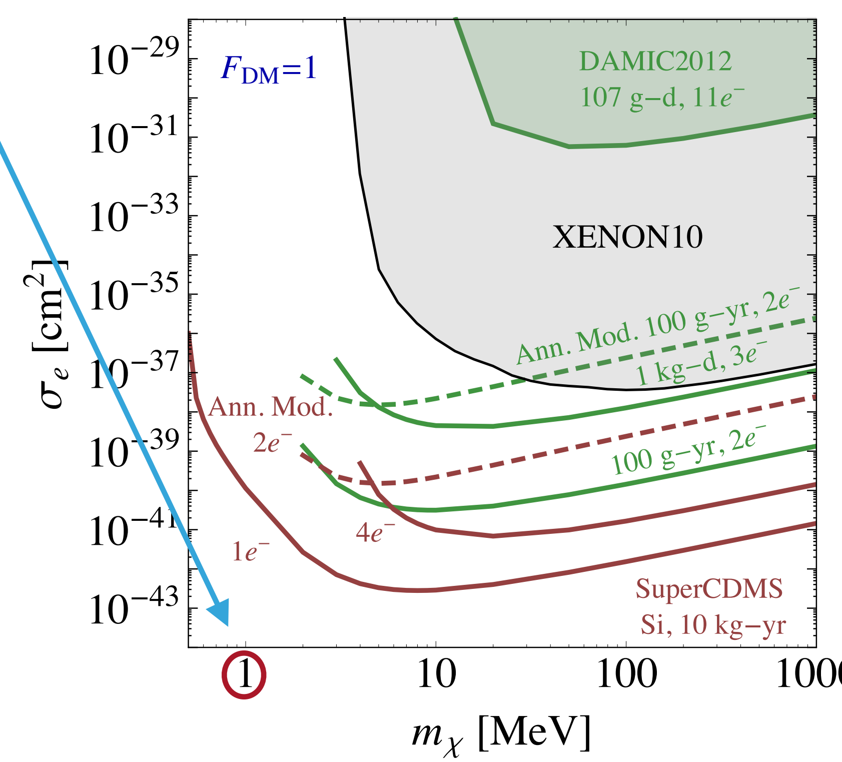


- In insulators, like xenon

  Tightly bound; ionize for signal

Gap = DM Kinetic Energy

Essig et al 1509.01598

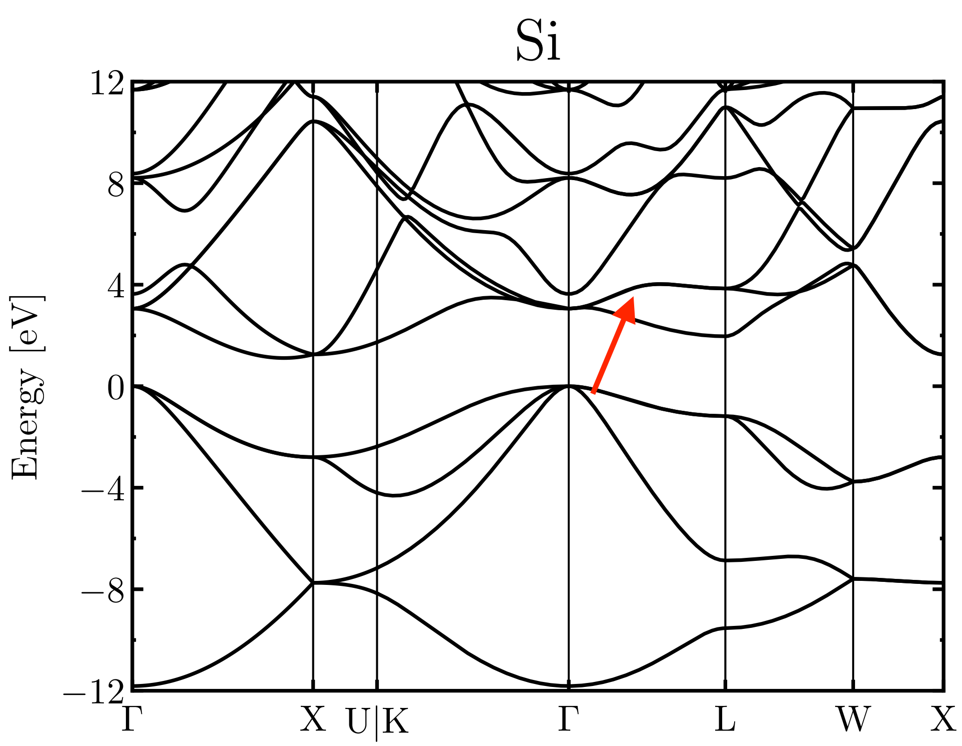


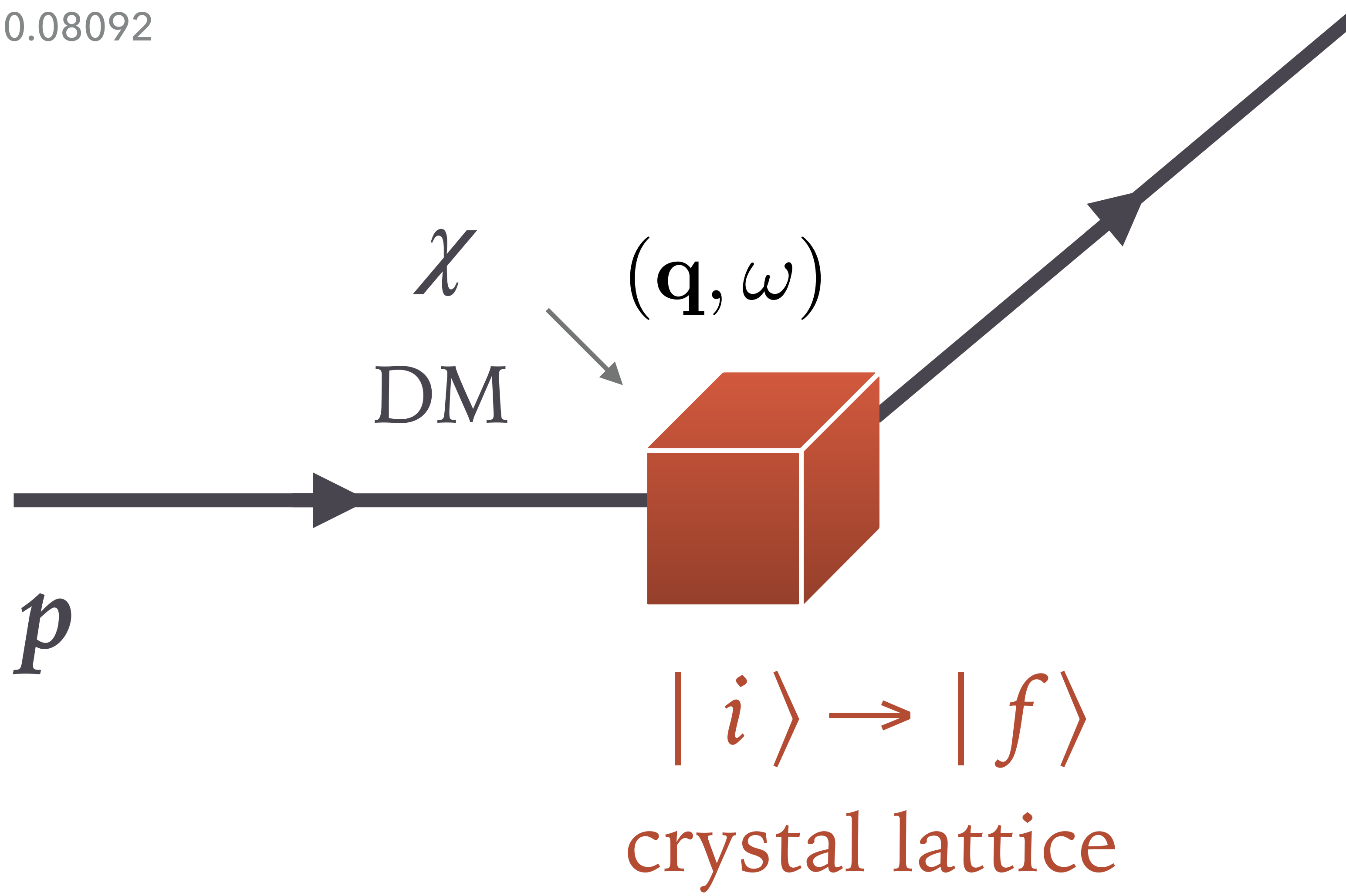
- In semi-conductors, like Ge, Si

  Excite electron to conduction band

EXCITATION OF ELECTRONIC STATES BY DARK MATTER

For summary of theoretical formalism, see 1910.08092

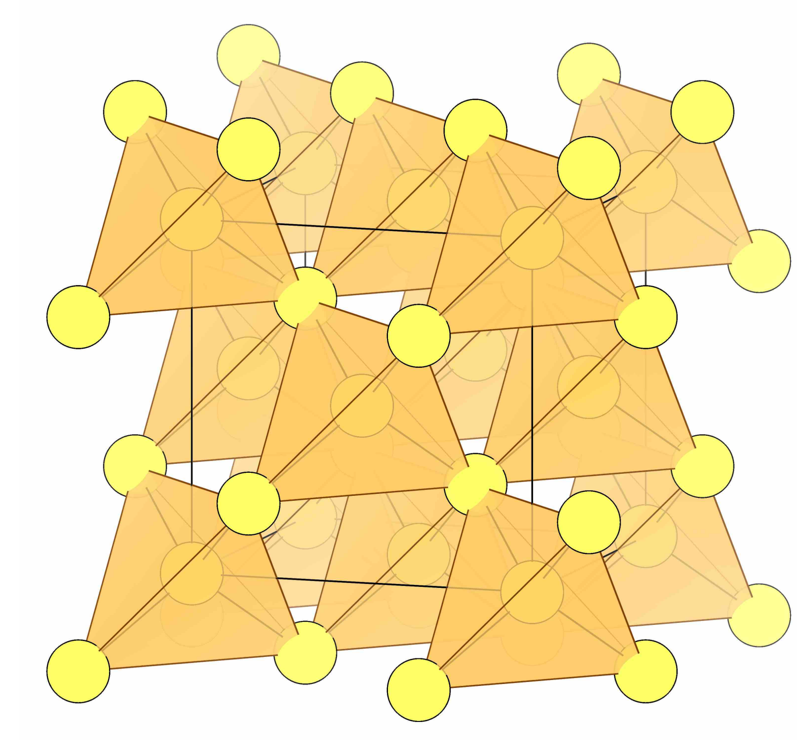


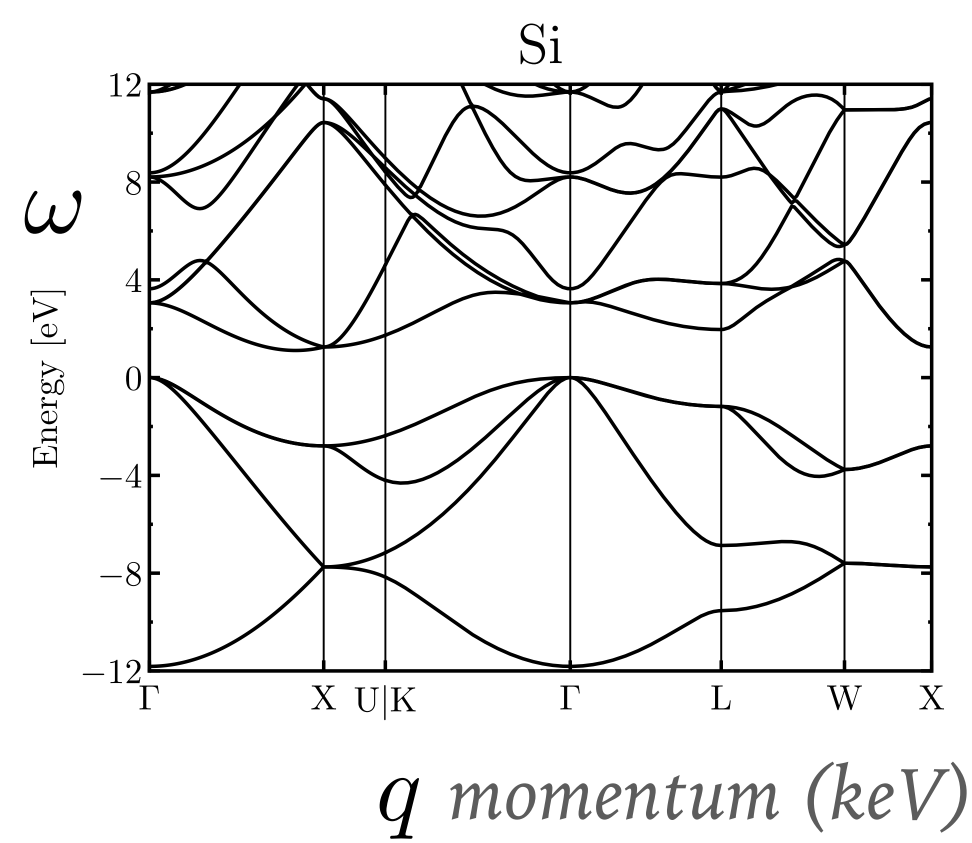


$$\Gamma_{i,s,\sigma\to f,s',\sigma'}(\mathbf{v}) = \frac{2\pi}{16 V m_e^2 m_\chi^2} \int \frac{d^3 q}{(2\pi)^3}\, \delta(E_{f,s'} - E_{i,s} - \omega_{\mathbf{q}}) \\ \times \left| \int \frac{d^3 k}{(2\pi)^3}\, \mathcal{M}_{\sigma' s' \sigma s}(\mathbf{p}-\mathbf{q}, \mathbf{k}+\mathbf{q}, \mathbf{p},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

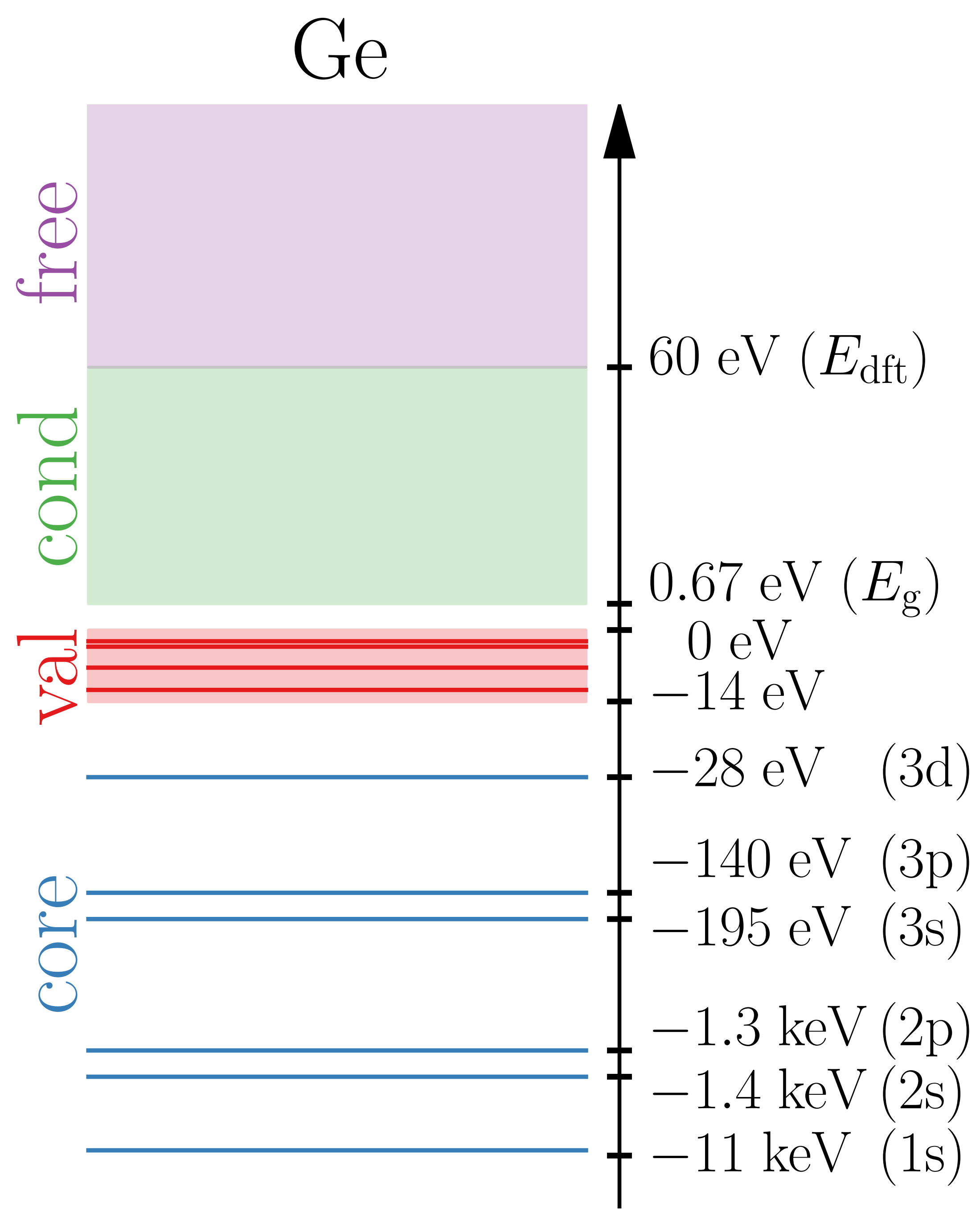
LATTICE DEGREES OF FREEDOM

- Lattice materials, such as semiconductors, share electrons between ions, making extracting their wave functions more involved
- Use a tool called density functional theory
- Iteratively solve the Schrodinger equation with known lattice potential
- The $\omega - q$ relation (= dispersion) of the available states is extremely important for determining viability of target

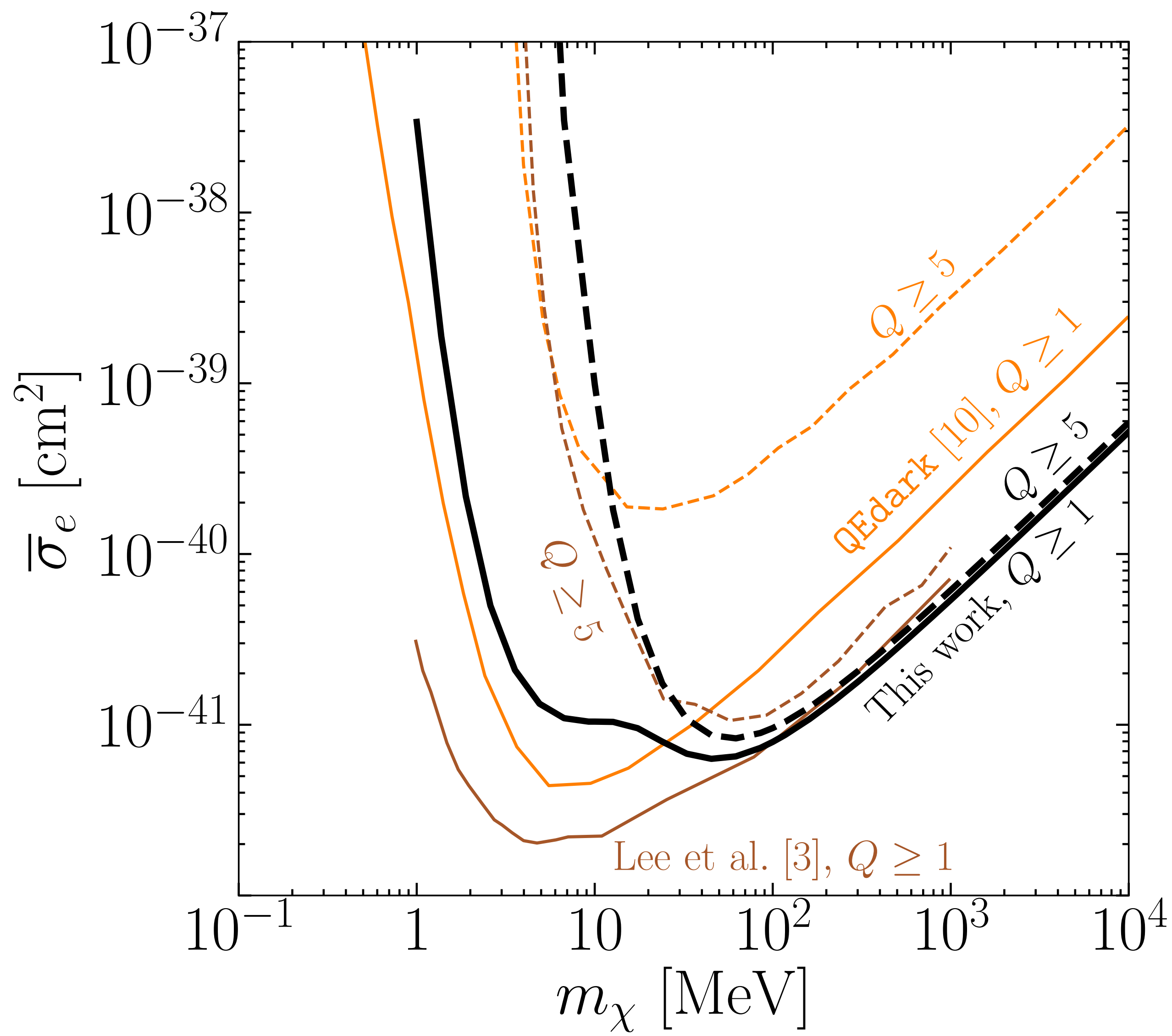




EXTENDED CALCULATION FOR ELECTRONIC EXCITATIONS



EXCEED-DM



Griffin, Inzani, Trickle, Zhang, KZ 2105.05253

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

COMMENTS ON UTILIZING THE DIELECTRIC TO COMPUTE THE RATE

- For spin-independent scattering, the *dielectric* is sufficient to describe the scattering rate

$$\Gamma(\mathbf{v}_\chi) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} |V(\mathbf{q})|^2 \left[2\frac{q^2}{e^2} \operatorname{Im}\left(-\frac{1}{\epsilon(\mathbf{q},\omega_\mathbf{q})}\right)\right]$$

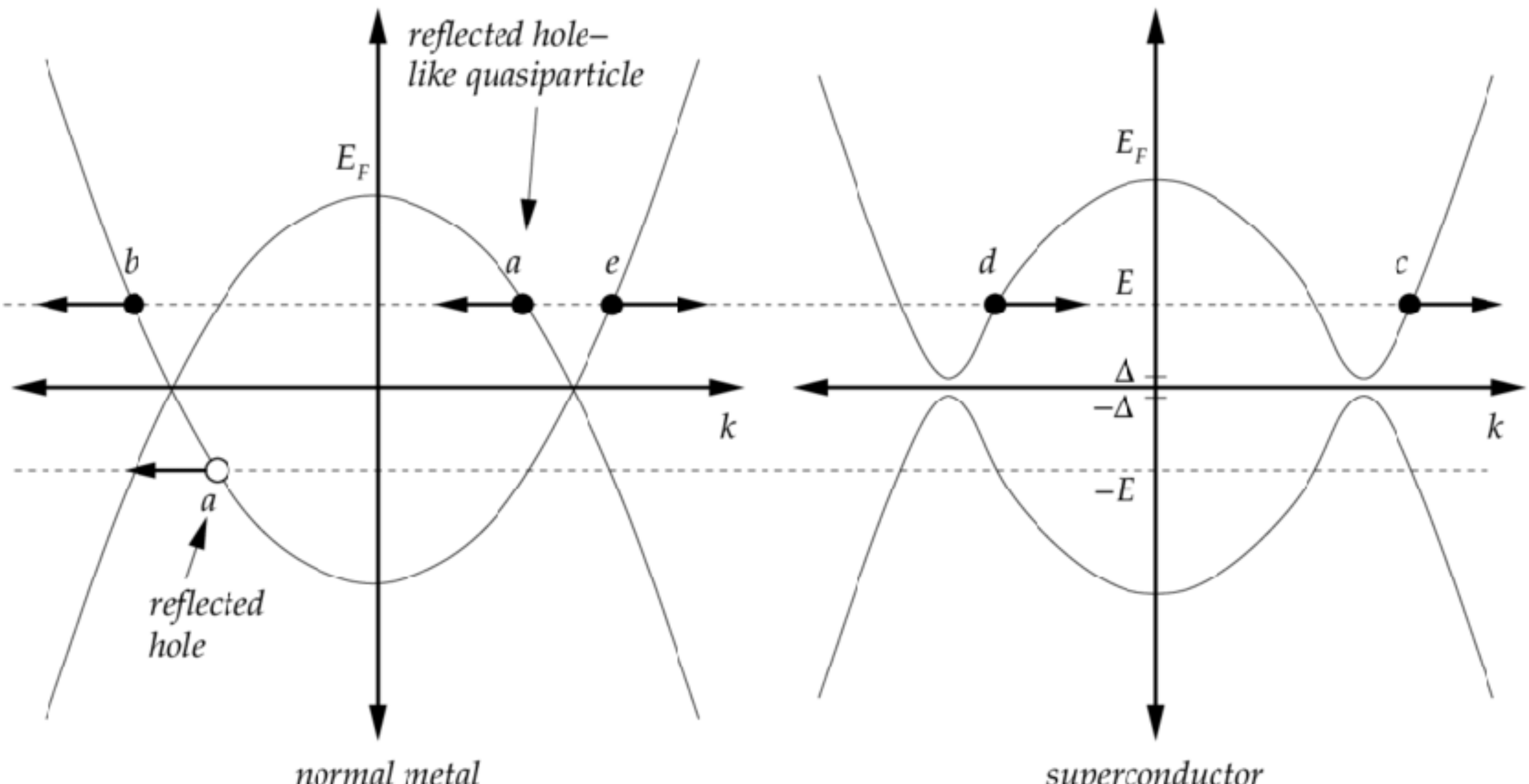
Hochberg et al 2101.08263 Lin et al 2010.08275

- For the moment this is a repackaging — $\epsilon(q,\omega)$ is typically not known for the (q,ω) needed for dark matter detection.
- Once the response is known for any (q,ω), spin-independent rates can be calculated
- Either new measurements or DFT calculations allow one to access this information

ELECTRONIC STRUCTURE IN MATERIALS

Hochberg, Pyle, Zhao, KZ 1512.04533
Hochberg, Kahn, Lisanti, KZ et al 1708.08929

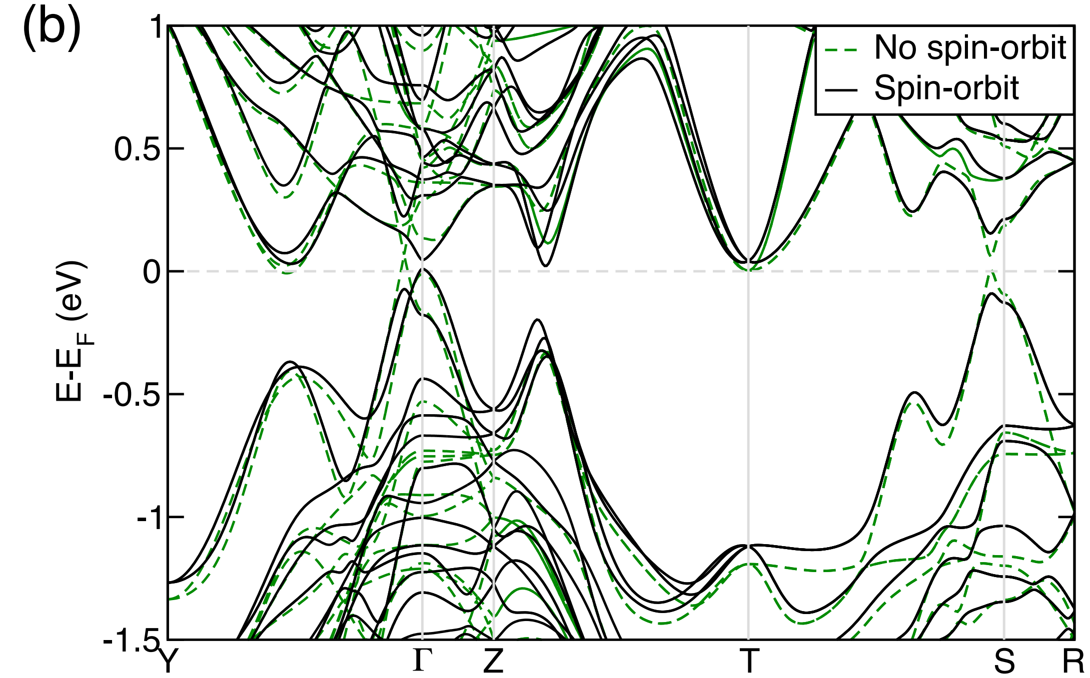
- Smaller gap materials are available to access lighter dark matter
- Simplest example is a superconductor — meV gap opens

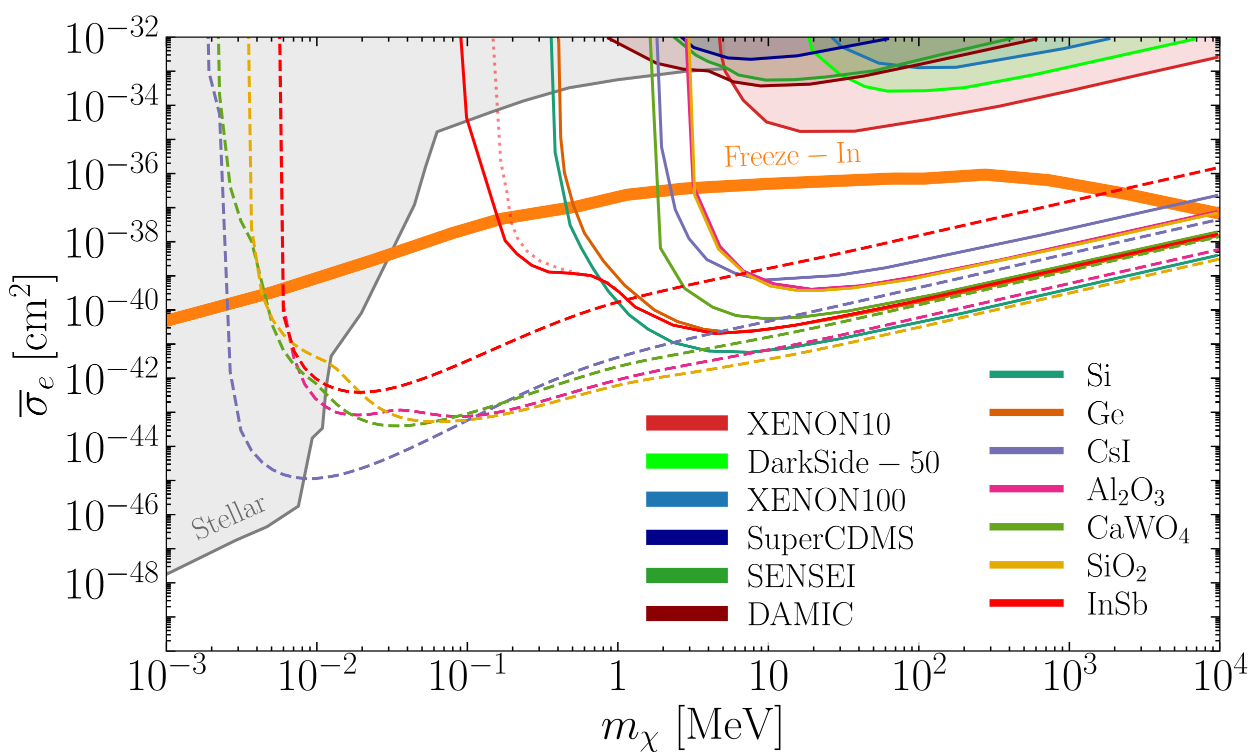


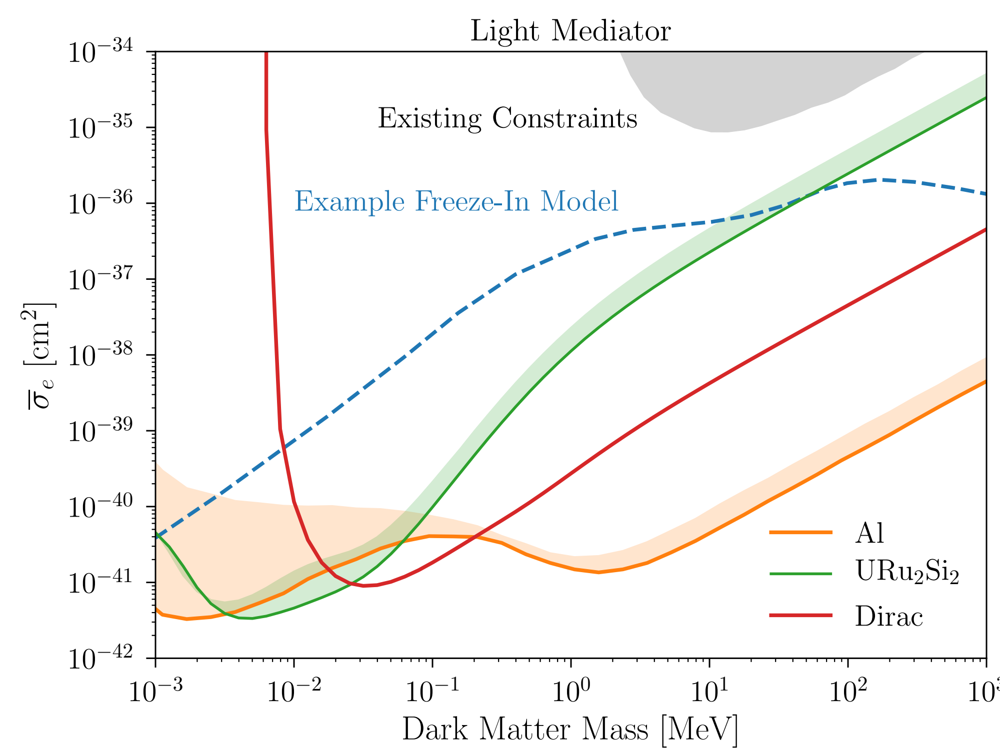
OPTICAL RESPONSE OF "SEMI-METALS"

Hochberg, Kahn, Lisanti, KZ et al 1708.08929

- Band structure can be "quantum engineered"
- The point-like nature of the density of states at Fermi level implies that screening is less problematic







Trickle, Zhang, KZ 1910.08092 Coskuner, Mitridate, Olivares, KZ 1909.09170 Hochberg et al 2101.08263

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Phonons

Power of Collective Excitations

EXCITING COLLECTIVE MODES

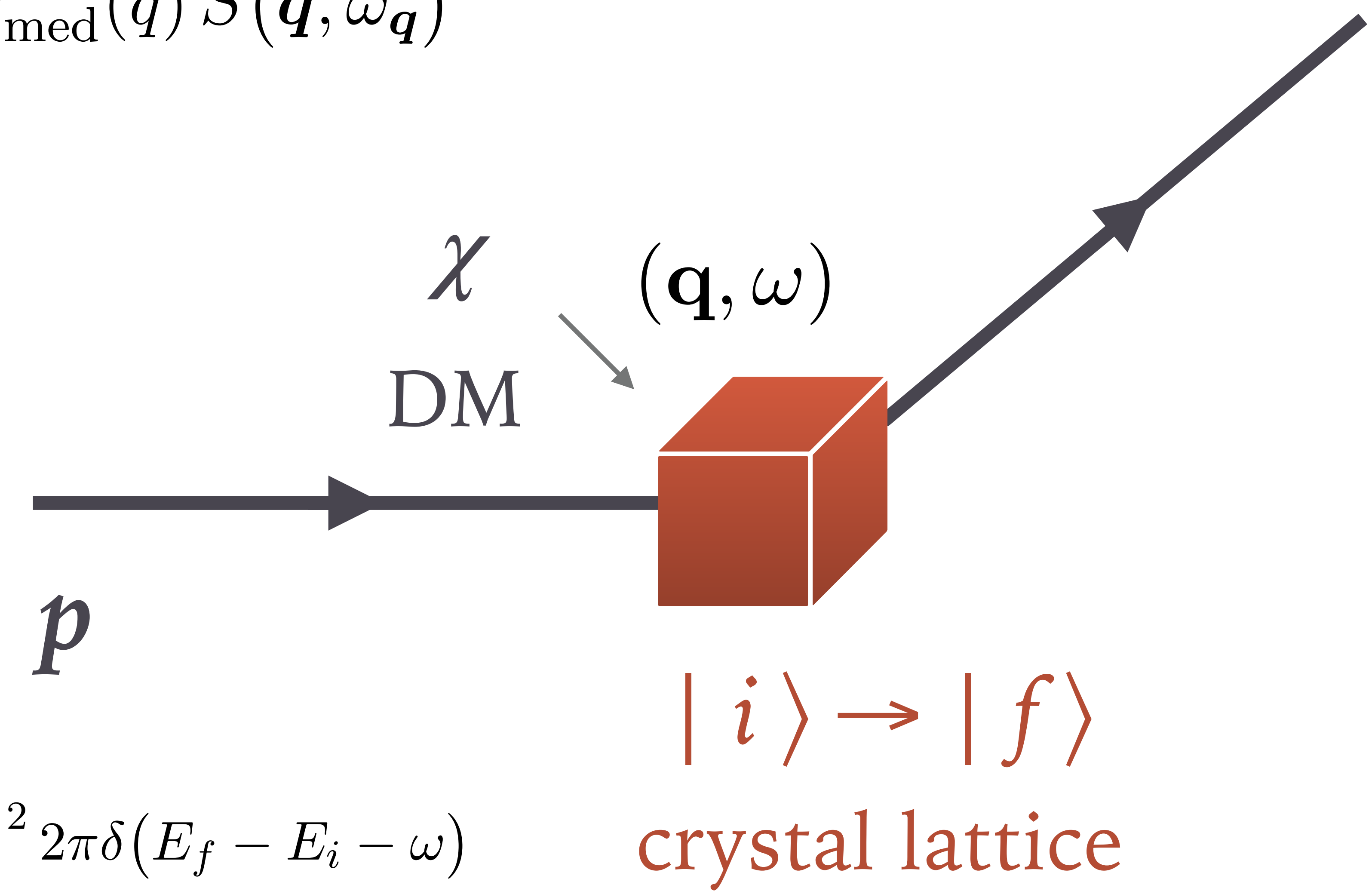
- Once momentum transfer drops below an keV, deBroglie wavelength is longer than the inter particle spacing in typical materials
- Therefore, relevant d.o.f. in target are no longer individual nuclei or ions
- Must coarse grain to describe DM coupling to "collective excitations"
- Collective excitations = 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

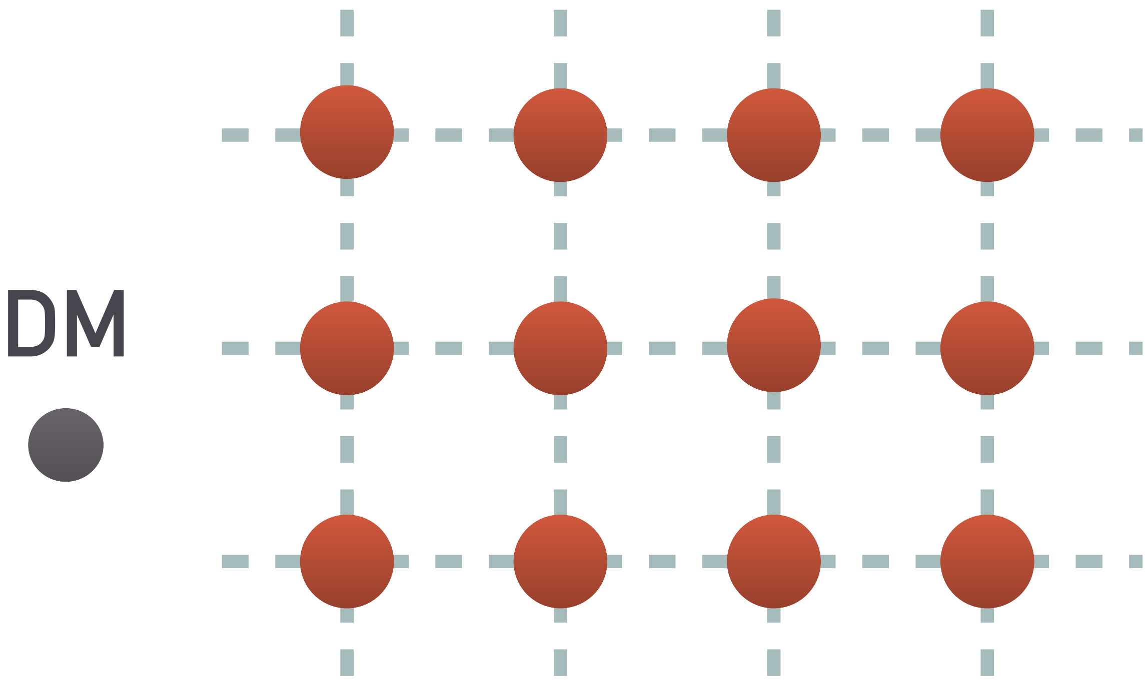


$$S(\boldsymbol{q},\omega) \equiv \frac{1}{V}\sum_f \big|\langle f|\mathcal{F}_T(\boldsymbol{q})|i\rangle\big|^2\,2\pi\delta\big(E_f - E_i - \omega\big)$$

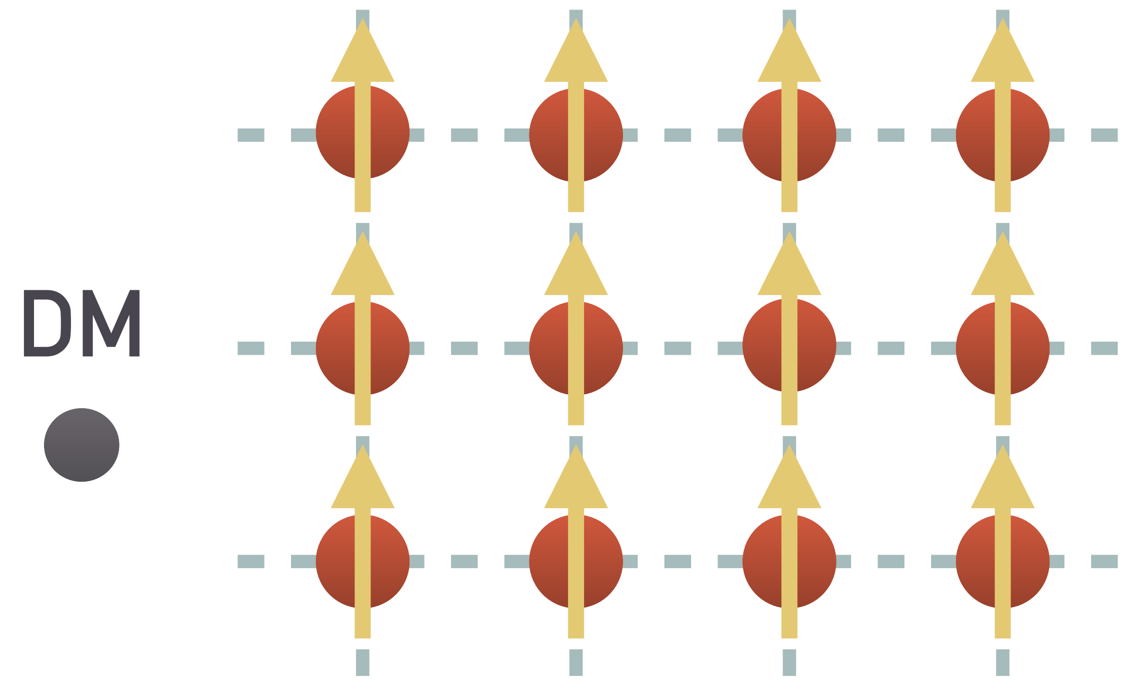
For summary of theoretical formalism, including nuclear recoils, electrons, collective excitations, see 1910.08092

LATTICE DEGREES OF FREEDOM

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



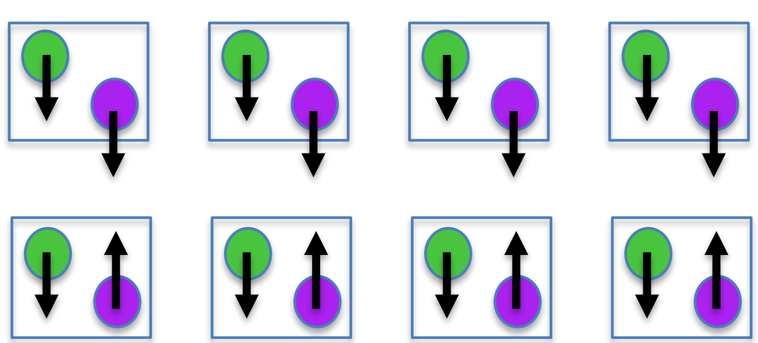
Phonons



Magnons

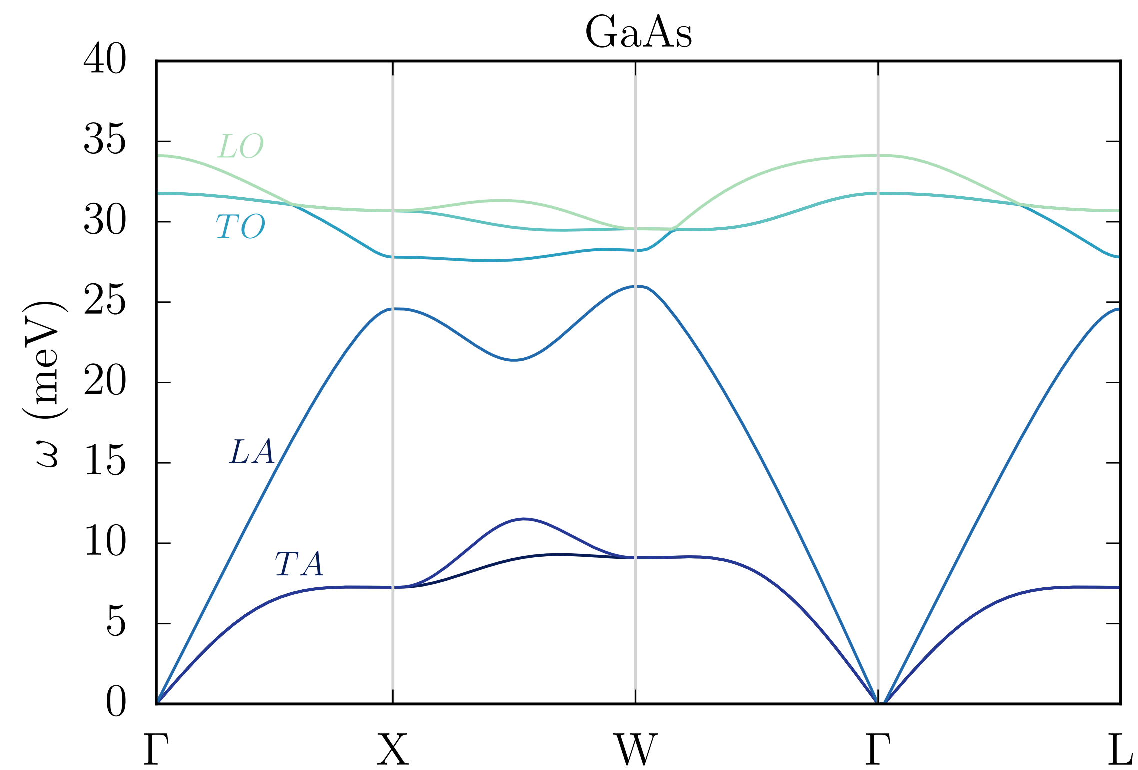
Acoustic

Optical

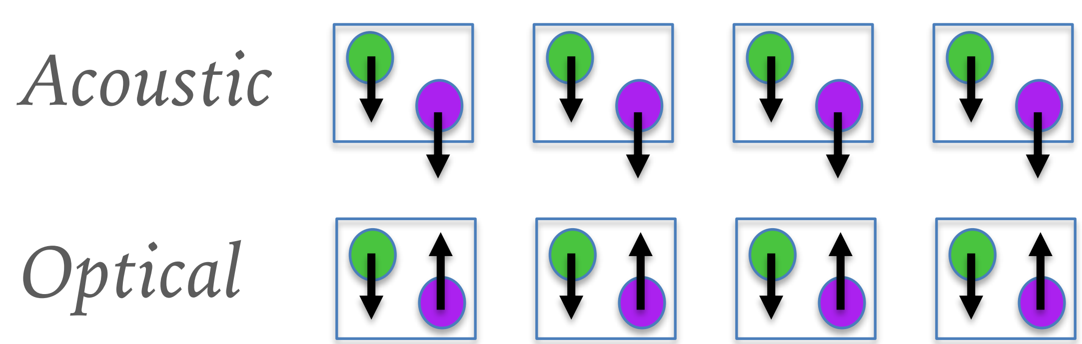


NATURE OF COLLECTIVE OSCILLATIONS OF IONS — PHONONS

- 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

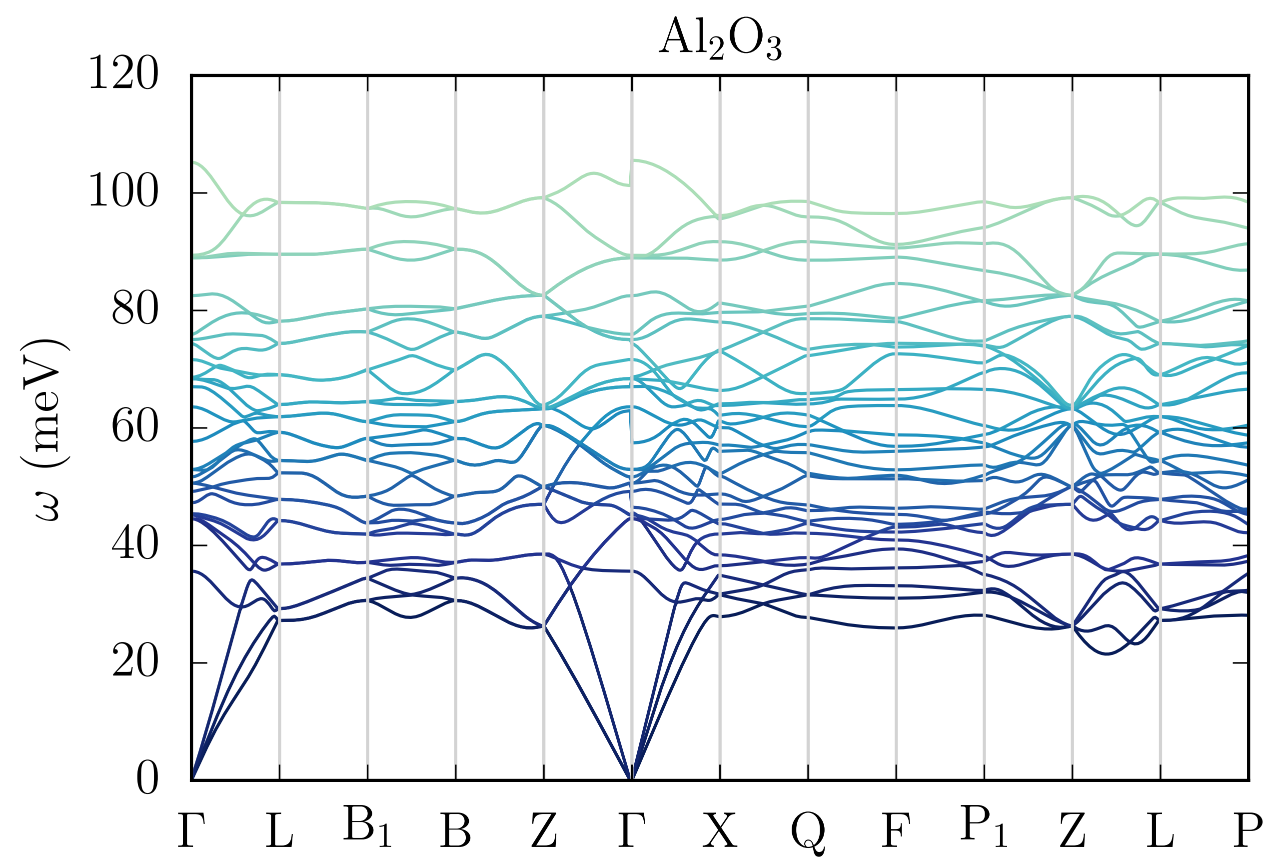


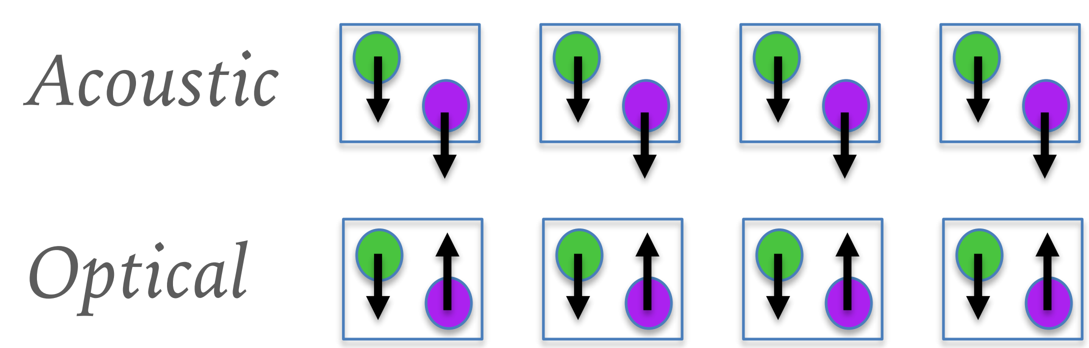
Knapen, Lin, Pyle, KZ 1712.06598 Griffin, Knapen, Lin, KZ 1807.10291

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

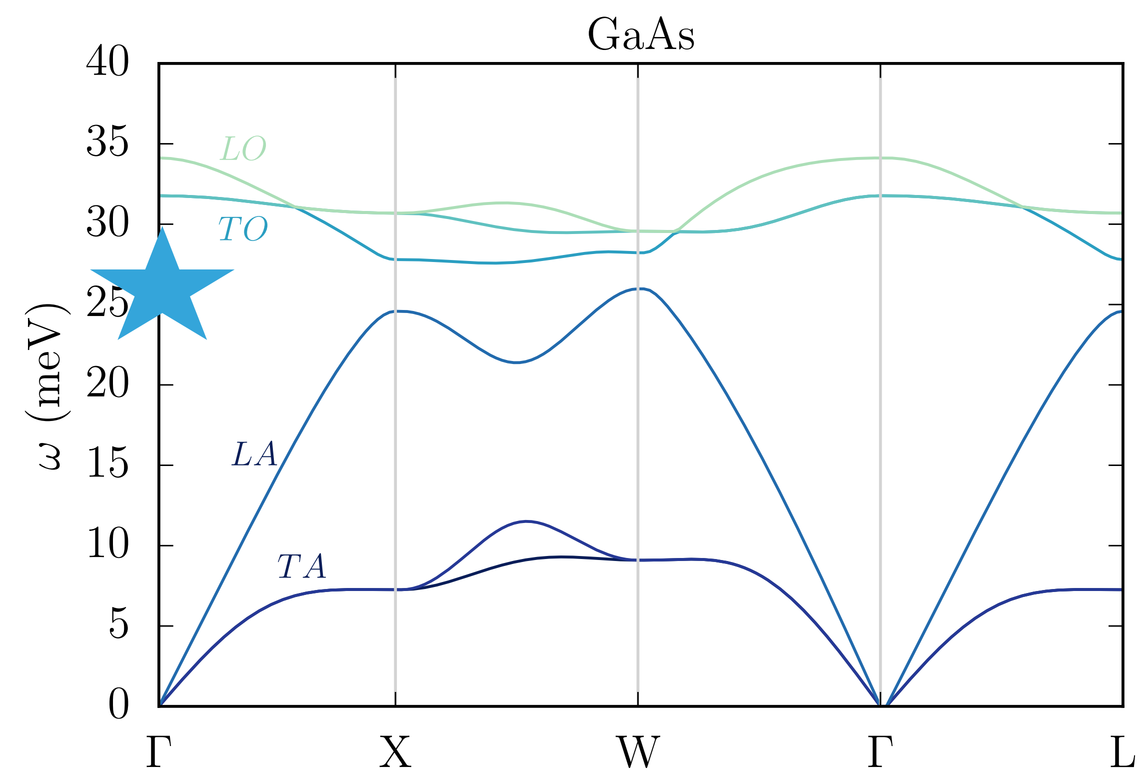
- Each phonon mode is a resonance. The DM needs to be well matched kinematically to the modes to excite large response

$$E_D \sim v_X q$$

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

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)

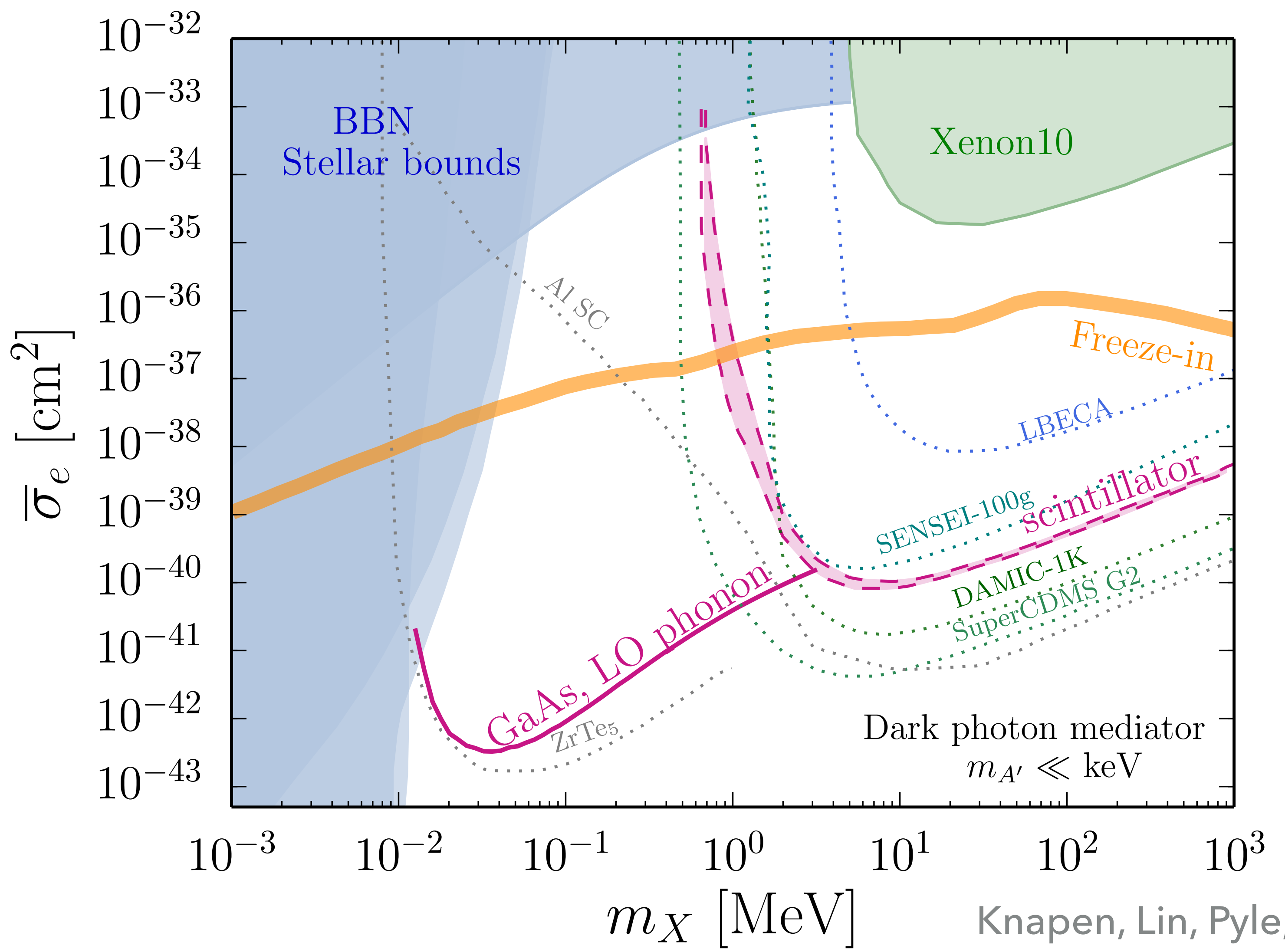
DM – COLLECTIVE MODE EFT

See Trickle, Zhang, KZ 2009.13534

Model		UV Lagrangian	NR EFT	Responses
Standard SI		$\phi\left(g_\chi J_{S,\chi} + g_\psi J_{S,\psi}\right)$ or $V_\mu\left(g_\chi J^\mu_{V,\chi} - g_\psi J^\mu_{V,\psi}\right)$	$c_1^{(\psi)} = \frac{g_\chi g_\psi^{\rm eff}}{\boldsymbol{q}^2 + m^2_{\phi,V}}$	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	$\phi\left(g_\chi J_{P,\chi} + g_\psi J_{S,\psi}\right)$	$c_{11}^{(\psi)} = \frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\rm eff}}{\boldsymbol{q}^2 + m_\phi^2}$	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	$V_\mu\Big(g_\chi J^\mu_{{\rm edm},\chi} + g_\psi\big(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{{\rm mdm},\psi}\big)\Big)$	$c_{11}^{(\psi)} = -\frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\rm eff}}{\boldsymbol{q}^2 + m_V^2}$	N
	Magnetic dipole	$V_\mu\Big(g_\chi J^\mu_{{\rm mdm},\chi} + g_\psi\big(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{{\rm mdm},\psi}\big)\Big)$	$c_1^{(\psi)} = \frac{\boldsymbol{q}^2}{4m_\chi^2}\frac{g_\chi g_\psi^{\rm eff}}{\boldsymbol{q}^2 + m_V^2}$ $c_4^{(\psi)} = \widetilde{\mu}_\psi \frac{\boldsymbol{q}^2}{m_\chi m_\psi}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_{5a}^{(\psi)} = \frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi^{\rm eff}}{\boldsymbol{q}^2 + m_V^2}$ $c_{5b}^{(\psi)} = \frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_6^{(\psi)} = -\widetilde{\mu}_\psi\frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$	$N,\ S,\ L$
	Anapole	$V_\mu\Big(g_\chi J^\mu_{{\rm ana},\chi} + g_\psi\big(J^\mu_{V,\psi} + \delta\widetilde{\mu}_\psi J^\mu_{{\rm mdm},\psi}\big)\Big)$	$c_{8a}^{(\psi)} = \frac{\boldsymbol{q}^2}{2m_\chi^2}\frac{g_\chi g_\psi^{\rm eff}}{\boldsymbol{q}^2 + m_V^2}$ $c_{8b}^{(\psi)} = \frac{\boldsymbol{q}^2}{2m_\chi^2}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_9^{(\psi)} = -\widetilde{\mu}_\psi\frac{\boldsymbol{q}^2}{2m_\chi^2}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$	$N,\ S,\ L$
$(\boldsymbol{L}\cdot\boldsymbol{S})$-interacting		$V_\mu\big(g_\chi J^\mu_{V,\chi} + g_\psi(J^\mu_{{\rm mdm},\psi} + \kappa J^\mu_{V2,\psi})\big)$	$c_1^{(\psi)} = (1+\kappa)\frac{\boldsymbol{q}^2}{4m_\psi^2}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_{3a}^{(\psi)} = c_{3b}^{(\psi)} = \frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_4^{(\psi)} = \frac{\boldsymbol{q}^2}{m_\chi m_\psi}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$ $c_6^{(\psi)} = -\frac{m_\psi}{m_\chi}\frac{g_\chi g_\psi}{\boldsymbol{q}^2 + m_V^2}$	$N, S,\ L\otimes S$

FROHLICH HAMILTONIAN AND EFFECTIVE INTERACTIONS

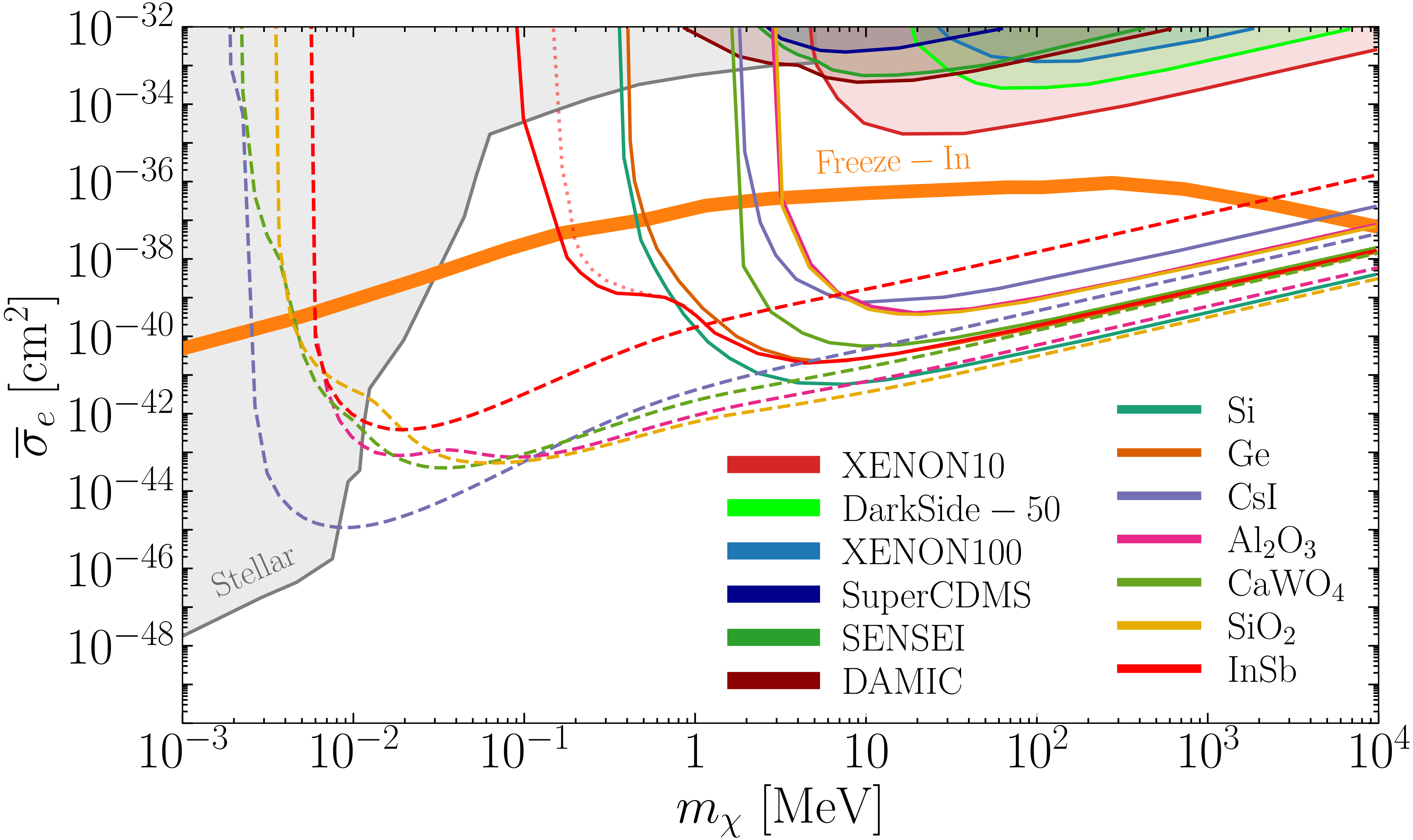
- For sufficiently simple interactions, the effective interaction is already known, e.g. Frohlich Hamiltonian:



Knapen, Lin, Pyle, KZ 1712.06598

OPTICAL PHONONS IN POLAR MATERIALS

Griffin, Inzani, Trickle, Zhang, KZ, 1910.10716



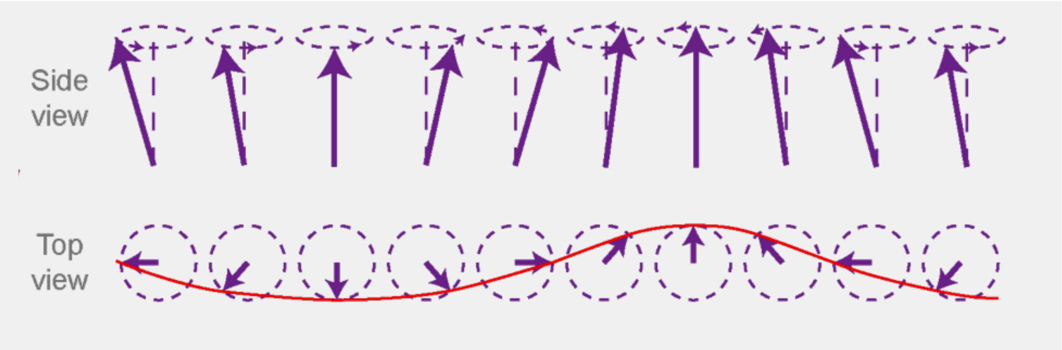
SPIN-DEPENDENT INTERACTIONS

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

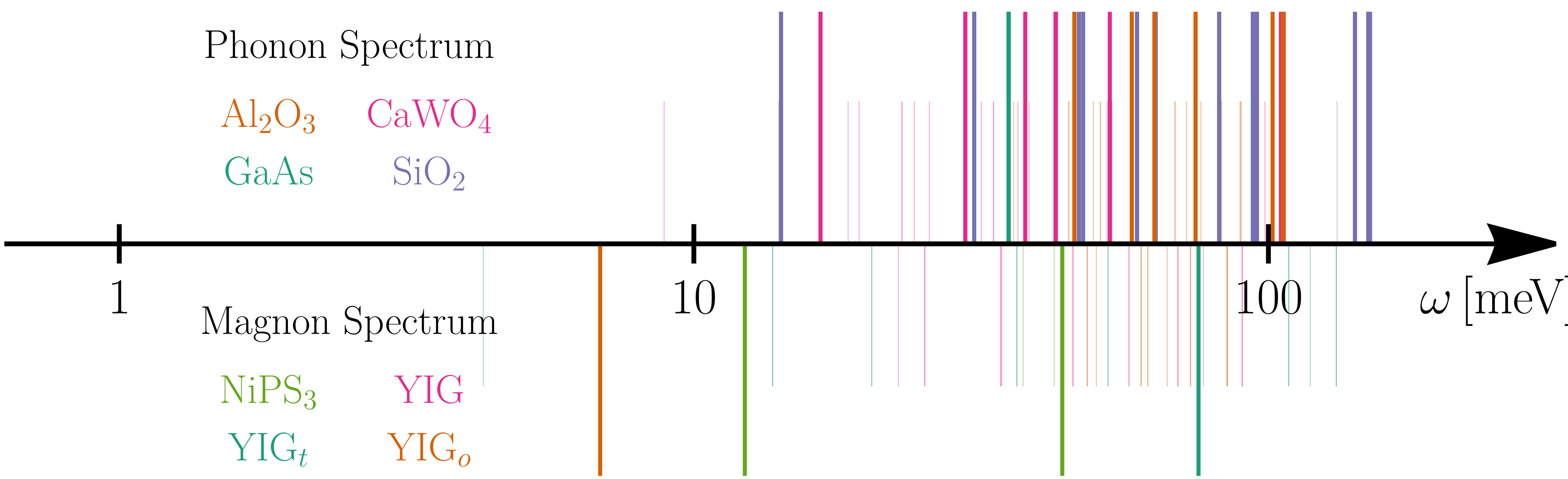
- Collective (electron) spin-waves = magnons
- Magnetically ordered materials (ferro- or ferri-magnets)



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	$a\boldsymbol{E}\cdot\boldsymbol{B}$	$\boldsymbol{f}_j = \frac{1}{\sqrt{2}}\, g_{a\gamma\gamma} \frac{e\sqrt{\rho_a}}{m_a}\, \boldsymbol{B}\cdot\boldsymbol{\varepsilon}_\infty^{-1}\cdot\mathbf{Z}_j^*$	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)

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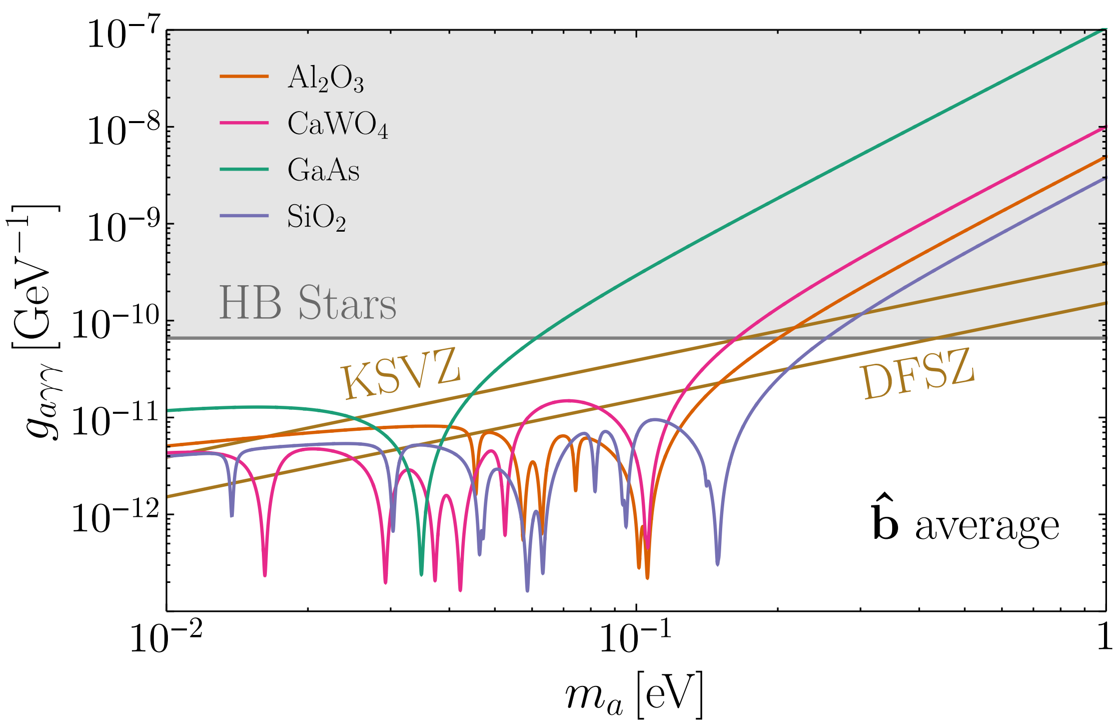

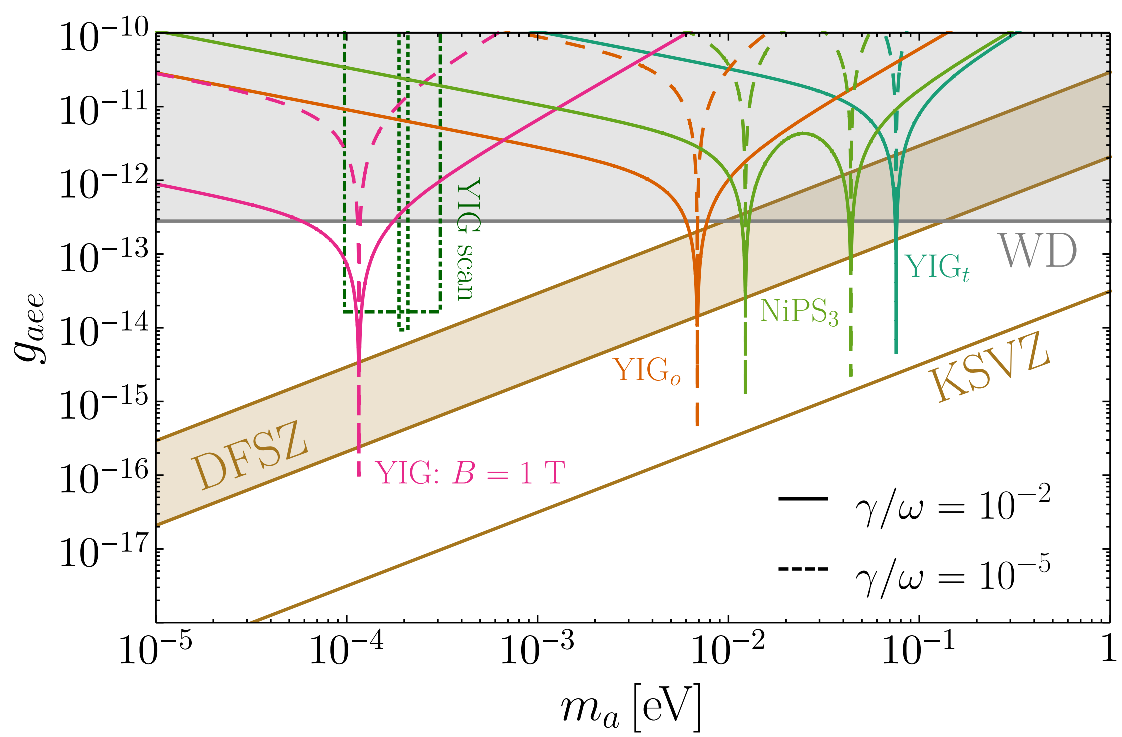

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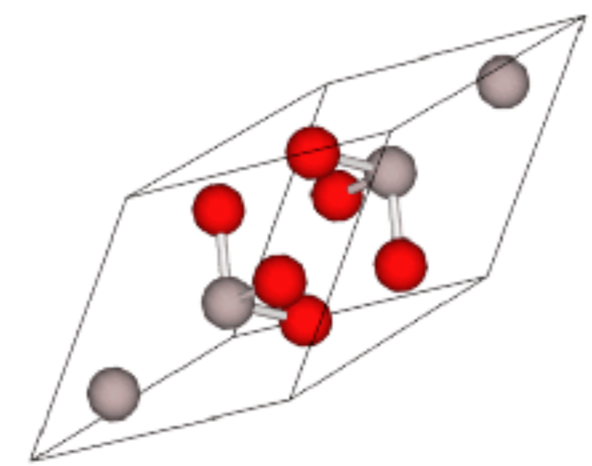
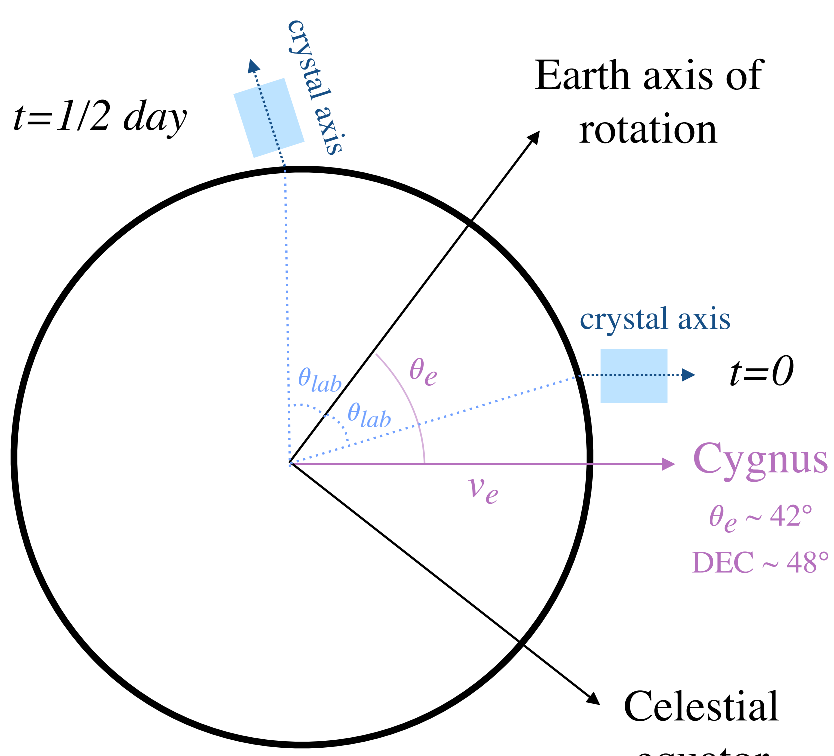
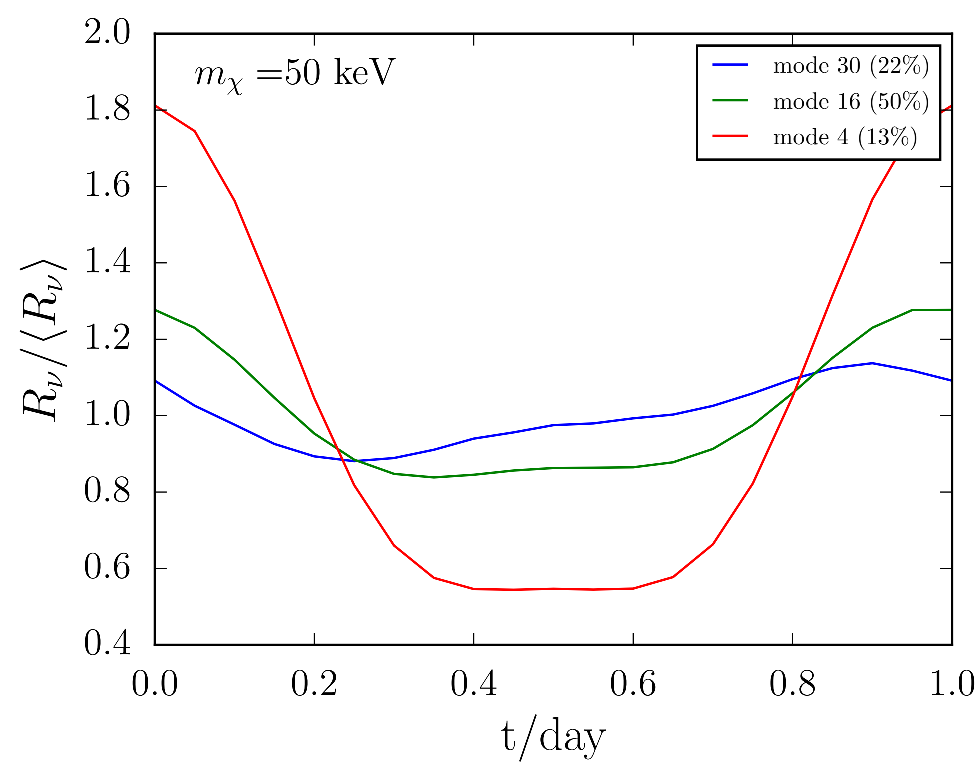
DIRECTIONALITY IN ANISOTROPIC MATERIALS!

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

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



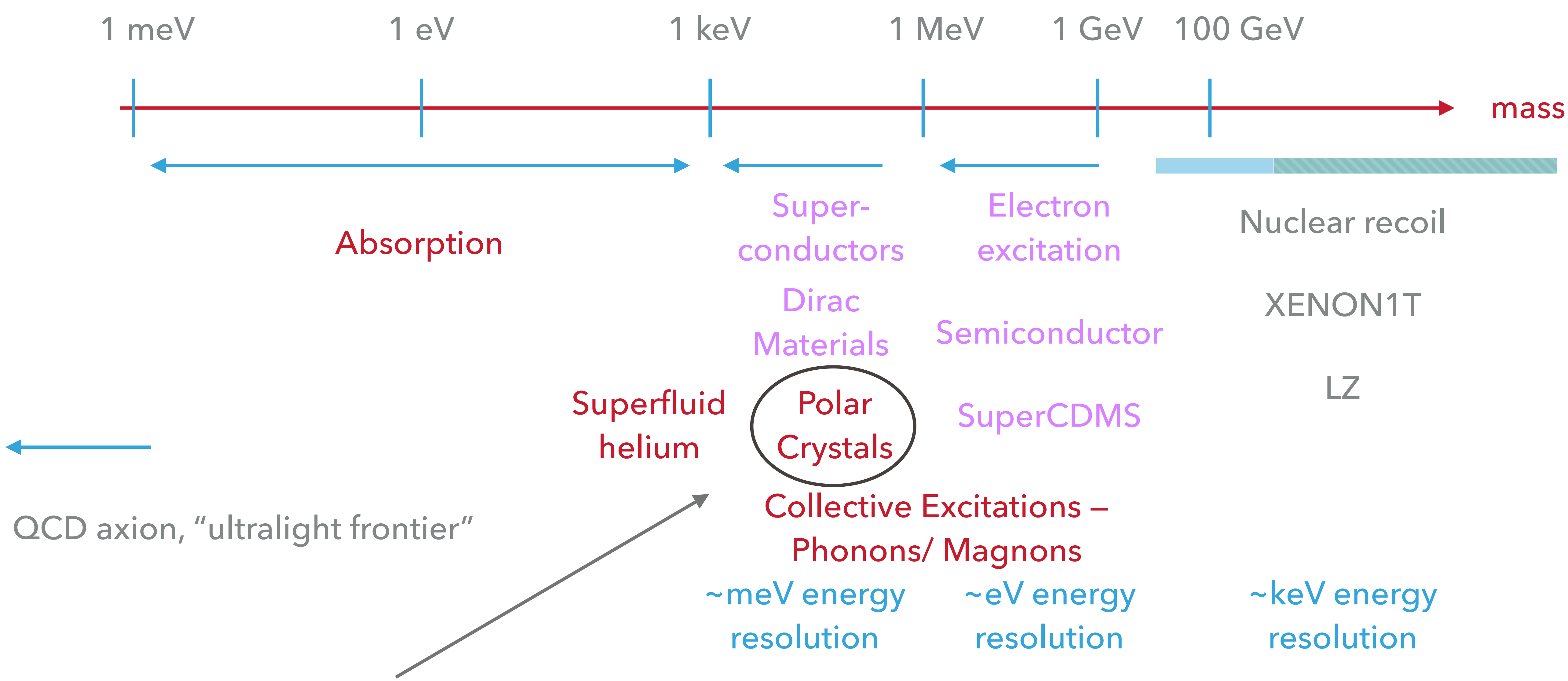




DM-PHONON DETECTION RATE CALCULATOR

- Codes are publicly available — see 2102.09567
- **phonodark.caltech.edu**
- Contains repository for rate calculator
- 26 materials possible, based on analysis of 2102.09567
- Only code to do fully directional rate calculation
- Only code to calculate rate for any of the EFT operators highlighted earlier
- Manual coming soon

COLLECTIVE PHENOMENA IN MATERIALS



Strong rate, immediate experimental feasibility

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

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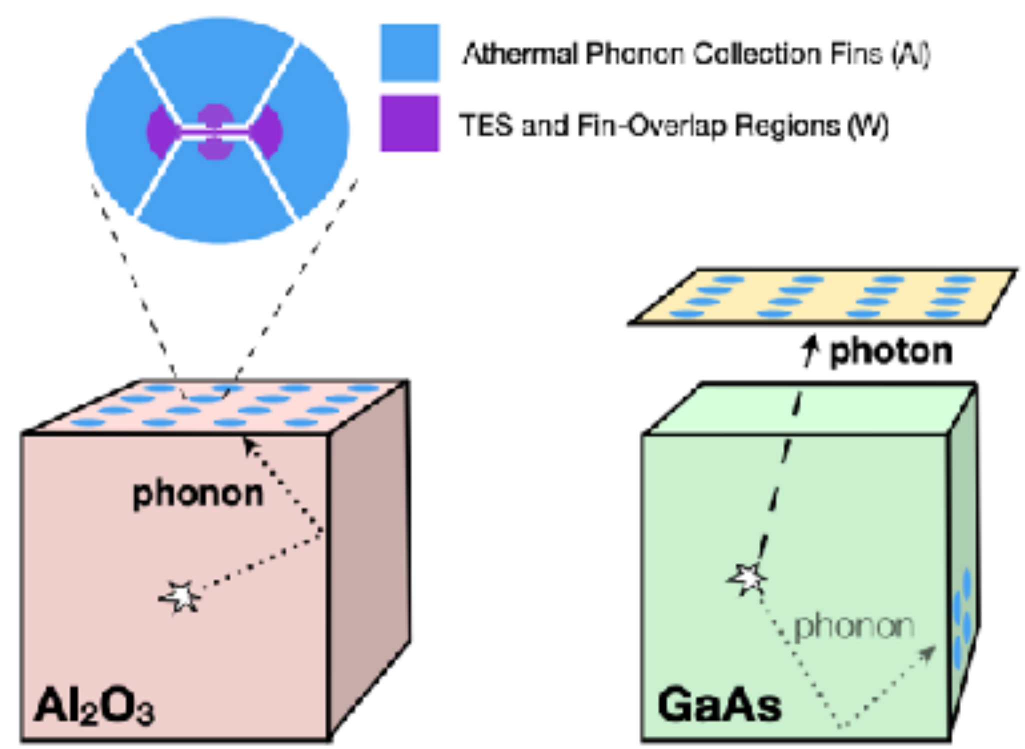

SUMMARY

- 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 have broad discovery potential for light DM