Particle Dark Matter Direct Detection

Lecture 4

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Direct Detection

- Lecture 1:
  – Brief review of the observational evidence for Dark Matter (DM)
  – What we know about DM and implications for DM candidates mass and interaction (PBH or particles? CDM, WDM, PIDM, DDDM, SIDM? Millicharge DM, kinetic mixing, Hidden (or Dark) Photons (HP or DP), Atomic DM, Mirror DM, WIMPs, FIMPs, SIMPs, ELDERs, Axions, ALPs, WISPs, FIPs...)
  – The Standard Halo Model (SHM) and its main parameters
- Lecture 2:
  – Introduction to DM Direct Detection (DD)
  – Non-directional DD of WIMPs
- Lecture 3:
  – Halo model implications, Halo-Independent Data Analysis, Directional DD
- Lecture 4:
  – DD of Light Dark Matter

Disclaimer: idiosyncratic choice of subjects and not complete lists of citations

- Difference between WIMPs and "Light DM" (LDM) This is a recent distinction: in direct DM detection, WIMPs scattering on nuclei deposits enough energy to be detected ($E_{\text{threshold}} \simeq$ keV). LDM does not.

Elastic non-relativistic DM-Nucleus collision: the maximum recoil energy imparted to a nucleus by a WIMP moving with v is

$$E_{max} = 2\mu^2 v^2/M$$

$\mu = \dfrac{mM}{(m+M)}$: reduced mass, m: WIMP mass, M: is the nucleus mass.

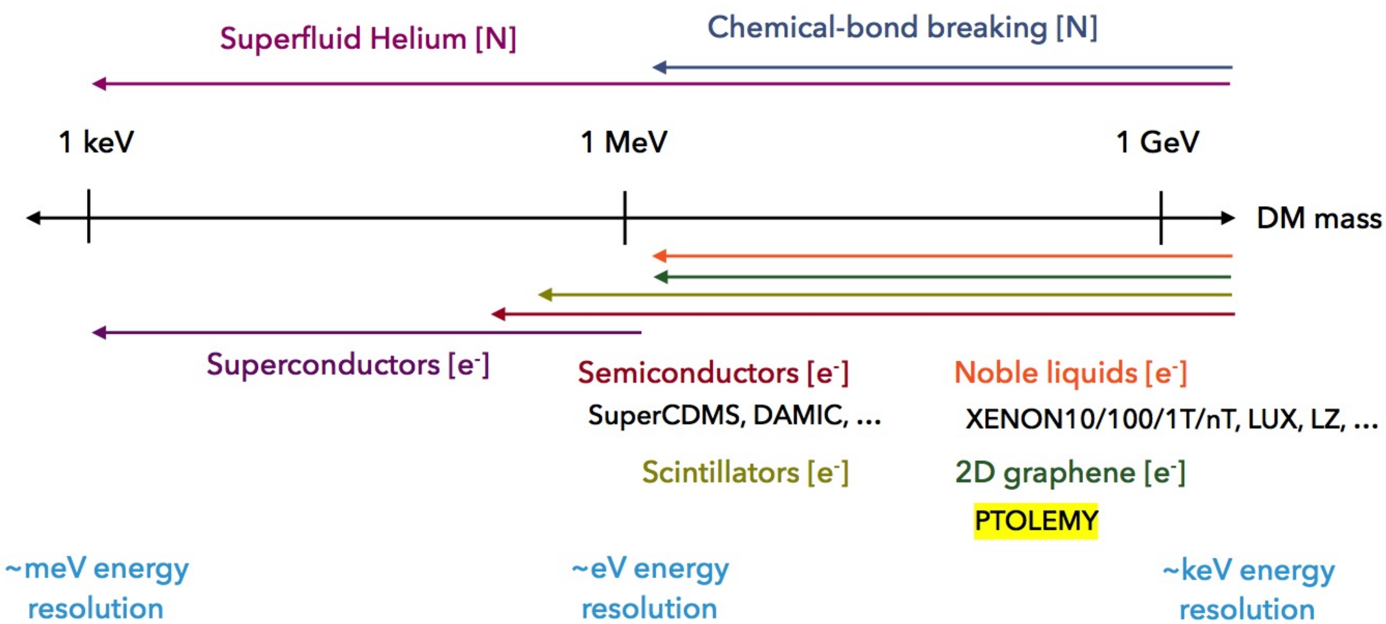
LDM with mass $m \simeq$ keV to GeV E_{max} for $v \simeq 10^{-3}$ is below threshold for most direct DM experiments: for $m << M$, $\mu = m$, thus

$$E_{max} = 2\mu^2 v^2/M \simeq 20\text{eV}\left(\frac{m}{100\text{MeV}}\right)^2 \left(\frac{10\text{GeV}}{M}\right) << E_k = mv^2/2$$

but LDM could deposit enough energy,1 to 10eV, interacting with electrons (electron ionization or electronic excitation or molecular dissociation) Bernabei et al. 0712.0562; Kopp et al. 0907.3159; Essig, Mardon & Volansky, 1108.5383; Essig et al. 1206.2644; Batell, Essig & Surujon 1406.2698...

Sub-GeV “Light Dark Matter” (LDM) direct detection

Dark Sector Workshop, 1608.08632



Materials that could be used to probe LDM, by scattering off electrons [e^-] or inelastic scattering nuclei [N] (photon emission in the nuclear recoil, breaking of chemical bonds in molecules or crystals, multi-phonon processes in superfluid helium or insulating crystals)

Energy matching of targets

- Nuclear size: $R_{\rm Nucleus} \simeq$1.25 fm $A^{1/3}$ or $1/R \simeq \dfrac{160{\rm MeV}}{A^{1/3}}$

- Atomic size, and interatomic separation in crystals: 1 Amgstrom $\simeq \dfrac{1}{12{\rm keV}}$

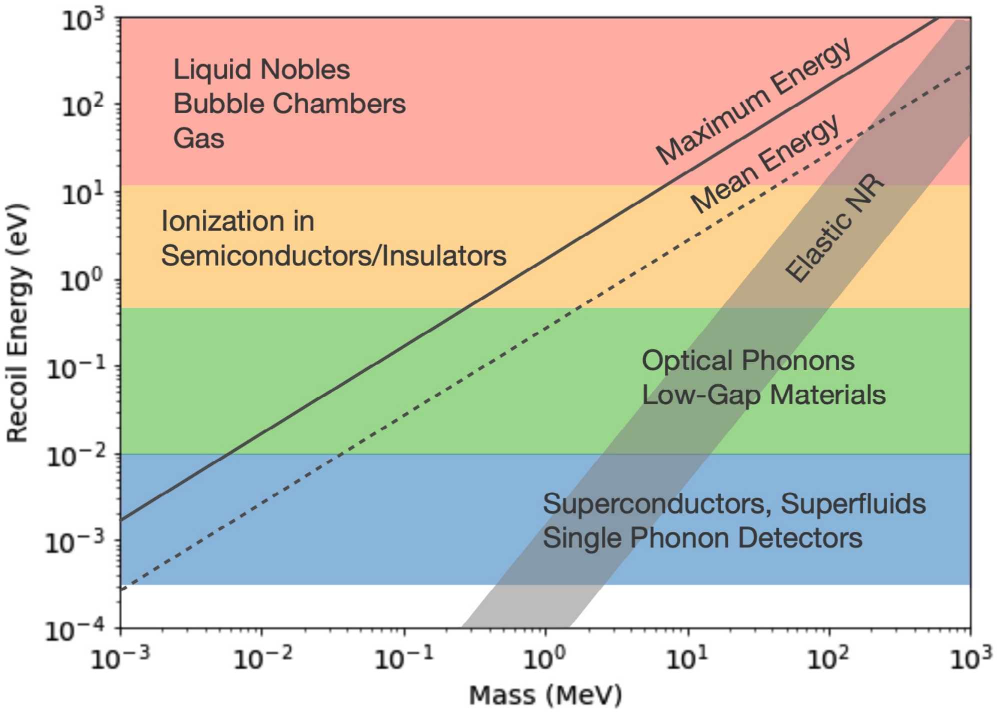
- The energy to be deposited in a DM colission is a fraction of initial dark matter particle $E_k \simeq 10^{-6} m$, and the momentum transfer $q \simeq 10^{-3} m \simeq \lambda_{dB}$, ($\lambda_{dB}$ is de Broglie wavelength of the DM particle.)

- WIMPs: $m>$ GeV, $q >$MeV interacts with single nuclei

- LDM with GeV$>m>$MeV, MeV$> q >$ keV interacts with atoms

- LDM with $m<$MeV, $q <$keV, e.g. λ_{dB} includes many atoms, particle does not see individual atoms, but collective atomic excitations (phonons, magnons...).

Light-DM, keV-GeV mass Detection via scattering (Fig. R Essig -UCLA-DM2023)



- $\Delta E \simeq$10 eV, e.g. Xe,Ar,He

- $\simeq$1eV, e.g. Si, Ge, GaAs, Quantum Dots, organic scintillators, diamond

- $\simeq$10-100 meV, e.g. GaAs, sapphire, Dirac materials

- $\simeq$1 meV, e.g. superfluid He, semi-metals. To reach down to m$\simeq$keV: need to detect single phonon excitation or e in low-gap materials

Elastic Scattering Nuclear Recoil (gray band), $E_{\rm max} = E_k$

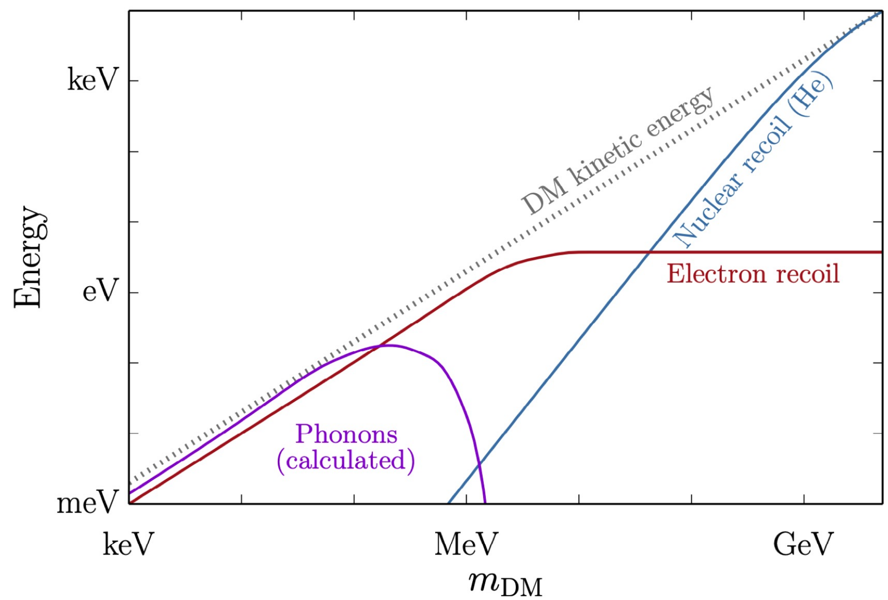
Inelastic scattering: -DM-e scattering,

-DM-Nucleus with Migdal Effect (i.e. excitation/ionization of the recoiling atom),

-DM-collective modes scattering (e.g. phonons, magnons). (See refs in review 2203.08297)

Sub-GeV LDM typical energy deposition

Tongyan Lin TASI lectures 1904.07915



- $E_{NR-max} = 2\mu^2 v^2/M << E_k = m_\chi v^2/2$

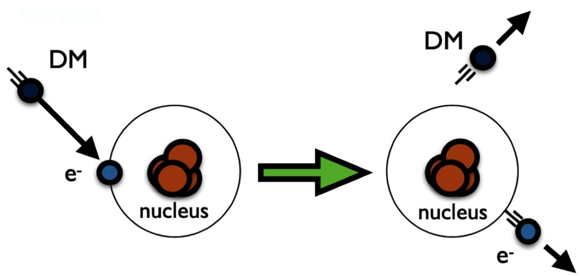
e-recoils: good for $E <$ few eV, ie. $m_\chi <$ few MeV

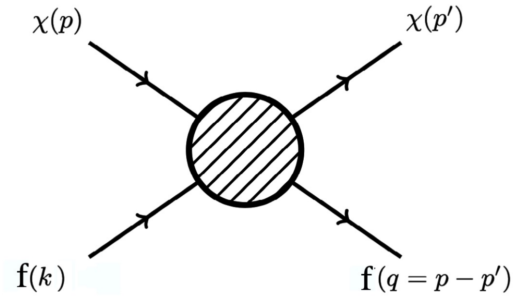
Atomic ionization in fluids: $E_{\rm th}$ is binding energy of outer electrons, e.g. 12 eV in Xe

Electron excitation in semiconductors (Si, Ge) have band gaps, between valence and conduction, $E <$ few eV, and in superconductors and "Dirac materials" (graphene) $E <$ meV gaps.

- Phonons, magnons: cutoff at meV because calculations have been done so far for sub-MeV DM

Kinematics of DM-scattering on bound electrons





$$E_{\chi-i} = \frac{\mathbf{p}^2}{2m_\chi},\ \mathbf{p} = m_\chi \mathbf{v} \quad E_{\chi-f} = \frac{(\mathbf{p}-\mathbf{q})^2}{2m_\chi}$$

$$\omega = E_{\text{deposited}} = E_{\chi-i} - E_{\chi-f} = \frac{(\mathbf{p}\cdot\mathbf{q})}{2m_\chi} - \frac{\mathbf{q}^2}{2m_\chi}$$

- for scattering on a nucleus initially at rest (kinetic energy $\simeq kT$ at very low T) $E_{\text{deposited}} = E_R$ (energy conservation gives $\dfrac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} = \dfrac{\mathbf{q}^2}{2\mu_{\chi N}}$)

- Bound e wavefunction size $R_{\text{Bohr}} = 1/(\alpha m_e)$ thus $k_e \simeq 1/R_{\text{Bohr}} = \alpha m_e$ and initial velocity $v_e \simeq \alpha > v_{\text{DM}}$ and initial and final wavefunctions are different

Kinematics of DM-scattering on bound electrons

Bound e wave-function size $R_{\rm Bohr} = 1/(\alpha m_e)$ thus $k_e \simeq 1/R_{\rm Bohr} = \alpha m_e \simeq 3.7$ keV and velocity $v_e \simeq \alpha > v_{\rm DM}$ and E conservation

$$\frac{\mathbf{p}^2}{2m_\chi} + E_e(\mathbf{k}) = \frac{(\mathbf{p}-\mathbf{q})^2}{2m_\chi} + E_e(\mathbf{k}')$$

where $E_e(\mathbf{k}')$ could be a free wave for ionization, or an in-medium energy eigenvalue. The momentum transfer is still $\mathbf{q} = \mathbf{p} - \mathbf{p}'$.

Useful toy model Lin 1904.07915: scattering off a free electron with initial velocity $v_{ei} = \alpha$. Then E conservation: $\dfrac{\mathbf{p}\cdot\mathbf{q}}{m_\chi} = \dfrac{\mathbf{k}\cdot\mathbf{q}}{m_e} - \dfrac{\mathbf{q}^2}{2\mu_{\chi e}}$, where $\mu_{\chi e}$ = DM-e reduced mass

Since $v_{e,i} = |\mathbf{k}|/m_e \gg v_{\chi,i} = |\mathbf{p}|/m_\chi$, we can drop the LHS, i.e. $\dfrac{\mathbf{k}\cdot\mathbf{q}}{m_e} \simeq \dfrac{\mathbf{q}^2}{2\mu_{\chi e}}$ and write $|\mathbf{q}| \simeq \mu_{\chi e} v_{e,i}$. Now estimate in two regimes:

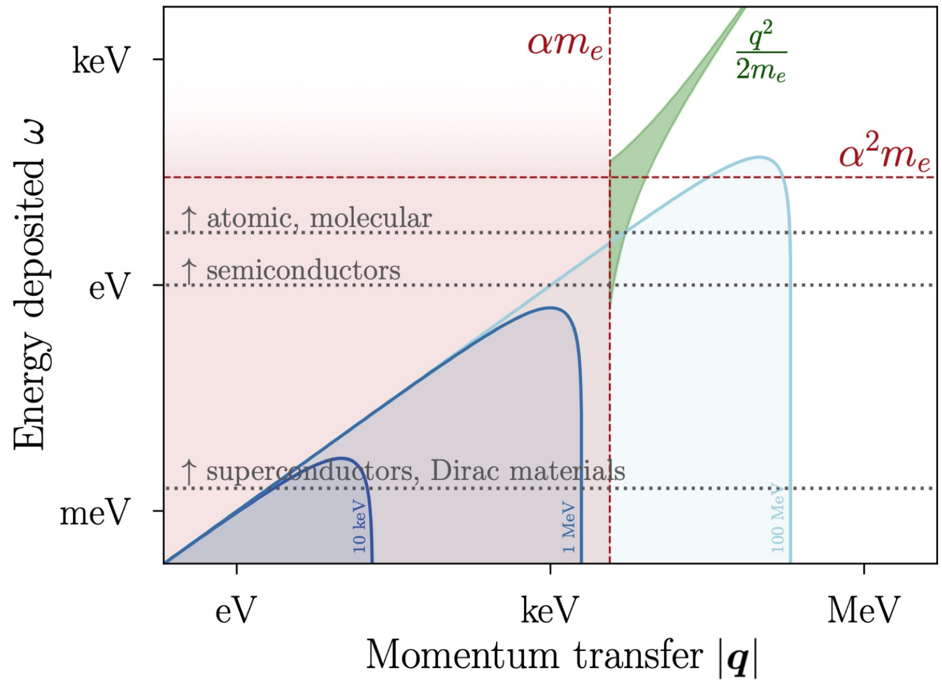
— $m_\chi \gtrsim m_e$, $|\mathbf{q}| \simeq m_e v_{e,i}$ and $\omega \simeq m_e v_{e,i} v_{\chi,i} \approx$ few eV independent of m_χ (this is typical, higher is possible such as for ionization of atoms in Xe ($\omega > 12$ eV).

—- $m_\chi \lesssim m_e$, $\omega \simeq \frac{1}{2} m_\chi v_{\chi,i}^2$ all DM $E_{k,i}$ (and $\omega > 0$ implies $|\mathbf{q}| < m_\chi v_{\chi,i}$)

Kinematics of DM-scattering on bound electrons

Cirelli, Strumia, Zupan 2406.01705 General kinematical upper limit ω below the parabola

$$\omega(\vec{q}) = E_1 - E_2 = \frac{1}{2}m_\chi v^2 - \frac{1}{2M}(m_\chi \vec{v} - \vec{q})^2 = \vec{q}\cdot\vec{v} - \frac{\vec{q}^2}{2m_\chi} \leq qv - \frac{q^2}{2m_\chi}\ .$$



Superconductors and Dirac materials Both with meV e excitations

- Superconductors: Cooper pairs have meV binding energy. But their Fermi level energy is $\sim$ 10 eV, so only those pairs within meV of the Fermi level are useful, the others suffer Pauli blocking. Supresses DP mediated scatterings: large polarization tensor, i.e. effective mass Hochberg et al 1512.04533

- "Dirac" semimetal (graphene): quantum engineered to have a quasiparticle with very small mass gap near the Fermi level, with a linear dispersion relation $\omega \sim k$, as a relativistic electron (obeying Dirac's eq.). Good for DP mediator (analogy with QED,where gauge symmetry protects $m_\gamma = 0$) Hochberg et al 1708.08929

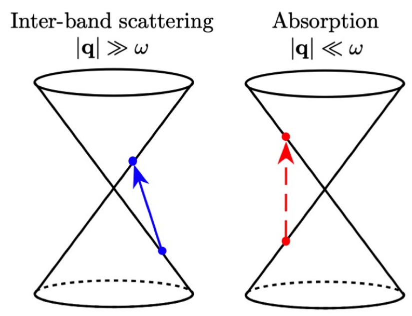
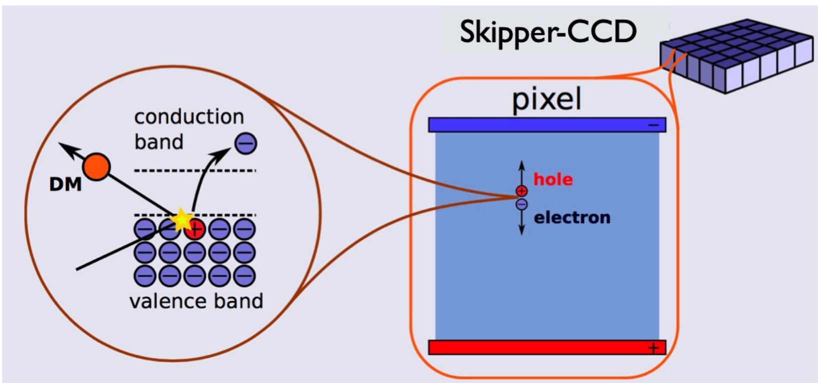


Figure 1: Cartoon of the two dark matter-initiated processes in Dirac materials that we consider in this paper: inter-band (valence to conduction) scattering (*left*) and absorption by valence-band electrons (*right*).

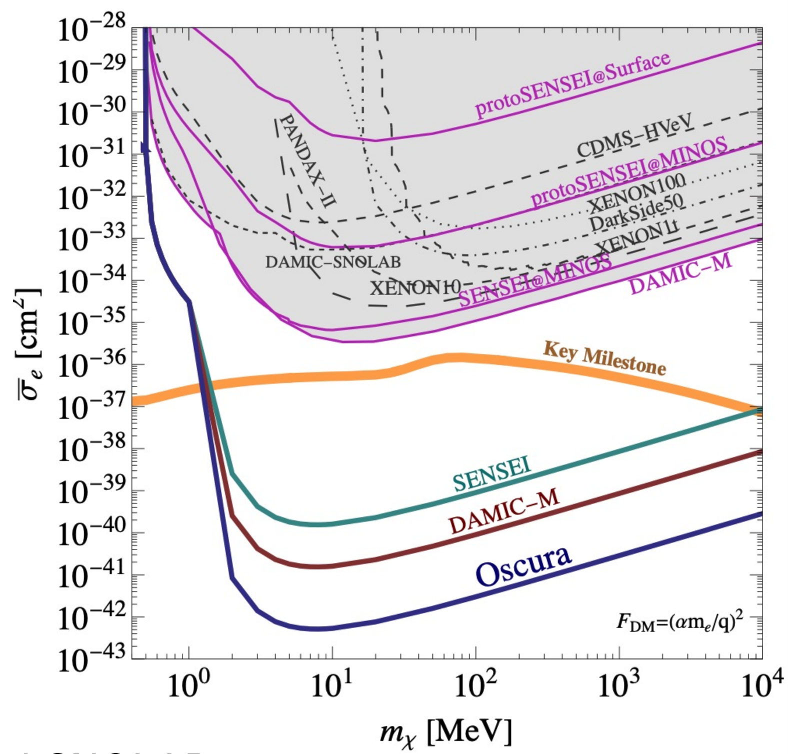
Light-DM Detection through DM-electron scattering in Skipper-CCD

(Fig. from R. Essig- UCLA DM2023)

SENSEI/DAMIC-M/Oscura: Detection concept



DM would create one or a few electrons in a pixel



- SENSEI: 100 g detector operating at Fermilab and SNOLAB (1804.00088,1901.10478, 2004.11378)
- DAMIC-M: 18g detector operating at Modane (Frejus, France) (2302.02372) goal 1kg (funded)
- OSCURA: project for 10 kg detector (2202.10518)

Let us see what is $\bar{\sigma}_e$ that appears in many plots

Event rate for general DM-scattering on bound electrons: ionization or excitation

Both e and nuclei are non-relativistic so one can use usual NR QM to evaluate matrix elements. The interaction Hamiltonian can be written

$$H_{\rm int} = \int \frac{d^3\vec{q}}{(2\pi)^3} e^{i\vec{q}\cdot(\vec{r}_{\rm el}-\vec{r}_{\rm DM})} \sum_j c_j^{\rm el}(q)\ \mathcal{O}^j_{\rm DM} \times \mathcal{O}^j_{\rm el}$$

where operators are the same as for DM-nucleon interactions but but with N replaced by e: $m_N \to m_e$ and $\vec{S}_N \to \vec{S}_e$.

$\vec{p}_1$ and $\vec{p}_2$: incoming and outgoing DM momenta, $\vec{q} = \vec{p}_2 - \vec{p}_1$

$|i\rangle$ $|f\rangle$: incoming and outgoing electron (target) states

The matrix elements factorize into DM and electron (target) parts,

$$\langle f, \vec{p}_2 | H_{\rm int} | i, \vec{p}_1\rangle \sim c^i_{\rm el} \langle \vec{p}_2 | \mathcal{O}^j_{\rm DM} | \vec{p}_1\rangle \langle f | \mathcal{O}^j_{\rm el} | i\rangle$$

The last is independent of the DM, and have been computed for isolated atoms and crystals (see e.g. Liang et al 405.04855, 2406.10912)

E.g. for a tree level exchange of a dark photon, $\mathcal{O}_1^{\rm el} = 1_{\rm DM} 1_{\rm el}$ with a coefficient $c_1^{\rm el}(q) = -\dfrac{\epsilon e g_{\rm D}}{q^2 + m^2_{A'}}$ where $L = \epsilon F'_{\mu\nu} F^{\mu\nu}/2$ and g_D DP coupling to DM.

Event rate for general DM-scattering on bound electrons

In a target of volume V, mass m_T, $\rho_T = m_T/V$. The kinematics is very different than in DM-nucleus scattering. Starting from Fermi's Golden rule, (e.g. Khan and Lin 2108.03239

$$\frac{dN_{\rm ev}}{dt}\frac{1}{m_T} = \frac{1}{\rho_T}\int dn_{\rm DM}(\vec{v})\frac{V d^3\vec{p}_2}{(2\pi)^3}\sum_f \left|\langle f, \vec{p}_2|H_{\rm int}|i, \vec{p}_1\rangle\right|^2 2\pi\delta(E_f - E_i + E_2 - E_1)$$

$\vec{p}_1$ E_1 and $\vec{p}_2$ E_2: incoming and outgoing DM momenta and energies,

$H_{\rm int}$: non-relativistic DM–electron interaction Hamiltonian,

$|i\rangle$ $|f\rangle$: initial/ final detector state, with energies E_i, E_f, and $\langle i|i\rangle = \langle f|f\rangle = \langle\vec{p}_i|\vec{p}_i\rangle = 1$

$n_{\rm DM}(\vec{v})$: volume density of DM particles with $\vec{v} = \vec{p}_1 m_{\rm DM}$,

$V d^3\vec{p}_2/(2\pi)^3$: density of states for the outgoing DM plane wave.

Number of DM particles, $V\int dn_{\rm DM}(\vec{v})$, divided by m_T, leads to the $\int dn_{\rm DM}(\vec{v})/\rho_T$ factor.

Event rate for SI DM-scattering on bound electrons

Many LDM models have SI interactions, so this has been the case most studied. For SI,

$$H_{\rm int} = \int \frac{d^3\vec{q}}{(2\pi)^3} e^{i\vec{q}\cdot(\vec{r}_{\rm e}-\vec{r}_{\rm DM})} c_1^{\rm el}(q) 1_{\rm DM} 1_{\rm e}$$

$$\frac{dN_{\rm ev}}{dt}\frac{1}{m_T} = \frac{1}{\rho_T}\int dn_{\rm DM}(\vec{v}) \int \frac{d^3\vec{q}}{(2\pi)^3} d\omega \frac{\pi\bar{\sigma}_e F_{\rm DM}^2(q)}{\mu_e^2} \delta(\omega + E_2 - E_1) S(\vec{q},\omega)$$

μ_e is the reduced e-DM mass;

ω is the energy deposited in the material;

$\bar{\sigma}_e = [c_1^{\rm el}(q_0)]^2(\mu_e^2/\pi)$, where q_0= fiducial fixed momentum= inverse Bohr radius,

$q_0 = \alpha m_e \simeq 3.7$ keV (Bohr radius=typical extent of the electron wave-function)

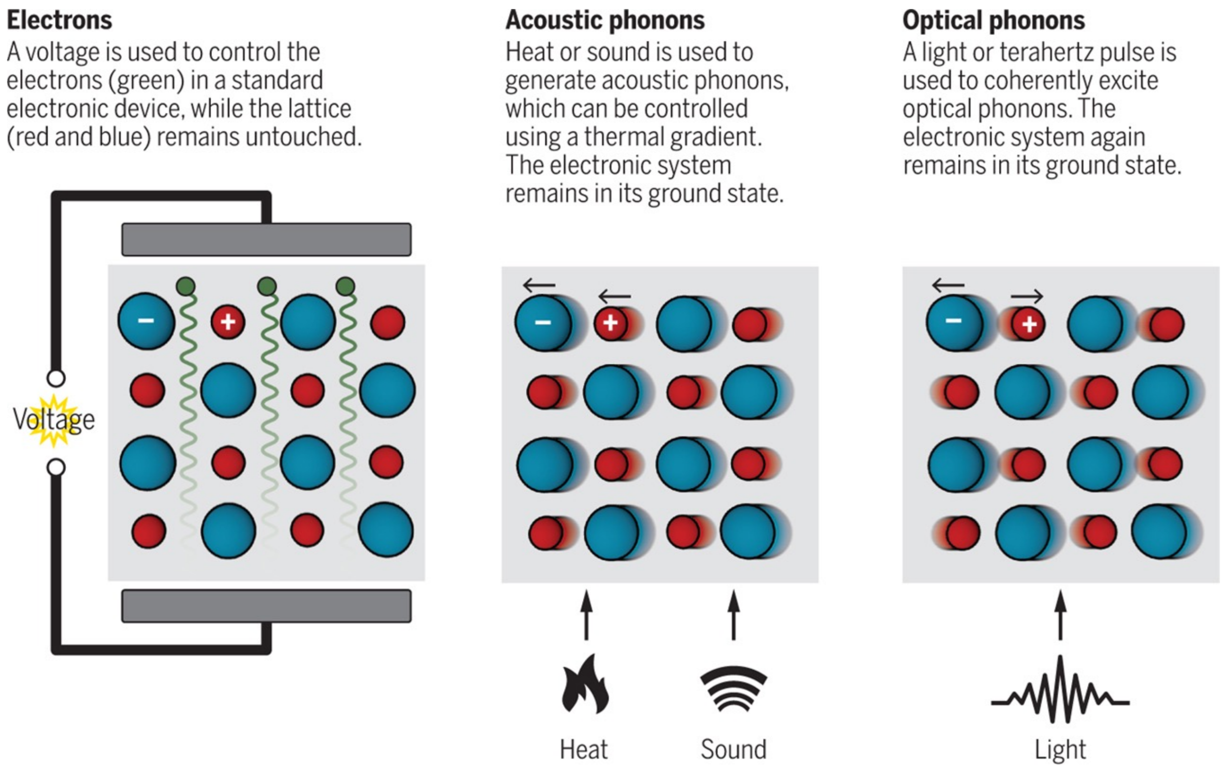
$F_{\rm DM}(q)$ accounts for DM mediator propagator: $F_{\rm DM}$=$1, (q_0/q)^2$ for heavy, light mediators

$S(\vec{q},\omega)$ is the Dynamic Structure Factor borrowed from condensed matter

$S(\vec{q},\omega) = \frac{2\pi}{V}\sum_f \left|\langle f\right|\sum_k e^{i\vec{q}\cdot\vec{r}_k}\left|i\rangle\right|^2 \delta(E_f - E_i - \omega)$, gives the response of the material to the probe $e^{i\vec{q}\cdot\vec{r}_{\rm el}} 1_{\rm el}$, sum $\sum_k$ is over all the electrons in the target.

For the simple case of e at rest $S(\vec{q},\omega) = 2\pi n_e\, \delta\left(\omega - \frac{q^2}{2m_e}\right)$, n_e= e number density

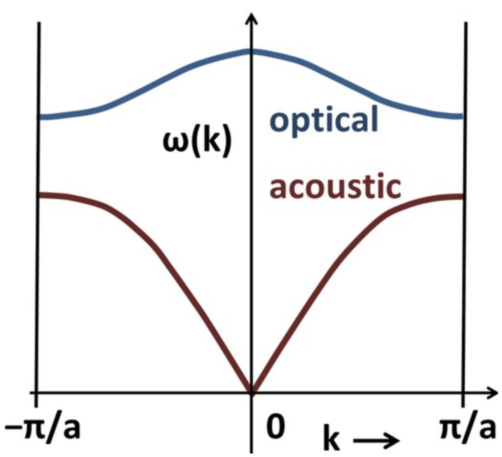
Phonons in crystals For DM couplings with nucleons- collective excitations relevant for $q < keV$

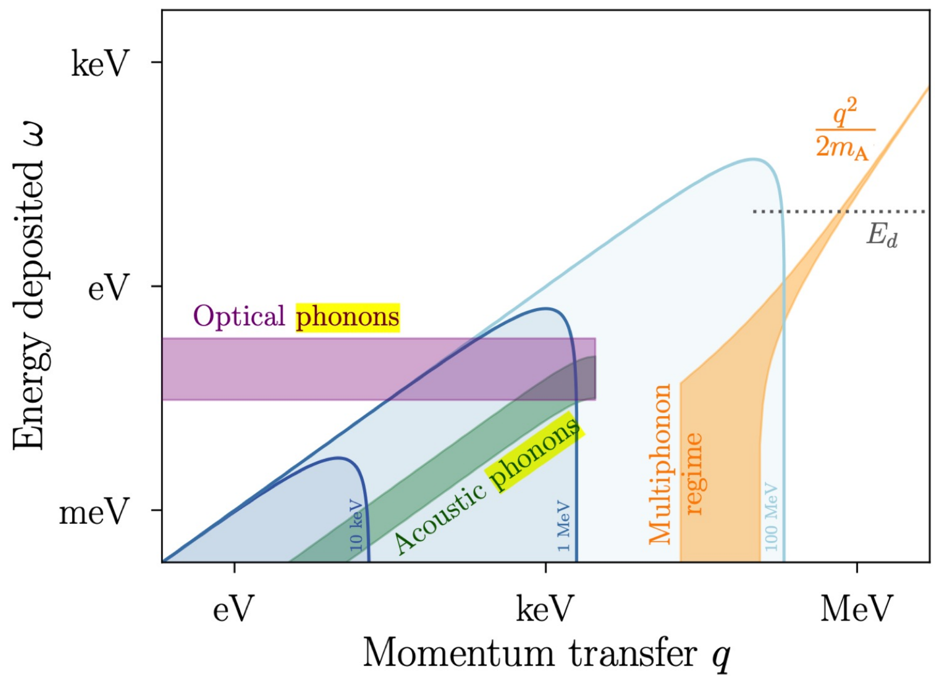


Phonons in crystals

Acoustic: in-phase oscillations transverse (T) and longitudinal (L), always present, some gapless, $\omega \simeq c_{\rm sound} q$ and if $c_{\rm sound} << v_\chi$ for small ω

Optical: out-of-phase oscill. transverse (T) and longitudinal (L), some have them e.g. GaAr, and Al_2O_3 (sapphire), these are "polar materials", gapped $\omega \simeq$ 10-100 meV (good for $m_\chi \simeq$ keV)





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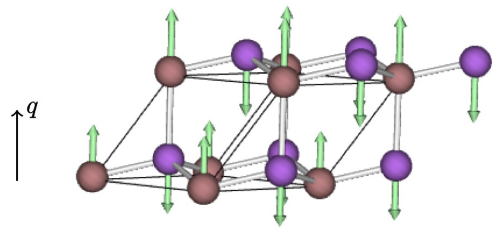
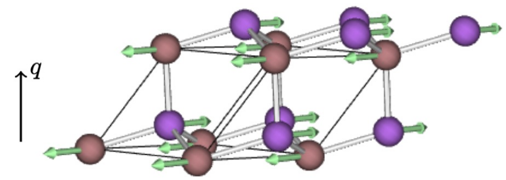
Scattering on phonons In Polar Materials, GaAs and Al_2O_3 (sapphire)

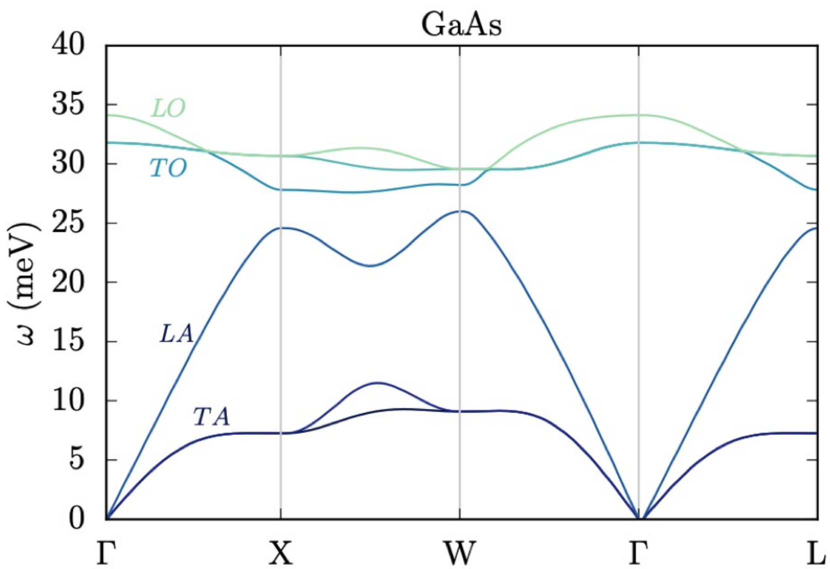
Knapen, Lin, Pyle, Zurek 1807.10291

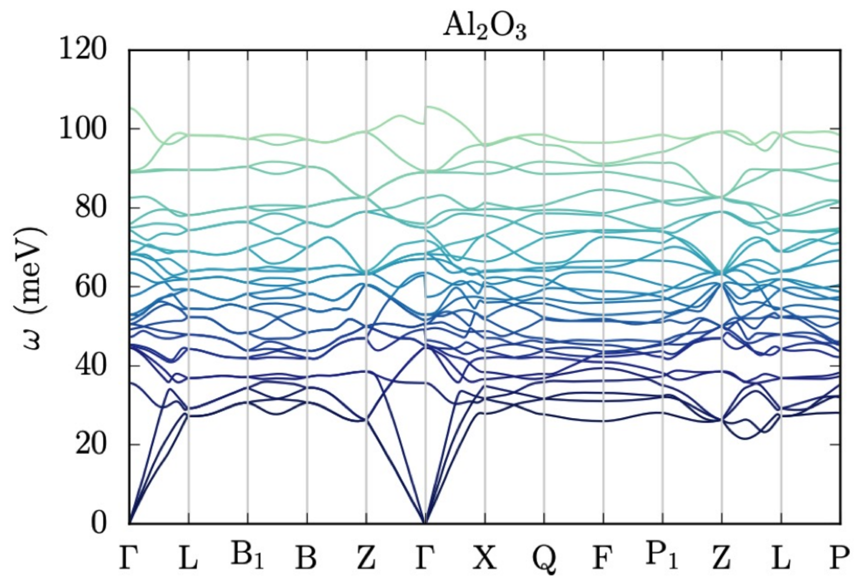


(a) LO mode



(b) TO mode

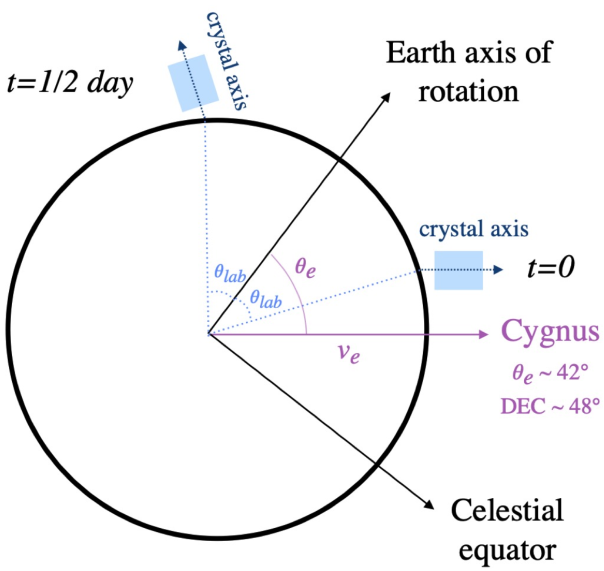


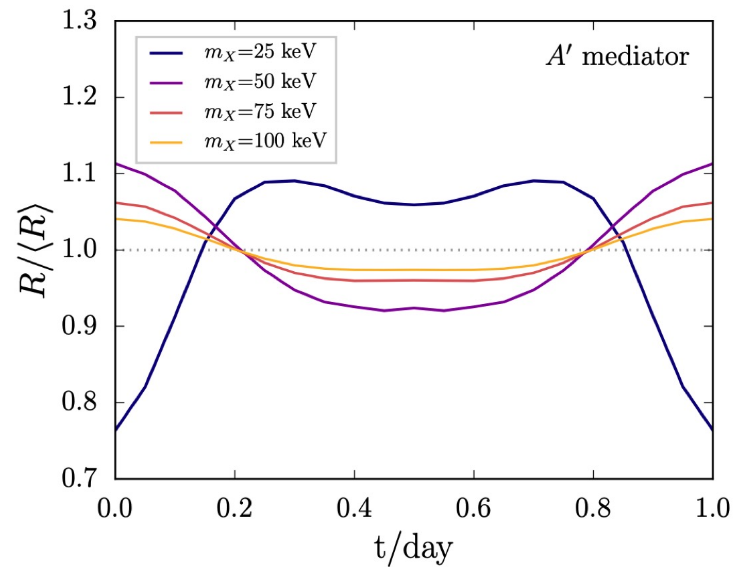


Scattering on phonons In Polar Materials, GaAs and sapphire

Polar materials, GaAs and sapphire, are highly anisotropic. Daily modulation in the interaction rate can be established at 90% C.L. with a gram-year of exposure.

Right fig. assumes a 25 meV threshold in sapphire Knapen, Lin, Pyle, Zurek 1807.10291





Phonons also in other condensed matter systems, besides crystals: e.g. superfluid ^{4}He (proposed in 1980's) besides phonons contains contains maxons and rotons; DM produce multiphonons.

Scattering on Phonons Cirelli, Strumia, Zupan 2406.01705

For SI scattering on nucleons

$$S(\vec{q},\omega) = \frac{2\pi}{V}\sum_f \left|\langle f|\sum_I f_I e^{i\vec{q}\cdot\vec{r}_I}|i\rangle\right|^2 \delta(E_f - E_i - \omega),$$

where I runs over all nuclides, with positions $\vec{r}_I$ and coupling f_I with the DM

$$f_I = \left(\frac{2}{|c_1^p|^2 + |c_1^n|^2}\right)^{1/2}\left[Z c_1^p + (A-Z)c_1^n\right]F(q)$$

c_1^N: coefficients the NREFT interaction Lagrangian.

For Isospin Conserving coupling, IC-SI, $c_1^p = c_1^n$, $f_I = A$ in the $q \to 0$ limit.

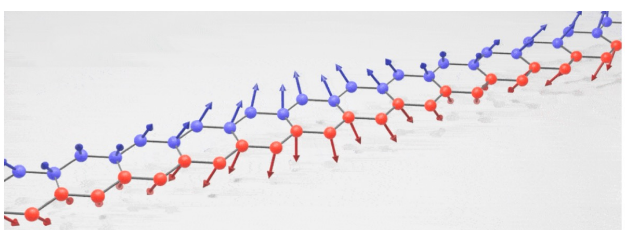
(In the limit $m_\chi >$GeV, $\omega >$ binding energy, S is that of the free-nucleon limit
$S(\vec{q},\omega) = 2\pi n_{\rm nuc} A^2 \left|F(q)\right|^2 \delta\left(\omega - \frac{\vec{q}^2}{2m_A}\right)$ and recover the result for WIMPs)

SD dependent DM-Magnons interaction Magnons are spinwaves.

$\omega_{th} < \omega < 100$ meV, i.e. keV $< m_{\rm scatter}$ or meV$< m_{\rm absorption}$

(Trickle, Zhang, Zurek3 1905.13744)

Magnetic dipole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi}\bar{\chi}\sigma^{\mu\nu}\chi V_{\mu\nu} + g_e\bar{e}\gamma^\mu e V_\mu$	$\hat{\mathcal{O}}^\alpha_\chi = \frac{4g_\chi g_e}{\Lambda_\chi m_e}\left(\delta^{\alpha\beta} - \frac{q^\alpha q^\beta}{q^2}\right)\hat{S}^\beta_\chi$	$\bar{\sigma}_e = \frac{g_\chi^2 g_e^2}{\pi}\frac{6m_\chi^2 + m_e^2}{\Lambda_\chi^2(m_\chi + m_e)^2}$
Anapole DM	$\mathcal{L} = \frac{g_\chi}{\Lambda_\chi^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu V_{\mu\nu} + g_e\bar{e}\gamma^\mu e V_\mu$	$\hat{\mathcal{O}}^\alpha_\chi = \frac{2g_\chi g_e}{\Lambda_\chi^2 m_e}\epsilon^{\alpha\beta\gamma} i q^\beta \hat{S}^\gamma_\chi$	$\bar{\sigma}_e = \frac{g_\chi^2 g_e^2}{\pi}\frac{3\alpha^2\mu_{\chi e}^2}{2\Lambda_\chi^4}$
Pseudo-mediated DM	$\mathcal{L} = g_\chi\bar{\chi}\chi\phi + g_e\bar{e}\,i\gamma^5 e\,\phi$	$\hat{\mathcal{O}}^\alpha_\chi = -\frac{g_\chi g_e}{q^2 m_e} i q^\alpha \mathbb{1}_\chi$	$\bar{\sigma}_e = \frac{g_\chi^2 g_e^2}{4\pi}\frac{\mu_{\chi e}^2}{\alpha^2 m_e^4}$



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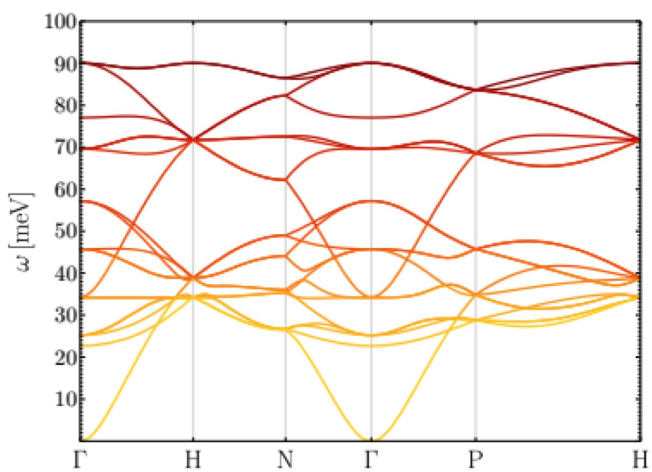


Light-DM (SubGeV mass) Multitarget proposal

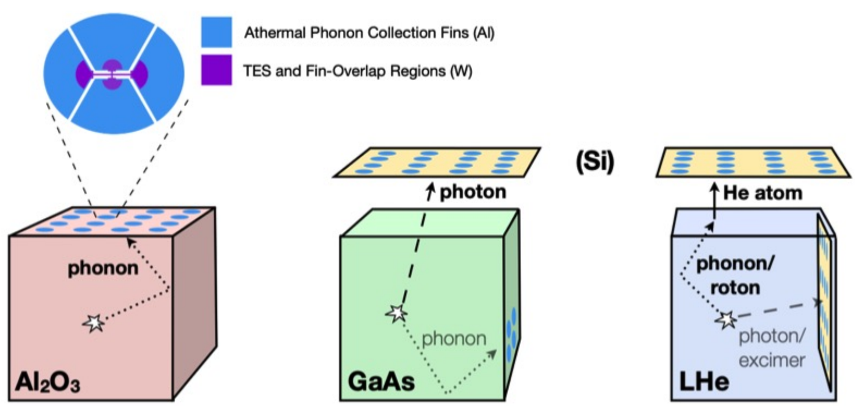
(Fig. from R. Essig- UCLA Dark Matter 2023)

TESSERACT

R&D funded by DoE DMNI program

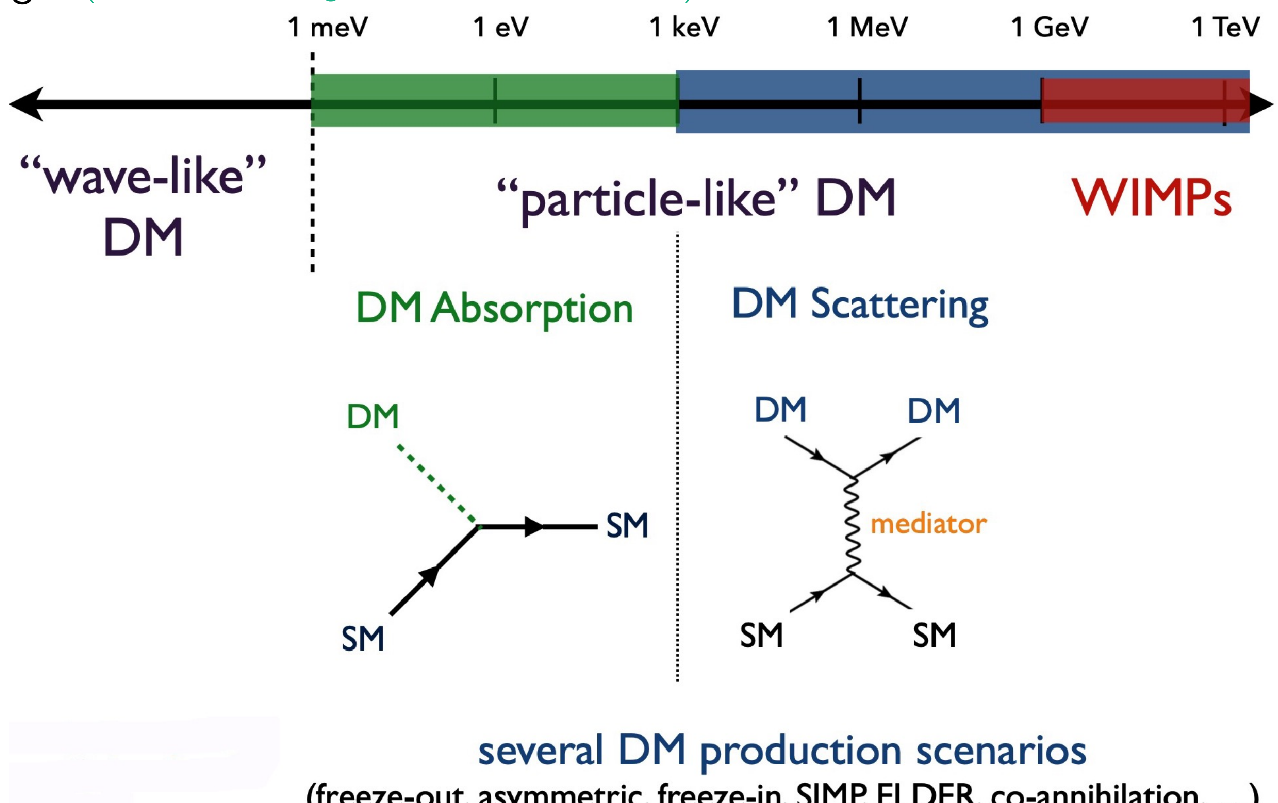
Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets

Goal: use multiple target materials + advances in TES sensor technology



Liquid helium experiment (HeRALD)
GaAs and Sapphire-based experiments (SPICE)

Light-DM (SubGeV mass) Detection via scattering or absorption depending on the mass range (from Rouven Essig- UCLA Dark Matter 2023)



Absorption for Dark Photons and Axions/ALPs DM: $\omega \simeq m_\chi >> |\vec{q}| \simeq 10^{-3} m_\chi$

While for scattering: $\omega \simeq 10^{-6} m_\chi << |\vec{q}| \simeq 10^{-6} m_\chi$

AXIONS: QCD-axions and Axion-Like Particles (ALPs):

Light pseudoscalar bosons that couple weakly to SM particles

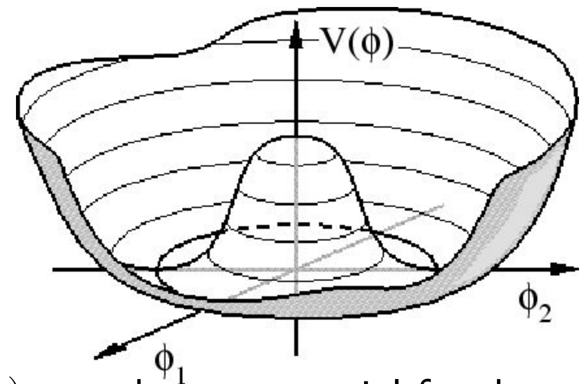
— **Field Theory Axions:** are pseudo-Nambu-Goldstone (NG) bosons of an approximate $U(1)$ global symmetry broken spontaneously at a large scale f_a (e.g. QCD-axions, Majorons, familons)

Light because of global symmetry: if exact, NG bosons have $m_a = 0$, thus
$m_a \sim$ (small explicit breaking $/f_a$)
Small couplings because GB couplings are $\sim 1/f_a$

— **String Theory Axions:** zero-modes of gauge fields corresponding to compactified extradimensions > 4 of linear size R. Here $f_a \sim 1/R$

Light because local gauge symmetry in 10 (or 11) dim implies $m_a = 0$,
but non-local violations (instantons) may give small m_a
Small couplings turn out again to be $\sim 1/f_a$

AXIONS: The only viable solution of the "strong-CP" problem of QCD proposed so far is to augment the SM to make the Lagrangian invariant under a global chiral symmetry $U(1)_{PQ}$ (Peccei-Queen 1977) spontaneously broken at a high scale f_a, whose Goldstone boson is the AXION a (Wilczek 1978, Weinberg 1978)

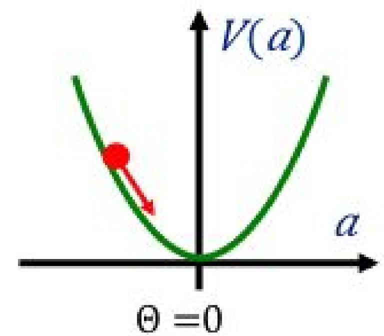


so that the CP violating parameter becomes

$$\theta = \bar{\theta} + \frac{< a >}{f_a}$$

Effects of the QCD anomaly generates an explicit breaking of $U(1)_{PQ}$, thus a potential for the field a,

$$V_{\rm eff} \sim cos\left(\bar{\theta} + \frac{< a >}{f_a}\right) = cos(\theta)$$



whose minimum is at $< a >= -f_a\bar{\theta}$, i.e. $\theta = 0$ thus the Lagrangian in terms of $a_{\rm phys} = a - < a >$ no longer has a CP violating θ-term. CP - symmetry is dynamically restored

Axions- ALPs

- Original axion model (Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)
  $U(1)_{PQ}$ - Explicit breaking at scale v due to QCD instanton effects $f_a > v \simeq \Lambda_{\rm QCD}$
  Failed experimentally almost immediately, f_a was at the Electro-Weak scale (too low)

- Invisible axion (now just called QCD axion) models (Kim 1979; Shifman, Vainshtein and Zakharov 1980; Zhitnitsky 1980; Dine, Fischler and Srednicki 1981)
  $U(1)_{PQ}$ - Explicit breaking due to QCD instanton effects $f_a \simeq 10^{16}{\rm GeV} >> v \simeq \Lambda_{\rm QCD}$

- Generic axion-like particle (ALP) models (Jaeckel and Ringwald 2010)
  Ad-hoc $U(1)$ and explicit breaking for ALPs to be dark matter $f_a >> v$,
  m_a f_a and v are arbitrary.

AXIONS- ALPs

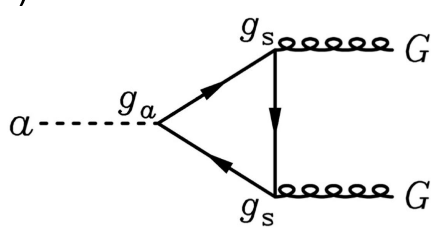
For QCD axions:

the mass m_a is related to the spontaneous U(1) symmetry breaking scale f_a,

$$m_a = \frac{\sqrt{m_u m_d} m_\pi}{(m_u + m_d) f_\pi f_a} \simeq 6.3 \text{ eV} \left(\frac{10^6 \text{GeV}}{f_a} \right)$$

there is a coupling with gluons (necessary for QCD axions)

$$L_{agg} = \frac{\alpha_s}{8\pi} \frac{a_{\text{phys.}}}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

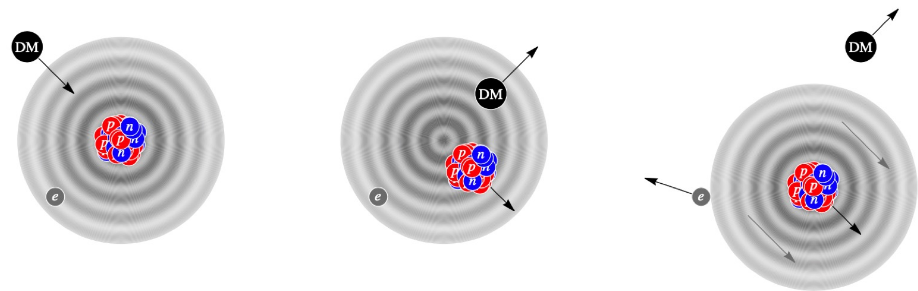


models of different types (Shifman, Vainshtein, Zakharov (SVZ) and Dine, Fischler, Srednicki and Zhitnisky (DFSZ)) produce different coupling of a with γ's and fermions.

$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{\text{phys.}}}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad\qquad L_{aff} = \frac{C_f}{2 f_a} \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f \partial_\mu a_{\text{phys.}}$$

For ALPs: m_a and f_a are independent, and each coupling may or not exist.

Migdal Effect (A. B. Migdal 1939) Fig and Eqs from Cirelli, Strumia, Zupan 2406.01705



DM $+$atom $\to$ DM $+$atom $+$e, charge collection extend reach of nuclear recoil to LDM. For IC-SI scattering on $N = p, n$, with q going mostly to the nuclear recoil, and taking $F(q \to 0) = 1$, the structure factor factorizes and it is $\dfrac{dS_{\rm Mig}(\vec{q},\omega)}{d\omega_e} \simeq 2\pi n_{\rm nuc} A^2\, \delta(\omega - \dfrac{\vec{q}^2}{2m_A} - \omega_e)\dfrac{dP}{d\omega_e}$

$dP/d\omega_e$: probability distribution for ω_e to be deposited in the e excitation

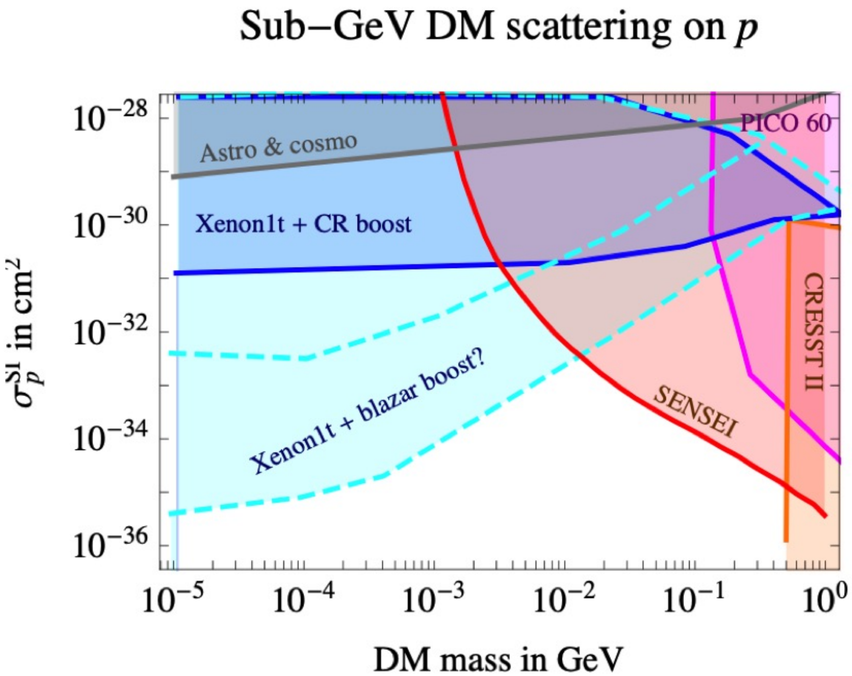
For atomic Migdal approximately $\dfrac{dR_{\rm Mig}/d\vec{q}}{dR_{\rm ion}/d\vec{q}} > Z^2 \left(\dfrac{m_e}{m_A}\right)^2 (\vec{q} r_{\rm atom})^2$,

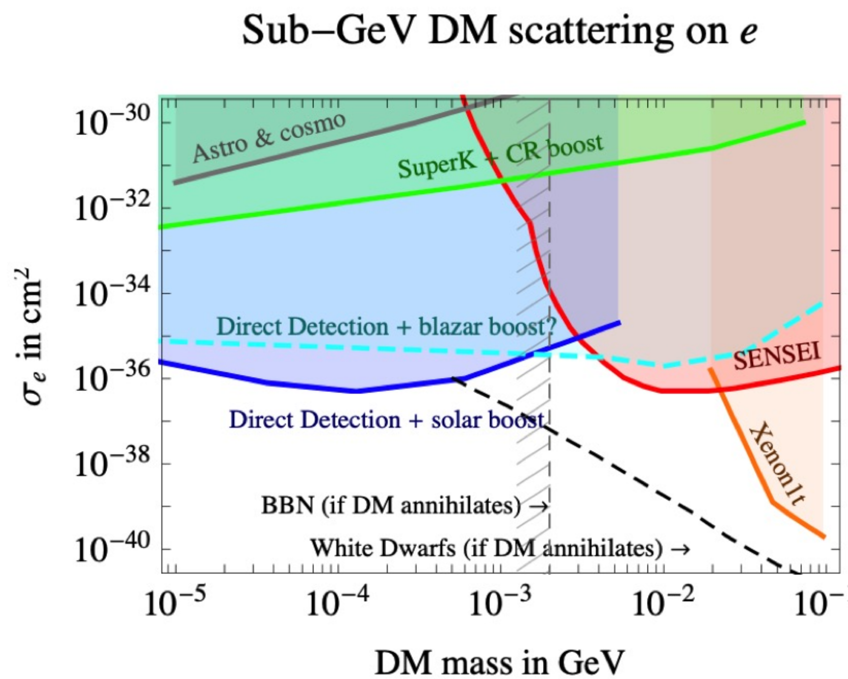
($(\vec{q} r_{\rm atom})^2$ implies Migdal spectrum is dominated by q than ionizations)

The effect should have been found using n-scatt. in Xe, but was not Xu et al 2307.12952

Migdal effect can also occur in crystals, and emit a γ instead of e

Boosted DM Different mechanisms (multiple scattering within the Sun, collisions with cosmic rays, evaporation of PBH at present, decays or annihilations of heavier DM) may accelerate a small fraction of DM particles, putting them above threshold for detection. This is specially important for LDM Kouvaris 1506.04316, An et al 1708.03642...see refs in review 2406.01705- Figs. from Cirelli, Strumia, Zupan 2406.01705





Halo-Independent analysis of LDM scattering) Chen, GG, Takhistov

105-08101 2209.10902 For fixed total energy gained by the electron,

$$E_e = E_R + E_{\rm Binding} = \Delta E_{\rm DM} = E_{\chi,i} - E_{\chi,f}$$

$q = |\vec{q}|$ as function of $v_{\rm min}$ has two solutions, which meet at the minimum $\tilde{v} = \sqrt{2E_e/m}$)

$$q_\pm(v_{\rm min}, E_e) = m v_{\rm min}\left[1 \pm \sqrt{1 - \frac{2E_e}{m v_{\rm min}^2}}\right]$$

We chose $v_{\rm min}$ as the independent variable instead of q, and change the integration variable using $dq_\pm = J_\pm(v_{\rm min}, E_R + E_{{\rm B}i})\, dv_{\rm min}$, with Jacobian factors $J_\pm$ to put the rate into the form

$$\frac{dR}{dE'} = \int_{\tilde{v}}^{v_{\rm max}} dv_{\rm min}\, \frac{d\mathcal{R}}{dE'}(v_{\rm min}, E')\, \tilde{\eta}(v_{\rm min})$$