Halo independent analysis of direct dark matter detection through electron scattering

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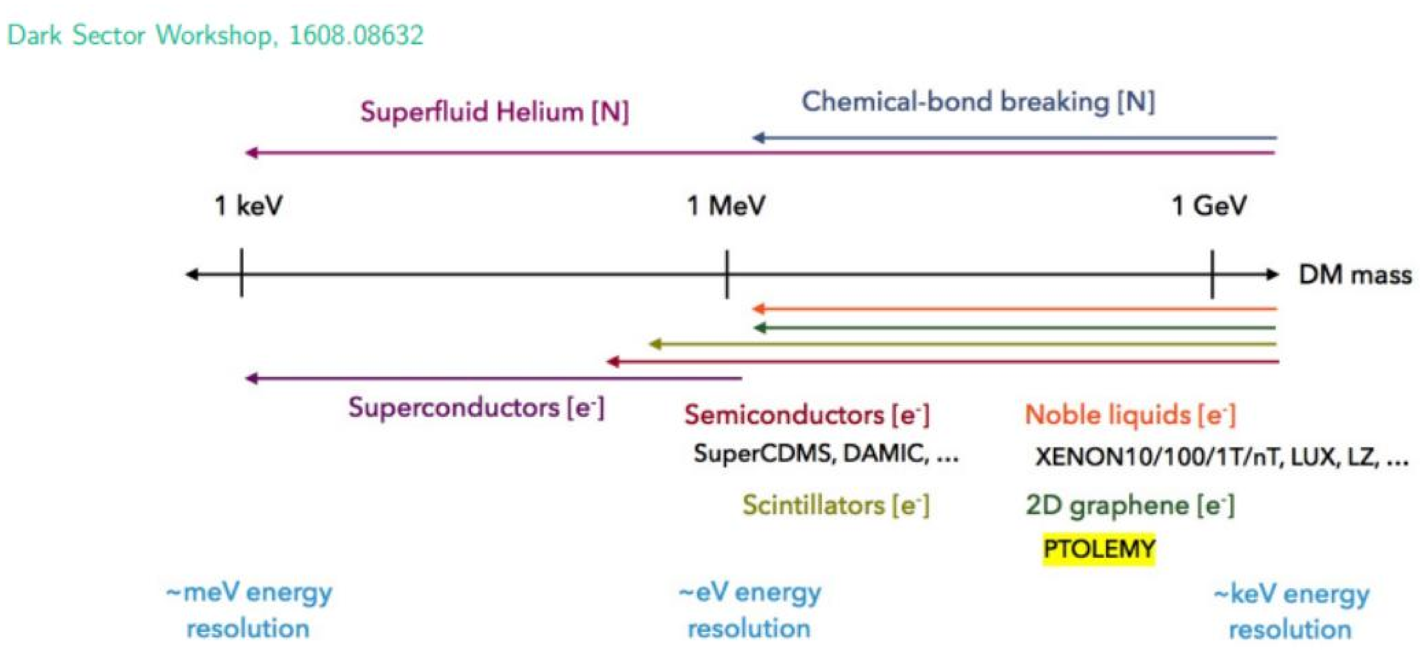
Direct detection

Direct DM detection attempts to measure the energy deposited within a detector by collisions of DM particles from the dark halo of our Galaxy passing through the detector.

DM-Nuclei scattering detectors (E_{thres}~keV) are used to detect DM heavier than 1 GeV (WIMP), whereas DM-electron scattering detectors (E_{thres}~eV) are used to detect sub-GeV DM (Light DM, or LDM).



Review of DM-Nucleus Scattering

The differential rate for target nuclide T,

$$\frac{dR_T}{dE_R} = N_T \int_{v>v_{\min}} \frac{d\sigma_T}{dE_R} \times \frac{\rho}{m} f(\vec{v},t)\, d^3v$$

Example: DM-Nuclei Spin Independent interaction,

$$\frac{d\sigma_T}{dE_R} = \frac{\sigma_T(E_R)\, M_T}{2\mu_T^2 v}$$

$$\frac{dR_T}{dE_R} = N_T \frac{\sigma_T(E_R)}{2m\mu_T^2}\rho\eta(v_{min}) \ , \quad \eta(v_{\min}) \equiv \int_{v>v_{\min}} d^3v\, \frac{f(\vec{v})}{v} = \int_{v_{\min}}^{\infty} dv\, \frac{F(v)}{v} \ .$$

Halo Dependent (HD) Analysis: Assume a local dark halo model, i.e., $\eta(v_{\min})$. Plots are made in (m, σ_{ref}) parameter space.

Halo Independent (HI) Analysis: The halo model is not assumed but is to be found using the observed rate. All the dependence on the halo is in $\eta(v_{\min})$, common to all experiments, . Plots are made in the $(v_{\min}, \tilde{\eta})$ plane.
(Fox, Liu and Weiner, PRD 83, 103514 (2011), [1011.1915])

Complications: experiments do not directly observe the recoil energy; instead, they observe a proxy E' for E_R with E' dependent energy resolutions/efficiencies.

The observed rate is $\frac{dR}{dE'} = \varepsilon(E') \int_0^{\infty} dE_R \sum_T G_T(E_R, E') \frac{dR_T}{dE_R}$

$\varepsilon(E')$: counting efficiency; $G_T(E_R, E')$: energy resolution.

Formulation for general nuclear form factor, interaction type and energy resolution
(Gelmini and Gondolo, JCAP 12 (2012) 015, [1202.6359])

$$\frac{dR}{dE'} = \int_0^{v_{\max}} dv_{\min}\, \frac{d\mathcal{R}}{dE'}(v_{\min}, E')\, \tilde{\eta}(v_{\min}) \ , \quad \tilde{\eta}(v_{\min}) = \frac{\rho\sigma_{\rm ref}}{m}\eta(v_{\min})$$

$d\mathcal{R}/dE'$: DM, particle model, and detector dependent response function.
It acts as a "window function" in $v_{\min}$. We can get information about $\tilde{\eta}(v_{\min})$, only for the $v_{\min}$ range in which it is significantly different from 0.

Convex geometry tells us that for d data points,

$$F(v) = \sum_{n=1}^{d} F(v_n)\delta(v - v_n)$$

$\tilde{\eta}$ can be parameterized by v_n and $F(v_n)$.

DM-electron Scattering

Due to their kinematic difference, the DM-Nuclei scattering cross section only depends on v, but DM-electron scattering depends on both v (DM velocity) and q (momentum transfer).

DM-Nucleus scattering: the target nuclei are free, the recoil energy $E_R = q^2/2m_N$.
DM-electron scattering: the target electrons are bounded and have an unknown initial momentum, the electron energy $E_e = \vec{q}\cdot\vec{v} - q^2/2m_\chi$. $E_e = E_R$ + binding energy.

DM-electron scattering rate:

$$\frac{dR}{dE_R} = \frac{1}{2\mu_{\chi e}^2}\frac{1}{E_R}\sum_{i,f}{}' \int_{q_{\min}}^{q_{\max}} dq\, q\, \tilde{\eta}(v_{\min}(q, E_R + E_{{\rm B}i}))\ |F_{\rm DM}(q)|^2 |f^{i,f}(q, E_R)|^2 .$$

DM form factor: $F_{DM}(q)$=1 or $F_{DM}(q) = 1/q^2$;
electron form factor: $f^{i,f}(q, E_R)$, overlap of the initial and final electron wavefunctions.

Change of variable, from $(q,\ E_R)$ to $(v_{\min},\ E_R)$ (two branches, $q_\pm(v_{\min},\ E_R)$), the response function

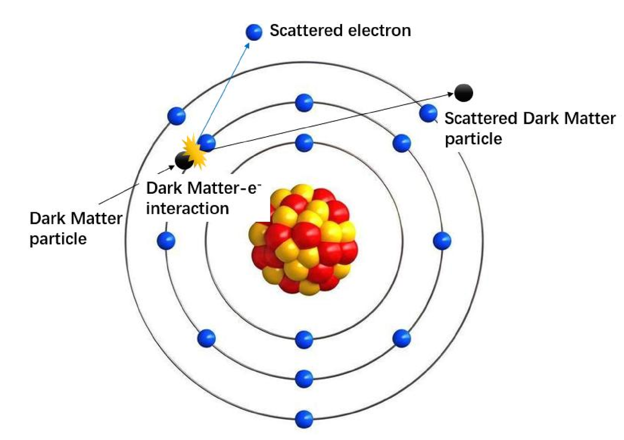
$$\frac{d\mathcal{R}_\pm}{dE'}(v_{\min}, E') = \sum_\pm \frac{\epsilon(E')}{2\mu_{\chi e}^2}\sum_{i,f}{}' \int_0^{E_{\max}} \frac{dE_R}{E_R} G(E', E_R) J_\pm(v_{\min}, E_R + E_{{\rm B}i})\ q_\pm(v_{\min}, E_R + E_{{\rm B}i})$$
$$|F_{\rm DM}(q_\pm(v_{\min}, E_R + E_{{\rm B}i}))|^2 |f^{i,f}(q_\pm(v_{\min}, E_R + E_{{\rm B}i}), E_R)|^2 \ .$$

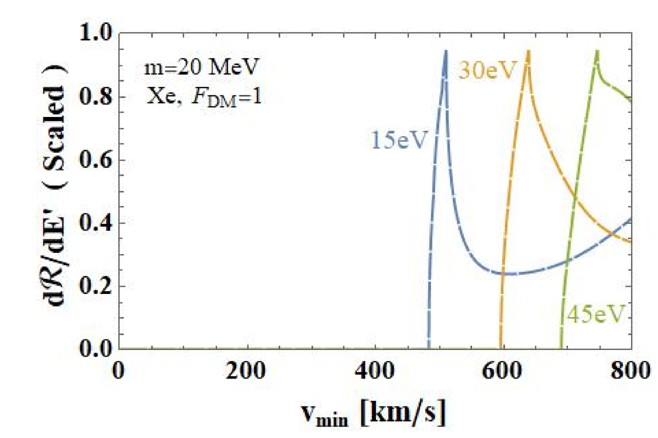
In free atoms, electrons are excited from an orbital to a free state, $E_e = E_R + E_{Bnl}$.
Differential rate: (Essig et al, JHEP 05 (2016) 046, [1509.01598].)

$$\frac{dR_{\rm ion}}{dE_R} = \sum_{nl} \frac{1}{8\mu_{\chi e}^2}\frac{1}{E_R}\int_{q_{\min}}^{q_{\max}} dq\, q\, \tilde{\eta}(v_{\min}(q, E_R + E_{Bnl}))\ |F_{\rm DM}(q)|^2\ |f_{\rm ion}^{nl}(q, E_R)|^2 \ ,$$

Response function:

$$\frac{d\mathcal{R}_{\rm ion}}{dE'}(v_{\min}, E') = \sum_\pm \frac{\epsilon(E')}{8\mu_{\chi e}^2}\sum_{nl}\int \frac{dE_R}{E_R} G_{\rm ion}(E', E_R) J_\pm(v_{\min}, E_R + E_{{\rm B}nl}) q_\pm(v_{\min}, E_R + E_{{\rm B}nl})$$
$$\times |F_{\rm DM}(q_\pm(v_{\min}, E_R + E_{{\rm B}nl}))|^2 |f_{\rm ion}^{nl}(q_\pm(v_{\min}, E_R + E_{{\rm B}nl}), E_R)|^2$$



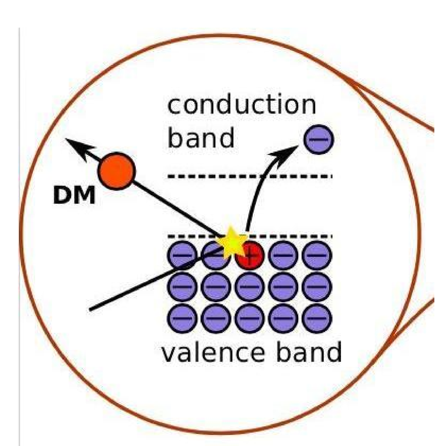


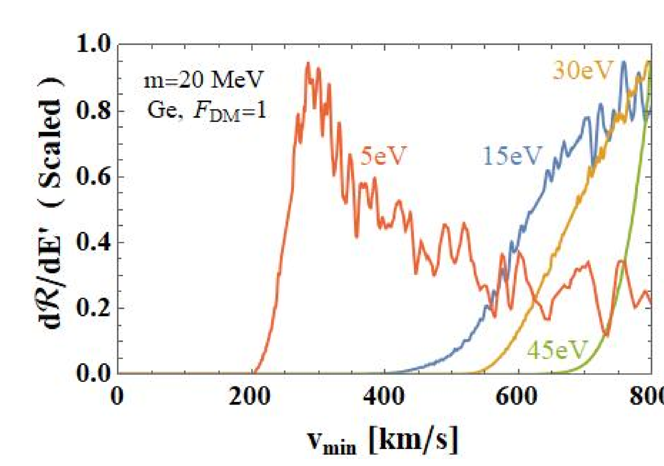
In Semiconductors, electrons are excited from the valence band to the conduction band, $E_e = E_R$.
Differential rate:

$$\frac{dR_{\rm crys}}{dE_R} = N_{\rm cell}\frac{\alpha m_e^2}{\mu_{\chi e}^2}\int dq\, \frac{1}{q^2}\tilde{\eta}(v_{\min}(q, E_R))\ |F_{\rm DM}(q, E_R)|^2\ |f_{\rm crys}(q, E_R)|^2|$$

Response function:

$$\frac{d\mathcal{R}_{\rm crys}}{dE'}(v_{\min}, E') = \sum_\pm \frac{N_{\rm cell}\epsilon(E')}{\mu_{\chi e}^2}(\alpha m_e^2)\int_0^{E_{\max}} dE_R\, G_{\rm crys}(E', E_R)\frac{J_\pm(v_{\min}, E_R)}{q_\pm^2(v_{\min}, E_R)}$$
$$\times |F_{\rm DM}(q_\pm(v_{\min}, E_R))|^2\ |f_{\rm crys}(q_\pm(v_{\min}, E_R), E_R)|^2.$$





In-medium Effect

The calculation for semiconductors can be further improved by including the in-medium effect. The differential rate becomes
(Knapen, Kozaczuk, and Lin, PRD 104, 015031 (2021), 2101.08275])

$$\frac{dR}{dE} = \frac{1}{\rho_T}\frac{1}{8\pi^2\mu_{\chi e}^2\alpha}\int dq\, q^3 |F_{\rm DM}(q)|^2 \frac{1}{1 - e^{-\beta E}}{\rm Im}\left[\frac{-1}{\epsilon(q, E)}\right]\tilde{\eta}(v_{\min}(q, E)) \ .$$

Where $\epsilon(q, E)$ is the dielectric function that contains all information about the material.

Response function

$$\frac{d\mathcal{R}}{dE'}(E', v_{\min}) = \sum_\pm \frac{1}{\rho_T}\frac{\varepsilon(E')}{8\pi^2\mu_{\chi e}^2\alpha}\int dE\, G(E', E) J_\pm(v_{\min}, E) q_\pm^3(v_{\min}, E)$$
$$\times |F_{\rm DM}(q_\pm(v_{\min}, E)|^2 \frac{1}{1 - e^{-\beta E}}{\rm Im}\left[\frac{-1}{\epsilon(E, q_\pm(v_{\min}, E))}\right] \ .$$

An example is shown in Fig. 3. The amplitude change due to the in-medium effect (screening) is significant, so this effect should always be included.

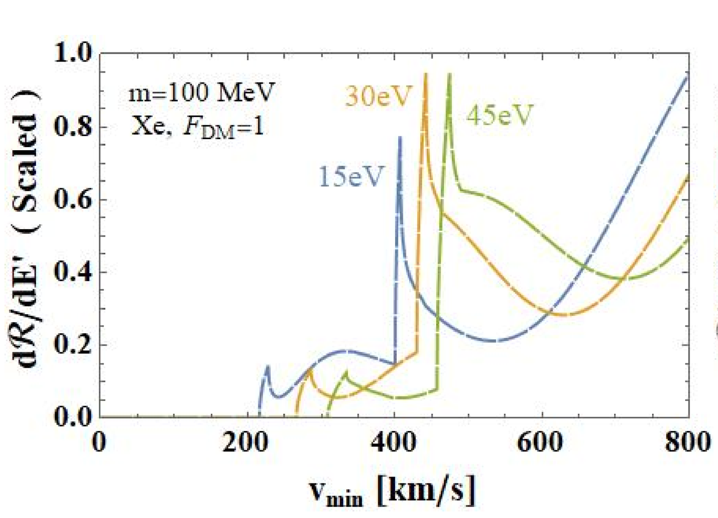


Fig. 1: Response function for Xe

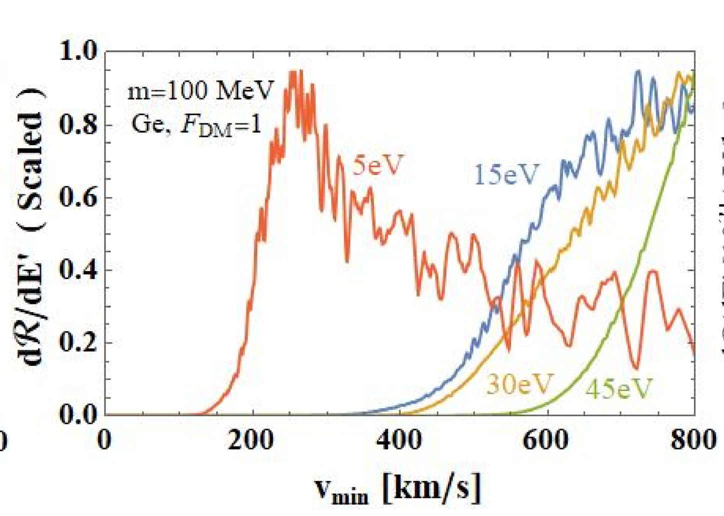


Fig. 2: Response function for Ge

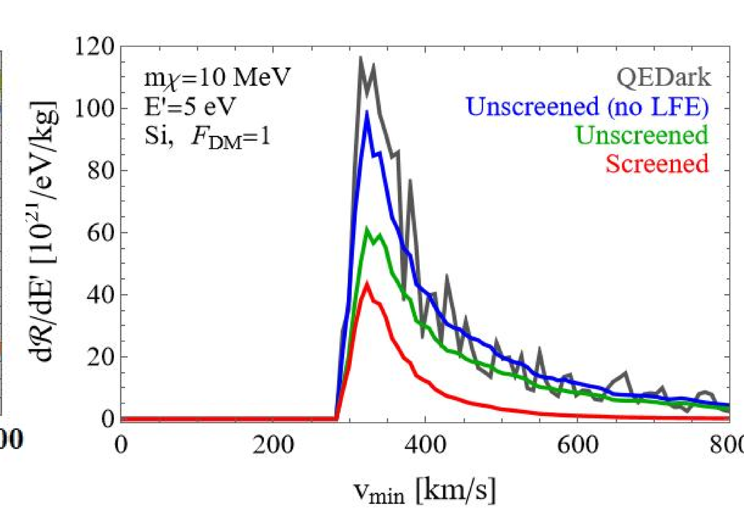


Fig. 3: Response function calculated with different methods

Results

Comparing window functions shown in Fig. 1 and Fig. 2,

- Reponse function is significantly larger in some ranges of $v_{\min}$, indicating the size of the "window."
- Semiconductor detectors have lower energy threshold than liquid gas detectors.

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