Dark Matter Absorption via Electronic Excitations

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References:

- arXiv:2106.12586: Dark Matter Absorption via Electronic Excitations

Outline

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The Hunt for Dark Matter

Potential Explanations

Light ($m \lesssim$ keV) bosonic dark matter (DM) are a class of motivated solutions:

- **Scalar DM**: Higgs portal DM models, compactification of extra dimensions
- **Pseudoscalar DM** (axion-like particles): solution to strong CP problem, simple production mechanism (misalignment)
- **Vector DM** (dark photon): generic prediction of a spontaneously broken gauge symmetries

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The Hunt for Dark Matter

Direct Detection Experiments

For DM with $m \lesssim$ keV, current thresholds $\mathcal{O}(\text{eV})$

- **Scattering**: $\omega \sim m\, v_{\text{DM}}^2 \sim$ meV
- **Absorption**: $\omega \sim m \sim$ keV

Sensitivity with current experiments based on semiconductors (DAMIC, EDELWEISS, SENSEI, SuperCDMS), and potential future experiments based on superconductors.

Outline

1. Overview
2. Absorption with NR EFT for Electrons
3. Vector & Pseudoscalar DM
4. Scalar DM

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Absorption Rate from the Self-Energy

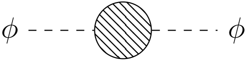
Background

Optical theorem:

$$\boxed{\Gamma_\phi} = -\frac{1}{m_\phi}\,\mathrm{Im}\,\boxed{\Pi_{\phi\phi}}$$

absorption rate self-energy

where $\Pi_{\phi\phi}$ is given by loop diagrams,



Absorption Rate from the Self-Energy

In-Medium Effects

A medium can *mix* states, i.e. $\Pi_{\phi A} \neq 0$.

$$\begin{pmatrix} m_\phi^2 + \Pi_{\phi\phi} & \Pi_{\phi A} \\ \Pi_{A\phi} & \Pi_{AA} \end{pmatrix} \rightarrow \begin{pmatrix} m_\phi^2 + \Pi_{\hat{\phi}\hat{\phi}} & 0 \\ 0 & \Pi_{\hat{A}\hat{A}} \end{pmatrix}$$

- This is the origin of *in-medium effects*.

Assuming the $\phi - A$ coupling is small,

$$\Gamma_\phi = -\frac{1}{m_\phi} \,\mathrm{Im}\, \left(\Pi_{\phi\phi} + \frac{\Pi_{\phi A}\Pi_{A\phi}}{m_\phi^2 - \Pi_{AA}} \right)$$

To compute the absorption rate, just compute $\Pi_{\phi\phi}, \Pi_{AA}$ and $\Pi_{\phi A}$.

NR EFT for Electrons

The NR electron field ($\hat{\psi}_+$) is found via an NR EFT calculation with expansion parameter $1/m_e$:

1. Start with standard EM, $\mathcal{L}_\psi = \bar{\psi}\left[i\gamma^\mu\left(\partial_\mu + ieA_\mu\right) - m_e\right]\psi$
2. Split ψ in to heavy ($\psi_- = P_-\psi$) and light ($\psi_+ = P_+\psi$) components
3. Integrate out ψ_-

$$\psi_- = \frac{i\gamma \cdot (\nabla - ie\mathbf{A})}{2m_e + i\partial_t - eA_0}\psi_+$$

4. Expand in $1/m_e$.
5. Perform field redefinition, $\psi_+ \to \hat{\psi}_+$ to remove ∂_t's introduced in step 3.

$\hat{\psi}_+ - \phi$ **coupling determines Feynman rules for self-energies.**

Computing the Self-Energies

Si/Ge (semiconductors)

- `absorption` module of `EXCEED-DM` + DFT wave functions.
- Wave functions for Si and Ge are publicly available: https://zenodo.org/record/4735777.YOn2XTOSnH0.

Al-SC (superconductors)

- Analytically in a free electron gas model.
- $\Pi \approx \text{Re}\,\Pi_{\text{1-loop}} + i\text{Im}\,\Pi_{\text{2-loop}}$
  - At one-loop Π's are real (no available on-shell transitions).
  - At two-loop electrons can interact with *phonons* which supply the necessary energy and momentum.

Data-driven: When appropriate, use measured optical data.

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Warm-up: Photon Absorption

Step 1: NR EFT

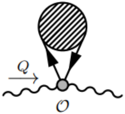
$$\mathcal{L}_{\text{EM}} \to \mathcal{L}_{\hat{\psi}_+ A} \supset -\, e\, \mathcal{A}_0\, \hat{\psi}_+^\dagger \hat{\psi}_+ - \frac{ie}{2m_e}\, \boldsymbol{\mathcal{A}} \cdot \left(\hat{\psi}_+^\dagger\, \overleftrightarrow{\nabla}\, \hat{\psi}_+ \right) + \frac{e}{2m_e} \left(\nabla \times \boldsymbol{\mathcal{A}} \right) \cdot \left(\hat{\psi}_+^\dagger\, \boldsymbol{\Sigma}\, \hat{\psi}_+ \right) - \frac{e^2}{2m_e}\, \boldsymbol{\mathcal{A}}^2\, \hat{\psi}_+^\dagger \hat{\psi}_+ + \mathcal{O}\left(\frac{1}{m_e^2} \right)$$

Step 2: Find Π_{AA} from $\mathcal{L}_{\hat{\psi}_+ A}$

$$\Pi^{00} = -e^2\, \Pi_{\mathbb{1}\mathbb{1}}\,, \qquad \Pi^{0j} = -e^2\, \Pi_{\mathbb{1} v^j}$$

$$\Pi^{ij} = -e^2\, \Pi_{v^i v^j} - \frac{e^2}{4m_e^2} (q^2 \delta^{ij} - q^i q^j)\, \Pi_{\mathbb{1}\mathbb{1}} + \frac{e^2}{m_e}\, \delta^{ij} \Pi'_{\mathbb{1}}$$

$-i\Pi_{\mathcal{O}_1 \mathcal{O}_2} =$ 

, $-i\Pi'_{\mathcal{O}} =$ 

Warm-up: Photon Absorption

$$\Gamma_A = -\frac{e^2}{\omega} \,\mathrm{Im}\, \Pi_{\mathbb{1}\mathbb{1}}$$

and $\Pi_{\mathbb{1}\mathbb{1}}$ can be related to optical data:

$$\varepsilon - 1 = \frac{i\sigma}{\omega} = -\frac{e^2}{q^2}\Pi_{\mathbb{1}\mathbb{1}}$$

- $\Pi_{\mathbb{1}\mathbb{1}} \propto q^2$ ($\varepsilon(q = 0)$− finite)

Absorption rates depending on only $\Pi_{\mathbb{1}\mathbb{1}}$ are related to optical data.

Vector and Pseudoscalar DM absorption rates can be related to optical data

Vector DM: $\mathcal{L}_{\psi\phi} = \kappa e\, \phi_\mu \bar{\psi}\gamma^\mu \psi$

$$\Pi_{\phi\phi} = -\kappa \Pi_{\phi A} = \kappa^2 \Pi_{AA}$$

$$R_\phi = -\kappa^2 \frac{\rho_\phi}{\rho_T} \, \text{Im} \left(\frac{1}{1 - \frac{e^2}{q^2}\Pi_{\mathbb{1}\mathbb{1}}} \right) = \frac{\kappa^2}{|\epsilon|^2} R_A$$

$$\frac{1}{|\epsilon|^2} \equiv \frac{m_\phi^4}{(m_\phi^2 - \text{Re}\,\Pi_L)^2 + (\text{Im}\,\Pi_L)^2}$$

- ϵ is a *screening* factor.

Vector and Pseudoscalar DM absorption rates can be related to optical data

Pseudoscalar DM: $\mathcal{L}_{\psi\phi} = -\frac{g}{2m_e}(\partial_\mu \phi)(\bar{\psi}\gamma^\mu\gamma^5\psi)$

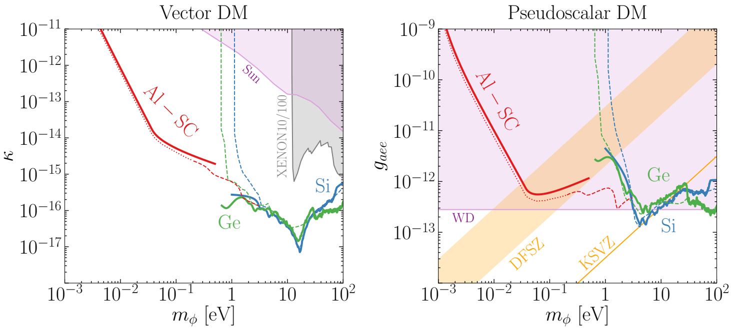
- $\mathcal{L}_{\hat{\psi}_+\phi} \supset -\frac{g}{2m_e}\,(\nabla\phi)\cdot\hat{\psi}_+^\dagger\,\Sigma\,\hat{\psi}_+ + \boxed{\frac{ig}{4m_e^2}\,(\partial_t\phi)\left(\hat{\psi}_+^\dagger\,\Sigma\cdot\overleftrightarrow{\nabla}\,\hat{\psi}_+\right)}$ (NLO)
- $\Pi_{\phi A} = 0$: No mixing with the photon.

Again, the absorption rate is related to optical data,

$$R_\phi = -g^2\frac{\rho_\phi}{\rho_T}\frac{3m_\phi^2}{4m_e^2}\frac{1}{q^2}\,\text{Im}\,\Pi_{\mathbb{1}\mathbb{1}} = \frac{g^2}{e^2}\frac{3m_\phi^2}{4m_e^2}R_A$$

- **No screening factor**.

Comparing the reach of Si/Ge/Al-SC



- **Dashed**: From optical data, **Solid**: Analytic (Al-SC), Numeric (Si/Ge), **Dotted**: previous work
- 95% C.L. constraints, kg-year exposure, no background.
- Good agreement between the numeric and data-driven approaches is validation of the electronic wave functions.

Outline

1. Overview
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Scalar DM absorption rate CANNOT be related to optical data

Scalar DM: $\mathcal{L}_{\psi\phi} = g\phi\bar{\psi}\psi$

(NLO - $\bar{v}^2$ - q^0)

$$\mathcal{L}_{\hat{\psi}_+\phi} \supset g\,\phi\,\hat{\psi}_+^\dagger\hat{\psi}_+ + \boxed{\frac{g}{8m_e^2}\,\phi\left(\hat{\psi}_+^\dagger\overleftrightarrow{\nabla}^2\hat{\psi}_+\right)}$$

$$R_\phi = -\,d_{\phi ee}^2\,\frac{4\pi m_e^2}{M_{\text{Pl}}^2}\,\frac{\rho_\phi}{\rho_T}\,\frac{1}{m_\phi^2}\,\text{Im}\left[\Pi_{\bar{v}^2,\bar{v}^2} + \frac{q^2}{e^2}\,\frac{\left(1-\frac{e^2}{q^2}\,\Pi_{\bar{v}^2,\mathbb{1}}\right)\left(1-\frac{e^2}{q^2}\,\Pi_{\mathbb{1},\bar{v}^2}\right)}{1-\frac{e^2}{q^2}\,\Pi_{\mathbb{1},\mathbb{1}}}\right]$$

- Ignoring the NLO operator gives $R_{\text{scalar}} \propto R_A$ (with screening factor).
- $\Pi_{\bar{v}^2\bar{v}^2}$ term is *unscreened*.

What is the difference in Vector DM and Scalar DM calculation?

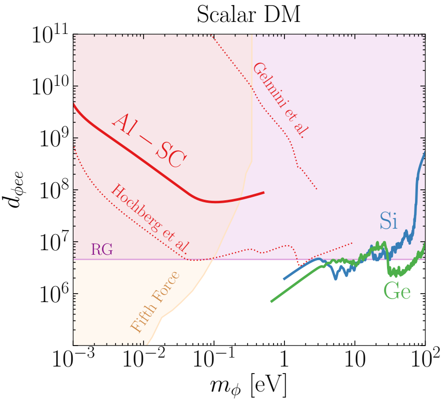
$$\psi_N = \frac{1}{\sqrt{2}} \begin{pmatrix} f_N + i g_N \\ f_N - i g_N \end{pmatrix} \quad \text{(Weinberg, Ch. 14)}$$

- **Orthogonality:** $\int d^3x \, (f_F^\dagger f_I + g_F^\dagger g_I) = \delta_{IF}$

- In $q \to 0$ limit, $(\mathcal{M} \propto \langle F | \delta \mathcal{L} | I \rangle)$
  - **Vector DM**:
    $\mathcal{M} \propto \langle F | \phi_0 \psi^\dagger \psi | I \rangle \ = \phi_0 \int d^3x \, (f_F^\dagger f_I + g_F^\dagger g_I) \to 0$
  - **Scalar DM**:
    $\mathcal{M} \propto \langle F | \phi \psi^\dagger \gamma^0 \psi | I \rangle = \phi \int d^3x \, (f_F^\dagger f_I - g_F^\dagger g_I) \to -2\phi \int d^3x \, g_F^\dagger g_I$

- Perturbatively, $g_I \sim \mathcal{O}(v_e) \to \mathcal{M}_{\text{scalar}} \sim v_e^2 \to R_{\text{scalar}} \sim v_e^4$.

Comparing the reach of Si/Ge/Al-SC



- **Dashed**: Previous estimates, **Solid**: Analytic (Al-SC), Numeric (Si/Ge)
- 95% C.L. constraints, kg-year exposure, no background.

Summary

- Systematic derivation of vector, pseudoscalar, and scalar DM absorption on electrons with NR EFT.

- Scalar DM absorption cannot be related to photon absorption/optical data. An NLO operator is dominant and unscreened.

- Computed scalar DM constraints analytically in an Al-superconductor target and numerically from first principles in Si and Ge targets
    - We find good agreement in the vector and pseudoscalar DM absorption rates between a data-driven and the first principles approach.
    - Numeric calculation implemented in open source program, `EXCEED-DM`, **useful for general semiconductors**

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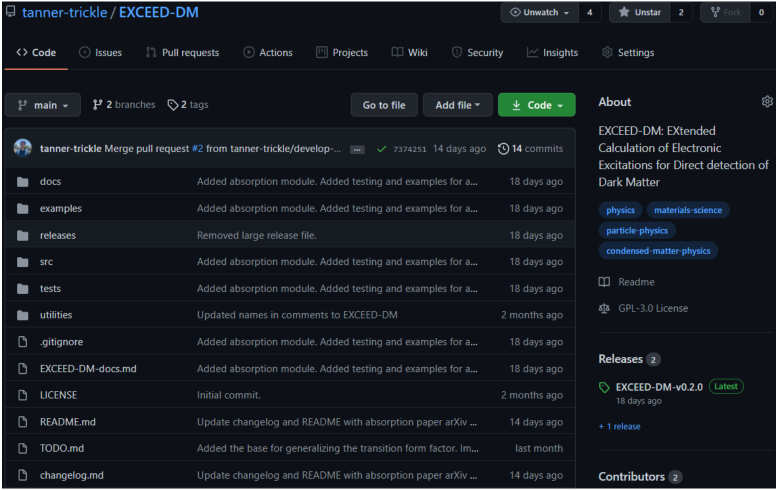
EXCEED-DM: Check out the project on !



tanner-trickle Merge pull request #2 from tanner-trickle/develop-... ✓ 7374251 14 days ago 14 commits

docs	Added absorption module. Added testing and examples for a...	18 days ago
examples	Added absorption module. Added testing and examples for a...	18 days ago
releases	Removed large release file.	18 days ago
src	Added absorption module. Added testing and examples for a...	18 days ago
tests	Added absorption module. Added testing and examples for a...	18 days ago
utilities	Updated names in comments to EXCEED-DM	2 months ago
.gitignore	Added absorption module. Added testing and examples for a...	18 days ago
EXCEED-DM-docs.md	Added absorption module. Added testing and examples for a...	18 days ago
LICENSE	Initial commit.	2 months ago
README.md	Update changelog and README with absorption paper arXiv ...	14 days ago
TODO.md	Added the base for generalizing the transition form factor. Im...	last month
changelog.md	Update changelog and README with absorption paper arXiv ...	14 days ago

About

EXCEED-DM: EXtended Calculation of Electronic Excitations for Direct detection of Dark Matter

physics materials-science particle-physics condensed-matter-physics

Readme

GPL-3.0 License

Releases 2

EXCEED-DM-v0.2.0 Latest
18 days ago

+ 1 release

Contributors 2

https://github.com/tanner-trickle/EXCEED-DM

Differences in the scalar DM Al-SC calculation?

Hochberg et al. (arXiv:1604.06800)

- m_* vs. m_e: Electrons in the loop are *in-medium* and, their "free" dispersion relation, is $k^2/2m^*$
- (minor) Soft phonon limit: A factor of $\left(1 - \frac{c_s q}{\omega}\right)^2$ was dropped before q was integrated over.
- (minor) Normalization of electron-phonon coupling constant

Gelmini et al. (arXiv:2006.13909)

- The scalar DM absorption rate is dominated by $\Pi_{\overline{v}^2\overline{v}^2}$ which is *unscreened*, in contrast to the terms depending on $\Pi_{\mathbb{1}\mathbb{1}}$ which are.

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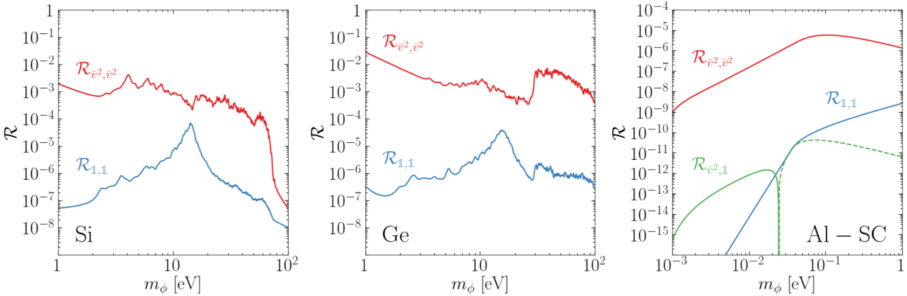
How dominant is NLO contribution for scalar DM?



$$R_{\text{scalar}} = d_{\phi ee}^2 \frac{4\pi m_e^2}{M_{\text{Pl}}^2} \frac{\rho_\phi}{\rho_T} \left(\mathcal{R}_{\bar{v}^2,\bar{v}^2} + \mathcal{R}_{\mathbb{1},\mathbb{1}} + \mathcal{R}_{\bar{v}^2,\mathbb{1}}\right)$$