# Modelling dark matter-electron interactions in materials

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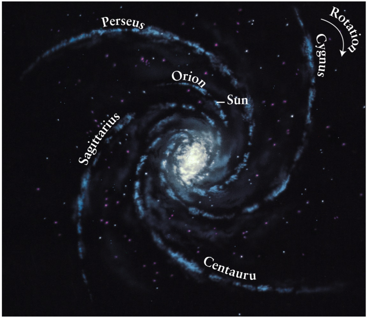
# Why?

# Basic principles of DM direct detection

- Face-on view of our galaxy:




- The sun's orbital motion induces a flux of DM particles through our planet

- When a DM particle crosses a terrestrial detector can deposit energy by interaction with its constituents
- DM direct detection experiments search for such *rare, energy depositions*
- Expected rate of DM "signal events"

$$\mathrm{d}\mathscr{R} = \frac{\rho_\chi}{m_\chi} \int \mathrm{d}\boldsymbol{v}\, |\boldsymbol{v}| f_\chi(\boldsymbol{v} + \boldsymbol{v}_\oplus)\, \mathrm{d}\sigma$$

**Astrophysics**

**Particle physics,**
**Nuclear physics,**
**Solid state physics**

# History of DM direct detection

- Exclusion limits and projected sensitivities on the strength of DM-nucleon interactions

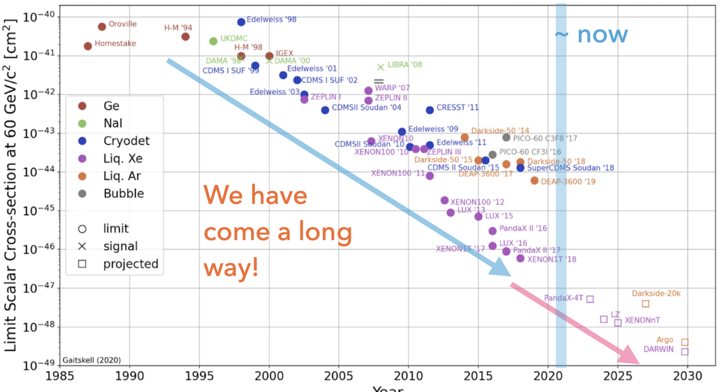
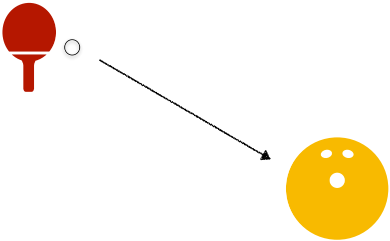



Figure: Rick Gaitskell, 2020

- Why has DM so far escaped a direct detection?

# A possible explanation for the lack of DM detection

- A simple explanation for the lack of DM detection is that it is lighter than nucleons (<1 GeV), and therefore too light to cause an observable nuclear recoil



- Not unlike a light pingpong ball being too light to move a heavy bowling ball ...

- If this is true, DM should be searched for in the recoils of a lighter target: **the electron**

# How?

# An effective theory approach

- Leveraging on previous results on the scattering of DM by nucleons bound in nuclei:

  J. Fan, M. Reece and L. T. Wang,
  JCAP **11** (2010), 042

  A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu,
  JCAP **02** (2013), 004

- We developed an effective theory to model DM-electron interactions in materials:

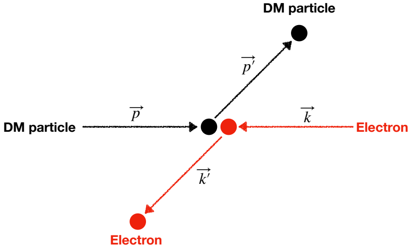
  R. Catena, D. Cole, T. Emken, M. Matas, N. Spaldin, W. Tarantino and E. Urdshals,
  JCAP **03** (2023), 052

  R. Catena, T. Emken, M. Matas, N. A. Spaldin and E. Urdshals,
  Phys. Rev. Res. **3** (2021) no.3, 033149

  R. Catena, T. Emken, N. A. Spaldin and W. Tarantino,
  Phys. Rev. Res. **2** (2020) no.3, 033195

# An effective theory approach / assumptions

- Consider the scattering of a DM particle of mass $m_\chi$ by a free electron of mass $m_e$,




- In the non-relativistic limit, this process is characterised by a double separation of scales:

$$|\boldsymbol{q}|/m_e \ll 1\,, \qquad \boldsymbol{q} = \boldsymbol{p} - \boldsymbol{p}'$$
$$|\boldsymbol{v}| \ll 1\,, \qquad \boldsymbol{v} = \boldsymbol{p}/m_\chi$$

- Its amplitude $\mathscr{M}_{\chi e}$ is invariant under Galilean transformations, translations and rotations

## An effective theory approach / amplitude

- What is the predicted form for $\mathscr{M}_{\chi e}$ in our non-relativistic effective theory? We find:

$$\mathscr{M}_{\chi e}(\boldsymbol{q}, \boldsymbol{v}^{\perp}) = \sum_i c_i \, \langle \mathscr{O}_i \rangle$$

Matrix elements

Out of the four momenta $\overrightarrow{p}$, $\overrightarrow{p}'$, $\overrightarrow{k}$ and $\overrightarrow{k}'$ only two are independent: $\overrightarrow{q}$ and $\overrightarrow{v}^{\perp}$

Sum over operator type

Unknown coupling constants

Rotationally invariant operators in the DM-electron spin space

Examples of $\mathscr{O}_i$ operators:

$\mathscr{O}_1 = \mathbb{1}_{\chi}\mathbb{1}_e$, $\mathscr{O}_4 = \mathbf{S}_{\chi} \cdot \mathbf{S}_e$, $\mathscr{O}_7 = \mathbf{S}_{\chi} \cdot \boldsymbol{v}^{\perp}$, $\mathscr{O}_{11} = i\mathbf{S}_{\chi} \cdot \boldsymbol{q}/m_e$, ...

# Electron wave function overlap integrals

- We use $\mathscr{M}_{\chi e}$ to calculate the rate of transitions from the electronic state "1" to "2"

$$\mathrm{d}\mathscr{R}_{1\to 2} \propto \left| \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3}\, \psi_2^*(\boldsymbol{k}+\boldsymbol{q})\mathscr{M}_{\chi e}(\boldsymbol{v}^\perp, \boldsymbol{q})\, \psi_1(\boldsymbol{k}) \right|^2$$

  where $\boldsymbol{v}^\perp = \boldsymbol{v} - \boldsymbol{q}/(2\mu_{\chi e}) - \boldsymbol{k}/m_e$

- For $\mathscr{M}_{\chi e}(\boldsymbol{v}^\perp, \boldsymbol{q}) \neq \mathscr{M}_{\chi e}(\boldsymbol{q})$, $\mathscr{M}_{\chi e}$ cannot be moved outside the integral sign

- $\mathscr{M}_{\chi e}$ depends on $\boldsymbol{v}^\perp$, and thus on $\boldsymbol{k}$ in the case of anapole and magnetic dipole interactions

- It also depends on $\boldsymbol{v}^\perp$ in a number of simplified models with vector mediators

  R. Catena, D. Cole, T. Emken, M. Matas, N. Spaldin, W. Tarantino and E. Urdshals, JCAP **03** (2023), 052

# DM-induced electronic transition rate

- Our total rate formula:

$$\mathscr{R}_{\rm theory} = \frac{n_\chi}{128\pi m_\chi^2 m_e^2} \int {\rm d}(\ln \Delta E) \int {\rm d}q \, q \, \hat{\eta}\,(q, \Delta E) \sum_{\ell=1}^{r} \Re \left[ \mathscr{R}_\ell^*(q, v) \overline{\mathscr{W}}_\ell(q, \Delta E) \right]$$

Velocity integral

Sum over up to
r=7
response functions

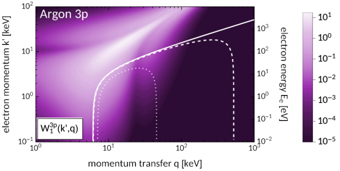
Free electron physics:
couplings and kinematics

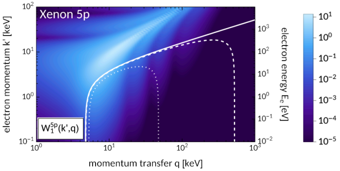
Response function:
electron wave function
overlap integral

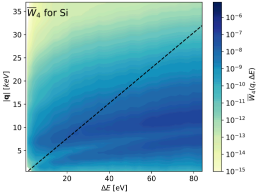
- It predicts a factorisation between the **free electron physics** encoded in $\mathscr{R}_\ell$ and the **material physics** encoded in the response functions $\mathscr{W}_\ell$

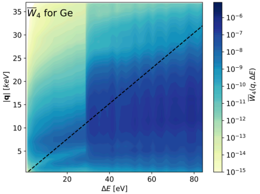
# Applications

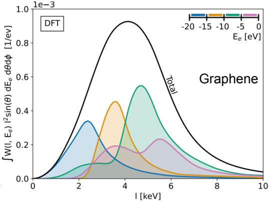
# Response function evaluation



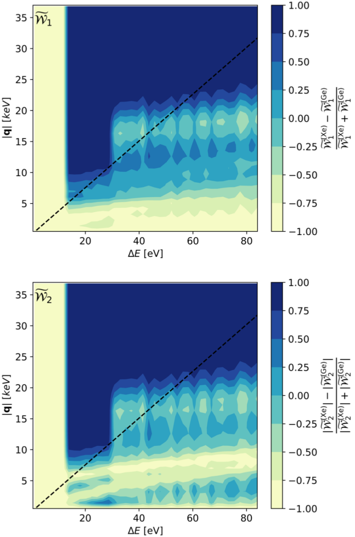




**Xenon and Argon**: R. Catena, T. Emken, N. A. Spaldin and W. Tarantino,
Phys. Rev. Res. **2** (2020) no.3, 033195

**Germanium and Silicon**: R. Catena, T. Emken, M. Matas, N. A. Spaldin and E. Urdshals,
Phys. Rev. Res. **3** (2021) no.3, 033149

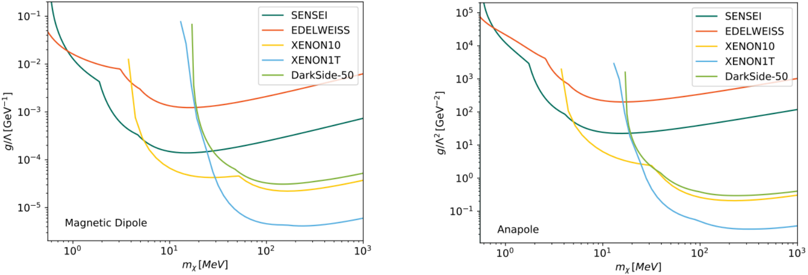
**Graphene**: R. Catena, T. Emken, M. Matas, N. A. Spaldin and E. Urdshals,
arXiv:2303.15497 [hep-ph]

# Response function comparison



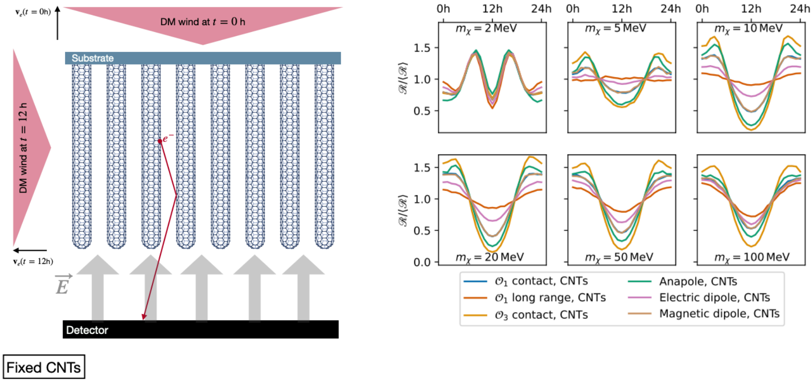

R. Catena, D. Cole, T. Emken, M. Matas, N. Spaldin, W. Tarantino and E. Urdshals,
JCAP **03** (2023), 052

- The formalism allows us to perform calculations within models, e.g. anapole and magnetic dipole DM, which were not tractable before (lacking the required $\mathscr{W}_\ell$'s)




R. Catena, T. Emken, M. Matas, N. A. Spaldin and E. Urdshals, arXiv:2303.15509 [hep-ph]

- It also allows us to make predictions for new direct detection materials, e.g. graphene, for general DM-electron interactions




R. Catena, T. Emken, M. Matas, N. A. Spaldin and E. Urdshals,
Phys. Rev. Res. **3** (2021) no.3, 033149

# Summary

- We developed a non-relativistic effective theory to model general DM-electron interactions in materials
- Our formalism predicts a factorisation between the **free electron physics** and the **material physics** encoded in the response functions $\mathscr{W}_\ell$
- It allows us to perform calculations within models, e.g. anapole and magnetic dipole DM, which were not tractable before (lacking the required $\mathscr{W}_\ell$'s)
- Furthermore, it enables us to assess the potential of new direct detection materials (graphene) for a general form of the underlying DM-electron interaction