Dark Matter phenomenology at direct detection experiments

Riccardo Catena

Chalmers University of Technology

November 14, 2022

CHALMERS

Swedish Research Council

Knut och Alice Wallenbergs Stiftelse

Overview

- The main purpose of this seminar is to review a selection of "theoretical frameworks" that are currently used in the analysis of DM direct detection data

- Each framework has an associated DM particle phenomenology which I will briefly review

- I will place the empahsis on the interdisciplinary character of the field, where astro-, particle, nuclear and solid state physics play an important role.

Outline

- Evidence for DM, and motivation for DM direct detection
- Basic principles of DM direct detection
- WIMP-induced nuclear recoils
- Sub-GeV DM-induced electron transitions
- Summary and conclusion

- How do we know that DM actually exist? The evidence for DM is based on the gravitational pull it exerts on stars, galaxies and light from luminous sources

- Specifically, the evidence for DM is based on:
  - Velocity dispersion of **stars**
  - Rotation curve of spiral **galaxies**
  - Velocity dispersion of galaxies in **galaxy clusters**
  - Bending of light from distant luminous sources (lensing)
  - **Cosmological structure** formation
  - Cosmic Microwave Background (**CMB**) anisotropies

Small scales

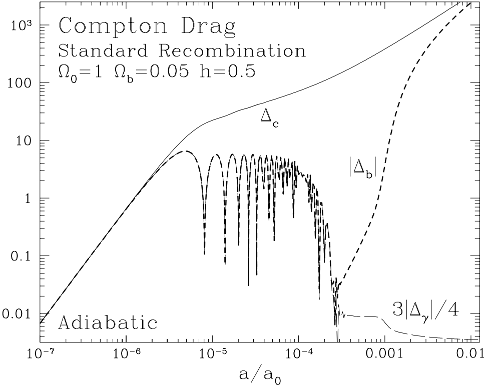
⋮

Large scales

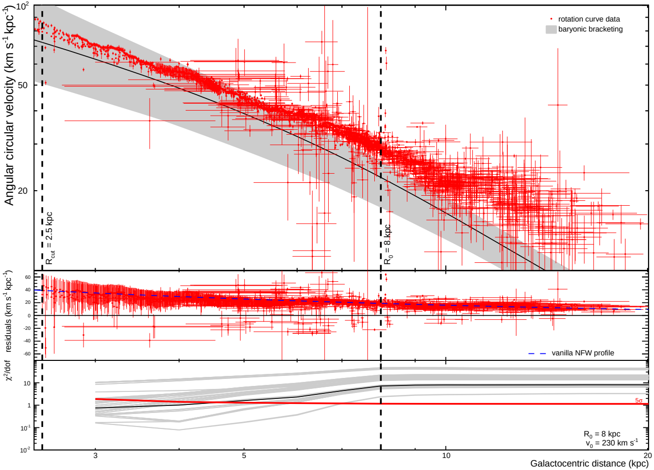
Evidence for DM / Large scale structures

Wayne T. Hu PhD thesis, "*Wandering in the Background: A CMB Explorer*";

astro-ph/9508126



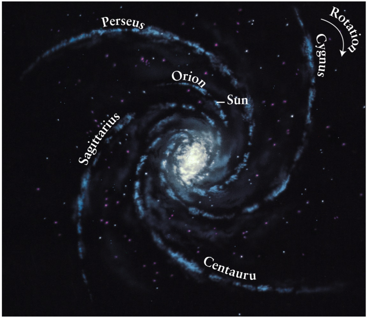
Evidence for DM in the Milky Way



F. Iocco, M. Pato and G. Bertone, "Evidence for dark matter in the inner Milky Way," Nature Phys. **11**, 245 (2015)

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

- DM direct detection experiments search for signals induced by this flux of DM particles in terrestrial detectors

- 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

Two examples of DM signals

- WIMP-induced nuclear recoils
- WIMP: DM candidate with mass in the GeV - 100 TeV range and with interactions "at the week scale"
- WIMPs with typical speeds around $v \sim 10^{-3}$ are expected to induce nuclear recoils of about few keV or so
- The search for WIMP-induced nuclear recoils is currently led by xenon and argon detectors, e.g. LZ, XENON1T, PandaX, Dark-Side

Two examples of DM signals

- WIMP-induced nuclear recoils
- WIMP: DM candidate with mass in the GeV - 100 TeV range and with interactions "at the week scale"
- WIMPs with typical speeds around $v \sim 10^{-3}$ are expected to induce nuclear recoils of about few keV or so
- The search for WIMP-induced nuclear recoils is currently led by xenon and argon detectors, e.g. LZ, XENON1T, PandaX, DarkSide

- Sub-GeV DM-induced electron transitions
- Sub-GeV DM: paradigm where DM has mass in the MeV - GeV range, and primarily interacts with electrons
- The energy deposited in sub-GeV DM-induced electron transitions is expected to be of the order of 10 eV
- The search for Sub-GeV DM-induced electron transitions is led by Si and Ge detectors in the 0.5 - 10 MeV mass range, and by argon and xenon detectors above 10 MeV
- E.g.: DAMIC, SENSEI, EDELWEISS, CDMS, XENON, DarkSide

WIMP-induced nuclear recoils

- In any theoretical framework for DM-nucleus scattering, the amplitude for non-relativistic DM scattering by free nucleons, $\mathscr{M}_{\chi N}$, plays an important role
- It is often *assumed* to be a function of the momentum transfer only, i.e. $\mathscr{M}_{\chi N} = \mathscr{M}_{\chi N}(\boldsymbol{q})$
- From $\mathscr{M}_{\chi N}$, one calculates the cross section for DM-target nucleus scattering

$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R} = \frac{m_T}{2\pi v^2} \frac{1}{2J_T+1} \sum_{\text{spins}} |T_{fi}|^2 ,$$

where $E_R = |\boldsymbol{q}|^2/(2m_T)$,

$$T_{fi} = -\sum_{j=1}^{A} \left(\prod_{\ell=1}^{A} \int \frac{\mathrm{d}^3\mathbf{k}_\ell}{(2\pi)^3} \right) \frac{\psi_f^*(\mathbf{k}_1^j, \dots, \mathbf{k}_A^j) M_{\chi N_j} \psi_i(\mathbf{k}_1, \dots, \mathbf{k}_A)}{\sqrt{16 E_{\mathbf{p}} E_{\mathbf{k}_j} E_{\mathbf{p}'} E_{\mathbf{k}'_j}}}$$

Nuclear wave functions

and $\mathbf{k}_i^j = \mathbf{k}_i + \boldsymbol{q}\delta_i^j$

Spin-independent and -dependent interactions

- For spin-independent interactions, $\mathscr{M}_{\chi N} = c_1^N \langle \mathbb{1}_{\chi N} \rangle$

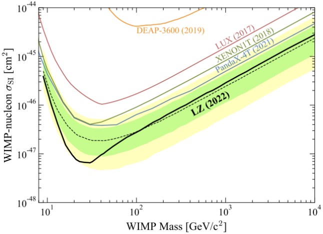
  Experimental results presented in terms of,

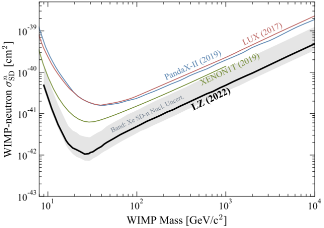
$$\sigma_{\mathrm{N}}^{SI} = \frac{\mu_{\chi N}^2}{\pi}(c_1^N)^2$$

- For spin-dependent interactions, $\mathscr{M}_{\chi N} = c_4^N \langle \mathbf{S}_N \cdot \mathbf{S}_\chi \rangle$

  Experimental results presented in terms of,

$$\sigma_N^{\mathrm{SD}} = \frac{\mu_{\chi N}^2 j_\chi (j_\chi + 1)}{4\pi}(c_4^N)^2$$





J. Aalbers *et al.*, "First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment," arXiv:2207.03764

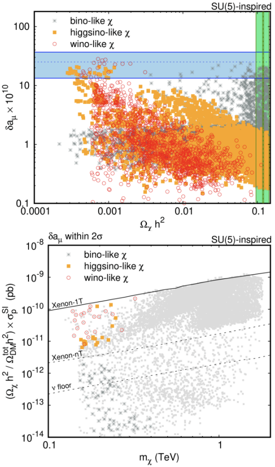
SUSY WIMPs

- SUSY neutralinos are the most extensively investigated DM candidate
- WIMP-quark interactions are given by

$$\mathscr{L}_{\mathrm{SI}} = f_q \bar{\chi} \chi \bar{q} q + g_q \bar{\chi} \gamma^\mu \partial^\nu \chi (\bar{q} \gamma_\mu \partial_\nu q - \partial_\nu \bar{q} \gamma_\mu q)$$

$$\mathscr{L}_{\mathrm{SD}} = f_q \bar{\chi} \gamma^\mu \gamma^5 \chi \bar{q} \gamma_\mu (c_q + d_q \gamma_5) q$$

- Effective couplings non-trivially depend on SUSY parameters: enhancements and cancellations are possible



M. Chakraborti, L. Roszkowski, S. Trojanowski, "GUT-constrained supersymmetry and dark matter in light of the new $(g-2)_\mu$ determination," JHEP **05** (2021), 252

Non-relativistic effective theories

- In the non-relativistic limit, $\mathscr{M}_{\chi N}$ is constrained by Galilean invariance and momentum conservation. Consequently it can at most depend on 2 3D momenta:

$$\mathscr{M}_{\chi N} = \mathscr{M}_{\chi N}(\boldsymbol{q}, \boldsymbol{v}^{\perp})$$

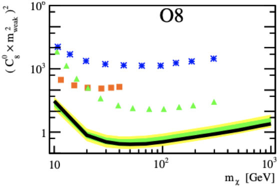
where $\boldsymbol{v}^{\perp} = \boldsymbol{v} + \boldsymbol{q}/(2\mu_{\chi N})$

- Furthermore, in the non-relativistic limit $|\boldsymbol{q}|/m_N \ll 1$ and $|\boldsymbol{v}| \ll 1$, which implies

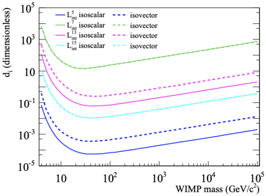
$$\mathscr{M}_{\chi N} = \sum_{i<\infty} c_i^N \langle \mathscr{O}_i \rangle$$

where $\mathscr{O}_i$ are quantum mechanical operators: $\mathscr{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N$, $\mathscr{O}_7 = \mathbf{S}_\chi \cdot \boldsymbol{v}^{\perp}$, etc...

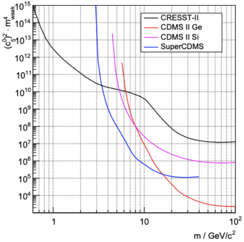
J. Fan, M. Reece and L. T. Wang, "Non-relativistic effective theory of dark matter direct detection," JCAP **11** (2010), 042
A. L. Fitzpatrick, W. Haxton, E. Katz, N. Lubbers and Y. Xu, "The Effective Field Theory of Dark Matter Direct Detection," JCAP **02** (2013), 004

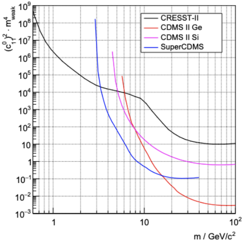


E. Aprile *et al.*, "Effective field theory search for high-energy nuclear recoils using the XENON100 dark matter detector," Phys. Rev. D **96** (2017) no.4, 042004



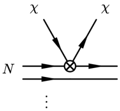
J. Xia *et al.*, "PandaX-II Constraints on Spin-Dependent WIMP-Nucleon Effective Interactions," Phys. Lett. B **792** (2019), 193-198

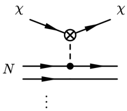




G. Angloher *et al.*, "Limits on Dark Matter Effective Field Theory Parameters with CRESST-II," Eur. Phys. J. C **79** (2019) no.1, 43

- Non-relativistic effective theories do not account for meson exchange effects in DM-nucleus scattering:





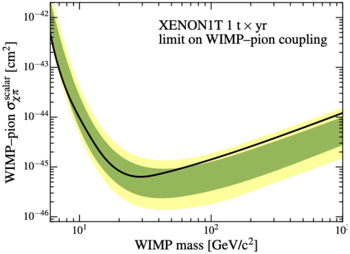
- Meson exchange effects induce a $\boldsymbol{q}$-dependence in the c_i^N coupling constants,

$$c_i^N = c_i^N(\boldsymbol{q})$$

- This $\boldsymbol{q}$-dependence can be computed in Chiral Effective Field Theory

  F. Bishara, J. Brod, B. Grinstein and J. Zupan, "Chiral Effective Theory of Dark Matter Direct Detection," JCAP **02** (2017), 009

- Experimental search for WIMP-pion couplings



E. Aprile *et al.*,"First results on the scalar WIMP-pion coupling, using the XENON1T experiment," Phys. Rev. Lett. **122** (2019) no.7, 071301

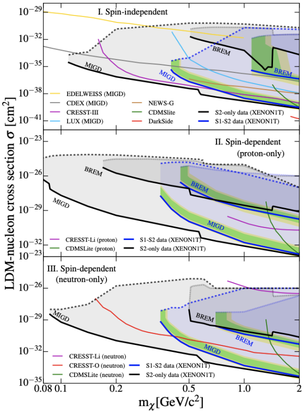
Light WIMPs: Migdal effect

- DM-nucleus scattering can ionise isolated atoms
- For light WIMPs, the energy of the ejected electron can be larger than the associated nuclear recoil energy
- To model this effect, one has to focus on the overall DM-atom scattering, rather than on DM-nucleus scattering.
- DM-atom scattering is described by the initial and final state atomic wave functions

$$\Psi_{E_i}(\boldsymbol{x}_N, \{\boldsymbol{x}\}) \simeq \Phi_{E_{ec}}(\{\boldsymbol{x} - \boldsymbol{x}_N\})$$

$$\Psi_{E_f}(\boldsymbol{x}_N, \{\boldsymbol{x}\}) \simeq e^{i\boldsymbol{p}_N \cdot \boldsymbol{x}_N} e^{i m_e \sum_i \boldsymbol{v} \cdot \boldsymbol{x}_i} \times \Phi_{E'_{ec}}(\{\boldsymbol{x} - \boldsymbol{x}_N\})$$

- The rate of atomic ionisations induced by this effect depends on the overlap of electron cloud wave functions



E. Aprile *et al.*, ‘Phys. Rev. Lett. **123** (2019) no.24, 241803

Sub-GeV DM-induced electron transitions

General considerations

- In any theoretical framework for Sub-GeV DM-electron scattering, the amplitude for non-relativistic DM scattering by free electrons, $\mathscr{M}_{\chi e}$, plays a key role
- It is often *assumed* to be a function of the momentum transfer only, i.e. $\mathscr{M}_{\chi e} = \mathscr{M}_{\chi e}(\boldsymbol{q})$

- From $\mathscr{M}_{\chi e}$, one calculates the rate of DM-induced electron transitions in detectors

$$\mathrm{d}\mathscr{R} = \frac{\rho_\chi}{m_\chi} \int \mathrm{d}\boldsymbol{v}\, |\boldsymbol{v}| f(\boldsymbol{v} + \boldsymbol{v}_\oplus)\, \mathrm{d}\sigma_{1\to 2}$$

where

$$\mathrm{d}\sigma_{1\to 2} = \frac{1}{16 m_\chi^2 m_e^2 |\boldsymbol{v}|} \frac{\mathrm{d}\boldsymbol{q}}{(2\pi)^3} \left| \int \frac{\mathrm{d}\boldsymbol{k}}{(2\pi)^3} \psi_2^*(\boldsymbol{k}+\boldsymbol{q}) \mathscr{M}_{\chi e}(\boldsymbol{q}) \psi_1(\boldsymbol{k}) \right|^2 \delta(E_2 - E_1)$$

The dark photon model

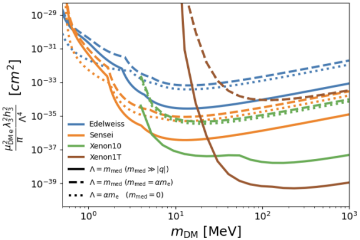
- It extends the Standard Model by an additional U(1) and a DM candidate
- The "dark sector" Lagrangian is given by

$$\mathscr{L}_D = \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi + \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2_{A'}A'_\mu A'^\mu + \varepsilon F_{\mu\nu}F'^{\mu\nu}$$

- The covariant derivative D_μ is defined as

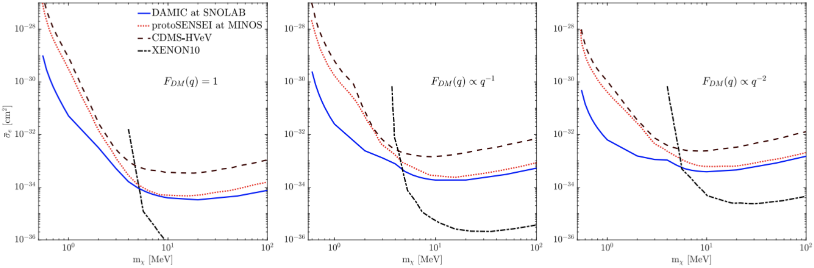
$$D_\mu\chi = \partial_\mu\chi - ig_D A'_\mu\chi$$

- Recent compilation of direct detection constraints



R. Catena, D. Cole, T. Emken, M. Matas, N. Spaldin, W. Tarantino and E. Urdshals, "Dark matter - electron interactions in materials beyond the dark photon model," arXiv:2210.07305

The dark photon model



A. Aguilar-Arevalo *et al.* "Constraints on Light Dark Matter Particles Interacting with Electrons from DAMIC at SNOLAB," Phys. Rev. Lett. **123** (2019) no.18, 181802

- If a perturbation of strength F couples DM to the electron density n

$$\mathscr{V}(t) = -\int \mathrm{d}\boldsymbol{r}\, n(\boldsymbol{r}) F(\boldsymbol{r}, t)$$

- then linear response theory predicts the DM-induced charged density

$$n_{\mathrm{ind}}(\boldsymbol{q}, \omega) = \Pi(\boldsymbol{q}, \omega)\, F(\boldsymbol{q}, \omega)$$

Density-density correlation function

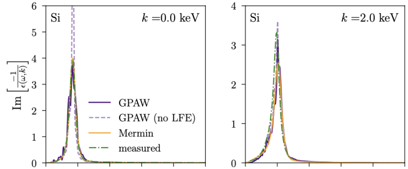
- $\Pi(\boldsymbol{q}, \omega)$ is related to the dielectric function

$$\frac{1}{\epsilon_r(\boldsymbol{q}, \omega)} = 1 + \frac{4\pi\alpha}{q^2}\, \Pi(\boldsymbol{q}, \omega)$$

- In addition, DM-induced electron transition rate $\mathrm{d}\mathscr{R}$ and ϵ_r are related by

$$\mathrm{d}\mathscr{R} = \frac{|F(\boldsymbol{q})|^2}{8 m_e^2 m_\chi^2} \frac{\mathrm{d}\boldsymbol{q}}{(2\pi)^3} \times \int \mathrm{d}\omega\, \frac{q^2}{4\pi\alpha}\, \mathfrak{I}\left(-\frac{1}{\epsilon_r(\boldsymbol{q}, \omega)}\right)$$

- Data-driven calibration of transition rates:



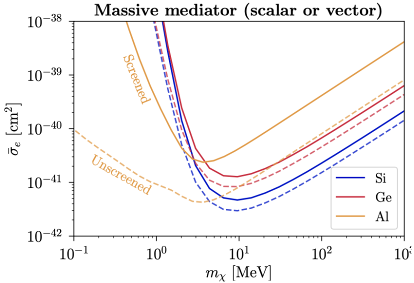
S. Knapen, J. Kozaczuk and T. Lin, Phys. Rev. D **104** (2021) no.1, 015031

In-medium effects: screening

- Density-density correlation function $\Pi(\boldsymbol{q},\omega)$ and $\epsilon_r(\boldsymbol{q},\omega)$ can be computed perturbatively:

$$\Pi(\boldsymbol{q},\omega) = \frac{\Pi^0(\boldsymbol{q},\omega)}{1 - U(\boldsymbol{q})\,\Pi^0(\boldsymbol{q},\omega)}$$

- For $|U(\boldsymbol{q})\Pi^0(\boldsymbol{q},\omega)| \gg 1$, the transition rate $\mathrm{d}\mathscr{R}$ is suppressed by screening effects
- Sensitivity projections with and without screening effects for selected materials:

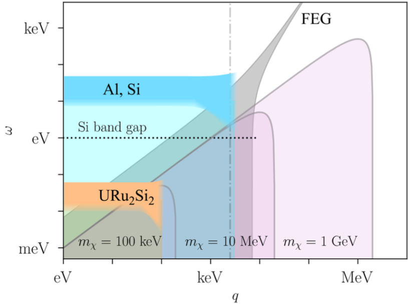


S. Knapen, J. Kozaczuk and T. Lin, Phys. Rev. D **104** (2021) no.1, 015031

- Density-density correlation function $\Pi(\boldsymbol{q},\omega)$ and $\epsilon_r(\boldsymbol{q},\omega)$ can be computed perturbatively:

$$\Pi(\boldsymbol{q},\omega) = \frac{\Pi^0(\boldsymbol{q},\omega)}{1 - U(\boldsymbol{q})\,\Pi^0(\boldsymbol{q},\omega)}$$

- For $U(\boldsymbol{q})\Re\left(\Pi^0(\boldsymbol{q},\omega)\right) \simeq 1$, the transition rate $\mathrm{d}\mathscr{R}$ is enhanced by collective excitations
- Regions where collective excitations enhance $\Im(-1/\epsilon_r)$ for selected materials:



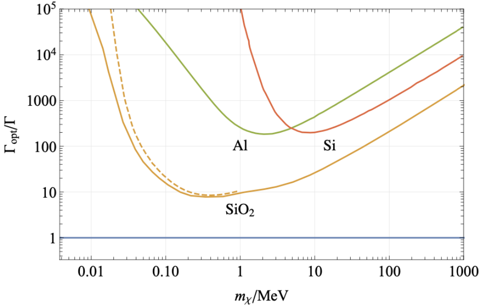
Y. Hochberg, Y. Kahn, N. Kurinsky, B. V. Lehmann, T. C. Yu and K. K. Berggren, Phys. Rev. Lett. **127** (2021) no.15, 151802

Kramer-Kronig relations

- From the basic requirement of $\Pi(\boldsymbol{q}, t)$ being causal, i.e. $\Pi(\boldsymbol{q}, t) = 0$ for $t < 0$, one finds

$$\int_{-\infty}^{+\infty} \frac{\mathrm{d}\omega}{\omega} \, \Im\left(-\frac{1}{\epsilon_r(\boldsymbol{q}, \omega)}\right) \leq \frac{\pi}{2}\left(1 - \frac{1}{\epsilon_r(\boldsymbol{q}, 0)}\right)$$

- which implies a theoretical upper bound on the DM-induced electron transition rate $\mathrm{d}\mathscr{R}$:



R. Lasenby and A. Prabhu, Phys. Rev. D **105** (2022) no.9, 095009

Electromagnetic moments

- When $\mathscr{M}_{\chi e}(\boldsymbol{q}) \to \mathscr{M}_{\chi e}(\boldsymbol{q}, \boldsymbol{k})$, $\mathscr{M}_{\chi e}$ cannot be factored out in the $\mathrm{d}\boldsymbol{k}$ integral in $\mathrm{d}\sigma_{1\to 2}$
- This occurs when, e.g.

$$\mathscr{L}_{\text{anapole}} = \frac{g}{2\Lambda^2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$$
$$\mathscr{L}_{\text{magnetic}} = \frac{g}{\Lambda}\,\bar{\psi}\sigma^{\mu\nu}\psi\,F_{\mu\nu}$$

and in a variety of "light mediator models":

R. Catena, *et al.* "Dark matter - electron interactions in materials beyond the dark photon model"

arXiv:2210.07305

- In this case, standard ionisation and crystal form factors do not provide an accurate description

Non-relativistic effective theories

- In the non-relativistic limit, i.e. $|\boldsymbol{q}|/m_e \ll 1$ and $|\boldsymbol{v}| \ll 1$, $\mathscr{M}_{\chi e}$ admits an effective theory expansion (analogous to the one in the case of nuclear recoils)

$$\mathscr{M}_{\chi e} = \sum_{i<\infty} c_i \langle \mathscr{O}_i \rangle$$

where $\mathscr{O}_i$ are quantum mechanical operators: $\mathscr{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N$, $\mathscr{O}_7 = \mathbf{S}_\chi \cdot \boldsymbol{v}^\perp$, etc...

- The rate of DM-induced electron transitions in materials can now be written as)

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

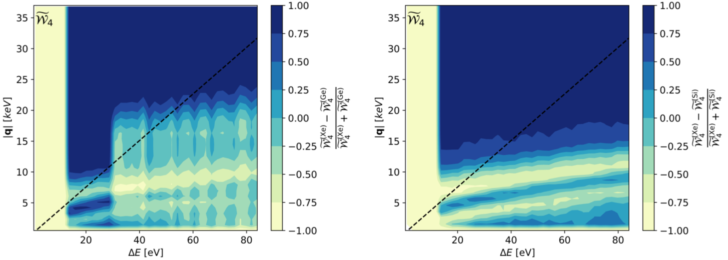
Particle physics input **Response functions from solid state physics**

R. Catena, T. Emken, N. A. Spaldin and W. Tarantino, "Atomic responses to general dark matter-electron interactions," Phys. Rev. Res. **2** (2020) no.3, 033195
R. Catena, T. Emken, M. Matas, N. A. Spaldin and E. Urdshals, "Crystal responses to general dark matter-electron interactions," Phys. Rev. Res. **3** (2021) no.3, 033149

- The response functions $\mathscr{W}_l(q, \Delta E)$ admit the following compact representation

$$\mathscr{W}_l(\boldsymbol{q}, \Delta E) = \frac{2}{\pi} \Delta E \sum_{\{1\},\{2\}} \mathscr{B}_l \, \delta(\Delta E - E_2 + E_1)$$

where the $\mathscr{B}_l$'s are (up to 5) material-specific electron wave function overlap integrals



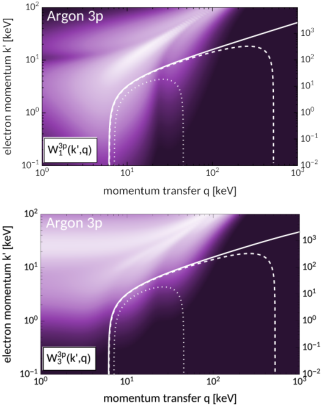
R. Catena, *et al.* "Dark matter - electron interactions in materials beyond the dark photon model"

arXiv:2210.07305

Response function formalism

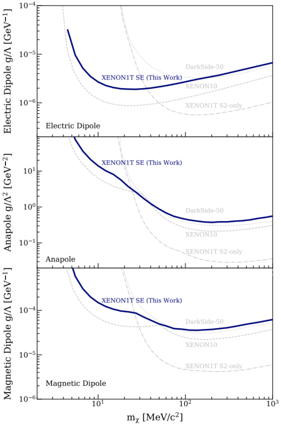
- Selected response functions for argon

  R. Catena, T. Emken, N. A. Spaldin and W. Tarantino, "Atomic responses to general dark matter-electron interactions," Phys. Rev. Res. **2** (2020) no.3, 033195



- Recent XENON1T analysis based on our response function formalism

  E. Aprile *et al.* (XENON Collaboration), Phys. Rev. D **106** (2022) no.2, 022001



Summary and conclusions

- I reviewed a selection of theoretical frameworks used in the analysis of DM direct detection data
- Focusing on WIMP-induced nuclear recoils, I highlighted some of the features of frameworks based on non-relativistic effective theories, and on chiral EFT
- Focusing on Sub-GeV DM-induced electron transitions, I placed the emphasis on the dielectric function formalism, and on non-relativistic effective theories
- The highly interdisciplinary character of the DM direct detection field calls for an increased collaboration between particle, nuclear and solid state physicists