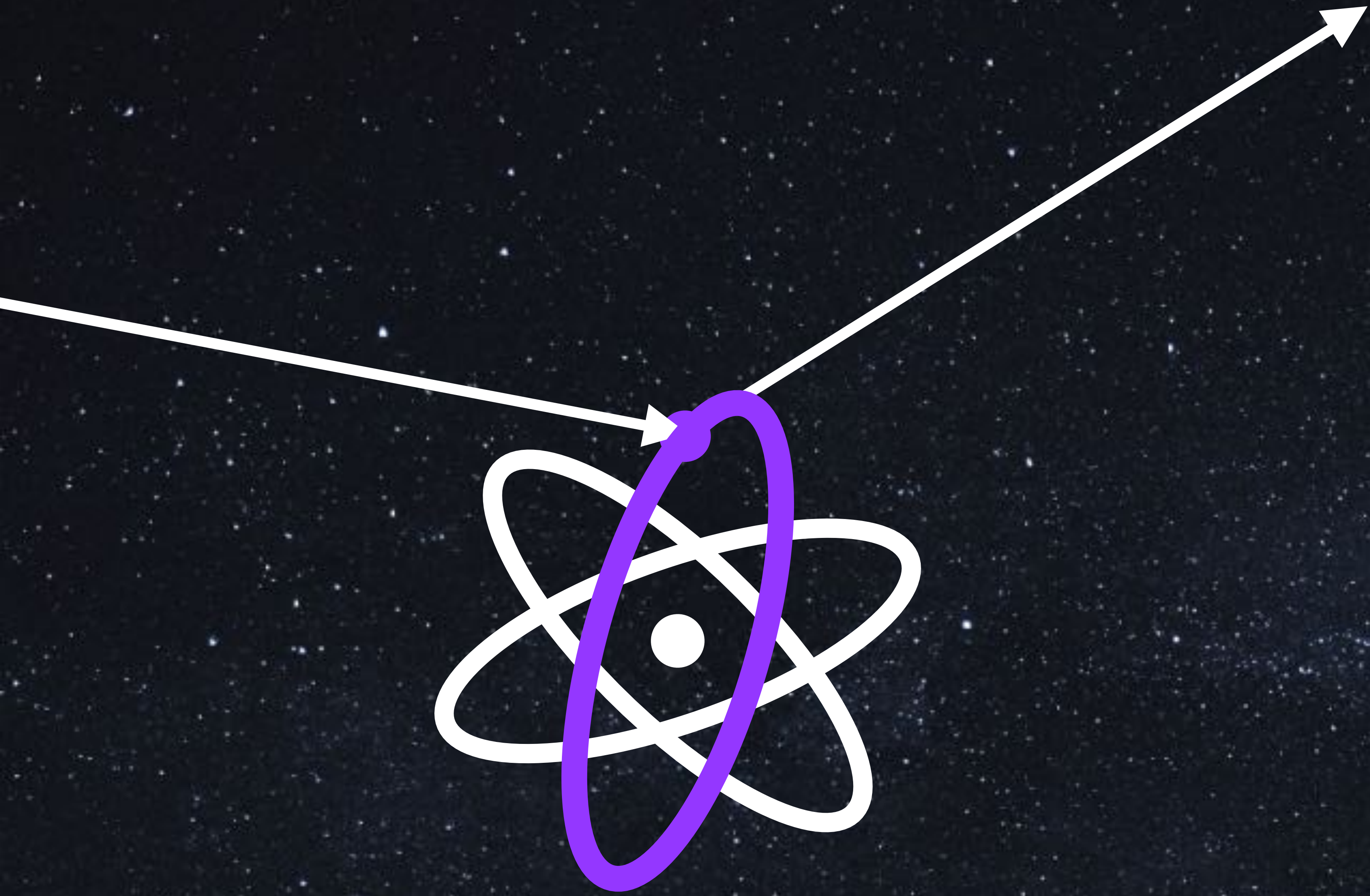

Partikeldagarna 2020
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Based on
[arXiv:1912.08204]

How atoms respond to general dark matter-electron interactions

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How atoms respond to general dark matter-electron interactions

I. Direct Searches for sub-GeV DM via electron scatterings

II. General DM-electron interactions and atomic responses

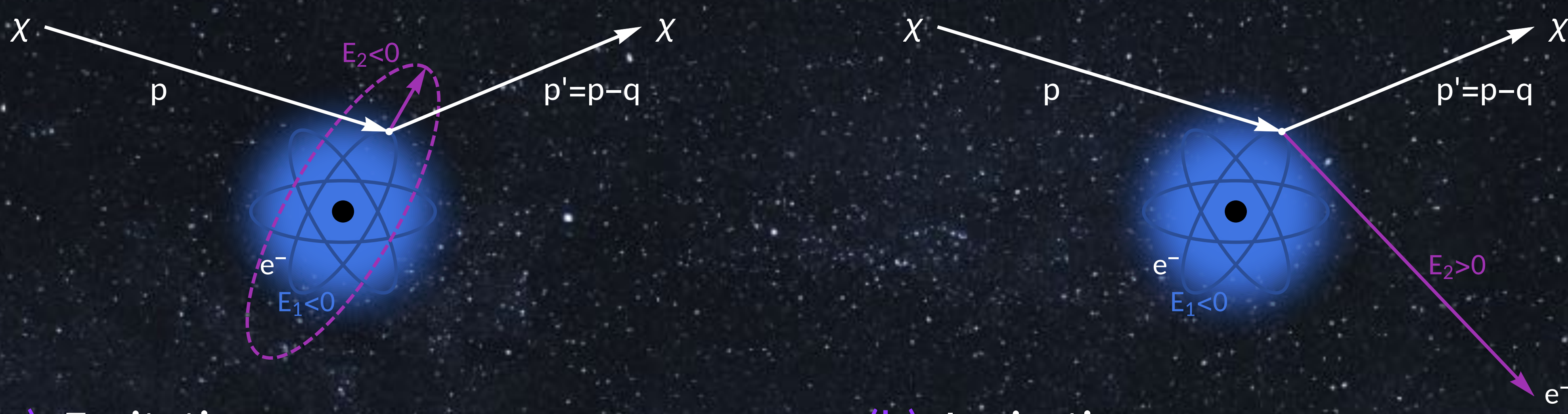
I.

Direct Searches for sub-GeV DM via electron scatterings

Direct Detection of Dark Matter via electron recoils

Instead of nuclear recoils, search for DM-electron interactions.

J. Kopp et al., PRD, [arXiv:0907.3159]
R. Essig et al., PRD [arXiv:1108.5383]



(a) Excitation (b) Ionization

- Different kinematics from nuclear recoils:

$$E_e^{\max} = \frac{1}{2}\mu_{\chi N} v^2 \lesssim E_\chi \sim 3\,\mathrm{eV}\left(\frac{m_\chi}{\mathrm{MeV}}\right)$$

Nuclear recoils:

$$E_{\mathrm{NR}}^{\max} = \gamma E_\chi$$
$$\gamma \approx 4\frac{m_\chi}{m_N} \ll 1 \quad \text{for } m_\chi \ll m_N$$

- Lowest DM mass to excite/ionize an electron in...
  - ...an isolated atom:

$$E_B \approx 10\,\mathrm{eV} \quad \Rightarrow \quad m_\chi^{\min} \approx 3\,\mathrm{MeV}$$

  - ...a semiconductor:

$$E_{\mathrm{gap}} \approx 1\,\mathrm{eV} \quad \Rightarrow \quad m_\chi^{\min} \approx 300\,\mathrm{keV}$$

Lee et al., PRD, [arXiv:1508.07361]
Essig et al., JHEP, [arXiv:1509.01598]

DM induced electron ionizations

- Complication: Target electrons are bound states.
- Electrons are not in a momentum eigenstate.
- Example: Ionization spectrum for isolated atoms:

$$\frac{\mathrm{d}R_{\mathrm{ion}}}{\mathrm{d}E_e} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\sum_{nl}\frac{\langle \mathrm{d}\sigma_{\mathrm{ion}}^{nl} v\rangle}{\mathrm{d}E_e}$$

$$\frac{\mathrm{d}\langle \sigma_{\mathrm{ion}}^{nl} v\rangle}{\mathrm{d}E_e} = \frac{\sigma_e}{8\mu_{\chi e}^2 E_e}\int \mathrm{d}q\, q \left|F_{\mathrm{DM}}(q)\right|^2 \left|f_{\mathrm{ion}}^{nl}(k', q)\right|^2 \eta\left(v_{\mathrm{min}}(\Delta E_e, q)\right)$$

- Predictions require the evaluation of an **ionization form factor**.
- There is still theoretical uncertainty in the evaluation of the ionization form factors.

See e.g. Roberts & Flambaum, [arXiv:1904.07127], and Pandey et al., [arXiv:1812.11759]

- For crystals, this requires methods from condensed matter physics.

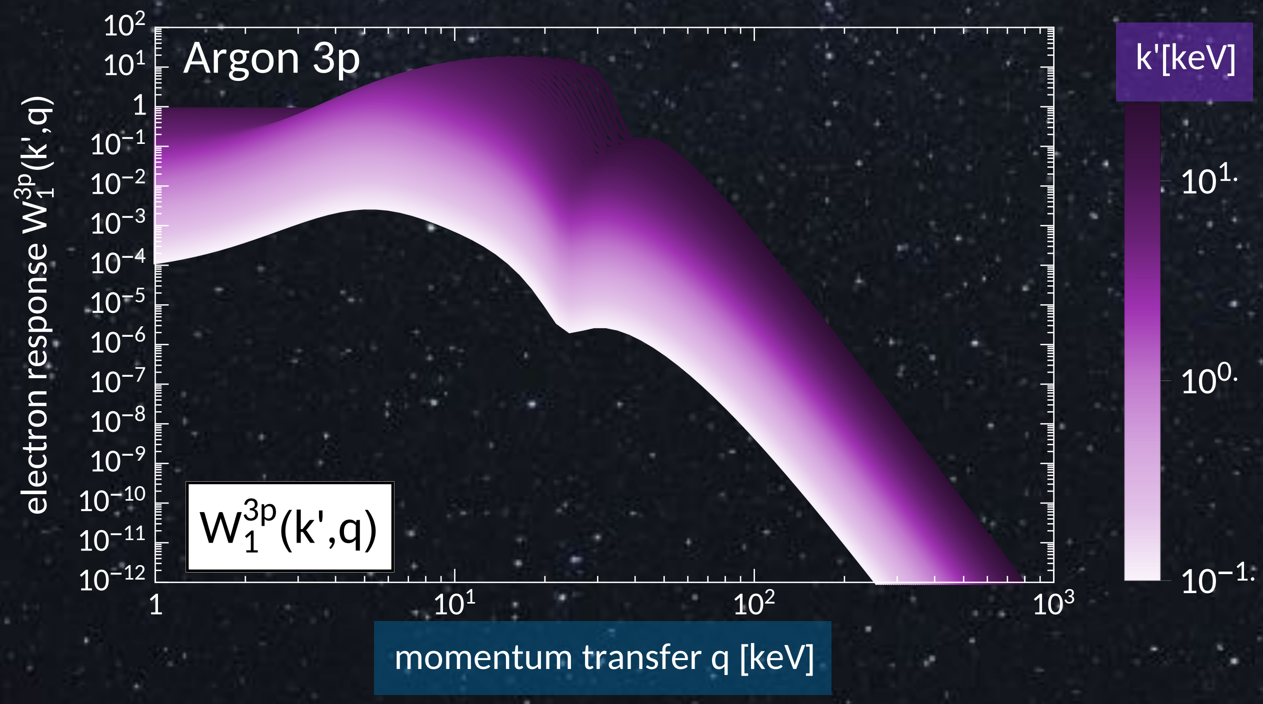
Essig et al., JHEP, [arXiv:1509.01598]

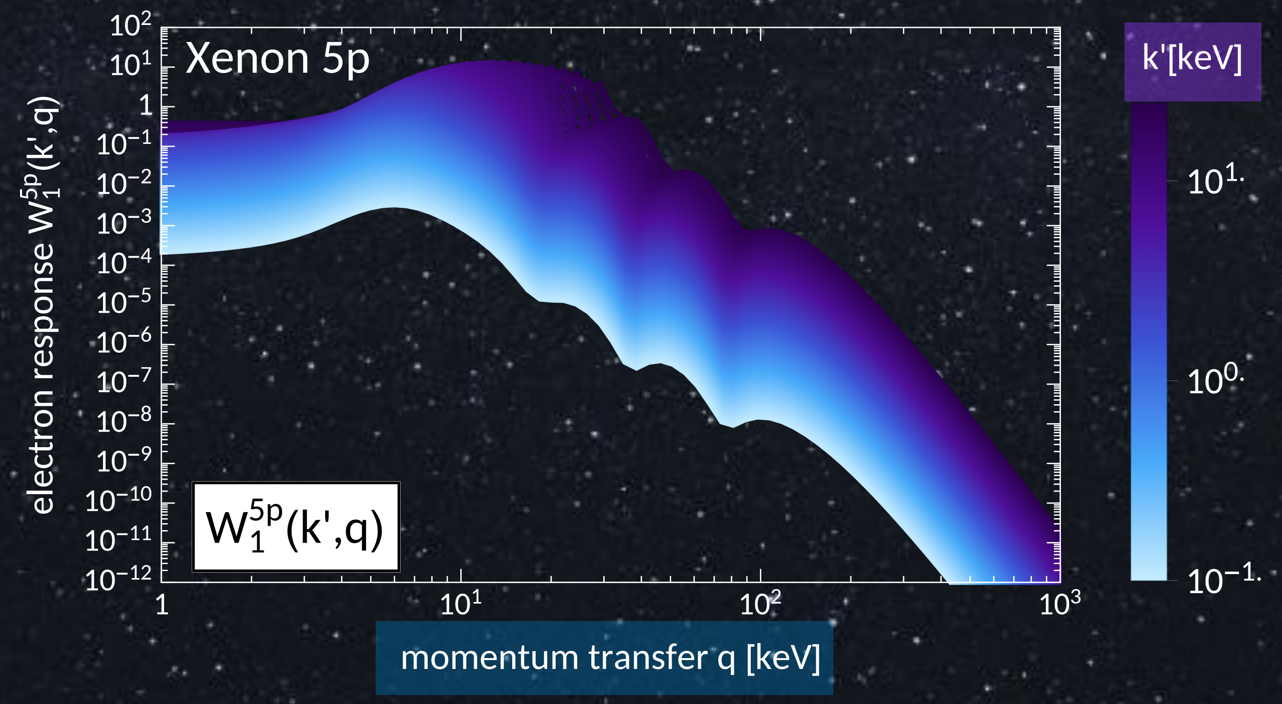
Atomic ionization form factors

- Complication: Target electrons are bound states.
- The electron transition is described by a "ionization form factor":

$$|f_{\text{ion}}^{n\ell}(k', q)|^2 = \frac{2k'^2}{(2\pi)^3} \sum_{\text{occupied states}} \sum_{\ell' m'} \left| \int d^3\mathbf{x}\, \tilde{\psi}^*_{k'\ell' m'}(\mathbf{x}) \psi_{n\ell m}(\mathbf{x}) e^{i\mathbf{q}\cdot\mathbf{x}} \right|^2$$

- Examples:





II.

General DM-electron interactions and atomic responses

The “Standard Model” of direct searches for sub-GeV DM

- Extend the SM by a DM particle and a U(1) gauge group with kinetic mixing.

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

Holdom, Phys. Lett. 166B (1986) 196

- Scattering amplitudes only depend on the momentum transfer.
- Transition rate between two electronic states $1 \rightarrow 2$:.

$$R_{1\rightarrow 2} \propto \overline{\left| \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \psi_2^*(\mathbf{k}+\mathbf{q}) \mathscr{M}_{\text{free}}(q) \psi_1(\mathbf{k}) \right|^2}$$

Initial bound state wave function.

Free scattering amplitude.

Final state wave function.

- The DM and atomic physics “factorize” conveniently.

$$R_{1\rightarrow 2} \propto \overline{|\mathscr{M}_{\text{free}}(q)|^2} \times \underbrace{\left| \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \psi_2^*(\mathbf{k}+\mathbf{q})\psi_1(\mathbf{k}) \right|^2}_{\equiv f_{1\rightarrow 2}(q)}$$

DM physics

atomic form factor

Effective description of DM-electron scatterings

- General non-relativistic amplitude:

$$\mathscr{M}(\mathbf{q}, \mathbf{v}_{\text{el}}^{\perp}) = \sum_i \left(c_i^s + c_i^\ell \frac{q_{\text{ref}}^2}{|\mathbf{q}|^2} \right) \langle \mathcal{O}_i \rangle$$

Contact interactions

Long-range interactions

- Effective operators

$\mathcal{O}_1 = \mathbb{1}_X \mathbb{1}_e$	$\mathcal{O}_{11} = i\vec{S}_X \cdot \frac{\vec{q}}{m_e} \mathbb{1}_e$
$\mathcal{O}_3 = i\vec{S}_e \cdot \left(\frac{\vec{q}}{m_e} \times \vec{v}^\perp \right) \mathbb{1}_X$	$\mathcal{O}_{12} = \vec{S}_X \cdot \left(\vec{S}_e \times \vec{v}^\perp \right)$
$\mathcal{O}_4 = \vec{S}_X \cdot \vec{S}_e$	$\mathcal{O}_{13} = i\left(\vec{S}_X \cdot \vec{v}^\perp \right) \left(\vec{S}_e \cdot \frac{\vec{q}}{m_e} \right)$
$\mathcal{O}_5 = i\vec{S}_X \cdot \left(\frac{\vec{q}}{m_e} \times \vec{v}^\perp \right) \mathbb{1}_e$	$\mathcal{O}_{14} = i\left(\vec{S}_X \cdot \frac{\vec{q}}{m_e} \right) \left(\vec{S}_e \cdot \vec{v}^\perp \right)$
$\mathcal{O}_6 = \left(\vec{S}_X \cdot \frac{\vec{q}}{m_e} \right) \left(\vec{S}_e \cdot \frac{\vec{q}}{m_e} \right)$	$\mathcal{O}_{15} = i\mathcal{O}_{11} \left[\left(\vec{S}_e \times \vec{v}^\perp \right) \cdot \frac{\vec{q}}{m_e} \right]$
$\mathcal{O}_7 = \vec{S}_e \cdot \vec{v}^\perp \mathbb{1}_X$	$\mathcal{O}_{17} = i\frac{\vec{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \vec{v}^\perp \mathbb{1}_e$
$\mathcal{O}_8 = \vec{S}_X \cdot \vec{v}^\perp \mathbb{1}_e$	$\mathcal{O}_{18} = i\frac{\vec{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \vec{S}_e$
$\mathcal{O}_9 = i\vec{S}_X \cdot \left(\vec{S}_e \times \frac{\vec{q}}{m_e} \right)$	$\mathcal{O}_{19} = \frac{\vec{q}}{m_e} \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\vec{q}}{m_e}$
$\mathcal{O}_{10} = i\vec{S}_e \cdot \frac{\vec{q}}{m_e} \mathbb{1}_X$	$\mathcal{O}_{20} = \left(\vec{S}_e \times \frac{\vec{q}}{m_e} \right) \cdot \boldsymbol{\mathcal{S}} \cdot \frac{\vec{q}}{m_e}$

A general expression for the event spectrum

- The general scattering amplitude $\mathscr{M}_{\text{free}}(q, v_{\text{el}}^{\perp})$ depends on the initial electron's momentum $\mathbf{k}$ via

$$\mathbf{v}_{\text{el}}^{\perp} = \frac{(\mathbf{p}+\mathbf{p}')}{2m_\chi} - \frac{(\mathbf{k}+\mathbf{k}')}{2m_e}\,.$$

- **The amplitude can no longer be taken out of the integral.**

$$R_{1\to 2} \propto \overline{\left| \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \psi_2^*(\mathbf{k}+\mathbf{q})\, \mathscr{M}_{\text{free}}(q, v_{\text{el}}^{\perp})\, \psi_1(\mathbf{k}) \right|^2}$$

- The energy spectrum can be written as

$$\frac{\mathrm{d}R_{\text{ion}}^{n\ell}}{\mathrm{d}\ln E_e} = \frac{n_\chi}{128\pi\, m_\chi^2 m_e^2} \int \mathrm{d}q\, q \int \frac{\mathrm{d}^3 v}{v} f_\chi(\mathbf{v})\Theta(v - v_{\text{min}}) \overline{\left| \mathscr{M}_{\text{ion}}^{n\ell} \right|^2},$$

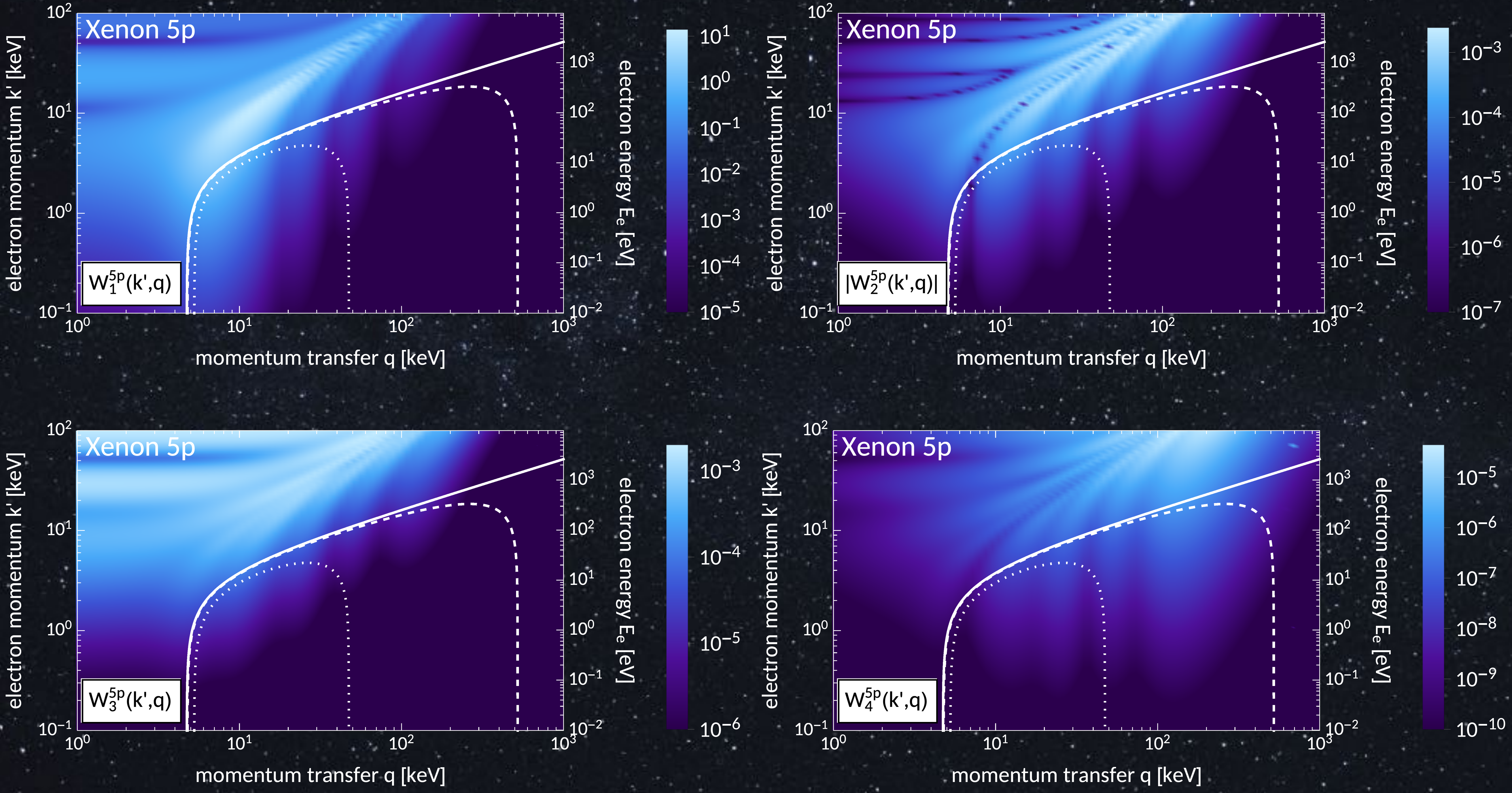
- Using the general effective amplitude, the "ionization amplitude" can be written as

$$\overline{|\mathscr{M}_{\text{ion}}^{n\ell}|^2} = \sum_{i=1}^{4} R_i^{n\ell}\left(\mathbf{v}_{\text{el}}^{\perp}, \frac{\mathbf{q}}{m_e}\right) \times W_i^{n\ell}(k', \mathbf{q})\,.$$

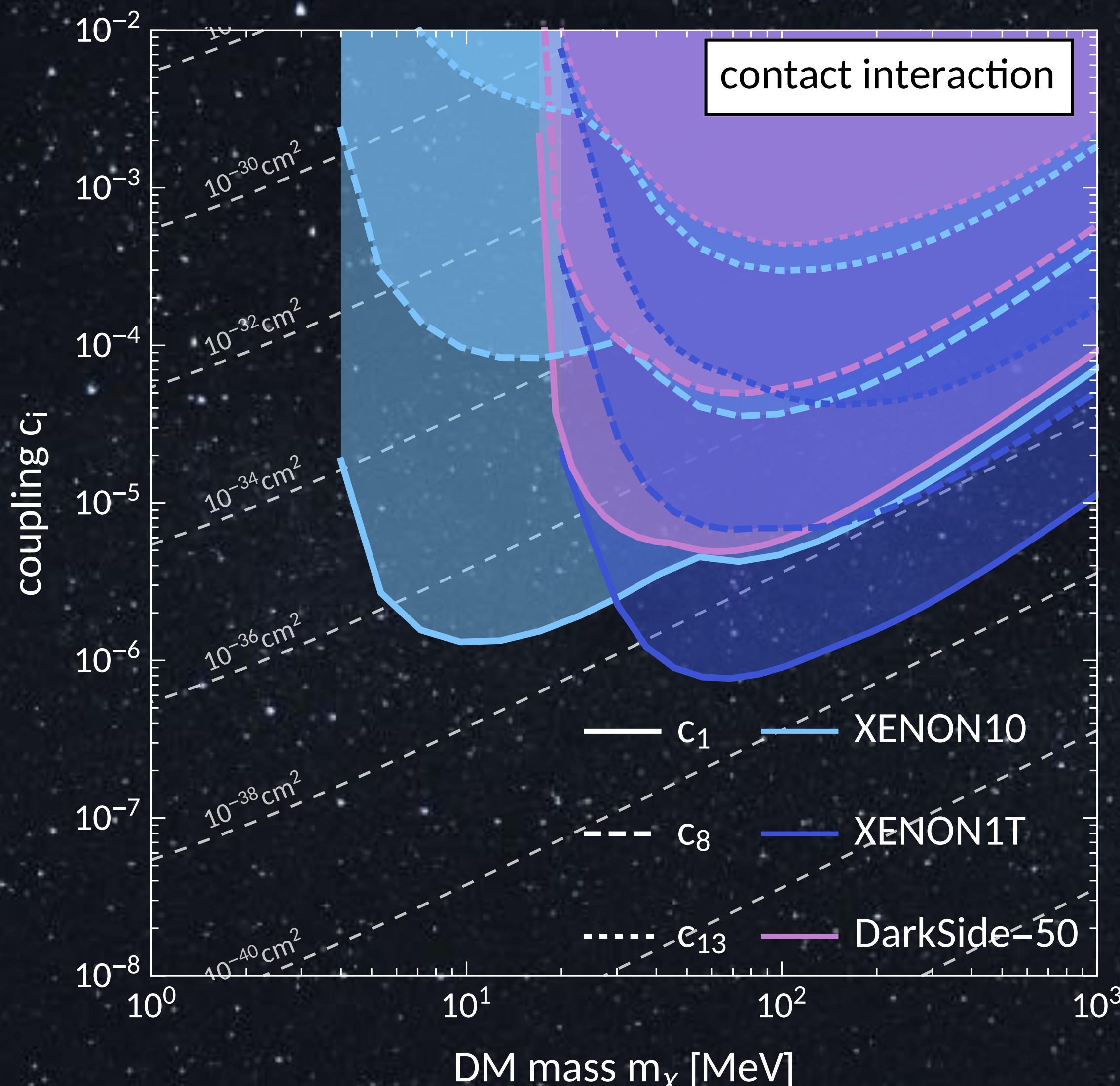
DM response function

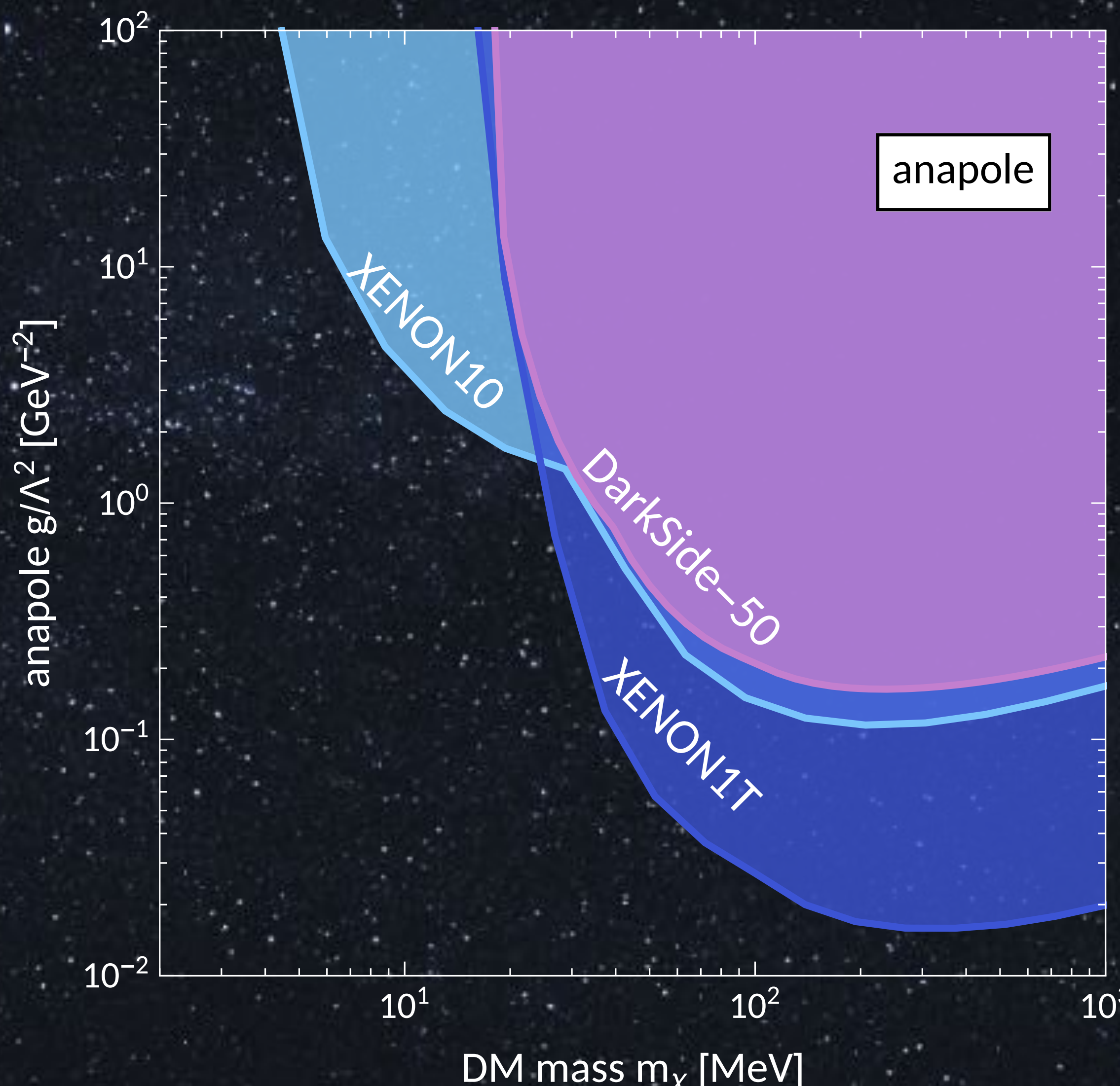
Atomic response function

The four atomic response functions of Xenon 5p



Exclusion limits on individual operators or BSM models





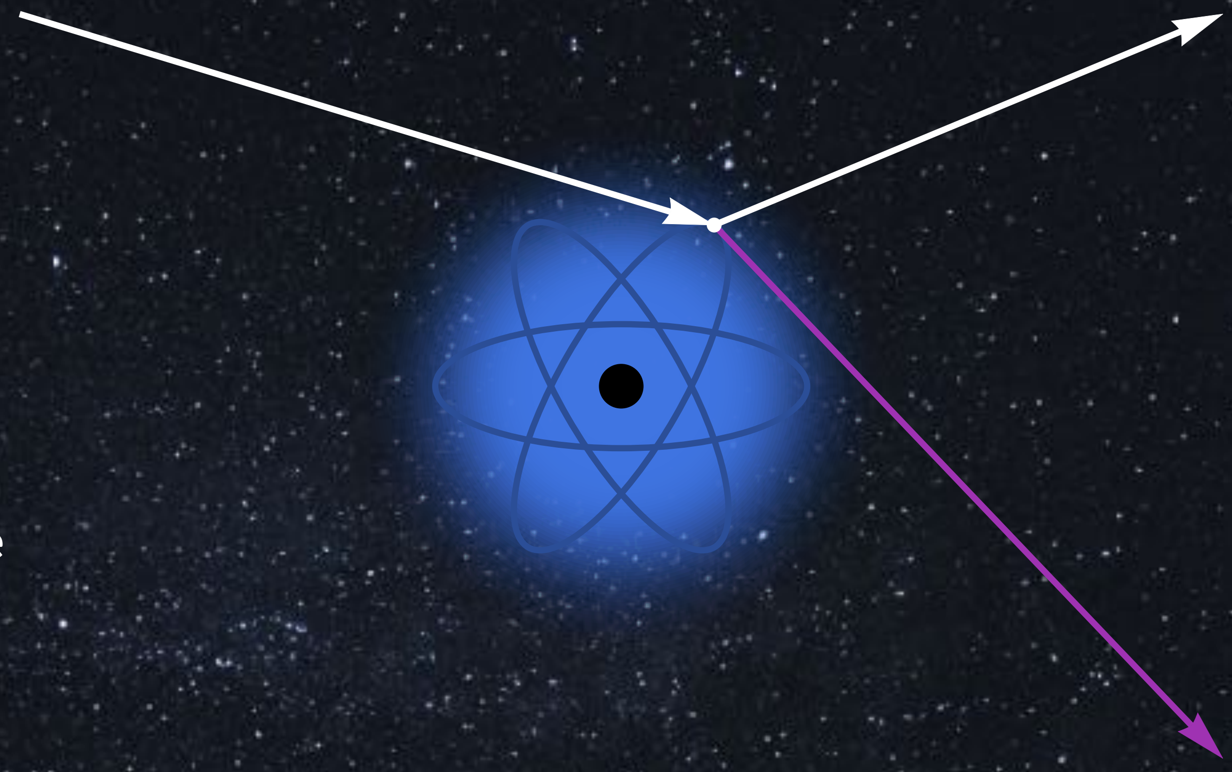
$$\overline{\sigma}_e \equiv \frac{\mu_{\chi e}^2 c_i^2}{16\pi m_\chi^2 m_e^2}$$

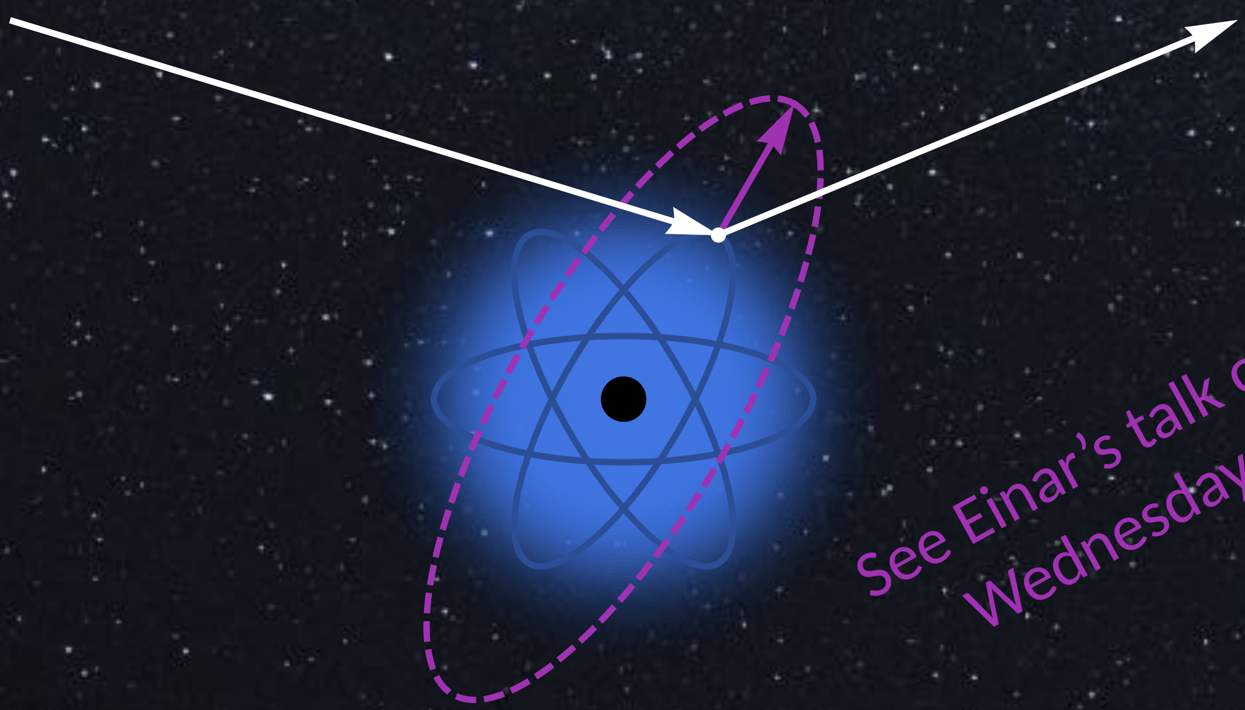
$$\mathscr{L} = \frac{1}{2}\frac{g}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}\,,$$

$$c_8 = \frac{8egm_\chi m_e}{\Lambda^2} \qquad c_9 = -\frac{4egm_\chi m_e}{\Lambda^2}$$

Summary

- DM-electron scatterings allow direct searches for sub-GeV DM masses.
- So far, only one class of DM-electron interactions has been studied.
- **General interactions give rise to new atomic response functions.**
- We studied the example of isolated xenon and argon atoms and derived first constraints based on DarkSide-50, XENON10, and XENON1T.





See Einar's talk on Wednesday.

Outlook

- **DM-electron interactions could probe completely new, so far hidden properties of materials.**
- Apply the idea to more complex targets: semiconductors, Dirac materials, liquid nobles,…
- Study of atoms as a starting point of an interdisciplinary program with many interesting directions to go.

Thank you!

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The four atomic response functions

- The general interactions give rise to four atomic response functions:

$$W_1^{n\ell}(k',\mathbf{q}) \equiv \frac{4k'^3}{(2\pi)^3}\sum_{m=-\ell}^{\ell}\sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}\left|f_{1\rightarrow 2}(q)\right|^2 ,$$

The standard ionization form factor

$$W_2^{n\ell}(k',\mathbf{q}) \equiv \frac{4k'^3}{(2\pi)^3}\sum_{m=-\ell}^{\ell}\sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}\frac{\mathbf{q}}{m_e}\cdot\left(f_{1\rightarrow 2}(\mathbf{q})\mathbf{f}^*_{1\rightarrow 2}(\mathbf{q})\right) ,$$

$$W_3^{n\ell}(k',\mathbf{q}) \equiv \frac{4k'^3}{(2\pi)^3}\sum_{m=-\ell}^{\ell}\sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}|\mathbf{f}_{1\rightarrow 2}(\mathbf{q})|^2 ,$$

$$W_4^{n\ell}(k',\mathbf{q}) \equiv \frac{4k'^3}{(2\pi)^3}\sum_{m=-\ell}^{\ell}\sum_{\ell'=0}^{\infty}\sum_{m'=-\ell'}^{\ell'}\left|\frac{\mathbf{q}}{m_e}\cdot\mathbf{f}_{1\rightarrow 2}(\mathbf{q})\right|^2$$

New atomic responses.

- Constructed from the scalar and vectorial atomic form factor:

$$f_{1\rightarrow 2}(\mathbf{q}) = \int\frac{\mathrm{d}^3k}{(2\pi)^3}\psi^*_{k'\ell'm'}(\mathbf{k}+\mathbf{q})\psi_{nlm}(\mathbf{k}) \qquad \mathbf{f}_{1\rightarrow 2}(\mathbf{q}) = \int\frac{\mathrm{d}^3k}{(2\pi)^3}\psi^*_{k'\ell'm'}(\mathbf{k}+\mathbf{q})\,\frac{\mathbf{k}}{m_e}\,\psi_{nlm}(\mathbf{k})$$