The relation between Migdal effect and dark matter-electron scatterings in atoms and semiconductors

based on arXiv:1908.10881 with R.Essig, J.Pradler and T.Yu

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Direct Detection of Sub-GeV Dark Matter

- Not enough energy in nuclear recoils !

$$E_{\mathrm{NR}}^{\mathrm{max}} \sim 2\ \mathrm{eV}\left(\frac{\mathrm{m}_\chi}{100\mathrm{MeV}}\right)^2\left(\frac{10\mathrm{GeV}}{\mathrm{m_N}}\right)$$

- Look for ionization/photon signals:
  - ➢DM-electron recoil
  - ➢DM-nucleus recoil with Bremsstrahlung
  - ➢DM-nucleus recoil with a Migdal electron

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DM-electron recoil

- Can probe DM-electron interactions for sub-GeV Dark Matter
- All the energy of the incoming DM particle can in principle be converted to electron recoil.
- The transition probability from electronic state $|\, i >$ to electronic state $|\, f >$ is proportional to,

$$\left|< f \left| e^{i\boldsymbol{q}.\boldsymbol{x}} \right| i >\right|^2$$

where $\boldsymbol{q}$ is the momentum lost by the dark matter particle.

DM-nucleus recoil with a Migdal electron

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- All the energy of the incoming DM particle can in principle be converted to electron ionization.
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where $\boldsymbol{q_e} \sim \left(\frac{\boldsymbol{m_e}}{\boldsymbol{m_N}}\right)\boldsymbol{q}$, $\boldsymbol{q}$ being the momentum lost by the dark matter particle.

Migdal effect in isolated atoms

- Bound, initial state of the electron: $| n , l >$

  n: Principal quantum number, l: Orbital quantum number

- Positive energy final state in a continuum: $| p_e , l' >$

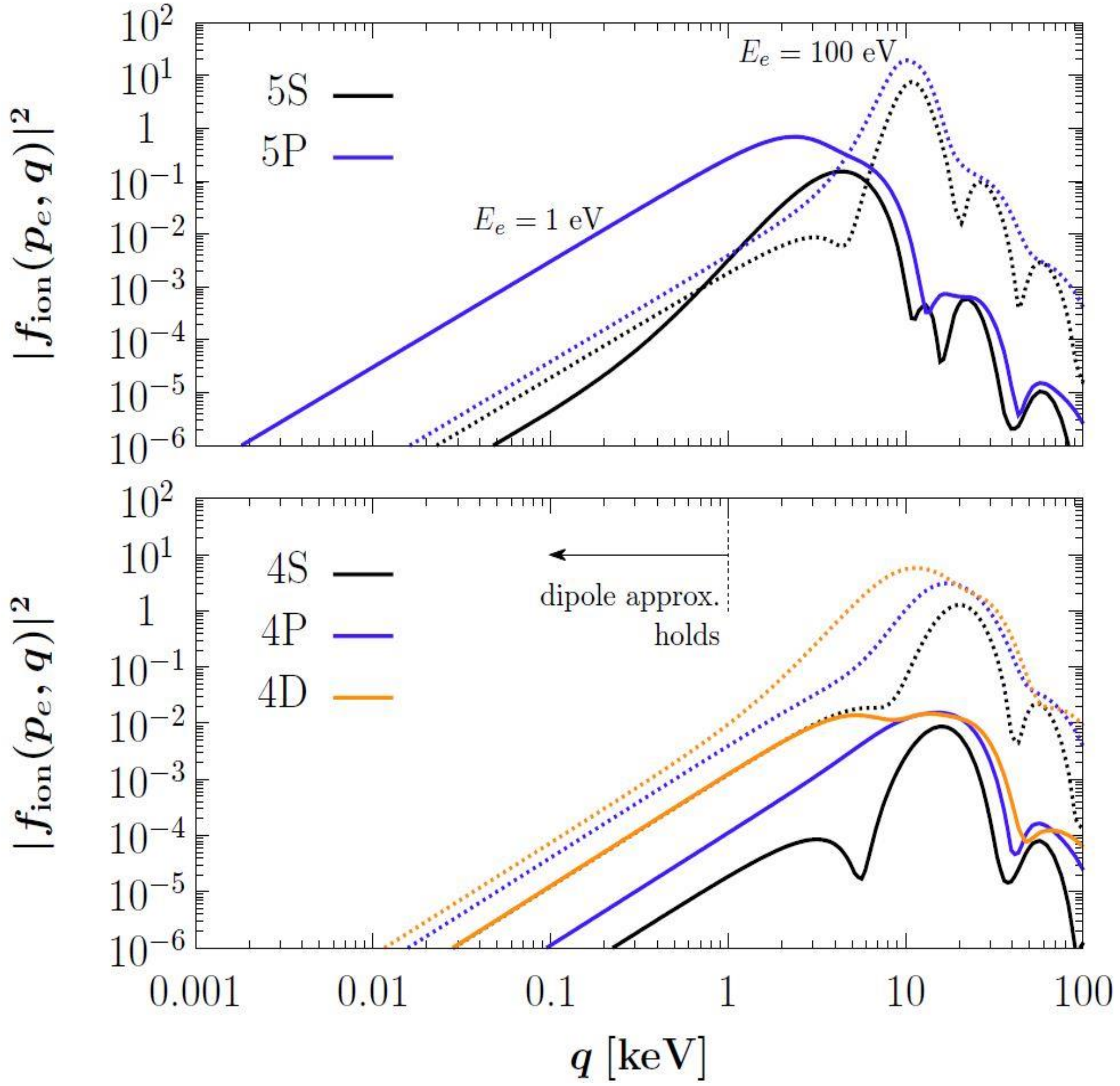
  p_e : Final momentum, l': Final angular momentum, E_e: Final energy

$$\left|< p_e , l' \middle| e^{i\boldsymbol{q_e}.\boldsymbol{x}} \middle| n , l >\right|^2 = \frac{1}{2\pi} \frac{dp_{nl \to p_e l'}}{dE_e}$$

$$\frac{dp_{nl \to p_e l'}}{d \ln E_e} = \frac{\pi}{2} |f_{nl}^{\text{ion}} (p_e , q_e)|^2$$

Ionization form factor

The Ionization Form Factor



- The ionization form factor is defined in the DM-electron scattering literature
- For a direct DM-electron scatter, the form factor is evaluated at $\boldsymbol{q}$, the momentum lost by the dark matter particle
- For Migdal effect, the form factor is evaluated at a suppressed momentum $\boldsymbol{q_e} \sim \left(\frac{\boldsymbol{m_e}}{\boldsymbol{m_N}}\right) \boldsymbol{q}$

Cross sections

$$\frac{d\sigma_{n,l}}{dE_R dE_e} \simeq \frac{d\sigma}{dE_R} \times \frac{1}{2\pi} \frac{dp_{n,l\rightarrow E_e}}{dE_e}$$

DM-Nucleus
cross section

Ionization
probability

$$\frac{d\langle\sigma_{n,l}v\rangle}{d\ln E_e} = \frac{\bar{\sigma}_n}{8\mu_n^2}[f_p Z + f_n(A-Z)]^2 \int dq\ \Big[q|F_N(q)|^2 \times |F_{\rm DM}(q)|^2 |f_{nl}^{\rm ion}(p_e, q_e)|^2 \eta(v_{\rm min}(q, \Delta E_{n,l}))\Big]$$

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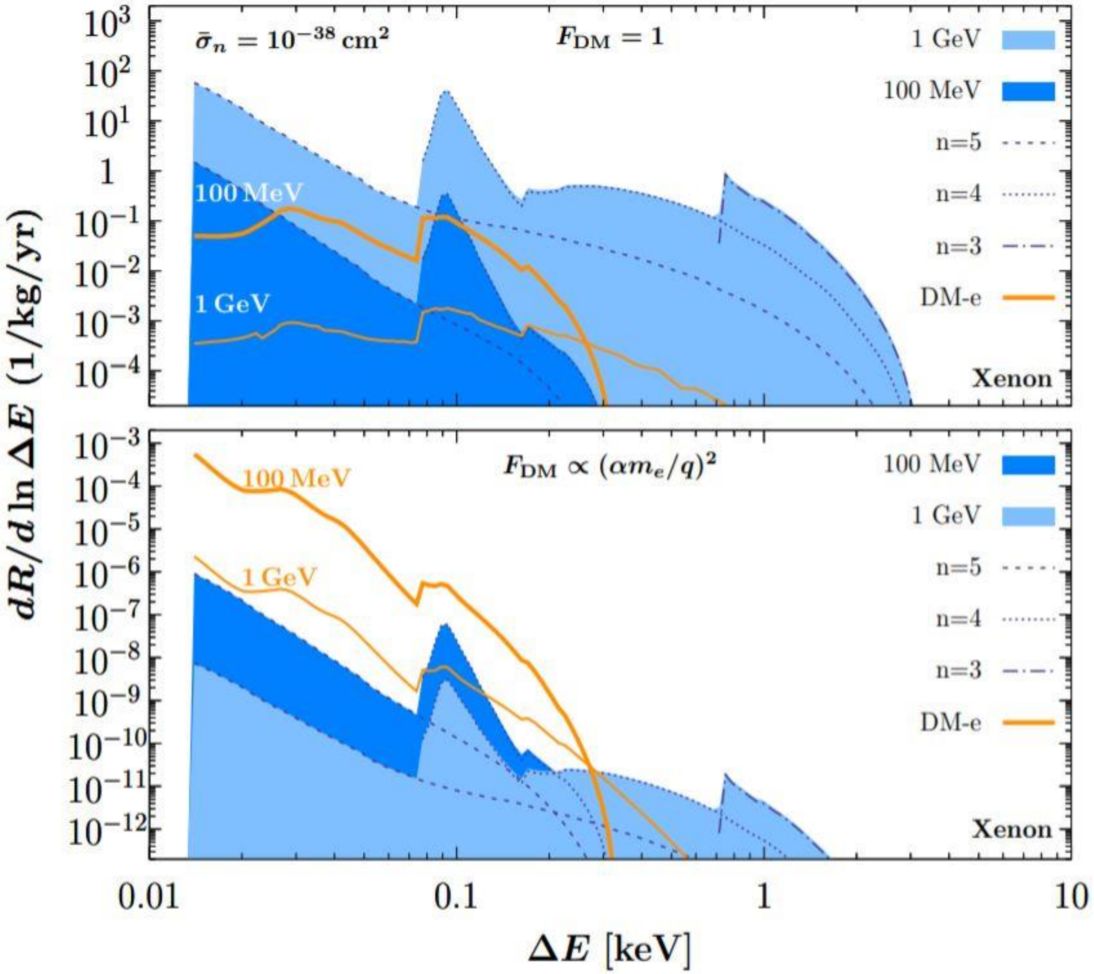
Compare with
DM-electron !

$$\boxed{\frac{d\langle\sigma_{n,l}^{\mathrm{DM-e}}v\rangle}{d\ln E_e} = \frac{\bar{\sigma}_e}{8\mu_e^2} \int dq\ \left[q|F_{\mathrm{DM}}(q)|^2 |f_{nl}^{\mathrm{ion}}(p_e, q)|^2 \times \eta(v_{\min}(q, \Delta E_{n,l}))\right]}$$

Comparison between Migdal and DM-electron scattering



- Any direct comparison is model-dependent (Dark photon model assumed here)
- For heavy dark photon, DM-electron dominates for low masses (< ~100 MeV) and Migdal dominates for heavier masses
- For ultralight dark photon, DM-electron dominates for all masses

Extension to semiconductors

- Analogous to the isolated atoms case, we have a crystal form factor in the case of semiconductors

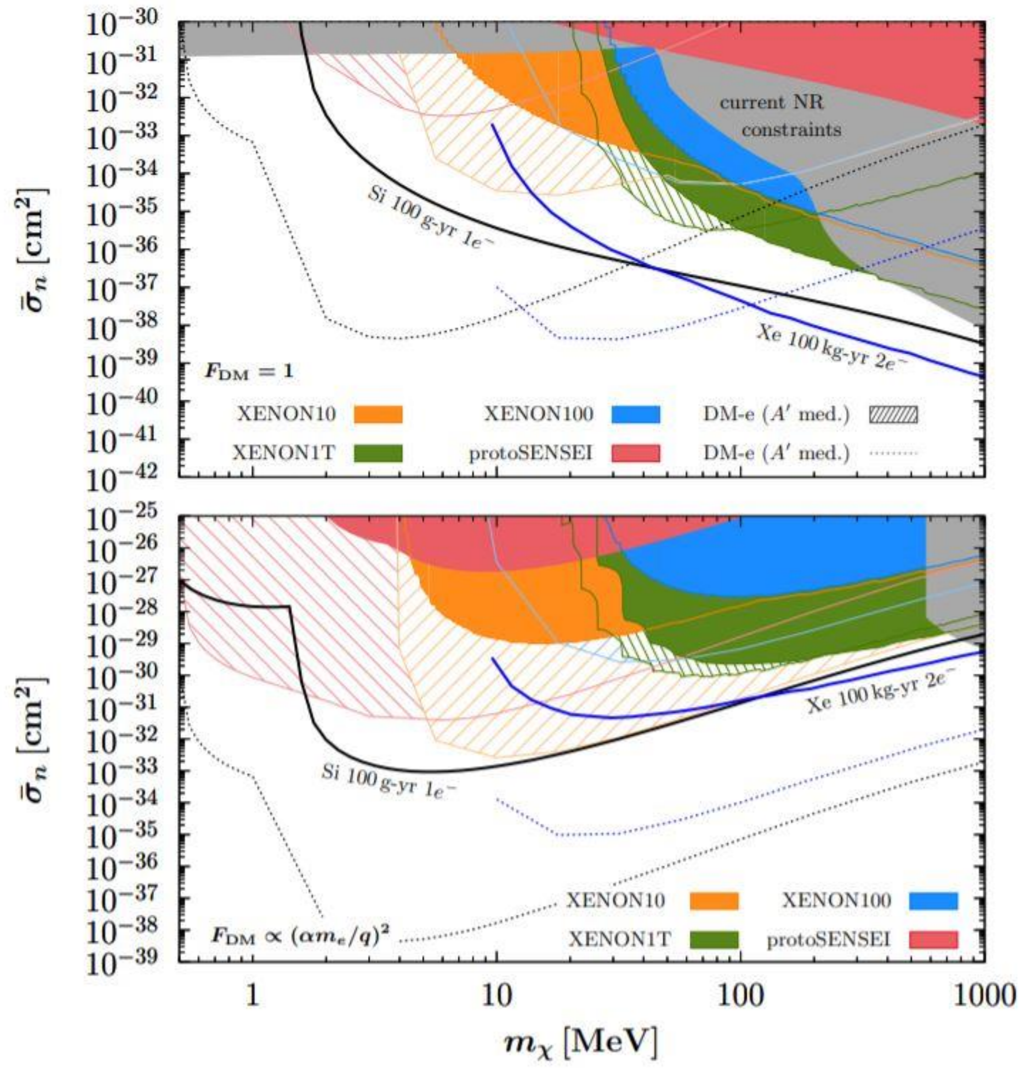
$|f_{\text{crystal}}(p_e\,, q)|^2$ → $|f_{\text{crystal}}(p_e\,, q_e)|^2$

DM-electron

Migdal

Evaluate the form factor at the suppressed momentum scale

Constraints and projections



- Constraints from XENON10, XENON100, XENON1T and protoSENSEI data
- Projections for SENSEI (Si), LBECA (Xe)
- Comparison shows that the Migdal dominates DM-electron scattering for high masses in the case of contact interactions

Summary and outlook

- The Migdal effect allows the noble liquid and semiconductor experiments to extend the sensitivity of DM-nuclear interactions into MeV mass region
- The theoretical description of Migdal effect is tied very closely to that of DM-electron scattering
- For dark photon model, Migdal effect dominates DM-electron scattering for higher masses in the case of contact interactions
- **Future work:** A more solid formulation of the Migdal effect in semiconductors and limits from various other experiments.