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 !

$$E_{\mathrm{NR}}^{\max} \sim 2 \text{ eV} \left(\frac{m_\chi}{100 \text{ MeV}}\right)^2 \left(\frac{10 \text{ GeV}}{m_{\mathrm{N}}}\right)$$

- 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 $\left|i\right\rangle$ to electronic state $\left|f\right\rangle$ is proportional to,

$$\left|\left\langle i|e^{i\mathbf{q}.\mathbf{x}}|f\right\rangle\right|^2$$

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

DM-nucleus recoil with a Migdal electron

- Can probe DM-nucleon interactions for sub-GeV Dark Matter

- All the energy of the incoming DM particle can in principle be converted to electron ionization.

- The transition probability from electronic state $\left|i\right\rangle$ to electronic state $\left|f\right\rangle$ is proportional to,

$$\left|\left\langle i\right|e^{i\mathbf{q_e}\cdot\mathbf{x}}\left|f\right\rangle\right|^2$$

where $\mathbf{q_e} \sim \left(\frac{m_e}{m_{\mathrm{N}}}\right)\mathbf{q}$, $\mathbf{q}$ being the momentum lost by dark matter.

Migdal effect in isolated atoms

- Bound, initial state of the electron: $\left|n, l\right\rangle$
  n: Principal quantum number, *l:* Orbital quantum number

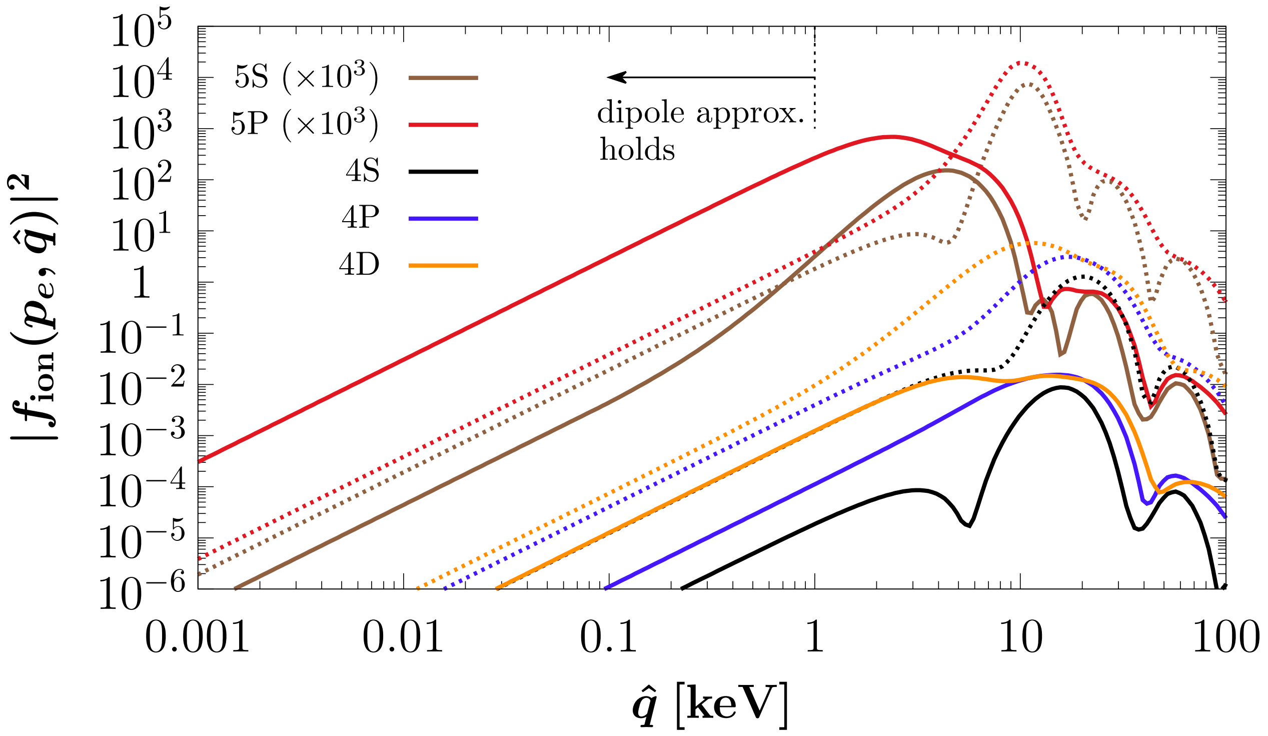
- Positive energy final state in a continuum: $\left|p_e, l'\right\rangle$
  p_e : Final momentum, l': Final angular momentum, E_e: Final energy

$$\left|\left\langle p_e, l'\right|e^{i\mathbf{q_e}\cdot\mathbf{x}}\left|n, l\right\rangle\right|^2 = \frac{1}{2\pi}\frac{dp_{nl\to p_e l'}}{dE_e}$$

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

→ 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 $\mathbf{q}$, the momentum lost by the dark matter particle
- For Migdal effect, the form factor is evaluated at a suppressed momentum $\mathbf{q_e} \sim \left(\frac{m_e}{m_N}\right)\mathbf{q}$

Cross sections

$$\frac{d\sigma_{n,l}}{dE_{\mathrm{R}}dE_e} \sim \frac{d\sigma}{dE_{\mathrm{R}}} \times \frac{1}{2\pi}\frac{dp_{n,l\to E_e}}{dE_e}$$

DM-Nucleus cross section

Ionization probability

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

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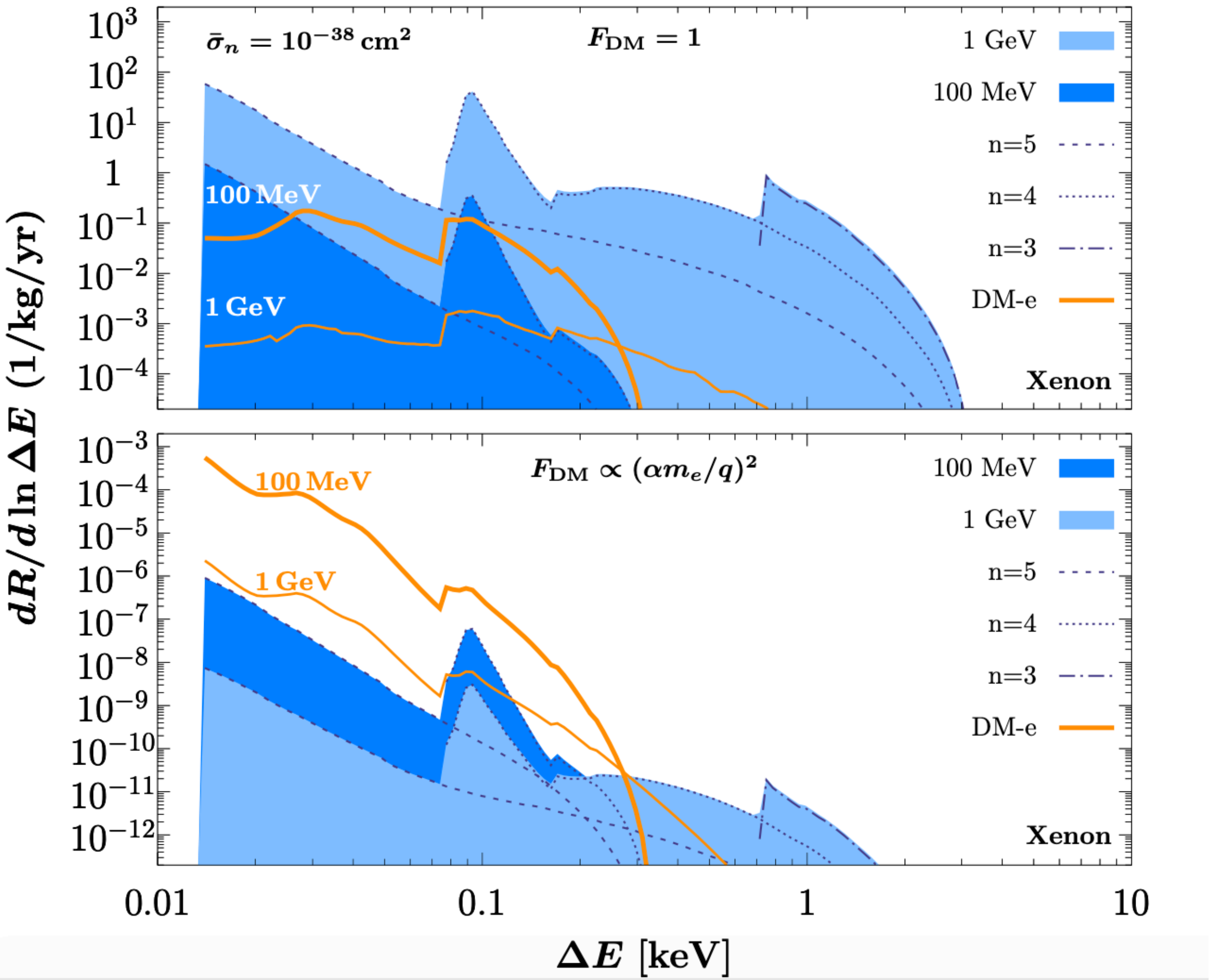
Compare with DM-electron !

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

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

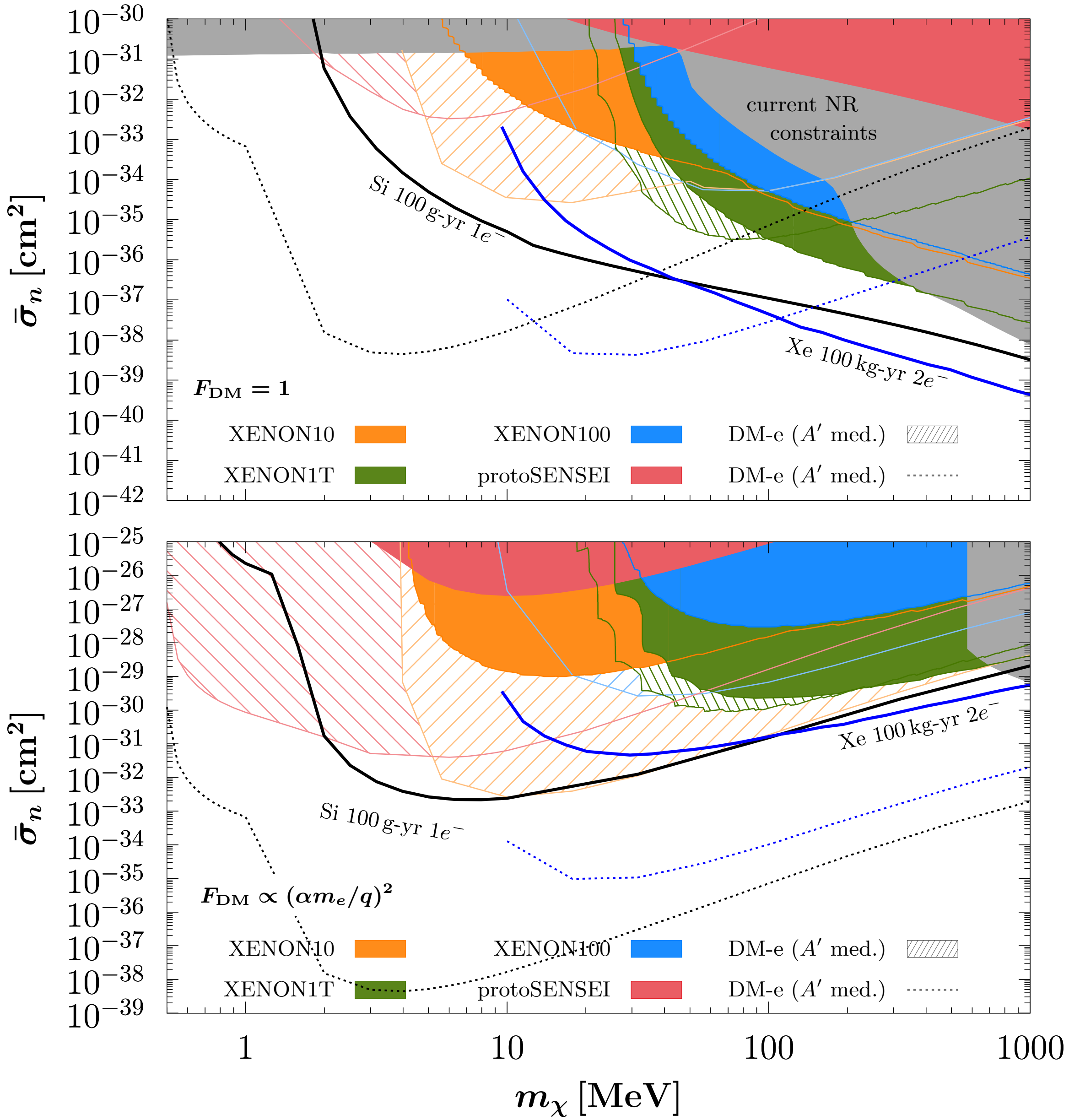
$$\left|f_{\mathrm{crystal}}(p_e, q)\right|^2 \longrightarrow \left|f_{\mathrm{crystal}}(p_e, q_e)\right|^2$$

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.