Dark Photon Mediator模型でのMigdal効果とElectron Scatteringの比較

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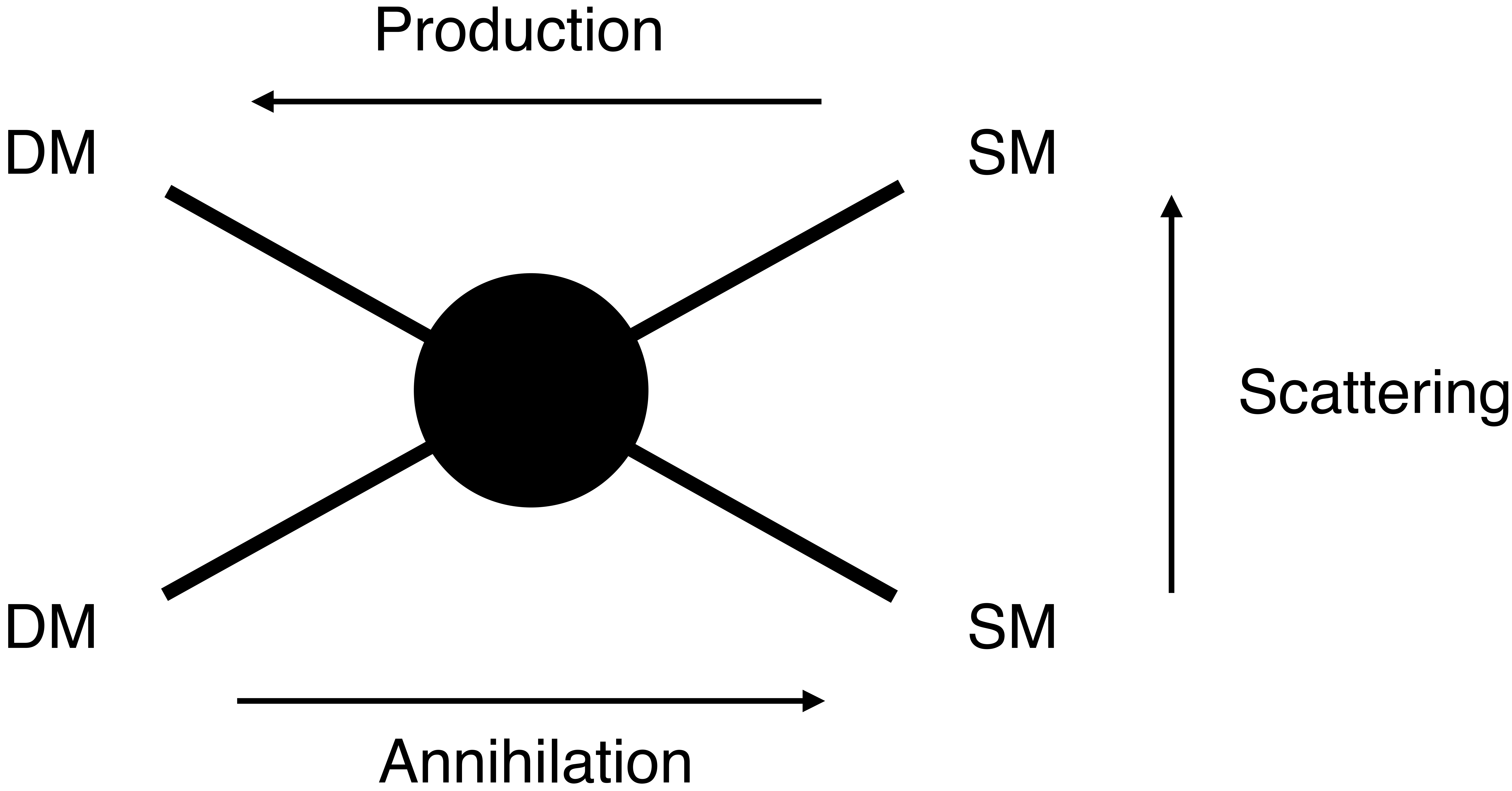
D. Baxter, Y. Kahn, G. Krnjaic, PRD 101, 076014 (2020)

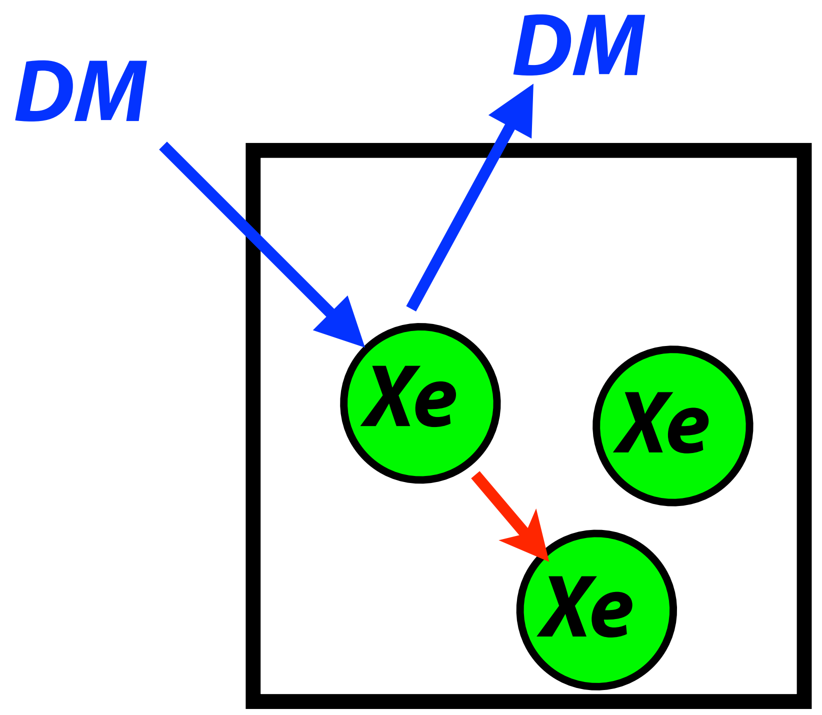
ミグダル観測検討会２０２０　DAY2　12/9

暗黒物質の反応



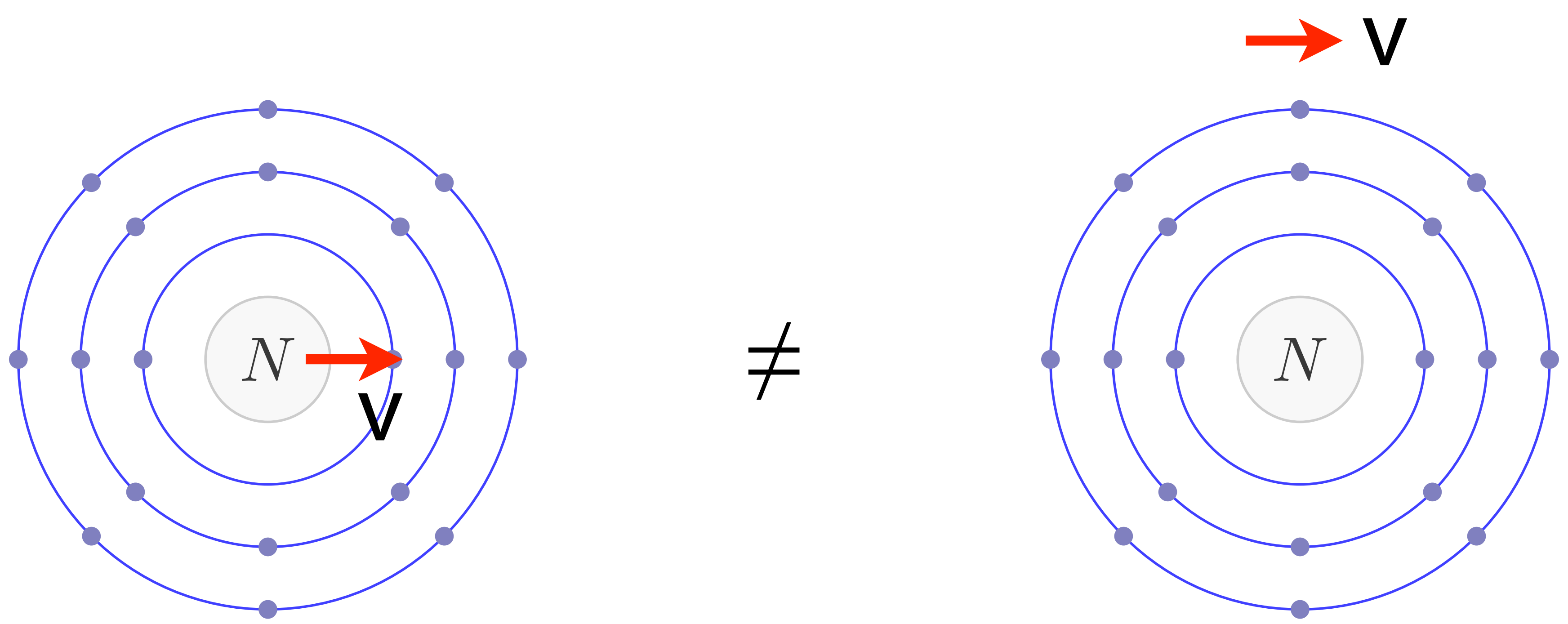
✓ *What is missing in the conventional analysis?*

DAY1での伊部さんのスライド



In conventional analysis, the ***recoiled nucleus*** is treated as a ***recoiled neutral atom***.

✓ In reality, it takes some time for the electrons to catch up…



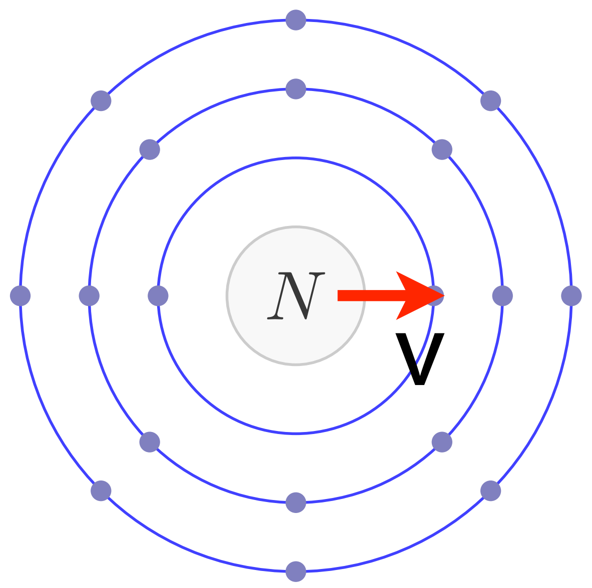
✓ The process to catch up causes electron excitations/ionizations!

→ ***Migdal Effect ! [1939, Migdal]***

['05 Vergados&Ejiri, '07 Bernabei et al. Application to DM detection]

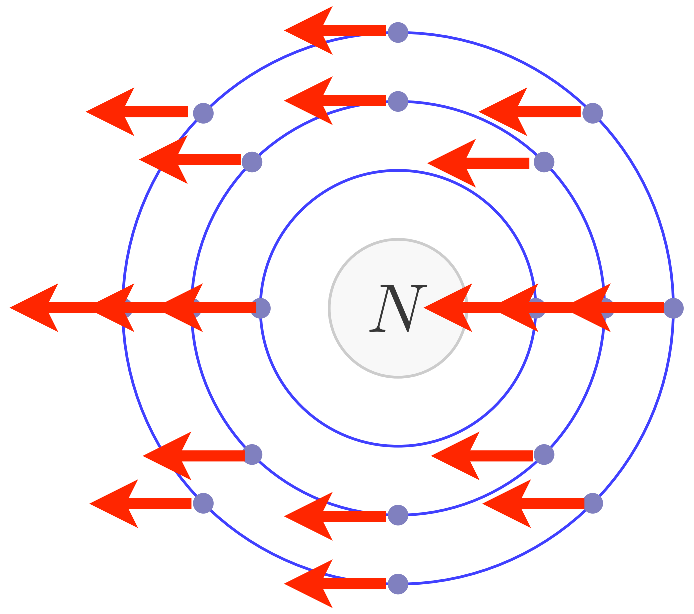
✔ *Migdal's approach*

DAY1での伊部さんのスライド



Just after the nuclear recoil, we assume only the nucleus is moving while the electron cloud is left behind.

(The electron clouds are no more in the energy eigenstates.)

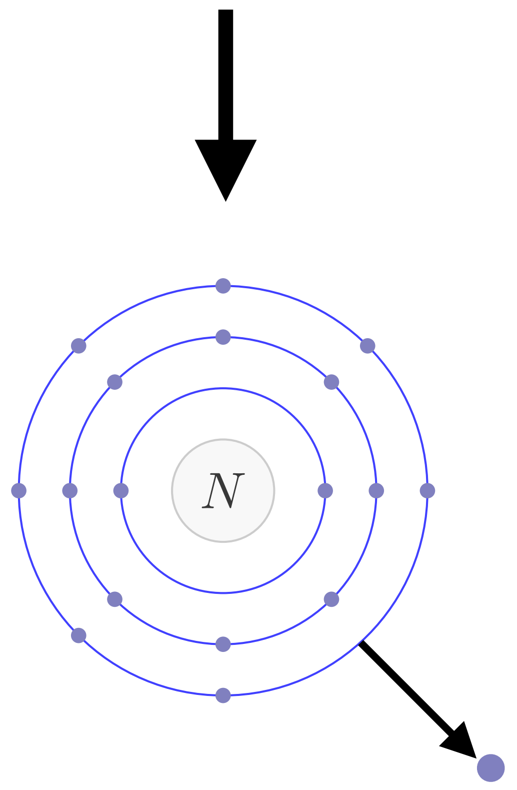


Take the rest frame of the nucleus by the Galilei transformation.

In this frame, the wave function of the electron cloud looks like :

$$|\Phi'_{ec}\rangle = e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle$$

Electron wave function in the initial state e.g. the ground state.



The probability of the excitation/ionization is given by

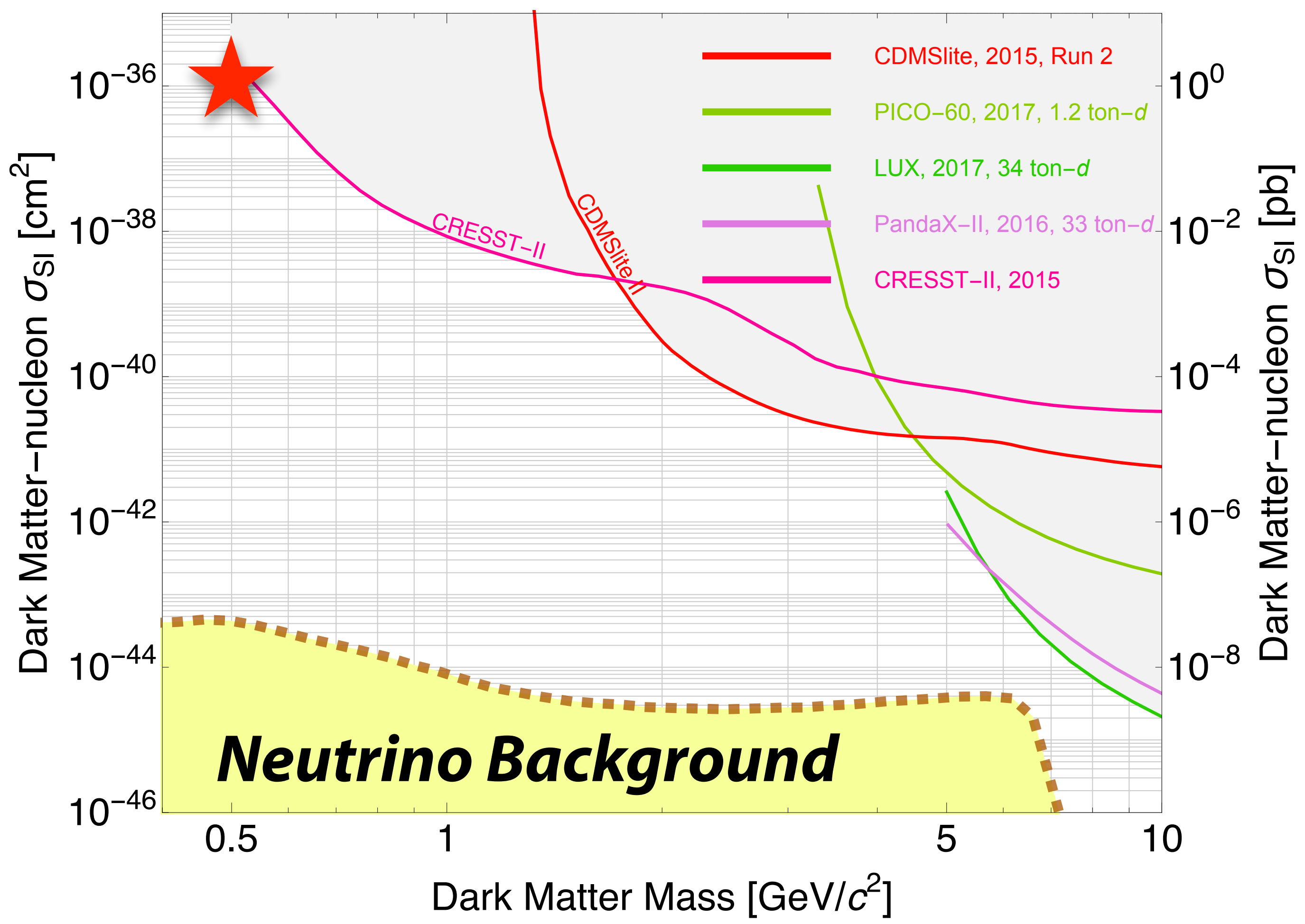
$$\mathcal{P} = |\langle\Phi^F_{ec}|\Phi'_{ec}\rangle|^2 = |\langle\Phi^F_{ec}|e^{-im_e \sum_i \mathbf{v}\cdot\hat{\mathbf{x}}_i}|\Phi_{ec}\rangle|^2$$

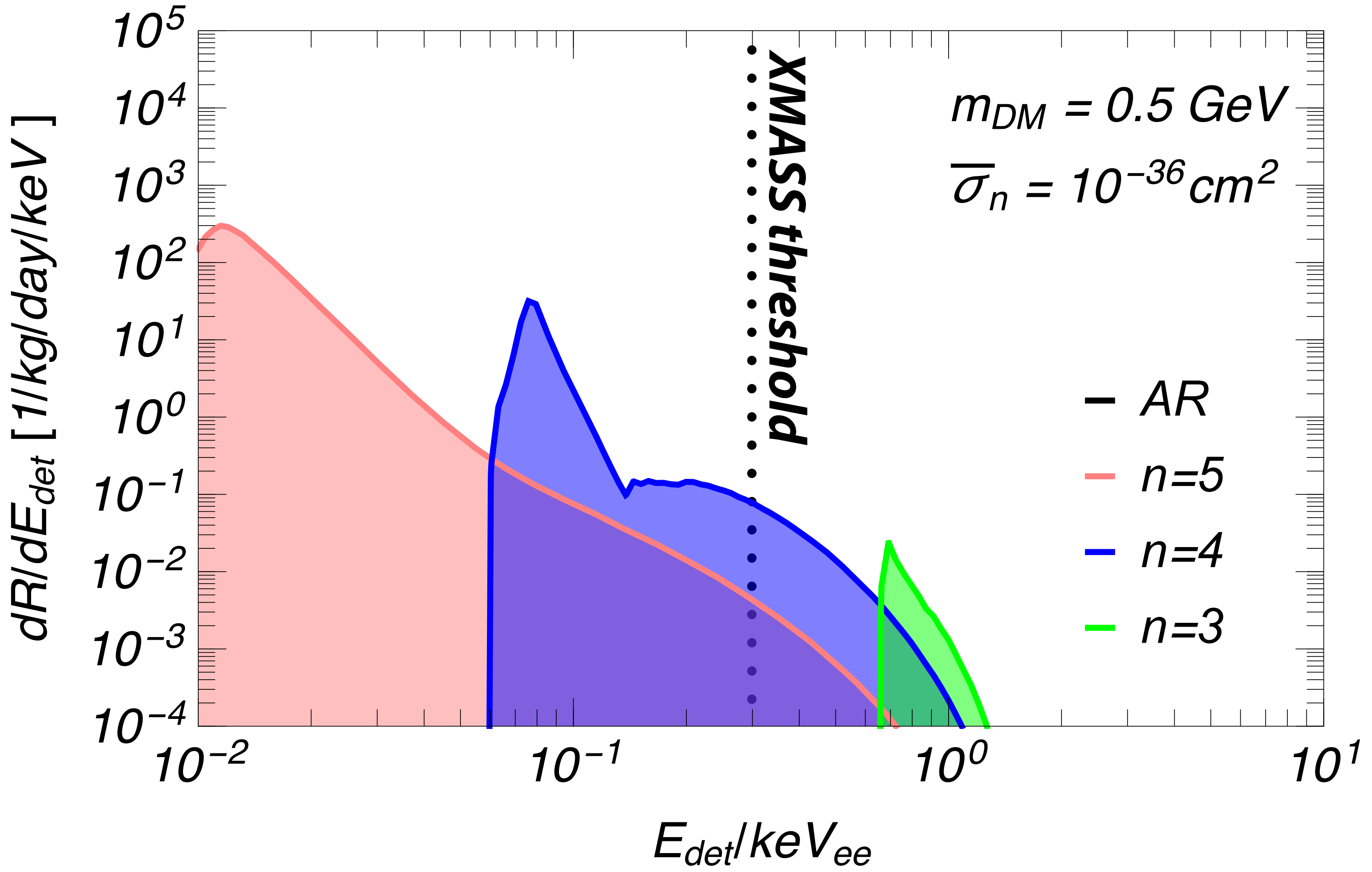
✔ *Implication on Dark Matter Direct Detection Experiments*

DAY1での伊部さんのスライド

✔ *Migdal Effect single-phase Liquid Xe detectors*

WIMP Limit Plotter





$$\frac{dR}{dE_{\rm det}} \simeq \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/o\ Migdal} + \left.\frac{dR}{dE_{\rm det}}\right|_{\rm w/\ Migdal}$$

$E_{det} = (0.1\text{-}0.2)\, E_R + E_{EM}$ $\quad E_{EM} = E_e + E_{dex} \sim E_e - E_n$

[Single phase Experiment ＝only scintillation energy : Only ***10-20 %*** of E_R is measured]

A few hundred events with E_{det} = O(1)keV are expected for 10^5 kg days !

The atom recoil energy is much lower than threshold $E_R < M_{DM}^2 / M_A \times v_{DM}^2 = O(1)$eV

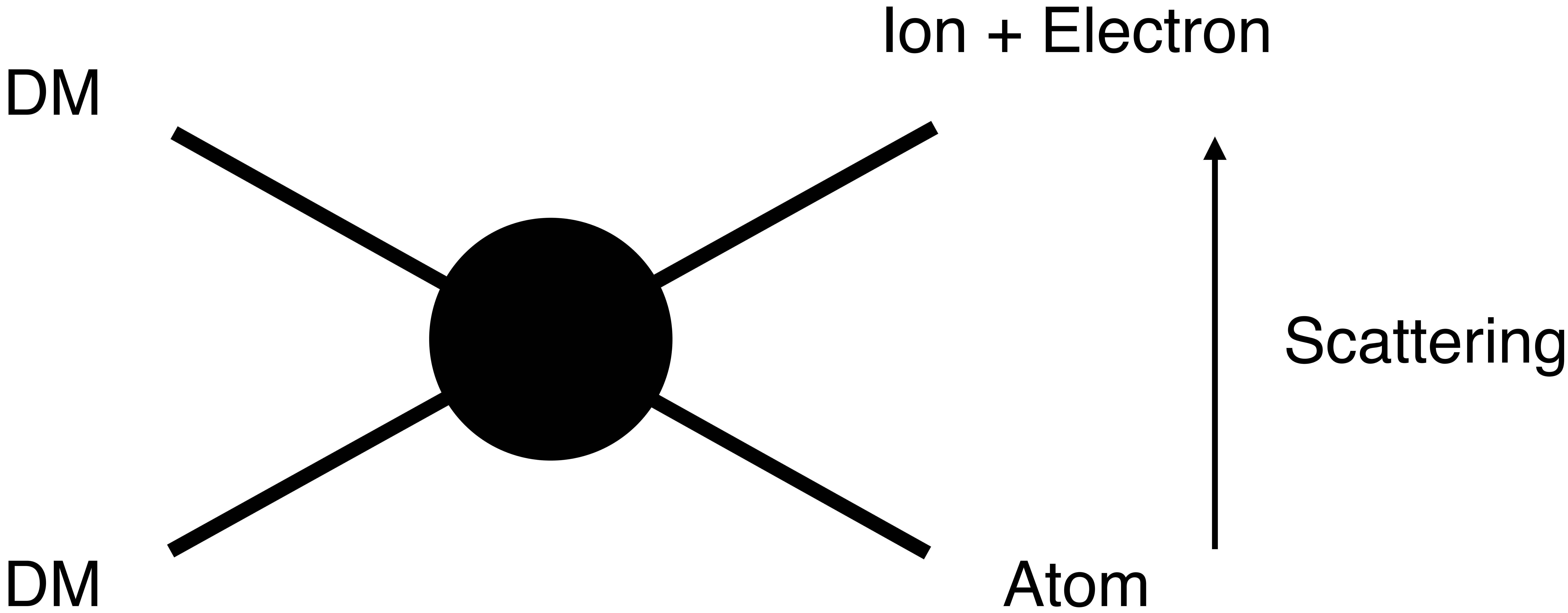
DMによる電子のイオン化

・Dark photonのような模型を考えた場合

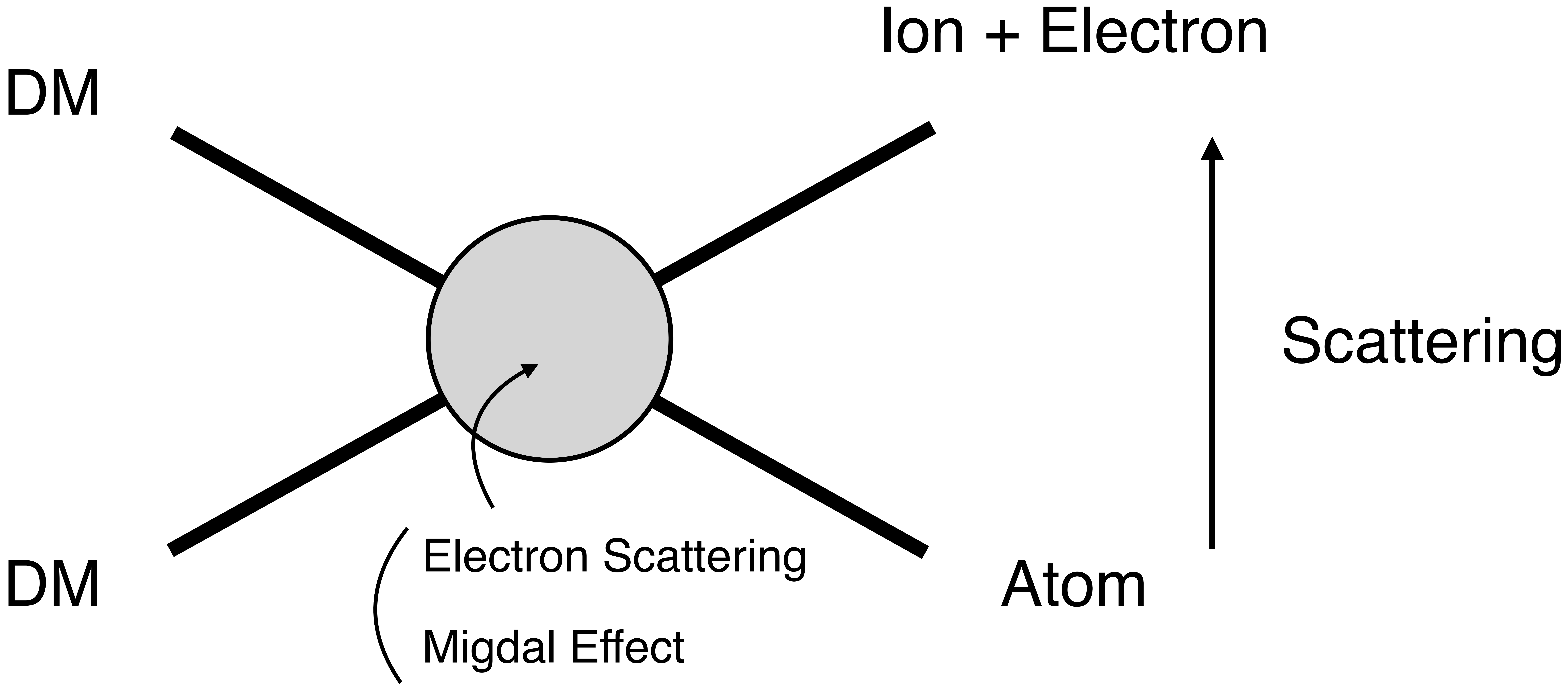
① DMと電子の相互作用による電子のイオン化

② DMと原子核の相互作用による電子のイオン化（Migdal効果）

DMによる電子のイオン化



DMによる電子のイオン化



Topics

・Dark Photon模型

・電子のイオン化率の比較

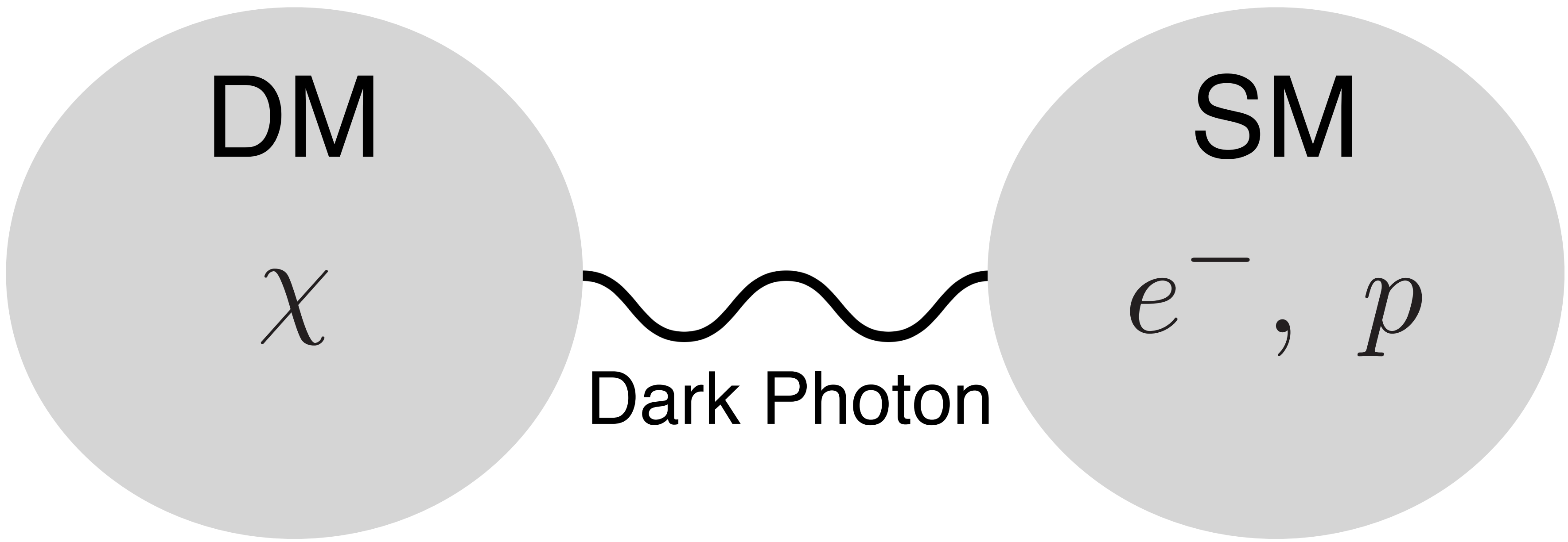
・XENONデータによる制限

・結論

Dark Photon模型

・benchmark modelとしてdark photonを考える

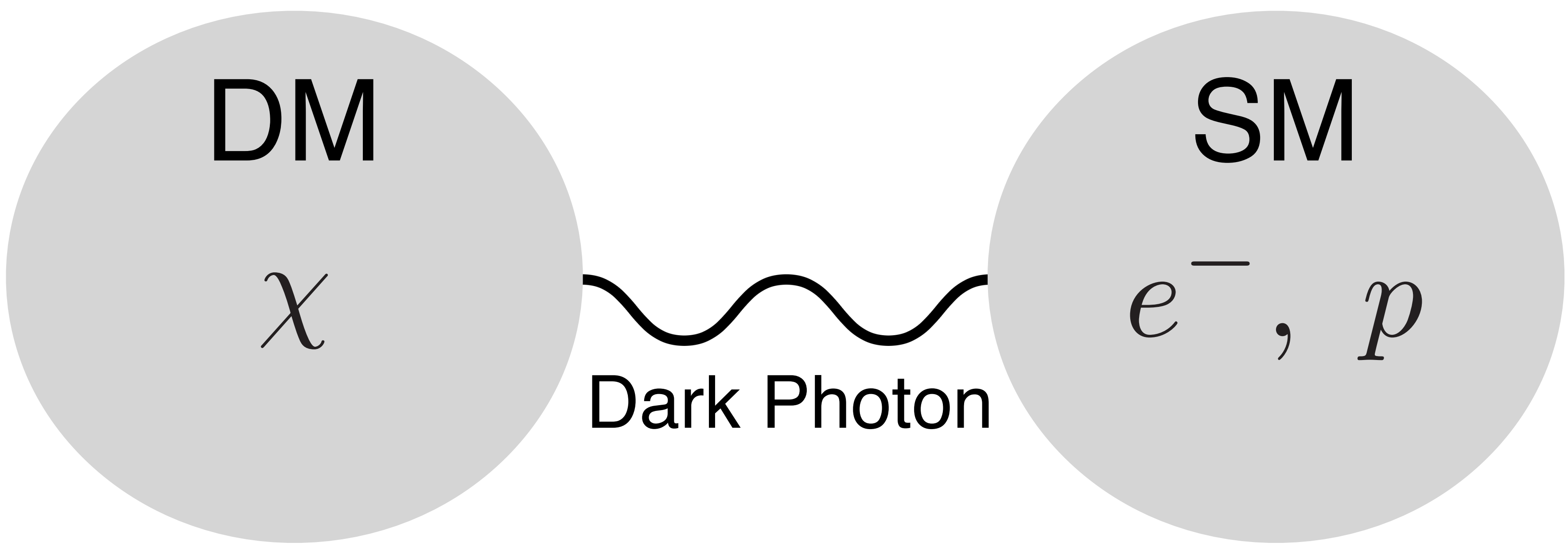
$$A'_\mu \left(g_D J^\mu_D + \epsilon e J^\mu_{\rm EM} \right)$$



Dark Photon模型

・benchmark modelとしてdark photonを考える

$$A'_\mu \left(g_D J^\mu_D + \epsilon e J^\mu_{\mathrm{EM}} \right)$$



・fiducial DM scattering cross section for target T

$$\overline{\sigma}_T = \frac{16\pi\epsilon^2\alpha\alpha_D\mu^2_{\chi T}}{(m^2_{A'} + |\mathbf{q}_0|^2)^2} \quad \Rightarrow \quad \frac{\overline{\sigma}_e}{\mu^2_{\chi e}} = \frac{\overline{\sigma}_p}{\mu^2_{\chi p}}$$

電子のイオン化率の計算

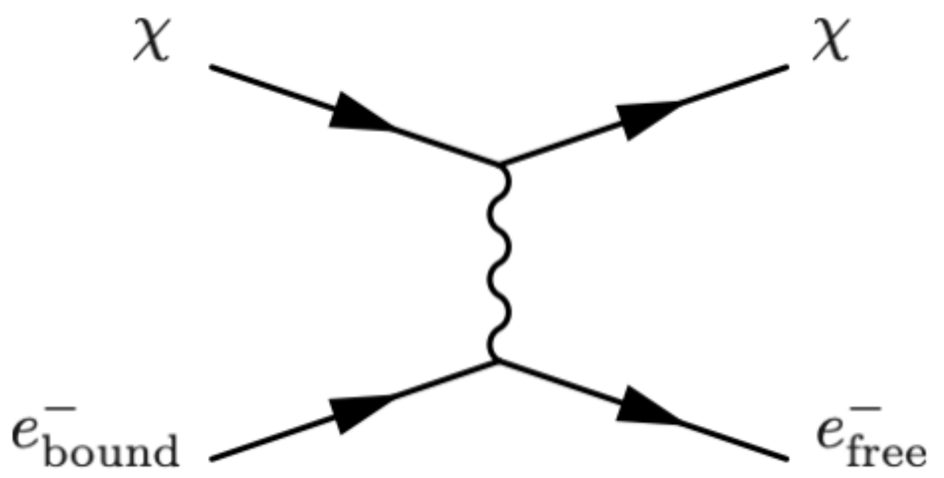
- $\chi + X \to \chi + X^+ + e^-$ を計算したい（isolated atomを仮定）

- Event rateはDM速度分布を使って表される

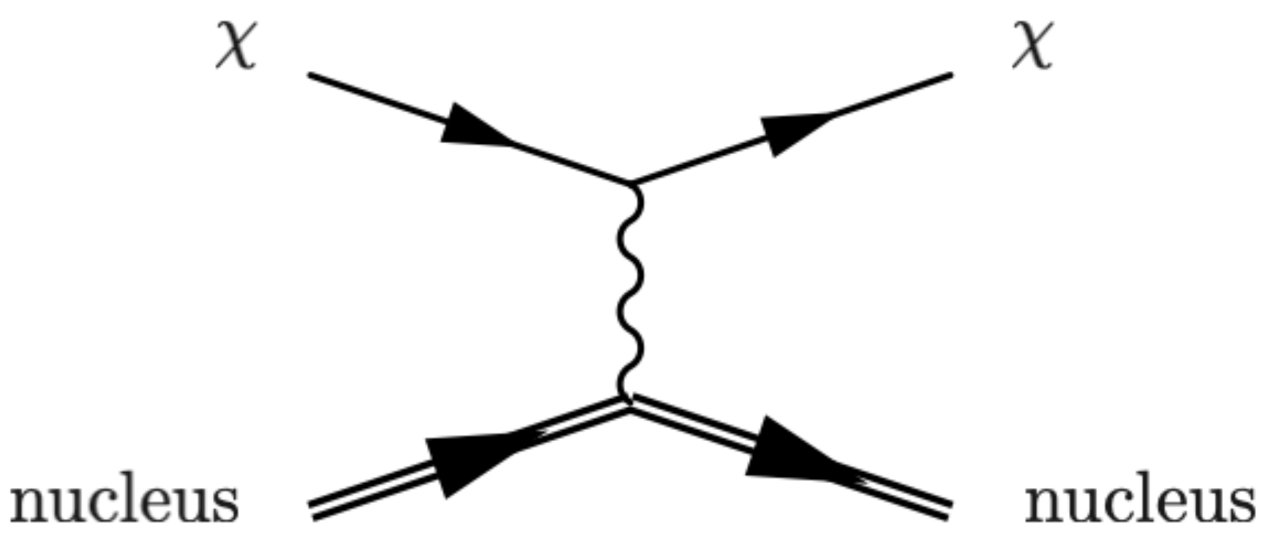
$$R_{i\to f} = \frac{\rho_\chi}{m_\chi}\int d^3v\, f(v)\, \underbrace{\sigma v_{i\to f}}_{\text{Targetに依存}}$$

電子のイオン化率の計算

・各散乱振幅はは次のように表される



$$|\mathcal{M}_{\chi e}(q)|^2 = \frac{16\pi m_\chi^2 m_e^2 \overline{\sigma}_e}{\mu_{\chi e}^2}|F_{DM}(q)|^2$$



$$|\mathcal{M}_{\chi N}(q)|^2 = \underline{Z^2}\frac{16\pi m_\chi^2 m_N^2 \overline{\sigma}_p}{\mu_{\chi N}^2}\underline{|F_N(q)|^2}|F_{DM}(q)|^2$$

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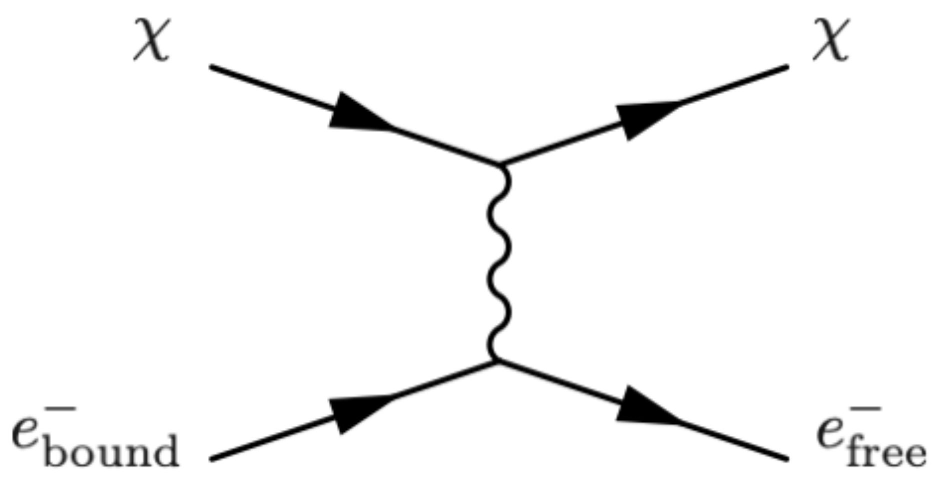

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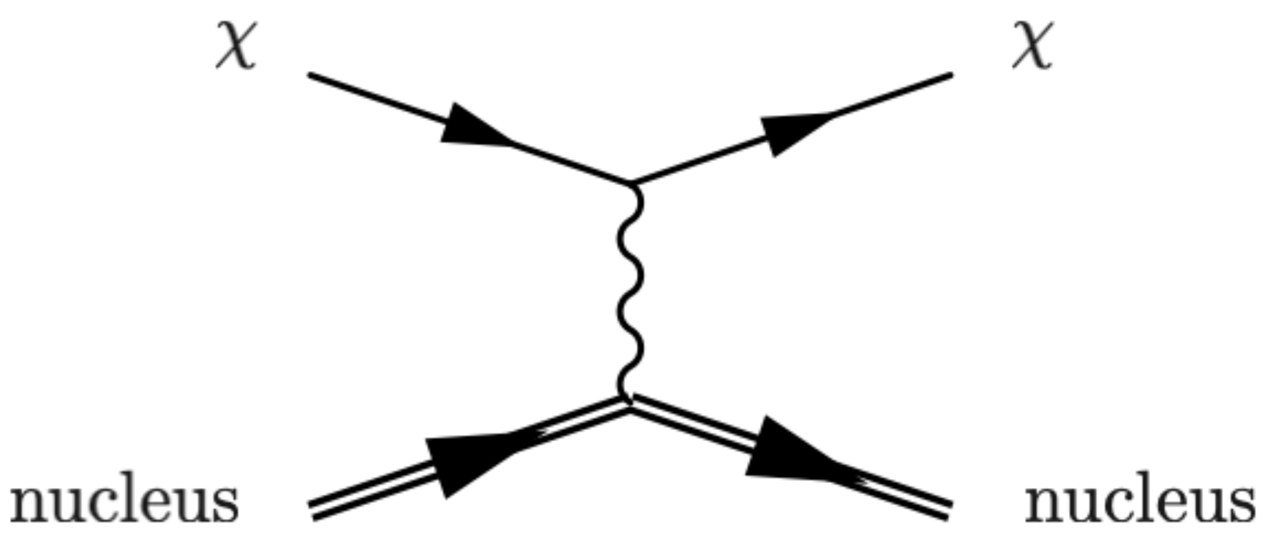
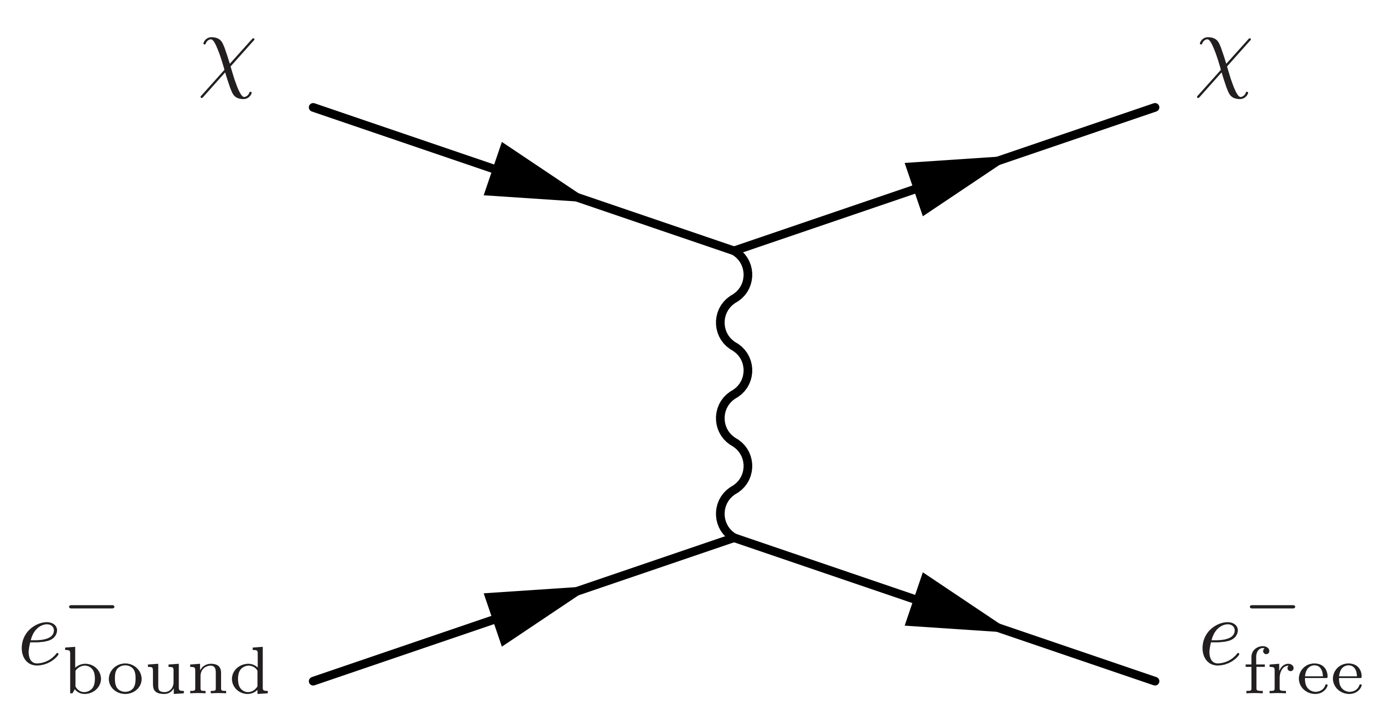


$$|\mathcal{M}_{\chi N}(q)|^2 = \underline{Z^2}\,\frac{16\pi m_\chi^2 m_N^2 \overline{\sigma}_p}{\mu_{\chi N}^2}\underline{|F_N(q)|^2}|F_{DM}(q)|^2$$

$$\frac{\overline{\sigma}_e}{\mu_{\chi e}^2} = \frac{\overline{\sigma}_p}{\mu_{\chi p}^2} \quad \Rightarrow \quad \frac{|\mathcal{M}_{\chi N}(q)|^2}{m_N^2} = Z^2|F_N(q)|^2\frac{|\mathcal{M}_{\chi e}(q)|^2}{m_e^2}$$

電子散乱の場合



- Event rateには遷移電子の行列要素が現れる

$$T_{fi} \approx \underbrace{i\mathcal{M}(q)}_{\text{scattering}}\underbrace{\langle\psi_f|e^{i\mathbf{q}\cdot\mathbf{x}}|\psi_i\rangle}_{\text{ionization}}(2\pi)^4\delta^4(p_f - p_i)$$

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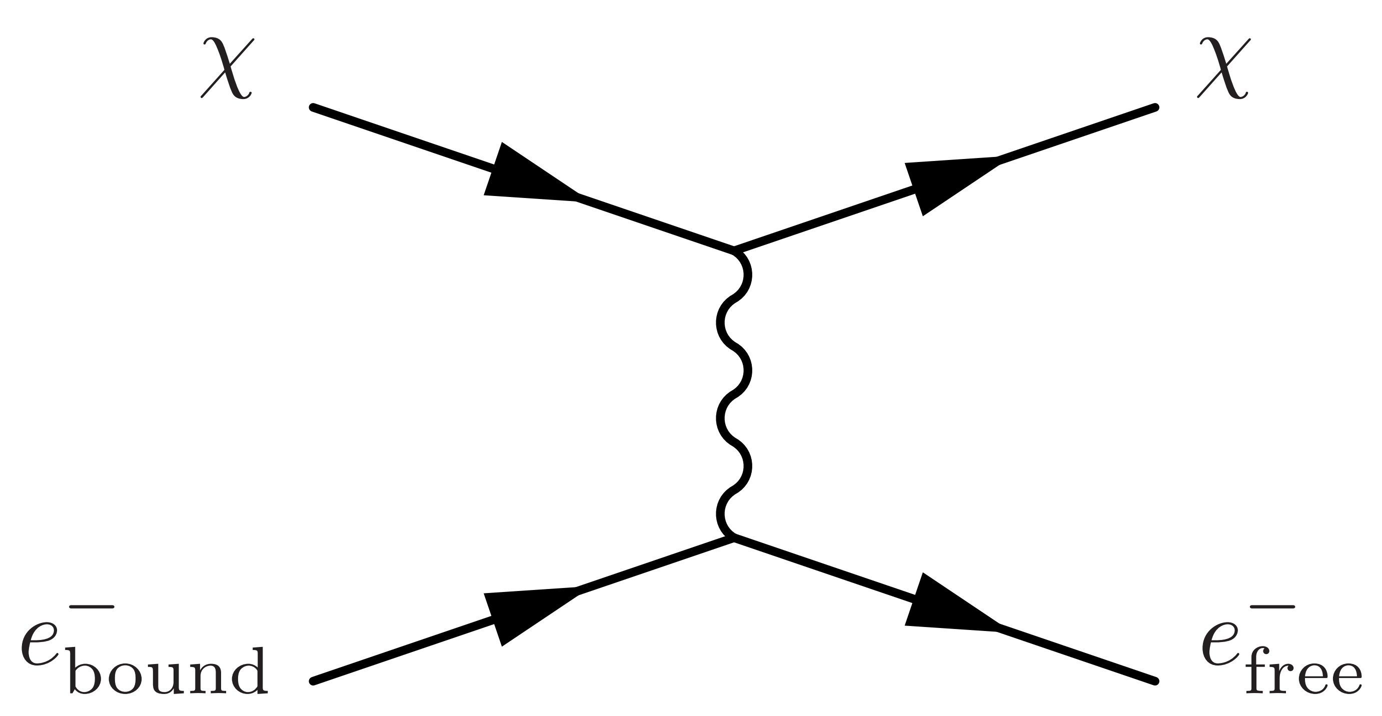

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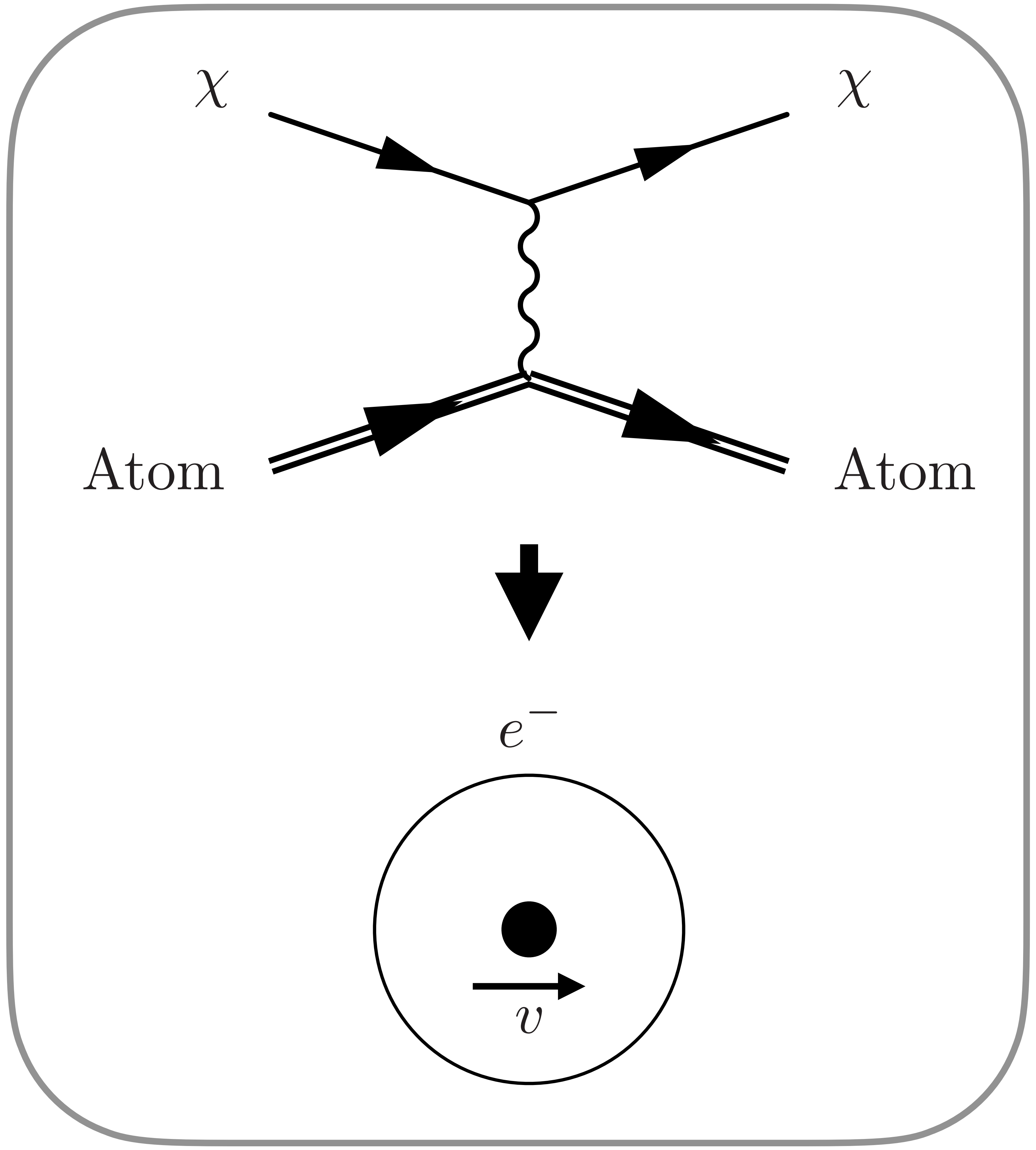
$$\Rightarrow \quad R_e \propto |\langle \psi_f | e^{i\mathbf{q}\cdot\mathbf{x}} | \psi_i \rangle|^2$$

- large q で振動によるsuppressionがある

Migdal散乱の場合

・Event rateは

$$T_{fi} \approx \underbrace{i\mathcal{M}(q)}_{\text{scattering}} \underbrace{\langle\psi_f|e^{i\mathbf{q}_e\cdot\mathbf{x}}|\psi_i\rangle}_{\text{Migdal}} (2\pi)^4\delta^4(p_f - p_i)$$



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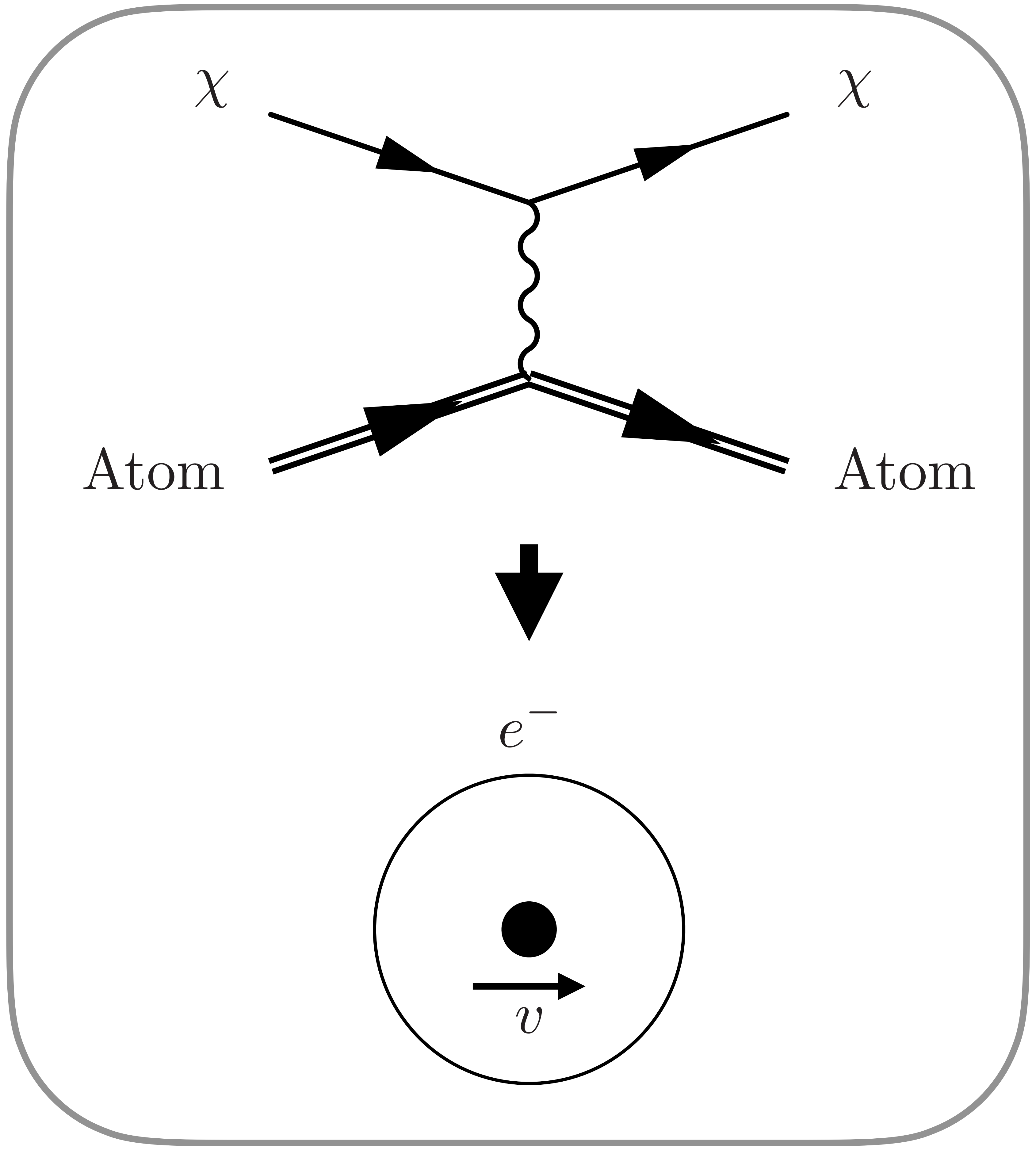
$$\Rightarrow \quad R_M \propto |\langle \Psi_{\mathbf{v}_A} | \Psi_i \rangle|^2 \sim |\langle \psi_f | e^{i\mathbf{q}_e \cdot \mathbf{x}} | \psi_i \rangle|^2$$



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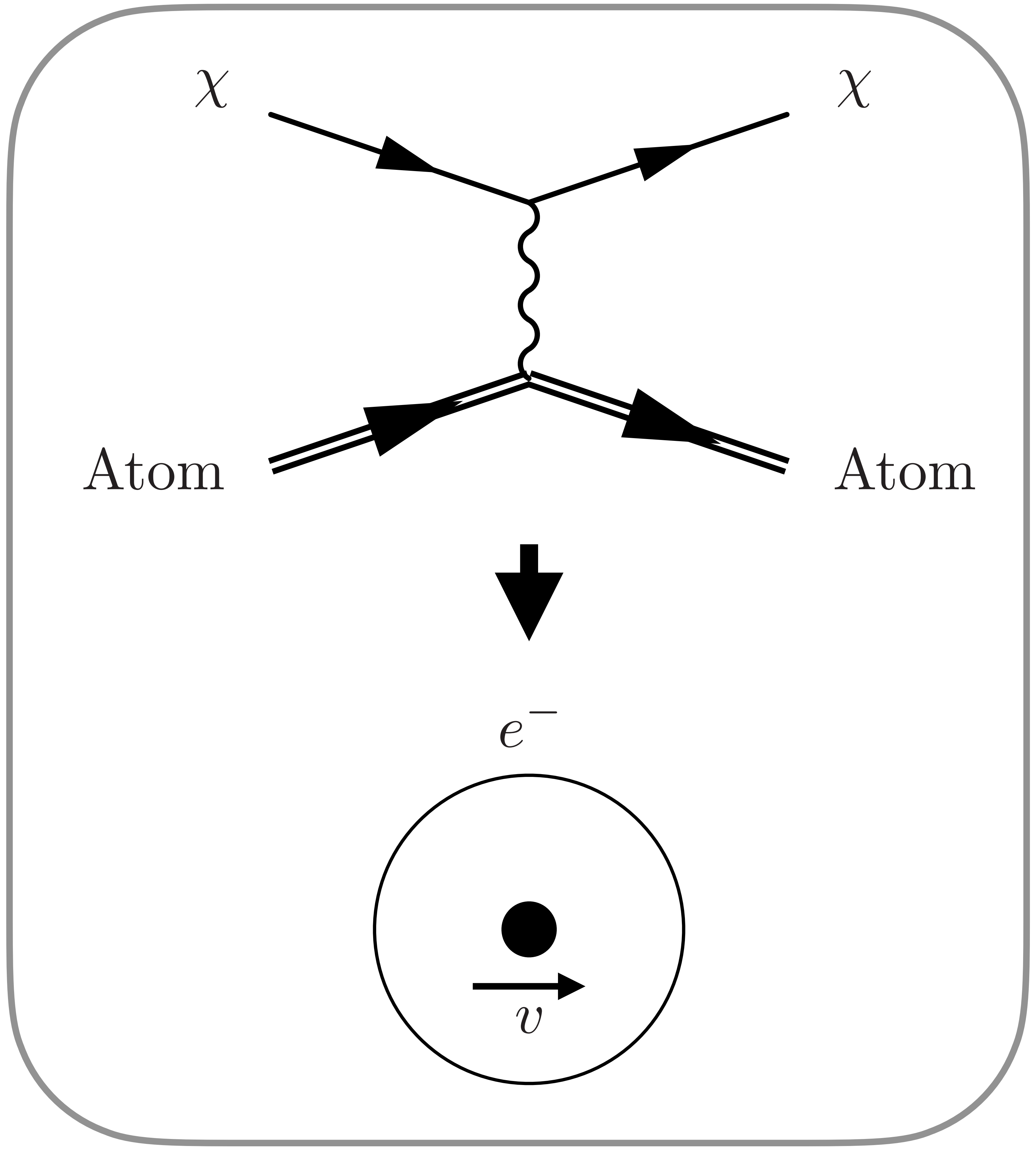
$$\Rightarrow \quad R_M \propto |\langle\Psi_{\mathbf{v}_A}|\Psi_i\rangle|^2 \sim |\langle\psi_f|e^{i\mathbf{q}_e\cdot\mathbf{x}}|\psi_i\rangle|^2$$

$$\mathbf{q}_e = \underbrace{\frac{m_e}{m_N}}_{\sim 10^{-3}}\mathbf{q}$$

$$\Rightarrow \quad R_M \propto |\langle\psi_f|\mathbf{q}_e\cdot\mathbf{x}|\psi_i\rangle|^2$$



２つの過程の比較

・比較すると

$$\left(\begin{array}{l} T^e_{fi} \approx i\mathcal{M}_{\chi e}(q)\langle\psi_f|e^{i\mathbf{q}\cdot\mathbf{x}}|\psi_i\rangle(2\pi)^4\delta^4(p_f - p_i) \\ \\ T^M_{fi} \approx i\mathcal{M}_{\chi N}(q)\langle\psi_f|e^{i\underline{\mathbf{q}_e}\cdot\mathbf{x}}|\psi_i\rangle(2\pi)^4\delta^4(p_f - p_i) \end{array}\right.$$

$$\mathbf{q}_e = \frac{m_e}{m_N}\mathbf{q}$$

$$\frac{|\mathcal{M}_{\chi N}(q)|^2}{m_N^2} = \underline{Z^2|F_N(q)|^2}\frac{|\mathcal{M}_{\chi e}(q)|^2}{m_e^2}$$

Ionization Form Factor

$$|f_e(E_e,\mathbf{q})|^2 = \frac{k'^3}{4\pi^3} \times 2 \sum_{n,l,l',m'} |\langle \psi^f_{E_e} | e^{i\mathbf{q}\cdot\mathbf{x}} | \psi^i_{E_{nl}} \rangle|^2$$

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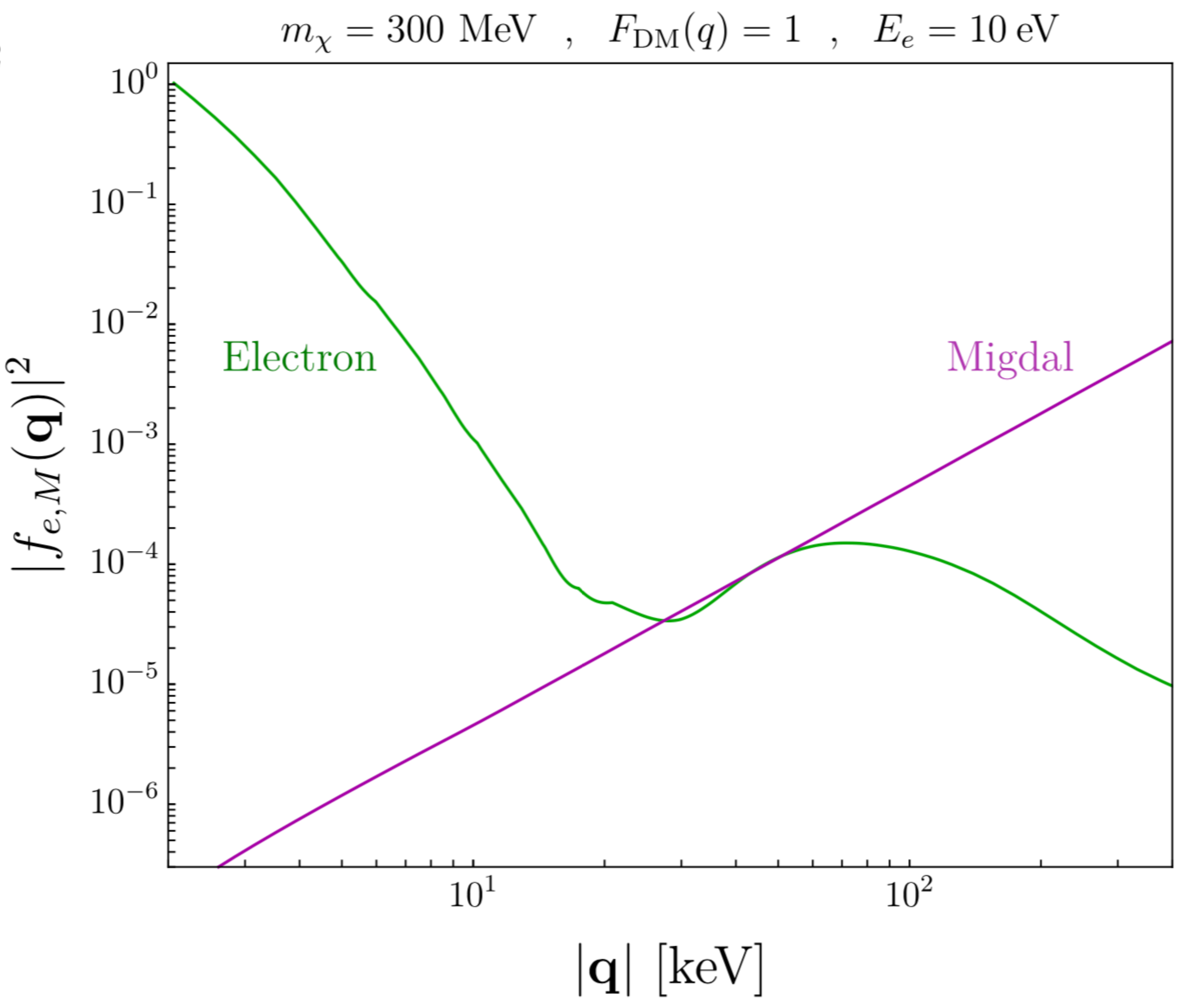
$$k'^2 = 2 m_e E_e$$



- $F_{DM}(q) \propto q^{-2}$ の場合又は m_{DM} が小さい場合

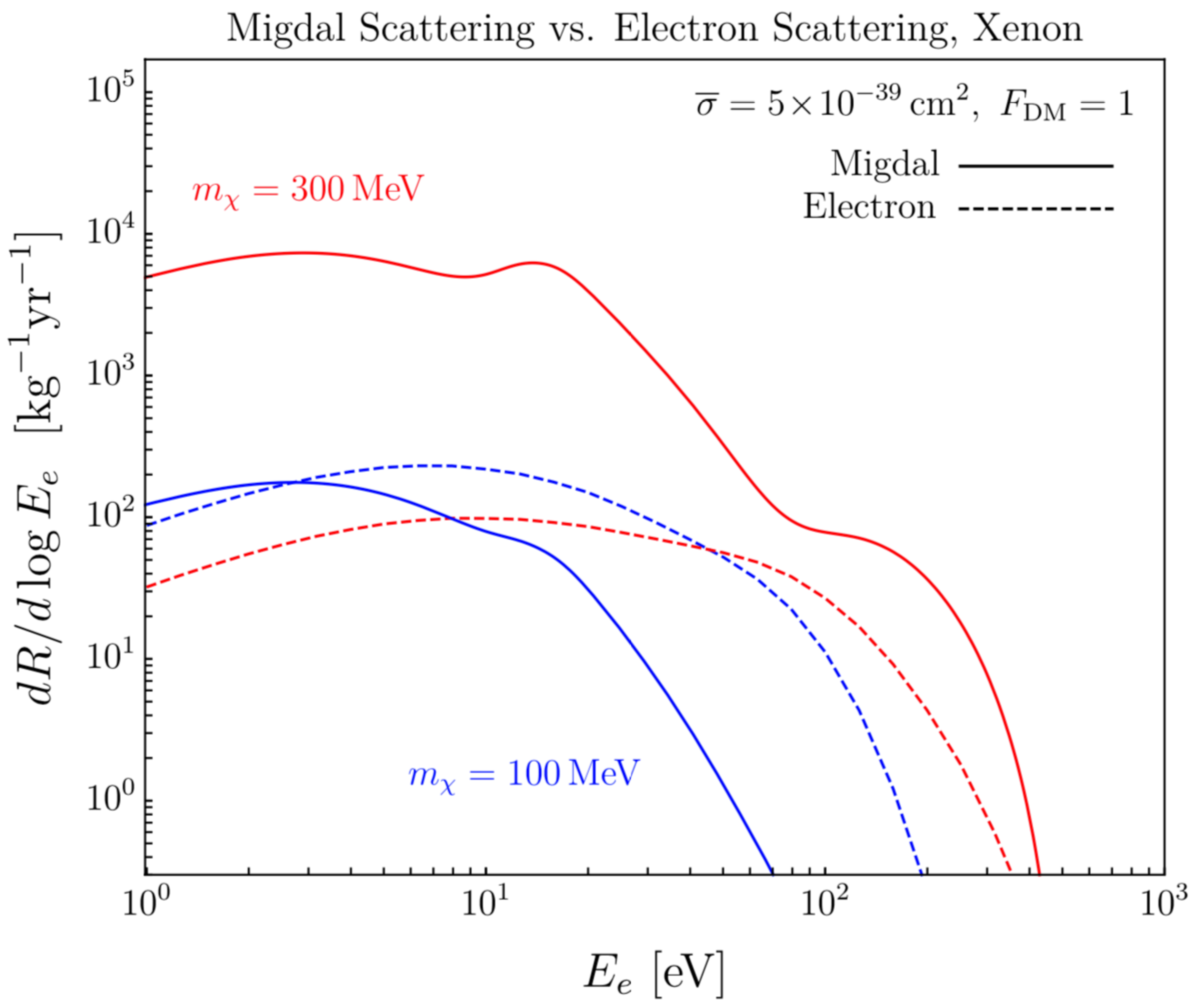
  Migdal factorはelectron factorに勝てない

Xe 5p state

Differential Event Rate

- 100 MeVではelectron scatteringが優勢だが、300 MeVでは逆転する

- Migdalのshapeは電子の波動関数の形を反映



Comparison to XENON

- XENONのデータと比較するために
  観測される電子の数を見積もる

  １回のイベントで作られるquantized signalは

$$n_t = \mathrm{floor}\left(\frac{E_e}{W}\right) + \mathrm{floor}\left(\frac{|E_{nl}| - E_b}{W}\right) \qquad W = 13.7\ \mathrm{eV}$$

Comparison to XENON

- XENONのデータと比較するために
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1回のイベントで作られるquantized signalは

$$n_t = \mathrm{floor}\left(\frac{E_e}{W}\right) + \mathrm{floor}\left(\frac{|E_{nl}| - E_b}{W}\right) \qquad W = 13.7 \text{ eV}$$

作られるquantaの数は

$$n_e = \underline{f_0} + {}_{n_t}C_{f_0} \qquad f_0 \text{：観測される確率}$$

最初に作られた電子に対する確率

電子状態の計算精度について

・Xeのエネルギー準位の比較

Method	E_b	$\lvert E_{5\mathrm{p}}\rvert$	$\lvert E_{5\mathrm{s}}\rvert$	$\lvert E_{4\mathrm{d}}\rvert$
Ibe et al. [32]	9.8	9.8	21	61
Essig et al. [16, 61]	12.4	12.4	25.7	75.6
Measured [62, 63]	12.1	12.8	23.3	68.5

・Essigの方法の方が実験値に近いが、波動関数が直行化されない

結果（XENON100, XENON1T）

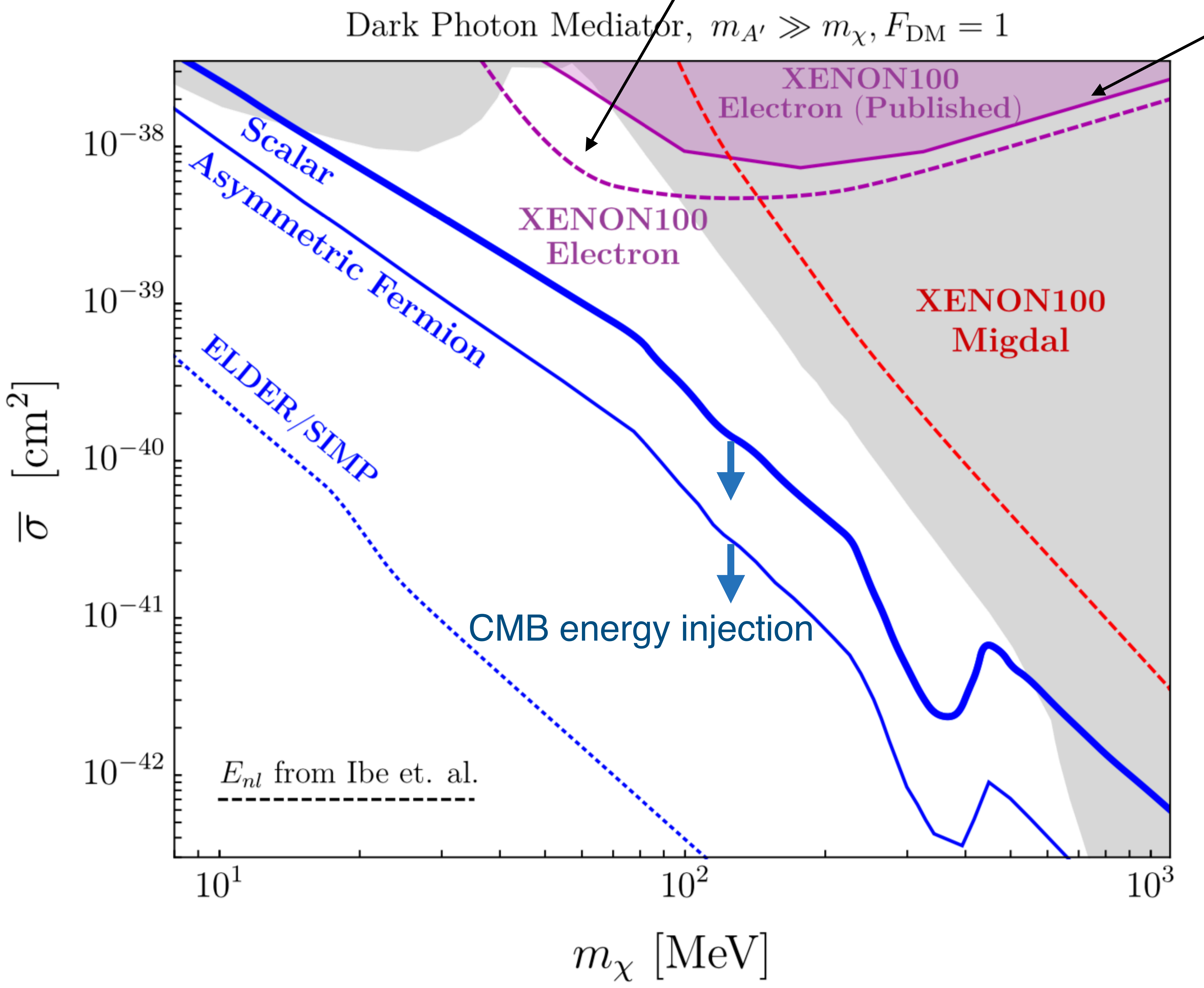
$$\overline{\sigma}_e = \overline{\sigma}$$

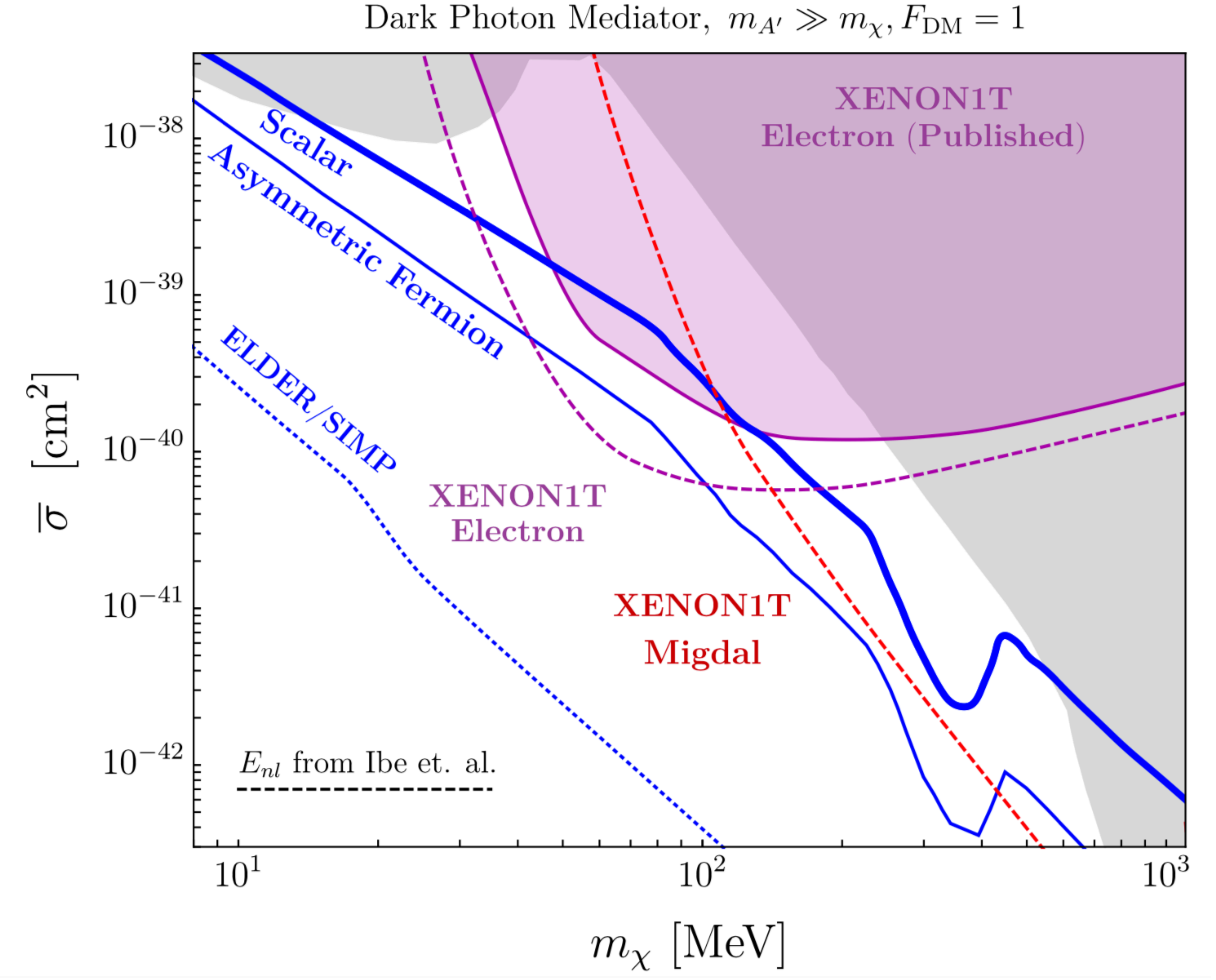
$$\overline{\sigma}_p = \left(\frac{\mu_{\chi p}^2}{\mu_{\chi e}^2}\right)\overline{\sigma}$$

S2 only

Ibe bound energy calculation

Essig bound energy calculation





Conclusion

・ミグダル効果は暗黒物質探索においてsub-GeV regionで有効なrare eventである

・ミグダル効果とelectron scatteringは似た様な構造を持っているが、
模型によってどちらがdominantか異なる

・電子状態の計算の精密化によってミグダル効果の計算精度の向上が見込める