Modulation Effects in Dark Matter-Electron Scattering Experiments

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Work with S.K. Lee, M. Lisanti and B.R. Safdi, to appear

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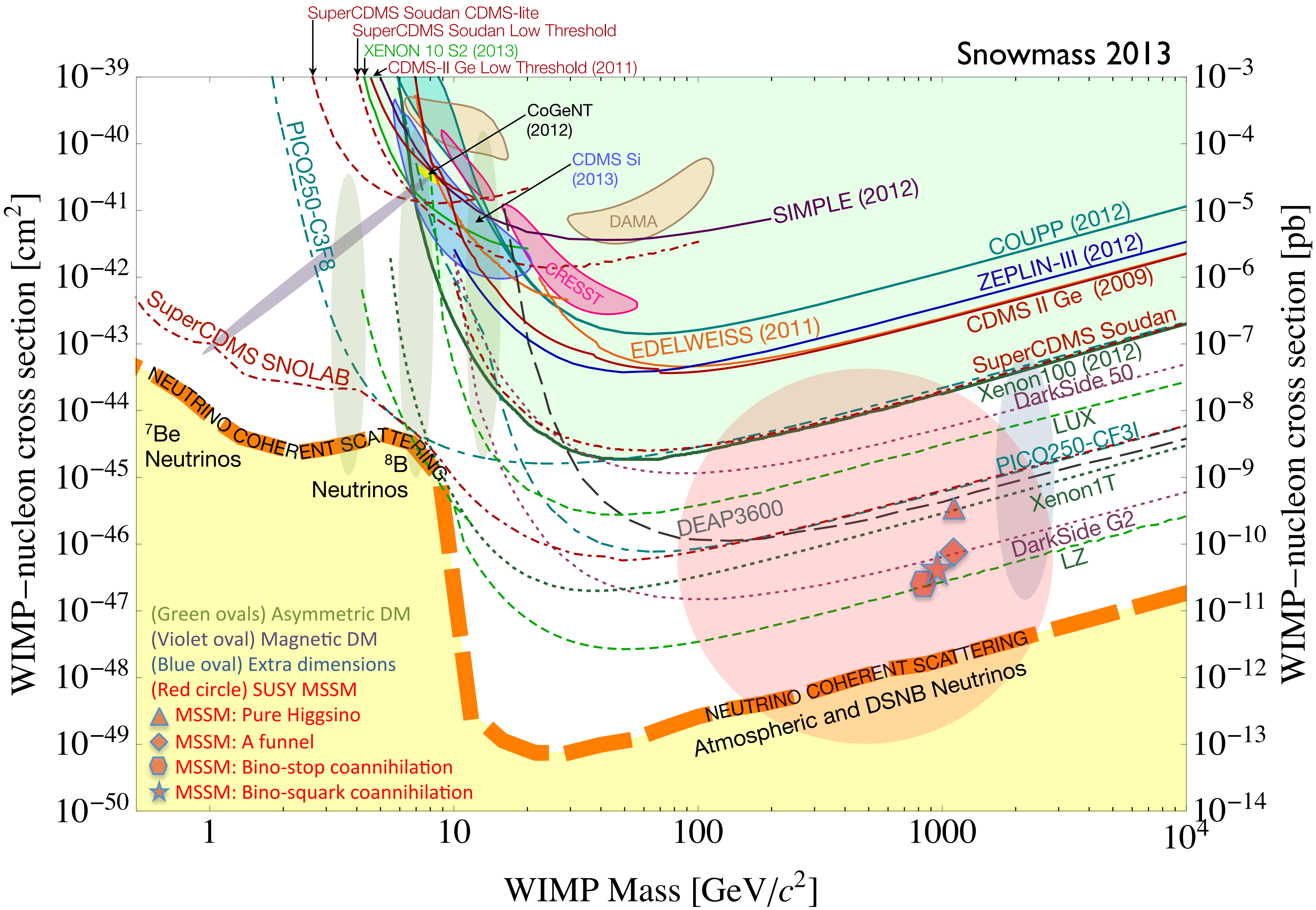
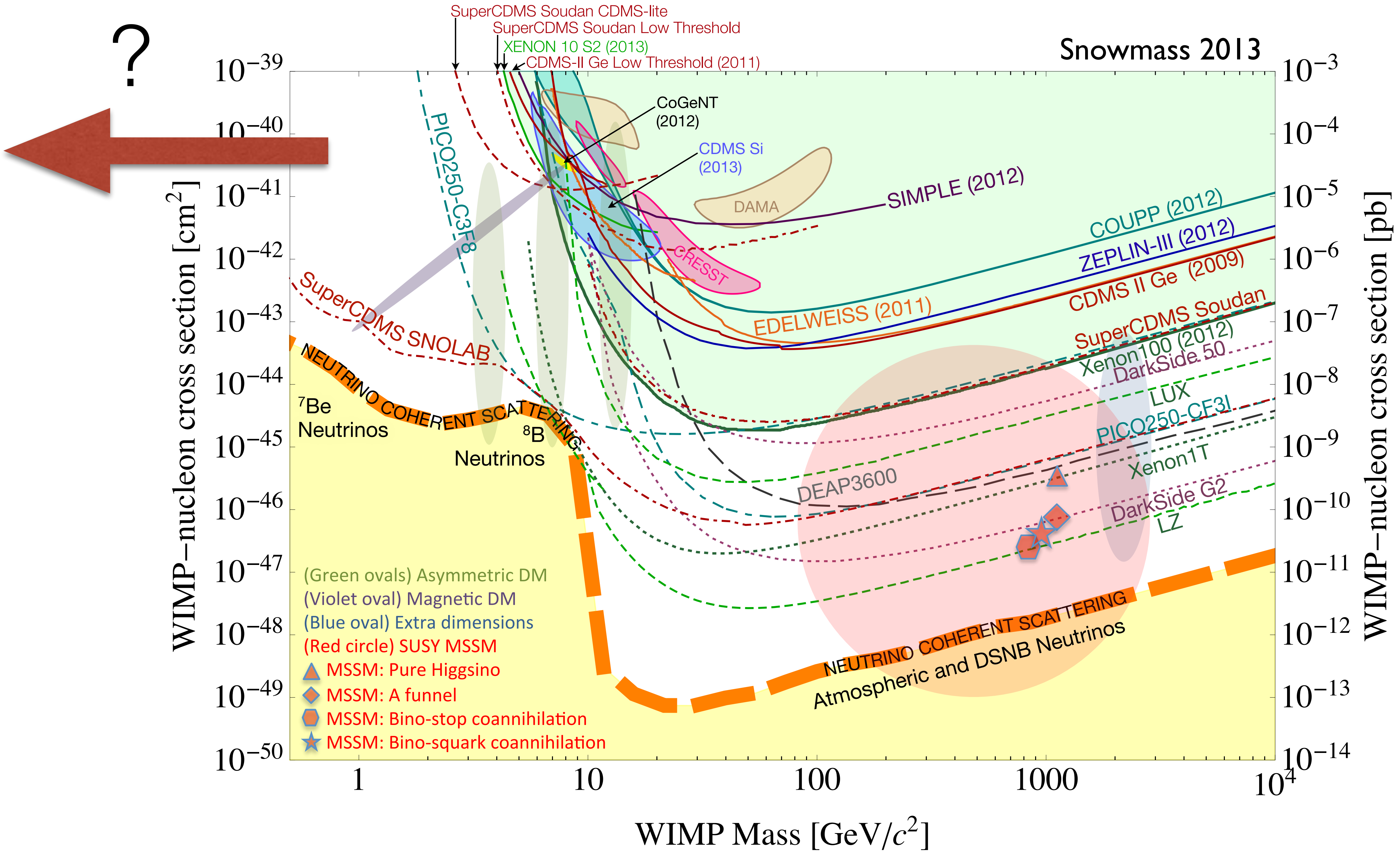
PRINCETON UNIVERSITY

Story so far



Snowmass 2013 `[arXiv:1310.8327]`

Looking ahead…



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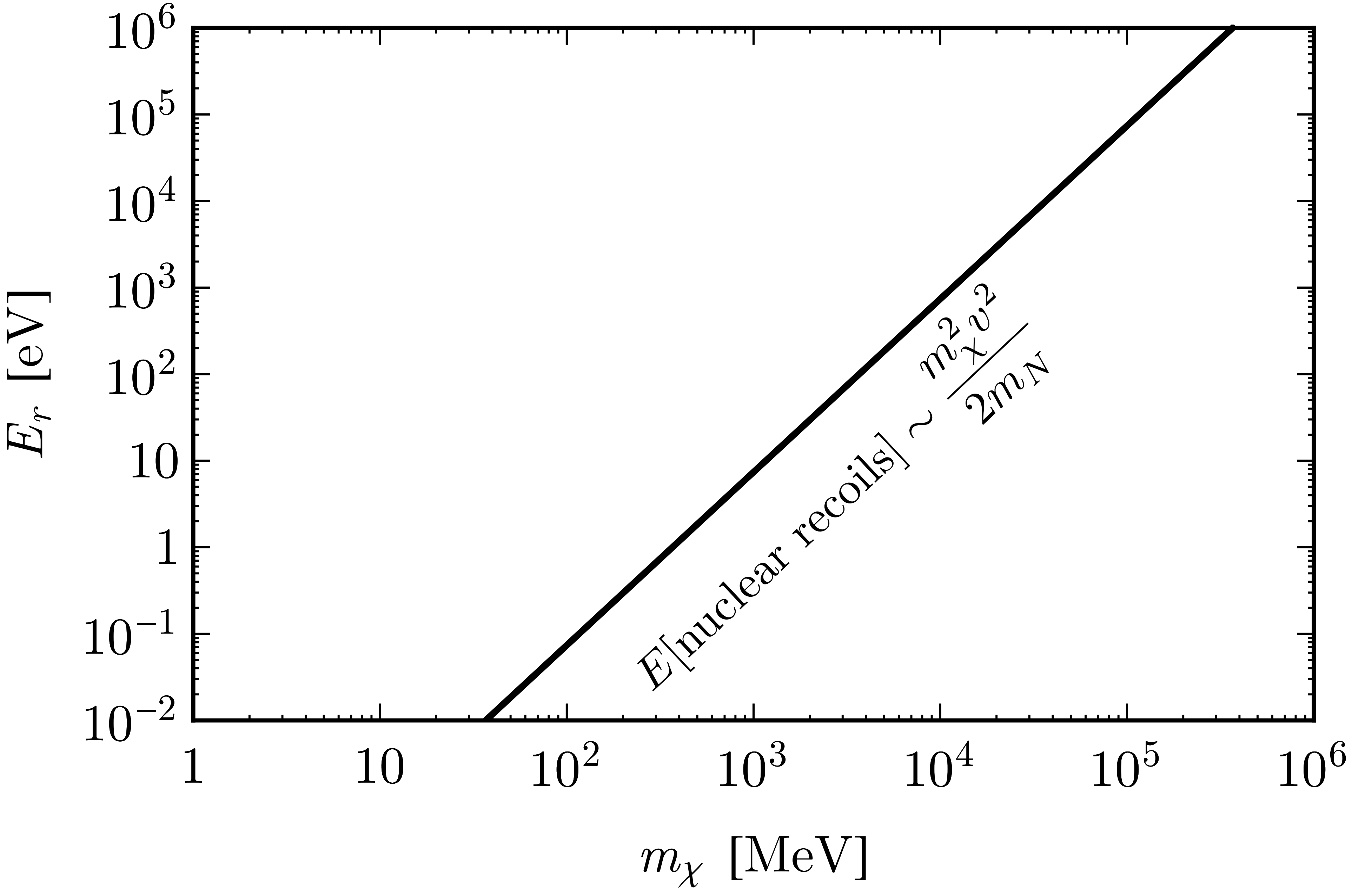
Searching for sub-GeV DM with electron recoils

$$\left(\text{Total energy available to scattering}\right) \gg \left(\text{Average energy transfer in nuclear recoil event}\right)$$



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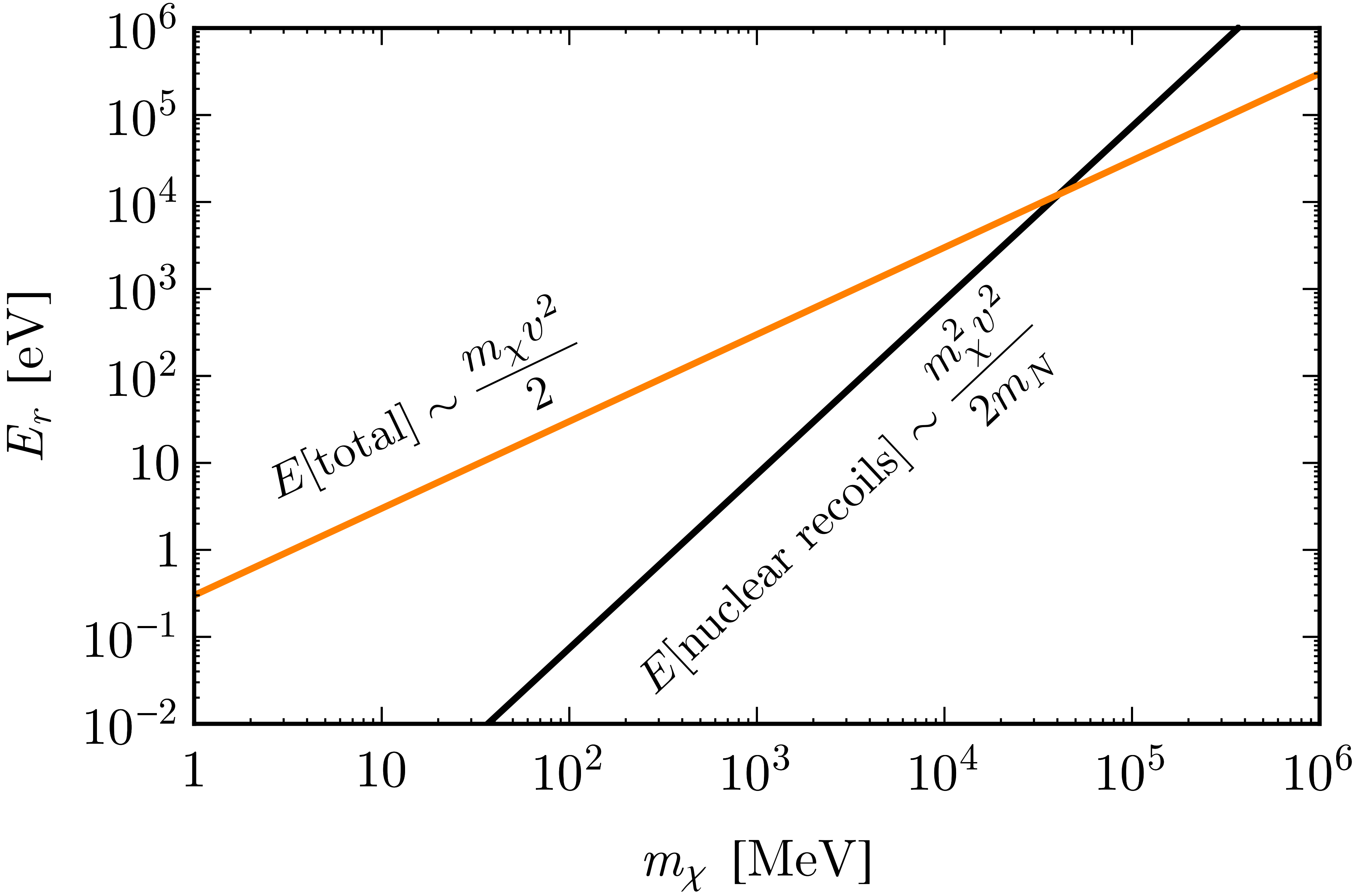
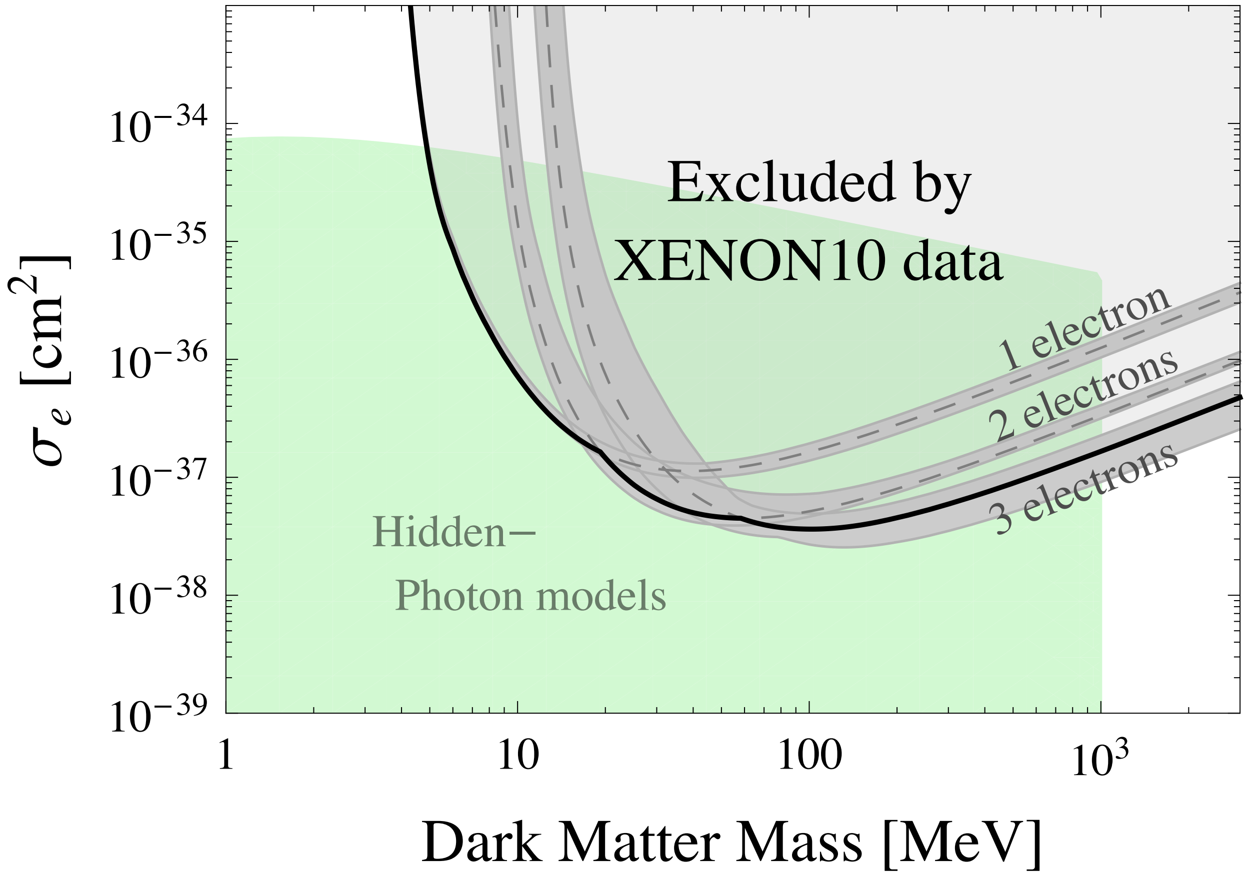
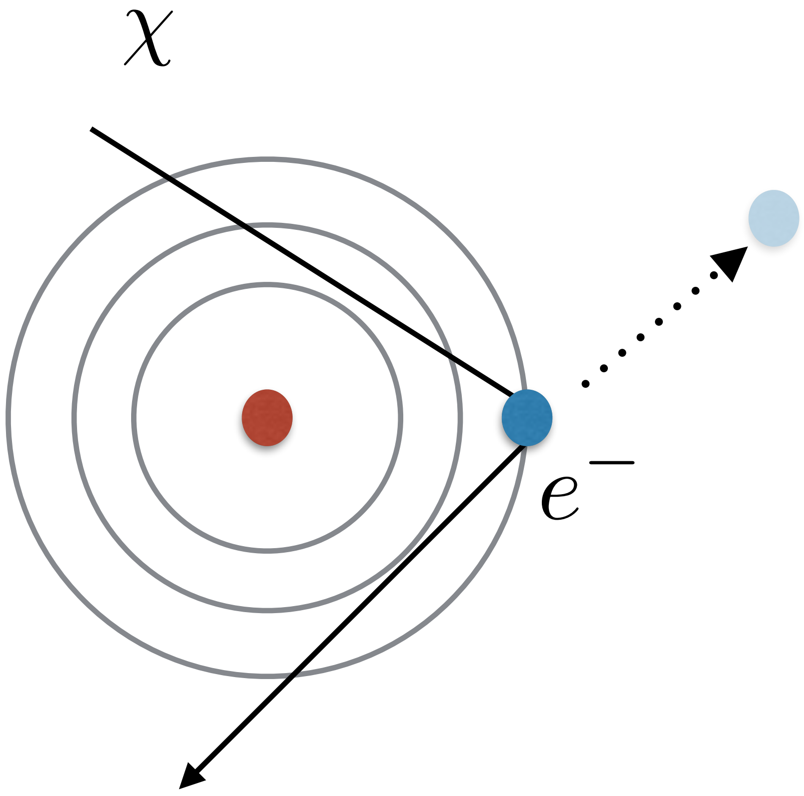


Searching for sub-GeV DM with electron recoils

- Idea first proposed by Essig et. al. `[arXiv:1108.5383]` and Graham et. al. `[arXiv:1203.2531]`
- First useful limits already set using 15 kg-days of XENON10 by Essig et. al. `[arXiv:1206.2644]`:





Calculating the event rate: Ingredients

1. Nuclear physics: transition amplitude between initial and final electron states

$$|f_{\mathrm{ion}}|^2 \sim \sum_{\mathrm{degen.}} \left|\langle\psi_{\mathrm{final}}|e^{i\mathbf{q}\cdot\mathbf{r}}|\psi_{\mathrm{bound}}\rangle\right|^2$$

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- **i.** Effective cross section, $\bar{\sigma}_e$
- **ii.** Momentum dependence, $\left|F_{\text{DM}}(q)\right|^2$

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$$\textbf{Total rate} \sim \sum_{e^{-}\text{ shells}} \int_q \textbf{Nuclear physics} \times \textbf{Particle physics} \times \textbf{Astrophysics}$$

Calculating the event rate: Kinematics

- Nuclear recoil does not contribute significantly to energy conservation:

$$(\mathbf{p}_\chi + \mathbf{q})^2 = {\mathbf{p}_\chi}^2 - 2m_\chi(E_{\mathrm{er}} + E_b^i)$$

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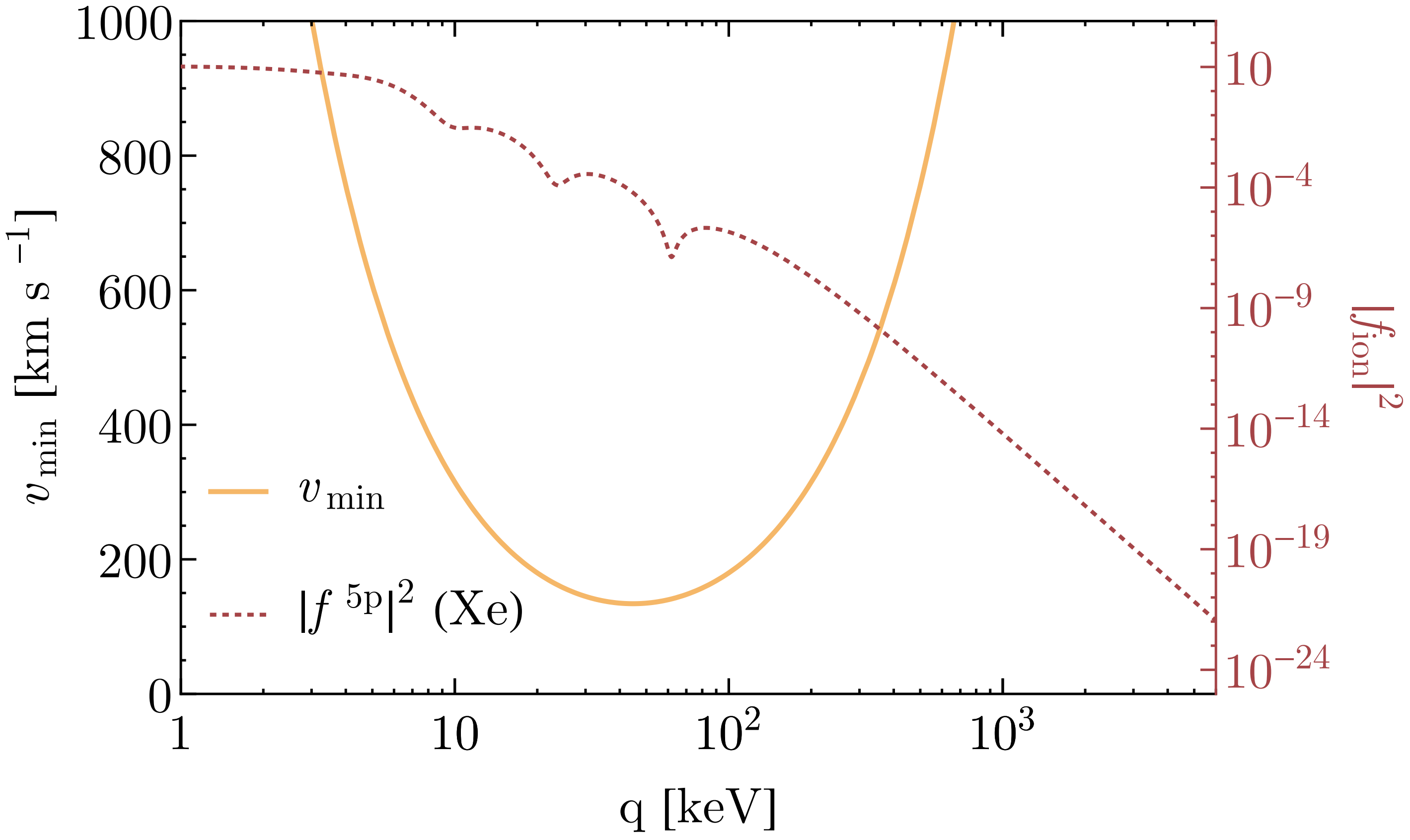
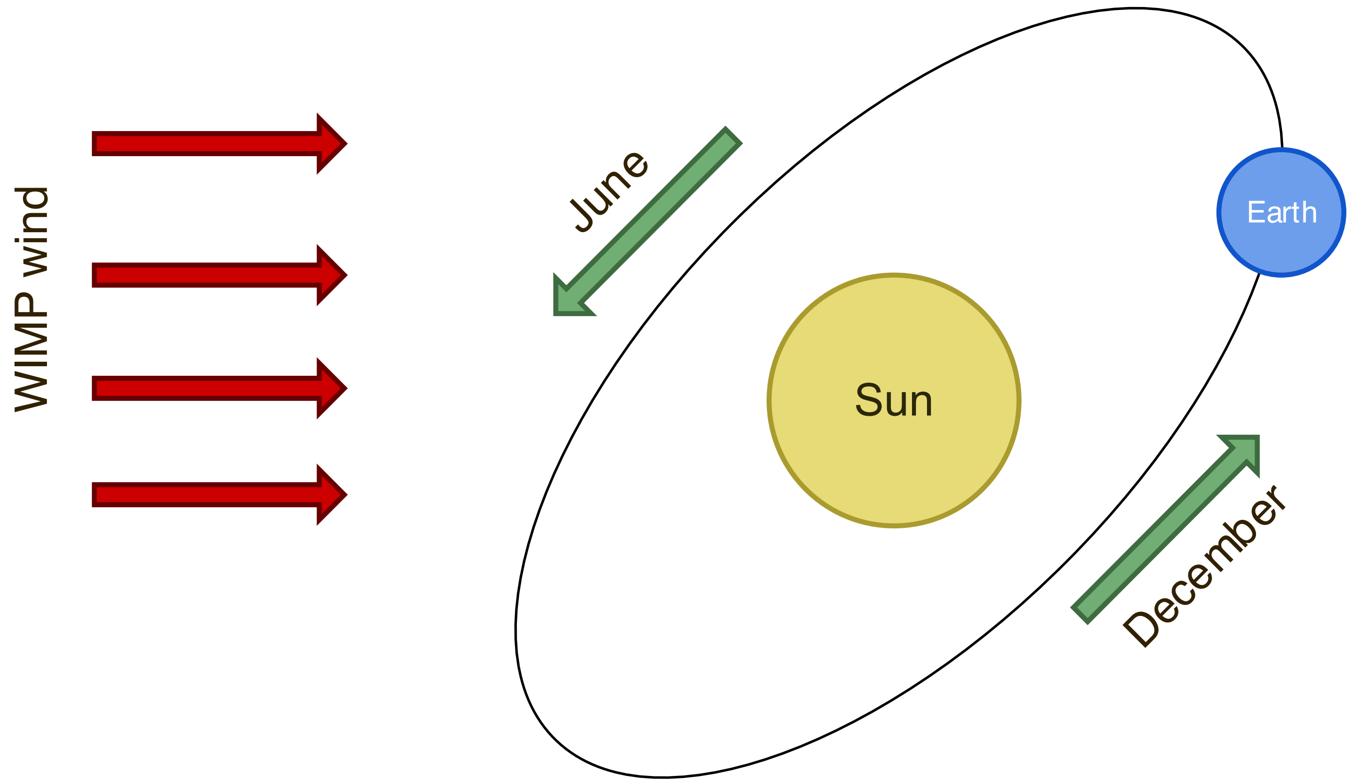


Higher momentum transfers strongly suppressed by nuclear factor — unlikely for atomic electron to be found at $p \gtrsim a_0^{-1} \sim 4$ keV

Annual modulation

Time-dependence in event rate due to relative motion of earth in DM frame

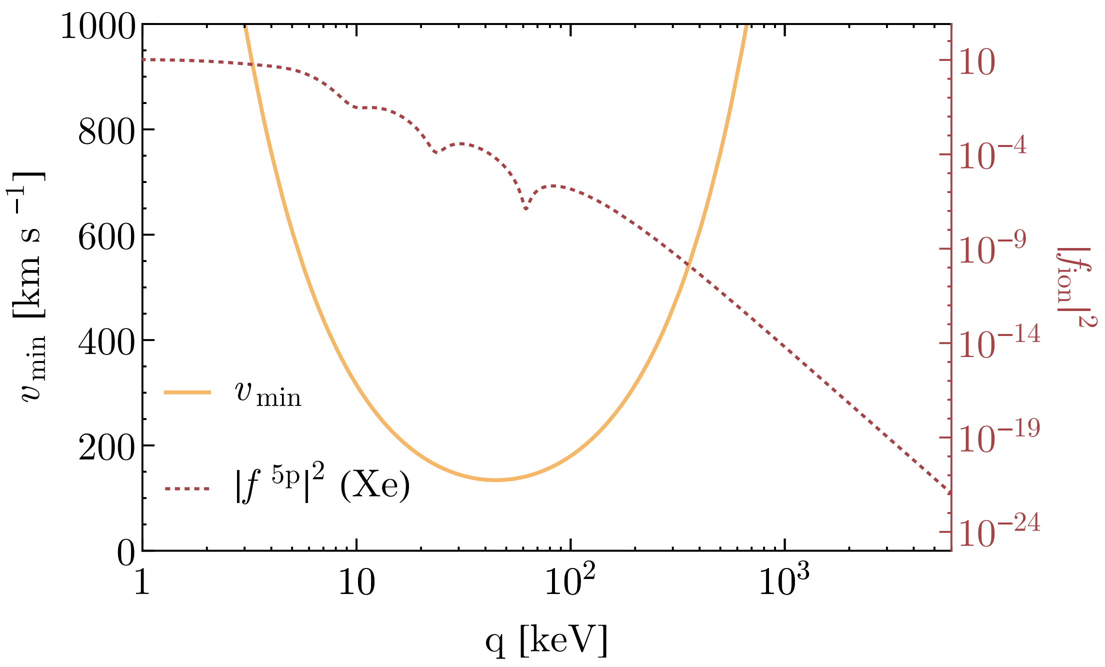


Important signature to distinguish a possible signal from background sources

Modulation fraction

DM-electron scattering samples tail of velocity distribution close to $v_{\rm esc}$ — faster moving particles lead to higher modulation fractions than in DM-nuclear scattering

$$v \leq v_{\rm esc} + |\mathbf{v}_E + \mathbf{v}_\odot|$$



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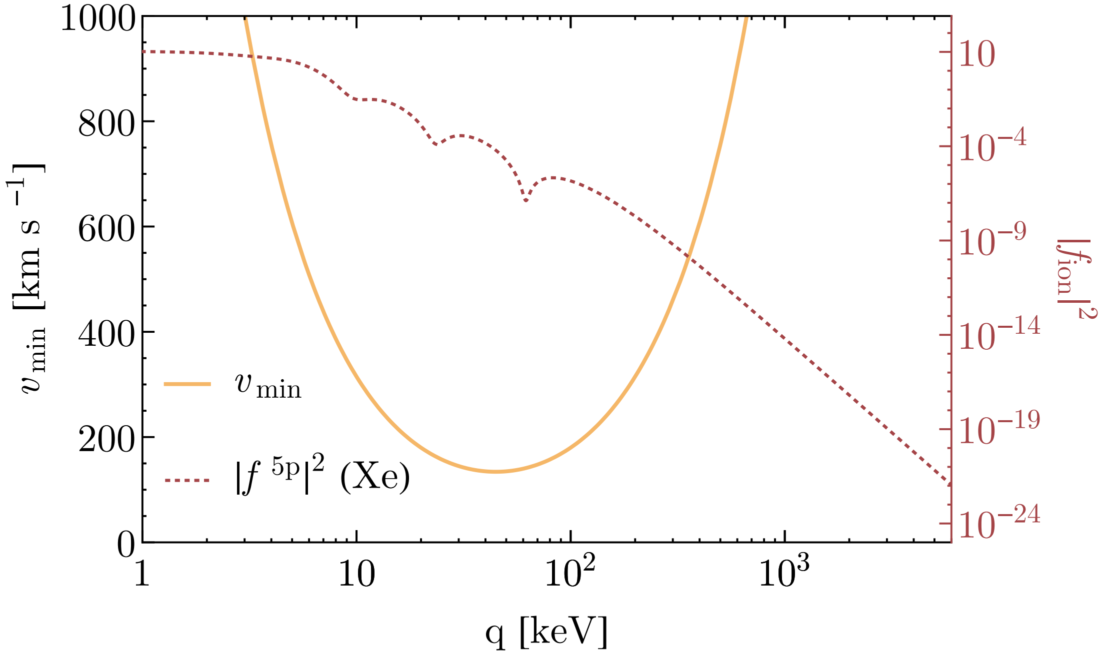
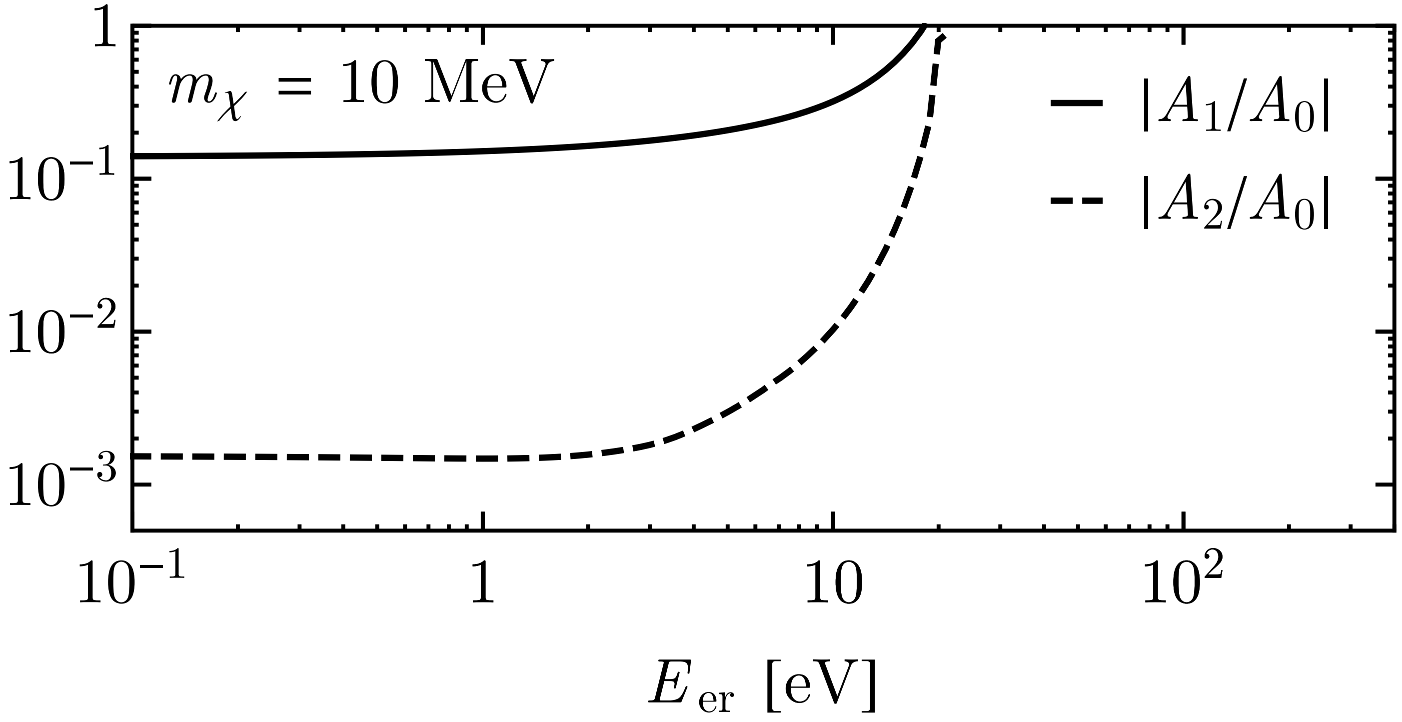
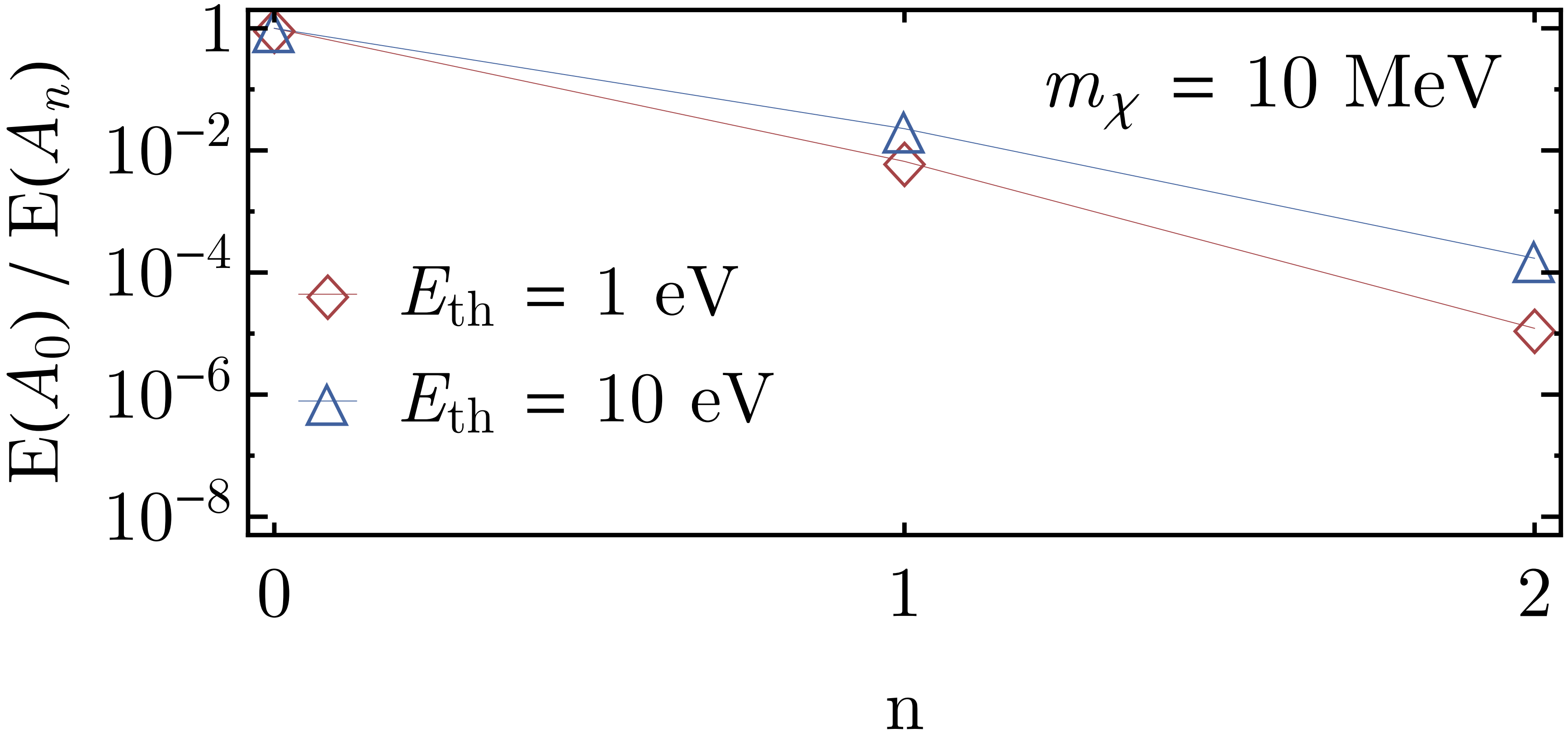




$$\frac{dR}{dE_{\mathrm{er}}} = A_0 + \sum_{n=1}^{\infty} \left[A_n \cos n\,\omega(t - t_n)\right]$$

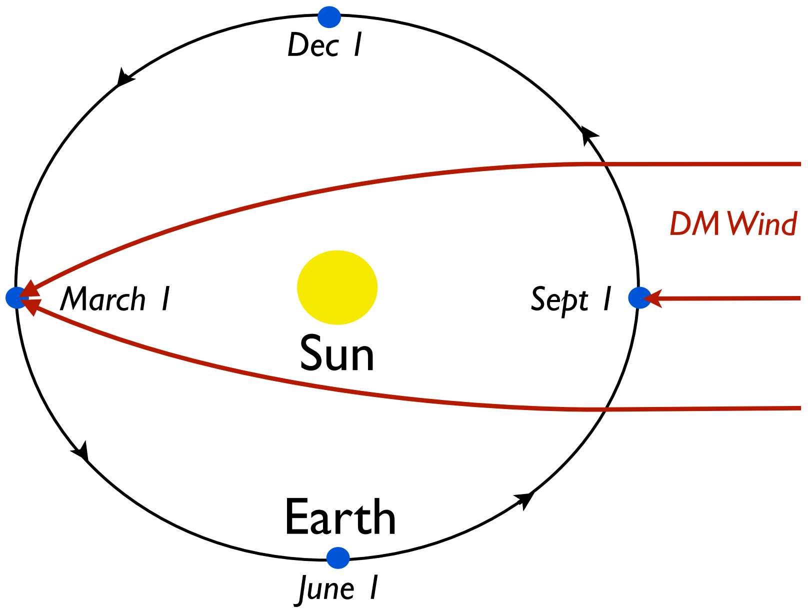
Expected modulation detection exposure

Exposure required to detect higher modes grows exponentially with n, making detection of the higher modes increasingly difficult.



Modulation phase

- Gravitational focusing due to the Sun can change phase of annual modulation
- For slower-moving DM particles, expect shift in phase of expected maximum rate from ~June to ~December in DM-nuclear scattering, affected by GF



Lee et. al. `[arXiv:1308.1953]`

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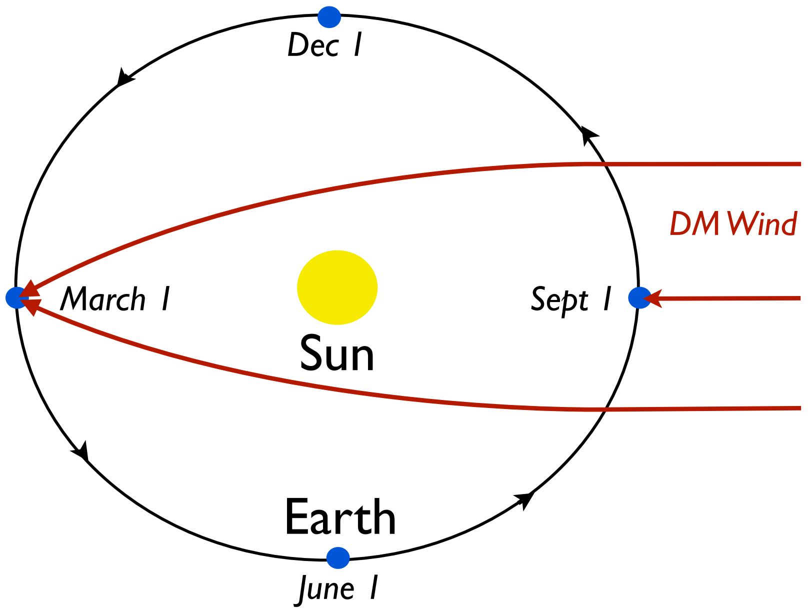

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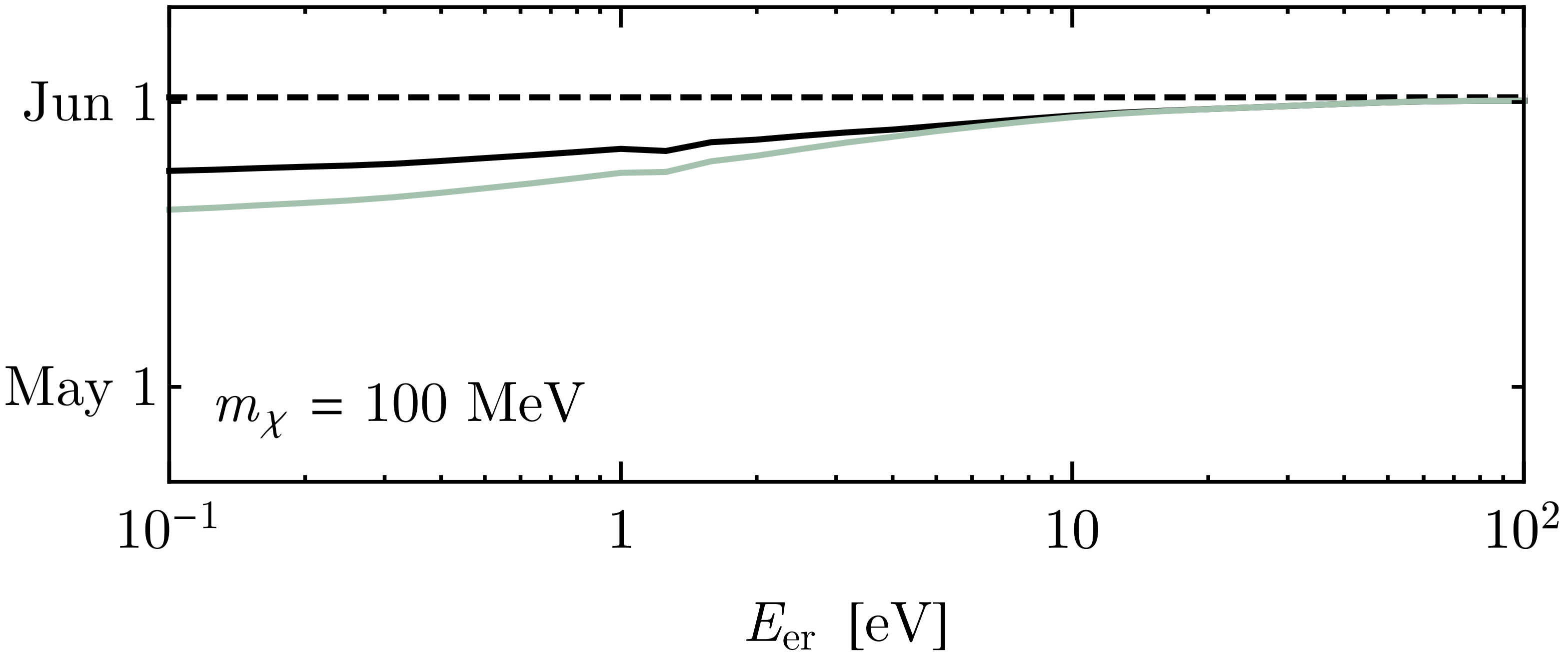
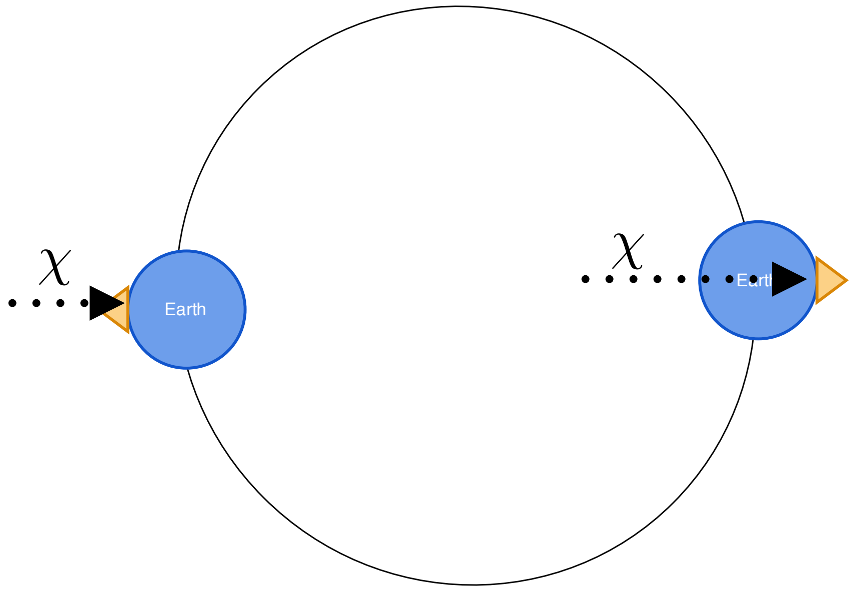
DM-electron scattering: sample mainly faster particles — <u>effect of GF suppressed</u>:



DM interactions inside the Earth

- Light DM does not produce observable nuclear recoils, but might still have large nuclear interaction cross-section
- May cause DM to be deviated during passage through the Earth



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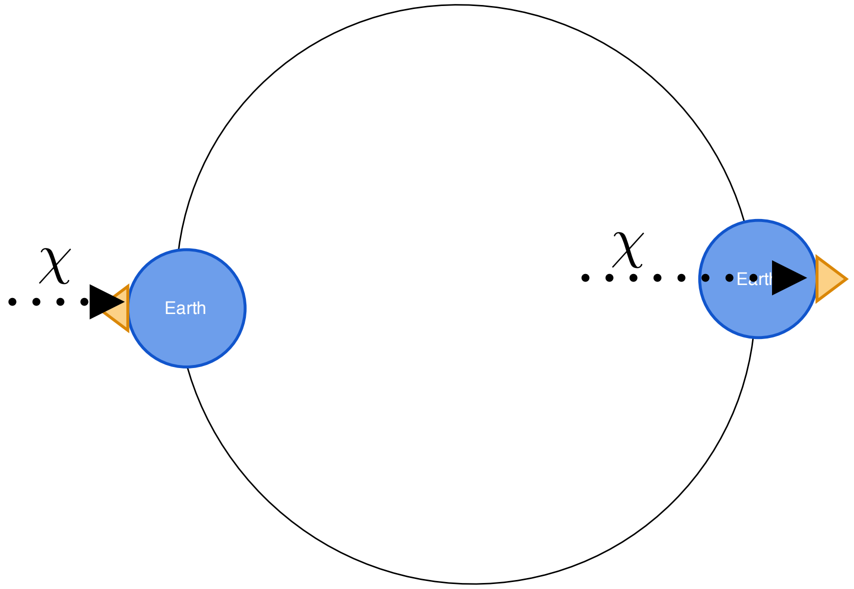
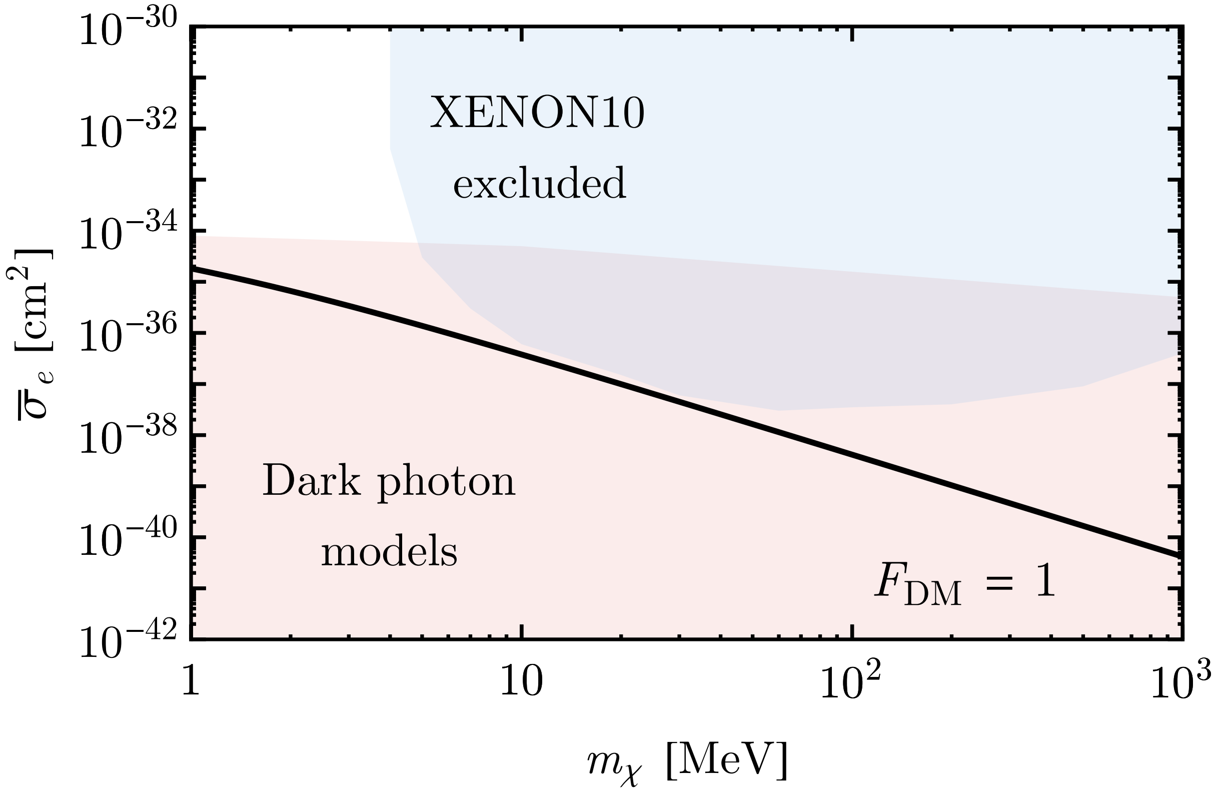
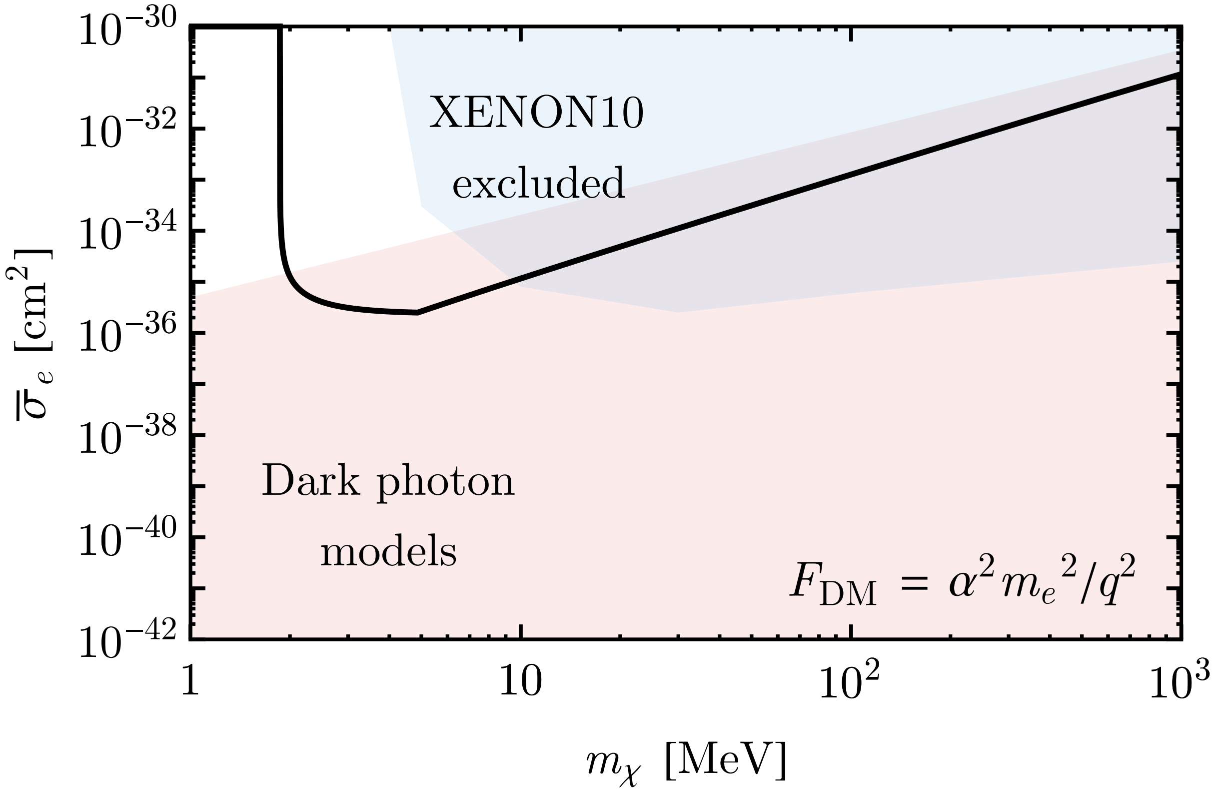






Summary

- Light, sub-GeV is one of the next frontiers in DM direct detection
- DM-electron scattering leads to novel effects due to the inelastic nature of the collision, and the electron's ionization form factor
- In this case, there are higher modulation fractions and less sensitivity to gravitational focusing
- DM interactions inside the Earth may also lead to daily modulations in the count rate

Backup

Calculating the event rate: Ingredients

Scattering cross-section for given initial state (shell)

Nuclear physics Particle physics Astrophysics

$$\frac{d\langle\sigma^i_{\rm ion}v\rangle}{d\ln E_{\rm er}} = \frac{\bar{\sigma}_e}{8\mu^2_{e\chi}}\int dq\, q|f^i_{\rm ion}(k',q)|^2|F_{\rm DM}(q)|^2\eta(v_{\rm min},t)$$

$$\sum\left|\langle\psi_{\rm ion}|e^{i\mathbf{q}\cdot\mathbf{r}}|\psi_{\rm bound}\rangle\right|^2$$

$$\int_{v_{\rm min}}^{\infty}\frac{f_\oplus(\mathbf{v},t)}{v}\,d^3v$$

Total rate given by sum over all accessible initial states

$$\frac{dR}{d\ln E_{\rm er}} = N_T\frac{\rho_\chi}{m_\chi}F(k')\sum_i\frac{d\langle\sigma^i_{ion}v\rangle}{d\ln E_{\rm er}}$$

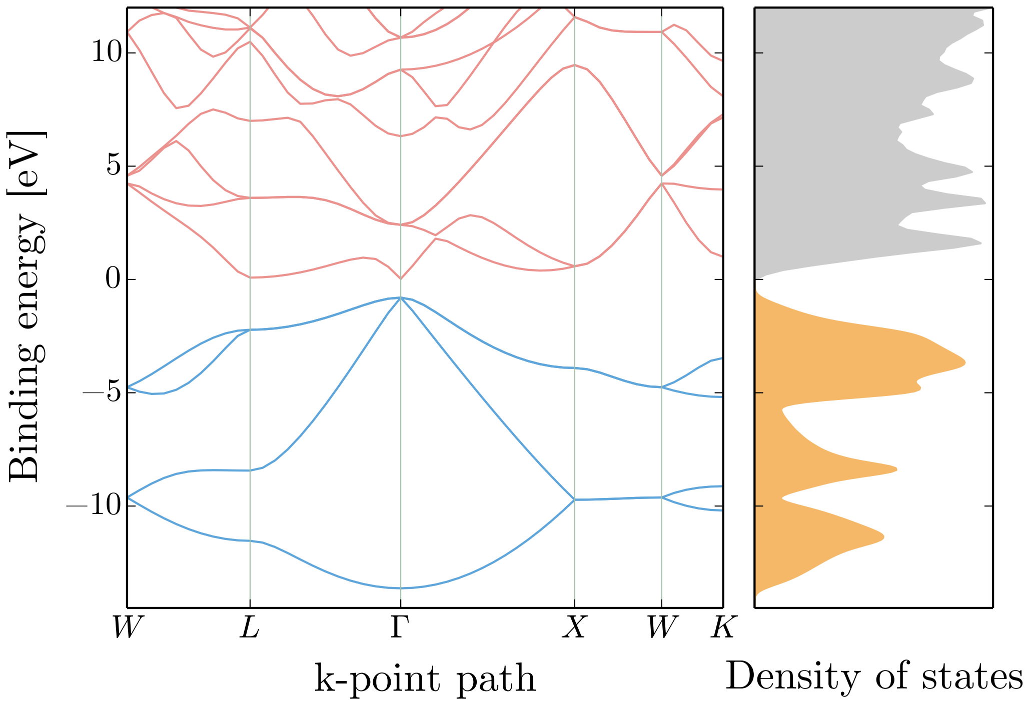
Calculating the event rate: Semiconductor target

Electron in periodic lattice generically described by a Bloch wavefunction

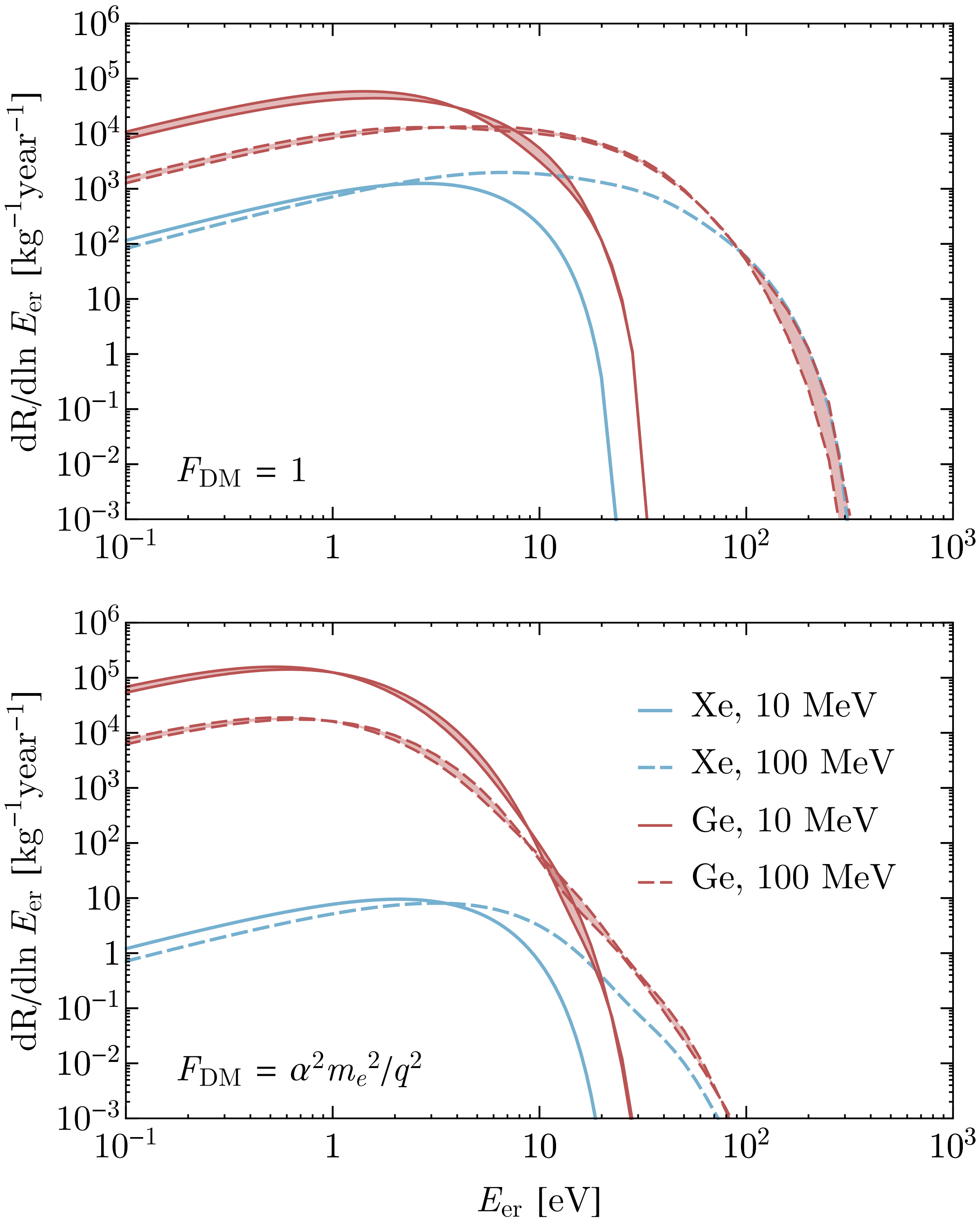
$$\Psi_{\mathbf{k}}(\mathbf{r}) = \underbrace{\sum_N}_{\text{Lattice sites}} e^{i\mathbf{k}\cdot\mathbf{R}_N} \underbrace{\phi(\mathbf{r}-\mathbf{R}_N)}_{\text{Localized wavefunction at lattice site}}$$

- Free-electron approximation — localized wavefunction reduces to outer-shell atomic wavefunction (4s or 4p)
- Localized interaction ($p \gtrsim a_0^{-1} \sim 4$ keV) — ignore neighbor interactions

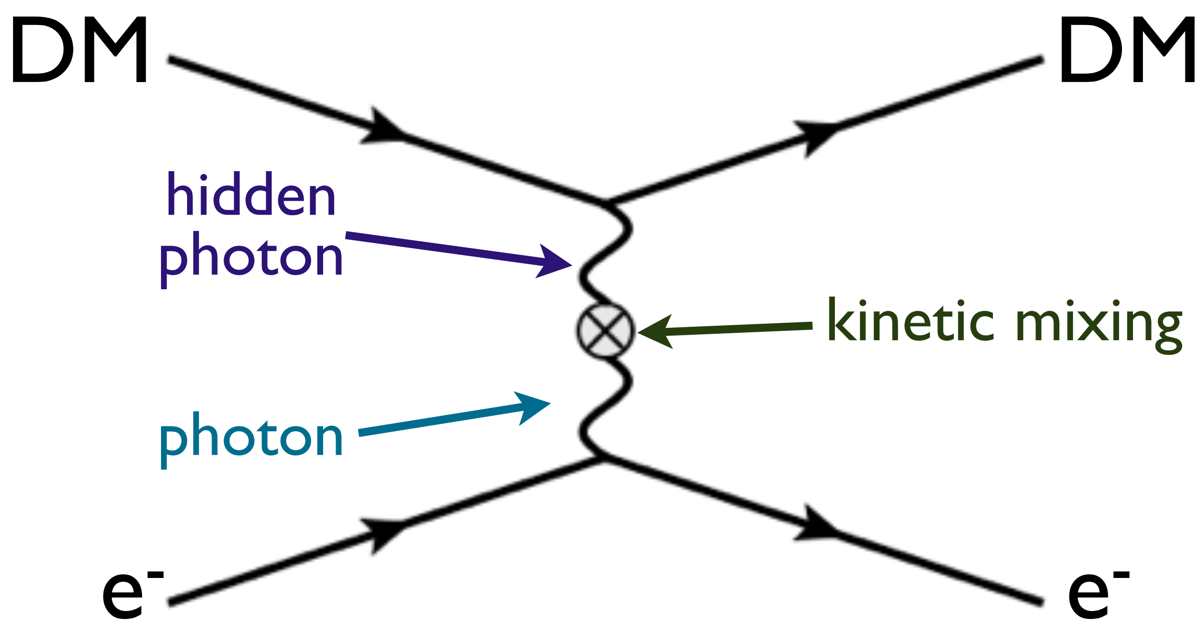
Account for initial-state degeneracy through valence band density of states



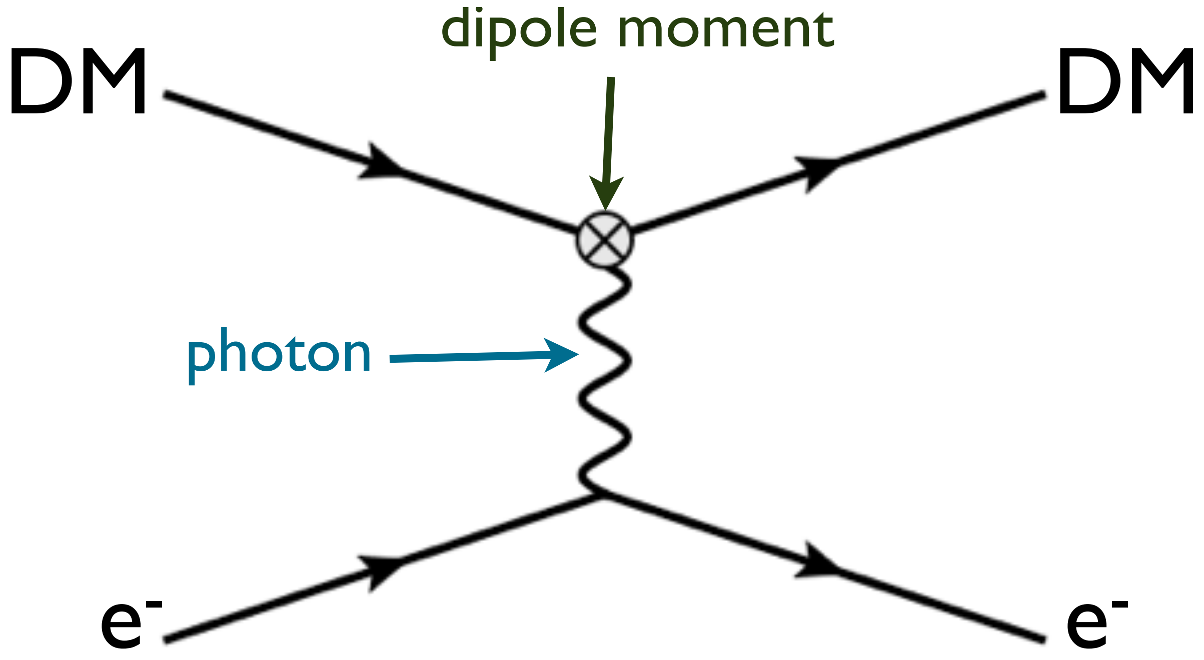
Event rates (preliminary)



Benchmark models



Light/heavy dark photon mediator
Essig et. al `[arXiv:1108.5383]`



Electric/magnetic dipole moment
Graham et. al `[arXiv:1203.2531]`