Terrestrial effects on sub-GeV dark matter detection via electron scatterings for heavy and ultralight mediators

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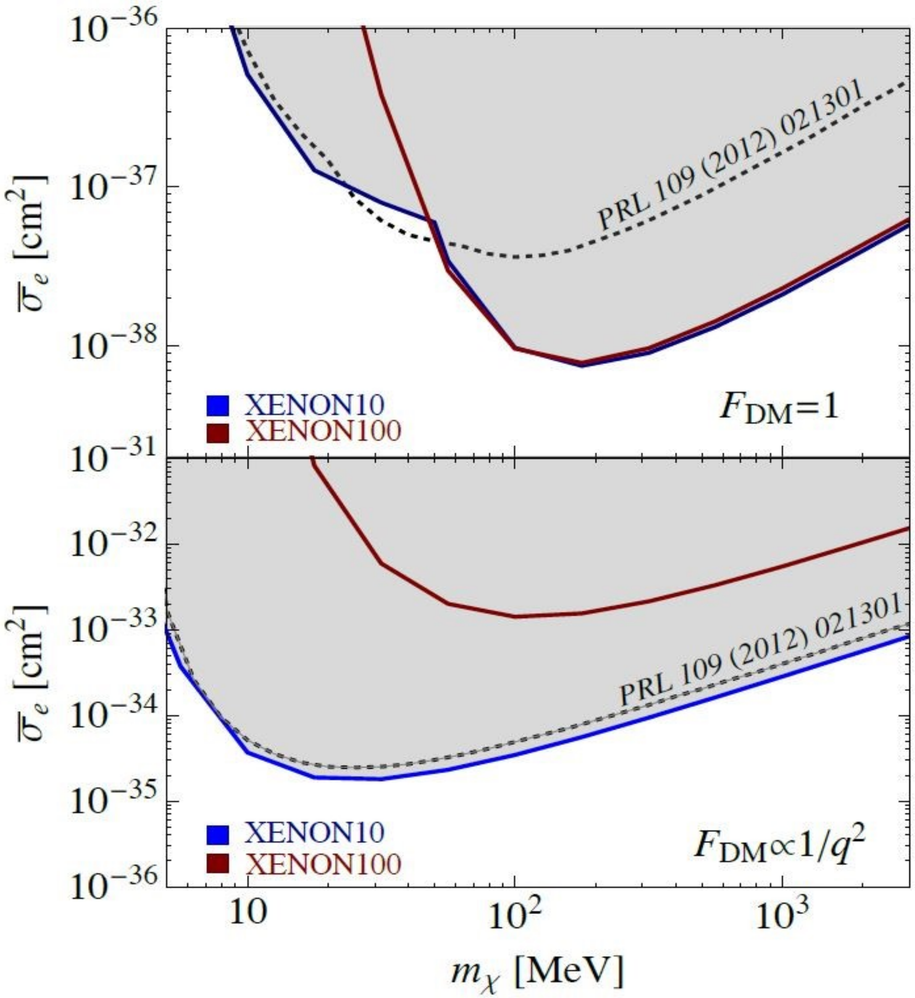
Sub-GeV dark matter direct detection

- Nuclear recoil energies produced by sub-GeV dark matter are too low to measure

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

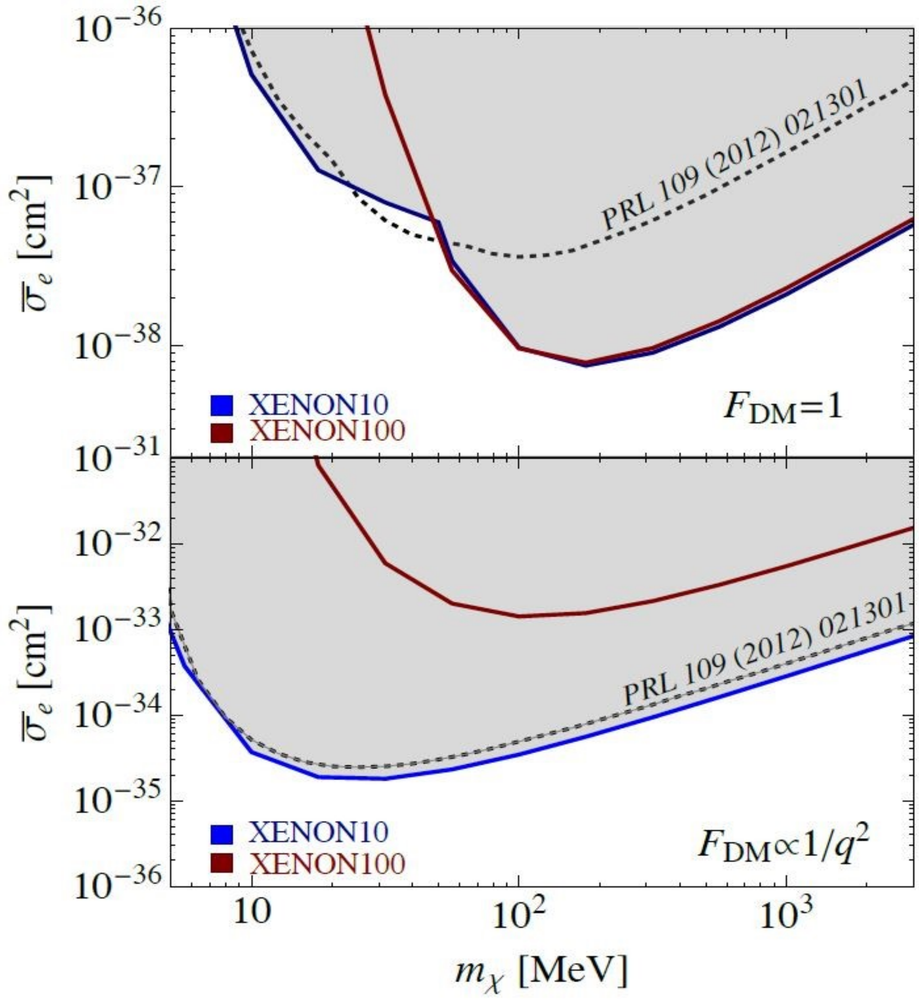
- Can look for electron recoils induced by sub-GeV dark matter
- Typical materials used :
  - Semiconductors (Si, Ge)
  - Noble gases (Xe, Ar)
  - Scintillators (GaAs, NaI, CsI)

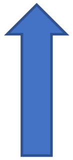
Existing constraints



* Essig, Volansky and Yu (1703.00910)

Existing constraints





What happens as we increase the cross section ?

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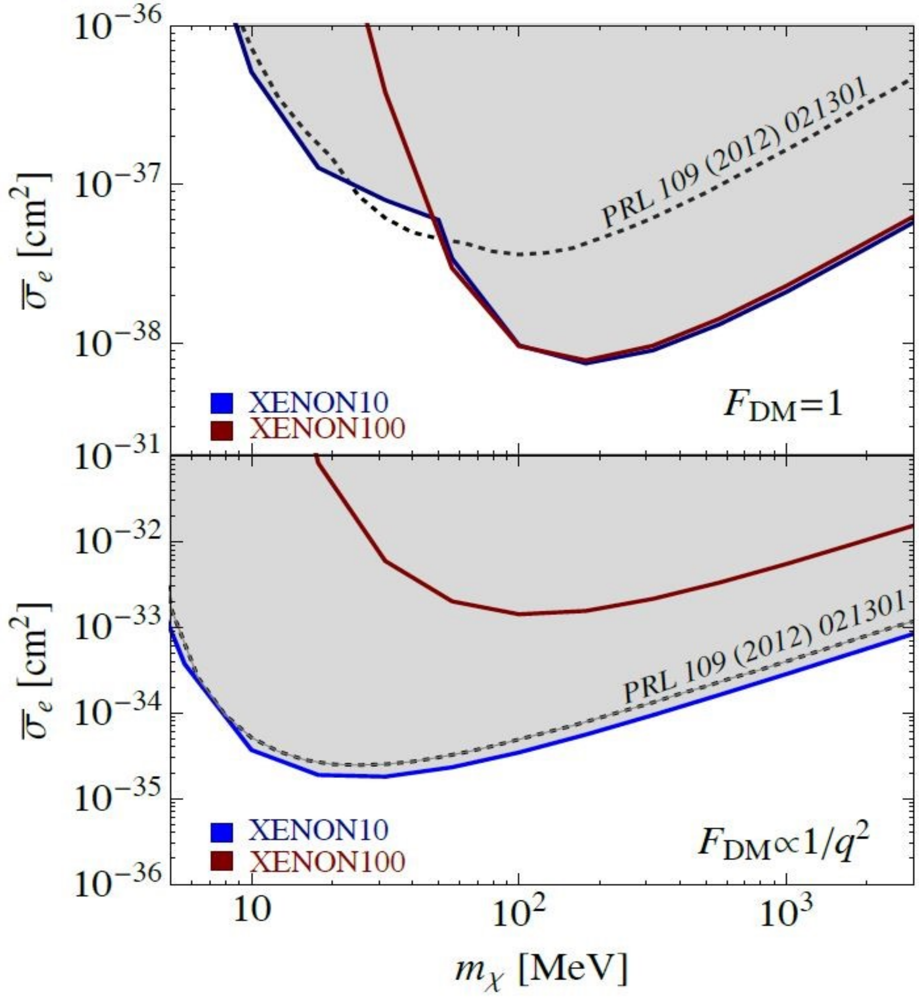
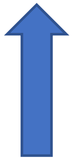
Existing constraints





What happens as we increase the cross section ?

- Dark matter can scatter off the nuclei and the electrons in the overburden (earth or atmosphere)
- Can become invisible to the detector above a critical cross section

* Essig, Volansky and Yu (1703.00910)

The model

- Dark photon (A') model

$$\mathcal{L}_{\mathrm{A}'} = -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B^{\mu\nu}F'_{\mu\nu} - \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu}$$

$$\overline{\sigma}_e \simeq \begin{cases} \frac{16\pi\mu^2_{\chi e}\alpha\alpha_D\epsilon^2}{m^4_{A'}}, & m_{A'} \gg \alpha m_e \\ \frac{16\pi\mu^2_{\chi e}\alpha\alpha_D\epsilon^2}{(\alpha\, m_e)^4}, & m_{A'} \ll \alpha m_e \end{cases}, \text{and} \quad F_{DM}(q) \simeq \begin{cases} 1\,, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}\,, & m_{A'} \ll \alpha m_e \end{cases}$$

- Differential cross section with nuclei :

$$\frac{d\sigma}{dE_{NR}} = \left(\frac{\overline{\sigma}_e}{2\mu^2_{\chi e}v^2}\right) \times m_N Z^2 \times F_{DM}(q)^2$$

The atomic screening

- Thomas-Fermi radius :

$$a = \frac{1}{4}\left(\frac{9\pi^2}{2Z}\right)^{1/3} a_0 \approx \frac{0.89}{Z^{1/3}} a_0$$

- The screening as a regulator in the millicharged case :

$$\mu \sim \frac{1}{a}$$

$$F_{DM}(q) \sim \frac{\alpha^2 m_e^2}{q^2} \quad \Rightarrow \quad F_{DM}(q) \sim \frac{\alpha^2 m_e^2}{q^2 + \mu^2}$$

Estimation of the stopping power

- **Monte Carlo simulations :**
    - Simulate the DM particles travelling through the Earth's crust or the atmosphere. (Reference : Emken and Kouvaris 1706.02249)
    - Analysis includes deflections in the trajectory.

- **Semi- analytic method :**
    - Calculate the final velocity distribution of the DM particles after passing through the crust or the atmosphere.
    - Analysis assumes no deflections in the trajectory.

Semi-analytic method

- **The energy-loss equations :**

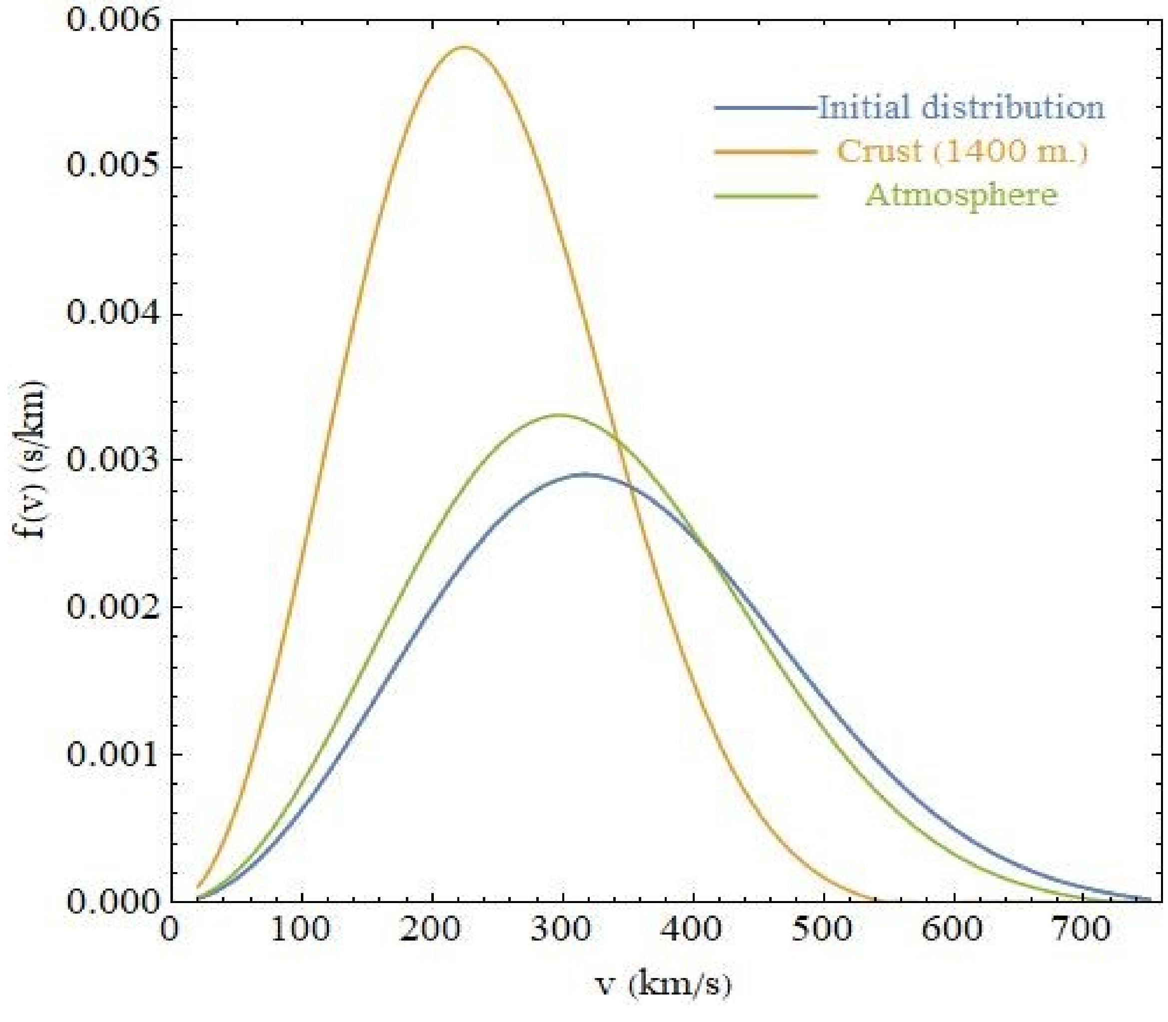
$$\frac{dE}{dx} = \sum_i -\frac{\Omega_i \rho(x)}{m_i} \int_0^{E_{R_i}^{max}} \frac{d\sigma_{\chi i}}{dE_R} E_R dE_R$$

$$\int_{E_0}^{E_d} \frac{dE}{\left(\sum_i \frac{\Omega_i}{m_i} \int_0^{E_{R_i}^{max}} \frac{d\sigma_{\chi i}}{dE_R} E_R dE_R\right)} = -\int_0^d \rho(x) dx$$

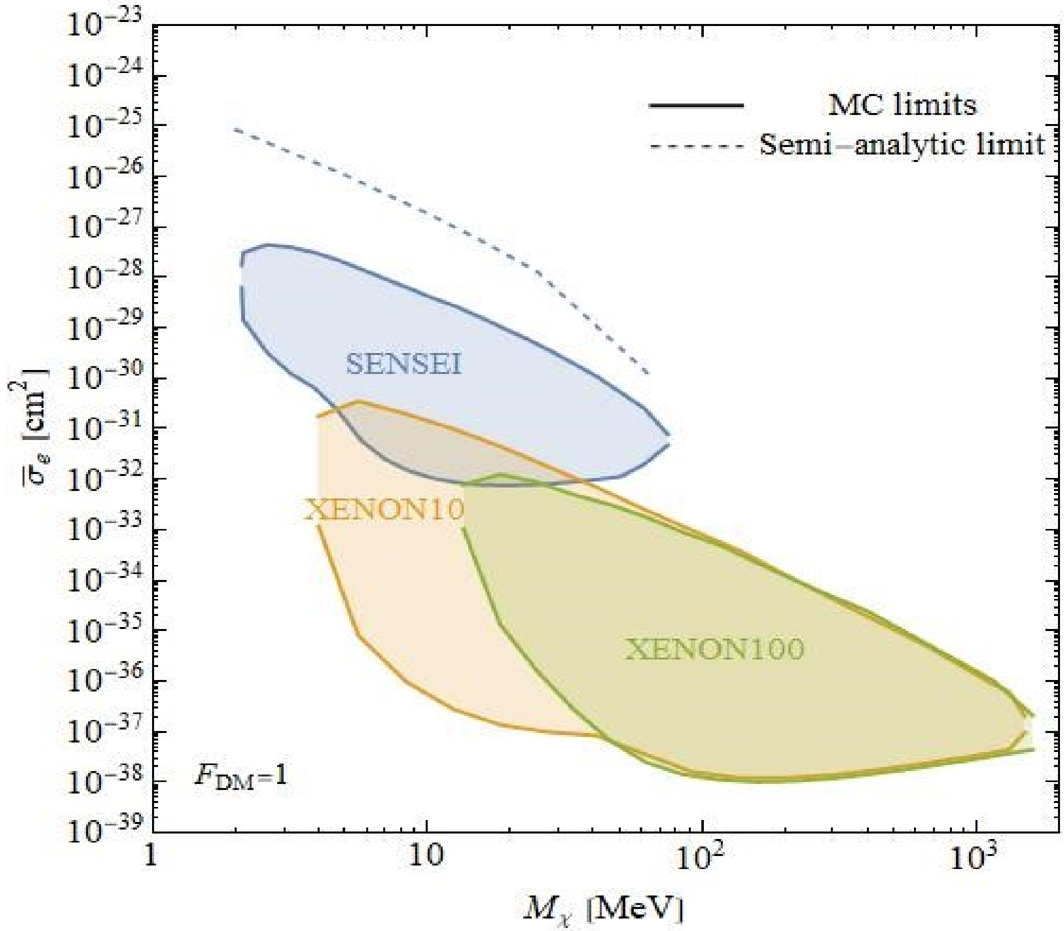
- **Flux conservation :**

$$f_d(v_d) v_d dv_d = f_0(v_0) v_0 dv_0$$

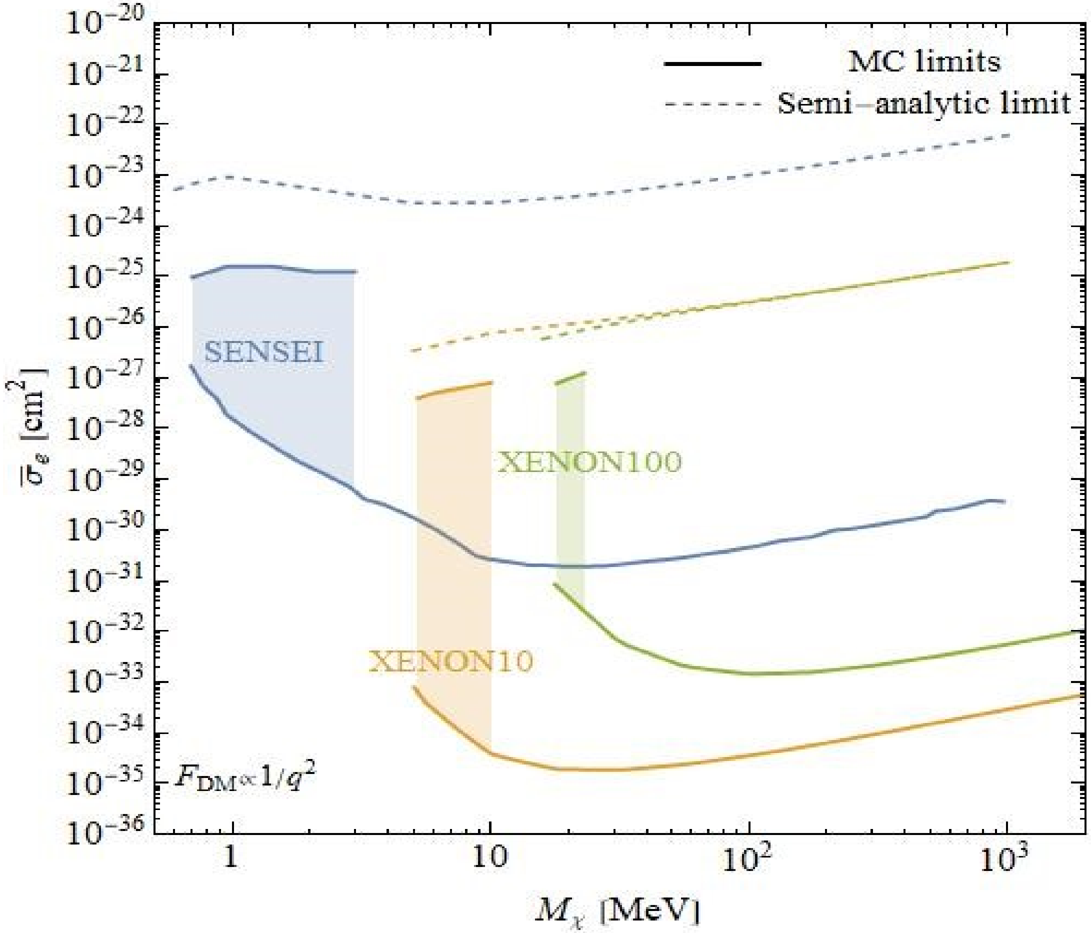
Distribution functions



Results: Heavy mediator



Results: Light mediator



Conclusion

- The terrestrial effect has to be taken into account while calculating the limits for a particular experiment.

- The semi-analytic method is a good approximation for calculating the stopping power for heavier dark matter.

- For low mass dark matter, deflections dominate and hence the analytic approximation breaks down.