Low-Energy Signals from the Formation of Dark Matter-Nuclear Bound States

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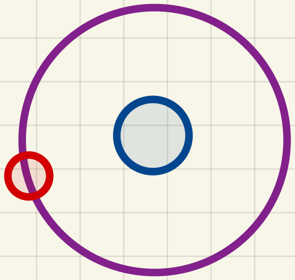
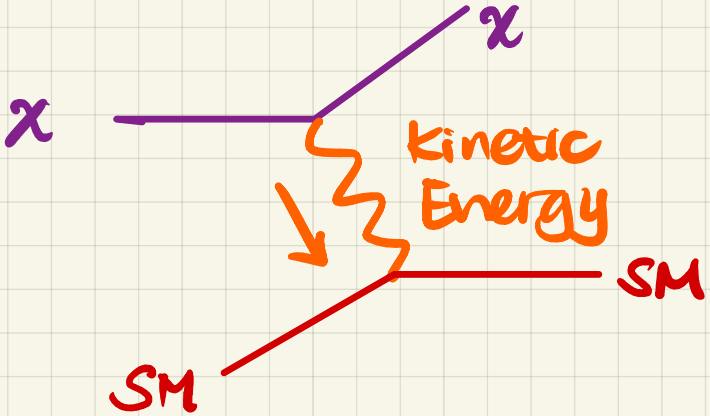
arXiv: 2110.06217

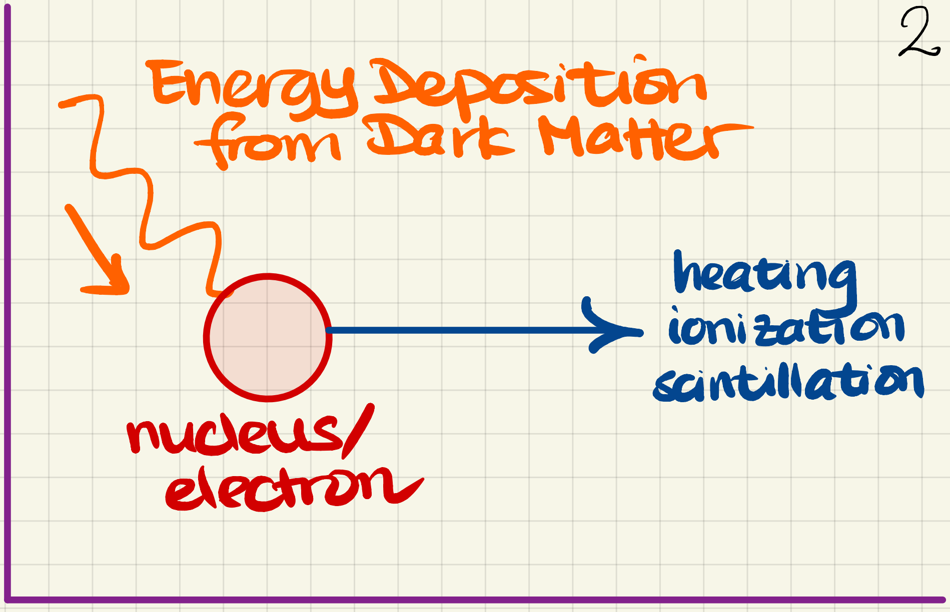


BSM Pandemic
9 Nov 2021

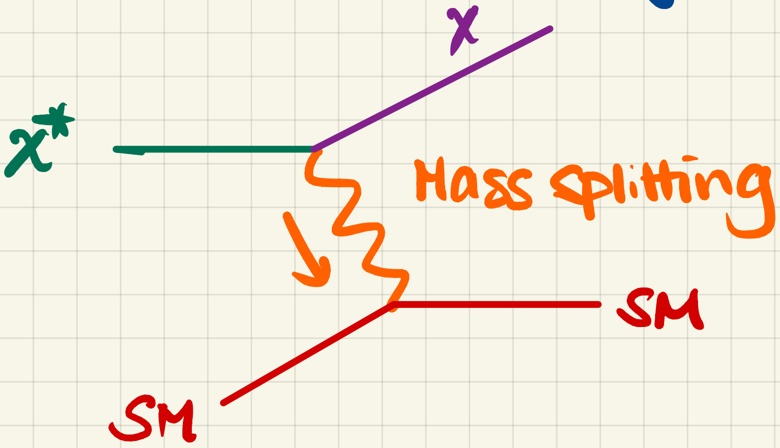
Direct Detection

Elastic Scattering

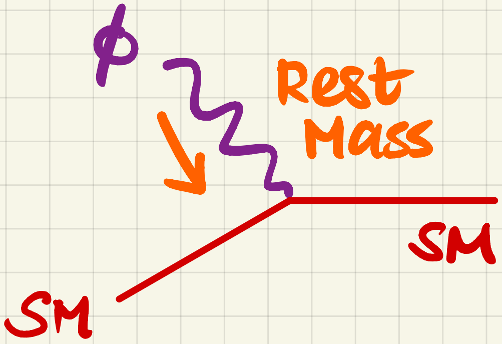


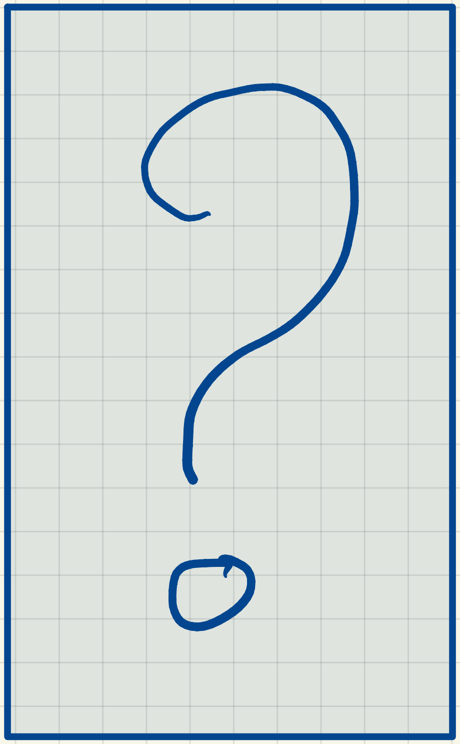

Energy Deposition from Dark Matter

Inelastic Scattering



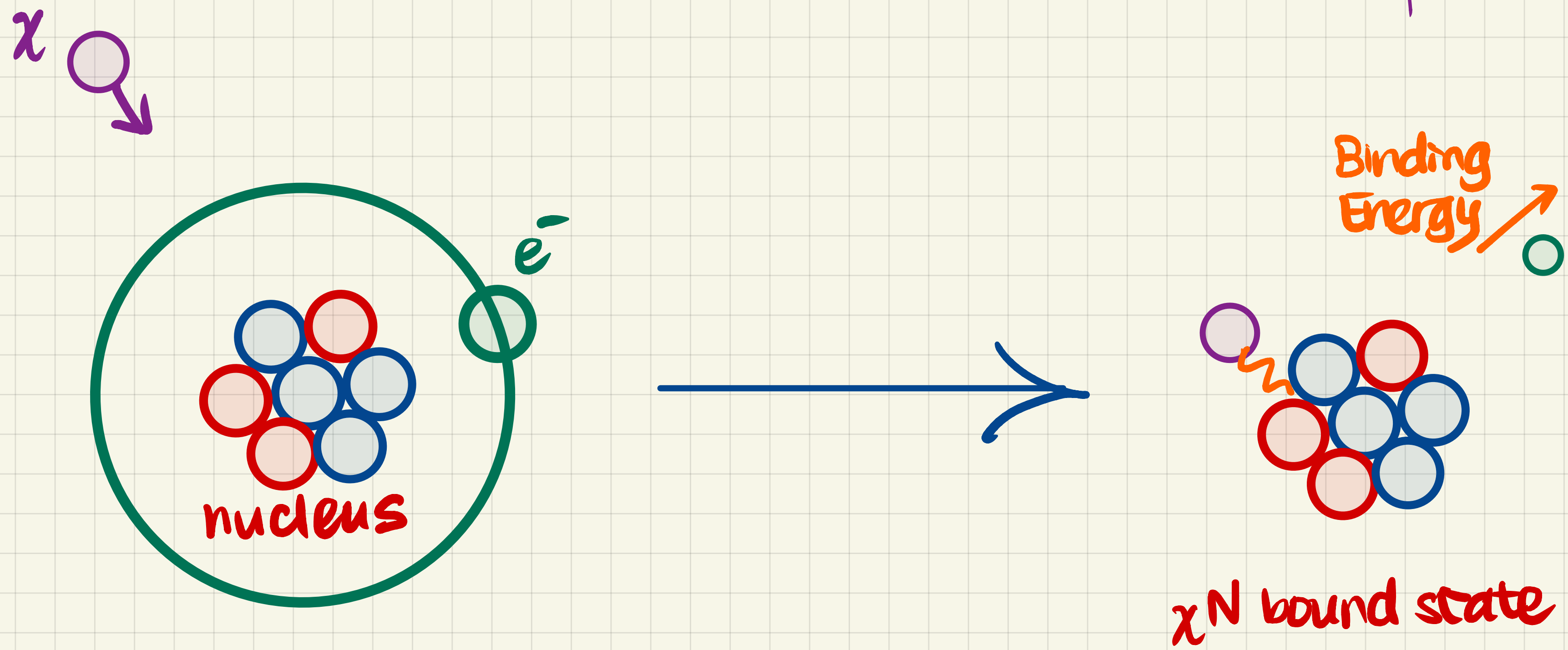
Absorption





Bound State Formation

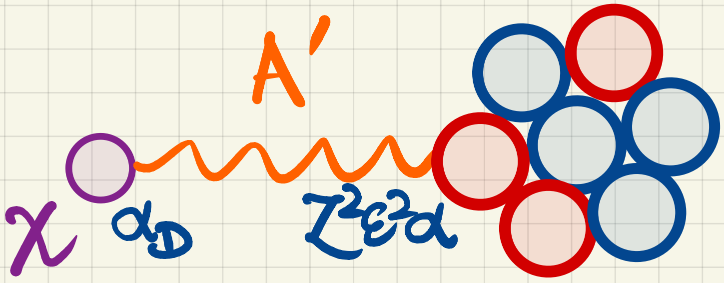
see also:
H. An+ 1209.6358
Fornal+ 2005.04240
Wallemacq+ 1307.7623
Khlopov+ 1012.0934



The Model

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

$$\mathcal{L} \supset -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 A_\mu^2$$
$$+ \bar{\chi}\left(i(\partial^\mu - i g_D A^\mu)\gamma_\mu - m_\chi\right)\chi$$



Yukawa Potential

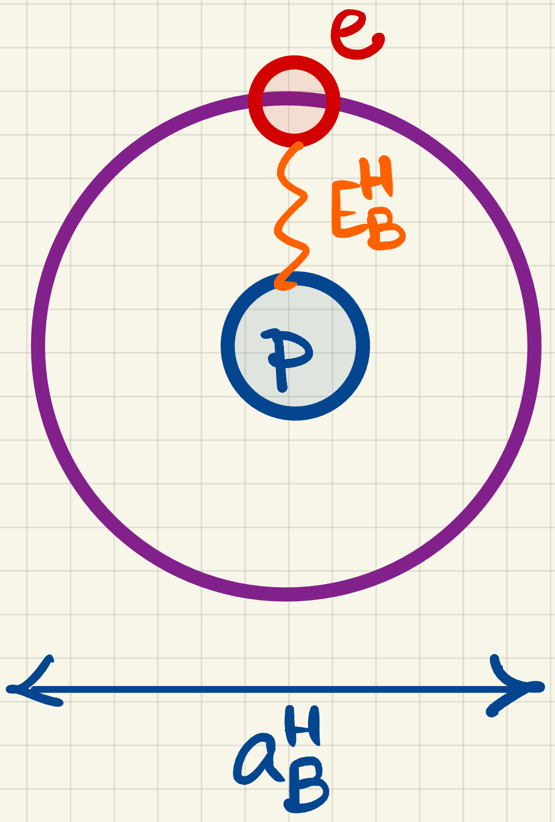
$$q_{eff} \equiv \varepsilon\sqrt{\frac{\alpha_D}{\alpha}}$$

$$V(r) = -\frac{\sqrt{\alpha_D Z^2 \varepsilon^2 \alpha}}{r} e^{-m_{A'} r} \equiv -\frac{Z q_{eff}\, \alpha}{r} e^{-m_{A'} r}$$

Target:

Find Yukawa bound state with $\mathcal{O}$(keV) binding energy — above threshold of Xenon1T.

Hydrogen: A Quick Revision



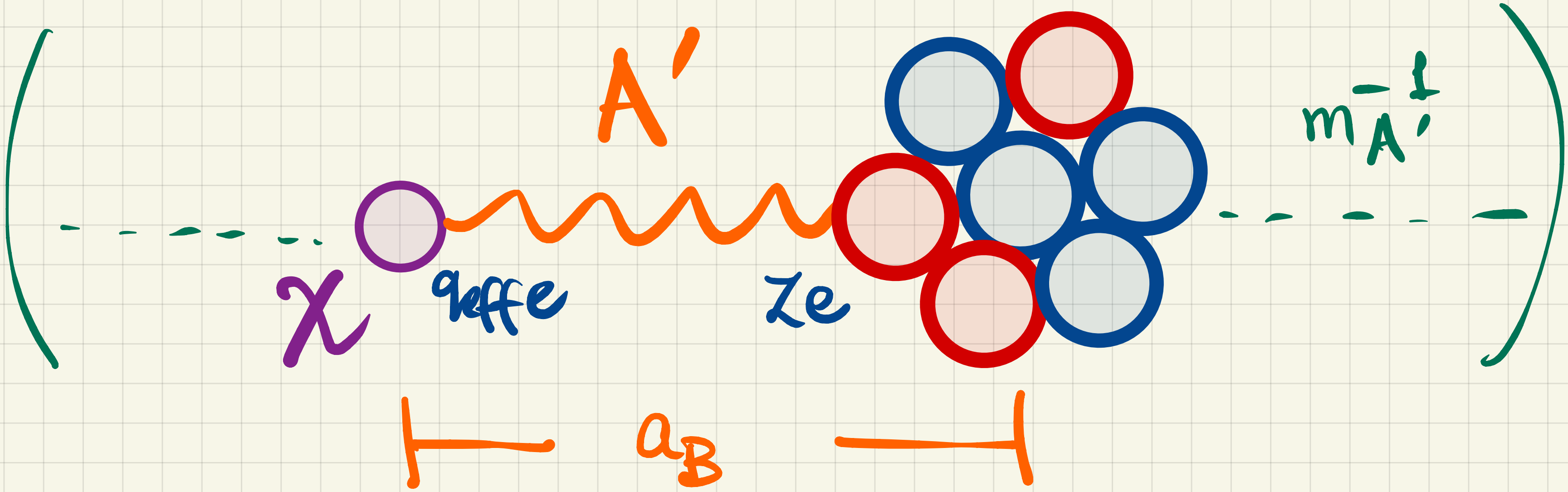
Binding Energy

$$E_B^H = \frac{1}{2}\alpha^2 \mu$$

Bohr Radius

$$a_B^H = \frac{1}{\alpha \mu}$$

Yukawa Bound State Condition



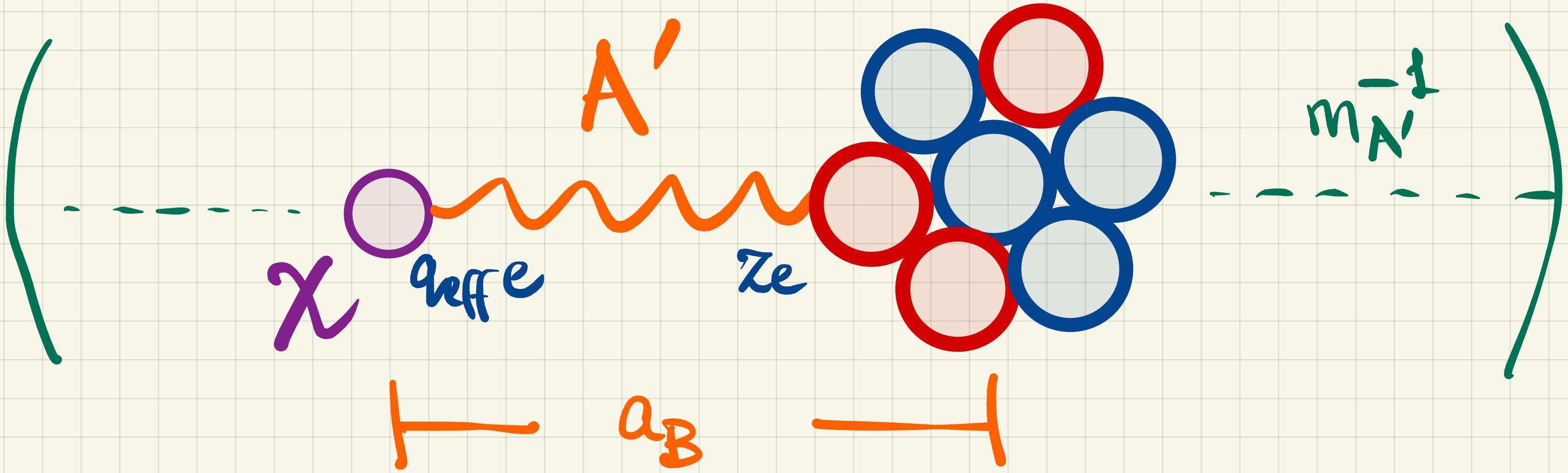
Force carrier has a finite range given by $m_{A'}^{-1}$.

Bound state only exists when:

$$a_B \lesssim m_{A'}^{-1} \Rightarrow Zq_{\rm eff}\alpha\mu \gtrsim m_{A'}$$

Easier to bind with heavier nuclei.

keV Binding Energy



For keV binding energy, we require

$$E_B \sim \frac{1}{2}(Z q_{\text{eff}}\alpha)^2\mu \sim \text{keV}$$

$$E_B \sim 2.5\,\text{keV}\left(\frac{q_{\text{eff}}}{5\times10^{-4}}\right)^2\left(\frac{Z}{54}\right)^2\left(\frac{\mu}{122\,\text{GeV}}\right)$$

xenon nucleus

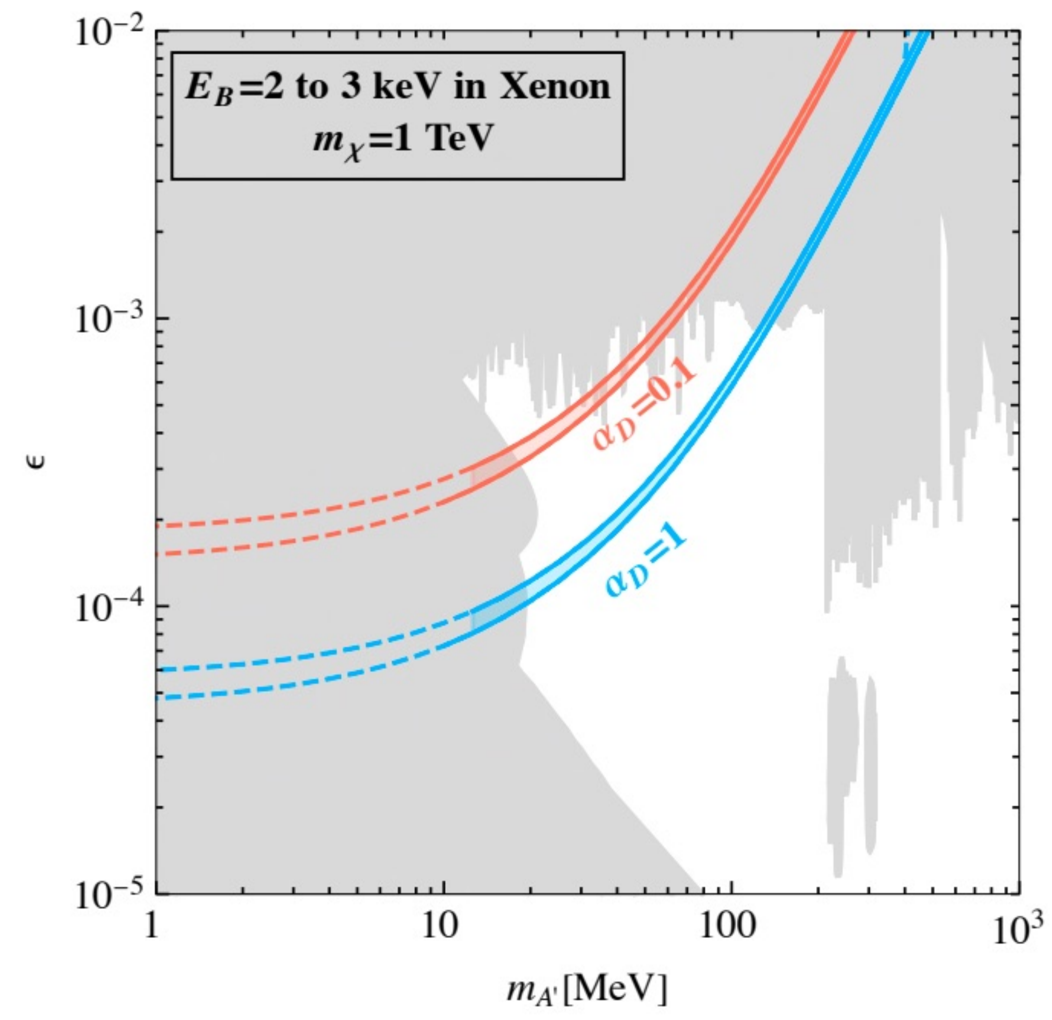
Dark Photon Properties

Kinetic Mixing Parameter

$$\varepsilon = q_{\text{eff}}\sqrt{\frac{\alpha}{\alpha_D}}$$

$$\sim 4\times10^{-4}\left(\frac{q_{\text{eff}}}{5\times10^{-4}}\right)\left(\frac{1}{\alpha_D}\right)^{1/2}$$

Visibly Decaying A′



Mass

$$m_{A'} \lesssim Z q_{\text{eff}}\,\alpha\,\mu$$

$$m_{A'} \lesssim 30\text{ MeV}\left(\frac{Z}{54}\right)\left(\frac{q_{\text{eff}}}{5\times10^{-4}}\right)\left(\frac{\mu}{122\text{ GeV}}\right)$$

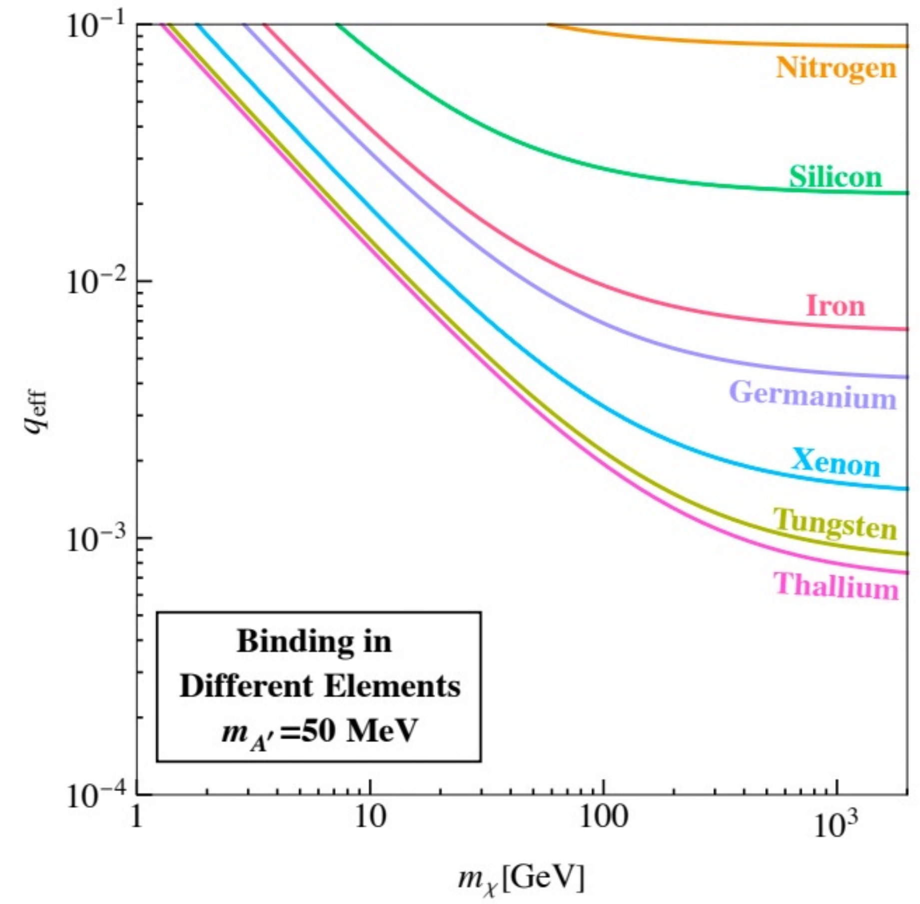
(for bound state to exist)

Preferential Binding

Bound state condition can be rewritten:

$$Z \gtrsim 54 \left(\frac{m_{A'}}{30\,\mathrm{MeV}}\right)\left(\frac{5\times 10^{-4}}{q_{\mathrm{eff}}}\right)\left(\frac{122\,\mathrm{GeV}}{\mu}\right)$$

At fixed $m_{A'}$, we require larger couplings q_{eff} to form bound states with lighter nuclei.

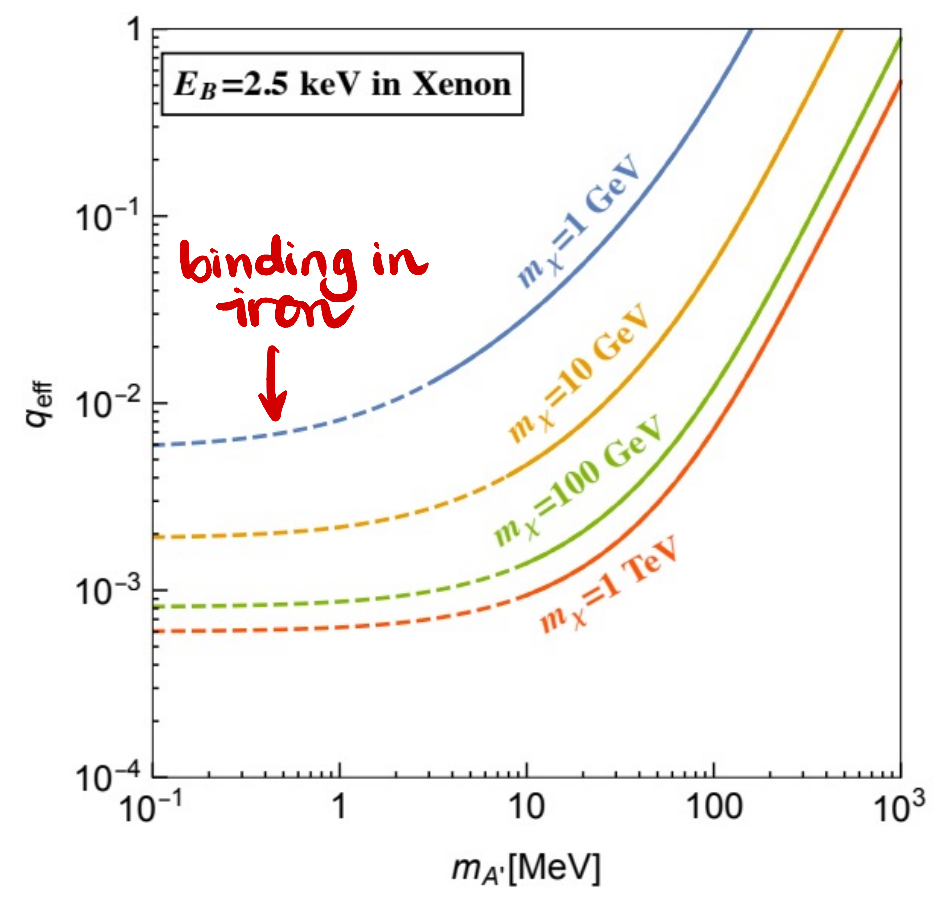


Preferential Binding

Suppose a bound state in Xe exists with $E_B^{Xe} = 2.5\,\text{keV}$.
Then χ can only bind with nuclei N where:

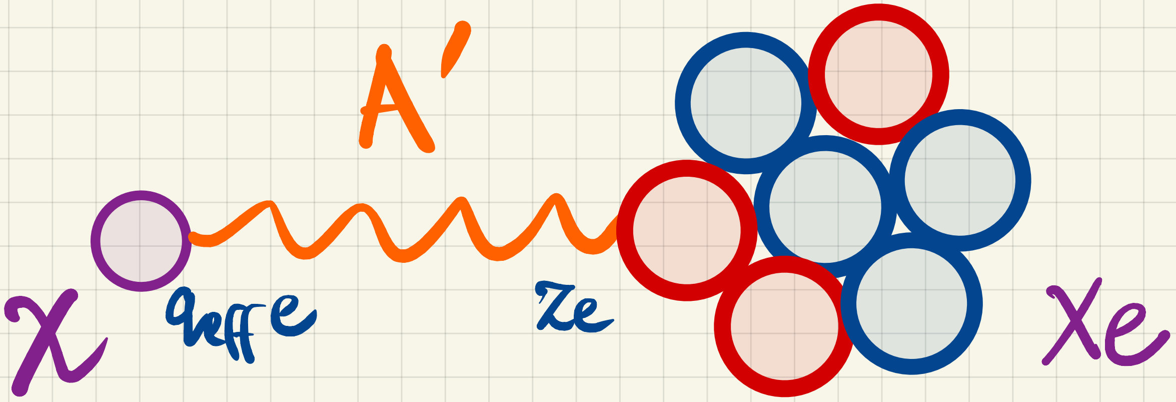
$$Z_N \gtrsim 54 \left(\frac{m_{A'}}{30\,\text{MeV}}\right)\left(\frac{2.5\,\text{keV}}{E_B^{Xe}}\right)^{1/2}\left(\frac{\mu_{\chi,Xe}}{122\,\text{GeV}}\right)^{1/2}\left(\frac{122\,\text{GeV}}{\mu_{\chi N}}\right)$$

Choice of $m_{A'}$ prevents binding in light elements that are abundant in direct detection overburden.



binding in iron

Taking Stock



To produce keV binding energy bound state in Xe,

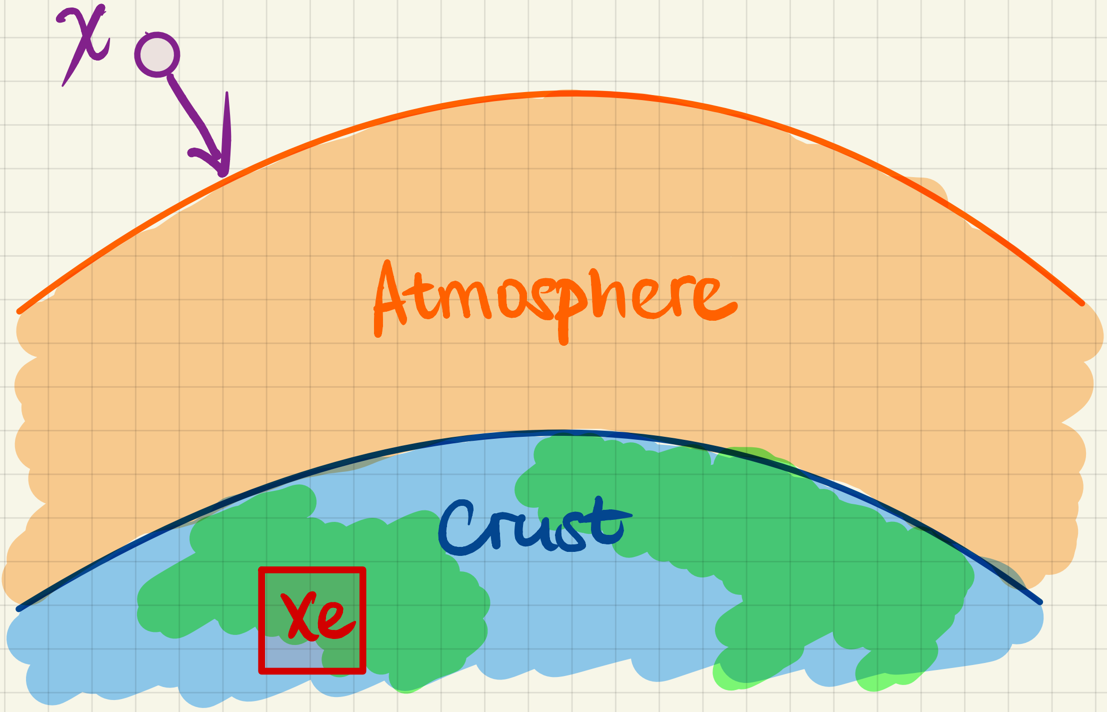
$m_{A'}$: ~50 MeV

m_χ : GeV — 10 TeV

$q_{eff} \gtrsim 10^{-3}$ (large interaction)

No binding in elements lighter than iron.

Momentum Transfer Cross Section



Negligible binding with light elements in atmosphere and crust.

Large scattering rate.

Momentum Transfer Cross Section

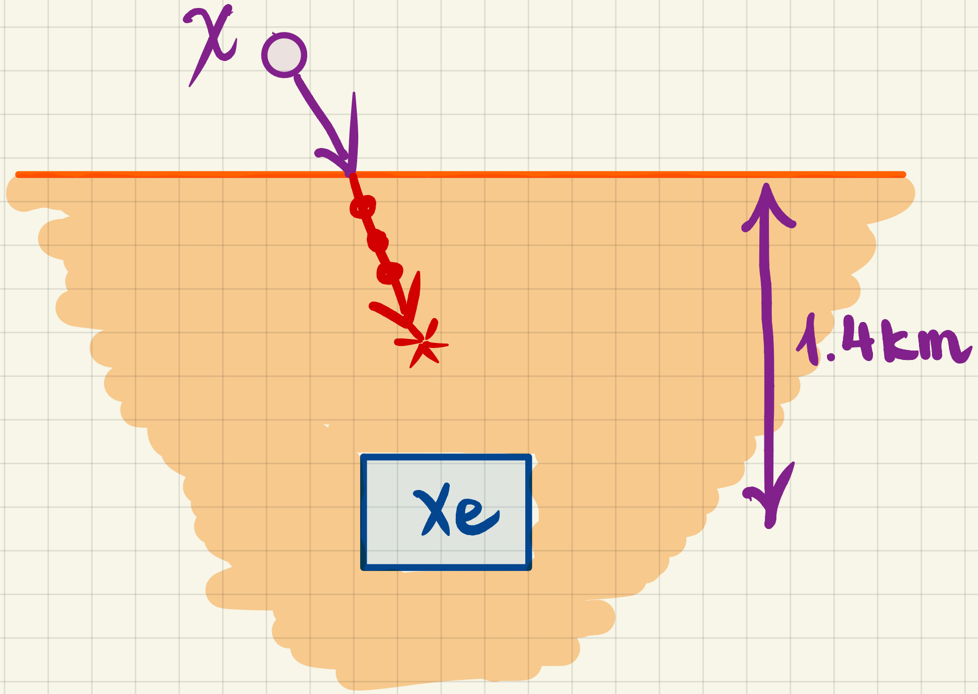
(Assuming Born approx.)

$$\sigma_T \sim \frac{16\pi Z^2 \alpha^2 q_{eff}^2 \mu^2}{m_{A'}^4}$$

$$\sim 2 \times 10^{-26}\,\text{cm}^2 \left(\frac{q_{eff}}{10^{-3}}\right)^2 \left(\frac{50\,\text{MeV}}{m_{A'}}\right)^4 \left(\frac{\mu_{\chi Si}}{m_{Si}}\right)^2$$

Assuming silicon

Thermalization



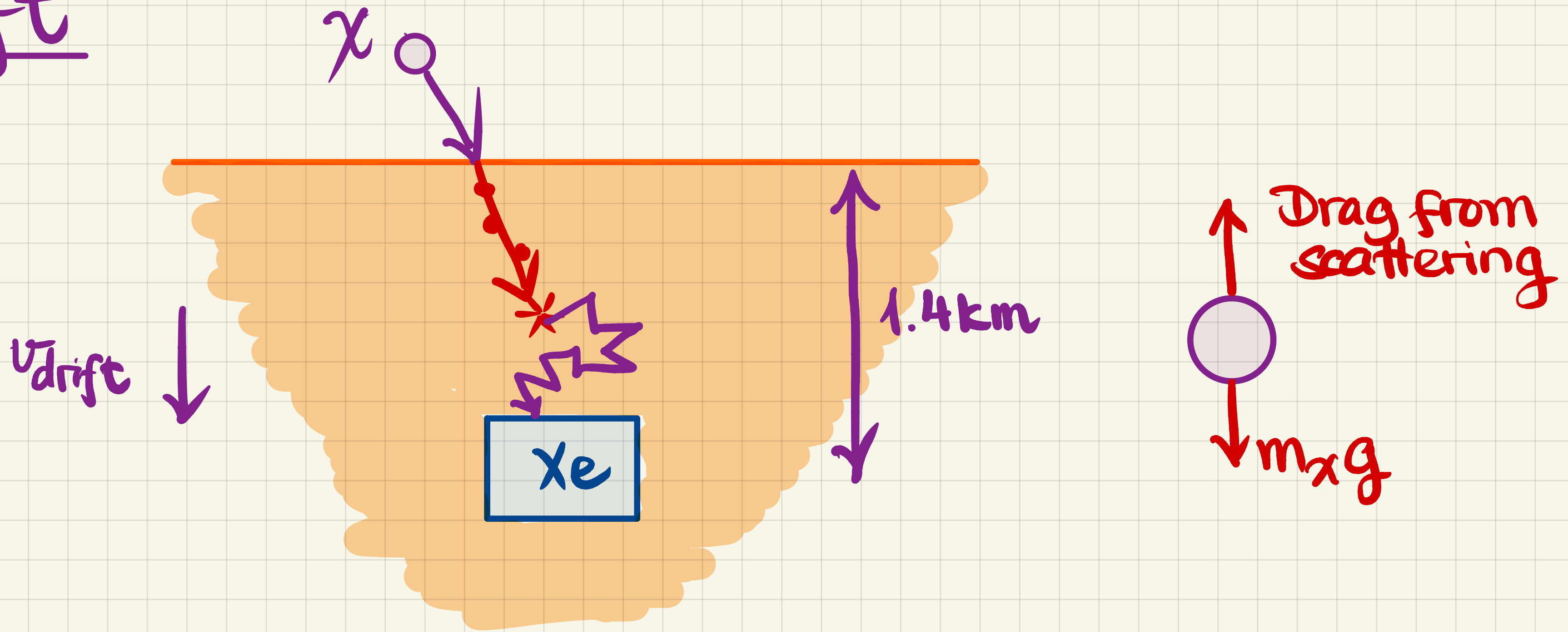
Thermalization occurs after multiple scatters:

$$\ell_{\mathrm{therm}} \sim \frac{m_\chi + m_{Si}}{\mu_{\chi,Si}} \frac{1}{n_{Si}\sigma_T} \sim 30\,\mathrm{m} \left(\frac{m_\chi + m_{Si}}{1\,\mathrm{TeV}}\right)\left(\frac{26\,\mathrm{GeV}}{\mu_{\chi,Si}}\right)\left(\frac{10^{-24}\,\mathrm{cm}^2}{\sigma_T}\right)$$

n_{Si} $\sim 10^{22}\,\mathrm{cm}^3$

$$\ell_{\mathrm{therm}} \sim \begin{cases} 10\,\mathrm{cm}, & m_\chi = 1\,\mathrm{GeV} \\ 10\,\mathrm{m}, & m_\chi = 1\,\mathrm{TeV} \end{cases} \ll 1\,\mathrm{km}$$

Drift



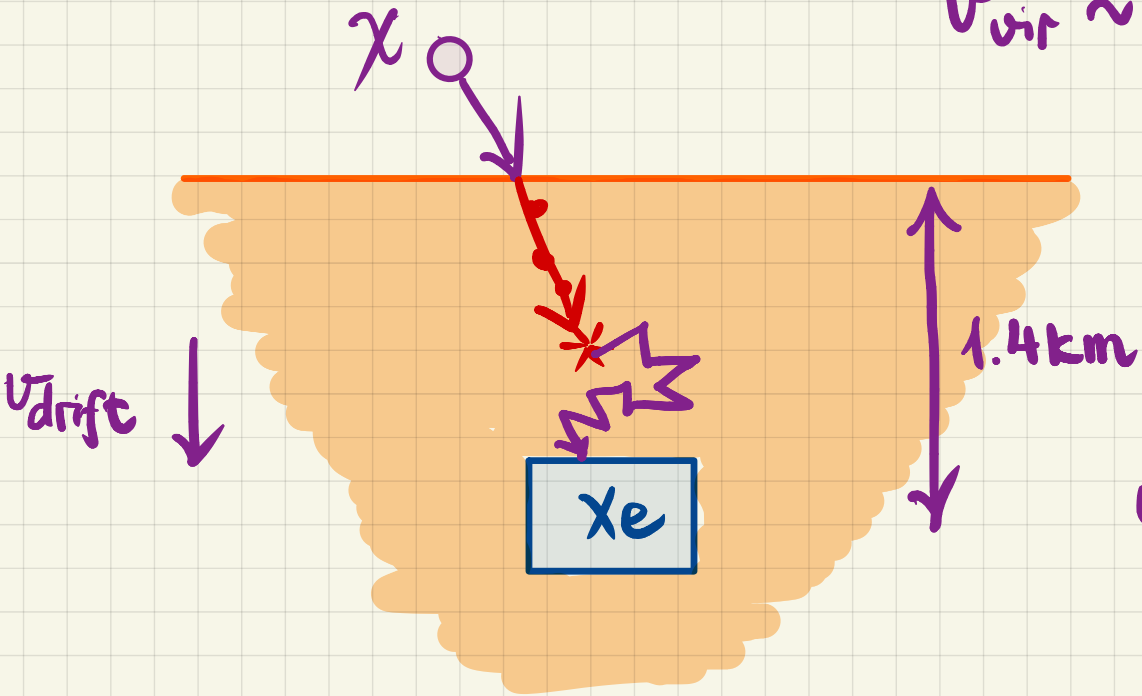
Undergoes biased random walk,
with downward drift at terminal velocity

$$v_{drift} \sim \frac{m_\chi}{\mu_{\chi,Si}} \frac{g}{n_{Si}\,\sigma_T\, v_{th}} \sim 10^{-8} \left(\frac{m_\chi}{1\,\mathrm{TeV}}\right)^{3/2} \left(\frac{26\,\mathrm{GeV}}{\mu_{\chi,Si}}\right) \left(\frac{10^{-24}\,\mathrm{cm}^2}{\sigma_T}\right)$$

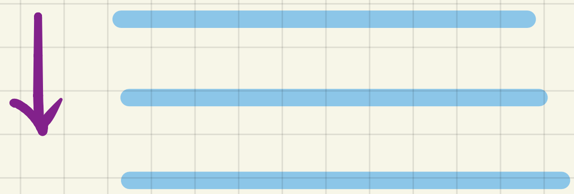
$$v_{drift} \sim \begin{cases} 10^{-13}, & m_\chi = \mathrm{GeV} \\ 10^{-9}, & m_\chi = \mathrm{TeV} \end{cases}$$

Traffic Jam

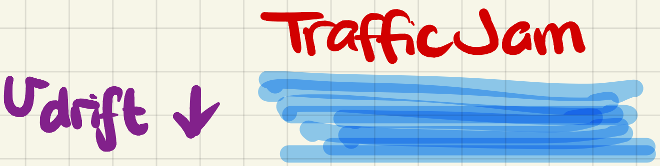
Pospelov & Ramani
arXiv:2012.03957



$v_{vir} \sim 10^{-3}$



$$n_{vir} \sim \frac{f_\chi}{m_\chi}\, 0.3\, \frac{\text{GeV}}{\text{cm}^3}$$

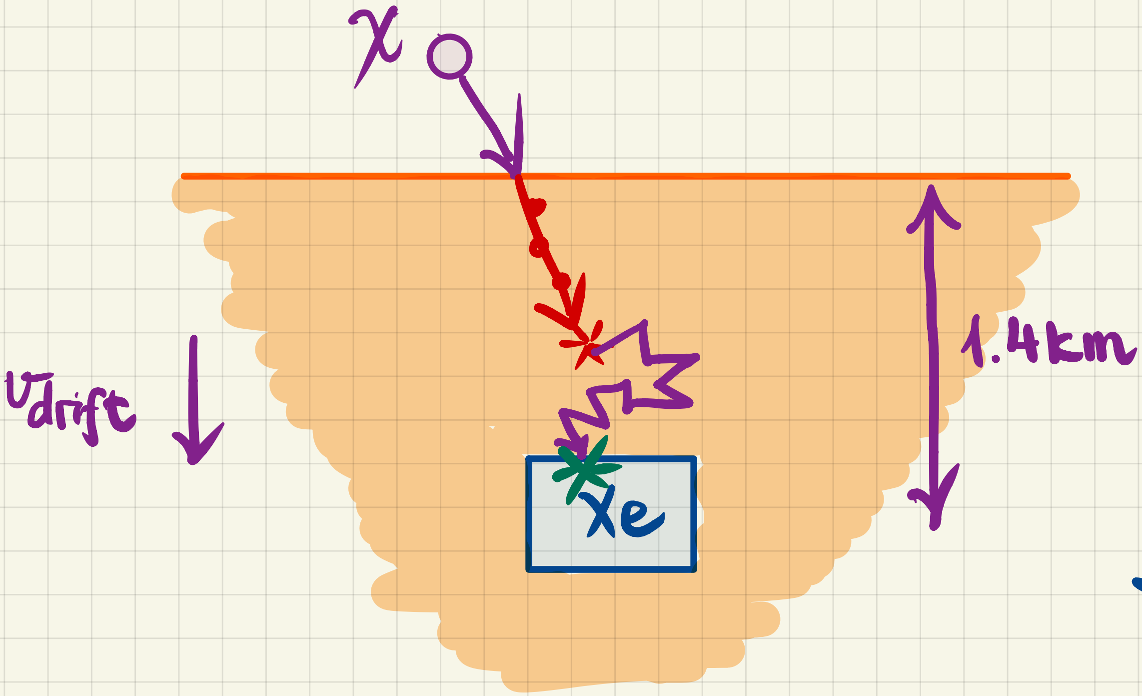


Accumulation of DM by flux conservation:

$$\boxed{n_{vir}\, v_{vir} = n_{detector}\, v_{drift}}$$

$$n_{detector} \sim f_\chi \times \begin{cases} 10^8\,\text{cm}^{-3},\ m_\chi = \text{GeV} & \quad n_{vir} \sim f_\chi\, 10^{-1}\,\text{cm}^{-3} \\ 10^2\,\text{cm}^{-3},\ m_\chi = \text{TeV} & \quad n_{vir} \sim f_\chi\, 10^{-4}\,\text{cm}^{-3} \end{cases}$$

Bound State Formation



Encounters first large concentration of heavy nuclei in Xenon1T:

Bound state can form!

$(\text{size of Xe})^{-1}$ $(\text{size of bound state})^{-1}$

$$\sigma_B v_{rel} \sim \frac{(Z\alpha m_e)^5}{(2\mu_{\chi,Xe}E_B)^{7/2}}\left(\frac{\mu_{\chi,Xe}}{m_{Xe}}\right)^4 \times O(10) \text{ form factors}$$

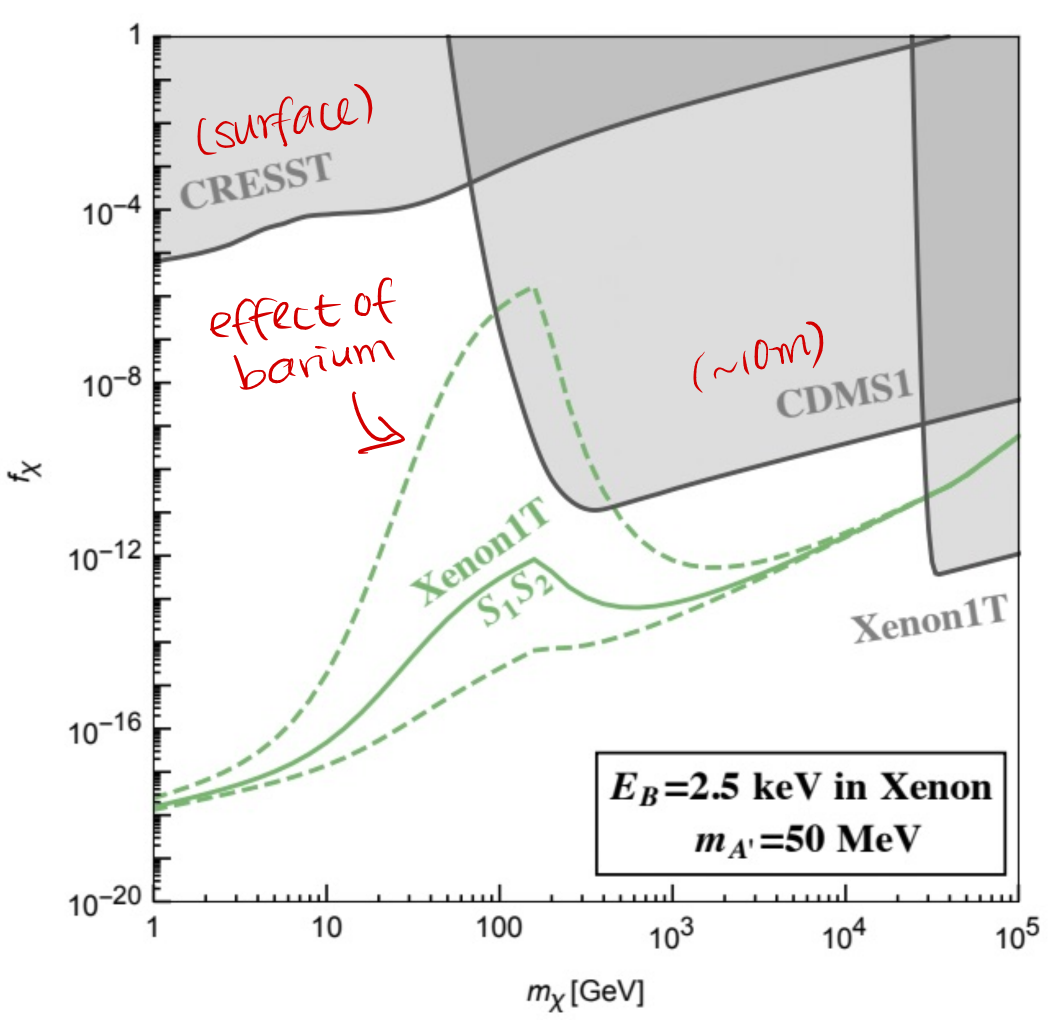
$$\sim 6\times 10^{-34}\,\text{cm}^2\left(\frac{\mu_{\chi,Xe}}{100\,\text{GeV}}\right)^{0.55}$$

Signal

Signal Rate

$$\sim 300\ \text{tonne}^{-1}\,\text{yr}^{-1}\left(\frac{f_\chi}{10^{-18}}\right)$$

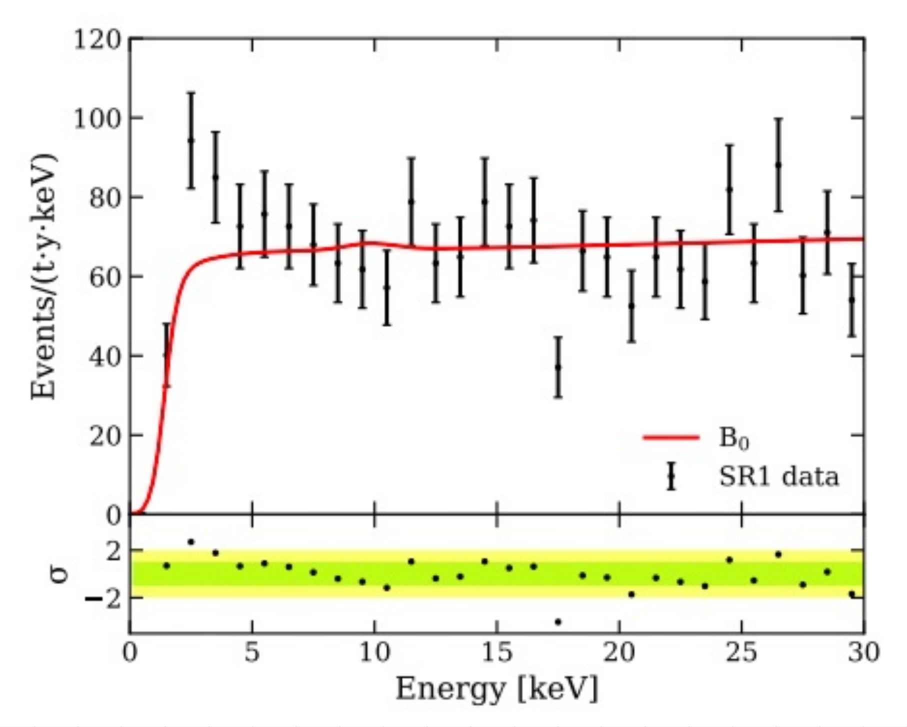
$$\times\left(\frac{n_{\text{detector}}}{10^{8}\,\text{cm}^{-3}}\right)\left(\frac{\sigma_B v_{\text{rel}}}{6\times10^{-34}\,\text{cm}^2}\right)$$

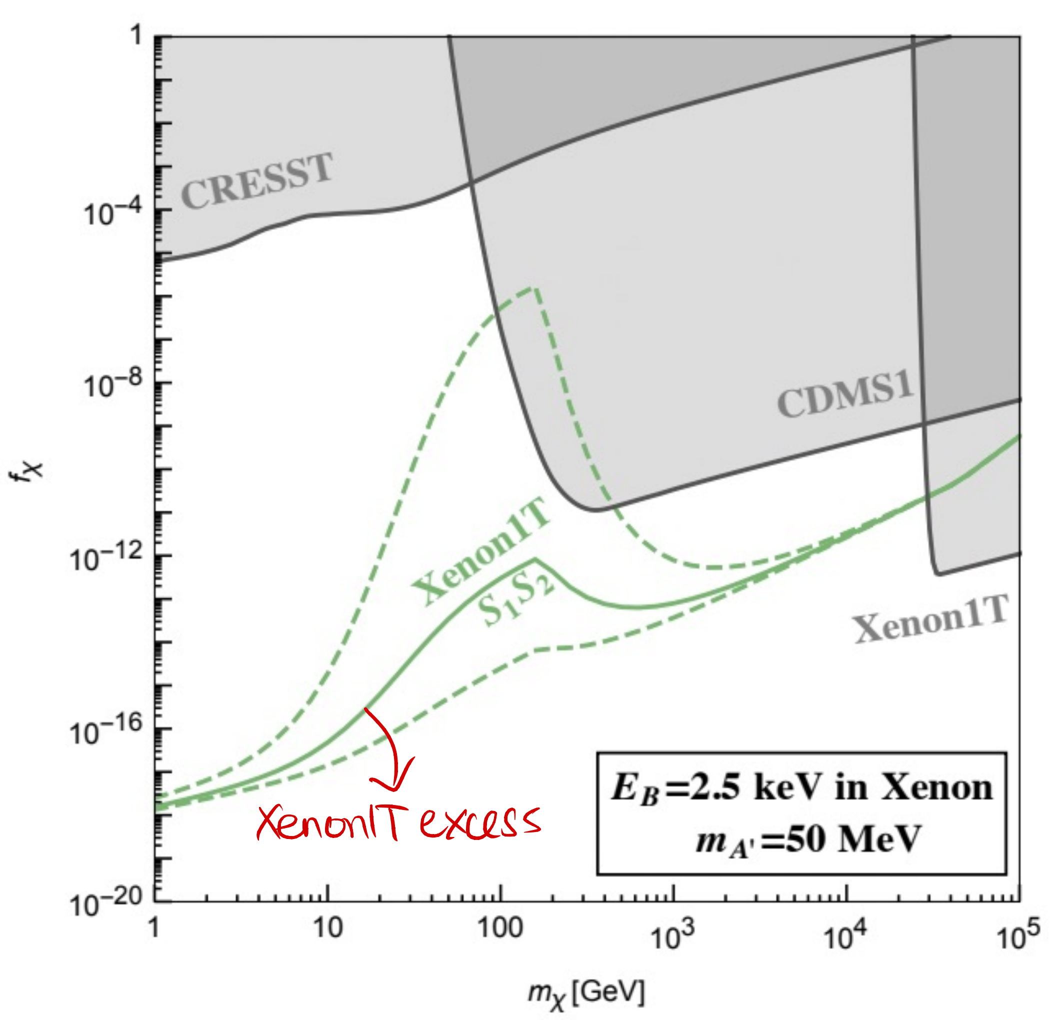


Constraints from experiments above thermalization length.

Signal

Xenon1T Collab.
arXiv:2006.09721





Xenon1T excess

Signal of $\sim 100\ \text{tonne}^{-1}\,\text{yr}^{-1}$ can produce signal consistent with Xenon1T excess.

Takeaways

- Bound state formation: novel direct detection electron recoil signals.
- Simple kinetic mixing model: $m_{A'} \sim 50\,\text{MeV}$, $g_{\text{eff}} \sim 10^{-3}$, m_χ: GeV — TeV, leads to keV scale binding energy.
- Naturally obtain preferential binding to heavier elements.
- Large interaction rate: produces traffic jam due to thermalization.
- Direct detection sensitive to small subcomponent of dark matter forming bound states: could be responsible for Xenon1T excess.

Backup — Formation Cross Section

$$\sigma_S v_{rel} = \frac{4\pi (Z\alpha)^2}{9} \left(\frac{\mu}{m_N}\right)^4 \left| \int dr\, r^4 R^{\chi}_{bs}(r)\, G(r) \right|^2$$

$$\times \sum_n 2 m_e p_e \left| \psi^*_{ef}(0)\, R_{n0}(0) \right|^2$$

$$\sim 7 \times 10^{-34}\,\mathrm{cm}^2 \left(\frac{Z}{54}\right)^5 \left(\frac{122\,\mathrm{GeV}}{m_N}\right)^4 \left(\frac{2.5\,\mathrm{keV}}{E_B}\right)^{7/2} \left(\frac{\mu}{100\,\mathrm{GeV}}\right)^{1/2}$$

$$\left(\frac{F^2_{\chi,s}}{49}\right) \left(\frac{F^2_e}{0.5}\right)$$