Dark magnetic dipole property in fermionic absorption

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Outline

- Motivation
- The dark photon model with magnetic dipole moment
- DM absorption by nuclear targets
- DM absorption by electron targets
- Summary

Motivation

- Existence evidences of DM:
  - Rotation curve of spiral galaxies
  - Gravitational lensing
  - Larger and cosmological scales
  - CMB anisotropies

  etc.

⚠ Terrestrial experiments give null results!

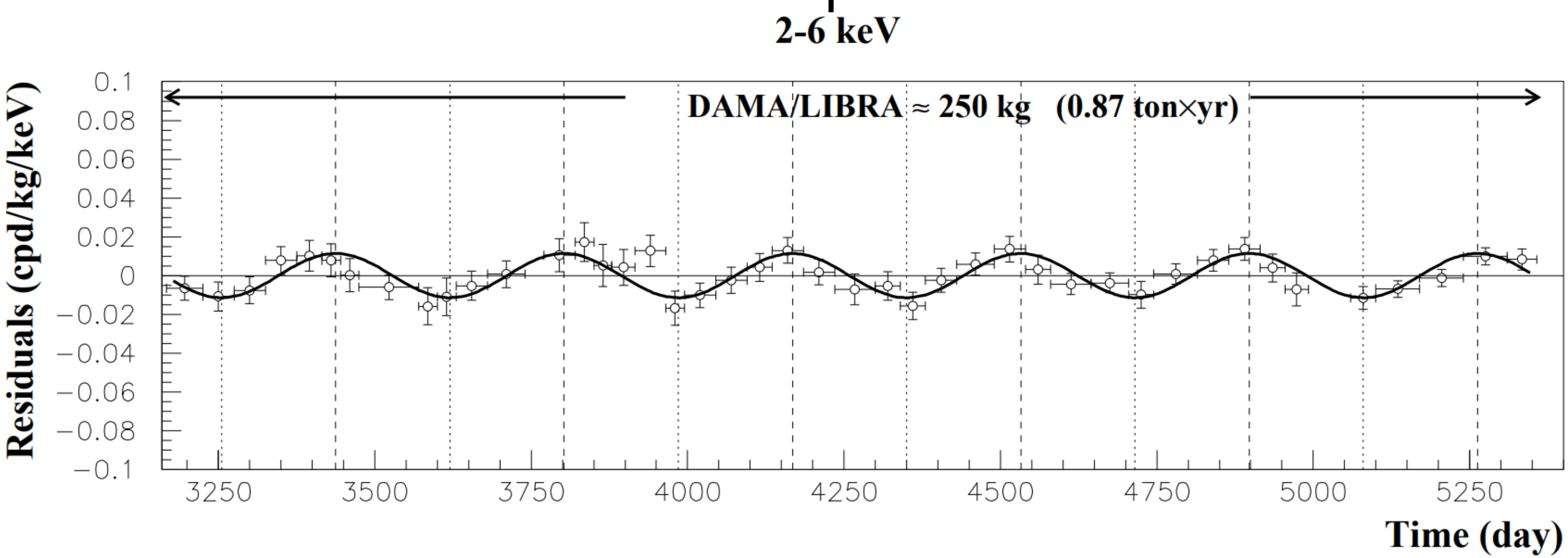
- DAMA collaboration, R. Bernabei et al. Phys. Lett. B 480 (2000) 23–31.

  8.9 σ C.L. for DM annual modulation signature in the galactic halo [1002.1028]

Motivation

Rotation curve of spiral galaxies

Gravitational lensing



8.9 σ C.L. for DM annual modulation signature in the galactic halo [1002.1028]

Motivation

could have off-diagonal magnetic dipole [hep-ph/0003010]]

- To explain the DAMA signal, the inelastic DM transition which induced by dark magnetic dipole is a good idea.

(dipole-charge)

[1007.4200] & [1007.4345] -- dipole-dipole NaI→Xe, Ar, W...

$$\chi + N(e) \to \nu + N(e)$$

A typical scattering of fermionic absorption

[1905.12635], [1908.10861] [2011.01940]. J. A. Dror et al.

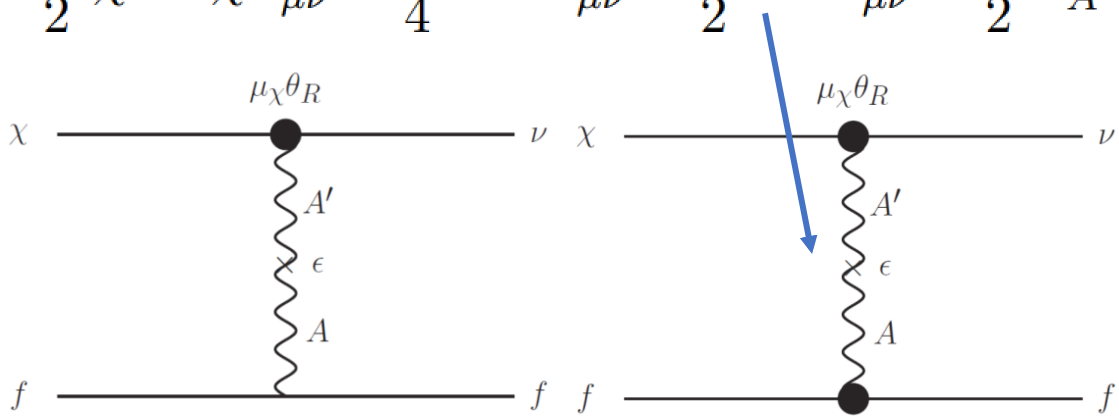
$$E_R = m_\chi^2 / 2m_{N,e}$$

The localized recoil energy of nucleus or electron which gives a peak-like signature in scattering rate.

The dark photon model with magnetic dipole moment

- We consider a Dirac fermion DM charged under a dark gauge group U(1)' and the magnetic dipole operator.

$$\mathcal{L} \supset \frac{\mu_\chi}{2}\bar{\chi}\sigma^{\mu\nu}\chi F'_{\mu\nu} + \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} \ ,$$



$$-e\epsilon A'_\mu J^\mu_{em}$$

$$\mathcal{L}_{eff} \supset \frac{\epsilon e Q_f \mu_\chi \theta_R}{q^2 - m^2_{A'}} q^\mu \overline{\chi_L}\sigma_{\mu\nu}\nu_R \bar{f}\gamma^\nu f + h.c. \ ,$$

dipole-charge

$$\frac{\epsilon \mu_\chi \mu_N \theta_R}{q^2 - m^2_{A'}} q^\mu q^\alpha g^{\nu\beta} \overline{\chi_L}\sigma_{\mu\nu}\nu_R \bar{N}\sigma_{\alpha\beta}N + h.c.$$

dipole-dipole

$$\chi + N \to \nu + N$$

DM absorption by nuclear targets

- The differential scattering cross section induced by neutral current (NC)

$$E_R^0 = m_\chi^2/2m_N$$

$$\frac{d\sigma_{NC}}{dE_R} = \frac{d\sigma_{DC}}{dE_R} + \frac{d\sigma_{DD}}{dE_R}$$

$$= \frac{\alpha \mu_\chi^2 \theta_R^2 \epsilon^2 m_\chi}{v m_N (m_{A'}^2 + 2m_N E_R)^2} Z^2 F_Z^2(E_R)\delta(E_R - E_R^0)$$

dipole-charge

$$\Big(6m_N^2 m_\chi E_R - 8m_N^2 E_R^2 - m_N m_\chi^3 + 4m_N m_\chi^2 E_R - 2m_N m_\chi E_R^2 + m_\chi^3 E_R\Big)$$

$$+ \frac{\mu_\chi^2 \mu_N^2 \theta_R^2 \epsilon^2 m_\chi E_R}{2\pi v (m_{A'}^2 + 2m_N E_R)^2} \frac{I+1}{3I} F_D^2(E_R)\delta(E_R - E_R^0)$$

dipole-dipole

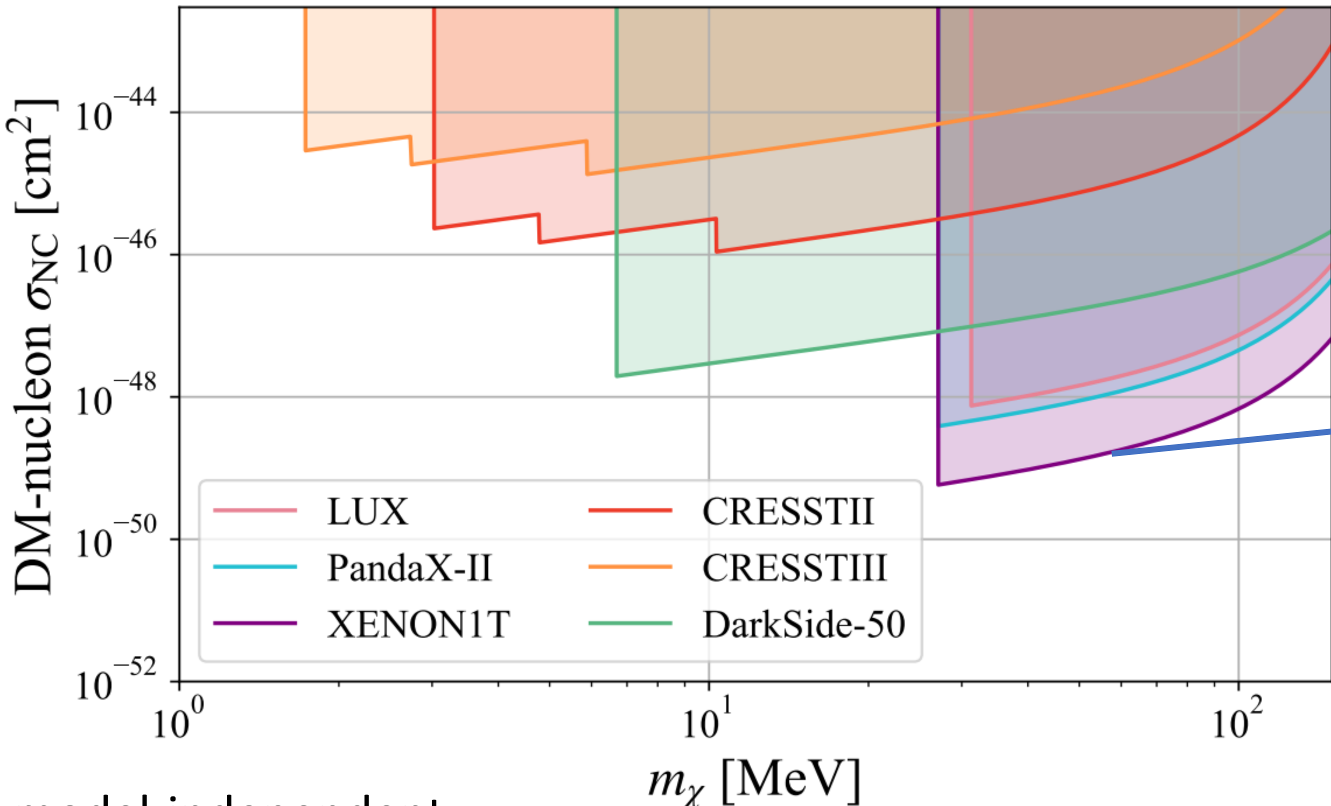
$$\Big(-4m_N^2 E_R^2 + 8m_N m_\chi^2 E_R - 8m_N m_\chi E_R^2 + 2m_N E_R^3 + m_\chi^4 + 4m_\chi^3 E_R - 3m_\chi^2 E_R^2\Big),$$

$$R = \frac{\rho_\chi}{m_\chi}\sigma_{NC} Z^2 \sum_j N_{T,j} F_j(q)^2 \Theta(E_{R,j}^0 - E_{th}),$$

[1908.10861].

$$\chi + N \to \nu + N$$

DM absorption by nuclear targets



$$m_\chi = \sqrt{2 m_N E_{th}}$$

XENON1T can probe the DM mass above 27 MeV.

- model-independent

$$R = \frac{\rho_\chi}{m_\chi} \sigma_{NC} Z^2 \sum_j N_{T,j} F_j(q)^2 \Theta(E^0_{R,j} - E_{th}) \ ,$$

[1908.10861].

$$\chi + N \to \nu + N$$

DM absorption by nuclear targets

define $U = \mu_\chi \epsilon \theta_R$

$$\frac{d\sigma_{NC}}{dE_R} = \frac{d\sigma_{DC}}{dE_R} + \frac{d\sigma_{DD}}{dE_R}$$

→ truncated Maxwell distribution f(v)

$$= \frac{\alpha \mu_\chi^2 \theta_R^2 \epsilon^2 m_\chi}{v m_N (m_{A'}^2 + 2m_N E_R)^2} Z^2 F_Z^2(E_R) \delta(E_R - E_R^0)$$
$$\left(6m_N^2 m_\chi E_R - 8m_N^2 E_R^2 - m_N m_\chi^3 + 4m_N m_\chi^2 E_R - 2m_N m_\chi E_R^2 + m_\chi^3 E_R\right)$$
$$+ \frac{\mu_\chi^2 \mu_N^2 \theta_R^2 \epsilon^2 m_\chi E_R}{2\pi v (m_{A'}^2 + 2m_N E_R)^2} \frac{I+1}{3I} F_D^2(E_R) \delta(E_R - E_R^0)$$
$$\left(-4m_N^2 E_R^2 + 8m_N m_\chi^2 E_R - 8m_N m_\chi E_R^2 + 2m_N E_R^3 + m_\chi^4 + 4m_\chi^3 E_R - 3m_\chi^2 E_R^2\right),$$

$$\frac{dR}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \int \frac{d\sigma}{dE_R} v f(\boldsymbol{v}) d^3\boldsymbol{v}$$

↓

$$\frac{dR_{DC}}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \sqrt{\frac{E_R}{2m_N}} \frac{e^2 U^2 m_N}{4\pi m_\chi p_\nu (m_{A'}^2 + 2m_N E_R)^2} Z^2 F_Z^2(E_R) \int d^3\boldsymbol{v} \frac{f(\boldsymbol{v})}{v} \Theta(v - v_{\min})$$
$$\times \left[6m_N^2 m_\chi E_R - 8m_N^2 E_R^2 - m_N m_\chi^3 + 4m_N m_\chi^2 E_R - 2m_N m_\chi E_R^2 + m_\chi^3 E_R\right], \quad (3.3)$$

$$\chi + N \to \nu + N$$

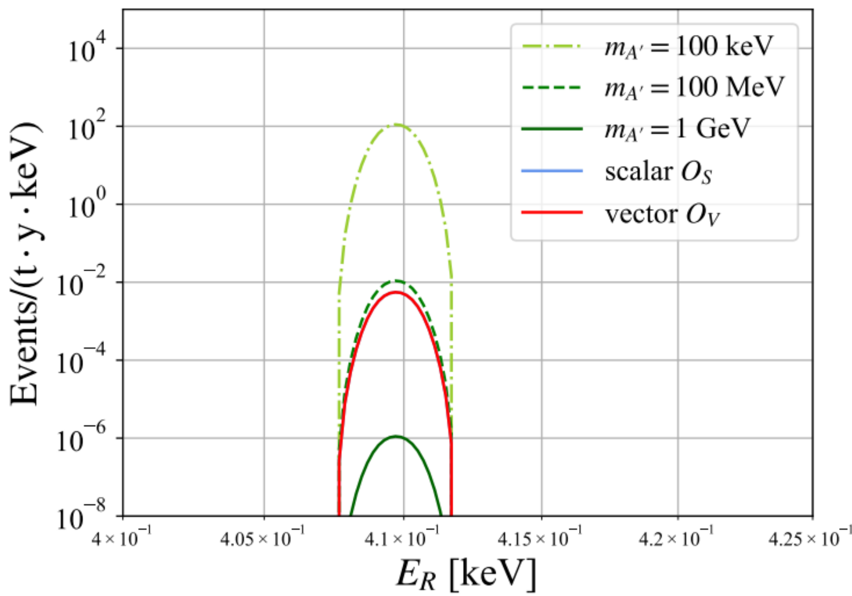
DM absorption by nuclear targets

$$\frac{dR_{DC}}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \sqrt{\frac{E_R}{2m_N}} \frac{e^2 U^2 m_N}{4\pi m_\chi p_\nu (m_{A'}^2 + 2m_N E_R)^2} Z^2 F_Z^2(E_R) \int d^3\boldsymbol{v} \frac{f(\boldsymbol{v})}{v} \Theta(v - v_{\min})$$
$$\times \left[6m_N^2 m_\chi E_R - 8m_N^2 E_R^2 - m_N m_\chi^3 + 4m_N m_\chi^2 E_R - 2m_N m_\chi E_R^2 + m_\chi^3 E_R\right], \quad (3.3)$$

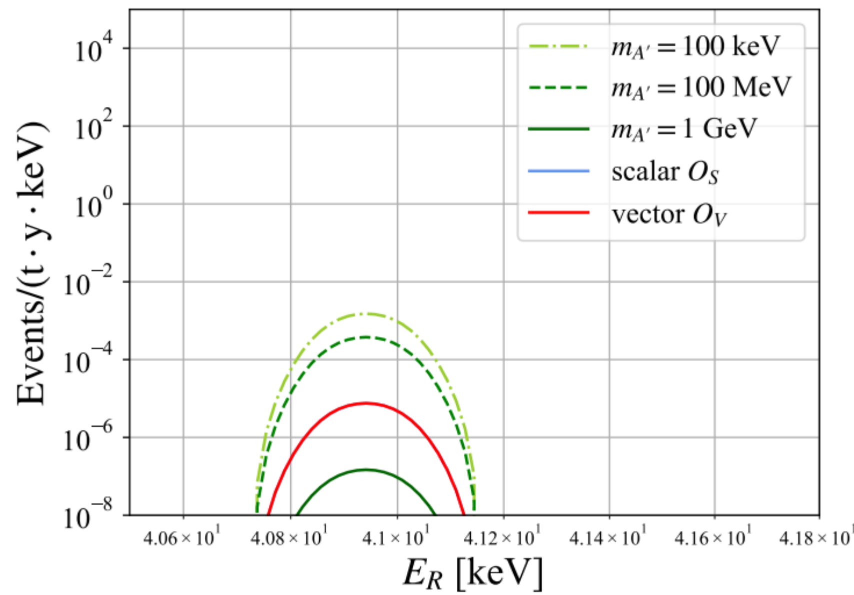
$e^2U^2 = 1/\Lambda^2 = 10^{-50}$ cm²

$$O_V = \frac{1}{\Lambda^2} (\bar{\chi}\gamma^\mu P_{L,R}\nu)(\bar{e}\gamma_\mu e),$$
$$O_S = \frac{1}{\Lambda^2} (\bar{\chi} P_{L,R}\nu)(\bar{e}e),$$

[2011.01940]

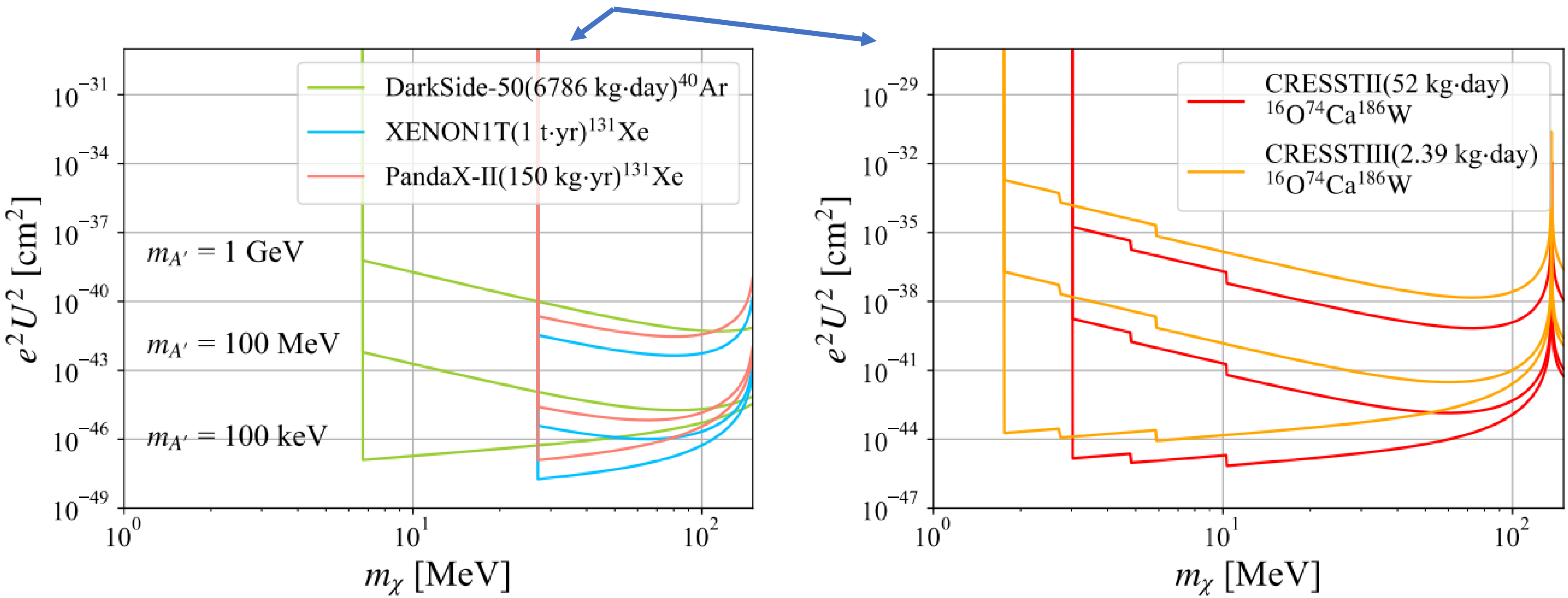


(a) m_χ = 10 MeV



(b) m_χ = 100 MeV

$$R_{DC} = N_T \left(\frac{\rho_\chi}{m_\chi}\right) \frac{e^2 U^2}{4\pi(m_{A'}^2 + m_\chi^2)^2} \left(2m_\chi^4\right) Z^2 F_Z^2(q) \Theta(E_R^0 - E_{th})$$

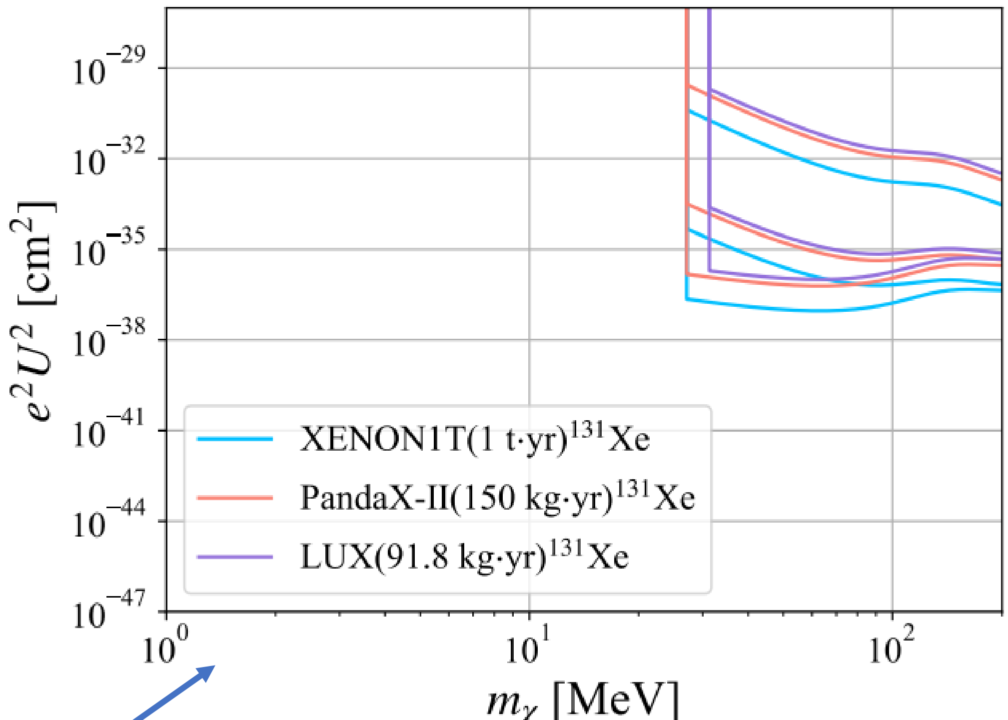


$$R_{DD} = N_T \left(\frac{\rho_\chi}{m_\chi}\right) \frac{\mu_N^2 U^2}{2\pi(m_{A'}^2 + m_\chi^2)^2} \frac{I+1}{3I} \left(\frac{m_\chi^3}{2m_N}\right) F_D^2(q) \frac{m_\chi^4}{2m_N^2} (8m_N^2 - m_\chi^2) \Theta(E_R^0 - E_{th})$$

$$F_D^2(q) = \left(0.4\frac{L(q)}{L(0)} + 0.6\sqrt{\frac{S(q)}{S(0)}}\right)^2$$

[1007.4200]

$$R_{DC} = N_T \left(\frac{\rho_\chi}{m_\chi}\right) \frac{e^2 U^2}{4\pi(m_{A'}^2 + m_\chi^2)^2} \left(2m_\chi^4\right) Z^2 F_Z^2(q) \Theta(E_R^0 - E_{th})$$



- No significant contribution from dipole-dipole interaction for the inelastic DM absorption.

- DM lifetime constraint is quite severe for the sensitive region of inelastic DM-nucleus scattering.

$$\Gamma(\chi \to \nu\gamma\gamma\gamma)$$

$$R_{DD} = N_T \left(\frac{\rho_\chi}{m_\chi}\right) \frac{\mu_N^2 U^2}{2\pi(m_{A'}^2 + m_\chi^2)^2} \frac{I+1}{3I} \left(\frac{m_\chi^3}{2m_N}\right) F_D^2(q) \frac{m_\chi^4}{2m_N^2} (8m_N^2 - m_\chi^2) \Theta(E_R^0 - E_{th})$$

$$F_D^2(q) = \left(0.4\frac{L(q)}{L(0)} + 0.6\sqrt{\frac{S(q)}{S(0)}}\right)^2$$

$$\chi + e \to \nu + e$$

DM absorption by electron targets

$$\frac{d\langle\sigma_{\rm ion}^{nl}v\rangle_{DC}}{dE_R} = \frac{\overline{|\mathcal{M}|^2}}{64\pi m_\chi m_e^2}\frac{q}{E_R}|f_{\rm ion}^{nl}(k',q)|^2\Theta(q)$$

$$= \frac{e^2U^2}{16\pi(m_{A'}^2 - m_\chi(m_\chi - 2q))^2}\frac{q}{E_R}\frac{m_\chi^2}{m_e^2}|f_{\rm ion}^{nl}(k',q)|^2\Theta(q)$$

$$\times[-4m_e m_\chi(m_e + m_\chi) - m_\chi^3 + 3(m_\chi^2 + 2m_e^2 + 4m_e m_\chi)q - 2(m_\chi + 4m_e)q^2]$$

→ Ionization form factor

($m_\chi \lesssim$ 50 keV)

$$|f_{\rm ion}^{nl}(k',q)|^2 = \frac{4k'^3}{(2\pi)^3}\sum_{l'L}(2l+1)(2l'+1)(2L+1)\times\begin{bmatrix} l & l' & L \\ 0 & 0 & 0\end{bmatrix}^2\left|\int r^2 dr R_{k'l'}(r)R_{nl}(r)j_L(qr)\right|^2$$

R. Essig et al.Physical Review Letters 109 (Jul, 2012) .

($m_\chi \gtrsim$ 50 keV)

$$|f_{\rm ion}^{nl}(k',q)|^2 = \frac{(2l+1)k'^2}{4\pi^3 q}\int_{|k'-q|}^{|k'+q|} kdk|\chi_{nl}(k)|^2$$

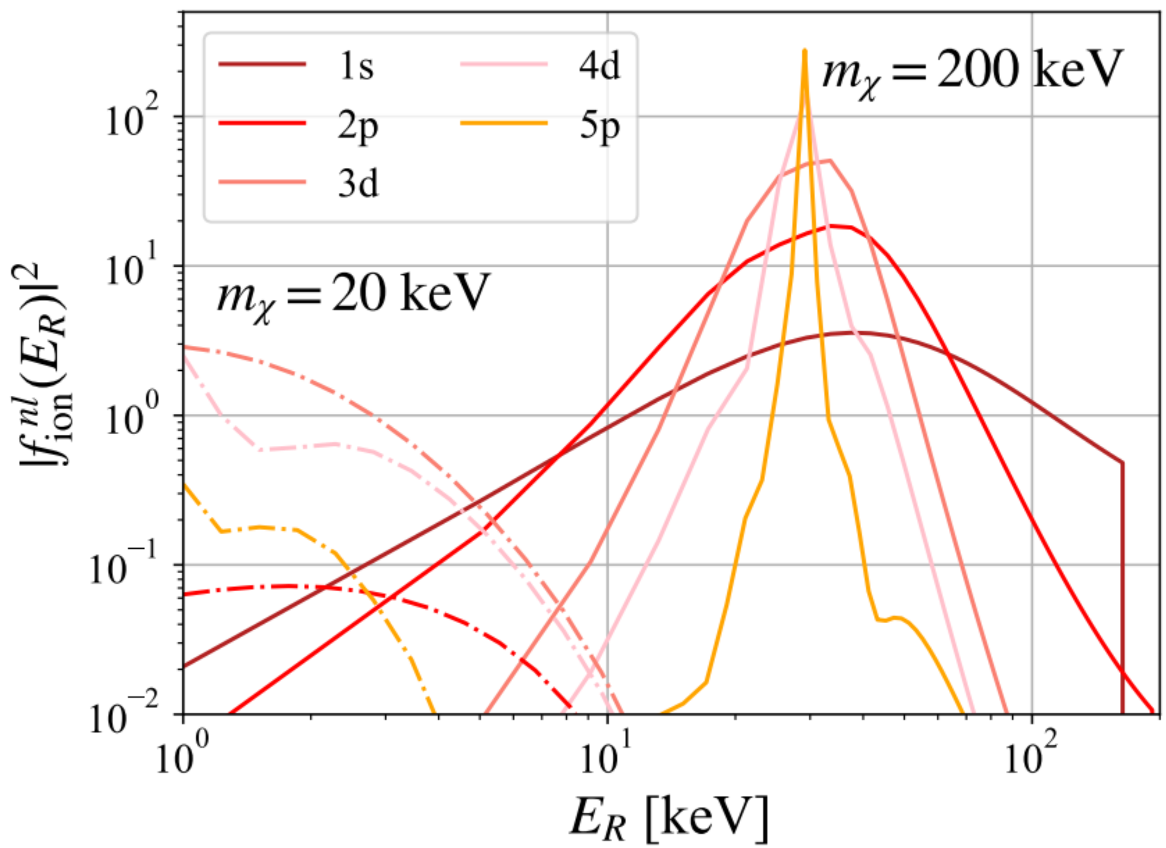
→ an analytical function in momentum space

R. Essig et al. Physical Review D 85 (Apr, 2012) .

Dark Matter Absorption by Electron Targets

$$\chi + e \to \nu + e$$

$\frac{d\langle\sigma_{\text{ion}}^{nl}v\rangle_{DC}}{dE_R}$



actor

$\chi + 4m_e)q^2]$

($m_\chi \gtrsim 50$

$|f_{\text{ion}}^{nl}(k', q$

$R_{k'l'}(r)R_{nl}(r)j_L(qr)\Big|^2$

ul, 2012) .

($m_\chi \lesssim 50$

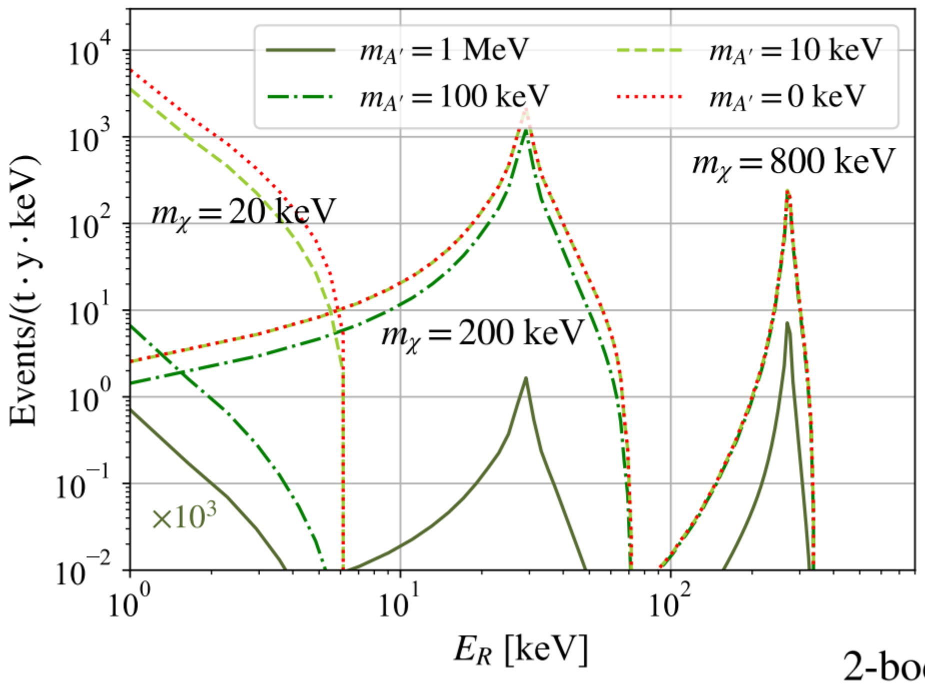
$|f_{\text{ion}}^{nl}(k', q$

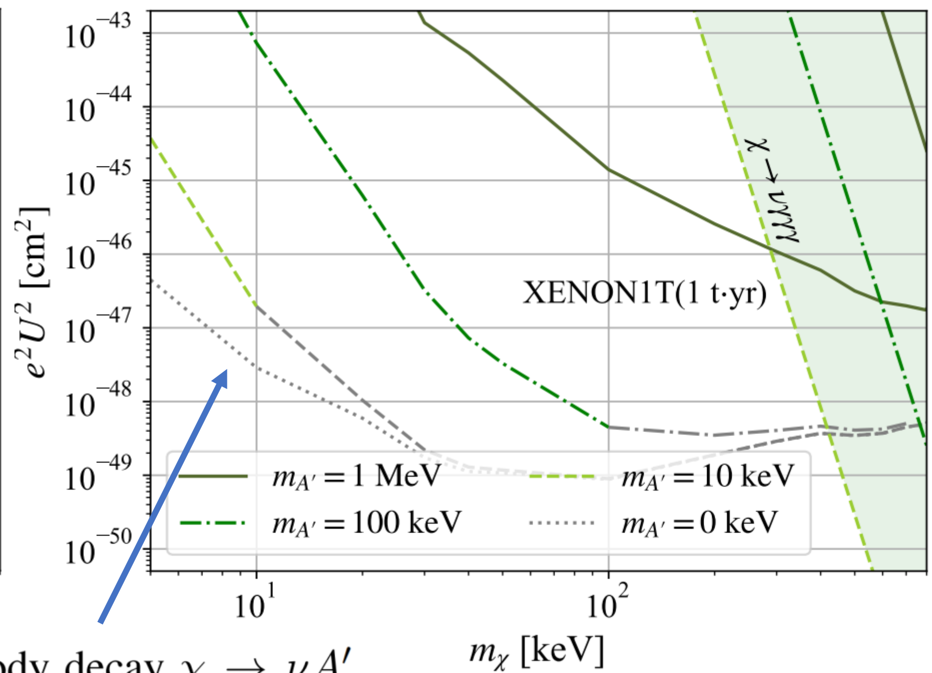
function in

space

R. Essig et al. Physical Review D 85 (Apr, 2012) .

The coupling e^2U^2 is fixed at 10^{-45} cm²





2-body decay $\chi \to \nu A'$

make the constraint more severe

- energy conservation:

$$q = m_\chi + E_B^{nl} - E_R > 0$$

$$\frac{dR_{\text{ion}}}{dE_R} = N_T \frac{\rho_\chi}{m_\chi} \sum_{nl} \frac{d\langle\sigma_{\text{ion}}^{nl} v\rangle_{DC}}{dE_R}$$

- DM lifetime should be longer than

$$t_{\text{Universe}} = 4.4 \times 10^{17} \text{ sec}$$

$$\Gamma(\chi \to \nu\gamma\gamma\gamma) \simeq 10^{-32}\,\text{s}^{-1} \left(\frac{m_\chi}{100\text{ keV}}\right)^{15} \left(\text{TeV} \cdot eU\right)^2 \left(\frac{\text{GeV}}{m_{A'}}\right)^4$$

[1905.12635].

Summary

- The fermionic DM absorption by nucleus or electron targets provides a distinctive signal to search for sub-GeV DM.
- Inelastic DM-nuclear absorption scattering is severely limited by DM lifetime.
- The absorption of DM by bound electron induces ionization signal and is sensitive to sub-MeV DM mass below 100 keV. For extremely small dark photon mass, the limit of coupling $e^2 U^2$ can reach as small as 10^{-49}cm².

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Thank you!