Direct Detection of Dark Matter with Electromagnetic Interactions

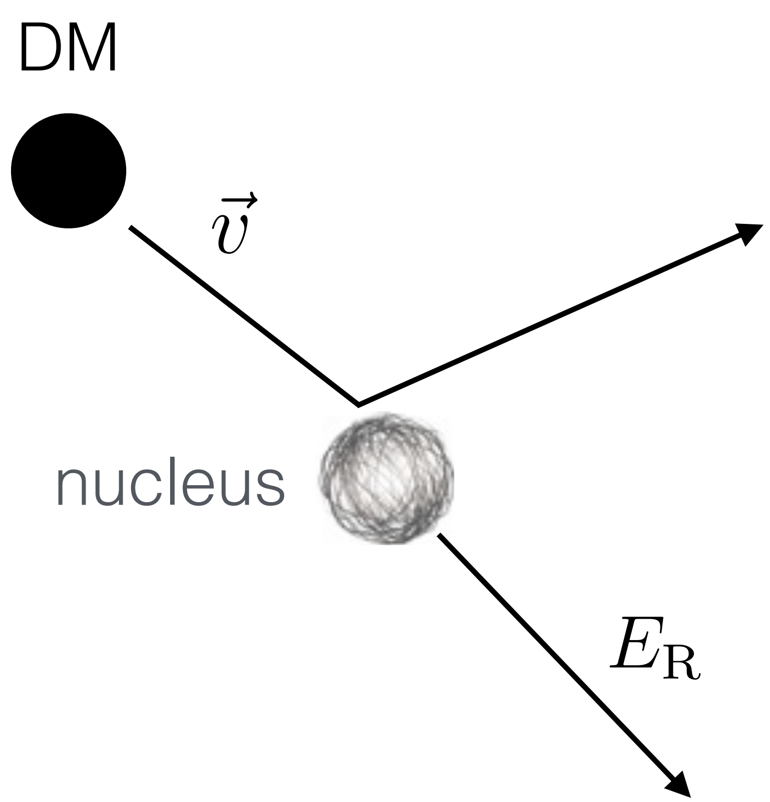
Eugenio Del Nobile

Università di Padova and INFN, Sezione di Padova

Dipartimento di Fisica e Astronomia Galileo Galilei

INFN Istituto Nazionale di Fisica Nucleare

Basics of direct detection



Basics of direct detection

The basic ingredient is the nuclear recoil rate

$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}} = \frac{\xi_T}{m_T}\Phi_\mathrm{DM}(t)\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}$$

Target density

DM-nucleus cross section

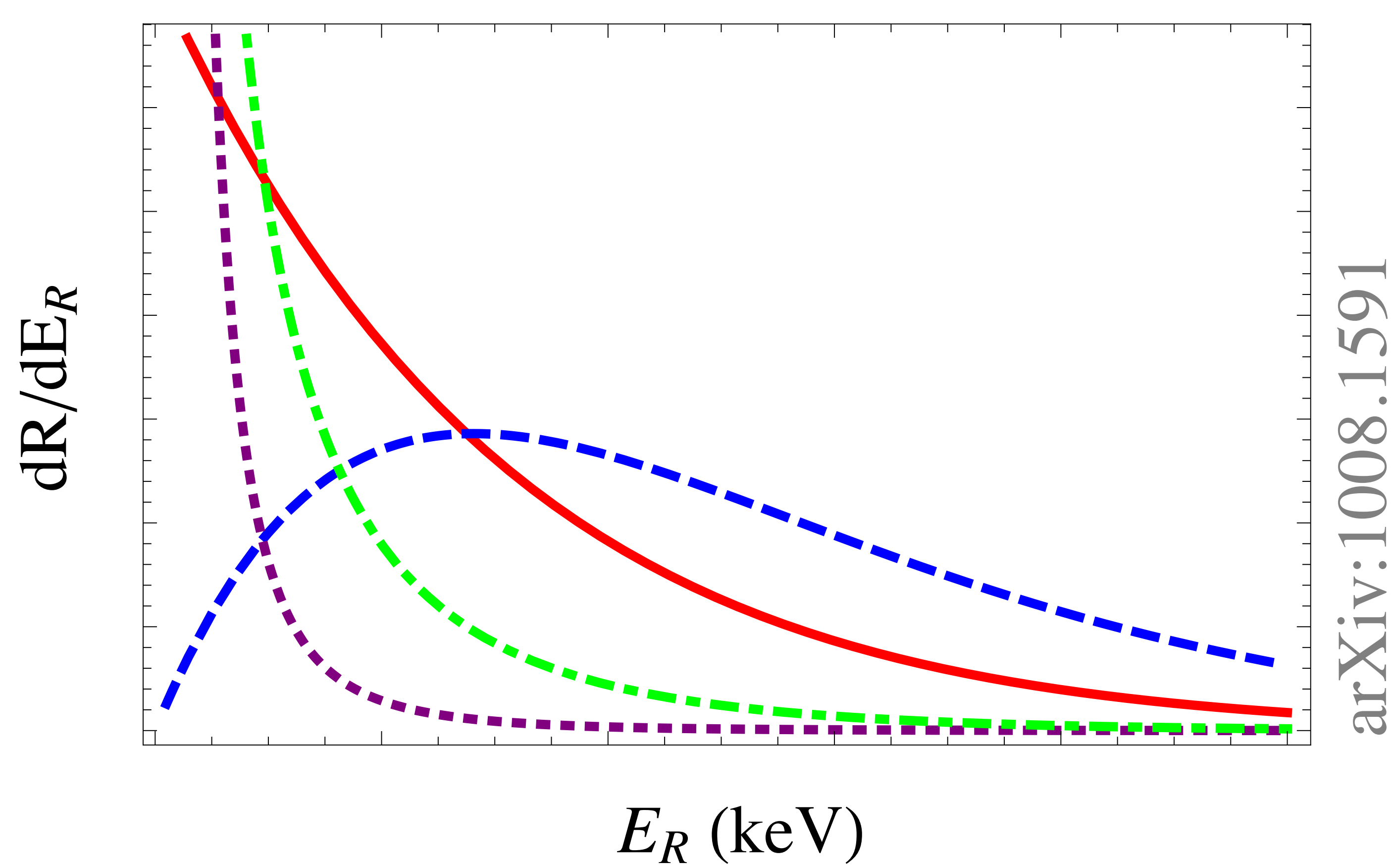
$$\Phi_\mathrm{DM} = \frac{\rho}{m_\mathrm{DM}} v\, f(\vec{v}, t)\, \mathrm{d}^3 v$$

DM flux (has an annual modulation due to Earth's rotation around the sun)

Basics of direct detection

$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}}(E_\mathrm{R}, t) = \frac{\xi_T}{m_T}\frac{\rho}{m_\mathrm{DM}}\int_{v \geqslant v_\mathrm{min}(E_\mathrm{R})} \mathrm{d}^3 v\, f(\vec{v}, t)\, v \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}(E_\mathrm{R}, \vec{v}\,)$$

v_min: minimum DM speed to kick the nucleus hard enough
(fixed by kinematics)



Non-relativistic limit

$$\frac{q}{m},\ v \sim 10^{-3}$$

$$\mathcal{M}_{\text{nucleon}} = \sum_{i=1}^{12} \left(\mathsf{c}_i^p + \mathsf{c}_i^n\right) \mathcal{O}_i^{\text{NR}}$$

$$\begin{aligned}
\mathcal{O}_1^{\text{NR}} &= \mathbb{1} & \mathcal{O}_2^{\text{NR}} &= (v^\perp)^2 \\
\mathcal{O}_3^{\text{NR}} &= i\,\vec{s}_N \cdot (\vec{q} \times \vec{v}) & \mathcal{O}_4^{\text{NR}} &= \vec{s}_\chi \cdot \vec{s}_N \\
\mathcal{O}_5^{\text{NR}} &= i\,\vec{s}_\chi \cdot (\vec{q} \times \vec{v}) & \mathcal{O}_6^{\text{NR}} &= (\vec{s}_\chi \cdot \vec{q})(\vec{s}_N \cdot \vec{q}) \\
\mathcal{O}_7^{\text{NR}} &= \vec{s}_N \cdot \vec{v}^\perp & \mathcal{O}_8^{\text{NR}} &= \vec{s}_\chi \cdot \vec{v}^\perp \\
\mathcal{O}_9^{\text{NR}} &= i\,\vec{s}_\chi \cdot (\vec{s}_N \times \vec{q}) & \mathcal{O}_{10}^{\text{NR}} &= i\,\vec{s}_N \cdot \vec{q} \\
\mathcal{O}_{11}^{\text{NR}} &= i\,\vec{s}_\chi \cdot \vec{q} & \mathcal{O}_{12}^{\text{NR}} &= \vec{v}^\perp \cdot (\vec{s}_\chi \times \vec{s}_N)
\end{aligned}$$

$$\left(E_{\text{R}} = \frac{q^2}{2m_T}\ ,\ \ \vec{v}^\perp \cdot \vec{q} = 0 \right)$$

Dark Matter with electromagnetic interactions

Examples are

$$\mathscr{L}_\epsilon = \epsilon e \, \bar{\chi} \gamma^\mu \chi \, A_\mu$$

Millicharge

$$\mathscr{L}_{\mathrm{M}} = \frac{\mu}{2} \, \bar{\chi} \sigma_{\mu\nu} \chi \, F^{\mu\nu}$$

Magnetic dipole

$$\mathscr{L}_{\mathrm{E}} = \frac{id}{2} \, \bar{\chi} \sigma_{\mu\nu} \gamma^5 \chi \, F^{\mu\nu}$$

Electric dipole

$$\mathscr{L}_{\mathrm{A}} = \frac{a}{2} \, \bar{\chi} \gamma^\mu \gamma^5 \chi \, \partial^\nu F_{\mu\nu}$$

Anapole moment

Dark Matter with electric dipole moment

$$\mathscr{L}_{\mathrm{E}} = \frac{id}{2}\,\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\,F^{\mu\nu}$$

$$H_{\mathrm{E}} = -\vec{d}\cdot\vec{E}$$

$$\frac{\mathrm{d}\sigma_T^{\mathrm{E}}}{\mathrm{d}E_{\mathrm{R}}} \sim \frac{Z^2 d^2}{E_{\mathrm{R}} v^2} F_{\mathrm{C}}^2(E_{\mathrm{R}})$$

$$d^{-1} \sim \mathrm{PeV} - \mathrm{EeV}$$

Dark Matter with electric dipole moment

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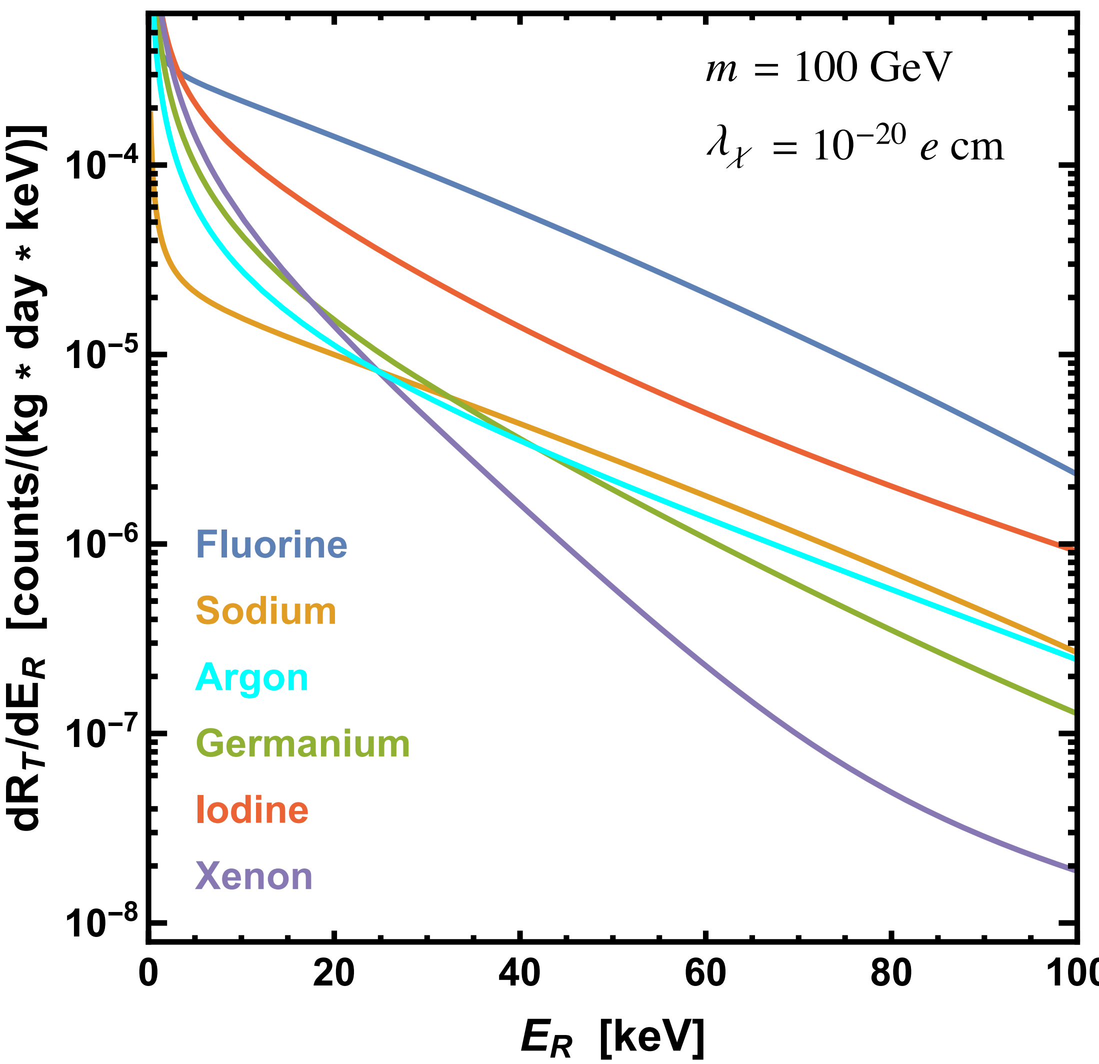
$$\frac{\mathrm{d}\sigma_T^{\mathrm{SI}}}{\mathrm{d}E_{\mathrm{R}}} \sim \frac{A^2 g^2}{v^2} F_{\mathrm{SI}}^2(E_{\mathrm{R}})$$

$$d^{-1} \sim \mathrm{PeV} - \mathrm{EeV}$$

Dark Matter with magnetic dipole moment

$$\mathscr{L}_{\mathrm{M}} = \frac{\mu}{2}\,\bar{\chi}\sigma_{\mu\nu}\chi\,F^{\mu\nu} \qquad\qquad H_{\mathrm{M}} = -\vec{\mu}\cdot\vec{B}$$

$$\frac{\mathrm{d}\sigma_T^{\mathrm{M}}}{\mathrm{d}E_{\mathrm{R}}} \sim \left(\frac{1}{E_{\mathrm{R}}} - \frac{\#}{v^2}\right)\mu^2 Z^2 F_{\mathrm{C}}^2(E_{\mathrm{R}}) + \frac{@}{v^2}\mu^2\mu_T^2 F_{\mathrm{M}}^2(E_{\mathrm{R}})$$

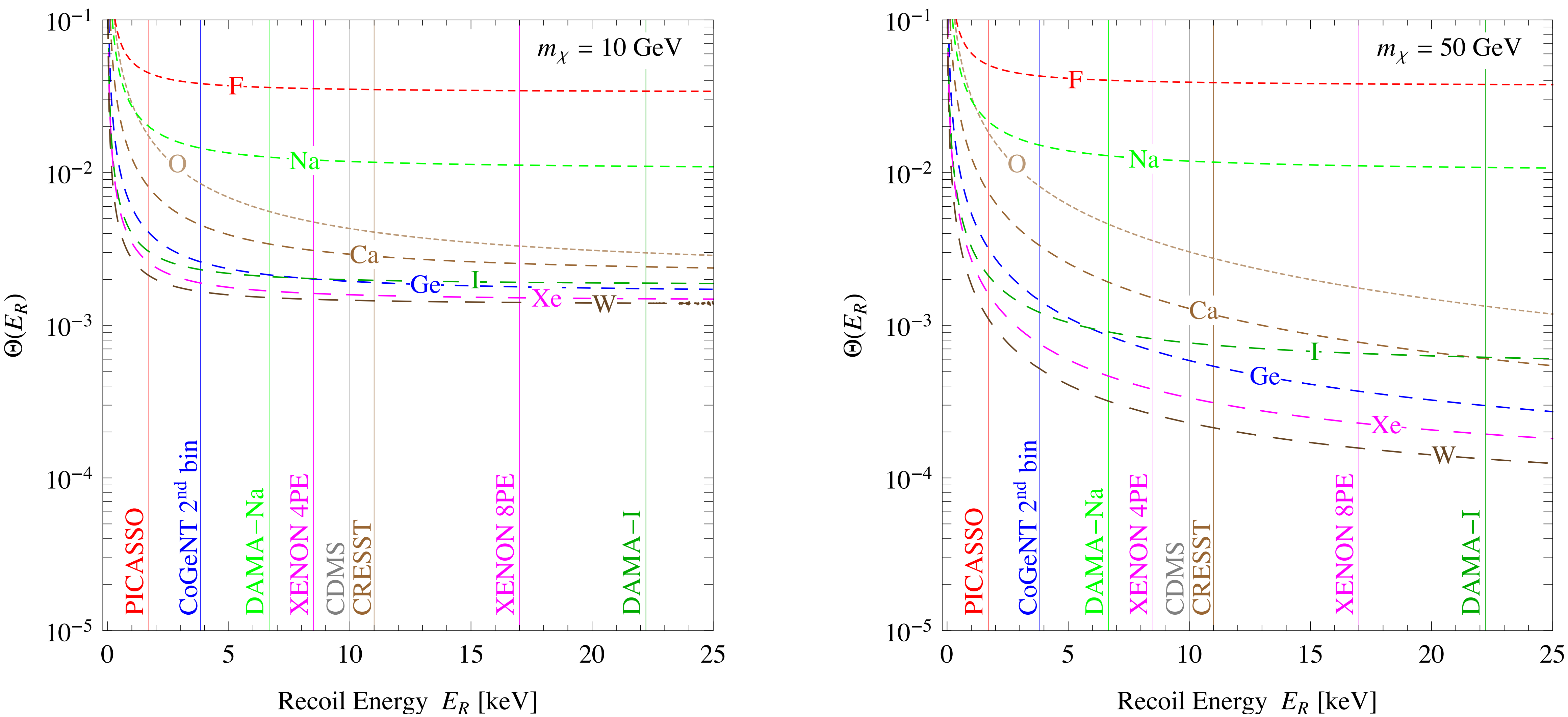


arXiv:1512.03961

Dark Matter with magnetic dipole moment

$$\mathscr{L}_{\mathrm{M}} = \frac{\mu}{2}\,\bar{\chi}\sigma_{\mu\nu}\chi\,F^{\mu\nu} \qquad\qquad H_{\mathrm{M}} = -\vec{\mu}\cdot\vec{B}$$

$$\frac{\mathrm{d}\sigma_T^{\mathrm{M}}}{\mathrm{d}E_{\mathrm{R}}} \sim \left(\frac{1}{E_{\mathrm{R}}} - \frac{\#}{v^2}\right)\mu^2 Z^2 F_{\mathrm{C}}^2(E_{\mathrm{R}}) + \frac{@}{v^2}\mu^2\mu_T^2 F_{\mathrm{M}}^2(E_{\mathrm{R}})$$



arXiv:1203.6652

Dark Matter with anapole moment

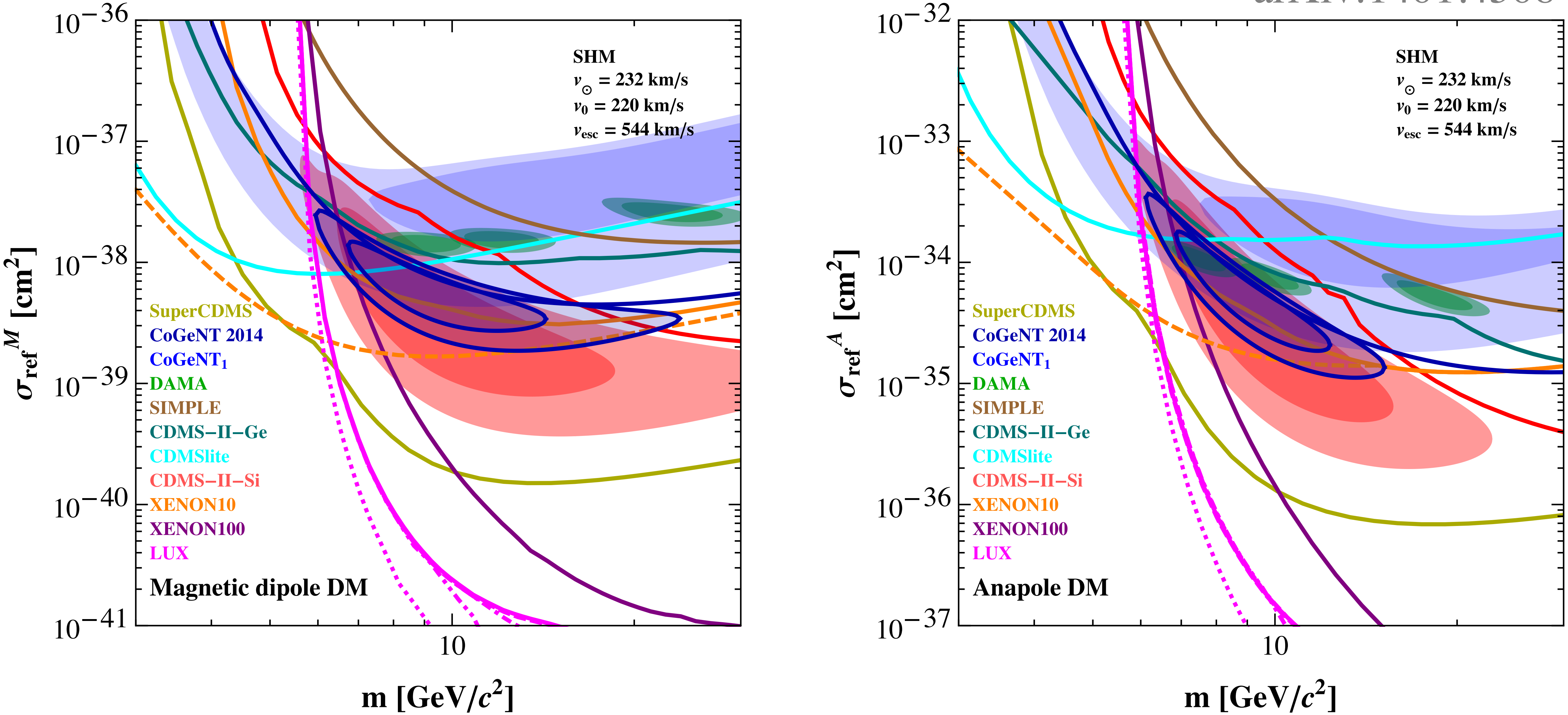
$$\mathscr{L}_{\mathrm{A}} = \frac{a}{2}\,\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\,\partial^{\nu}F_{\mu\nu}$$

$$H_{\mathrm{A}} = -\vec{a}\cdot(\vec{\nabla}\times\vec{B})$$

$$\frac{\mathrm{d}\sigma_T^{\mathrm{A}}}{\mathrm{d}E_{\mathrm{R}}} \sim E_{\mathrm{R}}\frac{\mathrm{d}\sigma_T^{\mathrm{M}}}{\mathrm{d}E_{\mathrm{R}}}$$

Dark Matter with magnetic/anapole moment

arXiv:1401.4508



Dark Matter with magnetic/anapole moment

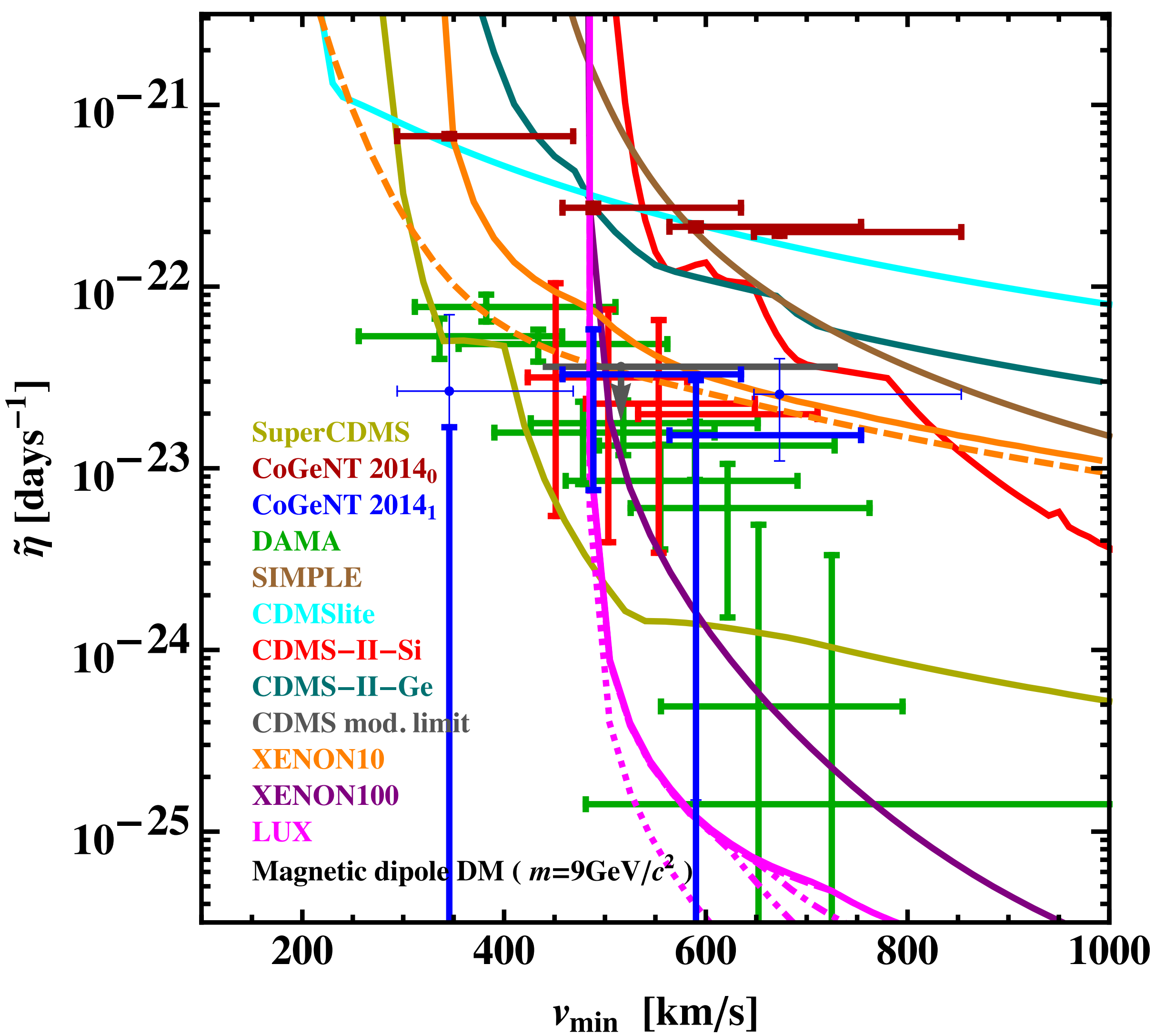
For

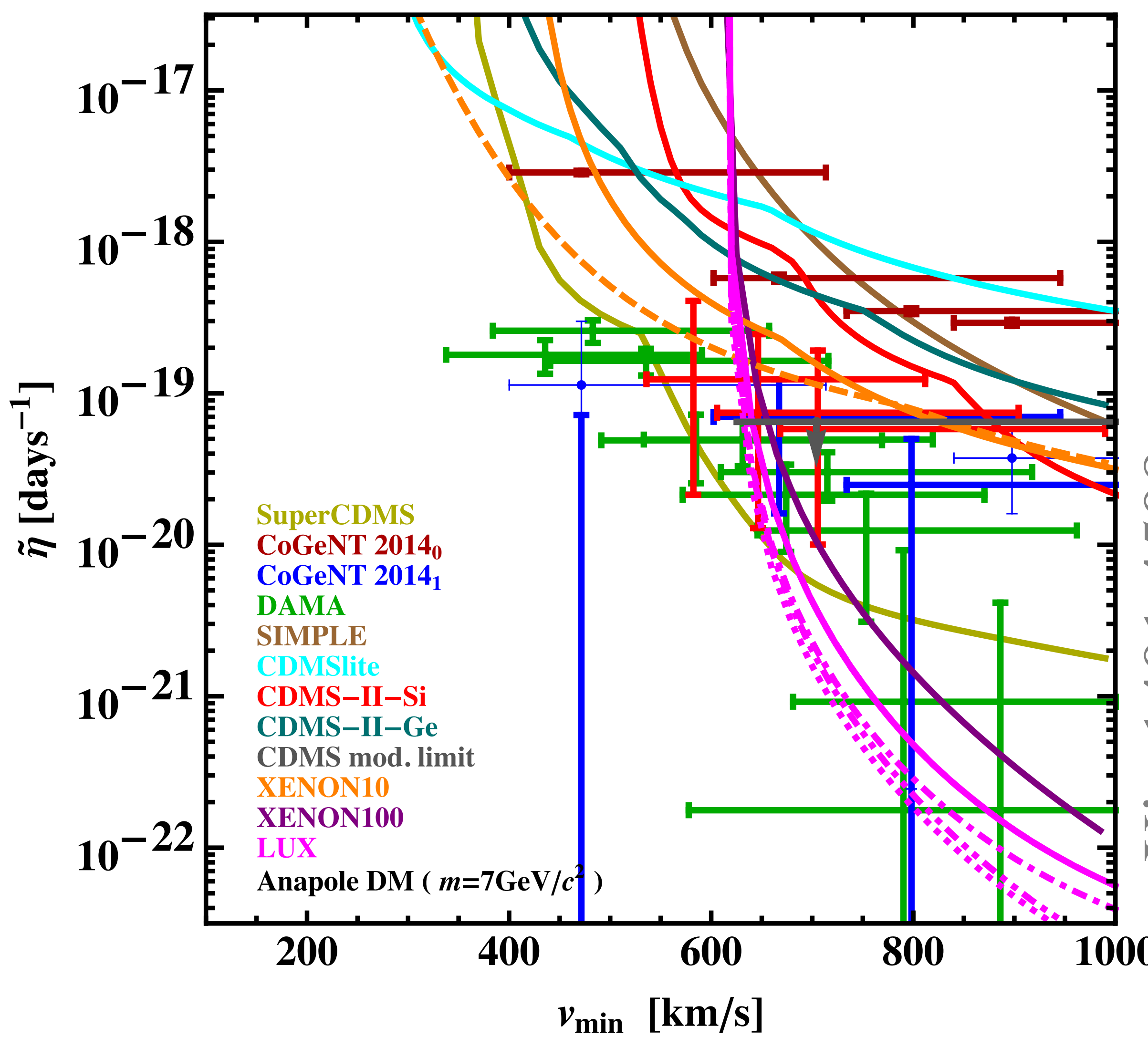
$$\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_{\mathrm{R}}} = g_T(E_{\mathrm{R}})\,h(\vec{v})$$

then

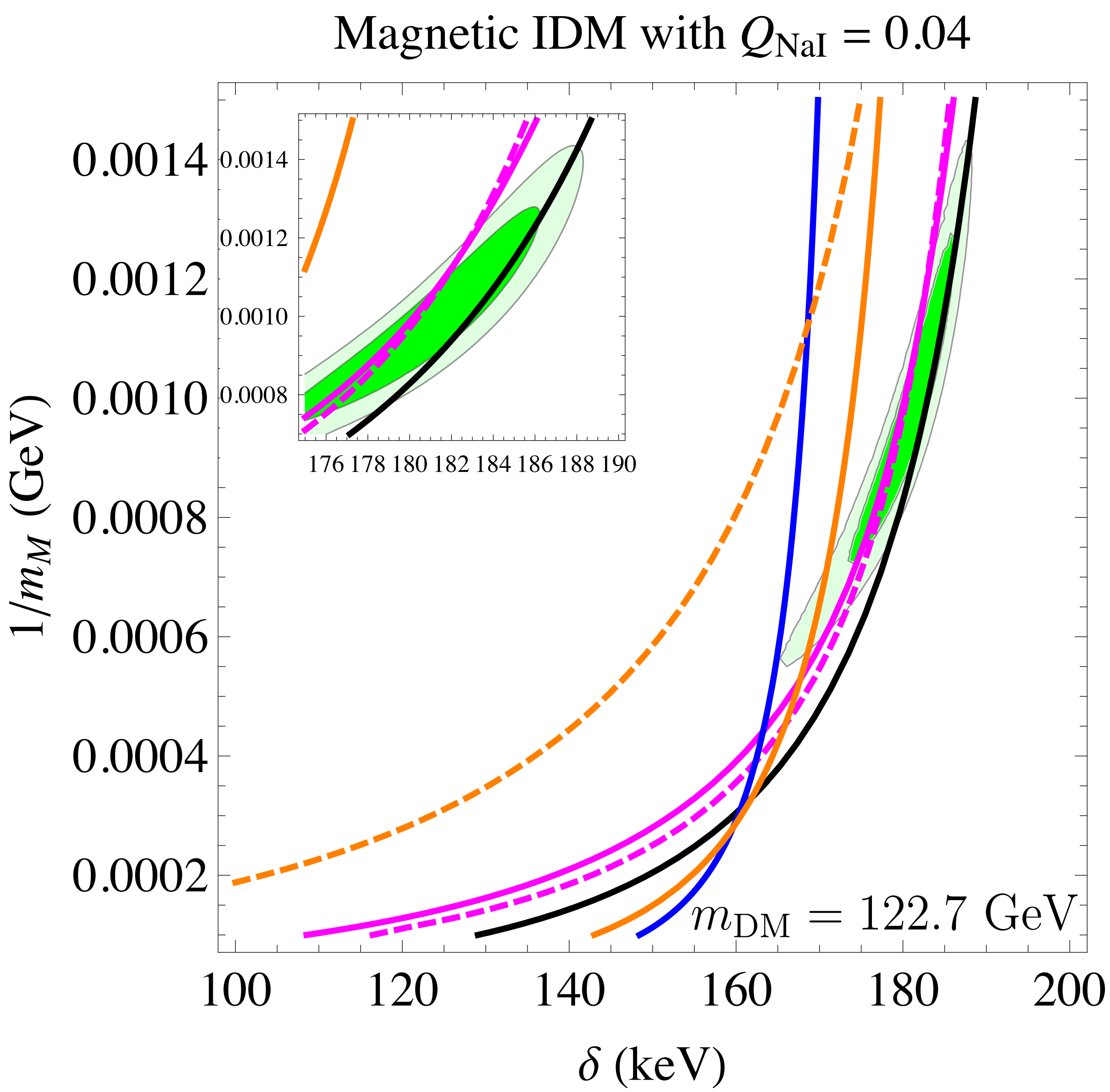
$$\frac{\mathrm{d}R_T}{\mathrm{d}E_{\mathrm{R}}} = \frac{\xi_T}{m_T}\frac{\rho}{m_{\mathrm{DM}}}\,g_T(E_{\mathrm{R}})\,\eta(v_{\min})$$

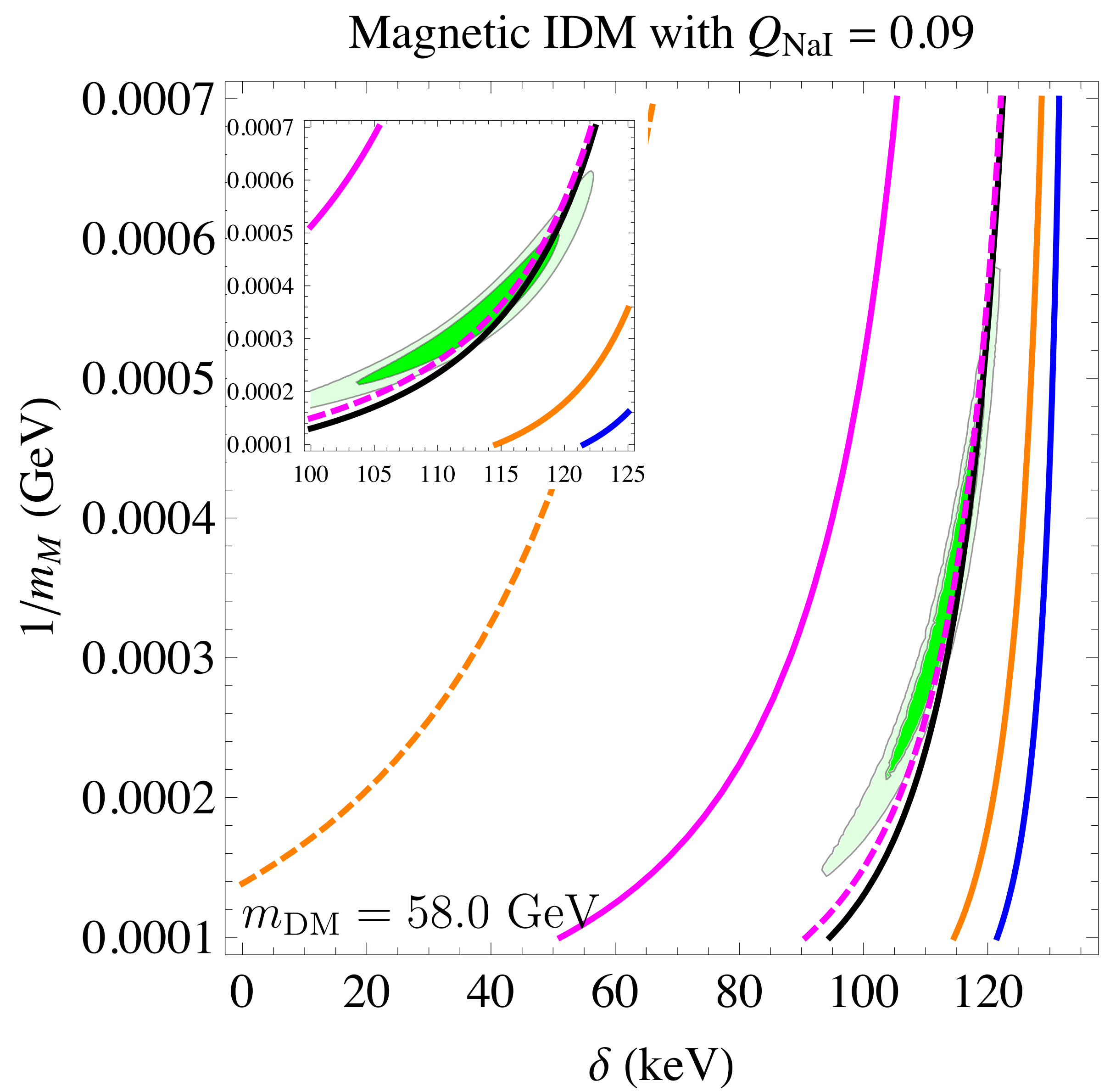
with $$\eta(v_{\min}) \equiv \int_{v \geqslant v_{\min}} \mathrm{d}^3 v\, f(\vec{v},t)\, v\, h(\vec{v})$$





Inelastic magnetic dipole Dark Matter





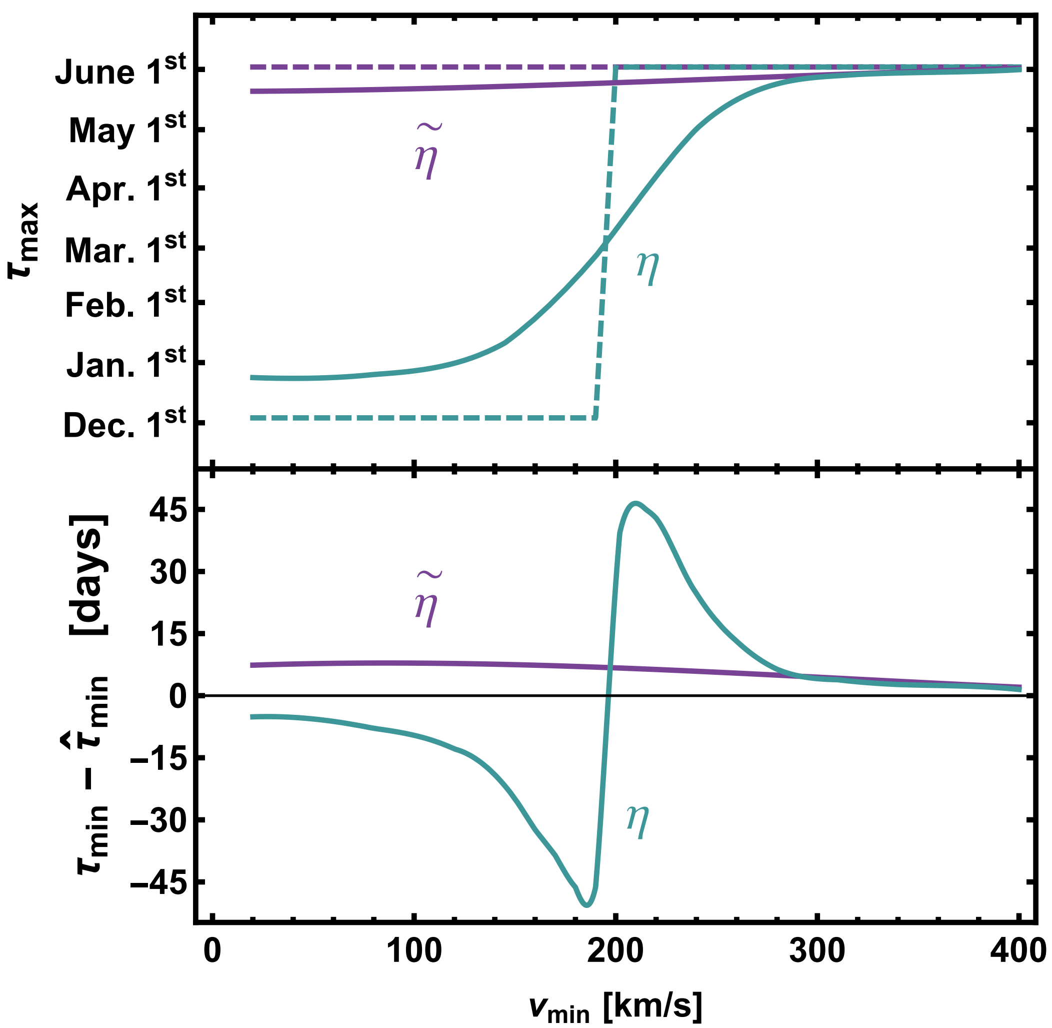
arXiv:1409.0536

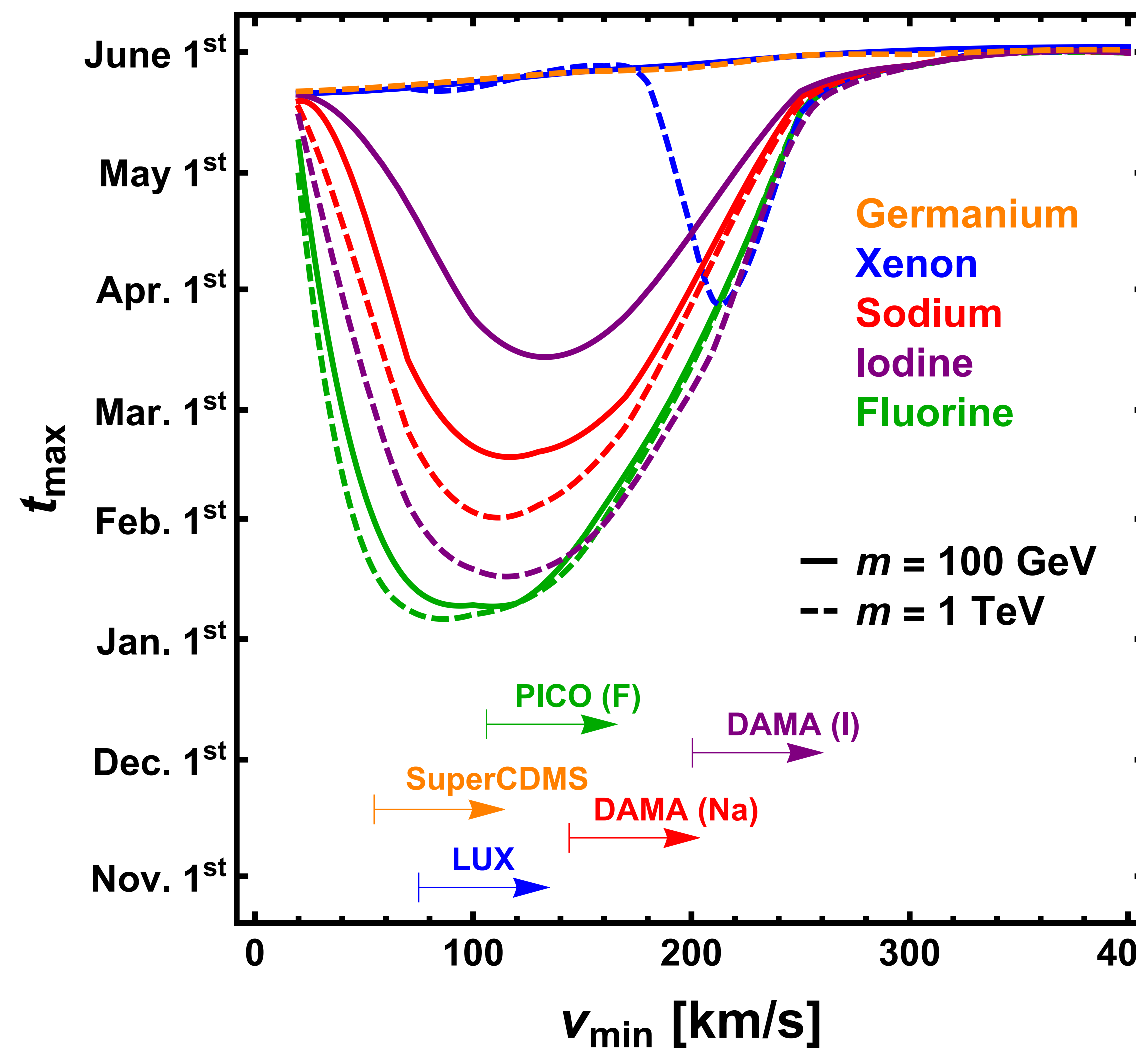
Annual modulation of magnetic dipole Dark Matter

$$\frac{\mathrm{d}\sigma_T^{\mathrm{M}}}{\mathrm{d}E_{\mathrm{R}}} \sim \left(\frac{1}{E_{\mathrm{R}}} - \frac{\#}{v^2}\right)\mu^2 Z^2 F_{\mathrm{C}}^2(E_{\mathrm{R}}) + \frac{@}{v^2}\mu^2\mu_T^2 F_{\mathrm{M}}^2(E_{\mathrm{R}})$$

$\tilde{\eta}$

η

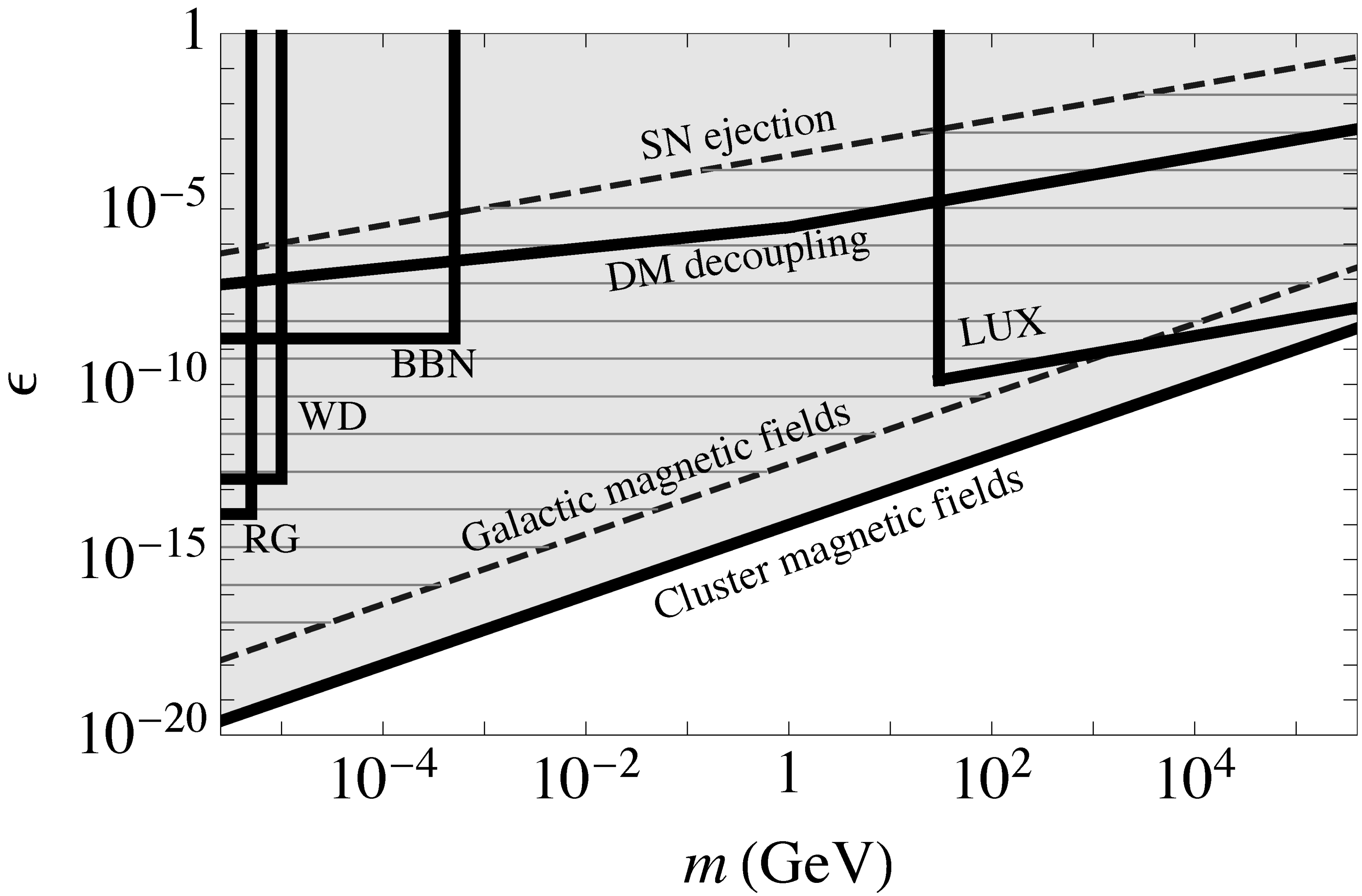




Millicharged Dark Matter

$$\mathscr{L}_\epsilon = \epsilon e\, \bar{\chi}\gamma^\mu\chi\, A_\mu$$

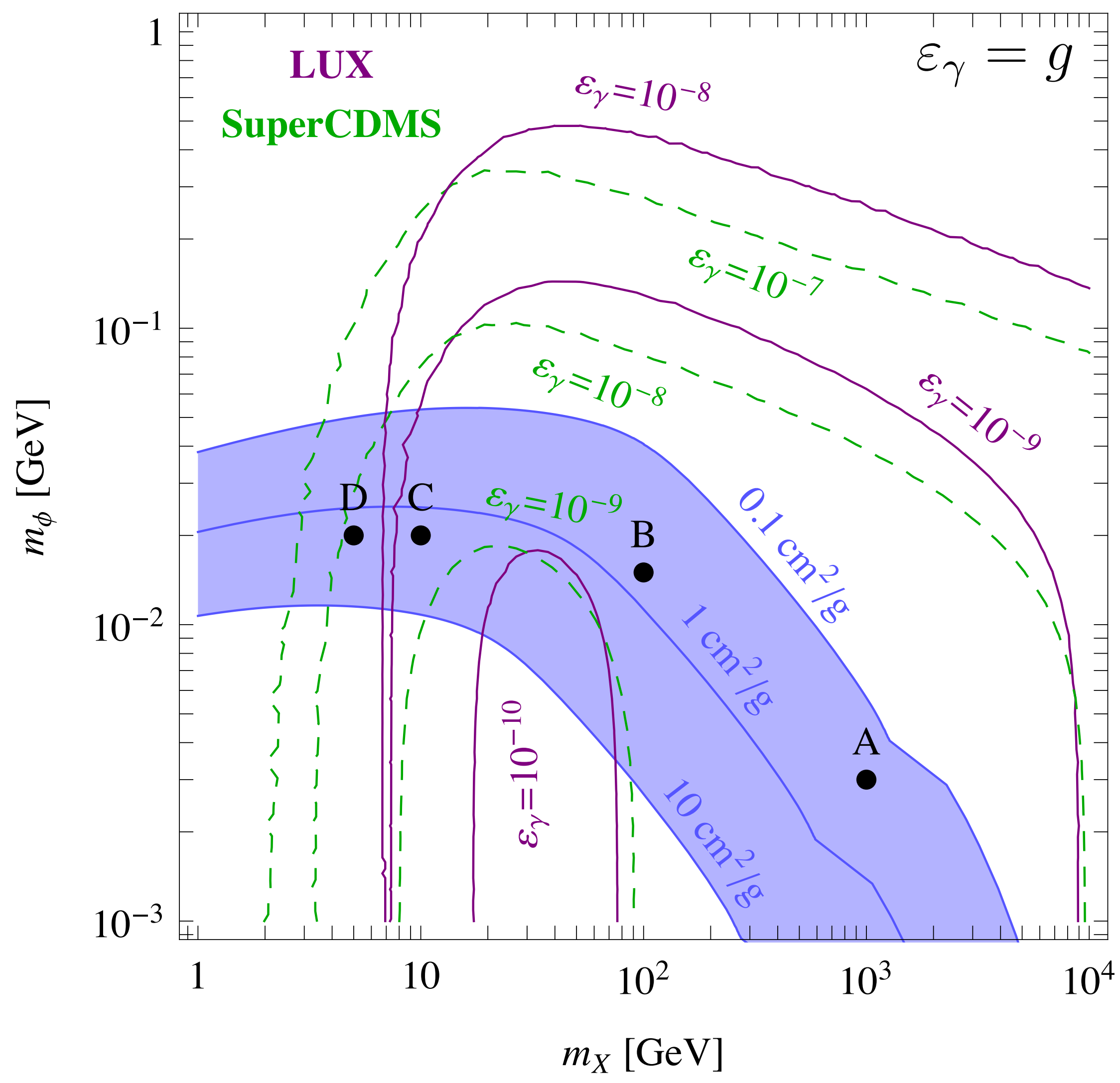
$$\frac{\mathrm{d}\sigma_T^\epsilon}{\mathrm{d}E_\mathrm{R}} \sim \frac{Z^2\epsilon^2}{E_\mathrm{R}^2 v^2} F_\mathrm{C}^2(E_\mathrm{R})$$



arXiv:1602.04009

Digression #1: light mediator

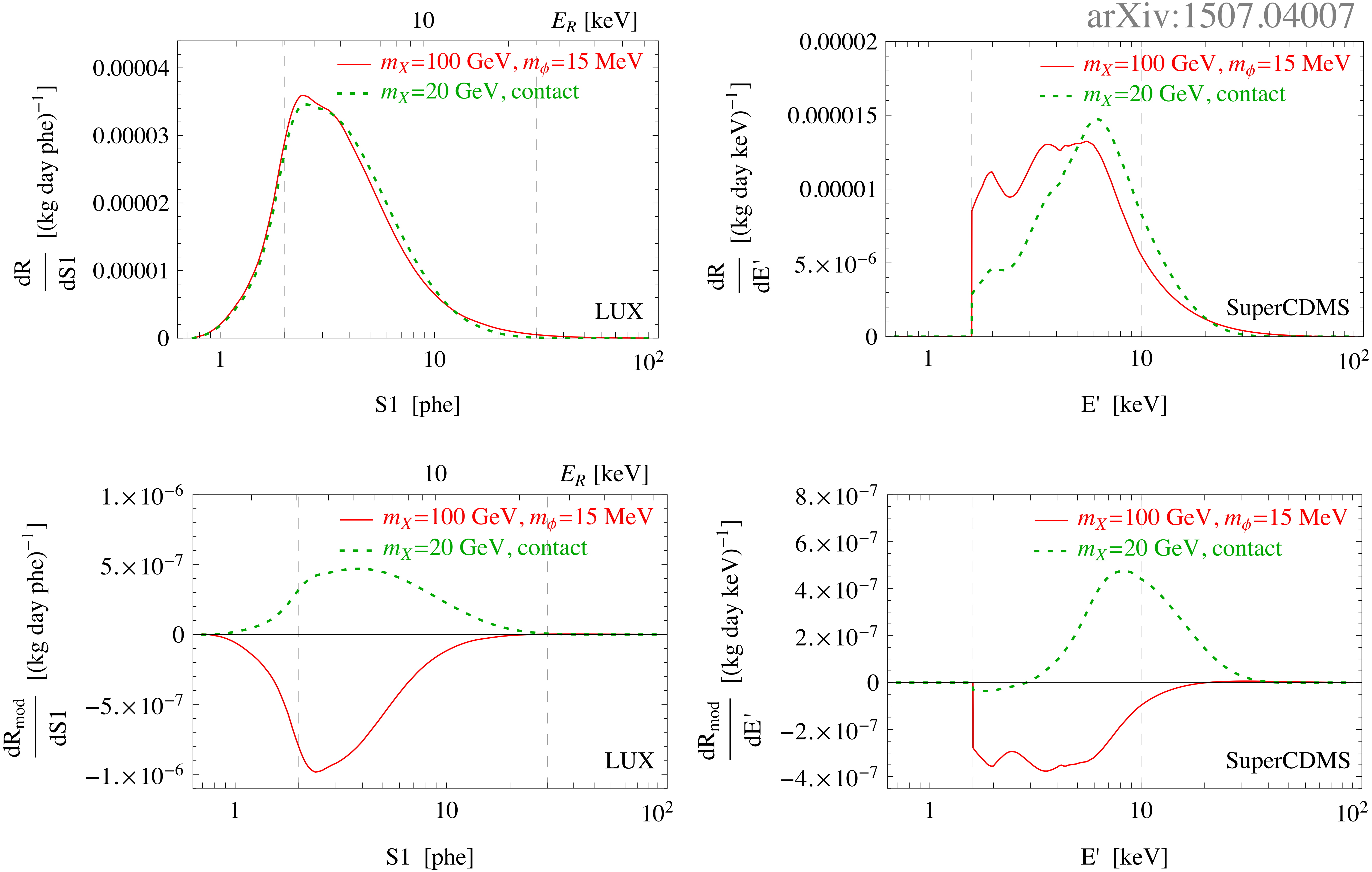
$$\frac{\mathrm{d}\sigma_T^{\phi}}{\mathrm{d}E_{\mathrm{R}}} \sim \frac{g^2}{(q^2 + m_{\phi}^2)^2 v^2} F^2(E_{\mathrm{R}})$$



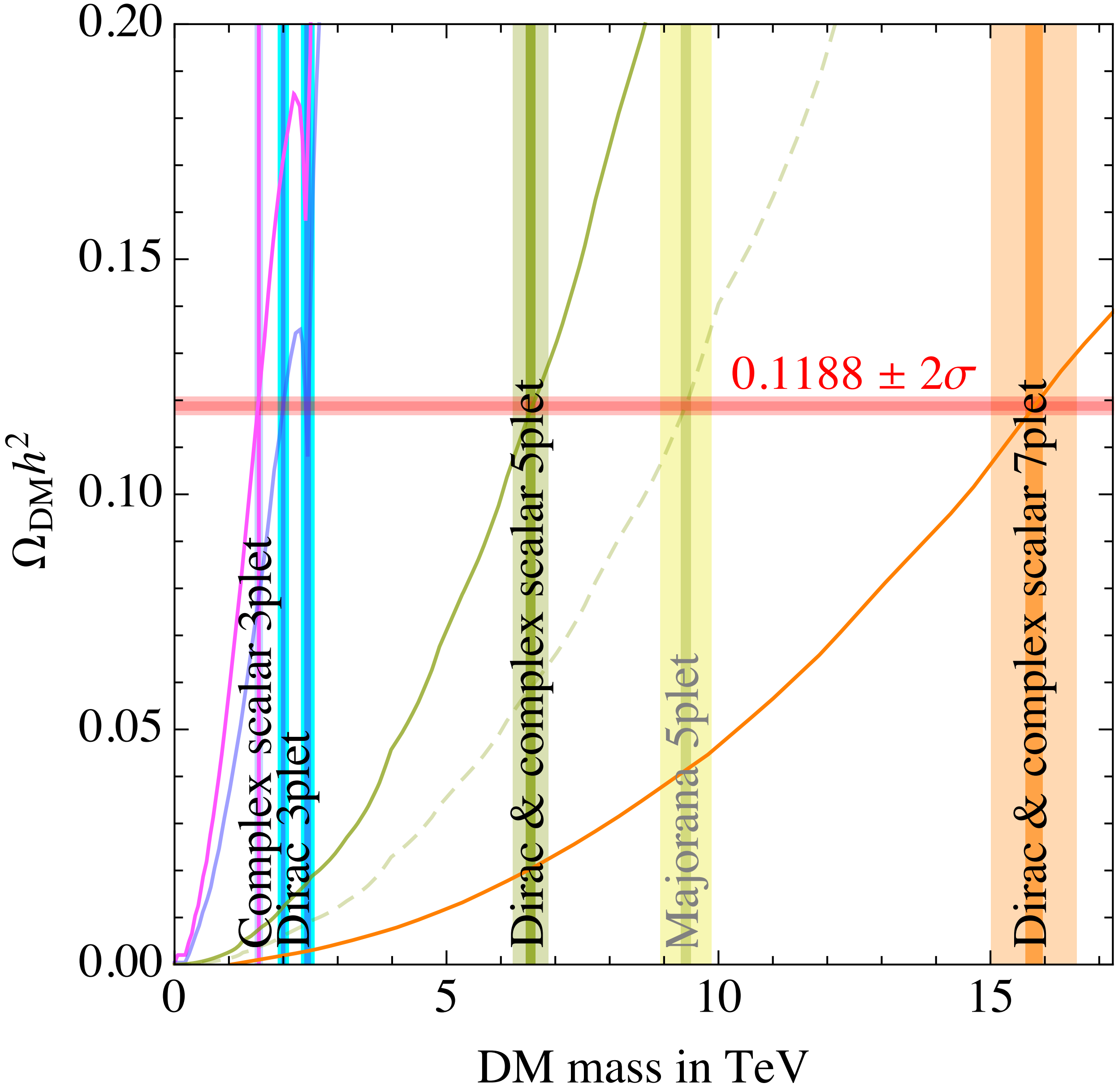
arXiv:1507.04007

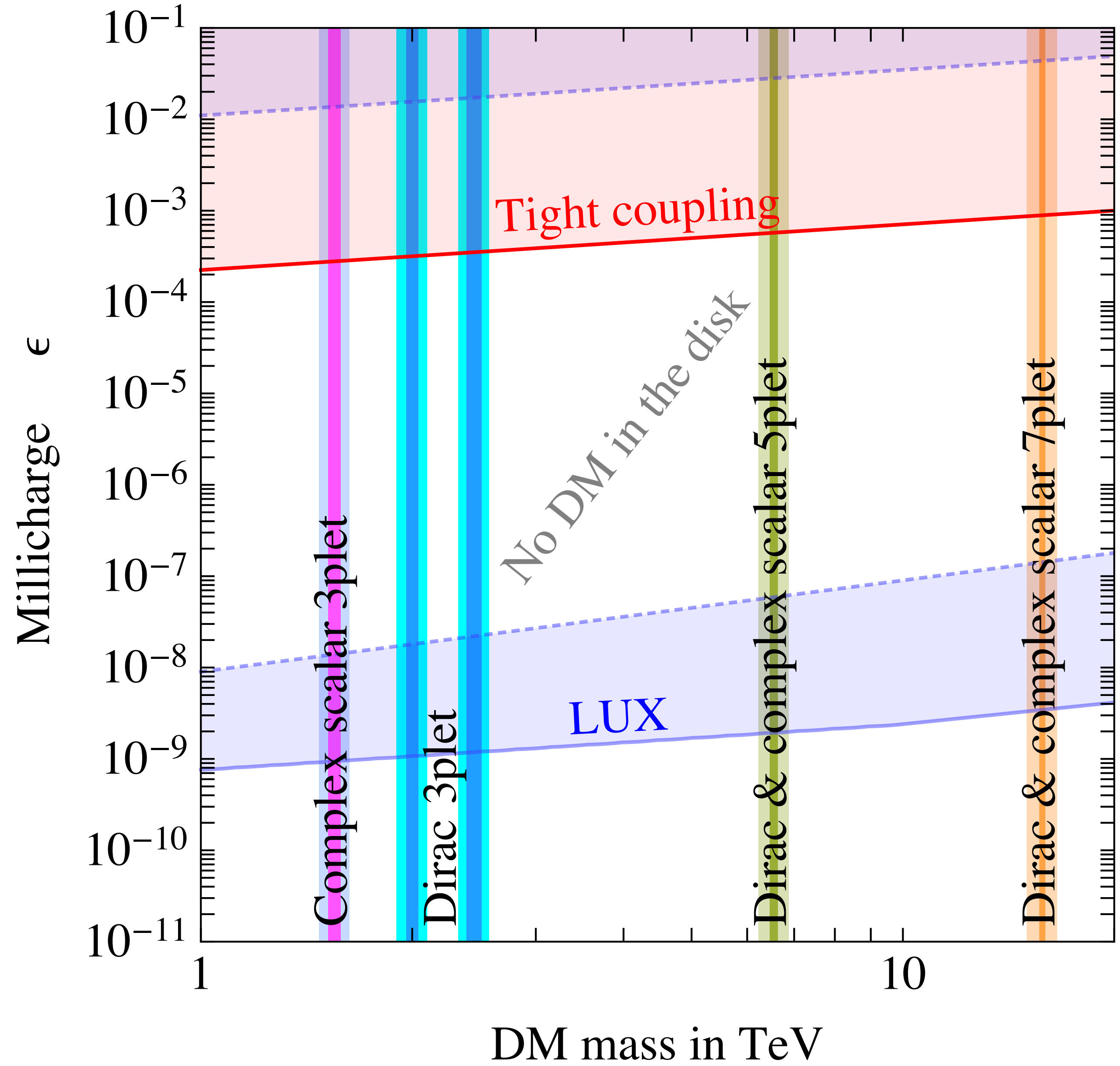
Digression #1: light mediator

arXiv:1507.04007



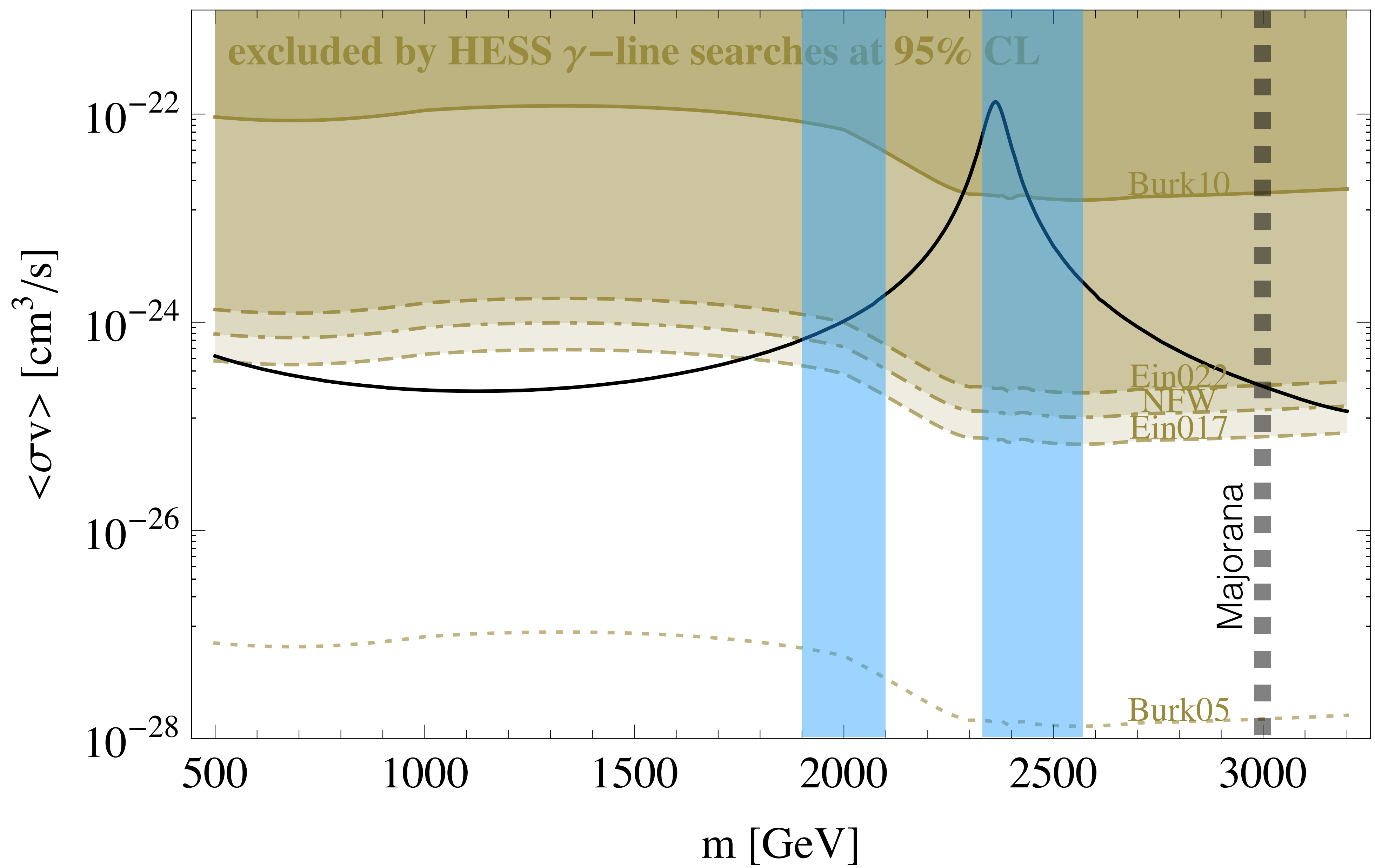
Digression #2: millicharged Minimal Dark Matter





arXiv:1512.05353

(millicharged) Dirac SU(2)$_L$ triplet



All bounds to be multiplied by 2 for the Dirac candidate

arXiv:1401.6212

Conclusions

I like Dark Matter with electromagnetic interactions