Direct detection signatures of standard and non-standard WIMPs

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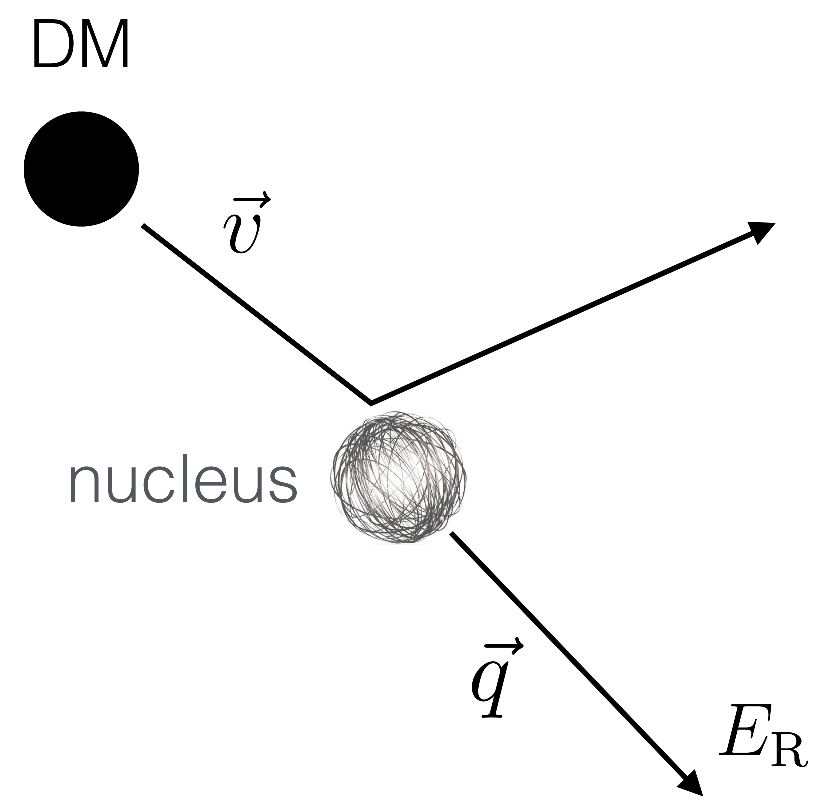
Basics of direct detection



For halo DM, v ~ 300 km/s ~ 10^{-3} c
1/q ~ O(fm): the interaction occurs with the whole nucleus
WIMP here = any stable particle detectable with direct searches (mass ≥ GeV)

Scattering rate

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)

Scattering rate

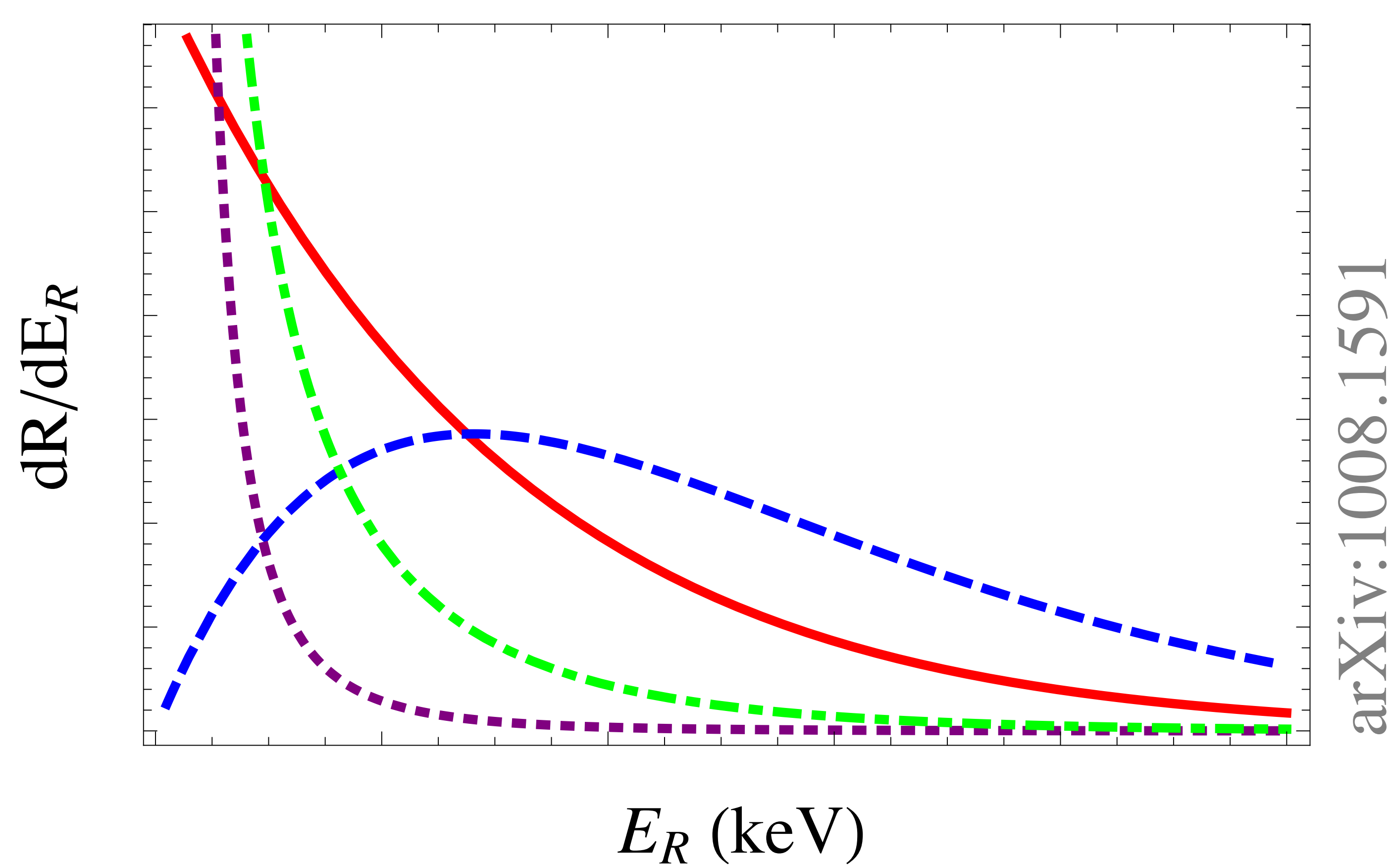
$$\frac{\mathrm{d}R_T}{\mathrm{d}E_\mathrm{R}}(E_\mathrm{R},t) = \frac{\xi_T}{m_T}\frac{\rho}{m_\mathrm{DM}}\int_{v\geqslant v_\mathrm{min}(E_\mathrm{R})}\mathrm{d}^3v\, f(\vec{v},t)\, v\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}(E_\mathrm{R},\vec{v})$$

ρ DM local density

ξ_T target mass fraction

$f(\vec{v},t)$ DM velocity distribution

v_min kinematic cutoff



Scattering rate

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

ρ DM local density

ξ_T target mass fraction

$f(\vec{v},t)$ DM velocity distribution

v_min kinematic cutoff

	LHC	Direct Detection
scattering type	deeply inelastic	mostly elastic
mom. transfer *q*	TeV	MeV
Mandelstam *s*	integrated (PDF)	integrated (f)
Mandelstam *t*	observed (p_T)	observed ($E_\mathrm{R} \sim q \sim v_\mathrm{min}$)

From theory to experiment

1. Write your favorite DM model in terms of interactions with **nucleons**

2. $v \sim 10^{-3} \Longrightarrow$ **non-relativistic** expansion of the scattering amplitude

3. Compute the **DM-nucleus** cross section (including form factors)

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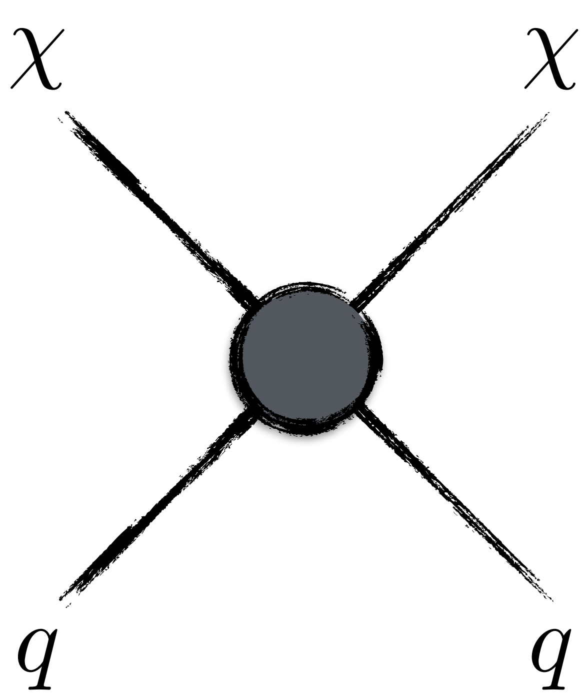
Example

$$(\bar{\chi}\Gamma_\chi \chi)(\bar{q}\Gamma_q q)$$



Γ_χ	Γ_q
γ^μ	γ_μ
$\gamma^\mu\gamma^5$	γ_μ
γ^μ	$\gamma_\mu\gamma^5$
$\gamma^\mu\gamma^5$	$\gamma_\mu\gamma^5$

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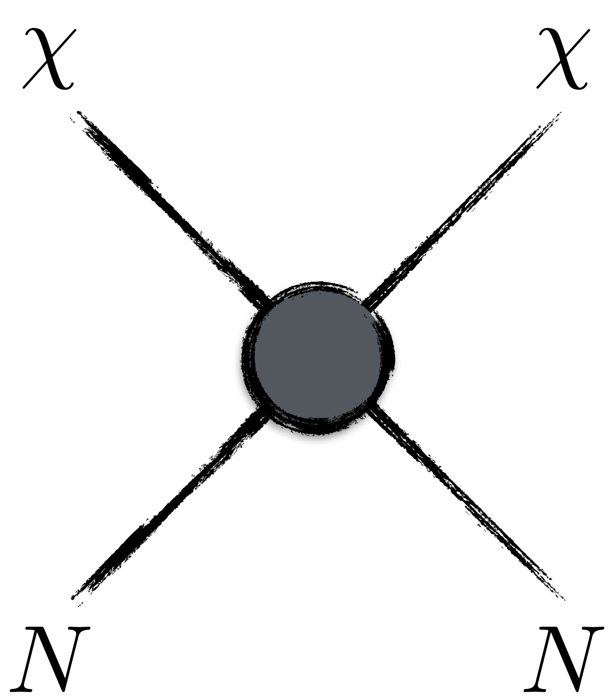
Example

$(\bar{\chi}\Gamma_\chi \chi)(\bar{N}\Gamma_N N)$



Γ_χ	Γ_N	non-relativistic limit
γ^μ	γ_μ	1
$\gamma^\mu\gamma^5$	γ_μ	$i\boldsymbol{s}_\chi \cdot (\boldsymbol{s}_N \times \boldsymbol{q}),\ \boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp$
γ^μ	$\gamma_\mu\gamma^5$	$i\boldsymbol{s}_\chi \cdot (\boldsymbol{s}_N \times \boldsymbol{q}),\ \boldsymbol{s}_N \cdot \boldsymbol{v}^\perp$
$\gamma^\mu\gamma^5$	$\gamma_\mu\gamma^5$	$\boldsymbol{s}_\chi \cdot \boldsymbol{s}_N$
γ^5	γ^5	$(\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q})$

pion exchange

From theory to experiment

1. Write your favorite DM model in terms of interactions with **nucleons**

2. $v \sim 10^{-3} \Longrightarrow$ **non-relativistic** expansion of the scattering amplitude

3. Compute the **DM-nucleus** cross section (including form factors)

Result

The non-relativistic amplitude is Galilean invariant at leading order

Ingredients

(Galilean invariant, hermitian)

$$i\boldsymbol{q},\ \boldsymbol{v}^{\perp},\ \boldsymbol{s}_N,\ \boldsymbol{s}_\chi$$

Exercise

Combine the ingredients in all possible rotationally-invariant ways

Non-relativistic theory

spin-0 DM

$$H_N = \sum_i c_i^N(q^2, {v^\perp}^2)\, O_i$$

$$O_1 \equiv \mathbb{1}$$

$$O_3 \equiv i\boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)$$

$$O_7 \equiv \boldsymbol{s}_N \cdot \boldsymbol{v}^\perp$$

$$O_{10} \equiv i\boldsymbol{s}_N \cdot \boldsymbol{q}$$

Non-relativistic theory

spin-1/2 DM

$$H_N = \sum_i c_i^N(q^2, {v^\perp}^2)\, O_i$$

$$O_1 \equiv \mathbb{1}$$

$$O_3 \equiv i\boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)$$

$$O_4 \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N$$

$$O_5 \equiv i\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)$$

$$O_6 \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q})$$

$$O_7 \equiv \boldsymbol{s}_N \cdot \boldsymbol{v}^\perp$$

$$O_8 \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp$$

$$O_9 \equiv i\boldsymbol{s}_\chi \cdot (\boldsymbol{s}_N \times \boldsymbol{q})$$

$$O_{10} \equiv i\boldsymbol{s}_N \cdot \boldsymbol{q}$$

$$O_{11} \equiv i\boldsymbol{s}_\chi \cdot \boldsymbol{q}$$

$$O_{12} \equiv \boldsymbol{v}^\perp \cdot (\boldsymbol{s}_\chi \times \boldsymbol{s}_N)$$

$$O_{13} \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp)(\boldsymbol{s}_N \cdot \boldsymbol{q})$$

$$O_{14} \equiv i(\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp)$$

$$O_{15} \equiv [\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)](\boldsymbol{s}_N \cdot \boldsymbol{q})$$

$$O_{16} \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp)(\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp)$$

$$O_{17} \equiv i[\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)](\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp)$$

Non-relativistic theory

spin-1 DM

$$H_N = \sum_i c_i^N(q^2, {v^\perp}^2)\, O_i$$

$$O_1 \equiv \mathbb{1}$$

$$O_3 \equiv i\boldsymbol{s}_N \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)$$
$$O_4 \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N$$

$$O_5 \equiv i\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)$$
$$O_6 \equiv (\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q})$$

$$O_7 \equiv \boldsymbol{s}_N \cdot \boldsymbol{v}^\perp$$
$$O_8 \equiv \boldsymbol{s}_\chi \cdot \boldsymbol{v}^\perp$$

$$O_9 \equiv i\boldsymbol{s}_\chi \cdot (\boldsymbol{s}_N \times \boldsymbol{q})$$
$$O_{10} \equiv i\boldsymbol{s}_N \cdot \boldsymbol{q}$$

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$$O_{17} \equiv i[\boldsymbol{s}_\chi \cdot (\boldsymbol{q} \times \boldsymbol{v}^\perp)](\boldsymbol{s}_N \cdot \boldsymbol{v}^\perp)$$

+ others…

Hierarchies I: nuclear spin

$$O_1, O_5, O_8, O_{11}$$

All nucleons interact equal

Spin independent: coherent enhancement $\quad \mathrm{d}\sigma_T \sim \mathcal{O}(A^2) \lesssim 10^4$

(however $v^\perp$ factors can imply a coupling to the nuclear spin)

$$O_3, O_4, O_6, O_7, O_9, O_{10}, O_{12}, O_{13}, O_{14}, O_{15}, O_{16}, O_{17}$$

Opposite spins cancel pairwise

Spin dependent: coherent cancellation $\quad \mathrm{d}\sigma_T \sim \mathcal{O}(A^0) \sim 1$

Hierarchies II: DM speed

$$\frac{q^2}{4\mu_T^2} = v_{\rm min}^2 \leqslant v^2 \sim 10^{-6} \qquad\qquad \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}} \sim \frac{|\langle O_i \rangle|^2}{v^2}$$

O_1, O_4	$\sim \mathcal{O}(v^0)$	$\mathrm{d}\sigma_T \sim \mathcal{O}(v^{-2})$
$O_7, O_8, O_9, O_{10}, O_{11}, O_{12}$	$\sim \mathcal{O}(v^1)$	$\mathrm{d}\sigma_T \sim \mathcal{O}(v^{0})$
$O_3, O_5, O_6, O_{13}, O_{14}, O_{16}$	$\sim \mathcal{O}(v^2)$	$\mathrm{d}\sigma_T \sim \mathcal{O}(v^{2})$
O_{15}, O_{17}	$\sim \mathcal{O}(v^3)$	$\mathrm{d}\sigma_T \sim \mathcal{O}(v^{4})$

(however $(\boldsymbol{q} \times \boldsymbol{s}_\chi) \cdot (\boldsymbol{q} \times \boldsymbol{s}_N) = q^2 O_4 - O_6$)

Hierarchies III: EFT cutoff

Some operators appear at tree level at dimension ≤6
in the EFT of a singlet Dirac DM. Others…

	Example of EFT operator	dimension
O_3	$-i\varepsilon^{\alpha\mu\nu\rho}[\partial_\rho(\bar{\chi}\gamma_\alpha\chi)][\bar{N}\gamma_\mu\gamma^5\overleftrightarrow{\partial_\nu}N]$	8
O_{13}	$i\,\bar{\chi}\gamma^\alpha\gamma^5\chi(\bar{N}\gamma^5\overleftrightarrow{\partial_\alpha}N)$	7
O_{14}	$i(\bar{\chi}\gamma^5\overleftrightarrow{\partial_\mu}\chi)\bar{N}\gamma^\mu\gamma^5 N$	7
O_{15}	$\varepsilon^{\alpha\mu\nu\rho}[\partial_\rho(\bar{\chi}\gamma_\alpha\gamma^5\overleftrightarrow{\partial_\mu}\chi)](\bar{N}\gamma^5\overleftrightarrow{\partial_\nu}N)$	9
O_{16}	$-(\bar{\chi}\gamma^\alpha\gamma^5\overleftrightarrow{\partial_\mu}\chi)(\bar{N}\gamma^\mu\gamma^5\overleftrightarrow{\partial_\alpha}N)$	8
O_{17}	$i\varepsilon^{\beta\mu\nu\rho}(\bar{\chi}\sigma_{\alpha\beta}\overleftrightarrow{\partial_\nu}\chi)][(\partial_\alpha\bar{N})\gamma_\mu\overleftrightarrow{\partial_\rho}N-\bar{N}\gamma_\mu\overleftrightarrow{\partial_\rho}(\partial_\alpha N)]$	9

(the dimension can be larger for Majorana DM)

arXiv:1806.01291

Cross section structure

Type	Lagrangian	NR operators	Nuclear responses	Structure of $\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}$
Spin independent	$\bar{\chi}\chi\,\bar{N}N$ or $\bar{\chi}\gamma^\mu\chi\,\bar{N}\gamma_\mu N$	$O_1 = \mathbb{1}$	M	$\frac{[f_n(A-Z)+f_pZ]^2}{v^2}$
Spin dependent	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{N}\gamma_\mu\gamma^5 N$ or $\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{N}\sigma_{\mu\nu}N$	$O_4 = \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N$	$\Sigma' + \Sigma''$	$\frac{(J+1)/J}{v^2}$
Pseudoscalar	$\bar{\chi}\gamma^5\chi\,\bar{N}\gamma^5 N$	$O_6 = (\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q})$	Σ''	$q^4\frac{(J+1)/J}{v^2}$
Millicharge	$Qe\,\bar{\chi}\gamma^\mu\chi\,A_\mu$	$O_1 = \mathbb{1}$	M	$\frac{Q^2Z^2\alpha^2}{q^4v^2}$
Electric dipole	$\frac{id}{2}\,\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\,F^{\mu\nu}$	$O_{11} = i\boldsymbol{s}_\chi \cdot \boldsymbol{q}$	M	$\frac{d^2Z^2\alpha}{q^2v^2}$
Magnetic dipole	$\frac{\mu}{2}\,\bar{\chi}\sigma_{\mu\nu}\chi\,F^{\mu\nu}$	O_1, O_4, O_5, O_6	M, Σ', Δ	$\mu^2\left[Z^2\alpha\left(\frac{1}{v_\mathrm{min}^2}-\frac{1}{v^2}\right)+\frac{\mu_T^2}{v^2}\right]$
Anapole moment	$\frac{a}{2}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial^\nu F_{\mu\nu}$	O_8, O_9	M, Σ', Δ	$E_\mathrm{R}a^2\left[Z^2\alpha\left(\frac{1}{v_\mathrm{min}^2}-\frac{1}{v^2}\right)+\frac{\mu_T^2}{v^2}\right]$

Cross section structure

Majorana DM

Neutralino

Type	Lagrangian	NR operators	Nuclear responses	Structure of $\frac{\mathrm{d}\sigma_T}{\mathrm{d}E_\mathrm{R}}$
Spin independent	$\bar{\chi}\chi\,\bar{N}N$ or $\bar{\chi}\gamma^\mu\chi\,\bar{N}\gamma_\mu N$	$O_1 = \mathbb{1}$	M	$\frac{[f_n(A-Z)+f_pZ]^2}{v^2}$
Spin dependent	$\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{N}\gamma_\mu\gamma^5 N$ or $\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{N}\sigma_{\mu\nu}N$	$O_4 = \boldsymbol{s}_\chi \cdot \boldsymbol{s}_N$	$\Sigma' + \Sigma''$	$\frac{(J+1)/J}{v^2}$
Pseudoscalar	$\bar{\chi}\gamma^5\chi\,\bar{N}\gamma^5 N$	$O_6 = (\boldsymbol{s}_\chi \cdot \boldsymbol{q})(\boldsymbol{s}_N \cdot \boldsymbol{q})$	Σ''	$q^4\frac{(J+1)/J}{v^2}$
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Magnetic dipole	$\frac{\mu}{2}\,\bar{\chi}\sigma_{\mu\nu}\chi\,F^{\mu\nu}$	O_1, O_4, O_5, O_6	M, Σ', Δ	$\mu^2\left[Z^2\alpha\left(\frac{1}{v^2_\mathrm{min}} - \frac{1}{v^2}\right) + \frac{\mu_T^2}{v^2}\right]$
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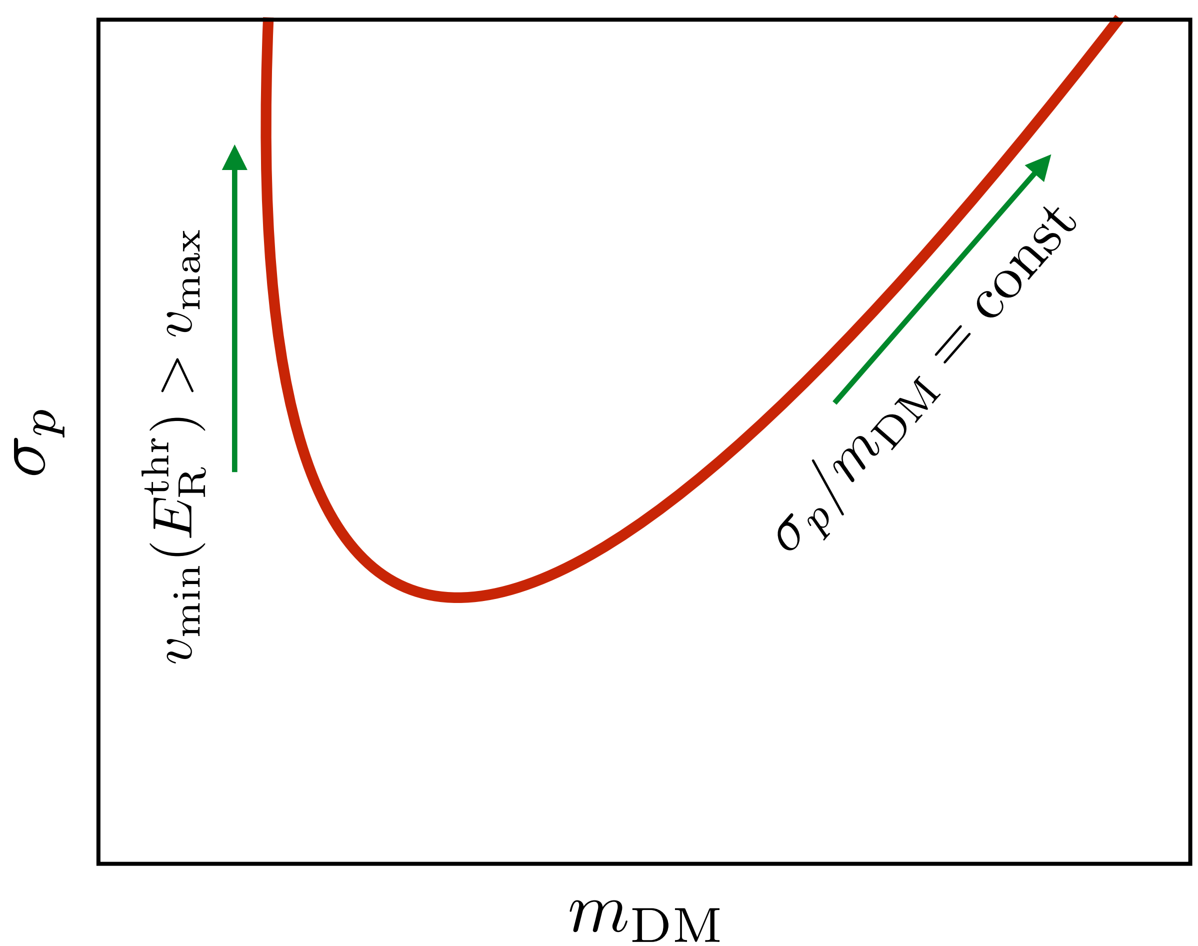
Spin-dependent & spin-independent

$$R \sim \frac{\rho \sigma_p}{m_{\rm DM}} \int_{E_{\rm R\,1}}^{E_{\rm R\,2}} \eta_0(v_{\rm min}(E_{\rm R}))\, {\rm d}E_{\rm R}$$

$$\eta_0(v_{\rm min}) \sim \int_{v \geqslant v_{\rm min}} \frac{f(\boldsymbol{v})}{v}\, {\rm d}^3 v$$



Scattering off Xe in LUX

arXiv:1507.04007

Spin-dependent vs spin-independent

For a given DM mass:

✘ Very similar spectrum

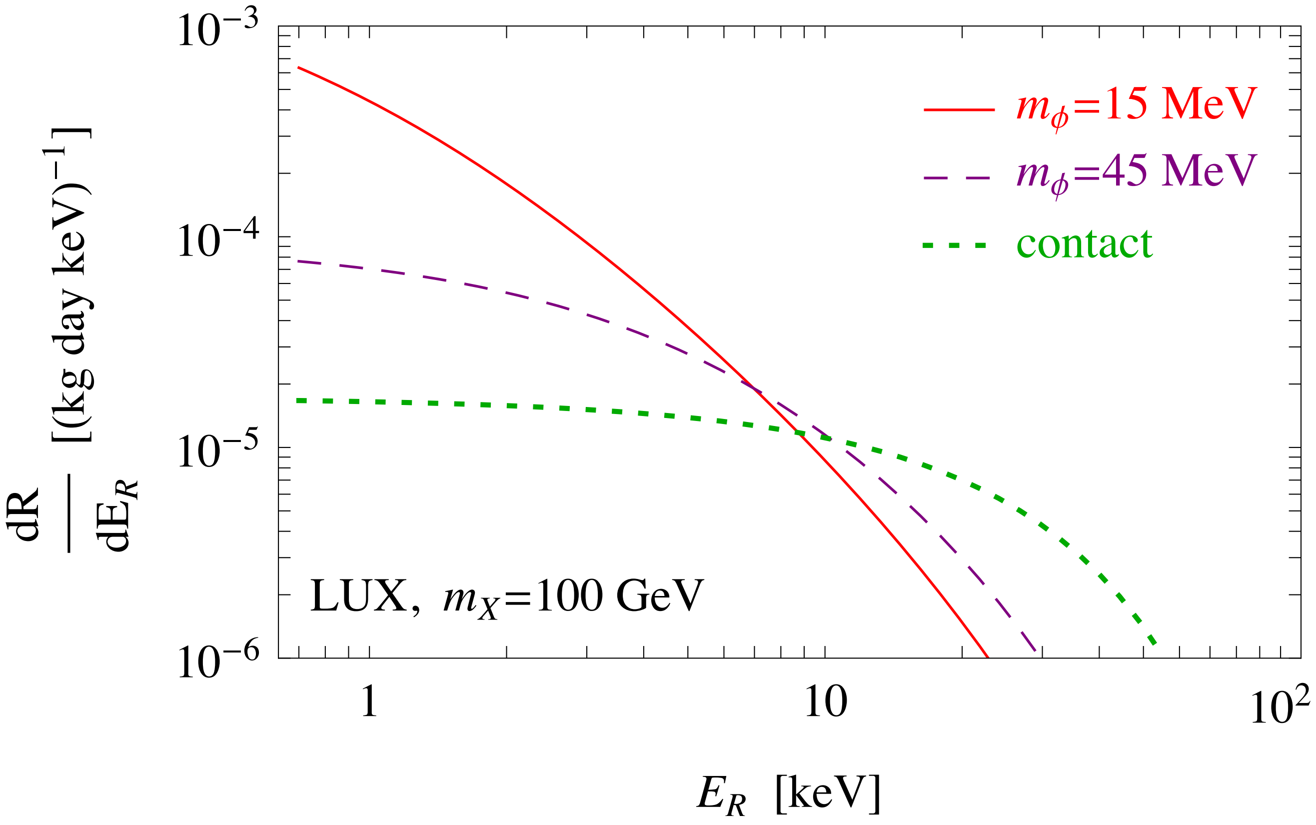
✘ Identical modulation

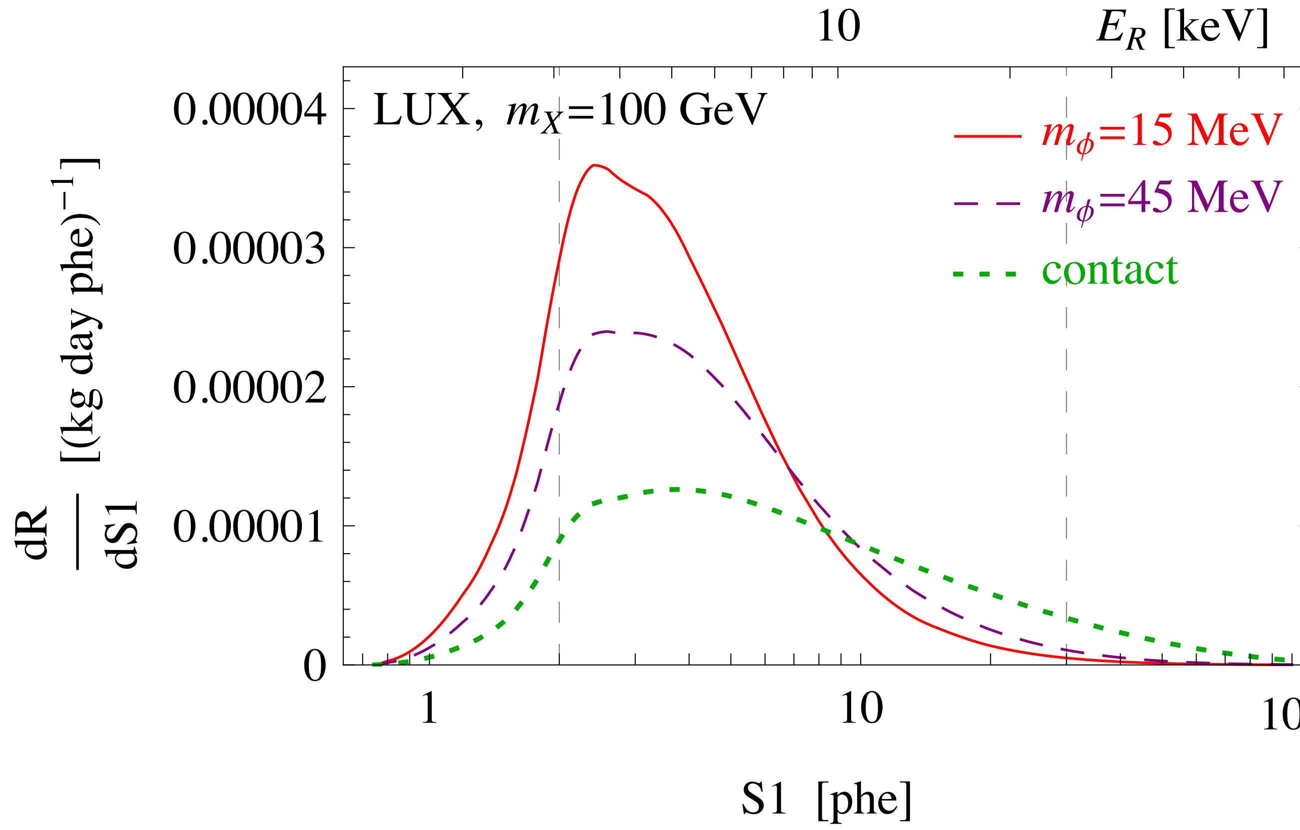
✔ Different A dependence

Several experiments employing different targets may be able to fit cross section dependence on A and J

Light mediator

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





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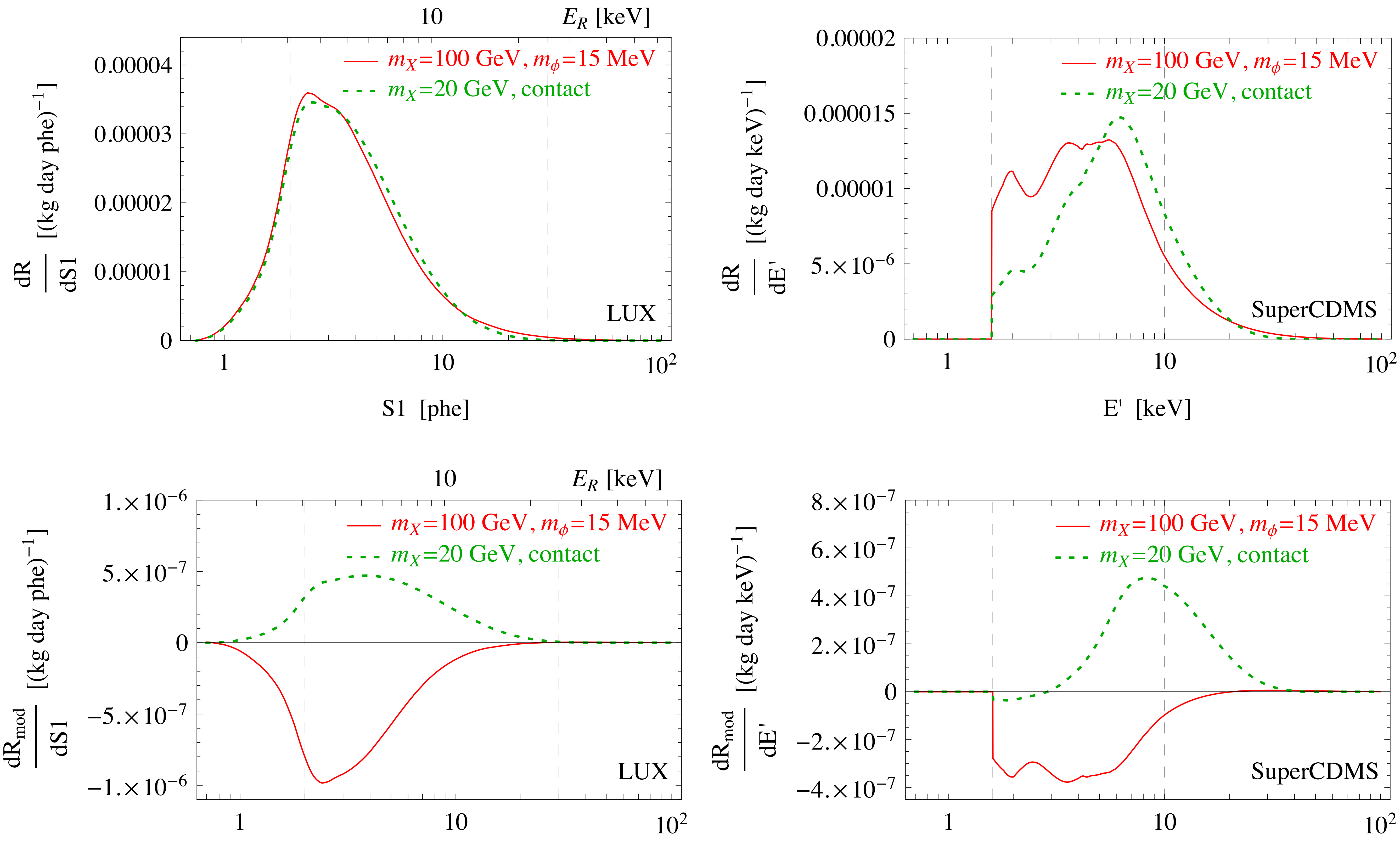
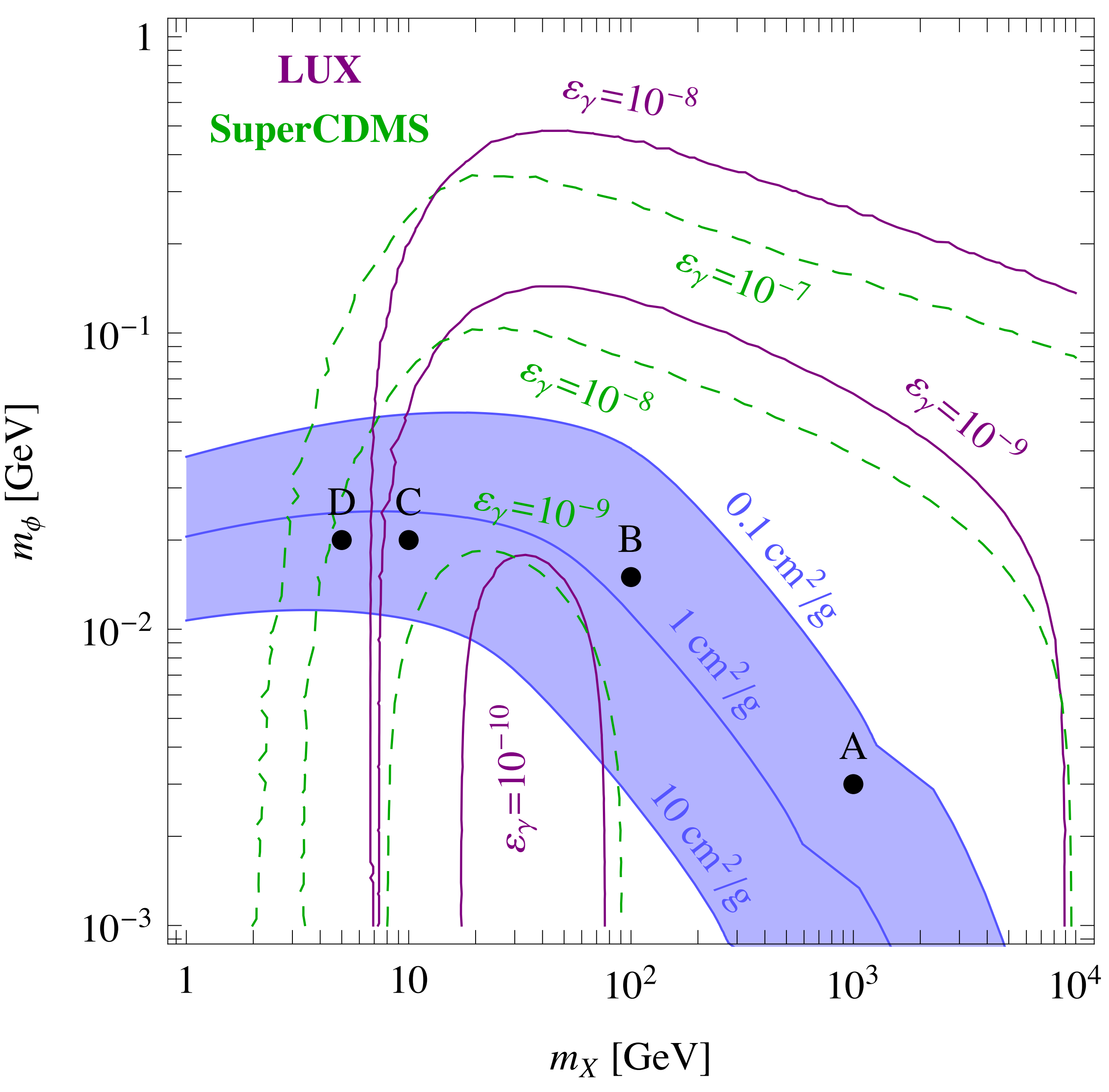
Light mediator



arXiv:1507.04007

Light mediator

Excluded below



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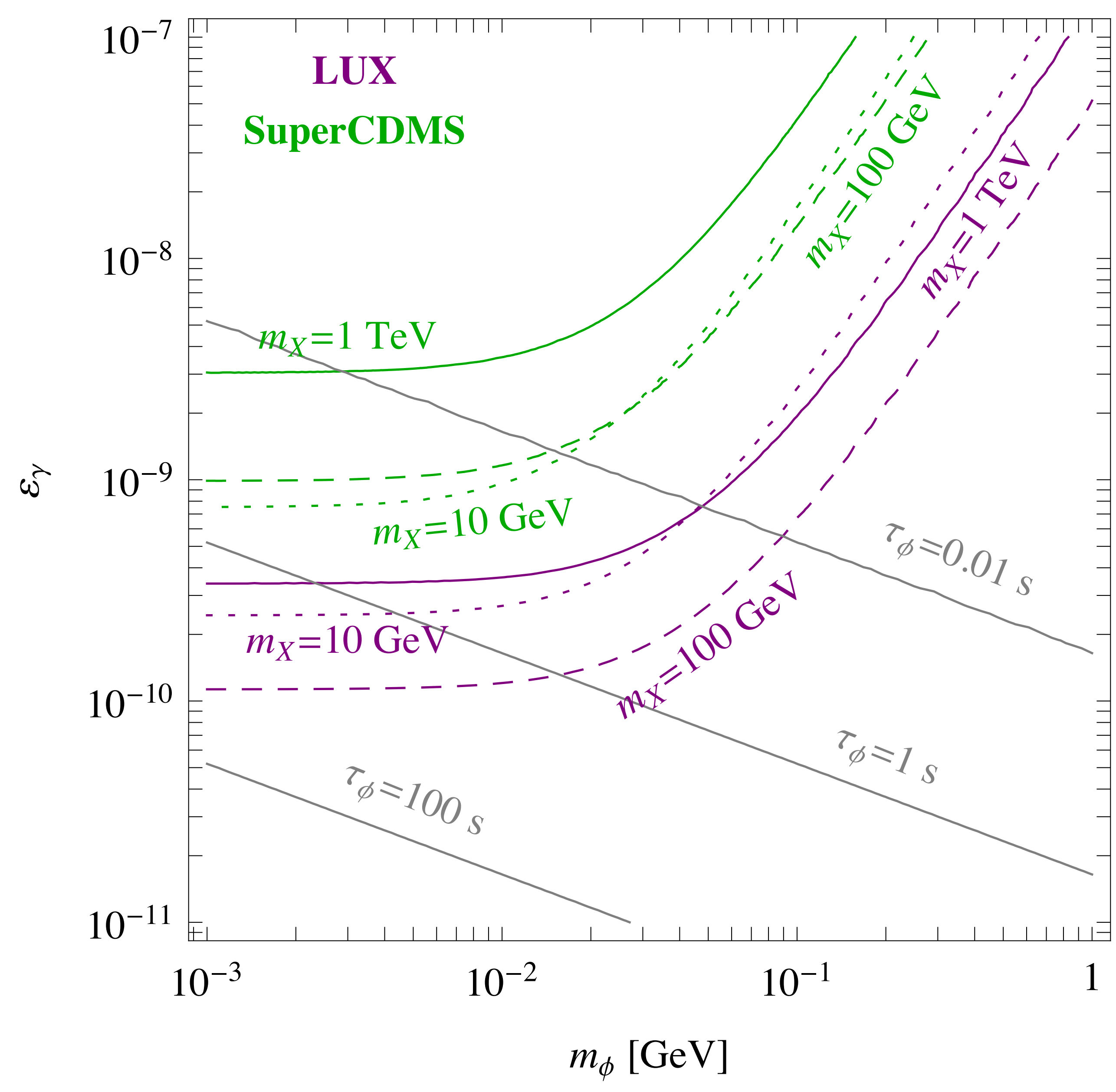

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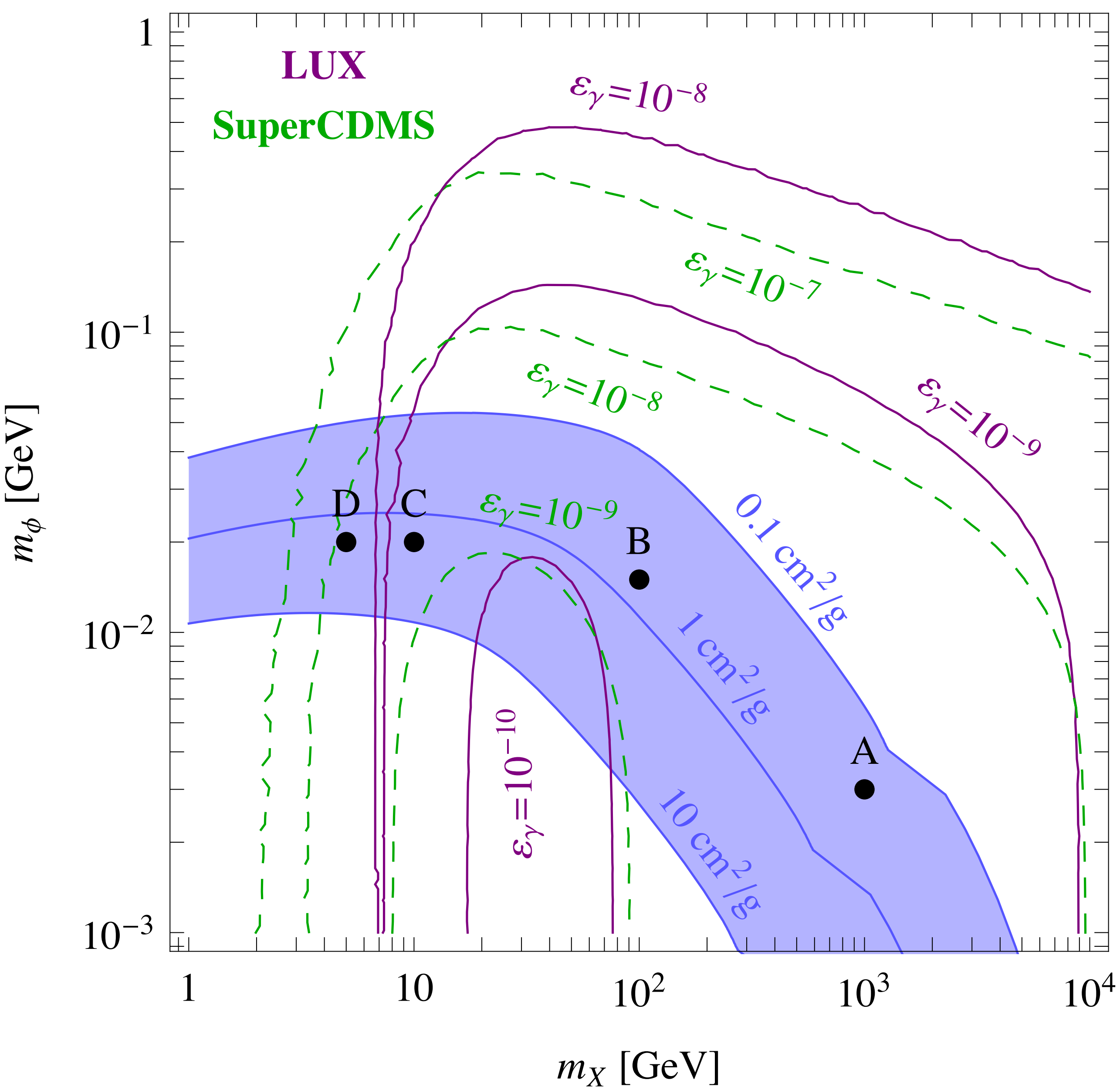
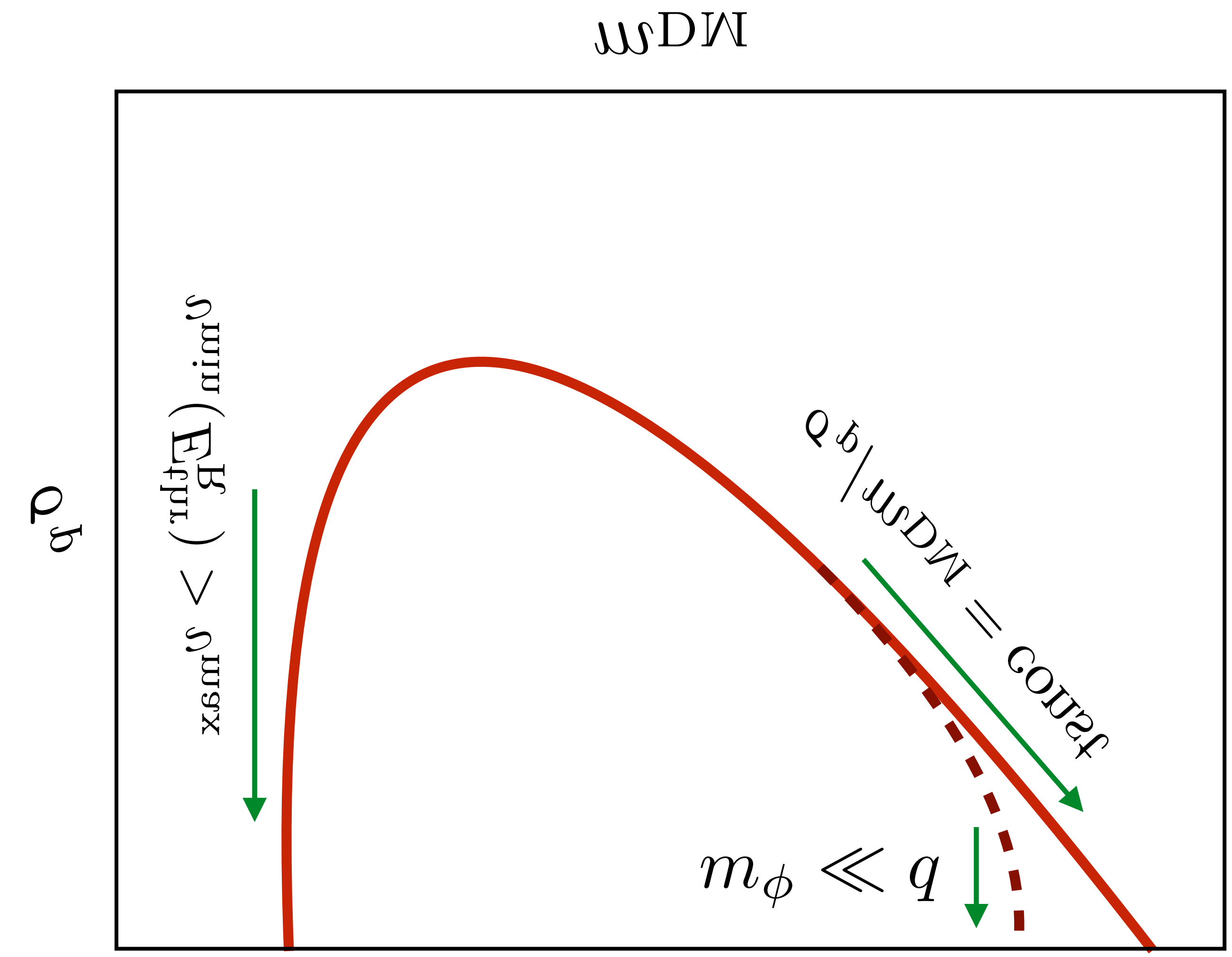


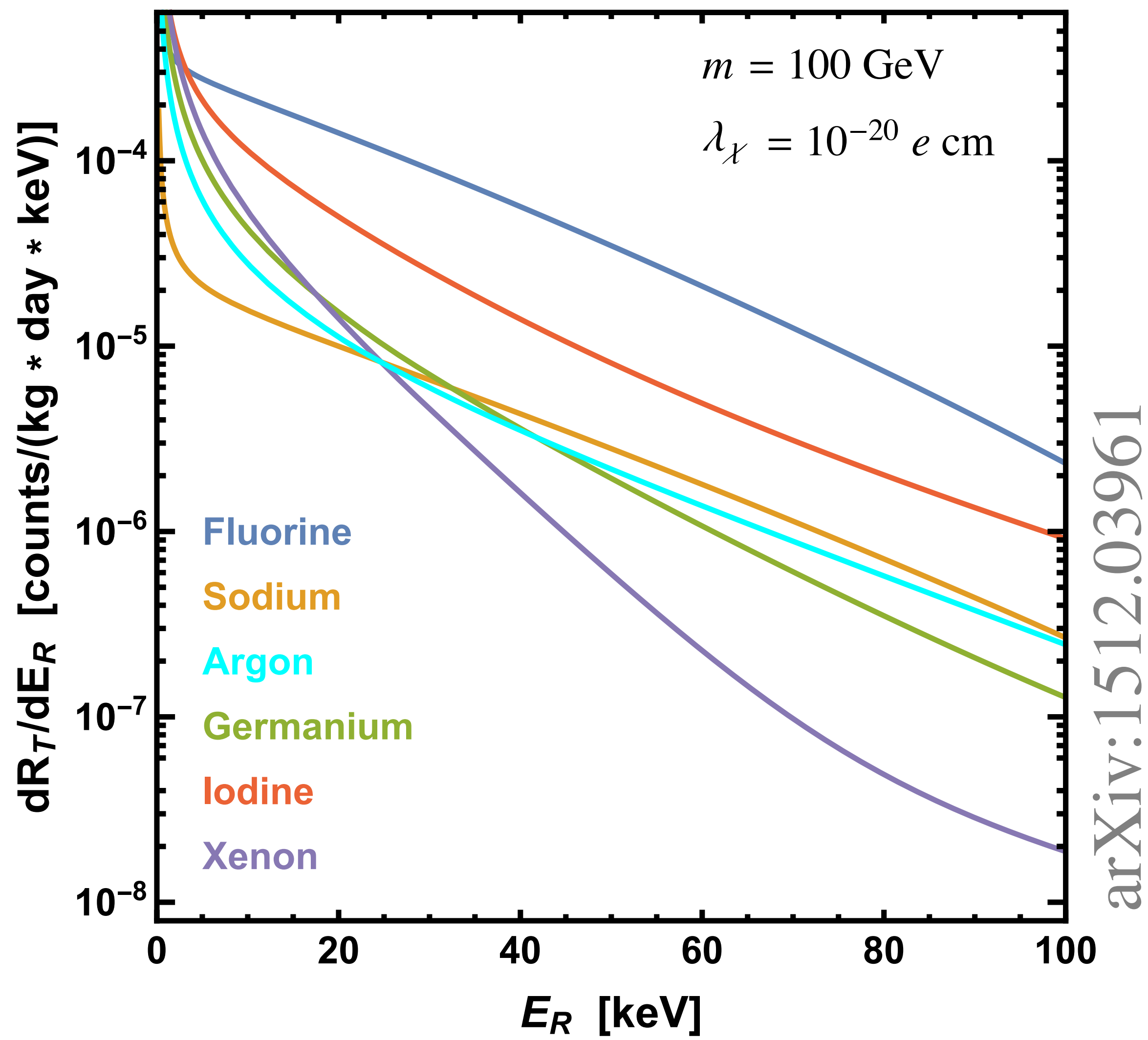


arXiv:1507.04007

Dark Matter with magnetic dipole moment

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

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



Dark Matter with magnetic dipole moment

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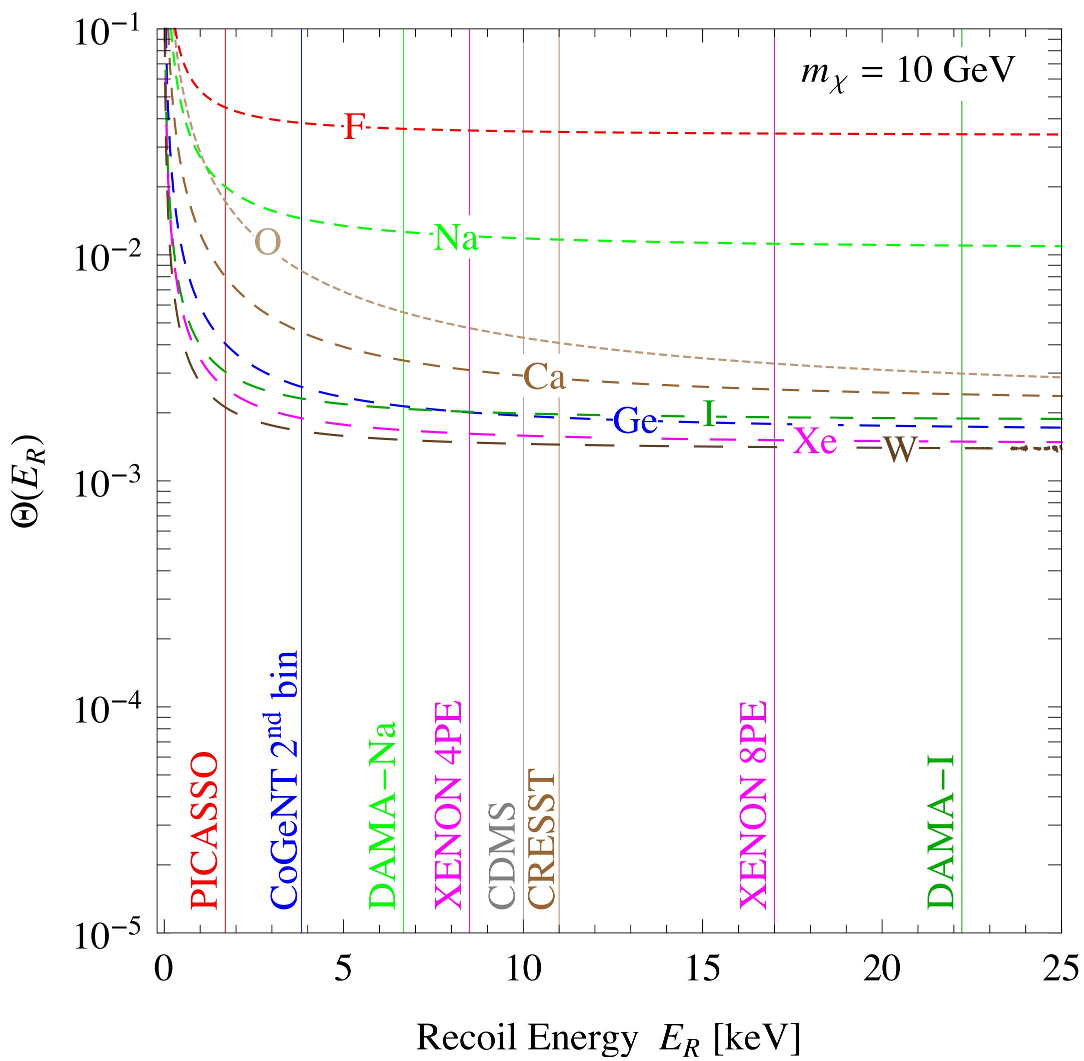
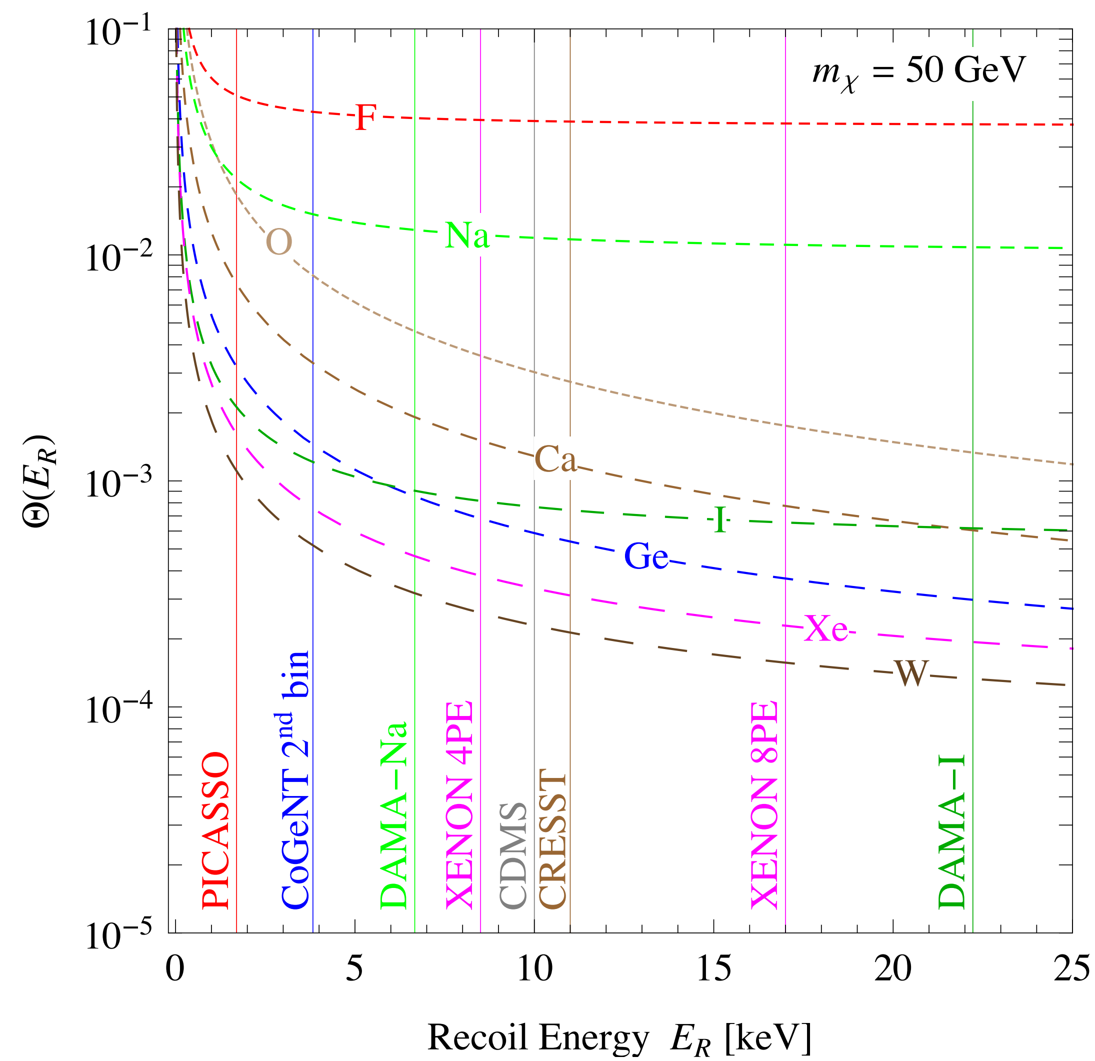


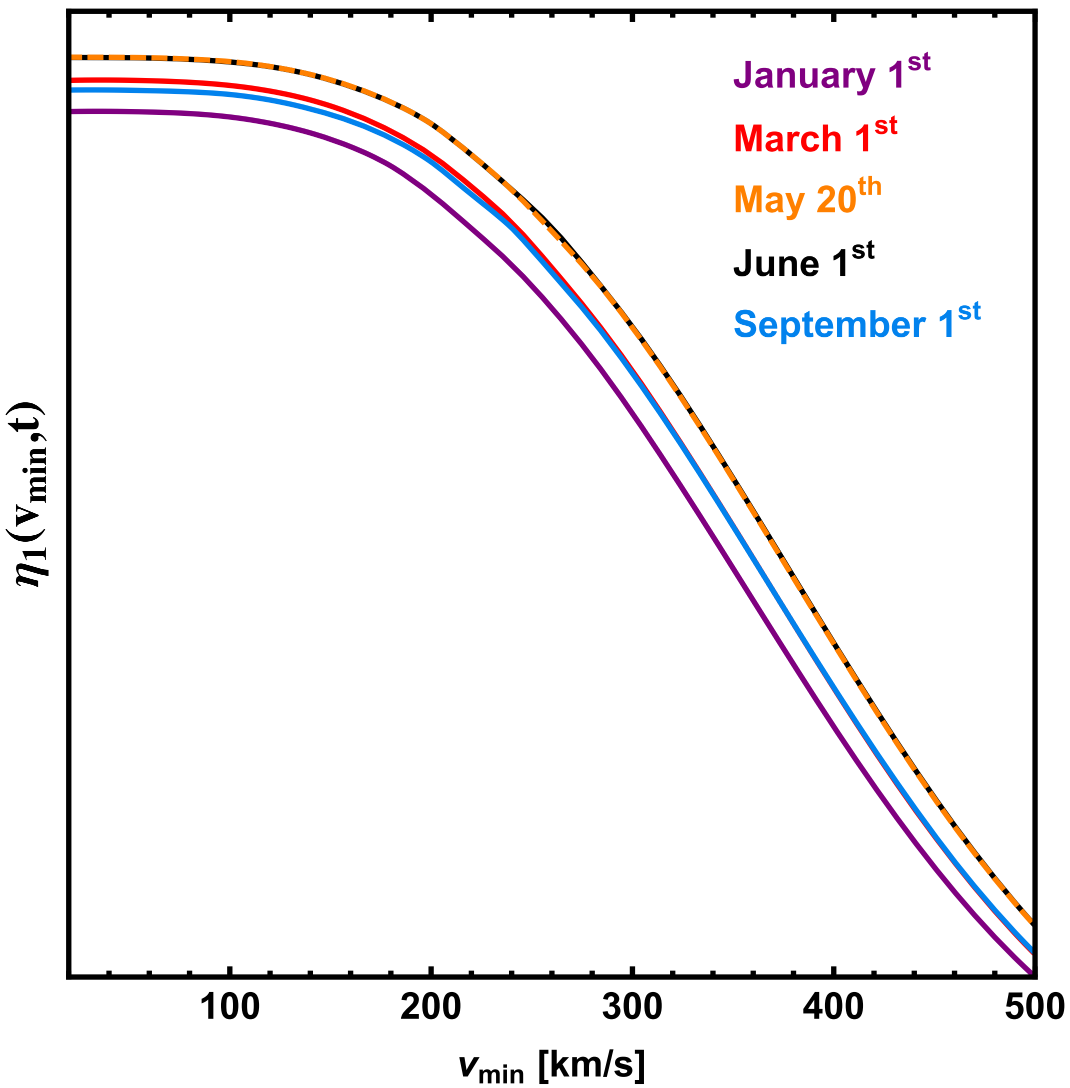


arXiv:1203.6652

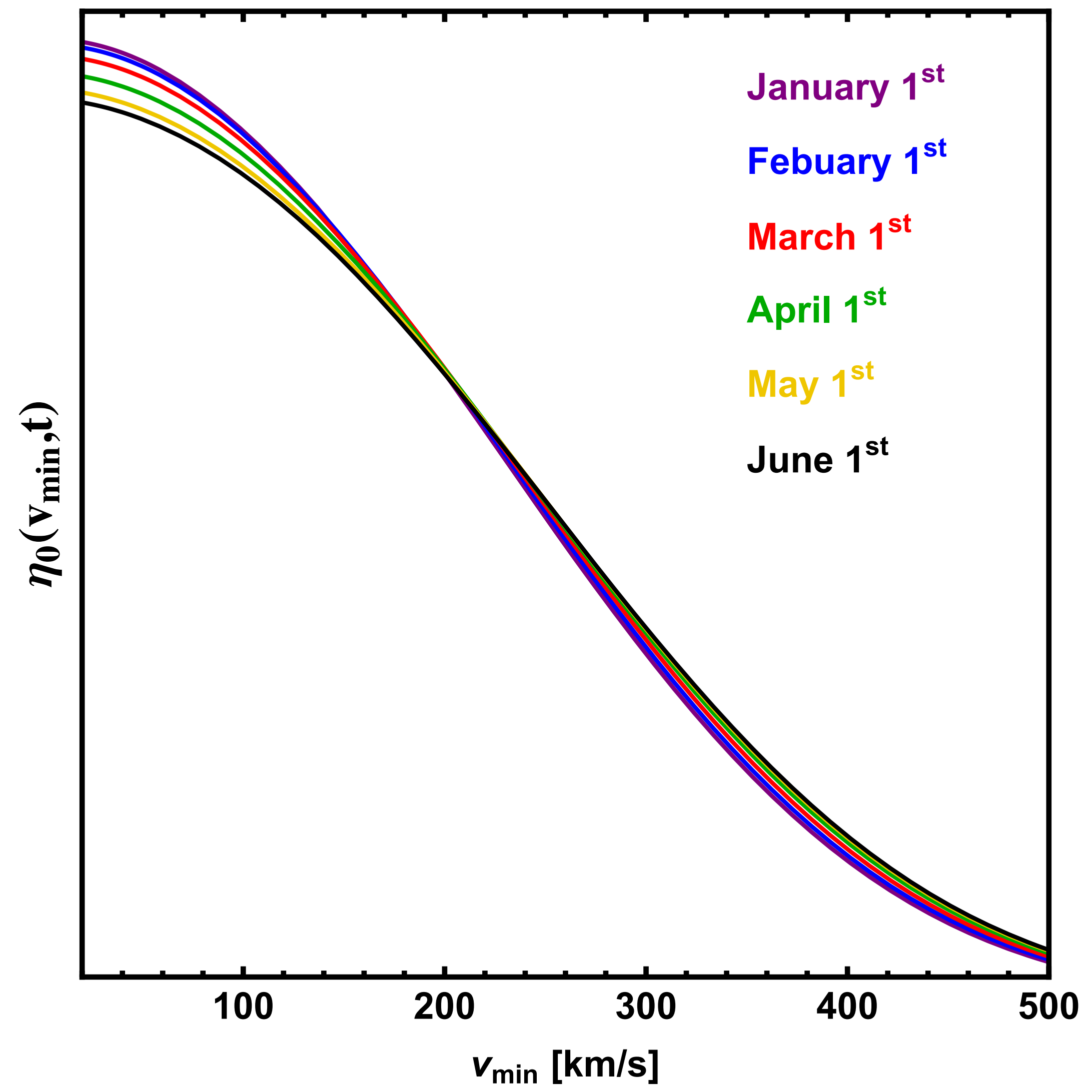
Modulation of magnetic dipole Dark Matter

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

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



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



Modulation of magnetic dipole Dark Matter

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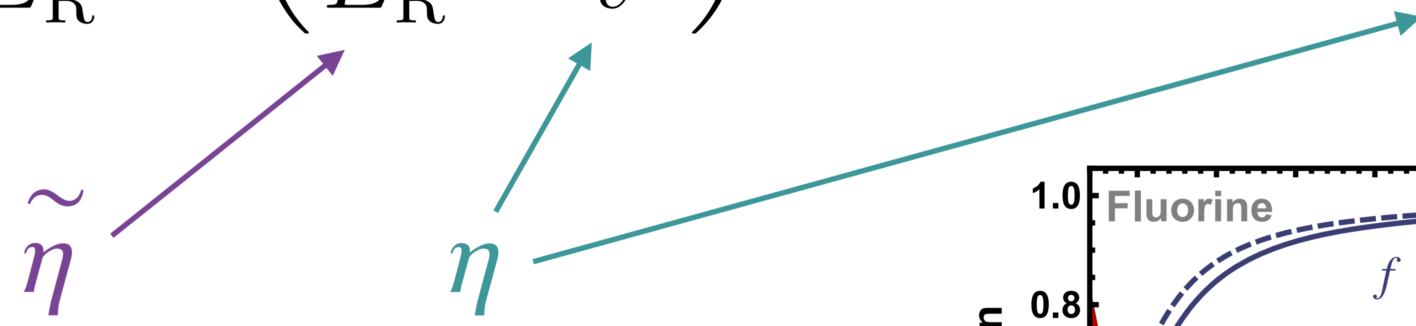
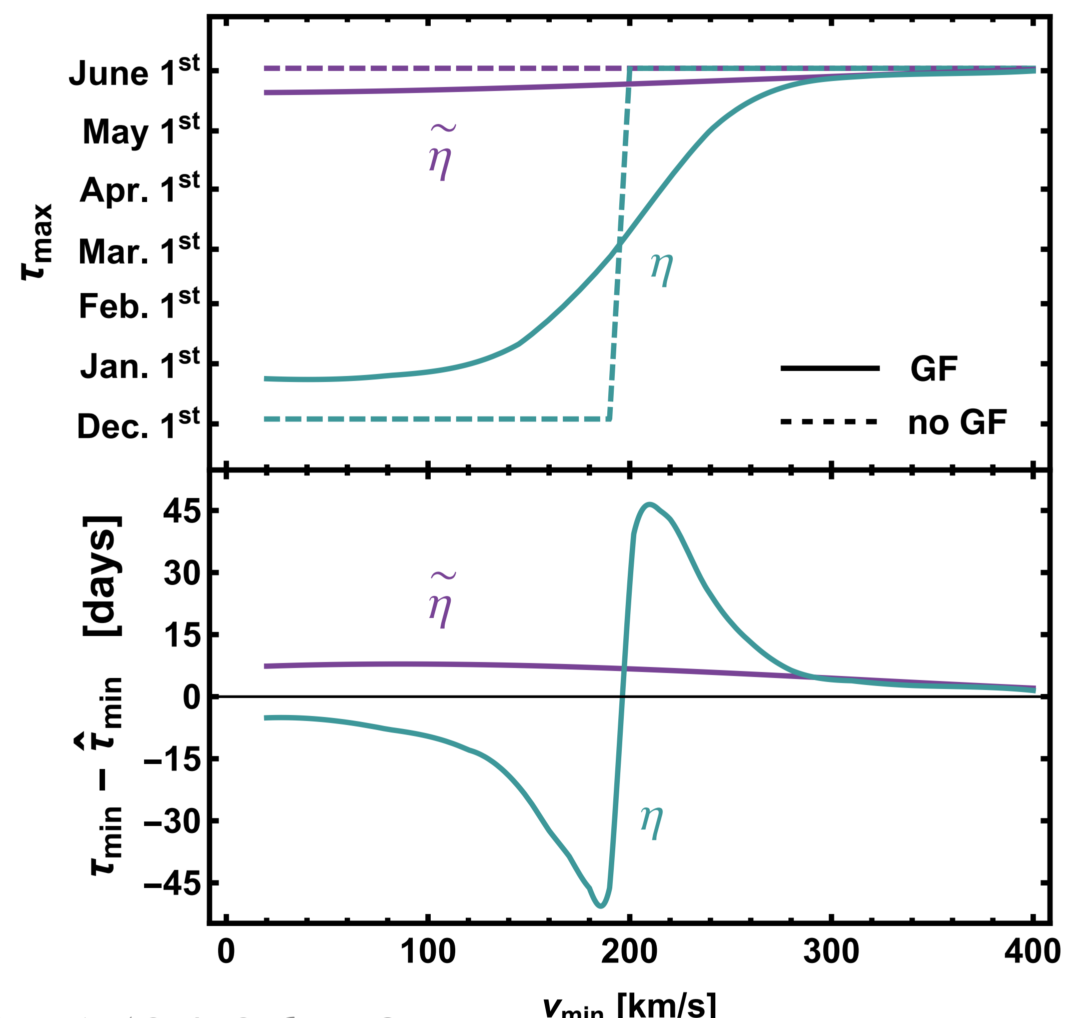
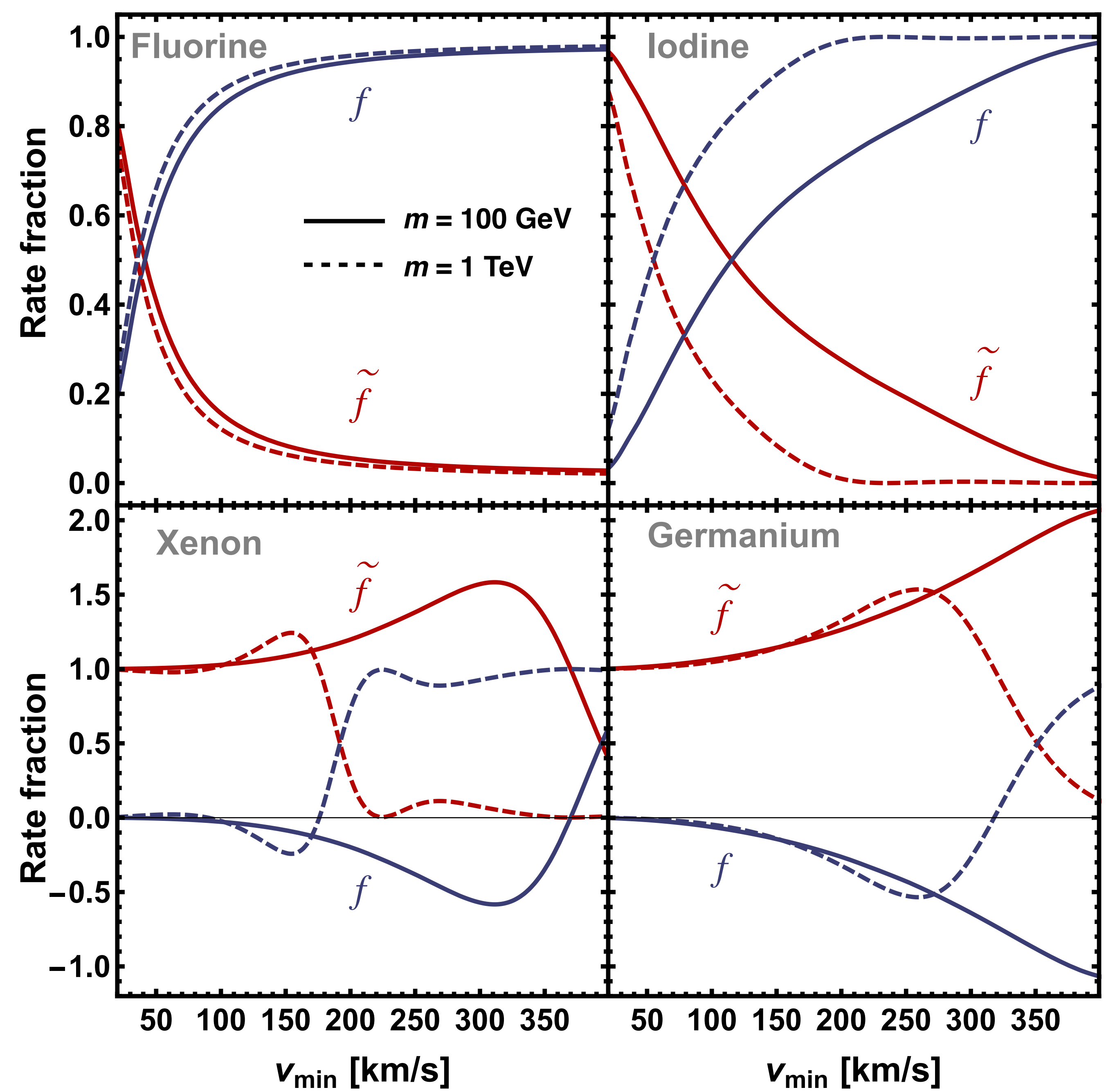




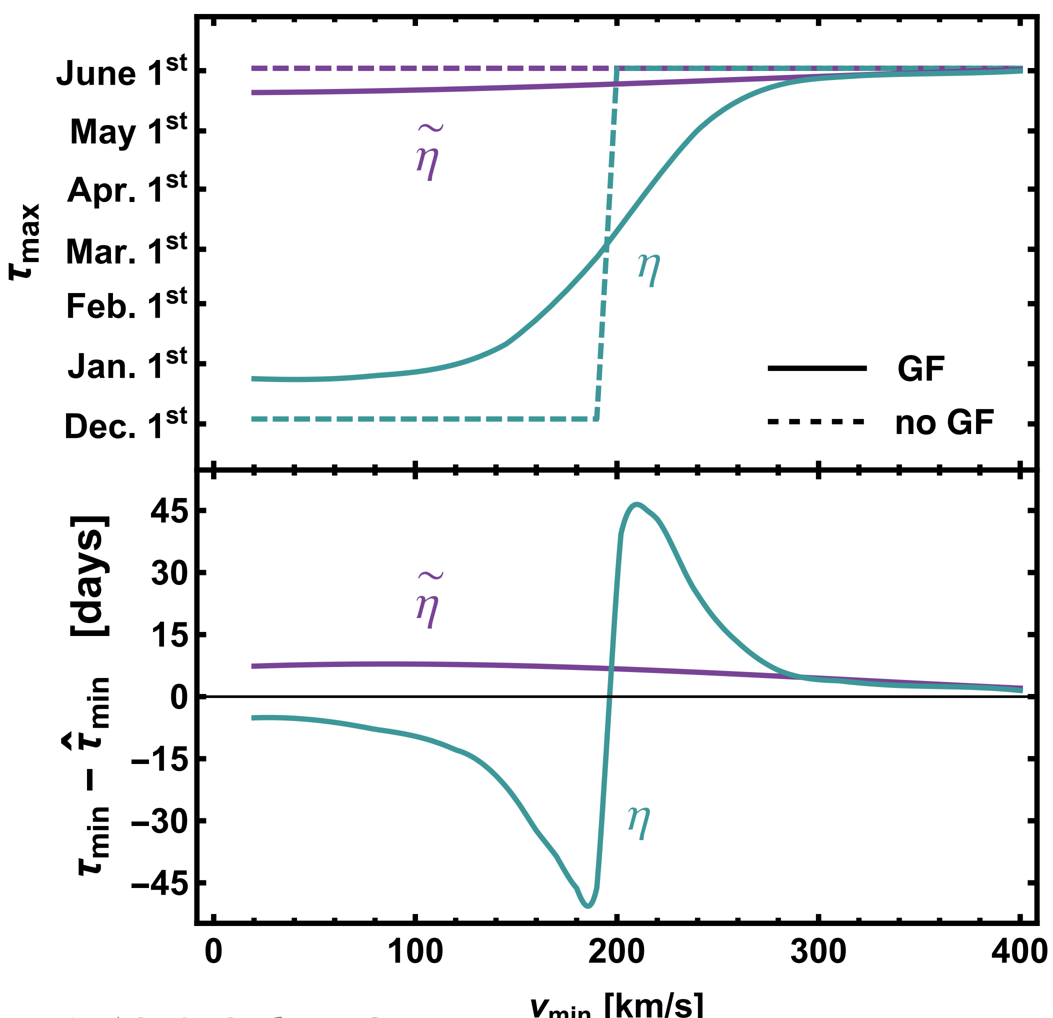


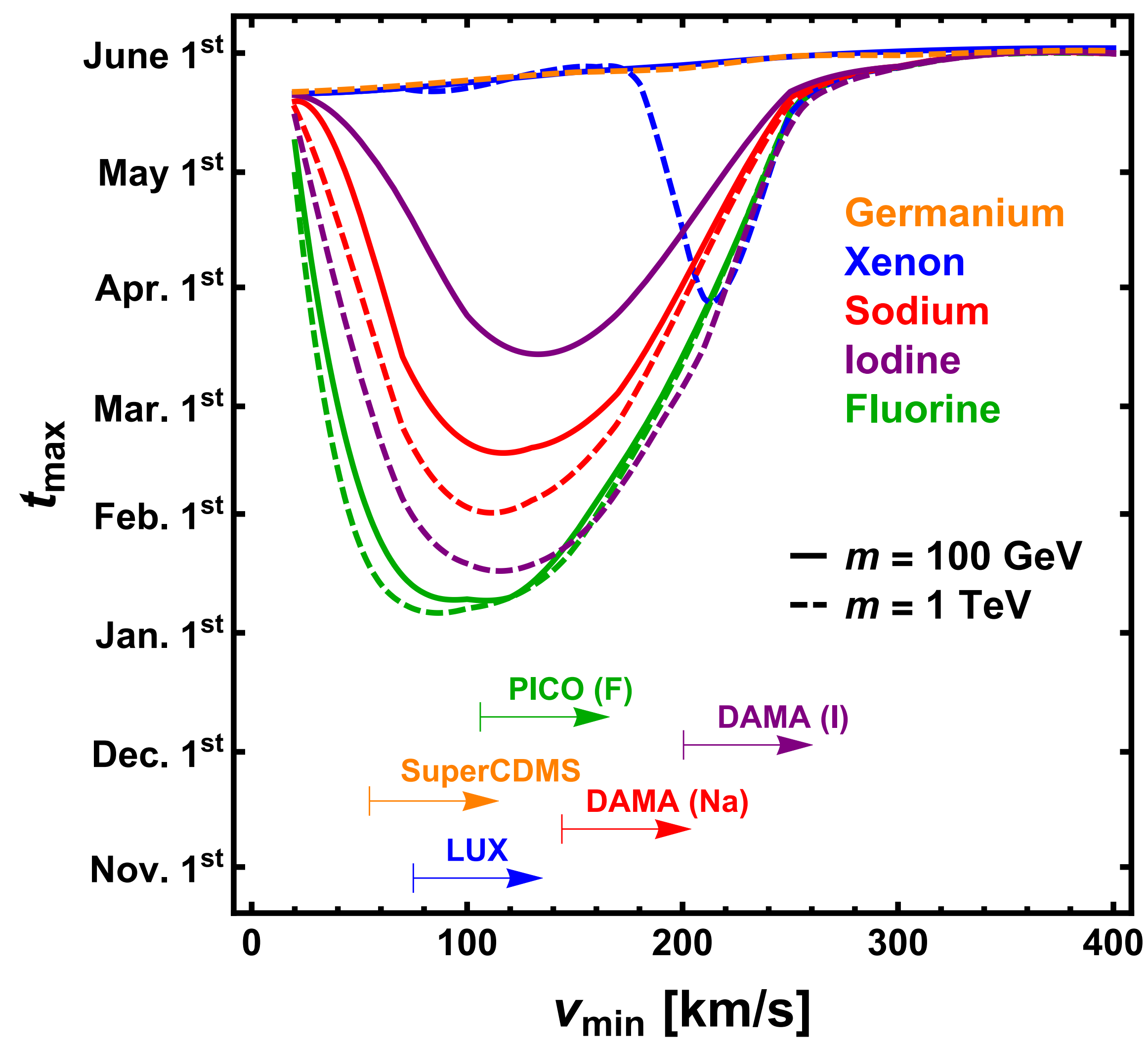
arXiv:1504.06772

Modulation of magnetic dipole Dark Matter

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

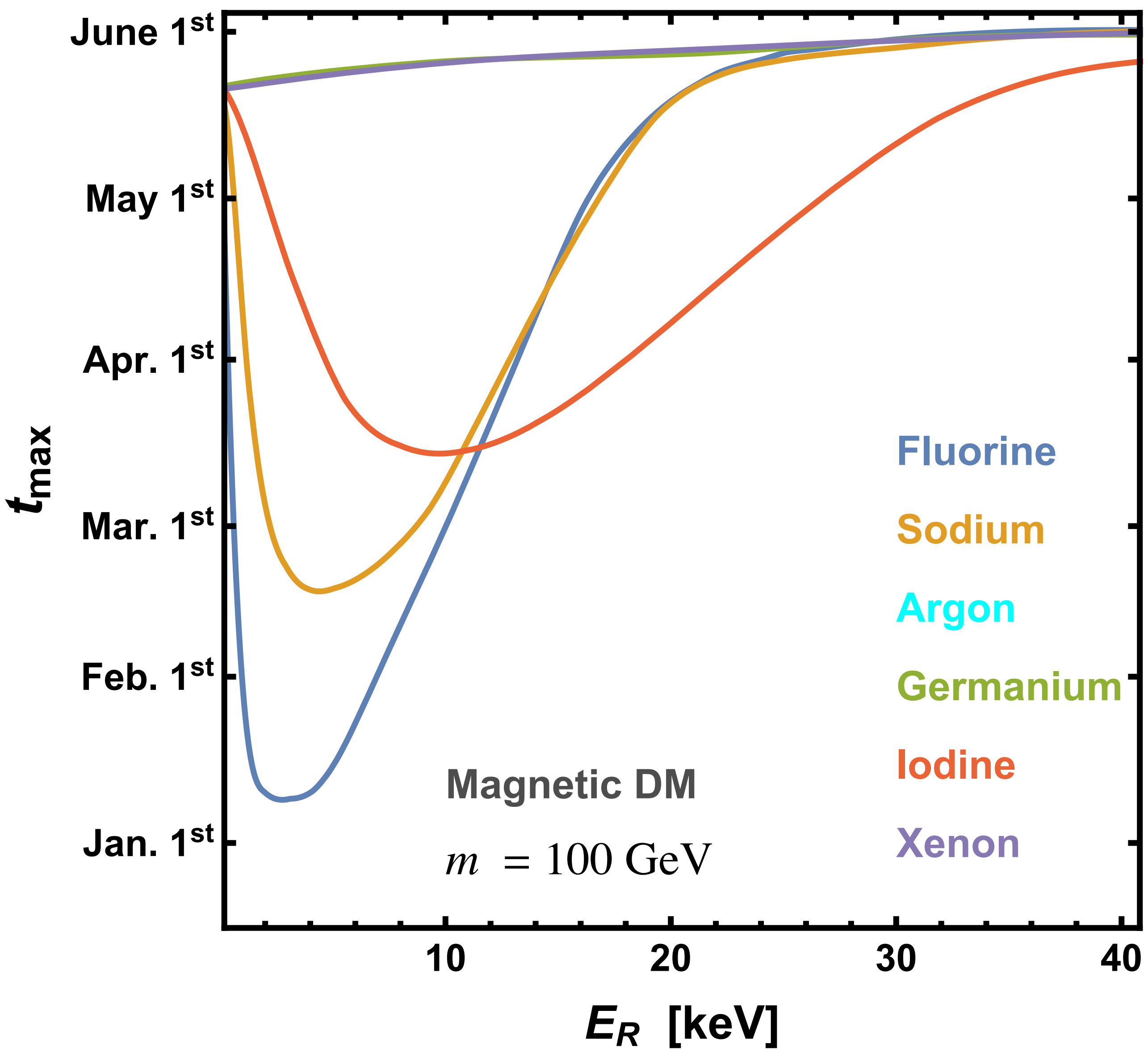
$\tilde{\eta}$ η

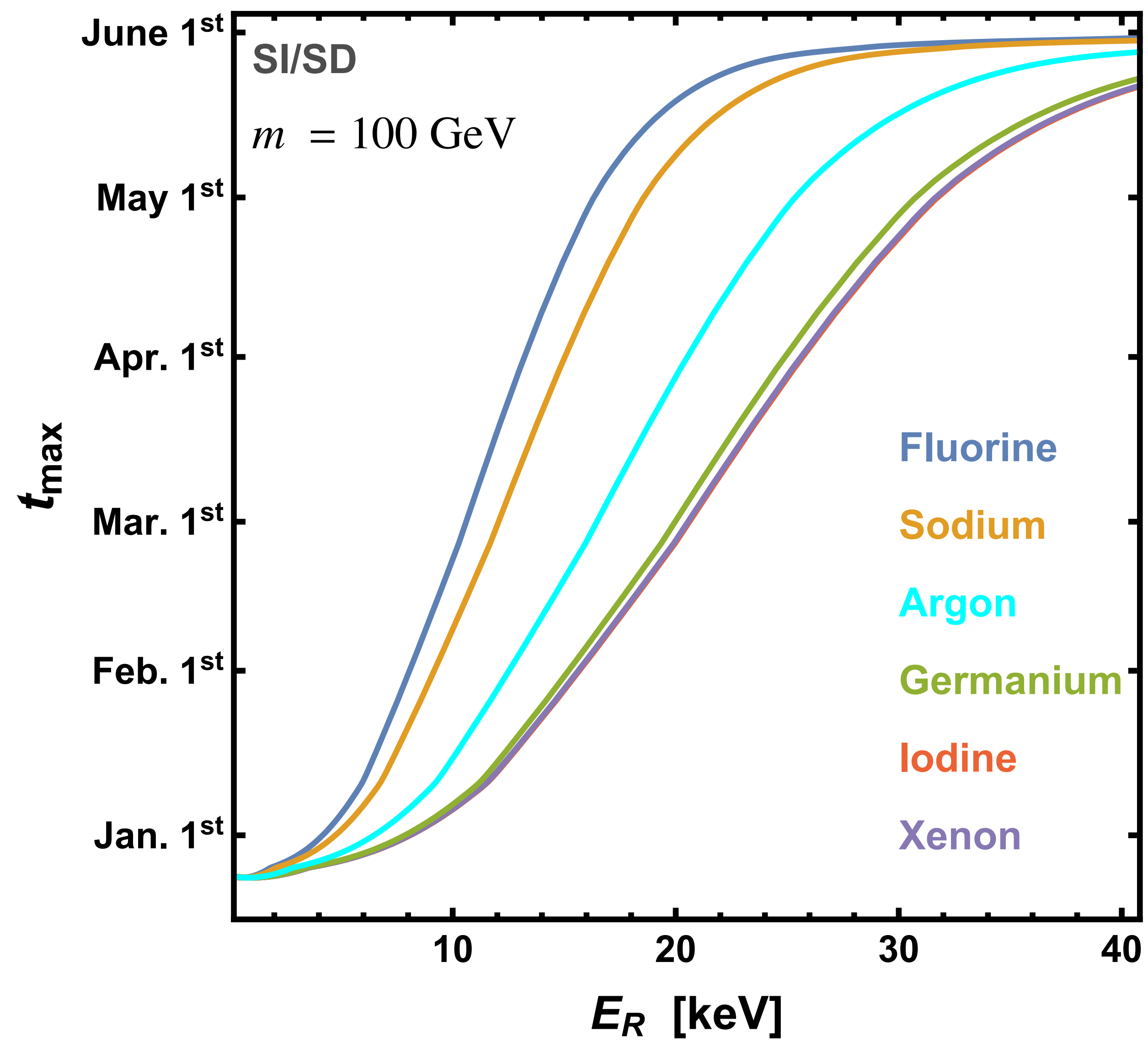




arXiv:1504.06772

Modulation of magnetic dipole Dark Matter





arXiv:1512.03961

Conclusions

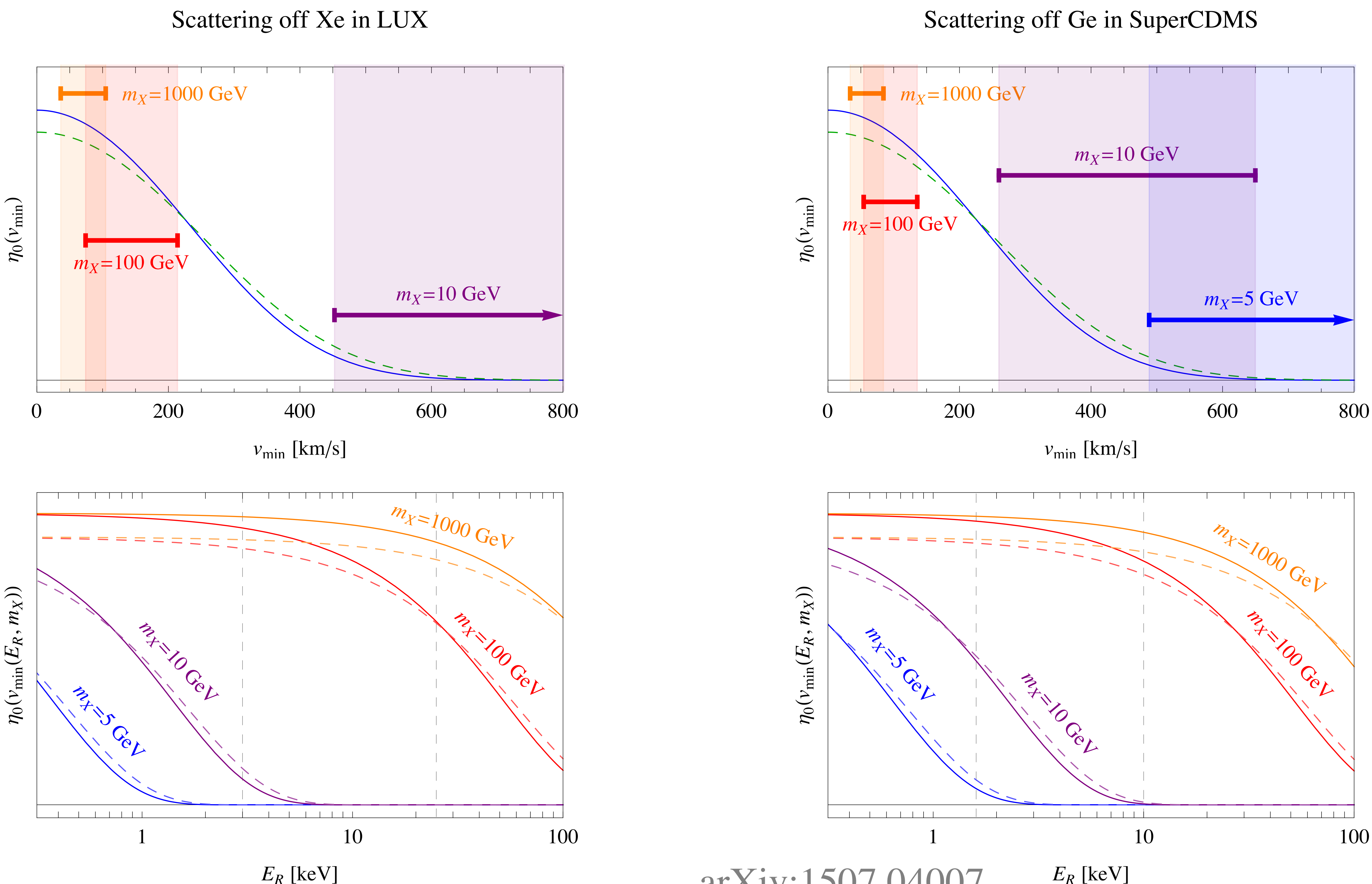
WIMPs don’t need to be standard

Direct detection can discriminate between different DM candidates (as long as any of them actually exists)

Look at: *A* dependence, energy spectrum, modulation

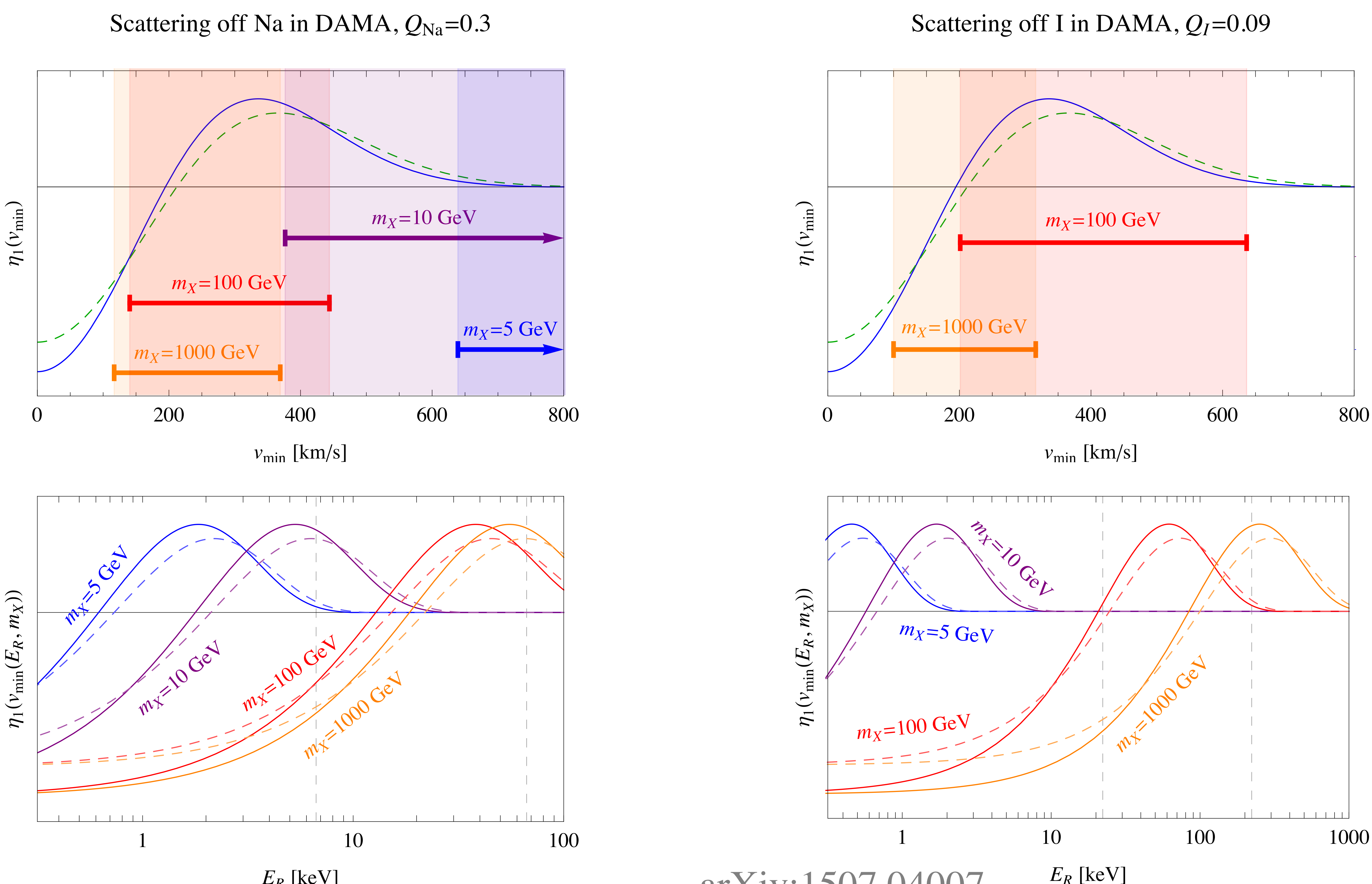
Backups

Velocity integral (time average)



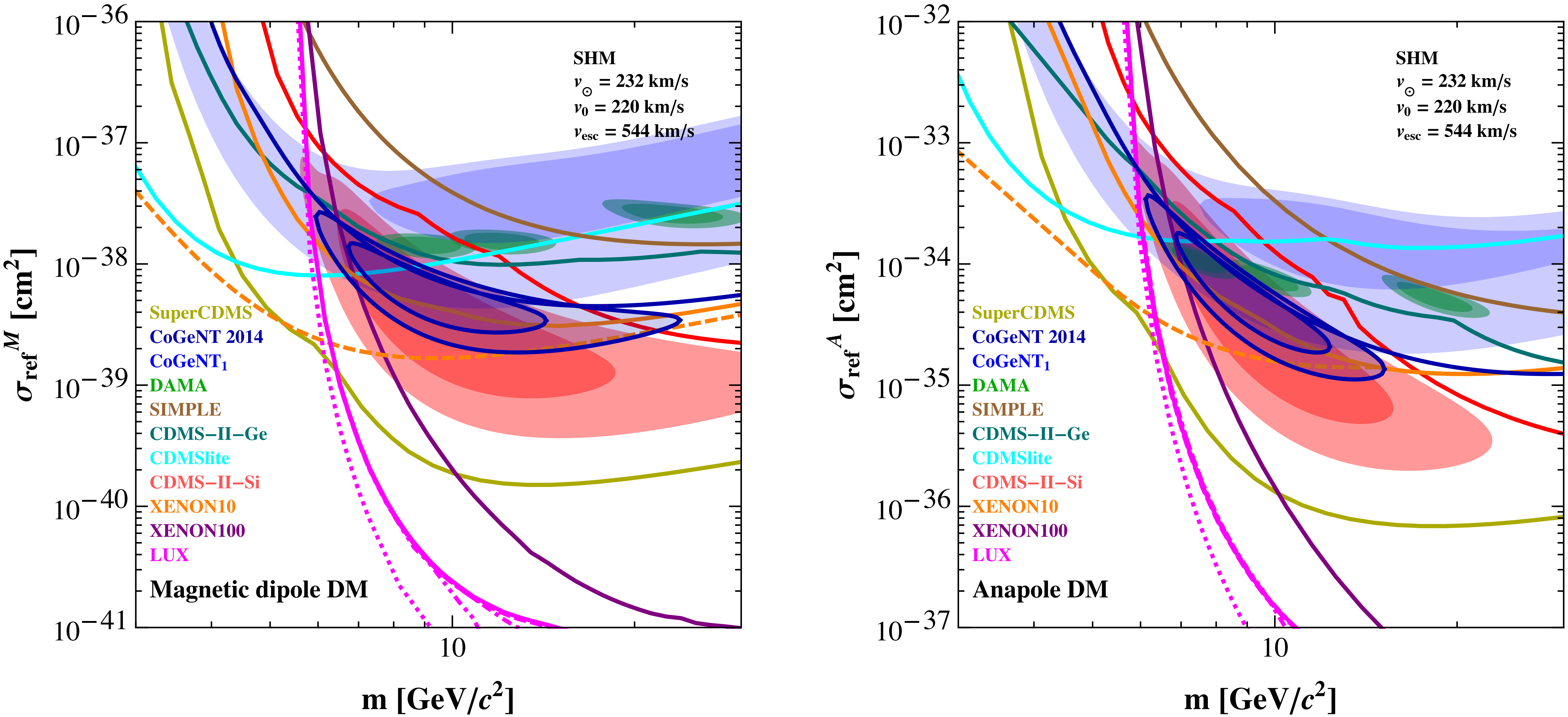
arXiv:1507.04007

Velocity integral (modulation)



arXiv:1507.04007

Dark Matter with magnetic/anapole moment



arXiv:1401.4508