DM electromagnetic interactions in direct detection experiments

Merlin Reichard

based on:
A. Ibarra, **MR**, G. Tomar: *JCAP 02 (2025) 072* (arXiv:2408.15760)

Korea Institute for Advanced Study (KIAS)

25.03.2026

Outline

1. Dark matter with electromagnetic interactions

2. Direct detection signals

3. Implications for renormalizable models

4. Summary

1. Dark matter with electromagnetic interactions

Motivation?

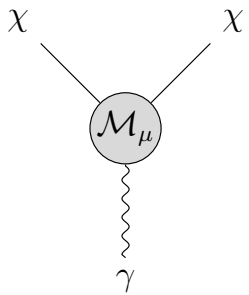
- **neutrons** are electrically neutral, but have:
  1. electric dipole moment [Barr et al. PRL 65 (1990) 21-24, ...]
  2. magnetic dipole moment [Ioffe & Smilga Nucl.Phys.B 232 (1984) 109-142, ...]
  3. charge radius [Atac et al. Nature Commun. 12 (2021) 1, 1759, ...]
  4. anapole moment [Flambaum et al. Nucl.Phys.A 449 (1986) 750-760, ...]

- non-trivial matching to the DM NREFT ("real world example")

  [see talks by: M. Iglick's, T. Trickle, M. McDuffie, R. Essig, ...]

Dark matter with electromagnetic interactions

Effective photon interaction



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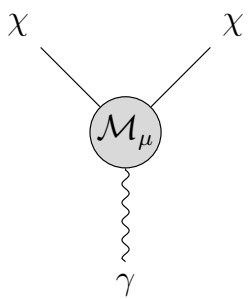
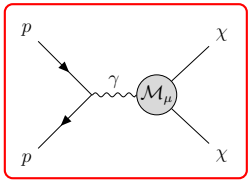


production



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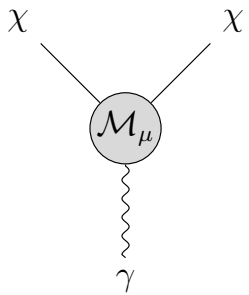

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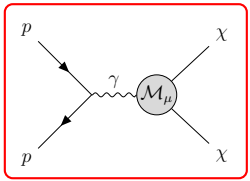

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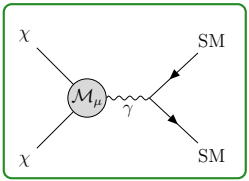

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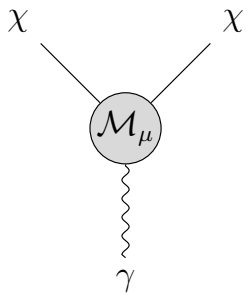

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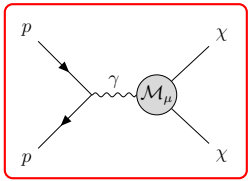

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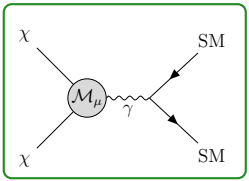

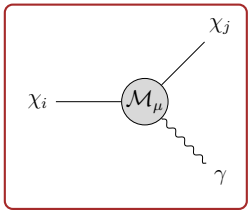

decay

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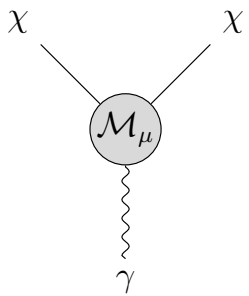

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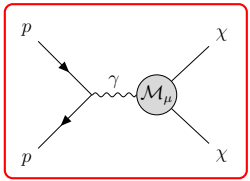

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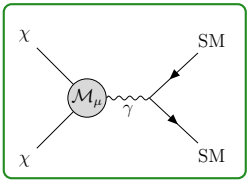

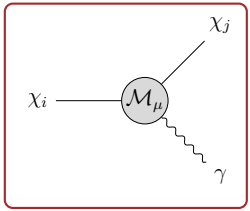

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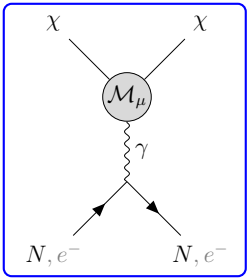

scattering

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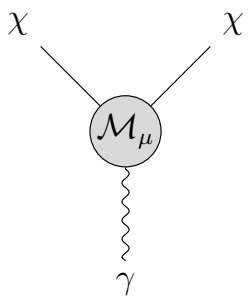

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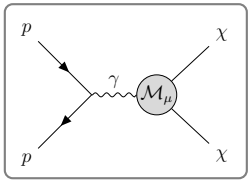

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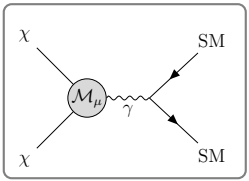

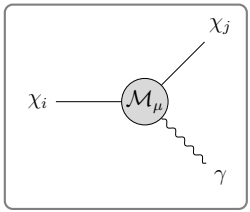

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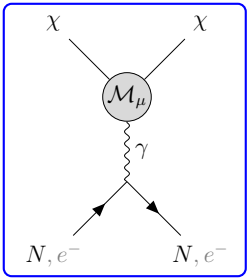

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EFT of electromagnetically interacting DM

Effective Lagrangian for spin-1/2 fermion interacting with a photon A^μ:

$$\mathcal{L} = eQ_\chi \bar{\chi}\gamma_\mu\chi A^\mu + \frac{\mu_\chi}{2}\bar{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu} + i\frac{d_\chi}{2}\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi F^{\mu\nu} + \mathcal{A}_\chi\bar{\chi}\gamma_\mu\gamma_5\chi\partial_\nu F^{\mu\nu} + b_\chi\bar{\chi}\gamma_\mu\chi\partial_\nu F^{\mu\nu}$$

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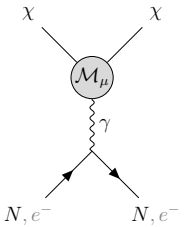
direct detection



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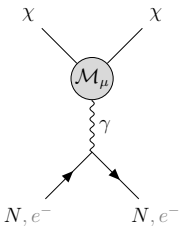

model prediction

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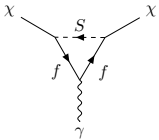

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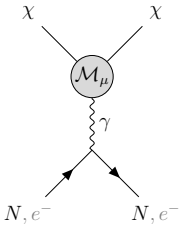

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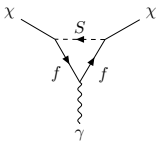
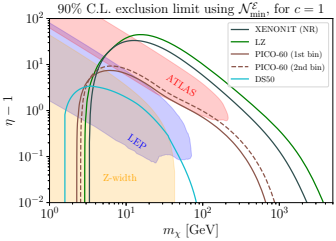


constrain UV model



2. Direct detection signals

Basics of direct detection experiments

- in direct detection (DD) experiment, the scattering rate is given by

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_0}{m_\chi m_N} \int \mathrm{d}^3 v \; v \; f_\oplus(\boldsymbol{v}, t) \; \frac{\mathrm{d}\sigma}{\mathrm{d}E_R}$$

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$$\mathcal{N}^{\mathcal{E}}_{\mathrm{sig}} = w_{\mathcal{E}} \int \mathrm{d}R = \sum_{\mathbb{M},\, \mathbb{M}' = Q_\chi, \ldots} \vec{v}^{\,T}_{\mathbb{M}} \, \mathbb{N}^{\mathcal{E}}_{\mathbb{M}\mathbb{M}'} \, \vec{v}_{\mathbb{M}'}$$

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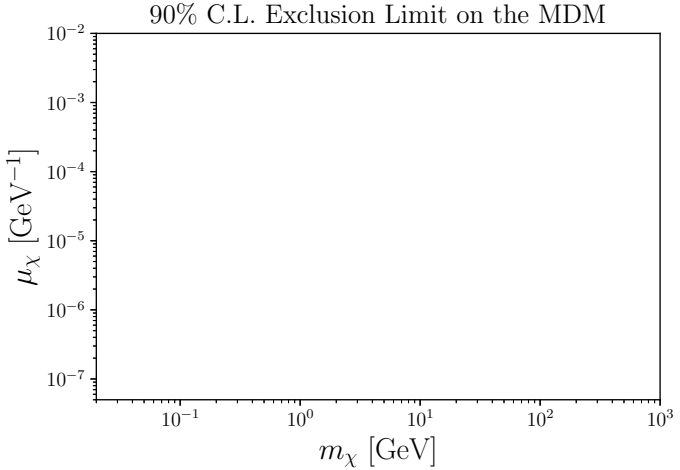
$\vec{v}^{\,T}_{\mathbb{M}} \, \mathbb{N}^{\mathcal{E}}_{\mathbb{M}\mathbb{M}'} \, \vec{v}_{\mathbb{M}'}$ contains all exp. and astrophysical details for experiment $\mathcal{E}$

$\vec{v} = (Q_\chi, \mu_\chi, d_\chi, \mathcal{A}_\chi, b_\chi)^T$

Exclusion limits on the magnetic dipole moment

provided in 2408.15760 & github

$$\mathcal{N}^{\mathcal{E}}_{\text{sig}} = \mu_\chi^2 \times \mathbb{N}^{\mathcal{E}}_{\mu_\chi \mu_\chi}$$



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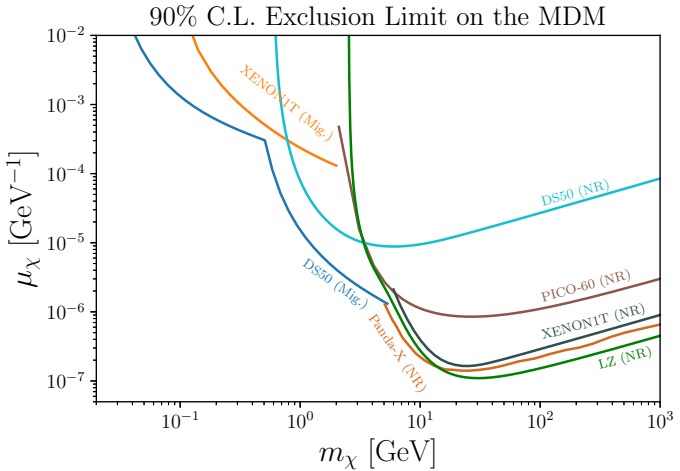

[NR: 2408.15760, Nature 618, 47–50 (2023); Migdal: 2408.15760;]

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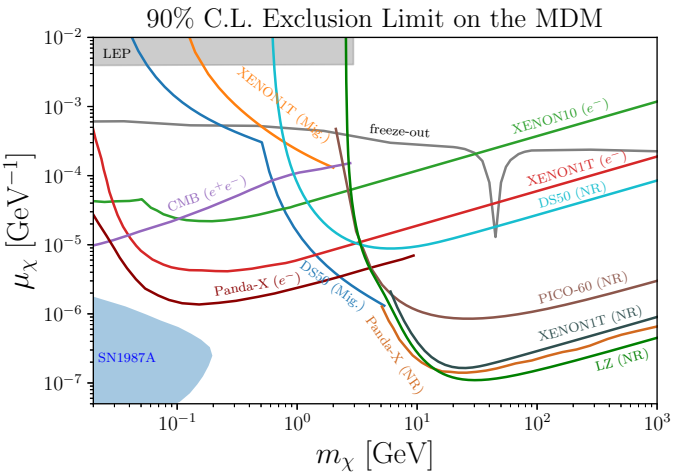
- nuclear recoils
- Migdal effect (e^- from NR)
- electron recoils
- LEP, CMB, SN
- thermal production ($\Omega h^2 \simeq 0.12$ [Planck 2018])



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Multiple EM moments and their interference I

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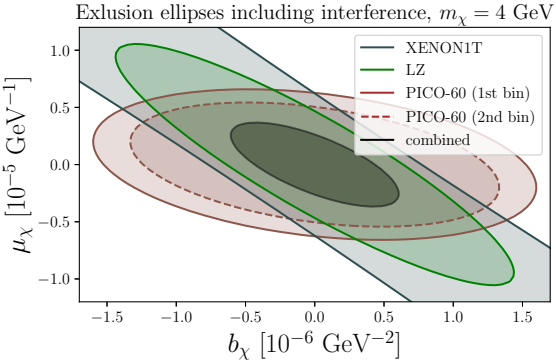

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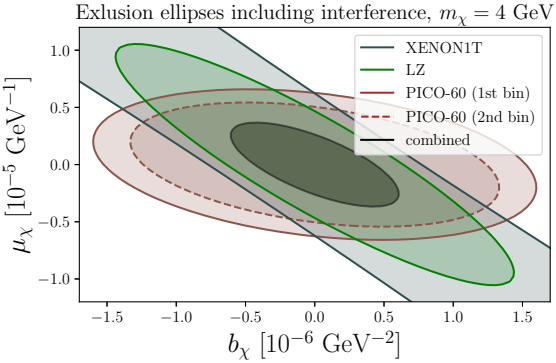

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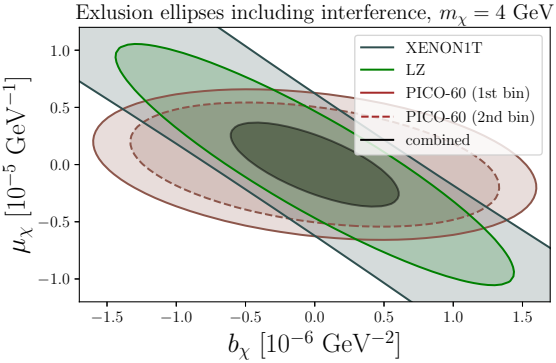
Combining experiments w/ different targets
$\rightarrow$ total sensitivity increases!



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Multiple EM moments and their interference II

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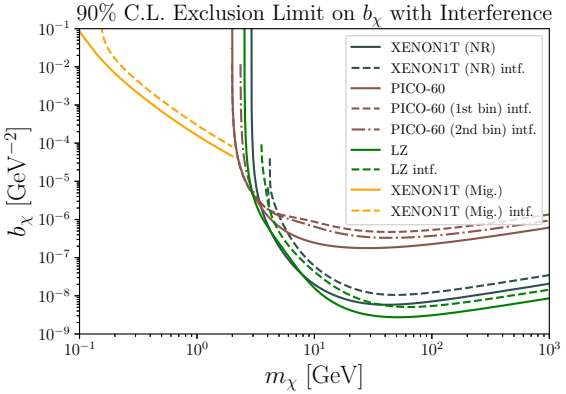

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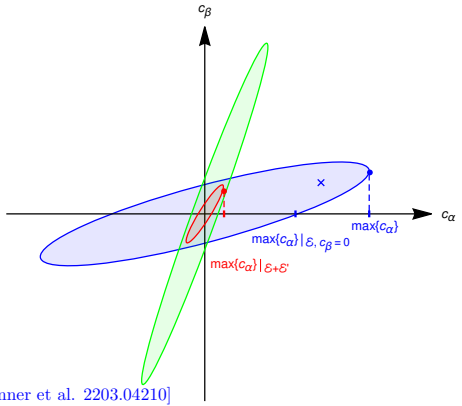

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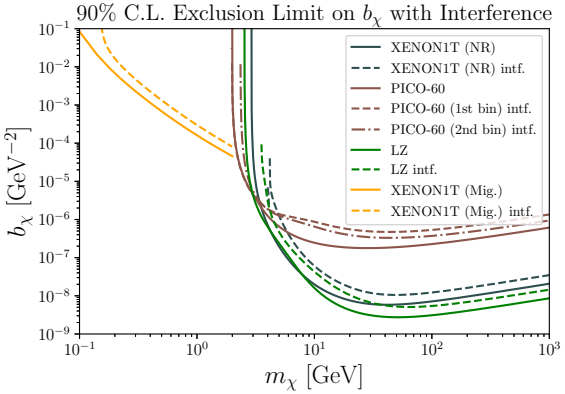

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3. Implications for renormalizable models

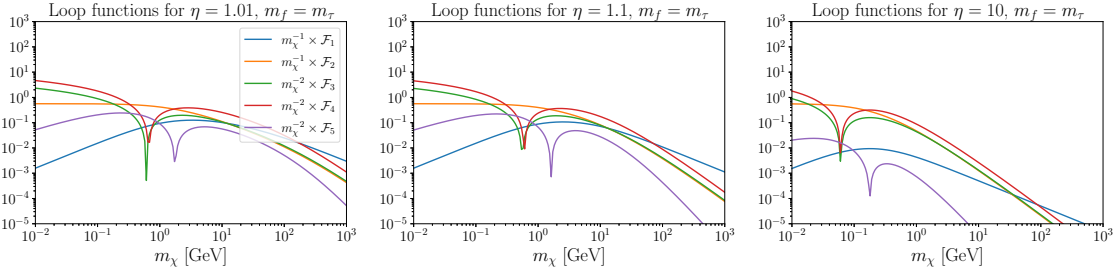
A τ-philic toy model

[A. Ibarra, **MR**, G. Tomar: 2408.15760]

$$\mathcal{L} \supset \bar{\chi}\left[c_L P_L + c_R e^{i\phi_{\rm CP}} P_R\right] \tau S_1^* + \text{h.c.}$$

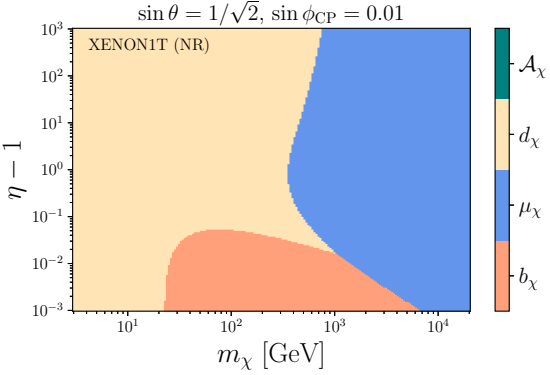
- at 1-loop:

$$\mu_\chi, d_\chi, b_\chi, \mathcal{A}_\chi \sim \frac{eQ_f}{32\pi^2} \times \text{Yukawa}^2 \times \text{loopfunction}\left(\frac{m_\tau}{m_\chi}, \frac{m_{S_1}}{m_\chi}\right)$$

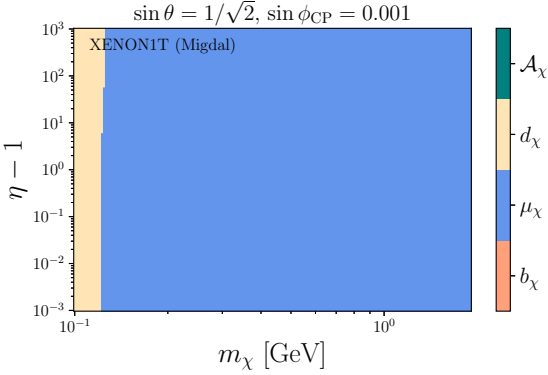


Regions of interest

NR



Migdal



[A. Ibarra, **MR**, G. Tomar: 2408.15760]

A τ-philic toy model

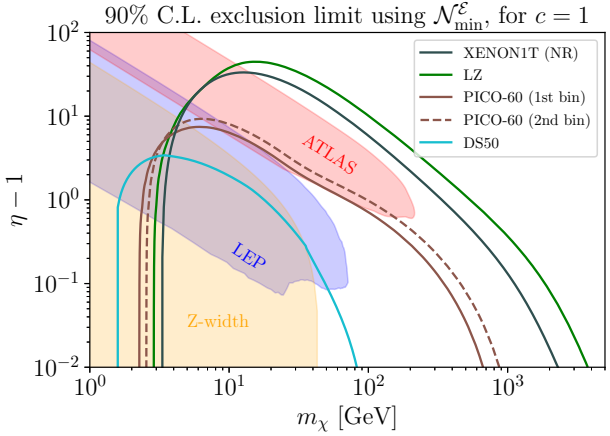
toy model:

$$\mathcal{L} \supset \bar{\chi}\left[c_L P_L + c_R e^{i\phi_{\rm CP}} P_R\right] \tau S_1^* + \text{h.c.}$$

- at 1-loop: μ_χ, d_χ, b_χ, $\mathcal{A}_\chi$
- $\mathcal{N}^{\mathcal{E}}_{\rm sig.} = \vec{v}^T\, \mathbb{N}^{\mathcal{E}}\, \vec{v}$
- conservative limits via

$$\mathcal{N}^{\mathcal{E}}_{\rm min} := \min_{\rm P,\,CP} \mathcal{N}^{\mathcal{E}}_{\rm sig}$$

- mass-splitting $\eta = m_{S_1}/m_\chi$



[ATLAS: 2402.00603, LEP: hep-ex/0311019, Z-width: hep-ex/0509008]

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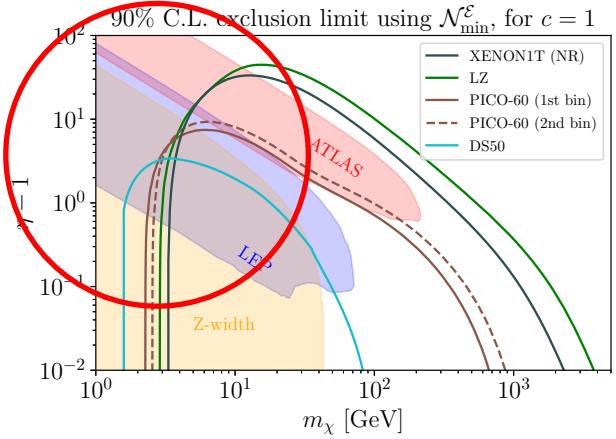
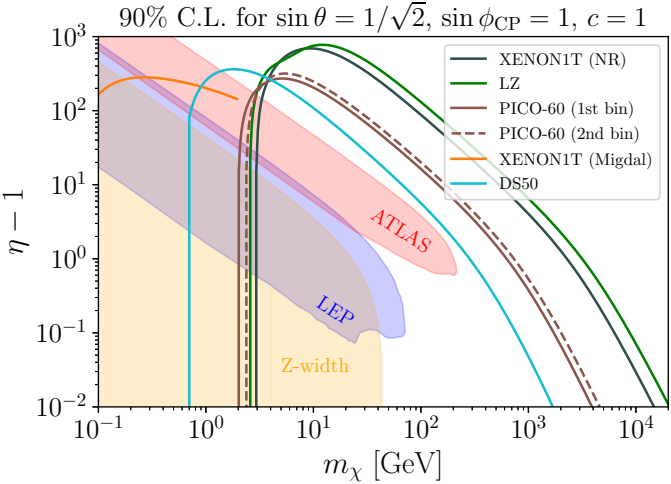


[ATLAS: 2402.00603, LEP: hep-ex/0311019, Z-width: hep-ex/0509008]

[A. Ibarra, **MR**, G. Tomar: 2408.15760]

What about Migdal?



[A. Ibarra, **MR**, G. Tomar: 2408.15760]

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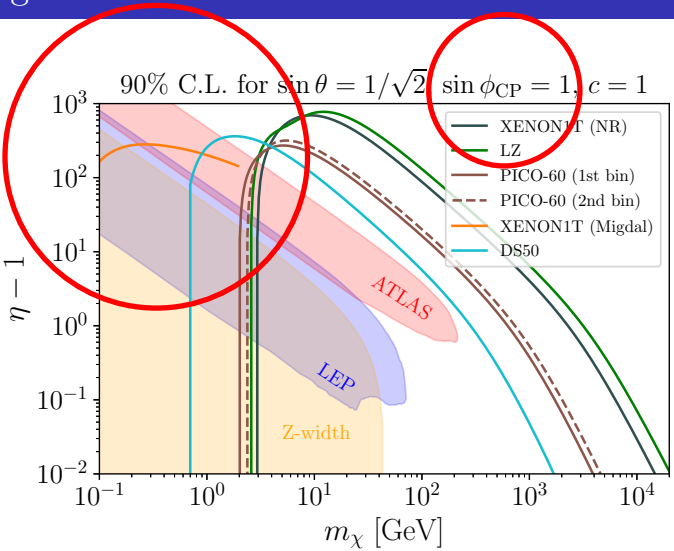

[A. Ibarra, **MR**, G. Tomar: 2408.15760]

Summary

- DM could have EM interactions $\rightarrow$ signals in DD experiments
- rate matrices $\mathbb{N}^{\mathcal{E}}$ are convenient to translate theory $\longleftrightarrow$ experiment
- EFT: study interference effects and interplay of different targets/experiments
- toy model: DD probes Dirac DM up to $m_\chi \sim 4\,\text{TeV}$ for small mass-splittings
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Thank you for your attention

Backup slides

Backup: DM NREFT

In DM-nucleus scattering we decompose the rel. operators into 14 independent non-relativistic operators $\mathcal{O}_i(\vec{q}, \vec{v}_{\rm el}^{\perp}, s_\chi, s_N)$

$$\mathcal{H} = \sum_{\tau=0}^{1} \sum_{i=1}^{15} c_i^\tau \mathcal{O}_i t^\tau, \quad t^0 = 1_{2\times 2},\, t^1 = \sigma_3$$

$$\frac{\mathrm{d}\sigma_{\chi N}}{\mathrm{d}E_R} \sim \sum_{\rm spins} |\mathcal{M}_{\rm NR}|^2 \sim \sum_{\tau,\tau'} R^{\tau\tau'} W^{\tau\tau'}$$

with dark matter response $R^{\tau\tau'}(c_i^\tau)$ and nuclear response $W^{\tau\tau'}$ function

$\rightarrow$ dictionary between operators and direct detection cross section (for a given velocity distribution)

[Fan et al. 1008.1591; Fitzpatrick et al. 1203.3542; Anand et al. 1308.6288; Catena & Schwabe 1501.03729]

Backup: EM moments in NR basis

For non-relativistic nuclear recoil matrix elements ($N = n, p$)

$$\mathcal{M}_{\text{milli}} = e^2 Q_\chi Q_N \frac{1}{q^2}\mathcal{O}_1$$

$$\mathcal{M}_{\text{ED}} = 2e d_\chi Q_N m_N \frac{1}{q^2}\mathcal{O}_{11}$$

$$\mathcal{M}_{\text{MD}} = 2e\mu_\chi \left[\frac{1}{4m_\chi} Q_N \mathcal{O}_1 + \frac{m_N}{q^2} Q_N \mathcal{O}_5 + \frac{1}{2m_N} g_N \mathcal{O}_4 - \frac{m_N}{2q^2} g_N \mathcal{O}_6\right]$$

$$\mathcal{M}_{\mathcal{A}} = \mathcal{A}(2eQ_N\mathcal{O}_8 - e g_N \mathcal{O}_9)$$

$$\mathcal{M}_{\text{CR}} = e b_\chi Q_N \mathcal{O}_1$$

[*E.g.* Nature 618, 47–50 (2023)]

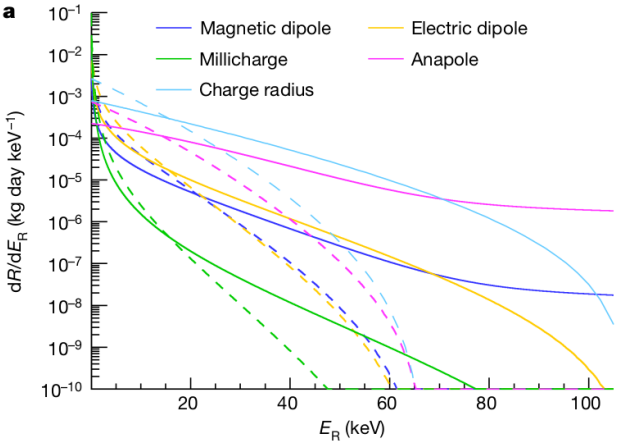
Backup: Basis operators for NR DM scattering

$\mathcal{O}_1 = 1_\chi 1_N$	$\mathcal{O}_9 = i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_3 = i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$	$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$
$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$	$\mathcal{O}_{12} = \vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_6 = (\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$	$\mathcal{O}_{13} = i(\vec{S}_\chi \cdot \vec{v}^\perp)(\vec{S}_N \cdot \frac{\vec{q}}{m_N})$
$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$	$\mathcal{O}_{14} = i(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})(\vec{S}_N \cdot \vec{v}^\perp)$
$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$	$\mathcal{O}_{15} = -(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\big((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\big)$

Table: Non-relativistic Galilean invariant operators for dark matter with spin 1/2.

[*E.g.* Del Nobile 2104.12785]

Backup: nuclear recoil spectrum

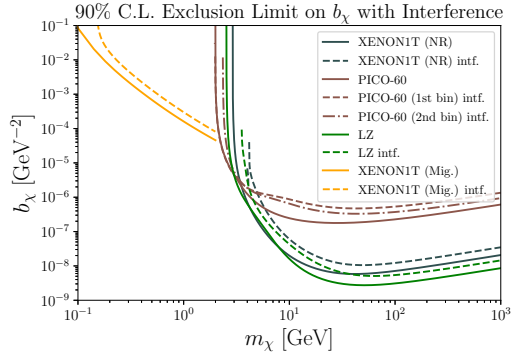


[Nature 618, 47–50 (2023)]

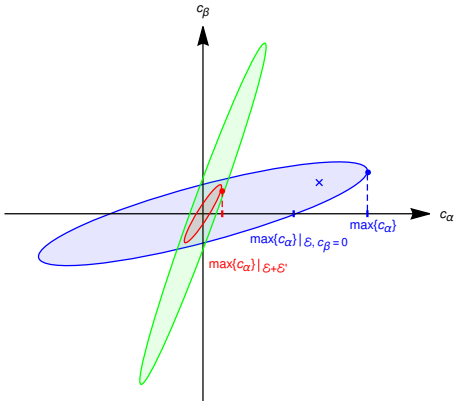
Backup: Multiple EM moments and their interference

- conservative limits

$$\mathbb{M}_\alpha^{\rm mom} = \sqrt{\mathcal{N}_\mathcal{E}^{\rm sig}(\mathbb{M}^{\rm max})(\mathbb{N}_\mathcal{E}^{-1})_{\alpha\alpha}}$$

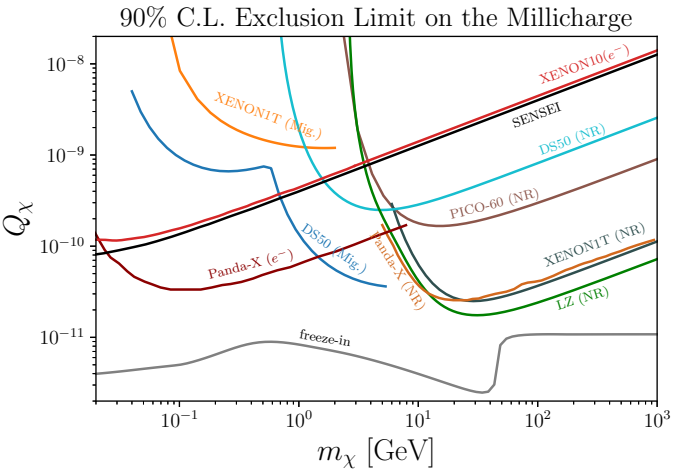


[A. Ibarra, **MR**, G. Tomar: 2408.15760]



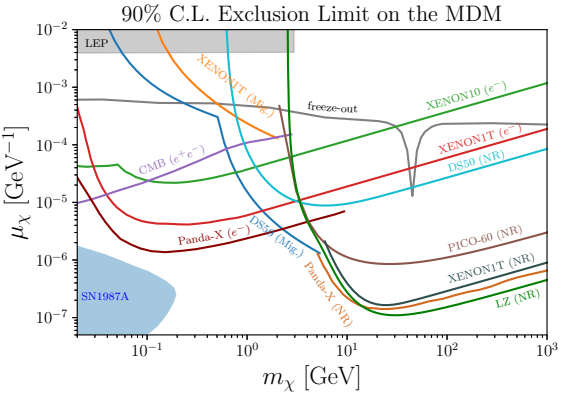
[Brenner et al. 2203.04210]

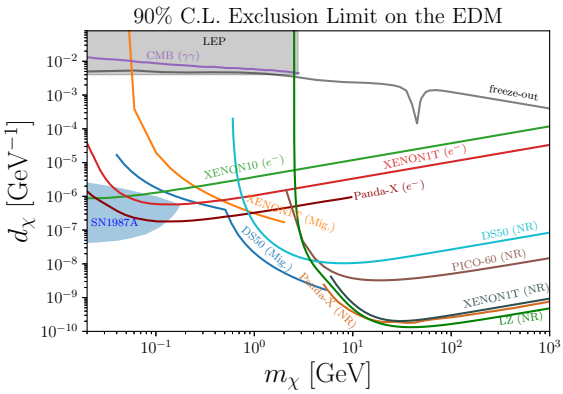
Backup: direct detection limits on dim-4 operators



[NR: 2408.15760, Nature 618, 47–50 (2023); Migdal: 2408.15760; ER: 1912.08204, 2406.10912; LEP, CMB, SN: 1811.04095]

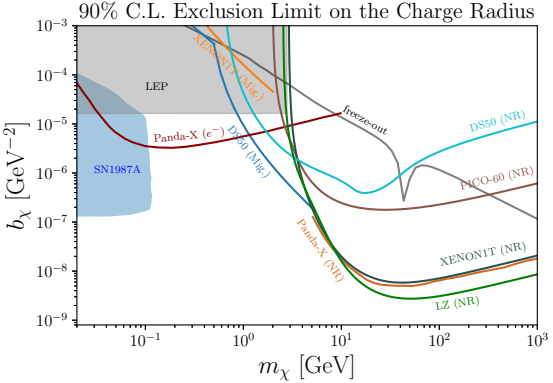
Backup: direct detection limits on dim-5 operators

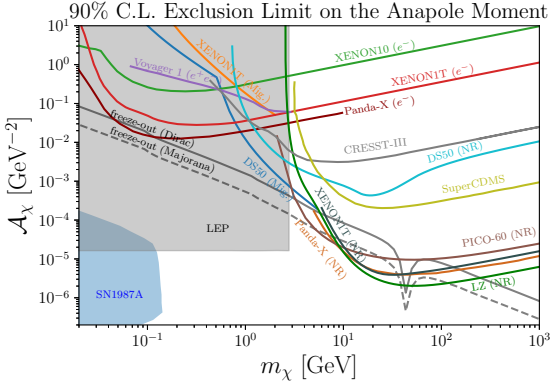




[NR: 2408.15760, Nature 618, 47–50 (2023); Migdal: 2408.15760; ER: 1912.08204, 2406.10912; LEP, CMB, SN: 1811.04095]

Backup: direct detection limits on dim-6 operators

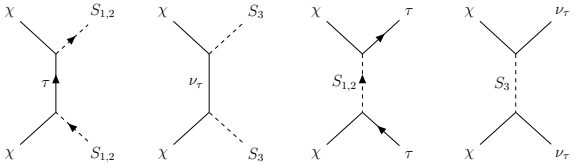


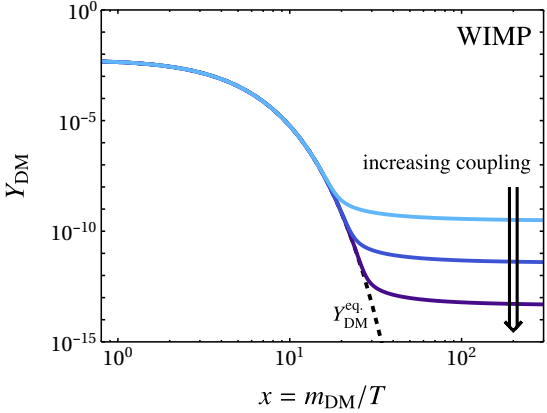


[NR: 2207.01014, 2408.15760, Nature 618, 47–50 (2023); Migdal: 2408.15760; ER: 1912.08204, 2406.10912; LEP, CMB, SN: 1811.04095]

Backup: Freeze-out

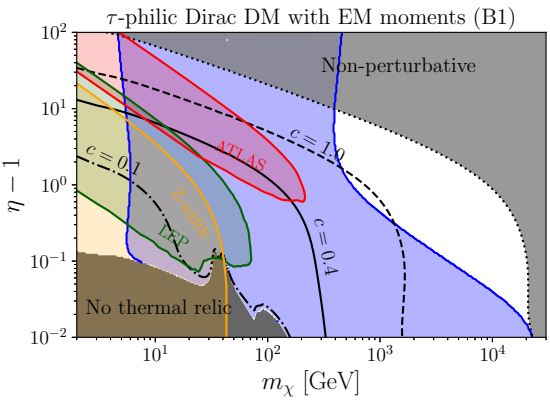
- $\dot{n}_\chi + 3Hn = -\langle\sigma v\rangle \left(n_\chi^2 - n_\chi^{\mathrm{eq}}\right)$
- freezes out once $\Gamma_\chi \sim H$

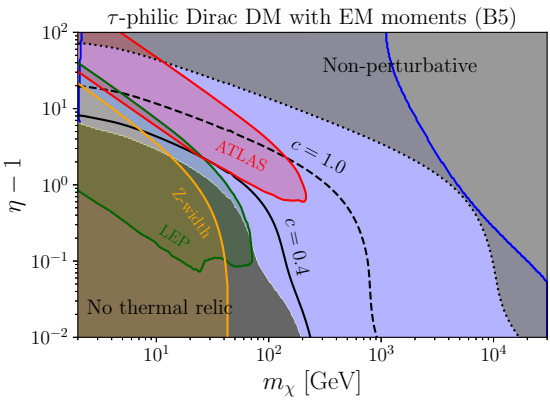




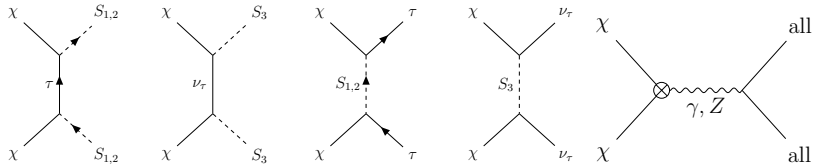
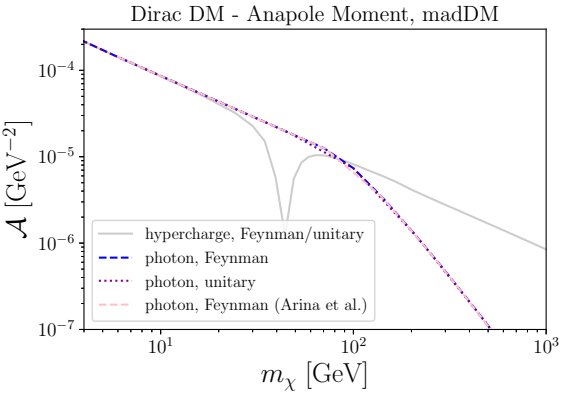
[Fig. from J. Herms: Dissertation]

Backup: Dirac toy model with CP violation





B1: $c_L = \text{fixed}$, $c_R = 0$, $\sin\phi_{\text{CP}} = 0$

B5: $c_L = 0.3/\sqrt{2}$, $c_R = \text{fixed}$, $\sin\phi_{\text{CP}} = 1$

Backup: Anapole relic density