Exploring DM electromagnetic moments with direct detection experiments

Merlin Reichard

(라이하드 메르린)

based on

A. Ibarra, **MR**, G. Tomar: JCAP 02 (2025) 072

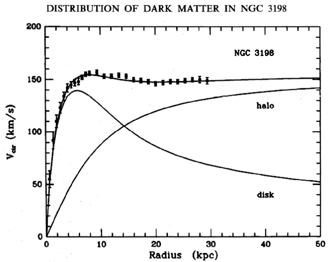
A. Ibarra, **MR**, R. Nagai: JHEP 01 (2023) 086

work in progress

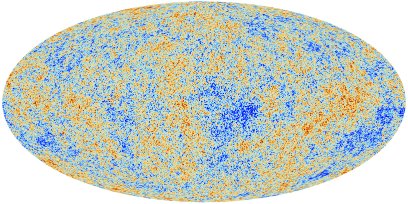
Outline

1. The quest of dark matter

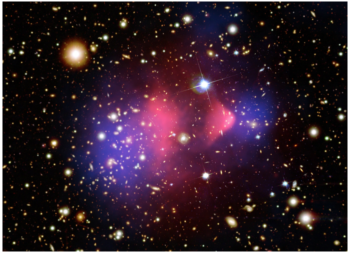
Dark matter evidence



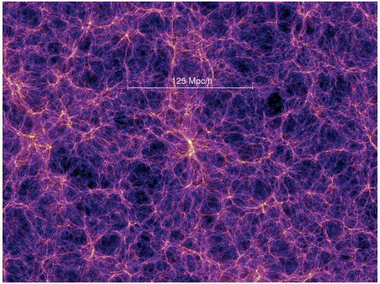
van Albada et al. 1985



Credit: ESA, Planck Collaboration

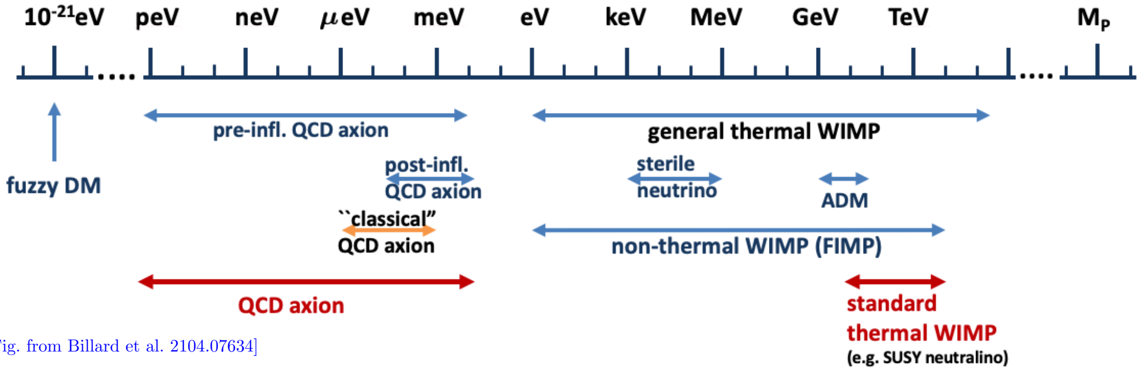


Credit: NASA (apod.nasa.gov/apod/ap060824.html)



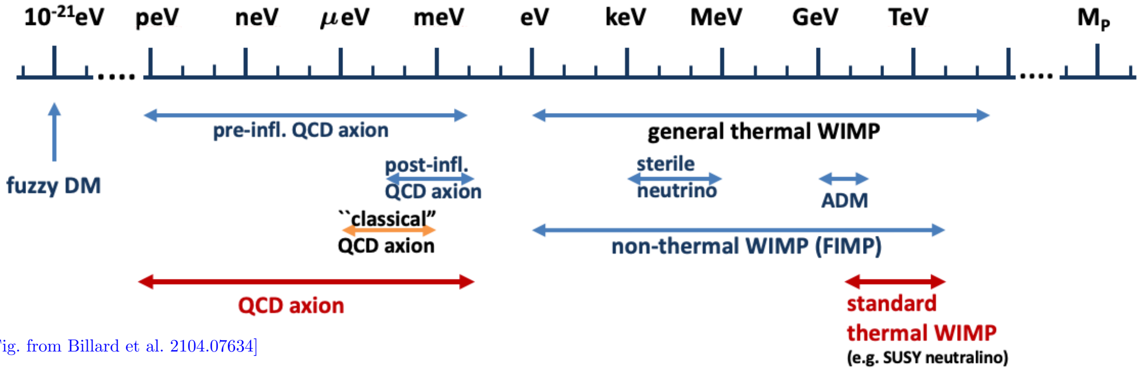
Credit: Springel et al. '05 (Millennium Simulation)

What is dark matter?



[Fig. from Billard et al. 2104.07634]

What is dark matter?



[Fig. from Billard et al. 2104.07634]

No clear (non-gravitational) evidence for DM

Can dark matter interact with light?

Why not?

Let's look at the SM:

- **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, ...]

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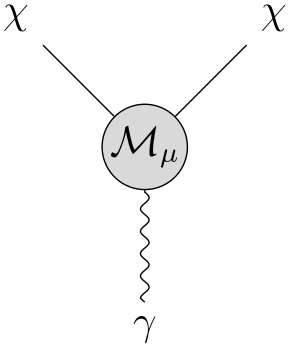
- similarly for neutrinos $\to$ shift in $\sin\theta_W$ [Giunti & Studenikin Rev.Mod.Phys. 87 (2015) 531, ...]

- leptons: $(g-2)_\ell$, EDM, ...

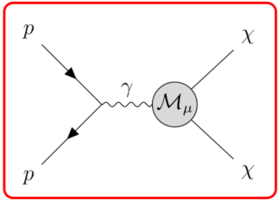
2. Dark matter with electromagnetic interactions

Electromagnetic vertex



Phenomenology I

production



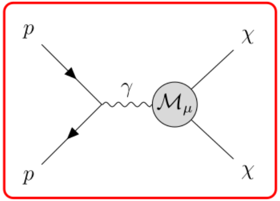
- looking for $p_{\text{miss.}}$ or $E_{\text{miss.}}$

  [Chu et al. 1811.04095, ...]

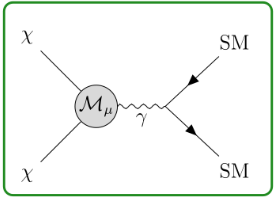
- relic density (freeze-in)

  [Ibarra et al. 2408.15760, ...]

production



annihilation



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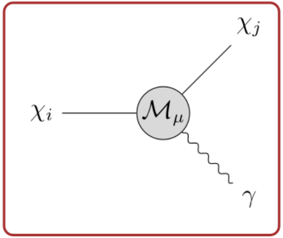
  [Chu et al. 1811.04095, ...]
- relic density (freeze-in)
  [Ibarra et al. 2408.15760, ...]
- dense regions → indirect signals
  [Kavanagh et al. JHEP 04 (2019) 089, ...]
- relic density (freeze-out)
  [Ho & Scherrer PLB 722 (2013) 341-346, ...]

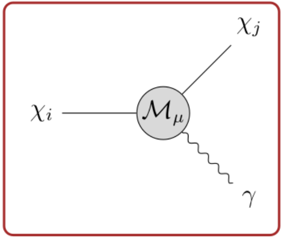
Phenomenology II



decay

- photon lines in dense regions
  [Garny et al. JCAP 01 (2011) 032, ...]
- could affect relic density
  [Herms & Ibarra JCAP 10 (2021) 026, ...]

Phenomenology II



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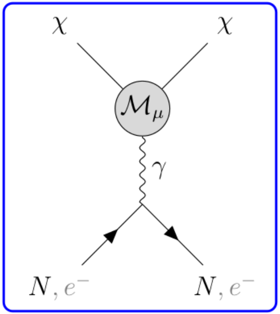


scattering

- photon lines in dense regions

  [Garny et al. JCAP 01 (2011) 032, ...]

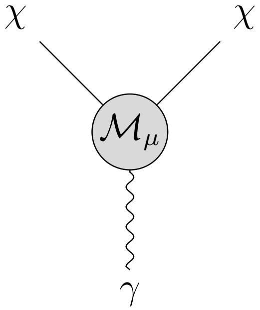
- could affect relic density

  [Herms & Ibarra JCAP 10 (2021) 026, ...]

- small momentum transfer $\rightarrow$ EFT

  [Pospelov & ter Veldhuis Phys.Lett.B 480 (2000) 181-186, ...]

From form factors to EM moments



$$\boxed{\mathcal{M}_\mu \supset 6s+1 \text{ form factors } f_{\mathbb{M}}(q^2)}$$

[Rahal & Ren PRD 41 (1990) 1989]

- scalar ($s=0$) can have a (milli-) charge
- fermion ($s=\frac{1}{2}$) up to 4 form factors
- vector ($s=1$) up to 7 form factor

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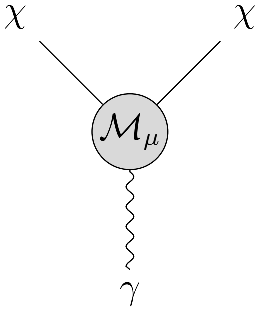

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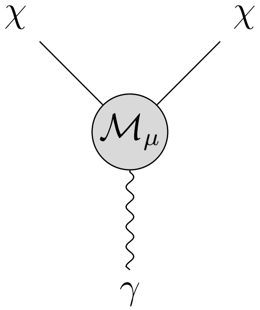
expand $f_{\mathbb{M}}(q^2) \simeq f_{\mathbb{M}}(0)$

EM moment

From form factors to EM moments



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e.g. charge radius

expand $f_{\mathbb{M}}(q^2) \simeq f_{\mathbb{M}}(0) + q^2(\partial f_{\mathbb{M}})(0) + \cdots$

EM moment

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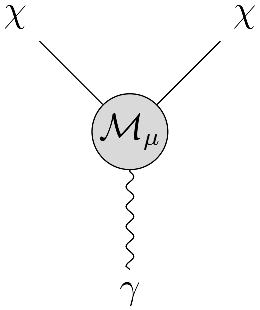

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EM moment

EFT of electromagnetically interacting DM

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

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

charge | magnetic dipole | electric dipole | anapole moment | charge radius

3. Connection to direct searches

Dark matter direct detection experiments

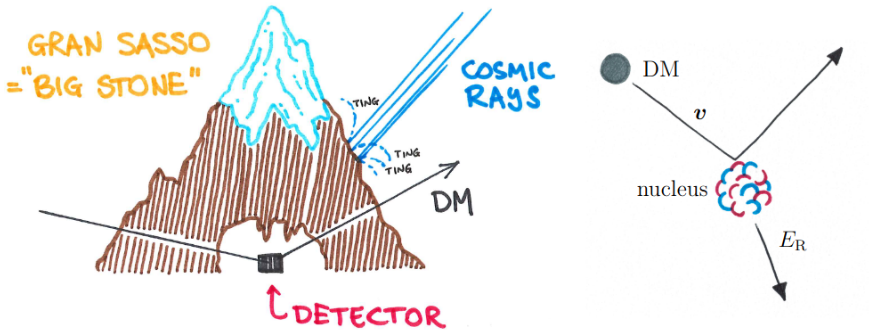

Figure 1: *Basics of direct DM detection.* ***Left:*** *on a* ~ km *scale.* ***Right:*** *on a* ~ fm *scale.*

[Fig. from Del Nobile 2104.12785]

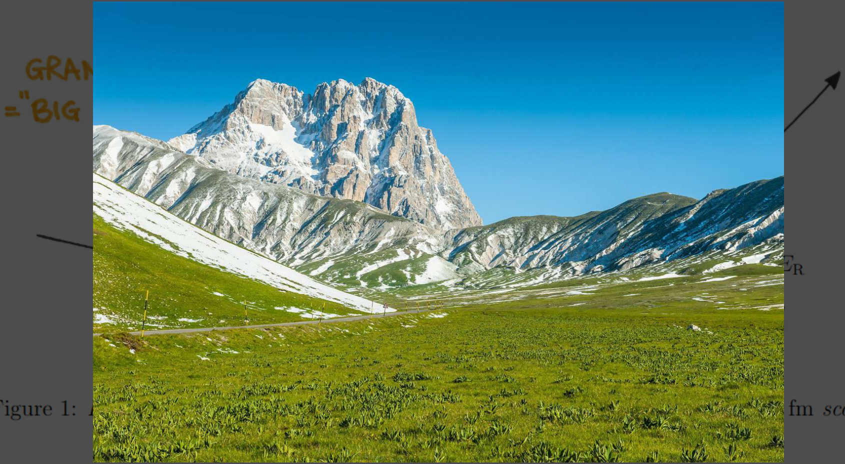

Figure 1: … fm *scale.*

[Fig. from Del Nobile 2104.12785]

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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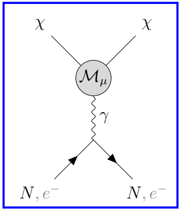

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- information from particle physics (DM mass, cross section) and astrophysics (local abundance, velocity distribution)
- number of events at the detector can be factorized as [2011.02929, 2203.04210, 2408.15760]:

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

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

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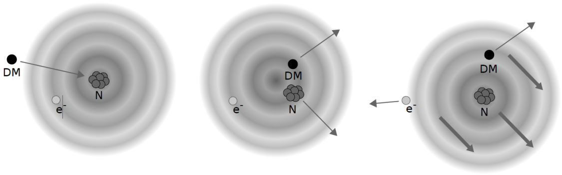
contains all exp. and astrophysical details for experiment $\mathcal{E}$

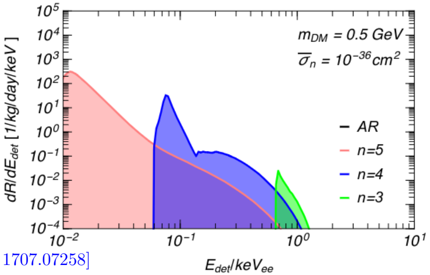
The Migdal effect in DD experiments

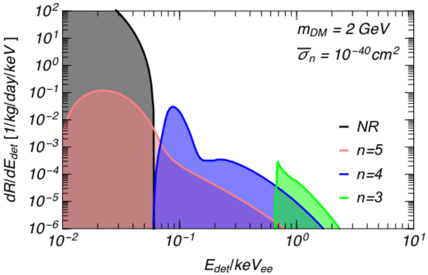


[Dolan et al. PRL 121, 101801]

$$\frac{d\sigma}{dE_R\, dE_{EM}} \simeq \frac{d\sigma}{dE_R} \times \frac{1}{2\pi} \frac{dp_{n,\ell\to E_{EM}}}{dE_{EM}}$$

This extends reach of nuclear recoils experiments to $m_\chi \sim \mathcal{O}(1\,\mathrm{GeV})$





[Ibe et al. 1707.07258]

$$\frac{d\sigma}{\ } \quad \frac{d\sigma}{\ } \quad \frac{1}{2\pi} \frac{dp_{n,\ell\to E_{EM}}}{dE_{EM}}$$

[Dolan et al. PRL 121, 10180

Article | Open access | Published: 14 January 2026

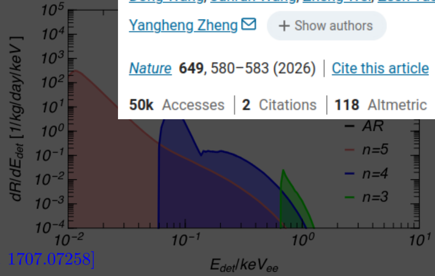
Direct observation of the Migdal effect induced by neutron bombardment

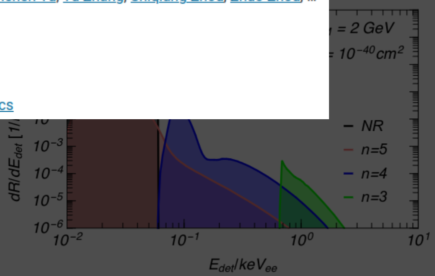
Difan Yi, Qian Liu, Shi Chen, Chunlai Dong, Huanbo Feng, Chaosong Gao, Wenqian Huang, Xinmei Jing, Lingquan Kong, Jin Li, Peirong Li, Enwei Liang, Ruiting Ma, Chenguang Su, Liangliang Su, Junwei Sun, Dong Wang, Junrun Wang, Zheng Wei, Zeen Yao, Yunlinchen Yu, Yu Zhang, Shiqiang Zhou, Zhuo Zhou, ... Yangheng Zheng

+ Show authors

Nature **649**, 580–583 (2026) | Cite this article

This ex... 1 GeV)



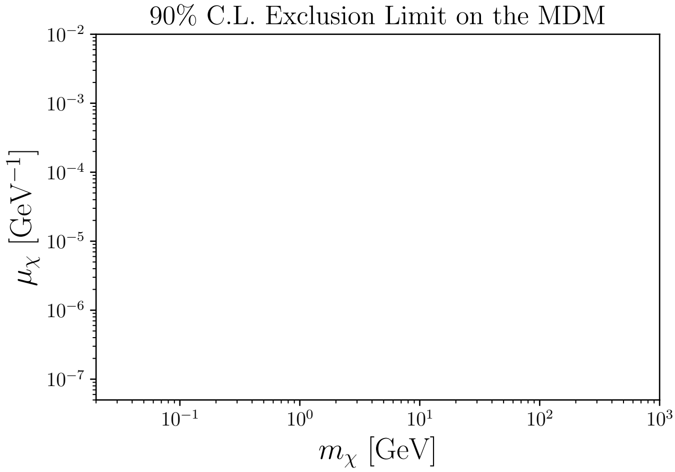


[Ibe et al. 1707.07258]

Exclusion limits on the magnetic dipole moment

provided in 2408.15760 & github

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



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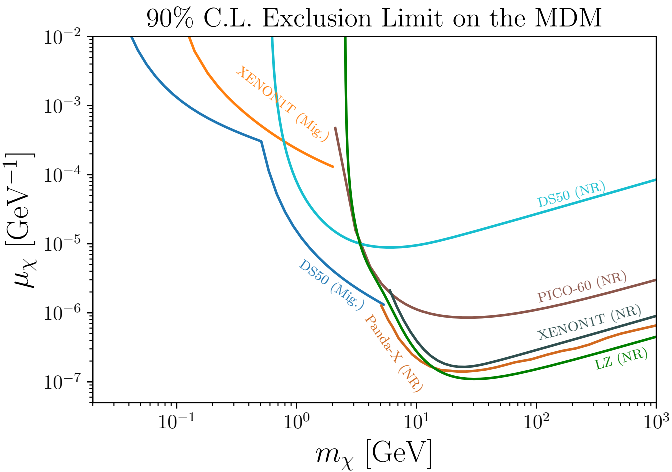

[NR: 2408.15760, Nature 618, 47–50 (2023); Migdal: 2408.15760;]

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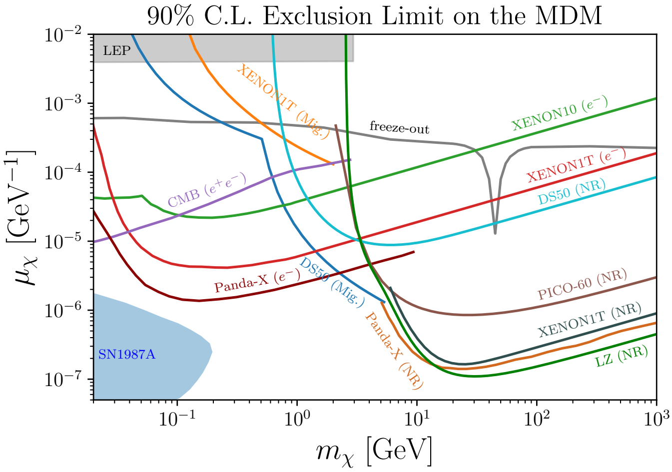
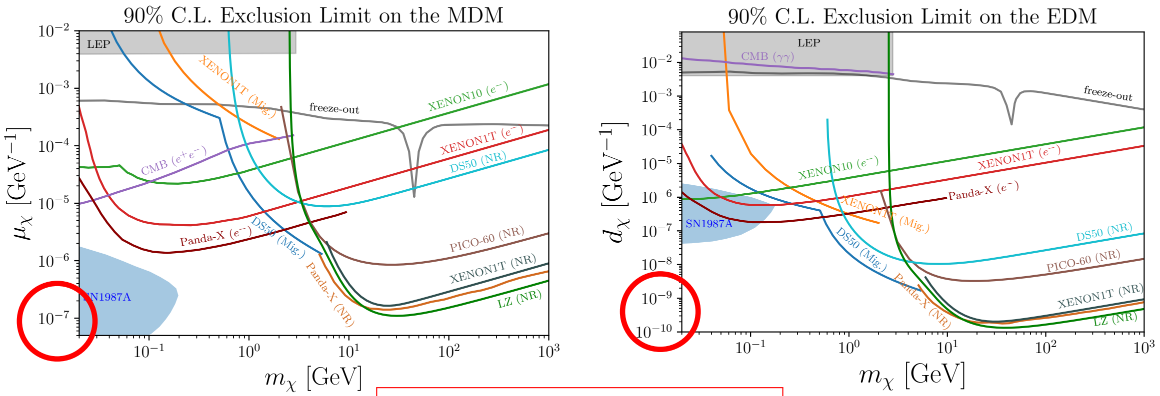
- nuclear recoils
- Migdal effect (e^- from NR)
- electron recoils
- LEP, CMB, SN
- thermal production ($\Omega h^2 \simeq 0.12$ [Planck 2018])



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

Constraints on the dipole moments



DD very sensitive to the EDM

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

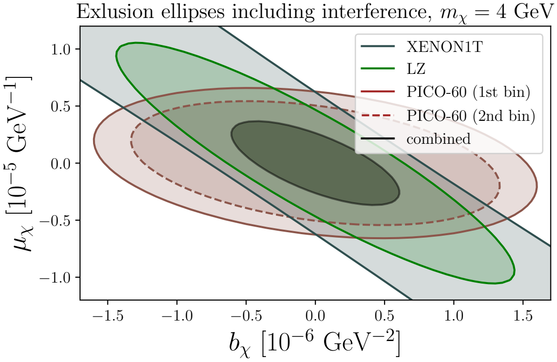
Multiple EM moments and their interference I

- **but:** why should only one moment $\neq 0$?
- Q_χ, μ_χ and b_χ interfere:

$$\mathcal{N}_{\text{sig}}^{\mathcal{E}} = \cdots + \mu_\chi b_\chi \mathbb{N}_{\mu_\chi b_\chi}^{\mathcal{E}} + \cdots$$

- target dependent → slope (C_3F_8 vs. Xe)

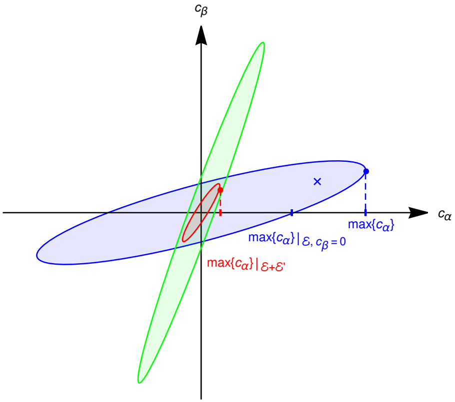
Combining experiments w/ different targets
→ total sensitivity increases!

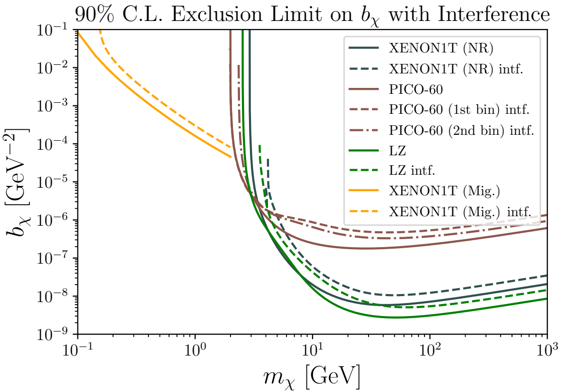


[A. Ibarra, **MR**, G. Tomar: 2408.15760]

Multiple EM moments and their interference II

- conservative limits (see [Brenner et al. 2203.04210])





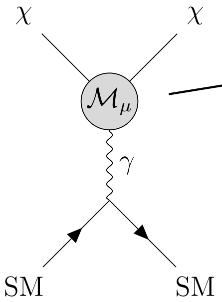
[Brenner et al. 2203.04210]

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

4.1 Loop-induced EM interactions

From the EFT to the UV

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



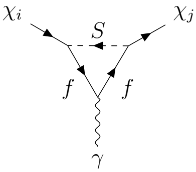
resolve the effective vertex

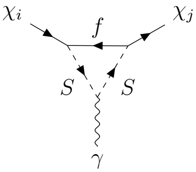
calculate Q_χ, μ_χ , …

$$\mathcal{L} = \bar{\chi}_i \left[c_L^i P_L + c_R^i P_R \right] f S^* + \text{h.c.}$$

[diagonal: 1401.6457, 1503.01500, 2408.15760, ...]

[transition dipoles: Haber & Wyler 1989, 1011.3786, ...]

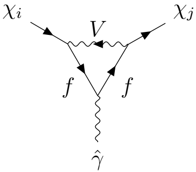


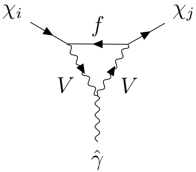


$$\mathcal{L} = \bar{\chi}_i \gamma^\mu \left[v_L^i P_L + v_R^i P_R \right] f V_\mu^+ + \text{h.c.}$$

[diagonal: 2207.01014]

[transition dipoles: Haber & Wyler 1989, 1011.3786, ...]





[A. Ibarra, **MR**: *work in progress*, **MR**: Dissertation]

Master formulas for the EM moments

General scalar result (Dirac):

$$\mathbb{M}^S_{ji} = \frac{eQ_f}{32\pi^2}\Bigg\{ \left[c^j_L (c^i_L)^* \pm c^j_R (c^i_R)^*\right] \mathcal{F}^S_{\mathbb{M}}\left(\frac{m_f}{m_{\chi_1}}, \frac{m_S}{m_{\chi_1}}, \frac{m_{\chi_2}}{m_{\chi_1}}\right) + \left[c^j_L (c^i_R)^* \pm c^j_R (c^i_L)^*\right] \mathcal{G}^S_{\mathbb{M}}\left(\frac{m_f}{m_{\chi_1}}, \frac{m_S}{m_{\chi_1}}, \frac{m_{\chi_2}}{m_{\chi_1}}\right)\Bigg\}$$

[A. Ibarra, **MR**: *work in progress*, **MR**: Dissertation]

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- structure: Yukawa coupling

[A. Ibarra, **MR**: *work in progress*, **MR**: Dissertation]

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- "plus" for μ_χ, b_χ, "minus" for d_χ, $\mathcal{A}_\chi$ (P-violation)

[A. Ibarra, **MR**: *work in progress*, **MR**: Dissertation]

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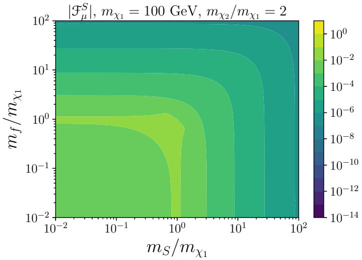
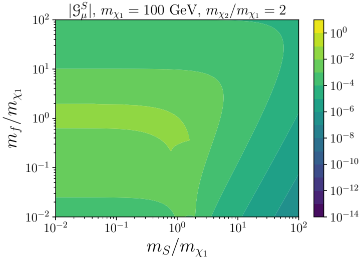
- structure: Yukawa coupling $\times$ loop function
- "plus" for μ_χ, b_χ, "minus" for d_χ, $\mathcal{A}_\chi$ (P-violation)





[A. Ibarra, **MR**: *work in progress*, **MR**: Dissertation]

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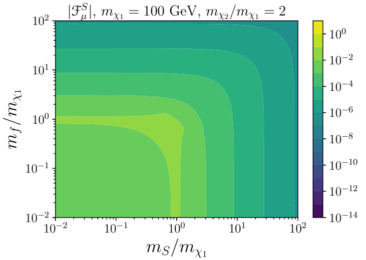
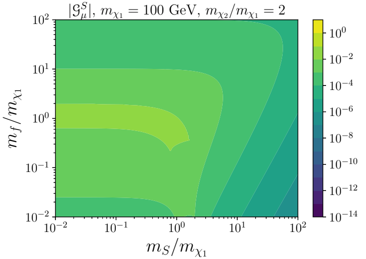
- Majorana: add conjugate diagrams





[A. Ibarra, **MR**: *work in progress*, **MR**: Dissertation]

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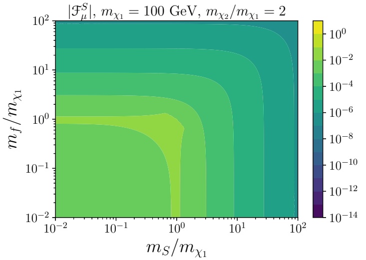
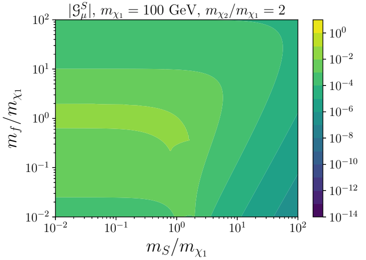
- structure: Yukawa coupling × loop function
- "plus" for μ_χ, b_χ, "minus" for d_χ, $\mathcal{A}_\chi$ (P-violation)
- Majorana: add conjugate diagrams
- versatile result: n-DM models, neutrinos, ...





[A. Ibarra, **MR**: *work in progress*, **MR**: Dissertation]

4.2 EM moments of UV complete DM models

An overview of Majorana vs. Dirac

Majorana

- Only $\mathcal{A}_\chi \neq 0$ due to Majorana condition
- DM-SM channel is "clean"
- Limits on $\mathcal{A}_\chi$ can be used directly

Dirac

- All moments are allowed by symmetries
- Operators can interfere
- Determining limits on the UV model is not trivial

Let's have a look at specific models in which DM has EM interactions

Simplified $\tilde{\chi}_1^0$ scenarios

split-SUSY: DM is a gaugino, all scalars are decoupled

- pure bino: no interactions with W/H
- pure higgsino: parity conserving interaction with W, Higgs int. is small
- pure wino: parity conserving interaction with W

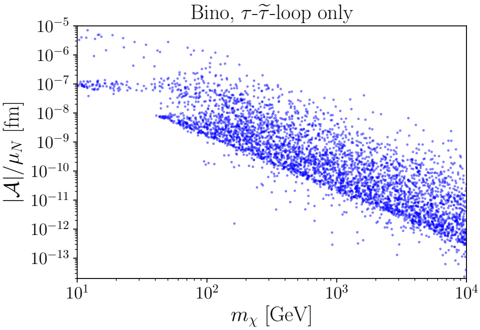
$$\boxed{\mathcal{A} \simeq 0 \text{ for all pure *-inos}}$$

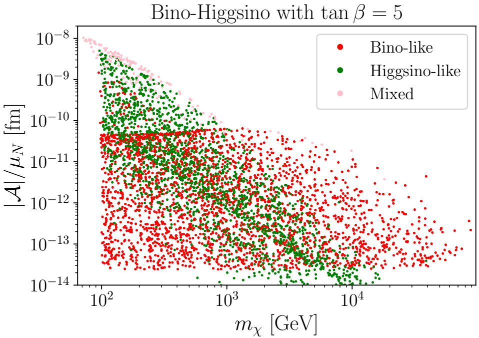
Two ways to generate an anapole moment:

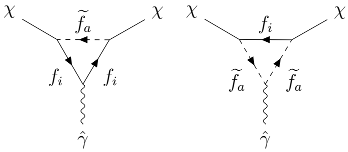
i) add light degrees of freedom (sfermions) $\longrightarrow$ scalar contribution with $c_L \neq c_R$

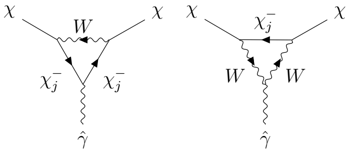
ii) allow mixings, *i.e.* $\tilde{\chi}_1^0 =$ "$\widetilde{B} + \widetilde{H}$", "$\widetilde{W} + \widetilde{H}$" $\longrightarrow v_L \neq v_R \rightarrow$ typically small

MSSM: Two Simplified Scenarios





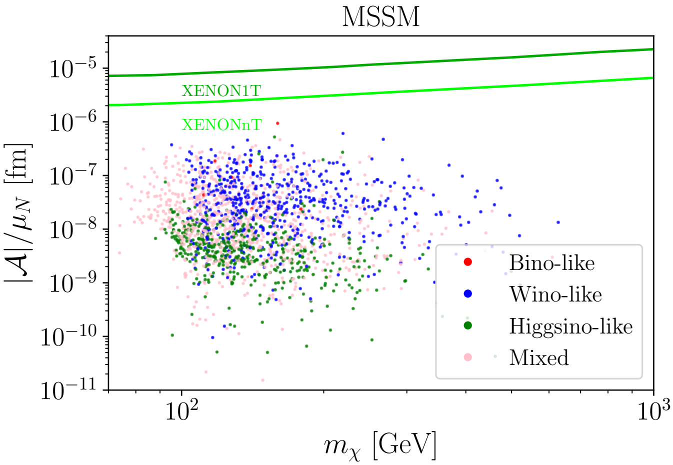




[A. Ibarra, **MR**, R. Nagai: 2207.01014]

Anapole moment of $\tilde{\chi}_1^0$ with the full MSSM

[A. Ibarra, **MR**, R. Nagai: 2207.01014]



Constraints:

- LEP, $\Gamma(Z \to \text{inv.})$
- Higgs sector
- LHC sparticle searches
- flavour physics
- **no DM constraints** $\to$ in DD other terms may dominate

Constraints derived using `micrOMEGAS`, `HiggsBounds`, `HiggsSignals`, `SModelS`, `SuperIso`, `GM2Calc`

A τ-philic toy model

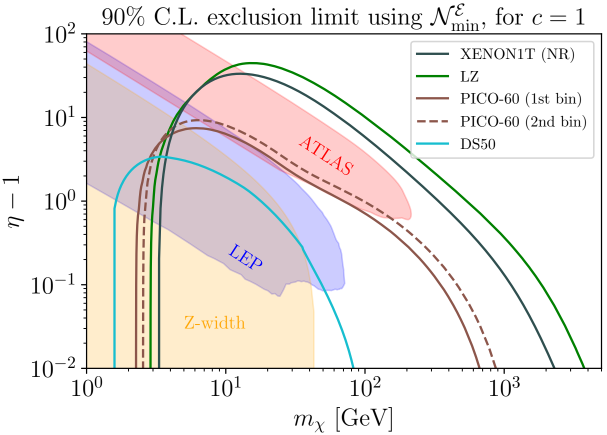
Dirac DM toy model:

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

- 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

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

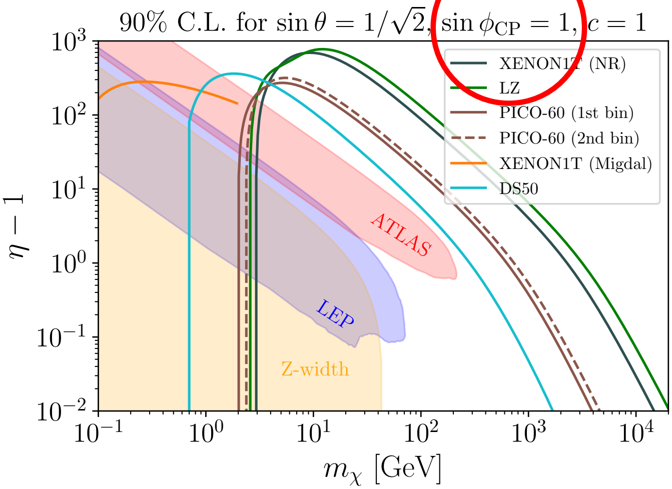
- mass-splitting $\eta = m_{S_1}/m_\chi$



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

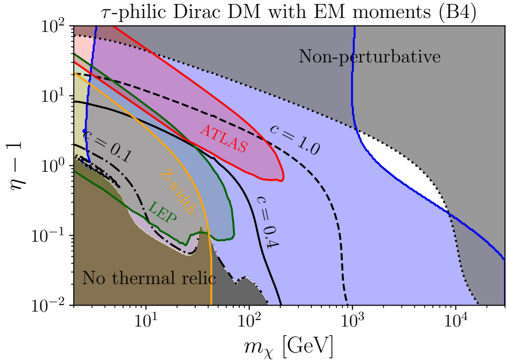
[A. Ibarra, **MR**, G. Tomar: 2408.15760]

Toy model with large CP violation

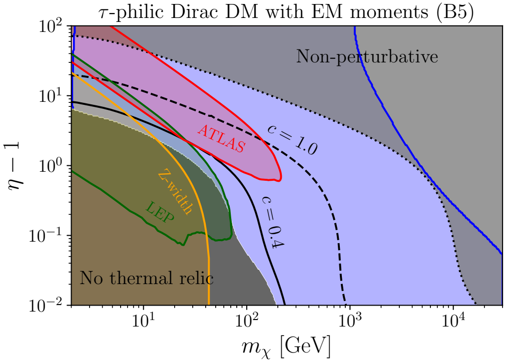


[A. Ibarra, **MR**, G. Tomar: 2408.15760]

Limits on the thermal relic



$c_R = \underline{\text{fixed}},\ c_L = 0.1/\sqrt{2},\ \sin\phi_{\text{CP}} = 0.1$



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

[ATLAS: 2402.00603, LEP: hep-ex/0311019, Z-width: hep-ex/0509008; relic density calculated using `micrOMEGAs`] [**MR**: Dissertation]

Summary

- DM could interact with the EM field
  - composite (*e.g.* neutron)
  - quantum effects (*e.g.* leptons)
  - phenomenology depends on spin, self-conjugacy
- Direct detection facilities can probe EM moments (EFT and UV)
- Thermal relic strongly constrained

Summary

- DM could interact with the EM field
  - composite (*e.g.* neutron)
  - quantum effects (*e.g.* leptons)
  - phenomenology depends on spin, self-conjugacy
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Thank you for your attention

Backup slides

Backup: DM NREFT

To obtain the cross section in the master formula

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

we decompose the rel. operators into 14 independent non-relativistic operators $\mathcal{O}_i$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} \sim \sum_{\text{spins}} |\mathcal{M}_{\text{NR}}|^2 \sim \sum_{\tau,\tau',\ell} R_\ell^{\tau\tau'}(c_i, q) W_\ell^{\tau\tau'}(q)$$

$$\mathcal{H} = \sum_{N=n,p} \sum_{i=1}^{15} c_i^N \mathcal{O}_i, \quad \text{with } c_i^{n,p} = \text{const.}$$

[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 $(N = n, p)$

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

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

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

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

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

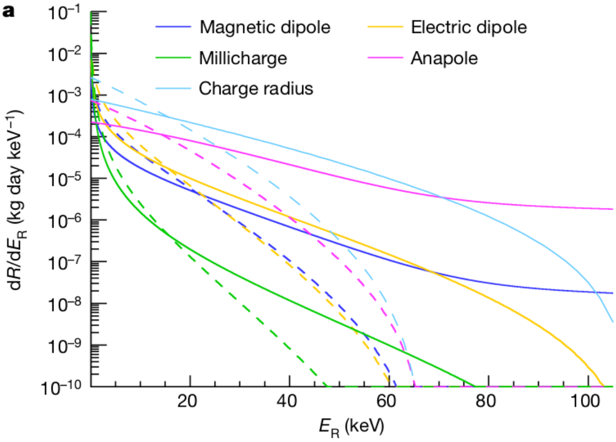
Backup: Basis operators for NR DM scattering

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

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

[*E.g.* Del Nobile 2104.12785]

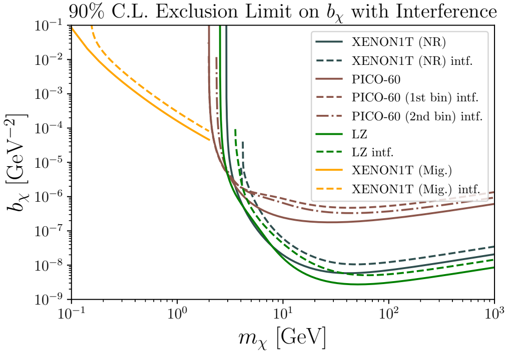
Backup: nuclear recoil spectrum

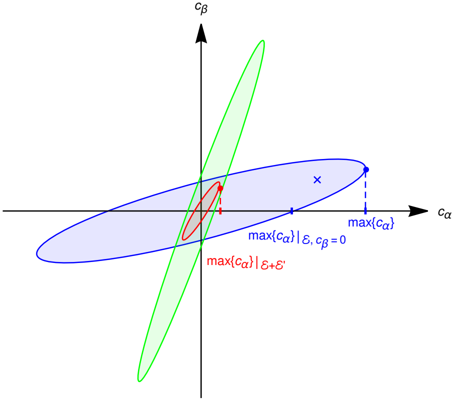


[PANDAX Collab., Nature 618, 47–50 (2023)]

- conservative limits

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

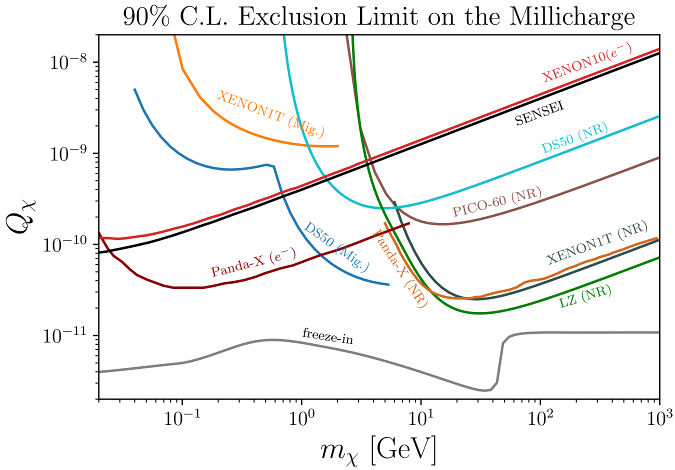




[A. Ibarra, **MR**, G. Tomar: 2408.15760]

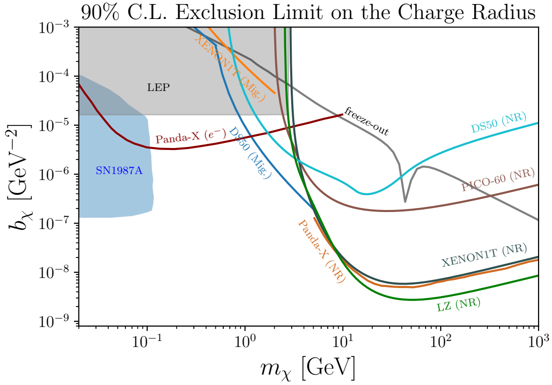
[Brenner et al. 2203.04210]

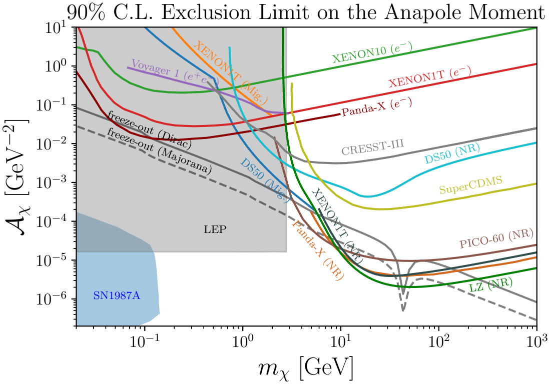
Backup: direct detection limits on dim-4 operators



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

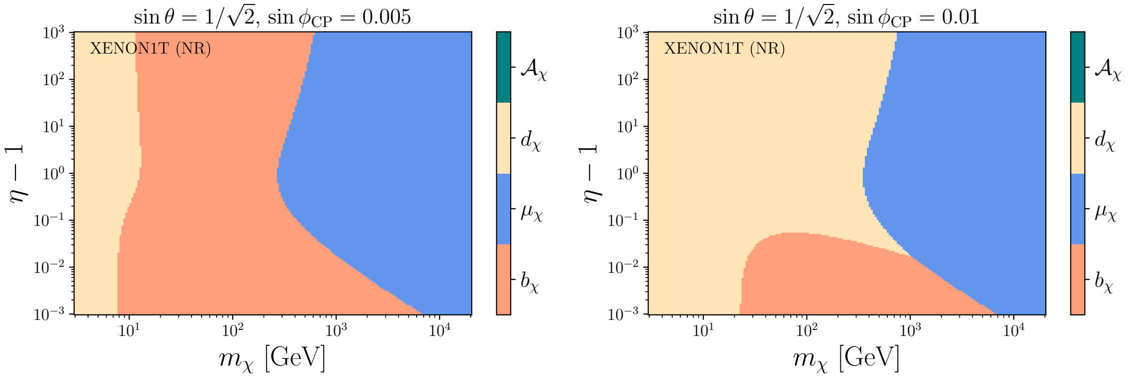
Backup: direct detection limits on dim-6 operators





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

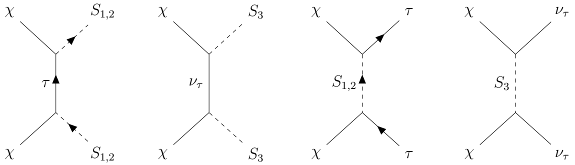
Backup: DD sensitivty to different EM moments

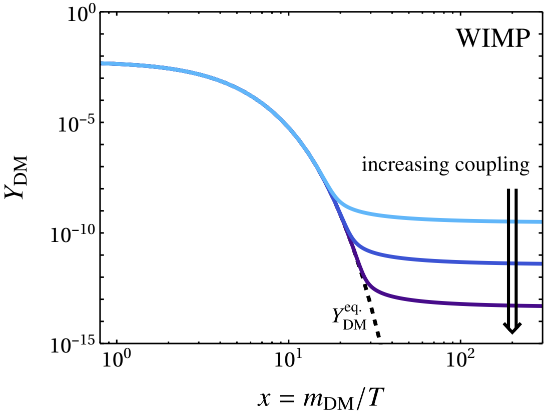


[A. Ibarra, **MR**, G. Tomar: 2408.15760, **MR**: Dissertation]

Backup: Freeze-out

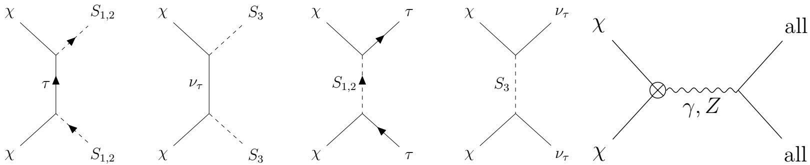
- $\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_\chi^{\text{eq}}\right)$
- freezes out once $\Gamma_\chi \sim H$

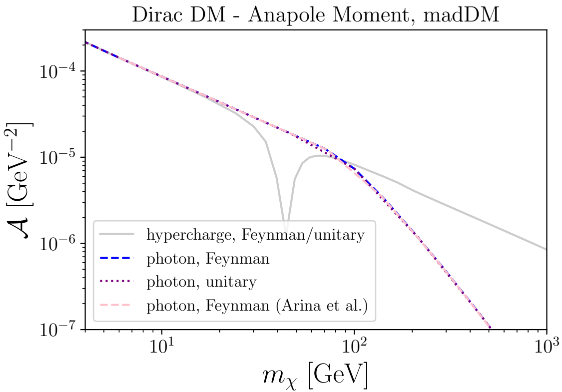




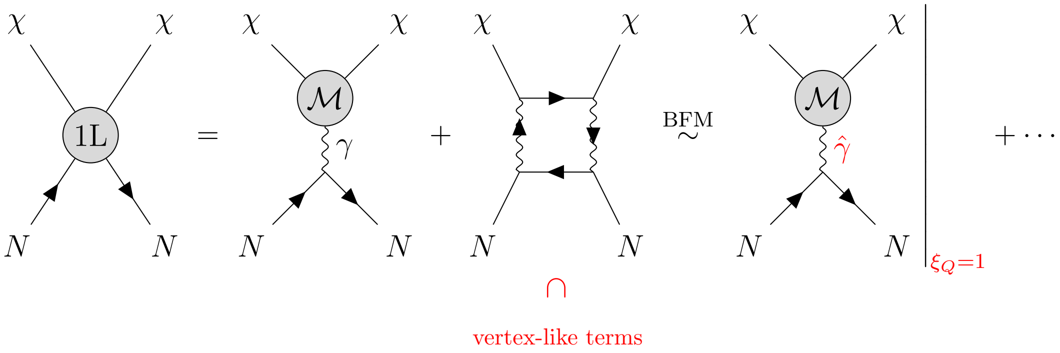
[Fig. from J. Herms: Dissertation]

Backup: Anapole relic density





Backup: BFM and Pinch Technique



[Hasimoto et al. '94; Papavassiliou '94; Denner et al. '94; Review by Binosi & Papavassiliou '09]

To Charginos

$$v_L^j = -gN_{12}U_{j1}^* - g\frac{1}{\sqrt{2}}N_{13}U_{j2}^*, \tag{1a}$$

$$v_R^j = -gN_{12}^*V_{j1} + g\frac{1}{\sqrt{2}}N_{14}^*V_{j2}, \tag{1b}$$

$$c_L^{G,j} = g\cos\beta\left[N_{13}^*U_{j1}^* - \frac{1}{\sqrt{2}}U_{j2}^*(N_{12}^* + \tan\theta_W N_{11}^*)\right], \tag{1c}$$

$$c_R^{G,j} = -g\sin\beta\left[N_{14}V_{j1} + \frac{1}{\sqrt{2}}V_{j2}(N_{12} + \tan\theta_W N_{11})\right], \tag{1d}$$

$$c_L^{H,j} = -g\sin\beta\left[N_{13}^*U_{j1}^* - \frac{1}{\sqrt{2}}U_{j2}^*(N_{12}^* + \tan\theta_W N_{11}^*)\right], \tag{2a}$$

$$c_R^{H,j} = -g\cos\beta\left[N_{14}V_{j1} + \frac{1}{\sqrt{2}}V_{j2}(N_{12} + \tan\theta_W N_{11})\right]. \tag{2b}$$

To Sfermion/fermions

$$c_L^{i,1} = G^{f_{iL}} \cos\theta_{\tilde{f}_a} + H^{f_{iR}} \sin\theta_{\tilde{f}_a}, \tag{3a}$$

$$c_R^{i,1} = G^{f_{iR}} \sin\theta_{\tilde{f}_a} + H^{f_{iL}} \cos\theta_{\tilde{f}_a}, \tag{3b}$$

$$c_L^{i,2} = -G^{f_{iL}} \sin\theta_{\tilde{f}_a} + H^{f_{iR}} \cos\theta_{\tilde{f}_a}, \tag{3c}$$

$$c_R^{i,2} = G^{f_{iR}} \cos\theta_{\tilde{f}_a} - H^{f_{iL}} \sin\theta_{\tilde{f}_a}, \tag{3d}$$

with

$$G^{f_{iL}} = -\sqrt{2} g \left[T_{3L}^{f_i} N_{12}^* + \tan\theta_W (Q_{f_i} - T_{3L}^{f_i}) N_{11}^* \right], \tag{4a}$$

$$G^{f_{iR}} = \sqrt{2} g \tan\theta_W Q_{f_i} N_{11}, \tag{4b}$$

$$H^{f_{iL}} = -\frac{g}{\sqrt{2} m_W} m_{f_i} \times \begin{cases} N_{14}/\sin\beta, & f_i = u\text{-type} \\ N_{13}/\cos\beta, & f_i = d\text{-type}, \ell \end{cases} \tag{4c}$$

$$H^{f_{iR}} = H^{f_{iL}*}. \tag{4d}$$