Anapole Moment of Neutralino Dark Matter

Merlin Reichard

m.reichard@tum.de

based on A. Ibarra, MR, R. Nagai [JHEP 01 (2023) 086]
(+ A. Ibarra, MR, G. Tomar *work in progress*)

Technical University of Munich

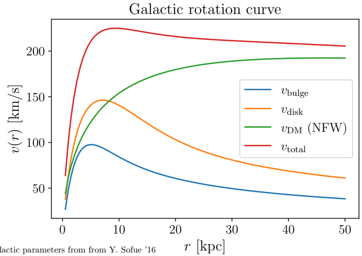
15.06.2023

Is dark matter really »dark«?

BlueWillow: ”a dark matter particle interacting with the electromagnetic field”

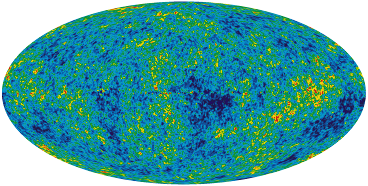
Outline

Motivation: DM Evidence



Galactic parameters from from Y. Sofue '16

Credit: NASA



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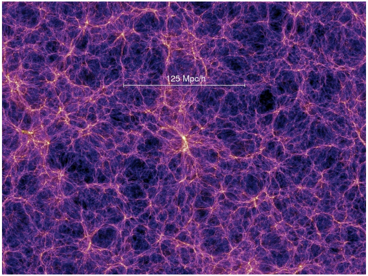

Credit: Springel et al. '05 (Millennium Simulation)

Motivation: DM Direct Searches

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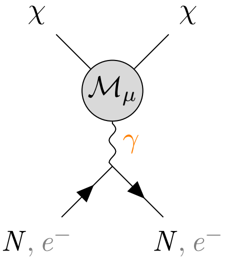
- Information from particle physics (DM mass, cross section) and astrophysics (local abundance, velocity distribution)
- For example: DM interacting electromagnetically

Anapole Moment: The Setup

Effective photon interaction



[See also hep-ph/0003010, 1401.6457, 1503.01500, 1608.00642, 1808.04112, 1806.07896, 2003.04039, ...]

Anapole Moment: The Setup

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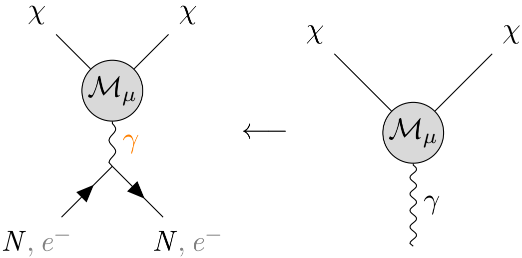
Theory



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Anapole Moment: The Setup

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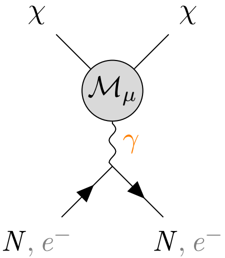
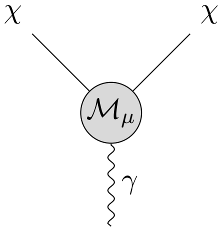
$$\text{Data} \overset{\text{DD}}{\longleftrightarrow} \frac{\mathrm{d}\sigma^{\gamma}_{\chi N}}{\mathrm{d}E_r} \longleftarrow$$



$\longleftarrow$



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Anapole Moment: The Setup

[see also talk by Xuyang Ning about Panda-X results (DM-1 on Monday)]

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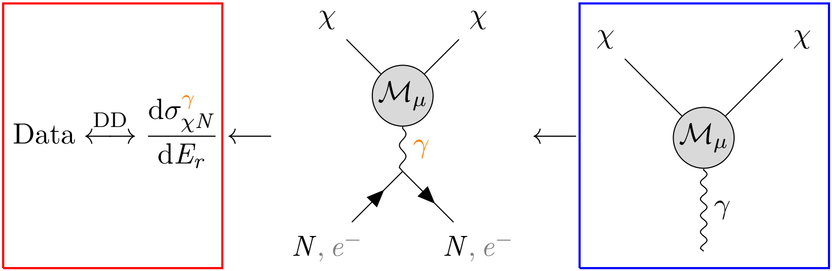

We want to compare DD limits with model predictions

[See also hep-ph/0003010, 1401.6457, 1503.01500, 1608.00642, 1808.04112, 1806.07896, 2003.04039, ...]

Electromagnetic Vertex Decomposition

- $\mathcal{M}_\mu(q) =$
  $(\gamma_\mu - q_\mu \not{q}/q^2)\left[f_Q(q^2) + f_A(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[f_M(q^2) + i f_E(q^2)\gamma_5\right]$

[Broggini, Giunti, Studenikin '12]

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f_Q(0) &= q && \text{charge} \\
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f_M(0) &= \mu && \text{magnetic dipole moment} \\
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- If χ Majorana: only $\mathcal{A}$ non-vanishing! $\mathcal{L} = \frac{\mathcal{A}}{2}\overline{\chi}\gamma_\mu\gamma_5\chi\partial_\nu F^{\mu\nu}$

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[Zel'dovich '58]

- If χ Majorana: only $\mathcal{A}$ non-vanishing! $\mathcal{L} = \frac{\mathcal{A}}{2}\overline{\chi}\gamma_\mu\gamma_5\chi\partial_\nu F^{\mu\nu}$
- $\mathcal{A}$ violates separately P and C

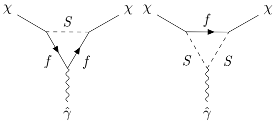
[Broggini, Giunti, Studenikin '12]

Anapole Moment: Calculation

- χ - Fermion - Scalar interaction:

$$\mathcal{L}_{\mathrm{FFS}} = \overline{\chi}\left[c_L P_L + c_R P_R\right] S^* f + \mathrm{h.c.}$$

$\rightarrow \mathcal{A}_S$ *scalar* contribution



[Kopp et al. '14; Garny et al. '15; Sandick et al. '16]

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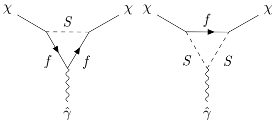

[Kopp et al. '14; Garny et al. '15; Sandick et al. '16]

- χ - Fermion - Vector interaction:

$$\mathcal{L}_{\text{FFV}} = \overline{\chi}\gamma^{\mu}\left[v_L P_L + v_R P_R\right]\chi^- V_\mu^+ + \text{h.c.}$$
$$+ \text{Goldstones}$$

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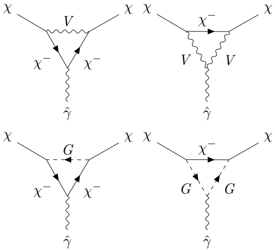

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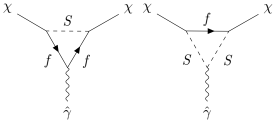

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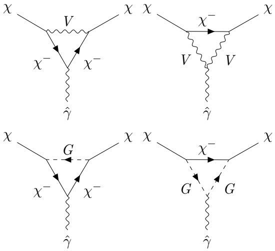
- Diagrams with vectors $\rightarrow$ unphysical result!



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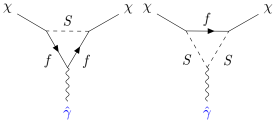

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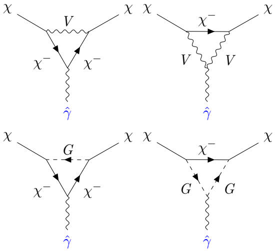
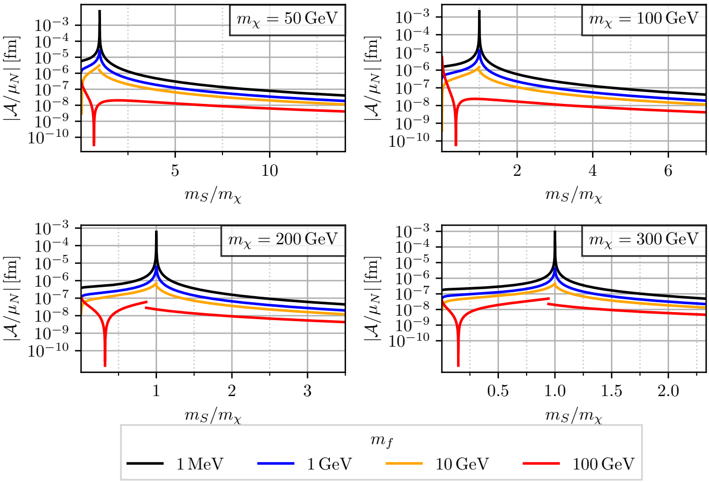


- Diagrams with vectors $\rightarrow$ unphysical result!
- Pinch Technique/Background Field Method: $\gamma \rightarrow \hat{\gamma}$, $\xi_{\mathrm{BFM}} = 1$

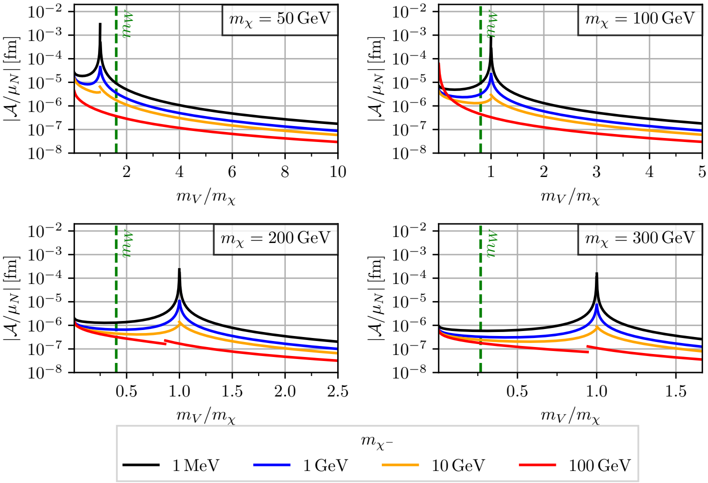
[Works by Cornwall, Papavassiliou, Bernabeu, Rosado, Vidal, Binosi, Cabral-Rosetti, ... See review Binosi & Papavassiliou '09]

Anapole Moment: Model-Independent Results (Scalar)



for $c_L = 1,\ c_R = 0$

Anapole Moment: Model-Independent Results (Vector)



for $v_L = 1,\ v_R = 0$

Model-dependent Goldstone loops are not included here

MSSM: The Situation in the MSSM

$$\mathcal{L}_{\mathrm{FFS}} = \overline{\chi}\,[c_L P_L + c_R P_R]\, S^* f + \mathrm{h.c.}$$

How is the anapole moment of $\widetilde{\chi}_1^0$ generated?

- Reminder: $\mathcal{A}$ breaks parity ($c_L \neq c_R$, $v_L \neq v_R$)
- Interactions w/ sfermions
- Interactions with $\widetilde{\chi}^{\pm}$ for non-trivial mixing

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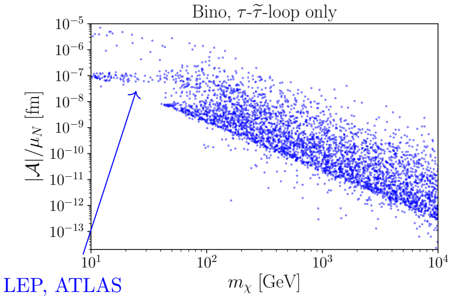
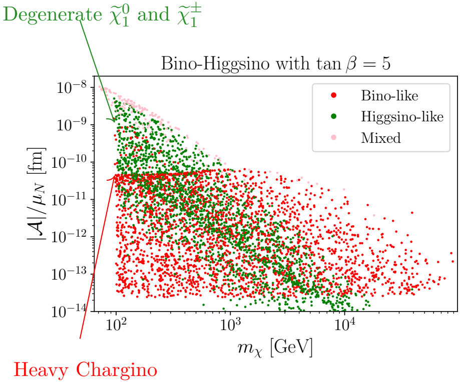
Two possibilities to enhance $\mathcal{A}$:

1) Light sfermions: $\mathcal{A}$ generated by scalar contribution $\mathcal{A}_S$
2) Mixing in the EW-ino sector: $\mathcal{A}$ generated by vector contribution $\mathcal{A}_V$

MSSM: Two Simplified Scenarios

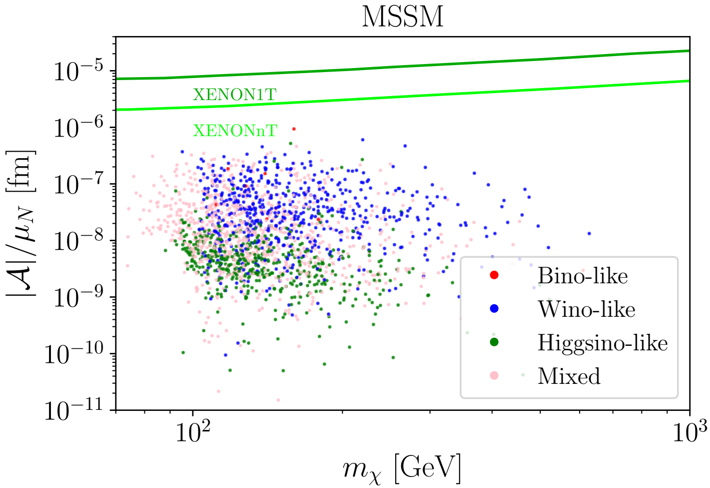


(a) Only $\mathcal{A}_S$



(b) Only $\mathcal{A}_V$

MSSM: Full Scan and DD limits



Constraints from LEP, $\Gamma(Z \to \text{inv.})$ [micrOMEGAS], Higgs sector [HiggsBounds, HiggsSignals], LHC [SModelS] and flavour physics [SuperIso, GM2Calc], but **no DM constraints**

Electromagnetic Vertex Decomposition: Dirac

Reminder:

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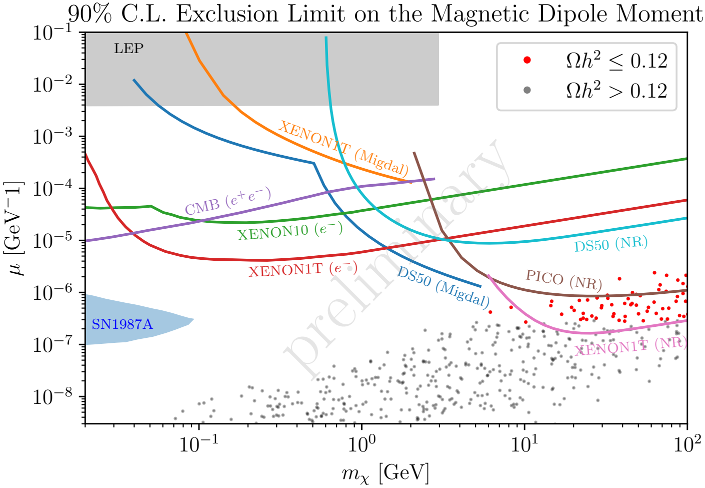
- If χ Dirac: dipole operators are allowed $\mathcal{L} = \frac{\mu}{2}\overline{\chi}\sigma_{\mu\nu}\chi F^{\mu\nu}$

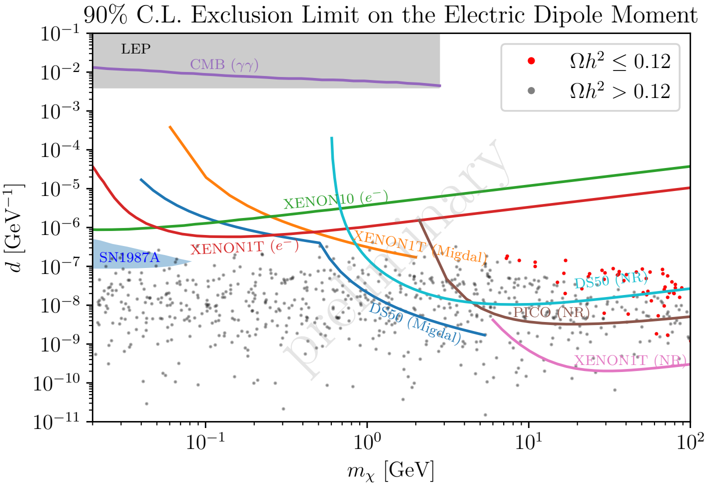
[Broggini, Giunti, Studenikin '12]

The Dirac Case: Magnetic Dipole (work in progress)



[A. Ibarra, **MR**, G. Tomar, *work in progress*]

The Dirac Case: Electric Dipole (work in progress)



[A. Ibarra, **MR**, G. Tomar, *work in progress*]

Summary

- We calculated two model-independent contributions: *scalar* $\mathcal{A}_S$ and *vector* $\mathcal{A}_V$
- Naive calculation of $\mathcal{A}_V$ leads to non-physical result $\rightarrow$ BFM
- Simplified Models: $\mathcal{A}_S \sim \mathcal{O}\big(10^{-6}\mu_N\,\mathrm{fm}\big)$ and $\mathcal{A}_V \sim \mathcal{O}\big(10^{-8}\mu_N\,\mathrm{fm}\big)$
- Anapole is not experimentally accessible (yet)
- Different situation for the dipole moments: already experimentally testable

ORIGINS Excellence Cluster

SFB 1258 Neutrinos Dark Matter Messengers

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Thank you for your attention

Backup: Analytical Anapole Expressions

- Scalar:

$$\mathcal{A}_S = -\frac{e}{96\pi^2 m_\chi^2} Q_f \left[\left|c_L\right|^2 - \left|c_R\right|^2 \right] \mathcal{F}_S\left(\frac{m_f}{m_\chi}, \frac{m_S}{m_\chi} \right)$$

- Vector:

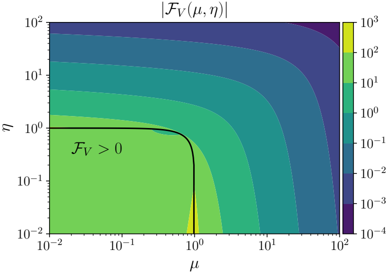
$$\mathcal{A}_V = \frac{e}{96\pi^2 m_\chi^2} \Big\{ 2 \left[\left|v_L\right|^2 - \left|v_R\right|^2 \right] \mathcal{F}_V\left(\frac{m_{\chi^-}}{m_\chi}, \frac{m_V}{m_\chi} \right) + \left[\left|c_L^G\right|^2 - \left|c_R^G\right|^2 \right] \mathcal{F}_S\left(\frac{m_{\chi^-}}{m_\chi}, \frac{m_V}{m_\chi} \right) \Big\}$$

- Loop functions:

$$\mathcal{F}_X(\mu, \eta) = \frac{3}{2} \log\left(\frac{\mu^2}{\eta^2} \right) + (3\eta^2 - 3\mu^2 + n_X) f(\mu, \eta),$$

with $n_V = -7$, $n_S = 1$

Backup: Loop Functions



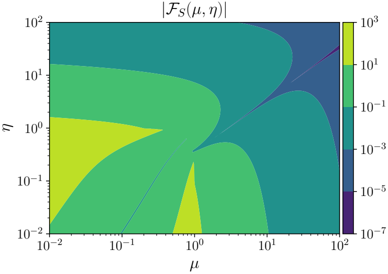
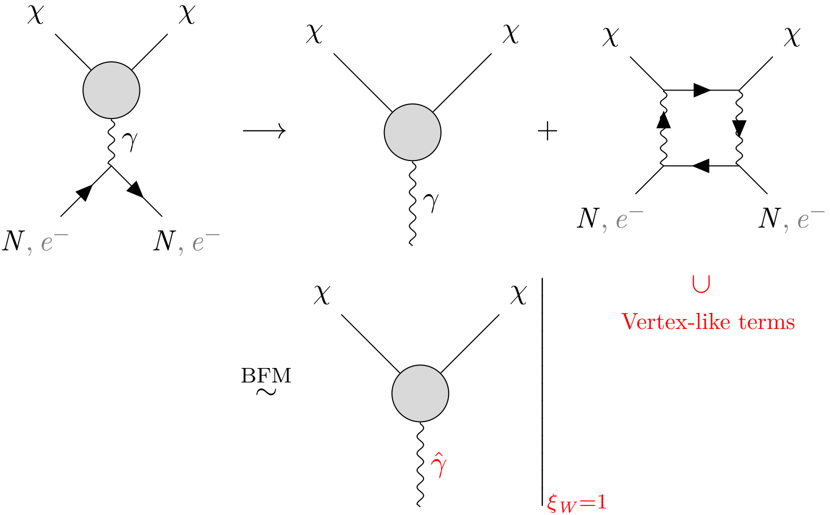


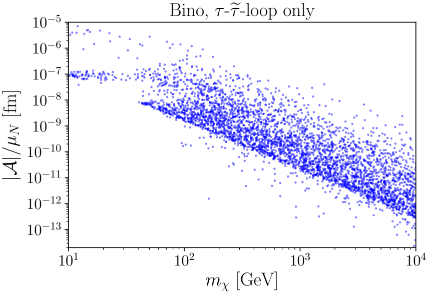
Figure: Contour plot of absolute values of $\mathcal{F}_V(\mu,\eta)$ (left) and $\mathcal{F}_S(\mu,\eta)$ (right).

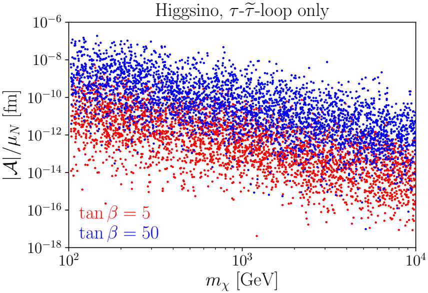
Backup: BFM and Pinch Technique

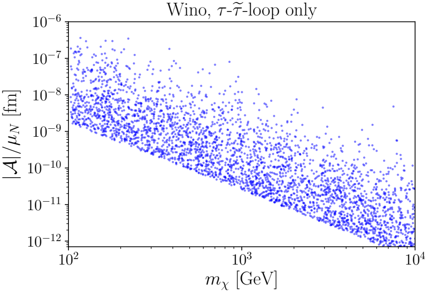


[Hasimoto, Kodaira, Yasui, Sasaki '94; Papavassiliou '94; Denner, Dittmaier, Weiglein '94; Review by Binosi & Papavassiliou '09]

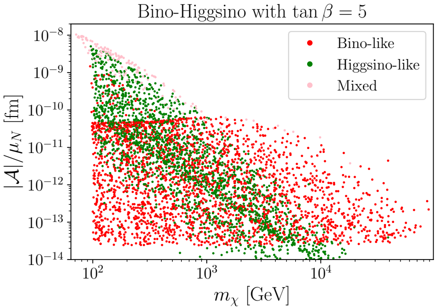
Backup: Pure EW-inos & light sfermions

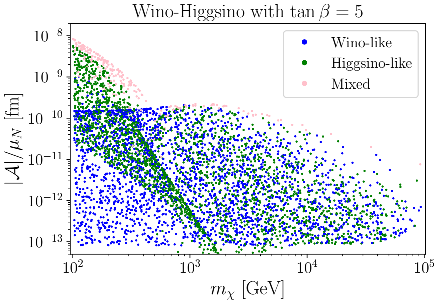




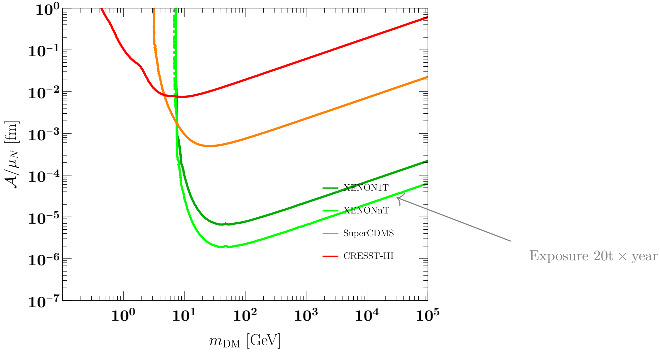


Backup: Mixed EW-inos & heavy sfermions



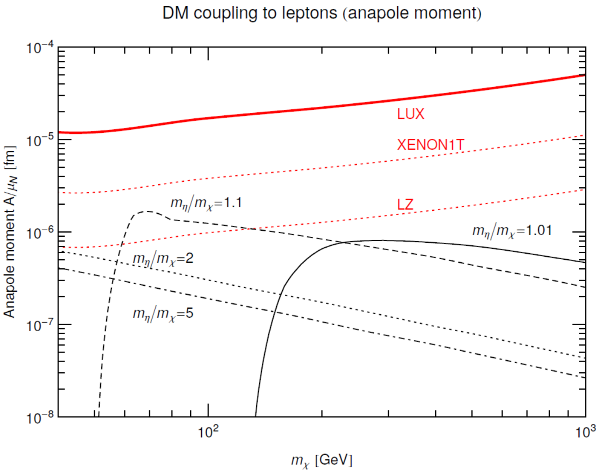


Backup: Scattering Rate for the Anapole Interaction



$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \alpha_{\mathrm{EM}}\,\mathcal{A}^2\left[Z^2\left(2m_T - \left(1+\frac{m_T}{m_\chi}\right)^2\frac{E_R}{v^2}\right)F_Z^2(q^2)\right.$$
$$\left. + \frac{1}{3}\frac{m_T}{m_\chi^2}\left(\frac{\bar{\mu}_T}{\mu_N}\right)^2\frac{E_R}{v^2}F_D^2(q^2)\right]$$

Relic density in simplified model

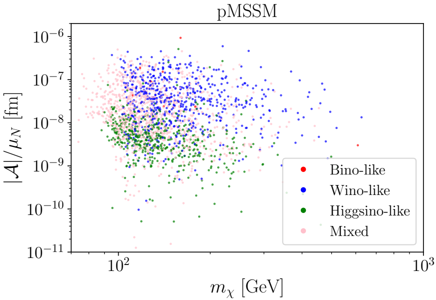


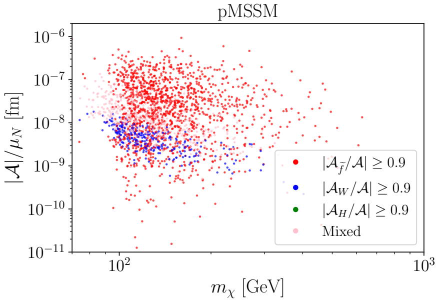
Garny et al. '15

Backup: pMSSM Parameter Space

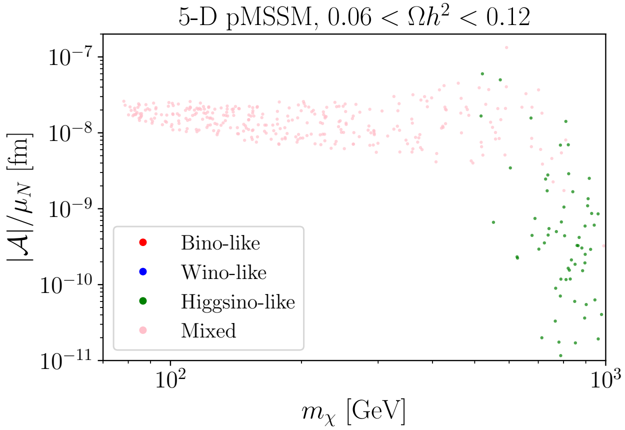
Parameter	Full	5-D
M_1	$[100, 2000]$ GeV	$[100, 2000]$ GeV
M_2	$[100, 2000]$ GeV	$[100, 2000]$ GeV
M_3	$[2000, 5000]$ GeV	3000 GeV
$A_{t,b,\tau}$	$[-4000, 4000]$ GeV	4000, 0, 0 GeV
m_A	$[10^3, 10^5]$ GeV	5000 GeV
$\tan\beta$	$[3, 50]$	50
μ	$[100, 2000]$ GeV	$[100, 2000]$ GeV
$m_{\widetilde{\ell}_{L,R}}$	$[100, 2000]$ GeV	$[100, 1000]$, 3000 ($\widetilde{\tau}$) GeV
$m_{\widetilde{q}_{L_{1,2}}}$	$[400, 2000]$ GeV	5×10^4 GeV
$m_{\widetilde{u}_{R_{1,2}}}$, $m_{\widetilde{d}_{R_{1,2}}}$	$[400, 2000]$ GeV	5×10^4 GeV
$m_{\widetilde{q}_{L_3}}$	$[300, 2000]$ GeV	10^4 GeV
$m_{\widetilde{u}_{R_3}}$, $m_{\widetilde{d}_{R_3}}$ GeV	$[300, 2000]$ GeV	10^4 GeV

Backup: MSSM Full Scan





Backup: 5-D pMSSM scan including $\Omega_\chi h^2$



Backup: MSSM Couplings I

To Charginos

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

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

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

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

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

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

Backup: MSSM Couplings II

To Sfermion/fermions

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

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

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

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

with

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

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

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

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