Well-tempered n-plet dark matter

[1703.00370]

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Motivations

WIMP miracle : The thermal relic density of stable, electrically neutral particle with EW-scale cross section and EW-scale mass corresponds to the observed dark matter abundance $\Omega h^2 \sim 0.1$

However, a closer look : [arXiv :hep-ph/0601041, arXiv :hep-ph/0903.3381]

- Higgsino DM (fermionic 2-plet) $\rightarrow m = 1.1\,\mathrm{TeV} \gg M_Z$
- Winos DM (fermionic 3-plet) $\rightarrow m = 2.5\,\mathrm{TeV} \gg M_Z$
- Minimal DM (fermionic 5-plet) $\rightarrow m = 10\,\mathrm{TeV} \ggg M_Z$

A WIMP with generic EW quantum numbers and a EW-scale mass annihilates too much to reproduce the observed Ωh^2.

Therefore a WIMP with a mass of $\mathcal{O}(100$ GeV$)$ must necessarily originate mostly from an $\mathrm{SU}(2) \times \mathrm{U}(1)$ singlet, and feel the EW gauge interactions at most through a small coupling to a non-singlet.

Assumptions

What we want :

- To have a good fermionic dark matter candidate.
- Mass of order $100\,\mathrm{GeV}$ to be within kinematic reach of the LHC.
- Sub-TeV content is minimal.
- To pass through DD limits.

What we do :

- Add a singlet χ and a n-plet ψ under $SU(2)_L \otimes U(1)_Y$.
- Induce a mixing of the neutral components $\Rightarrow$ DM is mosty a singlet of $SU(2)_L \otimes U(1)_Y$ with some admixture of n-plet state.
- Impose $\mathbb{Z}_2$ symmetry to ensure the stability of the DM.

About the mixing

- The mixing is induced through higher-dimensional operators.
- States inducing the mixing live at scales $\gtrsim 1\,\mathrm{TeV}$ $\Rightarrow$ mostly irrelevant for LHC if carrying only EW charges.

Familiar example : Split SUSY with heavy higgsinos and $M_1 < M_2$.
DM is mostly bino, mixing with wino through dimension-5 operator

$$\mathcal{L}_{mix} = \frac{\widetilde{g}_u \widetilde{g}'_d + \widetilde{g}'_u \widetilde{g}_d}{\mu}\, \phi^\dagger \tau^a \phi\, \widetilde{W}^a \widetilde{B} \quad (\mathrm{e.g.\ arXiv : hep-ph/0601041})$$

In the following :

- Agnostic about the UV theory $\rightarrow$ encoded through the cut-off Λ.
- Λ is sufficiently large for these new states to play essentially no role at electroweak energies, except to induce the higher-dimensional mixing operators ($\Lambda \geq 1\mathrm{TeV}$).

The Model

The Lagrangian for n odd

$$\mathcal{L}_{\rm DM} = i\,\psi^\dagger\overline{\sigma}^\mu D_\mu\psi + i\,\chi^\dagger\overline{\sigma}^\mu\partial_\mu\chi - \left(\frac{1}{2}M\psi\psi + \frac{1}{2}m\chi\chi + \text{h.c.}\right)$$

$$+\frac{1}{2}\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi + \text{h.c.} \qquad (\mathcal{L}_{\rm quartic})$$

$$+\frac{\lambda}{\Lambda^{n-2}}(\phi^\dagger\phi)^{\frac{n-1}{2}}\psi\chi + \text{h.c.} \qquad (\mathcal{L}_{\rm mix}\,,\text{schematical})$$

- $\mathbb{Z}_2$ symmetry to ensure the stability of the DM.
- ψ is a Majorana fermion in $SU(2)_L \otimes U(1)_Y$ $(\mathbf{n}_0)$.
- χ is a Majorana singlet.
- ϕ is a SM Higgs doublet.

κ, λ contribute to coannihilation (Ωh^2) and DM-nucleus scattering (DD).

Mixing and dark sector

Hypothesis

- The dark matter is mostly a singlet-like (χ-like).
- $\Rightarrow m < M$. ($(M-m) \sim \mathrm{few}10 \cdot \mathrm{GeV}$ for the case of interest).
- Our effective description valid up to $\Lambda \geq 1\mathrm{TeV}$.

What happened ?

- $\mathrm{EWSB} \Rightarrow \mathcal{L}_{\mathrm{mix}}$ induce a mixing between the neutral states.
- The **lightest** "neutralino" is the **dark matter**.

$n = 3$

Dark sector :

$$\chi_1^0 \qquad (\chi\text{−like})$$
$$\chi_2^0\,,\ \chi^{\pm} \qquad (\psi\text{−like})$$

Mixing : $\theta \simeq \dfrac{\sqrt{2}\lambda v^2}{\Lambda(M-m)}$

$n = 5$

Dark sector :

$$\chi_1^0 \qquad (\chi\text{−like})$$
$$\chi_2^0\,,\ \chi^{\pm}\,,\ \chi^{\pm\pm} \qquad (\psi\text{−like})$$

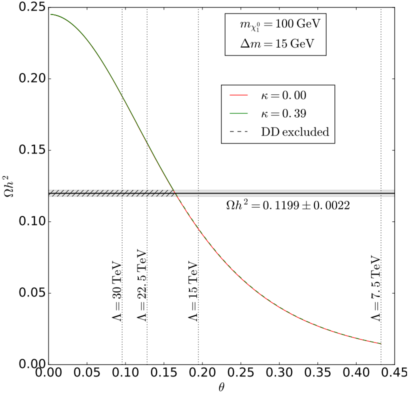
Mixing : $\theta \simeq \sqrt{\dfrac{2}{3}}\dfrac{\lambda v^4}{\Lambda^3(M-m)}$

DM properties

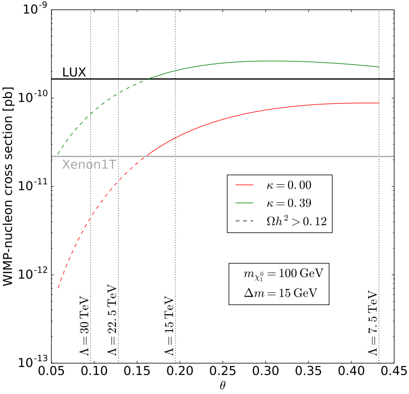
If $\mathcal{L}_{mix}$ dominates :

- Tiny θ : θ too small for χ_1^0 to be in equilibrium $\Rightarrow$ relic density predicted if initial conditions are assumed.
- Small θ : Equilibrium $\Rightarrow$ **freeze-out mechanism**.
  $\psi_i \to \chi_1^0 + \mathrm{SM}$ and $\chi_1^0 + \mathrm{SM} \to \psi_i + \mathrm{SM}$ occur.
  χ_1^0 abundance is determined by ψ_i annihilation.
  Ωh^2 effectively independent of the precise value of θ.
- Not so small θ : Processes directly involving χ_1^0 become important. The relic density is now a function of both the masses and θ.
- $\theta \sim \mathcal{O}(1)$: Our effective theory is approaching the limits of its validity.

Results : n=3

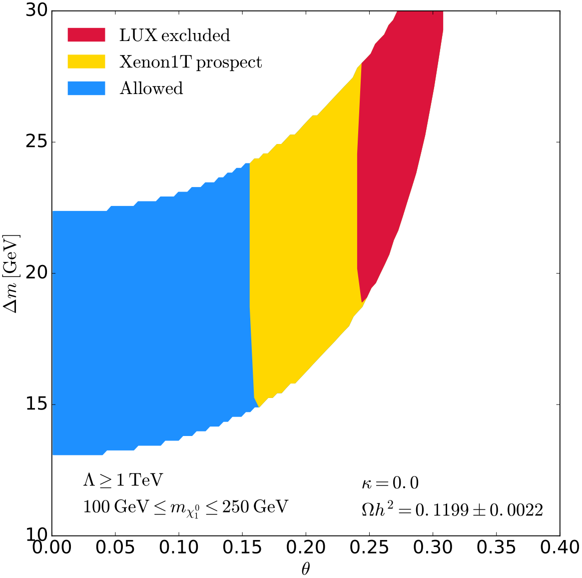


$m_{\chi_1^0} = 100$ GeV
$\Delta m = 15$ GeV
$\kappa = 0.00$
$\kappa = 0.39$
DD excluded
$\Omega h^2 = 0.1199 \pm 0.0022$
$\Lambda = 30$ TeV
$\Lambda = 22.5$ TeV
$\Lambda = 15$ TeV
$\Lambda = 7.5$ TeV
Ωh^2
θ



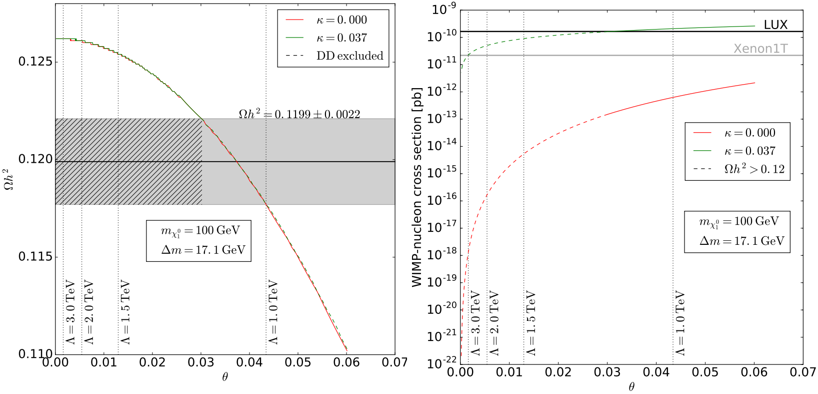
LUX
Xenon1T
$\kappa = 0.00$
$\kappa = 0.39$
$\Omega h^2 > 0.12$
$m_{\chi_1^0} = 100$ GeV
$\Delta m = 15$ GeV
$\Lambda = 30$ TeV
$\Lambda = 22.5$ TeV
$\Lambda = 15$ TeV
$\Lambda = 7.5$ TeV
WIMP-nucleon cross section [pb]
θ

Results : n=3



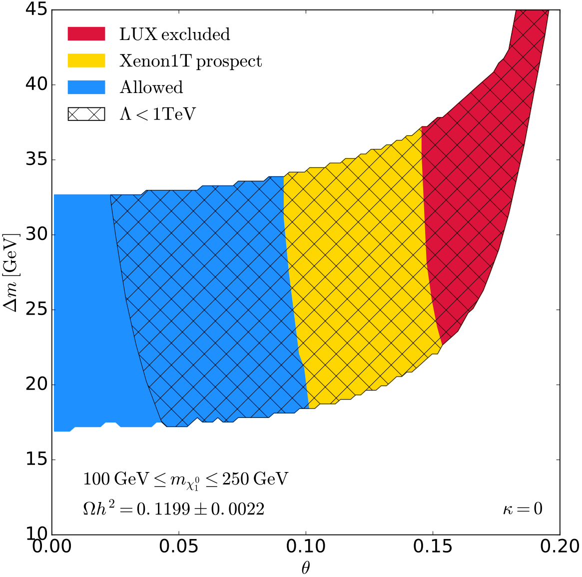
LUX excluded
Xenon1T prospect
Allowed
$\Lambda \geq 1$ TeV
100 GeV $\leq m_{\chi_1^0} \leq$ 250 GeV
$\kappa = 0.0$
$\Omega h^2 = 0.1199 \pm 0.0022$
Δm [GeV]
θ
30
25
20
15
10
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40

Results : n=5



κ = 0.000
κ = 0.037
DD excluded
Ωh² = 0.1199 ± 0.0022
m_χ₁⁰ = 100 GeV
Δm = 17.1 GeV
Λ = 3.0 TeV
Λ = 2.0 TeV
Λ = 1.5 TeV
Λ = 1.0 TeV
Ωh²
θ
LUX
Xenon1T
WIMP-nucleon cross section [pb]
Ωh² > 0.12

Results : n=5


LUX excluded
Xenon1T prospect
Allowed
$\Lambda < 1\text{TeV}$
$100\text{ GeV} \leq m_{\chi_1^0} \leq 250\text{ GeV}$
$\Omega h^2 = 0.1199 \pm 0.0022$
$\kappa = 0$
Δm [GeV]
θ
45
40
35
30
25
20
15
10
0.00
0.05
0.10
0.15
0.20

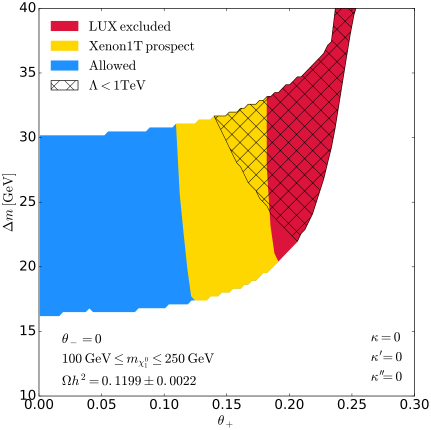
About the quadruplet (n=4)

Up to now we have considered only n-odd ($n = 3, 5$). But we can do the same for n even ! ($n = 4$). However the quadruplet is more complicated because :

- Dirac spinor $(\psi, \overline{\psi}^\dagger)$.
- mass eigenstates :

$$\chi_1^0 \qquad (\chi\text{−like})$$
$$\chi_{2,3}^0\ ,\ \chi_{1,2}^\pm\ ,\ \chi^{\pm\pm} \qquad (\psi\text{−like})$$

- $\Rightarrow$ Two neutral mixing angles.
- More than two higher dimensional operators ...
- $\Rightarrow$ More parameters !
- Similar results.



Conclusion

Summarize :

- Simple effective models for fermionic WIMP DM at EW scale.
- DM is the mixture of a singlet and a n-plet of $SU(2)_L \otimes U(1)_Y$.
- κ is strongly constraints by DD.
- Relic density must be dominated by $\mathcal{L}_{mix}$ rather than $\mathcal{L}_{quartic}$.
- Impact of κ (dim-5 operator) is more and more important when n increases. ($\mathcal{L}_{mix}$ is a dim-(n+2) operator).
- Suitable choice for the parameters can always be found.
- Potentially ruled out with the future DD experiment results.
- Testable at the LHC.

Perspectives : To study the phenomenology at the LHC.

(ISR + missing energy, Disappearing track, Displaced vertex, ...)

The end !

Thank you for your attention !

Back-up

The Model

The Lagrangian for n even

$$\mathcal{L}_{\rm DM} = i\,\psi^\dagger\overline{\sigma}^\mu D_\mu\psi + i\,\overline{\psi}^\dagger\overline{\sigma}^\mu D_\mu\overline{\psi} + i\,\chi^\dagger\overline{\sigma}^\mu\partial_\mu\chi - \left(M\psi\overline{\psi} + \frac{1}{2}m\chi\chi + \text{ h.c.}\right)$$

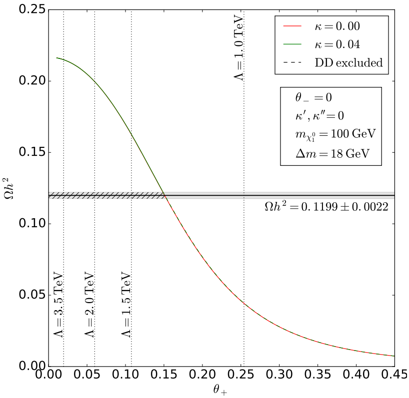
$$+\frac{1}{2}\frac{\kappa}{\Lambda}\phi^\dagger\phi\chi\chi + \text{ h.c.} \qquad (\mathcal{L}_{\rm quartic})$$

$$+\frac{1}{\Lambda^{n-2}}(\phi^\dagger\phi)^{\frac{n-2}{2}}\left(\lambda\,\phi\chi\psi - \lambda'\,\phi^\dagger\chi\overline{\psi} + \text{ h.c.}\right) \qquad (\mathcal{L}_{\rm mix}\,,\text{schematical})$$

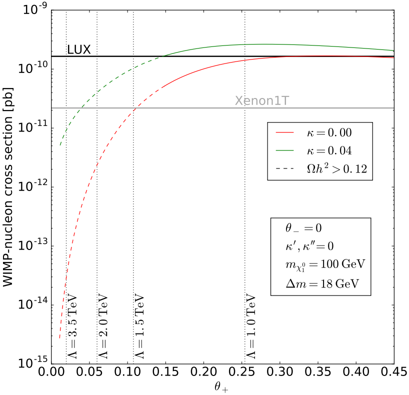
Comments

- $\mathbb{Z}_2$ symmetry to ensure the stability of the DM.
- $(\psi, \overline{\psi}^\dagger)$ form a Dirac spinor transforming in the $\mathbf{n}_{\frac{1}{2}}$.
- χ is a Majorana singlet.
- ϕ is a SM Higgs doublet.

Results : n=4

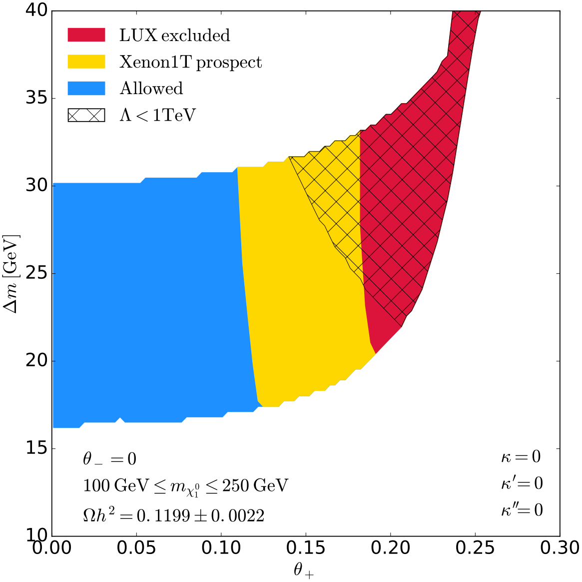


Ωh^2
θ_+
$\kappa = 0.00$
$\kappa = 0.04$
DD excluded
$\theta_- = 0$
$\kappa', \kappa'' = 0$
$m_{\chi_1^0} = 100$ GeV
$\Delta m = 18$ GeV
$\Omega h^2 = 0.1199 \pm 0.0022$
$\Lambda = 3.5$ TeV
$\Lambda = 2.0$ TeV
$\Lambda = 1.5$ TeV
$\Lambda = 1.0$ TeV



WIMP-nucleon cross section [pb]
θ_+
LUX
Xenon1T
$\kappa = 0.00$
$\kappa = 0.04$
$\Omega h^2 > 0.12$
$\theta_- = 0$
$\kappa', \kappa'' = 0$
$m_{\chi_1^0} = 100$ GeV
$\Delta m = 18$ GeV
$\Lambda = 3.5$ TeV
$\Lambda = 2.0$ TeV
$\Lambda = 1.5$ TeV
$\Lambda = 1.0$ TeV

Results : n=4



LUX excluded
Xenon1T prospect
Allowed
$\Lambda < 1\text{TeV}$
$\theta_- = 0$
$100\ \text{GeV} \leq m_{\chi_1^0} \leq 250\ \text{GeV}$
$\Omega h^2 = 0.1199 \pm 0.0022$
$\kappa = 0$
$\kappa' = 0$
$\kappa'' = 0$
Δm [GeV]
θ_+
40
35
30
25
20
15
10
0.00
0.05
0.10
0.15
0.20
0.25
0.30

About effective operators

Other effective operators than $\mathcal{L}_{mix}$ and $\mathcal{L}_{quartic}$ ...

dimension 5 (n even) :

- ψ-quartic : $\phi^\dagger\phi\ \psi\overline{\psi}$
- Dipole operators : $g'\ Y\ \psi\ (\sigma^{\mu\nu})\ \overline{\psi}\ B_{\mu\nu} + g\ \psi\ (\sigma^{\mu\nu})\ t^a\ \overline{\psi}\ \ W^a_{\mu\nu}$
- With generators : $(\phi^\dagger\tau^a\phi)(\psi t^a\overline{\psi})$, $(\phi^\dagger\tau^a\phi^\dagger)(\psi t^a\psi)$,$(\phi\tau^a\phi)(\overline{\psi}t^a\overline{\psi})$

χ-like DM $\Rightarrow$ mixing suppressed.
Operators with τ^a have an impact on the mass spectrum after EWSB.

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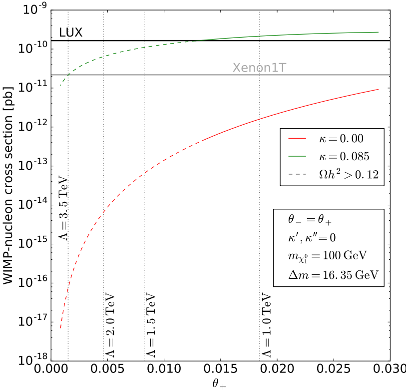
dimension 6 :

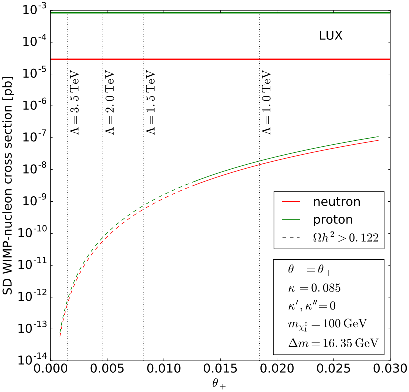
- 4 fermions : $(c^l_{ij}\ l^\dagger_i\overline{\sigma}_\mu l_j)(\chi^\dagger\overline{\sigma}^\mu\chi) + (c^q_{ij}\ q^\dagger_i\overline{\sigma}_\mu q l_j)(\chi^\dagger\overline{\sigma}^\mu\chi)$

Suppressed since these lead to FCNC.

SD limits ?

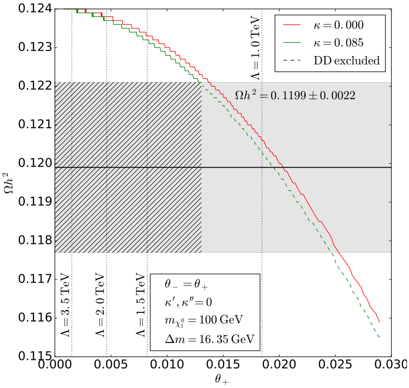


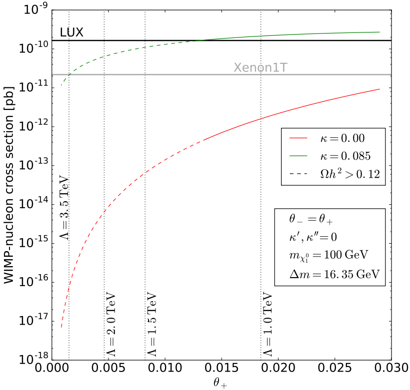
LUX
Xenon1T
WIMP-nucleon cross section [pb]
θ_+
$\Lambda = 3.5$ TeV
$\Lambda = 2.0$ TeV
$\Lambda = 1.5$ TeV
$\Lambda = 1.0$ TeV
$\kappa = 0.00$
$\kappa = 0.085$
$\Omega h^2 > 0.12$
$\theta_- = \theta_+$
$\kappa', \kappa'' = 0$
$m_{\chi_1^0} = 100$ GeV
$\Delta m = 16.35$ GeV



LUX
SD WIMP-nucleon cross section [pb]
θ_+
$\Lambda = 3.5$ TeV
$\Lambda = 2.0$ TeV
$\Lambda = 1.5$ TeV
$\Lambda = 1.0$ TeV
neutron
proton
$\Omega h^2 > 0.122$
$\theta_- = \theta_+$
$\kappa = 0.085$
$\kappa', \kappa'' = 0$
$m_{\chi_1^0} = 100$ GeV
$\Delta m = 16.35$ GeV

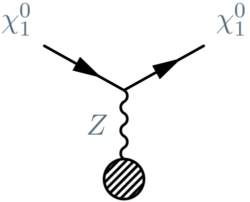
Results : n=4 with $\theta_- = \theta_+$



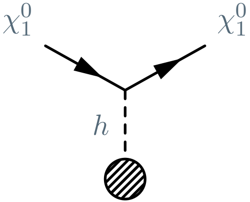


σ contributions

SI contributions :

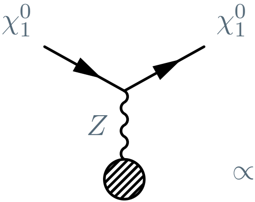


$\propto$
$\chi_1^0 \gamma^\mu \chi_1^0 Z_\mu = 0$
$(Majorana)$



$\propto$
$\kappa\, \chi_1^0 \chi_1^0 h,\, \theta\, \chi_1^0 \chi_1^0 h$

SD contributions :



$\propto \chi_1^0 \gamma^\mu \gamma_5 \chi_1^0 Z_\mu \theta_+\, \theta_-$

Context

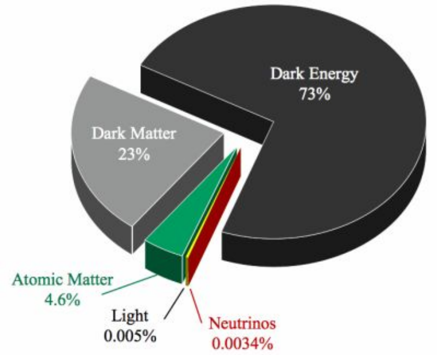
Standard Model (SM) of particle physic

Well-tested, very good agreement with the observations

But this is not the end of the story !

asymmetry matter-antimatter ? dark matter (DM) ? neutrino masses ?

...



Relic density

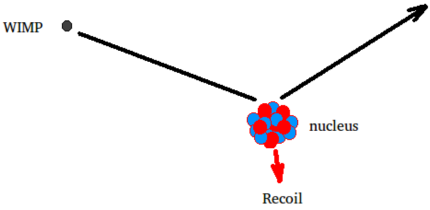
Measure the amount of DM in the universe.

Planck data :

$$\Omega h^2 = 0.1199 \pm 0.0022$$

arXiv :1502.01589

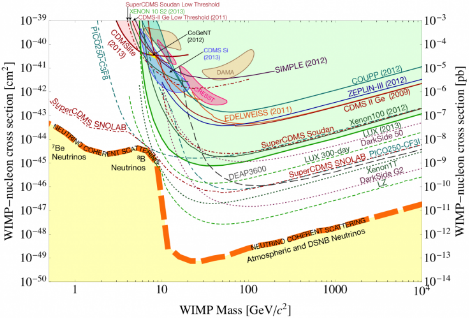
Direct detection



Principle

Detect a collision of a nucleus with a dark matter particle by measuring the recoil energy.

Expirements : LUX, Xenon1T, ...



Contraints

Upper limits on the cross-section WIMP-nucleon

Observables : σ_{SI}, σ_{SD}

Analysis

- The models are implemented with *FeynRules 2.0*. [1310.1921]
- The relic density and the DD cross-sections are computed with *micrOMEGAs 4.3*. [1305.0237]
- All the theoretical cross-sections are rescaled by a factor $\frac{\Omega h^2|_\chi}{\Omega h^2|_{exp}}$ in order to be compared with LUX results [1608.07648] and Xenon1T prospects [1512.07501]
- At one loop the masses received corrections from electroweak gauge bosons. In the absence of mixing : [arXiv :hep-ph/0512090]

$$\Delta^{\text{one loop}}_{m_Q - m_{\chi^0_2}} = \frac{g^2}{16\pi^2} M \left(Q^2 s_W^2 f\left(\frac{m_Z}{M}\right) + Q(Q-2Y)\, f\left(\frac{m_W}{M} - \frac{m_Z}{M}\right)\right)$$

$$f(x) = \frac{x}{2}\left(2\,x^3 \log x - 2\,x + \sqrt{x^2-4}(x^2+2)\log\frac{x^2 - x\sqrt{x^2-4} - 2}{2}\right)$$