Cancellation in Dark Matter-Nucleon Interactions: the Role of Non-Standard-Model-like Yukawa Couplings (IMEPNP 2022)

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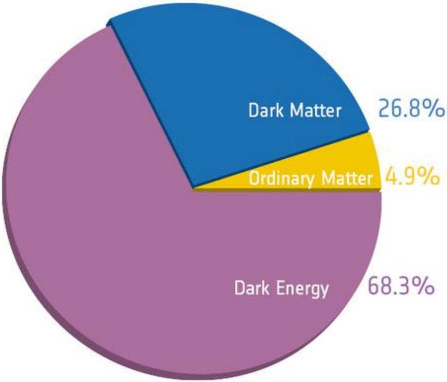
Outline

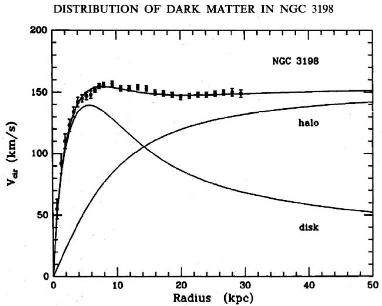
- Introduction to Dark Matter
- Theory of Direct Detection
- Present Picture of DD Experiments
- A General Approach
- Practical Realization
- Numerical Results
- Isospin Violation
- Summary

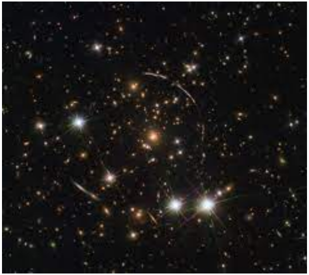
What is Dark Matter?

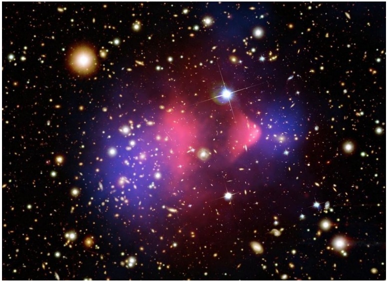


- **"Something"**, which shows gravitational interaction in the same way as usual matter does.
- **"Something"**, which is invisible to us ⇒ **No** EM interaction.
- **"Something"**, whose nature is still a mystry!

Signatures of Dark Matter







What can be inferred?

DM is **"Something"**, composed of **particles**, which may have **weak** interaction along with the **gravitational** one.

Basic Idea of Direct Detection

- Earth is moving through the **DM** **halo**.

- If **DM** is a **WIMP**, there must be **DM-quark** interaction ⇒ **DM-nucleus** scattering.

- The measure of this scattering cross section is a **direct** evidence of particle **DM**.

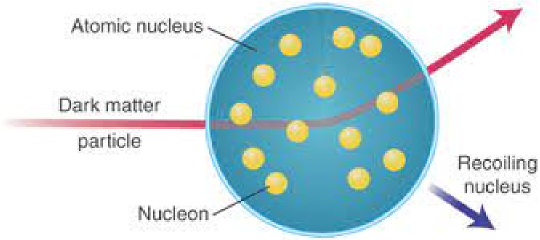
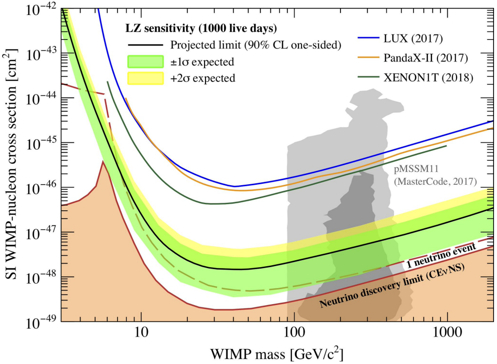


Figure : A schematic diagram showing the fundamental idea of DD

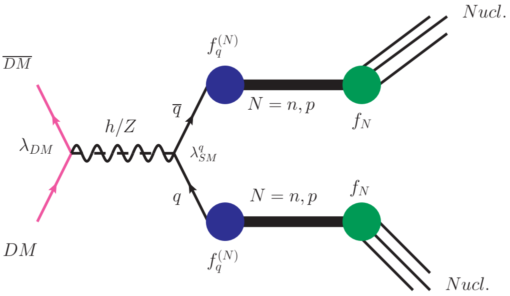
Present Picture: Experimental Aspects



[LZ Collaboration: Phys.Rev.D 101 (2020) 5, 052002]

- Null results from the DM-search experiments.
- Detector sensitivity is gradually approaching the **neutrino floor**.
- WIMP paradigm is losing its miracle!

And the Theory Says...



- Several **simple** extensions of SM (e.g. Z-portal, H-portal, Z'-portal etc.) have been proposed to explain the **DM** phenomenology.

- The **Higgs portal** models ⇒ most relevant in SI DD for many favoured **BSM** scenarios (e.g. **SUSY**).

- But the continuous null results have put strong constraints on these simple extensions, threatening them to be ruled out.

Are we missing something?

Some Attempts

- In some parts of the parameter space the DM couplings to Z or h may be highly suppressed or even zero $\Rightarrow$ Blind spots. [**Phys. Rev. D 79 (2009) 023521**, **J. High Energy Phys. 05 (2013) 100**]

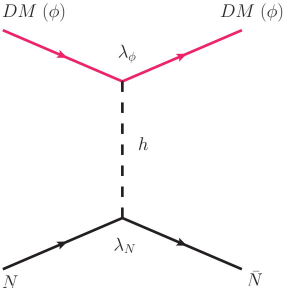
- A much suppressed σ_{SI} can be obtained if the DD proceeds only through the loops. [**Eur.Phys.J.C 78 (2018) 6, 471**]

- In a simple H-portal DM model with a complex scalar, a softly broken symmetry might ensure $\sigma_{SI} \to 0$. [**Phys. Rev. Lett. 119 (2017) 191801**, **J. Cosmol. Astropart. Phys. 11 (2018) 050**]

- Isospin-violating DM is another interesting scenario which assumes non-identical f_p and f_n. [**Phys. Rev. D 69 (2004) 063503**, **Phys. Lett. B 703 (2011) 124-127**]

More general approach?

Probably, Yes!



$\mathcal{L}_N^{\rm SI} = f_N(\phi\phi)(\bar{N}N) \Rightarrow$

$f_N = \frac{\lambda_\phi \lambda_N}{m_h^2}$ and $\sigma_{SI} \propto |\lambda_N|^2$

where,

$\frac{\lambda_N}{m_N} = \sum_{q=u,d,s} f_q^{(N)} \frac{y_q}{m_q} + \frac{2}{27} f_G^{(N)} \sum_{q=c,b,t} \frac{C_q y_q}{m_q} \qquad \cdots\cdots (A)$

- Almost all the earlier attempts tried to tune λ_ϕ.
- But what happens if $\lambda_N \to 0$ irrespective of λ_ϕ?
- $\lambda_N = 0 \Rightarrow$ *Non-SM-like* negative y_q.
- If y_c and y_s are allowed to deviate from **SM** :

$$y_s = -\frac{m_s}{f_s^{(N)}} \left(f_u^{(N)} \frac{y_u}{m_u} + f_d^{(N)} \frac{y_d}{m_d} \right)$$

$$y_c = -m_c \left(\frac{y_b}{m_b} + \frac{y_t}{m_t} \right)$$

But wait... in SM, $y_q \propto m_q/v$!!!

Here is the Path...

Let's have a particular type of effective dim-6 operators at some NP scale Λ in the quark Yukawa interaction Lagrangian,

$$\mathcal{L} \supset -Y_u \bar{q}_L \tilde{H} u_R - Y_d \bar{q}_L H d_R + \Delta\mathcal{L}_{eff} + H.c. \tag{1}$$

where,

$$\Delta\mathcal{L}_{eff} = \frac{H^\dagger H}{\Lambda^2} \left(Y_H^u \bar{q}_L \tilde{H} u_R + Y_H^d \bar{q}_L H d_R \right). \tag{2}$$

After EWSB,

$$m_q = v \left(Y_q - \epsilon Y_H^q \right), \tag{3}$$

$$y_q = \left(Y_q - 3\epsilon Y_H^q \right) = \frac{m_q}{v} - 2\epsilon Y_H^q \tag{4}$$

where, $\epsilon \equiv (v/\Lambda)^2$ and $v \simeq 174$ GeV.

And that's it! $y_q \neq m_q/v$

A Few Comments

$$\boxed{\Lambda \sim \textbf{TeV} \text{ and } Y_H^q \simeq \mathcal{O}(1)}$$

- The sign of y_q depends on the sign of the Wilson coefficients Y_H^q.

- For the first two gen. of quarks (u, d, s, c), $m_q/v \ll \epsilon Y_H^q \Rightarrow y_q$ may naturally become negative.

- To achieve the **correct** m_q with $y_q < 0$, the necessary condition is: $\boxed{Y_H^q \left(\frac{v}{\Lambda}\right)^2 > \frac{m_q}{2v}}$ $\Rightarrow$ sets an **upper** bound on Λ (e.g. $\Lambda \leq 2.9$ TeV for $m_c = m_c^{\text{SM}}$).

- On the contrary, $y_q > 0$ can only set a lower bound on Λ.

- The choice of **negative** values for y_q is more **natural** and **predictive**.

Experimental Bounds on y_q

- Projected reach in the absolute y_q values ($q = u,\ d,\ s,\ c$) at the LHC with 3000 fb^{-1} of IL : [J. High Energy Phys. 01 (2020) 139]

$$|y_u| < 560\ y_u^{\rm SM}, \quad |y_d| < 260\ y_d^{\rm SM}, \quad |y_s| < 13\ y_s^{\rm SM}, \quad |y_c| < 1.2\ y_c^{\rm SM}.$$

- Utilizing processes sensitive to the **sign** of y_q, the HL-LHC can restrict,
  - $-1550 < y_u/y_u^{\rm SM} < 700$ & $-800 < y_d/y_d^{\rm SM} < 300$. [arXiv:1608.04376]
  - $y_c/y_c^{\rm SM} \sim [-0.6, 3]$. [Phys. Rev. Lett. 118 (2017) 121801]

- A huge room is still available for the variation of first two gen. of quark Yukawa couplings.

Singlet Scalar DM and Negative y_q

Let's consider a specific realization of the dim-6 operators through new heavy VL particles at the NP scale Λ :

$$\boxed{\mathcal{L}_{eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP} + \mathcal{L}_{\rm DM}}$$

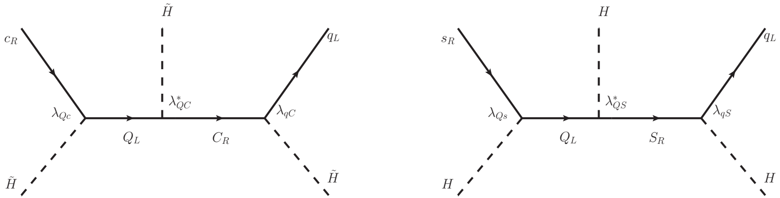
$\mathcal{L}_{\rm NP}$: Underlying New Physics

Considering only one gen. of VL quarks,

$SU(2)$ Doublet	$SU(2)$ Singlets
$Q = (C, S)(3, 2, 1/6)$	$C(3, 1, 2/3)$ & $S(3, 1, -1/3)$

$$\begin{aligned} -\mathcal{L}_{\rm NP} = \quad & \left(\lambda_{QC}\, \bar{Q}_L \tilde{H} C_R + \lambda_{QS}\, \bar{Q}_L H S_R\right) \\ & + \left(\lambda_{qC}\, \bar{q}_L \tilde{H} C_R + \lambda_{qS}\, \bar{q}_L H S_R\right) \\ & + \left(\lambda_{Qc}\, \bar{Q}_L \tilde{H} c_R + \lambda_{Qs}\, \bar{Q}_L H s_R\right) + H.c. \end{aligned} \tag{5}$$

$\mathcal{L}_{\rm NP}$: Underlying New Physics



• The dim-6 operators in Eq. (2) can be obtained after integrating out the heavy VL quarks.

$$Y_H^c = \lambda_{qC}\lambda^*_{QC}\lambda_{Qc} \quad , \quad \Lambda = \sqrt{M_C M_Q} \, , \tag{6}$$

$$Y_H^s = \lambda_{qS}\lambda^*_{QS}\lambda_{Qs} \quad , \quad \Lambda = \sqrt{M_S M_Q} \, . \tag{7}$$

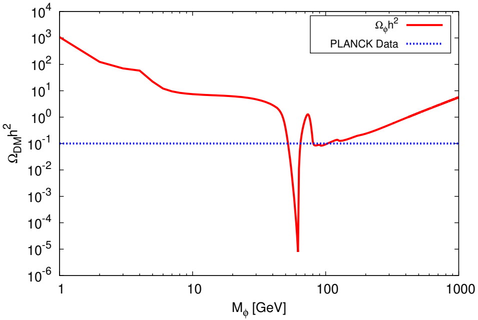
• Thus, with $M_{Q,C,S} \sim 2$ TeV and all the $\lambda_{NP} \sim \mathcal{O}(1)$, the $y_{q=c,s}$ can be considered for modification [Eq. (4)].

$\mathcal{L}_{\rm DM}$: DM Phenomenology

- For a real singlet scalar ϕ as the **DM** particle,

$$V = \frac{1}{2}\mu_\phi^2\phi^2 + \lambda_{H\phi}(H^\dagger H)$$

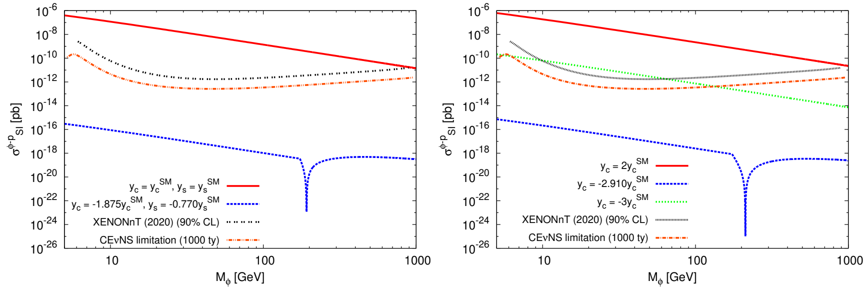
- After **EWSB**, the ϕ-mass term, $M_\phi = \sqrt{\mu_\phi^2 + 2\lambda_{H\phi}v^2}$.



- This variation is generated using *micrOMEGAs*.

- The dependence of $\Omega_\phi h^2$ on the variations of y_c and y_s is negligible.

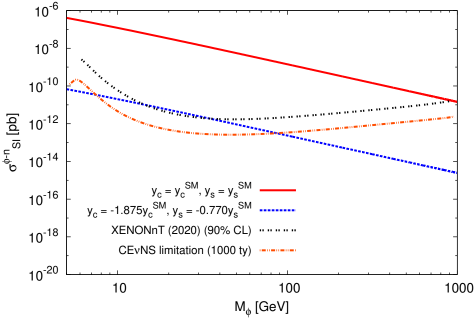
σ_{SI} and the Large Cancellation



- These exact cancellation values (i.e. $y_s = -0.77 y_s^{\rm SM}$ & $y_c = -1.875 y_c^{\rm SM}$ in 1st fig. and $y_c = -2.91 y_c^{\rm SM}$ in the 2nd) have been obtained for a typical set of $f_q^{(N)}$: [arXiv:1305.0237]

$$f_u^p = 0.0153, \quad f_d^p = 0.0191, \quad f_s^p = 0.0447,$$
$$f_u^n = 0.0110, \quad f_d^n = 0.0273, \quad f_s^n = 0.0447$$

Isospin Violation



- The fig. shows that $\sigma_{SI}^{\phi-n}$ lies below the proposed **DD** bounds for $M_\phi \geq 50$ GeV.

- For the same set of y_c and y_s where $\lambda_p \to 0$, $\lambda_n \neq 0 \Rightarrow$ **Isospin Violation**

- In this framework $\lambda_n/\lambda_p \equiv f_n/f_p > 0$ can be easily achieved, but $f_n/f_p < 0$ appears only within a narrow domain of $y_q/y_q^{\rm SM}$.

Summary

- We considered a **H-portal** DM model and assumed *non-SM-like* negative values for $y_q \Rightarrow \sigma_{SI} \to 0$.

- $y_q < 0$ can be realized in presence of a dim-6 effective operator $\Rightarrow$ an **upper** bound on the NP scale Λ.

- A model with **new particles** (VL quarks & ϕ) has been discussed as a practical realization of this idea.

- The proposed framework is able to accommodate isospin violation.

- Even though the future DM-search experiments are blind to our proposal, it might be tested at the **HL-LHC**.


Thank you