Dark Matter with Hidden U(1) Gauge Interaction and Kinetic Mixing

Zhao-Huan Yu（余钊焕）

School of Physics, Sun Yat-Sen University

Based on Juebin Lao, Chengfeng Cai, Zhao-Huan Yu, Yu-Pan Zeng, and Hong-Hao Zhang, 2003.02516, PRD

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Portals for Dark Matter Interactions

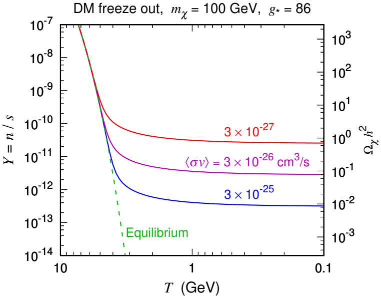
Thermal production mechanism

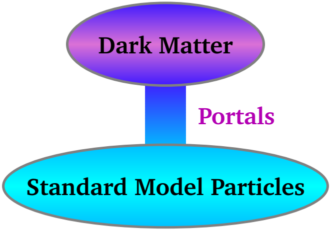
Dark matter (DM) is conventionally assumed to be thermally produced in the early Universe

Some mediators (**"portals"**) are typically required to induce adequate DM interactions with standard model (SM) particles

Inspired by the $\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ gauge interactions in the SM, it is natural to imagine dark matter participating **a new kind of gauge interaction**

The simplest attempt is to introduce an additional $\mathrm{U}(1)_\mathrm{X}$ **gauge symmetry**, whose **gauge boson** mediates the interactions between DM and SM particles





Hidden $\mathrm{U}(1)_\mathrm{X}$ Gauge Interaction

- Assume all SM fields **do not** carry any $\mathrm{U}(1)_\mathrm{X}$ charges
  - Minimize the impact on the interactions of SM particles

[Feldman, Liu, Nath, hep-ph/0702123, PRD; Pospelov, Ritz, Voloshin, 0711.4866, PLB; Mambrini, 1006.3318, JCAP; Chun, Park, Scopel, 1011.3300, JHEP; Liu, Wang, Yu, 1704.00730, JHEP; ...]

- Such a $\mathrm{U}(1)_\mathrm{X}$ gauge interaction belongs to a **hidden sector**
- Assume **dark matter** carries $\mathrm{U}(1)_\mathrm{X}$ **charge**
- **Mass of the** $\mathrm{U}(1)_\mathrm{X}$ **gauge boson** can be generated by
  - either the **Brout-Englert-Higgs mechanism** → an extra Higgs boson

    [Higgs, Phys. Lett. **12** (1964) 132; Englert & Brout, PRL **13**, 508 (1964)]
  - or the **Stueckelberg mechanism** → no extra Higgs boson

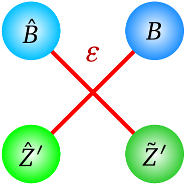
    [Stueckelberg, Helv. Phys. Acta **11** (1938) 225; Chodos & Cooper, PRD **3**, 2461 (1971)]
- **Gauge invariance** allows a renormalizable **kinetic mixing** term between the $\mathrm{U}(1)_\mathrm{X}$ and $\mathrm{U}(1)_\mathrm{Y}$ field strengths [Holdom, PLB **259**, 329 (1991)]
  - A **portal** connecting DM and SM particles

Kinetic Mixing

- For the $\mathrm{U}(1)_\mathrm{Y}$ and $\mathrm{U}(1)_\mathrm{X}$ gauge fields $\hat{B}_\mu$ and $\hat{Z}'_\mu$, the gauge invariant kinetic terms in the Lagrangian reads

$$\mathcal{L}_\mathrm{K} = -\frac{1}{4}\hat{B}^{\mu\nu}\hat{B}_{\mu\nu} - \frac{1}{4}\hat{Z}'^{\mu\nu}\hat{Z}'_{\mu\nu} - \frac{s_\varepsilon}{2}\hat{B}^{\mu\nu}\hat{Z}'_{\mu\nu} = -\frac{1}{4}\left(\hat{B}^{\mu\nu}, \quad \hat{Z}'^{\mu\nu}\right)\begin{pmatrix} 1 & s_\varepsilon \\ s_\varepsilon & 1 \end{pmatrix}\begin{pmatrix} \hat{B}_{\mu\nu} \\ \hat{Z}'_{\mu\nu} \end{pmatrix}$$

- Field strengths $\hat{B}_{\mu\nu} \equiv \partial_\mu \hat{B}_\nu - \partial_\nu \hat{B}_\mu$ and $\hat{Z}'_{\mu\nu} \equiv \partial_\mu \hat{Z}'_\nu - \partial_\nu \hat{Z}'_\mu$
- The **kinetic mixing** term is parametrized by $s_\varepsilon \in (-1, 1)$, beyond which the canonical kinetic terms have **wrong signs**
- Introduce $\varepsilon \in (-\pi/2, \pi/2)$ to express $s_\varepsilon = \sin\epsilon$
- $\mathcal{L}_\mathrm{K}$ can be made canonical via a $\mathrm{GL}(2, \mathbb{R})$ transformation



$$\begin{pmatrix} \hat{B}_\mu \\ \hat{Z}'_\mu \end{pmatrix} = V_\mathrm{K}\begin{pmatrix} B_\mu \\ \tilde{Z}'_\mu \end{pmatrix}, \quad V_\mathrm{K} \equiv \begin{pmatrix} 1 & -t_\varepsilon \\ 0 & 1/c_\varepsilon \end{pmatrix}, \quad \begin{aligned} t_\varepsilon &\equiv \tan\varepsilon \\ c_\varepsilon &\equiv \cos\varepsilon \end{aligned}$$

$$V_\mathrm{K}^\mathrm{T}\begin{pmatrix} 1 & s_\varepsilon \\ s_\varepsilon & 1 \end{pmatrix}V_\mathrm{K} = \begin{pmatrix} 1 & \\ & 1 \end{pmatrix} \quad \Rightarrow \quad \mathcal{L}_\mathrm{K} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}\tilde{Z}'^{\mu\nu}\tilde{Z}'_{\mu\nu}$$

Spontaneous Breaking of the $\mathrm{U(1)_X}$ Gauge Symmetry

✨ We assume that the $\mathrm{U(1)_X}$ gauge symmetry is **spontaneously broken** by a **hidden Higgs field** $\hat{S}$ with $\mathrm{U(1)_X}$ **charge** $q_S = 1$

🎐 $\mathrm{SU(2)_L} \times \mathrm{U(1)_Y} \times \mathrm{U(1)_X}$ gauge invariant Lagrangian

$$\mathcal{L}_\mathrm{H} = (D^\mu \hat{H})^\dagger (D_\mu \hat{H}) + (D^\mu \hat{S})^\dagger (D_\mu \hat{S}) + \mu^2 |\hat{H}|^2 + \mu_S^2 |\hat{S}|^2 - \frac{1}{2}\lambda_H |\hat{H}|^4 - \frac{1}{2}\lambda_S |\hat{S}|^4 - \lambda_{HS} |\hat{H}|^2 |\hat{S}|^2$$

🌕 $\hat{H}$ is the **SM Higgs doublet** with $D_\mu \hat{H} = (\partial_\mu - i\hat{g} W_\mu^a \sigma^a/2 - i\hat{g}' \hat{B}_\mu/2)\hat{H}$

🌔 $\hat{S}$ satisfies $D_\mu \hat{S} = (\partial_\mu - i g_X \hat{Z}'_\mu)\hat{S}$, where g_X is the $\mathrm{U(1)_X}$ **gauge coupling**

🌒 If $\mu^2 > 0$, $\mu_S^2 > 0$, $\lambda_H > 0$, $\lambda_S > 0$, and $|\lambda_{HS}| < \sqrt{\lambda_H \lambda_S}$

- 👉 $\hat{H}$ and $\hat{S}$ acquire **nonzero** vacuum expectation values (VEVs) v and v_S
- 👉 **Spontaneous breaking** of the $\mathrm{SU(2)_L} \times \mathrm{U(1)_Y} \times \mathrm{U(1)_X}$ gauge symmetry

Higgs Boson Mixing and Masses

- In the unitary gauge, the Higgs field can be expressed as

$$\hat{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H \end{pmatrix}, \quad \hat{S} = \frac{1}{\sqrt{2}}(v_S + S)$$

- Mass-squared matrix for **Higgs bosons** (H, S): $\mathcal{M}_0^2 = \begin{pmatrix} \lambda_H v^2 & \lambda_{HS} v v_S \\ \lambda_{HS} v v_S & \lambda_S v_S^2 \end{pmatrix}$

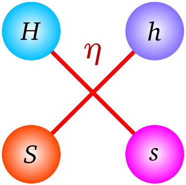
- Diagonalization by a rotation with an angle $\eta \in [-\pi/4, \pi/4]$

$$\begin{pmatrix} H \\ S \end{pmatrix} = \begin{pmatrix} c_\eta & -s_\eta \\ s_\eta & c_\eta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}, \quad \tan 2\eta = \frac{2\lambda_{HS} v v_S}{\lambda_H v^2 - \lambda_S v_S^2}$$

- Masses squared for the **mass eigenstates** (h, s)

$$m_h^2 = \frac{1}{2}\left[\lambda_H v^2 + \lambda_S v_S^2 + (\lambda_H v^2 - \lambda_S v_S^2)/c_{2\eta}\right]$$

$$m_s^2 = \frac{1}{2}\left[\lambda_H v^2 + \lambda_S v_S^2 + (\lambda_S v_S^2 - \lambda_H v^2)/c_{2\eta}\right]$$



- h should be the **125 GeV SM-like Higgs boson**

Gauge Boson Masses

- Mass-squared matrix for $(\hat{B}_\mu, W^3_\mu, \hat{Z}'_\mu)$ generated by the Higgs VEVs v and v_s

$$M_1^2 = \begin{pmatrix} \hat{g}'^2 v^2/4 & -\hat{g}\hat{g}' v^2/4 & \\ -\hat{g}\hat{g}' v^2/4 & \hat{g}^2 v^2/4 & \\ & & g_X^2 v_S^2 \end{pmatrix}, \quad W^\pm \textbf{ boson mass } m_W = \frac{1}{2}\hat{g} v$$

- Taking into account the **kinetic mixing** s_ε and the diagonalization of the mass-squared matrix, the **photon** γ remain **massless**, while the masses of the Z **boson** and a new **massive neutral vector boson** Z' are given by

$$m_Z^2 = \hat{m}_Z^2(1 + \hat{s}_W t_\varepsilon t_\xi), \quad m_{Z'}^2 = \frac{\hat{m}_{Z'}^2}{c_\varepsilon^2(1 + \hat{s}_W t_\varepsilon t_\xi)}$$

- Direct contributions from the VEVs: $\hat{m}_Z^2 \equiv (\hat{g}^2 + \hat{g}'^2)v^2/4, \quad \hat{m}_{Z'}^2 \equiv g_X^2 v_S^2$

- **Weak mixing angle** $\hat{\theta}_W$ satisfies $\hat{s}_W \equiv \sin\hat{\theta}_W = \dfrac{\hat{g}'}{\sqrt{\hat{g}^2 + \hat{g}'^2}}, \quad \hat{c}_W \equiv \cos\hat{\theta}_W$

- **Rotation angle** ξ is given by $\tan 2\xi = \dfrac{s_{2\varepsilon}\hat{s}_W v^2(\hat{g}^2 + \hat{g}'^2)}{c_\varepsilon^2 v^2(\hat{g}^2 + \hat{g}'^2)(1 - \hat{s}_W^2 t_\varepsilon^2) - 4 g_X^2 v_S^2}$

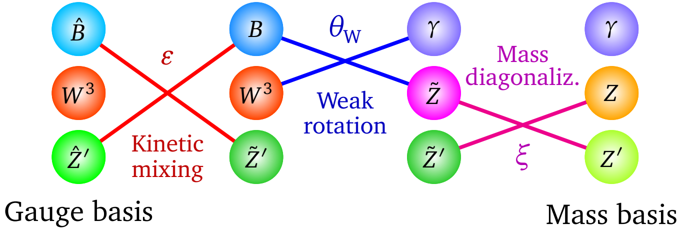
Neutral Gauge Boson Mixing

- Transform the **gauge basis** $(\hat{B}_\mu, W^3_\mu, \hat{Z}'_\mu)$ to the **mass basis** (A_μ, Z_μ, Z'_μ)

$$\begin{pmatrix} \hat{B}_\mu \\ W^3_\mu \\ \hat{Z}'_\mu \end{pmatrix} = V(\varepsilon) R_3(\hat{\theta}_W) R_1(\xi) \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

$$V(\varepsilon) = \begin{pmatrix} 1 & & -t_\varepsilon \\ & 1 & \\ 0 & & 1/c_\varepsilon \end{pmatrix}, \quad R_3(\hat{\theta}_W) = \begin{pmatrix} \hat{c}_W & -\hat{s}_W & \\ \hat{s}_W & \hat{c}_W & \\ & & 1 \end{pmatrix}, \quad R_1(\xi) = \begin{pmatrix} 1 & & \\ & c_\xi & -s_\xi \\ & s_\xi & c_\xi \end{pmatrix}$$

[Babu, Kolda, March-Russell, hep-ph/9710441, PRD]



Electroweak (EW) Current Interactions

At tree level, the **charge current interactions** of SM fermions are not affected by the kinetic mixing, remaining a form of

$$\mathcal{L}_{\mathrm{CC}} = \frac{1}{\sqrt{2}}(W_\mu^+ J_W^{+,\mu} + \mathrm{H.c.}), \quad J_W^{+,\mu} = \hat{g}(\bar{u}_{i\mathrm{L}}\gamma^\mu V_{ij} d_{j\mathrm{L}} + \bar{\nu}_{i\mathrm{L}}\gamma^\mu \ell_{i\mathrm{L}})$$

v is still directly related to the Fermi constant $G_{\mathrm{F}} = \dfrac{\hat{g}^2}{4\sqrt{2}m_W^2} = \dfrac{1}{\sqrt{2}v^2}$

Neutral current interactions become $\mathcal{L}_{\mathrm{NC}} = j_{\mathrm{EM}}^\mu A_\mu + j_Z^\mu Z_\mu + j_{Z'}^\mu Z'_\mu$

Electromagnetic current $j_{\mathrm{EM}}^\mu = \sum_f Q_f e \bar{f}\gamma^\mu f$ with $e = \hat{g}\hat{g}'/\sqrt{\hat{g}^2 + \hat{g}'^2}$

Z **current** $j_Z^\mu = \dfrac{e c_\xi (1 + \hat{s}_{\mathrm{W}} t_\varepsilon t_\xi)}{2\hat{s}_{\mathrm{W}}\hat{c}_{\mathrm{W}}} \sum_f \bar{f}\gamma^\mu (T_f^3 - 2Q_f s_*^2 - T_f^3\gamma_5) f + \dfrac{s_\xi}{c_\varepsilon} j_{\mathrm{DM}}^\mu$

Z' **current** $j_{Z'}^\mu = \dfrac{e(\hat{s}_{\mathrm{W}} t_\varepsilon c_\xi - s_\xi)}{2\hat{s}_{\mathrm{W}}\hat{c}_{\mathrm{W}}} \sum_f \bar{f}\gamma^\mu (T_f^3 - 2Q_f \hat{s}_{\mathrm{W}}^2 - T_f^3\gamma_5) f - \hat{c}_{\mathrm{W}} t_\varepsilon c_\xi j_{\mathrm{EM}}^\mu + \dfrac{c_\xi}{c_\varepsilon} j_{\mathrm{DM}}^\mu$

Dark matter $\mathrm{U}(1)_{\mathrm{X}}$ current $j_{\mathrm{DM}}^\mu \propto g_X$, $\quad s_*^2 \equiv \hat{s}_{\mathrm{W}}^2 + \hat{c}_{\mathrm{W}}^2 \dfrac{\hat{s}_{\mathrm{W}} t_\varepsilon t_\xi}{1 + \hat{s}_{\mathrm{W}} t_\varepsilon t_\xi}$

Independent Parameters

- In the **SM**, the weak mixing angle obeys $s_{\rm W}^2 c_{\rm W}^2 = \dfrac{\pi\alpha}{\sqrt{2}G_{\rm F} m_Z^2}$ at tree level
- Use this relation to define a **"physical" weak mixing angle** $\theta_{\rm W}$ via the best measured parameters α, $G_{\rm F}$, and m_Z [Burgess *et al.*, hep-ph/9312291, PRD]
- Similar relation in the **hidden** $\mathrm{U(1)_X}$ **gauge theory**: $\hat{s}_{\rm W}^2 \hat{c}_{\rm W}^2 = \dfrac{\pi\alpha}{\sqrt{2}G_{\rm F}\hat{m}_Z^2}$

$$\hat{s}_{\rm W}\hat{c}_{\rm W}\hat{m}_Z = s_{\rm W} c_{\rm W} m_Z \qquad s_{\rm W}^2 c_{\rm W}^2 = \frac{\hat{s}_{\rm W}^2 \hat{c}_{\rm W}^2}{1+\hat{s}_{\rm W} t_\varepsilon t_\xi}$$

- The angle ξ satisfies $t_\xi = \dfrac{2\hat{s}_{\rm W} t_\varepsilon}{1-r}\left[1+\sqrt{1-r\left(\dfrac{2\hat{s}_{\rm W} t_\varepsilon}{1-r}\right)^2}\,\right]^{-1}$ with $r \equiv \dfrac{m_{Z'}^2}{m_Z^2}$
- Utilizing these relations, we obtain $\hat{s}_{\rm W}$ and t_ξ as functions of s_ε and $m_{Z'}$
- **Independent parameters** can be chosen as $\{g_X,\ m_{Z'},\ m_s,\ s_\varepsilon,\ s_\eta\}$
- EW gauge couplings $\hat{g} = \dfrac{e}{\hat{s}_{\rm W}}$ and $\hat{g}' = \dfrac{e}{\hat{c}_{\rm W}}$ with $e = \sqrt{4\pi\alpha}$

Electroweak Oblique Parameters

Kinetic mixing s_ε modifies **EW oblique parameters S** and T at **tree level**

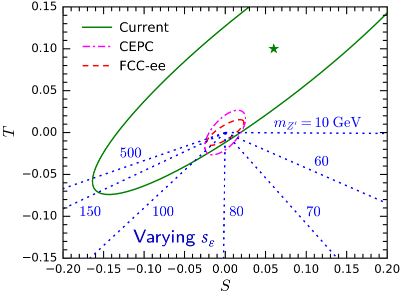
In the effective Lagrangian formulation, Zff neutral current interactions can be expressed as [Burgess *et al.*, hep-ph/9312291, PRD]

$$\mathcal{L}_{Zff} = \frac{e}{2s_\mathrm{W}c_\mathrm{W}}\left(1+\frac{\alpha T}{2}\right)Z_\mu \sum_f \bar{f}\gamma^\mu(T_f^3 - 2Q_f s_*^2 - T_f^3\gamma_5)f$$

$$s_*^2 = s_\mathrm{W}^2 + \frac{1}{c_\mathrm{W}^2 - s_\mathrm{W}^2}\left(\frac{\alpha S}{4} - s_\mathrm{W}^2 c_\mathrm{W}^2 \alpha T\right)$$

Applying it to the Hidden $\mathrm{U(1)_X}$ gauge theory, we find $\alpha T = 2c_\xi\sqrt{1+\hat{s}_\mathrm{W}t_\varepsilon t_\xi} - 2$

$$\alpha S = 4(c_\mathrm{W}^2 - s_\mathrm{W}^2)\left(\hat{s}_\mathrm{W}^2 - s_\mathrm{W}^2 + \frac{\hat{c}_\mathrm{W}^2\hat{s}_\mathrm{W}t_\varepsilon t_\xi}{1+\hat{s}_\mathrm{W}t_\varepsilon t_\xi}\right) + 4s_\mathrm{W}^2c_\mathrm{W}^2\alpha T$$



For $\varepsilon \ll 1$, we have $S \simeq \frac{4s_\mathrm{W}^2c_\mathrm{W}^2\varepsilon^2}{\alpha(1-r)}\left(1-\frac{s_\mathrm{W}^2}{1-r}\right)$, $T \simeq -\frac{rs_\mathrm{W}^2\varepsilon^2}{\alpha(1-r)^2}$

Upper Limits from EW Oblique Parameters

Current measurement: $S = 0.06 \pm 0.09, \quad T = 0.10 \pm 0.07, \quad \rho_{ST} = 0.91$

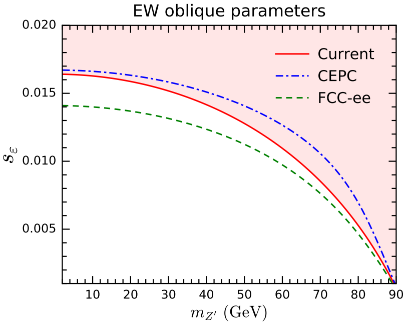
[Gfitter Group, 1407.3792, EPJC]

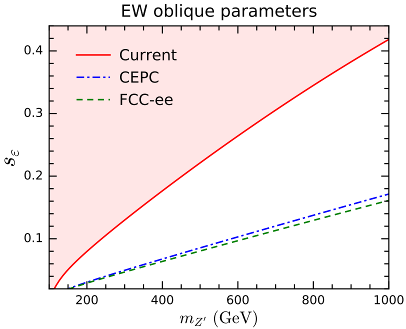
Projected CEPC precision: $\sigma_S = 0.010, \quad \sigma_T = 0.011, \quad \rho_{ST} = 0.62$

[CEPC Study Group, 1811.10545]

Projected FCC-ee precision: $\sigma_S = 0.0092, \quad \sigma_T = 0.0062, \quad \rho_{ST} = 0.79$

[Fan, Reece, Wang, 1411.1054, JHEP]





Dirac Fermionic Dark Matter

💡 Assume the DM particle is a **Dirac fermion** χ with $\mathrm{U}(1)_\mathrm{X}$ **charge** q_χ

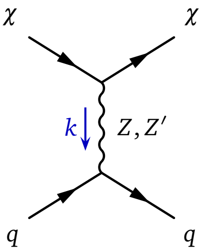
✏️ Related Lagrangian $\mathcal{L}_\chi = i\bar{\chi}\gamma^\mu D_\mu \chi - m_\chi \bar{\chi}\chi, \quad D_\mu\chi = (\partial_\mu - iq_\chi g_X \hat{Z}'_\mu)\chi$

👉 **DM neutral current** $j^\mu_{\mathrm{DM}} = q_\chi g_X \bar{\chi}\gamma^\mu\chi$

🎉 Based on the **kinetic mixing portal**, χ particles can communicate with SM fermions through the mediation of Z and Z' bosons

🌗 In the **zero momentum transfer limit** $k^2 \to 0$, interactions between χ and quarks $q = d, u, s, c, b, t$ can be described by an **effective Lagrangian**

$$\mathcal{L}_{\chi q} = \sum_q G^{\mathrm{V}}_{\chi q}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q, \quad G^{\mathrm{V}}_{\chi q} = -\frac{q_\chi g_X}{c_\varepsilon}\left(\frac{s_\xi g^q_Z}{m^2_Z} + \frac{c_\xi g^q_{Z'}}{m^2_{Z'}}\right)$$



🌓 **Vector current couplings** of quarks to Z and Z'

$$g^q_Z = \frac{ec_\xi(1+\hat{s}_\mathrm{W} t_\varepsilon t_\xi)}{2\hat{s}_\mathrm{W}\hat{c}_\mathrm{W}}(T^3_q - 2Q_q s^2_*)$$

$$g^q_{Z'} = \frac{e(\hat{s}_\mathrm{W} t_\varepsilon c_\xi - s_\xi)}{2\hat{s}_\mathrm{W}\hat{c}_\mathrm{W}}(T^3_q - 2Q_q \hat{s}^2_\mathrm{W}) - Q_q e\hat{c}_\mathrm{W} t_\varepsilon c_\xi$$

DM-nucleon Interactions

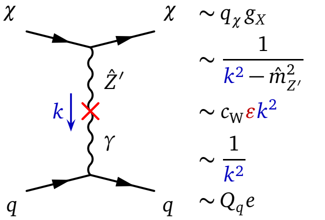
- **DM-nucleon effective interactions** are induced by DM-quark interactions

$$\mathcal{L}_{\chi N} = \sum_{N=p,n} G^{\mathrm{V}}_{\chi N} \bar{\chi}\gamma^{\mu}\chi \bar{N}\gamma_{\mu}N, \quad G^{\mathrm{V}}_{\chi p} = 2G^{\mathrm{V}}_{\chi u} + G^{\mathrm{V}}_{\chi d}, \quad G^{\mathrm{V}}_{\chi n} = G^{\mathrm{V}}_{\chi u} + 2G^{\mathrm{V}}_{\chi d}$$

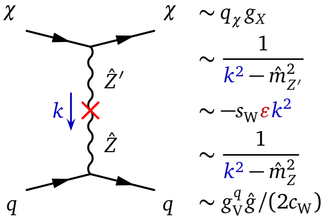
- Further calculation gives

$$G^{\mathrm{V}}_{\chi p} = \frac{q_\chi g_X e \hat{c}_{\mathrm{W}} t_\varepsilon c_\xi^2 (1 + t_\xi^2 r)}{c_\varepsilon m_{Z'}^2}, \quad G^{\mathrm{V}}_{\chi n} = 0$$

- For $\varepsilon \ll 1$, $G^{\mathrm{V}}_{\chi p} \simeq \dfrac{q_\chi g_X e c_{\mathrm{W}} \varepsilon}{m_{Z'}^2}$



- In the $k^2 \to 0$ **limit**, the **kinetic mixing factor** εk^2 can only picks up the $1/k^2$ **pole** in the massless **photon propagator**, while the lower diagram vanishes because $\hat{Z}$ is **massive**



- ☞ χq scattering is essentially induced by j^{μ}_{EM}
- n carries no net electric charge ☞ $G^{\mathrm{V}}_{\chi n} = 0$

Direct Detection

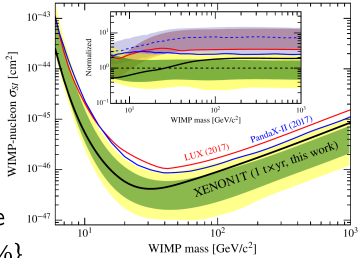
- $G^{\rm V}_{\chi n} = 0 \neq G^{\rm V}_{\chi p}$ ☞ **Isospin violation** in DM scattering off nucleons [Feng *et al.*, 1102.4331, PLB]
- Data analyses in direct detection experiments conventionally assume **isospin conservation** ☞ constraints on the **normalized-to-nucleon cross section** σ_N^Z
- Now the spin-independent (SI) normalized-to-nucleon cross section becomes

$$\sigma_N^Z = \sigma_{\chi p} \frac{\sum_i \eta_i \mu^2_{\chi A_i} [Z + (A_i - Z) G^{\rm V}_{\chi n}/G^{\rm V}_{\chi p}]^2}{\sum_i \eta_i \mu^2_{\chi A_i} A_i^2} = \sigma_{\chi p} \frac{\sum_i \eta_i \mu^2_{\chi A_i} Z^2}{\sum_i \eta_i \mu^2_{\chi A_i} A_i^2}$$

- Reduced mass $\mu_{\chi A_i} \equiv m_\chi m_{A_i}/(m_\chi + m_{A_i})$
- χp scattering cross section

$$\sigma_{\chi p} = \mu^2_{\chi p} (G^{\rm V}_{\chi p})^2/\pi$$

- For **xenon** ($Z = 54$) detection material, $A_i = \{128, 129, 130, 131, 132, 134, 136\}$
- Fractional number abundance of A_i in nature $\eta_i = \{1.9\%, 26\%, 4.1\%, 21\%, 27\%, 10\%, 8.9\%\}$



[XENON Coll., 1805.12562, PRL]

Phenomenological Constraints for $q_\chi = 1$

- Possible $\chi\bar{\chi}$ **annihilation channels**:

$$f\bar{f}, \quad W^+W^-, \quad h_i h_j, \quad Z_i Z_j, \quad h_i Z_j$$

with $h_i \in \{h, s\}$ and $Z_i \in \{Z, Z'\}$

- **Experimental constraints and sensitivity**

- **DM relic abundance** $\Omega_{\mathrm{DM}} h^2 = 0.120 \pm 0.001$

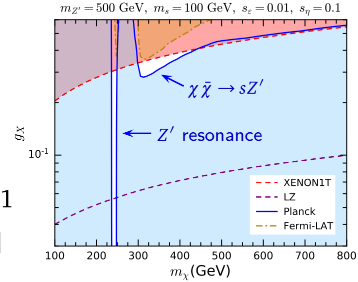
[Planck Coll., 1807.06209, Astron. Astrophys.]

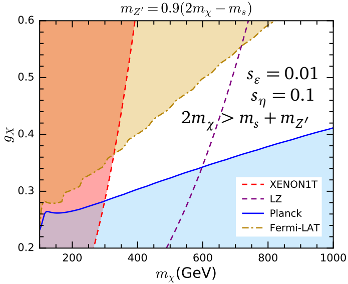
- 95% C.L. upper limits on DM annihilation cross section from **Fermi-LAT** γ**-ray** observations of dwarf galaxies [Fermi-LAT Coll., 1503.02641, PRL]

- 90% C.L. exclusion limits on σ_N^Z from the **XENON1T direct detection** experiment

[XENON Coll., 1805.12562, PRL]

- 90% C.L. sensitivity of the future **LZ direct detection** experiment [Mount *et al.*, 1703.09144]





Complex Scalar Dark Matter

- Assume the DM particle is a **scalar boson ϕ** with $\mathrm{U}(1)_\mathrm{X}$ **charge** $q_\phi = 1/4$

$$\mathcal{L}_\phi = (D^\mu\phi)^\dagger(D_\mu\phi) - \mu_\phi^2\phi^\dagger\phi + \lambda_{S\phi}\hat{S}^\dagger\hat{S}\phi^\dagger\phi + \lambda_{H\phi}\hat{H}^\dagger\hat{H}\phi^\dagger\phi + \lambda_\phi(\phi^\dagger\phi)^2$$

- $D_\mu\phi = (\partial_\mu - iq_\phi g_X \hat{Z}'_\mu)\phi$ ☞ **DM neutral current** $j^\mu_{\mathrm{DM}} = q_\phi g_X \phi^\dagger i\overleftrightarrow{\partial^\mu}\phi$
- **Global** $\mathrm{U}(1)$ **symmetry** $\phi \to e^{iq_\phi\theta}\phi$ should be **preserved** to protect j^μ_{DM}
- Assume the ϕ **does not** develop a VEV ☞ **stable** ϕ and $\bar{\phi}$ particles
- The charge choice $q_\phi = q_S/4$ **forbids** unwanted scalar interaction terms like $\hat{S}^\dagger\hat{S}^\dagger\hat{S}^\dagger\phi$, $\hat{S}^\dagger\hat{S}^\dagger\phi$, $\hat{S}^\dagger\hat{S}^\dagger\phi\phi$, $\hat{S}^\dagger\phi\phi$, and $\hat{S}^\dagger\phi\phi\phi$, which would violate the global $\mathrm{U}(1)$ symmetry $\phi \to e^{iq_\phi\theta}\phi$ after the $\mathrm{U}(1)_\mathrm{X}$ spontaneous symmetry breaking
- The ϕ mass is given by $m_\phi^2 = \mu_\phi^2 - \dfrac{1}{2}\lambda_{S\phi}v_S^2 - \dfrac{1}{2}\lambda_{H\phi}v^2$
- **Kinetic mixing portal**: mediation of the Z and Z' vector bosons
- **Higgs portal**: mediation of the h and s scalar bosons

$$\mathcal{L}_{\phi hs} = (\lambda_{S\phi}s_\eta v_S + \lambda_{H\phi}c_\eta v)h\phi^\dagger\phi + (\lambda_{S\phi}c_\eta v_S - \lambda_{H\phi}s_\eta v)s\phi^\dagger\phi$$

Effective DM Interactions

- **DM-quark** effective interactions

$$\mathcal{L}_{\phi q} = \sum_q \left[G^{\rm V}_{\phi q} (\phi^\dagger i \overleftrightarrow{\partial^\mu} \phi) \bar{q}\gamma_\mu q + G^{\rm S}_{\phi q} \phi^\dagger \phi \bar{q} q \right], \quad G^{\rm V}_{\phi q} = -\frac{q_\phi g_X}{c_\varepsilon} \left(\frac{s_\xi g^q_Z}{m_Z^2} + \frac{c_\xi g^q_{Z'}}{m_{Z'}^2} \right)$$

$$G^{\rm S}_{\phi q} = \frac{m_q}{v} \left[\frac{s_\eta}{m_s^2} (\lambda_{S\phi} c_\eta v_S - \lambda_{H\phi} s_\eta v) - \frac{c_\eta}{m_h^2} (\lambda_{S\phi} s_\eta v_S + \lambda_{H\phi} c_\eta v) \right]$$

- **DM-nucleon** effective interactions

$$\mathcal{L}_{\phi N} = \sum_{N=p,n} \left[G^{\rm V}_{\phi N} (\phi^\dagger i \overleftrightarrow{\partial^\mu} \phi) \bar{N}\gamma_\mu N + G^{\rm S}_{\phi N} \phi^\dagger \phi \bar{N} N \right]$$

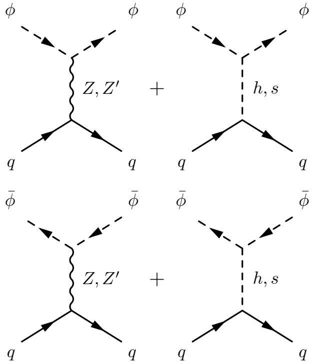
- Similar to the Dirac fermion case, we have

$$G^{\rm V}_{\phi p} = \frac{q_\phi g_X e \hat{c}_{\rm W} t_\varepsilon c_\xi^2 (1 + t_\xi^2 r)}{c_\varepsilon m_{Z'}^2}, \quad G^{\rm V}_{\phi n} = 0$$

- Scalar-type effective couplings

$$G^{\rm S}_{\phi N} = m_N \sum_q \frac{G^{\rm S}_{\phi q} f^N_q}{m_q}, \qquad f^N_q \text{ are quark form factors}$$

$$G^{\rm S}_{\phi p} \simeq G^{\rm S}_{\phi n}$$



Direct Detection

- ϕN and $\bar{\phi} N$ scattering cross sections

$$\sigma_{\phi N} = \frac{\mu_{\phi N}^2 f_{\phi N}^2}{\pi}, \quad f_{\phi N} = \frac{G_{\phi N}^{S}}{2m_\phi} + G_{\phi N}^{V}$$

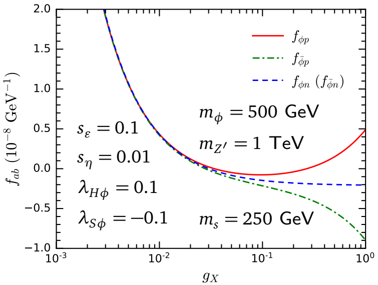
$$\sigma_{\bar{\phi} N} = \frac{\mu_{\phi N}^2 f_{\bar{\phi} N}^2}{\pi}, \quad f_{\bar{\phi} N} = \frac{G_{\phi N}^{S}}{2m_\phi} - G_{\phi N}^{V}$$

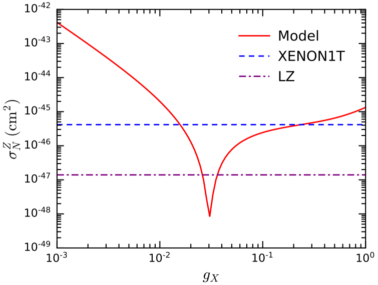
- The difference between $f_{\phi N}$ and $f_{\bar{\phi} N}$ comes from the **arrow directions** of the $\phi/\bar{\phi}$ lines in the Feynman diagrams

- $G_{\phi n}^{V} = 0$ 👉 $f_{\phi n} = f_{\bar{\phi} n} = G_{\phi n}^{S}/(2m_\phi)$

- Normalized-to-nucleon cross section

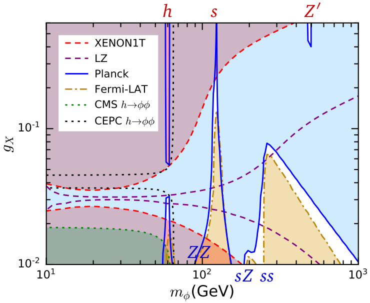
$$\sigma_N^Z = \frac{\sigma_{\phi p}}{2\sum_i \eta_i \mu_{\phi A_i}^2 A_i^2} \sum_i \eta_i \mu_{\phi A_i}^2 \times \{[Z + (A_i - Z) f_{\phi n}/f_{\phi p}]^2 + [Z f_{\bar{\phi} p}/f_{\phi p} + (A_i - Z) f_{\bar{\phi} n}/f_{\phi p}]^2\}$$



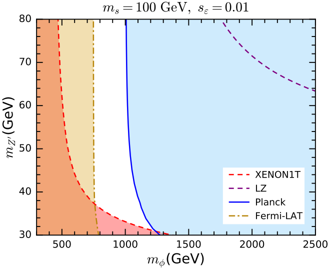


Phenomenological Constraints

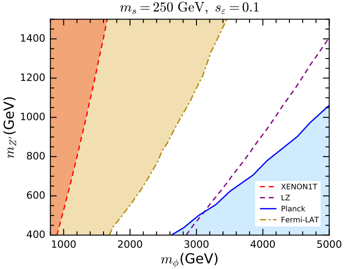
- Special $\phi\bar{\phi}$ annihilation regions:
  - h, s, and Z' **resonances**
  - ZZ, sZ, and ss **thresholds**
- **LHC** constraint on **invisible Higgs decays**: $\mathcal{B}_{\text{inv}} < 24\%$ @ 95% C.L. [CMS Coll., 1610.09218, JHEP]
- **CEPC sensitivity** for invisible Higgs decays: $\mathcal{B}_{\text{inv}} < 0.3\%$ @ 95% C.L. [CEPC Study Group, 1811.10545]



$s_\varepsilon = 0.1$
$s_\eta = 0.01$
$\lambda_{H\phi} = 0.01$
$\lambda_{S\phi} = -0.01$
$m_{Z'} = 1$ TeV
$m_s = 250$ GeV



$g_X = 0.01$
$s_\eta = 0.01$
$\lambda_{H\phi} = 0.1$
$\lambda_{S\phi} = 0.1$



Conclusions

- We explore **Dirac fermionic** and **complex scalar dark matter** in a **hidden $\mathrm{U}(1)_\mathrm{X}$ gauge theory** with kinetic mixing
- The $\mathrm{U}(1)_\mathrm{X}$ gauge symmetry is spontaneously broken due to a Higgs field
- The **kinetic mixing** provides a **portal** to dark matter
- An additional **Higgs portal** can be realized in the complex scalar DM case
- Dark matter interactions with nucleons are typically **isospin violating**, and **direct detection** constraints could be **relieved**
- We find that there are several available parameter regions predicting the **observed relic abundance** and have not been totally explored in current DM detection experiments

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Thanks for your attention!