Flavorful Dark Matter

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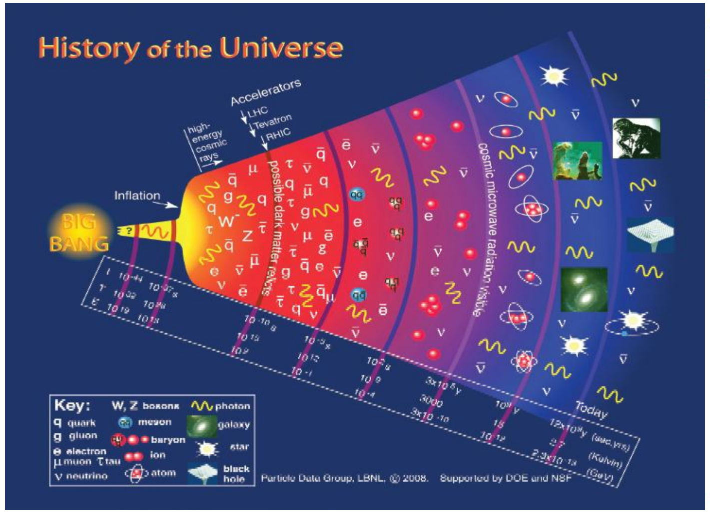
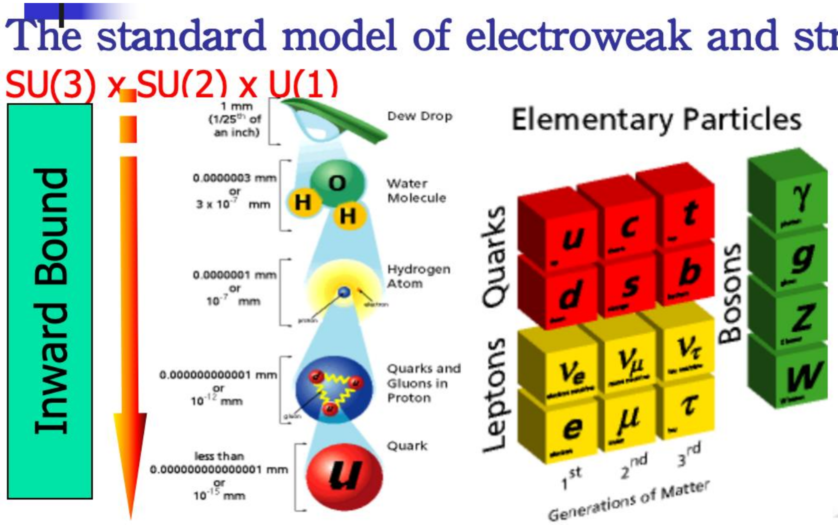
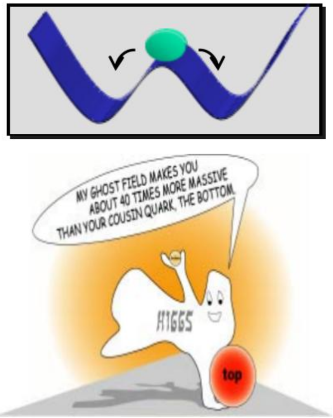
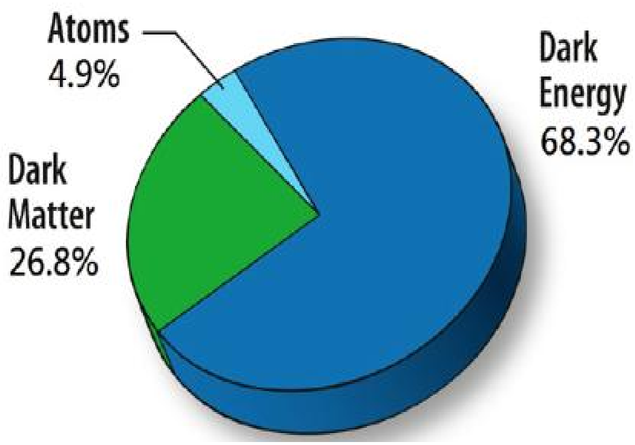
1. Flavorful Dark Matter









Gravitational effects from cosmology and astrophysics need the existence of Dark Matter! This is new physics beyond the standard model. WIMP is among the best candidates for DM. How it interacts with the SM sector, not known! Just gravity, may be other interactions or it may be specific particle-phlic or particle-phobic.

On the other hand, there are some puzzles or anomalies in particle physics, such as the recently reported excess of B^+ to K^+ $\nu\nu$ or K invisible. If confirmed, it must come from new physics beyond the SM.

Maybe these two problems are related?! Dark matter couplings to SM are flavor dependent may provid some hope.

Recent BELLE-II measurement

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\rm exp} = (2.3 \pm 0.7) \times 10^{-5}$$

The SM prediction

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\rm SM} = (4.43 \pm 0.31) \times 10^{-6}$$

There is an excess!

A flavorful dark matter solution

The B^+ -> K^+ invisible is due to B^+ -> K^+ Φ Φ (Φ dark matter)

At the quark level due to: b -> s Φ Φ

$$\mathcal{O}_{qdH\phi^2} = (\bar{q}_L d_R H)\,\phi^2$$

But also need to produce the right relic density for DM.

H Higgs double

After develops vev v/√2, the right operators.

At the quark level due to: Φ Φ -> s s!

How to achieve the above? Not jusk saying so, but numbers also work in a renormalizable model!

Introduce new particles:

Φ (1,1,0) as dark matter, $Q_{L,R}$: (3, 2, 1/6), $U_{L,R}$: (3,1,2/3, $D_{L,R}$: (3,1,-1/3) heavy particles.

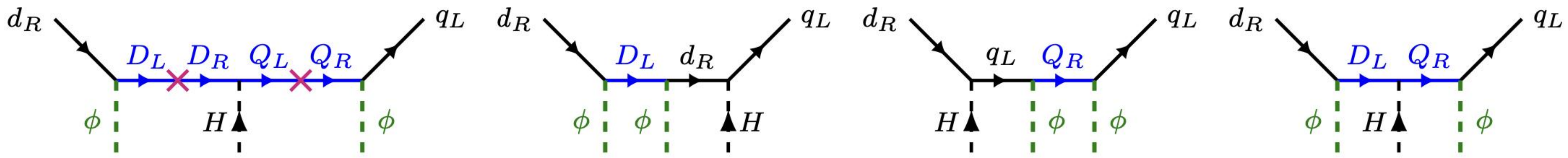
To stablize dark matter introduce Z_2 parity:

The above particles transform under Z_2 change signs. SM particles do not transform under Z_{2}.

$$\mathcal{L}^{\texttt{NP}}_{\texttt{kinetic}} = \bar{Q} i \not{D} Q - m_Q \bar{Q} Q + \bar{D} i \not{D} D - m_D \bar{D} D + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2,$$

$$\mathcal{L}^{\texttt{NP}}_{\texttt{Yukawa}} = y_q^p \bar{q}_{Lp} Q_R \phi + y_d^p \bar{D}_L d_{Rp} \phi - y_1 \bar{Q}_L D_R H - y_2 \bar{Q}_R D_L H + \text{h.c.}\ ,$$

$$V^{\texttt{NP}}_{\texttt{potential}} = \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{2}\kappa\, \phi^2 H^\dagger H\ ,$$



$$\mathcal{L}^{\texttt{SMEFT}}_{\phi\phi qq} = C^{pr}_{qdH\phi^2} \mathcal{O}^{pr}_{qdH\phi^2} + C^{pr}_{quH\phi^2} \mathcal{O}^{pr}_{quH\phi^2} + \text{h.c.}$$

$$C^{pr}_{qdH\phi^2} = \frac{y_q^p y_d^r y_1}{m_Q m_D} + \frac{y_q^p y_q^{x*} (Y_d)_{xr}}{2 m_Q^2} + \frac{(Y_d)_{px} y_d^{x*} y_d^r}{2 m_D^2}, \qquad C^{pr}_{quH\phi^2} = \frac{y_q^p y_q^{x*} (Y_u)_{xr}}{2 m_Q^2}$$

2. Flavor Anomaly in B to K νν

Combining previous bound,

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{2021}_{\text{exp}} = (1.1 \pm 0.4) \times 10^{-5}$$

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})^{\text{ave}}_{\text{exp}} = (1.3 \pm 0.4) \times 10^{-5}$$

Room for new physics:

$$\mathcal{B}(B^+ \to K^+ + \text{inv})_{\text{NP}} = (0.86 \pm 0.40) \times 10^{-5}$$

Also need to satisfy constraints

$$\mathcal{B}(B^0 \to K^0\nu\bar{\nu}) \leq 2.6 \times 10^{-5} \ (90\% \text{ c.l.})$$

$$\mathcal{B}(B^+ \to K^{+*}\nu\bar{\nu}) \leq 4.0 \times 10^{-5} \ (90\% \text{ c.l.})$$

$$\mathcal{B}(B^0 \to K^{0*}\nu\bar{\nu}) \leq 1.8 \times 10^{-5} \ (90\% \text{ c.l.})$$

$$\mathcal{L}^{\text{LEFT}}_{\phi\phi qq} = \frac{1}{2} C^{S,ij}_{d\phi} (\bar{d}_i d_j)\phi^2 + \frac{1}{2} C^{P,ij}_{d\phi} (\bar{d}_i i\gamma_5 d_j)\phi^2 + \frac{1}{2} C^{S,ij}_{u\phi} (\bar{u}_i u_j)\phi^2 + \frac{1}{2} C^{P,ij}_{u\phi} (\bar{u}_i i\gamma_5 u_j)\phi^2,$$

$$C^{S,ij}_{d\phi} = \frac{(y^i_q y^j_d y_1 + y^{j*}_q y^{i*}_d y^*_1)v}{\sqrt{2} m_Q m_D} + \left(\frac{y^i_q y^{j*}_q}{2m_Q^2} + \frac{y^{i*}_d y^j_d}{2m_D^2}\right)(m_{d_i} + m_{d_j}), \qquad C^{S,ij}_{u\phi} = \frac{\tilde{y}^i_q \tilde{y}^{j*}_q}{2m_Q^2}(m_{u_i} + m_{u_j}),$$

$$iC^{P,ij}_{d\phi} = \frac{(y^i_q y^j_d y_1 - y^{j*}_q y^{i*}_d y^*_1)v}{\sqrt{2} m_Q m_D} - \left(\frac{y^i_q y^{j*}_q}{2m_Q^2} - \frac{y^{i*}_d y^j_d}{2m_D^2}\right)(m_{d_i} - m_{d_j}), \qquad iC^{P,ij}_{u\phi} = -\frac{\tilde{y}^i_q \tilde{y}^{j*}_q}{2m_Q^2}(m_{u_i} - m_{u_j}),$$

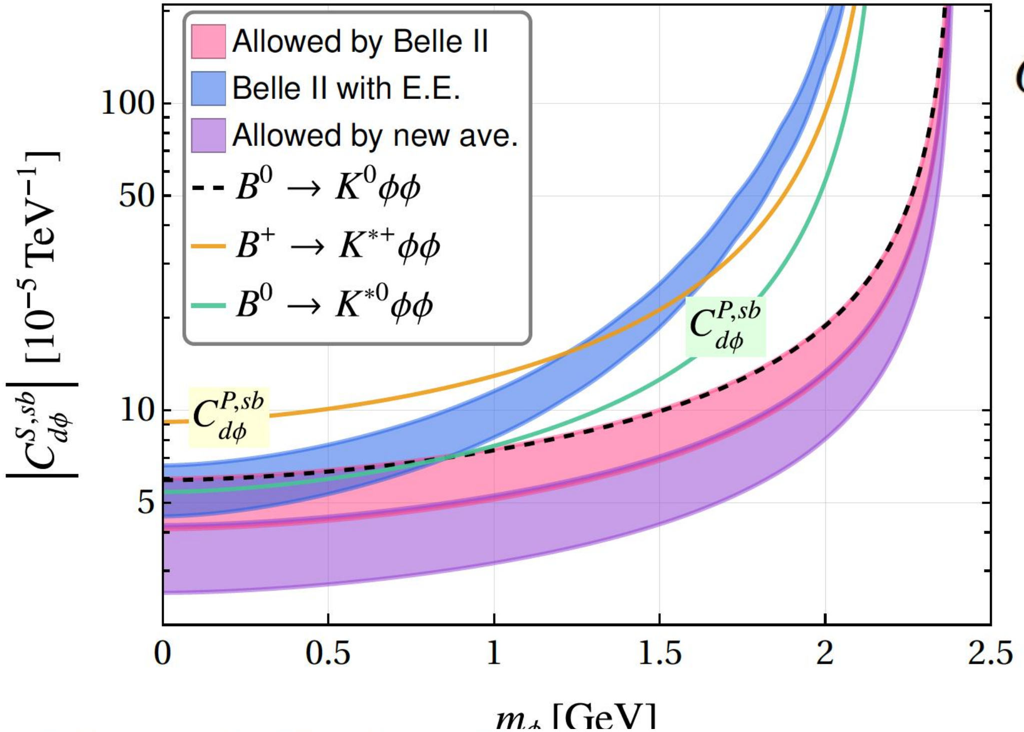
$$\frac{d\Gamma_{B\to K\phi\phi}}{ds_B} = \frac{\left|C_{d\phi}^{S,sb}\right|^2 m_B}{512\pi^3} f_0^2 \frac{(1-x_K)^2 \lambda^{\frac{1}{2}}(1, x_K, s_B)\sqrt{1-4x_\phi/x_B}}{(\sqrt{x_b}-\sqrt{x_s})^2},$$

$$\frac{d\Gamma_{B\to K^*\phi\phi}}{ds_B} = \frac{\left|C_{d\phi}^{P,sb}\right|^2 m_B}{512\pi^3} A_0^2 \frac{\lambda^{\frac{3}{2}}(1, x_{K^*}, s_B)\sqrt{1-4x_\phi/x_B}}{(\sqrt{x_b}+\sqrt{x_s})^2},$$

$$\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz. \qquad q^2 = s_B m_B^2$$

$$x_{K^{(*)}} = m_{K^{(*)}}^2/m_B^2,\ x_\phi = m_\phi^2/m_B^2,\ x_b = m_b^2/m_B^2, \text{ and } x_s = m_s^2/m_B^2.$$

f_0 and A_0 use numerical fitting from "Dispersive analysis of B → K(*) and Bs→ ϕ form factors," JHEP 12 (2023) 153, arrive:2305.06301 [hep-ph].



$C^{S,sb}_{d\phi} \sim (3-8)/(10^5\,\mathrm{TeV})$ for a DM mass of $m_\phi = 1$ GeV

Can solve the Belle-II excess.

Without conflicting bounds from other decay modes!

Figure 2: Preferred parameter space to explain the excess in $B^+ \to K^+ + \mathrm{inv}$ via additional decay channels to DM final states, $B^+ \to K^+\phi\phi$ based on the latest Belle II measurement [1] in red, with an additional reweighted one to account for the selection efficiency in blue, and finally based on the new average in purple [1]. The dashed line indicates the current constraint from $B^0 \to K^0 + \mathrm{inv}$ [4; 5] on $|C^{S,sb}_{d\phi}|$ and the solid orange and green lines the constraints on $|C^{P,sb}_{d\phi}|$ posed by the searches for $B^+ \to K^{+*} + \mathrm{inv}$ and $B^0 \to K^{0*} + \mathrm{inv}$ [4; 5], respectively.

3. Dark Matter Relic density and Other Constraints

Dark matter relic density: Φ Φ -> s s

$$\mathcal{L} \ni \mathcal{L}_{\rm QCD} - [\overline{q_R}(s+ip)q_L + \text{ h.c. }]$$

$$s = -\frac{1}{2}\begin{pmatrix} C_{u\phi}^{S,uu} & 0 & 0 \\ 0 & C_{d\phi}^{S,dd} & C_{d\phi}^{S,ds} \\ 0 & C_{d\phi}^{S,sd} & C_{d\phi}^{S,ss} \end{pmatrix}\phi^2, \quad p = \frac{1}{2}\begin{pmatrix} C_{u\phi}^{P,uu} & 0 & 0 \\ 0 & C_{d\phi}^{P,dd} & C_{d\phi}^{P,ds} \\ 0 & C_{d\phi}^{P,sd} & C_{d\phi}^{P,ss} \end{pmatrix}\phi^2 .$$

Chiral realization

$$\begin{aligned}\mathcal{L}_{\phi P} \ni \frac{B}{2}\phi^2 \Big\{ & \left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd}\right)\left(\pi^+\pi^- + \frac{1}{2}\pi^0\pi^0\right) + \left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,ss}\right)K^+K^- \\ & + (C_{d\phi}^{S,dd} + C_{d\phi}^{S,ss})K^0\bar{K}^0 + \frac{1}{6}\left(C_{u\phi}^{S,uu} + C_{d\phi}^{S,dd} + 4C_{d\phi}^{S,ss}\right)\eta^2 + \frac{1}{\sqrt{3}}\left(C_{u\phi}^{S,uu} - C_{d\phi}^{S,dd}\right)\pi^0\eta \\ & + \left[C_{d\phi}^{S,ds}\left(\pi^+K^- - \frac{1}{\sqrt{2}}\pi^0\bar{K}^0 - \frac{1}{\sqrt{6}}\eta\bar{K}^0\right) + \text{h.c.}\right]\Big\} .\end{aligned}$$

$$\langle\sigma v\rangle = \frac{4x}{K_2^2(x)}\int_0^\infty d\epsilon\, \epsilon\sqrt{1+\epsilon}K_1(2x\sqrt{1+\epsilon})\sigma$$

$$\sigma(\phi\phi \to K^+K^-, K^0\bar{K}^0) = \frac{B^2|C_{d\phi}^{S,ss}|^2}{16\pi s}\left(\frac{s-4m_K^2}{s-4m_\phi^2}\right)^{1/2} ,$$

$$\epsilon \equiv \frac{s-4m_\phi^2}{4m_\phi^2}$$

$$\sigma(\phi\phi \to \eta\eta) = \frac{B^2|C_{d\phi}^{S,ss}|^2}{18\pi s}\left(\frac{s-4m_K^2}{s-4m_\phi^2}\right)^{1/2} .$$

Produce the right relic density — $\Omega h^2 = 0.12$ $\langle \sigma v \rangle \simeq 2.4 \times 10^{-26} \frac{\text{cm}^3\text{s}^{-1}}{(\hbar c)^2 c} = 2.2 \times 10^{-9}\ \text{GeV}^{-2}$,

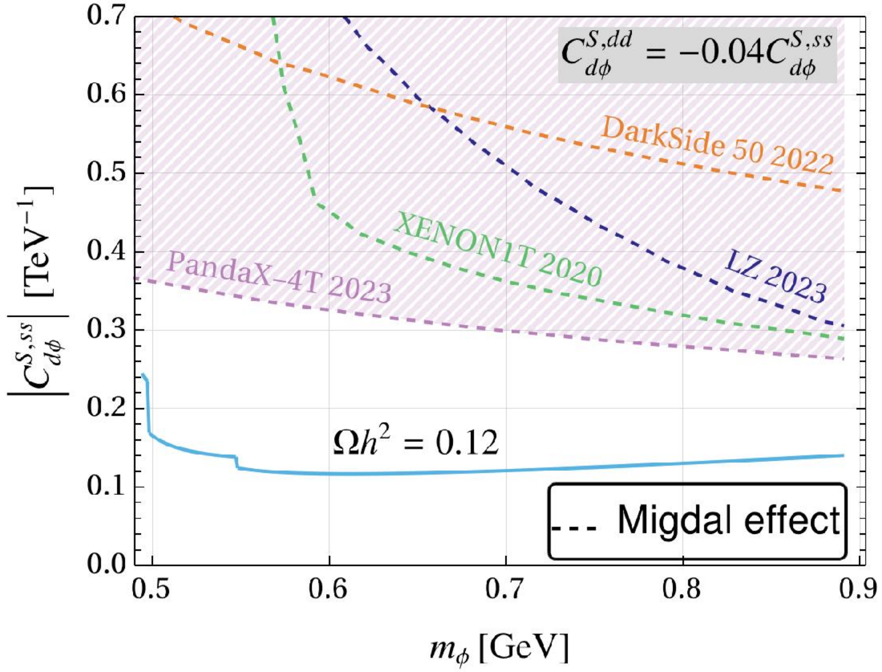
Solution: **Allow** **non-zero** $C_{d\phi}^{S,dd}$ **and** $C_{d\phi}^{S,ds}$

$$|C_{d\phi}^{S,dd}| \sim 0.2|C_{d\phi}^{S,ds}| \sim 0.04|C_{d\phi}^{S,ss}|;$$

$$\langle \sigma v(\phi\phi \to \pi^\pm K^\mp, \pi^0 K^0/\bar{K}^0)\rangle = (2,1) \times \frac{B^2 |C_{d\phi}^{S,ds}|^2 \eta(x, z_\pi, z_K)}{64\pi m_\phi^2};$$

$$\langle \sigma v(\phi\phi \to \eta K)\rangle = \frac{B^2 |C_{d\phi}^{S,ds}|^2 \eta(x, z_\eta, z_K)}{192\pi m_\phi^2},$$

$$\eta(x, z_1, z_2) \equiv \frac{4x}{K_2^2(x)} \int_0^\infty d\epsilon \frac{\sqrt{\epsilon}}{1+\epsilon} \lambda^{1/2}(1+\epsilon, z_1/4, z_2/4) K_1(2x\sqrt{1+\epsilon}).$$



Or make Φ Φ to annihilate into e+e- or μ+μ- pairs for DM relic density

Introducing heavy vector-like leptons, L_L+L_R (1,2)(-1/2), E_L+E_R (1,1)(-1)

4. Other Constraints

Produce the right relic density $\Omega h^2 = 0.12$

$$\langle \sigma v \rangle \simeq 2.4 \times 10^{-26} \frac{\mathrm{cm^3 s^{-1}}}{(\hbar c)^2 c} = 2.2 \times 10^{-9}\,\mathrm{GeV}^{-2},$$

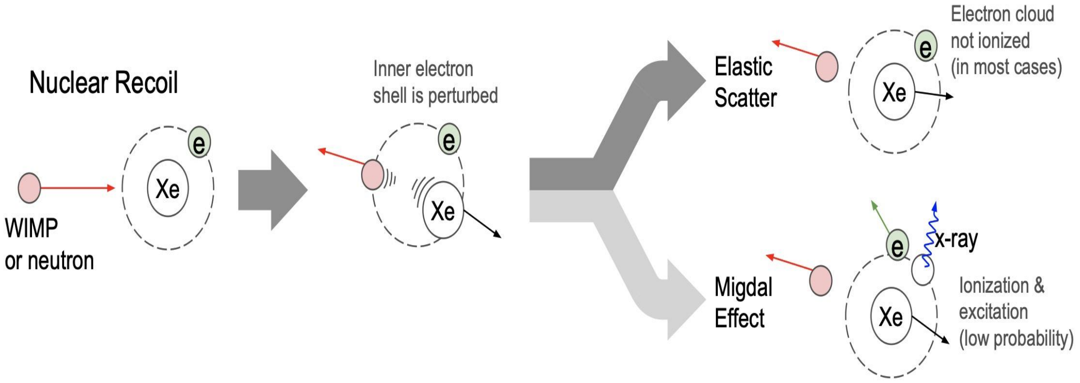
$$\left|C^{S,sb}_{d\phi}\right| \quad \left|C^{S,ss}_{d\phi}\right|$$

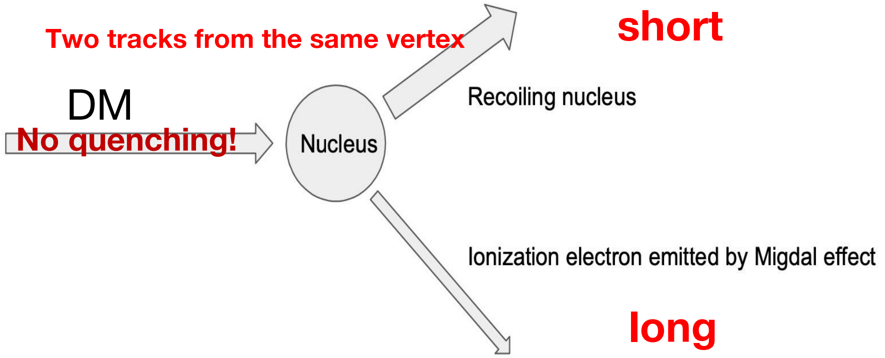
$$B_q^N \equiv \frac{\langle N(\boldsymbol{k},r)|\bar{q}q|N(\boldsymbol{k},r)\rangle}{2m_N} = \frac{m_N}{m_q} f_{Tq}^{(N)};$$

$$f_{Tu}^{(p)} = 0.018(5), \quad f_{Td}^{(p)} = 0.027(7), \quad f_{Ts}^{(p)} = 0.037(17)$$

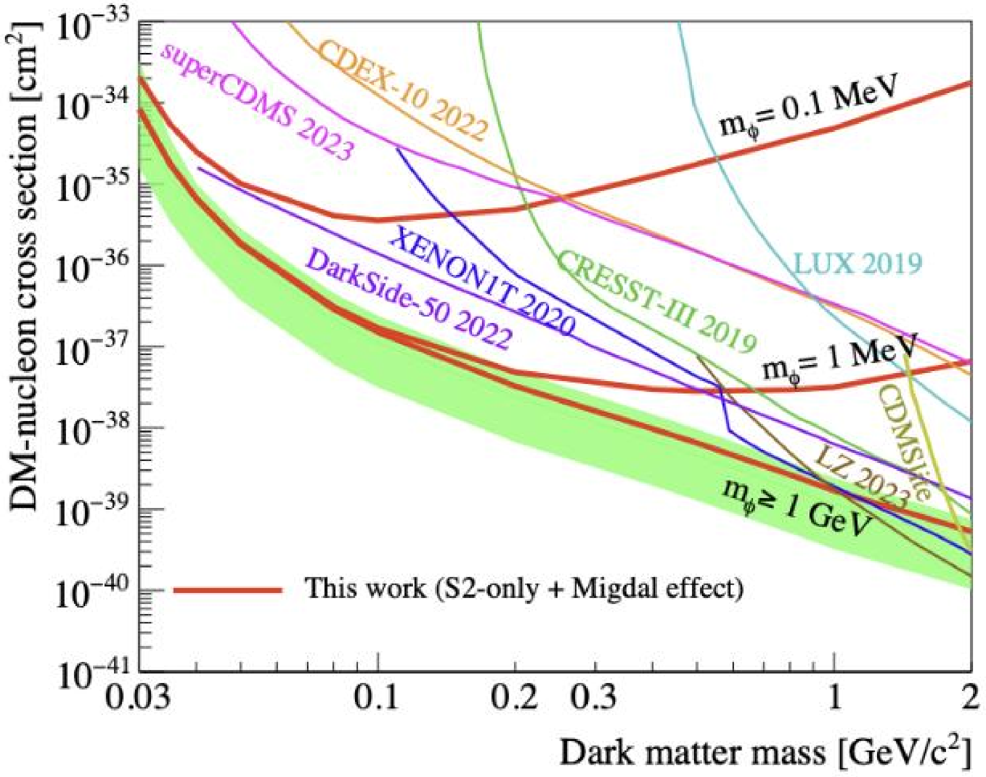
$$f_{Tu}^{(n)} = 0.013(3), \quad f_{Td}^{(n)} = 0.040(10), \quad f_{Ts}^{(n)} = 0.037(17)$$

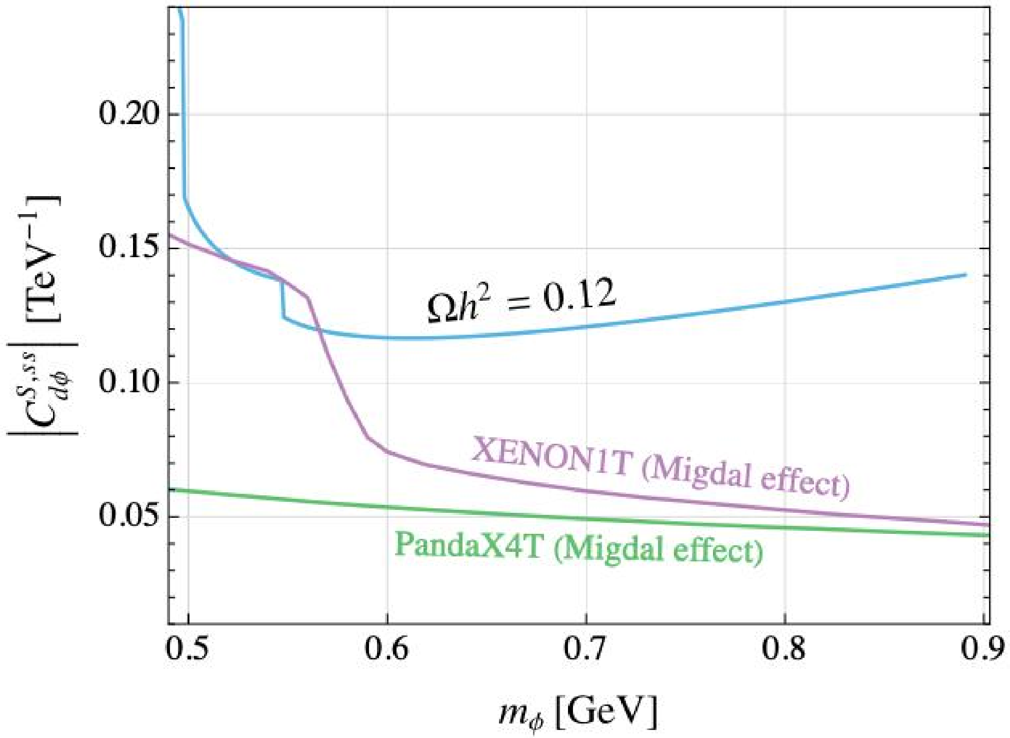
e.g. threshold of electron recoil for Xenon experiment : ~ 100 eV





$$\frac{d\langle \sigma_{n,l} v\rangle}{d\ln E_e} = \frac{\bar{\sigma}_n}{8\mu_n^2}[f_p Z + f_n(A-Z)]^2 \int dq \, \Big[q|F_N(q)|^2 \times |F_{\rm DM}(q)|^2 |f_{nl}^{\rm ion}(p_e, q_e)|^2 \eta(v_{\rm min}(q, \Delta E_{n,l}))\Big]$$





Left figure, m_Φ is mediator mass, not the dark mass.

Problem: If only a non-zero $|C_{d\phi}^{S,ss}|$, ruled out by PandaX4T data

Other constraints: No problems

B -> X_s γ;

Bs-Bsbar, K-Kbar mixing;

Bs -> ΦΦ;

D -> πΦΦ;

gg -> H,   H -> γ γ due to heavy quarks ...

4. Conclusion

It is viable to construct flavorful dark matter model .

At the same time solve some of the flavor anomalies,
in particular B^+ to K^+ invisible reported recently by Belle-II.

Thank you for Listening