Top-philic Scalar Dark Matter with a Vector-like Top Partner

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based on arXiv: 1606.00072
Outline

• Motivation
  • why flavored DM? why top-flavored?

• Model description

• Properties
  • Thermal relic density
  • Direct/Indirect detection
  • Collider search
  • Complementarity

• Conclusion
SUSY $\rightarrow$ SM flavor $\rightarrow$ Quark+DM flavor $\rightarrow$ MFV $\rightarrow$ $U$-flavored $\rightarrow$ top-flavored

• SUSY is beautiful and powerful
  • starts from
    • fine tuning of $\Delta m_h$
  • ends in
    • (partially) solve fine tuning of $\Delta m_h$
    • gauge coupling unification
    • DM candidate

• How about a different starting point?
SUSY → SM flavor → Quark+DM flavor → MFV → $U$-flavored → top-flavored

- **SM flavor structure**
  - all matters have 3 flavors/generations
  - significant mass hierarchy in both quark and lepton sector
  - broken by SM Yukawa interaction
  - approximate flavor symmetry $U(3)^5$
    - $U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$
    - ignore the neutrino masses
SUSY → SM flavor → Quark+DM flavor → MFV → U-flavored → top-flavored

• Maybe a similar flavor structure in new physics sector
  • extend SM flavor to \[ U(3)^5 \times U(3)^{\text{DM}}, \text{if DM is complex} \]
  • \[ U(3)^5 \times O(3)^{\text{DM}}, \text{if DM is real} \]
  • \[ U(3)^{\text{DM}}, O(3)^{\text{DM}} \text{ can be} \]
    • exact: degenerate DM multiplet
    • broken: mass splitting between DM flavors
  • DM is the lightest particle in the dark sector
• LHC is a hadron collider, consider the quark sector

• renormalizable interaction $\propto (Quark)^i \ast [\lambda]_i^\alpha \ast (DM)_\alpha \ast (med.)$
  
  • (med.) can transform under flavor of
    • both (Quark) and (DM)
    • one of them
    • none (simplest)

  • if (med.) is singlet
    • flavors of (Quark) and (DM) are associated
    • breaking of (Quark) flavor may transfer to (DM)
      • mass splitting in (DM) sector
SUSY → SM flavor → **Quark+DM flavor** → MFV → \(U\)-flavored → top-flavored

- Generally, FCNC generated by \((\text{Quark}) \ast [\lambda] \ast (\text{DM}) \ast (\text{med.})\)
  - alleviated by
    - \(m_{\text{med.}} \sim 500\ \text{GeV}\)
      - but harder to detect
    - \(\lambda \sim 10^{-2}\)
      - but **small annihilation**, cannot obtain \(\Omega_{\text{DM}}h^2 \sim 0.1\)
      - or, make DM couple to SM gauge bosons, more complex model
      - if DM is SM singlet, \([\lambda]\) should be \(O(1)\).
Minimal Flavor Violation (MFV)

All flavor violation comes only from SM Yukawa

$U(3)_\text{DM}$ is identified as $U(3)_{\text{Quark}} = \{Q, U, D\}$, which one?

- $Q$: more complicate spectrum
- $D$: flavor constraints from $K, B$ mesons
- $U$: simple and safe
  - top quark is special in SM, a portal to explore new physics
  - largest hierarchy in quark sector
    - may cause significant splitting in dark sector
SUSY $\rightarrow$ SM flavor $\rightarrow$ Quark+DM flavor $\rightarrow$ MFV $\rightarrow$ \textbf{U-flavored} $\rightarrow$ top-flavored

• Quark-flavored DM: $\mathcal{L} \supset U^i \lbrack \lambda \rbrack^j_i (DM)^j (med.)$

• under MFV, expansion of $\lambda^i_j, m_{DM}$ in terms of SM Yukawa $Y$
  
  • keep lowest order \cite{arXiv:1109.3516 Can Kilic et al} 

  • $[\lambda]^j_i = (\alpha \cdot 1 + \beta Y^+ Y)^j_i, \quad [m_{DM}]^j_i = (m_0 \cdot 1 + \Delta m Y^+ Y)^j_i$

  • $\{\alpha, \beta, m_0, \Delta m\}$ are constants determined by UV complete theory
SUSY → SM flavor → SM+DM flavor → MFV → $U$-flavored → **top-flavored**

- **Quark-flavored DM:** $\mathcal{L} \supset U^i [\lambda]_i^j (DM)_j (med.)$
- **under MFV**
  - $[\lambda]_i^j = (\alpha \cdot 1 + \beta Y^+Y)_i^j$,
  - $[m_{DM}]_i^j = (m_0 \cdot 1 + \Delta m Y^+Y)_i^j$
  - $\alpha \geq \beta y_t^2$, $m_0 \geq \Delta m y_t^2$
- almost **degenerate** in first 2 generation $DM_{u,c}$
  - small FCNC coupling, less flavor constraints
- considerable **splitting** between $DM_{u,c}$ and $DM_{top}$
  - $DM_{u/top}$ is the lightest, depending on (+/-) of $\Delta m$
- assume $DM_{top}$ is the lightest
  - arrange $\{\alpha, \beta, m_0, \Delta m\}$ to **decouple** masses/couplings of $DM_{u,c}$
SUSY → SM flavor → SM+DM flavor → MFV → $U$-flavored → top-flavored

• no valence top quark in nucleon
• DM coupling to gluons
  • loop calculation (SUSY) [arXiv: 1007.2601 Junji Hisano et al]
    • (DM, mediator) = (fermion, scalar)
    • (DM, mediator) = (scalar, scalar)
• top-philic DM, EFT operator [arXiv:1009.0618 Kingman Cheung et al]
  • (DM, mediator) = (fermion, scalar/vector)
• Our model: (DM, mediator) = (scalar, fermion)
Model description

• DM: real scalar $S$
  • SM singlet, couple only to top quark
  • Higgs portal, well studied [arXiv: 1306.4710 J. Cline et al]
    • $\lambda_{SH}S^2|H|^2$ turned off here
• top partner: Vector-like (VL) fermion $T$
• $Z_2$ parity: $S, T$ are odd
  • no mass mixing $(S, H), (T, t)$
  • $Br(T \rightarrow St^{(*)}) = 100\%$
  • LHC searches for VL $(T, B)$ do not apply
• gauge invariance
  • $(T, t_R)$ same quantum number

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_T + \mathcal{L}_Y + \mathcal{L}_G$$

$$\mathcal{L}_S = \frac{1}{2} \left( \partial_\mu S \right)^2 - \frac{1}{2} m_S^2 S^2$$

$$\mathcal{L}_T = \bar{T}(i\not\!D - m_T)T$$

$$\mathcal{L}_Y = -\left( y_{ST} S \bar{T} t_R + \text{h. c.} \right)$$

$$\mathcal{L}_G = C_{Sg} \frac{\alpha_s}{\pi} S^2 G^{\mu\nu} G^A_{\mu\nu}$$

see SUSY2016 talks by H. Tholen, D. Yamaguchi
Thermal Relic

• pair annihilation
  • $SS \rightarrow t\bar{t}$

• co-annihilation
  • $ST \rightarrow t^* \rightarrow bW^+$
  • $ST \rightarrow t + SM$
    • $SM = g, \gamma, Z, h$
  • $S + t/\bar{t} \rightarrow T/\bar{T} + SM$
  • $SS \rightarrow T\bar{T}$
  • $T\bar{T} \rightarrow SM + SM'$

• loop coupling $C_{Sg}$
  • [arXiv: 1502.02244, Junji Hisano et al]
  • $SS \rightarrow gg$
    • small for $SS \rightarrow SM + SM'$
      • $SM = g, \gamma, Z, h$
    • proportional to $y_{ST}^2$
      • important when $y_{ST} > O(1)$
Thermal Relic

• loop coupling $C_{Sg}$
  • proportional to $y_{ST}^2$
    • important when $y_{ST} > O(1)$
  • suppressed by large $r = m_T/m_S$
    • heavier particles in the loop
Thermal Relic

- $SS \rightarrow t\bar{t}, SS \rightarrow gg$
- channels evolve with $\gamma_{ST}$

\[ \gamma_{ST} = 0.3 \]

\[ \gamma_{ST} = 0.5 \]

\[ \gamma_{ST} = 1 \]

\[ \gamma_{ST} = 10 \]

\[ \gamma_{ST} = 0.3 \]
Thermal Relic

- \( SS \rightarrow gg \) ignored for \( y_{ST} < \mathcal{O}(1) \)

- when \( SS \rightarrow t\bar{t} \) is open
  - relaxed \( r \)
  - larger \( y_{ST} \) is more helpful
  - further suppressed \( C_{Sg} \)
    - affect the direct detection

\[ r = \frac{m_T}{m_S} \]

\( \lambda_{SH} = |C_{SSgg}| = 0 \)
Thermal Relic

- when $SS \rightarrow t\bar{t}$ is open
  - relaxed $r$
  - larger $\gamma_{ST}$ is more helpful
  - further suppressed $C_{Sg}$
    - affect the direct detection

$SS \rightarrow t\bar{t}, SS \rightarrow gg$

$\gamma_{ST} = 0.3$

$\gamma_{ST} = 0.5$

$\gamma_{ST} = 1$

$\gamma_{ST} = 10$
Direct detection

• large $\gamma_{ST}$
  • $SS \rightarrow gg$ can dominate in light $m_S$ region
  • $\sigma_{SI}$ is correlated with $\Omega_{DM} h^2$
  • excluded by LUX-2015

• $\gamma_{ST} \approx 1$
  • difficult for XENON-1T
  • possibly covered by LZ

• $\gamma_{ST} < 0.5$
  • difficult to detect
Indirect detection (gamma-ray)

- gamma-ray spectrum
  - continuous: dwarf galaxies
- line: galactic region
Indirect detection (gamma-ray)

- continuous: dwarf galaxies
  - [arXiv: 1503.02641, Fermi]

- no $t\bar{t}$?
  - rescale from $b\bar{b}$
  - $\langle \sigma v \rangle_{gg}$ obtained from $u\bar{u}$
    - [arXiv: 1511.04452 F. Giacchino et al]

\[
N_{\gamma,f} = \int_{E_{th}}^{m_{X}} \frac{dN_{f}}{dE} dE.
\]

\[
\langle \sigma v \rangle_{t\bar{t}} = \langle \sigma v \rangle_{b\bar{b}} N_{\gamma,bb}/N_{\gamma,t\bar{t}}
\]
Indirect detection (gamma-ray)

- line: galactic region
- [arXiv: 1506.00013, Fermi]
- conversion from $g g$ to $\gamma\gamma$

$$\frac{\langle \sigma v \rangle_{\gamma\gamma}}{\langle \sigma v \rangle_{gg}} = \frac{9}{2} Q^4 \left( \frac{\alpha_{em}}{\alpha_s} \right)^2 \approx 3.8 \times 10^{-3},$$
Indirect detection (gamma-ray)

• promising to detect $m_S > m_t$
  • complementary to DD
• current results just about to test this model
• improved sensitivity can cover wide regions in $m_S > m_t$
Collider search

• $pp \rightarrow T\bar{T} \rightarrow t\bar{t} + MET$
  • similar to stop search

• CMS 8 TeV [arXiv: 1504.01398]

\[ \mathcal{L}_{\text{EFT}} = \frac{m_t}{M_*^3} \bar{t}t\bar{\chi}\chi, \]

\( \chi: \) Dirac fermion

preselection: \( \not{E}_T > 160 \text{ GeV}, \)

\( \not{E}_T > 320 \text{ GeV}, \)

\( M_T > 160 \text{ GeV}, \)

\( M_{T2}^W > 200 \text{ GeV}, \)

\[ \min \Delta \phi(j_{1,2}, \bar{\not{p}}_T) > 1.2. \]
Collider search

• Validation
  • cut efficiency for a wide range of $m_\chi$

<table>
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<th>Signal Region</th>
<th>SR $pp \rightarrow tt\chi\chi$</th>
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<tr>
<td>1000</td>
<td></td>
</tr>
</tbody>
</table>
Collider search

• Validation

• kinematic variables: $E_T, m_T, m_T^W, \min \Delta \phi(j_{1,2}, \not{p}_T)$
Collider search

• Results
  • exclude $m_T$ from 300 (450)-850 GeV for $m_S = 0$ (200) GeV

• future improvement:
  • off-shell $t, W^\pm$
  • mono-jet
Combination

- complementarity between DD/ID
- large $\gamma_{ST}$: excluded by LUX and Fermi
- perturbative $\gamma_{ST} \in (0.5, 1)$: about to be tested in future

\[
\gamma_{ST} = 0.5
\]

\[
\gamma_{ST} = 1
\]
Conclusion

• **Flavored** DM is an interesting framework
  • rich particle spectrum

• Top-flavored, 3 parameters \( \{ y_{ST}, m_S, m_T \} \)
  • annihilation: \( m_S < m_t \): (ST), moderate \( m_t \): (SS), large \( m_t \): (T\(\bar{T}\))
  • DD/ID: large \( y_{ST}, SS \rightarrow gg \) dominant, excluded by LUX and Fermi
    • **Complementarity**: DD (ID) in \( m_S < (>)m_t \)
  • Collider: \( m_T \) excluded between 300 (450)-850 GeV for \( m_S = 0 \) (200) GeV

• LHC Run-2 will further test **Flavored** DM
Thank you
Back up
stop search, CMS

\[ m_{\tilde{t}} \text{ [GeV]} \]

\[ m_{\tilde{\chi}_1^0} \text{ [GeV]} \]

\[ m_{\tilde{t}} \text{ [GeV]} \]

\[ m_{\tilde{\chi}_1^0} \text{ [GeV]} \]
stop search, EXO vs SUSY in boosted top
Loop coupling $C_{sg}$ \cite{arXiv:1502.02244, Junji Hisano et al} 

\begin{align}
C_{s}^{g}q & = \frac{1}{4} \sum_{k=1}^{3} \left[ (a_{q}^{g} + b_{q}^{g}) f_{4}^{(i)}(M; m_{Q}, m_{W_{Q}}) + (a_{q}^{g} - b_{q}^{g}) f_{4}^{(i)}(M; m_{Q}, m_{W_{Q}}) \right], \tag{53}
\end{align}

where $f_{4}^{(i)}$ and $f_{4}^{(j)}$ ($i = a, b, c$) correspond to the contribution of the diagram $i$ in Fig. 2. They are given as follows:

\begin{align}
f_{4}^{(a)}(M; m_{1}, m_{2}) & = -m_{3}m_{2}(M^{2} + m_{1}^{2} - m_{3}^{2}) \Delta_{L}, \tag{54}
\end{align}

\begin{align}
f_{4}^{(b)}(M; m_{1}, m_{2}) & = \frac{m_{1}m_{2}(\Delta + m_{2}^{2}(M^{2} - m_{1}^{2} + m_{3}^{2}))}{6\Delta^{2}} L, \tag{55}
\end{align}

\begin{align}
f_{4}^{(c)}(M; m_{1}, m_{2}) & = m_{2}(-2m_{1}^{2} + m_{1}^{2} + 2m_{3}^{2} - 2m_{1}m_{2}(M^{2} + m_{1}^{2} - m_{3}^{2})) \frac{\Delta^{2}}{6m_{1}^{2}L}, \tag{56}
\end{align}

\begin{align}
f_{4}^{(d)}(M; m_{1}, m_{2}) & = f_{4}^{(i)}(M; m_{2}, m_{1}) \tag{56},
\end{align}

\begin{align}
f_{4}^{(e)}(M; m_{1}, m_{2}) & = f_{4}^{(i)}(M; m_{3}, m_{1}) \tag{57},
\end{align}

\begin{align}
f_{4}^{(f)}(M; m_{1}, m_{2}) & = \frac{M^{2} + m_{1}^{2} + m_{3}^{2}}{2\Delta} - \frac{m_{1}^{2}m_{3}^{2}}{\Delta} L, \tag{58}
\end{align}

\begin{align}
f_{4}^{(g)}(M; m_{1}, m_{2}) & = \frac{2m_{1}m_{2}}{\Delta} - m_{1}m_{2}(M^{2} + m_{1}^{2} + m_{3}^{2}) \frac{\Delta}{L}, \tag{59}
\end{align}

with

\begin{align}
\Delta(M; m_{1}, m_{2}) & = M^{4} - 2M^{2}(m_{1}^{2} + m_{2}^{2}) + (m_{1}^{2} - m_{2}^{2})^{2}, \tag{60}
\end{align}

\begin{align}
L(M; m_{1}, m_{2}) & = \begin{cases}
\frac{1}{\sqrt{\Delta}} \arctan \left( \frac{m_{1}m_{2} - M^{2} + \sqrt{\Delta}}{m_{1}m_{3} - M^{2} - \sqrt{\Delta}} \right) & (\Delta > 0) \\
\frac{2}{\sqrt{\Delta}} \arctan \left( \frac{\sqrt{\Delta}}{m_{1}m_{2} - M^{2}} \right) & (\Delta < 0)
\end{cases}, \tag{61}
\end{align}
co-annihilation

Conditions for coannihilation to reduce LSP relic density

If there is another R-odd species $\chi_2$ almost degenerate in mass with the LSP $\chi_1$,

and if $\chi_2$ has a big annihilation cross section with itself and/or with $\chi_1$,

and if $\chi_1$ can efficiently convert to $\chi_2$,

then $\chi_1$ and $\chi_2$ can freeze out together at a lower temperature resulting in a smaller dark matter abundance than if without the existence of $\chi_2$.

\[
\begin{align*}
\chi_1\chi_1 &\leftrightarrow SM, \quad \chi_1\chi_2 \leftrightarrow SM, \quad \chi_2\chi_2 \leftrightarrow SM \\
\chi_1 SM &\leftrightarrow \chi_2 SM, \quad \chi_2 \leftrightarrow \chi_1 SM
\end{align*}
\]

**efficient conversion:** $\langle \Gamma \rangle _{1SM \rightarrow 2SM} + \langle \Gamma \rangle _{1SM \rightarrow 2} \gg H$

$\Rightarrow \frac{n_1}{n_2} \approx \frac{n_{1eq}}{n_{2eq}}$ (this can be checked by explicitly solving for $n_1$ and $n_2$

\[
\frac{dn}{dt} + 3Hn = -\sum_{i,j=1}^{2} \langle \sigma v \rangle _{ij \rightarrow SM} \frac{n_{1eq} n_{2eq}^{i}}{n_{2eq}^{j}} [n^2 - n_{eq}^2]
\]

(Recall w/o coannihilation: $\frac{dn_X}{dt} + 3H(T)n_X = -\langle \sigma v \rangle _{XX \rightarrow SM'} \left[ n_X^2 - (n_{eqX})^2 \right]$)
3.1 Review of the Boltzmann equation with coannihilations

Consider annihilation of $N$ supersymmetric particles $\chi_i$ ($i = 1, \ldots, N$) with masses $m_i$ and internal degrees of freedom (statistical weights) $g_i$. Also assume that $m_1 \leq m_2 \leq \cdots \leq m_N < m_N$ and that $R$-parity is conserved. Note that for the mass of the lightest neutralino we will use the notation $m_{\chi}$ and $m_1$ interchangeably.

The evolution of the number density $n_i$ of particle $i$ is

$$\frac{dn_i}{dt} = -3H n_i - \sum_{j=1}^{N} (\sigma_{ij} v_i) (n_i n_j - n_i m_i n_j^m)$$
$$- \left[ \sum_{j \neq i} \left( \sigma_{X_{ij}} v_i \right) (n_i n_X - n_i m_i n_X^m) - \left( \sigma_{X_{ji}} v_j \right) (n_j n_X - n_j m_j n_X^m) \right]$$
$$- \sum_{j \neq i} \left[ \Gamma_{ij} (n_i - n_i^m) - \Gamma_{ji} (n_j - n_j^m) \right].$$

The first term on the right-hand side is the dilution due to the expansion of the Universe. $H$ is the Hubble parameter. The second term describes $\chi_i\chi_j$ annihilations, whose total annihilation cross section is

$$\sigma_{ij} = \sum_{X} \sigma_{(\chi_i\chi_j \rightarrow X)}.$$  \hspace{1cm} (28)

The third term describes $\chi_i \rightarrow \chi_j$ conversions by scattering off the cosmic thermal background,

$$\sigma_{X_{ij}} = \sum_{Y} \sigma_{(\chi_i X \rightarrow \chi_j Y)}$$  \hspace{1cm} (29)

being the inclusive scattering cross section. The last term accounts for $\chi_i$ decays, with inclusive decay rates

$$\Gamma_{ij} = \sum_{X} \Gamma_{(\chi_i \rightarrow Y_j X)}.$$  \hspace{1cm} (30)
Direct detection

- **parton effective coupling**
  - $\mathcal{L}_{eff} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p$
  - $\mathcal{O}_S^q = m_q S^2 \bar{q} q$
  - $\mathcal{O}_S^g = \frac{\alpha_s}{\pi} S^2 G^{A\mu\nu} G_{\mu\nu}^A$

- **nucleon effective coupling**
  - $\mathcal{L}_{SI}^{(N)} = f_N S^2 \bar{N} N$
  - $f_N/m_N = \sum_{q=uds} C_S^q f_{Tq}^{(N)} - \frac{8}{9} C_S^g f_{Tg}^{(N)}$

- **nucleus scattering**
  - $\sigma = \frac{1}{\pi} \left( \frac{m_{\text{tar}}}{m_S + m_{\text{tar}}} \right)^2 |n_p f_p + n_n f_n|^2$
Direct detection

- General formalism
  - refer to 1502.02244

- Effective Langragian

- DM-parton coupling
  - $C_S^p = C_S^p(y_{ST}, m_S, r)$

3 Formalism: real scalar boson DM

Next we briefly show the results for the case of real scalar boson DM. We may use a similar procedure to that given in the previous section to formulate effective theories for the WIMP.

3.1 Effective Lagrangian

The effective interactions of the real scalar $\phi$ with quarks and gluon are expressed by

$$L_{\text{eff}} = \sum_{p=q,g} C_S^p \mathcal{O}_S^p + \sum_{p=q,g} C_{T_2}^p \mathcal{O}_{T_2}^p ,$$

with

$$\mathcal{O}_S^q = \phi^2 m_q \bar{q} q ,$$

$$\mathcal{O}_S^g = \frac{g_s}{\pi} \phi^2 G^{\mu\nu} G_{\mu\nu} ,$$

$$\mathcal{O}_{T_2}^q = \frac{1}{M^2} \phi i \partial^\mu i \partial^\nu \phi \mathcal{O}_\mu^q ,$$

$$\mathcal{O}_{T_2}^g = \frac{1}{M^2} \phi i \partial^\mu i \partial^\nu \phi \mathcal{O}_{\mu\nu}^g .$$

Note that there is no spin-dependent interactions in the case of scalar boson DM.
Direct detection

• DM-nucleon coupling
  • $f_N = f_N(C_S^q, C_S^g)$

• scattering cross section
  • $\sigma = \sigma(f_N, m_S)$

3.3 Scattering cross sections

We now ready to evaluate the scattering cross section of the real scalar boson with a target nucleus. The spin-independent coupling of the real scalar boson with a nucleon defined by

$$\mathcal{L}_{\text{SI}}^{(N)} = f_N \phi^2 N N,$$

is evaluated as

$$f_N / m_N = \sum_{q=u,d,s} C_S^q(\mu_{\text{had}}) f_{Tq}^{(N)} - \frac{8}{9} C_S^q(\mu_{\text{had}}) f_{Tq}^{(N)} + \frac{3}{4} \sum_{q} C_{Tq}^q(\mu) [q(2; \mu) + \bar{q}(2; \mu)] - \frac{3}{4} C_{Tq}^q(\mu) g(2; \mu).$$

In the scalar boson case, there is no spin-dependent coupling with a nucleon. By using the effective coupling, we calculate the scattering cross section of the real scalar boson with a target nucleus as follows:

$$\sigma = \frac{1}{\pi} \left( \frac{M_T}{M + M_T} \right)^2 |n_p f_p + n_n f_n|^2.$$
Direct detection

- mass fraction $f_{Tq}^N$
- quantum mechanics
- expectation value

As for the scalar-type quark operators $\mathcal{O}^q$, we use the results from the lattice QCD simulations. The expectation values of the scalar bilinear operators of light quarks between the nucleon states at rest, $|N\rangle$ ($N = p, n$), are parametrized as

$$f_{Tq}^{(N)} \equiv \langle N|m_q\bar{q}|N\rangle/m_N,$$

which are called the mass fractions. These values are shown in Table 1. Here, $m_N$ is the nucleon mass. They are taken from Ref. 12, in which the mass fractions are computed by using the results from Refs. 13,14.

up to the leading order in $\alpha_s$. The relation beyond the leading order in $\alpha_s$ is also readily obtained from the trace-anomaly formula. By evaluating the operator (5) in the nucleon states $|N\rangle$, from $\langle N|\Theta^\mu\mu|N\rangle = m_N$ we then obtain

$$\langle N|\frac{\alpha_s}{\pi} G^A_{\mu\nu} G^{A\mu\nu}|N\rangle = -\frac{8}{9}m_N f_{Tq}^{(N)}.$$

with $f_{Tq}^{(N)} \equiv 1 - \sum_{q=u,d,s} f_{Tq}^{(N)}$. Notice that the r.h.s. of Eq. (6) is the order of the typical hadronic scale, $\mathcal{O}(m_N)$. That is, although we include a factor of $\alpha_s/\pi$ in the definition of $\mathcal{O}^q$, its nucleon matrix element is not suppressed by $\alpha_s/\pi$. This is the reason why we have defined $\mathcal{O}^q$ to contain $\alpha_s/\pi$. 
Indirect detection

• General formalism, two factors

  • astrophysical

  • particle physics

\[ \mu_\gamma (\Phi_{PP}) \equiv (A_{\text{eff}} T_{\text{obs}}) \Phi_{PP} J, \]

\[ J \equiv \int_{\Delta \Omega(\psi)} \int_{\ell} [\rho(\ell, \psi)]^2 d\ell d\Omega(\psi), \]

\[ \Phi_{PP} \equiv \frac{\langle \sigma_A v \rangle}{8\pi m_\chi^2} \int_{E_{th}}^{m_\chi} \sum_f B_f \frac{dN_f}{dE} dE, \]
2 Simplified Model

The basic module consists of a massive scalar (assumed complex for simplicity, though the modification to a real field is simple) $\chi$ that is a gauge singlet to play the role of dark matter, and a set of massive (typically complex) colored scalars $\phi$ (in representation $r$ of $SU(3)_C$) to act as the mediator with the SM. These basic pieces are described by the Lagrangian,

$$\mathcal{L} = \nabla\mu \chi^* \partial^\mu \chi - m_\chi^2 |\chi|^2 + (D_\mu \phi)^\dagger D^\mu \phi - m_\phi^2 |\phi|^2$$

(2.1)

where $D_\mu \phi$ is a covariant derivative that includes interactions with the electroweak gauge fields (in cases where $\phi$ is charged under $SU(2) \times U(1)$) and coupling to the gluons $G_\mu^a$:

$$D_\mu \phi \equiv \partial_\mu \phi - i g_s \frac{\lambda^a}{2} G^a_\mu \phi \quad \text{Electroweak}$$

(2.2)

Figure 2: The product of quartic interaction $\lambda_d$ with the square root of product of $r$ dimensional color representation of $\phi$ and $N_f$, number of flavors with mass less than $m_\chi$, required to saturate the observed dark matter density as a thermal relic, are represented as colored contours in the plane of $m_\phi$-$m_\chi$. Almost all the parameter space where $m_\phi < m_\chi$ is compatible with a thermal relic density. Where $m_\phi > m_\chi$, the DM annihilation proceeds via loops and, only a small region of parameter space is allowed without including any additional couplings.

Figure 3: Current (solid line) and projected (dashed line) bounds on $\sum \lambda_{d} T_{\nu} \sqrt{N_{f}}/m_{\phi}^{2}$ based on searches for dark matter-Xenon scattering by LUX. The region above the solid line is excluded.