The WIMP Miracle

Contains factors of $M_{\text{Pl}}$, $s_0$, \ldots

\[ \Omega_{\text{DM}} h^2 \approx 0.1 \left( \frac{X_f}{20} \right) \left( \frac{g_*}{80} \right)^{-\frac{1}{2}} \left( \frac{\langle \sigma v \rangle_0}{3 \times 10^{-26} \text{ cm}^3 / \text{s}} \right) \]

Within orders of magnitude!
\( \Omega h^2 \text{ vs direct detection} \)

Tension between annihilation cross section and direct detection bounds

\[ \sigma_{\text{ann.}} \sim 0.1 \text{ pb} \]

\[ \sigma_{\text{SI}} \sim 7.0 \times 10^{-9} \text{ pb} \]

50 GeV WIMP

Typical strategy: pick parameters such that \( \sigma_{\text{SI}} \) is suppressed, then use tricks to enhance \( \sigma_{\text{ann.}} \).
\( \Omega h^2 \) vs direct detection

![Diagram showing the relationship between \( \Omega h^2 \) and direct detection.]
Motivation I: a natural WIMP

Typical MSSM WIMP: $\sigma_{SI}$ too large

Want to naturally suppress direct detection while maintaining ‘miracle’ of successful abundance.

If LSP is part of a Goldstone multiplet, $(s + ia, \chi)$, additional suppression from derivative coupling.

- Like a weak scale axino, but unrelated to CP
- Like singlino DM, but global symmetry broken in SUSY limit
Motivation I: a natural WIMP

**Annihilation:** \( p \)-wave decay to Goldstones

\[
\frac{1}{f} \bar{\chi} \gamma^\mu \gamma^5 \chi \partial_\mu a \quad \Rightarrow \quad \langle \sigma v \rangle \approx \left( \frac{m_\chi}{f^2} \right)^2 \left( \frac{T_f}{m_\chi} \right) \approx 1 \text{ pb}
\]

**Direct detection:** CP-even Goldstone mixing with Higgs

\[
\frac{m_\chi v}{f^2} \sim 0.01 \quad \Rightarrow \quad \sigma_{SI} = \left( \frac{m_\chi v}{f^2} \right)^2 \sigma_{SI}^{MSSM} \approx \mathcal{O}(10^{-45} \text{ cm}^2)
\]
**Motivation II: Buried Higgs**

**Idea:** Light Higgs buried in QCD background

Global symmetry at $f \sim 500$ GeV with coupling $\frac{1}{f^2} h^2 (\partial a)^2$

Can we bury the Higgs through $a$ decays, but dig up dark matter in $\chi$?

0906.3026, 1012.1316, 1012.1347
The Goldstone Supermultiplet

\[ A = \frac{1}{\sqrt{2}} \left( s + i a \right) + \sqrt{2} \theta \chi + \theta^2 F \]

Carries the low-energy degrees of freedom of the UV fields,

\[ \Phi_i = f_i e^{q_i A/f} \quad f^2 = \sum_i q_i^2 f_i^2 \]

SUSY \Rightarrow \text{explicit } s \text{ mass, } m_\chi \approx q_i \langle F_i \rangle / f, \text{ a massless}
Interactions: Overview

- Coupling to $a$
- Coupling to $H$
- Coupling to $g, \gamma$

**Kähler potential**

- NL$\Sigma$M Kähler
- MSSM
- Explicit breaking
- Superpotential
- Anomaly
- Mixing

- Scalar
- Kinetic
Interactions: NLΣM Kähler potential

Non-linear realization of the global U(1)
⇒ Kähler interactions of the Goldstone multiplet:

\[
\frac{\partial^2 K}{\partial A \partial A^\dagger} = 1 + b_1 \frac{q}{f} (A + A^\dagger) + \cdots
\]

\[
b_1 = \frac{1}{q f^2} \sum_i q_i^3 f_i^2
\]

Note \( K = K(s) \), manifest shift-invariance.

\[
\mathcal{L} = \left(1 + b_1 \frac{\sqrt{2}}{f} s + \cdots \right) \left( \frac{1}{2} (\partial s)^2 + \frac{1}{2} (\partial a)^2 + \frac{i}{2} \bar{\chi} \gamma^\mu \partial_\mu \chi \right) + \frac{1}{2 \sqrt{2}} \left( b_1 \frac{1}{f} + b_2 \frac{\sqrt{2}}{f^2} s + \cdots \right) \left( \bar{\chi} \gamma^\mu \gamma^5 \chi \right) \partial_\mu a + \cdots
\]

\( b_1 \) controls the annihilation cross section.
Interactions: scalar mixing

MSSM fields are uncharged under the global U(1), but may mix with the Goldstone multiplet through higher-order terms in $K$:

$$K = \frac{1}{f} \left( A + A^\dagger \right) \left( c_1 H_u H_d + \cdots \right) + \frac{1}{2f^2} \left( A + A^\dagger \right)^2 \left( c_2 H_u H_d + \cdots \right)$$

The new scalar interactions take the form

$$\mathcal{L} \supset \left[ \frac{1}{2} (\partial a)^2 + \frac{1}{2} \bar{\chi} \Slash{D} \chi \right] \left( 1 + \frac{v}{f} c_h h + \cdots \right)$$

c$_h$ depends on c$_i$ and the Higgs mixing angles.
Interactions: kinetic mixing

The higher order terms in $K$ also induce kinetic $\tilde{H} - \chi$ mixing.

\[ \mathcal{L} \supset i \epsilon_u \bar{\chi} \gamma^\mu \partial_\mu \tilde{H}^0_u + i \epsilon_d \bar{\chi} \gamma^\mu \partial_\mu \tilde{H}^0_d + \text{h.c.} \]

where $\epsilon \sim v/f$. For large $\mu$, $\chi$ has a small $\tilde{H}$ of order $v m_\chi / f \mu$.

Mixing with other MSSM fields is suppressed. Assuming MFV,

\[ K = \frac{1}{f} \left( A + A^\dagger \right) \left( \frac{Y_u}{M_u} \bar{Q} H_u U + \cdots \right) \]

where the scales $M_{u,d,\ell}$ are unrelated to $f$ or $v$ and can be large and dependent on the UV completion.
Interactions: anomaly

Fermions $\Psi$ charged under global $U(1)$ and Standard Model

$$\mathcal{L}_{an} \ni \frac{c_{an}}{f \sqrt{2}} \left( a G_{\mu\nu}^a \tilde{G}_{\mu\nu}^a + 2 \bar{\chi} G_{\mu\nu}^a \sigma^{\mu\nu} \gamma^5 \lambda^a \right)$$

$$c_{an} = \frac{\alpha}{8\pi} \sqrt{2} \sum_{i}^{N_{\psi}} \left( \frac{y_i f}{m_{\psi_i}} \right) = \frac{\alpha}{8\pi} q_{\Psi} N_{\Psi}$$

Assumed: degenerate $m_{\psi}$ and $y = m_{\psi} q_{\Psi} / f \sqrt{2}$

Integrating out $\lambda^a$ generates $\chi$ couplings to gluons

$$\mathcal{L} \ni - \frac{c_{an}^2}{2M_{\lambda} f^2} \bar{\chi} \chi G G - i \frac{c_{an}^2}{2M_{\lambda} f^2} \bar{\chi} \gamma^5 \chi G \tilde{G}$$

These contribute to collider and astro operators.
Interactions: explicit breaking

Include explicit $\mathcal{U}(1)$ spurion $R_\alpha = \lambda_\alpha f$ with $\lambda_\alpha \ll 1$

$$W_{\mathcal{U}(1)} = f^2 \sum_{\alpha} R_{-\alpha} e^{aA/f}$$

Perserve SUSY $\Rightarrow$ at least two spurions with opposite charge.

This generates $m_a = m_\chi = m_s$ and couplings

$$\mathcal{L} \supset -\frac{m_a}{2\sqrt{2}f} (\alpha + \beta) \left[ i a \bar{\chi} \gamma^5 \chi + \frac{m_a}{8f^2} (\alpha^2 + \alpha \beta + \beta^2) a^2 \bar{\chi} \chi \right]$$

By integration by parts this is equivalent to a shift in the $b_1$ coefficient from the Kähler potential
Main parameters

coupling to $a$

coupling to $H$

coupling to $g, \gamma$

Kähler potential

Goldstone Fermion $m_\chi$; SSB at $f$

Superpotential

MSSM

collider, astro

Mixing

scalar

kinetic

Anomaly

$c_{an}$

NL$\Sigma$M Kähler

$b_1$

$\sigma_{\text{ann}}$

$m_a$

Explicit breaking

$\delta$

Goldstone Fermion Dark Matter

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Parameter space scan

Abundance: \( \langle \sigma v \rangle \approx b_1^4 \frac{T_f}{8\pi} \frac{m_\chi^2}{m_\chi f^4} \approx 1 \text{ pb} \)

\( p \)-wave: \( b_1 \gtrsim 1 \), all other parameters take natural values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Scan Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f )</td>
<td>Global symmetry breaking scale</td>
<td>500 GeV – 1.2 TeV</td>
</tr>
<tr>
<td>( m_\chi )</td>
<td>Goldstone fermion mass (SUSY)</td>
<td>50 – 150 GeV</td>
</tr>
<tr>
<td>( m_a )</td>
<td>Goldstone boson mass</td>
<td>8 GeV – ( f/10 )</td>
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<tr>
<td>( b_1 )</td>
<td>( \chi \chi a ) coupling</td>
<td>[0, 2]</td>
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<tr>
<td>( c_{an} )</td>
<td>Anomaly coefficient</td>
<td>0.06</td>
</tr>
<tr>
<td>( c_h )</td>
<td>Higgs coupling</td>
<td>[−1, 1]</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Explicit breaking ( ia\bar{\chi}\gamma^5\chi ) coupling</td>
<td>3/2</td>
</tr>
</tbody>
</table>

\[ \mathcal{L} \supset \left[ \frac{1}{2} (\partial a)^2 + \frac{1}{2} \bar{\chi} \phi \chi \right] c_h \frac{v}{f} h + \frac{b_1}{2\sqrt{2}f} (\bar{\chi} \gamma^\mu \gamma^5 \chi) \partial_\mu a + \frac{c_{an}}{f\sqrt{2}} a G \tilde{G} + i\delta a \bar{\chi} \gamma^5 \chi \]
Contours of fixed $\Omega$

$\Omega h^2 = 0.11$

Dominant contribution
Kähler, anomaly, $U(1)$

Subleading
Mixing with Higgs

Negligible
$\chi\chi \rightarrow s \rightarrow aa, \chi\chi \rightarrow hh$

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Goldstone Fermion Dark Matter
Direct Detection

Higgs exchange typically dominates by a factor of $O(10^3)$.

$$\sigma_{SI}^H \approx 3 \cdot 10^{-45} \text{ cm}^2 c_h^2 \left( \frac{115 \text{ GeV}}{m_h} \cdot \frac{700 \text{ GeV}}{f} \right)^4 \left( \frac{m_\chi}{100 \text{ GeV}} \cdot \frac{\mu_\chi}{\text{GeV}} \cdot \frac{\lambda_N}{0.5} \right)^2$$

Compare this to the MSSM Higgs with $\mathcal{L} = \frac{1}{2}cg\bar{\chi}\chi h$:

$$\sigma_{SI}^{\text{MSSM}} \sim \frac{c^2 g^2}{2\pi} \frac{\lambda_N^2 \mu^2 m_N^2}{m_h^2 v^2} \approx c^2 \times 10^{-42} \text{ cm}^2$$

**Natural suppression:** $(m_\chi v / f^2)^2$ due to Goldstone nature
Parameter space scan

Direct Detection

\[ \sigma \quad [\text{cm}^2] \]

\[ m_\chi \quad [\text{GeV}] \]

Ruled out

500 < f < 700 GeV
700 < f < 800 GeV
800 < f < 900 GeV
900 < f < 1000 GeV

XENON
**Indirect detection & Colliders**

* p spectrum: below PAMELA
  - (Einsasto DM Halo profile) \(1104.3572\)

* \(\gamma\)-ray line search: \(\mathcal{O}(10)\) smaller than bound
  - \(\chi\chi \rightarrow a \rightarrow \gamma\gamma\)

**Diffuse \(\gamma\)-ray spectrum**: \(\mathcal{O}(10)\) smaller than bound
  - \(\chi\chi \rightarrow a \rightarrow gg \rightarrow \pi's\)

* Photo-production from annihilation: \(\sigma 3x\) lower than bound
  - Low mass DM \(m_\chi \lesssim 60\) GeV, constrains \(bb\) decays

* ISR monojets at colliders: dim-7 operators too small

\[
\mathcal{L} \supset -\frac{c_{an}^2}{2M_\lambda f^2} \bar{\chi} \chi G \tilde{G} - \frac{i c_{an}^2}{2M_\lambda f^2} \bar{\chi} \gamma^5 \chi G \tilde{G}
\]
Non-standard Higgs decays

Hard to completely bury the Higgs. LEP: $\text{Br}(\text{SM}) \gtrsim 20\% \Rightarrow m_h \gtrsim 110 \text{ GeV}$

$f = 500 \text{ GeV}, m_a = 45 \text{ GeV}, m_\chi = 100 \text{ GeV}, c_h = 2$

![Graph showing Higgs branching ratio vs. Higgs mass](image-url)
Non-standard Higgs decays

Partially buried & invisible: Suppressed SM channels, MET, $\Gamma_{\text{tot}} < 1$

\[ f = 400 \text{ GeV}, \ m_a = m_\chi = 60 \text{ GeV}, \ c_h = 2 \]

Higgs branching ratio vs. Higgs mass $m_h [\text{GeV}]$

- $b\bar{b}$
- $aa$
- $\chi\chi$
- $ZZ^*$
- $WW^*$
Conclusions

Executive summary: Goldstone Fermion dark matter

• SSB: global U(1) $\Rightarrow$ Goldstone boson $a$ and fermion $\chi$
• $\chi$ is LSP and DM, $a$ gives ‘buried’ Higgs channel

Simple extension of MSSM with natural WIMP dark matter

• Kähler $\chi\chi a$ interaction controls abundance
• Higgs mixing, anomaly controls direct detection
• Novel collider signature: partially buried/invisible Higgs

Further directions:

• $p$-wave Sommerfeld enhancement (can push $m_a$, $m_\chi$ to 10 GeV)
• Non-abelian generalization
Extra Slides
Examples of Linear Models

Simplest example:

$$W = yS \left( \bar{NN} - \mu^2 \right) + \underbrace{N\phi\phi}_{\text{anomaly}} + \underbrace{SH_uH_d}_{\text{mixing}} + \underbrace{W_{\text{explicit}}}_{\text{explicit } U(1)}$$

Example with $|b_1| \geq 1$:

$$W = \lambda XYZ - \mu^2 Z + \frac{\tilde{\lambda}}{2} Y^2 N - \bar{\mu} \bar{N} N$$

$q_Z = 0$, $q_N = -q_{\bar{N}} = -2q_Y = 2q_X$. Goldstone multiplet:

$$A = \sum_i \frac{q_i f_i \psi_i}{f} = \frac{q_Y}{f} \left( Yf_Y - Xf_X + 2\bar{N}F_{\bar{N}} \right)$$

$$b_1 = \frac{-f_X^2 + f_Y^2 + 8f_{\bar{N}}^2}{f_X^2 + f_Y^2 + 4f_{\bar{N}}^2}$$
Tamvakis-Wyler Theorem


Global symmetry: $W[\Phi_i] = W[e^{i\alpha q_i} \Phi_i]$ so that

$$0 = \frac{\partial W[e^{i\alpha q_i} \Phi_i]}{\partial \alpha} = \sum_j W_j q_j \Phi_j,$$

Taking a derivative $\partial / \partial \Phi_i$ gives:

$$0 = \left. \frac{\partial}{\partial \Phi_i} \left( \sum_j W_j q_j \Phi_j \right) \right|_{\langle \Phi \rangle} = \sum_j W_{ij} q_j f_j + W_i q_i$$
Expand Kähler potential, drop total derivatives, integrate out $F$:

$$\mathcal{L} = K'' \left( \frac{i}{2} \partial \chi \sigma \bar{\chi} + |\partial \phi|^2 \right)$$

$$+ \frac{K'''}{4} i \chi \sigma \bar{\chi} \partial (\phi - \phi^*)$$

$$+ \frac{1}{4} \left( K''''' - \left( \frac{K'''}{K''} \right)^2 \right) \chi^2 \bar{\chi}^2$$

These terms can be understood in terms of geometric properties of the vacuum manifold, see e.g. hep-th/0101055.
We assume that soft SUSY terms that also explicitly break the global U(1) are negligible. Neglect $D$-term mixing with $\lambda^a$, then fermion mass matrix is $W_{ij}$. Tamvakis-Wyler:

$$\sum_j W_{ij} q_j f_j = -q_i W_i = -q_i F_i$$

so that $\chi = \sum_i q_i f_i \psi_i / f$ mass depends on how U(1)-charged $F$-terms in the presence of soft SUSY terms.

If $W$ has an unbroken $R$ symmetry, then $R[\chi] = -1$ which prohibits a Majorana mass. However, while soft scalar masses preserve $R$, $A$-terms are holomorphic and generally break $R$ symmetries to contribute to $m_\chi$. 
SUSY Breaking and $\chi$ mass

The $A$-term contribution to $m_\chi$ is equivalent to $F$-term mixing between $U(1)$ charged fields and the SUSY spurion, $X$. This was recently emphasized in 1104.0692 as an irreducible $O(m_{3/2})$ contribution to the Goldstone fermion.

For concreteness, consider gravity mediation with $m_{\text{soft}} \sim F/M_{\text{Pl}}$.

$$K = \sum_i Z(X, X^\dagger) \Phi_i^\dagger \Phi_i$$

Analytically continue into superspace hep-ph/9706540

$$\Phi \rightarrow \Phi' \equiv Z^{1/2} \left(1 + \frac{\partial \ln Z}{\partial X} F \theta^2 \right) \Phi$$

Canonical normalization generates $A$-terms:

$$\Delta \mathcal{L}_{\text{soft}} = \left. \frac{\partial W}{\partial \Phi} \right|_{\Phi=\phi} Z^{-1/2} \left( -\frac{\partial \ln Z}{\partial \ln X} \frac{F}{M} \right)$$
\[ \Delta \mathcal{L}_{\text{soft}} = \left. \frac{\partial W}{\partial \Phi} \right|_{\Phi = \phi} \ Z^{-1/2} \left( -\frac{\partial \ln Z}{\partial \ln X} \frac{F}{M} \right) \]

Completely incorporates \( F \)-term mixing of the form \( FF^\dagger \Phi_i \). The \( \chi \) mass is determined by the induced \( F_i \) obtained by minimizing

\[ V = \left| \frac{\partial W}{\partial \phi_i} \right|^2 + A_i \frac{\partial W}{\partial \phi_i} \phi_i + \text{h.c.} + m_i^2 |\phi_i|^2 \]

Assuming \( A_i, m_i < f_i \), generic size is \( |F_i| \approx A_i f_i \) so that \( m_\chi \sim A_i q_i \). Often the \( A \)-terms are suppressed relative to other soft terms, so it’s reasonable to expect \( \chi \) to be the LSP.

Contributions from soft scalar masses are on the order of \( m_i^2/f_i \) which can easily be suppressed.
Direct Detection

Relevant couplings from EWSB and anomaly:

\[
\mathcal{L} \supset \frac{c_h v}{2f} \bar{\chi} \partial \phi \chi h - \frac{c_{an}^2}{2M_\lambda f^2} \bar{\chi} \chi GG - \frac{ic_{an}^2}{2M_\lambda f^2} \bar{\chi} \gamma^5 \chi G\tilde{G}
\]

Effective coupling to nucleons: \( \mathcal{L} = G_{nuc} \bar{N}N\bar{\chi}\chi \),

\[
G_{nuc} = c_h \frac{\lambda_N}{2\sqrt{2}} \left( \frac{m_\chi m_N}{m_h^2 f^2} \right) + \frac{4\pi c_{an}^2}{9\alpha_s} \frac{m_N}{M_\lambda f} \left( 1 - \sum_{i=u,d,s} f_i^{(N)} \right)
\]
Direct detection: nucleon matrix elements

Nucleon matrix elements can be parameterized via

\[ m_i \langle N | \bar{q}_i q_i | N \rangle = f_i^{(N)} m_N \]

The heavy quark contribution via gluons can be calculated by the conformal anomaly, Phys. Lett. B78 433

\[ f_j^{(N)} m_N = \frac{2}{27} \left( 1 = \sum_{q=u,d,s} f_q^{(N)} \right) \quad j = c, b, t \]

Relevant quantity in Higgs exchange: \( c_q \), diagonalized Yukawa

\[ \lambda_N = \sum_{q=u,d,s} c_q f_q^{(N)} + \frac{2}{27} \left( 1 = \sum_{q=u,d,s} f_q^{(N)} \right) \sum_{q'=c,b,t} c_{q'} \]
Direct Detection

Some details:

\[ G_{\chi N} = c_h \frac{\lambda_N}{2\sqrt{2}} \left( \frac{m_\chi m_N}{m_h^2 f^2} \right) + \frac{4\pi c_{an}}{9\alpha_s} \frac{m_N}{M_\lambda f} \left( 1 - \sum_{i=u,d,s} f_i^{(N)} \right) \]

For reduced mass \( \mu_\chi = (m_\chi^{-1} + m_N^{-1})^{-1} \),

\[ \sigma_{SI}^{Higgs} = \frac{4\mu_\chi^2}{A^2 \pi} \left[ G_{\chi p} Z + G_{\chi n} (A - Z) \right] \]

\[ \sigma_{SI}^{H} \approx 3 \cdot 10^{-45} \text{ cm}^2 c_h^2 \left( \frac{115 \text{ GeV}}{m_h} \right)^4 \left( \frac{700 \text{ GeV}}{f} \right)^4 \left( \frac{m_\chi}{100 \text{ GeV}} \right)^2 \left( \frac{\mu_\chi}{1 \text{ GeV}} \right)^2 \left( \frac{\lambda_N}{0.5} \right)^2 \]

\[ \sigma_{SI}^{glue} \approx 2 \cdot 10^{-48} \text{ cm}^2 \left( \frac{700 \text{ GeV}}{M_\lambda} \right)^2 \left( \frac{700 \text{ GeV}}{f} \right)^4 \left( \frac{N_\psi}{5} \right)^4 \left( \frac{q_\psi}{2} \right)^4 \left( \frac{\mu}{1 \text{ GeV}} \right)^2 \]

using \( c_{an} = \alpha_s q_\psi N_\psi / 8\pi \)
Why are the $\chi\chi \to aa$ annihilations $p$-wave?

If the initial state is a particle-antiparticle pair with zero total angular momentum and the final state is CP even, then the process must vanish when $v = 0$.

Under CP a particle/antiparticle pair picks up a phase $(-)^{L+1}$. When $v = 0$ momenta are invariant and thus the initial state gets an overall minus sign. Since final state is CP even, the amplitude must vanish in this limit. For Dirac particles $P$ is sufficient, but for Majorana particles $CP$ is the well-defined operation.

This is why $\chi\chi \to G\tilde{G}$ is $s$-wave while $\chi\chi \to aa$ is $p$-wave.
Indirect detection: $\bar{\rho}$ flux vs. PAMELA

$f = 700$ GeV, $Q_\psi = 2$, $\delta = \frac{3}{2}$, $N_\psi = 5$

Dotted: $m_\chi = 150$ GeV, $b_1 = 1$

Solid: $m_\chi = 50$ GeV, $b_1 = 3$

Using Einasto DM Halo profile in 1012.4515, 1009.0224
Indirect detection: Fermi-LAT

**γ-ray line search:** 30 – 200 GeV
- Upper bound $\langle \sigma v \rangle_{\gamma\gamma} < 2.5 \times 10^{-27} \, \text{cm}^3/\text{s}$
- $\chi\chi \rightarrow a \rightarrow \gamma\gamma$ via anomaly
- For SU(5) fundamentals, $\langle \sigma v \rangle_{\gamma\gamma} \sim 2 \times 10^{-3} \langle \sigma v \rangle_{gg}$
- $\mathcal{O}(10)$ smaller than bound even for extreme parameters

**Diffuse γ-ray spectrum:** 20 – 100 GeV
- Bounds $\chi\chi$ to charged particles, $\pi^0$s
- $\chi\chi \rightarrow a \rightarrow gg$ via anomaly
- $\mathcal{O}(10)$ smaller than bound

**Photo-production from DM annihilation:** spheroidal galaxies
- Low mass DM $m_\chi \lesssim 60$ GeV, constrains $bb$ decays
- GF: annihilation $\sigma$ always at least a factor of 3 lower

Collider production

Collider production through gluons. **ISR monojet** signature is sensitive to $\sigma_{SI}^N \sim 10^{-46}$ cm$^2$ at the LHC with 100 fb$^{-1}$.

The dim-7 anomaly operators are too small:

$$\mathcal{L} \supset - \frac{c_{\text{an}}^2}{2M_\lambda f^2} \bar{\chi}\chi GG - \frac{ic_{\text{an}}^2}{2M_\lambda f^2} \bar{\chi}\gamma^5 \chi G \tilde{G}$$

$gg \to a^* \to \chi\chi$ may be within 5$\sigma$ reach with 100 fb$^{-1}$

1005.1286, 1005.3797, 1008.1783, 1103.0240, 1108.1196

**Cascade decays:** LOSP $\to \chi$ through

- $\bar{\chi}G\lambda$ anomaly
- $\chi - \bar{H}$ kinetic mixing

Decays typically prompt, a reconstruction is difficult for light masses. Heavy fermions $\Psi$ in anomaly may appear as “fourth generation” quarks
Nuclear matrix element and matching

The nucleon matrix element at vanishing momentum transfer:

\[ M_N = \langle \Theta_{\mu}^{\mu} \rangle = \langle N | \sum_{i=u,d,s} m_i \bar{q}_i q_i + \frac{\beta(\alpha)}{4\alpha} G^a_{\alpha\beta} G^a_{\alpha\beta} | N \rangle \]


\[ \beta = -\frac{9\alpha^2}{2\pi} + \cdots \] contains only the light quark contribution, \( M_N \) is the nucleon mass. The \( GG \) matches onto the nucleon operator \( \bar{N}N \).

\[ M_N f_{i=u,d,s}^{(N)} = \langle N | m_i \bar{q}_i q_i | N \rangle \quad f_g^{(N)} = 1 - \sum_{i=u,d,s} f_i^{(N)} \]
Nuclear matrix element and matching

\[
\frac{\beta(\alpha)}{4\alpha} G^a_{\alpha/\beta} G^a_{\alpha/\beta} \rightarrow M_N \left( 1 - \sum_{i=u,d,s} f^{(N)}_i \right) \bar{N}N
\]

Where \( f^{(N)}_{u,d} \ll f^{(N)}_s \approx 0.25 \). For a detailed discussion, see 0801.3656 and 0803.2360.
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