Dark Matters in Supersymmetry

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UC Berkeley

@Rutgers, April 22, 2013

Lawrence Hall, JTR, Tomer Volansky, 1302.2620
Cliff Cheung, Lawrence Hall, David Pinner, JTR 1211.4873
\[ m_h \]
$m_h$ \quad \overset{\sim}{\sim} \quad \tilde{m} \sim m_h$

\[125 \text{ GeV}\]
\[ m_h \]

natural

\[ \tilde{m} \sim m_h \]

unnatural

\[ \tilde{m} \gg m_h \]

125 GeV
- MSSM 1% tuned
- non-minimal options remain natural

\[ \tilde{m} \sim m_h \]

\[ \tilde{m} \gg m_h \]
For this talk, I am agnostic about naturalness.
a finely tuned world?

\[ \tilde{m} \gg m_h \]
a finely tuned world?

$$\tilde{m} \gg m_h$$

• what constrains $\tilde{m}$?
a finely tuned world?

\[ \tilde{m} \gg m_h \]

- what constrains \( \tilde{m} \)?

- what can we measure in experiments?
a finely tuned world?

\[ \tilde{m} \gg m_h \]

- what constrains \( \tilde{m} \) ?
- what can we measure in experiments?
The Future of Direct Dark Matter Searches

Spin-independent sensitivity

Graph showing the spin-independent sensitivity of WIMP-nucleon cross sections as a function of WIMP mass. The graph includes data from various experiments such as DAMA/Na, CoGeNT, CDMS (2010), CDMS (2011), CRESST (2011), EDELWEISS (2011), ZEPLIN-III, XENON100 (2010), XENON100 (2011), XENON100 (2012), and XENON1T (2017).
The Future of Direct Dark Matter Searches

Spin-independent sensitivity

experimental status of SUSY DM?
the plan

1. gravitino miracle

2. neutralino DM vs. experiment
the plan

1. gravitino miracle

2. neutralino DM vs. experiment
Gravitino Miracle

"I think you should be more explicit here in step two."

Lawrence Hall, JTR, Tomer Volansky, 1302.2620
\[ \langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2} \]

**WIMP miracle**

Comoving number density of a WIMP in the early Universe. The dashed curves are the actual abundance, and the solid curve is the equilibrium abundance.

From [31].

Increasing \( \langle \sigma v \rangle \)

**Figure 4.** Comoving number density of a WIMP in the early Universe.
WIMP miracle

\[ \langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2} \]

\[ x = \frac{m}{T} \] (time →)

The current entropy density is \( N \approx 4000 \) cm\(^{-3}\), and the critical density today is \( \rho_c \approx 10^{-5} \) GeV cm\(^{-3}\), where \( h \) is the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\), so the present mass density in units of the critical density is given by

\[ \frac{\rho}{\rho_c} = \frac{N}{N_{\text{eq}}} \]

The result is independent of the mass of the WIMP (except for logarithmic corrections), and is inversely proportional to its annihilation cross section.

Fig. 4 shows numerical solutions to the Boltzmann equation. The equilibrium (solid line) and actual (dashed lines) abundances per comoving volume are plotted as a function of \( x = \frac{m}{T} \).

Increasing \( \langle \sigma_A v \rangle \)
WIMP miracle

\[ \langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2} \]

\[ \tilde{m} Y_{FO} \leq T_{eq} \]
WIMP miracle

\[ \langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2} \]

\[ \tilde{m} Y_{FO} \leq T_{eq} \]

\[ Y_{FO} = \frac{n_{FO}}{s} = \frac{1}{M_p \langle \sigma v \rangle T_{FO}} \]
WIMP miracle

\[ \langle \sigma v \rangle = \frac{\alpha^2}{\tilde{m}^2} \]

\[ Y_{FO} = \frac{n_{FO}}{s} = \frac{1}{M_p \langle \sigma v \rangle T_{FO}} \]

\[ \tilde{m} Y_{FO} \leq T_{eq} \]

\[ \tilde{m} \leq \alpha \sqrt{T_{eq} M_p} \]
WIMP miracle

\[ \tilde{m} \leq \alpha \sqrt{T_{eq} M_p} \]

\[ \sqrt{T_{eq} M_p} \approx 60 \text{ TeV} \]

\[ \sim 1 \text{ eV} \quad \sim 10^{18} \text{ GeV} \]
WIMP miracle

\[ \tilde{m} \leq \alpha \sqrt{T_{eq} M_p} \]

\[ \sqrt{T_{eq} M_p} \approx 60 \text{ TeV} \]
WIMP miracle

applied to SUSY:

- mass scale of LSP is tied to the weak scale

• Goldberg, 1983
WIMP miracle

applied to SUSY:

- mass scale of LSP is tied to the weak scale
  - Goldberg, 1983
- in Split SUSY, invoked to keep fermions near weak scale
  - \( \tilde{q}, \tilde{l} \)
  - \( \tilde{B}, \tilde{W}, \tilde{g} \)
  - \( h \)
  - Wells, 2003
  - Arkani-Hamed, Dimopoulos 2004
WIMP miracle

applied to SUSY:

• mass scale of LSP is tied to the weak scale
  • Goldberg, 1983

• in Split SUSY, invoked to keep fermions near weak scale

  \[ \tilde{q}, \tilde{l} \]

  \[ \tilde{B}, \tilde{W}, \tilde{g} \]

  \[ h \]

• Wells, 2003
• Arkani-Hamed, Dimopoulos 2004

• relies on several assumptions!
WIMP miracle

key assumptions:
WIMP miracle

key assumptions:

1. stable LSP (R-parity)
WIMP miracle

key assumptions:

1. stable LSP (R-parity)
2. \[ T_R > \tilde{m} \]
WIMP miracle

key assumptions:

1. stable LSP (R-parity)
2. \( T_R > \tilde{m} \)
3. no dilution
key assumptions:

1. stable LSP (R-parity)
2. \( T_R > \tilde{m} \)
3. no dilution
4. LSP reaches equilibrium
WIMP miracle

key assumptions:

1. stable LSP (R-parity)
2. \( T_R > \tilde{m} \)
3. no dilution
4. LSP reaches equilibrium

\[ \alpha \sqrt{T_{eq} M_p} \quad T_R \quad \tilde{m} \]
WIMP miracle

key assumptions:

1. stable LSP (R-parity)
2. \( T_R > \tilde{m} \)
3. no dilution
4. LSP reaches equilibrium
WIMP miracle

key assumptions:

1. stable LSP (R-parity)
2. \( T_R > \tilde{m} \)
3. no dilution
4. LSP reaches equilibrium

what about gravitino LSP?
gravitino primer

\[
m_{3/2} \approx \frac{F}{M_p}
\]

\[
\tilde{m} = \frac{F}{M}
\]
gravitino primer

\[ m_{3/2} \approx \frac{F}{M_p} \]

\[ \tilde{m} = \frac{F}{M} \]
gravitino primer

\[ m_{3/2} \approx \frac{F}{M_p} \]

\[ \tilde{m} = \frac{F}{M} \]

\[ \frac{1}{F} J_{Q}^{\mu} \partial_{\mu} \tilde{G} \]

\[ M < M_p \]

\[ \tilde{N}_1 \]

\[ \tilde{G} \]
gravitino primer

\[ m_{3/2} \approx \frac{F}{M_p} \]

\[ \tilde{m} = \frac{F}{M} \]

\[ \frac{1}{F} \frac{m_\lambda}{4\sqrt{2}} \bar{\lambda} \sigma^{\mu\nu} F_{\mu\nu} \tilde{G} \]

\[ \frac{1}{F} \left( m_\psi^2 - m_\phi^2 \right) \bar{\psi}_L \phi \tilde{G} \]
gravitino loophole?

\[ \Omega_{3/2} = \frac{m_{3/2}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}} \]
gravitino production
gravitino production

scattering

\[ \tilde{g} \rightarrow T_R \]

\[ \tilde{G} \rightarrow T \]

\[ g \rightarrow \ldots \]
gravitino production

scattering

\[ \tilde{g} \rightarrow g \]

\[ \tilde{g} \rightarrow \tilde{G} \]

\[ \tilde{m} \rightarrow T_R \]

freeze-in

\[ \tilde{q} \rightarrow q \]

\[ \tilde{G} \rightarrow \tilde{G} \]
gravitino production

scattering

freeze-out and
decay
gravitino production

when is: \( \Omega_{3/2} \leq \Omega_{\text{obs}} \) ?
gravitino production

when is: \( \Omega_{3/2} \leq \Omega_{obs} \)?

a simple parameterization:

\[ \tilde{m}, \ m_{3/2}, \ T_R \]
gravitino production

\[ m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq} \]
gravitino production

\[ m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq} \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>scattering</td>
<td>( \frac{1}{m_{3/2}} \frac{m^2}{M_p} )</td>
</tr>
<tr>
<td>freeze-in</td>
<td>( \frac{1}{m_{3/2}} \frac{m^3}{M_p} )</td>
</tr>
<tr>
<td>freeze-out</td>
<td>( m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} )</td>
</tr>
</tbody>
</table>
gravitino production

\[ m_{3/2} Y_{UV} + m_{3/2} Y_{FI} + m_{3/2} Y_{FO} \leq T_{eq} \]

scattering \hspace{2cm} freeze-in \hspace{2cm} freeze-out

\[
\begin{array}{c}
m_{3/2} Y_{3/2} \\
\frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} \\
\frac{1}{m_{3/2}} \frac{\tilde{m}^3}{M_p} \\
m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p}
\end{array}
\]

constrains reheat temperature
constraining the reheat temperature

\[ m_{\tilde{q}} = 1 \text{ TeV} \]
\[ M_1 = 50 \text{ GeV} \]

Moroi, Murayama, Yamaguchi 1993
gravitino production

\[ m_{3/2} Y_{UV} + m_{3/2} Y_{FI} + m_{3/2} Y_{FO} \leq T_{eq} \]

<table>
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<tr>
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<th>freeze-in</th>
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<tbody>
<tr>
<td>( m_{3/2} Y_{3/2} )</td>
<td>( \frac{1}{m_{3/2}} ) ( \frac{T_R \tilde{m}^2}{M_p} )</td>
<td>( \frac{1}{m_{3/2}} ) ( \frac{\tilde{m}^3}{M_p} )</td>
</tr>
<tr>
<td></td>
<td>( \frac{m_{3/2}}{M_p} )</td>
<td>( m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} )</td>
</tr>
</tbody>
</table>
gravitino production

\[ m_{3/2}^Y_{UV} + m_{3/2}^Y_{FI} + m_{3/2}^Y_{FO} \leq T_{eq} \]

- **scattering**
  \[ \frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} \]
- **freeze-in**
  \[ \frac{1}{m_{3/2}} \frac{\tilde{m}^3}{M_p} \]
- **freeze-out**
  \[ m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \]

what about constraining \( \tilde{m} \)?

Wednesday, April 24, 13
gravitino production

\[ m_{3/2} Y_{UV} + m_{3/2} Y_{FI} + m_{3/2} Y_{FO} \leq T_{eq} \]

scattering \[ \frac{1}{m_{3/2}} \frac{\tilde{m}^2}{M_p} \]
freeze-in \[ \frac{1}{m_{3/2}} \frac{\tilde{m}^3}{M_p} \]
freeze-out \[ m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \]

different gravitino mass dependence
a bound with gravitino LSP

\begin{align*}
\tilde{m} &\rightarrow \\
m_{3/2} &\rightarrow \\
\text{overclosed}
\end{align*}
a bound with gravitino LSP

\[
\tilde{m} \quad \text{overclosed}
\]

scattering, freeze-in

\[
\Omega_{3/2} \propto \frac{1}{m_{3/2}}
\]

Wednesday, April 24, 13
a bound with gravitino LSP

\[ \tilde{m} \]

overclosed

\[ \Omega_{3/2} \propto \frac{1}{m_{3/2}} \]

scattering, freeze-in

freeze-out

\[ \Omega_{3/2} \propto m_{3/2} \]
a bound with gravitino LSP

overclosed

scattering, freeze-in
\[ \Omega_{3/2} \propto \frac{1}{m_{3/2}} \]

freeze-out
\[ \Omega_{3/2} \propto m_{3/2} \]

a bound!
the bound

\[ m_{3/2}Y_{UV} + m_{3/2}Y_{FO} \leq T_{eq} \]
the bound

\[ m_{3/2} Y_{UV} + m_{3/2} Y_{FO} \leq T_{eq} \]

\[ \frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} + m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \leq T_{eq} \]
the bound

\[ m_{3/2} Y_{UV} + m_{3/2} Y_{FO} \leq T_{eq} \]

\[ \frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} + m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \leq T_{eq} \]

abundance minimized when:

\[ m_{3/2} = \left( \frac{T_R}{\tilde{m}} \right)^{1/2} \alpha \tilde{m} \]
the bound

\[ m_{3/2}Y_{UV} + m_{3/2}Y_{FO} \leq T_{eq} \]

\[ \frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} + m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \leq T_{eq} \]

abundance minimized when:

\[ m_{3/2} = \left( \frac{T_R}{\tilde{m}} \right)^{1/2} \alpha \tilde{m} \]

\[ \tilde{m} \leq \left( \frac{T_R}{\tilde{m}} \right)^{-1/4} \alpha^{1/2} \sqrt{T_{eq} M_p} \]
the bound

\[ m_{3/2}Y_{UV} + m_{3/2}Y_{FO} \leq T_{eq} \]

\[
\frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} + m_{3/2} \frac{\tilde{m}}{\alpha^2 M_p} \leq T_{eq}
\]

abundance minimized when:

\[ m_{3/2} = \left( \frac{T_R}{\tilde{m}} \right)^{1/2} \alpha \tilde{m} \]

\[ \tilde{m} \leq \left( \frac{T_R}{\tilde{m}} \right)^{-1/4} \alpha^{1/2} \sqrt{T_{eq} M_p} \]

\[ \tilde{m} \leq \alpha^{1/2} \sqrt{T_{eq} M_p} \]
a bound with gravitino LSP

\[ \tilde{m} \]

\( \Omega_{3/2} \propto \frac{1}{m_{3/2}} \)

\[ \tilde{m} \leq \alpha^{1/2} \sqrt{T_{eq} M_p} \]

\( m_{3/2} \)

scatter, freeze-in

overclosed

freeze-out

\( \Omega_{3/2} \propto m_{3/2} \)
\( \frac{T_R}{\tilde{m}} = 1 \)

\( \tilde{m} \lesssim 38 \, \text{TeV} \)

\( \alpha_{\text{eff}} = 0.03 \) (wino)

\( \frac{m_3/2}{\tilde{m}} > 1 \)

overclosed

FI

BBN

FO
\[ \frac{T_R}{\tilde{m}} = 10^2 \]

\[ \tilde{m} \lesssim 16 \text{ TeV} \]
\[ \frac{T_R}{\tilde{m}} = 10^4 \]

\( \alpha_{\text{eff}} = 0.03 \) (wino)

\[ \tilde{m} \lesssim 5 \text{ TeV} \]
$\frac{T_R}{\tilde{m}} = 10^6$

$\alpha_{\text{eff}} = 0.03$ (wino)

$\tilde{m} \lesssim 1.1 \text{ TeV}$
thermalized gravitinos

• very light gravitinos thermalize: $Y_{UV} \sim \mathcal{O}(1)$
thermalized gravitinos

- very light gravitinos thermalize: $Y_{UV} \sim \mathcal{O}(1)$

\[
m_{3/2}^{2} \leq \left( \frac{T_R}{\tilde{m}} \right) \frac{\tilde{m}^{3}}{M_p} \approx \text{keV}^{2} \left( \frac{T_R}{\tilde{m}} \right) \left( \frac{\tilde{m}}{100 \text{ GeV}} \right)^{3}
\]
thermalized gravitinos

- very light gravitinos thermalize: \( Y_{UV} \sim \mathcal{O}(1) \)

\[
m^{2}_{3/2} \leq \left( \frac{T_R}{\tilde{m}} \right) \frac{\tilde{m}^3}{M_p} \approx \text{keV}^2 \left( \frac{T_R}{\tilde{m}} \right) \left( \frac{\tilde{m}}{100 \text{ GeV}} \right)^3
\]

- overclosure bound

\[
m_{3/2} \lesssim 100 \text{ eV}
\]

- Pagels, Primack 1982
thermalized gravitinos

• very light gravitinos thermalize: $Y_{UV} \sim \mathcal{O}(1)$

$$m_{3/2}^2 \lesssim \left( \frac{T_R}{\tilde{m}} \right) \frac{\tilde{m}^3}{M_p} \simeq \text{keV}^2 \left( \frac{T_R}{\tilde{m}} \right) \left( \frac{\tilde{m}}{100 \text{ GeV}} \right)^3$$

• overclosure bound

$$m_{3/2} \lesssim 100 \text{ eV}$$

• Pagels, Primack 1982

• free streaming length:

$$m_{3/2} \lesssim 16 \text{ eV}$$

• Viel et al., 2005
thermalized gravitinos

- implies low SUSY breaking scale

\[ m_{3/2} \lesssim 16 \text{ eV} \quad \rightarrow \quad \sqrt{F} \lesssim 260 \text{ TeV} \]

\[ \tilde{m} = \left( \frac{g_{\text{susy}}}{4\pi} \right)^2 \sqrt{F} \]
thermalized gravitinos

• implies low SUSY breaking scale

\[ m_{3/2} \lesssim 16 \text{ eV} \quad \Rightarrow \quad \sqrt{F} \lesssim 260 \text{ TeV} \]

\[ \tilde{m} = \left( \frac{g_{\text{susy}}}{4\pi} \right)^2 \sqrt{F} \]

• parametrically,

\[ m_{3/2} < T_{eq} \]

\[ F \leq T_{eq} M_p \quad \Rightarrow \quad \tilde{m} \leq \left( \frac{g_{\text{susy}}}{4\pi} \right)^2 \sqrt{T_{eq} M_p} \]
numerals

\[ \tilde{m} > \left( \frac{g_{\text{susy}}}{4\pi} \right)^2 \sqrt{F} \]

\[ g_{\text{susy}}^2 = 10 \]

\[ g_{\text{susy}}^2 = 3 \]

\[ g_{\text{susy}}^2 = 1 \]

\[ \alpha_{\text{eff}} = 0.03 \text{ (wino)} \]

\[ \text{overclosed} \]

\[ \text{Th} \]

\[ \text{FO} \]

\[ \text{UV} \]

\[ \text{BBN} \]

\[ \tilde{m} < m_{3/2} \]

\[ \text{Log}_{10} \frac{T_R}{\tilde{m}} \]
numerics

\[ m > \left( \frac{g_{\text{susy}}}{4 \pi} \right)^2 \sqrt{F} \]

\[ g_{\text{susy}}^2 = 10 \]

\[ g_{\text{susy}}^2 = 3 \]

\[ g_{\text{susy}}^2 = 1 \]

100\text{ warm}

thermalized

overclosed

\[ \alpha_{\text{eff}} = 0.03 \text{ (wino)} \]

\[ m_{3/2} [\text{GeV}] \]

\[ \tilde{m} > m_{3/2} \]

SM-superpartner LSP
non-thermal gravitino LSP
numerics

thermal gravitino LSP

\[ \tilde{m} > \left( \frac{g_{\text{susy}}}{4\pi} \right)^2 \sqrt{F} \]

\[ g_{\text{susy}}^2 = 10 \]

\[ g_{\text{susy}}^2 = 3 \]

\[ g_{\text{susy}}^2 = 1 \]

\[ \alpha_{\text{eff}} = 0.03 \text{ (wino)} \]

\[ \text{overclosed} \]

\[ \text{Th} \]

\[ \text{FO} \]

\[ \text{UV} \]

\[ \text{BBN} \]

\[ \tilde{m} < m_{3/2} \]

\[ \text{thermal gravitino LSP} \]
numerics

\[ \tilde{m} \leq 40 \text{ TeV} \]
generalizations

1. no freeze-out and decay
2. split SUSY
no freeze-out and decay
no freeze-out and decay
no freeze-out and decay

- RPV
- light hidden sector
- colored LOSP
no freeze-out and decay

- RPV
- light hidden sector
- colored LOSP

\[ \frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} \leq T_{eq} \]
no freeze-out and decay

- RPV
- light hidden sector
- colored LOSP

\[ \frac{1}{m_{3/2}} \frac{T_R \tilde{m}^2}{M_p} \leq T_{eq} \]

\[ m_{3/2} < \tilde{m} \]

\[ \tilde{m} \leq \left( \frac{T_R}{\tilde{m}} \right)^{-1/2} \sqrt{T_{eq} M_p} \]
no freeze-out and decay

\[ \tilde{m} \lesssim 1000 \text{ TeV} \]
split

\\ \tilde{q}, \tilde{l}

\tilde{B}, \tilde{W}, \tilde{g}

h
split

$T_R$

$\tilde{B}, \tilde{W}, \tilde{g}$

$h$
split

\[ T_R \]

\[ \tilde{B}, \tilde{W}, \tilde{g} \]

\[ h \]

- same as above with \( \tilde{m} \rightarrow m_f \)
split

\[ T_R \]

\[ \tilde{B}, \tilde{W}, \tilde{g} \]

\[ h \]

\[ \tilde{q}, \tilde{l} \]
gravitino production in split scattering

\[ m_{3/2} Y_{UV} + m_{3/2} Y_{FI} + m_{3/2} Y_{FO} \leq T_{eq} \]

<table>
<thead>
<tr>
<th>Term</th>
<th>Scattering</th>
<th>Freeze-in</th>
<th>Freeze-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{3/2} Y_{3/2} )</td>
<td>( \frac{1}{m_{3/2}} \frac{T_R \tilde{m}_f}{M_p} )</td>
<td>( \frac{1}{m_{3/2}} \frac{\tilde{m}_s^3}{M_p} )</td>
<td>( m_{3/2} \frac{\tilde{m}_f}{\alpha^2 M_p} )</td>
</tr>
</tbody>
</table>
gravitino production in split

\[ m_{3/2} Y_{UV} + m_{3/2} Y_{FI} + m_{3/2} Y_{FO} \leq T_{eq} \]

scattering \hspace{1cm} freeze-in \hspace{1cm} freeze-out

\[
\begin{array}{ccc}
\frac{1}{m_{3/2}} \frac{T_R \tilde{m}_f^2}{M_p} & \frac{1}{m_{3/2}} \frac{\tilde{m}_s^3}{M_p} & m_{3/2} \frac{\tilde{m}_f}{\alpha^2 M_p} \\
\end{array}
\]

depends on fermion mass
gravitino production in split scattering

\[ m_{3/2}Y_{UV} + m_{3/2}Y_{FI} + m_{3/2}Y_{FO} \leq T_{eq} \]

scattering: \[ \frac{1}{m_{3/2}} \frac{T_R \tilde{m}_f^2}{M_p} \]

freeze-in: \[ \frac{1}{m_{3/2}} \frac{\tilde{m}_s^3}{M_p} \]

freeze-out: \[ m_{3/2} \frac{\tilde{m}_f}{\alpha^2 M_p} \]

enhanced by large scalar mass
constraint on splitting
constraint on splitting

\[ \frac{\tilde{m}_s}{\tilde{m}_f} \lesssim 100 \]
DM and the Weak Scale

\[ m_{3/2} > \tilde{m} \]

\[ \alpha \sqrt{T_{eq} M_p} \]

\[ T_R \]

\[ \tilde{m} \]
DM and the Weak Scale

\[ m_{3/2} > \tilde{m} \]

\[ m_{3/2} < \tilde{m} \]
neutralino DM
-v-
experiment

\[ \tilde{G} \]

\[ \tilde{N}_1 \]

Cliff Cheung, Lawrence Hall, David Pinner, JTR 1211.4873
direct detection
direct detection

\begin{align*}
\text{spin-independent} & : & \overline{\chi} \chi \overline{N} N \\
\text{spin-dependent} & : & \overline{\chi} \gamma^\mu \gamma^5 \chi \ N \gamma_\mu \gamma^5 \ N
\end{align*}
direct detection

\[ \chi\chi\bar{N}N \]

spin-independent

\[ \sigma_{SI} \approx 6 \times 10^{-45} \text{ cm}^2 \left( \frac{c_{h\chi\chi}}{0.1} \right)^2 \]

spin-dependent

\[ \chi\gamma^\mu\gamma^5\chi \quad \bar{N}\gamma^\mu\gamma^5N \]

\[ \sigma_{SD} \approx 3 \times 10^{-39} \text{ cm}^2 \left( \frac{c_{Z\chi\chi}}{0.1} \right)^2 \]
direct detection

spin-independent

$\bar{\chi}\chi \bar{N}N$

$\sigma_{SI} \approx 6 \times 10^{-45} \text{ cm}^2 \left( \frac{c_{h\chi\chi}}{0.1} \right)^2$

spin-dependent

$\bar{\chi} \gamma^\mu \gamma^5 \chi \ N \gamma_\mu \gamma^5 N$

$\sigma_{SD} \approx 3 \times 10^{-39} \text{ cm}^2 \left( \frac{c_{Z\chi\chi}}{0.1} \right)^2$
spin-independent

\( \sigma_{p,n} [\text{cm}^2] \)

\( m_\chi [\text{GeV}] \)

\( \chi \chi h \)

XENON100
spin-independent
spin-independent
spin-dependent
Joint likelihood analysis of:

- Extended time period: 4 years
- Improved instrument response: P7REPCLEAN_V9
- Expanded photon energy range: 100 MeV - 500 GeV
- Constrain higher WIMP masses: 5 GeV - 10 TeV
- Same 10 dwarf galaxies

Model astrophysical backgrounds:

- 2FGL catalog sources (normalization free within 5˚)
- 2-year diffuse background models (normalization free)

Include statistical uncertainties in the solid-angle-integrated J-factor extended to 10 TeV.

updated in Alex Drlica-Wagner's talk, Fermi Symposium, 11/2012
collider

**LEP:** \( \mu, M_2 \gtrsim 100 \text{ GeV} \)

**CMS**

**ATLAS**
simplified model of neutralino DM

$$SM + \tilde{B}, \tilde{W}, \tilde{H}$$

$$\tilde{B}, \tilde{W}, \tilde{H}$$
simplified model of neutralino DM

\[ SM + \tilde{B}, \tilde{W}, \tilde{H} \]

- assume scalar superpartners can be decoupled when computing: \[ \sigma_{\chi N}, \Omega \]
simplified model of neutralino DM

\[ SM + \tilde{B}, \tilde{W}, \tilde{H} \]

- assume scalar superpartners can be decoupled when computing: \( \sigma_{\chi N}, \Omega \)
- assume CP
simplified model of neutralino DM

\[ SM + \tilde{B}, \tilde{W}, \tilde{H} \]

- assume scalar superpartners can be decoupled when computing: \( \sigma_{\chi N}, \Omega \)

- assume CP

- parameters:
  \( M_1, M_2, \mu, \tan \beta \)
thermal DM with pure eigenstates

- bino

- higgsino

- wino

$m_{\tilde{H}} \approx 1 \text{ TeV}$

$m_{\tilde{W}} \approx 2.7 \text{ TeV}$
well-tempered neutralino

\[ \Omega_X(\text{th}) \propto h^2 \]

\[ \mu = 500 \text{ GeV} \]
\[ M_2 \text{ decoupled} \]

\[ \Omega_{\text{obs}} \pm 3\sigma \]

\[ \tan \beta = 10 \]

well-tempered neutralino

\[ \Omega_{\chi} h^2 \]

\[ \mu = 500 \text{ GeV} \]

\[ M_2 \text{ decoupled} \]

\[ \Omega_{\text{obs}} \pm 3\sigma \]

\[ \tan \beta = 10 \]

\[ \tilde{b} \text{-like} \]

\[ \tilde{h} \text{-like} \]

well-tempered neutralino

\[ \Omega_{\chi}(\text{th}) \times h^2 \]

\[ \Omega_{\text{obs}} \pm 3\sigma \]

\[ \mu = 500 \text{ GeV} \]

\[ M_2 \text{ decoupled} \]

\[ \tan \beta = 10 \]

\[ \tilde{b} \text{-like} \]

\[ \tilde{h} \text{-like} \]

\[ M_1 [\text{GeV}] \]

\[ \tilde{B} \]

\[ \tilde{H} \]

under-abundant

**well-tempered neutralino**

\[ \Omega_{\chi} (\text{th}) h^2 \]

\[ \Omega_{\text{obs}} \pm 3\sigma \]

\[ \tan \beta = 10 \]

\[ M_1 \text{ [GeV]} \]

\[ \mu = 500 \text{ GeV} \]

\[ M_2 \text{ decoupled} \]

\[ \tilde{b}-\text{like} \]

\[ \tilde{h}-\text{like} \]

well-tempered

hidden dark matter
hidden dark matter

1. purity

\[ \chi \rightarrow \tilde{B}, \tilde{W}, \tilde{H} \]

\[ c_h x x \rightarrow 0 \]

decouple higgsinos or gauginos
hidden dark matter

1. purity

\[ \chi \rightarrow \tilde{B}, \tilde{W}, \tilde{H} \]
\[ c_{h\chi\chi} \rightarrow 0 \]

2. blindspots

\[ c_{h\chi\chi} = 0 \]

decouple higgsinos or gauginos

tuned cancellation
blindspots

\[ c_{h\chi \chi} = \frac{\partial m_\chi}{\partial v} = 0 \]
blindspots

\[
c_{h\chi\chi} = \frac{\partial m_\chi}{\partial v} = 0
\]

<table>
<thead>
<tr>
<th>( m_\chi )</th>
<th>condition</th>
<th>signs</th>
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<tr>
<td>( M_1 )</td>
<td>( M_1 + \mu \sin 2\beta = 0 )</td>
<td>( \text{sign}(M_1/\mu) = -1 )</td>
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<tr>
<td>( M_2 )</td>
<td>( M_2 + \mu \sin 2\beta = 0 )</td>
<td>( \text{sign}(M_2/\mu) = -1 )</td>
</tr>
<tr>
<td>( -\mu )</td>
<td>( \tan \beta = 1 )</td>
<td>( \text{sign}(M_{1,2}/\mu) = -1 )</td>
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<tr>
<td>( M_2 )</td>
<td>( M_1 = M_2 )</td>
<td>( \text{sign}(M_{1,2}/\mu) = -1 )</td>
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</tbody>
</table>

studied in singlet/doublet model by
Cohen, Kearney, Pierce, Tucker-Smith 1109.2604
bino-higgsino

- decouple wino
bino-higgsino

• decouple wino

• parameters

\[ M_1, \mu, \tan \beta \]
bino-higgsino

- decouple wino

- parameters
  \[ M_1, \mu, \tan \beta \]

- allow for non-thermal cosmology
  \[ \Omega_{FO} \neq \Omega_{obs} \]
non-thermal

\[ \tan \beta = 2 \]

\[ \Omega_{\text{thermal}} = \Omega_{\text{cdm}} \]

\[ c_{\text{ch})} = 0 \]

\[ \mu \text{ [GeV]} \]

\[ M_1 \text{ [GeV]} \]
non-thermal

\[ M_1 + \sin 2\beta \mu = 0 \]
non-thermal

**tan β = 2**

![Graph showing tan β = 2 with various regions labeled as LEP, Fermi, and XENON100]

**tan β = 20**

![Graph showing tan β = 20 with various regions labeled as LEP, Fermi, and XENON100]
non-thermal

\[ \tan \beta = 2 \]

\[ \tan \beta = 20 \]
non-thermal

\[ \tan \beta = 2 \]

\[ \tan \beta = 20 \]
non-thermal
non-thermal

\[ \tan \beta = 2 \]

\[ \tan \beta = 20 \]
\[ \Omega_{FO} = \Omega_{obs} \]

solve for:
\[ M_1 (\mu, \tan \beta) \]
well-tempered
M_1 + \sin 2\beta \mu = 0
well-tempered
well-tempered

\[ \tan \beta \]

\[ \mu \text{ [GeV]} \]

- LEP $\chi^- \chi^+$
- IceCube WW
- XENON100

\[ c_{\beta \beta} = 0 \]
well-tempered
well-tempered
well-tempered
target
Spin-independent sensitivity target
The Future of Direct Dark Matter Searches (next ~5 years)

Spin-independent sensitivity

Spin-independent cross-section for $\tilde{b}/\tilde{\chi}$
conclusions
conclusions

- gravitino miracle

\[ \tilde{m} < \alpha^n \sqrt{T_{eq} M_p} \]

LSP = \( \tilde{N}_1 \quad n = 1 \)

LSP = \( \tilde{G} \quad n = 1/2 \)
conclusions

- gravitino miracle

\[ \tilde{m} < \alpha^n \sqrt{T_{eq} M_p} \]

LSP =  \( \tilde{N}_1 \) \quad n = 1

LSP =  \( \tilde{G} \) \quad n = 1/2

- direct detection is now testing DM-Higgs coupling
conclusions

• gravitino miracle

\[ \tilde{m} < \alpha^n \sqrt{T_{eq} M_p} \]

LSP = \( \tilde{N}_1 \) \( n = 1 \)

LSP = \( \tilde{G} \) \( n = 1/2 \)

• direct detection is now testing DM-Higgs coupling

• but there are blindspots
backup
CDMS II silicon
gravitino bound

overclosure bound:

\[
C_{UV} \frac{T_R \tilde{m}^2}{m_{3/2}} + C_{FI} \frac{\tilde{m}^3}{m_{3/2}} + C_{FO} \frac{\tilde{m}m_{3/2}}{\alpha_{\text{eff}}^2} \leq aM_{Pl}T_{eq}
\]

rate coefficients:

\[
C_{UV} = \gamma_3 \frac{15\sqrt{90}}{2\pi^3 g_*^{3/2}} \quad C_{FI} = \frac{405}{2\pi^4} \sqrt{\frac{5}{2}} \frac{1}{g_*^{3/2}} \frac{n_{FI}}{4\pi} \quad C_{FO} = \frac{3\sqrt{5}x_f}{8\sqrt{2}g_*\pi^2}
\]

superpartner mass bound:

\[
\tilde{m}^2 \leq \frac{a/2}{\sqrt{C_{FO}C_D}} \alpha_{\text{eff}} M_{Pl} T_{eq} \quad C_D = C_{UV}(T_R/\tilde{m}) + C_{FI}
\]
variations on gravitino bound

Vary LOSP $\alpha_{\text{eff}}$

$T_R = \tilde{m}$

overclosed

$\tilde{m} < m_{3/2}$

Vary $\tilde{m}_c / \tilde{m}_{nc}$

$\alpha_{\text{eff}} = 0.03$ (wino)

$\frac{\tilde{m}_c}{\tilde{m}_{nc}} = 1, 10$

overclosed

$\tilde{m} < m_{3/2}$
neutralino mass matrix

\[
\begin{pmatrix}
M_1 & 0 & -\frac{g'}{\sqrt{2}} \cos \beta v & \frac{g'}{\sqrt{2}} \sin \beta v \\
0 & M_2 & \frac{g'}{\sqrt{2}} \cos \beta v & -\frac{g'}{\sqrt{2}} \sin \beta v \\
-\frac{g'}{\sqrt{2}} \cos \beta v & \frac{g'}{\sqrt{2}} \sin \beta v & 0 & -\mu \\
\frac{g'}{\sqrt{2}} \sin \beta v & -\frac{g'}{\sqrt{2}} \cos \beta v & -\mu & 0
\end{pmatrix}
\]
strange quark

\[ f_q = \frac{m_q}{m_N} \langle N | q\bar{q} | N \rangle \]

\[ \sigma \propto f^2 \]

\[ f = \sum_q f_q \]
strange quark

\[ f_s = 0.053 \]

Giedt, Thomas, Young, 0907.4177

<table>
<thead>
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<th>Method</th>
<th>( f_s )</th>
<th>Reference</th>
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<tr>
<td>Excluded</td>
<td>0.063(11)</td>
<td>[21] ( n_f = 2 + 1 )</td>
</tr>
<tr>
<td></td>
<td>0.032(25)</td>
<td>[14] ( n_f = 2 )</td>
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<tr>
<td></td>
<td>0.012(\pm 17)</td>
<td>[16] ( n_f = 2 )</td>
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<td>Direct</td>
<td>0.014(06)</td>
<td>[17] ( n_f = 2 + 1 + 1 )</td>
</tr>
<tr>
<td></td>
<td>0.048(15)</td>
<td>[18] ( n_f = 2 + 1 )</td>
</tr>
<tr>
<td>Direct</td>
<td>0.009(22)</td>
<td>[19] ( n_f = 2 + 1 )</td>
</tr>
<tr>
<td></td>
<td>0.046(11)</td>
<td>[20] ( n_f = 2 + 1 )</td>
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<tr>
<td></td>
<td>0.058(09)</td>
<td>[22] ( n_f = 2 + 1 )</td>
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<td>Feynman-Hellmann</td>
<td>0.023(40)</td>
<td>[19] ( n_f = 2 + 1 )</td>
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<td></td>
<td>0.033(17)</td>
<td>[13] ( n_f = 2 + 1, SU(3) )</td>
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<td></td>
<td>0.036(\pm 33)</td>
<td>[23] ( n_f = 2 + 1 )</td>
</tr>
<tr>
<td></td>
<td>0.075(73)</td>
<td>[24] ( n_f = 2 + 1 )</td>
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<td>0.023(22)</td>
<td>[25] ( n_f = 2 + 1, SU(3) )</td>
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<td>0.022(\pm 6)</td>
<td>[26] ( n_f = 2 + 1, SU(3) )</td>
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<td>0.134(63)</td>
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<td>0.053(19)</td>
<td>present work</td>
</tr>
<tr>
<td>Direct</td>
<td>0.043(11)</td>
<td>lattice average (see text)</td>
</tr>
</tbody>
</table>

Junnarkar, Walker-Loud 1301.1114
Figure 19: The impact of different choices of $f_s$ on the XENON100 limit for thermal bino/Higgsino DM, which was shown using the Giedt et al. value in the first panel of Fig. (7).

We compare the Giedt value to the default MicrOMEGAS value and $f_s = 0$, which is the most conservative choice.

To start, let us denote the log quantities, $\exp p_i \{ M_1, M_2, \mu, m_2 H_u, m_2 H_d, B_\mu \}$. (22)

Then it is natural to define a log gradient defined as a directional directive with respect to log parameters, $\sim r_i \partial \partial p_i$. (23)

We can now define a vector in this space equal to the gradient of the electroweak symmetry breaking vacuum expectation value, $\sim V_i \log v^2$. (24)

Here $\sim V$ is equal to the direction of steepest descent away from a particular value of $v$—thus, it is the combination of ultraviolet parameters which most strongly affect electroweak symmetry breaking. In order to remove dependence on the possible fine-tuning of the electroweak symmetry breaking sector, we are interested in dependencies on parameters orthogonal to $\sim V$. Explicitly, any $v$ dependent observable can be written as $\sim O_i = \partial O / \partial \log v^2 \sim V + ...$, (25)

strange quark
Figure 8: Relic density and SI cross-section tuning for well-tempered bino/Higgsino, with the reach of LUX and XENON1T also shown in the second panel. Tuning of the relic density is typically between 2 - 10%. If XENON1T does not see a signal, tuning of the SI cross-section will be ≈1%. The interpretation of this as being unnatural is unclear however, as most of the region of $1 < \tan \beta < 2$ with $|\mu| < |M_1|$ has large $\tan \beta$. We describe our methodology for computing tuning in App. B.

The correct relic abundance at low $\tan \beta$, since both a large mixing angle and a small Higgs coupling require $|\mu| \ll |M_1|$. Furthermore, many theories, both natural and unnatural, require small $\tan \beta$ in order to explain the 125 GeV Higgs mass, as in SUSY and Split Supersymmetry. Thus the region of parameter space which evades XENON1T is exactly the same region in which $2 < \mu < |M_1|$.
SD cross-section for $\tilde{b}/\tilde{h}$

\[ \sigma_{SD} \text{ [cm}^2] \]

- XENON100
- IceCube $t\bar{t}$
- IceCube $W^+W^-$
- $\tan \beta < 2$

$m_\chi$ [GeV]
blindspots

\[ \mathcal{L} \supset \frac{1}{2} m_\chi (v + h) \chi^2 = \frac{1}{2} m_\chi \chi^2 + \frac{1}{2} \frac{\partial m_\chi}{\partial v} h \chi^2 + \ldots \]

Higgs-DM-DM coupling:

\[ c_{h\chi\chi} = \frac{\partial m_\chi}{\partial v} = 0 \]

\[ \det(M_\chi - 1 m_{\chi_i}(v)) = 0 \]

\[ (m_{\chi_i}(v) + \mu \sin 2\beta) \left( m_{\chi_i}(v) - \frac{1}{2}(M_1 + M_2 + \cos 2\theta_W(M_1 - M_2)) \right) = 0 \]
multi-component

Figure 6: Limits and projected reaches for multi-component bino/Higgsino DM with $\tan \beta = \tan \beta^{(th)}$. Dotted brown lines are contours of $\Omega_x^{(th)}/\Omega_{\text{obs}}$ for $\tan \beta = 2$. The lighter region is excluded by overabundance of neutralino DM, while the edge of this region has $\Omega_x^{(th)}/\Omega_{\text{obs}} = \Omega_{\text{obs}}$. In the remainder of the plane is just one component of multi-component DM. The present limit from XENON100 is shown shaded, while the projected reaches of LUX and XENON1T, both SI and SD, are shown as dashed lines.

Some of these allowed regions will be probed by experiments sensitive to the SD scattering cross-section. Intriguingly, the case of non-thermal Higgsino DM at low $\tan \beta$ resides simultaneously in a blind spot for SI and SD scattering! Furthermore, this region allows low values of $\mu$, and therefore relatively natural theories of electroweak symmetry breaking. In addition, large unnatural regions with $\mu > 1 - 2$ TeV will remain viable, but require late entropy production, especially for low $M_1$.  

5.2 Multi-Component Dark Matter with $\Omega_x = \Omega_x^{(th)}$ Here we repeat the analysis of the previous section under the assumption that the present day relic abundance of neutralino DM is given by $\Omega_x^{(th)}$, with the balance of cosmological DM arising from some other source. Fig. (6) depicts both the current limit and the projected reach for such multi-component neutralino DM, for $\tan \beta = 2$. Regions shaded light gray have $\Omega_x^{(th)}/\Omega_{\text{obs}} > 1$ and are thus excluded, while regions with $\Omega_x^{(th)}/\Omega_{\text{obs}} < 1$ have a complete abundance.
indicating that our results are robust to loop corrections. However, we see that this ratio is small throughout most of parameter space, except for small regions near the blind spot. Even here, it is only at low parameter space, except for small regions near the blind spot. Even here, it is only at low

\[ \sigma_{\text{loop}} = |Z_{11}|^2(1 - |Z_{11}|^2) \times (2 \times 10^{-47} \text{ cm}^2) \]

The contours show the bino fraction of DM, \( \sin^2 \theta_b \), respectively, with the XENON1T reach as in Fig. (5).

Non-thermal and thermal DM are shown in the upper and lower panels, respectively, with the XENON1T reach as in Fig. (20): Estimated importance of loop corrections for bino/Higgsino DM, relative to the

The loop correction to the Higgsino cross-section from Ref. [3], respectively, with the XENON1T reach as in Fig. (20): Estimated importance of loop corrections for bino/Higgsino DM, relative to the

To the loop contribution coming from mixing, but the largest individual loop diagram for pure al a r g ew i n oc o m p o n e n t . I nt h i sc a s et h e r ea r ec o m p e t i n ge

The loop correction to the Higgsino cross-section from Ref. [3], respectively, with the XENON1T reach as in Fig. (20): Estimated importance of loop corrections for mixed DM with

We have not included an estimate of the importance of loop corrections for mixed DM with


D. S. Akerib


D. S. Akerib

et al. [XENON100 Collaboration], arXiv:1207.5988 [astro-ph.IM].


D. S. Akerib


with squarks

Figure 9: Impact of squarks on thermal bino/Higgsino DM, with $\mu < 0$. A specific point $M_1$ has been chosen so that $\Omega_\text{DM}/h^2 = \Omega_\text{DM}^{\text{obs}}$, except in the gray region where freeze-out always yields overclosure. The upper left region, where freeze-out is dominated by squark-neutralino coannihilation, is excluded by XENON100. However, in the lower right region the XENON100 limit becomes less powerful as the s-channel squark exchange amplitude has the opposite sign to the t-channel Higgs exchange diagram. The purple region is excluded by an LHC search for jets and missing transverse energy, with the gluino mass fixed at 2 TeV. This ATLAS search becomes less powerful as the gluino mass is increased, and the excluded region becomes bounded by the purple dashed line if the gluino is decoupled. The currently allowed region, shown in white, mostly has a SI scattering cross-section that is not far below the current bound, so that LUX will have a large discovery potential. In the absence of a signal at LUX (XENON1T) the only surviving region will be the narrow band between the dashed green (red) lines.

We now consider the effects of including the wino in the spectrum. Compared to the previous section, reintroducing the wino adds an extra parameter, so that now we have a four dimensional parameter space of $(M_1, M_2, \mu, \tan \beta)$. In general, the LSP is now a combination of bino, Higgsino and wino, but much of our attention will focus on the case of a dominant bino/wino mixture. Even when the dark matter has a very small Higgsino component, the value of the $\mu$ parameter is crucial for direct detection: in the limit of decoupled $\mu$, bino/wino dark matter has vanishingly...
non–thermal $\tilde{B}/\tilde{W}/\tilde{h}$

**current limits**

- $\Omega_\chi^{(th)} = \Omega_{\text{obs}}$
- $\tan \beta = 2$
- $\mu = 750 \text{ GeV}$
- $m_{\chi^*} < m_{\chi^0}$
- $c_{h\chi} = 0$

**future reach**

- $\Omega_\chi^{(th)} = \Omega_{\text{obs}}$
- $\tan \beta = 2$
- $\mu = 750 \text{ GeV}$
- $m_{\chi^*} < m_{\chi^0}$
- $c_{h\chi} = 0$
purity

- tree-level Higgs coupling vanishes for pure higgsino or Wino

- loop contribution smaller than expected

**Figure 1:** One-loop diagrams which induce effective coupling of EW-IMP with gluon. There are also boson crossing diagrams, which are not shown here. Consequently, the gauge invariance of the short-distance contribution is guaranteed since summation of the both contribution is obviously gauge invariant. This is applicable to compute the two-loop diagrams in our case. For the calculation of diagrams (b) and (c), on the other hand, we follow the steps corresponding to long-distance contribution. The Majura field $\tilde{\chi}$ is the weak mixing angle. The Majorana field $\tilde{q}$, $\tilde{g}$, and $\tilde{c}$ denote the short-distance and long-distance contributions of heavy quarks in the loop, and get $\tilde{h}$ because its contribution to the operator $(14)$ is evaluated from scalar-type effective coupling of EW-IMP with gluon. The Majorana field $\tilde{q}$, $\tilde{g}$, and $\tilde{c}$ correspond to $\tilde{h}$, $\tilde{W}$, and $\tilde{H}$

- **Figure 3:** Relevant two-loop diagrams which contribute to effective coupling of EW-IMP DM with gluon. There are also $W$-boson exchange diagrams, which are not shown here.

- **Figure 2:** $m_X = 250$ GeV

- [Hisano, Ishiwata, Nagata, Takesako 1104.0228]
- [Hill, Solon 1111.0016]