Beyond the WIMP Miracle

Shufang Su • U. of Arizona

Pitt-PACC LDM workshop
Nov 16, 2011
Beyond the WIMP Miracle

- WIMP miracle
- WIMPless
  - general framework
  - light dark matter
  - collider signature
- superWIMP
Zoo of dark matter

mass and interaction strengths span many, many orders of magnitude

Some Dark Matter Candidate Particles

- neutrinos
- neutralino
- KK photon
- branon
- LTP
- axion
- axino
- gravitino
- KK graviton
- SuperWIMPs: wimpzilla
- Black Hole Remnant
- Q-ball
- wimpless
- WIMPs: wimp
- fuzzy CDM

HEPAP/AAAC DMSAG Subpanel (2007)
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  - SuperWIMPs: wimpzilla
  - WIMPs: Black Hole Remnant, Q-ball, wimp-less
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- appear in particle physics models motivated independently by attempts to solve EWSB
  - relic density are determined by $m_{pl}$ and $m_{\text{weak}}$
  - naturally around the observed value
  - no need to introduce and adjust new energy scale

mass and interaction strengths span many, many orders of magnitude
WIMP

Weak Interacting Massive Particle

- $m_{\text{WIMP}} \sim m_{\text{weak}}$
- $g_{\text{weak}}^2$
WIMP miracle

**WIMP**: Weak Interacting Massive Particle

- $m_{\text{WIMP}} \sim m_{\text{weak}}$
- $\sigma_{\text{an}} \sim \alpha_{\text{weak}}^2 m_{\text{weak}}^{-2}$

$$\Omega h^2 \sim \frac{2.6 \times 10^{-10} \text{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

$$\langle \sigma_A v \rangle \sim \frac{\alpha^2}{m_{\text{weak}}^2} 0.1 \sim 10^{-9} \text{GeV}^{-2}$$

$$\Rightarrow \Omega h^2 \sim 0.3$$

*naturally around the observed value*

- **WIMP** appears in many BSM scenarios
  - lightest supersymmetric particles in SUSY models
  - lightest KK particles in extra dimension models
  - ...
**WIMP miracle**

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$$\langle \sigma A \nu \rangle \sim \frac{\alpha^2}{m_{\text{weak}}^2} 0.1 \sim 10^{-9} \text{GeV}^{-2}$$

⇒ $\Omega h^2 \sim 0.3$

- Naturally around the observed value

- **WIMP appears in many BSM scenarios**
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  - ...

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Is it necessary to have both?
Is it necessary to have both? 

WIMPless

- $m_{\text{WIMP}} \sim m_{\text{weak}}$
- $g_{\text{weak}}^2$
**WIMPless miracle**

\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

- only fixes one combination of dark matter mass and coupling
- \( m_X/g_X^2 \sim m_{\text{weak}}/g_{\text{weak}}^2, \Omega h^2 \sim 0.3 \)

**WIMPless DM**

J.L. Feng and J. Kumar, PRL 101, 231301 (2008)
Feng, Shadmi, PRD 83, 095011 (2011)
Feng, Rentala, Surujon, 1108.4689

- dark matter: no SM gauge interactions, not WIMP
- naturally obtain right relic density: similar to WIMP
WIMPless miracle

J.L. Feng and J. Kumar, PRL 101, 231301 (2008)

- Dark matter is hidden no SM interactions
- DM sector has its own particle content, mass $m_X$, coupling $g_X$
- Connected to SUSY breaking sector

\[ \frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M} \]

\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

right relic density!
(irrespective of its mass)
If no direct coupling to SM:
- interact only through gravity
- impact on structure formation
- no direct/indirect/collider signals
**WIMPless: not hidden**

If no direct coupling to SM:
- interact only through gravity
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\[ m_Y \sim \max (m_{\text{weak}}, m_x) \quad \text{interaction } \lambda \ X Y f \]
If no direct coupling to SM:
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\[ m_Y \sim \max (m_{\text{weak}}, m_X) \]

interaction \( \lambda XYf \)

- indirect detection
  \( XX \rightarrow ff, YY \)
- direct detection
  \( Xf \rightarrow Xf \)
- collider: 4th generation fermions
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open new possibility for
- DM model parameters
- new experimental search windows

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light dark matter
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interaction \( \lambda XYf \)

- indirect detection \( XX \rightarrow ff, YY \)
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WIMPless: not hidden

light dark matter

open new possibility for
- DM model parameters
- new experimental search windows

provide a framework that
- guarantee DM relic density
- allow freedom in DM-SM interaction
Two events around g keV expected limit in absence of a signal above background is negligible at a minimum confidence level. The limit is shown in Fig. 1 and incorporated into the limit. The resulting ndS in the background expectation and in Se energy resolution governed by Poisson fluctuations of Vihh WIMPs are assumed to be distributed in an isothermal germanium limit on the spin-independent WIMP-nucleon cross-section σ. 


Small mass, large σ_Si, DAMA vs. CoGeNT? Reconcile with CDMS/XENON? 

XENON 100: 1104.2549
Light dark matter

light DM with large $\sigma_{SI}$

- **not generic in typical WIMP**
  - $\sigma_{SI}$: chirality flip, proportional to Yukawa coupling


- **can be easily accommodated in WIMPless model with connector Y**


\[
W = \sum_i (\lambda_q^i XY q_L^i q_L^i + \lambda_u^i XY u_R^i u_R^i + \lambda_d^i XY d_R^i d_R^i)
\]

- $Y_{qL} : (3, 2, \frac{1}{6})$
- $Y_{uR} : (3, 1, \frac{2}{3})$
- $Y_{dR} : (3, 1, -\frac{1}{3})$

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Light dark matter

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- **can be easily accommodated in WIMPless model with connector $Y$**


\[ W = \sum_i (\lambda_i^q X Y_{qL} q_i^L + \lambda_i^u X Y_{uR} u_i^R + \lambda_i^d X Y_{dR} d_i^R) \]

- **not chirality opposite chirality of SM quark**

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Light dark matter

**light DM with large $\sigma_{SI}$**

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\]

- **not chirality opposite chirality of SM quark**

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- **Exotic mirror quarks**

  \[
  \begin{align*}
  Y_{qL} & : (3, 2, \frac{1}{6}) \\
  Y_{uR} & : (3, 1, \frac{2}{3}) \\
  Y_{dR} & : (3, 1, -\frac{1}{3})
  \end{align*}
  \]
Connector couple with first two gen.

- first two generations,
- tree level scattering $\Rightarrow \lambda \sim 0.03$

![Diagram of connector particles](image)

- Equations:
  - $\lambda$
  - $\gamma$

- Graph showing cross sections for spin-independent scattering with connector mass $m_X$.

- J.L. Feng and J. Kumar, PRL 101, 231301 (2008)

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### Connector couple with third gen.

- **third generation**
  - loop level scattering, $\lambda \sim 0.3-1$,
  - more natural
  - less constrained by FCNC

![Diagram of third generation](image)

![Graph of direct detection cross sections](image)

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**Isospin violating dark matter**

**DM scattering off a nucleus: coherent**

\[ \sigma_A \sim (f_p Z + f_n (A-Z))^2 \]

**usual assumptions:** \( f_p = f_n \)
- \( \sigma_A \sim (f_p A)^2 \)
- results for various target nuclei in \((m, \sigma_p)\) plane
- \( A^2 \) scaling

**isospin violation** \( f_p \neq f_n \)
- could appear in many BSM
- decouple one exp with \( f_n/f_p = -Z/(A-Z) \)
- not exact cancellation due to isotopes

\[
\sigma_N^Z = \sigma_p \sum_{i=iso} \eta_i \mu_{A_i}^2 \left[ Z + \frac{f_n}{f_p}(A_i - Z) \right]^2 \frac{\sum_i \eta_i \mu_{A_i}^2 A_i^2}{\sum_i \eta_i \mu_{A_i}^2 A_i^2}
\]

Giuliano (2005);
Feng, Kumar, Marfatia, Sanford (2011)
Isospin violating dark matter

$f_n / f_p = 1$

- hard to fit all three signals
- CDMS, CoGeNT both Germanium based
- SIMPLE gets tighter

$f_n / f_p = -0.7$

Feng, Kumar, Marfatia, Sanford (2011)
Realization of IVDM in WIMPless

- at nucleon level: $f_p \neq f_n$
- at quark level: $W = \sum_i (\lambda_q^i X Y_{qL} q^i_L + \lambda_u^i X Y_{uR} u^i_R + \lambda_d^i X Y_{dR} d^i_R)$

- SI operators
- isospin violating

$\mathcal{O}_i = \lambda_q^i \lambda_u^i X X \bar{u}^i u^i / m_Y + \lambda_q^i \lambda_d^i X X \bar{d}^i d^i / m_Y$

$f_{p,n}/M_*^2 = \sum_i (\lambda_q^i \lambda_u^i B_{u}^{p,n} + \lambda_q^i \lambda_d^i B_{d}^{p,n}) / (\sqrt{\pi} m_X m_Y)$

$f_n/f_p \sim -0.7$

$\lambda_u^1 \simeq -1.08 \lambda_d^1$, $0.013 \lesssim \lambda_q^1 \lambda_d^1 \lesssim 0.024$

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Collider constraints

\[ O_i = \frac{\lambda_q^i \lambda_{u,d}^i X X \bar{u}^i u^i}{m_Y} + \frac{\lambda_q^i \lambda_{u,d}^i X X \bar{d}^i d^i}{m_Y} \]

- monojet @ Tevatron: \( \lambda_q \lambda_{u,d} < 1 \), two orders of magnitude too weak

- jets+MET @ Tevatron and LHC, 1 fb\(^{-1}\): tension with IVDM

Feng, Kumar, Marfatia, Sanford, 1102.4331

Rajaramam, Shepherd, Tait, Wijangco, 1108.1196

- X: fermion (vs. scalar)
- minimal flavor violation
- SU(2) breaking term \( \sim m_q \)
jets+MET @ Tevatron and LHC, 1 fb^{-1}: tension with IVDM

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\[
O_i = \lambda^i_q \lambda^i_u X X \bar{u}^i u^i / m_Y + \lambda^i_q \lambda^i_d X X \bar{d}^i d^i / m_Y
\]

**Collider constraints**

- **X**: fermion (vs. scalar)
- **minimal flavor violation**
- **SU(2) breaking term**: $\sim m_q$

\[\text{IVDM (with scalar) is still a viable solution ...}\]
Collider signature: exotic quarks

Y particle appears as exotic mirror quarks $Q'$

 Collider Signal (4th gen)
$T'T' \rightarrow ttXX, B'B' \rightarrow bbXX$

- differ from SUSY searches: cascade decay
- differ from usual 4th generation quark $T' \rightarrow Wb, B' \rightarrow Wt$

J. Alwall, J.L. Feng, J. Kumar, SS 1002.3366; 1107.2919.
Collider Signature: exotic quarks

Collider Signal: $T'T' \to ttXX, B'B' \to bbXX$

- **Connection to solution for Hierarchy problem**
  - need top partner
  - the lighter, the more natural
  - decay straight to invisible particles
  - bottom partner

- **appears in a general set of new physics scenarios**
  - light stop/sbottom
  - asymmetric dark matter
  - little Higgs with T-parity
  - baryon and lepton number as gauge symmetry
  - ...

relevant for re-examine of naturalness based on LHC data, light stop/sbottom signatures.

B. Dutta and J. Kumar, arXiv: 1012.1341
Constraints

- **perturbativity constraints:** $m_{Q'} = y_{Q'} v$, $m_{Q'} \leq 600$ GeV (if through Yukawa)
- **precision electroweak data:** $|m_{T'} - m_{B'}| \sim 50$ GeV (for SU(2) doublet)
- **direct searches limits**

**B'B' \rightarrow bbXX**, similar to sbottom pair production with

![Graphs showing constraints on leptoquark and bottom squark masses](image)

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V. M. Abazov et al. [D0 Collaboration], 1005.2222
Constraints

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- direct searches limits

$B'B' \rightarrow bbXX$, similar to sbottom pair production with

$$m_{s_b} > 247 \text{ GeV} \Rightarrow m_{B'} > 365 \text{ GeV}$$

V. M. Abazov et al. [D0 Collaboration], 1005.2222
**B’: Tevatron Reach**

**Signal:** $B' B' \rightarrow b b X X$

**Bg:** $W(l\nu)jj, Z(\nu\nu) jj, WZ, \text{ttbar, single top.}$

- Optimal cuts (after precuts)
- $S/B > 0.1$, more than 2 events
- Poisson statistics

---

**Exclusion for $B' \overline{B'} \rightarrow b X \overline{b} X$ at Tevatron**

- $m_B = m_X + m_b$
- $m_X$ (GeV)
- $m_B$ (GeV)
- $m_B' = m_X + m_b$
- $m_B' = m_X + m_b$
- $10 \text{ fb}^{-1}$
- $20 \text{ fb}^{-1}$
- $5 \text{ fb}^{-1}$

---

**Discovery for $B' \overline{B'} \rightarrow b X \overline{b} X$ at Tevatron**

- $m_B = m_X + m_b$
- $m_B' = m_X + m_b$
- $10 \text{ fb}^{-1}$
- $20 \text{ fb}^{-1}$
- $5 \text{ fb}^{-1}$
**B': Tevatron Reach**

**Signal:** $B'B' \rightarrow bbXX$

**Bg:** $W(l\nu)jj, Z(\nu\nu) jj, WZ, tt\bar{t}, \text{single top.}$

- optimal cuts (after precuts)
- $S/B > 0.1$, more than 2 events
- Poisson statistics

### Exclusion for $B' \overline{B'} \rightarrow b \ X \overline{b} \ X$ at Tevatron

$m_{B'} > 440 \text{ GeV with 5 fb}^{-1}$

### Discovery for $B' \overline{B'} \rightarrow b \ X \overline{b} \ X$ at Tevatron

$m_{B'} = m_X + m_b$

- $20 \text{ fb}^{-1}$
- $10 \text{ fb}^{-1}$
- $5 \text{ fb}^{-1}$
LHC reach

B’B’ → bbXX

- optimal cuts (after precuts)
- $S/B > 0.1$, more than 2 events
- Poisson statistics

Exclusion for $B' \bar{B}' \rightarrow b \bar{b} X \bar{X}$ at 7 TeV LHC

Discovery for $B' \bar{B}' \rightarrow b \bar{b} X \bar{X}$ at 7 TeV LHC
Simulation

MadGraph - Pythia - PGS

Signal:

\[ T'^- \bar{T}' \rightarrow t^{(*)} X \bar{t}^{(*)} X \rightarrow bW^+ X \bar{b}W^- X \]

- **hadronic channel:** large cross section
  - SM backgrounds, tt, W, have MET with lepton
  - irreducible background: \( Z \rightarrow \nu\nu + \text{jets} \)
- **semi-leptonic channel:** isolated lepton, suppress QCD background
- **purely leptonic channel:** suppressed cross section

Similar analyses in the literature

- **semileptonic mode, high mass, large luminosity**
  

- **hadronic mode, spin and mass determination**

Exclusion for $T' \bar{T}' \rightarrow t \bar{t} \, X \, \bar{X}$ at the Tevatron

- Optimal cuts (after precuts)
- $S/B > 0.1$, more than 2 events
- Poisson statistics

J. Alwall, J.L. Feng, J. Kumar, SS, 1002.3366
optimal cuts (after precuts)
S/B > 0.1, more than 2 events
Poisson statistics

J. Alwall, J.L. Feng, J. Kumar, SS, 1002.3366

Exclusion for $T' \bar{T'} \rightarrow t \bar{t} X \bar{X}$ at the Tevatron

Figure 4 shows the $3\sigma$ exclusion reach at the Tevatron for $95\%$ C.L using the hadronic mode. For smaller luminosity and $\sigma$, the LHC exclusion reach for $T'$ exceeds the Tevatron exclusion reach with $20 \text{ fb}^{-1}$. With just $4.8 \text{ fb}^{-1}$, more than 2 events are produced nearly at rest in the transverse boost for the semileptonic channel.

For each point in parameter space, the $m_{T'} = m_{X} + m_{t}$ is decreased because of the softness of the $X$ particle distributions, while for larger $m_{X}$, the reach is extended to $400 \text{ GeV}$ for $2 \text{ fb}^{-1}$, $455 \text{ GeV}$ for $10 \text{ fb}^{-1}$, and $520 \text{ GeV}$ with $100 \text{ fb}^{-1}$.

For each point in parameter space, the $m_{T'}$ decreases.

By Gaussian equivalent, we mean that we have converted the on deviation in a two-sided Gaussian distribution, which is commonly used in the literature.

T. Aaltonen et al. [CDF Collaboration], arXiV:1103.2482

Exclusion curves at the Tevatron for $3\sigma$ confidence levels, with $m_{X}$ from $100 \text{ pb}$ to $1000 \text{ pb}$, for integrated luminosities 2, 5, 10, and 20 $\text{ fb}^{-1}$. The reach in $m_{X}$ for $20 \text{ fb}^{-1}$ integrated luminosity, the reach is extended to $400 \text{ GeV}$ for $T'$ up to 360 GeV and $455 \text{ GeV}$ for the Tevatron running, a reach of up to 490, 520, and 535 GeV could be achieved with 100, 200, and 300 $\text{ pb}^{-1}$, respectively.

Semileptonic channel (left) and the hadronic channel (right) for integrated luminosities 2, 5, 10, and 20 $\text{ fb}^{-1}$. The hadronic channel is more promising than the semi-leptonic channel (right) for integrated luminosities 2, 5, 10, and 20 $\text{ fb}^{-1}$.
ATLAS, 1.04 fb⁻¹, ttbar+MET, 1 lepton, >=4 j, + MET

Constraints: direct search

ATLAS, 1.04 fb⁻¹, ttbar+MET, 1 lepton, >=4 j, + MET

m_{T'} > 420 GeV for mX<10 GeV
m_{T'} > 370 GeV for mX<140 GeV

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ATLAS, 1109.4725
WIMP

- $m_{\text{WIMP}} \sim m_{\text{weak}}$
- $g_{\text{weak}}^2$
WIMP

\begin{itemize}
  \item \( m_{\text{WIMP}} \sim m_{\text{weak}} \)
  \item \( g_{\text{weak}}^2 \)
\end{itemize}

WIMPLESS

\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \quad \text{follow WIMP relation} \]
\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

Not follow WIMP relation, DM interaction $\ll$ Weak interaction. Possible?

- $m_{\text{WIMP}} \sim m_{\text{weak}}$
- $g_{\text{weak}}^2$
\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

\textit{WIMP}\hspace{2cm} \textit{WIMPLESS}\hspace{2cm} \textit{superWIMP}

- \( m_{\text{WIMP}} \sim m_{\text{weak}} \)
- \( g_{\text{weak}}^2 \)

Not follow WIMP relation, DM interaction \( \ll \) Weak interaction. Possible?
SuperWIMP / Extremely WIMP

Not follow WIMP relation, DM interaction $\ll$ Weak interaction. Possible?

CDM requirements

- Stable
- Non-baryonic
- Neutral
- Cold (massive)
- Correct density
- Gravitational interacting
  (much weaker than weak interaction)
Non-thermal production: WIMP decay

WIMP → superWIMP + SM particles

WIMPs freeze out as usual...

...but then decay to superWIMPs

$M_{Pl}^2 / M_W^3 \sim 10^3$-$10^6$ s

Feng, ARAA (2010)
Non-thermal production: WIMP decay

WIMP → superWIMP + SM particles

\[ \Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}} \]

WIMPs freeze out as usual...

...but then decay to superWIMPs

\[ M_{\text{Pl}}^2/M_W^3 \sim 10^3 - 10^6 \text{ s} \]

Feng, ARAA (2010)
Non-thermal production: WIMP decay

\[ \text{WIMP} \rightarrow \text{superWIMP} + \text{SM particles} \]

\[ \Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}} \]

Feng, Rajaraman, Takayama (2003); Bi, Li, Zhang (2003); Ellis, Olive, Santoso, Spanos (2003); Wang, Yang (2004); Feng, Su, Takayama (2004); Buchmuller, Hamaguchi, Ratz, Yanagida (2004); Roszkowski, Ruiz de Austri, Choi (2004); Brandenburg, Covi, Hamaguchi, Roszkowski, Steffen (2005); ...

WIMPs freeze out as usual...

...but then decay to superWIMPs

\[ M_{\text{Pl}}^2/M_W^3 \sim 10^3-10^6 \text{ s} \]

\( t(s) \)

\( Y \)

\( T(\text{GeV}) \)

Feng, ARAA (2010)
Non-thermal production: WIMP decay

\[ \Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}} \]

**WIMP → superWIMP + SM particles**

- Feng, Rajaraman, Takayama (2003);
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- Roszkowski, Ruiz de Austri, Choi (2004);
- Brandenburg, Covi, hamaguchi, Roszkowski, Steffen (2005);
- ...

**superWIMP**
- e.g. Gravitino LSP
- LKK graviton
- axino

**WIMP**
- neutral
- charged
**superWIMP in SUSY**

**SUSY case**

WIMP $\rightarrow$ superWIMP + SM particles

- **Charged slepton**
  - Superpartner of lepton
- **Gravitino**
  - Superpartner of graviton

EM, had. cascade

$\Rightarrow$ change CMB spectrum

$\Rightarrow$ change light element abundance predicted by BBN

Strong constraints!

**Decay lifetime**

$\propto \frac{1}{m_{pl}^2/m_{G^e}}$
Neutralino LSP vs. gravitino LSP

\[ \tilde{\chi}, \tilde{\chi} \quad \text{LSP (DM)} \quad \tilde{\chi}, \tilde{\chi} \quad \text{WIMP} \]

\[ \tilde{\chi}, \tilde{\chi} \quad \text{(DM)} \quad \text{WIMP} \]

\[ \text{SuperWIMP} \]
stau NLSP

\[ Y_{\text{NLSP}} = \frac{n_{\text{NLSP}}}{n_\gamma} \sim 3.0 \times 10^{-12} \left[ \frac{\text{TeV}}{m_{\tilde{G}}} \right] \left[ \frac{\Omega_{\tilde{G}}}{0.23} \right] \]

fix \( \Omega_{\tilde{G}} = 0.23 \)

200 GeV \( \leq \delta m \leq 400 \sim 1500 \) GeV
\( m_{\tilde{G}} \leq 200 \) GeV

solve \(^7\text{Li} \) anomaly

- Decay life time
- SM particle energy/angular distribution ...
  \[ \Rightarrow m_{\tilde{G}} \]
  \[ \Rightarrow m_{pl} \ldots \]
- Decay life time
- **SM particle energy/angular distribution** ...
  ⇒ $m_\tilde{G}$
  ⇒ $m_{pl}$ ...

- Probes gravity in a particle physics experiments!
- BBN, CMB in the lab
- Precise test of supergravity: gravitino is a graviton partner
Conclusion

- dark matter candidates naturally obtain relic density
  \[ \Rightarrow \text{WIMP, WIMPless, superWIMP, ...} \]
- **WIMPless miracle:**
  - hidden sector dark matter with \( \frac{m_X}{g_X^2} \sim \frac{m_{\text{weak}}}{g_{\text{weak}}^2} \)
  - with connector fields, allow DM-SM interactions
  - direct detection: light dark matter, IVDM, ...
  - collider signatures: 4th generation quarks, T', B'
- **superWIMP:** \( \text{WIMP} \rightarrow \text{superWIMP} + \text{SM particles} \)

\[
\Omega_{\text{SWIMP}} = \frac{m_{\text{SWIMP}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}
\]