Gluino Coannihilation

Feng Luo

w/ John Ellis, Jason Evans and Keith Olive, 1503.07142, 1510.03498

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KAVLI IPMU

Framework of this talk

- Consider R-parity conserving Minimal Supersymmetric extension of the Standard Model (MSSM)
- The lightest supersymmetric particle (LSP) is the lightest neutralino, χ
- χ is the dark matter particle
- Obtain χ relic abundance through thermal freeze-out mechanism

Background

- $\sim$3 TeV Wino or $\sim$1 TeV Higgsino can give thermal relic abundance consistent with the observational value $\Omega_{CDM} h^2 = 0.1193 \pm 0.0014$ (*Planck 1-σ, 1502.01589*)
- Pure Bino is a gauge singlet. Bino does not directly couple to another Bino, and it only directly couples to sleptons, squarks and Higgsinos
- Typically $\langle \sigma v \rangle_{ann}$ decreases with the increase of the annihilating particle masses

Background

Then

$>$ 3 TeV Wino LSP,

or, $>$ 1 TeV Higgsino LSP,

or, almost no self-annihilating Bino LSP (for large $m_{\tilde{l},\tilde{q},\tilde{H}}$)

$\Rightarrow$ *necessarily leads to a too large dark matter relic density?*

Not necessarily. One possibility is to have coannihilation.

(*Griest and Seckel, Phys. Rev. D 43, 3191*)

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If there is another R-odd species χ_2 almost degenerate in mass with the LSP χ_1,

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and if χ_1 can efficiently convert to χ_2,

then χ_1 and χ_2 can freeze out together at a lower temperature resulting in a smaller dark matter abundance than if without the existence of χ_2.

$$\begin{aligned} \chi_1\chi_1 &\leftrightarrow SM,\ \chi_1\chi_2 \leftrightarrow SM,\ \chi_2\chi_2 \leftrightarrow SM \\ \chi_1 SM &\leftrightarrow \chi_2 SM,\ \chi_2 \leftrightarrow \chi_1 SM \end{aligned}$$

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efficient conversion: $\langle\Gamma\rangle_{1SM\to 2SM} + \langle\Gamma\rangle_{1SM\to 2} \gg H$

$\Rightarrow n_1/n_2 \approx n_1^{eq}/n_2^{eq}$ (this can be checked by explicitly solving for n_1 and n_2)

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(Recall w/o coannihilation: $\boxed{\dfrac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle\sigma v\rangle_{\chi\chi\to SM's}\left[n_\chi^2 - \left(n_\chi^{eq}\right)^2\right]}$)

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Note that $n_i^{eq} = g_i \left(\frac{m_i T}{2\pi}\right)^{3/2} e^{-m_i/T}$ for $T \ll m_i$

- if $m_2 \gg m_1$, $\Rightarrow n_{eq} \approx n_1^{eq}$, ●● $\approx \langle\sigma v\rangle_{11\to SM}$

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London 2012


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In this talk:

- Gluino bound-state effect
  (how does this effect help to achieve the largest DM mass?)

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  (how does this effect help to achieve the largest DM mass?)
- Breakdown of coannihilation by large squark masses
  (how do large squark masses prevent from achieving the largest DM mass?)
- Results based on simplified supersymmetric spectra defined at the weak scale and from more complete CMSSM-like models

(CMSSM = Constrained MSSM, with the soft supersymmetry-breaking parameters constrained to be universal at the input GUT scale)

Gluino bound-state effect

$\chi\chi \leftrightarrow SM$, $\chi\tilde{g} \leftrightarrow q\bar{q}$, $\tilde{g}\tilde{g} \leftrightarrow q\bar{q}$ or gg,

$\tilde{g}\tilde{g} \leftrightarrow \tilde{R}g, \tilde{R} \leftrightarrow gg$

$\chi q \leftrightarrow \tilde{g}q$, $\tilde{g} \leftrightarrow \chi q\bar{q}$

Bound-state effects: $\tilde{g}\tilde{g} \leftrightarrow \tilde{R}g$, $\tilde{R} \leftrightarrow gg$

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Explanation:
(1) Similar to $e^- p \leftrightarrow H\gamma$, the attractive Coulomb like potential between the $\tilde{g}'s$ can make the formation of gluino-gluino bound state $\tilde{R}$ possible.

Gluino bound-state effect

(2) $\tilde{R}$ *annihilation decay*, $\tilde{R} \to gg$, removes two R-odd particles, and therefore helps to decrease the final R-odd particle number density (i.e., dark matter density)
(note that the $\tilde{R}$ annihilation decay rate is much larger than the single gluino decay rate for $m_{\tilde{q}} > m_{\tilde{g}}$: $\sim \alpha_s^5 m_{\tilde{g}}$ vs. $\sim (m_{\tilde{g}} - m_\chi)^5 m_{\tilde{q}}^{-4}$)

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Result:

$$\frac{dn}{dt} + 3Hn \approx \quad - \sum_{i,j=\chi,\tilde{g}} \langle \sigma v \rangle_{ij \to SM} \left[n_i n_j - n_i^{eq} n_j^{eq} \right]$$

$$- \langle \sigma v \rangle_{\tilde{g}\tilde{g} \to \tilde{R}g} \frac{\langle \Gamma \rangle_{\tilde{R} \to gg}}{\langle \Gamma \rangle_{\tilde{R} \to gg} + \langle \Gamma \rangle_{\tilde{R}g \to \tilde{g}\tilde{g}}} \left[n_{\tilde{g}} n_{\tilde{g}} - n_{\tilde{g}}^{eq} n_{\tilde{g}}^{eq} \right]$$

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$$\frac{dn}{dt} + 3Hn \approx - \sum_{i,j=\chi,\tilde{g}} \langle \sigma v \rangle_{ij \to SM} \left[n_i n_j - n_i^{eq} n_j^{eq} \right] - \langle \sigma v \rangle_{\tilde{g}\tilde{g} \to \tilde{R}g} \frac{\langle \Gamma \rangle_{\tilde{R} \to gg}}{\langle \Gamma \rangle_{\tilde{R} \to gg} + \langle \Gamma \rangle_{\tilde{R}g \to \tilde{g}\tilde{g}}} \left[n_{\tilde{g}} n_{\tilde{g}} - n_{\tilde{g}}^{eq} n_{\tilde{g}}^{eq} \right]$$

In the $v \to 0$ limit,

$$\frac{(\sigma v)_{\tilde{g}\tilde{g} \to \tilde{R}g}}{\text{Sommerfeld enhanced } (\sigma v)_{\tilde{g}\tilde{g} \to gg}} \approx 1.44$$

Breakdown of coannihilation by a large squark mass

$\chi\chi \leftrightarrow SM,\ \chi\tilde{g} \leftrightarrow q\bar{q},\ \tilde{g}\tilde{g} \leftrightarrow q\bar{q}$ or gg,

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Explanation:
$\tilde{g}$ only has colour charge, while χ does not have colour charge, so χ can only interact with $\tilde{g}$ through vertices involving a $\tilde{q}$ in the propagator: $\chi - q - \tilde{q}$ and $\tilde{q} - \tilde{g} - q$

Breakdown of coannihilation by a large squark mass

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$\Rightarrow$ coannihilation mechanism breaks down, $\tilde{g}\tilde{g} \to q\bar{q}$ or gg and bound-state effects *cannot* reduce the χ number density *even if* they are large and *even if* $\tilde{g}$ and χ are degenerate in mass


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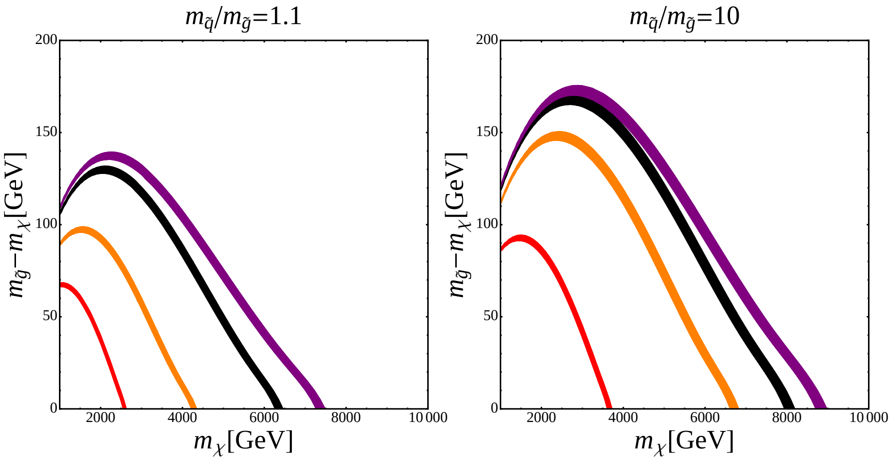
hand

Results based on simplified supersymmetric spectra

To illustrate the physics, let's first see results based on simplified supersymmetric spectra, assuming degenerate squark masses, and that χ is a pure state of either a Bino, Wino, or Higgsino.

Therefore, the free parameters are simply the neutralino mass, m_χ, the gluino mass, $m_{\tilde{g}}$ and the common squark masses, $m_{\tilde{q}}$.

Result: Bino



$\Omega_\chi h^2 = 0.1193 \pm 0.0042$ bands (3-σ Planck).

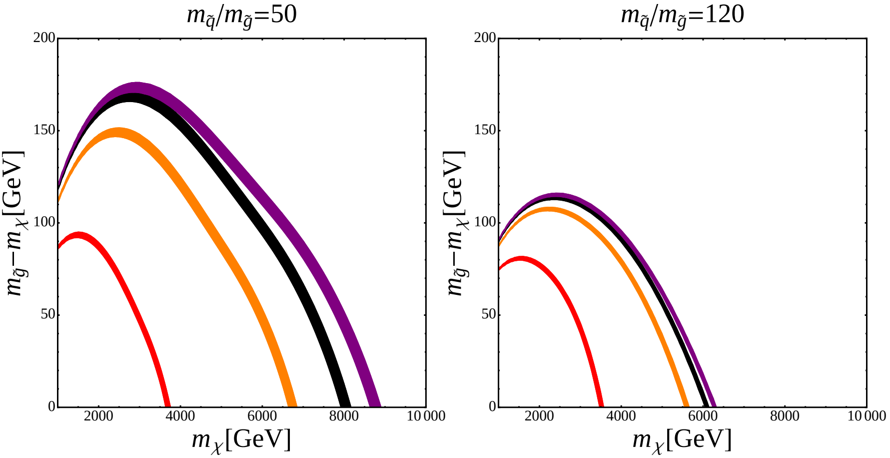
red: w/o Sommerfeld effects and w/o bound-state effects

orange: w/ Sommerfeld effects but w/o bound-state effects

black: w/ Sommerfeld effects and w/ bound-state effects

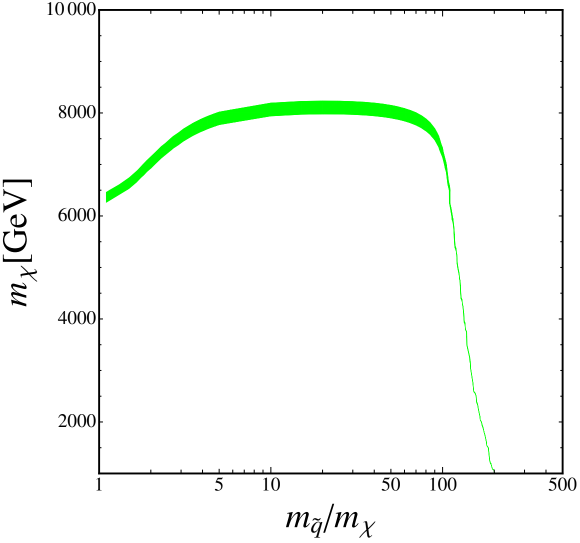
purple: w/ Sommerfeld effects and w/ 2 times bound-state effects

Result: Bino



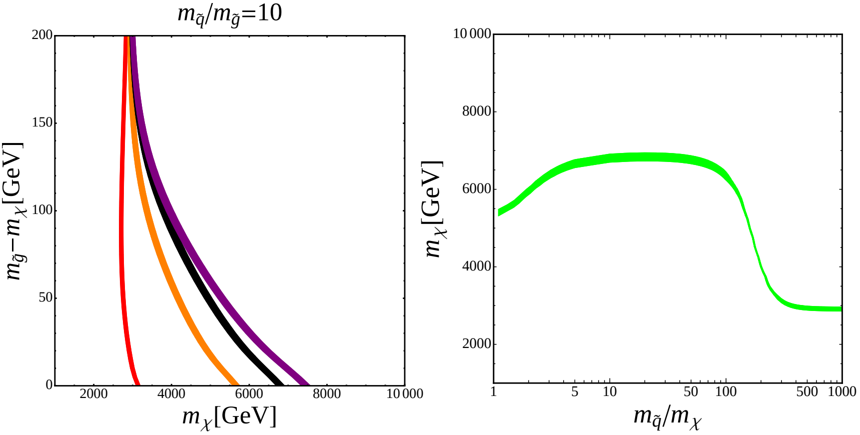
$m_{\tilde{q}}/m_{\tilde{g}}$=50
$m_{\tilde{q}}/m_{\tilde{g}}$=120
200
150
100
50
0
2000
4000
6000
8000
10 000
$m_{\tilde{g}}-m_\chi$[GeV]
m_χ[GeV]

Result: Bino



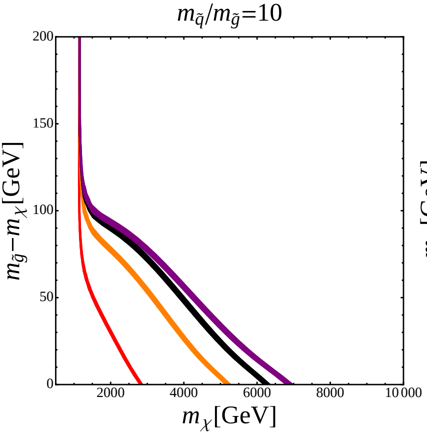
$m_{\tilde{g}} - m_\chi = 0$, 3-$\sigma$ Planck band.

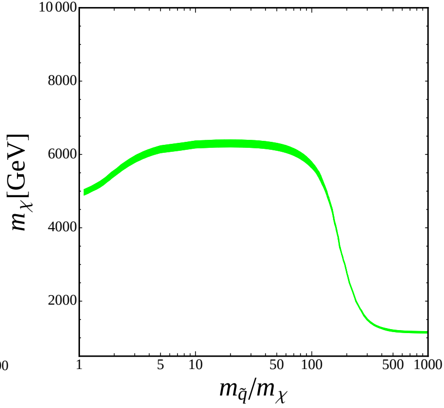
Result: Wino



$m_{\tilde{q}}/m_{\tilde{g}}=10$
$m_{\tilde{g}}-m_{\chi}$[GeV]
m_{χ}[GeV]
200
150
100
50
0
2000
4000
6000
8000
10 000
m_{χ}[GeV]
$m_{\tilde{q}}/m_{\chi}$
10 000
8000
6000
4000
2000
1
5
10
50
100
500
1000

Result: Higgsino





A remark

Why the maximum LSP mass is smaller for a Wino ($\sim$ 7 TeV) or a Higgsino ($\sim$ 6 TeV) compared to a Bino ($\sim$ 8 TeV)?

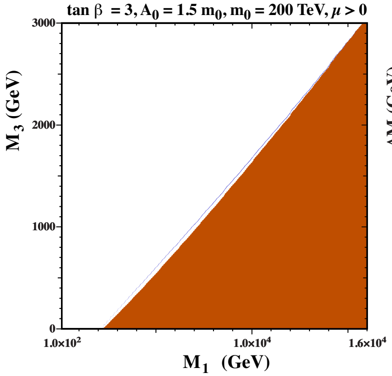
Because there are more *inert* degrees of freedom for Wino (=6) or Higgsino (=8) compared to Bino (=2) at large mass when $\chi\chi$ annihilation cross section is negligible compared to $\tilde{g}\tilde{g}$ annihilation cross section.

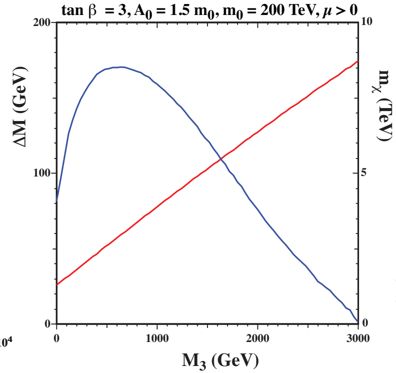
Results from CMSSM-like models

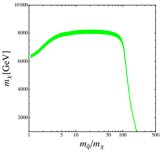
The possibility of gluino coannihilation does not arise in the CMSSM. However, gluino coannihilation can become important in variants of the MSSM such as a one-parameter extension of the CMSSM by allowing a restricted form of non-universality in the gaugino sector with $M_1 = M_2 \neq M_3$ at the input GUT scale.

Therefore, the results depend on M_1 and M_3 as well as the usual CMSSM parameters m_0, A_0, $\tan\beta$ and the sign of μ.

Gluino coannihilation can become important in other models as well, and in 1510.03498 we show results in models with pure gravity mediation of supersymmetry breaking with additional vector multiplets.



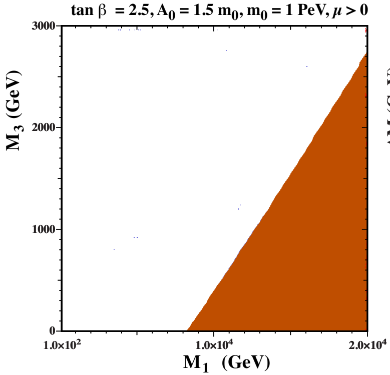


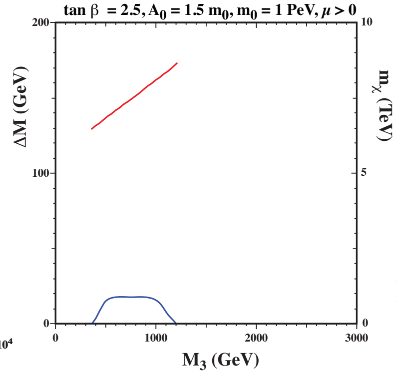


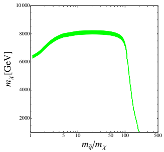
This choice of m_0 corresponds to values of $m_{\tilde{q}}/m_{\tilde{g}}$ along the plateau.

In the left panel, the dark blue strip shows where $\Omega_\chi h^2 = 0.1193 \pm 0.0042$, and gluino is the LSP in the brick-red shaded region.

In the right panel, the blue line shows the gluino-neutralino mass difference and the red line shows the neutralino mass, both along the dark blue strip in the left panel and as functions of M_3.







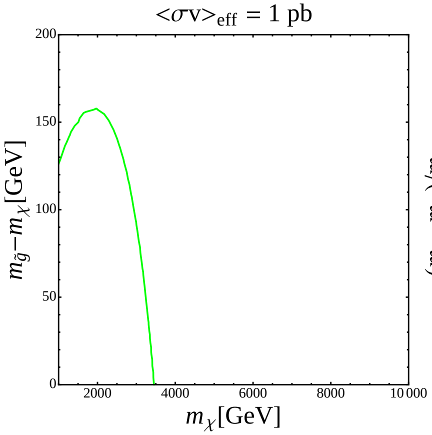
This choice of m_0 corresponds to values of $m_{\tilde{q}}/m_{\tilde{g}}$ extending from beyond the right-end of the plateau at small M_3 to values along the plateau at large M_3.

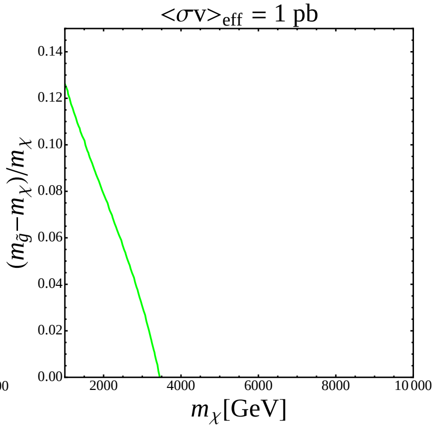
The gluino coannihilation strip therefore has two end-points where $\Delta M \to 0$.

Summary

- There could be a largest possible LSP mass achievable in the neutralino-gluino coannihilation scenario.
- Gluino-Gluino bound states effectively enhance the gluino annihilation cross section, and they help to achieve the largest DM mass.
- The neutralino-gluino coannihilation mechanism can be broken by large squark masses.
- Gluino coannihilation can become important in variants of the MSSM such as CMSSM-like models with non-universality in the gaugino sector.

backup: the reason why the dm vs. m plot has the shape





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Note that $n_i^{eq} = g_i \left(\frac{m_i T}{2\pi} \right)^{3/2} e^{-m_i/T}$ for $T \ll m_i$

backup: Sommerfeld enhancement

$$\chi\chi \leftrightarrow SM,\ \chi\tilde{g} \leftrightarrow q\bar{q},\ \tilde{g}\tilde{g} \leftrightarrow q\bar{q} \text{ or } gg$$
$$\chi q \leftrightarrow \tilde{g}q,\ \tilde{g} \leftrightarrow \chi q\bar{q}$$

Sommerfeld enhancement (and suppression) for $\tilde{g}\tilde{g} \rightarrow q\bar{q}$ or gg

Explanation:
depends on the colour configuration of the initial $\tilde{g}\tilde{g}$, the long range Coulomb like potential between $\tilde{g}\tilde{g}$ can be attractive (or repulsive)

$\Rightarrow$ modify the otherwise free initial particle wave function

$\Rightarrow$ enhance (or suppress) the $\tilde{g}\tilde{g}$ annihilation cross sections

(*Baer, Cheung, Gunion, hep-ph/9806361; De Simone, Giudice, Strumia, 1402.6287; Harigaya, Kaneta, Matsumoto, 1403.0715*)