QCD bound-state effect on dark matter relic abundance

Feng Luo

John Ellis, FL, **Keith** 

JHEP 2015

John Ellis, Jason Evans, FL, **Keith** 

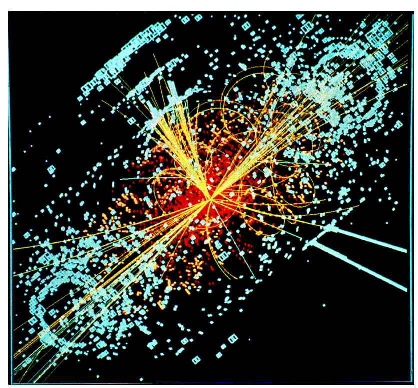
JHEP 2016

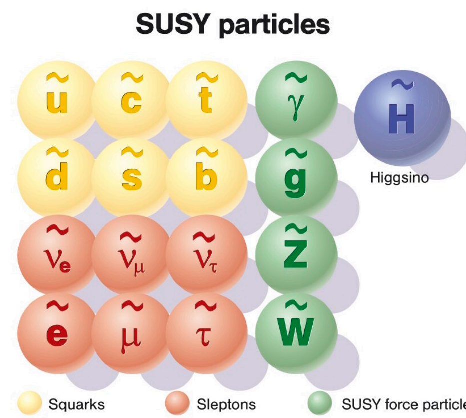
Seng Pei Liew, FL *JHEP 2017*

Kavli Institute for the Physics and Mathematics of the Universe
東京大学 国際高等研究所 カブリ数物連携宇宙研究機構
KAVLI IPMU

How heavy can dark matter be in supersymmetry?

The answer is important in assessing the center-of-mass energy needed for a collider to be *"guaranteed" to discover or exclude supersymmetric dark matter.*





No signal yet. Maybe just too heavy to be produced.

specify the question

- Consider the R-parity conserving minimal supersymmetric extension of the Standard Model (MSSM).
  (the *simplest* version of supersymmetry)

- Take the lightest neutralino as the dark matter (DM) particle.
  (the *most* studied DM candidate)

- Use thermal freeze-out mechanism to calculate DM relic abundance.
  (the *standard* mechanism to get the DM relic abundance)

- Consider neutralino coannihilation with some colored particle.
  (one of the most *common* and sometimes *unavoidable* “add-ons”)

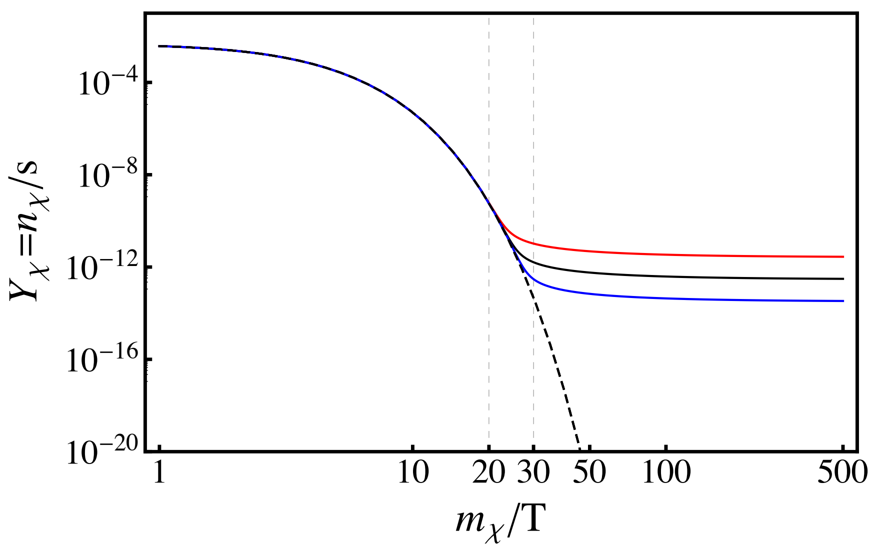
thermal freeze-out mechanism

Consider DM annihilation and creation: $\chi\chi \leftrightarrow SM's$,

$$\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle\sigma v\rangle_{\chi\chi\to SM's}\left[n_\chi^2 - \left(n_\chi^{eq}\right)^2\right]$$

Introduce the yield, $Y_\chi \equiv n_\chi/s$, to factor out the dilution due to the Cosmic expansion,

$$\Rightarrow \frac{d\ln Y_\chi}{d\ln(m_\chi/T)} = \frac{n_\chi\langle\sigma v\rangle_{\chi\chi\to SM's}}{H(T)}\left[(Y_\chi^{eq}/Y_\chi)^2 - 1\right]$$



$$\langle\sigma v\rangle_{\chi\chi\to SM's} = (0.1, 1, 10) \times 3 \times 10^{-26}\,\text{cm}^3/\text{s}$$
$$\Rightarrow \Omega_\chi h^2 \sim (1, 0.1, 0.01)$$

by dimensional analysis: $\langle\sigma v\rangle_{\chi\chi\to SM's} \propto m^{-2}$

coannihilation mechanism

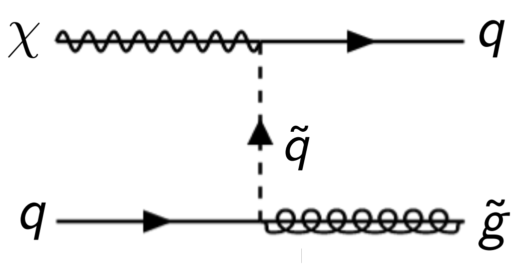
3 TeV Wino ✓

1 TeV Higgsino ✓

Here coannihilation is an unavoidable add-on.

Bino?

- Bino couples to slepton, squark and Higgsino, but not to another Bino.
- Therefore, it usually requires some coannihilation (e.g., with a stau or a stop) to reduce the relic abundance for a Bino of TeV scale.
- Bino-gluino coannihilation is possible by the help of a squark.



Conditions for coannihilation to reduce DM relic density

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

and if χ_2 has a big annihilation cross section with itself and/or with χ_1,

and if χ_1 can efficiently convert to χ_2,

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

Griest and Seckel, 1991

Conditions for coannihilation to reduce DM relic density

$$\chi_1\chi_1 \leftrightarrow SM, \ \chi_1\chi_2 \leftrightarrow SM, \ \chi_2\chi_2 \leftrightarrow SM$$
$$\chi_1 SM \leftrightarrow \chi_2 SM, \ \chi_2 \leftrightarrow \chi_1 SM$$

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)

Conditions for coannihilation to reduce DM relic density

Define $n \equiv n_1 + n_2$ and $n_{eq} \equiv n_1^{eq} + n_2^{eq}$,

$$\frac{dn}{dt} + 3Hn = -\sum_{i,j=1}^{2} \langle \sigma v \rangle_{ij \to SM} \frac{n_i^{eq} n_j^{eq}}{n_{eq}^2} \left[n^2 - n_{eq}^2 \right]$$

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

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 $m_2 \gg m_1 \Rightarrow n_{eq} \approx n_1^{eq} \Rightarrow$ ●● $\approx \langle \sigma v \rangle_{11 \to SM}$
- if $m_2 = m_1 \Rightarrow$ ●● $= \frac{g_1^2 \langle \sigma v \rangle_{11 \to SM} + g_2^2 \langle \sigma v \rangle_{22 \to SM} + 2 g_1 g_2 \langle \sigma v \rangle_{12 \to SM}}{(g_1 + g_2)^2}$

I’m a Bino.

I’m the expanding Universe.

$$\frac{dn_\chi}{dt} + 3H(T)n_\chi = -\langle \sigma v \rangle_{\chi\chi \to SM's} \left[n_\chi^2 - \left(n_\chi^{eq} \right)^2 \right]$$

I’m a coannihilator.

I’m a Bino.

I’m the expanding Universe.

$$\frac{dn}{dt} + 3Hn = -\sum_{i,j=1}^{2} \langle \sigma v \rangle_{ij \to SM} \frac{n_i^{eq} n_j^{eq}}{n_{eq}^2} \left[n^2 - n_{eq}^2 \right]$$

Bino-gluino coannihilation

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

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

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

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(1) Sommerfeld effects for $\tilde{g}\tilde{g} \to q\bar{q}$ or gg

Explanation:

Depending 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 and Gunion, 1999
Profumo and Yaguna, 2004

Bino-gluino coannihilation

(2) Gluino bound-state effect

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

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

Explanation:

- $\tilde{g}\tilde{g}$ can form a positronium-like bound state $\tilde{R}$
- $\tilde{R} \to gg$ removes two R-odd particles $\Longrightarrow$ decreases the final R-odd particle number density (i.e., DM number density)

Bino-gluino coannihilation

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

Coulomb potential	$\sim$	$-\alpha_s/r$
Bohr radius	$\sim$	$(\alpha_s m_{\tilde{g}})^{-1}$
binding energy	$\sim$	$\alpha_s^2 m_{\tilde{g}}$
$\tilde{R}$ annihilation decay rate	$\sim$	$\alpha_s^5 m_{\tilde{g}}$
individual $\tilde{g}$ decay rate	$\sim$	$(m_{\tilde{g}} - m_\chi)^5 m_{\tilde{q}}^{-4}$

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

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

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

coannihilation

I’m a coannihilator.

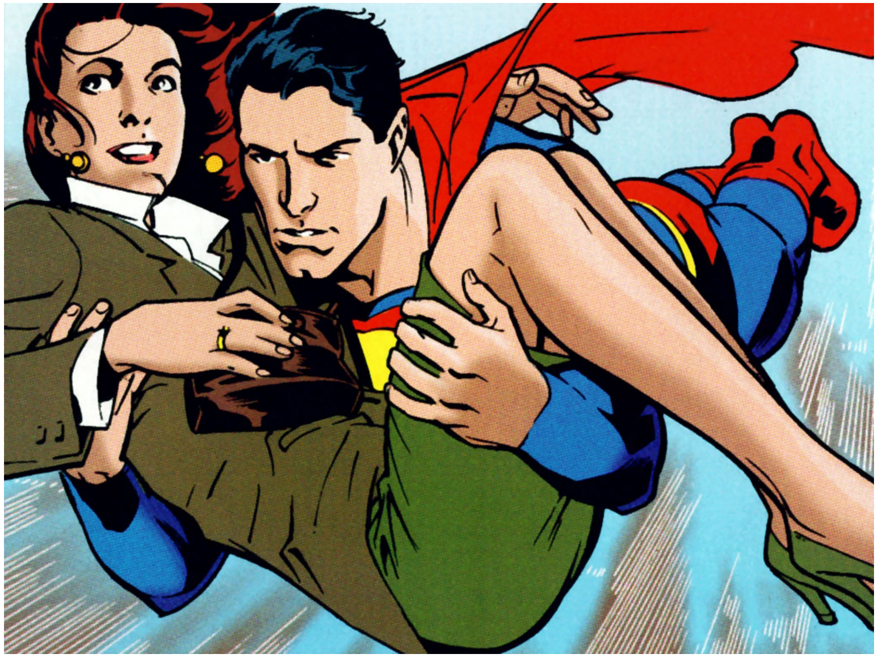
I’m a Bino.

I’m the expanding Universe.

coannihilation with Sommerfeld and bound-state effect

I’m a Bino.

I’m a gluino.



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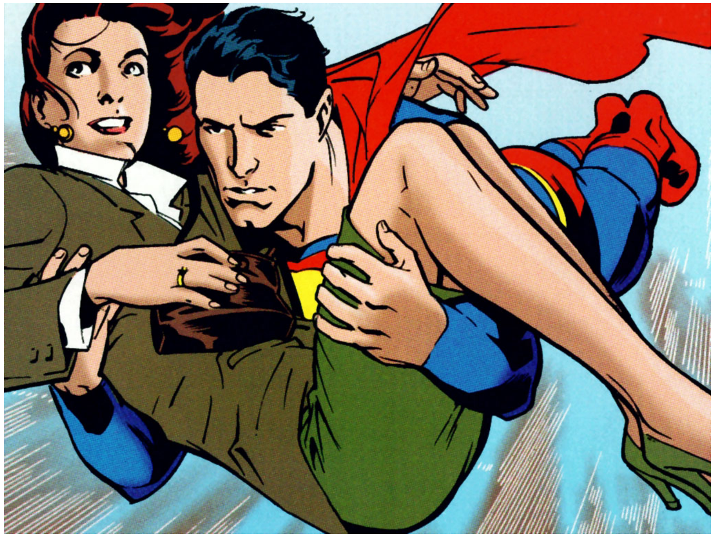
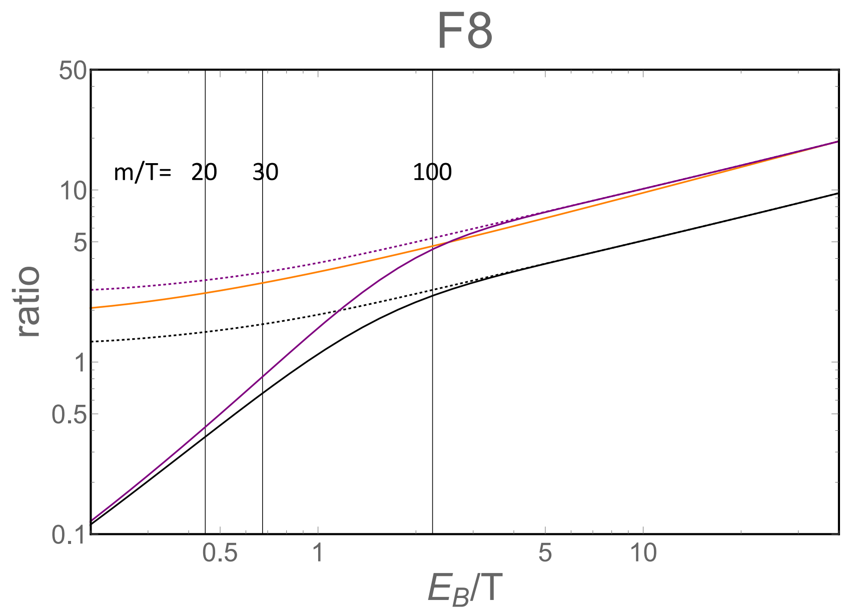
coannihilation with Sommerfeld and bound-state effect

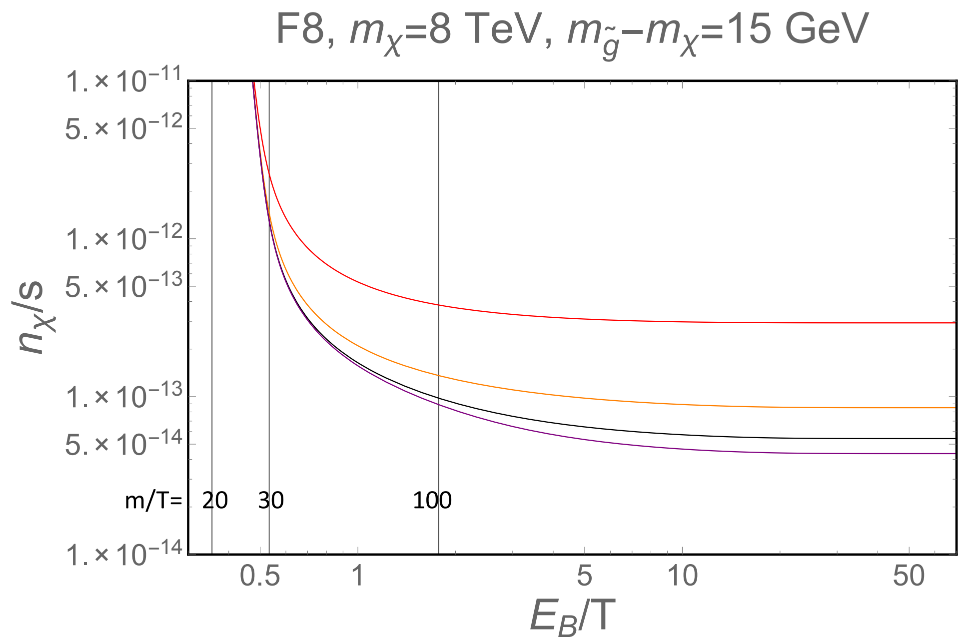


The gluino, $\tilde{g}$, with the largest colour charge, is the strongest coannihilation particle in the MSSM.

The gluino-neutralino coannihilation scenario may give the largest possible neutralino DM mass within the coannihilation thermal freeze-out mechanism.

Bino-gluino coannihilation





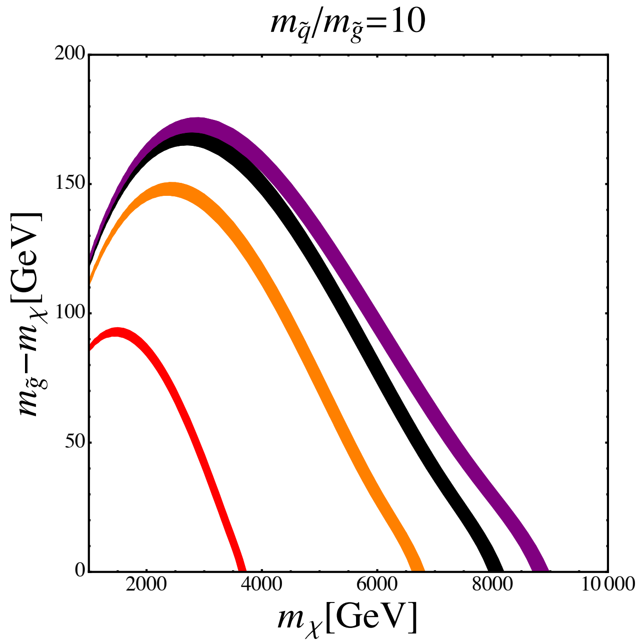
The "ratio" are the thermally averaged effective annihilation cross sections, normalized to the tree-level result.

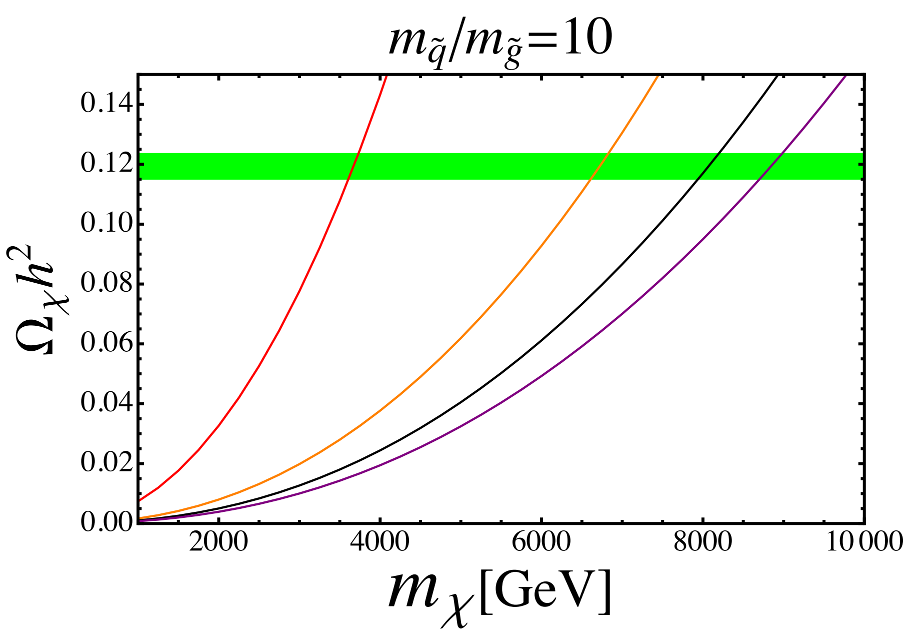
dashed black and purple line: if there were no dissociation process

gluino is a fermion octet, so call it "F8"

red: w/o Sommerfeld effect and w/o bound-state effect
orange: w/ Sommerfeld effect but w/o bound-state effect
black: w/ Sommerfeld effect and w/ bound-state effect
purple: w/ Sommerfeld effect and w/ 2 times bound-state effect

Bino-gluino coannihilation





Bino-gluino coannihilation

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

(3) Breakdown of coannihilation by large squark masses

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

Chung, Farrar and Kolb, 1997

Explanation:

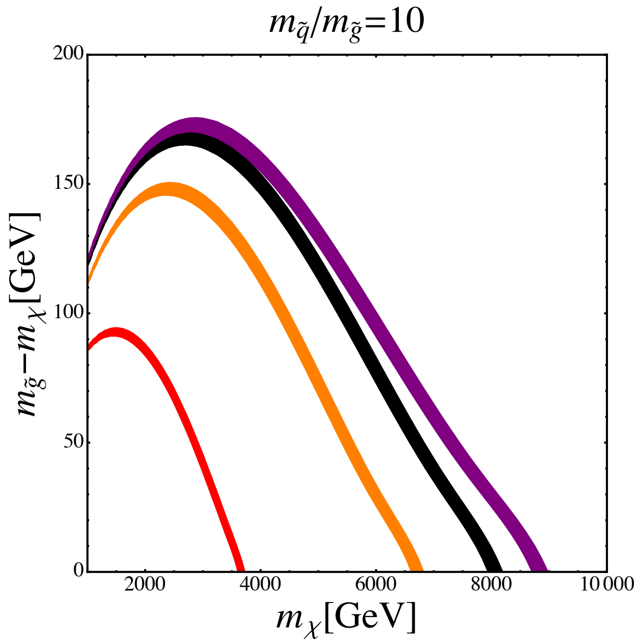
- $\tilde{g}$ only has color charge, while χ does not have color charge, so χ can only interact with $\tilde{g}$ through vertices involving a $\tilde{q}$ in the propagator: $\chi - q - \tilde{q}$ and $\tilde{q} - \tilde{g} - q$
- $\Rightarrow$ when $m_{\tilde{q}}$ is very large, $\chi q \leftrightarrow \tilde{g}q$ and $\tilde{g} \leftrightarrow \chi q\bar{q}$ are ineffective

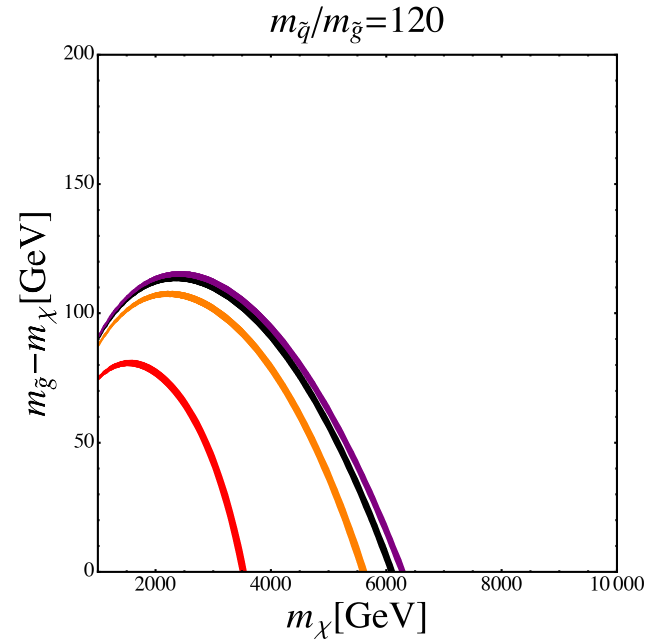
  $\Rightarrow$ coannihilation mechanism breaks down, and therefore Sommerfeld enhancement and bound-state effect cannot reduce the χ number density even if they are large and even if $\tilde{g}$ and χ are degenerate in mass

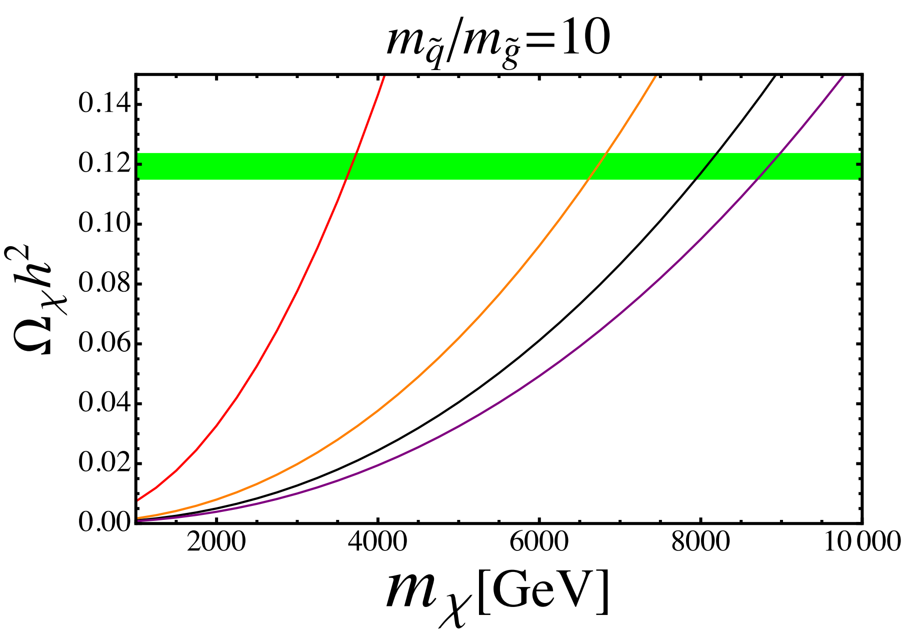
coannihilation breaks down

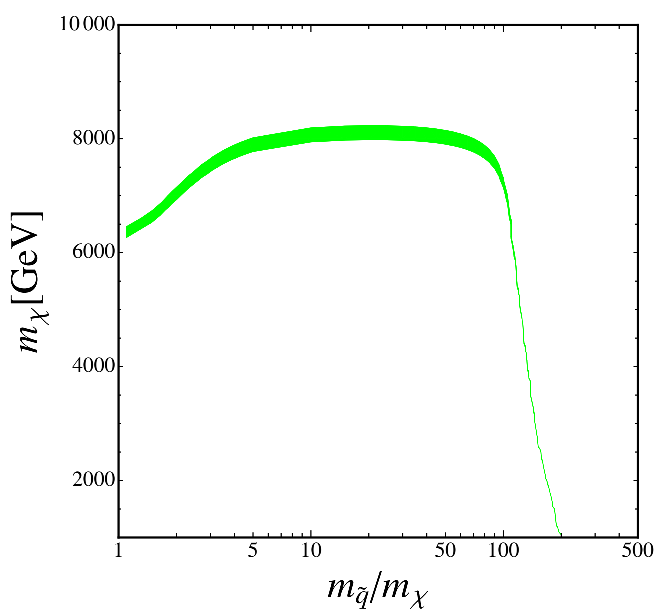
Sorry, squark are too heavy.
I cannot give you a hand…

Bino-gluino coannihilation

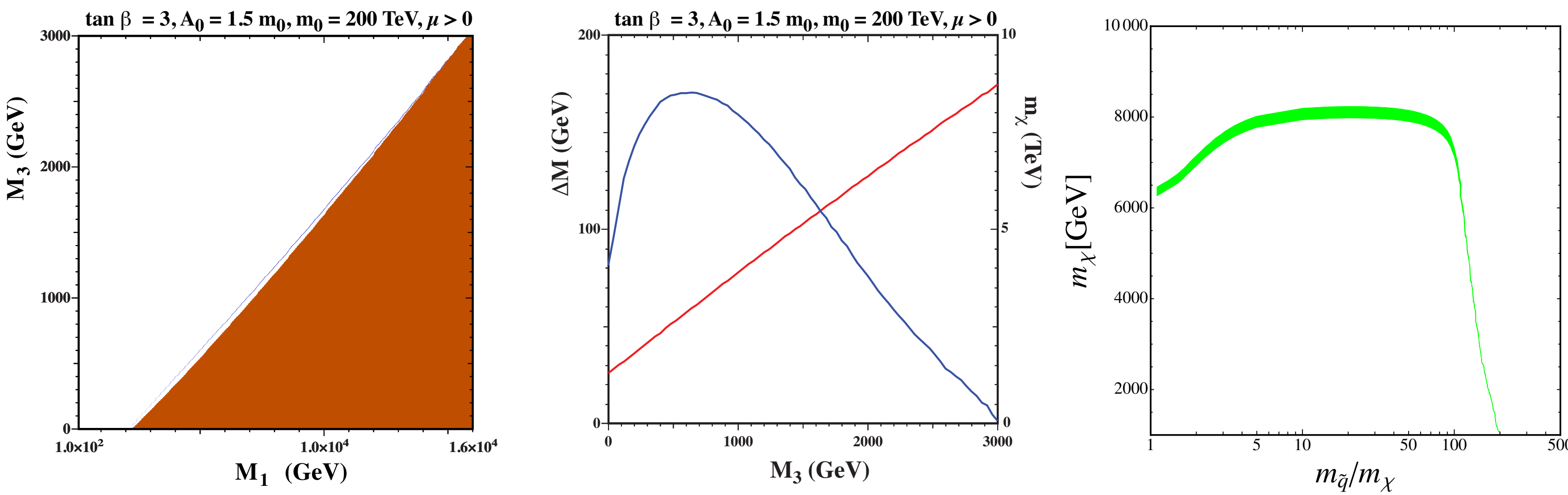








Bino-gluino coannihilation in CMSSM-like model with M1=M2≠M3 at GUT



This choice of m_0 corresponds to values of $m_{\tilde{q}}/m_{\tilde{g}}$ along the plateau found using the simplified supersymmetric spectra (right panel).

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 middle 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.

Bino-stop coannihilation

$$\tilde{t}\tilde{t}^* \leftrightarrow q\bar{q} \text{ or } gg\,,$$

$$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{R}g\,, \tilde{R} \leftrightarrow gg$$

Bino-stop coannihilation

$$\tilde{t}\tilde{t}^* \leftrightarrow q\bar{q} \text{ or } gg\,,$$

$$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{R}g\,,\, \tilde{R} \leftrightarrow gg$$

New ingredients compared to the gluino case:

✓ stop anti-stop color potential prior to forming a bound state is repulsive, while the one for gluino pair is attractive

$$\mathbf{3} \otimes \overline{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

vs. $$\mathbf{8} \otimes \mathbf{8} = \mathbf{1}_S \oplus \mathbf{8}_A \oplus \mathbf{8}_S \oplus \mathbf{10}_A \oplus \overline{\mathbf{10}}_A \oplus \mathbf{27}_S$$

stop is a scalar triplet

gluino is a fermion octet

Bino-stop coannihilation

$$\tilde{t}\tilde{t}^* \leftrightarrow q\bar{q} \text{ or } gg\,,$$
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stop is a scalar triplet

gluino is a fermion octet

✓ stop has electric charge, while gluino does not

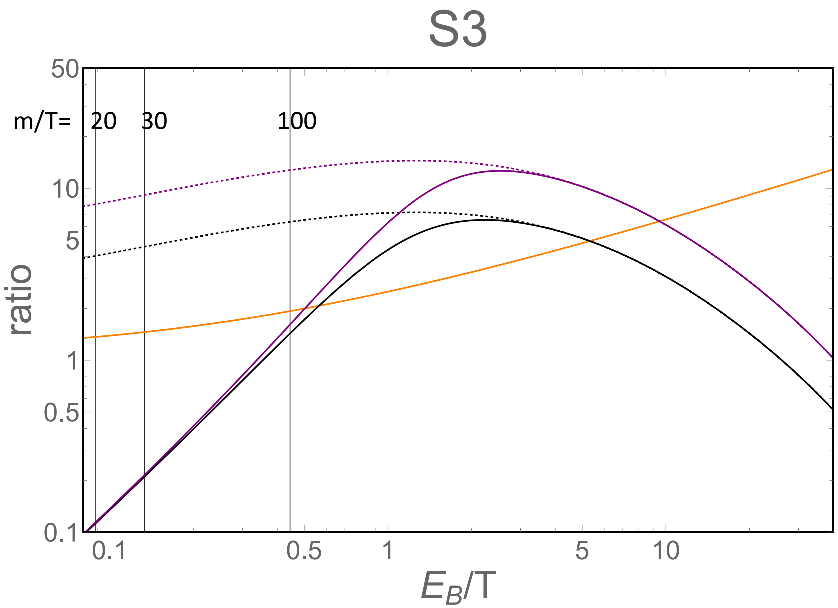
(1) affect the potential

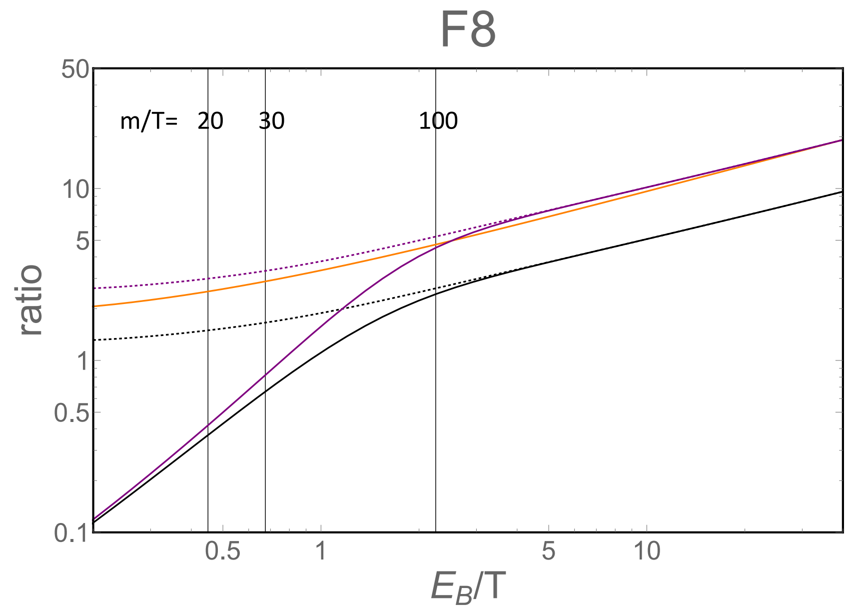
(2) photon emission/absorption processes

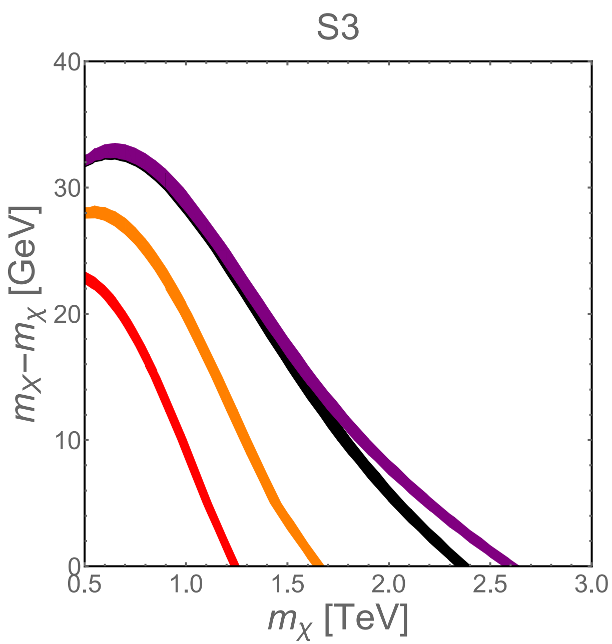
stop = S3
gluino = F8

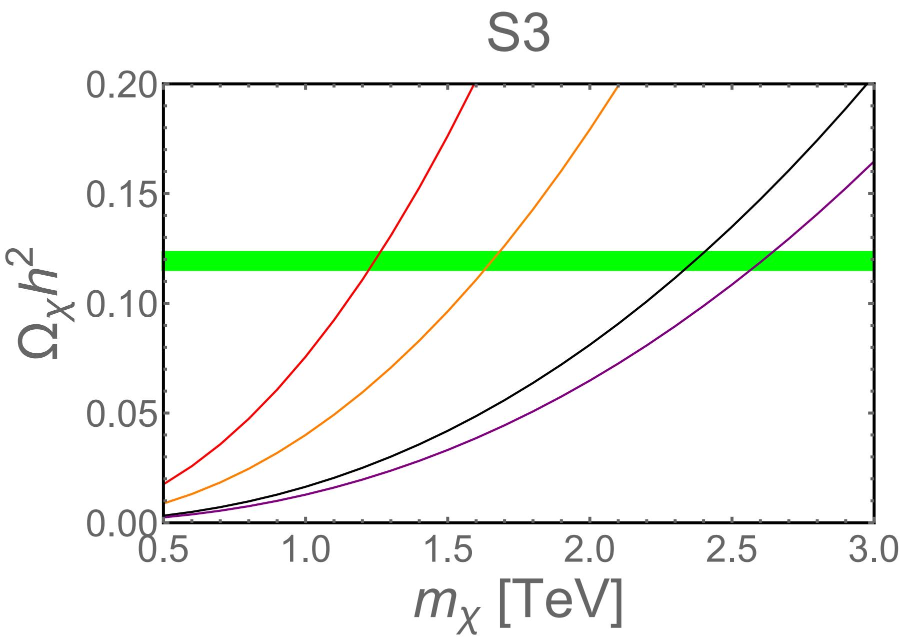
Bino-stop coannihilation

$\tilde{t}\tilde{t}^* \leftrightarrow q\bar{q}$ or gg,
$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{R}g,\ \tilde{R} \leftrightarrow gg$



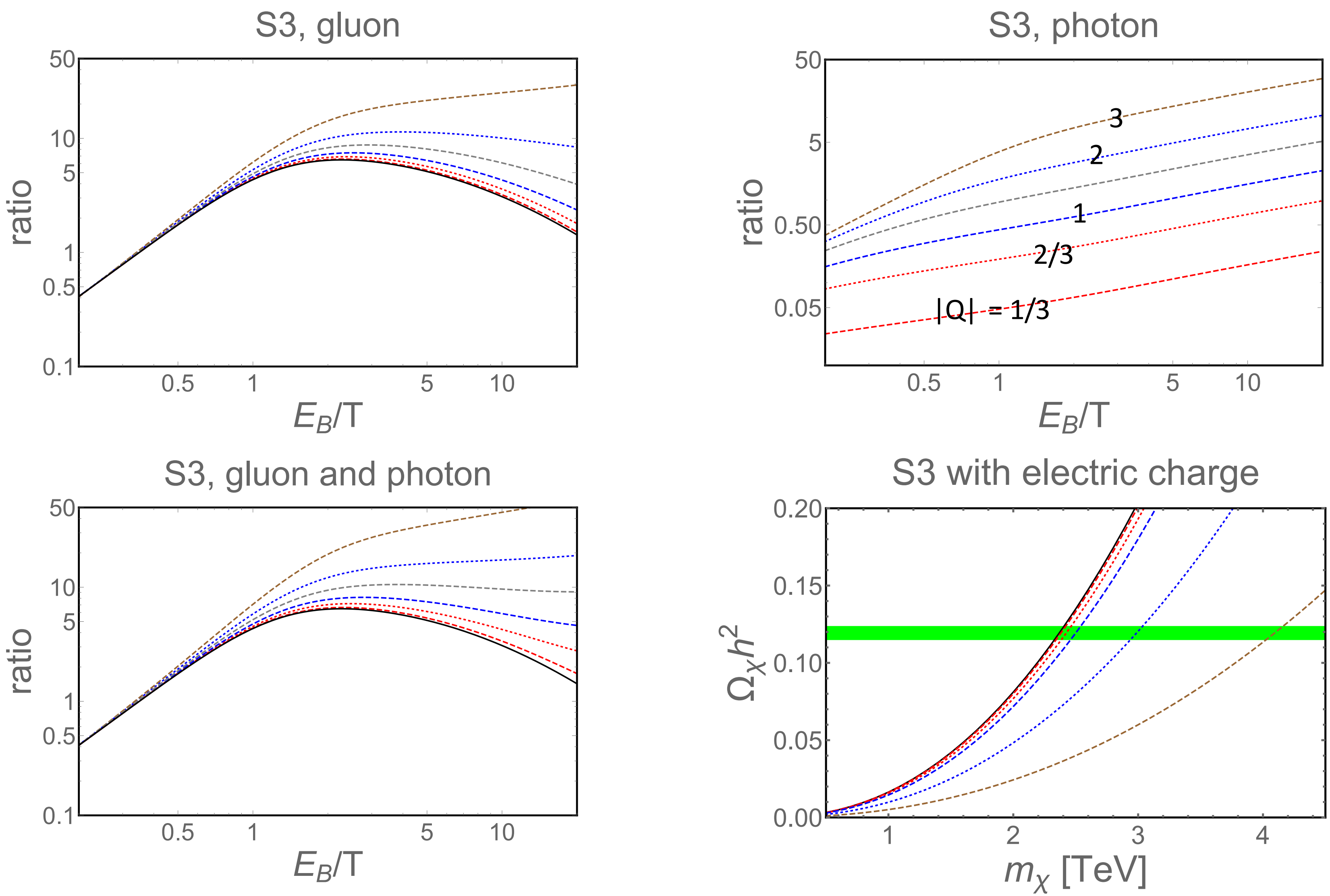






Bino-stop coannihilation

$$\tilde{t}\tilde{t}^* \leftrightarrow \tilde{R}g, \tilde{t}\tilde{t}^* \leftrightarrow \tilde{R}\gamma, \tilde{R} \leftrightarrow gg$$



probe strongly interacting particle coannihilation scenarios in colliders

monojet searches

(Low & Wang, 1404.0682)

coannihilator	bkgd. syst.	14 TeV 95% limit	14 TeV 5σ discovery	100 TeV 95% limit	100 TeV 5σ discovery
gluino	1%	1.1 TeV	950 GeV	6.2 TeV	5.2 TeV
	2%	1.0 TeV	850 GeV	5.8 TeV	4.8 TeV
stop	1%	530 GeV	420 GeV	2.8 TeV	2.1 TeV
	2%	470 GeV	330 GeV	2.4 TeV	1.7 TeV
squark	1%	740 GeV	600 GeV	4.0 TeV	3.0 TeV
	2%	630 GeV	495 GeV	3.5 TeV	2.6 TeV

long-lived colored particles with displaced vertices (for gluino)

(Nagata, Otono & Shirai, 1504.00504)

$$c\tau_{\tilde{g}} = \mathcal{O}(1) \times \left(\frac{\Delta M}{100\,\mathrm{GeV}}\right)^{-5} \left(\frac{m_{\tilde{q}}}{100\,\mathrm{TeV}}\right)^{4} \mathrm{cm}$$

squark-gluino associated production

(S. Ellis & B. Zheng, 1506.02644)

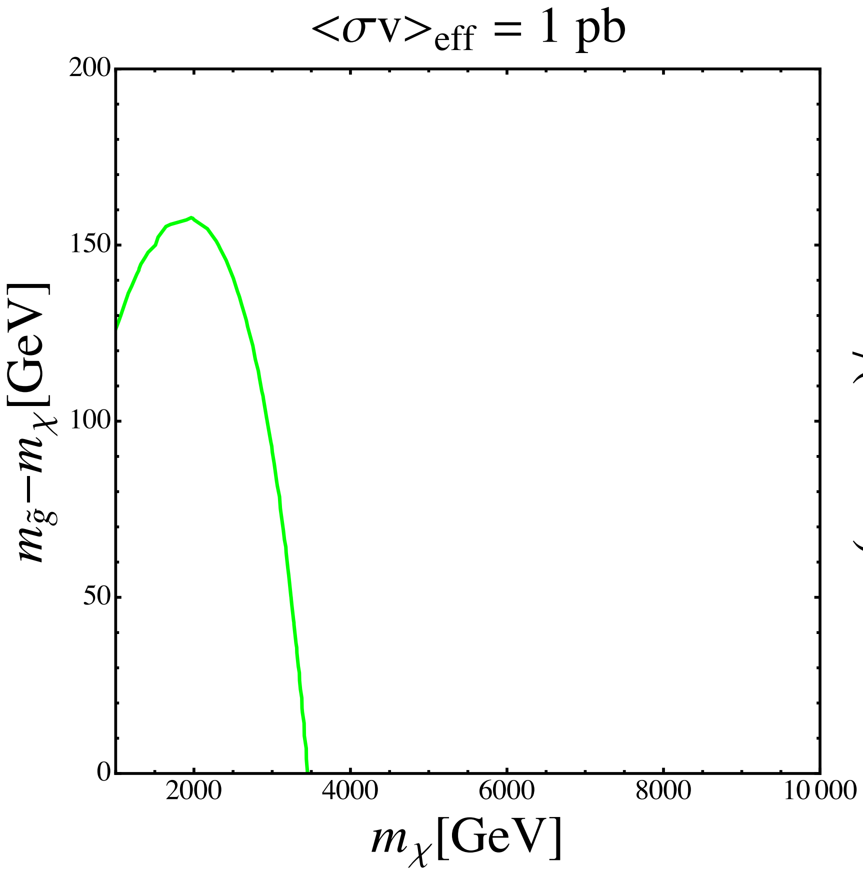
Summary

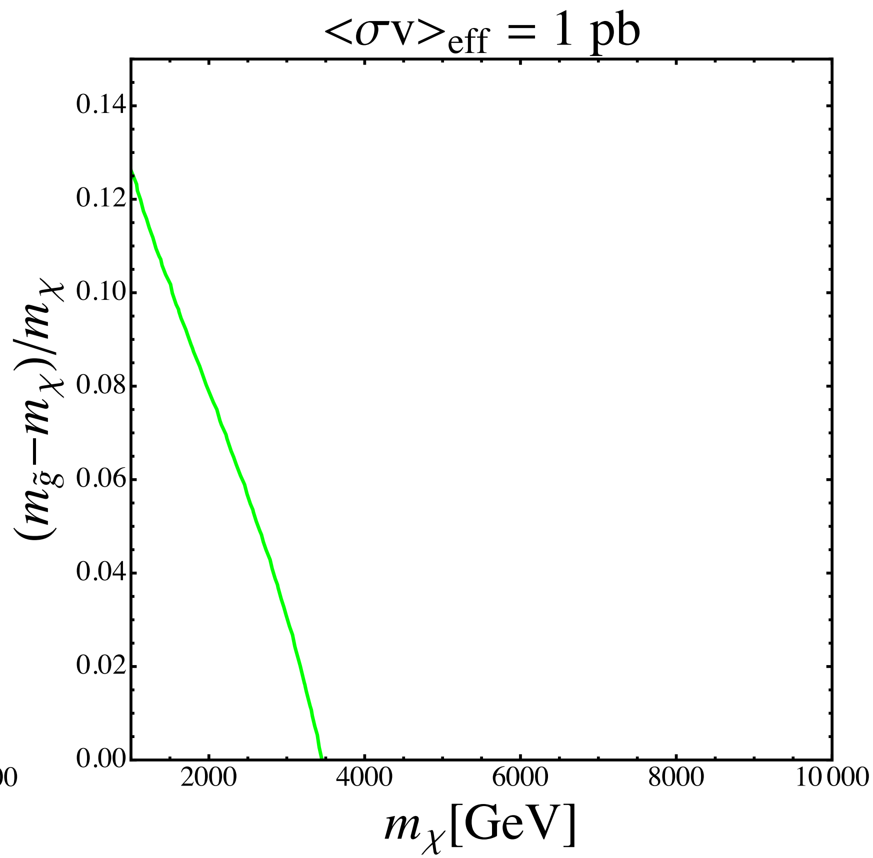
(1) In the coannihilation scenario, bound-state effect can significantly enhance the DM effective annihilation cross section. The size of the bound-state effect is comparable to the Sommerfeld effect.

(2) Too large squark masses can break down the neutralino-gluino coannihilation mechanism, due to not fast enough conversion rate between neutralino and gluino.

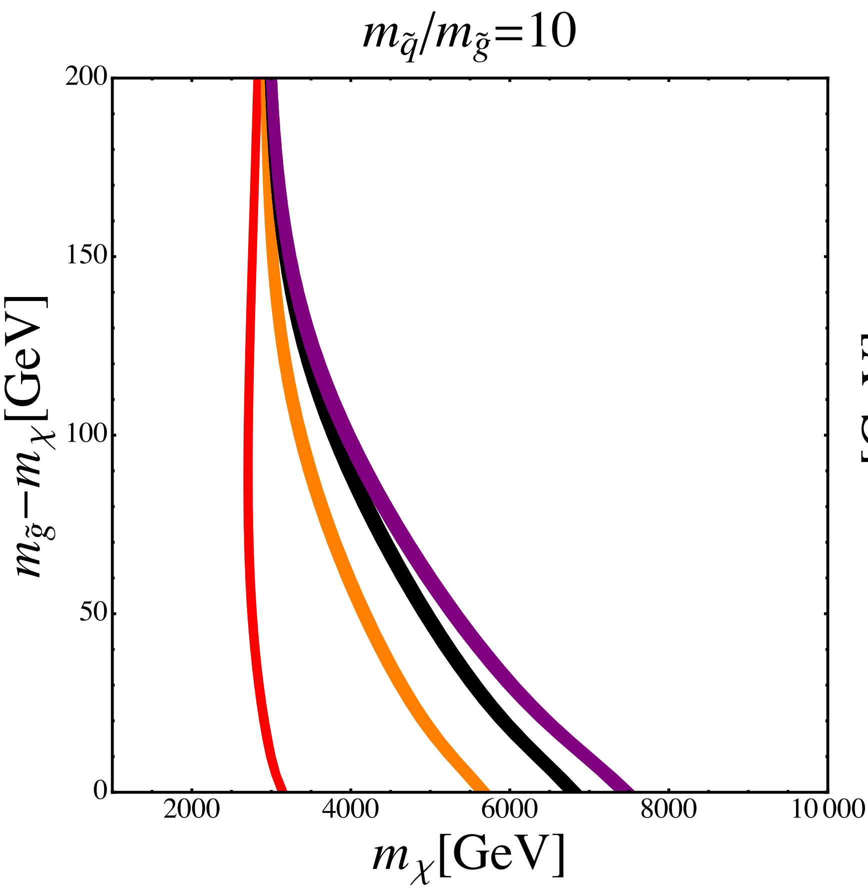
(3) The potential between the massive colored particles after forming a bound state is attractive, but the potential between them prior to forming a bound state can be either attractive or repulsive.

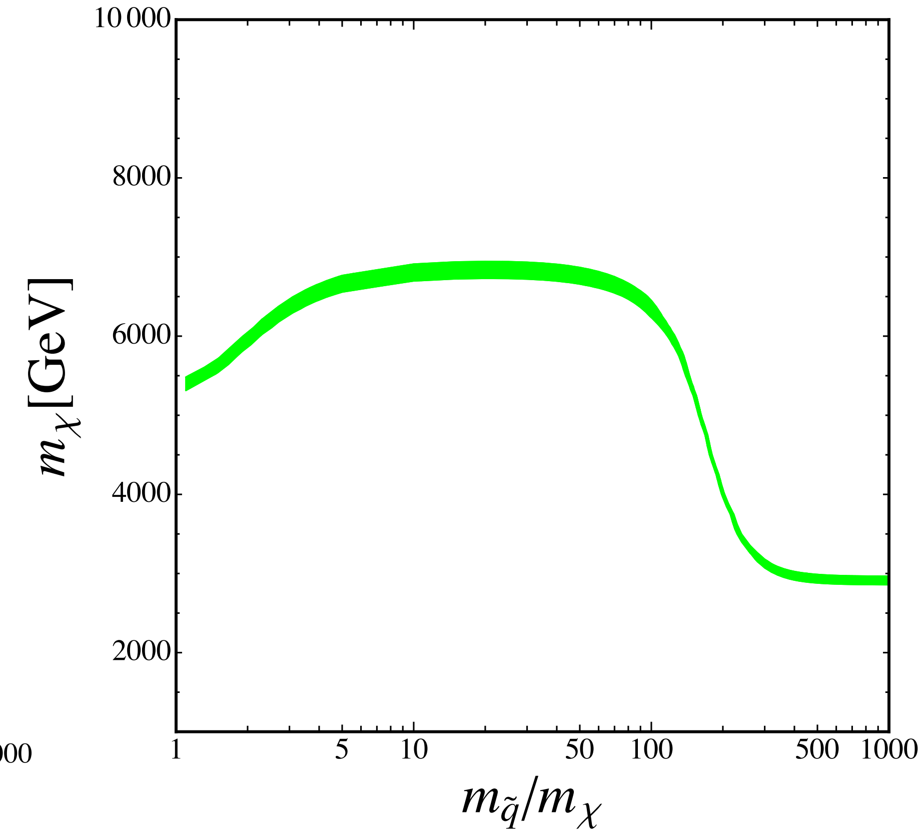
backup: the reason why the Δm vs. m_χ plot has the shape



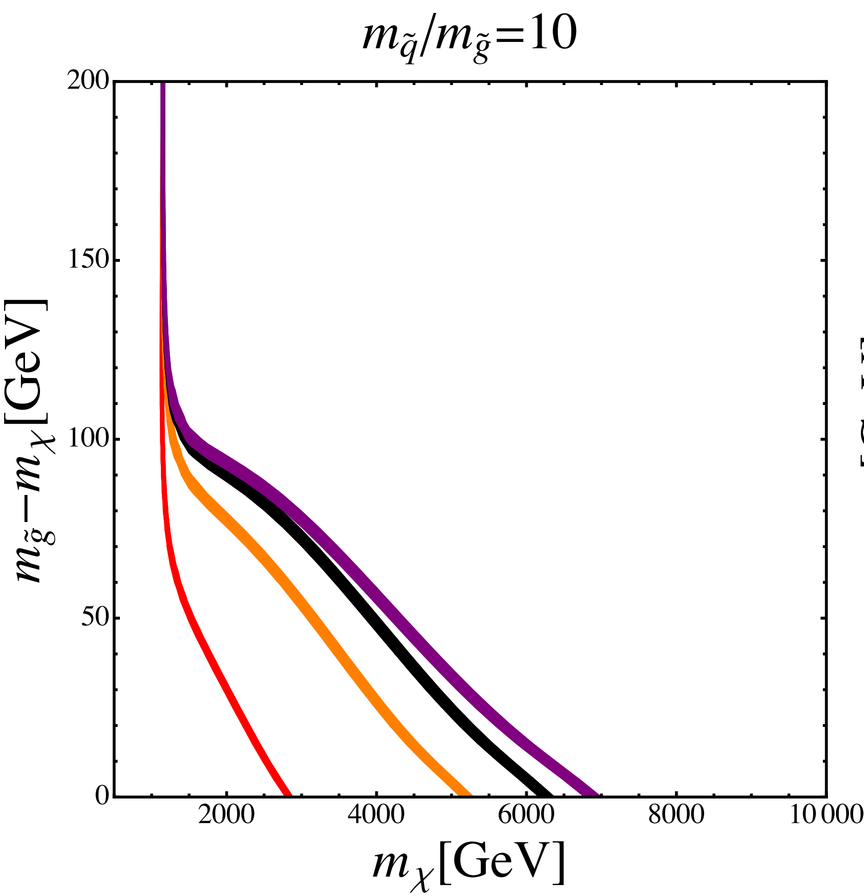


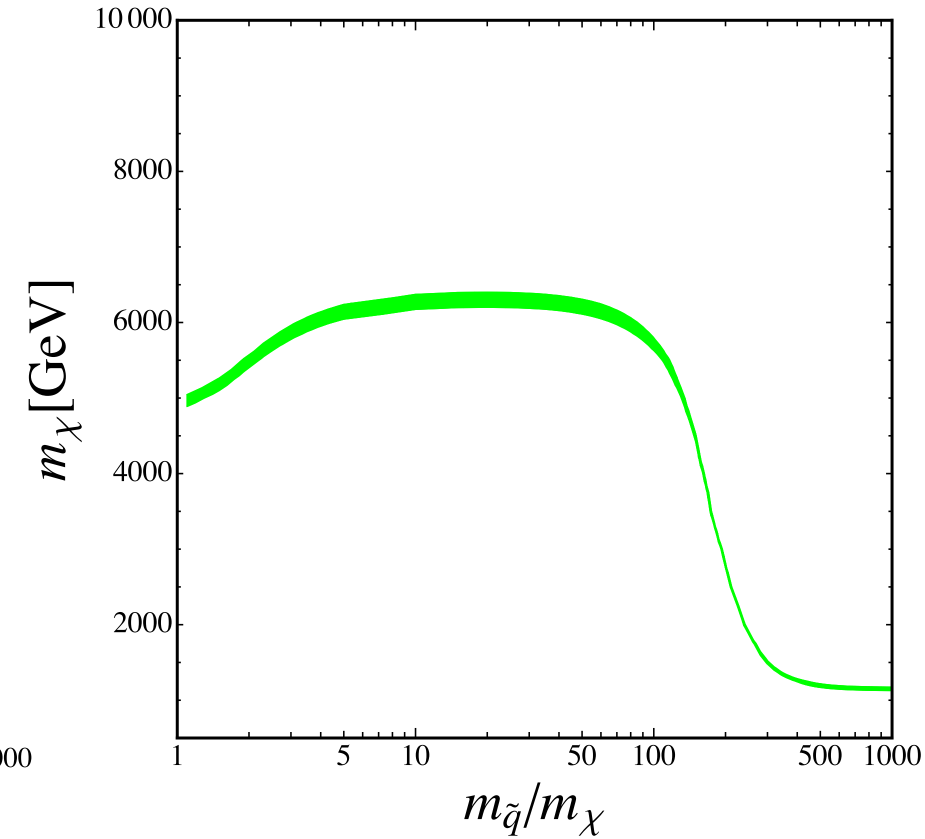
Wino-gluino coannihilation





Higgsino-gluino coannihilation





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 much smaller than $\tilde{g}\tilde{g}$ annihilation cross section.

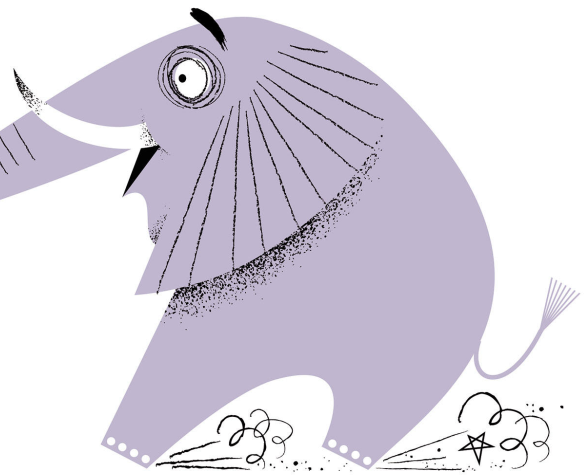
$$\frac{dn}{dt} + 3Hn = -\sum_{i,j=1}^{2} \langle \sigma v \rangle_{ij \to SM} \frac{n_i^{eq} n_j^{eq}}{n_{eq}^2} \left[n^2 - n_{eq}^2 \right]$$

- if $m_2 = m_1 \Rightarrow \bullet\bullet = \frac{g_1^2 \langle \sigma v \rangle_{11 \to SM} + g_2^2 \langle \sigma v \rangle_{22 \to SM} + 2 g_1 g_2 \langle \sigma v \rangle_{12 \to SM}}{(g_1 + g_2)^2}$

Profumo and Provenza, 2006

I’m a gluino…

I’m a Wino (Higgsino).



I’m the expanding Universe.