# Accurate determination of Baryon and DM abundances in Supersymmetric scenarios

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Based on work:
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(to appear soon)

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# Baryogenesis

Baryon abundance is originated by a dinamically generated matter-antimatter asymmetry.

Definite conditions should be fullfilled:

Violation of Baryon number.

Violation of CP

Departure from thermal equilibrium

# Dark Matter production

Many possibilities allowed.

No need of broken quantum numbers.

Dark matter can be a thermal relic.

Case of study: Implementation of a mechanism of baryogenesis and Dark Matter production in a definite particle physics framework, i.e. MSSM with R-parity violated.

# General idea

Production of baryon and DM densities from a WIMP-like mother particle.

(see also Cui 2013, Rompineve 2014, Baldes et al 2014)

$$\Omega_{\Delta B} = \xi_{\Delta B} \epsilon_{\rm CP} \frac{m_p}{m_X} \, BR(X \to b, \bar{b}) \, \Omega_X$$

$$\Omega_{DM} = \xi_{DM} \frac{m_{DM}}{m_X} BR\,(X \to DM + \text{anything})\, \Omega_X$$

$$\epsilon_{\rm CP} = \frac{\Gamma(X \to b) - \Gamma(X \to \bar{b})}{\Gamma(X \to b) + \Gamma(X \to \bar{b})}$$

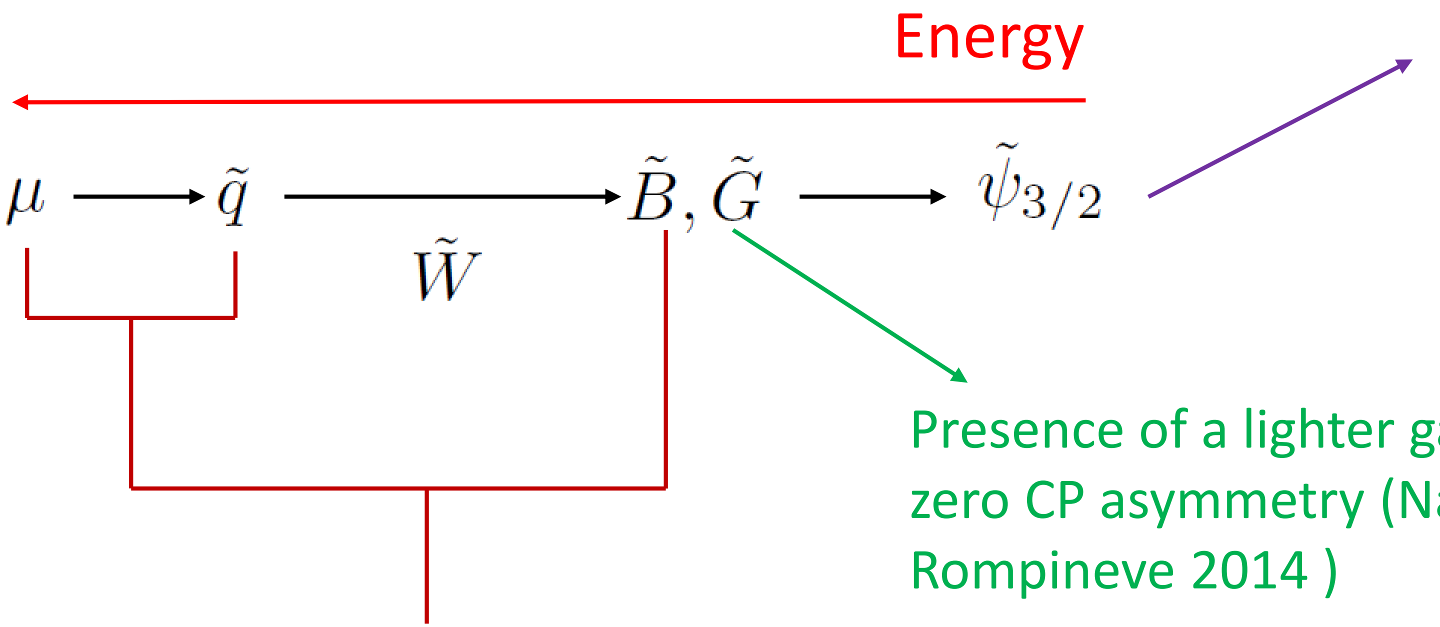
Relevant quantities depend on the underlying particle theory. (The mechanism is testable if it occurs at low enough mass scale). Moderate assumptions on the cosmological history needed.

Not trivial to implement in realistic frameworks.

# MSSM realization

B-violation provided by: $\lambda'' U^c D^c D^c$

Gravitino, only possible DM with RPV




Presence of a lighter gaugino needed for not zero CP asymmetry (Nanopoulos-Weiberg 1979, Rompineve 2014 )

Long-lived and overabundant mother particle needed.
Achievable for a Bino and very high scale of squarks and higgsinos.

# Complications in a realistic particle framework:

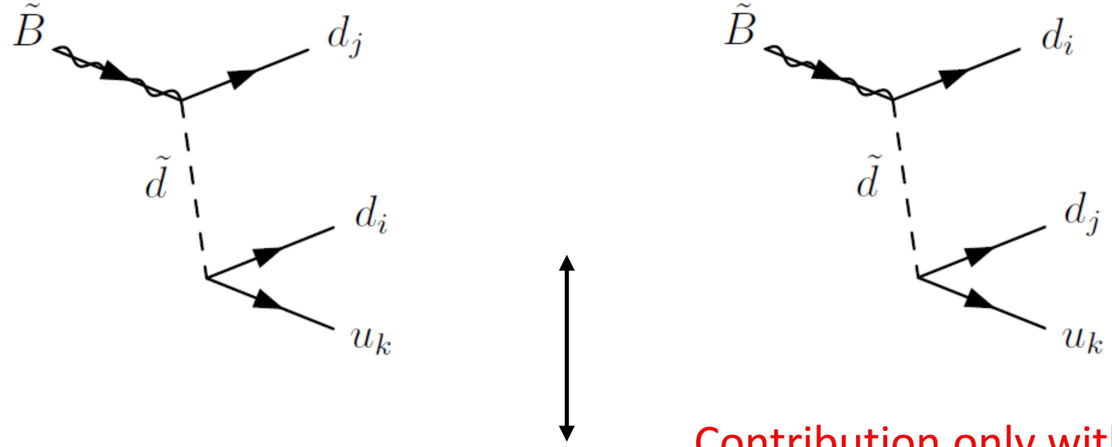
## Baryogenesis:

Non trivial determination of the abundance of the mother particle (coannihilation effects, presence of other light states).
Wash-out effects
Additional asymmetry generated by annihilations.

## Dark Matter:

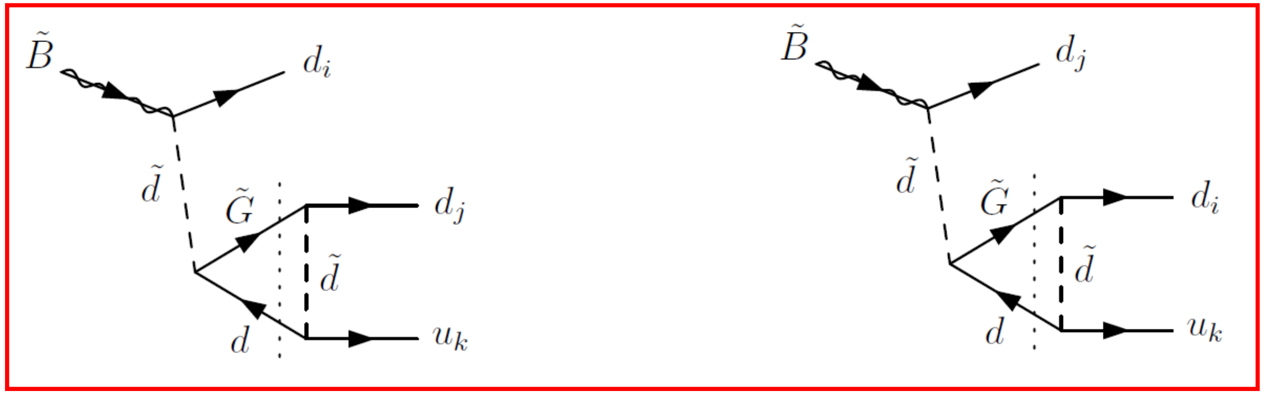
Additional production sources (effects of other states)

Need for a detailed numerical treatment…

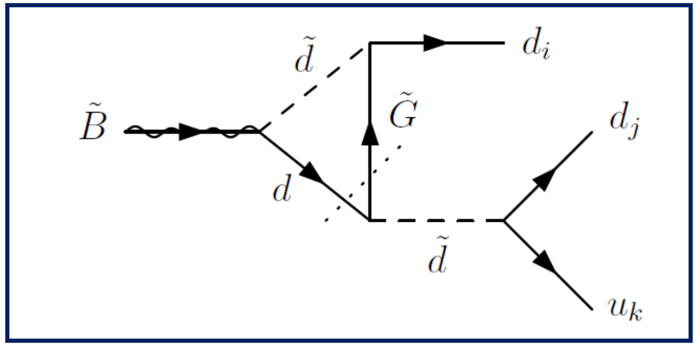



Asymmetry from annihilations induced by cross-symmetric diagrams

Contribution only with flavor violation




$$\epsilon_{CP} = \frac{\Delta\Gamma_{\text{dec}}}{\Gamma_{\text{tot,dec}}} + \frac{\Delta\Gamma_{\text{ann}}}{\Gamma_{\text{tot,ann}}}$$




Contribution also in
the flavor universal limit

(see also Cui 2013)

Subdominant contribution
in numerical results.

$$\Delta\Gamma_{\rm dec}=\sum_{\alpha\beta\gamma}\sum_{l,p,n}\frac{m_{\tilde B}^7}{m_{\tilde q_\alpha}^2 m_{\tilde q_\beta}^2 m_{\tilde q_\gamma}^2}\left[\left(A_1 Im\left[g_{\tilde B}^{RR*}g_{\tilde B}^{RR}g_{\tilde G}^{RR*}g_{\tilde G}^{RR}\Gamma^{D*}_{R\alpha i}\Gamma^{D}_{R\alpha n}\Gamma^{D}_{R\gamma p}\Gamma^{D*}_{R\gamma j}\Gamma^{D}_{R\beta i}\Gamma^{D*}_{R\beta l}\lambda^*_{knj}\lambda_{kpl}\right]\right.\right.$$

$$+A_2 Im\left[g_{\tilde B}^{RR*}g_{\tilde B}^{RR}g_{\tilde G}^{RR*}g_{\tilde G}^{RR}\Gamma^{D*}_{R\alpha j}\Gamma^{D}_{R\alpha n}\Gamma^{D}_{R\gamma p}\Gamma^{D*}_{R\gamma j}\Gamma^{D}_{R\beta i}\Gamma^{D*}_{R\beta l}\lambda^*_{kni}\lambda_{kpl}\right]+(i\leftrightarrow j)\Big)\, f_1\left(\frac{m_{\tilde G}^2}{m_{\tilde B}^2}\right)$$

$$+\frac{m_{\tilde G}}{m_{\tilde B}}\left(B_1 Im\left[g_{\tilde B}^{RR*}g_{\tilde B}^{RR*}g_{\tilde G}^{RR}g_{\tilde G}^{RR}\Gamma^{D*}_{R\alpha i}\Gamma^{D}_{R\alpha n}\Gamma^{D*}_{R\gamma p}\Gamma^{D}_{R\gamma l}\Gamma^{D}_{R\beta i}\Gamma^{D*}_{R\beta l}\lambda^*_{knj}\lambda_{kpj}\right]\right.$$

$$\left.\left.+\frac{m_{\tilde G}}{m_{\tilde B}}B_2 Im\left[g_{\tilde B}^{RR*}g_{\tilde B}^{RR*}g_{\tilde G}^{RR}g_{\tilde G}^{RR}\Gamma^{D*}_{R\alpha j}\Gamma^{D}_{R\alpha n}\Gamma^{D*}_{R\gamma p}\Gamma^{D}_{R\gamma l}\Gamma^{D}_{R\beta j}\Gamma^{D*}_{R\beta l}\lambda^*_{kni}\lambda_{kpj}\right]\right) f_2\left(\frac{m_{\tilde G}^2}{m_{\tilde B}^2}\right)\right]$$

CP-violating phases in the gaugino vertices

Not-trivial interplay from the flavor structure.
However flavor violating contribution GIM suppressed.

$$g_{\tilde B}^{\rm LL}=-\sqrt{2}g_1\left(Q_f-T_3\right)e^{i\phi_{\tilde B}}\quad g_{\tilde B}^{\rm RR}=\sqrt{2}g_1 Q_f e^{i\phi_{\tilde B}}$$

$$g_{\tilde G}^{\rm LL}=-\sqrt{2}g_3 e^{i\phi_{\tilde G}}\quad g_{\tilde G}^{\rm RR}=\sqrt{2}g_3 e^{i\phi_{\tilde G}}$$

$$\longrightarrow\qquad \epsilon_{\rm CP}=\frac{8}{3}Im\left[e^{2i\phi}\right]\frac{m_{\tilde B}m_{\tilde G}}{m_0^2}\alpha_s\left(1+\frac{\pi\alpha_s}{6\lambda^2}\right)^{-1} f_2\left(\frac{m_{\tilde G}^2}{m_{\tilde B}^2}\right)$$

Simple (but general limit) obtained in the case of only flavor diagonal degenerate d-squarks contributing

$$\phi=\phi_{\tilde G}-\phi_{\tilde B}$$

Asymptotic value at high RPV couplings

# Boltzmann equations

Three equations for the gauginos

B-violating processes

Single annihilations

$$\frac{dY_{\tilde{\alpha}}}{dx} = -\frac{1}{Hx}\Gamma_{\tilde{\alpha},\Delta B\neq 0}\left(Y_{\tilde{\alpha}} - Y_{\tilde{\alpha}}^{\rm eq}\right) - \frac{s}{Hx}\langle\sigma v\rangle_{\tilde{\alpha},\Delta B\neq 0} Y_X^{\rm eq}\left(Y_{\tilde{\alpha}} - Y_{\tilde{\alpha}}^{\rm eq}\right)$$

$$-\frac{s}{Hx}\sum_{\tilde{\beta}\neq\tilde{\alpha}}\langle\sigma v\rangle\left(\tilde{\alpha}\tilde{\beta}\to X\right)\left(Y_{\tilde{\alpha}}Y_{\tilde{\beta}} - Y_{\tilde{\alpha}}^{\rm eq}Y_{\tilde{\beta}}^{\rm eq}\right) - \frac{s}{Hx}\sum_{\tilde{\beta}\neq\tilde{\alpha}}\langle\sigma v\rangle\left(\tilde{\alpha}X\to\tilde{\beta}X\right)Y_X^{\rm eq}\left(Y_{\tilde{\alpha}} - \frac{Y_{\tilde{\alpha}}^{\rm eq}}{Y_{\tilde{\beta}}^{\rm eq}}Y_{\tilde{\beta}}\right)$$

$$-2\frac{s}{Hx}\langle\sigma v\rangle_{\tilde{\alpha}\tilde{\alpha}}\left(Y_{\tilde{\alpha}}^2 - Y_{\tilde{\alpha}}^{\rm eq\,2}\right) - \frac{1}{Hx}\sum_{\tilde{\beta}\neq\tilde{\alpha}}\Gamma_{\Delta B=0}\left(Y_{\tilde{\alpha}} - Y_{\tilde{\alpha}}^{\rm eq}\frac{Y_{\tilde{\beta}}}{Y_{\tilde{\beta}}^{\rm eq}}\right)$$

$$-\frac{1}{Hx}\Gamma\left(\tilde{\alpha}\to\tilde{\psi}_{3/2}+X\right)Y_{\tilde{\alpha}}$$

Conventional pair annihilations

Gravitino production

$\tilde{\alpha} = \tilde{B}, \tilde{W}, \tilde{G}$ $\qquad X = SM$

# Equation of the baryon density in the form of B-L

Source terms

$$\frac{dY_{\Delta B-L}}{dx} = \frac{1}{Hx}\Delta\Gamma_{\tilde{B},\Delta B\neq 0}\left(Y_{\tilde{B}} - Y_{\tilde{B}}^{\rm eq}\right) + \frac{s}{Hx}\langle\Delta\sigma v\rangle_{\tilde{B}}\left(Y_{\tilde{B}} - \frac{Y_{\tilde{B}}^{\rm eq}}{Y_{\tilde{G}}^{\rm eq}}Y_{\tilde{G}}\right)$$

$$- \frac{3}{Hx}\left(\langle\Gamma\left(\tilde{B}\to udd + \bar{u}\bar{d}\bar{d}\right)\rangle Y_{\tilde{B}}^{\rm eq} + \langle\Gamma\left(\tilde{G}\to udd + \bar{u}\bar{d}\bar{d}\right)\rangle Y_{\tilde{G}}^{\rm eq}\right)\left[\mu_u + \mu_c + \mu_t + 2\left(\mu_d + \mu_s + \mu_b\right)\right]$$

$$- \frac{6s}{Hx}\{\langle\sigma v\left(u\tilde{B}\to\bar{d}\bar{d}\right)\rangle\left[\left(\mu_u + \mu_c + \mu_t\right)Y_{\tilde{B}} + 2\left(\mu_d + \mu_s + \mu_b\right)Y_{\tilde{B}}^{\rm eq}\right]$$

$$+ \langle\sigma v\left(u\tilde{G}\to\bar{d}\bar{d}\right)\rangle\left[\left(\mu_u + \mu_c + \mu_t\right)Y_{\tilde{G}} + 2\left(\mu_d + \mu_s + \mu_b\right)Y_{\tilde{G}}^{\rm eq}\right]\}Y_q^{\rm eq}\frac{m_{\tilde{B}}}{x}$$

$$- \frac{12s}{Hx}\{\langle\sigma v\left(d\tilde{B}\to\bar{u}\bar{d}\right)\rangle\left[\left(\mu_d + \mu_s + \mu_b\right)Y_{\tilde{B}} + 2\left(\mu_d + \mu_s + \mu_b + \frac{1}{2}\mu_u + \frac{1}{2}\mu_c + \frac{1}{2}\mu_t\right)Y_{\tilde{B}}^{\rm eq}\right]$$

$$+ \langle\sigma v\left(d\tilde{G}\to\bar{u}\bar{d}\right)\rangle\left[\left(\mu_d + \mu_s + \mu_b\right)Y_{\tilde{G}} + 2\left(\mu_d + \mu_s + \mu_b + \frac{1}{2}\mu_u + \frac{1}{2}\mu_c + \frac{1}{2}\mu_t\right)Y_{\tilde{G}}^{\rm eq}\right]\}Y_q^{\rm eq}\frac{m_{\tilde{B}}}{x}$$

Wash-out terms

# Equation for the gravitino

$$\frac{dY_{3/2}}{dx} = \frac{1}{Hx}\sum_{\tilde{X}} \Gamma\left(\tilde{X} \to \tilde{\psi}_{3/2}\right) Y_{\tilde{X}} \qquad \tilde{X} = \tilde{B}, \tilde{W}, \tilde{G}$$

Freeze-in production from scalars also present in general.

Late time production (out-of-equilibrium)
Contribution only from the Bino.

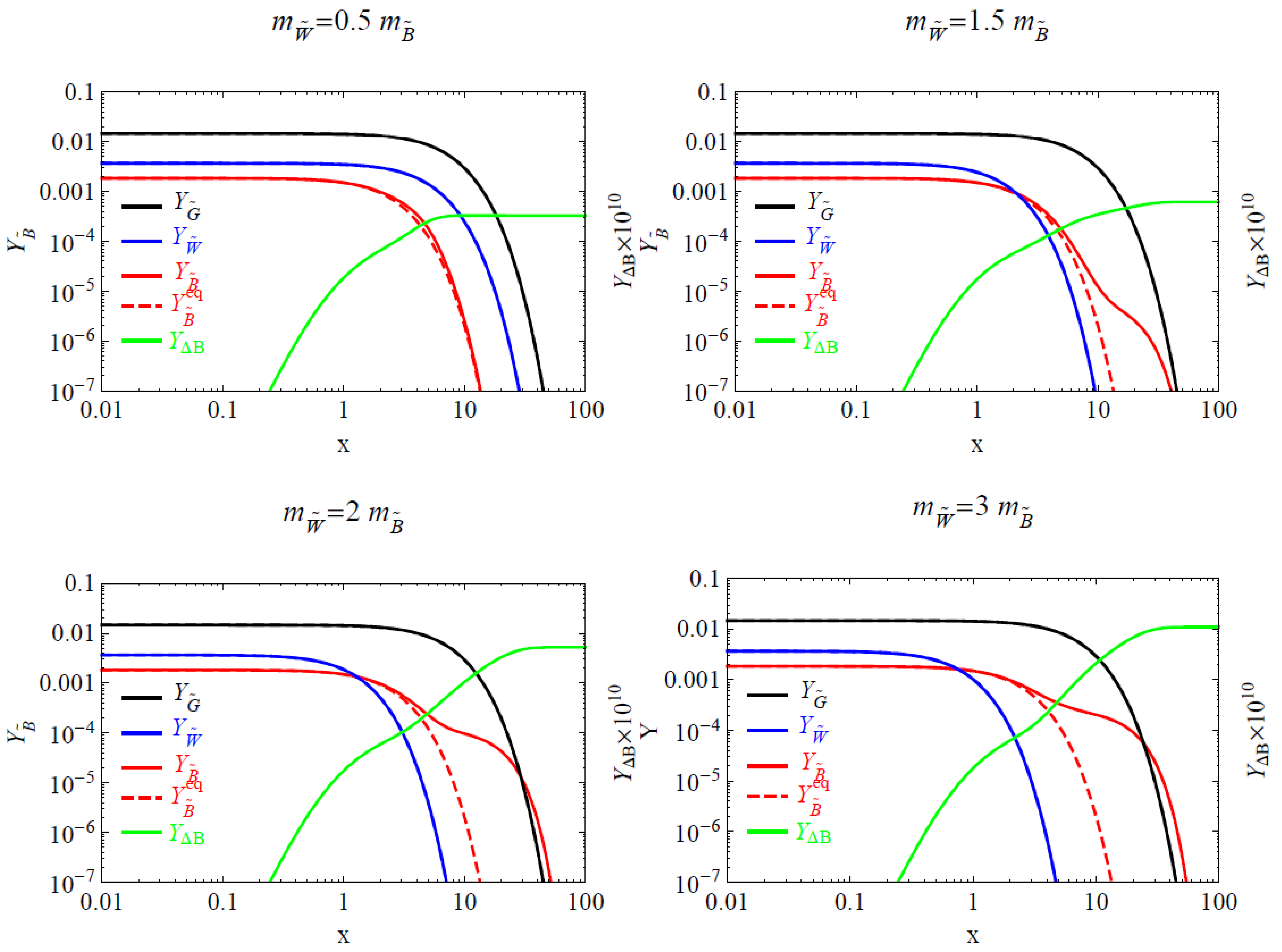
Early time production. (Freeze-in)

Overproduction of DM avoided for

$$T_{\rm R} < m_0$$

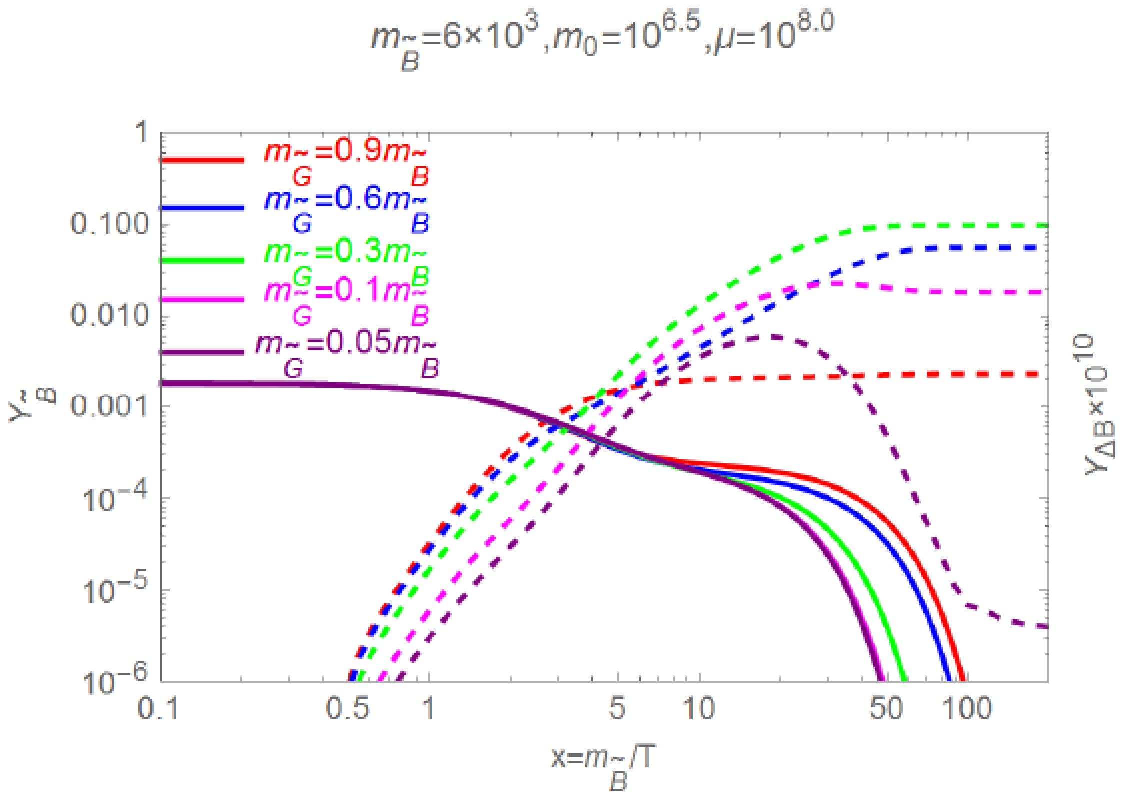
Contribution from thermal scatterings as well suppressed

Reheating temperature



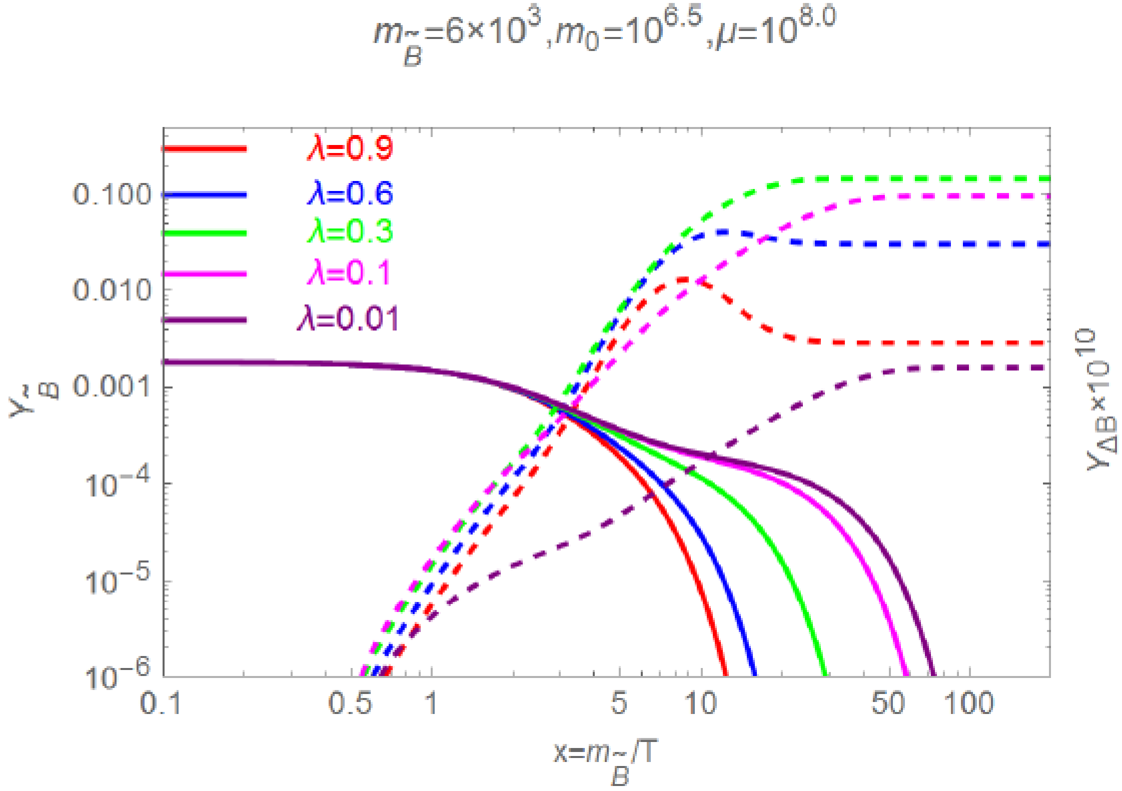

Strong coannihilation effects present even for sizable mass-splittings.

Strong hierarchy between the Wino and the other gauginos favored.




$\lambda \ll 1$ Suppressed asymmetry

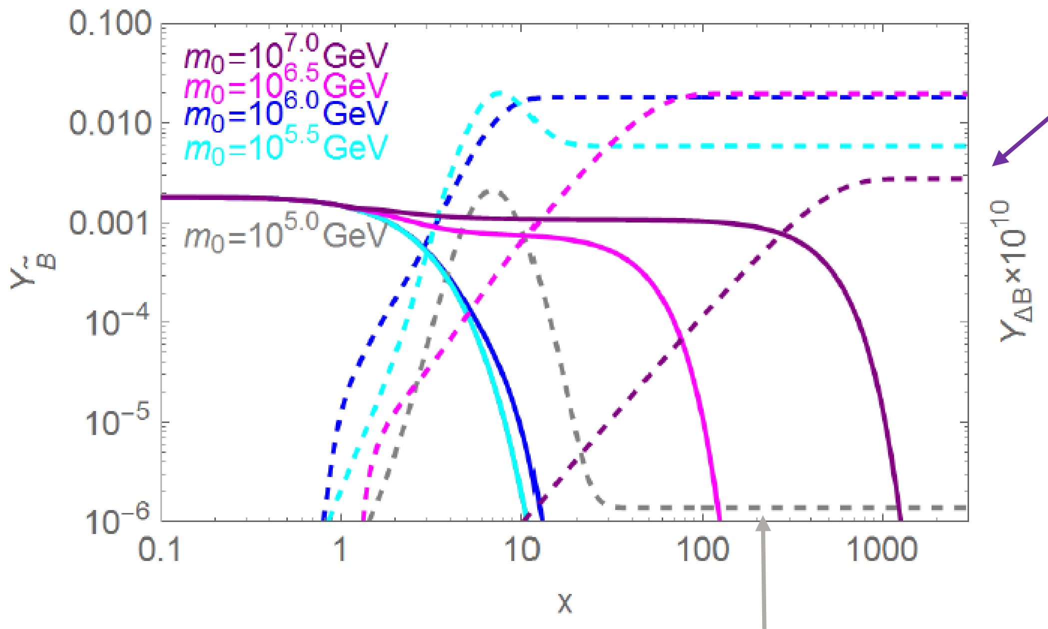
$\lambda \sim 1$ No increase of the asymmetry, suppression of the abundance of the Bino

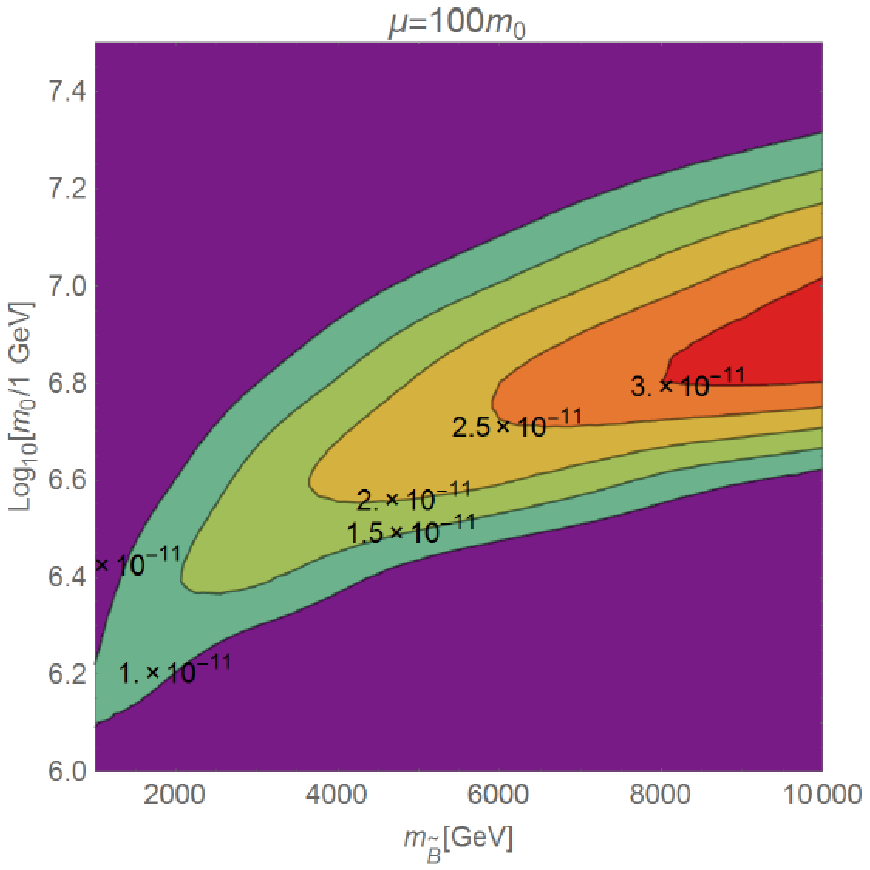



$m_{\tilde G}/m_{\tilde B} \ll 1$ Asymmetry depleted by wash-out

$m_{\tilde G} \simeq m_{\tilde B}$ Asymmetry tends to zero (Nanopoulos-Weiberg theorem)

Asymmetry suppressed by the high scalars




Asymmetry suppressed by wash-out

Rather definite prediction for range of scalar masses

Baryon abundance maximal for:

$$\frac{m_{\tilde{G}}}{m_{\tilde{B}}} \sim 0.3 - 0.6$$

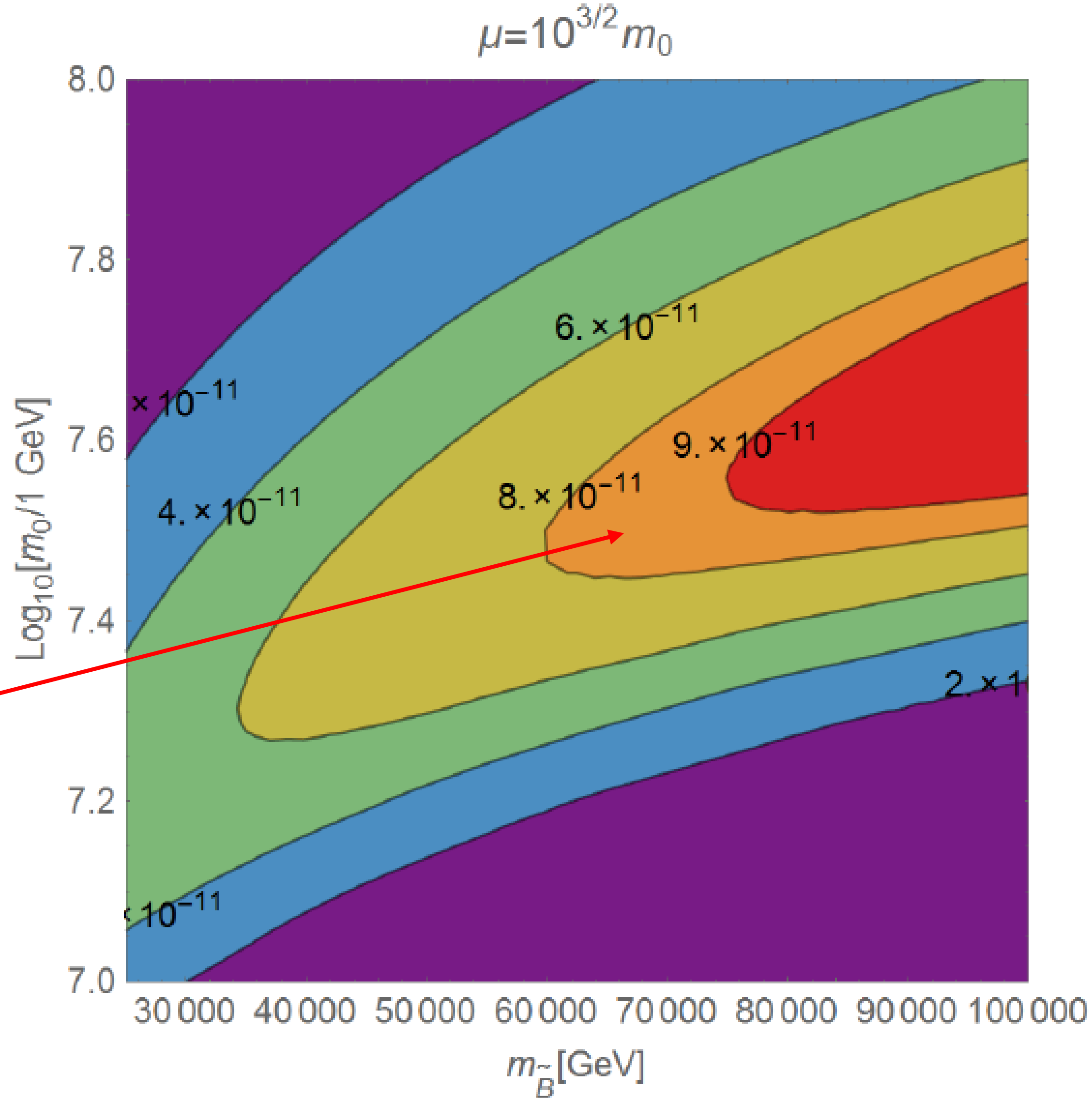
$$\lambda \sim 0.3 - 0.6$$

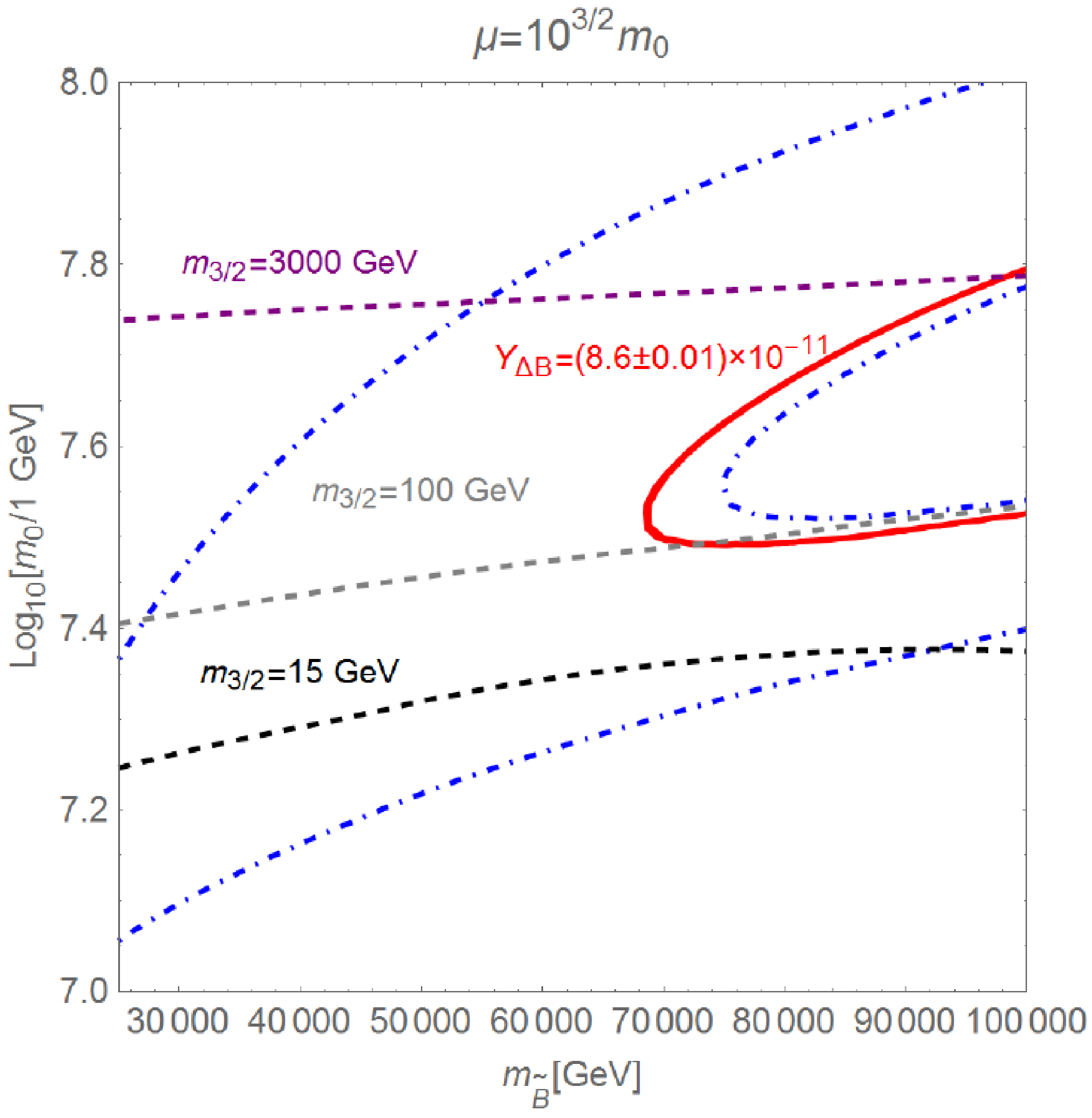
$$m_{\tilde{W}} > T_{\rm R}$$

Correct baryon asymmetry

$$Y_{\Delta B} = (0.86 \pm 0.01) \times 10^{-11}$$

obtained for a rather heavy spectrum.






Correct baryon density compatible with DM relic density for gravitino masses O(100 GeV-few TeV)

$$\Gamma\left(\tilde{\psi}_{3/2} \to udd\right) = N_c \frac{\lambda^2}{6144\pi^3}\frac{m_{3/2}^7}{m_0^4 M_{\rm Pl}^2}$$

$$\tau_{3/2} \approx \frac{4.6}{N_c} \times 10^{28}{\rm s}\left(\frac{\lambda}{0.4}\right)^{-2}\left(\frac{m_0}{10^{7.5}{\rm GeV}}\right)^4\left(\frac{m_{3/2}}{1{\rm TeV}}\right)^{-7}$$

Lifetime of the gravitino within the sensitivity of AMS.

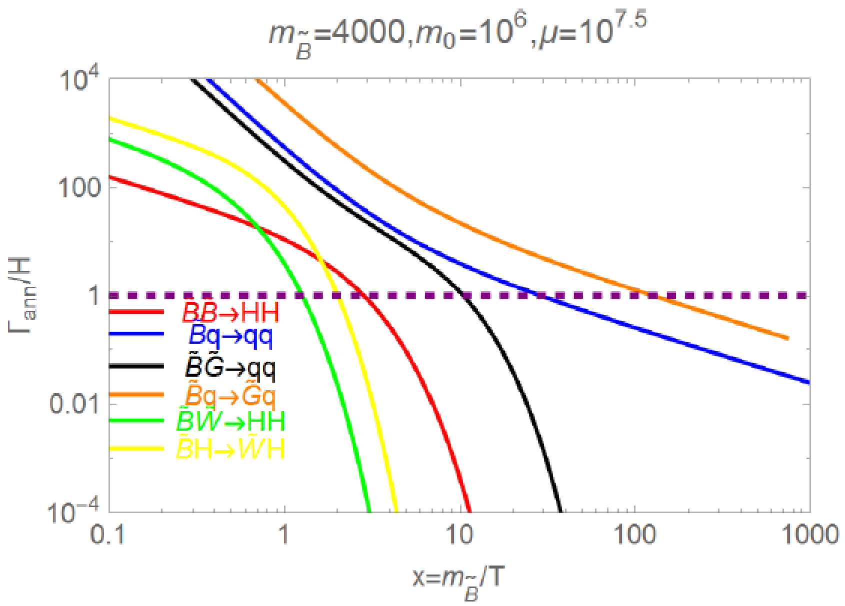
# Conclusions

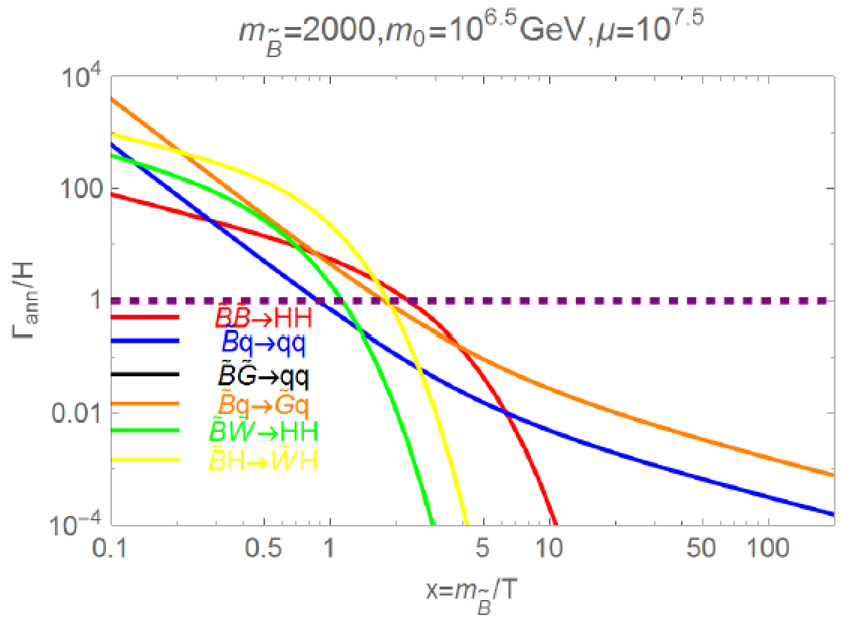
We have afforded in a systematic way the problem of DM production in the MSSM.

We have implemented a system of Boltzmann equations for the relevant particle spiecies including wash-out effects.

In the most simple realization, i.e. the flavor universal scenario, the viable Supesymmetric spectrum is heavy, probably beyond the LHC. The indirect detection of gravitino decays is instead possible.

# Back up




$$\xi_{\Delta B} = \xi_{\rm sp}\xi_{\rm w.o.}\xi_{\rm s}$$

Large amount of RPV increase the asymmetry but depletes the Bino abundance

$$\Omega_{\Delta B} = \xi_{\Delta B}\frac{m_p}{m_{\tilde{B}}}\epsilon_{\rm CP}\Omega_{\tilde{B}}^{\tau\to\infty}$$

$$Y_{\tilde{B}}(x_{\rm f}) = M(x_{\rm f})\left[\frac{M(x_{\rm i})}{Y_{\tilde{B}}(x_{\rm i})} + \frac{\langle\sigma v\rangle_{\rm p}}{\langle\sigma v\rangle_{\rm l}Y_{q,{\rm eq}}}\left(M(x_{\rm i}) - M(x_f)\right)\right]^{-1}$$

$$M(x) = \exp\left[\frac{a}{x}\langle\sigma v\rangle_{\rm l}Y_{q,{\rm eq}}\right]$$

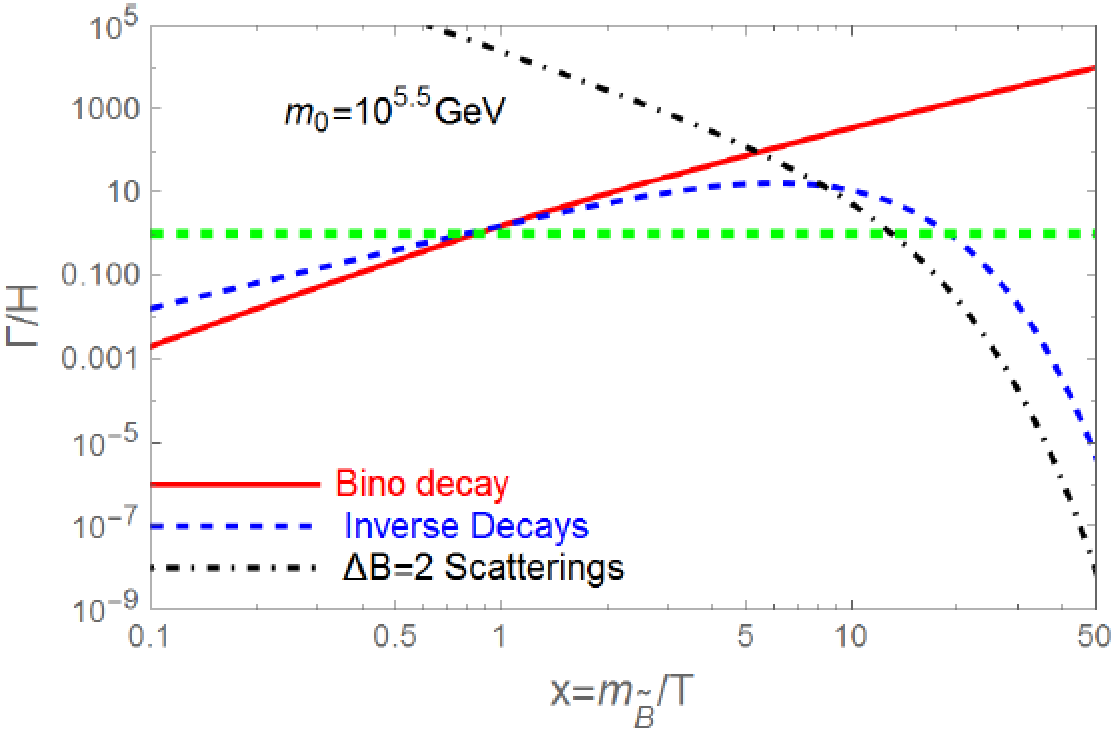
$$a = \sqrt{\frac{\pi}{45}}m_{\tilde{B}}M_{\rm Pl}$$

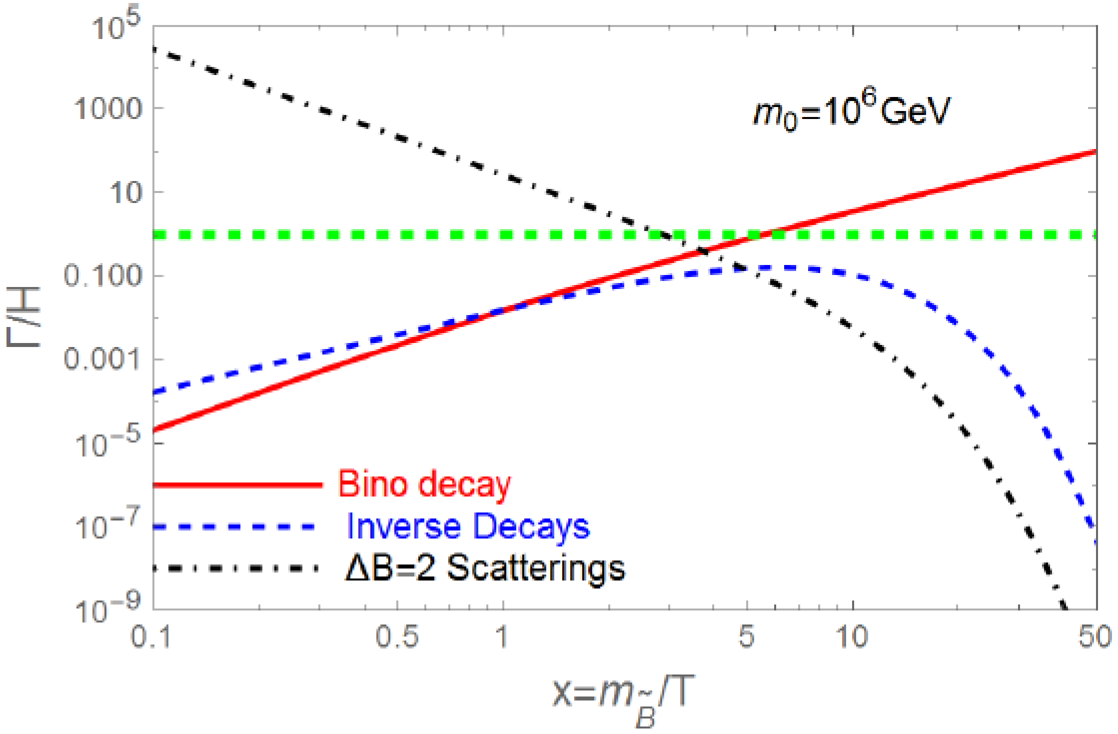
# Wash out-processes

$$\Gamma_{\rm ID} = \frac{\lambda^2 \alpha_s}{\pi^2} z^7 \frac{m_{\tilde{B}}^5}{m_0^4} x^2 K_2(zx) \qquad z = \frac{m_{\tilde{G}}}{m_{\tilde{B}}}$$

$$\Gamma_{\rm S} = \frac{16\alpha_s}{9\pi^2} |\lambda|^2 z^4 \frac{m_{\tilde{B}}^5}{m_0^4} \frac{1}{x} \left[5\frac{K_4(zx)}{K_2(zx)} + 1\right] K_2(zx)$$

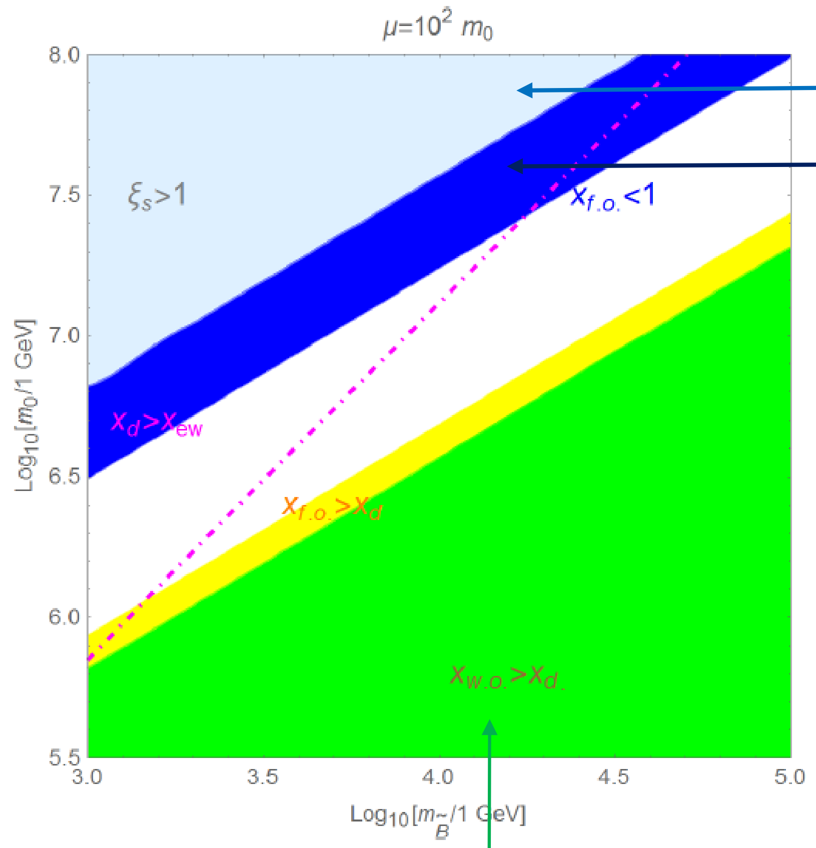
For heavy enough scalars the Bino decay after wash-out processes become ineffective and the baryon asymmetry is not depleted.



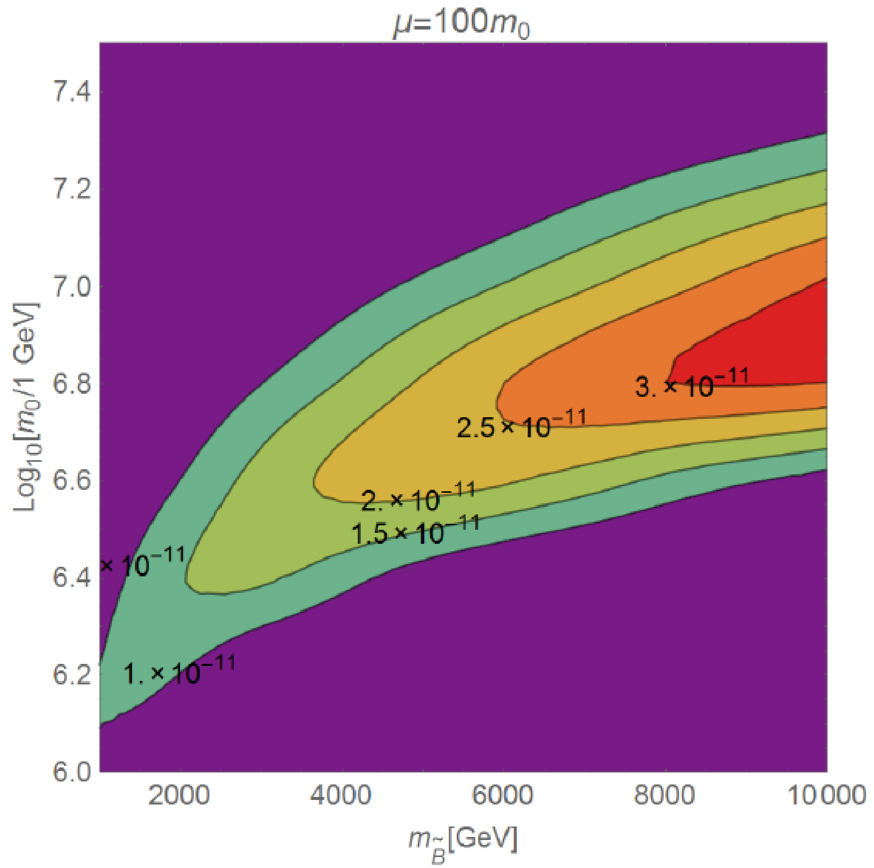



Asymmetry suppressed by entropy injection

Relativistic decoupling




Asymmetry suppressed from wash-out




Rather definite prediction for range of scalar masses

$$\Delta\Gamma_{\rm dec} = \sum_{\alpha\beta\gamma}\sum_{l,p,n} \frac{m_{\tilde{B}}^7}{m_{\tilde{q}_\alpha}^2 m_{\tilde{q}_\beta}^2 m_{\tilde{q}_\gamma}^2} \left[\left(A_1 Im\left[g_{\tilde{B}}^{RR*} g_{\tilde{B}}^{RR} g_{\tilde{G}}^{RR*} g_{\tilde{G}}^{RR} \Gamma_{R\alpha i}^{D*}\Gamma_{R\alpha n}^{D}\Gamma_{R\gamma p}^{D}\Gamma_{R\gamma j}^{D*}\Gamma_{R\beta i}^{D}\Gamma_{R\beta l}^{D*}\lambda_{knj}^{*}\lambda_{kpl}\right]\right.\right.$$

$$+A_2 Im\left[g_{\tilde{B}}^{RR*} g_{\tilde{B}}^{RR} g_{\tilde{G}}^{RR*} g_{\tilde{G}}^{RR} \Gamma_{R\alpha j}^{D*}\Gamma_{R\alpha n}^{D}\Gamma_{R\gamma p}^{D}\Gamma_{R\gamma j}^{D*}\Gamma_{R\beta i}^{D}\Gamma_{R\beta l}^{D*}\lambda_{kni}^{*}\lambda_{kpl}\right] + (i\leftrightarrow j)\Big) f_1\left(\frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2}\right)$$

$$+\frac{m_{\tilde{G}}}{m_{\tilde{B}}}\left(B_1 Im\left[g_{\tilde{B}}^{RR*} g_{\tilde{B}}^{RR*} g_{\tilde{G}}^{RR} g_{\tilde{G}}^{RR} \Gamma_{R\alpha i}^{D*}\Gamma_{R\alpha n}^{D}\Gamma_{R\gamma p}^{D*}\Gamma_{R\gamma l}^{D}\Gamma_{R\beta i}^{D}\Gamma_{R\beta l}^{D*}\lambda_{knj}^{*}\lambda_{kpj}\right]\right.$$

$$\left.\left.+\frac{m_{\tilde{G}}}{m_{\tilde{B}}} B_2 Im\left[g_{\tilde{B}}^{RR*} g_{\tilde{B}}^{RR*} g_{\tilde{G}}^{RR} g_{\tilde{G}}^{RR} \Gamma_{R\alpha j}^{D*}\Gamma_{R\alpha n}^{D}\Gamma_{R\gamma p}^{D*}\Gamma_{R\gamma l}^{D}\Gamma_{R\beta j}^{D}\Gamma_{R\beta l}^{D*}\lambda_{kni}^{*}\lambda_{kpj}\right]\right) f_2\left(\frac{m_{\tilde{G}}^2}{m_{\tilde{B}}^2}\right)\right]$$

$$g_{\tilde{B}}^{\rm LL} = -\sqrt{2} g_1\left(Q_f - T_3\right) e^{i\phi_{\tilde{B}}} \quad g_{\tilde{B}}^{\rm RR} = \sqrt{2} g_1 Q_f e^{i\phi_{\tilde{B}}}$$
$$g_{\tilde{G}}^{\rm LL} = -\sqrt{2} g_3 e^{i\phi_{\tilde{G}}} \quad g_{\tilde{G}}^{\rm RR} = \sqrt{2} g_3 e^{i\phi_{\tilde{G}}}$$

$$\Delta\Gamma_{\rm ann} = \langle\sigma v\rangle \Delta n_{\tilde{B}}, \quad \Delta n_{\tilde{B}} = n_{\tilde{B}} - n_{\tilde{B},\rm eq}$$

$$\langle\sigma v\rangle \Delta n_{\tilde{B}} = \sum_{\alpha\beta\gamma}\sum_{l,p,n} \frac{m_{\tilde{B}}^4}{m_{\tilde{q}_\alpha}^2 m_{\tilde{q}_\beta}^2 m_{\tilde{q}_\gamma}^2} \left[\left(C_1 Im\left[g_{\tilde{B}}^{RR*} g_{\tilde{B}}^{RR} g_{\tilde{G}}^{RR*} g_{\tilde{G}}^{RR} \Gamma_{R\alpha n}^{D*}\Gamma_{R\alpha i}^{D}\Gamma_{R\gamma p}^{D}\Gamma_{R\gamma i}^{D*}\Gamma_{R\beta l}^{D}\Gamma_{R\beta j}^{D*}\lambda_{knj}^{*}\lambda_{klp}\right]\right.\right.$$

$$+C_2 Im\left[g_{\tilde{B}}^{RR*} g_{\tilde{B}}^{RR} g_{\tilde{G}}^{RR*} g_{\tilde{G}}^{RR} \Gamma_{R\alpha j}^{D*}\Gamma_{R\alpha n}^{D}\Gamma_{R\gamma p}^{D}\Gamma_{R\gamma i}^{D*}\Gamma_{R\beta j}^{D}\Gamma_{R\beta l}^{D*}\lambda_{kni}^{*}\lambda_{klp}\right]\Big) I\Delta\Sigma_1\left(\frac{m_{\tilde{B}}}{T}, \frac{m_{\tilde{G}}}{T}\right)$$

$$+\frac{m_{\tilde{G}}}{m_{\tilde{B}}}\left(D_1 Im\left[g_{\tilde{G}}^{RR*} g_{\tilde{G}}^{RR*} g_{\tilde{B}}^{RR} g_{\tilde{B}}^{RR} \Gamma_{R\alpha i}^{D}\Gamma_{R\alpha l}^{D*}\Gamma_{R\gamma n}^{D}\Gamma_{R\gamma p}^{D*}\Gamma_{R\beta i}^{D*}\Gamma_{R\beta p}^{D}\lambda_{knj}^{*}\lambda_{kpj}\right]\right.$$

$$\left.\left.+\frac{m_{\tilde{G}}}{m_{\tilde{B}}} D_2 Im\left[g_{\tilde{B}}^{RR*} g_{\tilde{B}}^{RR*} g_{\tilde{G}}^{RR} g_{\tilde{G}}^{RR} \Gamma_{R\alpha j}^{D*}\Gamma_{R\alpha n}^{D}\Gamma_{R\gamma p}^{D*}\Gamma_{R\gamma l}^{D}\Gamma_{R\beta j}^{D}\Gamma_{R\beta l}^{D*}\lambda_{kni}^{*}\lambda_{klj}\right) I\Delta\Sigma_2\left(\frac{m_{\tilde{B}}}{T}, \frac{m_{\tilde{G}}}{T}\right)\right]\right]$$