Correlation of Dark Matter production mechanisms with Dark Matter Detection and Baryogenesis

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and
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in preparation

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invisibles
neutrinos, dark matter & dark energy physics

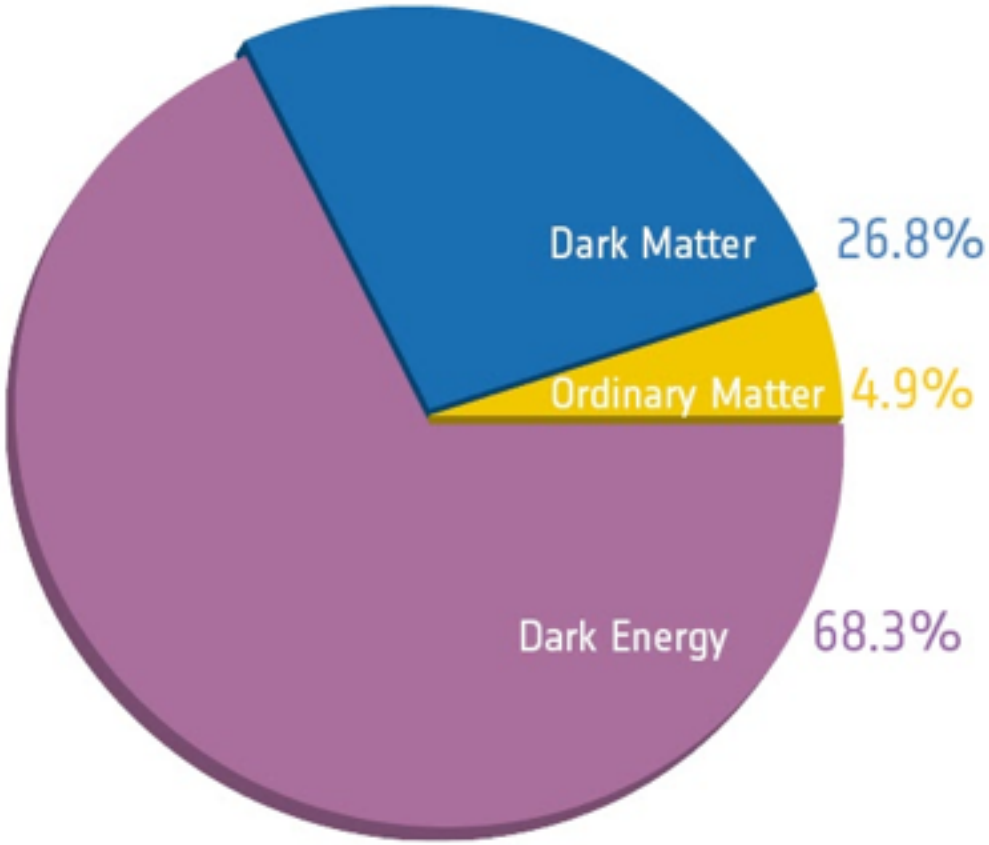
Outline of the talk

1)Review of Baryogenesis from WIMPs (WIMP-like):

- General mechanism
- Realizations in RPV SUSY

2)Common DM and Baryon generation from SuperWIMP mechanism.

-Realizations in SUSY with gravitino DM



Originated from

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Generation mechanism of DM and baryogenesis mechanism unknown at the moment. Both require extension of the SM.

$$\frac{\Omega_{\Delta B}}{\Omega_{DM}} \sim \frac{1}{5}$$

Baryogenesis and Dark Matter

One of the most interesting puzzles of cosmology is the similarity between the DM and baryon abundances.

A common origin is an intriguing prospective but is a difficult task.

In particular the generation of the baryon density must satisfy strong requirements:

Sakharov conditions: $\longrightarrow$

- Violation of Baryon number
- Presence of CP asymmetry
- Departure from thermal equilibrium.

Dark matter does not require the violation of a quantum number and can be produced in equilibrium.

Common generation mechanisms

The most intuitive option is an asymmetric generation for both baryons and DM.

Simplest realization:
The ratio between the densities is related to the DM and proton mass.

Scenario challenged by DM phenomenology.

More complex realizations:
Asymmetry generated in one sector (DM or baryonic) and then transferred to the other

Examples:
Darkogenesis (1008.1997)
Hylogenesis (1008.2399)
Xogenesis (1009.0227)

Another possibility is to relate both generations to the WIMP paradigm:

Production from decay of a WIMP-like particle

(Cui and Sundrum 2012, Cui 2013, Sorbello 2013)

Efficient production.
Infrared dependence of the mechanism.

Non trivial to accomplish in concrete realizations.

WIMPy production: production of baryon asymmetry from DM annihilations
(Randall et al 2011, Bernal et al 2012)

Baryogenesis from WIMPs

Basic idea arXiv:1212.2937

$$\Delta\mathcal{L} = \lambda_{ij}\phi d_i d_j + \varepsilon_i \chi \bar{u}_i \phi + M_\chi^2 \chi^2 + y_i \psi \bar{u}_i \phi + M_\psi^2 \psi^2 + \alpha\chi^2 S + \beta|H|^2 S + M_S^2 S^2 + \text{h.c.}$$

B-violating interaction

The coupling must be small in order to make the mother particle enough long-lived

$\chi =$ Wimp-like Mother particle

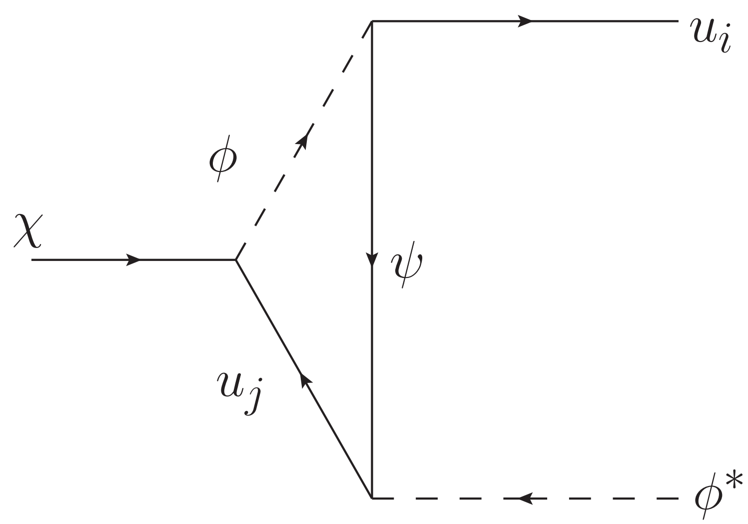
$\psi =$ Maiorana fermion

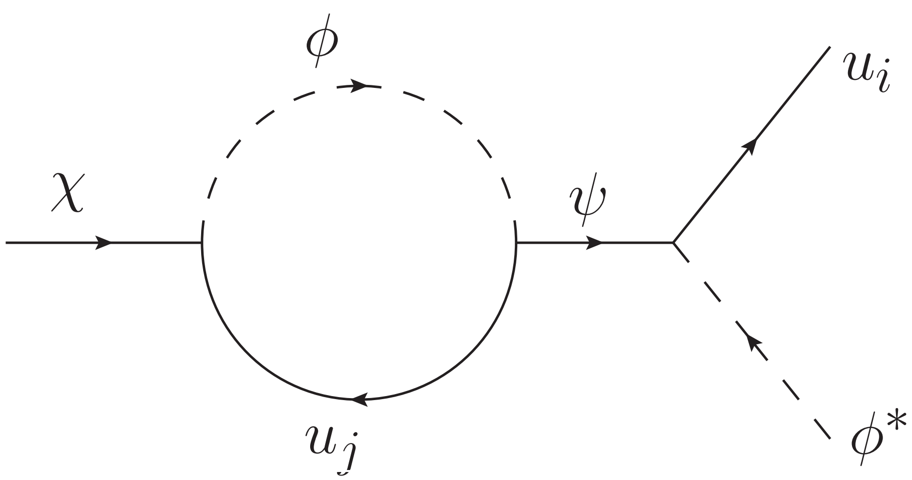
$\phi =$ Scalar quark-like state

$S =$ Mediator of Wimp annihilations

We need

$\psi < \chi$ or $\phi < \chi$





$$\epsilon_{\rm CP} \simeq \frac{1}{8\pi}\frac{1}{\sum_i |\varepsilon_i|^2} Im\left\{\left(\sum_i \varepsilon_i y_i^*\right)^2\right\}\frac{M_\chi}{M_\psi},$$

$$y_i \sim O(1)$$

$$10^{-11} \leq \epsilon_i \leq 10^{-8}$$

Guarantees long lifetime of the mother particle (compatibly with BBN)

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi}\epsilon_{\rm CP} BR\left(\chi \to \not{B}\right)\Omega_\chi^{\tau\to\infty}$$

Wash-out processes are not effective if the mother particle decays at sensitively lower temperatures with respect to its mass

DM is implemented by an additional state as well occuring conventional freeze-out

$$\frac{\Omega_{\Delta B}}{\Omega_{\rm DM}} = \boxed{\frac{m_p}{m_\chi}\epsilon_{\rm CP} BR\left(\chi \rightarrow \not{B}\right)} \boxed{\frac{\Omega_\chi^{\tau \rightarrow \infty}}{\Omega_{\rm DM}}}$$

Preferred to be not suppressed

Related by O(1) variations of the parameters of the theory

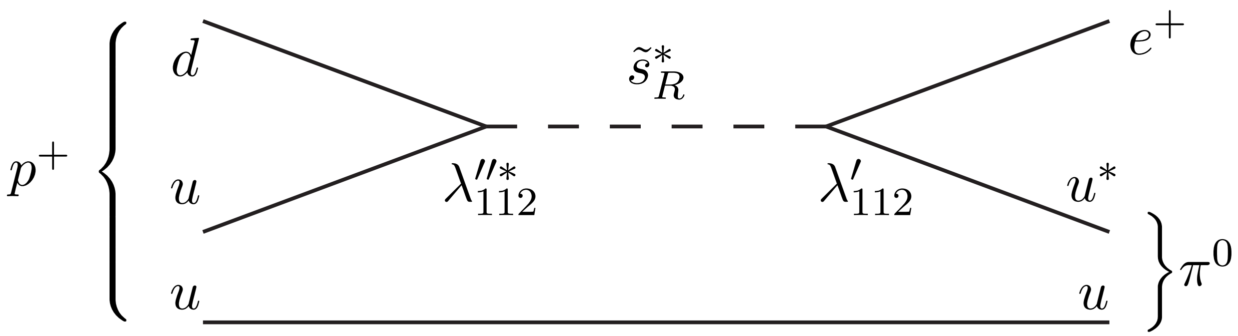
Not trivial to achieve in concrete realizations

Concrete application:RPV SUSY

In absence of R-parity we have the following additional Superpotential

$$W_{\Delta L=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \lambda'^{ijk} L_i Q_j \overline{d}_k + \mu'^i L_i H_u \longrightarrow \text{L-violation}$$

$$W_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk} \overline{u}_i \overline{d}_j \overline{d}_k \longrightarrow \text{B-violation}$$



Very strong limits from proton decay if both the B- and L-violating couplings present

Baryogenesis in RPV SUSY

B-violation provided by RPV superpotential (RPV soft-terms)

- Direct Baryogenesis through B-violating couplings
- Leptogenesis through L-violating couplings

CP-violation in soft-potential terms or in RPV superpotential couplings themselves

Baryon production through out-of-equilibrium decay of a superpartner

Concrete realizations

First scenario: implementation in the MSSM arXiv:1309.2952

$\chi = \tilde{B} \quad \psi = \tilde{g}$

$\phi = \tilde{d}$

B-number broken by $\lambda'' U^c D^c D^c$

$$m_{\tilde{g}} < m_{\tilde{B}} \ll m_{\tilde{d}} = m_0$$

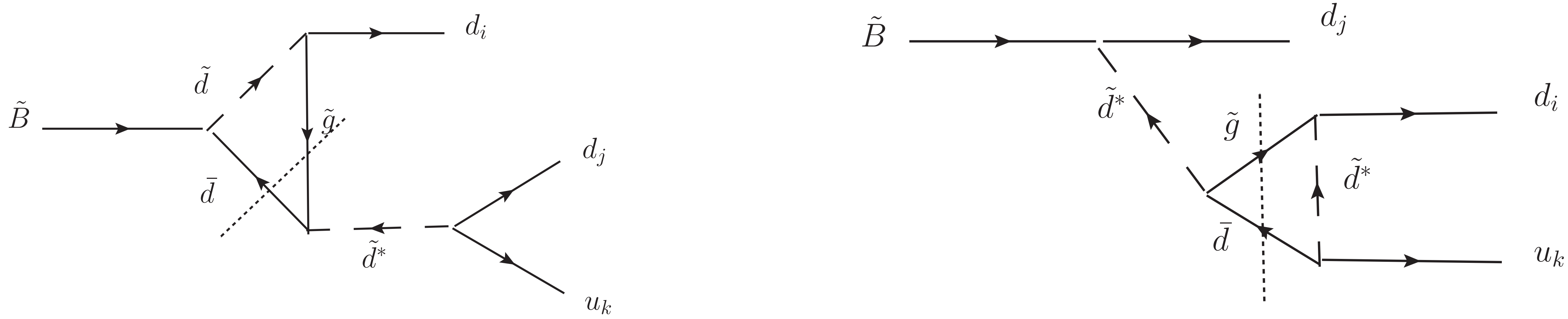
Bino features only three body decays

$$\Gamma\left(\tilde{B} \to udd + \overline{u}\overline{d}\overline{d}\right) = \frac{\lambda^2 g_1^2 N_{\rm RPV}}{768\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\Gamma\left(\tilde{B} \to \tilde{g} f \overline{f}\right) = \frac{\left(g_1 g_3 Q_f\right)^2 N_{\rm RPC}}{256\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$

Lifetime of the Bino enhanced by the high mass scale of the scalars even for O(1) RPV couplings.

Non null CP-asymmetry present only with flavor violation in the squark sector



$$\epsilon_{\rm CP} = \frac{4}{15\pi} Im\left[e^{i\phi}\right]\lambda^2\left(1+\frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC}\alpha_s}\right)^{-1}\frac{m_{\tilde{B}}^2}{m_0^2}$$

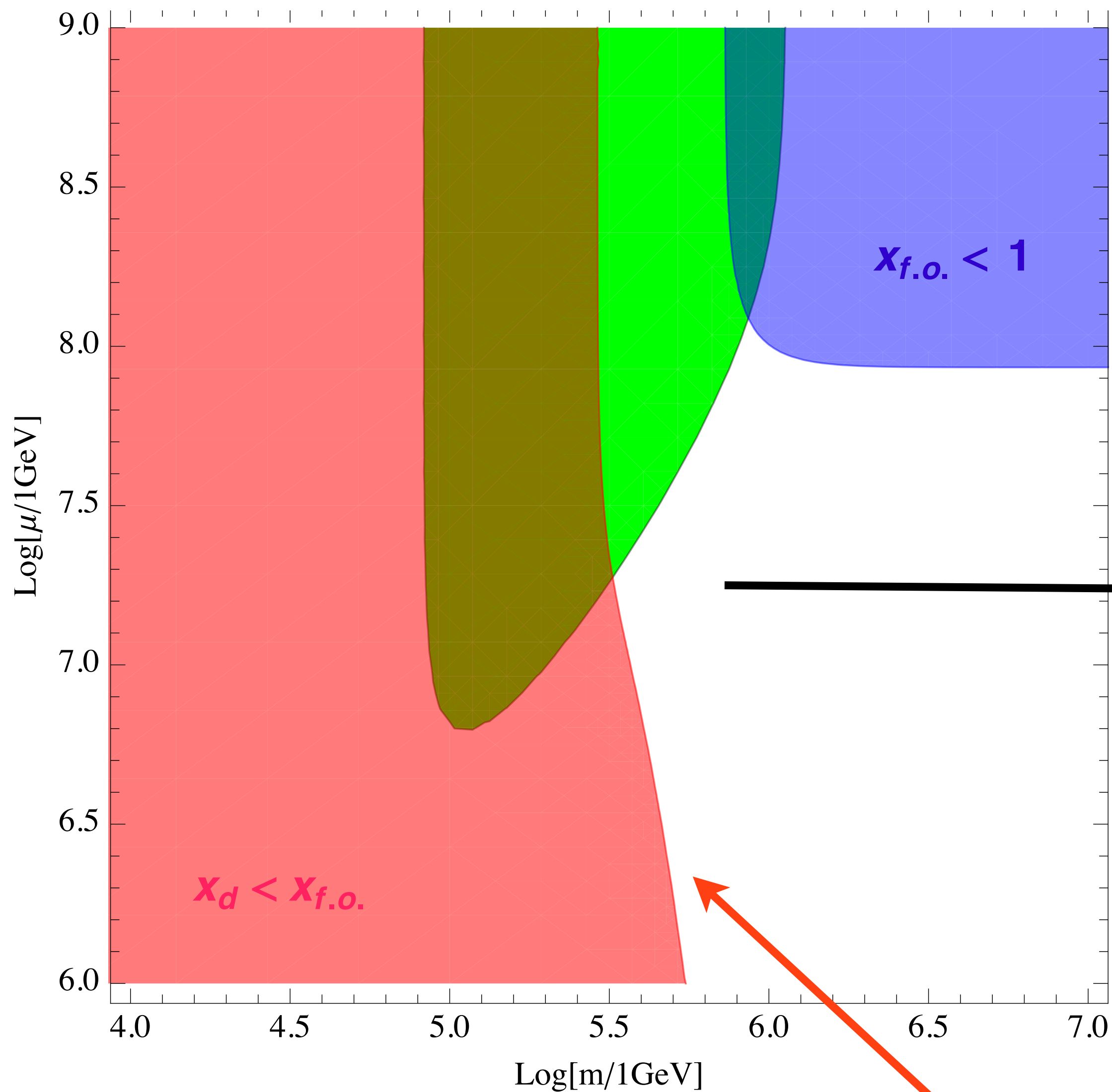
Very suppressed value. Compensated by an enhanced abundance of the Bino

$$\Omega_{\tilde{B}}^{\tau\to\infty} \simeq \frac{3.9\times 10^8 x_{\rm f.o.}}{g_*^{1/2} M_{\rm Pl}\langle\sigma_{\rm tot} v(x_{\rm f.o.})\rangle} \longrightarrow \Omega_{\tilde{B}}^{\tau\to\infty} \approx 4.1\times 10^9\left(\frac{\mu}{10^8\,{\rm GeV}}\right)^2\frac{x_{\rm f.o.}}{A(x_{\rm f.o.})}$$

$$\langle\sigma_{\rm tot} v\rangle \approx \frac{g_1^4}{128\pi}\frac{1}{\mu^2}\left[A(x)+7.19\times 10^{-2}\left(\frac{\lambda}{0.1}\right)^2\frac{m_B^2}{m_0^2}\left(\frac{\mu}{m_0}\right)^2 B(x)\right]$$

$$\Omega_{\Delta B} \approx 1.3 \times 10^{-2} \frac{x_{\rm f.o.}}{A(x_{\rm f.o.})} \left(\frac{m_{\tilde{B}}}{1{\rm TeV}}\right) \left(\frac{\mu}{10^{3/2} m_0}\right)^2 \left(\frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC} \alpha_s}\right) \left(1 + \frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC} \alpha_s}\right)^{-1}$$

Theoretically challenging



Relativistic decoupling

$\lambda \gtrsim O(0.1)$

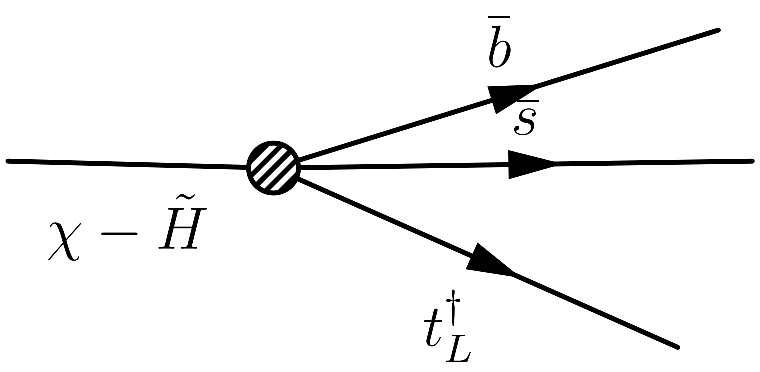
weakly bounded because high scale sfermions

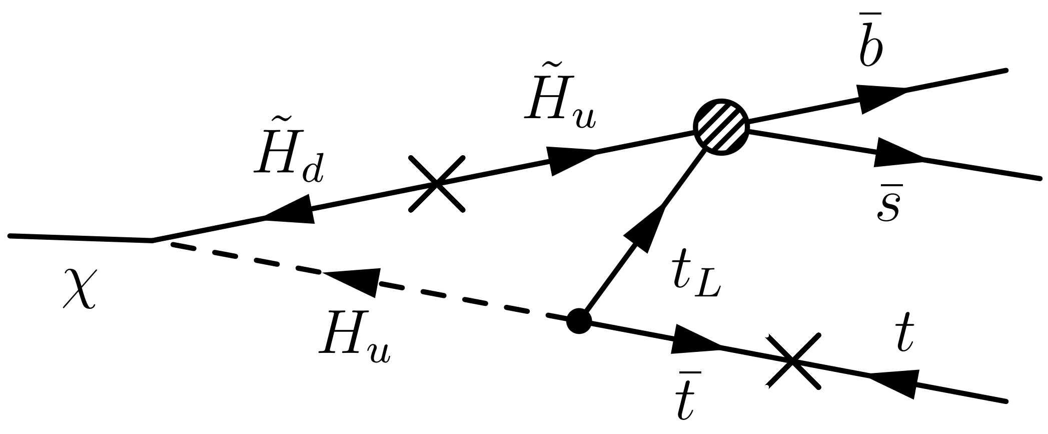
Annihilations and wash-out processes should be taken into account

Alternative scenario: MSSM+ 2 Maiorana states (arXiv:1310.0840)

$$W = \lambda_{3ij}\bar{t}\bar{d}_i\bar{d}_j + \epsilon\chi H_u H_d + y_t \bar{t} Q H_u + M_\chi \chi^2 + \mu H_u H_d + M_S S^2 + \alpha\chi^2 S + \beta S H_u H_d$$

Mother particle





First realization:

CP-asymmetry suppressed by the presence of a two body decay

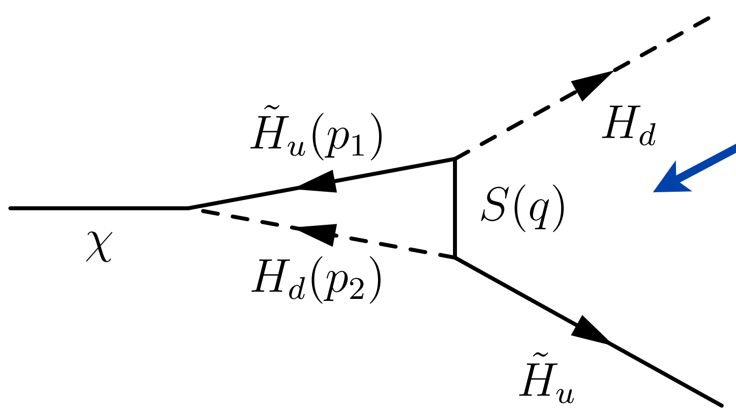
$$\epsilon_{CP} \approx \frac{1}{8\pi}\frac{Im\{\epsilon^{*2}e^{-i\phi_\mu}\}y_t}{|\epsilon|^2\sin\beta}\frac{|\mu|m_t}{vM_\chi}\frac{f(x_\mu,x_t,x_h)}{A}$$

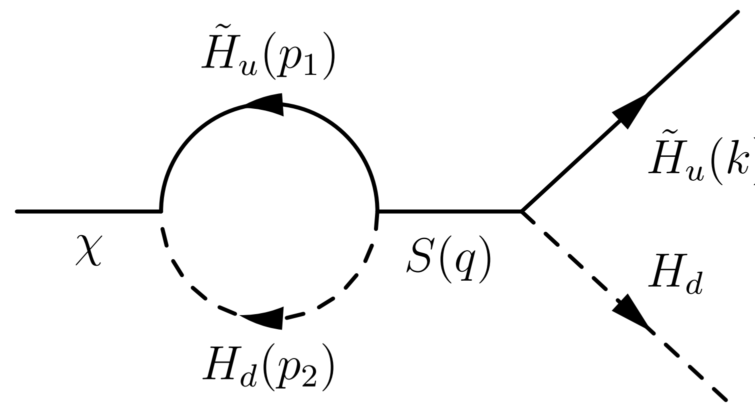
$$A = 1 + \frac{2^6\cdot 3\cdot\pi^2 M_{\tilde{t}}^4}{|\lambda''_{332}|^2|y_t|^2 M_\chi^2 v^2\sin^2\beta}.$$

CP asymmetry is again suppressed and need to be compensated by a high relic density of the mother particle.

Second realization

The field S can be replaced by the Bino but the asymmetry gets suppressed by the smaller coupling





Two step production: CP asymmetry produced in the two body decay, Baryon asymmetry produced by the RPV decay of higgsinos

$$\epsilon_B^{T\to\infty} \simeq \frac{\epsilon_{CP}^{\chi}}{1+\left[2^{10}\cdot 3\pi^3 g'^2 \frac{M_{\tilde{t}}^4 v_u^2}{M_{\tilde{B}}\mu^5}\right]^2}$$

$$\epsilon_{CP}^{\chi} = \frac{1}{8\pi}\frac{Im\{(\epsilon^*\beta)^2\}}{|\epsilon|^2}\frac{M_\chi}{M_S}$$

wash-out from

$\tilde{H}_u$ - $\bar{\tilde{H}}_u$

oscillations

CP-asymmetry not suppressed if the stops are close to the EW scale

Correlation with a WIMP DM achievable

Baryogenesis and SuperWimp mechanism

Baryon asymmetry and DM connected by the SuperWIMP mechanism.

Baryon and DM abundances generated by the out-of-equilibrium decays of a same mother particle.

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi}\epsilon_{\rm CP} BR\left(\chi \to \not{B}\right)\Omega_\chi^{\tau \to \infty}$$

Small parameter

$$\Omega_{\rm DM} = \frac{m_{\rm DM}}{m_\chi} BR\left(\chi \to DM + \text{anything}\right)\Omega_\chi^{\tau \to \infty}$$

Small parameter

$$\frac{\Omega_{\Delta B}}{\Omega_{\rm DM}} = \frac{m_p}{m_{\rm DM}} \epsilon_{\rm CP} \frac{BR\left(\chi \rightarrow \not{B}\right)}{BR\left(\chi \rightarrow DM + \text{anything}\right)}$$

The ratio between the baryon and the DM density is independent from the relic density of the mother particle.

Since normally the CP asymmetry is a small number we need a suppressed branching ratio of decay in DM.

↓

A natural playground of this scenario is RPV SUSY
with
Gravitino DM

Baryogenesis with gravitino DM

The gravitino is stable (on cosmological scales) even with high B-violating couplings.

Superpartners decay into gravitino with a Planck suppressed rate.

$$\Gamma_i = \frac{1}{48\pi} \frac{m_i^5}{m_{3/2}^2 M_{\rm Pl}^2}$$

The relative branching ratio is easily suppressed with respect to the other possible channels.

Case of study: MSSM

We reconsider the MSSM implementation of baryogenesis mechanism

Additional decay channel for the Bino:

$$\Gamma\left(\tilde{B} \to udd + \overline{udd}\right) = \frac{\lambda^2 g_1^2 N_{\rm RPV}}{768\pi^3} \frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\Gamma\left(\tilde{B} \to \tilde{g} f \overline{f}\right) = \frac{\left(g_1 g_3 Q_f\right)^2 N_{\rm RPC}}{256\pi^3} \frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\Gamma\left(\tilde{B} \to \tilde{G} + X\right) = \frac{1}{48\pi} \frac{m_{\tilde{B}}^5}{m_{3/2}^2 M_{\rm Pl}^2}$$

$$Br\left(\tilde{B} \to \tilde{G} + X\right) \approx 5.7 \times 10^{-10} \left(1 + \frac{N_{\rm RPV}\lambda^2}{\pi N_{\rm RPC}\alpha_s}\right)^{-1} \left(\frac{m_{3/2}}{1\rm GeV}\right)^{-2} \left(\frac{m_0}{10^6\rm GeV}\right)^4$$

→ The suppressed branching ratio does not influence the generation of the Baryon asymmetry

$$\Omega_{\Delta B} \approx 1.3 \times 10^{-2} \frac{x_{\rm f.o.}}{A(x_{\rm f.o.})} \left(\frac{m_{\tilde{B}}}{1{\rm TeV}}\right) \left(\frac{\mu}{10^{3/2} m_0}\right)^2 \left(\frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC} \alpha_s}\right) \left(1 + \frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC} \alpha_s}\right)^{-1}$$

$$\Omega_{3/2}^{\rm SW} \approx 2.34 \times 10^{-3} \left(\frac{\mu}{10^{3/2} m_0}\right)^2 \left(\frac{m_0}{10^6 {\rm GeV}}\right)^6 \left(\frac{m_{\tilde{B}}}{1{\rm TeV}}\right)^{-1} \left(\frac{m_{3/2}}{1{\rm GeV}}\right)^{-1} \frac{x_{\rm f.o.}}{A(x_{\rm f.o.})} \left(1 + \frac{N_{\rm RPV} \lambda^2}{\pi N_{\rm RPC}}\right)^{-1}$$

$$\frac{\Omega_{\Delta B}}{\Omega_{DM}} = \xi \frac{m_p}{m_{3/2}} \frac{\epsilon_{\rm CP}}{Br\left(\tilde{B} \to \tilde{G} + X\right)} \approx 1.32\, \xi \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{m_{3/2}}{m_p}\right) \left(\frac{m_{\tilde{B}}}{1{\rm TeV}}\right)^2 \left(\frac{m_0}{10^6 {\rm GeV}}\right)^{-6}$$

Limitations of the computations:

Wash-out processes. (Not effective if the decay occurs at temperatures below the Bino mass).

Effects of annihilations.

Chemical decoupling of the Bino.

Other production mechanisms of the gravitino.

Gravitino production

There are other two production mechanisms for gravitino:

Thermal scatterings: gravitino density dependent on gaugino masses and reheating temperature (Strumia et al 2007, Olechowski et al 2009)

Freeze-in production from decays of the superpartners while in equilibrium. (Cheung et al. 2011)

$$\Omega_{3/2}^{\rm FIMP} = \frac{1.09 \times 10^{27}}{g_*^{3/2}} m_{3/2} \sum_i g_i \frac{\Gamma_i}{m_i^2} \longrightarrow \Gamma_i \propto m_i^5$$

For gravitino production FI is dominated by heaviest states.

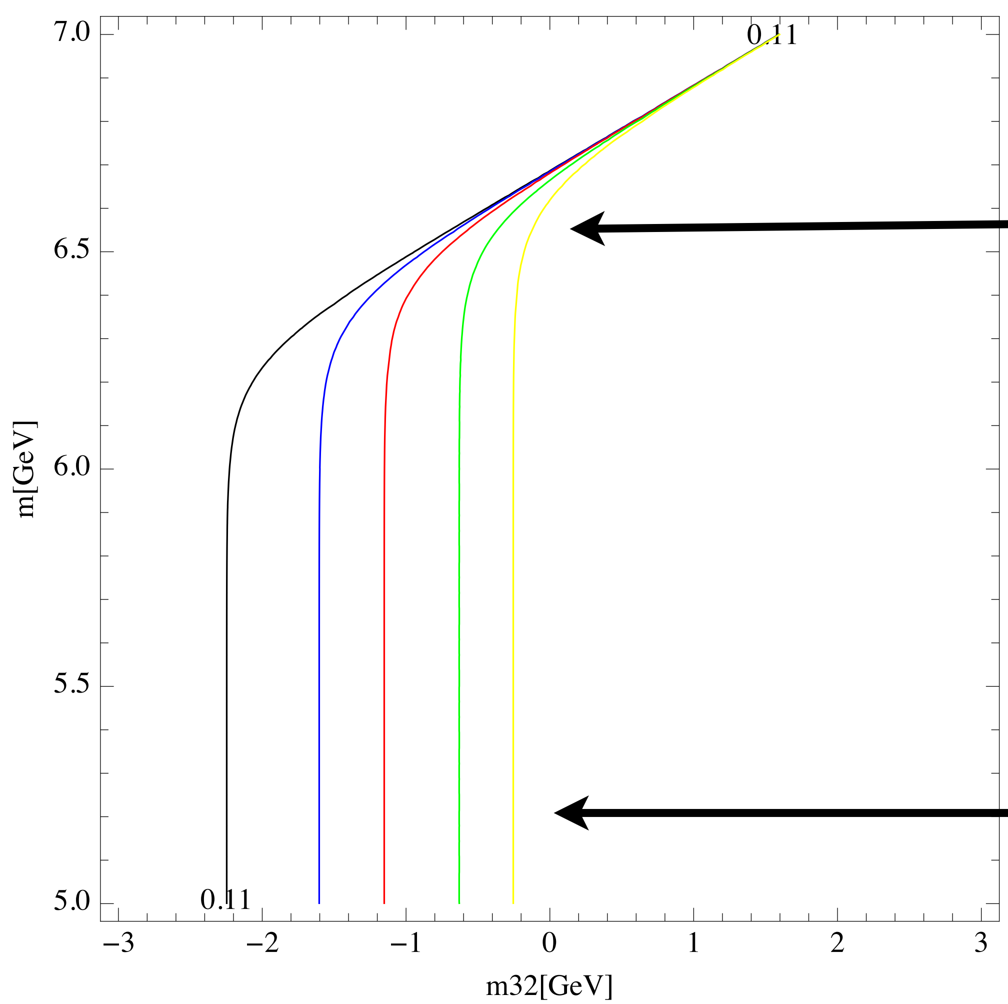
DM is oveproduced by the scalars unless.

$T_{\rm RH} < m_0 \longrightarrow$ This suppresses also thermal contributions.

$$\Omega_{3/2}^{\rm FI} \approx 7\times 10^{-4}\left(\frac{m_{\tilde B}}{1{\rm TeV}}\right)^3\left(\frac{m_{3/2}}{1{\rm GeV}}\right)^{-1}\left[1+3\left(\frac{m_{\tilde W}}{m_{\tilde B}}\right)^3+8\left(\frac{m_{\tilde g}}{m_{\tilde B}}\right)^3\right]$$

$$\frac{\Omega_{3/2}^{\rm SW}}{\Omega_{3/2}^{FI}} \approx 0.1\left(1+\frac{N_{\rm RPV}\lambda^2}{\pi N_{\rm RPC}\alpha_s}\right)^{-1}\left(\frac{m_{\tilde B}}{1{\rm TeV}}\right)^{-4}\left(\frac{\mu}{m_0}\right)^2\left(\frac{m_0}{10^6{\rm GeV}}\right)^6$$

$$\times \frac{x_{\rm f.o.}}{\left[A(x_{\rm f.o})+7.19\times 10^{-2}\left(\frac{\lambda}{0.1}\right)^2\frac{m_B^2}{m_0^2}\left(\frac{\mu}{m_0}\right)^2 B(x_{f.o})\right]}\frac{1}{\left[1+3\left(\frac{m_{\tilde W}}{m_{\tilde B}}\right)^3+8\left(\frac{m_{\tilde g}}{m_{\tilde B}}\right)^3\right]}$$



SW dominated

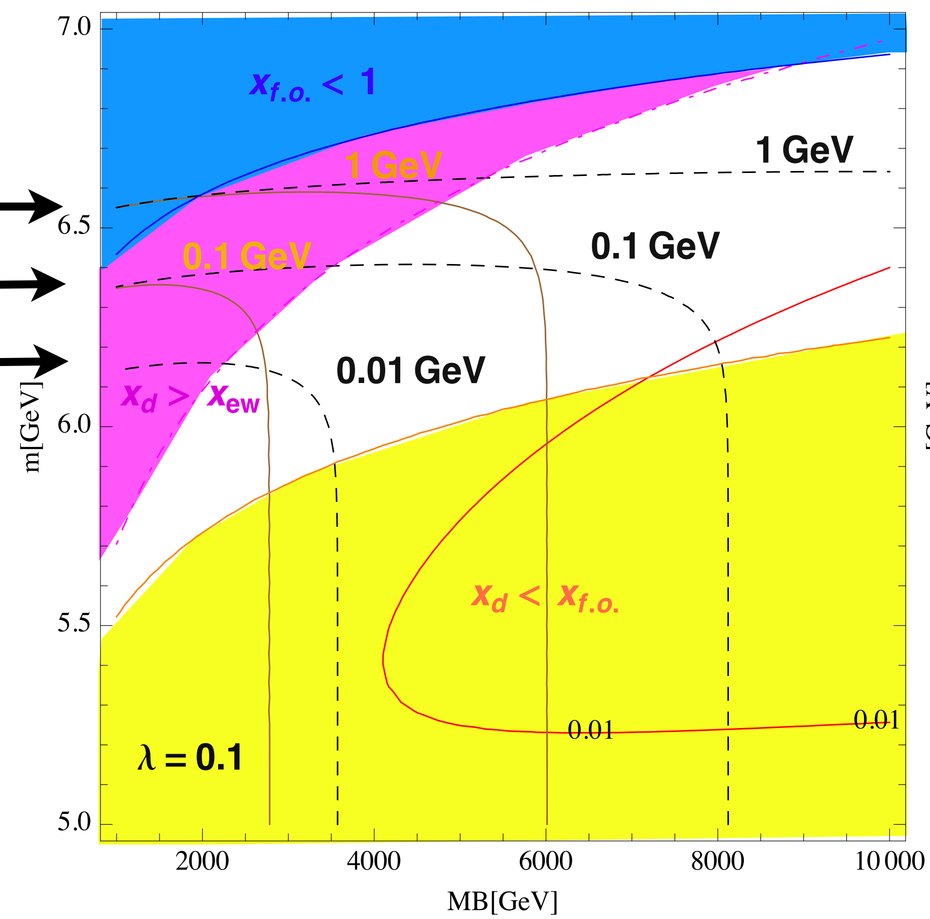
FI dominated

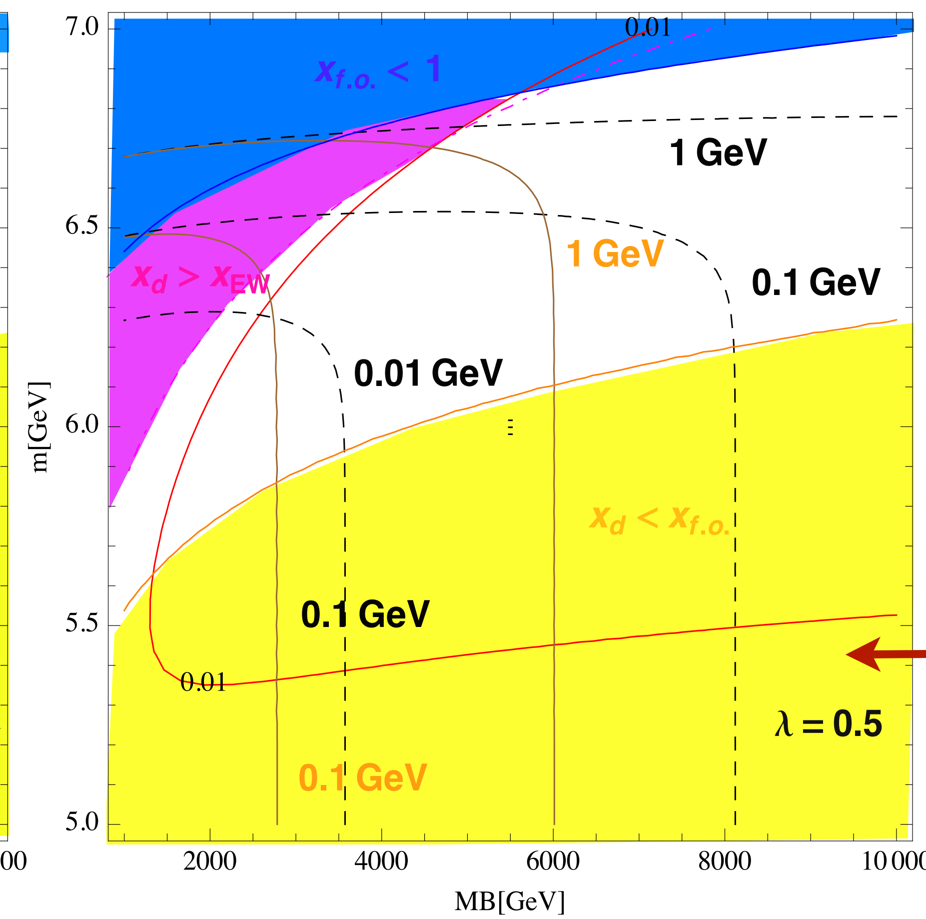
Results

DM relic density

Relativistic decoupling

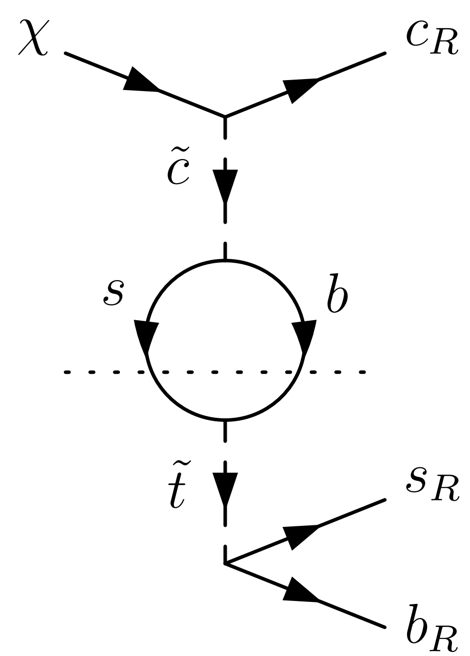
Baryon density





Annihilations and wash-out should be taken into account

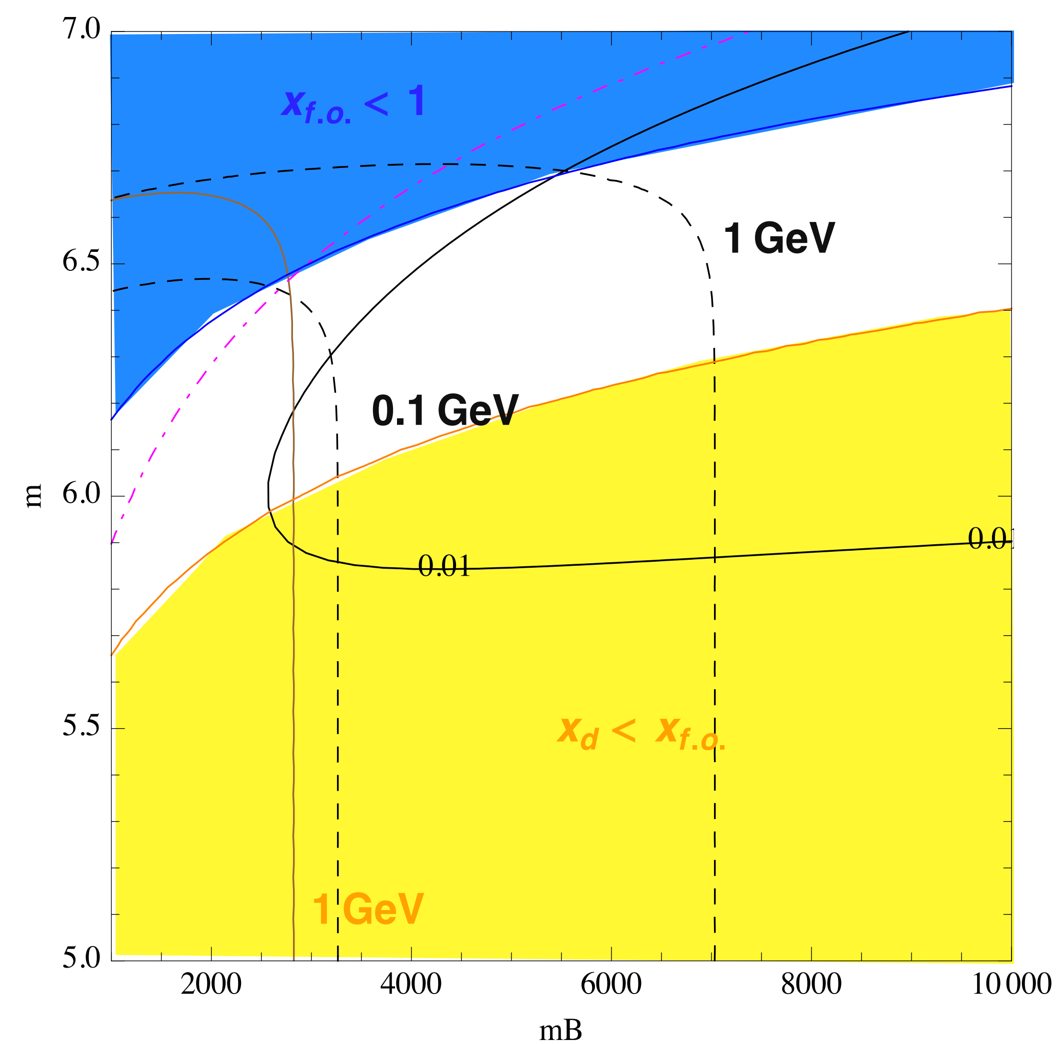
Alternative realization



CP-violation is encoded in RPV couplings.

Bino can be the NLSP.

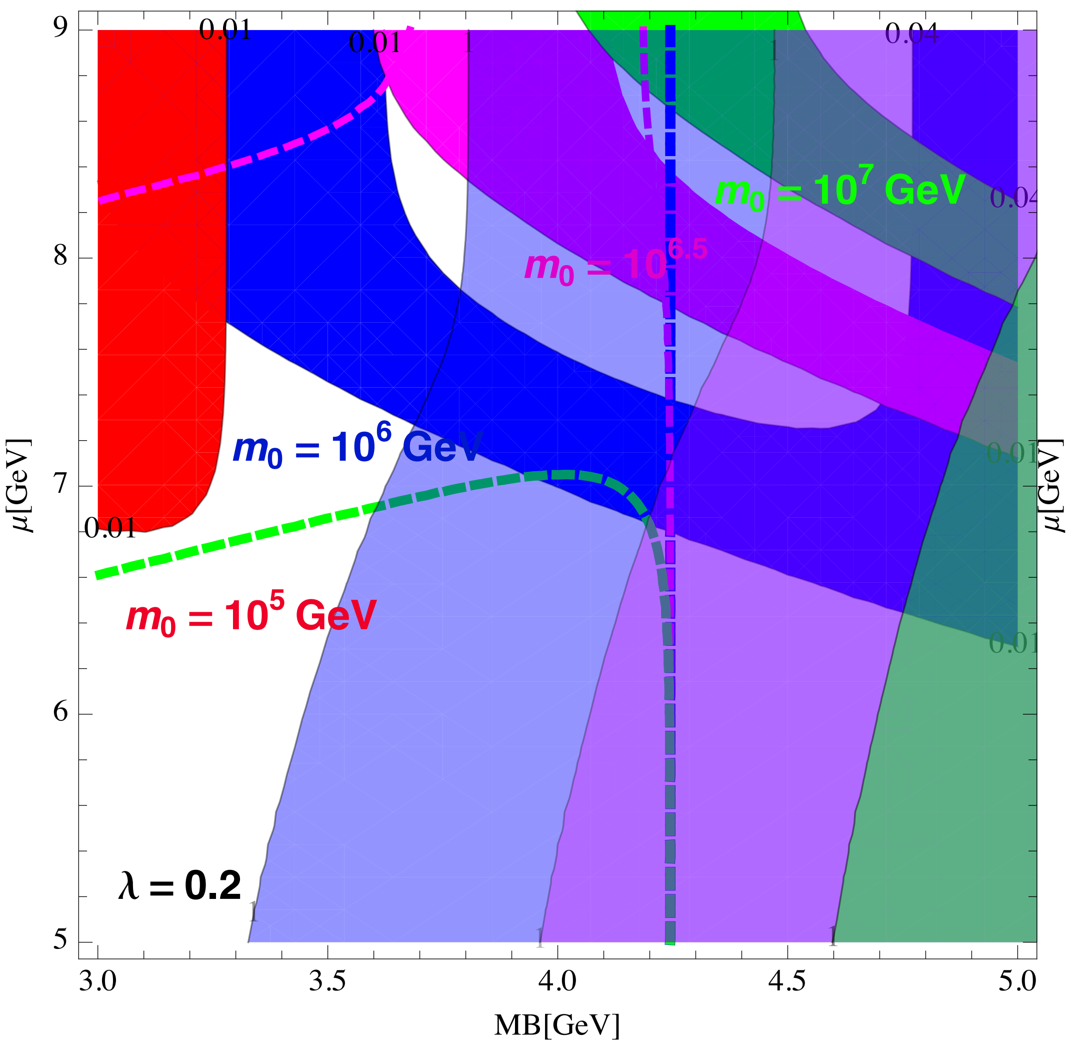
$$\epsilon_{\rm CP} = \lambda^2 \frac{1}{10\pi} \frac{m_{\tilde{B}}^2}{m_0^2}$$



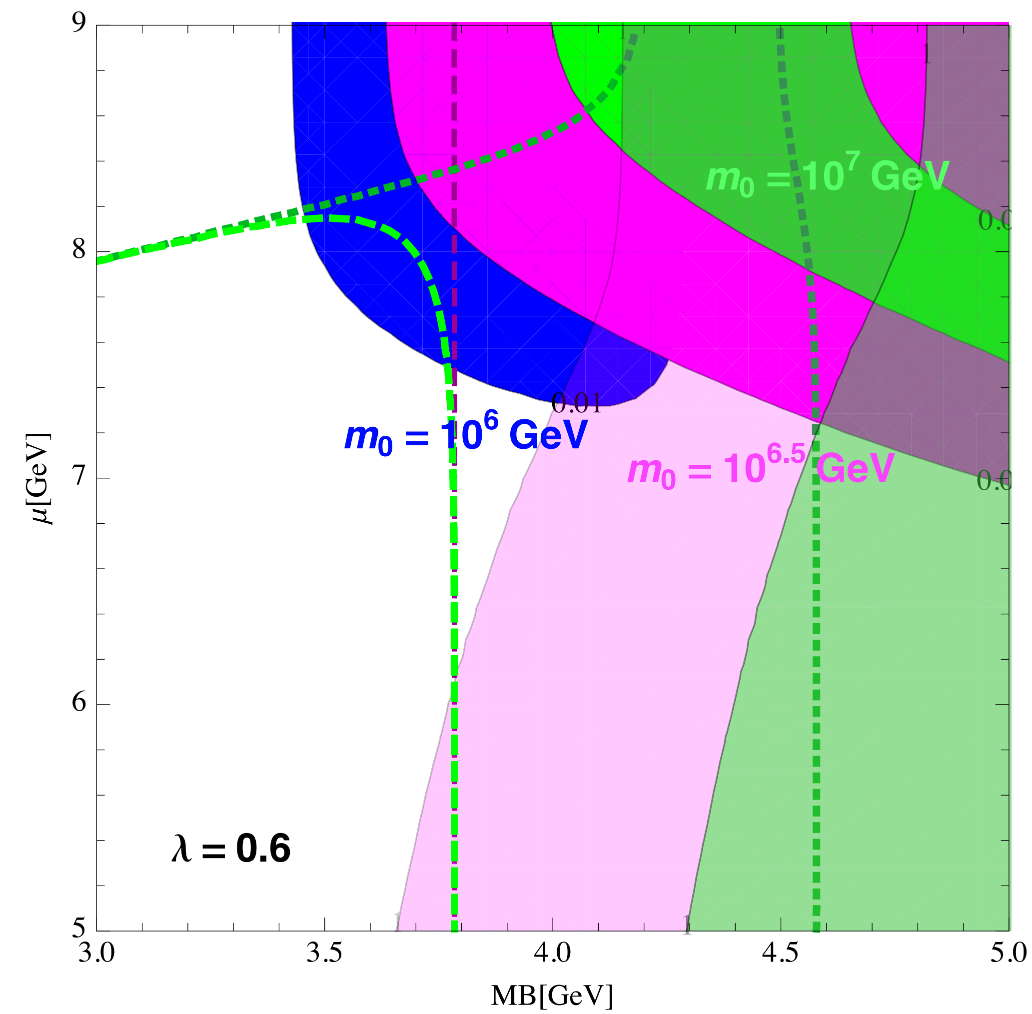
$$\Omega_{\Delta B} = 3.3 \times 10^{-4} \xi \frac{x_{\rm f.o.}}{A(x_{\rm f.o.})} \left(\frac{m_{\tilde{B}}}{1 {\rm TeV}}\right) \left(\frac{\mu}{10 m_0}\right)^2 \left(\frac{\lambda}{0.1}\right)^2$$

$$\frac{\Omega_{\Delta B}}{\Omega_{\rm DM}} \approx 0.04 \xi \left(\frac{\lambda}{0.1}\right)^4 \left(\frac{m_{3/2}}{m_p}\right) \left(\frac{m_{\tilde{B}}}{1 {\rm TeV}}\right)^2 \left(\frac{m_0}{10^6 {\rm GeV}}\right)^{-6}$$

CP-violation in soft masses



CP-violation in RPV-parameters



Contemporary production of DM and baryon asymmetry (at least the simplest setup) requires strong hierarchy between gauginos, scalars and higgsinos.

Detection prospects

$$\Gamma_{3/2} = N_c \frac{\lambda^2}{6144\pi^3} \frac{m_{3/2}^7}{m_0^4 M_{\rm Pl}^2} \longrightarrow \tau_{3/2} \approx \frac{7.4}{N_c} \times 10^{43}{\rm s} \left(\frac{\lambda}{0.1}\right)^{-2} \left(\frac{m_0}{10^6 {\rm GeV}}\right)^4 \left(\frac{m_{3/2}}{1{\rm GeV}}\right)^{-7}$$

The decay rate of the gravitino is highly suppressed by the scalar mass scales and is many orders of magnitude below the current and next future experimental capabilities.

The spectrum is beyond the LHC reach apart from the lightest gauginos.

Gluino NLSP

$$c\tau_{\tilde{g}} \approx \frac{14.1}{N_c} {\rm cm} \left(\frac{\lambda}{0.1}\right)^{-2} \left(\frac{m_0}{10^6 {\rm GeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{1{\rm TeV}}\right)^{-5}$$

The gluino is rather long lived, we expect displaced vertices of a detector stable particle.

Summary and Outlook

Common production from decay is an intriguing possibility for connecting the DM and baryogenesis puzzle.

We have presented a simple realization.

Future prospects

Look for further realizations.

Implementation of a proper numerical approach.

Thank you