Anomalies 2021 - IIT, Hyderabad, India

11th November 2021

HEAVY SUSY FOR BARYOGENESIS AND DARK MATTER

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

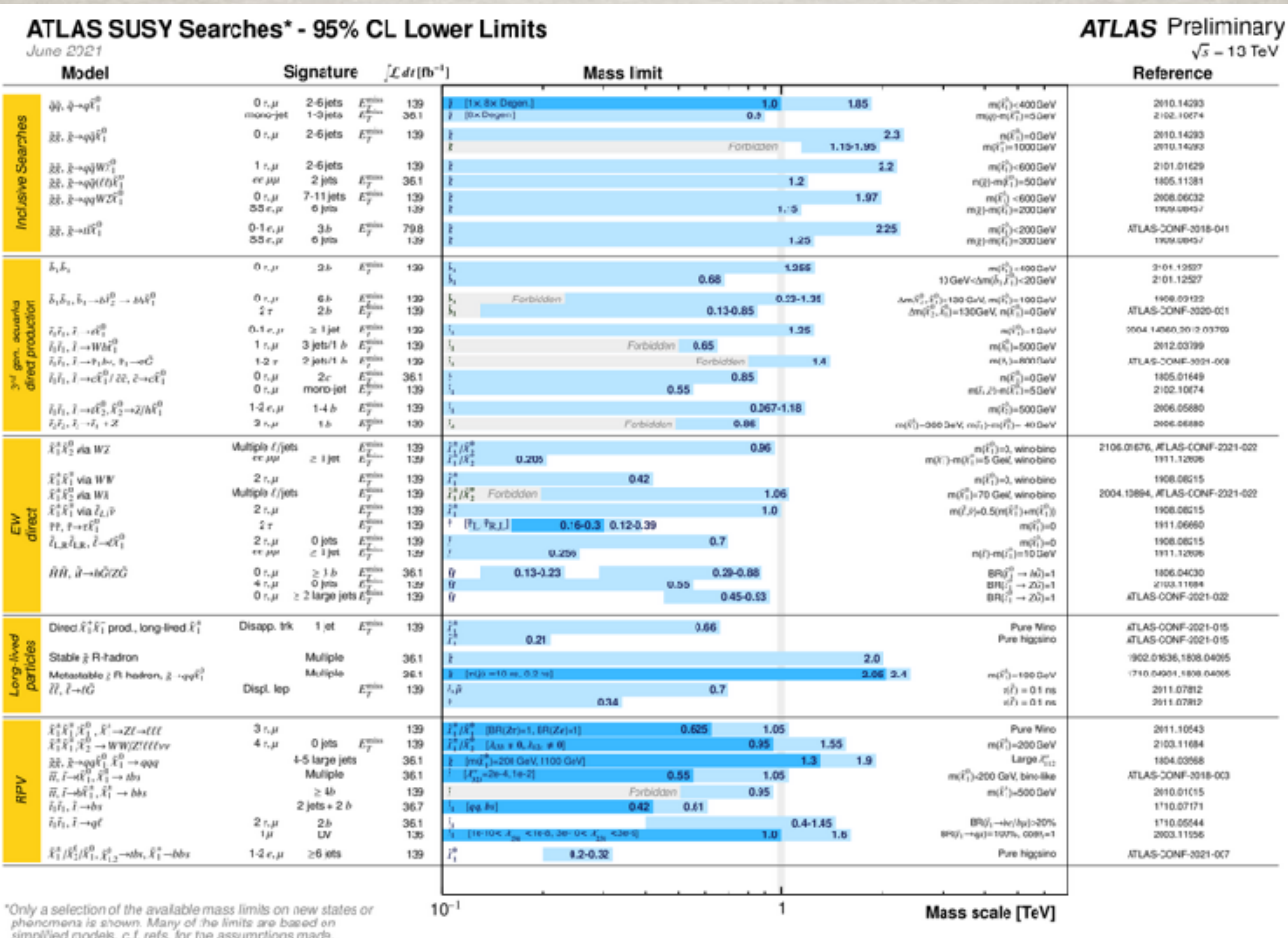
MARIE CURIE ACTIONS

Outline

- Introduction:
  - Supersymmetry after LHC run 1
  - The Gravitino Problem in Cosmology
- High scale SUSY for baryogenesis
- Co-genesis of Gravitino DM
- Outlook

Introduction

SUSY AT LHC 2021



Heavy SUSY ???

Maybe the arguments requiring SUSY at the EW scale like naturalness are just red-herrings and instead SUSY is much heavier…

Indeed there are instead some counterargument in favour of heavy SUSY from successful cosmology and not only: e.g.
Gravitino and moduli problems
as well as the flavour problem, i.e. heavy squarks fit better than light ones with the SM-like nature of the CP violation in the quark sector and other flavour observables like b to s gamma.

Gravitino & Cosmology

Gravitinos can interact very weakly with other particles and therefore cause trouble in cosmology, either because they decay too late, if they are not LSP, or, if they are the LSP, because the NLSP decays too late...

If gravitinos are in thermal equilibrium in the Early Universe, they decouple when relativistic with number density given by

$$\Omega_{3/2} h^2 \simeq 0.1 \left(\frac{m_{3/2}}{0.1 \mathrm{keV}} \right) \left(\frac{g_*}{106.75} \right)^{-1}$$

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

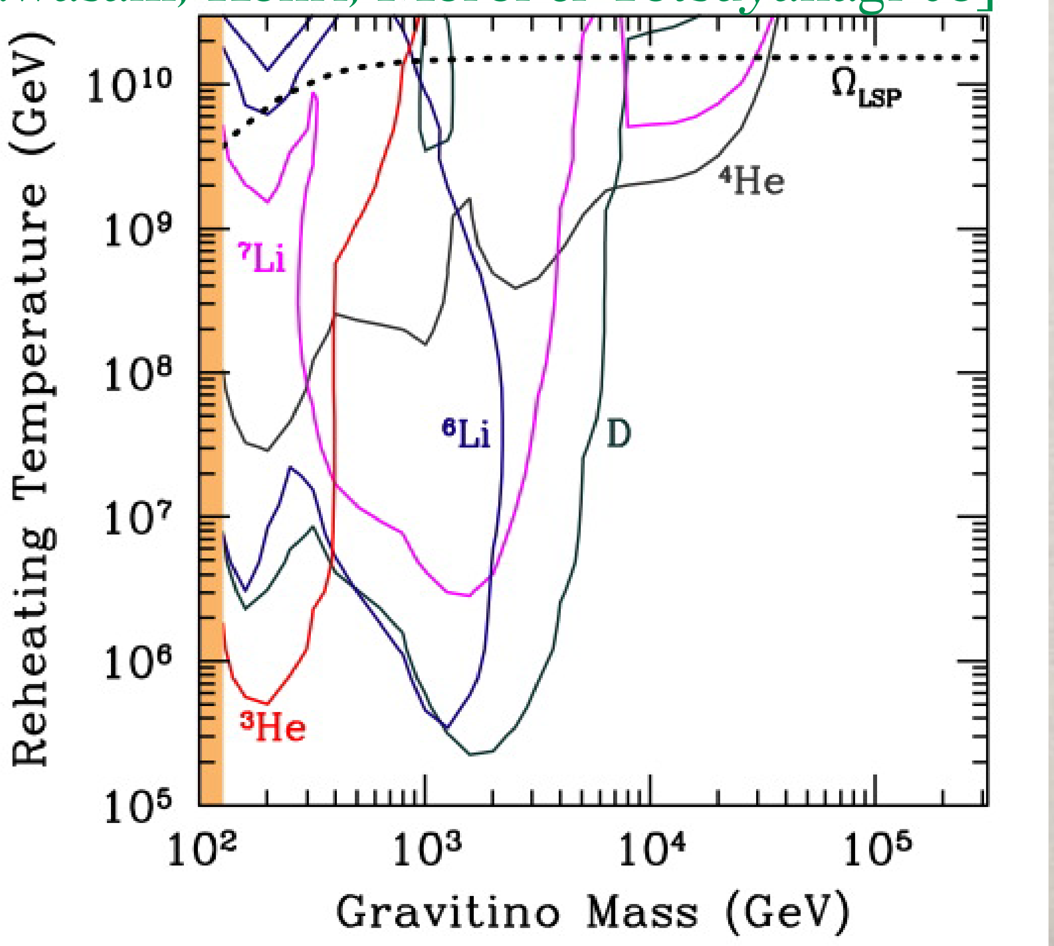
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1 \mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[Bolz,Brandenburg & Buchmuller 01],
[Pradler & Steffen 06, Rychkov & Strumia 07]

THE GRAVITINO PROBLEM

The gravitino, the spin 3/2 superpartner of the graviton, interacts only "gravitationally" and therefore decays (or "is decayed into") very late on cosmological scales.

[Kawasaki, Kohri, Moroi & Yotsuyanagi 08]

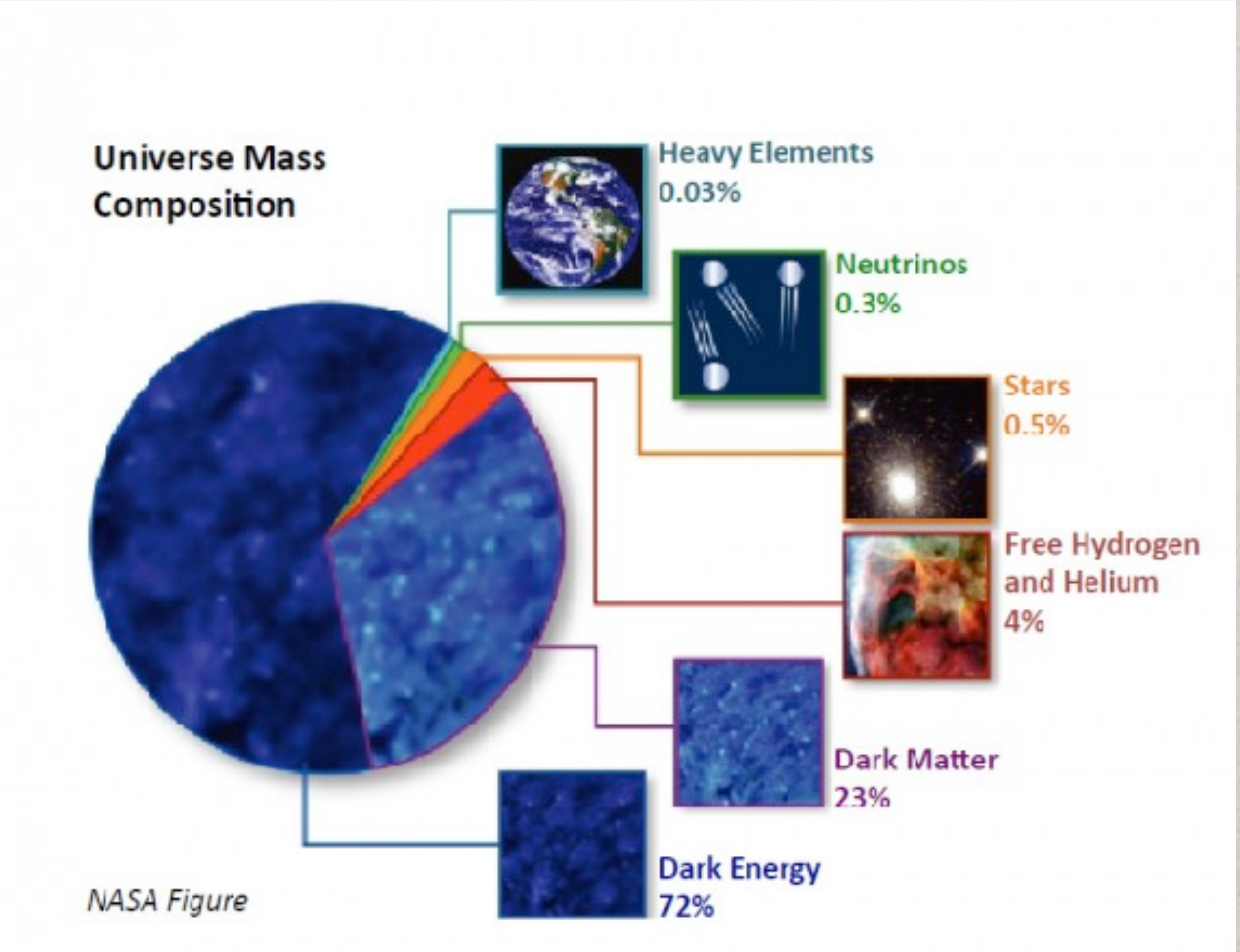


$$\tau_{3/2} = 6 \times 10^7 \mathrm{s} \left(\frac{m_{3/2}}{100\mathrm{GeV}} \right)^{-3}$$

BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature is small! Indeed due to non-renormalizable coupling

$$\Omega_{3/2} \propto T_R \, M_i^2 / m_{3/2}$$

Universe composition



Why $\Omega_{DM} h^2 \sim 5\, \Omega_B h^2$?

High scale SUSY for baryogenesis

Baryogenesis in RPV SUSY

RPV superpotential includes couplings that violate baryon number and can be complex, i.e.

$$W = \lambda''_{ijk} U_i D_j D_k$$

Possible to generate a baryon asymmetry from out-of-equilibrium decay of a superparticle into channels with different baryon number, e.g. for a neutralino

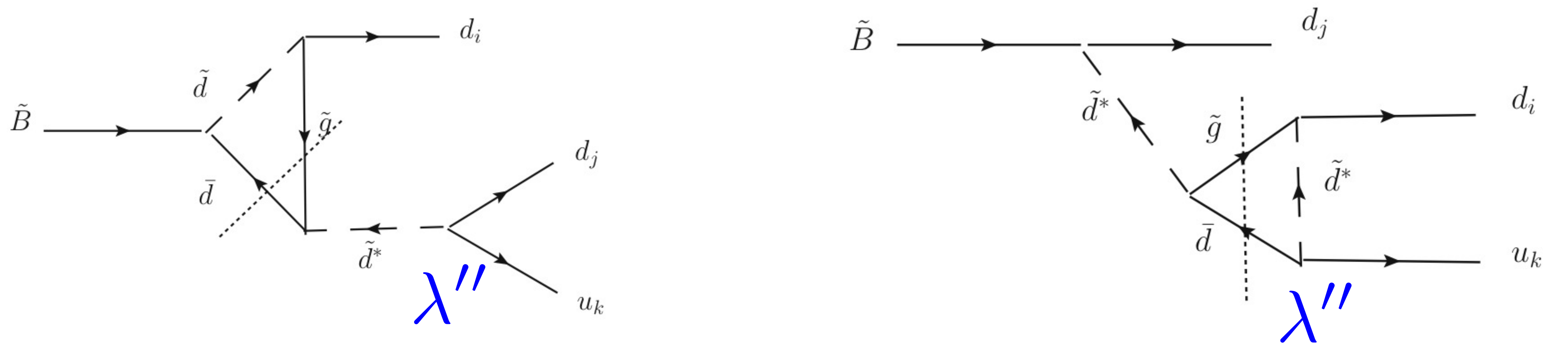
$$\tilde{B} \rightarrow udd,\ \bar{u}\bar{d}\bar{d},\ \tilde{g}\bar{q}q$$

Initial density of neutralino can arise from usual WIMP mechanism, since the decay rate is very suppressed !

Baryogenesis in RPV SUSY

[Sundrum & Cui 12, Cui 13, Rompineve 13, ...]

Realization of good old baryogenesis via out-of-equilibrium decay of a superpartner, possibly WIMP-like, e.g. in the model by Cui with Bino decay via RPV B-violating coupling.



CP violation arises from diagrams with on-shell gluino lighter than the Bino. To obtain right baryon number the RPC decay has to be suppressed, i.e. due to heavy squarks, the RPV coupling large and the Bino density very large...

Baryogenesis & SW DM

[Arcadi, LC & Nardecchia 1312.5703]

In such scenario it is also possible to get gravitino DM via the SuperWIMP mechanism and the baryon and DM densities can be naturally of comparable order due to the suppression by the CP violation and Branching Ratio respectively...

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

Small numbers

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

$$\to \quad \frac{\Omega_{\Delta B}}{\Omega_{DM}} = \frac{m_p}{m_{DM}} \frac{\epsilon_{CP}\, BR(\chi \to \not{B})}{BR(\chi \to DM + \text{anything})}$$

independent of Bino density

Gravitino DM: BR is naturally small and DM stable enough !

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

Simple scenario with no Flavour Violation: the CP phase comes from the gaugino mass phase difference

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

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

$$\longrightarrow \quad \epsilon_{\rm CP} = \frac{8}{3} Im\left[e^{i\phi}\right] \boxed{\frac{m_{\tilde{B}} m_{\tilde{g}}}{m_0^2}} \alpha_s \left(1 + \frac{2\pi N_{\rm RPC}\alpha_s}{N_{\rm RPV}\lambda^2}\right)^{-1}$$

Baryon Asymmetry

CP asymmetry is suppressed both for $m_{\tilde{g}} = m_{\tilde{B}}$ or $m_{\tilde{g}} = 0$

Neglecting wash-out processes we get

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

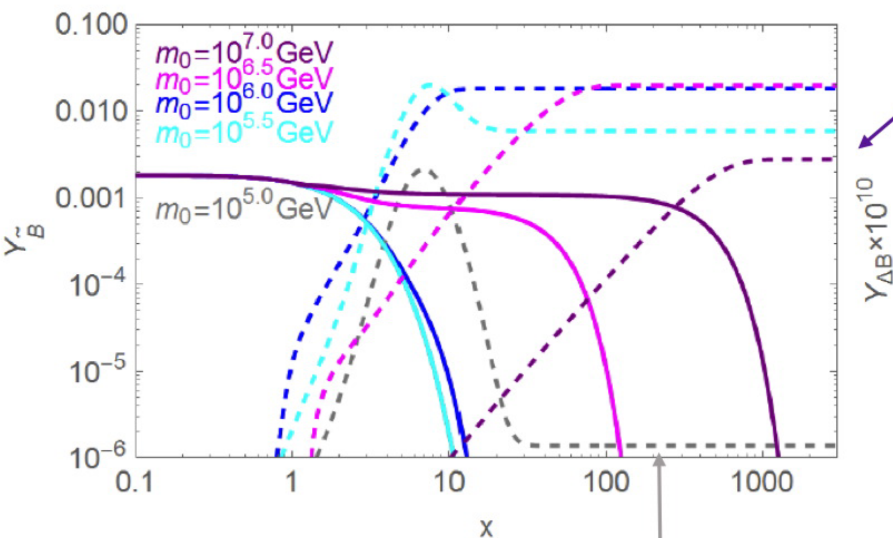
Need a very heavy spectrum to realise baryogenesis !

Baryogenesis in RPV SUSY

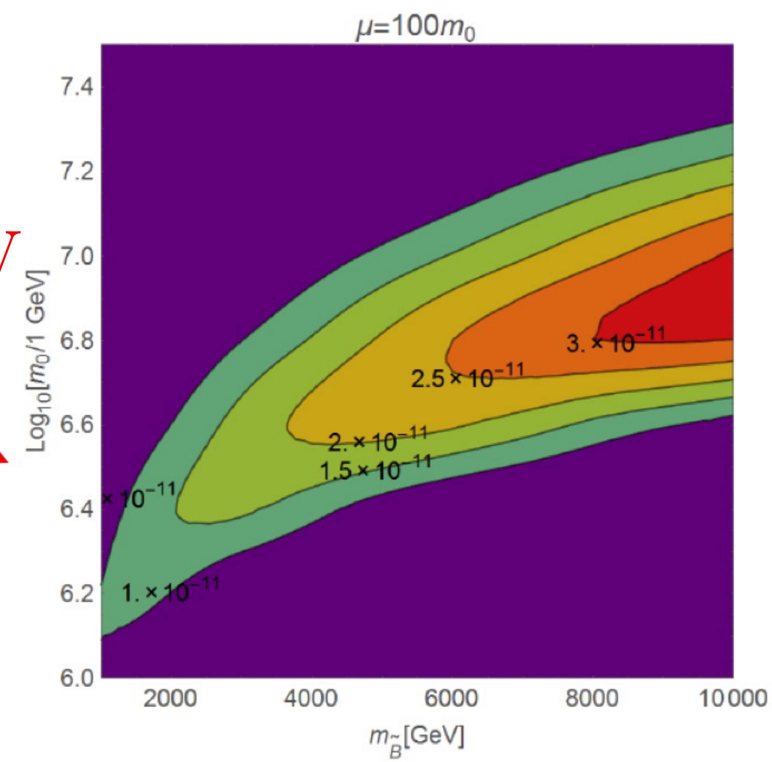
[Arcadi, LC & Nardecchia 1507.05584]

Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

Heavy squarks: Asymmetry suppressed by the high scalars



10^7GeV



Light squarks:

Asymmetry suppressed by wash-out

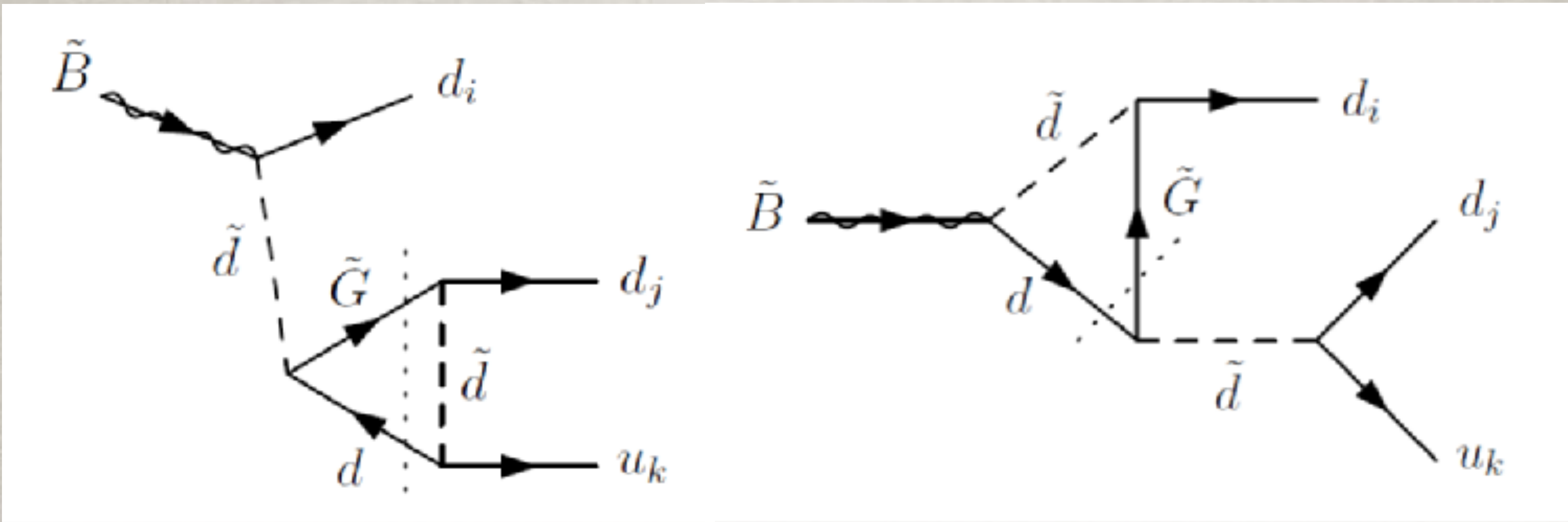
from G. Arcadi

Rather definite prediction for range of scalar masses

Heavy !!!

CP violation in RPV SUSY

The loop diagrams contributing to the CP violation are, e.g.



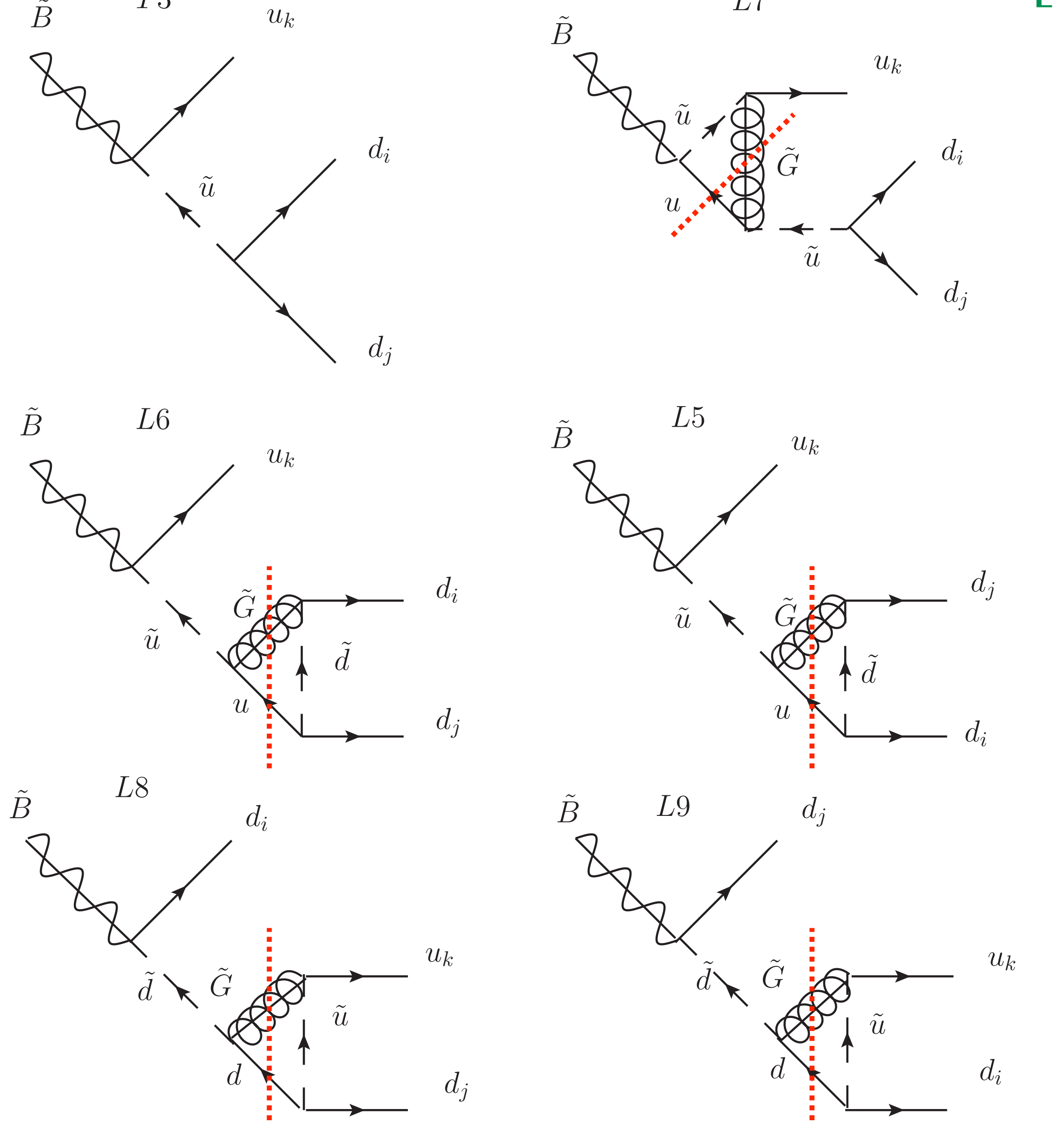
CP violation is provided either by a phase difference between the Bino and Gluino masses or by flavour effects in the RPV couplings and mixing for squarks. The latter two suffer unfortunately of GIM-like cancellations for degenerate squarks and also beyond that... Study of full flavour structure with general squark mass spectrum and mixing completed !

[G. Arcadi, LC & S. Khan, to appear]

CP violation in RPV SUSY

Add to the computation the u-type squark contributions, e.g.

[G. Arcadi, LC & S. Khan, to appear]



One more tree-level and five loop diagrams… Many interference terms !

Keep the full flavour structure and general squark masses trying to maximize the possible CP asymmetry in the Bino decay

CP violation from mixing

For squark masses much larger than the gaugino masses, the mixing is determined by the matrices:

$$(\mathcal{M}^{\tilde{q}}_{R/L\ R/L})_{ij} = \sum_{\alpha} (\mathcal{V}^{\tilde{q}}_{R/L})^*_{\alpha i} \frac{\overline{m}^2_{\tilde{q}}}{m^2_{\tilde{q}_\alpha}} (\mathcal{V}^{\tilde{q}}_{R/L})_{\alpha j}$$

where $\mathcal{V}^{\tilde{q}}_{R/L}$ denote the flavour mixing matrices of the u- or d-type squarks so that the mass eigenstates are

$$\tilde{q}_\alpha = (\mathcal{V}^{\tilde{q}}_R)_{\alpha i}\ \tilde{q}_{R\ i} + (\mathcal{V}^{\tilde{q}}_L)_{\alpha i}\ \tilde{q}_{L\ i}$$

Here the average mass scale is just $\overline{m}_{\tilde{q}}$ and it is immediate to see that for degenerate masses and pure R or L mixing, $\mathcal{M}^{\tilde{q}}_{RR/LL}$ becomes trivial giving a GIM cancellation.

Two flavour case

The two flavour case can be worked our analytically.
For pure RR flavour mixing in the down squark sector, all the CP asymmetries can be written as traces over the mixing matrices and the RPV coupling matrix, e.g.:

$$\Delta\Gamma_{\tilde{d}T1L1} \propto \sum_k Im\left[Tr\left(\mathcal{M}^{\tilde{d}}_{RR}\mathcal{M}^{\tilde{d}}_{RR}\lambda^*_k(\mathcal{M}^{\tilde{d}})^T_{RR}\lambda^T_k\right)\right]$$

but the trace is purely REAL:

$$Tr\left(\mathcal{M}^{\tilde{d}}_{RR}\mathcal{M}^{\tilde{d}}_{RR}\lambda^*_k(\mathcal{M}^{\tilde{d}})^T_{RR}\lambda^T_k\right) = Tr\left((\mathcal{M}^{\tilde{d}}_{RR}\mathcal{M}^{\tilde{d}}_{RR})^*\lambda_k(\mathcal{M}^{\tilde{d}})^\dagger_{RR}\lambda^\dagger_k\right)$$

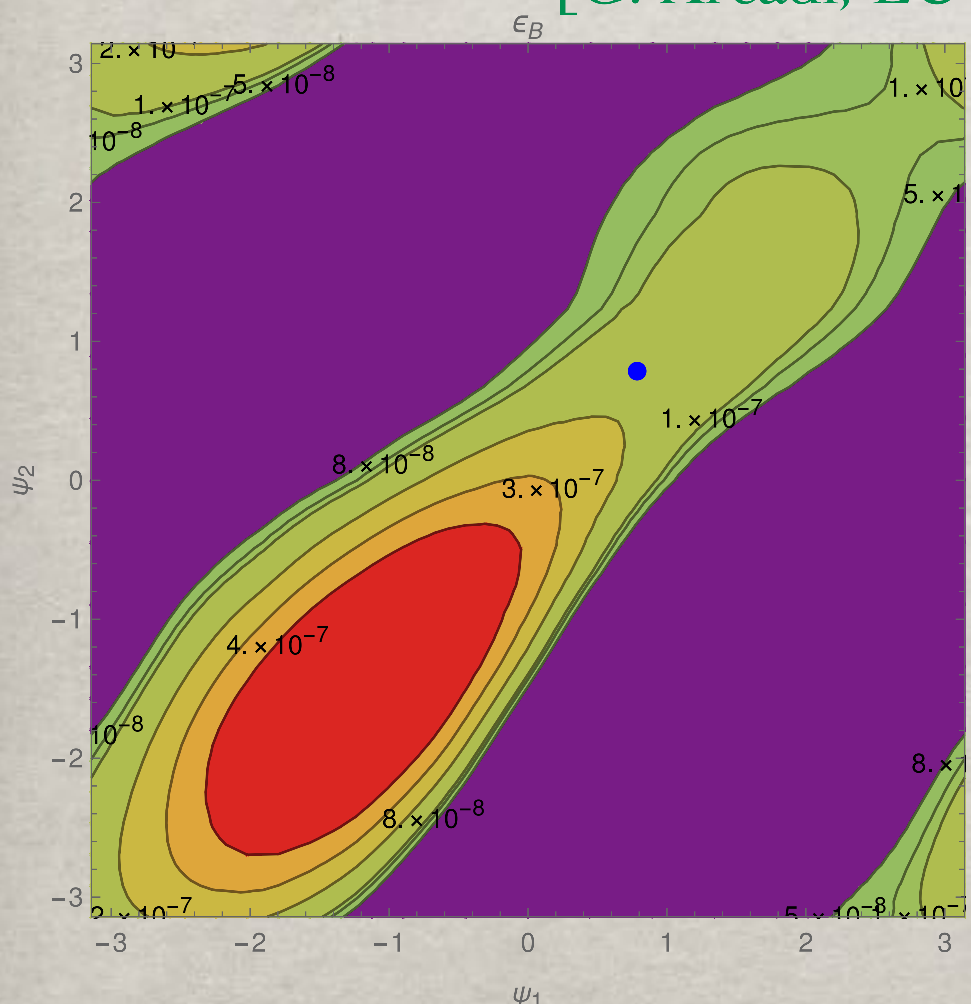
since the mixing matrix is unitary and so $(\mathcal{M}^{\tilde{d}}_{RR})^T = (\mathcal{M}^{\tilde{d}}_{RR})^*$

No contribution from the down squark mixing to the leading contribution to the imaginary part ! Need gaugino phase !

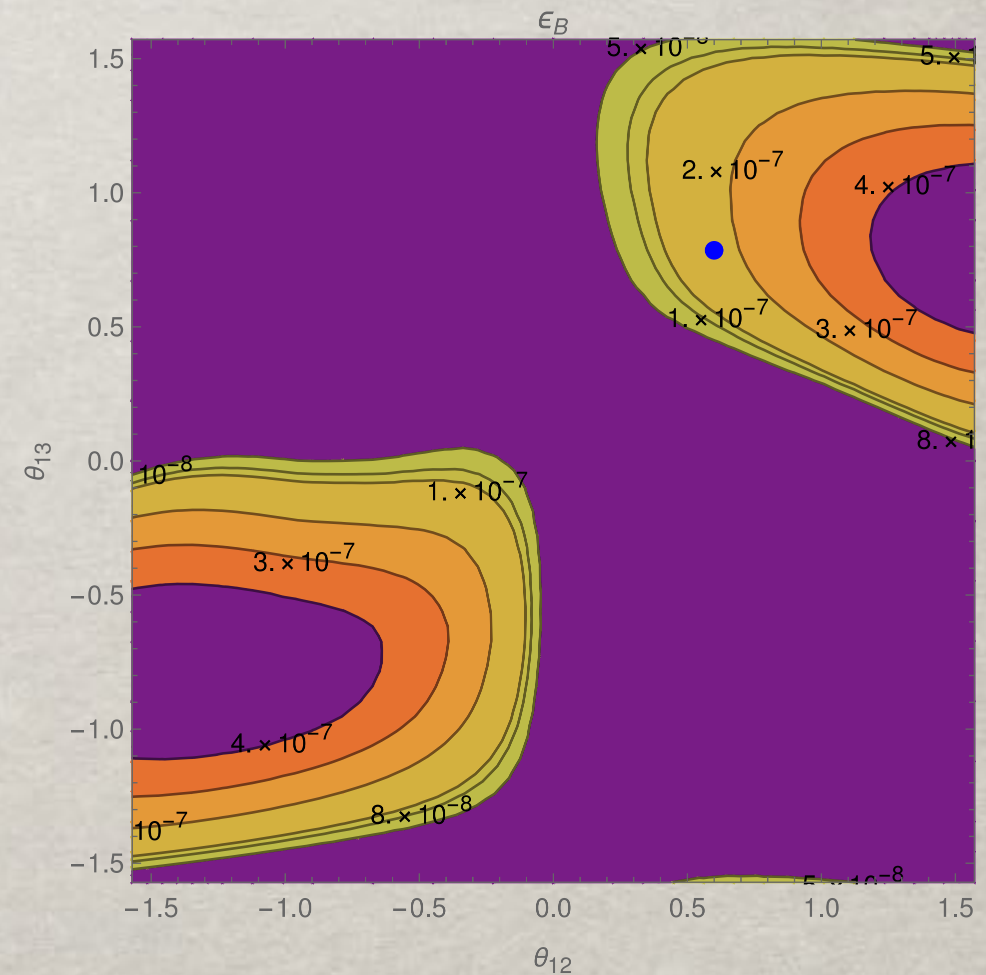
Three flavour case

Much more complicated expressions ! The CP asymmetry does depend on the mixing parameters, we try to optimise them

[G. Arcadi, LC & S. Khan, to appear]



CP violating phases

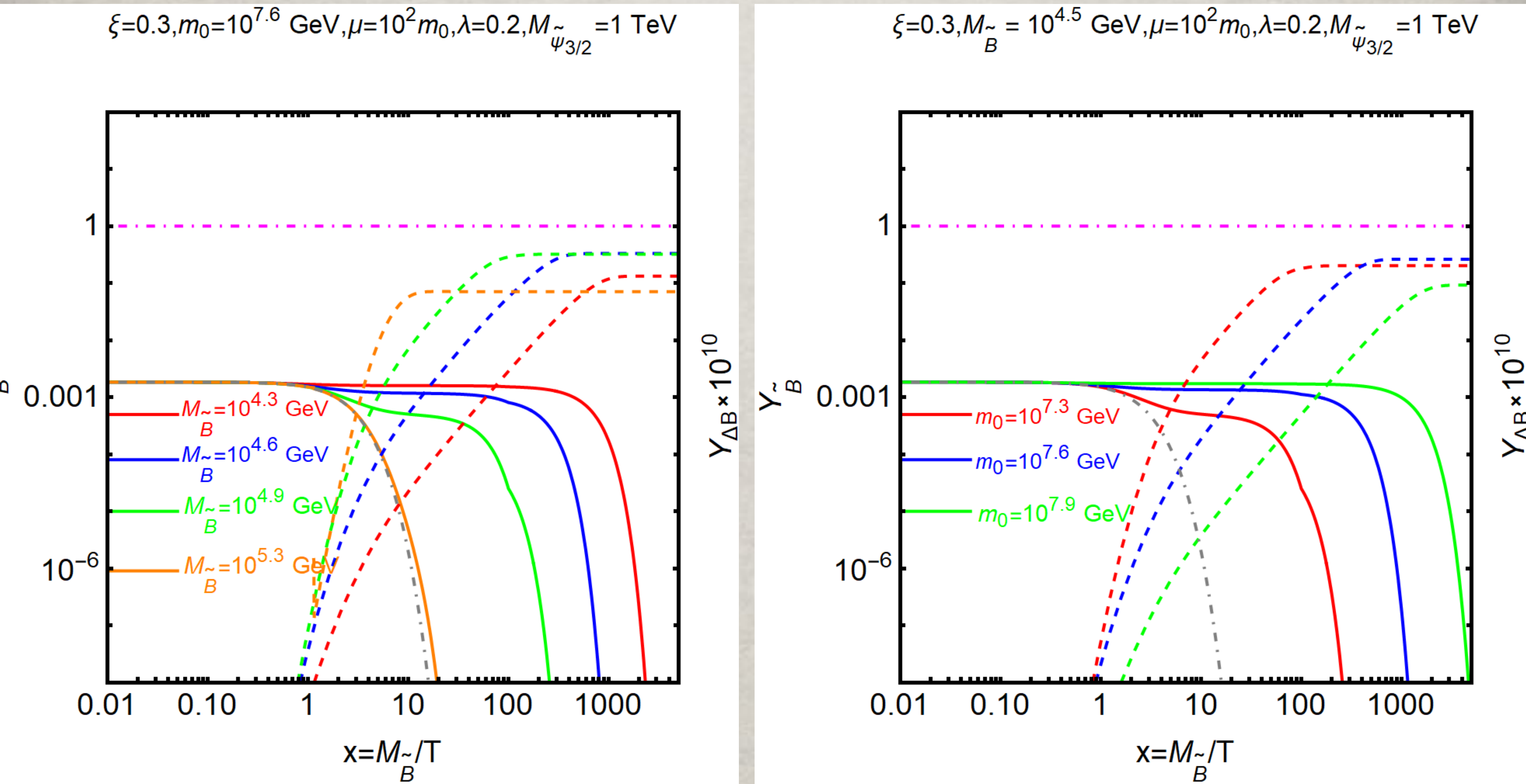


Mixing angles

Three flavour case

Solve the full system of Boltzmann equations with washouts:

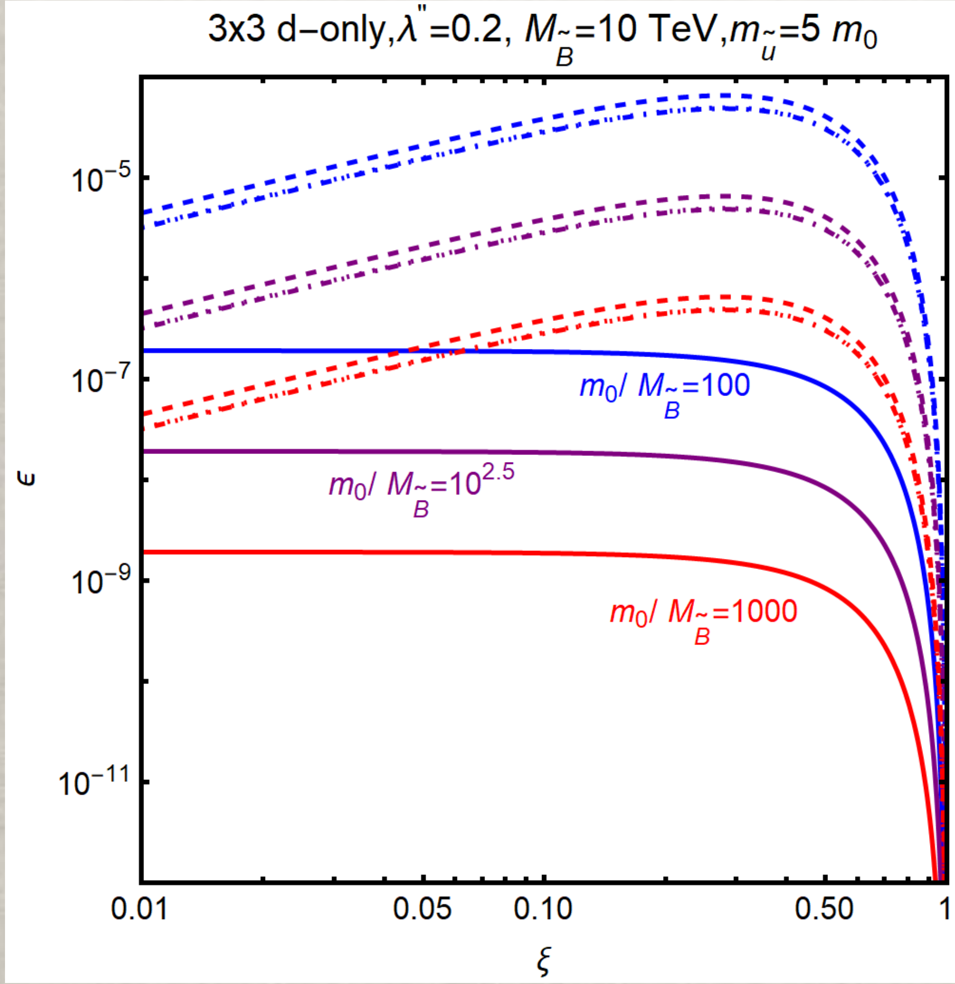
[G. Arcadi, LC & S. Khan, to appear]

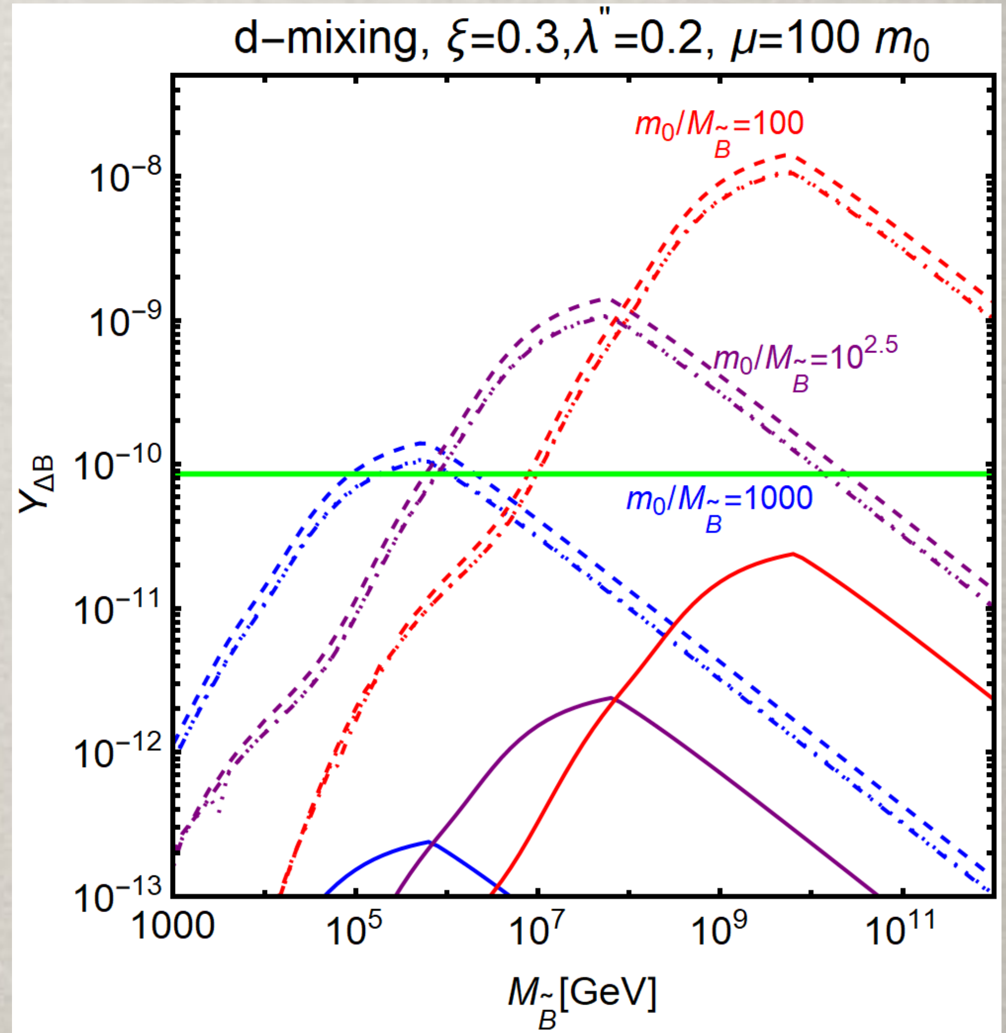


The Bino mostly decouples as relativistic !

Three flavour case

In general the presence of a phase difference in the gaugino masses does increase the asymmetry and is needed for the case of pure down squark mixing: [G. Arcadi, LC & S. Khan, to appear]

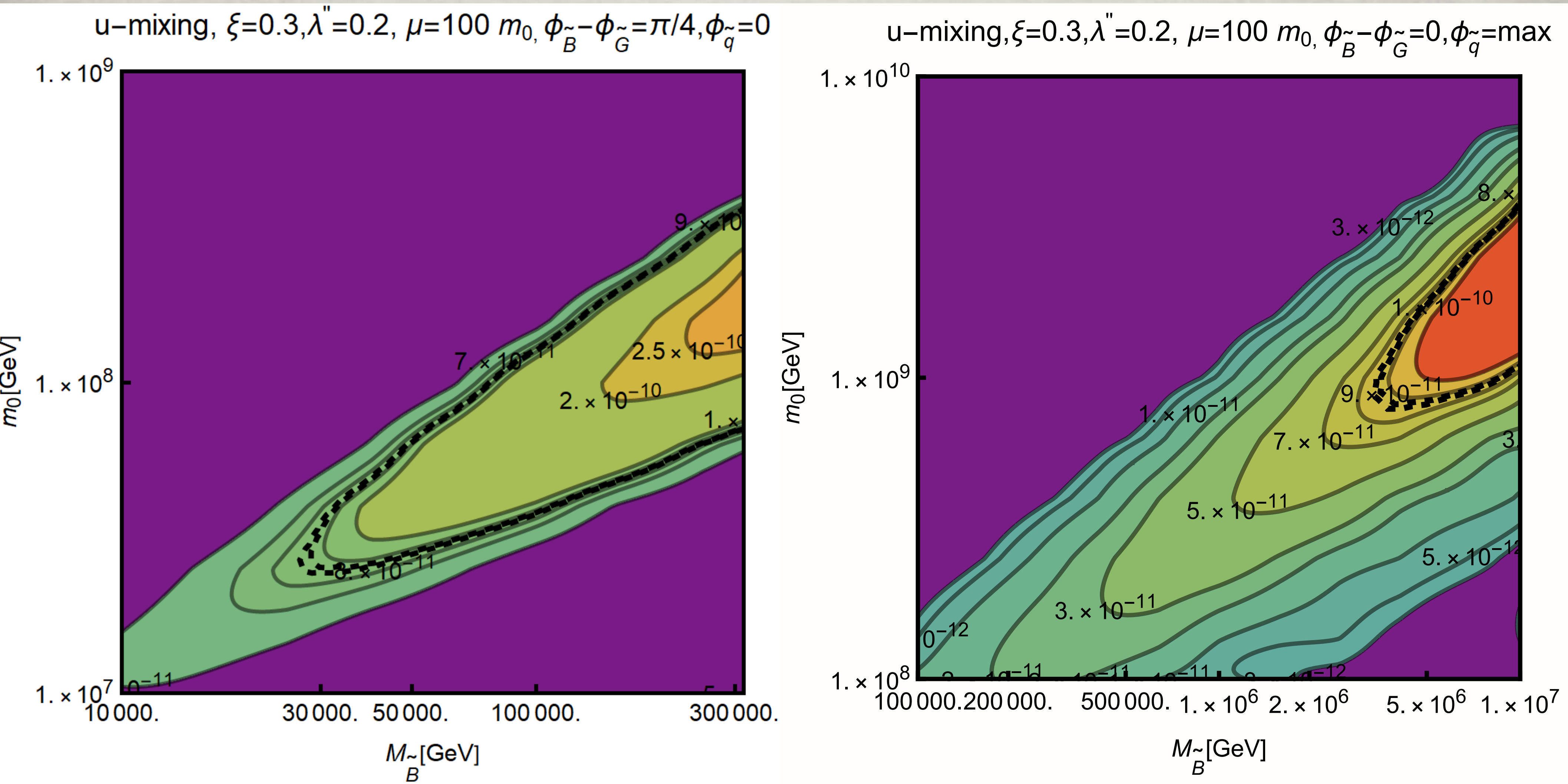




The gluino mass cannot be too small !!!

Three flavour case

For mixing in the up squark sector instead the gaugino phase is not absolutely necessary: [G. Arcadi, LC & S. Khan, to appear]

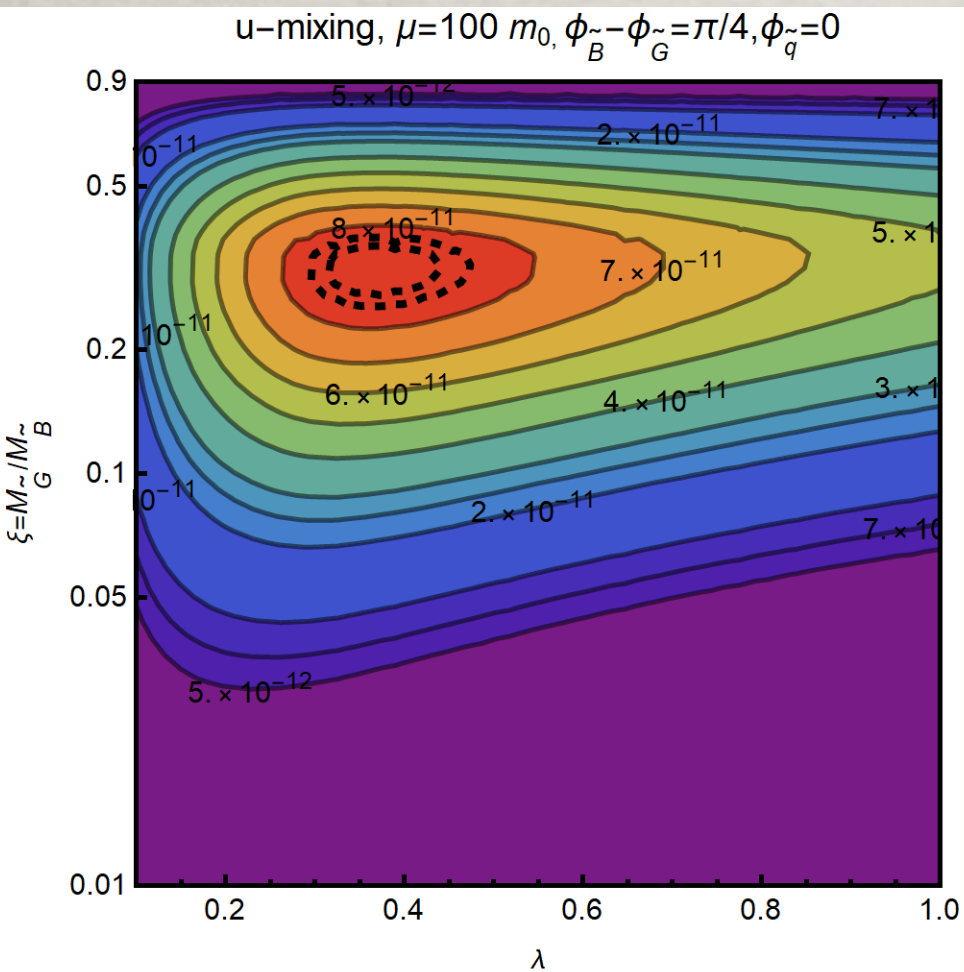


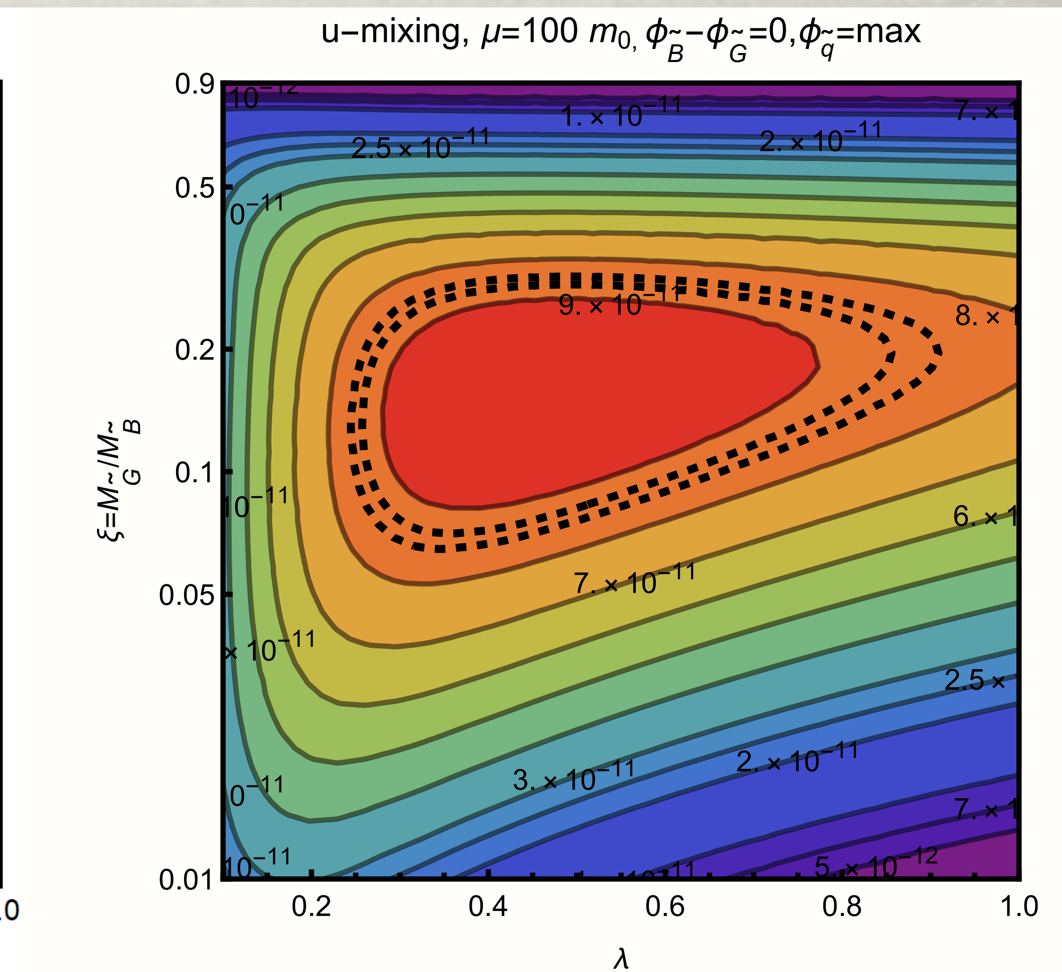
The squark and Bino masses become larger though!

Three flavour case

Wider region available in coupling and gluino mass:

[G. Arcadi, LC & S. Khan, to appear]





The ratio of gluino vs Bino mass can become smaller !!!

Gluino NLSP in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584, Arcadi, LC, Khan to appear]

The gluino is in this scenario the next-to-lightest SUSY particle and may be produced at colliders; we are still exploring how much lighter than the Bino it can be. For the range

$$m_{\tilde{g}} \sim 0.1 - 0.4\, m_{\tilde{B}} \sim 7 - 28 \text{ TeV}$$

it could be in the reach of a 100 TeV collider.

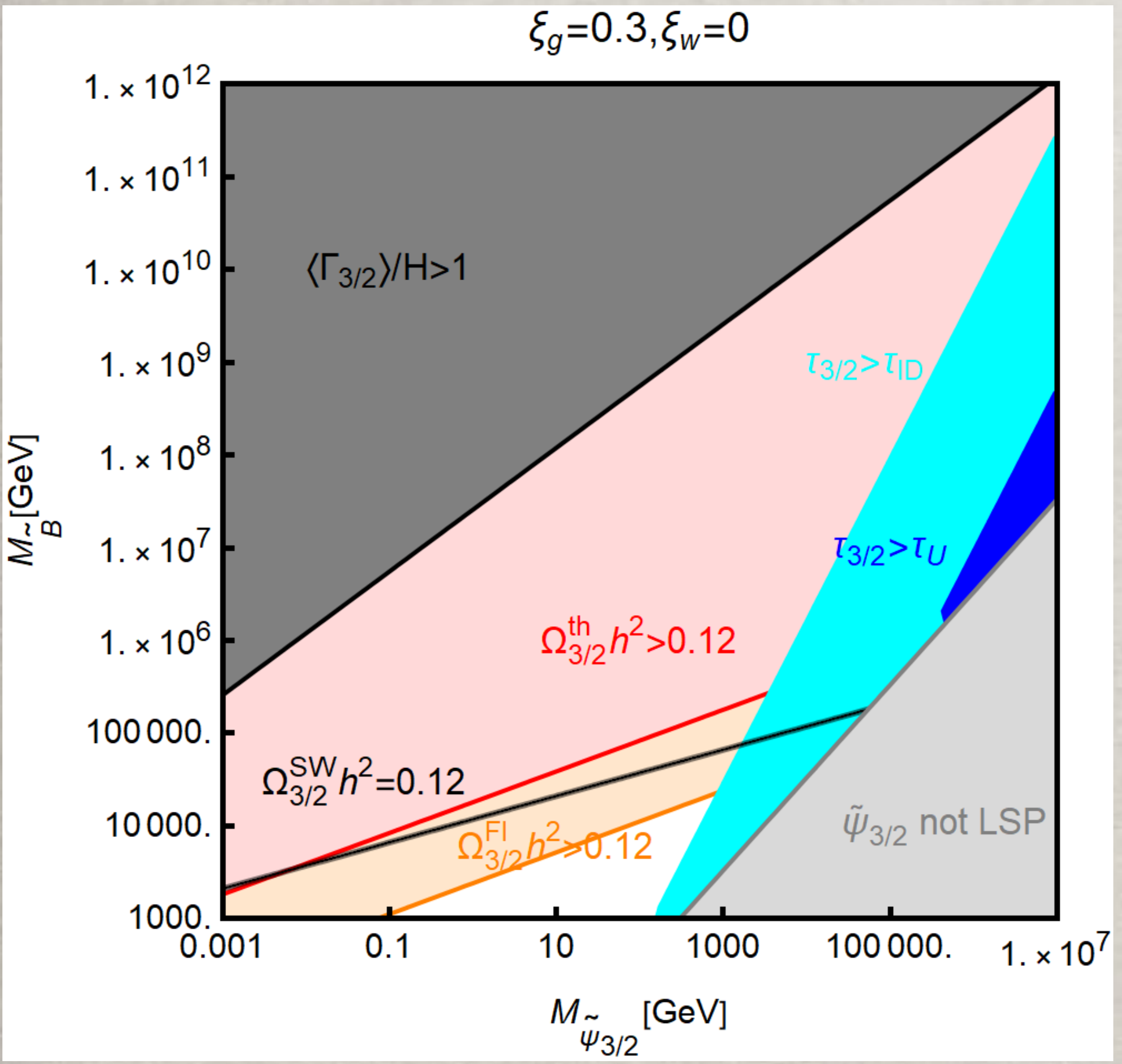
$$c\tau_{\tilde{g}} \sim 1,5 \text{ cm} \left(\frac{\lambda''}{0.4}\right)^{-2} \left(\frac{m_0}{4 \times 10^7 \text{GeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{7 \text{ TeV}}\right)^{-5}$$

The heavy squarks give displaced vertices for the gluino decay via RPV, even for RPV coupling of order 1.

Gluino decay into gravitino DM is much too suppressed to be measured.

Co-genesis of gravitino Dark Matter

Gravitino DM in RPV SUSY



Many mechanisms for gravitino production in SUSY…, stronger when SUSY spectrum is high !

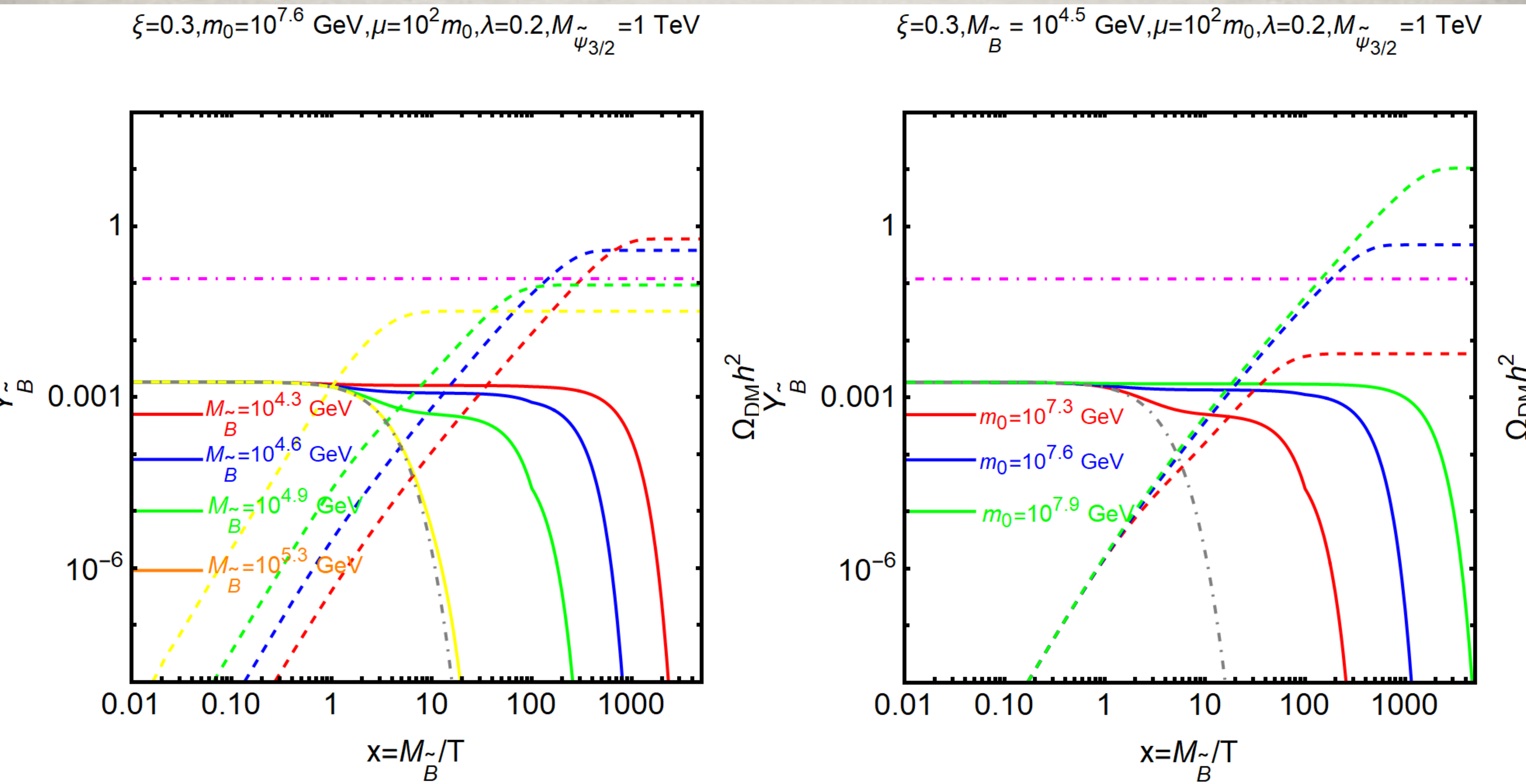
Only a relative small window provides DM with the right density and long enough lifetime.
Recall that we need

$$m_{3/2} < m_{\tilde{g}}$$

Non trivial to obtain gravitino DM in the scenario !

Gravitino DM in RPV SUSY

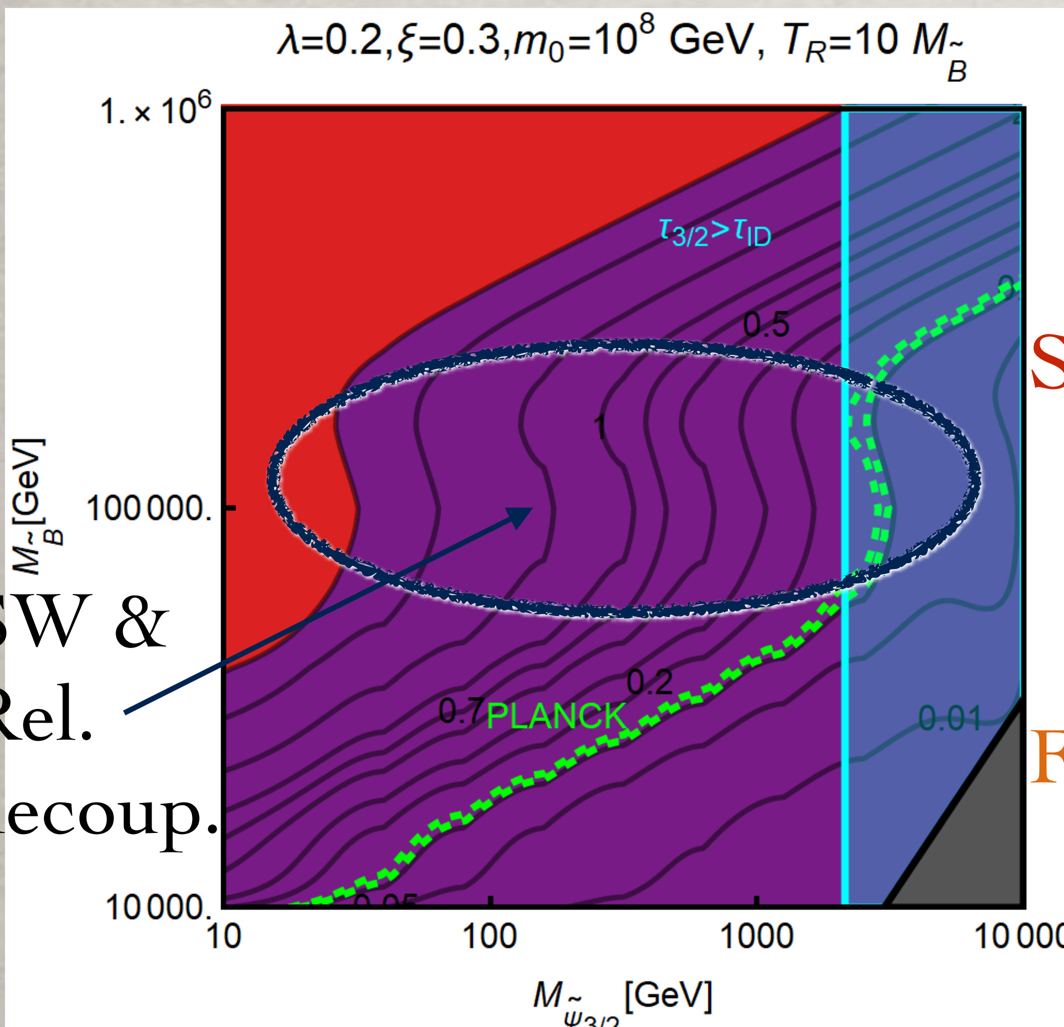
Consider the full gravitino production from Bino decay and more



For gravitino at TeV SWIMP production does dominate !

Gravitino DM in RPV SUSY

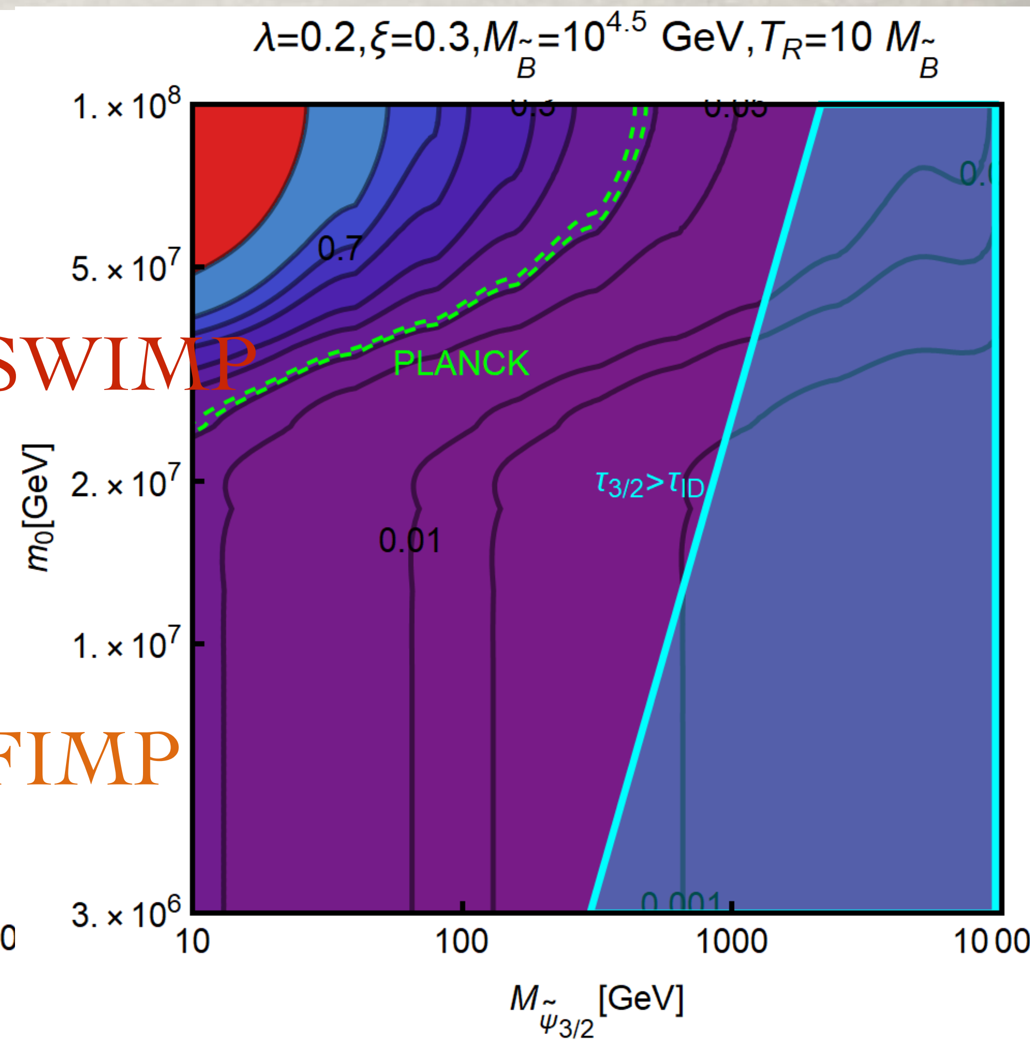
Full numerical treatment with all contributions gives



SW & Rel. decoup.

SWIMP

FIMP



Possible to obtain right abundance and long enough lifetime !

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584, Arcadi, LC, Khan to appear]

Thanks to the large gravitino mass, the squark mass suppression is partially compensated and a visible gravitino decay is possible:

$$\Gamma(\psi_{3/2} \to u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

$$\tau_{3/2} = 0.26 \times 10^{28}\mathrm{s} \left(\frac{\lambda}{0.4}\right)^{-2} \left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)^{-7} \left(\frac{m_0}{10^{7.5}\mathrm{GeV}}\right)^4$$

Right ballpark for indirect DM detection, but strongly dependent on the gravitino and squark masses…

Outlook

Outlook

- Supersymmetry is too rich a theory to be easily excluded... Heavy Supersymmetry can offer a few advantages in the cosmological scenario compared to SUSY at EW/TeV scale!
- In models with heavy SUSY, it is possible to realise scenarios for baryogenesis from RPV if sufficiently heavy squarks are present and the gluino is the NLSP !
- A full flavour analysis of the scenario has shown that the up squark contribution can be dominant and allows for a relatively light gluino, lower bound still to be determined.
- From the same decay also gravitino Dark Matter can be produced in the right amount, in a relatively small window of gravitino masses, but maybe not far in ID !