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Baryogenesis with RPV

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Outline

- Introduction:
  DM and Baryogenesis connection
- Baryogenesis from WIMPs
- Baryogenesis & DM from RPV

  with G. Arcadi & M. Nardecchia
- Phenomenological signatures

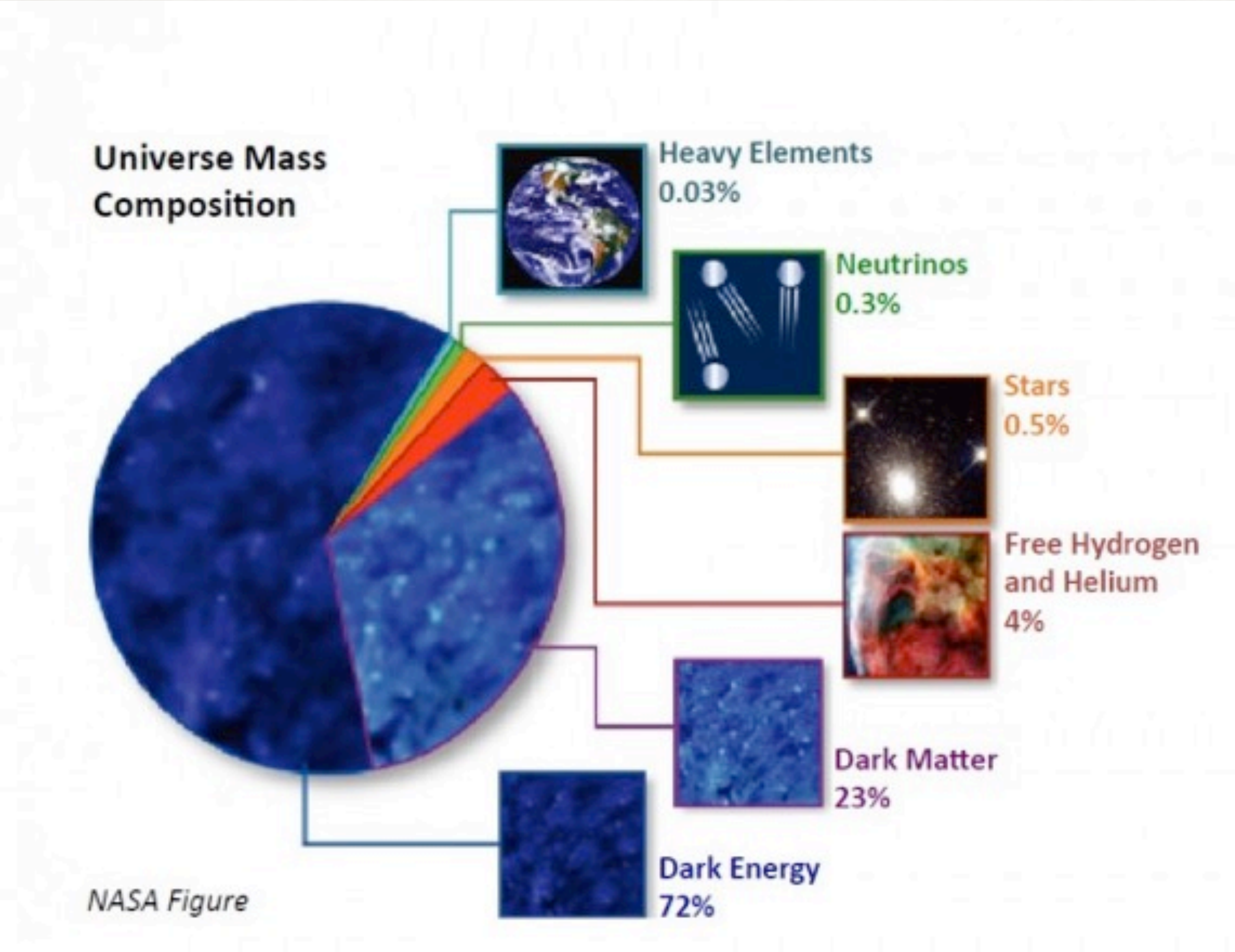
  with G. Arcadi &F. Dradi,
  Ch. Eckner & M.Gustafsson
- Outlook

The Dark Matter-baryogenesis connection

Baryogenesis

- The CMB data and BBN both require $\Omega_B \sim 0.05$
- Can it be a relic of thermal decoupling from a symmetric state ? NO ! Decoupling "a la WIMP" give a value $\Omega_B \sim 10^{-10}$, way too small...
- Are we living in a matter patch ??? No evidence of boundaries between matter/antimatter in gammas or antinuclei in cosmic rays... Our patch is as large as the observable Universe !
- No mechanism know can create such separation... The Universe is asymmetric !

Universe composition



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

Sakharov Conditions

Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: trivial condition since otherwise B remains zero...
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate
- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

Sakharov Conditions II

For the Standard Model actually we have instead:

- B-L violation: B+L violation by the chiral anomaly

$$\partial_\mu J^\mu_{B+L} = 2 n_f \frac{g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- C and CP violation: present in the CKM matrix, but unfortunately quite small ! Possibly also additional phases needed...

- Departure from thermal equilibrium: phase-transition or particle out of equilibrium ?

BARYOGENESIS FROM WIMPs

Baryogenesis for WIMPs

[Sundrum & Cui 12]

Realization of good old baryogenesis via out-of-equilibrium decay of a WIMP-like particle, with DM possibly provided by another WIMP.

Stage 1: freeze-out of a “WIMP-like” particle provides an initial abundance

Stage 2: the decay of that WIMP generates the baryon asymmetry via a CP-violating decay

Stage 3: the freeze-out of a second stable WIMP provides for the Dark Matter with similar densities…

Note: there is also the possibility of baryogenesis during the WIMP freeze-out process for CP-violating scatterings

[J. McDonalds 2011, Baldes et al. 2014]

THE WIMP PARADIGM

Primordial abundance of stable massive species

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle\sigma(X + X \to \text{anything})v\rangle \left(n_{eq}^2 - n_X^2\right)$$

Hubble expansion   Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq}\,\langle\sigma_A v\rangle_{x_f} = H(x_f)$ and that gives

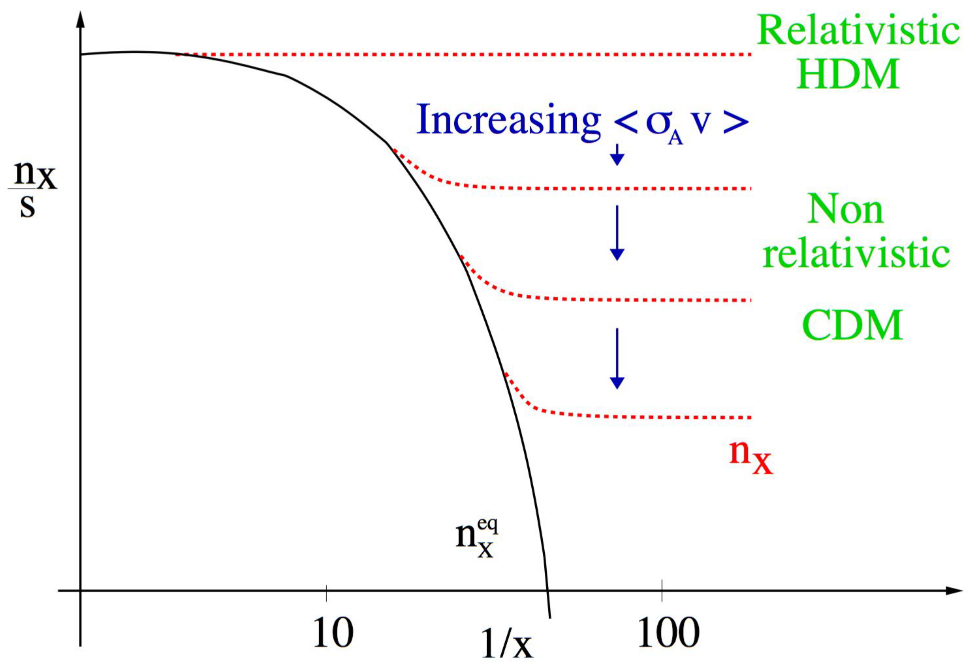
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle\sigma_A v\rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !



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

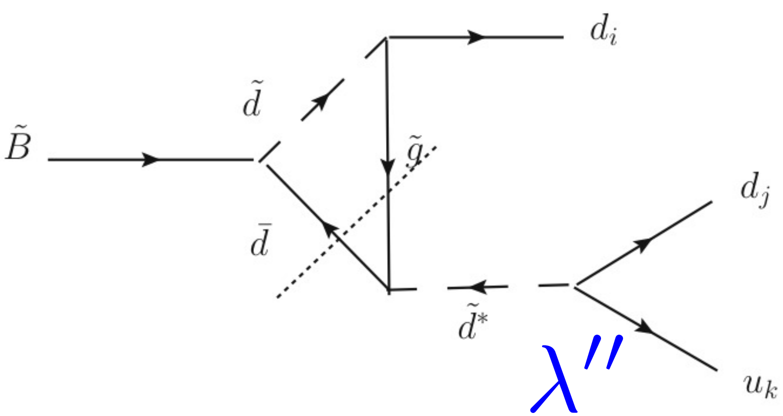
$$\tilde{B} \to udd,\ \bar{u}\bar{d}\bar{d},\ \tilde{g}\bar{q}q$$

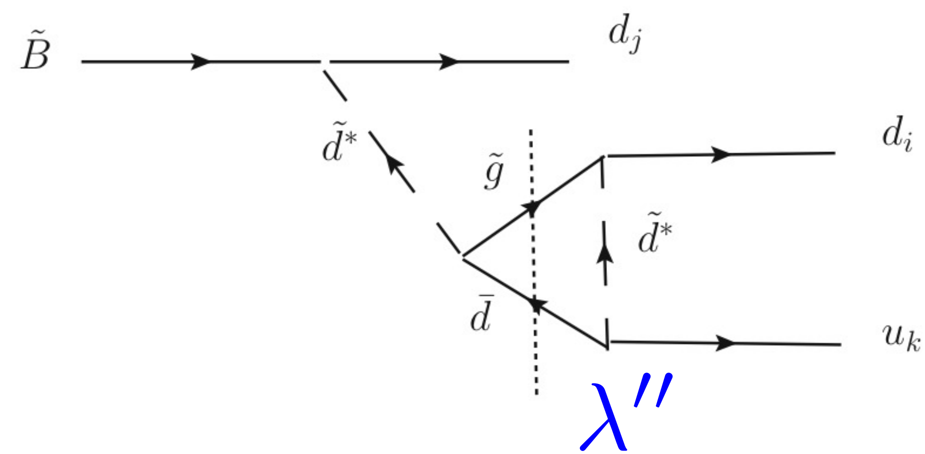
Initial density of neutralino can arise from usual WIMP mechanism, since the decay rate is very suppressed !

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.





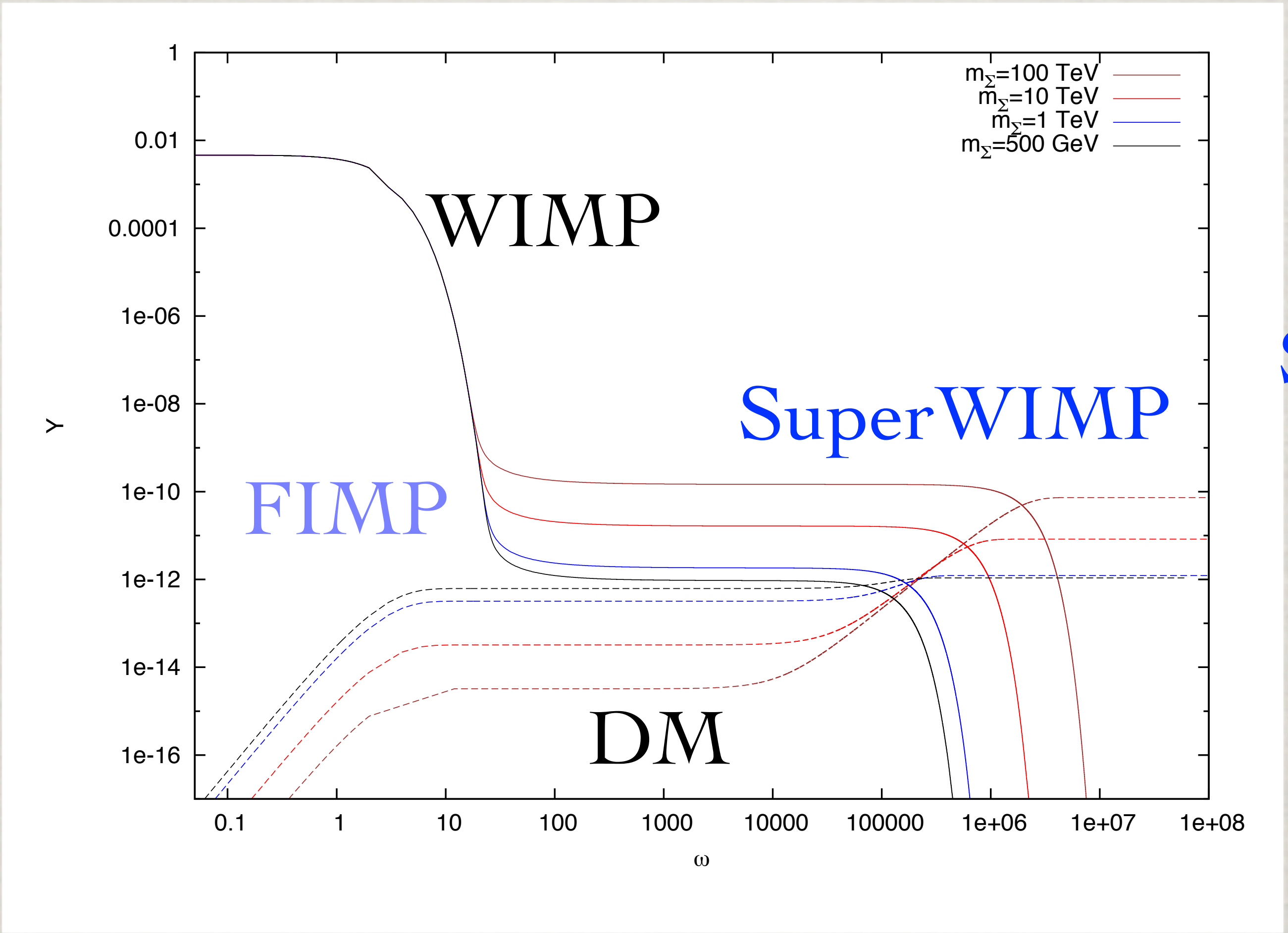
CP violation arises from diagrams with on-shell gluino lighter than the Bino. To obtain right baryon number the RPC decay has to be suppressed, i.e. due to heavy squarks, the RPV coupling large and the Bino density very large...

SuperWIMP/FIMP paradigms

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting (i.e. decaying !) DM particle:

[Hall et al 10]

FIMP DM produced by WIMP decay in equilibrium



[Feng et al 04]

SuperWIMP DM produced by WIMP decay after freeze-out

Two mechanism naturally giving "right" DM density depending on WIMP/DM mass & DM couplings

Baryogenesis & SWimp 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

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

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

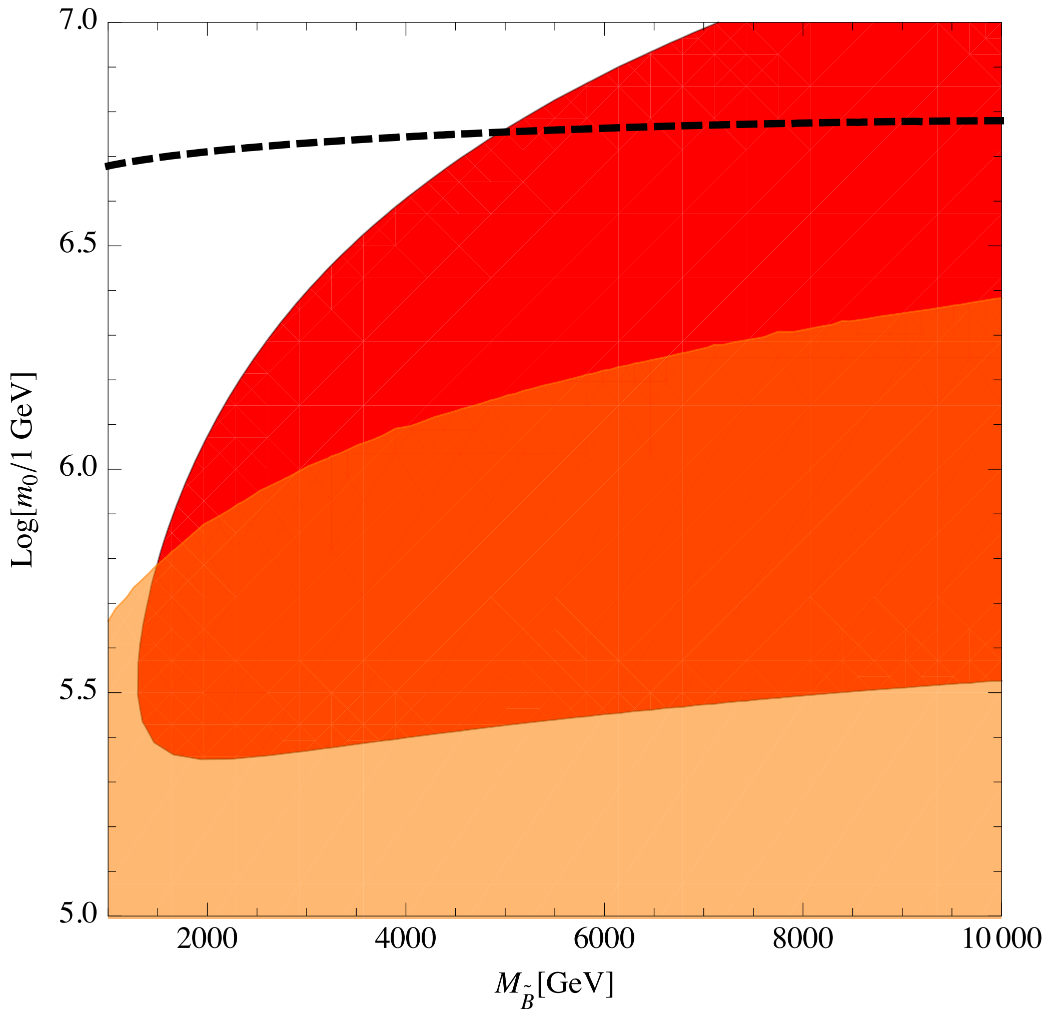
independent of Bino density

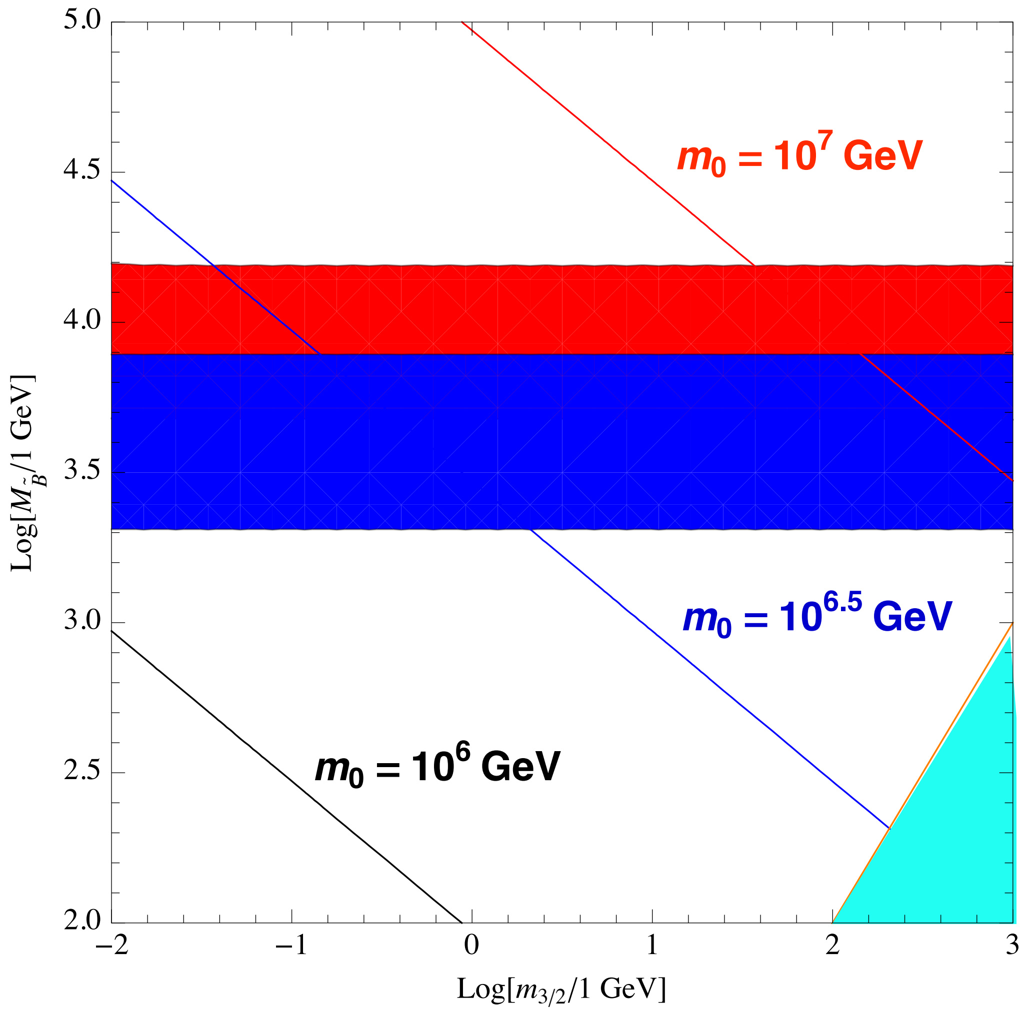
Gravitino DM: BR is naturally small and DM stable enough !

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1312.5703]

For obtaining both, need very heavy scalars, a Bino neutralino above 3 TeV, gluinos at 1 TeV and gravitino at 1-100 GeV...

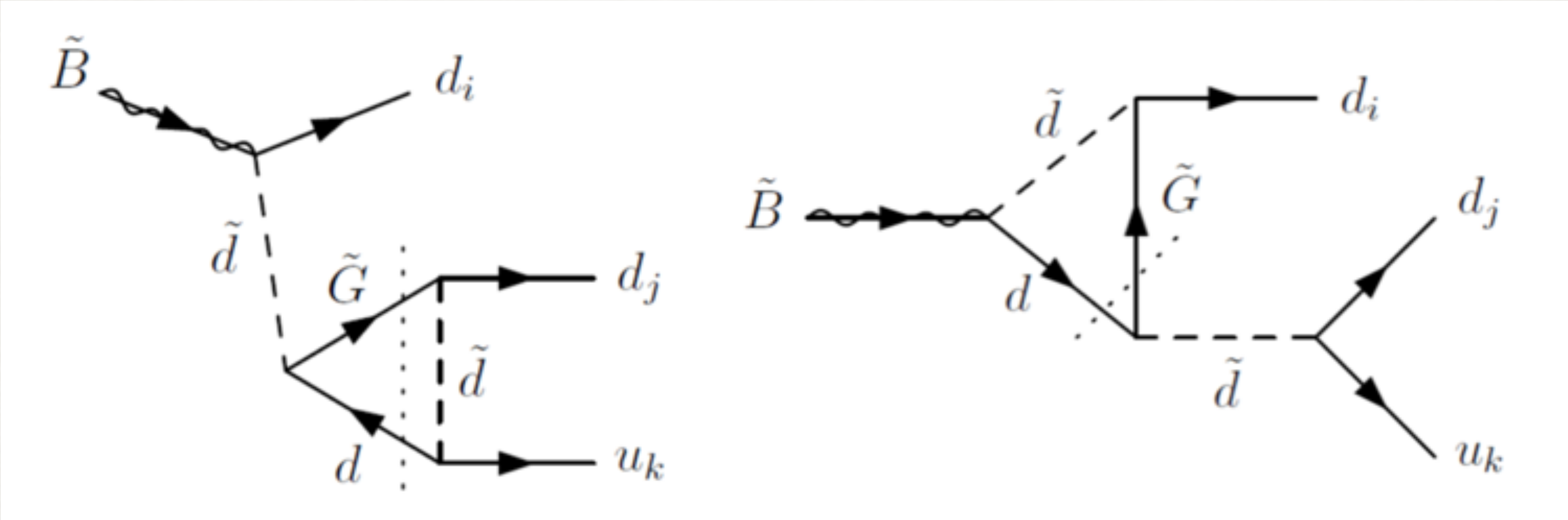




Baryogenesis & DM from RPV

CP violation in RPV SUSY

The loop diagrams contributing to the CP violation are



CP violation can be provided either by a phase difference between the Bino and Gluino masses or by flavour effects in the RPV couplings and CKM-mixing for squarks.
The latter suffers unfortunately of GIM-like cancellations for very heavy squarks...

Baryogenesis in RPV SUSY

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

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

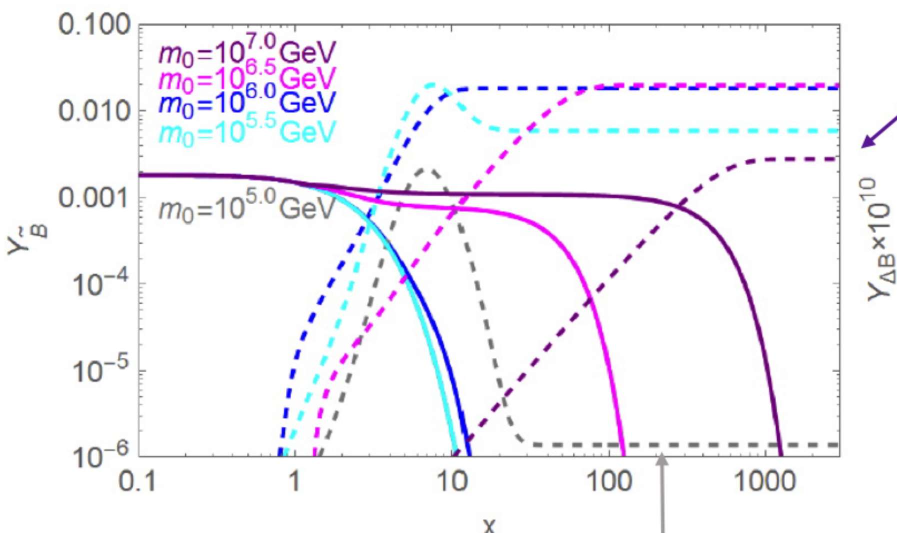
Need a very heavy spectrum to realize the scenario !

Baryogenesis in RPV SUSY

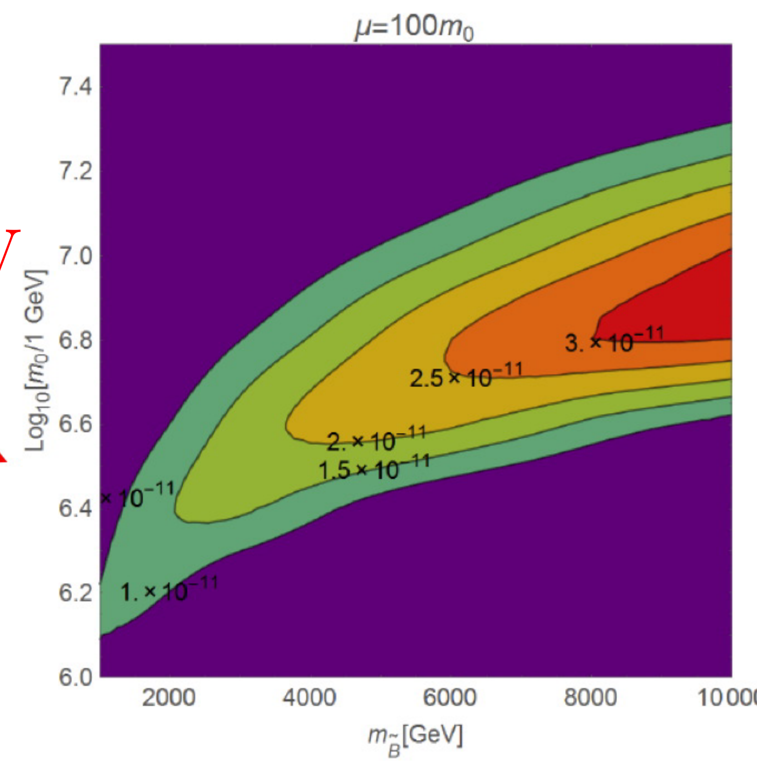
[Arcadi, LC & Nardecchia 1507.05584]

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

Asymmetry suppressed by the high scalars



10^7GeV



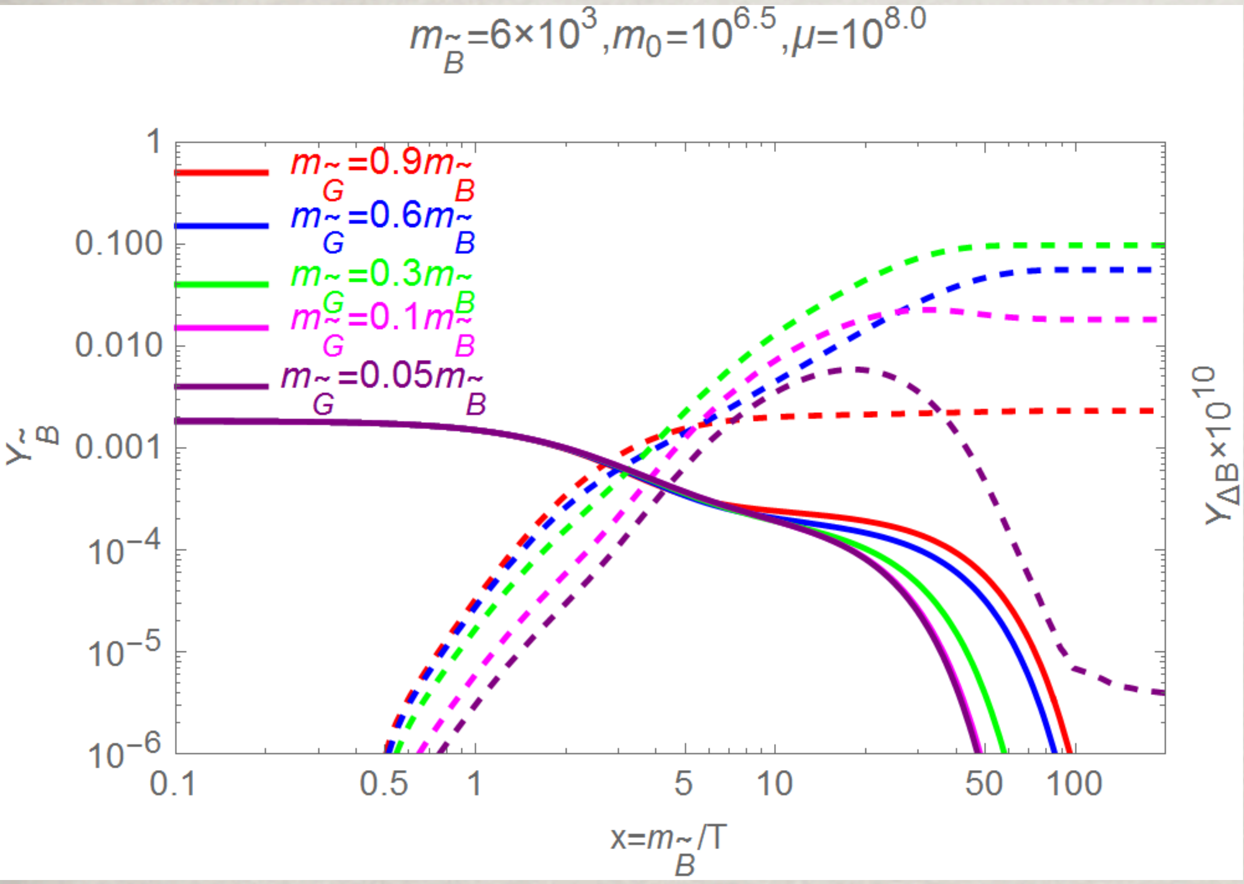
Asymmetry suppressed by wash-out

Rather definite prediction for range of scalar masses Heavy !!!

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

On the other hand the gluino mass must be not much smaller than the Bino mass to give sufficient CP violation/B asymmetry



Baryogenesis in RPV SUSY

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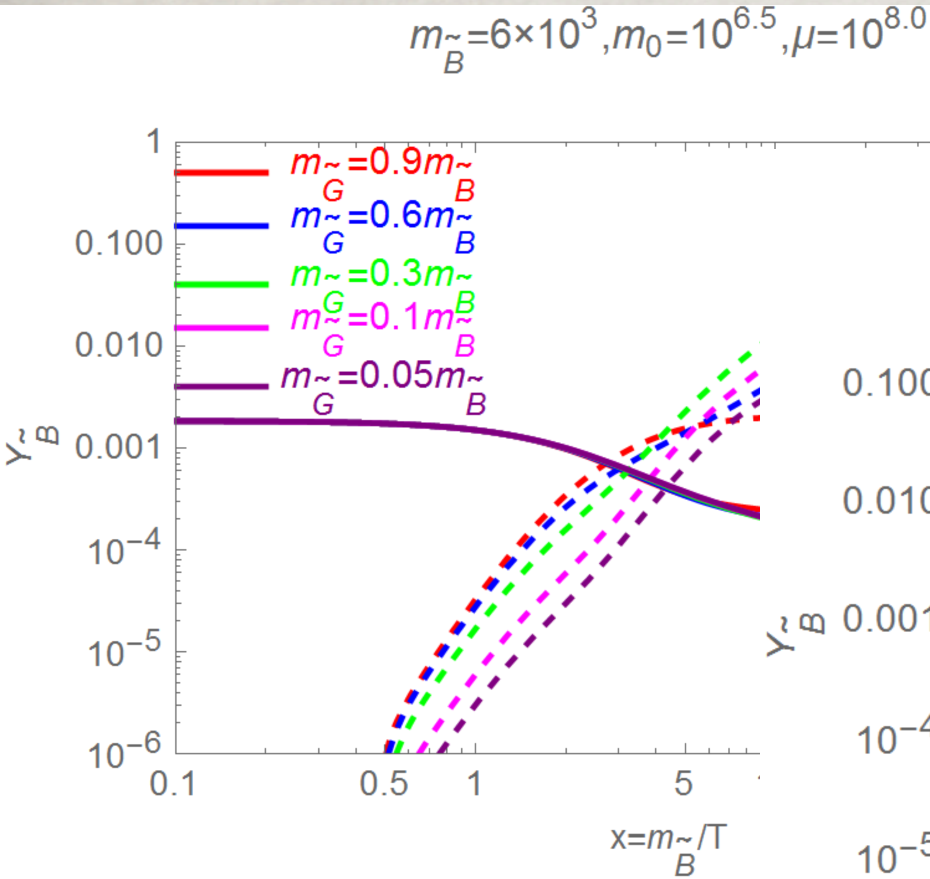
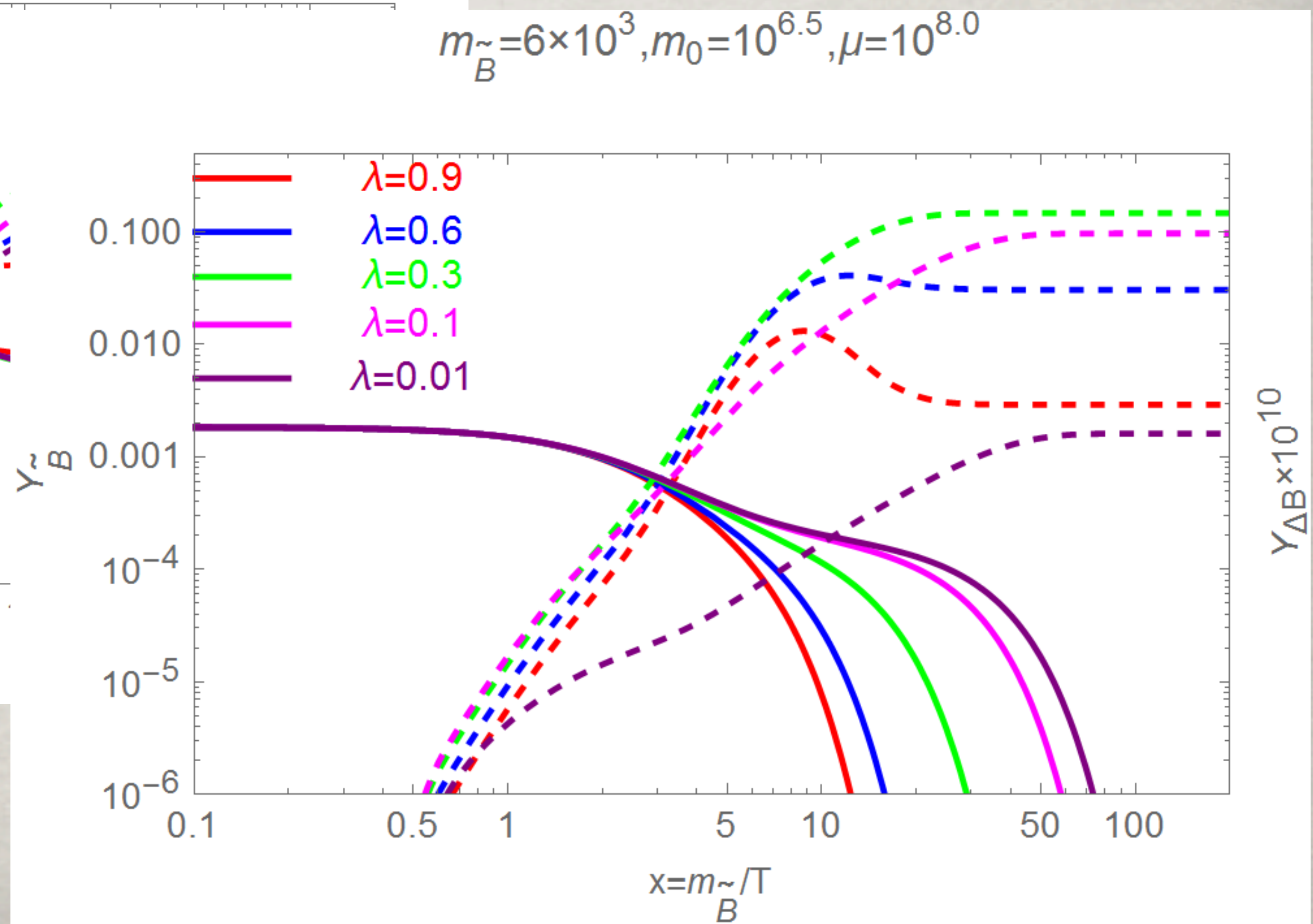


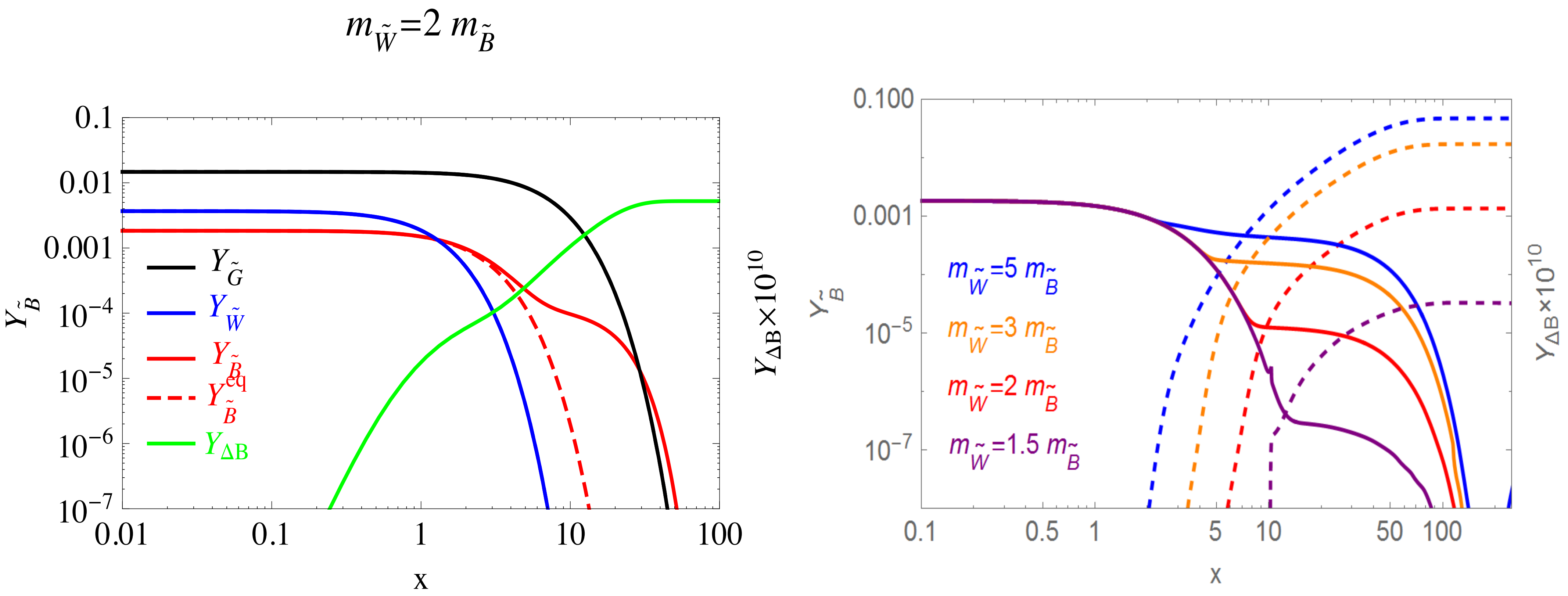


Similar for RPV coupling λ

The revenge of the Wino

[Arcadi, LC & Nardecchia 1507.05584]

Main contribution to the wash-out processes comes from the Wino, which can also coannihilate with the Bino !!!



The Wino has to be sufficiently heavy to avoid keeping Bino in equilibrium and suppressing its density !

The revenge of the Wino II

[Arcadi, LC & Nardecchia 1507.05584]

But with very heavy Wino, another problem arises: the gravitino can be overproduced by freeze-in from the Wino ! Same problem with the heavy squarks, but there one could think that they are too heavy to be in thermal equilibrium...

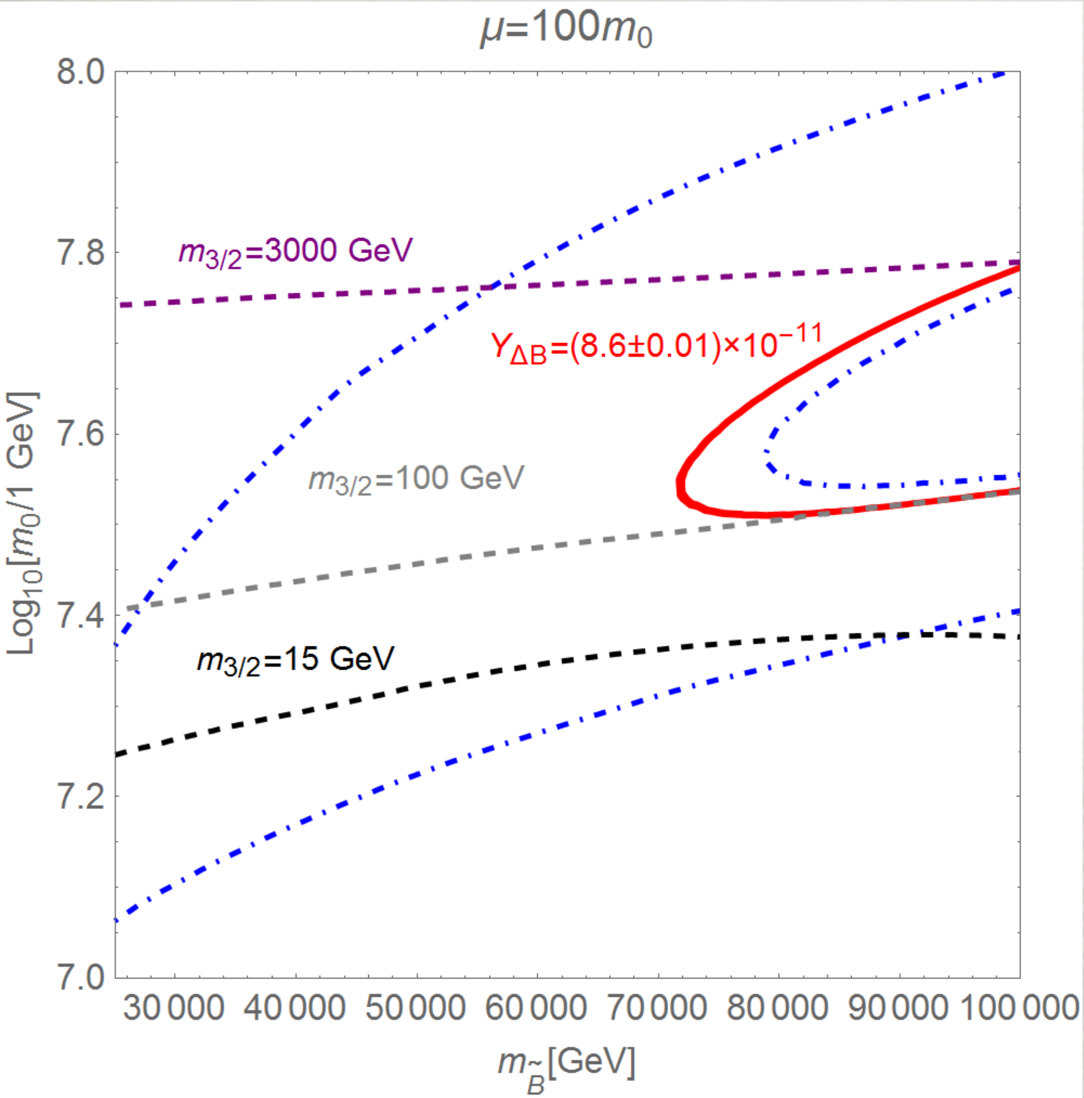
$$\Omega_{3/2}^{FI} h^2 \sim 0.002 \left(\frac{m_{\tilde{W}}}{10\ \mathrm{TeV}} \right)^3 \left(\frac{m_{3/2}}{1\ \mathrm{TeV}} \right)^{-1}$$

$$\rightarrow \quad m_{\tilde{W}} < 362\ \mathrm{TeV} \left(\frac{m_{3/2}}{1\ \mathrm{TeV}} \right)^{1/3}$$

SuperWIMP production of DM, together with baryogenesis, is realized only in a small window of Wino masses.

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]



Moreover the large scalar mass suppresses the branching ratio into gravitinos too much...

$$BR(\tilde{B} \to \psi_{3/2} + \text{any}) << \epsilon_{CP}$$

Need a large gravitino mass to compensate !
Not such a simple explanation for

$$\Omega_{DM} \sim 5\,\Omega_B$$

after all...

Phenomenology

Gluino NLSP in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

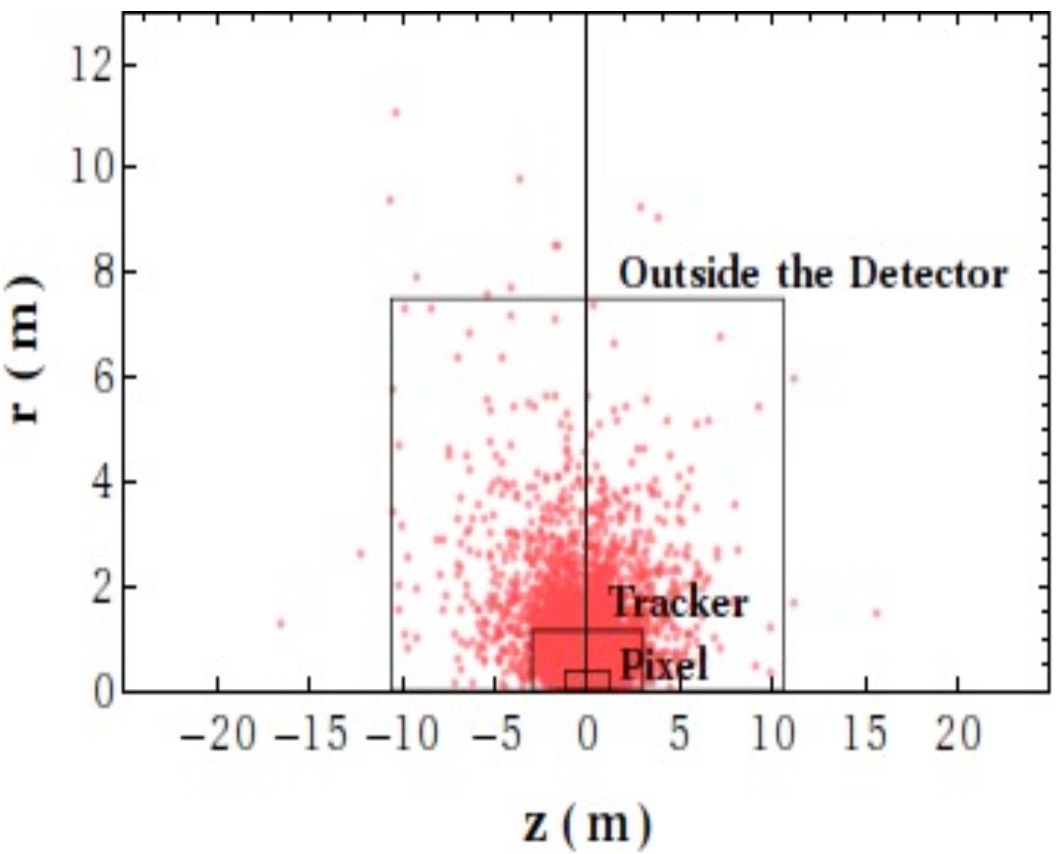
The gluino is in this scenario the lightest particle that may be produced at colliders; unfortunately it must be not too much lighter than the Bino, i.e. $m_{\tilde{g}} \sim 0.1 - 0.4\, m_{\tilde{B}} \sim 7 - 28$ TeV, possibly in the reach of a 100 TeV collider.

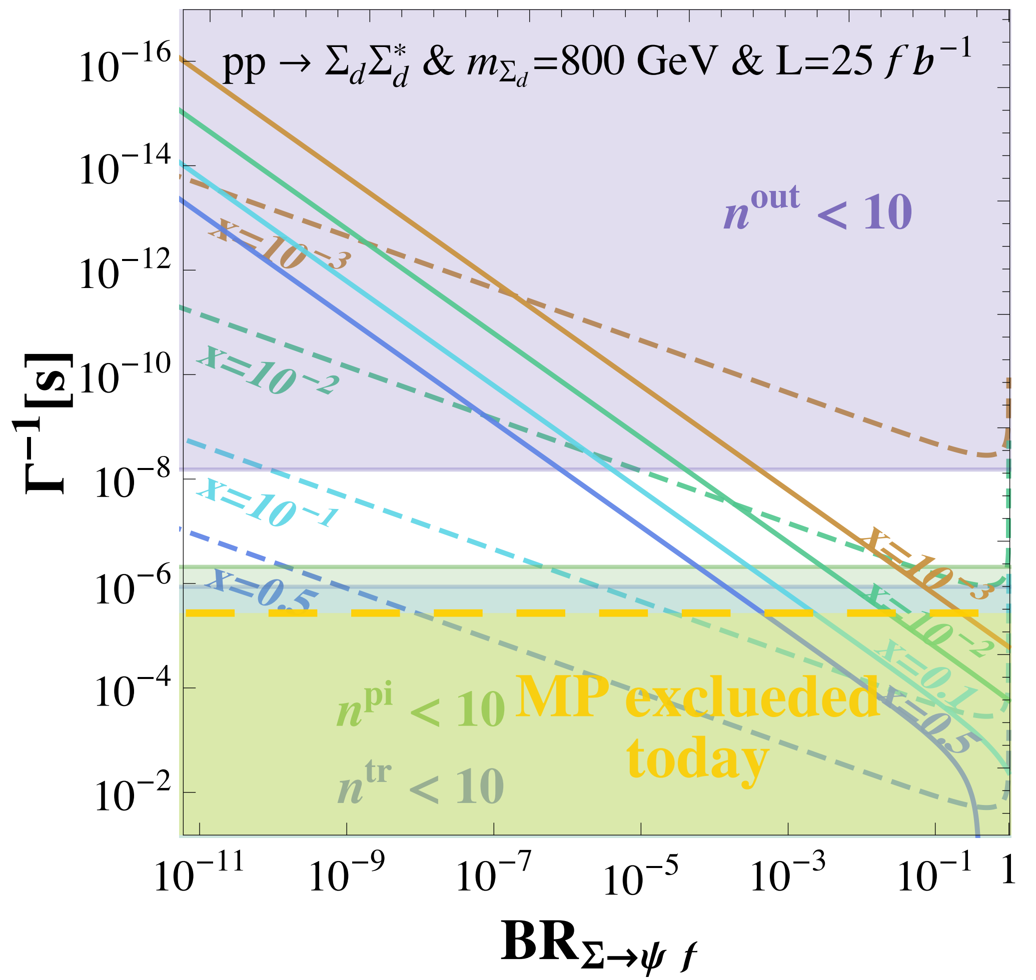
$$c\tau_{\tilde{g}} \sim 1,5 \text{ cm} \left(\frac{\lambda''}{0.4}\right)^{-2} \left(\frac{m_0}{4 \times 10^7 \text{GeV}}\right)^4 \left(\frac{m_{\tilde{g}}}{7 \text{ TeV}}\right)^{-5}$$

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 given that the branching fraction is so small.

FIMP/SWIMP & COLORED Σ

[G. Arcadi, LC & F. Dradi 1408.1005]

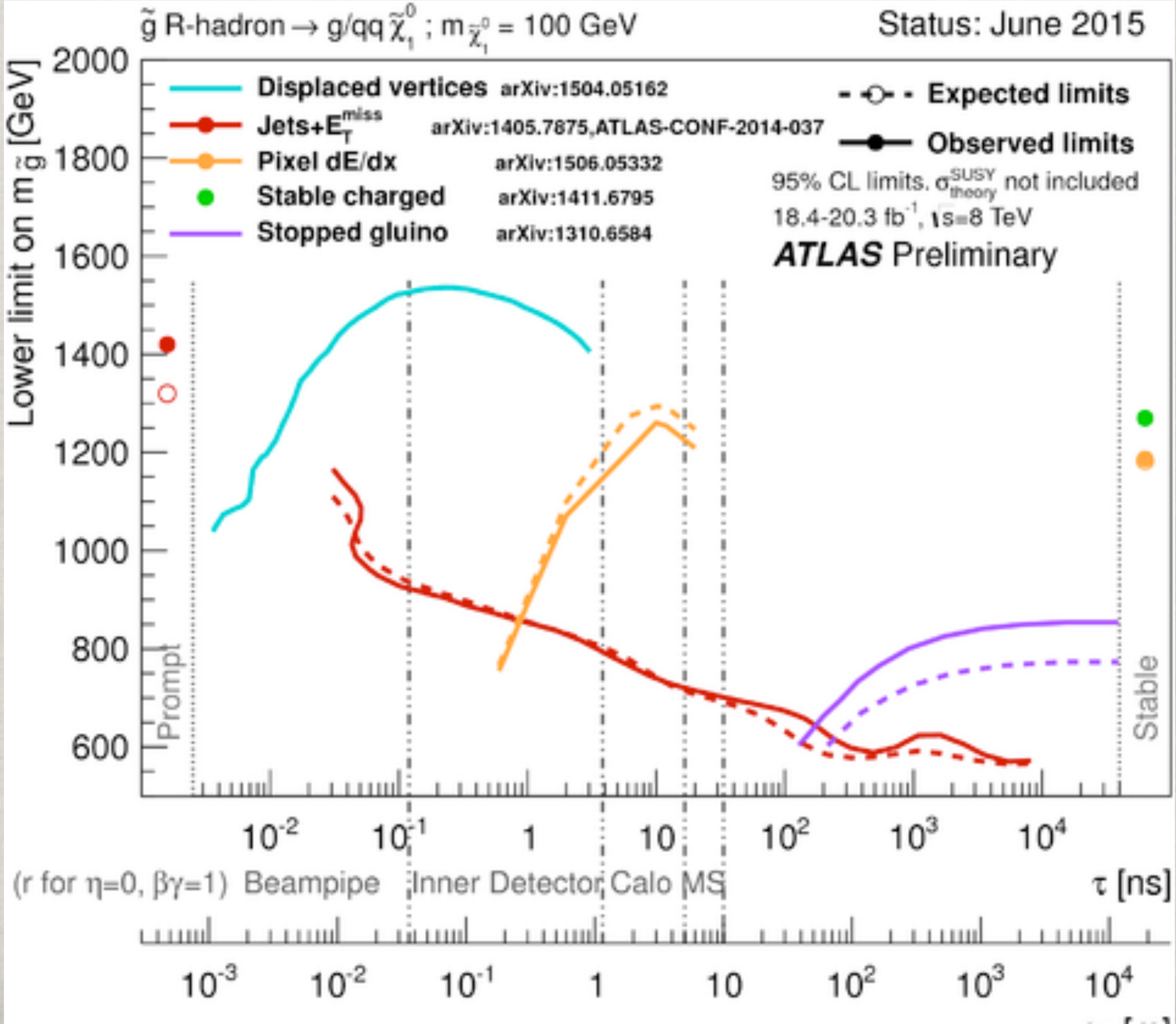




Similar phenomenology as minimal decaying DM case !

Long-lived particles @ LHC

[ATLAS combination]



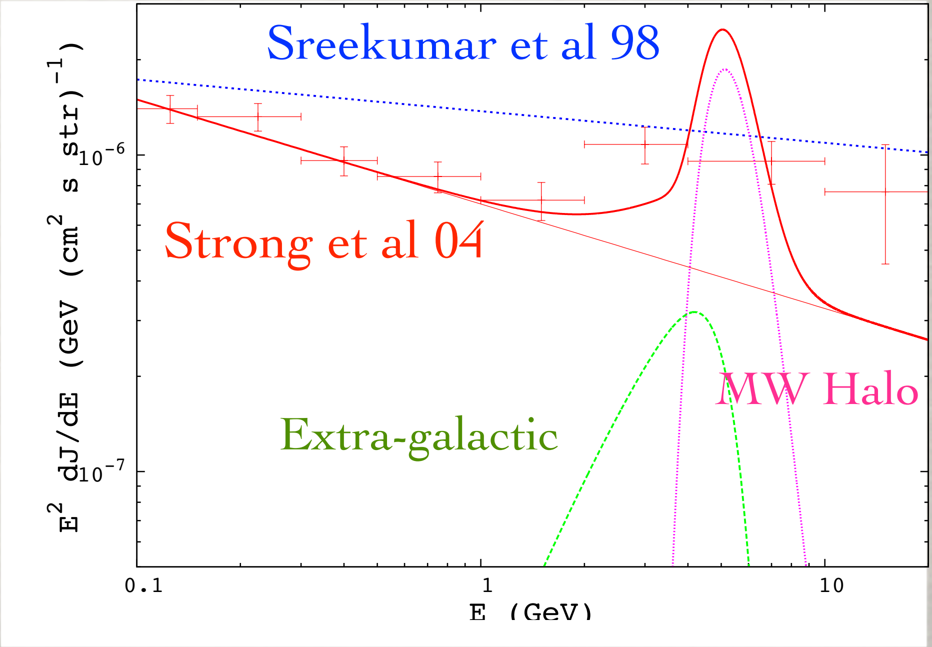
DECAYING DM

- The flux from DM decay in a species i is given by

$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\, \rho(r(s,\theta))$$

Particle Physics Halo property

- Very weak dependence on the Halo profile; key parameter is the DM lifetime...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...
- Galactic/extragalactic signal are comparable...



Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

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

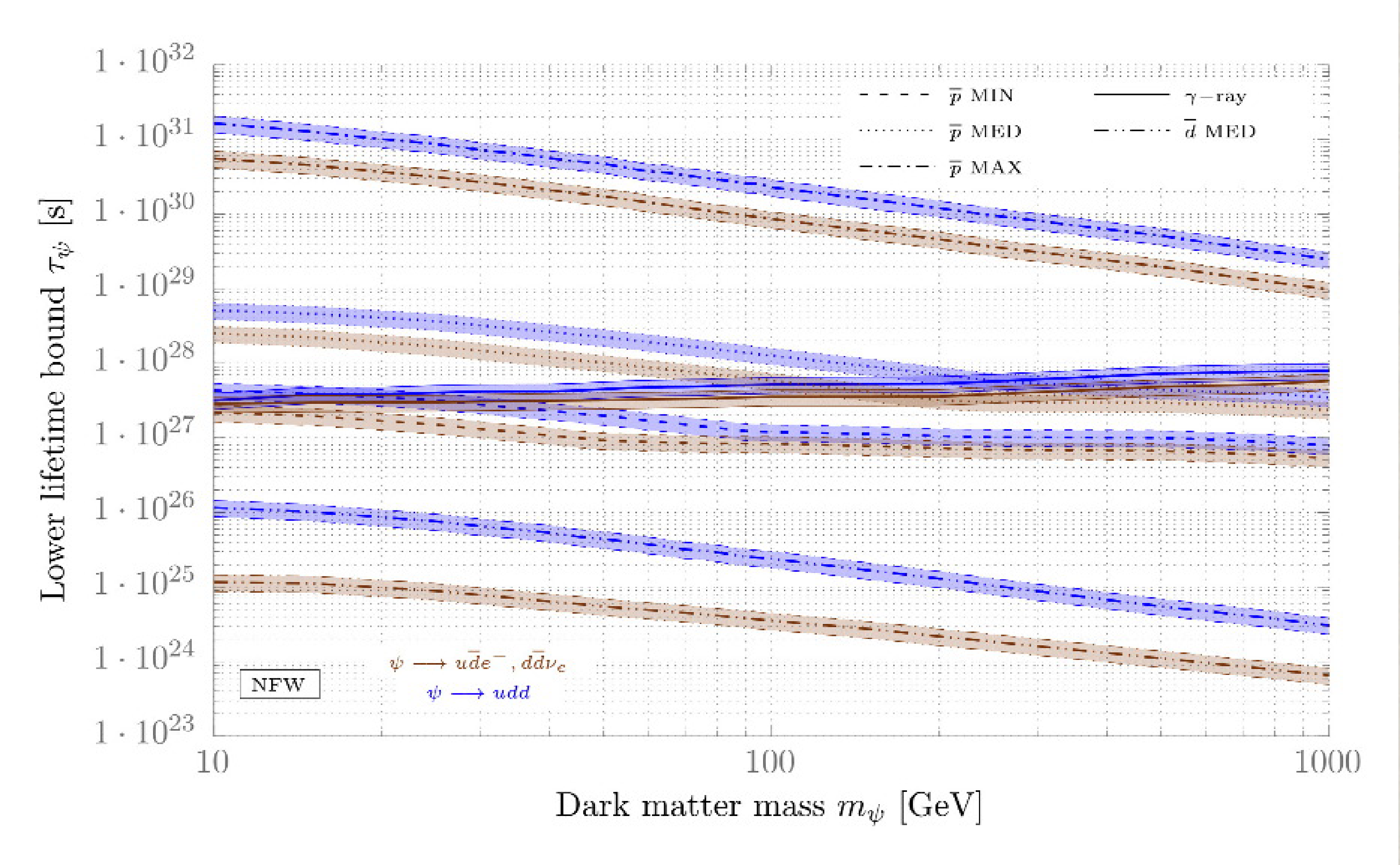
$$\Gamma(\psi_{3/2} \to u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

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

Right ballpark for indirect DM detection, but strongly dependent on the gravitino mass...

ID of Gravitino DM

[LC, Eckner & Gustafsson, work in progress]



Unfortunately bounds strongly depend on propagation...

Outlook

Outlook

- The presence of RPV couplings opens up new possibilities to realize baryogenesis at a low scale, if supersymmetry is heavy.
- In the same scenario gravitino DM is natural, since it is naturally produced as LSP from the SuperWIMP mechanism and could have comparable energy densities to the baryons.
- On the other hand, the scenario is not very natural with respect to the supersymmetric spectrum: needs heavy squarks and higgsinos to allow for large Bino density and out-of-equilibrium decay, light but not too light gluino, heavy but not too heavy Wino and gravitino mass in the TeV range...
- In this scenario, signals of SUSY could appear at a 100 TeV collider and possibly hints of DM decay in indirect detection.