Heavy Supersymmetry in the sky

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$[q,p]=i\hbar$

elusiVes-inVisiblesPlus
neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

Outline

- Introduction:
  -Theoretical guiding principles
  - Cosmology as a probe of particle physics
- Heavy Dark Matter in SUSY
- High scale SUSY for DM and baryogenesis
- Outlook

Introduction

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

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

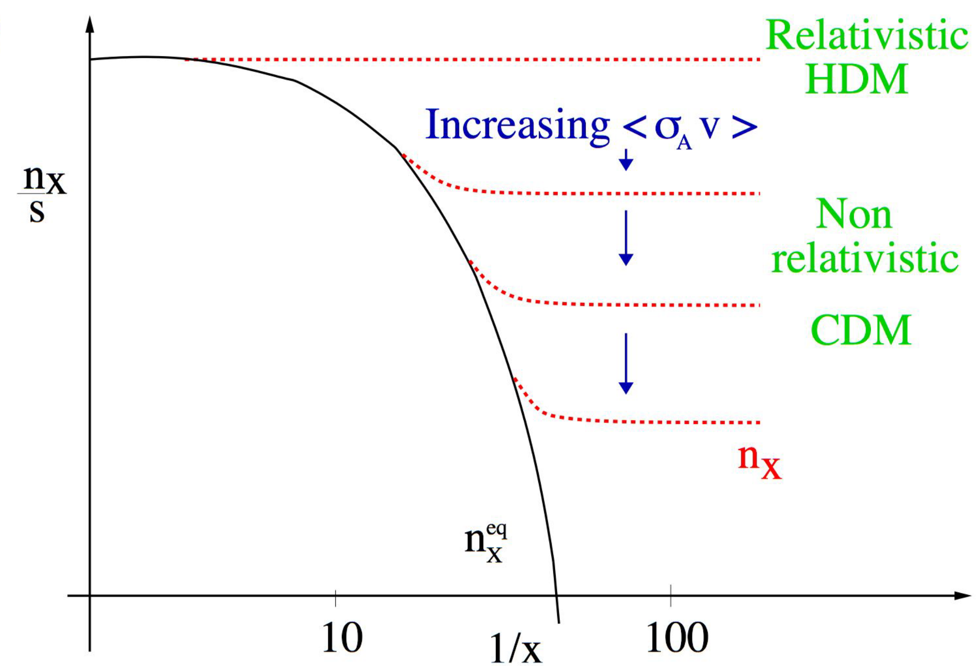
Hubble expansion — Collision integral

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



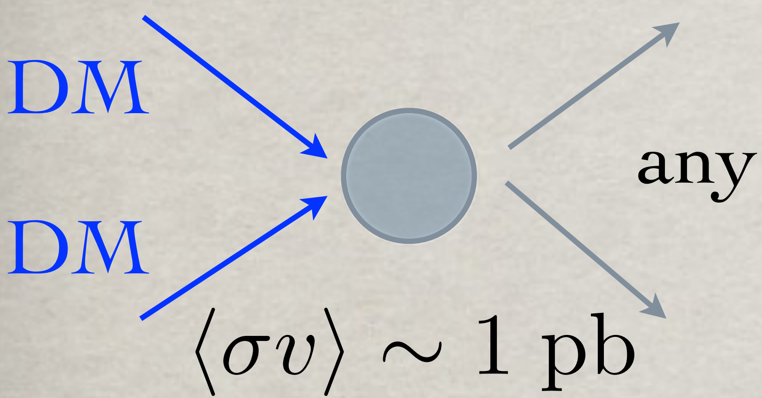
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

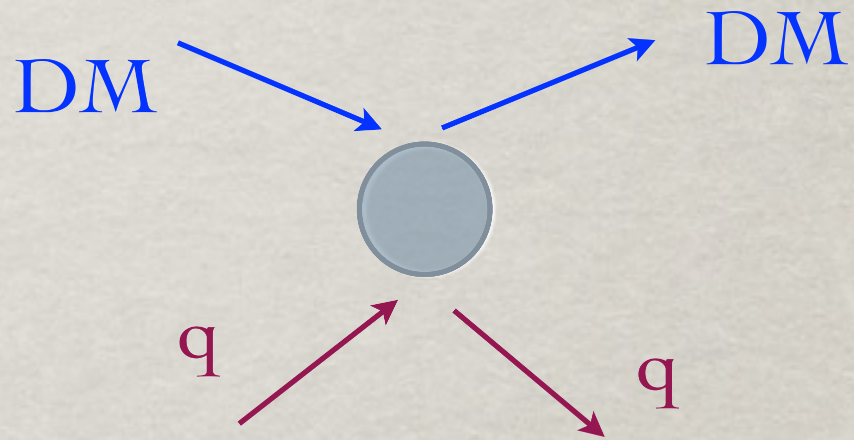
For weaker interactions need lighter masses HOT DM !

THE WIMP CONNECTION

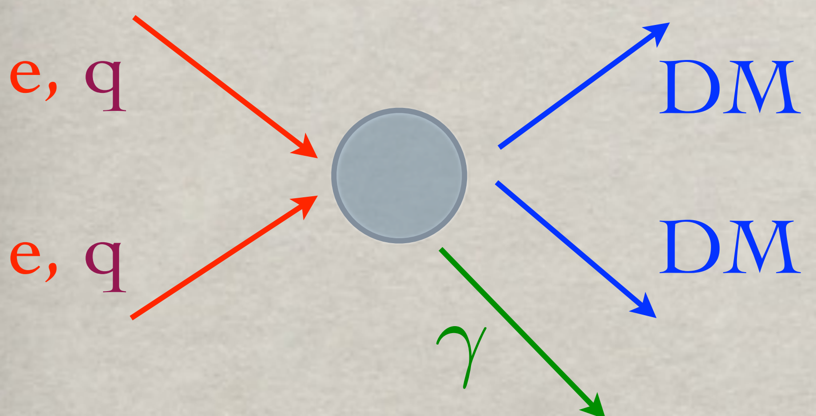
Early Universe: $\Omega_{CDM} h^2$



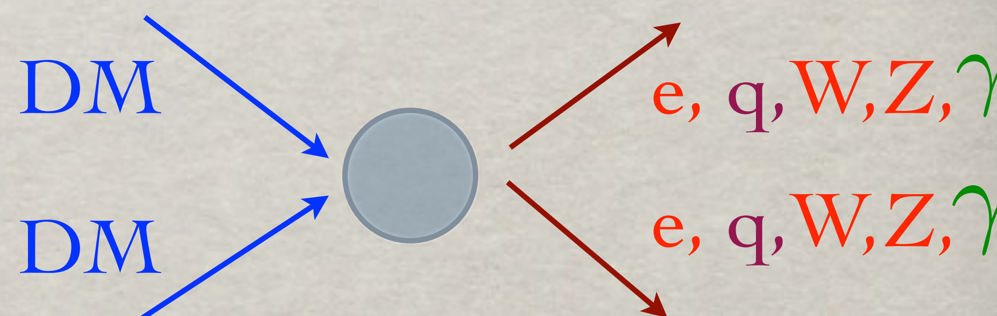
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:



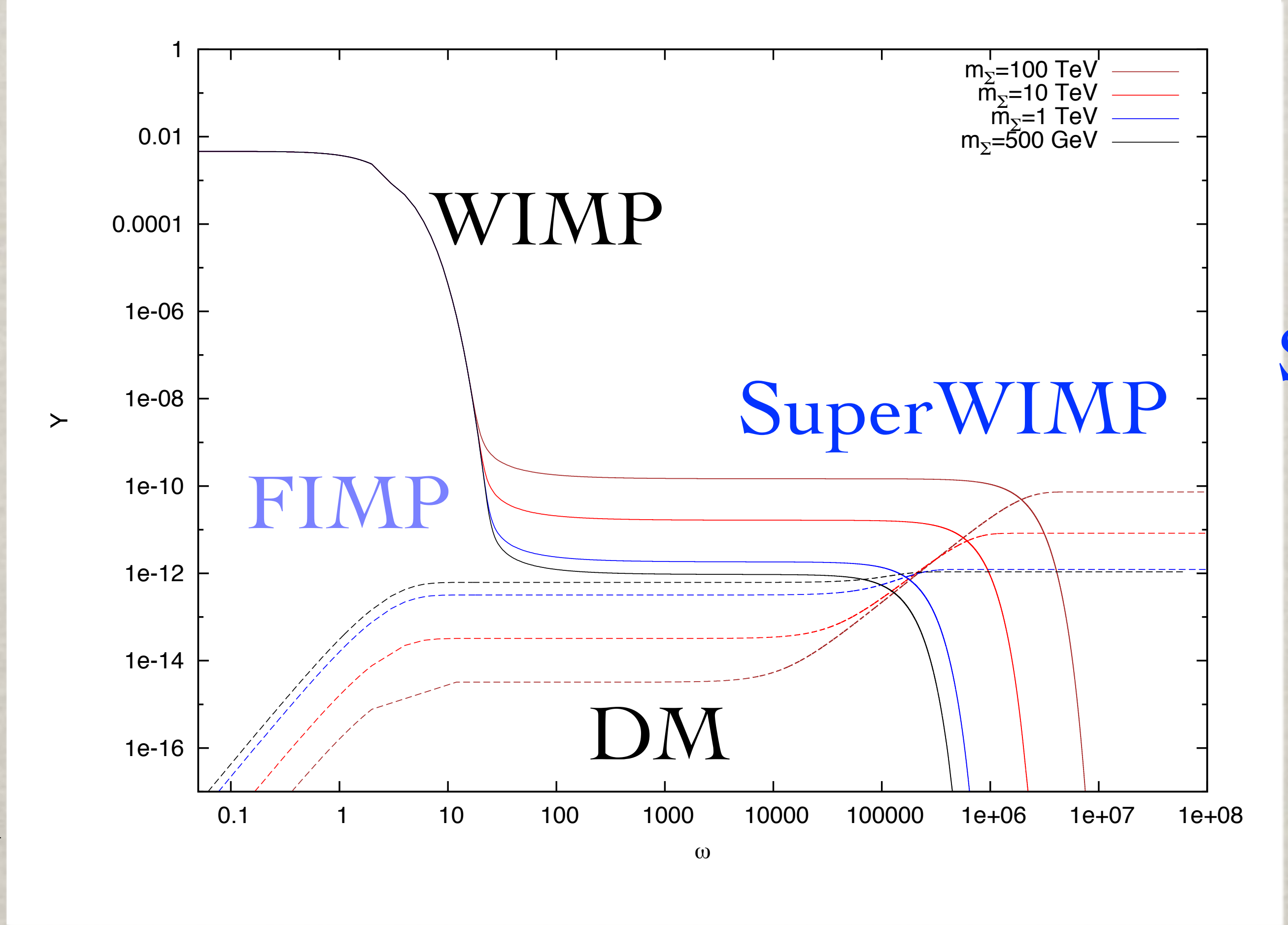
3 different ways to check this hypothesis !!!

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

FIMP/SWIMP

- The FIMP/SuperWIMP type of Dark Matter production is effective for any mass of the mother and daughter particle !
- Indeed if the mass ratio is large the WIMP-like density of the mother particle gets diluted:

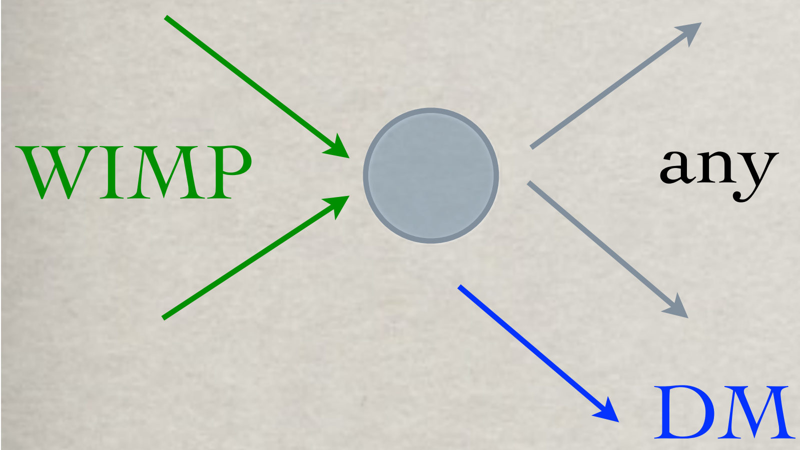
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma} \, BR(\Sigma \to \psi) \, \Omega_\Sigma h^2$$

- Moreover also the FIMP production is dependent on the decay rate of the mother particle not just the mass and can work also for larger masses…

$$\Omega^{FI} h^2 = 10^{27} \frac{g_\Sigma}{g_*^{3/2}} \frac{m_\psi \Gamma(\Sigma \to \psi)}{m_\Sigma^2}$$

F/SWIMP CONNECTION

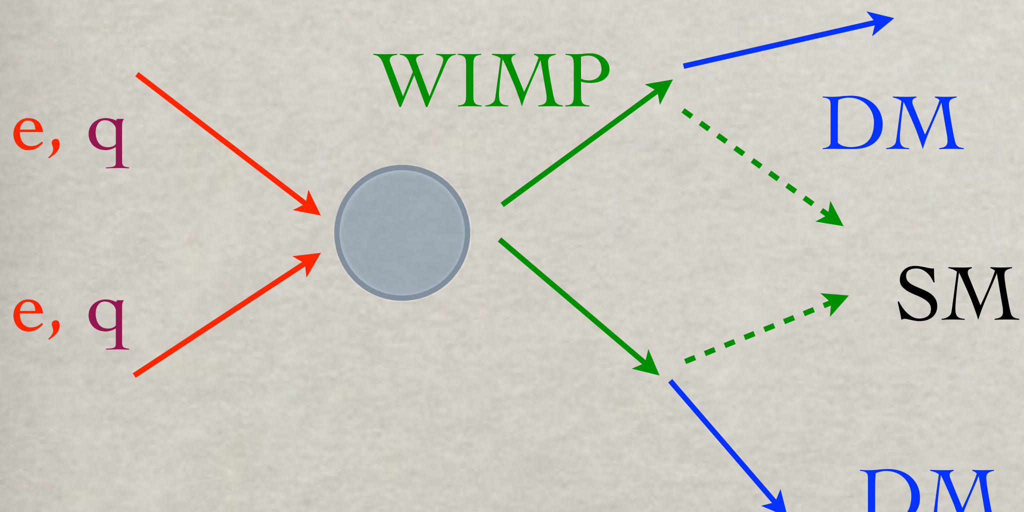
Early Universe: $\Omega_{CDM} h^2$



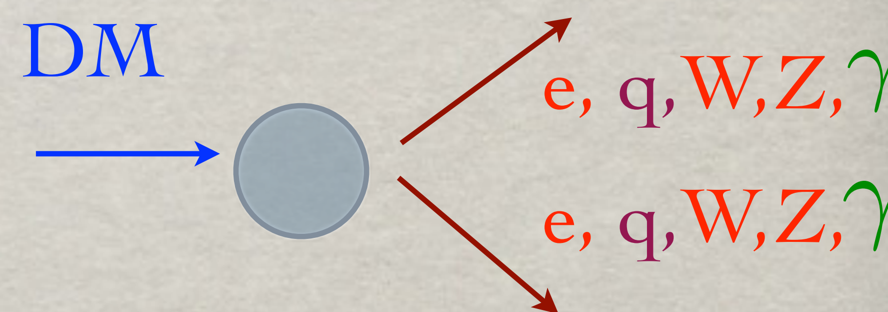
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

Which model Beyond the SM ?

weakly coupled ⟷ strongly coupled

Cosmology

(Collider-based) Particle Physics

To pinpoint the completion of the SM, exploit the complementarity between Cosmology and Particle Physics to explore all the sectors of the theory:
the more weakly coupled and the more strongly coupled to the Standard Model fields...

Best results if one has information from both sides, e.g. neutrinos, axions, DM, etc... ???

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

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

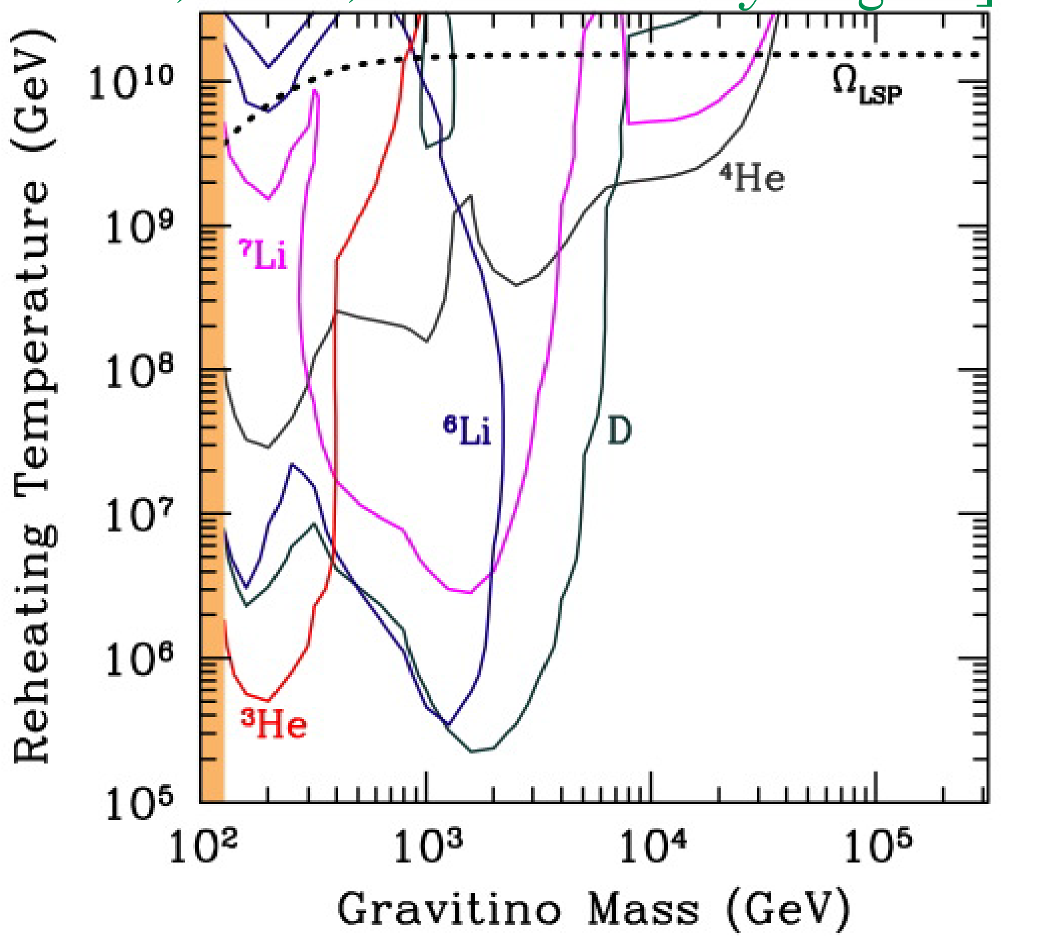
[Bolz,Brandenburg & Buchmuller 01],

[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]

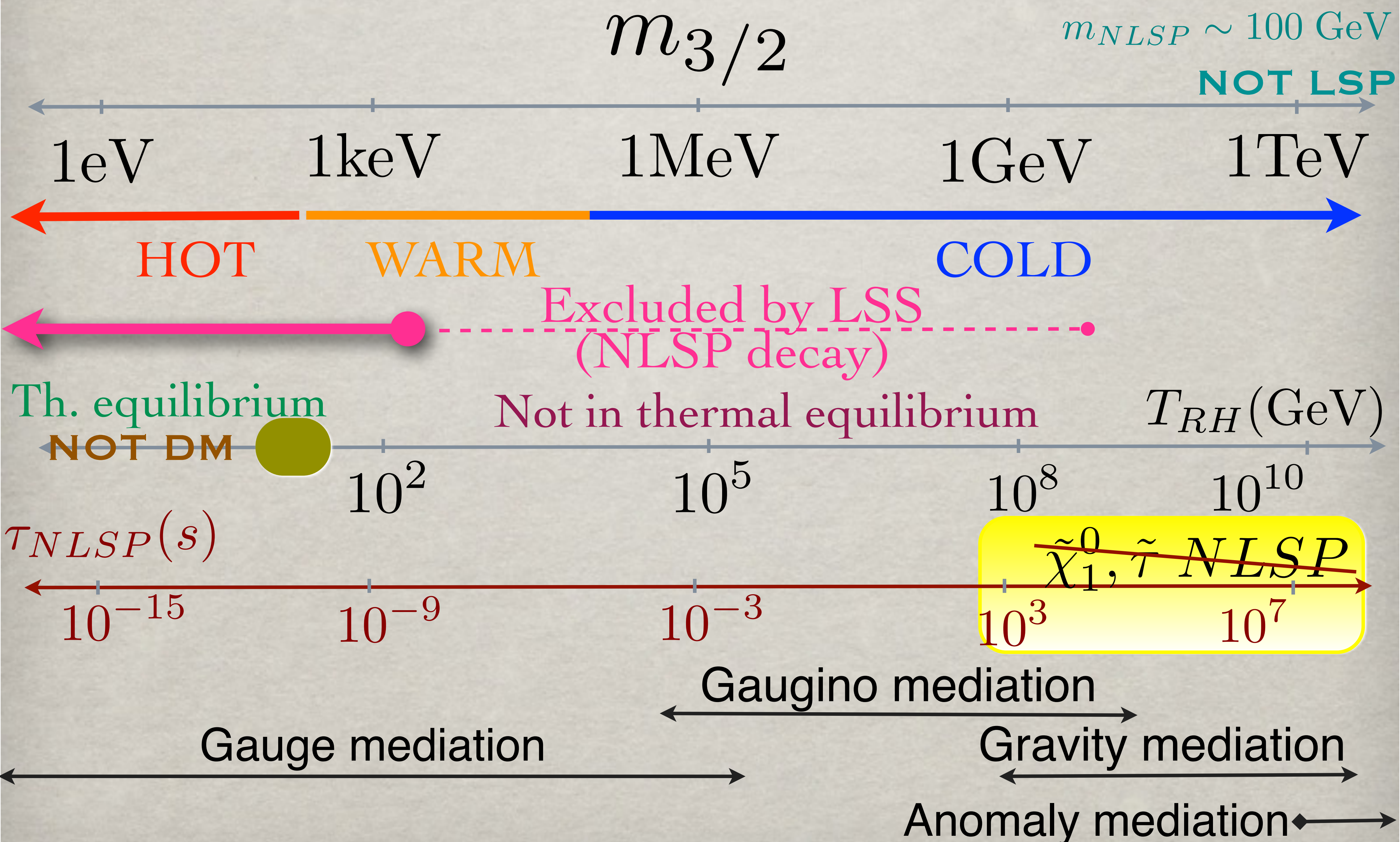


$$\tau_{3/2} = 6 \times 10^7 \mathrm{s} \left(\frac{m_{3/2}}{100\mathrm{GeV}} \right)^{-3}$$

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

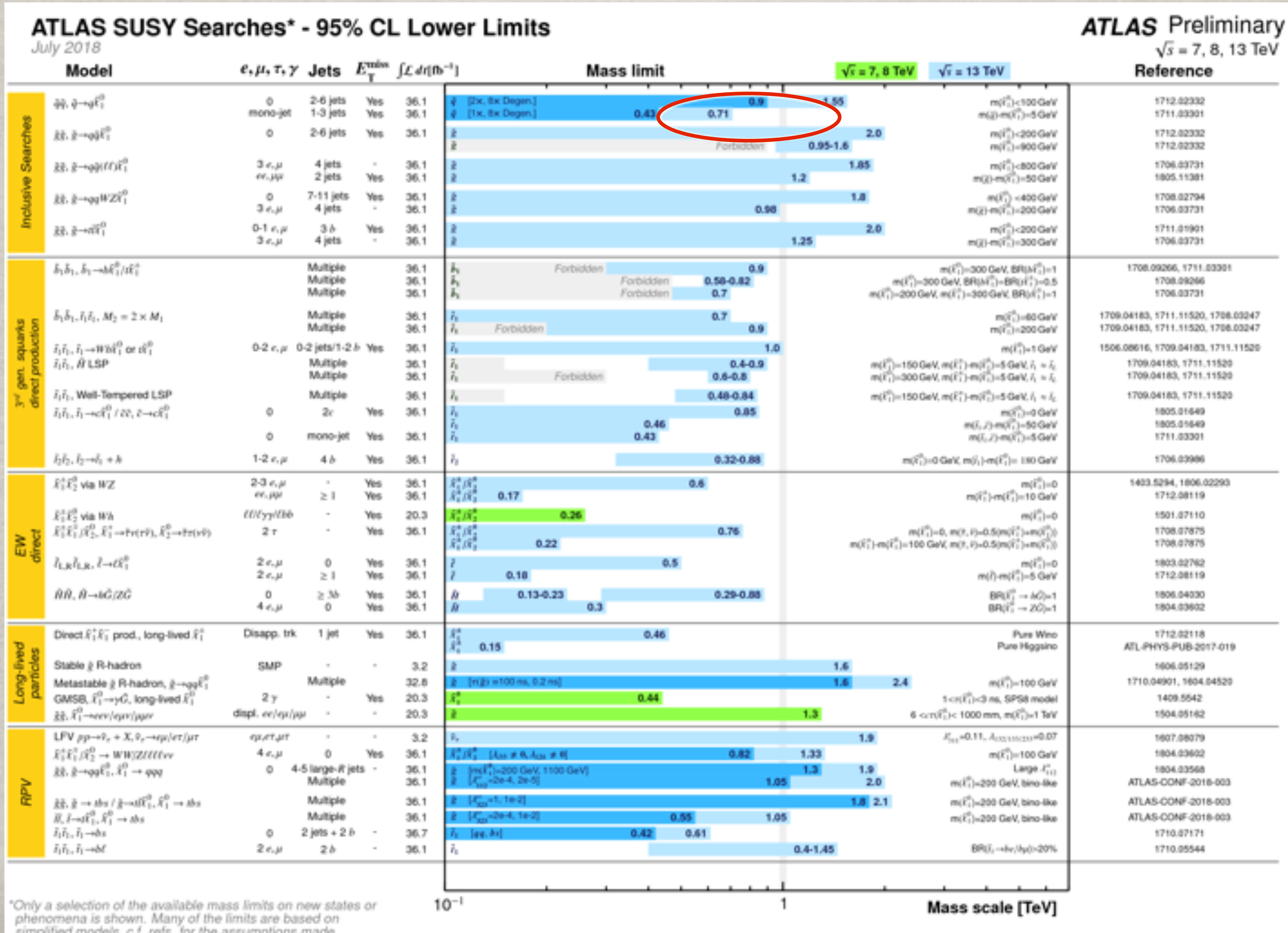
$$\Omega_{3/2} \propto T_R \, M_i^2 / m_{3/2}$$

Gravitino DM summary



Heavy Dark Matter in SUSY

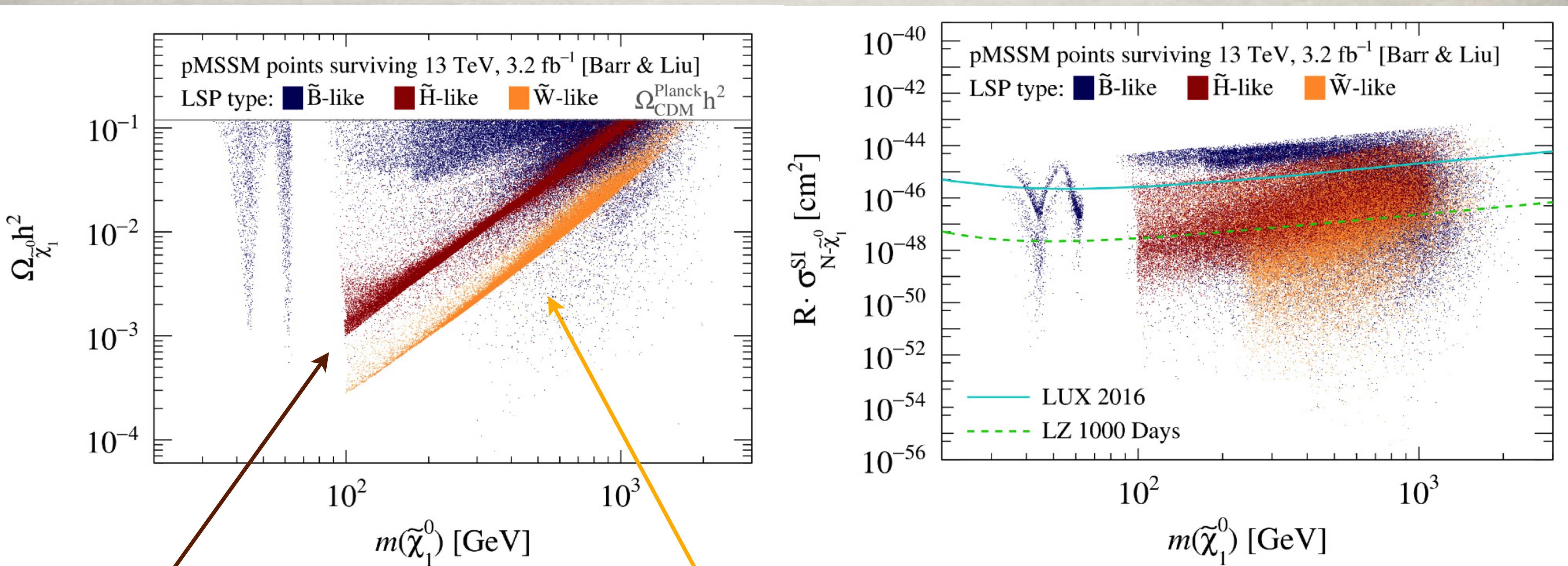
SUSY AT LHC RUN 2



SUSY MODELS STILL ALIVE

[Barr & Liu 2016]

pMSSM points surviving after LHC-13 data



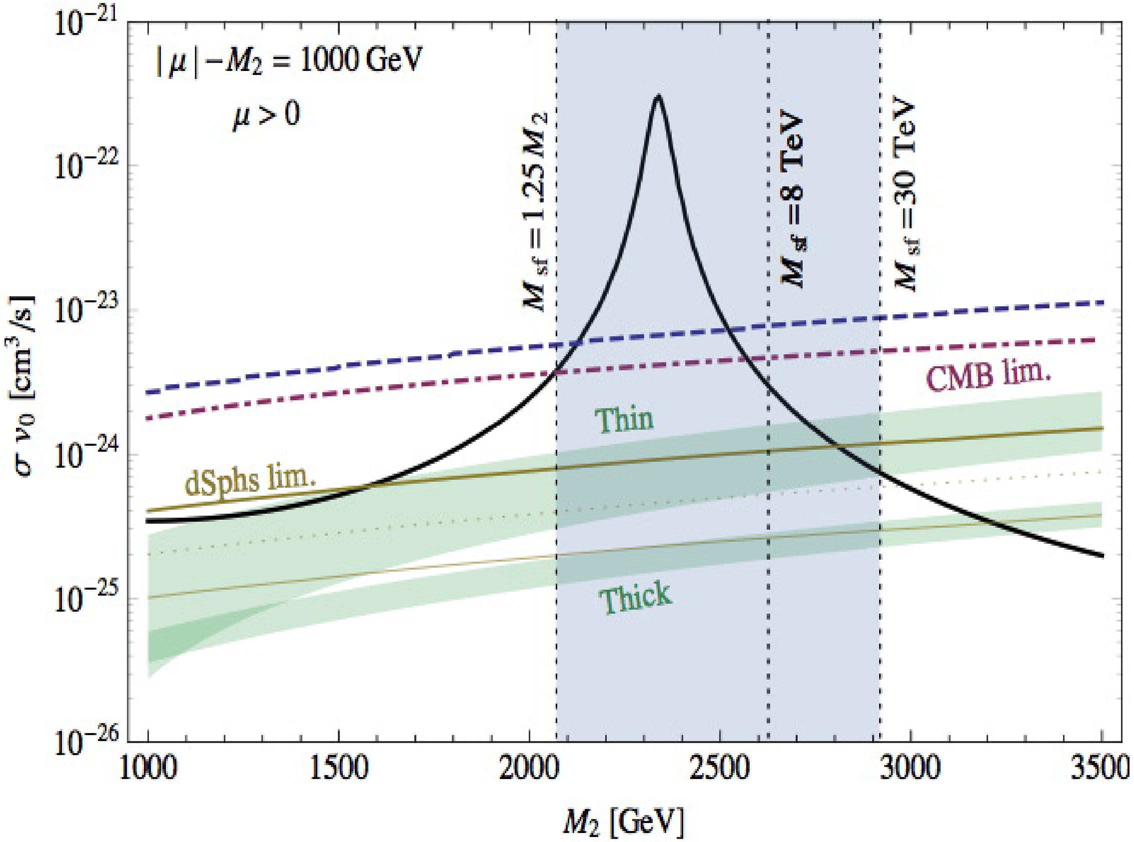
Higgsino band Wino band

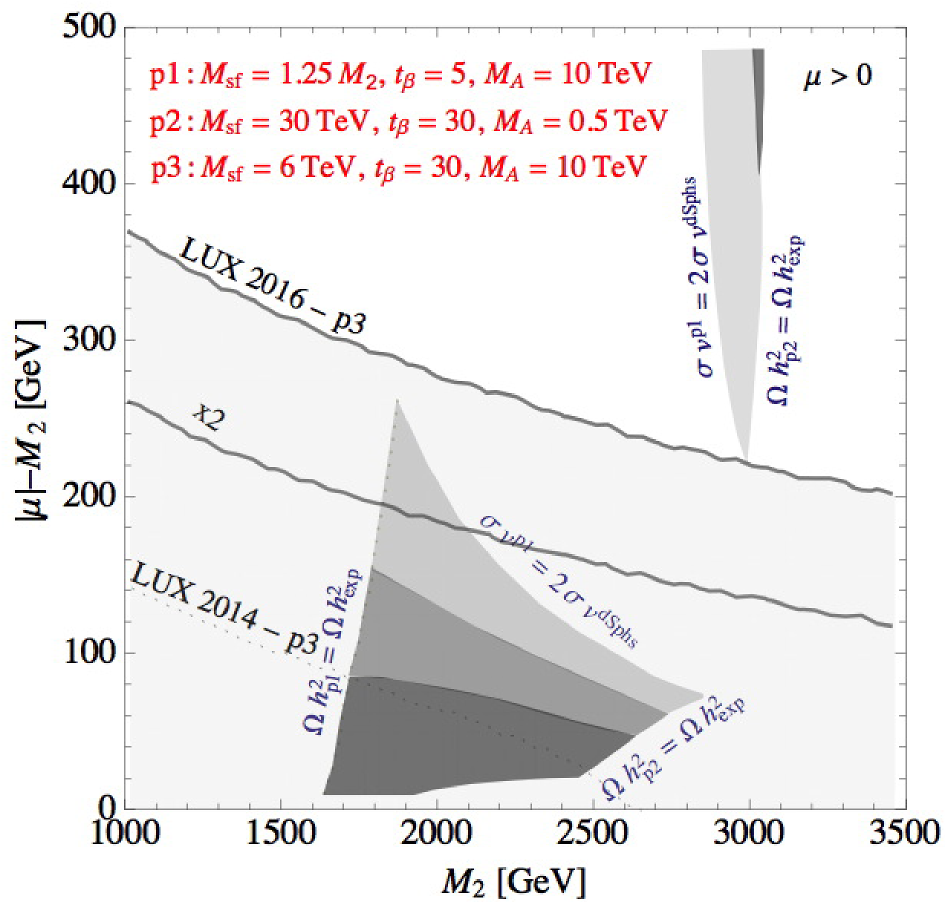
Wino DM challenged by Indirect Detection, but Higgsino parameter space still viable (and also some Bino-like…)

Wino Dark Matter

In the case of the Wino also the Sommerfeld enhancement of the cross-section plays an important role ! In this case indirect detection can exclude pure Wino and also most of the Wino-Higgsino parameter space...

[Beneke et al.1611.00804]

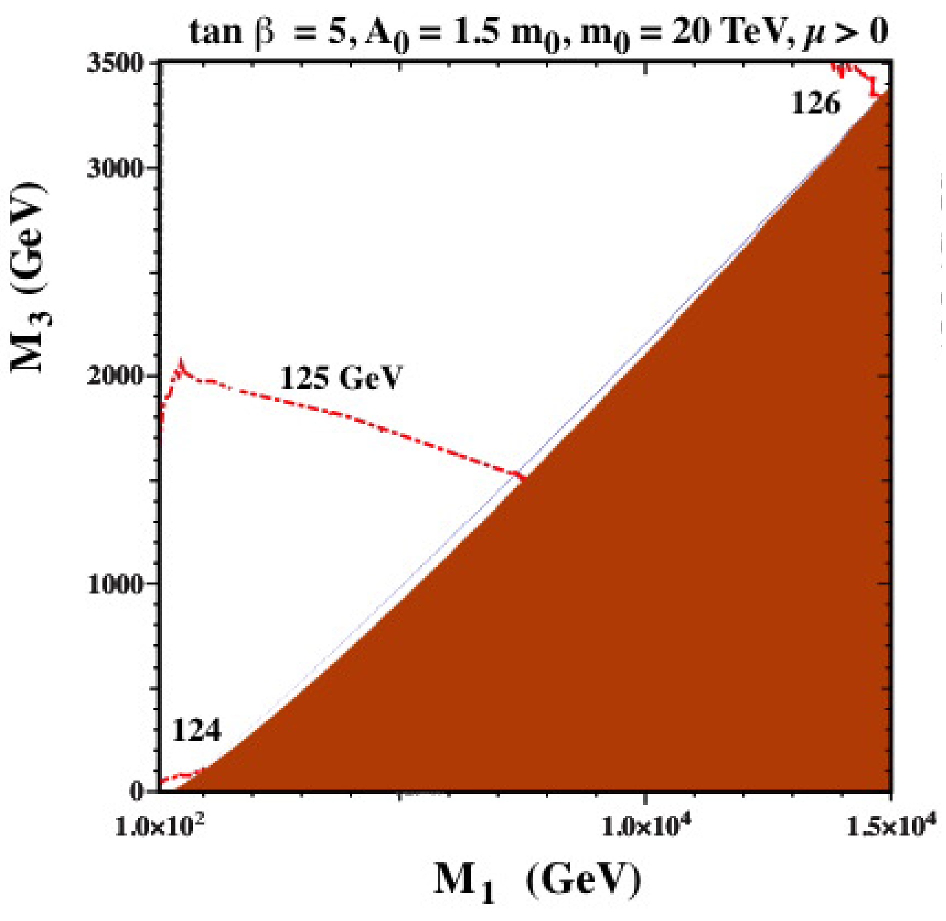




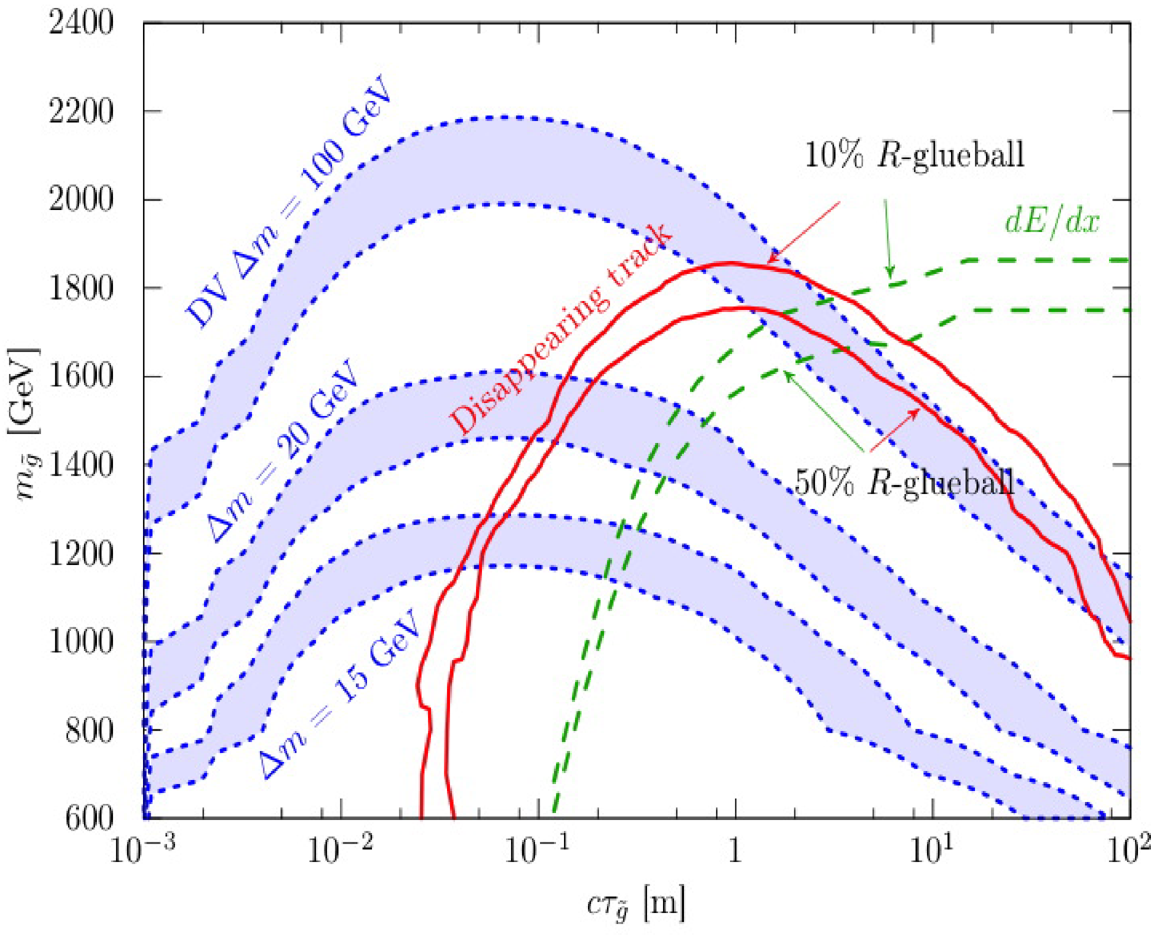
Bino-gluino coannihilation

For non-universal gaugino masses also the gluino plays a role and extends the mass to the multiTeVs !

[Ellis, Evans, Luo & Olive 1510.03498]



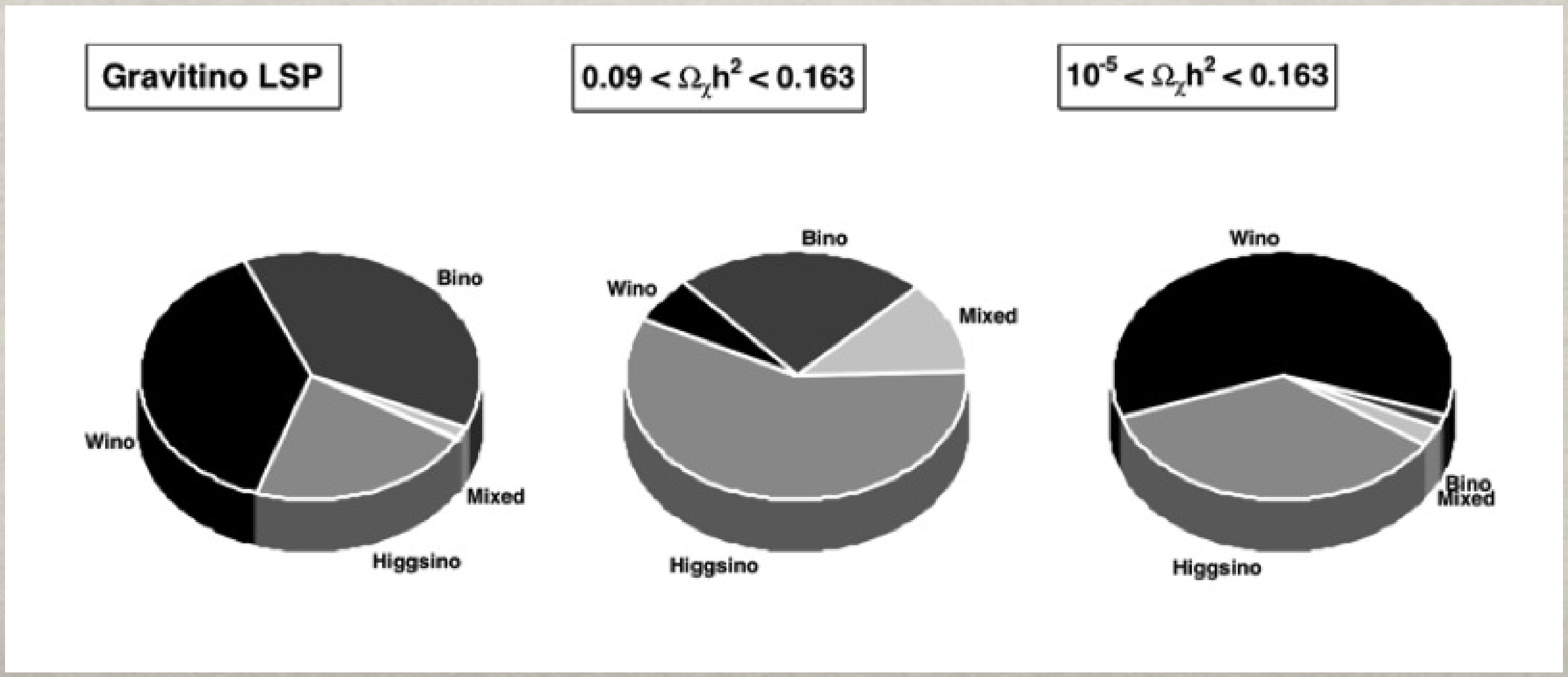
[Nagata, Otono & Shirai 1701.07664]



Gravitino DM in pMSSM

[Arbey et al. 1505.04595]

Take neutralino DM or gravitino DM with neutralino NLSP within the RPC pMSSM with 19+1 parameters, i.e. no unification assumption, flavour & CP conserving SUSY breaking. Impose all constraints from low energy, flavour observables, LHC SUSY searches and monojets, as well as DM density and BBN limits on neutralino NLSP...



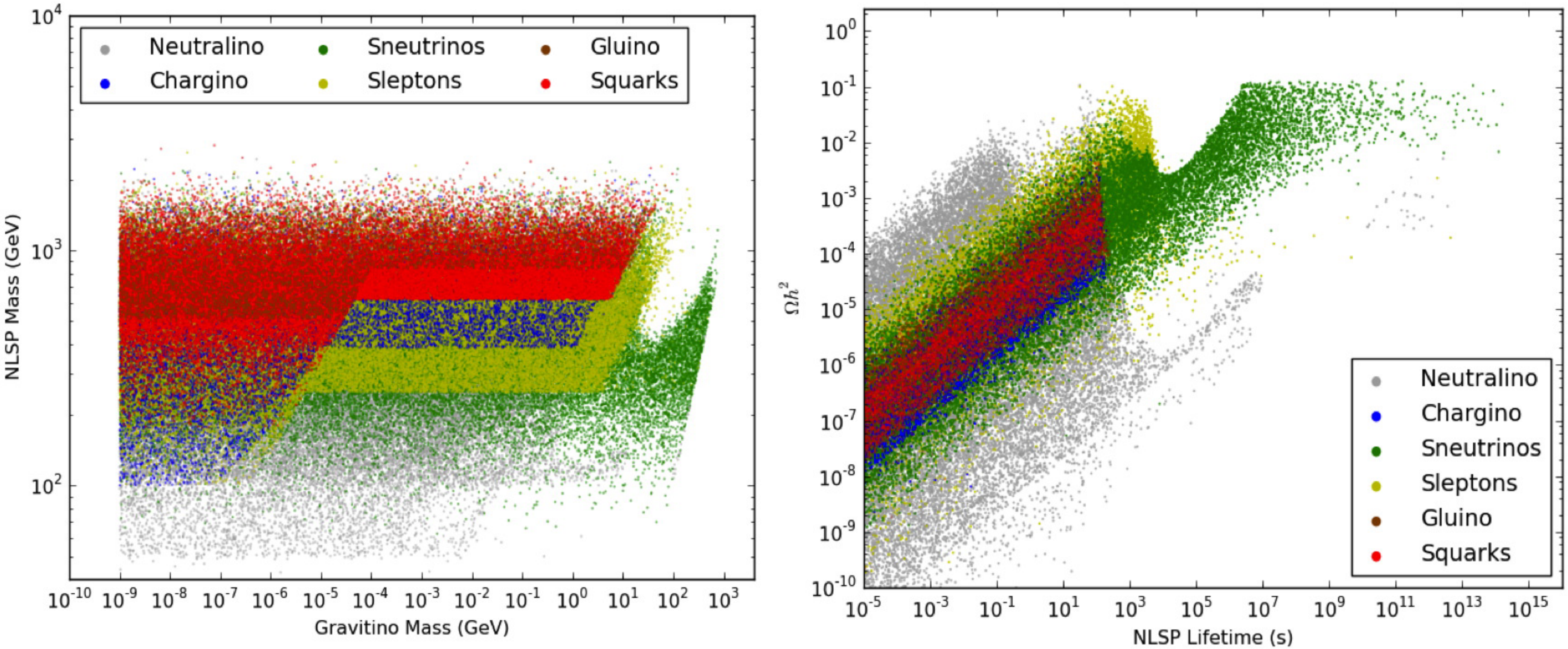
Heavy SUSY ???

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.

BBN bounds on pMSSM

[Cahill-Rawley et al 12]



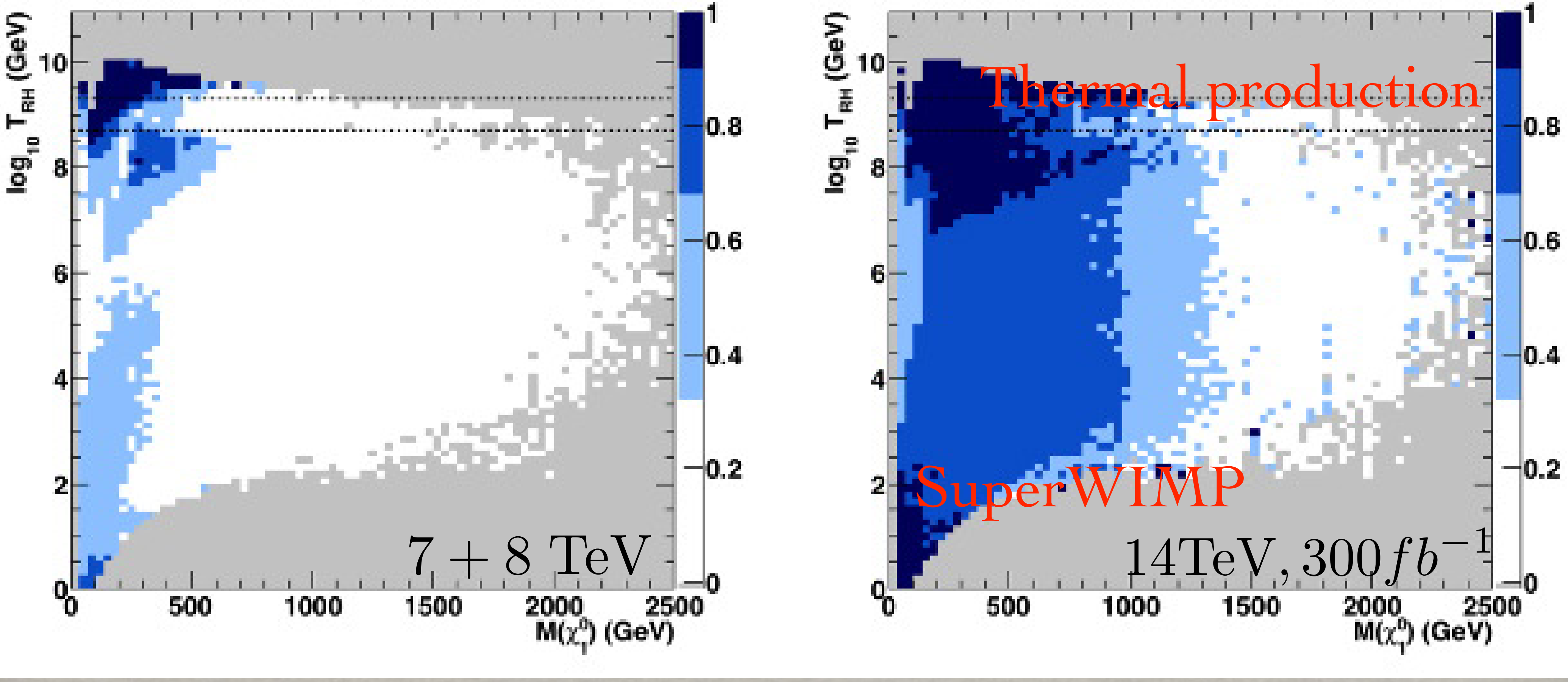
Many points for various NLSPs excluded by BBN: only the sneutrino survives to large gravitino masses.

Heavy NLSP is actually preferred !

Gravitino DM in pMSSM

[Arbey et al. 1505.04595]

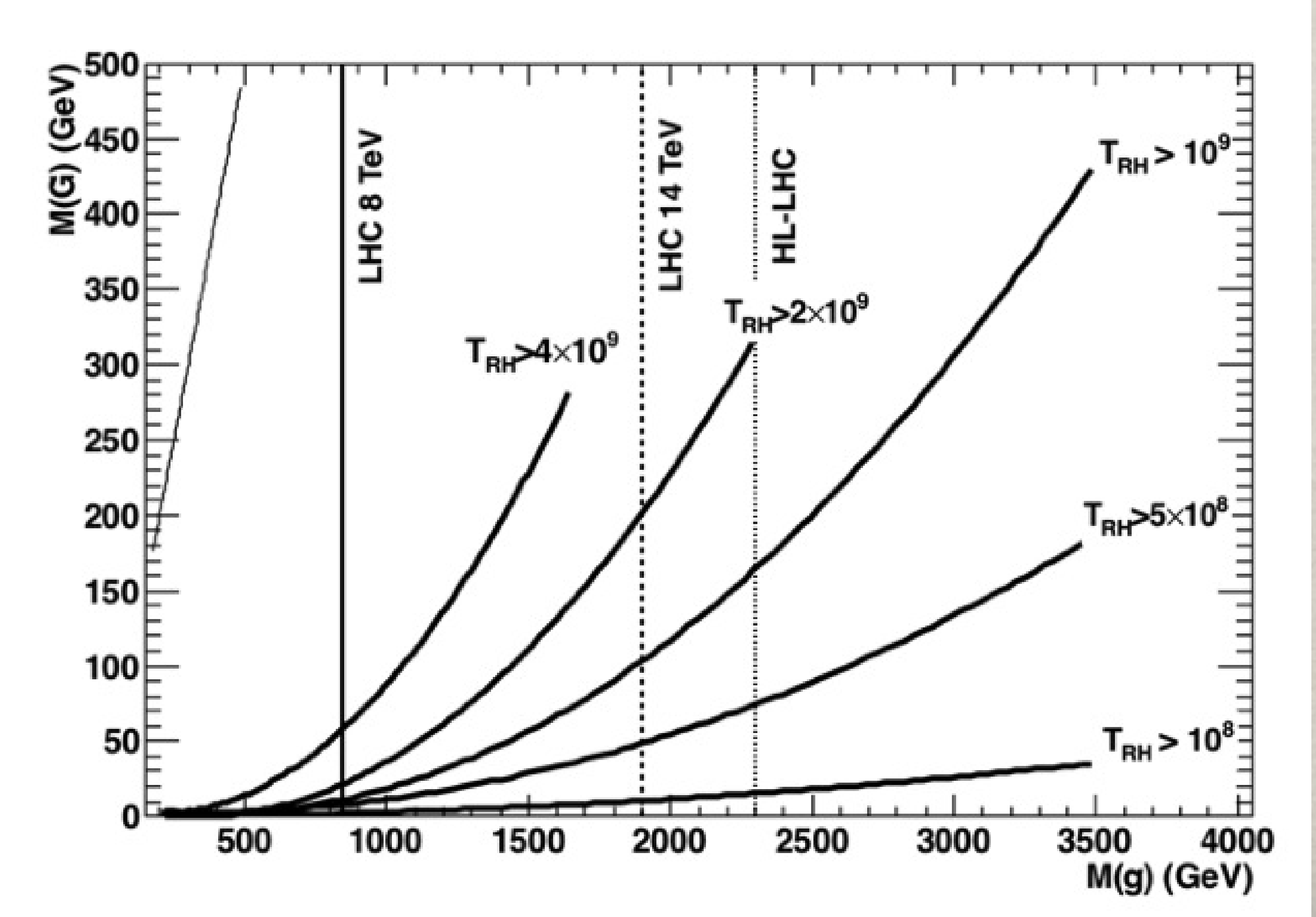
Interplay between gravitino production and gaugino masses very strong: high T_{RH} region corresponds to light gauginos and it is more easily tested as well as SuperWIMP region !



Gravitino DM & gluino

[Arbey et al. 1505.04595]

Gluino mass is an important parameter in gravitino thermal production: the next LHC run will probe the parameter space compatible with classical (no-flavour) thermal leptogenesis.



Minimal gravitino mass such that $\Omega_{\tilde{G}} h^2 < 0.12$ is given by

$$m_{\tilde{G}} \propto m_{\tilde{g}}^2$$

R-parity or not R-parity

[Buchmuller, LC, Hamaguchi, Ibarra & Yanagida 07]

Actually there is a simple way to avoid BBN constraints: break R-parity a little... ! Then the NLSP decays quickly to SM particles before BBN and the cosmology returns standard.

$$W_{R\!\!\!/p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \cancel{\lambda'' U^c D^c D^c}$$

no p decay

Open window:

$$10^{-12-14} < |\frac{\mu_i}{\mu}|, |\lambda|, |\lambda'| < 10^{-6-7}$$

For the NLSP to decay before BBN

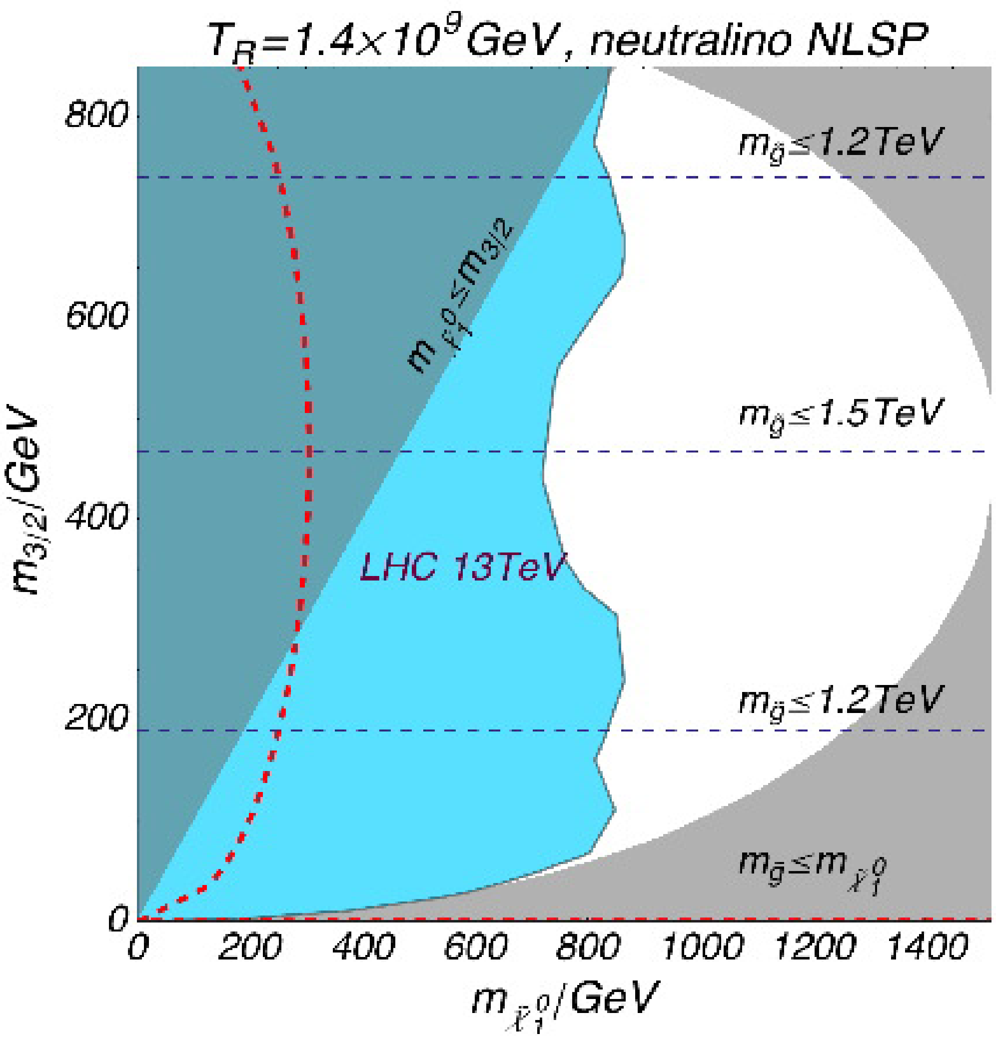
To avoid wash-out of lepton number

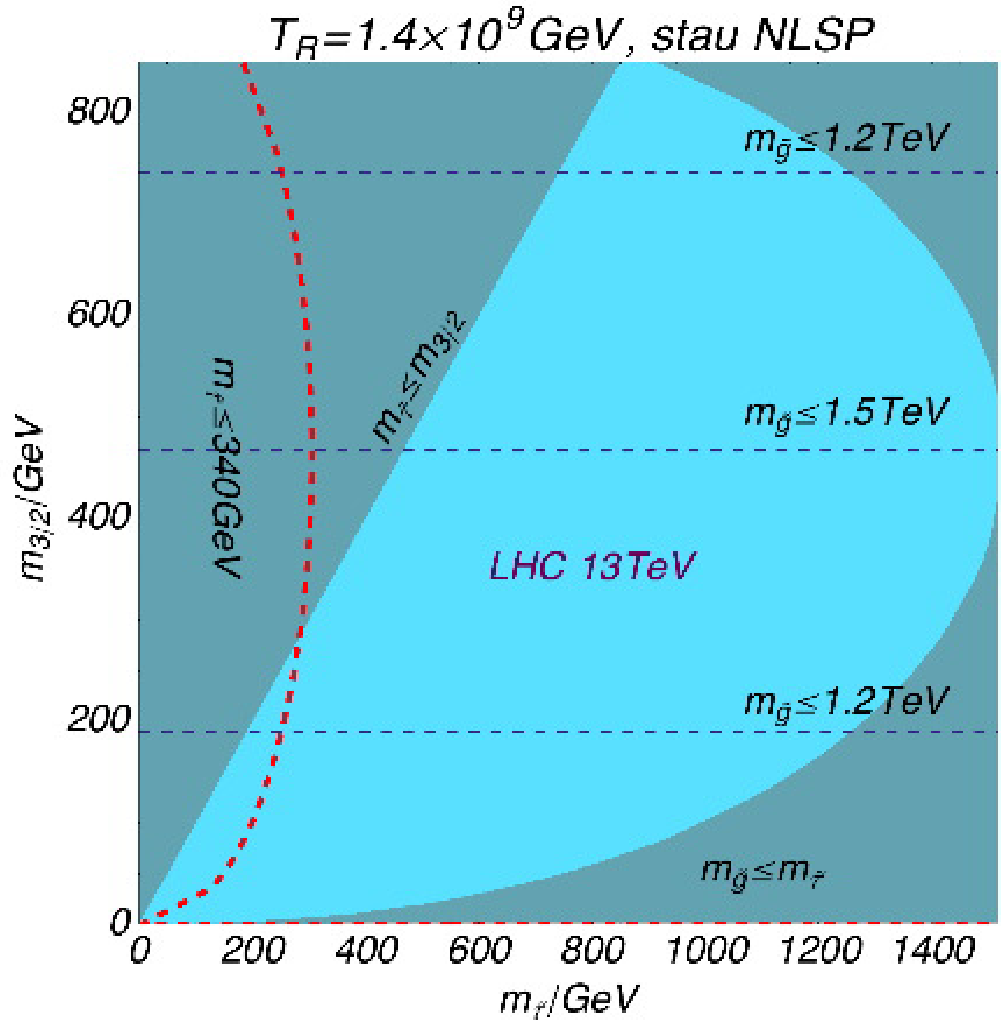
Explicit bilinear R-parity breaking model which ties R-parity breaking to B-L breaking and explains the small coupling.

Gravitino DM & T_RH

The LHC run 2 already constrains the heavy T_RH scenario for gravitino DM with bilinear RPV :

[Ibe, Suzuki & Yanagida 1609.06834]



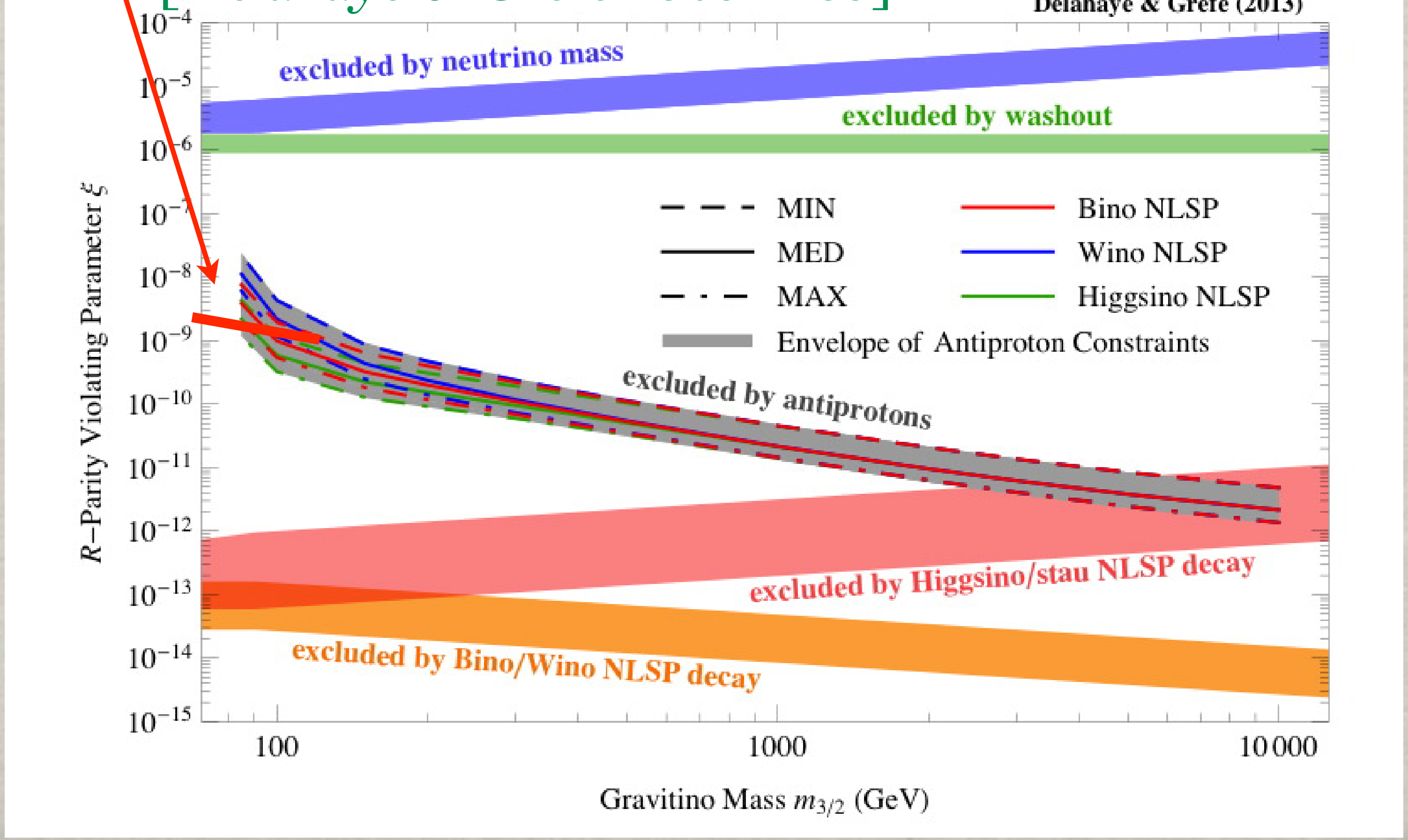


Antiproton constraints

Heavy gravitinos decay into RPV channel in EW gauge boson and lepton, producing gamma-rays and antiprotons. The antiproton constraints already limit strongly the R-parity breaking coupling.

From the FERMI gamma-line search: $\tau < 1 - 4 \times 10^{29} s \quad 95\%$ CL

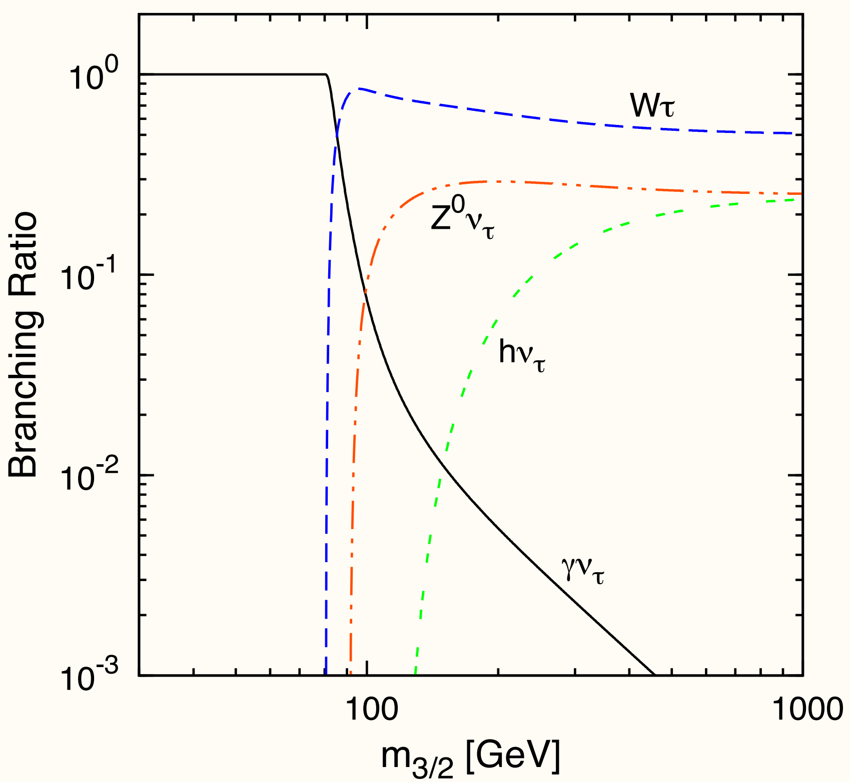
[Delahaye & Grefe 1305.7183]

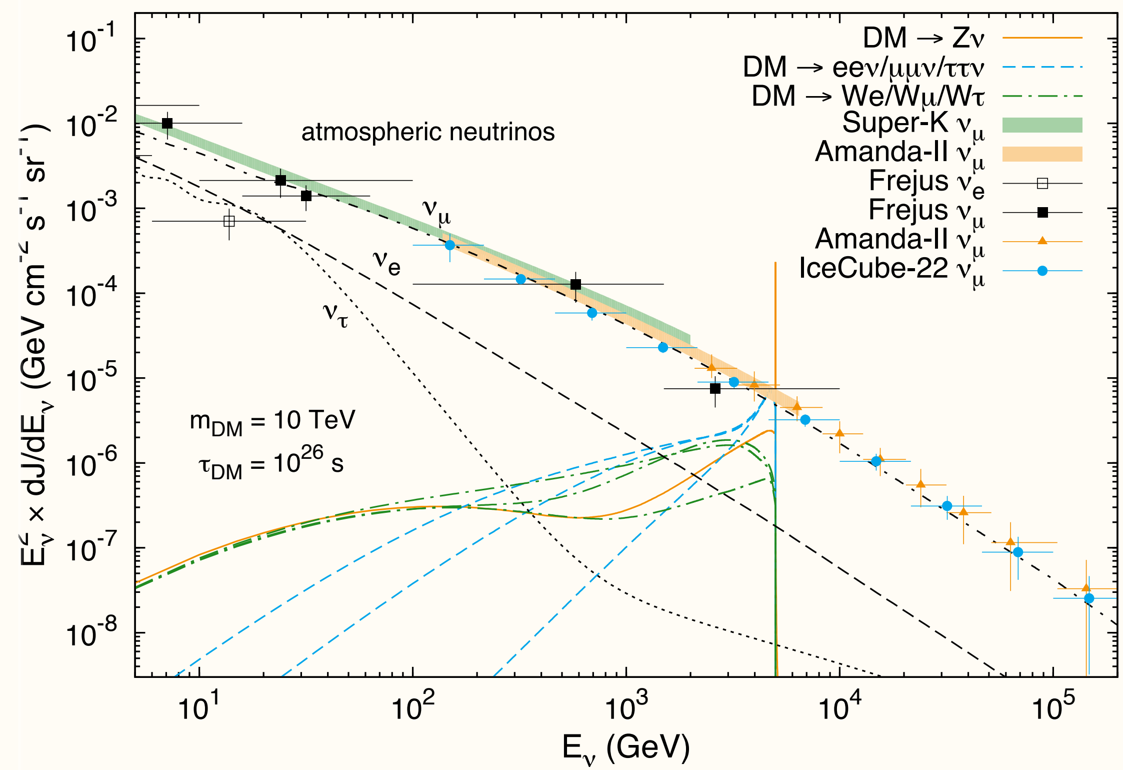


Gravitino DM decay

For bilinear RPV, one can even expect neutrino lines, especially for light gravitino, but also in the heavier case two lines from the decay into Z/h neutrino persists!

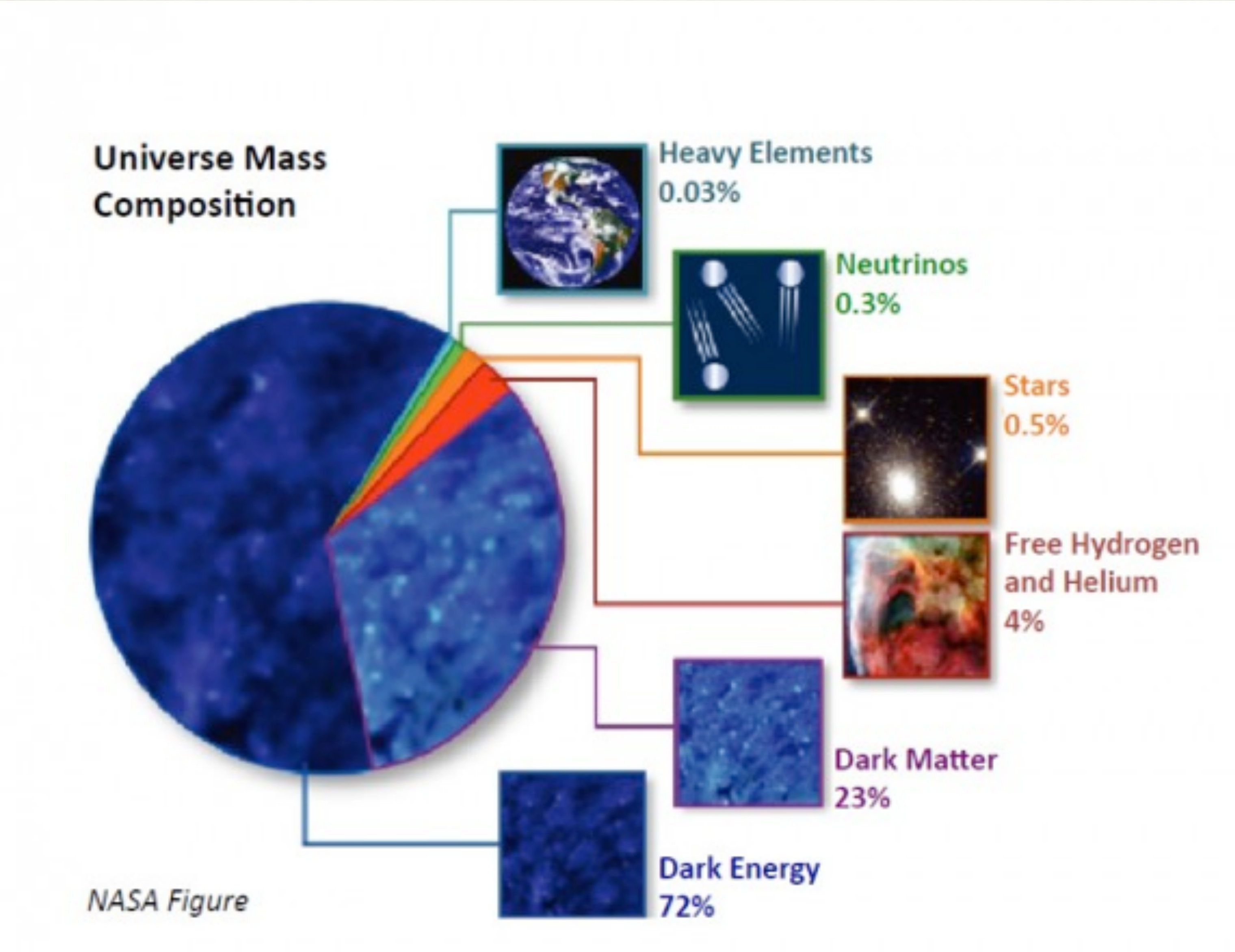
[LC, M. Grefe, A. Ibarra & D. Tran arXiv:0809.5030 & arXiv:0912.3521]





High scale SUSY for baryogenesis

Universe composition



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

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

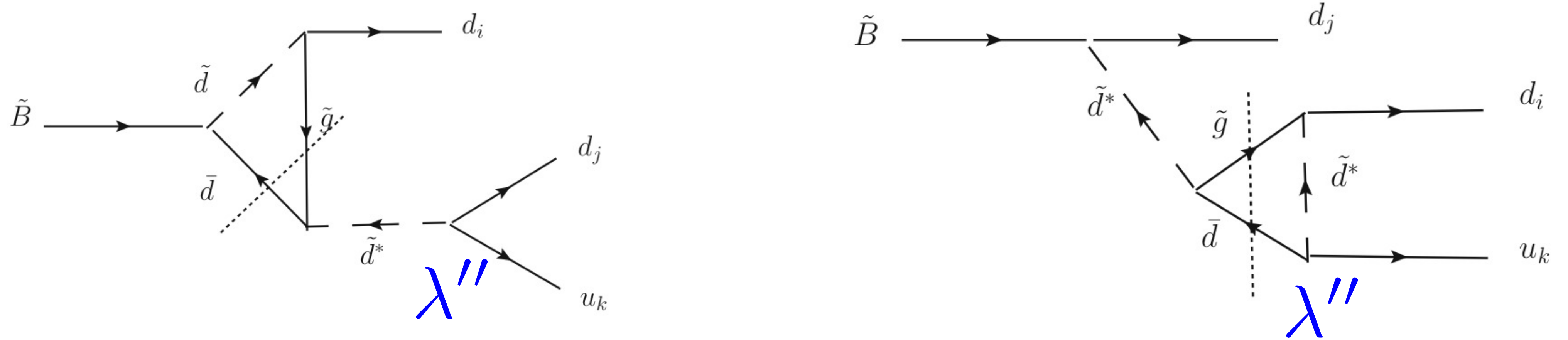
$$\tilde{B} \to udd,\ \bar{u}\bar{d}\bar{d},\ \tilde{g}\bar{q}q$$

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...

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

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

$$\Gamma\left(\tilde{B} \to udd + \overline{u}\overline{d}\overline{d}\right) = \frac{\lambda^2 g_1^2 N_{\rm RPV}}{768\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$
$$\Gamma\left(\tilde{B} \to \tilde{g} f \overline{f}\right) = \frac{(g_1 g_3 Q_f)^2 N_{\rm RPC}}{256\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$

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

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

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

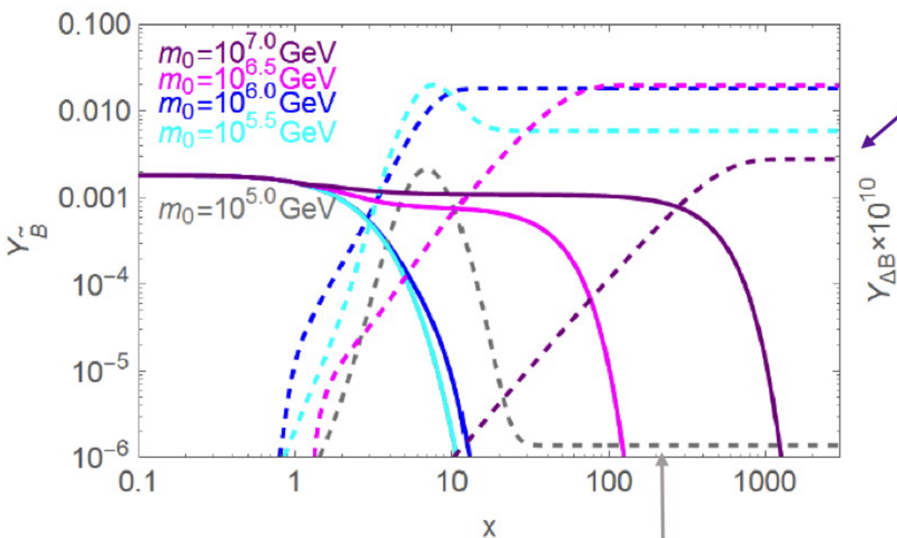
Need a very heavy spectrum to realize the scenario !

Baryogenesis in RPV SUSY

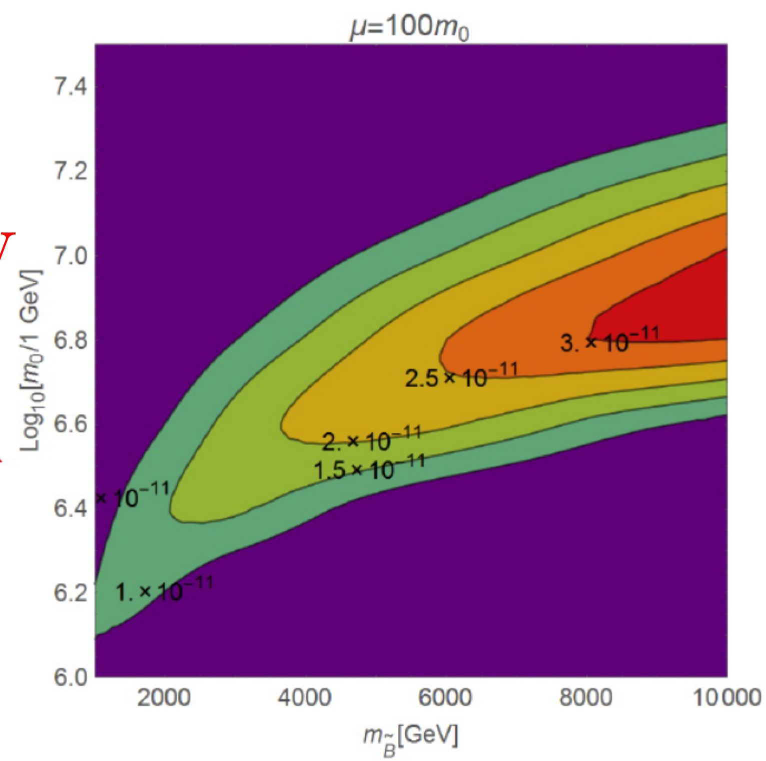
[Arcadi, LC & Nardecchia 1507.05584]

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

Asymmetry suppressed by the high scalars



10^7GeV



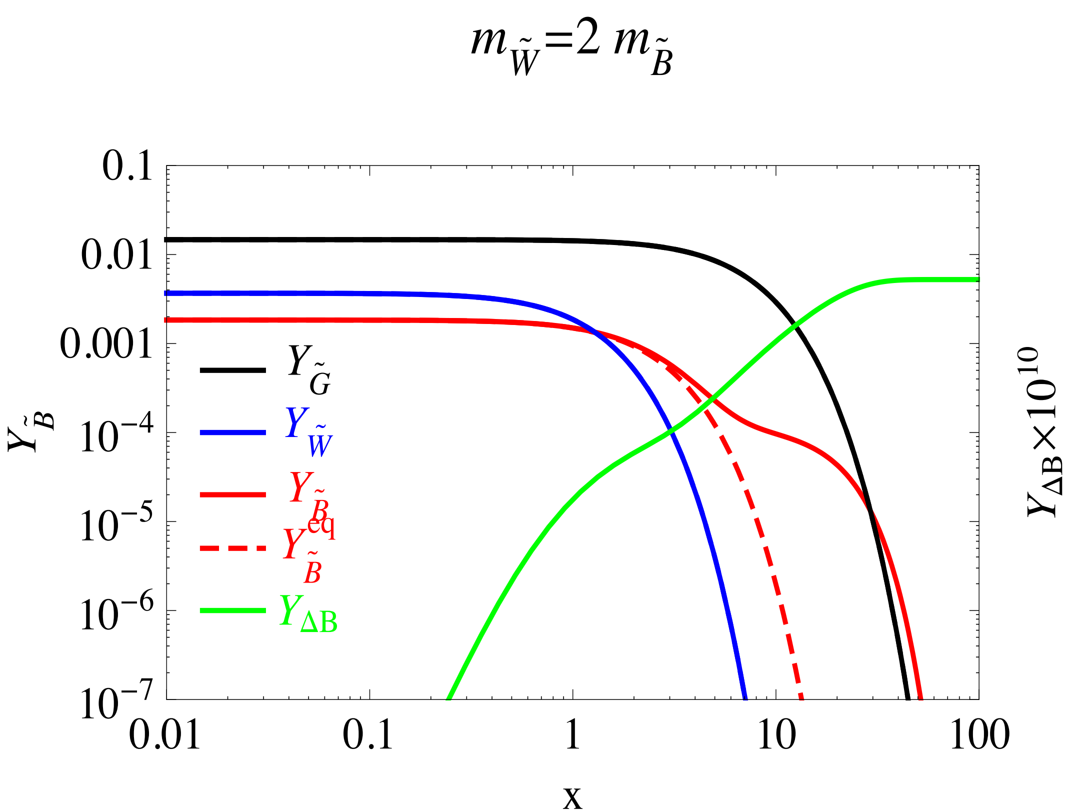
Asymmetry suppressed by wash-out

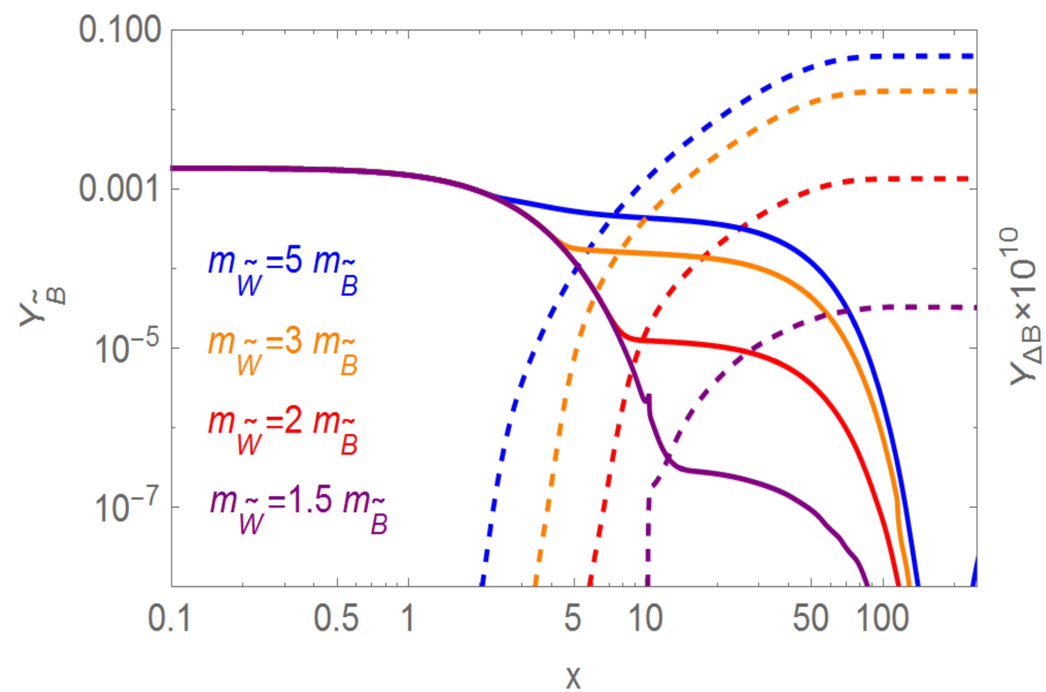
Rather definite prediction for range of scalar masses Heavy !!!

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...

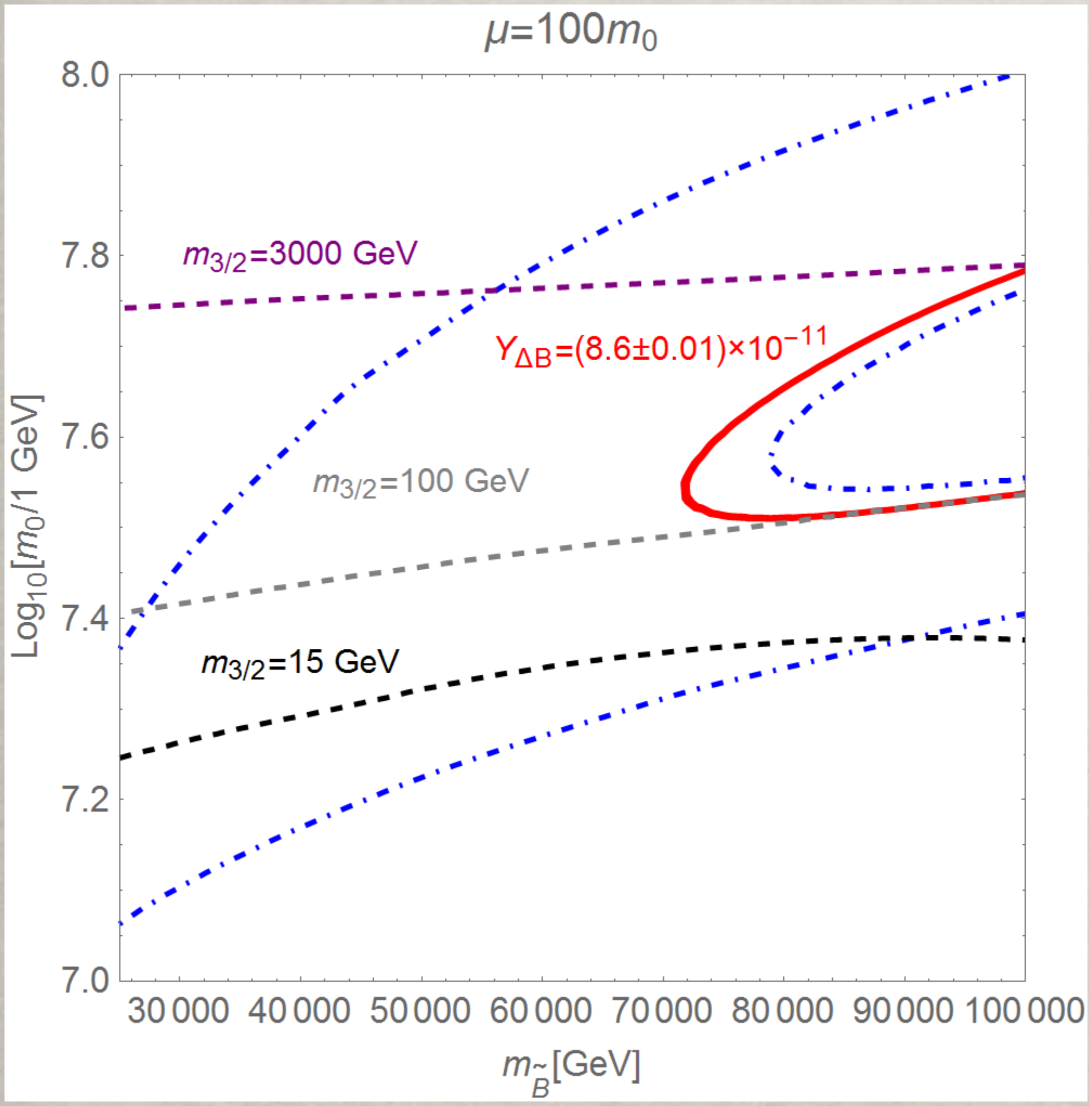
$$\Omega^{FI}_{3/2} h^2 \sim 0.002 \left(\frac{m_{\tilde{W}}}{10 \text{ TeV}} \right)^3 \left(\frac{m_{3/2}}{1 \text{ TeV}} \right)^{-1}$$

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

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 & obtain $\Omega_{DM} \sim 5\, \Omega_B$, not so simple explanation after all..., but still possible with $m_{3/2} < m_{\tilde{g}}$.

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:

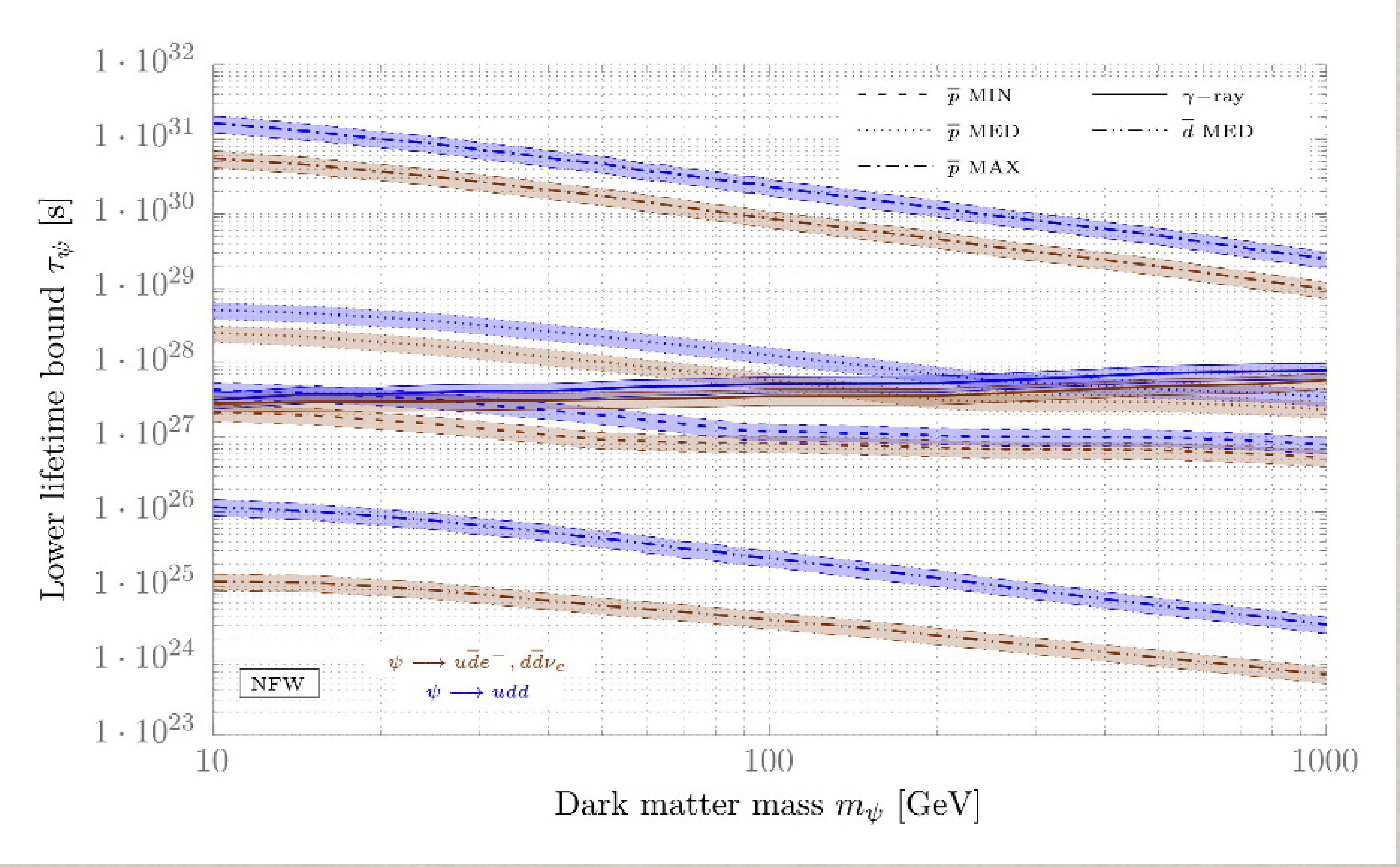
$$\Gamma(\psi_{3/2} \to u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

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

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

ID of FIMP/SWIMP DM

[LC, Eckner & Gustafsson, work in progress]



Dominant decay into antiprotons, possibly observable !!!

Gluino NLSP in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

The gluino is in this scenario the lightest SUSY particle that may be produced at colliders; but it should 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.

Outlook

Outlook

- We are exploring the Dark Matter parameter space, particularly for DM candidates with a working production mechanism, like WIMP/FIMP/SuperWIMPs.
- The FIMP/SuperWIMP framework is quite general and could point to decaying Dark Matter and possibly quite heavy metastable particles or displaced vertices at LHC (independently of SUSY).
- Supersymmetric models are still alive and actually heavi(er) than expected SUSY may give some advantages in cosmology, e.g. flavour problem or baryogenesis via RPV. For some of these models DM is heavy and could decay and be observed soon !