

Brussels, 13-14 November 2018



2nd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes

HEAVY SUPERSYMMETRY IN THE SKY

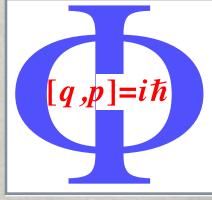


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elusi Des-in Disibles Plus neutrinos, dark matter & dark energy physics





OUTLINE

Introduction: -Theoretical guiding principles - Cosmology as a probe of particle physics Heavy Dark Matter in SUSY Generation High scale SUSY for DM and baryogenesis ⁹ 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

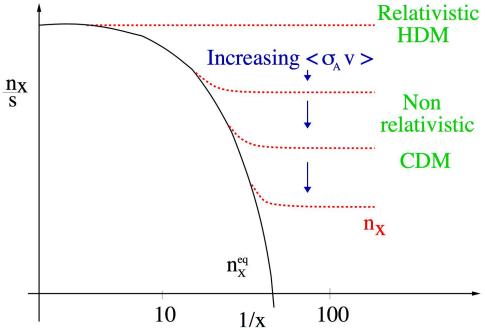
$$rac{dn_X}{dt} + 3Hn_X = \langle \sigma(X + X
ightarrow ext{anything}) v
angle \left(n_{eq}^2 - n_X^2
ight)$$

Hubble expansion Collision integral

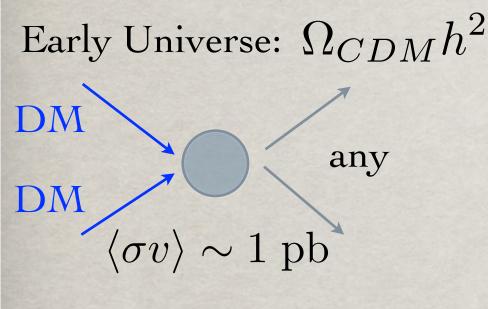
The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

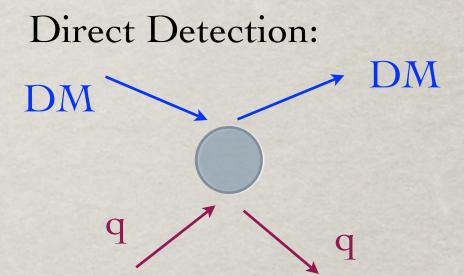
defined by $n_{eq} \langle \sigma_A v \rangle_{x_f} = H(x_f)$ and that gives $\Omega_X = m_X n_X(t_{now}) \propto \frac{1}{\langle \sigma_A v \rangle_{x_f}}$ Abundance \Leftrightarrow Particle properties

For $m_X \simeq 100$ GeV a WEAK cross-section is needed ! Weakly Interacting Massive Particle For weaker interactions need lighter masses HOT DM !

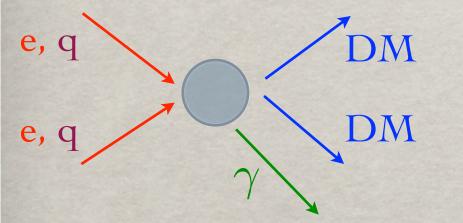


THE WIMP CONNECTION





Colliders: LHC/ILC



Indirect Detection:

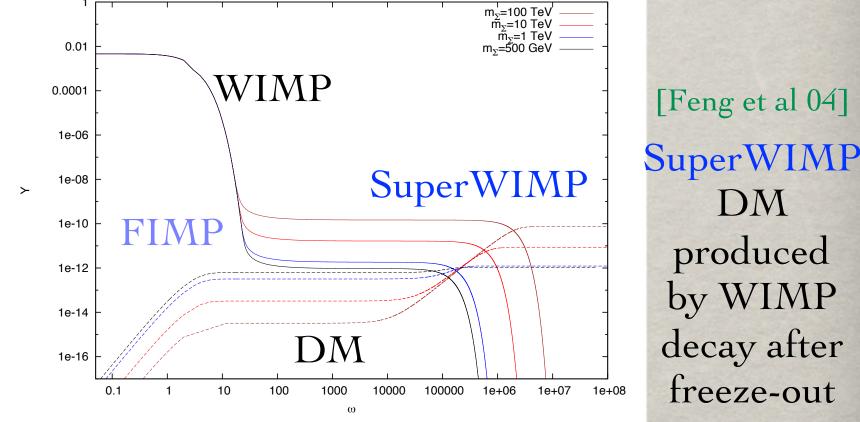
e, q,W,Z, γ e, q,W,Z, γ

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



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

FIMP/SWIMP

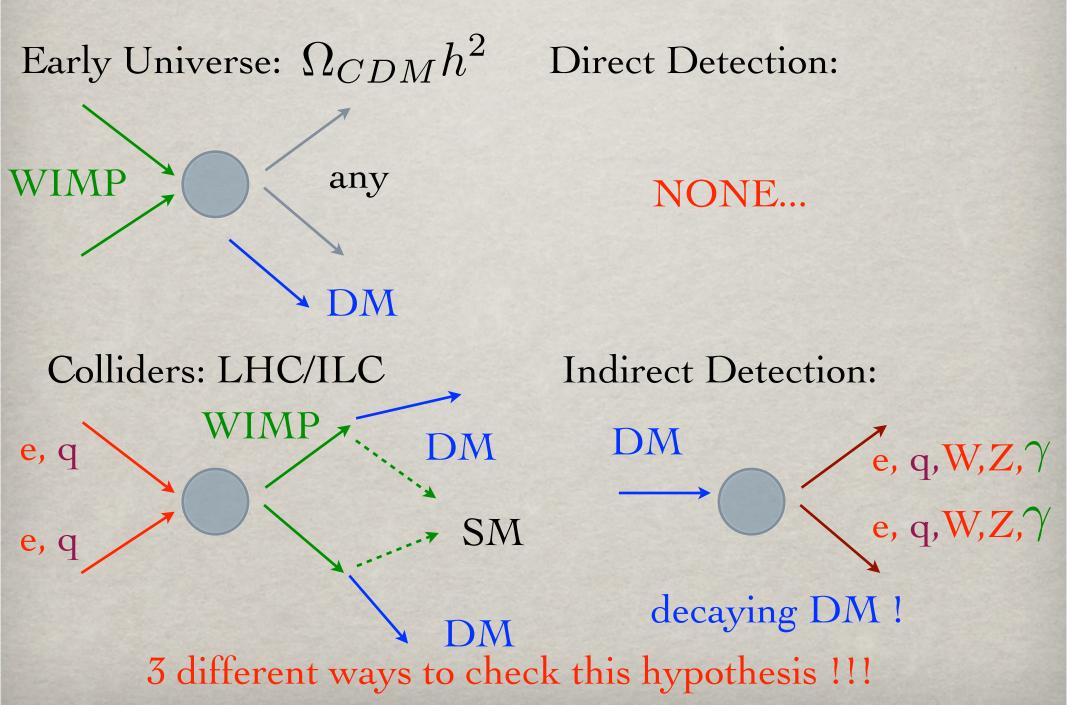
- The FIMP/SuperWIMP type of Dark Matter production is effective for any mass of the mother and daughter particle !
- Indeed if the mass ratio is large the WIMP-like density of the mother particle gets diluted:

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

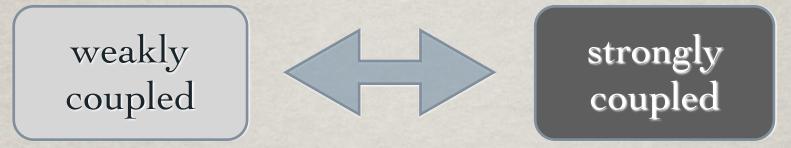
• Moreover also the FIMP production is dependent on the decay rate of the mother particle not just the mass and can work also for larger masses...

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

F/SWIMP CONNECTION



WHICH MODEL BEYOND THE SM ?



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

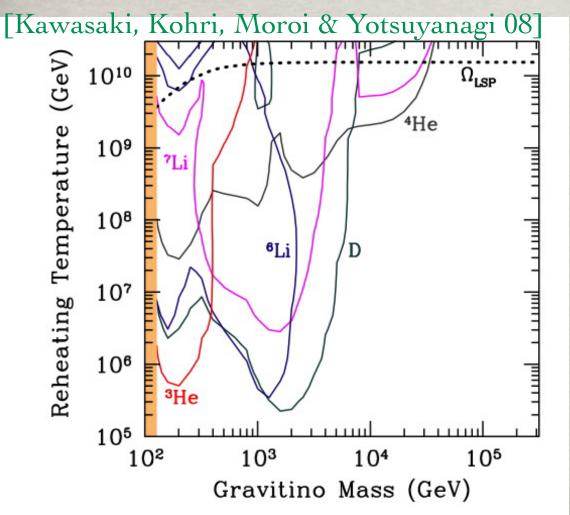
 $\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{m_{3/2}}{0.1 \text{keV}}\right) \left(\frac{g_*}{106.75}\right)^{-1} \frac{\text{Warm DM !}}{\text{[Pagels & Primack 82]}}$ If the gravitinos are NOT in thermal equilibrium instead

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

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

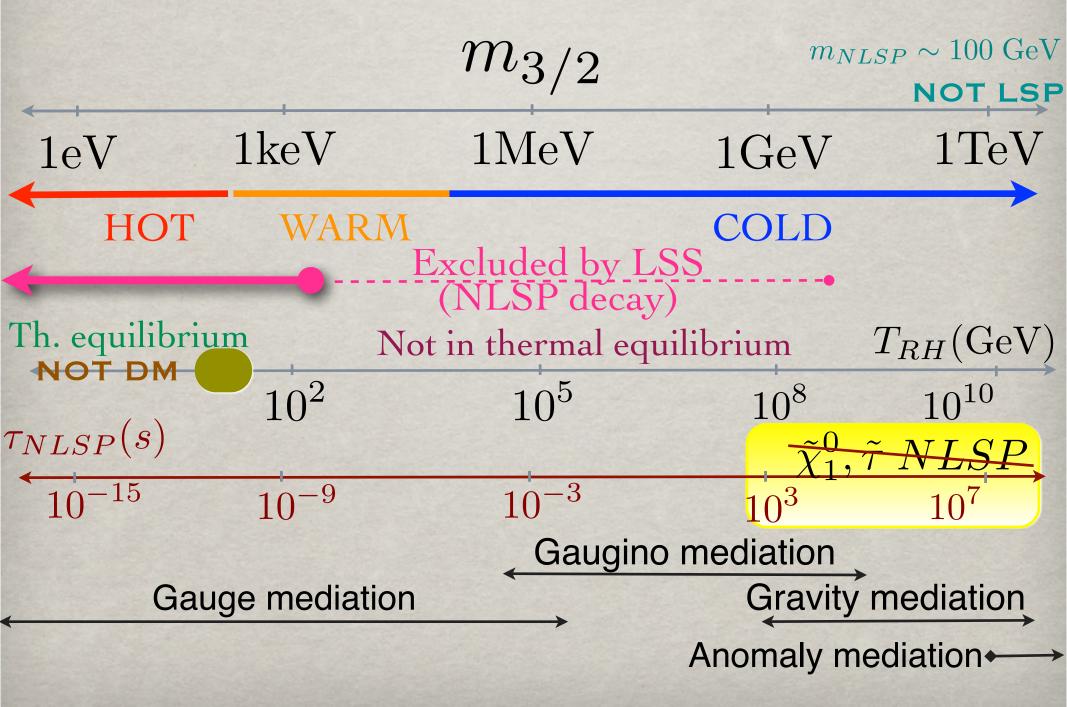
THE GRAVITINO PROBLEM

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.



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

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary $\sqrt{s} = 7.8.13$ TeV

July 2018

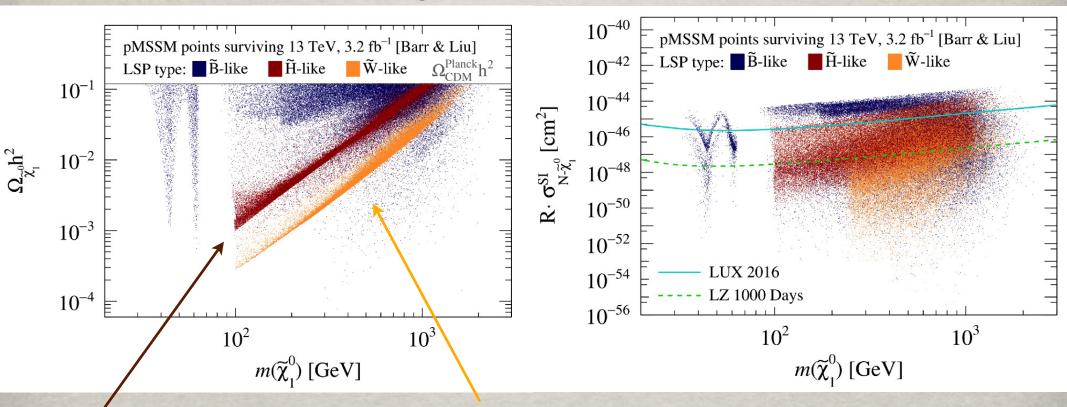
-	Model	e,μ,τ,γ Jets I	Emiss ∫£ dr[fb	-') Mass limit	√x = 7, 8 TeV √x = 13 TeV	Vs = 7, 8, 13 lev Reference	
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{t}_{1}^{0}$	0 2-6 jets mono-jet 1-3 jets	Yes 36.1 Yes 36.1		155 m(i)<100 GeV m(i)-m(i)-5 GeV	1712.02332 1711.03301	
	$gg, g \rightarrow q\bar{q}\bar{\ell}_1^0$	0 2-6 jets	Yes 36.1	a Portuiden	2.0 m(i ⁴)<200 GeV 0.95-1.6 m(i ⁴)-200 GeV	1712.02332 1712.02332	
	$\hat{g}\hat{g}, \hat{g} \rightarrow g\hat{g}(\ell\ell)\hat{t}_{1}^{0}$	3 e.μ 4 jets ee.μμ 2 jets	· 36.1 Yes 36.1	24 24	1.85 m(i ¹)<800 GeV 1.2 m(j)-m(i))-50 GeV	1706.03731 1805.11381	
	$\hat{g}\hat{g}, \hat{g} \rightarrow ggWZ\hat{x}_{1}^{0}$	0 7-11 jets 3 κ.μ 4 jets	Yes 36.1 - 36.1	2 2 0.98	1.0 m(i ²) <400 GeV m(j)-m(i ²) -200 GeV	1708.02794 1706.03731	
	$\underline{s}\underline{s}, \underline{s} \rightarrow d\overline{t}_1^0$	0-1 e.μ 3 b 3 e.μ 4 jets	Yes 36.1 - 36.1	2 2	2.0 m(i ² ₁)<200 GeV 1.25 m(j)-m(i ² ₁)=300 GeV	1711,01901 1706,03731	
3 rd gen. squarks direct production	$\delta_1 \delta_1, \delta_1 {\rightarrow} b \tilde{\kappa}_1^0 / t \tilde{\kappa}_1^+$	Multiple Multiple Multiple	36.1 36.1 36.1	Jr. Forbidden 0.9 Jr. Forbidden 0.50-0.82 Jr. Forbidden 0.7	$\begin{array}{c} m(\tilde{t}_1^2)\!=\!300 \; \text{GeV}, \\ BR(\mu\tilde{t}_2^2)\!=\!300 \; \text{GeV}, \\ BR(\mu\tilde{t}_2^2)\!=\!300 \; \text{GeV}, \\ BR(\mu\tilde{t}_2^2)\!=\!300 \; \text{GeV}, \\ m(\tilde{t}_1^2)\!=\!200 \; \text{GeV}, \\ m(\tilde{t}_1^2)\!=\!300 \; \text{GeV}, \\ BR(\mu\tilde{t}_2^2)\!=\!1 \end{array}$	1708.09286, 1711.03301 1708.09266 1706.03731	
	$\tilde{b}_1\tilde{b}_1,\tilde{r}_1\tilde{r}_1,M_2=2\times M_1$	Multiple Multiple	36.1 36.1	7, 0.7 7, Forbidden 0.9	m(x ²)=60 GeV m(x ²)=200 GeV	1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247	
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{t}_1^0 \text{ or } t \tilde{t}_1^0$ $\tilde{t}_1 \tilde{t}_1, \tilde{H} LSP$	0-2 e, µ 0-2 jets/1-2 b Multiple Multiple	Yes 36.1 36.1 36.1	Til 1.0 Til 0.4-0.9 Til 0.6-0.8	$m(\tilde{t}_{1}^{2})=150 \text{ GeV}, m(\tilde{t}_{1}^{2})-m(\tilde{t}_{2}^{2})=5 \text{ GeV}, \tilde{r}_{1} \simeq \tilde{r}_{2}, m(\tilde{t}_{1}^{2})=50 \text{ GeV}, \tilde{r}_{1} \simeq \tilde{r}_{2}, m(\tilde{t}_{1}^{2})=300 \text{ GeV}, m(\tilde{t}_{1}^{2})-m(\tilde{t}_{1}^{2})=5 \text{ GeV}, \tilde{r}_{1} \simeq \tilde{r}_{2}.$	1506.08616, 1709.04180, 1711.11520 1709.04180, 1711.11520 1709.04180, 1711.11520	
	$\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{t}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{t}_1^0$	Multiple 0 2c	36.1 Yes 36.1	ř. 0.48-0.84 ř. 0.85	$m(\tilde{k}_{1}^{0})=150 \text{ GeV}, m(\tilde{k}_{1}^{0})-m(\tilde{k}_{1}^{0})=5 \text{ GeV}, \tilde{r}_{1} \approx \tilde{r}_{2}$ $m(\tilde{k}_{1}^{0})=0 \text{ GeV}$	1709.04183, 1711.11520 1805.01649	
	shiftst-set is easily	o mono-jet	Yes 36.1	i, 0.46 i, 0.43	m(i, i)=m(i',)=50 GeV m(i, i)=m(i',)=5 GeV	1805.01649 1711.03301	
	$\tilde{t}_2\tilde{t}_2,\tilde{t}_2{\rightarrow}\tilde{t}_1+h$	1-2 e. µ 4 b	Yes 36.1	ž ₁ 0.32-0.88	$m(\tilde{x}_1^0)$ =0 GeV, $m(\tilde{r}_1)$ - $m(\tilde{x}_1^0)$ = 180 GeV	1706.03986	
EW direct	$\hat{x}_1^* \hat{x}_2^0$ via WZ	$2-3 e, \mu$ - $ee, \mu\mu \ge 1$	Yes 36.1 Yes 36.1	$\hat{s}_{\pm}^{+} \hat{s}_{\pm}^{+} = 0.6$ $\hat{s}_{\pm}^{+} \hat{s}_{\pm}^{+} = 0.17$	m($\tilde{t}_1^0)=0$ m($\tilde{t}_1^0)$ -m($\tilde{t}_1^0)=10$ GeV	1403.5294, 1006.02290 1712.00119	
	$\begin{array}{l} \hat{x}_1^{\pm} \hat{x}_2^{0} \; \text{via Wh} \\ \hat{x}_1^{\pm} \hat{x}_1^{\pm} \hat{x}_2^{0} \hat{x}_2^{0} \hat{x}_1^{\pm} {\rightarrow} \hat{\tau} \tau(\tau \hat{v}), \hat{x}_2^{0} {\rightarrow} \hat{\tau} \tau(\tau \hat{v}) \end{array}$	<i>llllyyllbb</i> - 2τ -	Yes 20.3 Yes 36.1	$\frac{\hat{x}_{\pm}^{*}\hat{x}_{\pm}^{*}}{\hat{x}_{\pm}^{*}\hat{x}_{\pm}^{*}}$ 0.26 $\frac{\hat{x}_{\pm}^{*}\hat{x}_{\pm}^{*}}{\hat{x}_{\pm}^{*}\hat{x}_{\pm}^{*}}$ 0.22	$m(\tilde{t}_{1}^{2})=0$ $m(\tilde{t}_{1}^{2})=0, m(\tilde{t}, \tilde{t})=0.5(m(\tilde{t}_{1}^{2})+m(\tilde{t}_{1}^{2}))$ $m(\tilde{t}_{1}^{2})=m(\tilde{t}_{1}^{2})=100 \text{ GeV}, m(\tilde{t}, \tilde{t})=0.5(m(\tilde{t}_{1}^{2})+m(\tilde{t}_{1}^{2}))$	1501.07110 1708.07875 1708.07875	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}{\rightarrow}\ell\tilde{\chi}_1^0$	2 e.μ 0 2 e.μ ≥ 1	Yes 36.1 Yes 36.1	2 0.10 0.5	m(i ²)=0 m(i)-m(i ²)=5 GeV	1803.02762 1712.08119	
	$\hat{R}\hat{R}, \hat{R} \rightarrow h\hat{G}/2\hat{G}$	$\begin{array}{ccc} 0 & \geq 3b \\ 4 e, \mu & 0 \end{array}$	Yes 36.1 Yes 36.1	R 0.13-0.23 0.29-0.88 R 0.3	$\begin{array}{c} \mathrm{BR}(\tilde{x}_{1}^{0} \rightarrow h\tilde{G}) {=} 1 \\ \mathrm{BR}(\tilde{x}_{1}^{0} \rightarrow 2\tilde{G}) {=} 1 \end{array}$	1606.04030 1804.03602	
Long-lived particles	$\operatorname{Direct} \widehat{x}_1^+ \widehat{x}_1^- \operatorname{prod.}$, $\operatorname{long-lived} \widehat{x}_1^+$	Disapp. trk. 1 jet	Yes 36.1	λ ⁺ λ ⁺ ₁ 0.15	Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019	
	Stable g R-hadron	SMP -	- 3.2	2	1.6	1606.05129	
	Metastable \hat{g} R-hadron, $\hat{g} \rightarrow qg \tilde{\ell}_1^0$ GMSB, $\hat{\ell}_1^0 \rightarrow \gamma \hat{G}$, long-lived \hat{k}_1^0	Multiple 2 y -	32.8 Yes 20.3	[g [π[g) =100 ms, 0.2 ms] χ ⁴ 0.44	1.6 2.4 m(ℓ ₁ ⁰)=100 GeV 1 ⊲r(ℓ ₁ ⁰)=3 ns, SPS8 model	1710.04901, 1604.04520 1409.5542	
	$\hat{\chi}_{\hat{X}}^{\hat{\alpha}}, \hat{\chi}_{1}^{\hat{\alpha}} \rightarrow eev/eµv/µµv$	displ. ee/ep/pp	· 20.3	2	1.3 6 <(r(β ² ₁)< 1000 mm, m(β ² ₁)=1 TeV	1504.05162	
	LFV $pp \rightarrow \hat{v}_r + X, \hat{v}_r \rightarrow e\mu/e\tau/\mu\tau$	ер,ет,ит -	· 3.2	8,	1.9 × 40.11, Acouncu=0.07	1607.08079	
RPV	$\hat{\chi}_{1}^{\pm}\hat{\chi}_{1}^{\pm}/\hat{\chi}_{2}^{0} \rightarrow WW)Z\ell\ell\ell\ell\nu_{YY}$	4 e. µ 0	Yes 36.1	$[\hat{X}_{1}^{*}]\hat{X}_{2}^{*} = [\lambda_{10} \neq 0, \lambda_{13} \neq 0]$ 0.82	1.33 m(t ²)=100 GeV	1804.03602	
	$\hat{g}\hat{g}, \hat{g} \rightarrow qq\hat{\xi}_{1}^{0}, \hat{\chi}_{1}^{0} \rightarrow qqq$	 4-5 large-<i>R</i> jets Multiple 	s - 36.1 36.1		1.3 1.9 Large <i>t</i> [*] ₁₁ 2.0 m(t [*] ₁)=200 GeV, bino-like	1804.03568 ATLAS-CONF-2018-003	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow tbs / \tilde{g} \rightarrow tb\tilde{t}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$	Multiple	36.1	2 (C_=1, 1e 2)	1.0 2.1 m(t_)=200 GeV, bino-like	ATLAS-CONF-2018-003	
	$gg, g \rightarrow ms r g \rightarrow mt_1, x_1 \rightarrow ms$ $\vec{n}, \vec{i} \rightarrow d\vec{k}_1^0, \vec{k}_1^0 \rightarrow ms$	Multiple	36.1	2 [4] -20-4, 10-2] 0.55 1.01		ATLAS-CONF-2016-003	
	$\vec{x}_1 \vec{r}_1, \vec{x}_1 \rightarrow bs$	0 2 jets + 2 b	- 36.7	T ₁ [eq. bi] 0.42 0.61	uniciliates and management	1710.07171	
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \ell$	2 e. µ 2 b	- 36.1	ř,	0.4-1.45 BR(J,-+br//bp()=20%	1710.05544	
	"Only a selection of the available mass limits on new states or 10 ⁻¹ 1 Mass scale [TeV]						

"Only a selection of the available mass limits on new states phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

SUSY MODELS STILL ALIVE

[Barr & Liu 2016]

pMSSM points surviving after LHC-13 data

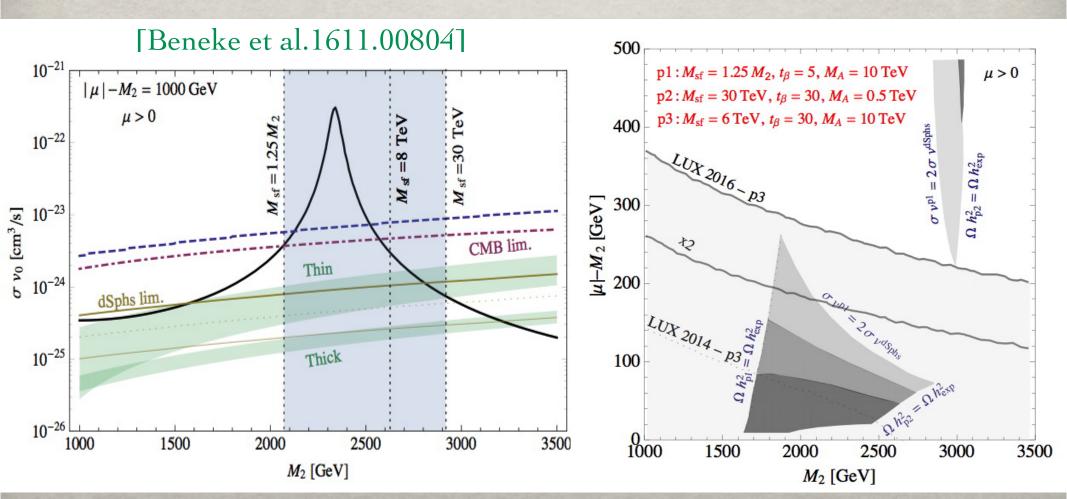


Higgsino band Wino band

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

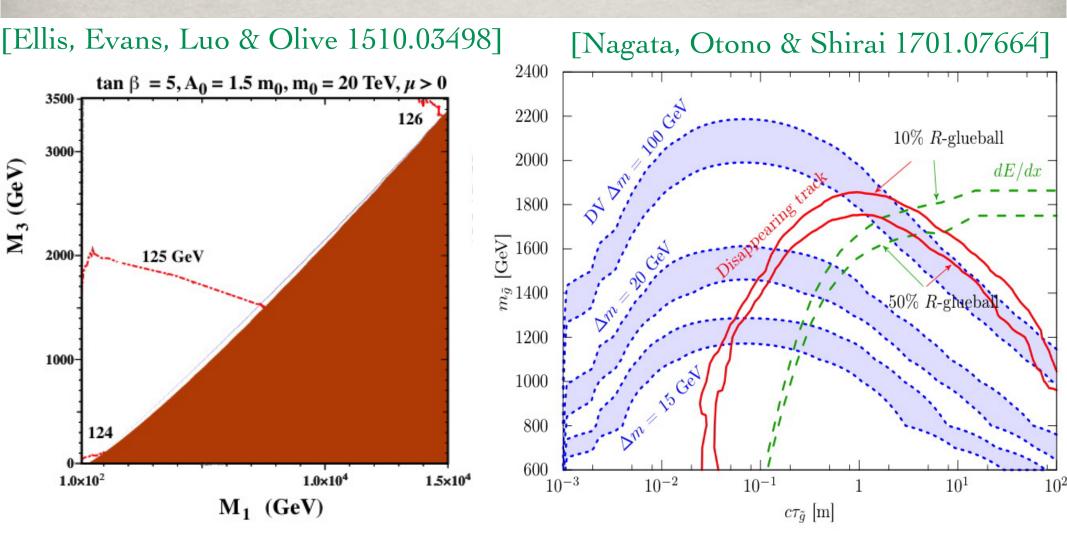
WINO DARK MATTER

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...



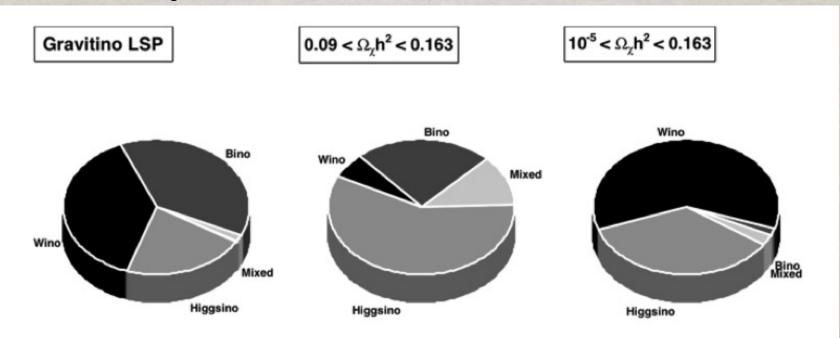
BINO-GLUINO COANNIHILATION

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



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...

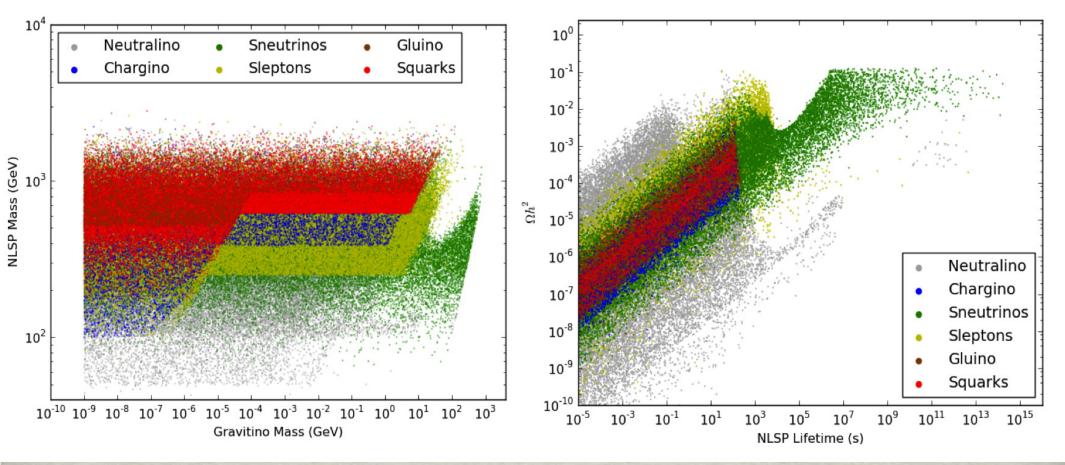
Indeed there are instead some counterargument in favour of heavy SUSY from successful cosmology and not only:

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]

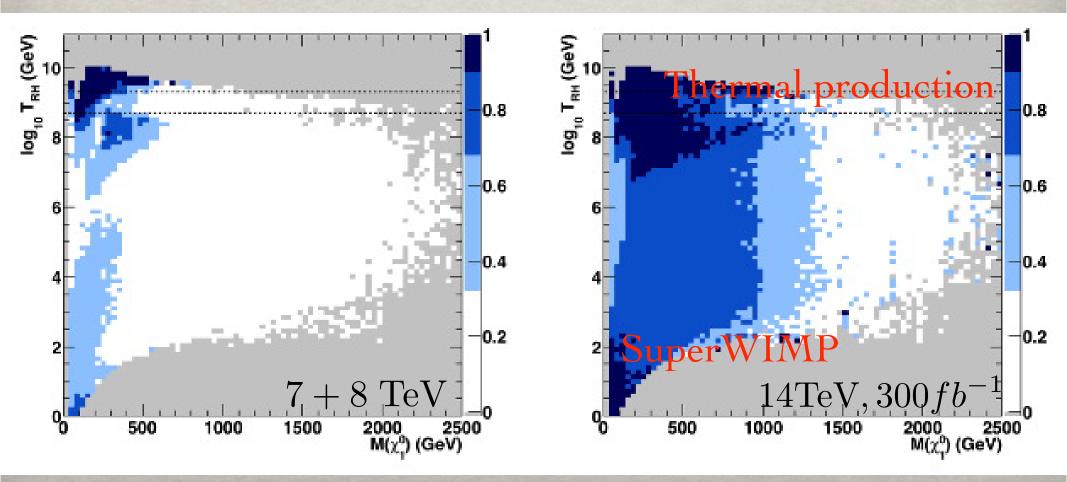


Many points for various NLSPs excluded by BBN: only the sneutrino survives to large gravitino masses. Heavy NLSP is actually preferred !

GRAVITINO DM IN PMSSM

[Arbey et al. 1505.04595]

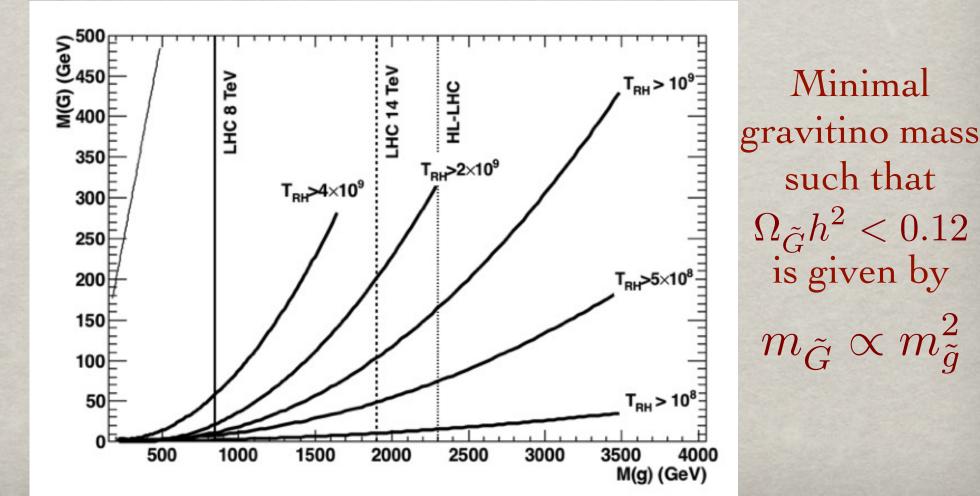
Interplay between gravitino production and gaugino masses very strong: high T_{RH} region corresponds to light gauginos and it is more easily tested as well as SuperWIMP region !



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.



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.

$$W_{R/p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c$$
no p decay

Open window:

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

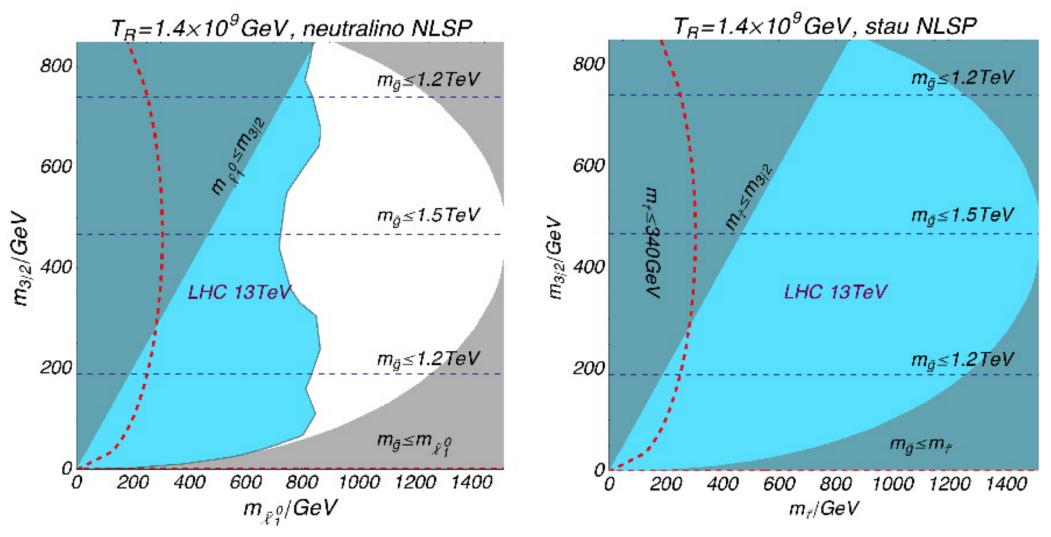
For the NLSP to
decay before BBN To avoid wash-out
of lepton number

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

GRAVITINO DM & T_RH

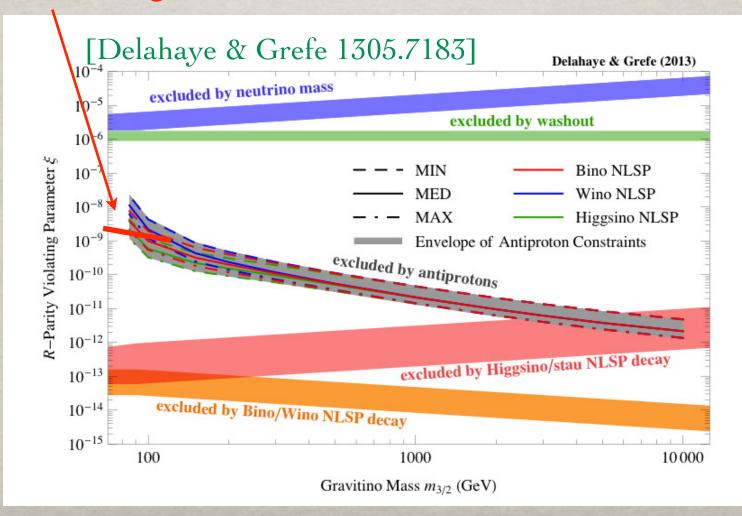
The LHC run 2 already constrains the heavy T_RH scenario for gravitino DM with bilinear RPV :

[Ibe, Suzuki & Yanagida 1609.06834]



ANTIPROTON CONSTRAINTS

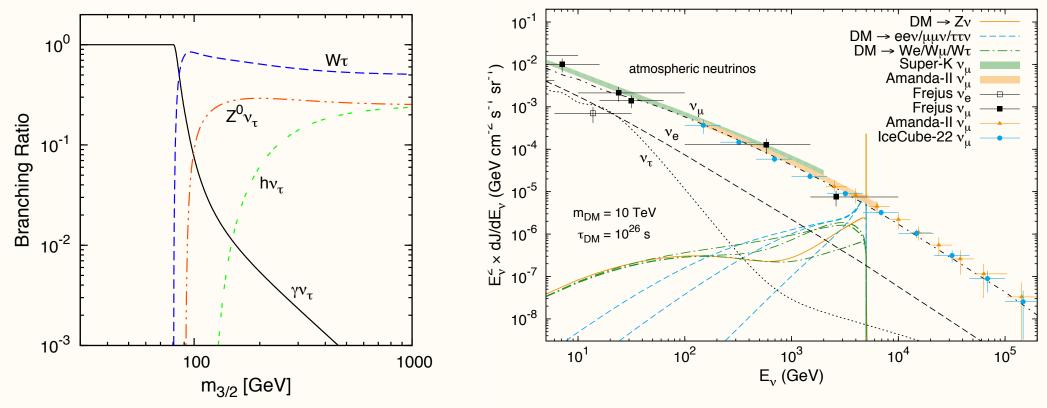
Heavy gravitinos decay into RPV channel in EW gauge boson and lepton, producing gamma-rays and antiprotons. The antiproton constraints already limit strongly the R-parity breaking coupling. From the FERMI gamma-line search: $\tau < 1 - 4 \times 10^{29} s$ 95% CL



GRAVITINO DM DECAY

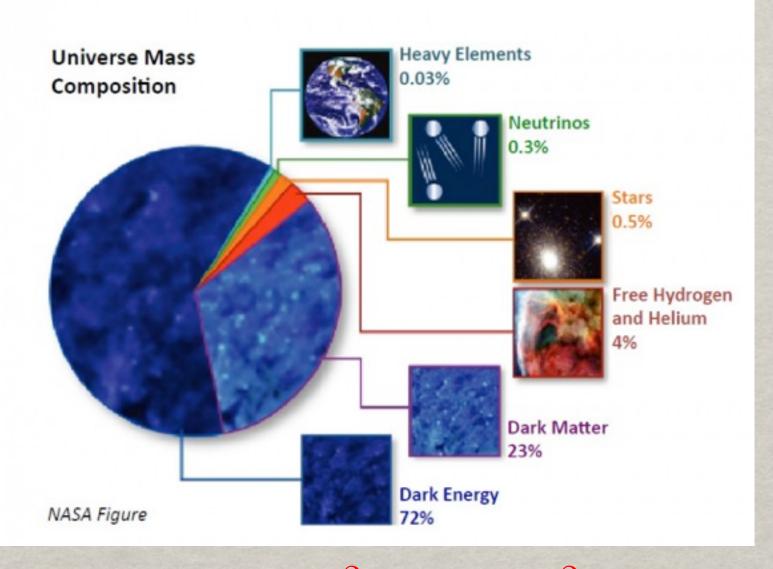
For bilinear RPV, one can even expect neutrino lines, especially for light gravitino, but also in the heavier case two lines from the decay into Z/h neutrino persists!

[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.

$$W = \lambda_{ijk}^{\prime\prime} U_i D_j D_k$$

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

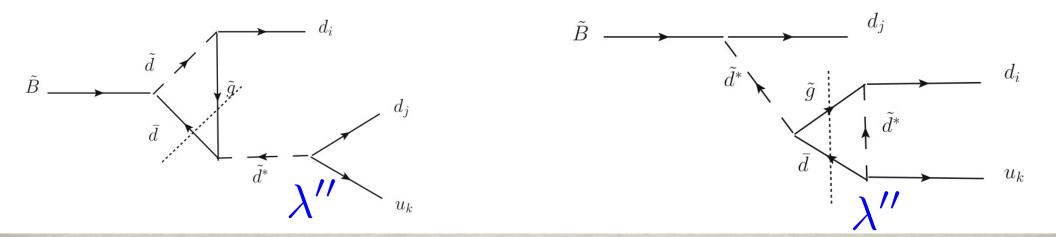
$\tilde{B} \rightarrow u dd, \ \bar{u} \bar{d} \bar{d}, \ \tilde{g} \bar{q} q$

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...

$$\Omega_{\Delta B} = \frac{m_p}{m_{\chi}} \underbrace{\epsilon_{CP}} BR\left(\chi \to \mathcal{B}\right) \Omega_{\chi}^{\tau \to \infty}$$
Small numbers
$$\Omega_{DM} = \frac{m_{DM}}{m_{\chi}} \underbrace{BR\left(\chi \to DM + \text{anything}\right)} \Omega_{\chi}^{\tau \to \infty}$$

$$\stackrel{\Omega_{\Delta B}}{\longrightarrow} = \frac{m_p}{m_{DM}} \underbrace{\frac{\epsilon_{CP}}{BR(\chi \to DM + \text{anything})}}_{BR(\chi \to DM + \text{anything})} \text{ independent of Bino density}$$
Fravitino 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

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

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

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

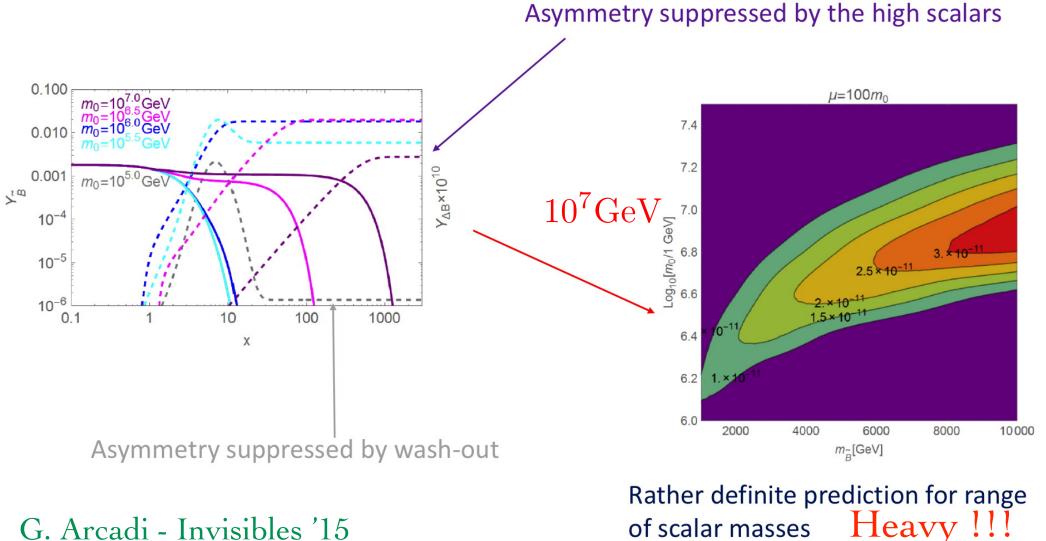
CP asymmetry is suppressed both for $m_{\tilde{g}} = m_{\tilde{B}}$ or $m_{\tilde{g}} = 0$ Neglecting wash-out processes we get

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

Need a very heavy spectrum to realize the scenario !

BARYOGENESIS IN RPV SUSY [Arcadi, LC & Nardecchia 1507.05584]

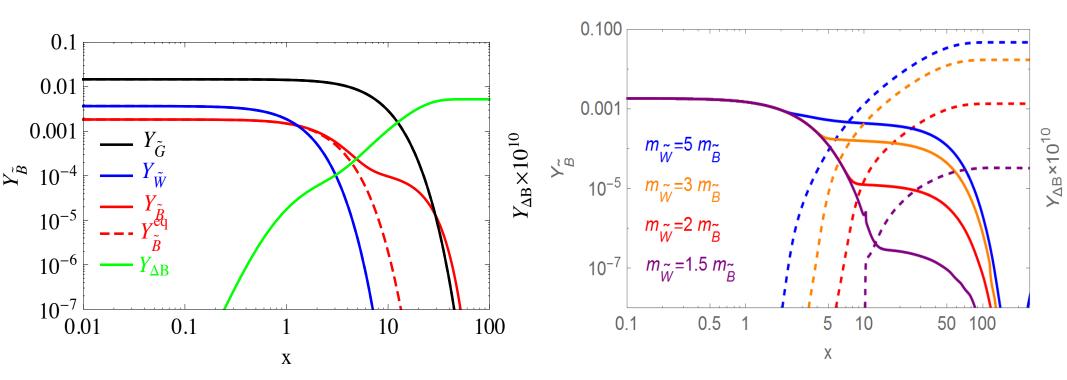
Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!



G. Arcadi - Invisibles '15

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 !!!



 $m_{\tilde{W}} = 2 m_{\tilde{B}}$

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...

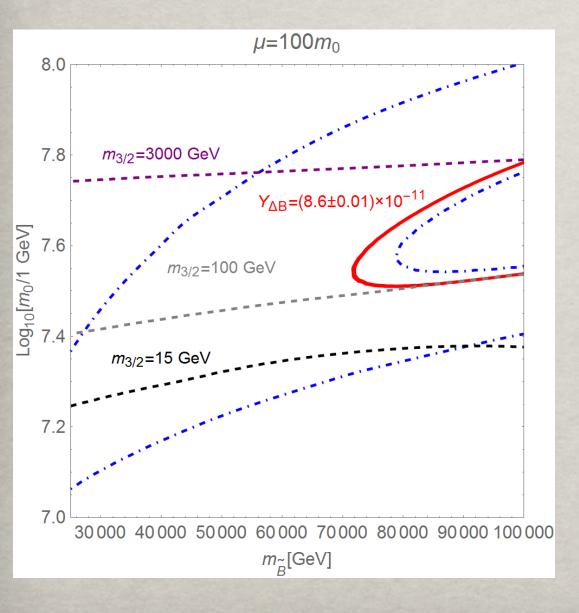
$$\Omega_{3/2}^{FI}h^2 \sim 0.002 \left(\frac{m_{\tilde{W}}}{10 \text{ TeV}}\right)^3 \left(\frac{m_{3/2}}{1 \text{ TeV}}\right)^{-1}$$

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

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

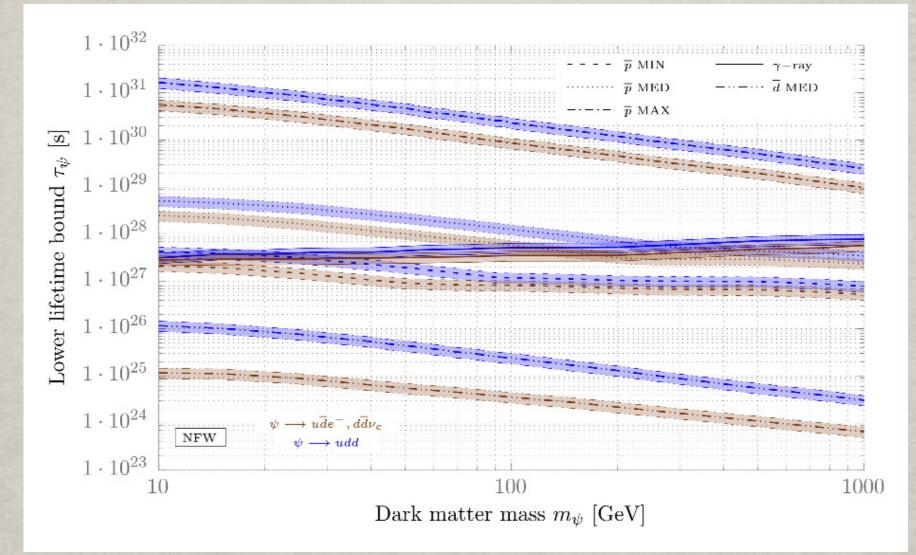
$$\Gamma(\psi_{3/2} \to u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}'}{m_0^4 M_P^2}$$

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

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. $m_{\tilde{g}} \sim 0.1 - 0.4 \ m_{\tilde{B}} \sim 7 - 28 \ \text{TeV}$, possibly in the reach of a 100 TeV collider.

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

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 !