Workshop “Preparing for the Dark Matter Particle Discovery”
Göteborg, 11th June 2018

DECAYING DARK MATTER WITH AND WITHOUT SUPERSYMMETRY

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elusives-invisiblesPlus
neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

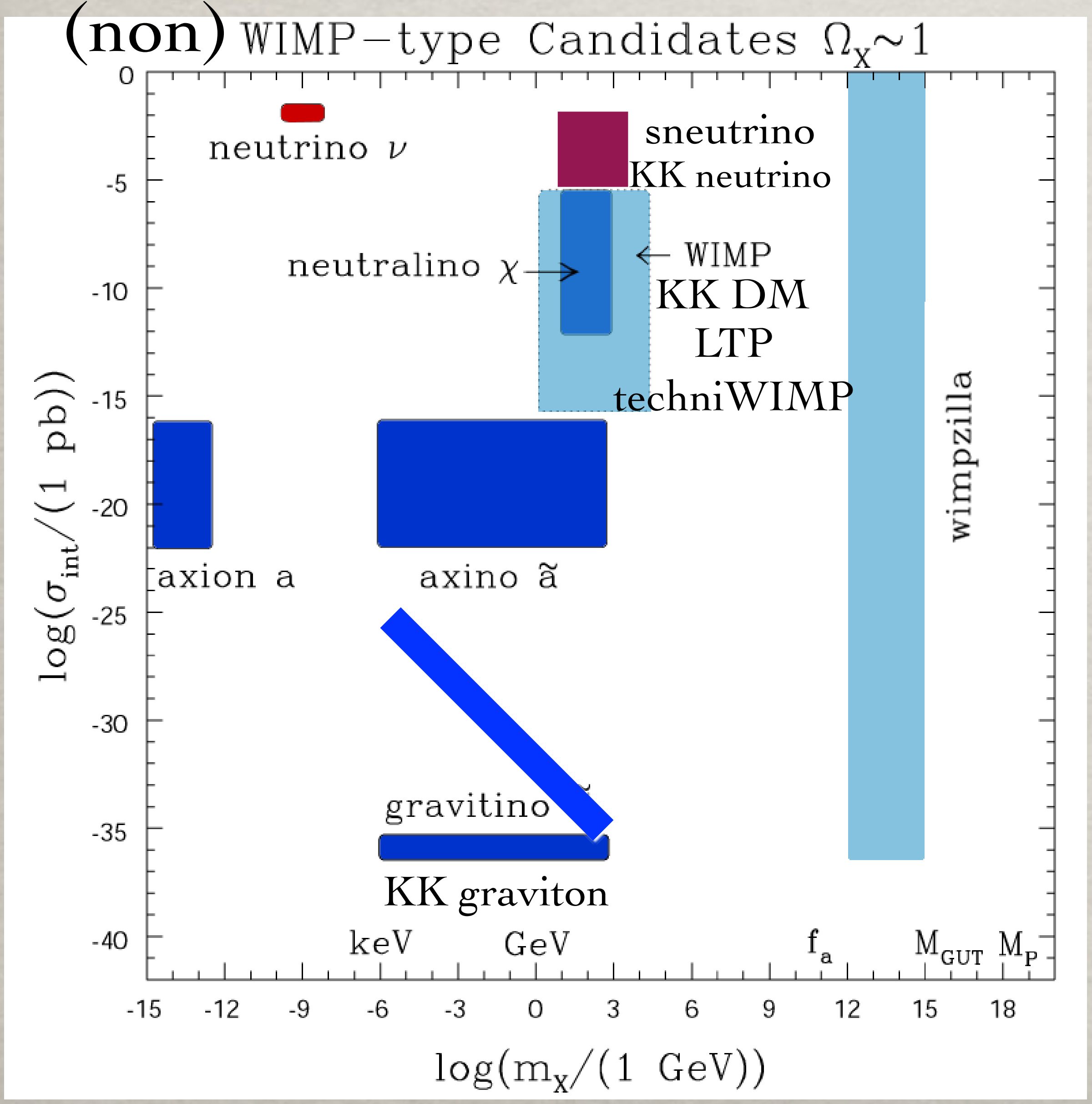
OUTLINE

- Introduction:
  -Theoretical guiding principles
  - Cosmology as a probe of particle physics
- Decaying Dark Matter without SUSY
- Decaying Dark Matter in SUSY
- High scale SUSY for baryogenesis
- Outlook

INTRODUCTION

DARK MATTER CANDIDATES

[Roszkowski 04]



Too many different candidates...

“Standard” DM production paradigms:
WIMPs
(i.e. neutralino)
&
“FIMP/SuperWIMPs”
(i.e. gravitino)
&
Misalignment
(i.e. axion/condensate)

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

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

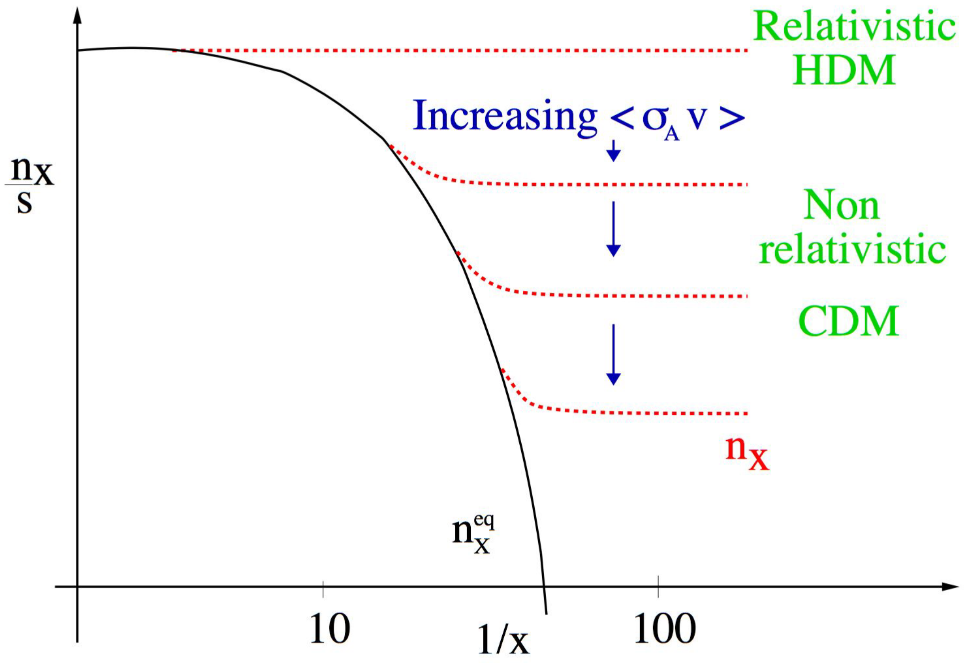
Hubble expansion Collision integral

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 ⇔ Particle properties



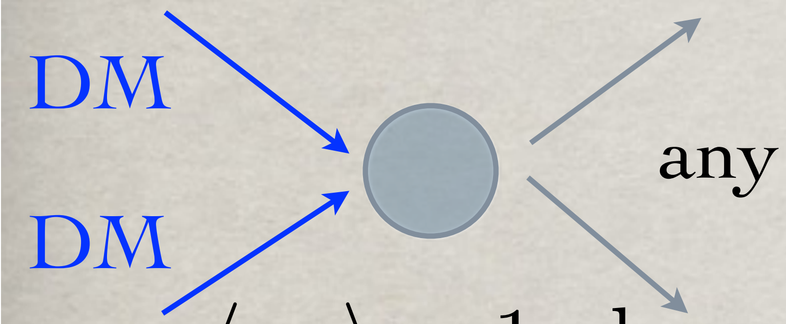
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

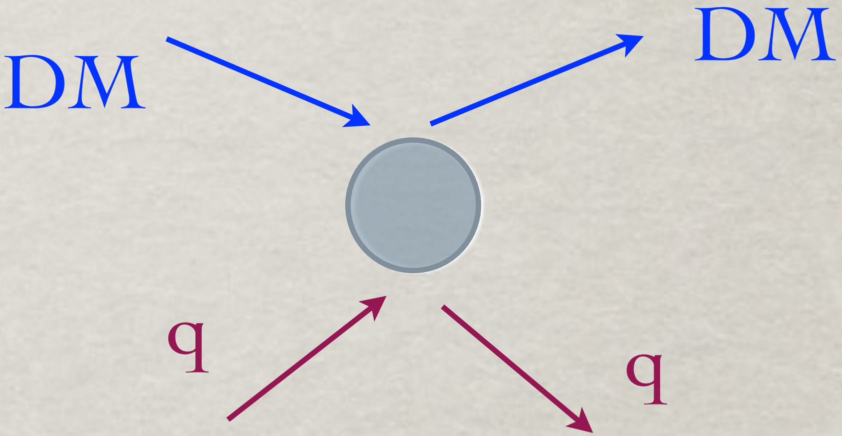
THE WIMP CONNECTION

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

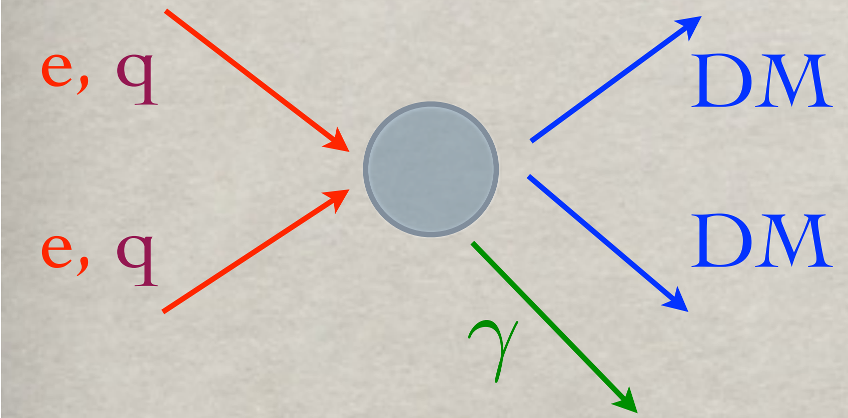


$\langle \sigma v \rangle \sim 1 \text{ pb}$

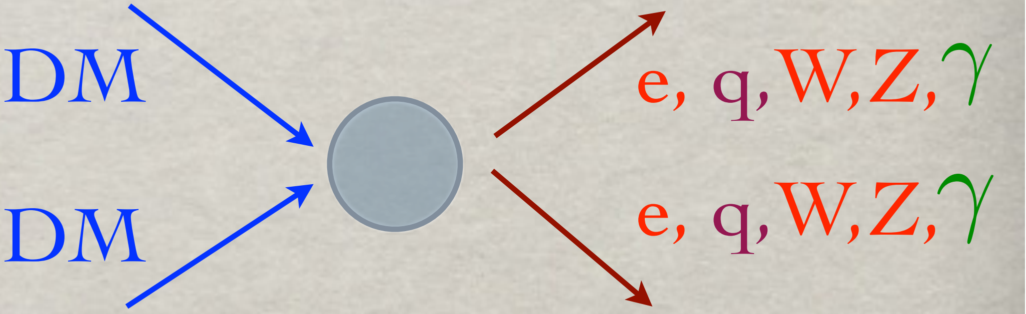
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:



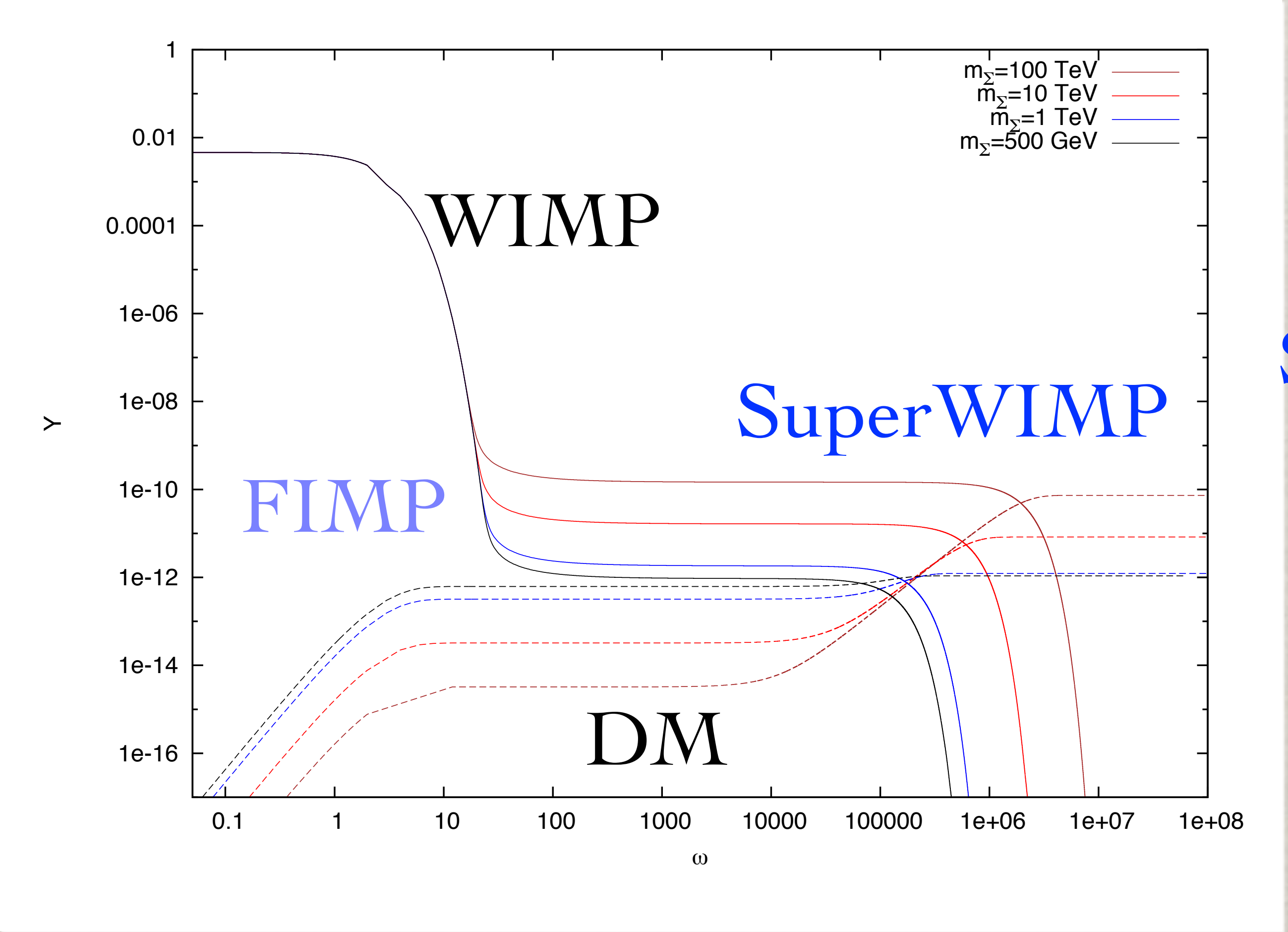
3 different ways to check this hypothesis !!!

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:

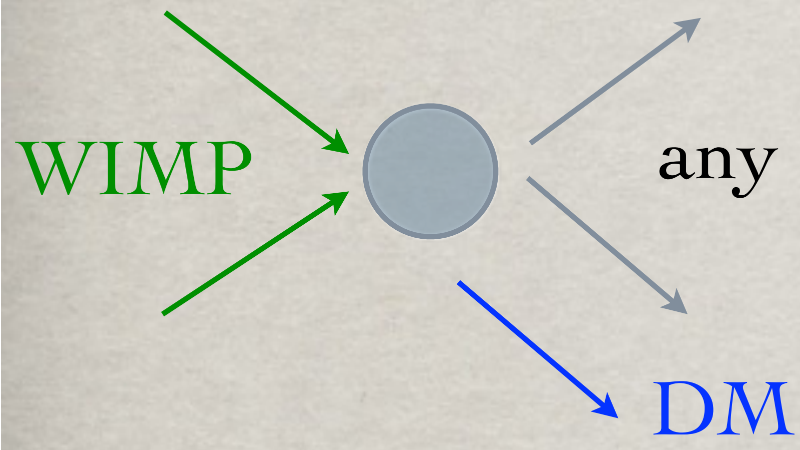
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma}\, BR(\Sigma \to \psi)\, \Omega_\Sigma h^2$$

- 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: $\Omega_{CDM} h^2$



WIMP

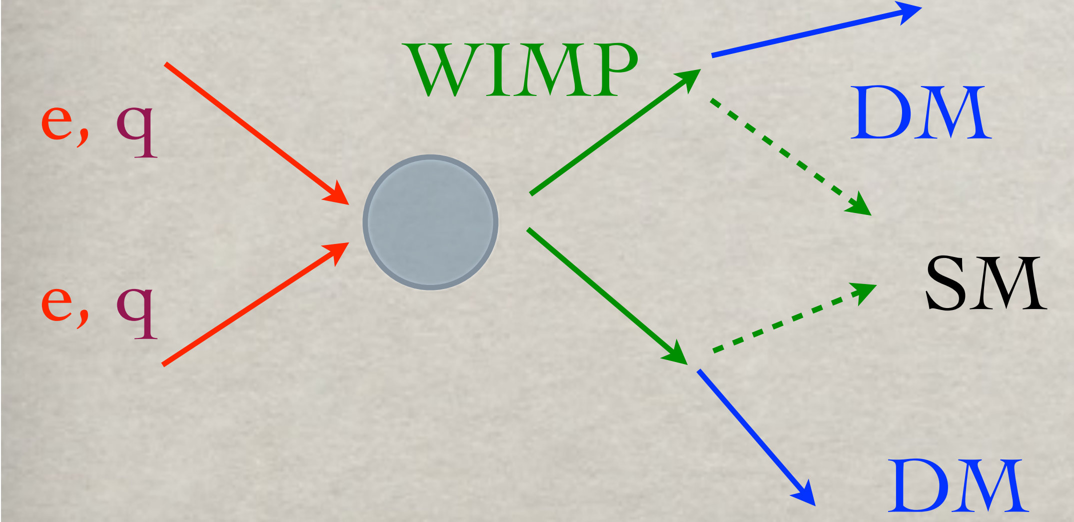
any

DM

Direct Detection:

NONE...

Colliders: LHC/ILC



e, q

e, q

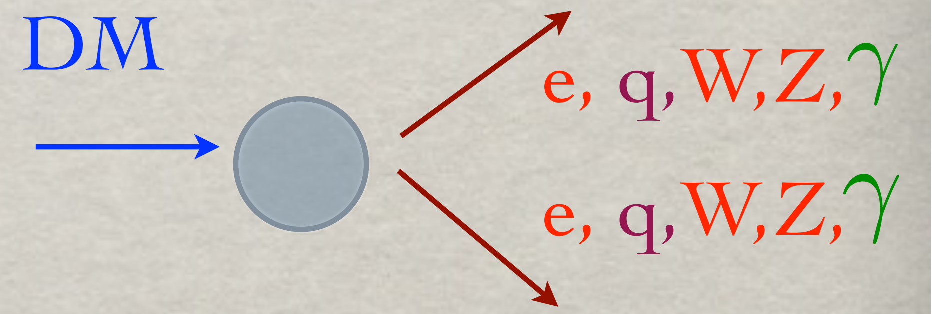
WIMP

DM

SM

DM

Indirect Detection:



DM

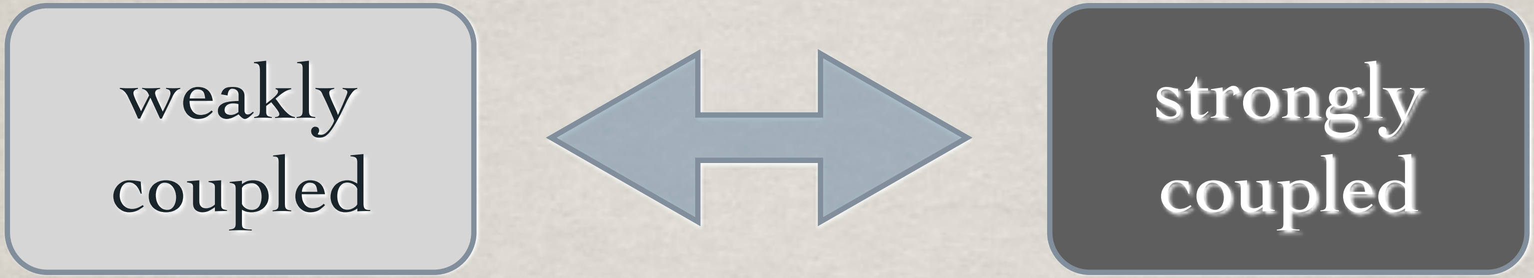
e, q, W, Z, γ

e, q, W, Z, γ

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

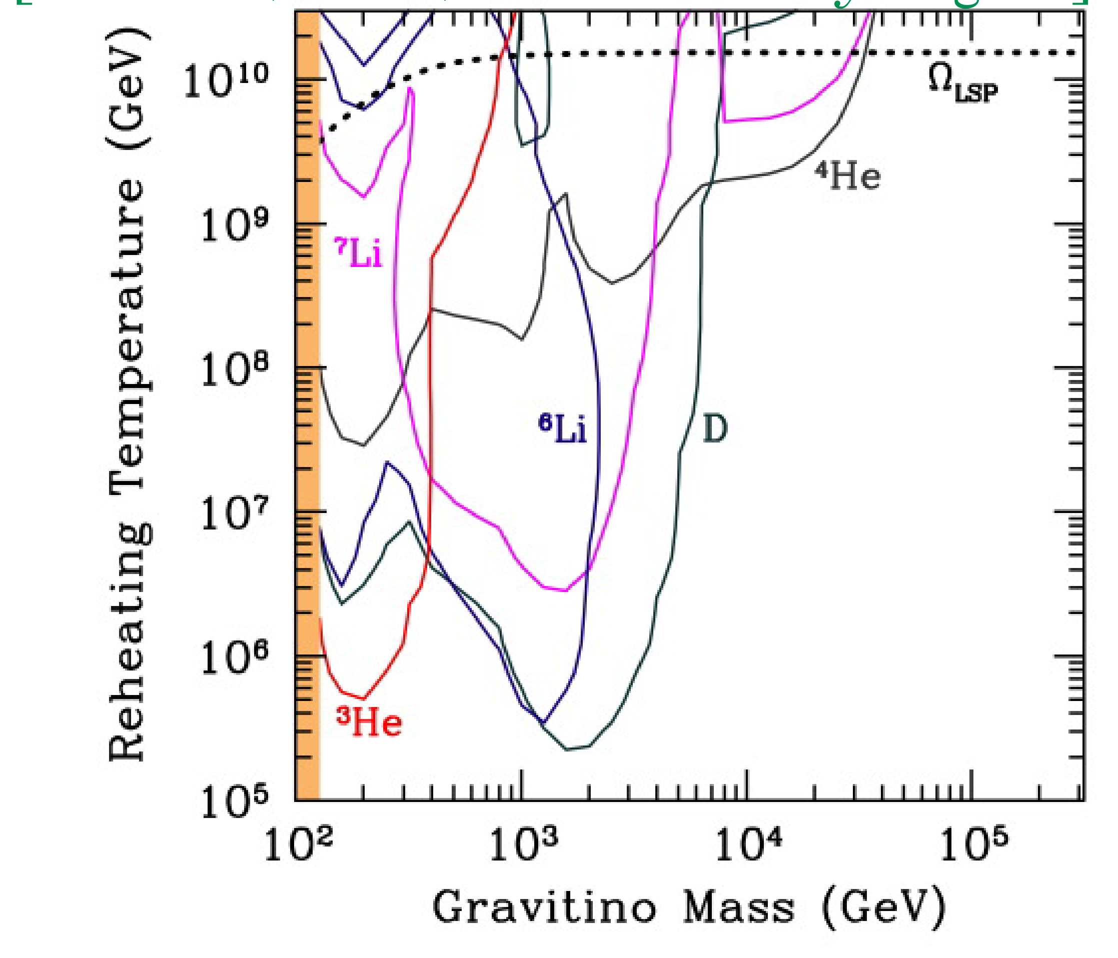
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[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]



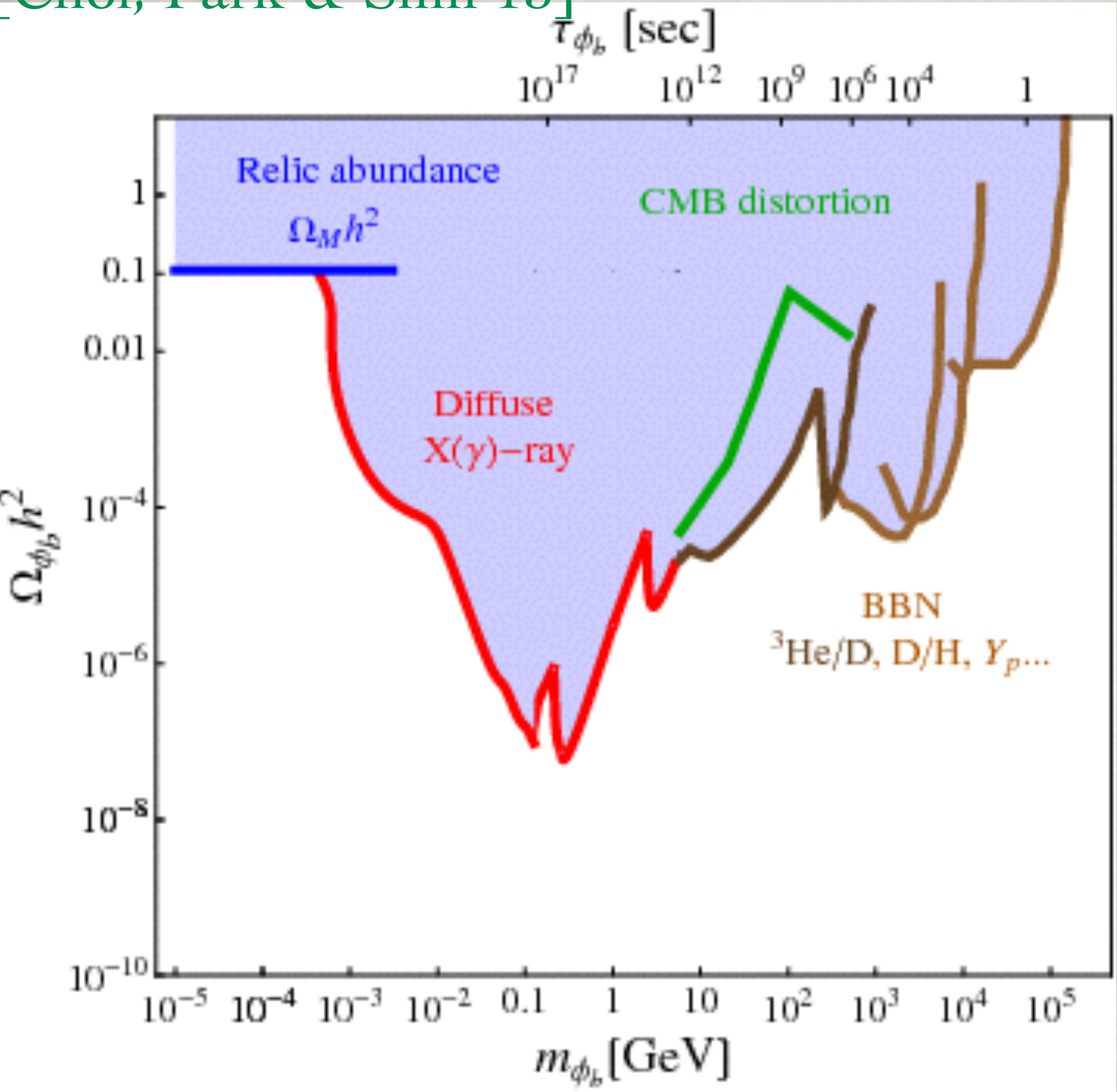
$$\tau_{3/2} = 6 \times 10^7 \mathrm{s} \left(\frac{m_{3/2}}{100\mathrm{GeV}} \right)^{-3}$$

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

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

THE MODULI PROBLEM

[Choi, Park & Shin 13]



$$\tau_{mod} \sim 0.6\ \mathrm{s}\ \left(\frac{100\ \mathrm{TeV}}{m_{mod}}\right)^3$$

$$m_{mod} \sim \mathcal{O}(1)\ m_{3/2}$$

Again generic trouble due to too many moduli around after inflation…

Ways out: heavy moduli or dilution factor, e.g. thermal inflation.

Decaying Dark Matter without SUSY

A SIMPLE WIMP/SWIMP MODEL

[G. Arcadi & LC 1305.6587]

Consider a simple model where the Dark Matter, a Majorana SM singlet fermion, is coupled to the colored sector via a renormalizable interaction and a new colored scalar Σ :

$$\lambda_\psi \bar{\psi} d_R \Sigma + \lambda_\Sigma \bar{u}^c_R d_R \Sigma^\dagger$$

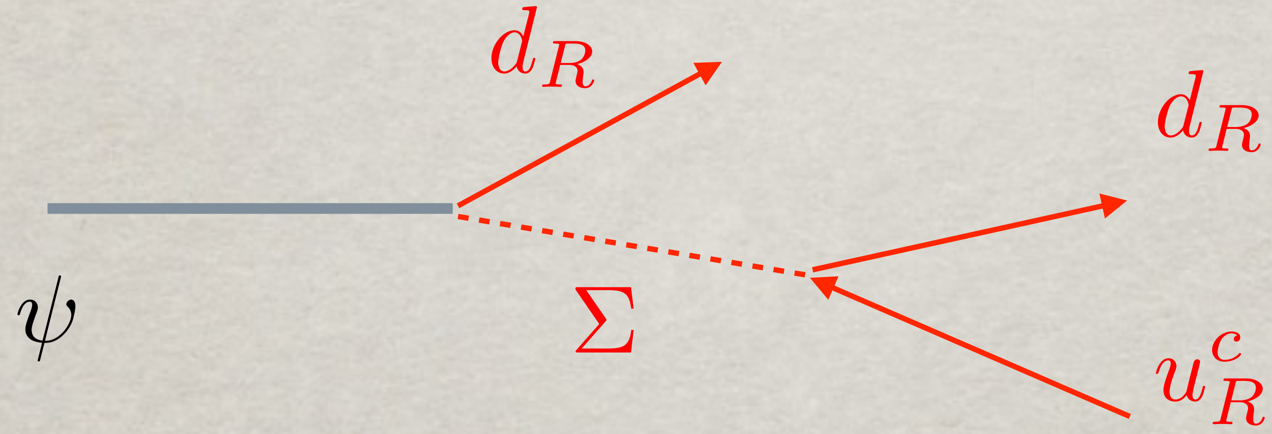
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ FIMP/SWIMP connection

A SIMPLE WIMP/SWIMP MODEL

[G. Arcadi & LC 1305.6587]

No symmetry is imposed to keep DM stable, but the decay is required to be sufficiently suppressed. For $m_\Sigma \gg m_\psi$:

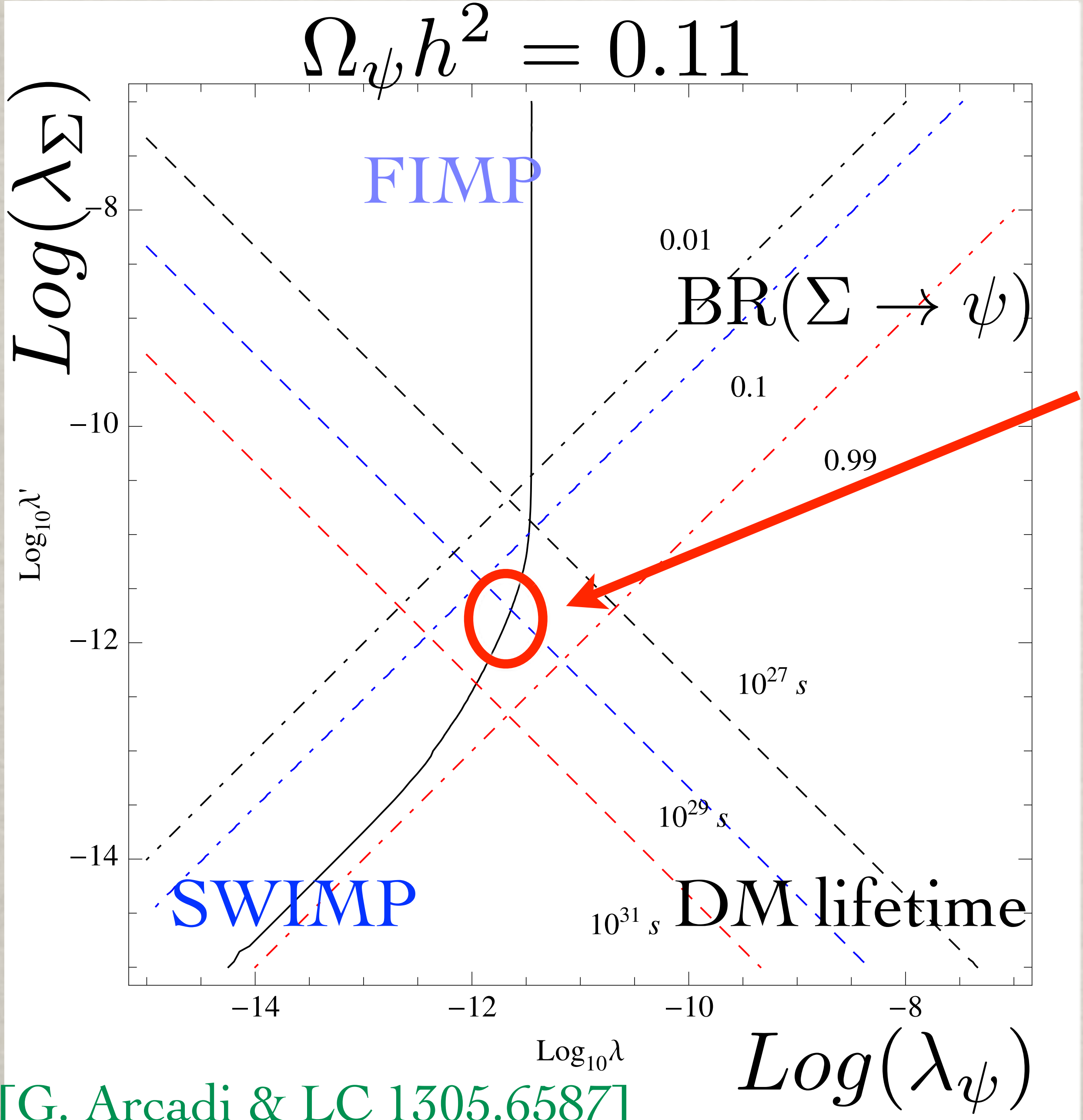


Decay into 3 quarks via both couplings !

To avoid bounds from the antiproton flux require then

$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

A SIMPLE WIMP/SWIMP MODEL



[G. Arcadi & LC 1305.6587]

DM decay observable in indirect detection & right abundance & sizable BR in DM

$$\lambda_\psi \sim \lambda_\Sigma$$

But unfortunately Σ decays outside the detector @ LHC! Perhaps visible decays with a bit of hierarchy...

FIMP/SWIMP AT LHC

At the LHC we expect to produce the heavy charged scalar Σ, as long as the mass is not too large... In principle the particle has two channels of decay with very long lifetimes. Fixing the density by FIMP mechanism we have:

$$l_{\Sigma,DM} = 2.1 \times 10^5 \mathrm{m}\, g_\Sigma x \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-1} \left(\frac{\Omega_{CDM} h^2}{0.11}\right)^{-1} \left(\frac{g_*}{100}\right)^{-3/2}$$

Very long apart for small DM mass, i.e. $x = \dfrac{m_{DM}}{m_{\Sigma_f}} \ll 1$

Moreover imposing ID “around the corner” gives

$$l_{\Sigma,SM} \simeq 55\,\mathrm{m}\, \frac{1}{g_\Sigma} \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4} \left(\frac{m_\psi}{10\mathrm{GeV}}\right)^{4} \left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right) \left(\frac{\Omega_{CDM} h^2}{0.11}\right) \left(\frac{g_*}{100}\right)^{3/2}$$

At least one decay could be visible !!!

Σ Combined detection

Still possible to have multiple detection of

- DM decay:

$$m_\psi \quad \Gamma_\psi \to \lambda\lambda'$$

- displaced vertices

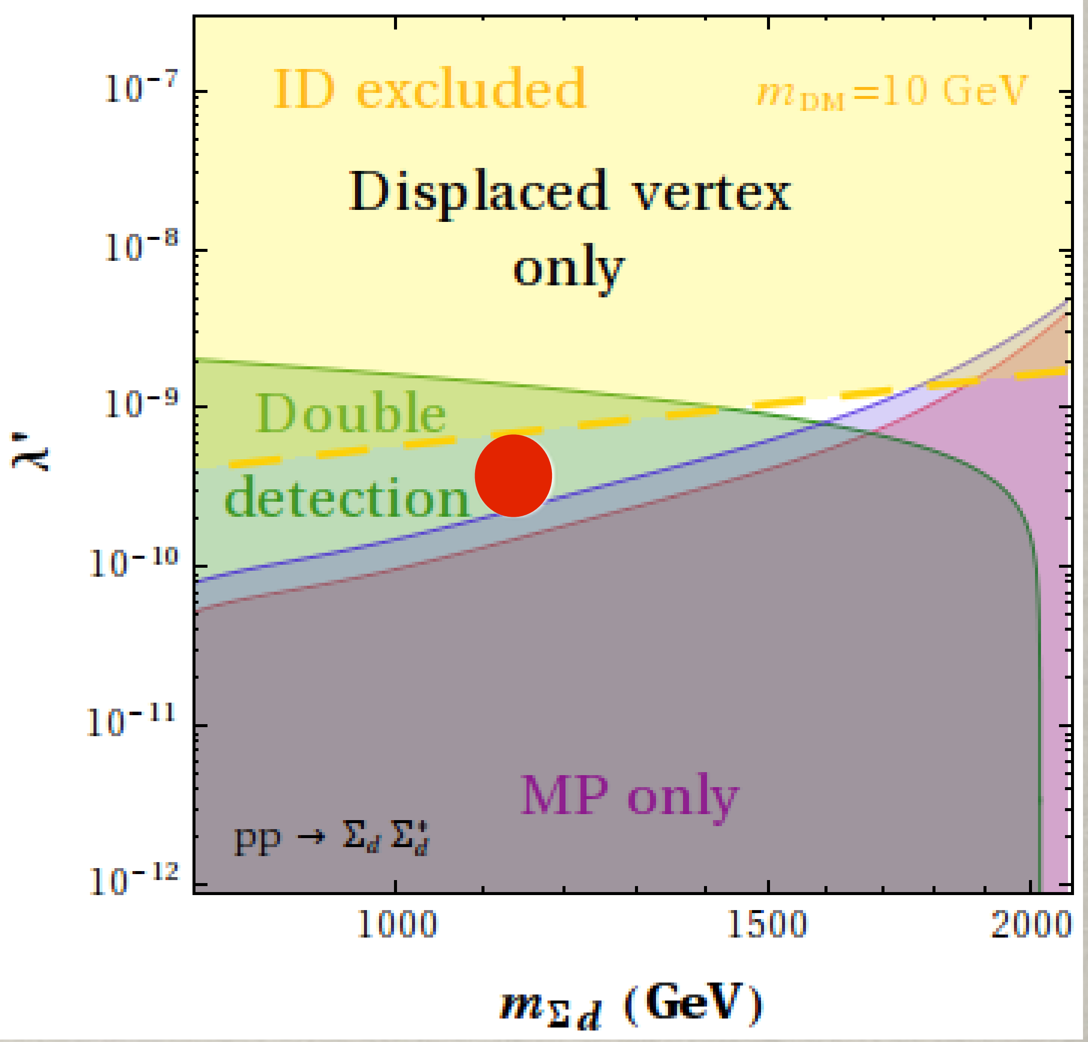
$$m_\Sigma \quad \Gamma_{\Sigma,SM} \to \lambda'$$

- metastable tracks

$$m_\Sigma \quad \Gamma_{\Sigma,SM} < X \to \lambda'$$

with stopped tracks maybe both $\Gamma_{\Sigma,SM}, \Gamma_{\Sigma,DM}$

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



It is possible to over-constraint the model and check the hypothesis of FIMP production !

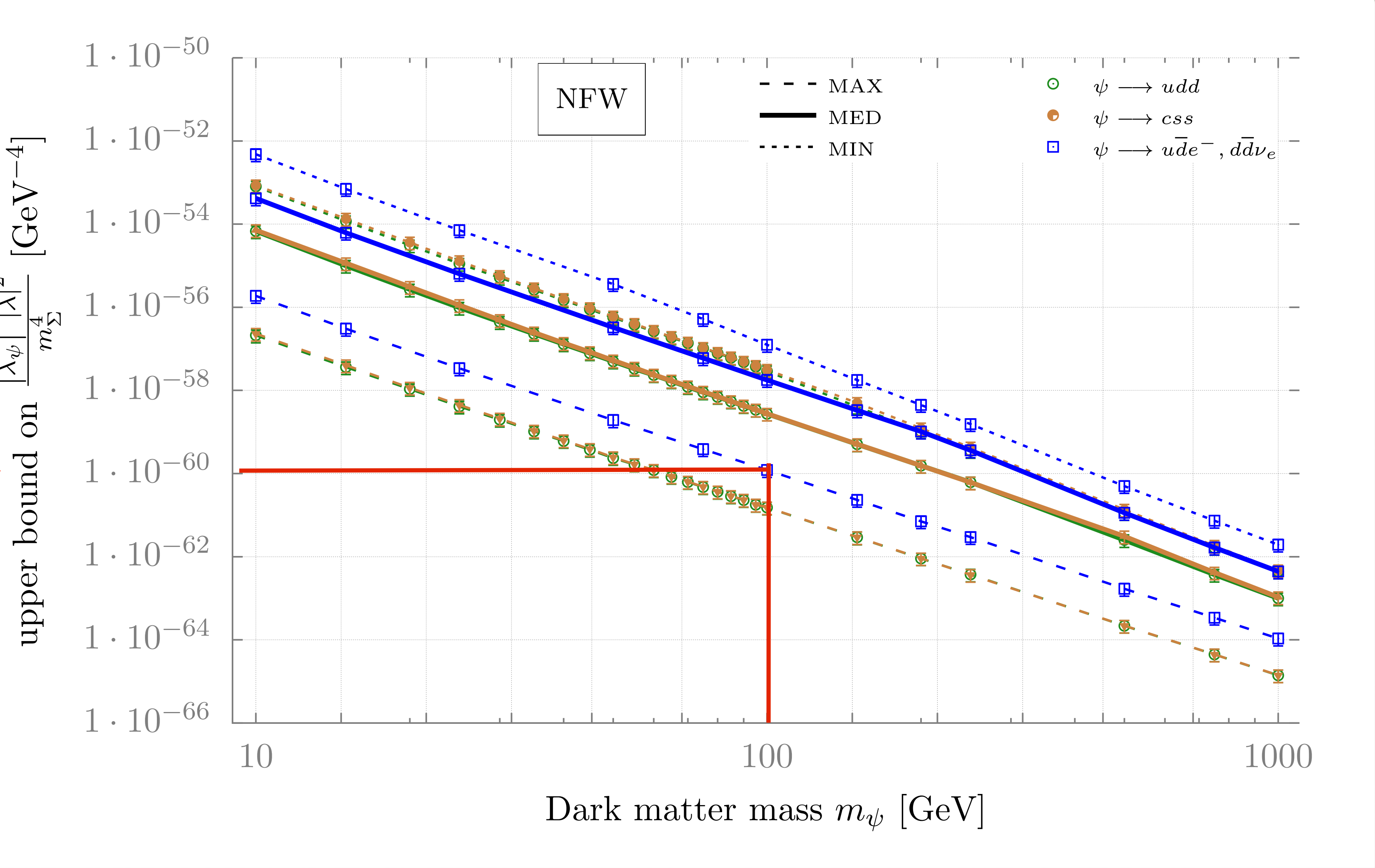
ID of FIMP/SWIMP DM

[LC, Eckner & Gustafsson, work in progress]

$\lambda\lambda' =$

10^{-18} →

$m_\Sigma = 1\text{TeV}$

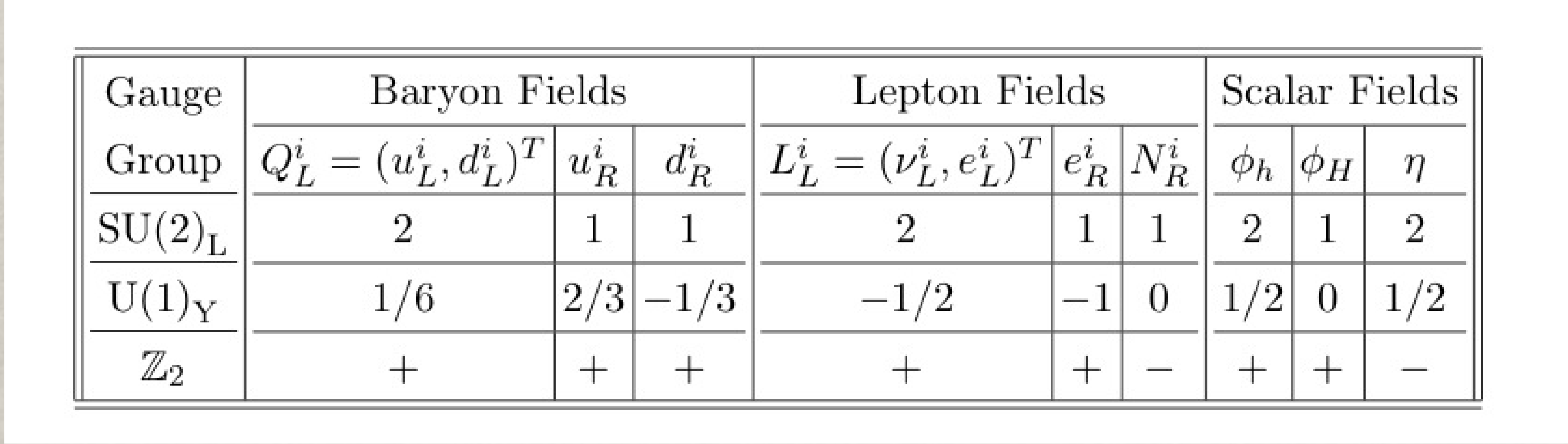


Unfortunately bounds strongly depend on propagation...

BEYOND THE SIMPLEST MODEL

[A. Biswas, S. Choubey, LC & S. Khan 2017]

Apart for minimal models, more complex models are possible, e.g. a gauged $U(1)_{L_\mu - L_\tau}$ where the neutrino masses are generated radiatively and two RH neutrinos are FIMP DM produced from the gauge boson, itself a FIMP…
One realisation is given by



Gauge	Baryon Fields			Lepton Fields			Scalar Fields		
Group	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	N_R^i	ϕ_h	ϕ_H	η
$\mathrm{SU(2)_L}$	2	1	1	2	1	1	2	1	2
$\mathrm{U(1)_Y}$	1/6	2/3	−1/3	−1/2	−1	0	1/2	0	1/2
$\mathbb{Z}_2$	+	+	+	+	+	−	+	+	−

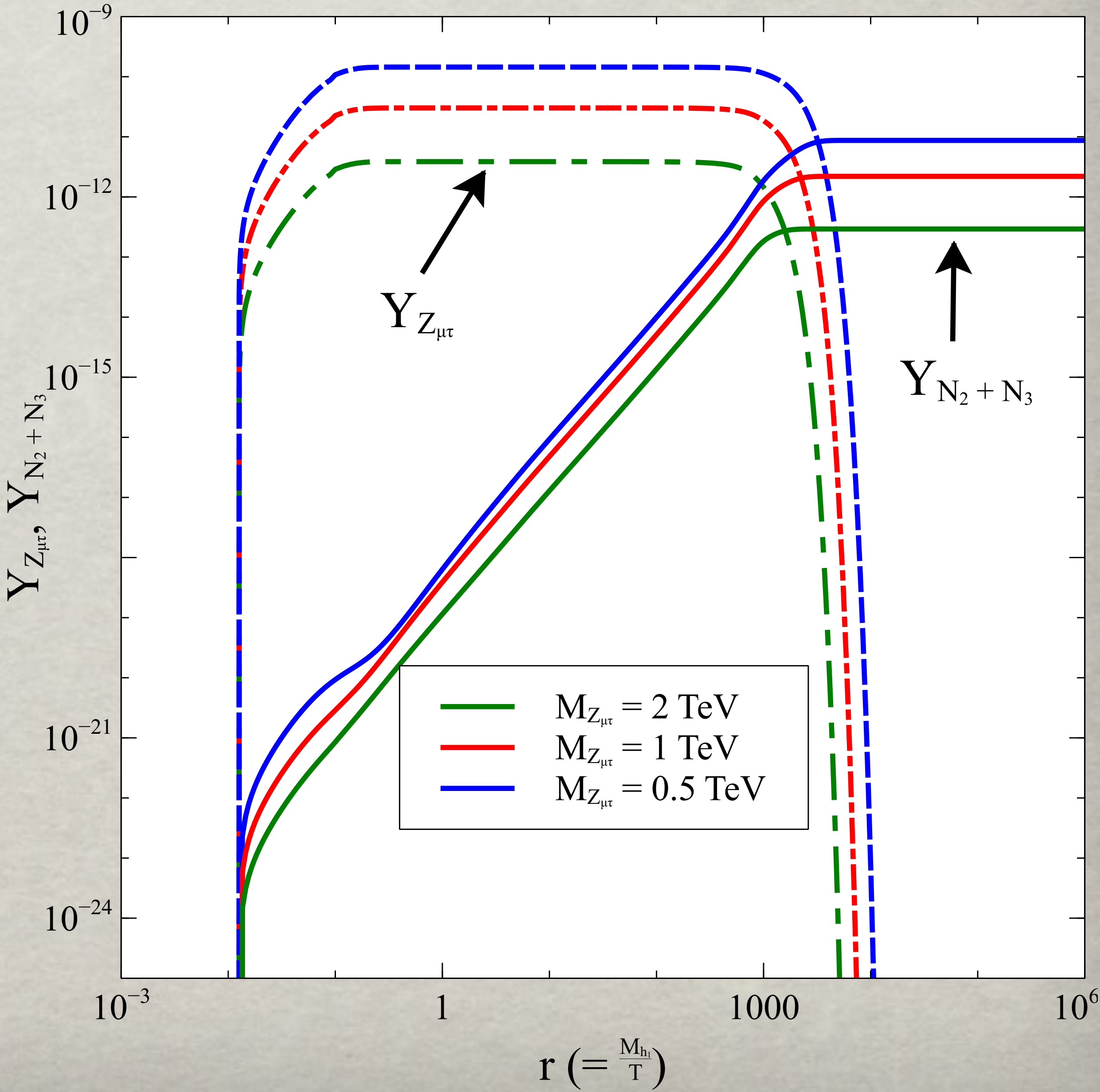
Contains an complex inert doublet η , an additional scalar ϕ_H to break the $U(1)_{L_\mu - L_\tau}$ and an additional massive gauge boson

FIMP FROM A FIMP

[A. Biswas, S. Choubey, LC & S. Khan 2017]

In this scenario, the two RH neutrinos can be FIMP DM produced from the gauge boson, itself a FIMP/SWIMP produced by Higgs decay…
Need though a very small gauge coupling to realise the FIMP mechanism:

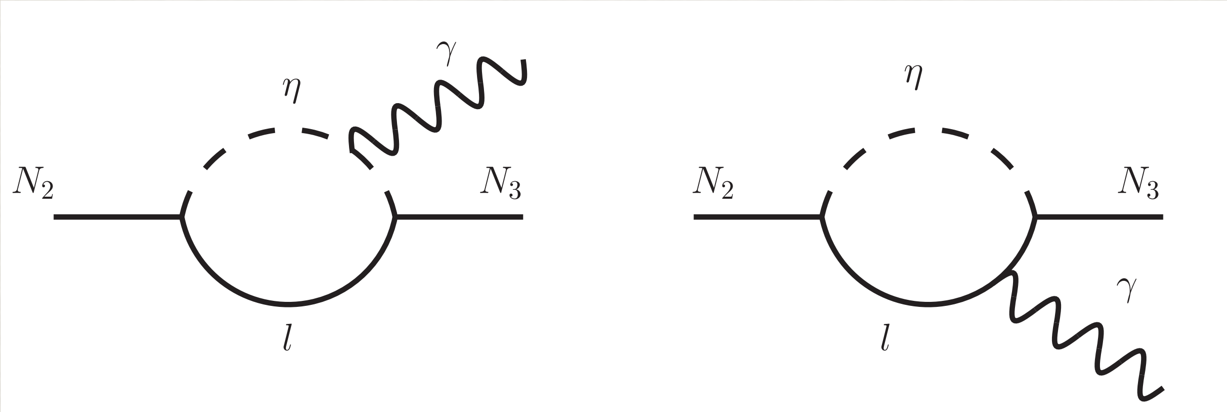
$$g_{\mu\tau} \sim 10^{-11}$$



DECAYING FIMP FROM A FIMP

[A. Biswas, S. Choubey, LC & S. Khan 2017]

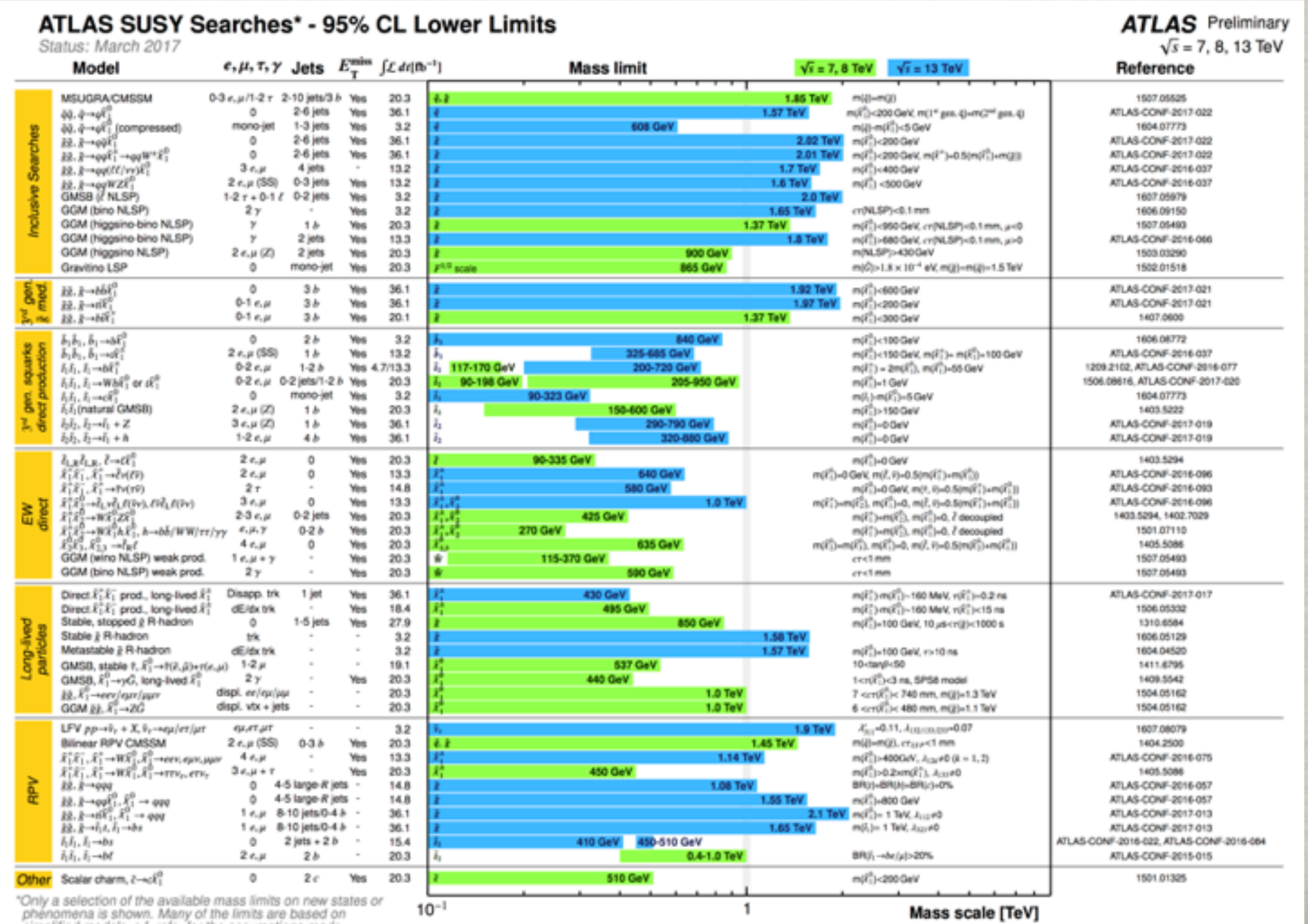
In this case the mass splitting between the RH neutrinos is small due to the $U(1)_{L_\mu - L_\tau}$ and the heavier can decay into the lighter one giving rise to a keV line if the mass splitting is in that range…



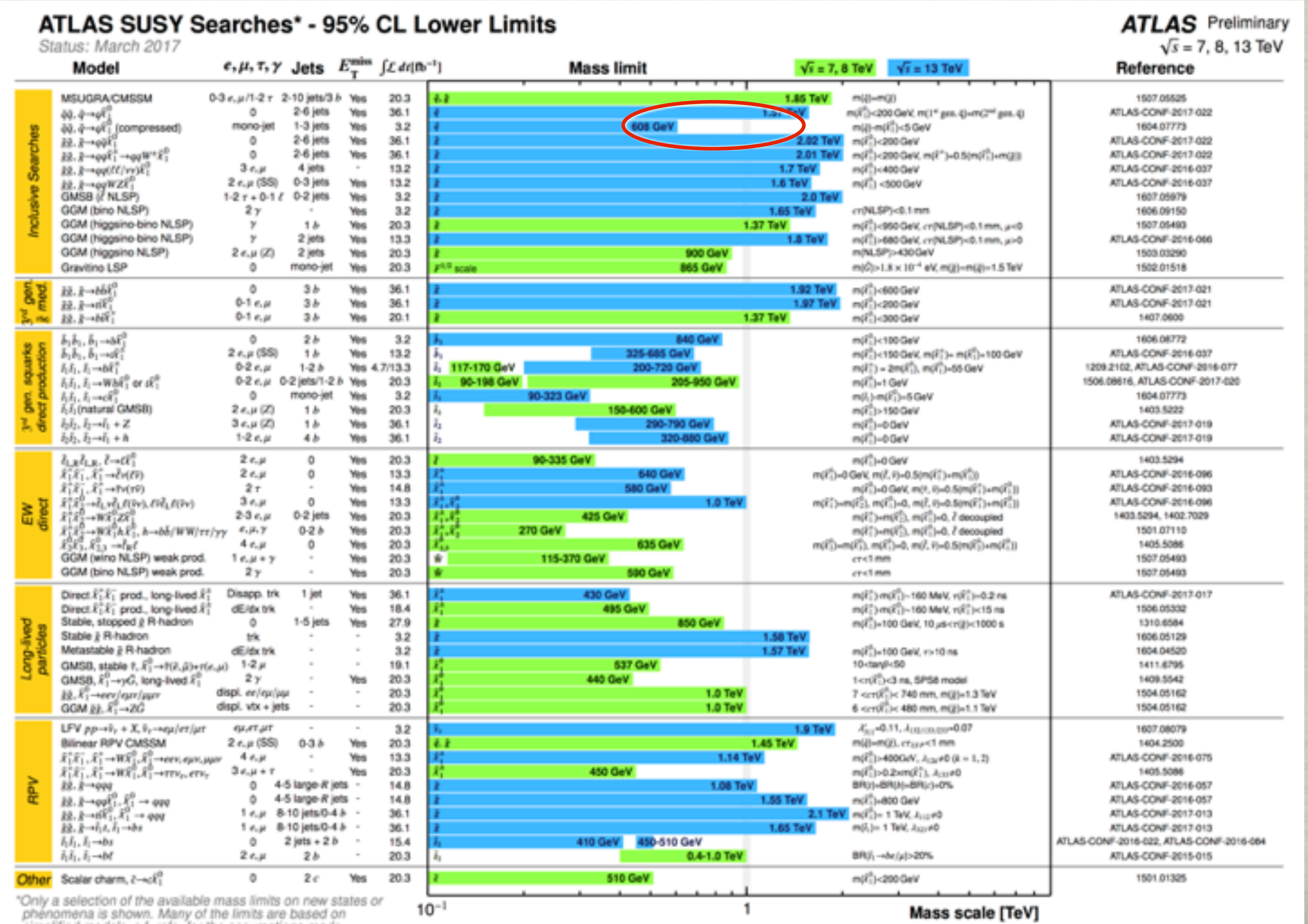
The right lifetime is obtained for masses of the RH neutrinos in the 100 GeV range and scalars in the 10^6 GeV range.

DECAYING DARK MATTER IN SUSY

SUSY AT LHC RUN 2



SUSY AT LHC RUN 2



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2017

ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

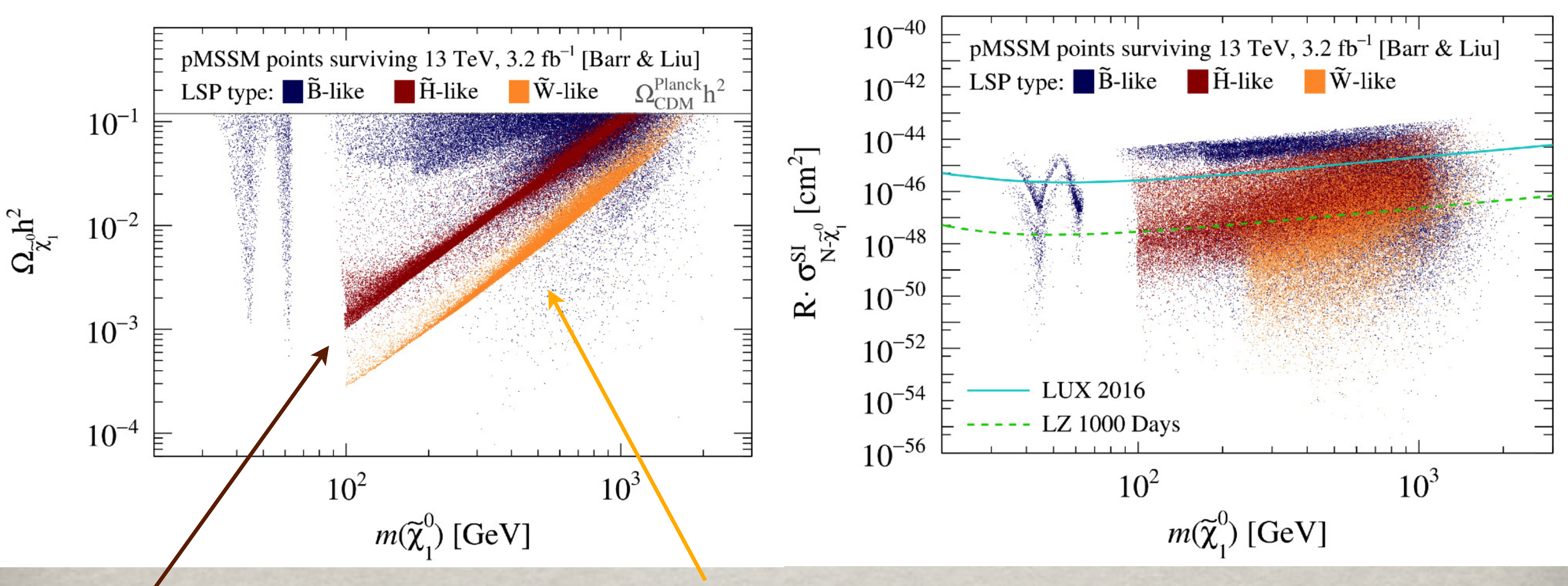
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 🟩 1.85 TeV	$m(\tilde{q})$=$m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 🟦 1.57 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(1^{st}$ gen. $\tilde{q})$=$m(2^{nd}$ gen. $\tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 🟦 608 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.02 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 🟦 2.01 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	13.2	$\tilde{g}$ 🟦 1.7 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	2 e,μ (SS)	0-3 jets	Yes	13.2	$\tilde{g}$ 🟦 1.6 TeV	$m(\tilde{\chi}_1^0)$ <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 🟦 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	$\tilde{g}$ 🟦 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$ 🟩 1.37 TeV	$m(\tilde{\chi}_1^0)$<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$ 🟦 1.8 TeV	$m(\tilde{\chi}_1^0)$>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$ 🟩 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 🟩 865 GeV	$m(\tilde{G})$>1.8 × 10^{-4} eV, $m(\tilde{g})$=$m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.92 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 🟦 1.97 TeV	$m(\tilde{\chi}_1^0)$<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 🟩 1.37 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$ 🟦 840 GeV	$m(\tilde{\chi}_1^0)$<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	1 b	Yes	13.2	$\tilde{b}_1$ 🟦 325-685 GeV	$m(\tilde{\chi}_1^0)$<150 GeV, $m(\tilde{\chi}_1^\pm)$= $m(\tilde{\chi}_1^0)$+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	$m(\tilde{\chi}_1^\pm)$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 🟩 90-198 GeV 🟩 205-950 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$ 🟦 90-323 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 🟩 150-600 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 🟦 290-790 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 🟦 320-880 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 🟩 90-335 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	13.3	$\tilde{\chi}_1^\pm$ 🟦 640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	$\tilde{\chi}_1^\pm$ 🟦 580 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2016-093
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	13.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 🟦 1.0 TeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 🟩 425 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 🟩 270 GeV	$m(\tilde{\chi}_1^\pm)$=$m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 🟩 635 GeV	$m(\tilde{\chi}_2^0)$=$m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}_2^0)$+$m(\tilde{\chi}_1^0)$)	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	$\tilde{W}$ 🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	$\tilde{W}$ 🟩 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 🟦 430 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$ 🟩 495 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$~160 MeV, $\tau(\tilde{\chi}_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 🟩 850 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 🟦 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 🟦 1.57 TeV	$m(\tilde{\chi}_1^0)$=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 🟩 440 GeV	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 🟩 1.0 TeV	7 <$c\tau(\tilde{\chi}_1^0)$< 740 mm, $m(\tilde{g})$=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$ 🟩 1.0 TeV	6 <$c\tau(\tilde{\chi}_1^0)$< 480 mm, $m(\tilde{g})$=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 🟦 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 🟩 1.45 TeV	$m(\tilde{q})$=$m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$ 🟦 1.14 TeV	$m(\tilde{\chi}_1^0)$>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 🟩 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 🟦 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	14.8	$\tilde{g}$ 🟦 1.55 TeV	$m(\tilde{\chi}_1^0)$=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 2.1 TeV	$m(\tilde{\chi}_1^0)$= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 🟦 1.65 TeV	$m(\tilde{t}_1)$= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 🟦 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$ 🟩 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 🟩 510 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on

SUSY MODELS STILL ALIVE

pMSSM points surviving after LHC-13 data

[Barr & Liu 2016]



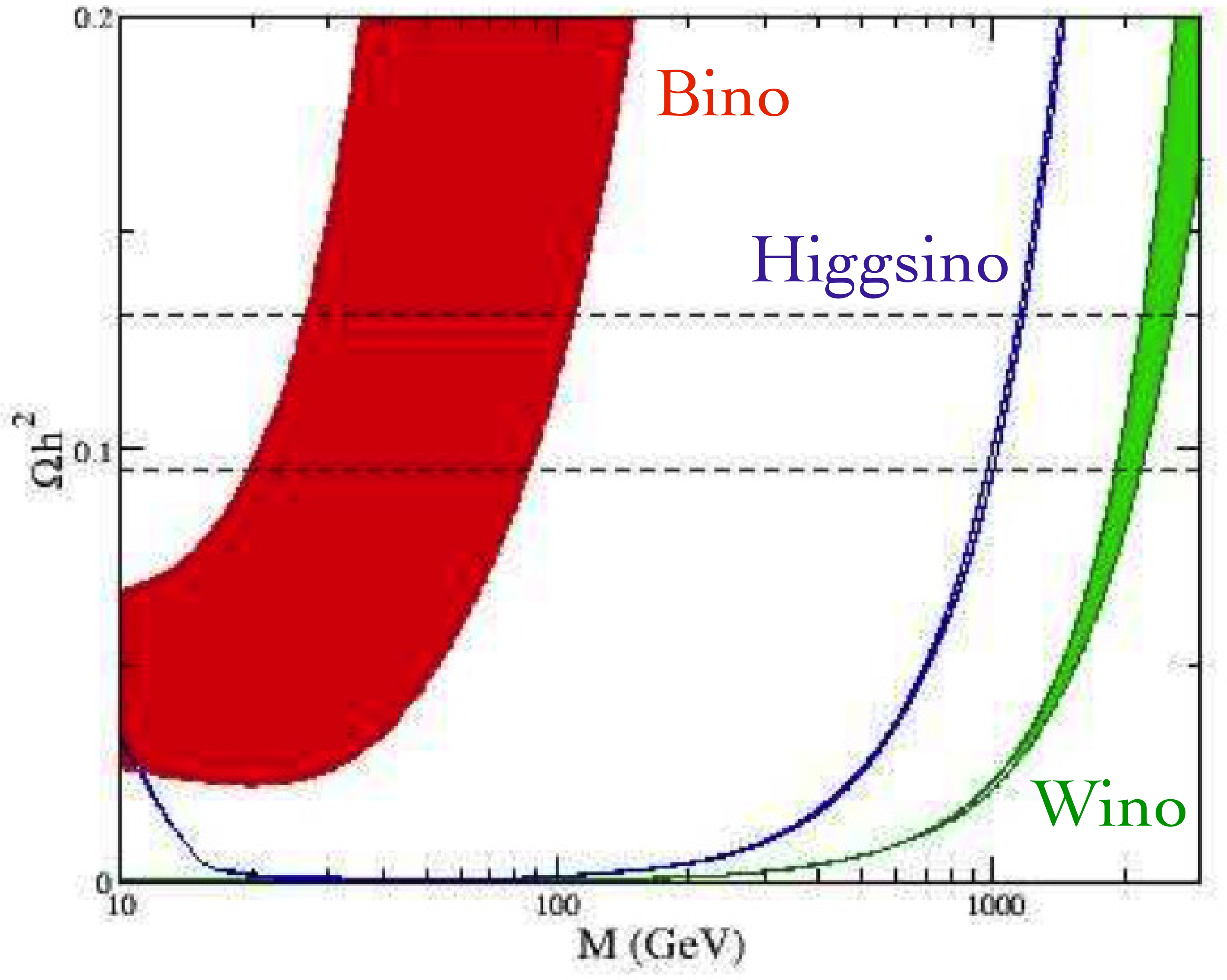
Higgsino band Wino band

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

WELL-TEMPERED NEUTRALINO

Relic density strongly dependent on neutralino nature !!!

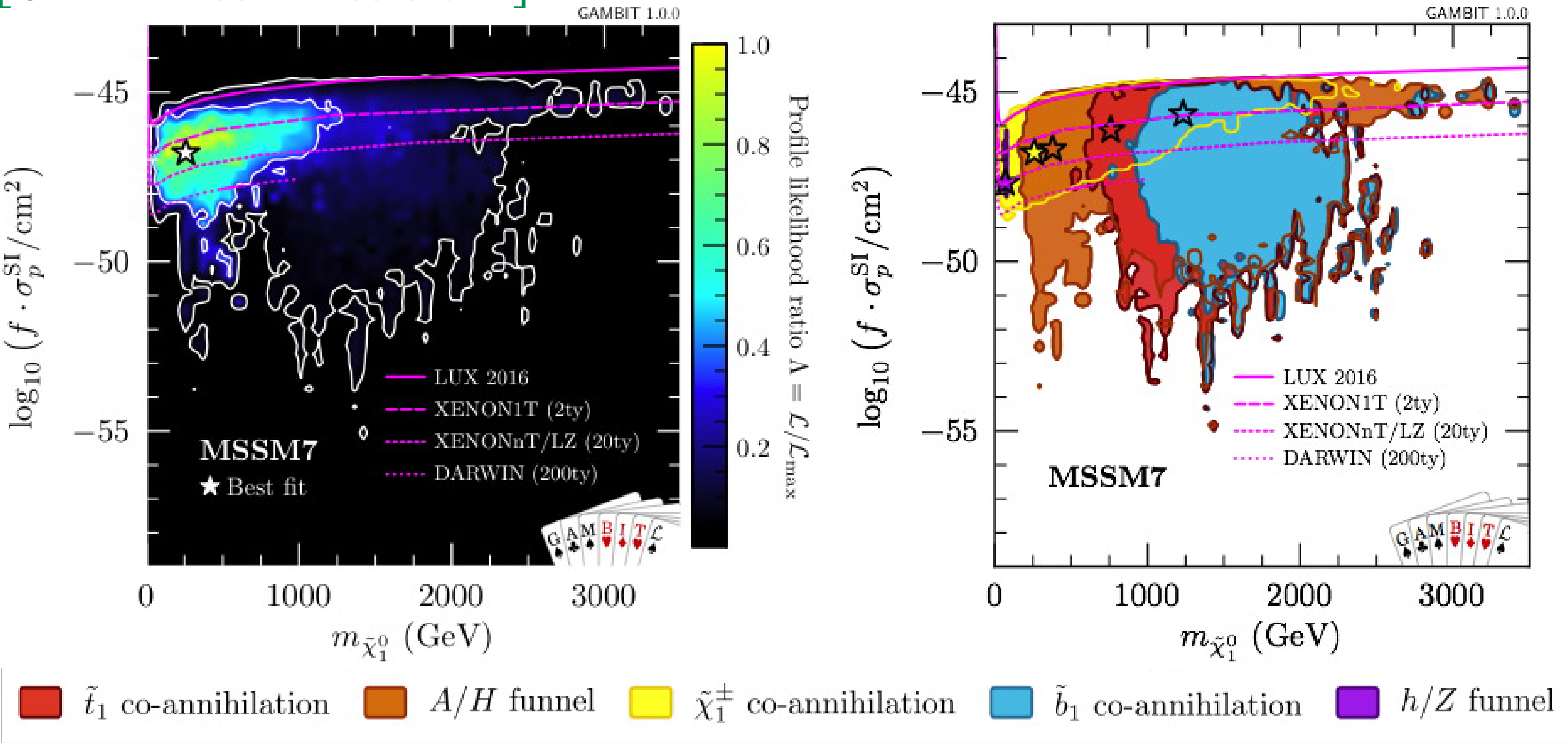
[Arkani-Hamed, Delgado & Giudice 0601041]



HIGGSINO DARK MATTER

The Higgsino DM region mostly covered by Direct Detection:

[GAMBIT coll. 1705.07917]

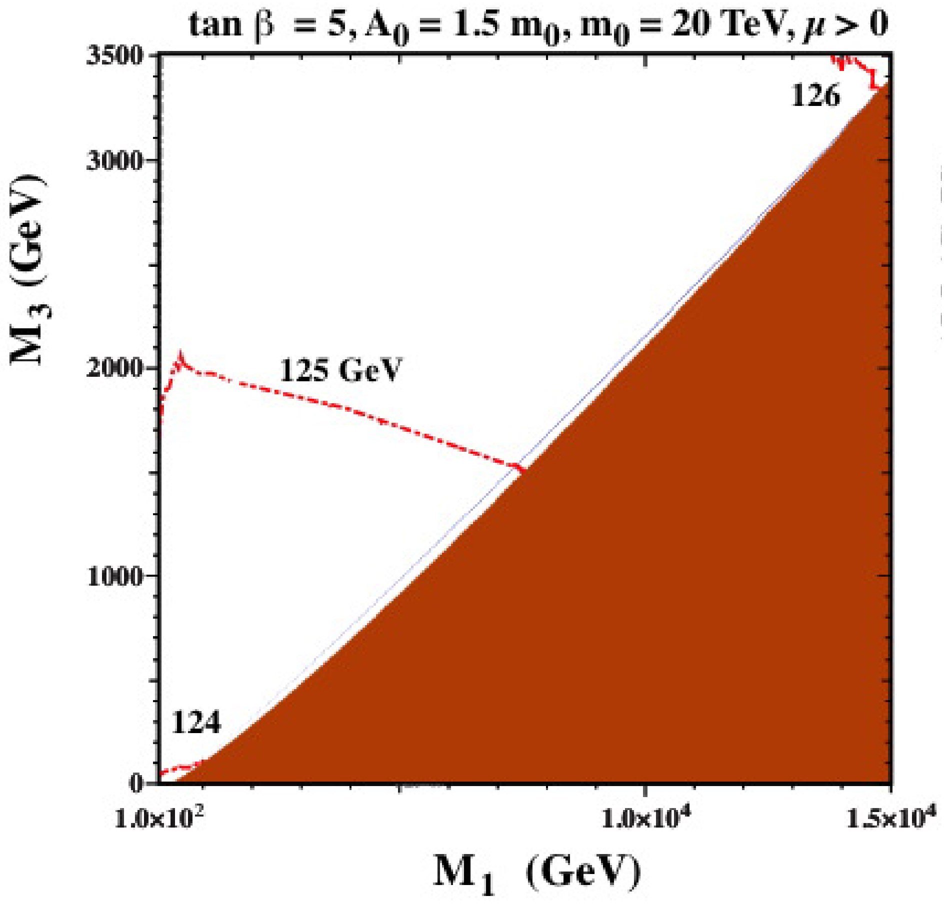


Nevertheless for other compositions low cross-section is possible

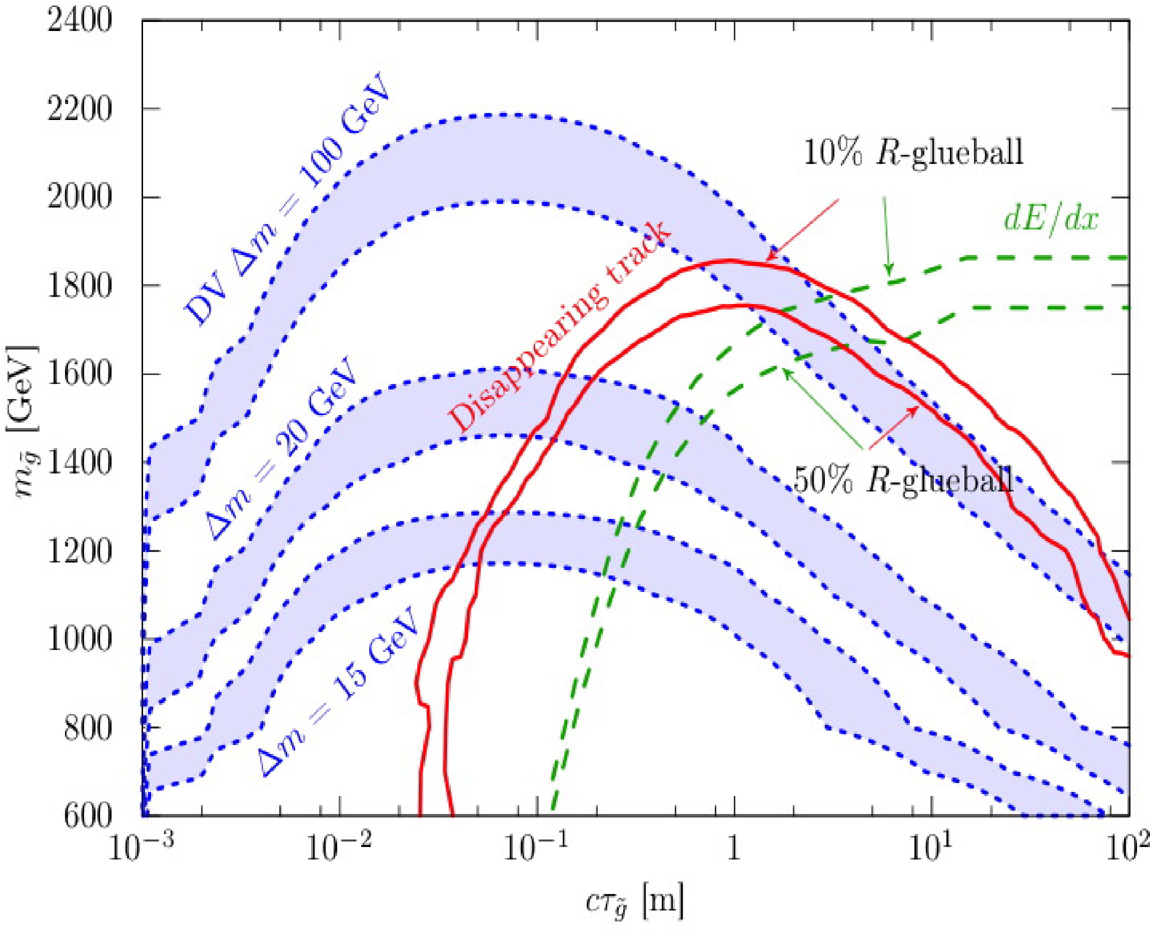
BINO-GLUINO COANNIHILATION

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

[Ellis, Evans, Luo & Olive 1510.03498]



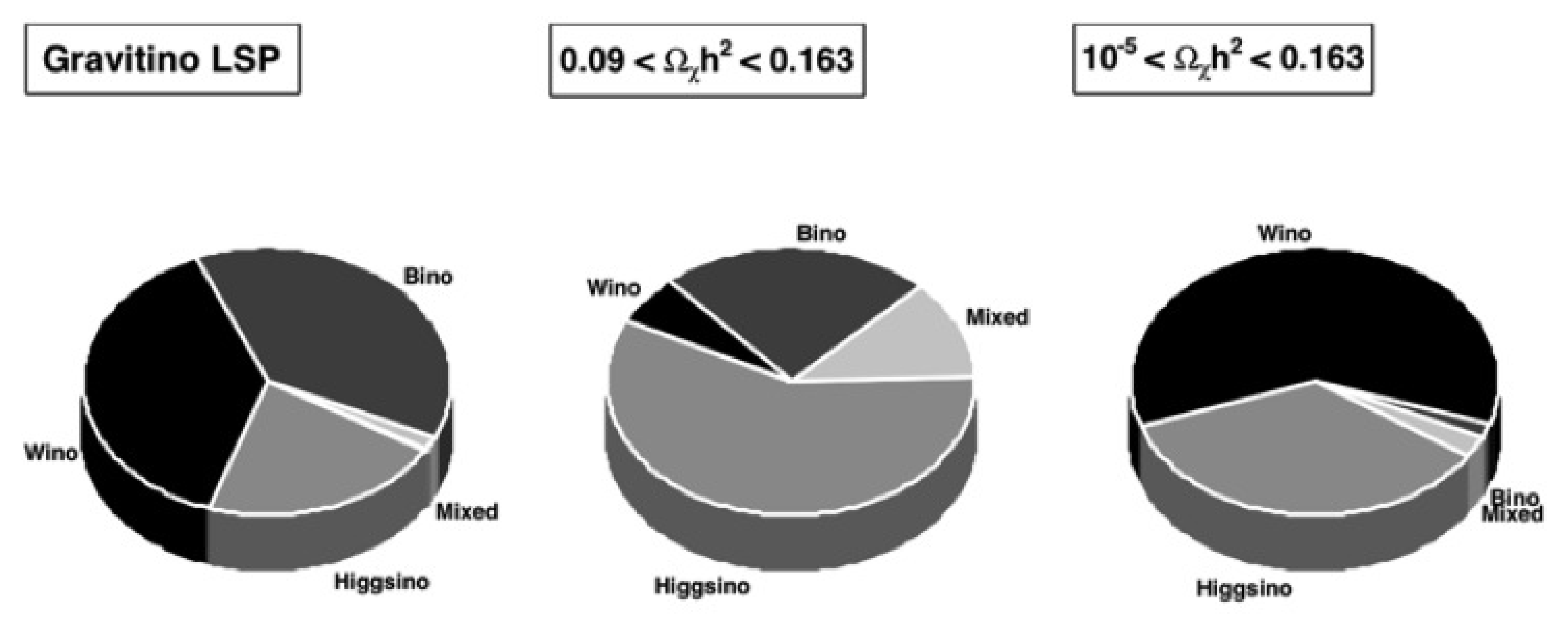
[Nagata, Otono & Shirai 1701.07664]



GRAVITINO DM IN PMSSM

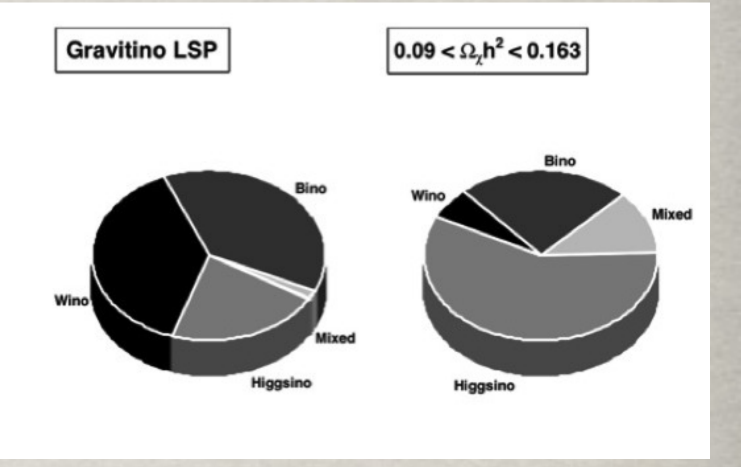
[Arbey et al. 1505.04595]

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...

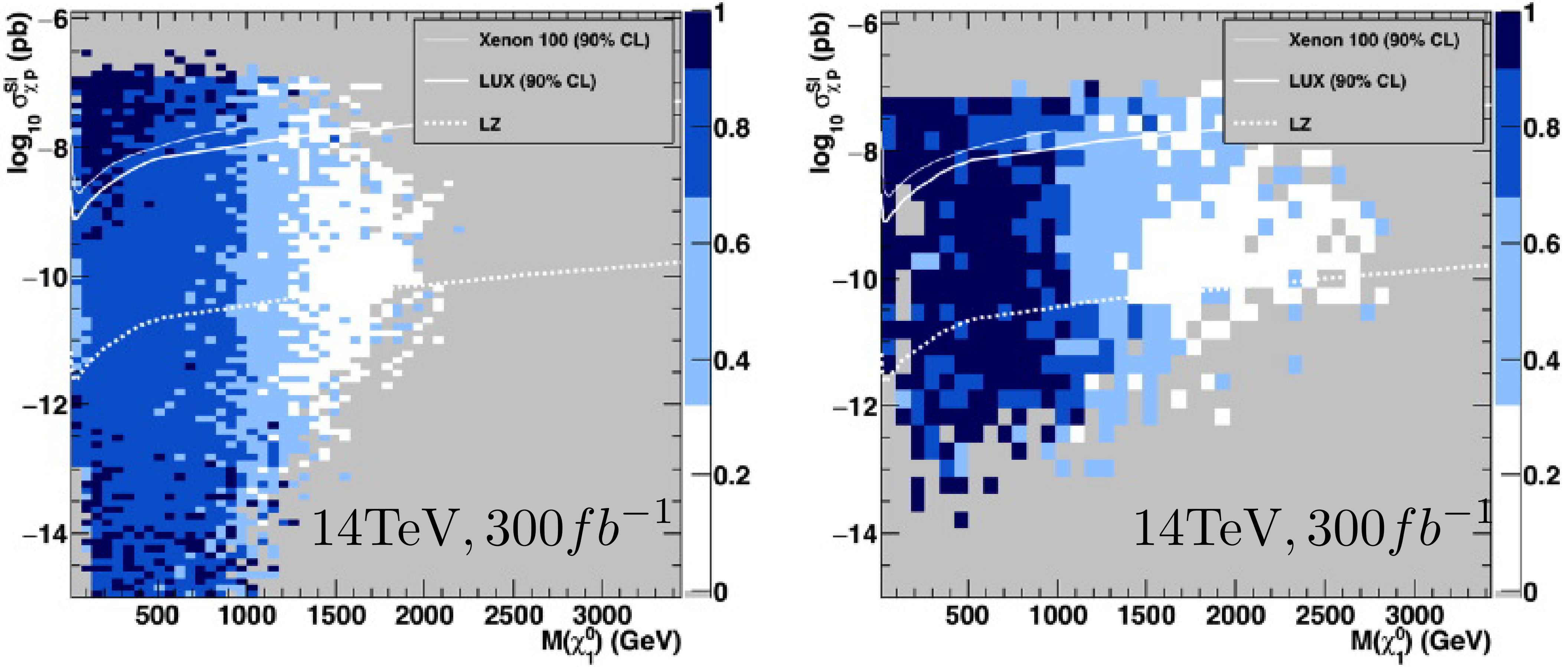


GRAVITINO VS NEUTRALINO DM

The neutralino compositions is very different, so only half the neutralino DM points will be excluded by LHC-14, while 75% of the gravitino DM points...



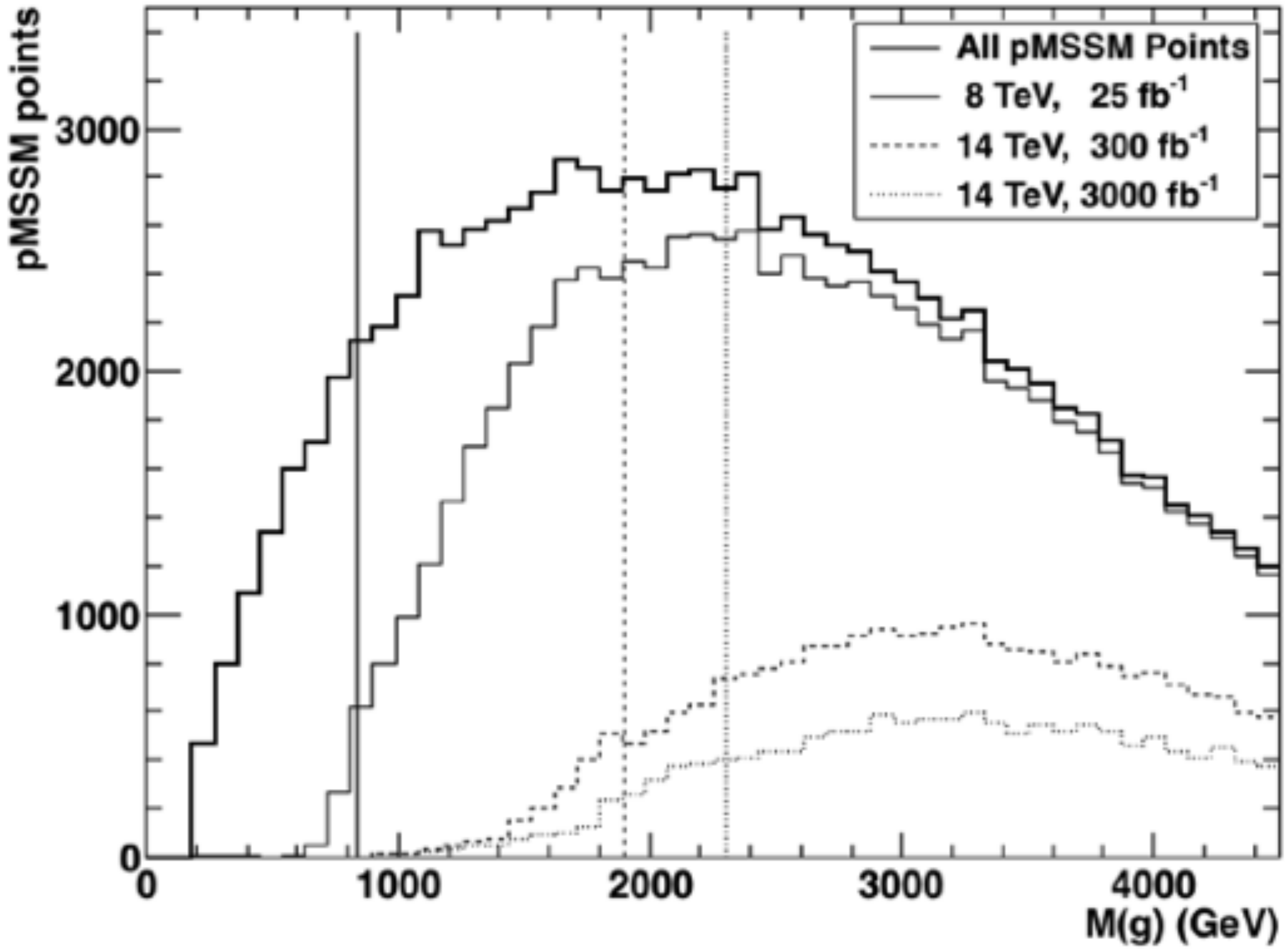
[Arbey et al. 1505.04595]



GLUINO MASS IN pMSSM

In the generic pMSSM limits on the gluino mass are less strong than in constrained/simplified models !

[Arbey et al. 1505.04595]



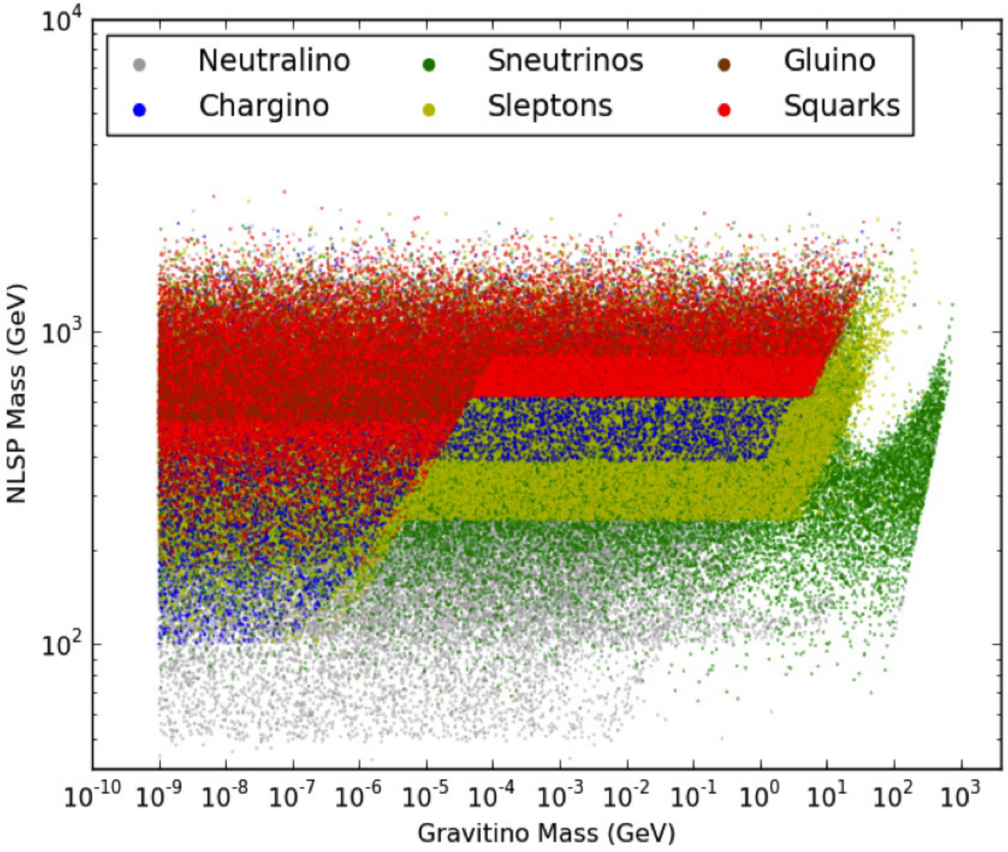
HEAVY SUSY ???

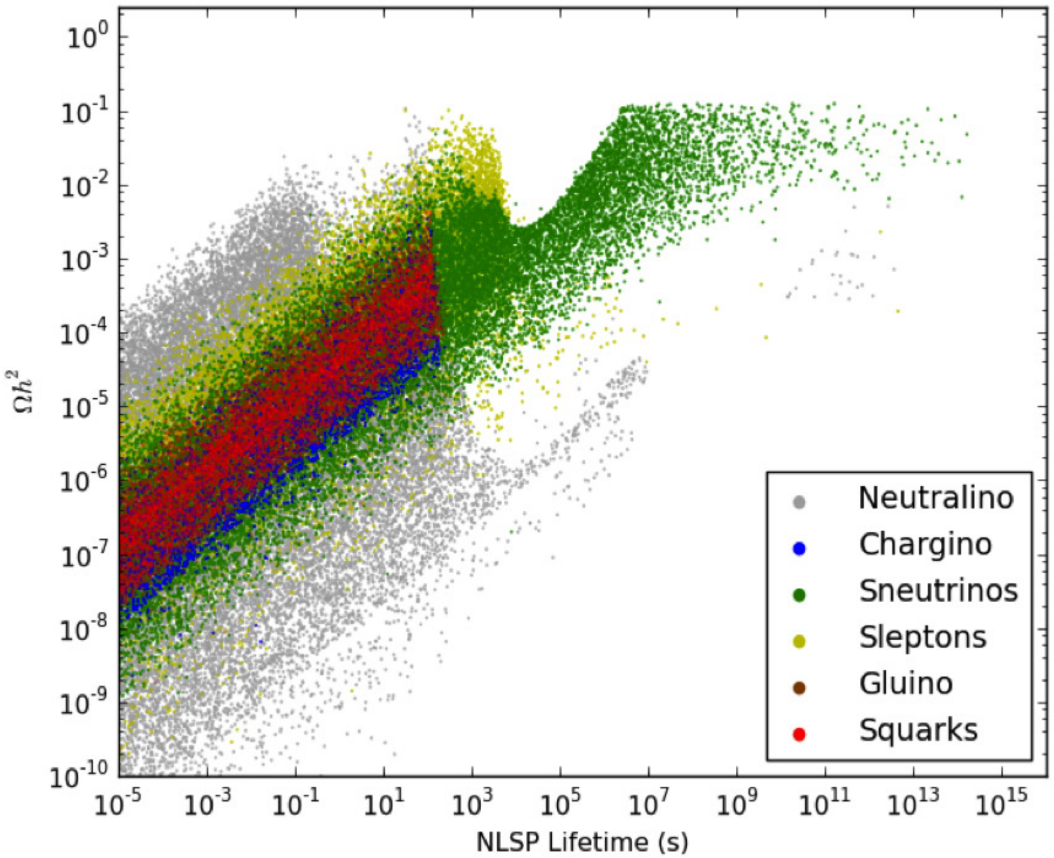
Maybe the arguments requiring SUSY at the EW scale like naturalness are just red-herrings and instead SUSY is much heavier…

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]





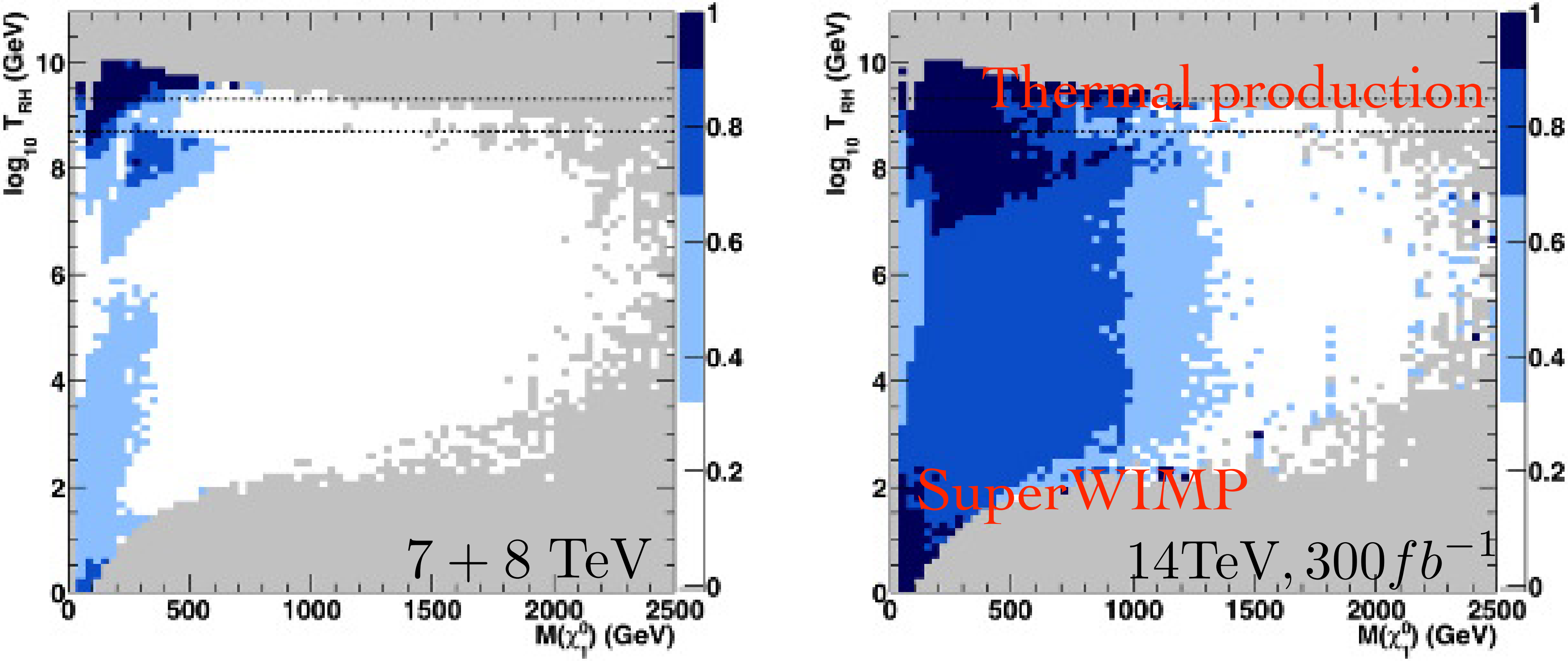
Many points for various NLSPs excluded by BBN: only the sneutrino survives to large gravitino masses.

Heavy NLSP is actually preferred !

GRAVITINO DM IN pMSSM

[Arbey et al. 1505.04595]

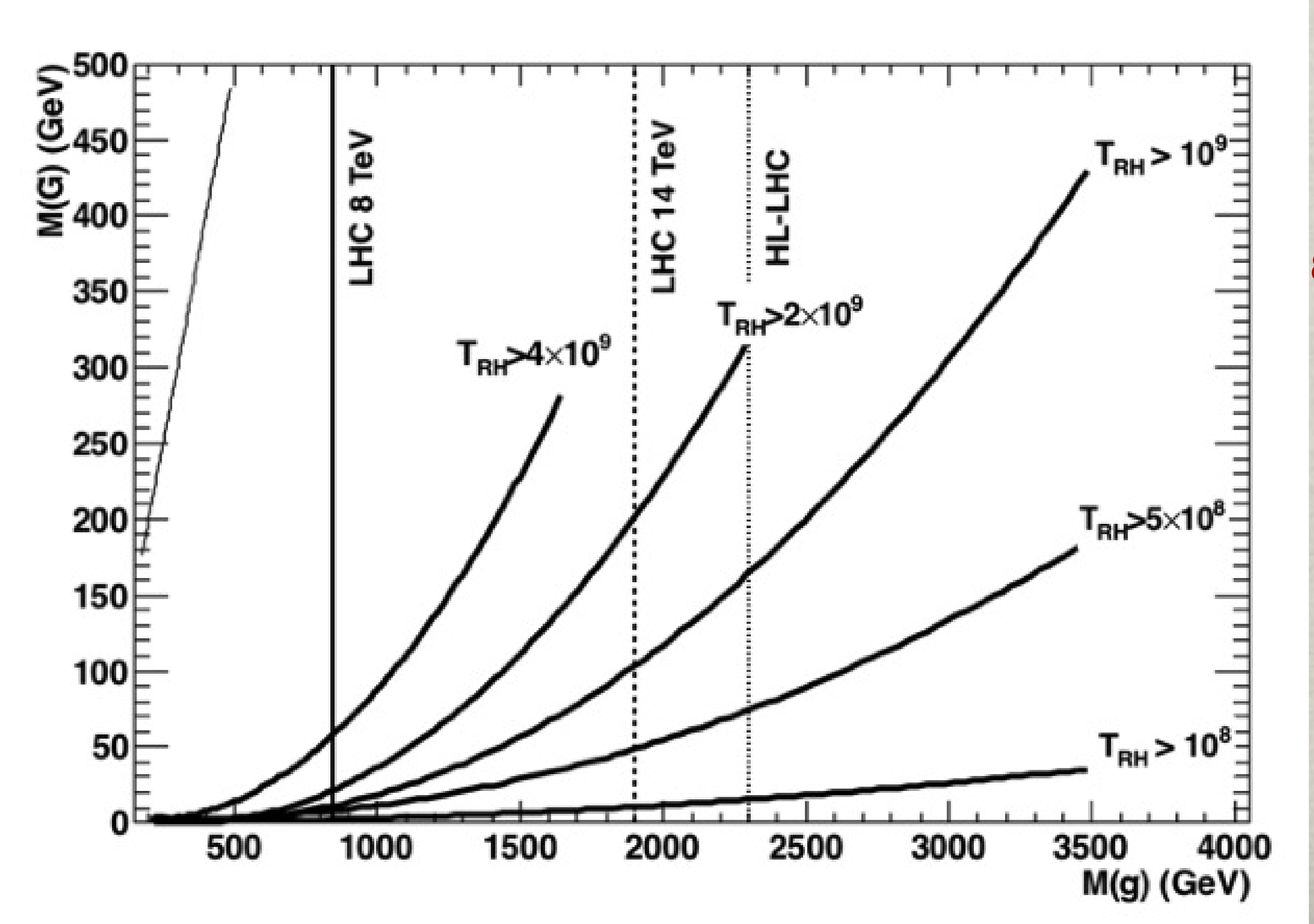
Interplay between gravitino production and gaugino masses very strong: high T_{RH} region corresponds to light gauginos and it is more easily tested as well as SuperWIMP region !



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.

$$W_{R\not p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \cancel{\lambda'' U^c D^c D^c}$$

no p decay

Open window:

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

For the NLSP to decay before BBN

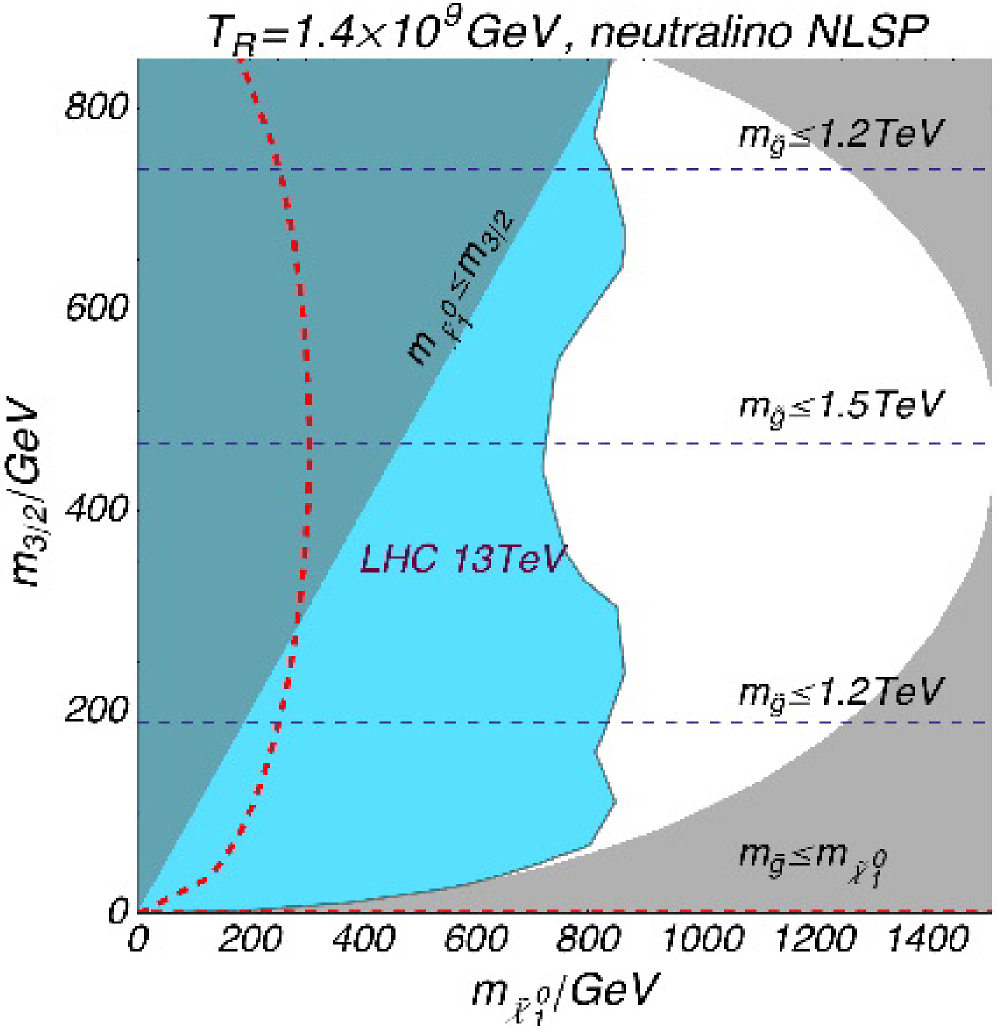
To avoid wash-out of lepton number

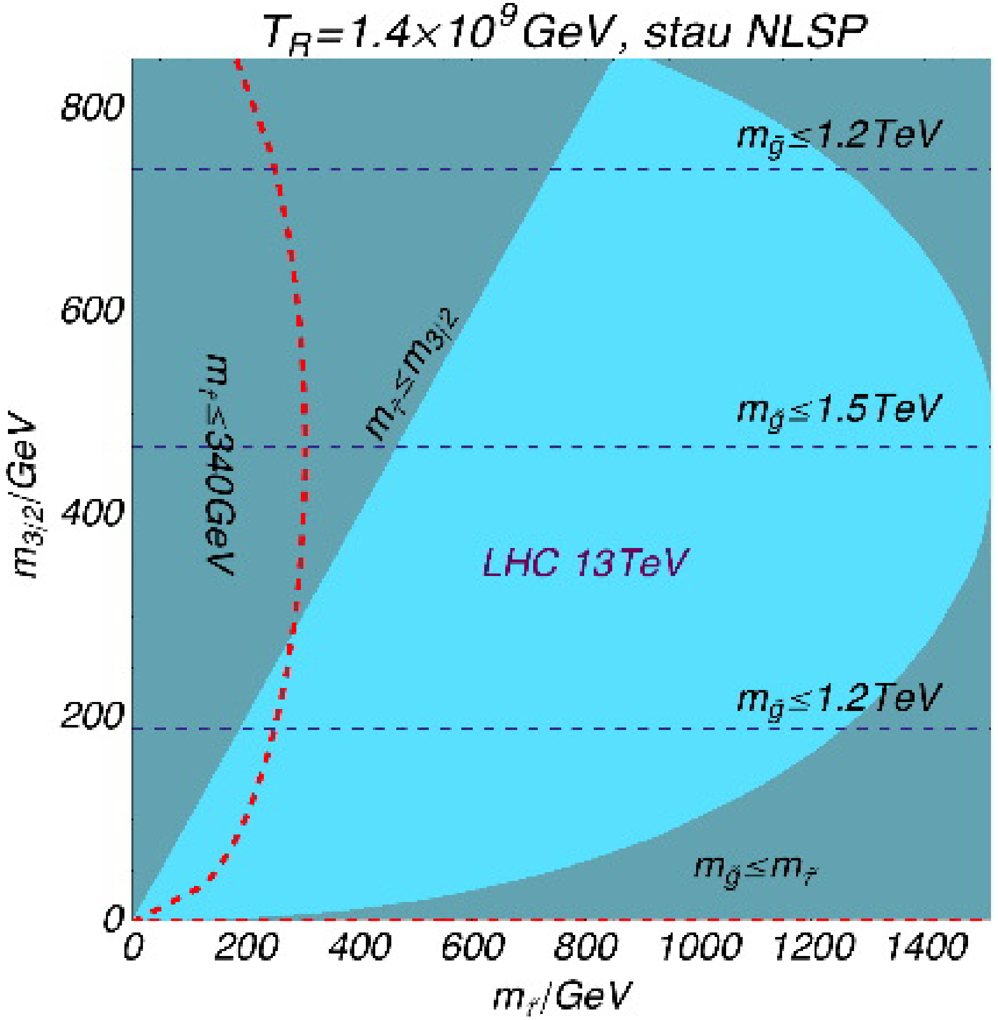
Explicit bilinear R-parity breaking model which ties R-parity breaking to B-L breaking and explains the small coupling.

Gravitino DM & T_RH

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

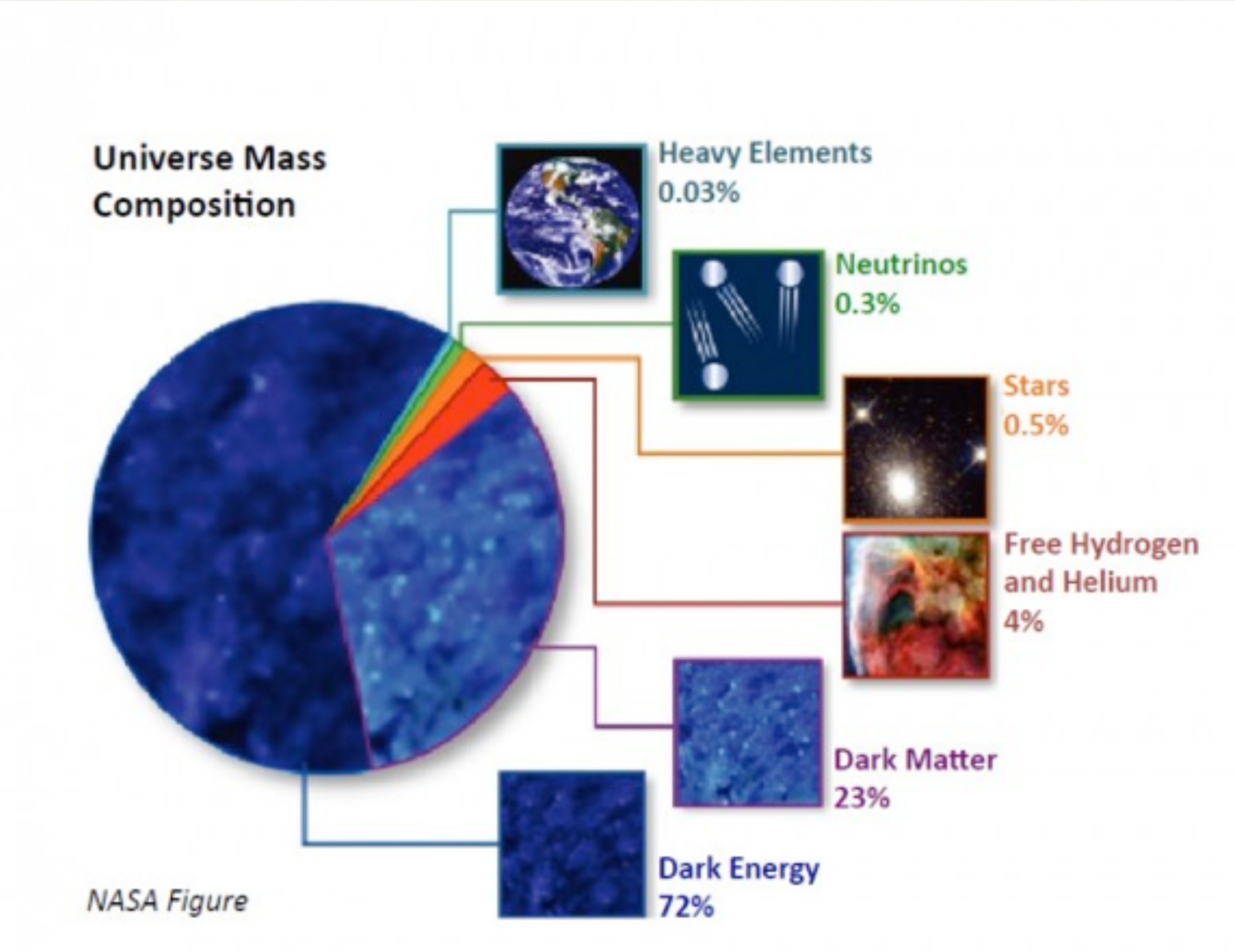
[Ibe, Suzuki & Yanagida 1609.06834]





HIGH SCALE SUSY FOR BARYOGENESIS

UNIVERSE COMPOSITION



Universe Mass Composition

NASA Figure

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

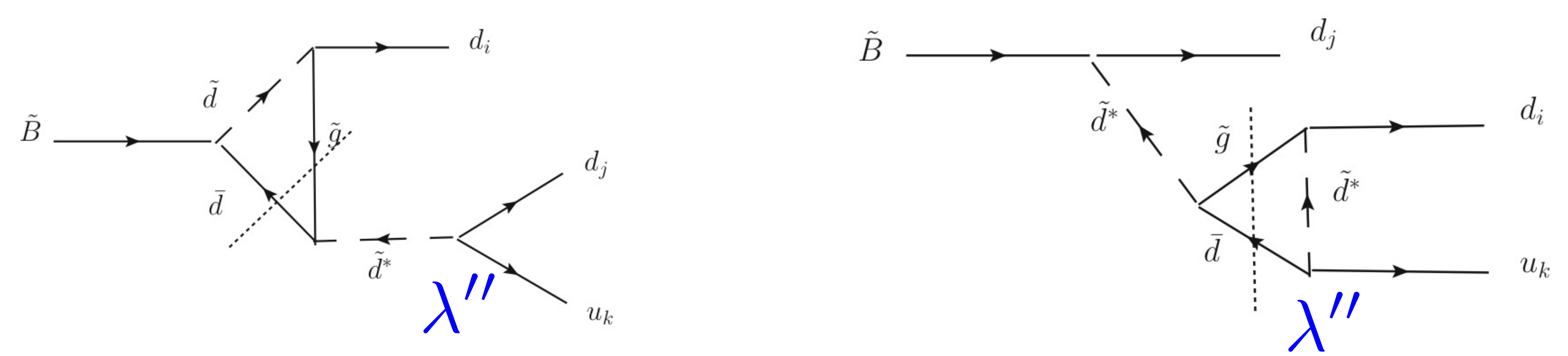
$$\tilde{B} \rightarrow udd,\ \ \bar{u}\bar{d}\bar{d},\ \ \tilde{g}\bar{q}q$$

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...

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

Small numbers

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

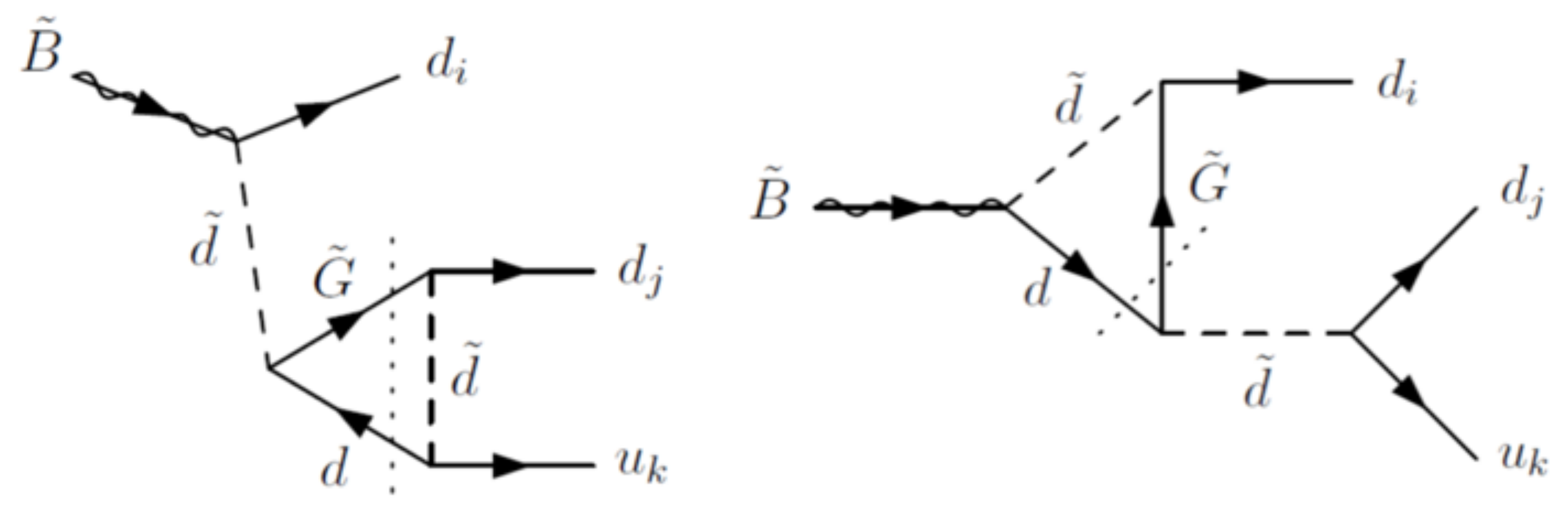
$$\longrightarrow \frac{\Omega_{\Delta B}}{\Omega_{DM}} = \frac{m_p}{m_{DM}} \frac{\epsilon_{CP}\, BR(\chi \to \not{B})}{BR(\chi \to DM + \text{anything})}$$

independent of Bino density

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

CP VIOLATION IN RPV SUSY

The loop diagrams contributing to the CP violation are



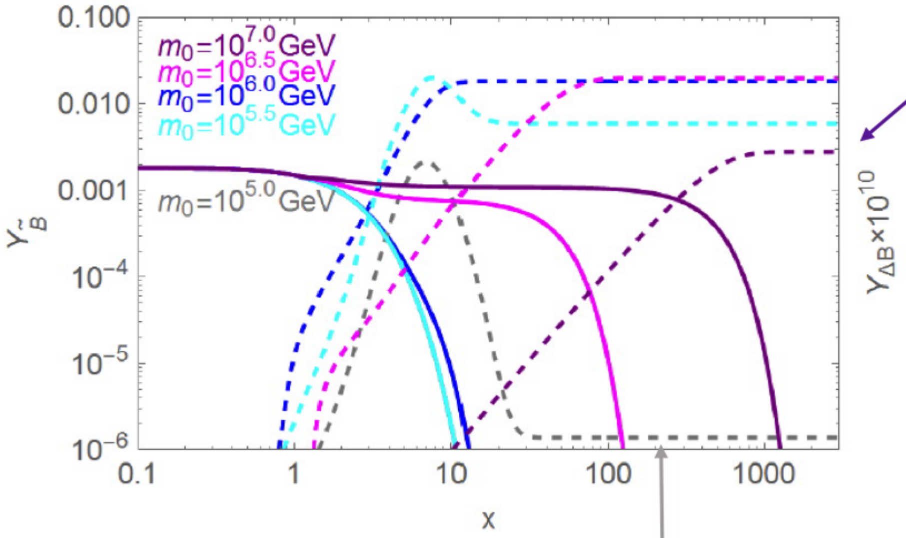
CP violation can be provided either by a phase difference between the Bino and Gluino masses or by flavour effects in the RPV couplings and CKM-mixing for squarks. The latter suffers unfortunately of GIM-like cancellations for degenerate squarks... Study of full flavour structure with general squark mass spectrum is on-going [G. Arcadi, LC & F. Kirk work in progress]

BARYOGENESIS IN RPV SUSY

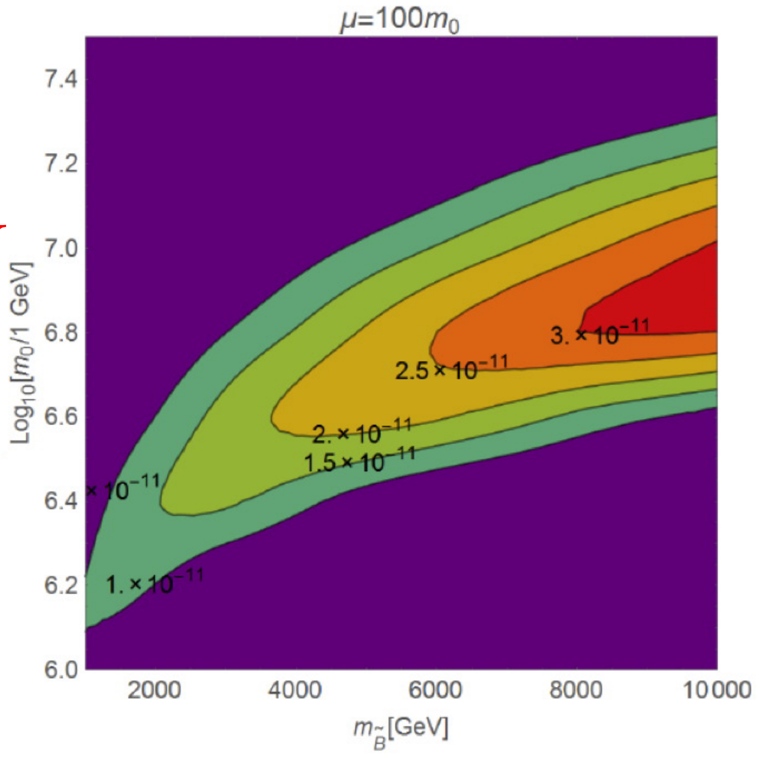
[Arcadi, LC & Nardecchia 1507.05584]

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

Asymmetry suppressed by the high scalars



$10^7\,\mathrm{GeV}$



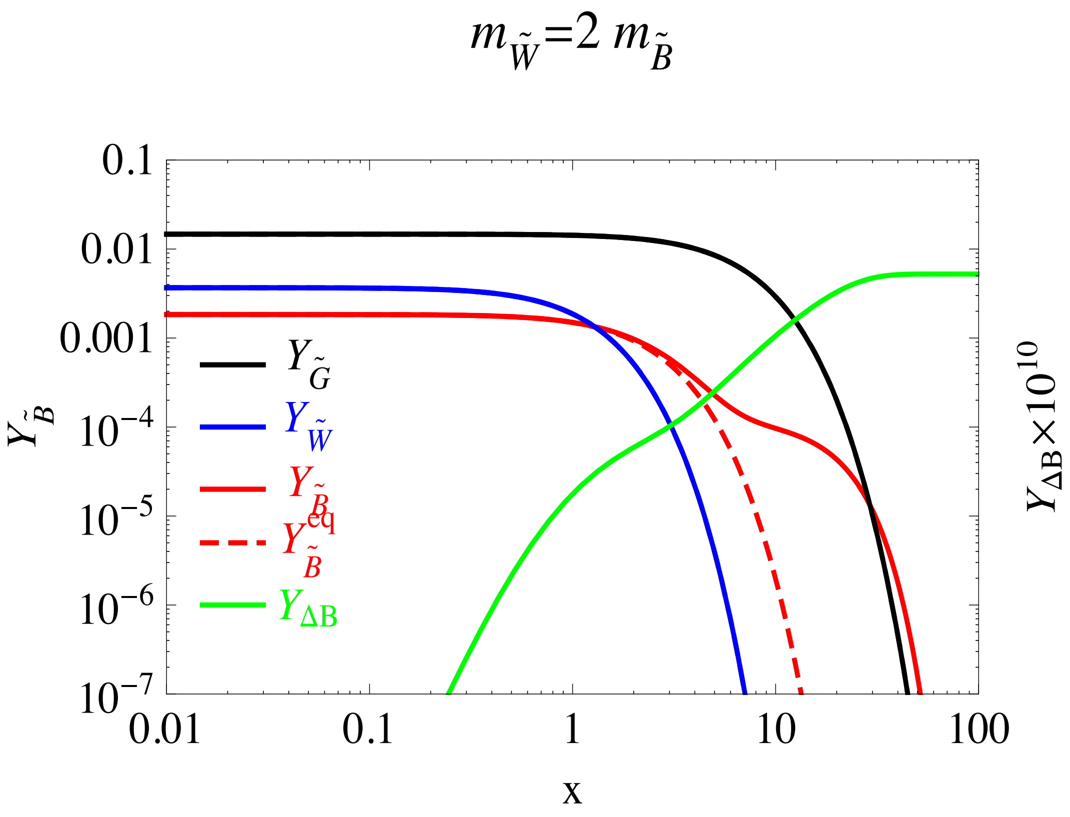
Asymmetry suppressed by wash-out

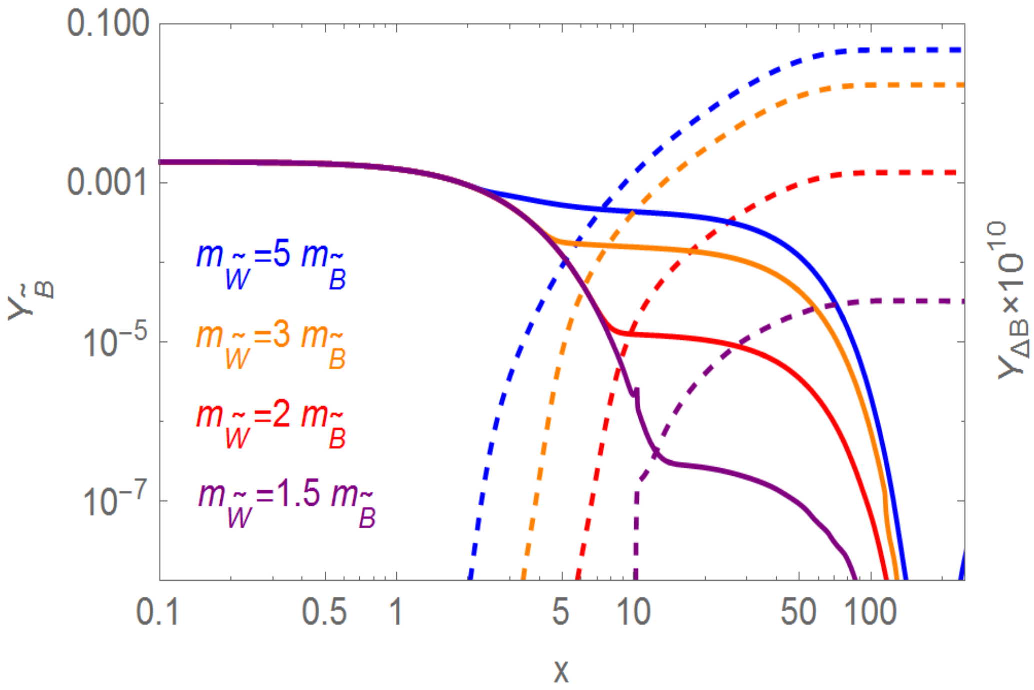
Rather definite prediction for range of scalar masses Heavy !!!

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...

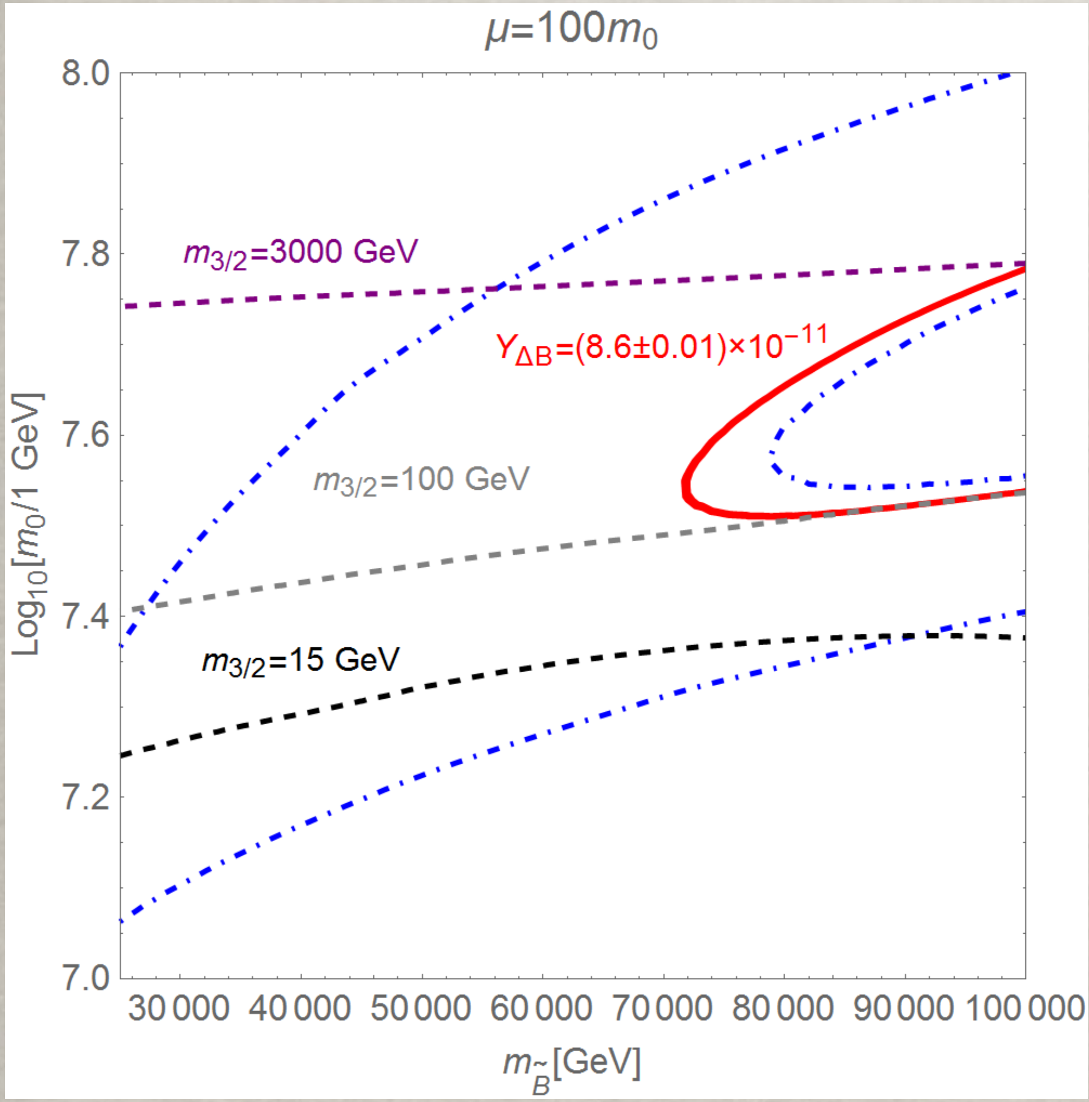
$$\Omega^{FI}_{3/2}h^2 \sim 0.002 \left(\frac{m_{\tilde{W}}}{10\ \text{TeV}}\right)^3 \left(\frac{m_{3/2}}{1\ \text{TeV}}\right)^{-1}$$

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

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...

GLUINO NLSP IN RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

The gluino is in this scenario the lightest SUSY particle and 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.

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

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

- The search for a DM particle continues on all fronts, but particularly for Dark Matter candidates with a working production mechanism, like FIMP/SuperWIMPs.
- The FIMP/SuperWIMP framework is quite general and could point to decaying Dark Matter and possibly heavy metastable particles or displaced vertices at LHC with different decay channels.
- Supersymmetric models are still alive and actually heavi(er) than expected SUSY may give some advantages in cosmology, e.g. baryogenesis via RPV
- We are still exploring the parameter space of Dark Matter interactions, and hopefully a discovery is on the way !