Supersymmetric dark matter with low reheating temperature of the Universe

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L. Roszkowski, ST, K. Turzyński hep-ph/1406.0012

Motivation

- What is the nature of dark matter (DM)?

  $\Rightarrow$ Lightest Supersymmetric Particle(?)

- LHC bounds $\Rightarrow$ SUSY scale $M_S \gtrsim 1$ TeV
  $\Rightarrow$ popular higgsino DM with $m_\chi \sim 1$ TeV...

- ...but what else? It's difficult to get neutralino dark matter with $m_\chi > 1$ TeV

- Any prospects for discovery such heavy DM?

- Gravitino DM – typically discussed upper limit on the reheating temperature $T_R \lesssim 10^7 - 10^8$ GeV

  What about lower limit on T_R?

Reheating period in the evolution of the Universe

At the end of a period of cosmological inflation:

- $T \approx 0$
- large potential energy of the inflaton field ϕ is transformed into the kinetic energy of recreated particles
- then $T \nearrow$ (reheating)

If instantaneous reheating: $\Gamma_\phi = H = \sqrt{\frac{8\pi}{3M_{Pl}^2}\rho_\phi}$ and $\rho_\phi = \rho_{rad}(T_R) \sim T_R^4$

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_*(T_R)}{45}}\frac{{T_R}^2}{M_{Pl}} \quad \text{defines reheating temperature } \mathrm{T_R}$$

If non-instantaneous reheating – Boltzmann equations:

G. F. Giudice, E. W. Kolb, A. Riotto hep-ph/0005123, G. Gelmini *et al.* hep-ph/0602230

$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi\rho_\phi \quad \text{inflaton field}$$

$$\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_\phi\rho_\phi + \langle\sigma v\rangle 2\langle E_X\rangle\left[n_X^2 - (n_X^{eq})^2\right] \quad \text{radiation}$$

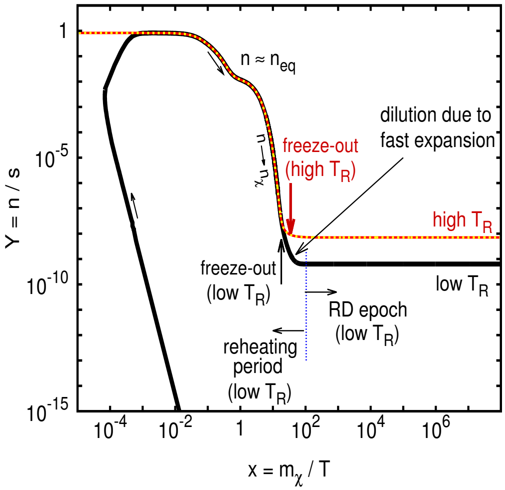
$$\frac{dn_X}{dt} = -3Hn_X - \langle\sigma v\rangle\left[n_X^2 - (n_X^{eq})^2\right] \quad \left(+ \frac{b}{m_\phi}\Gamma_\phi\rho_\phi\right) \quad \text{dark matter}$$

Radiation dominated (RD) epoch begins when $T \sim T_R$,

before – the reheating period

Reheating period – evolution of the total supersymmetric yield

$Y = \frac{n}{s}$ with $n = \sum_i n_i \xrightarrow{T\searrow} n_\chi$



Dark matter particles freeze-out in the reheating period:

- freeze-out occurs at a slightly higher temperatures than in the standard case
- after freeze-out, but before the end of the reheating period, the DM particles are effectively diluted away

$$\Omega_\chi h^2(\text{low } T_R) \sim \left(\frac{T_R}{T_{\text{fo}}^{\text{new}}}\right)^3 \left(\frac{T_{\text{fo}}^{\text{old}}}{T_{\text{fo}}^{\text{new}}}\right) \Omega_\chi h^2(\text{high } T_R)$$

G. F. Giudice, E. W. Kolb, A. Riotto
hep-ph/0005123

$\Omega_\chi h^2(\text{low } T_R) < \Omega_\chi h^2(\text{high } T_R)$

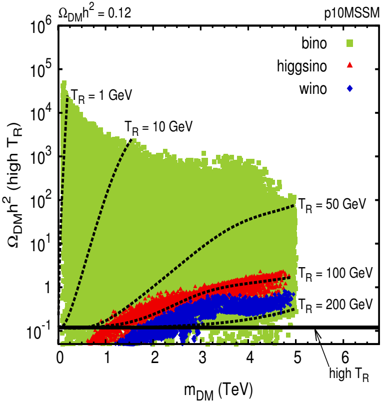
(w/o inflaton decays to DM)

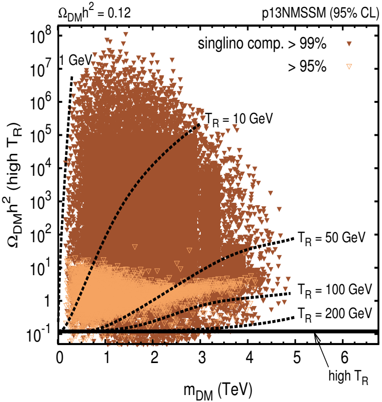
Supersymmetric dark matter with low T_R in the (N)MSSM

- the lightest neutralino is natural DM candidate (R-parity conservation)
- depending on its composition it can be: bino, higgsino, wino, singlino (NMSSM) or a mixed state
- for bino or singlino DM relic density can vary by several orders of magnitude for a fixed m_χ
- for bino DM $\Omega_{\widetilde{B}} h^2(\text{high } T_R) \lesssim g_{*,fo}^{-1/2} \left(\frac{m_{\tilde{l}}}{m_{\widetilde{B}}}\right)^2 \left(\frac{m_{\tilde{l}}}{460\ GeV}\right)^2$

M. Drees *et al.* hep-ph/9207234, J. D. Wells hep-ph/9809504

- for higgsino and wino DM $\Omega_\chi h^2 \sim m_\chi^2$, wino DM – Sommerfeld effect





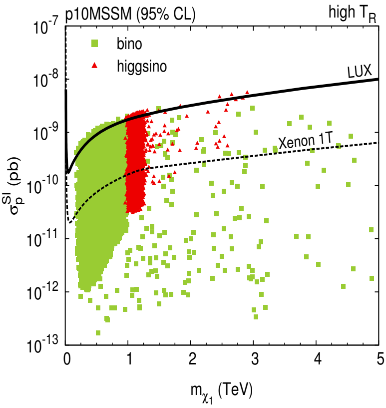
Higgsino DM

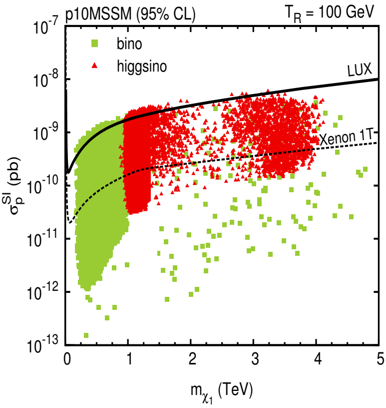
high T_R

- correct relic density for $m_\chi \sim 1$ TeV
- testable – DM direct detection σ_p^{SI} (Xenon1T)

low T_R (w/o inflaton decays to DM)

- correct relic density for $m_\chi \gtrsim 1$ TeV
- still testable



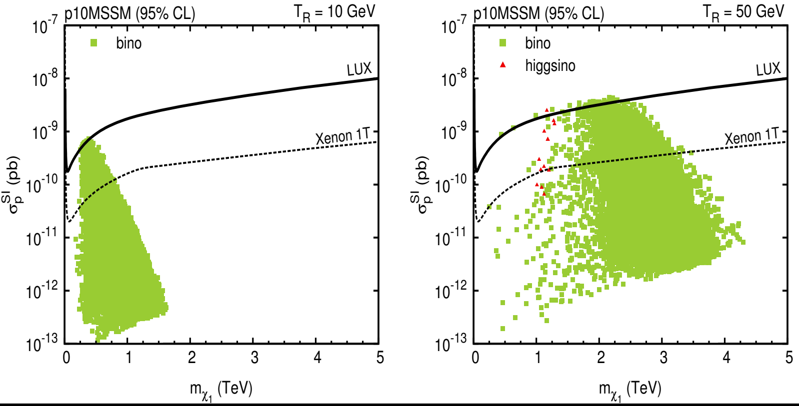


Bino DM – high T_R

- correct relic density in the bulk region or with some specific conditions: (co)annihilations, resonances
- only partly testable in DM direct detection experiments
- possibly some hints from colliders (stau-coannihilation region)

Bino DM – low T_R (w/o inflaton decays to DM)

- correct relic density for wide range of m_χ depending on T_R w/o specific mass patterns



Wino DM – high T_R

- correct relic density for $m_{\widetilde{W}} \sim 3$ TeV (including Sommerfeld effect)

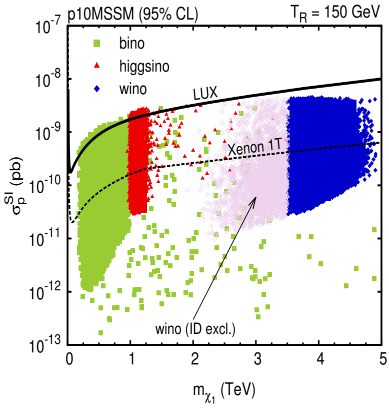
J. Hisano *et al.* hep-ph/0610249,A. Hryczuk *et al.* hep-ph/1010.2172

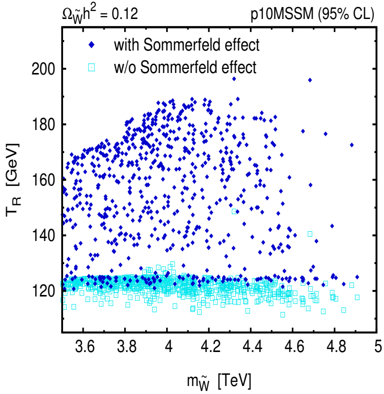
- excluded by DM indirect detection (γ-ray line) for $m_{\widetilde{W}} \lesssim 3.5$ TeV

T. Cohen *et al.* hep-ph/1307.4082, J. Fan *et al.* hep-ph/1307.4400, A. Hryczuk *et al.* hep-ph/1401.6212

Wino DM – low T_R (w/o inflaton decays to DM)

- correct relic density for heavy wino DM
- testable – direct and/or indirect DM detection





Gravitino $\widetilde{G}$ DM

- superpartner of graviton
- extremely weakly interacting massive particle (EWIMP) – interaction rate suppressed by $M_{\rm Pl} \sim 10^{18}$ GeV
- not directly testable, but some hints from the LHC may be possible
- cosmological constraints

Gravitino relic density

$$\Omega_{\widetilde{G}} h^2 = \Omega_{\widetilde{G}}^{\rm NTP} h^2 + \Omega_{\widetilde{G}}^{\rm TP} h^2 \overset{{\rm low}\ T_R}{\simeq} \Omega_{\widetilde{G}}^{\rm NTP} h^2 = \frac{m_{\widetilde{G}}}{m_\chi} \Omega_\chi h^2$$

Non-Thermal Production
late decays of the next-to-LSP

Thermal production
scatterings of superparticles in the thermal plasma

Big Bang Nucleosynthesis (BBN) constraints

- late-time decays of the next-to-LSP to gravitino initiate electromagnetic and hadronic cascades that destroy light nuclei in the early Universe
  $\rightarrow$ this alters BBN predictions
- constraints depend on the next-to-LSP's lifetime τ and relic density $\Omega_\chi h^2$ as well as on the hadronic branching fraction B_h

K. Jedamzik hep-ph/0604251, M. Kawasaki *et al.* hep-ph/0804.3745
K. Jedamzik hep-ph/0710.5153, M. Kawasaki hep-ph/0703122

Gravitino DM – low T_R

$$\Omega_{\tilde G} h^2 = \frac{m_{\tilde G}}{m_{\rm NLSP}}\, \Omega_{\rm NLSP}\, h^2$$

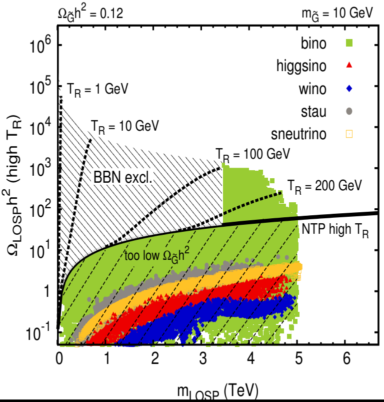
Bino next-to-LSP

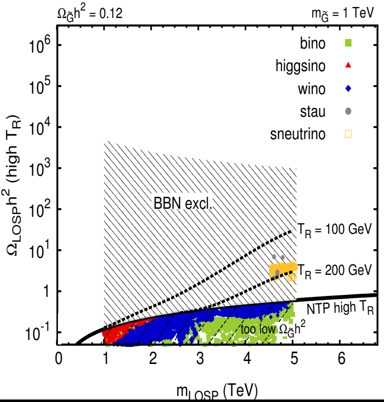
- $B_h \gtrsim 0.1$
- $\tau \sim \frac{m_{\tilde G}^2}{m_{\tilde B}^5}$ for $m_{\tilde B} \gg m_{\tilde G}$
- BBN requires $\tau \lesssim 0.1$ s

$$\Rightarrow \quad m_{\tilde B} \gtrsim 1.4 \left(\frac{m_{\tilde G}}{\rm GeV}\right)^{2/5} \rm TeV$$

Slepton next-to-LSP

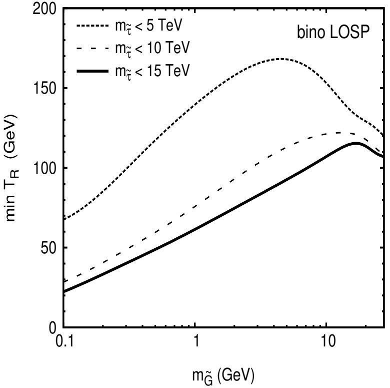
- lower $\Omega_{\tilde l} h^2 \Rightarrow$ larger $m_{\tilde G}$
- low B_h
- $\tau \sim \frac{m_{\tilde G}^2}{m_{\tilde l}^5}\left(1 - \frac{m_{\tilde G}^2}{m_{\tilde l}^2}\right)^{-4}$

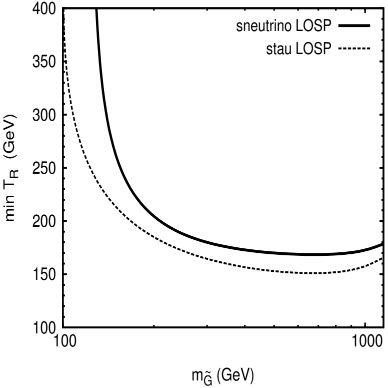




Gravitino DM – lower limit on T_R

BBN + relic density constraints $\Rightarrow$ lower limit on T_R





Conclusions

- for low enough reheating temperature T_R neutralino freeze-out may occur before the RD epoch – in the reheating period…
- ….this opens up new regions with neutralino dark matter
- regions with heavy higgsino or wino DM can be tested in direct/indirect detection experiments
- wino DM can be again allowed
- bino DM – correct relic density w/o specific mass patterns
- gravitino DM in such scenario is only produced in non-thermal production
- BBN constraints in case of gravitino DM introduce lower limit $T_R \gtrsim 100$ GeV