Macroscopic effects on neutralino dark matter depletion through large R-charge[a]

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[a] Awaiting pre-print and publication

Motivation

- There is evidence of a non-baryonic form of matter, approx. 85% of the total matter in the universe.
- An interesting WIMP candidate is the Lightest Supersymmetric Particle (LSP) which is absolutely stable when R-parity is conserved.
- Models like mSUGRA and strong direct detection constraints suggest a predominantly bino-like LSP $\tilde{B}$.
- Pure bino suffers from a small interaction with the primordial plasma cross section compared to wino/Higgsino (unless in coannihilation with almost-degenerate NLSP, requires light sfermions)[1]:

$$\langle \sigma_{\tilde{B}} v \rangle = \frac{3g^4 \tan^4 \theta_W r \left(1+r^2\right)}{2\pi m_{\tilde{e}_R}^2 x (1+r)^4}, \quad x \equiv \frac{M_1}{T}, \quad r \equiv \frac{M_1^2}{m_{\tilde{e}_R}^2}$$

$$\Omega_{\tilde{B}} h^2 = 1.3 \times 10^{-2} \left(\frac{m_{\tilde{e}_R}}{100\mathrm{GeV}}\right)^2 \frac{(1+r)^4}{r\left(1+r^2\right)} \left(1 + 0.07 \log \frac{\sqrt{r}100\mathrm{GeV}}{m_{\tilde{e}_R}}\right)$$

through right-handed slepton exchange $\tilde{e}_R$.

[1] N. Arkani-Hamed, A. Delgado, G.F. Giudice, Nucl.Phys.B741:108-130, (2006)

Motivation

Freeze-out temperature, $T_{\text{freeze-out}}$

$$x_{\text{freeze-out}} = X - \left(n + \frac{1}{2}\right) \log X, \quad X = 25 + \log\left[(n+1)\frac{g_\chi}{\sqrt{g_*}} m_\chi \sigma \, 6.4 \times 10^6 \mathrm{GeV}\right]$$

eg. $m_\chi \sim 100$ GeV, $m_{\tilde{e}_R} \sim$ many TeV $\rightarrow$ $x_{\text{freeze-out}} \sim 10$, $\Omega_{\tilde{B}} h^2 \sim O(10^5)$.

- Relic abundance is typically many orders larger then observed[2]:

$$\Omega_{\text{Planck}} h^2 = 0.112 \pm 0.006$$

- In cases like these, we can consider alternate (non-standard) cosmological histories and their effects on DM abundance. These models would otherwise be rejected due to DM overpopulation.

[2] Planck Collaboration et al., A A 594, A13 (2016)

Previous work: Spontaneous R-parity breaking[3]

Low-energy effective sneutrino-Higgs potential at zero temperature:

$$V_0 = -\frac{m_h^2}{4}h^2 + m_{\tilde{\nu}}^2|\tilde{\nu}|^2 + \frac{m_Z^2}{8v^2}\left(\frac{m_h}{m_Z}h^2 + 2|\tilde{\nu}|^2\right)^2$$

where $m_h \approx 125$ GeV and $m_{\tilde{\nu}}^2$ is the soft supersymmetry breaking sneutrino parameter.

Dominant high-temperature corrections to the potential

$$\begin{aligned}
V_T &= \frac{\alpha_h T^2}{2}h^2 + \alpha_{\tilde{\nu}}T^2|\tilde{\nu}|^2 \\
\alpha_h &= \frac{1}{8v^2}\left(4m_W^2 + 2m_Z^2 + 4m_t^2 + m_h^2 + \frac{2}{3}m_Z m_h\right) \approx 0.383 \\
\alpha_{\tilde{\nu}} &= \frac{1}{8v^2}\left(4m_W^2 + 4m_Z^2 + \frac{1}{3}m_Z m_h\right) \approx 0.129
\end{aligned}$$

[3] A. Kobakhidze, M. Schmidt, M. Talia, Phys. Rev. D 98, 095026 (2018)

Previous work: Spontaneous R-parity breaking[3]

The (physical) sneutrino mass-squared should be positive - requires negative mass-squared parameter*

$$-\left(\frac{m_Z m_h}{2} + \text{ rad. corr. }\right) < m_{\tilde{\nu}}^2 < 0$$

Minimizing the full potential $V_0 + V_T$:

1. Universe at high-T starts off in $\langle h \rangle_T = \langle \tilde{\nu} \rangle_T = 0$,
2. At $T_c^{\tilde{\nu}} \approx 2.78|m_{\tilde{\nu}}|$, sneutrino condenses: $\langle \tilde{\nu} \rangle_T = \frac{v}{m_Z}\left(-m_{\tilde{\nu}}^2 - \alpha_{\tilde{\nu}} T^2\right)^{1/2}$, $\langle h \rangle_T = 0$ (R-parity broken),
3. At $T_c^h \approx 143$ GeV, Higgs condenses: $\langle h \rangle_T = \frac{v}{m_h}\left(m_h^2 - 2\alpha_h T\right)^{1/2}$, $\langle \tilde{\nu} \rangle_T = 0$ (R-parity restored, EW symmetry broken).

*Although atypical, tachyonic soft masses may emerge at high energies in some specific SUSY breaking scenarios.

[3] A. Kobakhidze, M. Schmidt, M. Talia, Phys. Rev. D 98, 095026 (2018)

Previous work: Spontaneous R-parity breaking[3]

Phase where R-parity is spontaneously broken, allowing neutralino to decay to lighter states during the phase:

$$T_h^c \approx 143\,\mathrm{GeV} < T < T_{\tilde{\nu}}^c \approx 2.78\,|m_{\tilde{\nu}}|$$

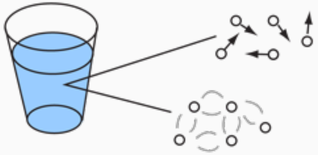
Duration of phase and decay rate depend *entirely* on **microscopic** physics description.

These scenarios have been explored in the so-called 'VEV Flip-Flop' models[3,4] which usually require additional fields/interactions or unusual parameter choices.

[4] M. J. Baker and J. Kopp, Phys. Rev. Lett. 119, no. 6, 061801 (2017)
[3] A. Kobakhidze, M. Schmidt, M. Talia, Phys. Rev. D 98, 095026 (2018)

Microscopic vs. macroscopic properties

1. **Microscopic** - Parameters in the Lagrangian where $\langle \phi \rangle \neq 0$ at high-T.
2. **Macroscopic** - Large background charge densities n_a induce high-T symmetry breaking over all parameter space of the microscopic description.
   Naturally useful for: L number in SM, R number in SUSY extensions.



General formulation for non-zero charge density[5]

Consider the potential with non-zero n_a and chemical potential μ_a:

$$\Delta V_n = -\frac{1}{2}\mu_a \mathcal{M}_{ab}\mu_b + \mu_a n_a$$

$$\mathcal{M}_{ab} = \frac{T^2}{6}\left(\sum_i f_a^i f_b^i + 2\sum_i b_a^i b_b^i\right) + 2\sum_i b_a^i b_b^i \left|\phi_i\right|^2$$

a, b - conserved symmetries (with chemical potentials $\mu_{a,b}$).

Obviously, with no R-symmetry, $f_a^i = b_a^i (= q_a^i)$.

Eliminating the chemical potentials $\mu_{a,b}$ in favour of the charge density, $n_{a,b}$ gives

$$\frac{\partial \Delta V_n}{\partial \mu_a} = 0 \to \mu_a = \left(\mathcal{M}^{-1}\right)_{ab} n_b$$

$$\Rightarrow \Delta V_n = \frac{1}{2} n_a \left(\mathcal{M}^{-1}\right)_{ab} n_b$$

[5] B. Bajc and G. Senjanovic, Phys. Lett. B 472, 373 (2000)

R-symmetry in the MSSM

The low-energy MSSM exhibits a global $U(1)_R$ R-symmetry[6] (excluding soft-breaking trilinear scalar terms):

$$V_0 = -\frac{m_h^2}{2}\phi^*\phi + m_{\tilde{\nu}}^2|\tilde{\nu}|^2 + \frac{m_Z^2}{8v^2}\left(\frac{2m_h}{m_Z}\phi^*\phi + 2|\tilde{\nu}|^2\right)^2$$

$$\phi \to \mathrm{e}^{i\alpha}\phi, \tilde{\nu} \to \mathrm{e}^{i\alpha}\tilde{\nu}, Q \to \mathrm{e}^{-i2\alpha/3}Q$$

$$U_L^c \to \mathrm{e}^{-i\alpha/3}U_L^c, D_L^c \to \mathrm{e}^{-i\alpha/3}D_L^c, E_L^c \to \mathrm{e}^{-i\alpha}E_L^c$$

R-charge assignments:

$$R_\phi = R_{\tilde{\nu}} = +1, R_{u_L} = R_{d_L} = -2/3, R_{u_L} = R_{d_L^c} = -1/3, R_{e_L} = R_{\nu_L} = 0$$

This is true even in the general case with all R-parity violating terms in the Lagrangian.

[6] G. Dvali, G. Senjanovic, Phys.Lett. B331 (1994) 63-68

Sneutrino-Higgs potential at high-T with non-zero n_R

Total effective potential:

$$V = V_0 + V_T + V_{n_R}$$

High-T contributions (leading-order terms):

$$\begin{aligned}
V_T &= \alpha_h T^2 \phi^* \phi + \alpha_{\tilde{\nu}} T^2 |\tilde{\nu}|^2 \\
\alpha_h &= \frac{1}{8v^2}\left(4m_W^2 + 2m_Z^2 + 4m_t^2 + m_h^2 + \frac{2}{3} m_Z m_h\right) \approx 0.383 \\
\alpha_{\tilde{\nu}} &= \frac{1}{8v^2}\left(4m_W^2 + 4m_Z^2 + \frac{1}{3} m_z m_h\right) \approx 0.129
\end{aligned}$$

Contribution from non-zero R-charge:

$$\begin{aligned}
V_{n_R} &= \frac{1}{2}\frac{n_R^2}{\mathcal{M}} \\
\mathcal{M} &= \frac{T^2}{6}\left(\sum_{i=\text{ fermions}} R_i^2 + 2\sum_{i=\text{ bosons}} R_i^2\right) + 2\left(|\phi|^2 + |\tilde{\nu}|^2\right) \\
&= \frac{7T^2}{3} + 2\left(|\phi|^2 + |\tilde{\nu}|^2\right)
\end{aligned}$$

Sneutrino-Higgs potential at high-T with non-zero n_R

Thermal masses:

$$\begin{aligned} m_h^2(T) &= -m_h^2 + 2\alpha_h T^2 \\ m_{\tilde{\nu}}^2(T) &= m_{\tilde{\nu}}^2 + \alpha_{\tilde{\nu}} T^2 \end{aligned}$$

Potential after R-symmetry breaking (excluding subdominant D-terms):

$$V = \frac{m_h^2(T)}{4} v_h^2 + \frac{m_{\tilde{\nu}}^2(T)}{2} v_{\tilde{\nu}}^2 + \frac{3n_R^2}{14T^2 + 6v_{\tilde{\nu}}^2 + 6v_h^2}$$

$v_h, v_{\tilde{\nu}}$ - vacuum expectation value for Higgs, sneutrino

Equations for $(v_{\tilde{\nu}}, v_h)$ from minimization:

$$\frac{m_{\tilde{\nu}}^2(T)}{2} - \frac{18n_R^2}{(14T^2 + 6v_{\tilde{\nu}}^2 + 6v_h^2)^2} = 0$$

$$\frac{m_h^2(T)}{4} + \frac{18n_R^2}{(14T^2 + 6v_{\tilde{\nu}}^2 + 6v_h^2)^2} = 0$$

Critical R-charge density, n_R^c

Density of R-charge is more *favourably* stored in the ground state (not thermal modes) through the condensation of the Higgs and/or sneutrino when satisfying the inequality

$$n_R \gtrsim n_R^c \simeq \max\left\{\frac{7}{6}T^2\left(\sqrt{m_{\tilde{\nu}}^2(T)} + \sqrt{\frac{m_h^2(T)}{2}}\right), \frac{7}{3}T^2\sqrt{m_{\tilde{\nu}}^2(T)}\right\}$$

where $m_{\tilde{\nu}}^2(T) > m_h^2(T)$ and the sneutrino is non-relativistic.

Sneutrino and Higgs condensates

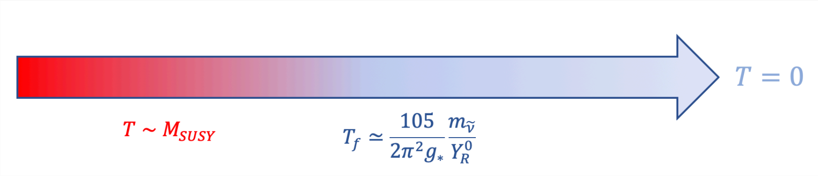
$$\begin{aligned} v_{\tilde{\nu}}^2 &\simeq \frac{n_R}{\sqrt{m_{\tilde{\nu}}^2(T)}} - \frac{7}{3}T^2 \approx \frac{n_R}{m_{\tilde{\nu}}} - \frac{7}{3}T^2 \\ v_h^2 &= 0 \end{aligned}$$

During this phase, R-parity is spontaneously broken.

Cosmological evolution

- Supersymmetric particles in chemical and kinetic equilibrium and carry a net (approximately) conserved R-charge, $n_R^0 < n_R^c$.
- At $M_{SUSY} \gg v$, sparticles decouple from thermal loops such that $n_R \gtrsim n_R^c$ and the sneutrino develops a vacuum expectation value (VEV).
- For $T < M_{SUSY}$, R-parity is spontaneously broken and the neutralino is no longer stable.

Cosmological evolution



- n_R has dominant contribution from relativistic quarks, Higgs and dilutes $\propto T^3$ with universal expansion.
- n_R^c decreases as $\propto m_{\tilde{\nu}} T^2$, so the sneutrino VEV is zero for $n_R \lesssim n_R^c$ which occurs at T_f.
- R-charge yield $Y_R(T_f) \simeq Y_R^0 \equiv \frac{n_R^0}{s}$ remains almost constant since decays inefficiently deplete R-charge (assuming no substantial changes in entropy density, s).
- Standard cosmology proceeds for $T < T_f$, with correct neutralino abundance.

Neutralino DM decay width, Γ_χ

During the R-violating phase, the neutralino mixes with the neutrino. The dominant decay process is $\chi \to Z\nu'$ where $m_\chi > m_Z + m_\nu$.

Mass matrix for neutralino-neutrino mixing

$$\hat{M}_{\chi\nu} = \begin{pmatrix} 0 & g\langle\tilde{\nu}\rangle_T & g'\langle\tilde{\nu}\rangle_T \\ g\langle\tilde{\nu}\rangle_T & M_2 & 0 \\ g'\langle\tilde{\nu}\rangle_T & 0 & M_1 \end{pmatrix}$$

$$\chi \simeq \tilde{B}\cos\beta - \nu\sin\beta$$

$$\sin\beta \simeq \frac{g' n_R^{1/2}}{m_\chi \, |m_{\tilde{\nu}}|^{1/2}}$$

where $M_1 \approx m_\chi$ (bino-like). The thermal VEV is $\langle\tilde{\nu}\rangle_T \approx (\frac{n_R}{m_{\tilde{\nu}}} - \frac{7}{3}T^2)^{1/2}$.

$$\Gamma_\chi \simeq \frac{\sin^2\beta}{8\pi}\frac{m_{\chi_1}^3}{v^2}\left(1 - \frac{m_Z^2}{m_\chi^2}\right)^2$$

$$\simeq \frac{g'^2}{4\pi}\frac{n_R}{|m_{\tilde{\nu}}|}\frac{m_\chi}{v^2}\left(1 - \frac{m_Z^2}{m_\chi^2}\right)^2$$

Evolution of DM yield, Y_χ

During the period $x \in [m_\chi/M_{SUSY}, x_f]$, the neutralino DM is unstable. Ignoring entropy changes, the Boltzmann equation in terms of the yield $Y_\chi \equiv n_\chi/s$ and $x \equiv m_\chi/T$ is

$$\frac{dY_\chi}{dx} = -\frac{\langle\Gamma_\chi\rangle x}{H_\chi}\left(Y_\chi - Y_\chi^{(eq)}\right) - \frac{\lambda}{x^{n+2}}\left(Y_\chi^2 - Y_\chi^{(eq)2}\right)$$

where $\lambda = \frac{s_\chi\langle\sigma v\rangle}{H_\chi}$ and $s_\chi = \left(2\pi^2/45\right) g_* m_\chi^3$ and $H_\chi = \left(\pi^2 g_*/90\right)\frac{m_\chi^2}{M_P}$,
$\langle\Gamma_\chi\rangle \simeq \Gamma_\chi$ (non-rel.) and $Y_\chi^{(eq)} = \frac{45}{2\pi^4}\left(\frac{\pi}{8}\right)^{1/2}\frac{g_\chi}{g_*}x^{3/2}\mathrm{e}^{-x}$ (non-rel.).
For large Γ_χ (negligible annihilations), we have $Y_\chi \simeq Y_\chi^{(eq)}$ - decays are kept exponentially close to equilibrium.

Ansatz: $Y_\chi(x) = Y_\chi^{(eq)}(x) + \delta_d$ into Boltzmann equation yields

$$\begin{aligned}\delta_d(x) &\approx -\frac{dY_\chi^{(eq.)}}{dx}\frac{H_\chi}{\Gamma_\chi x}\\ &\approx \frac{45}{4\pi^4}\left(\frac{\pi}{8}\right)^{1/2}\frac{g_\chi}{g_*}(2x-3)x^{-1/2}e^{-x}\frac{H_\chi}{\Gamma_\chi}\end{aligned}$$

Present-day Abundance, $\Omega_\chi h^2$

Decays keep the abundance close to equilibrium up to x_f, after the DM annihilations freeze out of the plasma in non-relativistic regime.

$$Y_\chi^\infty \simeq Y_\chi^{(eq)}(x_f)$$

Present-day abundance of χ:

$$\Omega_\chi = \frac{m_\chi Y_\chi^\infty s_0}{3H_0^2 M_P^2}$$

Important macroscopic (external) parameter Y_R^0 controlling abundance:

$$\Omega_\chi h^2 = 2.54 \times 10^6 \mathrm{GeV}^{-1} \left(Y_R^0\right)^{3/2} \left(\frac{m_\chi^5}{m_{\tilde{\nu}}^3}\right)^{1/2} e^{-\frac{40\pi^2 Y_R^0}{21} \frac{m_\chi}{m_{\tilde{\nu}}}}$$

Numerical example for $\Omega_\chi h^2 = 10^{-1}$:

$m_\chi = 5$ TeV, $g_\chi = 2$, $m_{\tilde{\nu}} = 5.1$ TeV, $M_{SUSY} = 50$ TeV, $Y_R^0 = 1.41$, $x_f \simeq 26.1$, $T_f \simeq 192$ GeV.

Wash-out of R-charge

- A large initial R-charge asymmetry $n_R^0 \sim s$ (on the order of entropy density) is required for the instability phase to occur.
- Sphaleron processes (which violate B+L) are suppressed from W bosons acquiring mass during the sneutrino condensate - avoids early R-charge wash-out that would cut-off the instability phase.
- After EWSB, the Higgs condensate should induce equilibrium R-symmetry breaking processes to eventually wash-out the R-charge primarily stored in the quarks/Higgs (although R-parity is conserved and the neutralino will be stable!).

Summary

- Can achieve correct neutralino DM relic abundance by assuming a large initial density of R-charge $n_R^0 \sim s$, modifying the early cosmology of the universe - particularly important for pure bino-like relics.
- The pattern of symmetry breaking and therefore the final abundance of DM is mainly influenced by the external parameter Y_R^0.
- We could expect this R-charge to be washed out by R-symmetry violating processes after the instability phase to avoid an unacceptably large baryon asymmetry.
- Implications for baryogenesis is another area to be explored.
- This can be applied to other DM models (not just SUSY) carrying global symmetries and associated non-zero charge asymmetry in the early universe.

Thank-you