Gauge Mediated SUSY Breaking with R-Parity Violation

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Dark Matter at the Crossroads, DESY Hamburg
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Outline

Supersymmetry

- SUSY is on of the most popular extensions of the Standard Model (SM)
- It has nice features, e.g. :
  - Solves hierarchy problem
  - Leads to gauge coupling unification
  - R-Parity:

$$R = (-1)^{3B+L+2S}.$$

$\rightarrow$ Leads to a Dark Matter Candidate: The Lightest Supersymmetric Particle (LSP)

- Must be broken & Constraints from FCNC, CP-Violation:
  $\rightarrow$ Embed the MSSM in a more fundamental theory
  (minimal) Supergravity, Anomaly Mediated SUSY Breaking, Gauge Mediated SUSY Breaking

Gravitino

- To include gravity, you have to add the Graviton to the SM
- The superpartner of the Graviton (Spin 2) is the Gravitino (Spin $\frac{3}{2}$)
- Graviton and Gravitino are massless, if SUSY is unbroken
- SUSY-breaking creates a massless Goldstino
- Super-Higgs-Mechanism: The Gravitino 'eats' the Goldstino and acquires a Mass $m_{\frac{3}{2}} \sim \frac{F}{M_P}$

Dark Matter candidate

Gravitino is the LSP in GMSB Models

Cosmology of the Gravitino

- For common values of M and Λ the $m_{3/2}$ is in keV range
- Light Gravitinos: Interactions of Spin-$\frac{1}{2}$-component (Goldstino) dominant
  $\rightarrow$ Approximations of Relic Density and Freeze Out Temperature:

$$\Omega h^2 \simeq \frac{m_{3/2}}{0.85\text{keV}} \frac{100}{g_*(T_{3/2})}, \; T_{3/2} \simeq 0.62 \frac{m_{3/2}^2 M_P \sqrt{g_*}}{\alpha_s M_{\tilde{g}}^2}$$

- Lower Bound on $m_{3/2}$ from Lyman-α-forest

Cosmological Gravitino Problem

The Relic Density for $m_{3/2} > 0.75\text{keV}$ is $\Omega_{3/2} h^2 > 0.6$

$\rightarrow$ Several Times too high !

Gauge Mediated SUSY breaking

- Messenger particles interact via gauge couplings
- In the minimal Model the Messengers $\Phi + \bar{\Phi}$ transform as $5 + \bar{5}$: Have Quantum Numbers of d_R^c and (ν, e_L)

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- In the minimal Model the Messengers $\Phi + \bar{\Phi}$ transform as $5 + \bar{5}$: Have Quantum Numbers of d_R^c and (ν, e_L)
- the Messengers couple to a superfield S via the Superpotential

$$W_M = \lambda S \Phi \bar{\Phi}$$

- SUSY in the hidden Sector broken by a VEV of the auxiliary component of S at Scale Λ

$$\langle S \rangle = M + \Theta^2 F$$

- SUSY masses are generated at Loop Level: 1 Loop Fermions, 2 Loop Scalars

Dilution Mechanism

- the Gravitino Relic Density must be diluted
- R-Symmetry is violated by a term in the superpotential [1]

$$W_{\not R} = f m_{3/2} \Phi_M \bar{\bar{\Phi}}_{SM}, \; \mathcal{O}(f) = 1$$

- Add also bilinear R-Parity violation:

$$W_{\not R} = \epsilon_i \tilde{L}_i H_u$$

$\rightarrow$ late time decay of the lightest messenger and SUSY particles possible

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Decays produce entropy

$\rightarrow$ Entropy dilutes propably the Gravitino relic density

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Lightest Messenger

- The Mass Matrix of scalars (ϕ_1, ϕ_2) is at tree level

$$\begin{pmatrix} M^2 & F \\ F & M^2 \end{pmatrix}$$

- Mass Eigenstates:
  $\phi_{H,L} = \frac{1}{\sqrt{2}}\left(\phi_1 \pm \phi_2\right)$ Masses: $m_{H,L} = \sqrt{M^2 \pm F}$

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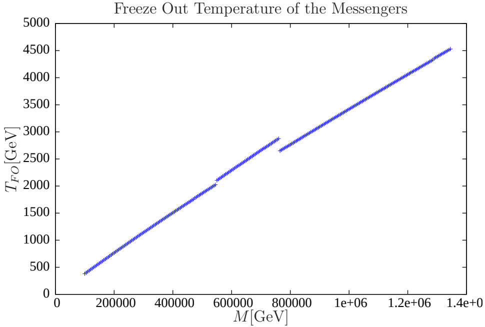
- One Loop corrections:
  - Lightest Messenger are Sneutrino-like
  - Minimal Mass in the limit $F \to M$: $m_{\text{min}} = \frac{1}{4\pi} C_i^2 g_i^2 M^2$
- Increase of the Mass because of RGE running

No very light messengers (EWSB-Scale) possible!

Relic Density and Freeze Out of the Messengers

All shown Results with $\tan\beta = 15, F \simeq M^2, m_\phi = m_{\text{min}} \sim \frac{M}{50}$

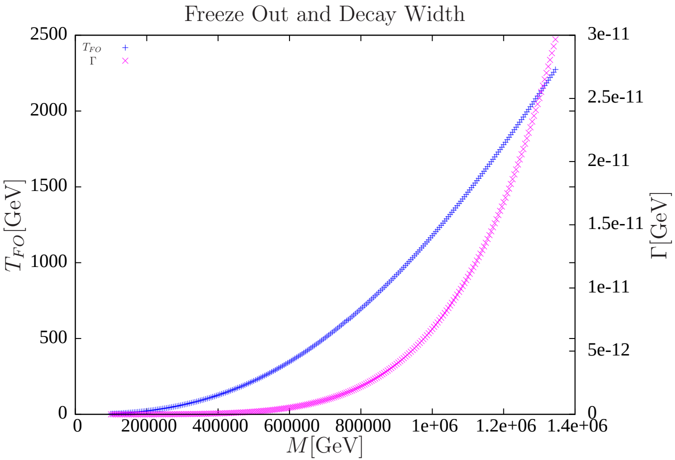
- Numerical Results with MicrOmegas:



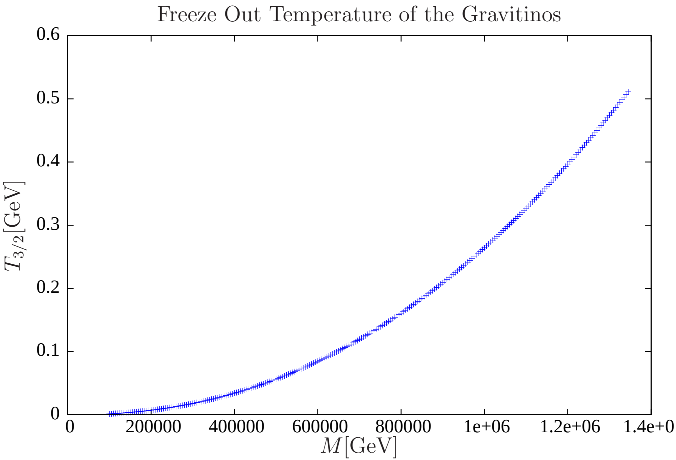
- Relic Density good approximated by:

$$\Omega_M h^2 \sim 10^5 \left(\frac{M}{10^6 \text{GeV}}\right)^2$$

Decay Widths and Decay Temperature of the Messengers



Freeze Out Temperature of the Gravitinos



Freeze Out Temperature of the Gravitinos

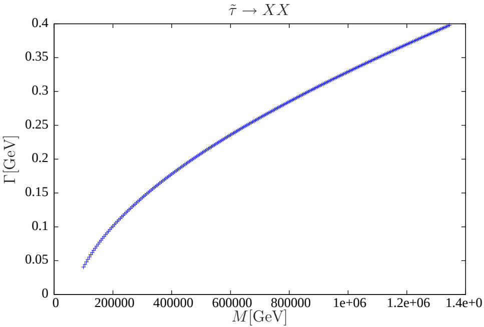
- Freeze Out too late!
- Approximated Condition for Freeze Out in Time:

$$\frac{T_D}{T_{3/2}} \approx 0.084\sqrt{M} \overset{!}{<} 1$$

$\rightarrow$ Model works only for unrealistic small Messenger Masses!

Decay of the NSLP

- The Stau is mostly the NSLP
- Decay Width via bilinear R-Parity violation (dominates over decay in LSP)



- Decay Temperature is much too high

Summary

- In GMSB the Gravitino is the LSP and therefore a Dark Matter candidate
- Without R-Parity violation the relic density of the Gravitino is too large
- With R-Parity violation the lightest messenger and SUSY particles could decay and produce entropy
- This entropy could dilute the relic density

Result

The mechanism doesn't work, because the Decays of the Messengers and SUSY particles are too fast!

The Model

Getting the effective Theory:

- Integrate out the heavy particles: Fermionic and heavy Scalar Messenger
- Six particles get a VEV: Lightest Messenger, Two Higgs, Three Sneutrinos
  $\rightarrow$ Tadpole Equations as Minimum Conditions:

$$\frac{\partial \mathcal{L}}{\partial v_i} = 0$$

- Values of bilinear R-Parity violation and Sneutrino VEVs constrained by Neutrino Physics
- Add Soft Breaking Parameters A_{f_i}, A_{ϵ_i}, A_M and m^2_{LH}
- Assume relations: f_i equal , A_{f_i} equal and A_{ϵ_i} equal
- A_M not even induced at two loop level: Set to zero.

Parameters of the model

- SUSY Parameters calculated with SPheno
- μ and $B\mu$ not fixed in GMSB, Six free parameters after fixing VEVs left

  $\longrightarrow$ Solve Tadpole Equations
- Masses and Vertices: Masses and Mixing matrices calculated by Diagonalizing the Mass Matrices of the Gauge Eigenstates

  Mathematica Package SARAH written for this purpose

Late Time Decays

- The particles decay at Temperature T_D with Hubble Parameter H:

$$H^2(T_D) \sim Y_i T_D^3 \frac{m}{m_P^2} \sim \tau^{-2}$$

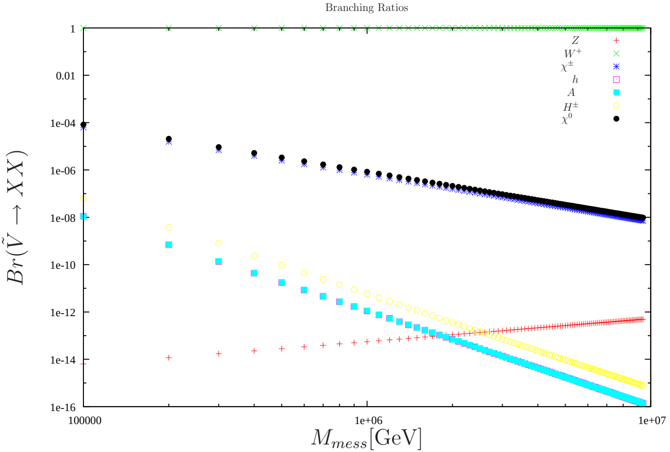
- Gravitinos must already be frozen out $\to T_D < T_{3/2}$.
- Entropy Production:

$$\frac{s_{\text{after}}}{s_{\text{before}}} = \frac{g_\star R^3 T_{RH}^3}{g_\star R^3 T_D^3} \sim g^{1/4} \frac{Y_i m \sqrt{\tau}}{\sqrt{m_P}}$$

leads to a Dilution Factor

$$\Omega_{\text{deluted}} = \Omega_{\text{initial}} \frac{1}{\Delta} \;\; \to \;\; \Delta_M \sim \tfrac{4}{3} \tfrac{M Y_M}{T_D}$$

Branching Ratios



Literature

- BALTZ, EDWARD A. und HITOSHI MURAYAMA: *Gravitino Warm Dark Matter with Entropy Production*.
  JHEP, 0305:067, 2003.
- FUJII, M. und T. YANAGIDA: *Natural gravitino dark matter and thermal leptogenesis in gauge-mediated supersymmetry breaking models*.
  Physics Letters B, 549:273–283, 2002.