Gravitino LSP as Dark Matter in the Constrained MSSM

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- Gravitino as Dark Matter
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Evidence for Dark Matter

- Rotation curves of galaxies in 21cm line from hyperfine splitting
- Flat behavior beyond the visible disks
- $M(r) \propto r$, $\rho \propto 1/r^2$

- Mass of a cluster of galaxies
- Distribution of hot gas from X-ray emission
- Shape of the potential well using weak gravitational lensing
Cosmic Microwave Background

WMAP satellite 3-year results (2006)

- $\Omega_m h^2 = 0.126 \pm 0.009$
- $\Omega_b h^2 = 0.0223 \pm 0.0008$
- $h = 0.734^{+0.028}_{-0.038}$
- $\Omega_{DM} = 0.192 \pm 0.017$
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“What is Dark Matter”
Particle Dark Matter

- Standard Model neutrinos
  \( \Omega_\nu h^2 = \sum \frac{m_i}{93 \text{ eV}} < 0.022 \) (WMAP)

- WIMP (Weak Interacting Massive Particle) is strongly favored

- Freeze-out of a massive particles
  \( \Omega_X = m_X n_X \sim \frac{10^9 \text{GeV}^{-1} x_f}{g_{*}^{1/2} M_P \langle \sigma A v \rangle} \)

- Beyond Standard Model

\[ \frac{Y}{Y_0}, Y = \frac{n_X}{s} \]

- Hot Relic
- Cold Relic

Increasing \( \langle \sigma v \rangle \)

\[ x = \frac{m_X}{T} \]
Supersymmetry

- Standard Model particles are doubled by superpartners.
- LSP (Lightest Supersymmetric Particle) is stable with R-parity and a good candidate for Dark Matter.
- Which is LSP?
Supersymmetry

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- Which is LSP? Neutralino?
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Supersymmetry

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- Which is LSP? Neutralino? or Gravitino?
**Gravitino Problem**

\( T_R > T_f \)
- Primordial Gravitino
- Freeze-out from thermal eq.
  \[ \Omega_{\tilde{G}} h^2 \simeq 1.17 \left( \frac{100}{g_*} \right) \left( \frac{m_{\tilde{G}}}{1 \text{ keV}} \right) \]
  - unstable: \( m_{\tilde{G}} \gtrsim 10 \text{ TeV} \)
  - stable: \( m_{\tilde{G}} \lesssim 1 \text{ keV} \)
  or Gravitino dilution

\( T_R < T_f \)
- Diluted out by inflation
- Reproduced by thermal scatterings
  \[ \Omega_{\tilde{G}} h^2 \simeq 0.2 \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \left( \frac{100 \text{ GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\tilde{g}}(T)}{1 \text{ TeV}} \right)^2 \]
  - unstable: \( T_R \lesssim 10^8 \text{ GeV} \) from BBN
  - stable: \( T_R \lesssim 10^{10} \text{ GeV} \) from \( \Omega_{\text{tot}} < 1 \)
Gravitino LSP in the CMSSM

Constrained MSSM
At $M_{GUT}$
- gauginos $M_1 = M_2 = M_3 = m_{1/2}$
- scalars $m_{\tilde{q}}^2 = m_{\tilde{l}}^2 = m_{H_b}^2 = m_{H_t}^2 = m_0^2$
- trilinear soft terms $A_b = A_t = A_0$
- radiative EWSB
- five independent parameters:
  $\tan \beta, m_{1/2}, m_0, A_0, \text{sgn}(\mu)$

Free parameter: $m_{\tilde{G}} \sim M_{SUSY}$

Experimental constraints
- $m_{\chi^\pm} > 104$ GeV (LEP)
- light higgs: $m_h > 114.4$ GeV (LEP)
- BR($B \to X_s \gamma$) = $(3.34 \pm 0.68) \times 10^{-4}$

DSU 2006
Gravitino Relic abundance

- **Thermal production**: from thermal scattering,

\[ \Omega_{\tilde{G}}^{TP} h^2 \simeq 0.2 \left( \frac{T_R}{10^{10} \text{GeV}} \right) \left( \frac{100 \text{GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\tilde{g}}(T)}{1 \text{TeV}} \right)^2 \]

[Bolz, Brandenburg, Buchmüller., (2001)]

- **Non-thermal production**: from the decay of NLSP \((\tau \sim 1 - 10^8 \text{sec})\)

\[ \Omega_{\tilde{G}}^{NTP} h^2 = \frac{m_{\tilde{G}}}{m_{NLSP}} \Omega_{NLSP} h^2 \]

- **Total Gravitino relic abundance**

\[ \Rightarrow \Omega_{\tilde{G}} h^2 \simeq \Omega_{\tilde{G}}^{TP} h^2 + \Omega_{\tilde{G}}^{NTP} h^2 \]
Gravitino Relic abundance

\[ m_{\tilde{G}} = m_0 \]

\[ \Omega_{\tilde{G}h^2} = \Omega_{\tilde{G}h^2}^{TP} + \Omega_{\tilde{G}h^2}^{NTP} \]

\[ 0.094 < \Omega_{\tilde{G}h^2} < 0.129 \] (WMAP)

\[ T_R = 10^9 \text{ GeV} \]

\[ T_R = 5 \times 10^9 \text{ GeV} \]

• NLSP decay produces photons and hadrons with high energy
  \( \chi \rightarrow \tilde{G}\gamma \Rightarrow \text{EM showers} \)
  \( \chi 
  \rightarrow \tilde{G}Z, \tilde{G}Higgs, \tilde{G}\gamma^*/Z^* \)
  \( \Rightarrow \text{had showers} \)
  \( \tilde{\tau} \rightarrow \tilde{G}\tau \Rightarrow \text{EM showers} \)
  \( \tilde{\tau} 
  \rightarrow \tilde{G}\tau Z, \tilde{G}\nu_\tau W, \tilde{G}\tau\gamma^*/Z^* \)
  \( \Rightarrow \text{had showers} \)

• Late time decay due to gravitational interaction: \( 1 \sim 10^{10} \text{ sec} \)

• The high energy injection(EM,had) at late times during or after BBN changes
  the light element abundances \( \Rightarrow \text{Strong constraints on NLSP} \)
BBN constraints

conservative observational limit

\[ 2.2 \times 10^{-5} < \frac{D}{H} < 5.3 \times 10^{-5} \]
\[ 0.232 < Y_p < 0.258 \]
\[ 1.11 \times 10^{-10} < \frac{^7\text{Li}}{\text{H}} < 4.5 \times 10^{-10} \]
\[ \frac{^3\text{He}}{\text{D}} < 1.72 \]
\[ \frac{^6\text{Li}}{^7\text{Li}} < 0.1875 \]

CMB constraints

dimensionless chemical potential \( \mu \)

\[ |\mu| < 9 \times 10^{-5} \]

\[ m_\tilde{G} = m_0, \quad T_R = 10^9 \text{ GeV} \]
**BBN constraints**

- $\chi$ NLSP is inconsistent with BBN: still possibility for sub-GeV Gravitino ($\tau_\chi < 1$ sec)
- $\tilde{\tau}$ NLSP region is allowed
- CMB constraint is weaker than BBN: potentially important for more precise CMB measurements
- How high $T_R$ is possible?

$$m_{\tilde{G}} = m_0, \quad T_R = 10^9 \text{ GeV}$$

D/H + $^7$Li/H + $^3$He/D + $^6$Li/$^7$Li

BBN constraints

$m_\tilde{G} = 0.2m_0, \; T_R = 10^9 \text{ GeV}$

$m_\tilde{G} = 100 \text{ GeV}, \; T_R = 10^9 \text{ GeV}$

Cosmic Lithium Problems

- Standard BBN predicts factor 2-3 more $^7\text{Li}$ than observed at low $[Z]$
- Standard BBN synthesize $^6\text{Li}$ around $^6\text{Li}/\text{H} \sim 10^{-14} - 10^{-13}$
  1-2 orders below than observed

$$\eta_{10} = \frac{n_B}{n_\gamma} \times 10^{10}$$
Cosmic Lithium Problems and Gravitino

- Relic particle decay destruct $^{7}\text{Li}$ and produce $^{6}\text{Li}$
- $^{7}\text{Li}$ overproduced, $^{6}\text{Li}$ solved
- $^{7}\text{Li}$ solved, $^{6}\text{Li}$ underproduced
- $^{7}\text{Li}$ solved, $^{6}\text{Li}$ solved

$\Omega_\tilde{G} h^2 - \tau_{NLSP}$

$m_{\tilde{G}} - m_{NLSP}$

$v_0 - \Omega_\tilde{G} h^2$

$\Omega_\tilde{G} h^2 \sim 0.01 - 0.1, \tau_{NLSP} \sim 10^3 \text{ sec}$

$m_{NLSP} \sim 1 \text{ TeV}, m_{\tilde{G}} \sim 100 \text{ GeV}$

$v_0 \sim 10^{-2} \text{ km/sec}$

Free streaming velocity at present $\lesssim 0.1$ from matter power spectrum Jedamzik et al., (2005)
Vacuum structure of the Universe

- charge and/or color breaking (CCB) minima
- unbounded from below (UFB) directions (UFB-1,2,3)
  \[ \Rightarrow \text{Among them, UFB-3} = \{H_u, \nu_{L_i}, e_{L_j}, e_{R_j}\}, i \neq j \text{ direction leads to electric charge breaking also (the strongest constraints)} \]  
  \[ [\text{Casas, Lleyda, Muñoz('96)}] \]
- Condition \( V_{\text{UFB-3}}(Q = \hat{Q}) > V_{\text{real min}} \)
- We live in a meta-stable state!

Vacuum structure of the Universe

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Summary

- Gravitino can be a good candidate for Dark Matter
- Neutralino NLSP and $O(100)$ GeV Gravitino LSP is disfavored by BBN
- Stau NLSP and Gravitino LSP is a possible combination in CMSSM
- Both Lithium problems can be solved simultaneously by the decay of a stau relic 1000 sec after the Big Bang
- Stau NLSP indicate a hint about the vacuum structure of our Universe
Constraint on Reheating Temperature
\[ \tan \beta = 10, \ m_{1/2} = 500 \text{GeV}, \ m_0 = 50 \text{GeV}(\tilde{\tau}\text{NLSP}) \]

\[ \Omega_{\text{G}} h^2 = \Omega_{\text{G}}^{\text{TP}} h^2 + \Omega_{\text{G}}^{\text{NTP}} h^2 \]

\[ T_R \lesssim 3 \times 10^9 \text{ GeV for } m_{\tilde{G}} \sim 30 \text{ GeV} \]

Contents of present Universe

WMAP data with other CMB experiments (ACBAR and CBI), 2dFGRAS measurements, and Lyα forest data determines the best-fit cosmological parameters [Spergel et al., (2003)]:

\[ \Omega_{tot} = \Omega_\Lambda + \Omega_m + \cdots = 1.02 \pm 0.02 \text{ (Flat Universe)} \]

\[ \begin{align*}
\text{energy} & \quad \Omega_\Lambda = 0.73 \pm 0.04 \text{ (accelerating)} \\
\text{matter} & \quad \Omega_m = 0.27 \pm 0.04
\end{align*} \]

\[ \Omega_{tot} = \begin{cases} 
\Omega_b h^2 = 0.0224 \pm 0.0009 \text{ (BBN, CMB)} \\
\Omega_{DM} h^2 = 0.113_{-0.009}^{+0.008} \\
\Omega_\nu h^2 < 0.0076 \quad (h = 0.71_{-0.03}^{+0.04}) \\
\Omega_\gamma = (2.471 \pm 0.004) \times 10^{-5} \quad (T_0 = 2.275 \pm 0.002K \text{ 95% CL})
\end{cases} \]
Supersymmetry

- Extends SM with superpartners
- Solves hierarchy problem
- Gauge coupling unification
- Radiative EW symmetry breaking
- Possible new source for CP and flavor
- Lightest Supersymmetric Particle: non-baryonic dark matter candidate
- Neutralino
Gravitino Problem

If $T_R > T_f$, Gravitino freezes out from thermal equilibrium with the relic density

$$\Omega_{\tilde{G}} h^2 = 1.17 \left( \frac{100}{g_*} \right) \left( \frac{m_{\tilde{G}}}{1 \text{ keV}} \right)$$

- **Stable**: $m_{\tilde{G}} \lesssim 1 \text{ keV}$ from $\Omega_{tot} < 1$ or Gravitino dilution

- **Unstable**: $m_{\tilde{G}} \gtrsim 10 \text{ TeV}$ from BBN constraint

If $T_R < T_f$, the freeze-out Gravitino is diluted away by Inflation and reproduced by thermal scattering in the reheating period with abundance

$$Y_{\tilde{G}} \equiv \frac{n_{\tilde{G}}}{n_\gamma} = 7.7 \times 10^{-12} \left( 1 + \frac{m_{\tilde{G}}^2}{12m_{\tilde{G}}^2} \right) \left( \frac{T_R}{10^{10} \text{ GeV}} \right)$$

$T_R$: Reheating temperature

[Ref: Bolz, Brandenburg, Buchmüller, (2001)]
• unstable: $T_R \lesssim 10^8 \text{ GeV}$ from BBN

• stable: $T_R \lesssim 10^{10} \text{ GeV}$ from $\Omega_{tot} < 1$

$\Omega h^2 = 3.63 \times 10^9 \frac{m}{100 \text{ GeV}} Y$
Gravitino Relic abundance

\[ m_{\tilde{G}} = m_0 \]

Non-thermal production: NLSP decay

\[ \chi \text{ NLSP} \]
\[ \chi \rightarrow \tilde{G}\gamma \]
\[ \chi \rightarrow \tilde{G}Z, \tilde{G}Higgs, \tilde{G}(\gamma^*/Z^*)q\bar{q} \]

\[ \tilde{\tau} \text{ NLSP} \]
\[ \tilde{\tau} \rightarrow \tilde{G}\tau \]
\[ \tilde{\tau} \rightarrow \tilde{G}\tau Z, \tilde{G}\nu_\tau Ws, \tilde{G}(\gamma^*/Z^*)q\bar{q} \]

\[ \Omega_{\tilde{G}}^{NTP} h^2 = \frac{m_{\tilde{G}}}{m_{NLSP}} \Omega_{NLSP} h^2 \]
Combining UFB and BBN

For $T_R = 10^9$ GeV,

- $m_{\tilde{G}} = m_0$, $\tan \beta = 10$
- $m_{\tilde{G}} = 0.2m_0$, $\tan \beta = 50$

DSU 2006
- $m_{\tilde{G}} = 10$ GeV, $\tan \beta = 10$

- $m_{\tilde{G}} = 100$ GeV, $\tan \beta = 50$

DSU 2006