Mixed Axion/Axino Dark Matter in mSUGRA and Yukawa-unified SUSY

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Outline

* Supersymmetric Dark Matter Candidates
  ▶ neutralino
  ▶ gravitino
  ▶ axions/axinos

* Mostly Axion CDM in mSUGRA

* Axion/Axino DM in Yukawa-unified SUSY
In supergravity models,\n\[ m_{\tilde{G}} = \frac{F}{\sqrt{3}M_P} \]

In many models, has too high relic density.

subject to the gravitino problem:

- gravitino is unstable, decays to modes such as \( \tilde{G} \rightarrow \gamma \tilde{\chi}_1^0 \)
- \( \tau_{\tilde{G}} \lesssim 1 \text{ s} \)

\[ \Rightarrow m_{\tilde{G}} \gtrsim 10^4 \text{ GeV} \]
SUSY Dark Matter
Neutralinos

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  - gravitino is unstable, decays to modes such as \( \tilde{G} \rightarrow \gamma \tilde{\chi}_1^0 \)
  - \( \tau_{\tilde{G}} \lesssim 1 \text{ s} \)
  \[ \Rightarrow m_{\tilde{G}} \gtrsim 10^4 \text{ GeV} \]
  - \( T_R \lesssim 10^5 \text{ GeV} \)
  \[ \rightarrow \text{ problem with leptogenesis (thermal leptogenesis requires } T_R > 10^{10} \text{ GeV)} \]

Kawasaki, Kohri, Moroi, Yotsuyanagi

Sunday, June 7, 2009
Also subject to the gravitino problem in SUGRA models.

- BBN constrains gravitino to be very light
Strong CP problem:

\[ \mathcal{L} \supset \frac{g_s^2 \theta}{32 \pi^2} G^\mu_\nu \tilde{G}_A^\mu_\nu, \quad \theta \leq 10^{-9} \]

Peccie-Quinn solution:

- Axions
- PQ breaking scale
  \[ f_a/N \approx 10^9 - 10^{12} \text{ GeV} \]
  \[ \Rightarrow \text{pseudo-Goldstone boson} \]

Axion cosmology constraints

- \[ f_a/N \approx 10^9 - 10^{12} \text{ GeV} \]
- \[ f_a/N \approx 10^{-9} \]

SUSY Dark Matter
Axions

\[ L \ni g_2 s \bar{\theta} \frac{\pi}{2} G_{\mu \nu} \tilde{G}_A, \bar{\theta} \leq 10^{-9} \]

\[ f_a/N \approx 10^9 - 10^{12} \text{ GeV} \]

\[ m_a (\text{eV}) \]

\[ f_a (\text{GeV}) \]

Sikivie

SN 1987a
red giants
accelerator searches
cosmology

Sunday, June 7, 2009
Non-thermal production via vacuum mis-alignment

$\Rightarrow$ CDM

$\Rightarrow m_a \simeq 6 \text{ eV} \frac{10^6 \text{ eV}}{f_a/N}$

$\Rightarrow \Omega_a h^2 \simeq \frac{1}{4} \left( \frac{6 \times 10^{-6} \text{ eV}}{m_a} \right)^{7/6}$

WMAP 5: $\Omega_{\text{CDM}} h^2 = 0.110 \pm 0.006$
SUSY Dark Matter
Axinos

- Superpartner of axion is the axino: $\tilde{a}$
  - mass is model-dependent $\sim$ keV $\rightarrow$ GeV
- Warm DM from non-thermal production via NLSP decay
  - NLSP lifetime: $10^{-3} - 10^1$ s
  - $\Omega_{\tilde{a}}^{\text{NTP}} h^2 = \frac{m_{\tilde{a}}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}} h^2$
  - warm DM for $m_{\tilde{a}} < 1 - 10$ GeV

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Axinos not in thermal equilibrium for $T_R < f_a/N$

Cold DM from thermal-production

- bremsstrahlung off particles in thermal equilibrium

$$\Omega_{\tilde{a}} h^2 \approx 5.5 g_s^6 \ln \left( \frac{1.108}{g_s} \right) \left( \frac{10^{11} \text{ GeV}}{f_a/N} \right)^2 \left( \frac{m_{\tilde{a}}}{0.1 \text{ GeV}} \right) \left( \frac{T_R}{10^4 \text{ GeV}} \right)$$

- CDM for $\tilde{a} > 100$ keV

Axino DM: Covi, Kim, Kim, and Roszkowski; Brandenberg and Steffen
For a fixed $\Omega_{\tilde{a}}^{TP} h^2$, a lower axino mass yields a higher $T_R$.
Axion/Axino CDM in mSUGRA

* Left frame shows the three-component combination of axions, TP axinos, and NTP axinos

$$\Omega_a h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_{\tilde{a}}^{NTP} h^2 = 0.11$$

* In the right frame, can see that a large $f_a/N$ saturates the relic density with axions

$$m_a = 100 \text{ keV (solid), 1 MeV (dashed)}$$
Axion CDM in mSUGRA

$m_{\text{Sugra with } \tan \beta = 10, A_0 = 0, \mu > 0}$

$m_0 (\text{GeV})$

$m_{1/2} (\text{GeV})$

$\ln(\chi/\text{DOF})$

No REWSB

$\sim 1$

not LSP

$m_h = 114.1 \text{GeV}$ LEP2 excluded

$f_a / N = 3 \times 10^{11} \text{ GeV}

\Omega_a h^2 = 0.11, \Omega_{aTP} h^2 = 0.006, \Omega_{aNTP} h^2 = 6 \times 10^{-6}$

Want $T_R > 10^6$ for non-thermal leptogenesis.
Yukawa-unified $SO(10)$ SUSY GUT

- Matter unification
- Superpotential:
  $\hat{f} \equiv f \hat{\psi}_{16} \hat{\psi}_{16} \hat{\phi}_{10} + \cdots$
- HS:
  $m_{H_u,d}^2 = m_{10} \mp 2M_D^2$
- Parameter Space:
  $m_{16}, m_{10}, M_D^2, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
Neutralino DM in Yukawa-Unified $SO(10)$ SUSY

$m(1, 2) \sim 10$ TeV
$m(3) \sim 1 - 2$ TeV
$m_{\tilde{g}} \sim 400$ GeV
$m_{\tilde{\chi}^0_1} \sim 50 - 80$ GeV

→ Neutralino relic abundance $\sim 10^3$ or more.

$$R \equiv \frac{\max(f_t, f_b, f_\tau)}{\min(f_t, f_b, f_\tau)}$$
Mixed Axion/Axino DM in Yukawa-Unified Models

Case C1
- \( f_a/N = 10^{11} \text{ GeV} \)
- mostly TP axino DM
- \( T_R \) too low unless warm axino DM

Case C2
- \( f_a/N = 4 \times 10^{11} \text{ GeV} \)
- mostly axion CDM
- can get \( T_R > 10^6 \text{ GeV} \) for \( m_{16} > 10 \text{ TeV} \)
Mixed Axion/Axino DM in Yukawa-Unified Models

Case C3
- \( f_a/N = 10^{12} \text{ GeV} \)
- mostly axion CDM
- can get \( T_R > 10^6 \) and higher for \( m_{16} > 8 \text{ TeV} \)

Case C4
- \( f_a/N = 10^{12} \text{ GeV} \)
- accidental axion vacuum alignment
- all axino DM
- can get high \( T_R > 10^6 \), but if axino mass is too low, DM becomes warm
Mixed Axion/Axino DM in Yukawa-Unified Models

* Need large
\[ \frac{f_a}{N} \sim 10^{12} \text{GeV} \]

* Best case is dominantly axion CDM as in C3 (C2 is also ok) with small axino component.
Conclusions

Neutralinos and gravitinos suffer from gravitino problem
  • Severe constraints from BBN and overclosure

Axion/Axino DM is a good CDM candidate

mSUGRA regions that disfavor neutralino DM prefer axion DM
  ▪ Cold axions comprise bulk of DM with possible small warm and cold axino components

Yukawa-unified $SO(10)$ is inconsistent with neutralino DM
  ▪ Mixed axion/axino DM gives consistent cosmology for Yukawa-unified model