Gravitino and axino dark matter with low reheating temperature

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Introduction

- What is the nature of dark matter (DM)?
  \[ \Rightarrow \text{Lightest Supersymmetric Particle(?)} \]

- if we find SUSY at the LHC and no sign of DM in upcoming experiments
  \[ \Rightarrow \text{maybe hint for supersymmetric DM with very tiny interaction rates: gravitino or axino} \]

  - gravitino \( \tilde{G} \) is a superpartner of graviton
  - QCD – strong CP problem \[ \Rightarrow \text{axion (Peccei-Quinn)} \]
  - axino \( \tilde{a} \) is a fermionic superpartner of axion
  - \( \tilde{G} \) and \( \tilde{a} \) are extremely weakly interacting massive particle (EWIMP) – interaction rates suppressed by \( M_{\text{Pl}} \) or \( f_{\tilde{a}} \sim 10^{11} \text{ GeV} \)

- cosmological constraints
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  - Gravitino and axino DM – typically discussed upper limit on the reheating temperature \( T_R \lesssim 10^7 - 10^8 \text{ GeV} \)
  - What about lower limit on \( T_R \)?
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How to produce relic supersymmetric EWIMPs?

Assumption: after inflation maximum temperature too low for EWIMPs to be in thermal equilibrium. We consider then two main mechanism of production:

$$\Omega_{\text{EWIMP}} h^2 = \Omega_{\text{EWIMP}}^{\text{NTP}} h^2 + \Omega_{\text{EWIMP}}^{\text{TP}} h^2$$

**Non-Thermal Production**
- late decays of the next-to-LSP
- possible electromagnetic and hadronic cascades that destroy light nuclei in the early Universe
- this alters predictions of the Big Bang Nucleosynthesis (BBN)
- late-time injection of light (fast) particles may cause problem with the Large Scale Structure (LSS) formation
- too warm dark matter (WDM)
- $T_R$-dependent only for low $T_R$

**Thermal production**
- scatterings of superparticles in the thermal plasma
- depends on $T_R$
- generally larger $T_R \Rightarrow$ larger yield $\gamma^{\text{TP}} = n^{\text{TP}}/s$
- different dependence on the $m_{\text{EWIMP}}$ for the axino and the gravitino

$$\Omega_{\text{EWIMP}}^{\text{TP}} h^2 \propto m_{\text{EWIMP}}$$

$$\gamma^{\text{TP}} \propto \begin{cases} T_R/m_\tilde{G} \\ T_R m_\tilde{\sigma} \end{cases}$$
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$$\Omega_{\text{EWIMP}}^{\text{TP}} h^2 \propto m_{\text{EWIMP}} \gamma_{\text{TP}} \propto \left\{ \begin{array}{c} T_R / m_\tilde{G} \\ T_R / m_\tilde{a} \end{array} \right.$$
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Non-thermal production of EWIMPs

\[ \chi \rightarrow \text{EWIMP} + \ldots \]

- in the early Universe \( \chi \) remained in thermal equilibrium
- when temperature \( T \) dropped down \( \Rightarrow \) freeze-out of \( \chi \)

\[ \Omega_{\text{NTP}}^{\text{EWIMP}} h^2 = \frac{m_{\text{EWIMP}}}{m_\chi} \Omega_\chi h^2 \]
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\[ \log Y = \frac{n_{\chi}}{s} \sim \text{comoving number density} \]

\[ x = \frac{m_{\chi}}{T} \text{ grows with time} \]
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\text{low } T_R \quad \Omega_\chi h^2(\text{low } T_R) < \Omega_\chi h^2(\text{high } T_R)
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\[ \Omega_{\chi} h^2 (\text{low } T_R) < \Omega_{\chi} h^2 (\text{high } T_R) \]

\[ \Omega_{\chi} h^2 (\text{low } T_R) \approx 0.12 \]

along the lines of constant \( T_R \)

\[ \Omega_{\chi} h^2 (\text{high } T_R) \]
Gravitino DM – low $T_R$ \[ \Rightarrow \text{NTP dominates for not very light } \tilde{G} \]

**Bino LOSP**

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

\[ \Rightarrow m_{\tilde{B}} \gtrsim 1.4 \left( \frac{m_{\tilde{G}}}{\text{GeV}} \right)^{2/5} \text{TeV} \]

\[ \Omega_{\tilde{G}} h^2 = \frac{m_{\tilde{G}}}{m_{\text{LOSP}}} \Omega_{\text{LOSP}} h^2 \]

more general notation

\[ \chi \rightarrow \text{LOSP} \]

lightest ordinary supersymmetric particle
Gravitino DM – low $T_R$

$\Rightarrow$ NTP dominates for not very light $\tilde{G}$

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BBN + relic density constraints

$\Rightarrow$ lower limit on $T_R$

$\min T_R \sim \mathcal{O}(100 \text{ GeV})$

Supersymmetric dark matter with low reheating temperature of the Universe
Gravitino DM – low $T_R$ (2) $\Rightarrow$ NTP dominates

$$\Omega_{\tilde{G}} h^2 = \frac{m_{\tilde{G}}}{m_{\text{LOSP}}} \Omega_{\text{LOSP}} h^2$$

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more general notation

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lightest ordinary supersymmetric particle

Slepton LOSP

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

![Graph showing the relationship between $m_{\text{LOSP}}$ and $\Omega_{\text{LOSP}} h^2$ for different values of $T_R$.]
Gravitino DM – low $T_R$ (2) \( \Rightarrow \) NTP dominates $\Omega_{\tilde{G}} h^2 = \frac{m_{\tilde{G}}}{m_{\text{LOSP}}} \Omega_{\text{LOSP}} h^2$ for not very light $\tilde{G}$

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"Supersymmetric dark matter with low reheating temperature of the Universe"
Axino DM – low $T_R$

Non-thermal production – analogous to the case of gravitino DM, but...

→ BBN constraints become milder (shorter lifetime) if $\chi \rightarrow \tilde{a}\gamma$ decays are allowed, i.e., if $C_{aYY} \neq 0$ where $\mathcal{L}_a^{\text{eff}} \supset i \frac{\alpha_Y}{16\pi} \frac{C_{aYY}}{f_a} \tilde{a} \gamma_5 [\gamma^\mu, \gamma^\nu] \tilde{B} B_{\mu\nu}$

$\Rightarrow$ if $C_{aYY} \neq 0$ BBN constraints become mild

→ if $C_{aYY} = 0$, decays to $\tilde{a}\gamma$ are suppressed, while $\chi \rightarrow \tilde{aq}\bar{q}$ becomes dominant with hadronic branching fraction $B_h = 1$ and larger lifetime

$$\tau_{\tilde{B}} \approx 120 \text{sec} \left( \frac{100 \text{ GeV}}{m_{\tilde{B}}} \right)^5 \left( \frac{m_{\tilde{q}}}{1 \text{ TeV}} \right)^4 \left( \frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^2 \left( \frac{f_{\tilde{a}}}{10^{11} \text{ GeV}} \right)^2 .$$

$\Rightarrow$ if $C_{aYY} = 0$ BBN constraints become strong
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⇒ if $C_{aYY} = 0$ BBN constraints become strong

**Thermal production**— can be non-negligible even for $T_R \sim 100 \text{ GeV}$

→ axino couplings are suppressed by $1/f_a$ with $f_a \sim 10^9 - 10^{12} \text{ GeV} \ll M_{\text{Pl}}$

→ for non-instantaneous reheating larger temperatures are attainable than in the radiation dominated epoch

⇒ modified $Y^{TP}$
Axino TP with non-instantaneous reheating

- for high $T_R - SU(3)_c$ scatterings dominate
- for $T_R \lesssim 10^3$ GeV – squark and gluino decays become dominant
- for $T_R \lesssim 100$ GeV – neutralino (being still in thermal equilibrium) decays to axino may dominate

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Axino DM with neutralino LOSP

- $T_R$-dependent upper bound on $m_{\tilde{a}}$
- max $m_{\tilde{a}}$ for narrow range of $T_R \sim \mathcal{O}(100 \text{ GeV})$
- lower limit on $T_R$ for higgsino LOSP ($T_R \sim \mathcal{O}(10 \text{ GeV})$) and bino LOSP with $C_{aYY} = 0$ ($T_R \sim \mathcal{O}(1 \text{ GeV})$)

![Graphs showing the constraints on $m_{\tilde{a}}$ and $T_R$ for bino and higgsino LOSP with KSVZ and WDM exclusions.](image-url)

"Supersymmetric dark matter with low reheating temperature of the Universe"
Efficient direct/cascade decays of the inflaton field to DM

- for low enough temperatures (after $\chi$ freezes-out) direct and/or cascade decays of the inflaton field can work as an additional source of $\chi$
- this requires low $T_R$
- one may then obtain even $\Omega_\chi h^2(\text{low } T_R) > \Omega_\chi h^2(\text{high } T_R)$ depending on
  \[ \eta = b \frac{100 \text{ TeV}}{m_\phi} \]
  $b$ - average number of $\chi$ particles produced per inflaton decay
  $m_\phi$ - inflaton mass

Gravitino DM

Axino DM

$\Omega_\chi h^2 = 0.12$

$b$ino LOSP

$p10MSSM$ (95% excl.)

higgsino LOSP

KSVZ

$f_a = 1 \times 10^{11}$ GeV

$\eta = 0$

$\eta = 10^{-9}$

$\eta = 10^{-7}$
Conclusions

- BBN and relic density constraints in case of gravitino DM introduce lower limit $\min T_R \gtrsim 100$ GeV
- it can be relaxed if for efficient direct/cascade decays of the inflaton to DM
- axino DM thermal production yield for non-instantaneous reheating increases up to $\sim 20 - 30\%$ with respect to an instantaneous reheating scenario
- taking into account non-instantaneous reheating leads to corrected $T_R$-dependent upper limit on the axino DM mass
- for axino DM $\min T_R \gtrsim \mathcal{O}(1 - 10$ GeV$)$ or even lower for bino LOSP and efficient decays $\tilde{B} \rightarrow \tilde{a} \gamma$
Reheating period in the evolution of the Universe

\[ T \propto a^{-3/8} \]

\[ V_{\phi} \]

INFLATION \hspace{1cm} REHEATING

\[ V_{\text{end}} \]

\[ \phi_{\text{end}} \]
Reheating period in the evolution of the Universe

\[ T \propto a^{-1} \]

\[ T \propto a^{-3/8} \]

Temperature vs. time diagram:

- **INFLATION**
- **REHEATING**

\[ T_{\text{max}} \]

"Supersymmetric dark matter with low reheating temperature of the Universe"
Reheating period in the evolution of the Universe (2)

At the end of a period of cosmological inflation:

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

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

$$\Gamma_\phi = \sqrt{\frac{4\pi^3 g_*(T_R)}{45} \frac{T_R^2}{M_{Pl}}}$$

defines reheating temperature $T_R$

If non-instantaneous reheating – Boltzmann equations:


$$\frac{d\rho_\phi}{dt} = -3H\rho_\phi - \Gamma_\phi \rho_\phi$$

inflaton field

$$\frac{d\rho_R}{dt} = -4H\rho_R + \Gamma_\phi \rho_\phi + \langle \sigma v \rangle_{eff} \langle E_X \rangle [n_X^2 - (n_{eq_X}^e)^2]$$

radiation

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle_{eff} [n_X^2 - (n_{eq_X}^e)^2] \left( + \frac{b}{m_\phi} \Gamma_\phi \rho_\phi \right)$$

dark matter

Radiation dominated (RD) epoch begins when $T \sim T_R$, before – the reheating period
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Radiation dominated (RD) epoch begins when \( T \sim T_R \), before – the reheating period
Direct and cascade decays of the inflaton field into DM with low $T_R$

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- additional non-thermal DM production in the reheating period after freeze-out
- possible increase of the relic density $\Omega_\chi h^2 \uparrow$
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$higgsino$ DM

$\Omega_\chi h^2 = 0.12$