Gravitino (Over-)Production from Heavy Scalar Decay

M. Yamaguchi (Tohoku Univ.)
with T. Asaka & S. Nakamura

Workshop “Dark Side of the Universe”, Madrid
June 23, 2006

Refs. Nakamura & MY, hep-ph/0602081 (to appear in PLB)
Asaka, Nakamura & MY, hep-ph/0604132 (to appear in PRD)

See also:
Endo, Hamaguchi & Takahashi, hep-ph/0602061
Kawasaki, Takahashi &Yanagida, hep-ph/0603265,0605297
Dine, Kitano, Morisse & Shirman, hep-ph/0604140
Endo, Hamaguchi & Takahashi, hep-ph/0605091

Talk Plan

- Motivation
- Heavy Scalar Decays
  - into gravitinos
  - into other particles
- Cosmology of Heavy Moduli Scenario
- Implications to Inflation models
- Ways Out
- Conclusions

1. Motivation

- Scalar Dynamics: important role in Cosmology
- Era of Scalar Domination (coherent oscillation)
- Examples:
  - moduli field (Planck VEV, Planck suppressed interaction)
  - inflaton

Cosmological Moduli Problem

Coughlan et al 83
de Carlos-Casas-Quevedo-Roulet 93
Banks-Kaplan-Nelson 93

- Coherent oscillation of moduli fields would dominate the energy density of the universe.

- Late decay → reheating of the universe
  → disaster for big-bang nucleosynthesis (BBN)

Hope: may be OK if moduli is heavy (Moroi-MY-Yanadiga 95)

Moduli Stabilization

- Flux compactifications
  - most of moduli stabilized near string scale
  - Remaining few moduli can get masses due to e.g. gauge dynamics on branes

- Non-perturbative effects such as KKLT, racetrack etc → large mass to moduli (~ $100m_{3/2}$ or even larger)

Buchmuller-Hamaguchi-Lebedev-Ratz 04
Kohri-MY-Yokoyama 05
Choi-Falkowski-Nillles-Olechowski 05
Endo-MY-Yoshioka 05
Choi-Jeong-Okumura 05
Falkowski-Lebedev-Mambrini 05 ….

- Mixed modulus-anomaly mediation
  - interesting phenomenology

Talks by Choi, Okumura

- This observation motivates us to investigate decay of moduli (heavy scalar decay as well) at a quantitative level.
  - We recognize that some essential properties of the decay have been overlooked (or understood incorrectly) for long time.
  - decay into gravitinos / decay into gauginos

cf. Hashimoto-Izawa-MY-Yanagida 96
Moroi-Randall 99

- Gravitinos tend to be over-produced by moduli decay!

- A typical scenario in mind:

little hierarchy among masses

moduli mass >> gravitino mass >> soft susy masses

2. Heavy Scalar Decay
2.1 Decay into Gravitino Pair

Nakamura-MY 06
Endo,Hamaguchi,Takahashi 06

Lagrangian (in Planck unit)

$$\mathcal{L}_{3/2} = -\epsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\bar{\sigma}_\nu\partial_\rho\psi_\sigma - \frac{1}{4}\epsilon^{\mu\nu\rho\sigma}(G_j\partial_\rho\phi^j - G_{j^*}\partial_\rho\phi^{*j})\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\sigma$$
$$-e^{G/2}(\psi_\mu\sigma^{\mu\nu}\psi_\nu + \bar{\psi}_\mu\bar{\sigma}^{\mu\nu}\bar{\psi}_\nu)$$

$$G(X,X^*) = K(X,X^*) + \log|W(X)|^2$$ total Kaehler potential

Interaction of X with gravitino bi-linear

$$-\frac{1}{4}\epsilon^{\mu\nu\rho\sigma}(\langle G_X\rangle\partial_\rho\delta X - \langle G_{X^*}\rangle\partial_\rho\delta X^*)\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\sigma$$
$$-\frac{1}{2}m_{3/2}(\langle G_X\rangle\delta X + \langle G_{X^*}\rangle\delta X^*)(\psi_\mu\sigma^{\mu\nu}\psi_\nu + \bar{\psi}_\mu\bar{\sigma}^{\mu\nu}\bar{\psi}_\nu)$$

Auxiliary field (SUSY breaking) $\langle F_X\rangle = -\langle (G_{XX^*})^{-1}e^{G/2}G_{X^*}\rangle$

expectation for moduli: $\langle G_X\rangle \sim m_{3/2}/m_X$

Decay amplitude

$$\mathcal{M}(X_R \to \psi_{3/2}\psi_{3/2}) = i\frac{1}{\sqrt{2}}\langle G_{XX^*}\rangle^{-1/2}\langle e^{G/2}G_X\rangle \bar{v}_\mu(k')u^\mu(k)$$

helicity ½ component

$$u_\mu(k;1/2) = \sqrt{\frac{2}{3}}\epsilon_\mu(k;0)u(k;1/2) + \sqrt{\frac{1}{3}}\epsilon_\mu(k;1)u(k;-1/2),$$

$\epsilon_\mu(k,\lambda)$: massive vector field with helicity λ

$u(k,h)$: spinor with helicity h.

Note: $\epsilon_\mu(k,0) \simeq k_\mu/m_{3/2}$ at a high-energy limit → enhancement

(no such enhancement for helicity 3/2)

Decay Rate

Nakamura-MY 06
Endo,Hamaguchi,Takahashi 06

$$\Gamma(X_R \to \psi_{3/2}\psi_{3/2}) = \frac{1}{288\pi}d_{3/2}^2\frac{m_X^3}{M_{Pl}^2} \quad (m_{3/2} \ll m_X)$$

$$\langle G_{XX^*}\rangle^{-1/2}\langle e^{G/2}G_X\rangle \equiv d_{3/2}\frac{m_{3/2}^2}{m_X}. \quad \text{expectation } d_{3/2} = O(1)$$

$$(\langle F_X\rangle = -\langle (G_{XX^*})^{-1}e^{G/2}G_{X^*}\rangle)$$

REMARKS

Possibile mixing with SUSY breaking field (Polonyi field) Z

Dine et al 06

$$-\frac{1}{4}\epsilon^{\mu\nu\rho\sigma}(\langle G_i\rangle\partial_\rho\delta\phi^i - \langle G_{\bar{i}}\rangle\partial_\rho\delta\phi^{*\bar{i}})\bar{\psi}_\mu\bar{\sigma}_\nu\psi_\sigma$$
$$-\frac{1}{2}m_{3/2}(\langle G_i\rangle\delta\phi^i + \langle G_{\bar{i}}\rangle\delta\phi^{*\bar{i}})(\psi_\mu\sigma^{\mu\nu}\psi_\nu + \bar{\psi}_\mu\bar{\sigma}^{\mu\nu}\bar{\psi}_\nu)$$

A combination $\langle G_Z\rangle Z + \langle G_X\rangle X$ couples to gravitino pair.

scalar partner of goldstino

Mass diagonalization is needed.

Coupling of heavy "X" field with gravitino is suppressed if

1) absence of certain coupling (e.g. ZZX*)

2) sufficiently light Z

These conditions are easily violated. Furthermore, light Z would cause conventional moduli (or Polony) problem.

We do not consider this possible suppression.

2.2 Decay into other particles

e.g. decay into gauge bosons & gauginos

$$\mathcal{L}_{Xgg} = -\frac{1}{4}S_R(X)F^a_{\mu\nu}F^{a\mu\nu} - \frac{1}{8}S_I(X)\epsilon^{\mu\nu\rho\sigma}F^a_{\mu\nu}F^a_{\rho\sigma}$$

$$\mathcal{L}_{X\tilde{g}\tilde{g}} = \frac{i}{2}S_R(X)[\lambda^{(a)}\sigma^\mu\tilde{\mathcal{D}}_\mu\bar{\lambda}^{(a)} + \bar{\lambda}^{(a)}\bar{\sigma}^\mu\tilde{\mathcal{D}}_\mu\lambda^{(a)}] - \frac{1}{2}S_I(X)\tilde{\mathcal{D}}_\mu\left[\lambda^{(a)}\sigma^\mu\bar{\lambda}^{(a)}\right] + \frac{1}{4}\frac{\partial S}{\partial X}F_X\lambda^{(a)}\lambda^{(a)} + \frac{1}{4}\left(\frac{\partial S}{\partial X}F_X\right)^*\bar{\lambda}^{(a)}\bar{\lambda}^{(a)}$$

Note: gaugino mass is a function of moduli fielld

Decay Rate

$$\Gamma(X \to gg) = \Gamma(X \to \tilde{g}\tilde{g}) = \frac{N_G}{128\pi}d_g^2\frac{m_X^3}{M_{\rm Pl}^2}$$

Nakamura-MY 06
Endo-Hamaguchi-Takahashi 06
Dine et al 06

$$d_g \equiv \langle K_{XX^*}\rangle^{-\frac{1}{2}}\langle S_R\rangle^{-1}|\langle\frac{\partial S}{\partial X}\rangle|$$

N_G: the number of the gauge bosons ($N_G = 12$ for MSSM)

Summary Sheet on Moduli Decay

total decay rate

$$\Gamma_X = \frac{d_{\rm tot}^2}{8\pi}\frac{M_X^3}{M_P^2} \qquad d_{\rm tot} = \mathcal{O}(1)$$

→ reheat temperature

$$T_R \equiv \left(\frac{90}{\pi^2 g_*(T_R)}\right)^{\frac{1}{4}} \sqrt{\Gamma_X M_P}$$

$$= 5.9 \times 10^{-2}\text{GeV}\, d_{\rm tot} \left(\frac{M_X}{10^6\text{GeV}}\right)^{\frac{3}{2}}$$

decay rate into gravitino pair

$$\Gamma_{3/2} = \frac{d_{3/2}^2}{288\pi}\frac{M_X^3}{M_P^2} \qquad d_{3/2} = \mathcal{O}(1)$$

→ branching ratio into gravitino

$$B_{3/2} \equiv \frac{\Gamma_{3/2}}{\Gamma_X} = \frac{d_{3/2}^2}{36\, d_{\rm tot}^2} \qquad \to B_{3/2} = \mathcal{O}(0.01)$$

3. Cosmology of Heavy Moduli Scenario

Namakura-MY 06
Endo-Hamaguchi
-Takahashi 06

Consider the case:

moduli mass>> gravitino mass >> soft masses

Assume that the LSP is a neutralino.

Moduli decay into

→ SM particles → reheating
→ SM sparticles → LSPs
→ gravitinos → hadronic/EM showers: BBN
→ LSPs

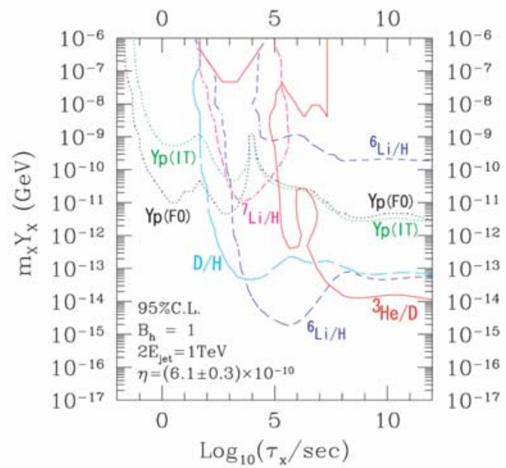
Constraints:

1) BBN constraint on gravitino decay
2) Overclosure (LSP overproduction)

Constraints from BBN

Kawasaki-Kohri
-Moroi 04

$Y_{3/2}^{\rm BBN} \sim 10^{-16}$	for	$M_{3/2} \sim 1$ TeV
$Y_{3/2}^{\rm BBN} \sim 10^{-15}$–$10^{-13}$	for	$M_{3/2} \sim 10$ TeV
No constraint	for	$M_{3/2} \gtrsim 100$ TeV



Gravitino yield from moduli decay

$$Y_{3/2}^X \simeq \frac{3}{2} B_{3/2} \frac{T_R}{M_X} \simeq 8.9 \times 10^{-8}\, B_{3/2} d_{\rm tot} \left(\frac{M_X}{10^6 {\rm GeV}} \right)^{\frac{1}{2}}$$

$B_{3/2} = \mathcal{O}(0.01),\ d_{\rm tot} \sim 1$

→BBN constraint pushes gravitino heavier than ~ 10^5 GeV

Constraint from LSP abundance

Gravitino→LSP

– Overabundance of the LSPs

Relic abundance of the LSPs

– LSPs are produced by gravitino decay
– Annihilation of LSPs
– Annihilation is not very efficient at low temperature (later epoch)

→ lower bound on the gravitino mass

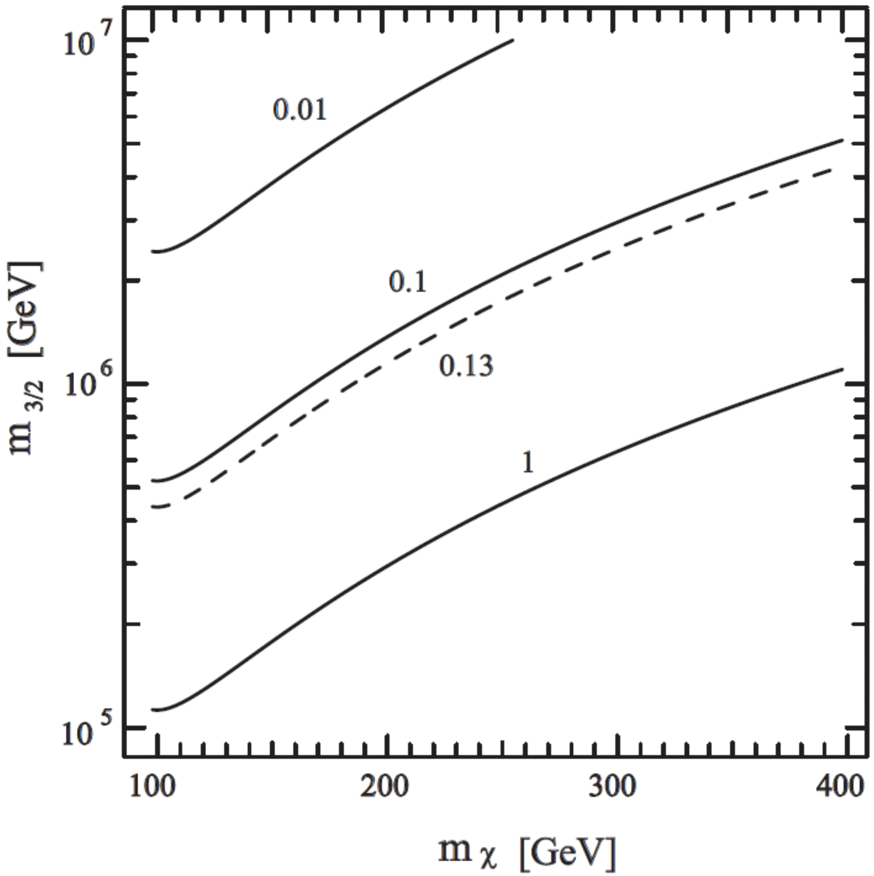
LSP abundance

Nakamura-MY 06

case study: LSP=neutral Wino

(largest annihilation cross section)

$\Omega_{\mathrm{LSP}} h^2$



Gravitino mass must be heavier than ~10^6 GeV to escape overclosure constraint. (wino case)

Even severer constraint on gravitino mass for other neutralino case

Low energy SUSY may be disfavored in the presence of moduli. (unstable gravitino)

4. Implications to Inflation models

Kawasaki-Takahashi-Yanagida 06
Asaka-Nakamura-MY 06

Inflaton decay into gravitino pair:

proportional to Fx: model dependent

- modular inflation: (inflaton=moduli)

  severely constrained

- other inflation scenarios $F_X \propto X \ll M_{Pl}$
  - chaotic inflation

    Z_2 symmetry→ F_X=0: no dangerous gravitino production
  - new inflation/hybrid inflation

Gravitino production may be suppressed
→ Model dependent analysis is required

5. Ways Out

- lighter LSP (such as axino)
  - how to realize lighter LSP? in particular within modulus-anomaly mediation
- Stable Gravitino: (Asaka,Nakamura&MY 06)
  - Constraint on gravitino relic abundance: less constrained
  - possibility of gravitino warm dark matter
  - give up moduli-anomaly mediation?
- Dilution by entropy production
  - thermal inflation (Lyth & Stewart 96, see also Lazarides,Panagiotakopoulos,Shafi 86)

Thermal inflation in modulus-anomaly mediation

Asaka-MY in preparation

Introduction of Singlet S

(a la deflected anomaly mediation) Pomaral-Rattazzi

Solution to μ-Bμ problem in MSSM

$$\left[\frac{S^\dagger}{S} H_1 H_2\right]_D$$

S field: very flat potential with TeV mass

→ flaton: Thermal inflation occurs

- Dilutes the primordial moduli
- Neutralino Dark matter: may come from the flaton decay, or moduli/graviitno decay

6. Conclusions

- Decay of heavy scalar field into gravitino pair was re-examined.

- Moduli decay into gravitinos is not suppressed in general

→ Recurrence of cosmological moduli/gravitino problems in heavy moduli case.

  – Very serious problem in particular for unstable gravitino

- Implications to inflation model building
  - modular inflation: seems problematic if gravitino is unstable
  - chaotic/new/hybrid inflations: more model dependent

◆ Ways Out

- lighter LSP other than neutralino (e.g. axino)
- Stable Gravitino (gravitino DM)
- dilution by thermal inflation:
  - interesting realization in modulus-anomaly mediation