hep-ph/0604140

Moduli Decays and Gravitinos

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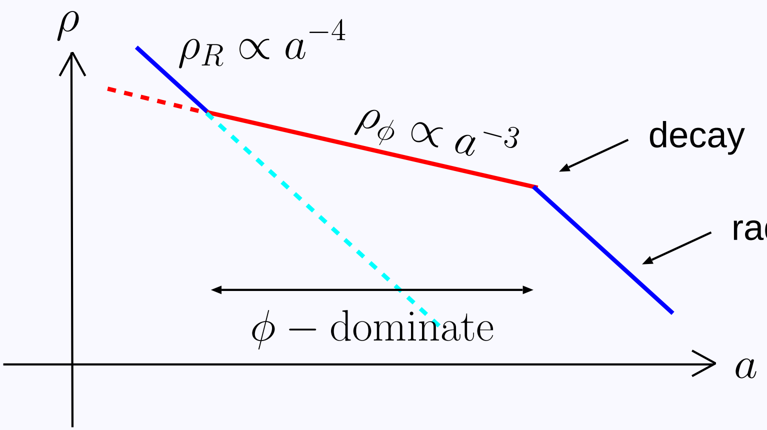
September 25, 2006, Cosmo06

Moduli Problem

Moduli: light and long-lived particle in String theory

Cosmological history:



- If $m_\phi \sim m_{3/2} \sim 100\ \mathrm{GeV}$

$$\tau_\phi \sim \left[\frac{1}{4\pi}\frac{m_\phi^3}{M_{\rm Pl}^2}\right]^{-1} \sim 10^7 \mathrm{sec}$$ --> Excluded by BBN

We need radiation dominated universe at $\tau \sim 10^{-2}\ \mathrm{sec}$

● $m_\phi \gg 100\ \mathrm{TeV}$ <== Supersymmetric stabilization e.g. KKLT

--> $\tau_\phi \sim 10^{-2}\ \mathrm{sec}$ --> BBN OK

But... $\phi \to \psi_{3/2}\psi_{3/2}$ —decay→ LSP ← dangerous for BBN!! / overclosure

[Endo, Hamaguchi,Takahashi 06]

[Nakamura, Yamaguchi 06]

decay → LSP

This is studied by Moroi and Randall [Moroi, Randall 99]

Moroi - Randall

$$\Gamma_{3/2} \sim \frac{1}{4\pi}\frac{m_{3/2}^2 m_\phi}{M_{\rm Pl}^2} \longrightarrow B_{3/2} \sim O\left(\frac{m_{3/2}^2}{m_\phi^2}\right)$$

Recent calculation

$$\Gamma_{3/2} \sim \frac{1}{4\pi}\frac{m_\phi^3}{M_{\rm Pl}^2} \longrightarrow B_{3/2} \sim O(1)$$

!

Are we doomed?

We found that the branching ratio depends on details of SUSY breaking sector and microscopic physics of moduli.

Interaction of gravitinos (Unitary gauge calculation)

[Endo, Hamaguchi,Takahashi 06]
[Nakamura, Yamaguchi 06]

$$\mathcal{L}_{\rm int} = -e^{G/2}\left[\psi_\mu \sigma^{\mu\nu}\psi_\nu + {\rm h.c.}\right] \qquad (G = K + \ln|W|^2)$$

Taylor expansion →

$$-\frac{e^{G/2}}{2} G_\phi \phi \left[\psi_\mu \sigma^{\mu\nu}\psi_\nu + {\rm h.c.}\right]$$

$$G_\phi \sim \frac{F_\phi}{m_{3/2}} \sim \frac{m_{3/2}}{m_\phi}$$ ← Supersymmetric mass term

$$\psi_\mu = \frac{k_\mu}{m_{3/2}} u(k)$$: Longitudinal mode

$$e^{G/2} = m_{3/2}$$

$$\Rightarrow M_{3/2} \sim m_\phi \qquad \Rightarrow \Gamma_{3/2} \sim \frac{m_\phi^3}{M_{\rm Pl}^2} \qquad \Rightarrow B_{3/2} \sim O(1)$$

quite generally

No suppression by $m_{3/2}$

Simple model

$$K = \phi^\dagger \phi + a(\phi + \phi^\dagger) + z^\dagger z$$

$$W = \frac{m_\phi}{2}\phi^2 + \mu^2 z + c$$

Supersymmetric mass term

SUSY breaking sector

$$F_z = \mu^2 \sim m_{3/2}$$

$$V = e^G(|G_\phi|^2 + |G_z|^2 - 3) \qquad (G = K + \ln|W|^2)$$

$$V_\phi = V_z = V = 0$$

$$\Rightarrow G_\phi = -\frac{3am_{3/2}}{m_\phi} \qquad G_z = \sqrt{3}$$

Naive estimation looks fine......

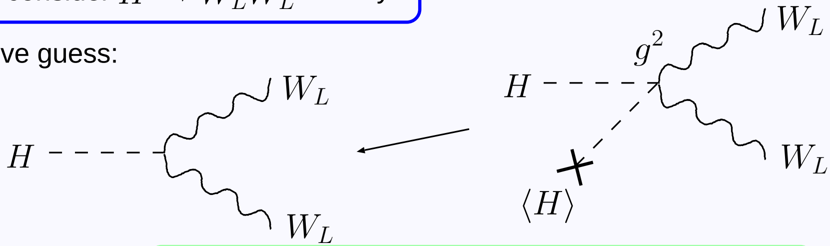
Caution! Calculation in unitary gauge is extremely dangerous for order estimate

Analogy: U(1) gauge theory

$$V = m_H^2 |H|^2 + \frac{\lambda}{4}\left(|h|^2 - v^2\right)^2 + \epsilon^2 (H^\dagger h + \text{h.c.}) \qquad (m_H \gg v)$$

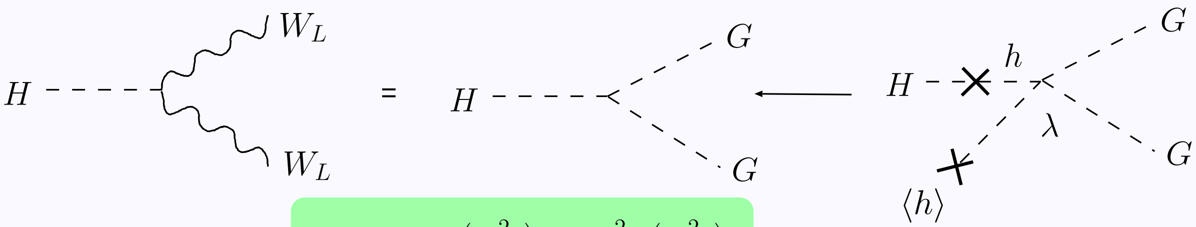
Let's consider $H \to W_L W_L$ decay

Naive guess:



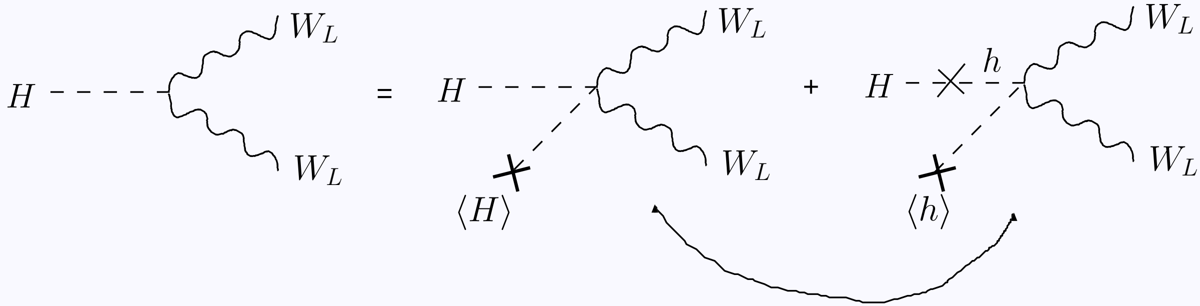
$$M \sim g^2 v \left(\frac{\epsilon^2}{m_H^2}\right) \left(\frac{k_\mu}{gv}\right) \left(\frac{k'^\mu}{gv}\right) \sim \frac{m_H^2}{v} \left(\frac{\epsilon^2}{m_H^2}\right)$$

But this is incorrect. Equivalence theorem saids



$$M \sim \lambda v \left(\frac{\epsilon^2}{m_H^2}\right) \sim \frac{m_h^2}{v} \left(\frac{\epsilon^2}{m_H^2}\right)$$

Acturally in unitary gauge



cancellation!

$$O(m_H^2) - O(m_H^2) = O(m_h^2)$$

Lesson: Goldstone picture is safer.

Goldstino Lagrangian

$$\mathcal{L}_{\chi\chi} = -\frac{1}{2}e^{G/2}\left(G_{zz} + \frac{1}{3}G_z G_z - \Gamma^z_{zz}G_z - \Gamma^\phi_{zz}G_\phi\right)\psi_z\psi_z$$

$$\Rightarrow \mathcal{L}_{\chi\chi\phi} = -\frac{1}{2}e^{G/2}\left(G_{zz\phi} + \frac{2}{3}G_{z\phi}G_z\right.$$

=O(1)

$$\left. -\Gamma^z_{zz,\phi}G_z - \Gamma^z_{zz}G_{z\phi} - \Gamma^\phi_{zz,\phi}G_\phi - \Gamma^\phi_{zz}G_{\phi\phi}\right)\phi\psi_z\psi_z$$

=0

$\Rightarrow M_{3/2} \sim m_{3/2}$ not m_ϕ !

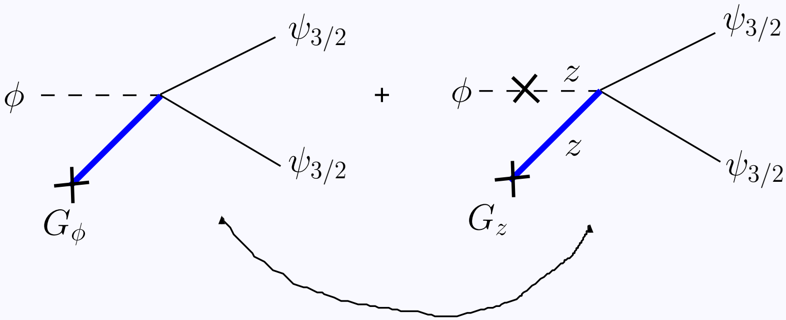
$$\Rightarrow B_{3/2} \sim \left(\frac{m_{3/2}}{m_\phi}\right)^2$$

There is a suppression.

It seems that unitary gauge calculation overestimated the branching ratio!!

What's wrong in unitary gauge calculation?

=> the same reason as that in U(1) example



cancellation! $O(1) - O(1) = O(m_{3/2}/m_\phi)$

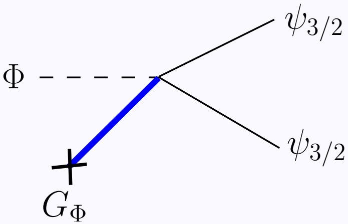
mass eigenstate of heavy scalar:

$$\Phi = \phi + \frac{G_{\bar{\phi}\bar{z}}}{G_{\bar{\phi}\bar{\phi}}} z \qquad \text{(up to } O(m_{3/2}^2/m_\phi^2)\text{)}$$

From $V_\phi = 0$ $\quad \Rightarrow G_\phi = -\frac{G_{\bar{\phi}\bar{z}}}{G_{\bar{\phi}\bar{\phi}}} G_z$

$$\Rightarrow G_\Phi = G_\phi + \frac{G_{\bar{\phi}\bar{z}}}{G_{\bar{\phi}\bar{\phi}}} G_z = 0$$

!



= 0

Is decay rate always suppressed by $\left(\frac{m_{3/2}}{m_\phi}\right)^2$?

There are two possibilities for non-suppressed decay:

1. $\delta K = -\frac{(z^\dagger z)^2}{\Lambda^2}$ ==> large SUSY breaking mass term for z

$$m_z \sim m_{3/2}\left(\frac{M_{\rm Pl}}{\Lambda}\right) \quad \Rightarrow \quad \Phi = \phi + \frac{m_{3/2} m_\phi}{m_z^2} z$$ (For $m_z \gg m_\phi$)

$$\mathcal{L} \ni -\frac{1}{2} e^{G/2} \Gamma^z_{zz,z} G_z z^\dagger \psi_z \psi_z \quad \rightarrow -\underbrace{\frac{1}{2} m_{3/2} \frac{1}{\Lambda^2} \frac{m_{3/2} m_\phi}{m_z^2}}_{\sim m_\phi} \Phi^\dagger \psi_z \psi_z$$

$$\Rightarrow \boxed{M \sim m_\phi}$$

If z has large SUSY breaking mass term as is happening in dynamical SUSY breaking models, there is no suppression.

2. $\delta K = \kappa \phi^\dagger z z$

$$= m_\phi / m_{3/2}$$

$$\mathcal{L} \ni -\frac{1}{2} e^{G/2} \underbrace{\Gamma^\phi_{zz}}_{= \kappa} \overbrace{G_{\phi\phi}} \phi \psi_z \psi_z \quad \Rightarrow \quad \boxed{M \sim \kappa m_\phi}$$

If there is direct coupling between moduli and SUSY breaking field of this type, there is no suppression.

Summary

- Moduli --> gravitino decay branching ratio can be of order $\left(\frac{m_{3/2}}{m_\phi}\right)^2$

--> Gravitino problem from moduli decay is model dependent

But if it is suppressed,

There is always lighter moduli z. This may cause another cosmological problem. But this again depends on SUSY breaking models.

- Branching ratio is O(1) when

1. $m_z \gg m_\phi$

or

2. $\delta K = \kappa \phi^\dagger z z$ with $\kappa \sim O(1)$

These give constraints on SUSY breaking models.