Non-thermal Gravitino Dark Matter in Gauge Mediation

Ryuichiro Kitano (Tohoku U.)

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* Summary

Let's start with a non-stringy motivation for non-thermal cosmology.

Standard WIMP scenario

Neutralino dark matter

What is neutralino? -- Gauge singlet fermions in the MSSM

* Bino $(\tilde{B}^0)$ U(1)Y gaugino
* neutral Wino $(\widetilde{W}^0)$ One of SU(2)L gauginos
* neutral Higgsinos $(\tilde{H}_u^0,\ \tilde{H}_d^0)$

They mix each other by EWSB.

If the lightest one is the lightest SUSY particle --> Stable

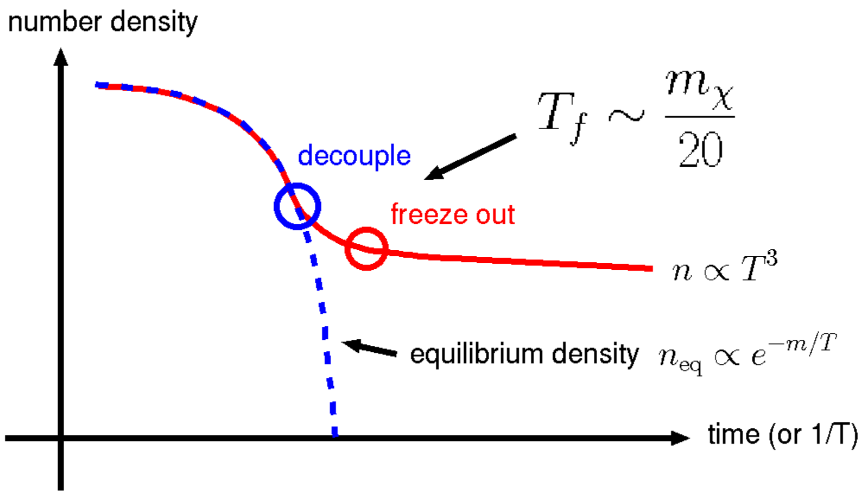
--> Candidate for dark matter

The "Standard" mechanism of the Dark Matter generation

Thermal decoupling

Boltzmann eq.

$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma v \rangle (n_\chi^2 - n_{\rm eq}^2)$$



unimportant after freeze out

unimportant after decouple

$$n_\chi \sim \frac{3H}{\langle \sigma v \rangle} \sim \frac{T_f^2}{M_{\rm Pl}} \left(\frac{\alpha}{M^2} \right)^{-1}$$

(number density at the time of freezing out)

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi / s}{\rho_c / s} \sim \frac{m_\chi n_\chi / T_f^3}{4 \times 10^{-9} \ {\rm GeV}} \sim 0.1 \left(\frac{M}{300 \ {\rm GeV}} \right)^2$$

great!!!

Assumptions made in this scenario:

1. Neutralino is the LSP (stable)
2. The universe is radiation dominated at the time of decoupling.
3. No entropy production below $T<O(100\text{GeV})$

Are these reasonable assumptions?

Assumption 1.

→ Gravity mediation

→ Moduli problem?

→ Inconsistent with Assumptions 2 and 3.

↓ Anomaly mediation

→ Wino LSP?

→ Too small abundance....

It seems that we need a special circumstance for the "Standard" mechanism to work....

Moduli/Gravitino Problem

In the gravity mediation scenario, there is always a singlet scalar field which obtain a mass mainly through the SUSY breaking.

$$\mathcal{L} \ni \left[\left(\frac{1}{g^2} + \frac{S}{M_{\rm Pl}}\right) W^\alpha W_\alpha\right]_F$$

This field must be singlet, and cannot be stabilized in a super-symmetric way otherwise it cannot carry a SUSY breaking Vev of order $m_{3/2}$ M_{pl}

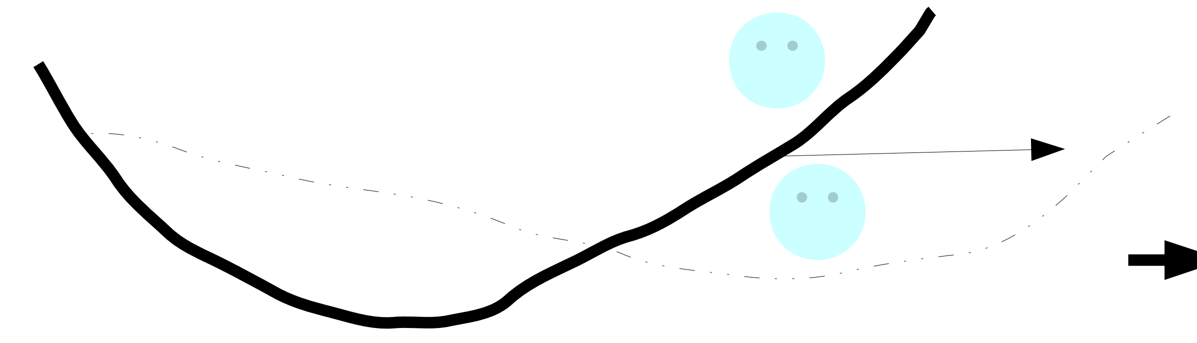
This is non-zero.

We need to include this field to consider the cosmological history.

Moduli cosmology

[Coughlan, Fischler, Kolb, Raby, Ross '83]
[Dine, Fischler, Nemeschansky '84]
[Banks, Kaplan, Nelson '93]
[Joichi, Yamaguchi '94]....

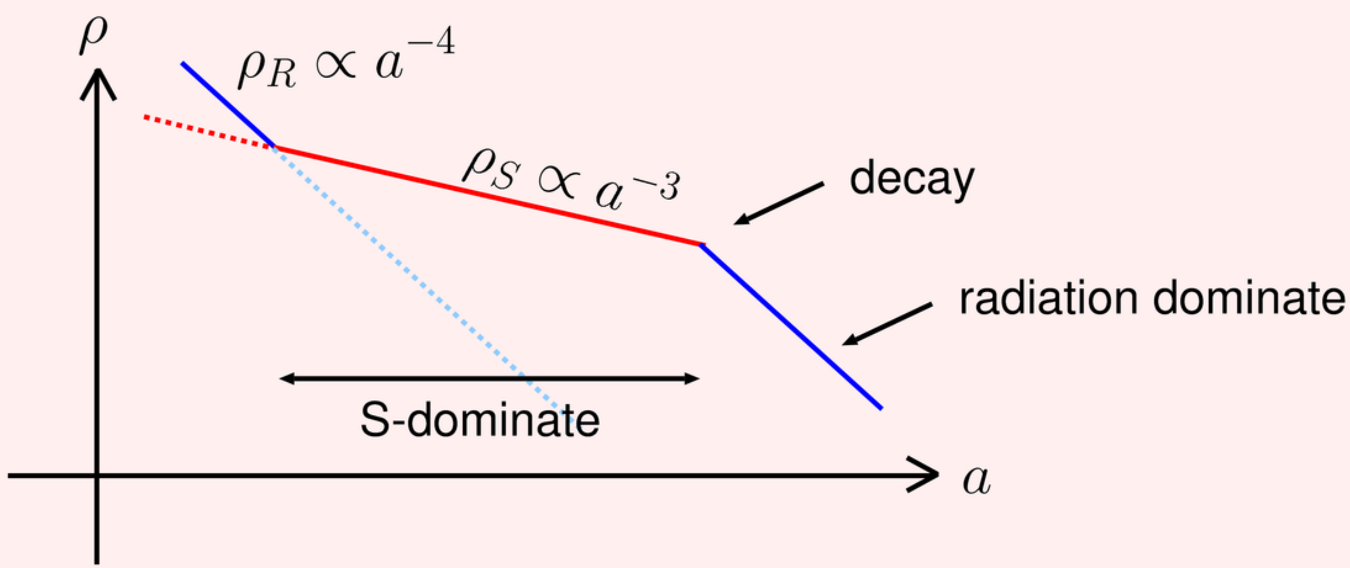
S is singlet → Moduli problem



During inflation,
S potential is deformed

→ Large initial amplitude

Cosmological history:



Once S-domination happens, it's a cosmological disaster.

In gravity mediation,

$S \to \psi_{3/2}\psi_{3/2}$ decay always has O(1) branching ratio (if open) because S couples to other fields only with 1/M_{Pl} suppressed operators.

→ Gravitino is a major energy density component.

→ If the gravitino is a stable particle (LSP), it is too much abundance.

If it is not the lightest, the gravitinos decay at τ~O(year). This destroys the standard BBN.

If the decay is kinematically forbidden, it means S has a lifetime of O(year).

... It's terrible.

It's clearly inconsistent with the neutralino dark matter scenario.

For the standard neutralino dark matter scenario to work, we need something like...

* an inflation model that does not couple to the S field.
* a low scale inflation such that the deformation of the S potential is small enough.
* an initial condition such that S domination doesn't happen.

....

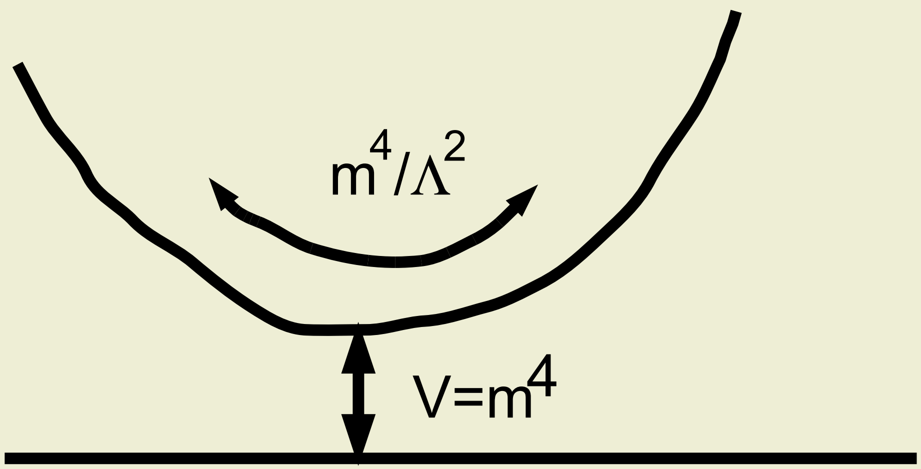
Wmm... It may be the case but it's worth considering possibilities other than neutralino WIMP.

Are there consistent SUSY cosmology with such a scalar field?

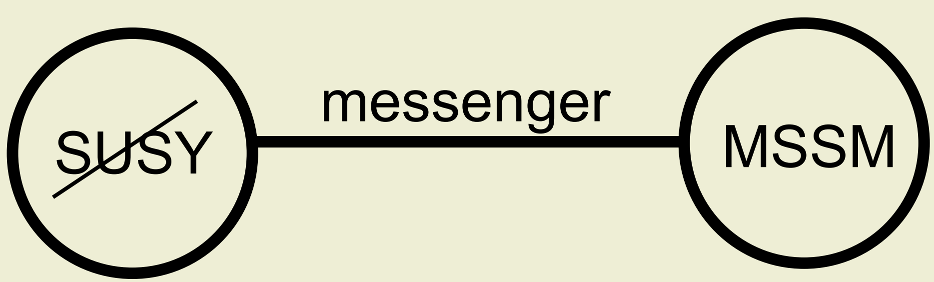
Yes, gauge mediation offers an interesting possibility of
non-thermal gravitino dark matter

Let's first fix the framework. [RK '06](See also [Murayama, Nomura '06])

SUSY breaking



Gauge Mediation



Effective Lagrangian:

$$K = S^\dagger S - \frac{(S^\dagger S)^2}{\Lambda^2}$$

$$W = m^2 S$$

$$W = k S \bar{f} f$$

Charged under the SM gauge group.

In this framework, the gravitino is the LSP.

There are three parameters in this model:

VEV (this should be non-zero for gauge mediation) → $\langle s \rangle$

$$\langle s \rangle, \; F_S, \; \text{and} \; \Lambda$$

m^2 → F_S

We can trade those with masses:

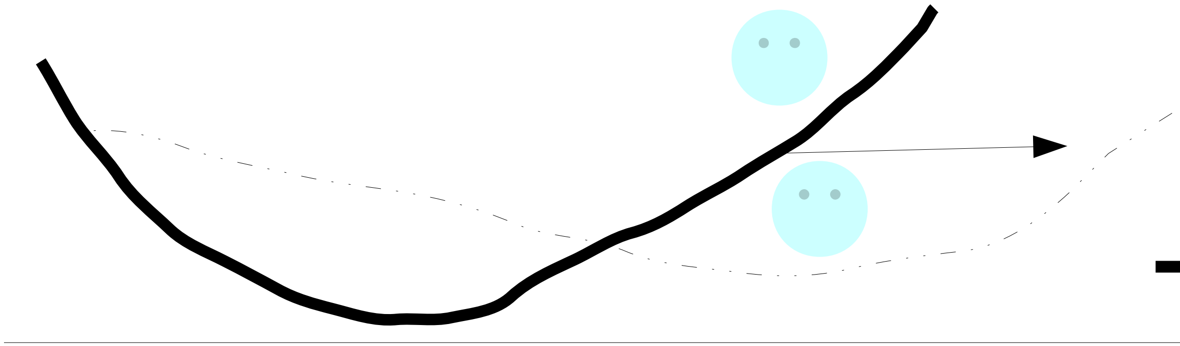
$$m_{\tilde{B}} = \frac{g_1^2 N}{(4\pi)^2} \frac{F_S}{\langle s \rangle}, \qquad \text{Bino mass}$$

$$m_S = \frac{2F_S}{\Lambda}, \qquad \text{mass of S}$$

$$m_{3/2} = \frac{F_S}{\sqrt{3} M_{\rm Pl}}, \qquad \text{Gravitino mass}$$

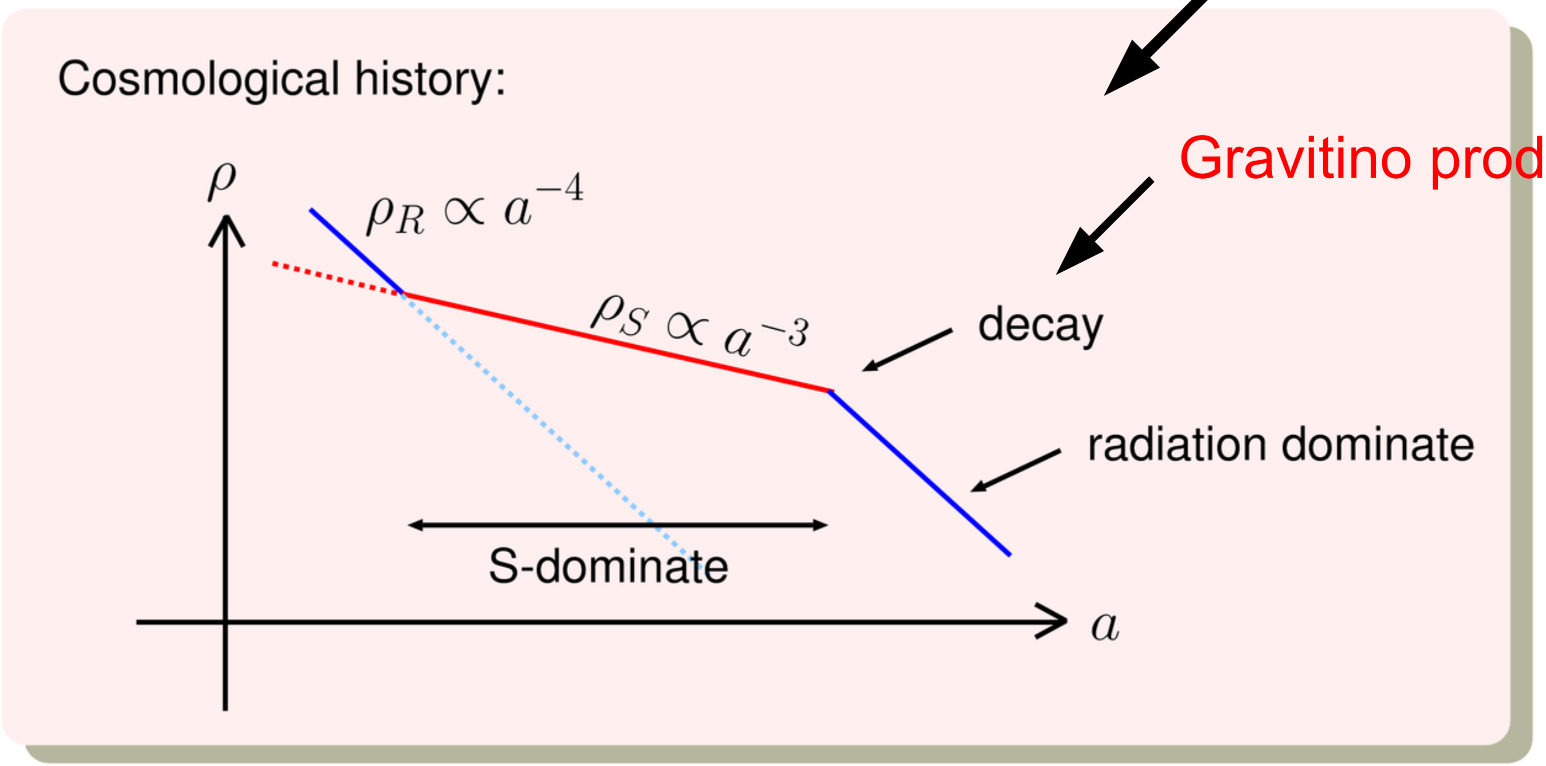
Non-thermal Gravitino dark matter

[Ibe, RK '06]
[Hamaguchi, RK, Takahashi '09]



During inflation,
S potential is deformed

Large initial amplitude



Gravitino production!

This I called 'moduli/gravitino problem,' but now it's a mechanism for the dark matter production.

Non-thermal gravitino production

Step 1: After inflation, S oscillation starts

Step 2: S decays and reheat the Universe

Step 3: gravitino cooling

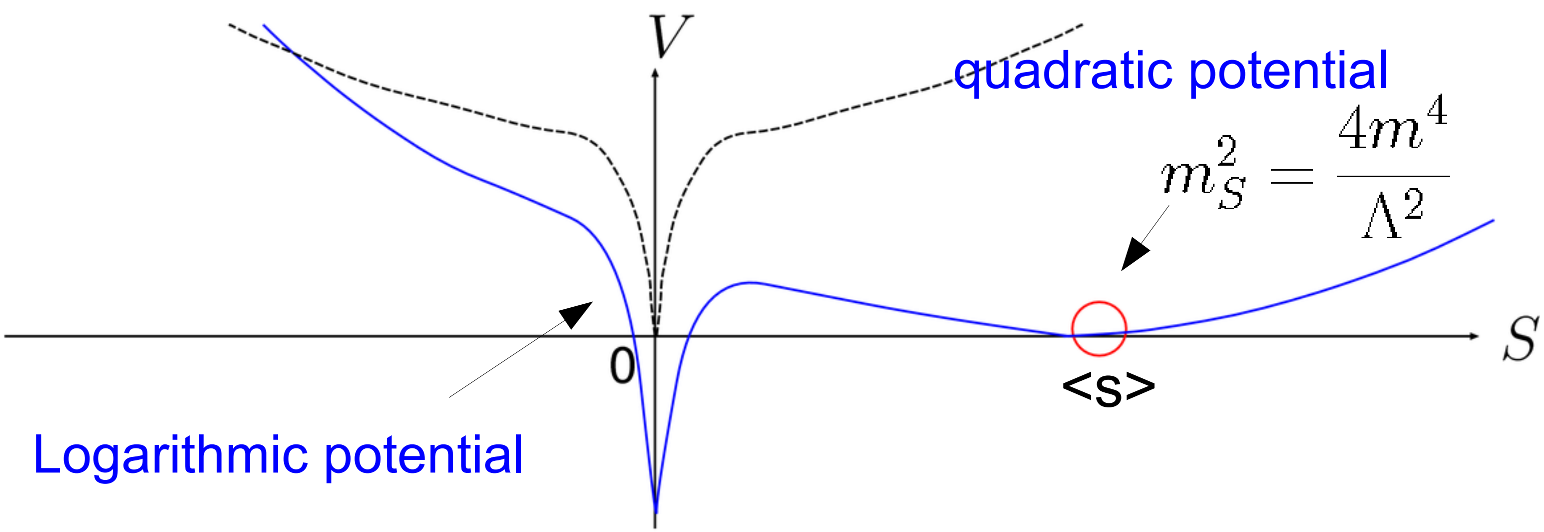
Let's discuss it step by step.

Step 1: oscillation

S-potential

$$V = m_S^2 |S - \langle s \rangle|^2 + \frac{k^2}{(4\pi^2)} m^4 \log |S|^2 / \Lambda_0^2$$

perturbative correction



$$m_{3/2} = \frac{m^2}{\sqrt{3} M_{\rm Pl}}$$

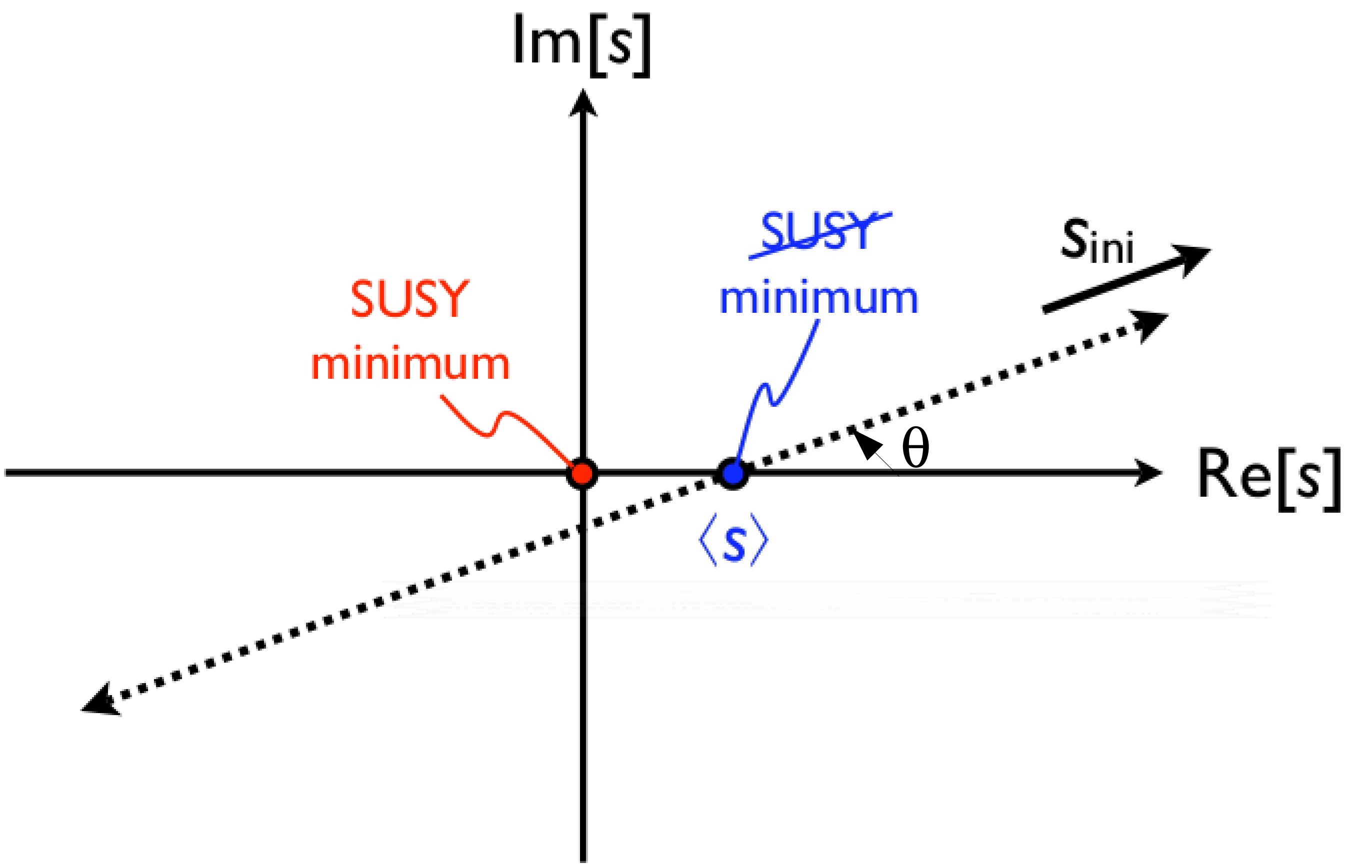
$$F_S = m^2$$

SUSY breaking vacuum is supported by $|S|^2$, while SUSY vacuum is log.

→ SUSY breaking vacuum is more attractive at most point on the complex S plane!

We are attractive!!

If initial value of S is not at <S>=0, S rolls down to the SUSY breaking vacuum when H~ms.



A more careful analysis show that s-domination can happen for

$10^{-5} < k < 10^{-3}$ $0.2 < \theta < \pi/2$ $10^5\text{GeV} < T_R < 10^6\text{GeV}$

for $m_{3/2}$=30MeV, m_{BINO}=200GeV, m_S=100GeV

Step 2: S decay

Interaction Lagrangian of S

We can read off from the S dependence of low energy parameters.

* S – gaugino coupling

$$\mathcal{L}_{\rm gaugino} = -\frac{1}{2} m_\lambda(S)\lambda\lambda + \text{h.c.}$$

with $m_\lambda(S) = \frac{g^2 N}{(4\pi)^2}\frac{m^2}{S}$

$$\rightarrow \quad \mathcal{L}_\lambda = \frac{1}{2}\frac{m_\lambda}{\langle S\rangle} S\lambda\lambda + \text{h.c.}$$

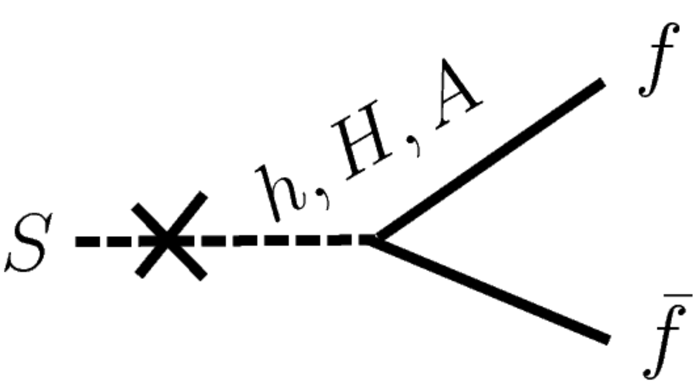
Only real part of S can decay through this.

* S – scalar coupling

$$\mathcal{L}_{\rm scalar} = \frac{m_{\tilde f}^2}{\langle S\rangle} S \tilde f^\dagger \tilde f + \text{h.c.}$$

* S – fermion coupling

$$\mathcal{L}_{\rm fermion} \sim \frac{m_f}{\langle S\rangle} S f f^c + \text{h.c.}$$



Couplings are proportional to their masses.

* S – gravitino coupling

Fermionic component of S → goldstino → gravitino

$$\mathcal{L}_{3/2} \in \left[-\frac{(S^\dagger S)^2}{\Lambda^2}\right]_D$$

$$\mathcal{L}_{3/2} = -\frac{2F_S^\dagger}{\Lambda^2} S^\dagger \tilde{s}\tilde{s} + \text{h.c.} \rightarrow -\frac{1}{2}\frac{m_{3/2}}{\langle S \rangle} S^\dagger \bar{\psi}_{3/2}\psi_{3/2} + \text{h.c.}$$

Point

Again, proportional to mass.

1. interactions are suppressed by 1/<S>.

→ Shorter lifetime compared to the gravity mediation case.

Good for BBN!

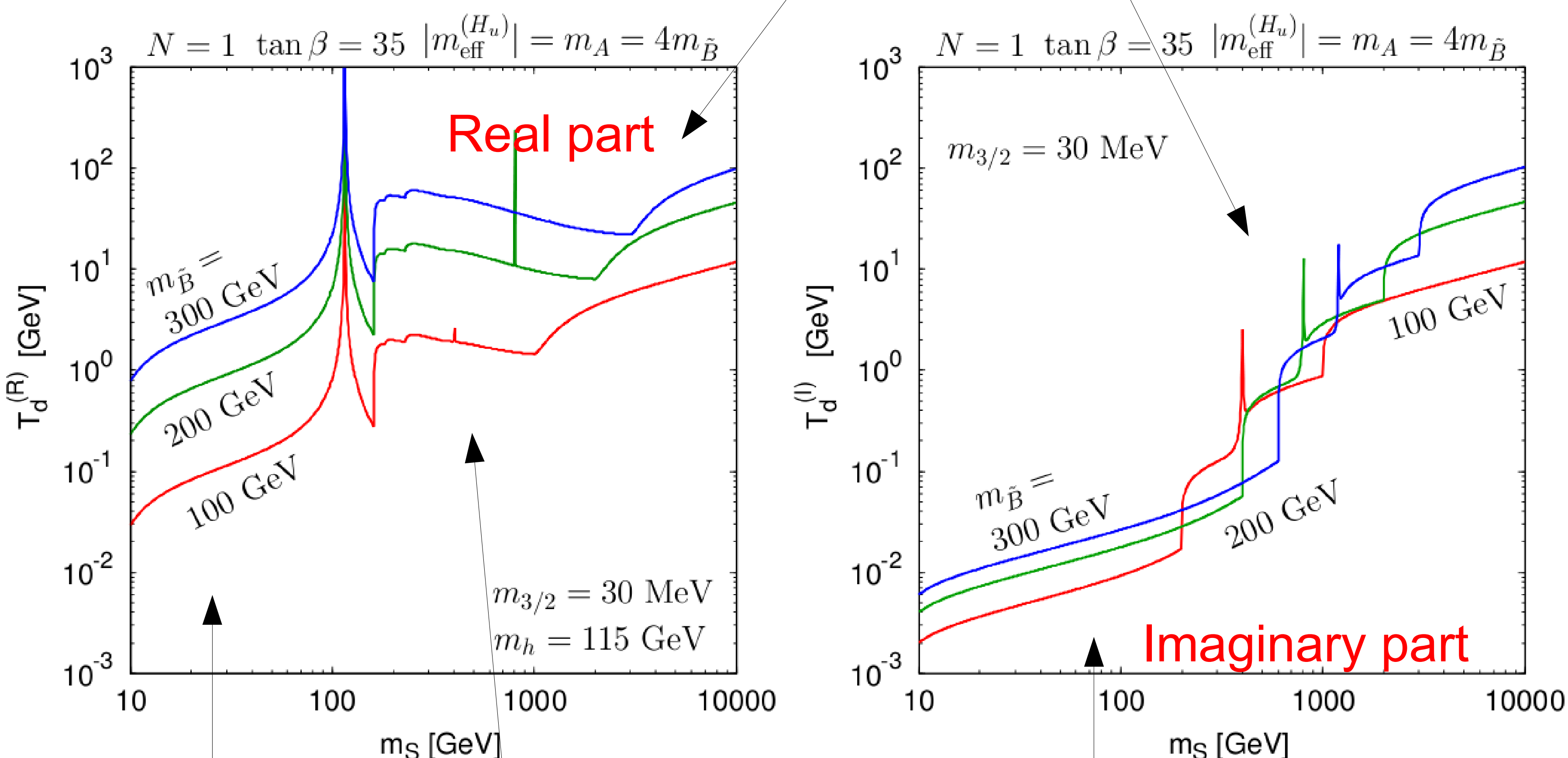
2. gravitino coupling is supressed by $m_{3/2}$!

→ Smaller branching ratio of $O\left(\frac{m_{3/2}^2}{m_{\text{SUSY}}^2}\right)$

Good for the gravitino abundance!

Decay temperatures

s-->gauginos



s–>bb

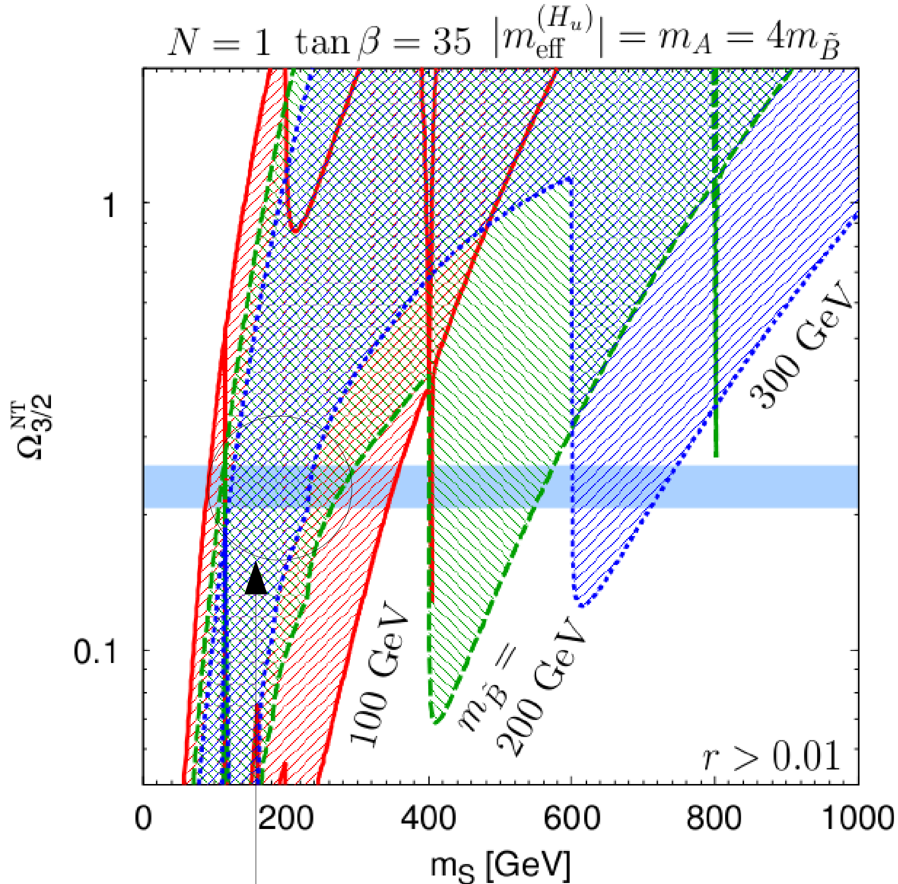
s-->hh, ZZ, WW

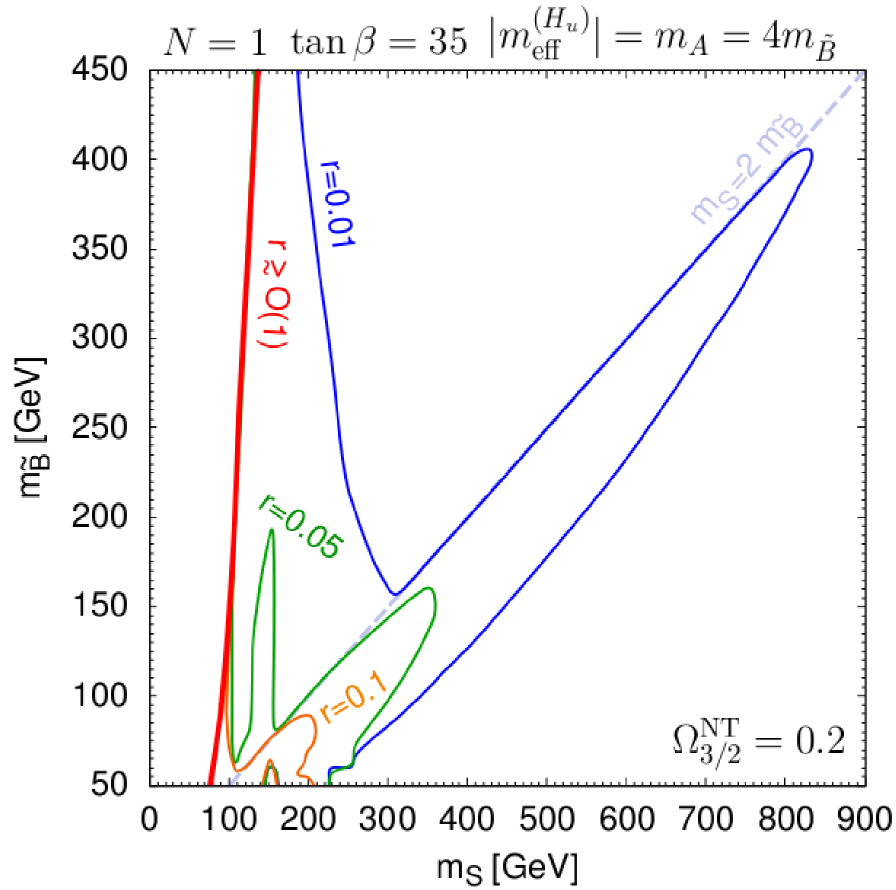
s–>bb

Imaginary part decays later --> main contribution to the gravitino abundance (if the energy fraction is O(1))

Gravitino abundance

$Y_{3/2} \sim T/m_S$ Br(s-->2 gravitinos)





Ω is independent of the gravitino mass.

This region is not very sensitive to the Bino mass. (s-->bb dominates.)

$$\Omega_{3/2}^{\rm NT} \simeq 0.2 \cdot N \left(\frac{m_S}{100~{\rm GeV}}\right)^{7/2} \left(\frac{m_{\tilde{B}}}{200~{\rm GeV}}\right)^{-1}$$

Although Ω doesn't depend on $m_{3/2}$, there are other constraint on $m_{3/2}$.

BBN (decay temperature should be T>O(10)MeV)

$$m_{3/2} \lesssim \mathcal{O}(100)\ \mathrm{MeV}$$

Thermal component (Ω from thermal production should not exceed 0.2)

$$m_{3/2} \gtrsim \mathcal{O}(10)\ \mathrm{MeV}$$

→ In conclusion, the non-thermal gravitino dark matter points at

$$m_{3/2} \sim 10 - 100\ \mathrm{MeV} \qquad m_S \sim 100\ \mathrm{GeV}$$

Step 3: gravitino cooling

Are gravitinos cold?

Well, they are non-thermally produced.

→ Their distribution is not the thermal one.

$E_{3/2} \sim \frac{m_S}{2}$ at the time of production, but it slows down by redshift.

Anyway, they must be non-relativistic at the time of the structure formation.

→ $\lambda_{FS} \lesssim \mathcal{O}(100)\,\mathrm{kpc}$.

In this scenario,

$$\lambda_{FS} \simeq 60\,\mathrm{kpc}$$

Marginal. Maybe interesting for future observation.

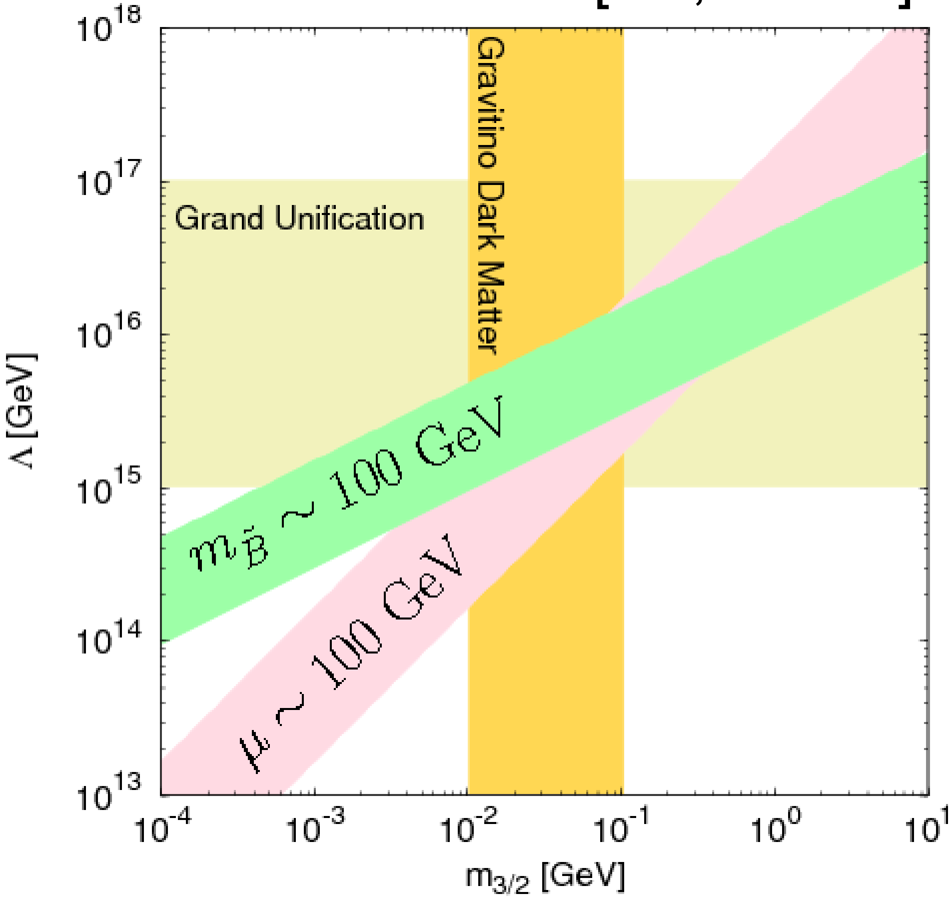
Are there models which naturally account for

$$m_{3/2} \sim 10 - 100 \text{ MeV} \qquad m_S \sim 100 \text{ GeV} \quad ?$$

→ $\langle s \rangle \sim 10^{12}$ GeV $\qquad \Lambda \sim 10^{15} - 10^{16}$ GeV

The gravitational stabilization: $\langle s \rangle \sim \Lambda^2 / M_{Pl}$ fits the scenario.

[Ibe, RK '06]



Also, the sweet spot relation for the μ-problem:

$$\mu \sim \frac{F_S}{\Lambda} \sim m_S$$

is consistent.

How to test the scenario?

1. observation of the long free streaming scale?

2. If the mechanism for generating μ is sweet spot, the LHC will be able to confirm the spectrum.

Especially, a long-lived stau is predicted in a wide range of parameter region. In that case, mass measurements of SUSY particles are much easier than the (long-lived) neutralino NLSP case.

[Hinchliffe, Paige '00][Ellis, Raklev, Oye '06][Ibe, RK '06]
[Feng et al. '09][Ito, RK, Moroi '09]

Summary

* When we think of SUSY cosmology, we should include the scalar partner of the goldstino and the gravitino in the discussion.

* A class of gauge mediation models provides viable cosmology with non-thermally produced gravitino dark matter.

* Baryogenesis, inflation model building etc. in this scenario are interesting to do. There may be some non-trivial predictions...