Title: Cascade supersymmetry breaking and low scale gauge mediation

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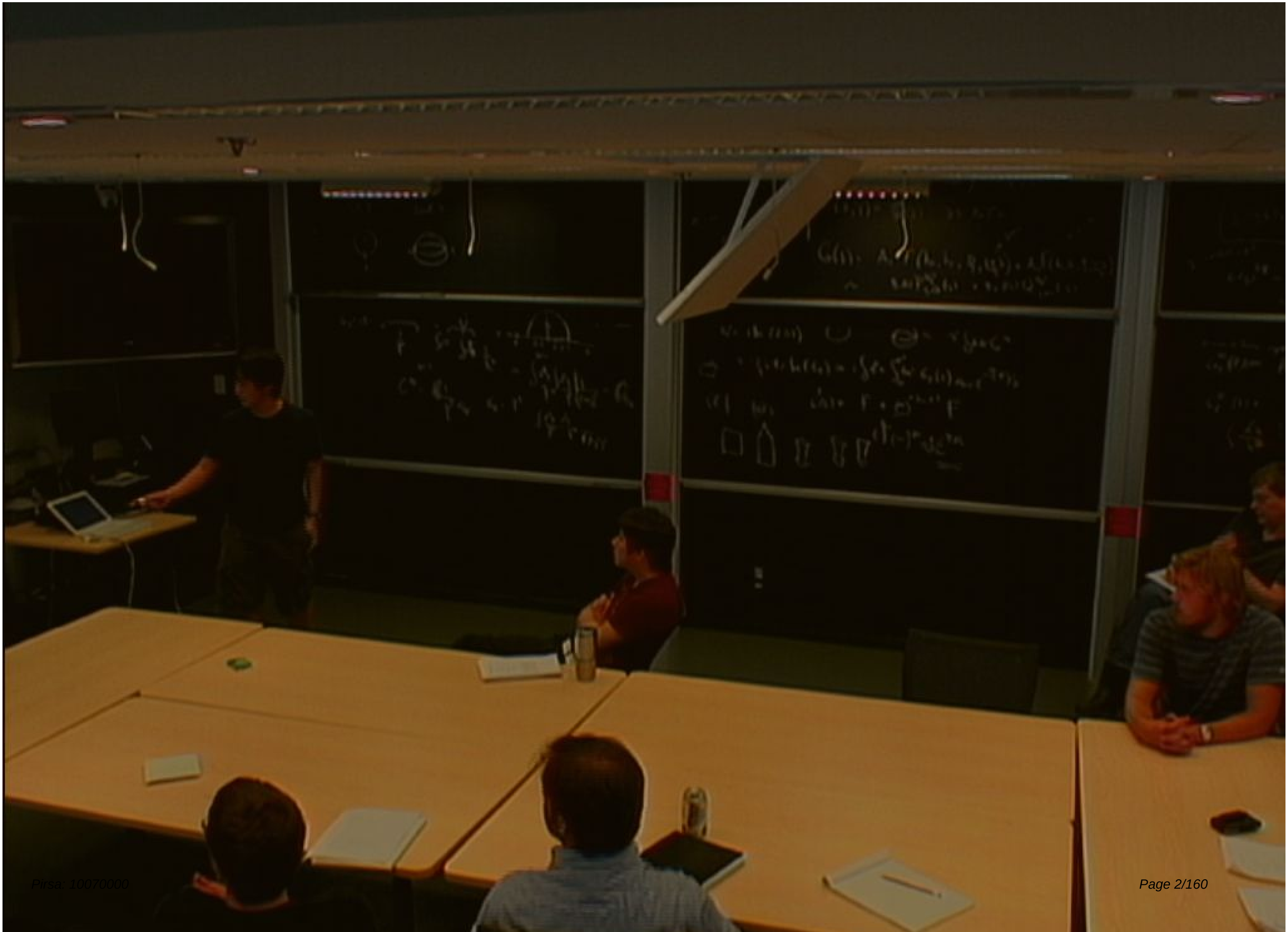
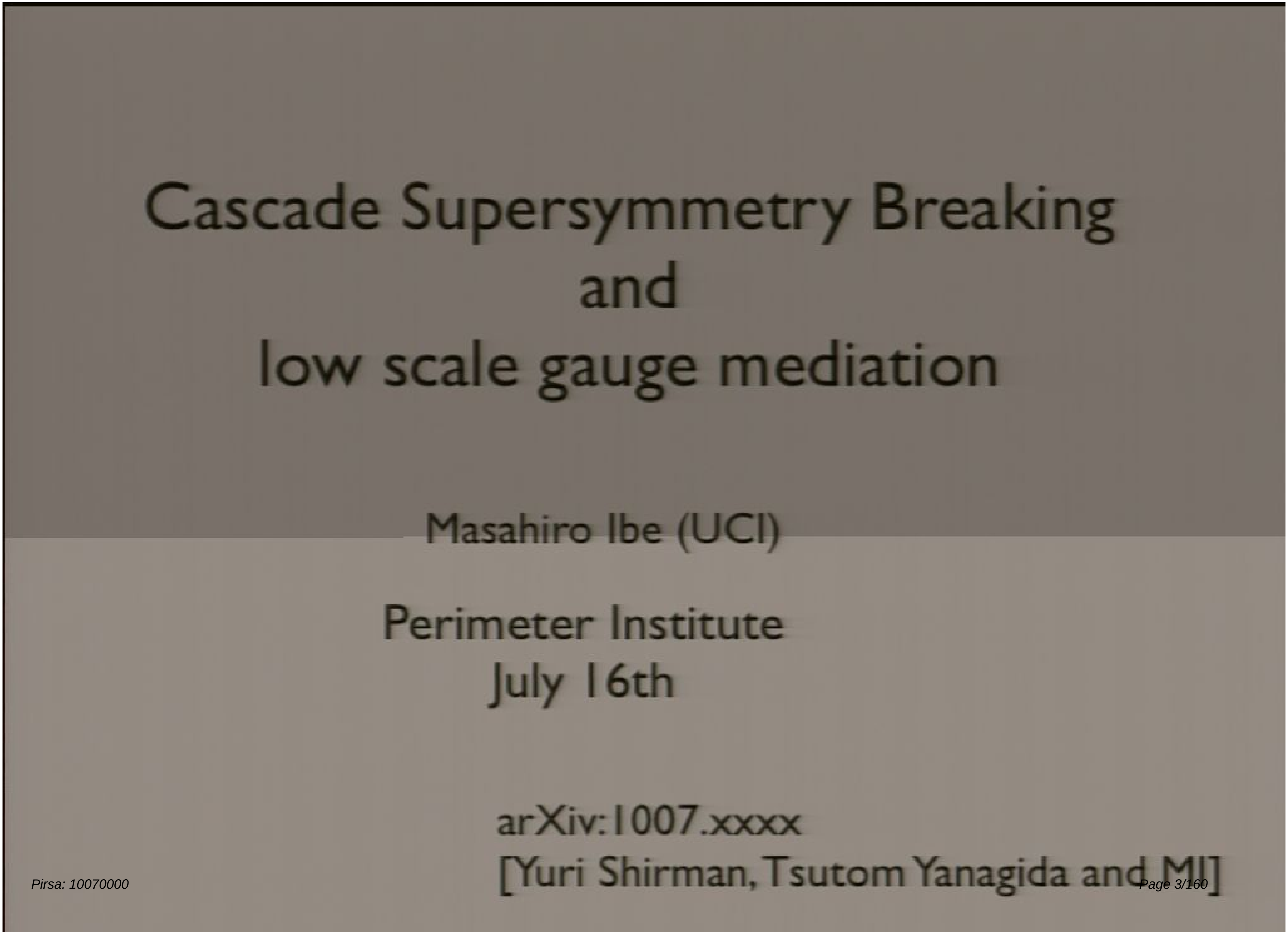
Abstract: The gauge mediation models with a gravitino mass in the eV range is a quite attractive scenario which causes no cosmological/astrophysical problems. The model construction with such a light gravitino is, however, quite challenging and in most cases ends up with the problems with the suppressed gaugino mass, the vacuum instability and the Landau pole problems of the Standard Model gauge coupling constants.

In this talk, I explain our proposal in which a gauge mediation model with the gravitino whose mass in the eV range is realized without having those problems.





Cascade Supersymmetry Breaking and low scale gauge mediation

Masahiro Ibe (UCI)

Perimeter Institute
July 16th

arXiv:1007.xxxx
[Yuri Shirman, Tsutom Yanagida and MI]

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Introduction

Gauge Mediation Supersymmetry Breaking Model

- Flavor Blind Mediation Mechanism
- SUSY CP problems can be solved

  (It depends on how μ/Bμ terms are generated)
- Positive sfermion mass squared

  (Let us remind ourselves that it's non-trivial!)
- Consistent with high reheating temperature

  (Especially, O(1)eV gravitino is interesting)

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Model building of the gauge mediation models with O(1) eV mass is not easy! (Almost NO GO)

- Vacuum instability
  - Color/Electroweak symmetry breaking vacuum
  - Supersymmetric vacuum
- Suppressed Gaugino Mass
  - Tevatron Wino mass bound [arXiv:0910.3606]

$$\longrightarrow \quad m_{\tilde{w}} > 270 \text{ GeV}$$

- Landau pole problem of the MSSM gauge coupling constants
  - No perturbative unification

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Introduction

We propose a new class of models which achieve the gravitino mass in the eV range with

- Stable vacuum
- Unsuppressed gaugino mass
- No Landau pole problems

Introduction

Contents

Relevant Parameters

- Naively expected soft mass in the MSSM

$$m_{soft} \sim \frac{\alpha}{4\pi} \frac{F_{GMSB}}{M_{mess}}$$

F_{GMSB} = (SUSY breaking scale)^2

M_{mess} = Messenger Scale

α: gauge coupling constant

$m_{soft} \sim$ TeV : $\frac{F_{GMSB}}{M_{mess}} = O(10\text{ -}100)$ TeV

Non-tachyonic messenger : $M_{mess}^2 > |F_{GMSB}|$

$\sqrt{F_{GMSB}}$ ranges from $O(10)$ TeV to $O(10^9)$ TeV

Relevant Parameters

- Gravitino mass $m_{3/2}$

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$m_{3/2}$ ranges O(1) eV to O(1) GeV

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The gravitino is the LSP and stable.

Dark Matter Candidate?

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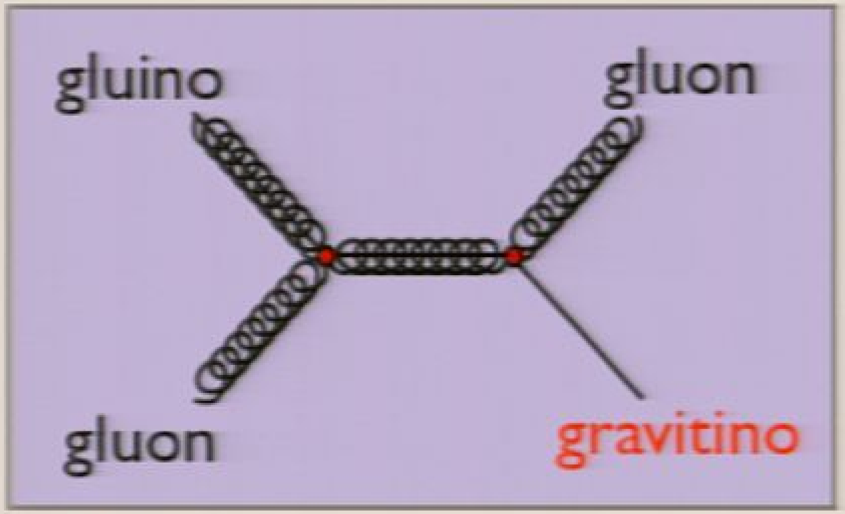
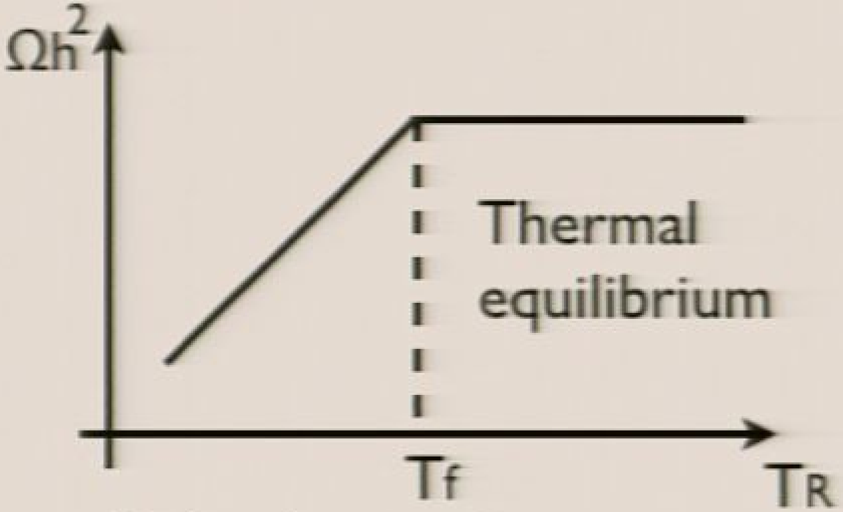
Cosmological gravitino problems

- Gravitino relic density [Phys.Lett.B303,289,Moroi,et.al.]



Main gravitino production process in thermal bath



Relic density for a given gravitino mass

$$T_f = 10^9 \text{ GeV} \left(\frac{m_{3/2}}{10 \text{ MeV}}\right)^2 \left(\frac{1 \text{ TeV}}{m_{gluino}}\right)^2$$

The gravitino relic density depends on the reheating temperature after inflation.

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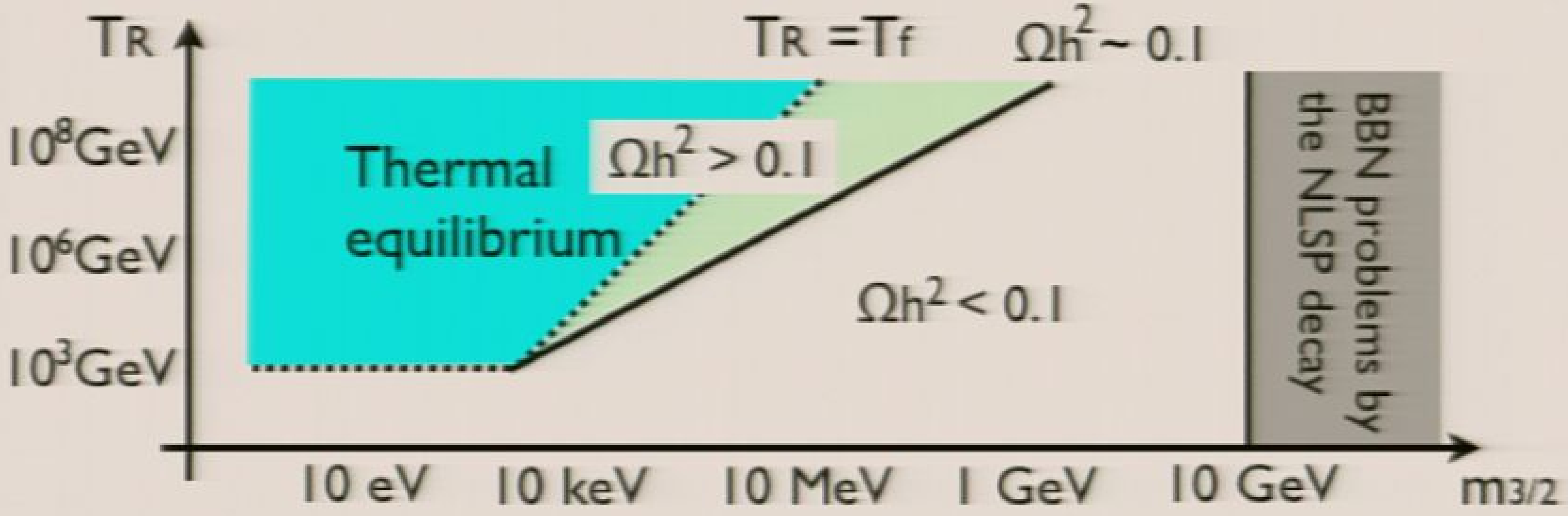

$$\Omega h^2 = 0.2 \times \left(\frac{T_R}{10^6\,\mathrm{GeV}}\right)\left(\frac{10\,\mathrm{MeV}}{m_{3/2}}\right)\left(\frac{m_{\mathrm{gluino}}}{1\,\mathrm{TeV}}\right)^2 \qquad (\,T_R < T_f\,)$$

$$\Omega h^2 = 0.1 \times \left(\frac{m_{3/2}}{100\,\mathrm{eV}}\right) \qquad (\,T_R > T_f\,)$$

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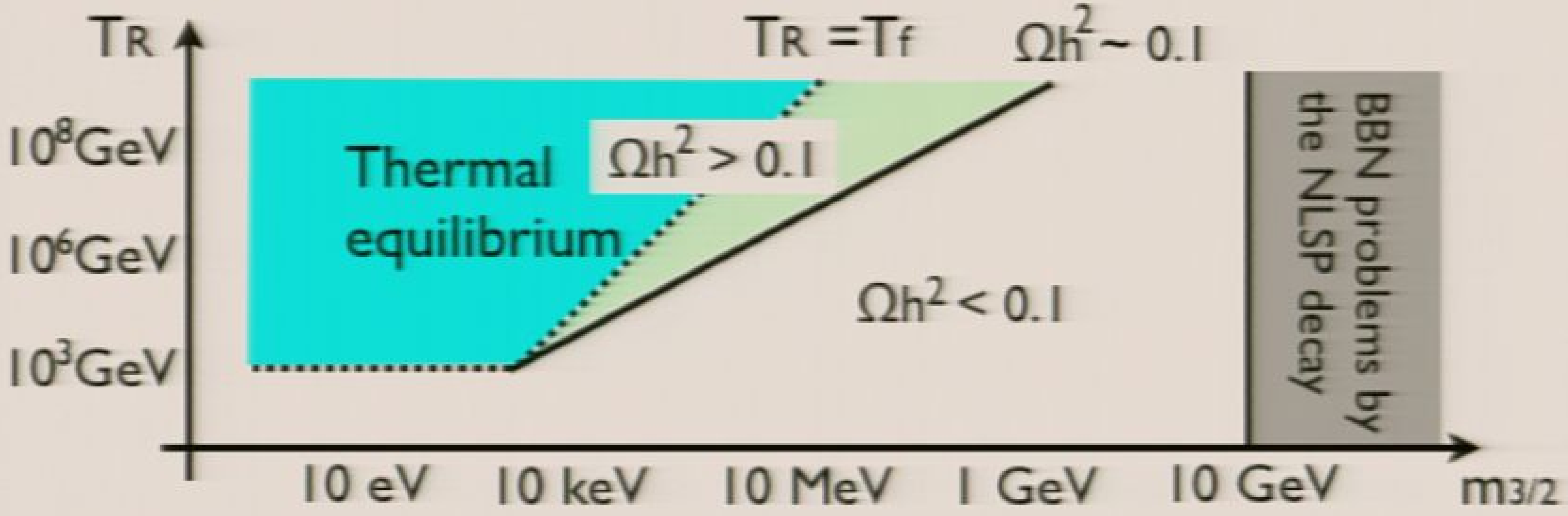

$m_{3/2}$ = 100 eV - O(1)GeV

T_R is needed to be tuned.

Inconsistent with high T_R baryogenesis!

(cf. WIMP density does not depend on T_R)

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- Gravitino relic density

Further constraint

Gravitino dark matter with $m_{3/2} < 2$ keV is not "cold" but "warm".

Warm dark matter component is constrained by the large scale structure of the universe.

Warm dark matter should be less than 10%

$$\frac{\Omega_{\text{gravitino}}}{\Omega_{\text{total}}} < 0.1 \longrightarrow \quad m_{3/2} < 16 \text{ eV}$$

[hep-ph/0501562, Viel et.al.]

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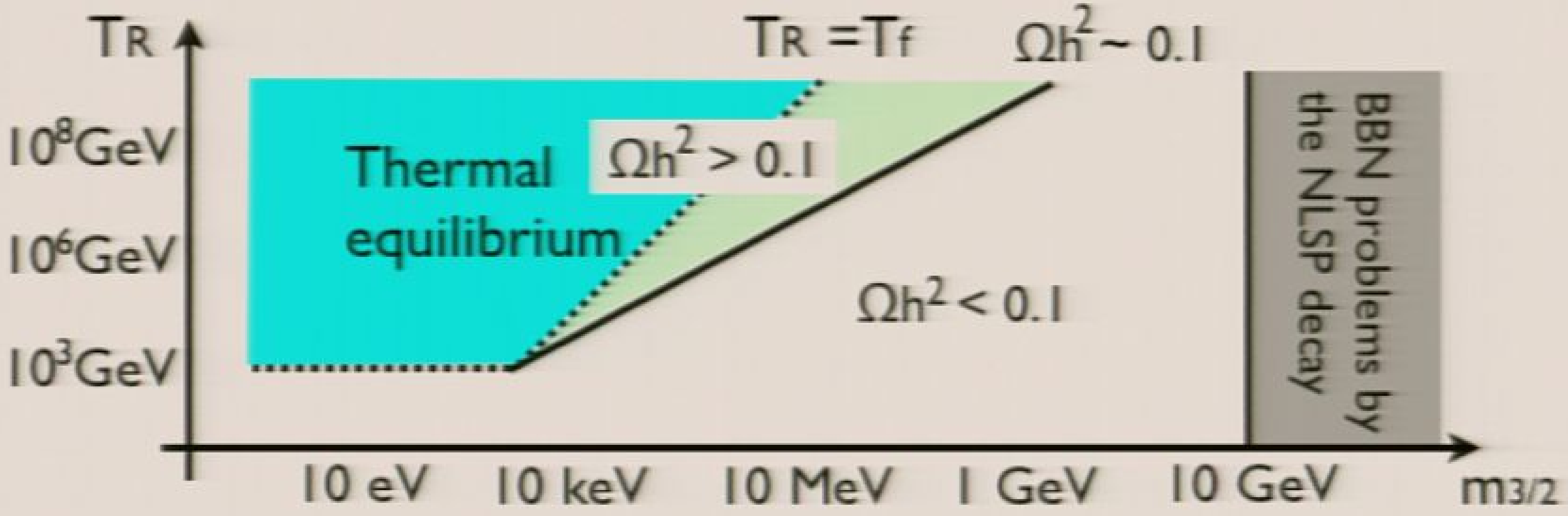

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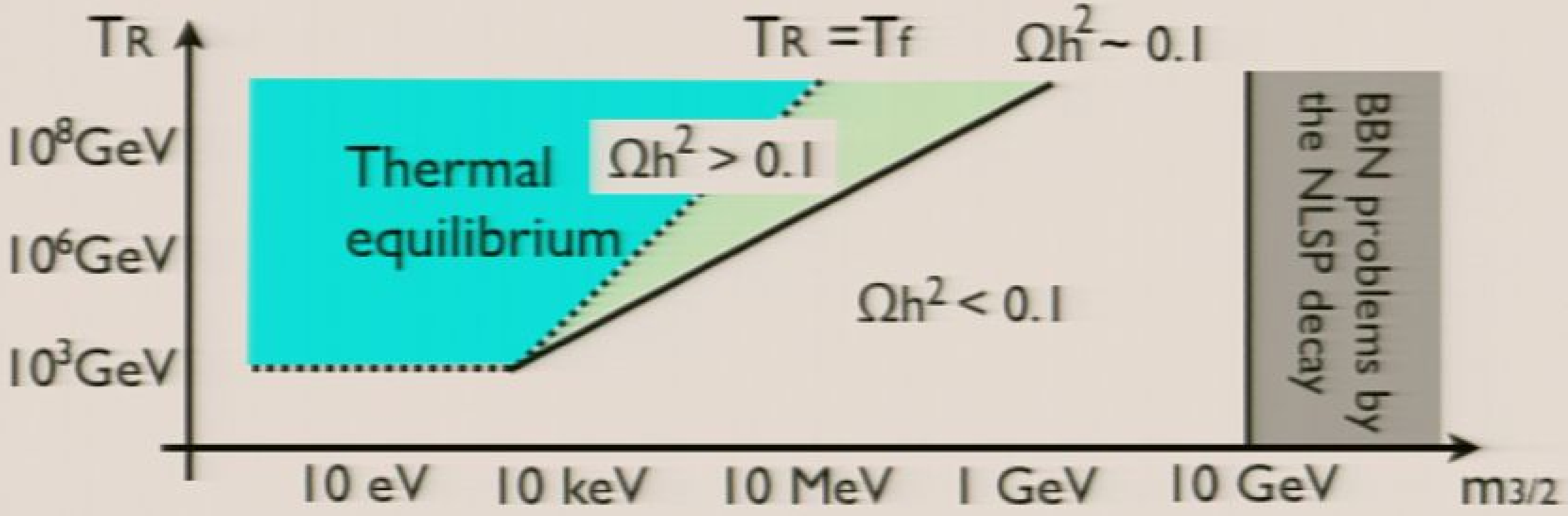

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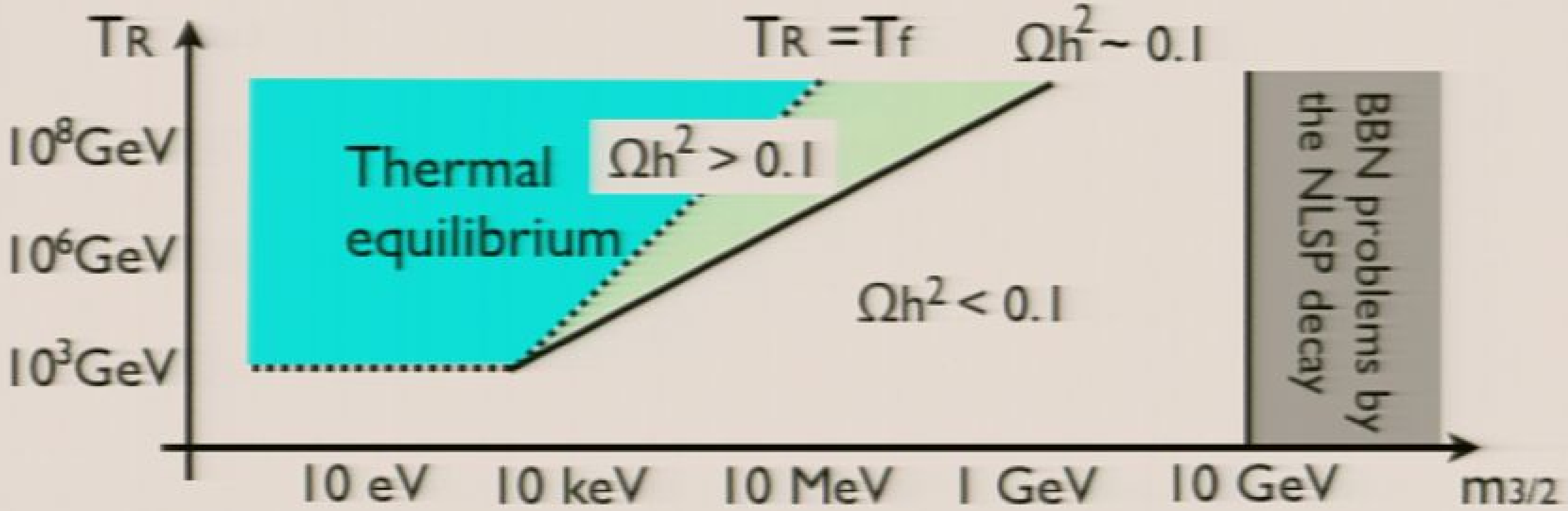

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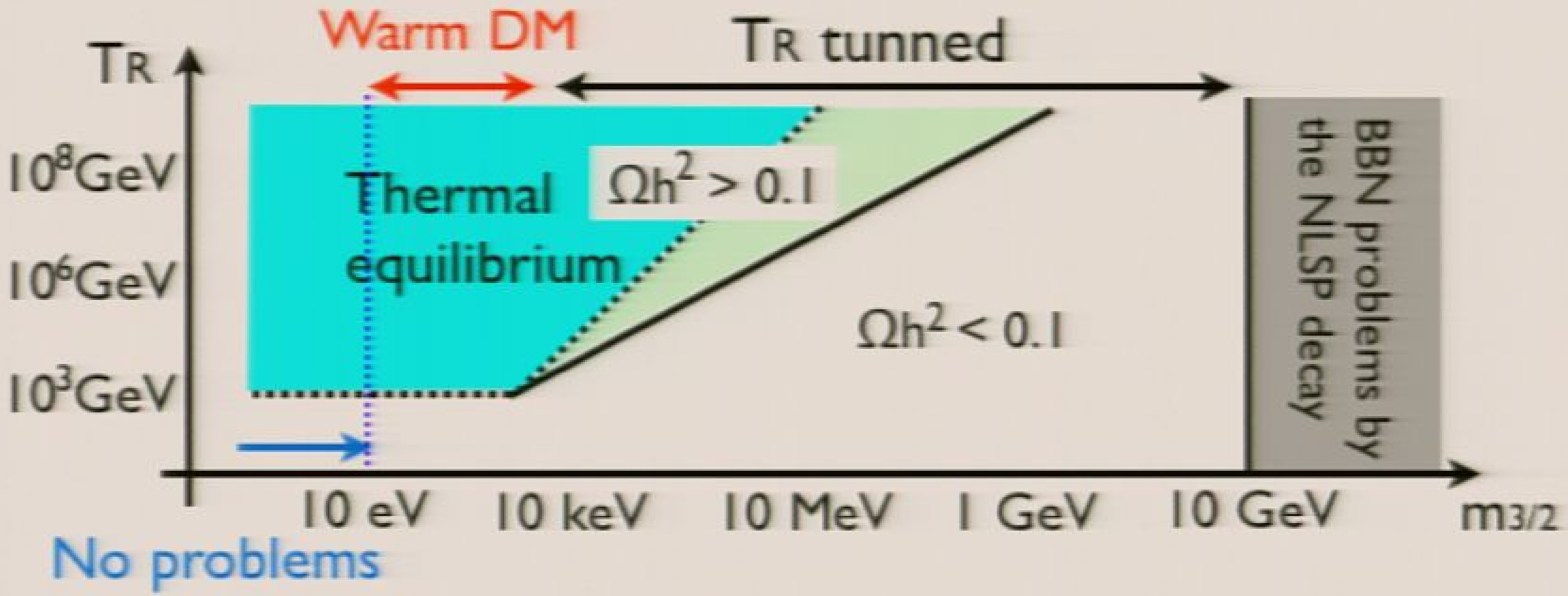

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[Consistent with thermal leptogenesis $T_R > 10^9$ GeV]

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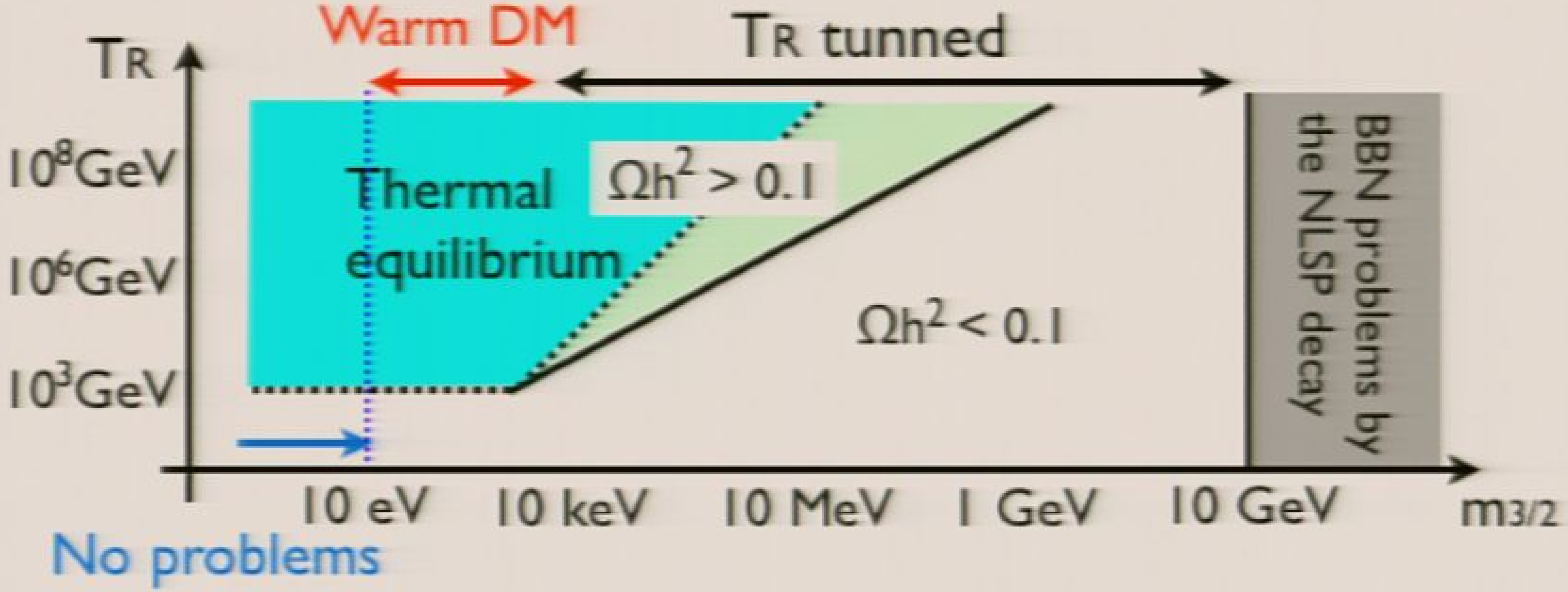

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Gauge Mediation Models @ Tree Level

- Basic Structure of Gauge Mediation

Supersymmetry Breaking

Messenger Fields

MSSM

$$\underbrace{\langle S \rangle = F_{\text{total}}\,\theta^2 \qquad\qquad (\Psi, \overline{\Psi})}$$

Charged under the MSSM gauge groups

There are a lot of ways to connect these two sectors.

- Stable connection
- Unstable connection
- Direct Gauge Mediation

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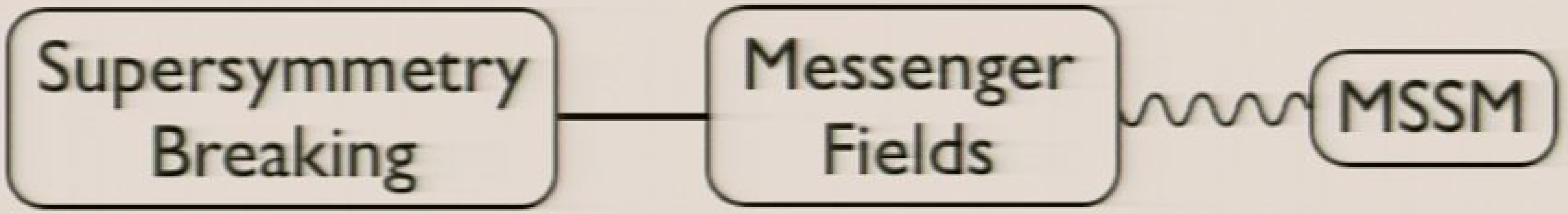

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The mass matrix of the messenger sector satisfies

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The messenger-SUSY breaking sector connection does not cause the restoration of supersymmetry.

[hep-ph/9705228, Izawa et.al.]

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[hep-ph/9706540, Giudice and Rattazzi]

The gaugino mass is suppressed compared with the naive expectation!

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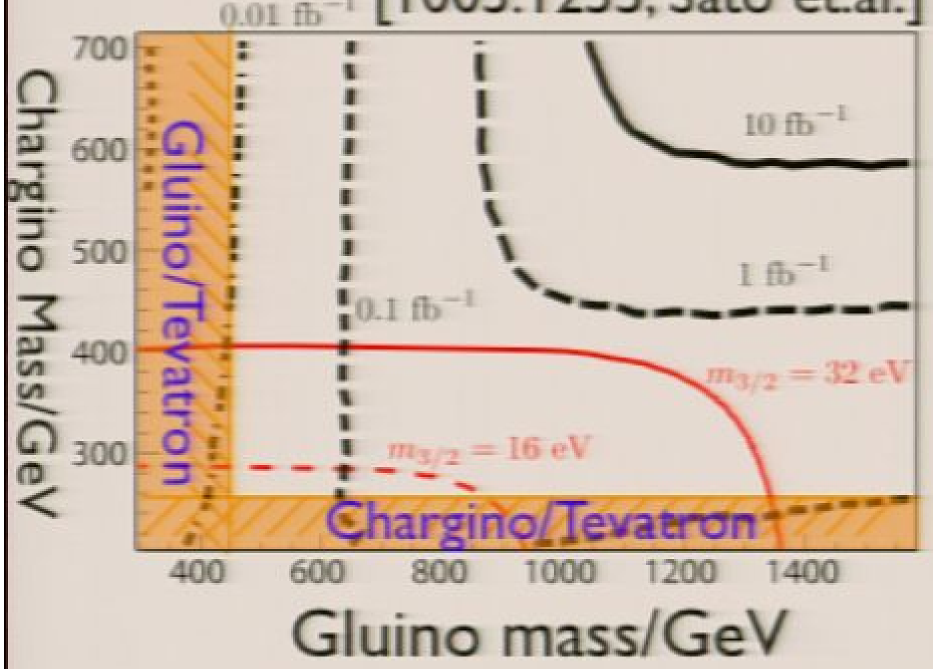
LHC 7TeV SUSY search

[1005.1255, Sato et.al.]



Most parameter space for m3/2<16eV has been excluded by Tevatron and will be proven/disproved by the early LHC studies.

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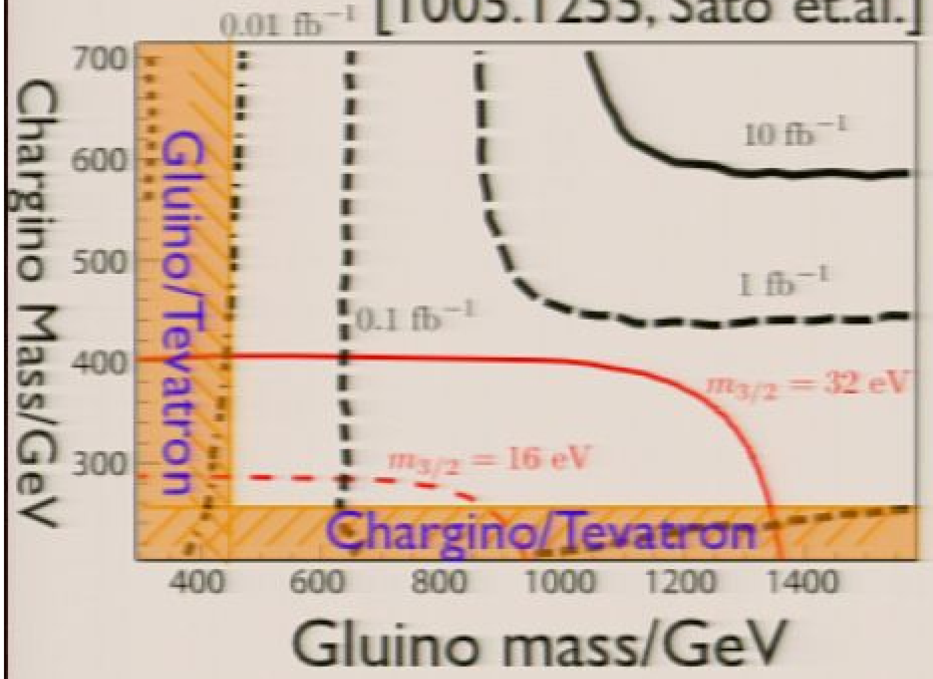

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- Almost No Go?
- Cascade supersymmetry breaking
- Conformal symmetry : does it help?
- Summary

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$$m_{3/2} = \frac{F_{total}}{\sqrt{3}\, M_{PL}}$$

F_{total} = (SUSY breaking scale)^2

$F_{GMSB} < F_{total}$

M_{PL} = Planck Scale

$$\longrightarrow \boxed{\sqrt{F_{total}} = 65\text{TeV} \times \left(\frac{m_{3/2}}{1\text{eV}}\right)^{1/2}}$$

The gravitino mass in the eV range is realized for

$$M_{mess} \sim \sqrt{F_{GMSB}} \sim \sqrt{F_{total}} = O(10 - 100)\text{TeV}$$

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$F_{\rm total}$ = (SUSY breaking scale)^2

$F_{\rm GMSB} < F_{\rm total}$

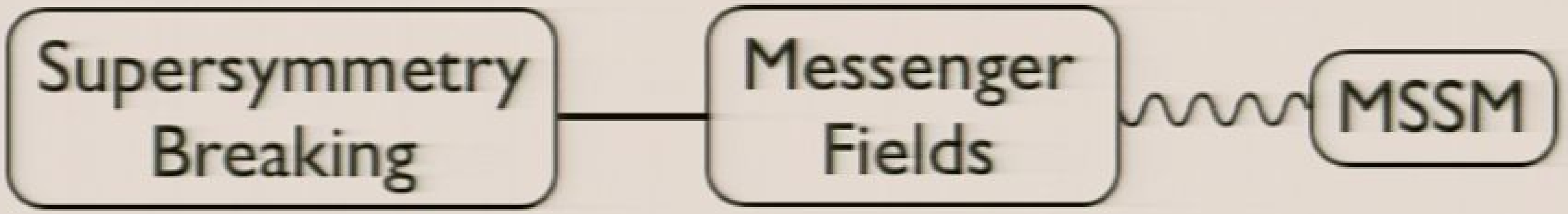
M_{PL} = Planck Scale

$m_{3/2}$ ranges O(1) eV to O(1) GeV
(cf. gravity mediation, $m_{\rm soft} \sim m_{3/2}$)

The gravitino is the LSP and stable.
Dark Matter Candidate?

Gauge Mediation Models @ Tree Level

- Basic Structure of Gauge Mediation



$$\underbrace{\langle S \rangle = F_{total}\, \theta^2 \qquad\qquad (\psi, \bar{\psi})}_{}$$

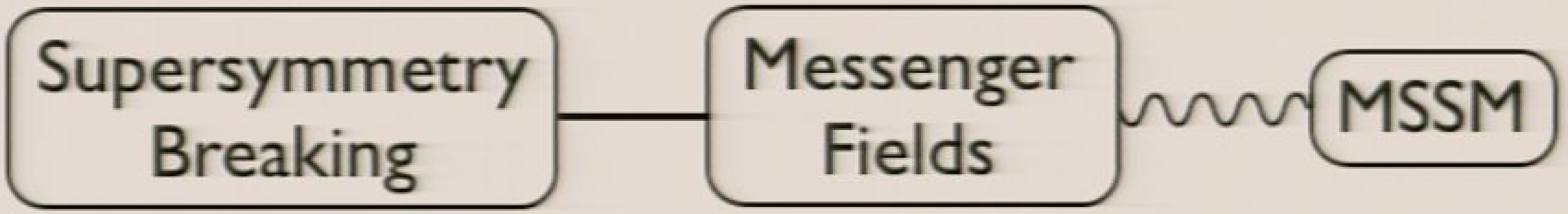
Charged under the MSSM gauge groups

There are a lot of ways to connect these two sectors.

- Stable connection
- Unstable connection
- Direct Gauge Mediation

Gauge Mediation Models @ Tree Level

- Basic Structure of Gauge Mediation



Supersymmetry Breaking

Messenger Fields

MSSM

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$$M_{mess} \sim \sqrt{F_{GMSB}} \sim \sqrt{F_{total}} = O(10\text{ - }100)\,\text{TeV}$$

How difficult to construct models?

Gauge Mediation Models @ Tree Level

- Stable connection

$$W = \underbrace{\Lambda_{SUSY}^{2}\, S}_{\text{The origin of SUSY breaking}} + \underbrace{\lambda S\, \bar{\psi}\psi + M_{mess}\, \bar{\psi}\psi' + M_{mess}\, \bar{\psi}'\psi}_{\text{Stable connection}}$$

The mass matrix of the messenger sector satisfies

$$\det[M_{mess}^{eff}] = -M_{mess}^{2}$$

The messenger-SUSY breaking sector connection does not cause the restoration of supersymmetry.

[hep-ph/9705228, Izawa et.al.]

Relevant Parameters

- Naively expected soft mass in the MSSM

$$m_{soft} \sim \frac{\alpha}{4\pi} \frac{F_{GMSB}}{M_{mess}}$$

F_{GMSB} = (SUSY breaking scale)^2

M_{mess} = Messenger Scale

α: gauge coupling constant

$m_{soft} \sim$ TeV : $\frac{F_{GMSB}}{M_{mess}} = O(10 - 100)$ TeV

Non-tachyonic messenger : $M_{mess}^2 > |F_{GMSB}|$

$\sqrt{F_{GMSB}}$ ranges from $O(10)$ TeV to $O(10^9)$ TeV

Gauge Mediation Models @ Tree Level

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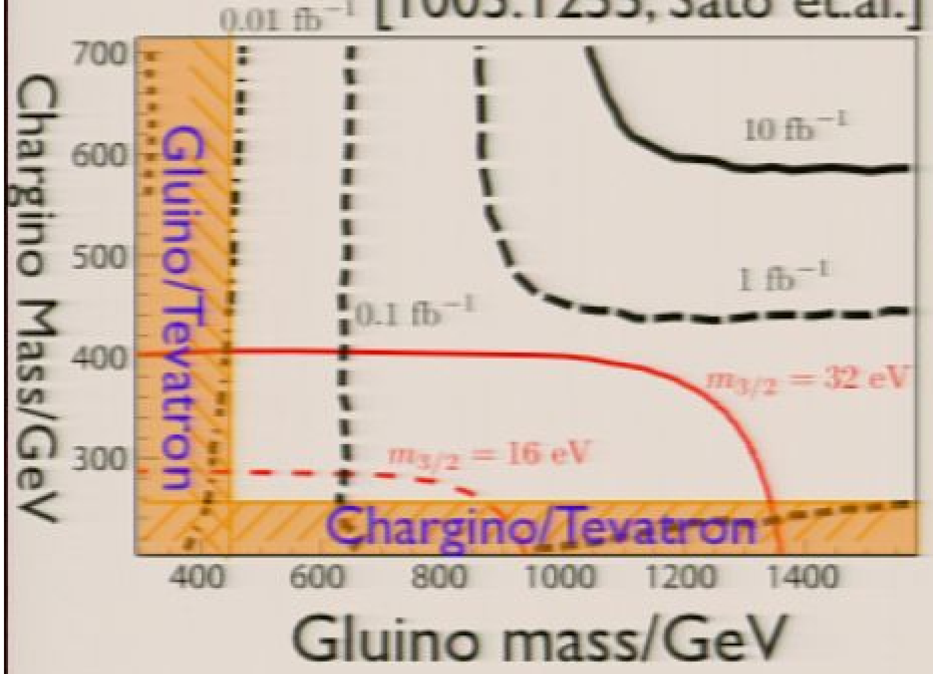
LHC 7TeV SUSY search

[1005.1255, Sato et.al.]



Most parameter space for m3/2<16eV has been excluded by Tevatron and will be proven/ disproved by the early LHC studies.

Gauge Mediation Models @ Tree Level

- Unstable connection

$$W = \underbrace{\Lambda_{SUSY}^{2}\, S}_{\text{The origin of SUSY breaking}} + (\underbrace{M_{mess} + \lambda\, S}_{\text{Unstable connection}})\, \bar{\psi}\, \psi$$

Effective gaugino mass term

$$W_{eff} = \frac{\alpha}{4\pi} \log(M_{mess} + \lambda\, S)\, W^{\alpha} W_{\alpha}$$

The leading contribution to the gaugino mass is unsuppressed!

$$m_{gaugino} = \frac{\alpha}{4\pi} \frac{\lambda F_s}{M_{mess}}$$

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$$\uparrow \qquad\qquad\qquad\qquad \uparrow$$

The origin of SUSY breaking

$$F_S = \Lambda_{SUSY}^2$$

Stable connection

$$\det[M_{mess}^{eff}] = -M_{mess}^2$$

The leading gaugino mass comes from the S derivative of

$$W_{eff} = \frac{\alpha}{4\pi}\log(\,\det[M_{mess}^{eff}]\,)W^{\alpha}W_{\alpha}$$

[hep-ph/9706540, Giudice and Rattazzi]

The gaugino mass is suppressed compared with the naive expectation!

Gauge Mediation Models @ Tree Level

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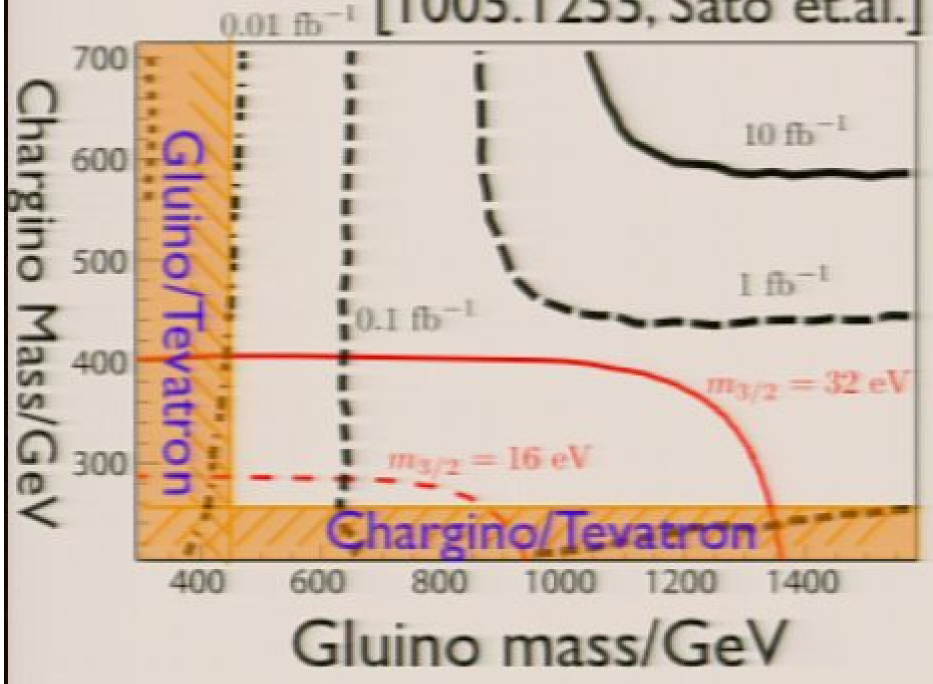

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$$\langle S \rangle = -\frac{M_{mess}}{\lambda} \qquad \langle \bar{\psi}\psi \rangle = -\frac{\Lambda_{SUSY}^2}{\lambda}$$

This vacuum is in the vicinity of the supersymmetry breaking vacuum for $\sqrt{F_S} \sim M_{mess}$ and $\lambda = O(1)$, which is required for the gravitino mass in the eV range.

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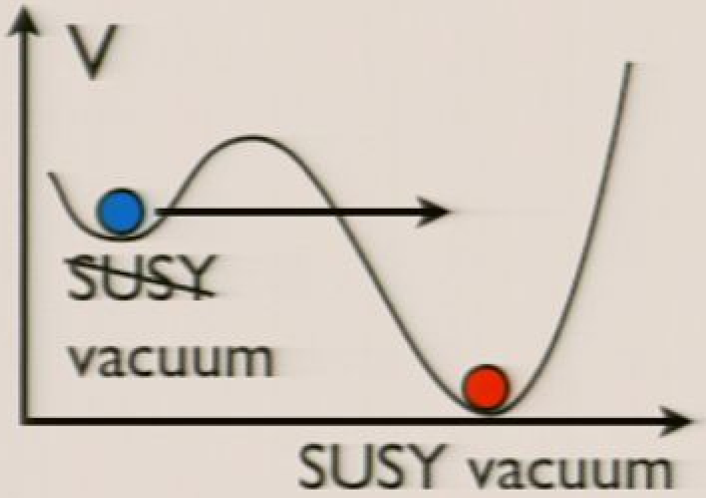

The vacuum is unstable.

For a given SUSY breaking scale, there is a lower bound on $M_{mess.}$

Upper limit on squark masses from the vacuum stability

$m_{3/2} < 16$ eV $\longrightarrow$ $m_{squark} \lesssim 1$ TeV

$m_{3/2} < 5$ eV $\longrightarrow$ $m_{squark} \lesssim 500$ GeV

[0804.2957, Hisano et.al.]

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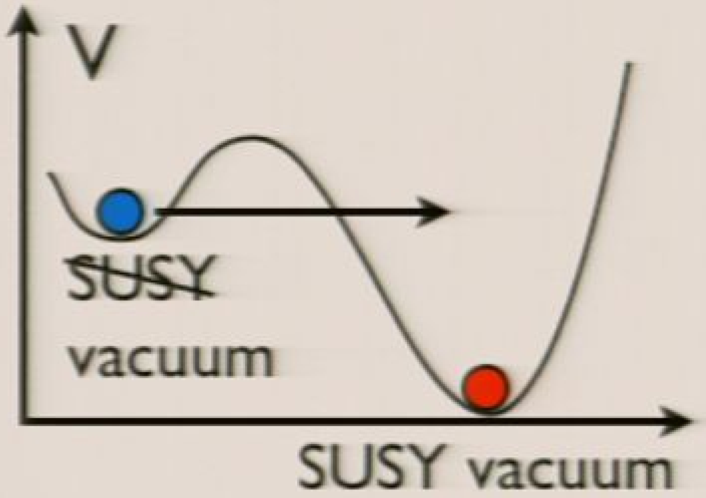

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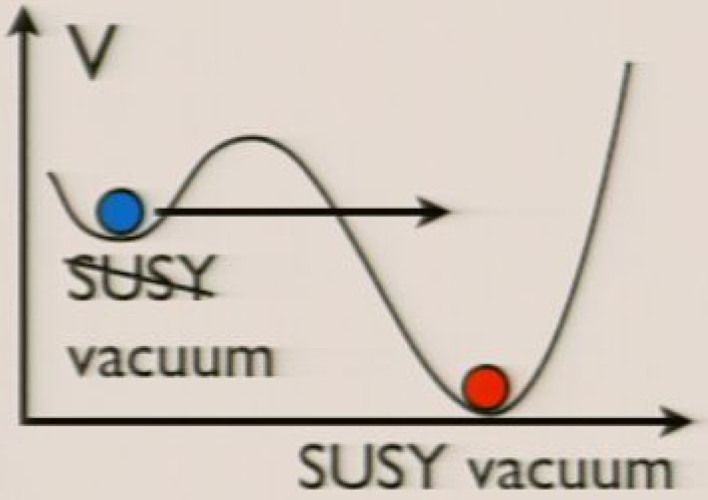

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Gauge Mediation Models @ Tree Level

- Direct Gauge Mediation

The MSSM gauge groups are embedded in the global symmetry of the dynamical supersymmetry breaking sector.

Dynamical supersymmetry breaking uses an asymptotic free gauge dynamics.

Large gauge group ⟷ A lot of messengers

[cf. SU(N)] [N messengers]

Direct Gauge Mediation suffers from the Landau pole problems of the MSSM gauge interactions when the mediation scale is low.

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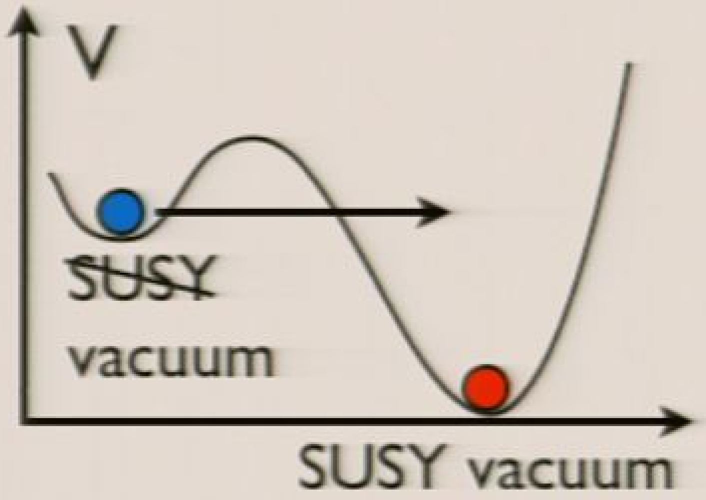

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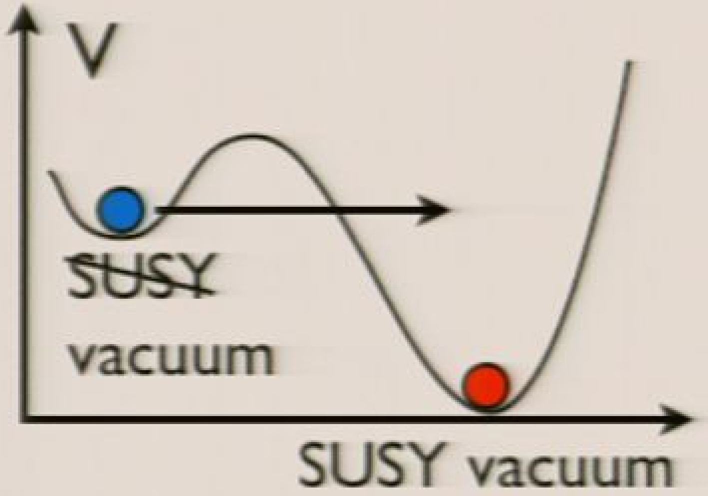

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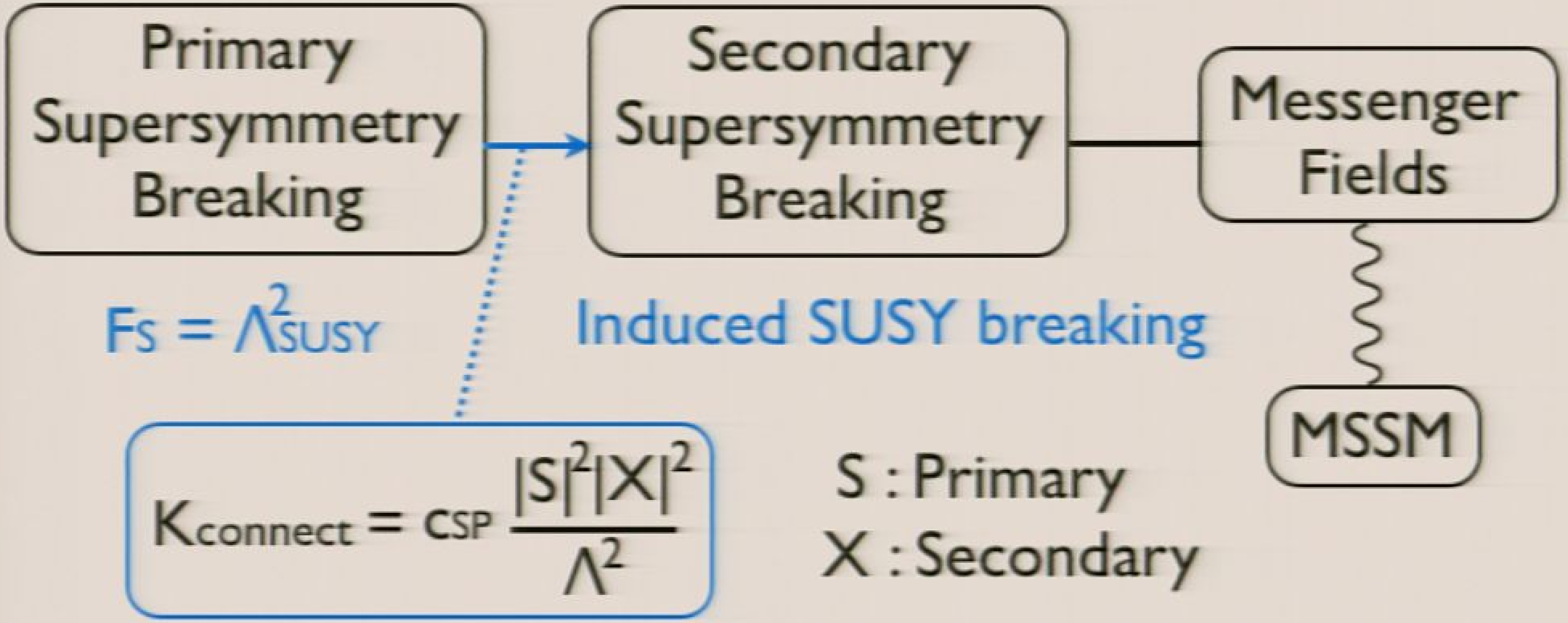
Gauge Mediation Models @ Tree Level

Gauge Mediation with the gravitino mass in the eV range.

	Gaugino mass	Vacuum stability	Perturbative unification
Stable connection	Suppressed	Stable	Yes
Unstable connection	Unsuppressed	Unstable	Yes
Direct Mediation	Unsuppressed	Stable	No

Almost No Go?

Cascade Supersymmetry Breaking



Primary Supersymmetry Breaking

Secondary Supersymmetry Breaking

Messenger Fields

MSSM

$F_S = \Lambda^2_{SUSY}$

Induced SUSY breaking

$$K_{connect} = c_{SP} \frac{|S|^2|X|^2}{\Lambda^2}$$

S : Primary
X : Secondary

Primary sector : No supersymmetric vacuum

Secondary sector : Supersymmetric vacuum in the limit of the vanishing connection

Cascade Supersymmetry Breaking

Toy Example

$$K = |S|^2 + |X|^2 + c_{SP}\frac{|S|^2|X|^2}{\Lambda^2}$$

$$W = \Lambda_{SUSY}^2 S + \Lambda_{2nd}^2 X - \frac{f}{3}X^3 + kX\overline{\psi}\psi$$

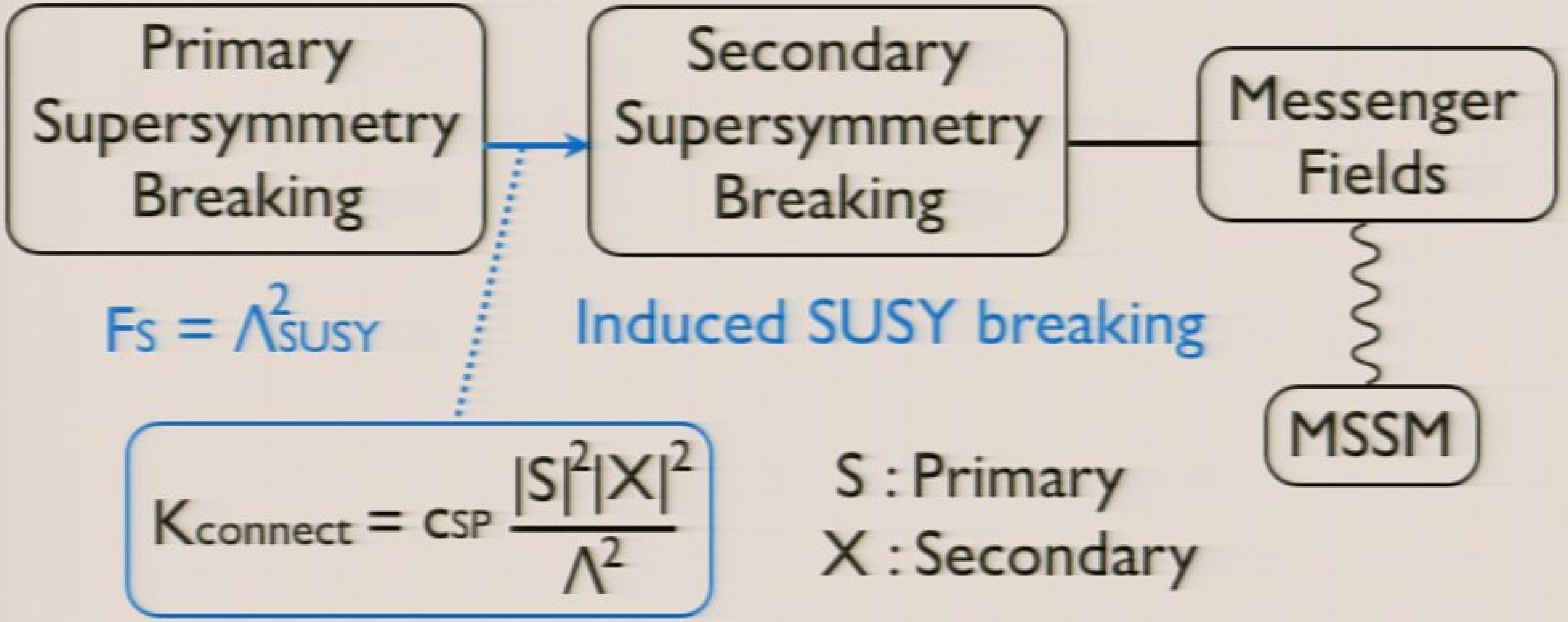
Primary sector : No supersymmetric vacuum

$$F_S = \Lambda_{SUSY}^2$$

Secondary sector : Supersymmetric vacuum for $c_{SP} = 0$

$$\langle X \rangle = \frac{\Lambda_{2nd}}{\sqrt{f}} \qquad F_X = 0$$

Cascade Supersymmetry Breaking



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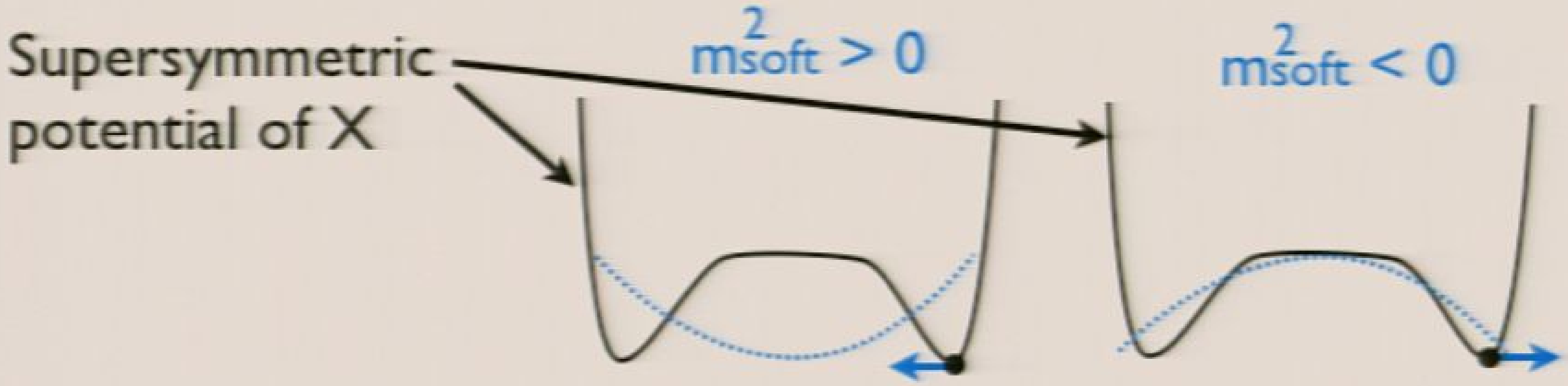
Cascade Supersymmetry Breaking

Connecting term induces the soft mass squared

$$K = c_{SP}\frac{|S|^2|X|^2}{\Lambda^2} \longrightarrow V = m_{soft}^2\,|X|^2$$



$F_X \neq 0$ is induced due to the vacuum shift.

Supersymmetry breaking in the secondary sector is induced by the connection in the Kahler potential.

Cascade Supersymmetry Breaking

Induced supersymmetry breaking is mediated to the MSSM via

$$W = kX\bar{\psi}\psi$$

Messengers do not couple to S directly.
No restoration of supersymmetry.

Effective gaugino mass term

$$W_{eff} = \frac{\alpha}{4\pi} \log(k X) W^{\alpha} W_{\alpha}$$

The leading order gaugino mass contribution is not suppressed!

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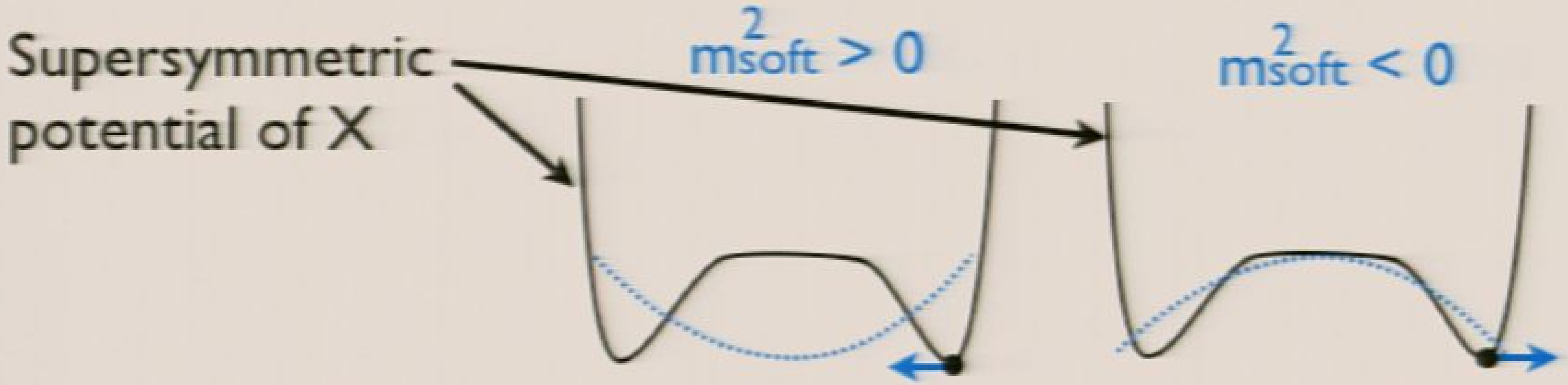

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$\Lambda \sim \Lambda_{SUSY} \sim \Lambda_{2nd} = O(10\text{-}100)\,\text{TeV}$

$c_{SP} \sim f \sim k = O(1)$

This toy model is not generic under symmetries.

This toy has an unwanted color breaking vacuum.

$c_{SP} = O(1)$ requires strong interactions.

Any viable models?

Cascade Supersymmetry Breaking

Dynamical Model : SP(Nc) x SU(4) gauge theory

	SP(Nc)	SU(4)
Q_i	2Nc	1
S_{ij}	1	1
$F^a, \bar{F}_a$	(1 , 1)	$(4, \bar{4})$
$R, \bar{R}$	(2Nc,2Nc)	$(4, \bar{4})$

} Primary sector (Q_i, S_{ij})

Secondary sector ($F^a, \bar{F}_a$)

Connector sector ($R, \bar{R}$)

[i, j = 1-4, a = 1-5]

$$K = |S|^2 + |Q|^2 + |R|^2 + |\bar{R}|^2 + |F|^2 + |\bar{F}|^2$$

$$W = \lambda S_{ij} Q_i Q_j + m_R \bar{R} R + m_F \bar{F} F$$

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[i, j = 1-4, a = 1-5]

Eventually, we embed the MSSM gauge groups into the SU(5) global symmetry.

Cascade Supersymmetry Breaking

Primary Sector : No supersymmetric vacuum

SP(Nc) gauge theory with four fundamental representations Q_i and six singlets $S_{ij} = -S_{ji}$.

$$W = \lambda S_{ij} Q_i Q_j$$

F-term conditions of S_{ij} are contradict with the quantum modified constraint.

$$F_S = \lambda Q_i Q_j = 0 \quad \longleftrightarrow \quad \mathrm{Pf}(Q_i Q_j) = \Lambda^4_{SP(N_c)}$$

Supersymmetry is spontaneously broken and this model does not have a supersymmetric vacuum.

[hep-th/9602180, Izawa&Yanagida]
[hep-th/9603158, Intriligator&Thomas]

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Cascade Supersymmetry Breaking

Secondary Sector :

SU(4) gauge theory with five flavors (F , $\bar{F}$) with a mass term,

$$W = m_F \bar{F} F .$$

Below the dynamical scale of SU(4), the secondary sector shows an s-confinement

$$W = m_F M + \boxed{\frac{\det M - \bar{B} M B}{\Lambda_{SU(4)}^7}}$$

$$M \sim \bar{F}F, \quad B \sim \bar{F}\bar{F}\bar{F}\bar{F}, \quad \bar{B} \sim FFFF$$

Cascade Supersymmetry Breaking

Secondary Sector :

Under the SU(5) global symmetry
M = SU(5) adjoint + Singlet X
$B, \bar{B}$ = SU(5) (anti) fundamental

$$W = m_F \Lambda_{SU(4)} X + \boxed{\frac{X^5}{\Lambda_{SU(4)}^2}}$$

Supersymmetric vacuum at

$$\langle X \rangle \sim \left(\frac{m_F}{\Lambda_{SU(4)}} \right)^{1/4} \Lambda_{SU(4)}\,, \qquad F_X = 0$$

No supersymmetric SU(5) breaking vacuum!

(The secondary sector does not have any flat directions.)

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$$W = m_F \bar{F} F .$$

Below the dynamical scale of SU(4), the secondary sector shows an s-confinement

$$W = m_F M + \boxed{\frac{\det M - \bar{B} M B}{\Lambda_{SU(4)}^{7}}}$$

$M \sim \bar{F}F$, $B \sim \bar{F}\bar{F}\bar{F}\bar{F}$, $\bar{B} \sim FFFF$

Cascade Supersymmetry Breaking

Secondary Sector :

Under the SU(5) global symmetry

M = SU(5) adjoint + Singlet X

B, $\bar{B}$ = SU(5) (anti) fundamental

$$W = m_F \Lambda_{SU(4)} X + \boxed{\frac{X^5}{\Lambda_{SU(4)}^2}}$$

Supersymmetric vacuum at

$$\langle X \rangle \sim \left(\frac{m_F}{\Lambda_{SU(4)}} \right)^{1/4} \Lambda_{SU(4)}, \qquad F_X = 0$$

No supersymmetric SU(5) breaking vacuum!

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Gravitino mass in the eV range is realized for

$$K = |S|^2 + |X|^2 + c_{SP}\frac{|S|^2|X|^2}{\Lambda^2}$$

$$W = \Lambda_{SUSY}^2 S + \Lambda_{2nd}^2 X - \frac{f}{3}X^3 + kX\bar{\psi}\psi$$

$$\Lambda \sim \Lambda_{SUSY} \sim \Lambda_{2nd} = O(10\text{-}100)\text{TeV}$$

$$c_{SP} \sim f \sim k = O(1)$$

This toy model is not generic under symmetries.

This toy has an unwanted color breaking vacuum.

$c_{SP} = O(1)$ requires strong interactions.

Any viable models?

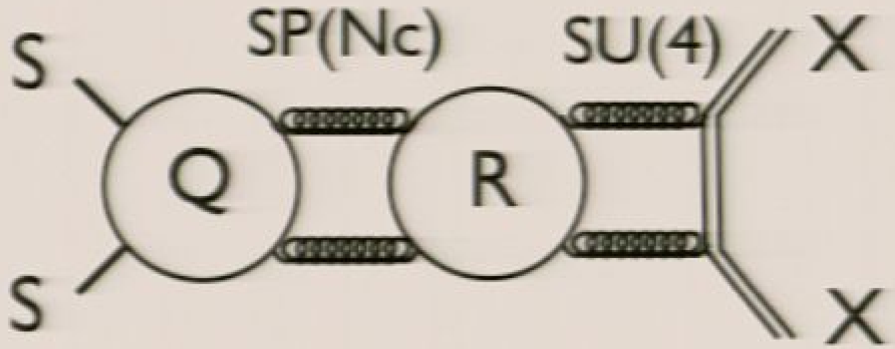
Cascade Supersymmetry Breaking

Connecting sector :

Bi-fundamental representation of SP(Nc)xSU(4) (R , $\bar{R}$) with a mass term,

$$W = m_R \bar{R} R .$$

Connecting fields induce the connecting term



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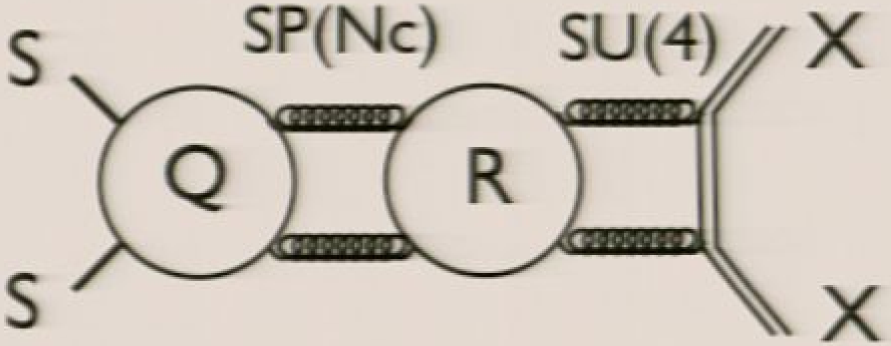

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Put all the sectors together :

$$K = |S|^2 + |Q|^2 + |R|^2 + |R|^2 + |F|^2 + |F|^2$$

$$W = \lambda S_{ij} Q_i Q_j + m_R \bar{R} R + m_F \bar{F} F$$

- SP(N_c)xSU(4) gauge interactions
- We embed the MSSM gauge groups into the SU(5) global symmetry in the secondary sector.

[F : five flavors]

The potentials are generic at the renormalizable level!

[The higher dimensional terms which could cause the restoration of the supersymmetry are suppressed!]

Cascade Supersymmetry Breaking

For $m_F < m_R, \Lambda_{SP(N_c)}, \Lambda_{SU(4)}$, we can integrate out heavy modes in SP(N_c) and SU(4) dynamics

$$K = |S|^2 + |X|^2 + c_{SP}\frac{|S|^2|X|^2}{m_R^2} + \cdots$$

$$W = \lambda\Lambda_{SP(N_c)} S + m_F\Lambda_{SU(4)} X + \boxed{\frac{X^5}{\Lambda_{SU(4)}^2} + \frac{X^3\tilde{M}\tilde{M}}{\Lambda_{SU(4)}^2} + X\bar{B}B}$$

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Messenger - X couplings are also generated dynamically!

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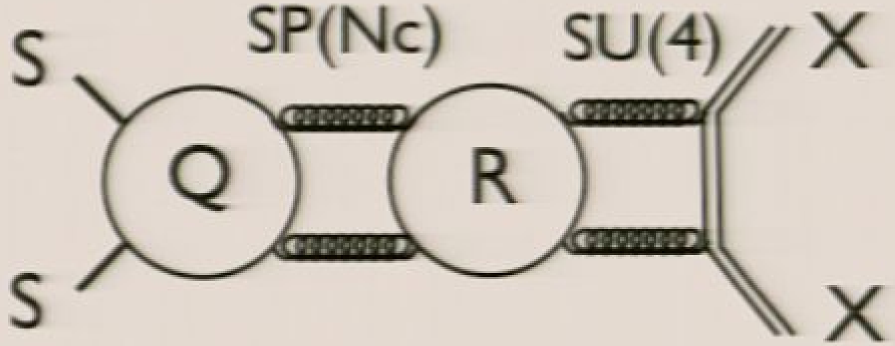

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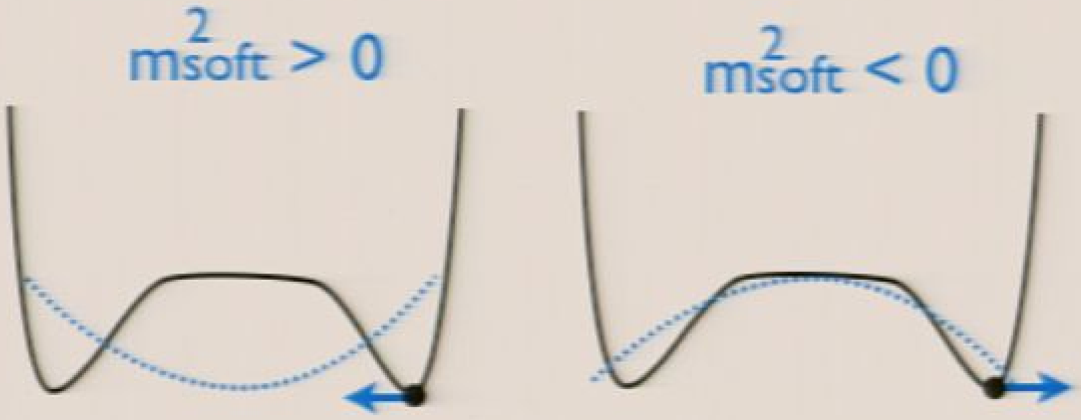

$\langle X \rangle \neq 0$

$F_X \neq 0$

Messengers obtain their mass and mass splittings via

$$W = \frac{X^3 \tilde{M}\tilde{M}}{\Lambda_{SU(4)}^2} + X\bar{B}B \longrightarrow M_M = \frac{X^3}{\Lambda_{SU(4)}^2} \quad M_B = X$$

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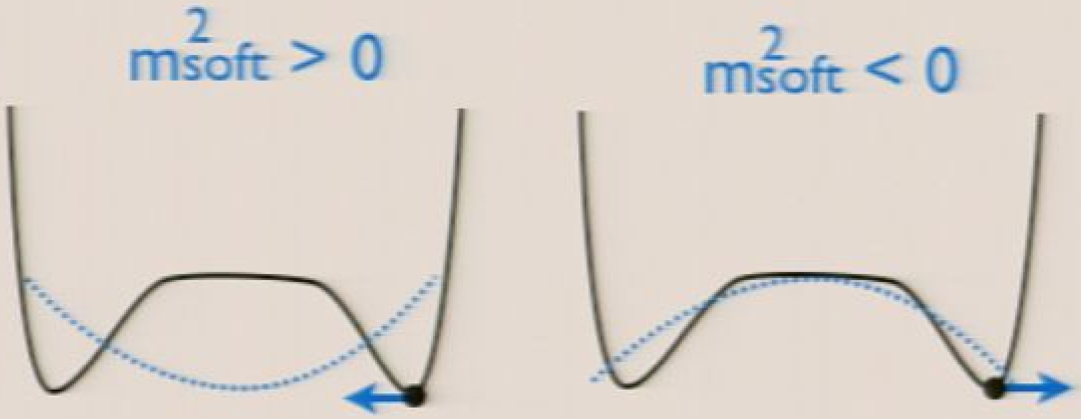

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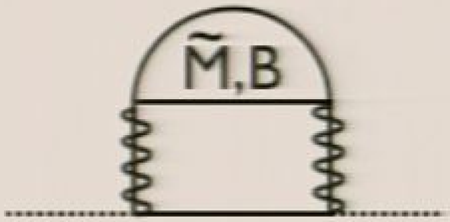
The supersymmetry breaking effects are mediated to the MSSM sector via usual gauge mediation.

Gaugino Mass

Squark Mass^2



Especially, the leading contributions to the gaugino masses are unsuppressed!

$$W_{eff} = \frac{\alpha}{4\pi}(5 \log M_M + \log M_B) W^{\alpha} W_{\alpha}$$

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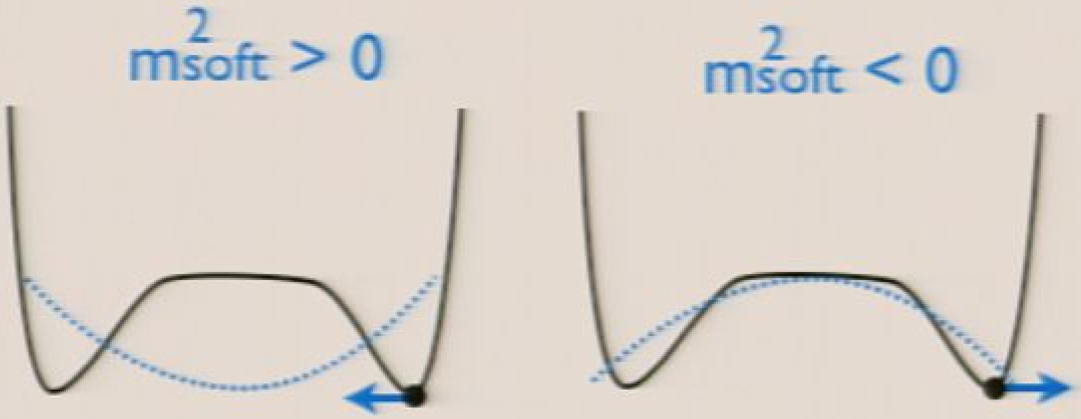

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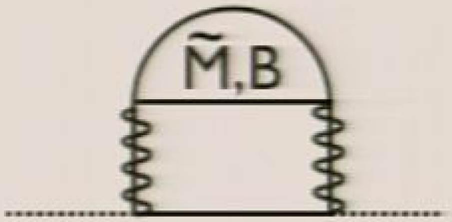

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The gravitino mass in the eV range is realized for

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No fully supersymmetric vacuum.

There is no worry about the vacuum decay into a supersymmetric vacuum.

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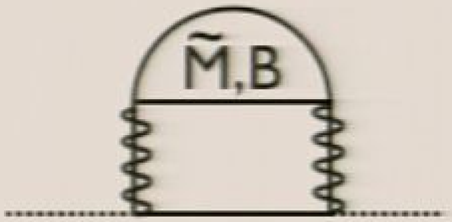

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Cascade Supersymmetry Breaking

Dynamical Model : SP(Nc) x SU(4) gauge theory

	SP(Nc)	SU(4)	
Q_i	2Nc	1	Primary sector
S_{ij}	1	1	
$F^a, \bar{F}_a$	(1 , 1)	$(4 , \bar{4})$	Secondary sector
$R , \bar{R}$	(2Nc,2Nc)	$(4 , \bar{4})$	Connector sector

[i,j = 1-4, a = 1-5]

Eventually, we embed the MSSM gauge groups into the SU(5) global symmetry.

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For $m_F < m_R, \Lambda_{SP(N_c)}, \Lambda_{SU(4)}$, we can integrate out heavy modes in SP(N_c) and SU(4) dynamics

$$K = |S|^2 + |X|^2 + c_{SP}\frac{|S|^2|X|^2}{m_R^2} + \cdots$$

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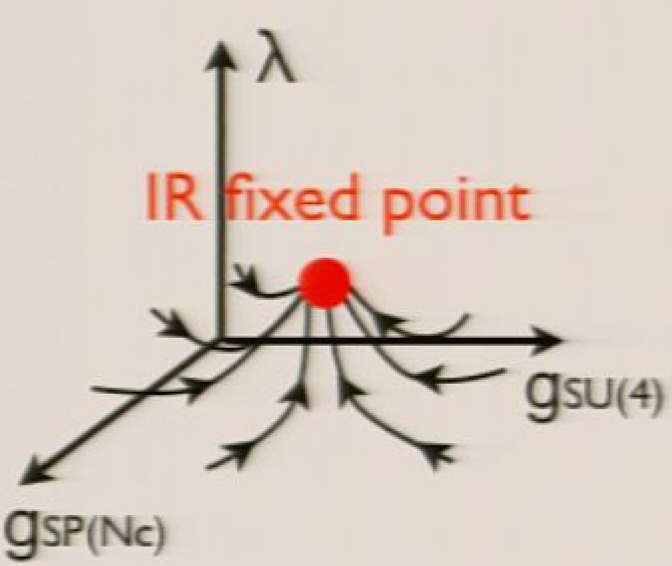

$g_{SP(N_c)}$

The model ($N_c = 2,3$) has an infrared fixed point for $m_R = m_F = 0$.

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Cascade Supersymmetry Breaking

Gauge Mediation with the gravitino mass in the eV range.

	Gaugino mass	Vacuum stability	Perturbative unification
Stable connection	Suppressed	Stable	Yes
Unstable connection	Unsuppressed	Unstable	Yes
Direct Mediation	Unsuppressed	Stable	No
Cascade	Unsuppressed	Stable	Yes

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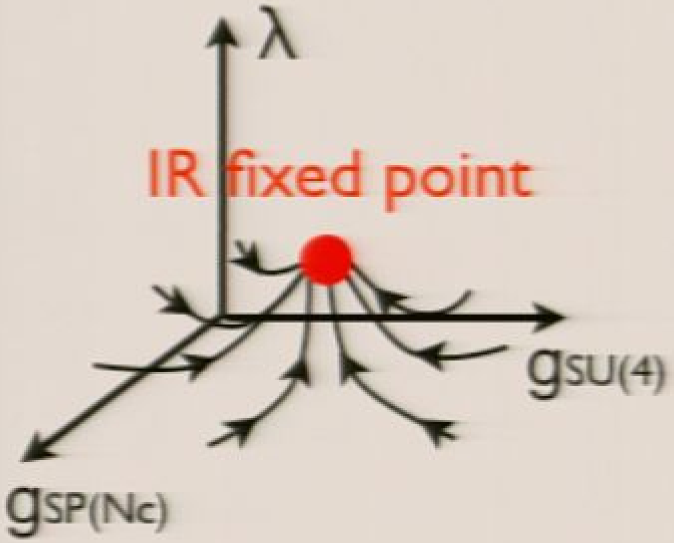

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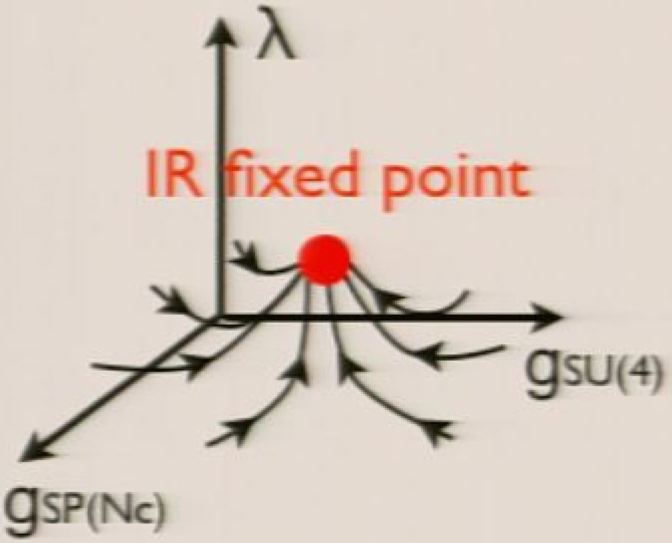

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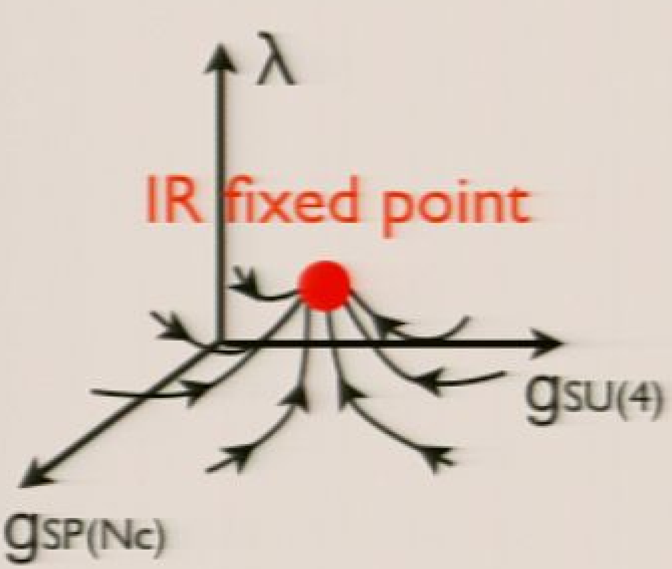

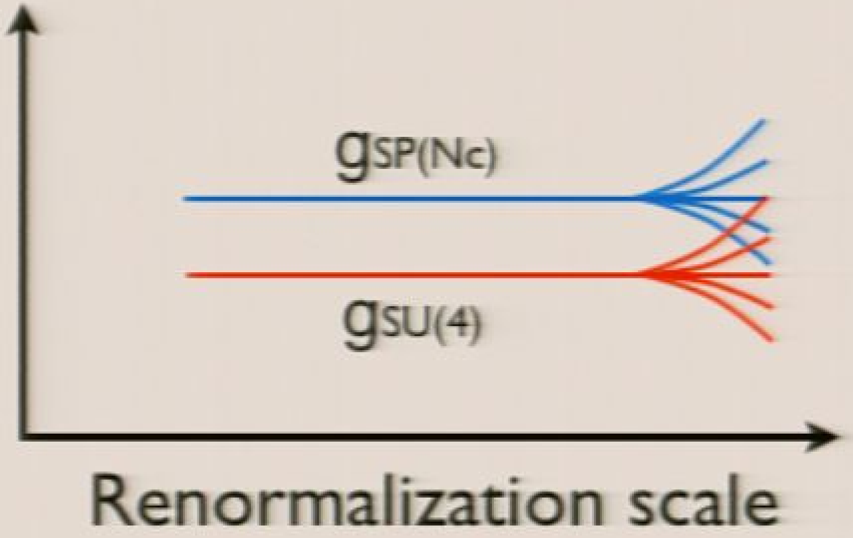

The coupling constants flow into the IR fixed point.

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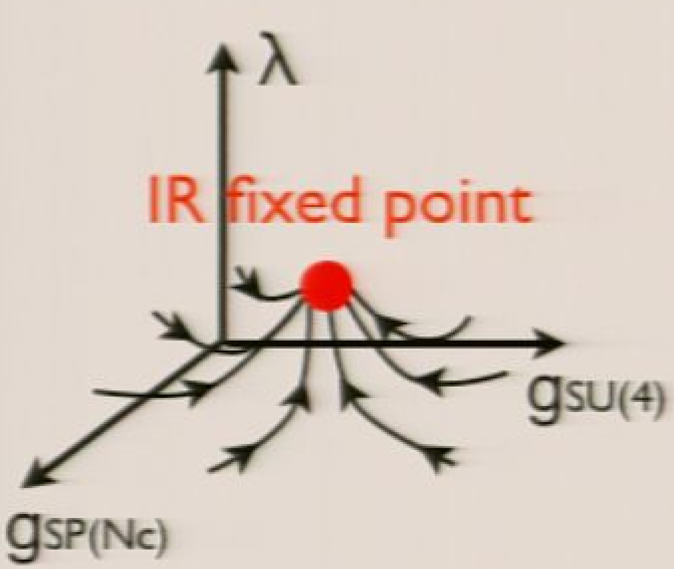

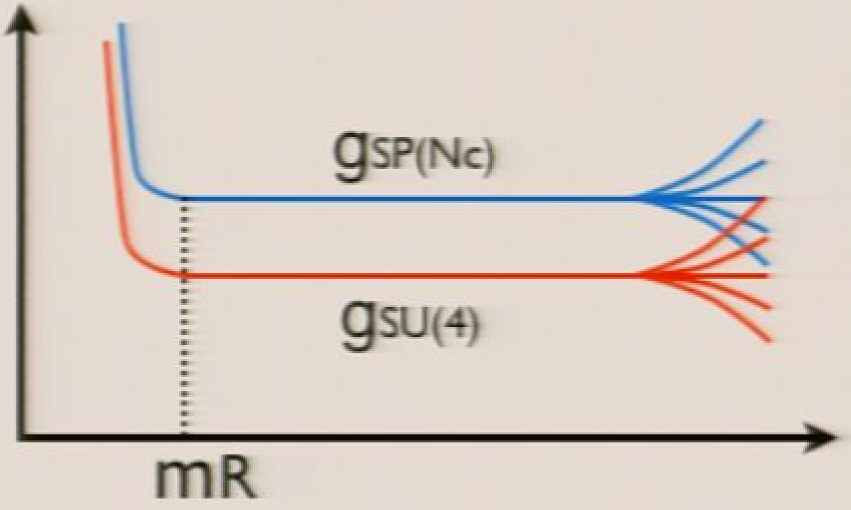

Eventually, the conformal symmetry is disturbed by the connector mass term and the model flows into the cascade supersymmetry breaking model!

Cascade Supersymmetry Breaking

Put all the sectors together :

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$$W = \lambda S_{ij} Q_i Q_j + m_R \bar{R} R + m_F \bar{F} F$$

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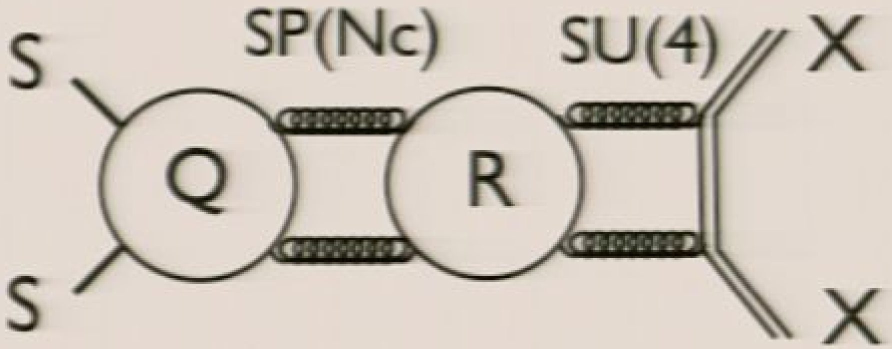

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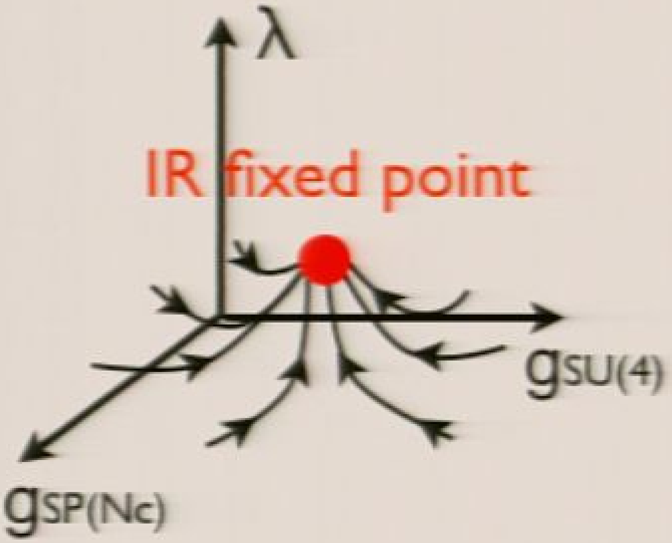

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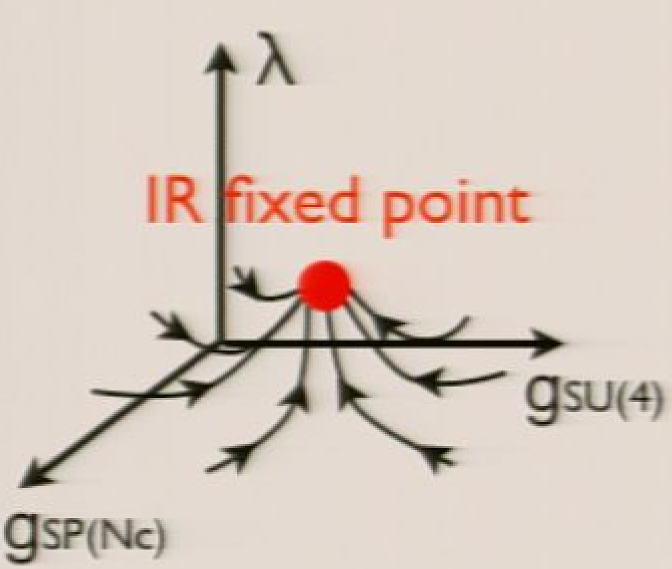

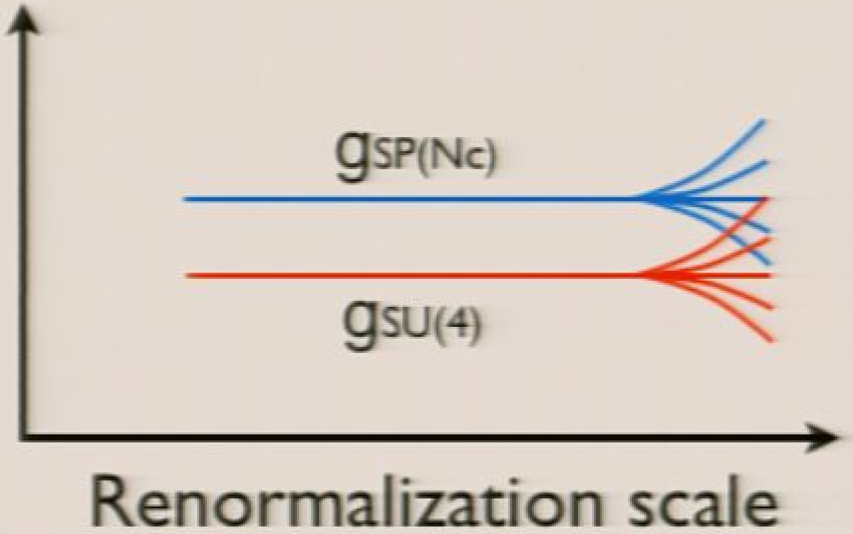

The coupling constants flow into the IR fixed point.

Conformal Symmetry?

Is it possible to explain

$$m_R \sim \Lambda_{SP(N_c)} \sim \Lambda_{SU(4)} = O(10 - 100)\,\mathrm{TeV}\ ?$$

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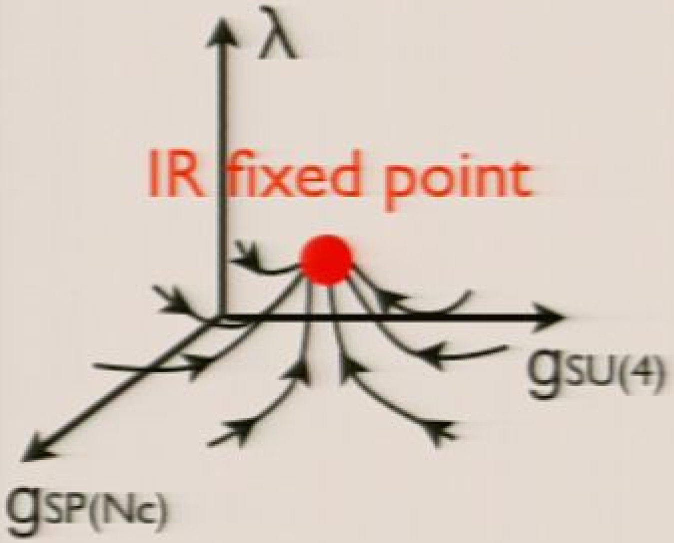

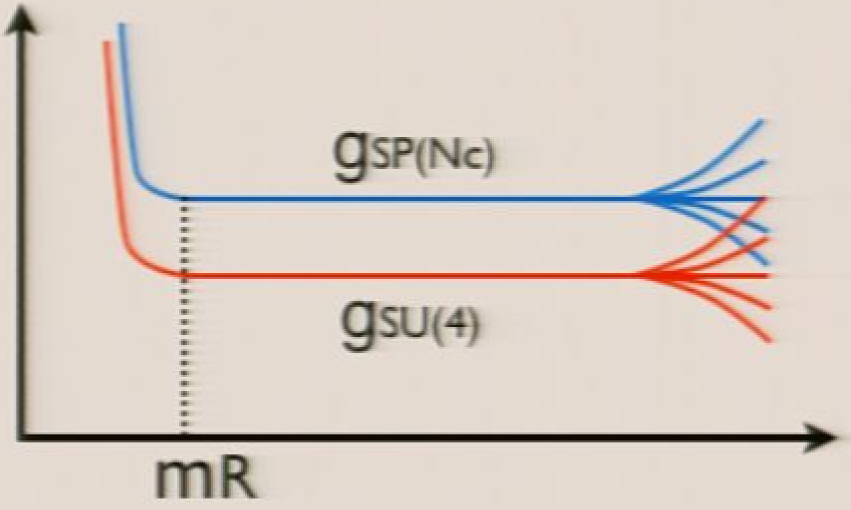

Eventually, the conformal symmetry is disturbed by the connector mass term and the model flows into the cascade supersymmetry breaking model!

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$m_R \sim \Lambda_{SP(N_c)} \sim \Lambda_{SU(4)} = O(10 - 100)$ TeV ?

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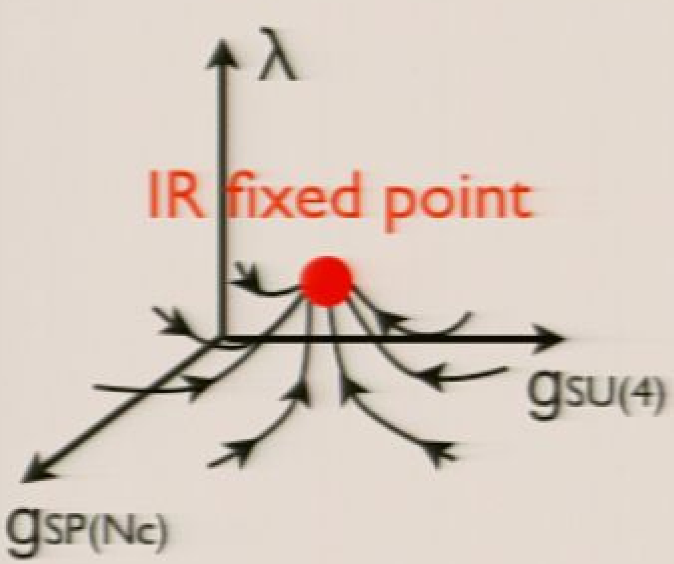

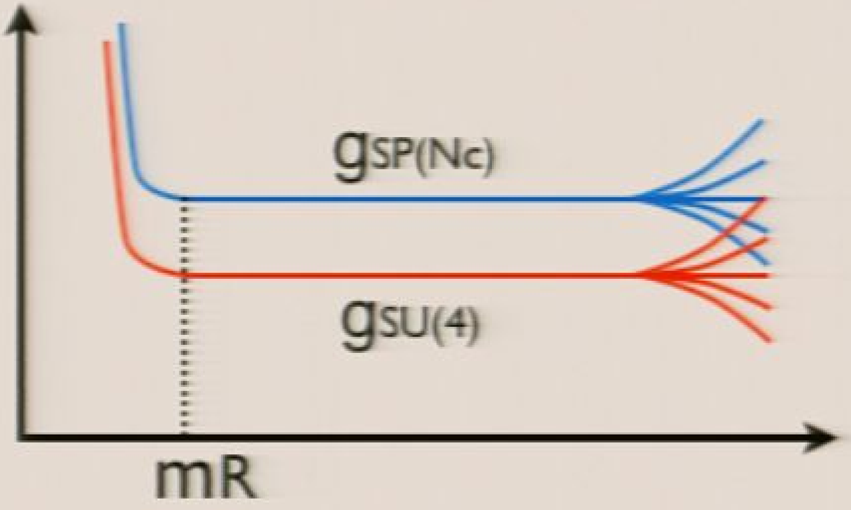

$m_R \sim \Lambda_{SP(N_c)} \sim \Lambda_{SU(4)}$ is realized when the model is strongly interacting on the IR fixed point!

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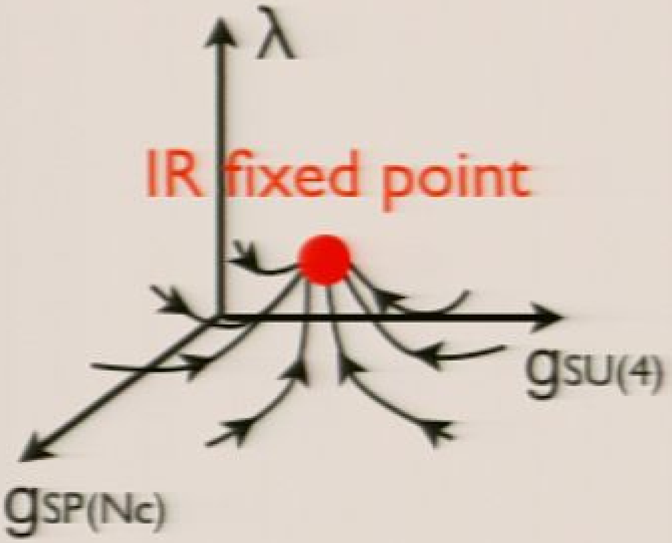

Anomalous dimensions

Nc	γ_Q	γ_R	γ_F	γ_S
2	-0.1	-0.4	-0.2	0.2
3	-0.4	-0.6	0.5	0.8

$[\ \gamma \sim O(\alpha/\pi)\ ]$

The model is strongly coupling at the IR fixed point!

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Summary

The model with a gravitino mass in the eV range is particularly interesting.

- No cosmological/astrophysical problem.
- Future large scale observation may probe the gravitino dark matter component with a mass down to the sub-eV range.

Traditional model building with such a light gravitino faces almost No Go!

- Suppressed gaugino masses
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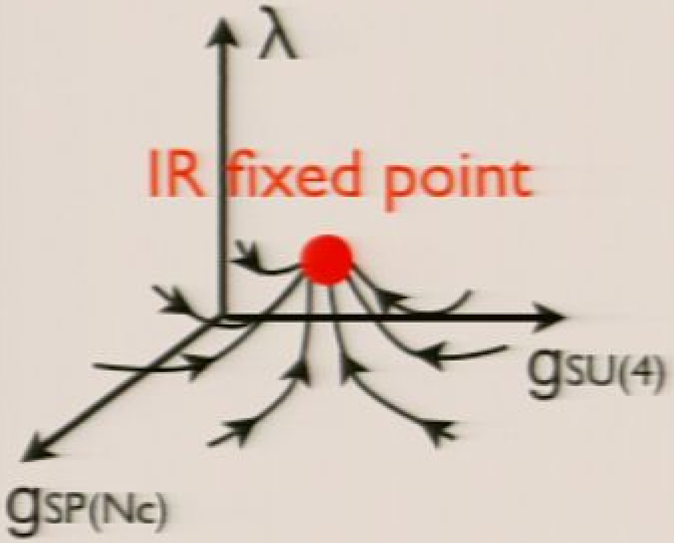

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In cascade supersymmetry breaking model, those problems are solved by separating the primary supersymmetry breaking sector from the secondary sector which includes the messenger fields.

Collider signals

Prompt NLSP decay into the gravitino.
e.g. missing ET + hard photon pair

The interplay between the LHC SUSY search and the future observation of the large scale structure is very important!

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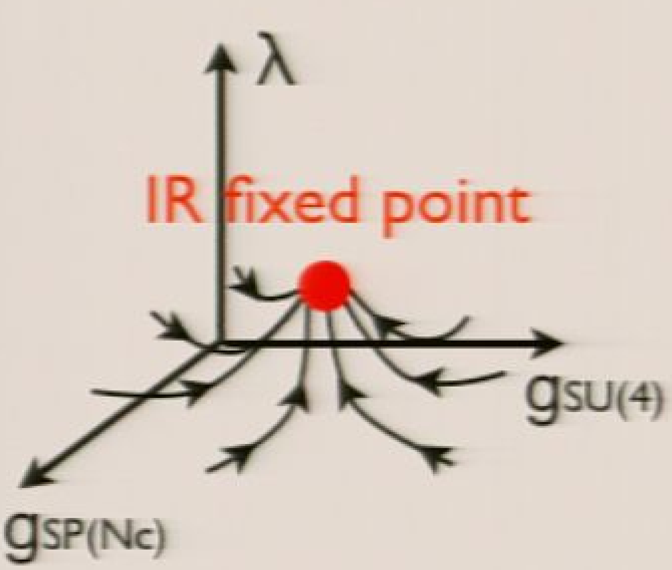

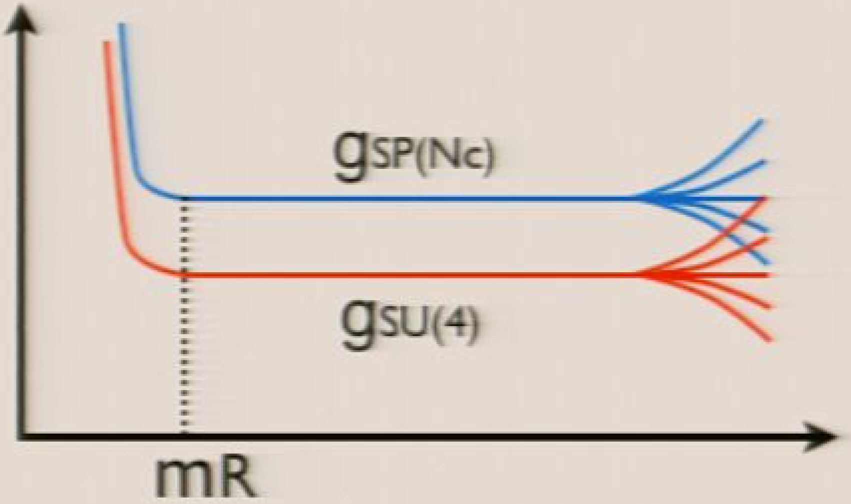

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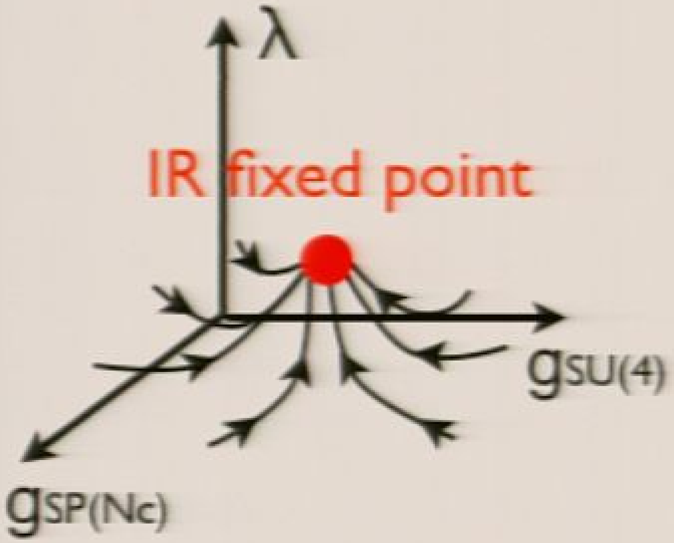

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Cascade Supersymmetry Breaking

The gravitino mass in the eV range is realized for

$$M_{mess} \sim \sqrt{F_{GMSB}} \sim \sqrt{F_{total}} = O(10\text{ -}100)\,\text{TeV}$$

These mass parameters are realized for

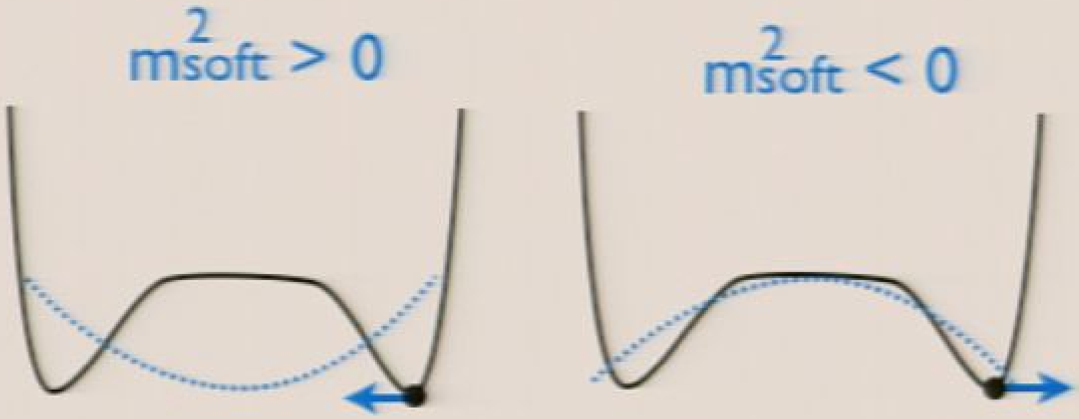
$$m_R \sim \Lambda_{SP(N_c)} \sim \Lambda_{SU(4)} = O(10 - 100)\,\text{TeV}$$

$$\lambda = O(1)$$

$$\longrightarrow \langle X \rangle \sim \sqrt{F_S} \sim \sqrt{F_X} = O(10 - 100)\,\text{TeV}$$

Cascade Supersymmetry Breaking

$$K = |S|^2 + |X|^2 + c_{SP}\frac{|S|^2|X|^2}{mR^2} + \cdots$$



$\langle X \rangle \neq 0$

$F_X \neq 0$

Messengers obtain their mass and mass splittings via

$$W = \frac{X^3\tilde{M}\tilde{M}}{\Lambda_{SU(4)}^2} + X\bar{B}B \longrightarrow M_M = \frac{X^3}{\Lambda_{SU(4)}^2} \quad M_B = X$$

Cascade Supersymmetry Breaking

Put all the sectors together :

$$K = |S|^2 + |Q|^2 + |R|^2 + |R|^2 + |F|^2 + |F|^2$$

$$W = \lambda S_{ij} Q_i Q_j + m_R \bar{R} R + m_F \bar{F} F$$

- SP(N_c)xSU(4) gauge interactions
- We embed the MSSM gauge groups into the SU(5) global symmetry in the secondary sector.

[F : five flavors]

The potentials are generic at the renormalizable level!

[The higher dimensional terms which could cause the restoration of the supersymmetry are suppressed!]

Cascade Supersymmetry Breaking

Dynamical Model : SP(Nc) x SU(4) gauge theory

	SP(Nc)	SU(4)	
Q_i	2Nc	1	Primary sector
S_{ij}	1	1	
$F^a, \overline{F}_a$	(1 , 1)	$(4 , \overline{4})$	Secondary sector
$R , \overline{R}$	(2Nc,2Nc)	$(4 , \overline{4})$	Connector sector

[i, j = 1-4, a = 1-5]

Eventually, we embed the MSSM gauge groups into the SU(5) global symmetry.

Cascade Supersymmetry Breaking

Secondary Sector :

SU(4) gauge theory with five flavors (F , $\bar{F}$) with a mass term,

$$W = m_F \, \bar{F} F \, .$$

Below the dynamical scale of SU(4), the secondary sector shows an s-confinement

$$W = m_F \, M \; + \boxed{\frac{\det M - \bar{B} M B}{\Lambda_{SU(4)}^{7}}}$$

$$M \sim \bar{F}F, \qquad B \sim \bar{F}\bar{F}\bar{F}\bar{F}, \qquad \bar{B} \sim FFFF$$

Cascade Supersymmetry Breaking

Secondary Sector :

Under the SU(5) global symmetry

M = SU(5) adjoint + Singlet X

$B, \bar{B}$ = SU(5) (anti) fundamental

$$W = m_F \Lambda_{SU(4)} X + \boxed{\frac{X^5}{\Lambda_{SU(4)}^2}}$$

Supersymmetric vacuum at

$$\langle X \rangle \sim \left(\frac{m_F}{\Lambda_{SU(4)}}\right)^{1/4} \Lambda_{SU(4)} , \qquad F_X = 0$$

No supersymmetric SU(5) breaking vacuum!

(The secondary sector does not have any flat directions.)

Cascade Supersymmetry Breaking

Put all the sectors together :

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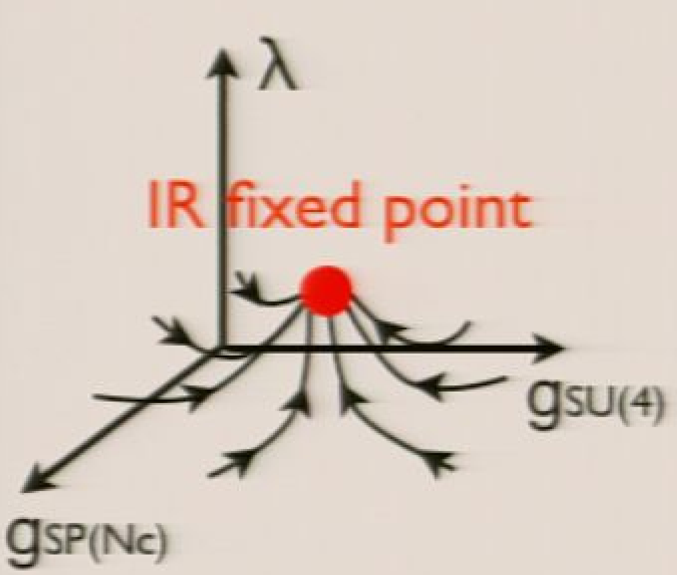

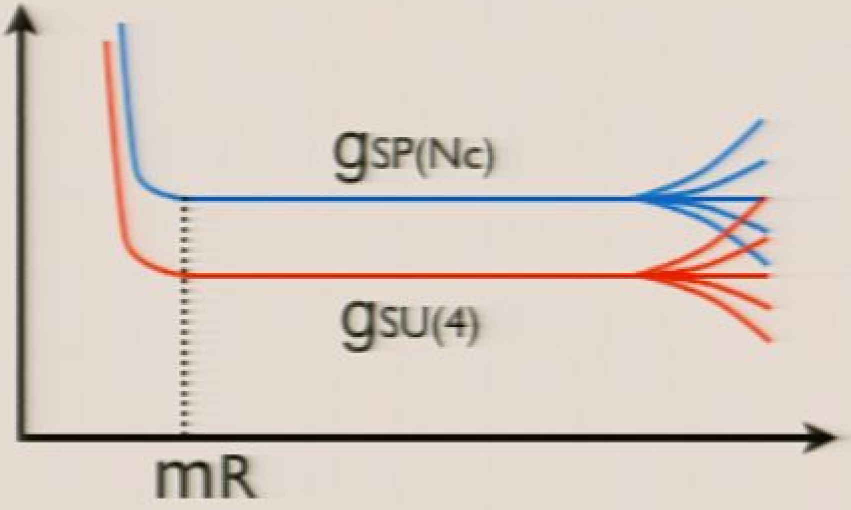

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Gauge Mediation Models @ Tree Level

- R-symmetric connection

Event selection @ LHC 7TeV

- At least two isolated photons with $p_{\mathrm{T}} > 20$ GeV.
- At least four jets with $p_{\mathrm{T}} > 50$ GeV.
- The leading jet with $p_{\mathrm{T}} > 100$ GeV.
- $E_{\mathrm{T,miss}} > \max(100\ \mathrm{GeV}, 0.2 M_{\mathrm{eff}})$, where

$$M_{\mathrm{eff}} \equiv \sum_{4\ \mathrm{leading\ jets}} p_{\mathrm{T},j} + E_{\mathrm{T,miss}} + \sum_{\mathrm{leptons}} p_{\mathrm{T},\ell}.$$

Dark Matter Candidate?

The stable particles with mass in O(10-100)TeV are good dark matter candidate if they annihilate through strong interactions.

[Phys.Rev.Lett.64,615, Griest, Kamionkowski]

We have several candidates in the primary, secondary, and connecting sectors.

$B_R \sim \bar{R}\bar{R}\bar{R}\bar{R}$ $\bar{B}_R \sim RRRR$ (MSSM neutral)

$B \sim \bar{F}\bar{F}\bar{F}\bar{F}$ $\bar{B} \sim FFFF$ (MSSM charged)

They are stable due to global U(1) symmetries.