The dark matter as a light gravitino[1],[2]

G. Moultaka

Laboratoire de Physique Théorique & Astroparticules
CNRS & University of Montepllier II

SUSY07, Karlsruhe, July 30, '07

[1] based on PRD73:043514,2006 , PLB645:222-227,2007, JCAP0607:010,2006
K. Jedamzik (*LPTA-Montpellier*), M. Lemoine (*IAP-Paris*)

[2] work in progress, M. Kuroda (Meiji-Gakuin), M. Lemoine (Paris), M. Capdequi-Peyranère (Montpellier)

Outline

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1)keV \rightarrow O(1)GeV$ and an essentially free $T_{RH} > M_{messengers}$

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1)keV \to O(1)GeV$ and an essentially free $T_{RH} > M_{messengers}$

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1)keV \to O(1)GeV$ and an essentially free $T_{RH} > M_{messengers}$

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1)keV \to O(1)GeV$ and an essentially free $T_{RH} > M_{messengers}$

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1) keV \to O(1) GeV$ and an essentially free $T_{RH} > M_{messengers}$

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1)keV \to O(1)GeV$ and an essentially free $T_{RH} > M_{messengers}$

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1)keV \rightarrow O(1)GeV$ and an essentially free $T_{RH} > M_{messengers}$

Introductory motivations

If Supersymmetry breaking and mediation to the MSSM happen to be of the gauge type (GSMB-like)...

then what can possibly be the dark matter in the Universe?

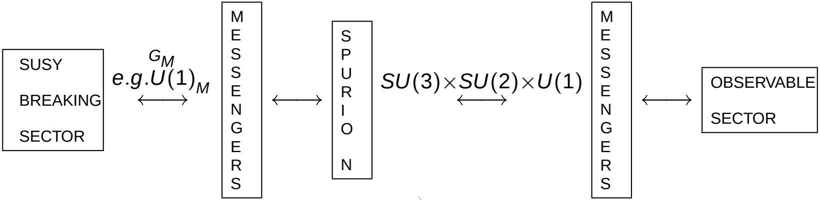
- by far less studied in the litterature than the dark matter candidates (Neutralino/Gravitino) in the gravity-mediated scenarios!
- ⋆ recently a renewed interest in dynamical SUSY breaking opening up many new possibilities for GMSB scenarios [→ Intriligator, Seiberg & Shi, JHEP 0604, 021 (2006), see also Murayama's talk in // session] ⋆
- typically, GMSB ⇒ new relatively light matter and gauge sectors, and a very light gravitino

→ will play a role in the early Universe, for sufficiently high T_{RH}

→ signatures at the colliders

→ In this talk, Gravitino Dark Matter with mass $m_{3/2} \sim O(1)keV \to O(1)GeV$ and an essentially free $T_{RH} > M_{messengers}$

Gauge Mediated Susy Breaking



$$W \supset \kappa \hat{S} \hat{\Phi}_M \hat{\bar{\Phi}}_M + \frac{\lambda}{3} \hat{S}^3 + \Delta W(\hat{S}, \hat{\phi}_i)$$

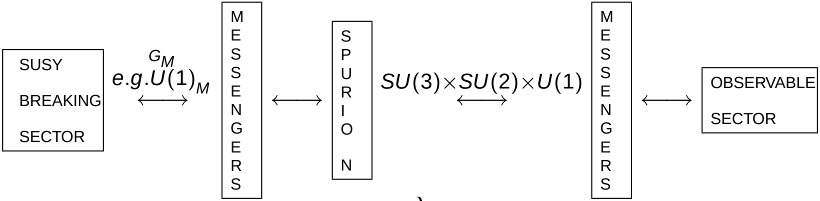
S: "spurion" field, singlet under all gauge groups
$\Phi_M, \bar{\Phi}_M$: quark-like or lepton-like charged messengers under $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\Phi \supset (3, 1, -\frac{1}{3}) \text{ and } (1, 2, \frac{1}{2})$$

$$\bar{\Phi}_M \supset (\bar{3}, 1, \frac{1}{3}) \text{ and } (1, 2, -\frac{1}{2})$$

$e.g.$ $\mathbf{5} + \bar{\mathbf{5}}$ or $\mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)_{GUT}$, $\mathbf{16} + \overline{\mathbf{16}}$ of $SO(10)_{GUT}$
ϕ_i messengers: charged under G_M

Gauge Mediated Susy Breaking



$$W \supset \kappa \hat{S}\hat{\Phi}_M\hat{\overline{\Phi}}_M + \frac{\lambda}{3}\hat{S}^3 + \Delta W(\hat{S},\hat{\phi}_i)$$

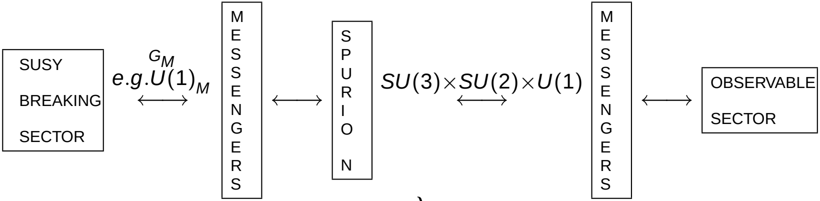
S: "spurion" field, singlet under all gauge groups
$\Phi_M, \overline{\Phi}_M$: quark-like or lepton-like charged messengers under $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\Phi \supset (3, 1, -\frac{1}{3}) \text{ and } (1, 2, \frac{1}{2})$$

$$\overline{\Phi}_M \supset (\bar{3}, 1, \frac{1}{3}) \text{ and } (1, 2, -\frac{1}{2})$$

$e.g.$ $\mathbf{5} + \bar{\mathbf{5}}$ or $\mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)_{GUT}$, $\mathbf{16} + \overline{\mathbf{16}}$ of $SO(10)_{GUT}$
ϕ_i messengers: charged under G_M

Gauge Mediated Susy Breaking



$$W \supset \kappa \hat{S}\hat{\Phi}_M\hat{\overline{\Phi}}_M + \frac{\lambda}{3}\hat{S}^3 + \Delta W(\hat{S}, \hat{\phi}_i)$$

S: "spurion" field, singlet under all gauge groups
$\Phi_M, \overline{\Phi}_M$: quark-like or lepton-like charged messengers under $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\Phi \supset (3, 1, -\frac{1}{3}) \text{ and } (1, 2, \frac{1}{2})$$

$$\overline{\Phi}_M \supset (\bar{3}, 1, \frac{1}{3}) \text{ and } (1, 2, -\frac{1}{2})$$

e.g. $\mathbf{5} + \bar{\mathbf{5}}$ or $\mathbf{10} + \overline{\mathbf{10}}$ of $SU(5)_{GUT}$, $\mathbf{16} + \overline{\mathbf{16}}$ of $SO(10)_{GUT}$
ϕ_i messengers: charged under G_M

SUSY Breaking $\Rightarrow \, < F_S > \neq 0$, also $< S > \neq 0$

$$\Downarrow \qquad\qquad \Downarrow$$

$$M_{s_\pm} = M_X (1 \pm \frac{\kappa < F_S >}{M_X^2})^{1/2}, \quad M_f = \kappa < S > \equiv M_X$$

$\Rightarrow \psi_S = \frac{< F_S >}{< F >} \tilde{G} + \dots$

$\Rightarrow m_{3/2} = \frac{< F_{TOT} >}{\sqrt{3} m_{Pl}}$ with $< F_{TOT} > \gtrsim < F_S >$

$$\Rightarrow m_{1/2} \sim \left(\frac{\alpha}{4\pi}\right) \frac{< F_S >}{M_X}, \qquad m_0^2 \sim \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{< F_S >}{M_X}\right)^2$$

Moreover, one expects $G_F^{-1/2} \sim \frac{< F_{TOT} >}{M_X} \sim m_{3/2} \left(\frac{m_{Pl}}{M_X}\right)$

$\Rightarrow$ very light gravitino

[compare mSUGRA $G_F^{-1/2} \sim \frac{< F_{TOT} >}{m_{Pl}} \sim m_{3/2}$]

SUSY Breaking $\Rightarrow < F_S > \neq 0$, also $< S > \neq 0$

$$\Downarrow \qquad\qquad \Downarrow$$

$$M_{s_\pm} = M_X (1 \pm \frac{\kappa < F_S >}{M_X^2})^{1/2}, \quad M_f = \kappa < S > \equiv M_X$$

$$\Rightarrow \psi_S = \frac{< F_S >}{< F >} \tilde{G} + \dots$$

$$\Rightarrow m_{3/2} = \frac{< F_{TOT} >}{\sqrt{3} m_{Pl}} \text{ with } < F_{TOT} > \gtrsim < F_S >$$

$$\Rightarrow m_{1/2} \sim \left(\frac{\alpha}{4\pi}\right) \frac{< F_S >}{M_X}, \qquad m_0^2 \sim \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{< F_S >}{M_X}\right)^2$$

Moreover, one expects $G_F^{-1/2} \sim \frac{< F_{TOT} >}{M_X} \sim m_{3/2} \left(\frac{m_{Pl}}{M_X}\right)$

$\Rightarrow$ very light gravitino

[compare mSUGRA $G_F^{-1/2} \sim \frac{< F_{TOT} >}{m_{Pl}} \sim m_{3/2}$]

SUSY Breaking $\Rightarrow < F_S > \neq 0$, also $< S > \neq 0$

$$\Downarrow \qquad\qquad \Downarrow$$

$$M_{s_\pm} = M_X(1 \pm \frac{\kappa<F_S>}{M_X^2})^{1/2}, \quad M_f = \kappa < S > \equiv M_X$$

$$\Rightarrow \psi_S = \frac{<F_S>}{<F>}\tilde{G} + \dots$$

$$\Rightarrow m_{3/2} = \frac{<F_{TOT}>}{\sqrt{3}m_{Pl}} \text{ with } < F_{TOT} > \gtrsim < F_S >$$

$$\Rightarrow m_{1/2} \sim \left(\frac{\alpha}{4\pi}\right)\frac{< F_S >}{M_X}, \qquad m_0^2 \sim \left(\frac{\alpha}{4\pi}\right)^2\left(\frac{< F_S >}{M_X}\right)^2$$

Moreover, one expects $G_F^{-1/2} \sim \frac{<F_{TOT}>}{M_X} \sim m_{3/2}\left(\frac{m_{Pl}}{M_X}\right)$

$\Rightarrow$ very light gravitino

[compare mSUGRA $G_F^{-1/2} \sim \frac{<F_{TOT}>}{m_{Pl}} \sim m_{3/2}$]

GUT groups: $SU(5)$, $SO(10)$

The lightest messenger scalar is:

- if $\mathbf{5} + \bar{\mathbf{5}}$, $\tilde{\nu}_L$-like or $\tilde{e}_L$-like
- if $\mathbf{10} + \overline{\mathbf{10}}$, electrically charged $SU(2)_L$ singlet
- if $\mathbf{16} + \overline{\mathbf{16}}$, an MSSM singlet

[S. Dimopoulos, G. F. Giudice, A. Pomarol, PLB 389 (1996) 37; T. Hahn, R. Hempfling, hep-ph/9708264]

Coupling to Supergravity

$$V_B = e^{K/m_{\rm Pl}^2}\left[K^{ij^*}\left(W\frac{K_i}{m_{\rm Pl}^2}+W_i\right)\left(W^*\frac{K_{j^*}}{m_{\rm Pl}^2}+W^*_{j^*}\right)-\frac{3WW^*}{m_{\rm Pl}^2}\right]$$

$$W \to W+<W>,\ \ <W>=\frac{1}{\sqrt{3}}<F_{TOT}>\times m_{\rm Pl}\simeq m_{3/2}m_{\rm Pl}^2$$

$\Downarrow$ $\not{R}$-Symmetry

$\Downarrow$ Cosmological Cte $\simeq 0$

holomorphic part:

$\Rightarrow K\supset f(\phi)\ \ \rightarrow\ \ W\supset\frac{<W>}{m_{\rm Pl}}f(\phi)=m_{3/2}f(\phi)$

Kähler, super-Weyl trans. $K\rightarrow K+f(\phi)+f^*(\phi^*)$, $W\rightarrow e^{-f(\phi)}W$

e.g. $K_{\rm ren}\supset \mathbf{5}_M\bar{\mathbf{5}}_F\ \ \rightarrow W\supset m_{3/2}\mathbf{5}_M\bar{\mathbf{5}}_F$

e.g. $K_{\rm non-ren}\supset\frac{1}{m_{Pl}}\{\bar{\mathbf{5}}_M\bar{\mathbf{5}}_{F,H}\mathbf{10}_F\ ,\ \mathbf{5}_M\mathbf{10}_F\mathbf{10}_F\ldots\}$

Coupling to Supergravity

$$V_B = e^{K/m_{\rm Pl}^2}\left[K^{ij^*}\left(W\frac{K_i}{m_{\rm Pl}^2}+W_i\right)\left(W^*\frac{K_{j^*}}{m_{\rm Pl}^2}+W^*_{j^*}\right)-\frac{3WW^*}{m_{\rm Pl}^2}\right]$$

$$W \to W + \langle W \rangle, \quad \langle W \rangle = \frac{1}{\sqrt{3}} \langle F_{TOT} \rangle \times m_{\rm Pl} \simeq m_{3/2} m_{\rm Pl}^2$$

$\Downarrow$ $\Downarrow$

$\not{R}$-Symmetry — Cosmological Cte $\simeq 0$

holomorphic part:

$\Rightarrow K \supset f(\phi) \quad \to \quad W \supset \frac{\langle W \rangle}{m_{\rm Pl}} f(\phi) = m_{3/2} f(\phi)$

Kähler, super-Weyl trans. $K \to K + f(\phi) + f^*(\phi^*)$, $W \to e^{-f(\phi)} W$

e.g. $K_{\rm ren} \supset \mathbf{5}_M \bar{\mathbf{5}}_F \quad \to W \supset m_{3/2} \mathbf{5}_M \bar{\mathbf{5}}_F$

e.g. $K_{\rm non-ren} \supset \frac{1}{m_{Pl}} \{ \bar{\mathbf{5}}_M \bar{\mathbf{5}}_{F,H} \mathbf{10}_F \, , \, \mathbf{5}_M \mathbf{10}_F \mathbf{10}_F \ldots \}$

Coupling to Supergravity

$$V_B = e^{K/m_{\rm Pl}^2}\left[K^{ij^*}\left(W\frac{K_i}{m_{\rm Pl}^2}+W_i\right)\left(W^*\frac{K_{j^*}}{m_{\rm Pl}^2}+W^*_{j^*}\right)-\frac{3WW^*}{m_{\rm Pl}^2}\right]$$

$$W \rightarrow W + <W>, \quad <W> = \frac{1}{\sqrt{3}} <F_{TOT}> \times m_{\rm Pl} \simeq m_{3/2} m_{\rm Pl}^2$$

$\Downarrow$ $\not{R}$-Symmetry

$\Downarrow$ Cosmological Cte $\simeq 0$

holomorphic part:

$\Rightarrow K \supset f(\phi) \quad \rightarrow \quad W \supset \frac{<W>}{m_{\rm Pl}} f(\phi) = m_{3/2} f(\phi)$

Kähler, super-Weyl trans. $K \rightarrow K + f(\phi) + f^*(\phi^*)$, $W \rightarrow e^{-f(\phi)} W$

e.g. $K_{\rm ren} \supset \mathbf{5}_M \bar{\mathbf{5}}_F \quad \rightarrow W \supset m_{3/2} \mathbf{5}_M \bar{\mathbf{5}}_F$

e.g. $K_{\rm non-ren} \supset \frac{1}{m_{Pl}} \{\bar{\mathbf{5}}_M \bar{\mathbf{5}}_{F,H} \mathbf{10}_F \, , \, \mathbf{5}_M \mathbf{10}_F \mathbf{10}_F \ldots\}$

Coupling to Supergravity

$$V_B = e^{K/m_{\rm Pl}^2}\left[K^{ij^*}\left(W\frac{K_i}{m_{\rm Pl}^2}+W_i\right)\left(W^*\frac{K_{j^*}}{m_{\rm Pl}^2}+W_{j^*}^*\right)-\frac{3WW^*}{m_{\rm Pl}^2}\right]$$

$$W \to W + < W >, \quad < W > = \frac{1}{\sqrt{3}} < F_{TOT} > \times m_{\rm Pl} \simeq m_{3/2} m_{\rm Pl}^2$$

$\Downarrow$ $\not{R}$-Symmetry

$\Downarrow$ Cosmological Cte $\simeq 0$

holomorphic part:

$\Rightarrow K \supset f(\phi) \quad \to \quad W \supset \frac{<W>}{m_{\rm Pl}} f(\phi) = m_{3/2} f(\phi)$

Kähler, super-Weyl trans. $K \to K + f(\phi) + f^*(\phi^*)$, $W \to e^{-f(\phi)} W$

e.g. $K_{\rm ren} \supset \mathbf{5}_M \bar{\mathbf{5}}_F \quad \to W \supset m_{3/2} \mathbf{5}_M \bar{\mathbf{5}}_F$

e.g. $K_{\rm non-ren} \supset \frac{1}{m_{Pl}} \{ \bar{\mathbf{5}}_M \bar{\mathbf{5}}_{F,H} \mathbf{10}_F \, , \, \mathbf{5}_M \mathbf{10}_F \mathbf{10}_F \ldots \}$

Coupling to Supergravity

$$V_B = e^{K/m_{\rm Pl}^2}\left[K^{ij^*}\left(W\frac{K_i}{m_{\rm Pl}^2}+W_i\right)\left(W^*\frac{K_{j^*}}{m_{\rm Pl}^2}+W^*_{j^*}\right)-\frac{3WW^*}{m_{\rm Pl}^2}\right]$$

$$W \to W + <W>, \quad <W> = \frac{1}{\sqrt{3}} <F_{TOT}> \times m_{\rm Pl} \simeq m_{3/2} m_{\rm Pl}^2$$

$\Downarrow$ $\Downarrow$

$\not{R}$-Symmetry Cosmological Cte $\simeq 0$

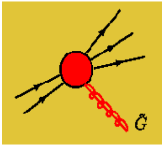
holomorphic part:

$\Rightarrow K \supset f(\phi) \quad \to \quad W \supset \frac{<W>}{m_{\rm Pl}} f(\phi) = m_{3/2} f(\phi)$

Kähler, super-Weyl trans. $K \to K + f(\phi) + f^*(\phi^*)$, $W \to e^{-f(\phi)} W$

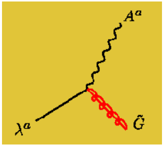
e.g. $K_{\rm ren} \supset \mathbf{5}_M \bar{\mathbf{5}}_F \quad \to W \supset m_{3/2} \mathbf{5}_M \bar{\mathbf{5}}_F$

e.g. $K_{\rm non-ren} \supset \frac{1}{m_{Pl}} \{\bar{\mathbf{5}}_M \bar{\mathbf{5}}_{F,H} \mathbf{10}_F \,,\, \mathbf{5}_M \mathbf{10}_F \mathbf{10}_F \ldots\}$

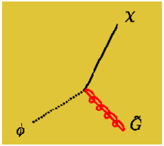


$$E \gg m_{3/2}$$

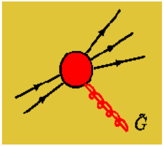
$$\Psi_\mu = i\sqrt{\frac{2}{3}}\,\frac{\partial_\mu \tilde{G}}{m_{3/2}} + \ldots$$



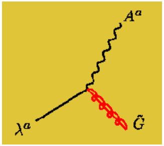
$$\sim \frac{m_\lambda}{m_{3/2} m_{Pl}} \times \partial$$



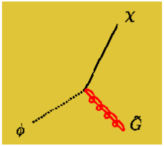
$$\sim \frac{m_\chi^2 - m_\phi^2}{m_{3/2} m_{Pl}}$$



$$E \gg m_{3/2}$$
$$\Psi_\mu = i\sqrt{\frac{2}{3}}\,\frac{\partial_\mu \tilde{G}}{m_{3/2}} + \ldots$$



$$\sim \frac{m_\lambda}{m_{3/2} m_{Pl}} \times \partial$$



$$\sim \frac{m_\chi^2 - m_\phi^2}{m_{3/2} m_{Pl}}$$

However...there is much more to it!

$\psi_S = \frac{F_S}{F_{TOT}} \tilde{G} + \ldots \Rightarrow$ Consider the full Supergravity Lagrangian

Gravitino Problem, Messenger Solution

Gravitino Problem

$T_{RH} \gtrsim T^f_{3/2}$

$< \sigma v > \simeq \frac{g_3^2 m^2_{gluino}}{m_{3/2} m^2_{Pl}}$

$\rightarrow < \sigma v > n_{rad} \lesssim H$

$\rightarrow T^f_{3/2} \simeq 1TeV \left(\frac{m_{3/2}}{10keV}\right)^2 \left(\frac{1TeV}{m_{gluino}}\right)^2 \left(\frac{g_*}{230}\right)^{\frac{1}{2}}$

$m_{3/2} \ll T^f_{3/2}$ relativistic at freeze-out

$$\Omega_{3/2} h^2 \simeq 5. \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$$

compare $\Omega_{3/2} h^2 \simeq 0.1$

dilution? $\simeq 40 \times \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$

Messenger Solution

$T_{RH} \gtrsim M_{s_-}$

$\Omega_M h^2 = \frac{s_0 Y_{s_-}}{\rho_c} M_{s_-}$

$Y_{s_-} \sim \frac{x_f}{M_{s_-} m_{Pl}} \frac{1}{<\sigma v>} \frac{1}{g_*^{1/2}}$

$\Omega_M h^2 \simeq 10^5 \left(\frac{M_{s_-}}{10^3 TeV}\right)^2$

IF STABLE $\Rightarrow \Omega_M \gg 1$!

$\Downarrow$

THE LMP MUST BE

UNSTABLE

$\Gamma_M \sim t_d^{-1} \sim H \sim T_d^2$

$$T_d \stackrel{?}{<} T_{MD} \stackrel{?}{<} T^f_{3/2} \Rightarrow \text{Important Gravitino Dilution}$$

M. Fujii & T. Yanagida, PLB **549** (2002) 273.
E. A. Baltz & H. Murayama, JHEP 0305:067 (2003).

Gravitino Problem

$T_{RH} \gtrsim T^f_{3/2}$

$< \sigma v > \simeq \frac{g_3^2 m^2_{gluino}}{m_{3/2} m^2_{Pl}}$

$\rightarrow < \sigma v > n_{rad} \lesssim H$

$\rightarrow T^f_{3/2} \simeq 1 TeV \left(\frac{m_{3/2}}{10keV}\right)^2 \left(\frac{1TeV}{m_{gluino}}\right)^2 \left(\frac{g_*}{230}\right)^{\frac{1}{2}}$

$m_{3/2} \ll T^f_{3/2}$ relativistic at freeze-out

$$\Omega_{3/2} h^2 \simeq 5. \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$$

compare $\Omega_{3/2} h^2 \simeq 0.1$

dilution? $\simeq 40 \times \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$

Messenger Solution

$T_{RH} \gtrsim M_{s_-}$

$\Omega_M h^2 = \frac{s_0 Y_{s_-}}{\rho_c} M_{s_-}$

$Y_{s_-} \sim \frac{x_f}{M_{s_-} m_{Pl}} \frac{1}{<\sigma v>} \frac{1}{g_*^{1/2}}$

$\Omega_M h^2 \simeq 10^5 \left(\frac{M_{s_-}}{10^3 TeV}\right)^2$

IF STABLE $\Rightarrow \Omega_M \gg 1$!

$\Downarrow$

THE LMP MUST BE

UNSTABLE

$\Gamma_M \sim t_d^{-1} \sim H \sim T_d^2$

$T_d \overset{?}{<} T_{MD} \overset{?}{<} T^f_{3/2} \Rightarrow$ Important Gravitino Dilution

M. Fujii & T. Yanagida, PLB **549** (2002) 273.
E. A. Baltz & H. Murayama, JHEP 0305:067 (2003).

Gravitino Problem

$T_{RH} \gtrsim T^f_{3/2}$

$< \sigma v > \simeq \frac{g_3^2 m^2_{gluino}}{m_{3/2} m^2_{Pl}}$

$\rightarrow < \sigma v > n_{rad} \lesssim H$

$\rightarrow T^f_{3/2} \simeq 1TeV \left(\frac{m_{3/2}}{10keV}\right)^2 \left(\frac{1TeV}{m_{gluino}}\right)^2 \left(\frac{g_*}{230}\right)^{\frac{1}{2}}$

$m_{3/2} \ll T^f_{3/2}$ relativistic at freeze-out

$$\Omega_{3/2} h^2 \simeq 5. \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$$

compare $\Omega_{3/2} h^2 \simeq 0.1$

dilution? $\simeq 40 \times \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$

Messenger Solution

$T_{RH} \gtrsim M_{s_-}$

$\Omega_M h^2 = \frac{s_0 Y_{s_-}}{\rho_c} M_{s_-}$

$Y_{s_-} \sim \frac{x_f}{M_{s_-} m_{Pl}} \frac{1}{<\sigma v>} \frac{1}{g_*^{1/2}}$

$\Omega_M h^2 \simeq 10^5 \left(\frac{M_{s_-}}{10^3 TeV}\right)^2$

IF STABLE $\Rightarrow \Omega_M \gg 1$!

$\Downarrow$

THE LMP MUST BE

UNSTABLE

$\Gamma_M \sim t_d^{-1} \sim H \sim T_d^2$

$$T_d \overset{?}{<} T_{MD} \overset{?}{<} T^f_{3/2} \Rightarrow \text{Important Gravitino Dilution}$$

M. Fujii & T. Yanagida, PLB ***549*** *(2002) 273.*
E. A. Baltz & H. Murayama, JHEP 0305:067 (2003).

⇒ Messenger number violating operators can originate from:

- a holomorphic contribution to the Kähler potential, with or without Planck scale suppression
- a renormalizable or non-renormalizable contribution to the superpotential
- a non-holomorphic contribution to the Kähler potential

⇒ for each case, take into account ALL couplings of the messenger and spurion sectors to the MSSM sector and to the gravitino (goldstino) in the Supergravity Lagrangian, to calculate:

- the yield Y_M and the thermal freeze-out density of the lightest messenger
- the background temperature at which the messenger dominates the energy density of the universe $T_{MD} \simeq \frac{4}{3} M_{S_-} \times Y_M$
- The decay temperature T_d of the lightest messenger

→ entropy release → $Y_{3/2}^{after} = Y_{3/2}^{before} / \Delta_{S_-}$

$$\Delta_{S_-} \approx 28 \left(\frac{M_{S_-}}{10^8 \mathrm{GeV}} \right) \left(\frac{Y_{S_-}}{10^{-10}} \right) \left(\frac{\Gamma_{S_-}}{10^{-25} \mathrm{GeV}} \right)^{-\frac{1}{2}} \left(\frac{g_>}{10} \right)^{\frac{1}{4}}$$

⇒ Messenger number violating operators can originate from:

- a holomorphic contribution to the Kähler potential, with or without Planck scale suppression
- a renormalizable or non-renormalizable contribution to the superpotential
- a non-holomorphic contribution to the Kähler potential

⇒ for each case, take into account ALL couplings of the messenger and spurion sectors to the MSSM sector and to the gravitino (goldstino) in the Supergravity Lagrangian, to calculate:

- the yield Y_M and the thermal freeze-out density of the lightest messenger
- the background temperature at which the messenger dominates the energy density of the universe $T_{MD} \simeq \frac{4}{3} M_{S_-} \times Y_M$
- The decay temperature T_d of the lightest messenger

→ entropy release $\to Y_{3/2}^{after} = Y_{3/2}^{before} / \Delta_{S_-}$

$$\Delta_{S_-} \approx 28 \left(\frac{M_{S_-}}{10^8 \mathrm{GeV}}\right) \left(\frac{Y_{S_-}}{10^{-10}}\right) \left(\frac{\Gamma_{S_-}}{10^{-25} \mathrm{GeV}}\right)^{-\frac{1}{2}} \left(\frac{g_>}{10}\right)^{\frac{1}{4}}$$

⇒ Messenger number violating operators can originate from:

- a holomorphic contribution to the Kähler potential, with or without Planck scale suppression
- a renormalizable or non-renormalizable contribution to the superpotential
- a non-holomorphic contribution to the Kähler potential

⇒ for each case, take into account ALL couplings of the messenger and spurion sectors to the MSSM sector and to the gravitino (goldstino) in the Supergravity Lagrangian, to calculate:

- the yield Y_M and the thermal freeze-out density of the lightest messenger
- the background temperature at which the messenger dominates the energy density of the universe $T_{MD} \simeq \frac{4}{3} M_{S_-} \times Y_M$
- The decay temperature T_d of the lightest messenger

→ entropy release → $Y_{3/2}^{after} = Y_{3/2}^{before} / \Delta_{S_-}$

$$\Delta_{S_-} \approx 28 \left(\frac{M_{S_-}}{10^8 \mathrm{GeV}}\right) \left(\frac{Y_{S_-}}{10^{-10}}\right) \left(\frac{\Gamma_{S_-}}{10^{-25} \mathrm{GeV}}\right)^{-\frac{1}{2}} \left(\frac{g_>}{10}\right)^{\frac{1}{4}}$$

⇒ Messenger number violating operators can originate from:

- a holomorphic contribution to the Kähler potential, with or without Planck scale suppression
- a renormalizable or non-renormalizable contribution to the superpotential
- a non-holomorphic contribution to the Kähler potential

⇒ for each case, take into account ALL couplings of the messenger and spurion sectors to the MSSM sector and to the gravitino (goldstino) in the Supergravity Lagrangian, to calculate:

- the yield Y_M and the thermal freeze-out density of the lightest messenger
- the background temperature at which the messenger dominates the energy density of the universe $T_{MD} \simeq \frac{4}{3} M_{S_-} \times Y_M$
- The decay temperature T_d of the lightest messenger

→ entropy release → $Y_{3/2}^{after} = Y_{3/2}^{before} / \Delta_{S_-}$

$$\Delta_{S_-} \approx 28 \left(\frac{M_{S_-}}{10^8 \mathrm{GeV}} \right) \left(\frac{Y_{S_-}}{10^{-10}} \right) \left(\frac{\Gamma_{S_-}}{10^{-25} \mathrm{GeV}} \right)^{-\frac{1}{2}} \left(\frac{g_>}{10} \right)^{\frac{1}{4}}$$

⇒ Messenger number violating operators can originate from:

- a holomorphic contribution to the Kähler potential, with or without Planck scale suppression
- a renormalizable or non-renormalizable contribution to the superpotential
- a non-holomorphic contribution to the Kähler potential

⇒ for each case, take into account ALL couplings of the messenger and spurion sectors to the MSSM sector and to the gravitino (goldstino) in the Supergravity Lagrangian, to calculate:

- the yield $Y_{_M}$ and the thermal freeze-out density of the lightest messenger
- the background temperature at which the messenger dominates the energy density of the universe $T_{_{MD}} \simeq \frac{4}{3} M_{S_-} \times Y_{_M}$
- The decay temperature T_d of the lightest messenger

→ entropy release → $Y_{3/2}^{after} = Y_{3/2}^{before} / \Delta_{S_-}$

$$\Delta_{S_-} \approx 28 \left(\frac{M_{S_-}}{10^8 \mathrm{GeV}} \right) \left(\frac{Y_{S_-}}{10^{-10}} \right) \left(\frac{\Gamma_{S_-}}{10^{-25} \mathrm{GeV}} \right)^{-\frac{1}{2}} \left(\frac{g_>}{10} \right)^{\frac{1}{4}}$$

...e.g. in $SU(5)$

$$K_{\rm ren} \supset \mathbf{5}_M \bar{\mathbf{5}}_F \quad \to W \supset m_{3/2} \mathbf{5}_M \bar{\mathbf{5}}_F$$

$$W_{\rm ren} \quad \supset \{ \quad \bar{\mathbf{5}}_M \bar{\mathbf{5}}_{F,H} \mathbf{10}_F \, , \, \mathbf{5}_M \mathbf{10}_F \mathbf{10}_F \, , \, \mathbf{5}_M \bar{\mathbf{5}}_{F,H} \mathbf{24}_H \, ,$$
$$\bar{\mathbf{5}}_M \mathbf{5}_H \mathbf{24}_H \, , \overline{\mathbf{10}}_M \mathbf{5}_H \mathbf{5}_H \, , \, \mathbf{10}_M \bar{\mathbf{5}}_{H,F} \bar{\mathbf{5}}_{H,F} \, ,$$
$$\mathbf{10}_M \mathbf{10}_F \mathbf{5}_H \, , \, \mathbf{10}_F \overline{\mathbf{10}}_M \mathbf{24}_H \} .$$

$$K_{\rm hol} = \frac{W_{\rm ren}}{m_{\rm Pl}} + h.c.$$

...other possibilities...

$$W_{\text{non-ren}} \supset \frac{1}{m_{\text{Pl}}} \{ \quad \bar{\mathbf{5}}_M \mathbf{10}_F \mathbf{10}_F \mathbf{10}_F \, , \, \mathbf{5}_M \mathbf{5}_H \bar{\mathbf{5}}_{H,F} \bar{\mathbf{5}}_{H,F} \, ,$$
$$\bar{\mathbf{5}}_M \mathbf{5}_H \mathbf{5}_H \bar{\mathbf{5}}_{H,F} \, , \, \mathbf{5}_M \mathbf{5}_H \mathbf{5}_H \mathbf{10}_F \, ,$$
$$\bar{\mathbf{5}}_M \bar{\mathbf{5}}_H \mathbf{10}_F \mathbf{24}_H \, , \, \mathbf{5}_M \bar{\mathbf{5}}_{H,F} \mathbf{24}_H \mathbf{24}_H \, ,$$
$$\bar{\mathbf{5}}_M \mathbf{5}_H \mathbf{24}_H \mathbf{24}_H \, , \, \mathbf{10}_F \overline{\mathbf{10}}_M \mathbf{5}_H \bar{\mathbf{5}}_{H,F} \, ,$$
$$\overline{\mathbf{10}}_M \bar{\mathbf{5}}_{H,F} \bar{\mathbf{5}}_{H,F} \bar{\mathbf{5}}_{H,F} \, , \, \mathbf{10}_M \mathbf{5}_H \mathbf{5}_H \mathbf{5}_H \, ,$$
$$\mathbf{10}_M \bar{\mathbf{5}}_{H,F} \mathbf{10}_F \mathbf{10}_F \, , \, \mathbf{10}_M \mathbf{10}_F \mathbf{5}_H \mathbf{24}_H \, ,$$
$$\overline{\mathbf{10}}_M \mathbf{5}_H \mathbf{5}_H \mathbf{24}_H \, , \, \mathbf{10}_M \bar{\mathbf{5}}_{H,F} \bar{\mathbf{5}}_{H,F} \mathbf{24}_H \, ,$$
$$\overline{\mathbf{10}}_M \mathbf{10}_F \mathbf{24}_H \mathbf{24}_H \, , \, \mathbf{5}_M \bar{\mathbf{5}}_M \mathbf{5}_M \bar{\mathbf{5}}_F \, ,$$
$$\mathbf{10}_M \overline{\mathbf{10}}_M \mathbf{10}_M \mathbf{10}_F \}$$

$$
\begin{aligned}
K_{\rm non-hol} \supset \frac{1}{m_{\rm Pl}}\Big\{ \; & \mathbf{5}^\dagger_M \bar{\mathbf{5}}_{H,F} \mathbf{10}_F \,,\; \bar{\mathbf{5}}_M \mathbf{5}^\dagger_H \mathbf{10}_F \,,\; \bar{\mathbf{5}}^\dagger_M \mathbf{10}_F \mathbf{10}_F \,, \\
& \mathbf{5}^\dagger_M \mathbf{5}_H \mathbf{24}_H \,,\; \mathbf{5}_M \mathbf{5}^\dagger_H \mathbf{24}_H \,,\; \bar{\mathbf{5}}_M \bar{\mathbf{5}}^\dagger_{H,F} \mathbf{24}_H \,, \\
& \bar{\mathbf{5}}^\dagger_M \bar{\mathbf{5}}_{H,F} \mathbf{24}_H \,,\; \mathbf{10}^\dagger_M \mathbf{5}_H \mathbf{5}_H \,,\; \overline{\mathbf{10}}_M \bar{\mathbf{5}}^\dagger_{H,F} \mathbf{5}_H \,, \\
& \overline{\mathbf{10}}^\dagger_M \bar{\mathbf{5}}_{H,F} \bar{\mathbf{5}}_{H,F} \,,\; \overline{\mathbf{10}}^\dagger_M \mathbf{10}_F \mathbf{5}_H \,,\; \mathbf{10}_M \mathbf{10}_F \bar{\mathbf{5}}^\dagger_{H,F} \,, \\
& \mathbf{10}^\dagger_M \mathbf{10}_F \mathbf{24}_H \,,\; \mathbf{10}_M \mathbf{10}^\dagger_F \mathbf{24}_H \,,\; + \text{h.c.} \Big\} \qquad (1)
\end{aligned}
$$

⇒ a few other things to worry about:

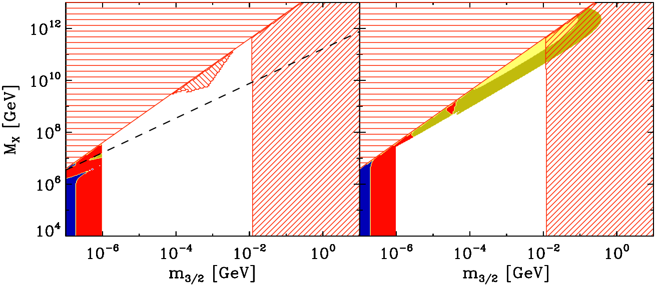
- gravitino regeneration through messenger decay
- MSSM particles production (especially NLSP) through messenger decay
- out-of-equilibrium NLSP decay into gravitinos
- BBN constraints
- hot/warm dark matter components

⇒ $\Omega_{3/2} \simeq \Omega_{3/2}^{th} + \Omega_{3/2}^{Mess} + \Omega_{3/2}^{NLSP}$

$SU(5)$

$\Rightarrow$ The lightest messenger is weakly charged ($\tilde{\nu}_L$-like)

$\Omega_{3/2}$ in the plane $M_X - m_{3/2}$; $T_{\rm RH} = 10^{12} GeV$; one pair of messengers sitting in $\mathbf{5} + \bar{\mathbf{5}}$; the lightest messenger X is $\tilde{\nu}_L$-like, NLSP bino-like both panels. Left panel S heavier than X; Right panel S lighter than X.



$$K_{\rm ren} \supset \mathbf{5}_M \bar{\mathbf{5}}_F \quad \longrightarrow W \supset m_{3/2} \mathbf{5}_M \bar{\mathbf{5}}_F$$

$X \longrightarrow lepton + gaugino$ (Fuji, Yanagida)
BUT other contributions from Supergravity sector and spurion field (depending on its mass) :

$XX \longrightarrow \tilde{G}\tilde{G}$, $X \longrightarrow \tilde{\nu}\tilde{G}\tilde{G}$, $X \longrightarrow S\tilde{\nu}$ (if S lighter than X)

$SO(10)$

$$
\begin{aligned}
\hat{S} &= (A_S, \varphi_S, F_S) && \sim \mathbf{1} \\
\hat{\Phi}_M &= (\mathbf{A_M}(\mathbf{16}), \varphi_{\mathbf{M}}(\mathbf{16}), \mathbf{F_M}(\mathbf{16})) && \sim \mathbf{16} \\
\hat{\Phi}_{\overline{M}} &= (\mathbf{A_{\overline{M}}}(\mathbf{16}), \varphi_{\overline{\mathbf{M}}}(\mathbf{16}), \mathbf{F_{\overline{M}}}(\mathbf{16})) && \sim \overline{\mathbf{16}}
\end{aligned}
$$

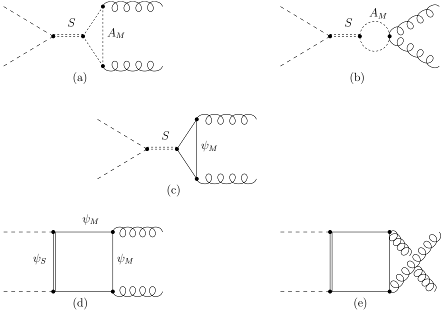
$$
\mathbf{A_M}(\mathbf{16}) = \begin{pmatrix} \tilde{d}_{1R} \\ \tilde{d}_{2R} \\ \tilde{d}_{3R} \\ \tilde{e}_L \\ -\tilde{\nu}_L \\ \tilde{u}_{1L} \\ \tilde{u}_{2L} \\ \tilde{u}_{3L} \\ \tilde{d}_{1L} \\ \tilde{d}_{2L} \\ \tilde{d}_{3L} \\ -\tilde{u}_{1R} \\ \tilde{u}_{2R} \\ -\tilde{u}_{3R} \\ \tilde{e}_R \\ \tilde{N}_R \end{pmatrix}
$$

$$
\begin{pmatrix} A_- \\ A_+ \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} A_M^\dagger \\ A_{\bar{M}} \end{pmatrix}
$$

A_-, A_+ mass eigenstates; mass degeneracy among the A_-'s lifted by radiative corrections.

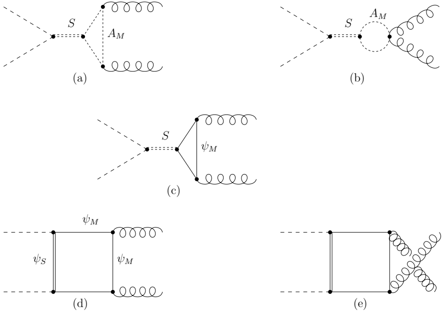
$\Rightarrow$ The lightest messenger is a MSSM singlet

$XX \to gg$



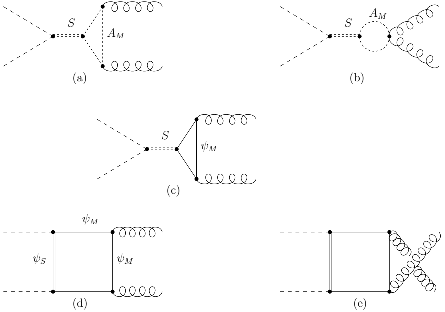
$XX \to \tilde{G}\tilde{G}$

$XX \to gg$

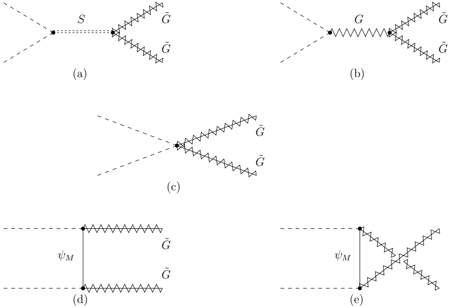


$XX \to \tilde{G}\tilde{G}$

$XX \to gg$



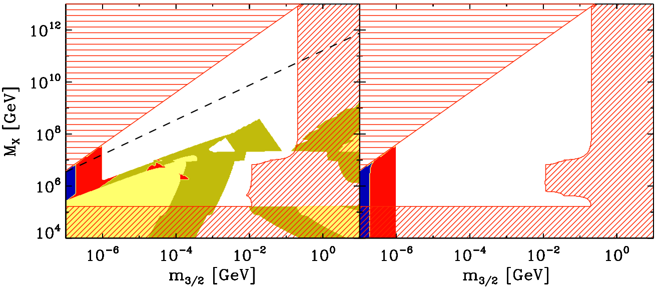
$XX \to \tilde{G}\tilde{G}$



$SO(10)$

$\Rightarrow$ The lightest messenger is a gauge singlet ($\tilde{\nu}_R$-like)

Contours of $\Omega_{3/2}$ in the plane $M_X - m_{3/2}$ for one pair of messengers sitting in $\mathbf{16} + \overline{\mathbf{16}}$ representations of $SO(10)$; the lightest messenger X is a singlet under $SU(3) \times SU(2) \times U(1)$. Its loop-suppressed annihilation cross-section scales as $(\alpha_S/4\pi)^2 \kappa^4 / M_X^2$, (in the plot $\kappa^2 \simeq \alpha_S/4\pi$) and it decays into sparticles through non-renormalizable operators with width $\Gamma \sim 10^{-3} M_X^3 / m_{\rm Pl}^2$



Concluding remarks

- gravitino LSP is most natural in GMSB-like models
- messenger (and secluded) degrees of freedom can affect the thermal history of the early Universe

$\Rightarrow$ provides a solution to the gravitino problem AND makes the gravitino a viable candidate for cold dark matter.
However, requires extensions of GMSB.
$\Rightarrow$ Generically favours $SO(10)$ over $SU(5)$ GUT groups.

- T_{RH} can be very high $\rightarrow$ thermal leptogenesis $\smile$, and entropy release not too high $\smile$
- right-handed stau or Neutralino NLSP, $\rightarrow$ short-lived $\tau \simeq$ a few ns - a few ms $\rightarrow$ collider searches $\smile$
- BBN constraints OK, bound state effects ($\tilde{\tau}NLSP$) irrelevant.
- other gravitino problems (e.g. inflaton gravitino production) can be avoided
- upper limits on thermal gravitino mass ($\lesssim$ 16 eV) do not apply $\smile$
- correlation between $m_{3/2}$ and the MSSM soft masses still model-dependent... role of the susy breaking sector, coupling to supergravity, etc... $\frown$. underway...

...an experimental direct hint for such dark matter can come only from the colliders! but not easy to distinguish from other scenarios if NLSP decays outside the detector