Gravitino Dark Matter In Gauge Mediated SUSY Breaking Models*†

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Karsten Jedamzik (*LPTA-Montpellier*)

Outline

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Does the Dark Matter puzzle have anything to do with particle physics beyond the Standard Model (i.e.(!) with Supersymmetry) ?

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... Neutralino?... Axino? ... Gravitino?...Otherino?

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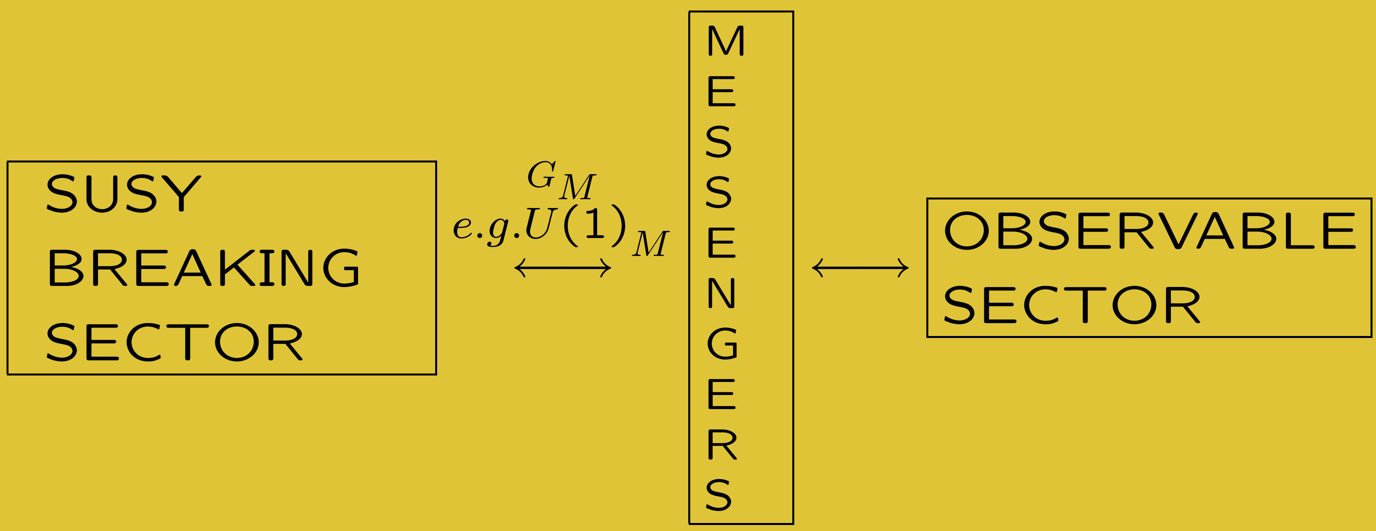
in this talk:

$\rightarrow$ Gravitino with mass $m_{3/2} \sim 1 keV \rightarrow 10 MeV$

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 $< S > \neq 0$

$\Downarrow$ $\Downarrow$

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

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

$\Rightarrow m_{3/2} = \frac{<F_{TOT}>}{\sqrt{3} m_{Pl}}$ 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 $G_F^{-1/2} \sim \frac{<F_{TOT}>}{m_{Pl}} \sim m_{3/2}$]

Coupling to Supergravity $\boxed{\pounds}$

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

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

$\Downarrow$ $\Downarrow$

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

holomorphic part:

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

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

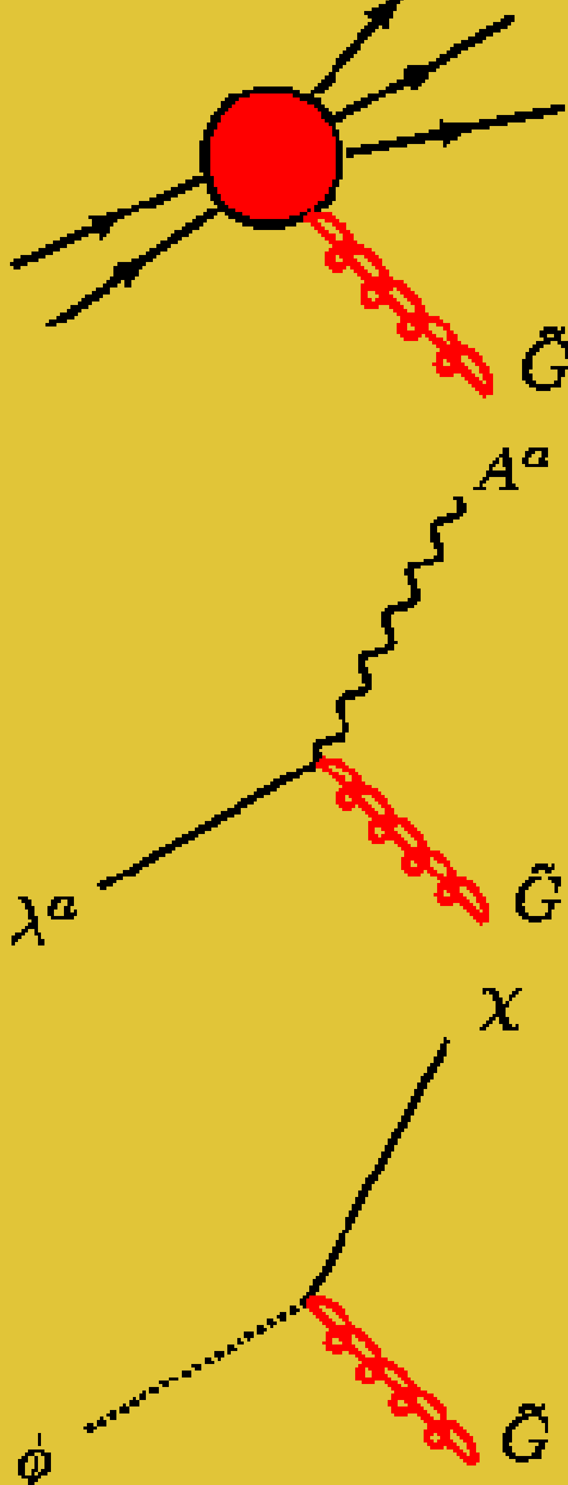
$$W \to e^{-f(\phi)} W$$

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

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

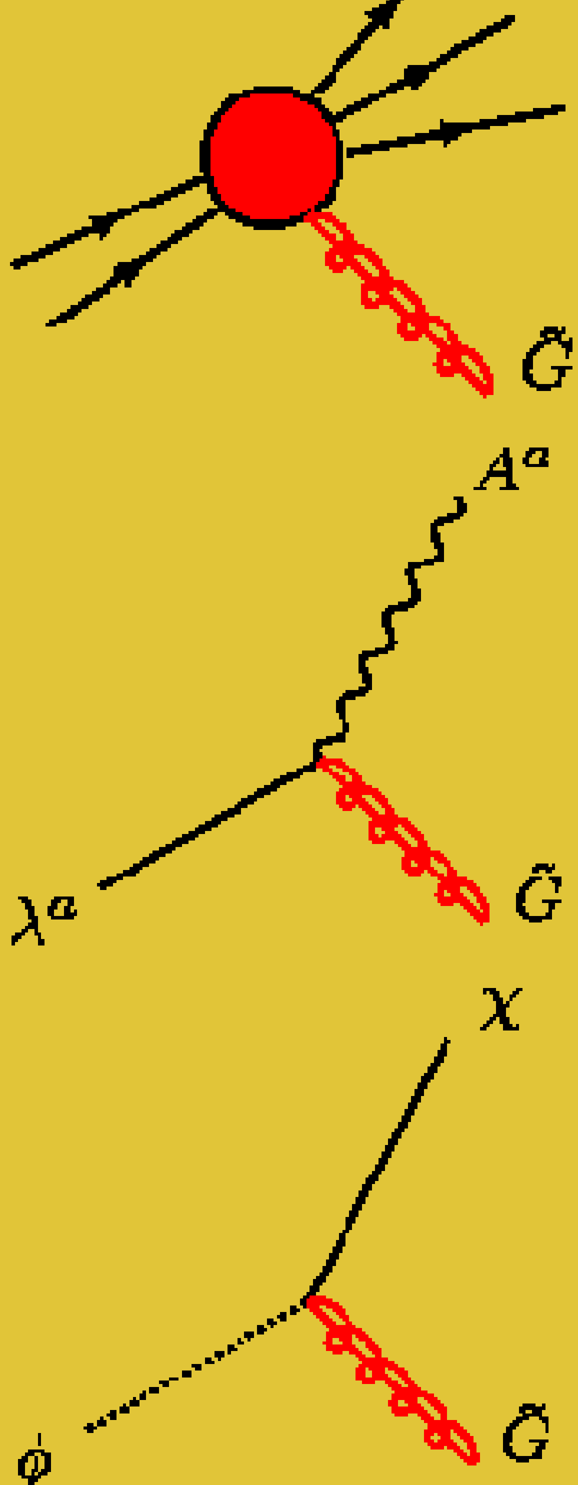
$E \gg m_{3/2}$

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



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

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



$E \gg m_{3/2}$

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

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

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

However...there is much more to it!

$$\rightarrow \psi_S = \frac{F_S}{F}\tilde{G} + \ldots$$

$\Rightarrow$ Consider the full Supergravity Lagrangian

Gravitino Problem – Messenger Solution $\boxed{\in}$

Gravitino Problem	Messenger Solution
$T_{RH} \gtrsim T^f_{3/2}$	$T_{RH} \gtrsim M_{mess}$
$< \sigma v > \simeq \frac{g_3^2 m^2_{gluino}}{m_{3/2} m^2_{Pl}}$	$\Omega_M h^2 = \frac{s_0 Y_M}{\rho_c} M_{mess}$
$\rightarrow < \sigma v > n_{rad} \lesssim H$	$Y_M \sim \frac{x_f}{M_{mess} m_{Pl}} \frac{1}{<\sigma v>} \frac{1}{g_*^{1/2}}$
$\rightarrow T^f_{3/2} \simeq 1TeV \left(\frac{m_{3/2}}{10keV}\right)^2 \left(\frac{1TeV}{m_{gluino}}\right)^2 \left(\frac{g_*}{230}\right)^{\frac{1}{2}}$	$\Omega_M h^2 \simeq 10^5 \left(\frac{M_{mess}}{10^3 TeV}\right)^2$
$m_{3/2} \ll T^f_{3/2}$ relativistic at freeze-out	IF STABLE $\Rightarrow \Omega_M \gg 1$! $\Downarrow$
$\Omega_{3/2} h^2 \simeq 5. \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$	THE LMP MUST BE UNSTABLE
compare $\Omega_{3/2} h^2 \simeq 0.1$ dilution? $\simeq 40 \times \left(\frac{m_{3/2}}{10keV}\right) \left(\frac{230}{g_*(T^f_{3/2})}\right)$	$\Gamma_M \sim t_d^{-1} \sim H \sim T_d^2$

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

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

⇒ 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 → $Y_{3/2}^{after} = Y_{3/2}^{before} / \Delta_{s_-}$

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

$\Rightarrow$ 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

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

GUT groups: $SU(5)$, $SO(10)$ $\boxed{\pounds}$

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

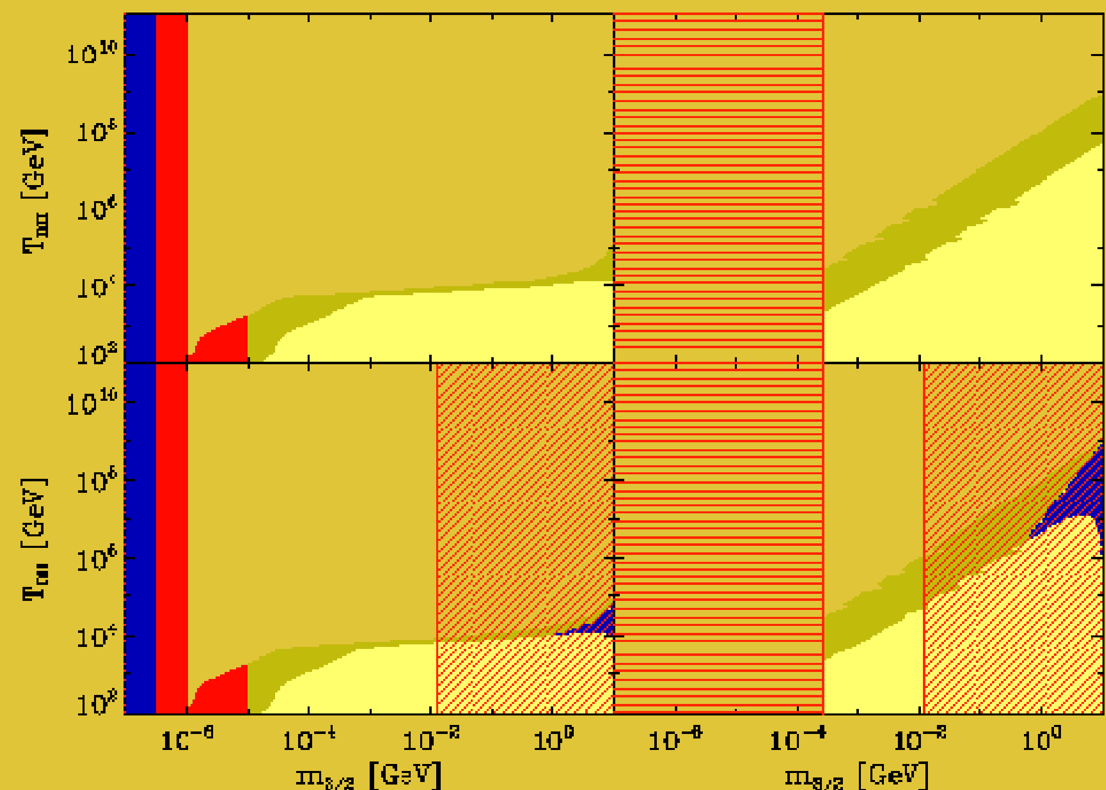
[S. Dimopoulos, G. F. Giudice, A. Pomarol, PLB 389 (1996) 37; T. Hahn, R. Hempfling, hep-ph/9708264]

Gravitino relic density

$SU(5)$

Contours of $\Omega_{3/2}$ in the plane $T_{\rm RH} - m_{3/2}$. $0.01 \leq \Omega_{3/2} \leq 1$ (white: $\Omega_{3/2} > 1$; yellow: $\Omega_{3/2} < 0.01$)

Bino-like NLSP lower panels; stau-like NLSP upper panels. $M_{NLSP} = 150 GeV$
$M_X = 10^5$ GeV left panels; $M_X = 10^{10}$ GeV right panels.



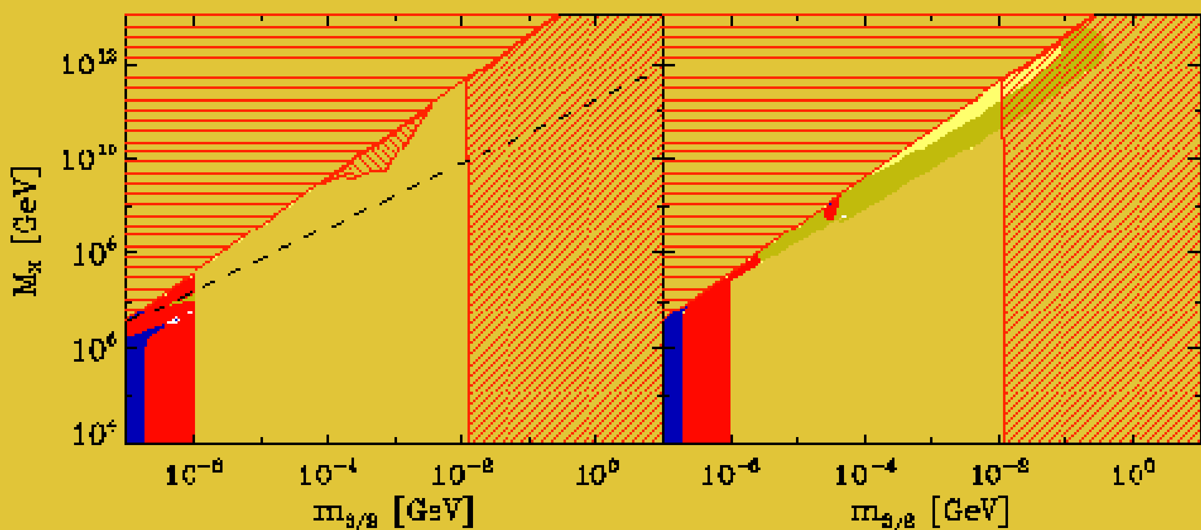
$$W_{\rm ren} \supset \{ \; \bar{\mathbf{5}}_M \bar{\mathbf{5}}_{F,H} \mathbf{10}_F \,,\, \mathbf{5}_M \mathbf{10}_F \mathbf{10}_F \,,\, \mathbf{5}_M \bar{\mathbf{5}}_{F,H} \mathbf{24}_H \,,\, \bar{\mathbf{5}}_M \mathbf{5}_H \mathbf{24}_H \,,\, \overline{\mathbf{10}}_M \mathbf{5}_H \mathbf{5}_H \,,\,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

NO ENTROPY DILUTION

$SU(5)$

$\Omega_{3/2}$ 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.



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

$X \rightarrow l + \lambda$ (Fuji, Yanagida)

BUT other contributions from Supergravity sector and spurion field (depending on its mass) :

$XX \rightarrow \tilde{G}\tilde{G}$, $X \rightarrow \tilde{\nu}\tilde{G}\tilde{G}$

$X \rightarrow S\tilde{\nu}$ (if S lighter than X)

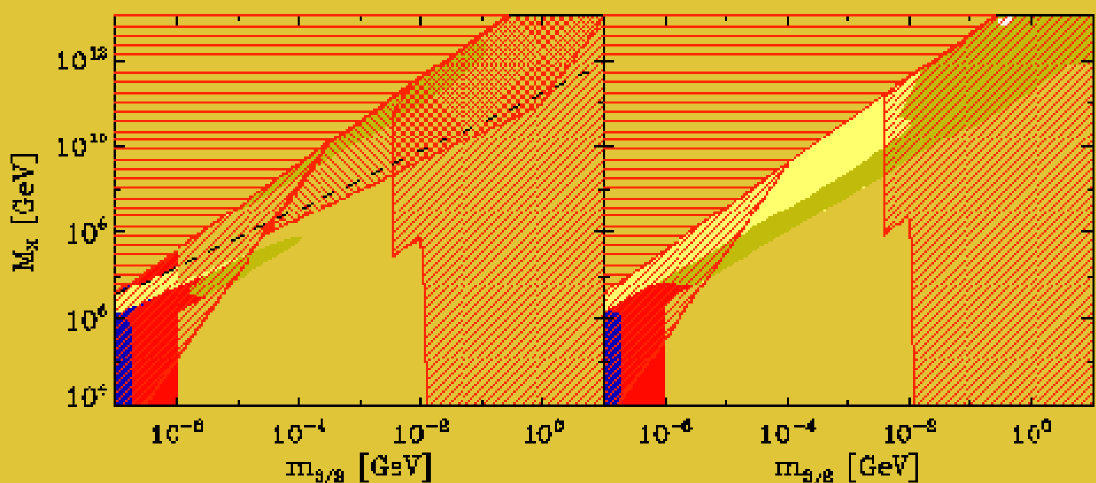
...other possibilities in $SU(5)$

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

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

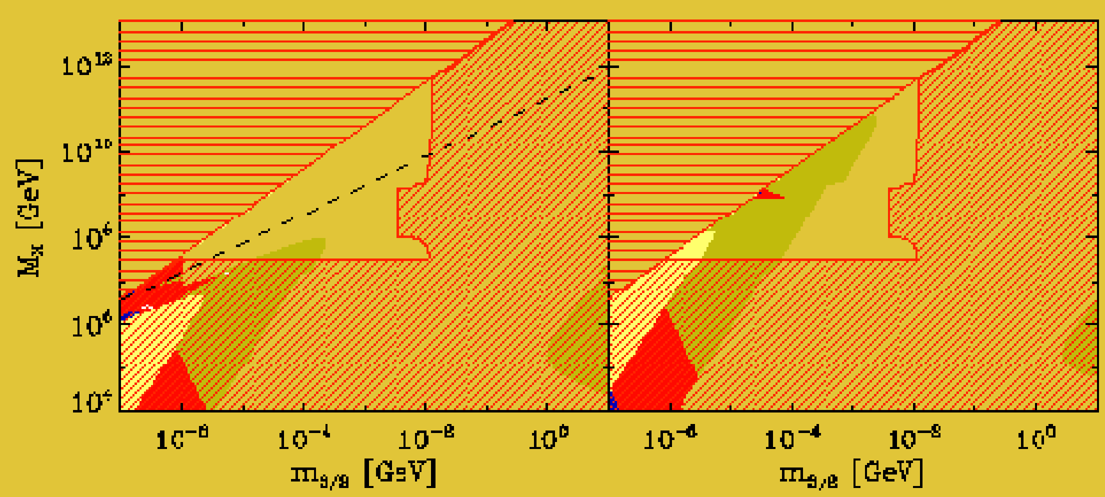
$$K_{\text{non-hol}} \supset \frac{1}{m_{\text{Pl}}}\{ \quad \mathbf{5}^\dagger_M\bar{\mathbf{5}}_{H,F}\mathbf{10}_F\,,\ \bar{\mathbf{5}}_M\mathbf{5}^\dagger_H\mathbf{10}_F\,,\ \bar{\mathbf{5}}^\dagger_M\mathbf{10}_F\mathbf{10}_F\,,$$
$$\mathbf{5}^\dagger_M\mathbf{5}_H\mathbf{24}_H\,,\ \mathbf{5}_M\mathbf{5}^\dagger_H\mathbf{24}_H\,,\ \bar{\mathbf{5}}_M\bar{\mathbf{5}}^\dagger_{H,F}\mathbf{24}_H\,,$$
$$\bar{\mathbf{5}}^\dagger_M\bar{\mathbf{5}}_{H,F}\mathbf{24}_H\,,\ \mathbf{10}^\dagger_M\mathbf{5}_H\mathbf{5}_H\,,\ \overline{\mathbf{10}}_M\bar{\mathbf{5}}^\dagger_{H,F}\mathbf{5}_H\,,$$
$$\overline{\mathbf{10}}^\dagger_M\bar{\mathbf{5}}_{H,F}\bar{\mathbf{5}}_{H,F}\,,\ \overline{\mathbf{10}}^\dagger_M\mathbf{10}_F\mathbf{5}_H\,,\ \mathbf{10}_M\mathbf{10}_F\bar{\mathbf{5}}^\dagger_H$$
$$\mathbf{10}^\dagger_M\mathbf{10}_F\mathbf{24}_H\,,\ \mathbf{10}_M\mathbf{10}^\dagger_F\mathbf{24}_H\,,\ +\text{h.c.}\}$$

$SU(5)$



Contours of $\Omega_{3/2}$ in the plane $M_X - m_{3/2}$ for one pair of messengers sitting in $\mathbf{5}+\overline{\mathbf{5}}$ representations; the lightest messenger X decays into two goldstinos and one sfermion or one sfermion and one gaugino via the mixing term $\sim X\phi_1(M_{\mathsf{GUT}}/m_{\mathsf{Pl}})$ in the Kähler function. The red NE-SW dashed area in the left part of the figure results from big-bang nucleosynthesis constraints on lightest messenger decay and the NW-SE area is forbidden by the contribution of gravitinos to the energy density at BBN.

$SU(5)$

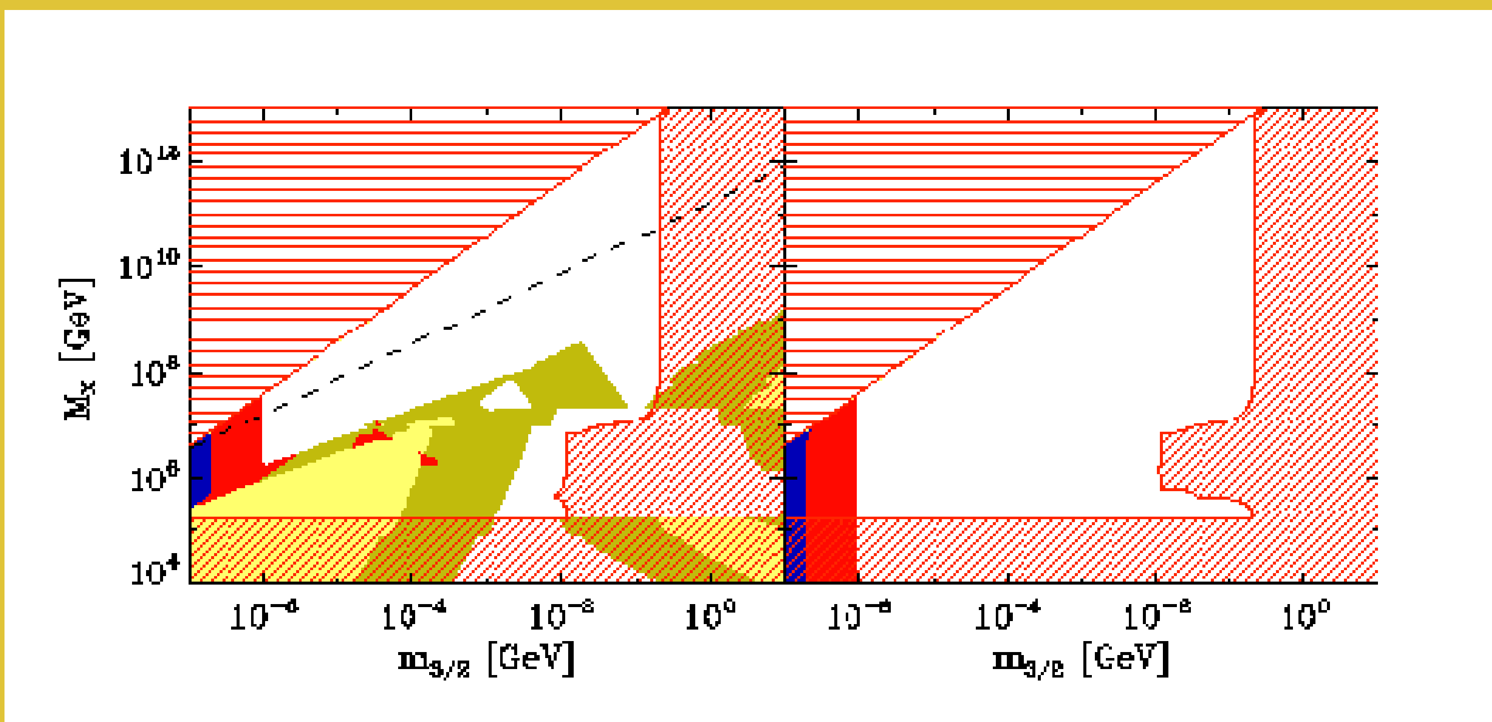


Contours of $\Omega_{3/2}$ in the plane $M_X - m_{3/2}$ for one pair of messengers sitting in $\mathbf{5} + \overline{\mathbf{5}}$, but for decay width $\Gamma \sim 10^{-10} M_X^3 / m_{\text{Pl}}^2$.

$SO(10)$

$\Rightarrow$ 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 $(\alpha/4\pi)^4/M_X^2$, and it decays into sparticles through non-renormalizable operators with width $\Gamma \sim 10^{-3} M_X^3/m_{\rm Pl}^2$.

Concluding remarks $\boxed{\pounds}$

- 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.

...an experimental direct hint for such dark matter can come only from the colliders!