

Very light gravitino dark matter^{*†}

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Physics @ LHC, Cracow Jul. 3-8 '06

^{*}based on [arXiv:hep-ph/0504021](#), [PLB](#), [arXiv:hep-ph/0506129](#),
[Phys.Rev.D73:043514,2006](#) & [arXiv:hep-ph/0508141](#), [JCAP](#)

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Outline



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- Introductory motivations

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- Concluding remarks

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An opportunity for the LHC:

→ missing E_T events → who is the LSP?

... Neutralino?... Axino? ... Gravitino?...Other...ino?

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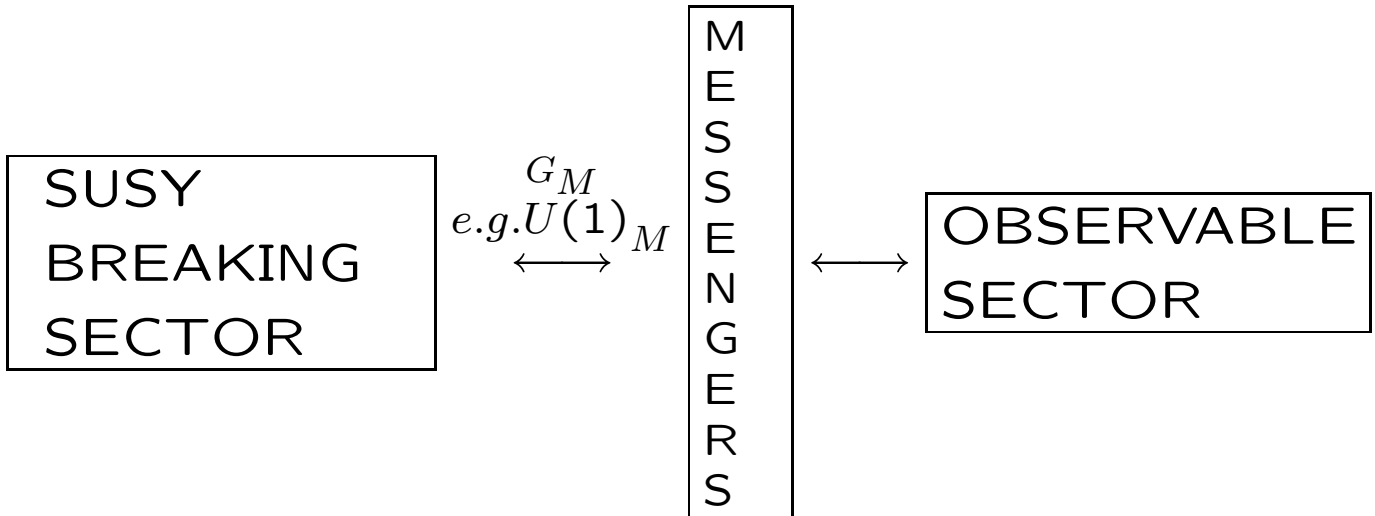
→ missing E_T events → who is the LSP?

... Neutralino?... Axino? ... Gravitino?...Other...ino?

in this talk:

→ Gravitino with mass $m_{3/2} \sim O(1)keV \rightarrow O(1)GeV$

Gauge Mediated Susy Breaking □



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

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. $5 + \bar{5}$ or $10 + \bar{10}$ of $SU(5)_{GUT}$
 $16 + \bar{16}$ of $SO(10)_{GUT}$

ϕ_i messengers: charged under G_M

SUSY Breaking $\Rightarrow \langle F_S \rangle \neq 0$, also $\langle S \rangle \neq 0$

$$M_{s_{\pm}} = M_X \left(1 \pm \frac{\langle F_S \rangle}{M_X^2}\right)^{1/2}, \quad M_f = \kappa \langle S \rangle \equiv M_X$$

$$\Rightarrow \psi_S = \frac{\langle F_S \rangle}{\langle F \rangle} \tilde{G} + \dots$$

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

$$\Rightarrow m_{1/2} \sim \left(\frac{\alpha}{4\pi}\right) \frac{\langle F_S \rangle}{M_X}, \quad m_0^2 \sim \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{\langle F_S \rangle}{M_X}\right)^2$$

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

\Rightarrow very light gravitino

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

Coupling to Supergravity \square

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

$$W \rightarrow W + \langle W \rangle, \quad \langle W \rangle = \frac{1}{\sqrt{3}} \langle F \rangle \times m_{Pl} \simeq m_{3/2} m_{Pl}^2$$



\mathbb{R} -Symmetry



Cosmological Cte $\simeq 0$

holomorphic part:

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

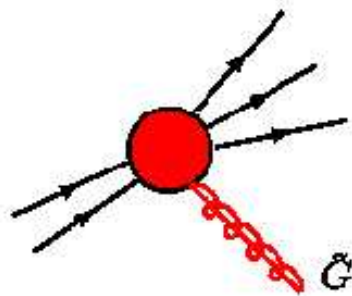
Kähler, super-Weyl trans. $K \rightarrow K + f(\phi) + f^*(\phi^*)$

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

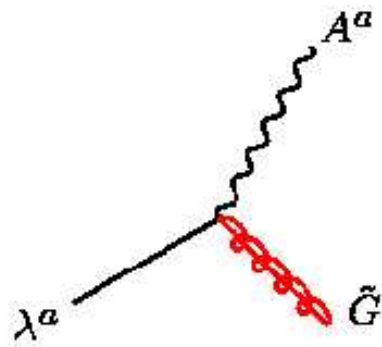
e.g. $K_{ren} \supset \mathbf{5}_M \bar{\mathbf{5}}_F \rightarrow W \supset m_{3/2} \mathbf{5}_M \bar{\mathbf{5}}_F$

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

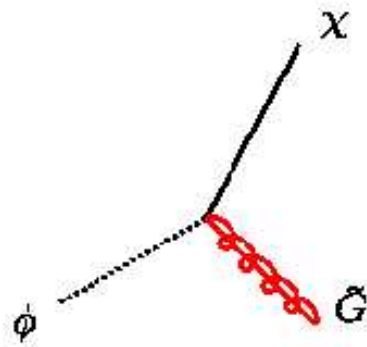
$$E \gg m_{3/2}$$



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

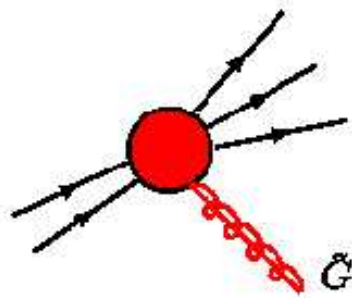


$$\sim \frac{m_\lambda}{m_{3/2} m_{Pl}} \times \partial$$

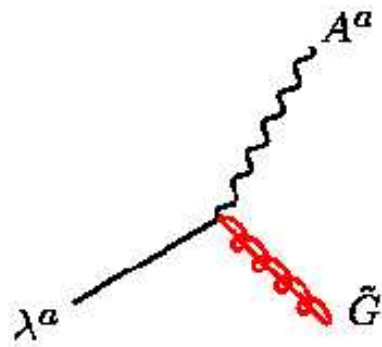


$$\sim \frac{m_\chi^2 - m_\phi^2}{m_{3/2} m_{Pl}}$$

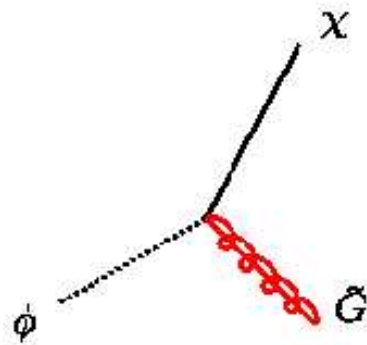
$$E \gg m_{3/2}$$



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



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



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

However...there is much more to it!

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

\Rightarrow Consider the full Supergravity Lagrangian

Gravitino Problem – Messenger Solution □

Gravitino Problem

$$T_{RH} \gtrsim T_{3/2}^f$$

$$\langle \sigma v \rangle \simeq \frac{g_3^2 m_{gluino}^2}{m_{3/2} m_{Pl}^2}$$

$$\rightarrow \langle \sigma v \rangle n_{rad} \lesssim H$$

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

$m_{3/2} \ll T_{3/2}^f$ relativistic at freeze-out

$$\Omega_{3/2} h^2 \simeq 5 \cdot \left(\frac{m_{3/2}}{10\text{keV}} \right) \left(\frac{230}{g_*(T_{3/2}^f)} \right)$$

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

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

Messenger Solution

$$T_{RH} \gtrsim M_{mess}$$

$$\Omega_M h^2 = \frac{s_0 Y_M}{\rho_c} M_{mess}$$

$$Y_M \sim \frac{x_f}{M_{mess} m_{Pl}} \frac{1}{\langle \sigma v \rangle} \frac{1}{g_*^{1/2}}$$

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

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



**THE LMP MUST BE
UNSTABLE**

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

$T_d \stackrel{?}{<} T_{MD} \stackrel{?}{<} T_{3/2}^f \Rightarrow$ 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 $\rightarrow Y_{3/2}^{after} = Y_{3/2}^{before} / \Delta_{s-}$

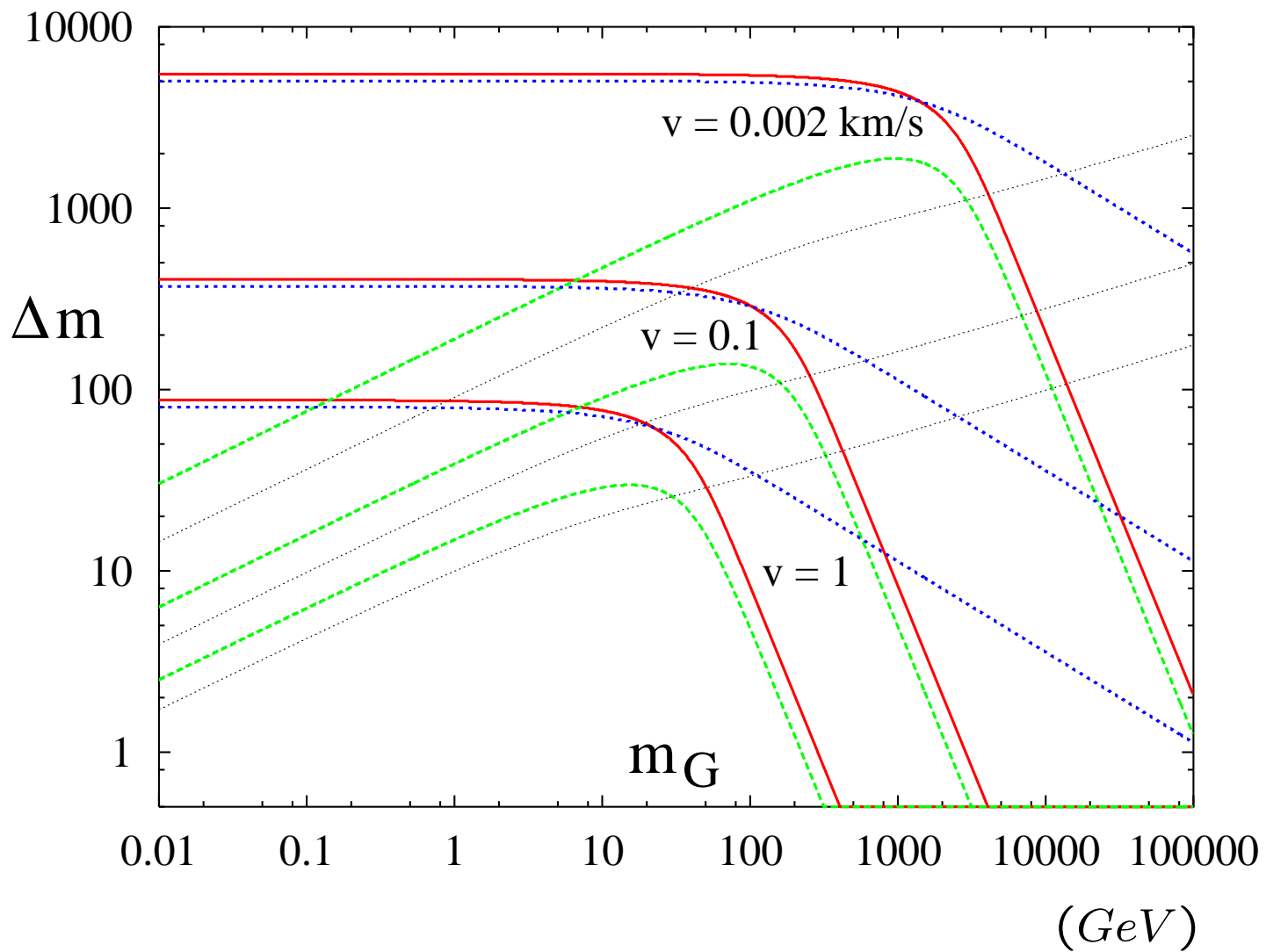
$$\Delta_{s-} \approx 28 \left(\frac{M_{s-}}{10^8 \text{GeV}} \right) \left(\frac{Y_{s-}}{10^{-10}} \right) \left(\frac{\Gamma_{s-}}{10^{-25} \text{GeV}} \right)^{-\frac{1}{2}} \left(\frac{g_{>}}{10} \right)^{\frac{1}{4}}$$

⇒ 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

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

(GeV)



$$\Delta m = m_{\text{NLSP}} - m_{\tilde{G}}$$

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

The lightest messenger scalar is:

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

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

Gravitino relic density \square

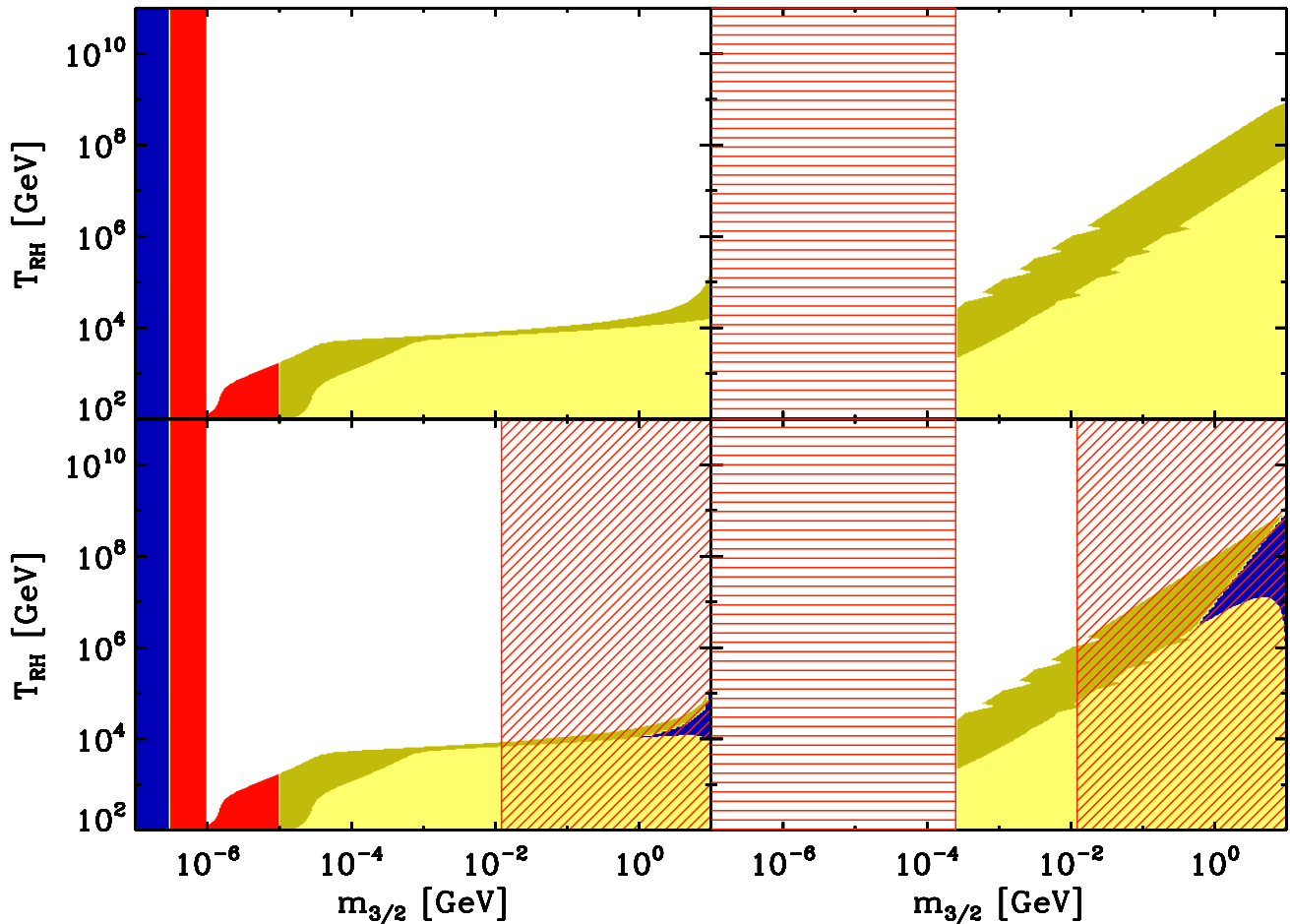
SU(5)

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

Bino-like NLSP lower panels; stau-like NLSP upper panels.

$M_{NLSP} = 150 \text{ GeV}$

$M_X = 10^5 \text{ GeV}$ left panels; $M_X = 10^{10} \text{ GeV}$ right panels.



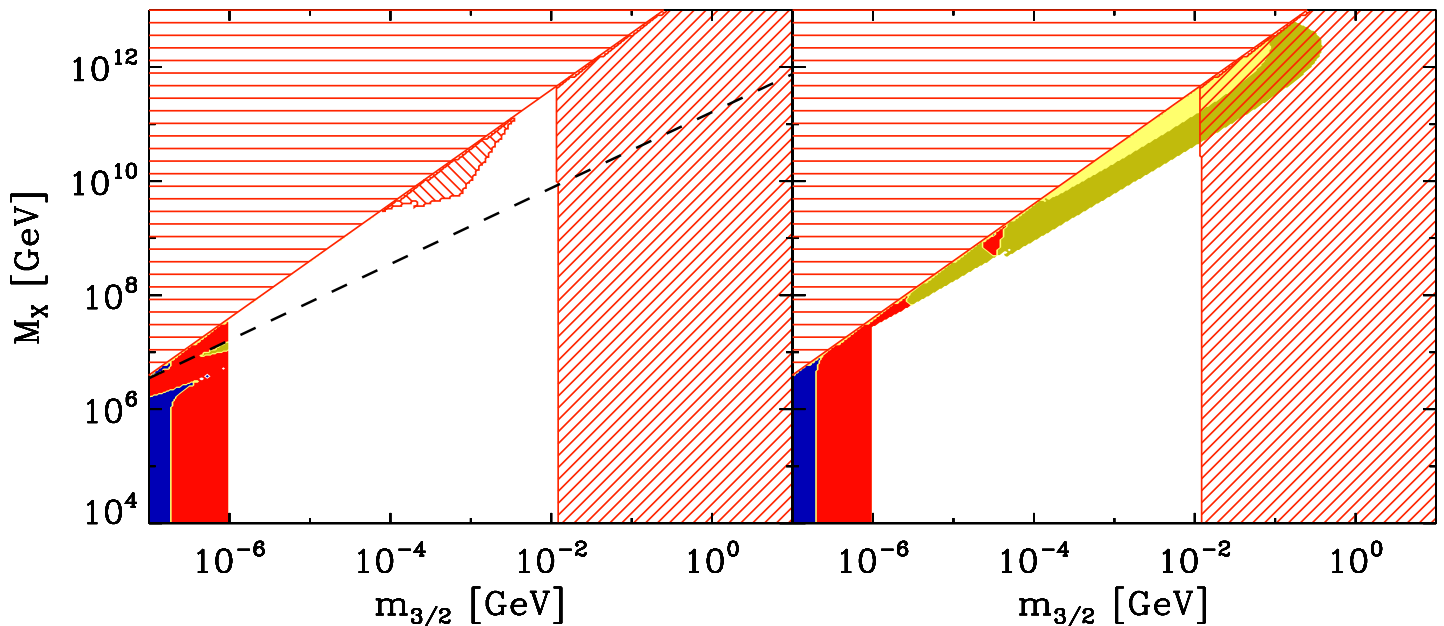
$$W_{\text{ren}} \supset \{ \bar{5}_M \bar{5}_{F,H} 10_F, 5_M 10_F 10_F, 5_M \bar{5}_{F,H} 24_H, \\ \bar{5}_M 5_H 24_H, \bar{10}_M 5_H 5_H, 10_M \bar{5}_{H,F} \bar{5}_{H,F}, \\ 10_M 10_F 5_H, 10_F \bar{10}_M 24_H \}.$$

NO ENTROPY DILUTION

SU(5)

$\Omega_{3/2}$ in the plane $M_X - m_{3/2}$; $T_{RH} = 10^{12} GeV$; one pair of messengers sitting in $5 + \bar{5}$; 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 .



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

$X \rightarrow l + \lambda$ (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)

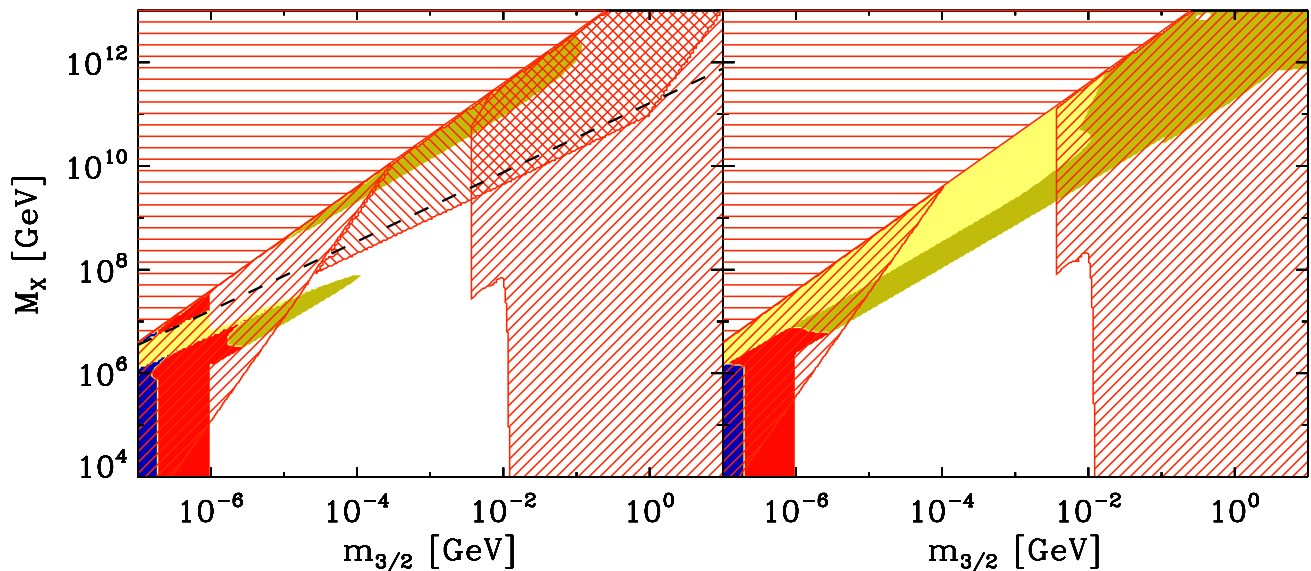
...other possibilities in $SU(5)$

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

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

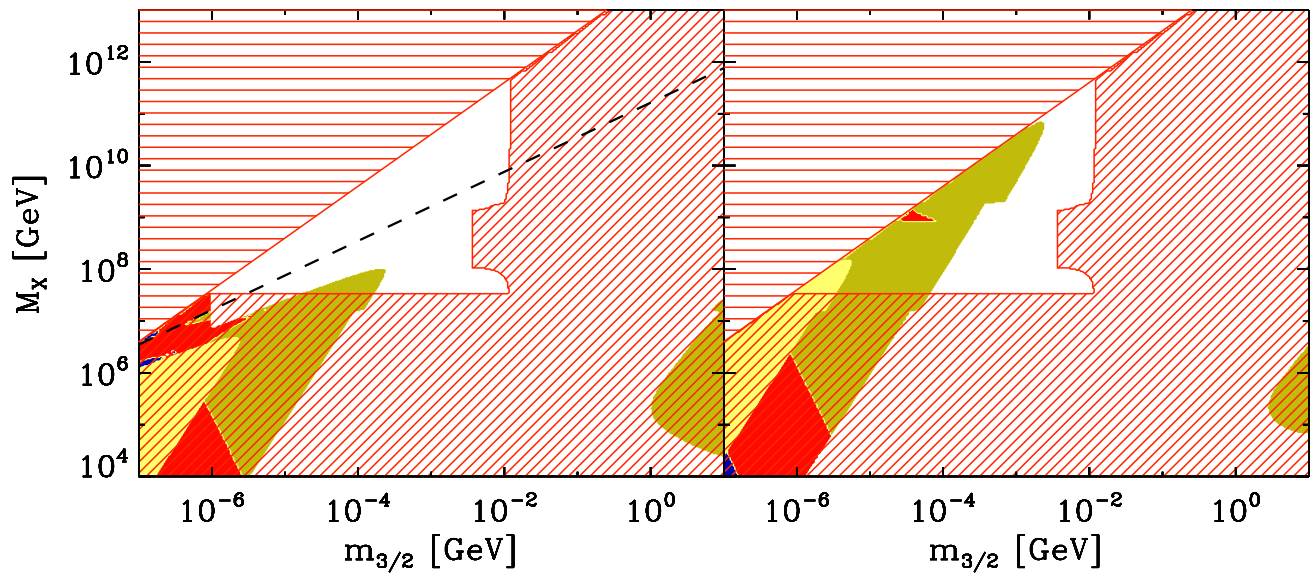
$$K_{\text{non-hol}} \supset \frac{1}{m_{\text{Pl}}} \{ 5_M^\dagger \bar{5}_{H,F} 10_F, \bar{5}_M 5_H^\dagger 10_F, \bar{5}_M^\dagger 10_F 10_F, \\ 5_M^\dagger 5_H 24_H, 5_M 5_H^\dagger 24_H, \bar{5}_M \bar{5}_{H,F}^\dagger 24_H, \\ \bar{5}_M^\dagger \bar{5}_{H,F} 24_H, 10_M^\dagger 5_H 5_H, \bar{10}_M \bar{5}_{H,F}^\dagger 5_H, \\ \bar{10}_M^\dagger \bar{5}_{H,F} \bar{5}_{H,F}, \bar{10}_M^\dagger 10_F 5_H, 10_M 10_F \bar{5}_H^\dagger, \\ 10_M^\dagger 10_F 24_H, 10_M 10_F^\dagger 24_H, + h.c. \}$$

$SU(5)$



Contours of $\Omega_{3/2}$ in the plane $M_X - m_{3/2}$ for one pair of messengers sitting in $\mathbf{5} + \bar{\mathbf{5}}$ representations; the lightest messenger X decays into two goldstinos and one sfermion or one sfermion and one gaugino via the mixing term $\sim X\phi_1(M_{\text{GUT}}/m_{\text{Pl}})$ 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.

$SU(5)$

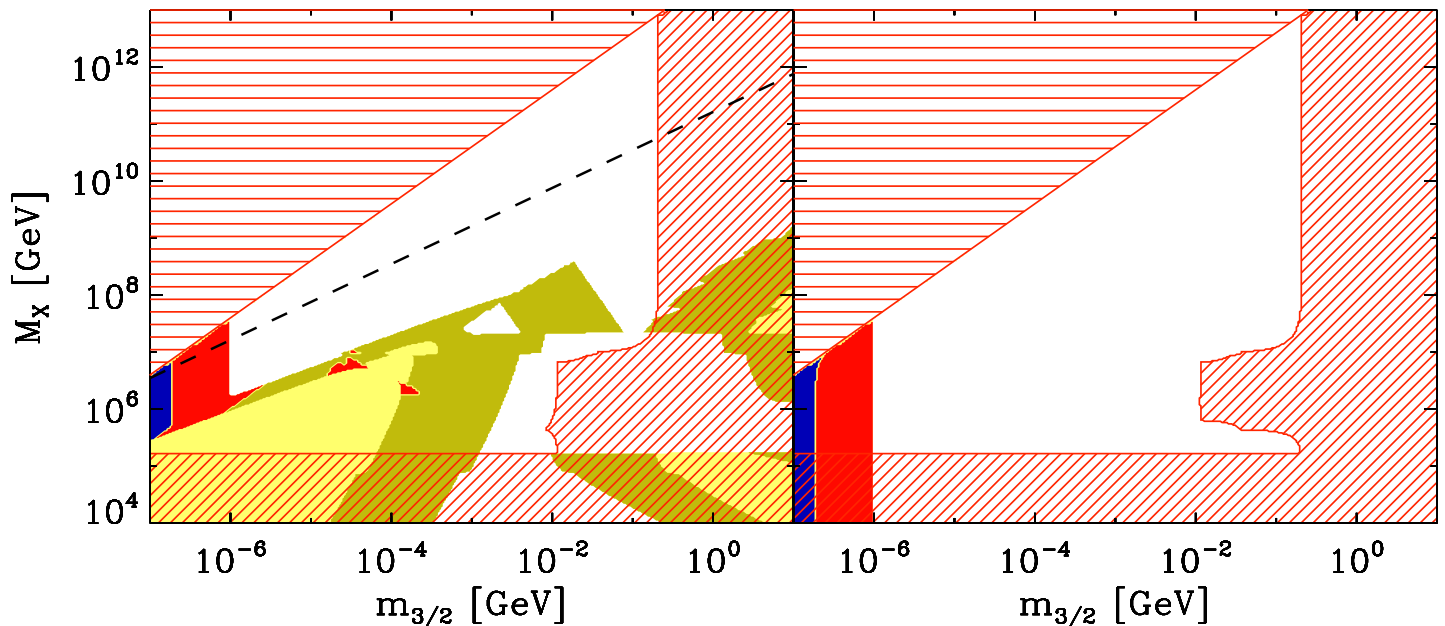


Contours of $\Omega_{3/2}$ in the plane $M_X - m_{3/2}$ for one pair of messengers sitting in $\mathbf{5} + \bar{\mathbf{5}}$, but for decay width $\Gamma \sim 10^{-10} M_X^3 / m_{\text{Pl}}^2$.

$SO(10)$

⇒ 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 $\Gamma \sim 10^{-3}M_X^3/m_{\text{Pl}}^2$.

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

⇒ provides a solution to the gravitino problem **AND** makes the gravitino a viable candidate for cold dark matter.

However, requires extensions of GMSB.

⇒ Generically favours $SO(10)$ over $SU(5)$ GUT groups.

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