Gravitino in the Past and in the Future

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Oct.1, at DESY workshop'04

PLAN

(I) Gravitino in the Past

= **Gravitino Cosmology**

(II) Gravitino in the Future

= **Gravitino in the future colliders**

(I) Gravitino in the Past

= gravitino cosmology

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review

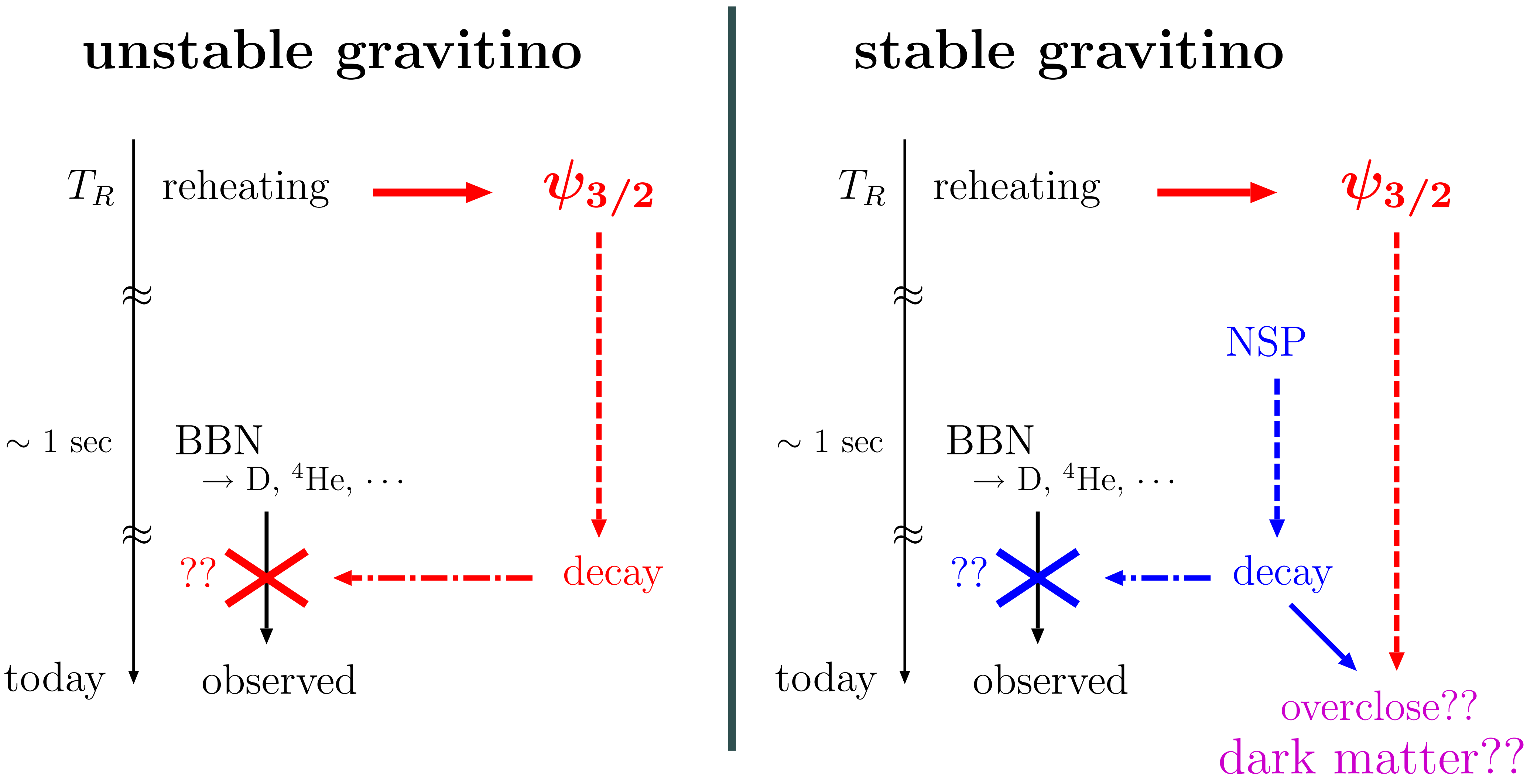
+ **W. Buchmüller, KH, M. Ratz,** hep-ph/0307184, PLB574

+ **W. Buchmüller, KH, O. Lebedev, M. Ratz,** hep-th/0404168

thermal history

time	temperature	
??	~ 0	inflation
??	T_R	reheating
$\approx$		baryogenesis $\rightarrow n_B/s \simeq 10^{-10}$
~ 1 sec	~ 1 MeV	Big Bang Nucleosynthesis $\rightarrow$ D, ^{4}He, $\cdots$
$\approx$		
14 Gyr	2.7 K	observed

thermal history with gravitino $\psi_{3/2}$

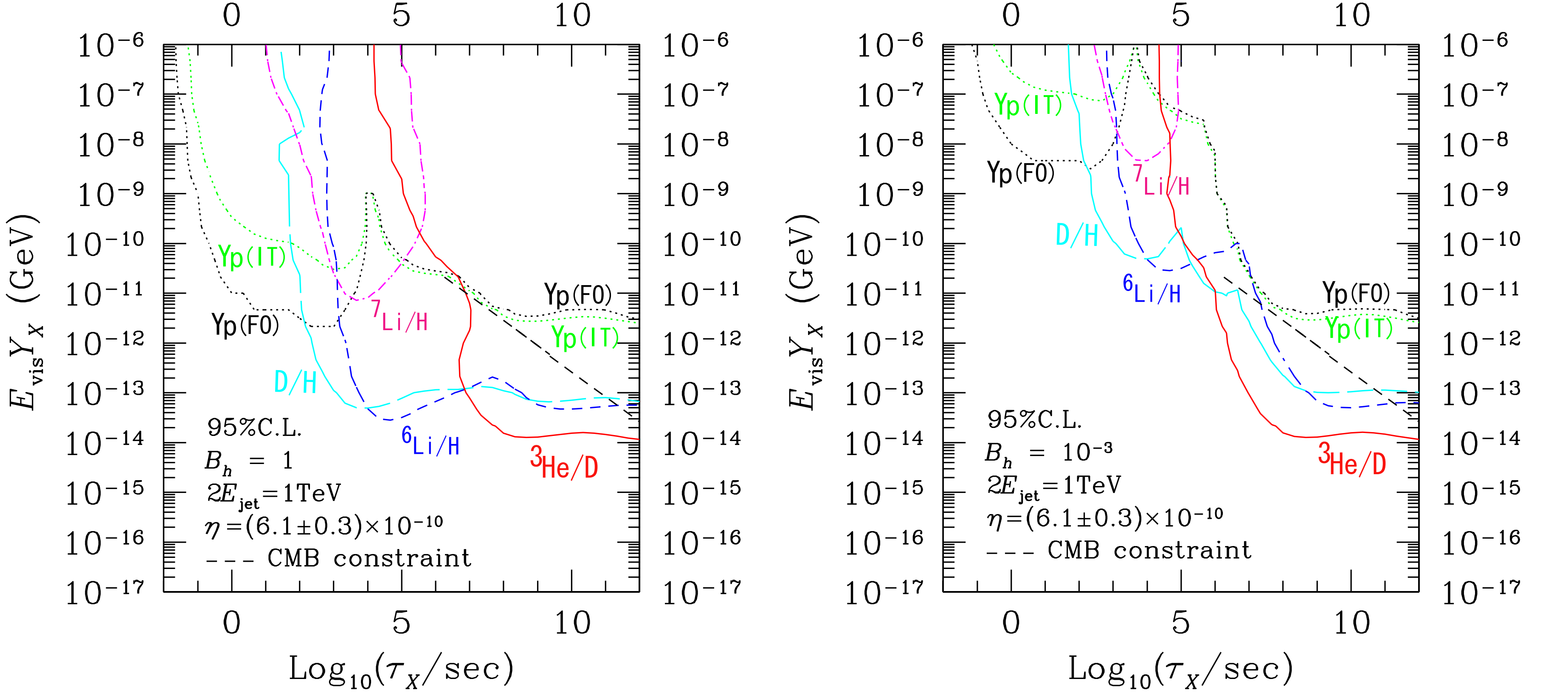


BBN constraints: in general

for a late-decaying particle X $\rightarrow$ **constraints on $(\tau_X, m_X Y_X)$.**

latest detailed analysis including hadronic decay modes:

M. Kawasaki, K. Kohri and T. Moroi, astro-ph/0402490 + 0408426. (cf. K. Jedamzik, astro-ph/0402344)



Br($X \rightarrow$ hadron) = 1 Br($X \rightarrow$ hadron) = 10^{-3}

unstable gravitino

BBN constraints: **late decaying particle $X = \psi_{3/2}$**

$$\boxed{\begin{array}{lcl} m_{3/2}Y_{3/2} & \propto & m_{3/2}T_R \\ \tau_{3/2} & \propto & m_{3/2}{}^{-3} \end{array}} \quad \begin{array}{l} +\mathcal{O}(m_{\tilde{g}}/m_{3/2})^2 + \text{log.corr.} \\ +\mathcal{O}(m_{\text{soft}}/m_{3/2})^2 \end{array}$$

$\longrightarrow$ upper bounds on T_R for a given $m_{3/2}$

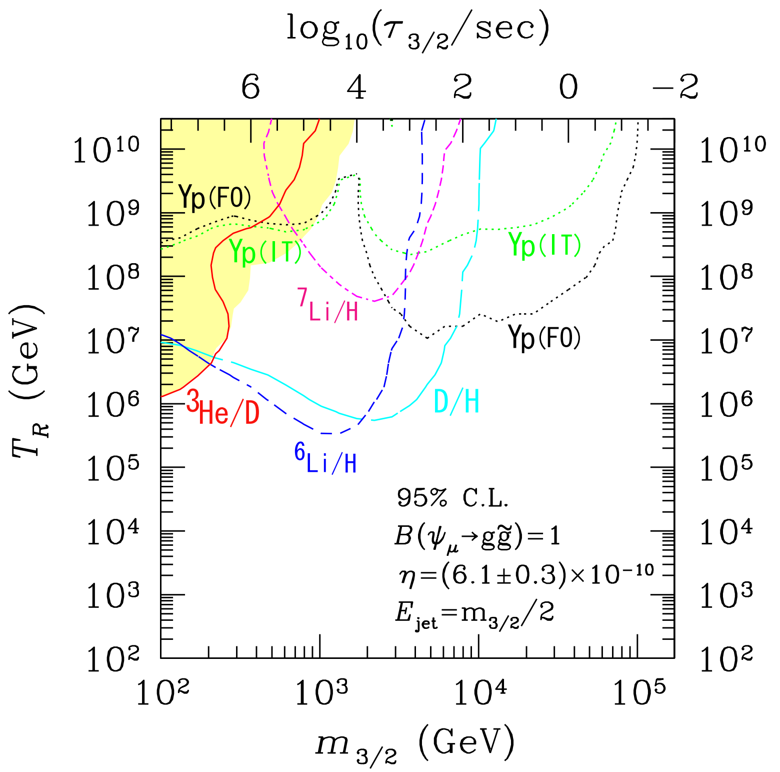


Fig. $Br(\text{gravitino} \to \text{gluino}) = 1$ from Kawasaki et.al. astro-ph/0408426

Solutions

- **very heavy gravitino (anomaly mediation)**

  cf. M.Ibe, R.Kitano, H.Murayama, T.Yanagida, hep-ph/0403198.

- **low scale inflation + baryogenesis**

  e.g. Affleck–Dine, EW baryogenesis, non–thermal/resonant/soft leptogenesis, $\cdots$

- **late-time entropy production**

  e.g. by moduli. but cf. K.Kohri, M.Yamaguchi, J.Yokoyama, hep-ph/0403043.

- **decays only into harmless particle**

  e.g. into axion and axino, T.Asaka, T.Yanagida, PLB**494**('00)

- $\cdots\cdots$

stable gravitino: NSP decay into gravitino

BBN constraints: **late decaying particle X = NSP**

$$\boxed{\begin{array}{lll} m_{\rm NSP} Y_{\rm NSP} & \propto & {m_{\rm NSP}}^2 \\ \tau_{\rm NSP} & \propto & {m_{3/2}}^2\, {m_{\rm NSP}}^{-5} \end{array}}$$

(roughly) $+\mathcal{O}(m_{3/2}/m_{\rm NSP})^2$ $\longrightarrow$

constraints on
$$(\, m_{3/2}\, , m_{\rm NSP}\,)$$

relic gravitino abundance (from NSP decay):

$$\boxed{\Omega_{3/2} \;\propto\; m_{3/2}\, m_{\rm NSP}}$$

(roughly)

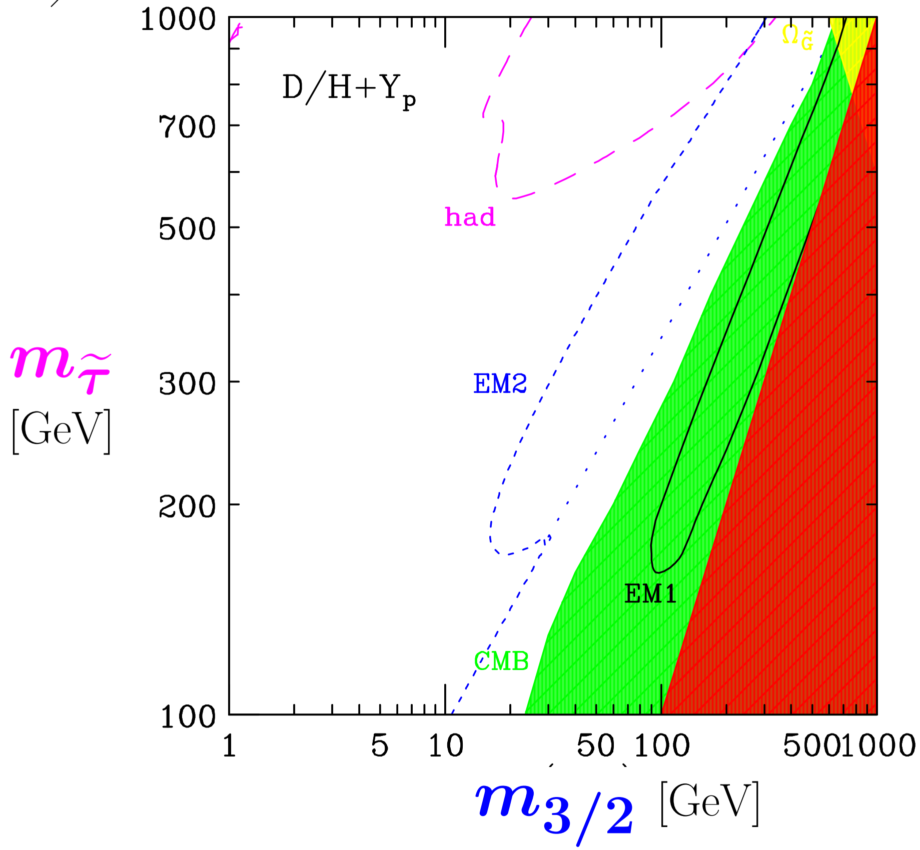
latest detailed analysis including

- **hadronic decay modes in 3-body decays**
- the CMB constraint

J. L. Feng, S. Su, F. Takayama, hep-ph/0404231.

e.g., for NSP = $\widetilde{\tau}$, $\longrightarrow$

(^{6}Li and ^{3}He not included here)



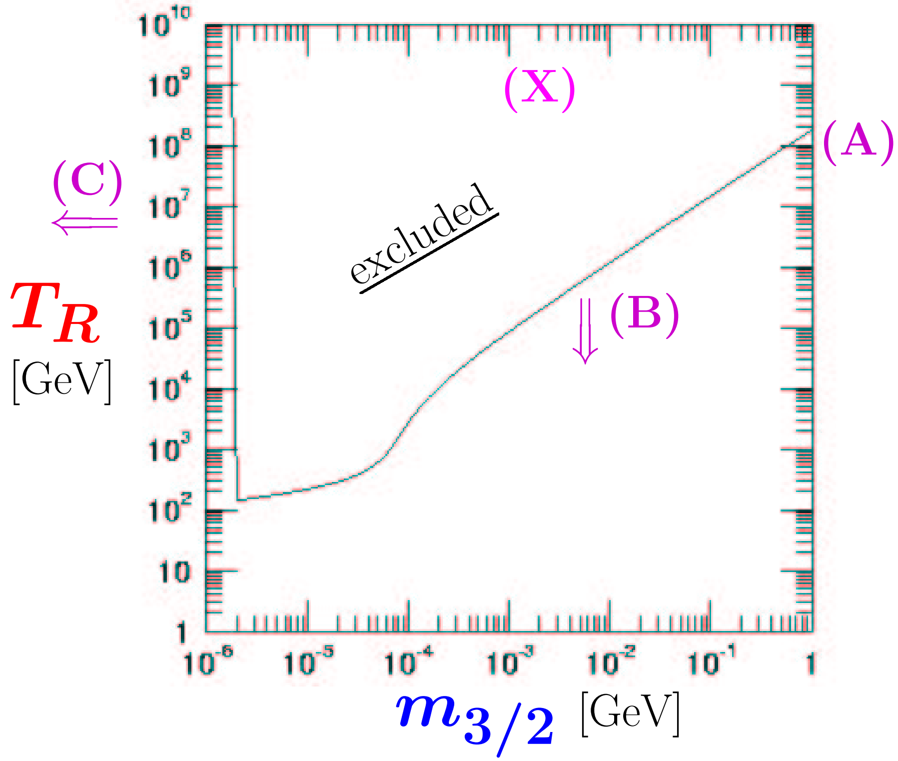
stable gravitino: thermal relic

relic gravitino abundance (thermal):

$$\boxed{\Omega_{3/2} \propto \frac{T_R}{m_{3/2}}} \quad + \mathcal{O}\left(\frac{m_{3/2}}{m_{\tilde{g}}}\right)^2$$

$\longrightarrow$ upper bounds on T_R for a given $m_{3/2}$

(↘ Fig. from A.de Gouvea, T.Moroi, H.Murayama, PRD**56**('97).)
(See latest calculation, M. Bolz, A. Brandenburg, W. Buchmüller, NPB**606**, 518 ('01).)



Solutions

- **(A)** $m_{3/2} \sim 10 - 100$ GeV, $T_R \sim 10^9 - 10^{10}$ GeV.
- **(B) low scale inflation + baryogenesis**
- **(C) very light gravitino**
- **late-time entropy production**

  cf. M.Fujii, T.Yanagida, PLB**549**('02); + M.Ibe, PRD**69**('04)
- $F_{\rm mess}/F_{\rm total} \lesssim 10^{-9}$ **and** $m_{3/2} \gtrsim 1$ **GeV in GMSB**

  K.Choi, K.Hwang, H.B.Kim, T.Lee, PLB**467**('99)
- ......

(X) vanishing gauge coupling at high T

W.Buchmüller, K.Hamaguchi, M.Ratz, PLB**574**('03)

gauge coupling at high T and gravitino abundance

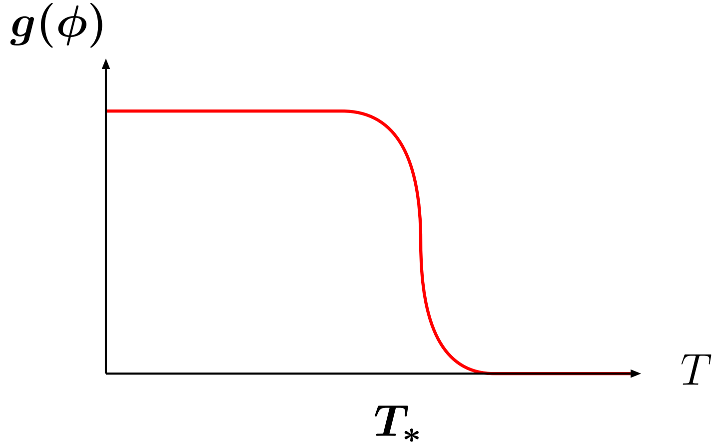
W.Buchmüller, KH, M.Ratz, PLB**574**('03)

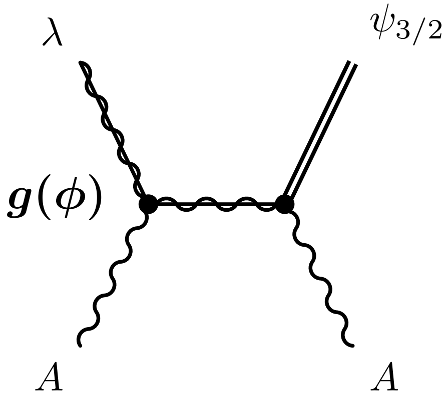
If gauge coupling $g = g(\phi)$, $\cdots$

$V(\phi) \xrightarrow{T>0} V(\phi) + a_2\, g^2(\phi) T^4$ (cf. W.Buchmüller, KH, O.Lebedev, M.Ratz, hep-th/0404168)

$\Longrightarrow$ ϕ is shifted

$\Longrightarrow$ **$g(\phi)$ decreases at high T.**





gravitino production **suppressed at $T > T_*$** !!

gauge coupling at high T and gravitino abundance

W.Buchmüller, K.Hamaguchi, M.Ratz, PLB**574**('03)

For a simple set-up

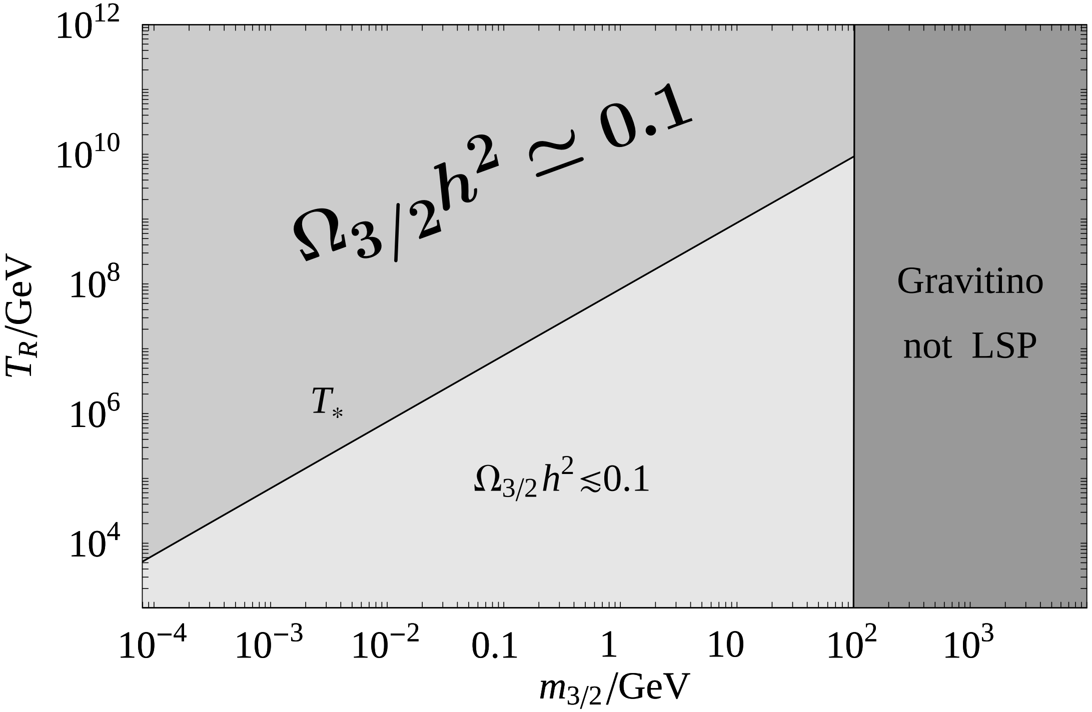
$$\mathcal{L} = \frac{1}{4}\int d^2\theta \left(\frac{1}{g_0^2} + \frac{\phi}{M}\right) \mathcal{W}_\alpha \mathcal{W}^\alpha \quad \Longrightarrow \quad \frac{1}{g_0^2} + \frac{\phi}{M} = \frac{1}{g^2(\phi)}, \quad m_{\tilde{g}} = g^2 \frac{F_\phi}{2M} \quad \Longrightarrow \quad T_* \sim m_{3/2}\left(\frac{M_{\rm P}}{m_{\tilde{g}}}\right)^{1/2}$$

$$\Downarrow$$

$$\boxed{\Omega_{3/2}h^2 \simeq 0.1 \left(\frac{m_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^{3/2} \left(\frac{\xi}{\eta^2}\right)^{1/4}}$$

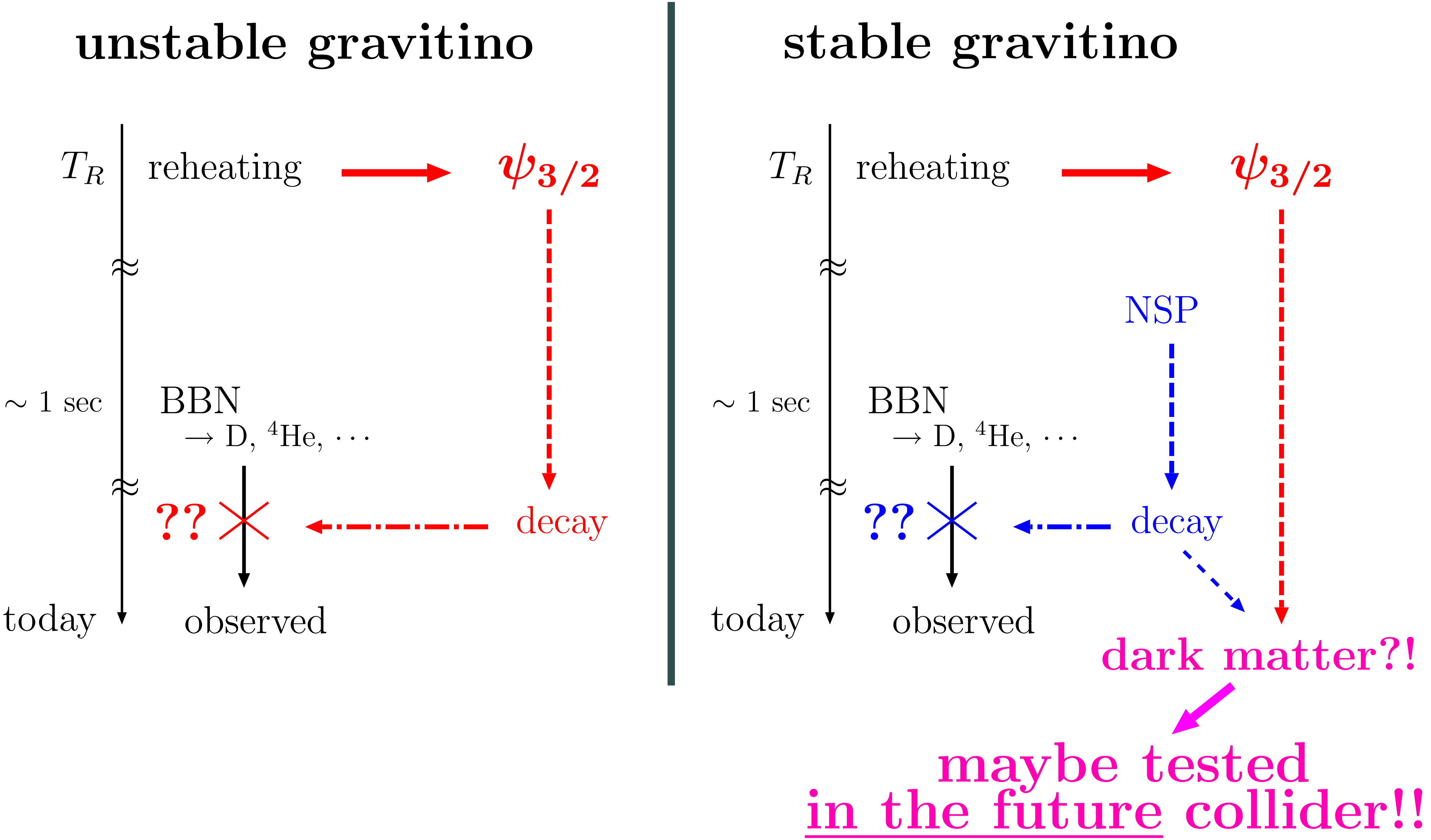
$$\xi = \frac{m_\phi^2}{m_{3/2}^2} \sim \mathcal{O}(1)\,,\ \eta = \frac{F_{\rm total}}{\sqrt{3}F_\phi} \sim \mathcal{O}(1)\,.$$

without any fine-tuning!!



But $\cdots$, moduli problem associated with ϕ field $\longrightarrow$ UNDER DISCUSSION

Gravitino in the Past: Summary



(II) Gravitino in the Future

= gravitino in the future colliders

based on .....

W. Buchmüller, KH, M. Ratz, Yanagida
hep-ph/0402179; PLB588 + hep-ph/0403203.

+ **KH, Y. Kuno, T. Nakaya, M. M. Nojiri** hep-ph/0409248.

▨ MOTIVATION:

Can we prove
the existence of supergravity
in nature?

■ CONCLUSION :

Can we prove the existence of supergravity in nature ?

Yes!!

if .....

• What would prove the supergravity?

Standard Model

||

spontaneously broken
local (gauge) symmetry

$\Downarrow$ Higgs mechanism

massive gauge (spin-1) bosons

Z & $W^{\pm}$

..... discovered in 1983.

• What would prove the supergravity ?

Standard Model

=

spontaneously broken local symmetry.

$\Downarrow$ Higgs mechanism

massive gauge (spin-1) bosons

Z & $W^{\pm}$

..... discovered in 1983

Supergravity

=

spontaneously broken local supersymmetry

$\Downarrow$ super-Higgs mechanism

massive spin-$3/2$ fermion

gravitino $\psi_{3/2}$

..... needs to be discovered!

We consider a scenario where .....

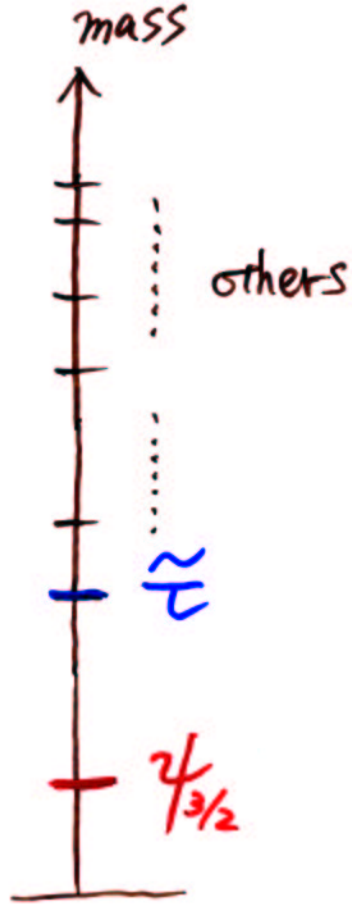
■ LSP (lightest SUSY particle) = gravitino $\psi_{3/2}$

$\longrightarrow$ stable

■ NSP (next-to-lightest SUSY particle) = charged slepton $\tilde{\tau}$

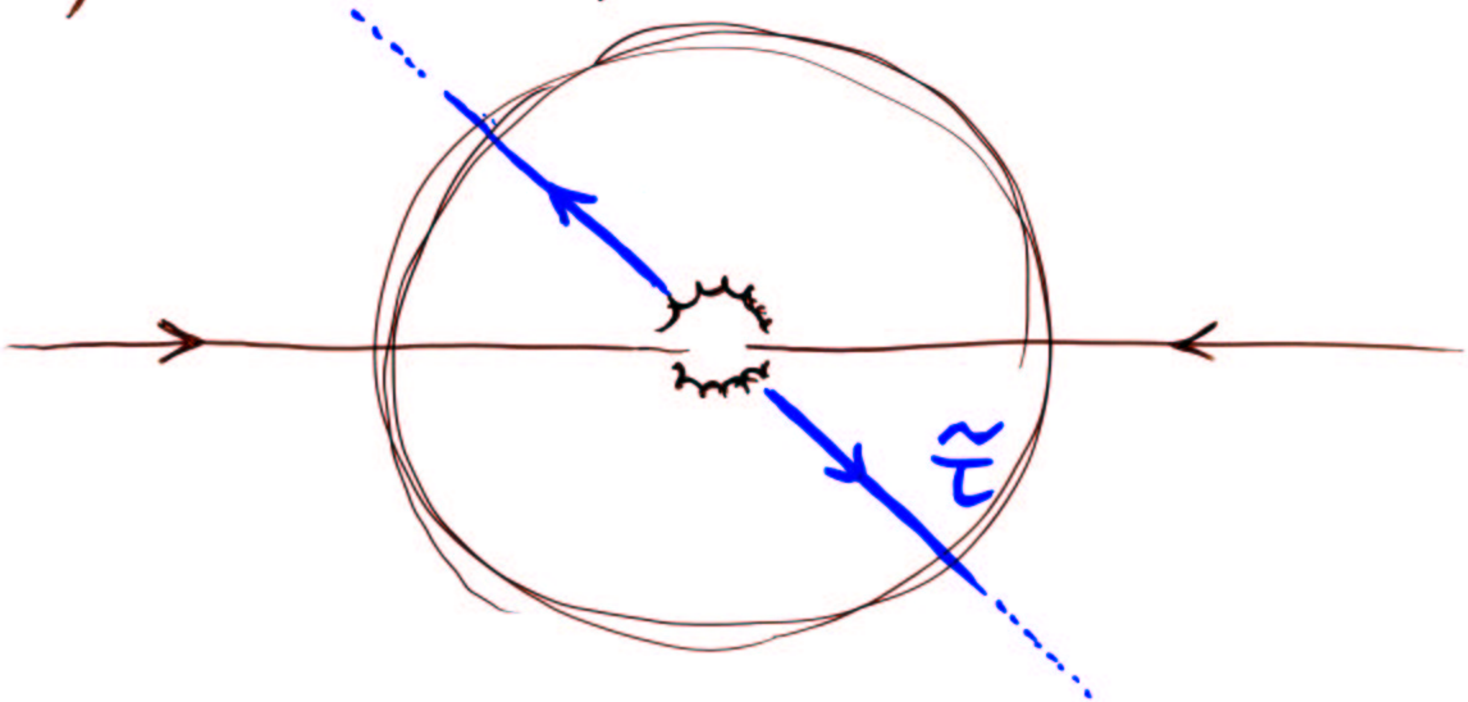
$\longrightarrow$ long-lived

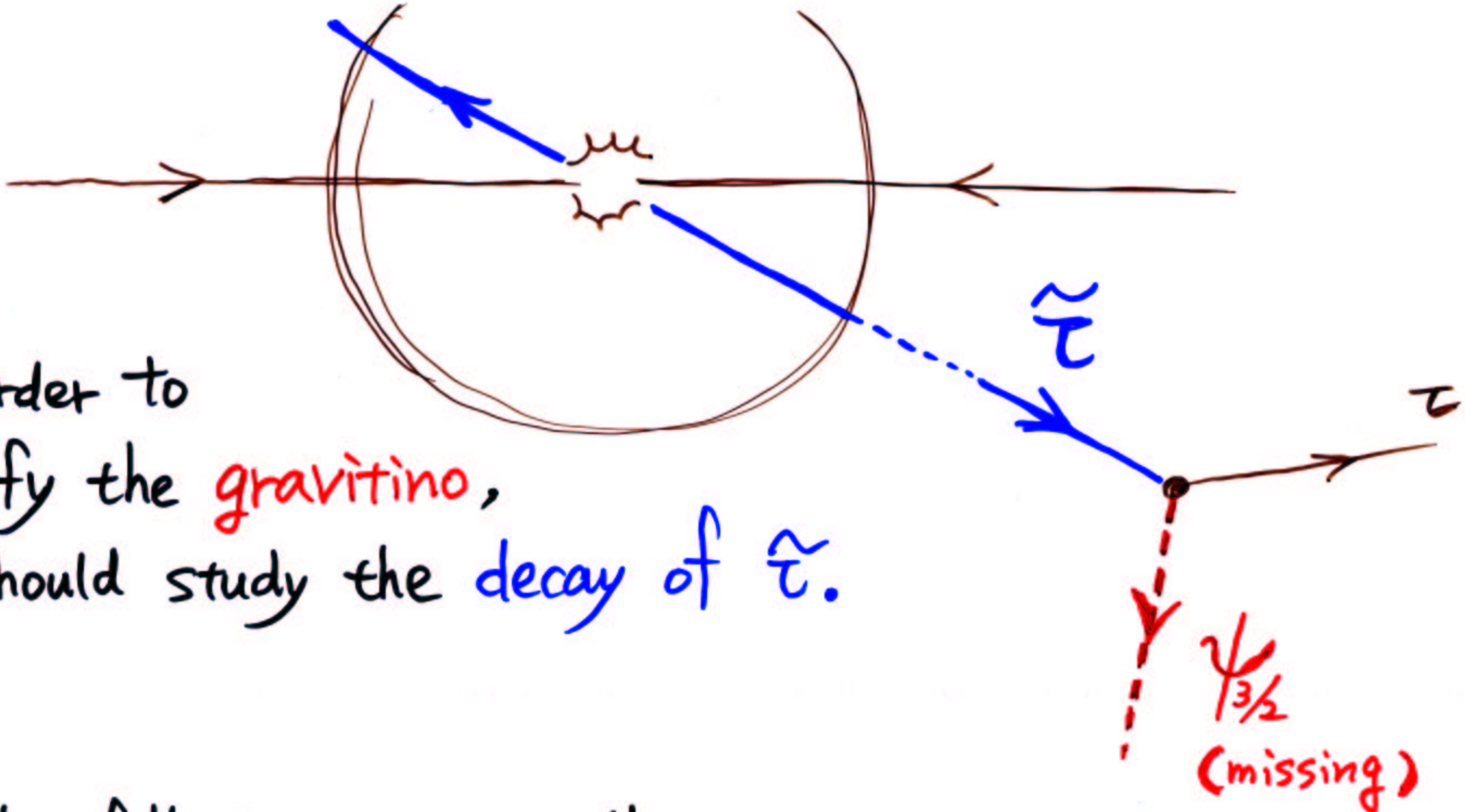
$$\left(\Gamma(\tilde{\tau} \to \tau + \psi_{3/2})^{-1} \simeq 9\,\text{days} \left(\frac{m_{3/2}}{10\,\text{GeV}}\right)^2 \left(\frac{150\,\text{GeV}}{m_{\tilde{\tau}}}\right)^5 \right)$$



At colliders, many (up to $10^5 \sim 10^6$) $\tilde{\tau}$s will be produced, and they look completely stable. (unless $m_{3/2} \ll 10$ keV)

(Tevatron
LHC
LC
⋮)





In order to identify the gravitino, one should study the decay of $\tilde{\tau}$.

In the following, we will .....

— assume that many $\tilde{\tau}$s are produced and somehow collected, → **See very recent works**

KH, Y.Kuno, T.Nakaya, M.M.Nojiri hep-ph/0409248

J.L.Feng, B.T.Smith hep-ph/0409278

— and study the decay of $\tilde{\tau}$.

Method ①

Measurement of the Planck scale M_P.

microscopic

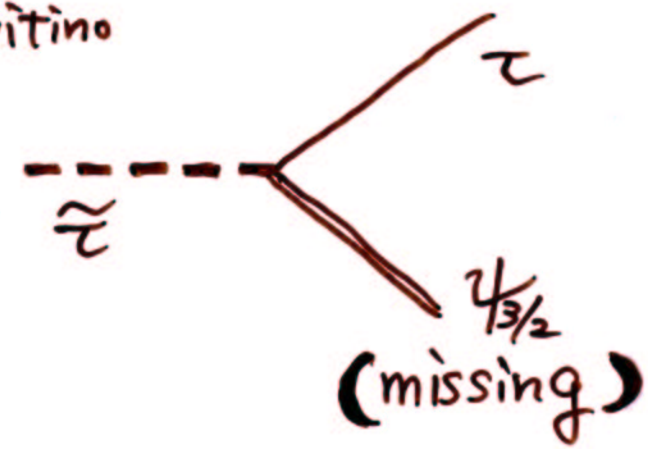
(W. Buchmüller, K.H., M. Ratz, T. Yanagida
hep-ph/0402179 (PLB 588))

slepton

lepton

$$\mathcal{L}_{\text{supergravity}} \supset \frac{-1}{\sqrt{2}\, M_P}\, \partial_\nu \tilde{\tau}_R^{*}\, \psi^\mu \gamma^\nu \gamma_\mu P_R \tau + \text{h.c.} + \cdots$$

gravitino



$$\Gamma_{\tilde\tau} = \Gamma_{\tilde\tau}(\tilde\tau \to \tau + \psi_{3/2}) = \frac{m_{\tilde\tau}^5}{48\pi m_{3/2}^2 M_P^2}\left(1 - \frac{m_{3/2}^2}{m_{\tilde\tau}^2}\right)^4$$

prediction of supergravity

$$\Longleftrightarrow \quad \boxed{M_P^2(\text{supergravity}) = \frac{1}{48\pi}\,\frac{1}{\Gamma_{\tilde\tau}}\,\frac{m_{\tilde\tau}^5}{m_{3/2}^2}\left(1 - \frac{m_{3/2}^2}{m_{\tilde\tau}^2}\right)^4}$$

will be measured

can be "measured" by kinematics

$$\left(m_{3/2}^2 = m_{\tilde\tau}^2 - m_\tau^2 - 2 m_{\tilde\tau} E_\tau \qquad \tau \longleftarrow \overset{\tilde\tau}{\bullet} \dashrightarrow \psi_{3/2} \right)$$

consistency check !!

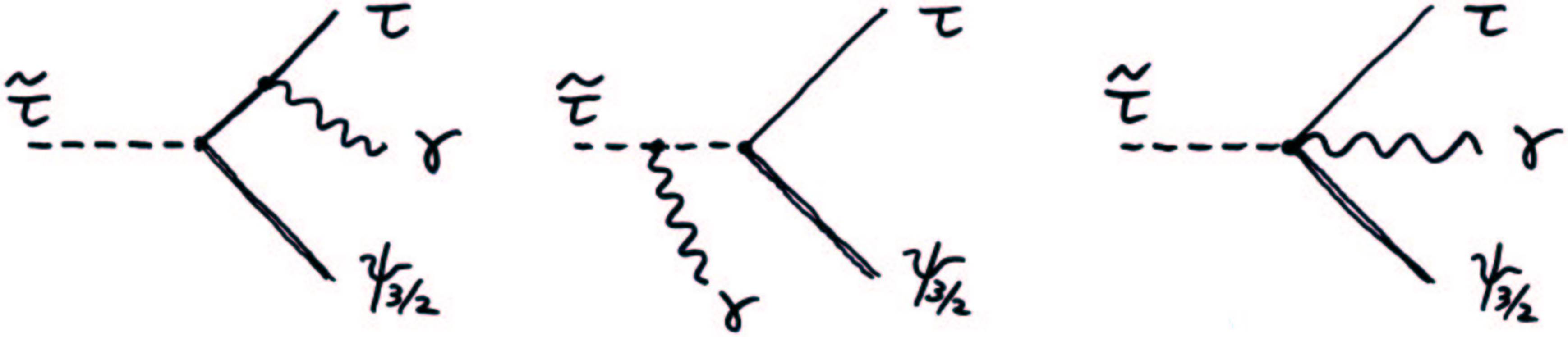
$$\boxed{M_P^2(\text{gravity}) = (8\pi G_N)^{-1} = (2.44 \times 10^{18}\,\text{GeV})^2}$$

Newton const

Method ②

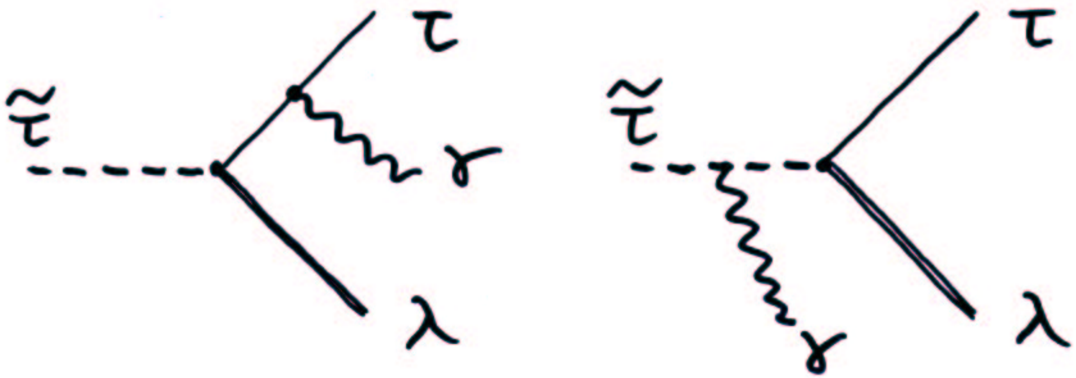
Test of particular gravitino couplings by 3-body decay

$$\mathcal{L} = \frac{-1}{\sqrt{2}M_P}(\partial_\nu + ieA_\nu)\tilde{\tau}_R^* \bar{\Psi}^\mu \gamma^\nu \gamma_\mu P_R \tau + \cdots$$

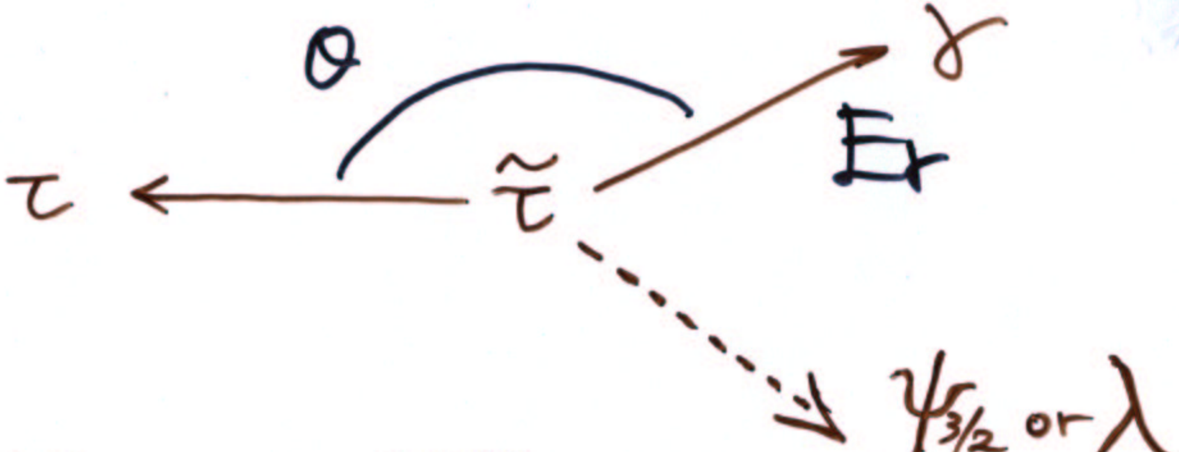


Compare with hypothetical spin-½ fermion λ.

$$\mathcal{L} = y(\tilde{\tau}_R^* \bar{\lambda} P_R \tau + \tilde{\tau}_L^* \bar{\lambda} P_L \tau) + h.c. \qquad y \ll 1$$



angular and energy distributions of τ and γ



Results (for right-handed $\tilde{\tau}_R$, $m_{\tilde{\tau}} = 150$ GeV, $m_{3/2} = m_\lambda = 75$ GeV)

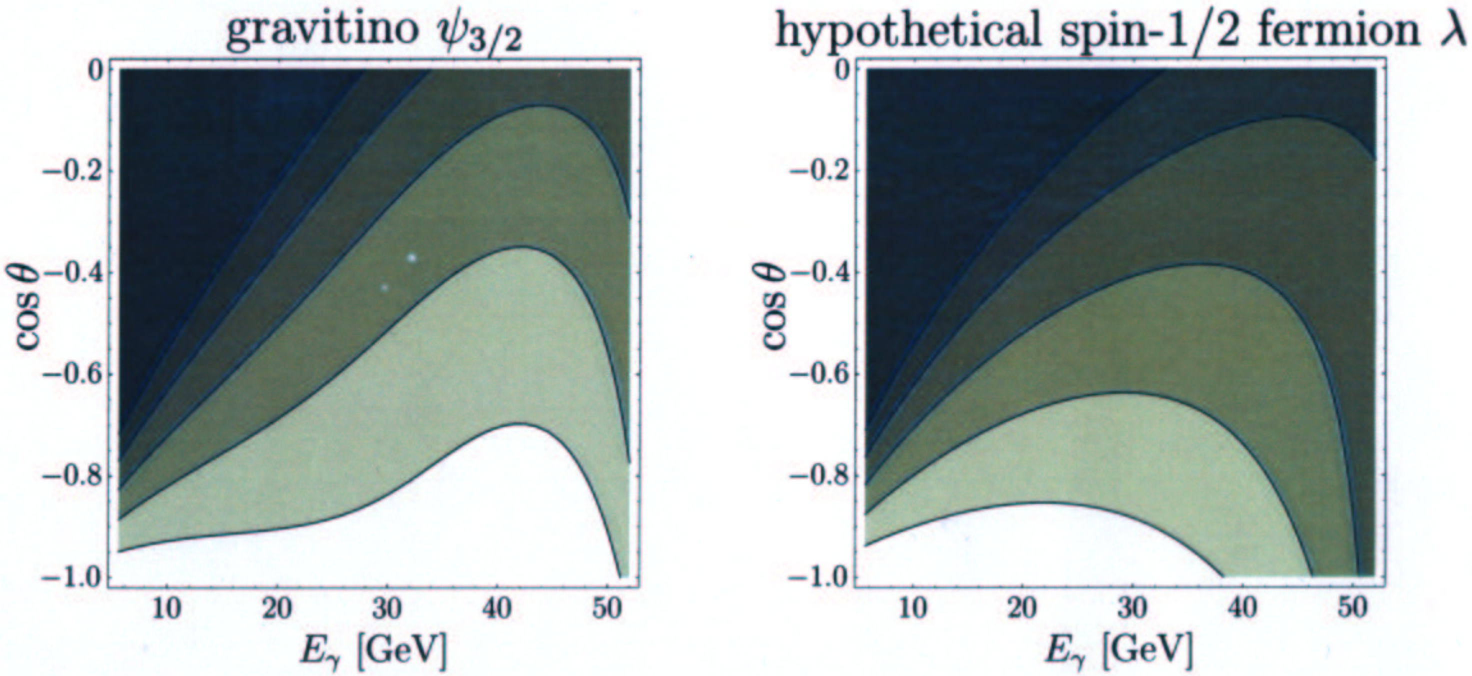


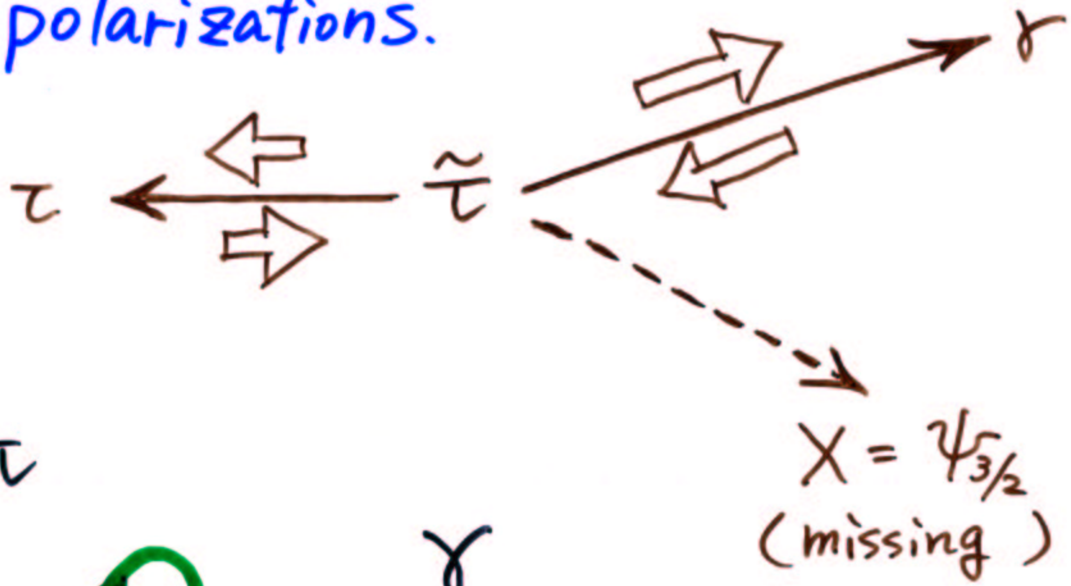
Figure: Contour plots of $\dfrac{d^2 B_r}{dE_\gamma d\cos\theta} = \dfrac{1}{\Gamma_{\tilde{\tau}}} \dfrac{d^2\Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tau + \gamma + X)}{dE_\gamma d\cos\theta}$ for $X = \psi_{3/2}$ and λ.

Darker shading = larger rate. (Boundaries are [1, 2, 3, 4, and 5] $\times 10^{-3}\alpha$ [GeV^{-1}].)

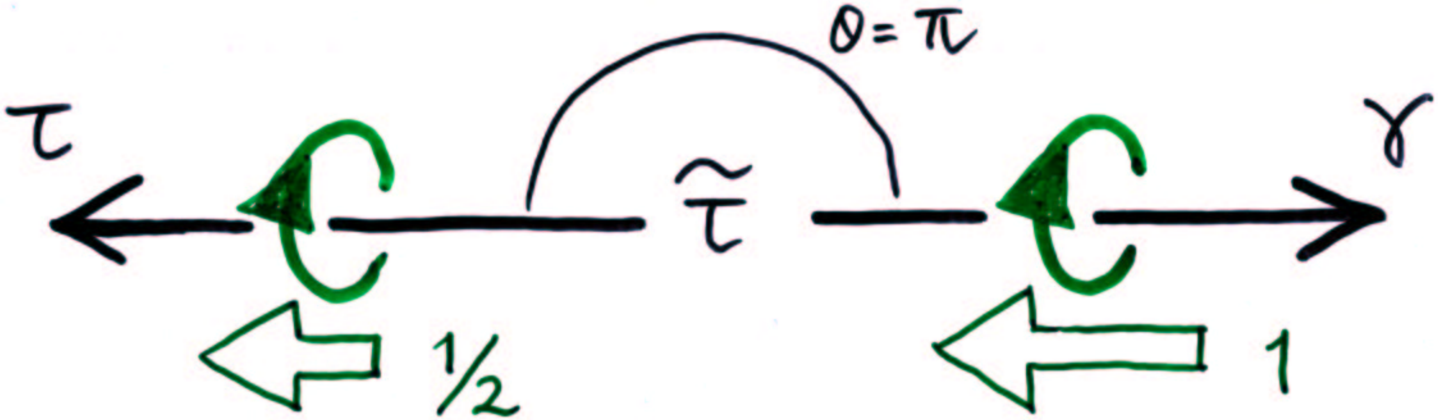
Method 3

Measurement of the gravitino spin $(= 3/2)$

by 3-body decay + polarizations.

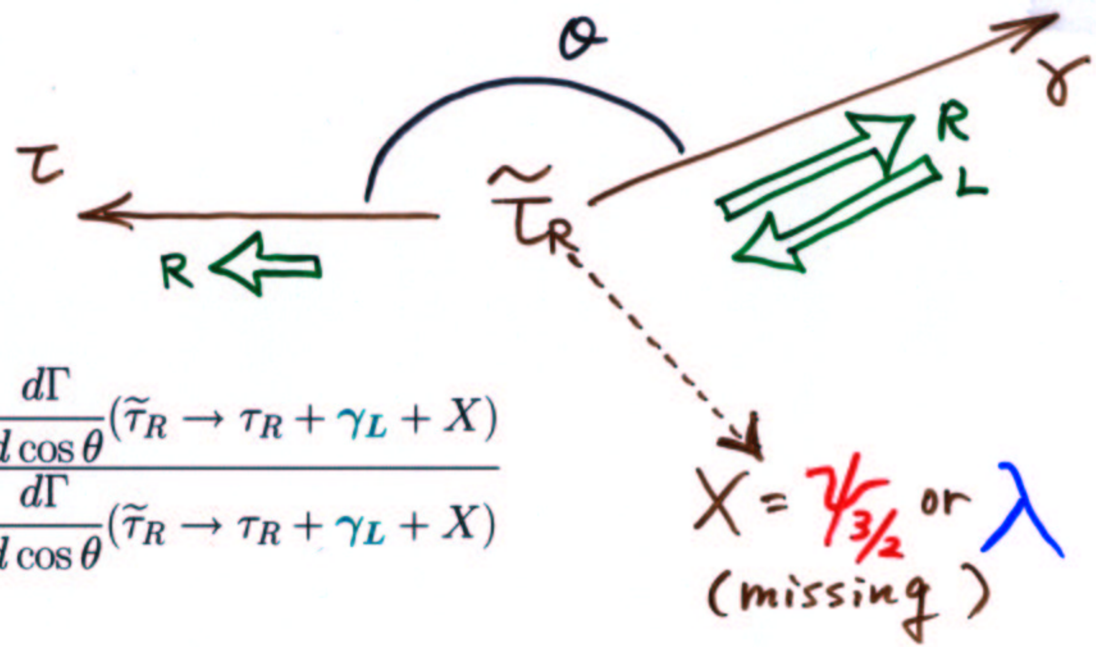


In particular, ...



$\tilde{\tau} \rightarrow \tau_R + \gamma_L + X$ at $\theta = \pi$ is possible only if the missing particle X has spin $3/2$.

angular distribution and polarizations of τ & γ



$$A_{RL}\,(\cos\theta\,) = \frac{\dfrac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_R + X) - \dfrac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_L + X)}{\dfrac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_R + X) + \dfrac{d\Gamma}{d\cos\theta}(\tilde{\tau}_R \to \tau_R + \gamma_L + X)}$$

Results (for right-handed $\tilde{\tau}_R$, $m_{\tilde{\tau}} = 150$ GeV)

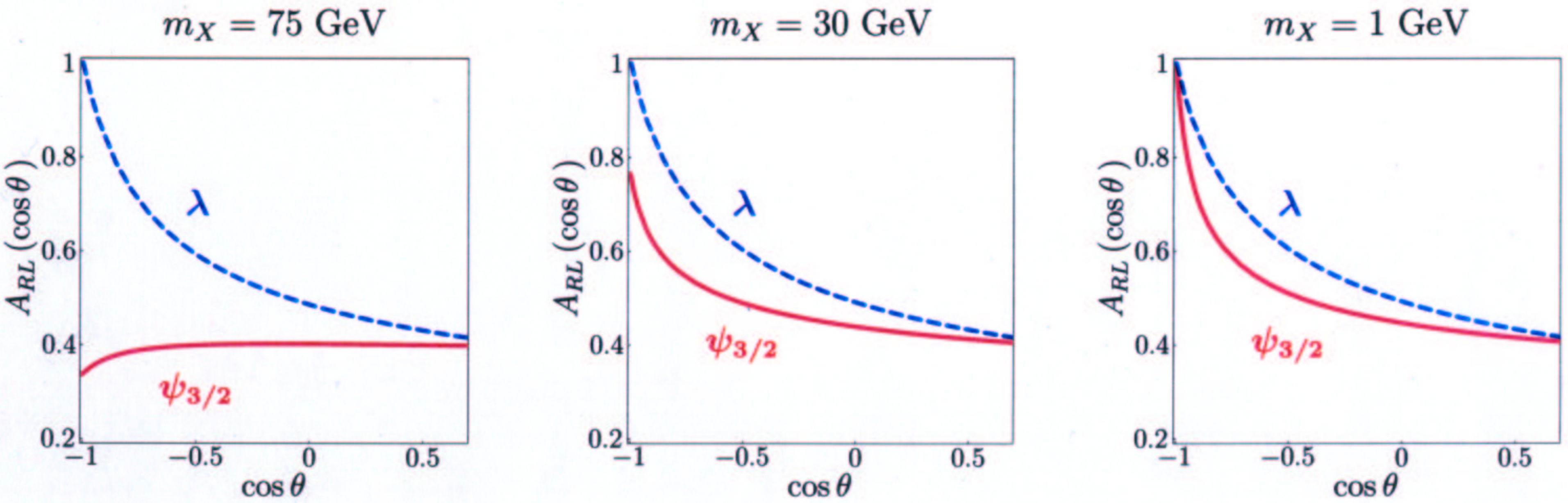


Figure: $A_{RL}\,(\cos\theta\,)$.

We cut the soft photon (energy below 10% of maximal photon energy, $E_\gamma^{\max} = (m_{\tilde{\tau}}^2 - m_{3/2}^2)/2m_{\tilde{\tau}}$).

▨ CONCLUSION: (of the 2nd part.)

Can we prove the existence of supergravity ?

Yes !!

If LSP = gravitino, and if we can collect NSPs at future colliders , we can .....

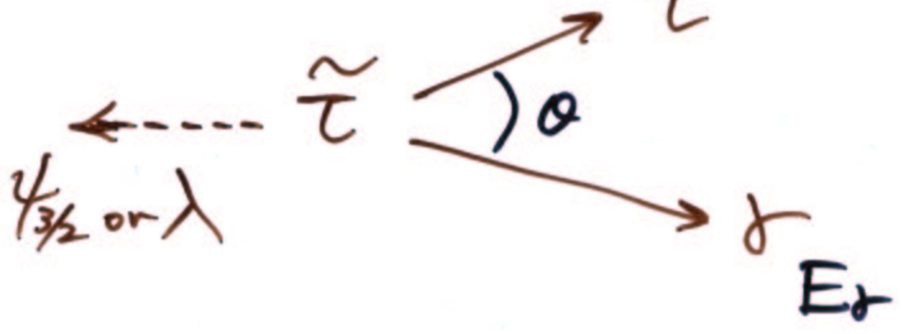
- measure the Planck scale M_P , ← 2-body
- test the gravitino couplings , ← 3-body
- measure the gravitino spin ←

by studying the NSP decays.

We can test the gravitino dark matter scenario!

For Questions and Comments

forward direction



Results (for right-handed $\tilde{\tau}_R$, $m_{\tilde{\tau}} = 150$ GeV, $m_{3/2} = m_\lambda = 75$ GeV)

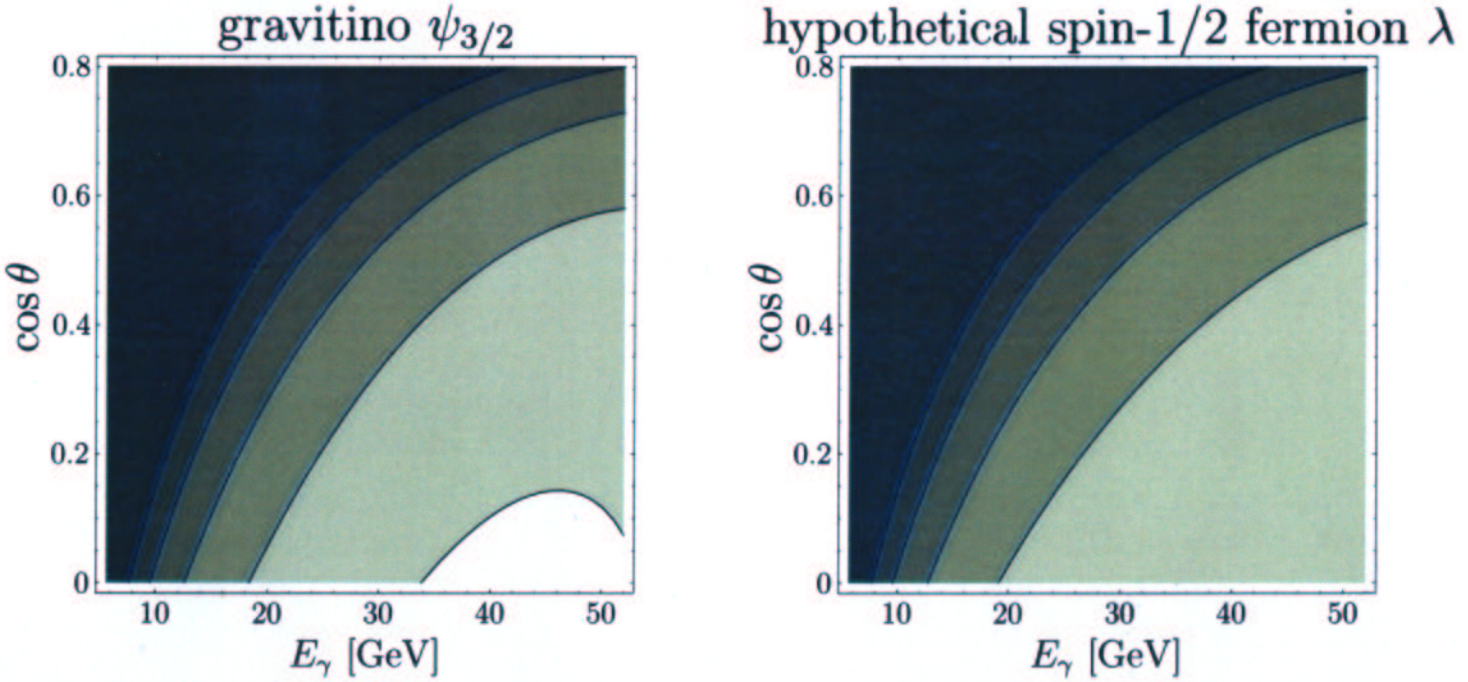


Figure: Contour plots of $\dfrac{d^2 B_r}{dE_\gamma d\cos\theta} = \dfrac{1}{\Gamma_{\tilde{\tau}}} \dfrac{d^2\Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tau + \gamma + X)}{dE_\gamma d\cos\theta}$ for $X = \psi_{3/2}$ and λ.

Darker shading = larger rate. (Boundaries are [4, 8, 12, 16, and 20] $\times 10^{-3}\alpha$ [GeV^{-1}].)

Comment.

$$\boxed{\text{Very light gravitino } (m_{3/2} \ll m_{\tilde{\tau}}) \simeq \text{goldstino (spin 1/2 fermion)}}$$

2-body decay

→ measurement of M_P is difficult.

$E_\tau \simeq \frac{1}{2} m_{\tilde{\tau}}$

$$(m_{3/2}^2 = m_{\tilde{\tau}}^2 + m_\tau^2 - 2 m_{\tilde{\tau}} E_\tau \simeq 0)$$

3-body decay

→ measurement of gravitino spin is difficult.

→ But we can still see the peculiar coupling. → See Fig.s

NOTE:

If $m_{3/2} \ll 10$ keV, $\tilde{\tau}$ can decay inside the detector!

(for comparison) define

"pseudo-goldstino" χ, which has .....

goldstino interactions

$$\mathcal{L}_{goldstino} = \left(\frac{m_{\tilde{\tau}}^2}{\sqrt{3}\, m_{3/2} M_P}\right)(\tilde{\tau}_R^* \bar{\chi} P_R \tau + h.c) - \frac{m_{\tilde{\gamma}}}{4\sqrt{6}\, m_{3/2} M_P} \bar{\chi} [\gamma^\mu, \gamma^\nu] \tilde{\gamma} F_{\mu\nu}$$

photino

$+$

a mass

$m_\chi \longrightarrow$ explicit breaking of global SUSY.

gravitino $\psi_{3/2}$ vs. (pseudo) goldstino χ vs. hypothetical spin-1/2 fermion λ

$$A_{RL}(\cos\theta) = \frac{\frac{d\Gamma}{d\cos\theta}(\widetilde{\tau}_R \to \tau_R + \gamma_R + X) - \frac{d\Gamma}{d\cos\theta}(\widetilde{\tau}_R \to \tau_R + \gamma_L + X)}{\frac{d\Gamma}{d\cos\theta}(\widetilde{\tau}_R \to \tau_R + \gamma_R + X) + \frac{d\Gamma}{d\cos\theta}(\widetilde{\tau}_R \to \tau_R + \gamma_L + X)}$$

$X = \psi_{3/2}, \chi$ or λ

Results (for right-handed $\widetilde{\tau}_R$, $m_{\widetilde{\tau}} = 150$ GeV)

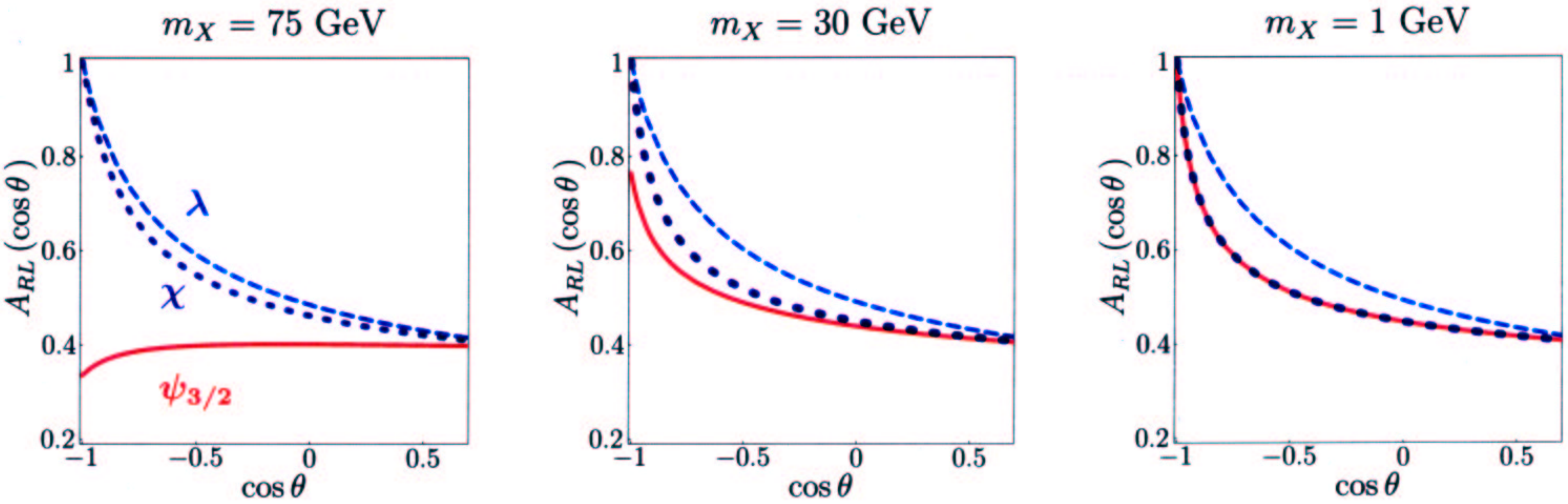
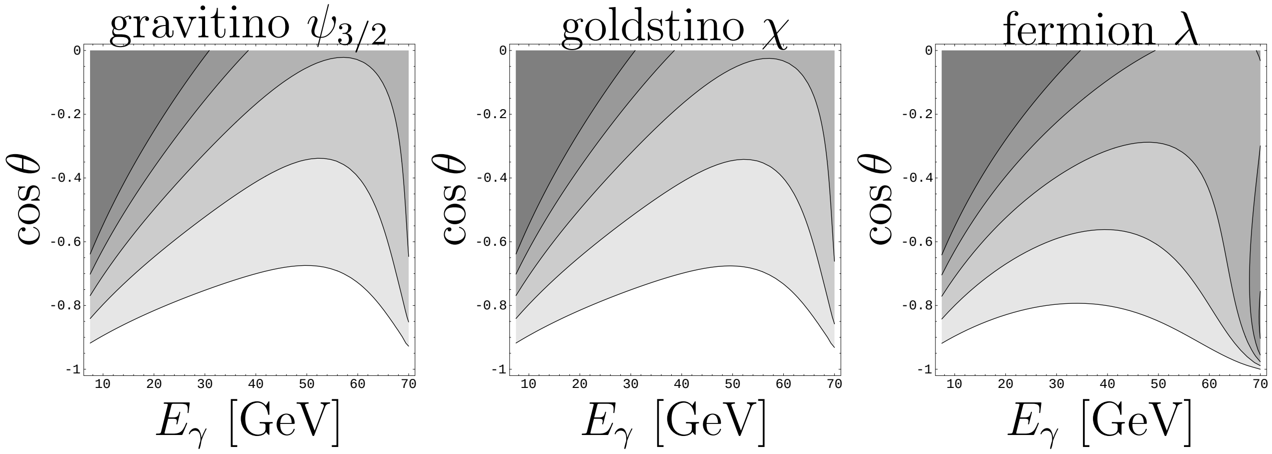
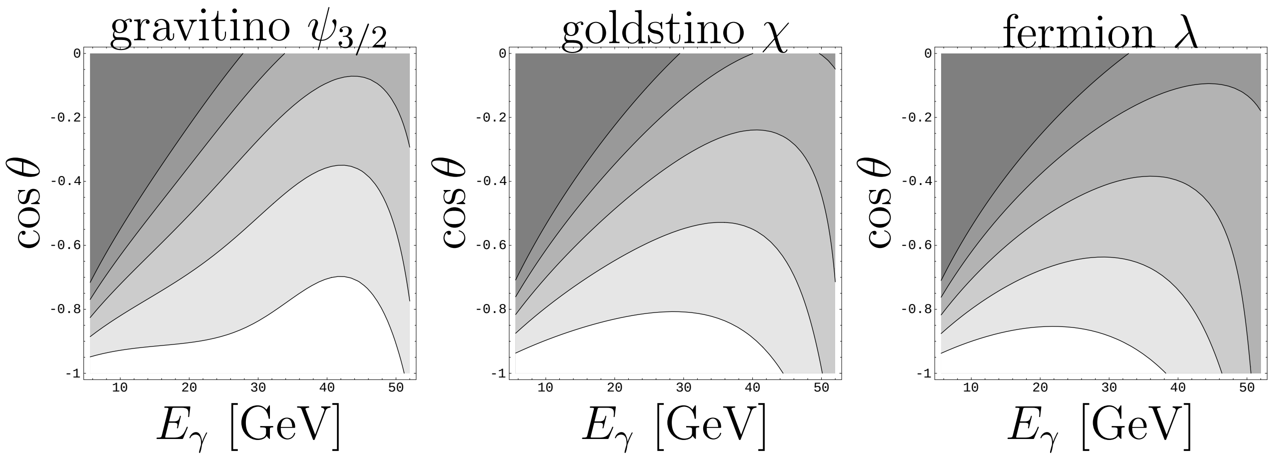


Figure: $A_{RL}(\cos\theta)$.

We cut the soft photon (energy below 10% of maximal photon energy, $E_\gamma^{\max} = (m_{\widetilde{\tau}}^2 - m_{3/2}^2)/2m_{\widetilde{\tau}}$).



$m_{\tilde{\tau}} = 150$ GeV, $m_X = 10$ GeV.



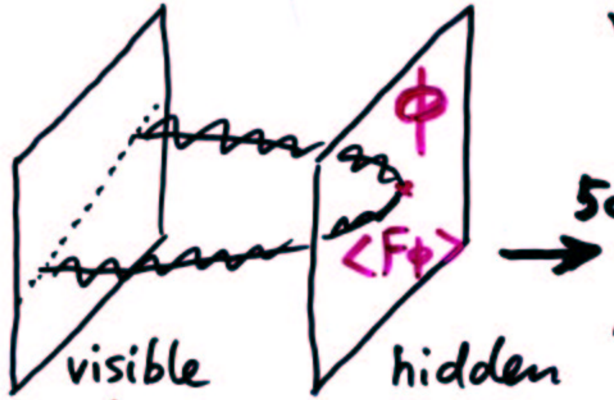
$m_{\tilde{\tau}} = 150$ GeV, $m_X = 75$ GeV.

gauge coupling at high T and gravitino abundance

Buchmüller, KH, Ratz '03

In higher dimensional theory, ...

(e.g., gaugino mediation
[Kaplan Kribs Schmaltz '99
Chacko Luty Nelson Ponton '99]



)

$$\mathcal{L}^{\rm eff}_{4d} = \left(\frac{1}{g_0^2} + \frac{\phi}{M} + \cdots\right)\left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \text{gaugino}\right)$$

$\ell^{-1} < M < M_{pl}$

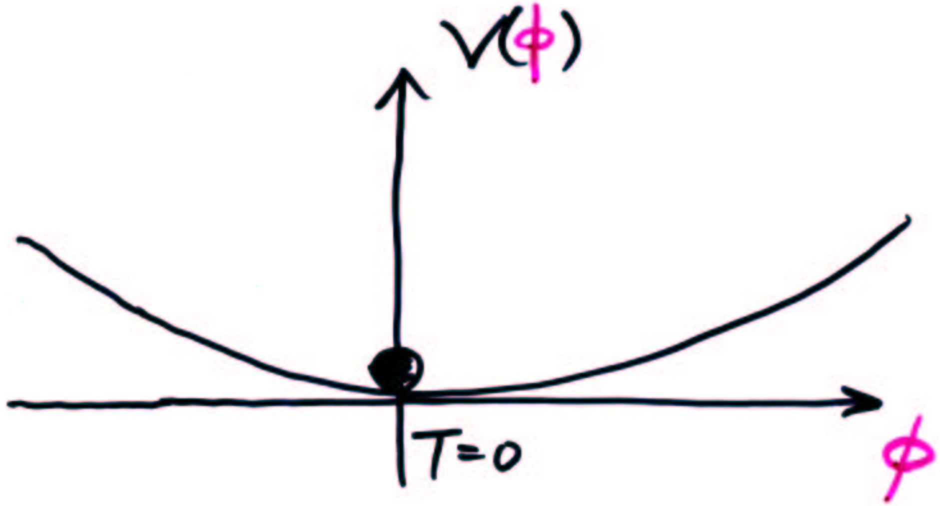
$$g_{\rm eff}^2 = g_0^2 \frac{1}{1 + g_0^2\left(\frac{\langle\phi\rangle}{M} + \cdots\right)} \quad , \quad m_{\tilde{g}} = \frac{1}{2} g_{\rm eff}^2 \frac{F_\phi}{M}$$

▨ gauge coupling at high T and gravitino abundance

$$g_{eff}^2(\phi) = g_0^2 \frac{1}{1 + g_0^2\left(\frac{\phi}{M} + \cdots\right)}$$

at zero temperature, ...

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$$



gauge coupling at high T and gravitino abundance

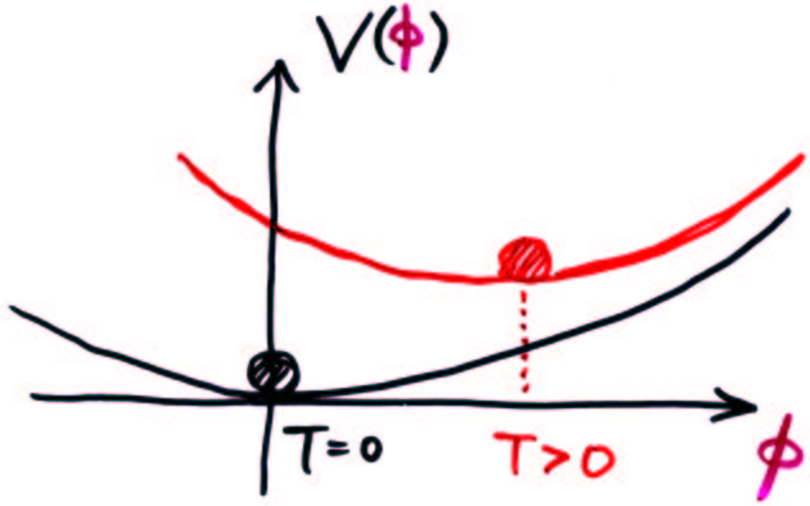
$$g_{\rm eff}^2(\phi) = g_0^2 \frac{1}{1 + g_0^2\left(\frac{\phi}{M} + \cdots\right)}$$

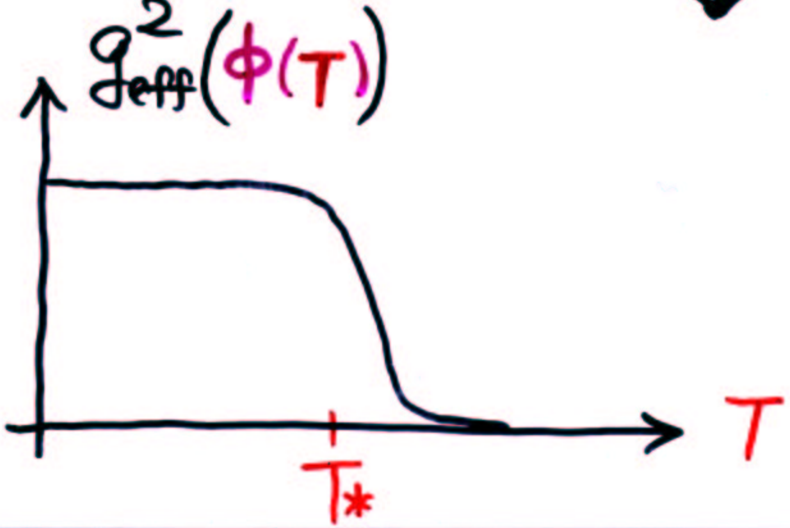
At high temperature

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 + \underbrace{\frac{3}{8} g_{\rm eff}^2(\phi)\, T^4}$$

$$= \frac{1}{2} m_\phi^2 \phi^2 + \frac{3}{8} g_0^2 \frac{1}{1 + g_0^2\left(\frac{\phi}{M} + \cdots\right)} T^4$$

(SU(3))





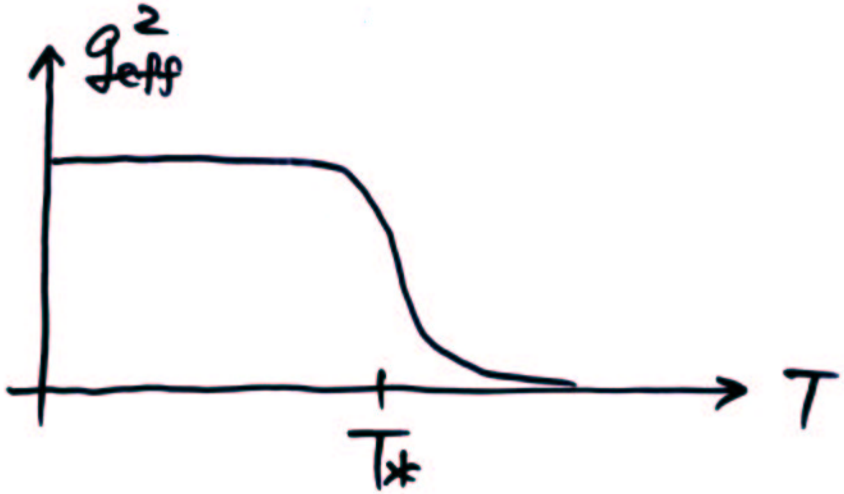
$$g_{\rm eff}^2 = g_0^2 \frac{1}{1 + \left(\frac{T}{T_*}\right)^\alpha} \qquad \alpha > 1$$

$T_* \sim \sqrt{m_\phi M}$

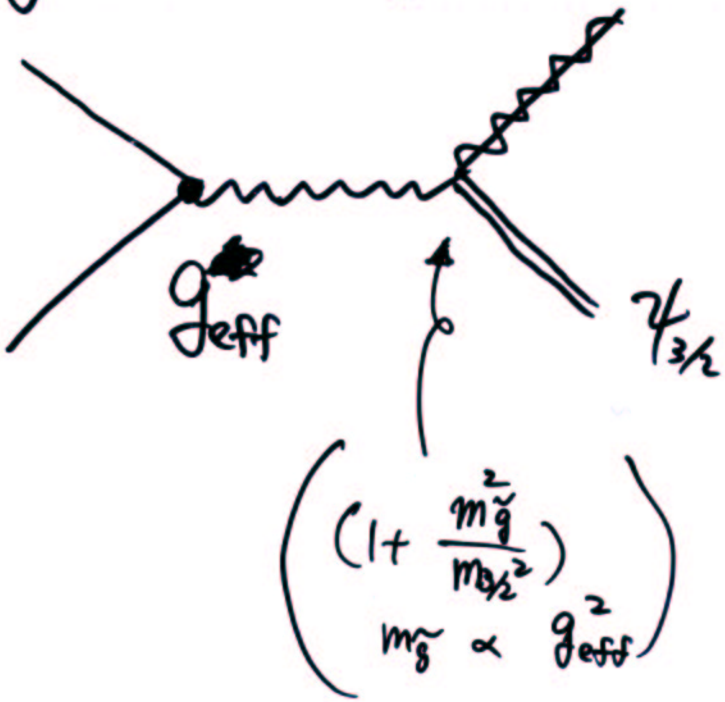
rapid decrease of coupling for $T > T_*$!!

■ gauge coupling at high T and gravitino abundance

$$g_{eff}^2 = g_0^2 \frac{1}{1 + \left(\frac{T}{T_*}\right)^{\alpha}}$$



gravitino production rate



suppressed for $T > T_*$!