Gravitino dark matter in high scale supersymmetry

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References:

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- KK, Y. Mambrini, K.A. Olive, 1901.04449
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SUSY breaking scale can be anywhere between EW scale and M_P

Why low-scale SUSY? What can low-scale SUSY do for us?

(A) gauge coupling unification

(B) Higgs vacuum stability

(C) radiative EW symmetry breaking

(D) dark matter

(E) ameliorate hierarchy problem

SUSY breaking scale can be anywhere between EW scale and M_P

Why low-scale SUSY? What can low-scale SUSY do for us?

threshold corrections → ✓ (A) gauge coupling unification

light GUT Higgs state → ✓ (B) Higgs vacuum stability, ✓ (C) radiative EW symmetry breaking

gravitino → ✓ (D) dark matter

(E) ameliorate hierarchy problem

How about high-scale SUSY?

e.g. minimal SUSY SO(10) with $\widetilde{m} \gtrsim m_{\rm inf} \simeq 3 \times 10^{13}$ GeV

[S. Ellis, T. Gherghetta, KK, K. Olive, '18]

In this talk, “high-scale” means…

$$\widetilde{m} \equiv \frac{F}{\Lambda_{\rm mess}} > m_{\rm inf} \simeq 3 \times 10^{13}\ {\rm GeV}$$

$$\Lambda_{\rm mess} > \widetilde{m} > m_{\rm inf}$$

$$m_{3/2} \sim \frac{F}{M_P} \gtrsim \frac{m_{\rm inf}\Lambda_{\rm mess}}{M_P} \gtrsim \frac{m_{\rm inf}^2}{M_P} \sim \mathcal{O}(0.1)\ {\rm EeV}$$

Any SUSY particles (except for gravitino) have never been produced after inflation

EeV gravitino is a good candidate for dark matter

[Benakli, Chen, Dudas, Mambrini]
[Dudas, Mambrini, Olive]

Gravitino is produced through gluon + gluon → gravitino + gravitino (gluino exchange) whose reaction rate is

$$\Gamma \sim \frac{T^9}{F^4} \sim \frac{T^9}{M_P^4 m_{3/2}^4}$$

Number density of gravitino is given by

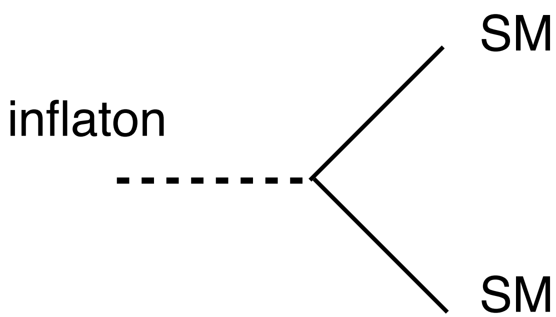
$$n_{3/2}/n_\gamma \sim \Gamma/H \propto T^7 \longrightarrow \Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1\ {\rm EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\rm RH}}{2.0 \times 10^{10}\ {\rm GeV}}\right)^7$$

How about inflaton decays? The detail depends on models?

— Tree-level decay depends on how the inflaton couples to the gravitino
— Loop-level decay depends on how the inflaton reheats the universe

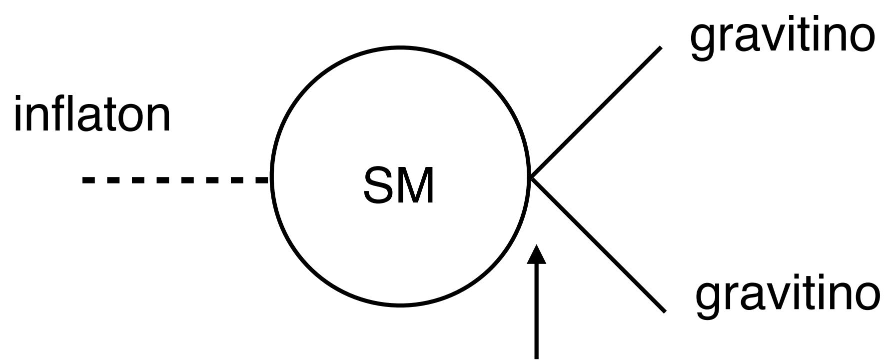
[KK, Y. Mambrini, K. Olive, '19]

reheating by inflaton decay



$$\Gamma^{\text{tree}} = \frac{y^2}{8\pi} m$$

gravitino production through the same coupling



$$\frac{1}{F^2} \sim \frac{1}{(m_{3/2} M_P)^2}$$

$$\Gamma^{\text{loop}} \sim \Gamma^{\text{tree}} \times \frac{1}{(4\pi)^2} \frac{m_{3/2}^2 m^6}{(m_{3/2} M_P)^4}$$

To be more concrete, we consider a no-scale inflation model

$$K = -3\ln\left[T + T^* - \frac{1}{3}(|\phi|^2 + |y_i|^2)\right] + |z|^2 - \frac{(zz^*)^2}{\Lambda_z^2}$$

$$W = \sqrt{3}M_T\phi\left(T - \frac{1}{2}\right) + \sqrt{3}m_{3/2}(z+\nu) + W_{\rm MSSM}$$

$${\rm Re}T = \frac{1}{2}e^{\sqrt{\frac{2}{3}}t} \simeq \frac{1}{2} + \frac{1}{\sqrt{6}}t$$

T : inflaton,
ϕ: matter-like field,
y_i: MSSM fields,
z: Polonyi field

➡ Starobinsky-like inflaton potential

Dominant inflaton decay channel: $t \to hh$ (the lightest Higgs)

$$\mathscr{L} \supset \sqrt{\frac{2}{3}}\mu^2\, t(|H_u|^2 + |H_d|^2) + \frac{\mu^2}{2\sqrt{6}}t(\widetilde{H}_u\widetilde{H}_d + h.c.) \qquad (W_{\rm MSSM} \supset \mu H_u H_d)$$

decay width: $\Gamma_{2h} = \dfrac{\mu^4}{48\pi M_T M_P^2} \equiv \dfrac{y^2}{8\pi}M_T$

$$y^2 \equiv \frac{\mu^4}{6M_T^2M_P^2} \simeq (5.6\times10^{-5})^2 \times \left(\frac{\mu}{10^{14}\ {\rm GeV}}\right)^4\left(\frac{3\times10^{13}\ {\rm GeV}}{M_T}\right)^2$$

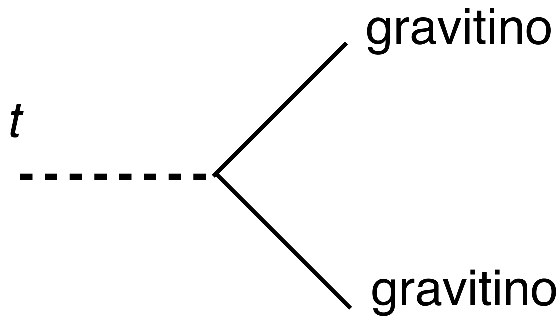
Since we consider $\mu > M_T$ in high-scale SUSY, this channel becomes much more significant, compared to the low-scale SUSY case.

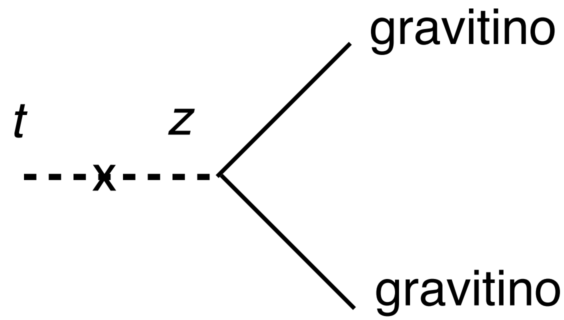
➡ $$T_{RH} \simeq 0.5(y/2\pi)\sqrt{M_TM_P} \simeq 3.8\times10^{10}\ {\rm GeV}\times\left(\frac{y}{5.6\times10^{-5}}\right)\left(\frac{M_T}{3\times10^{13}\ {\rm GeV}}\right)^{1/2}$$

$$T_{\rm max} \simeq 0.5(8\pi/y^2)^{1/4}T_{\rm RH}$$

Tree-level coupling of inflaton to gravitinos ($G = K + \ln|W|^2$):

$$\mathcal{L}_{3/2} \supset -\frac{1}{4} e^{G/2} \overline{\psi}_\mu [\gamma^\mu, \gamma^\nu] \psi_\nu \simeq -\frac{1}{4} \left(m_{3/2} + \frac{1}{2} \langle G_T + U_{Tz} G_z \rangle T + \cdots \right) \overline{\psi}_\mu [\gamma^\mu, \gamma^\nu] \psi_\nu$$



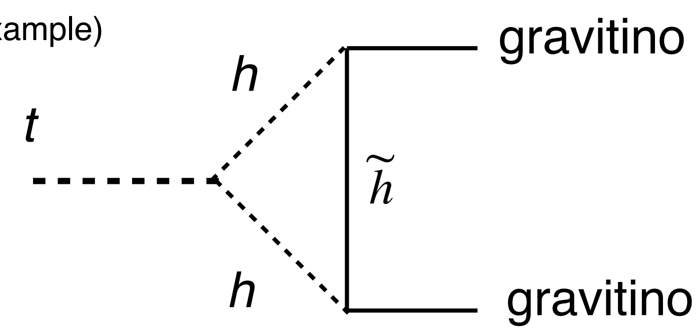


$$\Gamma^{\rm tree} = \left(\frac{\Lambda_z}{M_P} \right)^4 \frac{81 m_{3/2}^2 M_T}{128 \pi M_P^2}$$

$$B_R^{\rm tree} \simeq 5.5 \times 10^{-12} \left(\frac{\Lambda_z}{M_P} \right)^4 \left(\frac{m_{3/2}}{0.1\ {\rm EeV}} \right)^2 \times \left(\frac{M_T}{3 \times 10^{13}\ {\rm GeV}} \right)^2 \left(\frac{10^{14}\ {\rm GeV}}{\mu} \right)^4$$

One-loop decay of inflaton to gravitinos

(example)



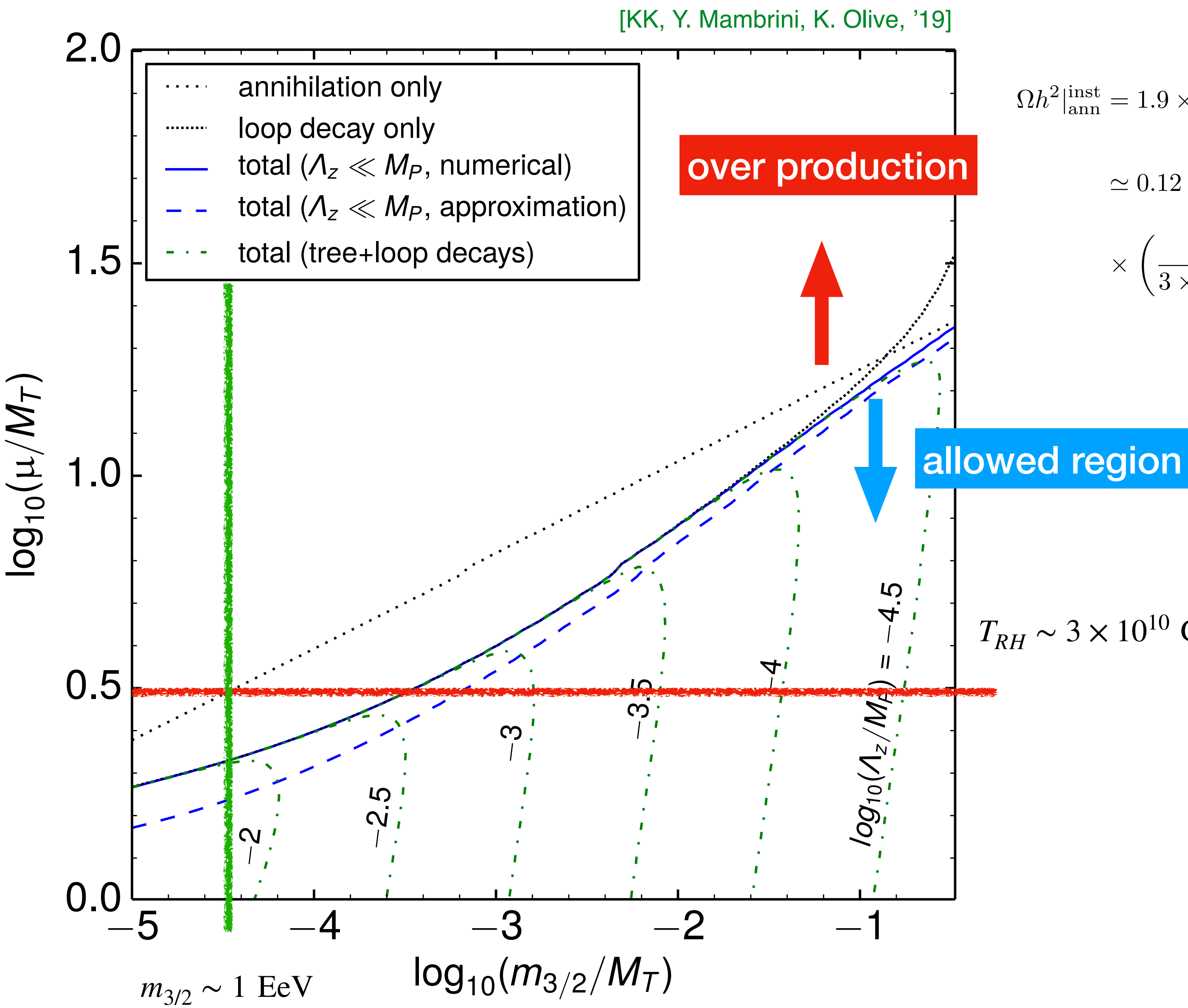
$$\Gamma^{\rm loop} \simeq \frac{2}{3^3 4^5 \pi^5} \left(\frac{1}{4} - \ln \frac{\mu^2}{M_T^2} \right)^2 \frac{\mu^4 M_T^5}{m_{3/2}^2 M_P^6}$$

$$B_R^{\rm loop} \simeq 9.8 \times 10^{-15} \left(\frac{0.1\ {\rm EeV}}{m_{3/2}} \right)^2 \left(\frac{M_T}{3 \times 10^{13}\ {\rm GeV}} \right)^6 \left[1 - 8 \ln \left(\frac{\mu}{M_T} \right) \right]^2$$

Because of large $t \to hh$ contribution, the loop-induced decay can be comparable with (or even larger than) the tree-level decay, depending on Λ_z

$$\Omega h^2|_{\rm decay} \simeq 0.1 \left(\frac{NB_R}{8.7\times10^{-7}}\right)\left(\frac{3\times10^{13}\ {\rm GeV}}{M_T}\right)\left(\frac{T_{RH}}{10^{10}\ {\rm GeV}}\right)\left(\frac{m_{3/2}}{\rm GeV}\right)$$

$$NB_R \equiv B_R^{\rm tree} + B_R^{\rm loop}$$



$$\Omega h^2|^{\rm inst}_{\rm ann} = 1.9\times10^{25}\,\frac{T_{RH}^7}{m_{3/2}^3 M_P^4}\ln\left[\frac{T_{\rm max}}{T_{\rm RH}}\right]$$

$$\simeq 0.12\left(\frac{0.1\ {\rm EeV}}{m_{3/2}}\right)^3\left(\frac{y}{2.3\times10^{-5}}\right)^7$$

$$\times\left(\frac{M_T}{3\times10^{13}\ {\rm GeV}}\right)^{7/2}\ln\left(1.1/y^{1/2}\right)$$

$T_{RH} \sim 3\times10^{10}$ GeV

How can this heavy gravitino be detected?

Gravitino can decay when R-parity is not conserved

The most generic form of the RPV interactions (at renormalizable level)

$$W_{\rm RPV} = \mu_i' H_u \cdot L_i + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j E_k^c + \lambda'_{ijk} L_i \cdot Q_i D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c$$

In low-scale SUSY, the RPV couplings are strongly constrained by, for instance, neutrino mass, proton decay, and baryon asymmetry preservation

In high-scale SUSY, most of the limits become significantly weak

For example, μ' is constrained by the neutrino mass:

$$\mathscr{L}_5 \simeq \frac{1}{M_5}\nu_L \nu_L hh \qquad \frac{1}{M_5} \simeq \left(\frac{\mu'}{\mu}\right)^2 \frac{g_2^2 M_1 + g_1^2 M_2}{M_1 M_2 (1+\tan^2\beta)}$$

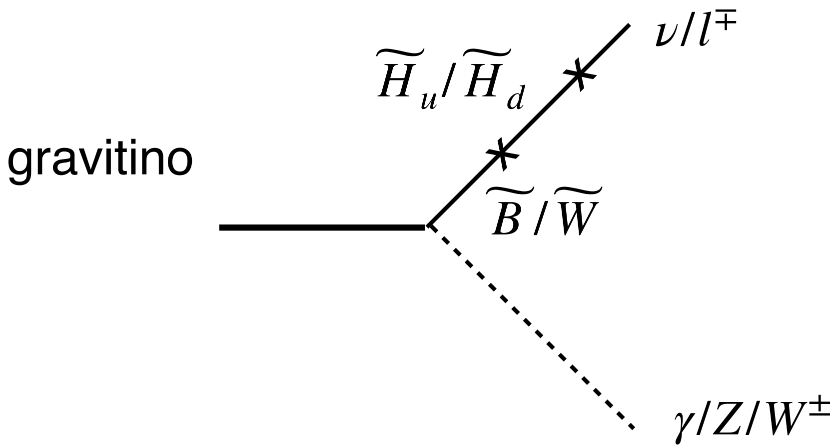
$$\mu' < 1.7 \times 10^{-7} {\rm GeV}^{-1/2} \widetilde{m}^{1/2} \mu (1+\tan^2\beta)^2 / g \simeq 6.6 \times 10^{13}\ {\rm GeV}$$

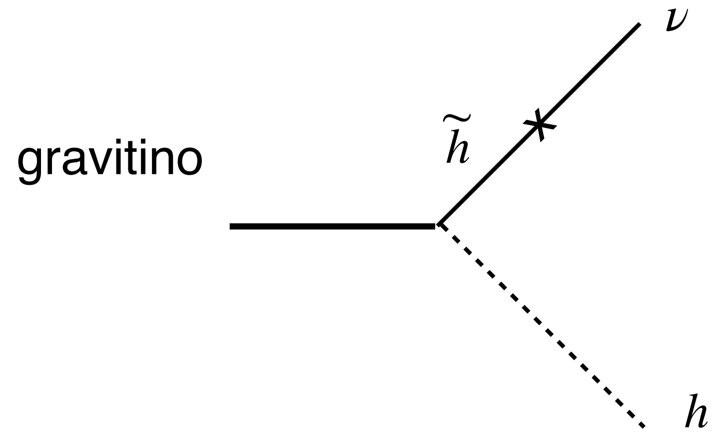
$$(\mu \sim M_1 \sim M_2 \sim \widetilde{m} \sim 3 \times 10^{13}\ {\rm GeV})$$

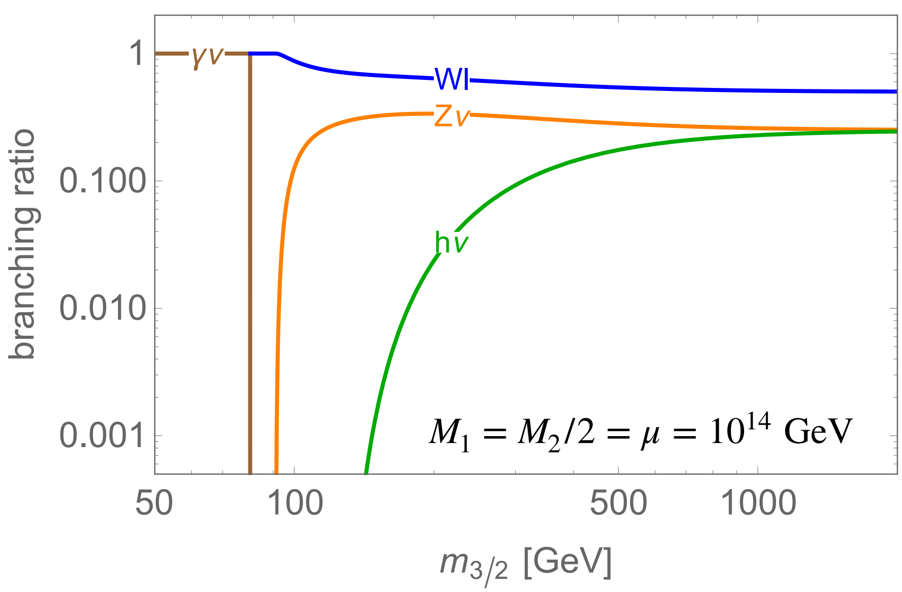
cf. in low (weak)-scale SUSY: $\mu' < 2.3 \times 10^{-5}$ GeV (*B-L* asym. preservation)

Gravitino decay is induced by the bilinear RPV coupling: $W_{\rm RPV} \supset \mu' H_u \cdot L$

$$\mathscr{L} \supset -\frac{i}{8M_P}\bar{\lambda}\gamma^\mu[\gamma^\nu,\gamma^\rho]\psi_\mu F_{\nu\rho} + \left[-\frac{i}{\sqrt{2}M_P}D_\mu\phi^\dagger\overline{\psi}_\nu\gamma^\mu\gamma^\nu\chi_L + h.c.\right]$$







Due to the longitudinal contributions in $Z\nu/Wl$ channels,
$\Gamma(\psi_\mu \to Z\nu/Wl) \gg \Gamma(\psi_\mu \to \gamma\nu)$ at $m_{3/2} \gg m_W$

Equivalence theorem: $2\Gamma_{Z\nu} = \Gamma_{Wl} = 2\Gamma_{h\nu}$

Total decay width: $\Gamma_{\rm tot} \simeq \dfrac{\epsilon^2 c_\beta^2 m_{3/2}^3}{16\pi M_P^2}$ $\qquad \epsilon \simeq \mu'/\mu$

Constraints/signals for the decaying gravitino dark matter

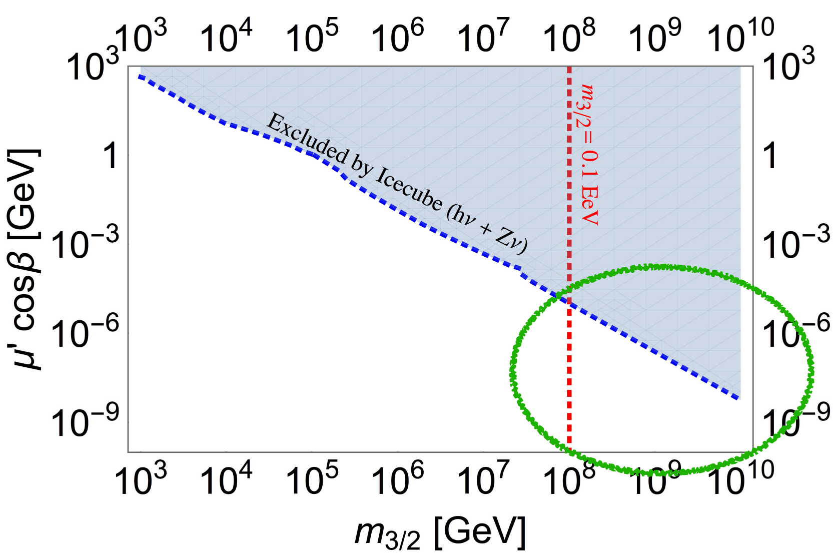
Lifetime: $\tau_{3/2} \simeq 10^{28} \left(\frac{\widetilde{m}}{10^{14}\ \mathrm{GeV}}\right)^2 \left(\frac{0.44\ \mathrm{keV}}{\mu' c_\beta}\right)^2 \left(\frac{\mathrm{EeV}}{m_{3/2}}\right)^3 \mathrm{s}\,.$ $(\mu \sim \widetilde{m})$

By using $\Omega_{3/2} h^2 \simeq 0.11 \left(\frac{0.1\ \mathrm{EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\mathrm{RH}}}{2.0 \times 10^{10}\ \mathrm{GeV}}\right)^7$, we can eliminate $m_{3/2}$ and obtain the RPV parameter scale:

$$\mu' c_\beta = 14\ \mathrm{keV} \left(\frac{\Omega_{3/2} h^2}{0.11}\right)^{1/2} \left(\frac{10^{28}\ \mathrm{s}}{\tau_{3/2}}\right)^{1/2} \left(\frac{\widetilde{m}}{10^{14}\ \mathrm{GeV}}\right) \left(\frac{2 \times 10^{10}\ \mathrm{GeV}}{T_{RH}}\right)^{7/2}$$

cf. in low (weak)-scale SUSY: $\mu' c_\beta \simeq 1.4\ \mathrm{keV} \left(\frac{10\ \mathrm{TeV}}{\widetilde{m}}\right)^2 \left(\frac{\Omega_{3/2} h^2}{0.11}\right)^{3/2} \left(\frac{10^{28}\ \mathrm{s}}{\tau_{3/2}}\right)^{1/2} \left(\frac{2.2 \times 10^6\ \mathrm{GeV}}{T_{RH}}\right)^{3/2}$

A smoking-gun signal could be EeV scale monochromatic neutrinos



$m_{3/2} \gtrsim 0.1\ \mathrm{EeV}$ is allowed for high-scale SUSY

By taking $m_{3/2} = 0.1\ \mathrm{EeV}, \tau_{3/2} = 1.4 \times 10^{28}\ \mathrm{s}$

The number of decaying gravitino per year ~ 0.0073, equivalently, one gravitino decay every 137 years in the volume of the Earth.

ANITA observed 2 neutrino evens around EeV in 3 years

Summary

- ✦ Many good features existed in low-scale SUSY are still preserved in high-scale SUSY
- ✦ EeV gravitino provides the right amount of dark matter number density
- ✦ In addition to the thermal production, non-negligible contributions from radiative inflaton decay always exist as they are related to the reheating processes
- ✦ EeV gravitino may slowly decay via the RPV coupling, and provides monochromatic neutrinos as a smoking-gun signal