# R-Parity Violation in High Scale Supersymmetry

- Strong Limits in Weak Scale Susy
- Do these carry over as the Susy scale is increased?

work with:E. Dudas, T. Gherghetta, K. Kaneta, Y. Mambrini

# 1st:

Congratulations Pierre!

Good Luck on Phase 2!

# *R*-PARITY BREAKING AND COSMOLOGICAL CONSEQUENCES*

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The breaking of *R*-parity allows the lightest supersymmetric particle (LSP) to decay, and we study the cosmological bounds on its mass and lifetime These bounds can be translated into a lower limit on the neutrino mass when *R*-parity is broken by a nonzero scalar neutrino VEV, and into lower limits on the symmetry breaking parameters when *R*-parity is broken by explicit couplings in the lagrangian

# R-Parity Violation

$$\begin{aligned} W^{(2)}_{\mathrm{RPV}} &= \mu'_i H_u \cdot L_i, \\ W^{(3)}_{\mathrm{RPV}} &= \frac{1}{2}\lambda_{ijk} L_i \cdot L_j E^c_k + \lambda'_{ijk} L_i \cdot Q_i D^c_k + \frac{1}{2}\lambda''_{ijk} U^c_i D^c_j D^c_k \,. \end{aligned}$$

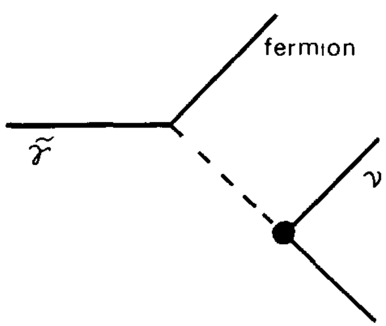
- LSP decay
- Baryon number violation
- Lepton number violation

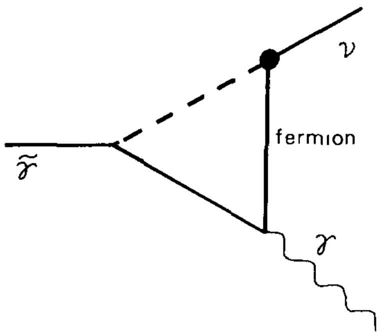
$$\tilde{\gamma} \to \gamma + \text{neutrino}\,.$$

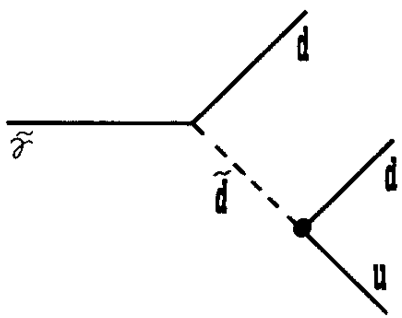
$$\tilde{\gamma} \to \text{fermion} + \text{antifermion} + \text{neutral lepton}\,.$$

$$\tilde{\gamma} \to \text{fermion} + \text{antifermion} + \text{charged lepton}\,,$$

$$\tilde{\gamma} \to 3 \text{ quarks}$$




Seems quaint to consider a photino LSP

# Money Plot

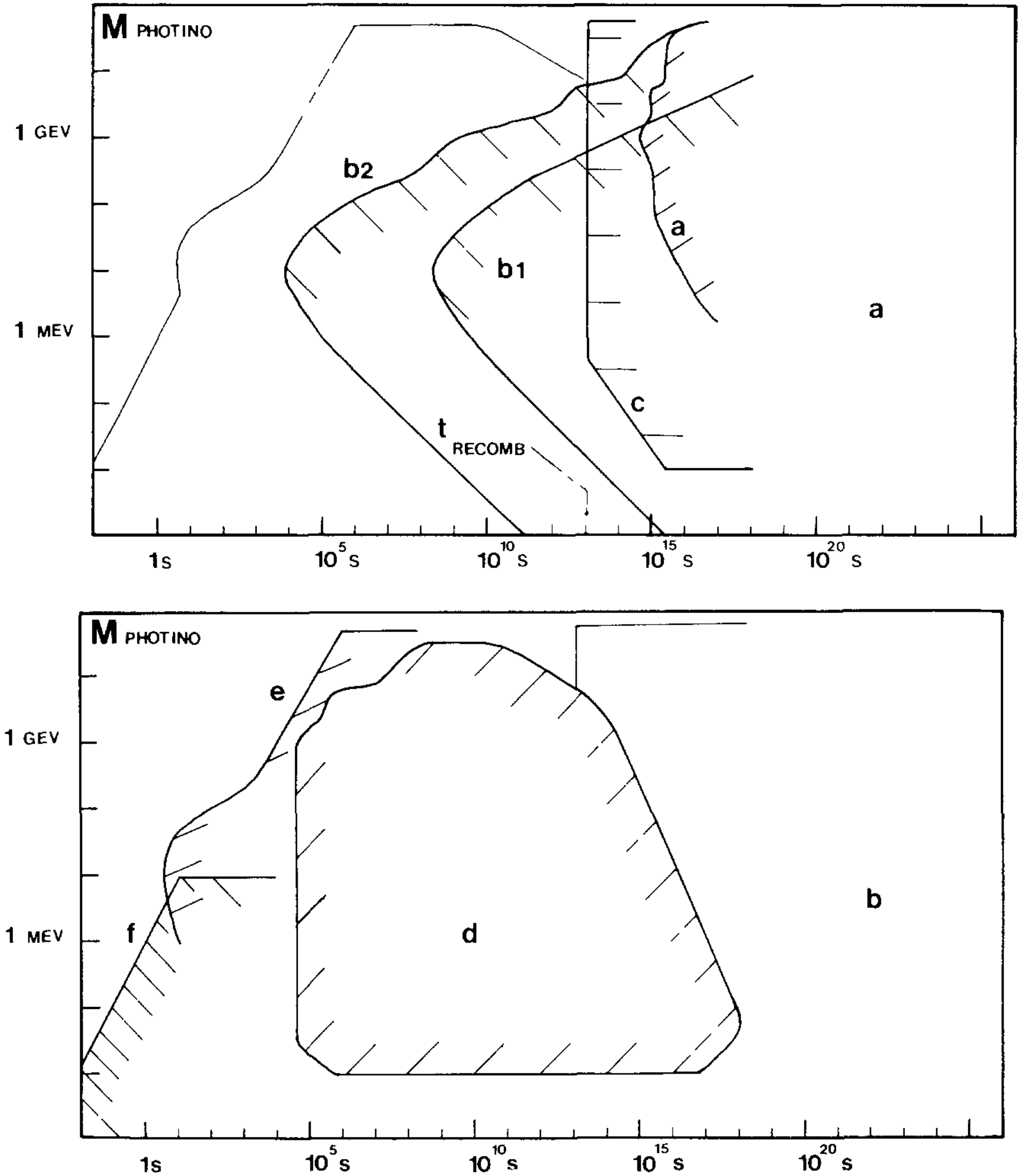



Fig 2 Cosmological bounds on the photino lifetime as a function of its mass Fig 2a shows the limit from Davis' experiment on solar neutrinos (curve a), the constraints from the energy density of the Universe (curve b1 from the overall density and curve b2 from the radiation density limit set by theories of galaxy formation), and the limit on the cosmic gamma-ray background (curve c) The overall envelope of the constraints shown in fig 2b is also drawn for comparison purposes Fig 2b shows the limit which comes from CBR distortion (curve d), the nucleosynthesis bound (curve e) and the supernova limit (curve f)

Pioneering work setting constraints from:

solar neutrinos,
cosmic energy density,
radiation density,
CMB distortion,
BBN,
Supernovae

# R-Parity Violation + Spalerons

Sphalerons in equilibrium between

160 GeV < T < $10^{12}$ GeV

If an additional B-L violating operator is in equilibrium at the same time

$\Rightarrow$ Washout of the primordial baryon asymmetry

$$
\begin{aligned}
W_{\rm RPV}^{(2)} &= \mu_i' H_u \cdot L_i , \\
W_{\rm RPV}^{(3)} &= \frac{1}{2}\lambda_{ijk} L_i \cdot L_j E_k^c + \lambda'_{ijk} L_i \cdot Q_i D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c \, .
\end{aligned}
$$

Constrains $\mu', \lambda, \lambda', \lambda''$

## Limits on $\mu'$

1 to 2 processes involving a Higgsino, lepton and gauge boson with rate:

$$\Gamma_{1\to 2} = \frac{g^2\theta^2 T}{16\zeta(3)\pi} \simeq 0.016 g^2 \frac{\mu'^2}{m_f^2} T \,,$$

Campbell, Davidson, Ellis, Olive;

Dudas, Gherghetta, Kaneta, Mambrini, Olive

Out of equilibrium $\Rightarrow$ $\mu' < 2.3 \times 10^{-5}\,\mathrm{GeV}\,.$

$\epsilon \lesssim 2.3 \times 10^{-7}.$ $\quad \epsilon = \mu'/\sqrt{\mu^2 + \mu'^2}\,.$

## Limits on $\lambda, \lambda', \lambda''$

1 to 2 processes involving a scalar and two fermions or
2 to 2 processes involving four scalars
with rates:

$$\Gamma_{2\to 2} = \frac{\lambda^2 y^2 T}{128\zeta(3)\pi^3} \simeq 2\times 10^{-4}\lambda^2 y^2 T\,,$$
$$\Gamma_{1\to 2} = \frac{\lambda^2 m_0^2}{16\zeta(3)\pi T} \simeq 0.016\lambda^2 \frac{m_0^2}{T}\,,$$

Campbell, Davidson, Ellis, Olive

Out of equilibrium $\Rightarrow$

$$\lambda < 1.2\times 10^{-6} y^{-1} \qquad 2\leftrightarrow 2\,,$$
$$\lambda < 1.4\times 10^{-7} \qquad 1\leftrightarrow 2\,,$$

Also limits from higher order operators

# Scale of Supersymmetry

100 GeV - Weak Scale

1 TeV - Still close to the Weak Scale

pushed by the
Higgs Mass

1 PeV - But still with ~ TeV scale DM

1 EeV - Susy out of reach, but gravitino DM

1 YeV - GUT scale

1 HeV* - Planck scale

*Hella

What if the entire SUSY matter spectrum were very large

with only the gravitino remaining “light”

Benakli, Chen, Dudas, Mambrini
Dudas, Mambrini, Olive

## Supersplit Supersymmetry

- 1 parameter model: $m_{3/2}$

# Gravitino Mass Limits

$m_{3/2} < 4$ TeV unless(!) the susy spectrum lies above the inflationary scale.

For $M_{susy} \sim F^{1/2} > m_{infl} \sim 3 \times 10^{13}$ GeV

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} > \frac{m_\phi^2}{\sqrt{3}M_P} \simeq 0.2 \text{ EeV}$$

# Gravitino Production

Standard Picture:

gluon + gluon $\rightarrow$ gluino + gravitino

$$\langle \sigma v \rangle \sim \frac{1}{M_P^2}\left(1 + \frac{m_{\tilde{g}}^2}{3m_{3/2}^2}\right)$$

$$\Gamma \sim T^3 \frac{m_{\tilde{g}}^2}{M_P^2 m_{3/2}^2}$$

$m_{\tilde{g}} > m_{3/2}$

$$\frac{n_{3/2}}{n_\gamma} \sim \frac{\Gamma}{H} \sim T \frac{m_{\tilde{g}}^2}{M_P m_{3/2}^2}$$

Not possible if $m_{\tilde{g}} > m_\phi$

# Gravitino Production

$$m_{\tilde{g}} > m_{\phi}$$

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} > \frac{m_\phi^2}{\sqrt{3}M_P} \simeq 0.2 \text{ EeV}$$

gluon + gluon → gravitino + gravitino

$$\langle \sigma v \rangle \sim \frac{T^6}{M_P^4 m_{3/2}^4}$$

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

$$\frac{n_{3/2}}{n_\gamma} \sim \frac{\Gamma}{H} \sim \frac{T^7}{M_P^3 m_{3/2}^4}$$

$$\Omega_{3/2} h^2 \simeq 0.11 \left( \frac{0.1 \text{ EeV}}{m_{3/2}} \right)^3 \left( \frac{T_{RH}}{2.0 \times 10^{10} \text{ GeV}} \right)^7$$

## Limits on $\mu'$

1 to 2 processes not applicable if all susy particles are heavy
But dimension 5 operators are still generated

$$\mathcal{L}_5 \simeq \frac{1}{M_5}\nu_L\nu_L hh, \quad \frac{1}{M_5} \simeq \epsilon^2 \frac{g_2^2 M_1 + g_1^2 M_2}{M_1 M_2 (1+\tan^2\beta)},$$

Dudas, Gherghetta, Kaneta, Mambrini, Olive

$$\epsilon = \mu'/\sqrt{\mu^2 + \mu'^2}$$

Out of equilibrium $\Rightarrow$ $$M_5 > \frac{(c_5 T M_P)^{1/2}}{\sqrt{0.33 g_*^{1/2}}} \approx 2.8 \times 10^{13}\,\mathrm{GeV},$$

or $$\mu' < 1.7 \times 10^{-7}\mathrm{GeV}^{-1/2}\tilde{m}^{1/2}\mu(1+\tan^2\beta)^{1/2}/g \approx 6.6 \times 10^{13}\,\mathrm{GeV}, \qquad \epsilon \lesssim 2.2.$$

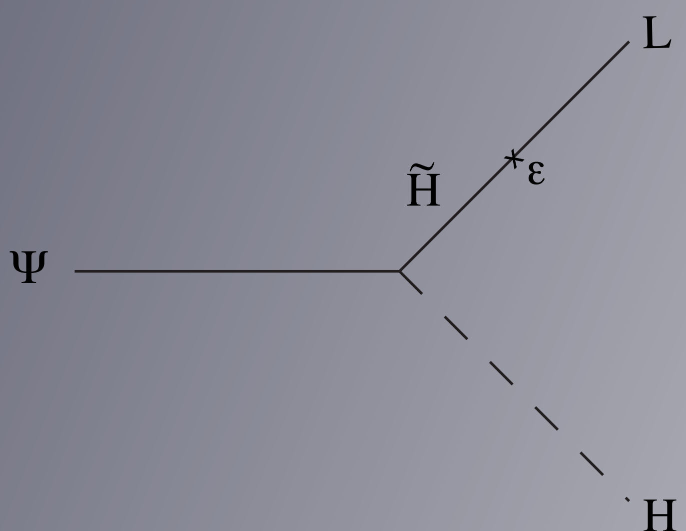
lab limits slightly better $\quad 1.7 \times 10^{13}\,\mathrm{GeV} \qquad \epsilon \lesssim 0.57.$

Signatures of decay with R-parity violation

$$W_{\rm RPV} \;=\; \mu' L H_u .$$

Normally, $\mu' < 2 \times 10^{-5}\,\mathrm{GeV}$ from L-violating interactions

High Scale Susy: $\mu' < 2 \times 10^{-7} \left( \dfrac{\mu \widetilde{m}^{1/2}}{\mathrm{GeV}^{3/2}} \right) \;\mathrm{GeV}$



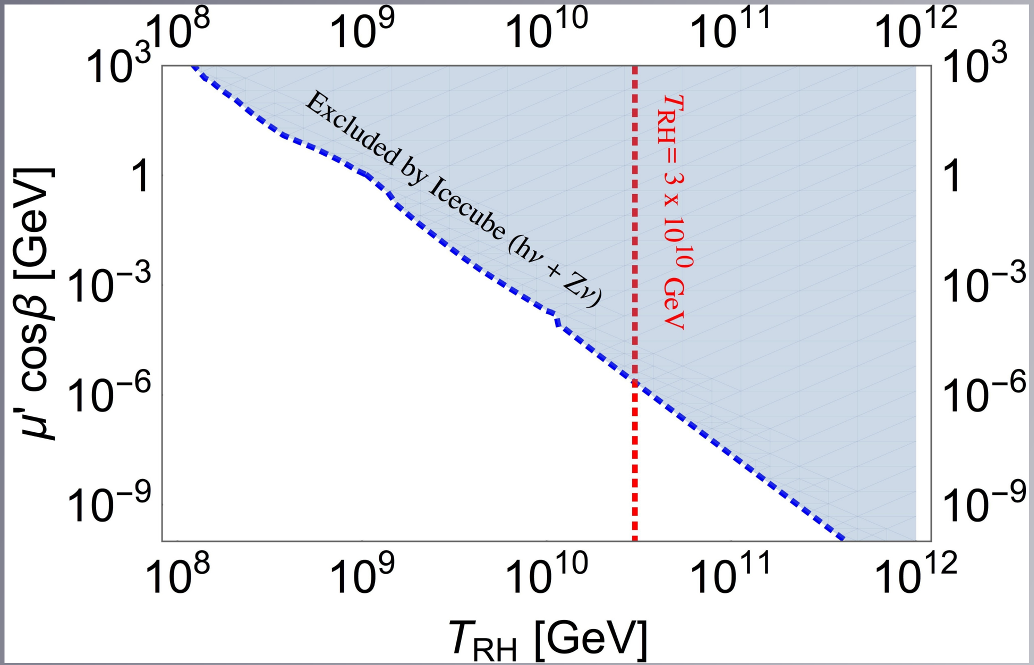

$$\Gamma_{\rm tot} \simeq \frac{\epsilon^2 c_\beta^2 m_{3/2}^3}{16\pi M_P^2} \qquad \epsilon = \mu'/\mu$$

$$\tau_{3/2} \simeq 10^{28} \left( \frac{0.44 \times 10^{-20}}{\epsilon c_\beta} \right)^2 \left( \frac{1\ \mathrm{EeV}}{m_{3/2}} \right)^3 \mathrm{s}.$$

# Detection?

$$\tau_{3/2} \simeq 10^{28} \left(\frac{\widetilde{m}}{10^{14}\ \mathrm{GeV}}\right)^2 \left(\frac{0.44\ \mathrm{keV}}{\mu' c_\beta}\right)^2 \left(\frac{1\ \mathrm{EeV}}{m_{3/2}}\right)^3 \mathrm{s} \qquad \mu \sim \widetilde{m} \gg \mu'$$

$$\mu' c_\beta = 14\ \mathrm{keV} \left(\frac{\Omega_{3/2} h^2}{0.11}\right)^{1/2} \left(\frac{10^{28}\ \mathrm{s}}{\tau_{3/2}}\right)^{1/2} \left(\frac{\widetilde{m}}{10^{14}\,\mathrm{GeV}}\right) \left(\frac{2.0 \times 10^{10}\,\mathrm{GeV}}{T_{\mathrm{RH}}}\right)^{7/2}$$




Expect about 1 event at ANITA every ~100 years.

ANITA has seen 2 O(EeV) events in 3 years

## Limits on $\lambda, \lambda', \lambda''$

Most of these disappear

particles not in the thermal bath

no D=6 B-L violating operators involving only SM fields

There are D=6 B-L conserving operators
and limits from p-decay can be derived

$$\left|\sum_{m=1}^{3} \lambda''^{*}_{11m}\lambda'_{11m}\right| < 2.3 \times 10^{-5} \left(\frac{\widetilde{m}}{3 \times 10^{13}\ \mathrm{GeV}}\right)^2$$

# Finally:

Congratulations Pierre!

Good Luck on Phase 2!


Its a tribute that your work remains relevant after 30-40 years!