BARYOGENESIS AND NEUTRON-ANTINEUTRON OSCILLATION IN R-PARITY VIOLATING SUSY

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INTRODUCTION

- Baryon Number Violation in your theory:
  - Origin of Baryogenesis
  - Observable $\Delta B = 2$ processes: $n \to \bar{n}$ transition

    di-nucleon decay $NN \to KK, \pi\pi$

- We work in R-parity/B-violating Supersymmetry to single out a promising coupling:
  - $W_{BNV} = \frac{1}{2}\,\lambda''_{ijk} U_i^c D_j^c D_k^c$

RPV (BNV) BARYOGENESIS

- Observed baryon asymmetry:

$$Y_B \equiv \frac{n_b}{s} \approx 10^{-10}$$

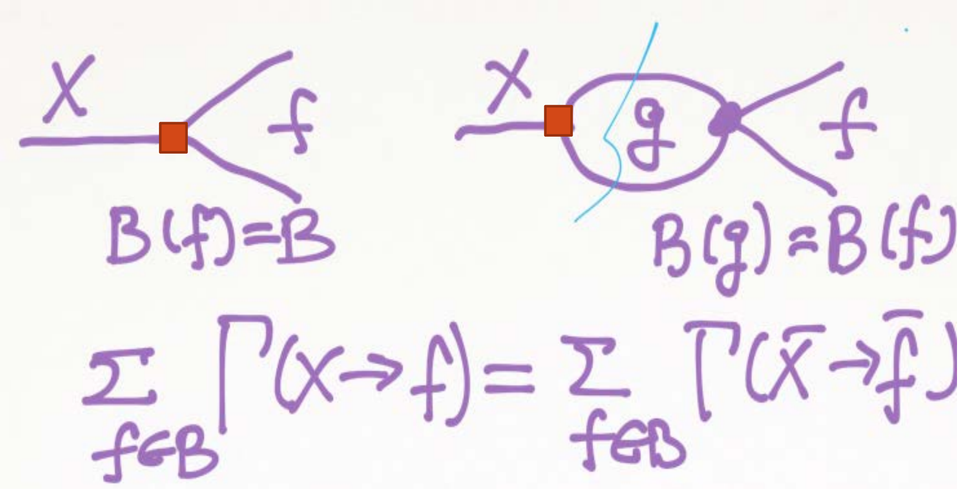
- Baryogenesis from out-of-equilibrium decay of a particle X:

$$Y_B \sim \epsilon_X \, Y_X \,, \quad \epsilon_X = \frac{\Gamma(X \to f) - \Gamma(\bar{X} \to \bar{f})}{\Gamma(X \to f) + \Gamma(\bar{X} \to \bar{f})}$$

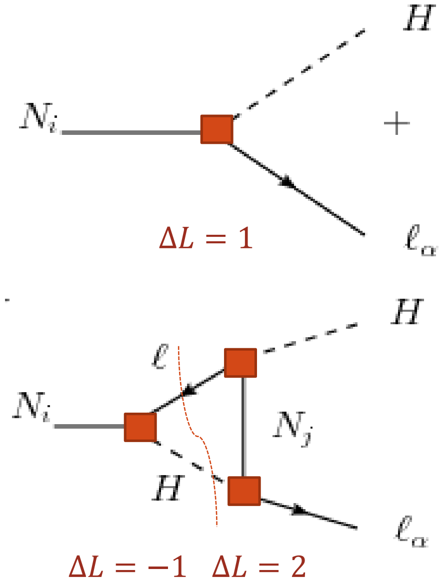
- Require a large initial abundance $Y_X \gg 10^{-10}$ → a super-WIMP.
- Require $\lambda'' > 10^{-3}$ → late baryogenesis $(T \ll T_{EW})$ to avoid wash out.
- Thus, X = inflaton, gravitino, axino, or sparticle with super-split spectrum, …

RPV (BNV) BARYOGENESIS

- Nanopoulos-Weinberg (1978): If X decays only through $\mathcal{L}_{BNV}$, no asymmetry is generated at the leading order of $\mathcal{L}_{BNV}$.



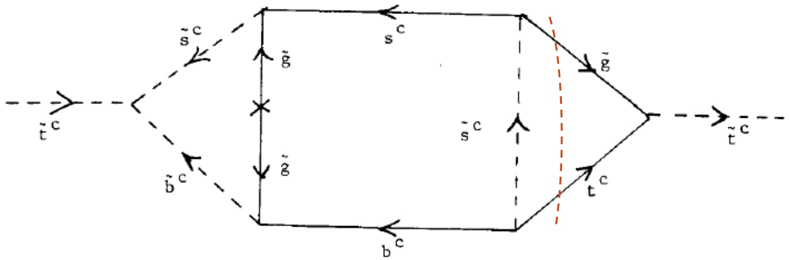
Nb) Leptogenesis



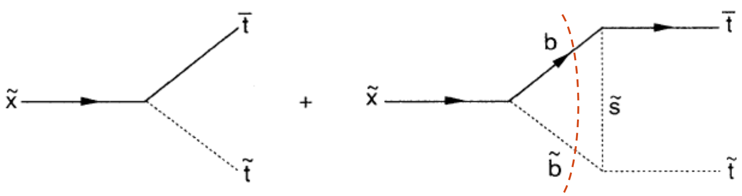
NON-LSP DECAYS

- X decaying through $\mathcal{L}_{BNV}$ as well as $\mathcal{L}_{BNC}$:

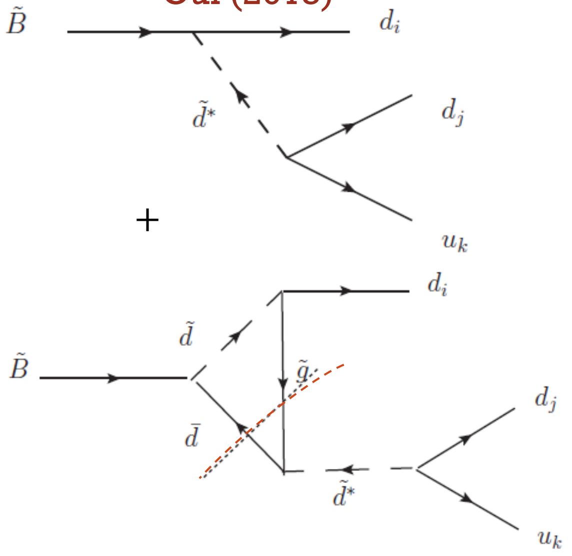
Dimopolous-Hall (1987)



Cline-Raby (1991)

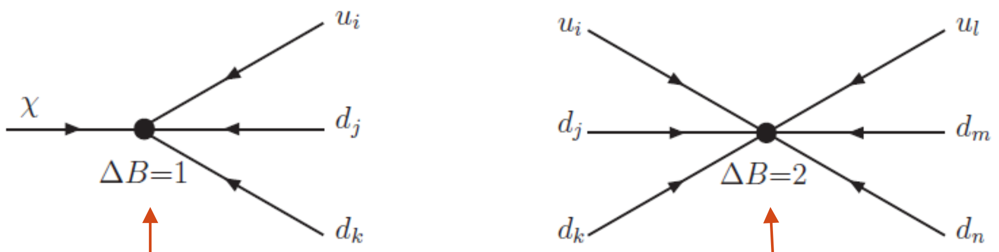


Cui (2013)



LSP DECAYS

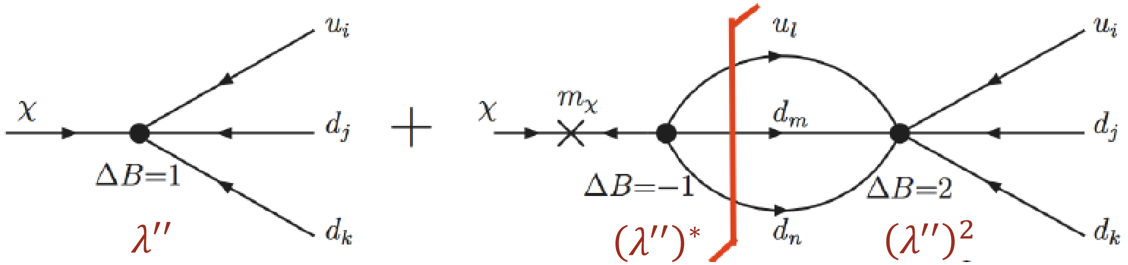
- Monteux-Shin (2014): LSP going to higher order in $\mathcal{L}_{BNV}$ (two-loop)



BNV decay (D=6)

Correlated with $n-\bar{n}$ oscillation (D=9)

- B/CP asymmetry: the interference between B=1 and B=2 operators



AXINO LSP BARYOGENESIS

Monteux-Shin 2013

- Axino decaying only through BNV.
- Its coupling suppressed by $1/f_a$ ($f_a = 10^{9-12} GeV$) → guaranteed late out-of-equilibrium decay.

  DFSZ model: $\mathcal{L} \sim \frac{m_t}{f_a} \tilde{a} t \tilde{t} + h.c.$

  KSVZ model: $\mathcal{L} \sim \frac{\alpha_s}{4\pi} \frac{1}{f_a} \tilde{a} G \tilde{G} + h.c.$

- B/CP asymmetry isinsensitive to the property of the decaying particle.
- Conditions to be satisfied:

  $Y_{\tilde{a}} \gg 10^{-10}$

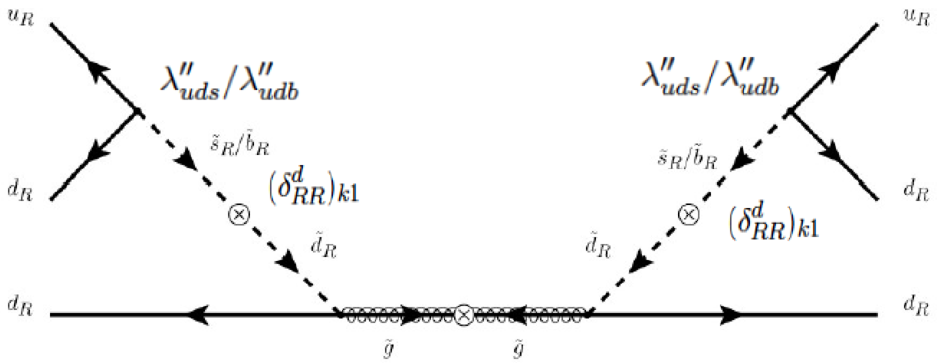
  $\tau_{\tilde{a}} < 1s \ (T_D > 1\ MeV)$

$\Delta B = 2$ PROCESSES

- Neutron-antineutron oscillation: $\tau_{n\bar{n}} > 0.86 \times 10^8\ s$ (ILL 1994)

  $\tau_{n\bar{n}} > 3 \times 10^9\ s$ (ESS 2023-25)
- Dineucleon decay, $NN \to KK$: $\tau_{n\bar{n}} > 2.7 \times 10^8\ s$ (SK 2014)
- Current limit: $\lambda''_{112} < 10^{-6,-7}$

  $\lambda''_{11k}\delta^d_{k1} < 10^{-8}$ with squark mixing (Calibbi, et.al., 2016)

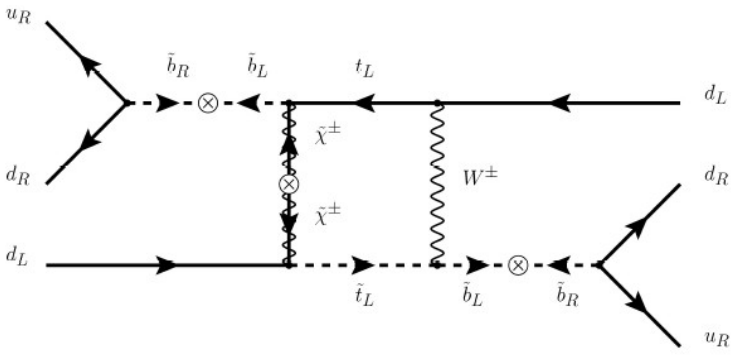


Zwirner 1983

OBSERVABLE $n-\bar{n}$ OSCILLATION

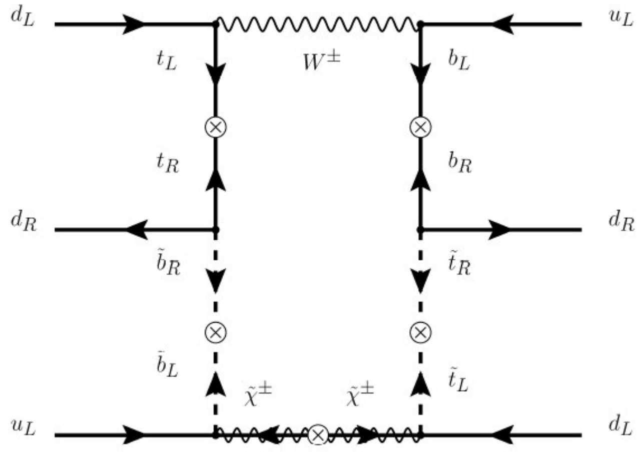
- Assume no squark flavor mixing.
- Sizable n-nbar oscillation through λ''_{113} & λ''_{313}

Goity-Sher (1995)



λ''_{113} too small for the Axino LSP baryogenesis

Chang-Keung (1996)



CK CONTRIBUTION

- B=2 Dimension-9 operator: $\mathcal{L}_{n\bar{n}} = C_{n\bar{n}}(udd)^2 + h.c.$

$$C_{n\bar{n}}^{CK} = \frac{g^4}{64\pi^2}(\lambda''_{313})^2(V_{td}V_{ub}^*)^2\, m_{\tilde{\chi}^\pm} m_t m_b c_{\tilde{t}} s_{\tilde{t}} c_{\tilde{b}} s_{\tilde{b}}$$
$$J_6(m_{\tilde{t}_1}^2, m_{\tilde{b}_1}^2, m_{\tilde{\chi}^\pm}^2, m_W^2, m_t^2, m_b^2)$$

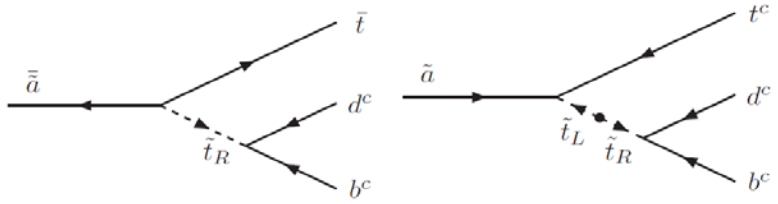
$$\text{where } J_6(a_1,a_2,a_3,a_4,a_5,a_6) = \sum_{i=1}^{6} \frac{a_i \log a_i}{\prod_{k\neq i}(a_k - a_i)}\,.$$

- The n-nbar transition: $< \bar{n}|\mathcal{L}_{n\bar{n}}|n >$
- Resulting n-nbar oscillation time:

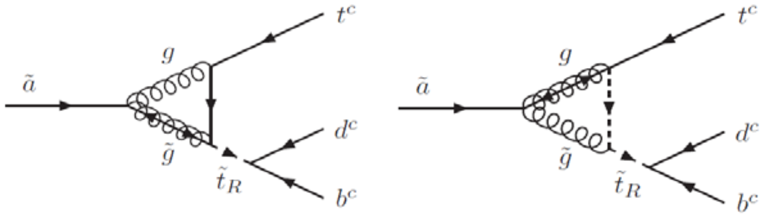
$$\tau_{n\bar{n}} \approx 10^9\,\mathrm{sec}\left(\frac{0.2}{\lambda''_{313}}\right)^2\left(\frac{m_S}{500\ \mathrm{GeV}}\right)^5\left(\frac{0.5}{c_{\tilde{t}} s_{\tilde{t}}}\right)\left(\frac{0.5}{c_{\tilde{b}} s_{\tilde{b}}}\right)\frac{(250\ \mathrm{MeV})^6}{\langle\bar{n}|(udd)^2|n\rangle}$$

B=1 & B=2 PROCESSES

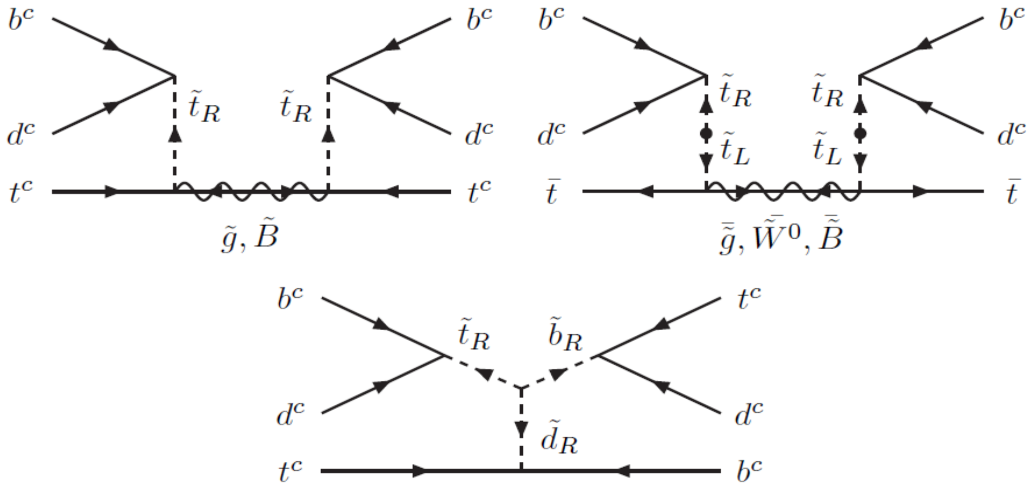
DFSZ axino decay



KSVZ axino decay



B=2 D=9 operator



Nb) Resonant enhancement
for $m_{\tilde{a}} \approx m_{\tilde{\lambda}}$

DFSZ AXINO BARYOGENESIS

- Effective B=1 decay operator:

$$\mathcal{L}_{\rm decay} \simeq \frac{\lambda''_{313} m_t}{f_a m^2_{\tilde{t}_1}} \left(c^2_{\tilde{t}}\, \overline{\tilde{a}} \bar{t} d^c b^c + c_{\tilde{t}} s_{\tilde{t}} e^{-i\varphi_{\tilde{t}}}\, \tilde{a} t^c d^c b^c \right) + h.c.$$

- Decay temperature:

$$T_D \approx 800 \text{ MeV} \left(\frac{|\lambda''_{313}|}{0.2} \right) \left(\frac{500 \text{ GeV}}{m_{\tilde{t}_1}} \right)^2 \left(\frac{|m_{\tilde{a}}|}{400 \text{ GeV}} \right)^{5/2} \left(\frac{10^{10}\text{GeV}}{f_a} \right)$$

- Axino abundance:

$$Y_{\tilde{a}} = \min \left[Y^{TP}_{\tilde{a}}, \frac{3}{4} \frac{T_D}{m_{\tilde{a}}} \right] \gtrsim 10^{-3} \left(\frac{\epsilon}{10^{-7}} \right)^{-1}$$

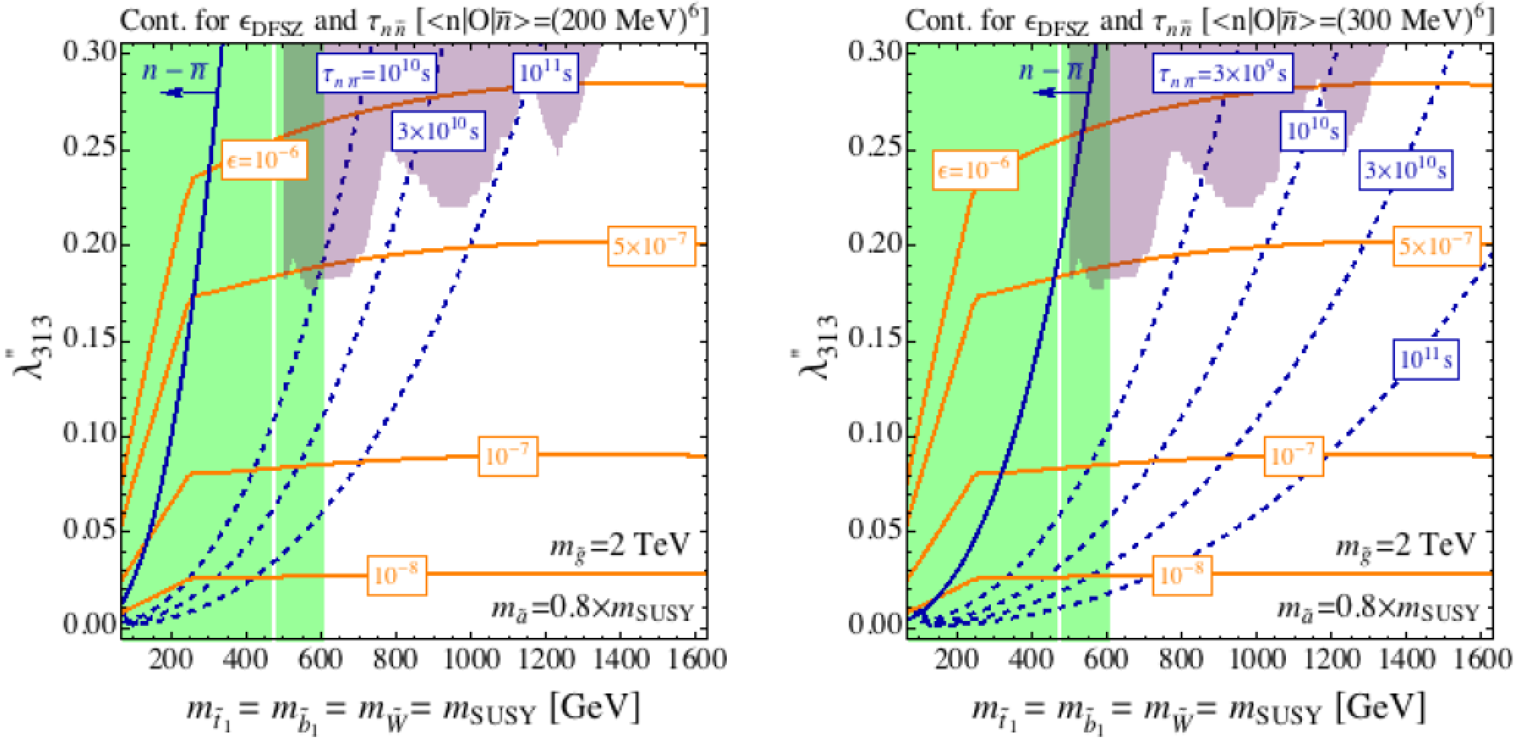
CP ASYMMETRY

$$\epsilon = \frac{\Gamma(\tilde{a} \to qqq) - \Gamma(\tilde{a} \to \bar{q}\bar{q}\bar{q})}{\Gamma(\tilde{a} \to qqq) + \Gamma(\tilde{a} \to \bar{q}\bar{q}\bar{q})}$$

- From the interference between B=1 and B=2 operators.
- CP phase from the axino/gaugino masses and A-terms.

$$\begin{aligned}
\epsilon = & \left| \frac{c_{\tilde{t}}^2 (c_{\tilde{t}}^2 - s_{\tilde{t}}^2) g_s^2 (\lambda''_{313})^2 m_{\tilde{a}}^5}{32\pi^3 m_{\tilde{g}} m_{\tilde{t}_1}^4} \right| \mathrm{Im}\left[\frac{m_t^2}{|m_{\tilde{a}}|^2} e^{i(\varphi_{\tilde{g}} + \varphi_{\tilde{a}})} + \frac{c_{\tilde{t}} s_{\tilde{t}} m_t}{2|m_{\tilde{a}}|} e^{i(\varphi_{\tilde{g}} - \varphi_{\tilde{t}})} \right] \\
& + \left| \frac{3 c_{\tilde{t}}^2 s_{\tilde{t}}^2 g^2 (\lambda''_{313})^2 m_{\tilde{a}}^5}{128\pi^3 m_{\tilde{t}_1}^4 m_{\widetilde{W}}} \right| \mathrm{Im}\left[\frac{s_{\tilde{t}}^2 m_t^2}{|m_{\tilde{a}}|^2} e^{-i(\varphi_{\widetilde{W}} + \varphi_{\tilde{a}})} + \frac{c_{\tilde{t}} s_{\tilde{t}} m_t}{2|m_{\tilde{a}}|} e^{-i(\varphi_{\widetilde{W}} - \varphi_{\tilde{t}})} + \frac{c_{\tilde{t}}^2}{4} e^{i(2\varphi_{\tilde{t}} - \varphi_{\widetilde{W}} + \varphi_{\tilde{a}})} \right] \\
& + \left| \frac{c_{\tilde{t}}^2 c_{\tilde{d}}^2 c_{\tilde{b}}^2 (\lambda''_{313})^4 A''_{313} m_{\tilde{a}}^5}{32\pi^3 m_{\tilde{t}_1}^2 m_{\tilde{b}_1}^2 m_{\tilde{d}_1}^2} \right| \mathrm{Im}\left[\frac{c_{\tilde{t}}^2 m_t^2}{|m_{\tilde{a}}|^2} e^{i(\varphi_{313} + \varphi_{\tilde{a}})} + \frac{c_{\tilde{t}} s_{\tilde{t}} m_t}{2|m_{\tilde{a}}|} e^{i(\varphi_{\tilde{3}13} - \varphi_{\tilde{t}})} + \frac{s_{\tilde{t}}^2}{4} e^{-i(2\varphi_{\tilde{t}} - \varphi_{\tilde{3}13} + \varphi_{\tilde{a}})} \right]
\end{aligned}$$

RESULT: DFSZ

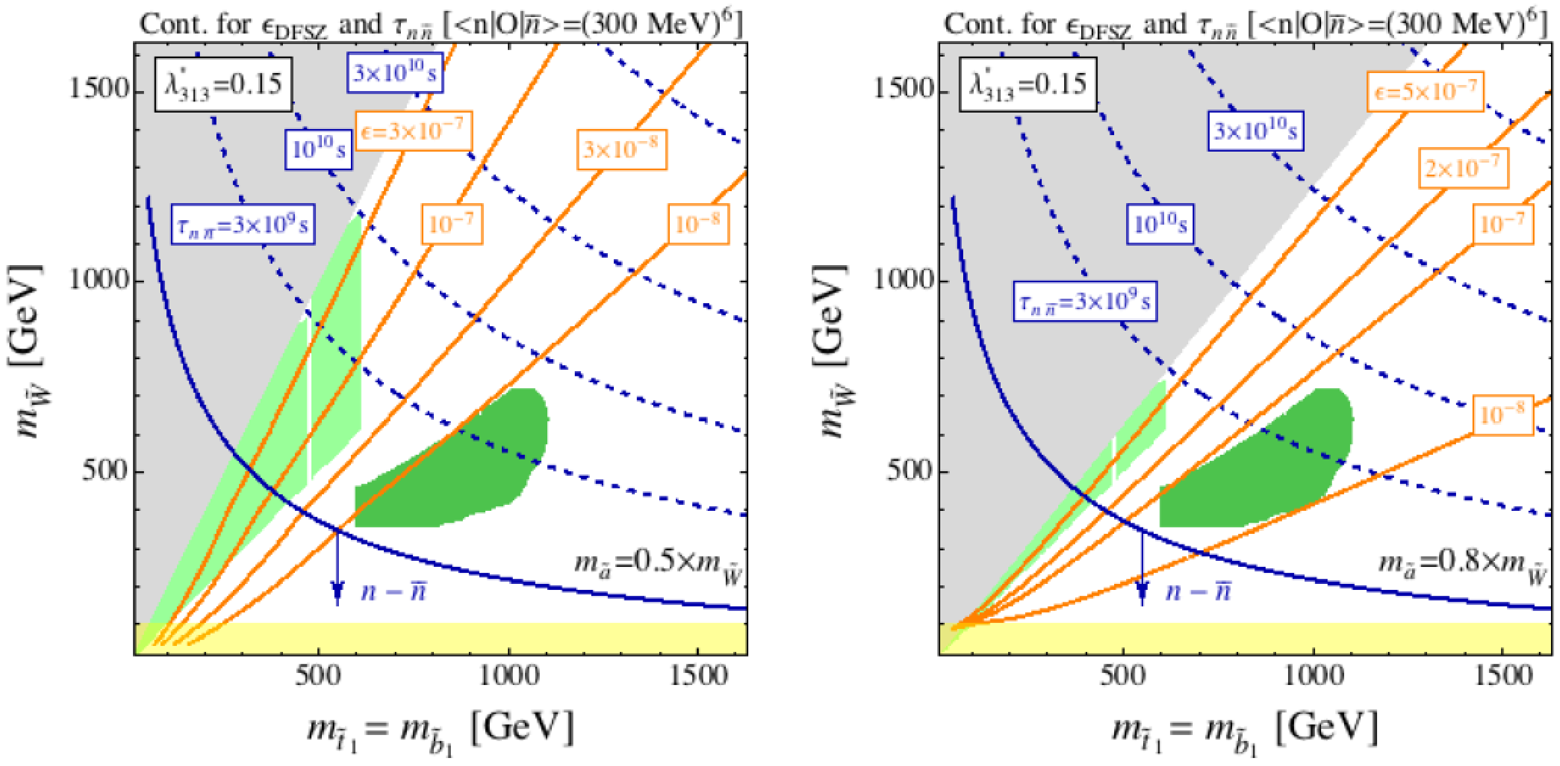


LHC limits on RPV squark decays:

ATLAS 4-jet search   Single stop production

Monteux 2016

RPV WINO SEARCH FROM STOP DECAY



LHC limits: ATLAS 4-jet search ATLAS multi-jet search

KSVZ AXINO BARYOGENESIS

- Effective B=1 decay operator:

$$\mathcal{L}_{\rm decay} \simeq \frac{g_2^4}{(16\pi^2)^2}\frac{\lambda''_{313}|m_{\tilde g}|}{f_a m_{\tilde t_1}^2}\ln\frac{f_a^2}{|m_{\tilde g}|^2}\left(c_{\tilde t}^2 e^{-i\varphi_{\tilde g}}\,\tilde a t^c d^c b^c + c_{\tilde t}s_{\tilde t}e^{-i(\varphi_{\tilde t}-\varphi_{\tilde g})}\,\overline{\tilde a}\tilde{\bar t} d^c b^c\right) + h.c.$$

- Decay temperature:

$$T_D \simeq 200\,\mathrm{MeV}\left(\frac{|\lambda''_{313}|}{0.2}\right)\left(\frac{500\,\mathrm{GeV}}{m_{\tilde t_1}}\right)^2\left(\frac{|m_{\tilde a}|}{400\,\mathrm{GeV}}\right)^{5/2}\left(\frac{|m_{\tilde g}|}{2\,\mathrm{TeV}}\right)\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$$

- Axino abundance

$$Y_{\tilde a} = \min\left[Y_{\tilde a}^{TP}, \frac{3}{4}\frac{T_D}{m_{\tilde a}}\right] \gtrsim 10^{-3}\left(\frac{\epsilon}{10^{-7}}\right)^{-1}$$

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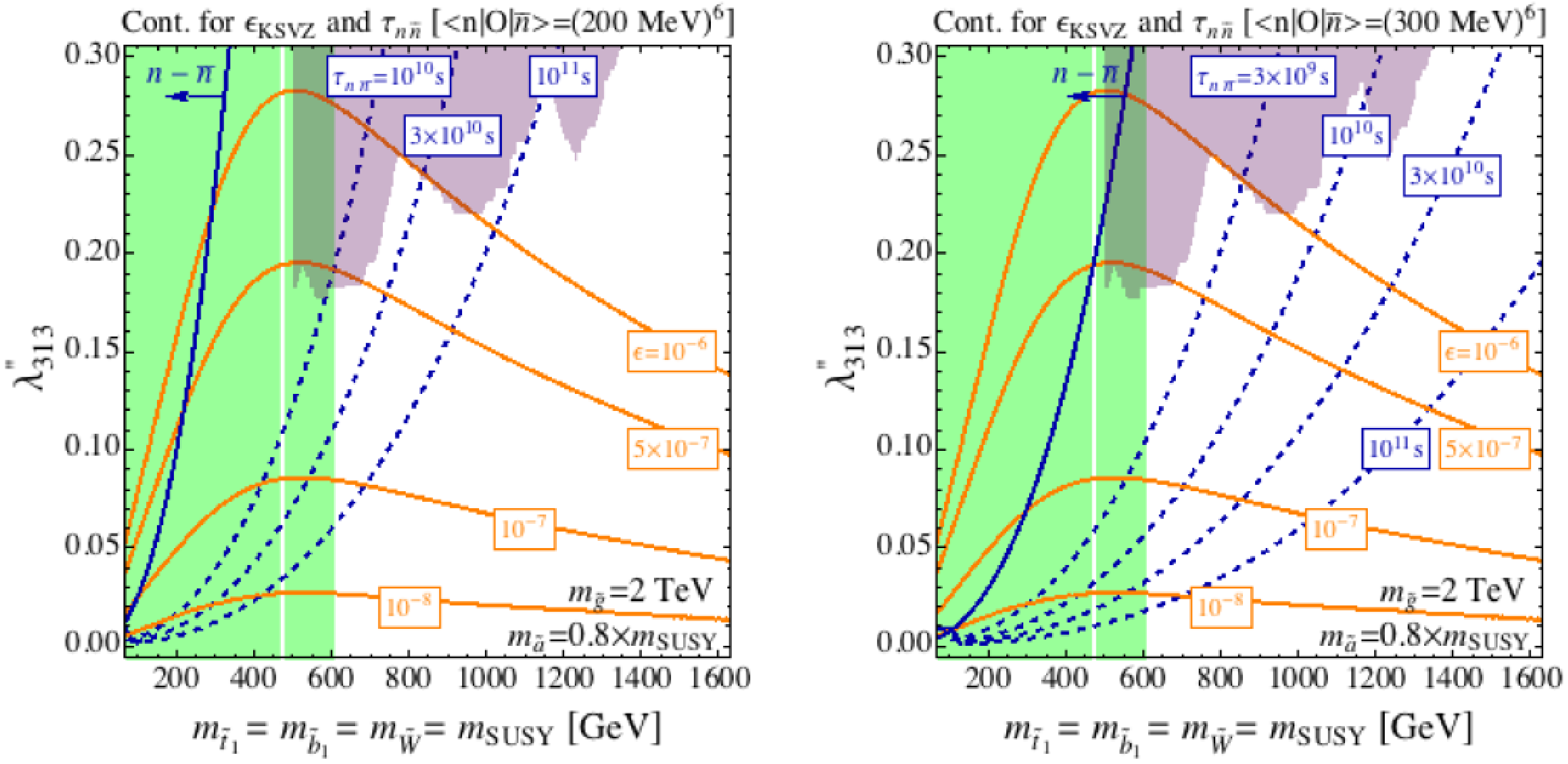
$$\epsilon = \frac{\Gamma(\tilde{a} \to qqq) - \Gamma(\tilde{a} \to \bar{q}\bar{q}\bar{q})}{\Gamma(\tilde{a} \to qqq) + \Gamma(\tilde{a} \to \bar{q}\bar{q}\bar{q})}$$

- From the interference between B=1 and B=2 operators.
- CP phase from the axino/gaugino masses and A-terms.

$$\begin{aligned}
\epsilon = & \left|\frac{c_{\tilde{t}}^2(c_{\tilde{t}}^2 - s_{\tilde{t}}^2)g_s^2(\lambda''_{313})^2 m_{\tilde{a}}^5}{32\pi^3 m_{\tilde{g}} m_{\tilde{t}_1}^4}\right| \mathrm{Im}\left[\frac{c_{\tilde{t}} s_{\tilde{t}} m_t}{2|m_{\tilde{a}}|} e^{i(\varphi_{\tilde{g}} - \varphi_{\tilde{t}})} + \frac{1}{4} e^{-i(\varphi_{\tilde{g}} + \varphi_{\tilde{a}})}\right] \\
& + \left|\frac{3c_{\tilde{t}}^2 s_{\tilde{t}}^2 g^2(\lambda''_{313})^2 m_{\tilde{a}}^5}{128\pi^3 m_{\tilde{t}_1}^4 m_{\widetilde{W}}}\right| \mathrm{Im}\left[\frac{c_{\tilde{t}}^2 m_t^2}{|m_{\tilde{a}}|^2} e^{-i(2\varphi_{\tilde{g}} + \varphi_{\widetilde{W}} - 2\varphi_{\tilde{t}} + \varphi_{\tilde{a}})} + \frac{c_{\tilde{t}} s_{\tilde{t}} m_t}{2|m_{\tilde{a}}|} e^{-i(\varphi_{\widetilde{W}} - \varphi_{\tilde{t}})} + \frac{s_{\tilde{t}}^2}{4} e^{i(2\varphi_{\tilde{g}} - \varphi_{\widetilde{W}} + \varphi_{\tilde{a}})}\right] \\
& + \left|\frac{c_{\tilde{t}}^2 c_{\tilde{d}}^2 c_{\tilde{b}}^2 (\lambda''_{313})^4 A''_{313} m_{\tilde{a}}^5}{32\pi^3 m_{\tilde{t}_1}^2 m_{\tilde{b}_1}^2 m_{\tilde{d}_1}^2}\right| \mathrm{Im}\left[\frac{s_{\tilde{t}}^2 m_t^2}{|m_{\tilde{a}}|^2} e^{i(2\varphi_{\tilde{g}} + \varphi_{313} - 2\varphi_{\tilde{t}} + \varphi_{\tilde{a}})} + \frac{c_{\tilde{t}} s_{\tilde{t}} m_t}{2|m_{\tilde{a}}|} e^{i(\varphi_{313} - \varphi_{\tilde{t}})} + \frac{c_{\tilde{t}}^2}{4} e^{-i(2\varphi_{\tilde{g}} - \varphi_{313} + \varphi_{\tilde{a}})}\right].
\end{aligned}$$

RESULT: KSVZ



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Monteux 2016

CONCLUSION

- BNV SUSY with Axino LSP to explain the matter-antimatter asymmetry of the Universe while providing an observable n-nbar oscillation effect.
- Super-weakly interacting axino → automatic out-of-equilibrium decay, but should decay before BBN.
- Baryogenesis a la Monteux-Shin: interference between B=1 and B=2 operators.
- Observable n-nbar oscillation through Chang-Keung diagram with $\lambda''_{313} \sim 0.1$.
- LHC probe: sub-TeV stop/sbottom/wino.