CONNECTING NEUTRON-ANTINEUTRON OSCILLATION TO BARYOGENESIS

2019 International Workshop on Baryon and Lepton Number Violation (**BLV2019**)

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based on

hep-ph 1806.00011 (PRL) with Christophe Grojean, James D. Wells, Zhengkang Zhang

hep-ph 1901.05493 (JHEP) with Aaron Pierce

NEUTRON-ANTINEUTRON OSCILLATION: EXPERIMENTAL STATUS

[also see Yuri Kamyshkov's talk (Monday)]

- with free neutrons: **Institut Laue-Langevin (ILL)**

$$\tau_{n\bar{n}} > 0.86 \times 10^8 \text{ s at } 90\% \text{ C.L.}$$

- intranuclear searches: **Super-K**

$$\tau_{n\bar{n}} > 2.7 \times 10^8 \text{ s at } 90\% \text{ C.L.}$$

Upcoming experiments will improve on sensitivity by up to three orders of magnitude

- **European Spallation Source (ESS)**
- **Deep Underground Neutrino Experiment (DUNE)**

[see Georgia Karagiorgi's talk (Monday)]

NEUTRON-ANTINEUTRON OSCILLATION: THEORETICAL MOTIVATION

- a test of baryon number violation $|\Delta B| = 2$
- complementary to proton decay: probes baryon number violation without lepton number violation
- $n - \bar{n}$ effective operator is dimension 9: probes new physics at a relatively low scale that could give companion signals at other experiments
- baryon number violation intricately tied to an important early Universe phenomenon:

baryogenesis

NEUTRON-ANTINEUTRON OSCILLATION: THEORETICAL MOTIVATION

- a test of baryon number violation $|\Delta B| = 2$
- complementary to proton decay: probes baryon number violation without lepton number violation
- $n - \bar{n}$ effect
  at a relative
- baryon nu

THIS TALK

Can upcoming $n - \bar{n}$ searches shed light on viable baryogenesis mechanisms? Can the new physics that gives rise to $n - \bar{n}$ also be responsbile for baryogenesis?

FROM $n - \bar{n}$ TO BARYOGENESIS: A SIMPLISTIC APPROACH

Consider a four-fermion BNV operator involving a SM singlet fermion X

$$(1/\Lambda^2)Xudd$$

Integrating X out gives the $n - \bar{n}$ operator

$$\mathcal{L} \supset c_1 \frac{1}{2} \epsilon_{ijk}\epsilon_{i'j'k'}(\bar{u}_i^c P_R d_j)(\bar{u}_{i'}^c P_R d_{j'})(\bar{d}_k^c P_R d_{k'}) \qquad c_1 \equiv (\Lambda_{n\bar{n}}^{(1)})^{-5}$$

Can X also be responsible for baryogenesis?

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Sakharov conditions:

- Baryon number violation ✓ (above operator violates B)
- Out of equilibrium condition ✓ ($X \to udd$ decays are out of eq. processes)
- C,CP violation ✗ (no CP asymmetry in the tree level decay process)

FROM $n - \bar{n}$ TO BARYOGENESIS: A SIMPLISTIC APPROACH

CP violation requires interference between tree+loop diagrams, with an on-shell propagator in the loop

Introduce two SM singlet fermions X_1, X_2 ($m_{X_1} < m_{X_2}$) with interactions

$$\begin{aligned}\mathcal{L} \supset\ & \eta_{X_1}\, \epsilon^{ijk} (\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_1) \\ & + \eta_{X_2}\, \epsilon^{ijk} (\bar{u}_i^c P_R d_j)(\bar{d}_k^c P_R X_2) \\ & + \eta_c\, (\bar{u}^i P_L X_1)(\bar{X}_2 P_R u_i) + \text{h.c.}\,, \\ & \text{with}\ \ |\eta_{X_1}| \equiv \Lambda_{X_1}^{-2}\,,\ |\eta_{X_2}| \equiv \Lambda_{X_2}^{-2}\,,\ |\eta_c| \equiv \Lambda_c^{-2}\end{aligned}$$

required for CP asymmetry to be first order in BNV coupling (Nanopoulos-Weinberg theorem)

CP phase: $\text{Im}(\eta_{X_1}^* \eta_{X_2} \eta_c)$

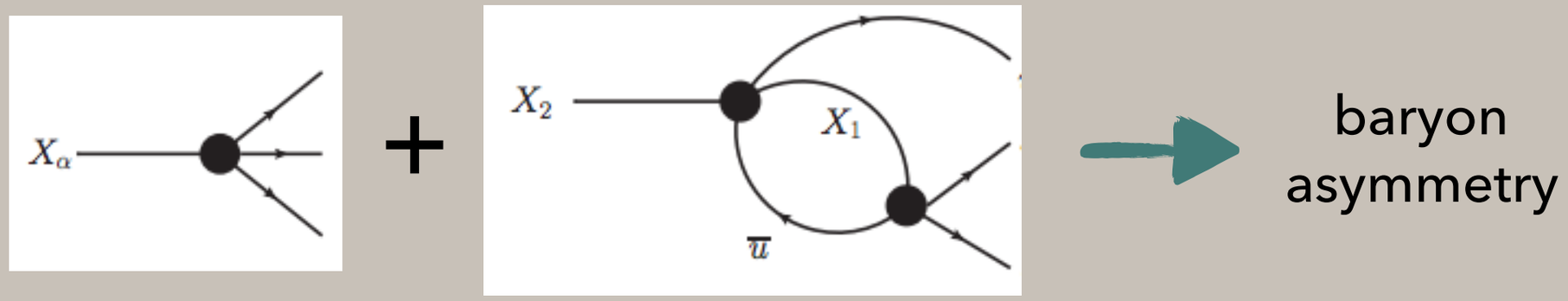
both X_1, X_2 can contribute to $n - \bar{n}$; effective dimensionful coupling:

$$c_1 = \frac{1}{\left(\Lambda_{n\bar{n}}^{(1)}\right)^5} = \frac{1}{M_{X_1}\Lambda_{X_1}^4} + \frac{1}{M_{X_2}\Lambda_{X_2}^4}$$

BARYOGENESIS: AN OUTLINE

Produce (thermalize) X_2 (X_1) in the early Universe

X_2 decays populate baryon asymmetry



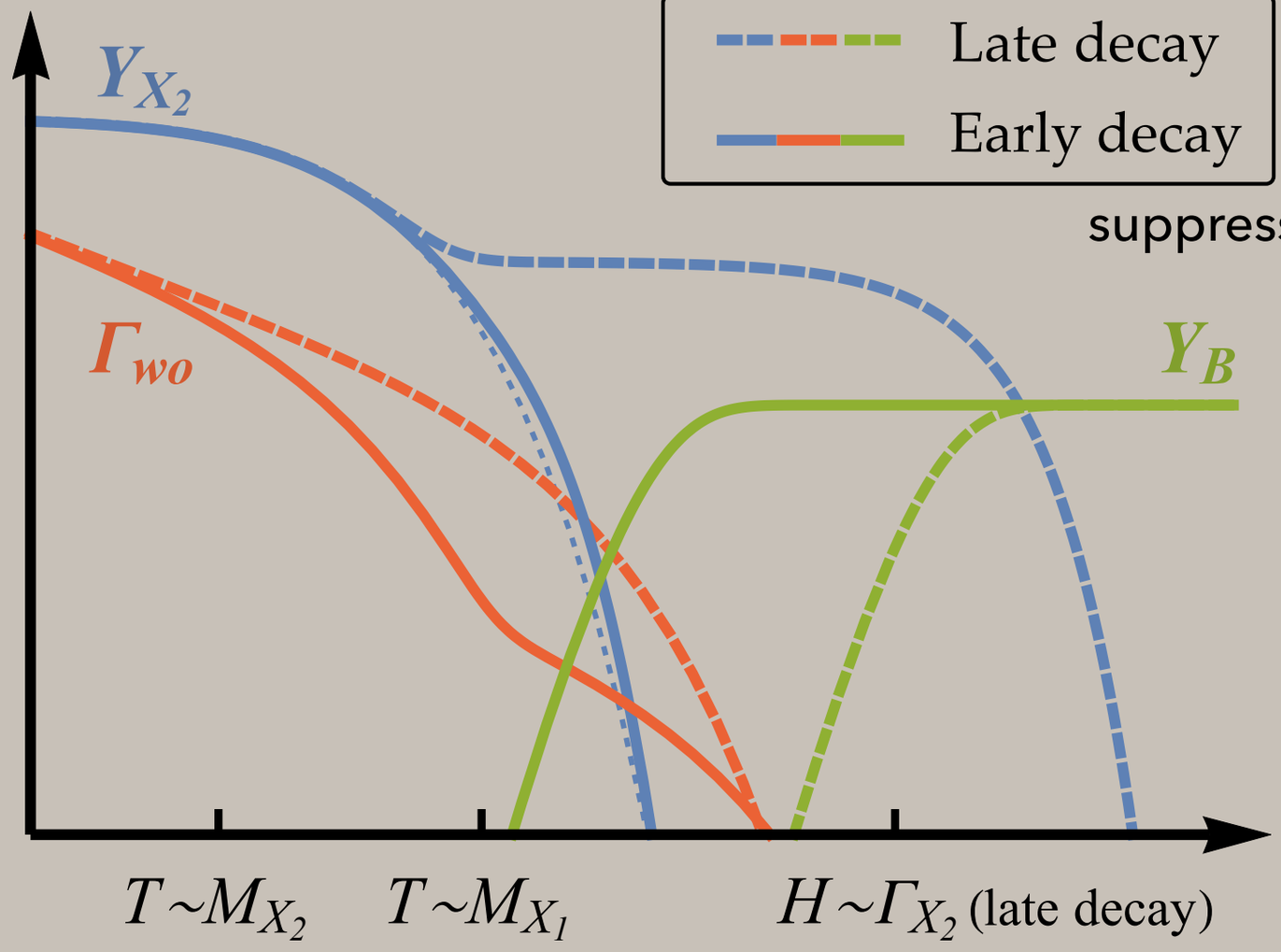
from hep-ph 1410.0108 Baldes et.al.

(also get contributions from scattering processes, which are subdominant in the parameter space relevant for $n - \bar{n}$)

washout: baryon asymmetry is washed out by BNV inverse annihilations and decays; are efficient at high temperatures, weaken at low temperatures

TWO SCENARIOS FOR BARYOGENESIS

produce asymmetry after washout processes have gone out of equilibrium



suppress washout processes early on

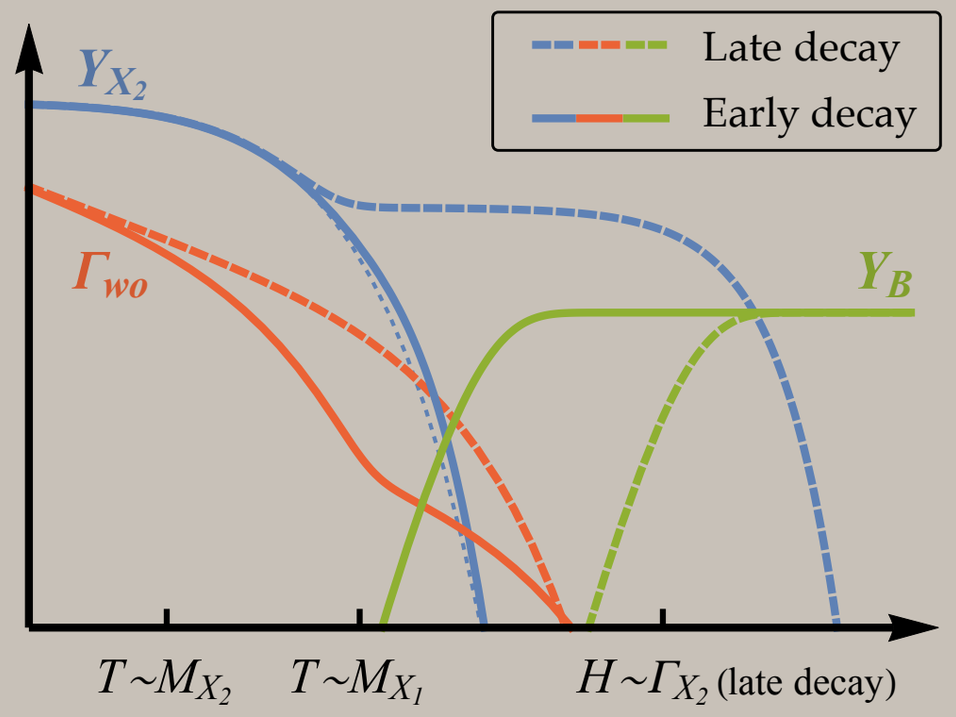
LATE DECAY SCENARIO

long lifetime for X_2 :

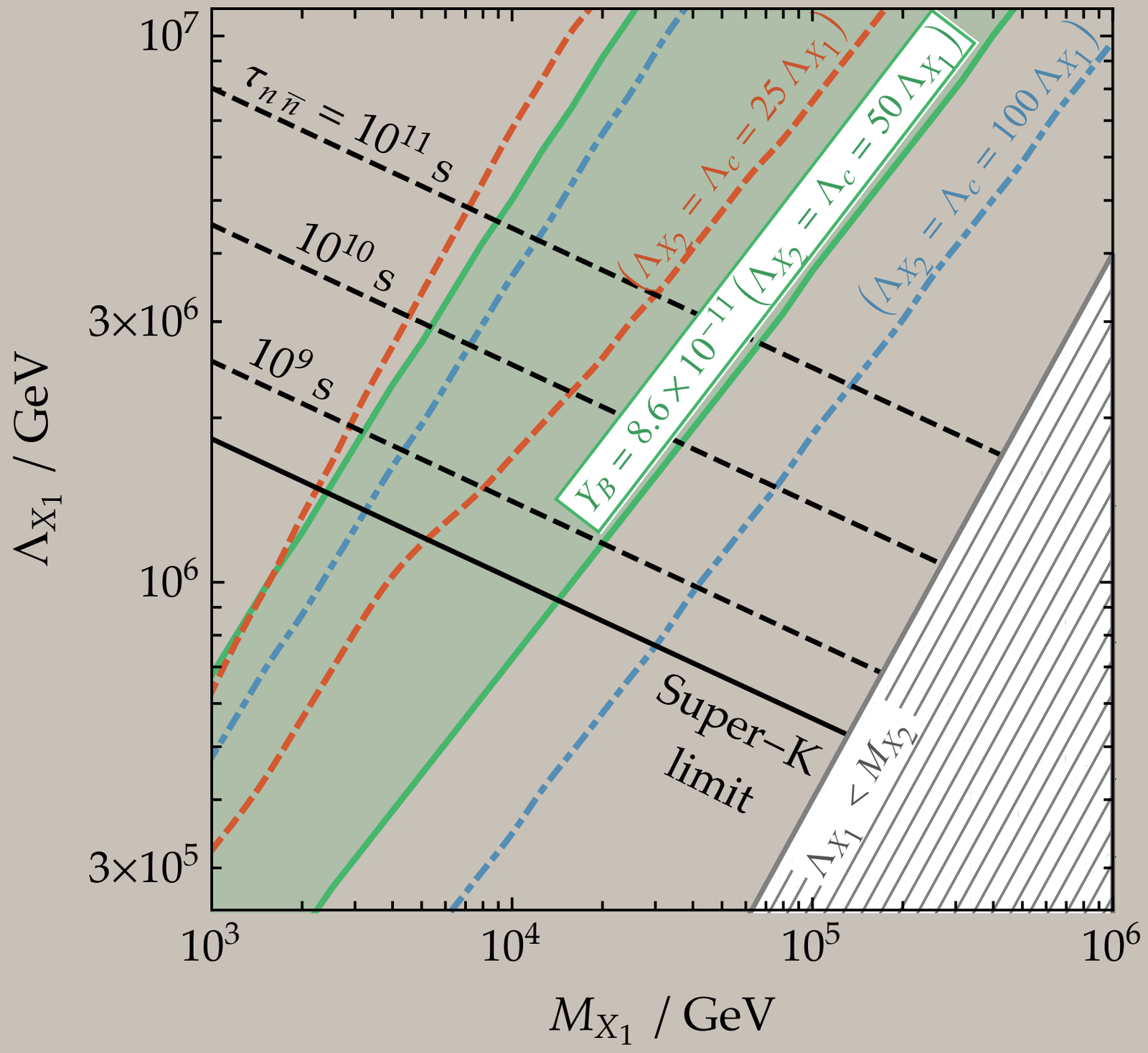
suppress all couplings of X_2 :

η_{X_2}, η_c small (Λ_{X_2}, Λ_c large)

$n - \bar{n}$ signal dominantly mediated by X_1



Late decay scenario



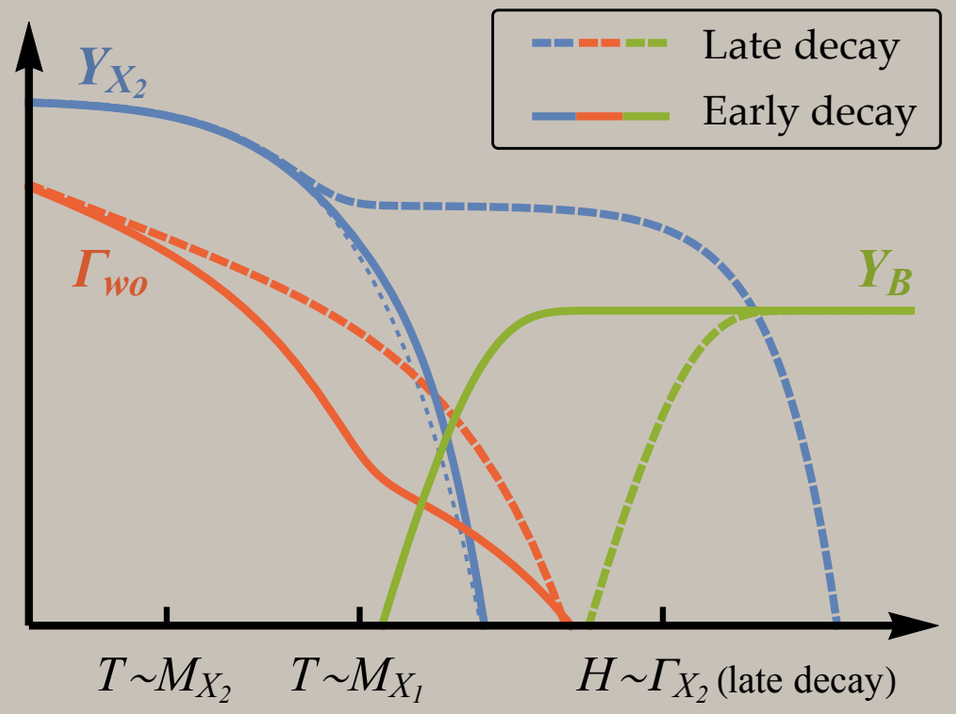
EARLY DECAY SCENARIO

$$\Lambda_{X_1} \gg \Lambda_{X_2}$$

X_2 not very long-lived: abundance closely follows equilibrium curve at all times

large Λ_{X_1}: washout processes related to X_1 decouple early

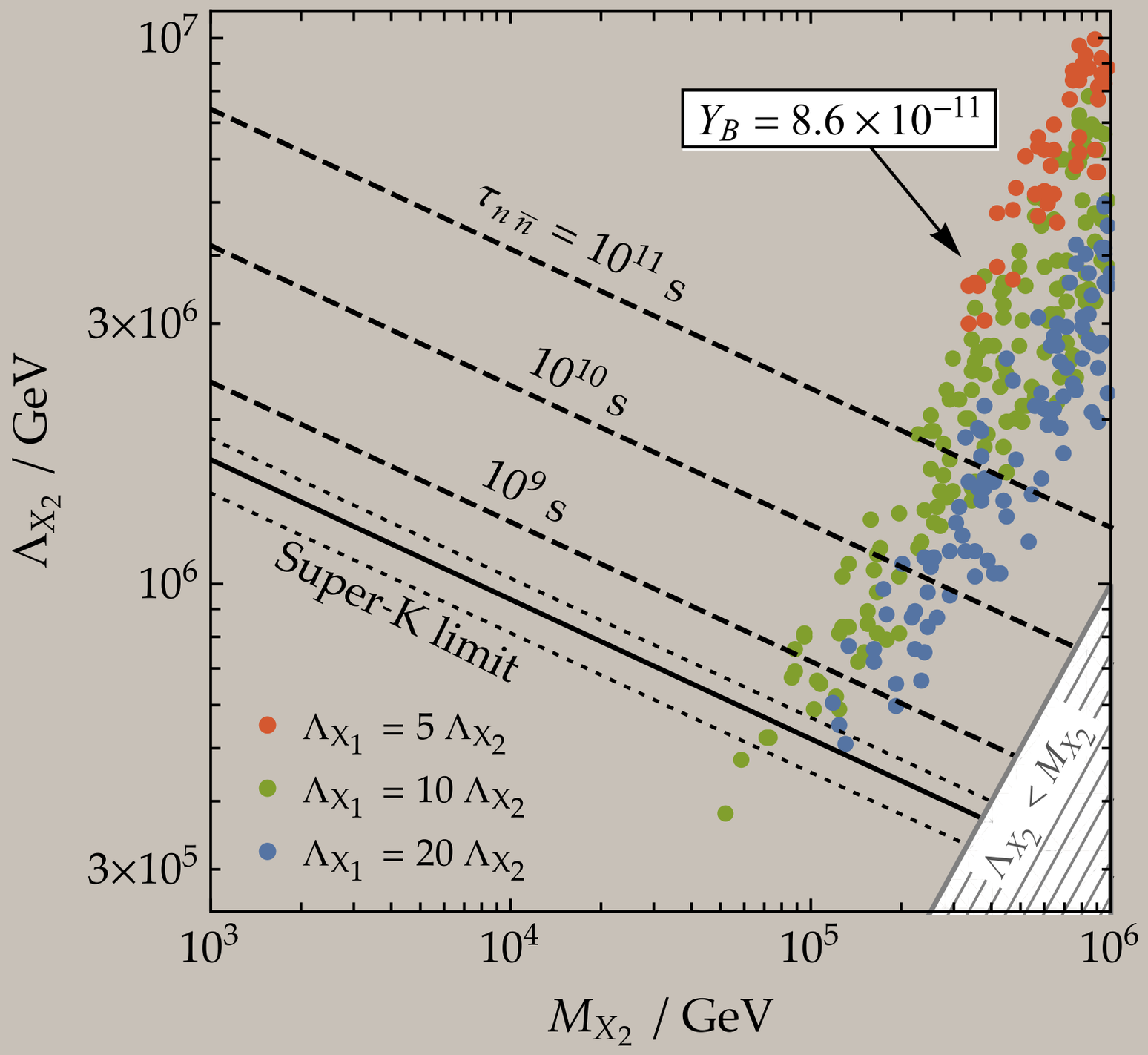
washout processes related to X_2 start to decouple below $T \sim m_{X_2}$



can get an early period of rapid asymmetry production while Y_{X_2} still large and washout processes suppressed

$n - \bar{n}$ signal now dominantly mediated by X_2

Early decay scenario



A SPECIFIC EXAMPLE: GAUGINO PORTAL BARYOGENESIS

A. Pierce, B. Shakya, hep-ph 1901.05493

consider a supersymmetric framework with a hidden sector connected to us via kinetic mixing portal (+ gaugino portal)

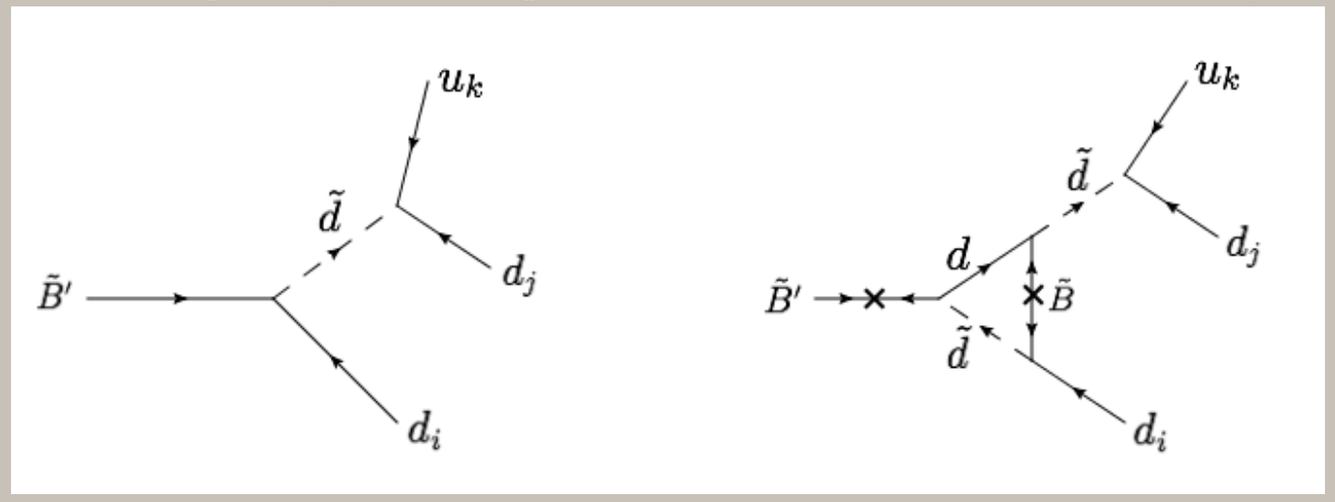
X_2 : (mostly) hidden sector gaugino

X_1 : (mostly) MSSM bino

baryon number violation from RPV coupling $W_{RPV} = \lambda''_{ijk} U^c_i D^c_j D^c_k.$

CP violation from $\mathrm{Im}(m_{\tilde{B}'} m^*_{\tilde{B}}) \neq 0$

integrating out (heavy) squarks give the four-fermion couplings, with $\Lambda \sim m_0$



baryon asymmetry populated via late decays of hidden sector gaugino

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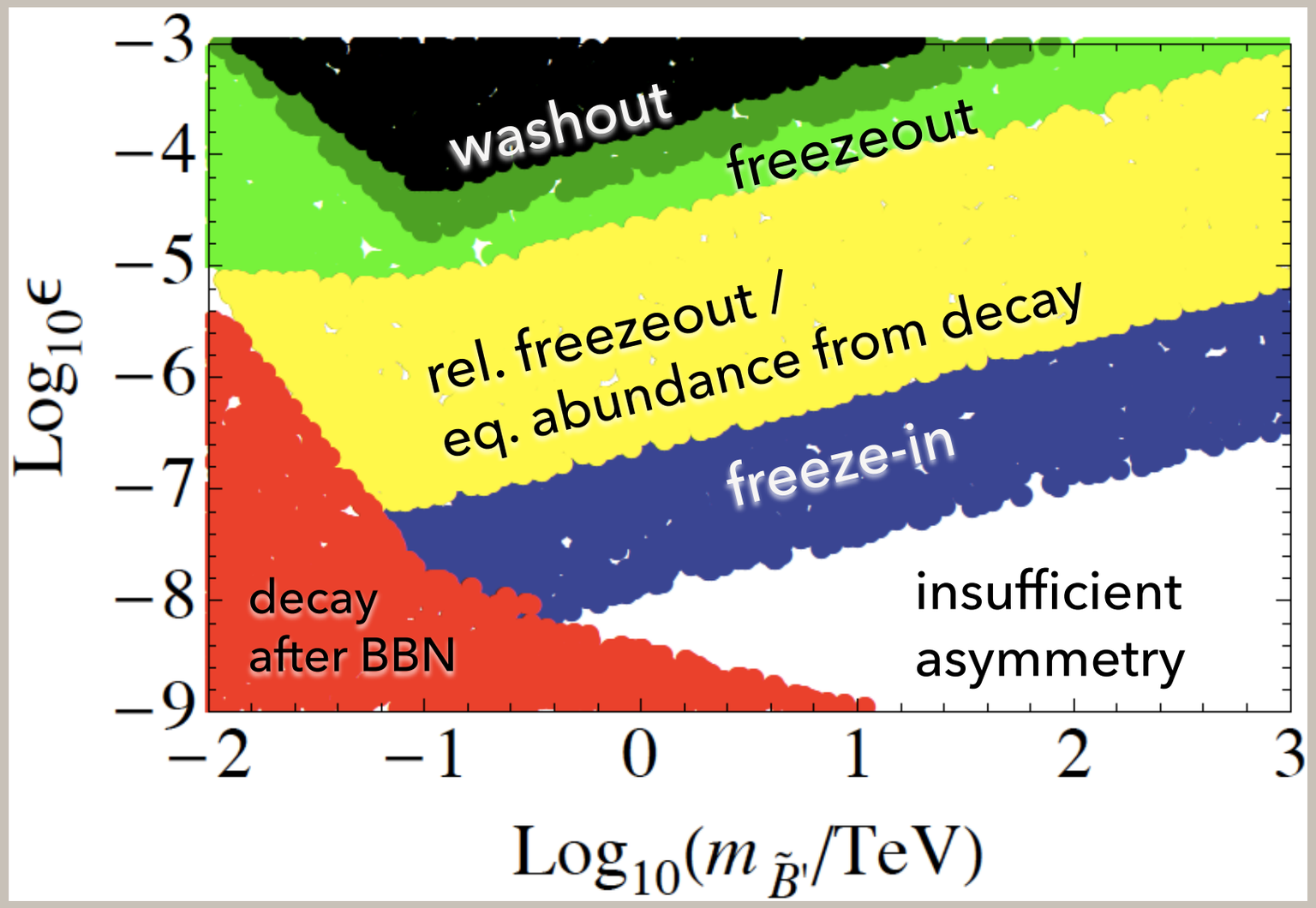
dark green: partial washout



$m_0 = \max(1\,\mathrm{TeV}, 10\,m_{\tilde{B}'})$, $m_{\tilde{B}} = 0.3\,m_{\tilde{B}'}$, and $\lambda'' = 0.1$

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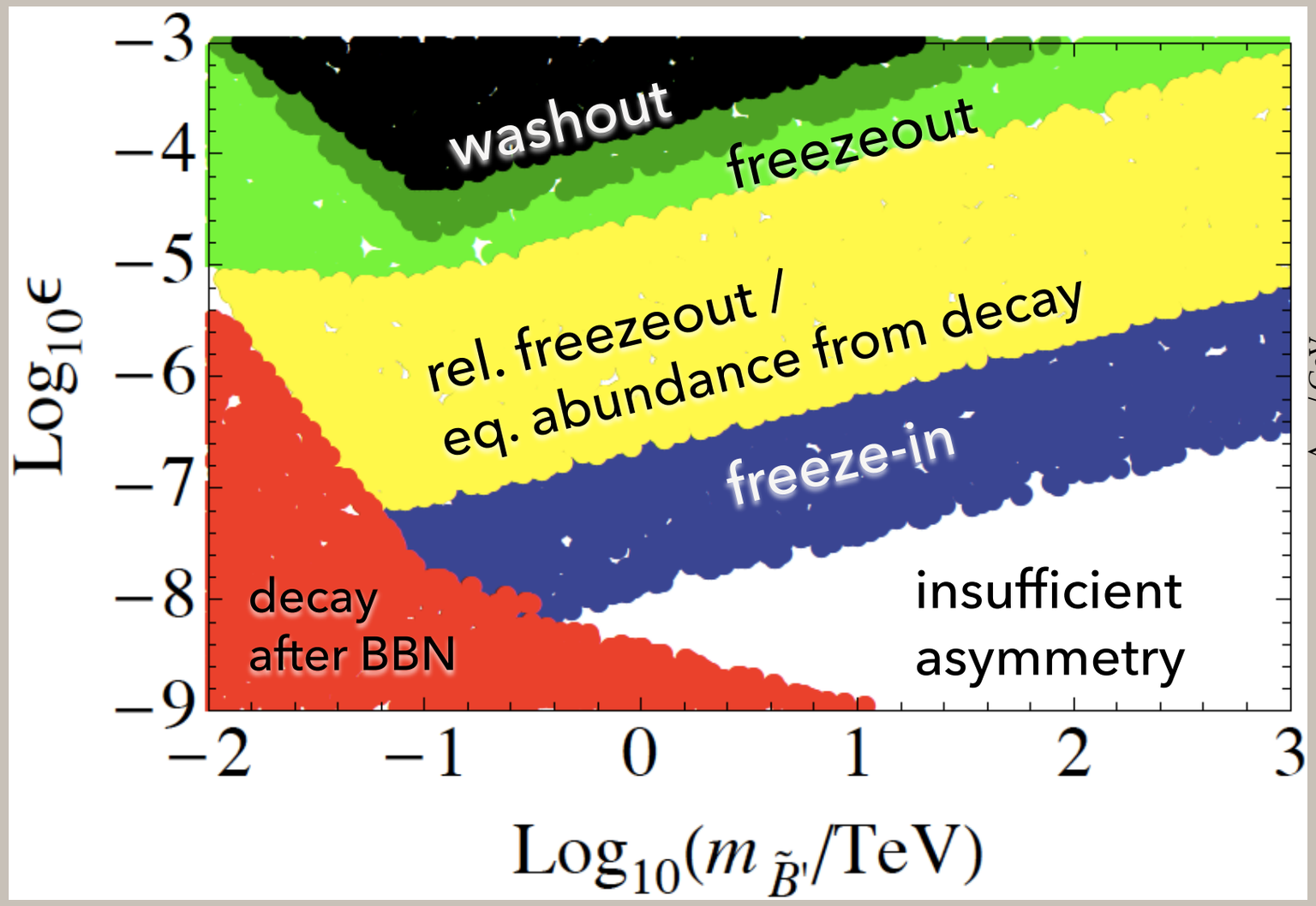
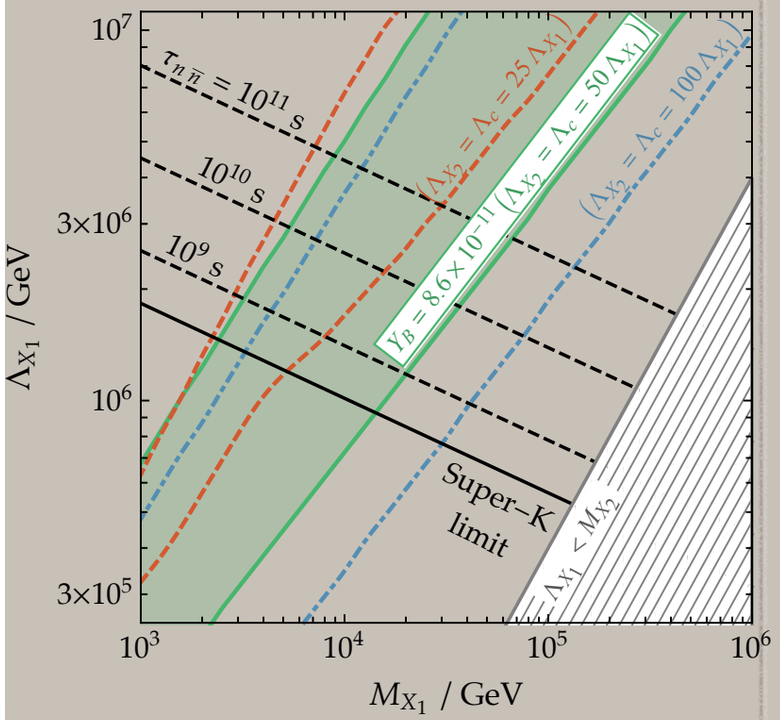


Late decay scenario



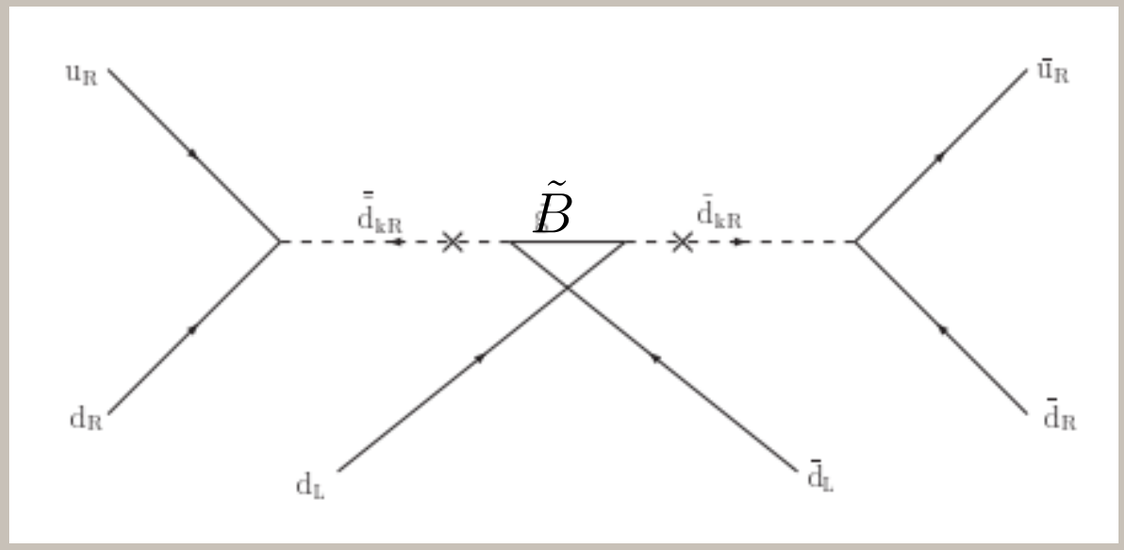
$m_0 = \max(1\,\mathrm{TeV}, 10\,m_{\tilde{B}'})$, $m_{\tilde{B}} = 0.3\,m_{\tilde{B}'}$, and $\lambda'' = 0.1$

$n - \bar{n}$ REVISITED

if RPV coupling involves first generation quarks, can get bino-mediated $n - \bar{n}$

However, $W_{RPV} = \lambda''_{ijk} U^c_i D^c_j D^c_k.$ is antisymmetric; vanishes if j=k=1.

at least one flavor off-diagonal mixing needed in the squark sector to get $n - \bar{n}$



current bounds roughly translate to

$$\tilde{\theta}_{1j} \lesssim \left(\frac{m_0}{100\,\mathrm{TeV}}\right)^2 \left(\frac{m_{\tilde{B}'}}{\mathrm{TeV}}\right)^{0.5} \left(\frac{0.01}{\lambda''}\right)$$

- other processes (e.g. dinucleon decays) do not involve this unknown mixing angle, but suffer from large uncertainties
- EDMs: suppressed by multiple powers of tiny portal coupling (CP phase resides in the hidden sector)

SUMMARY

- $n - \bar{n}$ an important test of baryon number violation
- sensitivity will increase by several orders of magnitude with upcoming experiments (ESS)
- could shed light on an important BNV process in the early Universe: baryogenesis

- within a simplified framework involving SM singlet fermions: could probe parameter space that produces the desired baryon asymmetry via late or early decays
- $n - \bar{n}$ can probe parameter space far beyond the reach of other traditional searches (colliders, EDMs etc)

- an explicit model: baryogenesis via a gaugino portal
- current $n - \bar{n}$ bounds already placing meaningful constraints on flavor off-diagonal mixing angles in the squark sector