GAUGINO PORTAL BARYOGENESIS

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BASED ON:
HEP-PH 1901.05493
WITH AARON PIERCE

SUPERSYMMETRY: EXPECTATION VS REALITY

HIERARCHY PROBLEM ✗ might not be at the weak scale

DARK MATTER ✗ might not be R-parity conserving

GAUGE COUPLING UNIFICATION ?

BARYOGENESIS ?

BARYOGENESIS: SAKHAROV CONDITIONS

	In Supersymmetry
• BARYON NUMBER VIOLATION	R-parity violation
• C,CP VIOLATION	phases on masses/couplings + interference between tree,loop diagrams
• OUT OF EQUILIBRIUM CONDITION	out of equilibrium production or late decays of SUSY particles

BARYOGENESIS FROM HEAVY SUSY PARTICLE DECAYS

[a partial list]

S. Dimopoulos and L. J. Hall, Phys. Lett. **B196**, 135 (1987).

M. Claudson, L. J. Hall, and I. Hinchliffe, Nucl. Phys. **B241**, 309 (1984).

F. Rompineve, JHEP **08**, 014 (2014), arXiv:1310.0840 [hep-ph].

Y. Cui and R. Sundrum, Phys. Rev. **D87**, 116013 (2013), arXiv:1212.2973 [hep-ph].

Y. Cui, JHEP **12**, 067 (2013), arXiv:1309.2952 [hep-ph].

G. Arcadi, L. Covi, and M. Nardecchia, Phys. Rev. **D92**, 115006 (2015), arXiv:1507.05584

...

Basic idea: RPV and CPV decays of neutralino/squark at late times (or produce them late), CP violation comes from tree+loop interference diagrams

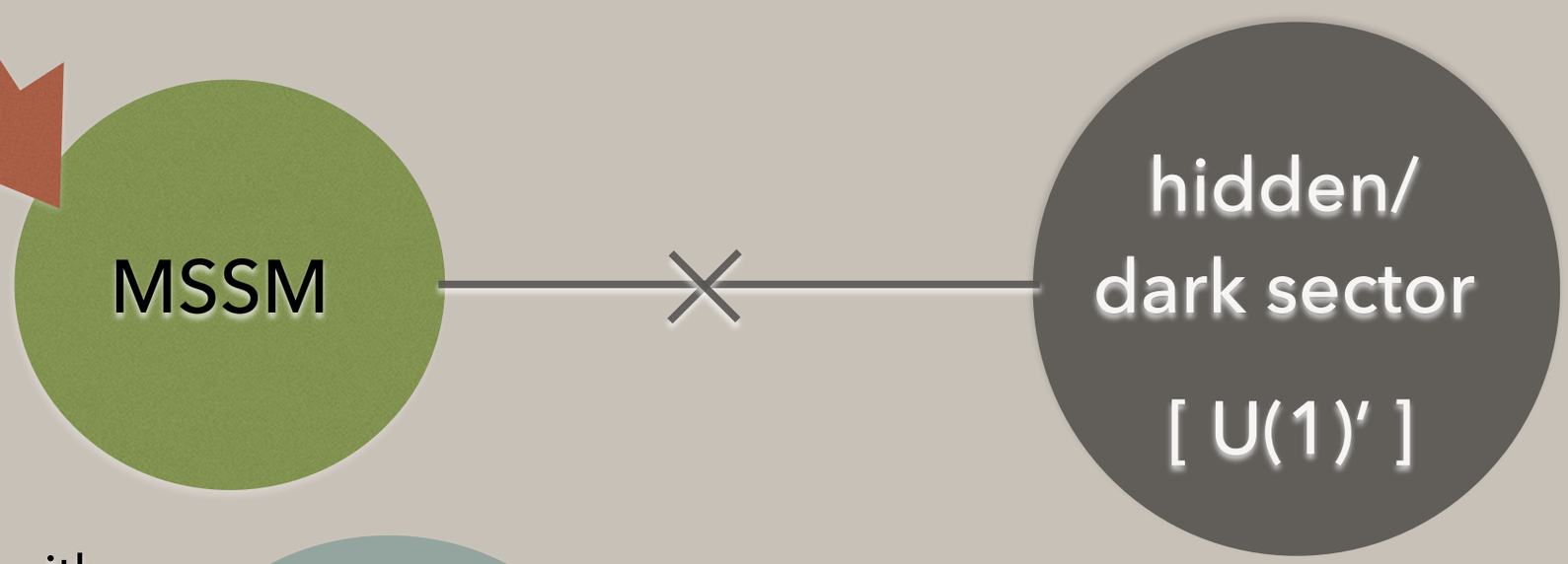
PITFALLS:

washout of asymmetry from BNV inverse interactions

large CP violation with low scale physics: other constraints (e.g. EDMs) are very severe

AN ADDITIONAL INGREDIENT: HIDDEN SECTORS

YOU ARE HERE



kinetic mixing with
Abelian gauge group
in a hidden sector

extensively studied!

vector portal $B_{\mu\nu} V^{\mu\nu},$

Higgs portal $H^\dagger H\, S,$

neutrino portal $\bar{L} H N$

PORTALS TO NEW PHYSICS

THE GAUGINO PORTAL

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} F^{\mu\nu}_{(a)} F_{(a)\mu\nu} - \frac{1}{4} F^{\mu\nu}_{(b)} F_{(b)\mu\nu} + \frac{\chi}{2} F^{\mu\nu}_{(a)} F_{(b)\mu\nu}$$

supersymmetry

$$\mathcal{L}_{\text{gauge}} = \frac{1}{32} \int d^2\theta \, \{W_a W_a + W_b W_b - 2\chi W_a W_b\}$$

mixing term between the MSSM bino and the hidden sector gaugino

(from both superfield rotations as well as an off diagonal gaugino mass term)

$$\mathcal{L} \supset -\frac{1}{2}(m_{\tilde{B}'} \tilde{B}' \tilde{B}' + m_{\tilde{B}} \tilde{B} \tilde{B} + \epsilon \, m_{\tilde{B}'} \tilde{B}' \tilde{B})$$

“define” the mixing angle to be ε

*cautionary footnote: gaugino portal coupling need not be the same as gauge boson portal coupling (but they are generally of similar size if arising from the same underlying physics)

CALCULATION OF BARYON ASYMMETRY

$$Y_{BA} \equiv \frac{n_b - n_{\bar{b}}}{s} = \epsilon_{CP}\, Y_{\tilde{B}'}\, W_I$$

baryon asymmetry, known to be ~ 10^{-10}

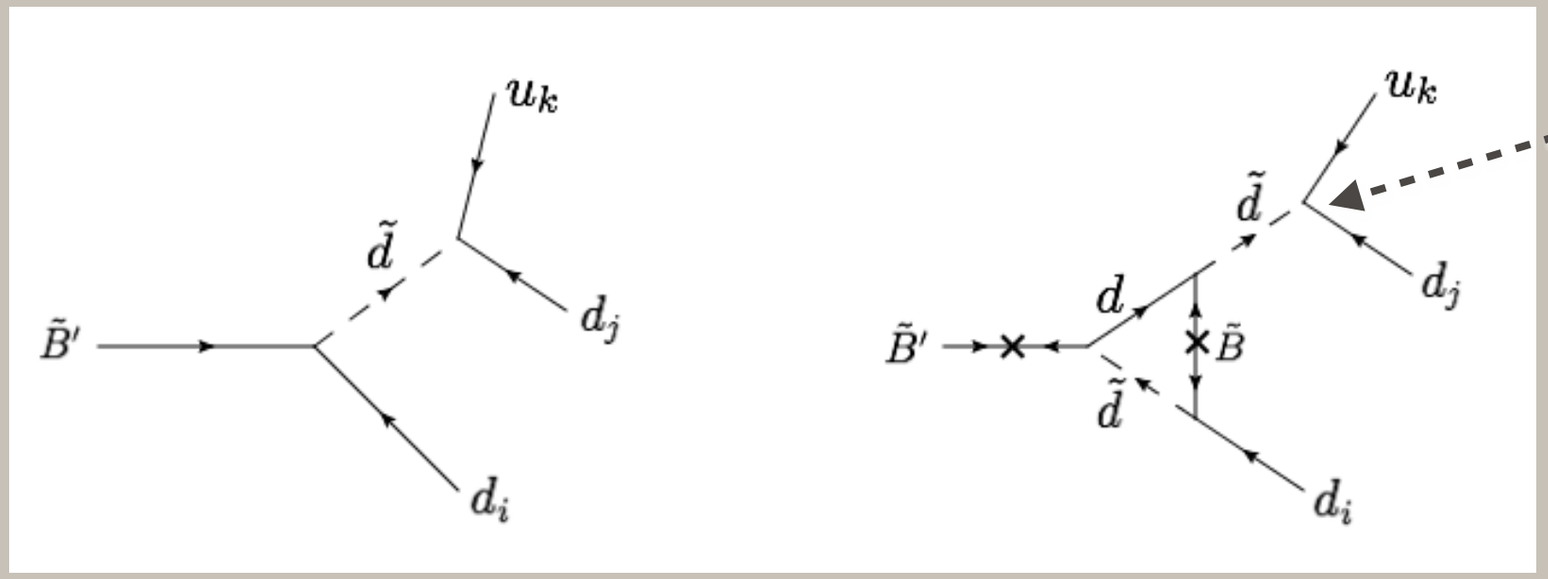
hidden gaugino abundance in early Universe

suppression from washout/dilution effects

$$\epsilon_{CP} \equiv \frac{\Delta\Gamma_{BV}}{\Gamma_{\tilde{B}'}} \equiv \frac{\Gamma_{\tilde{B}' \to u_i d_j d_k} - \Gamma_{\tilde{B}' \to \bar{u}_i \bar{d}_j \bar{d}_k}}{\Gamma_{\tilde{B}'}}$$

fraction of hidden gaugino decays that give baryon asymmetry

Calculation of ϵ_{CP}



R parity violation

$$W_{RPV} = \lambda''_{ijk} U^c_i D^c_j D^c_k.$$

relative phase between the two gaugino masses. set to 1 from hereon

$$\Delta\Gamma_{\tilde{B}'} = \Gamma(\tilde{B}' \to udd) - \Gamma(\tilde{B}' \to \bar{u}\bar{d}\bar{d}) = \frac{3\,\epsilon^2 \lambda''^2 \alpha_1^2}{256\pi^2} Im[e^{2i\phi}] \frac{m^6_{\tilde{B}'}\, m_{\tilde{B}}}{m_0^6}\, f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'}),$$

$$\Gamma(\tilde{B}' \to udd + \bar{u}\bar{d}\bar{d}) = \frac{3\,\epsilon^2 \lambda''^2 \alpha_1}{128\pi^2} \frac{m^5_{\tilde{B}'}}{m_0^4},$$

$$\Gamma(\tilde{B}' \to \tilde{B} f \bar{f}) = \frac{\epsilon^2 \alpha_1^2}{64\pi} \frac{m^5_{\tilde{B}'}}{m_0^4}\, f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'}).$$

$$\epsilon_{CP} = \frac{\Delta\Gamma_{\tilde{B}'}}{\Gamma_{\text{total}}} = \frac{3}{4\pi} \frac{\lambda''^2}{1 + 3\lambda''^2/[2\pi\alpha_1 f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'})]} \left(\frac{m_{\tilde{B}'} m_{\tilde{B}}}{m_0^2}\right)$$

WASHOUT/DILUTION EFFECTS

most dangerous **washout** effect:

baryon number violating inverse decays or $2 \to 2$ annihilations involving the $\tilde{B}$

$$\Gamma_{ID} = \frac{3\,\lambda''^2 \alpha_1}{128\pi^2} \frac{m_{\tilde{B}'}^5}{m_0^4} x^2 K_2(zx),$$

$$\Gamma_S = \frac{\alpha_1 \lambda''^2}{4\pi} \frac{m_{\tilde{B}'}^5}{m_0^4} \left(5\frac{K_4(x)}{K_2(x)} + 1\right) K_2(zx)$$

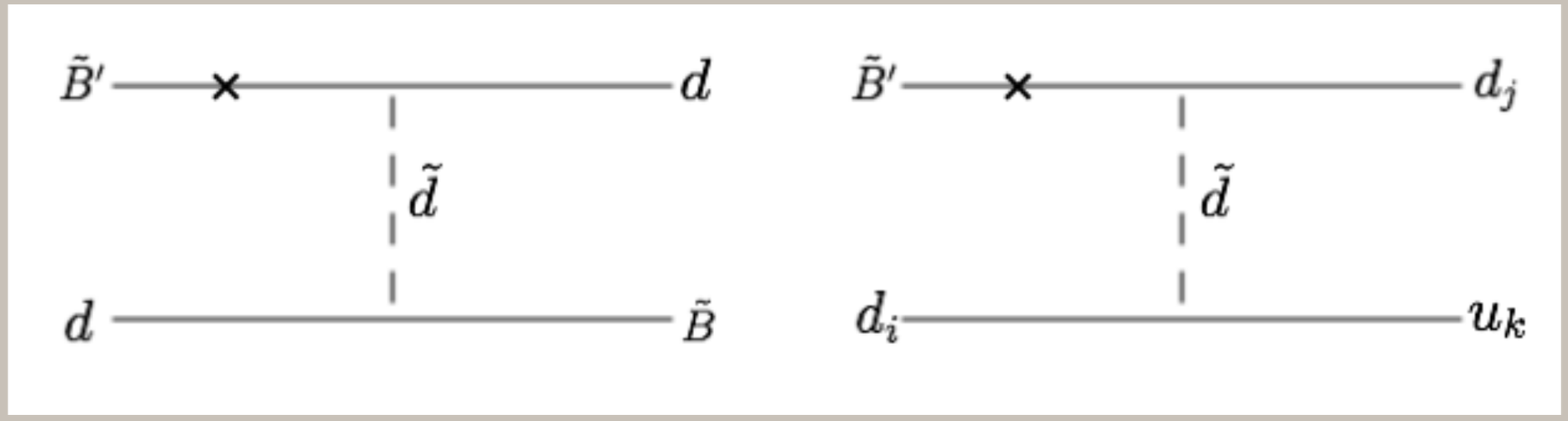
entropy dilution: if hidden gaugino is so long lived that it dominates the energy density of the Universe, its eventual decay injects this entropy into the thermal bath, which dilutes the baryon asymmetry by a factor

$$\frac{S_{\text{after}}}{S_{\text{before}}} \approx 1.83\, g_*^{1/4} Y_{\tilde{B}'} \frac{m_{\tilde{B}'}}{\sqrt{\Gamma_{\tilde{B}'} M_{Pl}}}$$

HIDDEN GAUGINO COSMOLOGY

Minimal hidden sector: decouple everything, so that hidden gaugino is the only relevant particle; all relevant phenomenology must come from mixing with the visible sector

can thermalize and freeze out via the following processes:



calculate freeze out “relic abundance” by solving Boltzmann eq

[if portal coupling too small, relativistic freezeout, or freeze in]

MAKING THINGS WORK:

$$Y_{BA} \equiv \frac{n_b - n_{\bar{b}}}{s} = \epsilon_{CP}\, Y_{\tilde{B}'}\, W_I$$

$$\Gamma(\tilde{B}' \to udd + \bar{u}\bar{d}\bar{d}) = \frac{3\,\epsilon^2 \lambda''^2 \alpha_1}{128\pi^2} \frac{m^5_{\tilde{B}'}}{m_0^4},$$

$$\Gamma(\tilde{B}' \to \tilde{B} f \bar{f}) = \frac{\epsilon^2 \alpha_1^2}{64\pi} \frac{m^5_{\tilde{B}'}}{m_0^4}\, f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'}).$$

$$\epsilon_{CP} = \frac{\Delta\Gamma_{\tilde{B}'}}{\Gamma_{\text{total}}} = \frac{3}{4\pi} \frac{\lambda''^2}{1 + 3\lambda''^2/[2\pi\alpha_1 f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'})]} \left(\frac{m_{\tilde{B}'} m_{\tilde{B}}}{m_0^2}\right)$$

WISHLIST:

make lifetime sufficiently long to avoid washout

have ε_{CP} and hidden photino abundance be sufficiently large to produce the observed baryon asymmetry

MAKING THINGS WORK:

$$Y_{BA} \equiv \frac{n_b - n_{\bar{b}}}{s} = \epsilon_{CP}\, Y_{\tilde{B}'}\, W_I$$

$$\Gamma(\tilde{B}' \to udd + \bar{u}\bar{d}\bar{d}) = \frac{3\,\epsilon^2 \lambda''^2 \alpha_1}{128\pi^2} \frac{m^5_{\tilde{B}'}}{m^4_0},$$

$$\Gamma(\tilde{B}' \to \tilde{B} f \bar{f}) = \frac{\epsilon^2 \alpha_1^2}{64\pi} \frac{m^5_{\tilde{B}'}}{m^4_0}\, f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'}).$$

Idea #1:
make RPV coupling λ′′ small

doesn't suppress decay rate: there is a decay channel that doesn't depend on this coupling [Nanopoulos-Weinberg theorem]

suppresses ε_{CP}

$$\epsilon_{CP} = \frac{\Delta\Gamma_{\tilde{B}'}}{\Gamma_{\text{total}}} = \frac{3}{4\pi} \frac{\lambda''^2}{1 + 3\lambda''^2/[2\pi\alpha_1 f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'})]} \left(\frac{m_{\tilde{B}'} m_{\tilde{B}}}{m^2_0}\right)$$

MAKING THINGS WORK:

$$Y_{BA} \equiv \frac{n_b - n_{\bar{b}}}{s} = \epsilon_{CP}\, Y_{\tilde{B}'}\, W_I$$

Idea #2:
make sfermions heavy

suppresses decay rate....

but also suppresses ε_{CP}

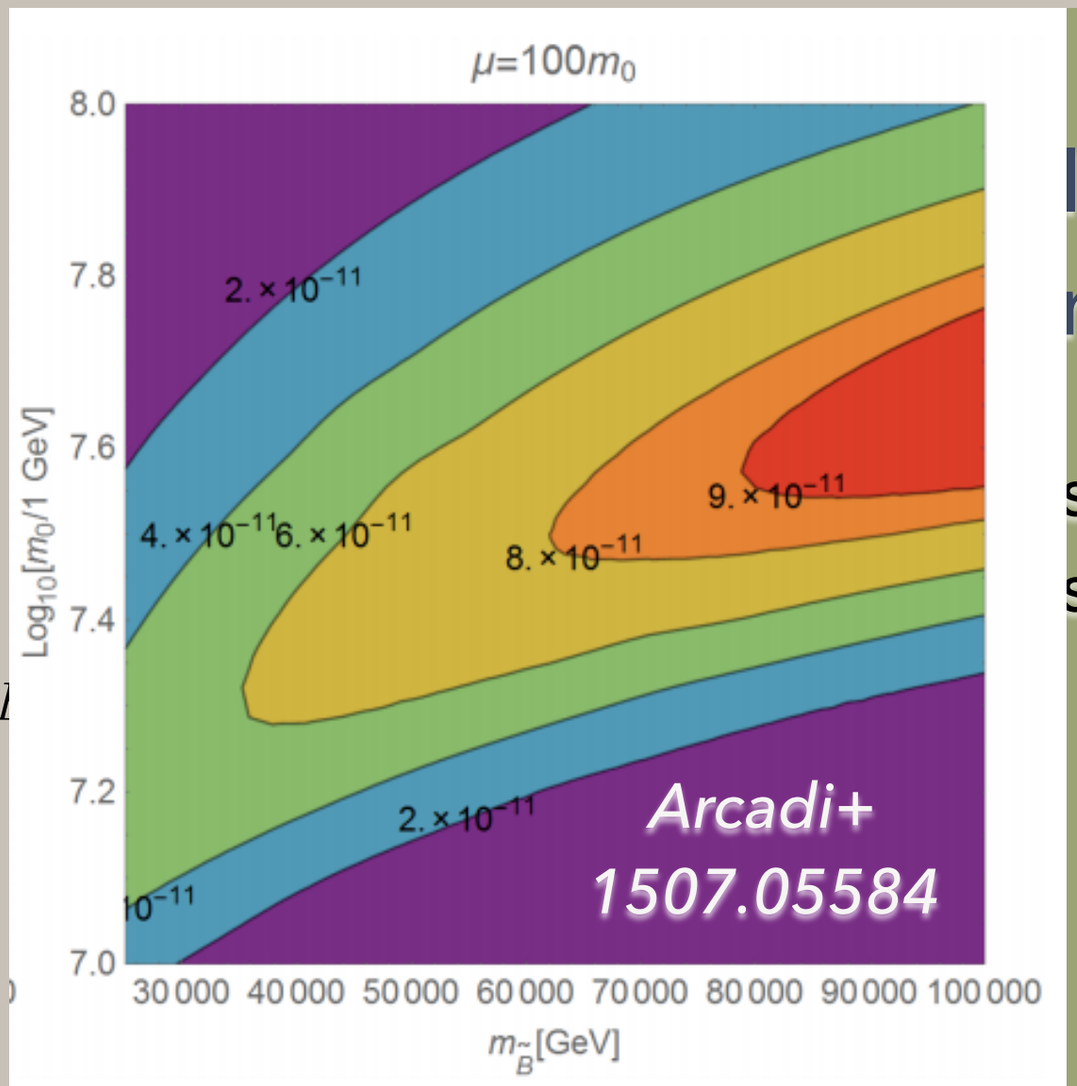
$$\Gamma(\tilde{B}' \to udd + \bar{u}\bar{d}\bar{d}) = \frac{3\,\epsilon^2 \lambda''^2 \alpha_1}{128\pi^2} \frac{m^5_{\tilde{B}'}}{m_0^4},$$

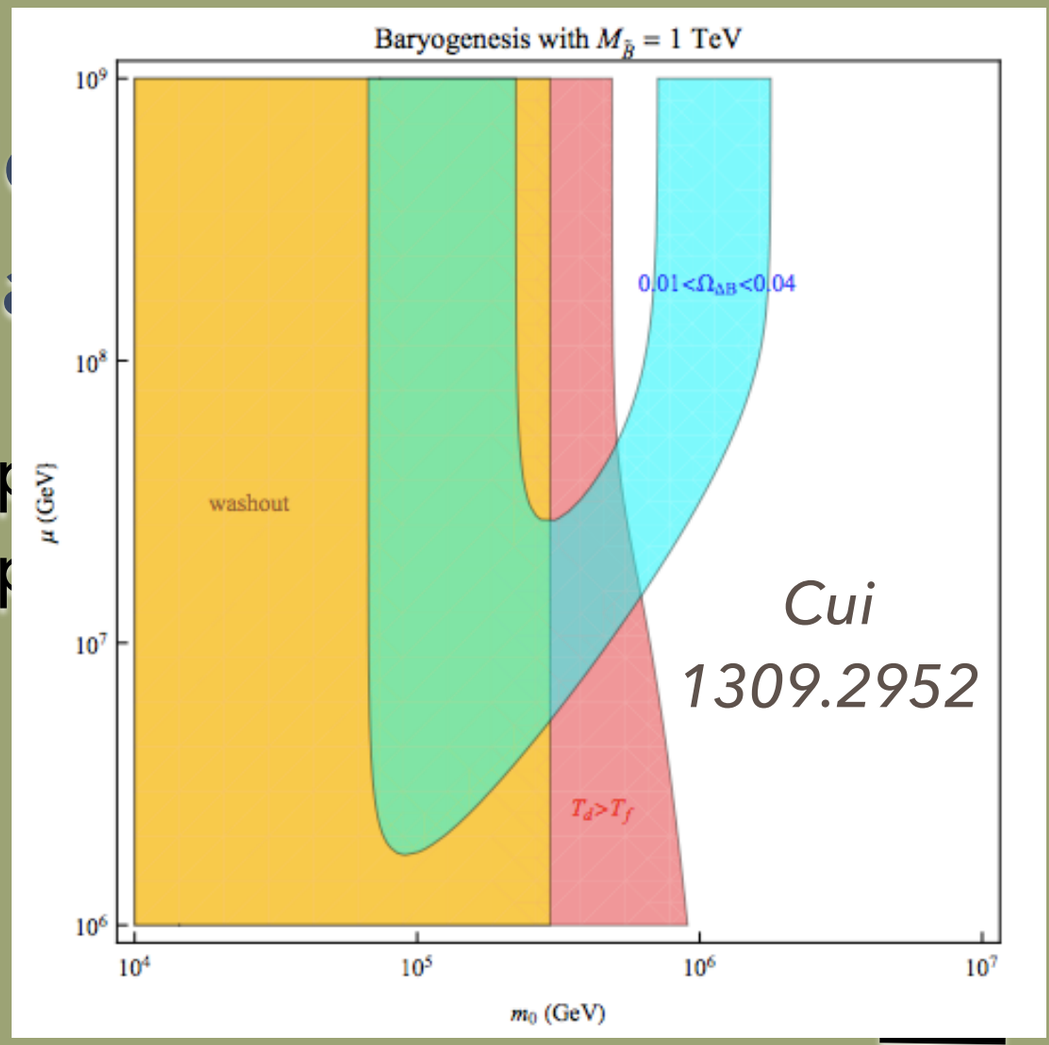
$$\Gamma(\tilde{B}' \to \tilde{B} f \bar{f}) = \frac{\epsilon^2 \alpha_1^2}{64\pi} \frac{m^5_{\tilde{B}'}}{m_0^4} f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'}).$$

:-

$$\epsilon_{CP} = \frac{\Delta\Gamma_{\tilde{B}'}}{\Gamma_{\text{total}}} = \frac{3}{4\pi} \frac{\lambda''^2}{1 + 3\lambda''^2/[2\pi\alpha_1 f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'})]} \left(\frac{m_{\tilde{B}'} m_{\tilde{B}}}{m_0^2}\right)$$

MAKING THINGS WORK:





MSSM only implementations use this, find that compatible regions of parameter space are narrow and correspond to mini-split spectra

MAKING THINGS WORK:

$$Y_{BA} \equiv \frac{n_b - n_{\bar{b}}}{s} = \epsilon_{CP}\, Y_{\tilde{B}'}\, W_I$$

$$\Gamma(\tilde{B}' \to udd + \bar{u}\bar{d}\bar{d}) = \frac{3\,\epsilon^2 \lambda''^2 \alpha_1}{128\pi^2} \frac{m^5_{\tilde{B}'}}{m_0^4},$$

$$\Gamma(\tilde{B}' \to \tilde{B} f \bar{f}) = \frac{\epsilon^2 \alpha_1^2}{64\pi} \frac{m^5_{\tilde{B}'}}{m_0^4}\, f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'}).$$

$$\epsilon_{CP} = \frac{\Delta\Gamma_{\tilde{B}'}}{\Gamma_{\text{total}}} = \frac{3}{4\pi} \frac{\lambda''^2}{1 + 3\lambda''^2/[2\pi\alpha_1 f_2(m^2_{\tilde{B}}/m^2_{\tilde{B}'})]} \left(\frac{m_{\tilde{B}'} m_{\tilde{B}}}{m_0^2}\right)$$

Idea #3:

make portal coupling ε small

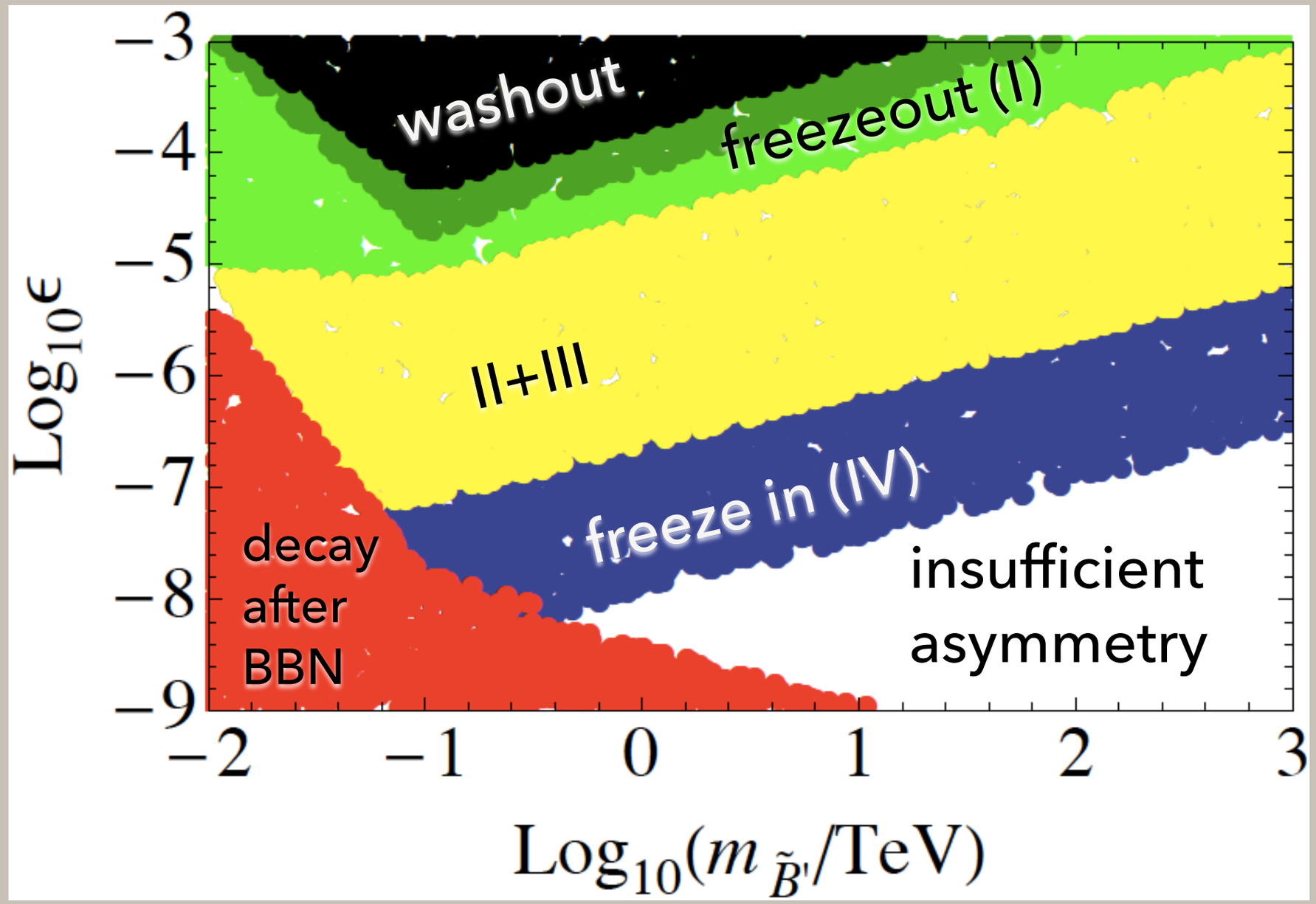
suppresses decay rate

ε_{CP} unaffected as ε cancels out in this ratio

[hidden photino abundance suppressed in extreme cases but mostly OK]

RESULTS

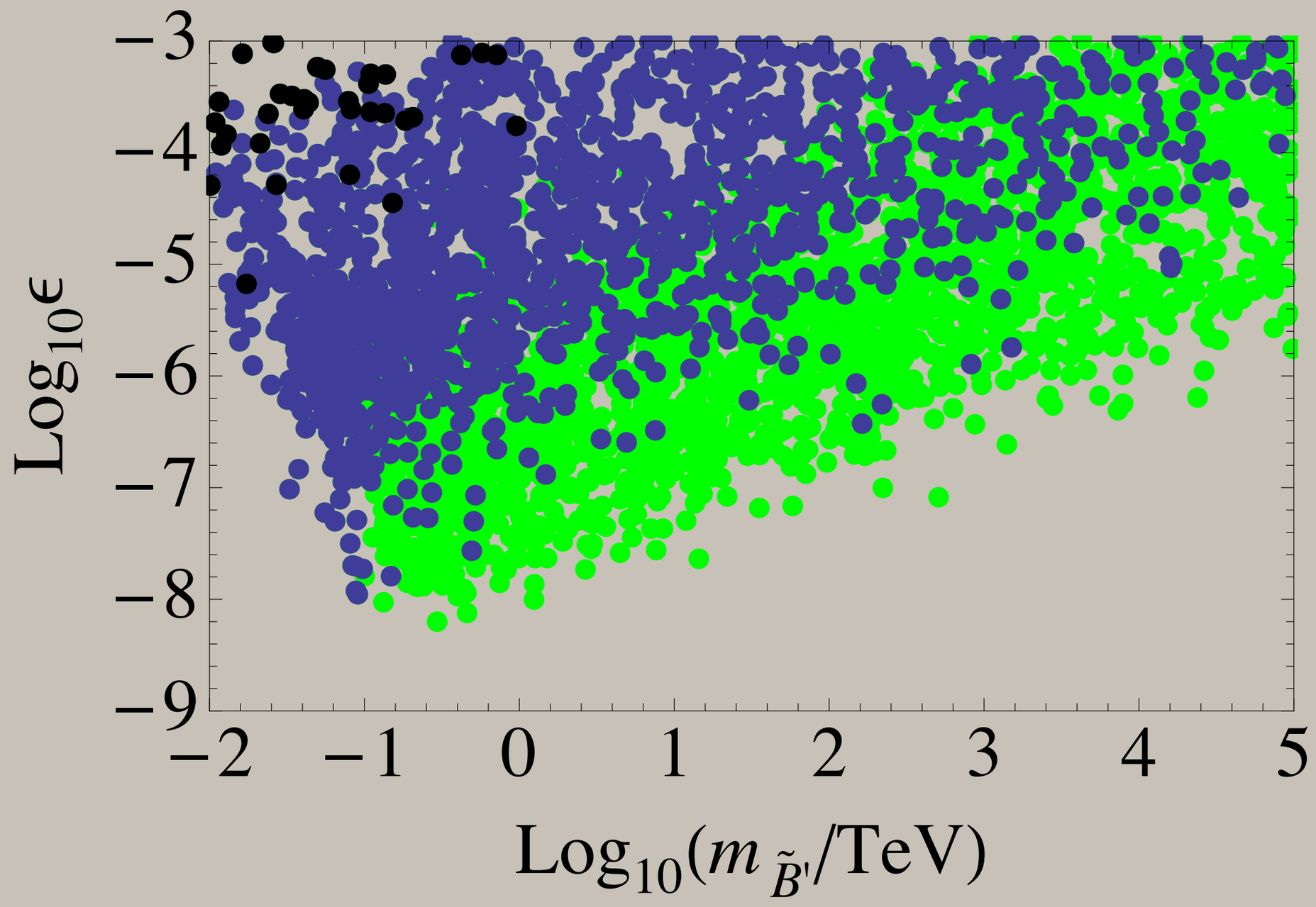
dark green: partial washout (but OK)



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

observed baryon asymmetry obtained over huge regions of parameter space!

RESULTS (SCAN OVER PARAMETER SPACE)



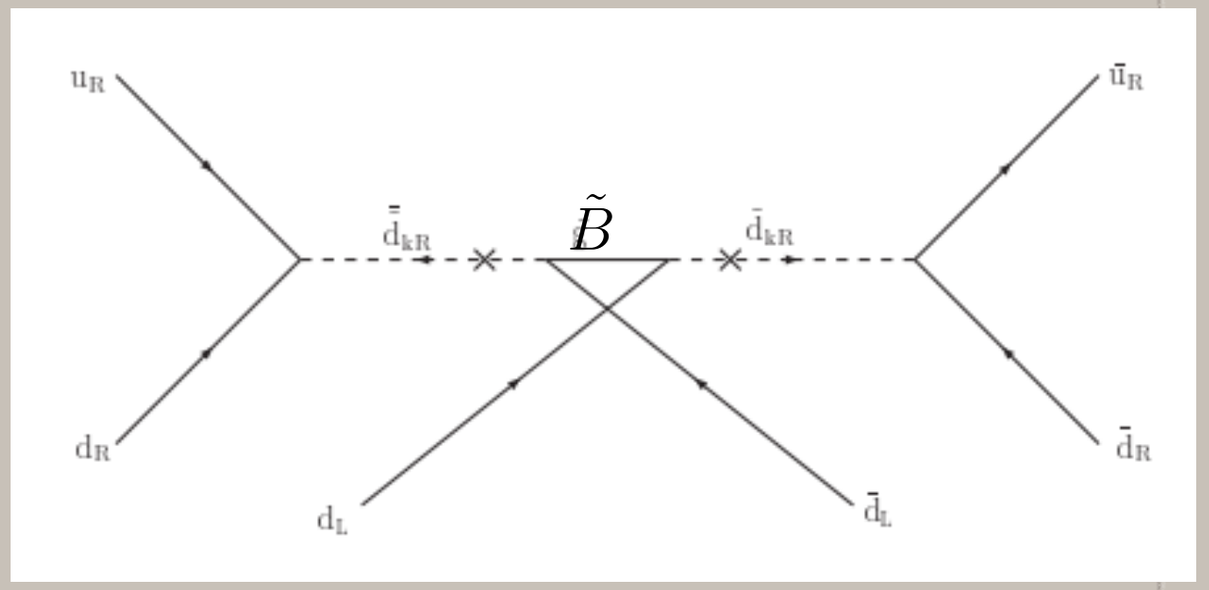
$m_0/m_{\tilde{B}'} < 10$ (green) < 100 (blue) < 1000 (black)

COMPLEMENTARY PHENOMENOLOGY

NEUTRON-ANTINEUTRON OSCILLATION

promising test of BNV if coupling to first generation quarks

needs at least one flavor off diagonal mixing term in the squark sector to get the correct couplings



current bounds roughly translate to

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

upcoming experiments will improve on this by about an order of magnitude

[other processes (e.g. dinucleon decays) do not involve this unknown mixing angle, but suffer from large uncertainties]

COMPLEMENTARY PHENOMENOLOGY

ELECTRIC DIPOLE MOMENTS

generated by a gaugino-sfermion loop

rule of thumb: if CPV phase is O(1), EDMs constrain sfermions to ~1000 TeV

(Altmannshofer+ [1308.3653], Cesarotti+[1810.07736])

however, in our setup, CPV arises from the relative phase between the two gaugino masses

-> need both gaugino mass insertions on the gaugino propagator in the loop to get the CP phase

-> EDM contribution is ε^2 suppressed

$$\frac{d_f}{10^{-29}\, e\,\mathrm{cm}} \approx \mathrm{Im}[e^{2i\theta}] \left(\frac{m_f}{\mathrm{MeV}}\right) \left(\frac{\epsilon}{10^{-3}}\right)^2 \left(\frac{\mathrm{TeV}}{m_0}\right)^6 \left(\frac{m_{\tilde{B}'}}{\mathrm{TeV}}\right)^2 \left(\frac{m_{\tilde{B}}}{\mathrm{TeV}}\right) \left(\frac{\mu}{100\,\mathrm{TeV}}\right) \tan\beta$$

EXTENDED SETUP
(WITH WIMP DARK MATTER)

The hidden sector can contain additional field content charged under the U(1)'

Recall **RPV means LSP is unstable, so there is no good DM candidate**
(except possibly a light gravitino)

Adding new field content: need to ensure **cancellation of anomalies**.
Most straightforward: add U(1)' singlets, or vector-like fermions

Consider: vector-like fermion X

mass m_X, charged under U(1)' with gauge coupling g_D

stable under a Z_2 symmetry; can realize the correct relic abundance via the **WIMP miracle**, through

$$X\bar{X} \rightarrow Z'Z'$$

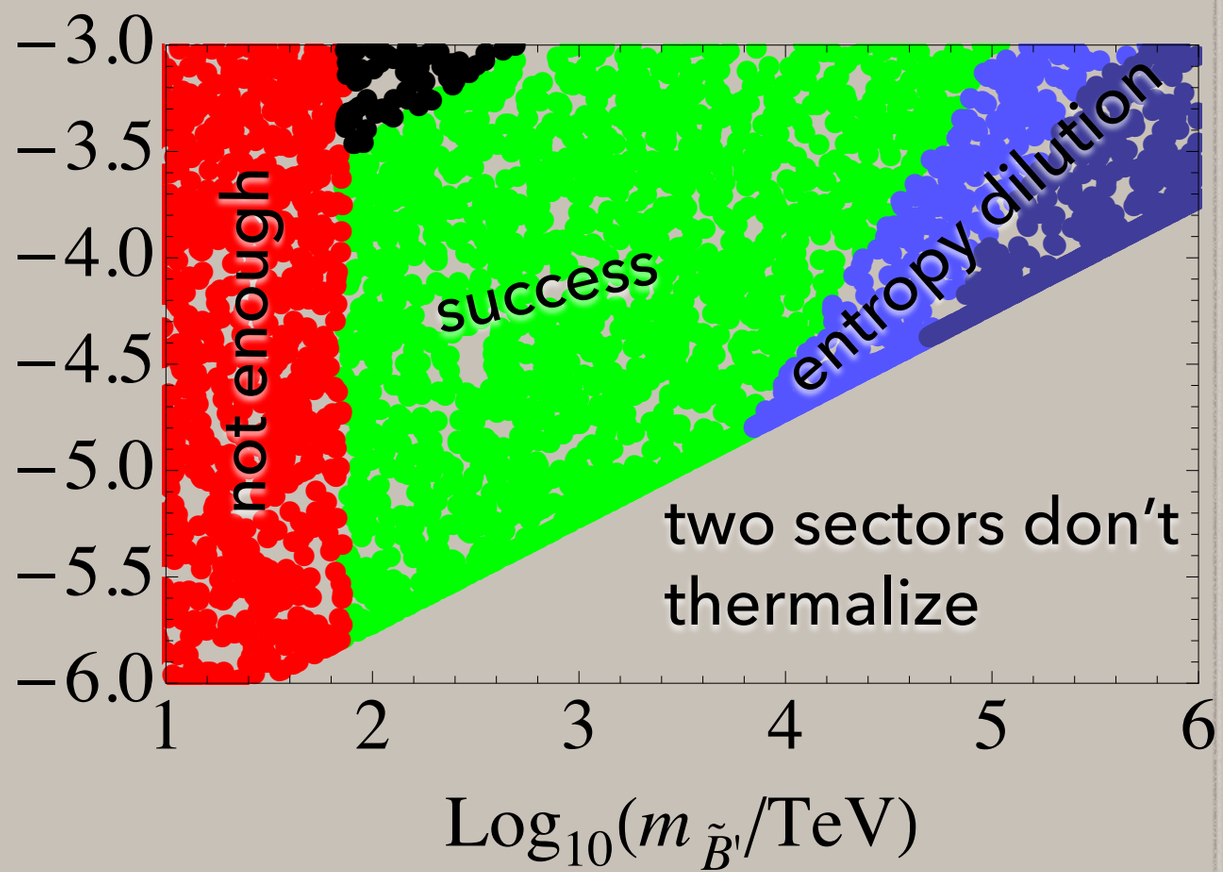
DM direct detection: spin independent through Z', but ε suppressed

DM indirect detection: ε unsuppressed: cascade decays, measurable signals in gamma rays, antiprotons, CMB etc

EXTENDED SETUP
(WITH WIMP DARK MATTER)

POTENTIAL CONCERNS

- new decay channels for hidden gaugino: suppresses ε_{CP}
- nonrel. freezeout of hidden gaugino: suppressed abundance
- entropy dilution from hidden gaugino decays dilutes DM abundance, spoiling"WIMP miracle"



$m_X = 1$ TeV (which fixes $g_D \approx 0.5$), $m_0 = 7\, m_{\tilde{B}'}$, $m_{\tilde{B}} = 0.25\, m_{\tilde{B}'}$, and $\lambda'' = 0.1$

SUMMARY

hidden sector+SUSY+RPV: late decays of hidden gaugino can populate the baryon asymmetry of the Universe in large regions of parameter space, in **both minimal and extended hidden sectors**

portal coupling ε plays several roles:

- **long lifetime for hidden gaugino** without suppressing ε_{CP}
- **suppresses constraints from EDMs**, which are severe, even for low mass particles

COMPLEMENTARY PHENOMENOLOGY

- low energy signatures: neutron antineutron oscillation, EDMs, dinucleon decays
- direct searches: squarks at LHC, Z' production
- dark matter: direct detection, indirect detection