# Baryogenesis from WIMPs
## - from cosmology to the LHC

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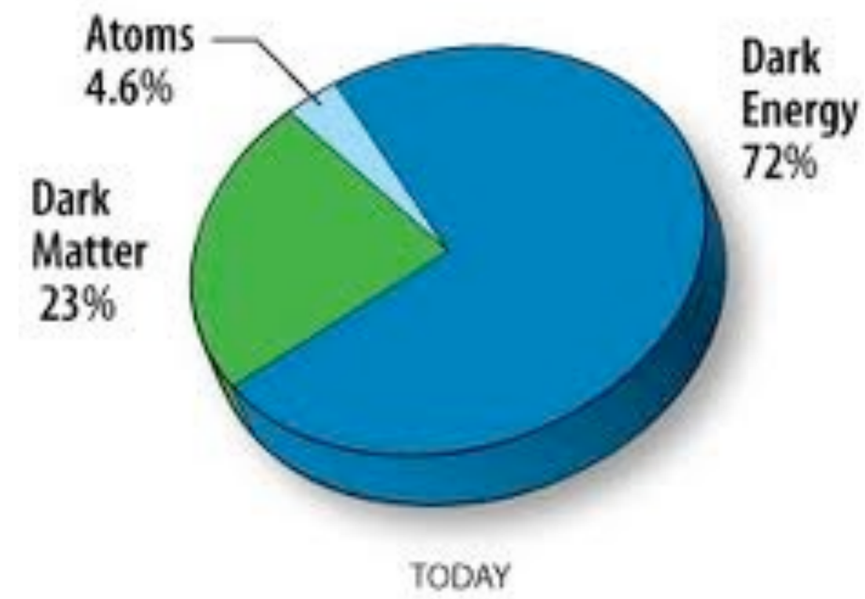
- Phys.Rev.D, 87,11603 (arXiv:1212.2973), YC and Raman Sundrum
- JHEP 1312 (2013) 067 (arxiv:1309.2952), YC
- Work in preparation, YC and Brian Shuve

# Baryon, Dark Matter

Accurate measurements of cosmic microwave background

Cosmic Pie Chart:

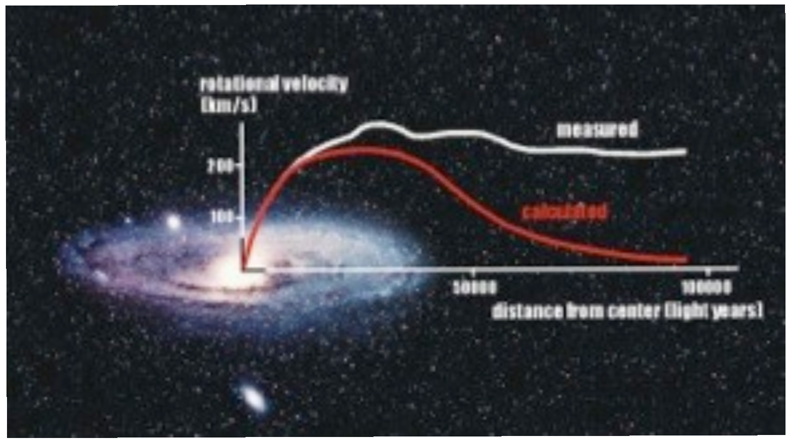



- Focus of this talk:

Baryon (atomic matter) $\Omega_B \approx 4\%$

& Dark matter

$\Omega_{\rm DM} \approx 23\%$




& Coincidence/Similarity: $\Omega_{\rm DM} \sim \Omega_{\rm B}$

# Dark matter

- **Dark matter:** Stable, neutral,

$\notin$ Standard Model particles → New physics!?

- **Origin of masses:** Higgs mechanism, Planck-electroweak Hierarchy problem

→ New physics at weak scale ( $\sim$ TeV )

→ **Paradigm: WIMP dark matter**

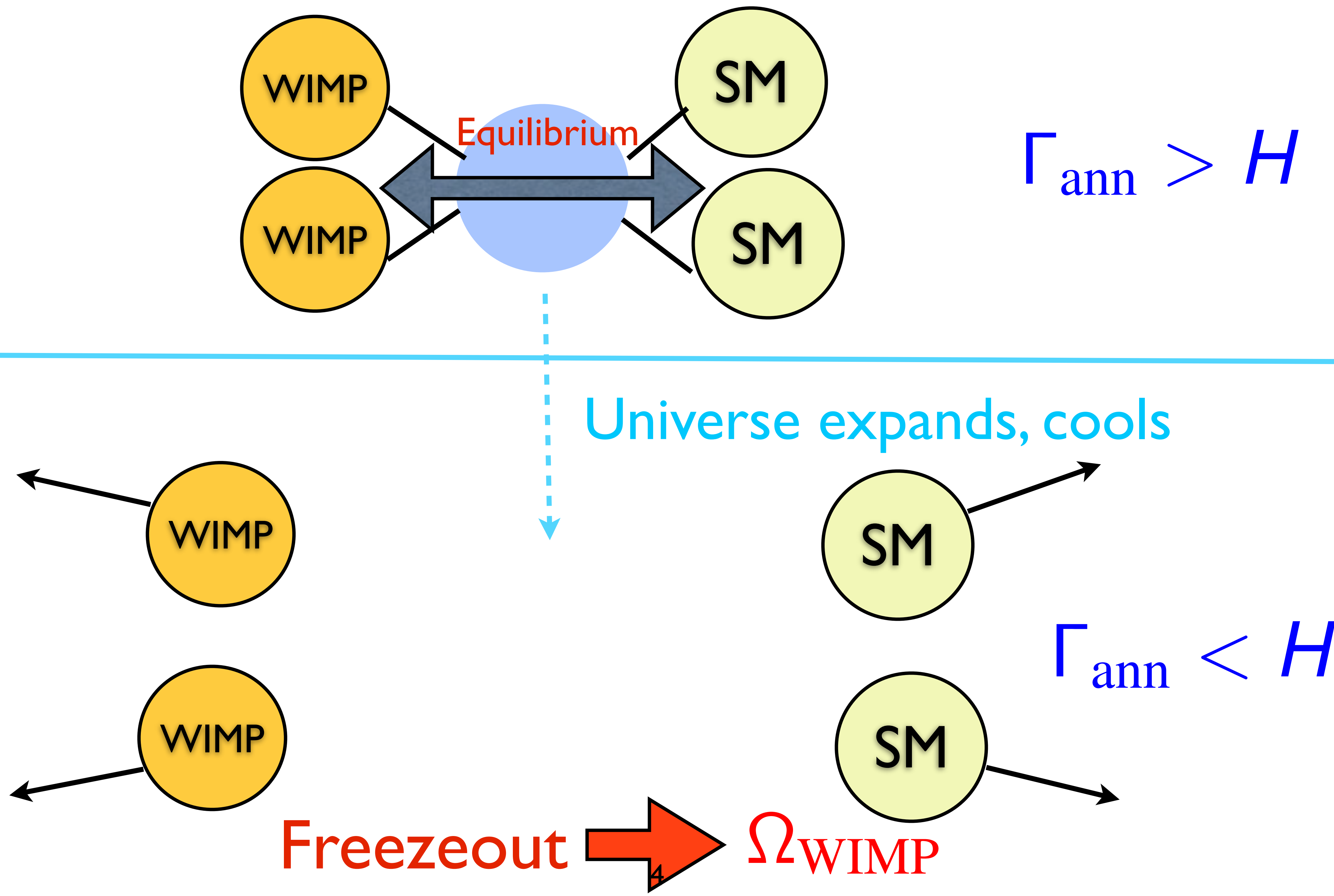
**(Weakly Interacting Massive Particle)**

Well motivated candidates, experimentally detectable

Ex.: Neutralino LSP in SUSY

# Relic abundance of WIMP DM
## (general, independent of SUSY)

- Thermal freezeout of WIMP DM:



# WIMP Miracle

-- Crude quantitative success of WIMP DM in general

- A thermal WIMP $\chi$ freezes out around $T_f \sim \frac{1}{20} m_\chi$ ,

$$\Omega_\chi \simeq 0.1 \frac{\alpha^2_{\rm weak}/({\rm TeV})^2}{\langle \sigma_{\rm A} v \rangle}$$

$$\simeq 0.1 \left( \frac{g_{\rm weak}}{g_\chi} \right)^4 \left( \frac{m^4_{\rm med}}{m^2_\chi \cdot {\rm TeV}^2} \right)$$

Can readily fit $\Omega_{\rm DM} \approx 23\%$ , **WIMP miracle!**

Remarkable quantitative success, but **NOT PRECISE**: natural **range** up to $g_\chi, m_{\rm med}$ etc.

# Baryons $\Omega_B \approx 5\%$

Asymmetric abundance: $B$ **excess** over $\bar{B}$

$$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$$

## Baryogenesis: intricate, puzzling

- (Necessary) *Sakharov conditions*: $\not{CP}$, $\not{B}$, out of equilibrium
- Suppress *"washout effect"*: persistent $\not{B}$ interactions ($B \to \bar{B}$) during/after baryogenesis, threat to Baryogenesis efficiency!
- **When? How?** various mechanisms:

  GUT baryogenesis, leptogenesis, EW sphalerons... (typically $T \gtrsim T_{EW}$ )

**RECAP:** $\Omega_B$ , $\Omega_{DM}$ apparently from separate mechanisms, at separate scales...

$$\Omega_{DM} \sim \Omega_B$$

# "Coincidence" or Connection?

drawn more attention recently

**Paradigm: Asymmetric Dark Matter**

(Nussinov 1985; Kaplan 1992; Kaplan, Luty, Zurek 2009...)

- Dark matter is also asymmetric,

  Co-generation of dark & baryon asymmetry or asymmetry transfer ⇒ $\Omega_{DM} \sim \Omega_B$

# Summary: scorecard of existing paradigms

| | $\Omega_{DM}$ | $\Omega_B$ | $\Omega_B \sim \Omega_{DM}$ |
|---|---|---|---|
| WIMP Miracle DM | ✓ − | ✗ | ✗ |
| Baryogenesis | ✗ | ✓ − − | ✗ |
| Asymmetric DM | ✗ | ✗ | ✓ − |
| **?unified paradigm?** | ✓ − | ✓ − | ✓ − |

✓ − : readily at right ballpark of observation, yet NOT PRECISE

✓ − − : can FIT observed value, but no typical ballpark prediction

# The goal and challenge for getting

$\Omega_{DM}$ ✓ $\Omega_B$ ✓ $\Omega_B \sim \Omega_{DM}$ ✓

➡ WIMP miracle + $\Omega_{\rm DM} \sim \Omega_{\rm B}$ in a natural way

A few attempts made, only very recently, but all have sensitivity to model detail (washout, long lifetime...), tuning

- McDonald, Phys. Rev. D 83, 083509 (2011)
- **Cui**, Randall and Shuve, JHEP1204, 075 (2012): novel baryogenesis triggered by WIMP DM annihilation around freeze-out time
- Davidson and Elmer, JHEP1210, 148 (2012)

# A New Paradigm:

# **Baryogenesis from WIMPs**

(Phys.Rev.D, 87,11603 [arXiv:1212.2973], **Cui** and Sundrum)

$\Omega_{DM}$ ✔ $\Omega_B$ ✔ $\Omega_B \sim \Omega_{DM}$ ✔

- An alternative mechanism, more robust connection to WIMP miracle, less sensitive to model detail
- Other related constraints checked ➡ viability ✓

**Novel Baryogenesis at low scale** $T \lesssim T_{\rm EW}$

✦ Independent of its relation to DM (even if DM is not WIMP...)

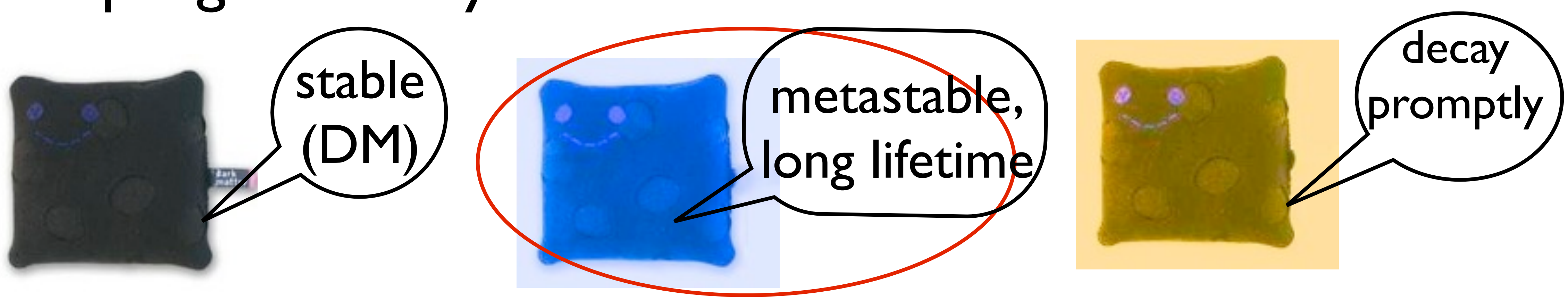
✦ Related new physics signals accessible at LHC etc.

✦ Can be a remedy: Some beyond-the-Standard Model physics calls for low scale baryogenesis (later: e.g. RPV natural SUSY...)

# General Philosophy/Principle

- WIMP type new particles: <u>ubiquitous</u> in scenarios addressing Planck-electroweak Hierarchy Problem
- Most familiar, yet special case: stable WIMP as DM candidate

- **More generic possibility**: An array of WIMPs, with diverse lifetimes - depending on symmetry protection, mass/ coupling hierarchy




<u>Does Nature "mind" such diversity/complexity?</u> No!

Known physics: long lifetime of b-quark, muon( $m_W \gg m_b, m_\mu$ );

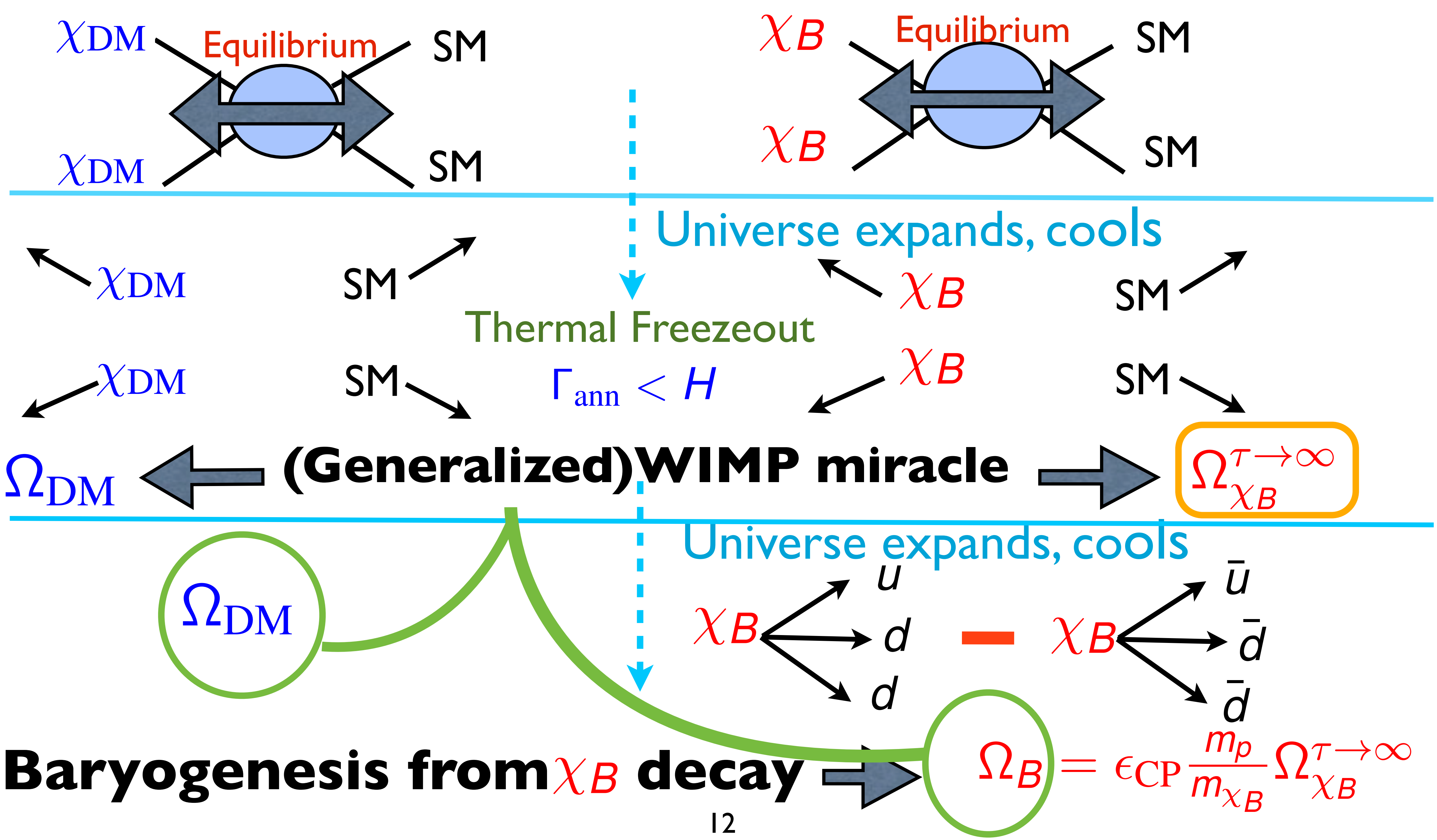
hierarchical fermion Yukawa couplings( $y_e \approx 10^{-6} \ll y_t \approx 1$ )

Assume a stable WIMP $\chi_{\rm DM}$ as DM;

In addition, a metastable WIMP $\chi_B$ as baryon parent:

$\chi_B$ : $\not{B}$, $\not{CP}$ decay after thermal freezeout ⇒ Baryogenesis

- **Cosmic evolution of the two WIMPs:**



# Central Result:

**Generalized WIMP Miracle**

$$\Omega_{\rm DM} \sim \Omega_B = \epsilon_{\rm CP}\frac{m_p}{m_{\chi_B}}\Omega_{\chi_B}^{\tau\to\infty}$$

- **Robustness**: insensitive to precise long-lifetime $\tau$
- Caveat: washout processes ($B \to \bar{B}$) needs to be suppressed to avoid extra reduction on $\Omega_B$, ⇨ Easy to realize (later...)
- Extra factor $\epsilon_{\rm CP}\frac{m_p}{m_{\chi_B}} \sim 10^{-4} - 10^{-3}$ (large CPV at 1-loop: $\epsilon_{\rm CP} \sim 1 - 10\%$) compensation factor from $\Omega_{\chi_B}^{\tau\to\infty} \sim 10^2 - 10^3$ to get $\frac{\Omega_B}{\Omega_{\rm DM}} \sim O(0.1)$ ,
- Easy to accommodate by different masses/couplings associated with $\chi_{\rm DM}$ and $\chi_B$ ($\chi_B$ : a "weaker" WIMP)

⇨ **Recall: WIMP miracle is a rough guideline!**

$$\Omega_\chi \simeq 0.1\frac{\alpha_{\rm weak}^2/({\rm TeV})^2}{\langle\sigma_A v\rangle} \simeq 0.1\left(\frac{g_{\rm weak}}{g_\chi}\right)^4\left(\frac{m_{\rm med}^4}{m_\chi^2\cdot{\rm TeV}^2}\right)$$

# Outline

- General formulation
- A minimal model, constraints/viability;
  Embedding in $\not{B}$ "natural SUSY"
- Embedding in RPV Mini-Split SUSY
- LHC Phenomenology: Displaced Vertex Search
- Outlook

# General Formulation

- A thermal WIMP $\chi$ freezes out when $\Gamma_{\rm ann} \simeq H$

$$T_f \simeq m_\chi \left[\ln\left(0.038(g/g_*^{1/2}) m_\chi M_{\rm pl} \langle \sigma_{\rm A} v \rangle\right)\right]^{-1} \sim \frac{1}{20} m_\chi$$

Co-moving density: $Y_\chi(T_{\rm f}) = \dfrac{n_\chi^{\rm eq}(T_{\rm f})}{s(T_{\rm f})} \simeq 3.8 \dfrac{g_*^{1/2}}{g_{*s}} \dfrac{m_\chi}{T_{\rm f}} \left(m_\chi M_{\rm pl} \langle \sigma_{\rm A} v\rangle\right)^{-1}$

*If $\chi$ is stable,* $Y_\chi(T_{\rm f}) \simeq Y_\chi(T_0)$, relic density today:

$$\Omega_\chi = \frac{m_\chi Y_\chi(T_{\rm f}) s_0}{\rho_0} \simeq 0.1 \frac{\alpha_{\rm weak}^2/({\rm TeV})^2}{\langle \sigma_{\rm A} v\rangle}$$

- **Consider two species of WIMPs :**

★ Stable WIMP DM $\chi_{\rm DM}$ : $\Omega_\chi \equiv \Omega_{\rm DM} \approx 27\%$ (WIMP miracle)

★ Metastable WIMP (baryon parent) $\chi_B$: $\not{CP}$, $\not{B}$ decay at

$T_D < T_f$ , $Y_{\chi_B}(T_{\rm f}) \equiv Y_{\chi_B}^{\rm ini}$ ⇨ initial condition for baryogenesis

# Baryogenesis from late decay of WIMP $\chi_B$

- Assume well separated scales: $1\ \mathrm{MeV} \sim \mathrm{T_{BBN}} < \mathrm{T_D} < \mathrm{T_f}$

→ Freeze-out and baryogensis as decoupled processes, retain conventional success of BBN

- Solving Boltzmann equations, co-moving baryon density today:

$$Y_B(0) = \epsilon_{\mathrm{CP}} \int_0^{T_\mathrm{D}} \frac{dY_{\chi_B}}{dT} \exp\left( - \int_0^{T} \frac{\Gamma_\mathrm{W}(T')}{H(T')} \frac{dT'}{T'} \right) dT$$

$\epsilon_{\mathrm{CP}}$: CP asymmetry in $\chi_B$ decay, $\Gamma_\mathrm{W}$: the rate of $\not{B}$ washout processes

- **Weak washout:** $\Gamma_\mathrm{W} < H$

→ $Y_B(0) \simeq \epsilon_{\mathrm{CP}} Y_{\chi_B}(T_\mathrm{f}), \;\; \Omega_B(0) = \epsilon_{\mathrm{CP}} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau \to \infty} \sim \Omega_{\mathrm{DM}}$

# Minimal Model: setup

We add to the Standard Model (SM) Lagrangian($\not{B}$)(complex couplings)

$$\Delta\mathcal{L} = \lambda_{ij}\phi d_i d_j + \varepsilon_i \chi \bar{u}_i \phi + M_\chi^2 \chi^2 + y_i \psi \bar{u}_i \phi + M_\psi^2 \psi^2 + \alpha\chi^2 S + \beta|H|^2 S + M_S^2 S^2 + \text{h.c.}$$

- $\phi$: di-quark scalar with same SM gauge charge as u-quark
- $\chi, \psi$: SM singlet Majorana fermions.

  $\chi \equiv \chi_B$, the WIMP parent for baryogenesis.
- $\varepsilon_i \ll 1$: formal small parameter(small breaking of a $\chi$-parity symmetry)

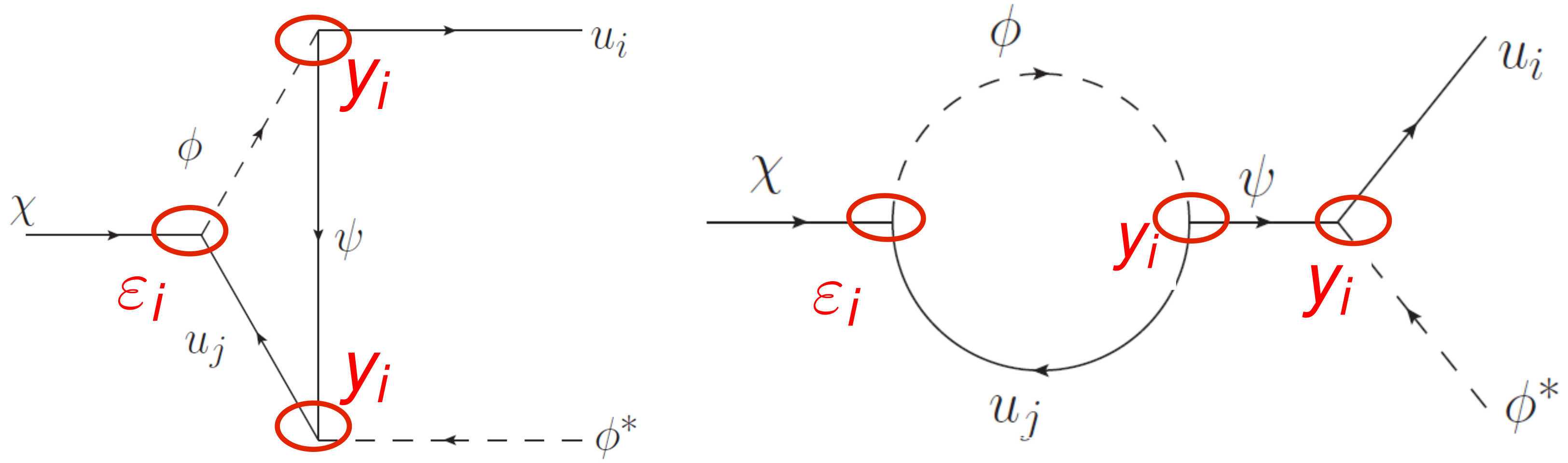
  ⇒ long-lived $\chi$ $(\chi \rightarrow u\phi^*)$
- Singlet scalar $S$ : mediates WIMP annihilation $\chi\chi \rightarrow \text{SM}$

**Incorporate DM?** + $\chi_{\text{DM}}$ singlet, interactions analogous to $\chi$, except for exact $\chi_{\text{DM}}$-parity ⇒ $\varepsilon_{\text{DM}} = 0$

# Minimal Model: Baryogenesis

- Out-of-equilibrium decay $\chi \to \phi^* u \; (\phi^* \to dd)$ with
  $\Delta B = 1, \epsilon_{CP} \neq 0$
- CP asymmetry: $\epsilon_{CP} \equiv \frac{\Gamma(\chi \to \phi^* u) - \Gamma(\chi \to \phi \bar{u})}{\Gamma(\chi \to \phi^* u) + \Gamma(\chi \to \phi \bar{u})}$ from
  interference between tree-level and $\psi$-mediated loop

  diagrams:




  Compute $\epsilon_{CP}$ (close analogy to leptogenesis), e.g. for $M_\psi > M_\chi$:

$$\epsilon_{CP} \simeq \frac{1}{8\pi} \frac{1}{\sum_i |\varepsilon_i|^2} Im \left\{ \left( \sum_i \varepsilon_i y_i^* \right)^2 \right\} \frac{M_\chi}{M_\psi}$$

➡ To maximize CP asymmetry: $\varepsilon_i \ll y_i \sim 1$

# Minimal Model: Constraints

- Lifetime of $\chi$ : recall ansatz $T_{\rm BBN} < T_{\rm D} < T_{\rm f}$

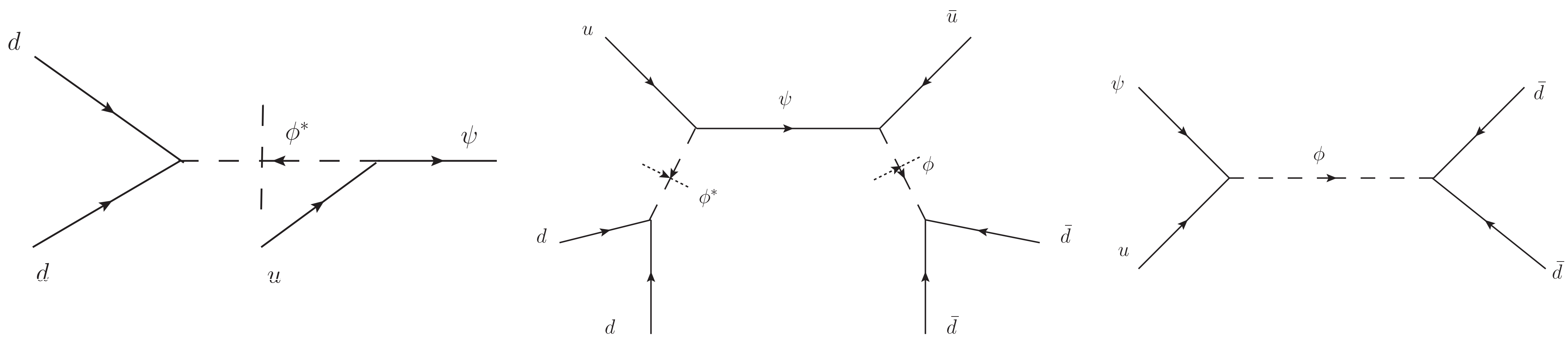
  ⇨ wide range $10^{-13} \lesssim \varepsilon \lesssim 10^{-8}$, with $m_\chi \sim 1\,\mathrm{TeV}$.

- Weak washout requirement:

  *"Washout"*: $\not B$ interactions ($B \to \bar{B}$), can erase part or all baryon asymmetry during or after baryogenesis

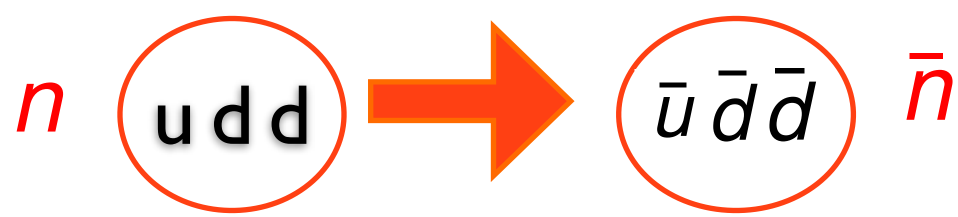
  Consider washout processes in timeline：

- Before QCD phase transition: quarks $\not{B}$ inverse decay/ scatterings ✓ (Boltzmann/power law suppression)



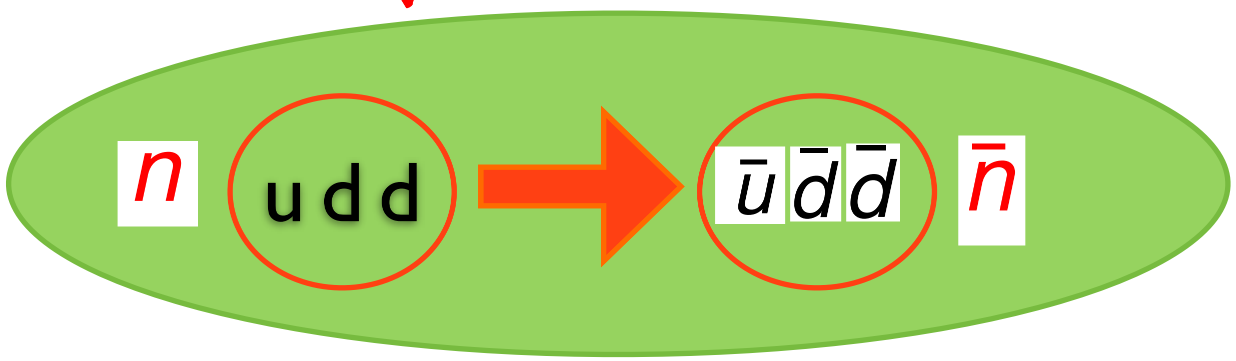

- After QCD PT, before BBN: free neutron, proton;

  $n \to \bar{n}$ oscillation ✓



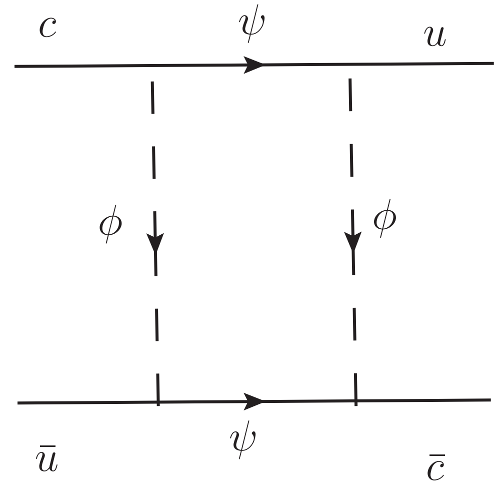

- After BBN: bound-state neutron, proton;

  $n \to \bar{n}$ oscillation in medium ✓



# Current-day precision tests

- $n-\bar{n}$ **oscillation reactor experiments** ✓
- **Flavor changing neutral currents:** ✓




- **Neutron electric dipole moment** (nEDM) ✓

# Summary/Implications of the constraints

- Assume all new fields have weak scale masses,

  Precision constraints ⇒ New couplings involving first two generation quarks (e.g. $\lambda_{ij}$ for $\phi d_i d_j$ (i,j=1,2)) need to be suppressed

- **Simple, natural Solution:** Third-generation dominated pattern, new fields couple mostly to b, t (just like Higgs!), with "CKM-like mixing"suppressions to light quarks

# Meeting Particle Physics Frontier: Embedding in SUSY

- **Our framework:** generic mechanism of baryogenesis, intriguing, neater to embed in existing theories related to Higgs mechanism, Planck-weak hierarchy problem, e.g. SUSY!

- **Status of Supersymmetry:**

✦ *Conventional* low scale SUSY- tension with LHC data:
125 GeV higgs mass, exclusion: $m_{\tilde{q}_1}, m_{\tilde{g}} \gtrsim 1$ TeV ⇨ fine-tuning

✦ Continue to be attractive: new spacetime symmetry, improve gauge coupling unification, solve the original severe Planck-weak hierarchy problem, LSP WIMP DM (RPC), $m_h \approx 125$ GeV still close to SUSY prediction...

✦ Currently favored SUSY models:

- Preserve Naturalness: "Natural SUSY" (light $\tilde{t}, \tilde{b}$) and/or R-parity violating (RPV) SUSY (Barbieri, Giudice; Cohen, Kaplan, Nelson; Brust, Katz, Lawrence, Sundrum; Graham,Kaplan,Rajendran, Saraswat...)

- Give up Full Naturalness, anthropic (string theory landscape ):

  (mini-) Split SUSY( $m_{\rm scalar} \gg m_{\rm gaugino(Higgsino)} \sim$ TeV )

  (Arkani-Hamed, Dimopoulos; Wells; Yanagida; Arvanitaki, Craig, Dimopoulos, Villadoro; Arkani-Hamed, Gupta, Kaplan, Weiner, Zorawski; Hall, Nomura, Shirai...)

  **Attractions:** Generically realized in gravity-mediated $\not{S}\!\!\!\not{U}\!\!\not{S}\!\!\!\not{Y}$ models, easily fit 125 GeV Higgs mass, satisfy flavor constraints generically...

**Natural ``incarnation" of our paradigm in these viable SUSY models?**

✦ **SUSY⟷Cosmology:** RPC SUSY ➡ LSP DM (well known);

CPV + RPV SUSY + late-decayed particle ➡ Baryogenesis???

# Embedding in Natural SUSY: Model

**Our minimal model: direct "blueprint"**

- Promote singlets $\chi, S$ to chiral superfields, add to the MSSM. $\not{B}$ superpotential:

$$W \supset \lambda_{ij} T D_i D_j + \varepsilon' \chi H_u H_d + y_t Q H_u T + + \mu_\chi \chi^2$$
$$+ \mu H_u H_d + \mu_S S^2 + \alpha \chi^2 S + \beta S H_u H_d .$$

- Assume $\not{SUSY}$ pattern: scalar $\chi$ and $\tilde{q}_{1,2}$ heavy, decoupled, as in "natural SUSY"
- Mapping: (minimal model $\longrightarrow$ SUSY model)
  - Diquark $\phi \longrightarrow$ light $\tilde{t}_R$ in superfield $T$
  - Baryon parent singlet $\chi \longrightarrow$ fermion singlet $\chi$
  - Majorana $\psi \longrightarrow$ MSSM gaugino
  - Singlet scalar $S \longrightarrow$ singlet $S$, mixes with $H_u$, enables $\chi$ annihilation
  - Small parameter $\varepsilon \longrightarrow \varepsilon'$, enables late decay $\chi \to \tilde{\bar{t}} t$ via $\chi - \tilde{H}_u$ mixing

# Embedding in Natural SUSY: Also a remedy!

## Potential cosmological crisis of $\not{B}$ natural SUSY:

- An intriguing, less studied/less constrained regime of natural SUSY for collider search: light $\tilde{t}$ with $\not{B}$ prompt decay
  ⇒ $TD_iD_j$ coupling $\lambda_{ij} \gtrsim 10^{-7}$
- **Cosmological problem:**

  Assume conventional baryogenesis at $T \gtrsim m_{EW}$ ⇒ pre-existing $Y_B^{\rm init}$ can be efficiently erased by $\not{B}$ scattering e.g. $\tilde{H}_u t \to \bar{d}_i \bar{d}_j$ with $\lambda_{ij} \gtrsim 10^{-7}$ !

  Estimate of washout: exponential reduction!

$$Y_B(0) = Y_B^{\rm ini} e^{-\int_0^{T_{\rm ini}} \frac{\Gamma_{\rm W}(T)}{H(T)} \frac{dT}{T}} \sim Y_B^{\rm init} e^{-\frac{\lambda_{ij}^2 y_t^2}{g_*^{1/2}} \frac{M_{\rm pl}}{m_{\rm EW}}}$$

- **Our model in Natural SUSY:** Baryogenesis below weak scale when all washout effects decouple

⇒ **A robust cure to this problem!**

# Embedding in Mini-Split SUSY

(Cui, JHEP 1312 (2013) 067(arxiv:1309.2952))

- Conventional motivation for mini-split SUSY (as discussed): solve Planck/weak hierarchy problem, improve GUT, flavor physics, LHC data, anthropic...

- **Motivation from Baryogenesis:**

Minimal model (MSSM)+RPV works! ⇨ Mini-split scale

**Sakharov#1: out-of equilibrium** ✓

Recall *natural SUSY model:* $\epsilon\chi t\tilde{t}^*$ ⇨ $\chi \to t\tilde{t}^*$

Late decay ⇨ $10^{-13} \lesssim \epsilon \lesssim 10^{-8}$ technically natural, $\chi$ -parity

In split SUSY+RPV: Natural long life-time of TeV gauginos

Split spectrum $O(100-1000)\mathrm{TeV} \sim \mathrm{m}_{\mathrm{scalar}} \gg \mathrm{m}_{\mathrm{gaugino}} \sim \mathrm{TeV}$ + RPV

⇨ Late decay automatic! e.g. $\chi \to udd$ (heavy mediator, 3-body...)

# Embedding in Mini-Split SUSY

★ Sakharov #2,#3 (CP-, B/L-violation) ✓

$m_{\rm scalar} \sim O(100-1000){\rm TeV}$ ➡ Large ~~CP~~ phase (e.g. Majorana gaugino masses), large $\not{B}$ ($\not{L}$) RPV couplings: much safer to exploit

★ WIMP parent $\chi$ for baryons with "would-be" over-abundance ✓ : Bino $\tilde{B}$! (not desirable if it is DM in RPC SUSY...)

★ Nanopoulos-Weinberg Theorem for Baryogenesis: ✓

additional $\not{B}$ source in the interference loop

➡ Another Majorana fermion in MSSM? $\tilde{W}$, $\tilde{g}$!

**Minimal** model (MSSM+RPV) gives everything needed for baryogenesis!

# Embedding in Mini-Split SUSY

$\tilde{B} \to \Delta B$ !

- Relevant Lagrangian terms:

$$W = \mu H_u H_d + \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k + h.c.$$

$$\mathcal{L}_{\text{gauge}} = \frac{\sqrt{2}}{2} g_1 (H_u^* \tilde{H}_u \tilde{B} - H_d^* \tilde{H}_d \tilde{B}) + \sqrt{2} g_1 Y_{f_{L/R,i}} \tilde{f}_i^{*L/R,\alpha} f_i^{L/R,\alpha} \tilde{B}$$
$$+ \sqrt{2} g_2 \tilde{f}_i^{*L/R,\alpha} T^a f_i^{L/R,\alpha} \tilde{W}^a + \sqrt{2} g_3 \tilde{f}_i^{*L/R,\alpha} T^a f_i^{L/R,\alpha} \tilde{g}^a + h.c.$$

$$\mathcal{L}_{\text{soft}} = -\frac{1}{2} M_1 \tilde{B}\tilde{B} - \frac{1}{2} M_2 \tilde{W}\tilde{W} - \frac{1}{2} M_3 \tilde{g}\tilde{g} - \tilde{f}_i^{*L/R,\alpha} (\mathbf{m^2_{L/R,\alpha}})_{ij} \tilde{f}_j^{L/R,\alpha} + h.c.,$$

- Sources of $\not{CP}$ :
  - Gaugino masses: $M_i, \ (n(i) \geq 2)$
  - Sfermion mass matrices: $(m^2_{L/R,\alpha})_{ij}$ -- large $\not{CP}$ possible, only with large flavor violation. May be allowed in split-SUSY... *(Hall, Nomura, Shirai, 2012)*

# CP Asymmetry in $\tilde{B}$ Decay

- Nanopoulos-Weinberg Theorem + $\not{CP}$ *(regardless of flavor structure)* ➡ Majorana $\tilde{W}$ or $\tilde{g}$ appears in the the loop diagram that interferes with tree-level $\not{B}$ decay (lighter than bino to allow kinematic cut, later...)

- Color charge, chirality of couplings:

➡ $\tilde{W}$ only couples to $\not{L}$ operators: $LL\bar{e}, LQ\bar{d},$

$\tilde{g}$ only couples to $LQ\bar{d}$ or $\bar{u}\bar{d}\bar{d}.$

- **Consider two example models:**

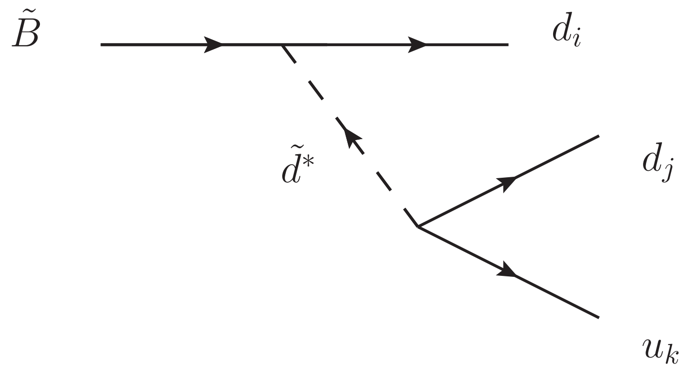
✤ Direct baryogenesis with light $\tilde{g}$ ($M_1 > M_3$) with $\bar{u}\bar{d}\bar{d}$

✤ Leptogenesis with light $\tilde{W}$ ($M_3 > M_1 > M_2$) with $LQ\bar{d}$

# Model-1: Baryogenesis with light gluino

- Tree-level decays:

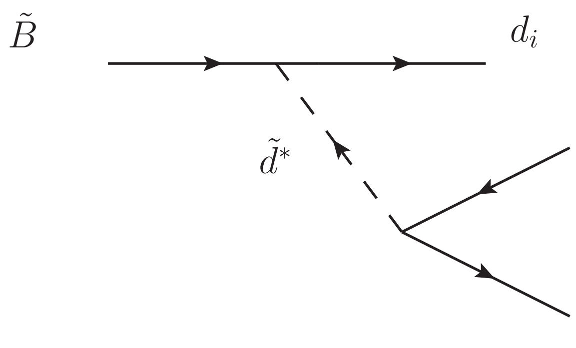
B-violating decay (baryogenesis):




(a)

$$\Gamma_{\tilde{B},\not{B}} = \frac{(\sqrt{2}\lambda'' Y_d g_1)^2}{512\pi^3} \frac{m_{\tilde{B}}^5}{m_0^4} \times 18$$

B-conserving decay (competing):



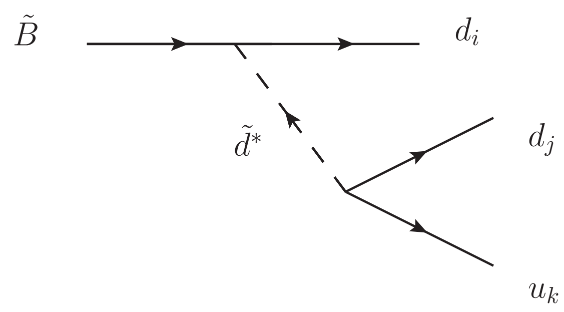

(b)

$$\Gamma_{\tilde{B}\to d\bar{d}\tilde{g}} = \frac{(Y_d g_1 g_3)^2}{1024\pi^3} \frac{m_{\tilde{B}}^5}{m_0^4} \times 3$$

⇨ $\not{B}$ decay dominates/comparable with $\lambda'' \gtrsim O(0.1)$.

# Model-I: Baryogenesis with light gluino

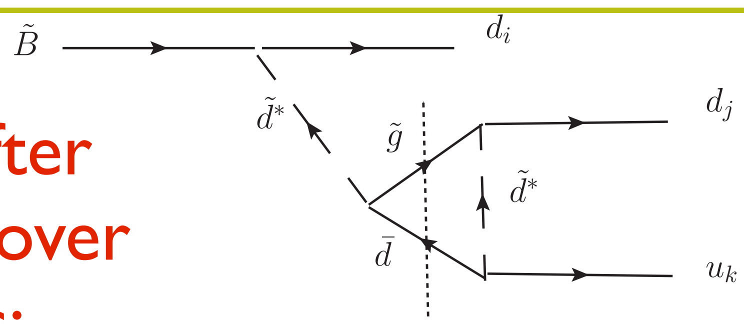
Tree-level $\not{B}$ decay:




- Interference loops:

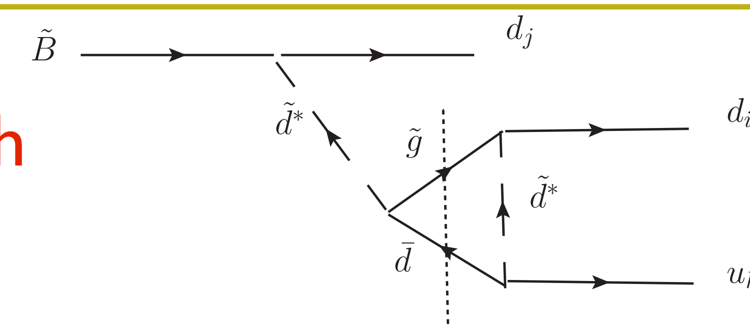
Lowest order candidates diagrams:

$\epsilon_{CP} = 0$ after summing over flavors:

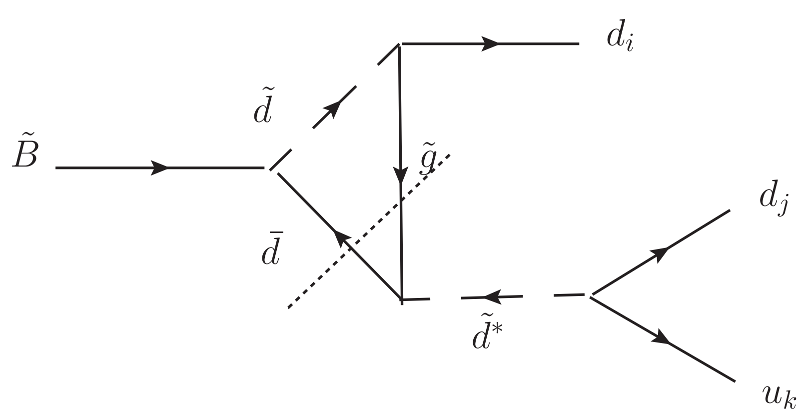



(a)

$\epsilon_{CP} \neq 0$ only with large flavor-violation:




(b)




(c)

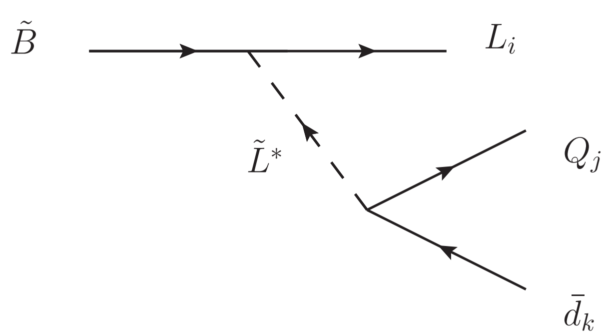
$\epsilon_{CP} \neq 0$ regardless of flavor-violation

$$\epsilon_{CP} \simeq \frac{Im[e^{i\phi}]}{10\pi} \frac{m_{\tilde{B}}^2}{m_0^2}$$

# Model-II: Leptogenesis with light wino

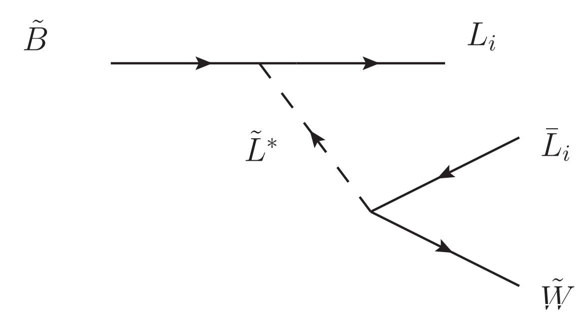
- Tree level decays:

L-violating decay (leptogenesis):

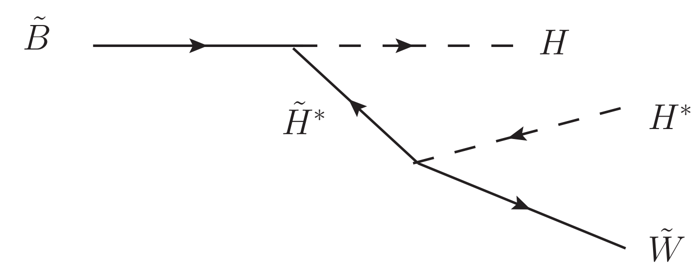



(a)

L-conserving decay (competing):




(b)




(c)

$$\Gamma_{\tilde{B},\not{L}} = \frac{(\sqrt{2}\lambda' Y_L g_1)^2}{512\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4} \times 27$$

$$\Gamma_{\tilde{B}\to L\bar{L}\tilde{W}} = \frac{(Y_L g_1 g_2)^2}{3072\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4} \times 3$$

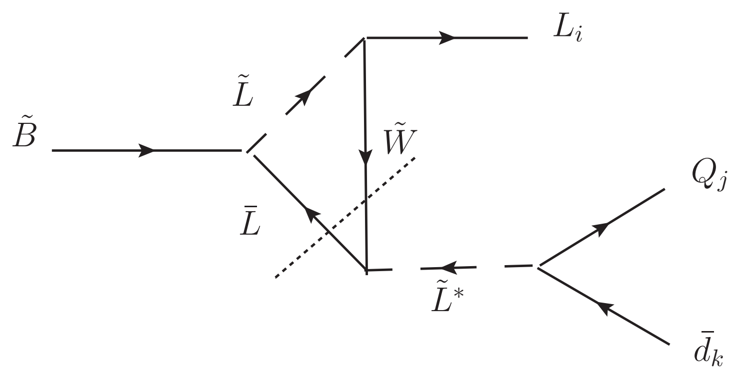
$$\Gamma_{\tilde{B}\to H^* H\tilde{W}} = \frac{(Y_H g_1 g_2)^2}{384\pi^3}\frac{m_{\tilde{B}}^3}{\mu^2}$$

$\not{L}$ decay dominates/comparable, with $\mu \gg m_0$ and $\lambda' \gtrsim O(0.1)$.

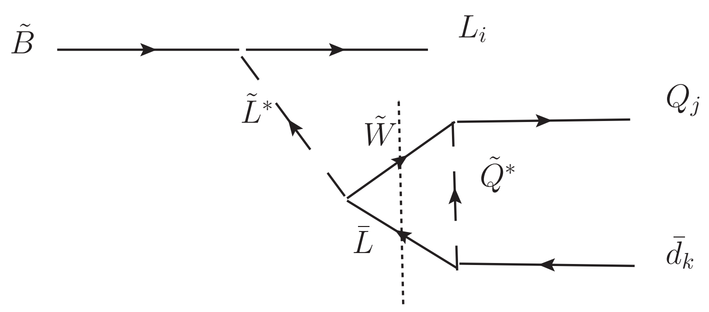
large $\mu$ -term: *supersymmetric* mass parameter, in general can be different from both $m_0$ and $m_{\rm gaugino}$ (Arkani-hamed et.al 2012); exempt from the " $\mu$-problem"

# Model-II: Leptogenesis with light wino

- Interference loops:




(a)




(b)

$\epsilon_{CP} \neq 0$ regardless of flavor-violation

$\epsilon_{CP} \neq 0$ with large flavor violation

$$\epsilon_{CP} \simeq \frac{Im[e^{i\phi}]}{50\pi} \frac{m_{\tilde{B}}^2}{m_0^2}$$

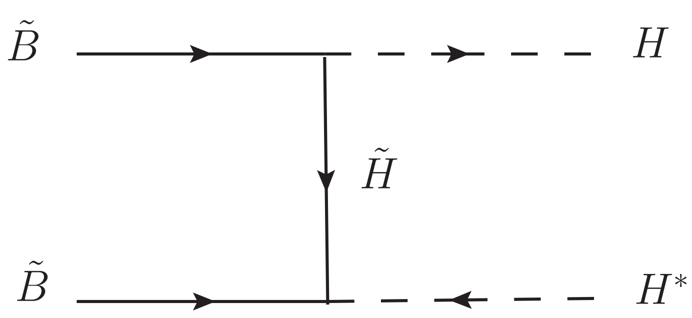
# Computation of $\Omega_{\Delta B}$

- Recall general prediction for baryon asymmetry:

$$\Omega_{\Delta B} = \epsilon_{\rm CP}\frac{m_p}{m_{\chi_B}}\Omega^{\tau\to\infty}_{\chi_B} \text{ (with negligible washout)} \qquad \epsilon_{CP} \checkmark \qquad \Omega^{\tau\to\infty}_{\tilde{B}}$$

- Thermal annihilation of $\tilde{B}$ ⇒ would-be Relic abundance $\Omega^{\tau\to\infty}_{\tilde{B}}$

Leading process with small/moderate $\mu$ :



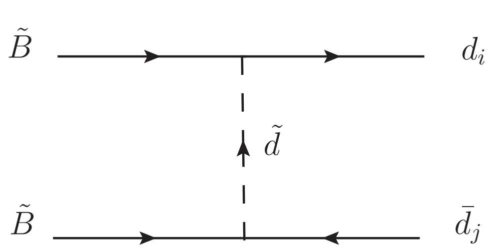
(a)

$$\sigma_{HH^*}(s) = \frac{g_1^4}{32\pi}\frac{s-4M_1^2}{s\sqrt{1-4M_1^2/s}}\frac{1}{\mu^2}$$

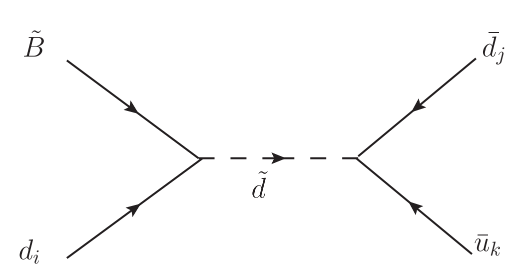
$$\langle\sigma_{HH^*}v\rangle = \frac{1}{8M_1^4TK_2^2(M_1/T)}\int_{4M_1^2}^{\infty} ds\,\sigma_{HH^*}(s)(s-4M_1^2)\sqrt{s}K_1\left(\frac{\sqrt{s}}{T}\right)$$

⇒ $$\Omega_{\Delta B} \sim 10^{-2}\left(\frac{m_{\tilde{B}}}{1\ \text{TeV}}\right)\left(\frac{\mu}{10m_0}\right)^2$$ need $\mu \gtrsim 10m_0$

Other processes, dominate at $\mu\to\infty$ :



(b)



(c)

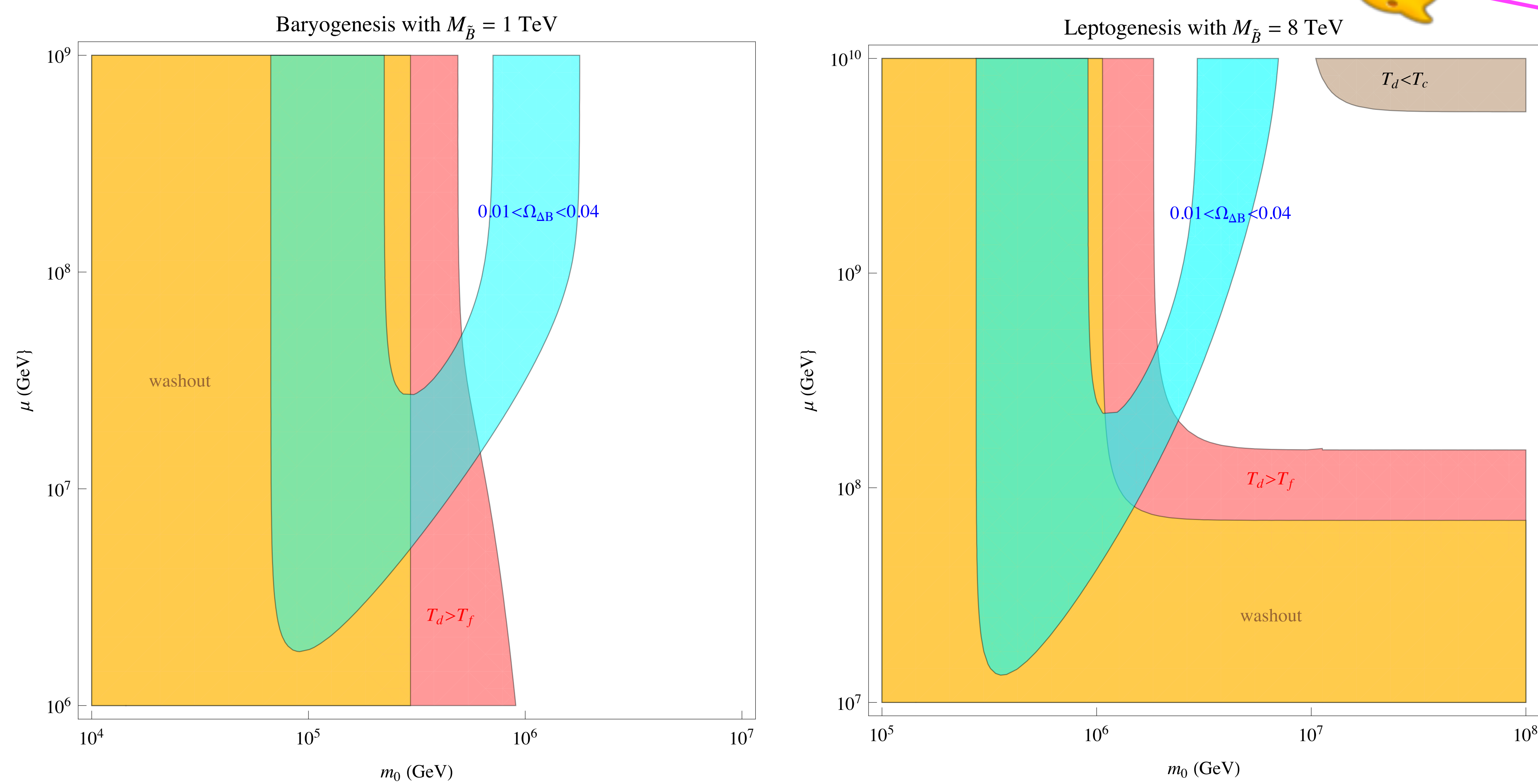
$$\langle\sigma_{\not B(\not L)}v\rangle \simeq \frac{\xi^2}{10\pi}\frac{M_1^2}{m_s^4}\left[5\frac{K_4(M_1/T)}{K_2(M_1/T)}+1\right]$$

# Numerical Results, examples

Include cosmological constraints: $\Omega_{\Delta B}$, lifetime, washout,

mini-split: $m_{\rm scalar} \sim O(100-1000){\rm TeV}$ !

*Loss of full naturalness: a compromise with anthropic/ environmental selection?*




(a) (b)

Figure 7: Cosmologically allowed regions of parameter space for (a) baryogenesis and (b) leptogenesis models. We set RPV couplings $\lambda'' = \lambda' = 0.2$, $\phi = \frac{\pi}{2}$. Cyan region provides baryon abundance $10^{-2} < \Omega_{\Delta B} < 4 \cdot 10^{-2}$. In the case of leptogenesis the brown region is excluded by decay after EWPT at $T_c \approx 100$ GeV. The pink region is excluded by our simple basic assumption that bino decays after freezeout. Yellow region is excluded by requiring that washout processes are suppressed ($T_d < M_{\tilde{B}}$). Yellow region is in fact all included in the pink region (so appear to be orange in the overlapped region).

# LHC Phenomenology

(work in preparation, YC and B. Shuve)

**Universal features of WIMP BG:**

- Long-lived WIMP: decay after thermal-freezeout *(Sakharov)*

⇨ $\tau_{\rm dec} \gtrsim t_{\rm fo} \sim \left(\frac{\rm MeV}{T_{\rm fo}}\right)^2 \cdot 1 \text{ sec}, \quad T_{\rm fo} \sim 100 \text{ GeV} \Rightarrow \tau_{\rm dec} \gtrsim 1 \text{ cm}$

-- Displaced vertex inside collider! *(our focus)*

★ DV in general: not well-covered search, rising interest, low bkg

☞ ★ Cosmological motivation for DV search from WIMP BG!

- CP-, B/L-violation in WIMP decay: Measure charge asymmetry in final states system *(interesting next step)*

# Simplified Models Approach

## for LHC DV Searches of WIMP BG

WIMP BG: general mechanism, vast landscape for model-building, examples shown (in natural SUSY, mini-split SUSY).

Collider Study: should be model-independent

⇒ Simplified models/Effective Lagrangians approach

- Classify by production channel: charges of the metastable $\chi$

✦ Carry SM gauge charge: e.g. wino, gluino in split SUSY model

pair production: $pp \to V^*_{\rm gauge} \to \chi\chi$ sizable cross-section

# Simplified Models Approach

for LHC DV Searches of WIMP BG

✦ (Mostly) Singlet under SM gauge groups:

e.g. $\chi$ in natural SUSY BG model, couples via higgs portal

Pair production: $gg \to h^{(*)} \to \chi\chi$

Small cross-section, esp. when $m_\chi > m_h/2$

✤ Also motivated by hidden-valley, twin-Higgs (naturalness)...
Important! But...

Search can be challenging if $\chi$ decays invisibly/promptly

E.g. invisible $\chi$, $m_\chi = 100$ GeV, $c_{h\chi\chi} = 1$, far off reach @LHC, $\sigma_S \ll \sigma_B$!

barely @ILC/TLEP (YC, Chacko and Hong arxiv:1311.3306, PLB )

What about $\chi$ with displaced decay? low bkg, no cost of associated ISR jet/Z, $m_\chi > 100$ GeV, $c_{h\chi\chi} \sim O(0.1)$ reachable at LHC?

# Simplified Models Approach

for LHC DV Searches of WIMP BG

- Classify by decay channels: (assume decayed $\chi$ is fermion)

  SM $\not{B}(\not{L})$ fermion trilinear operators, couple to $\chi$ (inspired by RPV SUSY) ➡ final state combination: jet/lepton/MET

  - $\mathcal{O}_{bL}$: $\lambda'\, QDL,\ \eta'\, QUL^\dagger,\ \eta''\, QQd^\dagger$
  - $\mathcal{O}_{bR}$: $\lambda''\, UDD,\ \eta\, UED^\dagger$
  - $\mathcal{O}_{lL}$: $\lambda\, LLE$

- Effective Lagrangians (classified production&decay channels)

$$\mathcal{L}_{\rm gaugino} = g_i f^{abc} \chi_i^{a\dagger} \bar{\sigma}^\mu A^b_{\mu,i} \chi_i^c + \frac{\tilde{g}\,(\mathcal{O}_{bL}, \mathcal{O}_{bR})}{\Lambda_{\tilde{g}}^2} + \frac{\tilde{W}^a\,(\mathcal{O}_{bL}, \mathcal{O}_{lL})}{\Lambda_{\tilde{W}}^2} + \frac{\tilde{B}\,(\mathcal{O}_{bL}, \mathcal{O}_{bR}, \mathcal{O}_{lL})}{\Lambda_{\tilde{B}}^2}$$

$$\mathcal{L}_{\rm singlet} = \xi \frac{|H|^2 \chi_s \chi_s}{\Lambda_H} + \frac{\chi_s\,(\mathcal{O}_{bL}, \mathcal{O}_{bR}, \mathcal{O}_{lL})}{\Lambda_s^2},$$

# LHC DV Searches of WIMP BG

- Relevant searches (sensitivity depends on $\tau_{\rm dec}$ , boost...), e.g.:

✦ CMS displaced dijet (2013): on resonance heavy H dijet decay

✦ ATLAS displaced muon+tracks (arxiv: 1210.7451): RPV neutralino from squark decays

- **Preliminary** studies:

★ Recast CMS dijet search for direct pair-produced wino w/3-jet decay: efficient constraint, $M_{\tilde{W}} \gtrsim 900$ GeV for $L_{\rm dec} \sim O(1) - O(10)$ cm

★ Higgs portal models: current DV search may not be sensitive enough, ways to improve?... *(work in progress)*

# Conclusions

- Our simple, robust mechanism realizes the challenging goal: $\Omega_{DM}$ ✓ $\Omega_B$ ✓ $\Omega_B \sim \Omega_{DM}$ ✓
- Unique low scale baryogensis mechanism independent of DM story: WIMP miracle predicts right ball park of $\Omega_B$
- Natural embedding in $\not{B}$ Natural SUSY, also a remedy to a potential cosmological problem
- Embedding in RPV Split SUSY: works within minimal model (MSSM), *independently* motivates mini-split spectrum

# Outlook

- New particle physics related to EW hierarchy problem

(Appeals: motivated theories, LHC search...)

New cosmology

- Conventional focus: WIMP DM (e.g. RPC SUSY)

- New Perspective: Baryogenesis from metastable WIMP decay (e.g. RPV SUSY)

*Exciting possibility:*

Test the cosmological origin of matter(cosmology frontier) at energy frontier- current-day colliders (LHC), intensity frontier - improved low energy experiments ( $n-\bar{n}$ oscillation, flavor physics...)!