Implications of SUSY Phenomenology for Baryogenesis

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Baryogenesis and Phenomenology

Terrestrial Experiments: Colliders, EDM Searches,...

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Theoretical Parameters (M)SSM

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Cosmology:
$\eta_B = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$,
dark matter, ...

This work: establish (new) connections & improve predictions for η_B .

Leptogenesis:

Point out that $\phi_\mu^{M_{1,2}}$, ϕ_μ^A lead to leptogenesis in νMSSM.
New connection of leptogenesis to *CP*-violating phenomenology.

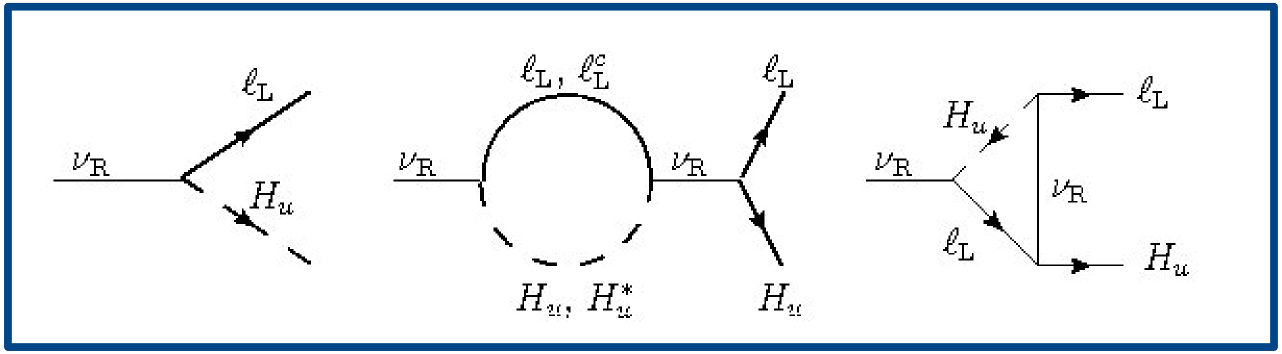
DJH Chung, BG, MJ Ramsey-Musolf, arxiv:0904:1591 [hep-ph]

EWBG:

Besides *CP*-phases $\phi_\mu^{M_{1,2}}$, ϕ_μ^A, also sparticle mass spectrum and $\tan\beta$ are crucial.

DJH Chung, BG, MJ Ramsey-Musolf, S Tulin, PRL.(2009), [arXiv:0808.1144 [hep-ph]]

Leptogenesis from Leptonic *CP*-Phases



Yukawa interactions:

$$H_u {\nu^c_{\rm R}}^T \mathbf{Y}_\nu \ell_{\rm L} + \text{h.c.}$$

Fukugita, Yanagida '86; Covi, Roulet, Vissani '96

→ each vertex suppressed by $\mathbf{Y}_\nu$, *CP*-asymmetry by $\mathbf{Y}_\nu^4$

- Type I see-saw: $\tilde{\mathbf{m}} = \mathbf{Y}_\nu^T \mathbf{Y}_\nu \dfrac{v^2}{\mathbf{m}_{\nu_{\rm R}}} \lesssim O(\text{eV})$ → $m^i_{\nu_{\rm R}} \gtrsim 10^8\text{GeV}$

  Davidson, Ibarra '02

- Loophole: Resonant Leptogenesis   Pilaftsis '97; Pilaftsis, Underwood '04

- *CP*-violating phases for leptogenesis in general unrelated to *CP*-violating observables at low energies. but: flavor effects: Pilaftsis, Underwood '05; Abada, Davidson, Josse-Michaux, Losada, Riotto '06; Nardi, Nir, Roulet, Racker '06; Pascoli, Petcov, Riotto '07

- Small Yukawa couplings and/or large $m_{\nu_{\rm R}}$

  → leptogenesis effectively decoupled from (MS)SM.

for loopholes, see e.g.: Pilaftsis '04; Blanchet, Chacko, Granor, Mohapatra '09

Leptogenesis from Non-Leptonic *CP*-Phases

DJH Chung, BG, MJ Ramsey-Musolf, arxiv:0904:1591 [hep-ph]

- Avoid suppression by powers of neutrino Yukawa couplings.
- Take *CP*-violating phases from Higgs sector beyond the SM.
- Add $\nu_{\rm R}$ ($m_{\nu_{\rm R}}$ unrelated to *CP*-asymmetry), but no extra symmetries/particles/interactions/tuning in lepton sector.

Worked examples:

- Non-SUSY two Higgs doublet model and *CP*-violation from 3rd generation Yukawa couplings.
- Leptogenesis in νMSSM
  - bino driven ⟵ this talk
  - wino driven ⟵ completely analogous to bino driven
  - $A_{t,b,\tau}$ -term driven ⟵ very similar to bino driven scenario

Bino-Driven Leptogenesis in the νMSSM

The main ingredients:

b -term provides mixing between H_u, H_d

$$\mathcal{L} \supset -(m_{H_u}^2 + \mu^2) H_u^\dagger H_u - (m_{H_d}^2 + \mu^2) H_d^\dagger H_d - b\left(H_u^T H_d + H_u^\dagger H_d^*\right)$$
$$-\frac{1}{2} M_1 \bar{\Psi}_{\widetilde{B}} \Psi_{\widetilde{B}} - \mu \bar{\Psi}_{\widetilde{H}^0} \Psi_{\widetilde{H}^0} - \mu \bar{\Psi}_{\widetilde{H}^+} \Psi_{\widetilde{H}^+}$$
$$-\frac{g_1}{\sqrt{2}}\Big[\bar{\Psi}_{\widetilde{H}^+}\left(-H_d^{-*} P_{\rm L} + {\rm e}^{{\rm i}\phi_\mu^{\rm M_1}} H_u^+ P_{\rm R}\right)\Psi_{\widetilde{B}}$$
$$+\bar{\Psi}_{\widetilde{H}^0}\left(-H_d^{0*} P_{\rm L} - {\rm e}^{{\rm i}\phi_\mu^{\rm M_1}} H_u^0 P_{\rm R}\right)\Psi_{\widetilde{B}} + {\rm h.c.}\Big]$$

Have chosen μ, M_1 to be real.
CP-violation the resides in this interaction term.

$$\Psi_{\widetilde{H}^+} = \begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_d^{-\dagger} \end{pmatrix}, \quad \Psi_{\widetilde{H}^0} = \begin{pmatrix} -\widetilde{H}_u^0 \\ \widetilde{H}_d^{0\dagger} \end{pmatrix},$$

$$\Psi_{\widetilde{B}} = \begin{pmatrix} \widetilde{B} \\ \widetilde{B}^\dagger \end{pmatrix}$$

Higgs Mixing

$$\begin{pmatrix} H_u^+ \\ H_d^{-\,*} \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^+ \\ H_2^+ \end{pmatrix}, \quad \begin{pmatrix} H_u^0 \\ H_d^{0\,*} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

$$\tan 2\alpha = \frac{2b}{m_{H_u}^2 - m_{H_d}^2}$$

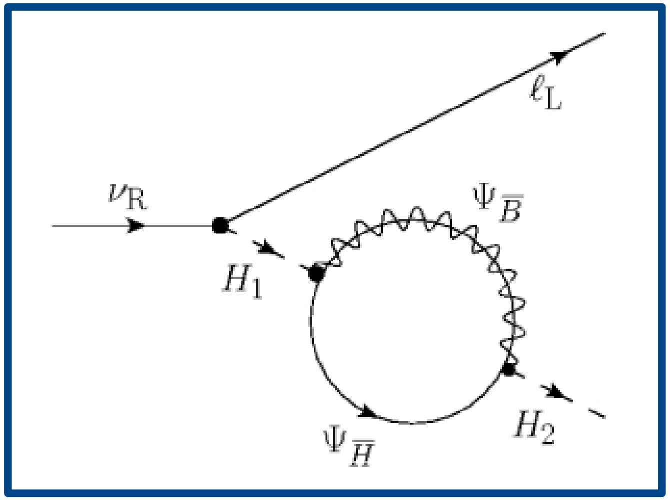
Recall: b-term is related to $\tan\beta$ in the MSSM: $b = m_A^2 \sin\beta\cos\beta$

For $m_A \gg m_Z$: $\alpha \approx \frac{1}{\tan\beta}$

CP-Asymmetry

Assume $m_{H_1} < m_{\widetilde{B}} + m_{\widetilde{H}} < m_{H_2}$

$$\varepsilon = \frac{\Gamma_{\nu_R \to \ell_L + H_2} - \Gamma_{\nu_R \to \ell_L^c + H_2^*}}{\Gamma_{\nu_R \to \ell_L + H_2} + \Gamma_{\nu_R \to \ell_L^c + H_2^*} + \Gamma_{\nu_R \to \ell_L + H_1} + \Gamma_{\nu_R \to \ell_L^c + H_1^*}}$$

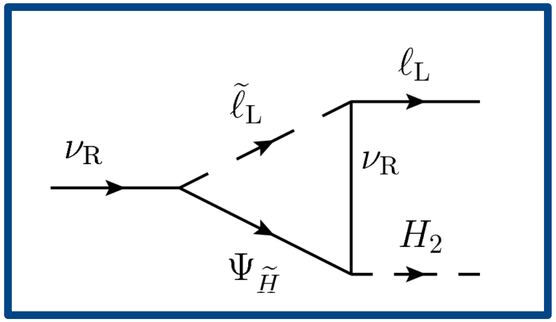


$$\varepsilon \approx \frac{\cos\alpha \sin\alpha \sin\phi_\mu^{M_1}}{8\pi} \frac{g_1^2 \mu M_1}{m_{H_2}^2 - m_{H_1}^2}$$

This vanishes if either $\mu \to 0,\ M_1 \to 0,$ as it should.

Thermal corrections will be sizable.

Also vertex correction can contribute.



Strong Washout

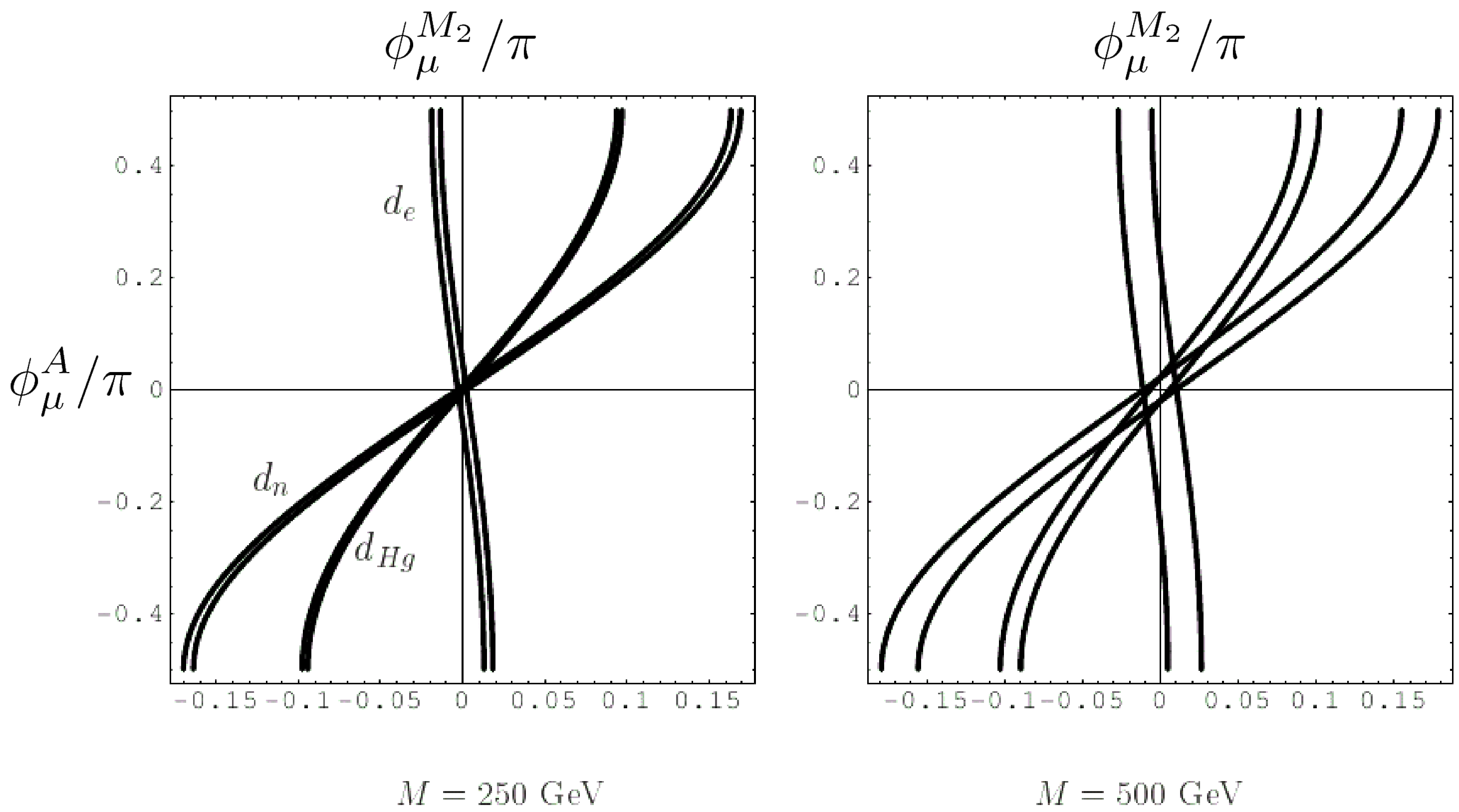
- Take $m_{\nu_\mathrm{R}} = O(\mathrm{TeV})$, assume that the ν_R were in thermal equilibrium before their decay.
- Suppression of lepton asymmetry due to inverse decays.

For analytical calculation, see Buchümller, Di Bari, Plümacher '04

Necessary *CP*-phase to explain the observed baryon asymmetry:

$$\sin\phi_\mu^{M_1} \approx -2\times 10^{-6}\frac{\tilde{m}}{10^{-3}\mathrm{eV}}\frac{m_{H_2}^4}{b g_1^2 \mu M_1}\,.$$

Electric Dipole Moments



Erler, Ramsey-Musolf '04 (plot by Perelstein)
for recent updates, see: Li, Profumo, Ramsey-Musolf '08; Ellis, Lee, Pilaftsis '09

Higgs Sector/Collider Pheno: Pilaftsis, Wagner '99; Pilaftsis, Ellis, Wagner '00; Kittel '09;...

A very testable scenario for baryogenesis.

Sterile Neutrinos as Drain for Lepton Number

- An alternative to conventional washout scenarios.
- If $m_{\nu_{\rm R}} < m_{H_2}$, *CP*-violating decays $H_2^* \to \ell_{\rm L} + \nu_{\rm R}, \; H_2 \to \ell^c_{\rm L} + \nu_{\rm R}$
- Yuakwa interaction y_ν is out of equilibrium above $T_{\rm EW} = 100{\rm GeV}$, if

$$y_\nu \ll 10^{-7} \Leftrightarrow \frac{m_{\nu_R}}{10^3{\rm eV}} \frac{\tilde{m}}{10^{-3}{\rm eV}} \ll 10^9$$

- Washout from inverse decays is completely negligible
- Cosmic exclusion window for light $\nu_{\rm R}$

$$20\,{\rm keV} \lesssim m_{\nu_{\rm R}} \lesssim 1\,{\rm GeV}$$

Dodelson, Widrow '94; Akhmedov, Rubakov, Smirnov '98; Shaposhnikov et.al.; Kusenko et. al.

OK, keV neutrinos may serve as warm dark matter

Overclosure/ BBN conflict

OK, decay before BBN

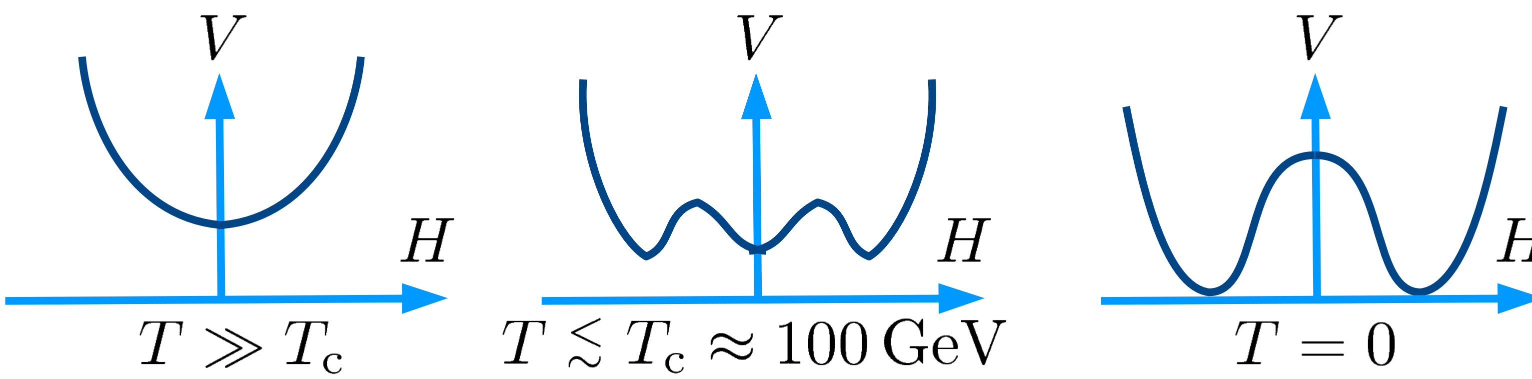
- Predicted *CP*-phase:

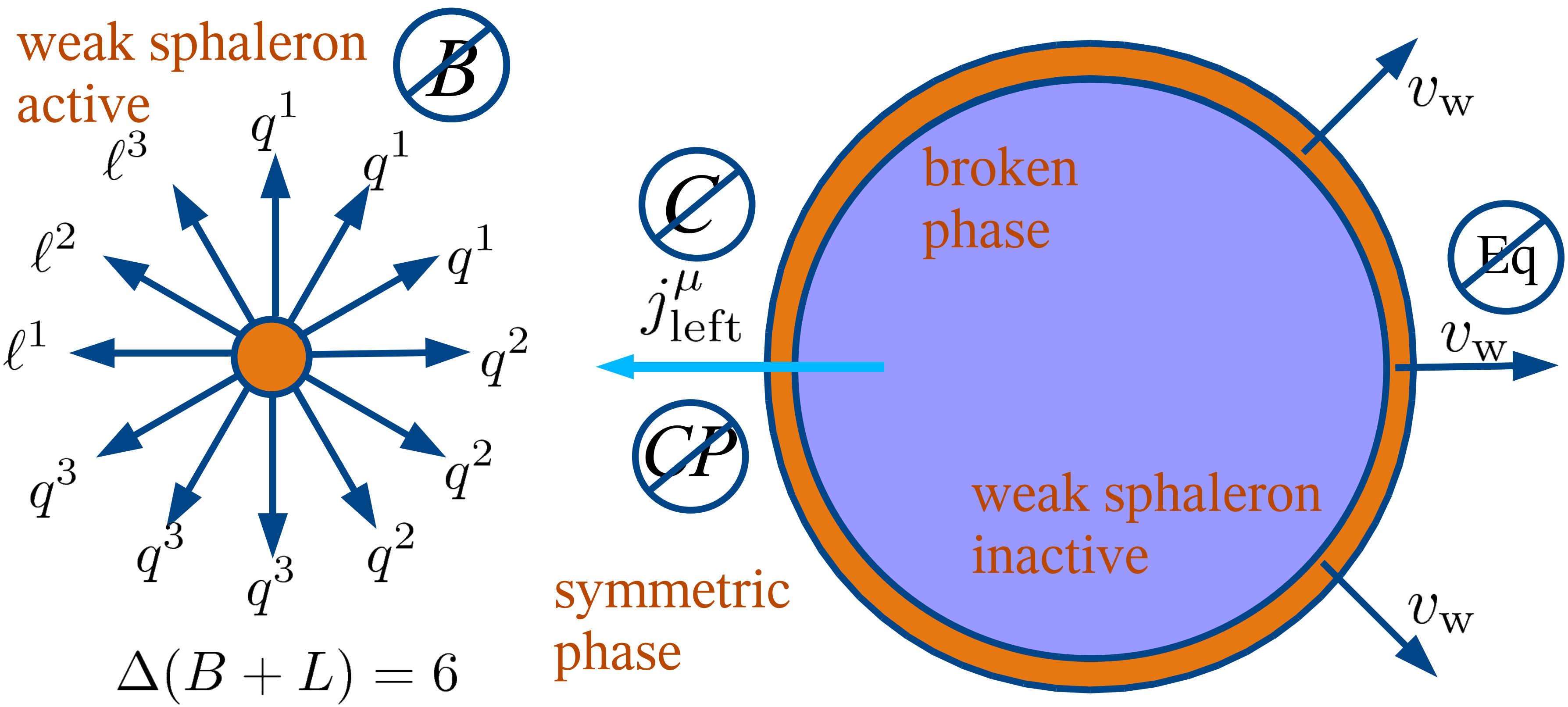
$$\sin\phi_\mu^{M_1} = -2\times 10^3 \frac{m_{H_2}^4}{b g_1^2 \mu M_1} \frac{m_{H_2}}{100\,{\rm GeV}} \frac{10^3\,{\rm eV}}{m_{\nu_{\rm R}}} \frac{10^{-3}\,{\rm eV}}{\tilde{m}}$$

Electroweak Baryogenesis

[Kuzmin, Rubakov, Shaposhnikov (1985); McLerran, Shaposhnikov, Turok, Voloshin (1990), Cohen, Kaplan, Nelson (1990)]

strong first order phase transition not with Standard Model



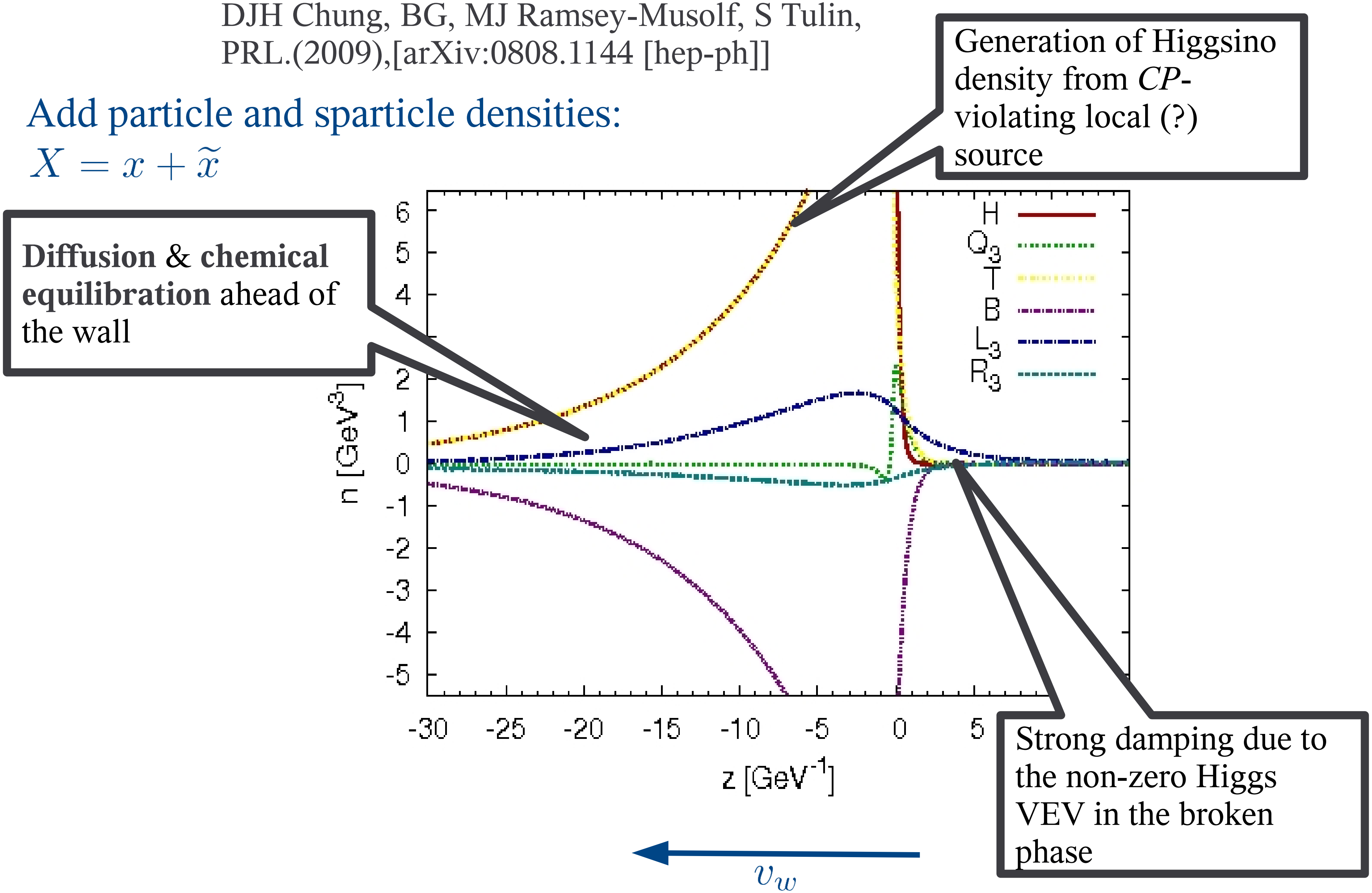


Diffusion at the Bubble Wall

DJH Chung, BG, MJ Ramsey-Musolf, S Tulin, PRL.(2009),[arXiv:0808.1144 [hep-ph]]

Add particle and sparticle densities:

$X = x + \widetilde{x}$



Sparticle Masses and Yukawa Couplings

Particle-sparticle equilibrium:
Introduce common charge densities and mass-dependent *k*-factors, e.g.

$$Q = q + \widetilde{q} = t_L + b_L + \widetilde{t}_L + \widetilde{b}_L \qquad k_Q = k_q + k_{\widetilde{q}} \qquad Q = \frac{T^2}{6} k_Q \mu_Q$$

$$T = t_R + \widetilde{t}_R \qquad k_T = k_{t_R} + k_{\widetilde{t}_R} \qquad T = \frac{T^2}{6} k_T \mu_T$$

$\ldots \qquad \ldots \qquad \ldots$

Yukawa & Triscalar Equilibrium:

$$\mu_Q + \mu_H = \mu_T$$

$$\mu_Q - \mu_H = \mu_B$$

→

$$\frac{T}{k_T} + \frac{B}{k_B} - 2\frac{Q}{k_Q} = 0$$

Local baryon number conservation (WS slow):

$$T + B + Q = 0$$

↓

if $m_{\widetilde{t}} = m_{\widetilde{b}} \Rightarrow k_T = k_B$
$\Rightarrow Q = 0$

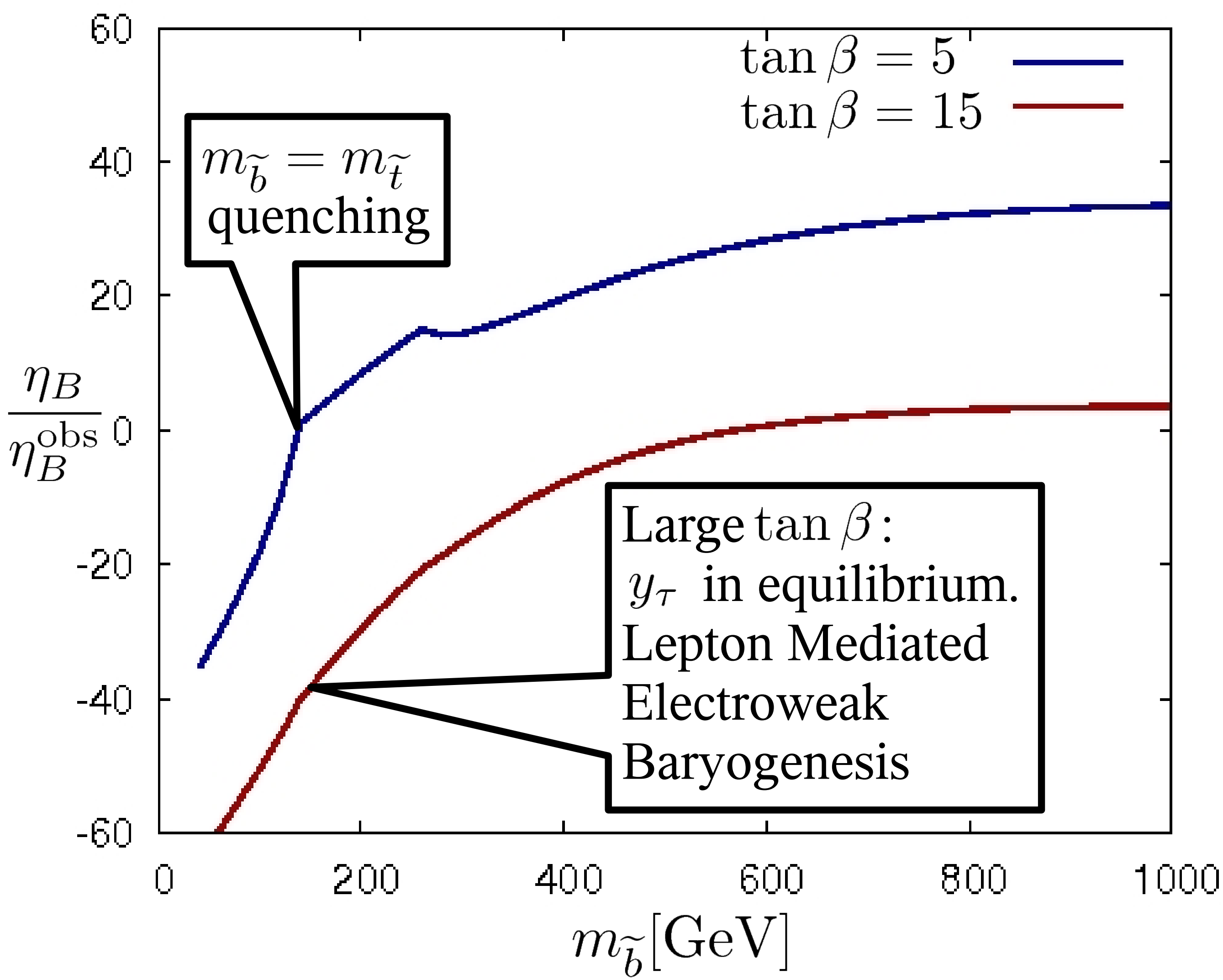
Conversely, the sign of the baryon asymmetry depends on whether
$m_{\widetilde{b}} > m_{\widetilde{t}}$ or $m_{\widetilde{t}} > m_{\widetilde{b}}$

Sparticle Mass and $\tan\beta$ Dependences

$m_{\tilde{t}} = 102\,\mathrm{GeV}$
$m_{\tilde{\tau}} = 104\,\mathrm{GeV}$
$\mu = M_2 = 200\,\mathrm{GeV}$

All other sparticles heavy.

Assume fixed CP-violating source.



Summary

Leptogenesis:

- New scenario for leptogenesis with right handed neutrinos of TeV scale or below.
- Works within a conservative model: $\nu\mathrm{MSSM}$.
- New connections of leptogenesis to phenomenology: EDMs, probes of Higgs sector.

Electroweak Baryogensis:

- Improved treatment of diffusion for electroweak baryogenesis.
- Magnitude and sign of baryon asymmetry are completely dependent on sparticle mass spectrum.
- Strong sensitivity also on size of Yukawa couplings and hence $\tan\beta$.