Recent Progress in Baryo/lepto-genesis

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PONT Avignon, April 2011

Questions & Progress:

- *How & when was the baryon asymmetry (Y_B) produced ?*
- *Which scenarios are most/least favored by experimental observations ?*
- *How reliable are theoretical computations of Y_B ?*

Ingredients: EW Baryo & leptogenesis:

EW Baryogenesis

- *1^{st} order EWPT*
- *Bubble nucleation*
- *CPV interactions w/ bubble walls: $A^{CP}{}_{BSM}$*
- *Particle transfer rxns: $A^{CP}{}_{BSM} \rightarrow A^{CP}{}_{SM}$*

Most testable

Leptogenesis

- *Out of eq ν_{heavy} decay*
- *CPV in ν_{heavy} interactions*
- *Suppression of washout rxns*

Most popular

Questions & Progress:

- *How & when was the baryon asymmetry (Y_B) produced ?*
- *Which scenarios are most/least favored by experimental observations ?*
- *How reliable are theoretical computations of Y_B ?*

- *Improvements in formal machinery, particularly in performing systematic quantum transport calculations for EW baryogenesis & leptogenesis* $\rightarrow$ *Focus on flavor*
- *New phenomenological implications for MSSM EWB*
- *New challenges for exploring a possible EWPT*
- *New ideas for linking Y_B & Ω_{CDM}* $\rightarrow$ *See J. March-Russell*

Outline

- *Systematic Quantum Transport*
- *Flavor Effects in Leptogenesis*
- *Flavor Effects in EW Baryogenesis*
- *EWPT: Progress & Questions*

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- *Systematic Quantum Transport* *
- *Flavor Effects in Leptogenesis*
- *Flavor Effects in EW Baryogenesis*
- *EWPT: Progress & Questions*

** " the flavor of flavor "*

I. Systematic Quantum Transport

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

CTP or Schwinger-Keldysh Green's functions

$$\tilde{G}(x,y) = \left\langle P\varphi_a(x)\varphi_b^*(y)\right\rangle \boldsymbol{\tau}_{ab} = \begin{bmatrix} G^t(x,y) & -G^<(x,y) \\ G^>(x,y) & -G^{\bar{t}}(x,y) \end{bmatrix}$$

- *Appropriate for evolution of "in-in" matrix elements*
- *Contain full info on number densities:* $n_{\alpha\beta}$
- *Matrices in flavor space:* (e,μ,τ) , $(\tilde{t}_L, \tilde{t}_R)$, …

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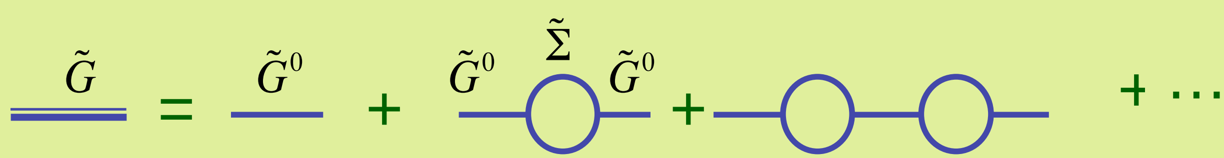

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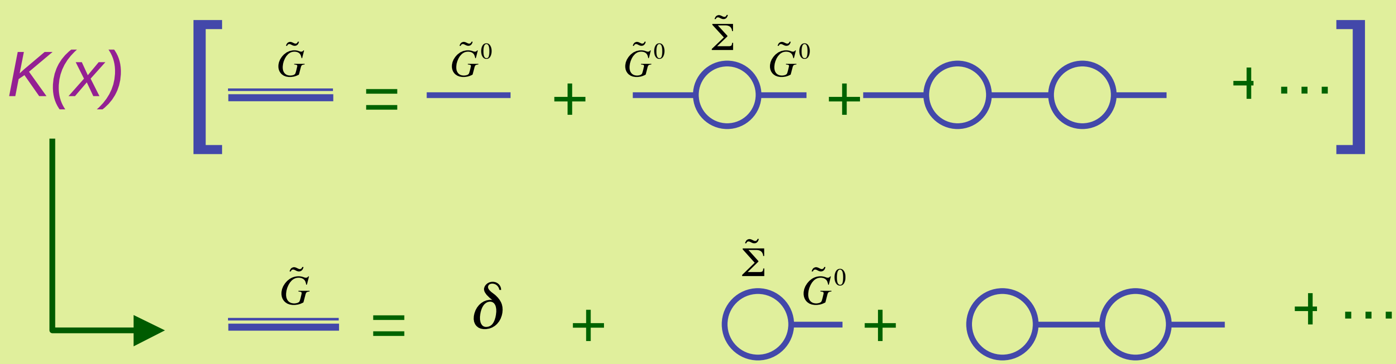
Schwinger-Dyson to Kadanoff-Baym



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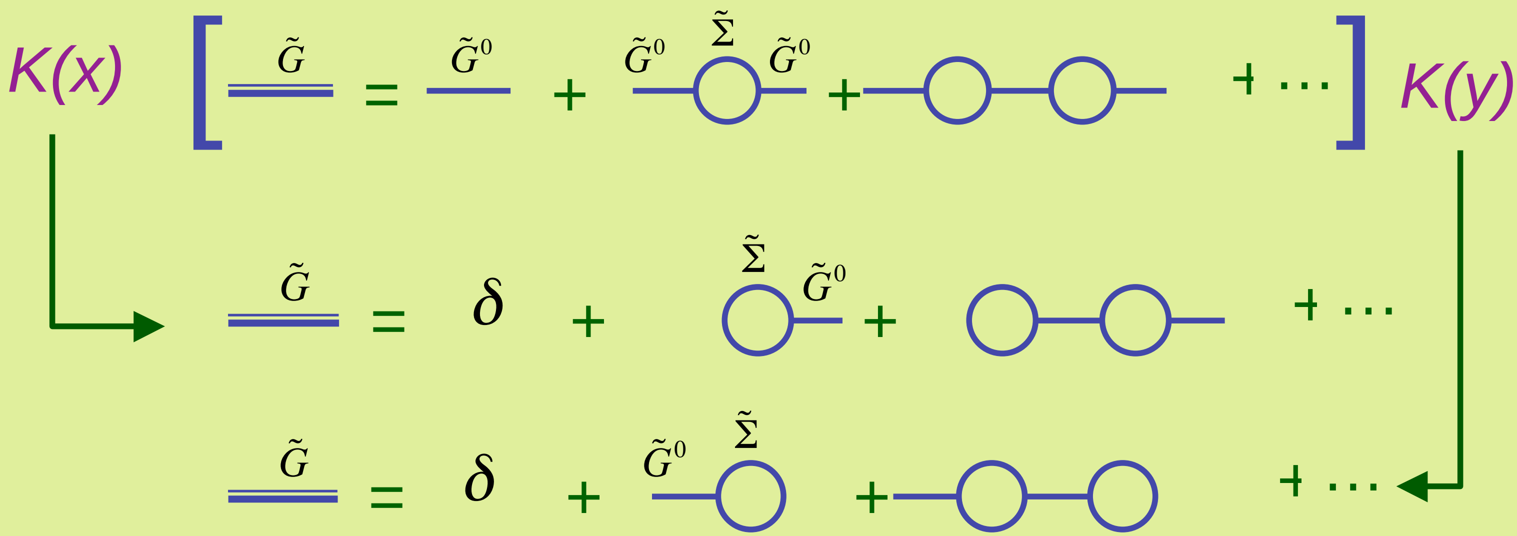

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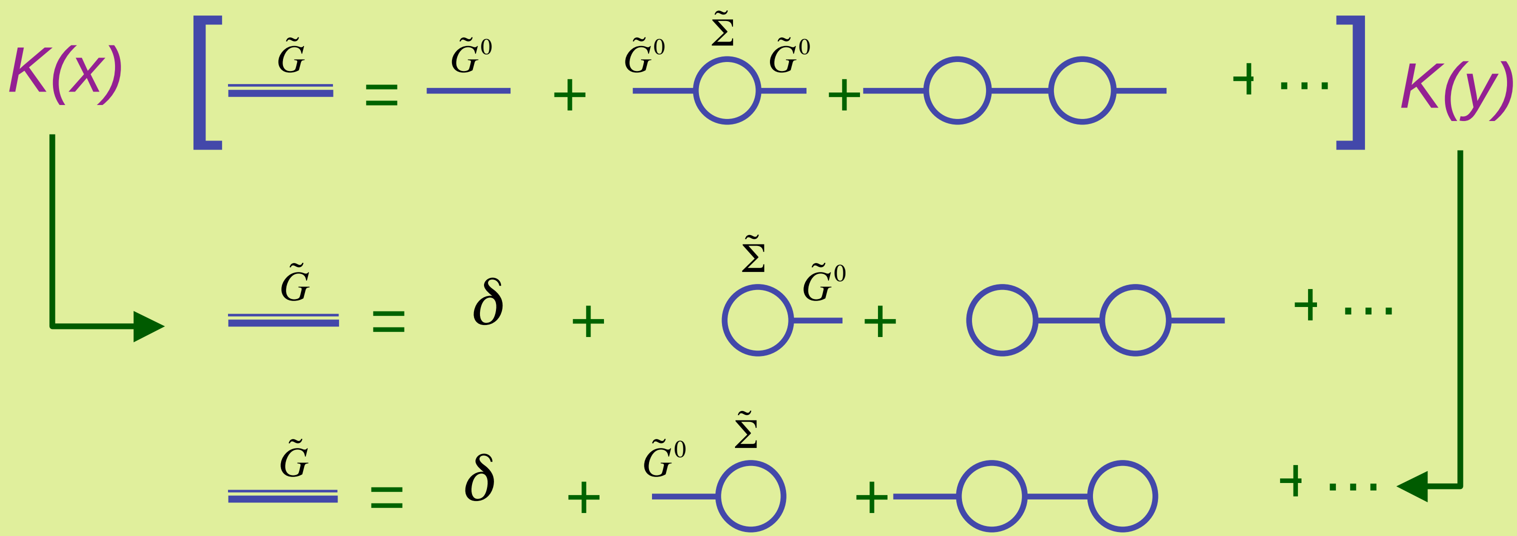

Sum: *Constraint eq* $\rightarrow$ *disp relation*

Difference: *Kinetic eq* $\rightarrow$ *dynamics*

Systematic Baryo/leptogenesis:

Scale Hierarchies $\rightarrow$ *power counting*

EW Baryogenesis

Gradient expansion

$\varepsilon_w = v_w (k_w / \omega) << 1$

Quasiparticle description

$\varepsilon_p = \Gamma_p / \omega << 1$

Thermal, but not too dissipative

$\varepsilon_{coll} = \Gamma_{coll} / \omega << 1$

Plural, but not too flavored

$\varepsilon_{osc} = \Delta\omega / T << 1$

Leptogenesis

Gradient expansion

$\varepsilon_{LNV} = \Gamma_{LNV} / \Gamma_H < 1$

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Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

Lowest non-trivial order in grad's

$$2\,k\cdot\partial_X\;G^<(k,X) = -i\left[M^2(X),G^<(k,X)\right] - 2\left[k\cdot\Sigma,G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

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Diagonal after rotation to local mass basis:

$$M^2(X) = U^+ m^2(X) U$$

$$\Sigma_\mu(X) = U^+ \partial_\mu U$$

$(\tilde{t}_{L,} \tilde{t}_R) \rightarrow (\tilde{t}_{1,} \tilde{t}_2)$

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Flavor oscillations: flavor off-diag densities

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CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields

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✔ *= recent progress*

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CPV in m²(X): for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields ✔

Resonant enhancement of CPV sources for small ε_{osc}

✔ *= recent progress*

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EW Baryogenesis

$\Gamma_Y(\tilde{Q} \to t\tilde{H})$ — $A^{CP}{}_{BSM} \to A^{CP}{}_{SM}$

$\Gamma_V(\tilde{Q} \to Q\tilde{V})$ — *"Superequilibrium"*

$\Gamma_D(\tilde{Q} + q \to \tilde{Q} + q)$ — *Diffusion*

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

(s)botton & (s)tau dynamics import for moderate tanβ ; identify conditions for superequilibrium

$$-2\left[k \cdot \Sigma, G^{<}(k,X)\right] + \Lambda\left[G(k,X)\right]$$

EW Baryogenesis

$\Gamma_Y(\tilde{Q} \to t\tilde{H})$	$A^{CP}{}_{BSM} \to A^{CP}{}_{SM}$	✔
$\Gamma_V(\tilde{Q} \to Q\tilde{V})$	*"Superequilibrium"*	✔
$\Gamma_D(t + H \to Q + g)$	*Diffusion*	

Systematic Baryo/leptogenesis:

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Leptogenesis

$\Gamma_N(\nu_{\text{heavy}} \to \ell H) \neq \Gamma_N(\nu_{\text{heavy}} \to \bar{\ell} H^*)$ *CPV decays*

$\Gamma_W(\ell H \to \nu_{\text{heavy}} \to \bar{\ell} H^*)$ *Washout*

$\Gamma_Y(L \to \ell_R H)$ *Flavor sensitive rxns*

$\Gamma_V(L \to W L)$ *Gauge interactions*

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

Determine transition from "unflavored" to "flavored" regime w/ implications for m_1 bound

$$-2\left[k\cdot\Sigma, G^{<}(k,X)\right] + \boxed{\Lambda\left[G(k,X)\right]}$$

Leptogenesis

$\Gamma_N(\nu_{\rm heavy} \to \ell H) \neq \Gamma_N(\nu_{\rm heavy} \to \bar{\ell} H^*)$	*CPV decays*
$\Gamma_W(\ell H \to \nu_{\rm heavy} \to \bar{\ell} H^*)$	*Washout*
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II. Flavor effects in leptogenesis

Flavor Effects in Leptogenesis

Y_B may depend on flavor-dependent interactions

EW sphalerons preserve $B - 3\,L_{e,\mu,\tau}$

Two limiting regimes:

"Unflavored": flavor content defined by RH neutrino Yukawa interactions; no charged lepton Yukawas in equilibrium

"Fully flavored": flavor content defined charged lepton Yukawa interactions; at least some in equilibrium

Flavor Effects in Leptogenesis

Questions:

1. *What are the regimes of validity of fully flavored and unflavored leptogenesis?*
2. *For a given model and parameter choice, which regime (if either) applies and what are the implications ?*

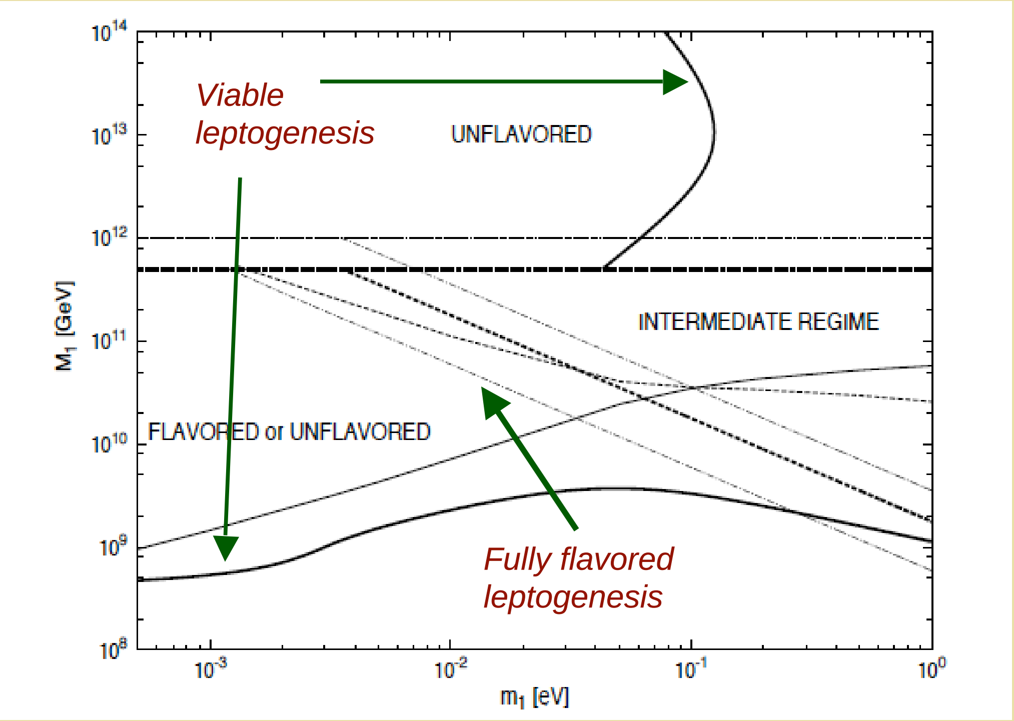
Flavor Effects in Leptogenesis

Implications: *Lightest neutrino mass (m_1) bound:*

Unflavored: $\varepsilon \sim M_1 / m_1$;
M_1 *bounded by* $\Delta L=2$ *interactions being out of equilibrium:* $m_1 < 0.15$ *eV*

Fully flavored: $\varepsilon \sim m_1$ *: no* m_1 *bound*

De Simone & Riotto '07

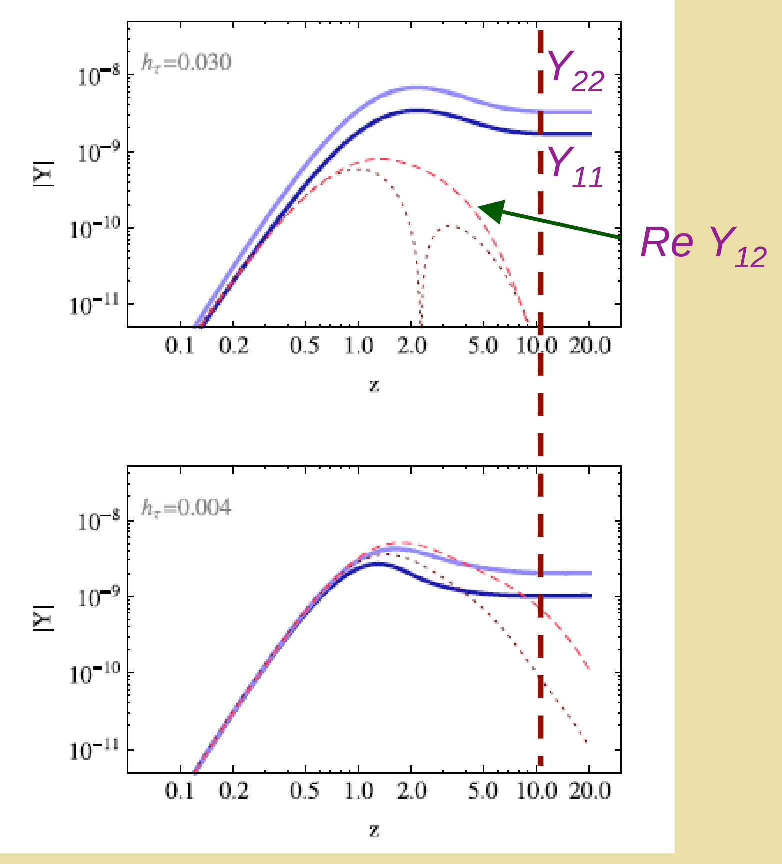


Blanchet, Di Bari, Raffelt '06

Flavor Effects in Leptogenesis

Full quantum Boltzmann: Beneke et al (2010)

Two-flavor toy model: $h_\tau > 0$, $h_2 = 0$

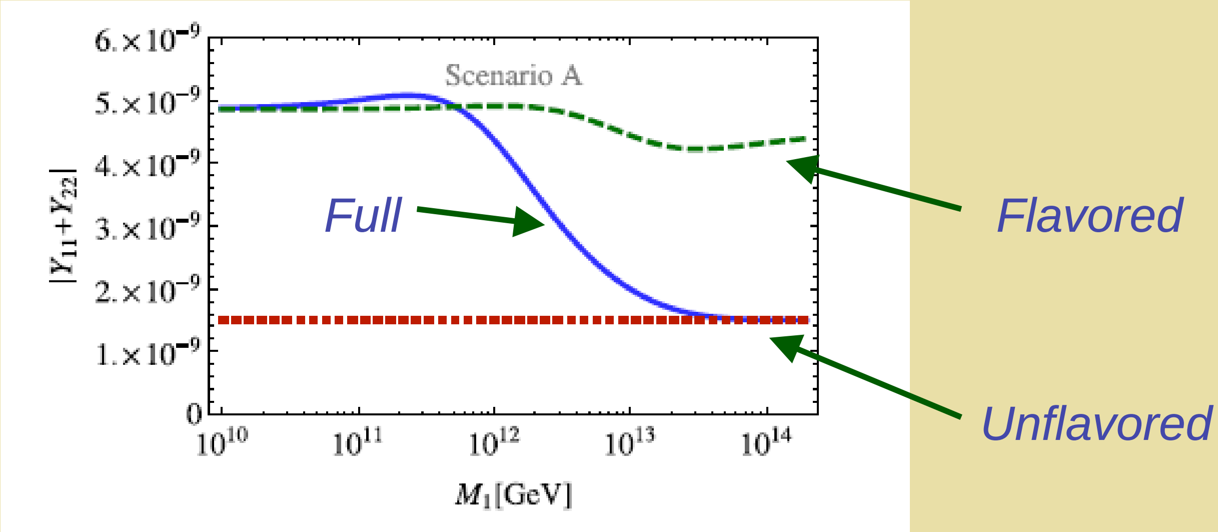


Flavored: off-diag Y damped long before freeze-out

Unflavored: off-diag Y persists up to freeze-out

Flavor Effects in Leptogenesis

Two-flavor toy model



- *Yukawa's in eq*
- *weak or no m_1 bound*

- *No Yukawa's in eq*
- *$m_1 < 0.15$ eV*

III. Flavor effects in EW baryogenesis

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- For a given BSM CPV source how effectively does it give rise to a non-zero LH fermion density?
- For a given set of BSM CPV parameters, how large is the CPV source?
- For a given BSM scenario, are Y_B -viable CPV parameters phenomenologically allowed?

Flavor effects in EW baryogenesis

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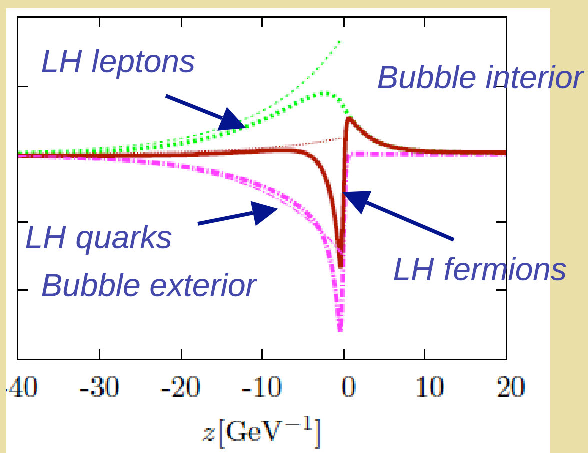

MSSM: Chung, Garbrecht, R-M, Tulin '09

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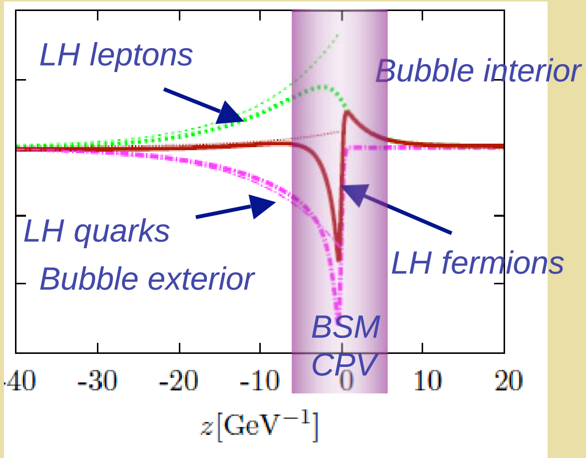

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Flavor Effects in EW Baryogenesis

Superequilibrium: $\mu_X = \mu_{\tilde{X}}$ *?*

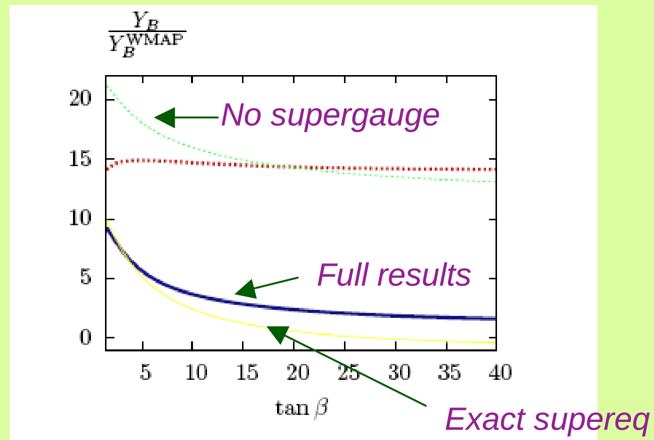
Supergauge interactions

$$q + \tilde{V} \leftrightarrow \tilde{q}$$

Chain of Yukawa interactions

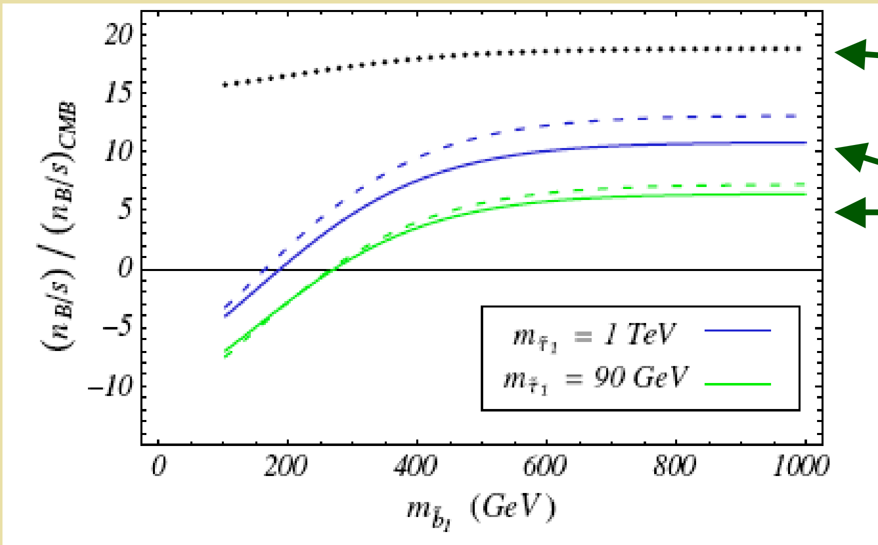
$$q_L + H = t_R \quad q_L + \tilde{H} = \tilde{t}_R \ldots$$

Chung, Garbrecht, R-M, Tulin '09



Flavor Effects in EW Baryogenesis

Down-type Yukawa's & tanβ



Small tanβ : negligible $Y_{b,\tau}$ effects

tanβ=20: impt $Y_{b,\tau}$ effects (g_μ-2)

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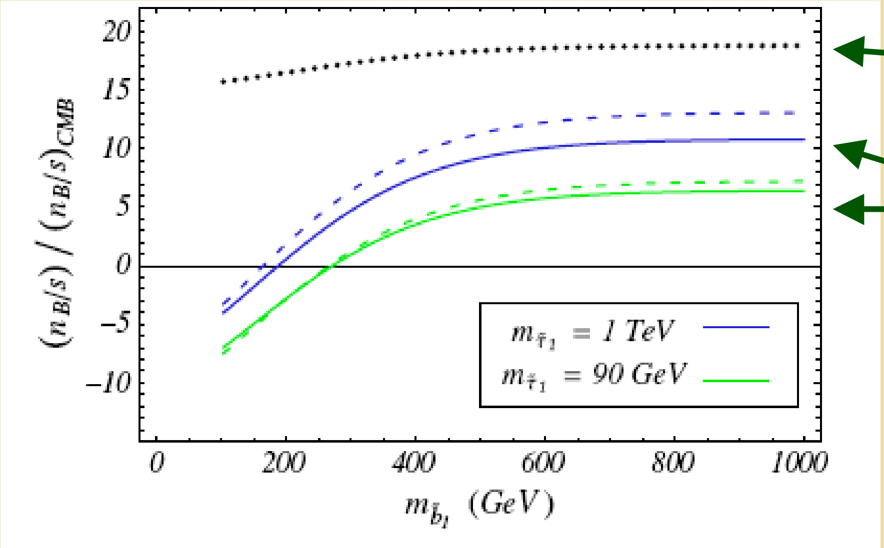

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tanβ=20: impt $Y_{b,\tau}$ effects (g_μ-2)

$$\frac{Y_{b,\tau}^{\mathrm{MSSM}}}{Y_{b,\tau}^{\mathrm{SM}}} = \tan\beta$$

$$\tilde{t}_L \leftrightarrow \tilde{t}_R + H$$

$$\tilde{b}_L \leftrightarrow \tilde{b}_R + H$$

Down-type Yukawa int impt when $\Gamma_Y > \Gamma_D$

Flavor Effects in EW Baryogenesis

CPV Sources

Kinetic eq (approx) in Wigner space:

$$2\,k\cdot\partial_X\;G^{<}(k,X) = -i\left[M^2(X),G^{<}(k,X)\right] - \boxed{2\left[k\cdot\Sigma,G^{<}(k,X)\right]} + \Lambda\left[G(k,X)\right]$$

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VEV insert approx

- *Riotto*
- *Carena et al*
- *Cirigliano et al*

Large resonant enhancement but not realistic in small ε_{osc} regime

Resummed vevs

- *Konstandin, Prokpec, Schmidt*

Small resonant effect but neglected diffusion and off-diag $\Sigma_{ii}\,G_{ij}$ terms

Resummed vevs

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Exact solution in two-flavor toy model: large resonant enhancement

Flavor Effects in EW Baryogenesis

CPV Sources: how large a sinϕ_{CPV} necessary ?

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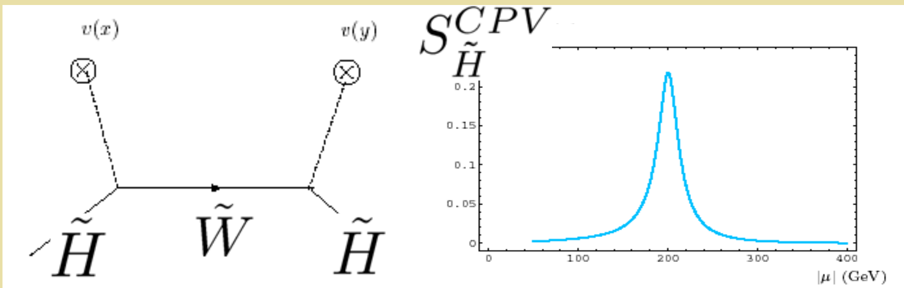

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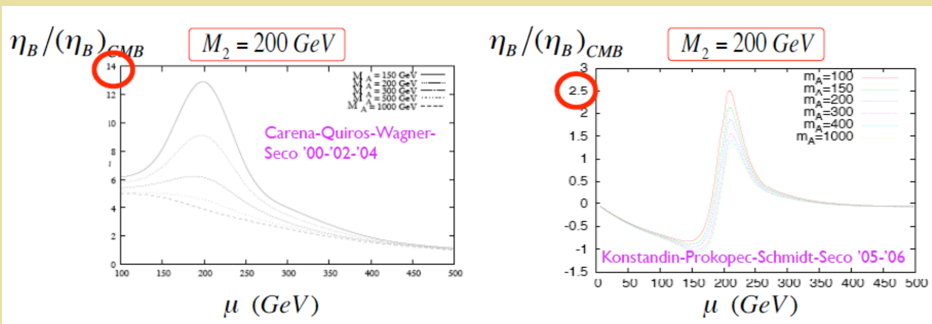

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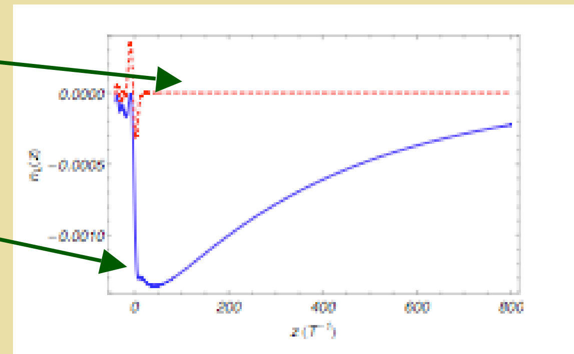
Kinetic eq (approx) in Wign

$$2k \cdot \partial_X \; G^{<}(k,X) = -i\left[M^2(\right.$$

Neglect o-d $\Sigma_{ii} G_{ij}$ terms & approx Λ

Full solution



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- Carena et al
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Exact solution in two-flavor toy model: large resonant enhancement

Flavor Effects in EW Baryogenesis

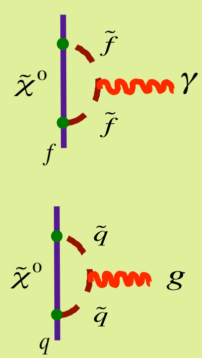
EDM constraints: how large a $\sin\phi_{CPV}$ possible ?

$$W_{\rm MSSM} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\rm yukawa}$$

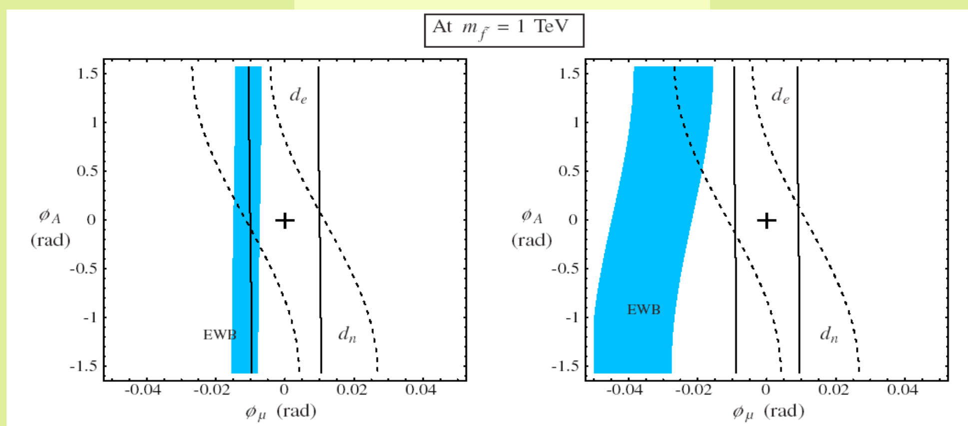
$$\begin{aligned}\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}\left(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}\right) + c.c. \\ & -\left(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{a_e}\tilde{L}H_d\right) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q} - \tilde{L}^\dagger \mathbf{m_L^2}\tilde{L} - \tilde{\bar{u}}\mathbf{\bar{m}_{\bar{u}}^2}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m_{\bar{d}}^2}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m_{\bar{e}}^2}\tilde{\bar{e}}^\dagger - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d \\ & -\left(bH_u H_d + c.c.\right)\end{aligned}$$

$\phi_j = \arg\,(\mu M_j b^*)$

One-loop EDMs



Phase Universality



Cirigliano, Lee, Tulin, R-M

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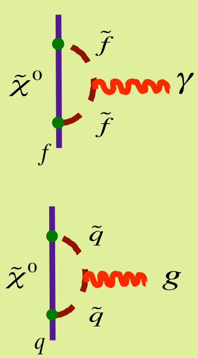
EDM constraints: how large a sinϕ_{CPV} possible ?

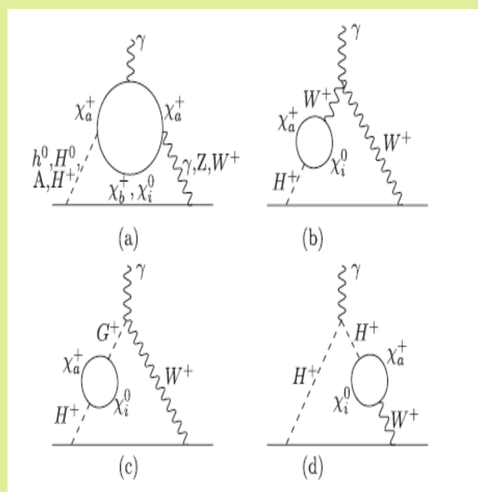
$$W_{\rm MSSM} = \mu \hat{H}_u \cdot \hat{H}_d + W_{\rm yukawa}$$

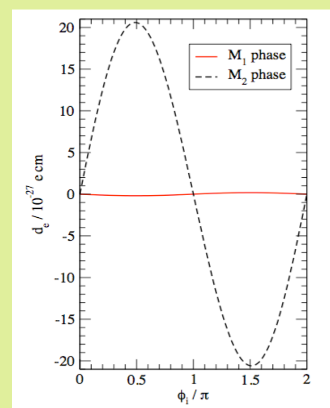
$$\begin{aligned}\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c. \\ & -(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{a_e}\tilde{L}H_d) + c.c. \\ & -\tilde{Q}^\dagger \mathbf{m^2_Q}\tilde{Q} - \tilde{L}^\dagger \mathbf{m^2_L}\tilde{L} - \tilde{\bar{u}}\mathbf{\bar{m}^2_{\bar{u}}}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m^2_{\bar{d}}}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m^2_{\bar{e}}}\tilde{\bar{e}}^\dagger - m^2_{H_u}H_u^* H_u - m^2_{H_d}H_d^* H_d \\ & -(bH_uH_d + c.c.)\end{aligned}$$

$\phi_j = \arg(\mu M_j b^*)$

Decouple in heavy sfermion regime







2-loop: Non-universal Phases

Li, Profumo, R-M 09

Flavor Effects in EW Baryogenesis

EDM constraints: how large a sinϕ_{CPV} possible ?

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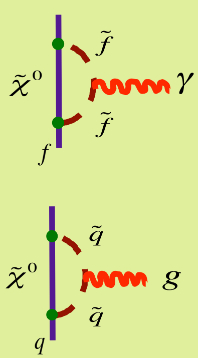
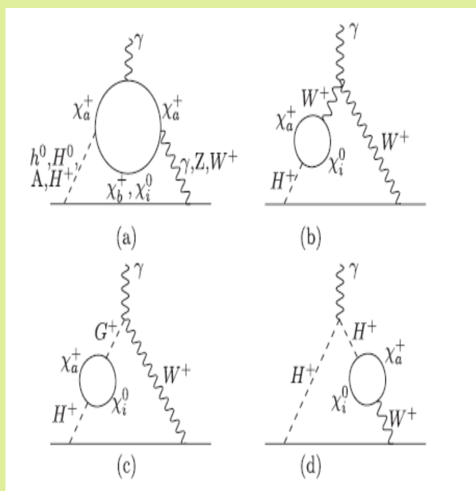
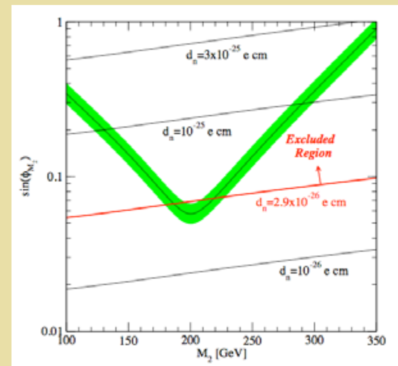
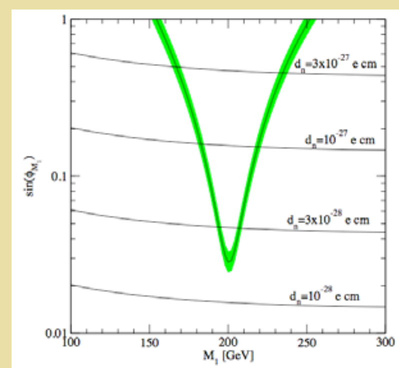
Decouple in heavy sfermion regime









2-loop: Non-universal Phases

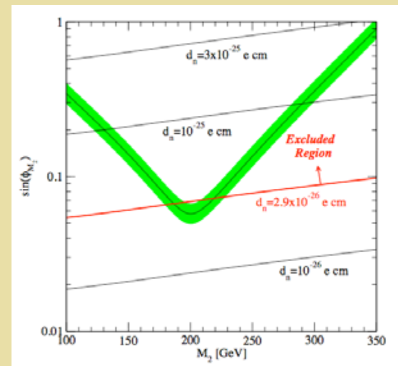
Li, Profumo, R-M 09

Flavor Effects in EW Baryogenesis

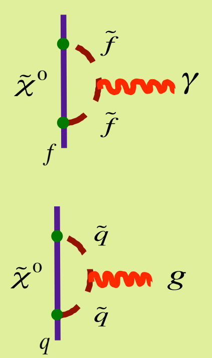
EDM constraints: how large a $\sin\phi_{CPV}$ possible ?

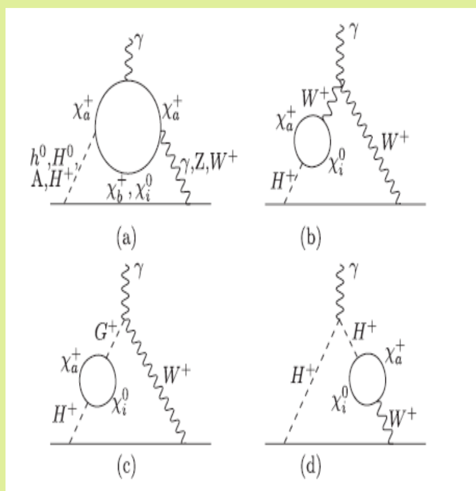
$$-(bH_u H_d + c.c.)$$

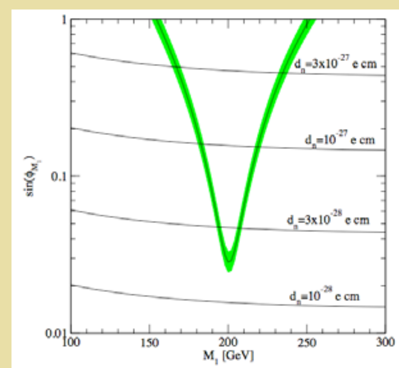
MSSM EWB requires phase non-universality & is bino-driven; conclusive test with probe of $d_{n,e}$ ~ 10^{-28} e-cm level



Decouple in heavy sfermion regime







2-loop: Non-universal Phases

Li, Profumo, R-M 09

Systematic Baryo/leptogenesis:

Outlook

EW Baryogenesis

- *Full solution for realistic fermion CPV sources & apply beyond two-flavor toy models*
- *Beyond the gradient expansion to full K-B sol'n*
- *Limiting case of very weakly coupled BSM sector: Kadanoff-Baym may not be needed (Gagnon & Shaposhnikov '10)*

Leptogenesis

- *Beyond two-flavor toy models to realistic scenarios*
- *Beyond the gradient expansion to full K-B sol'n (Anisimov et al '10)*

Summary

- *Definitively explaining the origin of the baryon asymmetry remains a key unsolved problem at the interface of cosmology with particle & nuclear physics*

- *Considerable recent progress achieved in obtaining systematic quantum transport computations relevant for two broad baryogenesis scenarios: leptogenesis & EW baryogenesis* $\rightarrow$ *On the way to clarifying the role of flavor*

- *New phenomenological implications are emerging (EDM's & light neutrino masses)*

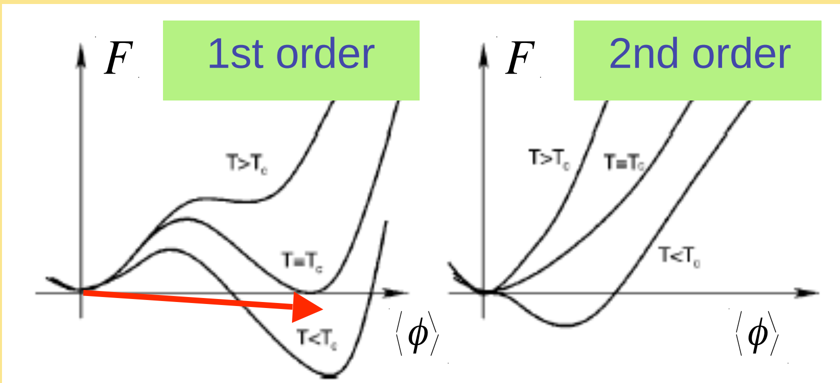
- *Many challenges remain*

Back Matter

IV. EWPT: Progress & Questions

- *Was there a first order EWPT? (bubble nucleation for EWB; B-L $\rightarrow$ B for leptogenesis)*
- *Was it sufficiently strong to preserve initial Y_B ?*
- *How reliably can we address these questions? (pert theory vs lattice; low energy phenomenology; gravity waves)*

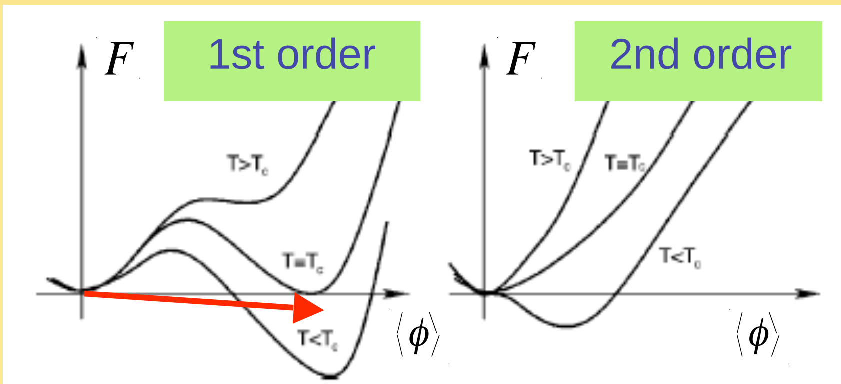
EW Phase Transition: New Scalars



Increasing m_h →

← *New scalars*

EW Phase Transition: New Scalars

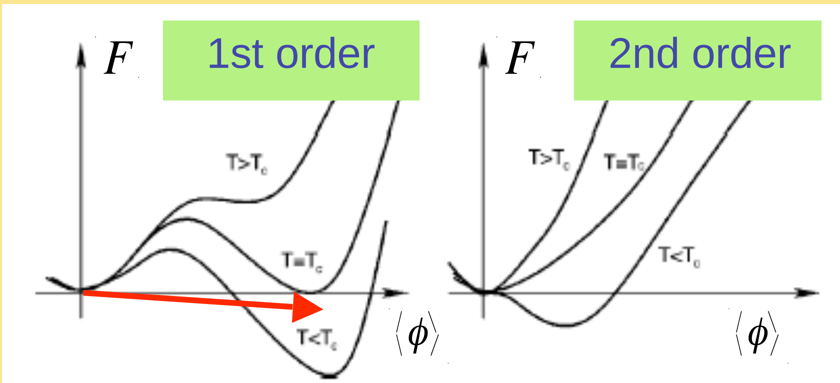


Increasing m_h →

← *New scalars*

LHC Searches
Scalar DM

EW Phase Transition: New Scalars



Increasing m_h →

← New scalars

LHC Searches
Scalar DM

Theory Challenges

- Lattice: most robust theoretically but expensive $\rightarrow$ Not optimal for broad BSM exploration
- Pert th'y: tool of choice for BSM exploration but (a) computations to date not robust and (b) reliability as EWPT indicator uncertain

Baryon Number Preservation

"Washout factor"

$$S \equiv \rho_B(\Delta t_{\mathrm{EW}})/\rho_B(0) > e^{-N}$$

Final baryon asymmetry

Initial baryon asymmetry

Baryon Number Preservation

"Washout factor"

$$S \equiv \rho_B(\Delta t_{\mathrm{EW}})/\rho_B(0) > e^{-N}$$

$$\ln S \sim A(T_C)\, e^{\zeta}$$

$$\zeta = F(\varphi) \longleftarrow \zeta \equiv \frac{\hat{E}_{\mathrm{sph}}}{T}\bigg|_{T=T_C}$$

Two qtys of interest:

- T_C from V_{eff}
- E_{sph} from Γ_{eff}

Baryon Number Preservation: Pert Theory

$$S \equiv \rho_B(\Delta t_{\rm EW})/\rho_B(0) > e^{-N}$$

$\zeta = F(\varphi)$

Conventional treatments

$$\frac{\varphi(T_C)}{T_C} \gtrsim 1$$

H. Patel & MRM, arXiv: 1101.4665

Baryon Number Preservation: Pert Theory

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Gauge Dep

H. Patel & MRM, arXiv: 1101.4665

Baryon Number Preservation: Pert Theory

H. Patel & MRM, arXiv: 1101.4665

$$S \equiv \rho_B(\Delta t_{\mathrm{EW}})/\rho_B(0) > e^{-N}$$

$\zeta = F(\varphi)$

Conventional treatments

~~$\frac{\varphi(T_C)}{T_C} \gtrsim 1$~~

Gauge Dep

- *GI T_C from either hbar exp or $V_{eff}(\phi^+\phi)$*
- *Use GI scale in E_{sph} computation*

H. Patel & MRM, arXiv: 1101.4665

Baryon Number Preservation: Pert Theory

$$S \equiv \rho_B(\Delta t_{\mathrm{EW}})/\rho_B(0) > e^{-N}$$

$$\zeta - 6\ln\zeta > \ln\left(\mathcal{Z}t_H\right) - 6\ln\left(\frac{4\pi B}{g}\right) + \ln\kappa + \ln\left(\frac{\Delta t_{\mathrm{EW}}}{t_H}\right) - \ln N$$

Freq of sph unstable mode

Fluct Det ratio

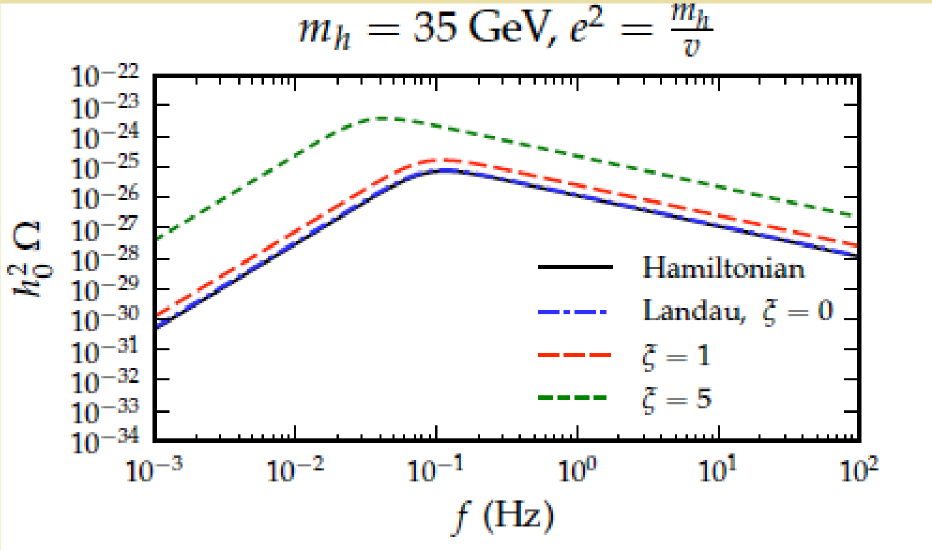
Duration of EWPT

Y_B^{init} & entropy dilution

H. Patel & MRM, arXiv: 1101.4665

Gravity Waves from EWPT: Pert Theory

Abelian Higgs Model

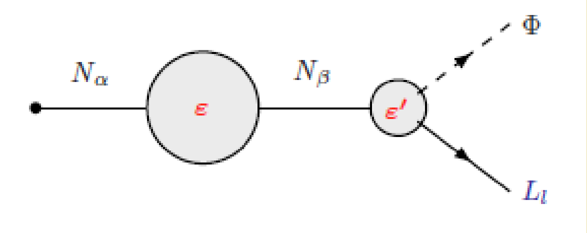


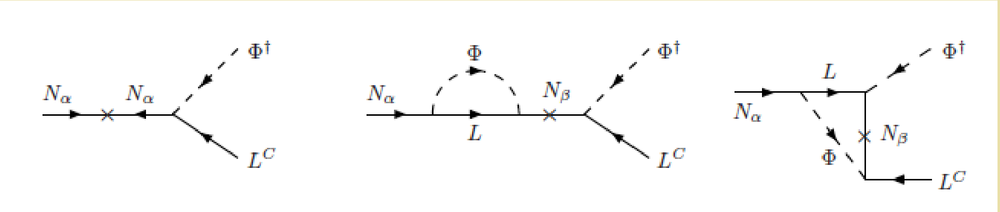
C. Wainwright, H. Patel, S. Profumo, R-M in prep

V. Other

Flavor Effects in Leptogenesis

Preliminaries: Lepton asymmetries





$$\varepsilon'_{N_\alpha} = \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^\nu)^2_{\alpha\beta}}{(h^{\nu\dagger}\,h^\nu)_{\alpha\alpha}\,(h^{\nu\dagger}\,h^\nu)_{\beta\beta}} \left(\frac{\Gamma_{N_\beta}}{m_{N_\beta}}\right) f\left(\frac{m^2_{N_\beta}}{m^2_{N_\alpha}}\right)$$

$$\varepsilon_{N_\alpha} = \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^\nu)^2_{\alpha\beta}}{(h^{\nu\dagger}\,h^\nu)_{\alpha\alpha}\,(h^{\nu\dagger}\,h^\nu)_{\beta\beta}} \left(\frac{\Gamma_{N_\beta}}{m_{N_\beta}}\right) \frac{(m^2_{N_\alpha} - m^2_{N_\beta})\,m_{N_\alpha}\,m_{N_\beta}}{(m^2_{N_\alpha} - m^2_{N_\beta})^2 + m^2_{N_\alpha}\,\Gamma^2_{N_\beta}}$$