Non-standard Higgs and electroweak baryogenesis

Stephan Huber, CERN

CPNSH4, December 2005

The baryon asymmetry

$$\eta_B = \frac{n_B}{s} = (8.9 \pm 0.4) \times 10^{-11}$$

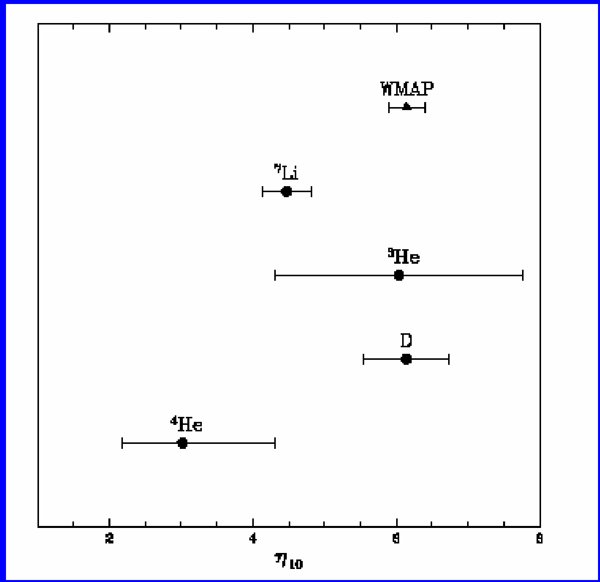
WMAP, SDSS '03

from cosmic microwave background and

large scale structure

in reasonable agreement with

primordial nucleosynthesis



Steigman, astro-ph/0511534

Outline

- Short review of the mechanism of electroweak baryogenesis:
  - electroweak phase transition
  - transport + CP violation
- models:
  - SM with higher-dimensional operators
  - 2HDM
  - MSSM
  - MSSM + singlets
- summary + outlook

Sakharov's (anti)-shopping list

$$\eta_B = \frac{n_B}{s} = (8.9 \pm 0.4) \times 10^{-11}$$

Baryon number

C

CP

Equilibrium

Sakharov's (anti)-shopping list

$$\eta_B = \frac{n_B}{s} = (8.9 \pm 0.4) \times 10^{-11}$$

~~Baryon number~~

~~C~~

~~CP~~

~~Equilibrium~~

SM

Sphalerons

Gauge interactions

Yukawa interactions

Electroweak phase transition

Sakharov's (anti)-shopping list

$$\eta_B = \frac{n_B}{s} = (8.9 \pm 0.4) \times 10^{-11}$$

Baryon number

C

CP

Equilibrium

SM

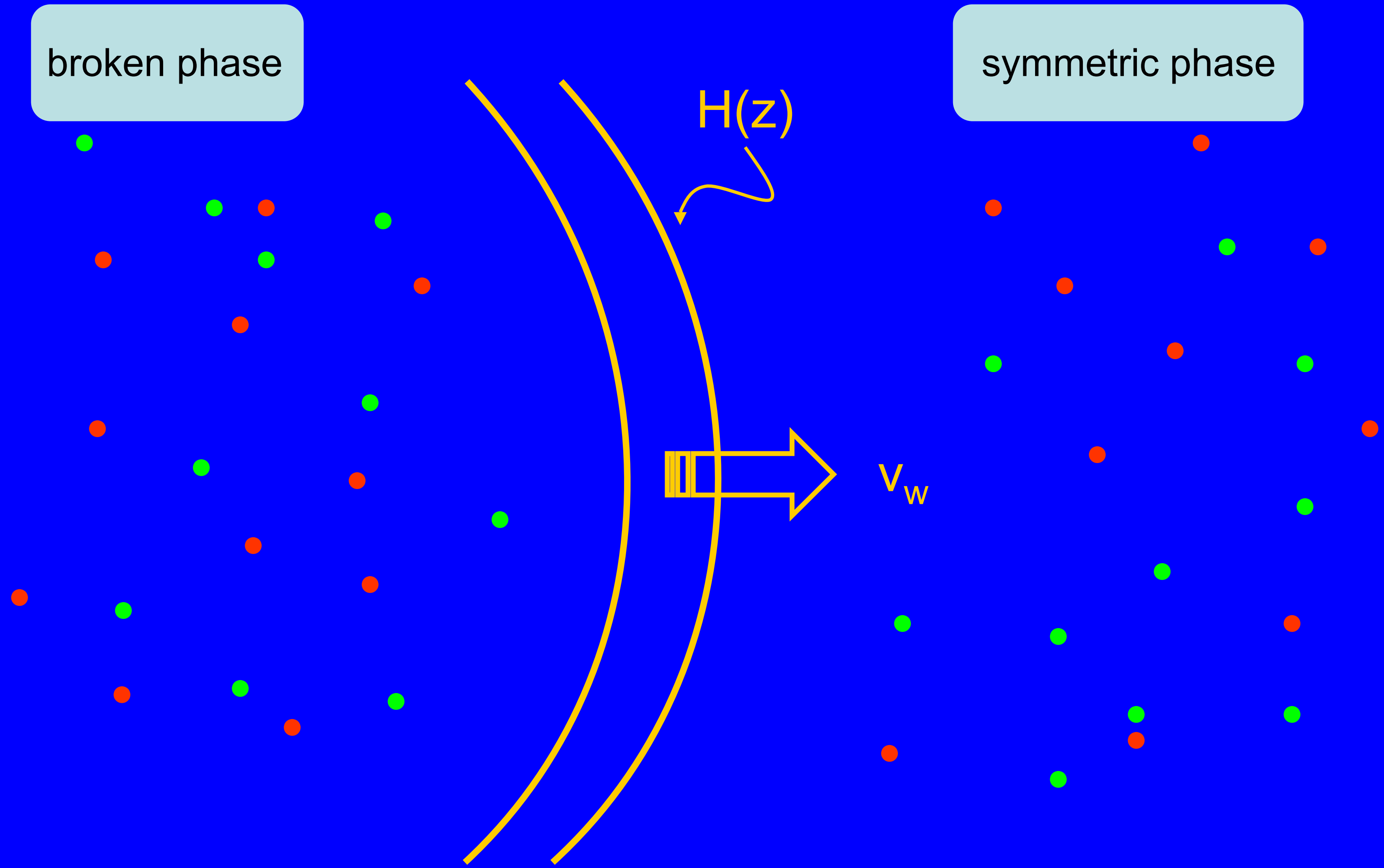
Sphalerons +

Gauge interactions +

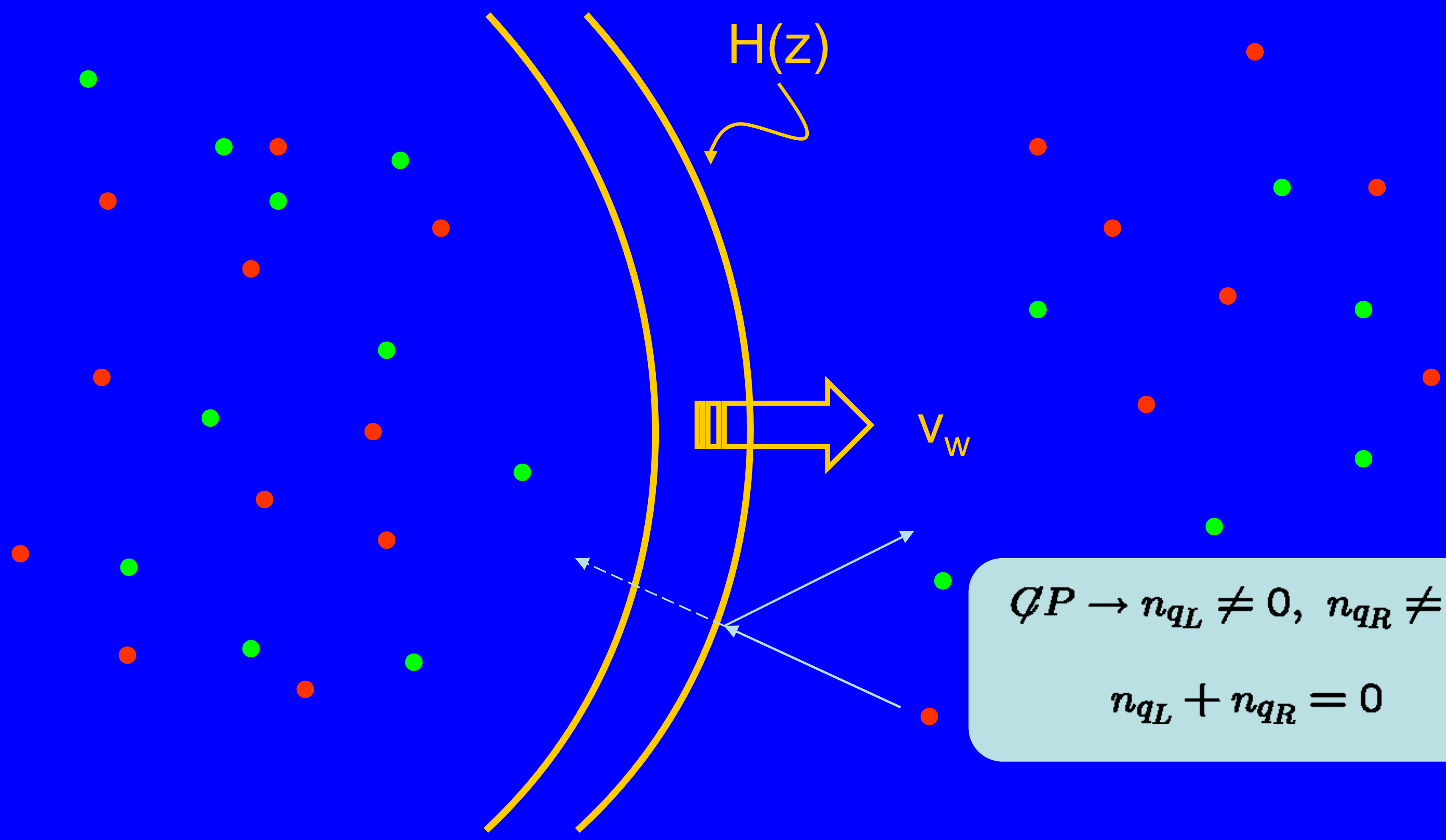
Yukawa interactions ?

Electroweak phase transition ?

The mechanism



The mechanism



$$\not{C}P \rightarrow n_{q_L} \neq 0,\ n_{q_R} \neq 0$$

$$n_{q_L} + n_{q_R} = 0$$

The mechanism

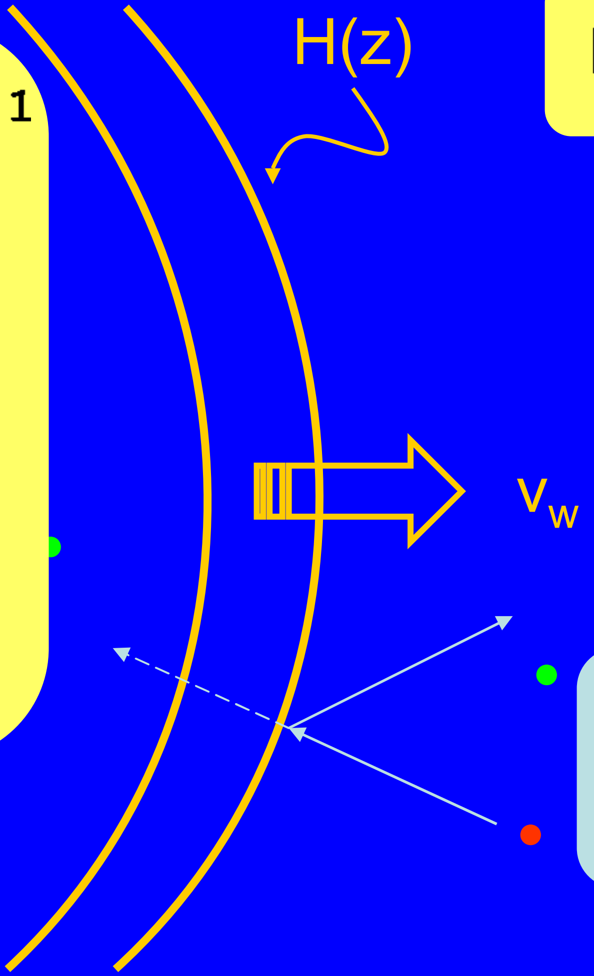
$$\Gamma_{\text{sph}} \sim T_c^4 \exp(-\kappa v_c/T_c) \ll 1$$

$$\Downarrow$$

$$\frac{v_c}{T_c} > 1.0$$

$$\Updownarrow$$

"strong PT"



$$\Gamma_{\text{sph}} \sim T_c^4 \longrightarrow \not{B}$$

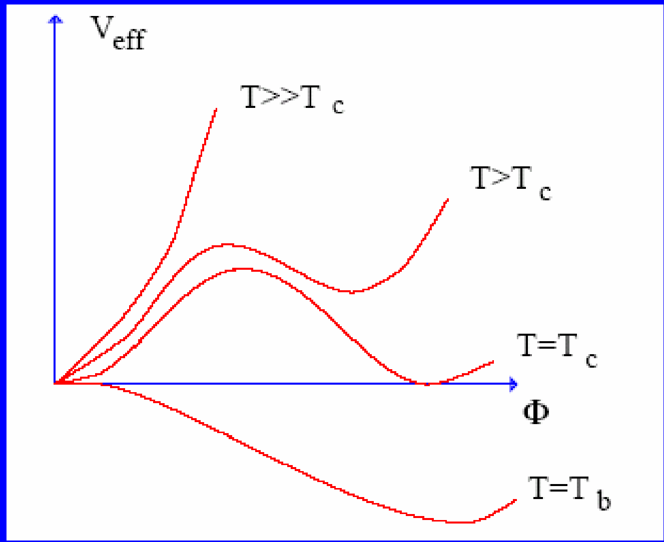
$$\not{C}P \rightarrow n_{q_L} \neq 0, \;\; n_{q_R} \neq 0$$

$$n_{q_L} + n_{q_R} = 0$$

The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$



- Boson loops:

SM: gauge bosons

strong PT: m_h<40 GeV (no top)

never (with top)

Lattice: crossover for m_h>80 GeV → the SM fails

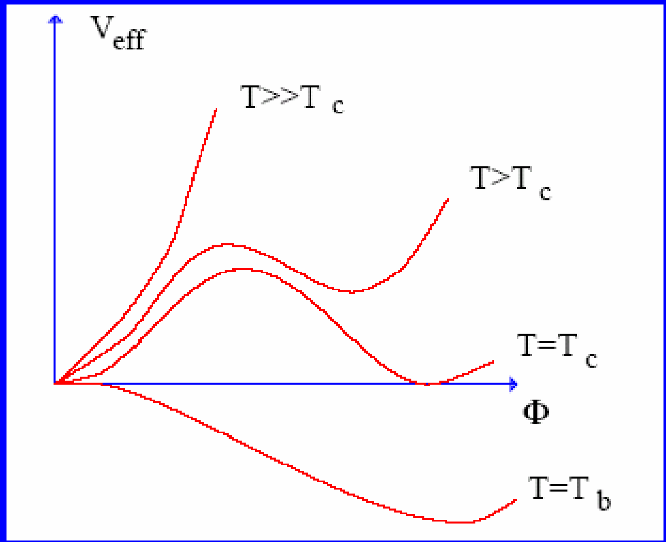
Kajantie, Laine, Rummukainen, Shaposhnikov 1996

Csikor, Fodor, Heitger 1998

(1) The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$



- Boson loops:

  SM: gauge bosons

  SUSY: light stops

  2HDM: heavy Higgses

- tree-level: extra singlets: λSH^2, NMSSM, etc.
- replace H^4 by H^6, etc.

(2) Transport equations

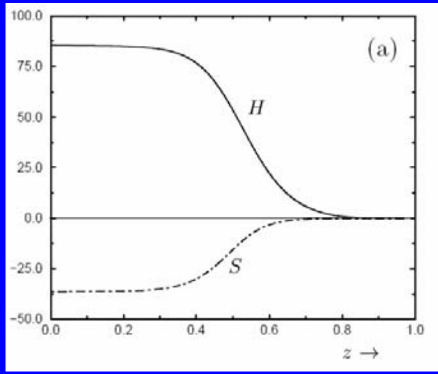
We want to write down a set of Boltzmann equations

The interaction with the bubble wall induces a force on the particles, which is different for particles and antiparticles if CP is broken

$$(\partial_t + \dot{z}\partial_z + \dot{p}_z\partial_{p_z})f = \mathcal{C}[f]$$

z is the coordinate along the wall profile
H(z)~tanh(z/L_w) with wall width L_w

collision terms



Compute the force term from dispersion relations

$$\dot{p}_z = -\partial_z E(z, p_z)$$

WKB approximation

Elektroweak bubbles have typically thick walls, i.e. $L_w T_c \gg 1$
$(L_w)^{-1} \ll p$ for a typical particle in the plasma

Compute the dispersion relation via an expansion in $1/(L_w T_c)$

Consider a free fermion with a complex mass

$$M(z) = m(z) e^{i\theta(z)}$$

$$(i\partial - P_L M(z) - P_R M^*(z))\psi = 0$$

$$\psi \sim \exp(-iEt - i\int^z p_z(z')dz')$$

$$\begin{aligned} E_\pm &= E_0 \pm \Delta E_0 \\ &= \sqrt{p^2 + m^2} \pm \theta' \frac{m^2}{2(p^2+m^2)} \end{aligned}$$

Joyce, Prokopec, Turok '95
Cline, Joyce, Kainulainen '00

more rigorous, using the Schwinger-Keldysh formalism:
Kainulainen, Prokopec, Schmidt, Weinstock '01-'04
Konstandin, Prokopec, Schmidt, Seco '05

alternative:
Carena, Moreno, Quiros, Seco, Wagner '00

only a varying θ contributes!

no effect for scalars in LO!

Diffusion equations

Fluid ansatz for the phase space densities: $f_i = \frac{1}{e^{(E_i - v_i p_z - \mu_i)/T} \pm 1}$

to arrive at diffusion equations for the μ's

$$-(D_i \mu_i'' + v_w \mu_i') + \Gamma_{ij} \mu_j = S_i$$

diffusion constant — wall velocity — interaction rates — CP violating source terms

relevant particles: top, Higgs, super partners,…

interactions: top Yukawa interaction
strong sphalerons
top helicity flips (broken phase)
super gauge interactions (equ.)

Step 1: compute n_{B_L} $(= -n_{B_R})$

Step 2: switch on the weak sphalerons

$$\eta_B \sim \Gamma_{\mathrm{ws}} \int^{\infty} dz\, n_{B_L}(z)$$

Models

need to improve on the PT and CP violation

- SM with higher-dimensional operators
- 2HDM
- MSSM
- MSSM + singlets

SM + higher-dim. operators

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{M^2}|H|^6$$

Zhang '93

maybe related to strong dynamics at the TeV scale, such as technicolor or gravity?

two parameters, $(\lambda, M) \leftrightarrow (m_h, M)$

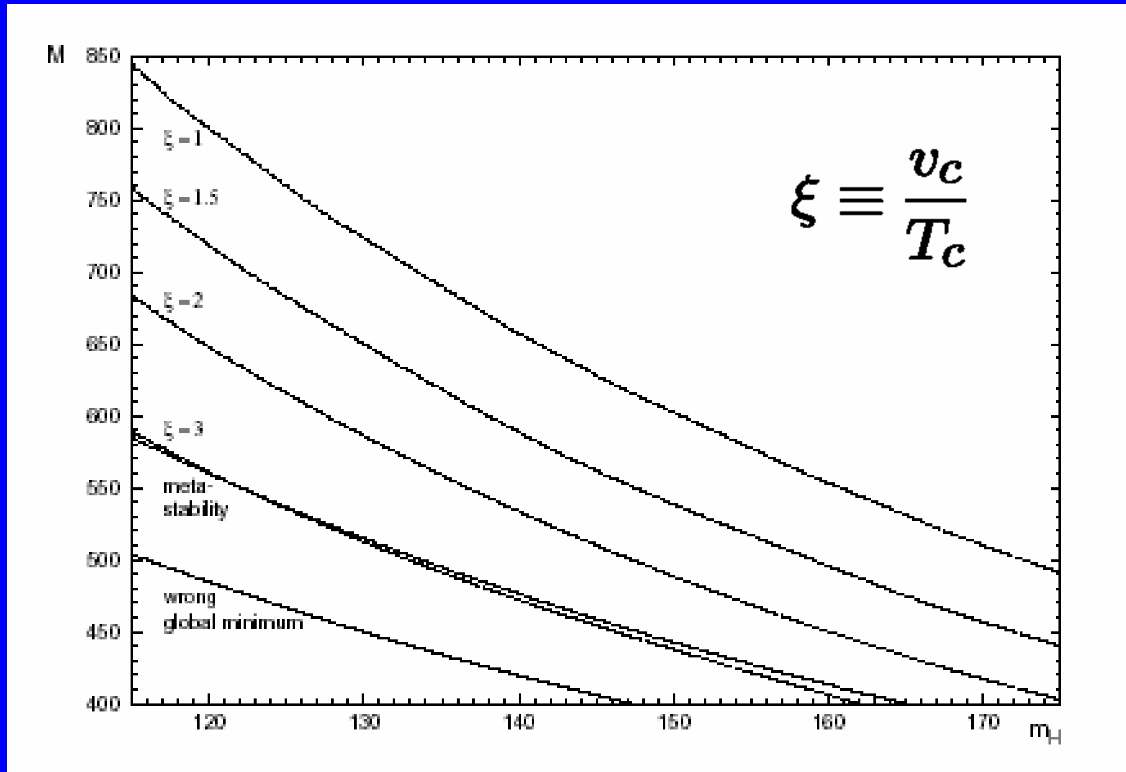
λ can be negative $\rightarrow$ bump because of $|H|^4$ and $|H|^6$

Results for the PT

Evaluating the 1-loop thermal potential:

strong phase transition for M<850 GeV up to m_h ~170 GeV

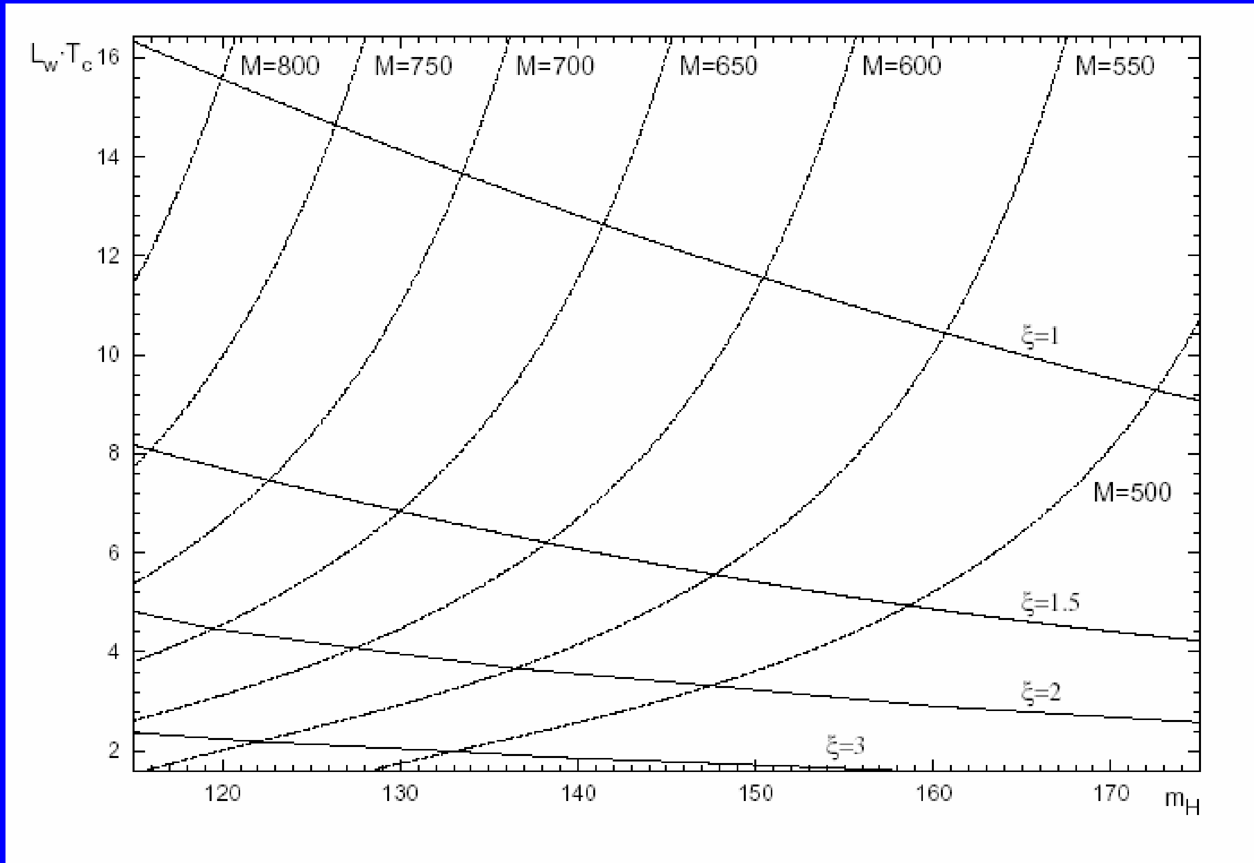
(LEP bound applies, m_h >114 GeV)



Bödeker, Fromme, S.H., Seniuch '04

Wall thickness

$2 < L_w T_c < 16$



Bödeker, Fromme, S.H., Seniuch '04

Phenomenology

1) operators which contribute to EW observables

must be suppressed by Λ>>M~TeV, e.g.

$$\frac{1}{\Lambda^2}(H^\dagger D_\mu H)^2$$

with Λ> 10 TeV → 1% tuning required?

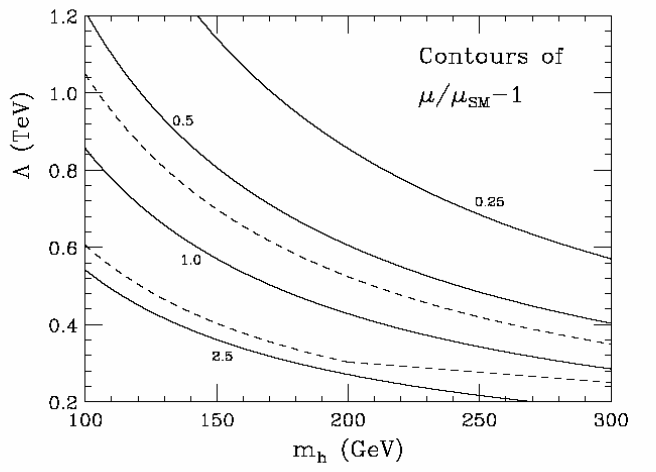
Grojean, Servant, Wells ‘04

2) deviations from the SM cubic Higgs

self coupling

LHC: order unity test

ILC: 20%



SM + higher-dim. operators

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{M^2}|H|^6$$

Zhang '93

maybe related to strong dynamics at the TeV scale, such as technicolor or gravity?

two parameters, $(\lambda, M) \leftrightarrow (m_h, M)$

λ can be negative → bump because of $|H|^4$ and $|H|^6$

CP violation:

$$\frac{x}{M^2}(H^\dagger H)Ht^c q$$

Zhang, Lee, Whisnant, Young '94

contributes to the top mass: $m_t = yH + \frac{x}{M^2}(H^\dagger H)H$

induces a varying phase in m_t if xy^* is complex, with $\theta \sim \frac{|H|^2}{M^2}\frac{\text{Im}(x)}{y}$

The baryon asymmetry

for Im(x)=1 and

v_w=0.01, 0.3

η inreases rapidly

with smaller M

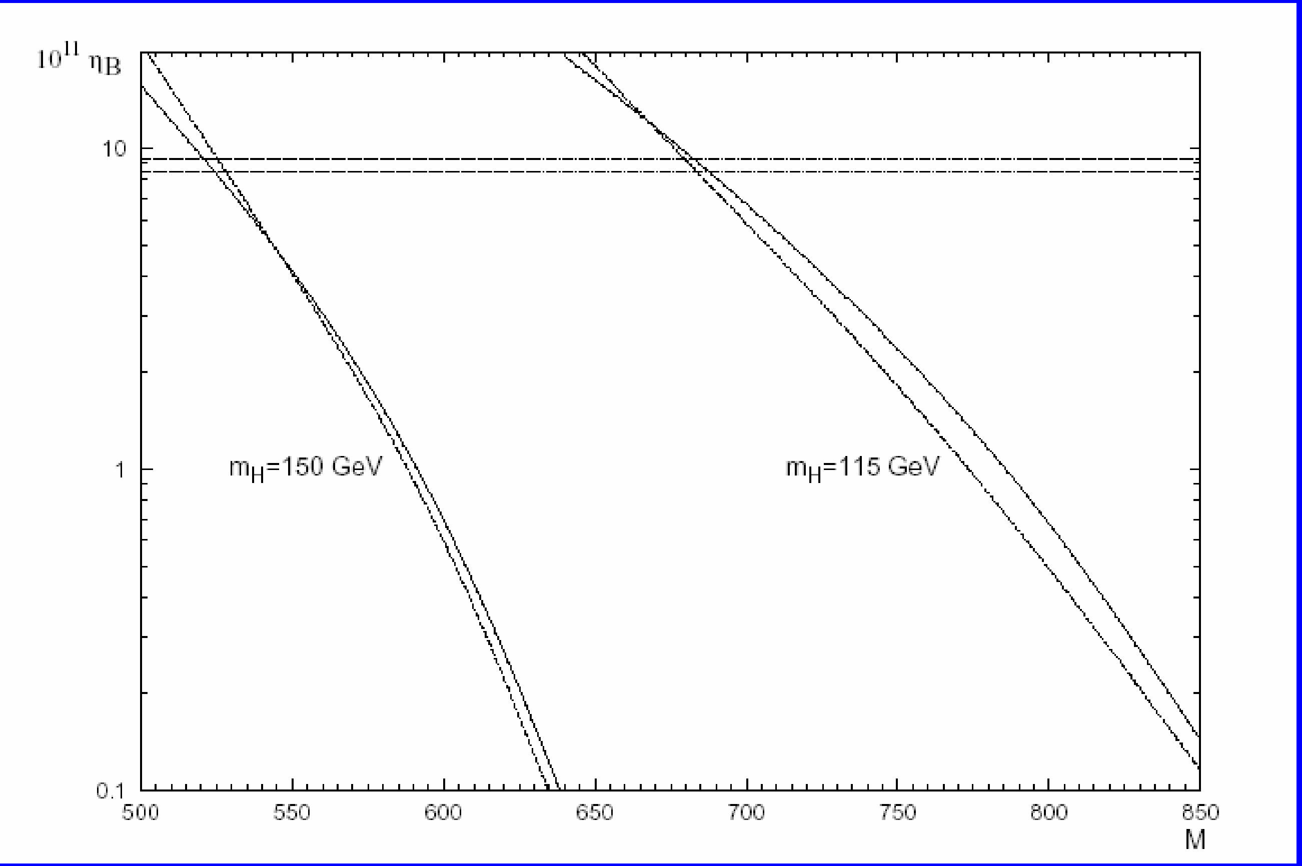
because of the

stronger PT

prediction for EDMs

work in progress

with M. Pospelov, A. Ritz



Bödeker, Fromme, S.H., Seniuch ‘04

The 2HDM

$$
\begin{aligned}
V(H_1,H_2) \;=\; & -\mu_1^2 H_1^\dagger H_1 - \mu_2^2 H_2^\dagger H_2 - (\mu_3^2 e^{i\phi} H_1^\dagger H_2 + \mathrm{h.c.}) \\
& + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\
& + \lambda_4 |H_1^\dagger H_2|^2 + \left(\frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \mathrm{h.c.}\right).
\end{aligned}
$$

Type II model → no tree-level FCNC

top couples only to H_2

Z_2 symmetry softly broken by $\mu_3^2 e^{i\phi}$

→ CP violation, phase Φ

simplified parameter choice:

tanβ=1 → helps with CP violation

1 light Higgs m_h → SM-like, so LEP bound applies

3 degenerate heavy Higgses m_H → keeps EW corrections small

work in progress with Fromme, Seniuch

earlier work:

Turok, Zadrozny ’91

Davies, Froggatt, Jenkins, Moorhouse ’94

Cline, Kainulainen, Vischer ’95

Cline, Lemieux ‘96

The phase transition

Evaluate 1-loop thermal potential:

loops of heavy Higgses generate a cubic term

→ strong PT for

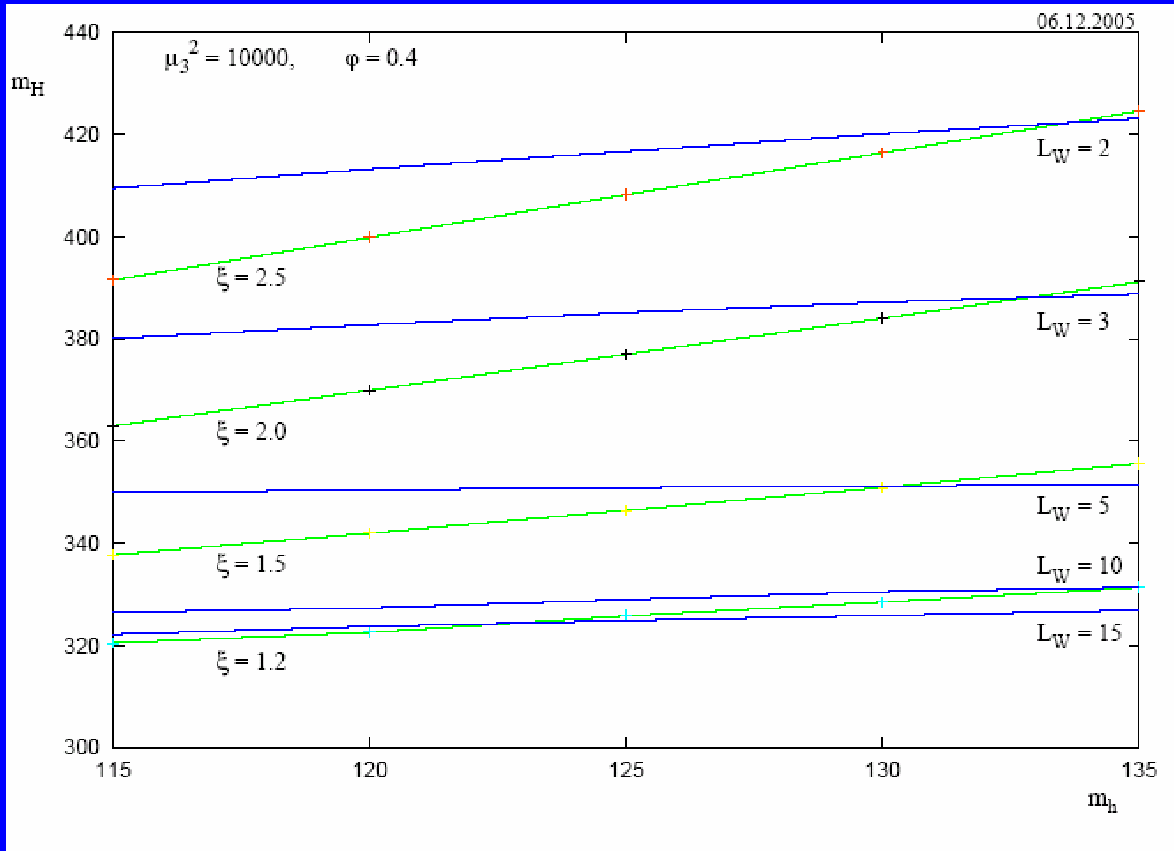
m_H>300 GeV

m_h up to 150 GeV

→ PT ~ independent of Φ

→ thin walls only for very strong PT

(agrees with Cline, Lemieux ’96)



Fromme, S.H., Senuich

Baryogenesis: successful

The relative phase between the Higgs vevs, θ, changes along the bubble wall

→ phase of the top mass varies

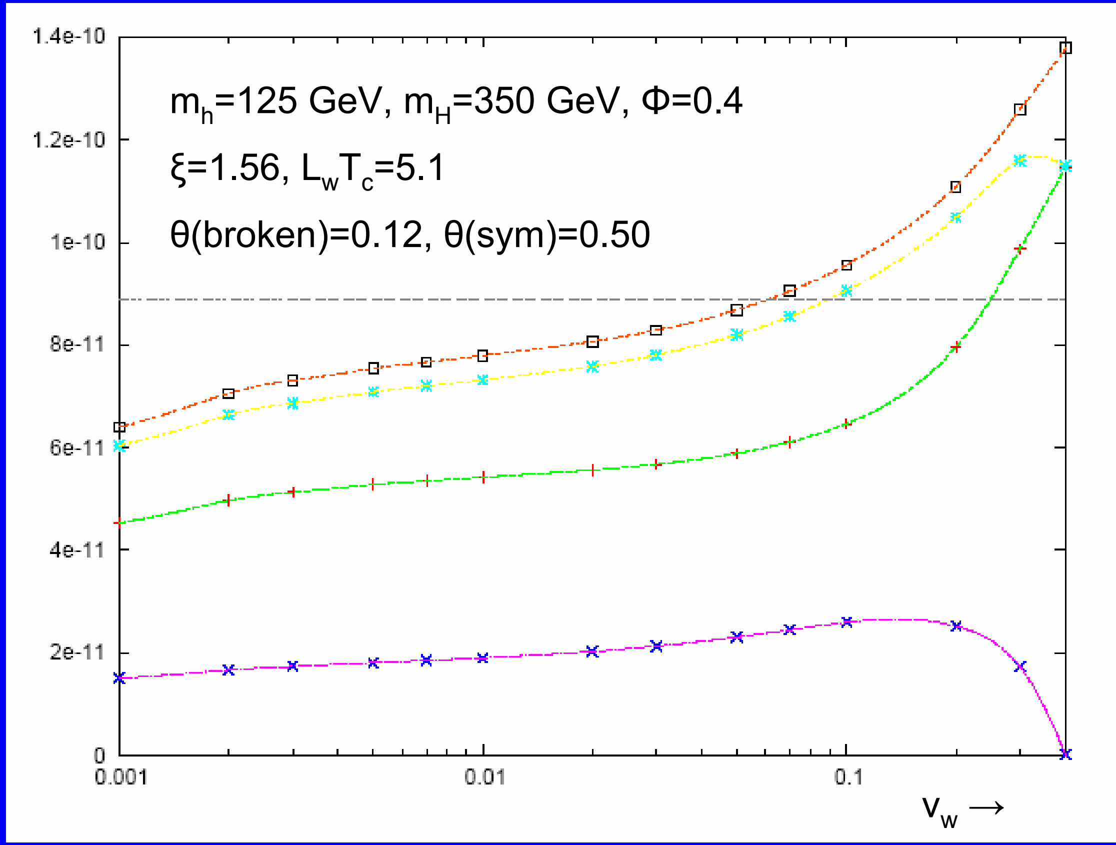
$\theta_t = \theta/(1+\tan^2\beta)$

top transport generates a baryon asymmetry, but $\tan\beta < 3$

→ only one phase, so EDMs can be predicted:

e.g. $d_e = 2\ 10^{-28}$ ecm ($< 1.6\ 10^{-28}$)

$d_n = 1\ 10^{-26}$ ecm ($< 6\ 10^{-26}$)



note: Cline, Kainulainen, Vischer '95 found a negative result, using reflections coefficients

The MSSM

strong PT from stop loops

Carena, Quiros, Wagner ’96

Bödeker, John, Laine, Schmidt ’96

de Carlos, Espinosa ’97

Laine, Rummukainen ‘98

→ right-handed stop mass below m_{top}

left-handed stop mass above 1 TeV

to obtain m_h~115 GeV

and $\tan\beta>5$

source terms from charginos

→ masses with varying phases after diagonalization, proportional to the relative phases of M_2 and μ

$$m = \begin{pmatrix} M_2 & gH_2 \\ gH_1 & \mu_c \end{pmatrix}$$

resonant enhancement of η for $M_2 \sim \mu$

due to flavor oscillations of charginos

chargino mass < 300 GeV

large phases > 0.2 required

→ 1st and 2nd generation squarks

heavy to keep 1-loop EDMs small

charged Higgs heavy (>500 GeV?)

to keep 2-loop EDMs small

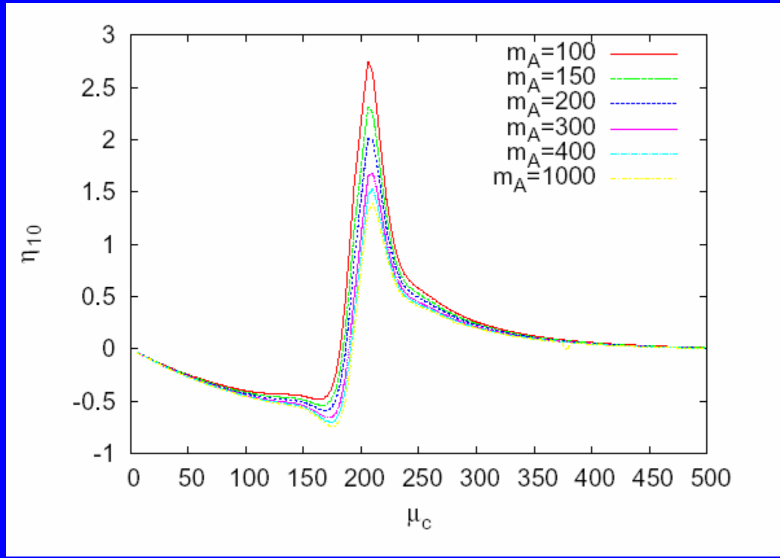
similar but somewhat more optimistic

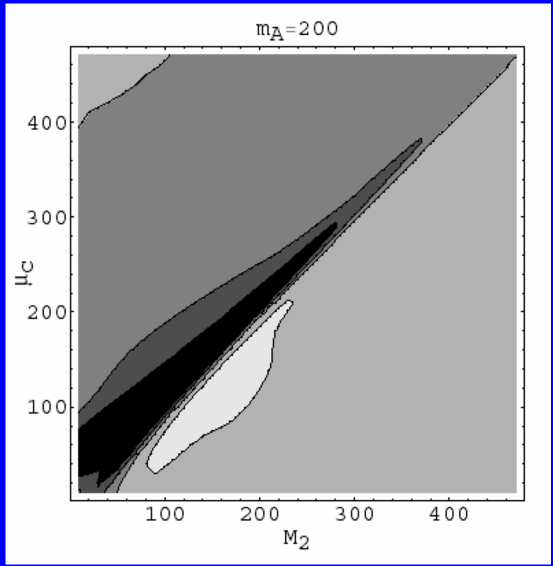
results in Carena, Quiros, Seco, Wagner '02

→ scenario is tightly constrained!

Konstandin, Prokopec, Schmidt, Seco '05

v_w=0.05, M_2=200 GeV, maximal phase





MSSM + singlets

singlets models contain cubic (SHH) terms

at tree-level → stronger PT

also new sources of CP violation

model building problems: domain walls vs.

destabilization of the weak scale

which model to take?

Z_3 symmetry (NMSSM)

$Z_{5,7}$ R-symmetries (nMSSM)

extra U(1)'s (ESSM,…)

fat Higgs…

Pietroni '92

Davies, Froggatt, Moorhouse '96

S.H., Schmidt '98

Bastero-Gil, Hugonie, King, Roy, Vespati '00

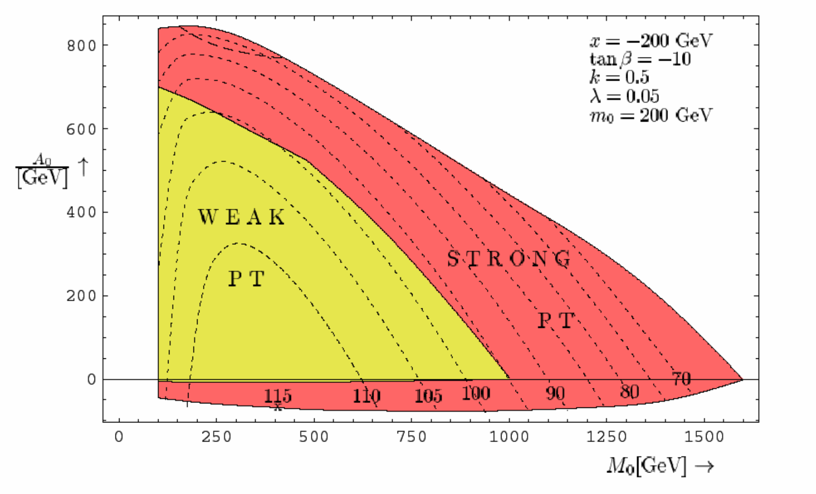
Kang, Langacker, Li, Liu '04

Menon, Morrissey, Wagner '04

Strong phase transition

singlet model without discrete sym.

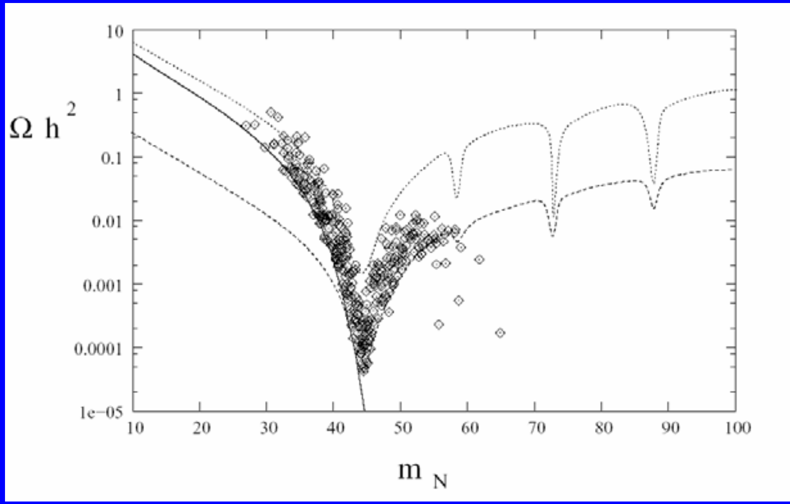
$$W = \lambda S H_1 H_2 + \frac{k}{3} S^3 + \mu H_1 H_2 + r S$$



S.H.,Schmidt '00

nMSSM

$$W_{nMSSM} = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \frac{m_{12}^2}{\lambda} \hat{S}$$



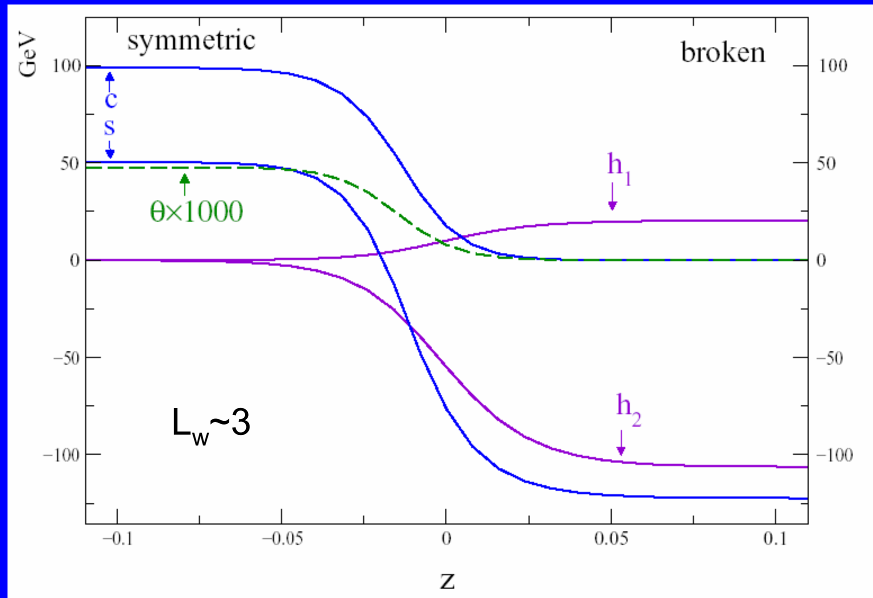
Menon, Morrissey, Wagner '04

Transitional CP violation

in the general singlet model the broken minimum can be CP conserving, but the symmetric minimum violates CP

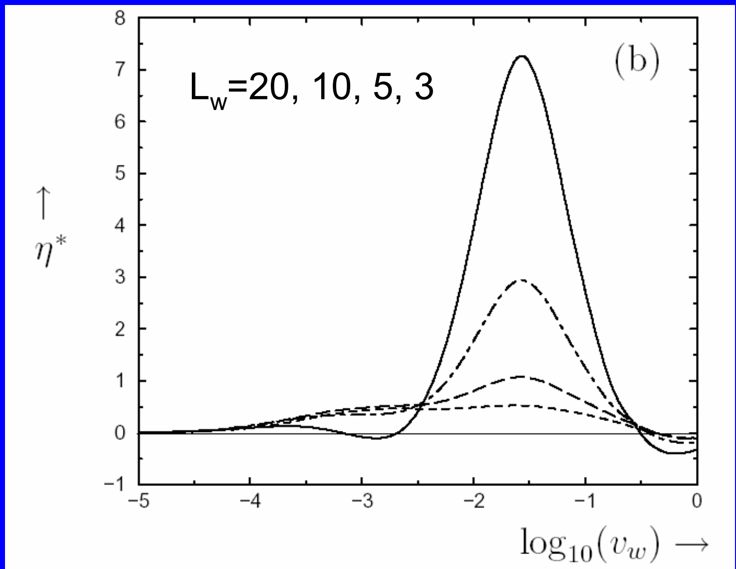
→ CP violating wall profile

CP conservation at T=0



x	$\tan\beta$	λ	k	M_0	A_0	m_0	A_λ	A_k	m_S^2
-150	-5	0.05	0.4	100	-100	200	−150	50	−2000

S.H., John, Laine, Schmidt '99



S.H., Schmidt '00

Summary

Electroweak baryogenesis is still viable in extended Higgs sectors

It would offer the possibiliy to compute the baryon asymmetry from parameters measured in collider experiments

If the result would match the observations, we could claim to understand the early universe up to electroweak temperatures

viable models:

SM with a dim-6 Higgs potential for $M<800$ GeV and $m_h<170$ GeV
2HDM for $m_H>300$ GeV and $m_h<150$ GeV
MSSM ?
Singlet models: many possiblities

connection to EDMs

everything depends on the Higgs sector: what does the LHC will find??

Outlook

computation of the wall velocities in extended models

extended models have a large parameter space which is typically only partially explored

take into account additional constraints from dark matter, electroweak bounds, EDMs, etc.…

use more general Boltzmann equations with less rates put to equlilibrium

more fancy models, such as Wilson line Higgs,…