Electroweak Baryogenesis

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Outline

- Short review of the mechanism of electroweak baryogenesis:
  - electroweak phase transition
  - CP violation & transport
- models: MSSM
  - Two Higgs doublet model
  - SM with higher-dimensional operators
  - models with singlets or extra U(1)'s
- summary + outlook

The baryon asymmetry

$$\eta_B = \frac{n_B}{s} = (8.7 \pm 0.3) \times 10^{-11}$$

[WMAP, SDSS ’06]

Reasonable agreement between CMBR+LSS and primordial nucleosynthesis

→we understand the universe up to T~MeV

Can we repeat this success for the baryon asym.?

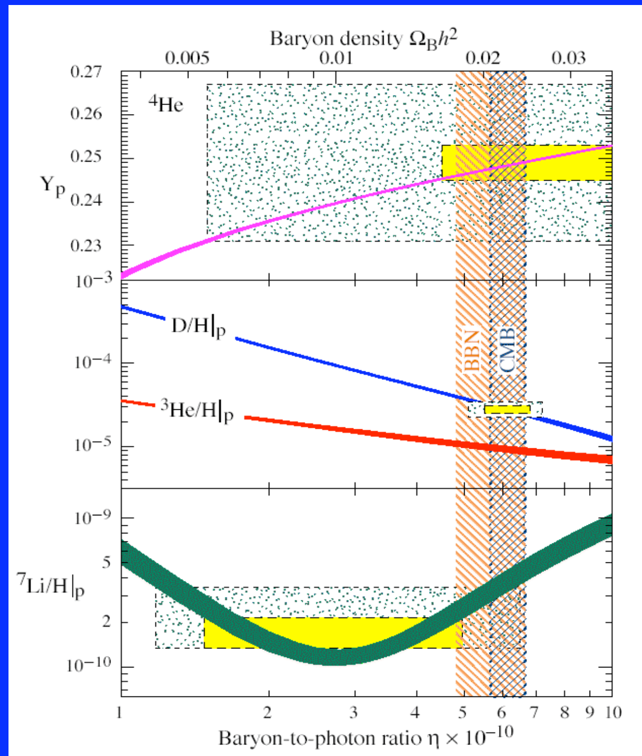
Problem: only 1 observable

→Need to be convinced by a specific model:

Theory?, Experiment? (Belief??) …

⇕

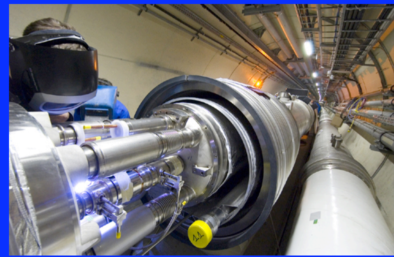
T < TeV scale? →EWBG



[Particle Data Group]

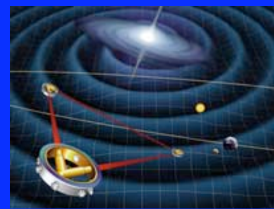
Why is it interesting?

There are testable consequences:



- New particles (scalars?!) at the LHC
  (Higgs sector is crucial!)

- New sources of CP violation which should show up soon in electric dipole experiments



- Could the electroweak phase transition produce observable gravitational waves?

If confirmed, it would constrain the early universe up to T~100 GeV (nano sec.), like nucleosynthesis does for the MeV-scale (min.)

The basics

$$\eta_B = \frac{n_B}{s} = (8.7 \pm 0.3) \times 10^{-11}$$

~~Baryon number~~

~~C~~

~~CP~~

~~Equilibrium~~

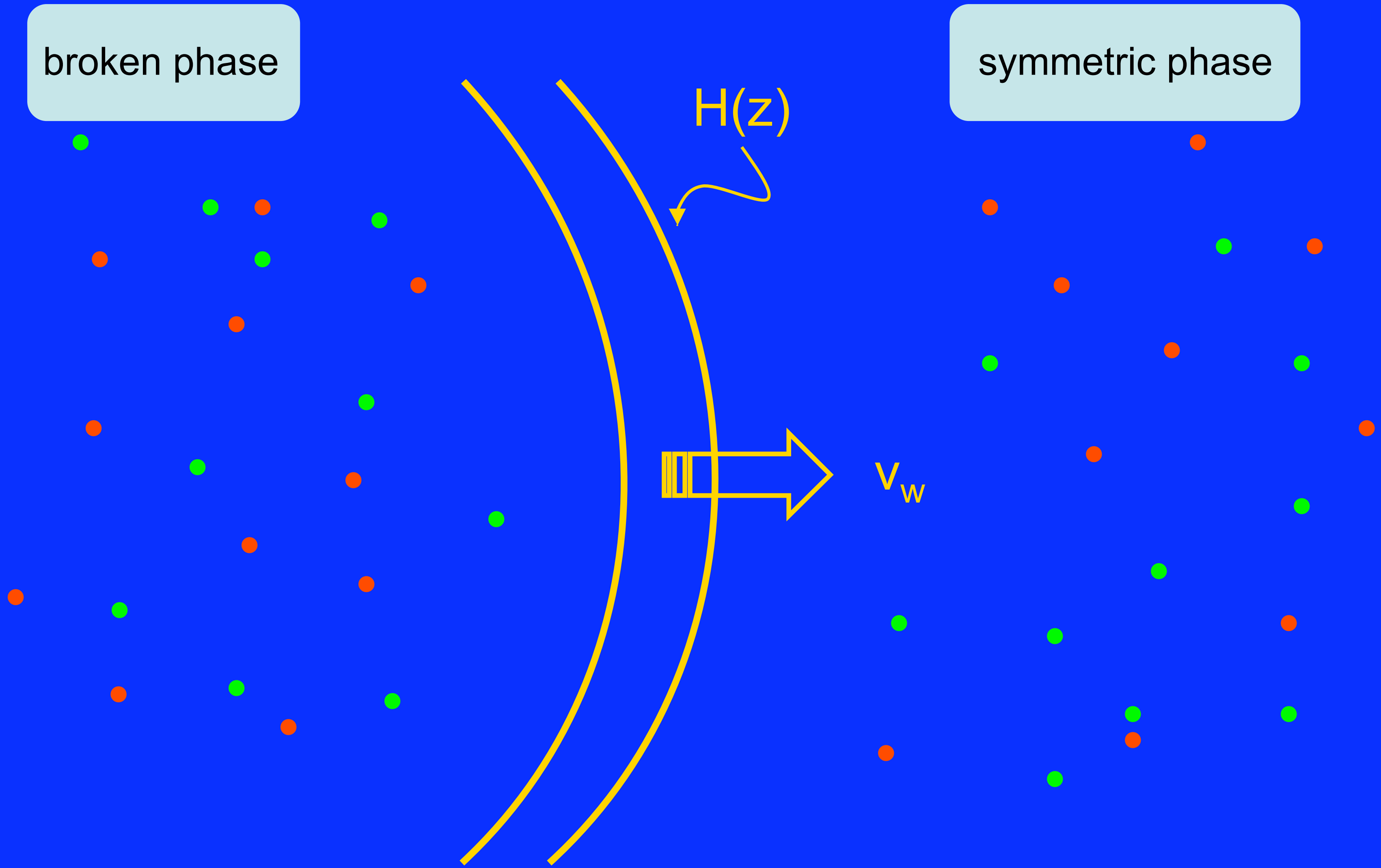
Sakharov '67

SM

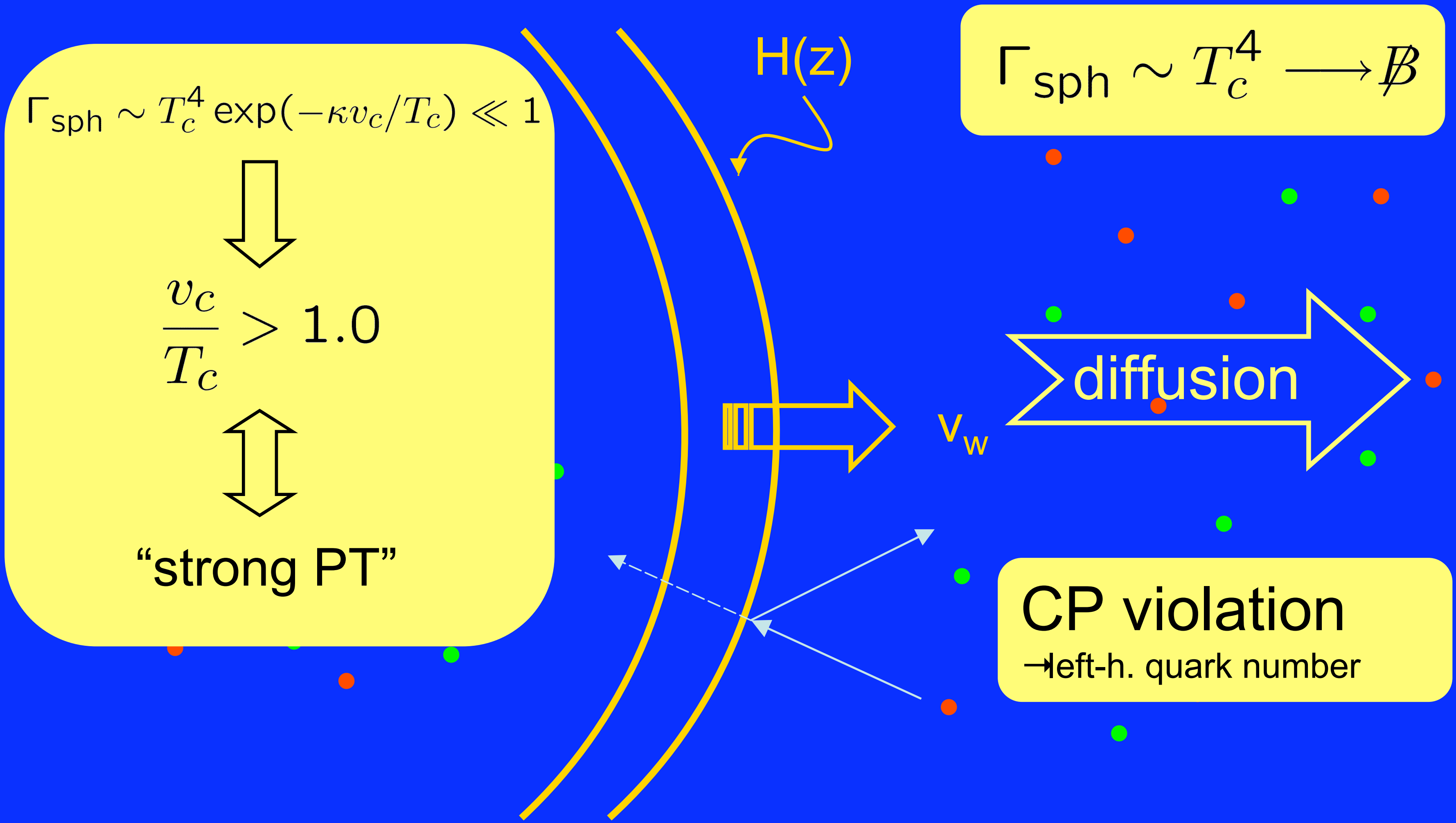
Sphalerons	+
Gauge interactions	+
Yukawa interactions	?
Electroweak phase transition	?

Kuzmin, Rubakov, Shaposhnikov '85

The mechanism



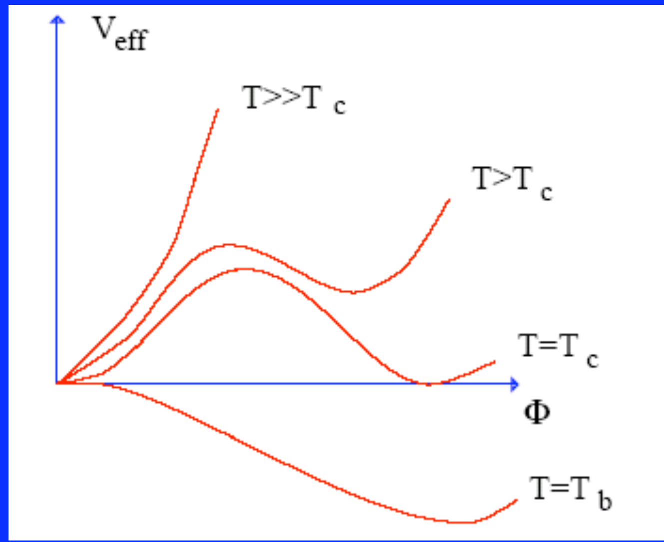
The mechanism



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 (plasma effects):

  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

The strength of the PT

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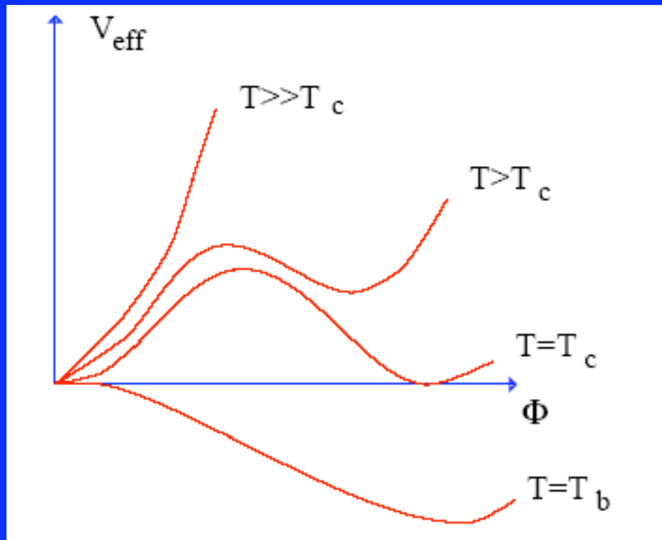


- Boson loops (plasma effects):

  SM: gauge bosons

  SUSY: light stops

  2HDM: heavy Higgses

- tree-level: extra singlets: λSH^2, NMSSM, etc.

- replace H^4 by H^6, etc.

Transport equations

EWBG relies on diffusion of charges: use 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

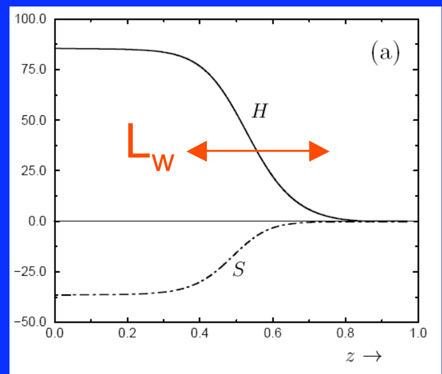
$$(\partial_t + \dot{z}\partial_z + \dot{p}_z\partial_{p_z})f = \mathcal{C}[f]$$

Compute the force from dispersion relations

collision terms

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

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



WKB approximation

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

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

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

(Carena, Moreno, Quiros, Seco, Wagner '00)

Consider a free fermion with a complex mass

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

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

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

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

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 ($v_w < v_s = 0.58$)

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

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

Classic: The MSSM

strong PT from stop loops

→ right-handed stop mass below m_{top}

left-handed stop mass above 1 TeV

to obtain m_h~115 GeV [Carena et al.'96]

CP violation from varying chargino mixing:

$$\theta(z) = \arg(M_2\mu^*)f(z) \qquad m = \begin{pmatrix} M_2 & gH_2 \\ gH_1 & \mu_c \end{pmatrix}$$

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

chargino mass < 300 GeV

large phases > 0.2 required

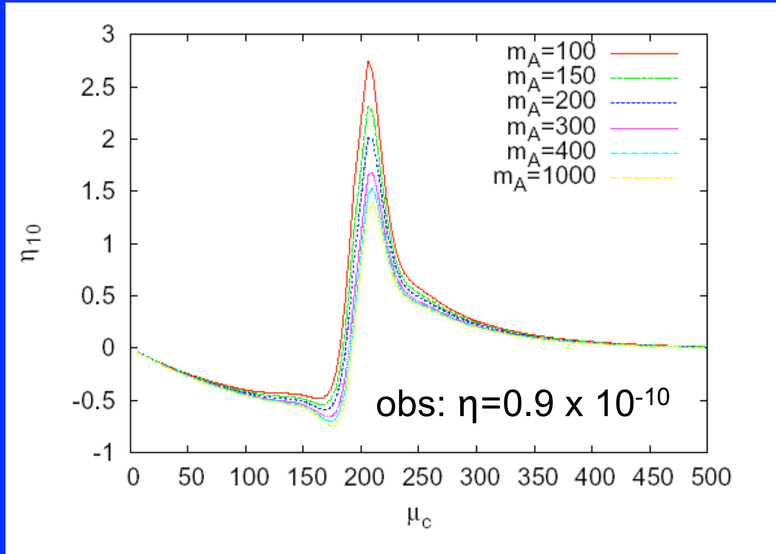
→ 1st and 2nd generation squarks

heavy to keep 1-loop EDMs small

→"Split SUSY + light stop"

Konstandin, Prokopec, Schmidt, Seco '05

v_w=0.05, M_2=200 GeV, maximal phase



similar but somewhat more optimistic

results in Carena, Quiros, Seco, Wagner '02

Cirigliano, Profumo, Ramsey-Musolf '06

→ scenario is tightly constrained!

The 2HDM

$$V(H_1,H_2) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \mu_3^2 e^{i\phi} H_1^\dagger H_2 + \lambda_1 |H_1|^4 + \ldots$$

→ 4 extra physical Higgs degrees of freedom: 2 neutral, 2 charged

→ CP violation, phase Φ (μ_3 breaks Z_2 symmetry softly)

→ there is a phase induced between the 2 Higgs vevs

$$v_1 = \langle H_1 \rangle, \qquad v_2 e^{i\theta} = \langle H_2 \rangle$$

early work:

Turok, Zadrozny '91

Davies, Froggatt, Jenkins, Moorhouse '94

Cline, Kainulainen, Vischer '95

Cline, Lemieux '96

simplified parameter choice: only 2 scales

1 light Higgs m_h → SM-like, so LEP bound of 114 GeV applies

3 degenerate heavy Higgses m_H → keeps EW corrections small

The phase transition

Evaluate 1-loop thermal potential:

loops of heavy Higgses generate a cubic term

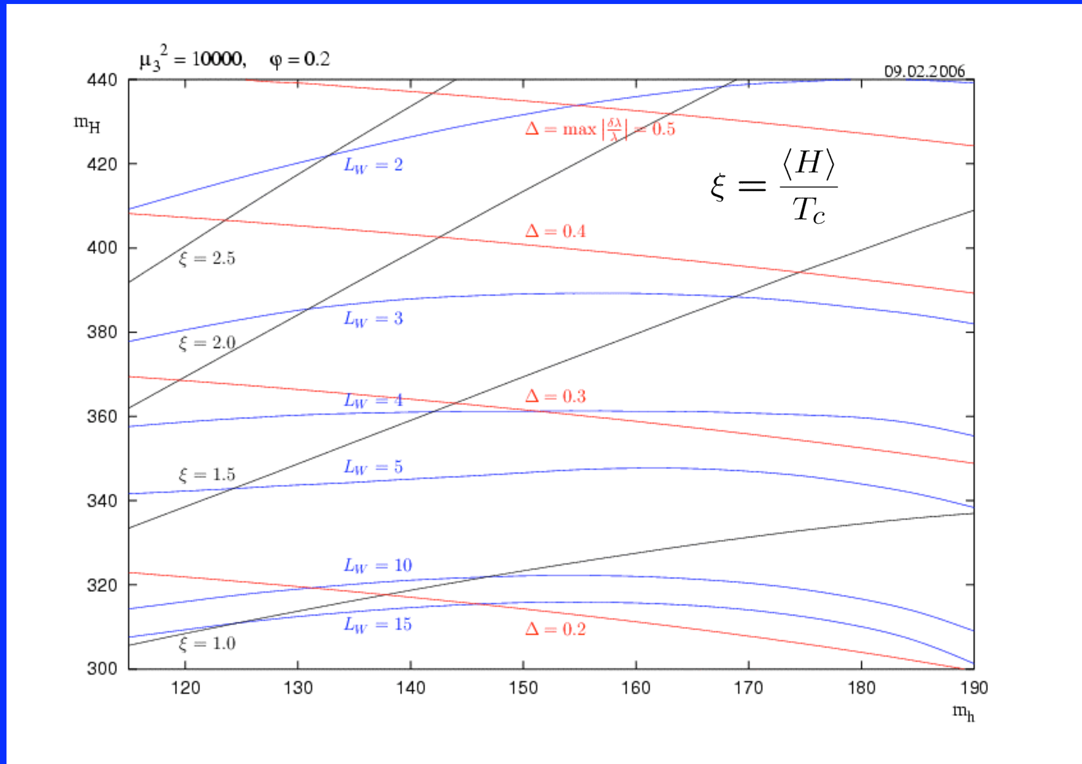
→ strong PT for

m_H>300 GeV

m_h up to 200 GeV

→ PT ~ independent of Φ

→ thin walls only for very strong PT (agrees with Cline, Lemieux '96)



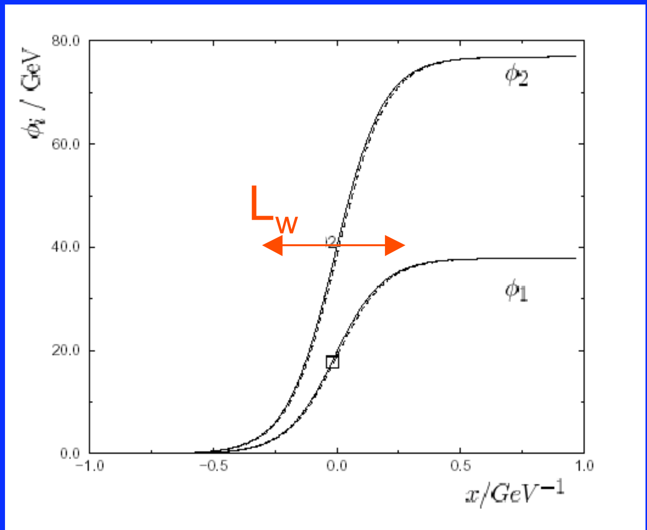
[Fromme, S.H., Senuich '06]

missing: 2-loop analysis of the thermal potential; lattice; wall velocity

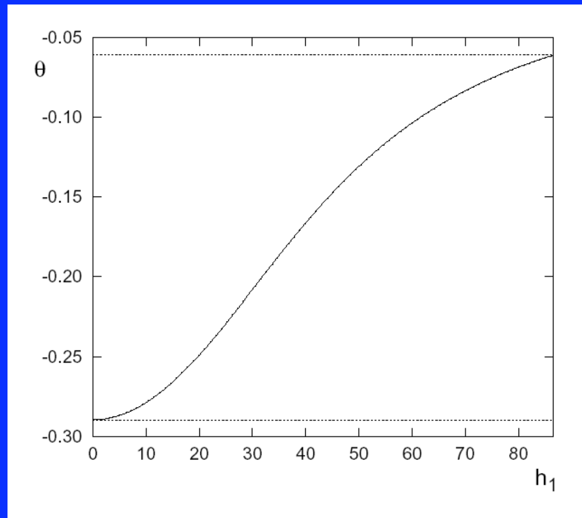
The bubble wall

Solve the field equations with the thermal potential → wall profile $\Phi_i(z)$

kink-shaped with wall thickness L_w



θ becomes dynamical



(numerical algorithm for multi-field profiles, T. Konstandin, S.H. ´06)

The baryon asymmetry

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

→ phase of the top mass varies

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

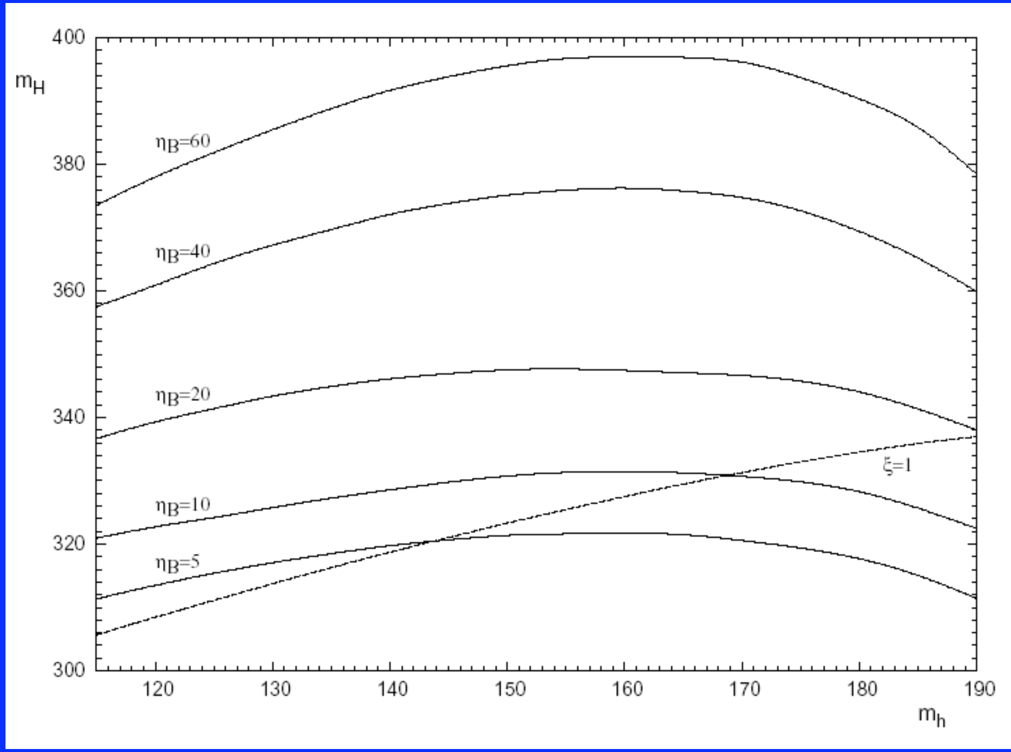
top transport generates a baryon asymmetry, but

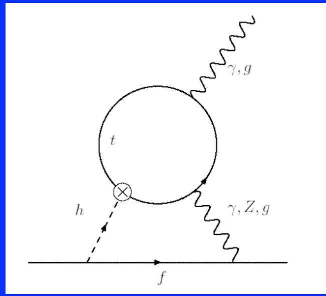
$\tan\beta < 10$ (?)

→ only one phase, so EDMs can be predicted: here

$d_n = 0.1\ 10^{-26} - 7\ 10^{-26}$ e cm

exp. bound: $d_n < 3.0\ 10^{-26}$ e cm





η_B in units of 10^{-11}, φ=0.2

Moretti et al. '07: LHC could see a triple Higgs coupling Hhh

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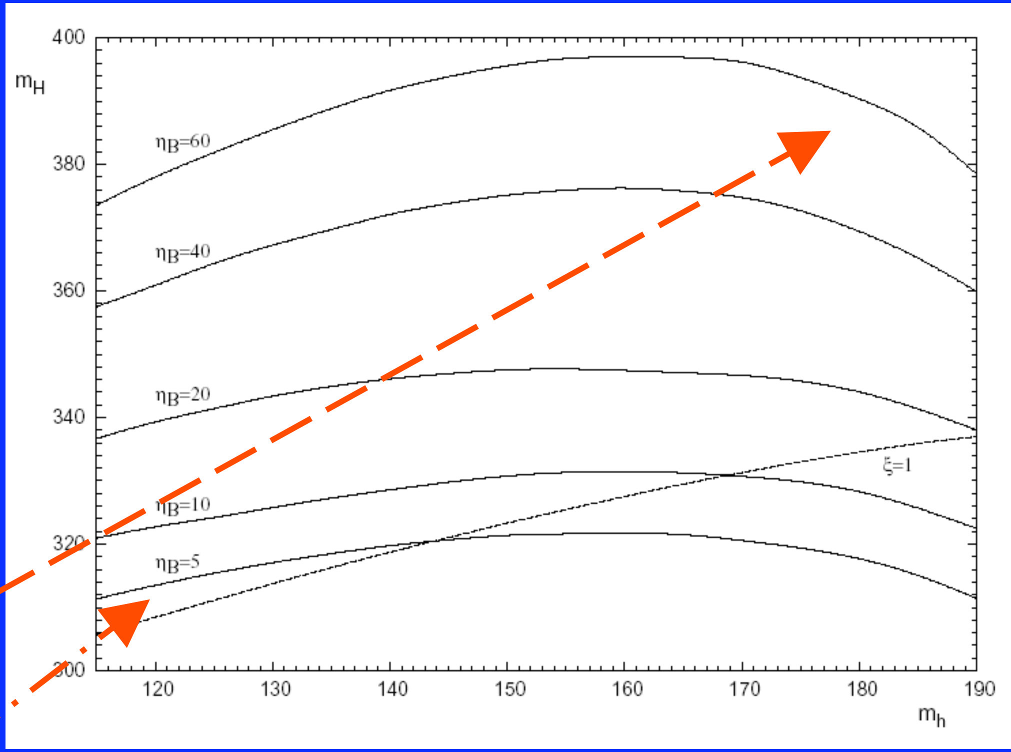
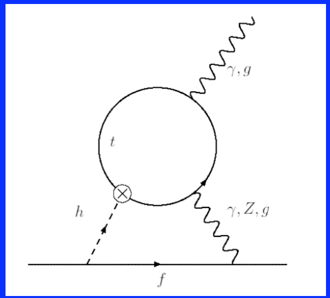




η_B in units of 10^{-11}, $\varphi=0.2$

Moretti et al. '07: LHC could see a triple Higgs coupling Hhh

SM + higher-dim. operators

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

Zhang '93
Grojean, Servant, Wells '04

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 $|H|^6$: M < ~800 GeV

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 $\theta \sim \frac{|H|^2}{M^2}\frac{\text{Im}(x)}{y}$

Can produce the baryon asymmetry
without violating EDM bounds

Bödeker, Fromme, S.H., Seniuch '04
S.H., Pospelov, Ritz '06

MSSM + “singlets”

singlets models contain cubic terms: ~SHH

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

S.H., Konstandin, Prokopec, Schmidt ‘06

Balazs, Carena, Freitas, Wagner ‘07

(Profumo, Ramsey-Musolf, Shaughnessy ‘07)

computation of bubble profiles?

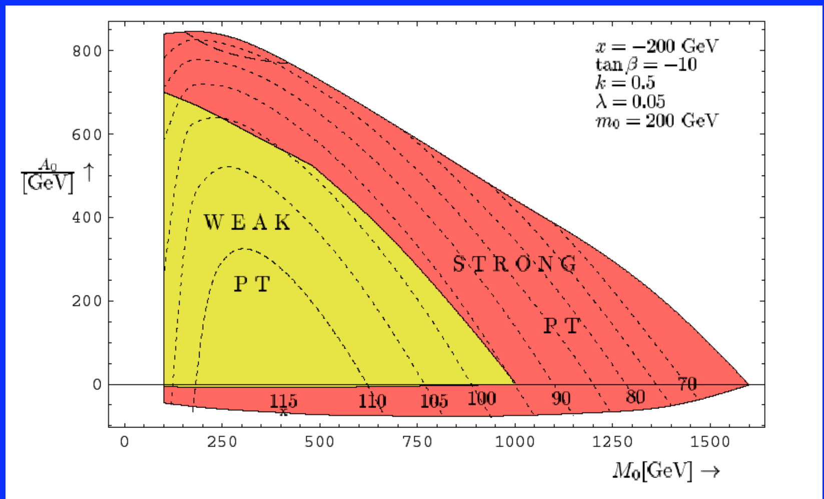
Konstandin, S.H. ‘06

$\boxed{\text{problem with 1-loop EDM‘s remains!}}$

Strong phase transition

singlet model without discrete symmetries

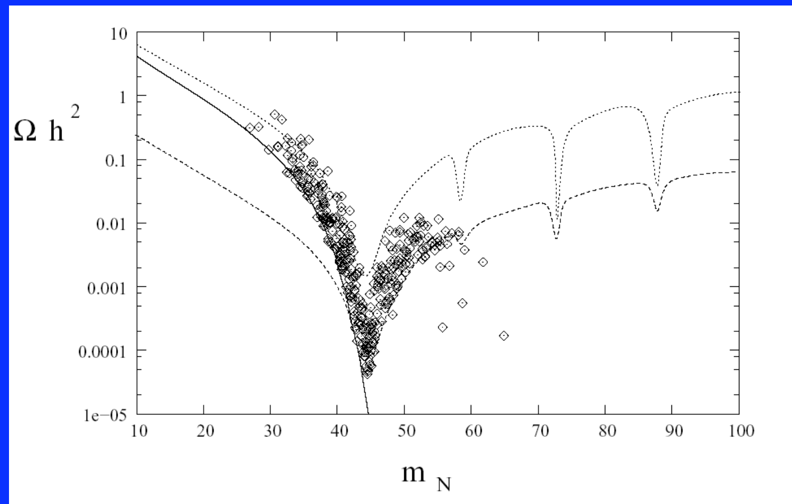
$$W = \lambda S H_1 H_2 + \frac{k}{3} S^3 + \mu H_1 H_2 + r S$$



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

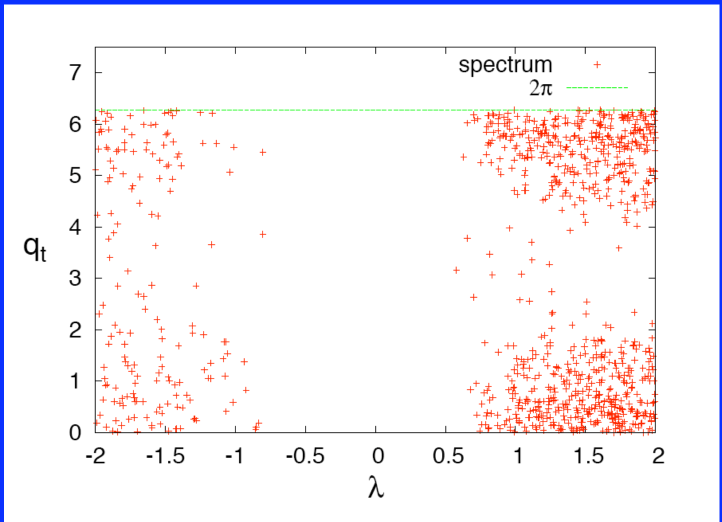
(S.H., Konstandin, Prokopec, Schmidt '06)

Baryogenesis in the nMSSM

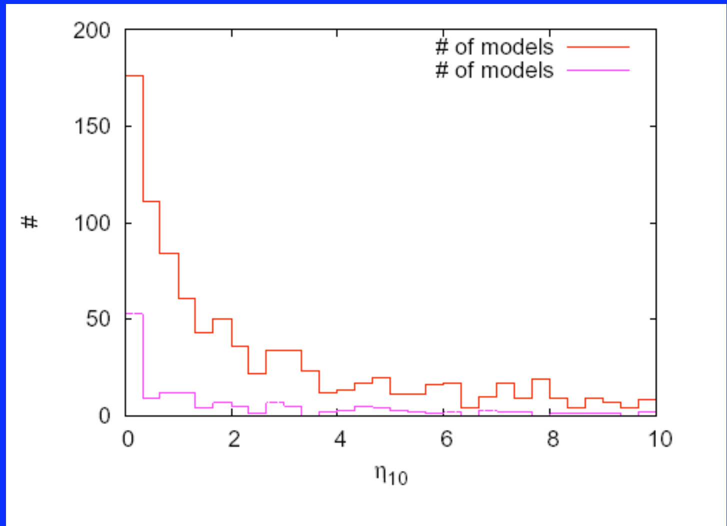
λ above Landau pole prefered:

(and tan β ~1)

CP violation in $t_S e^{iq} S$ (phase in μ parameter induced, not constant along the bubble wall)



EDM constraints with 1TeV sfermions (1. & 2. generation):

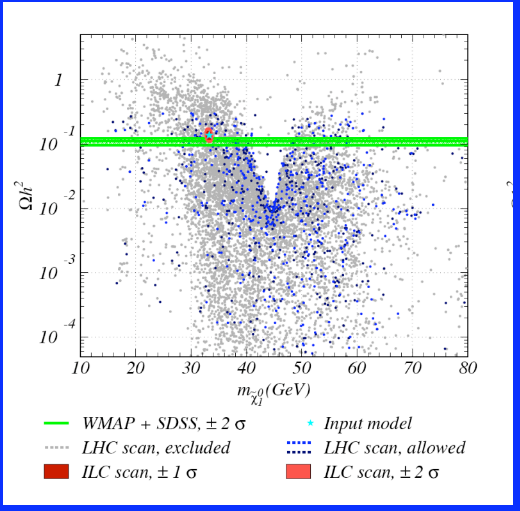


S.H., Konstandin, Prokopec, Schmidt ‘06

Colliders vs. cosmology: nMSSM

[Balazs, Carena, Freitas, Wagner '07]

Dark matter:



(problem: large error on neutralino mass at LHC)

Baryogenesis:

Presence of light charginos could be shown, especially at ILC

LHC could see a Higgs signal, but difficult to separate the different states (ILC!)

ILC could determine crucial parameters for the phase transition A_λ, t_s, m_s at 10-20% (still not sufficient to establish a strong PT)

EDMs should (probably) be seen by next generation experiments

→ predicts new physics at LHC

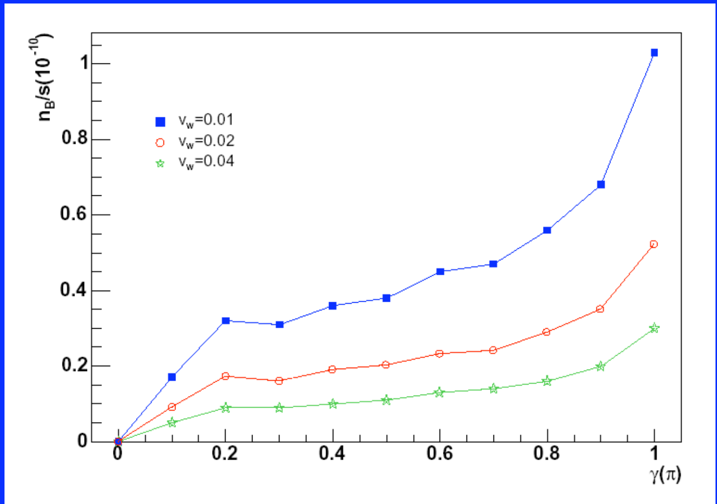
Keep in mind: model dependence!! (only an example case)

(Also the non-SUSY singlet models have been studied recently, e.g. Profumo et al. '07)

Extra U(1)´s

Kang, Langacker, Li, Liu '04

$$W_H = hSH_dH_u + \lambda S_1 S_2 S_3$$



$$m^2_{S_1S_2} \equiv |m^2_{S_1S_2}|e^{i\gamma}$$

thin wall approximation used,
tau lepton contribution only

Ham, Oh '07

$$W \approx h_t Q H_2 t^c_R + \lambda N H_1^T \epsilon H_2$$

Strong phase transition possible

No computation of the BAU

Examples have large λ=0.7, 0.8

Summary

viable models:

- SM with a dim-6 Higgs potential for M<800 GeV and m_h<170 GeV
  (EDMs similar to 2HDM)
- 2HDM: m_H>~300 and m_h<~200 GeV
- MSSM: light stop for the phase transition and a Higgs mass < ~120 GeV
  transport by the charginos (instead of tops)
  severe constraints from EDMs
- Singlet models (NMSSM): many possiblities
  cubic terms in the tree-level potential induce a strong phase transition
  EDM constraints somewhat relaxed (or totally absent for transitional $\not{C}P$)
- Gravitational waves: difficult to detect

what is the LHC going to find??

Outlook

- 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….
- establish a closer link to collider physics
- computation of the wall velocities in extended models
- more fancy models, such as Wilson line Higgs,…

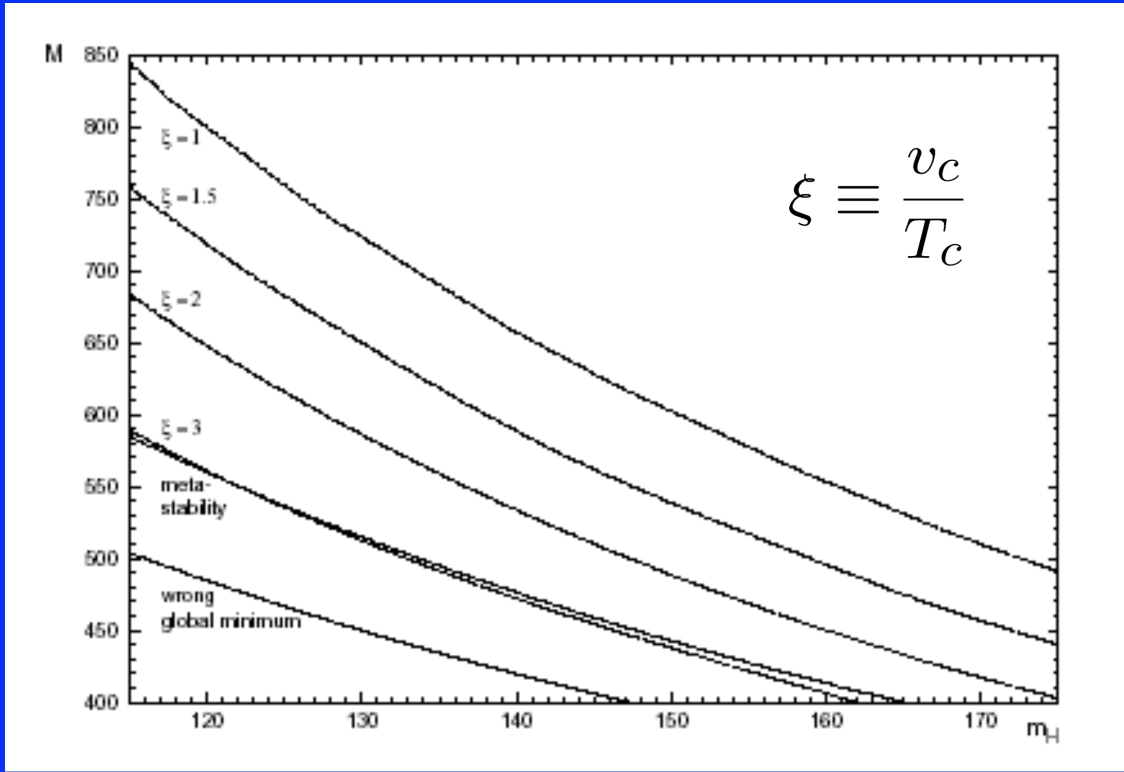
Results for the PT

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)

wall thickness $2 < L_w T_c < 16$



Bödeker, Fromme, S.H., Seniuch ‘04

The baryon asymmetry

for Im(x)=1 and

v_w=0.01, 0.3

η_B inreases rapidly

with smaller M

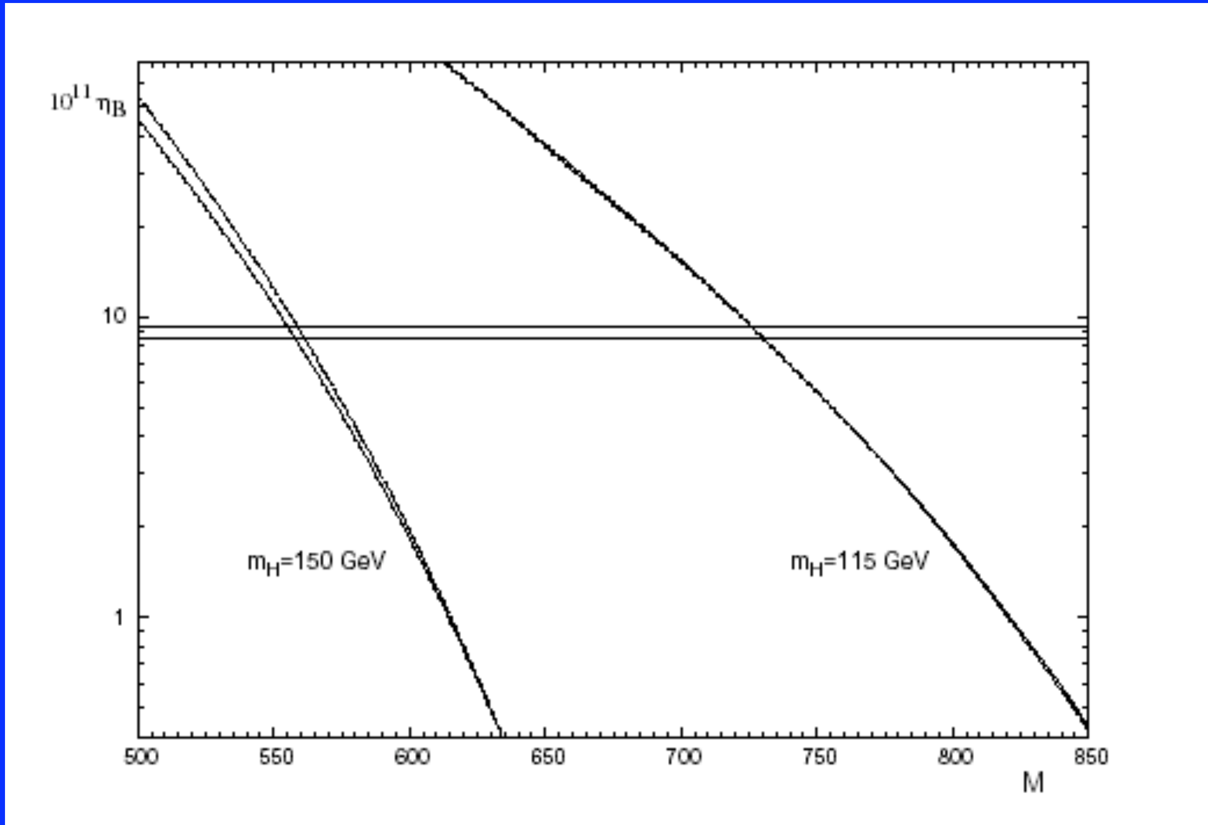
because of the

stronger PT

prediction for EDMs

with M. Pospelov, A. Ritz

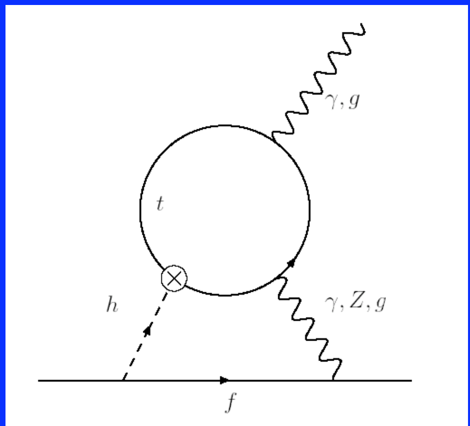
→ testable with next generation experiments!



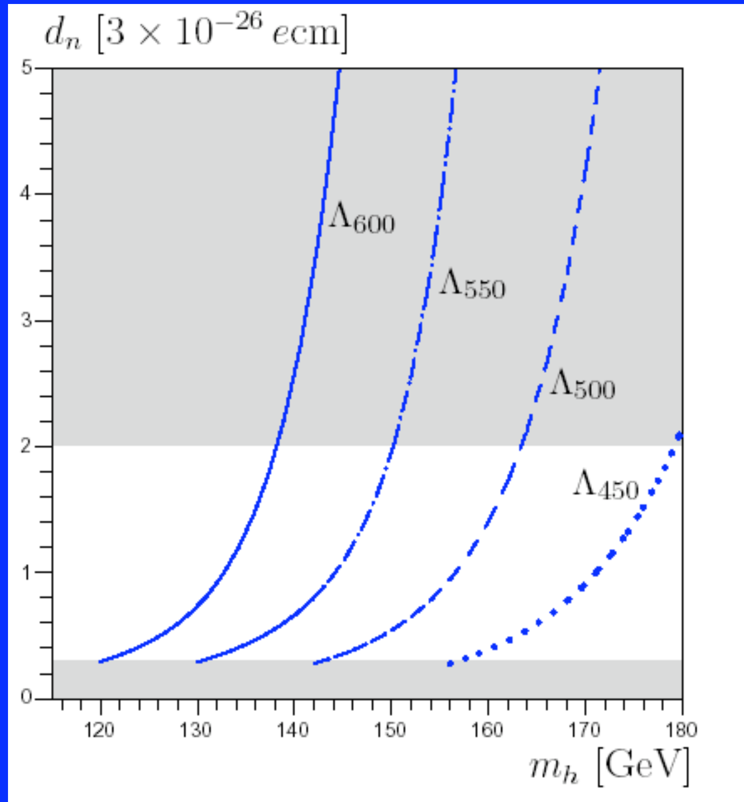
Fromme, S.H. '06

EDM from dim-6

x adjusted to get $\eta=\eta_{obs}$:



Barr, Zee '90



Experimental bounds:

d_e<1.6 10^{-27} e cm

d_n<3.0 10^{-26} e cm

S.H., Pospelov, Ritz '06

Phenomenology

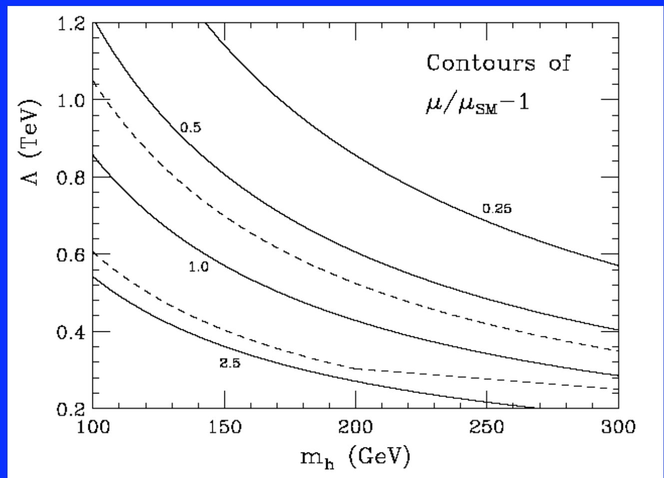
1) operators which contribute to EW observables

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 μH^3

LHC: order unity test

ILC: 20%