The electroweak phase transition

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Final Colloquium

Bielefeld, September 2012

Outline

- introduction to the phase transition
  (strength of the transition & dynamics)

- baryogenesis
  (basic picture, examples of the MSSN and 2HDM)

- gravitational waves

- bubble wall velocity

- summary and outlook

The electroweak theory

the standard model:

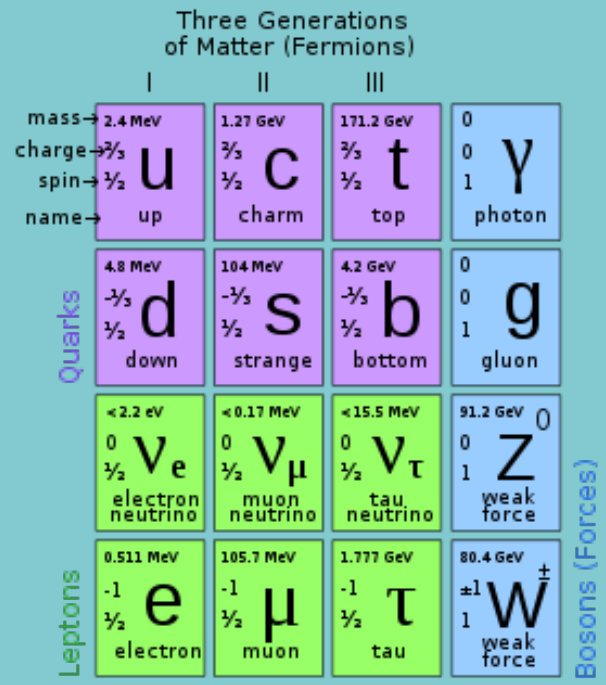
* gauge theory: SU(3) x SU(2) x U(1)

* chiral (parity violating)

* matter: 3 generations of quarks and leptons

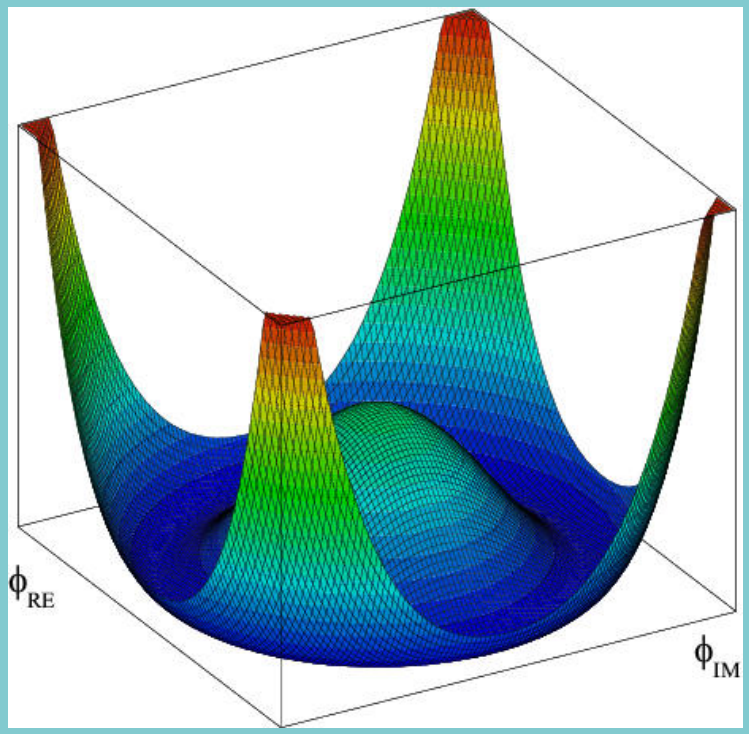
* symmetry breaking: Higgs boson

→ fermion and gauge boson masses



Electroweak symmetry breaking

$$V(H) = -m^2|H|^2 + \lambda|H|^4$$



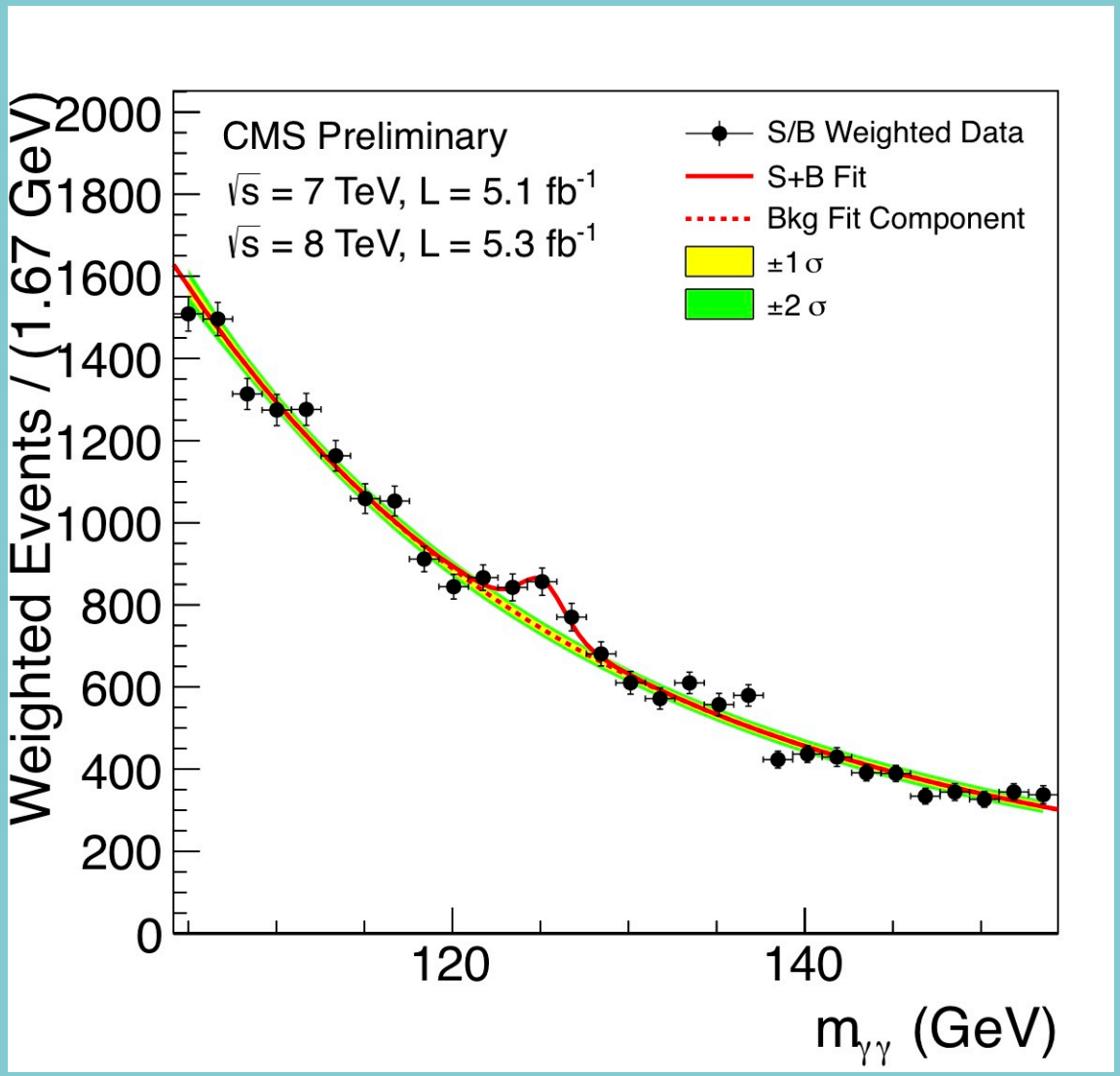
We have measured the vev, v=246 GeV

and the Higgs mass, m_h=125 GeV

The Higgs field generates masses for elementary particles (quarks, leptons, W, Z)

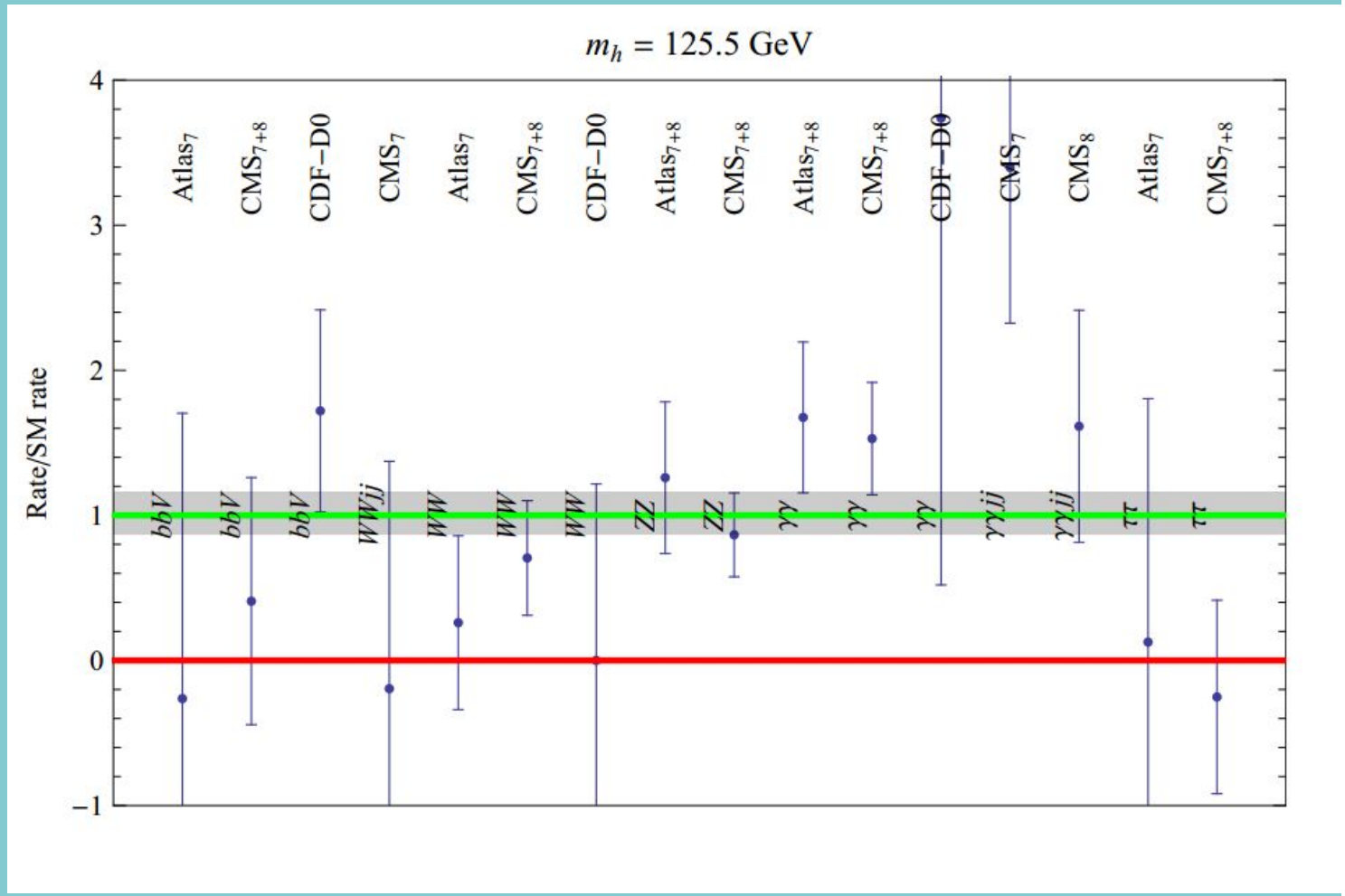
Here it is:

The Higgs boson



m_h=125.3 ± 0.6 GeV

Looking closer….



- We are surrounded by a constant Higgs field
- This field was not present at high temperatures in the early universe
- How did it come about?
- Are there observable relics?

- Gravitational waves?
- Primordial magnetic fields?
- Baryon asymmetry?

First order electroweak phase transition

Electroweak Phase Transition

Bubbles

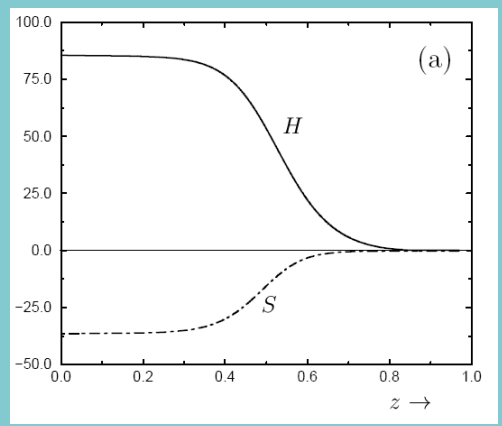
broken phase

symmetric phase

H(z)

v_w

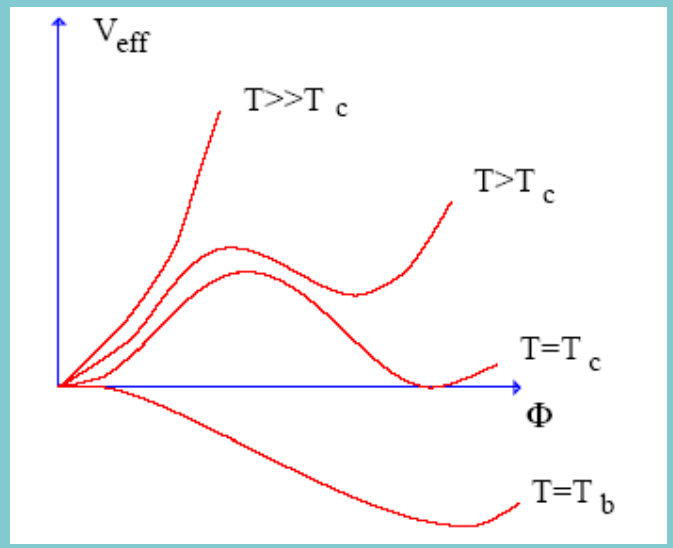
- temperature T_c
- vev in the broken phase v_c
- wall width L_w
- wall velocity v_w



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 realistic top mass)

Lattice: crossover for m_h>80 GeV → no phase transition in the SM

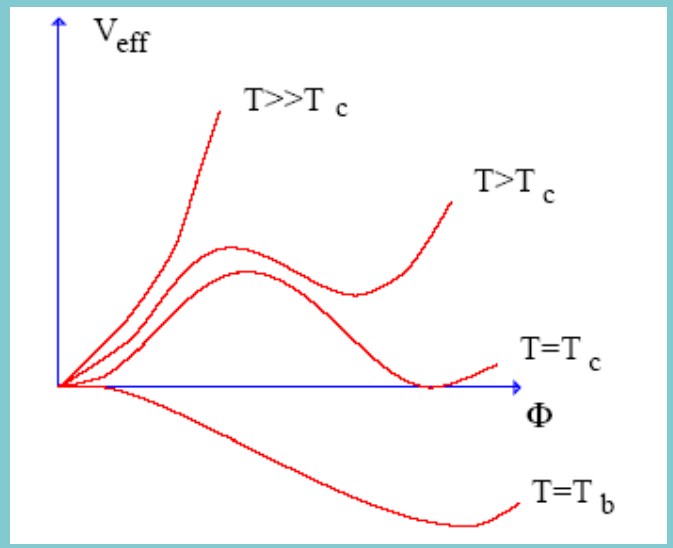
Kajantie, Laine, Rummukainen, Shaposhnikov 1996

Csikor, Fodor, Heitger 1998

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

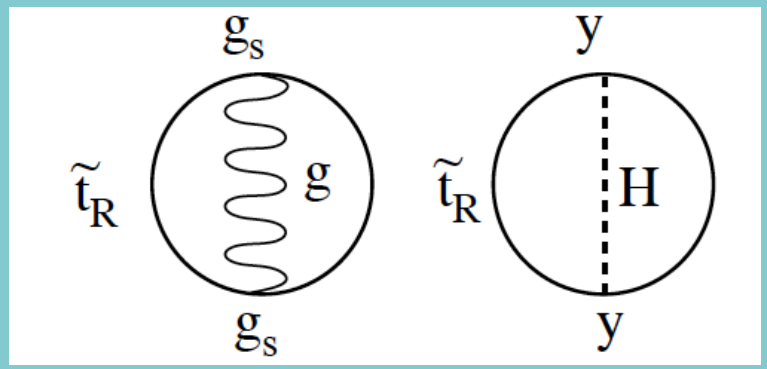
  SUSY: light stops

  2HDM: extra Higgses

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

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

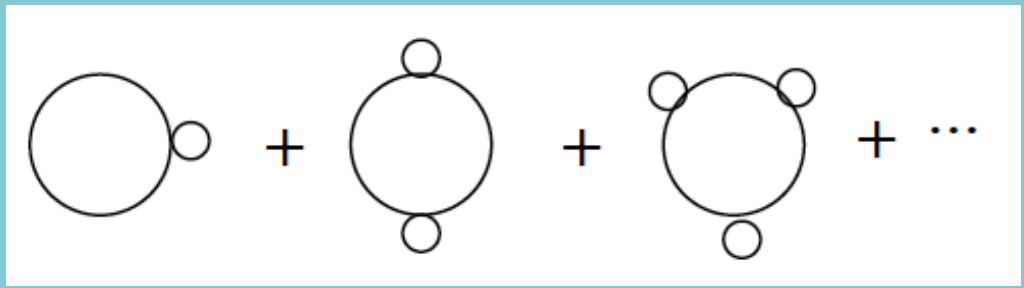
2-loop contributions can be important:



$$V_{SM}^{(2)} = \frac{g^2}{16\pi^2}T^2\left[M^2\left(\frac{3}{4}\log\frac{M_L}{T} - \frac{51}{8}\log\frac{M}{T}\right) + \frac{3}{2}\left(M^2 - 4M_L^2\right)\log\frac{M+2M_L}{3T} + 3MM_L\right]$$
$$+\frac{m_t^2(\varphi)T^2}{64\pi^2}\left[16g_s^2\left(\frac{8}{3}\log 2 - \frac{1}{2} - c_B\right) + 9h_t^2\sin^2\beta\left(\frac{4}{3}\log 2 - c_B\right)\right] \qquad (22)$$

Daisy resummation:

➔ thermal masses



IR problems: loop expansion parameter is g^2T/m (➔ lattice?)

Electroweak Baryogenesis

The baryon asymmetry

$$\eta_B = \frac{n_B}{n_\gamma} = (6.2 \pm 0.2) \times 10^{-10}$$

[WMAP, SDSS ' 08]

Two measurements:

1) CMBR+LSS
2) primordial nucleosynthesis

→ reasonable agreement
→ we understand the universe up to T~MeV

Can we repeat this success for the baryon asym.?

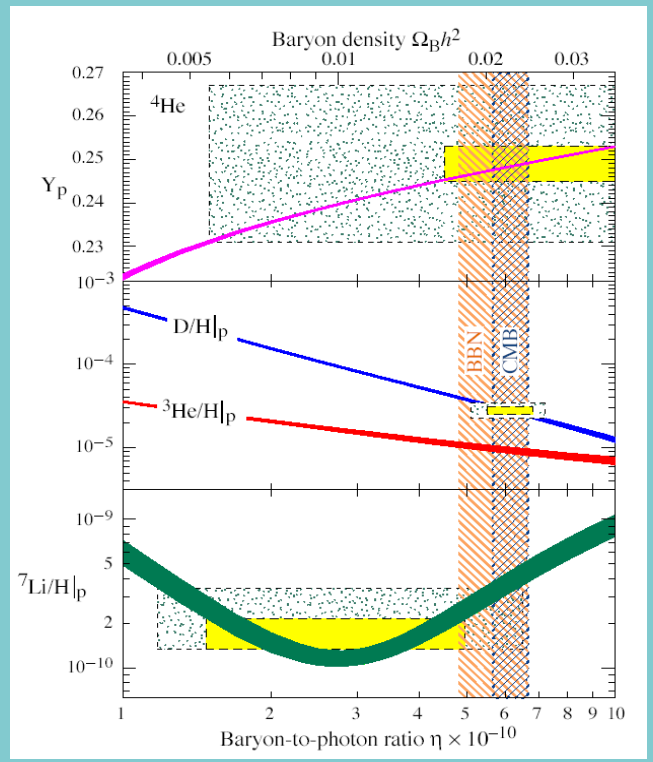
problem: only 1 observable

→ need to be convinced by a specific model:

theory?, experiment? (insight …??)

⇕

T < TeV scale? → EWBG



[Particle Data Group]

The basics

$$\eta_B = \frac{n_B}{n_\gamma} = (6.2 \pm 0.2) \times 10^{-10}$$

~~Baryon number~~

~~C~~

~~CP~~

~~Equilibrium~~

Sakharov '67

SM

Sphalerons +

Gauge interactions +

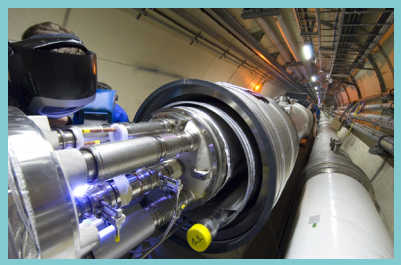
Yukawa interactions ?

Electroweak phase transition ?

Kuzmin, Rubakov, Shaposhnikov '85

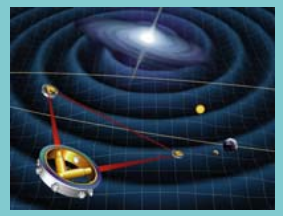
Electroweak baryogenesis?

There are testable consequences:



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

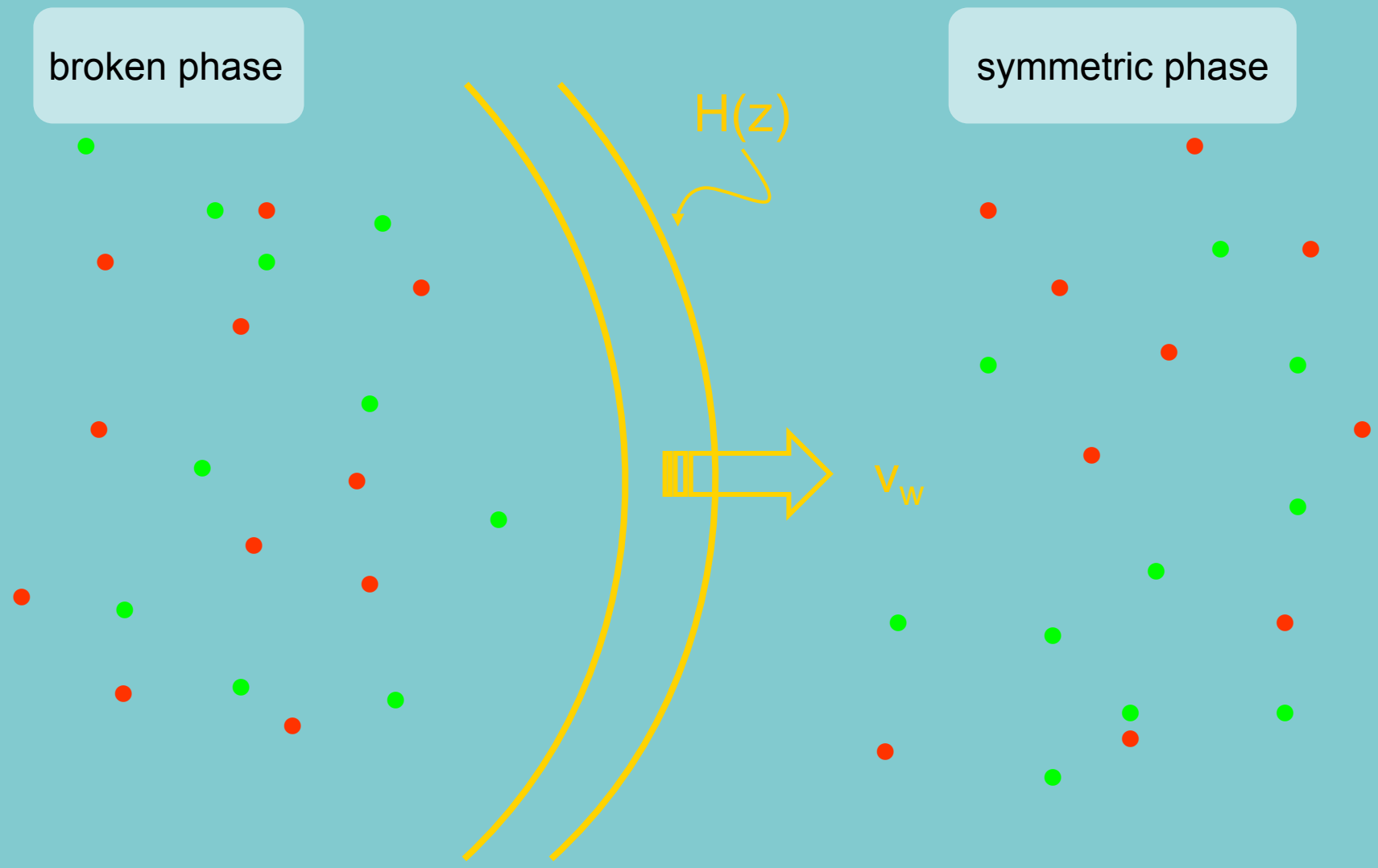
- New sources of CP violation which should show up soon in electric dipole experiments



- 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 mechanism



The mechanism

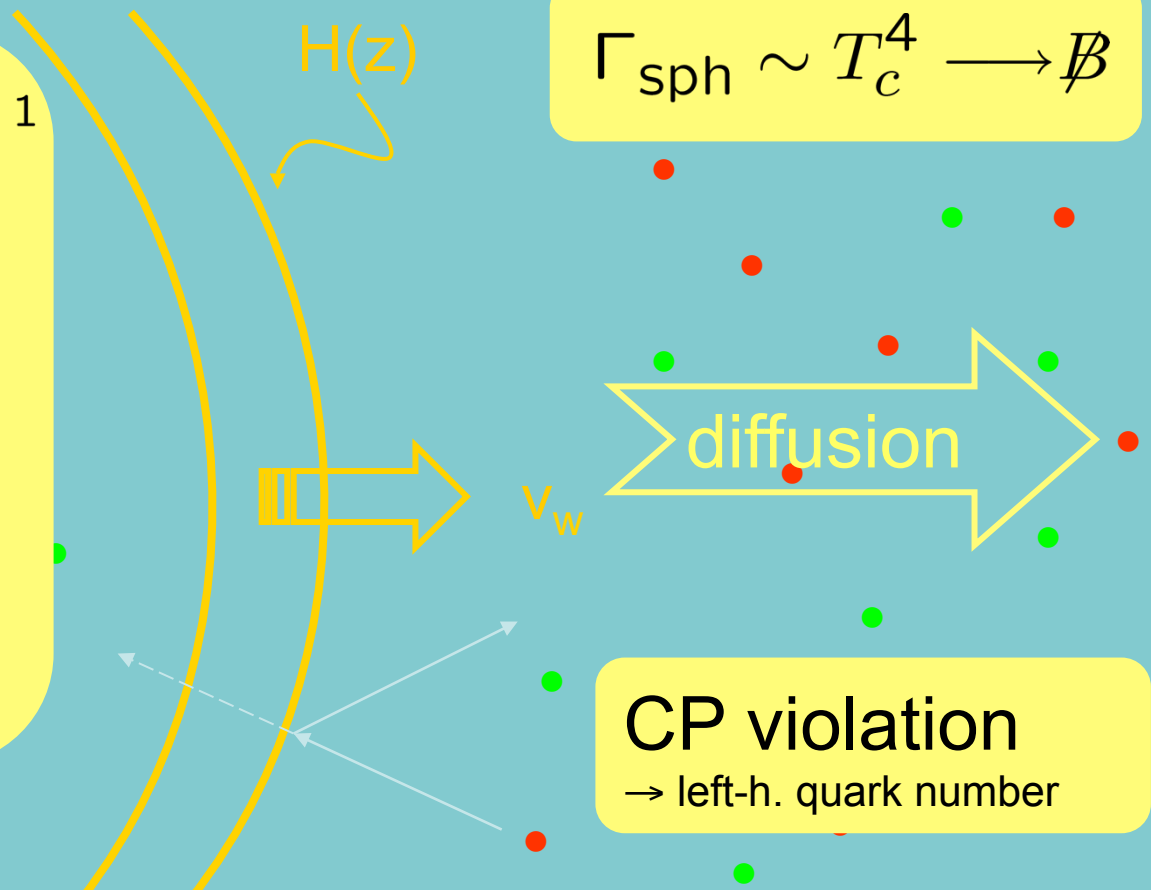
$\Gamma_{\text{sph}} \sim T_c^4 \exp(-\kappa v_c/T_c) \ll 1$

$\Downarrow$

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

$\Updownarrow$

"strong PT"



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

CP violation

→ left-h. quark number

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

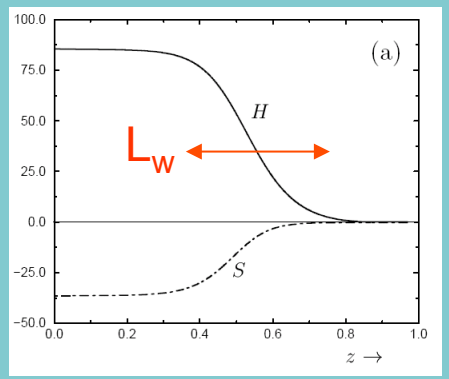
$$(\partial_t + \dot{z}\partial_z + \dot{p}_z\partial_{p_z})f = \mathcal{C}[f]$$

collision terms

Compute the force from dispersion relations

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

z is the coordinate along the wall profile with wall width L_w



WKB approximation

Elektroweak bubbles have typically thick walls: $L_w >> (T_c)^{-1}$
$(L_w)^{-1} << p$ 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

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

only a varying θ contributes!

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

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

And so it looks in practice…

$$(3\kappa_t + 3\kappa_b) v_{\mathrm{w}} \mu'_{q_3,2} - (3K_{1,t} + 3K_{1,b}) v'_{q_3,2} - 6\Gamma_y (\mu_{q_3,2} + \mu_{t,2})$$
$$-6\Gamma_m (\mu_{q_3,2} + \mu_{t,2}) - 6\Gamma_{ss} \left[(2 + 9\kappa_t + 9\kappa_b) \mu_{q_3,2} + (1 - 9\kappa_t) \mu_{t,2} \right]$$
$$= -3K_{6,t} m_t^2 \theta'_t \mu'_{q_3,1}$$

$$-(K_{1,t} + K_{1,b}) \mu'_{q_3,2} + (K_{2,t} + K_{2,b}) v_{\mathrm{w}} v'_{q_3,2} - \left(\frac{K_{1,t}^2}{\kappa_t D_Q} + \frac{K_{1,b}^2}{\kappa_b D_Q} \right) v_{q_3,2}$$
$$= K_{4,t} v_{\mathrm{w}} m_t^2 \theta''_t + K_{5,t} v_{\mathrm{w}} (m_t^2)' \theta'_t - K_{7,t} m_t^2 \theta'_t v'_{q_3,1}$$

$$3\kappa_t v_{\mathrm{w}} \mu'_{t,2} - 3K_{1,t} v'_{t,2} - 6\Gamma_y (\mu_{q_3,2} + \mu_{t,2}) - 6\Gamma_m (\mu_{q_3,2} + \mu_{t,2})$$
$$-3\Gamma_{ss} \left[(2 + 9\kappa_t + 9\kappa_b) \mu_{q_3,2} + (1 - 9\kappa_t) \mu_{t,2} \right]$$
$$= -3K_{6,t} m_t^2 \theta'_t \mu'_{t,1}$$

$$-K_{1,t} \mu'_{t,2} + K_{2,t} v_{\mathrm{w}} v'_{t,2} - \frac{K_{1,t}^2}{\kappa_t D_Q} v_{t,2}$$
$$= K_{4,t} v_{\mathrm{w}} m_t^2 \theta''_t + K_{5,t} v_{\mathrm{w}} (m_t^2)' \theta'_t - K_{7,t} m_t^2 \theta'_t v'_{t,1}.$$

[Bodeker, Fromme, Huber, Seniuch]

Models of new physics

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

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

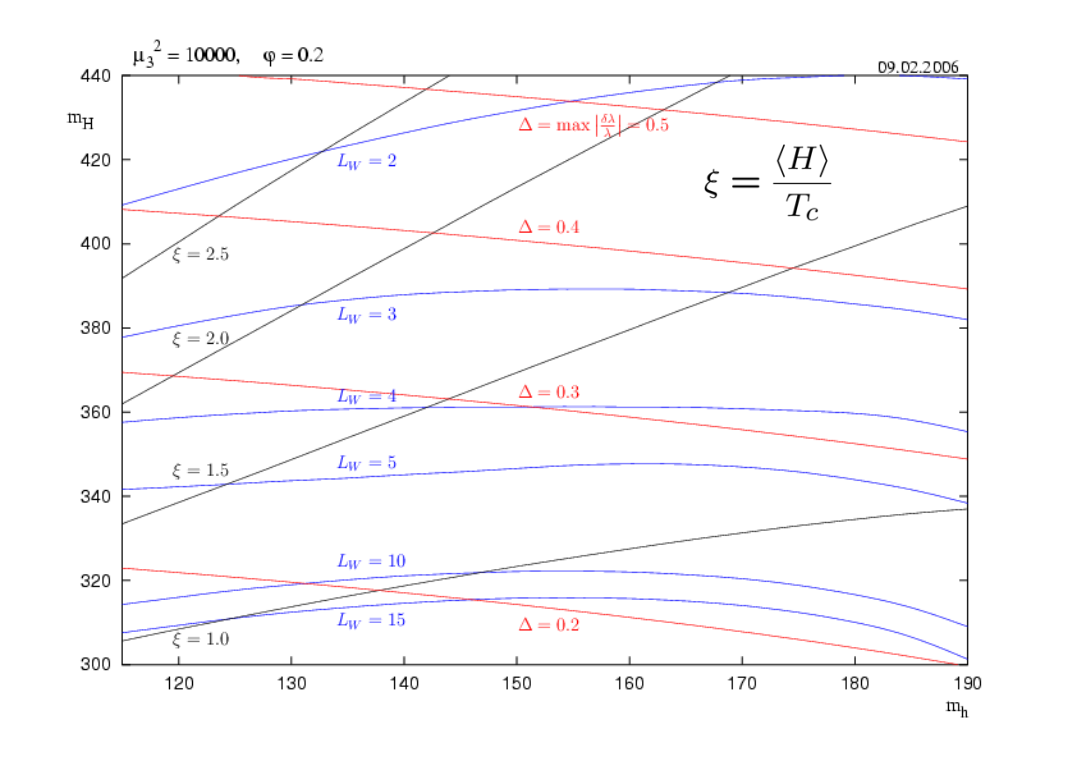
→ strong PT for

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]

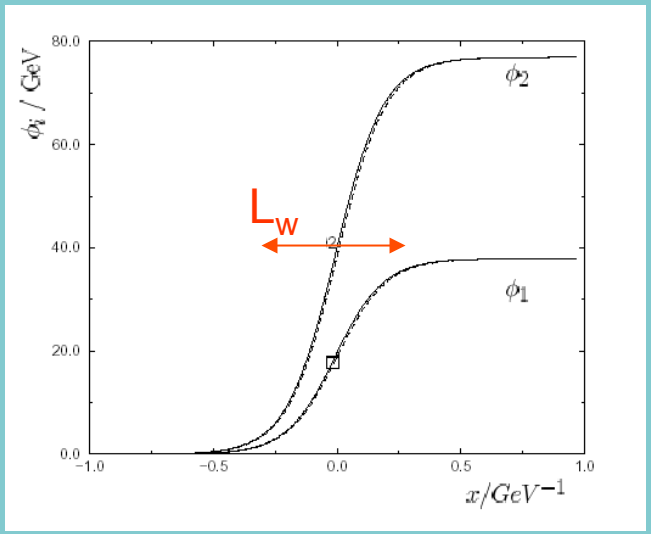
missing: 2-loop analysis of the thermal potential; lattice; wall velocity

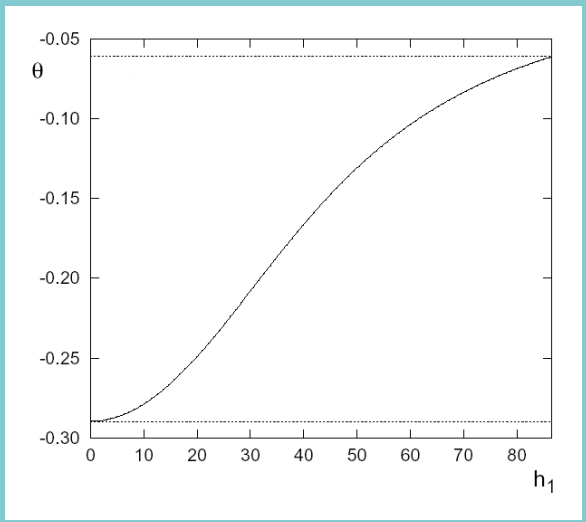
The bubble wall

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

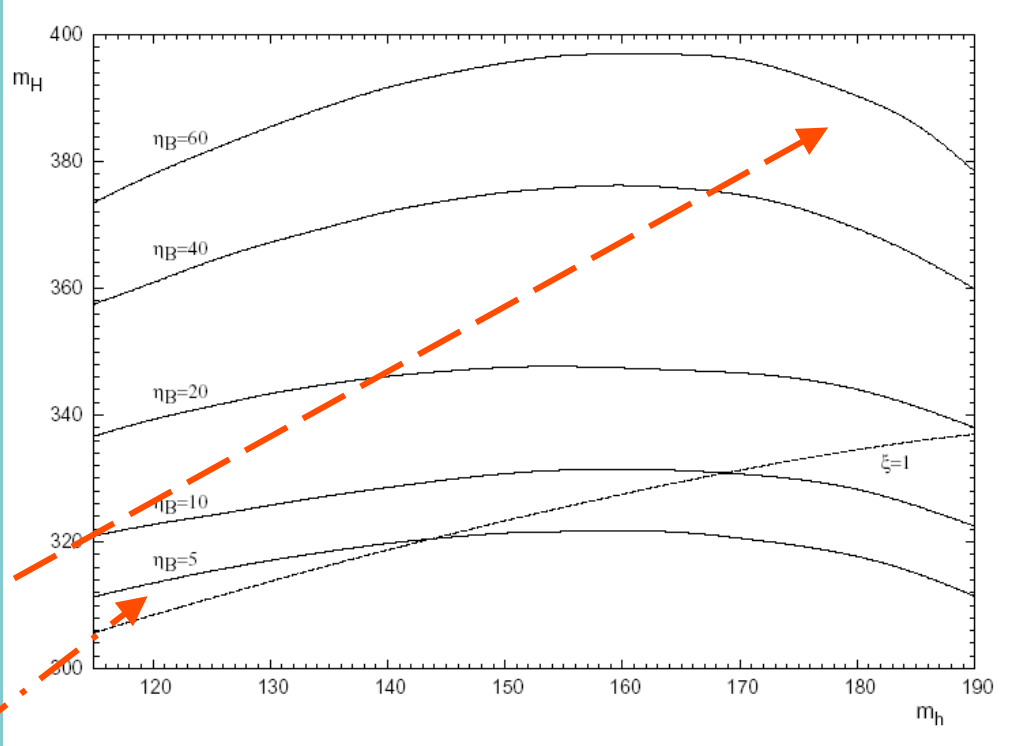
$\theta_t = \theta/(1+\tan^2\beta)$

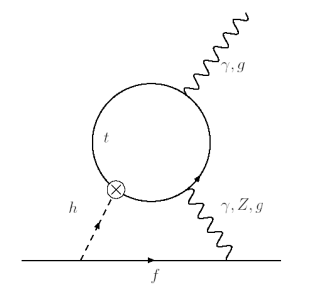
top transport generates a baryon asymmetry

→ 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

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

Could LHC see these extra Higgses?

Inert 2HDM:

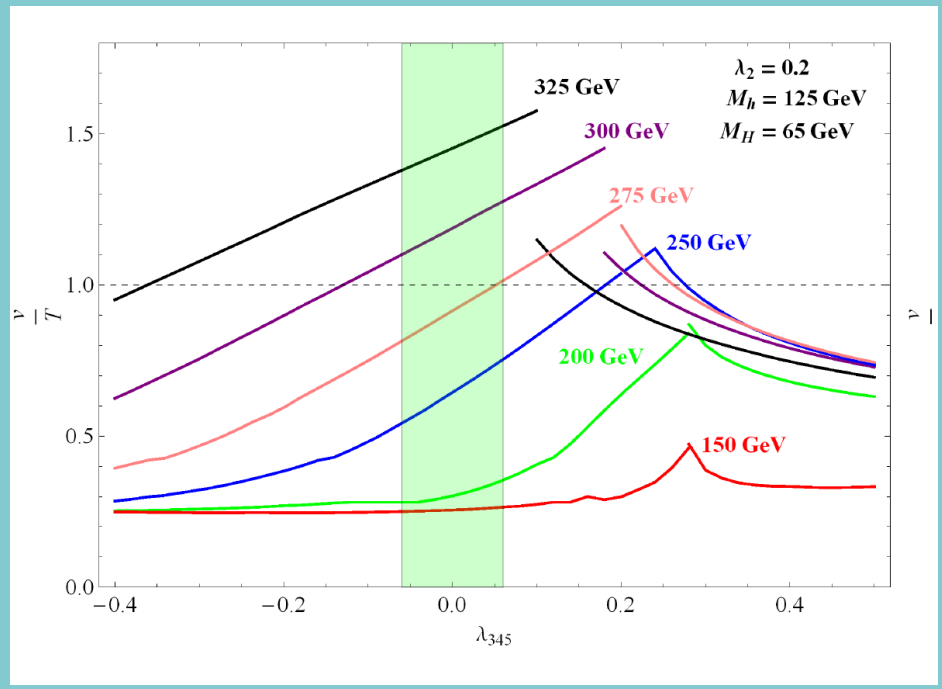
$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

doublet 2 does not get a vev

➔ Dark matter

CP violation from higher-dim. operators

$$\mathbb{Z}_2: \quad \Phi_1 \to \Phi_1\,, \qquad \Phi_2 \to -\Phi_2\,,$$
$$\mathbb{Z}_2': \quad \Phi_1 \to -\Phi_1\,, \qquad \Phi_2 \to \Phi_2\,, \qquad f_R \to -f_R\,,$$



[Gil, Chankowski, Krawczyk 2012]

SM + higher-dim. operators

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

Zhang '93

Grojean et al. '04

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

(or simply comes from integrating out extra scalars)

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

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

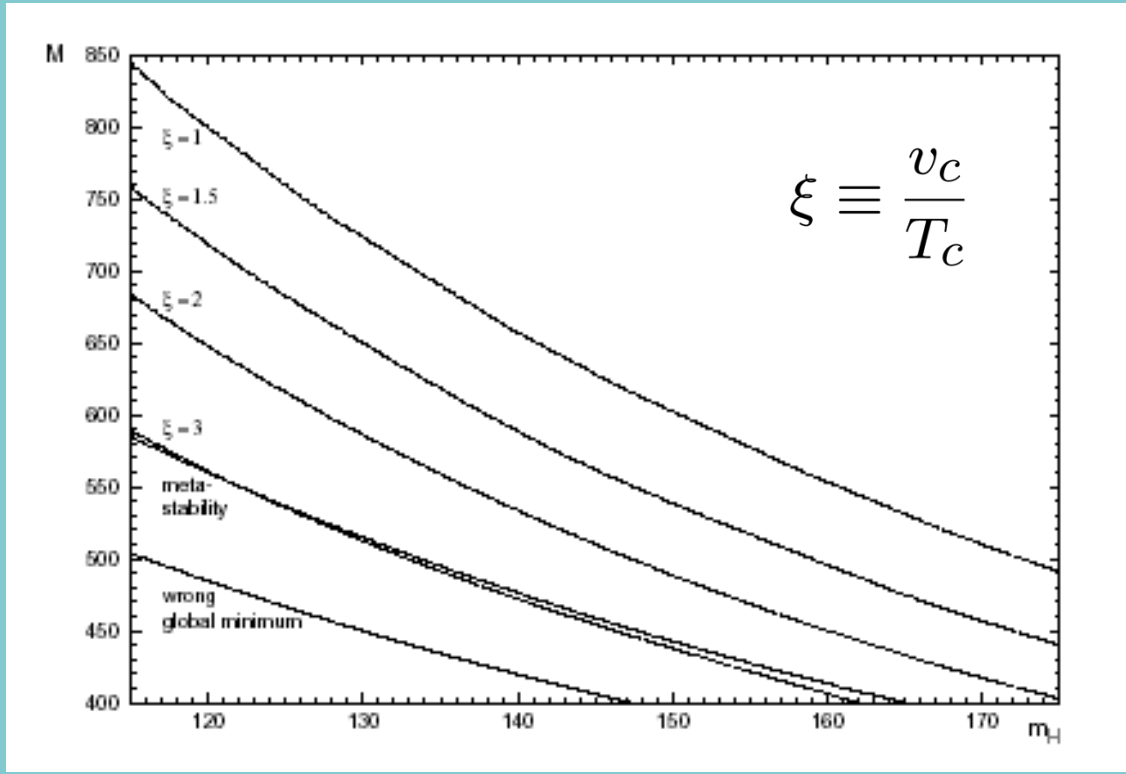
$$\begin{aligned} V_{\rm eff}(\phi, T) = \quad & \frac{1}{2}\left(-\mu^2 + \left(\frac{1}{2}\lambda + \frac{3}{16}g_2^2 + \frac{1}{16}{g_1}^2 + \frac{1}{4}y_t^2\right)T^2\right)\phi^2 \\ & - \frac{g_2^3}{16\pi}T\phi^3 + \frac{\lambda}{4}\phi^4 + \frac{3}{64\pi^2}y_t^4\phi^4 \ln\left(\frac{Q^2}{c_F T^2}\right) \\ & + \frac{1}{8M^2}(\phi^6 + 2\phi^4 T^2 + \phi^2 T^4). \end{aligned}$$

Results for the PT

Evaluating the 1-loop thermal potential:

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

wall thickness
$2 < L_w T_c < 16$



Bödeker, Fromme, S.H., Seniuch '04

Similar results, including Higgs cubic terms

Delaunay, Grojean, Wells '07

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, (λ, M) $\leftrightarrow$ (m_h, M)

λ can be negative $\rightarrow$ 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

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

The baryon asymmetry

for Im(x)=1 and

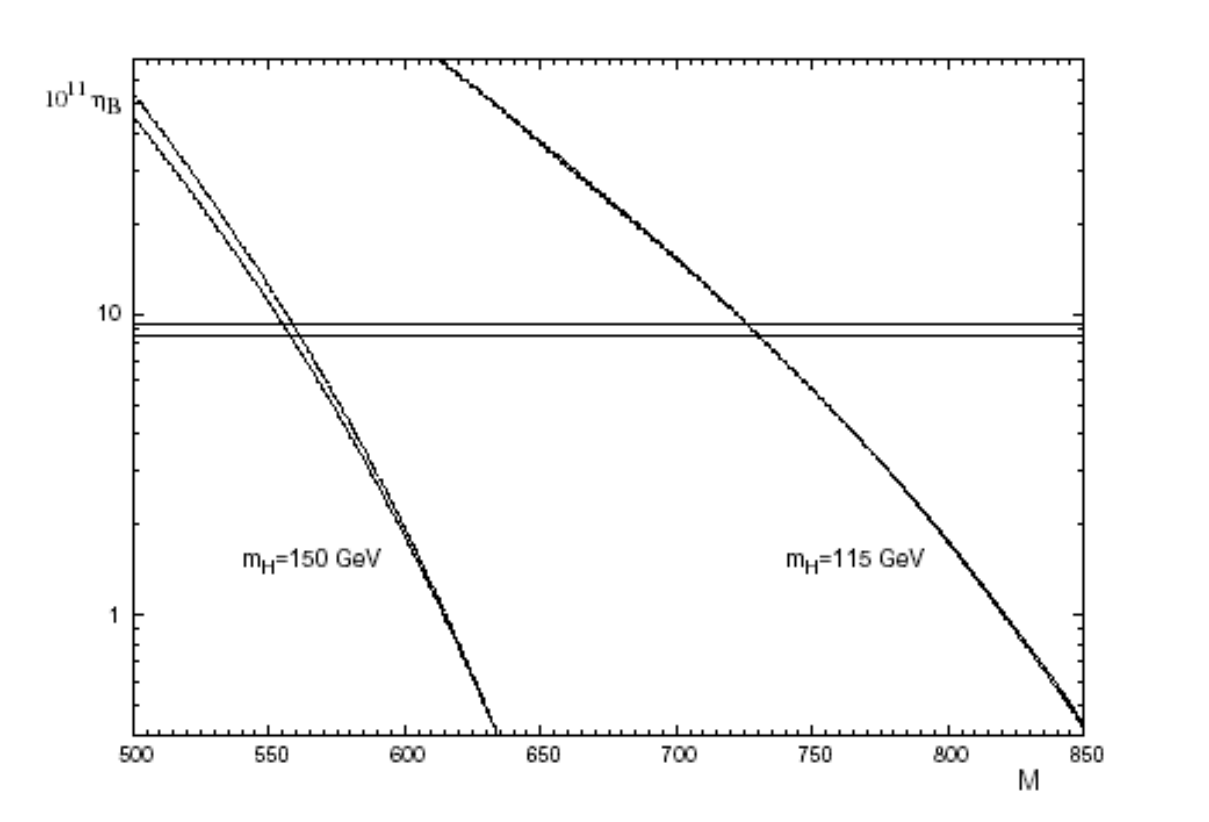
v_w=0.01, 0.3

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!

→ LHC: deviations in the triple Higgs coupling?

Fromme, S.H. ‘06

Classic: The MSSM

strong PT from stop loops

→ right-handed stop mass ~100 GeV

left-handed stop mass ~1000 TeV

[Carena, Nardini, Quiros, Wagner]

CP violation from varying chargino mixing

$$\theta(z) = \arg(M_2\mu^*) f(H_1(z), H_2(z))$$

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

chargino mass < ~300 GeV

large phases > 0.2 required

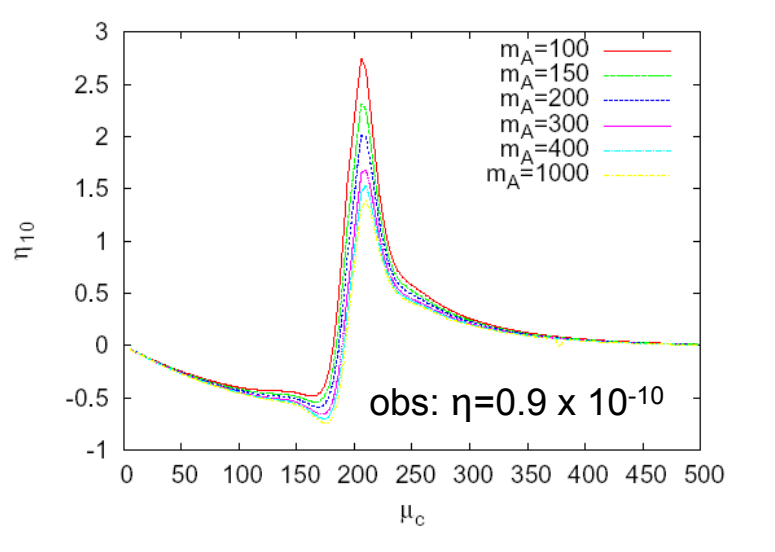
→ 1st and 2nd generation squarks

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



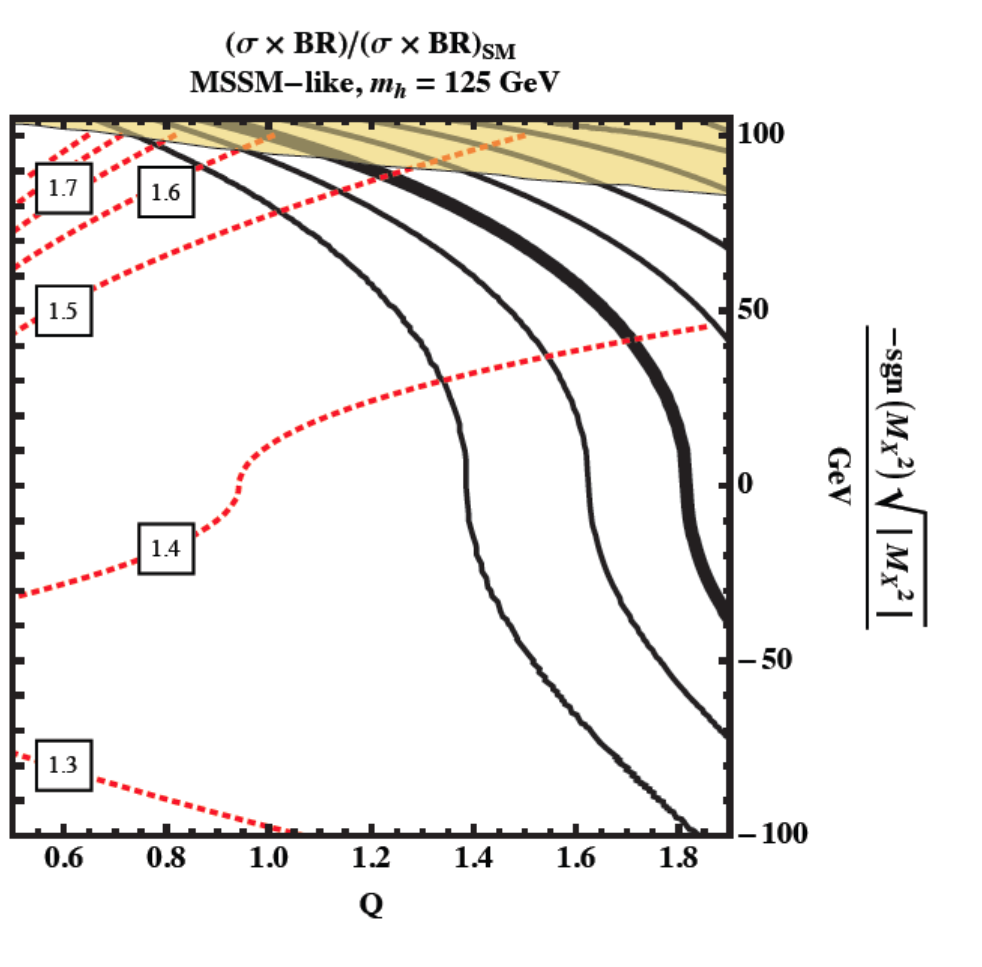
similar but somewhat more optimistic

results in Carena, Quiros, Seco, Wagner '02

Cirigliano, Profumo, Ramsey-Musolf '06

→ scenario is tightly constrained!

Possible test: modified Higgs branching ratios, e.g. into two photons:



[Cohen, Morrissey, Pierce 2012]

[see also e.g. Curtin, Jaiswal, Meade 2012]

MSSM + "singlets"

singlets models contain cubic terms: ~SHH

at tree-level → stronger PT

also new sources of CP violation

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)

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…

computation of bubble profiles?

Konstandin, S.H. '06

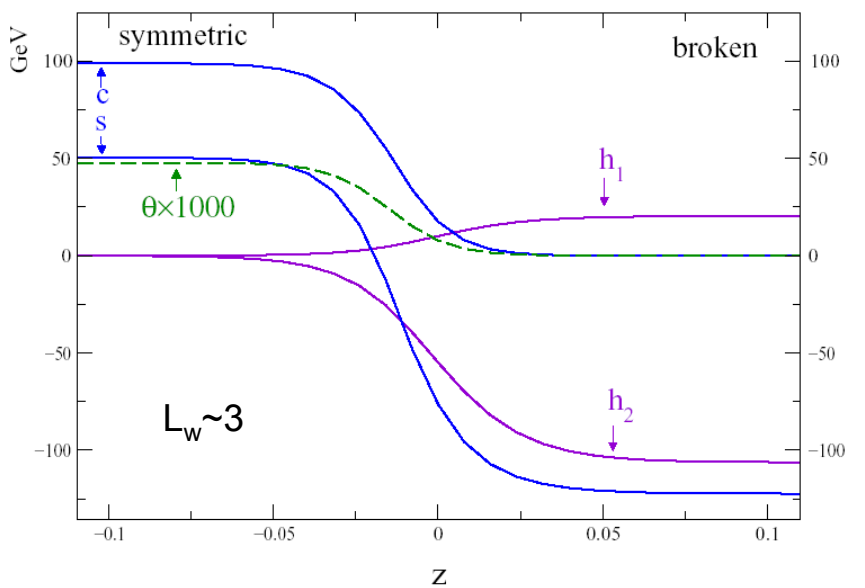
problem with 1-loop EDM's remains!

Transitional CP violation

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

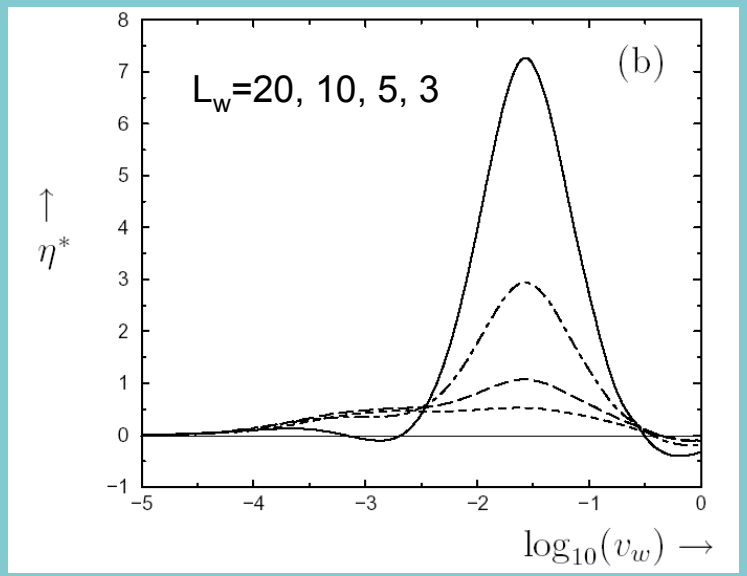
→ CP violating wall profile

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

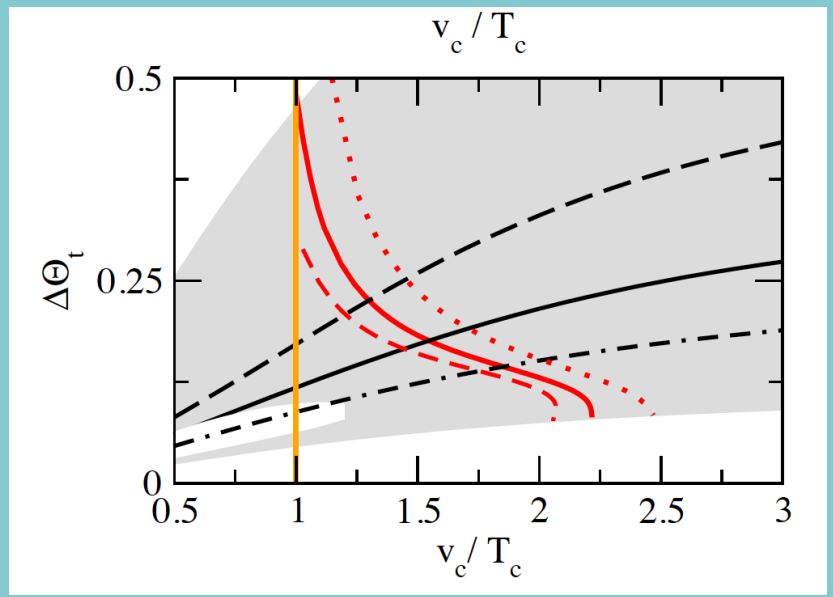
A composite Higgs model

Higgs arising as a pseudo Nambu Goldstone boson, eg. in

SO(6) → SO(5): Higgs + singlet [Espinosa, Gripaios, Konstadin, Riva '11]

$$V = V^{\text{even}} + V^{\text{odd}} \ ,$$

$$\begin{aligned} V^{\text{even}} &\equiv -\mu_h^2|H|^2 + \lambda_h|H|^4 \\ &\quad - \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{2}\lambda_m s^2|H|^2, \\ V^{\text{odd}} &\equiv \frac{1}{2}\mu_m s|H|^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3 \ , \end{aligned}$$

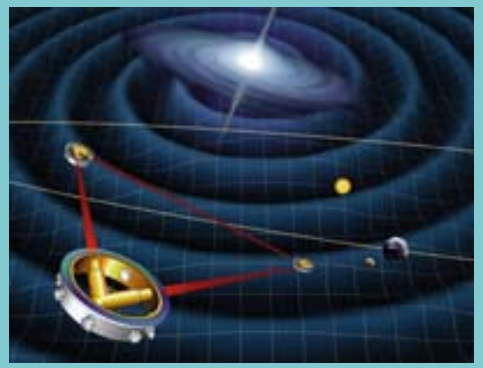


CP violation: $\frac{s}{f} H \bar{Q}_3 (a + ib\gamma_5) t$

Gravitational waves

Gravitational waves

LISA → ??



sources of GW's: direct bubble collisions

turbulence

magnetic fields

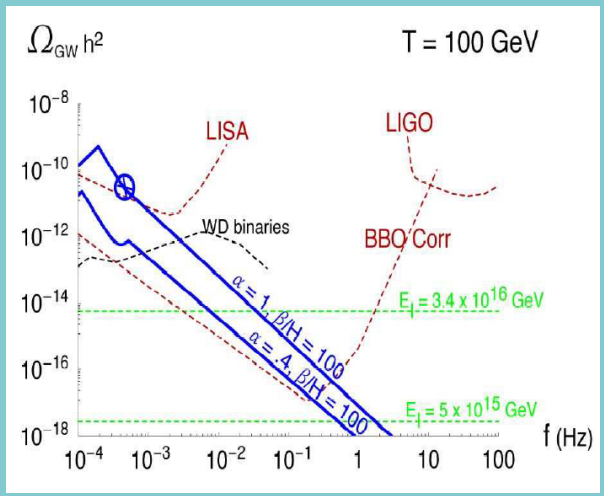
key parameters: available energy

$$\alpha = \frac{\text{latent heat}}{\text{radiation energy}}$$

typical bubble radius

$$\langle R \rangle \propto v_b \tau \approx \frac{v_b}{\beta}.$$

v_b wall velocity: supersonic!?



Grojean, Servant '06

$$f_{\rm turb} = 3.4\times10^{-3}{\rm mHz}\, u_s \left[\frac{1}{RH_*}\right]\left[\frac{T_*}{100{\rm GeV}}\right]\left[\frac{g_*}{100}\right]^{1/6}$$

$$h_0^2\Omega_{\rm turb} = 1.4\times10^{-4} u_s^5 (RH_*)^2 \left[\frac{g_*}{100}\right]^{-1/3}$$

Turbulence: Kosowsky, Mack, Kahniashvili '01

Dolgov, Grasso, Nicolis '02

Turbulence: Caprini, Dürrer '06

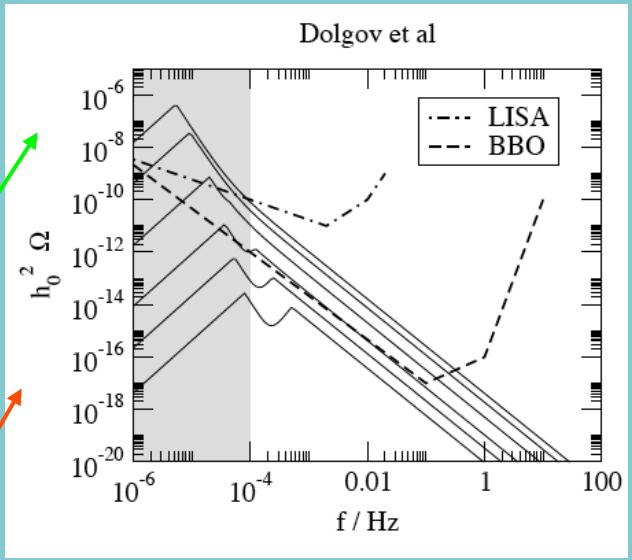
Collisions: Kamionkovski, Kosowsky, Turner '93

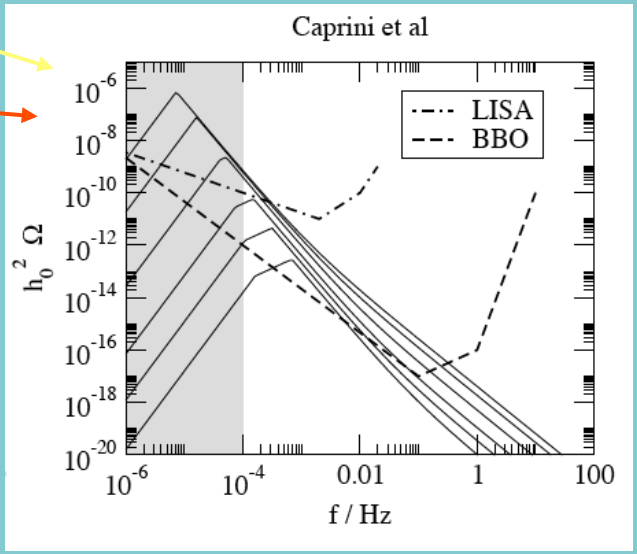
*: quantities at the PT temperature

u_s: eddy velocity (dep. on α)

strong PT: α~1, but RH_* gets larger (fewer bubbles, growing larger)

→ stronger signal, but at smaller f !!

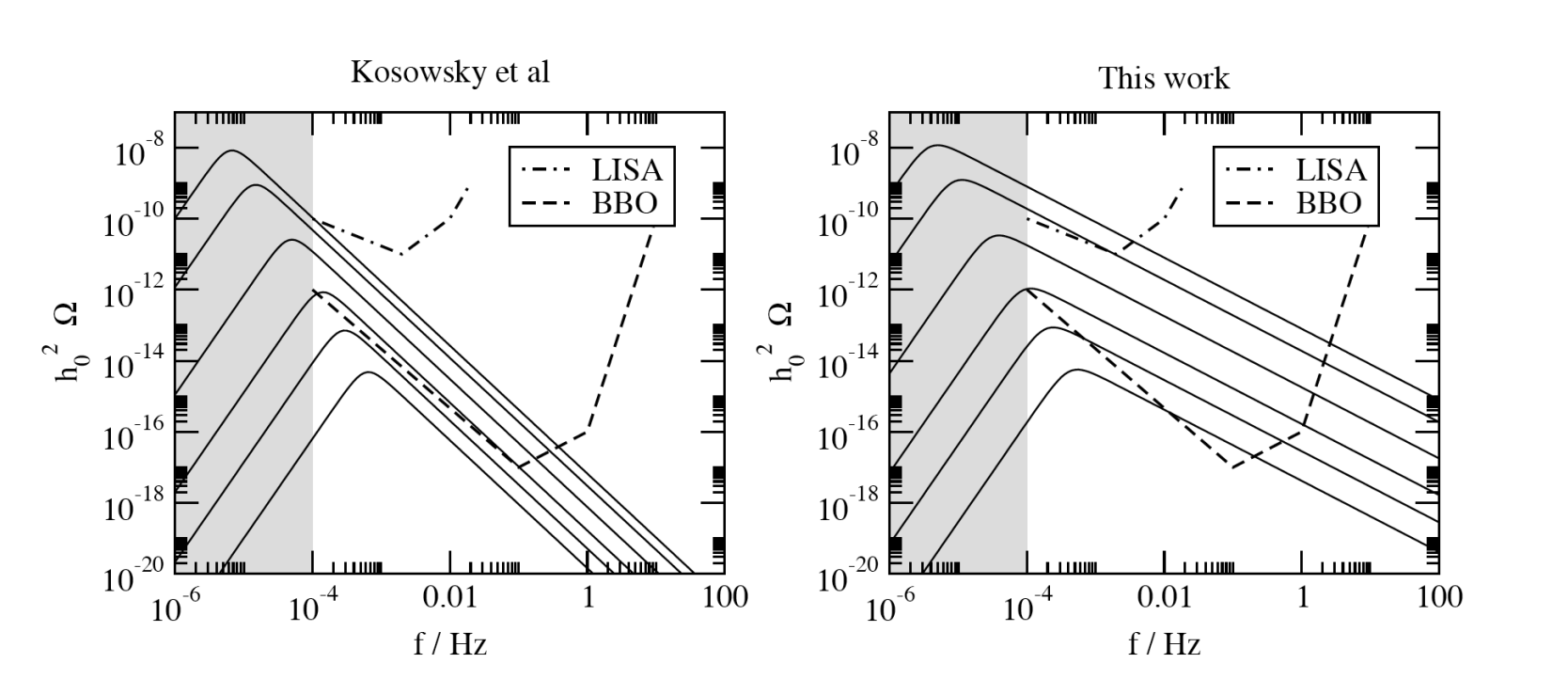




discrepancy between Dol. and CD!

double peak structure?

Results in the Φ^6 model



$\boxed{GW \sim f^{1.8} \;\Rightarrow\; GW \sim f^{1}}$

(related to small bubbles!)

T. Konstandin, S.H. ‘08

Bubble velocity

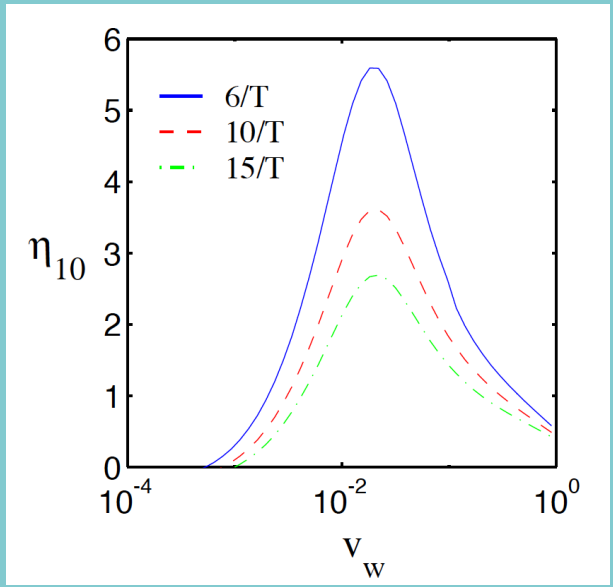
Knowing the wall velocity is important:

- Strong gravitational wave signal only for $v_w > v_s$

$$h_0^2 \Omega_{\rm det} \simeq 1.2 \times 10^{-7} \kappa^2 \langle R \rangle^2 H_*^2 \left[\frac{\alpha}{\alpha+1} \right]^2 \left[\frac{v_b^2}{0.24 + v_b^3} \right]^2 \left[\frac{100}{g_*} \right]^{1/3} .$$

- Standard baryogenesis needs $v_w < v_s = 0.58$ (diffusion!)

- Sometimes the baryon asymmetry depends crucially on v_w



[Cline, Joyce, Kainulainen '01]

The wall velocity:

Friction with the plasma balances the pressure

Distinguish: supersonic vs. subsonic ($v_s^2=1/3$)

Standard model: v_w~ 0.35 - 0.45 for low Higgs masses [Moore, Prokopec '95]

MSSM: v_w~0.05 [John, Schmidt '00]

All other models: no detailed computations

bubble walls can run away, i.e. approach $v_w=1$ [Bodeker, Moore '09]

How to compute the wall velocity?

Main ingredients: pressure difference vs. plasma friction

Also important: reheating due to release of latent heat

Microscopic description: Moore, Prokopec '95

$$\Box\phi + V_T'(\phi) + \sum \frac{dm^2}{d\phi} \int \frac{d^3p}{(2\pi)^3\, 2E} \delta f(p,x) = 0$$

$$\frac{df}{dt} = \partial_t f + \dot{\vec{x}} \cdot \partial_{\vec{x}} f + \dot{\vec{p}} \cdot \partial_{\vec{p}} f = -C[f]$$

$$\begin{aligned} a v_w \frac{\mu'}{T} + v_w \frac{\delta T'}{T} + \frac{1}{3} v' + F_1 &= -\Gamma_{\mu 1} \frac{\mu}{T} - \Gamma_{T1} \frac{\delta T}{T} \\ b v_w \frac{\mu'}{T} + v_w \frac{\delta T'}{T} + \frac{1}{3} v' + F_2 &= -\Gamma_{\mu 2} \frac{\mu}{T} - \Gamma_{T2} \frac{\delta T}{T} \\ b \frac{\mu'}{T} + \frac{\delta T'}{T} + v_w v' + 0 &= -\Gamma_v v \end{aligned}$$

$$\dot{\vec{p}_z} = -\frac{\partial E}{\partial z} \vec{u_z} = -\frac{1}{2E} \frac{d(m^2)}{dz} \vec{u_z}$$

$$f = \frac{1}{1 + \exp \frac{E - E\delta T/T - p_z v - \mu}{T}}$$

(fluid ansatz)

→ Complicated set of coupled field equations

and Boltzmann equations

need many scattering rates

$$F_1 = -\frac{v_w \ln 2}{9\zeta_3} \frac{(m^2)'}{T^2}, \qquad F_2 = -\frac{v_w \zeta_2}{42\zeta_4} \frac{(m^2)'}{T^2}$$

(force terms)

SM: v ~ 0.35 - 0.45

Simplified approach: (Ignatius, Kajantie, Kurki-Suonio, Laine ‘94)

1) describe friction by a friction coefficient η

2) model the fluid by a fluid velocity and temperature

$$\frac{d^2\phi(x)}{dx^2} = \frac{\partial V(\phi,T)}{\partial\phi} + \eta\frac{\phi^2}{T_{s1}} v\gamma\frac{d\phi(x)}{dx}$$

$$(4aT^4 - T\frac{\partial V(\phi,T)}{\partial T})\gamma^2 v = C_1$$

$$(4aT^4 - T\frac{\partial V(\phi,T)}{\partial T})\gamma^2 v^2 + P_r - V(\phi,T) + \frac{1}{2}(\frac{d\phi}{dx})^2 = C_2$$

← 1 + 1 dimensions

3) Determine η from fitting the to the full result by Moore and Prokopec

[with Miguel Sopena, see also Megevand, Sanchez ’09]

→ the formalism should describe situations with SM friction well

→ study models with SM friction, but different potential, e.g. phi^6 model

→ same for the MSSM

→ such a model can be used for numerical simulations of the phase transition

[work in progress with Hindmarsh, Rummukainen, Weir]

Friction in relaxation time approximation:

$$-\frac{(m^2)'}{2E} v\beta\gamma \frac{e^{\beta\gamma(E-vp_z)}}{(e^{\beta\gamma(E-vp_z)} \pm 1)^2} + \frac{p_z}{E}\delta f' = -\frac{\delta f}{\tau}.$$

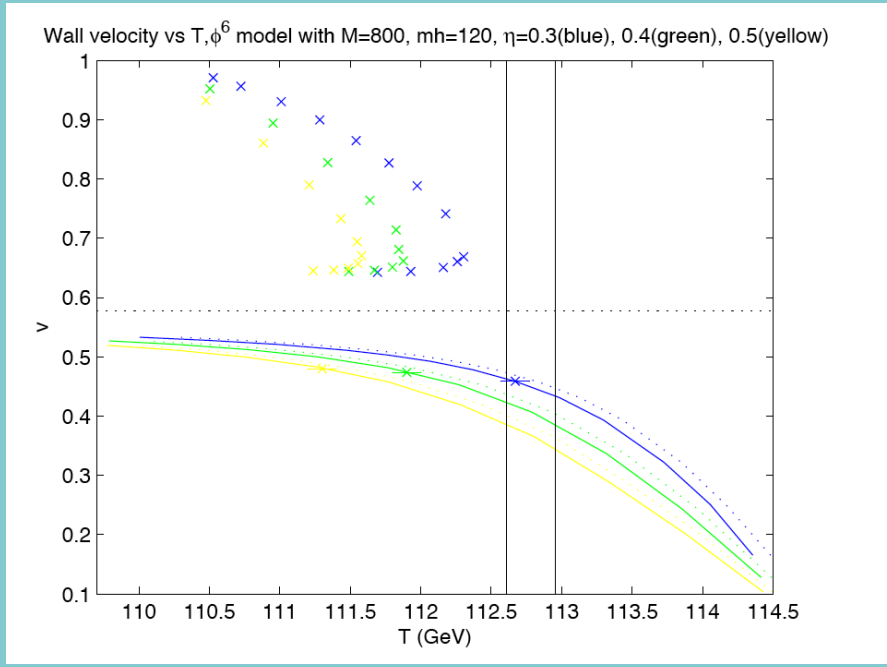
$$\frac{d^2\phi}{dz^2} + \frac{\partial V(\phi,T)}{\partial\phi} + \sum \frac{dm^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E} \tau\beta\gamma v \frac{(m^2)'}{2E} \frac{e^{\beta\gamma(E-vp_z)}}{(e^{\beta\gamma(E-vp_z)} \pm 1)^2} = 0.$$

Tau needs to be fixed from the microscopic calculations

momentum integral can done numerically

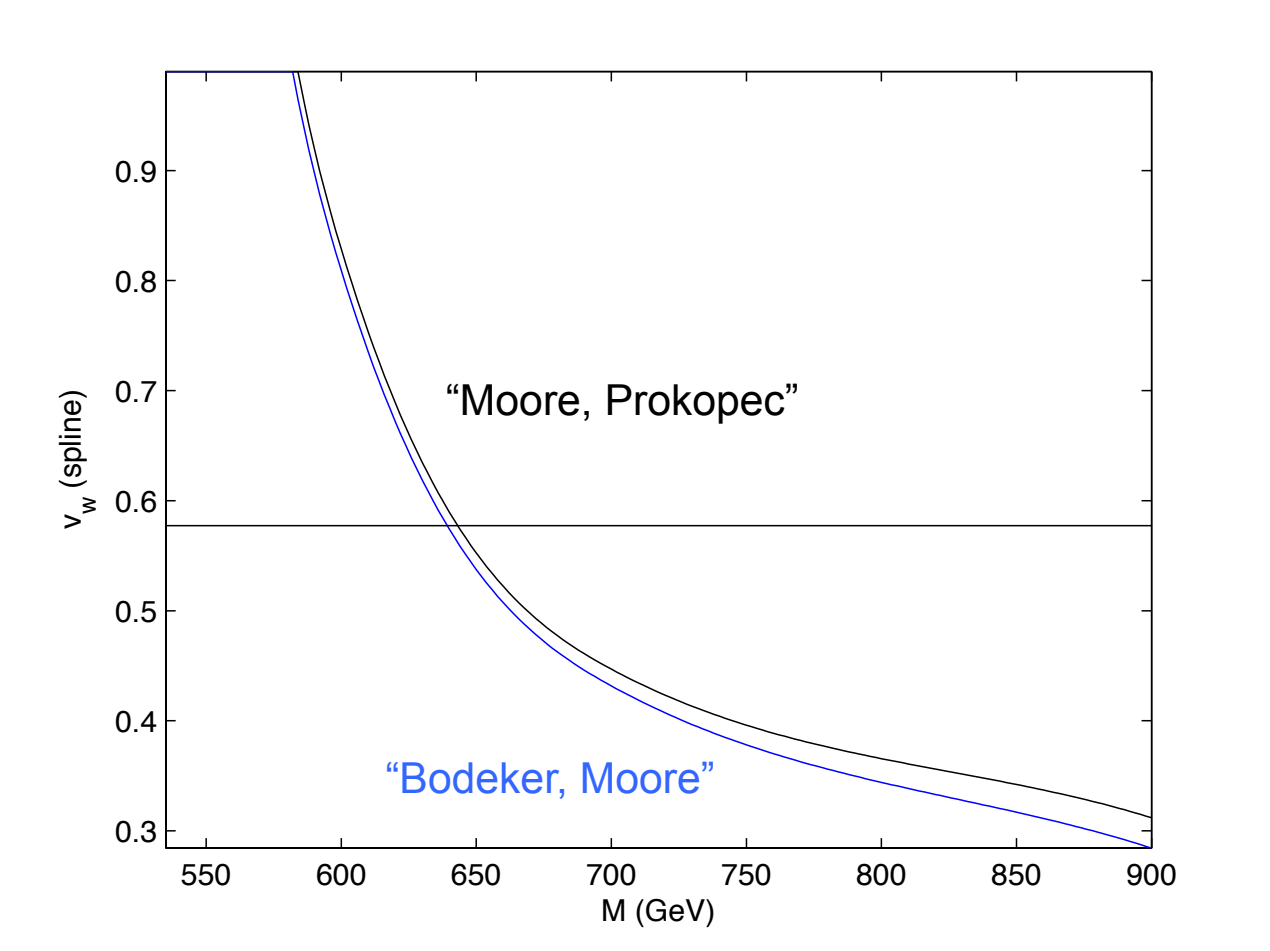
➔ In essence gives η(v/T) successfully capturing the Boltzmann factor

Results for Φ^6 model



- for a moderately strong phase transition, the wall moves subsonic in the dim-6 model (good for baryon asymmetry, bad for GW's)
- relative mild dependence on the friction coefficient eta
- instable bubbles for some temperatures?

Wall velocity for m_h=125 GeV



Find runaway behavior

Good agreement between different ways of determining tau

SH, Sopena, to appear

MSSM: S.H., M. Sopena 2011

Input:

$\tan\beta$	m_U^2	v_w (John and Schmidt)	Fitted η
2	-60^2	0.060	4.58
	0	0.090	3.36
	$+60^2$	0.160	1.92
4	-60^2	0.080	4.35
	0	0.115	3.16
	$+60^2$	0.140	2.72
6	-60^2	0.085	4.65
	0	0.120	3.06
	$+60^2$	0.155	2.55

1-loop potential

m_Q=2000 GeV

Output:

$\tan\beta$	T	$\xi = \frac{v}{T}$	Fitted η	v_w
4	T_n	0.92	6.10	0.044
	T_f	0.94		0.051
	T'_f	0.94		0.054
6	T_n	0.95	6.88	0.039
	T_f	0.96		0.045
	T'_f	0.96		0.047

2-loop potential

m_h=112 GeV

for m_h=125 we get v_w~0.03

Summary

viable models for a strong first order phase transition:

- ►2HDM: m_H>~300 (transport by tops)
- ►SM with a dim-6 Higgs potential for M<800 GeV

  (EDMs similar to 2HDM)
- ►MSSM: light stop for the phase transition (very constrained now!)

  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 $\not{C}\not{P}$)
- ►Gravitational waves: considerable uncertainties (f^{-1} fall off!), probably difficult to detect

what else is the LHC going to find??

Outlook

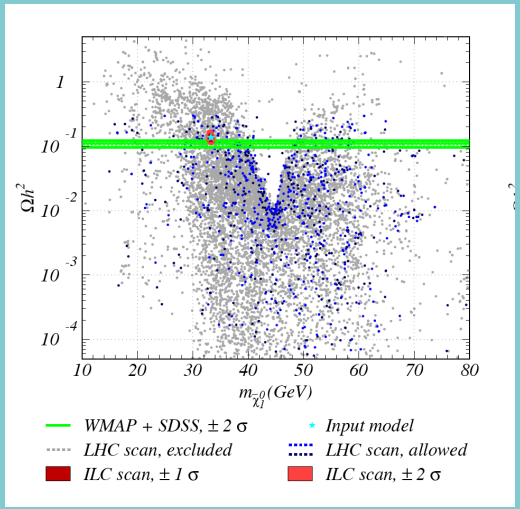
- extended models have a large parameter space which is typically only partially explored
- take into account additional constraints from dark matter, electroweak bounds, EDMs, etc.…
- establish a closer link to collider physics
- computation of the wall velocities in extended models
- more fancy models, such as Wilson line Higgs,…

what else is the LHC going to find??

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 can see the Higgs signal, but difficult to identify the different Higgs 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.)

electroweak phase transition

Electroweak symmetry was (probably) restored in the early universe at

T > ~ 100 GeV

t < ~ 1 nano second after the big bang

by thermal effects

How did the symmetry break?

** first order phase transition (bubbles!)

* second order phase transition

* cross over

→ does depend on particle properties at the weak scale!

→ LHC!?

Depending on the question, there are different problems to be addressed, however two are universal:

*strength of the phase transition (size of the order parameter)

*bubble dynamics (nucleation, wall velocity,…)

Status and outlook (1)

1) Strength of the phase transition: under control

strong phase transition from singlets, higher-dim operators, etc.

2-loop, lattice for the 2HDM?

2) Wall velocity: unknown in most cases

slow walls in the MSSM

velocities on extended models (singlets, 2HDM,…)

effect of infrared gauge field modes

3) Baryon asymmetry: good progress

CP violation for mixing fermions (quantum Boltzmann eqs.)

more realistic set of Boltzmann eqs. (Yukawas, etc…)

supersonic baryogenesis, transitional CP violation

Status and outlook (2)

4) Gravitational waves: lot's of activity recently

requires supersonic bubbles

how to model the source correctly?

turbulence?

full simulations?

5) Magnetic fields

mechanisms for their generation?

source of cosmic magnetic fields?

effect on the phase transition, baryogenesis?

Status and outlook (3)

6) Model building

NMSSM type, extra U(1)'s, E6SSM

extra Higgses (2HDM,…)

extra dimensional models (gauge-Higgs, AdS/CFT)

little Higgs models

7) Collider and other signatures

new particles at the LHC

can one reconstruct the potential

signals of CP violation

Further Aims:

Produce: up to date review on the physics of the electroweak phase transtion?

Think about a follow up meeting next year

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 $\not{C}\not{P}$)

- ►Gravitational waves: difficult to detect

what is the LHC going to find??

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- 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,…

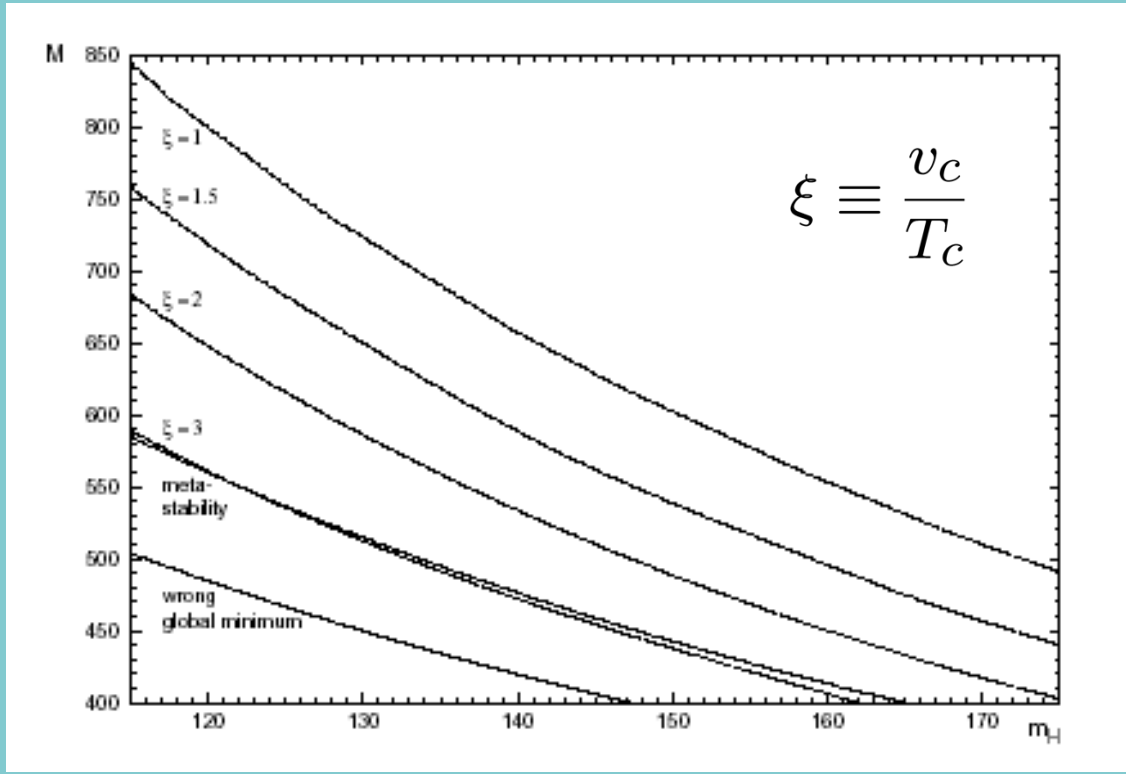
Results for the PT

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 $2 < L_w T_c < 16$



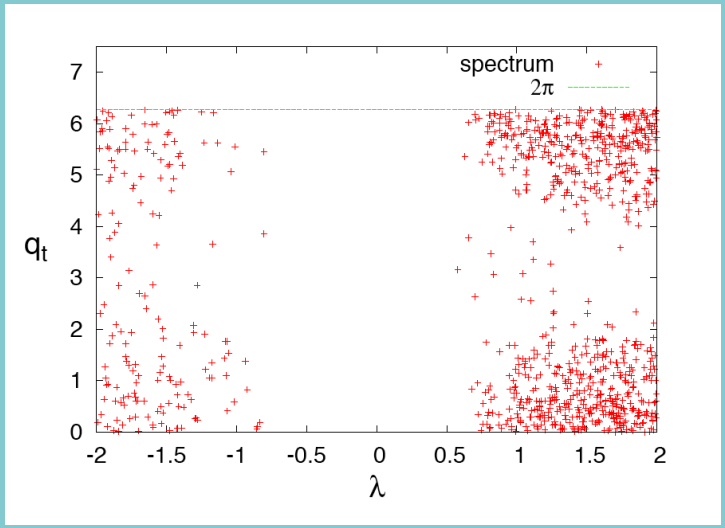
Bödeker, Fromme, S.H., Seniuch '04

Baryogenesis in the nMSSM

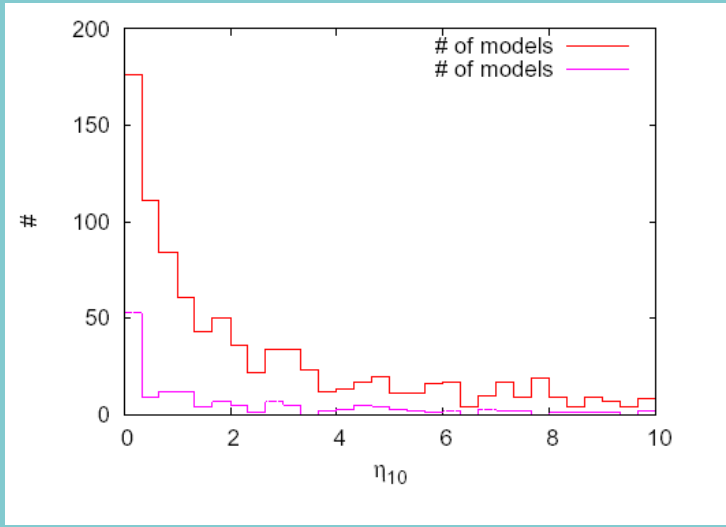
λ above Landau pole prefered:

(and tan β ~1)

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

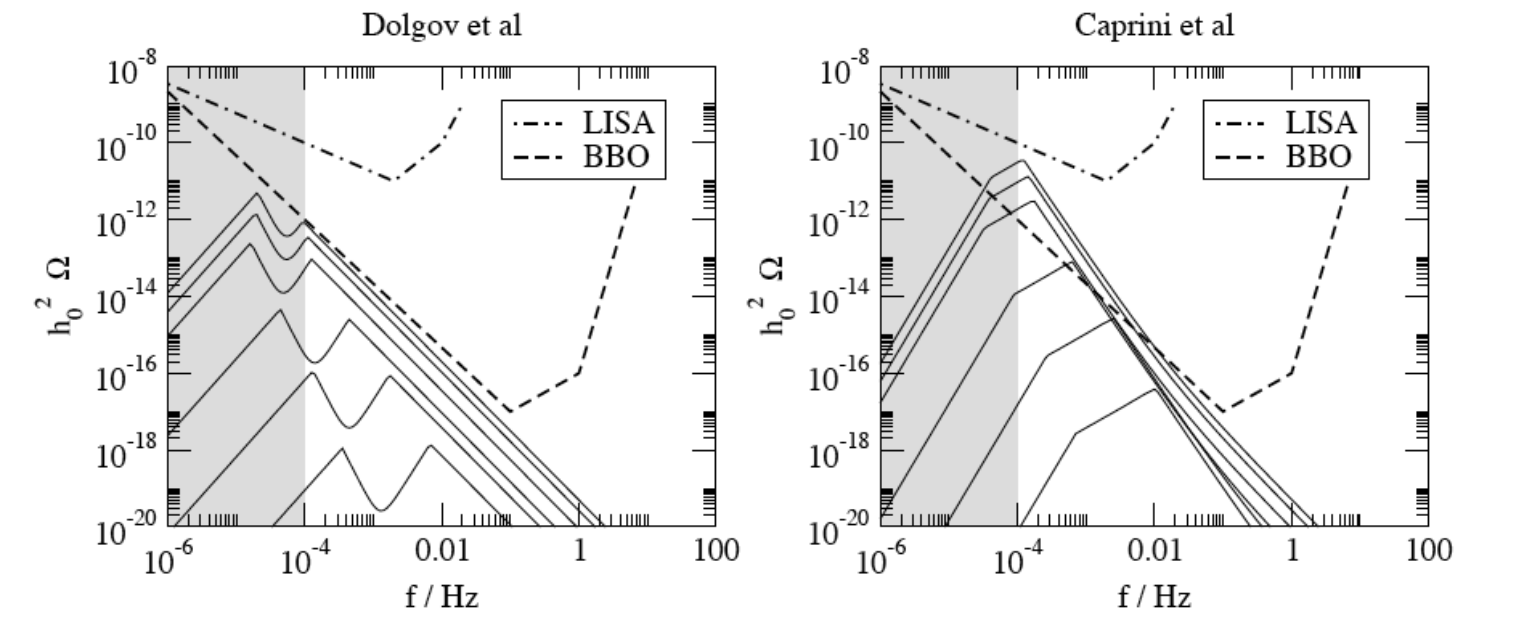


EDM constraints with 1TeV sfermions (1. & 2. generation):



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

Gravitational waves in the nMSSM



S. H., Konstandin '07

Cannot confirm the much larger results of Apreda, Maggiore, Nicolis, Riotto '01 (important to compute the bubbles shapes correctly!)

Baryogenesis: strong GW signal only for $v_b > v_s$ → no diffusion. Baryogenesis would at least look different

The baryon asymmetry

for Im(x)=1 and

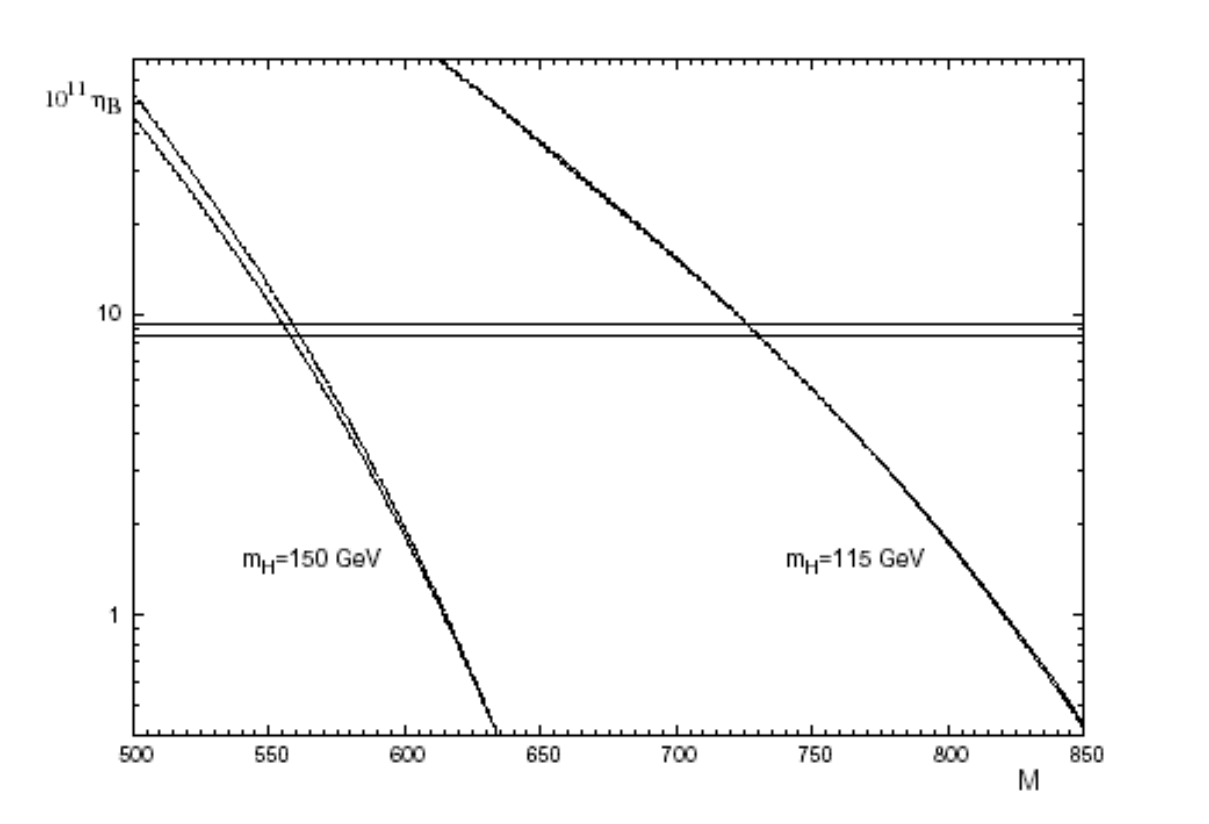
v_w=0.01, 0.3

η_B inreases rapidly

with smaller M

because of the

stronger PT



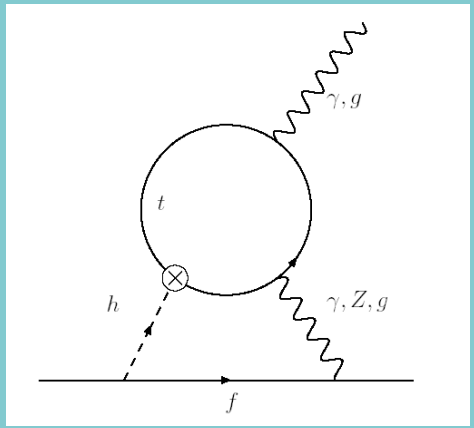
prediction for EDMs

with M. Pospelov, A. Ritz

→ testable with next generation experiments!

Fromme, S.H. ‘06

EDM from dim-6



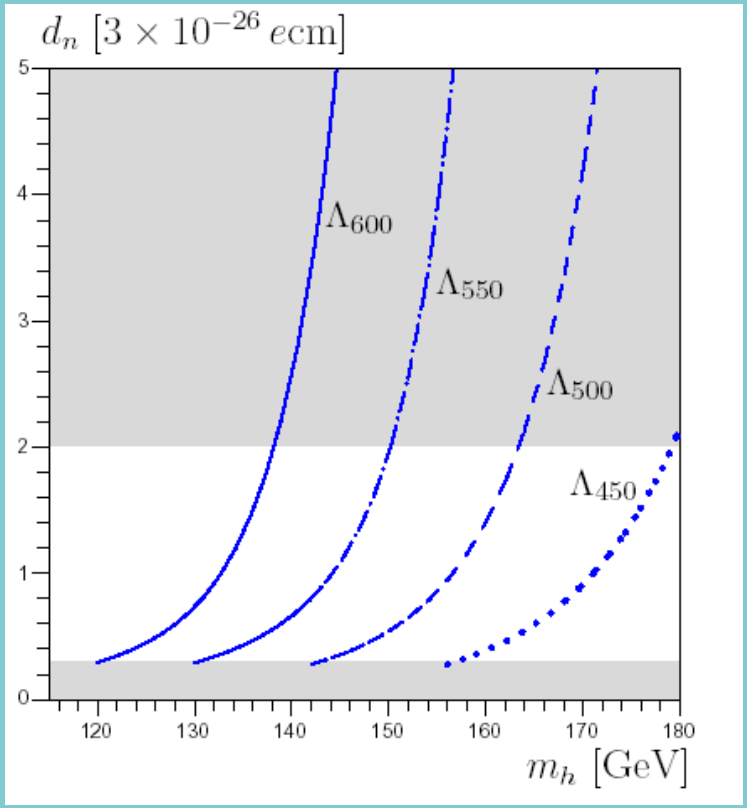
Barr, Zee '90

Experimental bounds:

d_e<1.6 10^{-27} e cm

d_n<3.0 10^{-26} e cm

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



S.H., Pospelov, Ritz '06

Phenomenology

1) operators which contribute to EW observables must be suppressed by Λ>>M~TeV, e.g.

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

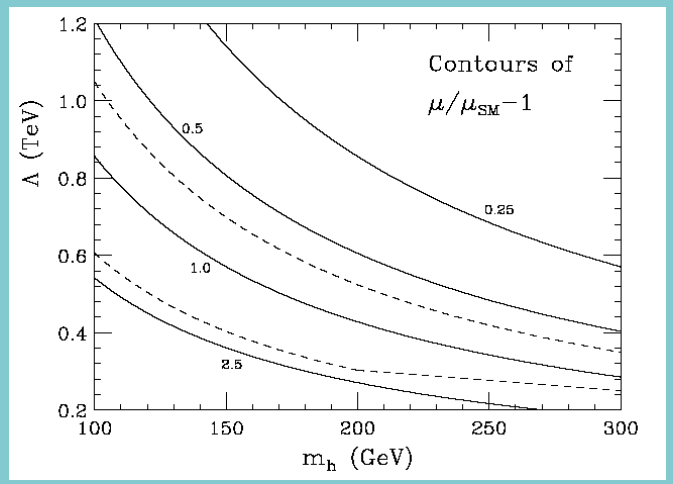
with Λ> 10 TeV → 1% tuning required?

Grojean, Servant, Wells '04

2) deviations from the SM cubic Higgs self coupling μH^3

LHC: order unity test

ILC: 20%



The baryon asymmetry

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

→ phase of the top mass varies

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

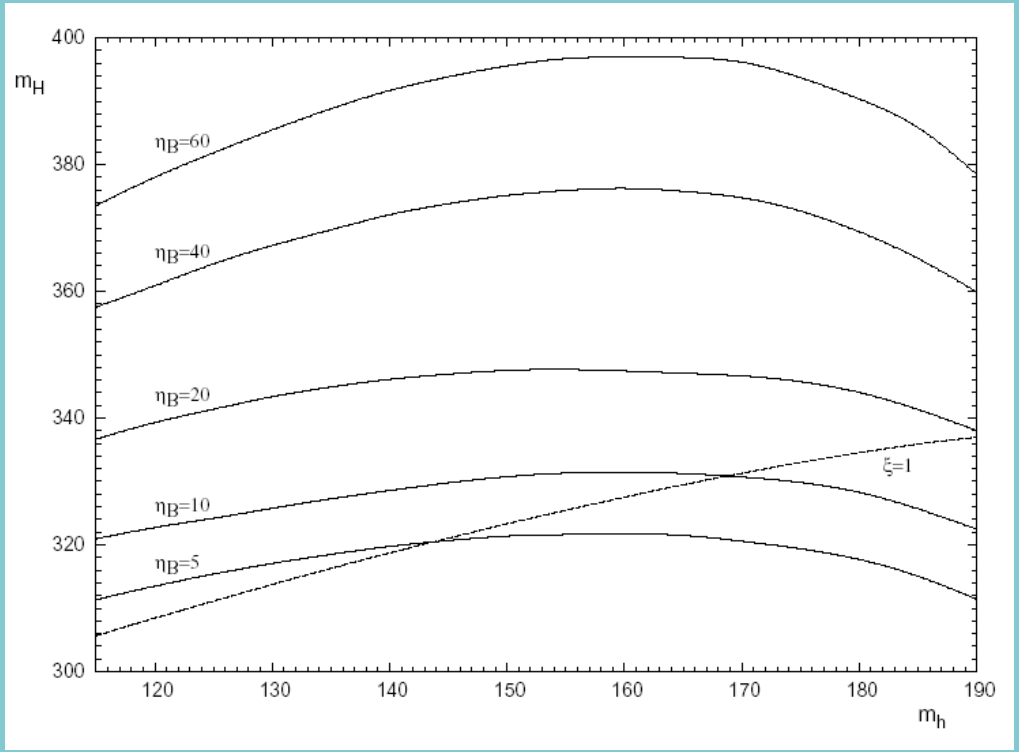
top transport generates a baryon asymmetry, but

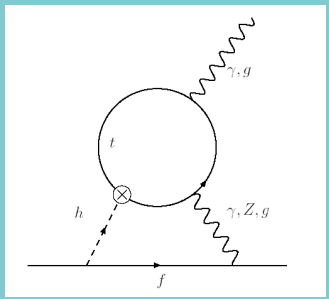
$\tan\beta < 10$ (?)

→ 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

The phase transition

Evaluate 1-loop thermal potential:

loops of heavy Higgses generate a cubic term

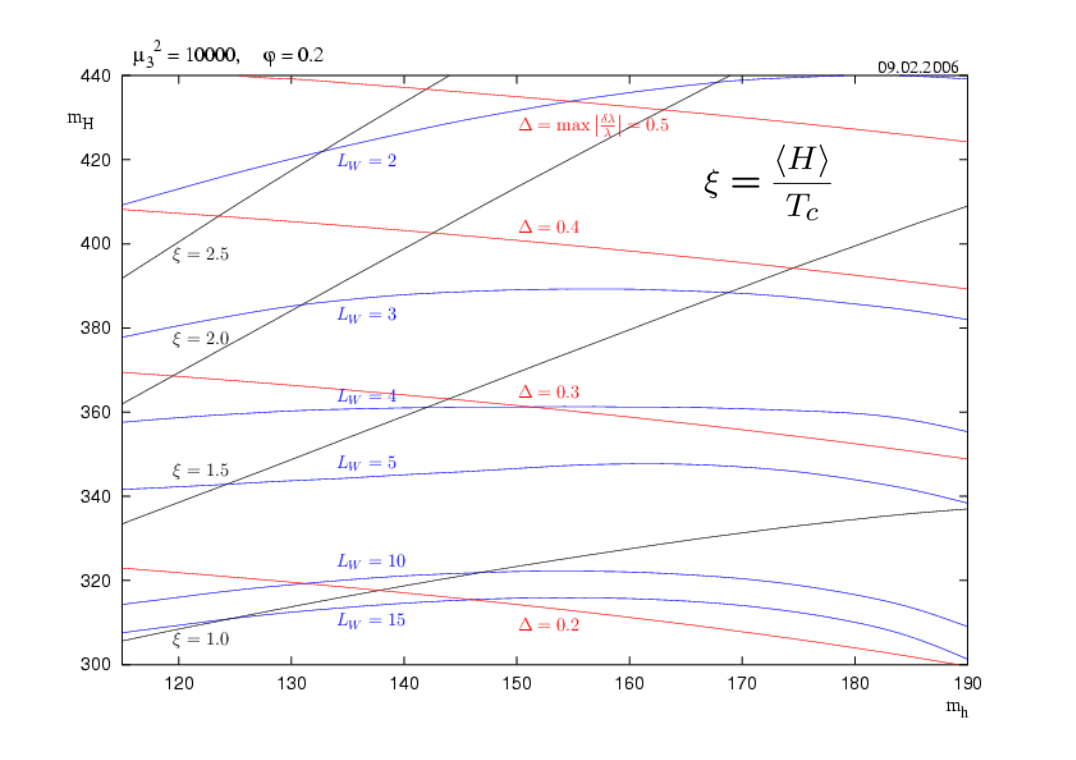
→ strong PT for

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)



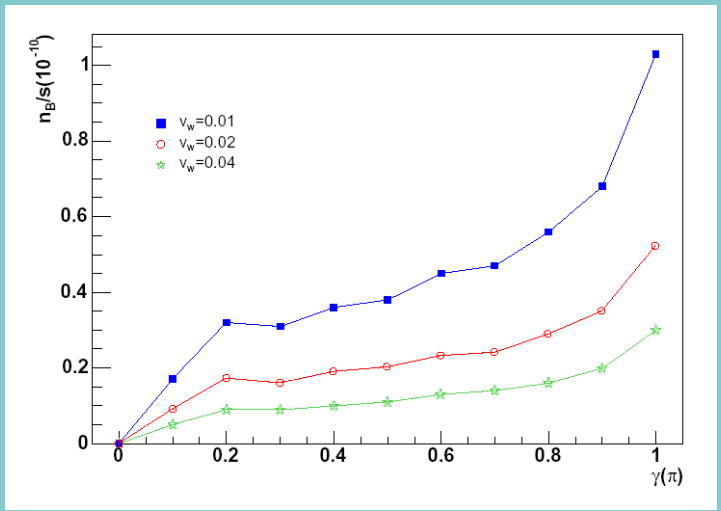
[Fromme, S.H., Senuich ' 06]

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

Extra U(1)´s

Kang, Langacker, Li, Liu ’04

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



$$m^2_{S_1 S_2} \equiv |m^2_{S_1 S_2}| e^{i\gamma}$$

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

$$f_{\rm turb} = 3.4\times10^{-3}{\rm mHz}\, u_s \left[\frac{1}{RH_*}\right]\left[\frac{T_*}{100{\rm GeV}}\right]\left[\frac{g_*}{100}\right]^{1/6}$$

$$h_0^2\Omega_{\rm turb} = 1.4\times10^{-4} u_s^5 (RH_*)^2 \left[\frac{g_*}{100}\right]^{-1/3}$$

Turbulence: Kosowsky, Mack, Kahniashvili '01

Dolgov, Grasso, Nicolis '02

Turbulence: Caprini, Dürrer '06

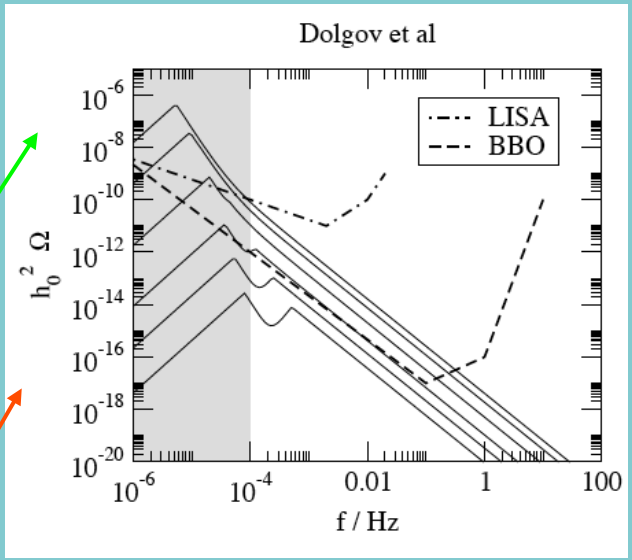
Collisions: Kamionkovski, Kosowsky, Turner '93

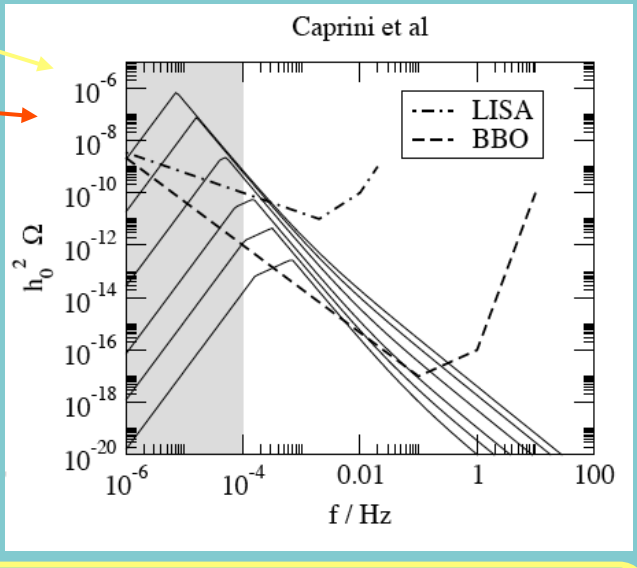
*: quantities at the PT temperature

u_s: eddy velocity (dep. on α)

strong PT: α~1, but RH_* gets larger (fewer bubbles, growing larger)

→ stronger signal, but at smaller f !!





discrepancy between Dol. and CD!

double peak structure?

Dynamics of the transition

At the critical temperature T_c the two minima are degenerate

Bubble nucleation starts at $T < T_c$ with a rate

$$\Gamma = A\,T^4\,e^{-S_3/T},$$

Where the bubble energy is

$$S_3 = 4\pi \int dr\, r^2 \left[\frac{1}{2}\left(\frac{d\varphi}{dr}\right) + V(\varphi, T)\right]$$

The bubble configuration follows from

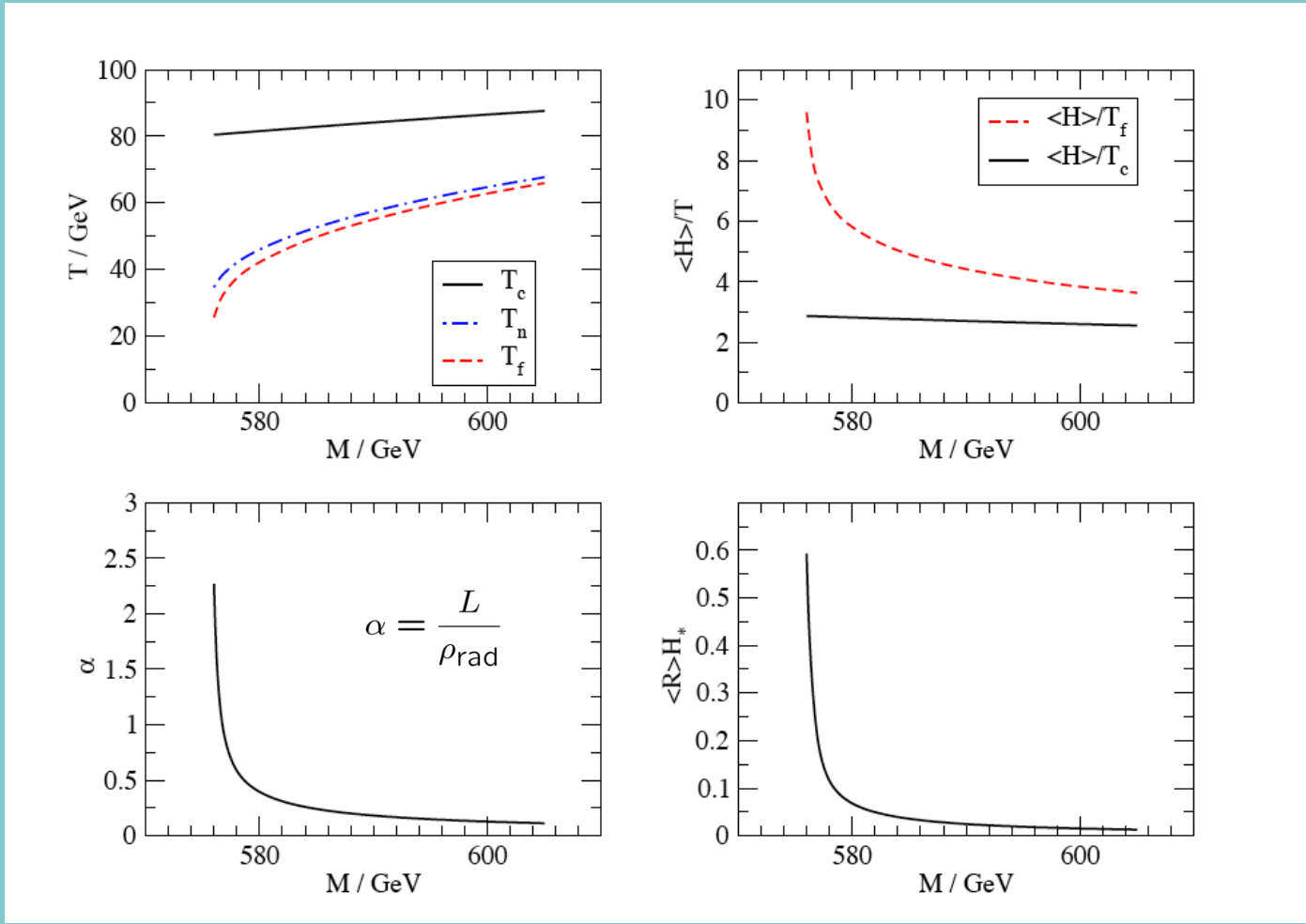
(with appropriate BC's)

$$\frac{\partial^2\phi}{\partial r^2} + \frac{2}{r}\frac{\partial\phi}{\partial r} = V'(\phi)$$

This bounce solution is a saddle point, not a minimum
→ difficult to compute for multi field models (one field: shooting)

For a algorithm see Konstandin, S.H. '06

Key parameteres of the phase transition: Φ^6 model, m_h=120 GeV



S. H. & Konstandin '07

Compute as function of temperature: bubble configurations → E

nucleation rate Γ~exp(-E)

bubble distribution → R

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

The wall velocity:

Friction with the plasma balances the pressure

Distinguish: supersonic vs. subsonic (v_s^2=1/3)

Standard model: v_b~ -0.35 - 0.45 for low Higgs masses [Moore, Prokopec '95]

MSSM: v_b~0.05 [John, Schmidt '00]

All other models: no detailed computations

For very strong phase transitions: bubbles become supersonic, velocity dominated by hydrodynamics (neglect friction) [Steinhardt '82]

$$v_b(\alpha) = \frac{1/\sqrt{3} + \sqrt{\alpha^2 + 2\alpha/3}}{1+\alpha}.$$

(for sufficiently large α > few %?)

When does this fail ??

**Recently: can the walls run away? [Bodeker, Moore '09]

Phenomenology

1) operators which contribute to EW observables must be suppressed by Λ>>M~TeV, e.g.

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

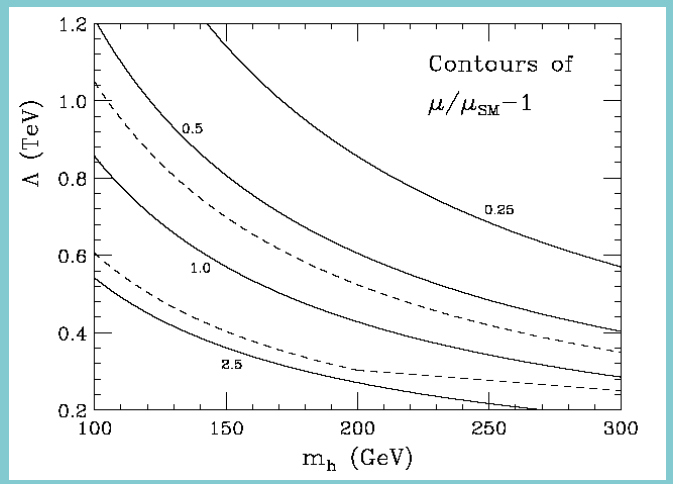
with Λ> 10 TeV → 1% tuning required?

Grojean, Servant, Wells '04

2) deviations from the SM cubic Higgs self coupling μH^3

LHC: order unity test

ILC: 20%



How to compute the wall velocity?

Main ingredients: pressure difference vs. plasma friction

Also important: reheating due to release of latent heat

Microscopic description: Moore, Prokopec '95 $(\partial_t + \dot{z}\partial_z + \dot{p}_z\partial_{p_z})f = \mathcal{C}[f]$

$$\Box\phi + V_T'(\phi) + \sum \frac{dm^2}{d\phi}\int \frac{d^3p}{(2\pi)^3\,2E}\delta f(p,x) = 0$$

$$f = \frac{1}{1+\exp\frac{E-E\delta T/T-p_z v-\mu}{T}}$$

(fluid ansatz)

$$\begin{aligned} a v_w \frac{\mu'}{T} + v_w\frac{\delta T'}{T} + \frac{1}{3}v' + F_1 &= -\Gamma_{\mu 1}\frac{\mu}{T} - \Gamma_{T1}\frac{\delta T}{T} \\ b v_w \frac{\mu'}{T} + v_w\frac{\delta T'}{T} + \frac{1}{3}v' + F_2 &= -\Gamma_{\mu 2}\frac{\mu}{T} - \Gamma_{T2}\frac{\delta T}{T} \\ b\frac{\mu'}{T} + \frac{\delta T'}{T} + v_w v' + 0 &= -\Gamma_v v \end{aligned}$$

$$F_1 = -\frac{v_w \ln 2}{9\zeta_3}\frac{(m^2)'}{T^2}, \qquad F_2 = -\frac{v_w\zeta_2}{42\zeta_4}\frac{(m^2)'}{T^2}$$

(force terms)

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

→ Complicated set of coupled field equations

and Boltzmann equations

need many scattering rates, infrared gauge fields??

SM: v ~ 0.35 - 0.45

Simplified approach: (Ignatius, Kajantie, Kurki-Suonio, Laine '94)

1) describe friction by a friction coefficient $1/\Gamma$

2) Model the fluid by a fluid velocity and temperature

$$\phi''(x) = \frac{\partial V}{\partial \phi} + \frac{v\gamma}{\Gamma}\phi'(x)$$

$$(4aT^4 - T\frac{\partial V}{\partial T})\gamma^2 v = \text{const.}$$

$$(4aT^4 - T\frac{\partial V}{\partial T})\gamma^2 v^2 + aT^4 + \frac{1}{2}\phi'(x)^2 - V = \text{const.}$$

3) Determine Γ from fitting the to the full result by Moore and Prokopec

(with Miguel Sopena)

We find: a good fit with a universal Γ is possible

→ the formalism should describe situations with SM friction well

→ study models with SM friction, but different potential, e.g. phi^6 model

see also Megevand, Sanchez '09

After understanding the phase transition:

What can we learn from it?

The baryon asymmetry


antimatter?

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:

$$\theta(z) = \arg(M_2 \mu^*) f(z)$$

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

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

wall velocity ~0.05 [John, Schmidt '00]

large phases > 0.2 required

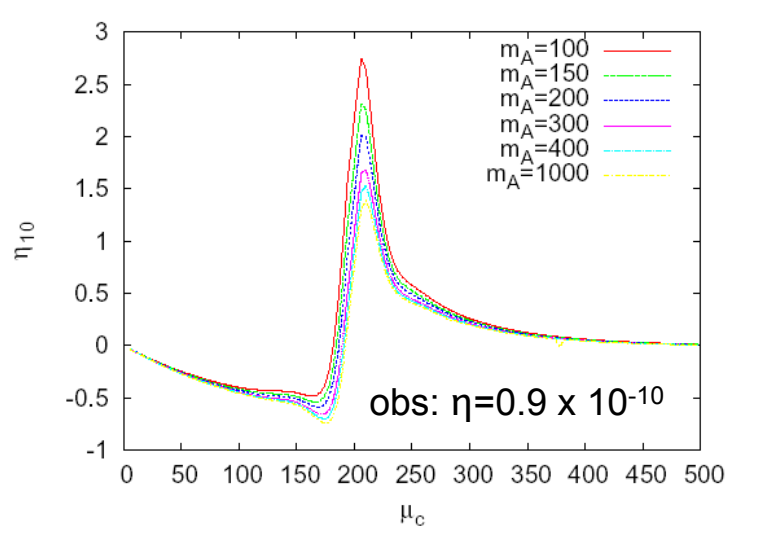
→ 1st and 2nd generation squarks

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!

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, (λ, M) $\leftrightarrow$ (m_h, M)
λ can be negative $\rightarrow$ 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 $\theta \sim \frac{|H|^2}{M^2}\frac{\mathrm{Im}(x)}{y}$

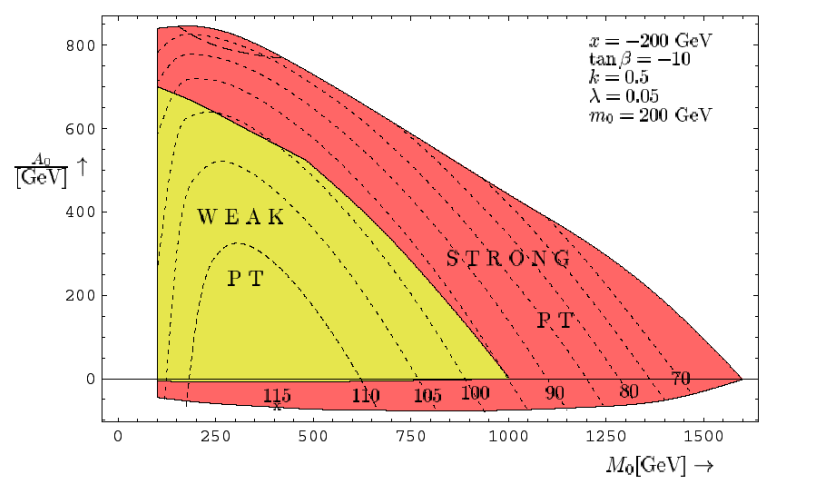
Can produce the baryon asymmetry
without violating EDM bounds

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

Strong phase transition

singlet model without discrete symmetries

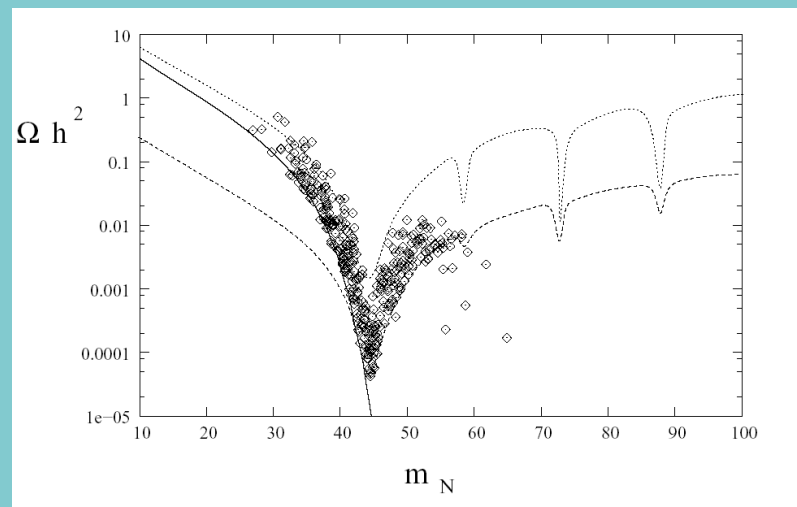
$$W = \lambda S H_1 H_2 + \frac{k}{3} S^3 + \mu H_1 H_2 + r S$$



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

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

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

Balazs, Carena, Freitas, Wagner '07

(Profumo, Ramsey-Musolf, Shaughnessy '07)

Carena, Shaw, Wagner '11

computation of bubble profiles?

Konstandin, S.H. '06

problem with 1-loop EDM's remains!

Is there antimatter in the universe?

We can “easily“ produce antimatter in particle colliders

Is there natural antimatter?

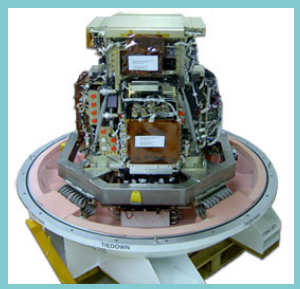
1) Direct search: balloon experiments

BESS has detected over 2000 antiprotons
(well explained by particle collisions)

But: in 10 million helium nuclei there
was not a single antihelium

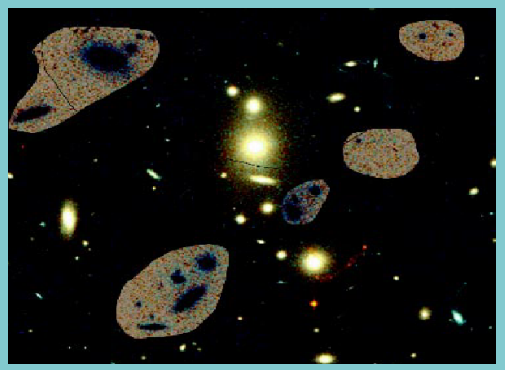
→ there is almost no antimatter in our cosmic neighbourhood

BESS, first flight 1993

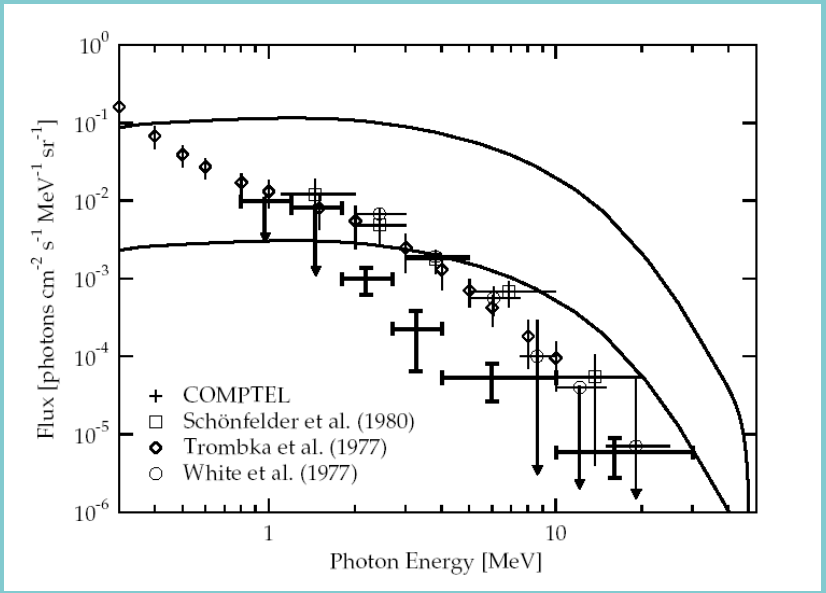


June 2006: satellite mission PAMELA

2) Indirect search for gamma rays from annihilation at the boundaries of matter-antimatter domains



Even anti-galaxies or clusters would not be completely separated!



Cohen, De Rujula, Glashow, astro-ph/9707087

domains of antimatter do not fit the observed gamma ray spectrum

→ there is virtually no antimatter in the universe!

Similar: gamma rays from colliding cluster, e.g. bullet cluster: no antimatter at the scale of tens of Mpc [Steigman arXiv:0808.1122]