Heidelberg Physics Graduate Days - 7-10 April 2015

BARYOGENESIS IN THE EARLY UNIVERSE

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invisibles
neutrinos, dark matter & dark energy physics

Outline

- Lecture I: Basics
- Lecture II: ElectroWeak Baryogenesis
- Lecture III: Leptogenesis
- Lecture IV: Affleck-Dine, etc...
- Outlook

Outline

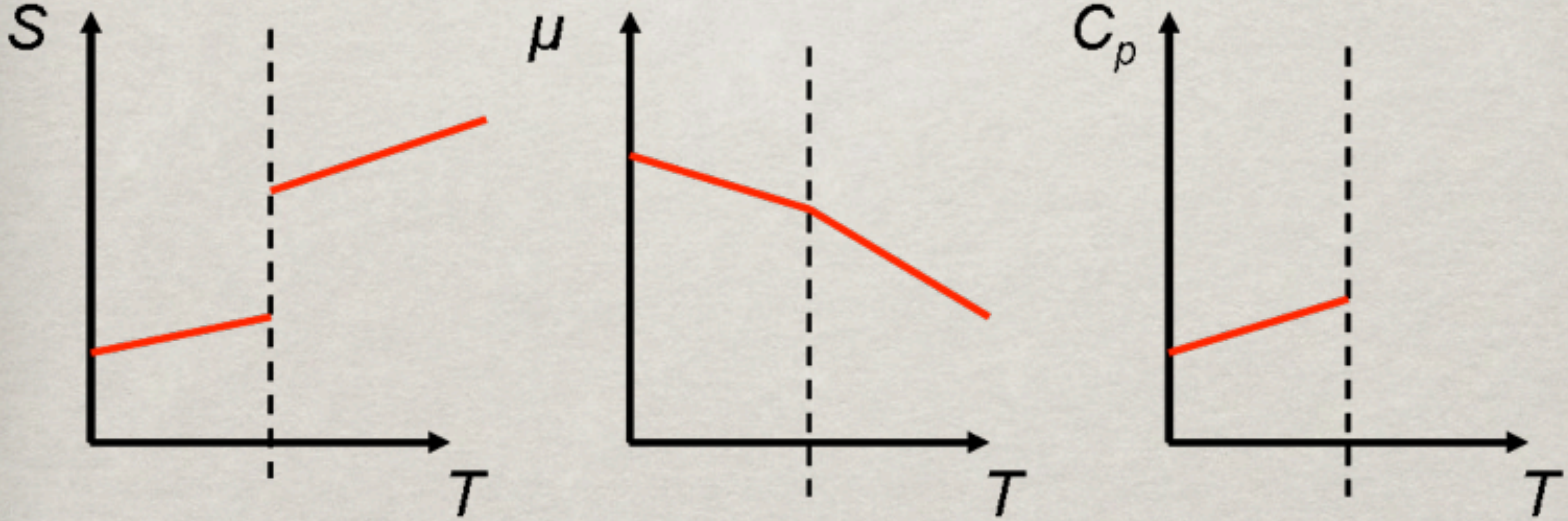
- Introduction: Phase transition classification
- Electroweak Baryogenesis in the SM
- Electroweak Baryogenesis in BSM
- Baryogenesis from R-parity violation
- Outlook

Phase transitions

PHASE TRANSITIONS IN TD

Ehrenfest classification: FIRST ORDER phase transition

The fist derivatives of the free energy are discontinuous, i.e. the entropy is discontinuous and the heat capacity (derivative of the entropy) diverges at the transition

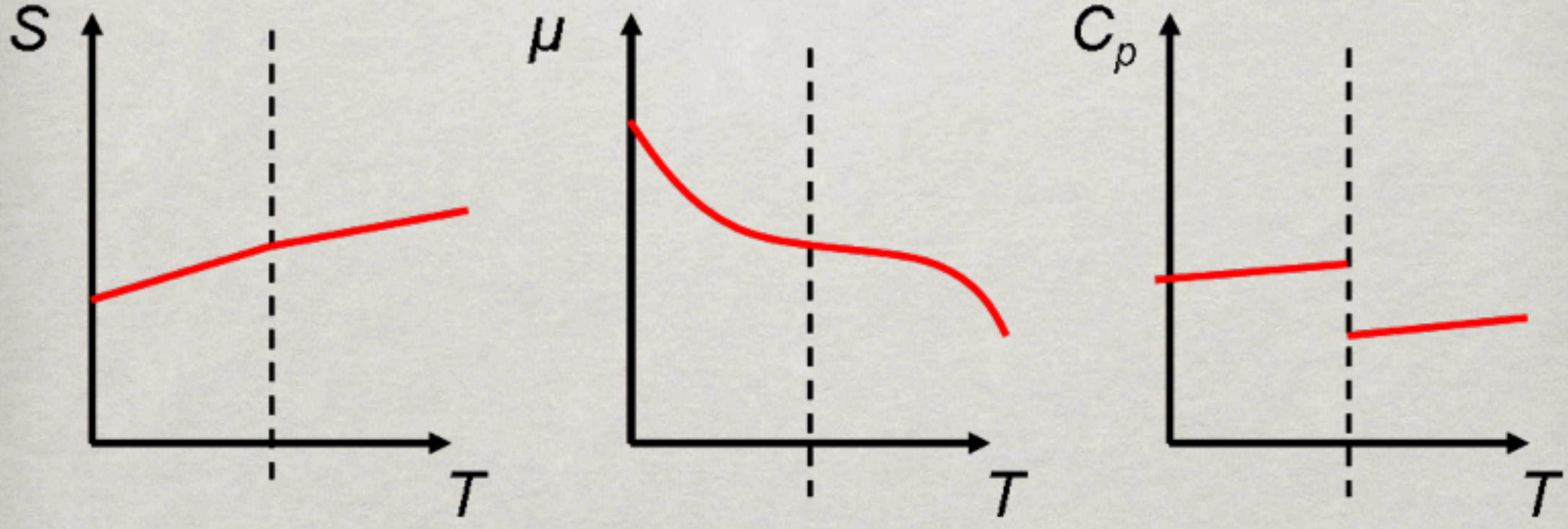


Also the order parameters display a discontinuity !

PHASE TRANSITIONS IN TD

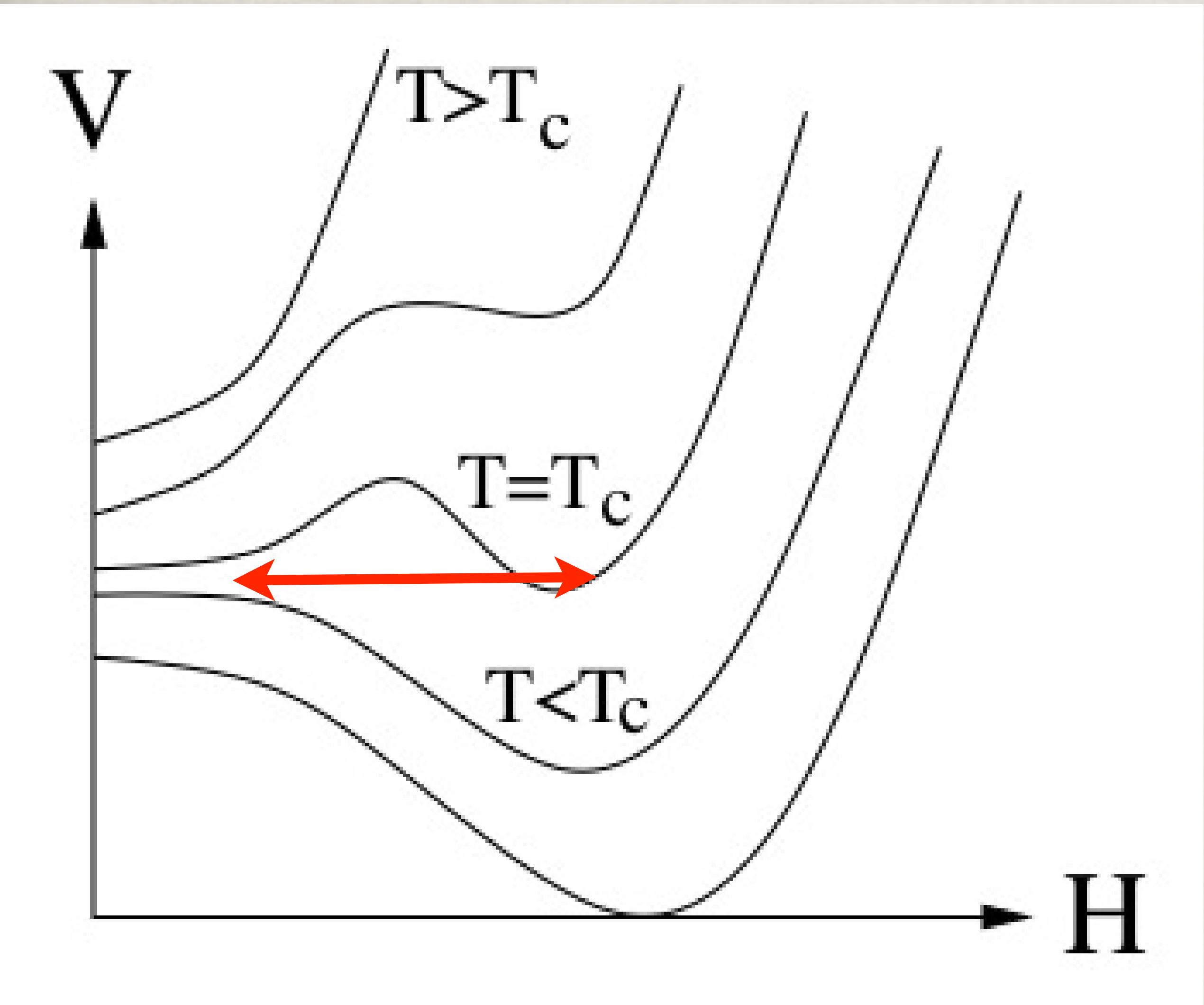
Ehrenfest classification: SECOND ORDER phase transition

The second derivatives of the free energy are discontinuous, i.e. the entropy has a kink and the heat capacity (derivative of the entropy) has a a discontinuity



The order parameter also changes continuously...

1st order transition

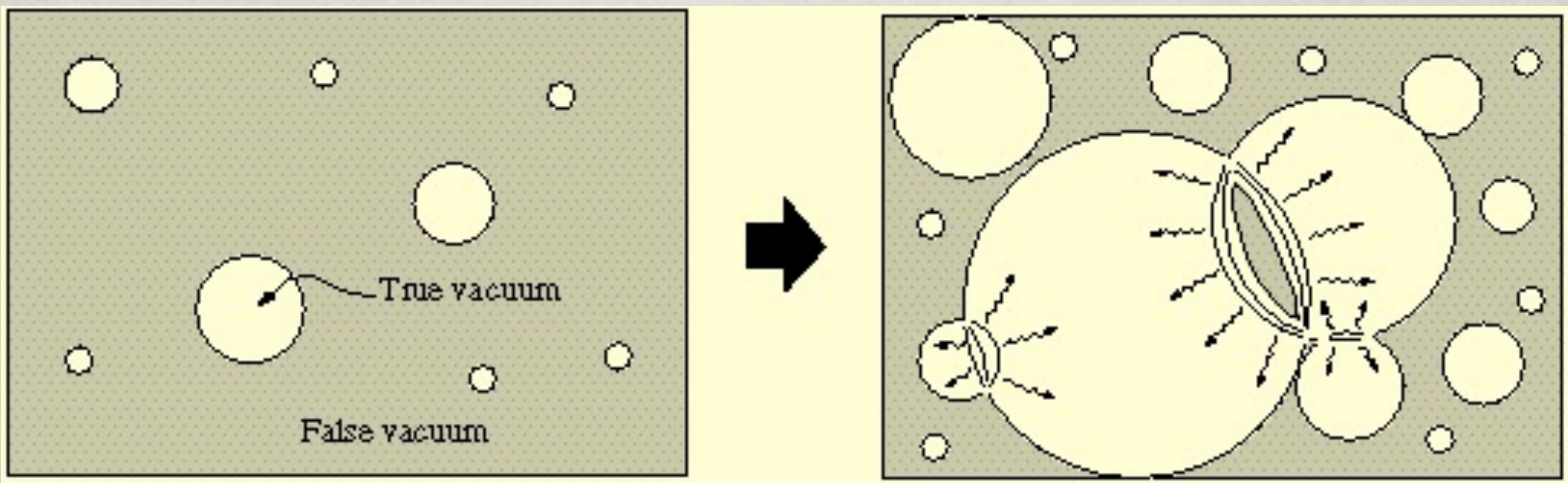


At the critical temperature the two vacuum are degenerate. After that temperature, the phase transition proceeds through a tunneling process from the unstable vacuum at H=0 to the true vacuum with non-zero v.e.v.

The order parameter v jumps from zero to a finite value !

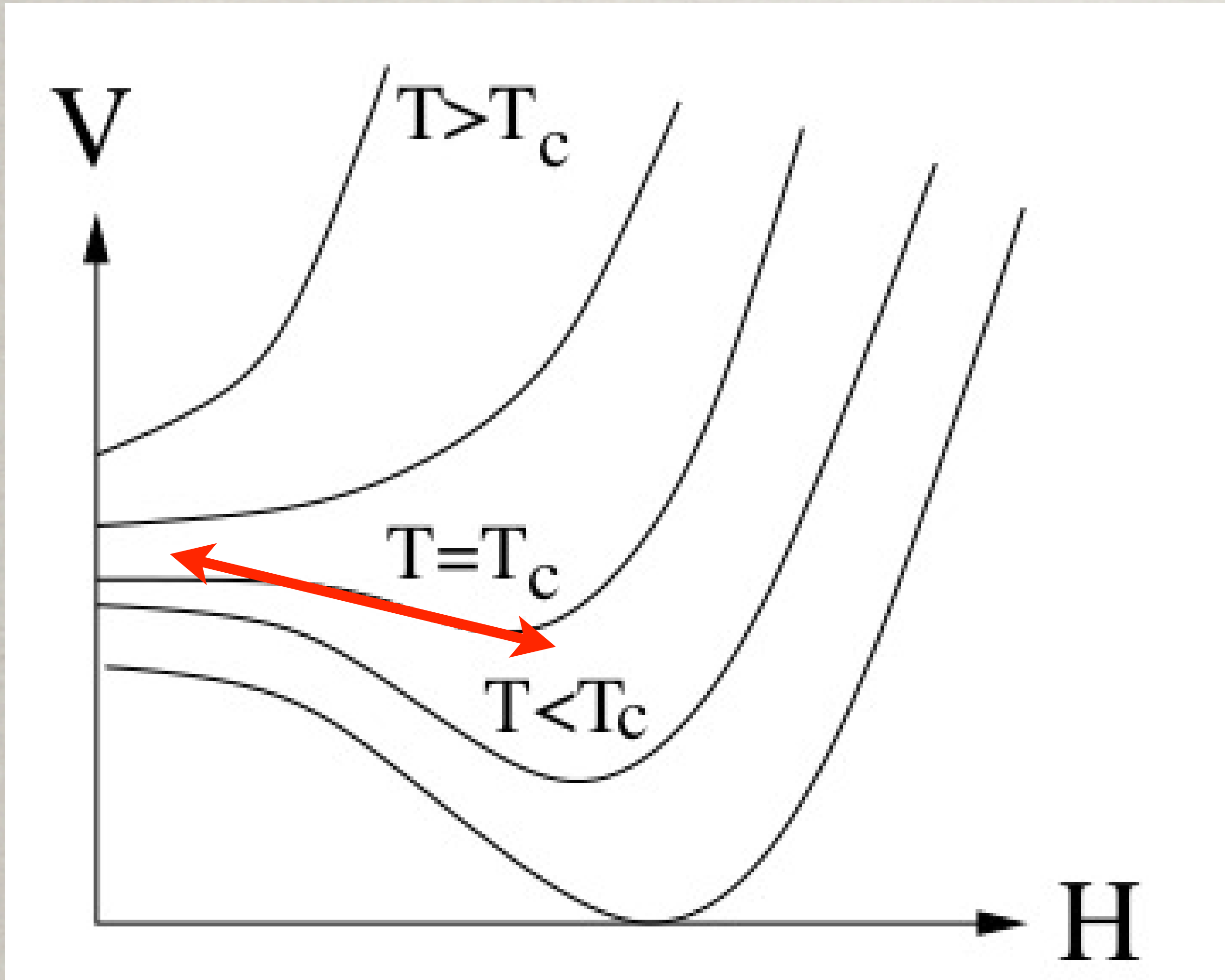
1st order transition

The transition generates locally a bubble of true vacuum in the middle of the unbroken phase; the bubble wall then expands until it hits other bubbles and the true vacuum takes over everywhere.



Non-equilibrium conditions are present in the bubble wall !

2nd order transition

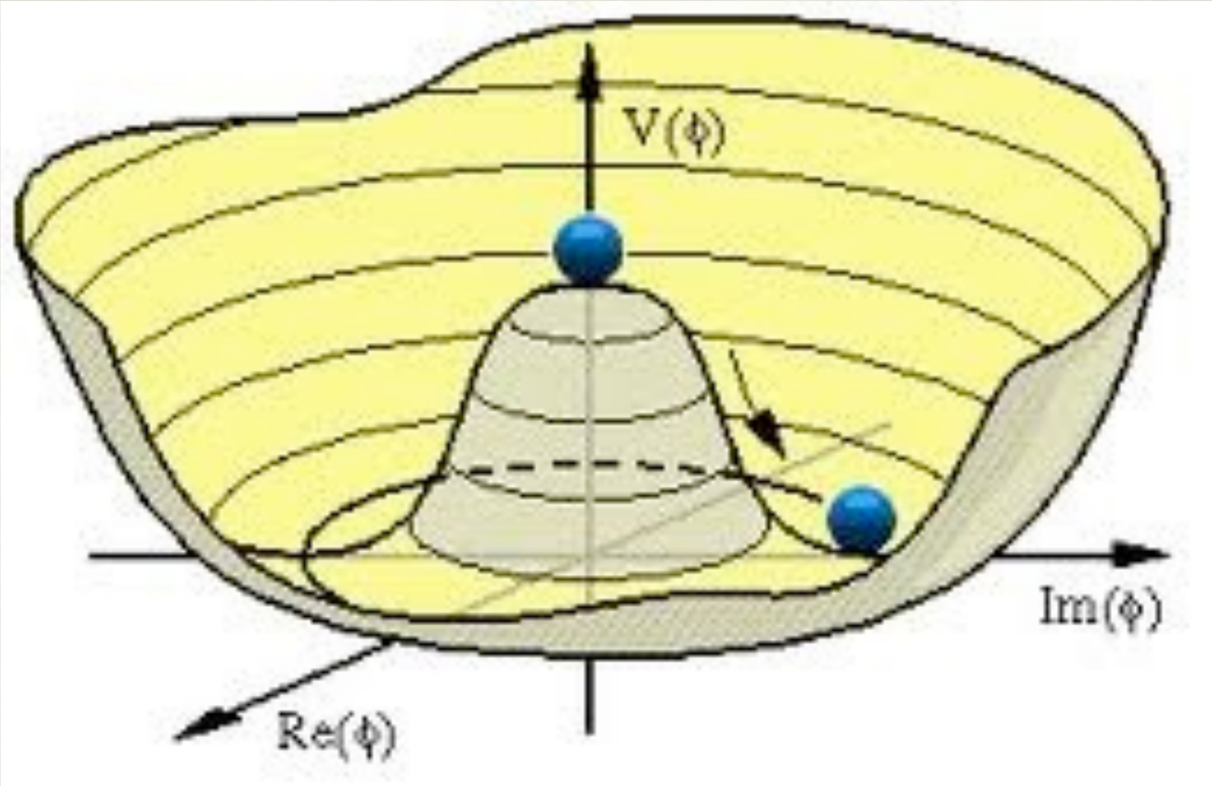


At the critical temperature the two vacuum are degenerate. After that temperature, there is no barrier and the phase transition proceeds smoothly from the unstable vacuum at H=0 to the true vacuum with non-zero v.e.v.

The order parameter v grows continuously from zero to a finite value !

THE Higgs mechanism

$$V(H) = -\mu^2 \bar{H} H + \lambda(\bar{H} H)^2$$



Non-vanishing v.e.v.: massive gauge bosons and fermions !

But in the early Universe the symmetry was restored

EW PHASE TRANSITION !

Electroweak Baryogenesis in the SM

Sakharov conditions for SM

Let us check the Sakharov conditions for the SM:

- B violation: OK
  Sphaleron processes violating B+L
- C and CP violation: OK
  Weak interaction and Yukawa couplings
- Departure from thermal equilibrium: OK
  the electroweak (first order) phase transition

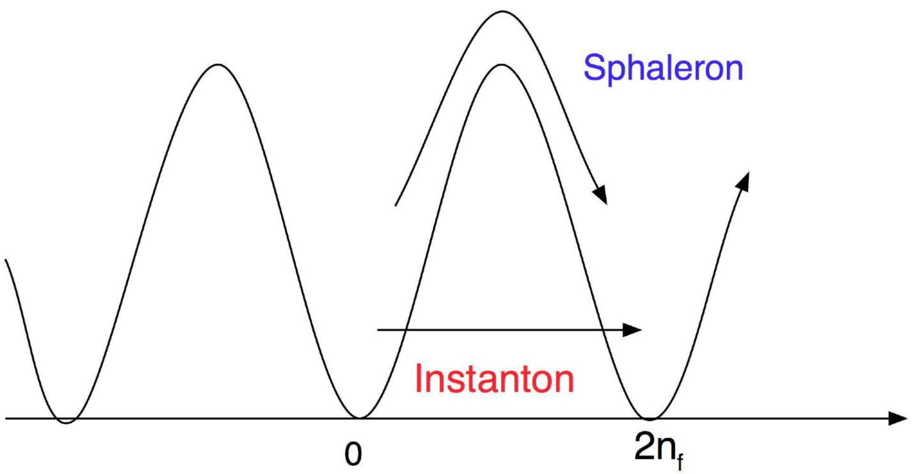
Possible to generate the BAU at the electroweak scale !

[Kuzmin, Rubakov & Shaposhnikov 1985]

Spheleron Processes

$B+L$ violation in the Standard Model

In the SM the global $U(1)_{B+L}$ is anomalous. This is related to the complex vacuum structure of the theory, which contains vacua with different configurations of the gauge fields and different topological number. Non-perturbative transitions between the vacua change $B+L$ by $2n_f$.



– $T=0$: tunneling and is suppressed by $e^{-\frac{4\pi}{\alpha_W}} \ll 1$

$\rightarrow B$ & L practically conserved!

– $T>0$: the transition can happen via a sphaleron

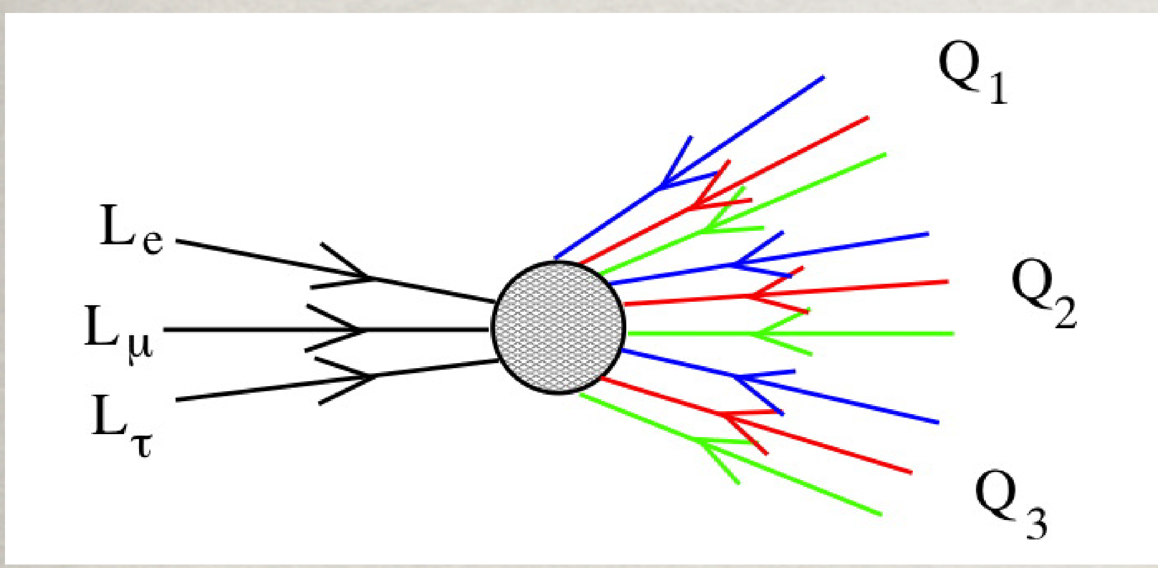
with rate $\Gamma_{sph}(T) \sim \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 e^{-E_{sph}/T}$

So at temperatures $T \geq 100$ GeV sphaleronic transitions are in equilibrium in the Universe $\rightarrow B+L$ erased if $B-L=0$, otherwise

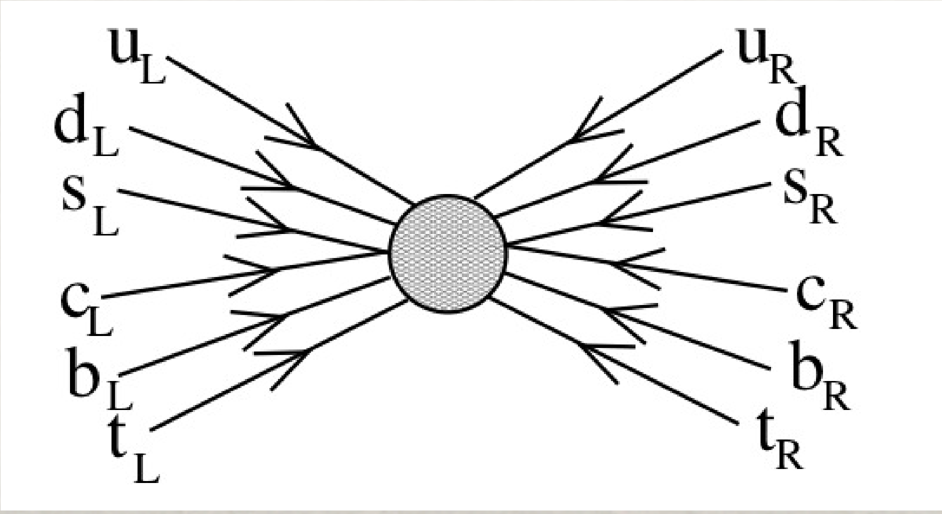
$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H}(B-L)$$

A $B-L$ number is reprocessed into B number !

Spheleron Processes



EW Sphaleron:
B and L both change
by -3 units, for n=1
change in Chern-Simons
(winding) number,
while B-L is conserved



QCD Sphaleron:
chirality charge Q_5
changes by $2n_f$ units

EW baryogenesis

Broken phase

$$\Gamma_{sph} \sim 0$$

$$\frac{v_c}{T_c} > 1$$

Strong 1st order PT

B > 0

$\not{CP}$

$\not{CP}$

v_W

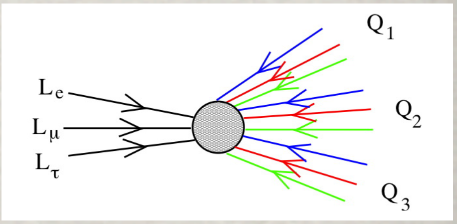
L_W

$\not{CP}$

$\not{CP}$

Unbroken phase

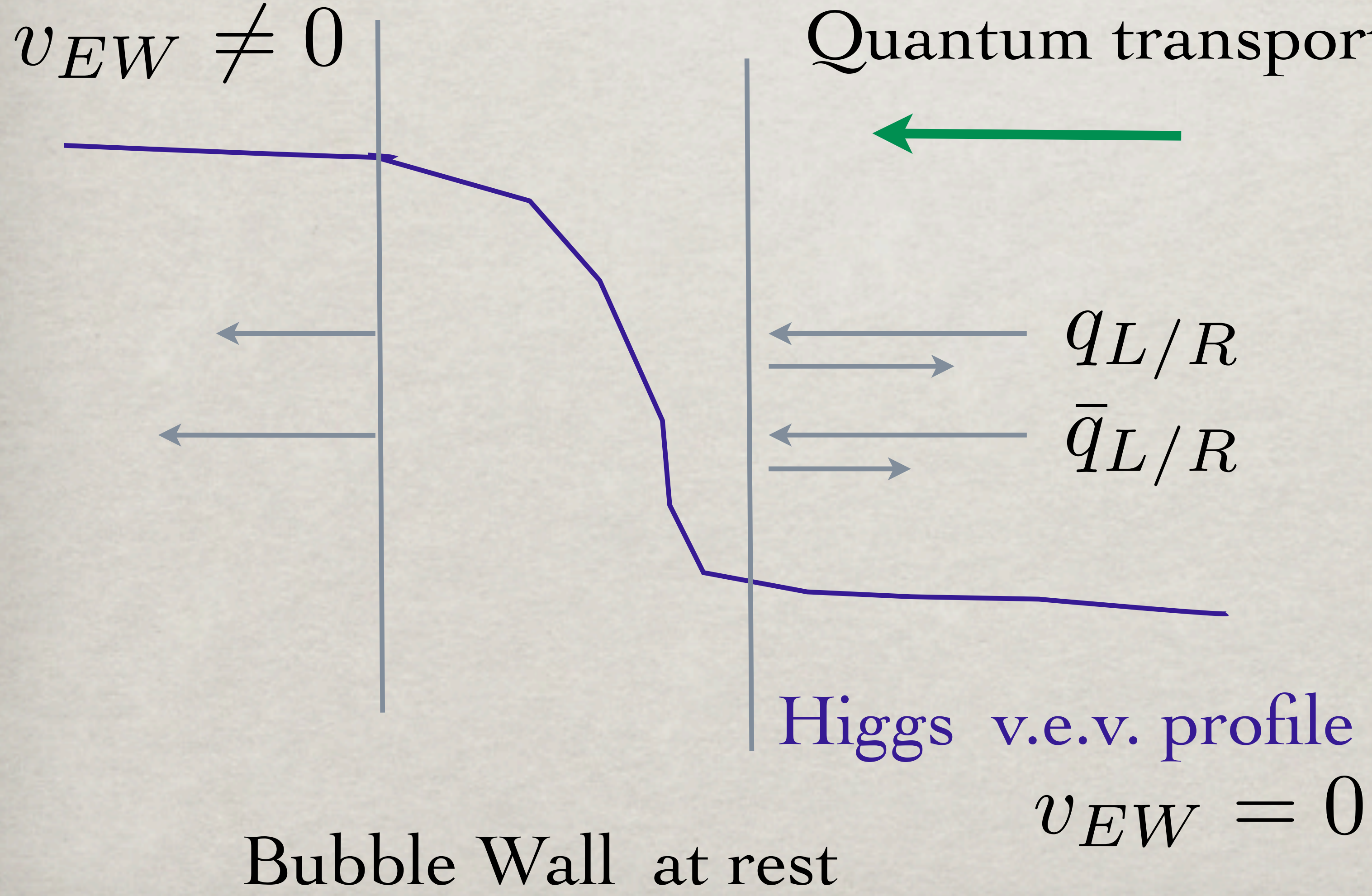
$$\Gamma_{sph} > H$$

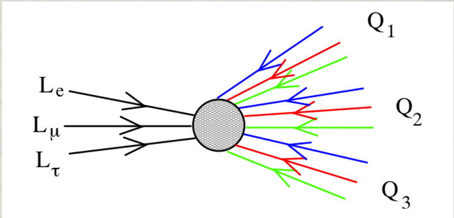


B=0

EW Baryogenesis

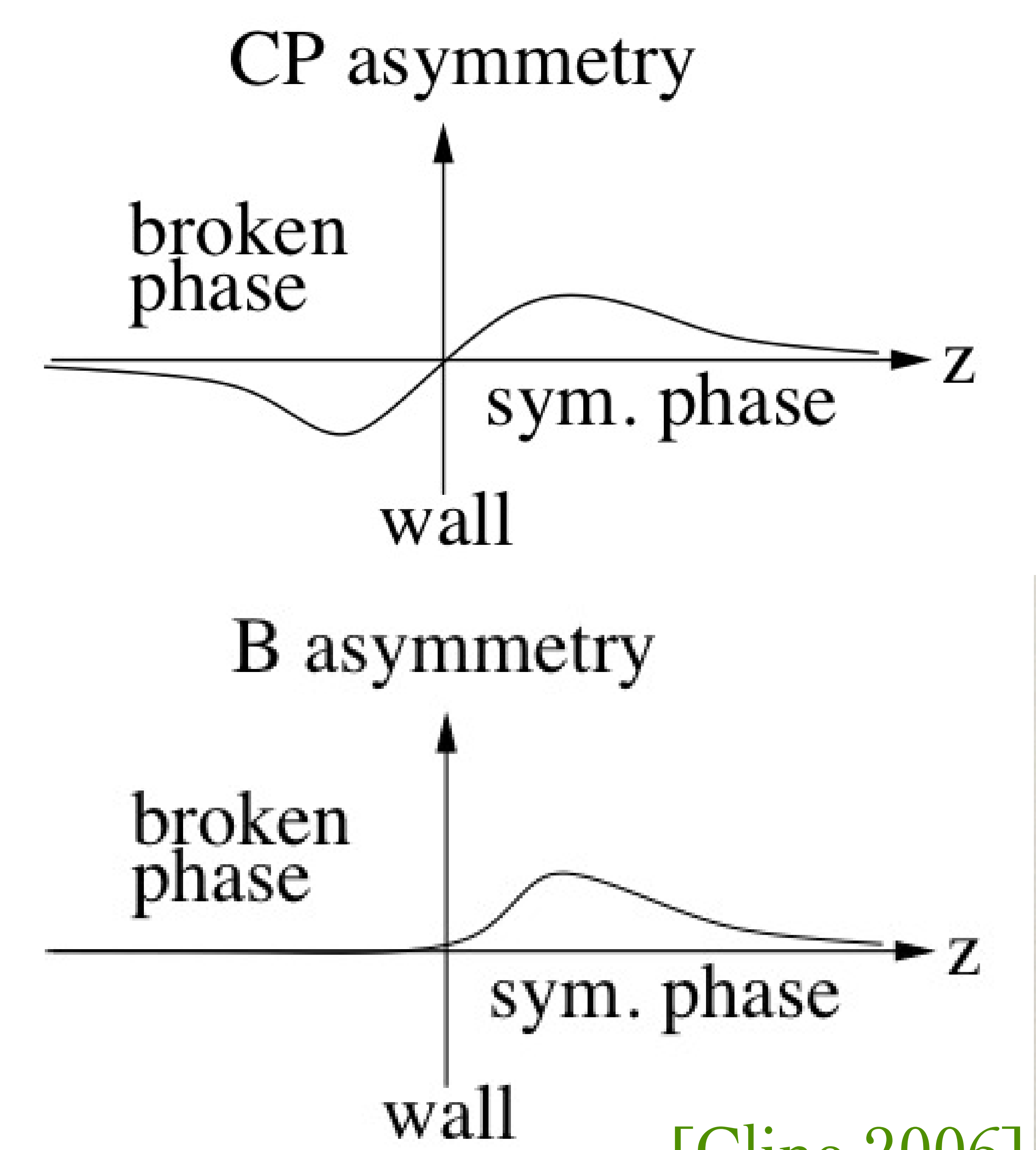
The bubble wall corresponds to a non-trivial v.e.v. profile. C, CP violation is provided by the different reflection/ transmission probabilities across the bubble wall.





EW sphalerons translate the CP asymmetry into BAU that then drifts into bubble

EW Baryogenesis



[Cline 2006]

EW Phase Transition in SM

Compute the effective potential at finite temperature:

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

The cubic term determines mostly the presence of a barrier

Bosonic Loops contribute to E(T), increasing the strength of the phase transition

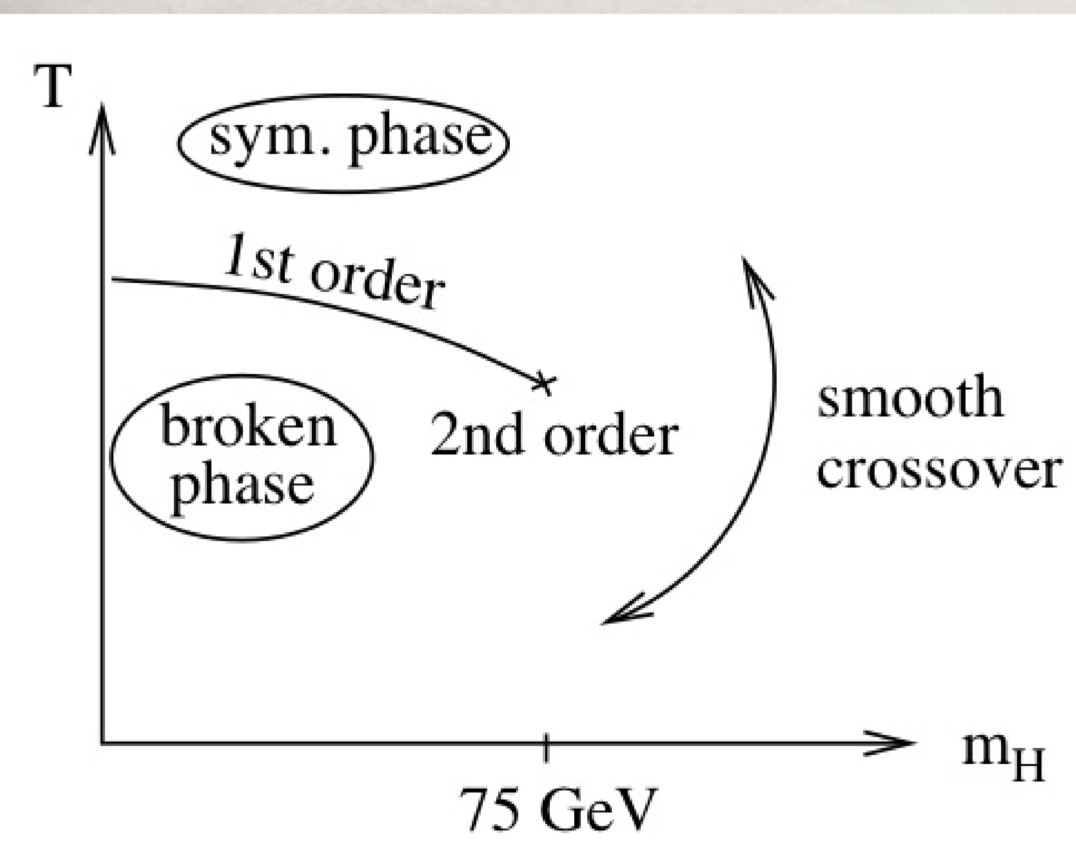
Caveat: perturbative computation is not trustworthy at the critical temperature

→ Lattice computations

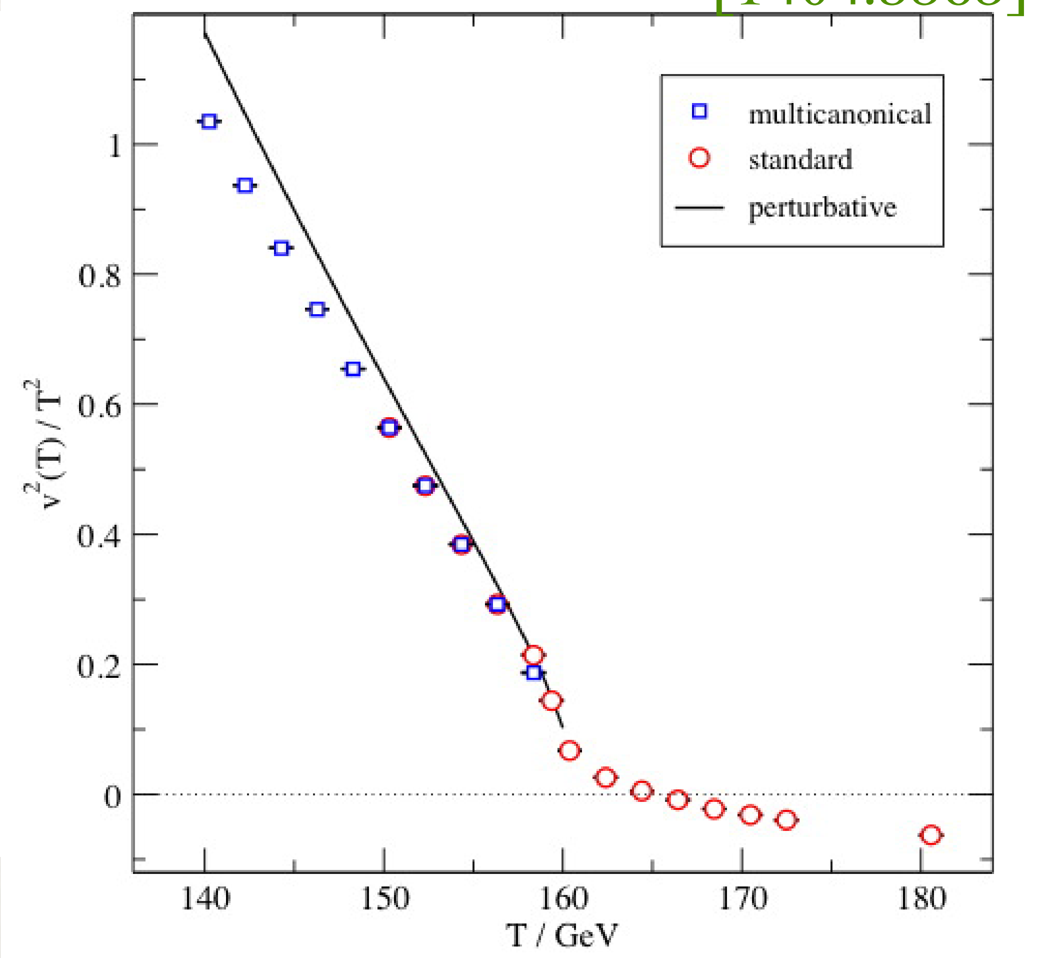
Only if the transition is sufficiently strong, i.e. $\frac{v_c}{T_c} > 1$ EW baryogenesis can work !

EW Phase Transition in SM

Compute the phase diagram for the EW phase transition:
for the physical Higgs mass it is a smooth cross-over !



[1404.3565]



NO EW baryogenesis in the SM !

Sakharov conditions for SM

Let us check the Sakharov conditions for the SM:

- B violation: OK
  Sphaleron processes violating B+L
- C and CP violation: OK, but not clear if sufficient
  Weak interaction and Yukawa couplings
- Departure from thermal equilibrium: NO !
  the electroweak phase transition is a cross-over...

Not possible to generate the BAU at the electroweak scale in the Standard Model !

Electroweak Baryogenesis beyond the SM

EW Phase Transition BSM

Again compute the effective potential at finite temperature:

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

The cubic term determines mostly the presence of a barrier

Bosonic Loops contribute to E(T), increasing the strength of the phase transition, so in order to make it first order increase the number of bosons in the model !

Many different possibilities, the simplest ones are:

- extend the Higgs sector of the SM;
- add supersymmetry;
- add higher dimensional operators.

THE HIGGS MECHANISM

The Higgs boson in the SM is an EW doublet:

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad \Rightarrow \quad H = e^{i\vec{\sigma}\cdot\vec{\pi}} \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

The 4 degrees of freedom give: 3 Goldstone bosons, π^i that are eaten by the gauge fields to give the 3 massive electroweak gauge bosons, $W^{\pm}, Z$ and one physical neutral Higgs field h remains !

Important characteristic of the Higgs fields: it couples to all fields (even itself) proportional to the field masses !

$$\frac{g_2^2}{2}(v+h)^2 W_\mu^+ W_\nu^- g^{\mu\nu} = M_W^2 W_\mu^+ W_\nu^- g^{\mu\nu} \left(1 + \frac{h}{v}\right)^2$$

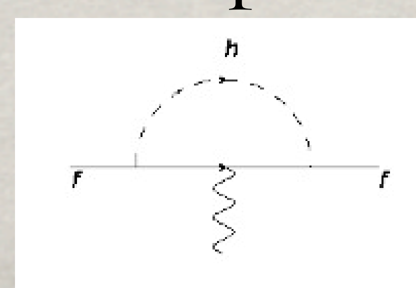
EW Baryogenesis 2HDM

Introduce a second Higgs doublet in the model

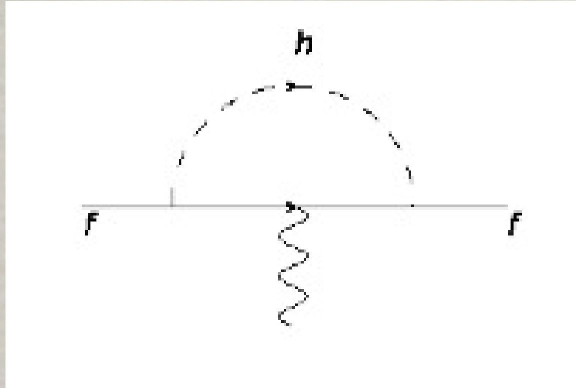
$$H_1 = \begin{pmatrix} H^+ \\ H_{1,0} \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_{2,0} \\ H^- \end{pmatrix}$$

The 8 degrees of freedom give: 3 Goldstone bosons, π^i that are eaten by the gauge fields to give the 3 massive electroweak gauge bosons, $W^\pm, Z$ and 5 physical neutral Higgs fields $h, H, A, H^\pm$ remain !

In the general model also many more couplings and phases, but restricted by Electric Dipole Moments measurements



EDMs in 2HDM



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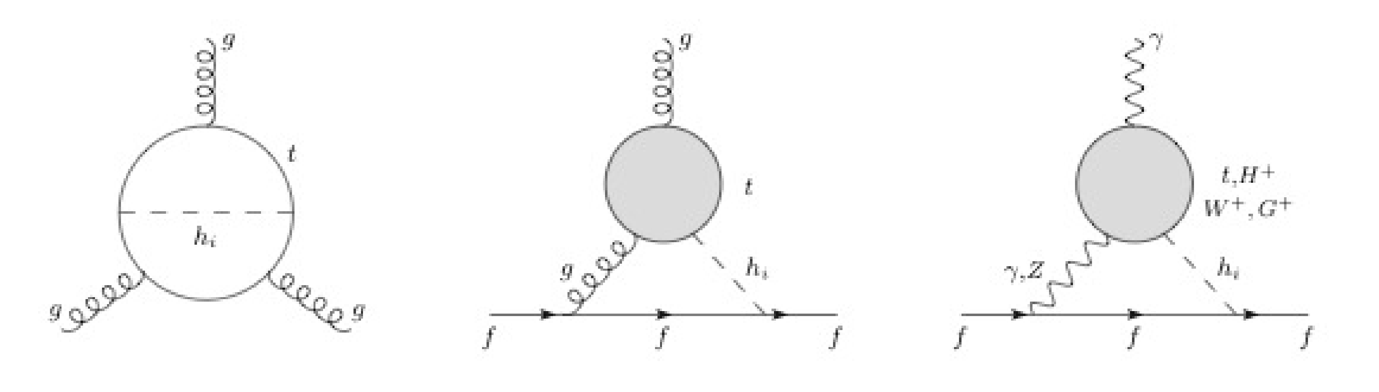
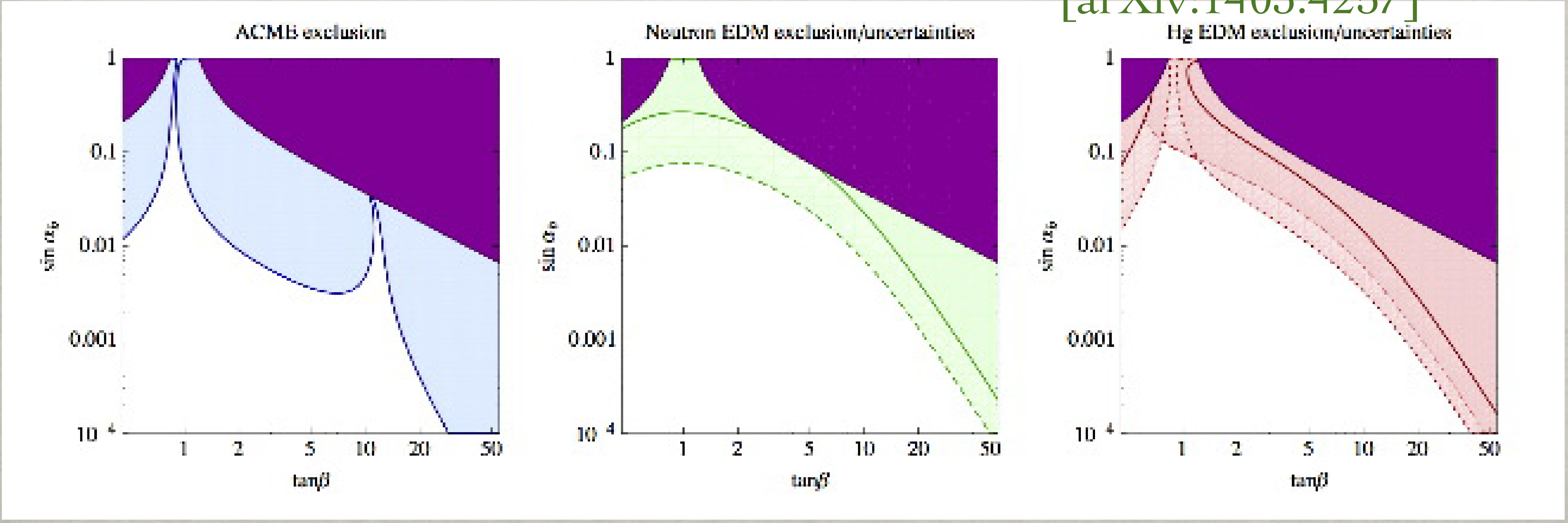


Due to Yukawa suppression, the two loop contribution, involving as well QCD couplings, dominates in 2HDM

[arXiv:1403.4257]



S. Huber

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

S. Huber

Evaluate 1-loop thermal potential:

loops of heavy Higgses generate a cubic term

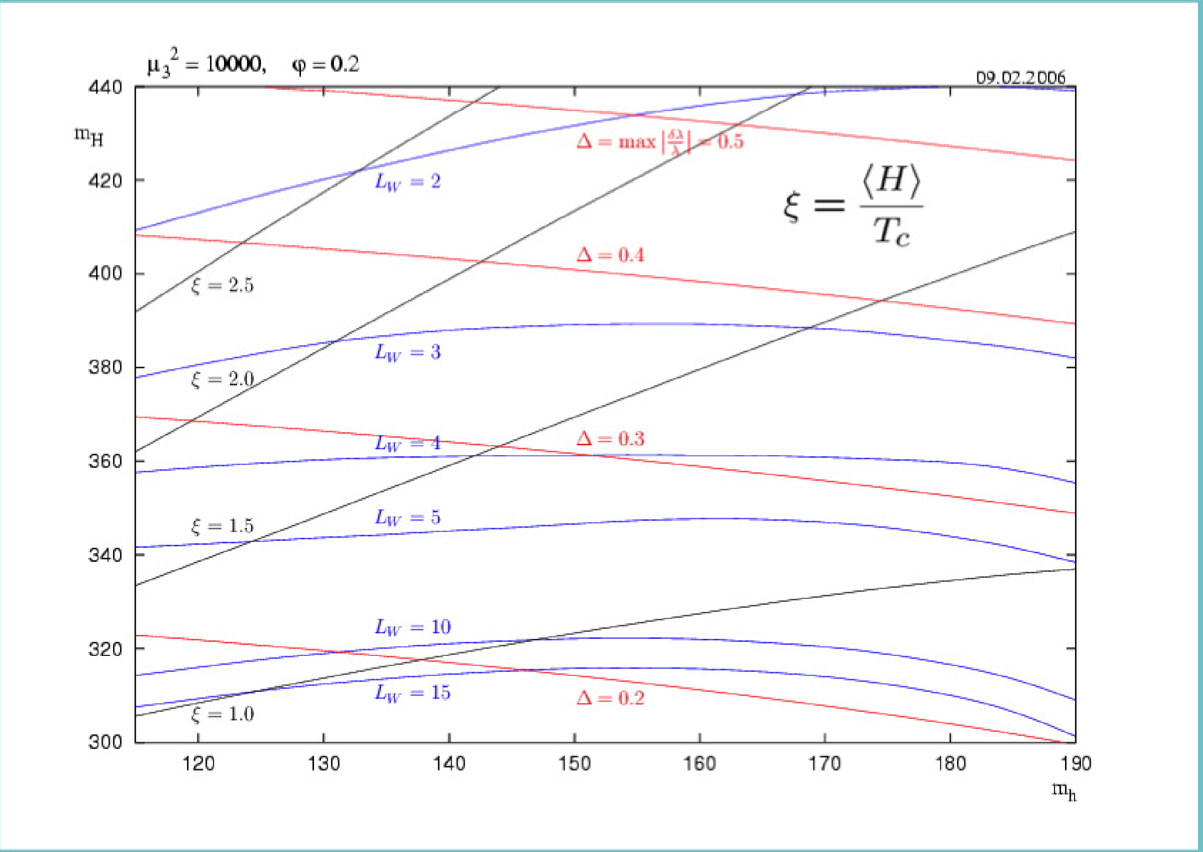
→ strong PT for

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 baryon asymmetry

S. Huber

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

→ phase of the top mass varies

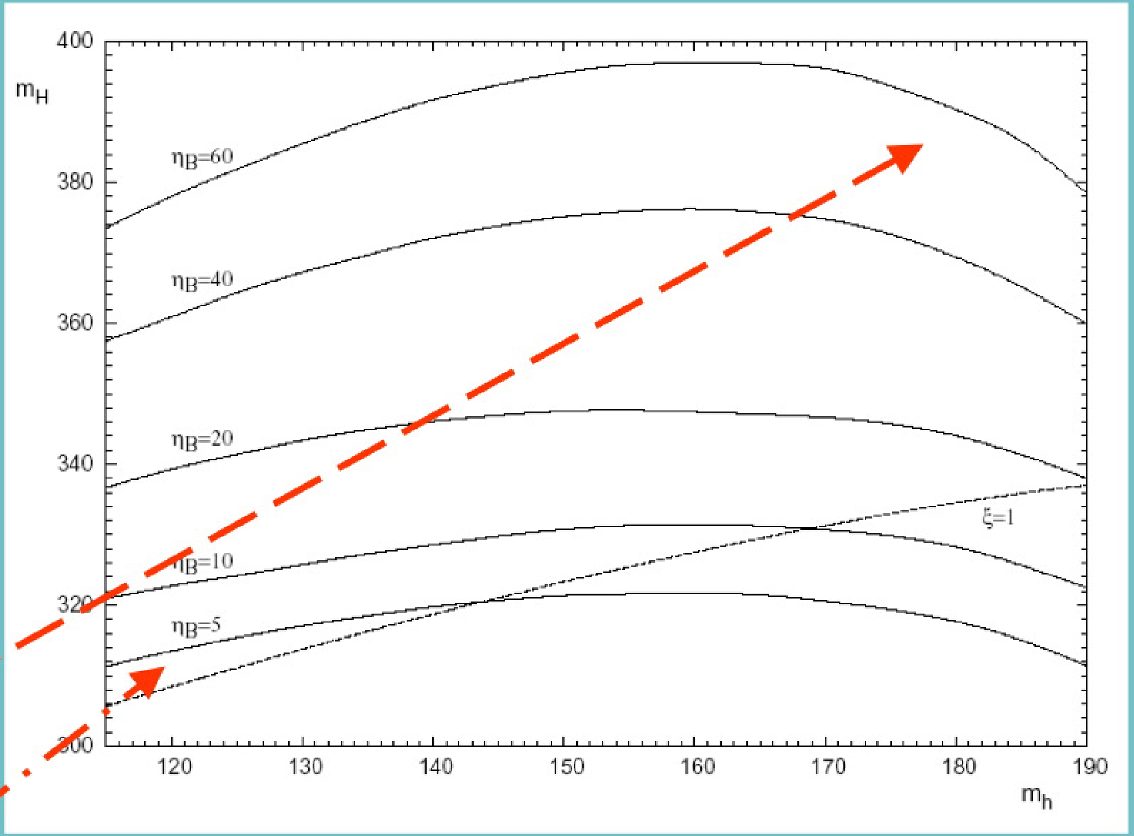
$\theta_t = \theta/(1+\tan^2\beta)$

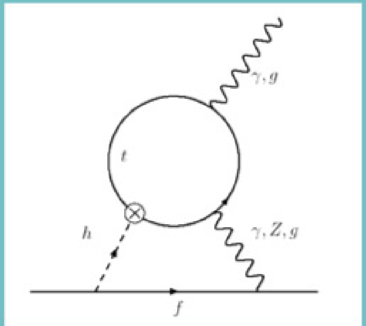
top transport generates a baryon asymmetry

→ 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?

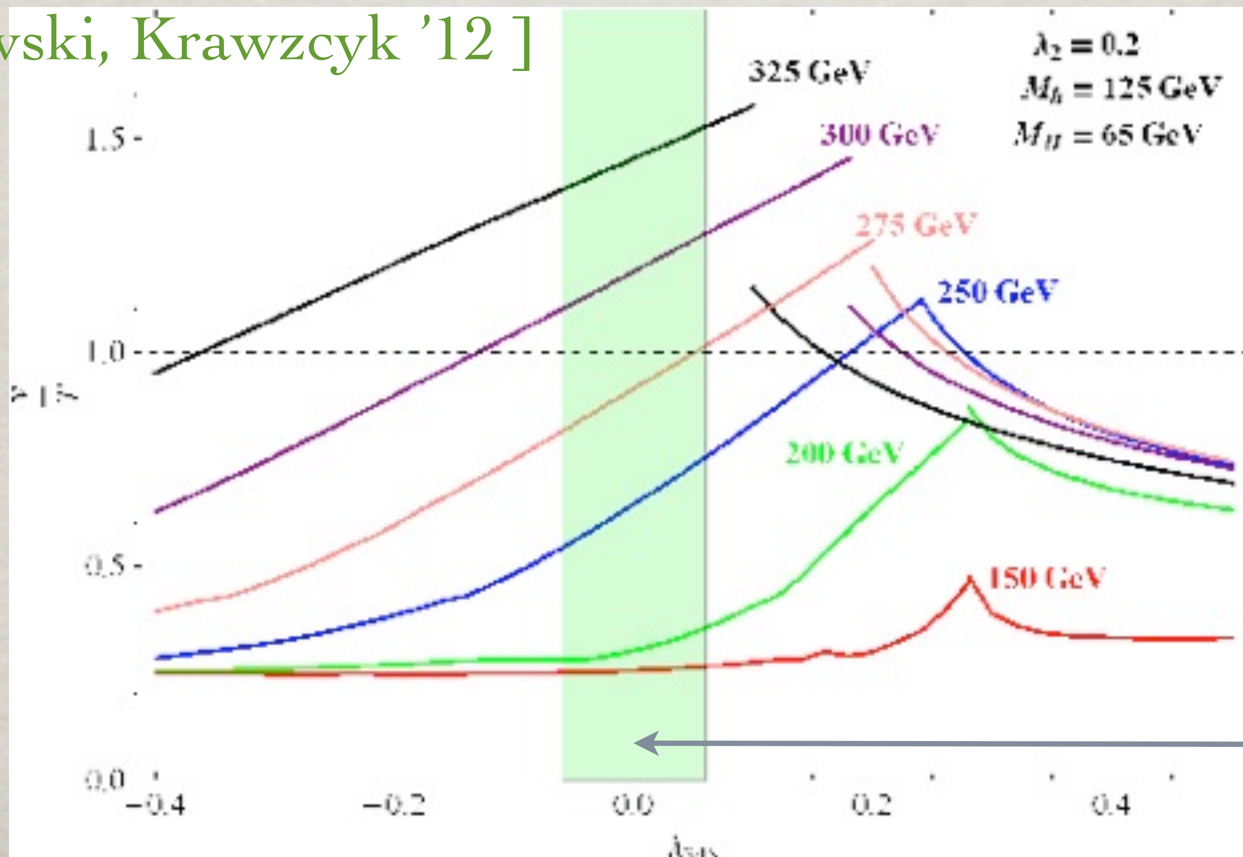
EW Baryogenesis 2HDM

Inert Higgs Model: no second v.e.v, one stable Higgs   DM !
more couplings and phases present

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

[Gil, Chankowski, Krawzcyk '12]

v/T



Heavy charged Higgs masses

DD allowed DM band

What is supersymmetry?

Its generators are fermionic operators, building a graded Lie algebra together with the generators of the Poincare` group:

SUPERSYMMETRY: boson <-> fermion

Standard Model			
Matter			Forces
e	μ	τ	γ
ν_e	ν_μ	ν_τ	$W^\pm, Z$
u	c	t	g
d	s	b	G

SUSY SM			
SMatter			SForces
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{\gamma}$
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{W}^\pm, \tilde{Z}$
$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{G}$

SUSY is broken: MASSIVE !

Lots of massive new particles... any good one for baryogenesis ?

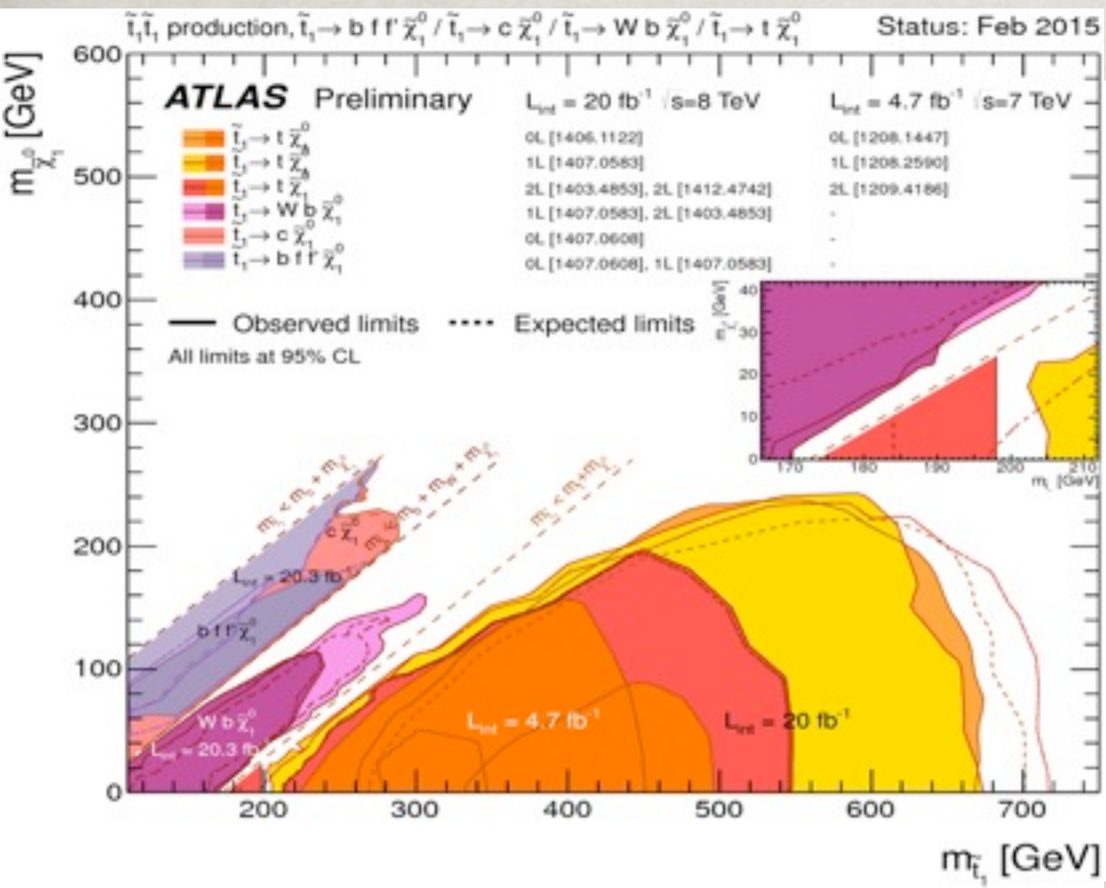
EW Baryogenesis in SUSY

In SUSY extensions of the SM EW baryogenesis is possible if

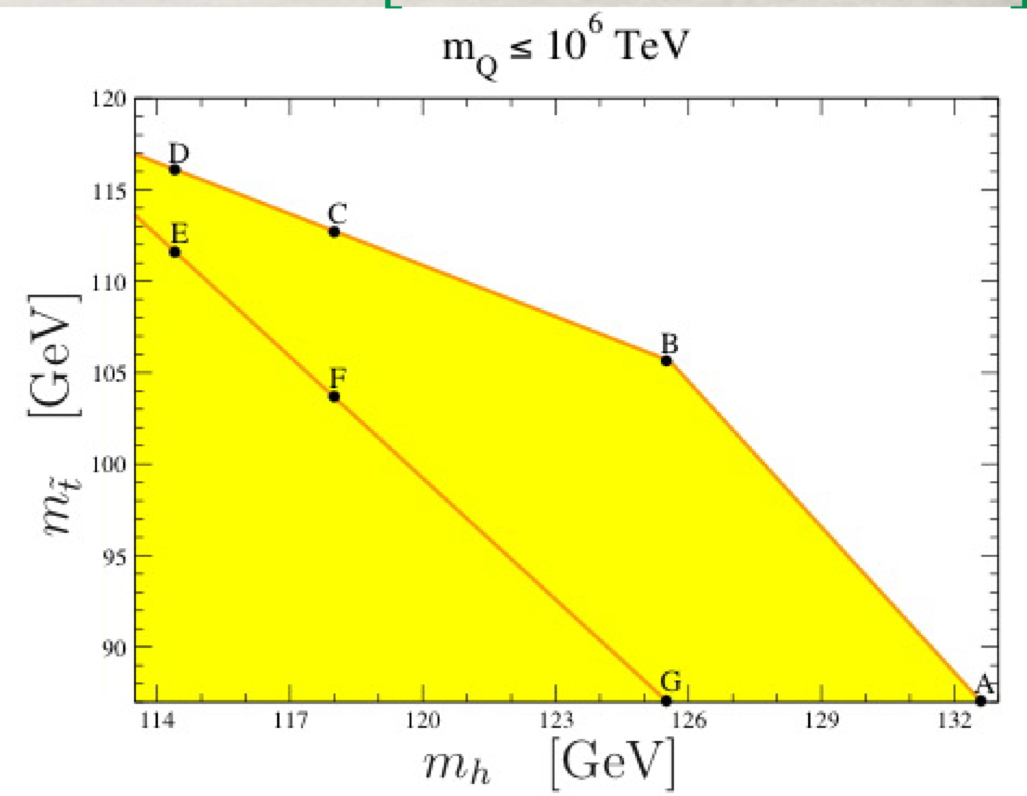
- The phase transition is stronger: e.g. by enhancing the cubic term in the Higgs potential thanks to (light) scalars, e.g. in SUSY stops or singlets !
- There are additional CP violating phases to increase the amount of CP violation.
- Still the Higgs has to be light... in MSSM EW baryogenesis ~ 120 GeV with one stop state below the top... Is it possible with a 125 GeV Higgs ?

EW Baryogenesis in SUSY

In the MSSM a 125 GeV Higgs is still OK for heavy squarks. Still the light stop should be lighter than the top, some region of parameters is already probed by LHC…



[Carena et al 1207.6330]



On the other hand, the light stop enhances ALL Higgs-VV couplings and seem not to be what LHC finds for the Higgs…

Beyond minimal SUSY

With larger SUSY extensions all becomes easier...

- The presence of a singlet field S either in the NMSSM or in the nMSSM can also make the phase transition stronger !
- More phases are present and less constrained .
- Still often one needs light fields to be present to have large effects.
- COLD EW Baryogenesis from a phase transition after inflation also becomes possible

SM + higher-dim. operators

S. Huber

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

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

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

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

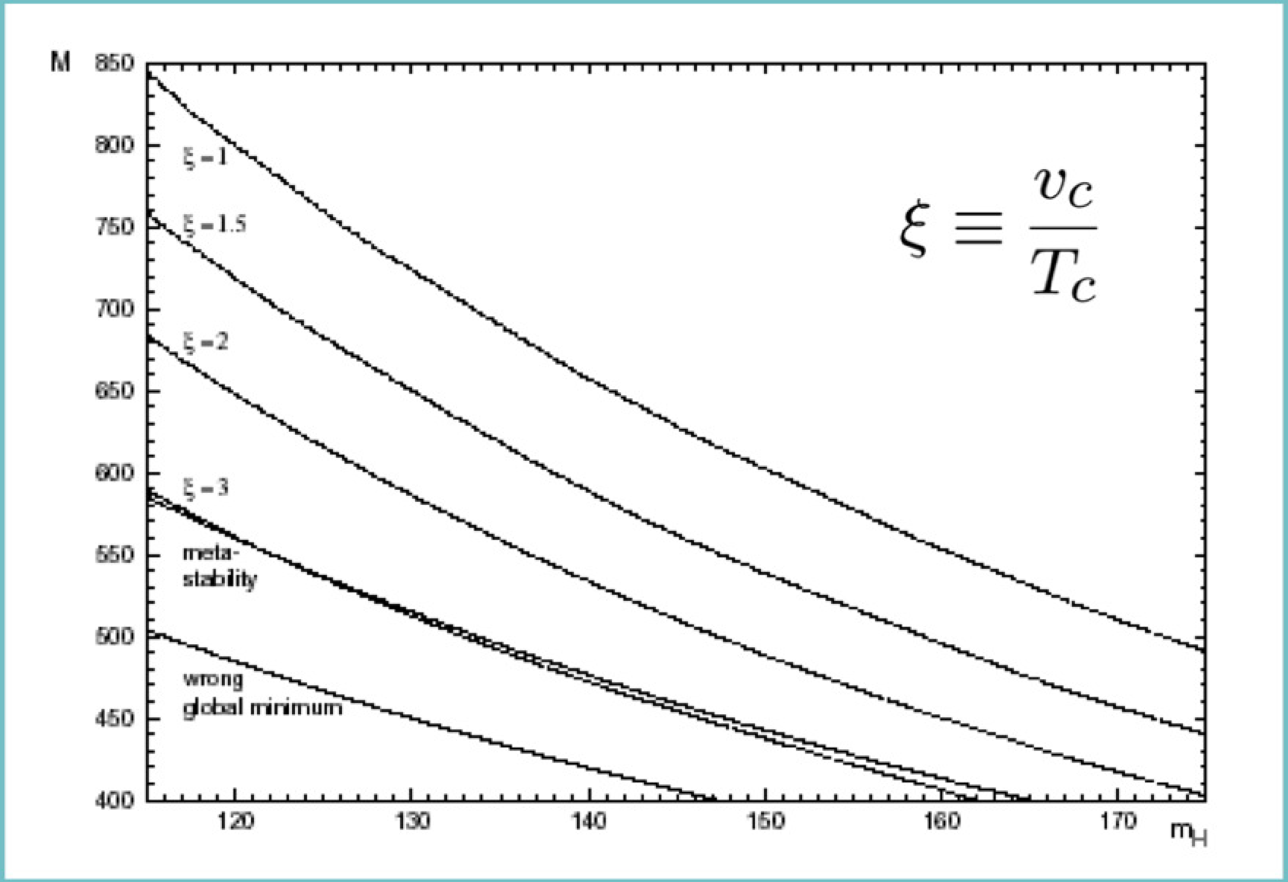
Results for the PT

S. Huber

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

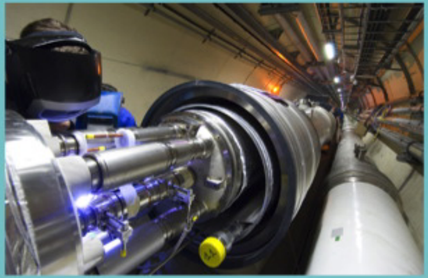
Delaunay, Grojean, Wells '07

Electroweak baryogenesis?

S. Huber

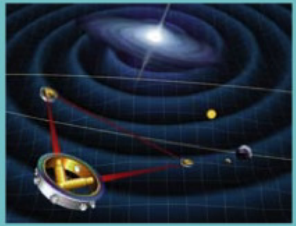
There are testable consequences:

- 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.)

Baryogenesis with R-parity violation

Baryogenesis in RPV SUSY

RPV superpotential includes couplings that violate baryon number and can be complex, i.e.

$$W = \lambda''_{ijk} U_i D_j D_k$$

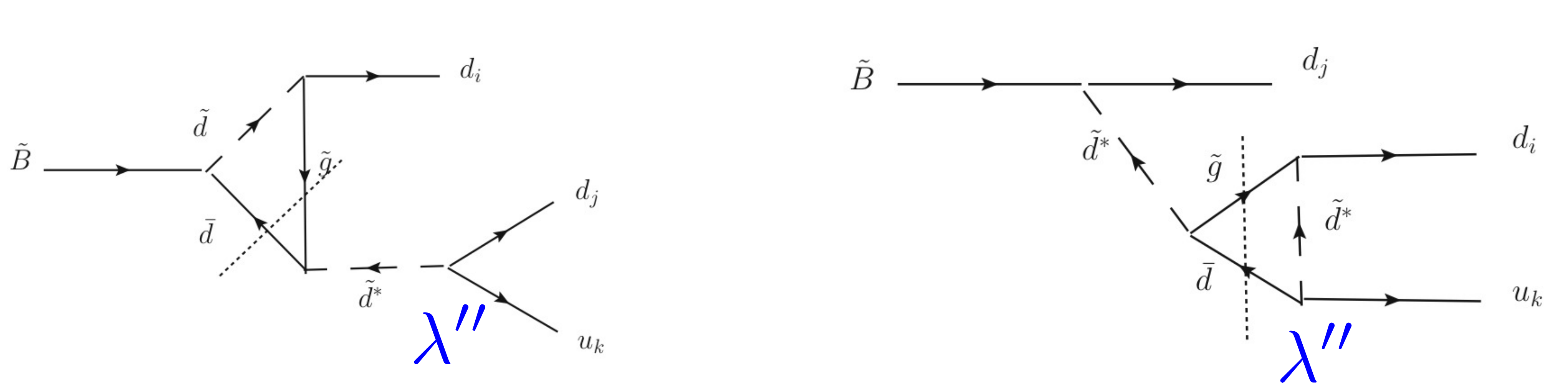
Possible to generate a baryon asymmetry from out-of-equilibrium decay of a superparticle into channels with different baryon number, e.g. for a neutralino

$$\tilde{B} \rightarrow udd,\ \bar{u}\bar{d}\bar{d},\ \tilde{g}\bar{q}q$$

Baryogenesis in RPV SUSY

[Sundrum & Cui 12, Cui 13, Sorbello 13, ...]

Realization of good old baryogenesis via out-of-equilibrium decay of a superpartner, possibly WIMP-like, e.g. in the model by Cui with Bino decay via RPV B-violating coupling.



CP violation arises from diagrams with on-shell gluino lighter than the Bino. To obtain right baryon number the RPC decay has to be suppressed, i.e. due to heavy squarks, and the Bino density very large...

Baryogenesis in RPV SUSY

Simple scenario with no Flavour Violation: the CP phase comes from the gaugino mass phase difference

$$\Gamma\left(\tilde{B} \to udd + \overline{udd}\right) = \frac{\lambda^2 g_1^2 N_{\rm RPV}}{768\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\Gamma\left(\tilde{B} \to \tilde{g} f \overline{f}\right) = \frac{(g_1 g_3 Q_f)^2 N_{\rm RPC}}{256\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\longrightarrow \quad \epsilon_{\rm CP} = \frac{8}{3} Im\left[e^{i\phi}\right]\boxed{\frac{m_{\tilde{B}} m_{\tilde{g}}}{m_0^2}}\alpha_s\left(1 + \frac{2\pi N_{\rm RPC}\alpha_s}{N_{\rm RPV}\lambda^2}\right)^{-1}$$

Baryon Asymmetry

Neglecting wash-out processes we get

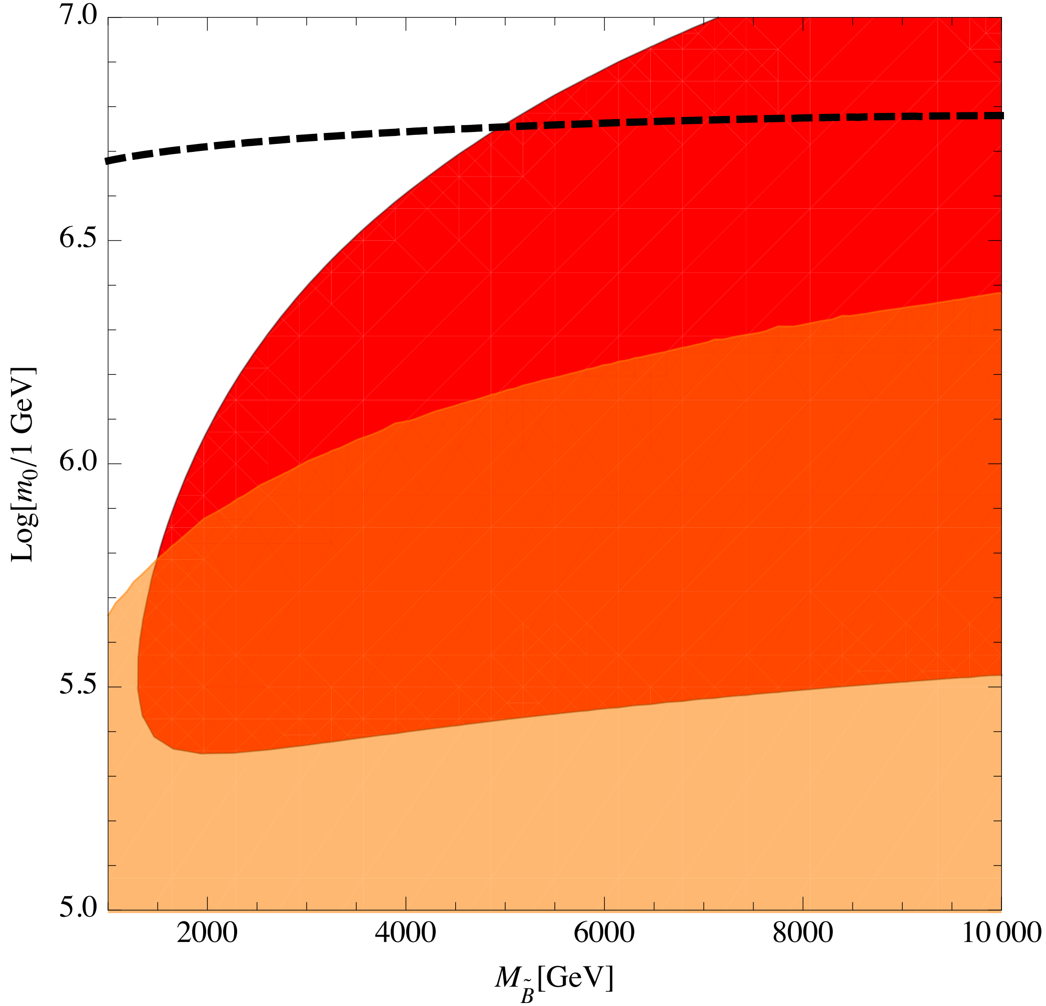
$$\Omega_{\Delta B} \approx 1.3\times 10^{-2}\frac{x_{\rm f.o.}}{A(x_{\rm f.o.})}\left(\frac{m_{\tilde{B}}}{1\,{\rm TeV}}\right)\left(\frac{\mu}{10^{3/2} m_0}\right)^2\left(\frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC}\alpha_s}\right)\left(1 + \frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC}\alpha_s}\right)^{-1}$$

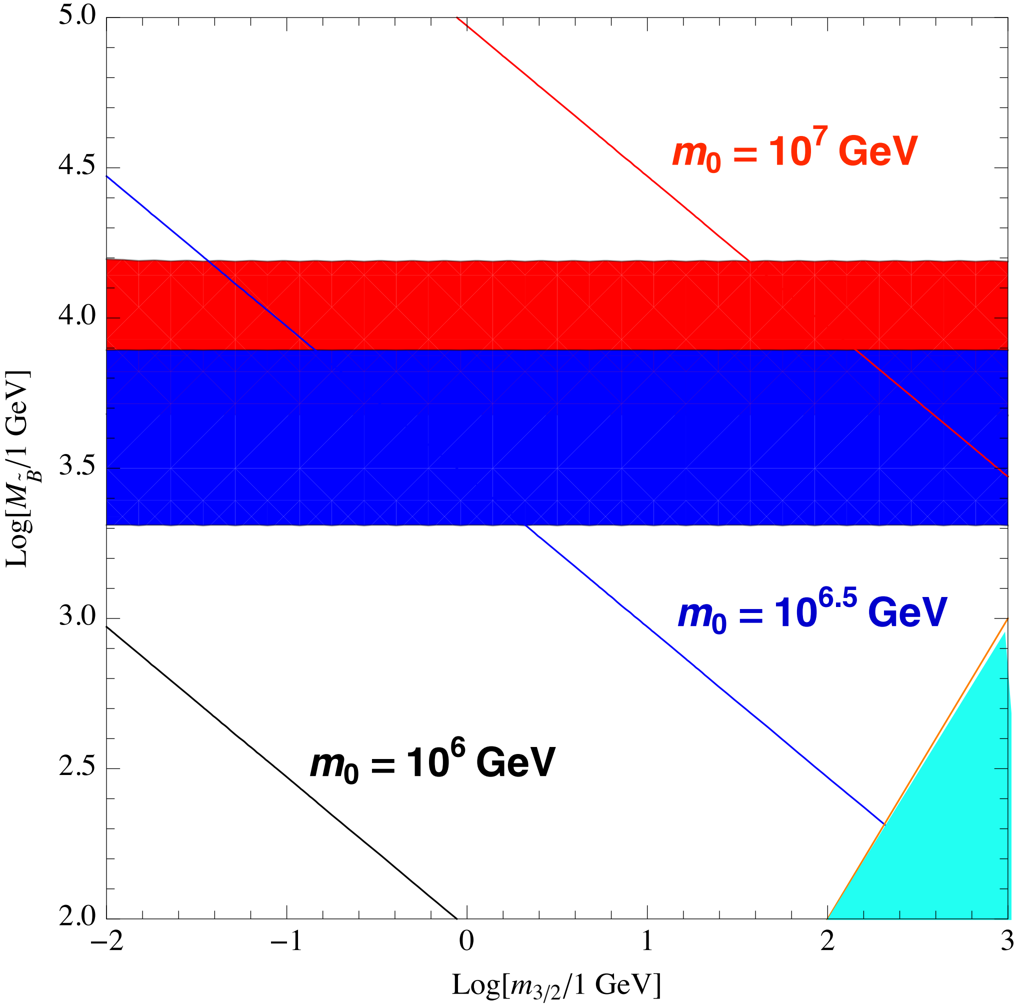
Need a very heavy spectrum to realize the scenario !

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1312.5703]

For obtaining both, need very heavy scalars, a Bino neutralino above 3 TeV, gluinos at 1 TeV and gravitino at 1-100 GeV...





Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 2013]

In such scenario it is also possible to get gravitino DM via the SuperWIMP mechanism and the baryon and DM densities can be naturally of comparable order due to the suppression by the CP violation and Branching Ratio respectively...

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi} \epsilon_{\rm CP} BR\left(\chi \to \not{B}\right) \Omega_\chi^{\tau \to \infty}$$

$$\Omega_{\rm DM} = \frac{m_{\rm DM}}{m_\chi} BR\left(\chi \to DM + \text{anything}\right) \Omega_\chi^{\tau \to \infty}$$

$$\to \quad \frac{\Omega_{\Delta B}}{\Omega_{\rm DM}} = \frac{m_p}{m_{\rm DM}} \epsilon_{\rm CP} \frac{BR\left(\chi \to \not{B}\right)}{BR\left(\chi \to DM + \text{anything}\right)}$$

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 2013]

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Small numbers

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independent of Bino density

Conclusions & Outlook

- Electroweak baryogenesis is a wonderful idea, unfortunately not realized in the SM...
- Still it can work in many realizations with physics beyond the Standard Model !
- Basic ingredients for EW baryogenesis: strong 1st order phase transition and sufficient CP violation.
- In many cases observables are soon to be expected, i.e. new (light) states at LHC, EDMs or even gravitational waves !

References

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