GRK2044 Fall Workshop 2017

Breisach, 4-6 October 2017

Baryogenesis

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elusiVes-inVisiblesPlus
neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

Outline

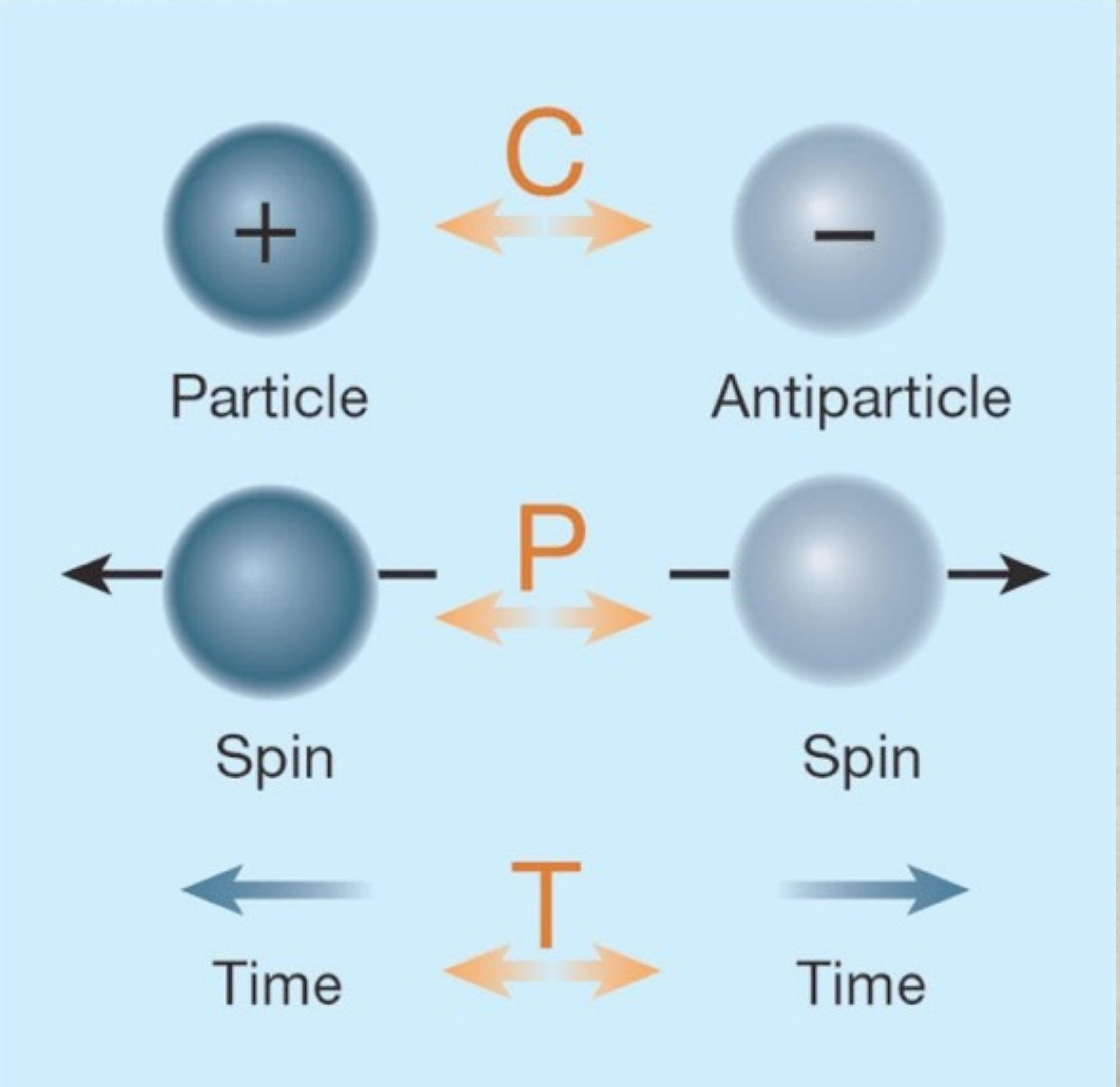
- Lecture 1:
  Introduction to CP violation & Baryogenesis
  Baryogenesis in the Standard Model
  Electroweak Baryogenesis BSM
- Lecture 2:
  Leptogenesis
  Affleck-Dine Baryogenesis
  Other mechanisms

Lecture 1: Outline

- CP violation in the SM and beyond
- Cosmology, Baryogenesis and the Sakharov Conditions
- Electroweak baryogenesis

CP violation in the SM & beyond

C, P, & T symmetries



C,P,CP,T symmetries

- Charge conjugation symmetry:

$$u_L \leftrightarrow -i\gamma^2 v_L^*$$

- Parity symmetry: $x, p \to -x, -p$

$$u_L \leftrightarrow u_R$$

- CP symmetry: $x, p \to -x, -p$

$$u_L \leftrightarrow -i\gamma^2 v_R^*$$

- T symmetry: antiunitary ! $t \to -t$

$$u_L, u_R \leftrightarrow u_L^*, u_R^*$$

CPT theorem

A Lorentz-invariant QFT with an hermitian Hamiltonian cannot violate the CPT symmetry !

[Lueders & Pauli 1954]

CP violation ⟷ T violation

Consequence of CPT theorem and locality: particle and antiparticle have the same mass !

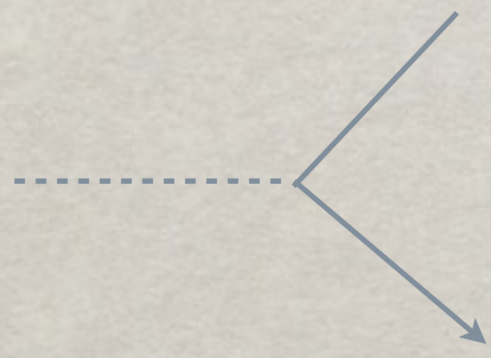
But not the same decay rate or scattering rate in the full quantum theory...

CP violation is quantum

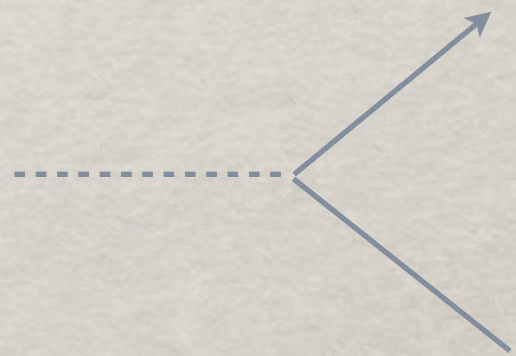
A theory violates CP if complex couplings are present, i.e.

$$\lambda\, h\bar{q}u + \lambda^*\, h^*\bar{u}q$$

If $\lambda \neq \lambda^*$ particle and antiparticle have to start with different couplings, but since $|\lambda| = |\lambda^*|$ the effect reveals itself only via quantum loops !



$i\,\lambda$



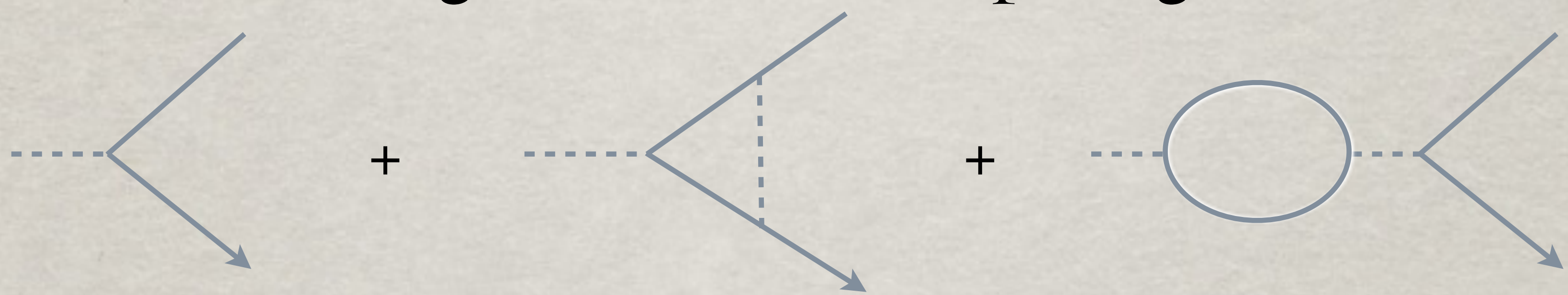
$i\,\lambda^*$

At Born level the matrix element for both decays is

$\mathcal{M} \propto |\lambda|^2 = |\lambda^*|^2$ No CP violation at tree level !

CP VIOLATION IS QUANTUM

At one loop level first signs of CP violation can appear, the most dominant usually the interference effect between tree-diagram and one-loop-diagrams



$i\,\lambda \qquad i\,\lambda\, i\,\lambda^* i\,\lambda \qquad i\,\lambda\;\; i\,\lambda^*\, i\,\lambda$

So we have for particle $\mathcal{M} \propto |\lambda|^2 + 2Re\left[\lambda\lambda^*\lambda\lambda^*\; L(x)\right] + \ldots$

& antiparticle: $\overline{\mathcal{M}} \propto |\lambda^*|^2 + 2Re\left[\lambda^*\lambda\lambda^*\lambda\; L(x)\right] + \ldots$

$$\Delta\mathcal{M} \propto 2Re\left[\lambda\lambda^*\lambda\lambda^*\; L(x) - \lambda^*\lambda\lambda^*\lambda\; L(x)\right] + \ldots$$

$$\Delta\mathcal{M} \propto -4\, Im\left[\lambda\lambda^*\lambda\lambda^*\,\right] Im[L(x)] + \ldots$$

NB: Vanishing for a single coupling, need flavour dependence !

Unitarity relation

We can obtain the same result and the interpretation of the imaginary part of a loop function from the unitarity relation for the scattering matrix & CPT: $S = I - i\,T$

From unitarity: $S^\dagger S = I = I - i(T - T^\dagger) + T^\dagger T$

$$\longrightarrow \quad T = T^\dagger - i\,T^\dagger T$$

Therefore if we square the amplitude we get

$$|T_{fi}|^2 = |T^*_{if}|^2 + 2Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2$$

From CPT we obtain $T_{if} = T_{\bar{f}\bar{i}}$ and so

$$|T_{fi}|^2 - |T_{\bar{f}\bar{i}}|^2 = 2Im\left[(T^\dagger T)_{fi} T_{if}\right] + |(T^\dagger T)_{fi}|^2$$

CP violation is SMALL

CP violation in particle physics arises as a quantum effect from the interference of tree-level and loop diagrams.
For these reasons it is multiply suppressed:

- It is higher order in the couplings, e.g.
  $\Delta\mathcal{M} \propto |\lambda|^4$ compared to $\mathcal{M} \propto |\lambda|^2$

- It contains a loop suppression factor
  $$L(x) \propto \frac{1}{4\pi^2} \sim 0.025$$

- It often needs a non-trivial flavour structure and it is therefore even more suppressed in presence of small mixing between generations.

Yukawa couplings

In the SM the symmetries C and P are violated maximally due to the chiral coupling of the EW interaction.
CP is instead violated just by the complex Yukawa matrices, i.e. by the non-diagonal fermion masses:

$$\frac{\lambda_{ij}}{\sqrt{2}} (v_{EW} + h)\bar{u}_{Li} u_{Rj} \longrightarrow m_{ij}\ \bar{u}_{Li} u_{Rj}$$

The diagonalization of the mass matrix to obtain the physical masses can be done with two unitary matrices (different for left-handed and right-handed fields !) for up, down and charged leptons (slightly different for neutrinos, see later...)

$$u'_{L/R} = U_{L/R} u_{L/R} \qquad d'_{L/R} = V_{L/R} d'_{L/R}$$

CP & Charged current

The mixing matrices cancel out for all interactions between the same type fields, even in the coupling with the Higgs, which is diagonalized at the same time as the mass. Therefore no Flavour Changing Neutral Currents exist at tree level in the SM !

$$j^{\mu}_{L/R} = \bar{u}_{L/R}\gamma^{\mu}u_{L/R} \longrightarrow j^{'\mu}_{L/R} = \bar{u}'_{L/R}\gamma^{\mu}u'_{L/R}$$

But the charged current involves both up- and down-quarks (or charged leptons and neutrinos !) therefore a non-trivial mixing matrix remains, due to the mismatch in the unitary matrices U_L and V_L:

$$j^{\mu}_{-} = \bar{u}_L\gamma^{\mu}d_L \qquad j^{'\mu}_{-} = \bar{u}'_L U_L V_L^{\dagger}\gamma^{\mu}d'_L = \bar{u}'_L V_{CKM}\gamma^{\mu}d'_L$$

No effects of RH rotations in the SM !

CabibboKobayashiMaskawa Matrix

The CKM matrix is a unitary 3x3 matrix and can in principle contain up to 3 mixing angles and 6 complex phases (recall for nxn: $n(n-1)/2$ angles $n(n+1)/2$ phases), but 5 (2n-1) phases can be reabsorbed in the definition of the fermions, so that only one ($(n-1)(n-2)/2$) phase is physical.

[Wolfenstein 1983]

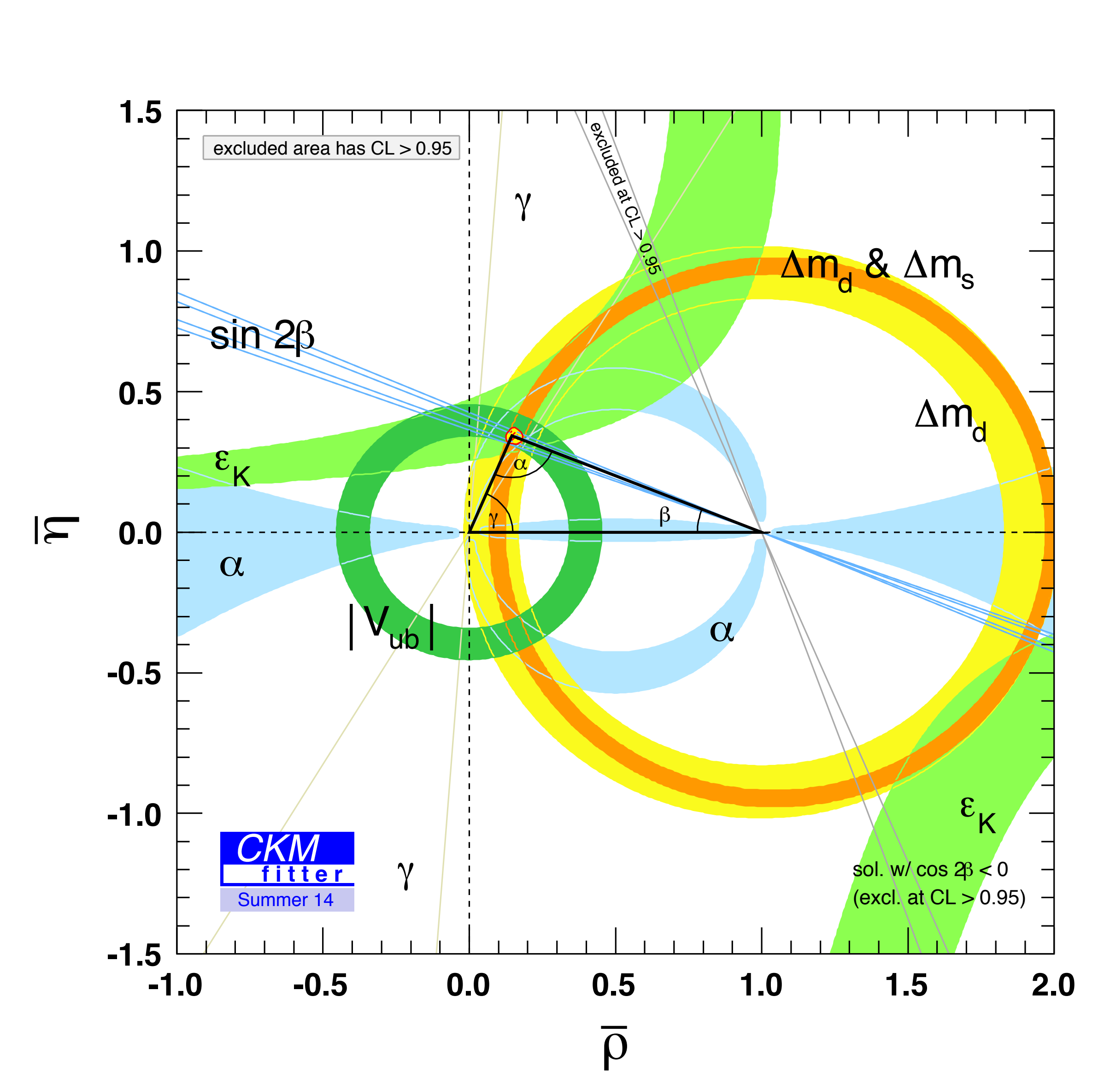
$$V_{CKM} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

The parameter η determines the CP violation and in the SM it is not small ! The area of the unitarity triangles is given by the Jarlskog invariant, measured in K/B decays:

$$J \sim \lambda^6 A^2 \eta \sim 10^{-6}$$

Unitarity triangle

In the SM the CKM matrix is unitary, i.e. $V_{CKM}^{\dagger} V_{CKM} = I$, so closed triangles correspond to the off-diagonal elements of the unity matrix:



So far all measurements fit with the CKM matrix explanation and one single phase (not so small !)

The area of the triangle is related to

$$J \sim \lambda^6 A^2 \eta \sim 10^{-6}$$

Neutrino masses

The neutrinos are neutral and do not carry a conserved (local) charge, therefore in their case we can also write down a Majorana mass term in addition to the Dirac mass term.

e.g. dimension 5 Weinberg operator:

$$\frac{y}{M_P} H^* \bar{\ell}^c H \ell \quad \longrightarrow \quad \frac{y v_{EW}^2}{2 M_P} \bar{\nu}_L^c \nu_L$$

A Majorana mass matrix is symmetric and can be diagonalized by an orthogonal rotation, leaving more physical phases !

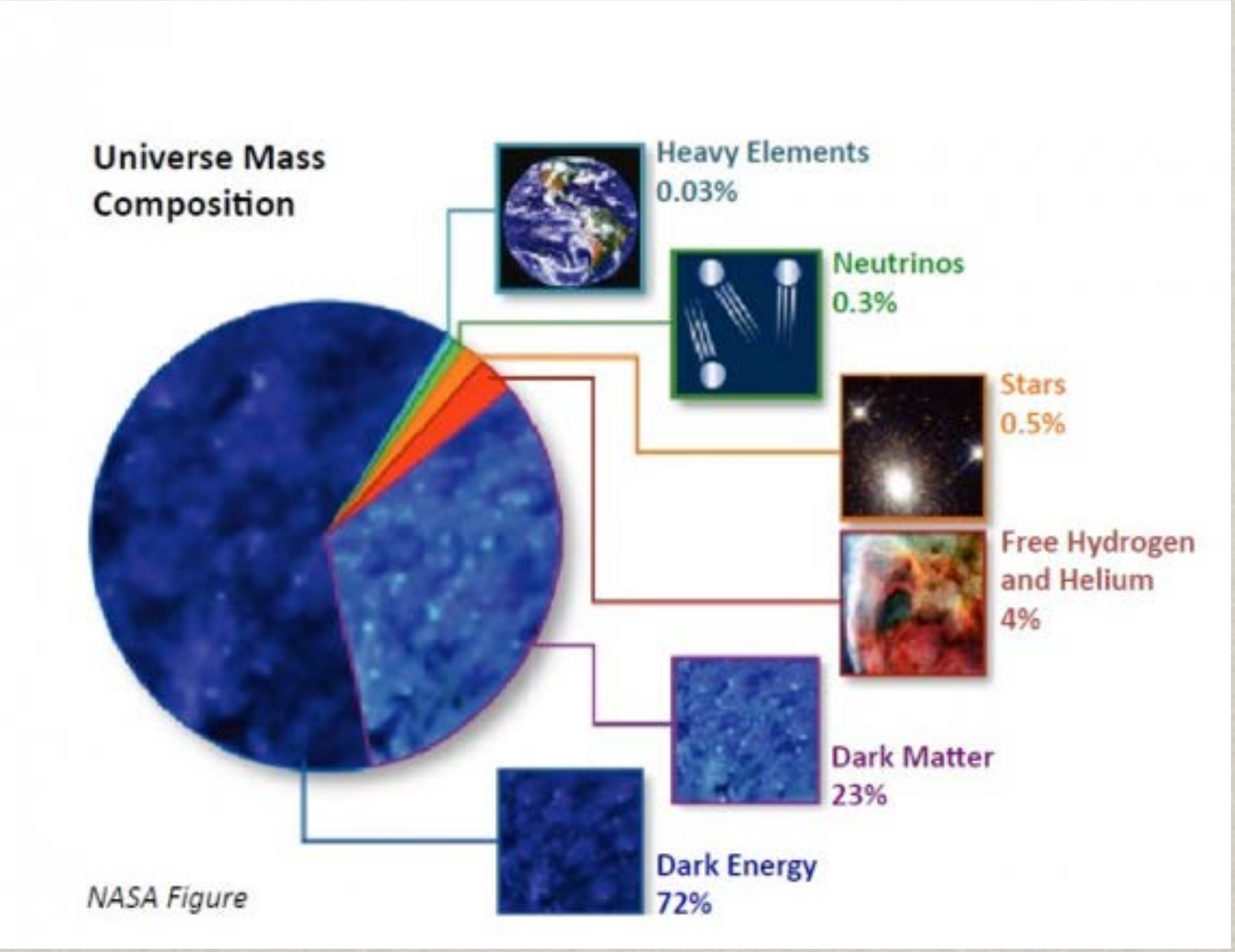
→ Pontecorvo-Maki-Nakagawa-Sakata mixing matrix with one Dirac phase δ and two Majorana phases α, β:

$$U_{PMNS} = P \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

with P = $\mathrm{diag}(e^{i\alpha}, e^{i\beta}, 1)$ $\qquad s_{ij}, c_{ij} = \sin\theta_{ij}, \cos\theta_{ij}$

Baryogenesis & the Sakharov conditions

Universe composition

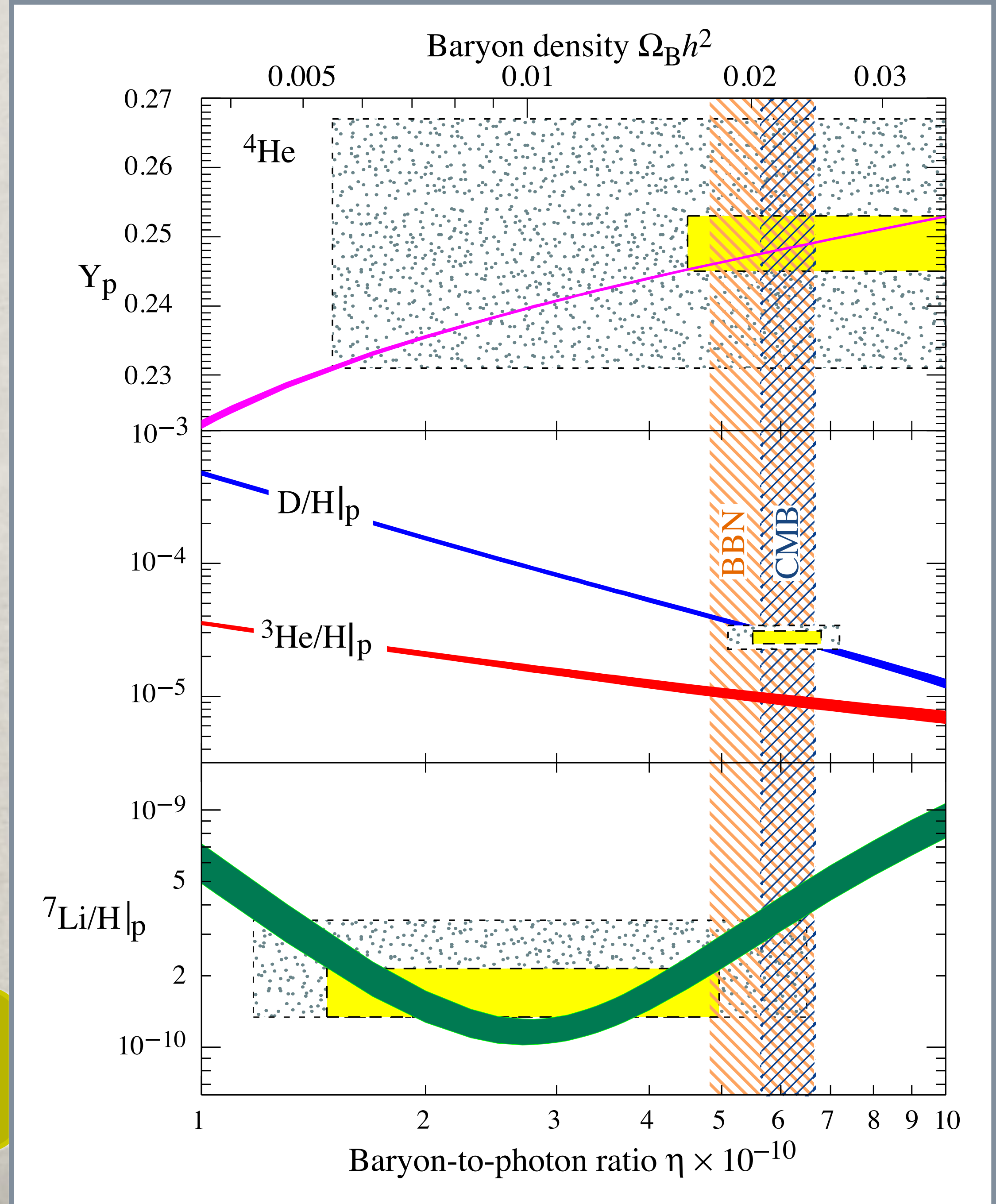


Big Bang Nucleosynthesis

[Fields & Sarkar PDG 07]

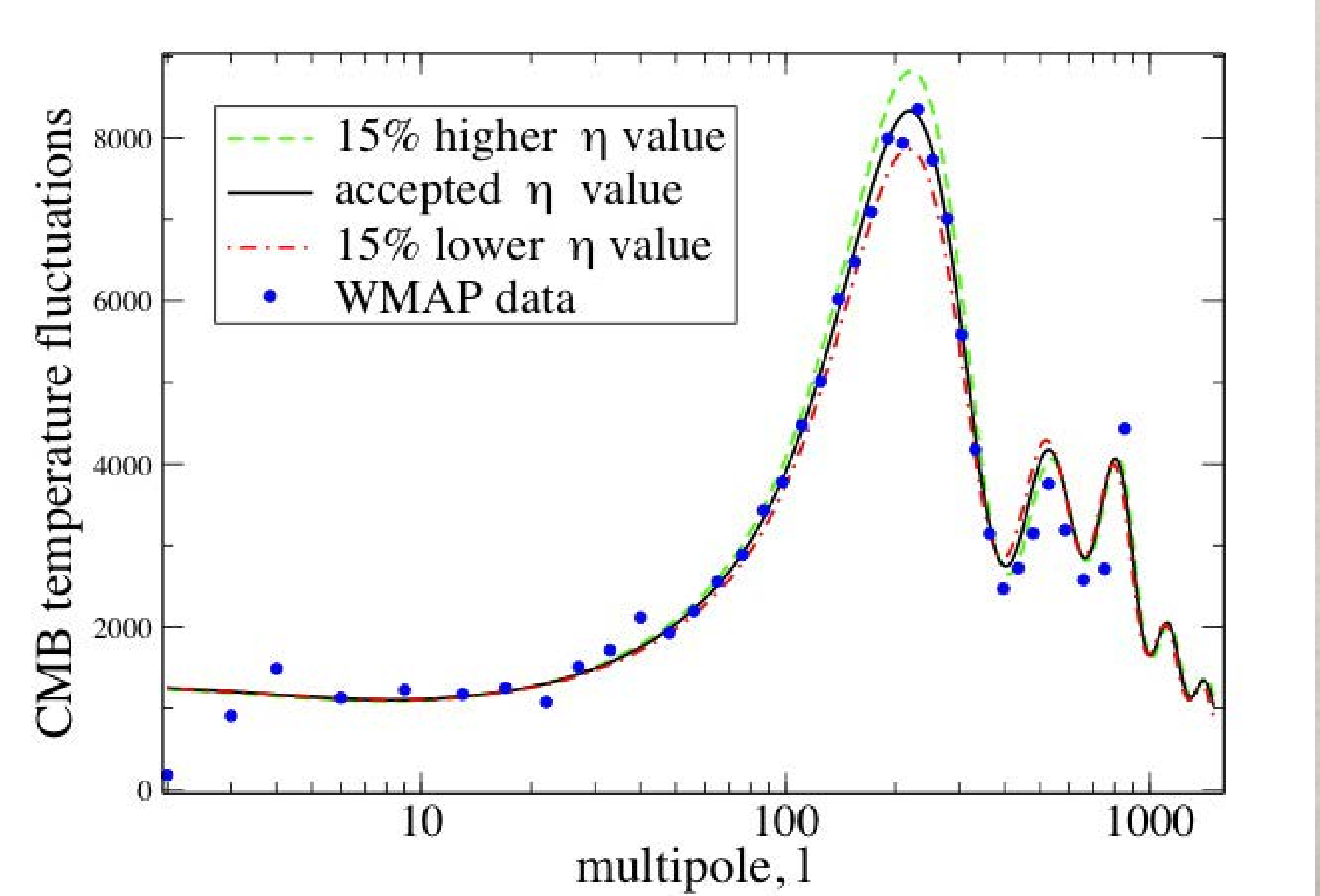
- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7

$$\Omega_B h^2 = 0.02 < \Omega_{DM} h^2$$



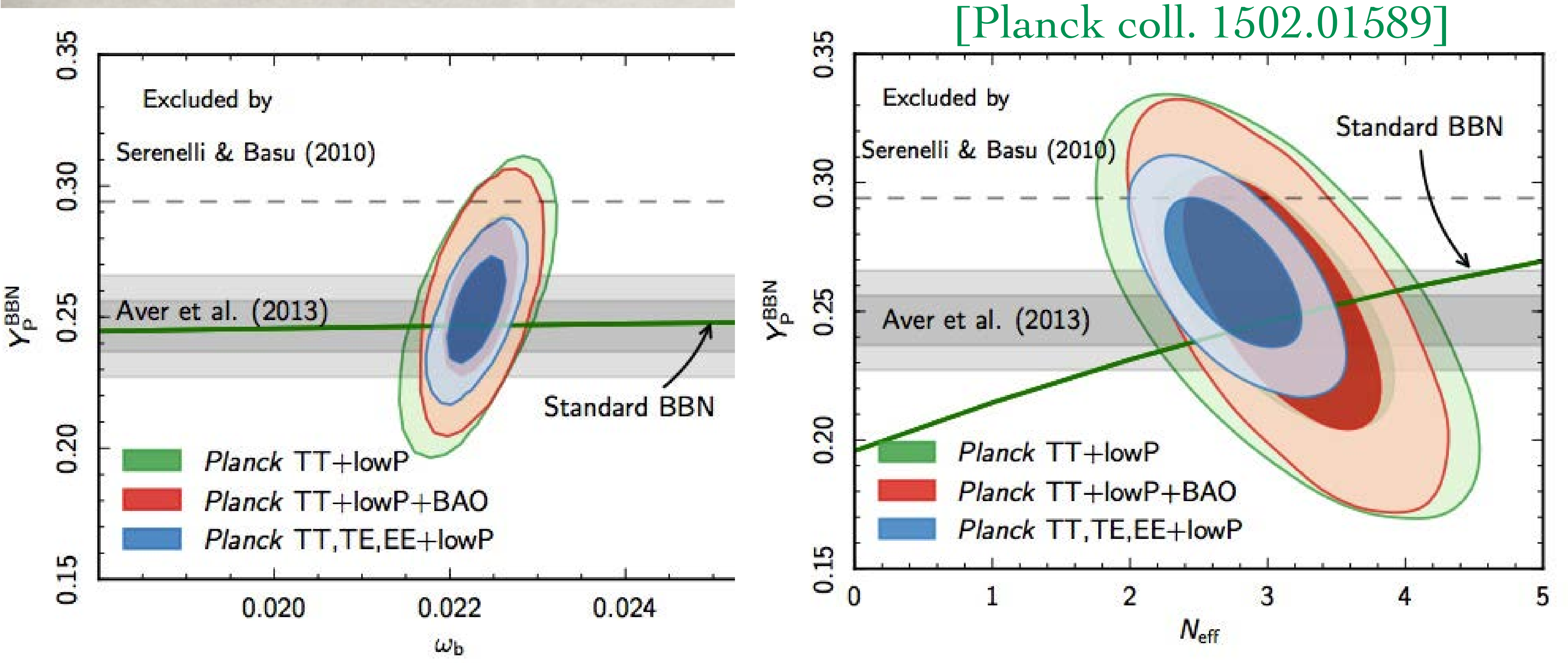
Baryonic Matter evidence

The relative height between the odd (compression) and the even (rarefaction) peaks in the CMB power spectrum depends on the amount of baryons since the mass of the plasma is due to the baryons and DM is decoupled from the photon gas...



Planck:Nucleosynthesis

[Planck coll. 1502.01589]

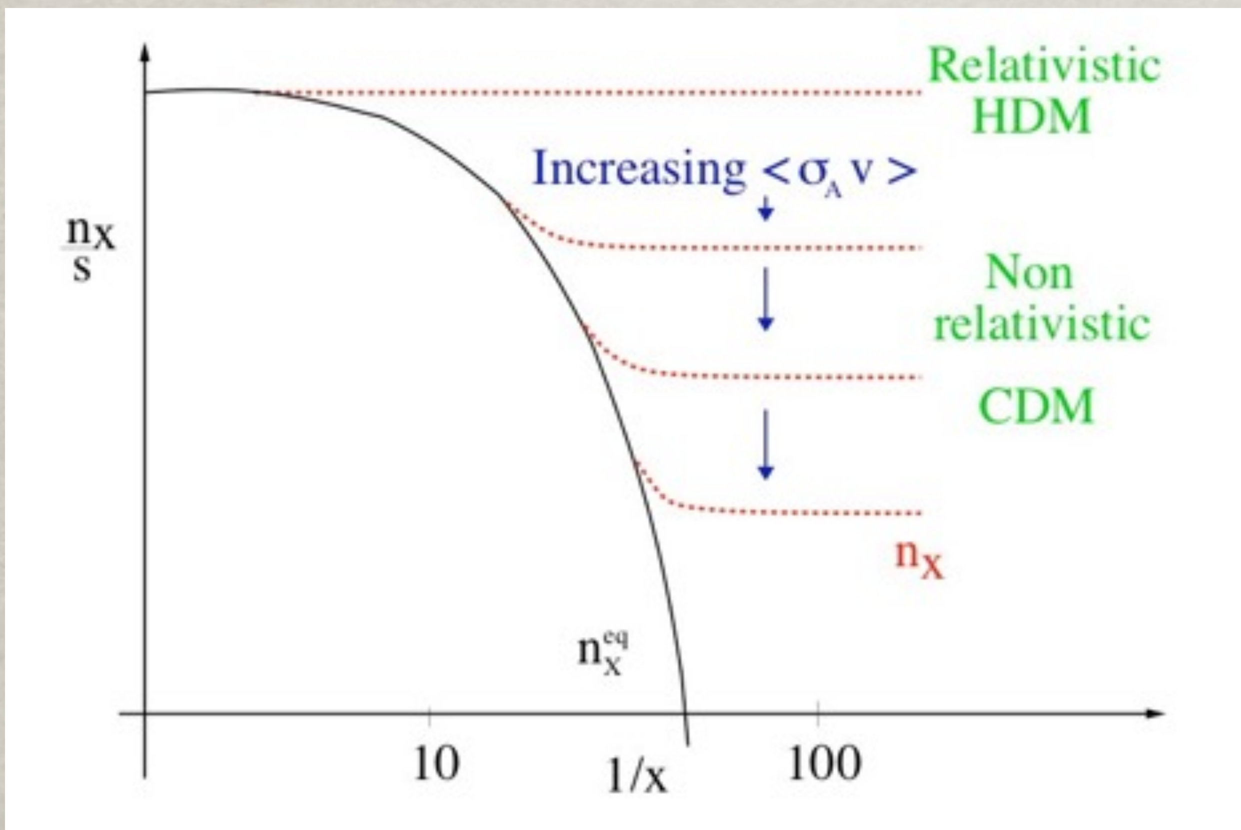


CMB consistent with BBN even fitting both N_{eff} & Y_p .

Note the degeneracy between these two parameters, but orthogonal compared to BBN !

Baryonic Matter

Baryons annihilate very strongly so that the symmetric Baryonic component is erased very efficiently to leave only $\Omega_B \sim 10^{-10}$.



Moreover, how to "segregate" it ?

If an asymmetric baryon component is already present, it survives the freeze-out process !

Baryogenesis

- The CMB data and BBN both require $\Omega_B \sim 0.05$
- Can it be a relic of thermal decoupling from a symmetric state ? NO ! Decoupling “a la WIMP” give a value $\Omega_B \sim 10^{-10}$, way too small…
- Are we living in a matter patch ??? No evidence of boundaries between matter/antimatter in gammas or antinuclei in cosmic rays… Our patch is as large as the observable Universe !
- No mechanism know can create such separation… The Universe is asymmetric !

Sakharov Conditions

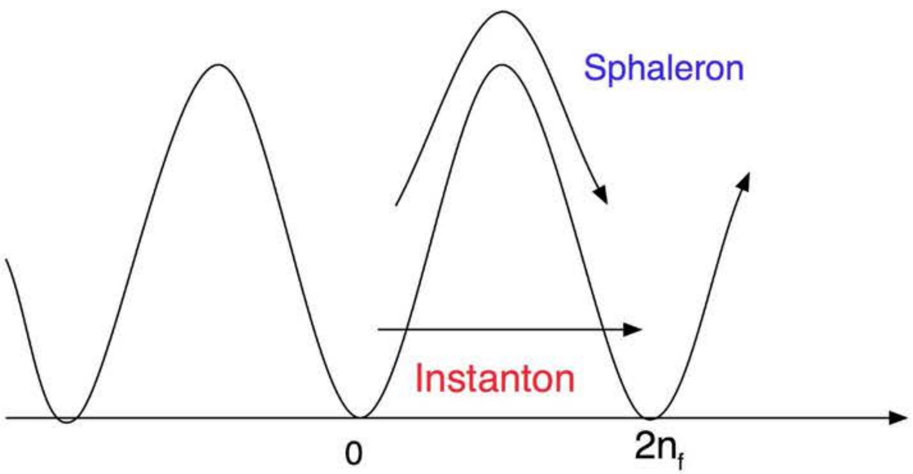
Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: trivial condition since otherwise B remains zero...
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate
- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

Sphaleron 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

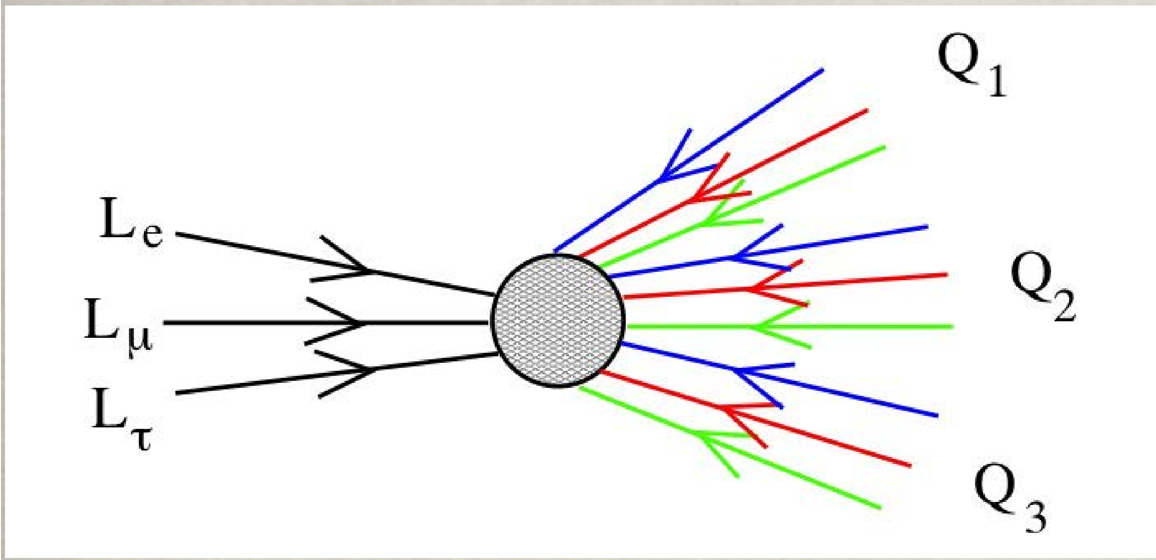
with rate $\Gamma_{sph}(T) \sim \left(\frac{M_W}{\alpha_W T}\right)^3 M_W^4 e^{-E_{sph}/T}$

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

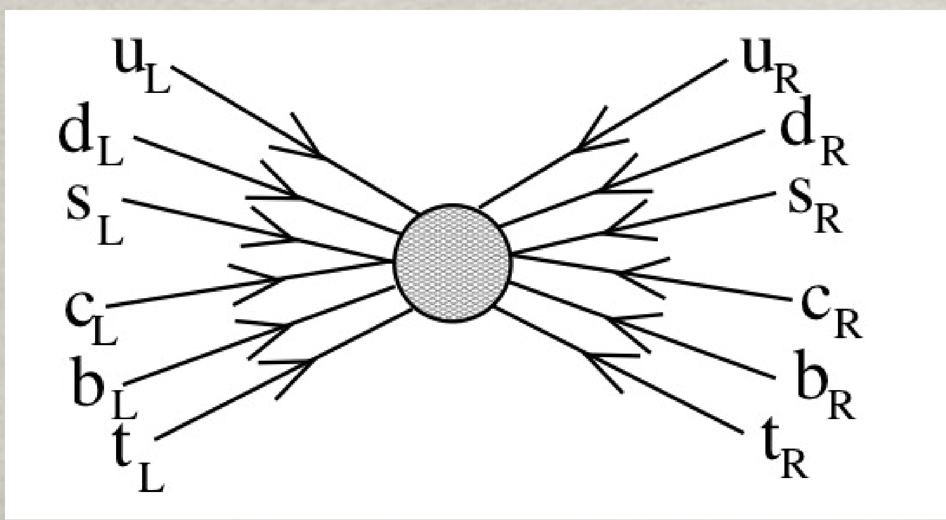
$$B = \frac{8n_f + 4n_H}{22n_f + 13n_H}(B - L)$$

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

Sphaleron 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

Sakharov Conditions II

For the Standard Model actually we have instead:

- B-L violation: B+L violation by the chiral anomaly

$$\partial_\mu J^\mu_{B+L} = 2n_f \frac{g^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- C and CP violation: present in the CKM matrix, but unfortunately quite small ! Possibly also additional phases needed...

- Departure from thermal equilibrium: phase-transition or particle out of equilibrium ?

ELECTROWEAK BARYOGENESIS

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

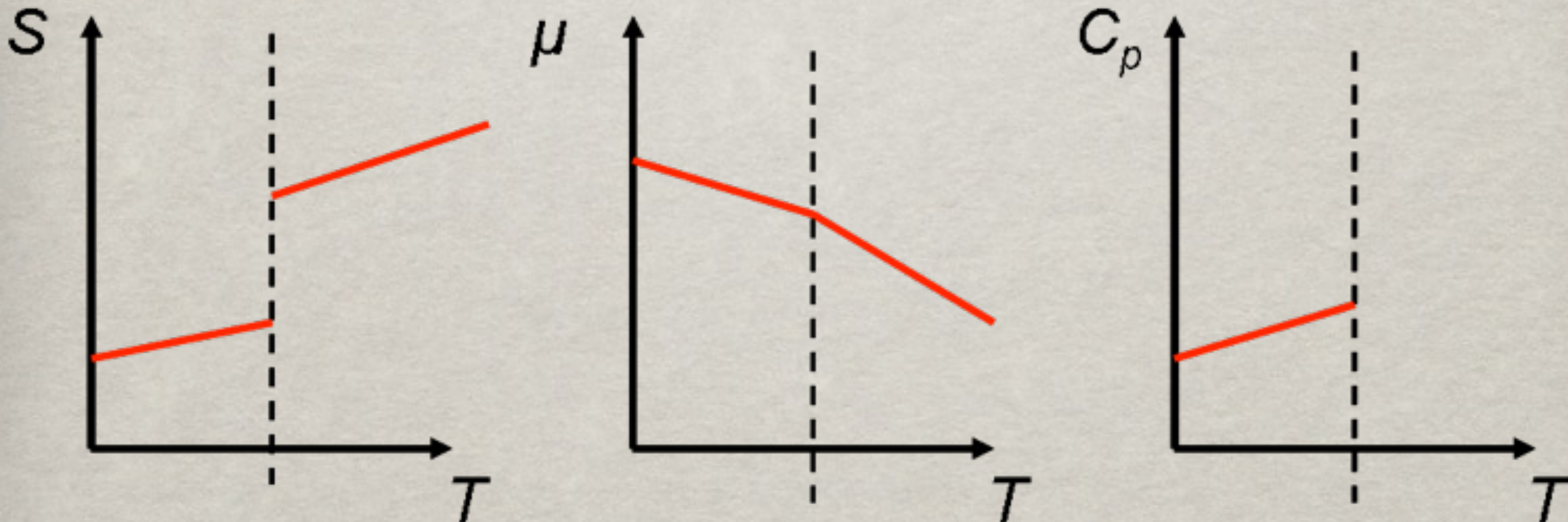
Possible to generate the BAU at the electroweak scale !

[Kuzmin, Rubakov & Shaposhnikov 1985]

PHASE TRANSITIONS IN TD

Ehrenfest classification: FIRST ORDER phase transition

The first 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

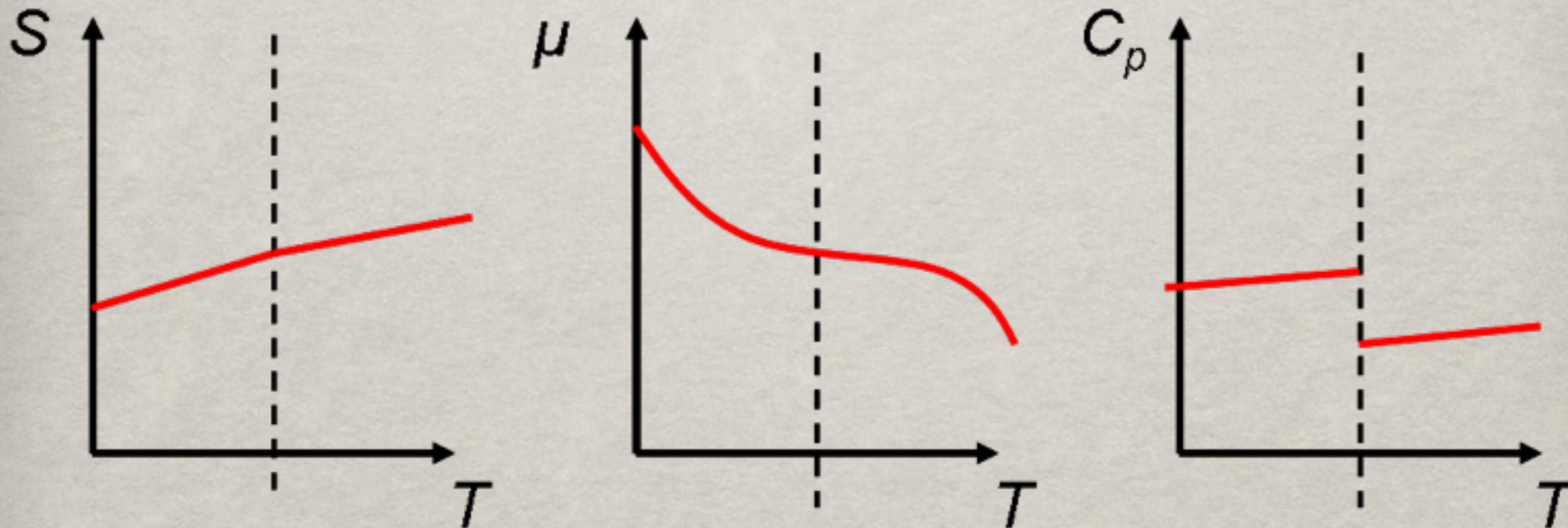


Also the order parameters display a discontinuity !

PHASE TRANSITIONS IN TD

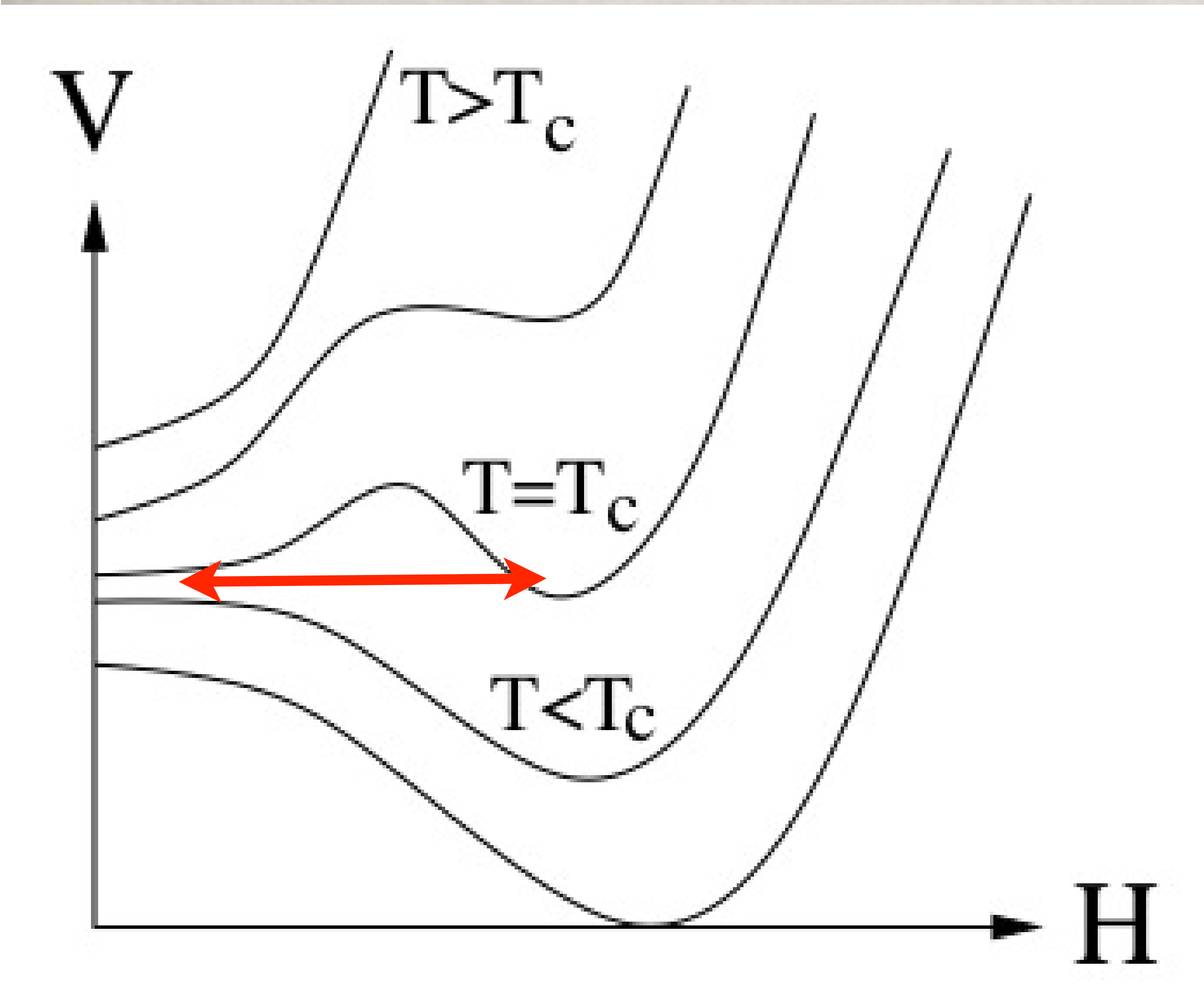
Ehrenfest classification: SECOND ORDER phase transition

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 changes continuously...

1st order transition

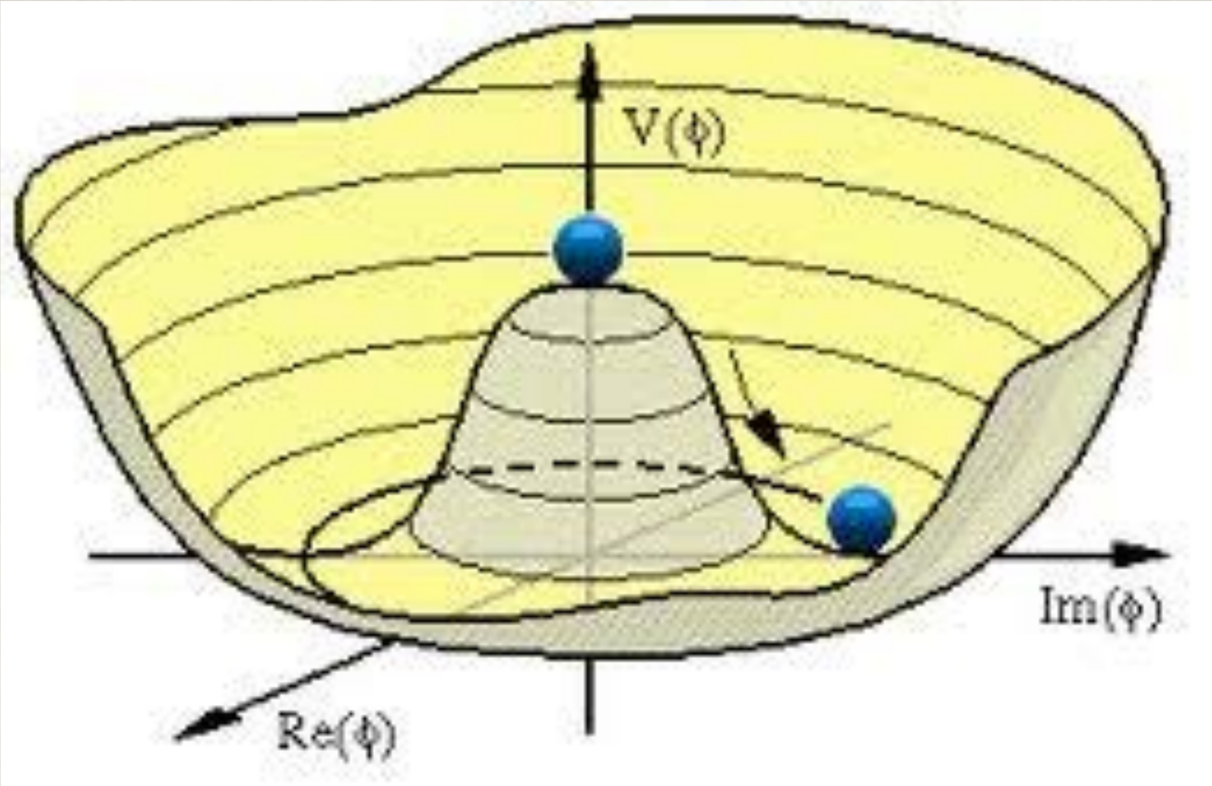


At the critical temperature the two vacuum are degenerate. After that temperature, the phase transition proceeds through a tunnelling process from the unstable vacuum at H=0 to the true vacuum with non-zero v.e.v.

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

THE HIGGS MECHANISM

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



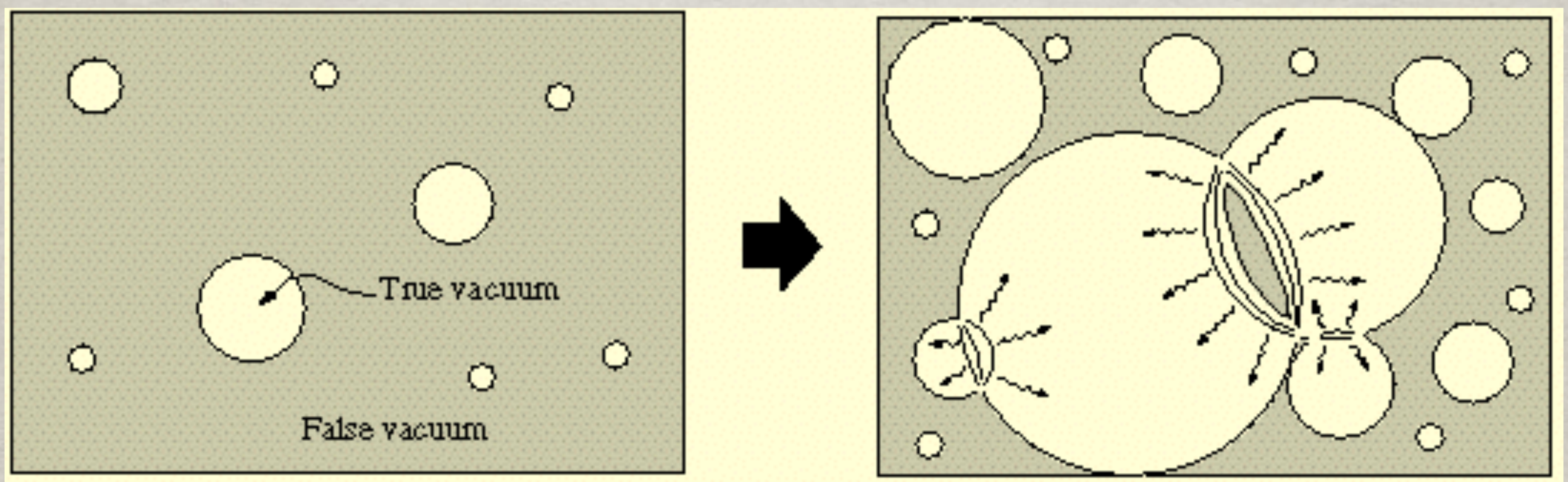
Non-vanishing v.e.v.: massive gauge bosons and fermions !

But in the early Universe the symmetry was restored

EW PHASE TRANSITION !

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 !

Note: violent bubble collision can also generate gravity waves.

EW baryogenesis

Broken phase

$\not{CP}$

Unbroken phase

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

$$\Gamma_{sph} > H$$

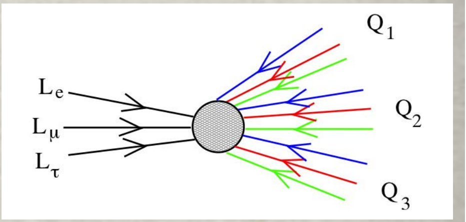
$$\frac{v_c}{T_c} > 1$$

$\not{CP}$

Strong 1st order PT

B > 0

v_W



L_W

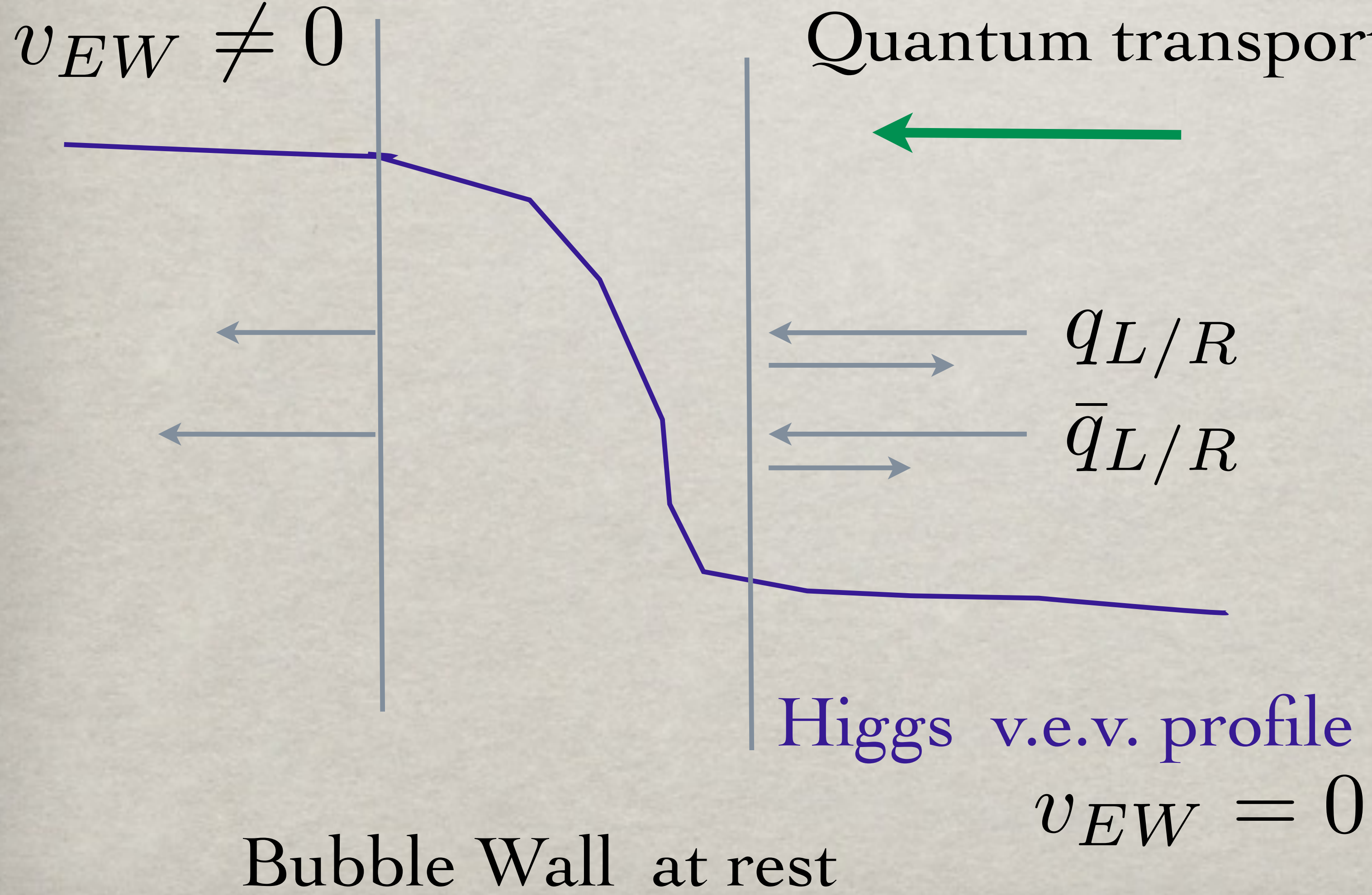
$\not{CP}$

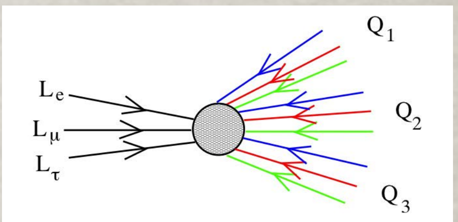
B=0

$\not{CP}$

EW Baryogenesis

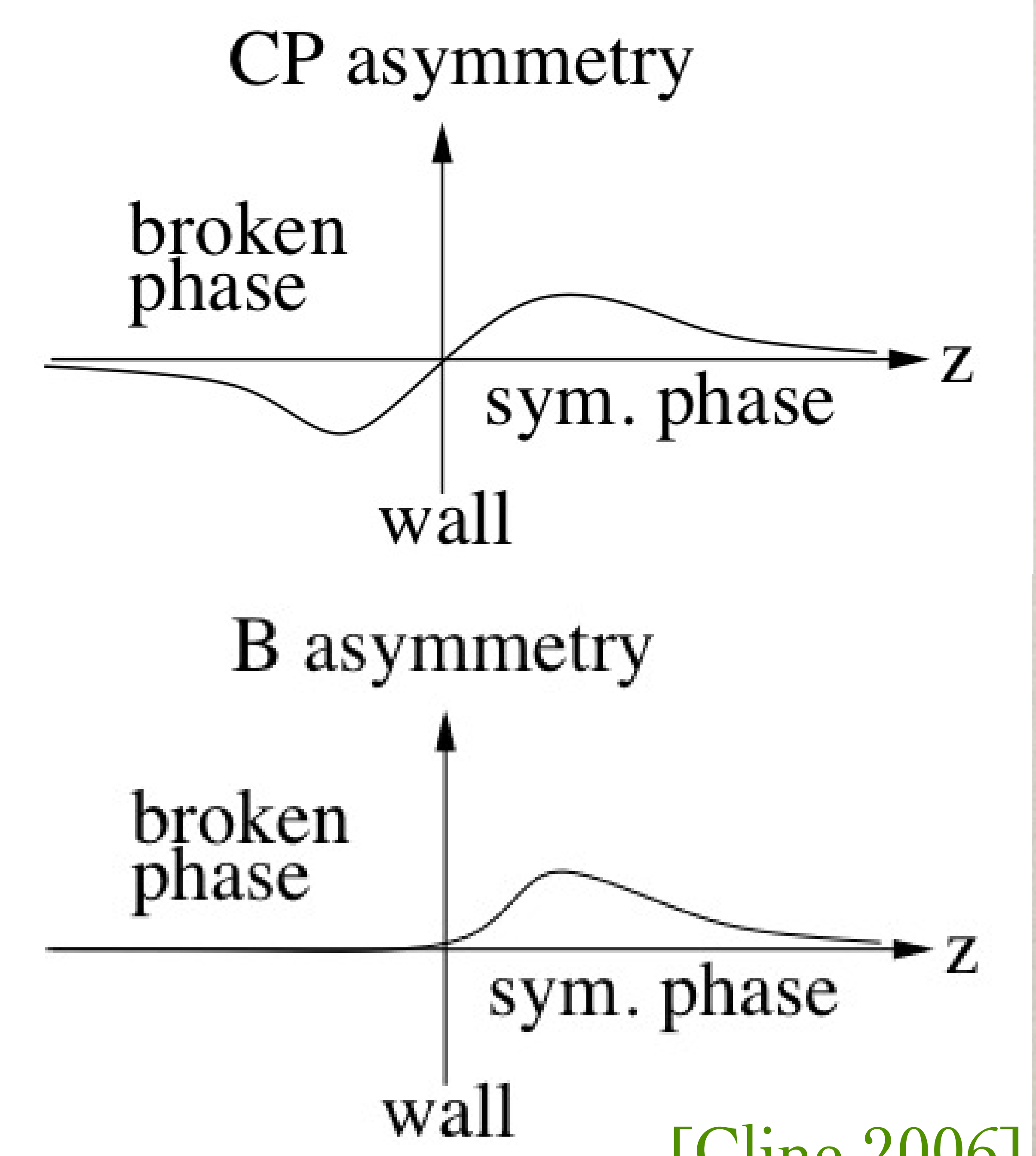
The bubble wall corresponds to a non-trivial v.e.v. profile. C, CP violation is provided by the different reflection/ transmission probabilities across the bubble wall.





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

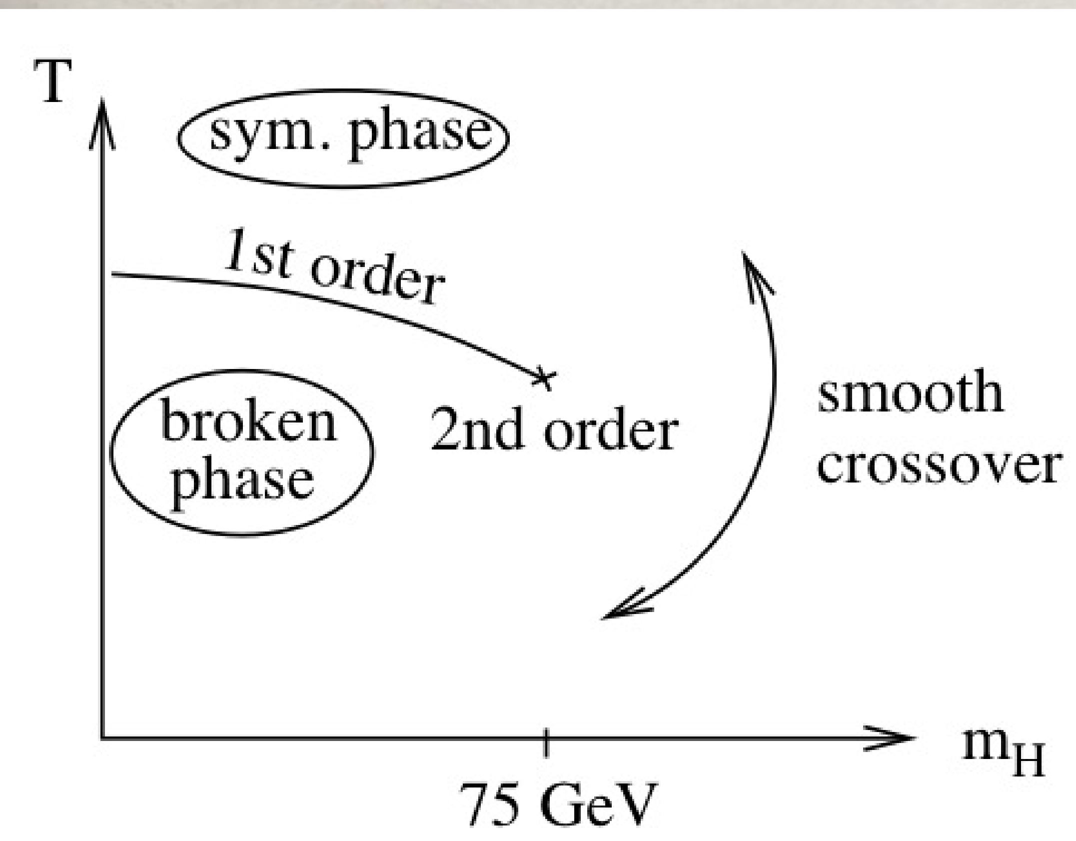
Caveat: perturbative computation is not trustworthy at the critical temperature

→ Lattice computations

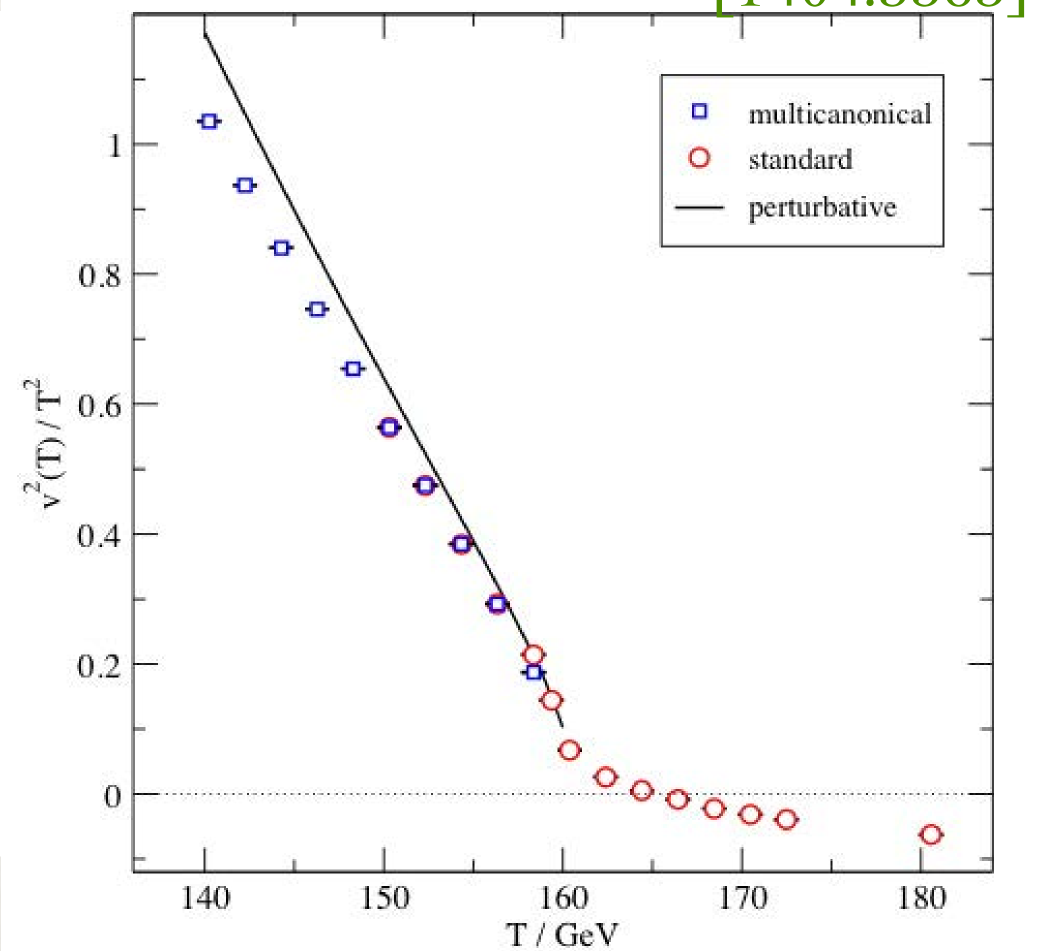
Only if the transition is sufficiently strong, i.e. $\frac{v_c}{T_c} > 1$
EW baryogenesis can work !

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 !

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

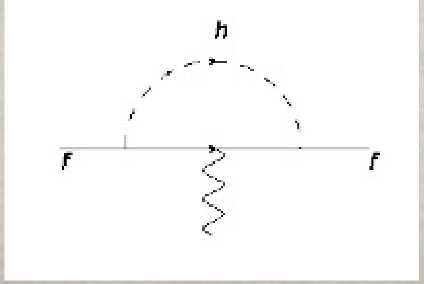
EW Baryogenesis 2HDM

Introduce a second Higgs doublet in the model

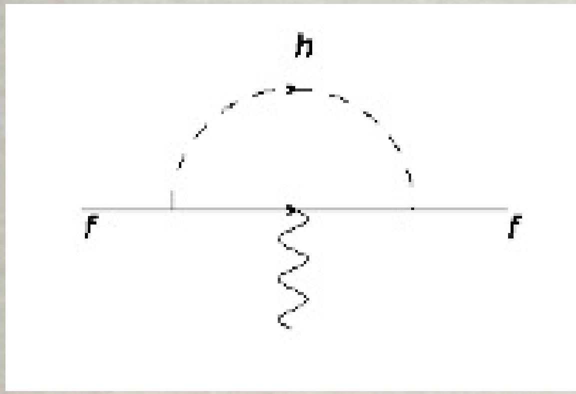
$$H_1 = \begin{pmatrix} H^+ \\ H_{1,0} \end{pmatrix} \qquad H_2 = \begin{pmatrix} H_{2,0} \\ H^- \end{pmatrix}$$

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 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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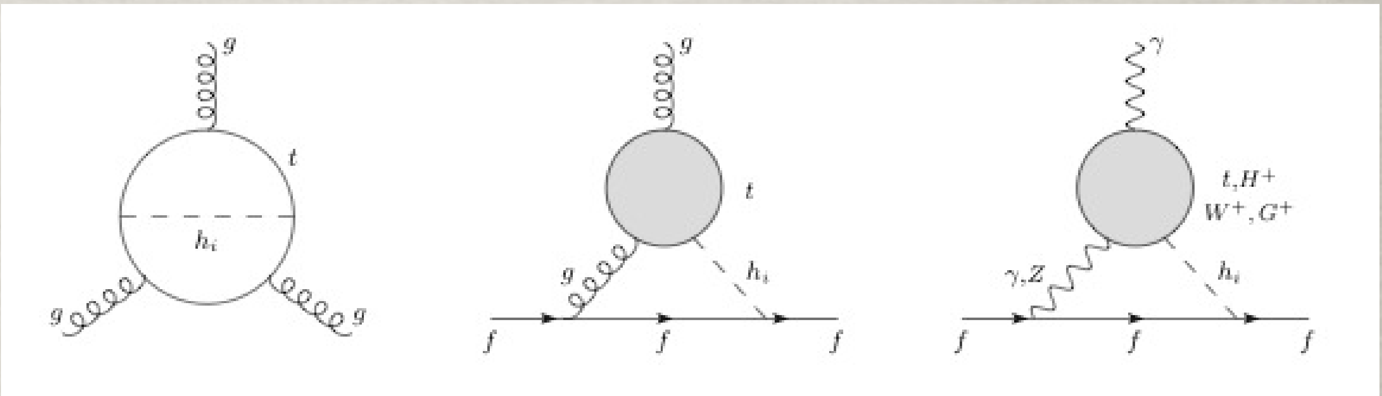
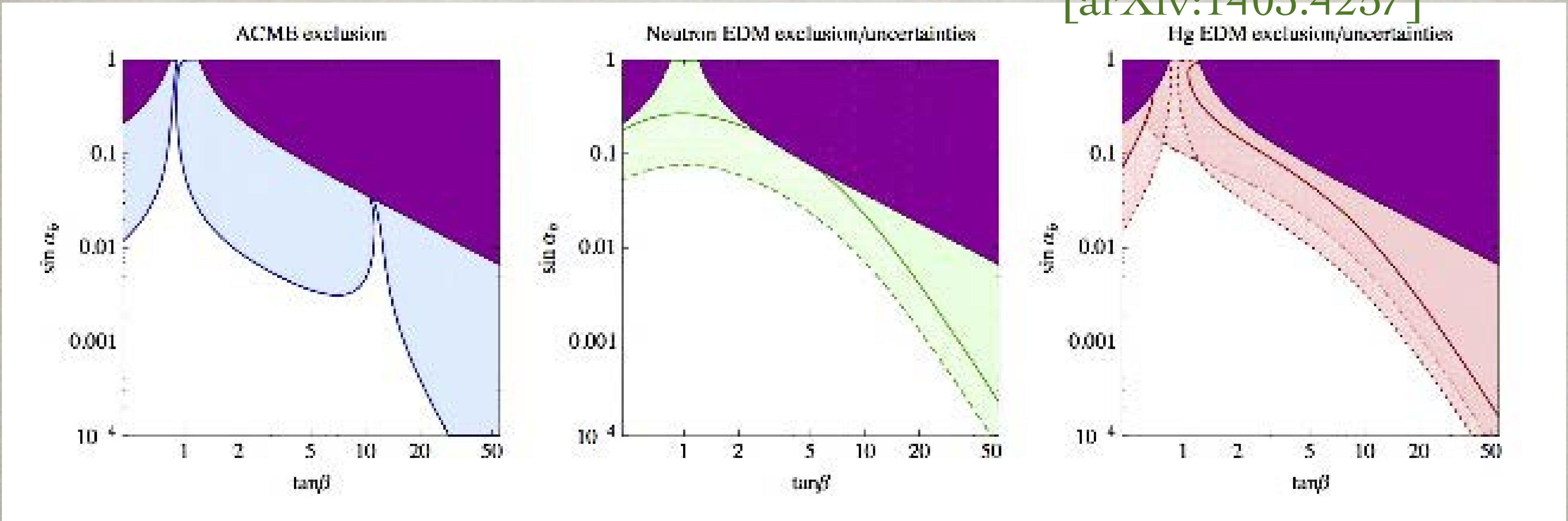


Due to Yukawa suppression, the two loop contribution, involving as well QCD couplings, dominates in 2HDM

[arXiv:1403.4257]



The 2HDM

S. Huber

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

→ 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

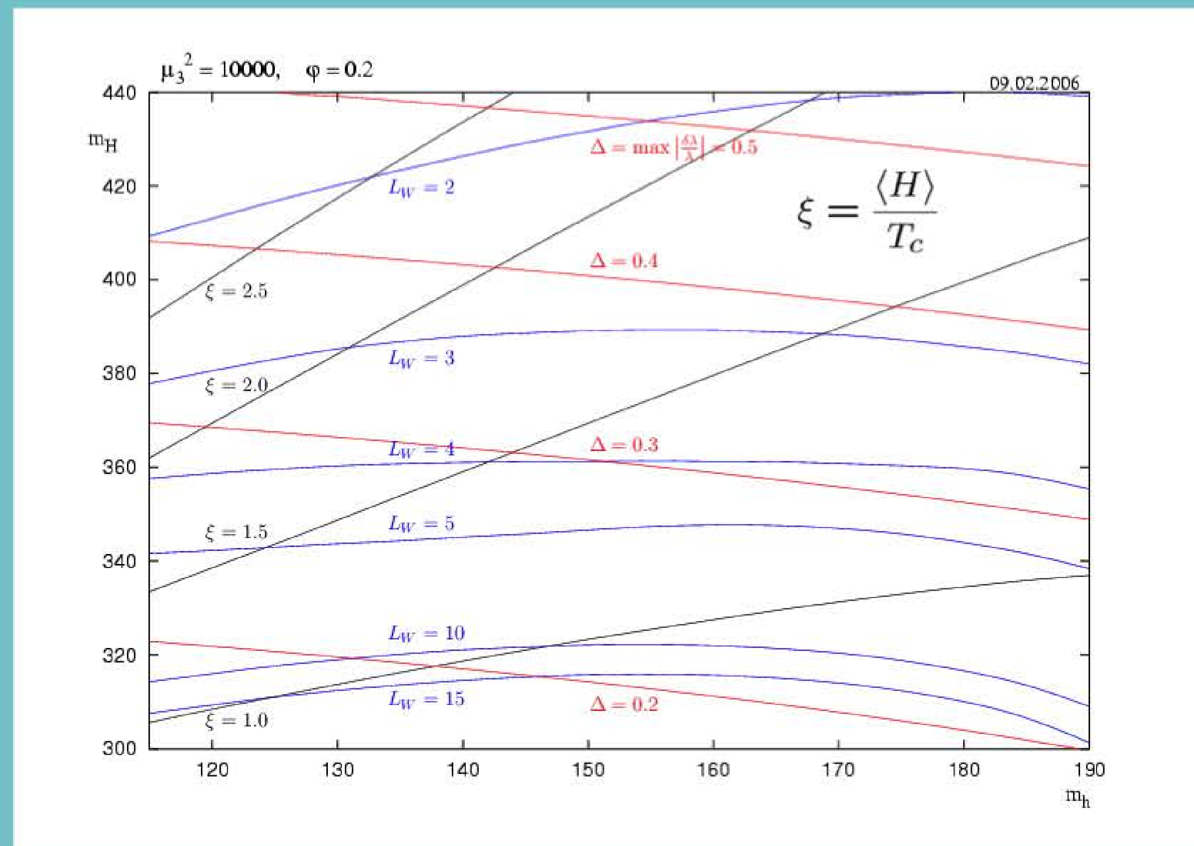
→ strong PT for

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 from S. Huber

The baryon asymmetry

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

→ phase of the top mass varies

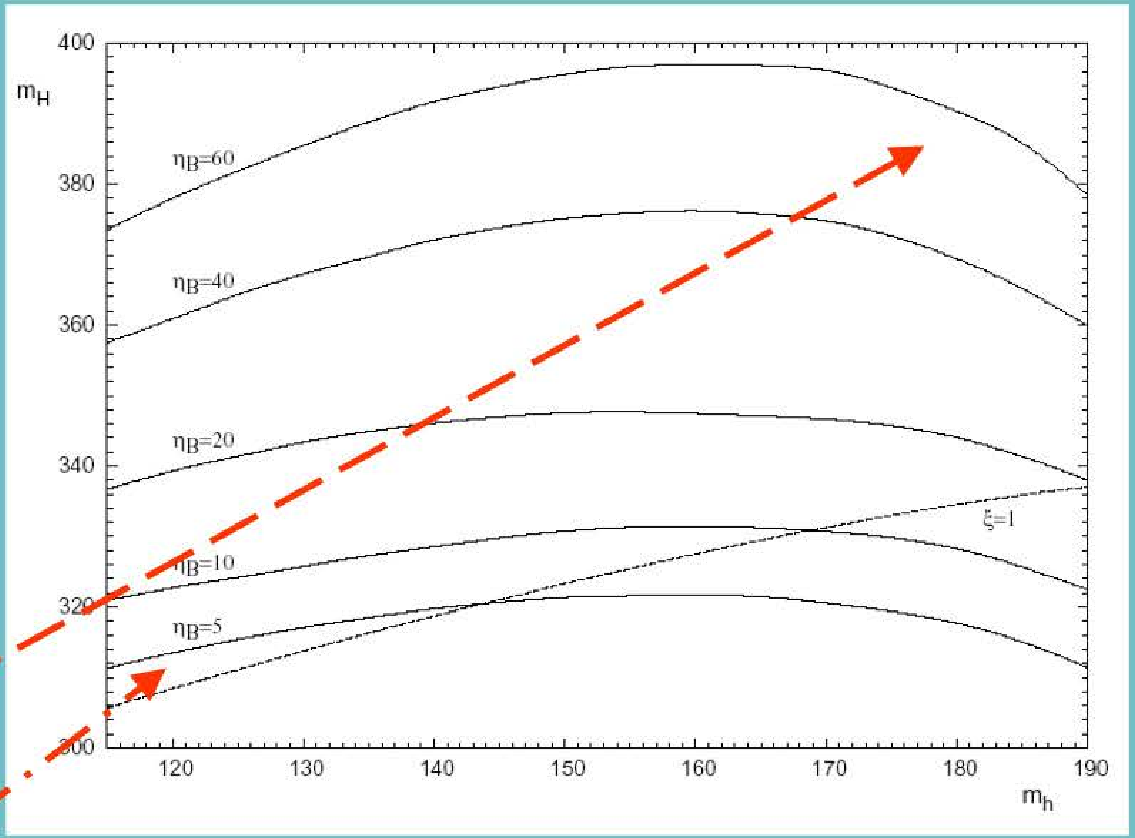
$\theta_t = \theta/(1+\tan^2\beta)$

top transport generates a baryon asymmetry

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

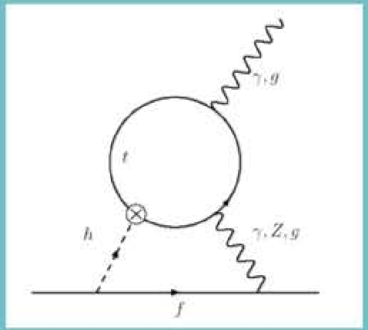
$d_n = 0.1\ 10^{-26} - 7\ 10^{-26}$ e cm

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



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

[Fromme, S.H., Senuich ’06]



Could LHC see these extra Higgses?

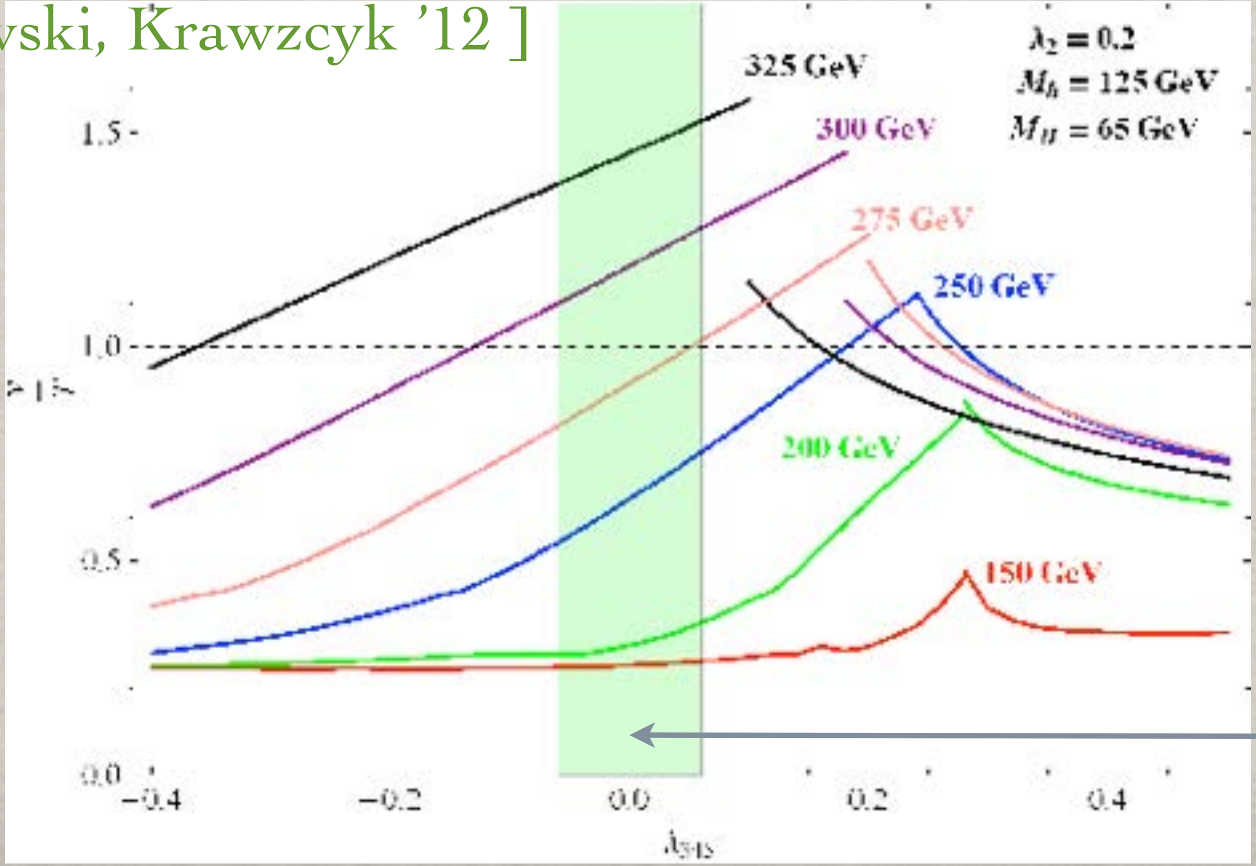
EW Baryogenesis 2HDM

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 ?

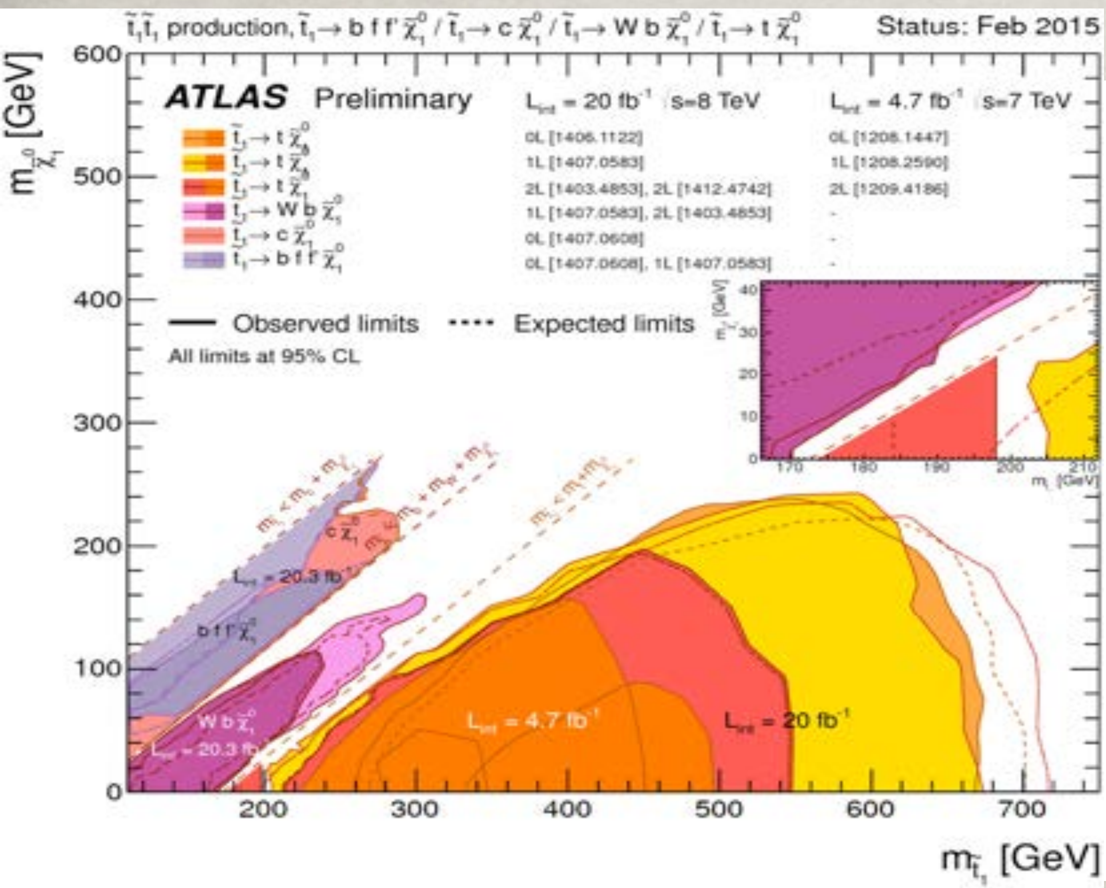
EW Baryogenesis in SUSY

In SUSY extensions of the SM EW baryogenesis is possible if

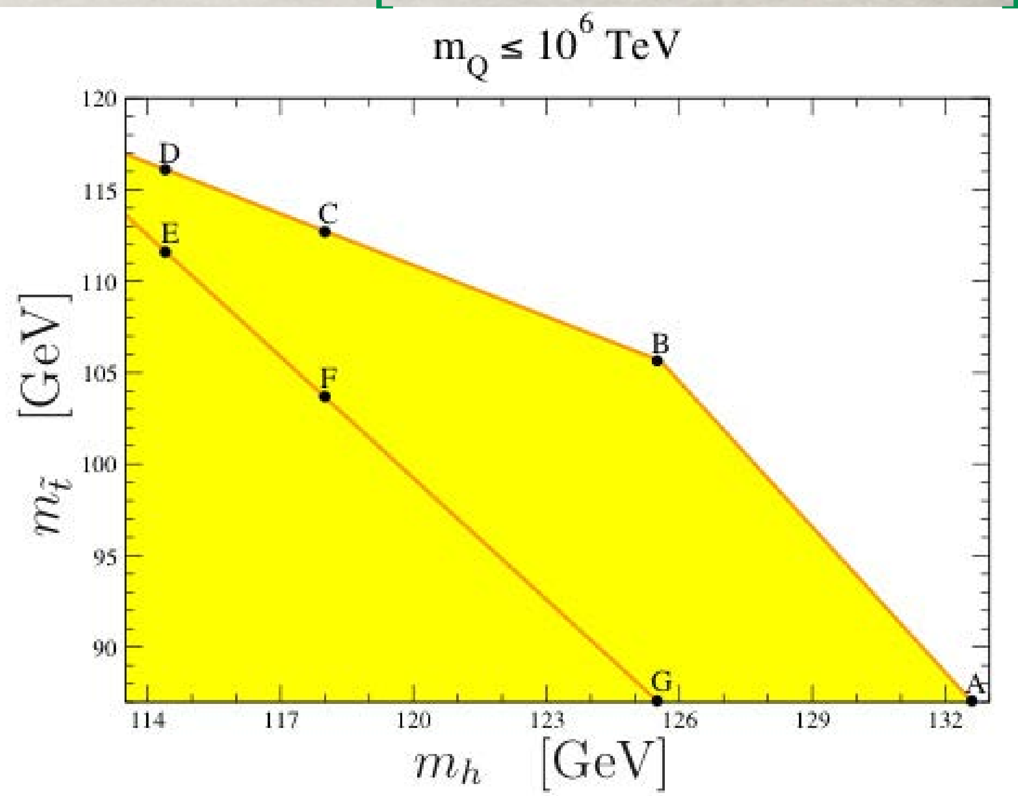
- The phase transition is stronger: e.g. by enhancing the cubic term in the Higgs potential thanks to (light) scalars, e.g. in SUSY stops or singlets !
- There are additional CP violating phases to increase the amount of CP violation.
- Still the Higgs has to be light... in MSSM EW baryogenesis ~ 120 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...

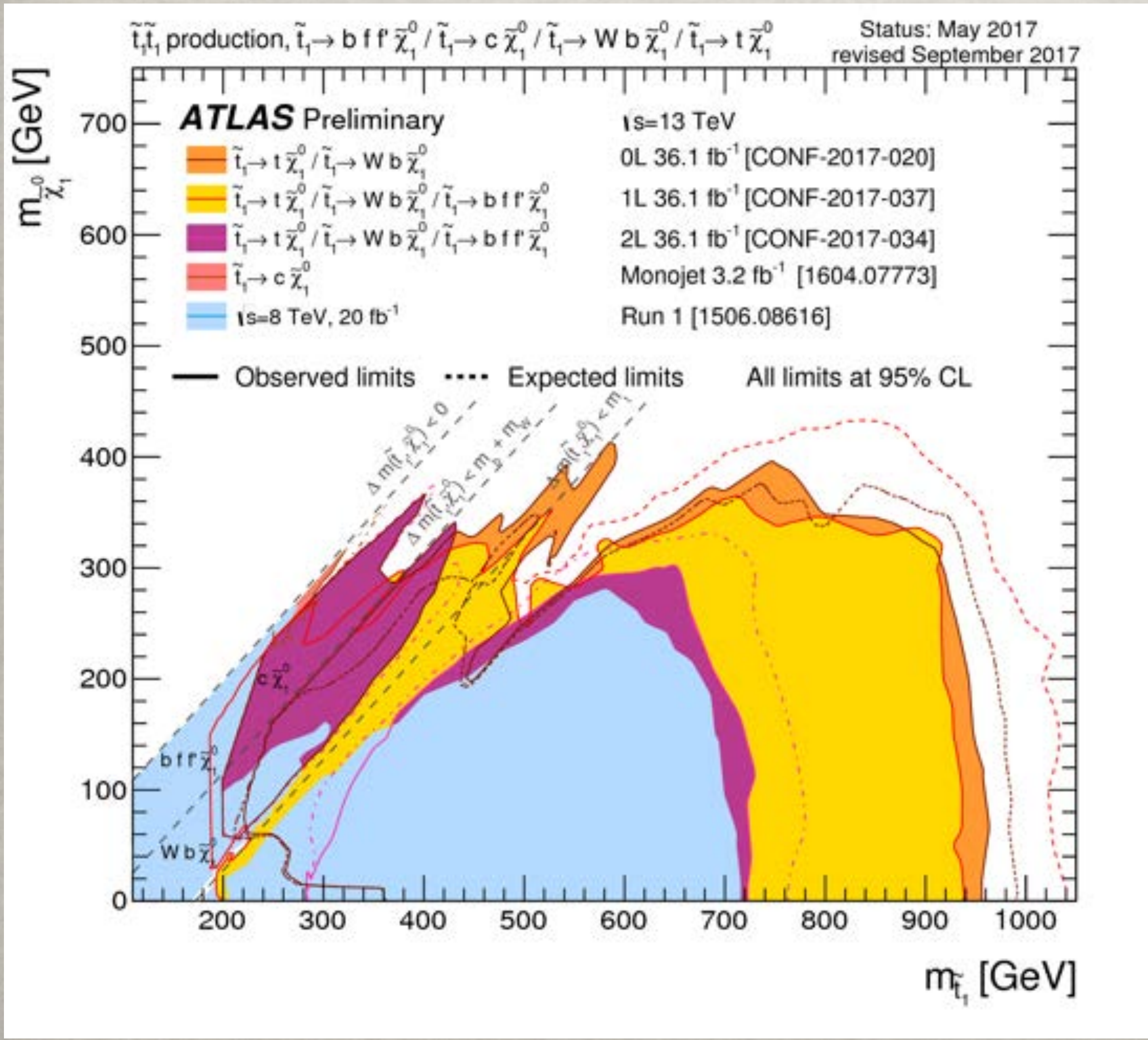


[Carena et al 1207.6330]



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

EW Baryogenesis in SUSY



New bounds on the stop mass seem to exclude nearly all the light stop mass region: probably need to go beyond MSSM for a 1st order phase transition !

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 $|H|^6$

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

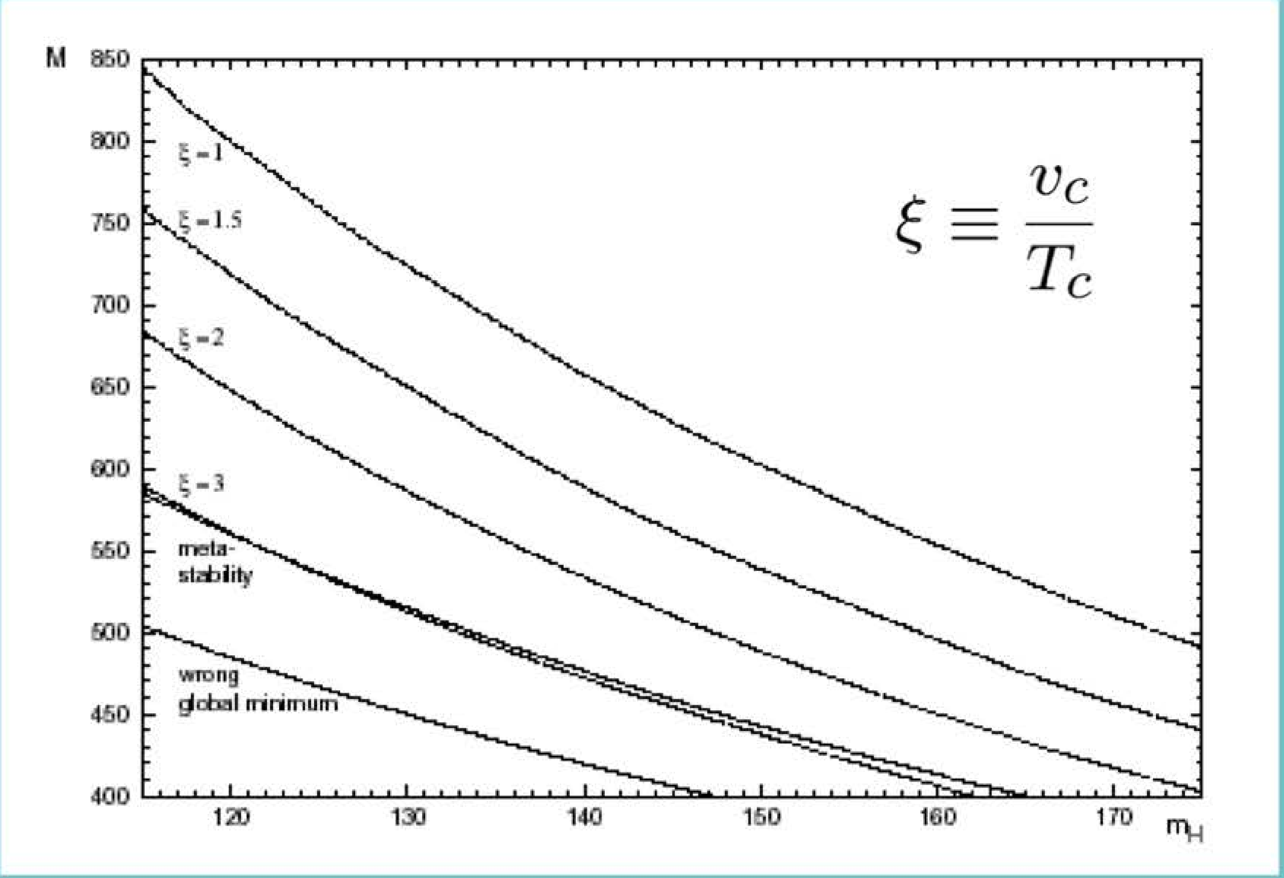
Results for the PT

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

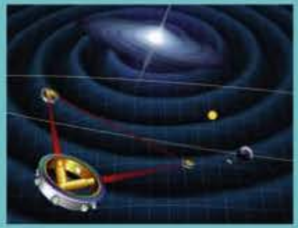
Electroweak baryogenesis?

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.)

Conclusions & Outlook

- In Cosmology we observe a non-vanishing baryon number suggesting the need of a mechanism for Baryogenesis. The SM does not seem to satisfy the Sakharov conditions, so we need to go Beyond the Standard Model !
- One possibility is to have baryogenesis at the electroweak phase transition, if it is strongly of the first order. It does not work for the SM, but it does in simple extensions: 2HDM, SUSY, Dimension 6 Operators, etc… Expect new particles/interactions even at LHC !!!