ICTP-TS/ICTP-SAIFR Summer School 2018

Sao Paulo, 18th - 29th June 2018

Particle Physics & the Early Universe

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen

$[q, p] = i\hbar$

elusives-invisiblesPlus
neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

Outline

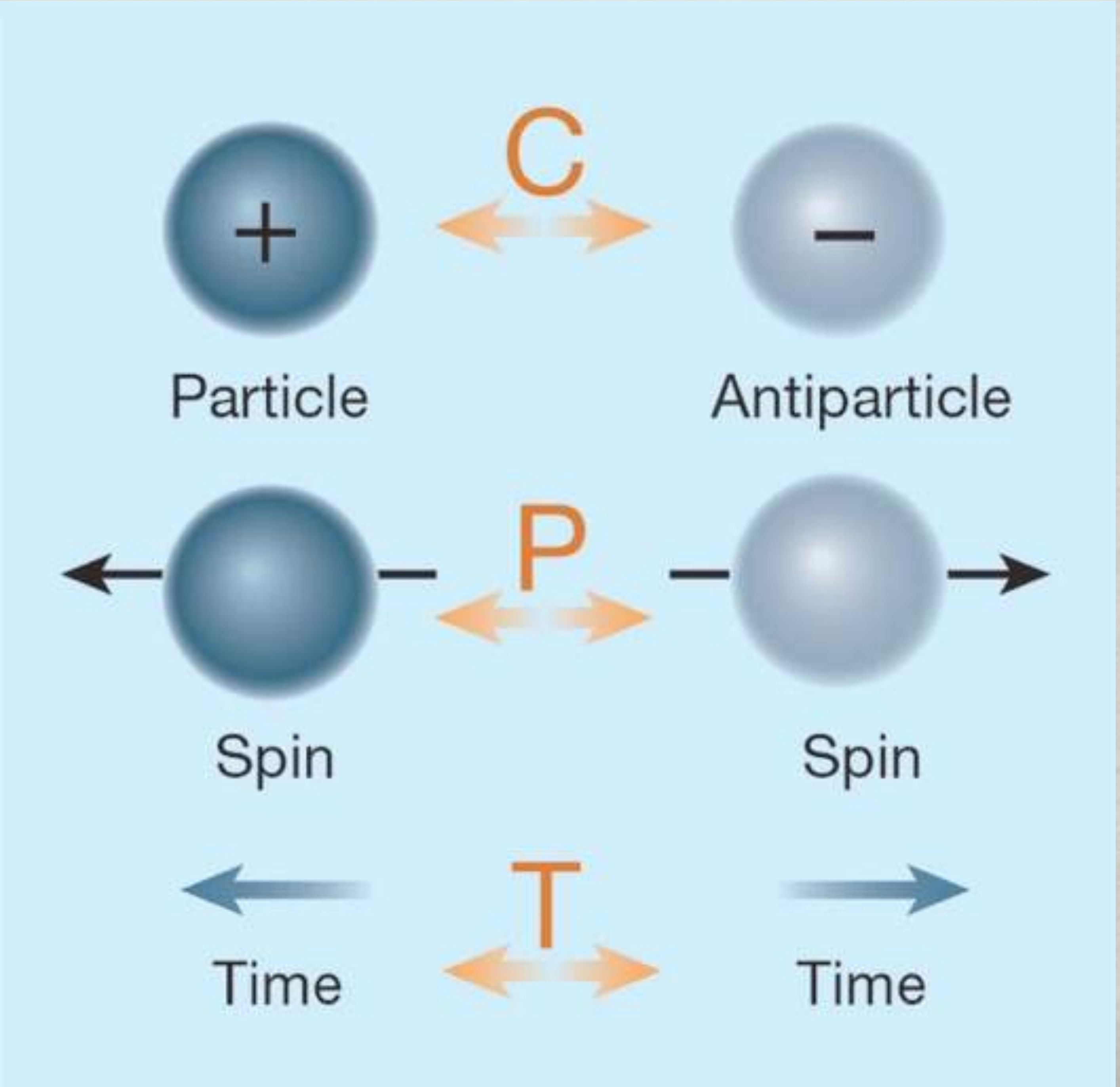
- Lecture 1: Standard Cosmology & the cosmological parameters
- Lecture 2: Thermal Universe and Big Bang Nucleosynthesis
- Lecture 3: Inflation & the CMB
- Lecture 4: Structure Formation & Dark Matter
- Lecture 5: Baryogenesis

Lecture 5: Outline

- CP violation in the SM and beyond
- Baryogenesis mechanisms
- Electroweak baryogenesis
- Leptogenesis
- Affleck-Dine baryogenesis
- Conclusions

CP violation in the SM & beyond

C, P, & T symmetries



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 !

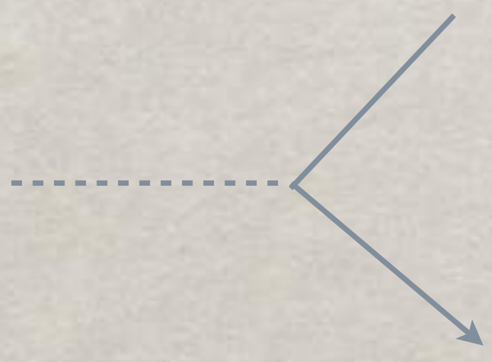
But not the same decay rate or scattering rate in the full quantum theory...

CP violation is quantum

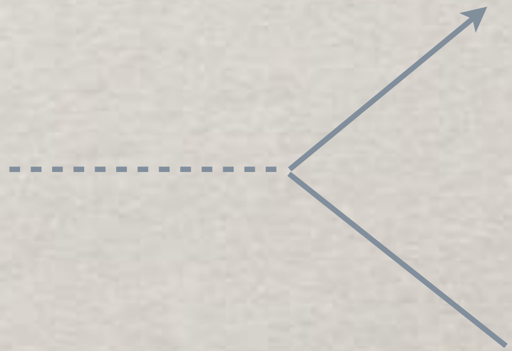
A theory violates CP if complex couplings are present, i.e.

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

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 !



$i\,\lambda$



$i\,\lambda^*$

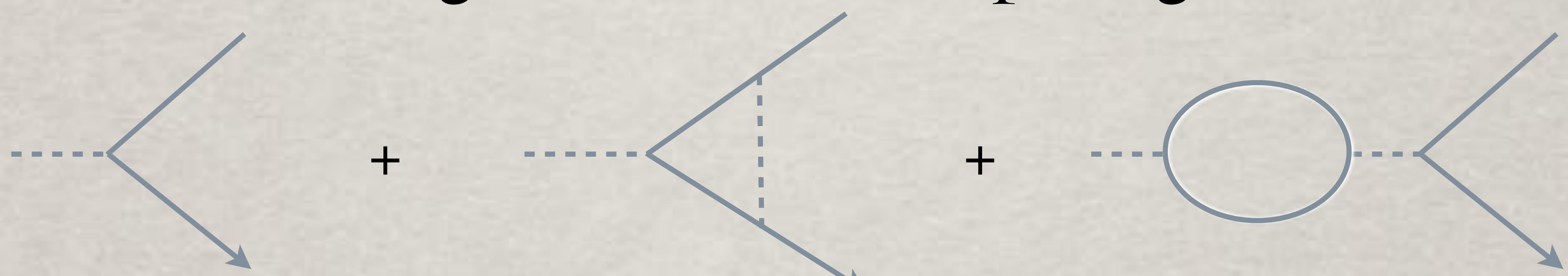
At Born level the matrix element for both decays is

$$\mathcal{M} \propto |\lambda|^2 = |\lambda^*|^2$$

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



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

So we have for particle & antiparticle:

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

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

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

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

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

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

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.

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:

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

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:

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

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

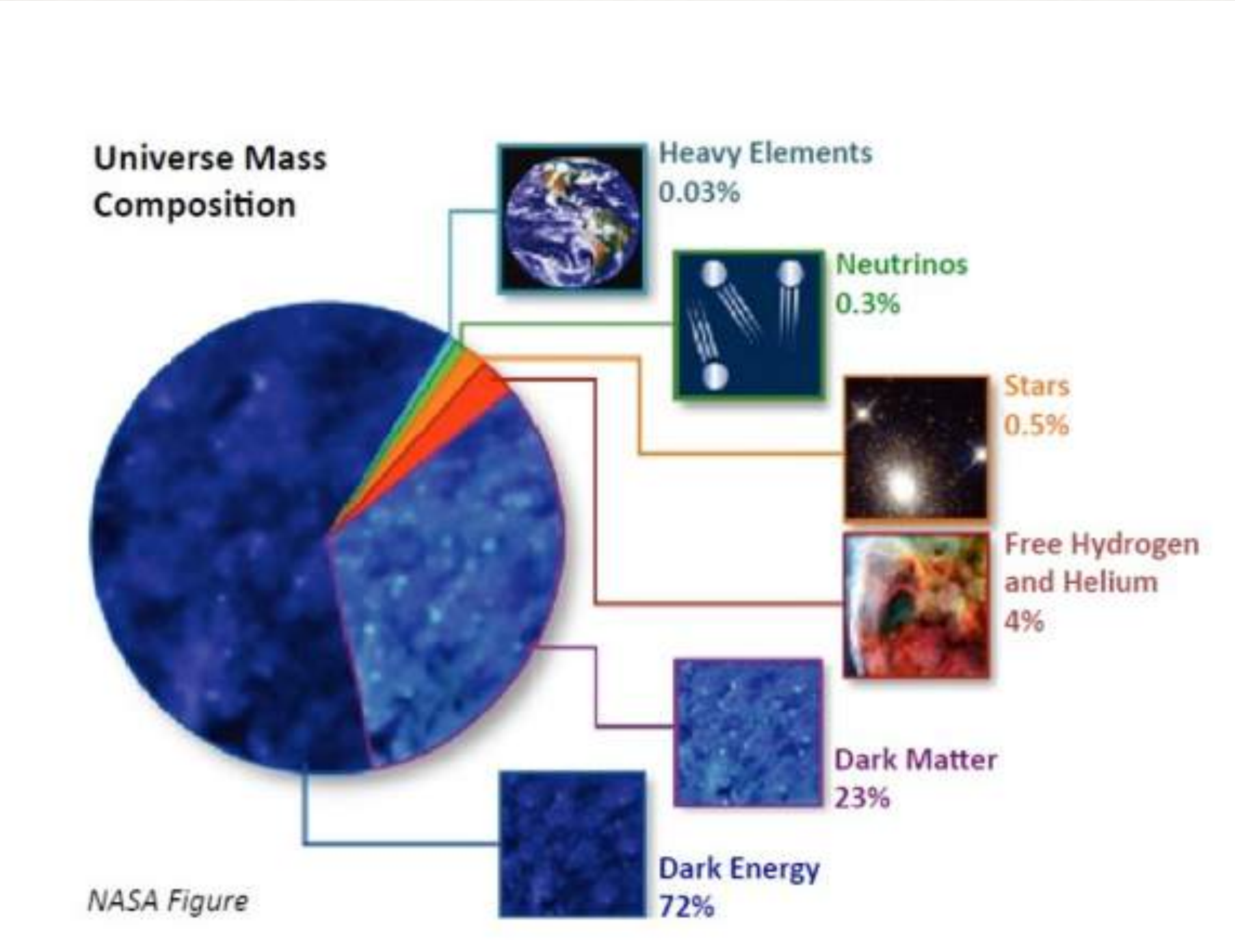
Pontecorvo-Maki-Nakagawa-Sakata mixing matrix with one Dirac phase δ and two Majorana phases α, β:

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

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



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

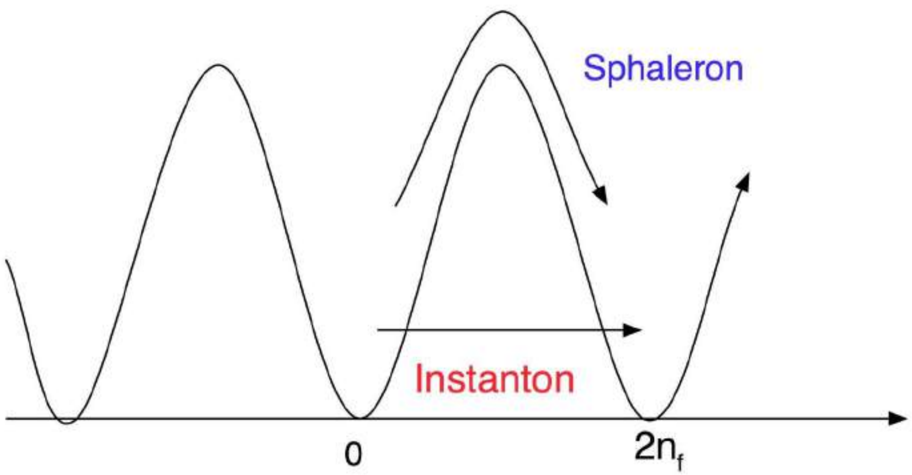
Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- 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 !

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

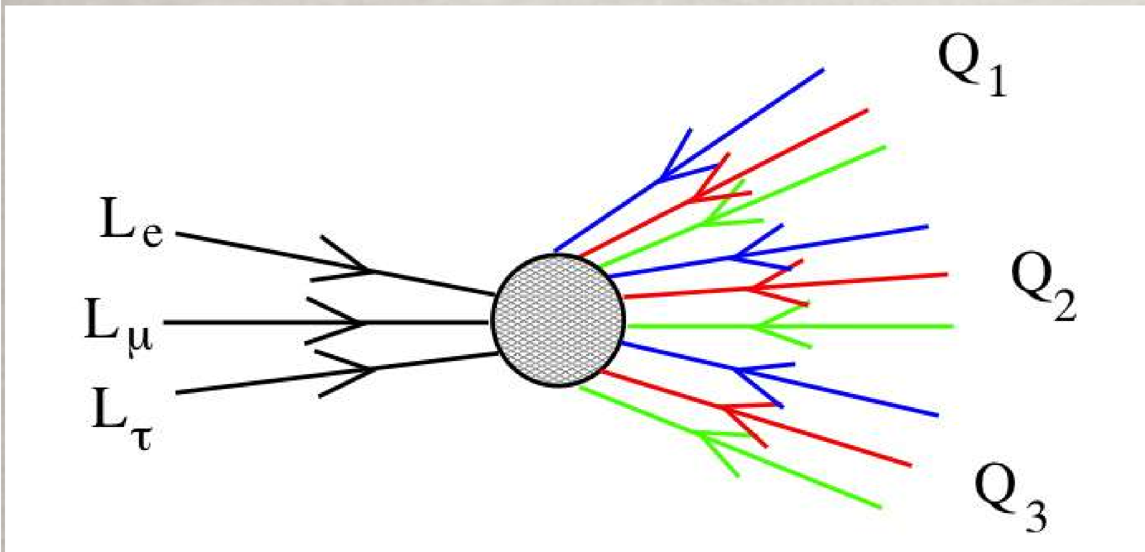
Let us check the Sakharov conditions for the SM:

- 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

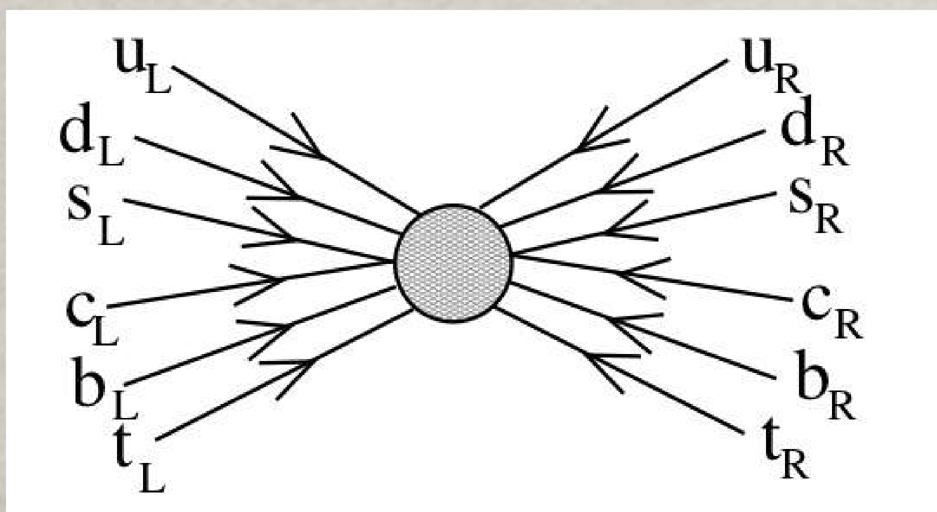
Possible to generate the BAU at the electroweak scale !

[Kuzmin, Rubakov & Shaposhnikov 1985]

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

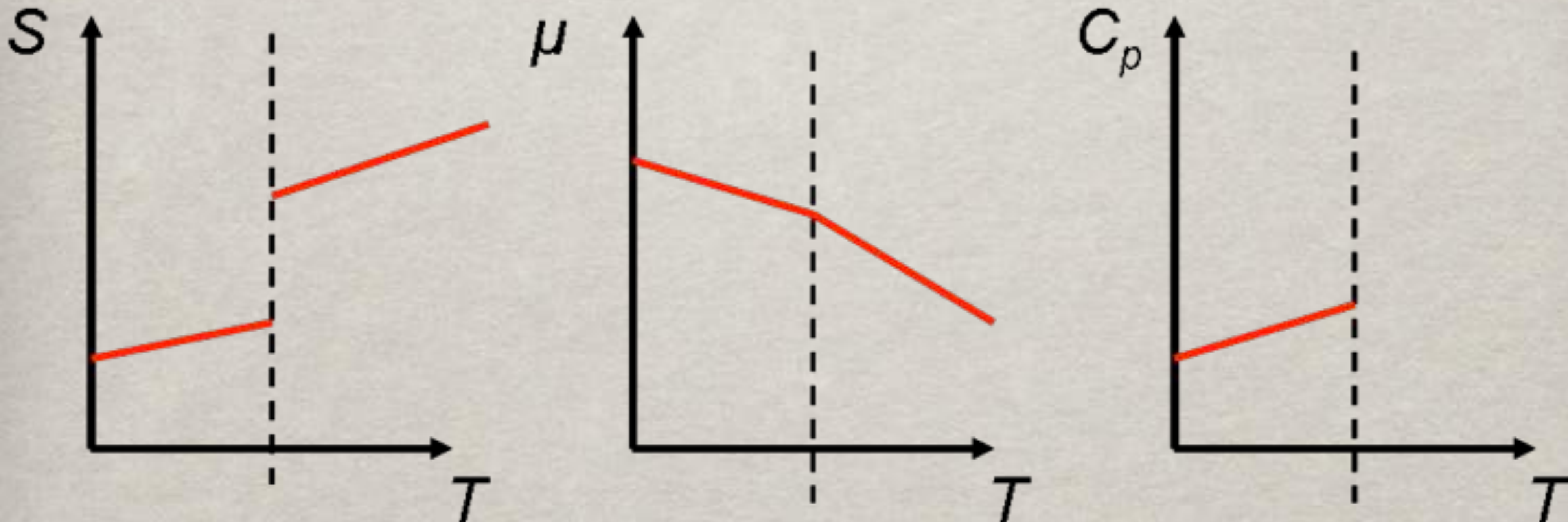


QCD Sphaleron:
chirality charge Q_5
changes by $2n_f$ units

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

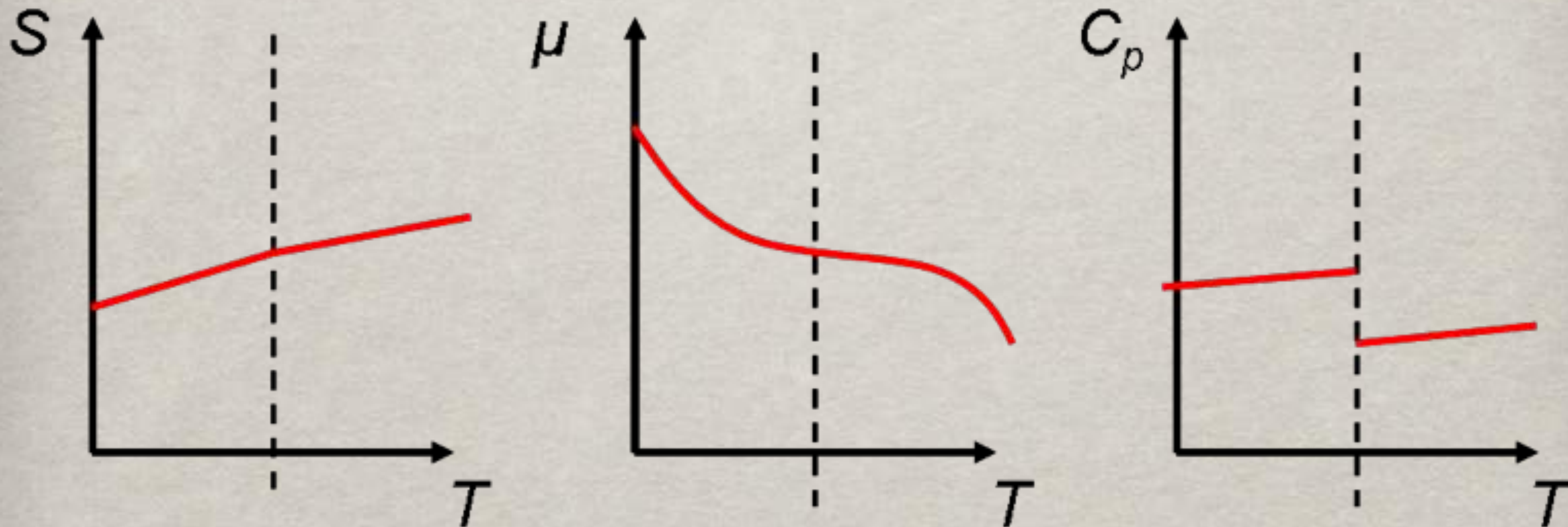


Also the order parameters display a discontinuity !

PHASE TRANSITIONS IN TD

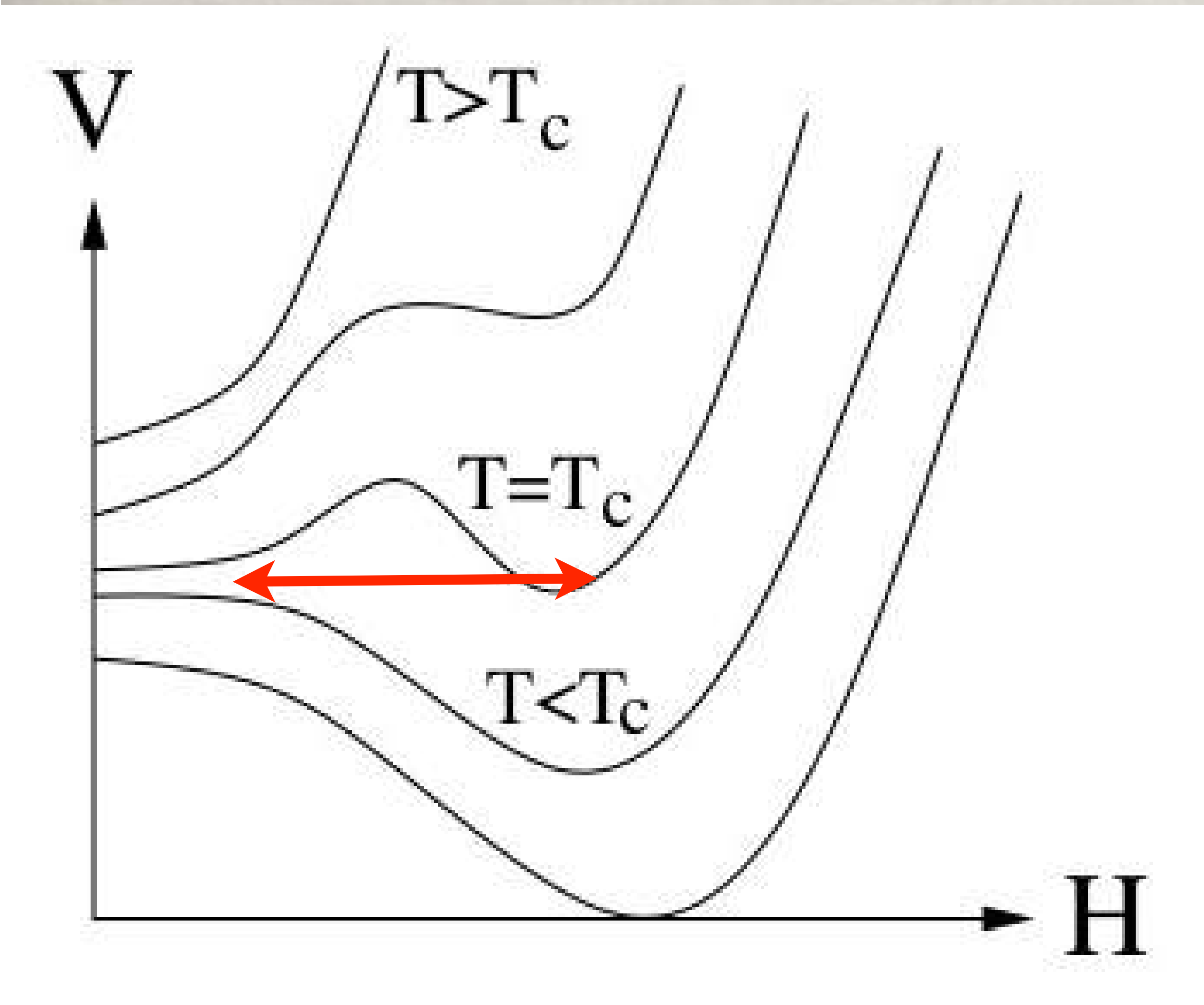
Ehrenfest classification: SECOND ORDER phase transition

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 changes continuously...

1st order transition

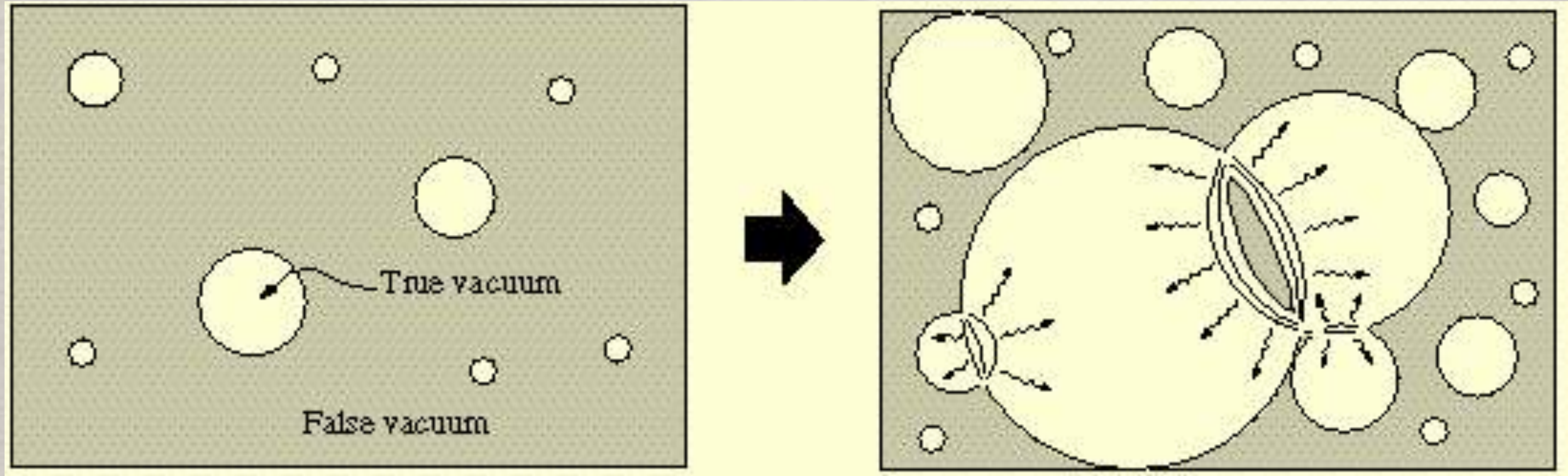


At the critical temperature the two vacuum are degenerate. After that temperature, the phase transition proceeds through a tunnelling process from the unstable vacuum at H=0 to the true vacuum with non-zero v.e.v.

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

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

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

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

Strong 1st order PT
B > 0

$\not{C}P$

$\not{C}P$

v_W

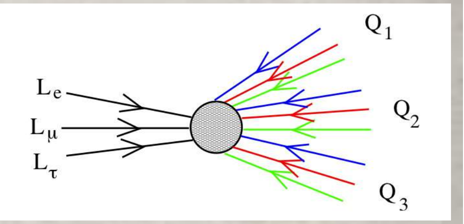
L_W

$\not{C}P$

$\not{C}P$

Unbroken phase

$$\Gamma_{sph} > H$$

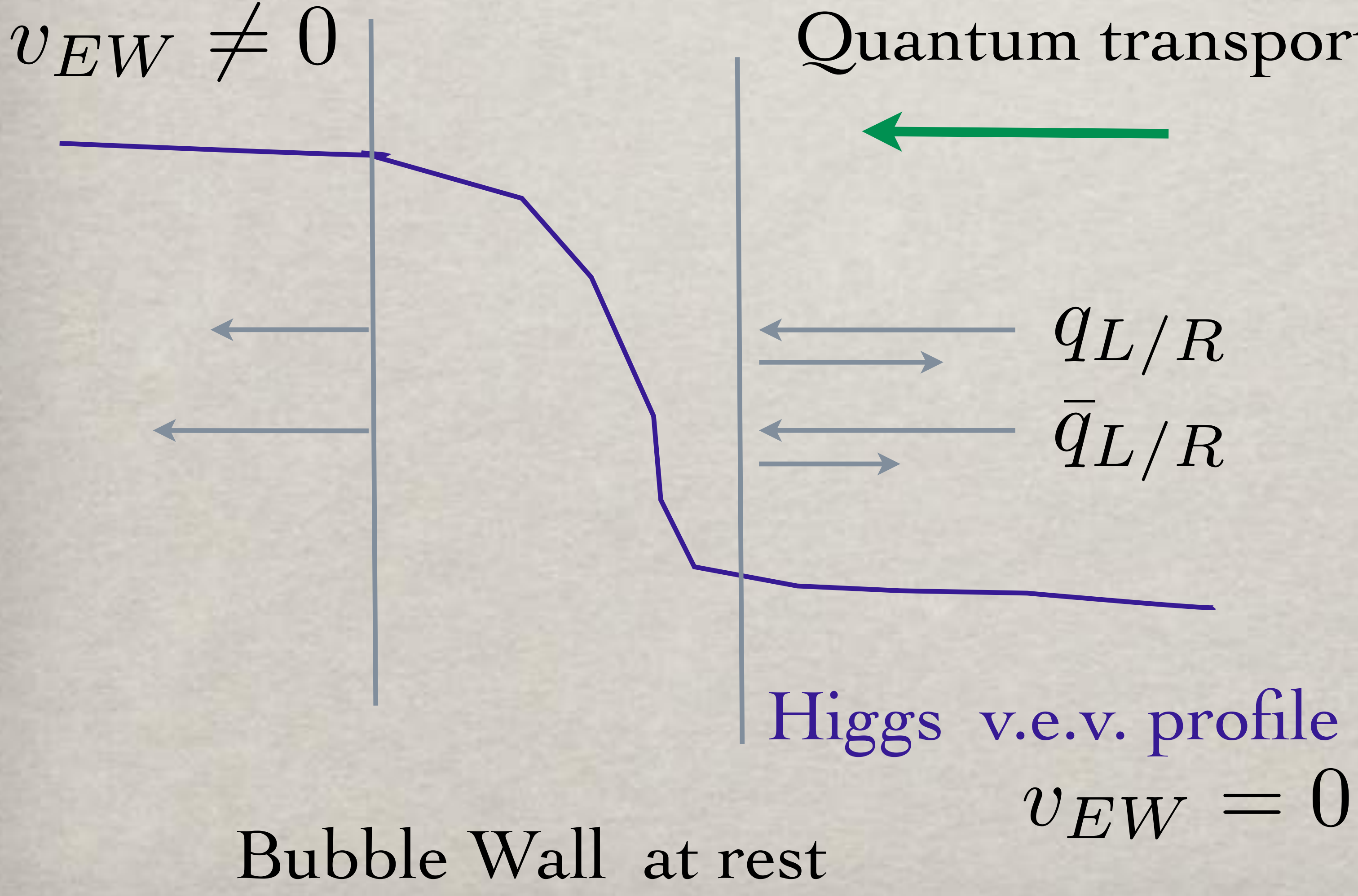


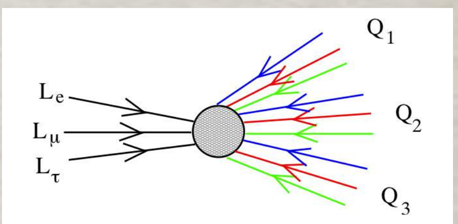
B=0

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.

Quantum transport equation





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

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

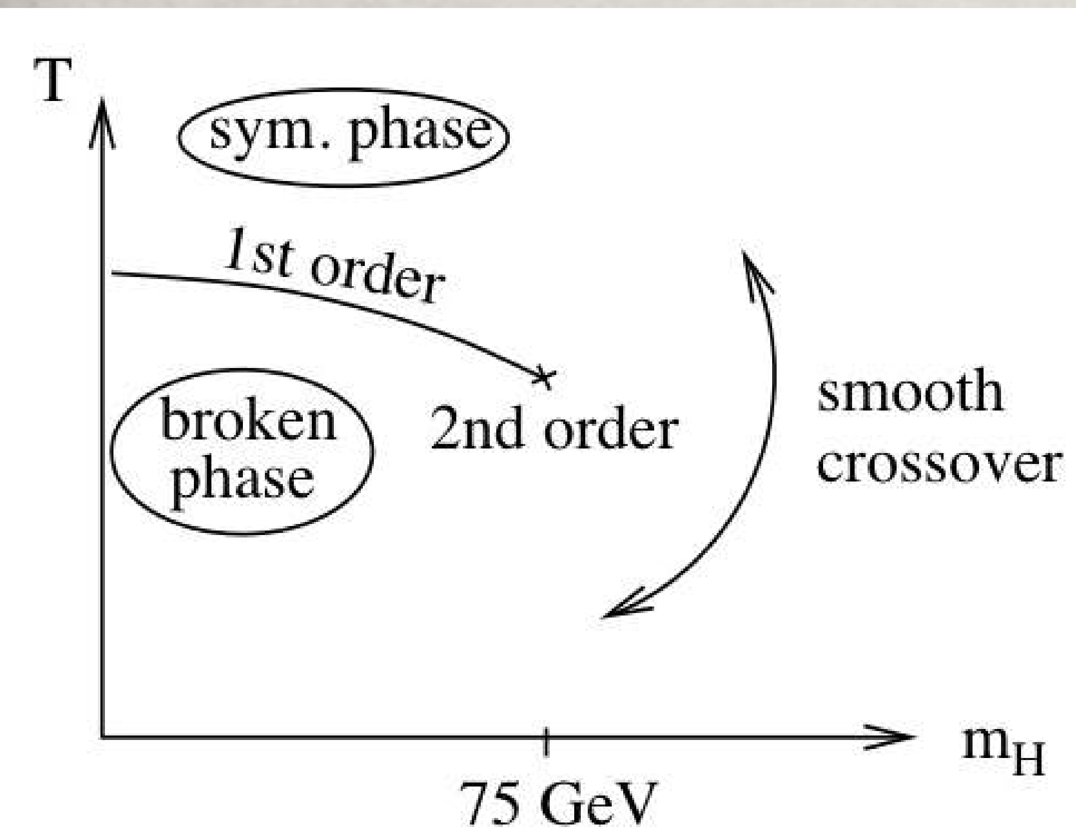
Caveat: perturbative computation is not trustworthy at the critical temperature

$\longrightarrow$ Lattice computations

Only if the transition is sufficiently strong, i.e. $\dfrac{v_c}{T_c} > 1$ 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 !



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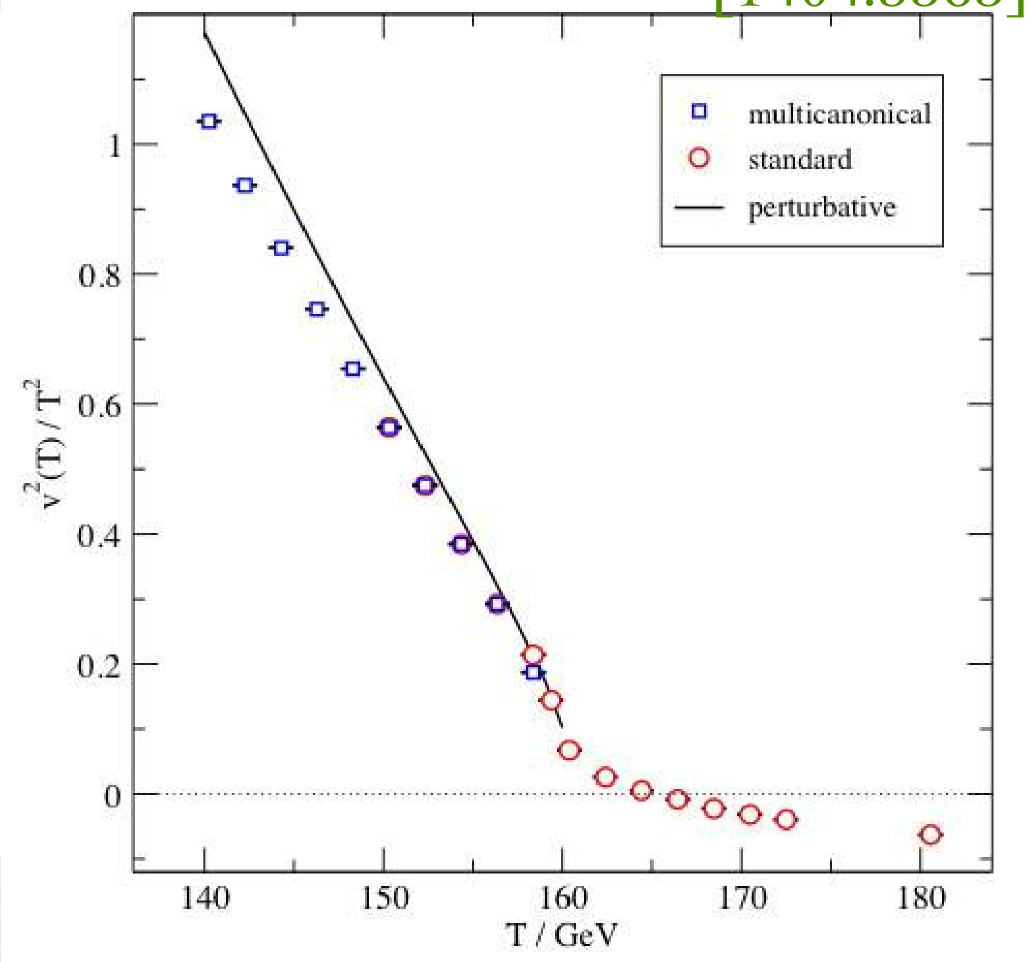


NO EW baryogenesis in the SM !

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 !

Baryogenesis mechanisms

Again need to go beyond the Standard Model :

- EW baryogenesis in extensions of the SM with: more scalars, more CP violations... This is possible in Supersymmetry, but also without.
- Leptogenesis: generate first L via decay of heavy Majorana neutrinos -> connection to the see-saw mechanism and neutrino masses.
- Affleck-Dine baryogenesis: store baryon number in a scalar condensates and transfer it to particles when the condensate decays. Mostly studied in SUSY !

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

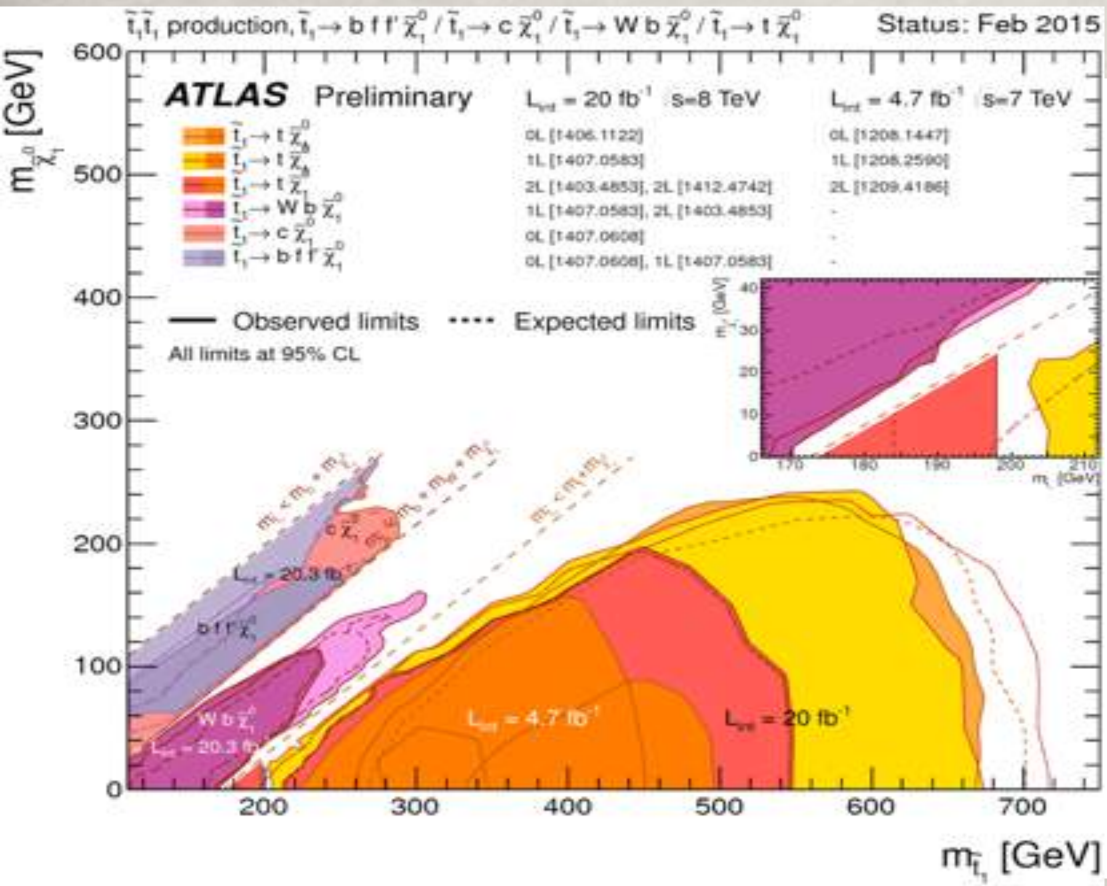
Bosonic Loops contribute to E(T), increasing the strength of the phase transition, so in order to make it first order increase the number of bosons in the model !

Many different possibilities, the simplest ones are:

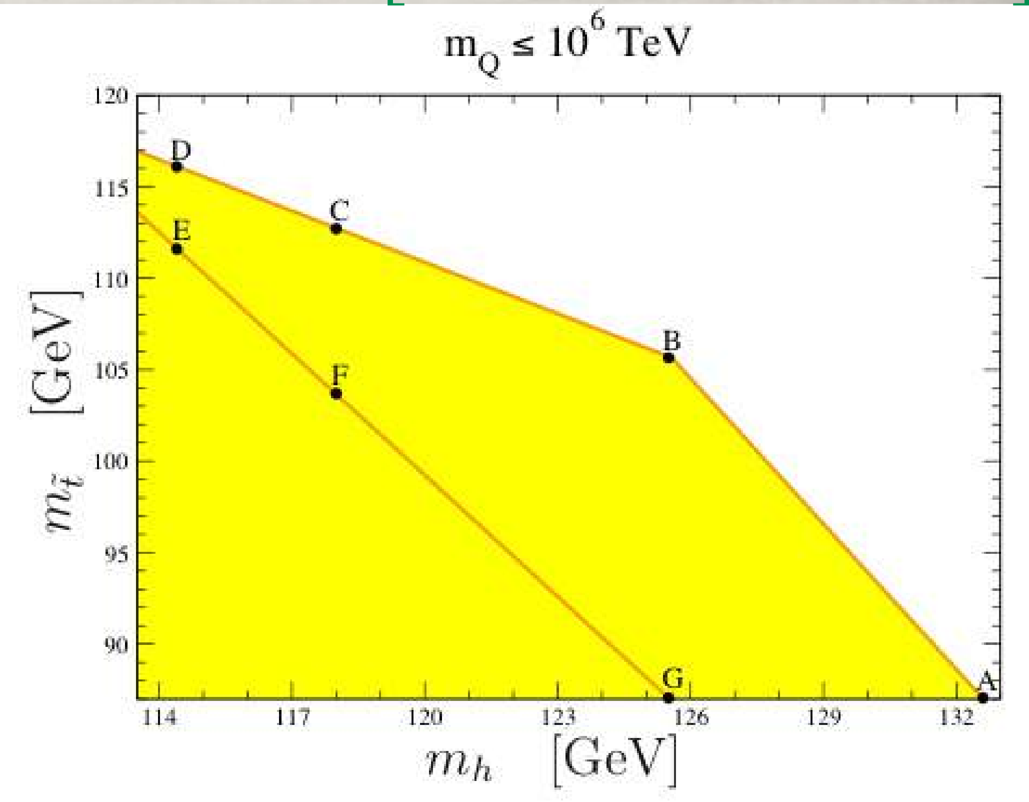
- extend the scalar/Higgs sector of the SM;
- add supersymmetry;
- add higher dimensional operators.

EW Baryogenesis 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...

Leptogenesis

Baryogenesis via Leptogenesis

[Fukugita & Yanagida '86]

Produce the baryon asymmetry from an initial lepton asymmetry reprocessed by the sphaleron transitions. Naturally possible in the case of see-saw mechanism for generating the neutrino masses.

$$W = Y_\nu LHN + \frac{1}{2} M_R NN \quad \longrightarrow \quad \text{see-saw}$$

Moreover the RH Majorana neutrino can generate a lepton asymmetry via decay if the rate also violates CP

$$N \to \ell \, H \qquad N \to \bar{\ell} \, H^\star$$

Both channel are possible due Majorana nature of N !

Neutrino masses & seesaw

[Minkowski 77, Gell-Mann, Ramond & Slanski 79, Yanagida 80]

Try to explain why the neutrino masses are so small: via the mixing with a very heavy state, the RH neutrino N !

$$W = Y_\nu L H N + \frac{1}{2} M_R N N$$

After the EW symmetry breaking we have a mixing between the LH neutrino and N and a Majorana mass term:

$$m_{N\nu} = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

Eigenvalues:

$$m_\nu = -\frac{m_D^2}{M_R}, \; m_N = M_R$$

→ see-saw mechanism   The larger M_R the smaller m_ν

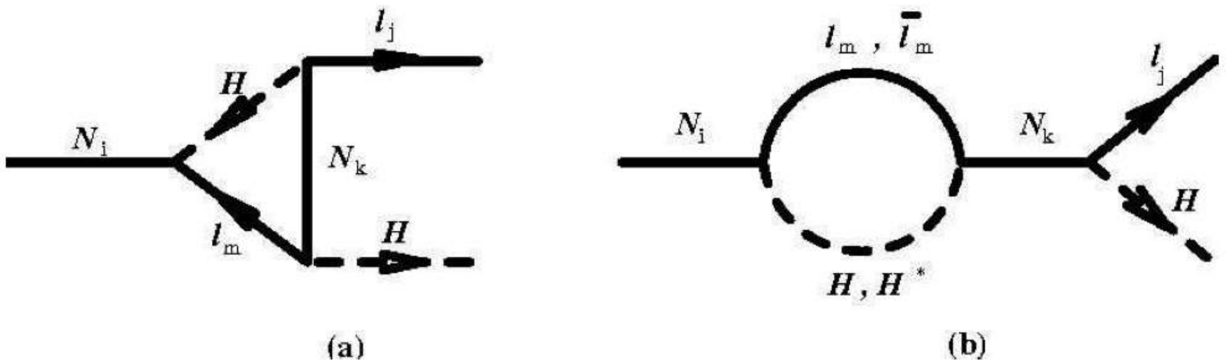
For $m_D \sim m_t$ need $M_R \sim 10^{15}\text{GeV}$

Thermal Leptogenesis

CP violation in N decay

We have CP in the decay of N if the couplings are complex.

CP violation always arises from an interference: tree + one-loop diagrams



We can define

$$\epsilon_i = \frac{\Gamma(N_i \to L) - \Gamma(N_i \to \bar{L})}{\Gamma(N_i \to L) + \Gamma(N_i \to \bar{L})} = -\frac{3}{16\pi} \sum_{i \neq j} \frac{M_i}{M_j} \frac{\Im[(Y_\nu^\dagger Y_\nu)^2_{ji}]}{(Y_\nu^\dagger Y_\nu)_{ii}} \text{for} M_i \ll M_j$$

It is bounded !

$\rightarrow$relation to neutrino masses via Y_ν...

$$\epsilon \leq 10^{-6} \left(\frac{M_1}{10^{10}\ \mathrm{GeV}} \right) \frac{m_{atm}}{m_1 + m_3}$$

[Davidson & Ibarra 02]

Thermal Leptogenesis

The "back of the envelope" computation:

Out of equilibrium decay

To generate the lepton asymmetry we need also departure from thermal equilibrium: out of equilibrium decay of the lightest N. This happens if $\Gamma_1 \leq H$ at $T \sim M_1$.

$$\Gamma_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_1 \leq H = \sqrt{\frac{\pi^2 g_*}{90}} \frac{M_1^2}{M_P}$$

$\Rightarrow M_1 \geq \sqrt{\frac{90}{\pi^2 g_*}} \frac{(Y_\nu^\dagger Y_\nu)_{11}}{16\pi} M_P$, i.e. the RH neutrino have to be sufficiently massive. Or one can refrase it as

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} \leq \sqrt{\frac{\pi^2 g_*}{90}} \frac{v^2}{M_P} \sim 10^{-3}\text{eV}$$

If this condition is satisfied, then it is trivial to see that every N gives an ϵ amount of lepton number and the final asymmetry is simply

$$\frac{n_L}{s} = \frac{n_{B-L}}{s} = \frac{135\zeta(3)g}{8\pi^4 g_S}\epsilon_1 \simeq 4 \times 10^{-3}\epsilon_1 \quad \rightarrow \frac{n_B}{s} \sim -1.5 \times 10^{-3}\epsilon_1$$

Otherwise one has to solve a couple of Boltzmann equations...

Thermal Leptogenesis

The solution of the coupled Boltzmann equations:

$$x = \frac{M_1}{T} \qquad Y_i = \frac{n_i}{s}$$

[Buchmüller, Di Bari & Plümacher '04]

$$\begin{cases} \dfrac{dY_{N_1}}{dx} = -(\Gamma + \sigma)(Y_{N_1} - Y_{N_1}^{eq}) \\ \dfrac{dY_{B-L}}{dx} = -\epsilon_1 \Gamma (Y_{N_1} - Y_{N_1}^{eq}) - W\, Y_{B-L} \end{cases}$$

Decay+Scattering

Asymmetry in the Decay

Wash-out term

Source of Lepton number

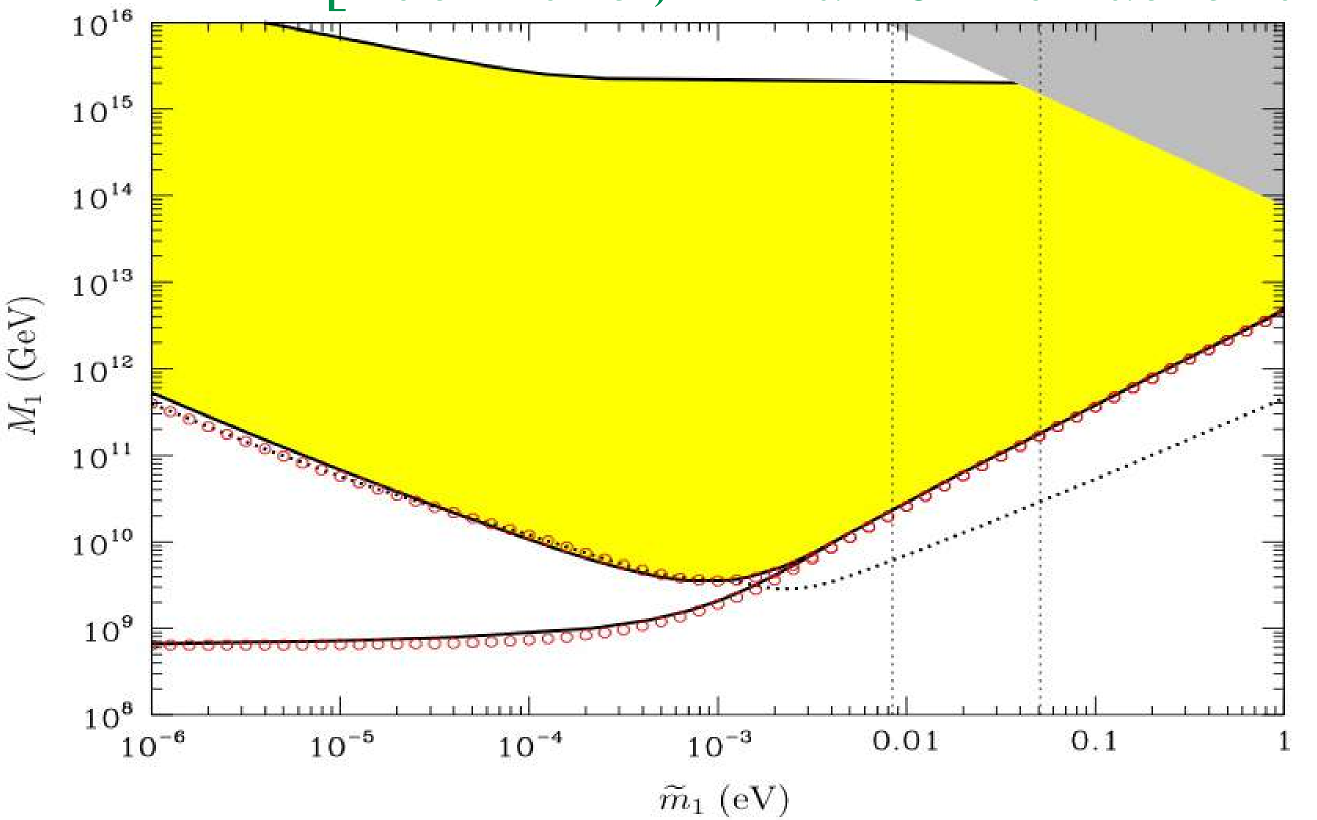
Final result: $Y_{B-L} = \epsilon_1\, \kappa\, Y_{N_1}(x \sim 1)$

Efficiency factor

Thermal Leptogenesis

M_1 must be large enough to generate the baryon asymmetry, for small M_1 the CP violation is just too small. Need large T_{RH} to produce the RH neutrino...

[Buchmüller, Di Bari & Plümacher 04]



Ways out: enhanced CP violation due to degenerate N's, non-thermal leptogenesis, etc...

Low E vs high E CP ?

One important question is if the low energy leptonic CP violation observables are related to the CP violation in leptogenesis... Unfortunately not directly !

Simple parameter counting:

the 3x3 Majorana (low energy) mass matrix contains 9 real parameters, i.e. 3 masses, 3 mixings and 3 phases (1 Dirac & 2 Majorana phases), while the (high energy) Yukawa matrix & RH neutrino mass matrix amount instead to 18 real parameters.

In general the measurable low-energy Dirac phase in the neutrino sector is given by a complicated of the high energy parameters ! Nevertheless in specific models definite predictions are possible, e.g. 2 RH neutrino case or some flavoured leptogenesis cases...

Flavored Leptogenesis

[Abada et al, Nardi et al ‘06, De Simone et al ‘07....]

In the early universe the charged leptons have different thermal equilibration time due to the different Yukawa couplings, so the coherence of the light neutrino combination coupling to N_1 is not always ensured.

$T > 10^{12}\mathrm{GeV}$	Single flavour: all leptons NEQ	
$T \sim 5 \times 10^{11}\mathrm{GeV}$	Tau Yukawa is in equilibrium	2Flav
$T \sim 2 \times 10^{9}\mathrm{GeV}$	Muon Yukawa is in equilibrium	3Flav
$T \sim 4 \times 10^{4}\mathrm{GeV}$	Electron Yukawa is in equilibrium	

Depending on the epoch of leptogenesis, one may have to consider flavour effects !

Flavored Leptogenesis

[Abada et al, Nardi et al '06, De Simone et al '07....]

In presence of flavour, Yukawa scattering processes destroy coherence and project the lepton combination down to the flavour eigenstates. One can then define a CP asymmetry for every relevant flavour:

$$\epsilon_{1\alpha} = \frac{P_{1\alpha}\Gamma_1 - \bar{P}_{1\alpha}\bar{\Gamma}_1}{\Gamma_1 + \bar{\Gamma}_1}$$

Similarly also wash-out processes can be different for the different flavours. So the possibility arises to store lepton number in the flavour with smaller wash-out rate !

More successful leptogenesis regions open up in general, but the prediction become flavour model-dependent.

Flavored Leptogenesis

[Abada et al, Nardi et al '06, De Simone et al '07....]

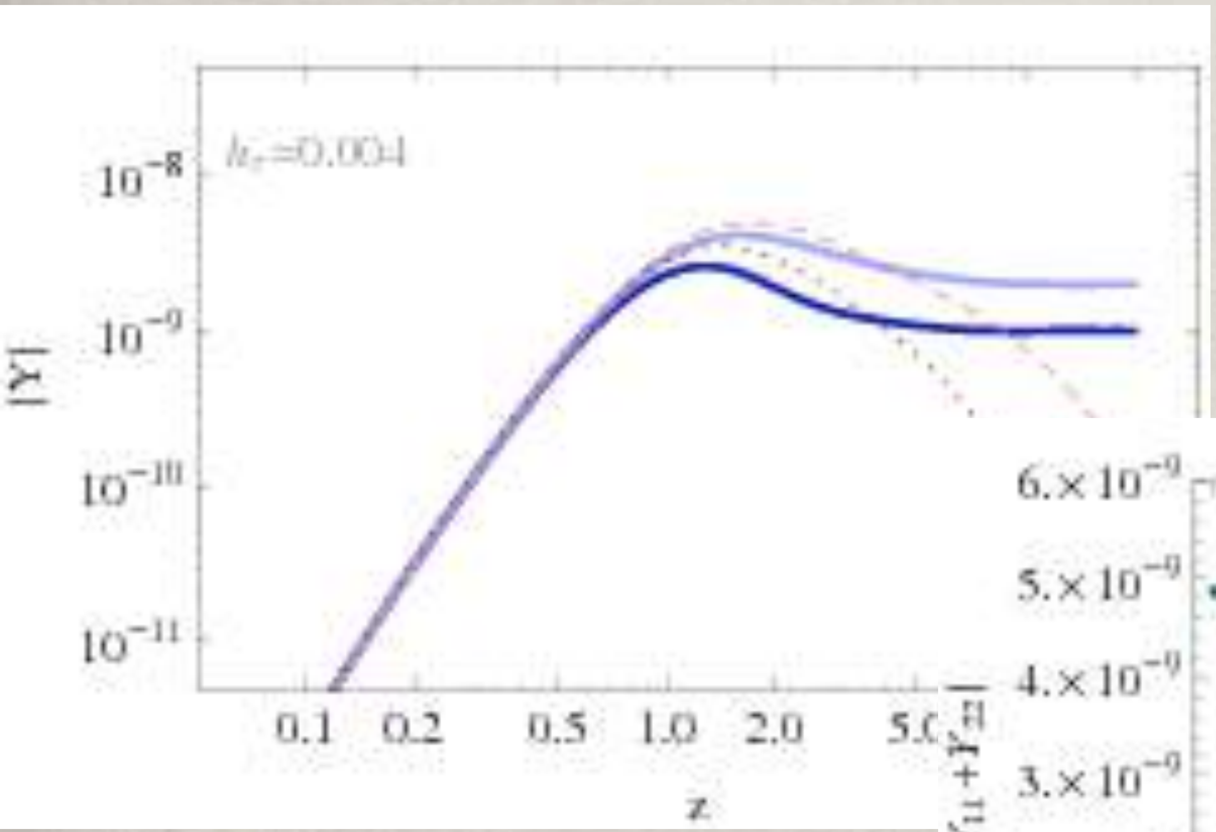
Different formalisms can be used to take into account flavour, depending on the regime.
Away from the transition between 1 - 2 flavours, one can use a flavoured Boltzmann equation, but this cannot take into account oscillations effects !

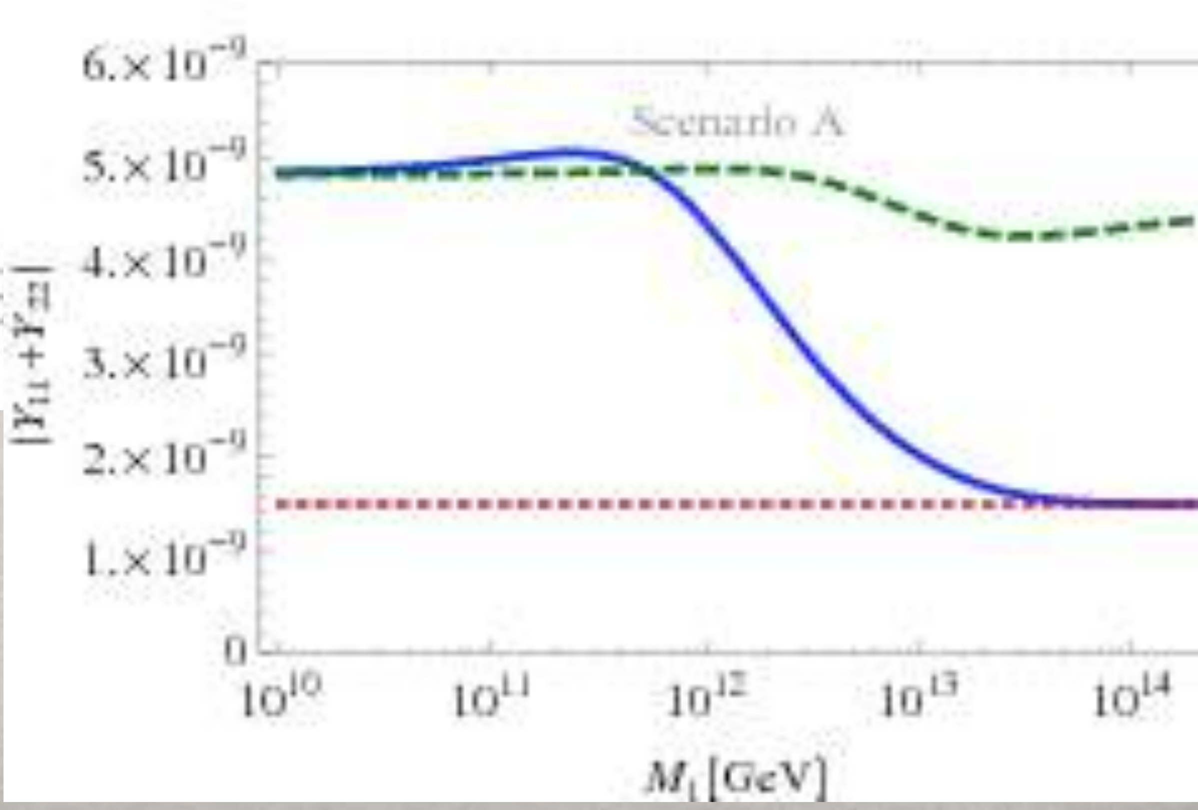
Another formalism is based on the full density matrix in flavour space and takes into account also the off-diagonal part, not included in the Boltzmann equations.

$$i\hbar\frac{\partial\rho}{\partial t} = [H, \rho]$$

Quantum flavored Leptogenesis

[Beneke et al, 1007.4783]



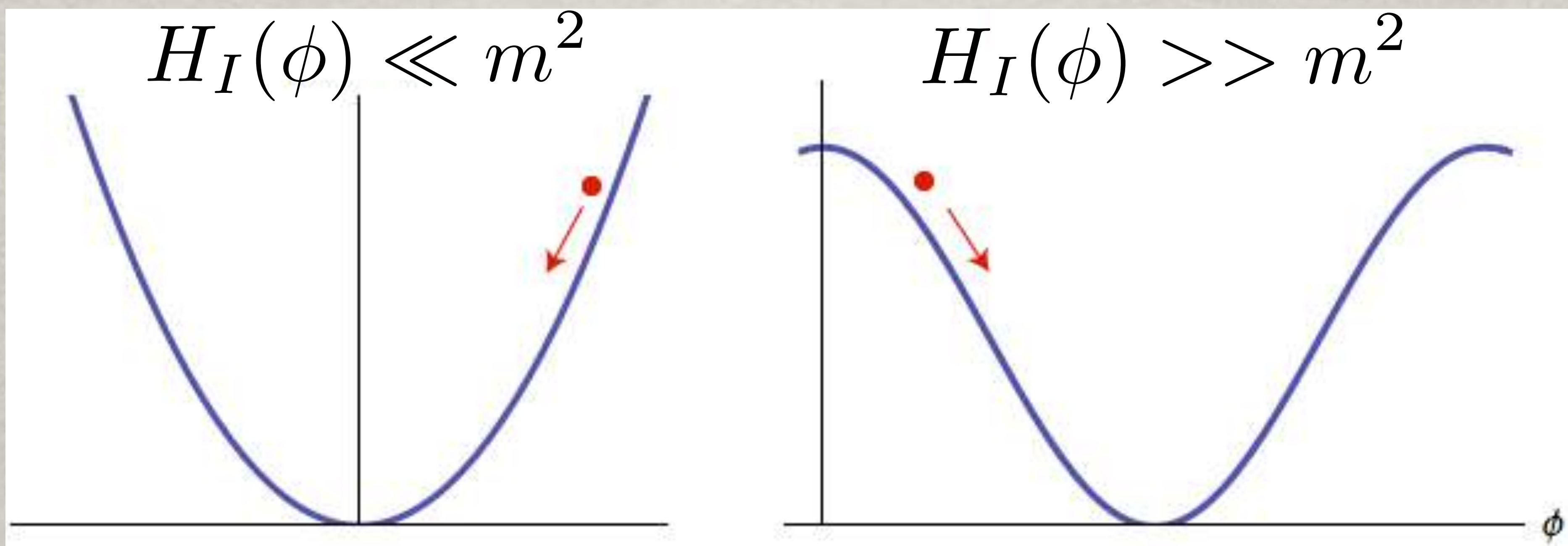


Affleck-Dine baryogenesis

Light Field in cosmology

During inflation all scalar fields obtain a mass of order H_I which can be even negative and can effectively change the minimum of the scalar potential.

$$V(\chi) = \frac{1}{2}m^2\phi^2 - c\,H_I^2(\phi)\chi^2 + \ldots$$



Light Field in cosmology

Moreover in cosmology a friction term appears in the equation of motions, due to the Universe's expansion:

$$\ddot{\chi} + 3H\dot{\chi} + (m^2 - 2c\, H^2)\chi + \ldots = 0$$

As long as $H > m$ the friction term dominates and the equation of motion is that of an overdamped harmonic oscillator. Therefore the field remains blocked at a constant value, even if it is not the minimum of the potential !

Only when H decreases sufficiently, can the force term overcome the friction and the classical field value goes towards the minimum.

Affleck-Dine Baryogenesis

[Affleck & Dine '85]

In the presence of Baryon-number carrying (complex) scalar fields, we see that the baryonic current is proportional to the time-derivative of the field phase:

$$n_b = j_b^0 = -i(\phi^* \partial^0 \phi - \phi\, \partial^0 \phi^*) = |\phi|^2\, \dot{\theta}$$

A non-trivial dynamic in the angular direction in a scalar condensate can generate a baryon asymmetry !

Need CP violating equation of motions, so that Real and Imaginary part of the scalar condensate evolve differently. In supersymmetric models such CP violating terms are naturally given by complex trilinear couplings A. "Out of equilibrium" condition provided by inflation...

Affleck-Dine Baryogenesis

[Affleck & Dine '85]

Consider for example a SUSY colored flat direction lifted only at the non-renormalizable level by

$$W = \frac{\lambda\, \chi^n}{n\, M_P^{n-3}}$$

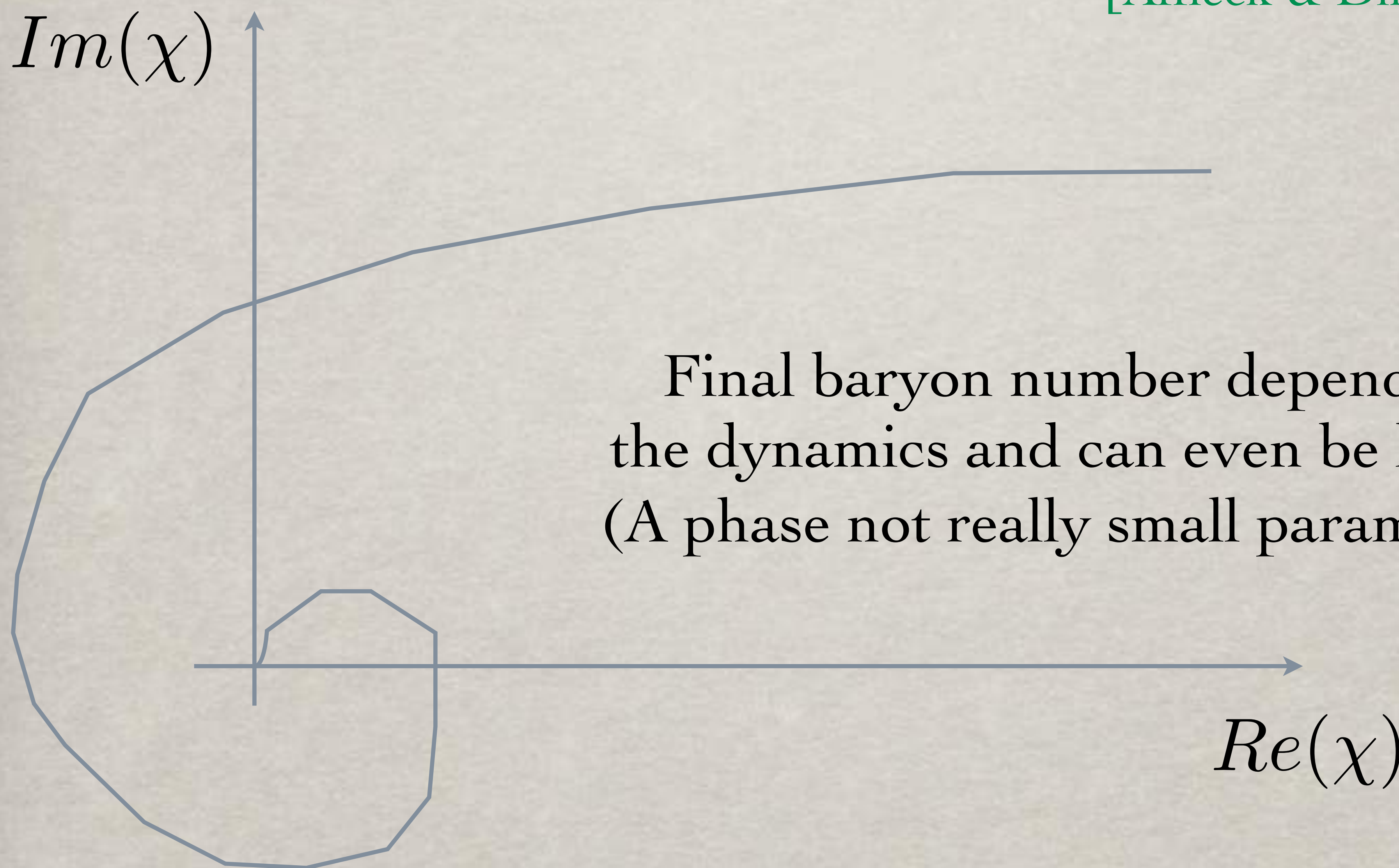
during inflation ($H_I >> m_{3/2}$) the v.e.v. sets at a large scale, while it relaxes later to the minimum at 0

$$V(\chi) = (m_{3/2} - cH_I^2)|\chi|^2 + \left[\lambda(aH_I + Am_{3/2})\frac{\chi^n}{nM_P^{n-3}} + h.c.\right] + |\lambda|^2 \frac{|\chi|^{2n-2}}{M_P^{2n-6}}$$

As long as $H_I >> m_{3/2}$ the mass term is negative and the scalar field acquires a non-zero vacuum expectation value away from the true minimum for $H_I \sim 0$.

Affleck-Dine Baryogenesis

[Affleck & Dine '85]



Final baryon number depends on the dynamics and can even be large...
(A phase not really small parameter !)

But advantage: AD mechanism also effective at low T !

Affleck-Dine Baryogenesis

[Affleck & Dine '85]

During the relaxation we obtain a non-trivial baryon number if the trilinear coupling is complex since

$$\partial^0 n_b \sim -i(\chi^* \frac{\partial V}{\partial \chi} - h.c.) = -i|\chi|^2 m_{3/2} \left(\lambda A \frac{\chi^{n-2}}{M_P^{n-3}} - h.c. \right)$$

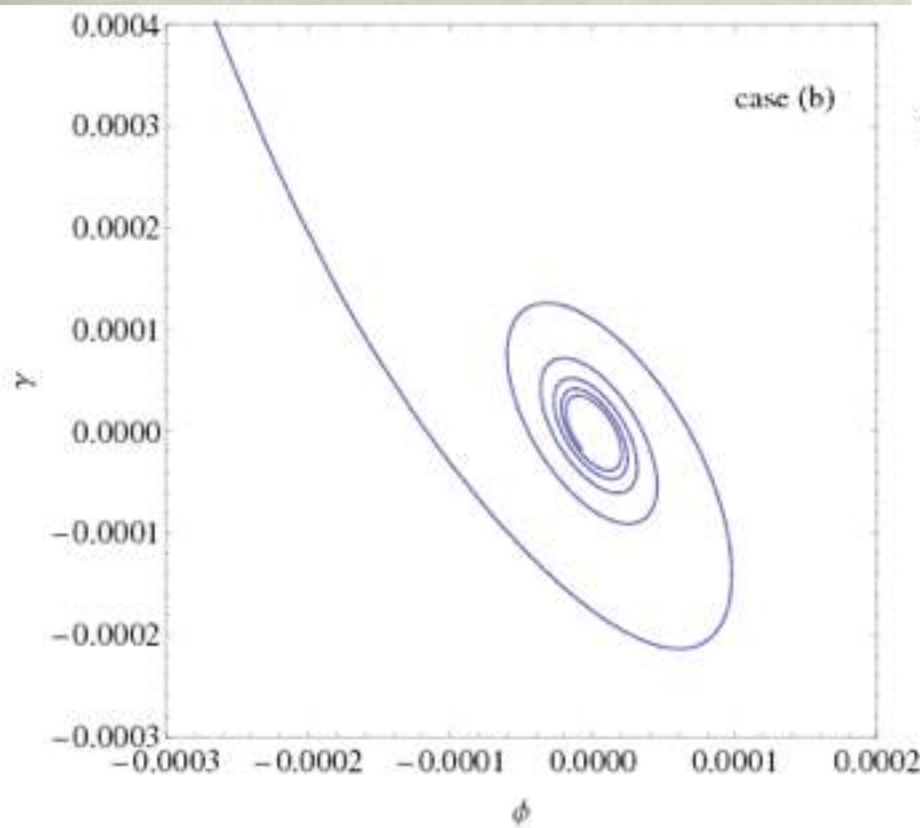
The main effect arises for large v.e.v of the field !
The value can oscillate with χ and it is transferred to fermions at the time the condensate decays:

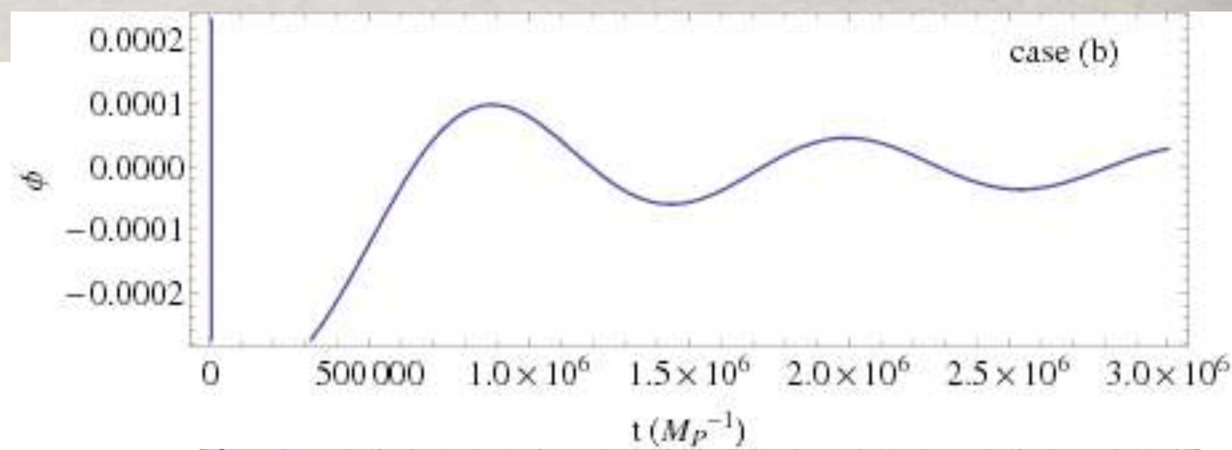
$$Y_B = \frac{n_b}{n_\chi} \frac{T_{RH} \rho_\chi}{m_{3/2} \rho_\phi} \sim 10^{-10} \left(\frac{T_{RH}}{10^6 \mathrm{GeV}} \right) \left(\frac{10^{-3}}{\lambda} \right)$$

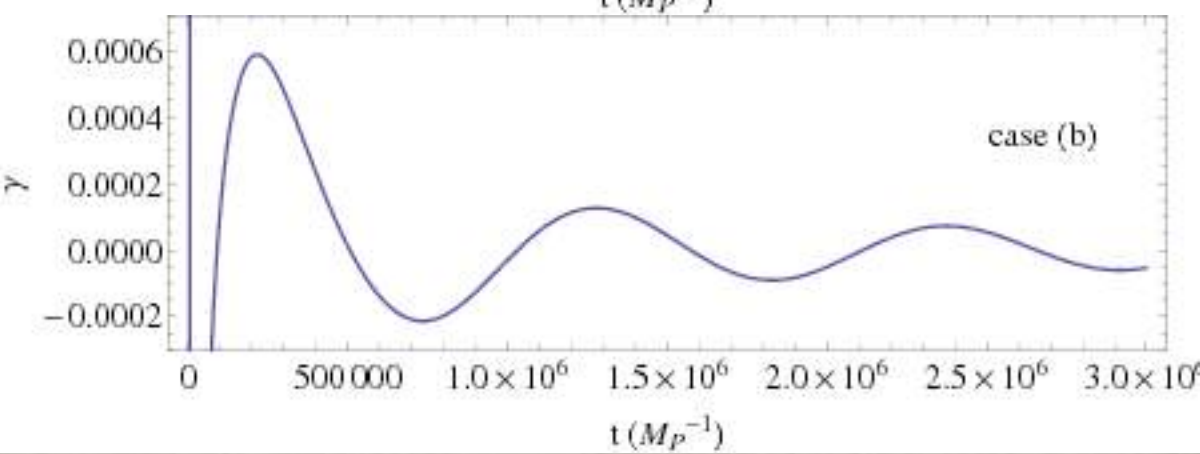
AD Baryogenesis in SUGRA

[Garcia & Olive '13]

Model of inflation with additional flat direction along LH direction producing AD leptogenesis. During inflation the flat direction follows the local minimum of the potential and at the end of inflation starts oscillating around the true vacuum



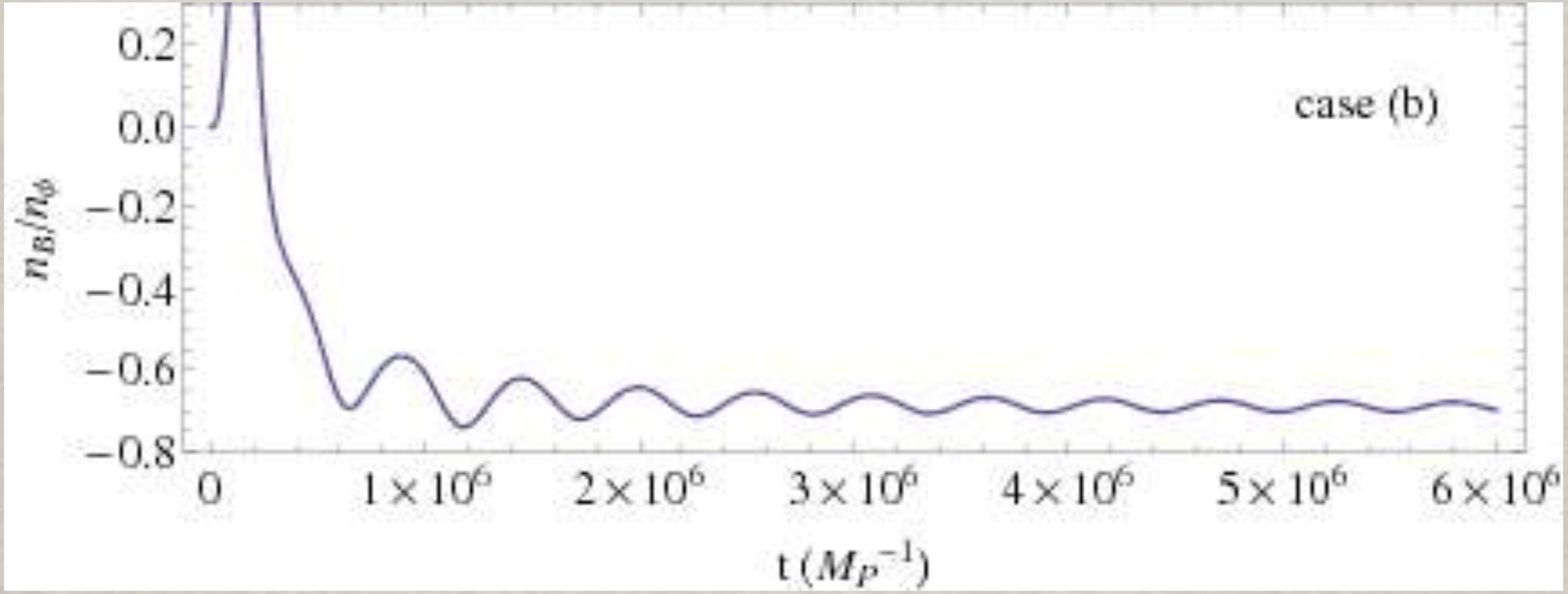




AD Baryogenesis in SUGRA

[Garcia & Olive '13]

While the LH flat direction oscillates, the lepton number is produced and then oscillates around a constant value.



In this case need sufficiently high T_RH to allow for sphaleron processes to reprocess L into B

Conclusions & Outlook

- Cosmology and astroparticle physics still provides a lot of puzzles to solve !
  Still unclear are the nature of the Inflaton and Dark Matter and the mechanism for Baryogenesis, but they mostly require to go Beyond the Standard Model !
- Some classes of models/mechanisms are being probed already by astrophysical observations and particle physics experiments.
- Unification of two Standard Models still missing

Lots of OPEN QUESTIONS remain...

Numerical codes

- CMB anisotropies: CAMB, CMBfast: http://camb.info
- Parameter estimations:
  CosmoMC @ http://cosmologist.info/cosmomc/
- BBN: Parthenope @ http://parthenope.na.infn.it
- Inflation and inflationary perturbations:
  MultiModeCode @ www.modecode.org
- WIMP Dark Matter & beyond:
  DarkSUSY @ www.darksusy.org
  MicrOMEGAs @ https://lapth.cnrs.fr/micromegas/