Electroweak baryogenesis and flavor

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DESY

Toyama, March 4, 2017

in collaboration with

G. Servant, I. Baldes, S. Bruggisser

The serendipity of electroweak baryogenesis

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Outline

Introduction

SM + S

Intermezzo

EWBG + FN

Baryogenesis

[Sakharov '69]

Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 10^{-10}$$

The main ingredients for viable baryogenesis are stated by the celebrated Sakharov conditions:

- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

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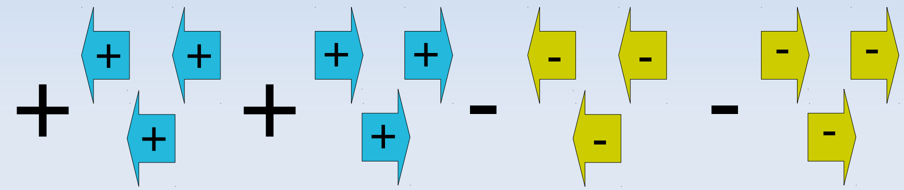

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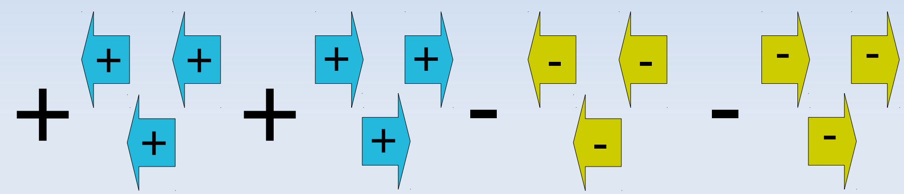

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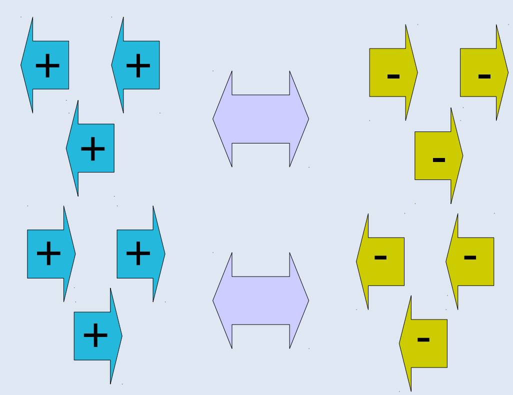

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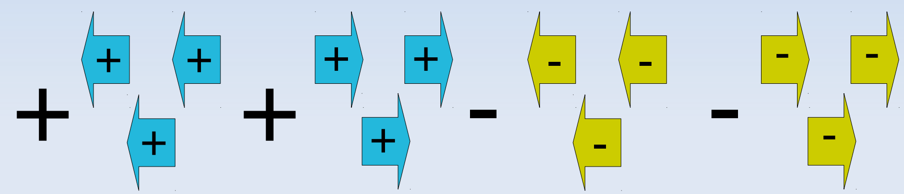

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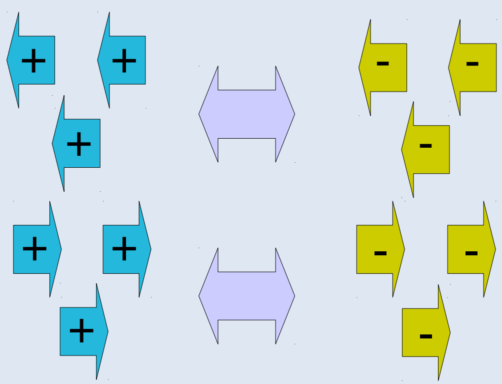

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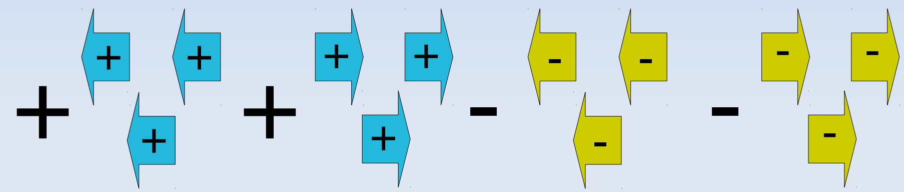

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$$n = n(m/T)$$

$$m = \bar{m}$$

$$n_B = n_{\bar{B}}$$

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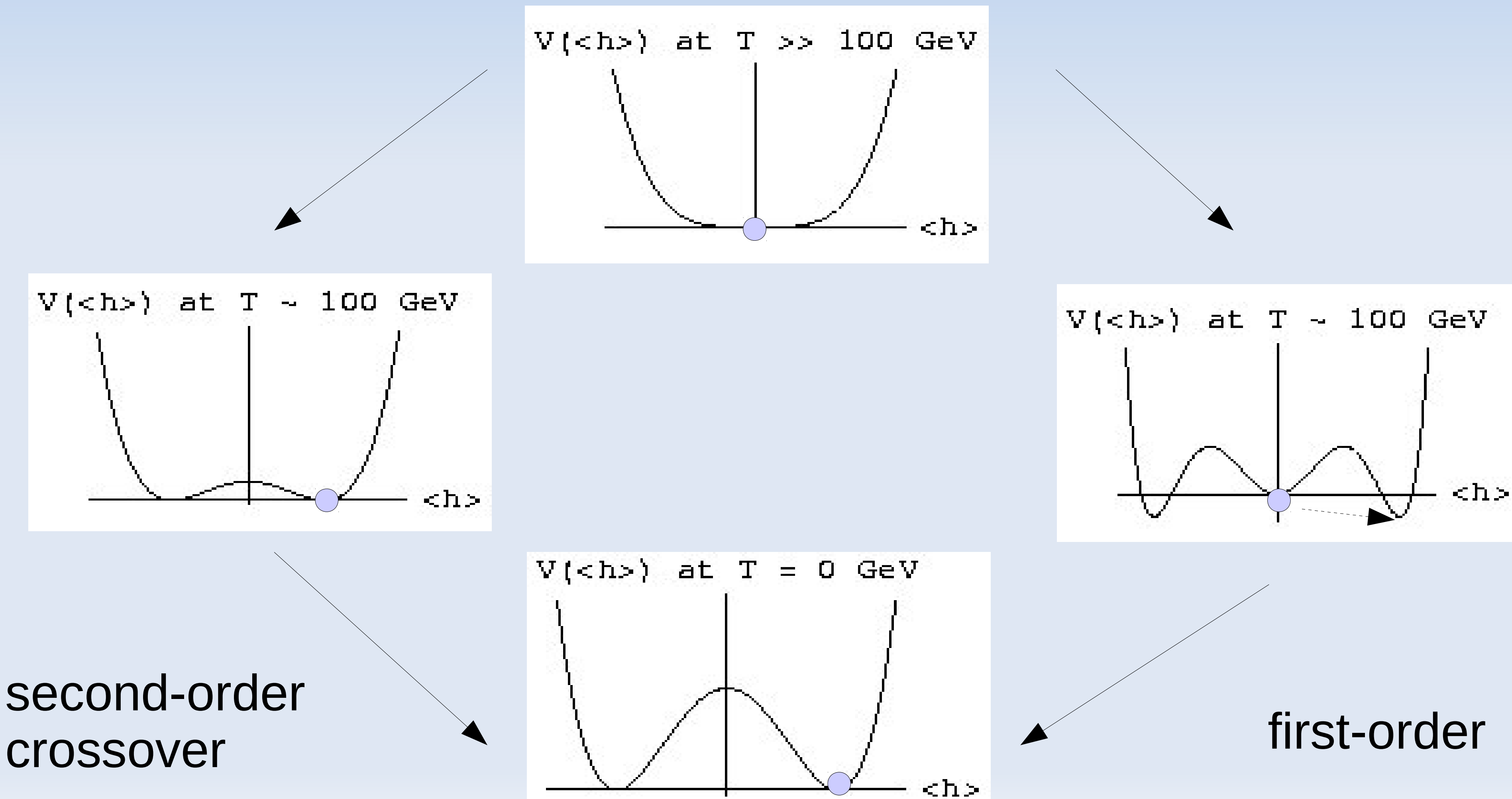
SM @
EW temp

~~C~~ ~~B~~	✔	B+L anomaly	sphaleron
~~CP~~	✘	Jarlskog invariant	beyond the SM physics essential
~~eq~~	✘	expansion slow EW PT?	

First-order phase transition

The free energy (as a function of the Higgs vev) decides the nature of the phase transition:



First-order phase transitions

- first-order phase transitions proceed by bubble nucleations

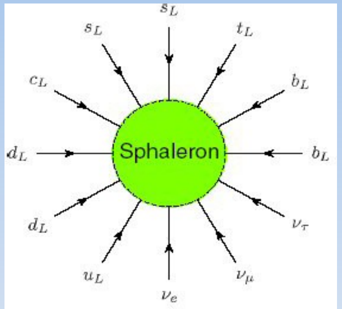
- in case of the electroweak phase transition, the ”Higgs bubble wall” separates the symmetric from the broken phase

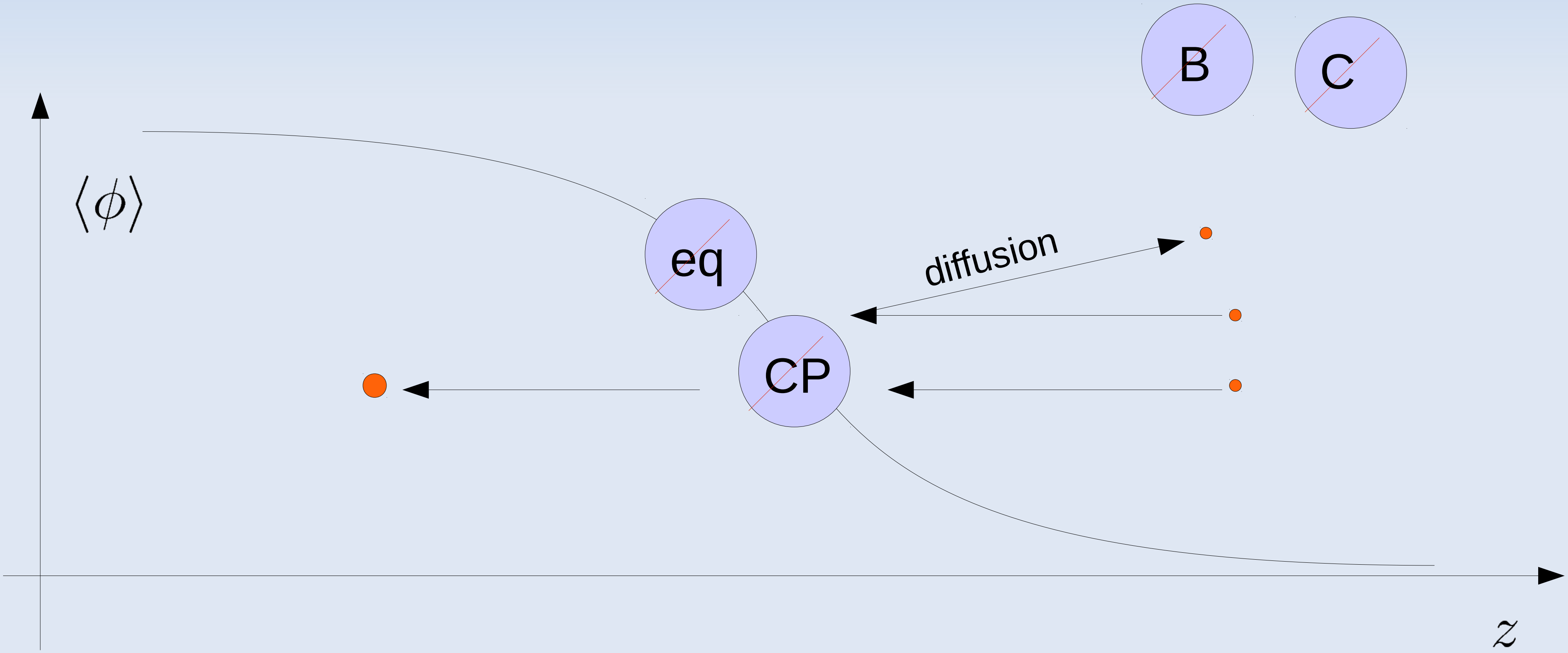
- this is a violent process ($v_b = O(1)$) that drives the plasma out-of-equilibrium

- bosons that are strongly coupled to the Higgs tend to make the phase transition stronger

Electroweak baryogenesis

[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]





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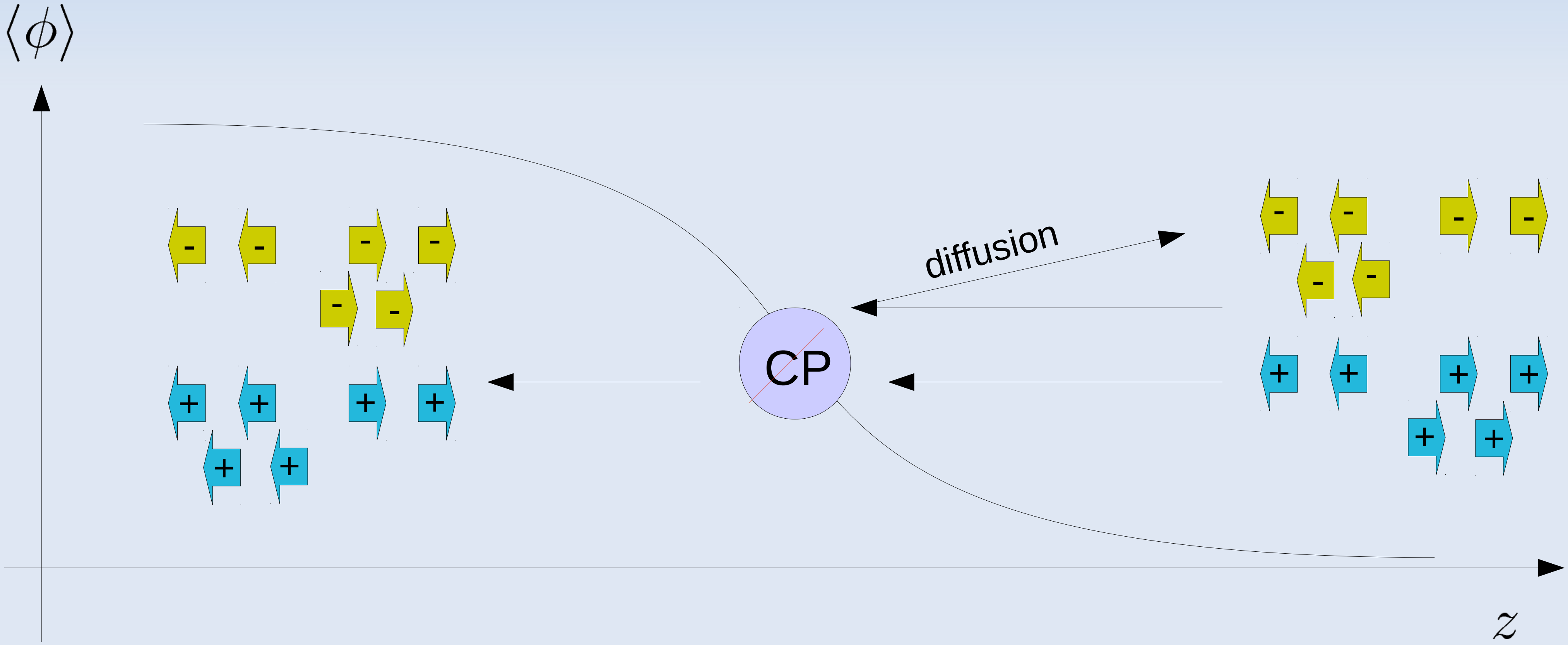

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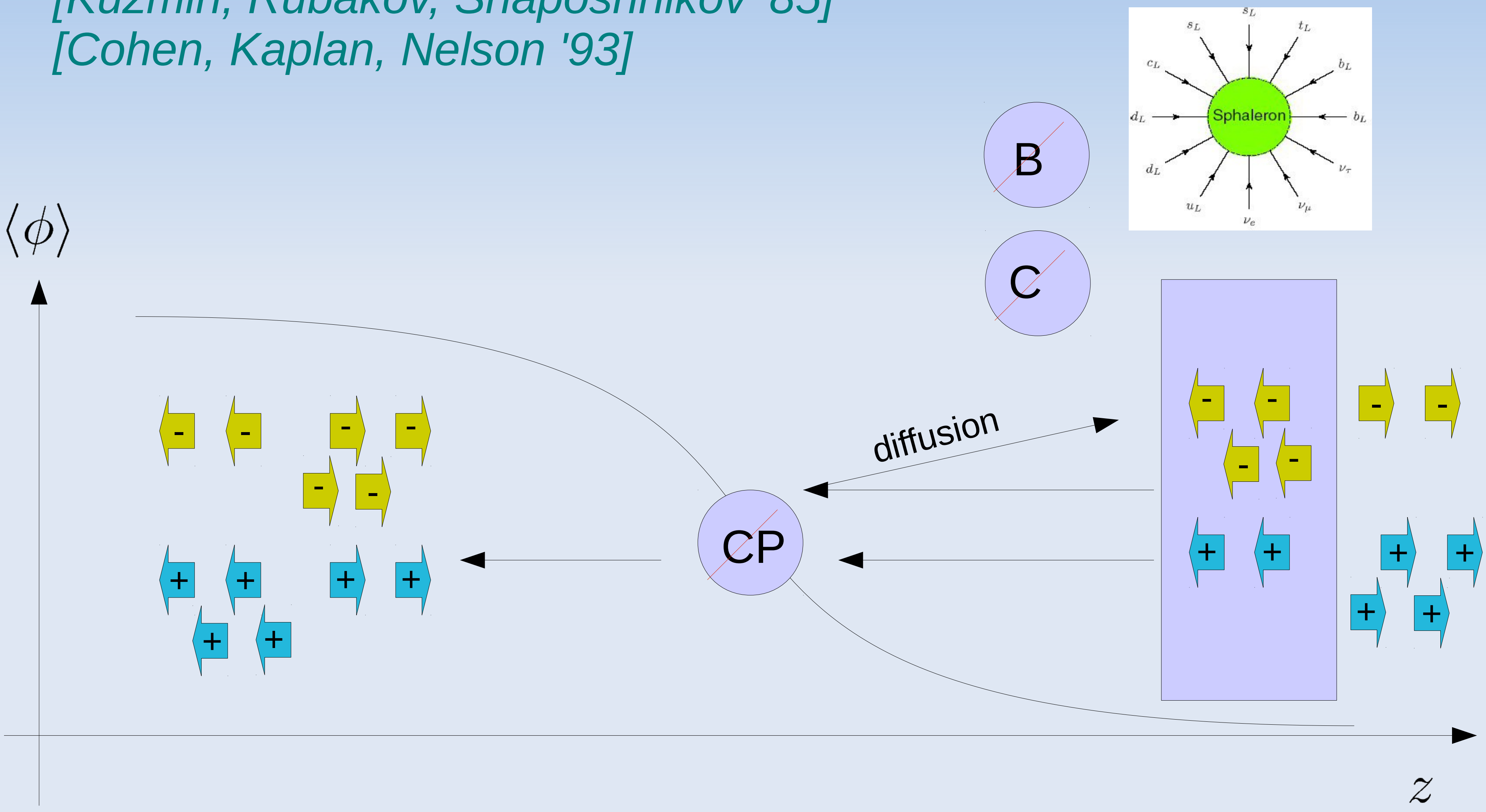

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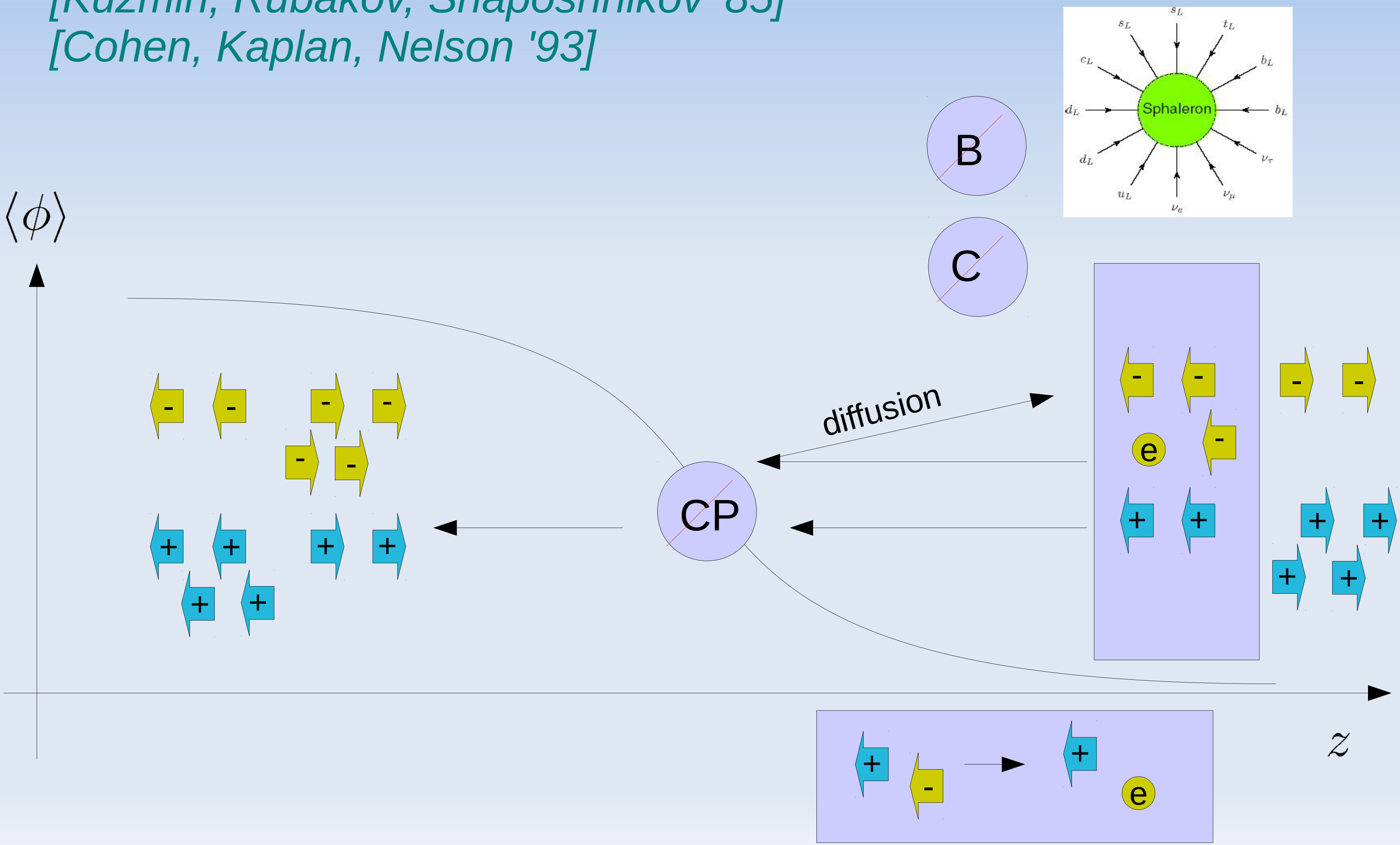

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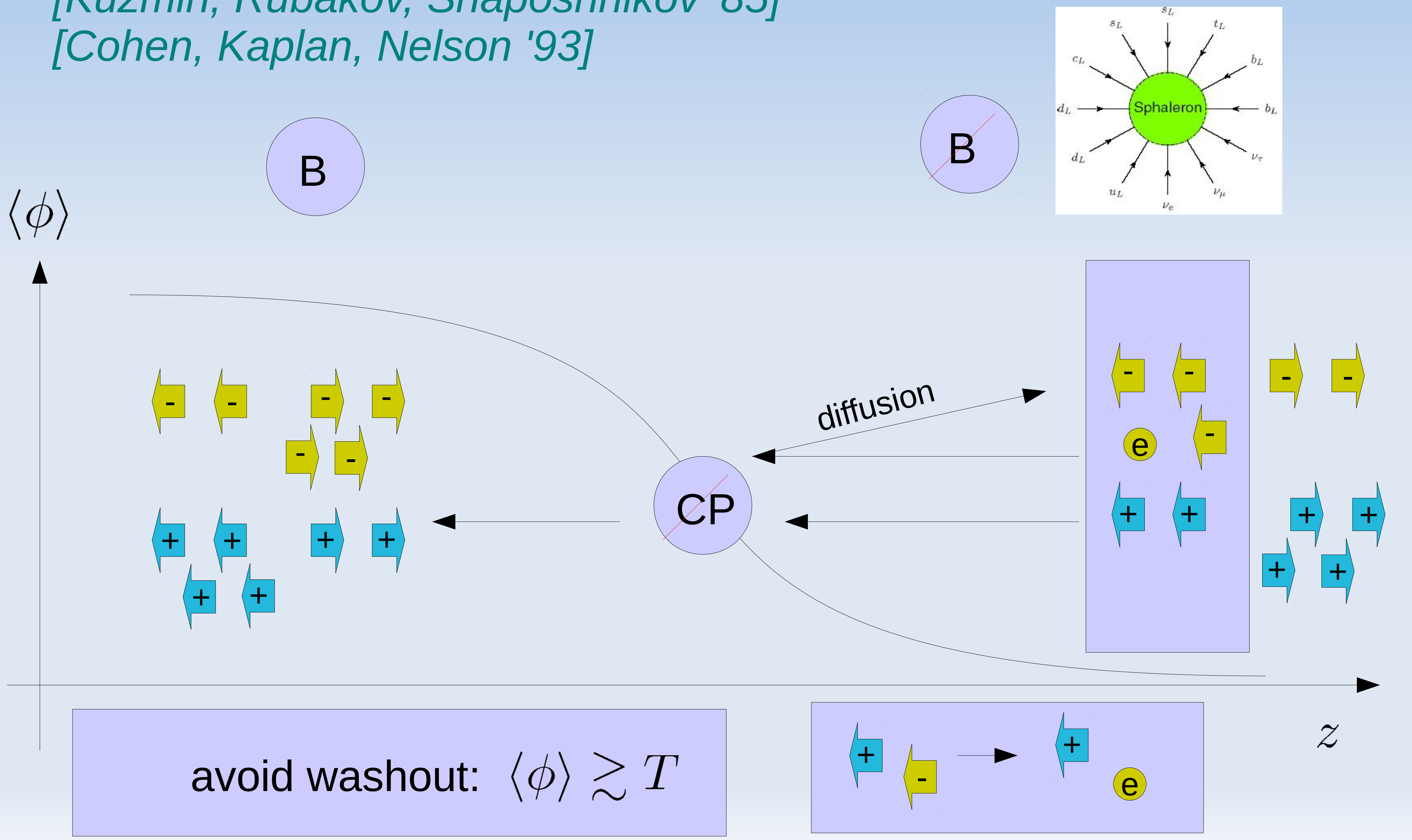


avoid washout: $\langle\phi\rangle \gtrsim T$

Why is this interesting?

- The hierarchy problem indicates that there is some BSM physics at EW scales

- Electroweak baryogenesis involves only physics at the electroweak scale that is accessible to collider experiments

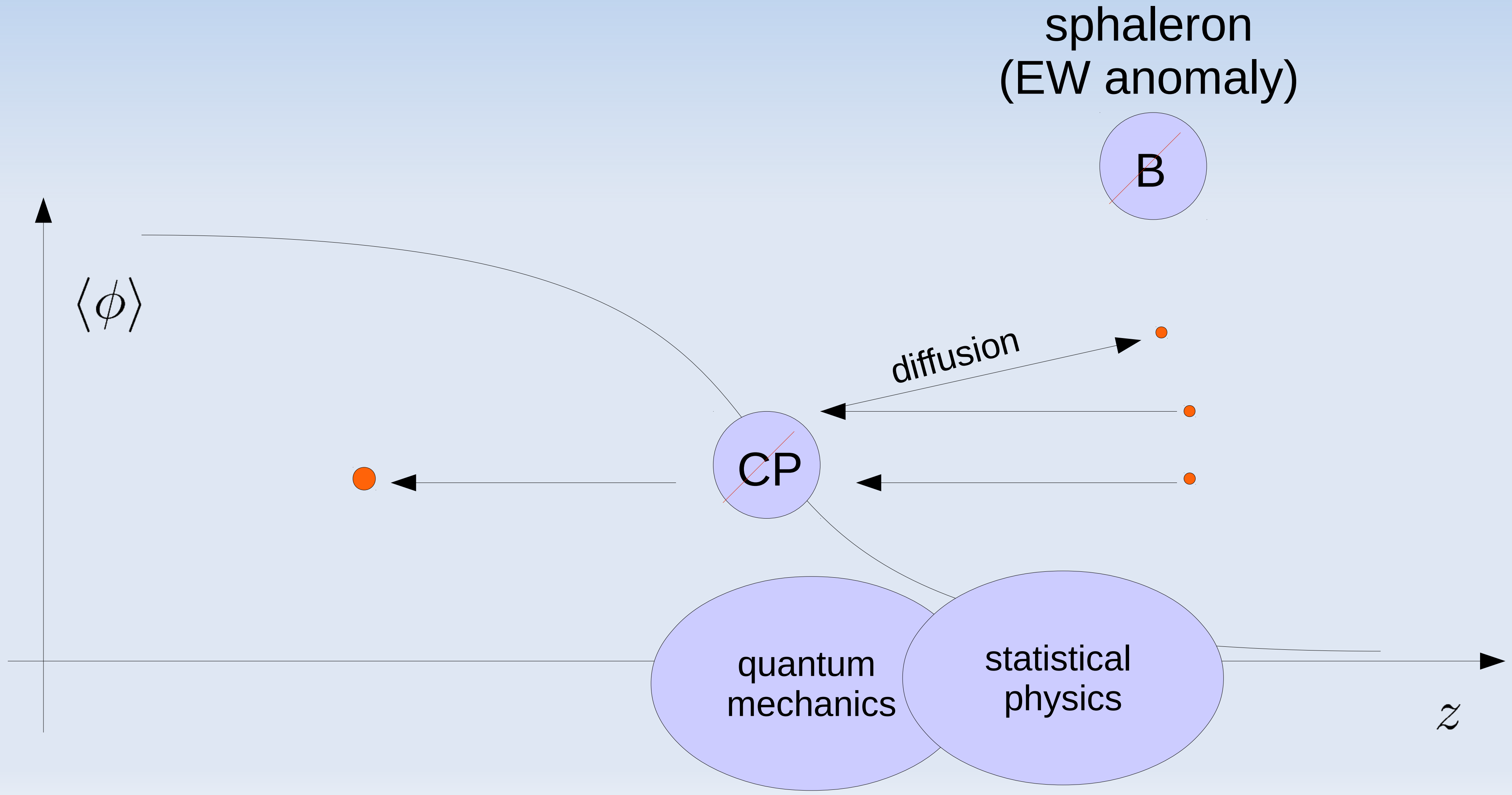
- Electroweak baryogenesis leads naturally to the observed baryon asymmetry

$$\eta_B \sim \frac{\Gamma_{ws}}{l_w T^2}\, \delta_{CP}\, e^{-m_\chi/T} \sim 10^{-11} - 10^{-9}$$

beyond SM?

What are the challenges?

[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]



Ingredients

1 $\cancel{\text{eq}}$ Strong first-order electroweak phase transition $\phi > T$

2 $\cancel{\text{CP}}$ Some fermion species that changes its mass in a CP violating way during the electroweak phase transition
(and prefereably charged under $SU(2)_L$)

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Ingredients

Two ingredients of baryogenesis are missing in the Standard Model. These are provided in models that have an additional singlet in the low energy effective description

~~eq~~

Strong first-order electroweak phase transition

$$V(s,h)$$

~~CP~~

CP violation from dimension-five operators

$$\mathcal{L} \ni y_t \bar{\psi}_Q H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_Q H \psi_t + h.c.$$

$$\Im(y_t \tilde{y}_t^*) \neq 0$$

Composite Higgs models

The Higgs could be a Pseudo-Goldstone boson of a broken global symmetry

QCD: $$\frac{SU(2)_L \times SU(2)_R}{SU(2)_V} \to 3\pi$$

The broken symmetry will determine the light degrees of freedom and their quantum numbers

$$\frac{SO(5)}{SO(4)} \to H$$

but also

$$\frac{SO(6)}{SO(5)} \to H + S \qquad \frac{SO(6)}{SO(4) \times SO(2)} \to 2H$$

[Kaplan, Georgi '84]

Holographic techniques in composite Higgs models

Lately, this old idea underwent a renaissance due to holographic models to determine some quantity of the strongly coupled theory (like the Higgs potential) in a 5D setup.

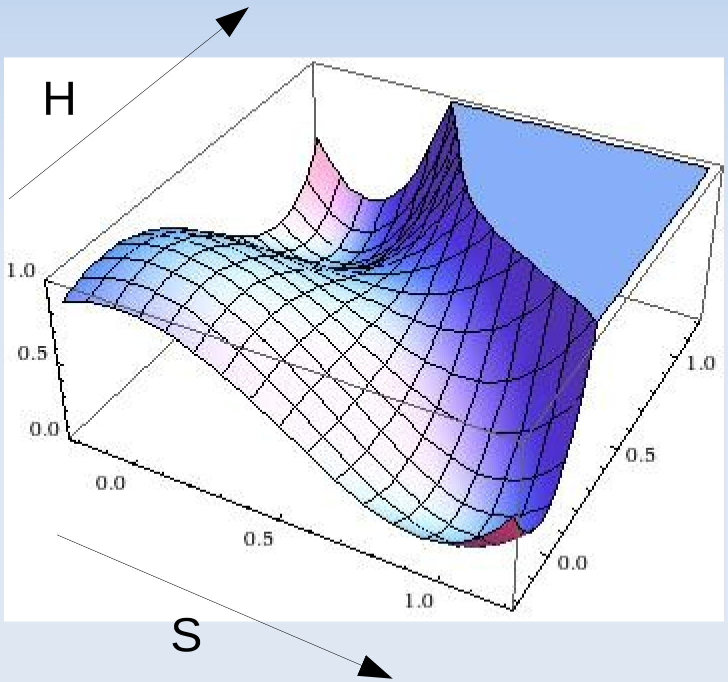
[Contino, Nomura, Pomarol '03]
[Agashe, Contino, Pomarol '04]

- 5D GIM mechanism for flavor problems
- oblique parameters better than in technicolor
- many parameters and a certain arbitrariness in the scalar sector

Phase transition

The construction of a potential barrier and hence first-order phase transitions are easily achieved in extended scalar sectors:

$$V(h,s) = \frac{\lambda}{4}(h^2 - v^2)^2 + m_s^2 s^2 + a_s s^3 + \lambda_s s^4 + a_m s\, h^2 + \lambda_m s^2 h^2$$



For example consider deformations of the $\mathbb{Z}_2$ - symmetric ”super-Mexican-hat”

$$V(s,h) = \frac{\lambda}{4}(h^2 + s^2/\alpha^2 - v^2)^2 + \lambda_m h^2 s^2$$

that has a phase transition (two-stage phase transition)

$$(h,s) = (0, \alpha v) \rightarrow (h,s) = (v, 0)$$

CP violation

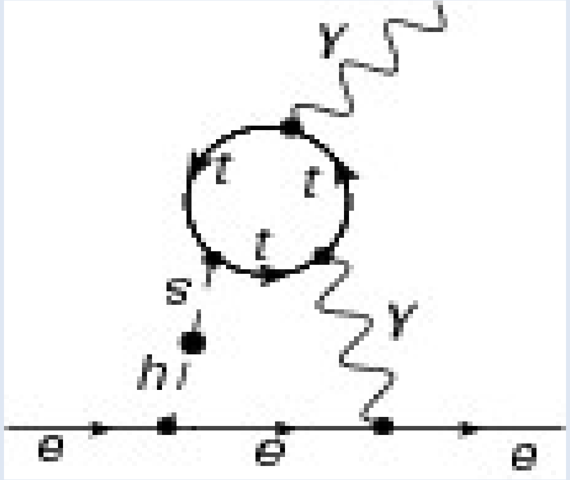
$$\mathcal{L} \ni y_t \bar{\psi}_t H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_t H \psi_t$$

During the phase transition this leads to a top mass of the form

$$m_t = |m_t| e^{i\theta_t} = \frac{y_t h}{\sqrt{2}} \left(1 + \frac{\tilde{y}_t}{y_t} \frac{s}{f} \right)$$

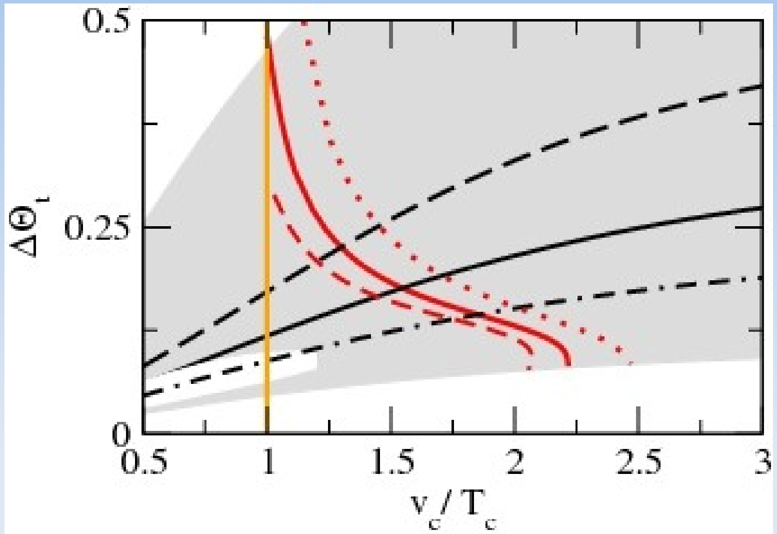
So, the complex phase during the phase transition behaves as

$$\theta_t \simeq \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{s}{f}$$



This is a one flavor system and the BAU can be reliably determined with the semi-classical force approach.

Baryogenesis



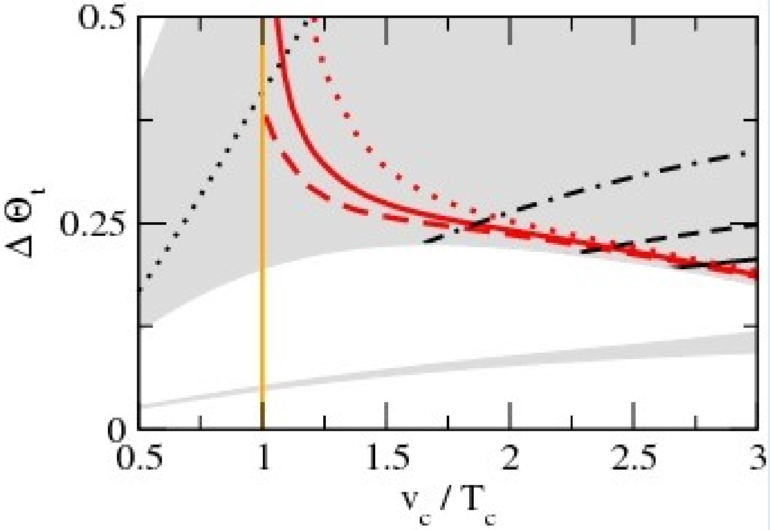
$$m_s = 130\,\mathrm{GeV}$$

$$\Delta\theta_t \gtrsim 0.15$$

strength of CP violation

strength of the phase transition

$$\Delta\theta_t \simeq \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{\Delta s}{f}$$



$$m_s = 80\,\mathrm{GeV}$$

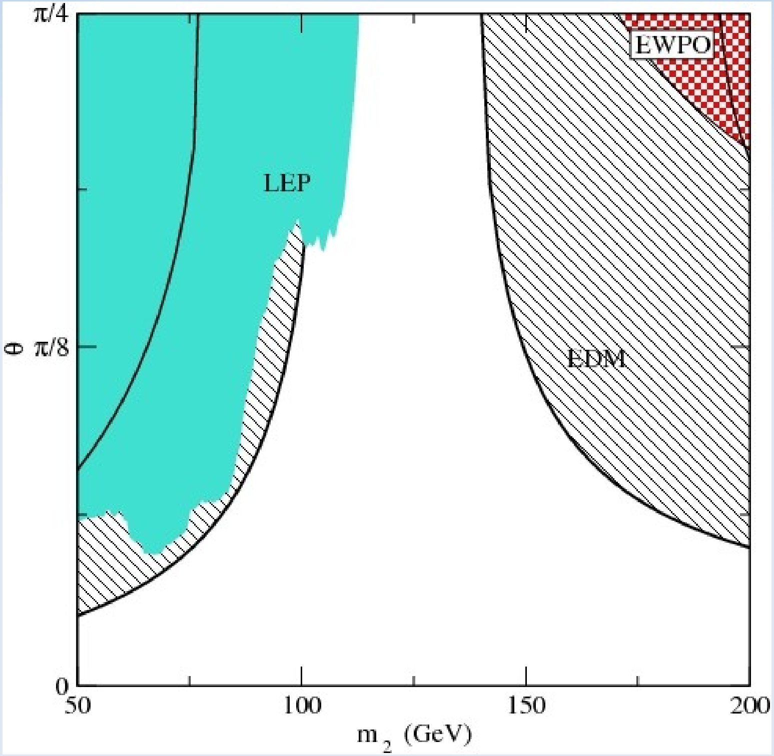
$$\Delta\theta_t \gtrsim 0.25$$

[Espinosa, Gripaios, TK, Riva '11]

Signals

$$m_h = 120\,\mathrm{GeV}$$

Higgs-singlet mixing ~
CP violation



singlet mass

[Espinosa, Gripaios, TK, Riva '11]

$$\frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*}\,\frac{1}{f} = (500\,\mathrm{GeV})^{-1}$$

Conclusions composite Higgs

Baryogenesis in composite Higgs models is generically possible if the sector of pseudo-Goldstone bosons is non-minimal.

In the case of a scalar extension of the low energy theory, this leads to

- rich phenomenology
- traces of CP violation in terms of EDMs

However, the setup assumes that the **top sector is special**. A sizable dim 5 or dim 6 involving the first two families would violate many flavor constraints.

In composite Higgs models this is justifiable.

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Jarlskog invariant

The flavor structure of the Standard Model stems from the Yukawa couplings of the up- and down-quarks.

$$Y_{u/d} \simeq U_{u/d}\,\bar{Y}\,V^{\dagger}_{u/d}$$

Out of the 2 x 18 parameters, very few are observable. In particular, the right-handed rotation matrices V are unobservables. The left-handed ones will show up in the weak interactions

$$\mathrm{CKM} = U_u U_d^{\dagger}$$

In this basis, changing phases in the quark fields is still possible → only 3 observable angles and 1 CP phase in CKM.

[Jarlskog '85]

Jarlskog invariant

In turn, observables can only depend on the combination that is invariant under right-handed transformations

$$Y_{u/d} Y_{u/d}^{\dagger} \simeq U_{u/d} \bar{Y}_{u/d}^{2} U_{u/d}^{\dagger}$$

The simplest CP odd quantity that does not depend on the flavor basis is the Jarlskog determinant

$$\det \left[Y_u Y_u^{\dagger}, Y_d Y_d^{\dagger} \right] = \Pi_{i \neq j} (y_i^2 - y_j^2) \ \times \ J \simeq 10^{-20}$$

Where J is a rephasing invariant combination of the angles in CKM matrix.

In particular, all three families have to enter for CPV.

Rephasing invariants in EWBG

During the electroweak phase transition, the masses of the quarks change and one can in principle construct many more rephasing invariants

$$\mathrm{Im}\left[M^\dagger \partial_z M\right]_{ii}$$

This works for even for one flavor

$$m = |m| e^{i\theta} \to \mathrm{Im}[m^* m'] = \theta' |m|^2$$

This is the dominant source of CPV in the singlet extension of the SM

$$\theta_t \simeq \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{s}{f}$$

Notice however that in the SM the combination above vanishes due to

$$\partial_z M = \mathrm{real}\# \times M$$

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[Baldes, TK, Servant '16]

Froggatt-Nielsen mechanism

The Froggatt-Nielsen mechanism is based on a global $U(1)_{FN}$ symmetry. All quarks are charged under this symmetry.

When different FN charges are assigned for left- and right-handed quarks, Yukawa couplings are forbiden.

Now consider a scalar S (= flavon) that has a unit FN charge. If this scalar acquires a VEV σ, the $U(1)_{FN}$ symmetry is broken what induces the Yukawa couplings. A spurion analsis gives

$$Y_{ij} \simeq \left(\frac{\sigma}{\Lambda_s}\right)^{q_i - \bar{q}_j + q_h}$$

charges of the left-handed quark **i** and the right-handed quark **j**

scale where the $U(1)_{FN}$ is broken

For $\sigma/\Lambda_s \sim 0.2$ this construction can explain the mass hierarchies in the SM

[Froggatt & Nielsen ’78]

Phase transition

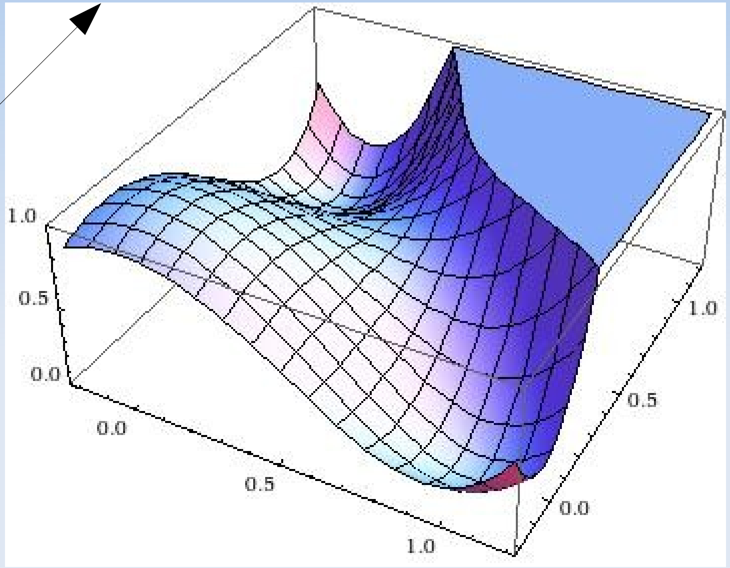
Now, consider that the flavon follows the two-stage phase transition. This means σ ~ 0 at very high temperatures.

At lower temperatures
$\sigma \rightarrow \Lambda_s$.

Finally, at electroweak temperatures
$\sigma \rightarrow 0.2\,\Lambda_s$

All Yukawa couplings are of O(1) during the EWPT. CPV is O(1).

H

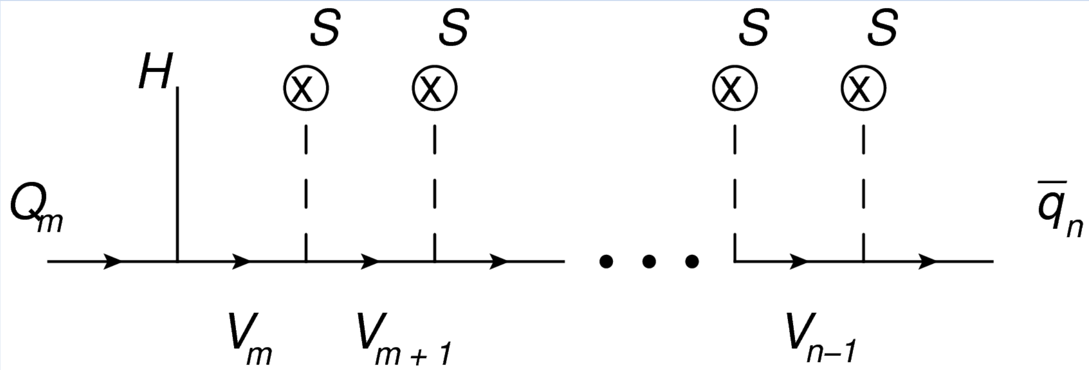


S

$$\mathrm{Im}\left[M^\dagger \partial_z M\right]_{ii} \simeq v^2$$

UV realizations

UV realizations of this idea are often quite baroque. They involve many vector-like quarks



This is the price to pay to kill three birds with one (or 1000) stone

- mass hierarchies explained
- O(1) CP violation
- Strong phase transition

Model A

The model is subject to severe constraints from B-$\bar{B}$ and D-$\bar{D}$ mixing leading to $\sqrt{m_s \Lambda_s} > 8\,\mathrm{TeV}$
Which is inconsistent with sphaleron washout ($\varphi/T > 1$)

[Knapen & Robinson '15]

two ways to avoid this constraint:

A1

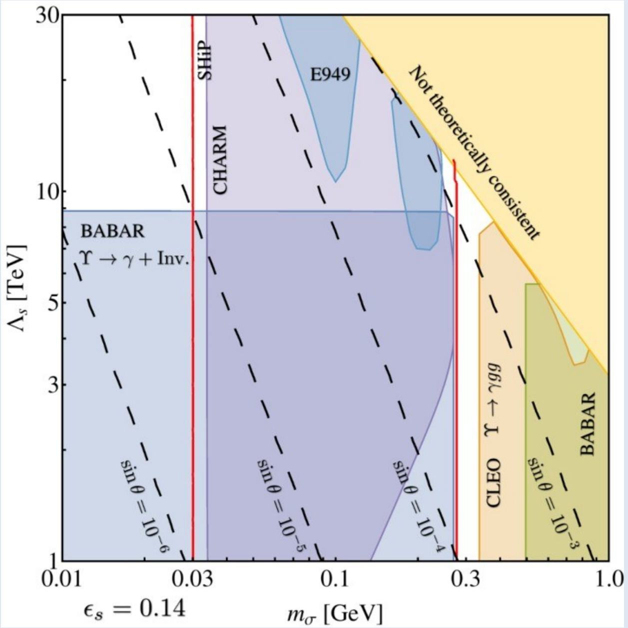
$$m_s < m_K\,, \quad \Lambda_s > 10^{12}\,\mathrm{GeV}$$

A strong phase transition requires extreme tuning

$$\lambda_s \lesssim 10^{-40}$$

A2

Use low-scale FN only to explain the mass hierarchy, no new flavor structure induced



various experiments pose very strong constraints through the bottom Yukawa and Higgs-flavon mixing

Model B

Most flavor constraints can be relaxed by introducing a second flavon field X

EWPT:

$$\begin{array}{llcl} \varphi : & 0 & \rightarrow & v \\ \sigma : & 0.2\,\Lambda_s & \rightarrow & 0.2\,\Lambda_s \\ \chi : & \Lambda_s & \rightarrow & 0 \end{array}$$

The field S is only a spectator during the electroweak phase transition and produces the mass hierarchies at low temperatures

The field X changes from the broken to the symmetric phase at electroweak temperatures and leads to sizable CP violation during the electroweak phase transition

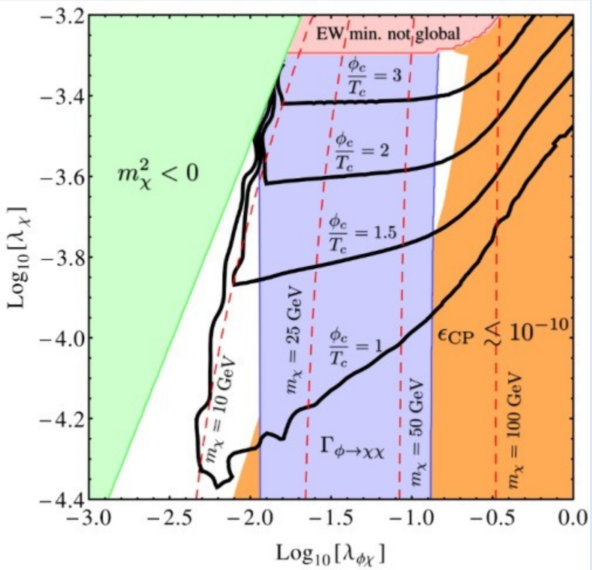
More models

In order to achieve this symmetry breaking pattern one has to ensure that the mixing between X and the other scalars is small at low temperatures. This is potentially destroyed by operators of the form

$$X^\dagger S \, S^\dagger S$$

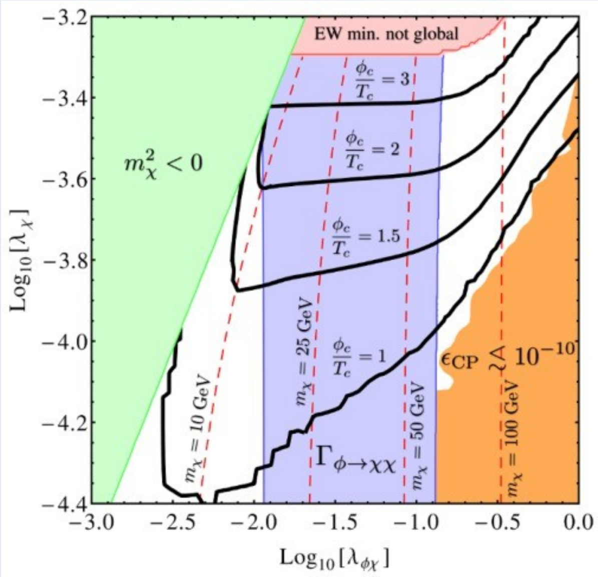
B1

$Q_{FN}(X) = Q_{FN}(S) / 2$



B2

tuning



Additional comments

- electroweak baryogenesis in this kind of model involves all families and not only the third family
(currently under investigation with S. Bruggisser)
- eventually sizable contributions to the invisible Higgs width through exotic Higgs decays
- exotic top decays
- the $U(1)_{FN}$ has to be explicitly broken to give a mass to the pseudo-scalar component of the FN field
- X is rather light and predominantly decays into charm pairs
- vector-like quarks are a standard signal of FN
- X cannot be stable and DM since it would be typically over-abundant

[Baldes, TK, Servant '16]

Conclusions

A tight link between flavor physics and baryogenesis is intriguing.

Our first attempts in Froggatt-Nielsen models met with significant challenges in model building

Alternative frameworks for BSM flavor physics (Randall-Sundrum and composite Higgs models) have potential advantages

[v. Harling, Servant '16]