Electroweak baryogenesis after LHC run II

Thomas Konstandin

GRC, HKUST, June 28, 2017

Outline

- Introduction
- Models

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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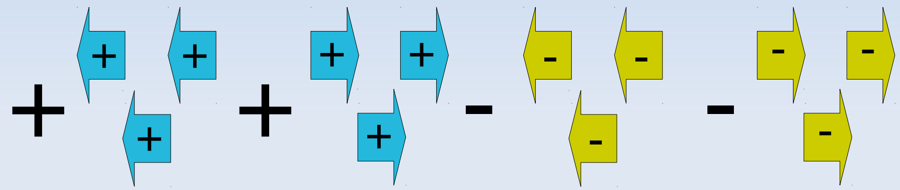

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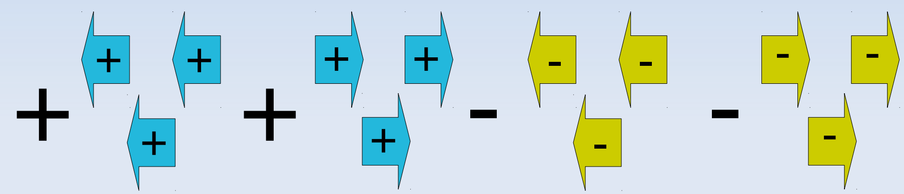

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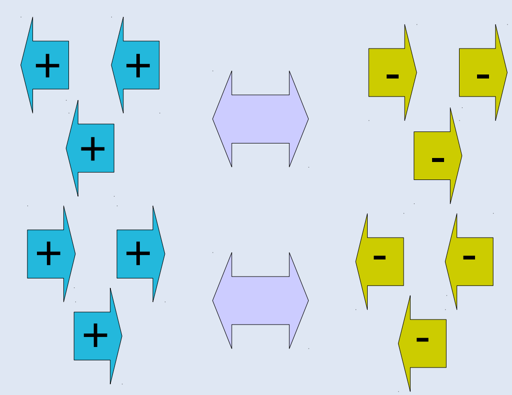

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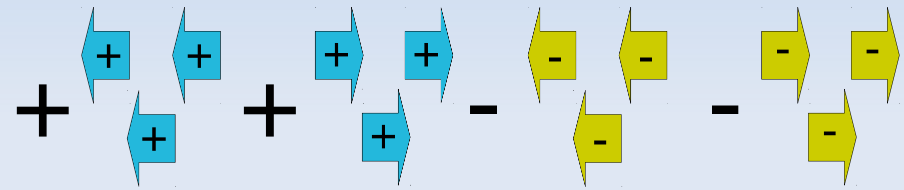

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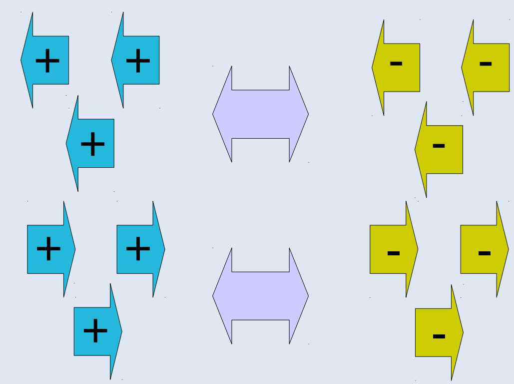

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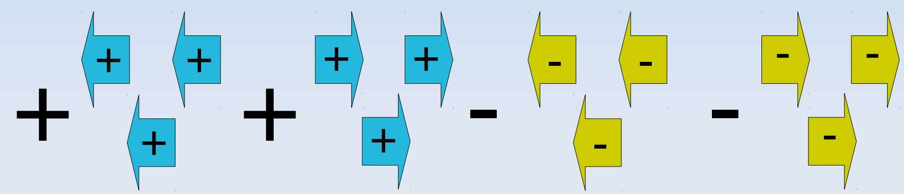

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$$n = n(m/T)$$

$$m = \bar{m}$$

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

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SM @ EW temp

~~C~~ ~~B~~ ~~CP~~ ~~eq~~

✔ B+L anomaly — sphaleron

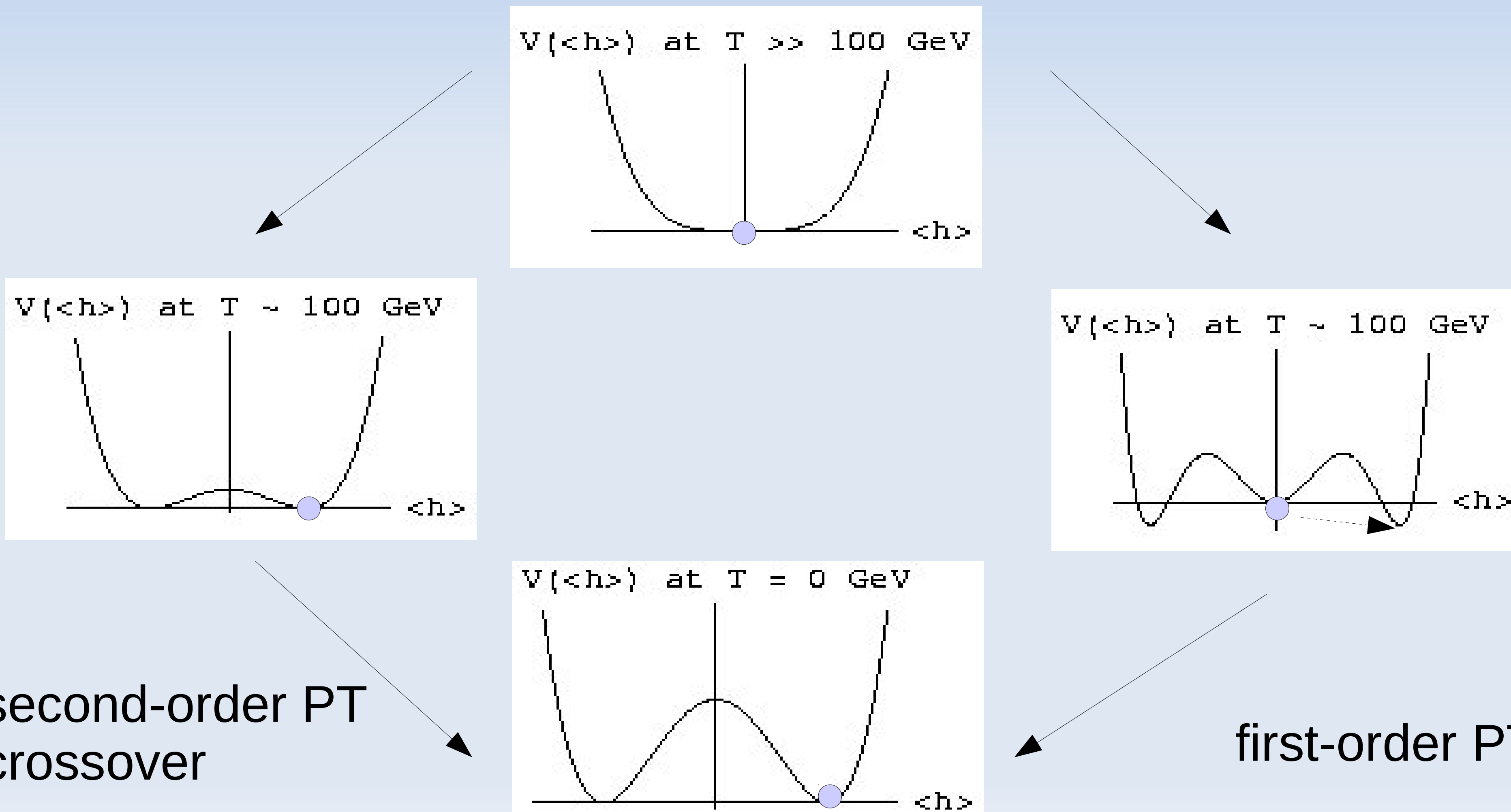
✘ Jarlskog invariant

✘ expansion slow EW PT?

beyond the SM physics essential

First-order phase transition

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



second-order PT
crossover

first-order PT

eq

First-order phase transitions

- first-order phase transitions proceed by bubble nucleations

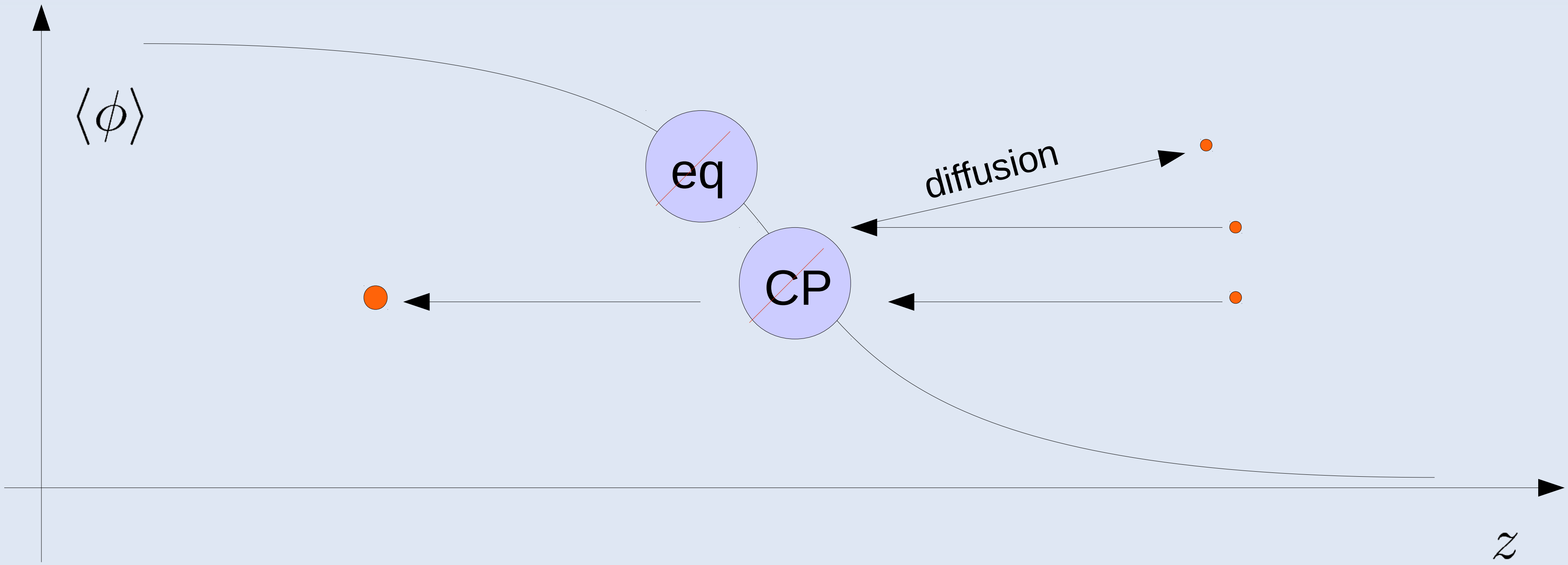
- in case of the electroweak phase transition, the "Higgs bubble wall" separates the symmetric from the broken phase

- 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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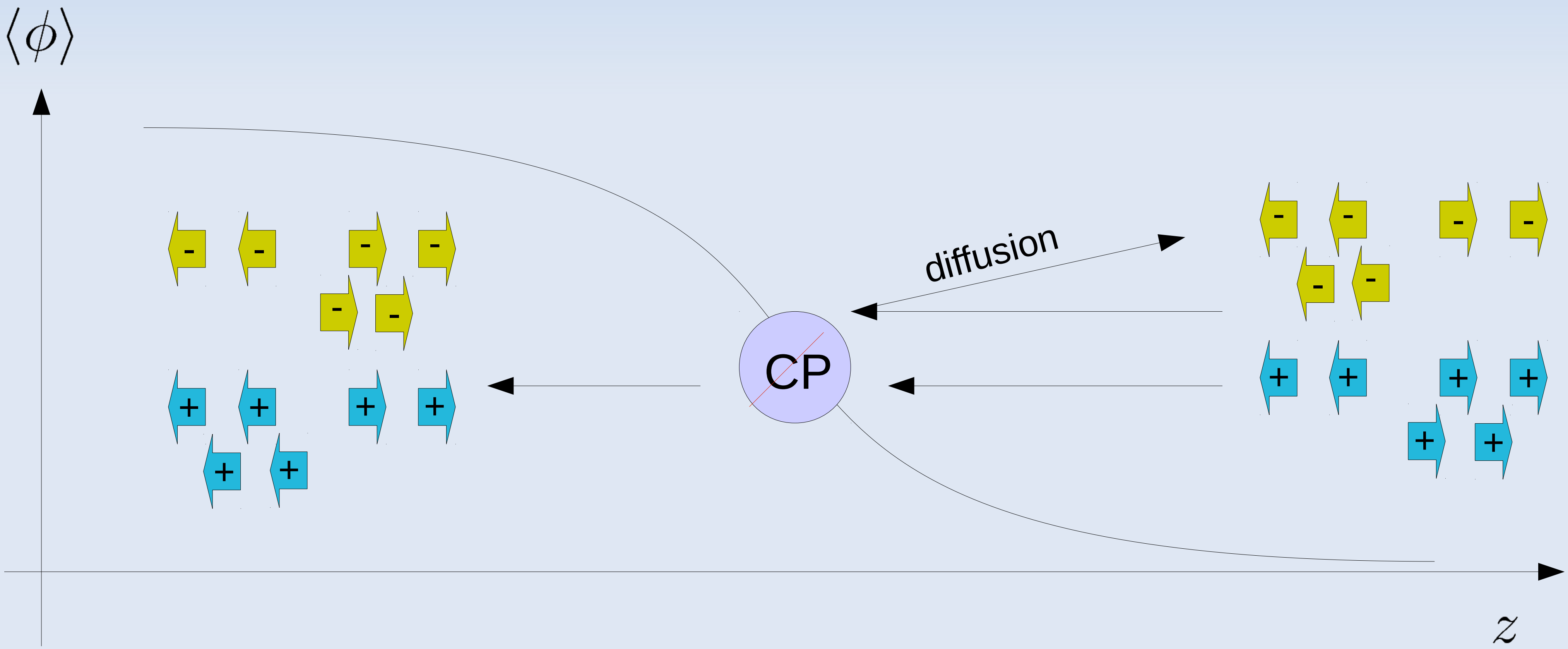

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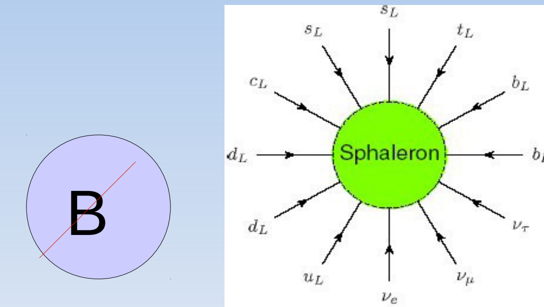

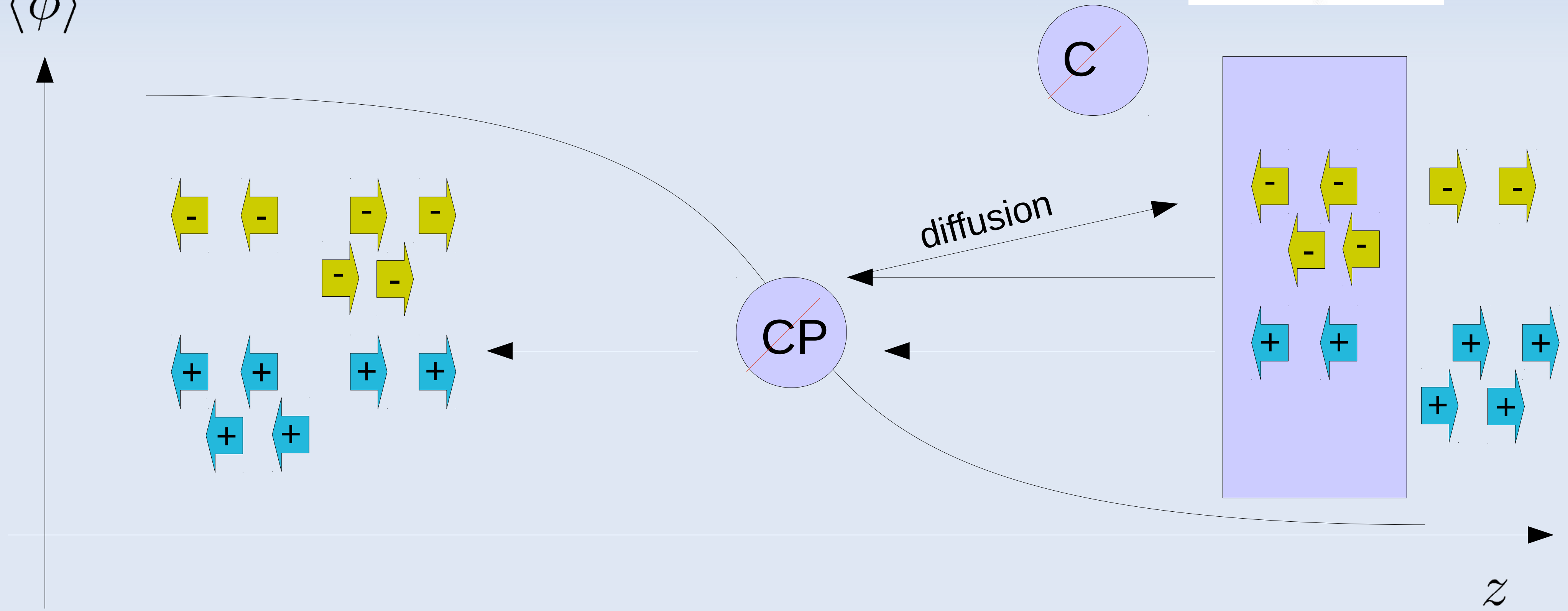

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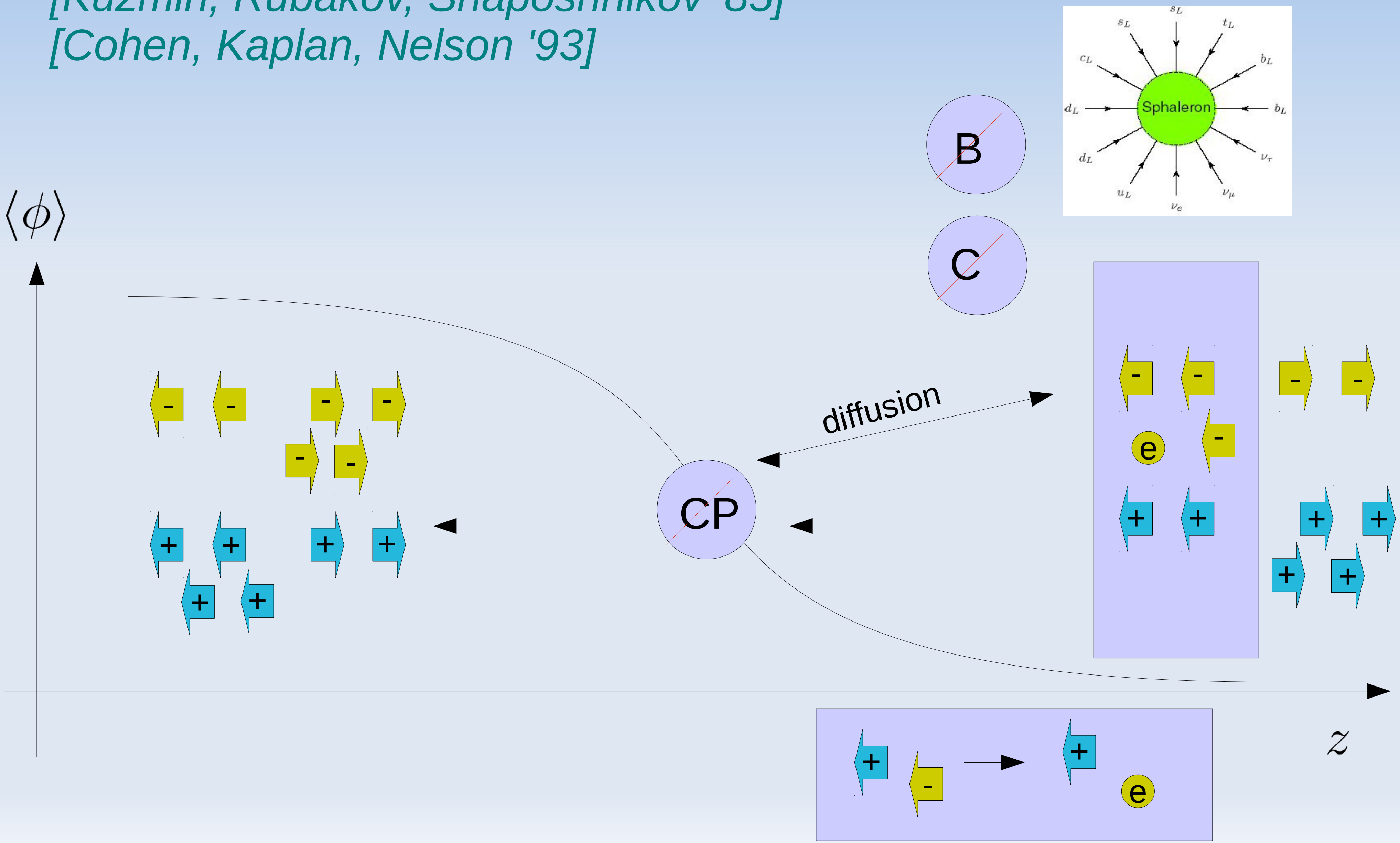

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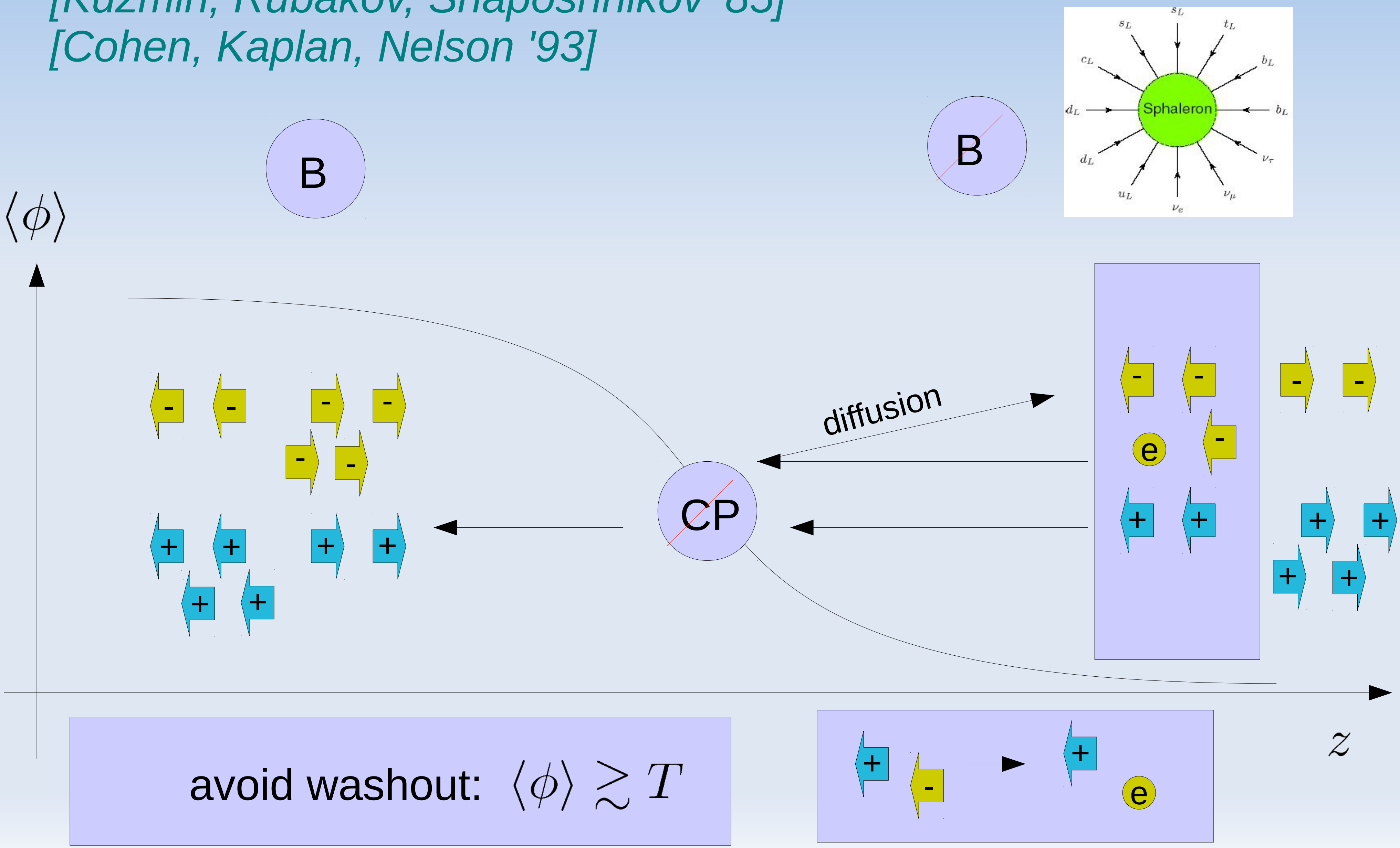


Why is this interesting?

- 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

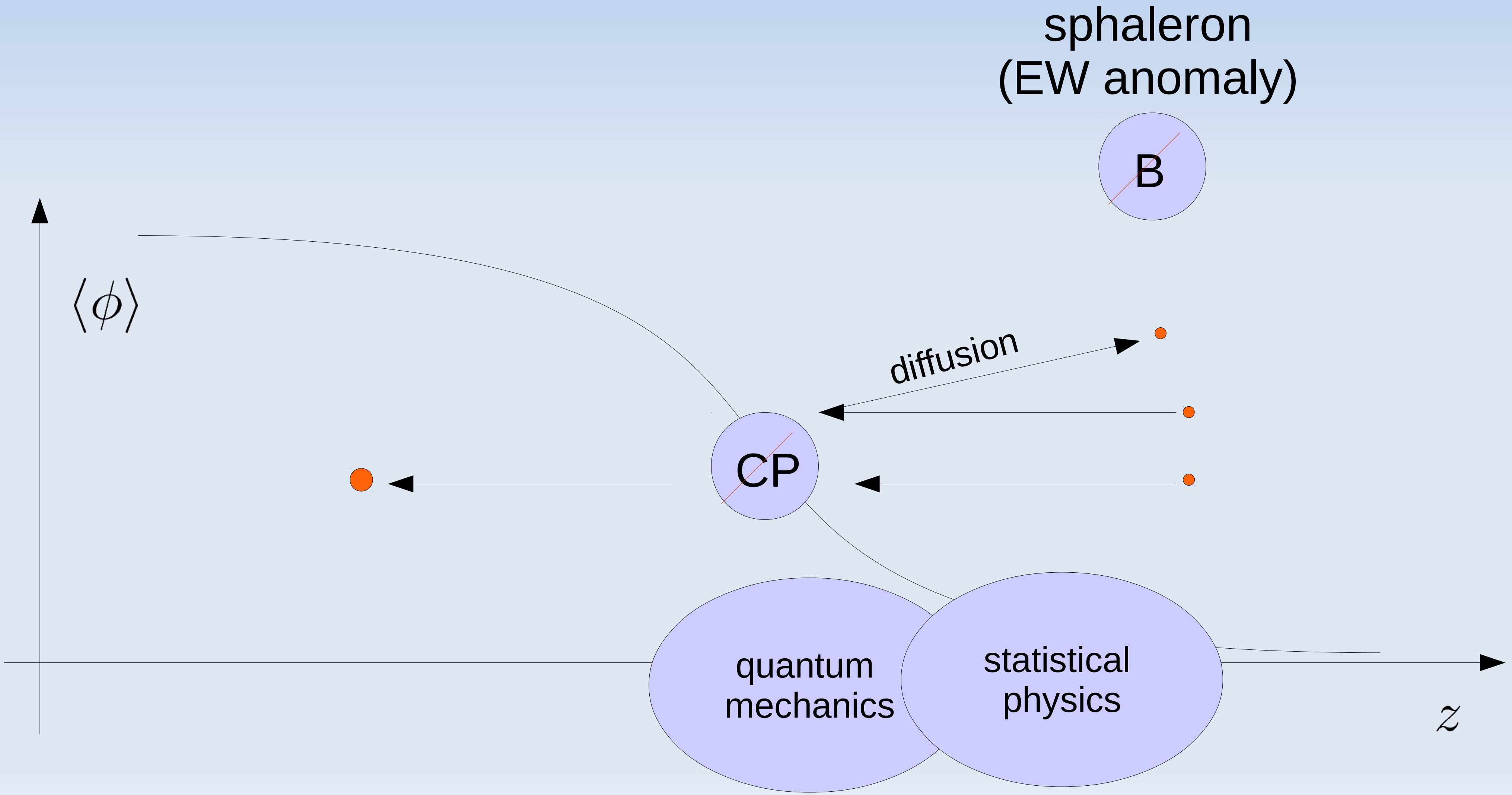
- Electroweak baryogenesis leads naturally to the observed baryon asymmetry

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

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 $SU(2)_L$)

Outline

Introduction

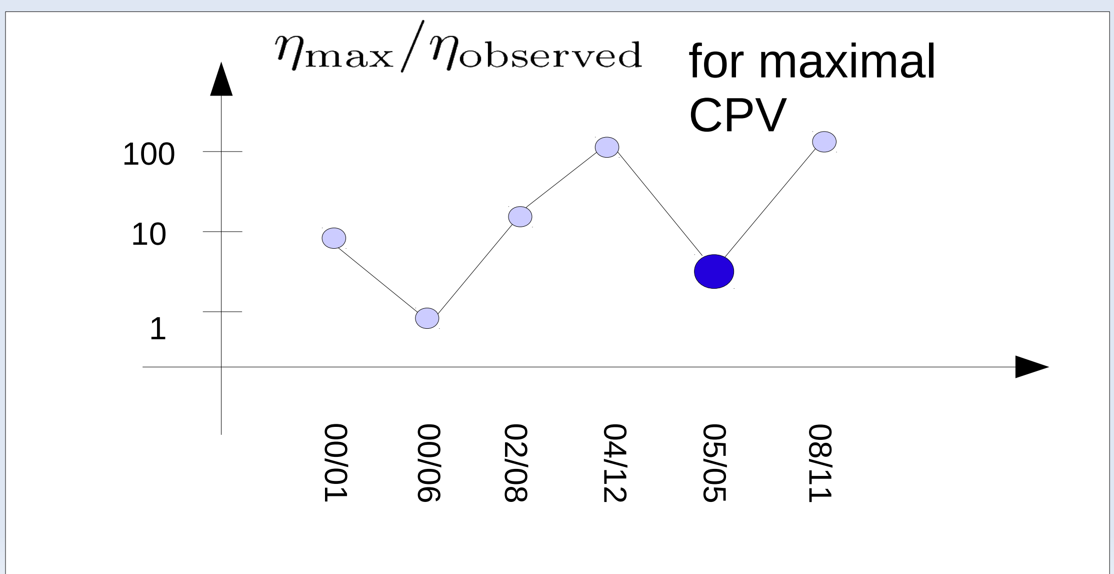
Models

Pre LHC EWBG

Before LHC, the main focus was on supersymmetric models, namely the MSSM

~~eq~~ Strong first-order electroweak phase transition from light stops $m_{\tilde{t}} \lesssim m_t$

~~CP~~ CP violation from the chargino sector $m_{\chi^\pm} \lesssim 200\,\mathrm{GeV}$



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[Hue & Nelson '95]
[Carena, Quiros, Riotto, Vilja & Wagner ’97]
[Cline, Joyce & Kainulainen ’00]
[Carena, Quiros, Seco & Wagner ’03]
[TK, Prokopec, Schmidt, Seco ’05]
[Cirigliano, Profumo, Ramsey-Musolf ’06]

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NMSSM *[Menon, Morrisey, Wagner '04]*
[Huber, TK, Prokopec, Schmidt '06]

U'(1) MSSM *[Kang, Langacker, Li, Liu '04]*

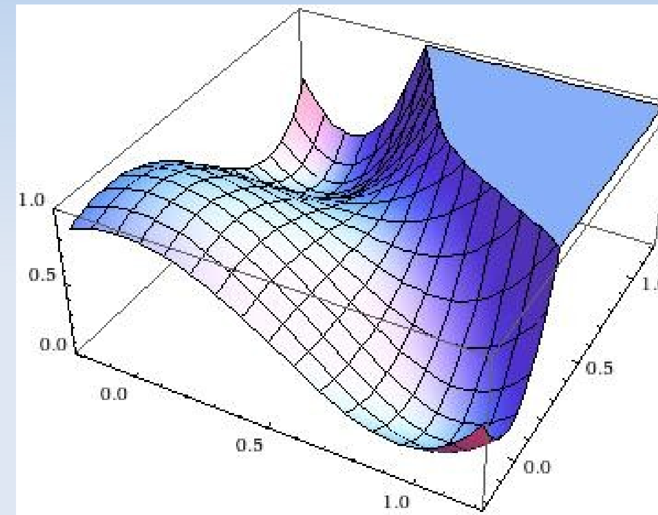
~~CP~~ CP violation
From the chargino sector

$$m_{\chi^\pm} < 200\,\mathrm{GeV}$$

problematic, also because of EDMs

EWBG in the LHC era

After LHC run II, the focus in EWBG is more on minimal models:



$\cancel{\text{eq}}$ Strong first-order electroweak phase transition from extended scalar sector

Two Higgs doublet model

$\cancel{\text{CP}}$ CP violation
from the Higgs sector

Singlet extension with a low cutoff

$\cancel{\text{CP}}$ CP violation
from the dim-5 top-singlet operators

new dof
low cutoff
in principle testable

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]

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

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

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

Baryogenesis

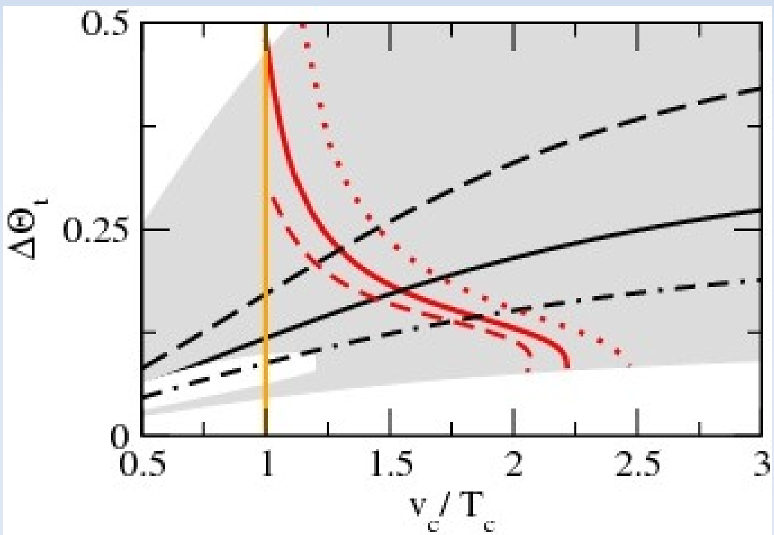
$$\Delta\theta_t \simeq \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{\Delta s}{f}$$

$$\Delta\theta_t \gtrsim 0.15$$

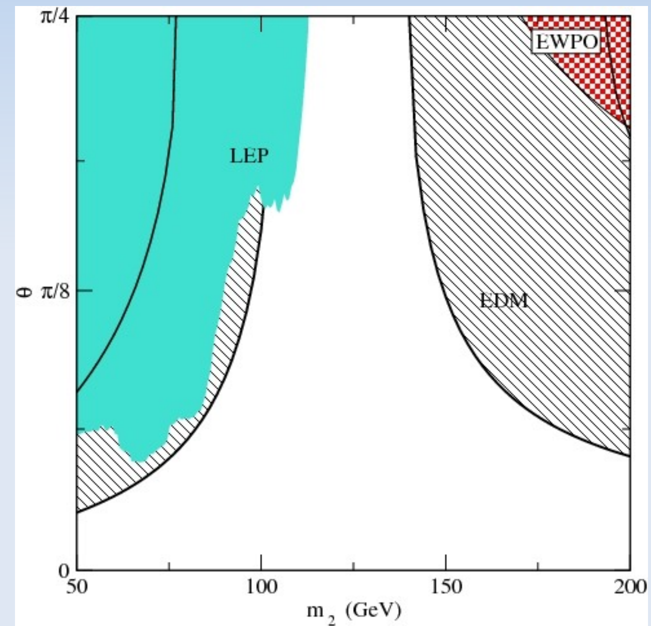
$$m_s = 130\,\mathrm{GeV}$$

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

strength of CP violation



Higgs-singlet mixing ~ CP violation



strength of the phase transition

singlet mass

[Espinosa, Gripaios, TK, Riva '11]

CPV is mostly present during the phase transition and does not require sizable mixing the broken phase → nightmare scenario

New avenues

Connecting EWBG to lepton flavor violation
[Guo, Li, Liu, Ramsey-Musolf, Shu ’16]
[Chiang, Fuyuto, Senaha ’16]

Electroweak bayogenesis from the dark sector (EWBG + DM)
[Lewicki, Rindler-Daller, Wells ’16]
[Chala, Nardini, Sobolev ’16]
[Beniwal, Lewicki, Wells, White, Williams ’17]
[Cline, Kainulainen & Tucker-Smith ’17]

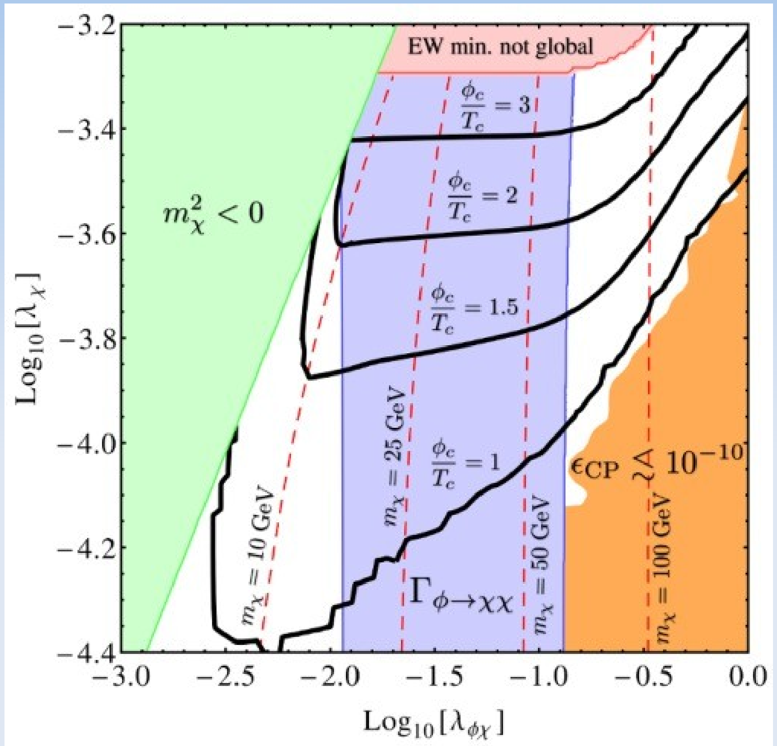
Electroweak bayogenesis and gravitational waves
[Dorsch, Huber, Konstandin, No ’16]
[Huang, Wan, Wang, Cai, Zhang ’16]

New avenues

If new CP violation in the top sector is used, a connection to the SM flavor puzzle seems obvious.

A light flavon can lead to varying Yukawa couplings during the electroweak phase transition

strong PT & new CPV
from varying Yukawa couplings



Generic flavor bounds on the flavon sector are ~ few TeV
Some tuning needed for a flavon – Higgs interplay

Alternative frameworks for BSM flavor physics (e.g. Randall-Sundrum models) have potential advantages

[Baldes, TK, Servant ’16]   [v. Harling, Servant ’ 17]

Conclusions

Electroweak baryogenesis is still a viable option to explain the observed BAU

The main focus of EWBG model building moved from SUSY models to minimal models after LHC run I+II

Minimal models are much harder to test at a collider than generic SUSY models

Some new developements (flavor puzzle, flavor anomalies, hidden sectors, DM)

Next generation EDM experiments will be the true litmus test for (most) models of EWBG

Observations of GWs from the phase transition are complementary to EDM and collider constraints