Quantum transport and electroweak baryogenesis

Thomas Konstandin

Mainz, August 7, 2014

review: arXiv:1302.6713

Outline

Introduction

MSSM

Composite Higgs

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:

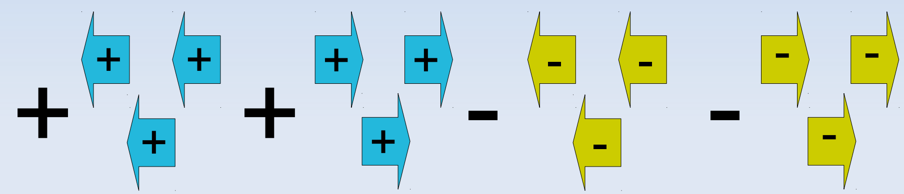
- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

Baryogenesis

[Sakharov '69]

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

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



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

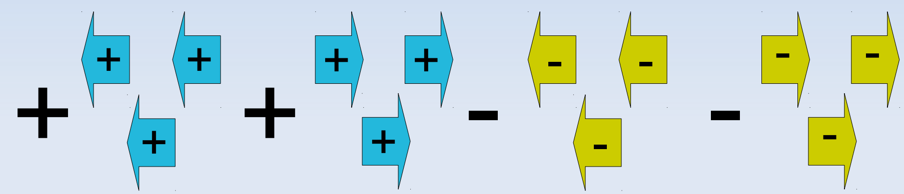
- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

Baryogenesis

[Sakharov '69]

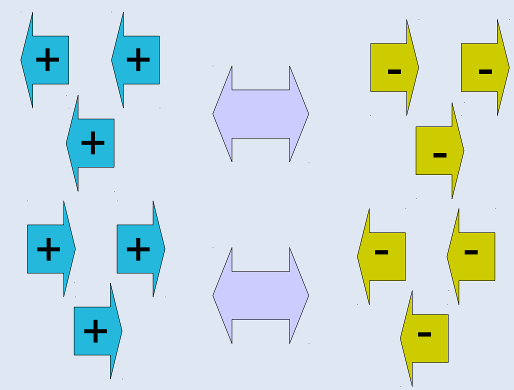
Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

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



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



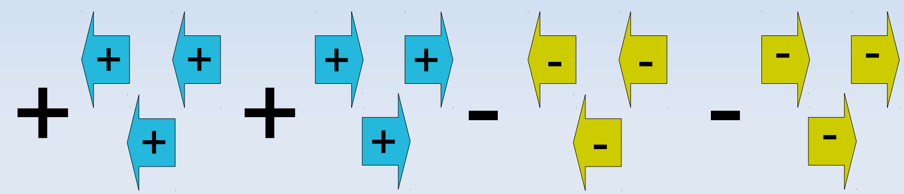
$$n_B \leftrightarrow n_{\bar{B}}$$

Baryogenesis

[Sakharov '69]

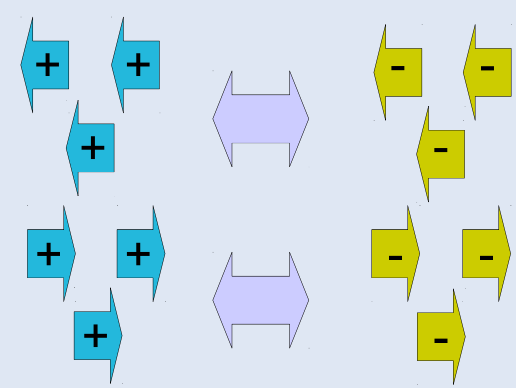
Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

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



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



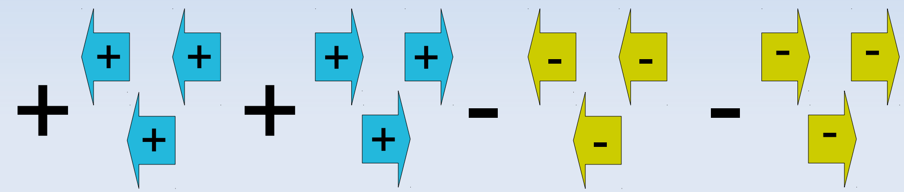
$$n_B \leftrightarrow n_{\bar{B}}$$

Baryogenesis

[Sakharov '69]

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

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



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

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

$$m = \bar{m}$$

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

Baryogenesis

[Sakharov '69]

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

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

SM @ EW temp

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

 B+L anomaly — sphaleron

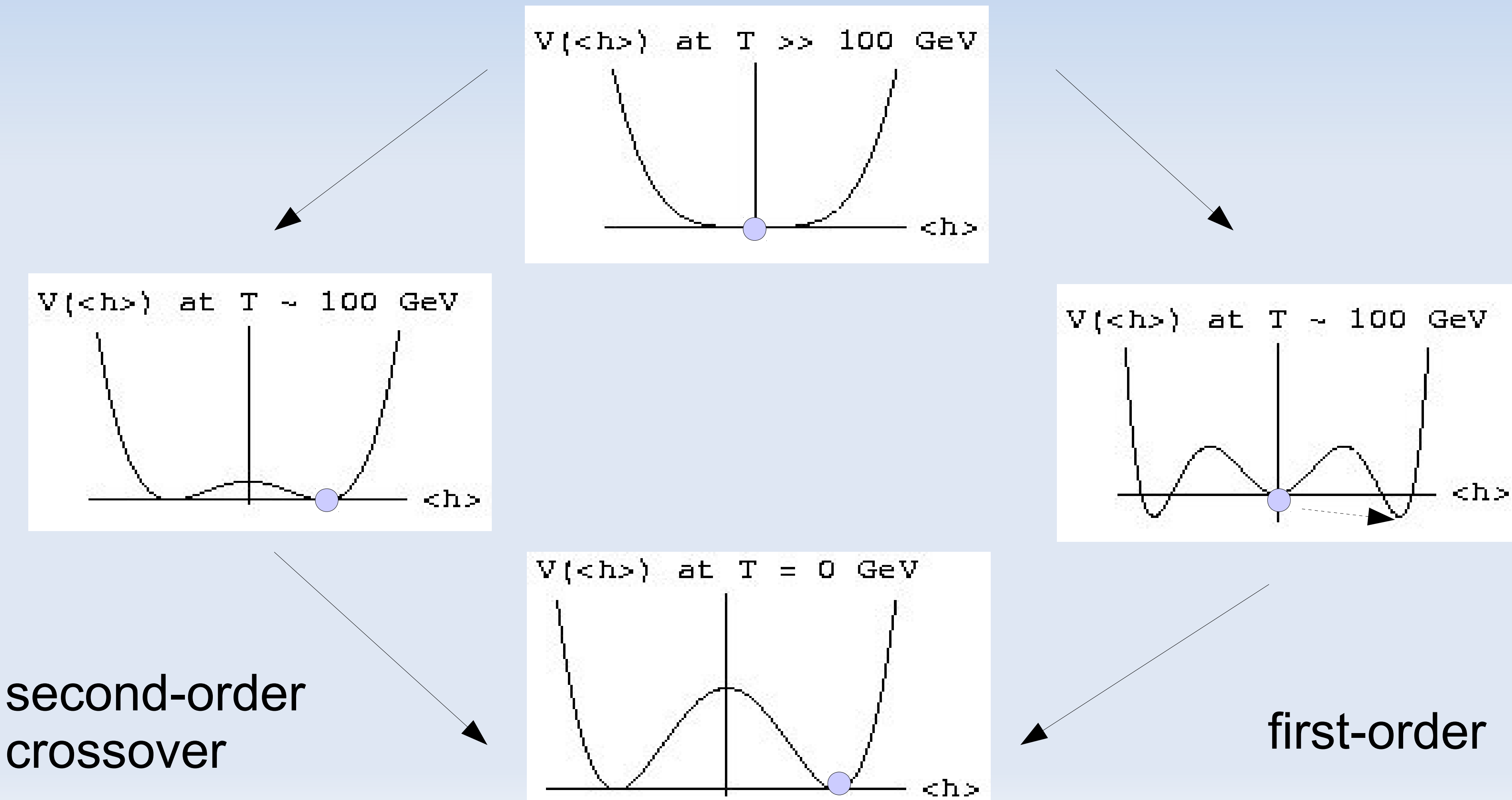
 Jarlskog invariant

 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:

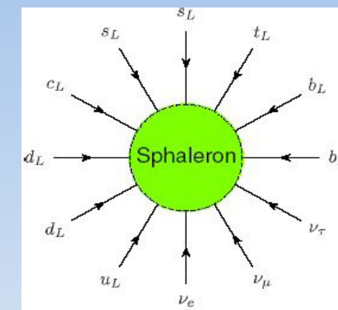


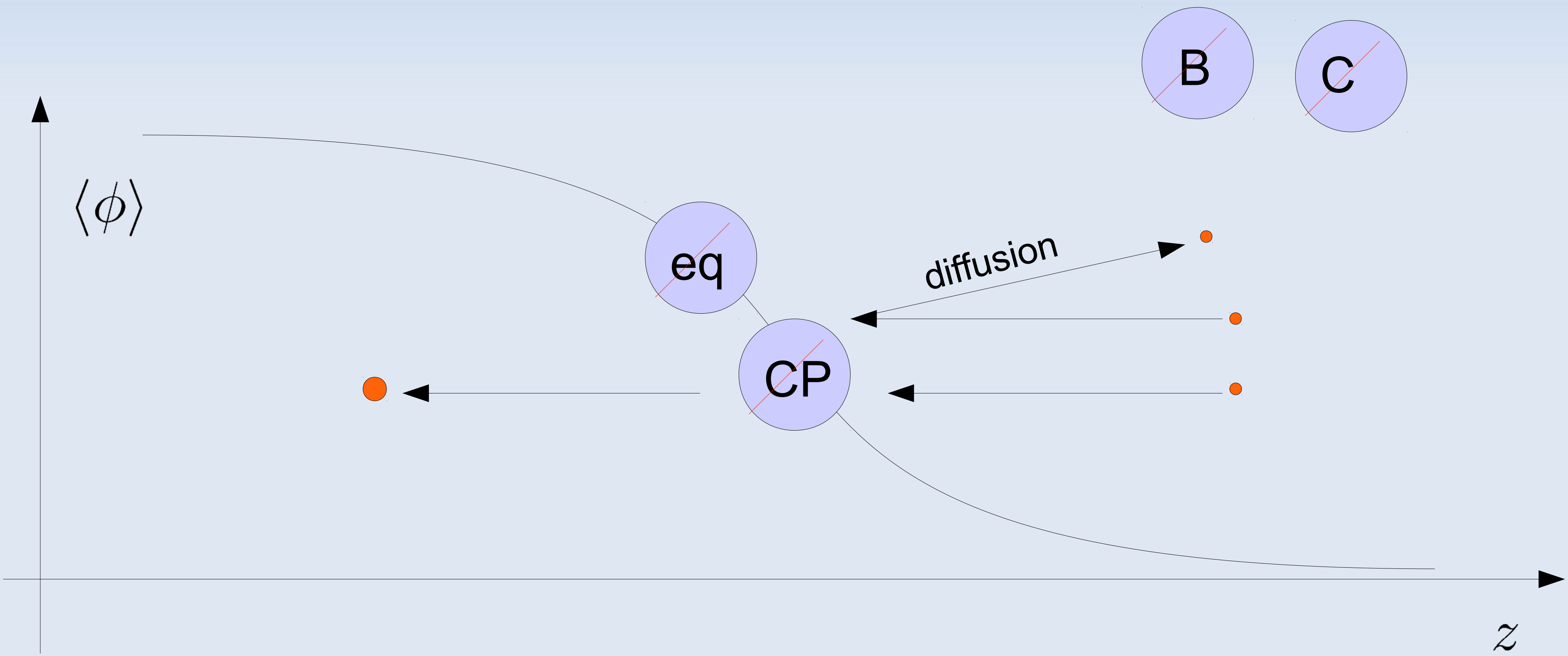
eq First-order phase transitions

- 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

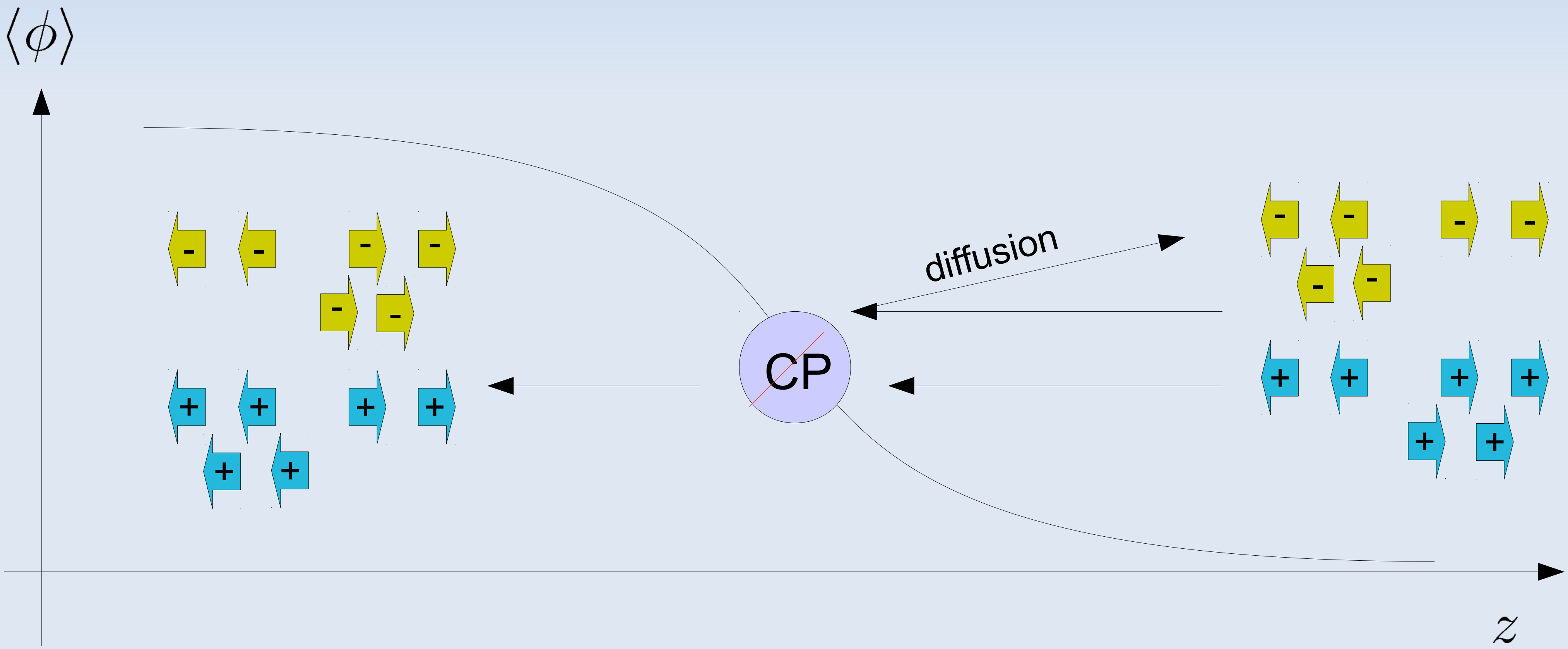
[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]





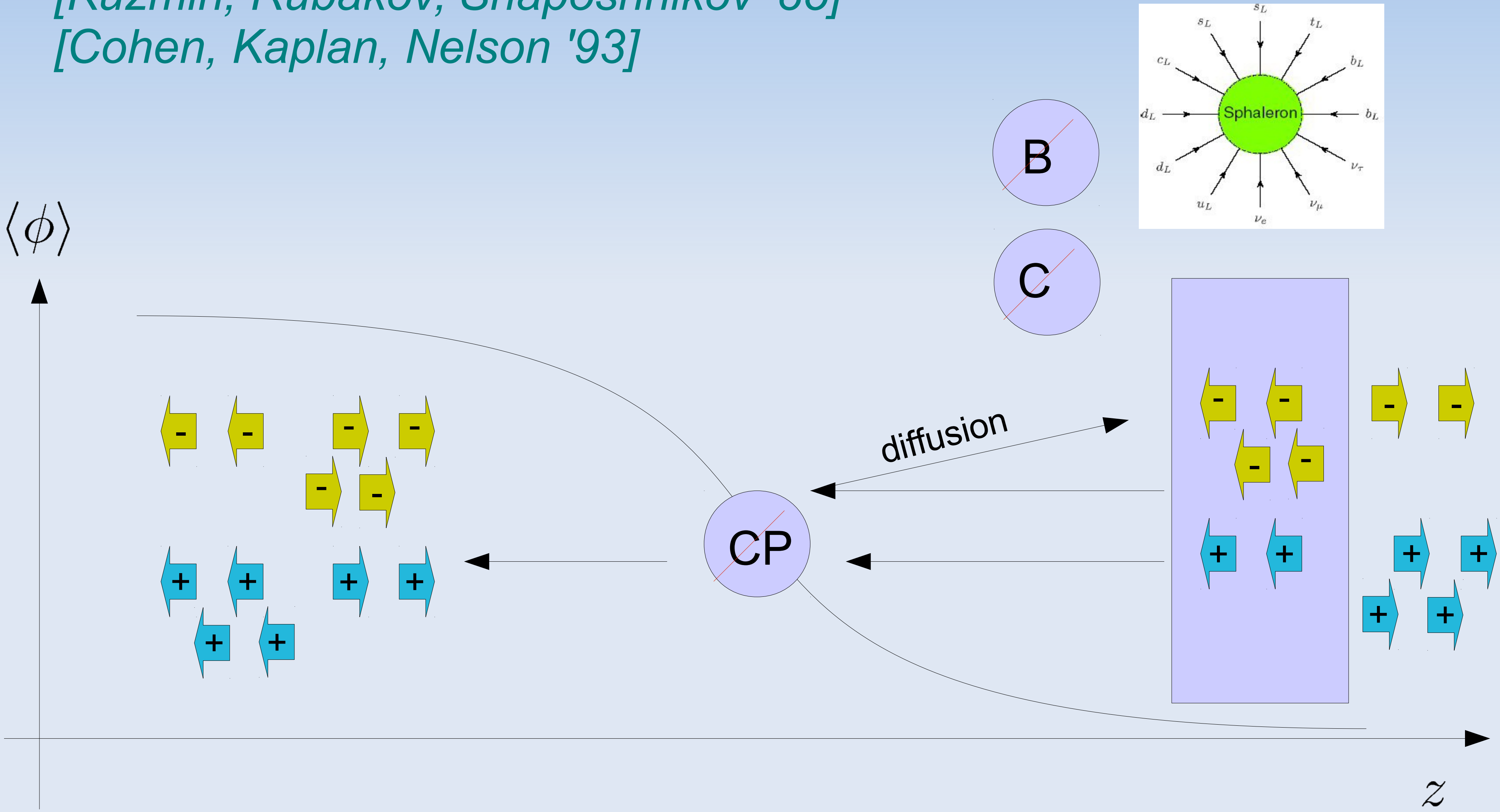
Electroweak baryogenesis

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



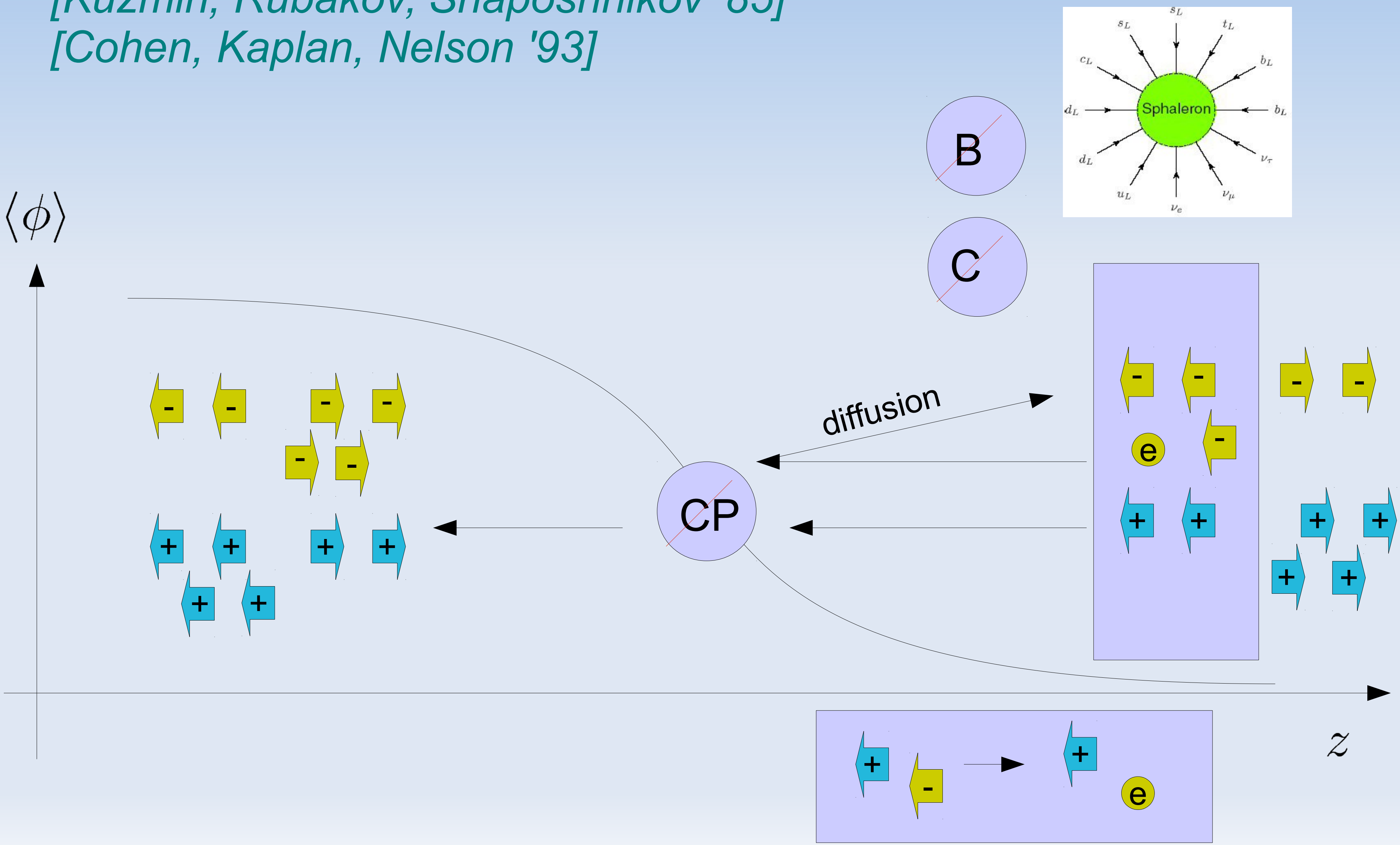
Electroweak baryogenesis

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



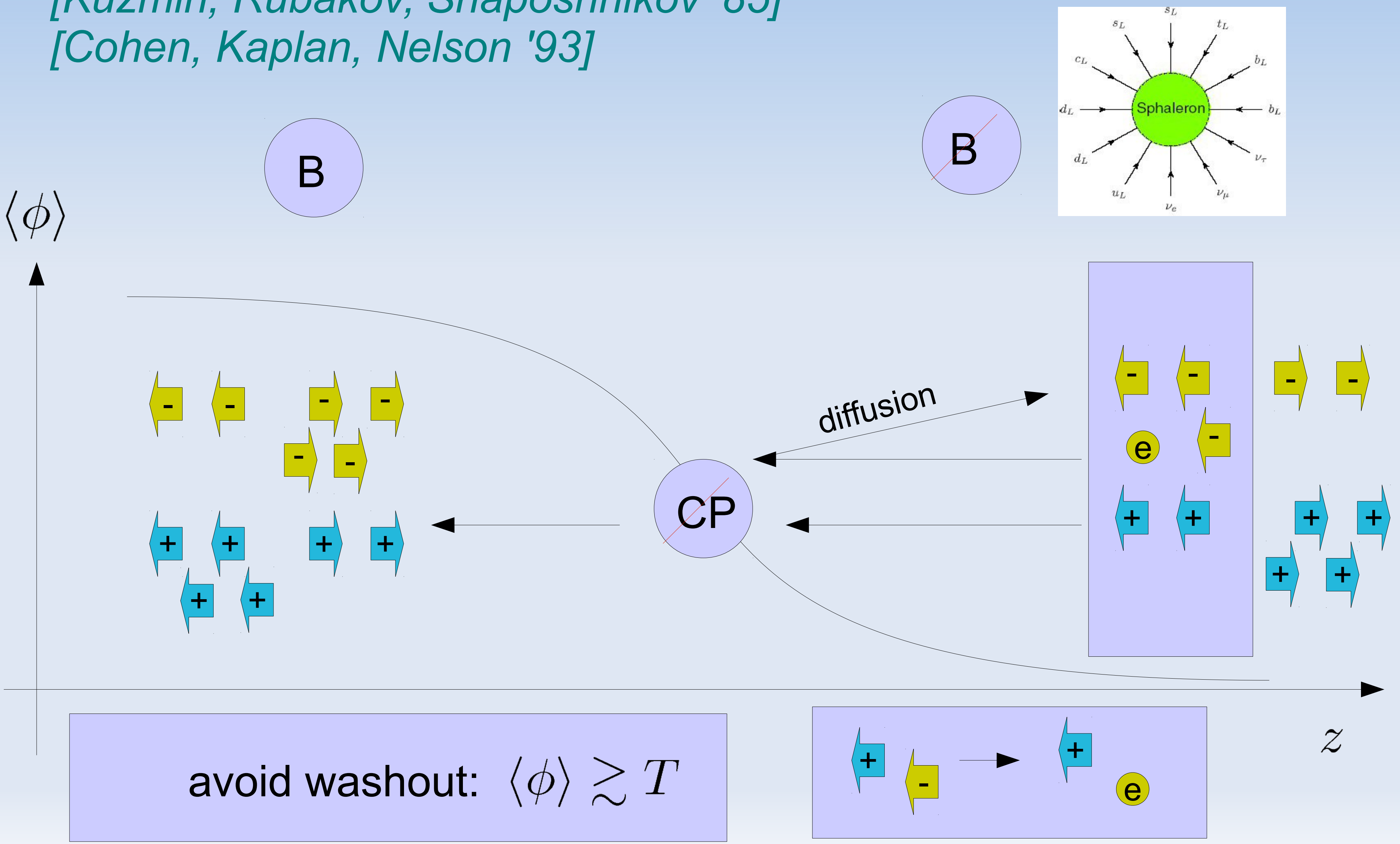
Electroweak baryogenesis

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

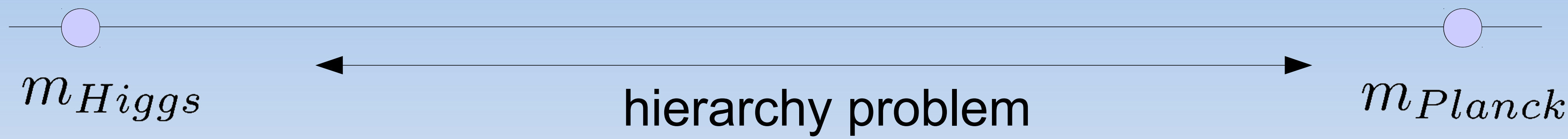


Electroweak baryogenesis

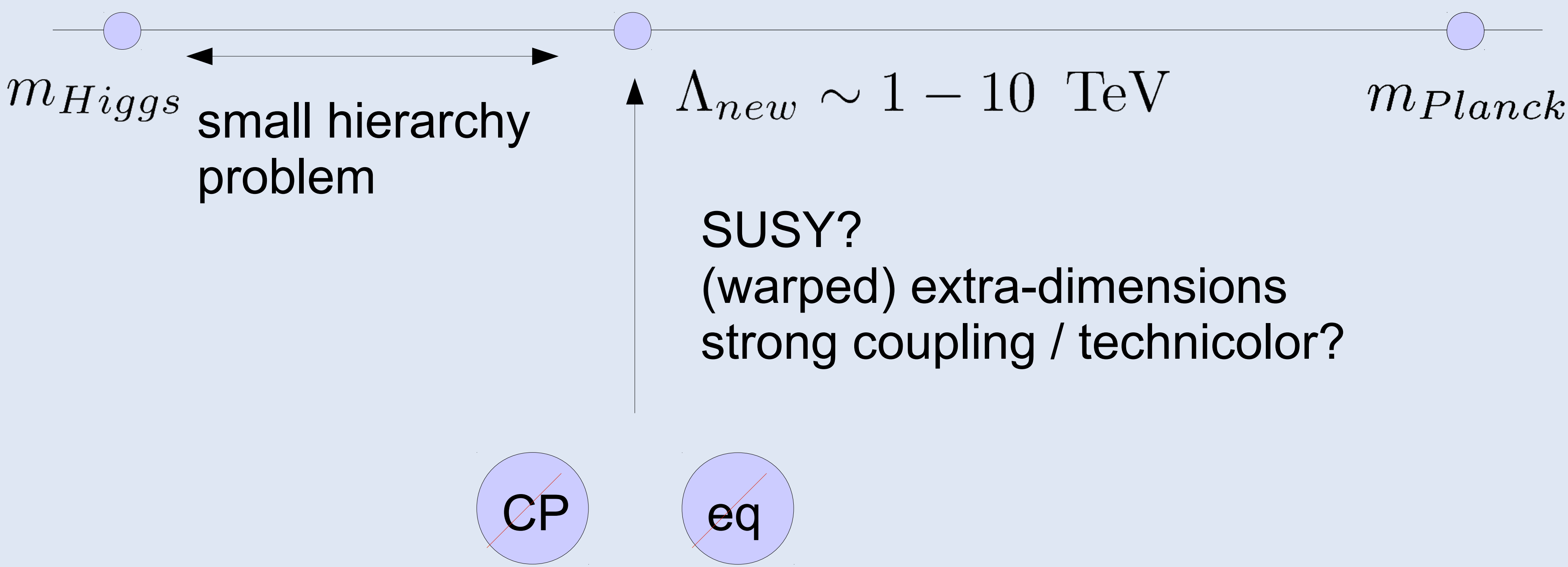
[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]



Hierarchy problem



This indicates that there is some kind of new physics around the corner that did not appear in collider experiments yet



Why is this interesting?

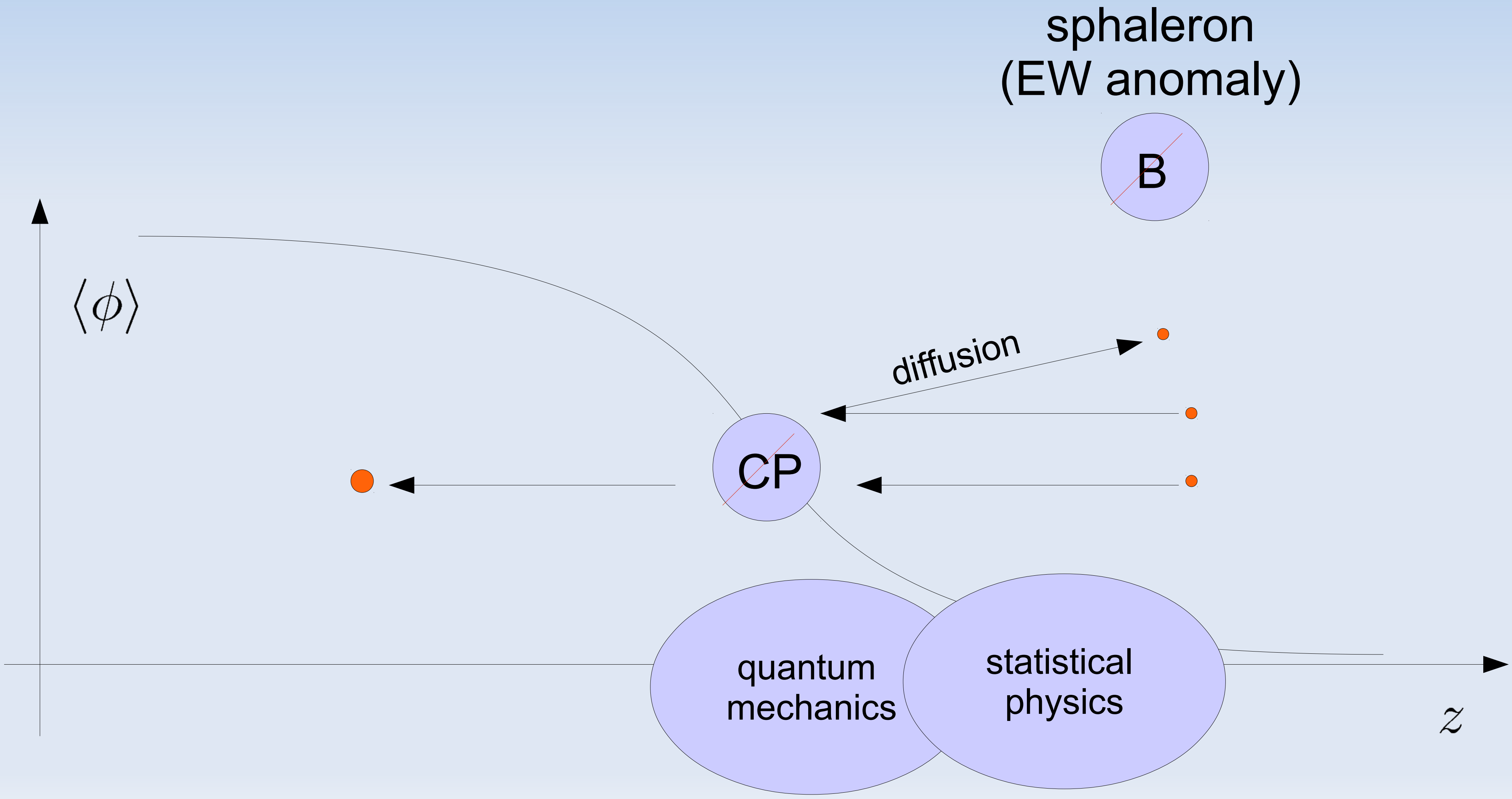
- The hierarchy problem indicates that there is some BSM physics at EW scales
- Electroweak baryogenesis involves only physics at the electroweak scale that is accessible to collider experiments
- Electroweak baryogenesis leads naturally to the observed baryon asymmetry

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

beyond SM?

What are the challenges?

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



Technical details

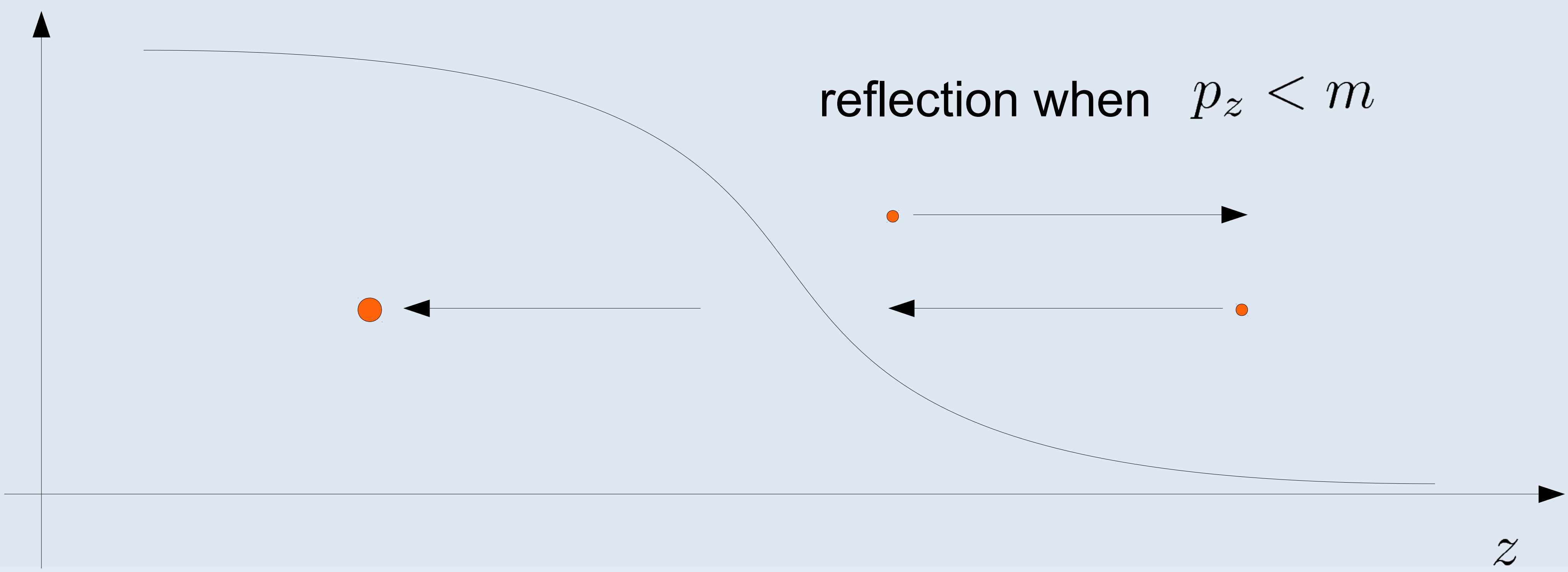
Semi-classical reflection

Many particles change their mass when passing into the Higgs bubble

$$m > 0 \qquad\qquad m = 0$$

$$\tilde{p}^2 = m^2 \qquad\qquad p^2 = 0$$

wall frame → $\tilde{E} = E$ and $\tilde{p}_z^2 = p_z^2 - m^2$



Transport equations

In case of a statistical system with particle distribution function

$$f(p_z, x, t)$$

the change in momentum

$$\tilde{E} = E \qquad \text{and} \qquad \tilde{p}_z^2 = p_z^2 - m^2$$

translates into

$$f(p_z, left) = f(\sqrt{p_z^2 - m^2}, right)$$

or

$$\underbrace{p_z \partial_z f}_{\text{flow term}} + \underbrace{\frac{1}{2}\partial_z m(z)^2 \partial_{p_z}}_{\text{force}} f = 0$$

~~CP~~ ?

transport equation
of Boltzmann type

Kadanoff-Baym equations

[Kadanoff, Baym '61]

In order to quantify electroweak baryogenesis one needs a formalism that includes quantum effects (CP violation) as well as statistical effects (diffusion/transport)

This is achieved by the Kadanoff-Baym equations that are a statistical generalisation of the Schwinger-Dyson equations of QFT (Schwinger-Keldysh formalism)

$$(\Box + m^2 + \Sigma)G(x,y) = \delta(x-y)$$

Formally the equation looks like SD, but

- The 2-point function depends on x and y seperately
  $\rightarrow$ X and p in Fourier (Wigner) space
- There is an additional 2x2 structure from the
  in-in-formalism

Kadanoff-Baym equations

In Wigner space this leads to the Moyal star product

$$(p^2 - m(X)^2 - \Sigma)e^{i\diamond}G(X,p) = \mathbf{1}$$

With $\diamond = \overleftarrow{\partial_X}\overrightarrow{\partial_p} - \overleftarrow{\partial_p}\overrightarrow{\partial_X}$ $\qquad X = \dfrac{x+y}{2}$

One of the Green functions (Wightman function) encodes the particle distribution function and is in equilibrium given by

$$G^{<}_{eq}(X,p) = 2\pi i\, f^{eq}(p,X)\,\delta(p^2 - m^2)$$

and $\qquad f^{eq} = \dfrac{1}{e^{p_0/T} \pm 1}$

One fermion flavor

For one fermion flavor with a space-time dependent mass, the Kadanoff-Baym equation reads

$$(\not{p} - m P_L - m^* P_R - \Sigma^R)\, e^{i\diamond}\, G^< = \text{collisions}$$

In order to do progress analytically, one typically uses several approximations/techniques:

1) Neglect most interactions: $\Sigma^R \to 0$

2) Planar approximation (z): $\hat{S} \propto (p_0\gamma_0 - p_\perp \cdot \gamma)\gamma_3\gamma_5$

3) Gradient expansion: $\diamond \sim \partial_x \partial_p \sim (LT)^{-1} \ll 1$

[Kainulainen, Prokopec, Schmidt, Weinstock '02]

One fermion flavor

For one fermion flavor with a space-time dependent mass, an expansion in gradients leads to the equations

$$(p^2 - m^2 + \cdots)G^< = 0$$

and with $m(z) = |m(z)|e^{i\theta(z)}$ and spins s

$$\left(p \cdot \partial_X + \frac{1}{2}(m^2)'\partial_p + \frac{s}{2p_z}(m^2\theta')'\partial_p\right) f_s = \text{collisions}$$

$m(\partial_t + \vec{v} \cdot \nabla)$

forces

CP

decays
scatterings

[Cline, Joyce, Kainulainen '00]

[Kainulainen, Prokopec, Schmidt, Weinstock '02]

Technical details

Ingredients

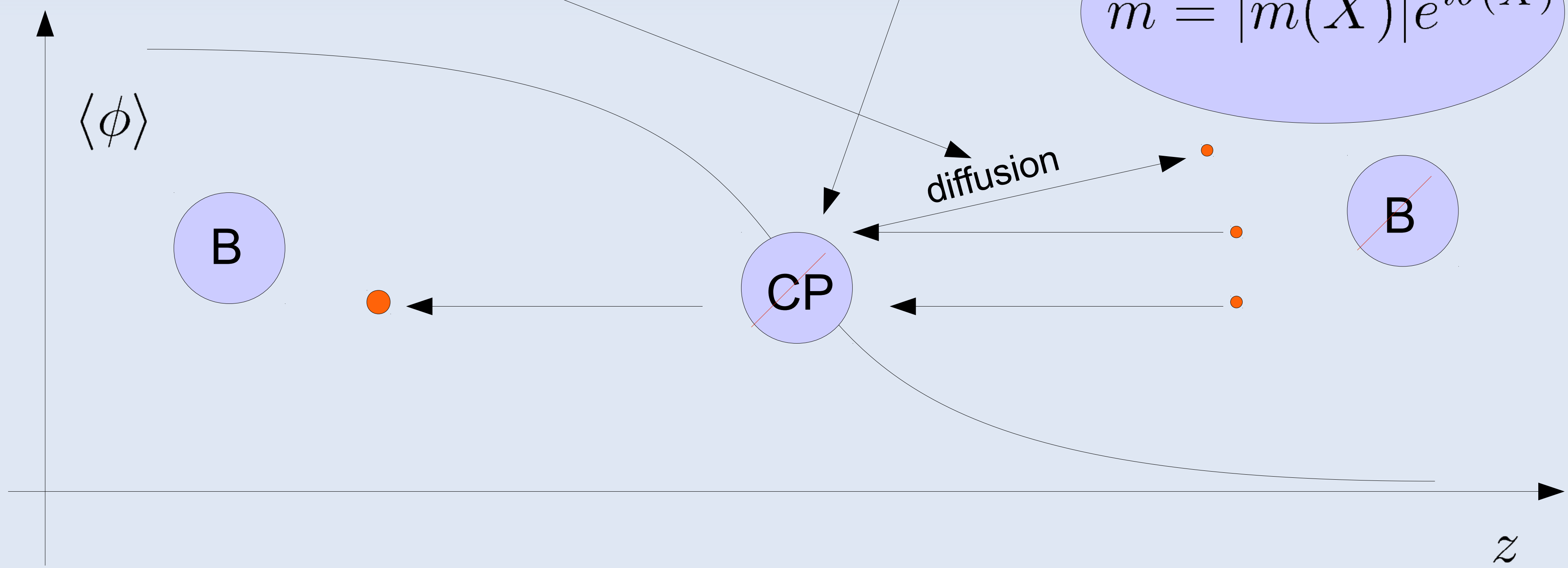
1 ~~eq~~ Strong first-order electroweak phase transition $\phi > T$

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

Summary

$$\left(p \cdot \partial_X + \frac{1}{2}(m^2)'\partial_p + \frac{s}{2p_z}(m^2\theta')'\partial_p \right) f_s = \text{collisions}$$

$$m = |m(X)| e^{i\theta(X)}$$



Outline

Introduction

MSSM

Composite Higgs

MSSM

CP

In the minimal supersymmetric standard model, the leading CP violation comes from the mass matrix of the charginos

$$m = \begin{pmatrix} M_2 & g\, v_1(X) \\ g\, v_2(X) & \mu_c e^{i\varphi} \end{pmatrix} \qquad \varphi \neq 0$$

eq

The strength of the electroweak phase transition

- is reduced by larger Higgs masses
- is enhanced by bosonic degrees of freedom that couple strongly to the Higgs - stops important

$$m_{\rm stop} \lesssim m_{\rm top}$$

Several flavours

In the most prominent case (MSSM), CP violation results from mixing effects between different flavors.
[Careno, Moreno, Quiros, Seco, Wagner '00]

In this case, new CP-violating sources occur

$$\mathrm{forces} \ni -\frac{1}{4}\{m^{2\prime}, \partial_p .\} + \frac{i}{16}[m^{2\prime\prime}, \partial_p^2 .]$$

but also additional complications arise due to flavor oscillations

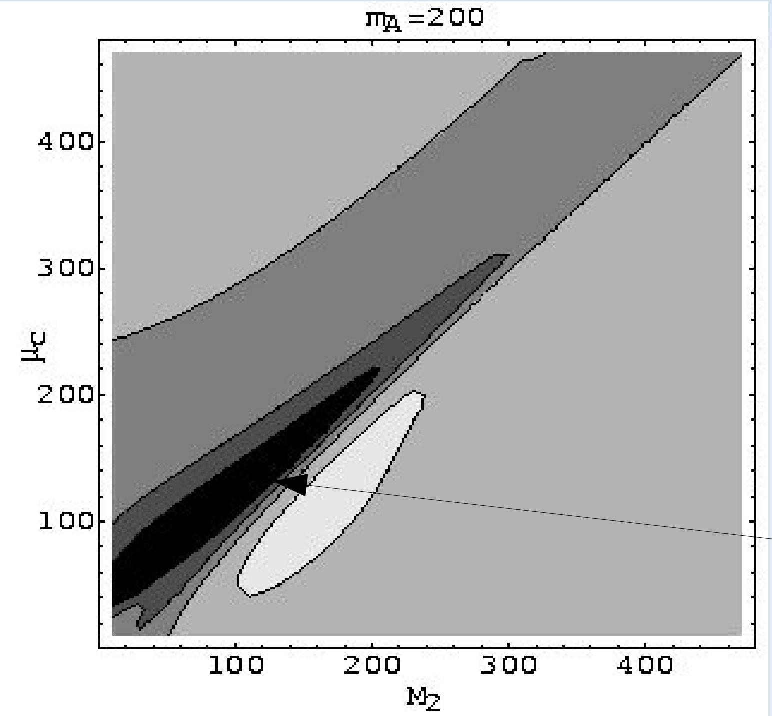
$$\left(p \cdot \partial_X + \frac{i}{2}[m^2, .] + \mathrm{forces}\right) f_s = \mathrm{collisions}$$

$e^{i\frac{\Delta m^2}{p_z} z}$ ⟷ gradient expansion?

[TK, Prokopec, Schmidt '05]

MSSM

Assuming a strong first-order phase transition, the baryon assymetry depends mostly on the chargino mass and the CP violation in the chargino sector



$$m = \begin{pmatrix} M_2 & g\,v_1(X) \\ g\,v_2(X) & \mu_c\,e^{i\varphi} \end{pmatrix}$$

$$\varphi = \frac{\pi}{2}$$

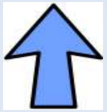
$$\frac{\eta_{\rm max}}{\eta_{\rm observed}} \simeq 5$$

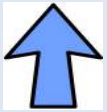
[TK, Prokopec, Schmidt, Seco '05]

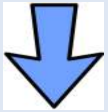
MSSM

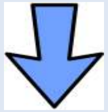
In the minimal supersymmetric standard model, the leading CP violation comes from the mass matrix of the charginos

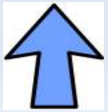
$$m = \begin{pmatrix} M_2 & g\, v_1(X) \\ g\, v_2(X) & \mu_c\, e^{i\varphi} \end{pmatrix}$$

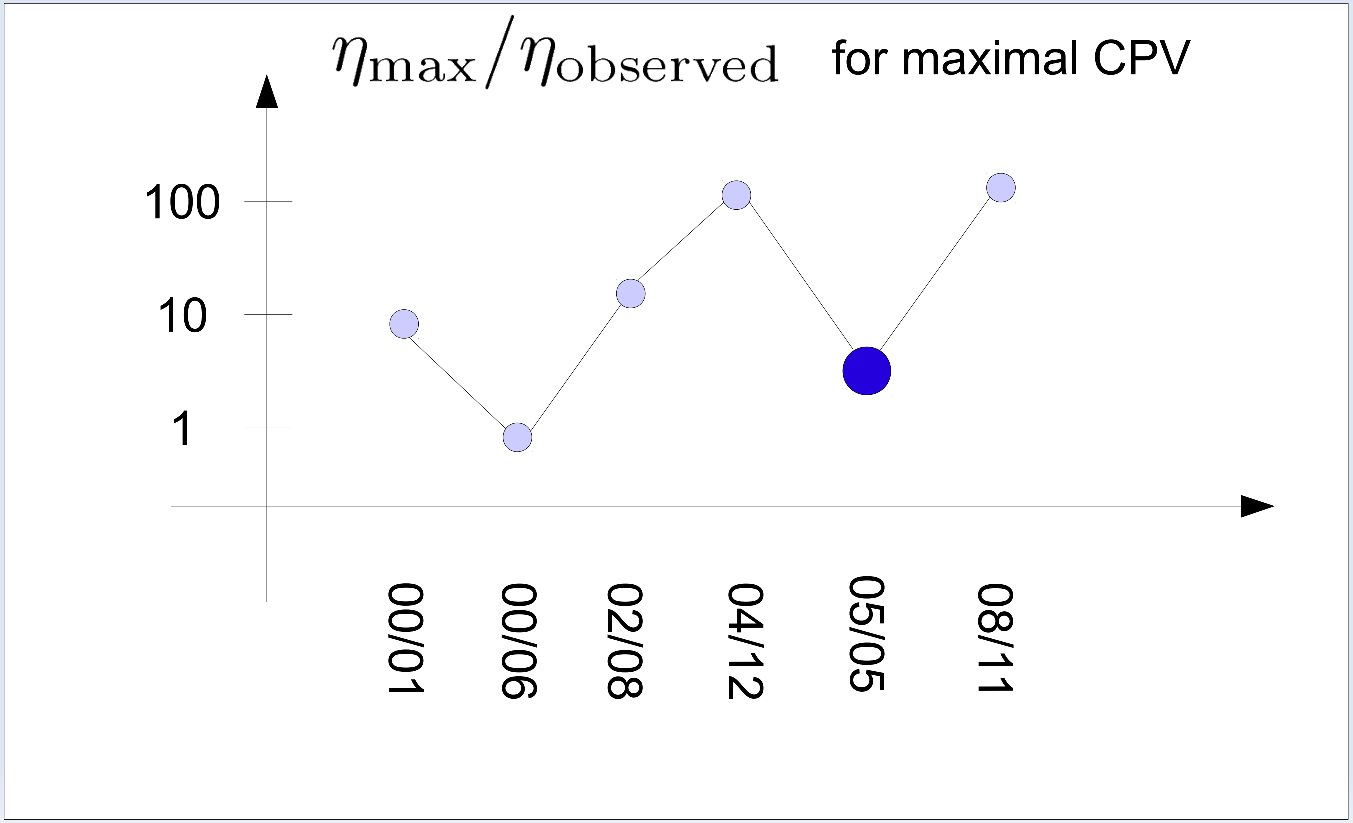
Flavor mixing? 

Resonances? 

Higgs resummation? 

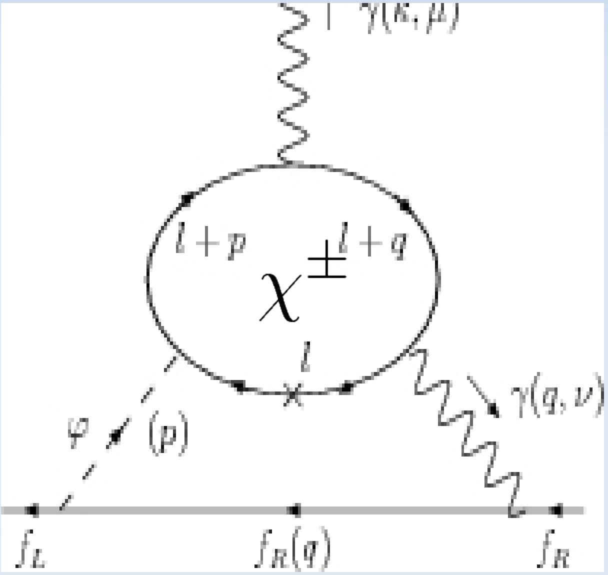
Flavor oscillations? 

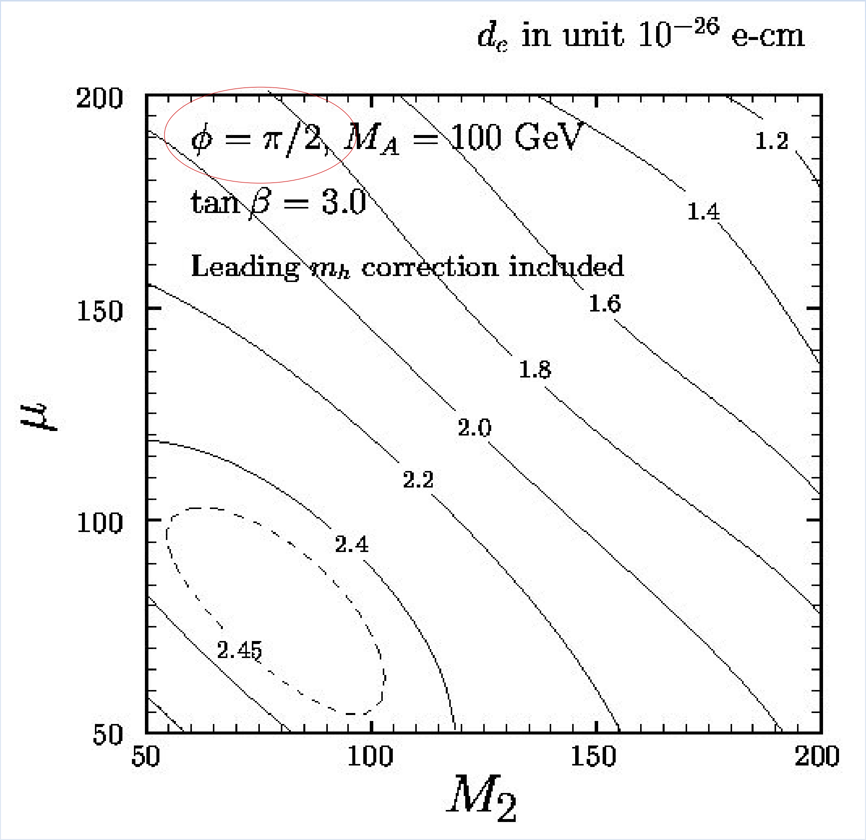
Higgs transport? 



Electric dipole moments

Even if all sfermions are heavy, there are two-loop (Barr-Zee) contributions from the chargino to the EDM of the electron and the neutron



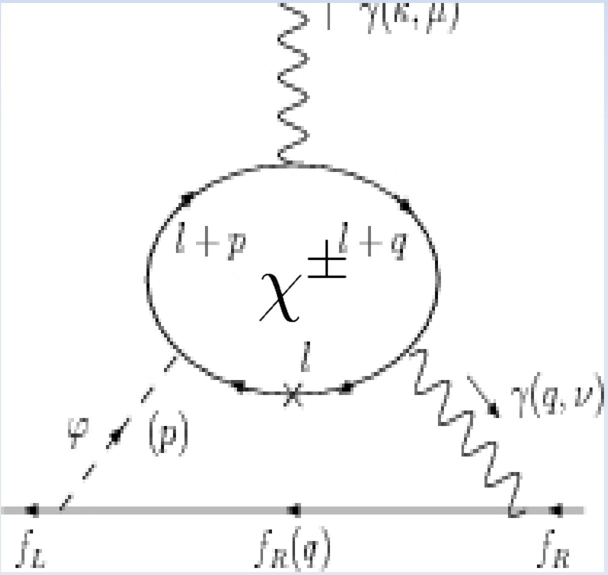


[Chang, Chang, Keung '02]

EDMs

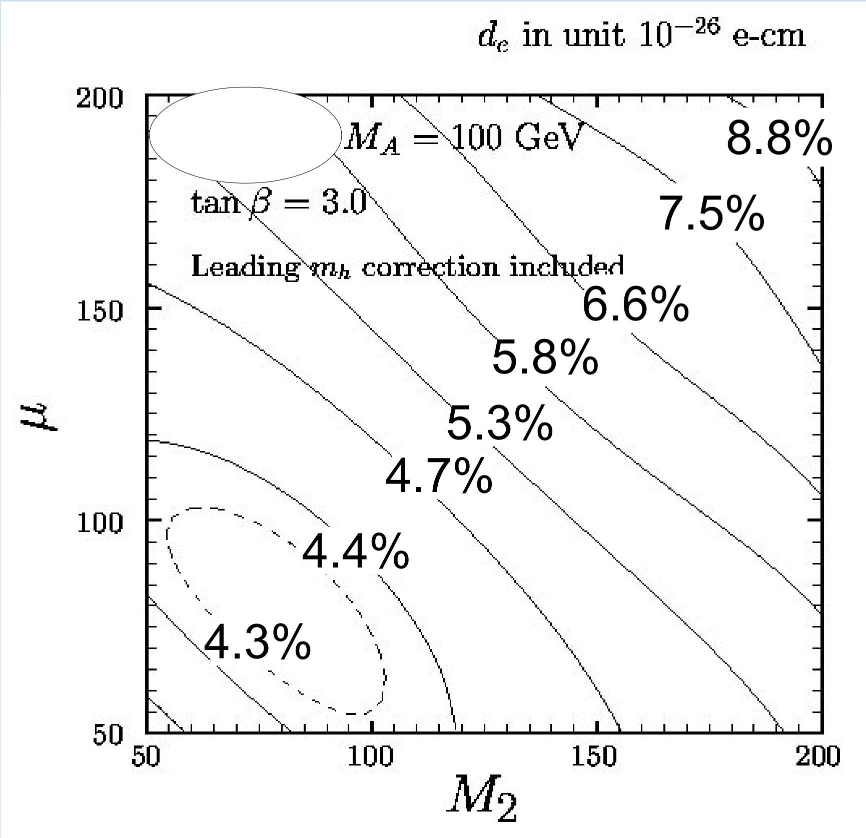
Even if all sfermions are heavy, there are two-loop (Barr-Zee) contributions from the chargino to the EDM of the electron and the neutron

$$\sin\varphi <?$$



[Hudson et al. '11]

$$d_e < 1.05 \times 10^{-27}\, e\,\mathrm{cm}$$

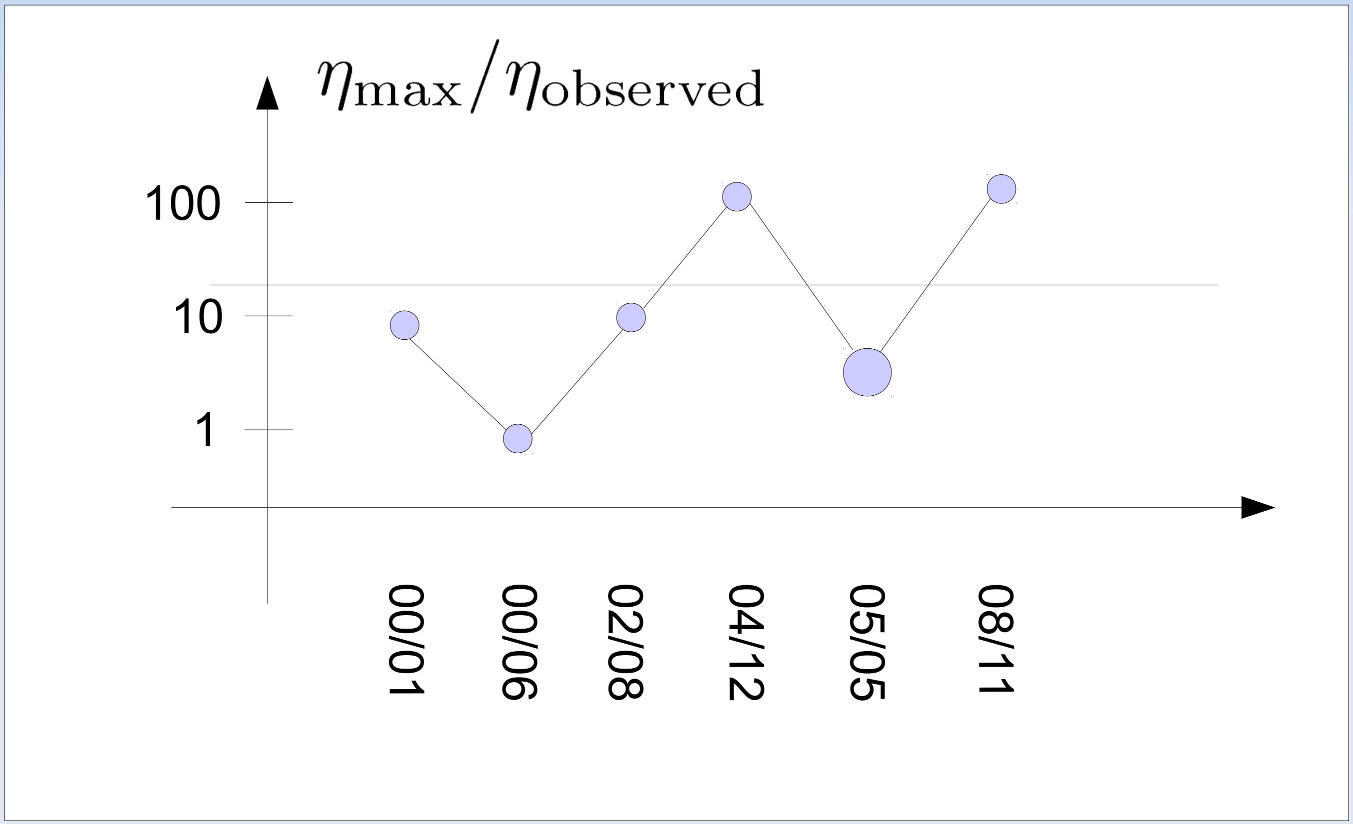


[Chang, Chang, Keung '02]

MSSM baryogenesis

[Hudson et al. '11]

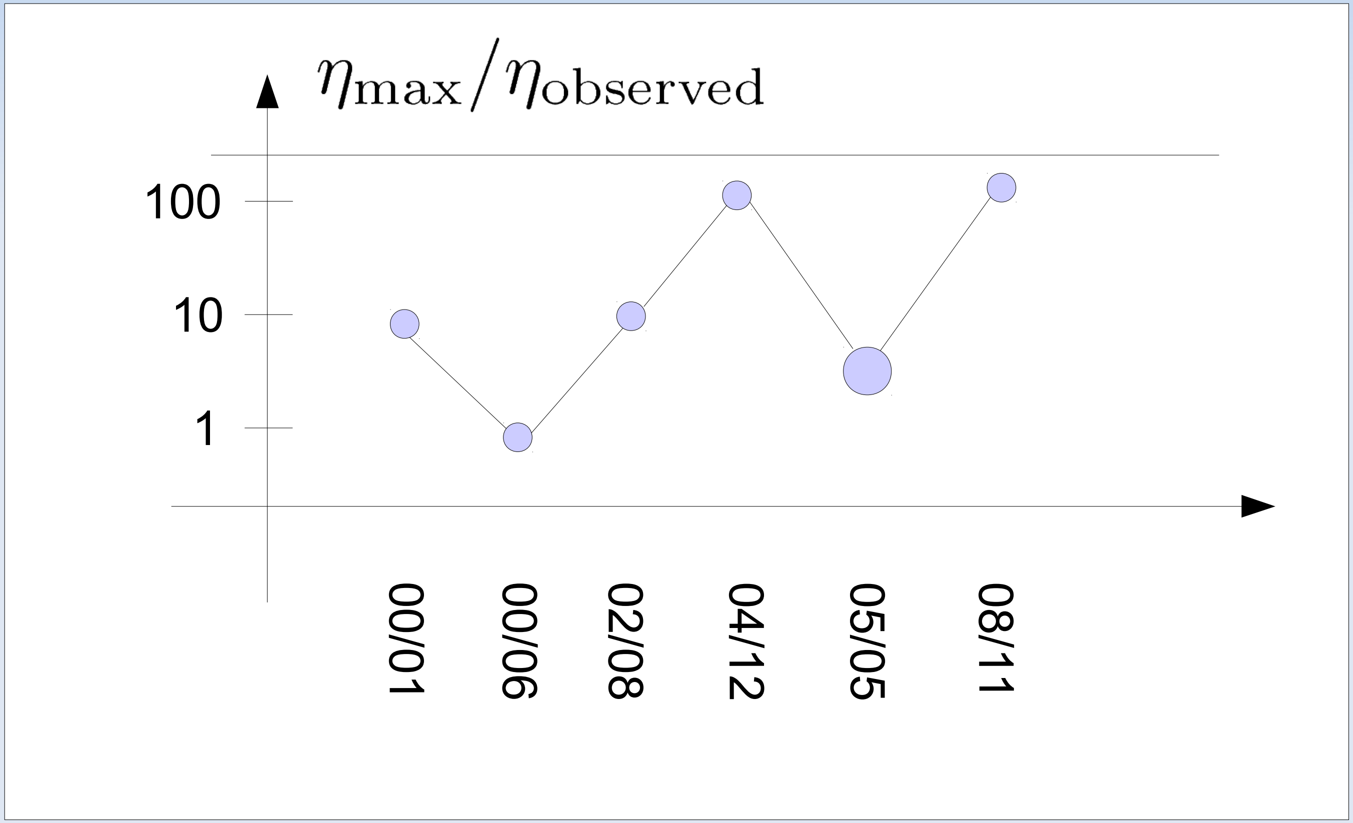
The EDM constraints translate into $\eta_{\max}/\eta_{\rm observed} \gtrsim 23$



Chargino driven MSSM baryogenesis ruled out

[Baron et al. '13]

The EDM constraints translate into $\eta_{\max}/\eta_{\text{observed}} \gtrsim 250$



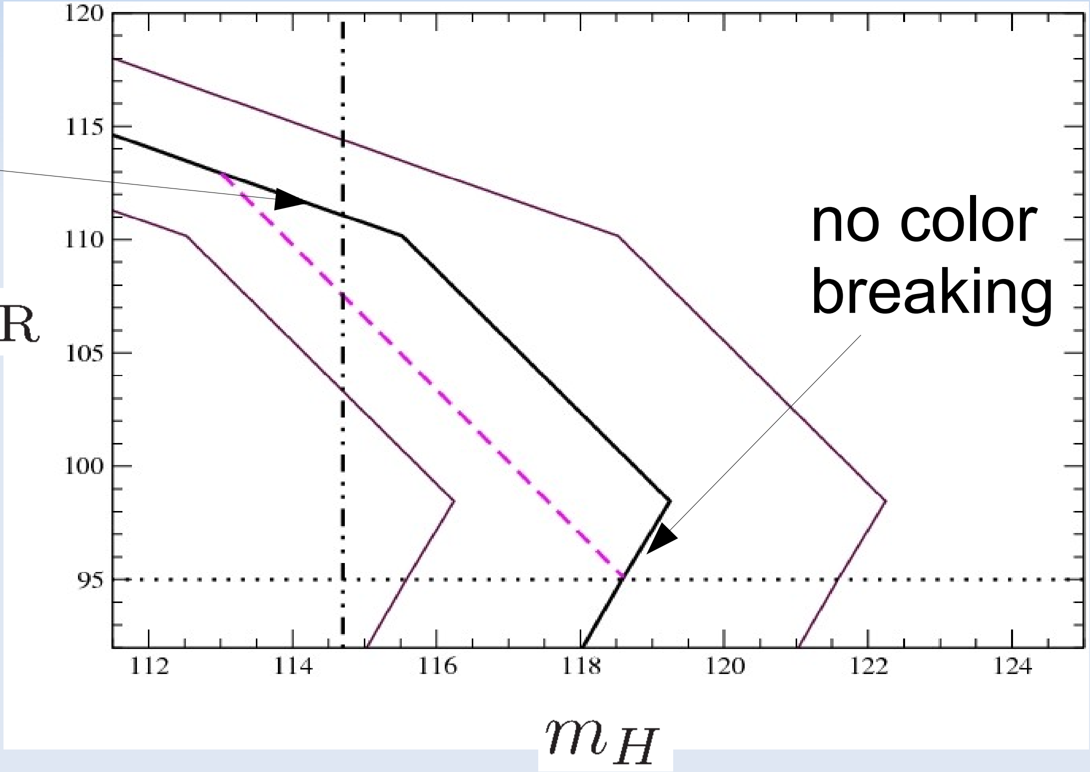
Caveat: EDM bounds avoided by using binos
[Li, Profumo, Ramsey-Musolf '08]

Phase transition

MSSM phase transition after LEP:
very heavy left-handed stop required

$m_{\mathrm{stop,L}} \sim 500\,\mathrm{TeV}$

$\frac{\phi_c}{T_c} > 1.0$



$m_{\mathrm{stop,R}} \lesssim 110\,\mathrm{GeV}$ $m_{\mathrm{stop,L}} \gtrsim 30\,\mathrm{TeV}$

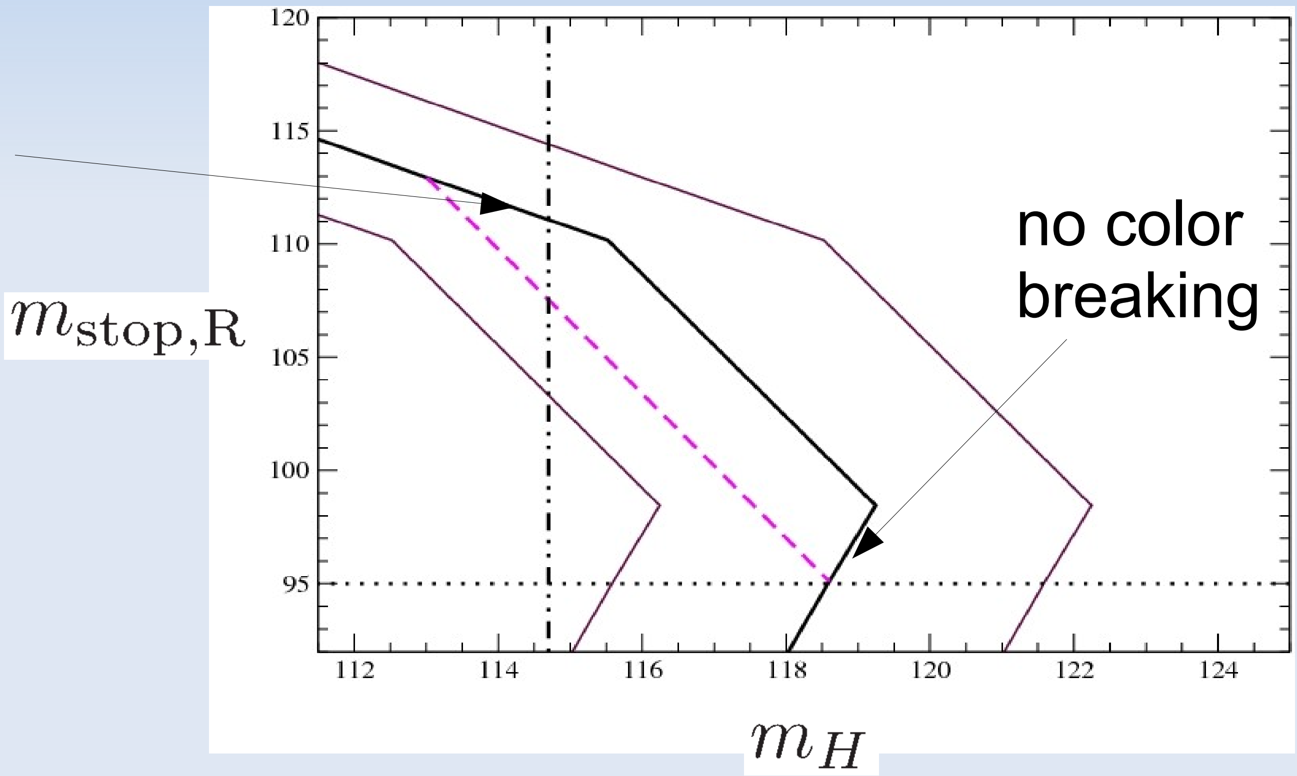
[Carena, Nardini, Quiros, Wagner '08]

Phase transition

eq

MSSM phase transition after LEP:
very heavy left-handed stop required

$$\frac{\phi_c}{T_c} > 1.0$$



you are here!

$$m_{\text{stop,L}} \gtrsim 10^6\ \text{TeV}$$

and hide right-handed stop from LHC

[Carena, Nardini, Quiros, Wagner '08]

Conclusions MSSM

Electroweak baryogenesis in SUSY models is technically not ruled out yet, but with current experimental constraints it is a reather contrived scheme

- Light (< 200 GeV) and almost mass degenerate charginos or binos
- CP violation for charginos that in the most optimistic cases is at the verge of beeing seen in EDM experiments (caveat: binos)
- very specific spectrum required for a strong first-order phase transition (or extended Higgs sector?)

Outline

Introduction

MSSM

Composite Higgs

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

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

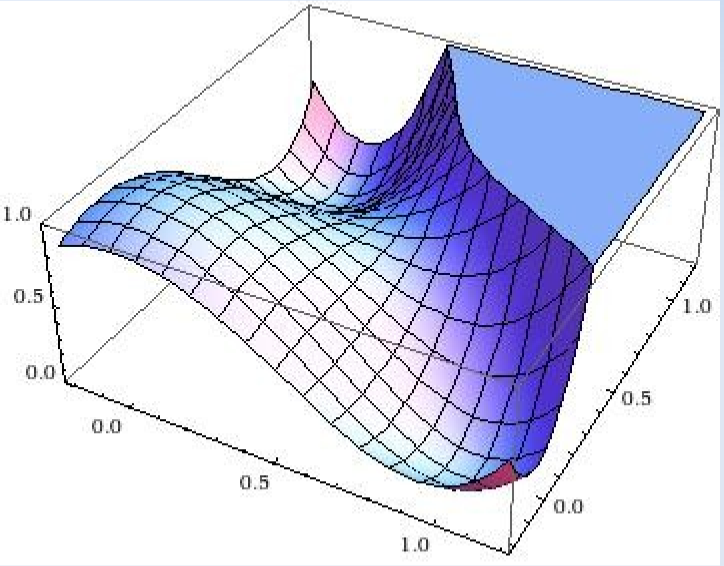
$$\mathcal{L} \ni y_t \bar{\psi}_Q H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_Q H \psi_t + h.c.$$

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

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

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

CP violation

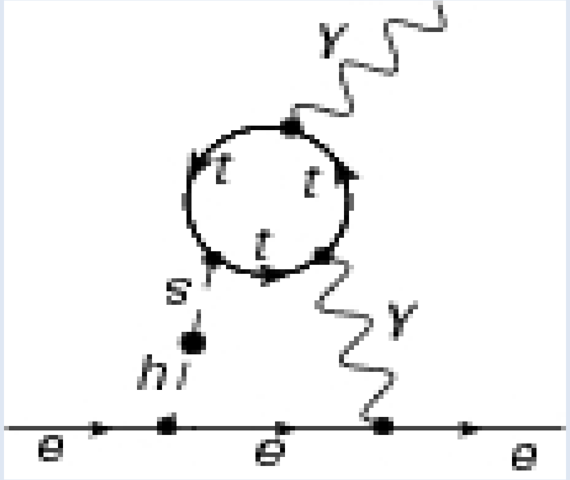
$$\mathcal{L} \ni y_t \bar{\psi}_t H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_t H \psi_t$$

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

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

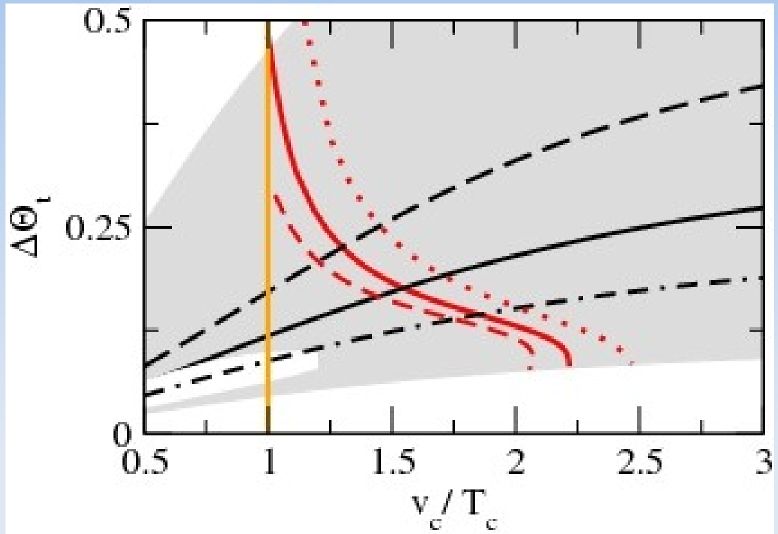
So, the complex phase during the phase transition behaves as

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



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

Baryogenesis



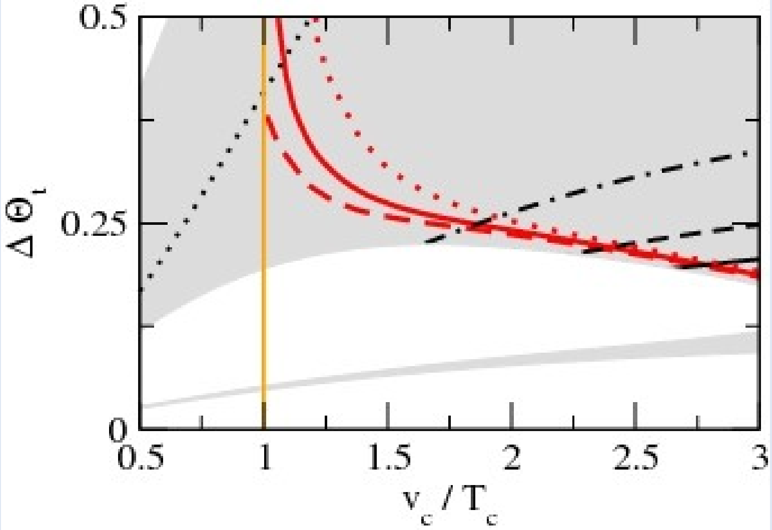
$$m_s = 130\,\text{GeV}$$

$$\Delta\theta_t \gtrsim 0.15$$

strength of
CP violation

strength of the phase transition

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



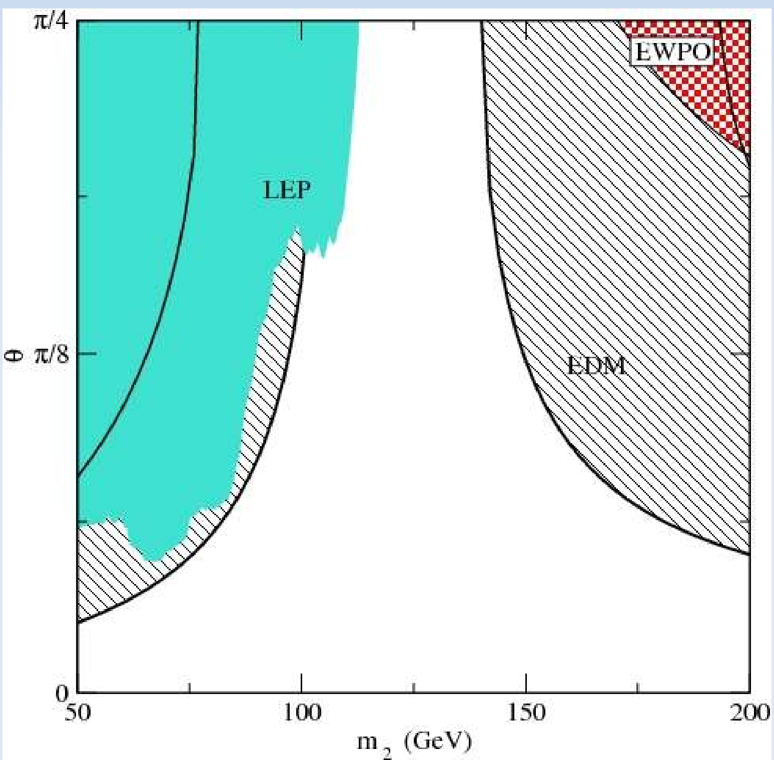
$$m_s = 80\,\text{GeV}$$

$$\Delta\theta_t \gtrsim 0.25$$

[Espinosa, Gripaios, TK, Riva '11]

Signals

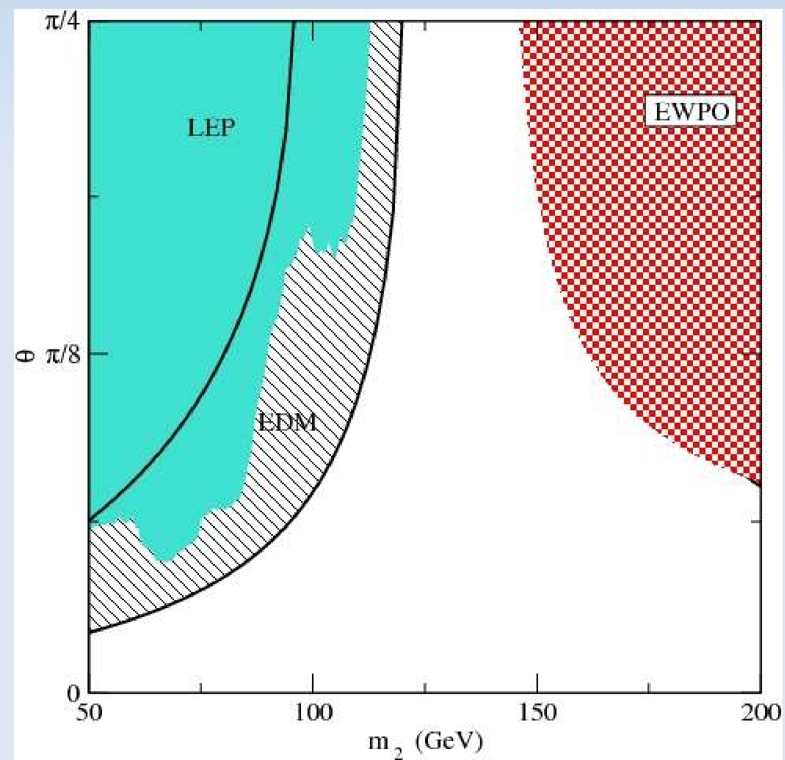
$m_h = 120\,\mathrm{GeV}$



singlet mass

Higgs-singlet mixing ~ CP violation

$m_h = 140\,\mathrm{GeV}$



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

[Espinosa, Gripaios, TK, Riva '11]

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
- no $\mathbb{Z}_2$ (Higgs-singlet mixing; singlet is not DM)

Conclusions

Electroweak baryognesis is still a compelling framework to explain the observed baryon asymmetry.

Higgs found

No EDMs

No minimal SUSY

Conclusions

Electroweak baryognesis is still a compelling framework to explain the observed baryon asymmetry.

Higgs found

No EDMs

No minimal SUSY