

# Electroweak Baryogenesis from a Composite Higgs Sector

Francesco Riva, IFAE Barcelona & University of Padova

in collaboration with: J.R.Espinosa, B.Gripaios, T.Konstandin

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Electroweak Baryogenesis in the Standard Model with a Singlet



...minimal

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# Motivation

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \neq 0$$


$$\approx 6 \times 10^{-10}$$

# WHY EWBG?

• Is the only testable scenario:

GUT BG,

Affleck-Dine BG,

Leptogenesis,...



not falsifiable

# HOW Baryogenesis?

## Sakharov's Conditions

### B violation

- Why? Initially  $B = 0$  , now  $B \neq 0$
- In SM? Sphalerons

$U(1)_{B+L}$  anomaly  
Topological defects  
Finite T

### Out of Equilibrium

- Why? Otherwise  $+B \leftrightarrow -B$
- In SM? ElectroWeak Phase Transition

### C, CP violation

- Why? Otherwise  $\Gamma(X \rightarrow q_L q_L) + \Gamma(X \rightarrow q_R q_R) = \Gamma(\bar{X} \rightarrow \bar{q}_R \bar{q}_R) + \Gamma(\bar{X} \rightarrow \bar{q}_L \bar{q}_L)$
- In SM?  $\delta_{CKM}$

# HOW Baryogenesis?

## Sakharov's Conditions

### B violation

- In SM? Sphalerons ✓

### Out of Equilibrium

- In SM? ElectroWeak Phase Transition ✗

2nd order for  $m_H \gtrsim 75 \text{ GeV}$

### C, CP violation

- In SM?  $\delta_{CKM}$  ✗

Invariant too small?  $\frac{J}{(100 \text{ GeV})^{12}} \sim 10^{-20}$

# HOW Baryogenesis?

## Sakharov's Conditions

### B violation

- In SM? Sphalerons ✓

### Out of Equilibrium

2nd order for  $m_H \gtrsim 75 \text{ GeV}$

- In SM? ElectroWeak Phase Transition ✗
- In BSM? EWPT, Massive Particle

### C, CP violation

Invariant too small?

- In SM?  $\delta_{CKM}$  ✗  $\frac{J}{(100\text{GeV})^{12}} \sim 10^{-20}$
- In BSM? extra couplings

# HOW Baryogenesis?

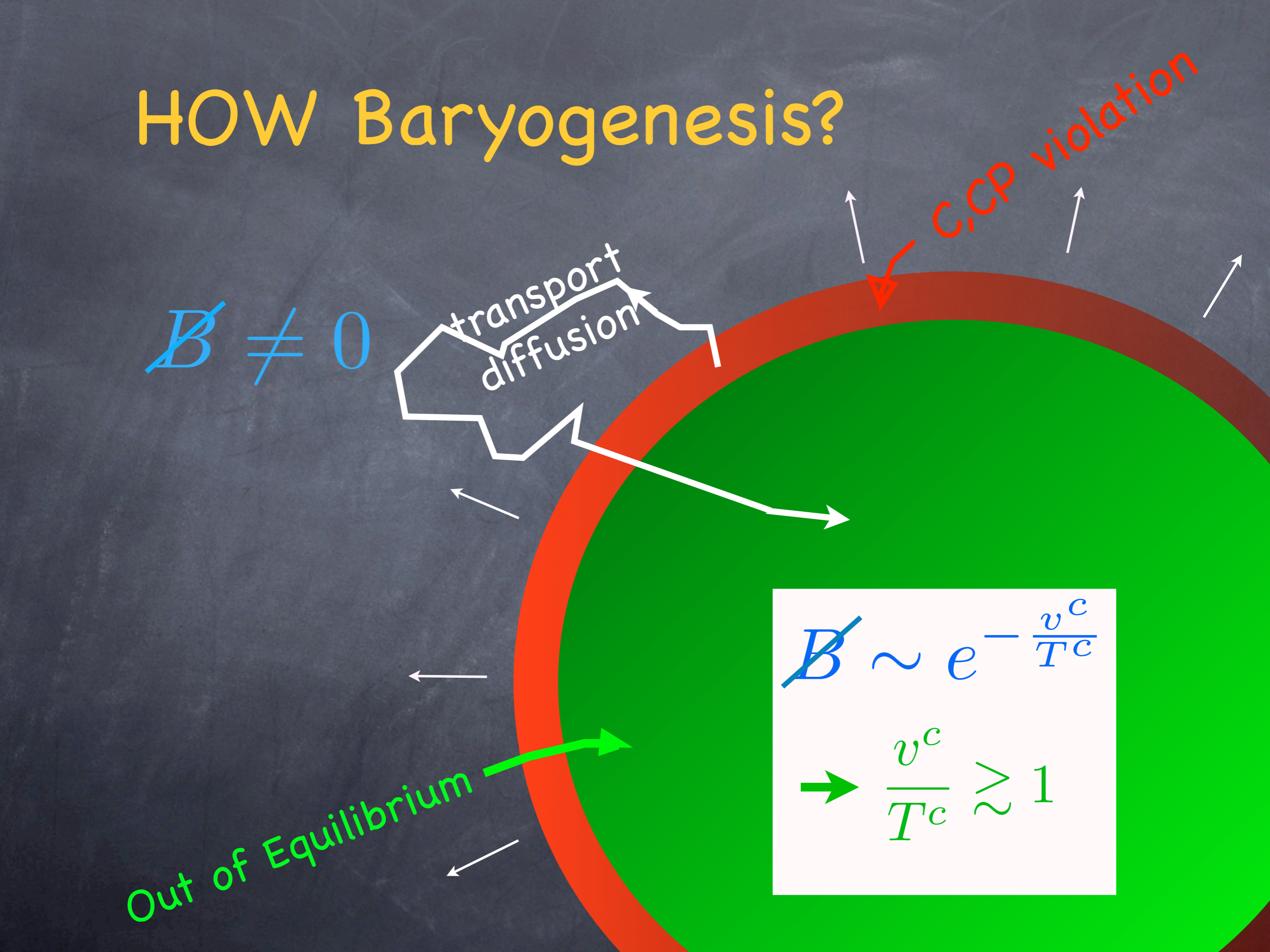
$$B \neq 0$$

transport  
diffusion

C, CP violation

Out of Equilibrium

$$B \sim e^{-\frac{v^c}{T^c}}$$
$$\rightarrow \frac{v^c}{T^c} \gg 1$$



# EWBG in BSM?

A Swiss-German, a Swiss-French and a Swiss-Italian were talking about EWBG beyond the standard model...

# EWBG in BSM?

Cline, Joyce, Kainulainen, Huet, Nelson,  
Carena, Quiros, Riotto, Vijlila, Wagner  
Delaunay, Bernal, Blum, Nir, Losada,  
Huber, Schmidt,

... the Swiss-German: Let's study all well motivated  
extensions of the SM

- MSSM ✗
- CMSSM ✗
- BMSSM ✓
- NMSSM ✓
- ...
- ... ?

# EWBG in BSM?

... the Swiss-Fench: Let's do the most general analysis,  
Effective Field Theory!

• Out of  
Equilibrium

$$V(H) = V_{SM}(H) + \frac{(H^\dagger H)^3}{\Lambda^2}$$

→ Strong Phase Transition  
for  $\Lambda \lesssim 1.2 \text{ TeV}$

Unspecified BSM  
at scale  $\Lambda$

• CP violation

Quark Masses:  $m_{jk} = y_{jk} v + ix_{jk} \frac{v^3}{\Lambda_{CP}^2}$

→ Enough CP violation for  $\Lambda_{CP} \lesssim 0.6 \text{ TeV}$

# EWBG in BSM?

Espinosa, Gripaios, Konstandin, FR

... the Swiss-Italian: Let's do the LESS general analysis, the MINIMAL extension of the SM that gives BG!

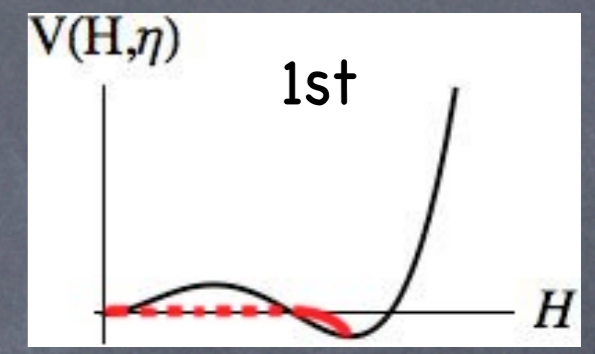
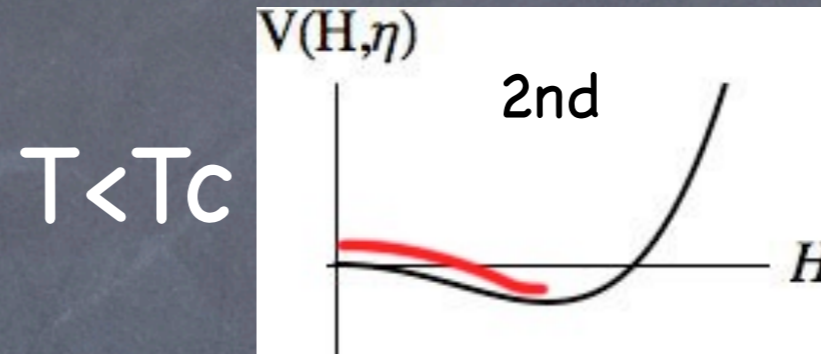
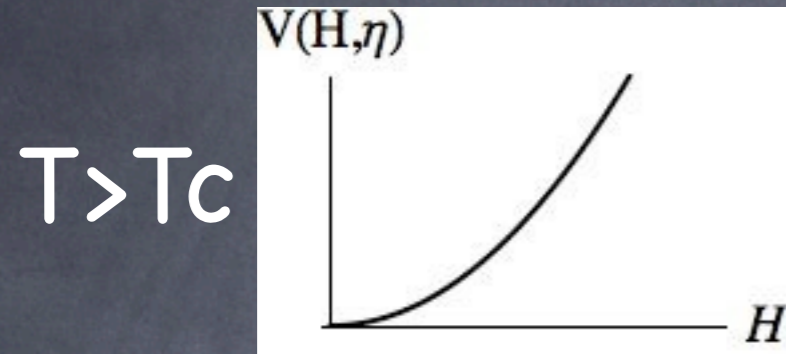
→ SM + a real CP-Odd scalar  $\eta$  (SM singlet)

- **B violation** – as in the SM (since  $\eta$  is singlet)
- **Out of Equilibrium** – Scalar potential includes  $\eta$ , so is less constrained
- **CP violation** –  $\eta$  has pseudoscalar couplings to quarks

# Out of Equilibrium

Anderson, Hall, Profumo,  
 Ramsey-Musolf, Shaughnessy  
 Cline, Laporte, Yamashita, Kraml  
 Ashoorion, Konstandin,  
 Espinosa, Gripaios, FR

Barrier in Scalar potential at  $T_c$



Contribution of  $\eta$  to the strength of the Phase Transition:

• Loop Effects:  $1 \lesssim \frac{v^c}{T^c} \approx \frac{E}{\lambda}$  ← Boson loops  $(W, Z, \eta) \sim T^c$

• Tree-level Effects:

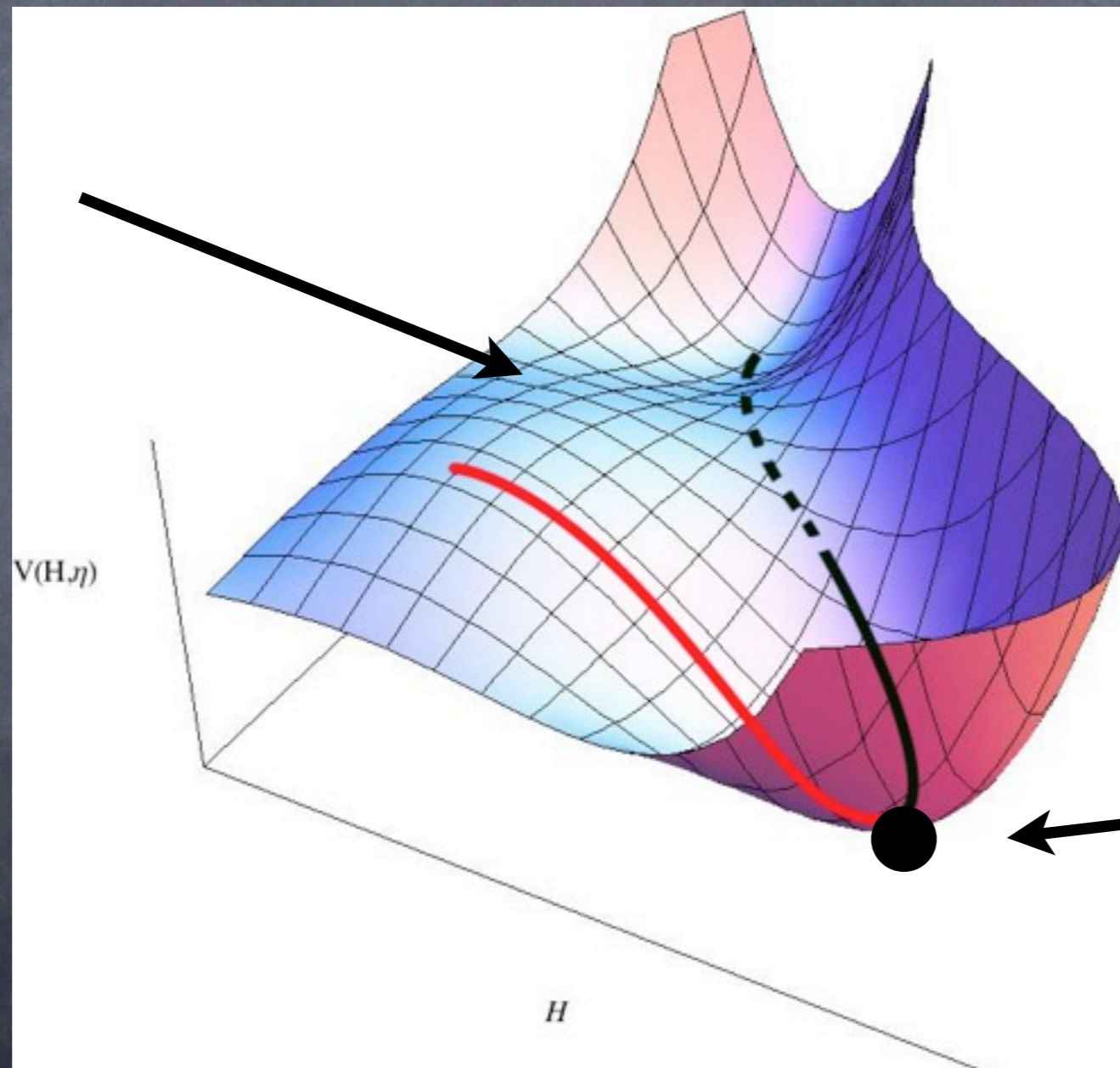
Bigger, since T-independent → still there at T=0

# Out of Equilibrium

Ashoorion, Konstandin  
Espinosa, Gripaios, Konstandin, FR

$$V(H, \eta) = -H^2 + H^4 + H^2\eta^2 - \eta^2 + \eta^4$$

EW preserving  
Minima



EW breaking  
Minimum

# CP Violation

- CP:  $\eta \rightarrow -\eta$

- Coupling to top quarks:  $y_t \bar{\psi} H \left(1 + i\epsilon_t \gamma_5 \frac{\eta}{\Lambda}\right) \psi$

$\Rightarrow$  top mass:  $m_t = m_t(v_H, v_\eta) e^{i\theta(v_\eta)}$

- Violates CP, if it varies during the EWPT  $\frac{\partial v_\eta}{\partial t} \neq 0$

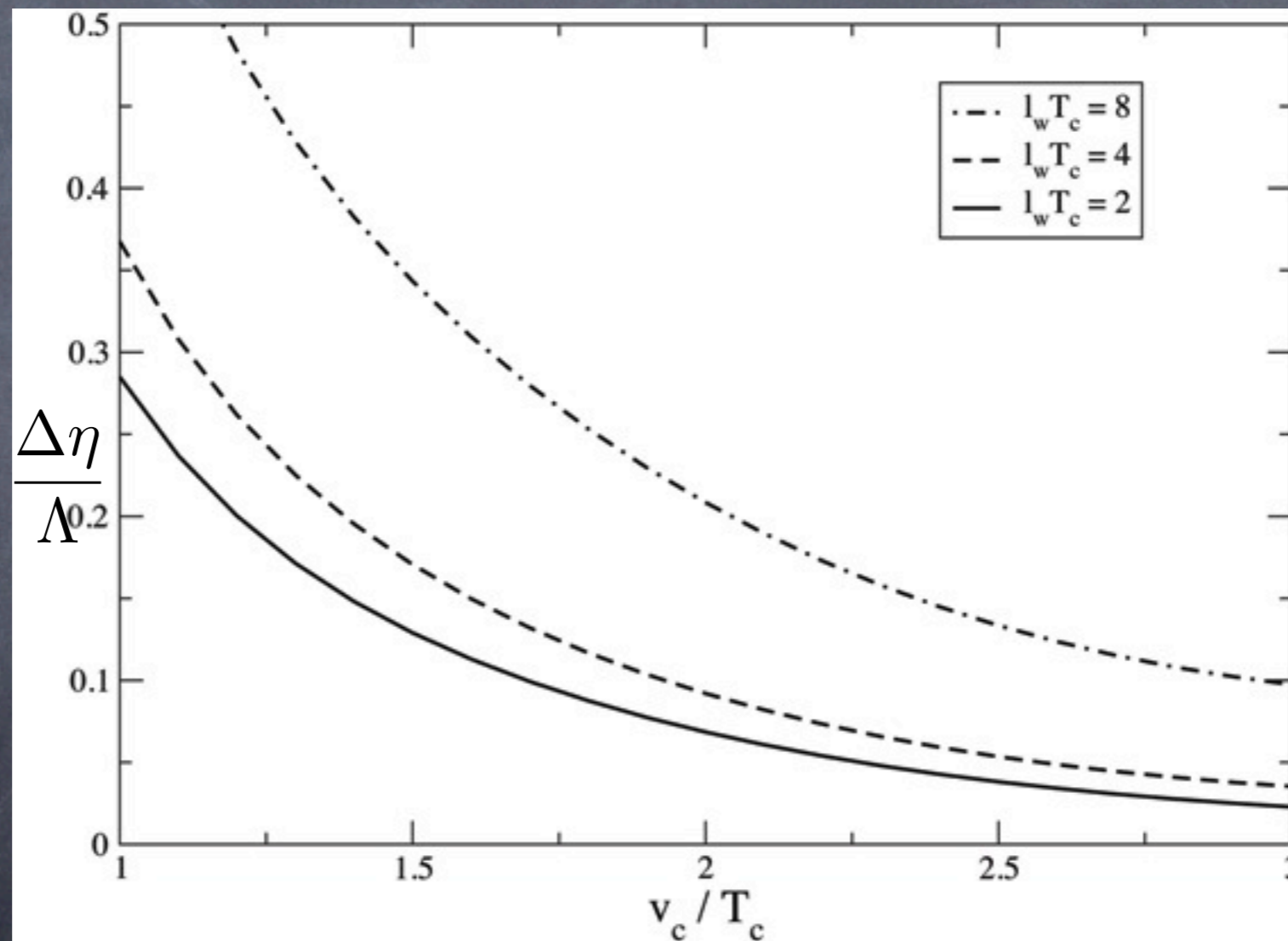
- NO contribution to CKM phase



This is the extra CP violation needed, only present during early universe and not now (EDM)

# CP Violation

How much must  $\eta/\Lambda$  change to produce enough baryon asymmetry?

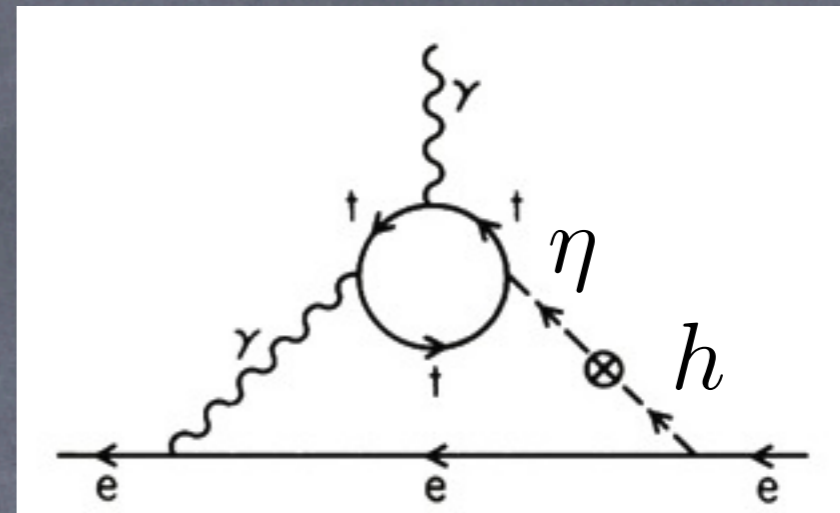


# CP Violation

Barr, Weinberg, Zee

Bounds on  $\eta$  ?

• Electric Dipole Moments:



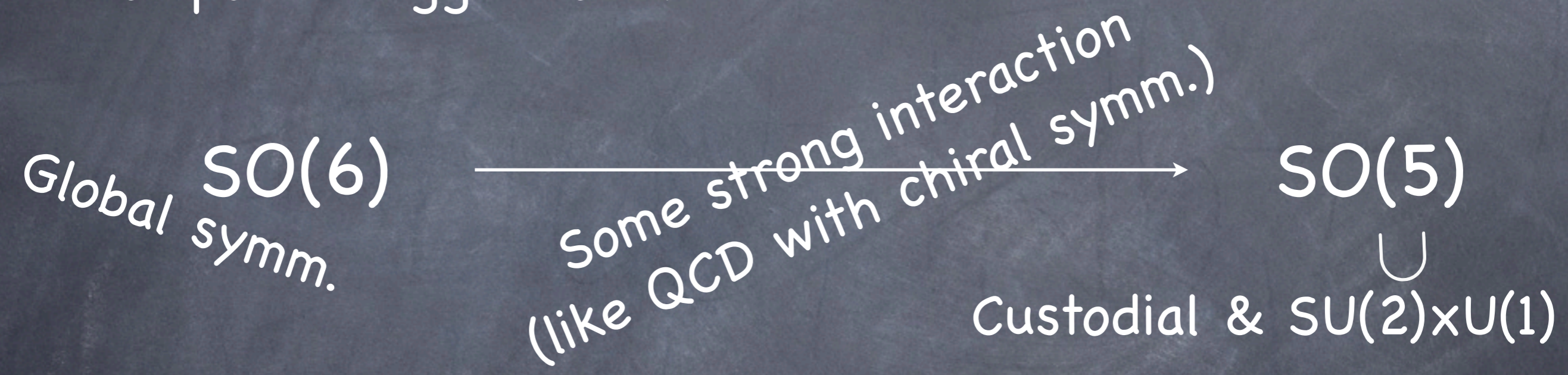
$$\frac{d}{e} \approx \left( Z \epsilon \frac{v}{\Lambda} \right) 4 \times 10^{-26} \text{ cm} \lesssim 10^{-27} \text{ cm}$$

$(\eta, h)$  mixing  $< 0.5$

$\Rightarrow$  Close to saturation (similar to 2HDM)

# Are there models that realize this minimal BG? YES

- Composite Higgs Model:



$\Rightarrow$  5 PNGB (like QCD  $\pi$ ) from  $SO(6)/SO(5)$ :  $H, \eta$

$$\left. \begin{aligned} \mathcal{L} \supset \lambda_{jk}(Q) \bar{\psi}^j H \left(1 + i\epsilon^k \gamma_5 \frac{\eta}{f}\right) \psi^k \\ V(h, \eta) = V(h, \eta, \epsilon_t) \end{aligned} \right\} \epsilon_k \text{ depends on fermion reps}$$

# Conclusions

- “Minimal” scenario of Baryogenesis:

SM + real CP-Odd scalar, SM singlet

- EDM close to bounds (like 2HDM)
- **Naturally** realized in Composite Higgs Model based on  $SO(6)/SO(5)$