Electroweak Symmetry Breaking in the Early Universe

~ II ~

COSMOLOGY

The Next Three Minutes

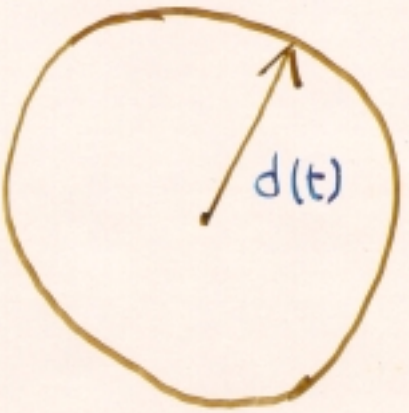
COSMOLOGY

THE UNIVERSE

is

EXPANDING

!



$$d(t) = d_0 R(t)$$

∴ All distances on sufficiently large scales

Cosmological Principle

→ Uniform Scaling

$$\frac{\dot{R}}{R} \equiv H \qquad H_0 \sim 70 \frac{km}{s} \frac{1}{Mpc}$$

GRAVITY

$$H^2 = \frac{8\pi G_N}{3}\rho$$

ρ ← Energy Density

ρ {
- radiation — T^4
- dust — T^3
- curvature — $1/R^2$

THERMAL

ISENTROPIC

$S \sim (TR)^3 = \text{constant}$

$T \propto 1/R$

∴ Not always true:

- $e^+ + e^- \longleftrightarrow \gamma$
- phase transition

EXPANSION

radiation

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \sigma T^4$$

$$\sigma T^4 \hookrightarrow \frac{1}{R^4}$$

$$R(t) = R_0 \left[\frac{t}{t_0}\right]^{1/2}$$

$$H(t) = \frac{1}{2t} \sim \frac{T^2}{M_p}$$

$\therefore$ H measures age of the Universe

ELECTROWEAK

$M \sim 100$ GeV

$$t_{ew} \sim \frac{M_P}{M^2} \sim 10^{-11} \text{ s}$$

Causal Domain

cm

Today: $T_0 \sim 3 \text{ k} \sim 10^{-4}$ el

$D_{today} \sim 10^{15}$ cm

REMNANTS

Domain Size Small

∴ Not Observable

BUT:

* BARYON VIOLATION

$B = 0$

↓ t evolves

$B \neq 0$

BARYOGENESIS

Uniform Effect on Average

Large Scale

BARYON VIOLATION

CP VIOLATION

Non EQUILIBRIUM

Sakharov 1968 !

★ C,CP VIOLATION

Quarks

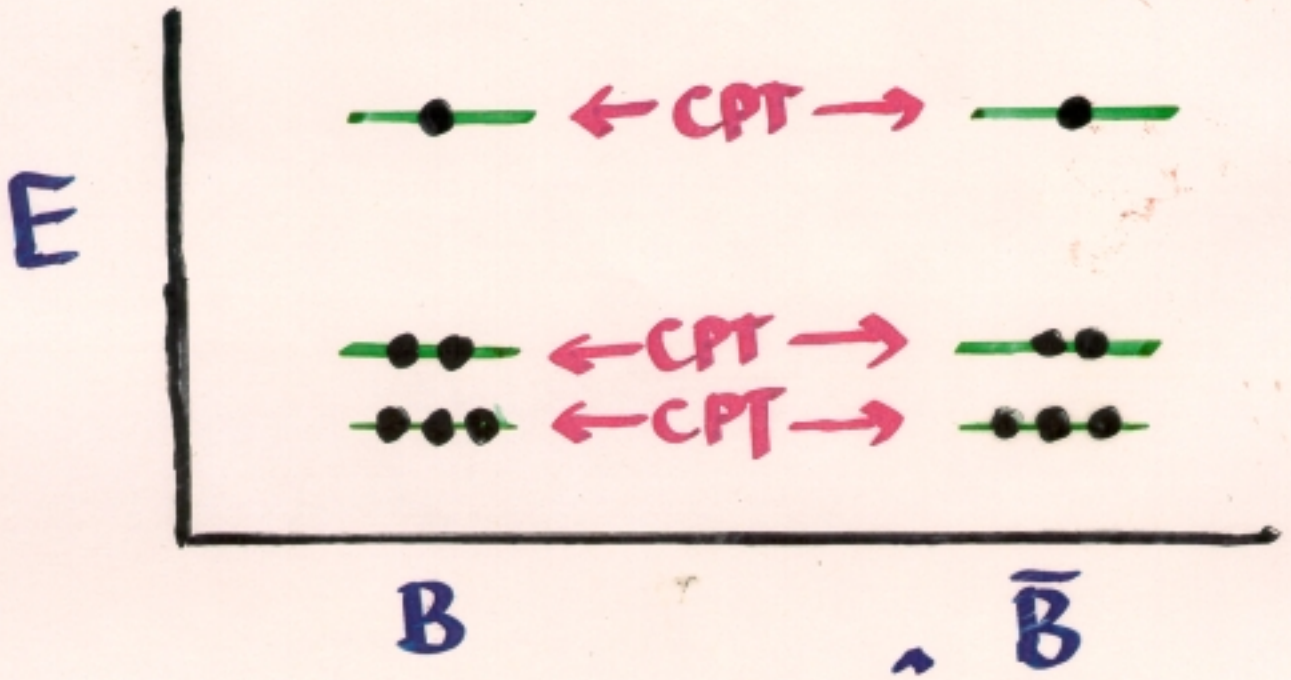
anti-Quarks

$\hat{B}$ odd under C,CP

$$\frac{\text{Rate}[K_L \to e^+ + \pi^- + \nu]}{\text{Rate}[K_L \to e^- + \pi^+ + \bar{\nu}]} \simeq 1.006$$

$\sim 10^{-3}$ effect

★ DEPARTURE FROM THERMAL EQUILIBRIUM



$$\langle B \rangle = \mathrm{Tr}\, \hat{B} e^{-\beta \hat{H}} = 0$$

Odd under CPT

$\hat{B} \to -\hat{B}$

Even under CPT

$\hat{H} \to \hat{H}$

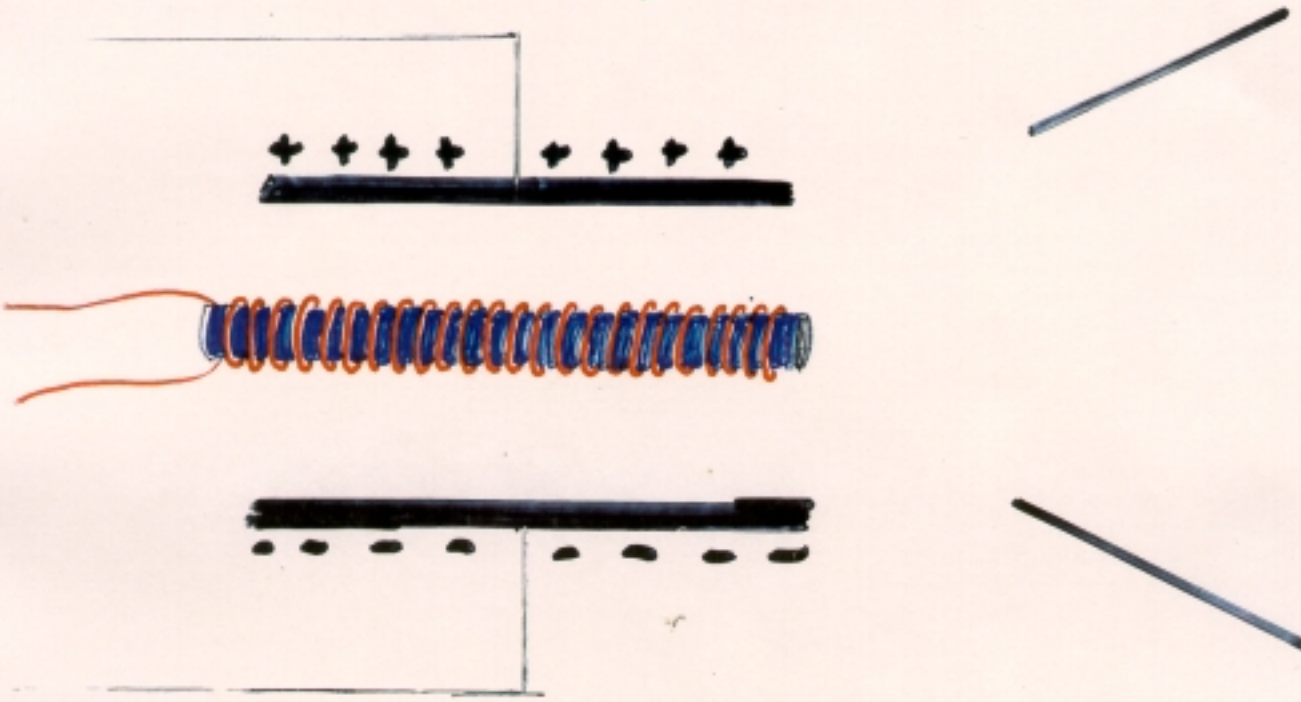
ELECTROWEAK BARYOGENESIS

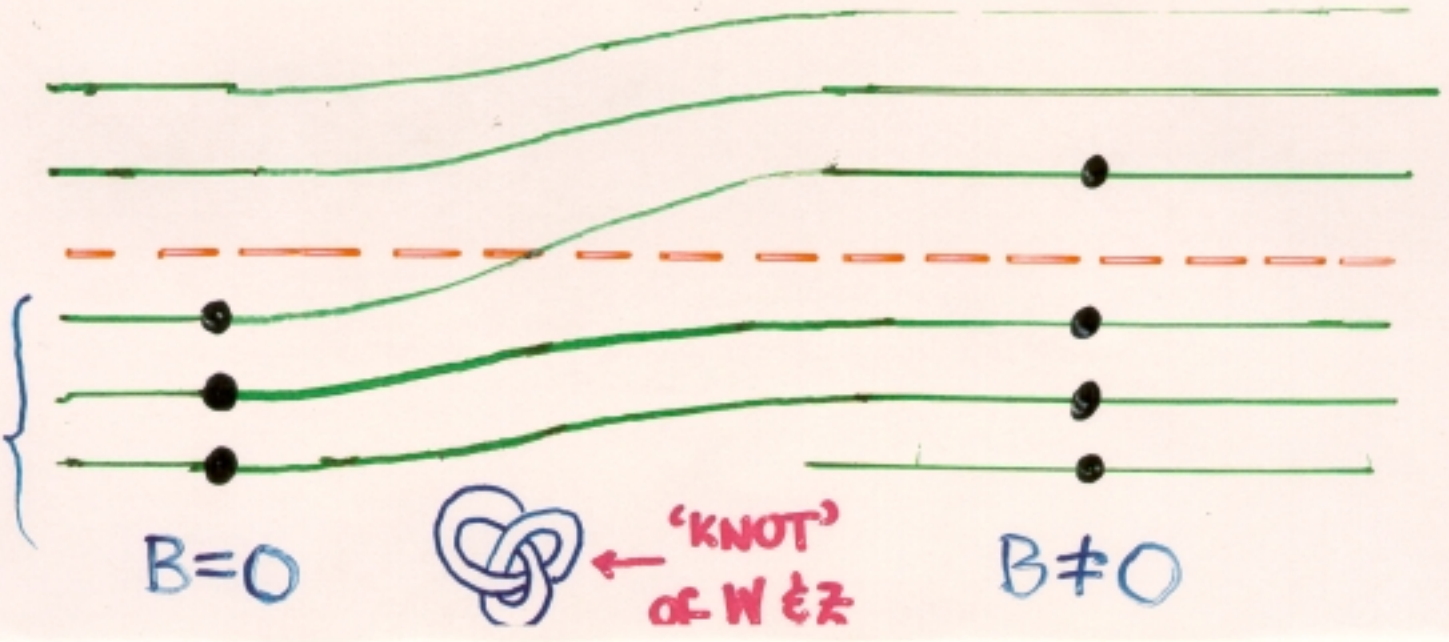
All of Sakharov's criteria may be met in the

Standard Model

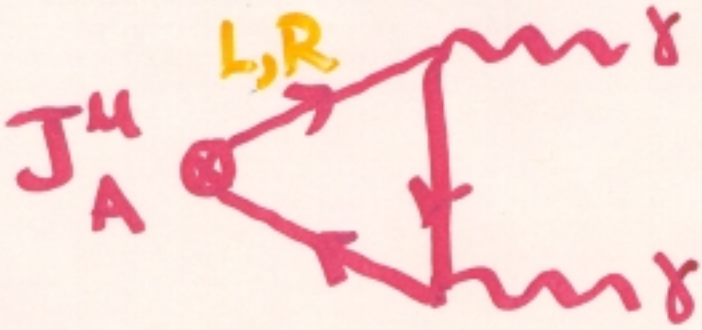
!

BARYON VIOLATION in WEAK INTERACTION ? ?





QED

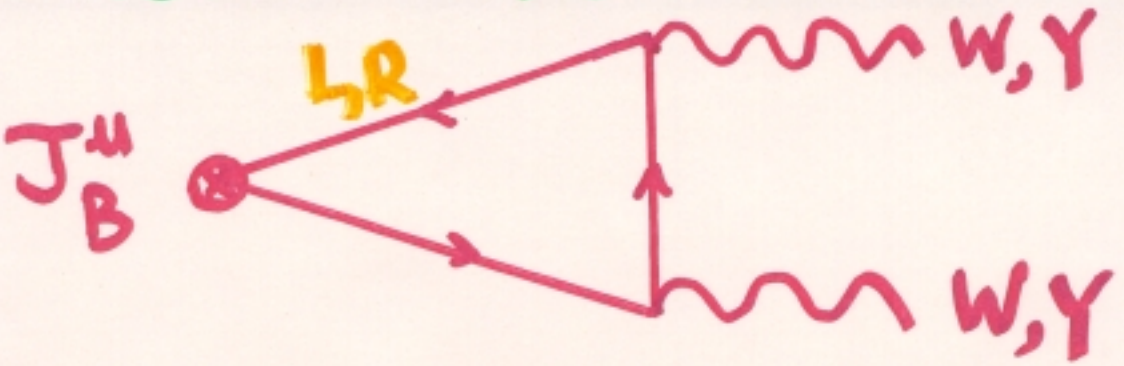


$$\partial_\mu J^\mu_A = \frac{e^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad (\vec{E}\cdot\vec{B})$$

↑ chiral

'Anomaly'

ELECTROWEAK



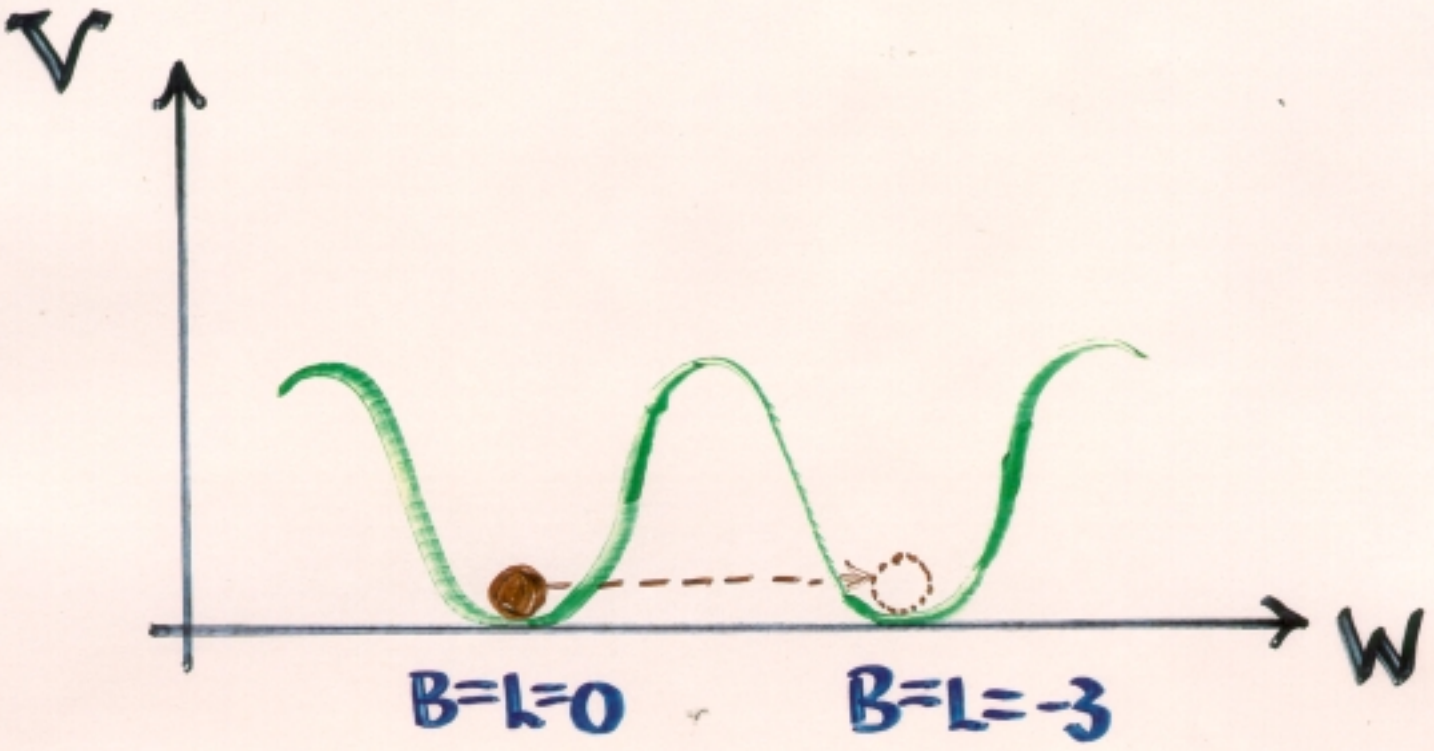
$$\partial_\mu J^\mu_B = 3\left[\frac{g^2}{32\pi^2} W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{g'^2}{32\pi^2} F_{Y\mu\nu}\tilde{F}_Y^{\mu\nu}\right]$$

↑ chirel

$$= \partial_\mu J^\mu_L$$

B-L conserved!

WHY IS THE PROTON STABLE ?



Quantum Tunneling

$$\Gamma \propto e^{-4\pi/\alpha_{WK}} \sim 10^{-140} !$$

Weak Fine Structure Constant

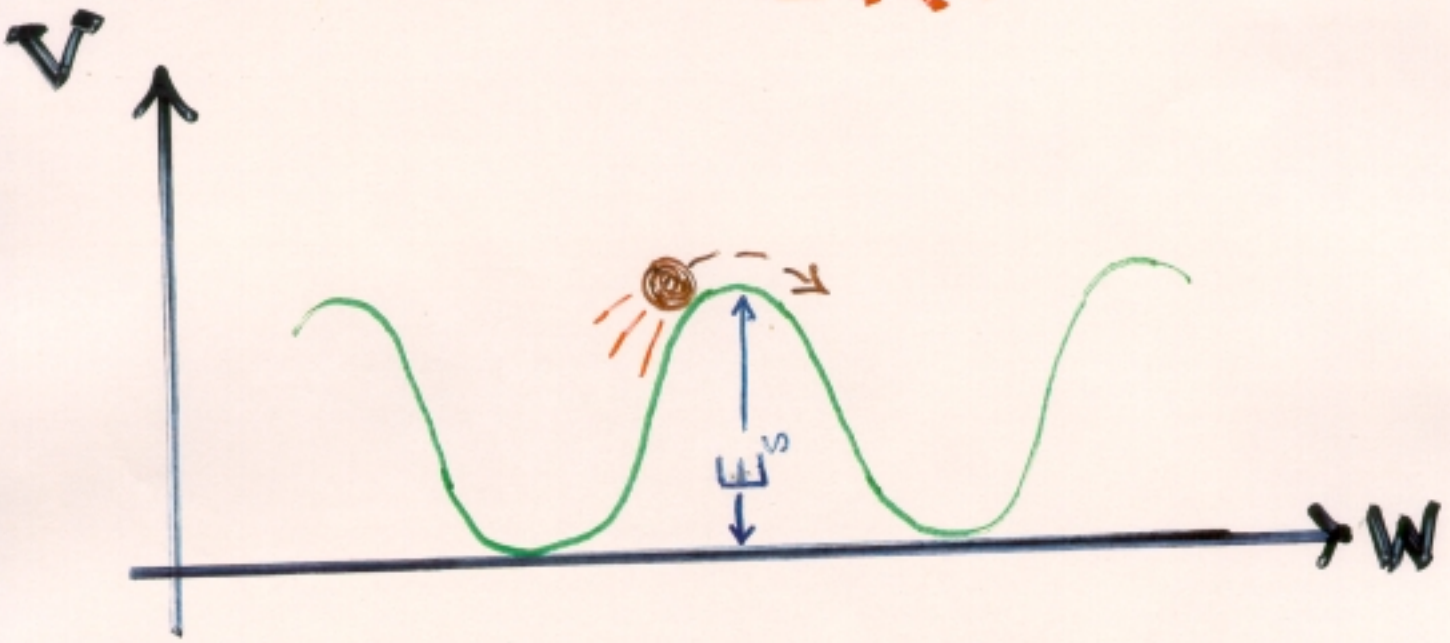
Really Small number

ACTUALLY...

- Proton absolutely stable

$$\Delta B = 3$$

HOWEVER:



THERMAL ACTIVATION

$$\Gamma \propto e^{-\beta E_s}$$

← 'sphaleron'

$$E_s \sim \frac{M_Z}{\alpha_{WK}}$$ ← gv

Barrier rather than

Mass suppresses low Energy B-violation

$E_s \sim$ TeV

↓

$T \gtrsim$ TeV

B violation unsuppressed

↓

GUT Wipeout!

B-L ←

DEPARTURE FROM EQUILIBRIUM

Expansion Rate $H \sim -\frac{\dot{T}}{T} \sim +\frac{T^2}{M_{Pl}}$

very small at $T \lesssim$ TeV.

$\left(\Gamma \sim \alpha_{WK} T \sim 10^{13} H \right)$

Need something more

Violent

PHASE TRANSITION

UNBROKEN PHASE

$M_W = M_Z = 0 \rightarrow$ Long Range Forces

$v = \langle \phi \rangle = 0$

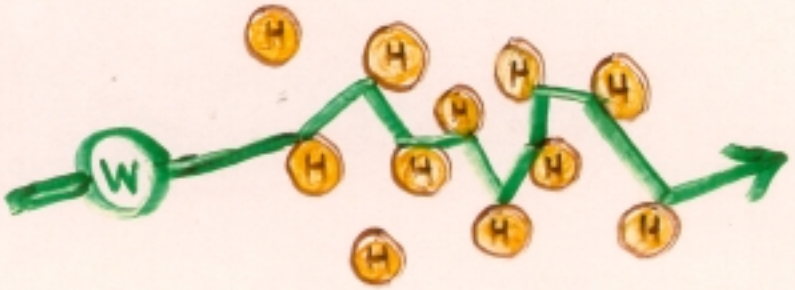
$\text{Rate} \propto e^{-\beta v/g} \sim 1$

$T \sim 100\,\text{GeV}$ — ~~WEAK PHASE TRANSITION~~

$M_W, M_Z \neq 0 \rightarrow$ Short Range Forces

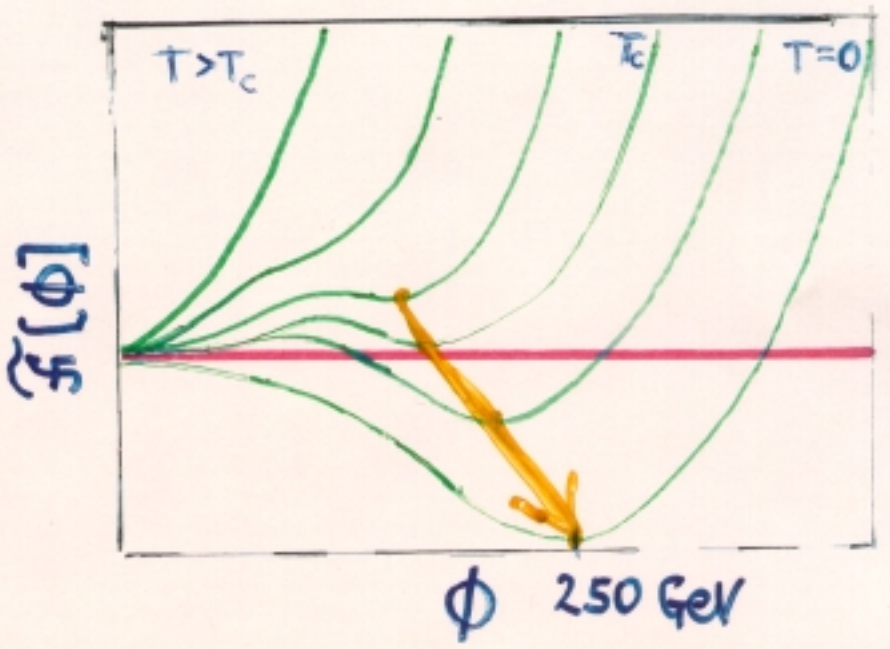
$v = \langle \phi \rangle \sim 250\,\text{GeV}$

BROKEN PHASE

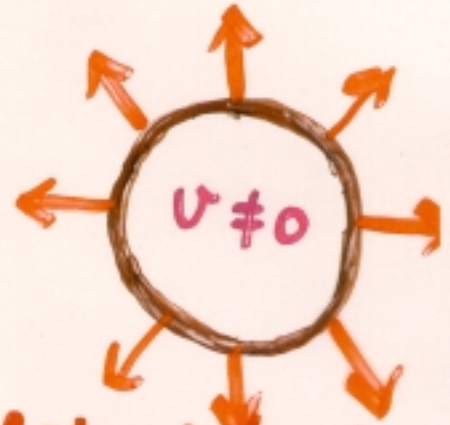


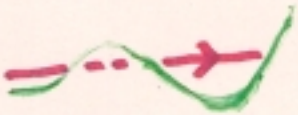
$\text{Rate} \propto e^{-\beta v/g} \ll 1$

1st ORDER PHASE TRANSITION



- Supercool below T_c ($\phi=0$)
- Nucleate Bubbles





- Bubbles Expand, release latent heat

OUT-OF-EQUILIBRIUM B-VIOLATION

Outside Bubble

$$\Gamma_{\Delta B} \sim \alpha_{wk}^5 T \rightarrow \text{rapid}$$

Inside Bubble

$$\Gamma_{\Delta B} \propto e^{-\frac{4\pi v}{g}\frac{1}{T}} \ll \frac{T^2}{M_{Pl.}}$$

$v \neq 250$ GeV.

Transition must be strongly

1st Order: $\Delta\phi$ large

PHASE TRANSITIO

?

What breaks the Weak Symmetr

??

SM → probably not 1st-o

MSSM → small region of parameter space

NMSSM → Easy!

NEW MODELS

'Deconstructed' Models

Phase Transitions

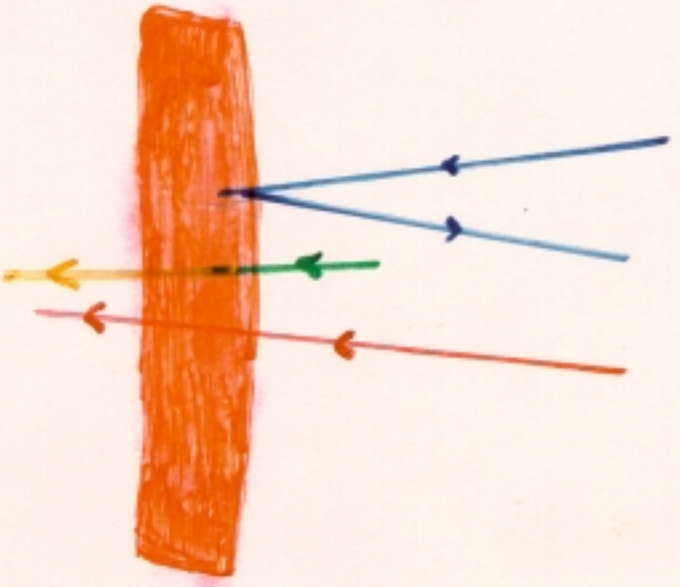
!

Strongly 1st Order

CP Violation

!

CP VIOLATION



1) Interaction of quarks, leptons, ...
with CP violating phases

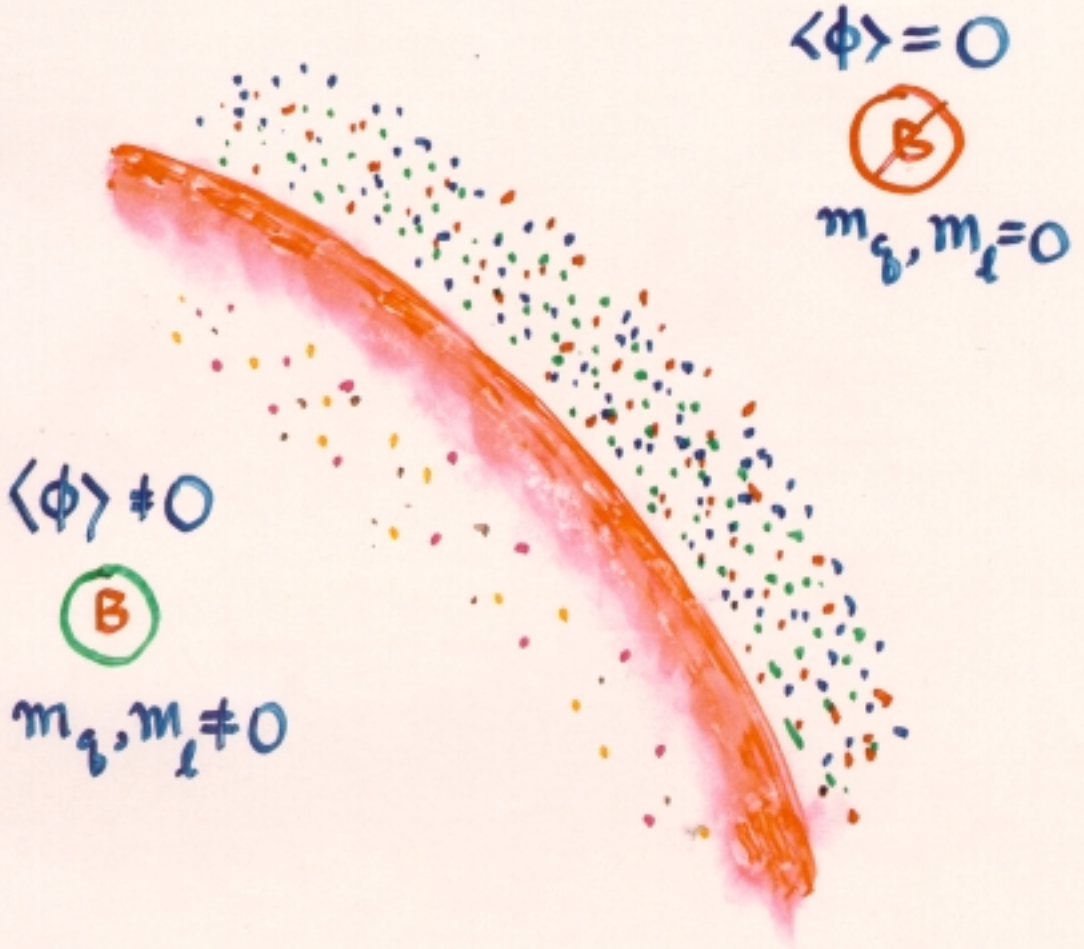
2) Plasma transport properties
move charges around

3) Thick Wall – 

Thin Wall – 

4) Expanding Wall

HOW DOES THIS MAKE AN ASYMMETRY ?



Non Equilibrium – Spatial Separati

of B violation

CP VIOLATION

CKM

$$\delta_{CP} \sim \mathrm{Im}\left[M_u^3 M_d^2 M_u M_d\right]$$

$$M_d \equiv \frac{g_W^2}{2M_W^2} K M_d^2 K^+$$

$$M_u \equiv \frac{g_W^2}{2M_W^2} M_u^2$$

* $$\delta_{CP} \sim \left[\frac{g_W^2}{2M_W^2}\right]^7 s_1^2 s_2^2 s_3 s_\delta \, m_t^6 m_b^4 m_c^2 m_s^2$$

$$\sim 10^{-22}$$

NEW CP VIOLATION!

CKM CP VIOLATION

$$\delta_{CP} \sim \mathrm{Im}\left[VV, V^*V^*\right]$$

$$V \sim Y_u Y_d^+$$

8 Yukawa Couplings
4 Weak Interactions

$$\alpha^2 \; \lambda_t^4 \lambda_b^2 \lambda_s \lambda_d \; s_1^2 s_2 s_3 s_\delta$$

$$\sim 10^{-16}$$

CKM in K System?

$E \ll v$

$\therefore$ Effective Field Theory is different!

$\frac{1}{m_b^2}, \frac{1}{m_t^2}$ 

- m_t dependence may be different

NEW CP VIOLATION

Multi-Higgs ✓

MSSM ✓

NMSSM ✓

Deconstruction ✓

THE GOOD NEWS

New CP violation is observable!

Electroweak Phase Transition Computable

If we know EW Symmetry breaking

Were going to find out.

THE BAD NEWS

No generic predictions

EDM

B,D mixing

top Physics

Higgs Physics

THE REALLY BAD NEWS

Non-Electroweak models also work, but are untestable

Ex: CP violation in super heavy right handed neutrino

Yukawa Couplings → Late Decays violate lepton number

∴ Electroweak B, L violation Equilibrates with

$B \neq 0$

EW Symmetry Breaking & The Origin of Matter

Baryogenesis may be connected with the physics of EW symmetry breaking.