GUT WIPE-OUT

$$\frac{1}{U_{GUT}^4} T^5$$

$$\Gamma_{\Delta B} \ll H$$

or B wiped-out

GUT BARYOGENESIS

Late (out-of-equilibrium) decays of GUT particles (Scalars) with CP violation in decay amplitudes can produce B asymmetry

!

Size? K physics?

B-factory?

GUT SHORTCOMINGS

- Rates (Late Decay, Wipeout)

  Thermal Equilibrium?

  (Gauge Interactions do not maintain Eq. at high T)

- Relics (Inflation, low reheat)

- Removal ($\Gamma_{\Delta B}$ at low Energies)

- Unobservable

ALTERNATIVES

- Non-thermal Re'heating'

  Parametric Reasonance

- More Couplings

  Yukawa → Neutrinos

A. Cohen, SSI 1999

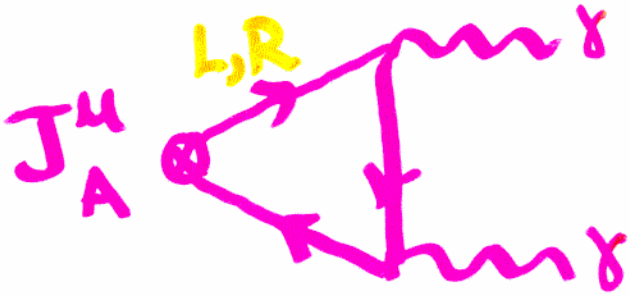
ELECTROWEAK BARYOGENESIS

All of Sakharov's criteria may be met in the

Standard Model

!

QED

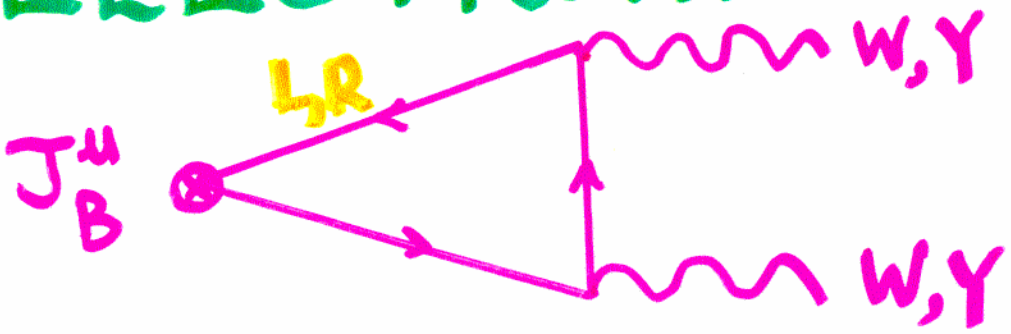


$$\partial_\mu J^\mu_A = \frac{e^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad (\vec{E}\cdot\vec{B})$$

chiral

'Anomaly'

ELECTROWEAK



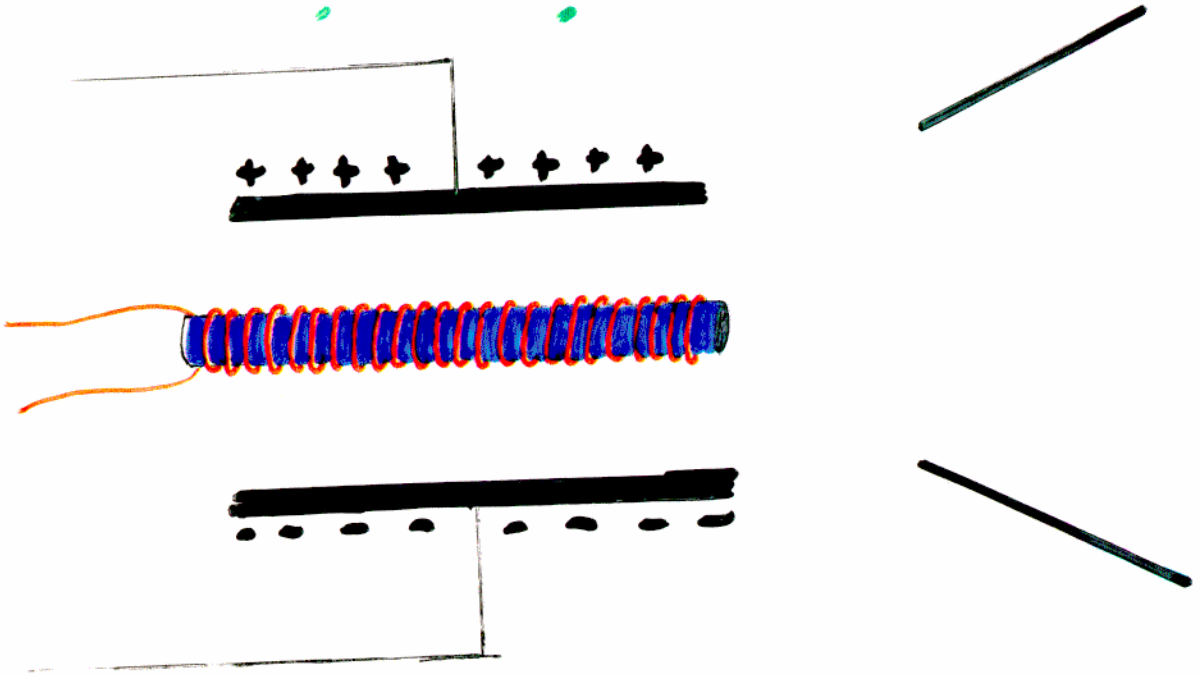
$$\partial_\mu J^\mu_B = 3\left[\frac{g^2}{32\pi^2} W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{g'^2}{32\pi^2} F_{Y\mu\nu}\tilde{F}_Y^{\mu\nu}\right]$$

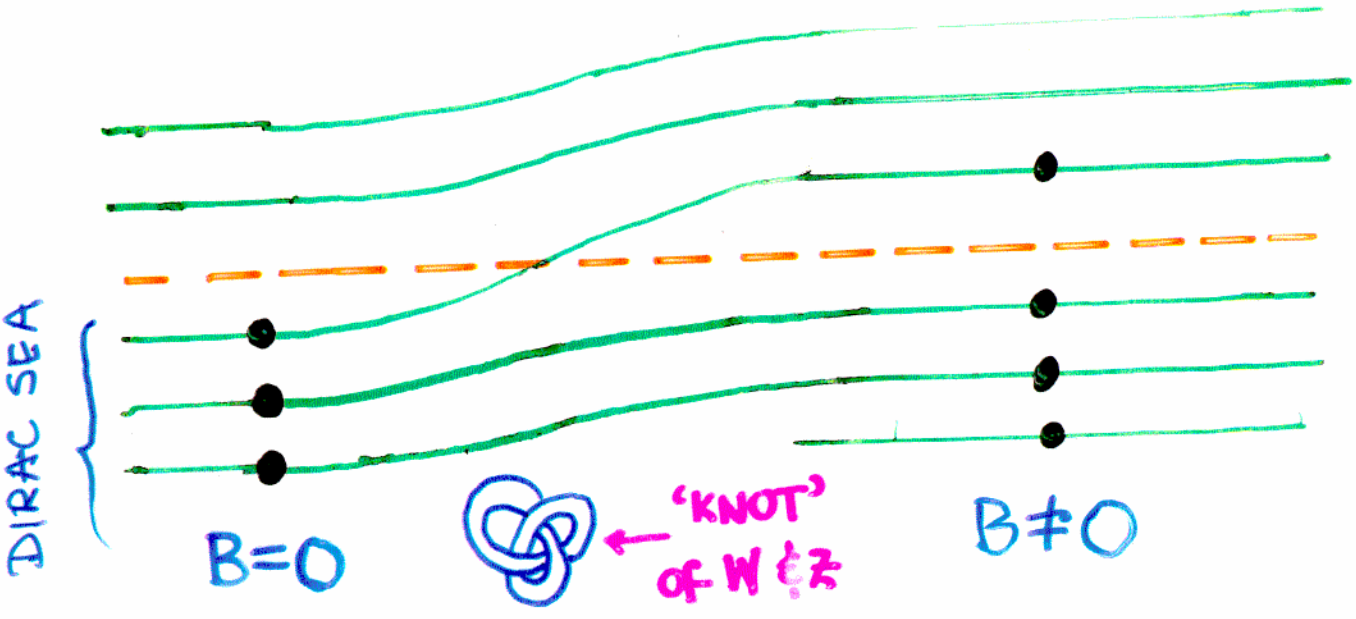
↑ chiral

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

B-L conserved!

BARYON VIOLATION in WEAK INTERACTIONS ? ?





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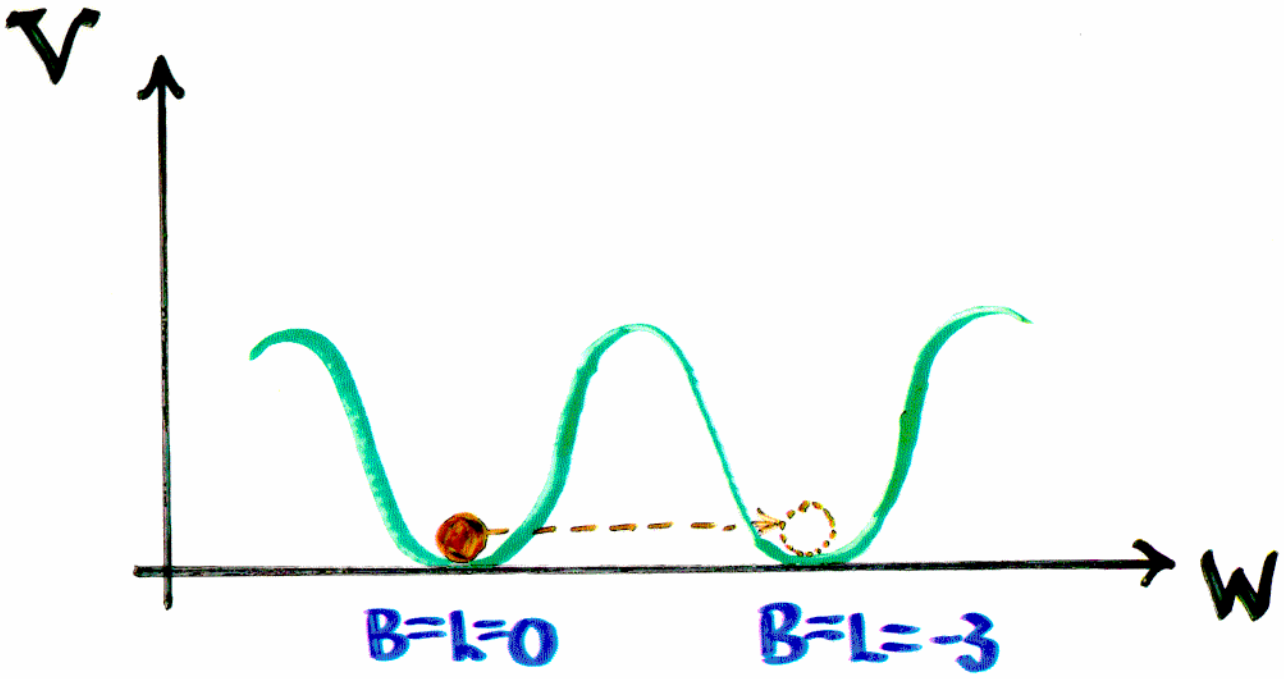
WHY IS THE PROTON STABLE ?



Quantum Tunneling

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

Weak Fine Structure Constant

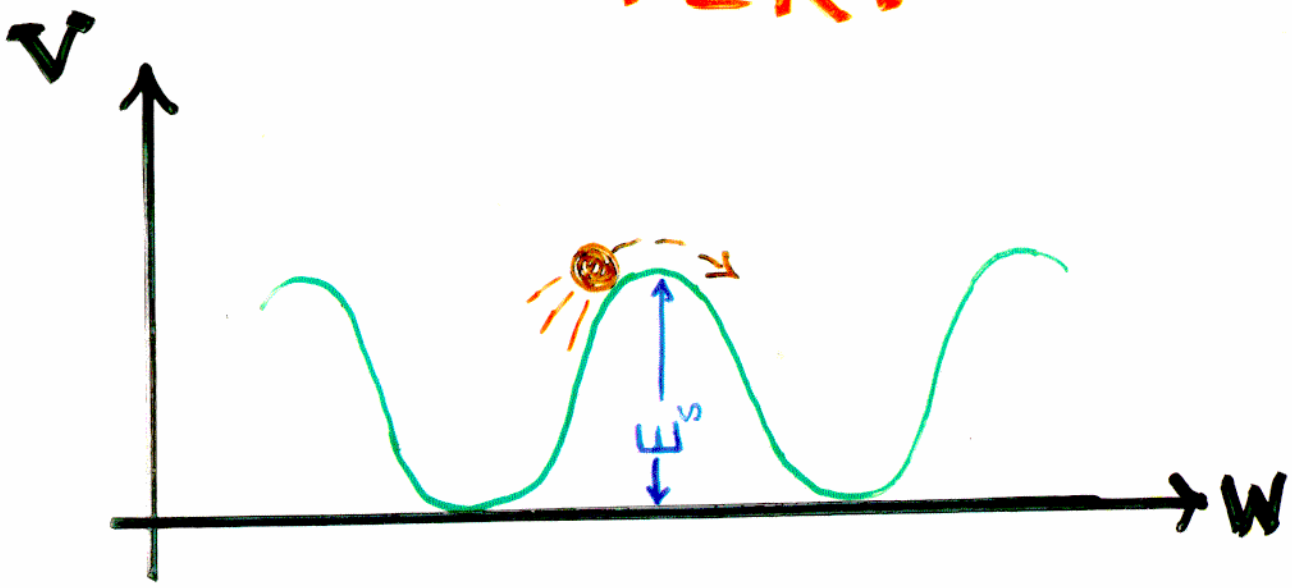
Really Small number

ACTUALLY...

- Proton absolutely stable

$$\Delta B = 3$$

HOWEVER:



THERMAL ACTIVATION

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

← 'sphaleron'

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

Barrier rather than **Mass** suppresses low Energy B-violation

$E_s \sim$ TeV

↓

$T \gtrsim$ TeV

B violation unsuppressed

↓

GUT Wipeout!

B-L ←

GUTs II

$\Gamma_{\Delta B}$ (Electroweak)

in equilibrium for

$T \gtrsim E_s \sim$ TeV

GUTs with late-decaying B violating X boson do NOT make a B asymmetry!

GUT must make a B-L asymmetry

BACK TO ELECTROWEAK

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

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

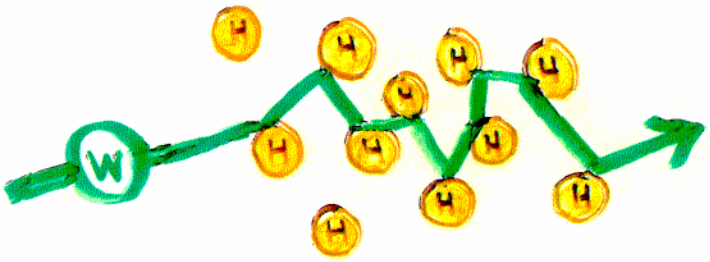
Rate $\propto e^{-\beta v/g} \sim 1$

$T \sim 100$ GeV — ~~WEAK PHASE TRANSITION~~

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

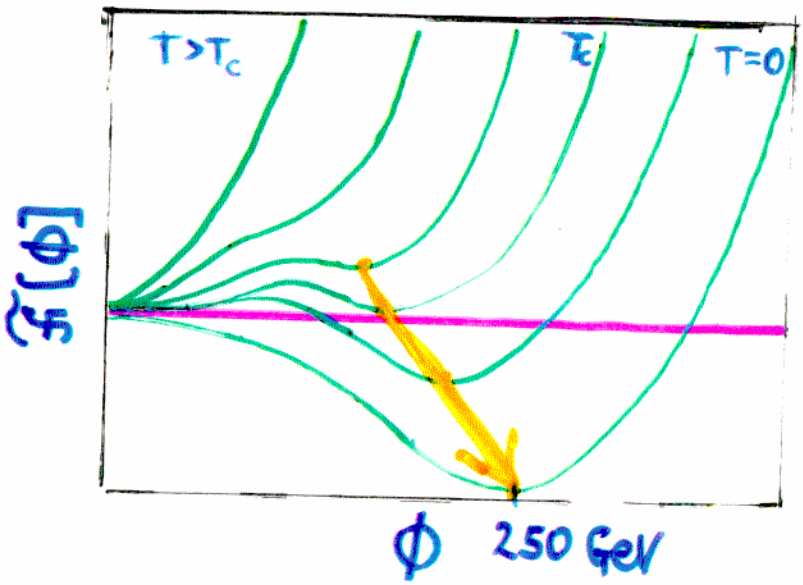
$v = \langle \phi \rangle \sim 250$ GeV

BROKEN PHASE

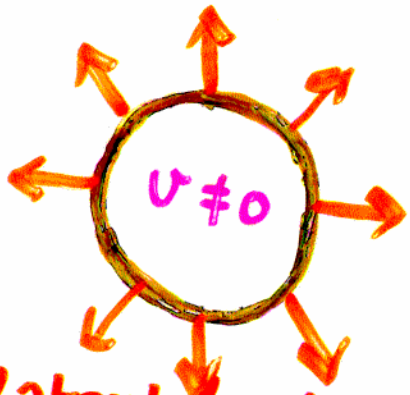


Rate $\propto e^{-\beta v/g} \ll 1$

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 TRANSITION ?

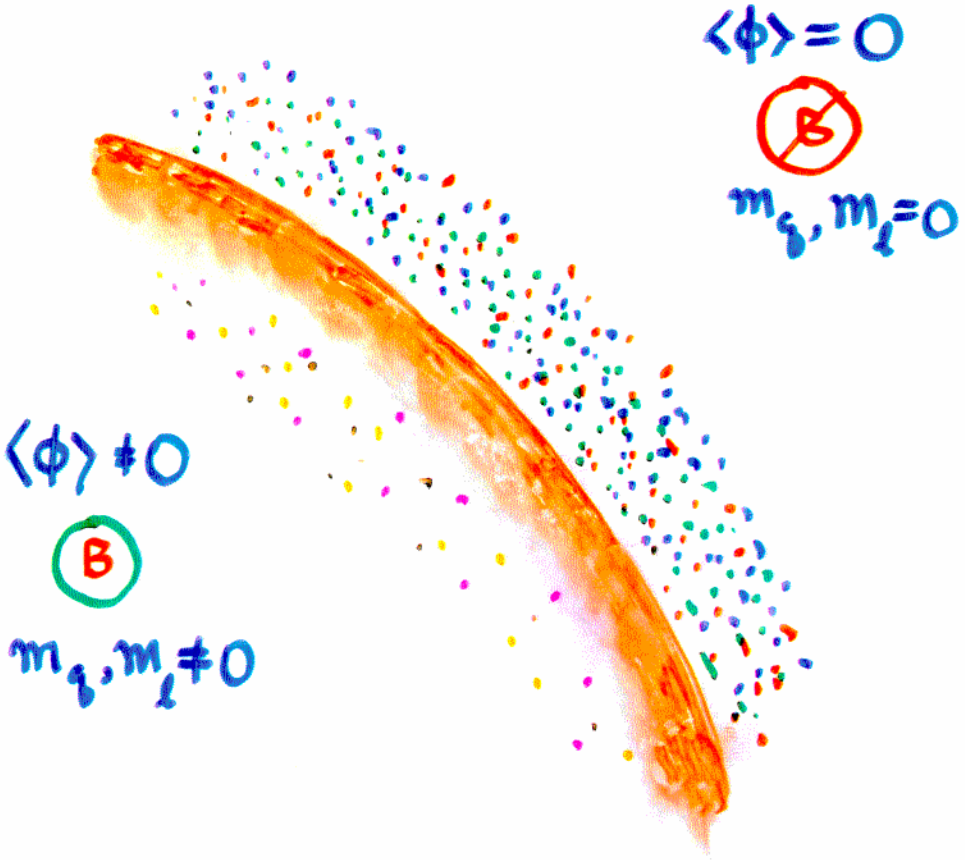
What breaks the Weak Symmetry ??

SM → probably not

MSSM → small region of parameter space

NMSSM → Easy!

HOW DOES THIS MAKE AN ASYMMETRY ?

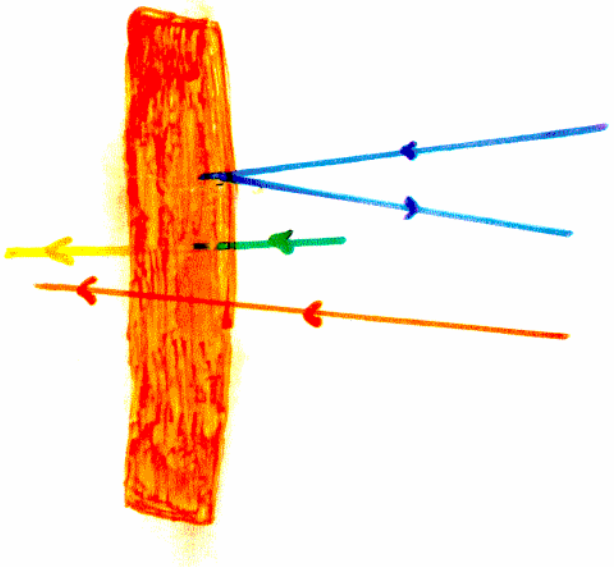


Non Equilibrium – Spatial Separatio

of B violation

A. Cohen, SSI 1999

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

CP VIOLATION?

CKM

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

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

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

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

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

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

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

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

NEW CP VIOLATION

Multi-Higgs ✓

MSSM ✓

NMSSM ✓

THE GOOD NEWS

New CP violation is observable!

Electroweak Phase Transition Computable

} If we know EW symmetry breaking

We're 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 work, but are untestable

Ex: CP violation in super heavy right handed neutrinos

Yukawa Couplings → Late Decays violate lepton number

∴ Electroweak B, L violation Equilibrates with

$B \neq 0$

OTHER IDEAS

- Affleck-Dine
- Spontaneous Baryogenesis
- Topological Defects
- ?

L ASYMMETRY → B ASYMMETRY

Minimize $\widetilde{f_i}$ subject to conserved Q (electric charge)

Ex. $B = \dfrac{8n_f + 4n_H}{22n_f + 13n_H}(B-L)$