GUT WIPE-OUT

\[ \Gamma_{AB} \left\{ \bar{q} \rightarrow \bar{l}_{\pm} \right\} \]

\[ \frac{1}{v_4^2} \frac{T^5}{\text{GUT}} \]

\[ \Gamma_{AB} \ll H \]

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!

$\Sigma \pi e$? $K$ 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 (Far at Low Energies)

- Unobservable
ALTERNATIVES

• Non-thermal Reheating
  Parametric Resonance

• More couplings
  Yukawa $\rightarrow$ Neutrinos
ELECTROWEAK BARYOGENESIS

All of Sakharov's criteria may be met in the Standard Model
QED

\[ \omega_{\mu} J_A^\mu = \frac{e^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \]  
\[ (E \cdot B) \]

chiral

'Anomaly'
ELECTROWEAK

\[ J^\mu_B \]

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

\[ \uparrow \text{chiral} \]

\[ = \partial_\mu J^\mu_L \]

\[ B-L \text{ conserved!} \]
BARYON VIOLATION
in
WEAK INTERACTIONS

DIRAC SEA

\[ B = 0 \quad \text{or} \quad B \neq 0 \]

'KNOT' of \( W \) and \( Z \)
Why is the proton stable?

Quantum Tunneling

\[ \Gamma \propto e^{-\frac{4\pi}{d_{WK}}} \approx 10^{-140} \]

Weak Fine Structure Constant

Really Small number
ACTUALLY...

- Proton absolutely stable
  \[ \Delta B = 3 \]

HOWEVER:

THERMAL ACTIVATION

\[ \Gamma \propto e^{-\beta E_s} \]

\[ E_s \sim \frac{M_2^2}{\alpha_{\text{NK}}} \]

'sphaleron'
Barrier rather than Mass suppresses low Energy B-violation

\[ E_s \sim \text{TeV} \]

\[ T \gtrsim \text{TeV} \]

B violation unsuppressed

\[ \Rightarrow \]

GUT Wipeout!

B-L
GUTs II

$\Gamma_{AB} (\text{Electroweak})$

in equilibrium for

$T \geq E_{\text{TeV}}$

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 $H \sim \frac{1}{T} \gg \frac{\Gamma^2}{M_{\text{Pl}}}$

Very small at $T \lesssim \text{TeV}$.

$(\Gamma \sim \sigma_{\text{WKT}} T \sim 10^{13} H)$

Need something more

Violent
PHASE TRANSITION

\[ M_w = M_z = 0 \rightarrow \text{Long Range Forces} \]
\[ u = \langle \phi \rangle = 0 \]
\[ \mathbb{B} \quad \text{Rate} \propto e^{-u/\lambda} \sim 1 \]

T \sim 100 \text{GeV} \quad \text{WEAK PHASE TRANSITION}

\[ M_w, M_z \neq 0 \rightarrow \text{Short Range Forces} \]
\[ u = \langle \phi \rangle \sim 250 \text{ GeV} \]

\[ \mathbb{B} \quad \text{Rate} \propto e^{-u/\lambda} \ll 1 \]
1st ORDER PHASE TRANSITION

- Supercool below $T_c$ ($\phi = 0$)
- Nucleate Bubbles
- Bubbles expand, release latent heat

$\phi$ 250 GeV
OUT-OF-EQUILIBRIUM B-VIOLATION

Outside Bubble

\[ \Gamma_{AB} \sim \alpha_\text{ew}^5 T \rightarrow \text{rapid} \]

Inside Bubble

\[ \Gamma_{AB} \propto e^{-4\pi \nu \frac{1}{\Delta}} \ll \frac{T^2}{M_\text{Pl}}. \]

\( \nu \approx 250 \text{ GeV}. \)

Transition must be strongly 1st order: \( \Delta \Phi \) large.
PHASE TRANSITION

What breaks the Weak Symmetry?

$\text{SM} \rightarrow \text{probably not}$

$\text{MSSM} \rightarrow \text{small region of parameter space}$

$\text{NMSSM} \rightarrow \text{Easy!}$
How does this make an asymmetry?

\[ \langle \phi \rangle = 0 \]

\[ m_1, m_2 \neq 0 \]

\[ \langle \phi \rangle \neq 0 \]

B

Non Equilibrium - Spatial separation of B violation
1) Interaction of quarks, leptons, ... with CP violating phases

2) Plasma transport properties move charges around

3) Thick Wall - \( \text{CP} \)
   Thin Wall - \( \text{CP} \) \( \text{B} \)

4) Expanding Wall
CP VIOLATION?

CKM

\[ \delta_{CP} \sim \text{Im} \left[ M_u M_d^2 M_u M_d \right] \]

\[ M_d = \frac{g_w^2}{2M_w^2} K M_d^2 K^+ \]

\[ M_u = \frac{g_w^2}{2M_w^2} M_u \]

\[ \delta_{CP} \sim \left[ \frac{g_w^2}{2M_w^2} \right]^7 s_1^2 s_2 s_3 s_8 m_t m_b m_c m_s \]

\[ \sim 10^{-22} \]

NEW CP VIOLATION!
CKM CP VIOLATION

\[ \delta_{cp} \sim \text{Im} \left[ VV, V^* V^* \right] \]

\[ V \sim Y_u Y_d^+ \]

8 Yukawa Couplings
4 Weak Interactions

\[ a^2 \lambda_t^4 \lambda_b^2 \lambda_s^2 \lambda_d \sin^2 \theta_1 \sin \theta_2 \sin \theta_3 \sin \delta \]

\[ \sim 10^{-16} \]
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

\[ \text{Yukawa Couplings} \rightarrow \text{Late Decays violate lepton number} \]

\[ \therefore \text{Electroweak } B, L \text{ violation equilibrates with } B \neq 0 \]
OTHER IDEAS

- Affleck-Dine

- Spontaneous Baryogenesis

- Topological Defects
L ASYMMETRY
→ B ASYMMETRY

Minimize $\mathcal{F}$ subject to

conserved $Q$ (electric charge)

Ex.

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