Baryogenesis and the Standard Model

What's the Problem?

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Sakharov conditions are met!

- Baryon Number violation
  - Sphaeleron Process
- Non-equilibrium dynamics
  - Phase Transitions
- Charge and CP-violation
  - CKM - matrix

Observed baryon density is not!

- B-violation
  - Sphaeleron Process
- Non-equilibrium
  - Phase Transitions
- C and CP-violation
  - CKM - matrix

10 Orders of magnitude less than measured!

$$\Delta_B = (3 - 10) \times 10^{-11}.$$

Why Not?

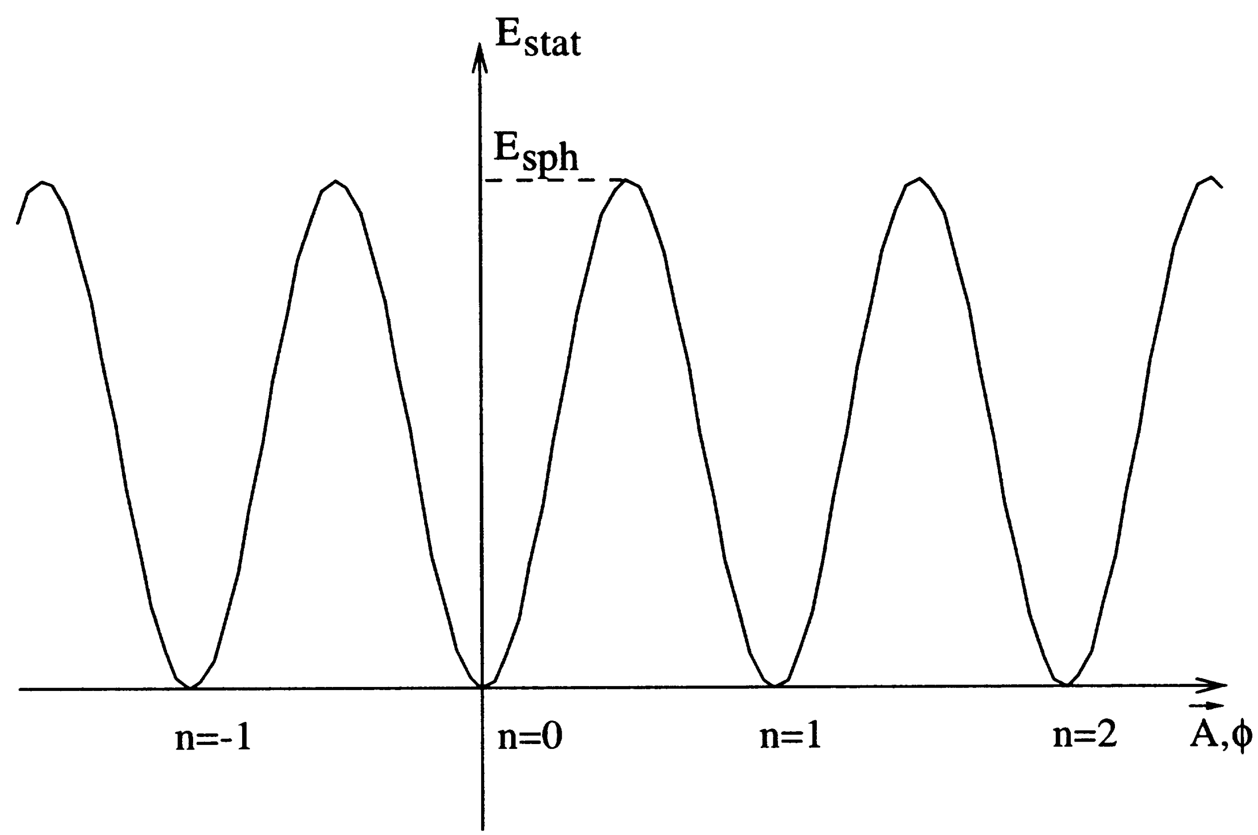
- **B-violation**
    - **Sphaeleron Process**
- **Non-equilibrium**
    - **Phase Transitions**
- C and CP-violation
    - CKM - matrix

Thermal Equilibrium

- Equilibrium would mean the system was stationary
- Must stay out of equilibrium **from the creation of the imbalance and for the entire rest of the evolution of the universe**
    - Otherwise the B or CP violation gets washed back out and the system is returned to its equilibrium state
- Condition to be out of equilibrium : $\Gamma < H = \dot{a}/a$

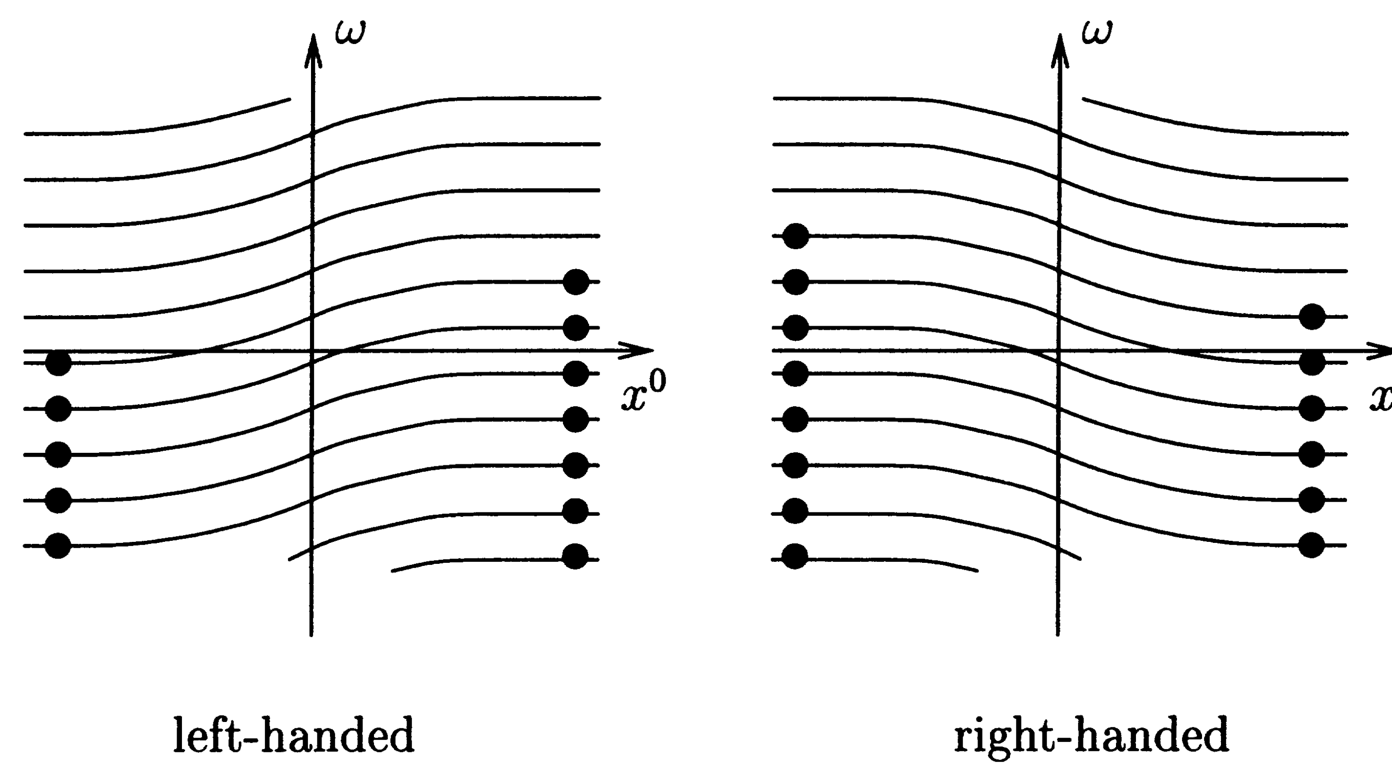
B-violation from Gauge Structure

- Infinite number of Vacua from different gauge choices
- Vacua do not smoothly map from one to the other !
  → Energy Barrier
- Vacua defined by a winding number



B-violation from Gauge Structure

- EW-anomaly conserves B-L number
- So changing between vacua changes B+L:
- ΔB = 3 per winding number



B-violation: Sphaelerons

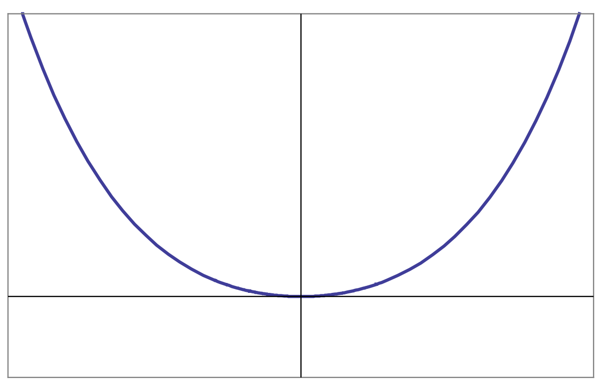
- Sufficient energy to pass over barrier
- Boltzmann suppression if temperature below barrier height
- Height of barrier depends on the Higgs VEV and the W-coupling:

$$E_{\rm sph} = f\left(\frac{\lambda}{g^2}\right)\frac{4\pi v}{g} \cong f\left(\frac{\lambda}{g^2}\right)\frac{2m_W}{\alpha_W} = \frac{8\pi v}{g},$$

Electro-Weak Symmetry Breaking

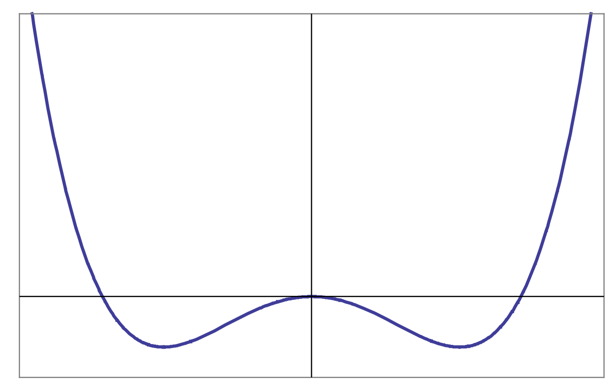
$$\mathcal{L}_\phi = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

V(ϕ)



ϕ

V(ϕ)



ϕ

Sign of μ^2 depends on loop-corrections —

Higgs potential is temperature dependent!

All particles become massless above T_C!

m_H	T_c
115 GeV	160.5 GeV
140 GeV	191.3 GeV
160 GeV	216.4 GeV

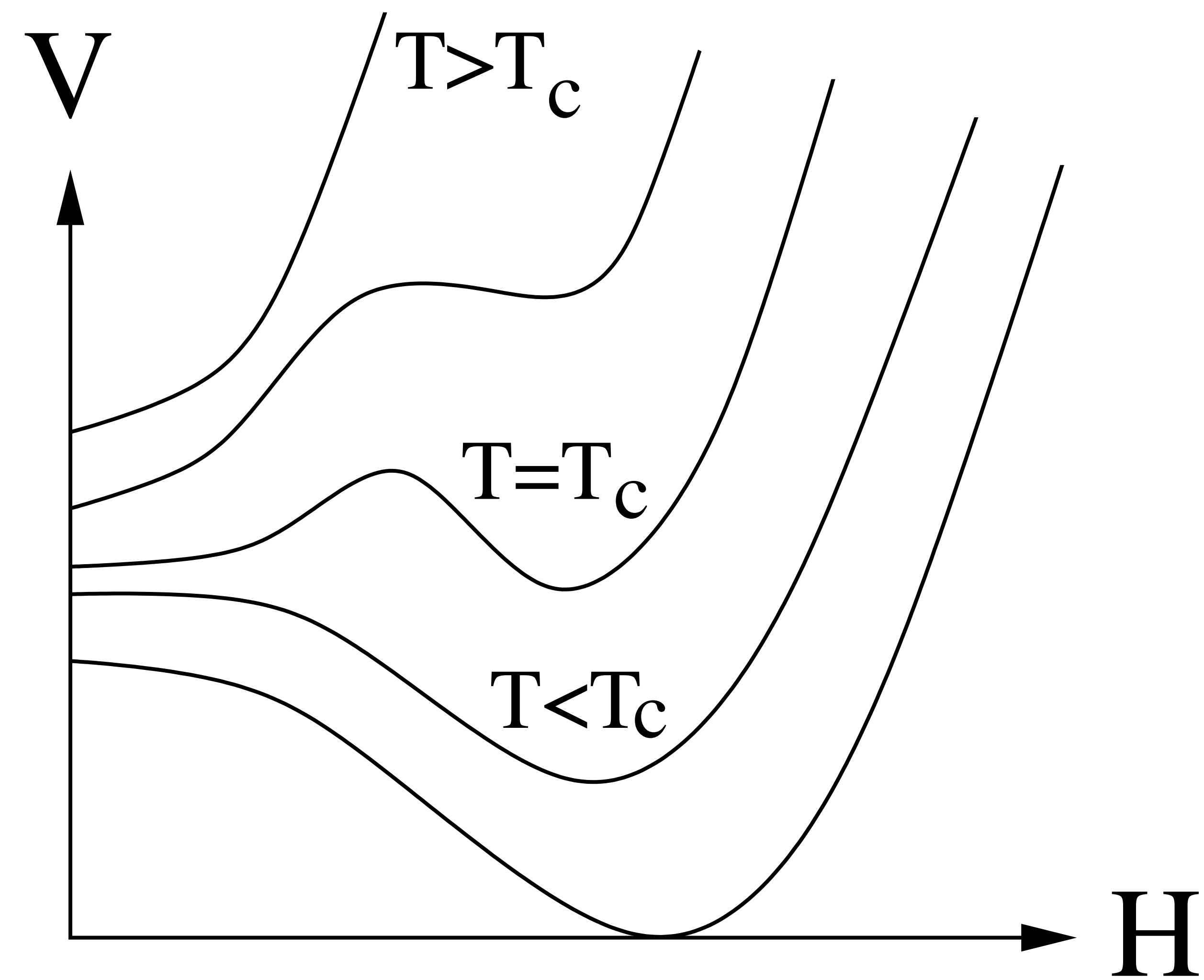
Sphaelerons out of equilibrium

- Above T_c the Higgs vev is 0 so the Sphaelerons energy barrier is also 0

- Below T_c Sphaeleron process must freeze out so that B-number does not wash-out

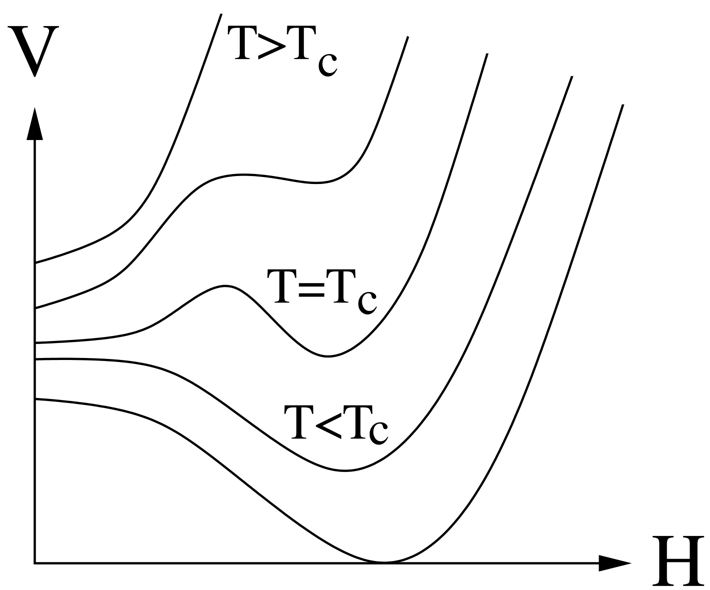
- Expansion of the universe is slow, so suppression must be large

$$\Gamma_{sph} \sim T \exp\left(-\frac{E_{sph}(T)}{T}\right)$$

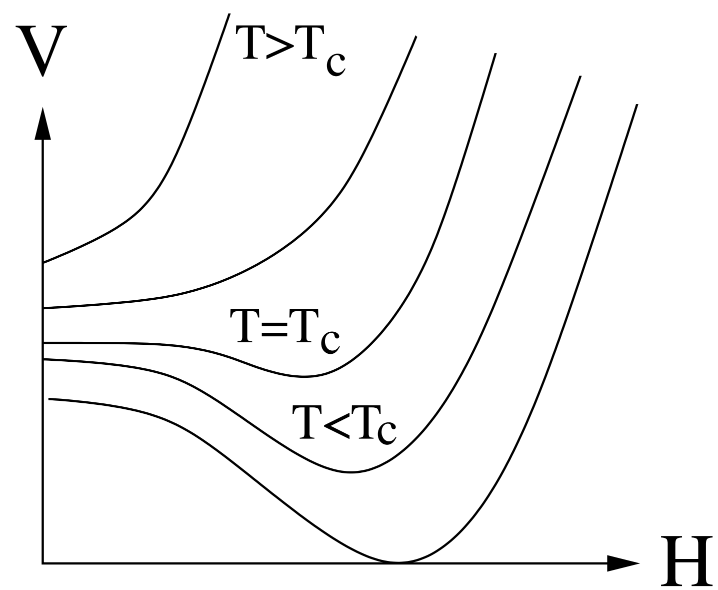


$$\frac{E_{sph}(T_c)}{T_c} > 45.$$

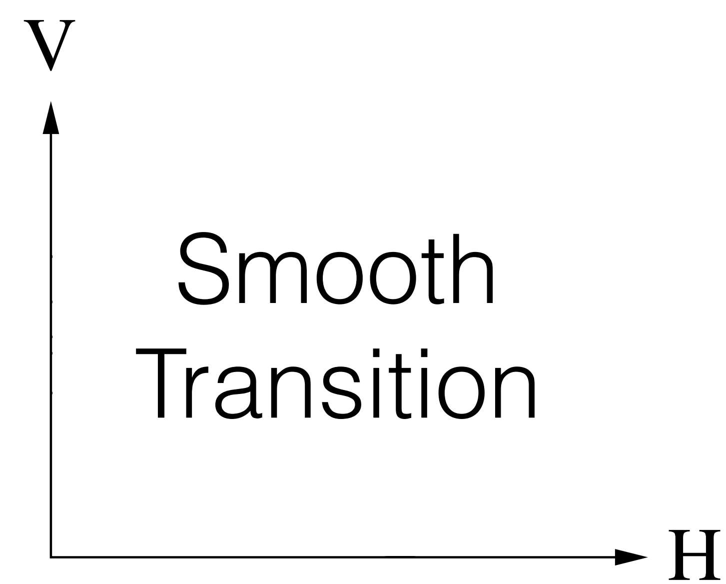
Electroweak Phase Transition



First Order:
$M_h < 75$ GeV



Second Order:
$M_h < 85$ GeV



Crossover:
$M_h = 126$ GeV

Only first order transitions can produce non-zero Baryon number!

Bubble-wall separation

- Assume first-order phase transition: “Bubbles” of Higgs phase expanding into symmetric phase
- Known CP-violating effects at the bubble-walls preferentially allow Baryons (over anti-Baryons) to cross in to the Higgs phase
- Sphaeleron effects are shut-off in the Higgs phase so Baryon number is conserved
- Baryon/entropy produced is correct magnitude

Importance of EDM experiments

- Beyond the standard model physics (multi-Higgs, SUSY) must be invoked to make a first order phase transition
- All these new particles produce new opportunities for CP-violation… usually too much
- These particles also allow for new EDM generating loops —
- EDMs larger than the Standard Model values are always predicted!

Some useful References

Review article, slightly dated but readable and my main reference:
Baryon Asymmetry of the Universe
V.A. Rubakov (Moscow, INR). 2001. 45 pp.
Published in **NATO Sci.Ser.C 566 (2001) 97-141**
DOI: 10.1007/978-94-010-0522-7_3
Conference: C00-06-15 Proceedings

Masters thesis with some extra detail on electroweak
symmetry breaking and sphalerons etc.:
http://www.helsinki.fi/~donofrio/MastersThesis.pdf

Article first describing Higgs phases:
http://ac.els-cdn.com/0370269372901098/1-s2.0-0370269372901098-main.pdf?_tid=aa5b9e76-fc2e-11e5-a375-00000aab0f02&acdnat=1459971486_841e508634ab83296976e0d0f4f7b6b2

Article describing how bubble wall CP-violation works out:
http://journals.aps.org.eaccess.ub.tum.de/prd/pdf/10.1103/PhysRevD.50.774

Higgs Properties

$$\mathcal{L}_\phi = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2$$

$$\frac{\partial V}{\partial(\phi^\dagger \phi)} = 0,$$

$$(\phi^\dagger \phi) = \frac{1}{2}({\phi_1^0}^2 + {\phi_2^0}^2 + {\phi_1^+}^2 + {\phi_2^+}^2) = -\frac{\mu^2}{2\lambda}.$$

$$v = \sqrt{-\mu^2/\lambda},$$

$$\mathcal{L}_\phi = \left(\partial_\mu \phi + ig\frac{\sigma_a}{2} W_\mu \phi\right)^\dagger \left(\partial^\mu \phi + ig\frac{\sigma_a}{2} W^\mu \phi\right) - V(\phi) - \frac{1}{4} W_{\mu\nu} W^{\mu\nu}.$$

$$(D_\mu \phi)^\dagger (D^\mu \phi) = \frac{g^2 v^2}{8} W_\mu W^\mu + \frac{g^2 v}{8} W_\mu W^\mu 2h + ...$$

$$m_W = \frac{gv}{2},$$