8/11/2004

Baryogenesis & Leptogenesis

Mark Trodden
Syracuse University

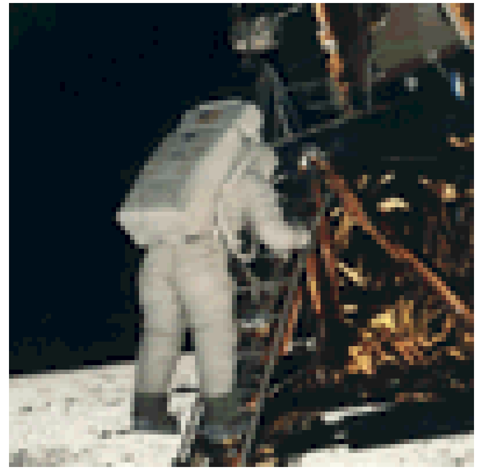
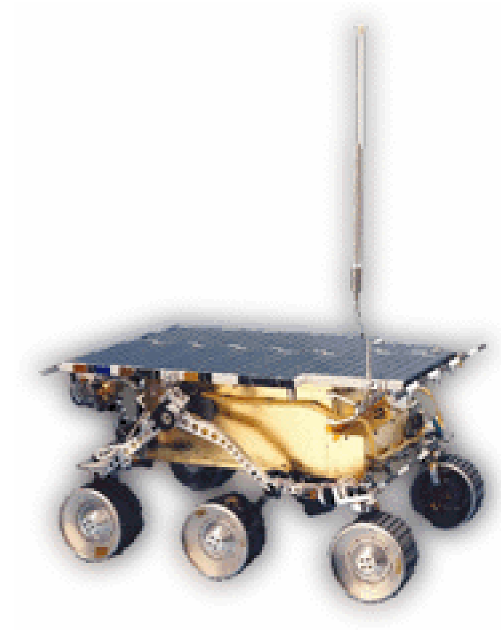
Outline

My brief: A general and broad introduction to the ideas behind baryogenesis and leptogenesis.

- Why is the Baryon Asymmetry of the Universe (BAU) a problem for either particle physics or cosmology?
- The general principles behind candidate models.
- Some popular *particle physics motivated* examples
  - Baryogenesis in Grand Unified Theories (GUTs)
  - Electroweak baryogenesis
  - Affleck-Dine baryogenesis
  - Vanilla leptogenesis
- General comments and summary

This should provide the necessary background for the next, more technical lecture by Carlos Wagner

A Fundamental Problem

- Can construct a ladder of evidence
- Observable universe, out to the Hubble size, is made of matter and not antimatter

(See talks by Coppi and Streitmatter)

A Quantitative Measure

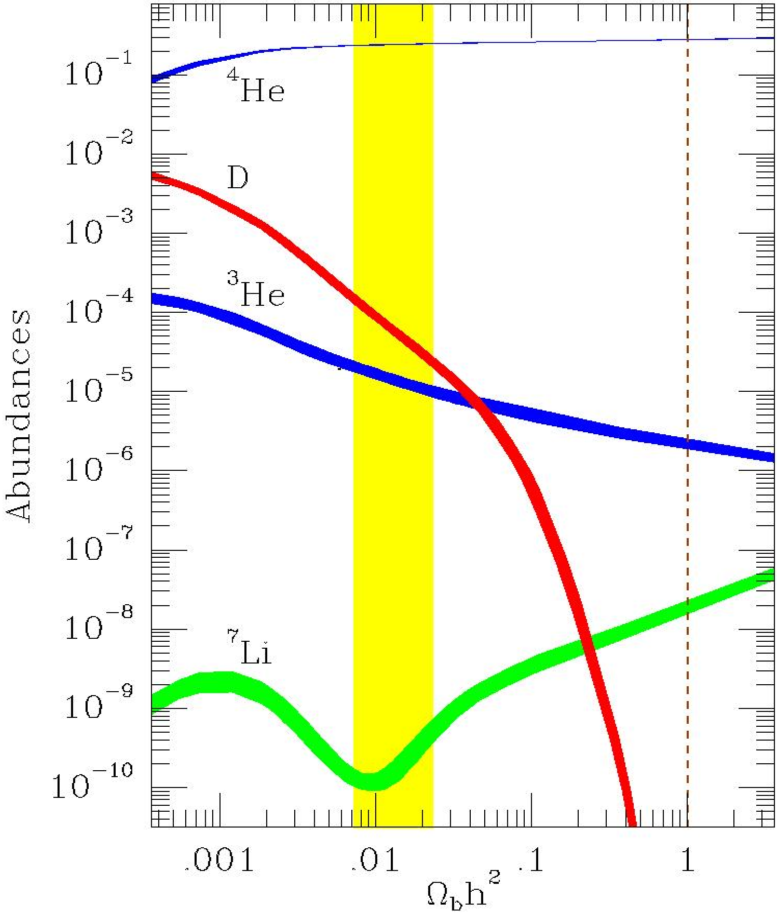
- The lightest elements - D, ^3He, ^4He and Li were produced through fusion processes in the very early universe (~mins)
- Their abundances are well-measured.
- A theoretical calculation of the expected abundances is extremely sensitive to the baryon to entropy ratio:

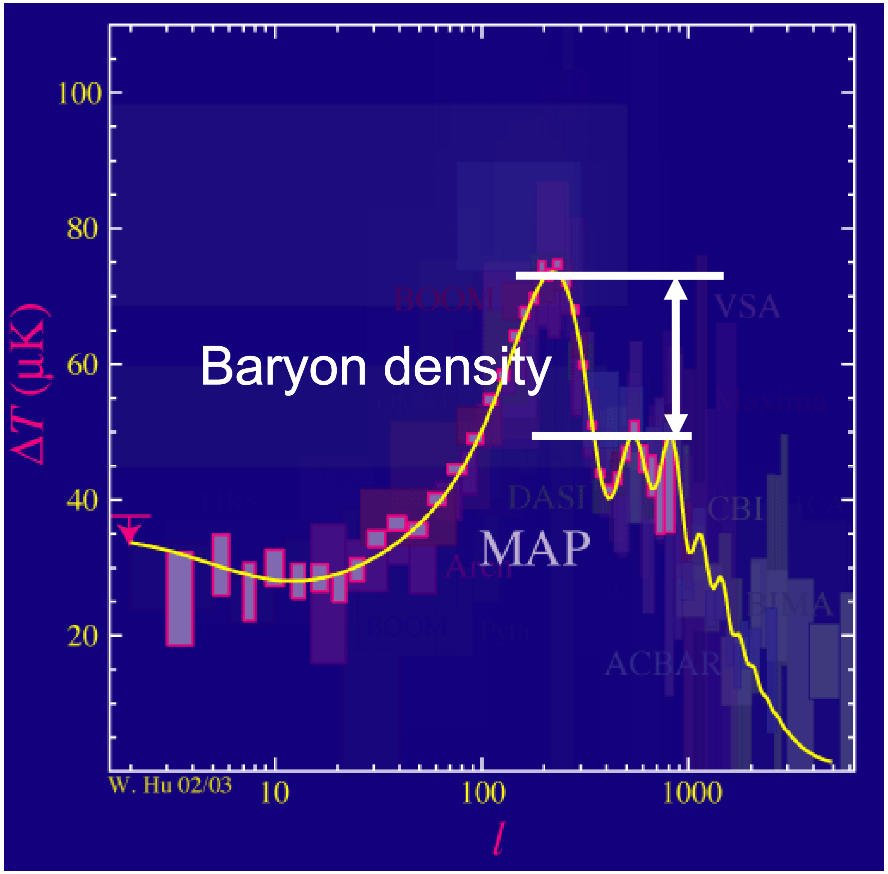
$$\eta \equiv \frac{n_b - n_{\bar{b}}}{s}$$

- Sometimes it is more convenient to use the known density of photons in the universe (CMB) to convert this to $\Omega_b h^2$

where $\Omega_b \equiv \frac{\rho_b}{\rho_c}$ $\quad h \equiv \frac{H}{(100\text{km s}^{-1}\ \text{Mpc}^{-1})}\ ;\ 0.72$

Data





Big Bang Nucleosynthesis (BBN) and precision CMB data give

$$\Omega_b h^2 = 0.024 \pm 0.001$$

How did this arise dynamically?

The Goals of Baryogenesis

To understand how well-motivated particle physics theories in a cosmological setting might generate this value while remaining consistent with all other particle physics and cosmological data

- Typical example of interplay between particle physics and cosmology (particle cosmology)
- Use particle physics to explain cosmological problems
- Use cosmology to constrain putative new particle physics
- Very successful strategy of last ~30 years
  - Inflation, density perturbations, topological defects, dark matter candidates, …
- How might it work here?

The Sakharov Conditions

In order to have a hope of generating the baryon asymmetry, a model (particle physics + cosmological evolution) must:

- Violate baryon number (B) symmetry (obviously)
- Violate both the charge (C) and charge-parity (CP) symmetries
- Depart significantly from thermal equilibrium

$$n(X) \leftrightarrow m(X)$$

$$m(X) \underset{\text{CPT}}{=} m(\bar{X}) \qquad \Rightarrow n(X) = n(\bar{X})$$

Look at some examples of how these can be achieved

Grand Unified Baryogenesis

- A single particle physics interaction at high energy (temp)

$$G \to H \to \ldots$$

$$\to SU(3)_c \times SU(2)_L \times U(1)_Y \to U(1)_{\rm em}$$

- B violation:
  - quarks and leptons in same representation of the GUT gauge group
  - superheavy gauge bosons mediate B-changing processes
- C and CP violation:
  - Natural and easy to build into the theory
- Equilibrium:
  - GUTs effective at very early times
  - Cosmic expansion was much faster then (faster than interactions of gauge bosons
  - Decays are inherently out of equilibrium

$$\Gamma < H^{-1}$$

Some Problems with GUT BG

1. Requires a high reheat temperature after inflation. Can lead to dangerous production of relics - gravitino and moduli problems.
2. GUTs predict topological remnants (monopoles).
3. Extremely hard to test experimentally - can't probe the GUT scale directly in colliders.
4. The electroweak theory (coming soon!). This violates baryon number and can erase a pre-existing asymmetry.

There are ways around most of these:

- Preheating to non-thermally produce superheavy bosons
- choosing a GUT that violates B-L and hence is immune to EW effects (since that theory preserves this combination). E.g. SO(10).

Electroweak Baryogenesis

Spontaneously broken SU(2)xU(1) gauge plus Higgs theory

Take a look in more detail at how the Sakharov criteria are satisfied in the electroweak theory

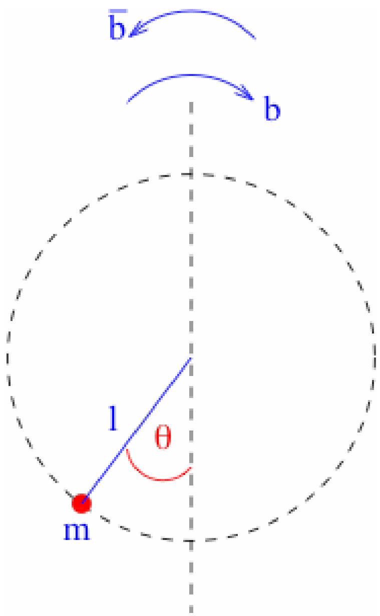
- B is a symmetry of the classical Lagrangian
- B is not violated in any perturbative quantum process (Feynman diagrams respect B)
- Nevertheless, B is an *anomalous* symmetry of the theory.

Involves beautiful nonperturbative physics connected with the vacuum structure of chiral gauge theories.

Sometimes the following analogy is useful...

An Anomalous Analogy

A simple pendulum



$$L = \frac{1}{2} m l^2 \dot{\theta}^2 - mgl(1 - \cos\theta)$$

Vacua:

$$\theta_n = 2n\pi \qquad n \in \mathbf{Z}$$

Periodic potential means periodic wave-functions

New Definitions

$$\chi \equiv \frac{\theta}{2}$$

$$\omega \equiv \frac{g}{l}$$

$$\alpha \equiv \frac{\hbar\omega}{4mgl} << 1$$

Schrödinger Equation

$$\frac{\hbar\omega}{2}\left(-\alpha \frac{d^2}{d\chi^2} + \frac{1}{\alpha}\sin^2\chi\right)\psi_n(\chi) = E_n \psi_n(\chi)$$

Perturbative Approach (expand about a minimum)

$$\sin^2\chi = \chi^2 - \frac{\chi^4}{3} + \ldots$$

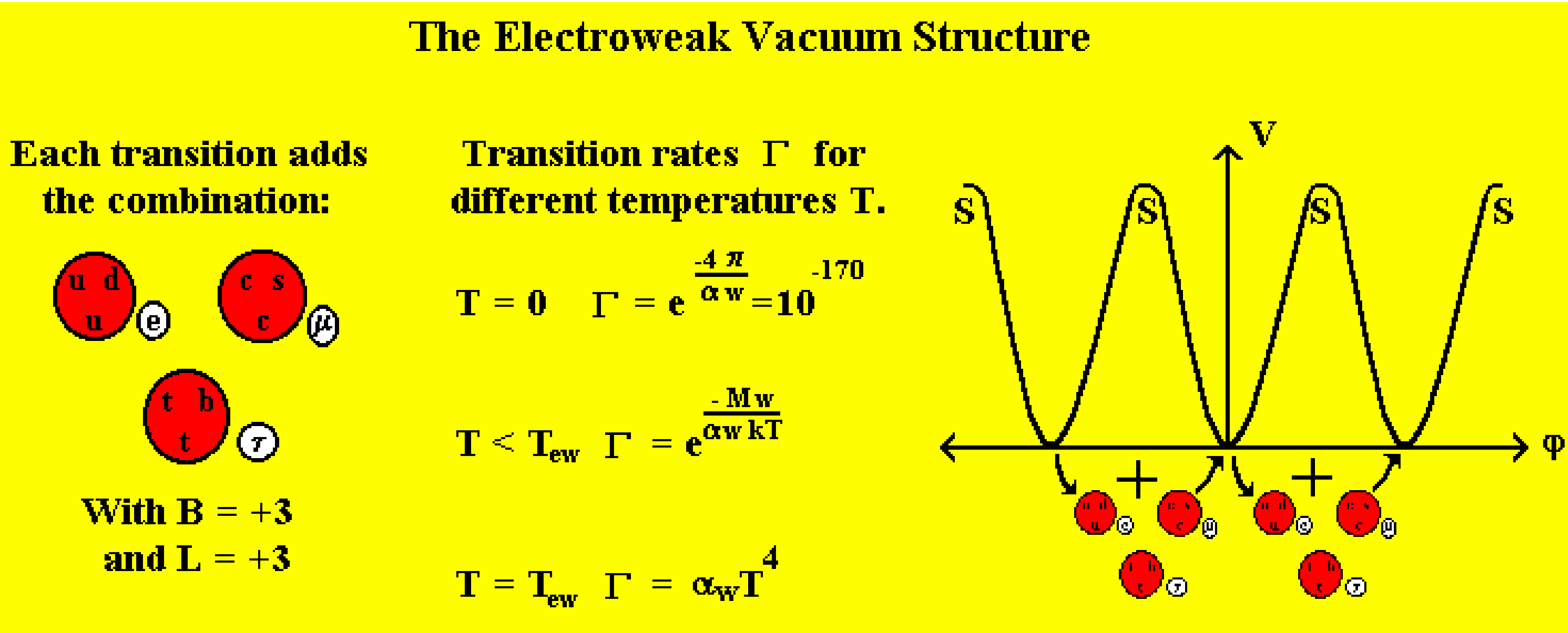
Keep only first term: Harmonic Oscillator!

- Approach valid for Energies « barrier height
- Periodicity lost in approximation
- Only affects high-energy physics

At high temperatures, processes probing the multiple vacua are easily possible

This model is a useful analogy for many features of the electroweak theory

Basics of the EW Vacuum



- T=0 result is reassuring (we would prefer it if protons didn't decay too often!
- For $T>T_{ew}$, things become very interesting - baryon number violation is unsuppressed and copious!

Electroweak C and CP Violation

- EW theory is maximally C-violating (chiral).
- CP-violation, seen in the Kaon system and understood via the CKM matrix, is insufficient to generate the BAU
- Must turn to extra sources.
- Many examples: phases between extra Higgs doublets, or in the squark or gaugino mass matrices, ...

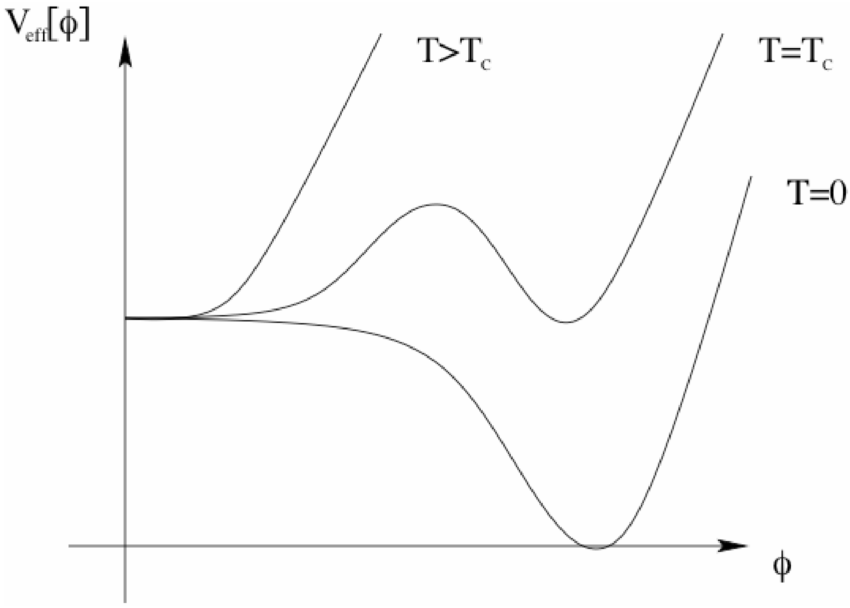
e.g.

$$L_{\mathrm{CP}} = b\frac{\Phi^{\dagger}\Phi}{M^{2}}F_{\mu\nu}\tilde{F}^{\mu\nu} \Rightarrow L_{\mathrm{CP}} = b\frac{\partial_{\mu}(\Phi^{\dagger}\Phi)}{M^{2}}J_{\mathrm{B}}^{\mu} \propto \frac{b}{M^{2}}(\Phi^{\dagger}\Phi)\frac{\partial}{\partial t}n_{\mathrm{B}}$$

- Acts like a time-dependent "chemical potential" for baryon number
- Only active when the higgs field is changing rapidly, otherwise a total derivative.

The Phase Transition

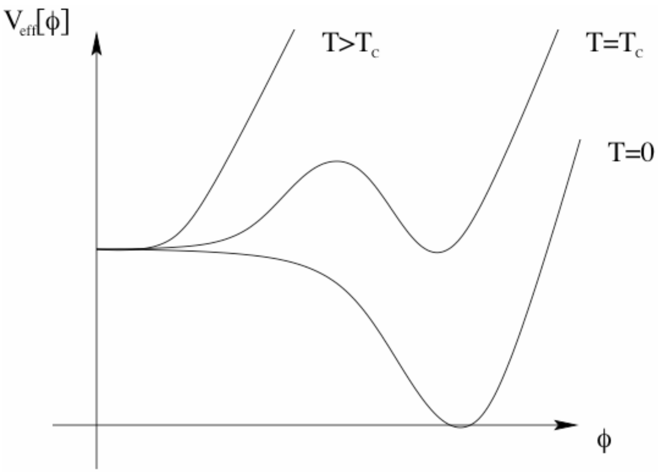
- At high temp, EW symmetry restored: <ϕ>=v=250 GeV
- At low temp, <ϕ>=v=250 GeV
- At a critical temperature T_c, a phase transition occurs



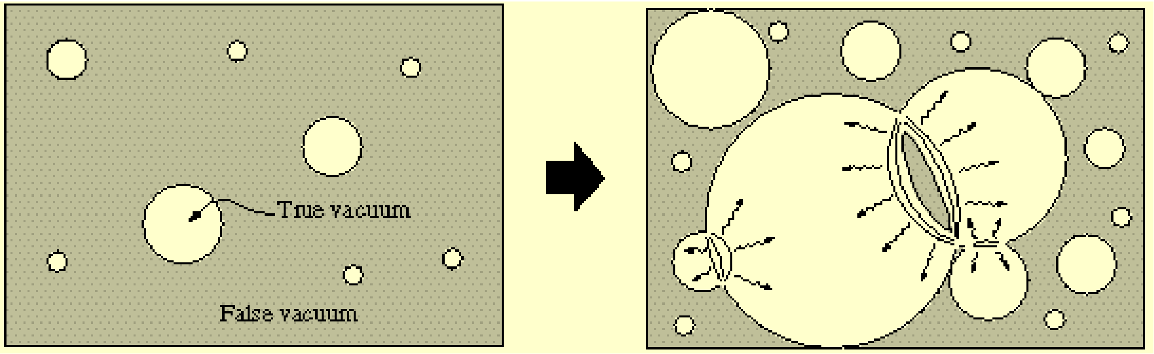
- Order depends on the presence of sufficiently light scalars
- For successful EWBG, usually need PT to be strongly 1st order to get required departure from equilibrium
- In the minimal SM, there is only the Higgs to play with and it would need to be <80 GeV!
- Obviously more is needed

Explain how momentarily. For now, how does it all hang together?

The Phase Transition



- At critical temperature bubbles of true vacuum nucleate in the sea of false.
- Boundaries are approx. planar bubble walls; sweep through space, eventually percolating

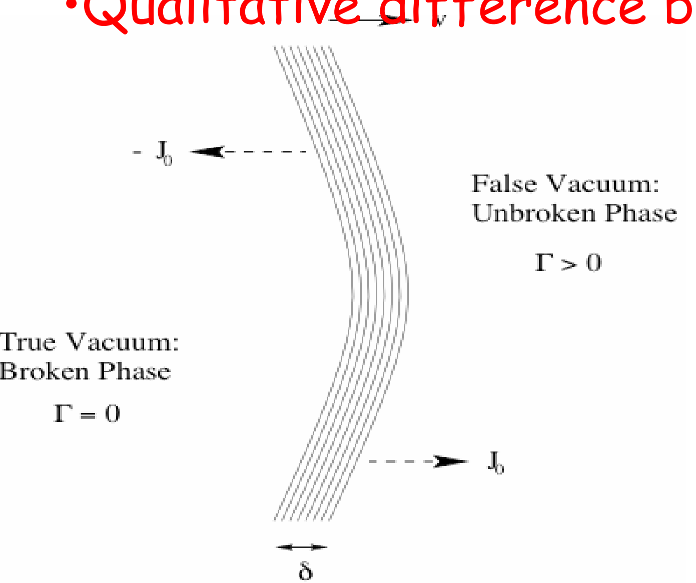


- These boundaries are the site of a large departure from equilibrium if the phase transition is strongly enough first order.
- As they traverse the whole space, each point becomes a site for the production of the BAU

Generation of the BAU

- A number of different ways in which generation takes place. Focus here on a sketch of "nonlocal, thin wall ewbg"

- Applies if mean free path of fermions is >> wall thickness.
- Can neglect scatterings - fermions are free particles interacting w/ wall.
- In rest frame of wall, particles see sharp potential barrier -undergo CP violating interactions w/ wall due to gradient in Higgs phase.
- Asymmetric reflection and transmission of L and R handed particles, injected chiral current into the unbroken phase in front of bubble wall.
- Asymmetries diffuse both behind and in front of the wall left.
- Qualitative difference between the interiior and exterior diffusion.



- At boundaries all Sakharov criteria satisfied.
- After boundary passes, if PT is strong enough, excess baryon number is frozen in

•In exterior EW symmetry is restored - sphalerons unsuppressed.
•Chiral asymmetry converted to an asymmetry in baryon number.
•BUT, particles injected into broken phase (interior) only diffuse by baryon number conserving decays.
• Hence, net asymmetry is generated!

CP phase Lepton mass Diffusion constants

$$\frac{n_{\mathrm{B}}}{\mathrm{s}} \sim 0.2 \frac{\alpha_W^4}{g_*} \kappa \Delta\theta_{\mathrm{CP}} \frac{1}{v_W} \left(\frac{m_l}{T} \right)^2 \frac{m_h}{T} \frac{\xi_L}{D_L}$$

Wall velocity

For the right values of these constant, this can easily be the correct order of magnitude (10^{-10}) to explain the BAU

Since the standard model is insufficient, are there simple extensions that will do the job with the same structure?

Electroweak Baryogenesis II

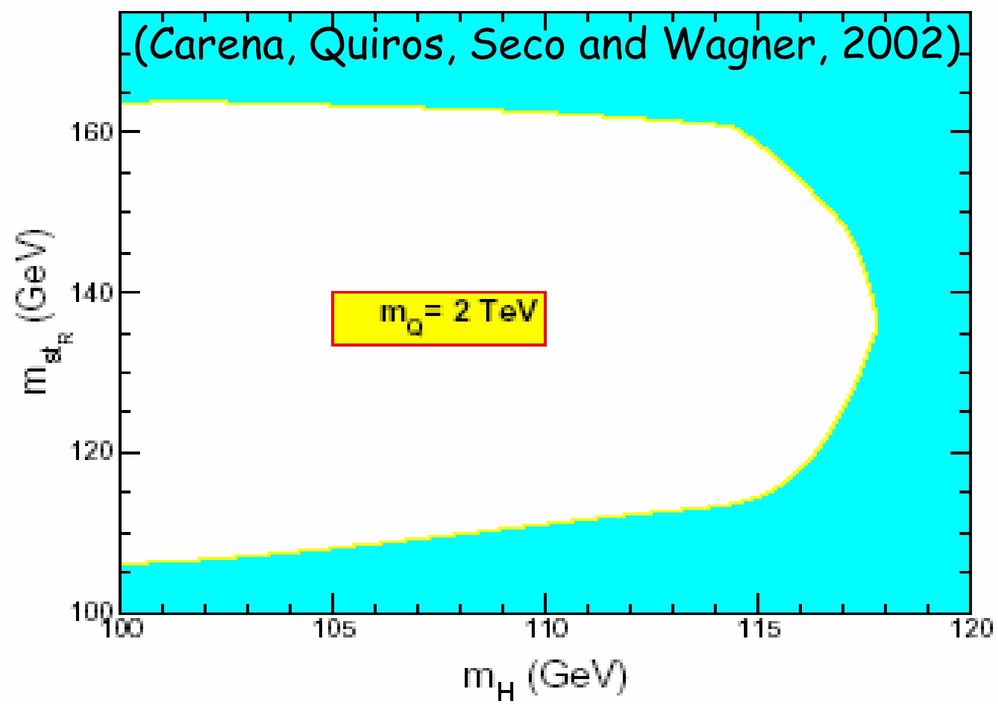
- Requires more CP violation than in SM
- (Usually) requires a (sufficiently strong) 1^{st} order thermal EW phase transition in the early universe.
- Our most popular model of recent years

- Popularity of this idea is tightly bound to its testability.
- Physics involved is all testable in principle at realistic colliders.
- Small extensions needed can all be found in SUSY, which is an independently attractive
- However, the testability of electroweak scenarios also leads to tight constraints.

Bounds and Tests

- Exists only a small window of parameter space in extensions of the electroweak theory in which baryogenesis is viable
- Because electroweak baryogenesis requires a strong enough first order phase transition
- Severe upper bound on lightest Higgs boson mass, $m_h < 120$ GeV (in the MSSM)

- Stop mass may be close to experimental bound and must be < top quark mass.



Direct Tests

- Search for the lightest Higgs at Tevatron or LHC. Explore its properties at LC.
- Search for the lightest stop at the Tevatron or LHC.

- Crucial test may come from B-physics - CP-violating effects (but not guaranteed at B factories)
- Essential to have new measurements of CP-violation, particularly in the B-sector

CP-Violation

- In allowed parameter space - BR($b \to s\gamma$) different from the Standard Model case.
- BUT : exact value depends strongly on, for example, value of the μ-parameter
- Typical difference with respect to SM is of order present experimental sensitivity
- In principle testable in the near future.
- For typical spectrum (light charged Higgs) BR($b \to s\gamma$) somewhat higher than in the SM case, but not always

Leptogenesis (a quick summary)

- SM sphalerons violate both B & L, but preserve B-L
- If can generate lepton asymmetry above EW scale, can be converted to a B asymmetry by EW processes

- Can violate L by decays of right-handed Majorana neutrinos.
- Attractive because same particles yield light left-handed mass through MSW effect. (scalar neutrinos also important in SUSY case)

$$L = \overline{\ell}_L \Phi h_\nu N_L^c + \frac{1}{2}\overline{N}_L^c M N_L^c + h.c.$$

Leptogenesis II

$$N_L^c \to \overline{\Phi} + \ell$$

$$N_L^c \to \Phi + \overline{\ell}$$

Interference between tree-level & absorptive part of 1-loop vertex gives asymmetry.

- Usually requires right-handed mass ~ 10^{10} GeV
- Decays are out of equilibrium because of expansion of universe

- Attractive because such massive RH neutrinos needed to get now-observed neutrino masses.
- Less attractive because hard to test in colliders.
- Some low-scale versions exist, but not compelling.

This is More Popular than Ever

Neutrinos, **by John Updike**

Neutrinos: they are very small
They have no charge; they have no mass;
They do not interact at all.
The Earth is just a silly ball
To them, through which they simply pass
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me. Like tall
And painless guillotines they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed. You call
It wonderful; I call it crass.

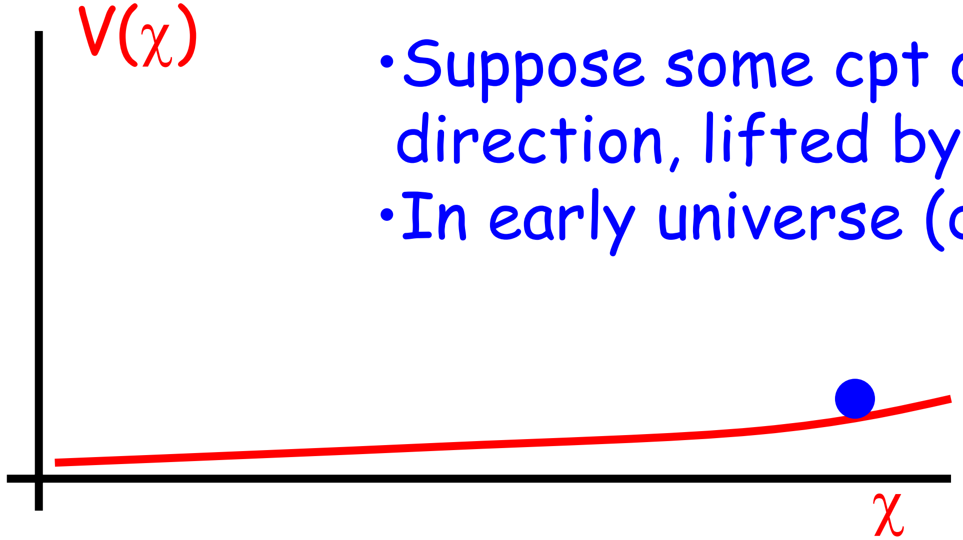
- We now know neutrinos do have mass!
- In fact, as much of the mass of the Universe comes from neutrinos as from stars and galaxies

- Most popular way to explain this (the seesaw mechanism) requires a heavy right-handed neutrino of about the right scale for leptogenesis

Affleck-Dine Baryogenesis

- Involves cosmological evolution of scalar fields carrying baryonic charge.
- Most naturally implemented in SUSY theories - sketch this.

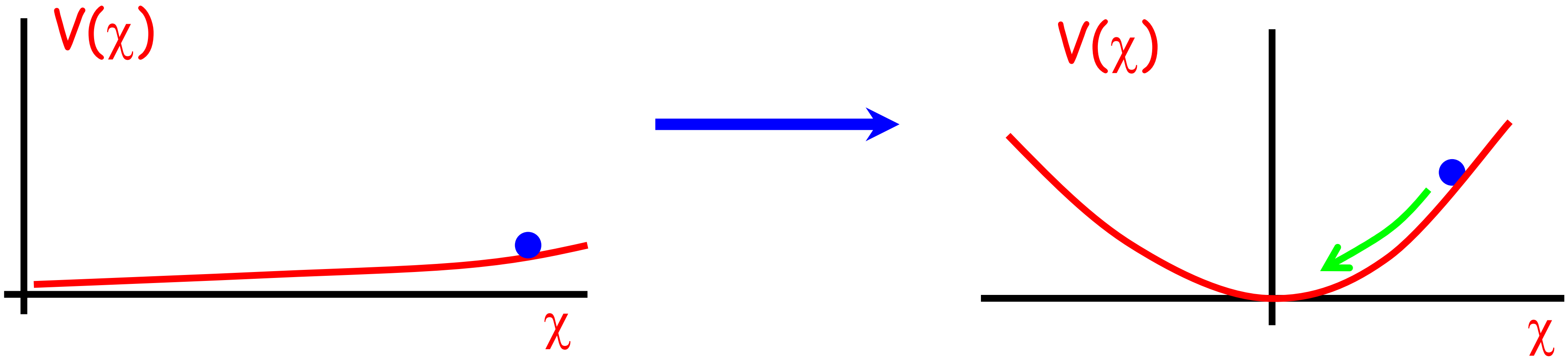
- Suppose have colorless, electrically neutral combination of quarks and leptons.
- Then ∃ scalar superpartner χ (made from squarks & sleptons)



- Suppose some cpt of χ lies along a SUSY flat direction, lifted by SUSY breaking.
- In early universe (during inflation), expect it to be displaced from its minimum.

Affleck-Dine BG II

- Generally there will be B-violating, irrelevant operators in $V(\chi)$ - determine initial phase of χ
- When $H \sim m_{3/2}$, χ starts to oscillate around minimum



Some General References

More general

- **Recent Progress in Baryogenesis**, Antonio Riotto and Mark Trodden *Ann. Rev. Nucl. Part. Sci.* **49**, 35 (1999).
- **ICTP Summer School Lectures,** Antonio Riotto, hep-ph/9807454, (1998).
- **NonGUT Baryogenesis**, A. Dolgov, Physics Reports, 222, 309 (1992).
- **The Early Universe,** E.W. Kolb and M.S. Turner, Addison-Wesley (1990).

Mostly EWBG

- **Electroweak Baryogenesis**, Mark Trodden *Rev. Mod. Phys.* **71**, 1463 (1999).
- V.A. Rubakov and M. E. Shaposhnikov, Phys. Usp. 39, 461 (1996).
- **Electroweak Baryogenesis,** Neil Turok, in *Perspectives on Higgs Physics*, edited by G.L. Kane, p. 300 (1992).
- A.G. Cohen, D.B. Kaplan and A.E. Nelson, Ann.~Rev.~Nucl.~Part.~Sci. 43, 27 (1993).

Final Comments

-Thank You -