The Origin of Matter-Antimatter Asymmetry

BARYOGENESIS

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Outline

- Evidence for baryon asymmetry
- General conditions for baryogenesis
- Specific theories of baryogenesis
  - Electroweak baryogenesis
  - Leptogenesis
  - Affleck-Dine baryogenesis
  - Speculative theories
    - GUT baryogenesis
    - Planck-scale baryogenesis
- Conclusions and Experimental Prospects

What is Baryogenesis?

- Baryogenesis is the process of creating an asymmetry between baryons and antibaryons in the Universe.

$$\frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

- The net baryon number n_B of the Universe, as calculated from Big Bang nucleosynthesis, is much less than the photon number in the CMB.
- Baryon number is likely an excess after annihilation rather than an initial condition.

Evidence for Matter/Antimatter Asymmetry

- Obviously in our local area of the Universe (solar system, Milky Way) consists of matter.
- Can't tell if distant galaxies consist of matter or antimatter– spectra etc. all the same. Universe could consist of domains of matter and antimatter, with net baryon asymmetry.
- If matter/antimatter domains are in contact, gamma rays produced at boundary from annihilation → Cosmic gamma ray background indicates domains must be at least ~Gpc in size.
- Voids between domains would show up in the CMB.

Consequences of Inflation for Baryogenesis

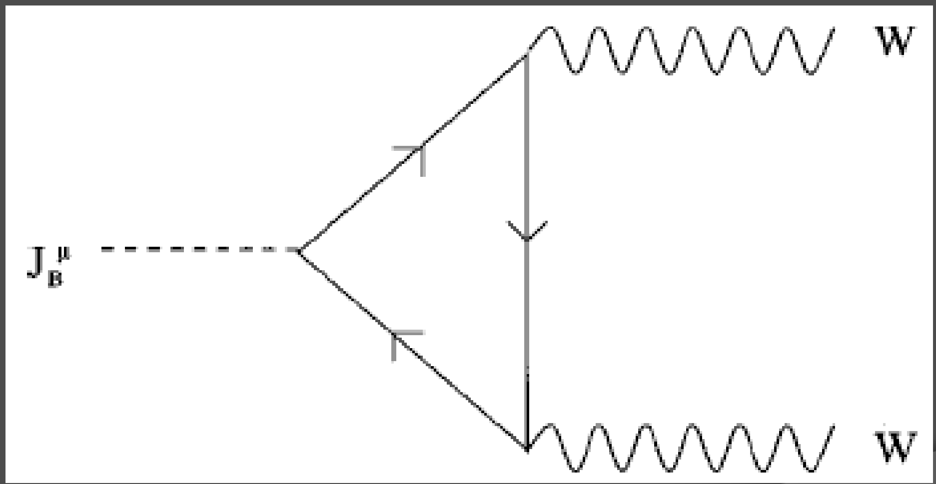
- Theory of inflationary stage in expansion of early Universe (exponential growth)
  - Explains homogeneity, isotropy of Universe
  - Explains flatness of Universe
- Initial particle densities would be diluted exponentially, explaining lack of magnetic monopoles produced in GUTs
- Same argument indicates that initial baryon number would be diluted greatly by now.

Sakharov Conditions

- Baryon number (*B*) violation
- C and CP violation
- Departure from thermal equilibrium at time of above (Arrow of time)
  - CPT violation?

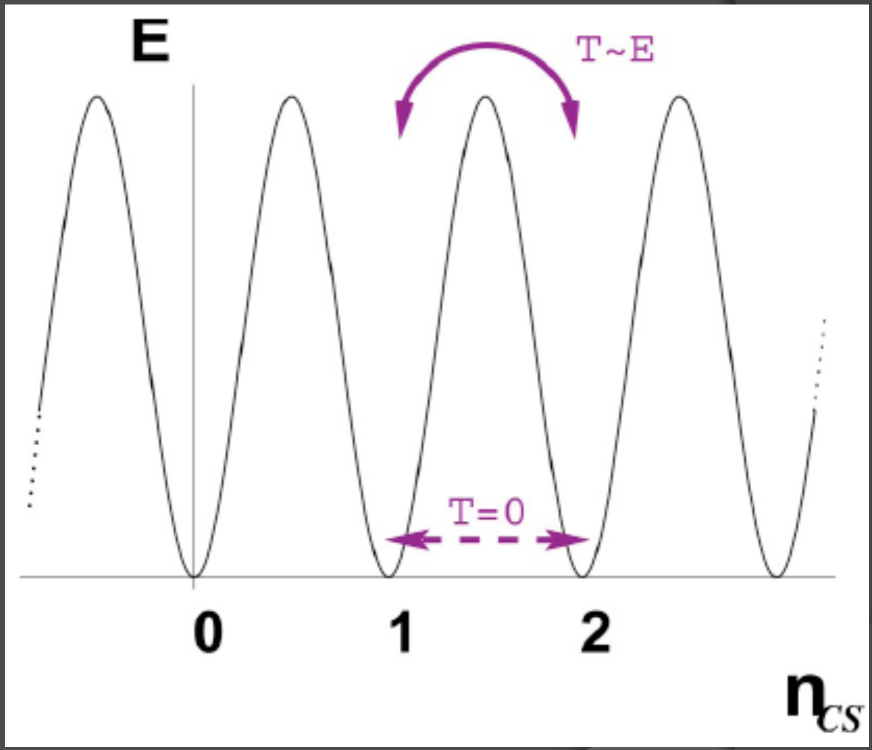
Electroweak Baryogenesis

- Standard Model technically has all the elements for baryogenesis.
- B and L (lepton number) are not exact conserved quantities in SM, but B – L is.



B Violation in Standard Model

- B and L violation occur in transition between different vacuum states (sphaleron process), which is suppressed at energies lower than ~TeV (proportional to Higgs vev).
- Universe after inflation was probably cooler than this.



Electroweak Phase Transition

- Departure from equilibrium may be provided by electroweak phase transition– transition to lower “true” vacuum state due to electroweak symmetry breaking
- This requires the EWPT to be first-order: vacuum expectation values must change non-smoothly.

EWPT Continued

- Directional B violation takes place on frontiers of expanding bubbles of true vacuum
- Higgs vev varies smoothly (second-order) for masses $m_H > \sim 100$ GeV
- Also, must have large enough vev after transition that the sphaleron process does not continue to proceed and wash out the baryon asymmetry- requires similar bound on m_H

Issues with Baryogenesis in the Standard Model

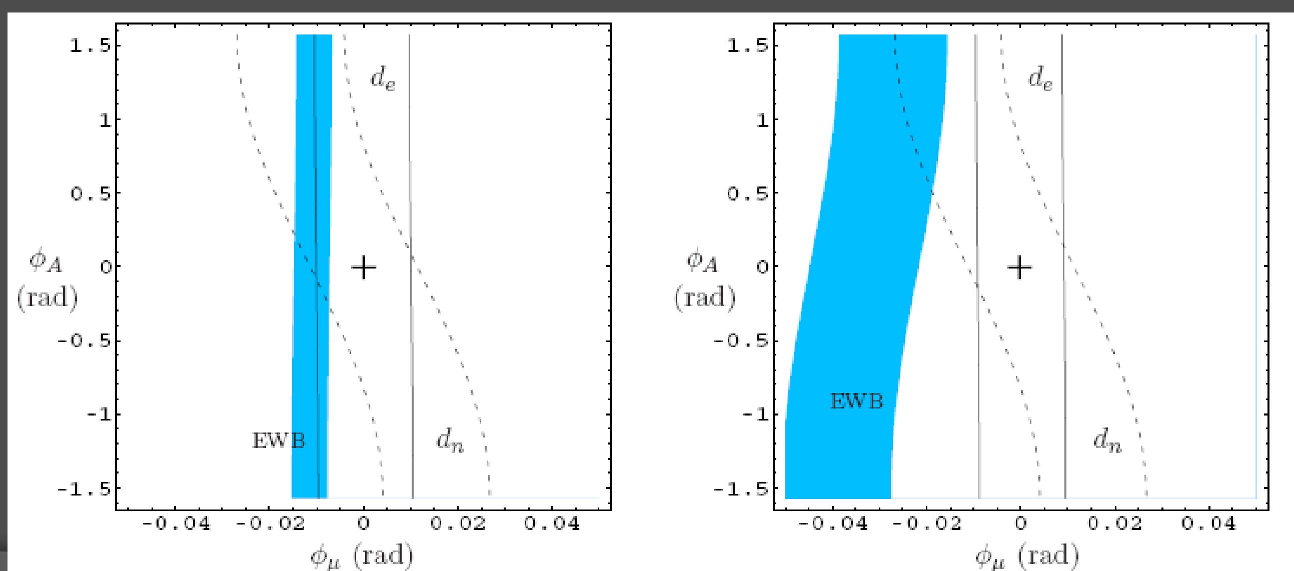
- As seen above, the lower bound on the Higgs mass is too high to prevent thermal equilibrium during EWPT– bubbles do not form.
- Although CP violation occurs in the SM through the CKM mass matrix for quarks, it is too small: suppresses possible asymmetry by 10^{-20}.

What About Supersymmetry?

- SUSY may relax the bound on the Higgs mass for the EWPT to be first-order (more Higgs fields introduced, coupling of stop to Higgs)
- More CP violation may be introduced in mass matrices for superpartners
- In the MSSM, the required lower bound on the Higgs is $m_H > \sim 125$ GeV

Experimental Input for Electroweak Baryogenesis

- Current bounds on the Higgs mass leave EWBG in the MSSM just barely viable– bounds on the Higgs mass from the LHC likely to constrain scenarios of supersymmetric EWBG
- EDM experiments may determine if there is sufficient CP violation:



Leptogenesis

- Leptogenesis makes use of the sphaleron process described above that violates *B* and *L* but conserves *B* – *L*.
- Since *B* – *L* conserved, a net lepton number can be converted into a baryon number through this process.
- Don't need EWPT– since leptons are lighter than baryons, they go into equilibrium preferentially.
- Parameter space for this theory is accessible to current neutrino experiments.

Neutrino Theory Background

- Observation of neutrino-less double beta decay would indicate that neutrinos are their own antiparticle; i.e. they are Majorana fermions.
- Trying to make $B - L$ a gauge symmetry forces the existence of right-handed neutrinos
- Right-handed neutrinos can obtain large Majorana masses because they are singlets

Seesaw Mechanism

- Right-handed Majorana neutrinos can give left-handed ones mass. The mass matrix for these neutrinos can be written

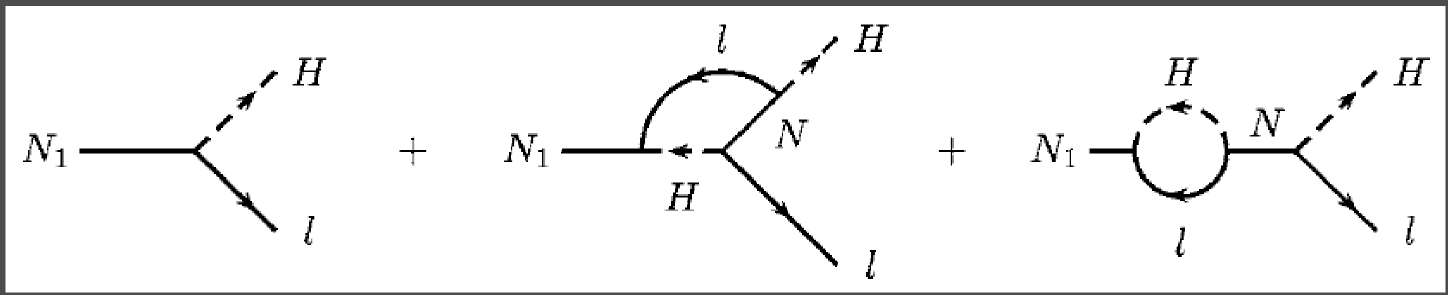
$$\begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix}$$

- With eigenvalues *M* and $m_\nu \simeq \frac{m^2}{M}$

- For neutrino masses ~.05 eV, need M ~10^{15} GeV.

Generating Lepton Asymmetry

- Majorana neutrinos can decay into a Higgs and a lepton or antilepton. Since the Majorana neutrino has no (undefined) lepton number, these decays violate *L*.



- CP violation occurs due to one-loop diagram and CP violation in neutrino mixing.
- Once temperature of Universe drops below Majorana mass, Majorana neutrinos are out of equilibrium and produce net lepton asymmetry.

Generating Baryon Asymmetry

- Balancing the chemical potentials for neutrinos, baryons, leptons, etc. gives the result for baryon asymmetry, where N_g is the number of neutrino generations.

$$B = \frac{8N_g + 4}{22N_g + 13}(B - L)_0$$

- In order to avoid washout of the lepton asymmetry by inverse decays, require upper bound on neutrino masses $m_\nu < .1$ eV

Baryogenesis through Coherent Scalar Fields

- SUSY yields scalar fields carrying baryon and lepton number.
- Coherent production of baryons is thus possible.
- In regimes where SUSY remains intact, the flat directions of the potentials make displacement from their minima relatively simple in high energy systems
- The foremost example of this form of theory is Affleck Dine Baryogenesis

Not that Affleck

Affleck-Dine Baryogenesis

- Supersymmetry introduces scalar fields partnered to fermions. Those partnered with quarks carry baryon number.

$$\mathcal{L} = |\partial_\mu \phi|^2 - m^2 |\phi|^2$$

- Phase symmetry → conserved current from Noether's Theorem, which we associate with baryon number.
- Supersymmetry can introduce quartic couplings to the potential that violate this conserved current, and also CP.

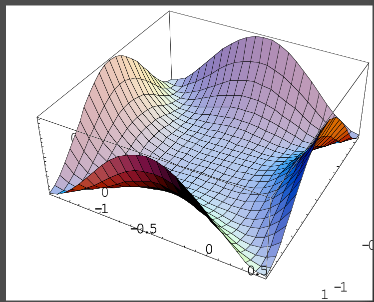
Toy Example

- Consider a complex scalar field χ that carries baryonic charge:

$$j_\mu^{(\chi)} = i\left[\chi^* \partial_\mu \chi - (\partial_\mu \chi^*)\chi\right] = -2|\chi|^2 \partial_\mu \theta$$

- Baryonic charge can be visualized as angular momentum of a particle in χ space
- Consider a potential with flat directions:

$$U(\chi) = m^2|\chi|^2 + \frac{1}{2}\lambda_1|\chi|^4 + \frac{1}{4}\lambda_2\left(\chi^{*4} + \chi^4\right)$$



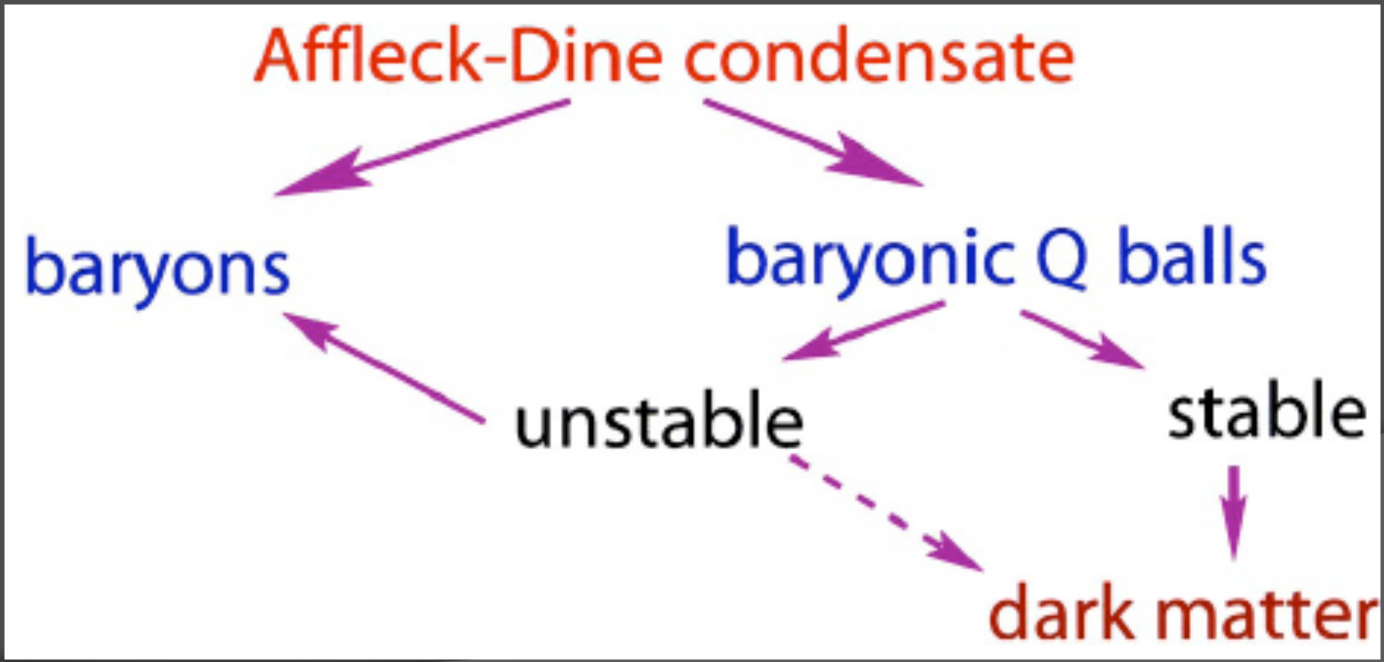
- Particle can travel freely in flat directions; quantum fluctuations can displace it slightly in an orthogonal direction
- When particle relaxes down center, angular momentum (baryonic charge) remains.

Affleck-Dine

- In reality, the χ field is displaced from its minimum due to quantum fluctuations during inflation.
- As the Hubble rate decreases after inflation, the baryon number associated with χ freezes out.
- Scalar field decays into fermions, creating observable baryon density.

Affleck-Dine and Dark Matter

- The Affleck-Dine mechanism may also produce a candidate for dark matter, called B-balls.



B-Balls

- B-balls are solitons of the scalar field of Affleck-Dine baryogenesis.
- Individual B-balls have baryon numbers ~10^{26} , and thus can pass through stars with minimal velocity loss (.001%), so they appear non-interacting and thus may qualify as candidates for dark matter.

Planck-Scale Baryogenesis

- Quantum gravity can't be expected to conserve quantum numbers
- At Planck energy and scale, CP violation is probably greater, and thermal equilibrium is likely broken or even meaningless.

- Physics is obviously highly speculative
- Not clear how Planck-scale baryogenesis would generate the small baryon-photon ratio we observe.
- Inconsistent with inflation (discussed above)

GUT Scale Baryogenesis

- Earliest plausible scenario for baryogenesis.
- Grand Unified Theories (GUTs) include B-violating processes, such as the decay of new gauge bosons into baryons.
- GUTs also incorporate much more CP violation than the SM.

- Physics is obviously highly speculative
- Inconsistent with inflation (discussed above)

Summary

- We've discussed five major theories of baryogenesis.
- Two of these theories, GUT and Planck Scale, are largely ruled out by inflation.
- A third candidate, electroweak, is very dependent on EWPT's, and thus is considered unlikely without SUSY. Its viability within SUSY depends on the results of experimental Higgs searches.
- The last two candidates, leptogenesis and Affleck-Dine, remain viable but are less well understood. The parameter space for leptogenesis may be explored by current neutrino experiments.
- Affleck Dine baryogenesis not only gives us a candidate for explaining baryon asymmetry in the universe, but also gives us a potential Dark Matter candidate in Affleck Dine B-balls.