Matter - Antimatter Asymmetry in the Universe

Standard Model Course Presentation

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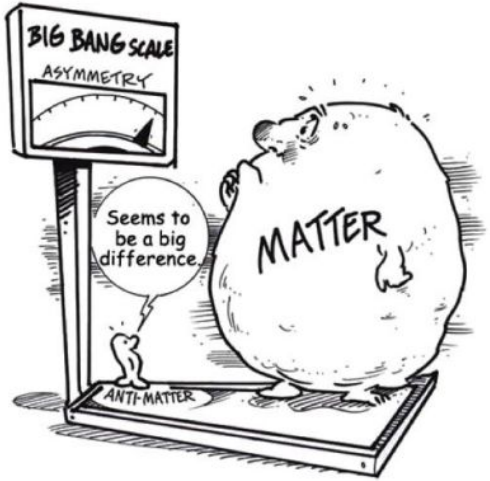
Matter-Antimatter Asymmetry

- The current Universe is dominated by matter, with very tiny antimatter.
- The puzzle of matter dominating over antimatter in the Universe has been one of the important questions in understanding the evolution of our Universe.
- Antimatter particles share the same mass ($m = \overline{m}$) and decay widths ($\Gamma = \overline{\Gamma}$) as their matter counterparts, but qualities such as electric charge ($Q = \overline{Q}$) are opposite.



Evidence of Matter-Antimatter Asymmetry

I. Cosmic Microwave Background (CMB)

- Observational data from Planck reveals the baryon density parameter :

$$\Omega_b h^2 \sim 0.022$$

- The baryon-photon ratio almost constant in time:

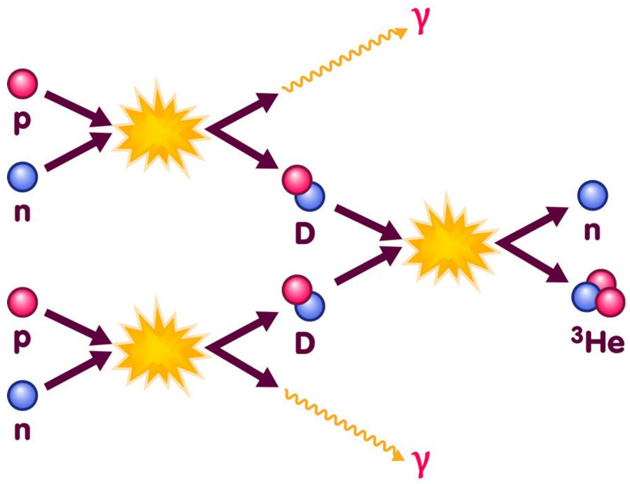
$$\eta_B \approx \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

- The tiny value implies that for every billion photons, there is roughly one excess baryon, meaning a massive annihilation of primordial matter–antimatter must have occurred, leaving behind only the small surplus that forms all visible matter.

Evidence of Matter-Antimatter Asymmetry

II . Big Bang Nucleosynthesis

- BBN predicts the primordial abundance of light elements : H^2, He^3, He^4 and Li^7.
- The theoretical predictions agree with observed abundances only if $\eta_B = 5 - 6 \times 10^{-10}$ which is consistent with the CMB value.



Evidence of Matter-Antimatter Asymmetry

III . Absence of Gamma-Ray Signals from Matter–Antimatter Annihilation

- If large antimatter domains existed near our galaxy or within the visible Universe, annihilation at their boundaries with matter domains would produce intense gamma-ray emission around the characteristic 100 MeV scale ($p\,\bar{p} \rightarrow \pi$ mesons => $\pi^0 \rightarrow 2\gamma$).

- However, no diffuse γ-ray background consistent with such annihilation is observed.

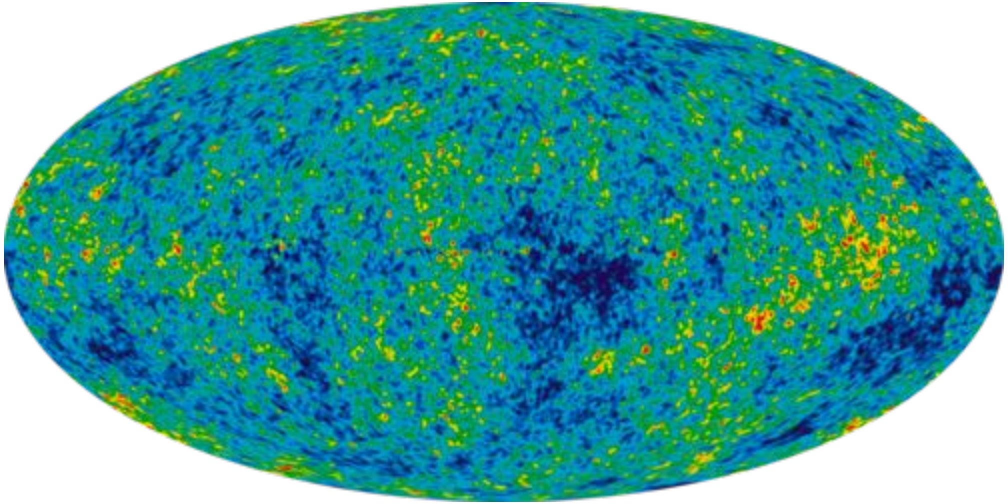
- Fermi-LAT places extremely strong limits on annihilation signatures. any antimatter domains must be separated from us by at least gigaparsec scales, otherwise we would see unavoidable annihilation flux.

Baryogenesis

- Baryogenesis is a theoretical framework proposed to understand the generation of more baryons (matter) than antibaryons (antimatter) in the early universe.

- This process is crucial for the existence of the matter-dominated universe we live in.

- Andrei Sakharov (1967) identified three conditions that must be fulfilled for baryogenesis to occur.



The detailed, all-sky picture of the infant universe created from nine years of WMAP data

Sakharov Conditions

I.

Baryon Number Violation

II.

C &
CP Violation

III.

Departure from thermal equilibrium

Baryon Number Violation

- Baryon number (B) is a quantum number representing the difference between baryons (e.g., protons, neutrons) and antibaryons.
- Baryogenesis requires baryon number violation to explain the observed matter-antimatter asymmetry.
- Without violation, matter and antimatter would be produced in equal amounts.
- No net baryon asymmetry could develop, leaving a universe dominated by radiation (annihilation of matter and antimatter).
- Can be seen in proton decay and neutron-antineutron oscillations.

C & CP Violation

- C Symmetry : Invariance when particles are replaced by their antiparticles.
- P Symmetry : Spatial inversion or ”mirror reflection” symmetry.
- CP Symmetry : CP symmetry is the combined transformation of charge conjugation (C) and parity (P).
- CP violation breaks the symmetry between matter and antimatter. Without it, matter and antimatter would be created in equal amounts.
- CP violation creates an imbalance favoring more baryons than antibaryons.
- In Standard Model, this violation occurs naturally in complex phase of CKM Matrix but CP violation is too small (which gives, $\eta_B \sim 10^{-20}$) compared to the observed $\eta_B \sim 10^{-10}$.

Departure from Thermal Equilibrium

- Thermal equilibrium refers to a state where all parts of a system are at the same temperature and no net energy is transferred between them.

- Departure from this state means that different parts of the system are at different temperatures or that there is a net transfer of energy between parts of the system.

- In thermal equilibrium, particles and antiparticles are continuously produced and annihilated, maintaining a balance.

- For baryogenesis to occur, there must be deviations from this equilibrium to allow for the creation of an excess of baryons.

Narrative of Cosmic History

Before $t \sim 10^{-25}$ s, the Universe was highly inhomogeneous with extremely large energy density.

↓

Inflation began around $t \sim 10^{-25}$ s, driven by slow roll of the inflaton field.

↓

The scale factor increased by at least 10^{60} , diluting all conserved or approximately conserved quantities (including baryon number) by enormous factors.

↓

Inflation ended when the inflaton reached the minimum of its potential, reheating the Universe to a high temperature set by its decay rate.

↓

The baryon asymmetry(observed today) must therefore have been generated after inflation. Any upper bound on the reheating temperature directly restricts which baryogenesis scenarios are viable.

GUT Baryogenesis

- Grand Unified Theories propose that at very high energies, strong, weak and electromagnetic interactions were actually unified into a single force described by **one larger symmetry group**.

- Predicts heavy gauge bosons (e.g., X, Y) that mediate interactions violating baryon number. These **bosons then decay to leptons and quarks**.

- GUTs naturally contain CP violation through **complex phases** in their coupling constants, similar to (but more general than) the Kobayashi-Maskawa mechanism in the Standard Model.

- As the Universe expands and cools, T drops below M_{GUT}, the production of X bosons becomes slower and their abundance **freezes out**, achieving the third condition.

- GUT theories **fail without supersymmetry**, which has not been observed yet. The problem of Gravitinos and inflation are also potential problems with GUTs.

Electroweak Baryogenesis

- Electroweak baryogenesis tries to explain the matter–antimatter imbalance using physics at the **electroweak scale (around 100 GeV)**, meaning it could be tested in experiments like the LHC.
- The idea is that during the early Universe, the Higgs field went through a **phase transition**. If this transition was "strongly first-order," it would create expanding bubbles that provide the needed out-of-equilibrium conditions.
- At the bubble walls, **CP-violating interactions** can make particles and antiparticles behave differently, generating a small excess of matter.
- Electroweak **sphaleron processes** convert these CP-generated asymmetries into a net baryon number, helping produce more matter than antimatter.
- In the Standard Model, this **mechanism fails** because the electroweak phase transition is not first-order and the CP violation is far too small.
- However, some extensions of the Standard Model—like two-Higgs doublet models or singlet-extended Higgs sectors—can still make electroweak baryogenesis possible if they add new CP violation and strengthen the phase transition.

Leptogenesis

- Generates the matter-antimatter asymmetry not directly through baryons, but **through leptons** (electrons, muons, and their associated neutrinos).

- Processes which conserve B-L are active in early Universe at high temperatures. If we create an excess of leptons over antileptons (a lepton asymmetry), **sphalerons will redistribute this asymmetry**, converting some of it into a baryon asymmetry.

- It relies on the existence of **heavy right-handed neutrinos**, predicted by the seesaw mechanism, whose decays can violate lepton number and CP symmetry.

- When these heavy neutrinos decay out of thermal equilibrium, they produce more leptons than antileptons due to **CP-violating effects**.

- Electroweak sphaleron processes active in the early Universe then convert part of this lepton asymmetry into a baryon asymmetry, giving rise to the matter we observe today.

- Leptogenesis is appealing because it is directly linked to **neutrino mass generation,** meaning the same physics that gives neutrinos mass may also explain why the Universe contains matter.

Affleck-Dine Mechanism

- Works in supersymmetric theories, where certain combinations of squark and slepton fields can move freely along **“flat directions” without costing energy**.

- The scalar field gets displaced from its minimum energy state during **cosmic inflation**. As the universe expands and cools, this field begins to oscillate and rotate in a complex way, naturally generating a matter-antimatter asymmetry.

- Unlike mechanisms that produce the tiny asymmetry we observe ($\eta \sim 10^{-10}$), Affleck-Dine can initially generate much **larger asymmetries** that later get diluted, making it particularly useful in certain cosmological scenarios.

- AD baryogenesis is attractive because it works even with **low reheating temperatures** and appears naturally in many SUSY and string-inspired models.

Other Mechanisms

- Spontaneous Baryogenesis
- Inflaton or Moduli Decay
- Baryogenesis from Primordial Black Holes
- CPT-Violating Baryogenesis
- Topological Defect Baryogenesis
- Post-Sphaleron Baryogenesis
- Asymmetric Dark Matter Baryogenesis
- Gravitational Baryogenesis

Conclusion

- Baryogenesis remains a vital area of research in understanding the universe's matter-antimatter asymmetry.
- Leptogenesis and Affleck-Dine Mechanism seem promising but require more support to be proven true.
- Experimental efforts continue to search for evidence of baryon number violation, CP violation, and non-equilibrium dynamics to support these theories.
- Challenges remain, particularly in reconciling theoretical predictions with experimental results.
- Future discoveries in particle physics may provide deeper insights into the origins of baryon asymmetry and the fundamental laws of nature.

References

- **AD Doglov (1997)** – Baryogenesis 30 Years After
- **Mark Trodden (2004)** – Baryogenesis and Leptogenesis (Lecture Notes)
- **Canetti et al. (2012)** – Constraints on the Matter–Antimatter Asymmetry
- **Michael Dine (2003)** – Origin of Matter Antimatter Asymmetry

Thank you for being a patient listener.

Questions??