Baryogenesis

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Ignatiev, Krasnikov, Kuzmin and Tavkhelidze, 1978; Yoshimura, 1979; Weinberg, 1979;....

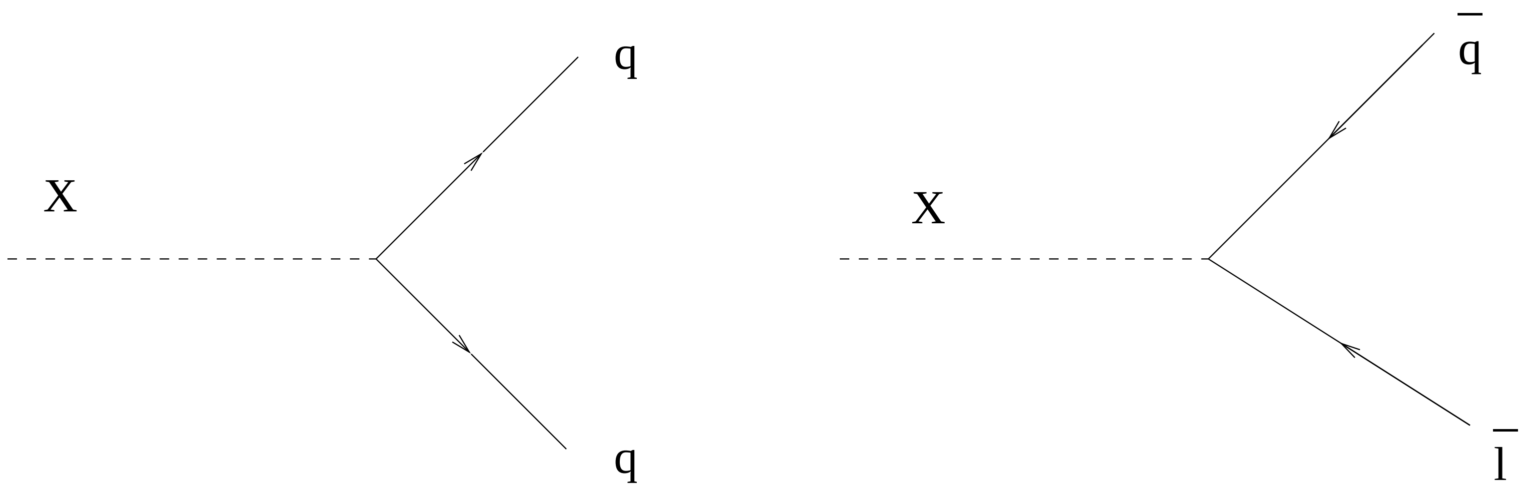
Grand Unification $\Rightarrow$ baryon and lepton number non-conservation

Scale of GUTS is close to the Planck scale $\Rightarrow$ rapid Universe expansion

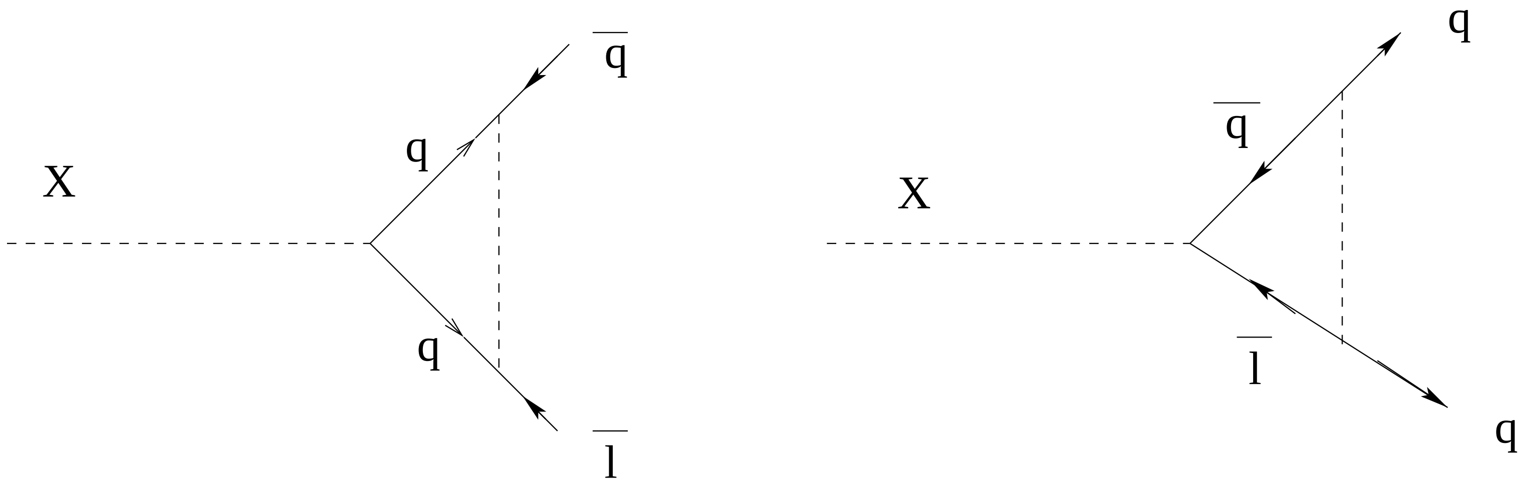
Grand unified baryogenesis

Step No 1: Consider B-violating leptoquark decays

$$X \to q\ell,\ \bar{q}\bar{q}\ \ and\ \ \bar{X} \to \bar{q}\bar{\ell}, qq$$



Step No 2: To account for CP-violation, compute radiative corrections



Step No 3: Find baryon asymmetry from

$$\frac{n_B}{n_\gamma} = \Delta \sim \frac{1}{N_{\rm eff}} \delta_{CP} \cdot S_{\rm macro},$$

δ_{CP} is the asymmetry in leptoquark decays,

$$\delta_{CP} = \frac{\Gamma(X \to qq) - \Gamma(\bar{X} \to \bar{q}\bar{q})}{\Gamma_{\rm tot}},$$

$\Gamma_{\rm tot}$ is the total width, $S_{\rm macro}$ is a factor taking into account the kinetics of the leptoquark decays

Progress over last 25 years

Today we know exactly 42 different ways to create baryons in the Universe!

1. GUT baryogenesis
2. GUT baryogenesis after preheating
3. Baryogenesis from primordial black holes
4. String scale baryogenesis
5. Affleck-Dine (AD) baryogenesis
6. Hybridized AD baryogenesis
7. No-scale AD baryogenesis
8. Single field baryogenesis
9. Electroweak (EW) baryogenesis
10. Local EW baryogenesis
11. Non-local EW baryogenesis
12. EW baryogenesis at preheating

How to create baryons

13. SUSY EW baryogenesis
14. String mediated EW baryogenesis
15. Baryogenesis via leptogenesis
16. Inflationary baryogenesis
17. Resonant baryogenesis
18. Spontaneous baryogenesis
19. Coherent baryogenesis
20. Gravitational baryogenesis
21. Defect mediated baryogenesis
22. Baryogenesis from long cosmic strings
23. Baryogenesis from short cosmic strings
24. Baryogenesis from collapsing loops

25. Baryogenesis through collapse of vortons
26. Baryogenesis through axion domain walls
27. Baryogenesis through QCD domain walls
28. Baryogenesis through unstable domain walls
29. Baryogenesis from classical force
30. Baryogenesis from electrogenesis
31. B-ball baryogenesis
32. Baryogenesis from CPT breaking
33. Baryogenesis through quantum gravity
34. Baryogenesis via neutrino oscillations
35. Monopole baryogenesis
36. Axino induced baryogenesis

How to create baryons

37. Gravitino induced baryogenesis
38. Radion induced baryogenesis
39. Baryogenesis in large extra dimensions
40. Baryogenesis by brane collision
41. Baryogenesis via density fluctuations
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Please tell me if something is missing!

Common features

In short: the universe is asymmetric because baryon number is not conserved in C- and CP-violating reactions which produce more baryons than antibaryons in expanding universe.

Andrei Sakharov, 1967 (see also Kuzmin, 1970):

“According to our hypothesis, the occurrence of C-asymmetry is the consequence of violation of CP-invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

Crucial questions:

For particle physics:

- Nature of B-violation
- Nature of CP non-conservation

For cosmology

- When did it happen

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We do not know for sure!

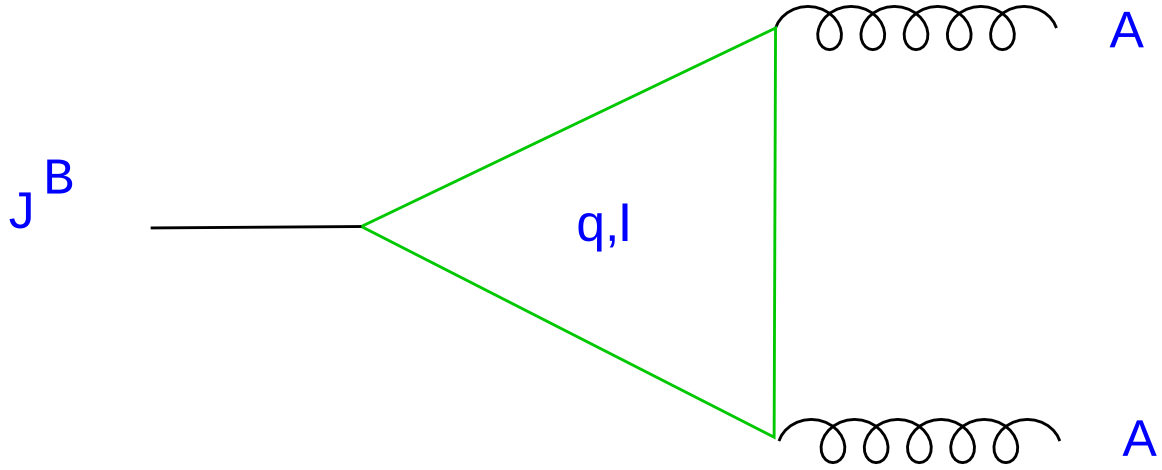
What we are certain about

Baryon number non-conservation

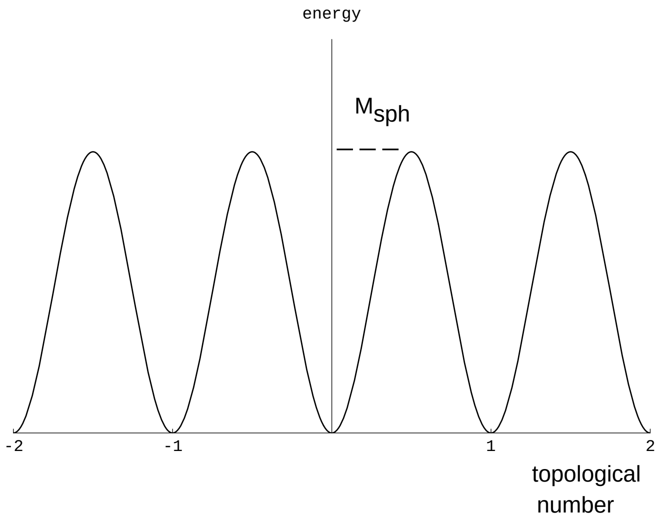
The only sure source: EW baryon number non-conservation:

Quantum anomaly:

$$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{n_f}{32\pi^2} \mathrm{Tr}\left(F_{\mu\nu} \tilde{F}_{\mu\nu} \right)$$



Rate of B-nonconservation



$$\Gamma \sim \begin{cases} \exp(-\frac{4\pi}{\alpha_W}) \sim 10^{-160}, & T = 0 \\ \exp\left(-\frac{M_{sph}}{T}\right), & T < T_c \\ (\alpha_W)^5 T^4, & T > T_c \end{cases}$$

These reactions are in thermal equilibrium for

$$100 GeV \sim T_c < T < (\alpha_W)^5 M_{Pl} \sim 10^{12} GeV$$

EW anomaly

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The argument:

$$\Delta \sim \frac{1}{N_{\text{eff}}} \delta_{CP} \cdot S_{\text{macro}},$$

$$S_{\text{macro}} \sim \frac{\tau_{EW}}{t_U} \sim \frac{T_{EW}}{\alpha_W M_{Pl}} \sim 10^{-14}$$

in the absence of the first order EW phase transition

($m_H > 72.3$ GeV)

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Physics beyond the standard model!

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The argument:

$$\Delta \sim \frac{1}{N_{\text{eff}}}\delta_{CP} \cdot S_{\text{macro}},$$

Assume that δ_{CP} is analytic with respect to quark masses:

$$\delta_{CP} \sim D_{CP}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \times$$
$$(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)\frac{1}{T_{EW}^{12}} \sim 10^{-19}$$

Too small!

$$\Downarrow$$

Physics beyond the standard model!

Sure physics beyond SM

Experimental indication: neutrino masses and oscillations.

What we are somewhat less certain about

Neutrino masses $\Rightarrow$ natural source of CP breaking and lepton number violation.

A lowest-order SU(2)$\times$U(1) gauge-invariant operator that can be added to the SM Lagrangian:

$$\Delta L = f_{ab} \frac{(\bar{\nu_\alpha^c} \phi)(\phi^\dagger \nu_\beta)}{M}$$

$\Downarrow$

Majorana neutrino masses

$\Downarrow$

Lepton number non-conservation and CP violation in ν sector

Leptogenesis

Ask Pasquale Di Bari!

What we are not certain about

Cosmology: When did baryogenesis happen?

- GUT : $T \sim O(10^{16})$ GeV
- Leptogenesis: $T \sim O(10^{10})$ GeV
- Electroweak: $T \sim O(10^{2})$ GeV
- Affleck-Dine: above nucleosynthesis

Conclusions

Baryon asymmetry of the universe

$\Updownarrow$

Particle physics beyond the Standard Model

Main features to be incorporated in true particle model:

- baryon or lepton number violation, proton decay or neutrino masses
- new sources for C and CP violation
- thermal non-equilibrium, new physics at low or high energy scales

Experimental input is a must!

Theoretical challenge

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$$\Delta \sim \frac{1}{N_{\rm eff}} \delta_{CP} \cdot S_{\rm macro}$$

$$\delta_{CP} \sim 10^{-4} m_t^4 m_c^2 m_b^4 m_s^2 / E_{EW}^{12}$$

$$S_{\rm macro} \sim \tau_{EW} / t_U$$

What if $E_{EW} \rightarrow$ 1GeV? $\delta_{CP} \rightarrow 10^{-6}$...

What if $\tau_{EW} \sim \frac{1}{f_e \alpha_W T}$ (related to the right electron chirality flip) ? $S_{\rm macro} \rightarrow 10^{-2}$...