Baryogenesis

Topics

Introduction

The baryonic number

Sakharov Conditions

GUT baryogenesis

EWBG

Conclusion

By: Gonçalo Freitas
Nº 44237

Topics of presentation:

- Introduction, what is baryogenesis?
- The baryonic number and Sakharov Conditions.
- GUT Baryogenesis.
- Electroweak baryogenesis

What is Baryogenesis?

Baryogenesis is the term used to describe an hypothetical process in the early universe that explains the imbalance of baryonic matter and antimatter

CPT symmetry and expectation

Observations :

- laboratory
- nature

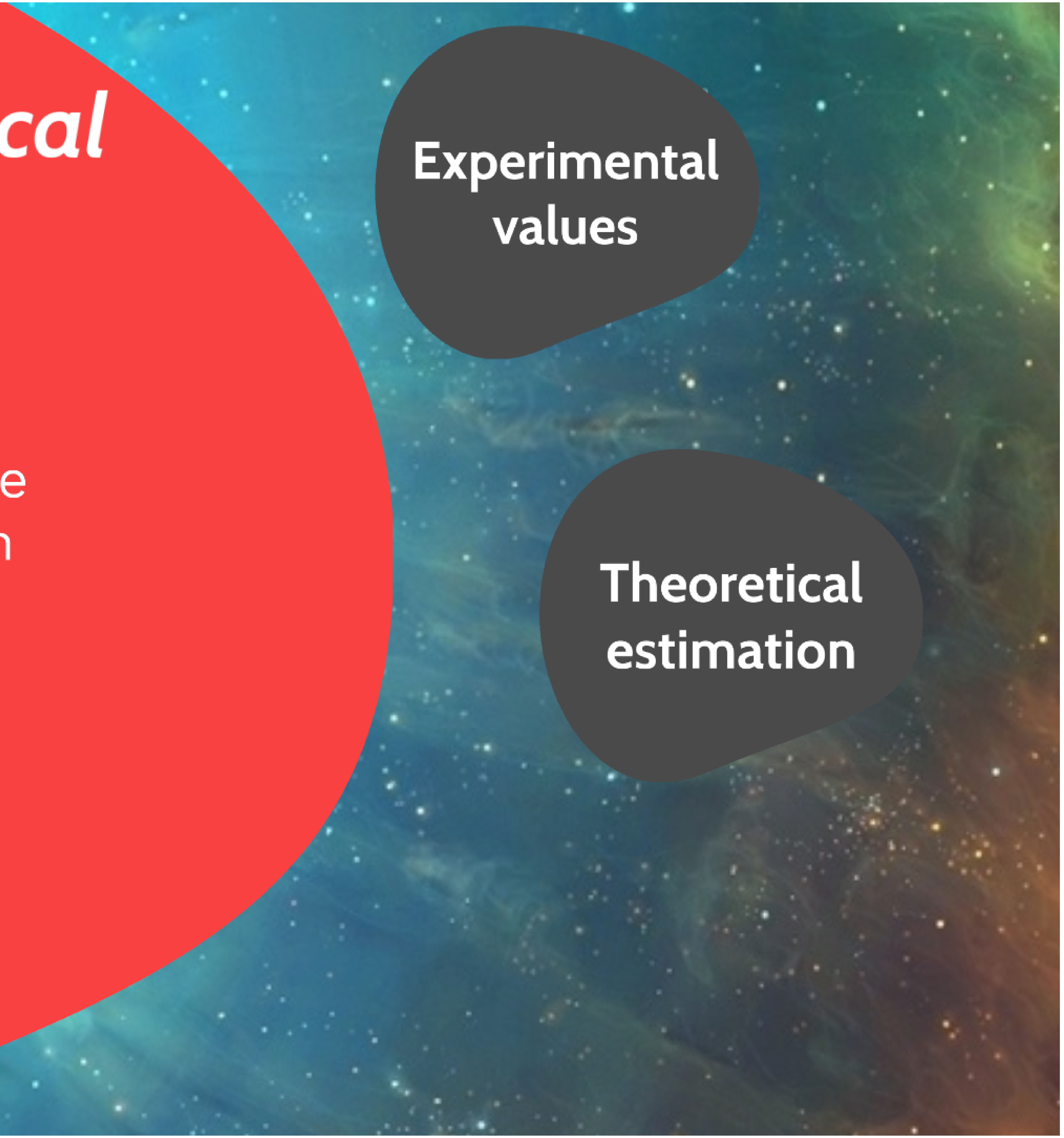
Potential explanations:

- Total baryon number was always non zero
- Some initial phenomena broke the symmetry

The standard cosmological model isn't enough to describe baryogenesis:

The baryon number density can be defined as the difference between baryonic matter and anti-matter densities: $n_B = n_b - n_{\overline{b}}$

With this in mind, we attempt to calculate using the standard cosmological model the asymmetry parameter: $\eta = \frac{n_B}{n_\gamma}$



Experimental values

Theoretical estimation

Experimental values using CMB observations and BBN abundances:

- The BBN experimental values, give us an asymmetry parameter of:
  $5.92 \text{ x } 10^{-10} \pm 0.56 \leq \eta \leq 6.28 \text{ x } 10^{-10} \pm 0.35$
- While Wilkinson Microwave Anisotropy Probe, gives us:
  $\eta = (6.14 \pm 0.25) \text{x} 10^{-10}$

$$n_\gamma \approx 415(\frac{T_0}{2.735})^3(cm^{-3})$$

$$n_B = 1.1 \text{ X } 10^{-5} h^2 \Omega_B (cm^{-3})$$

$$\eta = 2.65 \times 10^{-8} h^2 \Omega_B (\frac{T_0}{2.735})^{-3}$$

We can calculate a theoretical value for the asymmetry parameter, using the following expression:

$$\frac{n_b}{n_\gamma} = (\frac{m_p}{T})^{3/2} e^{\frac{-m_p}{T}} \qquad \frac{n_b}{n_\gamma} \approx 10^{-18}$$

for temperatures bellow 1(GeV).More or less the mass of a proton. We can clearly see that this value is orders of magnitude lower than the experimental values by BBN and CMB.

In 1967, a set of necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates was proposed by Andrei Sakharov:

- Baryon number violation
- C and CP violation
- Loss of thermal equilibrium

C and CP violation

Loss of thermal equilibrium

CP violation

CP symmetry is merely a combination of C symmetry with that of parity symmetry, it states that the laws of physics should be the same if a particle is interchanged with its antiparticle (C symmetry) while its spatial coordinates are inverted (P symmetry).

Loss of thermal equilibrium entails that for some reaction (decays for example), the rate of this process occuring is the same as its inverse reaction

Details on CP violation:

We can imagine a set of reations:

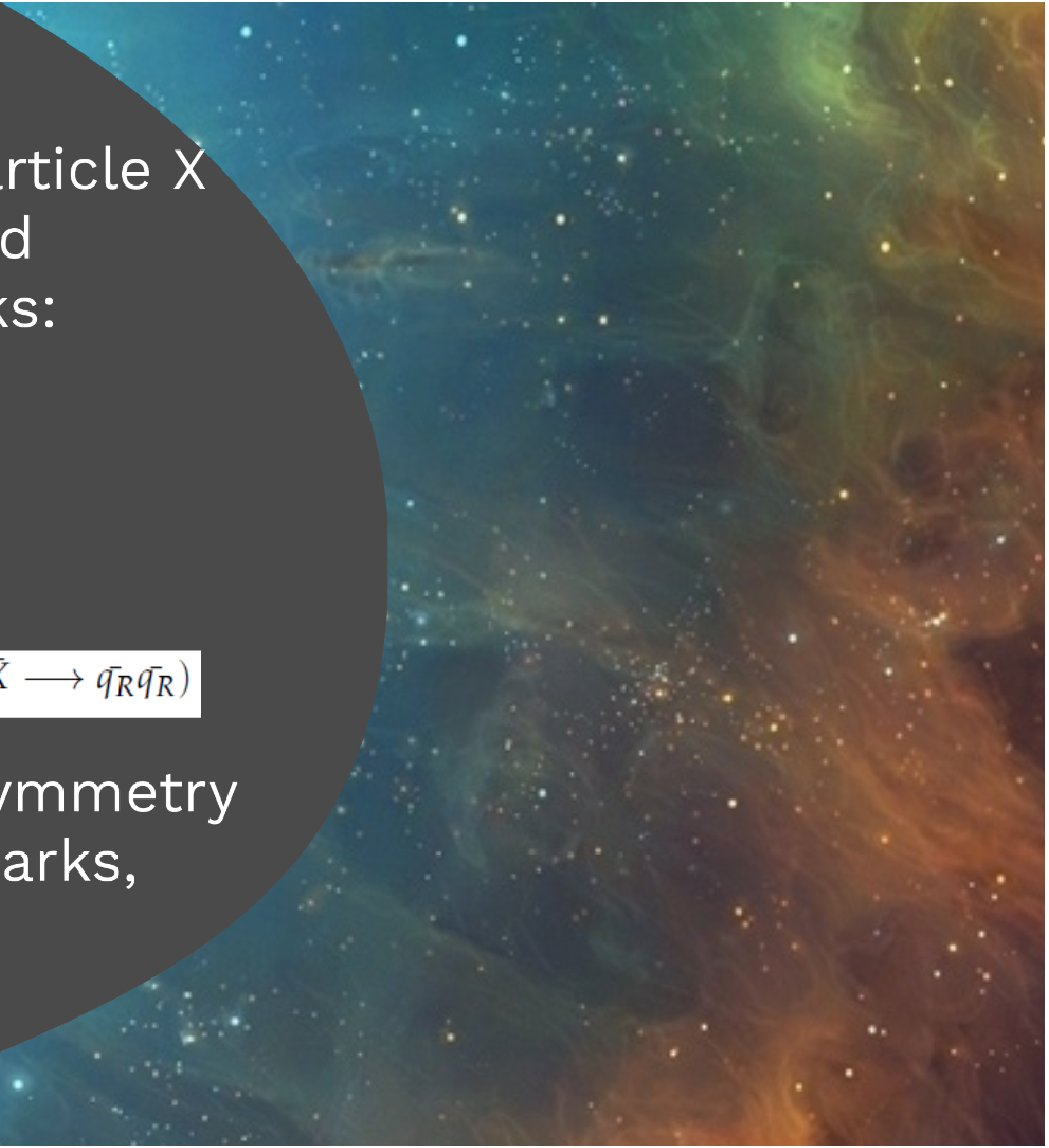
$$X \longrightarrow Y + B$$
$$\bar{X} \longrightarrow \bar{Y} + \bar{B}$$

with a net baryon production rate given by their diference of rate:

$$\frac{dB}{dt} \propto \Gamma(X \longrightarrow Y + B) - \Gamma(\bar{X} \longrightarrow \bar{Y} + \bar{B})$$

Obviously, if C were to be a symmetry, there would be no baryon production

Helicity



If CP was conserved and some particle X decays into either two left-handed quarks or two right-handed quarks:

$$\Gamma(X \longrightarrow q_R q_R) = \Gamma(\bar{X} \longrightarrow \bar{q_L}\bar{q_L})$$

$$\Gamma(X \longrightarrow q_L q_L) = \Gamma(\bar{X} \longrightarrow \bar{q_R}\bar{q_R})$$

It follows that:

$$\Gamma(X \longrightarrow q_R q_R) + \Gamma(X \longrightarrow q_L q_L) = \Gamma(\bar{X} \longrightarrow \bar{q_L}\bar{q_L}) + \Gamma(\bar{X} \longrightarrow \bar{q_R}\bar{q_R})$$

We see that we could have an asymmetry between left and right handed quarks, but not a baryon asymetry

The decay and inverse decay for plasma temperatures high enough, are the same.
When the plasma cools down with the expansion of the Universe, the inverse process will become more and more rare:

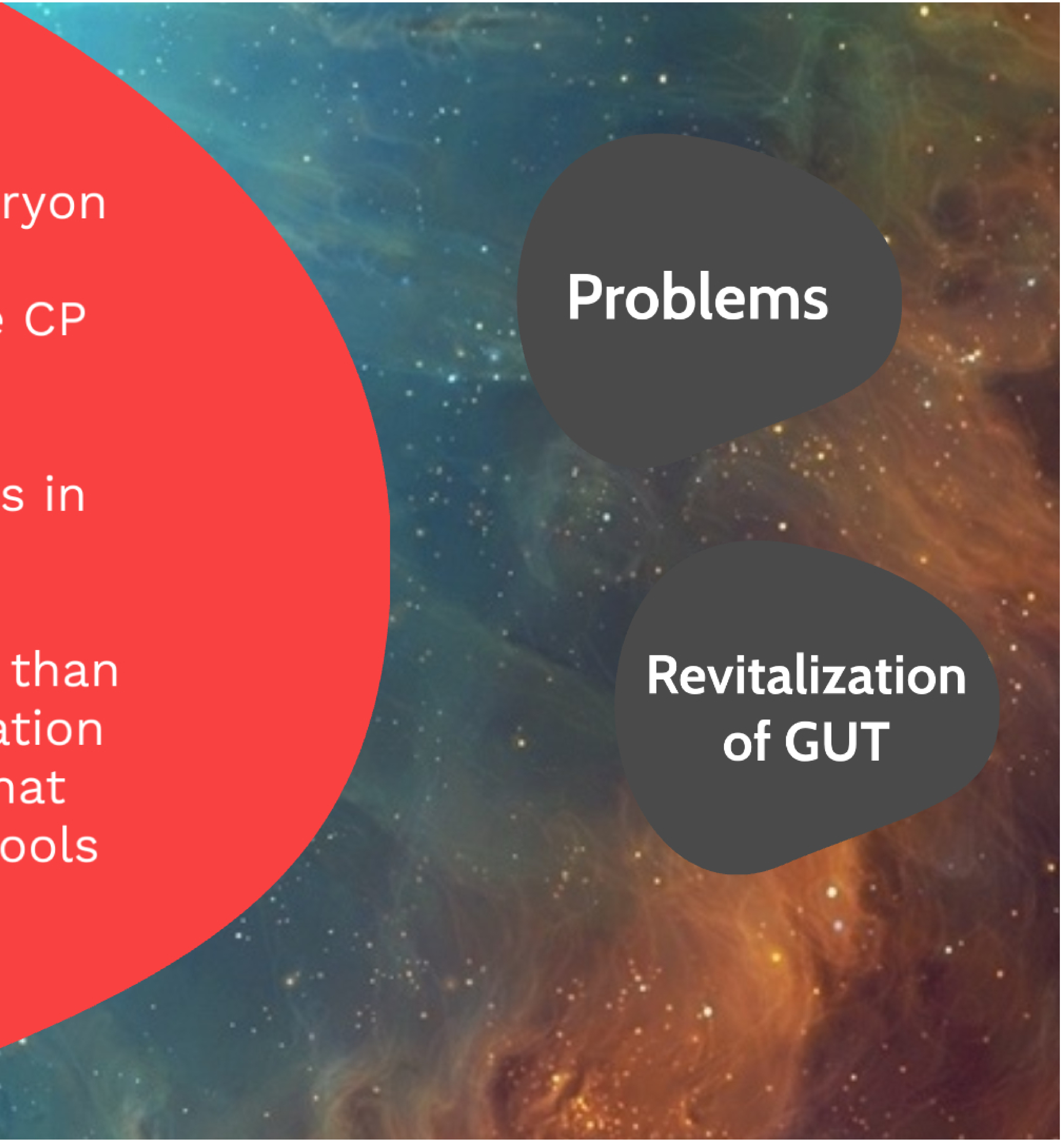
$$\Gamma_{inv}(t) \approx \Gamma(t) \times \begin{cases} 1, & T > M_X \\ (\frac{M_X}{T})^{\frac{3}{2}} e^{\frac{-M_X}{T}}, & T \leq M_X \end{cases}$$

A good way to understand the effectiveness of decays is through the following parameter:

$$K = \frac{\Gamma_X}{H}\Big|_{T=M_X}$$

In models of baryogenesis based on Grand Unified Theories (GUTs), the baryon asymmetry of
the universe is generated through the CP and baryon number violating, out-of-equilibrium decays
of very massive gauge or Higgs bosons in the very early universe.

All of this happens at energies higher than the energy threshold for grand unification (10^16 GeV) with group symmetry G that progressivly breaks, as the universe cools down to the SM gauge symmetry



Problems

Revitalization of GUT

Problems with this idea:

- We don’t really know if the universe ever reached temperatures higher than the treshold for grand unification
- The reason why plasma temperatures might not reach these energies, has to do with temperature fluctuations observed in the present day

$$\frac{\delta T}{T} \approx 10^{-5}$$

Reheating temperatures

Gravitino Relics

Assuming the simplest inflation potential: $V(\phi) = \frac{1}{2}M_{\phi}^{2}\phi^{2}$

We can obtain the temperature for Reheating:

$$T_{RH} \approx 10^{15}\sqrt{\alpha_{\phi}}(GeV)$$

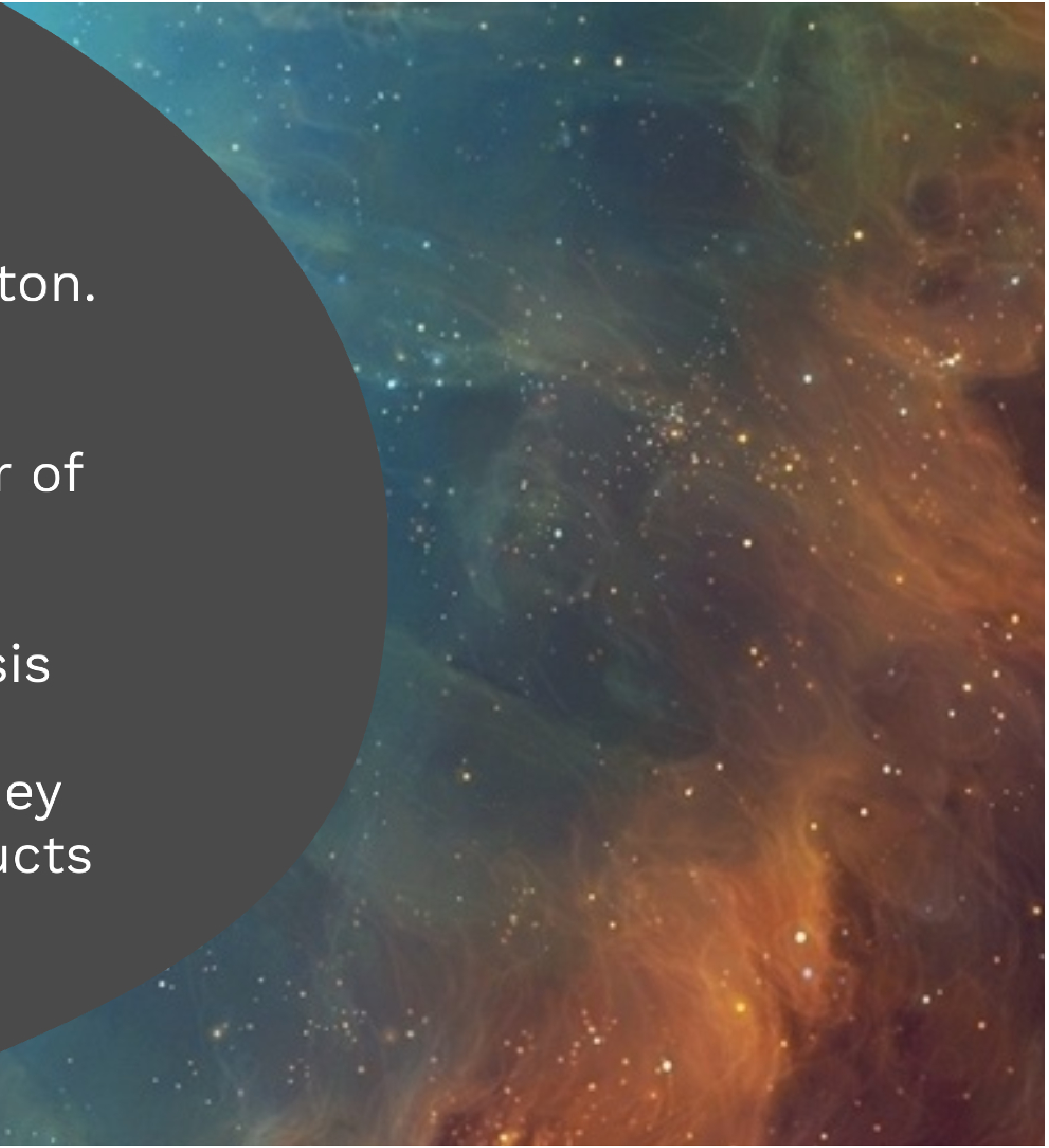
In order to recreate the temperature anisotropies seen in the microwave background, it follows that:

$$M_{\phi} \sim 10^{13}\ \mathrm{GeV} \qquad \alpha_{\phi} \ll 1$$

And so the reheating phase temperature is predicted to be orders of magnitude lower than the required by GUT

Another problem related to GUT baryogenesis is the existence of gravitino relics, gravitino being the fermionic superpartner of the graviton.

It turns out that if the treshold temperature was of the same order of magnitude as the reheating temperature, gravitos would be abundant during the nucleosynthesis epoch.
This would be problematic since they decay in this epoch and their products annihalate helium and deuterium nuclei through photodissociation.



Instabilities

Even though GUT baryogenesis has all this problems, new compelling theories are emerging with emphasis on the preheating phase of inflation

During the preheating phase, particles can be produced in the regime of a broad parametric resonance with the inflation field

Two types of parametric resonance can occur:

- Broad parametric ressonance
- Narrow parametric resonance

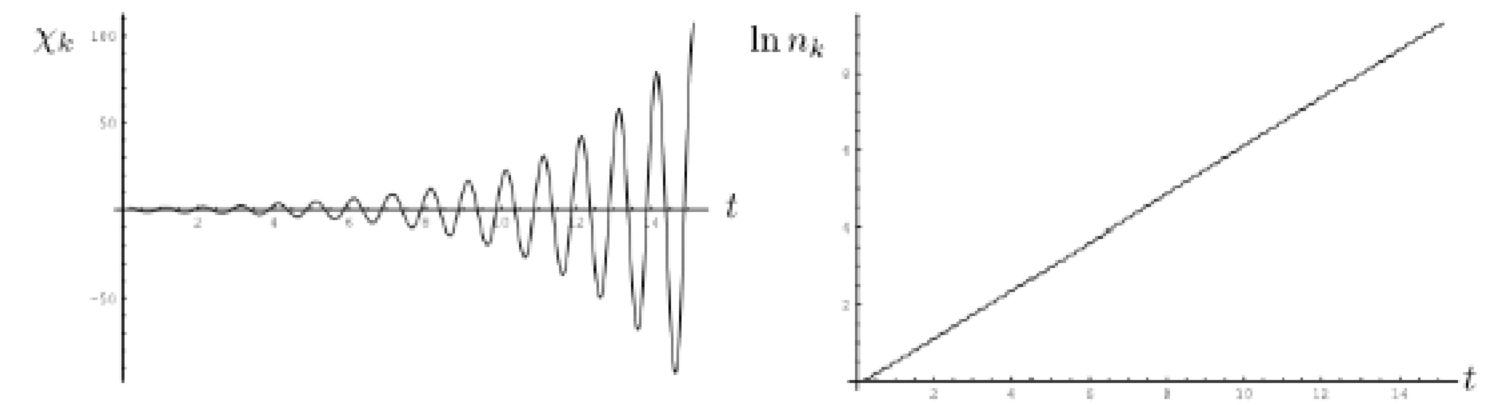


Figure 1. Narrow parametric resonance for the momentum K, here time is in units of $\frac{m}{2\pi}$, which is equivalent to the number of oscillations of the inflaton field ϕ.We can see that for each oscillation of ϕ the mode k of field X also oscillates one time.In right figure we have the ocupation number for mode k with respect to time.In these solutions, the value of q was set to $q = 0.1$ and $m = k$ [4]

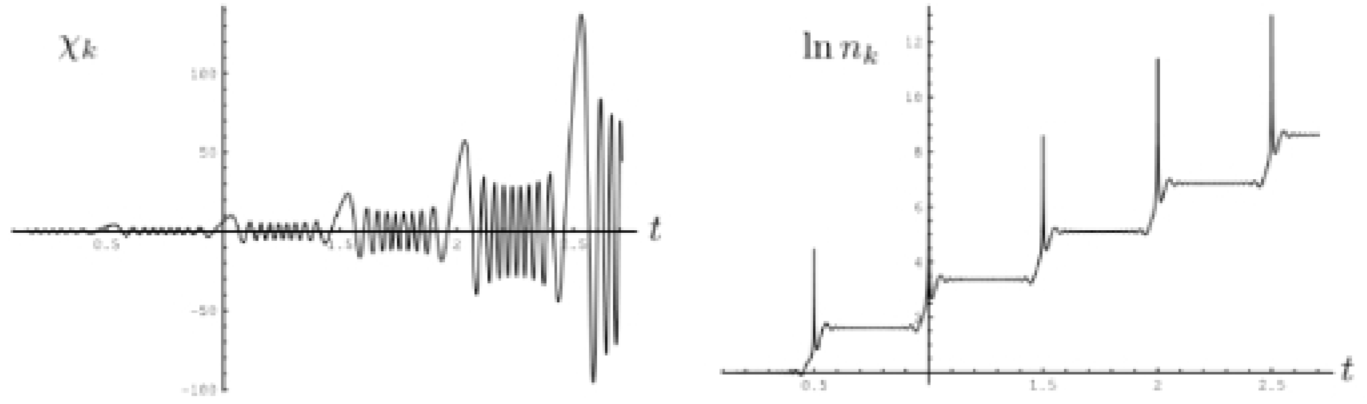


Figure 2. Broad parametric resonance for the momentum k, here we can see that the field X oscilates may times for each ϕ oscillation.the value of q here was set to $q = 200$ and $m = k$ [4]

The occupation number of bosons can be estimated, using Mathieu's differential equation

$$\ddot{X}_k = [A_k - 2q\cos(2mt)]X_k$$

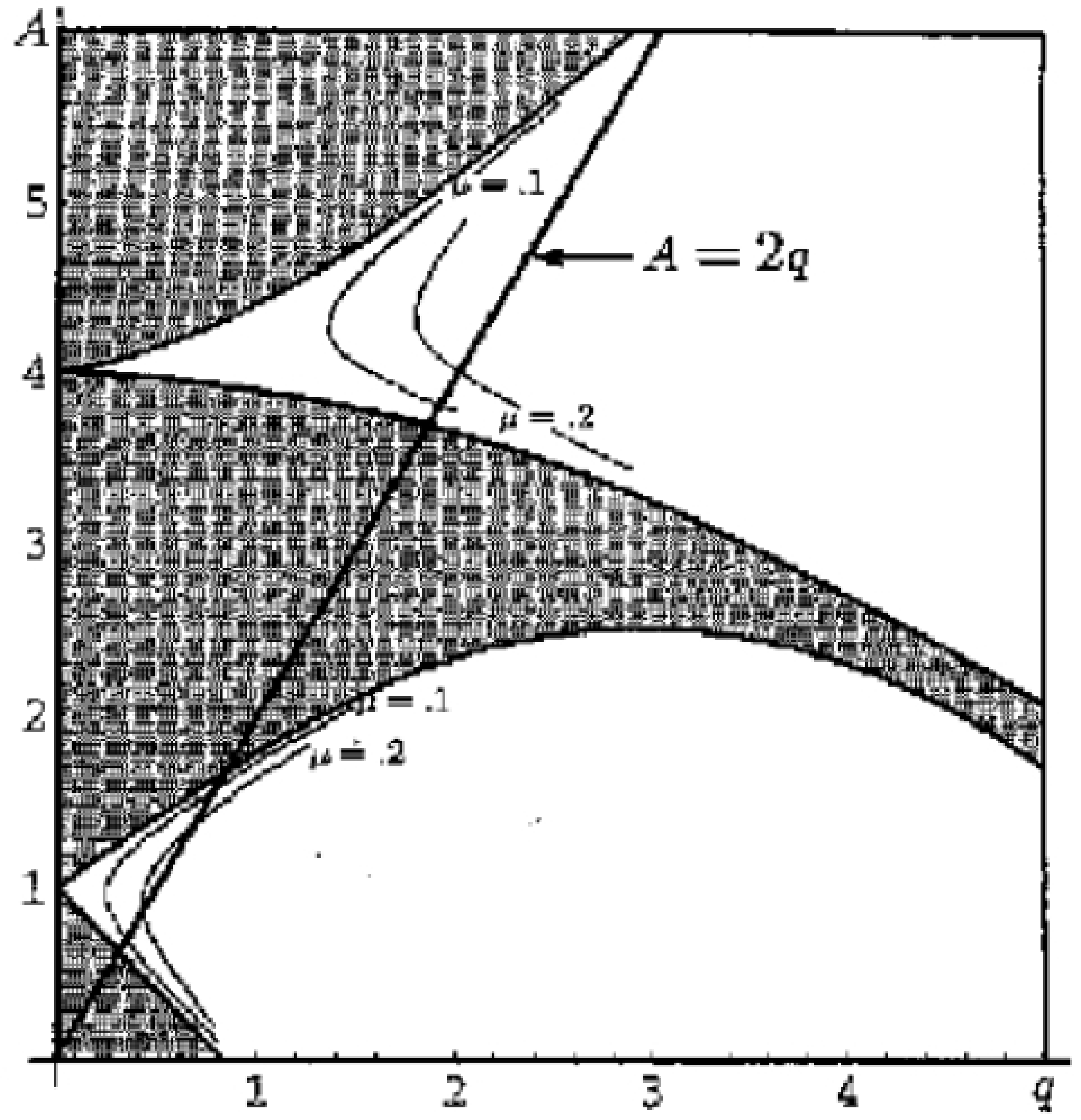
$$A_k = \frac{k^2}{m^2} + 2q$$

$$q = \frac{g^2\Phi^2}{4m^2}$$

With the following solution: $n_k \approx e^{2\mu_k m_k t}$

Only for certain conditions we have particle production:

$$\begin{cases} \mu_k(q) = 0, & |X_k| \quad \text{is stable} \\ \mu_k(q) > 0, & |X_k| \quad \text{is unstable, and grows exponentially} \end{cases}$$



Electroweak baryogenesis

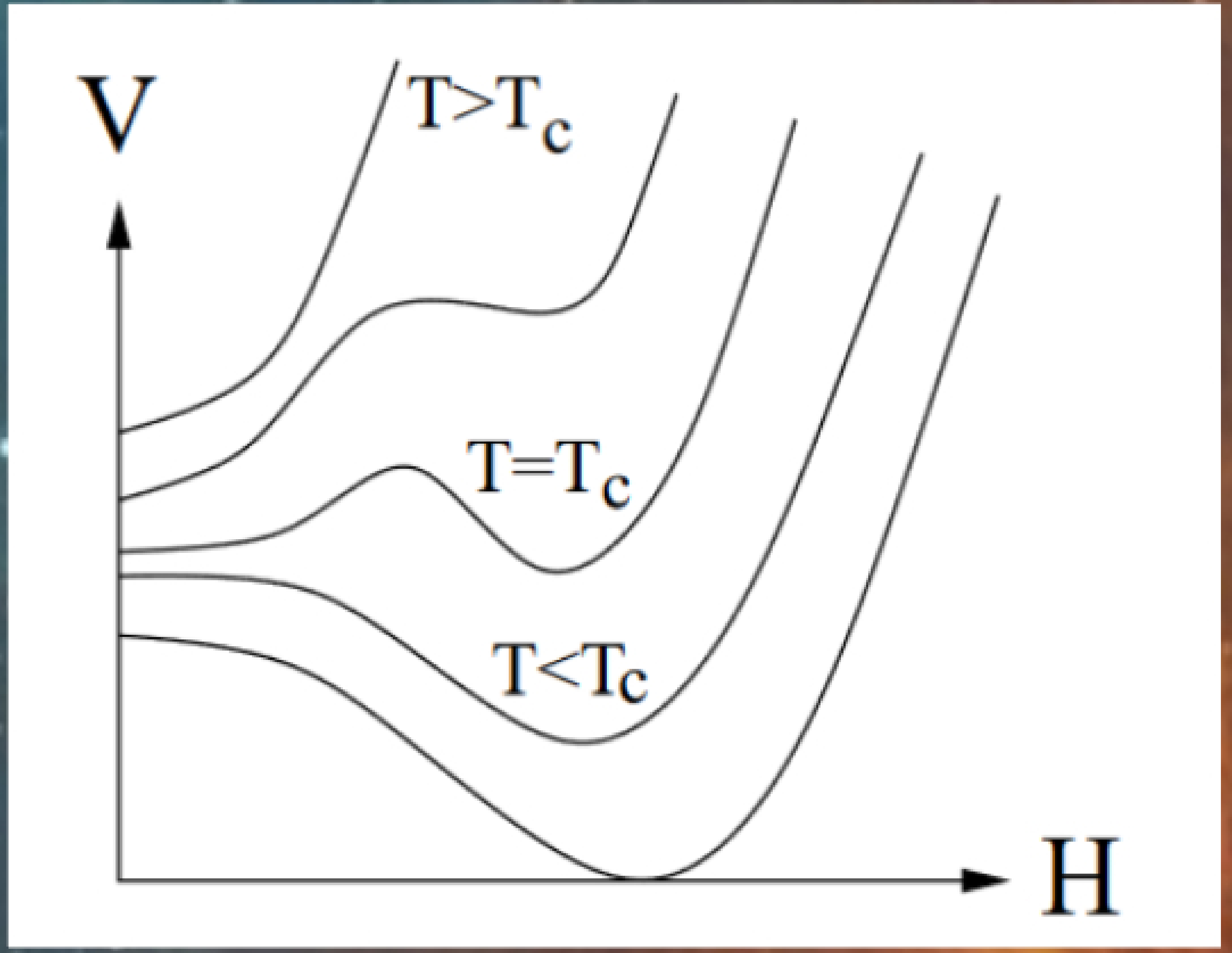
- Conditions for EWBG to manifest are a hot, radiation-dominated early universe containing zero net baryon charge with full electroweak symmetry manifested
- The main ideia behind EWGB, is to produce asymmetries in the density of baryons during the electroweak phase transition

The Higgs field

Bubbles

The SM model

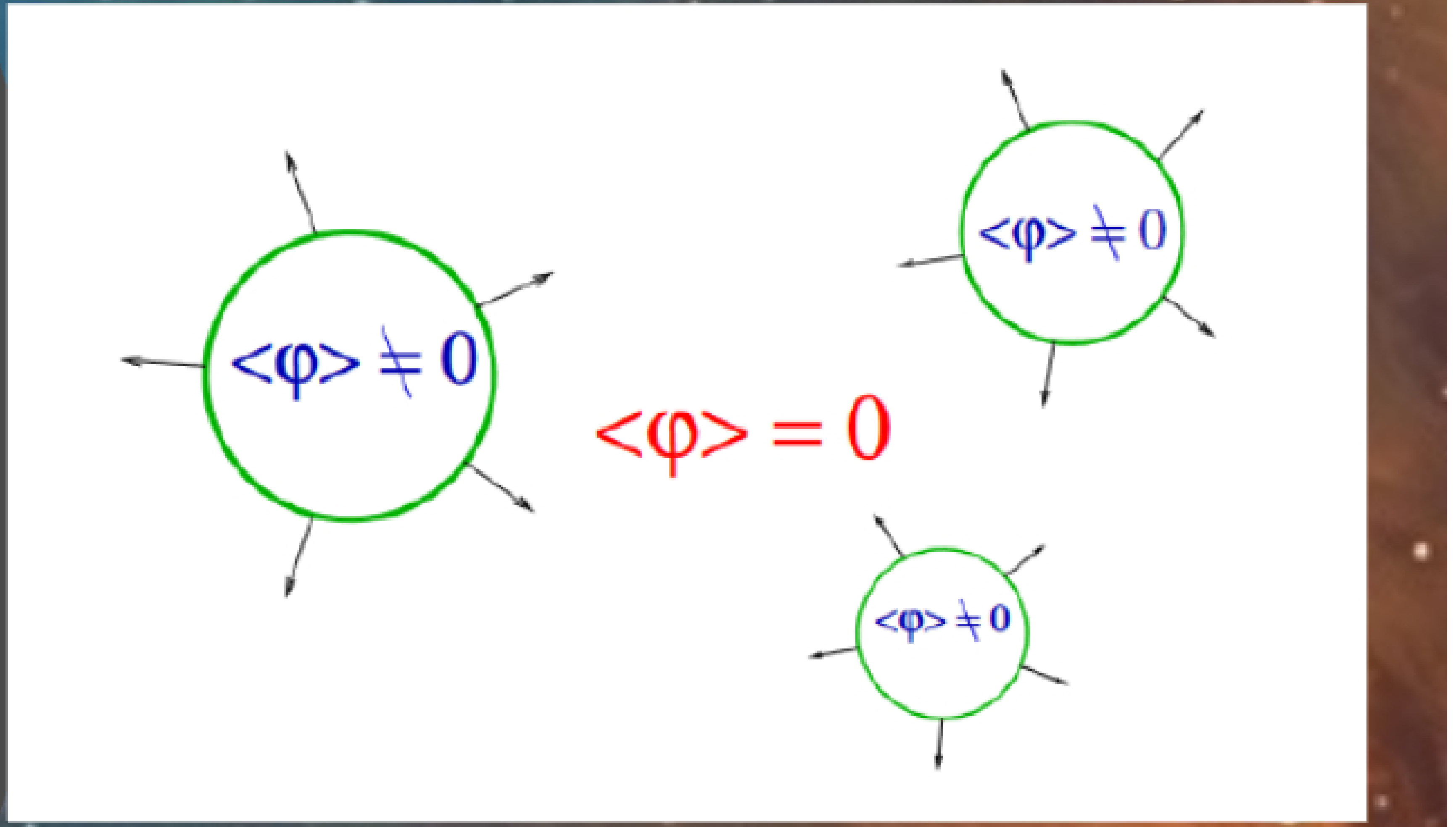
- A Sucessful EWBG requires a first-order electroweak phase transition
- The Higgs potential develops a bump that separates the symmetric and broken phases of the transition when the universe cools down to temperatures below the electroweak scale (T ≤ 100)GeV



At critical temperature, bubbles form and sepparate the broken phase from the unbroken phase

Baryon creation in EWBG, where departure from thermal equilibrium occurs, takes place in the vicinity of the expanding bubble walls

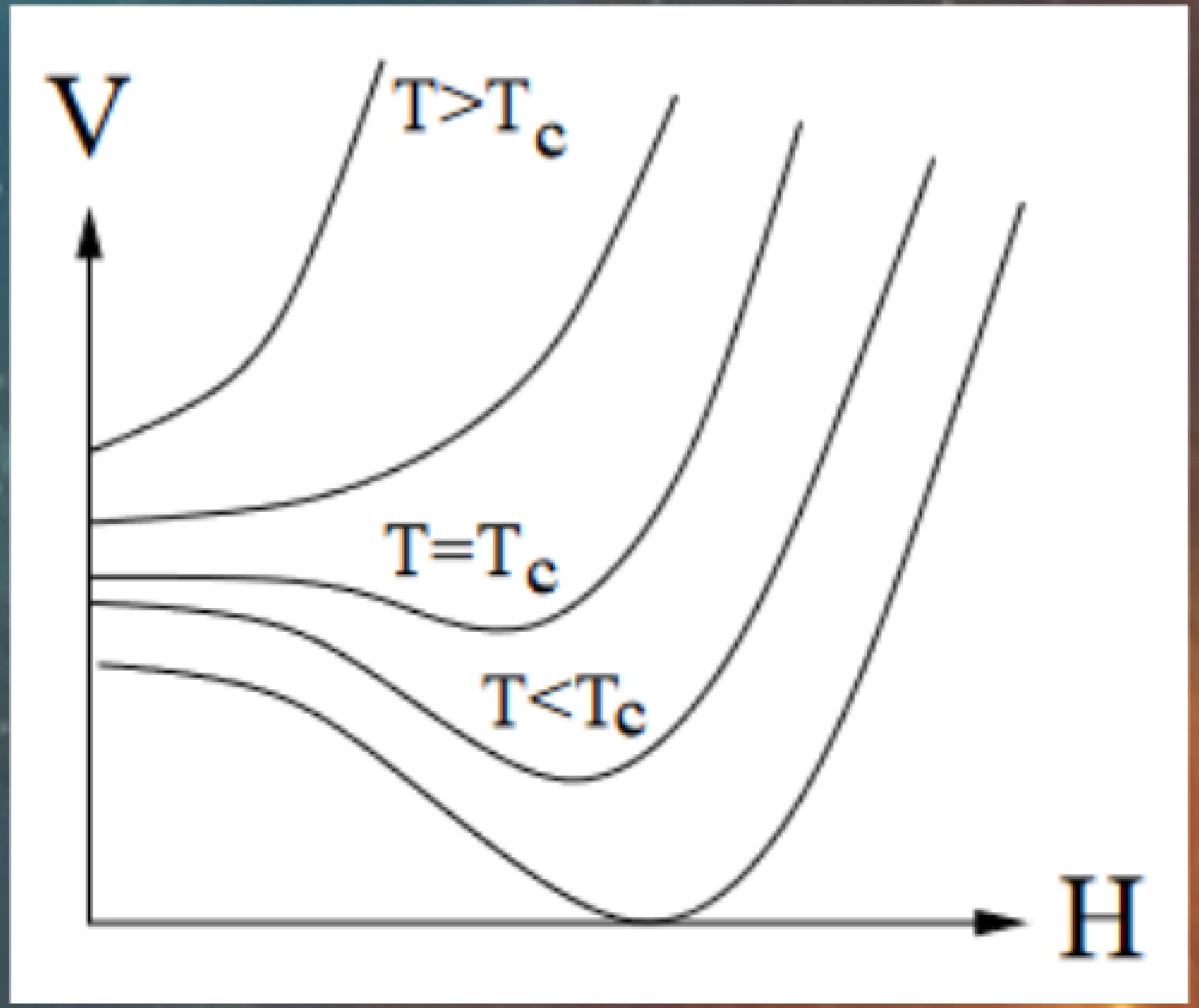
These bubbles will eventually expand and collide until only the broken phase remains



The standard model has all the necessary conditions for EWBG to occur, except that the Higgs mass for SM electroweak transitions is lower than the experimental value

This implies that there would be no first order transition and broken symmetry bubbles wont form

So in order for EWBG to work, we need physics beyond the SM



Conclusion:

- With the Standard model for weak interactions failing to provide an explanation for observed baryon asymmetry we can expect new physics corroborated by experiments to detect super heavy particles

- Thank you!