The QCD Phase Transition in the Early Universe

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Introduction

From the microwave background radiation and the light element abundances from big bang nucleosynthesis one knows that the **ratio of baryon to photon number is tiny**: $n_B/s \sim n_B/n_\gamma \sim \mu_B/T \sim 10^{-9}$.

In standard cosmology, one concludes that the early universe evolves along $\mu_B \sim 0$. Thus, the early universe would cross the QCD phase transition where one expects a **crossover transition** from lattice gauge calculations.

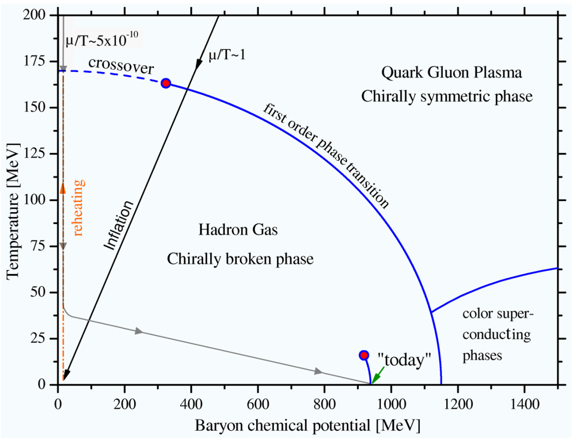

Fig. 1: Evolution through the QCD phase diagram in the **standard cosmological scenario**: The universe passes through the crossover region of the QCD phase diagram at $\mu/T \sim 0$. Evolution through the QCD phase diagram for the **little inflation scenario**: The universe is trapped in a metastable vacuum at the first order phase transition line, supercools and is reheated back close to the critical temperature.

Little Inflation at Phase Transition

What would happen if the early universe passes through a **first order QCD phase transition**?

A first order phase transition allows for a false metastable vacuum state where the universe could be trapped for some time → **Inflationary Phase**.

The baryon to photon ratios before and after the inflationary period should scale with the ratio of the scale parameters cubed as entropy is produced during reheating while baryon number is conserved so that

$$\left(\frac{\mu_B}{T}\right)_f \approx \left(\frac{a_i}{a_f}\right)^3 \left(\frac{\mu_B}{T}\right)_i \quad .$$

The final ratio should be 10^{-9} as observed. So we need just a boost of $N = \ln(a_f/a_i) \sim \ln(10^3) \sim 7$, i.e. seven e-folds, to get an initial ratio of $(\mu_B/T)_i \sim \mathcal{O}(1)$.

Our scenario [1] is as follows:

- The early universe is at large baryochemical potentials $\mu_B/T \gtrsim 1$ initially.
- The early universe reaches the first order phase transition line of QCD at high baryochemical potentials and is trapped in the false vacuum.

  The inflationary period starts with supercooling and dilution with $\mu_B/T = \text{const.}$
- The decay to the true vacuum state will release latent heat, so that the universe is reheated to $T \sim T_c$.

  Due to the entropy produced during the transition the final baryon to photon ratio is given by $\mu_B/T \sim 10^{-9}$.
- Finally, the universe evolves along the standard cosmological path.

The path through the QCD phase diagram for the little inflation scenario is depicted in Fig. 1.

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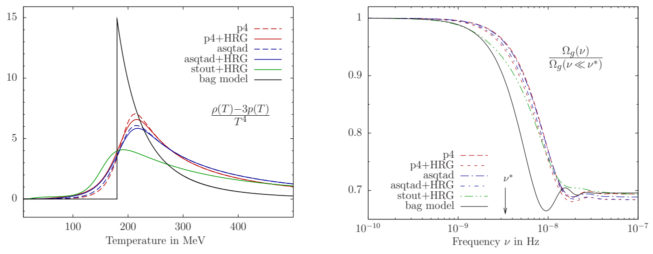

Fig. 2: The energy spectrum of gravitational waves after the QCD phase transition (right) depends on the trace anomaly (left) as determined by lattice data (see also ref. [4]).

Cosmological Implications

There are **observable differences** between the Little Inflation scenario and the standard model of cosmology [1, 7].

Large Scale Structures

- Density and pressure perturbations depend on the energy density, pressure and speed of sound during inflation.

→ The little inflationary epoch **modifies the large-scale structure power spectrum** responsible for galaxy formation **up to the typical mass scale of globular clusters** ($\sim 10^6 M_\odot$) [1].

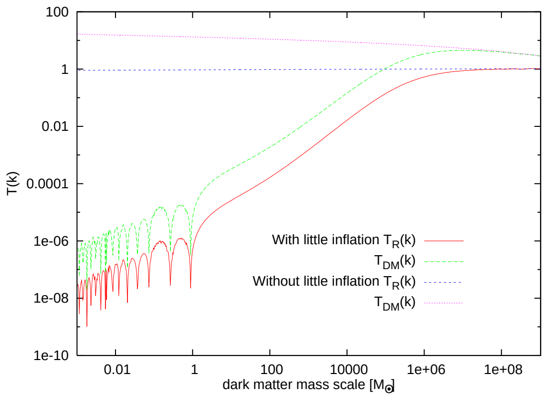

Fig. 3: The spectrum of primordial fluctuations in terms of the transfer function shown versus the length scale given by the enclosed dark matter mass.

Potential Barrier and Nucleation

- An important issue of this approach is the **stability of the barrier** between the quark and hadron phase up to very low temperatures $T \to 0$.

This is indeed the case in chiral models of QCD including gluonic degrees of freedom in the form of a dilaton field [2].

We use the model of Ref. [3] for different bag constants.

→ The **surface tension** needed for nucleation to fail, so that the nucleation time scale exceeds the expansion time, is $\mathbf{124\,MeV/fm^2}$ [1].

Refs. [5] give possible ranges of $\sigma = 50 - 150\,\text{MeV/fm}^2$ and even up to $300\,\text{MeV/fm}^2$ at very high densities.

- After some supercooling inflation comes to an end and the phase transition to the true minimum occurs.

This could either take place due to a strong drop in the surface tension or even due to a complete vanishing of the barrier between the two phases in the effective potential (**spinodal decomposition**).

Strong sensitivities of nucleation rates on the surface tension have been also found for high-density matter as encountered in the interior of neutron stars or in core-collapse supernovae [6].

Gravitational waves

- Even for standard cosmology the gravitational spectrum will have a step due to the QCD crossover transition [4], see Fig. 2.
- Due to the inflationary period **primordial gravitational** waves are **highly suppressed** [7].
- During a first order transition, **bubble collisions** and **turbulences** are a **source of gravitational radiation** [8].

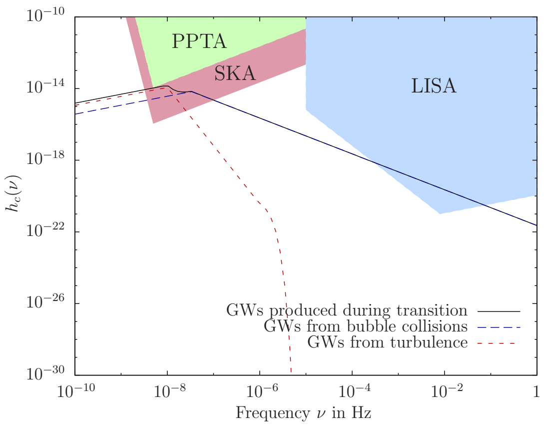

Fig. 4: The gravitational wave spectrum from a first order QCD phase transition is **observable with pulsar timing**. The Parkes Pulsar Timing Array PPTA gives limits on the maximum amplitude. The Square Kilometre Array SKA will push these limits down by a few orders of magnitude. For a flat spectrum at high frequencies, LISA would be also sensitive. From Refs. [7, 1], see also [8].

(Extra)Galactic Magnetic Fields

- **Seeds of (extra)galactic magnetic fields** can be generated by **charged bubble collisions** during the phase transition.

→ A first order QCD phase transition in the early universe would provide a possible explanation of those cosmological magnetic fields [9].

Dark Matter

- The cold dark matter density is diluted by the same factor as the baryon number density, i.e. by up to a factor 10^{-9}.

→ One needs a **lower WIMP annihilation cross section** to explain the present cold dark matter relic density. That can be probed at the LHC. [1]

Summary and Outlook

The QCD phase transition can be probed by cosmological observations: by the gravitational wave background, by large-scale structure formation, and even by dark matter properties. The scenario needs to be treated in a field theoretical approach incorporating chiral symmetry and the Polyakov loop. The cosmological signals depend on

- Potential barrier → inflation, nucleation timescales
- Equation of state, speed of sound → structure formation
- Trace anomaly → gravitational wave spectrum

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