Lepton asymmetry and the cosmic QCD transition

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Outline

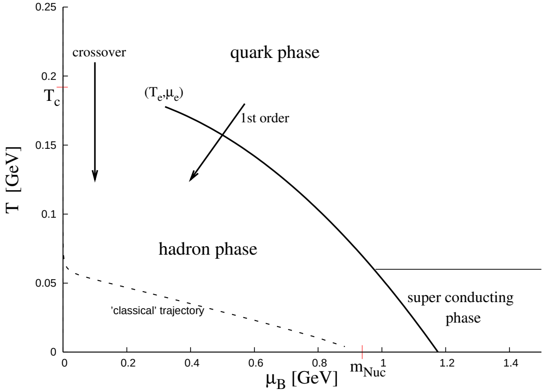
The goal of this work is to describe the cosmic trajectory in QCD phase diagrams.

The cosmic QCD transition – quarks confine to hadrons :

- Starting condition for BBN.
- Possible generation of relics like QCD dark matter (quark nuggets, . . .), modification of gravitational waves, . . .
- Crossover or 1st order? Knowing the order would rule out many scenarios.

QCD transition so far

So far most reliable description via lattice simulation with three quarks at almost physical masses and vanishing chemical potential.



Is there an effect of leptons at the Cosmic QCD phase transition?

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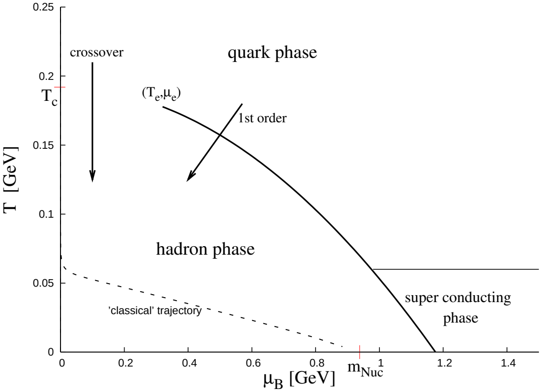

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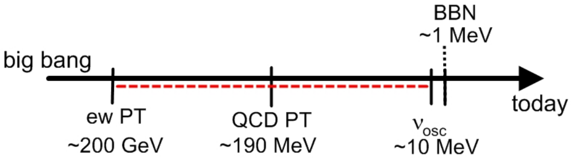
Particles around the cosmic QCD transition



Lifting global conservation laws to local ones:

$$l_f = \frac{n_f + n_{\nu_f}}{s} \qquad \text{with } f = e,\ \mu,\ \tau,$$
$$b = \sum_i \frac{b_i n_i}{s} \qquad \text{with } b_i = \text{baryon number of species } i,$$
$$0 = \sum_i q_i n_i \qquad \text{with } q_i = \text{charge of species } i,$$

with $n_i = \frac{g_i}{2\pi} \int_{m_i}^{\infty} E\sqrt{E^2 - {m_i}^2} \left(\frac{1}{\exp(\frac{E-\mu_i}{T}) \pm 1} - \frac{1}{\exp(\frac{E+\mu_i}{T}) \pm 1} \right) dE$,
and $s = s(T)$ the entropy density.

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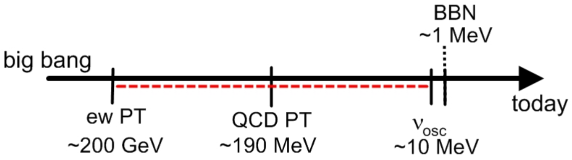

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Cosmic (SM) particle fluid in chemical quilibrium for
$T_{ew} > T > T_{\nu_{osc}}$:

- charge conservation and neutrality $q = 0$. Siegel & Frye, 2007
- baryon number conservation, $b = (8.85 \pm 0.24) \times 10^{-11}$.

Komatsu *et al.* WMAP Coll., 2009

- lepton flavour number conservation, $l_f = ???$

$\rightarrow$ experimental: $|l_f| \leq 0.02$ Simha & Steigmann; Popa & Vasile, 2008

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Chemical potentials

Each conserved quantum number associated with a chemical potential. The particle contribution to the free energy:

$$\mu_Q n_Q + \mu_B n_B + \sum_f \mu_{L_f} n_{L_f} \stackrel{T>T_{\rm QCD}}{=} \sum_q \mu_q n_q + \sum_l \mu_l n_l + \sum_g \mu_g n_g$$

$$\stackrel{T<T_{\rm QCD}}{=} \sum_b \mu_b n_b + \sum_m \mu_m n_m + \sum_l \mu_l n_l,$$

Comparison of coefficients leads to:

$$\mu_B(T > T_{\rm QCD}) = \mu_u + 2\mu_d, \qquad \mu_B(T < T_{QCD}) = \mu_n,$$
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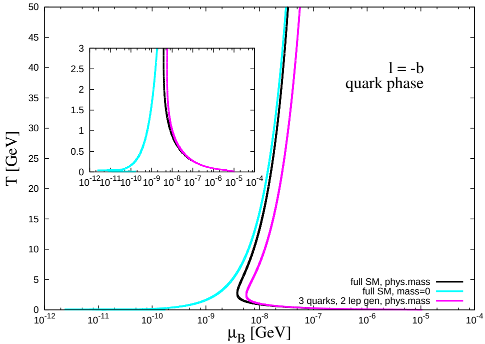
$\mu_{L_f}(T > T_{\rm QCD}) = \mu_{\nu_f}$ $\mu_{L_f}(T < T_{QCD}) = \mu_{\nu_f}.$

Analytical approaches for $T \gg T_{QCD}$ incl. u,d,c,s-quarks and e,μ,τ, all massless leads to:

$$\mu_B(T \gg T_{\rm QCD}) = \left(\frac{39}{4}b - l\right)\frac{s(T)}{8T^2}.$$

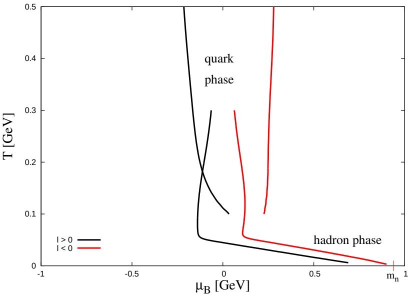
$$\Longrightarrow \mu_B = \mu_B(b,l), \text{ for } b \ll l \Rightarrow \mathcal{O}(\mu_B) = \mathcal{O}(l).$$

Small T: $\mu_B(T < m_\pi/3) \approx m - T\ln\left[\frac{c(T)}{2bs(T)}\right]$ independent of l.

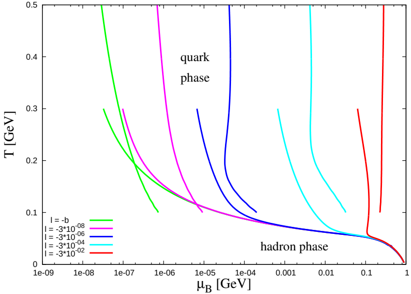


Comparison of some high temperature approaches with the numerics in the quark gluon phase.

Trajectories of the baryochemical potential μ_B

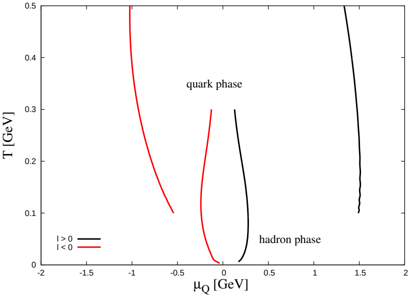


The sign dependence of the trajectory.



Evolution of the baryochemical potential for negative lepton asymmetries.

Trajectories of the charge chemical potential μ_Q



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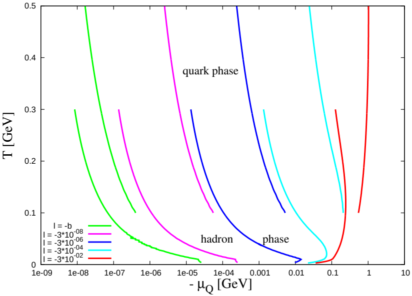

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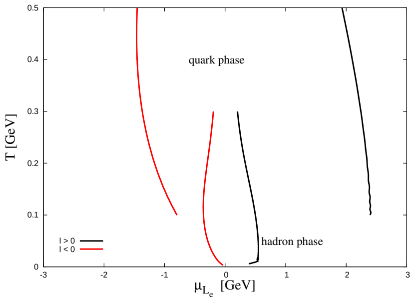
Trajectories of the leptochemical potential μ_{L_e}



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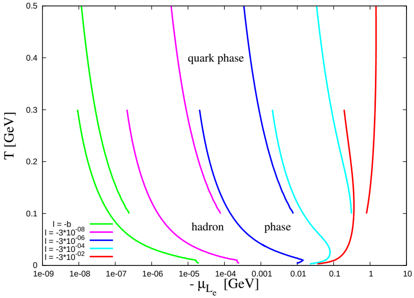

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Conclusions

- $I \neq 0 \Rightarrow \mu_b = \mu_b(b, I, T)$.
- $b \ll |I| \leq 0.01$ can significantly influence dynamics of the QCD phase transition and maybe even the order of the transition in the $\mu_B - T$-plane.

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