Particle asymmetries in the early universe

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based on arXiv:0906.3434 (hep-ph)

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Outline

The goal of this work is to describe evolution of the SM particles in the early universe between the
electroweak transition ($T_{ew} \simeq 200$GeV, $t_H \simeq 10$ ps, $r_H \simeq 10$ mm) and the neutrino oscillation at ($T_{osc} \simeq 10$ MeV, $t_H \simeq 1$ s, $r_H \simeq 10^5$ km).

Influence of large neutrino asymmetries on the QCD transition and (briefly) on WIMPs.

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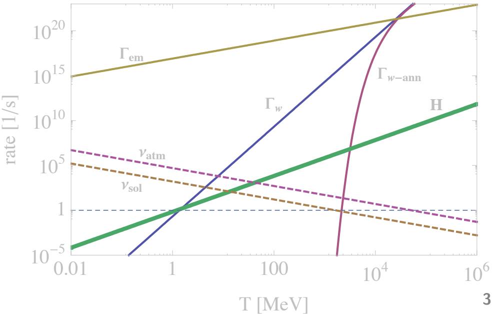
- Hubble time $t_H = 1/H$ is the scale of interest.
- All interaction rates larger for $T \geq$ few MeV.
- Thermal and chemical equilibrium excellent approximation.



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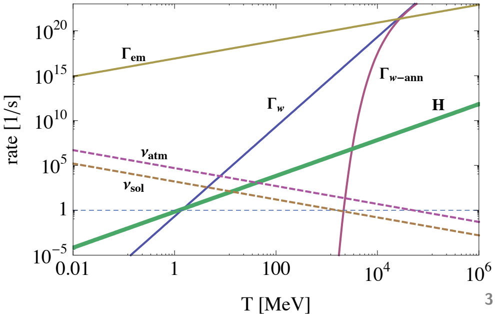

Thermodynamics in a FLRW- universe

Net particle density for a species i:

$$n_i = \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} E(E^2-m^2)^{1/2}\left(f(i)-f(\bar{i})\right)\mathrm{dE}$$
$$= \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} E\sqrt{E^2-{m_i}^2}\left(\frac{1}{\exp\frac{\mathrm{E}-\mu_\mathrm{i}}{\mathrm{T}}\pm 1}-\frac{1}{\exp\frac{\mathrm{E}+\mu_\mathrm{i}}{\mathrm{T}}\pm 1}\right)dE$$

Energy density:

$$\epsilon_i = \frac{g_i}{2\pi^2}\int_{m_i}^{\infty} E^2\sqrt{E^2-{m_i}^2}\left(\frac{1}{\exp\frac{\mathrm{E}-\mu_\mathrm{i}}{\mathrm{T}}\pm 1}+\frac{1}{\exp\frac{\mathrm{E}+\mu_\mathrm{i}}{\mathrm{T}}\pm 1}\right)dE$$

Effective (relativistic) degrees of freedom:

$$g_* = \frac{30}{\pi^2 T^4}\epsilon$$

Conserved quantum numbers

All particle interactions follow:

- 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, $l_f = ???$

Lepton flavour number???

For $T < T_{osc} \simeq 10 MeV$

experimental: $|l_f| \leq 0.02$, after T_{osc}. Simha & Steigmann; Popa & Vasile, 2008
theoretical: $b \ll |l_f|$ possible. Several leptogenesis models in which l may be larger than b.

Flanz et al., 1996; L.Covi & E.Roulet, 1996; Casas *et al.*, 1997; T.Hambye, 2002

We can assume $l_e = l_\mu = l_\tau$.
Different flavour asymmetries equilibrate through oscillations
A.D.Dolgov, 2002; Y.Y.Y.Wong, 2002

For $T > T_{osc}$

A scenario with single flavours much larger is possible.
For example $\sum_f l_f = b$ but $l_e \simeq b$ and $l_\mu = -l_\tau = \mathcal{O}(1)$.
Numerous theories can explain a large lepton flavour asymmetry with the observer small baryon asymmetry.

B.A.Campbell *et al.*, 1998; J.March-Russell *et al.*, 1999; J.McDonald, 2000

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Lifting global conservation laws to local ones:

$$l_f = \frac{n_f + n_{\nu_f}}{s}$$ with $f = e, \mu, \tau$,

$$b = \sum_i \frac{b_i n_i}{s}$$ with b_i =baryon number of species i,

$$0 = \sum_i q_i n_i$$ with q_i = charge of species i,

with $s = s(T)$: entropy density.

$\Longrightarrow$ Solvable system of equations for net particle densities $n_i(T, \mu_i)$ in the QP and the HG.

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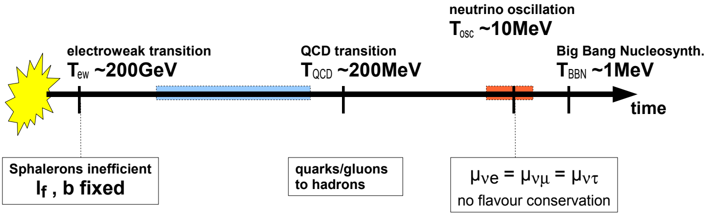
Cosmology



Freeze out: 40 GeV < T_f < 0,4 GeV of a WIMP 1TeV < m_χ < 10 GeV

Kinetic decoupling of a WIMP

The QCD transition

- The SM predicts a spontaneous breaking of chiral symmetry of QCD $\Rightarrow$ Phase transition at a certain temperature T_c where quarks confine to hadrons.
- One would like to have a phase diagram (like i.e. for water) to locate the different states of nuclear matter, spanned by T and the baryon chemical potential μ_B.
- Quantitative calculation of PD from 1st principles extraordinarily difficult – strongly innteraction / asymptotic freedom. Most reliable tool so far *Lattice Simulations*.

Overview: M.A.Stephanov, hep-lat/0701002, or O.Philipsen, arXiv:0808.0672.

The cosmic QCD

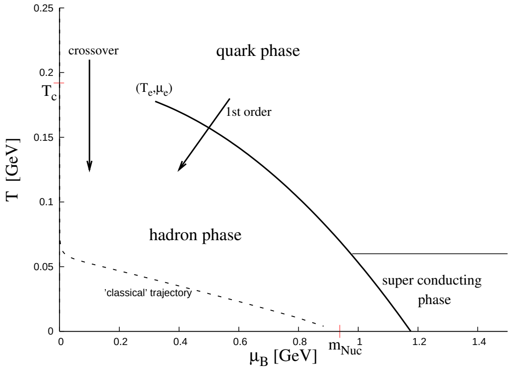
The universe underwent some phase transitions, one is the cosmic QCD transition – quarks confine to hadrons :

- Starting condition for BBN.
- Possible generation of relics observable today: quark nuggets, magnetic fields . . . D.J.Schwarz, 2003.
- Formation of CDM clumps. C.Schmid et al., 1997 & 1999.
- Modification of primordial background of gravitational waves. R.Durrer, 2010.
- A short inflationary phase (see talk of J.Schaffner-Bielich on Monday)

Crossover or 1st order? Knowing the order would rule out many scenarios.

QCD transition so far

So far most reliable description comes from a combination of lattice simulation, perturbative calculations and heavy ion collisions. All in the baryon sector.



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

Chemical potentials

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

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

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

Comparison of coefficients leads to:

$$\mu_B(T > T_{\mathrm{QCD}}) = \mu_u + 2\mu_d, \qquad \mu_B(T < T_{QCD}) = \mu_n,$$

$$\mu_Q(T > T_{\mathrm{QCD}}) = \mu_u - \mu_d, \qquad \mu_Q(T < T_{QCD}) = \mu_p - \mu_n,$$

$$\mu_{L_f}(T > T_{\mathrm{QCD}}) = \mu_{\nu_f} \qquad \mu_{L_f}(T < T_{QCD}) = \mu_{\nu_f}.$$

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Baryochemical potential

Analytical approaches for $T \gg T_{QCD}$ incl. u,d,c,s-quarks and e,μ,τ, all massless and $3l_f = \sum_f l_f$ leads to:

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

$T \gg m, \mu$

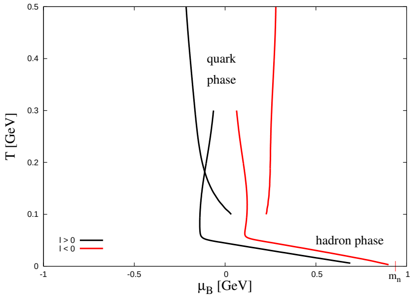
$$\mu_B = \mu_B(b, l)$$

$$b \ll l \Rightarrow \mathcal{O}(\mu_B) = \mathcal{O}(l)$$

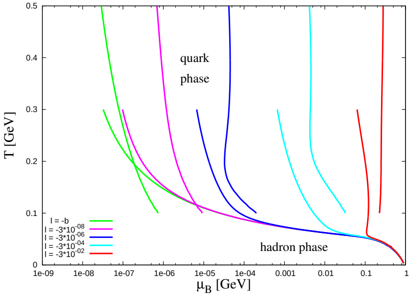
Small T: $\mu_B(T < m_\pi/3) \approx m - T \ln\left[\frac{c(T)}{2bs(T)}\right]$ independent of l.

Baryochemical potential

Trajectories of the baryochemical potential μ_B



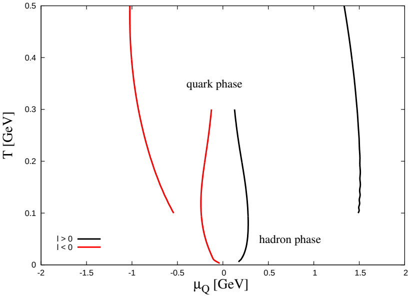
The sign dependence of the trajectory.



Evolution of the baryochemical potential for negative lepton asymmetries.

Charge Chemical potential

Trajectories of the charge chemical potential μ_Q



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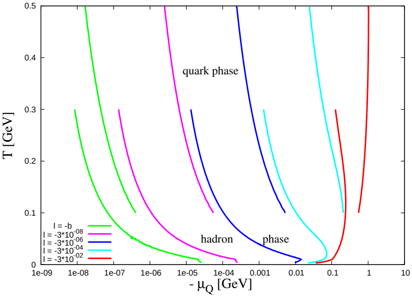

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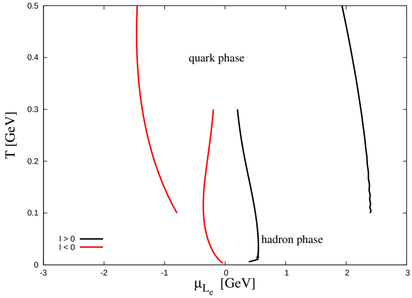
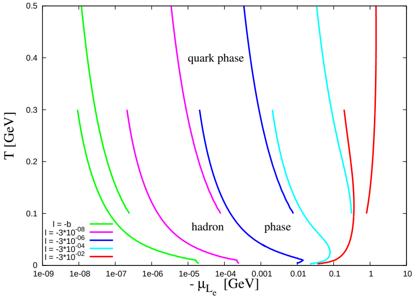
Trajectories of the leptochemical potential μ_{L_e}





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Evolution of the leptochemical potential for negative lepton asymmetries.

For the freeze out of the relic abundance of a WIMP

$$\mathrm{Y} \simeq \left(\frac{45}{\pi}\right)^{1/2} \frac{1}{\mathrm{m}_\chi \mathrm{M}_\mathrm{p} \langle\sigma|\mathrm{v}|\rangle_{\mathrm{T_f}}} \frac{\mathrm{x_f}}{\sqrt{\mathrm{g}_\epsilon}},$$

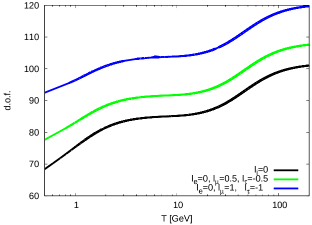
with $x_f \propto \ln(1/\mathrm{g}_\epsilon)$.

A.Green, S.Hofmann, D.J.Schwarz, 2005

$$g_\epsilon(T, \{\mu_i\}) \equiv \frac{30}{\pi^2 T^4} \epsilon(T, \{\mu_i\})$$

$$\overset{m=0}{=} \frac{15}{T^4 \pi^4} \sum_i g_i \int_0^\infty \frac{E^3}{\exp[\frac{\mathrm{E}-\mu}{\mathrm{T}}]+1} \mathrm{dE}$$

$$= \sum_F \frac{7}{4} g_F + \frac{15}{2} g_F \left(\frac{\mu_F}{\pi T}\right)^2 + \frac{15}{4} g_F \left(\frac{\mu_F}{\pi T}\right)^4 + \sum_B g_B$$



We see, that $\Delta g_\epsilon = \frac{15}{2} \sum_{i=\mathrm{ferm}} g_i \left[\left(\frac{\mu_i}{\pi T}\right)^2 + \frac{1}{2}\left(\frac{\mu_i}{\pi T}\right)^4\right]$ leads to an effect of order few percent in the d.o.f. and in the relic abundance of the one component WIMP dark matter.

Conclusions

- Large lepton asymmetries do have an impact on the evolution of the early universe.
- $b \ll |l| \leq 0.01$ can significantly influence dynamics of the QCD phase transition and maybe even the order of the transition in the $\mu_B - T$-plane.
- The cosmic QCD phase transition lives at least in 5 dimensions (l_f, b, $q = 0$) and even more for an inhomogeneous universe.
- Even for $\mathcal{O}(l) = \mathcal{O}(b) \Rightarrow \mu_Q \neq 0$. Comparison with lattice QCD studies for $\mu_Q \neq 0$ and $\mu_B \neq 0$ needed.
- For flavour asymmetries $l_i = -l_j = \mathcal{O}(1)$ and $l_k \simeq b$ we found a few percent effect on the relic WIMP abundance.