Thermodynamics with physical mass staggered quarks

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arxiv:1606.07494: "Lattice QCD for Cosmology"

Axions

What is an axion, A?

Hypotethical elementary particle, leading candidate for dark matter.

What is the mass of the axion, m_A?

Related to the topological susceptibility of QCD

$$m_A^2 = \chi / f_A^2, \text{ where } \chi = \langle Q^2 \rangle / V$$

What is the scale of the axion, f_A?

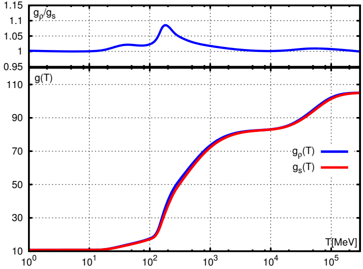
Axions are produced during the evolution of the early Universe. Density depends on f_A: the larger the f_A the more axions are produced. Determine f_A from

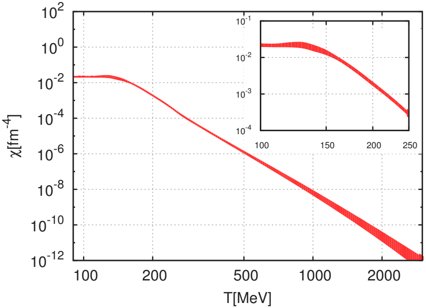
$$\rho_A = \rho_{\text{dark matter}}$$

Lattice QCD

Calculate the density of axions produced in the early Universe!

expansion of the universe → **Equation of State**
(→ see next-to-next talk)
evolution of the axion field → **Topological Susceptibility**



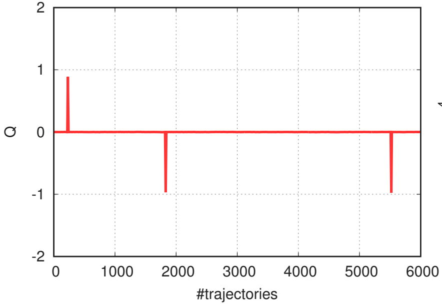


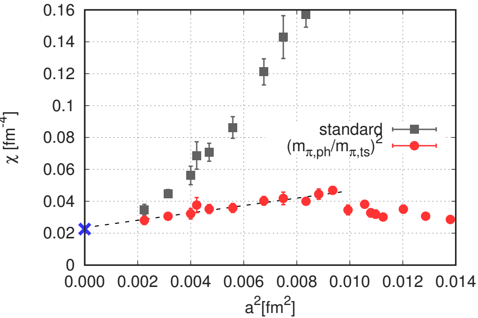
For χ see also recent [Bonati et al 1512.06746] and [Petreczky et al 1606.03145].

The challenges

1. Very few tunneling for large temperatures and/or fine lattices

2. Very large lattice artefacts.





Fixed sector integral

See also Frison,Kitano,Matsufuru,Mori,Yamada 1606.07175.

Instead of waiting for tunneling events, we make simulations in **fixed Q sectors**. Howto get

$$Z_1/Z_0 = ?$$

First calculate **derivative** of $\log Z_1/Z_0$:

$$b_1(T) \equiv \frac{d \log Z_1/Z_0}{d \log T}$$

Use fixed N_t-approach, ie. $T = (aN_t)^{-1}$ is changed by β:

$$b_1(T) = \frac{d\beta}{d \log a} \left(\langle S_g \rangle_1 - \langle S_g \rangle_0 \right)$$

Fixed sector integral

Integration gives the relative ratio:

$$Z_1/Z_0|_T = \exp\left(\int_{T_0}^{T} d\log T' \; b_1(T')\right) Z_1/Z_0|_{T_0}$$

Start from a temperature T_0, where standard approach is feasible.

Remark: b_1 is directly related to the **fall-off exponent**:

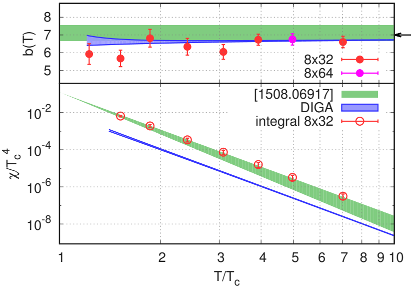
$$b(T) = \frac{d\log\chi}{d\log T} \simeq b_1(T) - 4$$

(For high temperatures, where only $Q = 0$ and 1 are contributing $\langle Q^2\rangle \simeq \frac{2Z_1}{Z_0 N_t N_s^3 a^4}$)

Fixed Q integral - quenched

Fixed Q simulation: extra acc/rej step at the end of each update, as lattice spacing decreased the acceptance gets better.

Test in quenched case: pure Wilson action upto $7 \cdot T_c$ and 8×64^3



standard method: extrapolation using a fit; **integral method**;
Dilute Instanton Gas Approximation: exponent agrees nicely, but order of magnitude difference in χ

Fixed Q integral - fermions

Lattice spacing is changed by β and quark masses m_f:

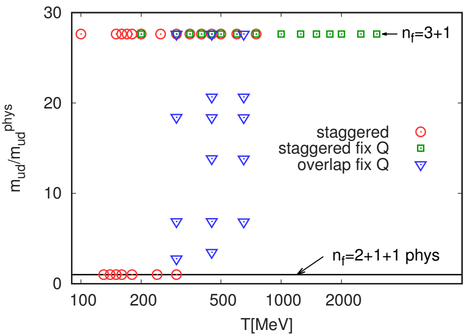
$$b_1(T) = \frac{d \log Z_1/Z_0}{d \log a} =$$

$$= \frac{d\beta}{d \log a} \langle S_g \rangle_{1-0} + \sum_f \frac{d \log m_f}{d \log a} m_f \langle \overline{\psi} \psi_f \rangle_{1-0}$$

Remarks:

1. Very large cutoff effects on $\langle \overline{\psi} \psi \rangle$ ($\rightarrow$ see next talk).
2. Gauge action part is much noiser, than the fermion part.

Simulation strategy

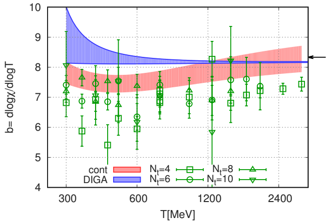


Evaluate susceptibility and decay exponent at a quark mass, where the simulation is less expensive than at phys. point. **Three flavor symmetric point.**

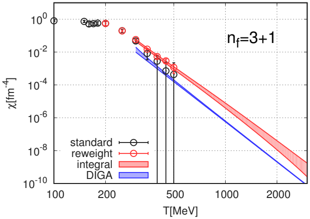
Carry out an **integration in light quark mass** from m_s to m_{ud}.

Results

The fall-off exponent agrees with DIGA/SB limit for temperatures above $T \sim 1\text{GeV}$, for smaller T's somewhat smaller.

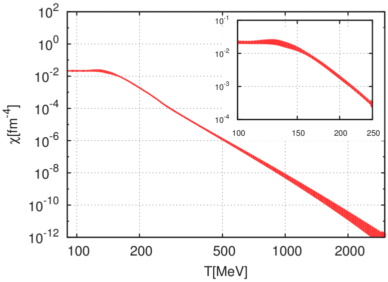


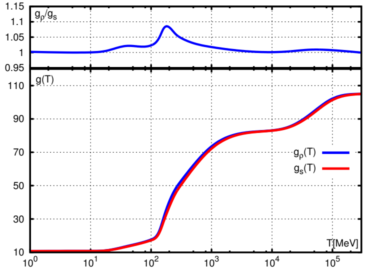
The susceptibility is considerably larger than the DIGA prediction.



Final results

Equation of State and Topological Susceptibility.





They give an axion mass of $m_A = 50(4)\ \mu\text{eV}$ (in post-inflation with same amount of topological defects as misalignement).