Axion mass from lattice QCD

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We determine the **topological susceptibility** and the thermodynamical **equation of state** for temperatures relevant for the axion production in the early Universe. We use lattice QCD with dynamical fermions. We point out several difficulties in these calculations and address them by introducing **novel techniques**. Assuming the standard QCD axion scenario and no topological defects we obtain a **lower bound on the axion mass**.

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Calculate the mass of the axion m_a!

Assume: standard QCD axion and all dark matter is made of axions.

Strategy: calculate the number of axions produced in the early Universe as a function of m_a and make it equal to the observed dark matter $\to m_a$

Necessary input: The production depends on

a. topological susceptibility $\to$ axion potential in the early Universe

$$\chi(\mathbf{T}) = ?$$

b. equation of state (energy,pressure) $\to$ rate of expansion of the Universe

$$\rho(\mathbf{T}) = ? \quad \mathbf{p}(\mathbf{T}) = ?$$

Tool: use **lattice QCD** to calculate χ, ρ, p in a non-perturbative region $T \lesssim 1$ GeV

Topological susceptibility χ

Axion mass comes from the curvature of the axion potential at $\theta = 0$

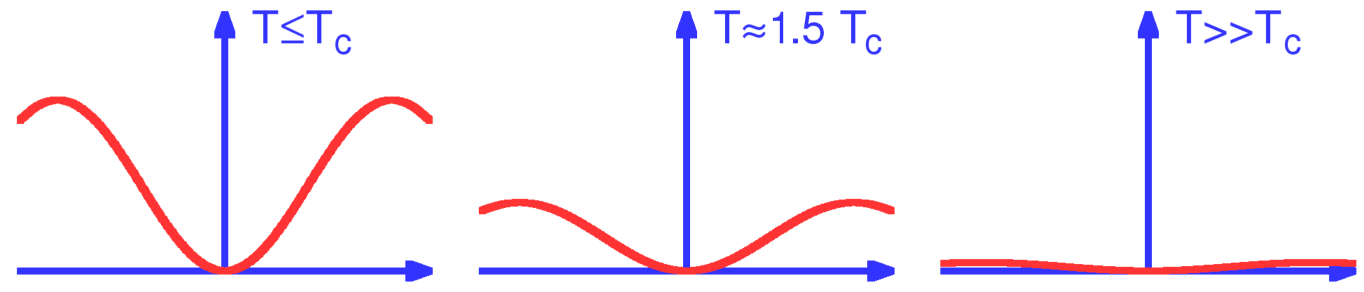
$$V_{\text{eff}}[\theta] \approx \tfrac{1}{2}\chi \cdot \theta^2 + \ \dots \quad \to \quad m_a^2 = \chi / f_a^2$$

χ is topological susceptibility of QCD, Q is topological charge:

$$\chi = \langle Q^2 \rangle / V$$

At $T = 0$ χ is well known from eg. lattice $\chi(T = 0) = 0.0216(21)(11)\ \text{fm}^{-4}$

Axion effective potential becomes flat at QCD transition $T_c \approx 150$ MeV:



For relevant temperature regime χ is a tiny number: $\chi(T \sim \text{GeV}) \sim 10^{-10}\ \text{fm}^{-4}$

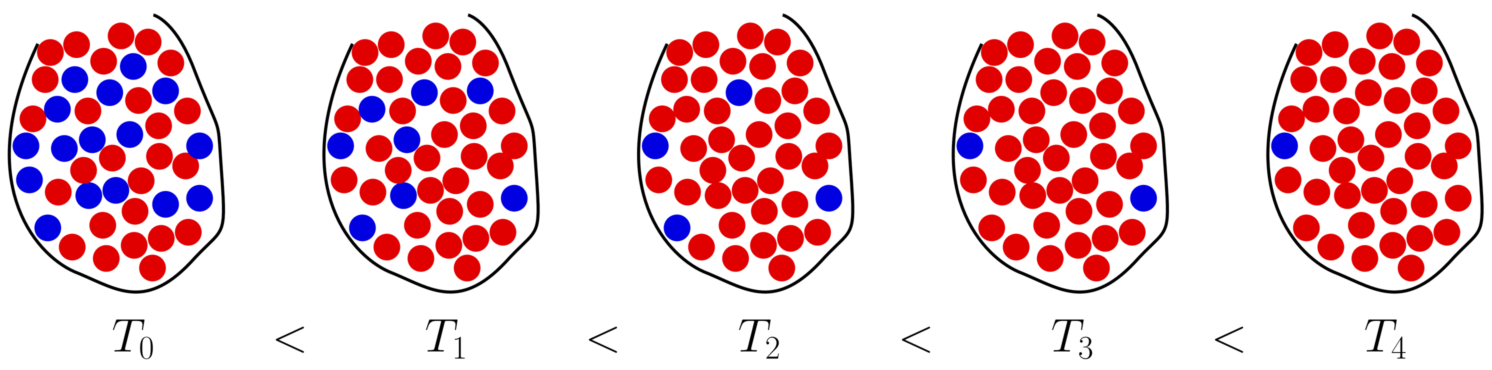
Very hard to measure precisely!

1. statistical error 2. lattice artefacts

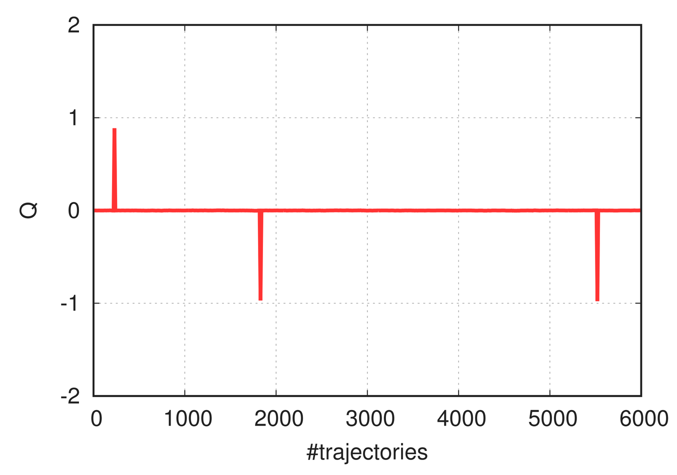
Measure χ on the lattice! - standard way

$\chi \sim \frac{2Z_1}{Z_0}$ fraction of gauge field configurations with non-trivial topology

Determine the ratio of blue (non-trivial Q) and red (trivial Q) balls by randomly picking from a bag

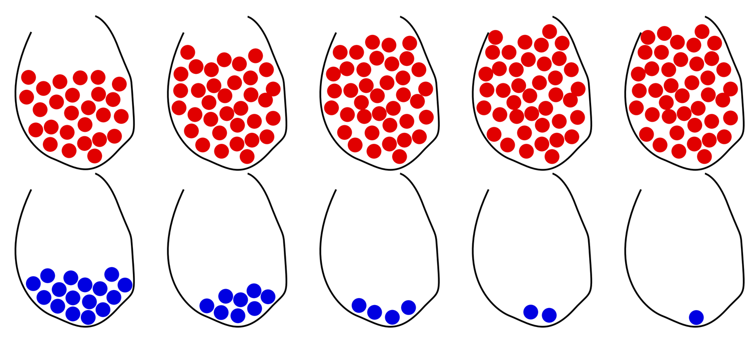


Gets **prohibitively expensive** for large temperatures!

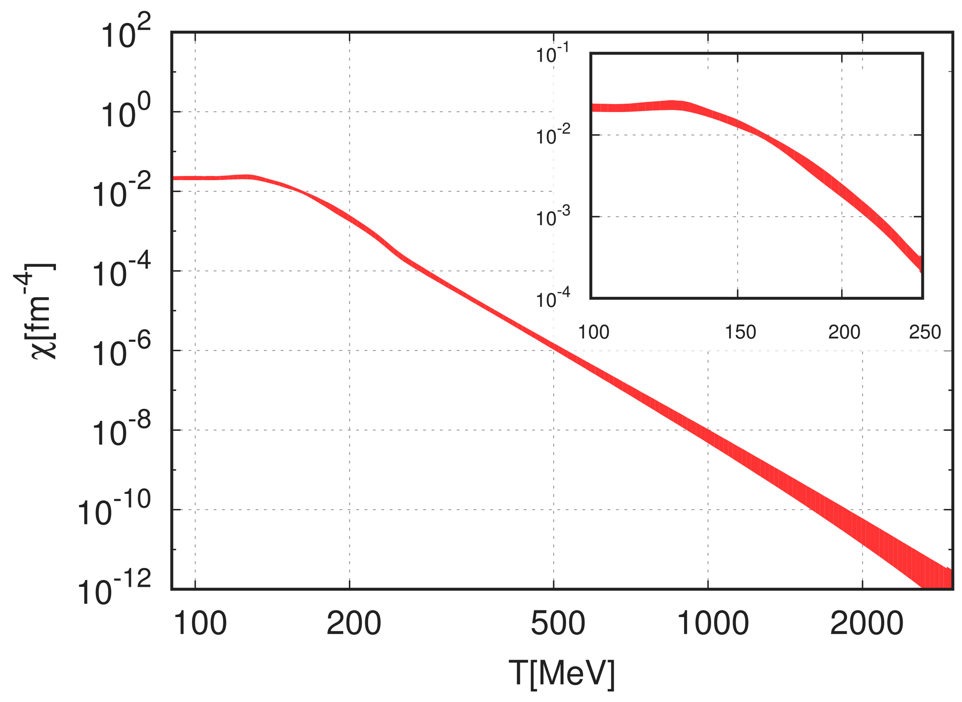


Monte-Carlo time evolution of Q. Few tunnelings $\to$ hard to measure χ.

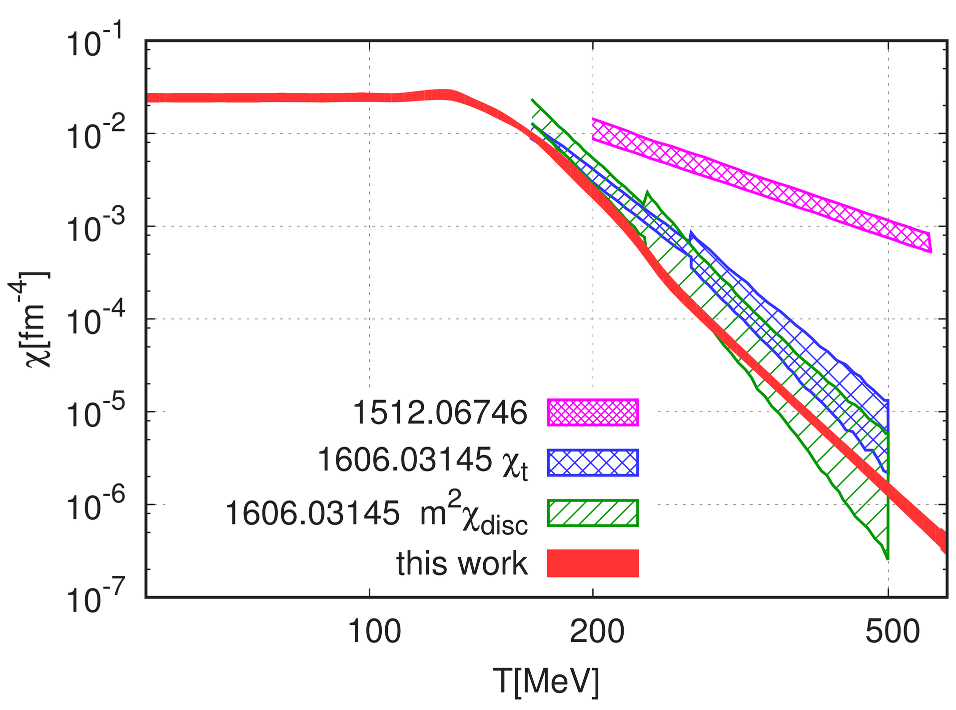
Measure χ on the lattice! - novel way

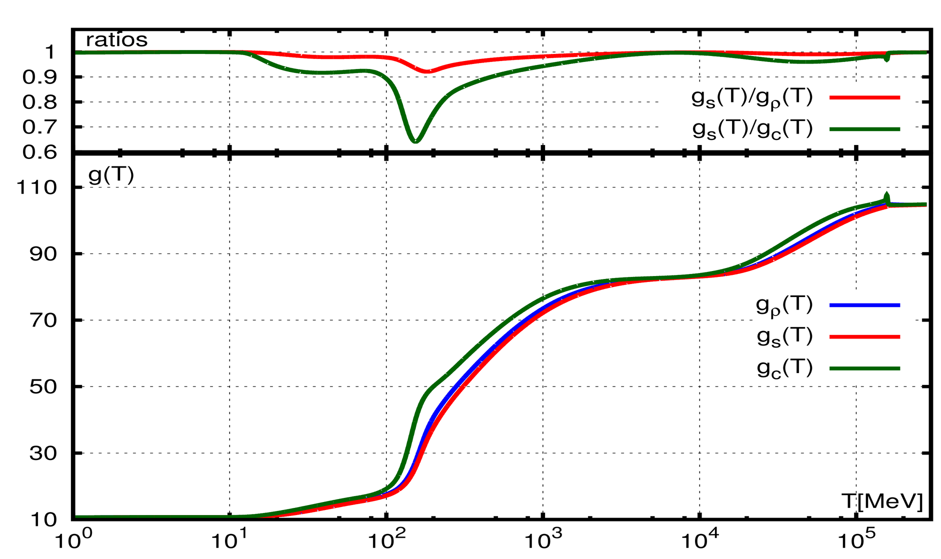


Separate balls and measure how the number of balls changes with temperature $\to$ temperature difference $\frac{d \log \chi}{d \log T} \to \chi(T)$



Many other lattice QCD efforts

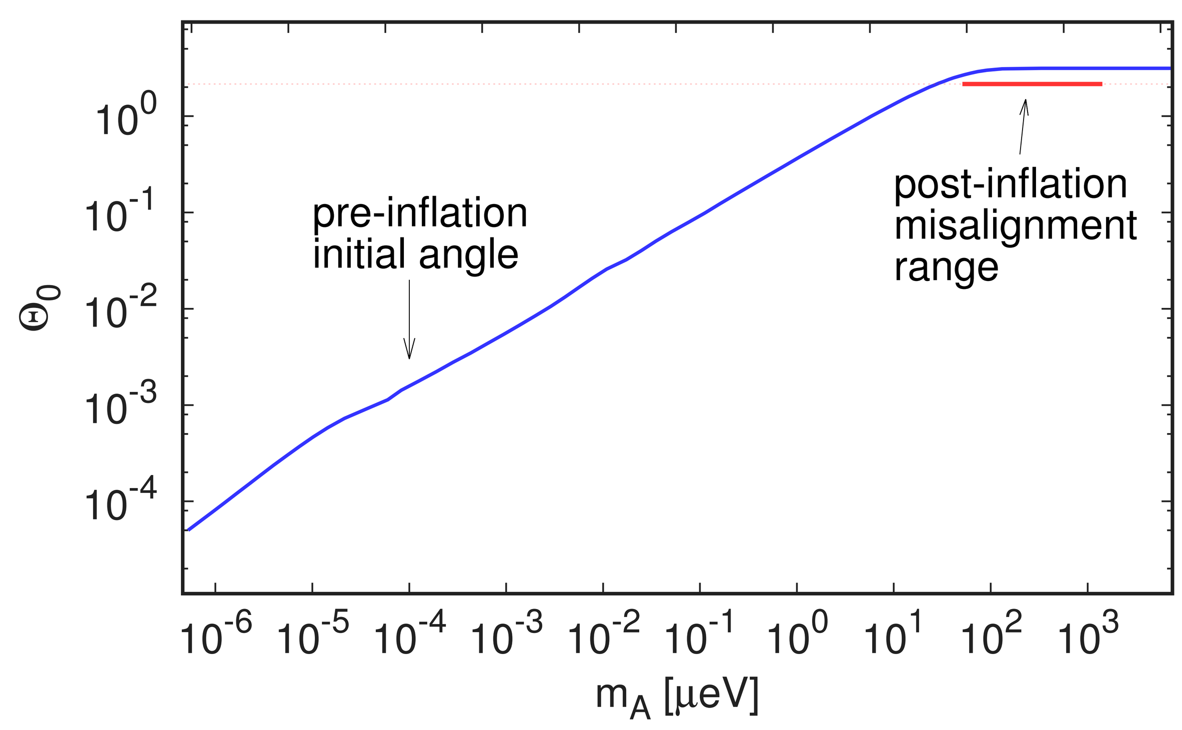




Equation of state Full SM result= lattice QCD + weak + photon + neutrinos + leptons

Axion mass and initial angle

Assume homogeneous axion field (no strings, walls, ...) and no sphaleron effects.



post-inflation average all possible θ_0 values

$\langle m_a(\theta_0) \rangle = 28(1)\ \mu\text{eV}$

(If not all DM is axion, then this is a lower bound.)

pre-inflation single θ_0 in Universe, m_a can be anything