The physics case for axion searches in the 0.5-2 μeV mass range

Enrico Nardi

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

February 17th & 18th, 2022

Basic ingredients of the PQ solution

[Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

- A scalar potential invariant under a **global** U(1): $\Phi \to e^{i\xi}\,\Phi$, $\delta\mathcal{L}(\Phi) = 0$
- U(1) **SSB:** $\Phi \to v_a\, e^{ia(x)/v_a}$. Shift symmetry $a(x) \to a(x) + \xi v_a$, $\delta\mathcal{L}(a) = 0$
- Couplings between the scalars and some quarks $\bar{Q}_L\, \Phi\, q_R \to \bar{Q}_L\, v_a\, q_R\, e^{ia(x)/v_a}$
  U(1) is then enforced by identifying chiral PQ charges $X(Q) - X(q) = X(\Phi)$
- The symmetry must have a mixed U(1)-SU(3)$_c^2$ anomaly: $\Sigma_q(X_Q - X_q) \neq 0$

By redefining the quark fields in the basis of real masses $\bar{Q}_L v_a\, q_R$:

$$\Theta G\tilde{G} \quad \to \quad (a(x)/v_a + \Theta)\, G\tilde{G} \quad \to \quad (a(x)/v_a)\, G\tilde{G}$$

Instanton related non-perturbative QCD effects generate a potential

$V_{QCD}(a) = -(m_\pi\, f_\pi)^2 \cos(a/v_a)$ that drives $\langle a/v_a \rangle \to 0$ at the minimum

Vacuum realignment mechanism

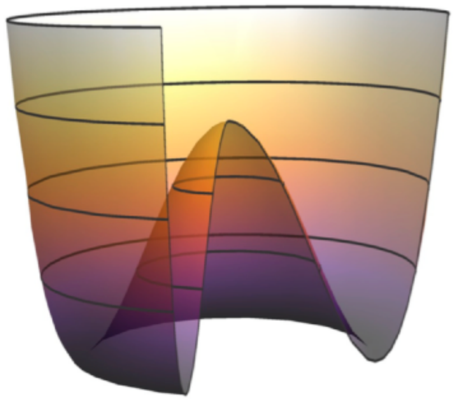
[Abbott, Sikivie (1983), Dine, Fischler (1983), Preskill, Wise, Wilczek (1983)]

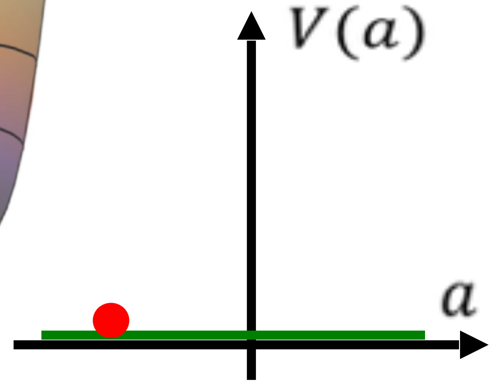
With the PQ solution, a relic population of non-rel. axions is <u>unavoidable</u>

- **After SSB: $T < f_a$, $T \gg \Lambda_{QCD}$ ($\alpha_s \ll 1$):**

$U(1)_{PQ}$ is broken only spontaneously,
Instanton effects suppressed as ~ $e^{-2\pi/\alpha_s}$

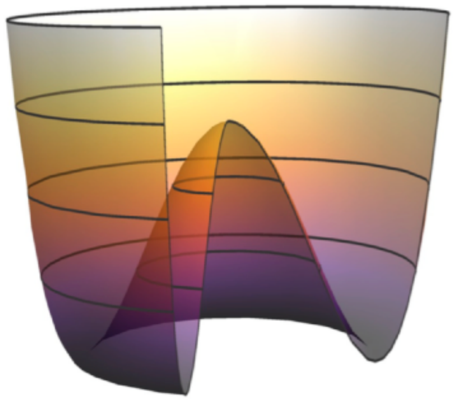
$m_a = 0$, $a_i = \theta_i f_a$, $\theta_i \in [-\pi,\pi]$

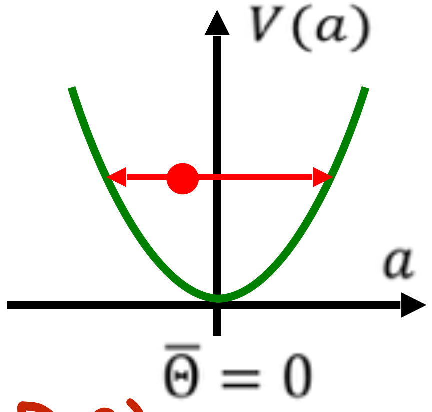




- **When $T \sim \Lambda_{QCD}$ ($\alpha_s \sim 1$)** $[e^{-2\pi/\alpha_s} \sim O(1)]$

$U(1)_{PQ}$ suffers an explicit breaking: $m_a(T)$ turns on. When $m_a(T) \sim H(T)$ ($H \sim 10^{-9}$ eV), ($\nu_a \cdot \tau_U \sim 1$) a -> min. and starts oscillating





- **Energy stored in oscillations behaves as CDM ($\rho_a \sim R^{-3}$)**

Equation of motion for the axion field

Define $\theta = a/f_a$

$$\ddot{\theta} + 3H(T)\,\dot{\theta} + m_a^2(T)\,\theta = 0$$

$$[\theta_i = ?\,,\ \dot{\theta}_i = 0]$$

$H(T) \sim \sqrt{g^*(T)}\ T^2/m_P$ <- Standard cosmology

$m_a(T) = m_0\,(T_C/T)^4$ <- Standard QCD result ($T>T_C \sim 160$ MeV)

T_1 : Critical damping temperature such that $m_a(T_1) \approx 3\,H(T_1)$

Energy density at T_1: $\rho_a(T_1) \sim \frac{1}{2}\, m_a^2(T_1)\, a_i^2 = \frac{1}{2}\, m_a^2(T_1)\, f_a^2\, \theta_i^2$

No. of axions per comv. vol.: $N = V_1\, \rho_a(T_1)/m_a(T_1)$ is conserved

Present contrib. to Cosm. energy density

$T_1 \to T_0$;
$V_1 \to V_0$;
$m_a(T_1) \to m_0$;

<- Entropy conserv. $V_1 g_s(T_1) T_1^3 = V_0 g_s(T_0) T_0^3$

<- Standard $\chi_{pt.th.}$ result $m_0 \approx m_\pi f_\pi / f_a$

$$\rho_a(T_0) \propto m_\pi f_\pi T_0 \left(\frac{T_0}{m_P}\right)^{3/2} \sqrt{\frac{T_0}{H(T_1)}} \frac{g_s(T_0)}{g_s(T_1)} f_a \theta_i^2$$

Standard cosmology and (QCD) $m_a(T)$: $T_1 \sim 800$ MeV

Standard Universe thermal history: $g_s(T_1) = 61.75$

$$\Omega_a^{\rm mis} h^2 \approx 0.12 \left(\frac{10\,\mu{\rm eV}}{m_0}\right)^{\frac{7}{6}} \theta_i^2$$

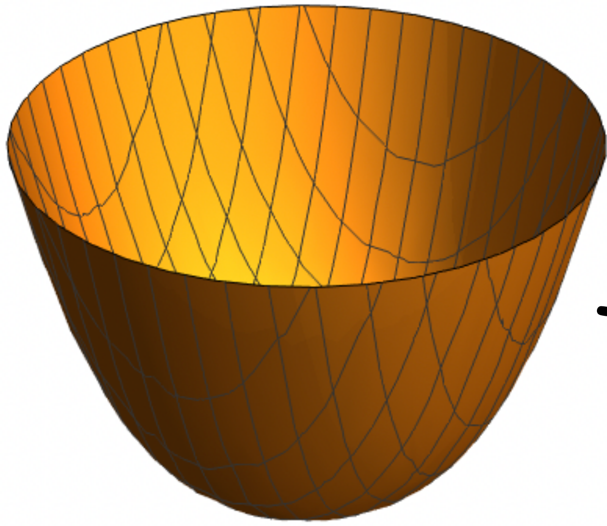
For $m_0 \in [0.5, 2.0]$ μeV

$\theta_i \in [0.17, 0.39]$rad

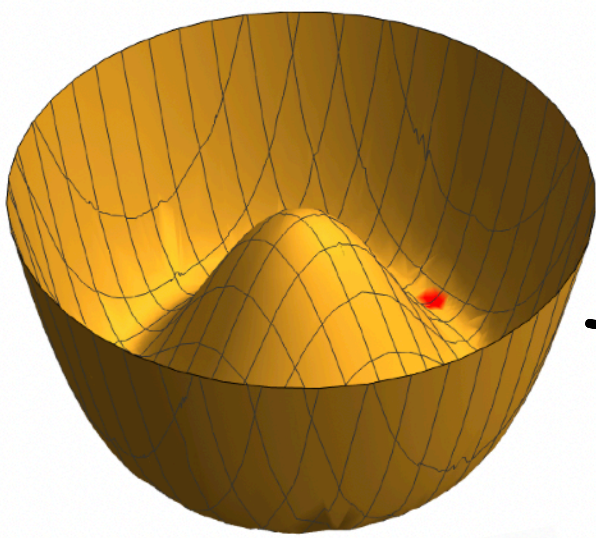
i.e. 3.5% of the circle

Pre-inflationary scenario $T_{PQ} > H_I, T_{rh}$

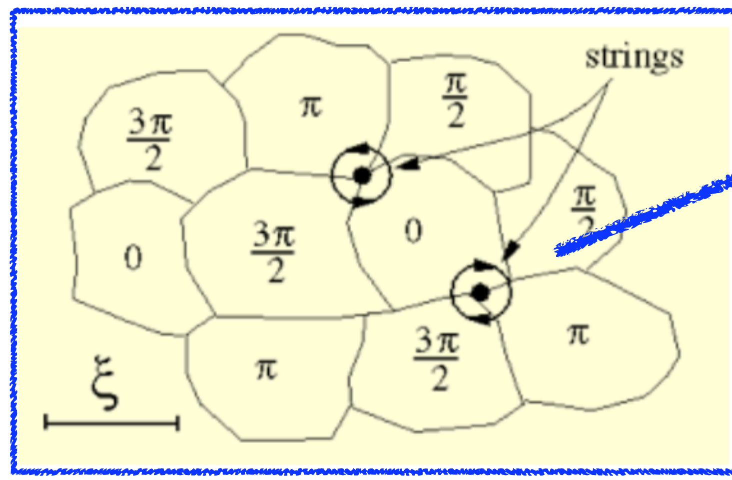
Complex scalar $V(\Phi) = (|\Phi|^2 - v^2)^2 + \lambda|\Phi|^4$



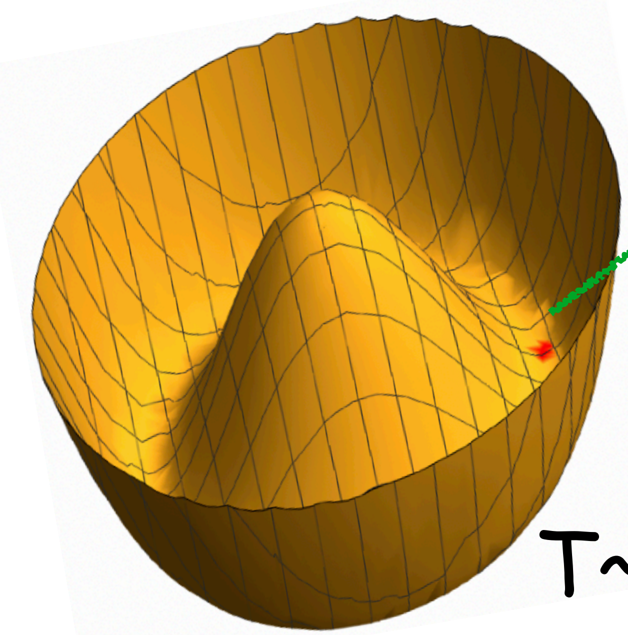
$T > T_{PQ}$



$T < T_{PQ} \sim v_\Phi$

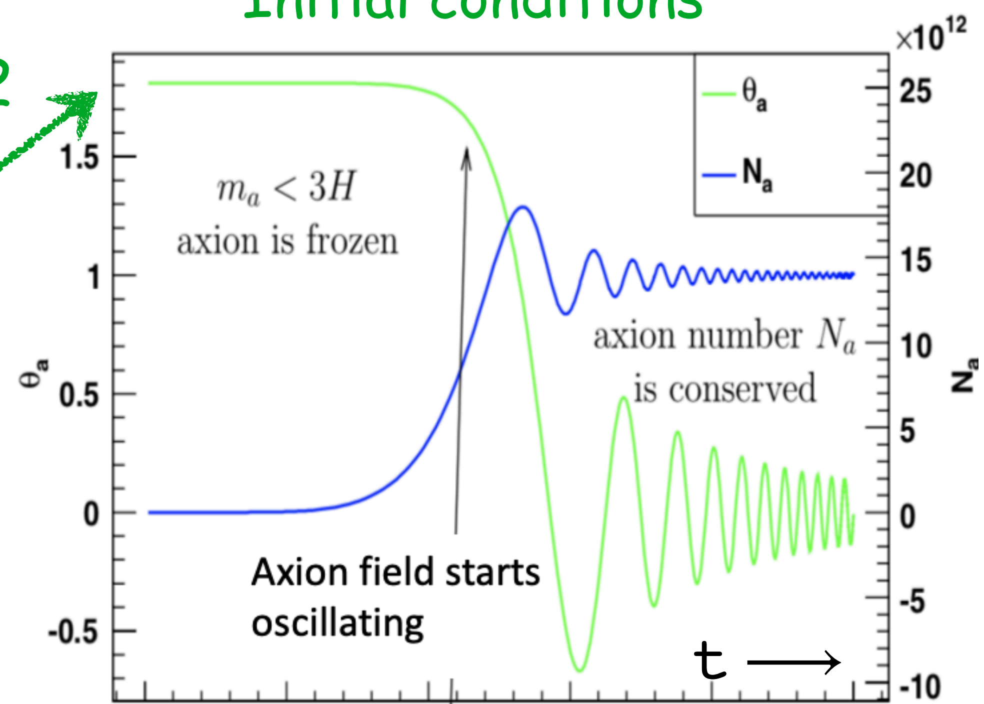


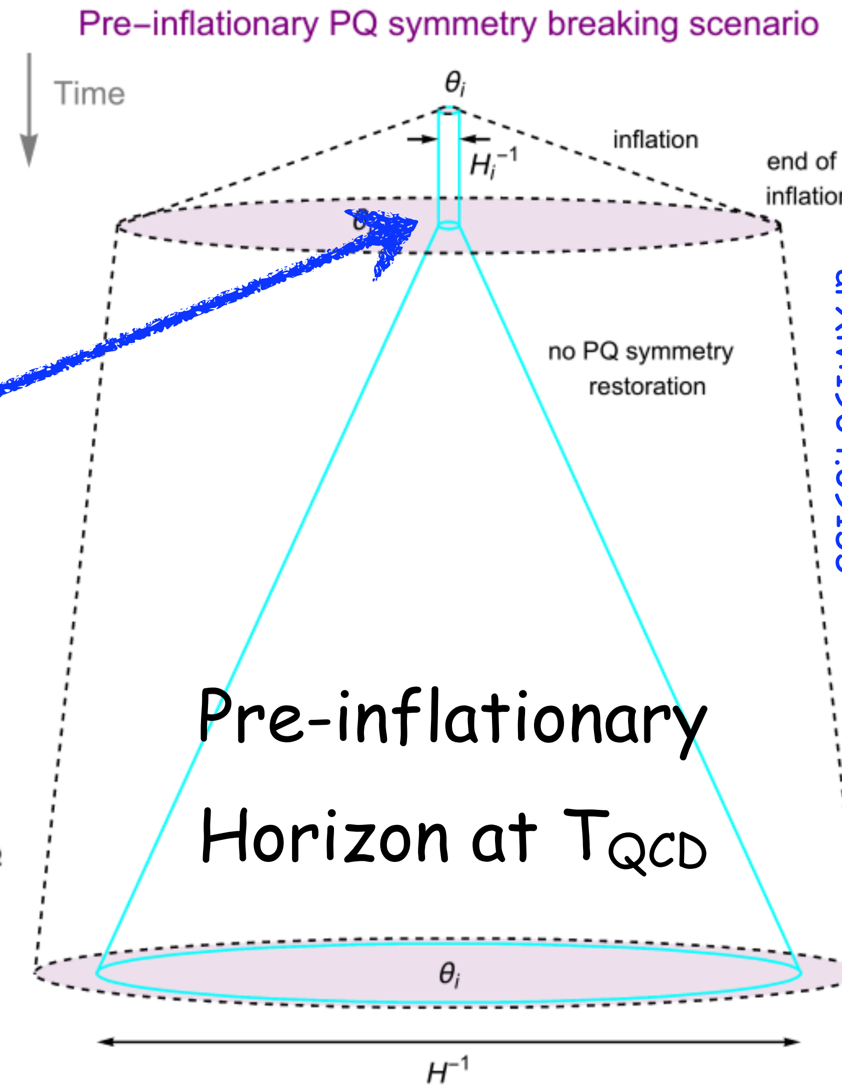
$\theta_i \sim \pi/2$



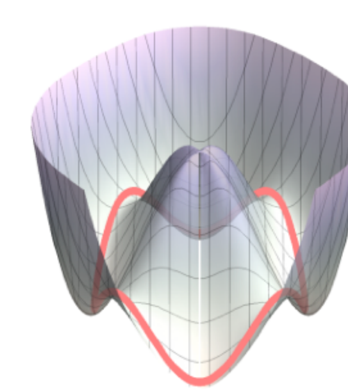
$T \sim \Lambda_{QCD}$

Initial conditions

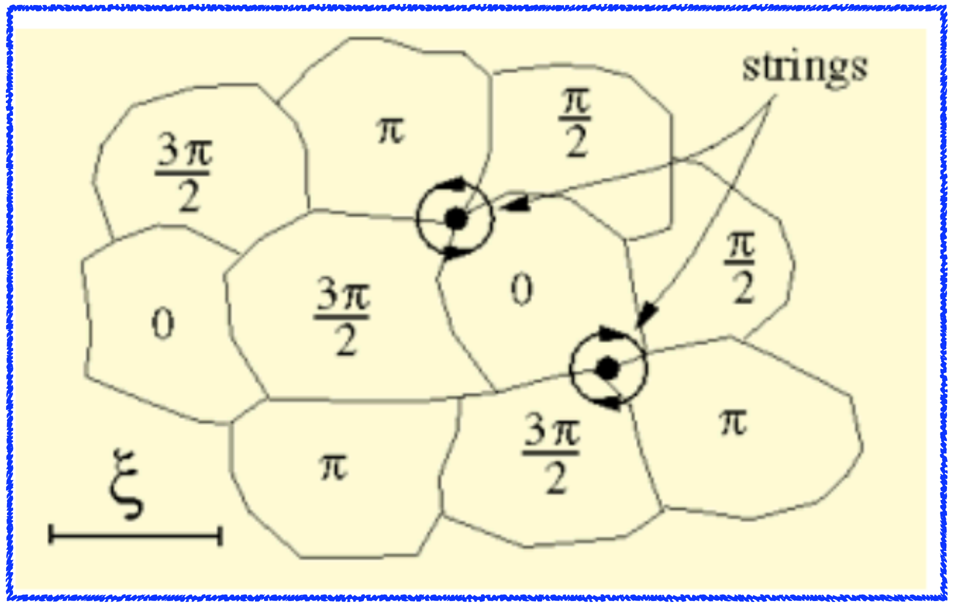




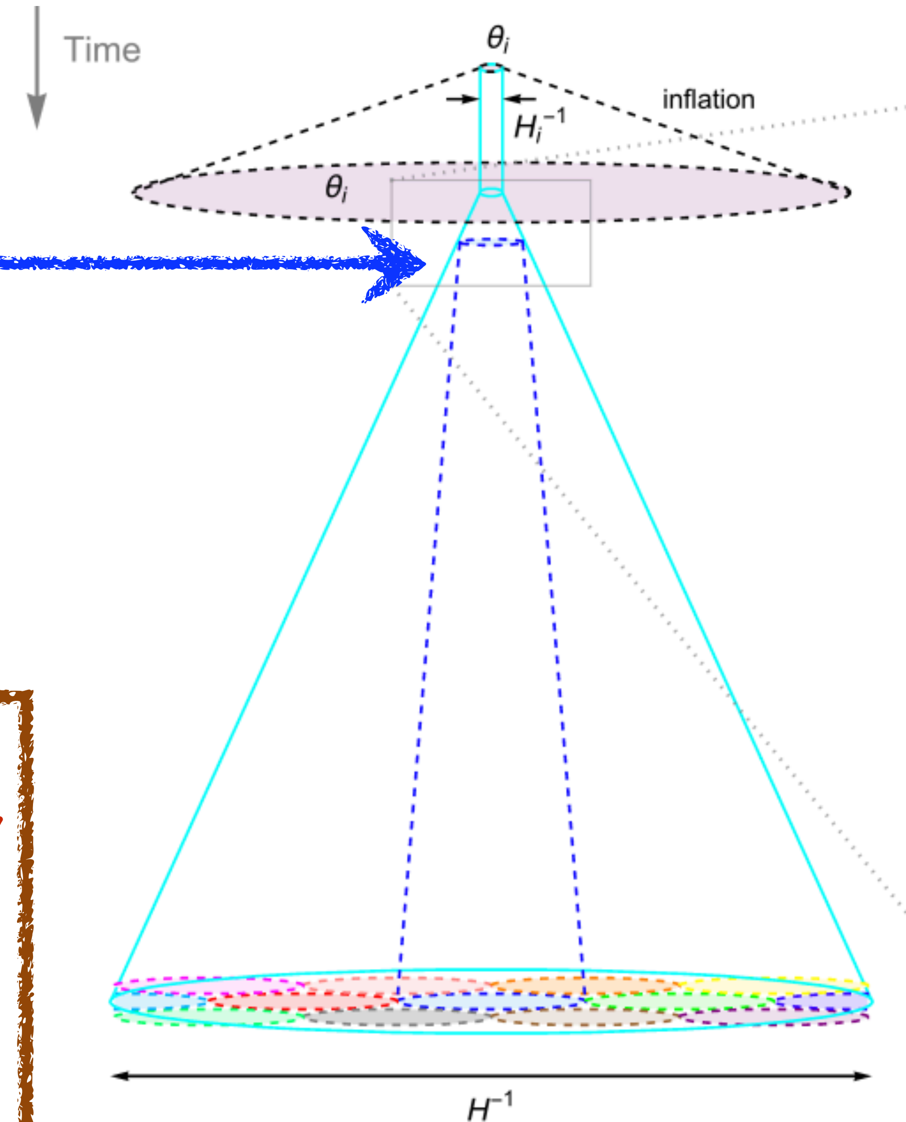
arXiv:1904.09155

[$N_{DW} > 1$ ]

Post-inflationary scenarios: $T_{PQ} < H_I, T_{rh}$

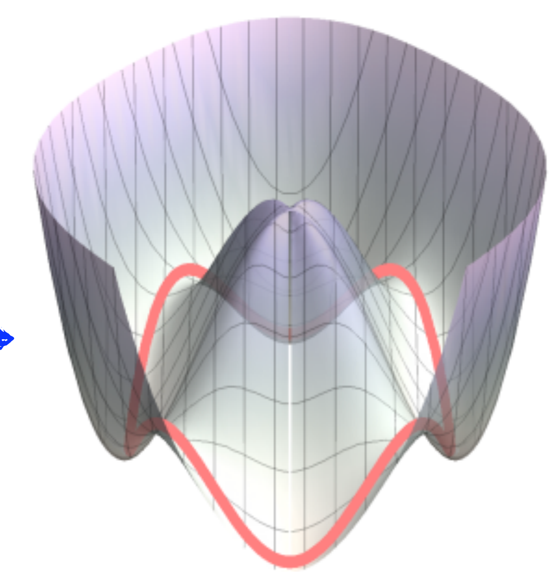


$T \sim T_{PQ}$



arXiv:1904.09155

- n_a independent of initial conditions: $\langle \theta_i^2 \rangle = \pi^2/3$. More predictive for misalignment $\rho_{a\text{-mis}} \approx \rho_{DM} \rightarrow m_a \sim$ 30-100μeV
- Strings remain within the horizon (enter/annihilate) Eventually decay and contribute to ρ_a (important debate: spectrum/string density) masses up to $m_a \sim$ 0.5-3.5meV
- O(1) density contrasts: at matter/radiation equality (T ~ 1eV) overdensities start growing: axion miniclusters $R_{MC} \sim 1$ AU, $M_{MC} \sim 10^{-3} M_☾$, $\rho_{MC} \sim 10^6 \rho_{DM\text{-local}}$
- $N_{DW} > 1$:
  Strings-DW network is stable. ρ_{DW} dominates $\rho_{Universe}$
  Solutions exist (e.g. small non-QCD explicit breaking)



1st takeaway message:

Haloscopes sensitivity projections assume $\rho_a = \rho_{CDM}$ (locally)

Assuming a standard Cosmology, a standard Universe thermal history, and standard particle physics:

- For the range 0.1-0.5Ghz ($m_a \sim 0.5$-2.0 μeV) axion discovery requires a pre-inflationary scenario with initial conditions

$$\theta_i \in [0.2, 0.4]$$

- This is not a “fine tuned” condition (just a small prmt. region):

$$P(\theta_i \in [0.2,0.4]) \quad = \quad P(\theta_i \in [1.2, 1.4])$$

- The theoretical estimate is solid: it does not depend on unknown contributions from topological defects: $\rho_{a(tot)} = \rho_{a(mis)}$

Other Possibilities ? Post-inflationary scenarios ?

$$\ddot{\theta} + 3H(T)\,\dot{\theta} + m_a^2(T)\,\theta = 0$$

Non standard Cosmology (slower expansion, higher T_1)

$m_a(T)$ evolution beyond QCD

$$\rho_a(T_0) \propto m_\pi f_\pi \, T_0 \left(\frac{T_0}{m_P}\right)^{3/2} \sqrt{\frac{T_0}{H(T_1)}} \, \frac{g_s(T_0)}{g_s(T_1)} \, f_a \, \theta_i^2$$

Non standard $m_a f_a$-$m_\pi f_\pi$ relation

Non standard thermal history (entropy injection)

Post-Inflationary:
rather large O(10) effects required

$$\langle \theta_i^2 \rangle \approx \pi^2/3 \;\Rightarrow\; \Omega_a^{\rm mis} h^2 \approx 0.12 \left(\frac{28\,\mu\mathrm{eV}}{m_0}\right)^{\frac{7}{6}}$$

Entropy Injection:

Requires new particles decaying between $T_1 > T_{decay} > T_{BBN}$

entropy increased $g_s(T) \longrightarrow g_s(T)\,\Delta$ and $m_a^{DM} \longrightarrow m_a^{DM}/\Delta^{6/7}$

A rather large factor $\Delta \approx 20 \div 30$ is needed

Modified $m_a(T)$ evolution (mirror world)

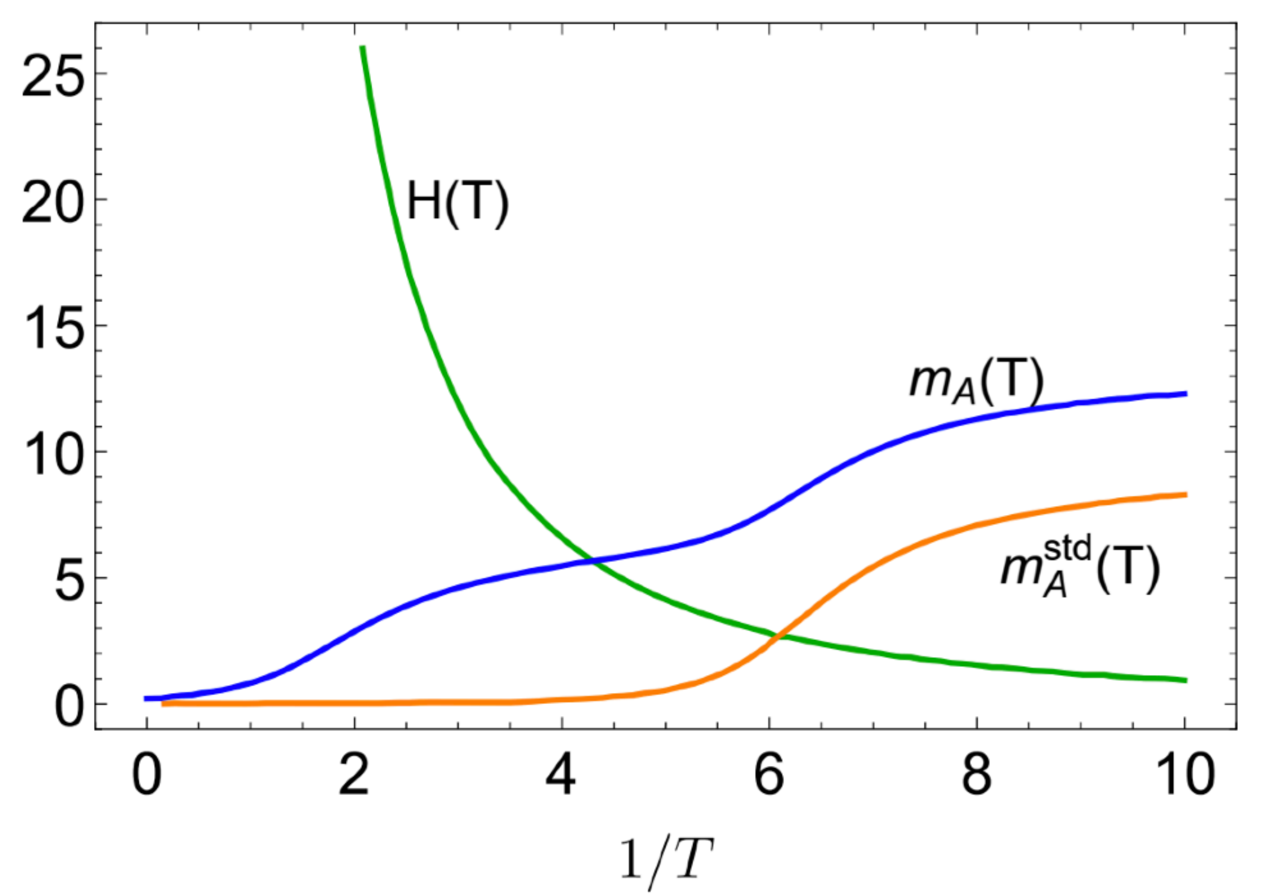
Assume a mirror copy of the SM $G_{SM} \times G_{MIR}$;

BBN constrains $T_{MIR} \lesssim 0.4\, T_{SM}$.

QCD_{MIR} instantons kick in at

$T_1 \gg T_1^{SM}$, oscillations start

earlier, when $H(T_1)$ is larger



Non-standard mass-decay constant relation

[A. Hook, PRL 120 (2018)]

Multi $SU(3)_c$ construction: $QCD \times QCD' \times \ldots \times QCD^N$;

Z_N : $a \longrightarrow a + 2\pi f_a/N$; $q_k \longrightarrow q_{k+1}$

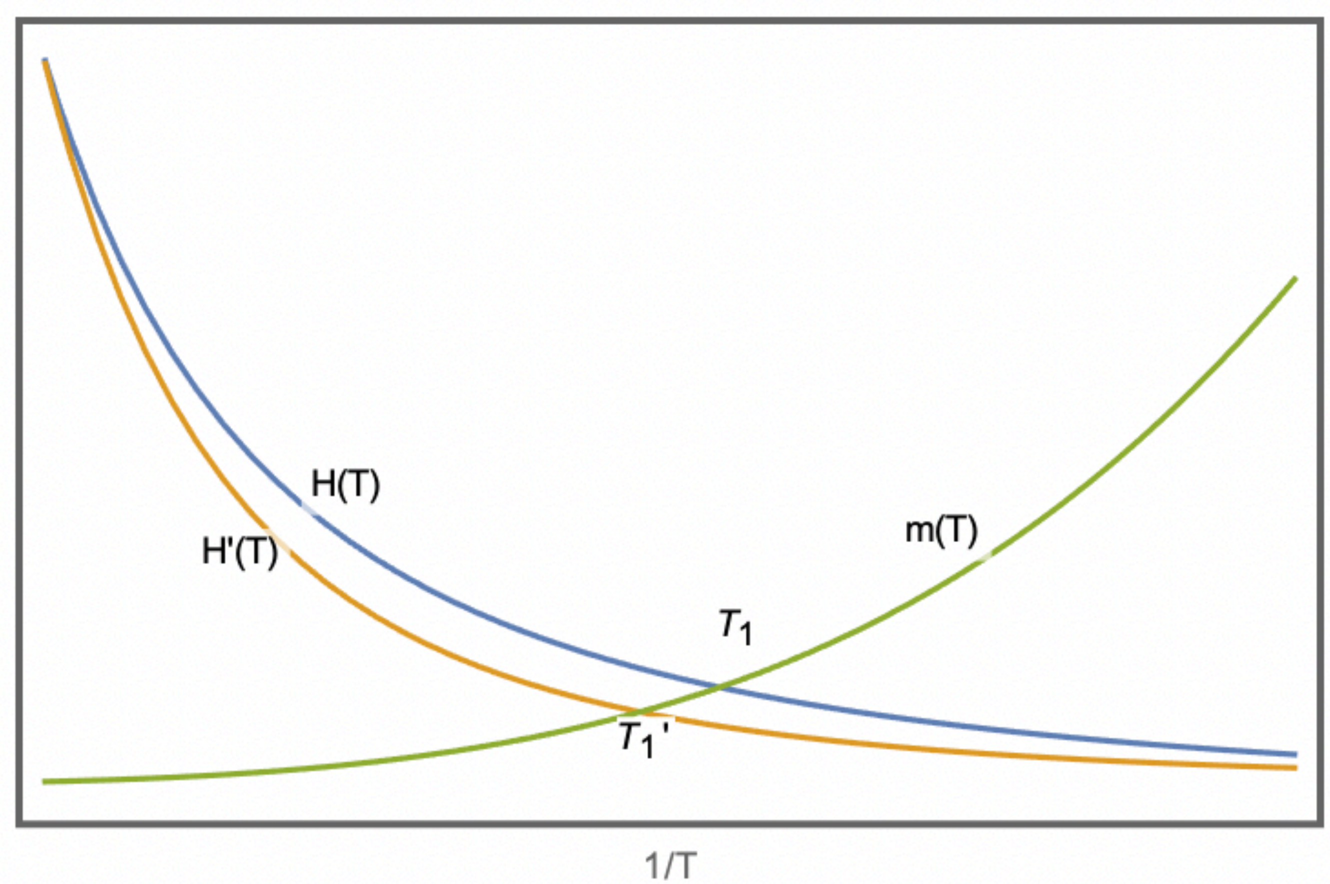
One obtains: $m_0(N) = 2^{2-N/2}\, m_\pi f_\pi / f_a$ requires $N \gtrsim 12$

Non standard Cosmologies

(scalar-tensor gravity)

Periods of decelerated (or accelerated) expansion can occur, before converging to GR as $T \longrightarrow 0$

Oscillations start at $T_1' > T_1$



2nd takeaway message:

- Reducing the axion DM mass in post-inflationary scenarios is difficult, but can be done. It requires a non-standard Universe thermal history, or rather "exotic" particle physics models, or a non-standard cosmology.

- The m_a suppression factors required are rather large (~20) even when considering only $\rho_{a(mis)}$. Sizeably larger factors will be needed in the realistic case: $\rho_{a(tot)} = \rho_{a(mis)} + \rho_{a(top.def.)}$

Thanks for your attention