Relic Density of Axion Dark Matter in Standard and Non-Standard Cosmological Scenarios

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Overview: Axion DM

Dark Matter (DM): Cold,Invisible

Physics beyond the Standard Model: axion (WISP)

Motivated as a solution of the strong CP problem [1]

Spontaneous breaking of global U(1) symmetry at a scale f_a (axion decay constant)

Emergence of axion (massless)

Axion has a small mass [2] (QCD effect at scale Λ_{QCD})

$$m_a \sim 6\,\mu eV \left(\frac{10^{12}\,GeV}{f_a}\right)$$

Non thermal production: Misalignment mechanism

[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)

[2] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978), F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

Standard Cosmology ΛCDM

A success of this model: Big Bang Nucleosynthesis epoch (BBN).

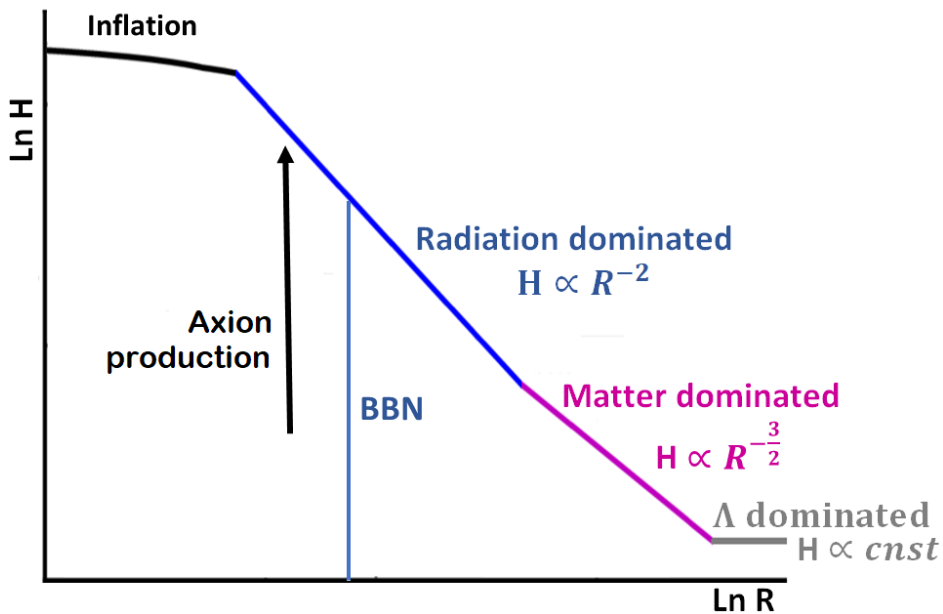
After inflation ends with temperature T_{RH}, radiation dominated era begins.

Equation of state $P = \omega\rho$,

$$\rho \propto R^{-3(1+\omega)},$$

$$\rho \propto \begin{cases} R^{-3} & \text{Matter} \\ R^{-4} & \text{Radiation} \\ const & \Lambda \end{cases}$$

$$H(R) = \sqrt{\frac{1}{3M_{pl}^2}\sum_i \rho_i(R)}.$$



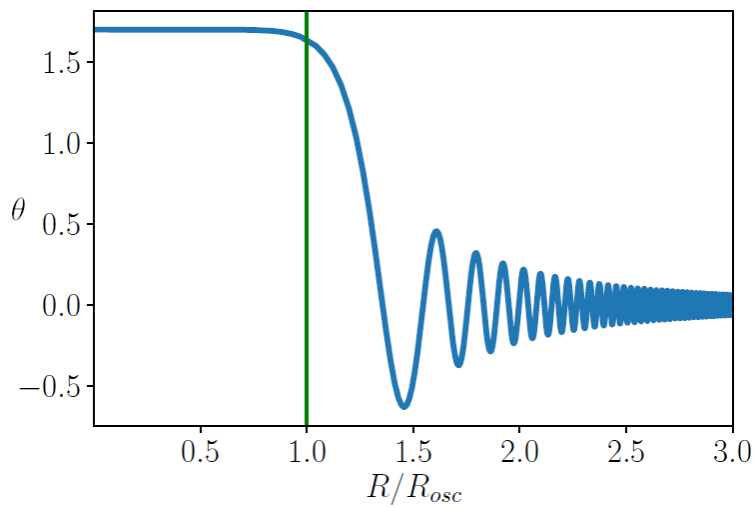
Expansion rate by considering standard cosmology, (vertical blue) BB Nucleosynthesis.

Axion production in SC: Misalignment Mechanism

The equation of motion

$$\ddot{a} + 3H(T)\dot{a} + m_a(T)^2 f_a \, sin(\frac{a}{f_a}) = 0$$

Initial misalignment angle θ_i



Axion field evolution, green line indicates when oscillations start

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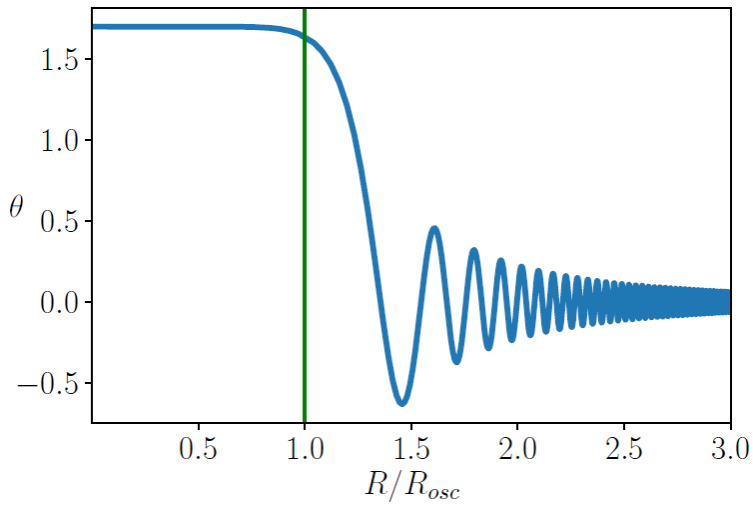
$H \sim m_a$: Coherent axion oscillations start at temperature T_{osc}

$$3H(T_{osc}) = m_a(T_{osc})$$

Conservation of comoving axion number gives present energy density:

$$\rho_{a,mis}(t_0) \simeq \frac{f_a^2 \theta_i^2}{2} m_a \, m_a(t_{osc}) \left(\frac{R_{osc}}{R_0}\right)^3$$



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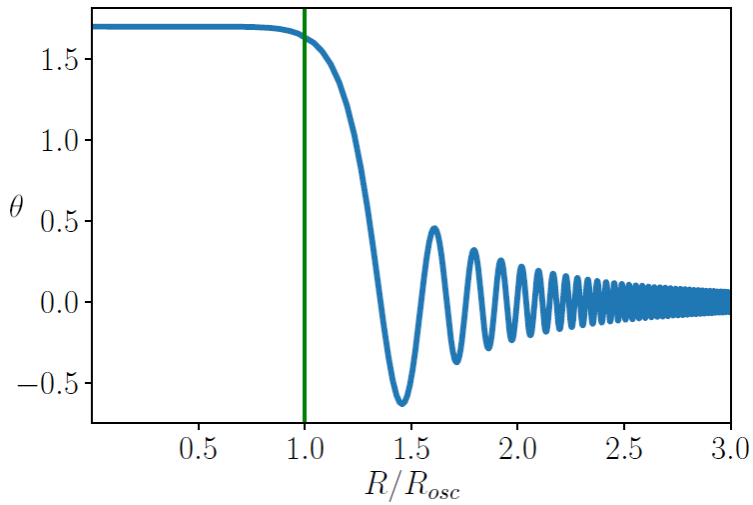

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$$\rightarrow \quad \rho_{a,mis} \propto R^{-3}$$

No relativistic matter

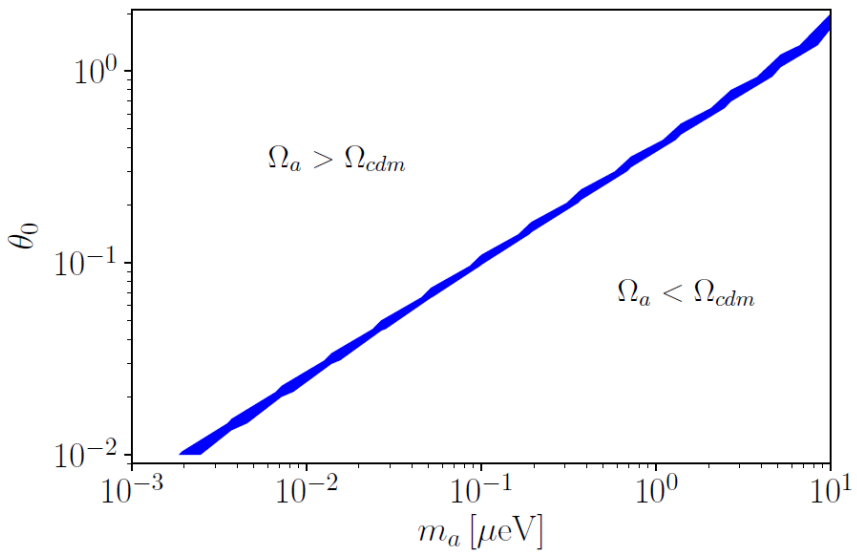
Entropy is conserved since the oscillations began

$$\rho_{a,mis}(t_0) \simeq \frac{f_a^2 \theta_i^2}{2} m_a \, m_a(t_{osc}) \frac{s(T_0)}{s(T_{osc})}$$

The relic density of Axion cold dark matter

$$\Omega_{a,mis} \propto \left(\frac{6\,\mu eV}{m_a}\right)^{\frac{7}{6}} \left(\frac{\theta_i}{\pi}\right)^2$$

Axion 100% DM
$\Omega_{DM} = 0.265$[3]



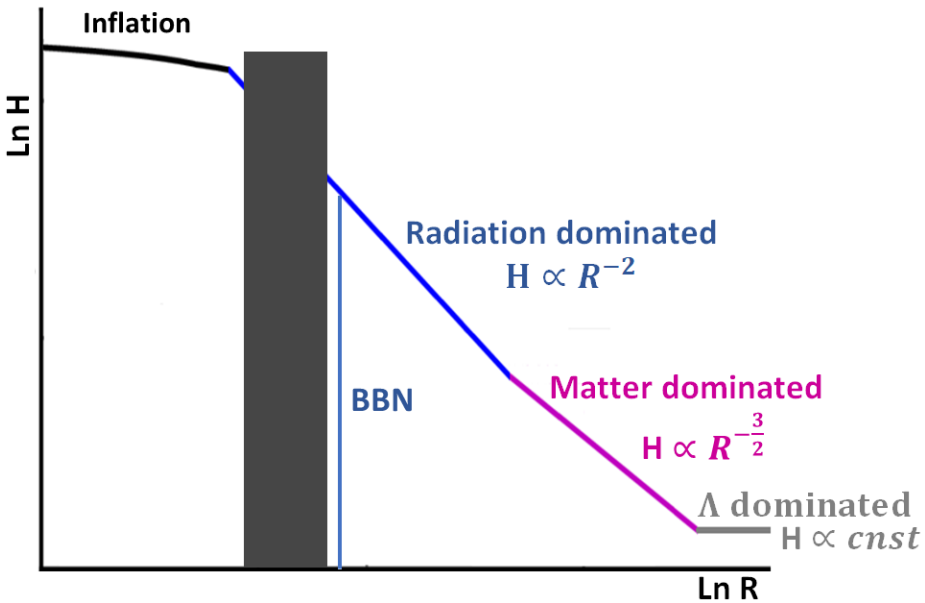
The blue line represents the values for misalignment angle which the axions DM is the total dark matter as function of axion mass.

[3] Planck Collab. 2018 Results VI (2018), [arXiv:1807.06209]

Non Standard Cosmology

A new extra scalar field ϕ that Prior to BBN dominates the energy density of the universe $\rho_\phi \propto R^{-3(1+\omega)}$

the new field decays at temperature T_{end} with a decay rate Γ_ϕ and the universe is radiation dominated.



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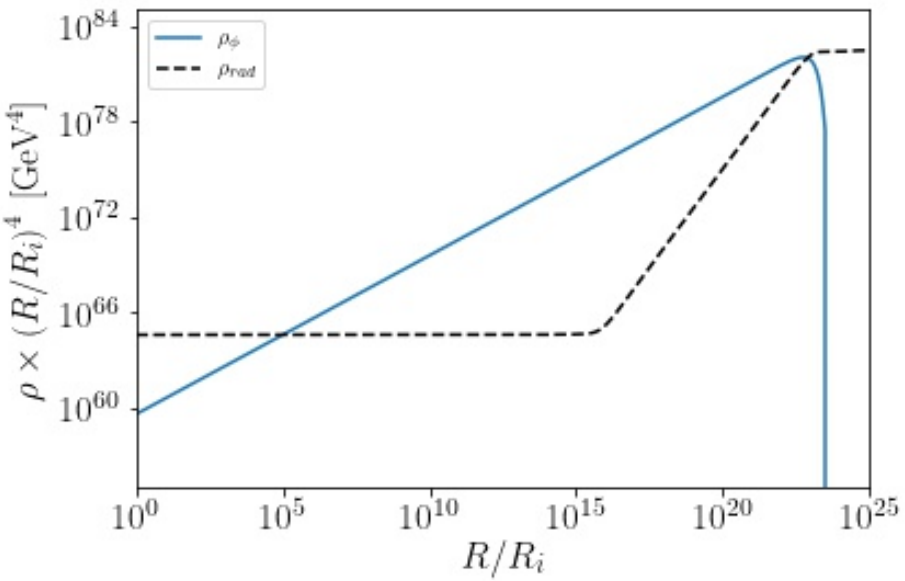


Energy density $\times$ R^4 for radiation an the new field ϕ, with parameters: $\omega = 3, \kappa = 10^{-5}, T_{end} = 4 \times 10^{-3} MeV$

Initial condition $\kappa = \frac{\rho_{\phi,i}}{\rho_{rad,i}}$

Expansion rate $H = \sqrt{\frac{\rho_\phi + \rho_{rad}}{3M_p^2}}$

Free parameters ω, κ and T_{end}

Axion production in NSC: Misalignment Mechanism

Coherent axion oscillations start at temperature T_{osc}

$$3H(T_{osc}) = m_a(T_{osc})$$

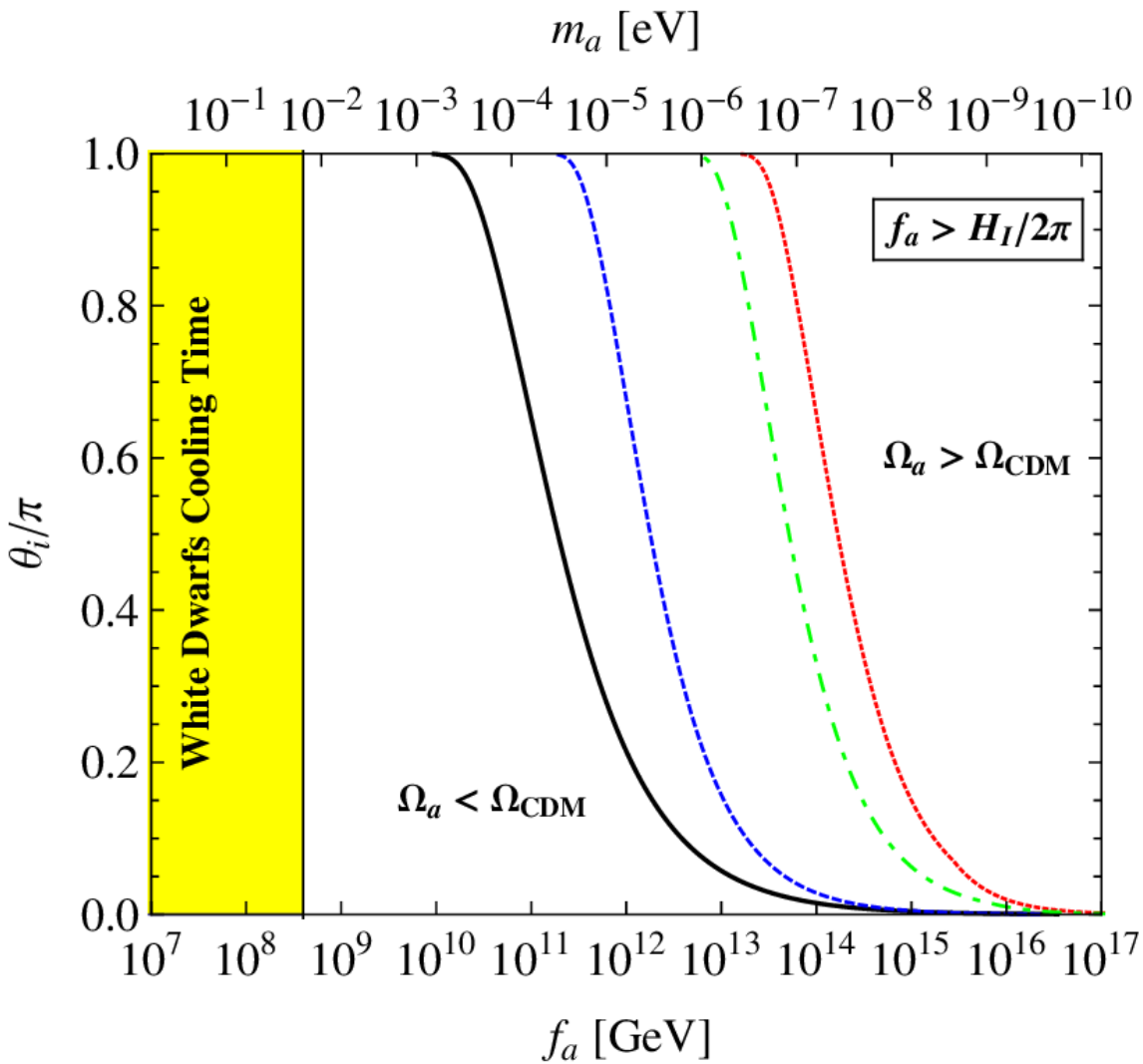
Due to the decay of ϕ, entropy injection[4] occurs.

$\rightarrow$ dilution of the axion density

$$\rho_a(T_0) = \rho_a(T_{osc}) \frac{m_a}{m_a(T_{osc})} \frac{s(T_0)}{s(T_{osc})} \gamma$$

Dilution factor: $\gamma \equiv \frac{S(T_{osc})}{S(T_{end})}$

[4] G.Lazarides, Dilution of cosmological axions by entropy production.Nuclear Physics B346 (1990)



The initial misalignment angle θ_i vs scale f_a for the axion to be 100% of the CDM, SC(black solid line), LTR cosmology with: T_{RH} = 4MeV (red dotted line), 15MeV (green dot-dashed line) or 150MeV (blue dashed line).
Ref: L. Visinelli, P. Gondolo, arXiv:0912.0015

Comments

The predictions of Axion relic density depend strongly on the early history of the universe.

Non Standard Cosmologies give us new parameter spaces to search axions.

Future Work: consider the contribution of other production mechanisms to the axion relic density (decay of topological defects[5]).

[5] A. Vilenkin, Phys. Rev. D 24, 2082 (1981))