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

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June 9, 2020

CAP Virtual Congress 2020
Overview: Axion DM

Introduction
Axion as dark matter candidate
Standard Cosmology (SC)
Misalignment Mechanism in SC

Non Standard Cosmology (NSC)
Misalignment production in NSC

Conclusion
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 \(\Lambda_{QCD}\))

\[
m_a \sim 6 \mu eV \left( \frac{10^{12} \text{ GeV}}{f_a} \right)
\]

Non thermal production: Misalignment mechanism

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\(^1\) 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 $\Lambda CDM$

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

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

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

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

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

Expansion rate by considering standard cosmology, (vertical blue) BB Nucleosynthesis.
Axion production in SC: Misalignment Mechanism

The equation of motion

\[ \ddot{a} + 3H(T) \dot{a} + m_a(T)^2 f_a \sin\left(\frac{a}{f_a}\right) = 0 \]

Initial misalignment angle \( \theta_i \)

Axion field evolution, green line indicates when oscillations start
Axion production in SC: Misalignment Mechanism

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Initial misalignment angle $\theta_i$

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

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

Conservation of comoving axion number gives present energy density:

$$\rho_{a,\text{mis}}(t_0) \sim \frac{f_a^2 \theta_i^2}{2} m_a m_a(t_{osc}) \left(\frac{R_{osc}}{R_0}\right)^3$$
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\[ \rightarrow \quad \rho_{a,\text{mis}} \propto R^{-3} \]

No relativistic matter
Entropy is conserved since the oscillations began

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

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.

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3 Planck Collab. 2018 Results VI (2018), [arXiv:1807.06209]
A new extra scalar field $\phi$ that Prior to BBN dominates the energy density of the universe $\rho_\phi \propto R^{-(1+\omega)}$

the new field decays at temperature $T_{\text{end}}$ with a decay rate $\Gamma_\phi$ and the universe is radiation dominated.
Non Standard Cosmology

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

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

Free parameters $\omega$, $\kappa$ and $T_{\text{end}}$

Energy density $\times R^4$ for radiation an the new field $\phi$, with parameters: $\omega = 3, \kappa = 10^{-5}, T_{\text{end}} = 4 \times 10^{-3} \text{MeV}$
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 $\phi$, 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: $\gamma \equiv \frac{S(T_{osc})}{S(T_{end})}$

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$^4$ G.Lazarides, Dilution of cosmological axions by entropy production. Nuclear Physics B346 (1990)
The initial misalignment angle $\theta_i$ vs scale $f_a$ for the axion to be 100% of the CDM, SC(black solid line), LTR cosmology with: $T_{RH} = 4\text{MeV}$ (red dotted line), 15MeV (green dot-dashed line) or 150MeV (blue dashed line).

Ref: L. Visinelli, P. Gondolo, arXiv:0912.0015
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\textsuperscript{5}).

\textsuperscript{5} A. Vilenkin, Phys. Rev. D 24, 2082 (1981)
