QCD Axion Dark Matter from a Late Time Phase Transition

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Pheno 2020
5/5/2020

arXiv: 1910.04163
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QCD Axion Dark Matter is produced after a late time phase transition by two (unequal) effects: cosmic strings and parametric resonance.

Viable production mechanism for low values of $f_a$ – as low as $10^9$ GeV for certain couplings to the Standard Model.

Axion dark matter is warm and should lead to observable signals in 21cm WDM studies.

Parameter space of very low $f_a$ values leads to rare Kaon decays.
The Model

\[ V(P) \]

\[ \mathcal{L} \supset yP \bar{\psi} \psi \]

\[ T^4 \gg m_s^2 f_a^2 \]
The Model: Late Time Phase Transition

\[ V(P) \]

\[ \mathcal{L} \supset yP \bar{\psi} \psi \]

\[ T_c \ll f_a \]

\[ V''(P = 0, T = T_c) = 0 \]

\[ T^4 < m_s^2 f_a^2 \]
The Model: Late Time Phase Transition

• First Order Phase Transition?
• No – numerical analysis finds that the PT proceeds via phase mixing [5]:
  • Before bubbles form, thermal fluctuation can bump field from origin
  • Symmetric and asymmetric phases coexist and the PT completes at *

\[ T_s > T_p > T_c \]
The late time phase transition can also be cast as the condition

\[ m_s \ll f_a \]

This hierarchy is natural in supersymmetric scenarios where \( P \) is stabilized by higher dimensional interactions:

\[
V = \left( \frac{2^{n-2} m_s^2}{n(n-1) f_a^{2n-2}} \right) |P|^{2n} - \frac{m_s^2}{2n-2} |P|^2 + \frac{m_s^2 f_a^2}{4n}
\]

We assume that the potential energy dominates and a period of thermal inflation occurs:

\[
y \gtrsim \sqrt{\frac{m_s}{f_a}} \quad H_{PT} \sim \frac{m_s f_a}{M_{pl}}
\]
Axions from Cosmic Strings

- After phase transition, cosmic strings form with approximate energy density

\[ \rho_{str} \sim \frac{f_a^2}{r_{c}^2} \]

\[ r_c = \alpha m_s^{-1} \ll r_H \]

- Energy should be lost producing axions with momenta \( \sim m_s \). However, this population is subdominant to parametric resonance
Axions from Parametric Resonance

• Qualitatively:

\[ \ddot{x} + \omega_k^2(t) x = 0 \]
\[ \omega_k^2(t) = k^2 + S_0 \sin(\omega t) \]

For certain values of k, some solutions that exponentially grow

• Decompose the field \( P = s + ia \) and get equations of motion
  • Oscillating saxion background:

\[ \ddot{s} + \left( m_s^2 + \frac{m_s^2}{4f_a} s^4 + \frac{5m_s^2}{4f_a^3} s^3 + \frac{5m_s^2}{2f_a^2} s^2 + \frac{5m_s^2}{2f_a} s \right) s = 0 \]

• Axion modes:

\[ \ddot{a}_k + k^2 a_k + \left( \frac{m_s^2}{4f_a^4} s^4 + \frac{m_s^2}{f_a^3} s^3 + \frac{3m_s^2}{2f_a^2} s^2 + \frac{m_s^2}{f_a} s \right) a_k = 0 \]

unstable modes grow as

\[ a_k \sim \exp \left( \mu_k m_s t \right) \]
Axions from Parametric Resonance

• The dominant band is

\[ k_a = \frac{m_s}{2} \]

• Axion growth continues until

\[ \rho_{a}^{PR} \sim V(0) = m_s^2 f_a^2 \]

• Thus we get a population of PR produced axions:

\[ \frac{n_{a}^{PR}}{\rho_s} \sim \frac{1}{m_s} \]

• Note that in this scenario, parametric resonance is occurring without the large field displacements
Neglecting the axions produced by the cosmic strings, the axion yield is

\[ Y_a = \frac{T_{RH}}{m_s} \]

To get the observed dark matter abundance, the reheat temperature must be at least

\[ T_{DM} \sim 0.7 \text{ GeV} \left( \frac{m_s}{10 \text{ MeV}} \right) \left( \frac{f_a}{10^9 \text{ GeV}} \right) \]
• The thermalization rate for the axion satisfies

\[ \frac{\Gamma_a}{H} < b \left( \frac{m_s}{f_a} \right)^{3/2} \frac{M_{pl}}{f_a} \]

so late time phase transition is critical!

• Assuming DM abundance, axion velocity can be expressed as

\[ v_a \simeq 6 \times 10^{-4} \left( \frac{f_a}{10^9 \text{ GeV}} \right)^{2/3} \left( \frac{m_s}{\text{GeV}} \right) \left( \frac{T}{\text{eV}} \right) \]

which must satisfy

\[ v_a \big|_{T=1 \text{ eV}} \leq 10^{-4} \]

giving bound

\[ m_s \leq 30 \text{ MeV} \left( \frac{10^9 \text{ GeV}}{f_a} \right) \]
We consider \( n = 3 \) for definiteness.

The slanted, dashed green lines are contours for the axion velocity at \( T = 1 \text{ eV} \).

The region under the dashed orange curve is unconstrained if we are in the trapping regime.

It would appear that \( f_a = 10^9 \text{ GeV} \) is ruled out. However, this is too strong a statement given the uncertainty in the supernovae constraints \([4]\).
• Supernovae Constraints & the Trapping Regime
  - Large Saxion-Higgs coupling can prevent efficient energy loss as the saxions get “trapped”

• Relativistic Degrees of Freedom
  - In the trapping regime, saxion can be in thermal equilibrium with electrons even after the neutrinos decouple.
  - Thus the depletion of saxion energy heats up the photons, resulting in $N_{\text{eff}} < 3$
  - Assuming the neutrinos suddenly decouple at $T = 2$ MeV, the saxion mass must satisfy

$$m_s > 4 \, \text{MeV}$$
21 cm lines & structure
- High axion velocity -> warm dark matter scenario
- Future observations of the 21cm should probe $m_{\text{wdm}} < 10-20$ keV, which corresponds to $v > 10^{-5}$.
- Our parameter space will be explored.

NA62 & KLEVER
- Assuming a large saxion-Higgs coupling, one gets rare Kaon decays

$$K \rightarrow \pi + S$$
Conclusions

• QCD axion dark matter can be produced by a late time phase transition
  • Two mechanisms contribute – early cosmic string network dynamics and parametric resonance. Parametric resonance dominates over the axions from cosmic strings

• Features:
  • The parametric resonance does not require large field displacement, in contrast to previous scenarios
  • Low values of the axion decay constant are permitted, especially if large saxion-Higgs mixing is introduced or one relaxes supernovae bounds.
  • The axion dark matter is warmer than other scenarios – should leave detectable imprints on structure formation visible in future 21 cm line studies
  • If the saxion is in the trapping regime, there should be signals from rare Kaon decays at the NA62 and KLEVER experiments.
References

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• [2]. QCD Axion Dark Matter with a Small Decay Constant – R. Co, L. Hall, K. Harigaya
• [3]. Towards the theory of Reheating after Inflation – L. Kofman, A. Linde, A. Starobinsky
• [4]. Light Dark Matter: Models and Constraints – S. Knapen, T. Lin, K. Zurek and references [54-59] of our paper.
• [5]. Effects of thermal fluctuations on thermal inflation – T. Hiramatsu, Y. Miyamoto, J. Yokoyama
• [6]. Parametric Resonance Production of Ultralight Vector Dark Matter – J. Dror, K. Harigaya, V. Narayan
• Stellar Cooling
  • The axion coupling to electrons and nucleons can give rise to rapid cooling in stars
  • For Red Giant and Horizontal Branch stars, the energy loss rate due to axions must be less than
    \[ \epsilon < 10 \text{ erg/g/s} \]

• Supernovae - 1987A
  • The energy loss for new particles in supernovae is constrained by the 1987A observations to be
    \[ \epsilon < 10^{19} \text{ erg/g/s} \]
  • However, there are is at least an O(10) degree of uncertainty regarding this constraint [4]
• The saxion must be thermalized at or above TDM. We could consider a coupling between $\bar{P}$ and a new pair of fermions as

$$\mathcal{L} \supset \frac{\mu}{f_a} \bar{P} f \bar{f}$$

• Then the saxions would thermalize at a rate $\sim 0.1 T \mu^2 / f_a^2$, which leads to a reheat temperature

$$T_{RH} \sim 100 \text{ GeV} \left( \frac{\mu}{100 \text{ GeV}} \right)^2 \left( \frac{10^9 \text{ GeV}}{f_a} \right)^2$$

• If the fermions have SM charges, $\mu$ must be greater than 100 GeV. This results in a reheat temperature that is larger than $T_{DM}$.

• To get the right reheat temperature, one can consider coupling to SM particles
The thermalization rate for the axion is

\[ \Gamma_a = b \frac{k_a^2}{f_a^2} T \]

During matter domination era of saxion oscillations, \( \frac{k_a^3}{\rho_s} = \text{constant} \)

\[ k_a \sim \left( \frac{m_s \rho_s}{f_a^2} \right)^{1/3} \]

The energy density of the thermal bath never exceeds that of the saxion, so

\[ \frac{\Gamma_a}{H} < b \frac{m_s^{2/3} \rho_s^{5/12} M_{\text{pl}}}{f_a^{10/3}} < b \frac{m_s^{3/2} M_{\text{pl}}}{f_a^{5/2}} \]

The late time phase transition is critical!
Consider a Weyl fermion that decouples while relativistic and dilutes later:

\[
\frac{n}{k^3} = \frac{3}{2} \frac{\zeta(3)}{\pi^2} \frac{T^3}{(3T)^3} = \frac{\zeta(3)}{18\pi^2}
\]

\[
k^3 = \frac{\rho_{DM}}{m s_0} \frac{18\pi^2}{\zeta(3)} = \frac{0.4 \text{ eV}}{m} \frac{36\pi^4}{45\zeta(3)} g_s T^3
\]

\[
k \frac{m}{m} \sim 10^{-4} \left( \frac{T}{\text{eV}} \right) \left( \frac{3.3 \text{ keV}}{m} \right)^{4/3}
\]

Warm dark matter mass bound \( m_{WDM} > 3.3 \text{ keV} \) gives velocity bound \( v < 10^{-4} \) at \( T = 1 \text{ eV} \).
• Axion Warmness
  • Redshift Invariant combination:
    \[ \frac{k_a}{n_a^{1/3}} \sim \left( \frac{m_s}{f_a} \right)^{2/3} \]
  • Along with observed dark matter abundance gives
    \[ \nu_a \approx 6 \times 10^{-4} \left( \frac{f_a}{10^9 \text{ GeV}} \right)^{2/3} \left( \frac{m_s}{\text{GeV}} \right) \left( \frac{T}{\text{eV}} \right) \]
    which must satisfy
    \[ \nu_a \bigg|_{T=1 \text{ eV}} \leq 10^{-4} \]
  • This gives us a bound on the saxion mass:
    \[ m_s \leq 30 \text{ MeV} \left( \frac{10^9 \text{ GeV}}{f_a} \right) \]
The Model: Axions from the Early String Network

• Numerical analysis of [5] indicates that the phase transition may occur at a temperature $T_s$ that is within a few per cent of $T_c$

$$r_s = m_s^{-1}|1 - \alpha|^{-1/2} \quad T_s = \alpha T_c$$

• Giving string density

$$\rho_{str}^{early} = m_s^2 f_a^2 |1 - \alpha|$$

• And axion number density and yield

$$n_a^{str} \sim m_s f_a^2 |1 - \alpha|^{1/2}$$

$$Y_a^{str} \sim \frac{|1 - \alpha|^{1/2}}{m_s} T_{RH}$$