QCD Axion Dark Matter from a Late Time Phase Transition

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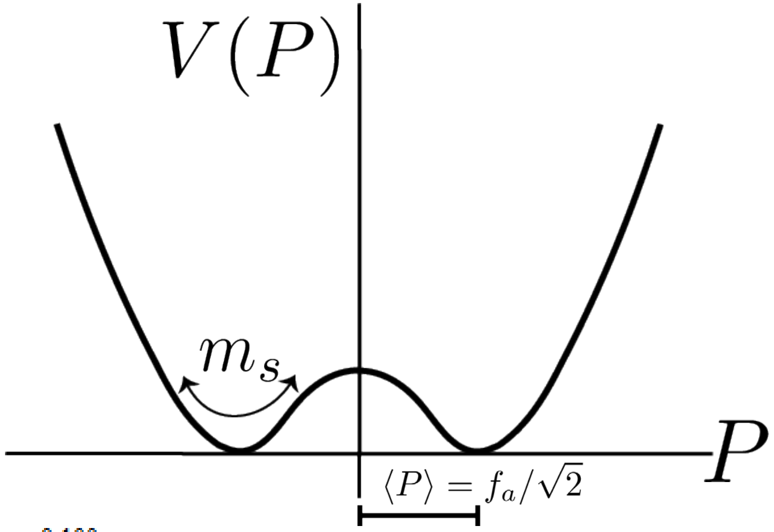
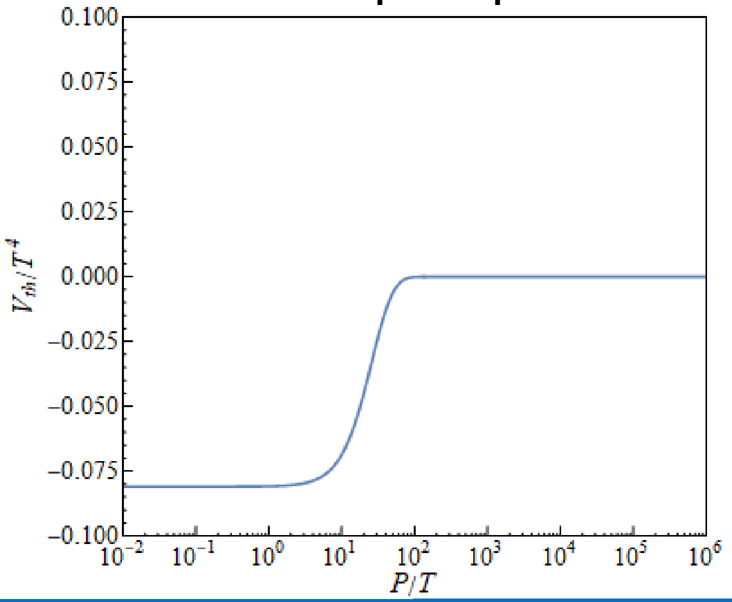
Results

- 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

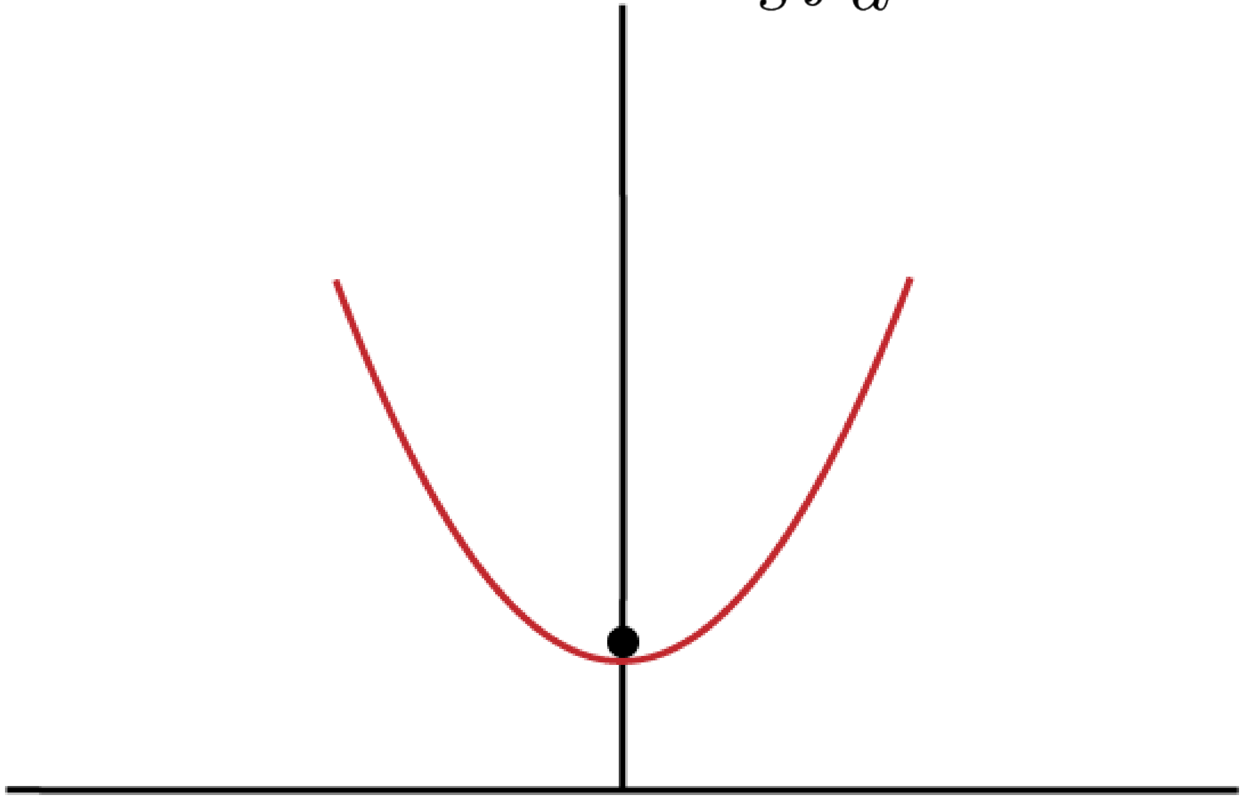
The Model



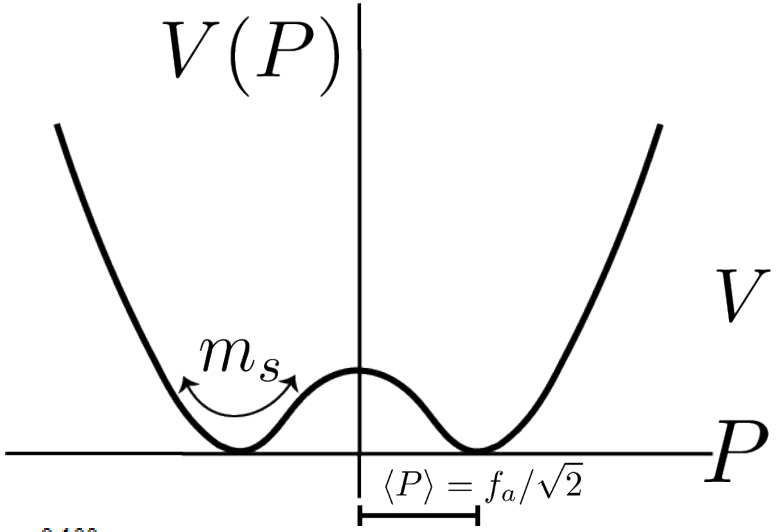


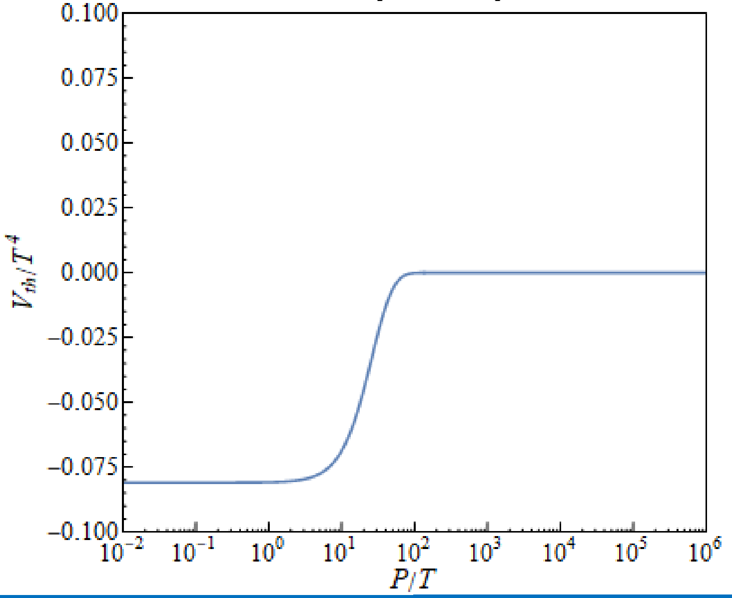
$$\mathcal{L} \supset yP\psi\bar{\psi}$$

$$T^4 >> m_s^2 f_a^2$$



The Model: Late Time Phase Transition

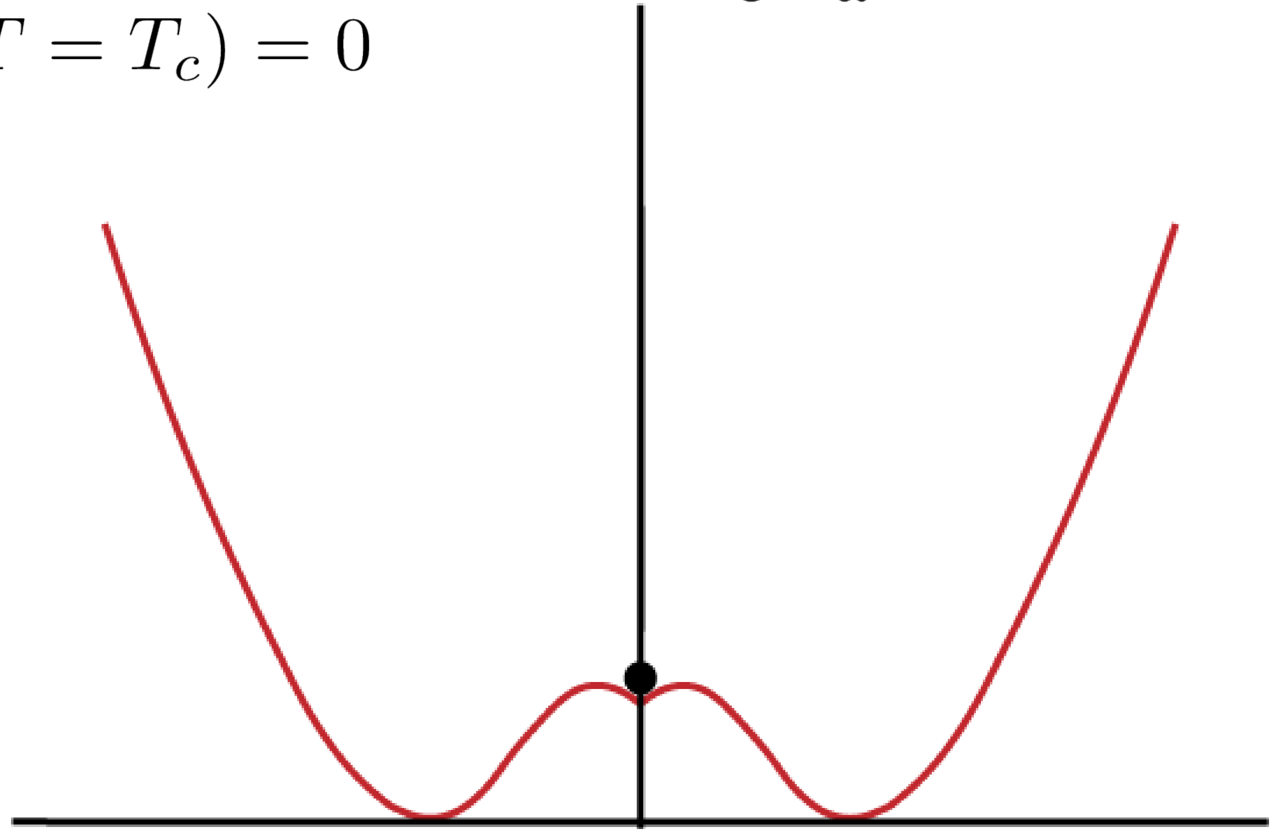




$$\mathcal{L} \supset yP\psi\bar{\psi}$$

$$T_c \ll f_a \qquad T^4 < m_s^2 f_a^2$$

$$V''(P=0, T=T_c) = 0$$



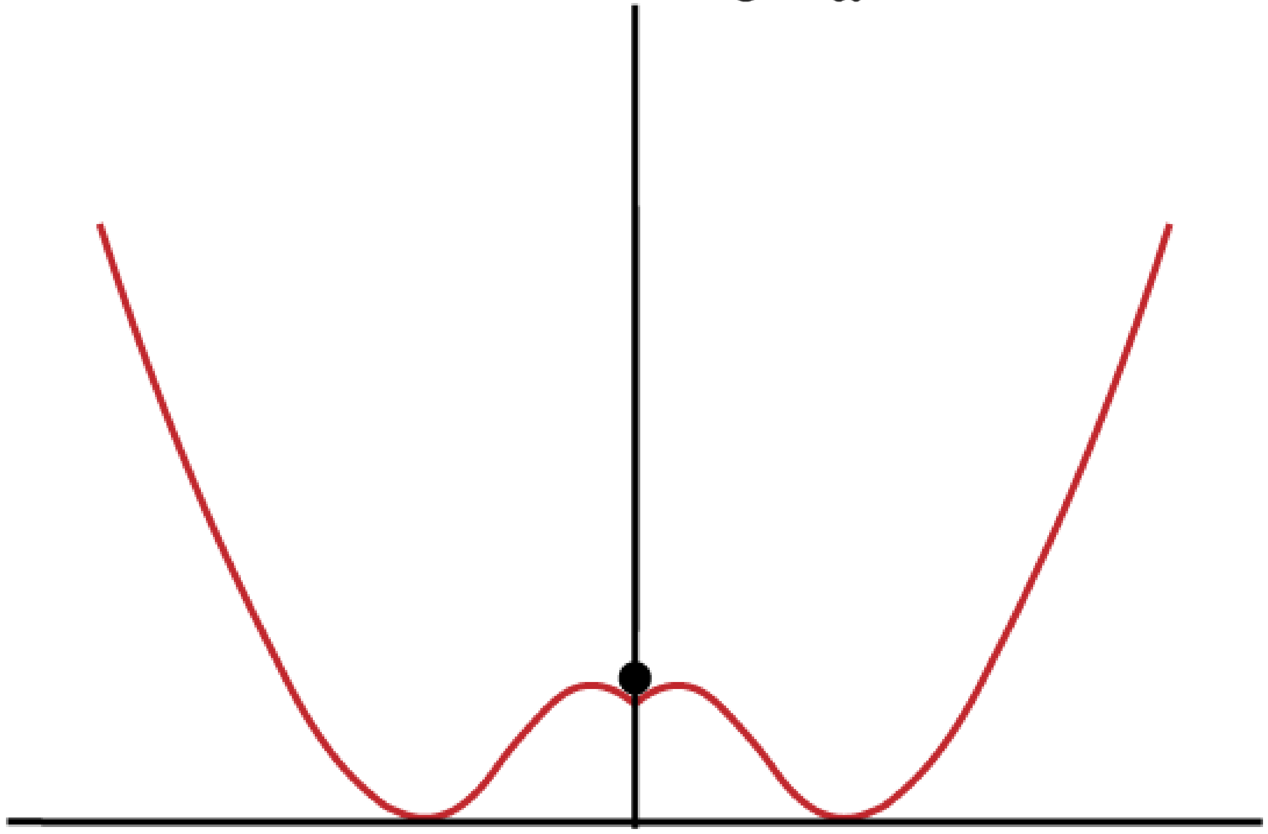
The Model: Late Time Phase Transition

$$\mathcal{L} \supset yP\psi\bar{\psi}$$

$$T_c \ll f_a \qquad T^4 < m_s^2 f_a^2$$

- 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*

$$T_s > T_p > T_c$$



Potential & Thermal Inflation

- 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:

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

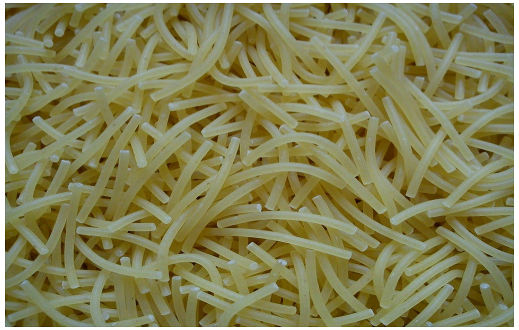
- We assume that the potential energy dominates and a period of thermal inflation occurs:

$$y \gtrsim \sqrt{\frac{m_s}{f_a}} \qquad H_{PT} \sim \frac{m_s f_a}{M_{pl}}$$

Axions from Cosmic Strings

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

$$\rho_{str} \sim \frac{f_a^2}{r_c^2} \qquad r_c = \alpha m_s^{-1} << r_H$$



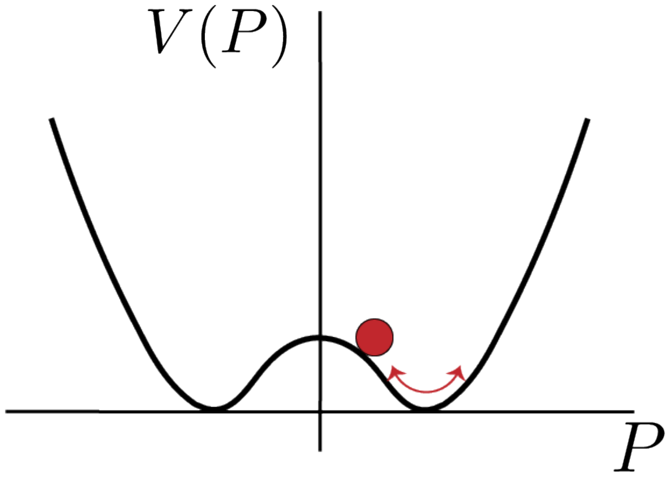
- Energy should be lost producing axions with momenta $\sim m_s$. However, this population is subdominant to parametric resonance

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:

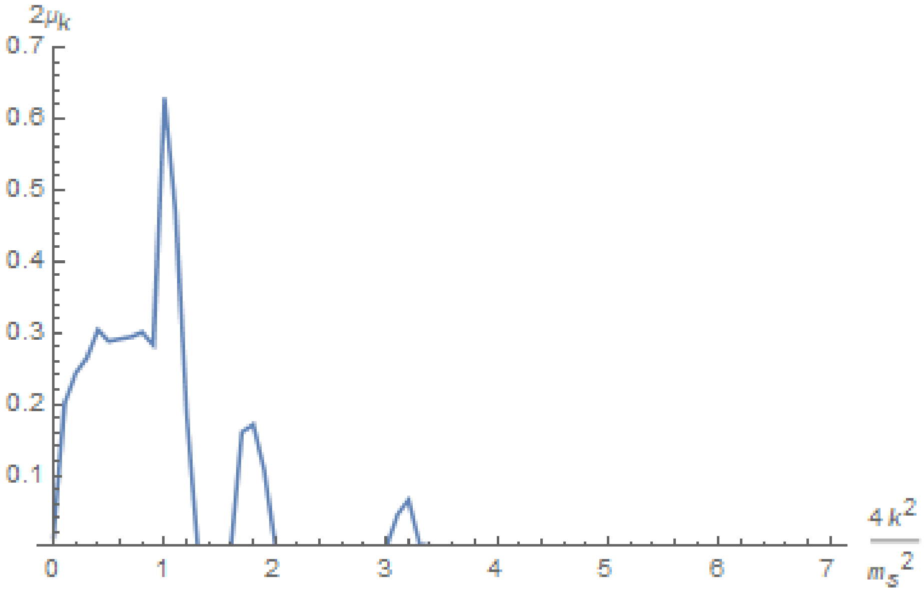
$$\ddot{s} + \left(m_s^2 + \frac{m_s^2}{4f_a^4}s^4 + \frac{5m_s^2}{4f_a^3}s^3 + \frac{5m_s^2}{2f_a^2}s^2 + \frac{5m_s^2}{2f_a}s\right)s = 0$$

  - 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

Axions as Dark Matter

- 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

$$T_{DM} \sim 0.7 \text{ GeV} \left(\frac{m_s}{10 \text{ MeV}}\right) \left(\frac{f_a}{10^9 \text{ GeV}}\right)$$

Thermalization & Warmness

- 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

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

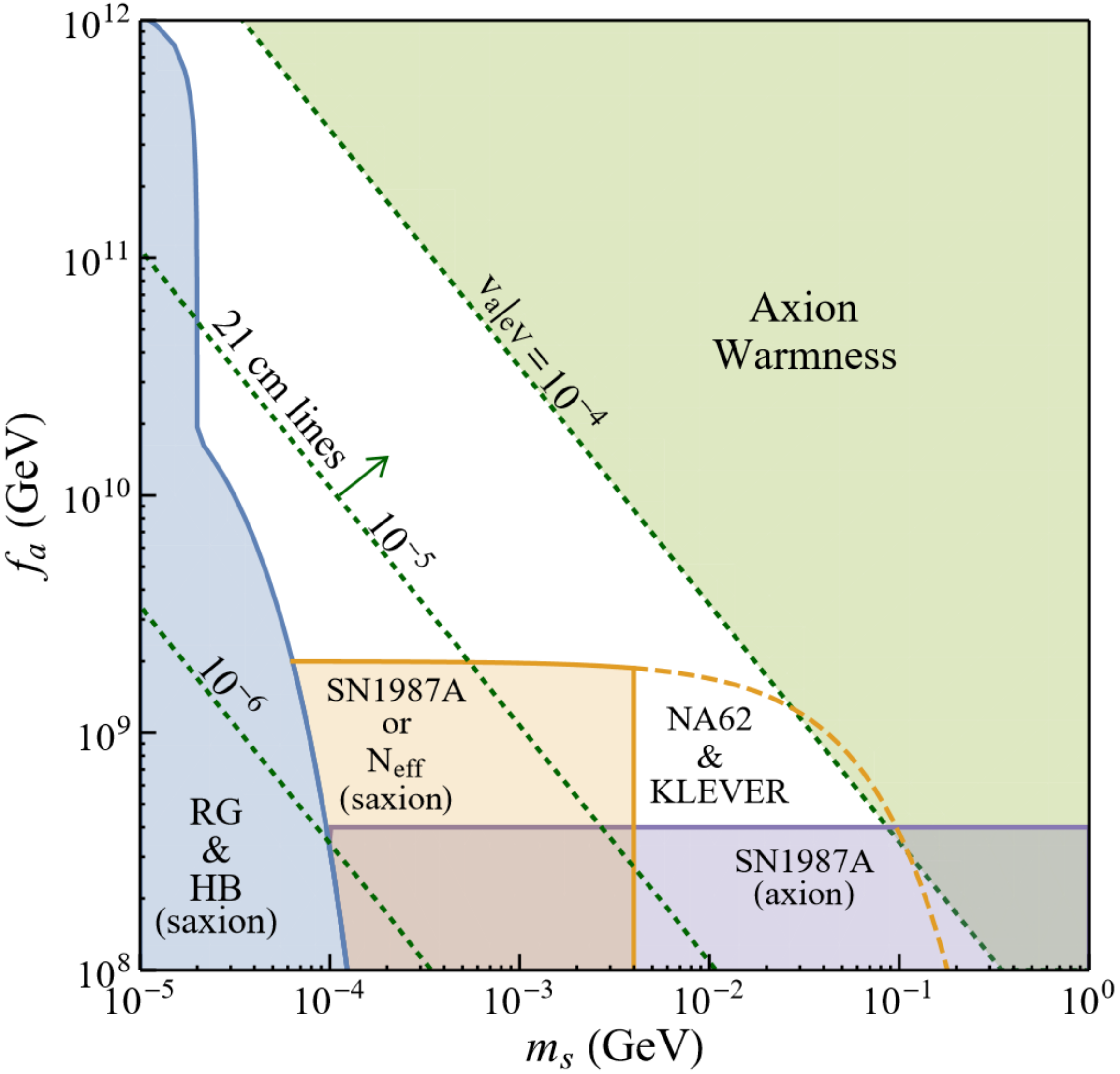
which must satisfy

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

giving bound

$$m_s \leq 30 \text{ MeV} \left(\frac{10^9 \text{ GeV}}{f_a}\right)$$

Parameter Space

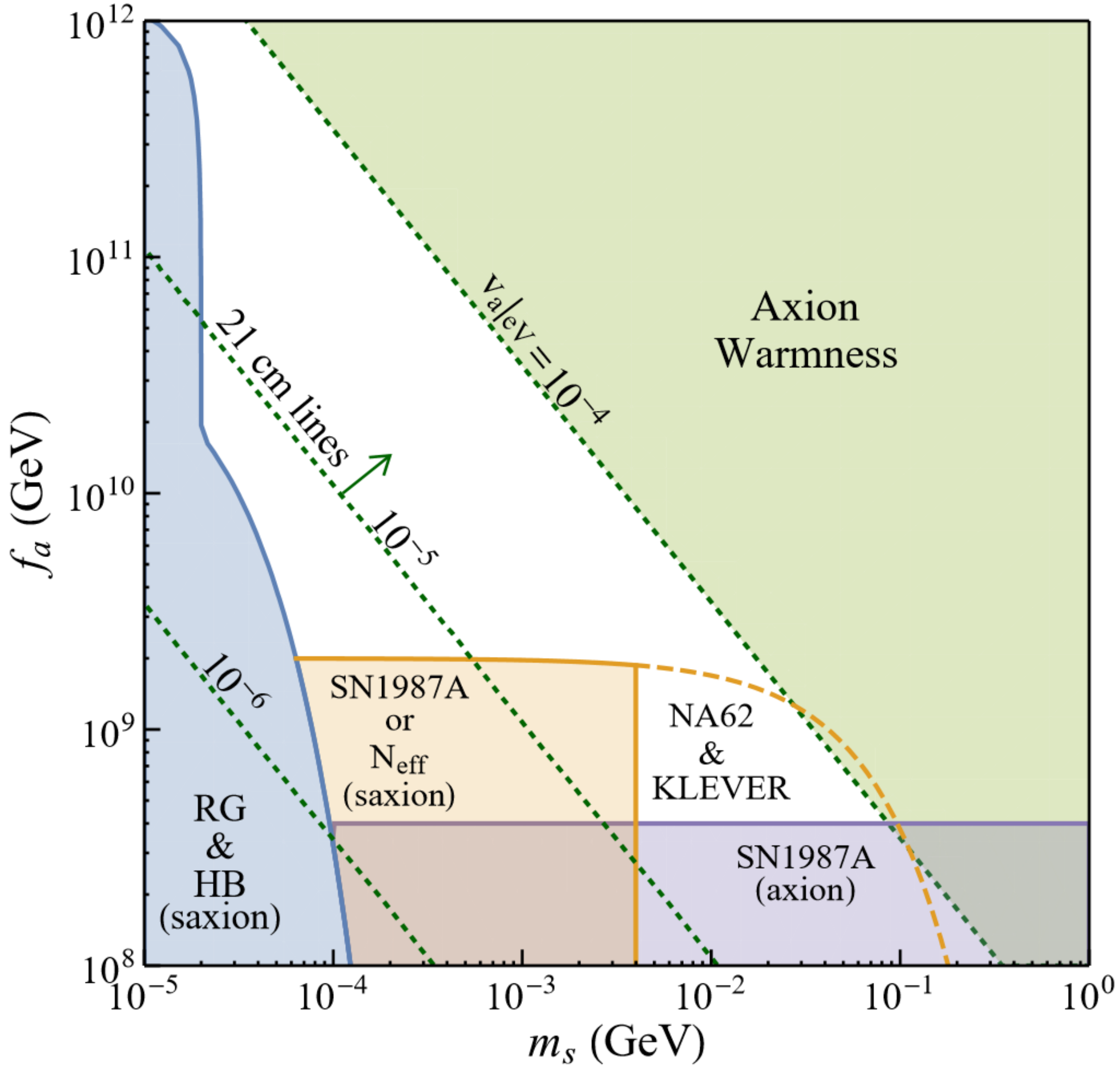


- We consider n=3 for definiteness
- The slanted, dashed green lines are contours for the axion velocity at T = 1 eV

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

- It would appear that fa = 10^9 GeV is ruled out. However, this is too strong a statement given the uncertainty in the supernovae constraints [4].

Parameter Space



- 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 $N_{eff} < 3$
  - Assuming the neutrinos suddenly decouple at T = 2 MeV, the saxion mass must satisfy

$$m_s > 4\ \mathrm{MeV}$$

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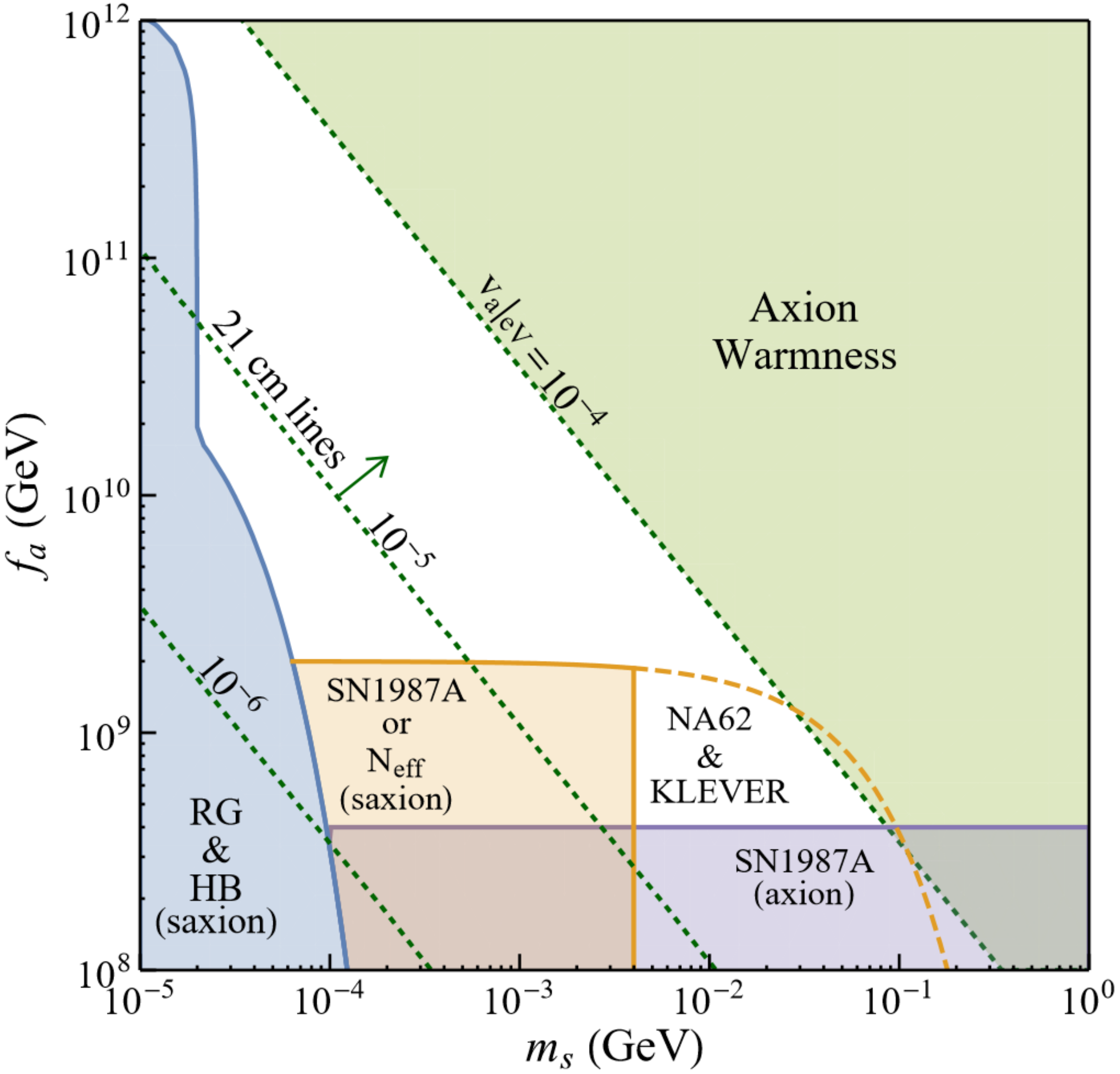
Experimental Signatures



- 21 cm lines & structure
  - High axion velocity -> warm dark matter scenario
  - Future observations of the 21cm should probe m_{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

$$K \to \pi + S$$

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

- [1]. Topological Dark matter – H. Murayama, J. Shu
- [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

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Back Up Slide: Stellar Constraints

- 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]

Back Up Slide: Reheating

- The saxion must be thermalized at or above TDM. We could consider a coupling between P and a new pair of fermions as

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

- 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, μ 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

Back Up Slide: Thermalization Details

- 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, $k_a^3/\rho_s = \text{constant}$

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

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

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

- The late time phase transition is critical!

Back Up Slide: Velocity Bound Details

- Consider a Weyl fermion that decouples while relativistic and dilutes later:

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

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

$$\frac{k}{m} \simeq 10^{-4}\left(\frac{T}{\mathrm{eV}}\right)\left(\frac{3.3\ \mathrm{keV}}{m}\right)^{4/3}$$

- Warm dark matter mass bound m_{WDM} > 3.3 keV gives velocity bound $v < 10^{-4}$ at T = 1 eV

Back Up Slide: Warmness Details

- 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

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

    which must satisfy

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

  - 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

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

- Giving string density

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

- And axion number density and yield

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

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