

Axions with “Maglev”



Gustavo Marques-Tavares,
University of Maryland & Johns Hopkins University

In collaboration with Anson Hook and Yuhsin Tsai

Basic Idea

- Consider axion – dark photon mixing in a magnetic field background

$$\frac{\phi}{f} F_d \tilde{F}$$

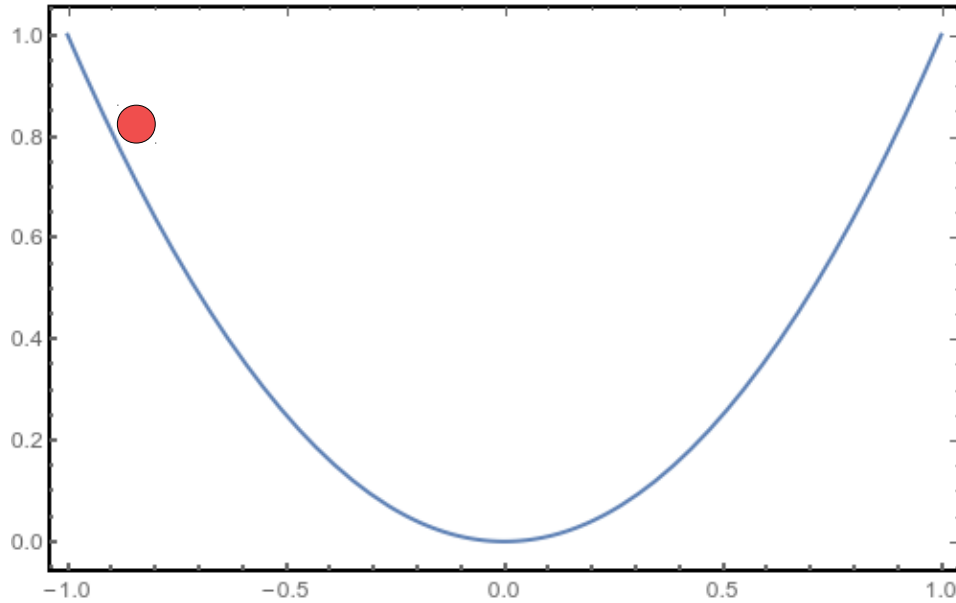
- Goals for the talk
 - show that this coupling reduces the axion oscillation frequency
 - show that it reduces the effect of Hubble friction
 - apply this mechanism to enhance small f_a axion abundance

Cosmological B

Disclaimer: Cosmological magnetic fields will play an important role. The standard picture is that a 1st order EW phase transition can generate magnetic fields with energy density of $O(1\%)$ of the plasma energy. I will assume there is such a magnetic field.

* see e.g. Durrer & Neronov <1303.7121>; Ellis et al. <1907.04315>

Axion cosmology review

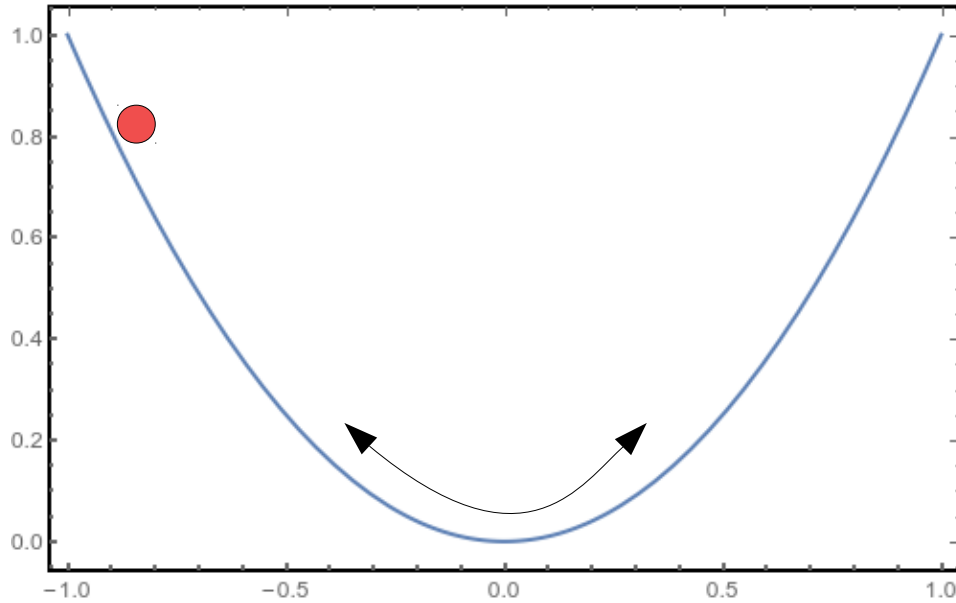


$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi$$

ϕ remains constant until

$$H \sim m$$

Axion cosmology review



$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi$$

ϕ remains constant until

$$H \sim m$$

After that it oscillates with frequency m :

$$\phi \approx \phi_0 (a_0/a)^{3/2} \cos mt$$

Mixing with dark photon

$$\frac{\phi}{f} F_d \tilde{F}$$

- Assume a background magnetic field: $\vec{B} = B(t)\hat{n}$

Mixing with dark photon

$$\frac{\phi}{f} F_d \tilde{F}$$

➤ Assume a background magnetic field: $\vec{B} = B(t)\hat{n}$

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = \frac{B}{af}\dot{A}_d$$

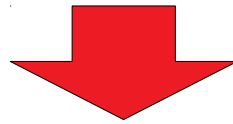
$$\ddot{A}_d + H\dot{A}_d + M_d^2 A_d = -\frac{aB}{f}\dot{\phi}$$

Ignore expansion 1st

- Assume a background magnetic field: $\vec{B} = B\hat{n}$

$$\ddot{\phi} + \cancel{3M^2}\dot{\phi} + m^2\phi = \frac{B}{\cancel{f}}\dot{A}_d$$

$$\ddot{A}_d + \cancel{M^2}A_d + M_d^2 A_d = -\frac{\cancel{B}}{f}\dot{\phi}$$



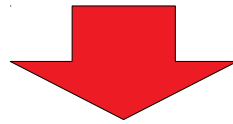
$$\omega_{\mp}^2 = \frac{B^2/f^2 + M_d^2 + m^2 \mp \sqrt{(B^2/f^2 + M_d^2 + m^2)^2 - 4m^2 M^2}}{2}$$

Ignore expansion 1st

- Assume a background magnetic field: $\vec{B} = B\hat{n}$

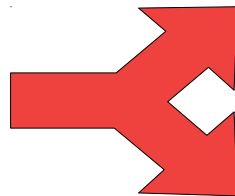
$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = \frac{B}{f}\dot{A}_d$$

$$\ddot{A}_d + M_d^2 A_d = -\frac{B}{f}\dot{\phi}$$



$$\omega_{\mp}^2 = \frac{B^2/f^2 + M_d^2 + m^2 \mp \sqrt{(B^2/f^2 + M_d^2 + m^2)^2 - 4m^2 M_d^2}}{2}$$

$$m \ll B/f$$



$$\omega_{-}^2 = \frac{m^2 M_d^2}{M_d^2 + B^2/f^2}$$

$$\omega_{+}^2 = B^2/f^2 + M_d^2$$

Focus on slow mode

$$\omega_-^2 = \frac{m^2 M_d^2}{M_d^2 + B^2/f^2} \xrightarrow{m \ll M \ll B/f} \omega_- \ll m \ll M$$

$$A_d \approx -i \frac{m}{M} \frac{B/f}{\sqrt{B^2/f^2 + M^2}} \phi$$


We will now use the intuition from this simple case to investigate the same system in an expanding universe

Focus on slow mode

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = \frac{B}{af}\dot{A}_d$$

$$\ddot{A}_d + H\dot{A}_d + M_d^2 A_d = -\frac{aB}{f}\dot{\phi}$$

$$\omega_-^2 = \frac{m^2 M_d^2}{M_d^2 + B^2/f^2}$$


While $H \gg M \gg m$  $\phi \approx \phi_0$
 $A_d \approx 0$

Focus on slow mode

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = \frac{B}{af}\dot{A}_d$$

$$\omega_-^2 = \frac{m^2 M_d^2}{M_d^2 + B^2/f^2}$$


~~$$\ddot{A}_d + H\dot{A}_d + M_d^2 A_d = -\frac{aB}{f}\dot{\phi}$$~~

Once $H \ll \omega_s$  $A_d = -\frac{aB/f}{M_d^2} \dot{\phi}$


$$\ddot{\phi} + \left[\left(3 - \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \right) H + \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \frac{\dot{B}(t)}{B} \right] \dot{\phi} = \frac{m^2 M_d^2}{B(t)^2/f^2 + M_d^2} \phi$$

Axions on “Maglev”

$$\ddot{\phi} + \left[\left(3 - \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \right) H + \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \frac{\dot{B}(t)}{B} \right] \dot{\phi} = \frac{m^2 M_d^2}{B(t)^2/f^2 + M_d^2} \phi$$



$$\begin{cases} 1, & B/f \gg M_d \\ 3, & B/f \ll M_d \end{cases}$$

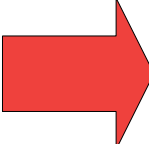


$$\omega_s^2$$

Axions on “Maglev”

$$\ddot{\phi} + \left[\left(3 - \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \right) H + \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \frac{\dot{B}(t)}{B} \right] \dot{\phi} = \underbrace{\frac{m^2 M_d^2}{B(t)^2/f^2 + M_d^2}}_{\omega_s^2} \phi$$

$$\begin{cases} 1, & B/f \gg M_d \\ 3, & B/f \ll M_d \end{cases}$$

 $\phi \approx \phi_0 e^{\int_{t_0}^t dt' \omega_s(t')} \times \begin{cases} \left(\frac{a_0}{a} \right)^{1/2}, & a < a_M \\ \left(\frac{a_0}{a_M} \right)^{1/2} \left(\frac{a_M}{a} \right)^{3/2}, & a > a_M \end{cases}$

$$H(a_0) \approx \omega_s(a_0)$$

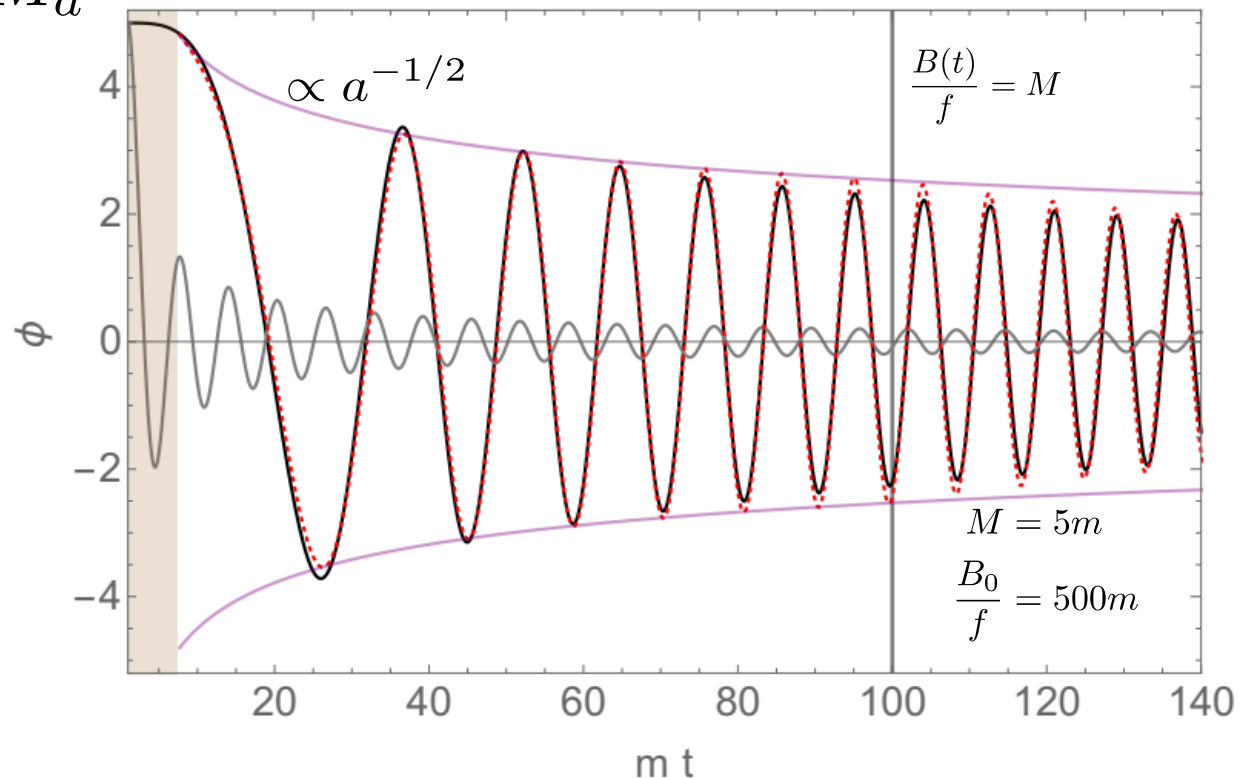
$$B(a_M)/f = M_d$$

Axions on “Maglev”

$$\ddot{\phi} + \left[\left(3 - \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \right) H + \frac{2B^2/f^2}{B^2/f^2 + M_d^2} \frac{\dot{B}(t)}{B} \right] \dot{\phi} = \frac{m^2 M_d^2}{B(t)^2/f^2 + M_d^2} \phi$$

$$\begin{cases} 1, & B/f \gg M_d \\ 3, & B/f \ll M_d \end{cases}$$

$$\omega_s^2$$



Big Picture



Big Picture



When $B/f \gg M_d \gg m$

$$\Rightarrow \omega \rightarrow m \frac{M_d}{B/f}$$

$$\Rightarrow \phi \propto \left(\frac{a_0}{a} \right)^{1/2}$$

Axion starts oscillating later (longer time as c.c) and Hubble friction greatly reduced.

\Rightarrow Enhance final axion abundance

Exploring new tool

Make QCD axion models with $f_a < 10^{12}$
GeV viable dark matter



*last train picture

QCD axion abundance

$$\frac{\alpha_s \phi}{8\pi f_a} G\tilde{G} \longrightarrow m_\phi(T) \approx \frac{m_\pi f_\pi}{f_a} \times \begin{cases} \left(\frac{T_0}{T}\right)^4, & \text{for } T > T_0, \\ 1, & \text{for } T \leq T_0 \end{cases}$$

QCD axion abundance

$$\frac{\alpha_s \phi}{8\pi f_a} G\tilde{G} \quad \longrightarrow \quad m_\phi(T) \approx \frac{m_\pi f_\pi}{f_a} \times \begin{cases} \left(\frac{T_0}{T}\right)^4, & \text{for } T > T_0, \\ 1, & \text{for } T \leq T_0 \end{cases}$$

$$\text{For } f_a < 10^{15} \text{ GeV, } m_\phi \approx H \quad \text{for } T \gtrsim 1 \text{ GeV}$$

After oscillations start, comoving number density is conserved

$$m_\phi(T) \phi^2(T) \approx m_\phi(T_{\text{osc}}) \phi^2(T_{\text{osc}}) \left(\frac{T}{T_{\text{osc}}}\right)^3$$

$$\Omega_a \sim 0.1 \left(\frac{f_a}{10^{12} \text{ GeV}}\right)^{7/6}$$

QCD axion with “Maglev”

$$\Omega_a \sim 0.1 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6}$$

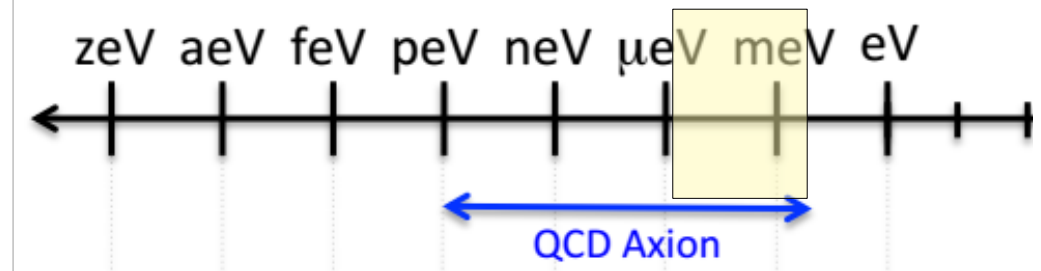
Astrophysical bounds

$$f_a \gtrsim 10^9 \text{ GeV}$$

Low f_a axions would require 3 order of magnitude increase in abundance to explain all of dark matter.

$$f_a = 10^{12} \text{ GeV} \leftrightarrow m_\phi \approx 10 \mu\text{eV}$$

$$f_a = 10^9 \text{ GeV} \leftrightarrow m_\phi \approx 10 \text{ meV}$$



QCD axion with “Maglev”

$$\Omega_a \sim 0.1 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \quad \text{Astrophysical bounds} \quad f_a \gtrsim 10^9 \text{ GeV}$$

Low f_a axions would require 3 order of magnitude increase in abundance to explain all of dark matter.

$$\frac{\phi}{f} F_d \tilde{F} - M_d^2 A_d^2 \quad \longrightarrow \quad \frac{\Omega_\phi(B)}{\Omega_\phi(B=0)} \approx \left(\frac{T_{\text{osc}}(B=0)}{T_{\text{osc}}(B)} \right)^{13}$$

Can get up to $\sim 10^4$ enhancement

Conclusion

- Magnetic mixing between axions and massive vectors can dramatically change axion cosmology
- Leads to a delayed oscillation and reduced Hubble friction effects while dynamics is dominated by the magnetic mixing term
- Allows for smaller f_a (heavier) axion dark matter
- Probably many other interesting applications...