The Cosmological Tension of Ultralight Axion Dark Matter and its Solutions

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Jeff Dror, JML
Ultraslight Dark Matter: $m \sim 10^{-22} - 10^{-13}$ eV

"Fuzzy" Regime: $m \sim 10^{-22} - 10^{-21}$ eV
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Consider \( a \) as the goldstone boson of some global symmetry breaking or zero mode of higher form field

Continuous Shift Symmetry \( \rightarrow \) Small mass natural
Ultralight Dark Matter: $m \sim 10^{-22} - 10^{-13}$ eV

“Fuzzy” Regime: $m \sim 10^{-22} - 10^{-21}$ eV

Consider $a$ as the goldstone boson of some global symmetry breaking or zero mode of higher form field

Continuous Shift Symmetry $\Rightarrow$ Small mass natural

Broken to discrete shift symmetry:

$$V(a) = \mu^4 \cos \left( \frac{a}{f_a} \right) \Rightarrow m_a \sim \frac{\mu^2}{f_a}$$

Today: Derive bounds on ULA DM from the matter-power spectrum & describe model building techniques to (partially) evade these bounds.
Couplings to Standard Model

- Anomalous & derivative couplings $\propto 1/f_a$
- Axion - Photon Coupling
  \[ \mathcal{L} \supset \frac{C_{a\gamma}}{8\pi f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]
- Axion - Nucleon Coupling
  \[ \mathcal{L} \supset \frac{C_{aN}}{f_a} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N \]
- Other Couplings
  - Electron: [1709.07852 - Graham et al]
  - Muon: [2005.11867 - Graham et al] & [2006.10069 - Janish et al]
Photon Coupling Parameter Space

\[ g_{\alpha\gamma}[\text{GeV}^{-1}] \]

\[ m_a[\text{eV}] \]

SN-1987A
Nucleon Coupling Parameter Space

\[ g_{aN} \text{[GeV}^{-1}] \]

\[ m_a \text{[eV]} \]

SN-1987A

CASPEr

atom interferometry

comagnetometer

storage ring

\[ \alpha_N \]

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Cosmological Tension of Ultralight Axion Dark Matter
Bounds from the Matter-Power Spectrum (Rough)

- $V = \mu^4 \cos \frac{a}{f_a}$

$$m_a^2 \sim \frac{\mu^2}{f_a} \quad \lambda_a \sim \frac{\mu^4}{f_a^4}$$
$V = \mu^4 \cos \frac{a}{f_a}$

$m_a^2 \sim \frac{\mu^2}{f_a}$ \quad \lambda_a \sim \frac{\mu^4}{f_a^4}$

Using

$\left( \frac{\delta \rho}{\rho} \right)_{eq} \leq 10^{-3} \quad \& \quad \rho_{DM}^{eq} \sim eV^4 \implies a_{eq} \sim \frac{eV^2}{m_a}$
Bounds from the Matter-Power Spectrum (Rough)

- \( V = \mu^4 \cos \frac{a}{f_a} \)
  
  \( m_a^2 \sim \frac{\mu^2}{f_a} \) \quad \lambda_a \sim \frac{\mu^4}{f_a^4} \)

- Using

  \( \left( \frac{\delta \rho}{\rho} \right)_{eq} \lesssim 10^{-3} \quad \& \quad \rho_{DM}^{eq} \sim eV^4 \implies a_{eq} \sim \frac{eV^2}{m_a} \)

- We find

  \( \left. \frac{\lambda_a a^4}{m_a^2 a^2} \right|_{eq} \lesssim 10^{-3} \implies \frac{eV^4}{m_a^2 f_a^2} \lesssim 10^{-3} \)

**The Rough Cosmological Bound**

\( f_a \gtrsim 3 \times 10^{12} \text{ GeV} \left( \frac{10^{-20} \text{ eV}}{m_a} \right) \)
Numerical studies of the Matter-Power Spectrum

Hubble friction freezes axion until $H(z_c) \approx m_a$ and oscillations begin

Ultralight axion acts similar to warm dark matter: require $z_c \gtrsim 10^5$

$$\rho_{DM} \simeq \frac{1}{2} m_a^2 a(z)^2$$

$$a(z) \propto (1 + z)^{3/2}$$

The Numerical Cosmological Bound

$$f_a \gtrsim 1.2 \times 10^{13} \text{ GeV} \left( \frac{10^{-20} \text{ eV}}{m_a} \right)$$

Very close to rough bound

[1806.10608 - Poulin et al]
Photon Coupling Parameter Space

\[ g_{\alpha\gamma} \text{[GeV}^{-1}] \]

\[ m_\alpha \text{[eV]} \]

- CMB birefringence
- AGN
- PPD
- Ly\(\alpha\)
- Generic axion
- SN-1987A

optical ring
Photon Coupling Parameter Space

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Cosmological Tension of Ultralight Axion Dark Matter
Photon Coupling Parameter Space

$g_{\alpha\gamma} [\text{GeV}^{-1}]$

$m_{a} [\text{eV}]$

CMB birefringence
AGN
pulsar
generic axion
Ly $\alpha$
PPD
SN-1987A
optical ring

Cosmological Tension of Ultralight Axion Dark Matter
Nucleon Coupling Parameter Space

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Cosmological Tension of Ultralight Axion Dark Matter
Q: What are experiments looking for?
Need to raise coupling to visible matter for a given mass

$\implies$ non-trivial model building

Focus on photon coupling:

$$\mathcal{L} \supset \mu^4 \cos \frac{a}{f_a} + \frac{C_{a\gamma} \alpha_{EM}}{8\pi f_a} a F \tilde{F}$$

Need strategies to increase the value of $C_{a\gamma}$

Considered in the literature for QCD axions & axion inflation

- [hep-ph/0409138 - Kim, Nilles Peloso]
- [1611.09855 - Farina et al]
- [1503.01015 - Shiu, Staessens, Ye]
- [1709.06085 - Agrawal et al]
- [1503.02965 - Shiu, Staessens, Ye]
- [1806.09621 - Agrawal, Fan, Reece]
- [1511.00132 - Choi, Im]
- [1909.11685 - Choi, Shin, Yun]
- [1511.01827 - Kaplan, Rattazzi]
- [1910.11349 - Fraser, Reece]

...
Q: What are experiments looking for?

A: Rube Goldberg (Axion) Model: An axion that requires additional model building to be detectable.
**Large Charges:** simple idea - adjust fermion content

\[ C_{a\gamma} = \text{Tr}(Q_{EM}^2) \sim N_f Q_{EM}^2 \]

\[
\gamma \sim \bigcirc \sim \gamma \quad \Rightarrow \quad \frac{N_f Q^2 e^2}{(4\pi)^2} \lesssim 1
\]
**Large Charges:** simple idea - adjust fermion content

\[
C_{a\gamma} = \text{Tr}(Q_{EM}^2) \sim N_f Q_{EM}^2
\]

\[N_f Q^2 e^2 \left(\frac{4\pi)^2}{(4\pi)^2}\right) \lesssim 1\]

Can get \( C_{a\gamma} \sim \mathcal{O}(10^2) \)
**Large Charges:** simple idea - adjust fermion content

\[ C_{a\gamma} = \text{Tr}(Q_{EM}^2) \sim N_f Q_{EM}^2 \]

\[ \gamma \sim \gamma \implies \frac{N_f Q^2 e^2}{(4\pi)^2} \lesssim 1 \]

Can get \( C_{a\gamma} \sim O(10^2) \)

**Kinetic Mixing:** with two axions

\[ \mathcal{L} \supset \frac{1}{2}(\partial a_1)^2 + \frac{1}{2}(\partial a_2)^2 + \epsilon \partial a_1 \partial a_2 + \mu^4 \cos \frac{a_1}{F_1} + \frac{\alpha}{8\pi F_2} a_2 F \tilde{F} \]

\[ \implies \mathcal{L} \supset \frac{\epsilon F_1}{F_2} \frac{\alpha}{8\pi F_1} a_1 F \tilde{F} \]

If \( C_{a\gamma} = \epsilon F_1/F_2 \gg 1 \), then axion-photon coupling is enhanced.
**Large Charges**: simple idea - adjust fermion content

\[ C_{a\gamma} = \text{Tr}(Q_{EM}^2) \sim N_f Q_{EM}^2 \]

\[ \gamma \sim -\gamma \implies \frac{N_f Q^2 e^2}{(4\pi)^2} \lesssim 1 \]

**Can get** \( C_{a\gamma} \sim \mathcal{O}(10^2) \)

**Kinetic Mixing**: with two axions

\[ \mathcal{L} \ni \frac{1}{2}(\partial a_1)^2 + \frac{1}{2}(\partial a_2)^2 + \epsilon \partial a_1 \partial a_2 + \mu^4 \cos \frac{a_1}{F_1} + \frac{\alpha}{8\pi F_2} a_2 F \tilde{F} \]

\[ \implies \mathcal{L} \ni \frac{\epsilon F_1}{F_2} \frac{\alpha}{8\pi F_1} a_1 F \tilde{F} \]

If \( C_{a\gamma} = \epsilon F_1/F_2 >> 1 \), then axion-photon coupling is enhanced.

**This is not easily achieved in field theory**
Discrete Symmetry:

1 axion and $N$ non-abelian confining gauge sectors $G(n)$

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \sum_{i=1}^{N} \left( \frac{a}{F_a} + \frac{2\pi i}{N} \right) G(i) \tilde{G}(i) + \frac{\alpha_{EM}}{8\pi F_a} aF \tilde{F}$$

[1802.10093 - Hook]
Discrete Symmetry:

1 axion and \( N \) non-abelian confining gauge sectors \( G(n) \)

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\mathcal{L} \supset \frac{\alpha_s}{8\pi} \sum_{i=1}^{N} \left( \frac{a}{F_a} + \frac{2\pi i}{N} \right) G(i) \tilde{G}(i) + \frac{\alpha_{EM}}{8\pi F_a} aF \tilde{F}
\]

\[
V(a) = -\mu^4 \sum_{n=0}^{N-1} \sqrt{1 - z \sin^2 \left( \frac{a}{2F_a} + \frac{\pi n}{N} \right)}
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\[
V(a) = \frac{C_2}{2} \frac{\mu^4}{F_a^2} a^2 - \frac{C_4}{4!} \frac{\mu^4}{F_a^4} a^4 + \cdots
\]

$C_{a\gamma} = C_2^{-1/2}$
Discrete Symmetry:

1 axion and \( N \) non-abelian confining gauge sectors \( G(n) \)

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\mathcal{L} \supset \frac{\alpha_s}{8\pi} \sum_{i=1}^{N} \left( \frac{a}{F_a} + \frac{2\pi i}{N} \right) G(i) \tilde{G}(i) + \frac{\alpha_{EM}}{8\pi F_a} a F \tilde{F}
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\[ C_{a\gamma} = C_2^{-1/2} \]

Large enhancement gives large deviations in matter-power spectrum
**Clockwork**: $N$ axions $a_i$ & $N$ non-abelian confining gauge sectors $G_{(i)}$

$$
\mathcal{L} \supset \sum_{i=1}^{N-1} \frac{\alpha_{i+1}}{8\pi} \left( \frac{\beta_i a_i}{F_i} + \frac{a_{i+1}}{F_{i+1}} \right) G_{(i+1)} \tilde{G}_{(i+1)} + \frac{\alpha_1}{8\pi F_1} a_1 G_1 \tilde{G}_1 + \frac{\alpha_{EM}}{8\pi F_N} a_N F \tilde{F}
$$
**Clockwork**: $N$ axions $a_i$ & $N$ non-abelian confining gauge sectors $G_{(i)}$

$$\mathcal{L} \supset \sum_{i=1}^{N-1} \frac{\alpha_{i+1}}{8\pi} \left( \frac{\beta_i a_i}{F_i} + \frac{a_{i+1}}{F_{i+1}} \right) G_{(i+1)} \tilde{G}_{(i+1)} + \frac{\alpha_1}{8\pi F_1} a_1 G_1 \tilde{G}_1 + \frac{\alpha_{EM}}{8\pi F_N} a_N F \tilde{F}$$

$$V \simeq \sum_{i=1}^{N-1} \mu_{i+1}^4 \cos \left( \frac{\beta_i a_i}{F_i} + \frac{a_{i+1}}{F_{i+1}} \right) + \mu_1^4 \cos \frac{a_1}{F_1}$$
Clockwork: $N$ axions $a_i$ & $N$ non-abelian confining gauge sectors $G_{(i)}$

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\mathcal{L} \supset \sum_{i=1}^{N-1} \frac{\alpha_{i+1}}{8\pi} \left( \frac{\beta_i a_i}{F_i} + \frac{a_{i+1}}{F_{i+1}} \right) G_{(i+1)} \tilde{G}_{(i+1)} + \frac{\alpha_1}{8\pi F_1} a_1 G_1 \tilde{G}_1 + \frac{\alpha_{EM}}{8\pi F_N} a_N F \tilde{F}
$$

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V \simeq \sum_{i=1}^{N-1} \mu_{i+1}^4 \cos \left( \frac{\beta_i a_1}{F_i} + \frac{a_{i+1}}{F_{i+1}} \right) + \mu_1^4 \cos \frac{a_1}{F_1}
$$

Integrating out heavy axions

$$
\mathcal{L} \supset \mu_1^4 \cos \frac{a_N}{F_N \prod_i \beta_i} + \frac{\alpha_{EM}}{8\pi F_N} a_N F \tilde{F}
$$

$$
C_{\alpha \gamma} = \prod_i \beta_i
$$
Clockwork: $N$ axions $a_i$ & $N$ non-abelian confining gauge sectors $G_{(i)}$

$$\mathcal{L} \supset \sum_{i=1}^{N-1} \frac{\alpha_{i+1}}{8\pi} \left( \frac{\beta_i a_i}{F_i} + \frac{a_i+1}{F_i+1} \right) G_{(i+1)} \tilde{G}_{(i+1)} + \frac{\alpha_1}{8\pi F_1} a_1 G_1 \tilde{G}_1 + \frac{\alpha_{EM}}{8\pi F_N} a_N F \tilde{F}$$

$$V \simeq \sum_{i=1}^{N-1} \mu_{i+1}^4 \cos \left( \frac{\beta_i a_1}{F_i} + \frac{a_i+1}{F_i+1} \right) + \mu_1^4 \cos \frac{a_1}{F_1}$$

Integrating out heavy axions

$$\mathcal{L} \supset \mu_1^4 \cos \frac{a_N}{F_N \prod_i \beta_i} + \frac{\alpha_{EM}}{8\pi F_N} a_N F \tilde{F}$$

$$C_{\alpha \gamma} = \prod_i \beta_i$$

Even for modest $\beta_i$, large enough $N$ gives significant enhancement
Conclusions

- The matter-power spectrum places strong constraints on ultralight axion dark matter models.
Conclusions

- The matter-power spectrum places strong constraints on ultralight axion dark matter models
- Can you model build the bound away? Sort of.
  - Large Charges/Lots of fermions - limited effectiveness
  - Kinetic mixing - doesn't seem to work from the EFT perspective. String constructions could work, but no concrete examples.
  - Using discrete symmetry - matter-power spectrum bound gets stronger, not viable.
  - Clockwork - viable. Unlimited effectiveness from EFT perspective, limited effectiveness in UV completions (?).