Title: Probing the String Axiverse with Galaxy Surveys

Speakers: Alex Lague

Series: Cosmology & Gravitation

Date: August 02, 2022 - 11:00 AM

URL: https://pirsa.org/22080001

Abstract: String theory suggests the existence of multiple axion species forming what is known as an "axiverse". The axions in this model are thought to have logarithmically-distributed masses extending far below $10^{-21}$ eV, leading to the presence of ultralight axions. The latter have astrophysical de Broglie wavelength and affect the cosmic structures in which they cluster by erasing small-scale features. In contrast to other ultralight or fuzzy dark matter models, the string axiverse allows for a mixed dark sector with a subdominant ultralight component. Trace amounts of ultralight axions have been shown alleviate some observational discrepancies in cosmology such as the missing satellite problem and the Hubble-S8 tensions. Using an effective field theory approach and data from the Baryon Oscillation Spectroscopic Survey, we reach the strongest constraints on the axion relic density for axions with masses below $10^{-25}$ eV. To study heavier axions, we develop a new algorithm capable of simulating the formation of large-scale structure in the presence of more than one axion species. Making use of this code, we isolate new observational features in the cosmic web which may help us detect the presence of a plenitude of axions with weak lensing surveys.

Zoom Link: https://pitp.zoom.us/j/95089179013?pwd=NTBIeitScFRhYnBBSnlrcnoyVEhydz09
Probing the String Axiverse with Galaxy Surveys

Alex Laguë
Perimeter Institute Seminar, Aug. 2022
The multiple components that compose our universe
Current composition (as the fractions evolve with time)

- Dark energy: 69%
- Dark matter: 25%
- Atomic matter: 5%
- Neutrinos: 0.1%
- Photons: 0.01%
- Black holes: 0.005%

Science/AAAS
The multiple components that compose our universe
Current composition (as the fractions evolve with time)

- Dark energy: 69%
- Dark matter: 25%
- Atomic matter: 5%
- Neutrinos: 0.1%
- Photons: 0.01%
- Black holes: 0.005%
ΛCDM Tensions

Joudaki et al.

H0LiCOW Collaboration
Small-Scale Tensions

Bullock et al.

Santos-Santos et al.
Ultralight Axions, Fuzzy Dark Matter, ULDM, Wave DM, ψDM…

\[ m_a \lesssim 10^{-21} \text{ eV} \]
\[ m \sim 10^{-22} \text{ eV} \]

\[ \lambda_{dB} = \frac{h}{mv} \sim 1 \text{ kpc} \]
\[ m \sim 10^{-22} \text{ eV} \]

\[ \lambda_{dB} = \frac{h}{mv} \sim 1 \text{ kpc} \]
The QCD Axion

$m_{a,\text{QCD}} \gtrsim 10^{-6}$ eV

Source: https://cajohare.github.io/AxionLimits/docs/am.html
The String Theory Axion

Axions In String Theory

Peter Svěck
Department of Physics and SLAC, Stanford University, Stanford CA 94305/94309 USA
and
Edward Witten
Institute For Advanced Study, Princeton NJ 08540 USA

String Axiverse

Asimina Arvanitaki\textsuperscript{a,b}, Savas Dimopoulos\textsuperscript{c}, Sergei Dubovsky\textsuperscript{c,d}, Nemanja Kaloper\textsuperscript{e}, and John March-Russell\textsuperscript{f}

Multiple-axion framework

Thomas C. Bachlechner\textsuperscript{1}, Kate Eckerle\textsuperscript{1}, Oliver Janssen\textsuperscript{2,3}, and Matthew Kleban\textsuperscript{2,3}

Axionic Band Structure of the Cosmological Constant

Thomas C. Bachlechner

\[ N_{\text{ax}} = \mathcal{O}(10) - \mathcal{O}(100) \]
The String Axiverse
The String Axiverse (simplified)
The String Axiverse (simplified)

$$f = \frac{\Omega_a}{\Omega_a + \Omega_{CDM}}$$

$$\Omega_a$$

UL Axion

$$\Omega_{CDM}$$

$$\log_{10} m_a$$
**Partially Ultralight DM**

- 10% of $10^{-25}$ eV for $H_0$ tension  
  \[ \text{(Blum & Teodori, 2021)} \]
- 6% of $10^{-26}$ eV for $H_0 + S_8$ tensions (with EDE)  
  \[ \text{(Ye et al. 2021)} \]
- 5% of $10^{-26}$ eV for $H_0 + S_8$ tensions (with DDE)  
  \[ \text{(Allali et al. 2022)} \]
- 1% of $10^{-27}$ eV for $H_0 + S_8$ tensions (with KMIX)  
  \[ \text{(Alexander et al. 2022)} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m_a \simeq 10^{-28}$ eV</th>
<th>$m_a \simeq 10^{-27}$ eV</th>
<th>$m_a \simeq 10^{-26}$ eV</th>
<th>$m_a \simeq 4 \times 10^{-26}$ eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_0$ [km/s/Mpc]</td>
<td>70.7 (70.2)$^{+1.0}_{-1.0}$</td>
<td>71.2 (71.4)$^{+1.1}_{-1.1}$</td>
<td>71.56 (70.99)$^{+0.99}_{-0.98}$</td>
<td>71.0 (70.9)$^{+1.1}_{-1.1}$</td>
</tr>
<tr>
<td>$S_8$</td>
<td>0.812 (0.812)$^{+0.010}_{-0.010}$</td>
<td>0.804 (0.797)$^{+0.013}_{-0.013}$</td>
<td>0.784 (0.789)$^{+0.014}_{-0.014}$</td>
<td>0.792 (0.783)$^{+0.017}_{-0.017}$</td>
</tr>
<tr>
<td>Tension with SH$_0$ES</td>
<td>1.9 $\sigma$</td>
<td>1.6 $\sigma$</td>
<td>1.4 $\sigma$</td>
<td>1.7 $\sigma$</td>
</tr>
<tr>
<td>Tension with $S_8$</td>
<td>2.6 $\sigma$</td>
<td>2.1 $\sigma$</td>
<td>1.2 $\sigma$</td>
<td>1.6 $\sigma$</td>
</tr>
<tr>
<td>$X_{DS}^2 - X_{LCDM}^2$</td>
<td>-6.9</td>
<td>-9.7</td>
<td>-17.9</td>
<td>-11.7</td>
</tr>
</tbody>
</table>
**Partially Ultralight DM**

- 10% of $10^{-25}$ eV for $H_0$ tension
  
- 6% of $10^{-26}$ eV for $H_0 + S_8$ tensions (with EDE)
  
- 5% of $10^{-26}$ eV for $H_0 + S_8$ tensions (with DDE)
  
- 1% of $10^{-27}$ eV for $H_0 + S_8$ tensions (with KMIX)

(Blum & Teodori, 2021)

(Ye et al. 2021)

(Allali et al. 2022)

(Alexander et al. 2022)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m_a \simeq 10^{-28}$ eV</th>
<th>$m_a \simeq 10^{-27}$ eV</th>
<th>$m_a \simeq 10^{-26}$ eV</th>
<th>$m_a \simeq 4 \times 10^{-26}$ eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_0$ [km/s/Mpc]</td>
<td>70.7 (70.2)(^{+1.0}_{-1.0})</td>
<td>71.2 (71.4)(^{+1.1}_{-1.1})</td>
<td>71.56 (70.99)(^{+0.99}_{-0.98})</td>
<td>71.0 (70.9)(^{+1.1}_{-1.1})</td>
</tr>
<tr>
<td>$S_8$</td>
<td>0.812 (0.812)(^{+0.010}_{-0.010})</td>
<td>0.804 (0.797)(^{+0.013}_{-0.013})</td>
<td>0.784 (0.789)(^{+0.014}_{-0.014})</td>
<td>0.792 (0.783)(^{+0.017}_{-0.017})</td>
</tr>
<tr>
<td>Tension with SH(_0)ES</td>
<td>1.9 $\sigma$</td>
<td>1.6 $\sigma$</td>
<td>1.4 $\sigma$</td>
<td>1.7 $\sigma$</td>
</tr>
<tr>
<td>Tension with $S_8$</td>
<td>2.6 $\sigma$</td>
<td>2.1 $\sigma$</td>
<td>1.2 $\sigma$</td>
<td>1.6 $\sigma$</td>
</tr>
<tr>
<td>$\chi^2_{DS} - \chi^2_{\Lambda CDM}$</td>
<td>-6.9</td>
<td>-9.7</td>
<td>-17.9</td>
<td>-11.7</td>
</tr>
</tbody>
</table>
How to Deal with Larger Parameter Space?
Constraints

\[ \frac{\Omega_a}{\Omega_d} \]

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

Source: https://keirkwame.github.io/DM_limits/
\[ \delta = \frac{\rho}{\bar{\rho}} - 1 \]

\[ P(k) \sim \langle \delta^2 \rangle \]
CDM

\[ \frac{\partial^2 \delta}{\partial t^2} + 2H \frac{\partial \delta}{\partial t} = 4\pi G \bar{\rho} \delta_{\text{tot}} \]

Total Density
Ultralight Axions

\[
\frac{\partial^2 \delta_a}{\partial t^2} + 2H \frac{\partial \delta_a}{\partial t} = 4\pi G \bar{\rho} \delta_{\text{tot}} - \frac{\hbar^2 k^4}{4m^2 a^4} \delta_a
\]

Total Density

Axion Effective Sound Speed
Scale-Mass Relation

\[ m_a \leftrightarrow k_J \]
Theory to Data

\[ P_{\text{lin, ax}} \]
Theory to Data

$P_{\text{lin, ax}}$ → EFT of LSS → $P_{\ell}(k)$ → BOSS

DES
Galaxy Power Spectrum
via EFT of LSS

\[ P_g(k) = b_1^2 P_{\text{lin}}(k) + P_{1-\text{loop}}(k) + P_{\text{counter}}(k) + P_{\text{stoch}}(k) \]

\[ k \rightarrow (k, \mu) \]

\[ P_\ell(k) = \frac{2\ell + 1}{2} \int_{-1}^{+1} d\mu \ P_g(k, \mu) \mathcal{P}_\ell(\mu) \]
Galaxy Power Spectrum

Right ascension

Redshift space

0.02

0.04

0.06

0.08

Re-real space

Right ascension

Redshift

0.02

0.04

0.06

0.08

SDSS
Simplified Model

\[ P_\ell(k) = \frac{2\ell + 1}{2} b^2 P_{\text{lin}}(k) \int_{-1}^{1} d\mu \ e^{-\left(k u f_\ell\sigma_v\right)^2} \left(1 + f\mu^2\right)^2 \mathcal{P}_\ell(\mu) \]

\[ \mathcal{B}_\ell \equiv \int_{-1}^{1} d\mu \ e^{-\left(k u f_\ell\sigma_v\right)^2} \left(1 + f\mu^2\right)^2 \mathcal{P}_\ell(\mu) \]
Simplified Model

\[ \mathcal{B}_\ell \equiv \int_{-1}^{1} d\mu \, e^{-(k\mu \sigma_v)^2} (1 + f\mu^2)^2 \mathcal{P}_\ell(\mu) \]
Validation

Laguë et al. (2021)
BOSS Data

\[ m_a = 10^{-27} \text{ eV} \]

LOWZ \( z_{\text{eff}} = 0.32 \)

CMASS \( z_{\text{eff}} = 0.57 \)

\[
\begin{align*}
\Delta P_l / \sigma_l & \\
& = f(k, z) \\
& = g(k, z)
\end{align*}
\]

Laguë et al. (2022)
Constraints

Fraction of DM

Axion Mass

Laguë et al. (2021)
Constraints

Disfavoured

Fraction of DM

Allowed
Constraints

Most scenarios: under 5% of DM

Fraction of DM

5% of DM

1% of DM

Laguë et al. (2021)
In prep.

Inclusion of $P_4$, $B_0$ & validation with CLASS – PT

D'Amico et al. (2022)
Constraints

Most scenarios: under 5% of DM

Fraction of DM

5% of DM

1% of DM

Laguë et al. (2021)
Constraints

Fraction of DM

Axion Mass

$\Omega_{a}/\Omega_{d}$

Galaxy Clustering (2\sigma)
CMB (2\sigma)
Combined (2\sigma)
Combined (1\sigma)

Laguë et al. (2021)
In prep.

Inclusion of $P_4$, $B_0$ & validation with CLASS – PT

D'Amico et al. (2022)
Theory to Data

\{m_a, \Omega_a / \Omega_d\} \rightarrow \text{Halo Model} \rightarrow \xi_{\pm}(\theta) \rightarrow \text{DES}

\rightarrow \text{EFT of LSS} \rightarrow P_{\ell}(k) \rightarrow \text{BOSS}
The Halo Model

\[ P_{NL} = P_{2h} + P_{1h} \]
The Halo Model

\[ P_{NL} = P_{2h} + P_{1h} \]
\[ P_{NL} = P_{2h} + P_{1h} \]

\[ \approx P_{\text{lin}} \]

\[ \propto \int_0^\infty M^2 W^2(k, M) F(M) dM \]

\[ = \frac{1}{M} \int_0^{r_v} \frac{\sin(kr)}{kr} 4\pi r^2 \rho(r, M) dr \]
The Halo Model with (100%) ULAs

Schive et al. (2014/2015)
DES and Fuzzy Dark Matter

$m > 10^{-23}$ eV (95% C.L.)

Dentler et al. (incl. AL) (2021)
The Halo Model with (100%) ULAs

Schive et al. (2014/2015)
DES and Fuzzy Dark Matter

$m > 10^{-23}$ eV (95% C.L.)
Mixed Dark Matter Simulations
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \\
\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \Phi
\]
\[ i \frac{\partial \psi}{\partial t} = \left( -\frac{\nabla^2}{2m} + m\Phi \right) \psi \]
\[ \nabla^2 \Phi = 4\pi G \left( |\psi|^2 + \rho \right) \]

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

\[ \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \Phi \]

\[ i \frac{\partial \psi}{\partial t} = \left( -\frac{\nabla^2}{2m} + m\Phi \right) \psi \]
Mixed Dark Matter Simulations

100% CDM
50% - 50%
100% ULA

Laguë et al. (in prep.)
NL Power Spectra

Lagué et al. (in prep.)
Halo Density Profiles

50% ULA

Density $[M_\odot/\text{Mpc}^3]$

- FDM
- CDM
- Soliton
- SP Solution

$z = 2.0$
$f = 0.5$

Radius [kpc]

10% ULA

Density $[M_\odot/\text{Mpc}^3]$

- FDM
- CDM
- SP Solution

$z = 2.0$
$f = 0.1$

Radius [kpc]

Laguë et al. (in prep.)
Halo Density Profiles

10% ULA density profile

Laguë et al. (in prep.)
Halo Density Profiles

50% ULA

10% ULA

Laguë et al. (in prep.)
Halo Density Profiles

10% ULA

100% ULA density profile

Laguë et al. (in prep.)
Small-Scale Tensions vs Mixed DM

- Core-Cusp: depends on fraction and baryons
- Missing Satellites: sub-halos suppressed at low fraction
- Rotation Curve Diversity: depends on distribution of ULAs
Summary

- The Axiverse and its many axions
- Sub-dominant ultralight DM
- Extra motivation from cosmological tensions
- Improved modelling on semi-linear scales
- Strong constraints from galaxy and lensing surveys
- New simulation tools