Forecasting the Axiverse

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Oxford Physics
Outline

- Introduction: standard models
- The “String Axiverse”
- Axions and Cosmology
- Forecasts (“Euclid-like”)
- Conclusions and outlook
The Concordance Model

• Radiation: $T_{CMB}$ Photons

• Ordinary matter: $\Omega_b$ Baryons

• Dark sector: $\Omega_d$ Dark matter $\Omega_m = \Omega_b + \Omega_d$

• Dark energy $\Omega_\Lambda$

• Initial conditions: $n_s, A_s$ ... Inflation

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The Standard Model

• Gauge forces: EM, strong and weak forces.
  
  nucleosynthesis, recombination...

• Matter: quarks and leptons
  
  baryons, massless neutrinos

• Neutrino masses?

• Strong CP problem and axions?
The Dark Sector

- Standard model has no candidates.

- Cosmology: CDM and a c.c. can fit all data.  
  Komatsu et al (WMAP 7, 2011)

- Extra relativistic species?  
  Dunkley et al (ACT, 2010)

- DE equation of state or EDE?

- Particle Physics: CDM = WIMP (e.g. LSP).

- In addition, need massive neutrinos (observationally) and possibly axions (theoretically).  
  Peccei and Quinn, PRL 38,1440 (1977)

Dark Matter is multi-component!
"String theory suggests the simultaneous presence of many ultra-light axions, possibly populating each decade of mass down to the Hubble scale, $10^{-33}$ eV"
• String theory has extra dimensions: compactify.

• Axions are KK zero-modes of antisymmetric tensor fields compactified on closed cycles.

• Potentials from non-perturbative physics (D-branes, instantons etc.).

Many pseudo Goldstone bosons
The Axiverse and QCD

• Require the QCD axion to solve strong CP:

\[ \mathcal{L} \supset \theta \tilde{F} \mu \nu F ^{\mu \nu} \]
\[ \theta = \theta_T + \theta_M \]
\[ \theta \lesssim 10^{-10} \]

• SSB at scale \( f_a \), then instantons tilt the hat.

• The QCD axion must remain light to achieve this.

Many axions will remain light

http://www.hep.ph.ic.ac.uk/cms/physics/higgs.html
• Scales depend on the action of the instantons:

\[ \mathcal{L} = \frac{f_a^2}{2} (\partial \theta)^2 - \Lambda^4 U(\theta) \]

\[ f_a \sim \frac{M_{pl}}{S} \quad f_a \sim 10^{16}\text{GeV} \quad \Lambda^4 = \mu^4 e^{-S} \]

• Instanton action scales with the area of a cycle.
The Axiverse in this work (and why)

- Canonically normalised axions are weakly coupled

\[ \mathcal{L} = \frac{1}{2} (\partial \phi)^2 - V(\phi) \]

\[ V(\phi) = \frac{1}{2} m_a^2 \phi^2 \quad m_a^2 = \frac{\Lambda^4}{f_a^2} \]

- Masses distribute on a log scale:

\[ 10^{-33} \text{eV} \lesssim m_a \lesssim 10^{-28} \text{eV} \]

A source of ultra-light scalar dark matter

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You observe a flat table in a room with a slanted floor. How?

You propose a mechanism to straighten it accurately: gravity.

The required accuracy requires a long arm and heavy weight.

How can you test this? Look for relic oscillations from production.
• Well defined measure for abundance.  
  Tegmark et al, PRD (2006)
• Fine tuning?  
  Mack and Steinhardt, JCAP (2011)
• Isocurvature and gravity waves give constraints.  
  Fox et al, hep-th/0409059
• Motivated as dark matter in many different contexts.  
  Sikivie, arXiv:1003.2426
• Couplings give further constraints.  
  Mortsell and Goobar, JCAP (2003)
• Axions and inflation.  
  Linde, PLB (1991)
• Monodromy quintessence, BH superradiance, ...  
  Panda et al, arXiv:1011.5877
  Arvanitaki and Dubovsky, PRD (2011)
• Coupling to a modulus:

\[ V(\phi, \chi) = B e^{-2C\chi} - D e^{-C\chi} + \frac{1}{2} e^{-\tilde{C}\chi} M^2 \phi^2 \]

• Stabilisation in an attractor.

• Potential to solve initial conditions problem for axion?

• EDE and dark energy dynamics.

• Collapsing universe is asymptotic future.
Cosmology of the Axiverse

- Equations of motion:
  
  $\ddot{\phi}_0 + 2H\dot{\phi}_0 + m_a^2 a^2 \phi_0 = 0$
  
  $\ddot{\phi}_1 + 2H\dot{\phi}_1 + (m^2 a^2 + k^2)\phi_1 = -\frac{1}{2} \phi_0 h$

- Stress energy tensor:
  
  $\rho_a = \frac{a^{-2}}{2} \dot{\phi}_0^2 + \frac{m_a^2}{2} \phi_0^2$
  
  $P_a = \frac{a^{-2}}{2} \dot{\phi}_0^2 - \frac{m_a^2}{2} \phi_0^2$
  
  $\delta \rho_a = a^{-2} \dot{\phi}_0 \dot{\phi}_1 + m_a^2 \phi_0 \phi_1$
  
  $\delta P_a = a^{-2} \dot{\phi}_0 \dot{\phi}_1 - m_a^2 \phi_0 \phi_1$
  
  $(\rho + P)\theta_a = a^{-2} k^2 \dot{\phi}_0$
• Different background scaling implies different effects on matter-radiation equality, and hence on the CMB.

• Relic density is non-thermal.
Cosmology of the Axiverse II

- WKB approx. gives a scale dependent sound speed:

\[ c_s^2 = \frac{k^2}{4m_a a^2}; \quad k < 2m_a a \]

\[ c_s^2 = 1; \quad k > 2m_a a \]

Hu et al, PRL (2000)
Amendola and Barbieri, PLB (2006)

- Process analogous to neutrino free-streaming:

\[ \frac{k_m}{H_0} = (2\Omega_m)^{1/3} \left( \frac{m_a}{H_0} \right)^{1/3}; \quad k_m < k_{eq} \]

\[ \frac{k_m}{H_0} = \left( \frac{4\Omega_m}{1+z_{eq}} \right)^{1/4} \left( \frac{m_a}{H_0} \right)^{1/2}; \quad k_m > k_{eq} \]
• This leads to steps in the matter power spectrum:

\[ T_m(k, z, \tilde{f}_{ax}) = \tilde{f}_a T_{ax}(k, z, \tilde{f}_{ax})T_c(k, \tilde{f}_{ax} = 0) + \tilde{f}_b T_b(k, \tilde{f}_{ax}) \]

DJEM and Ferreira, PRD (2010)

Eisenstein and Hu, APJ (1997)

• Many degeneracies as for massive neutrinos.

### Important Scales

<table>
<thead>
<tr>
<th>$m_a$ (eV)</th>
<th>$k_m (h \text{Mpc}^{-1})$</th>
<th>$\bar{k}_m (h \text{Mpc}^{-1})$</th>
<th>$z_{osc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-29}$</td>
<td>0.0058</td>
<td>0.0575</td>
<td>350</td>
</tr>
<tr>
<td>$10^{-30}$</td>
<td>0.0027</td>
<td>0.0267</td>
<td>74</td>
</tr>
<tr>
<td>$10^{-31}$</td>
<td>0.0012</td>
<td>0.0124</td>
<td>15</td>
</tr>
<tr>
<td>$10^{-32}$</td>
<td>0.0006</td>
<td>0.0057</td>
<td>2.4</td>
</tr>
</tbody>
</table>

\[
k_{eq}(f_{ax} = 0) = 0.0136h \text{ Mpc}^{-1}
\]
\[
k_{eq}(f_{ax} = 0.01) = 0.0135h \text{ Mpc}^{-1}
\]
\[
k_{FS}(m_{\nu} = 0.055 \text{ eV}, z = 0) = 0.0451h \text{ Mpc}^{-1}
\]

\[
\tilde{f}_{ax} = \frac{\Omega_a}{\Omega_m}
\]
\[
f_{ax} = \frac{\Omega_a}{\Omega_d}
\]

DJEM et al, arXiv:1110.0502

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Implementation

- Module for CAMB solves field equations and oscillations.
- Mass range restricted by this choice.

Amendola and Barbieri, PLB (2006)
Observables: $P(k)$ and BAO

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• Model for smooth part changes: bias?

• Small change in sound horizon from background.
Observables: Growth Rate

\[ f = \frac{d \ln \delta}{d \ln a} = \frac{\dot{\delta}}{\mathcal{H} \delta} \]

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• Scale dependent growth, degenerate with more CDM.

• Unique signal needs large scale measurement.
Observables: Weak Lensing

- Convergence power spectrum measures dark matter density directly from galaxy shear.

\[ P_l^\kappa = \int_0^{\chi_{\infty}} d\chi \frac{W^2(\chi)}{r^2(\chi)} P(l/r(\chi), z) \]

- Window function sets redshift bin: tomography.
Observables: Weak Lensing

- Indistinguishable from LCDM in single bin.
- Growth amplitude from tomography gives very strong constraints.

Hu, PRD (2002)
Observables: CMB

• Most effects can be removed due to total degeneracy with horizon size and equality redshift.

• Breaks degeneracy with neutrino mass and number.

• Constraining power in ISW due to oscillations near recombination: used in checks.

• Larger effects in lensing not used because of correlations.
Forecasts: Implementation

- Fisher Matrix forecast for Planck + Euclid.
- CMB uses FisherCodes by Sudeep Das.
  http://www.astro.princeton.edu/~sudeep/fisherCodesDoc
- GRS and WLT are our own, by Edward and Maxime.
“The Euclid survey can be thought of as the low-redshift, 3-dimensional analogue and complement to the map of the high redshift Universe provided by ESA’s Planck mission”.

Forecasts: Euclid

http://sci.esa.int/euclid
arXiv:1110.3193
Forecasts: Survey Parameters

• Planck: TT, TE, EE in 100, 143 and 217 GHz.

\[ f_{\text{sky}} = 0.8 \quad \ell_{\text{max}} = 2000 \]

• Euclid GRS: 15 redshift bins of varying volume.

\[ 0.5 < z < 2 \]

\[ 0.146h \text{ Mpc}^{-1} \leq k_{\text{max}} \leq 0.2h \text{ Mpc}^{-1} \]

43.68 million galaxies at a constant density of:

\[ 1 \times 10^{-3}[h\text{Mpc}^{-1}] \]

• Euclid WLT: 5 redshift bins, with constant # of sources.

\[ 0 < z < 3 \]

\[ f_{\text{sky}} = 0.5 \quad \ell_{\text{max}} = 1900 \]
Forecasts: Fiducial Models

- Fixed Hubble: \( H_0 = 71.9 \text{ km s}^{-1} \text{Mpc}^{-1} \)
- Test 4 axion masses: \( m_a = 10^{-32}, 10^{-31}, 10^{-30}, 10^{-29} \text{eV} \)
Forecasts: Fiducial Models

- Fiducial cosmology:
  \[ \Omega_b h^2 = 0.02258 \]
  \[ A_s = 2.3 \times 10^{-9} \]
  \[ N_{\text{eff}} = 3.04 \]
  \[ f_{\text{ax}} = 0.01 \]
  \[ \Omega_c h^2 = 0.1109 \]
  \[ n_s = 0.963 \]
  \[ m_\nu = 0.055 \text{ eV} \]
  \[ w = -1 \]

- Marginalise over:
  \[ Y_{\text{He}} = 0.24 \]
  \[ b = 1.7 \]
  \[ \tau = 0.166 \]
  \[ \sigma_v = 350 \text{ km s}^{-1} \]
Forecasts: Results

- Compare with massive neutrinos:

DJEM et al, arXiv:1110.0502

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Forecasts: Results

• Strong CMB degeneracies:

[Graph showing various mass values and their implications on a plot]

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• Value of combining redshift information:

GRS alone can constrain 1% at 1σ
Forecasts: Results

- Combined results:

Mass independent constraints

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Outlook

- Still much work to do for param. estimation.
- Fits comparing to specific neutrino models.
- Multiple, heavier species: Ly-alpha?
- Anharmonic potentials.
- Dynamics of extended model.
  DJEM et al, in prep.
- Isocurvature?
Thank You!

Questions?