Isotropic Birefringence Signals from Axion-like Dark Matter

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Work in collaboration with Günter Sigl
(to be submitted; analysis beyond arXiv:1811.07873 Sigl & Trivedi)
Cosmological Birefringence from Axions

Inhomogeneous axion (or axion-like) field $a$

$\rightarrow$ optically active medium

$\rightarrow$ rotation of polarization of light (birefringence)

achromatic effect (cf. Faraday rotation $\propto 1/\lambda^2$)

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$10^{-33}$ eV $\lesssim m_a \lesssim 10^{-28}$ eV $\rightarrow$ cosm. birefringence. But $a$ cannot be DM at CMB epoch

$m_a \gtrsim 10^{-28}$ eV $\rightarrow$ $a$ can be DM - but (so far): birefringence suppressed if $T_a(m_a) \ll \Delta \tau_{\text{rec}}$

$\Delta \alpha = s_{\alpha \gamma} = \frac{s_{\alpha \gamma}}{2\pi f_a}$

$r = (1/2) m_a^2 a^2$

$\Delta \alpha \approx g_{\alpha \gamma} \int ds \, n^\mu \partial_\mu a \approx \frac{g_{\alpha \gamma}}{2} \Delta a$

(re rapid oscillations of $a$ during $\Delta \tau_{\text{rec,99\%}} \sim 0.5$ Myr)

$T_a = 2\pi/m_a \approx (1 \text{ year}) (1.22 \times 10^{-22} \text{ eV})/m_a$
Birefringence from oscillating Axion DM

Inhomogeneous axion (or axion-like) field $a$

$\rightarrow$ optically active medium

$\rightarrow$ rotation of polarization of light (birefringence)

achromatic effect (cf. Faraday rotation $\propto 1/\lambda^2$)

\[ \Delta \alpha \approx \frac{g_{a\gamma}}{2} \int C \, d\eta \, n^\mu \partial_\mu a \approx \frac{g_{a\gamma}}{2} \Delta a \]

\[ g_{a\gamma} = \frac{s_{\alpha_{em}}}{2\pi f_a} \]

\[ \Delta a = [a(z_*) - a_{\text{local}}] \]

\[ \rho_a = (1/2) m_a^2 a^2 \]

This work:

- Consider oscillating $a(t)$, $\omega_a = m_a$, phase, start of oscillation
- Recombination Visibility fn. $V(\eta)$ from Planck, local obs. Window $W(t)$
- Difference of recombination & local signals
- Obs. CMB are photons arriving together from across $V(\eta)$
• Our recent work:
  - Consider oscillating \( a(t) \), \( \omega_a = m_a \), phase, start of oscillation
  - Recombination Visibility \( V(\eta) \), local Window \( W(t) \)
  - Obs. CMB are photons arriving together from across \( V(\eta) \)
  - Difference of recombination & local signals: birefringence

\[ \Delta a = a(z_\ast) - a_{\text{local}} \]

\[ a(\eta, m_a) = \Theta [\eta - \eta_{\text{osc}}(m_a)] \times a_0 \cos [m_a (\eta - \eta_{\text{osc}}(m_a) - (\eta_{\text{peak}} - \eta)) + \delta_0] , \]

\[ a_0 = \int_{\text{rec.}} \delta(\eta - z_\ast) a(\eta) \, d\eta \]
**Axion DM Birefringence**

- **Our recent work:**
  - Consider oscillating $a(t), \omega_a = m_a$, phase, start of oscillation
  - Recombination Visibility $V(\eta)$, local Window $W(t)$
  - Obs. CMB are photons arriving together from across $V(\eta)$
  - **Difference** of recombination & local signals: birefringence

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**Table:**

<table>
<thead>
<tr>
<th>Time scale or Frequency</th>
<th>$\text{Planck Mission}$</th>
<th>Corresponding $m_a$ (eV)</th>
<th>$T_a(m_a) = 2\pi/m_a$ (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{full survey}}$</td>
<td>885 days</td>
<td>$5.41 \times 10^{-23}$</td>
<td>2.423</td>
</tr>
<tr>
<td>$T_{\text{time-ordered data}}$</td>
<td>1 day 2 m 03 s</td>
<td>$4.78 \times 10^{-20}$</td>
<td>2.74 $\times 10^{-3}$</td>
</tr>
<tr>
<td>$T_{\text{rotation}}$</td>
<td>1 min</td>
<td>$3.45 \times 10^{-17}$</td>
<td>3.80 $\times 10^{-5}$</td>
</tr>
<tr>
<td>$T_{\text{sampling}}$</td>
<td>180.4 Hz</td>
<td>$3.73 \times 10^{-13}$</td>
<td>3.51 $\times 10^{-10}$</td>
</tr>
</tbody>
</table>
Constraints on the Fraction of DM in the form of ALPs

\[ F = \frac{\Omega_a}{\Omega_c} \]

\[ \sqrt{F_a} \text{ multiplies } (\Delta a/a_0) \text{ below} \]

To give constraints on axion-photon coupling.....
Isotropic Birefringence Constraints

Axion–photon coupling $g_{\gamma\gamma} (\text{GeV}^{-1})$

ALP mass $m_a (\text{eV})$

- $t_{\text{osc}}(m_a) \lesssim t_{\text{rec, end}}$
- $T_a(m_a) \lesssim \Delta t_{\text{rec}}$
- $t_{\text{osc}}(m_a) \approx t_{\text{eq}}$
- $T_a(m_a) \ll \Delta t_{\text{rec}}$

$g_{\gamma\gamma} \approx \frac{\Delta \phi}{\sqrt{F_a} \Delta a} = \frac{2 \Delta \alpha}{\sqrt{F_a} \Delta a}$

$\Delta \alpha$ (degrees) $\lesssim 1.0$

$0.31 \pm 0.05 (\pm 0.28)$ Planck (2016) XLIX

<table>
<thead>
<tr>
<th>Epochal Time $t$ or $\tau$</th>
<th>Corresponding ALP mass $m_a (\text{eV})$</th>
<th>Time Period $T_a(m_a) = 2\pi/m_a (\text{Myr})$</th>
<th>Redshift of Oscillation $z_{\text{osc}}$</th>
<th>Oscillation Epoch $t_{\text{osc}} = \tau_{\text{age}}(z_{\text{osc}}) (\text{Myr})$</th>
<th>Feature produced in the Birefringence Signal $\Delta a$ from Recombination</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{osc}}(m_a) \lesssim t_{\text{rec, end}}$</td>
<td>$3.9 \times 10^{-29}$</td>
<td>3.4</td>
<td>600</td>
<td>0.99</td>
<td>$a_{\text{rec}}$ signal rises above zero</td>
</tr>
<tr>
<td>$T_a(m_a)/2 \lesssim \Delta t_{\text{rec}}$</td>
<td>$1.7 \times 10^{-28}$</td>
<td>0.75</td>
<td>1530</td>
<td>0.21</td>
<td>maximum $a_{\text{rec}}$ signal at 1st peak</td>
</tr>
<tr>
<td>$T_a(m_a) \approx \Delta t_{\text{rec}}$</td>
<td>$2.6 \times 10^{-28}$</td>
<td>0.50</td>
<td>1950</td>
<td>0.14</td>
<td>1st null of $a_{\text{rec}}$ signal</td>
</tr>
<tr>
<td>$t_{\text{osc}}(m_a) = t_{\text{eq}}$</td>
<td>$6.8 \times 10^{-28}$</td>
<td>0.19</td>
<td>3400</td>
<td>0.051</td>
<td>T-indep. $m_a$ limit: std. ALP DM</td>
</tr>
<tr>
<td>$T_a(m_a) \ll \Delta t_{\text{rec}}$</td>
<td>$2.9 \times 10^{-27}$</td>
<td>0.046</td>
<td>7570</td>
<td>0.012</td>
<td>exponential damping of $a_{\text{rec}}$ signal</td>
</tr>
</tbody>
</table>
Isotropic Birefringence Forecasts

Birefringence from Axion-like Dark Matter

Pranjal Trivedi (Hamburg)
Isotropic Birefringence Forecasts

Birefringence from Axion-like Dark Matter

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Hint! of Cosmic Birefringence

Breakthrough analysis of Planck 2018 CMB polarization data

Compared Birefringence from CMB ↔ Galactic CMB foreground

→ isolated detector (HFI) miscalibration angle uncertainty

→ reduced systematic error by x 2

Y. Minami

cf. 0.31 ± 0.05 (±0.28) Planck Collaboration I. XLIX 2016

New Extraction of the Cosmic Birefringence from the Planck 2018 Polarization Data

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Eiichiro Komatsu†

We search for evidence of parity-violating physics in the Planck 2018 polarization data and report on a new measurement of the cosmic birefringence angle $\beta$. The previous measurements are limited by the systematic uncertainty in the absolute polarization angles of the Planck detectors. We mitigate this systematic uncertainty completely by simultaneously determining $\beta$ and the angle miscalibration using the observed cross-correlation of the $E$- and $B$-mode polarization of the cosmic microwave background and the Galactic foreground emission. We show that the systematic errors are effectively mitigated and achieve a factor-of-2 smaller uncertainty than the previous measurement, finding $\beta = 0.35 \pm 0.14$ deg (68% C.L.), which excludes $\beta = 0$ at 99.2% C.L. This corresponds to the statistical significance of 2.4$\sigma$. 
Axion-Like Dark Matter Constraints from Parametric Resonance & CMB Birefringence

Interpretation of Cosmic Birefringence

\[ \beta = 0.35 \pm 0.14 \]

Critical Assessment
- Dust effects: full investigation (see recent Galactic dust EB - Clark 2105.00120)
- Foreground effects and EB
- Fresh look at systematics, instrument modelling
- Low significance 2.4\(\sigma\) : needs to be compared to other CMB data
- Independent Verification!

Future Observations:
- SO, BICEP Array, CMB-S4, CMB-HD, LiteBIRD, PICO

Our theory constraints & forecasts:

Y. Minami

Pranjal Trivedi (Hamburg) Axion-Like Dark Matter Constraints from Parametric Resonance & CMB Birefringence

Planck Collaboration I. XLIX 2016

cf.

\[ 0.31 \pm 0.05 \text{ (} \pm 0.28 \text{) } \]
Cosmic birefringence constraints are up to 4 orders stronger than x-ray AGN in cluster constraints (Chandra).

- Mass scales probed by CMB in $\log (m_a/\text{eV})$:
  -29 to -27 and -26 to -21 (up to FDM)

- CMB-S4, PICO, CMB-HD can all improve by 1-2 orders of magnitude in axion-photon coupling

- Exciting obs. hint of 0.35 (0.14) isotropic birefringence $\rightarrow$ if confirmed could reveal axions contributing to dark matter
Thank you