Cosmic Birefringence

The Universe filled with a “birefringent material”

➢ If the Universe is filled with a pseudo-scalar field, $\phi$, (e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

$$\mathcal{L} \supset -\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \ldots (1)$$

Chern-Simons term

$$\tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

Turner & Widrow (1988)

$$\beta = \frac{g_{\phi\gamma}}{2} \int_{\text{observer}}^{\text{emission}} dt \dot{\phi}$$

$$= \frac{g_{\phi\gamma}}{2} (\phi_{\text{observer}} - \phi_{\text{emission}}) \quad \ldots (2)$$

Difference of the field values rotates the linear polarization!
Birefringence from background and fluctuation

\[ \phi_{LSS}(t = t_{LSS}, d_{LSS}\hat{n}) = \bar{\phi}_{LSS} + \delta \phi_{LSS}(\hat{n}) \]

\[ \phi_{obs}(t = t_0, \mathbf{0}) = \bar{\phi}_{obs} + \delta \phi_{obs} \]

\[ \beta(\hat{n}) = \frac{g \phi \gamma}{2} \left( \frac{\Delta \bar{\phi} + \delta \phi_{obs} - \delta \phi_{LSS}(\hat{n})}{\beta \text{ (isotropic)}} - \frac{A_\alpha}{A_{\alpha} \text{ (anisotropic)}} \right) \]
Cosmic Birefringence
with Cosmic Microwave Background (CMB)

Birefringence from background and fluctuation

Last Scattering Surface (LSS)
Observer

This talk only targets isotropic rotation $\beta$

$$\phi_{LSS}(t = t_{LSS}, d_{LSS} \hat{n}) = \phi_{LSS} + \delta \phi_{LSS}$$
$$\phi_{obs}(t = t_0, \mathbf{0}) = \phi_{obs} + \delta \phi_{obs}$$

$$\beta(\hat{n}) = \frac{g \phi \gamma}{2} \left( \frac{\Delta \bar{\phi} + \delta \phi_{obs} - \delta \phi_{LSS}(\hat{n})}{\beta \text{ (isotropic)}} - A_\alpha \text{ (anisotropic)}} \right) \quad \cdots (3)$$
**EB** correlation from the cosmic birefringence

*Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)*

- Cosmic birefringence convert $E \leftrightarrow B$ as

\[
\begin{pmatrix}
E_{\ell m}^{obs} \\
B_{\ell m}^{obs}
\end{pmatrix} =
\begin{pmatrix}
\cos(2\beta) & -\sin(2\beta) \\
\sin(2\beta) & \cos(2\beta)
\end{pmatrix}
\begin{pmatrix}
E_{\ell m} \\
B_{\ell m}
\end{pmatrix}
\] … (4)

- In power spectra:

\[
\langle C_{\ell}^{EB,obs} \rangle = \frac{1}{2} \left( \langle C_{\ell}^{EE} \rangle - \langle C_{\ell}^{BB} \rangle \right) \sin(4\beta) + \langle C_{\ell}^{EB} \rangle \cos(4\beta)
\]

Need to assume a model!

- Traditionally, one would find $\beta$ by fitting $C_{\ell}^{EE,CMB} - C_{\ell}^{BB,CMB}$ to the observed $C_{\ell}^{EB,obs}$ using the best-fitting CMB model

- Assuming the intrinsic $\langle C_{\ell}^{EB} \rangle = 0$, at the last scattering surface (LSS) (justified in the standard cosmology)
The Biggest Problem in observations: Miscalibration of detectors

- Is the polarization plane rotated by the genuine cosmic birefringence, $\beta$?
- Are the polarisation-sensitive detectors rotated by miscalibration, $\alpha$, on the sky coordinate (and we did not know)?

We can only measure the sum, $\alpha + \beta$

Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

Polarisation-sensitive detectors on the focal plane

Miscalibration

rotated by an angle “$\alpha$” (but we do not know it)
The past measurements with the traditional way

Systematic errors on $\alpha$ limited the measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$\beta + \text{stat.} + \text{sys.} ,(\text{deg.})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feng et al. 2006</td>
<td>$-6.0 \pm 4.0 \pm ??$</td>
</tr>
<tr>
<td>WMAP Collaboration, Komatsu et al. 2009; 2011</td>
<td>$-1.1 \pm 1.4 \pm 1.5$</td>
</tr>
<tr>
<td>QUaD Collaboration, Wu et al. 2009</td>
<td>$-0.55 \pm 0.82 \pm 0.5$</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Planck Collaboration 2016</td>
<td>$0.31 \pm 0.05 \pm 0.28$</td>
</tr>
<tr>
<td>POLARBEAR Collaboration 2020</td>
<td>$-0.61 \pm 0.22 +??$</td>
</tr>
<tr>
<td>SPT Collaboration, Bianchini et al. 2020</td>
<td>$0.63 \pm 0.04 +??$</td>
</tr>
<tr>
<td>ACT Collaboration, Namikawa et al. 2020</td>
<td>$0.12 \pm 0.06 +??$</td>
</tr>
<tr>
<td>ACT Collaboration, Choi et al. 2020*</td>
<td>$0.09 \pm 0.09 +??$</td>
</tr>
</tbody>
</table>

*used optical model, “as-designed” angles

Other way to calibrate?

| Crab nebula, Tau A (Celestial source)            | 0.27 deg. (Aumont et al.(2018))                  |
| Wire grid (Planck / Tajima et al. (2011))       | 1.00 deg.? / 0.8 deg.                            |

First measurement

Uncertainty in the calibration of $\alpha$ has been the major limitation
Simultaneous determination of $\alpha$ and $\beta$

➢ The key idea: use the polarised Galactic foreground emission as a calibrator

➢ FG is rotated by $\alpha$

➢ CMB is rotated by $\alpha + \beta$

\[
\langle C_{\ell}^{EB,\circ} \rangle = \frac{\tan(4\alpha)}{2} \left( \langle C_{\ell}^{EE,\circ} \rangle - \langle C_{\ell}^{BB,\circ} \rangle \right) + \frac{\sin(4\beta)}{2 \cos(4\alpha)} \left( \langle C_{\ell}^{EE,\text{CMB}} \rangle - \langle C_{\ell}^{BB,\text{CMB}} \rangle \right) + \frac{1}{\cos(4\alpha)} \langle C_{\ell}^{EB,fg} \rangle + \frac{\cos(4\beta)}{\cos(4\alpha)} \langle C_{\ell}^{EB,\text{CMB}} \rangle.
\]

➢ When we ignore the intrinsic $EB$ correlations of the FG and the CMB, we can determine both $\alpha$ and $\beta$

➢ The latter is justified but the former is not

➢ Using Planck PR3 data, $\beta = 0.35 \pm 0.14$ [Minami & Komatsu 2020b]

➢ $\beta > 0$ at 99.2% C.L. (2.4$\sigma$)
How about the foreground $EB$?

If the intrinsic foreground (FG) $EB$ exists, our method interprets it as a miscalibration angle $\alpha$

- Thus, $\alpha \rightarrow \alpha + \gamma$, where $\gamma$ is the parameter of the intrinsic $EB$
- The sign of $\gamma$ is the same as the sign of the foreground $EB$
- We thus can determine:

  - FG: $\alpha + \gamma$
  - CMB: $\alpha + \beta$

  \[ \beta - \gamma = 0.35 \pm 0.14 \text{ deg.} \]

- There is evidence for the dust-induced $TE_{dust} > 0 \& TB_{dust} > 0$; then, we’d expect $EB_{dust} > 0$ [Huffenberger et al.], i.e., $\gamma > 0$. If so, $\beta$ increased further...
- We can give a lower bound on $\beta$

We would be happy if CMB-S4 can test this.
With CMB channels

➢ At least, we need to observe bright FG region
  ➢ FG is needed to determine $\alpha$
➢ Most of the ground based experiments didn’t observe foreground dominated regions
  ➢ lose sensitivity

ACT DR4 coverage [Choi et.al (2020)]

Demonstration with a LiteBIRD like experiment

Foreground level (band) and CMB power spectra [Choi et.al (2020)]
With FG-dominated channels

- We can use strong foreground signal even with Galactic mask
  - We can determine $\beta$
- Assuming Simons Observatory Large Aperture Telescope’s 280 GHz channel
  - $\alpha$ and $\gamma$ are well determined

Planck’s LR42 mask (fsky~0.4)
Summary

➢ Cosmic birefringence: difference of field values with Chern-Simons coupling rotates linear polarization of the CMB photons

\[ \beta = \frac{g\phi_\gamma}{2} (\phi_{obs} - \phi_{LSS}) \]

➢ Calibration uncertainty on detector rotation \( \alpha \) has limited the measurements of \( \beta \)

➢ When we use the Galactic foreground as a calibrator, we can determine \( \alpha \) and \( \beta \) simultaneously

\[ \beta = 0.35 \pm 0.14 \]

➢ The measurements with CMB-S4 are highly expected
  ➢ Reducing calibration uncertainty with the ground calibrator
  ➢ Observing FG-dominated regions and channels
Bonus:

Does $\beta = 0.35 \pm 0.14$ deg. disturb the measurement of primordial $B$-mode?
Backups