COSMOLOGICAL PARITY VIOLATION:

Tracing E and B Mode Signatures of Primordial Gravitational Waves

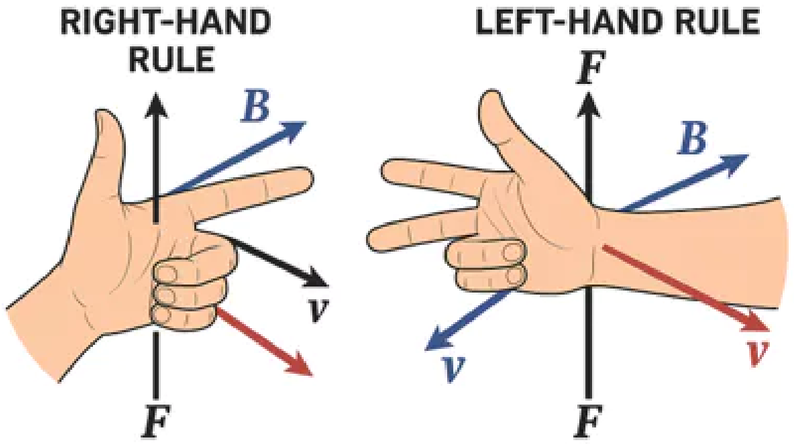
Antonia Cisternas
Lead professor: Gonzalo Palma
Class: Seminario de Investigación I
Professor: Pablo Moya

PARITY SYMMETRY

- Parity transformation: Inversion of all spatial coordinates:

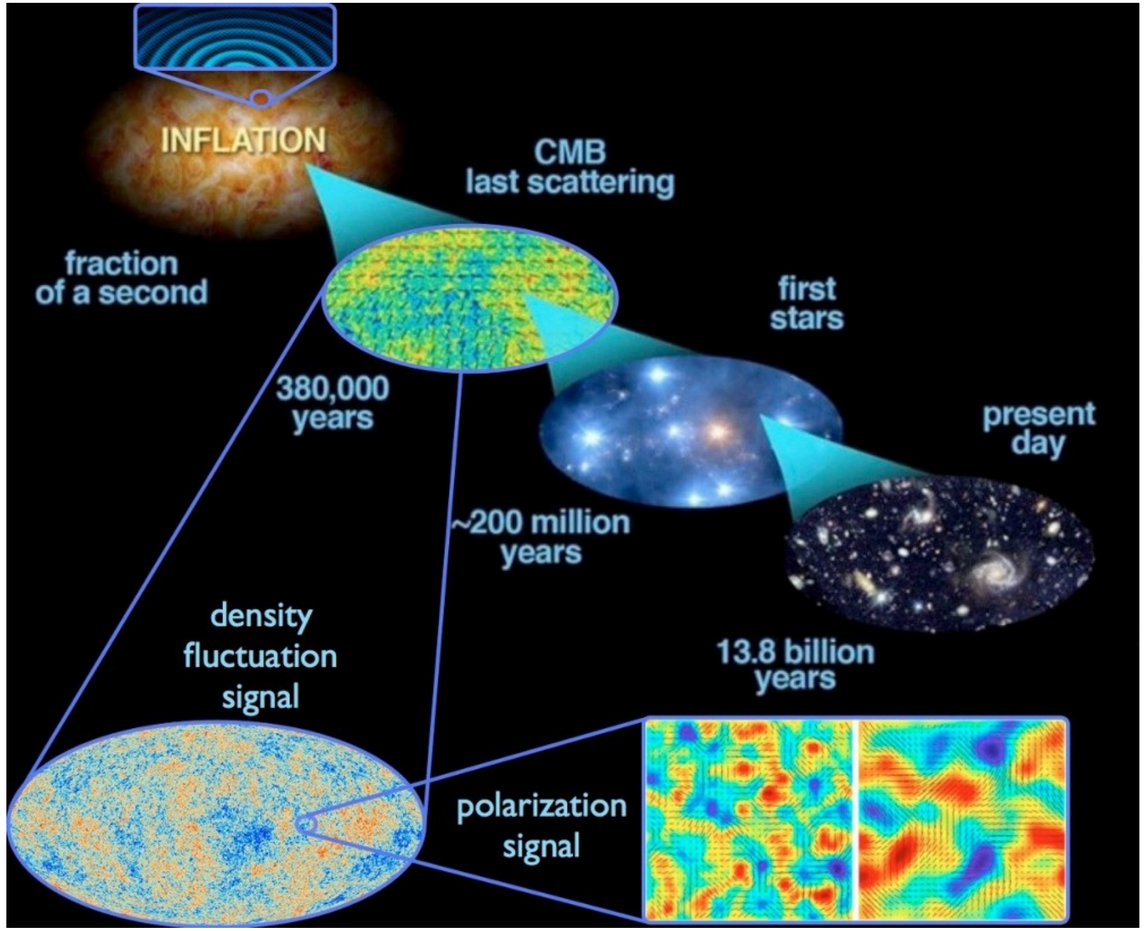
$$\mathbf{P}: \begin{pmatrix} x \\ y \\ z \end{pmatrix} \mapsto \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}.$$

- **Parity symmetry:** The laws of physics are invariant under inversion of all spatial coordinates.



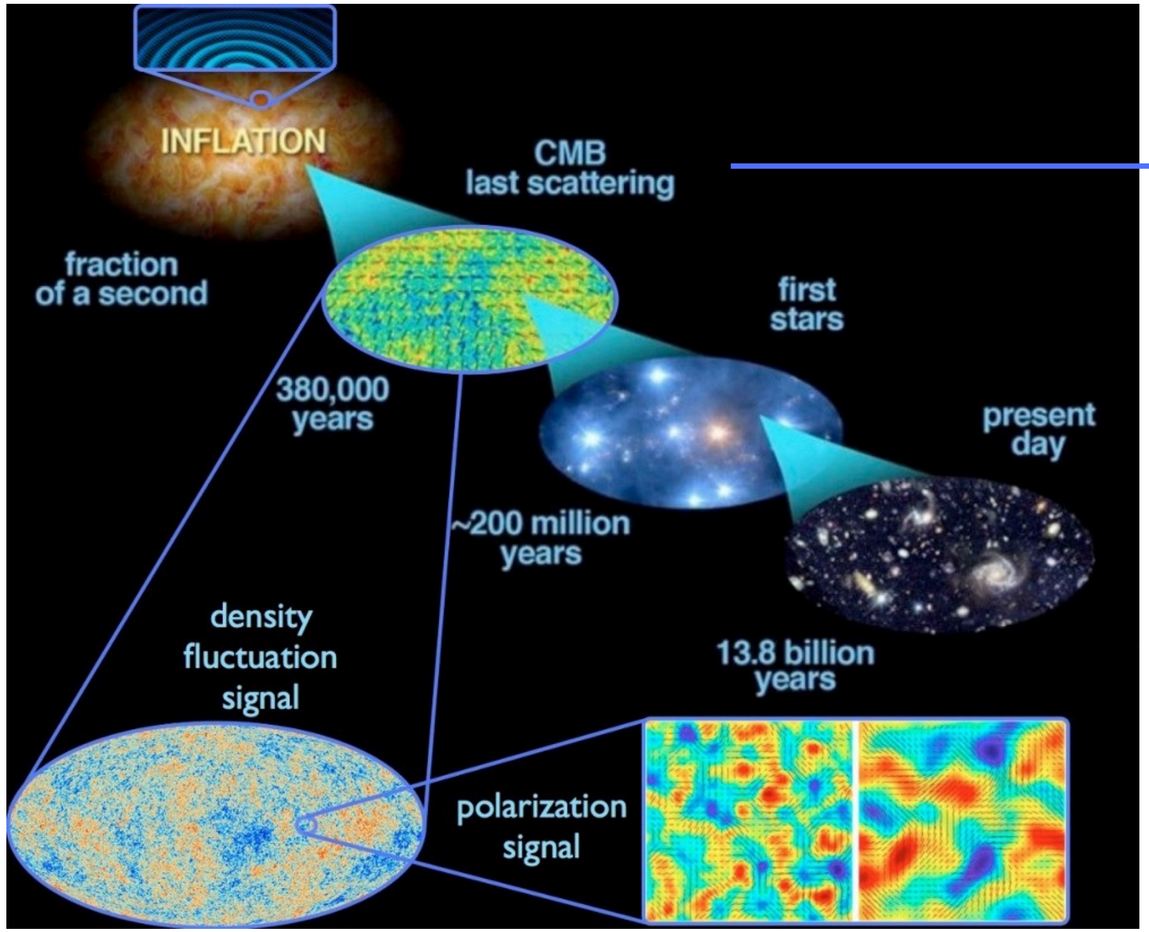
When we observe a certain phenomenon in nature, do we also observe its mirror image with equal probability?

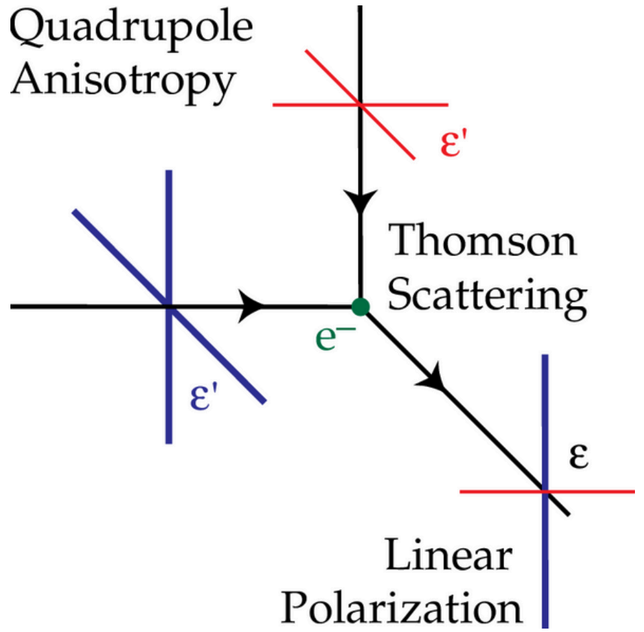
INFLATION AND CMB



DERIVED FROM ESA/PLANCK AND THE DOE/NASA/ NSF INTERAGENCY TASK FORCE ON CMB RESEARCH

INFLATION AND CMB

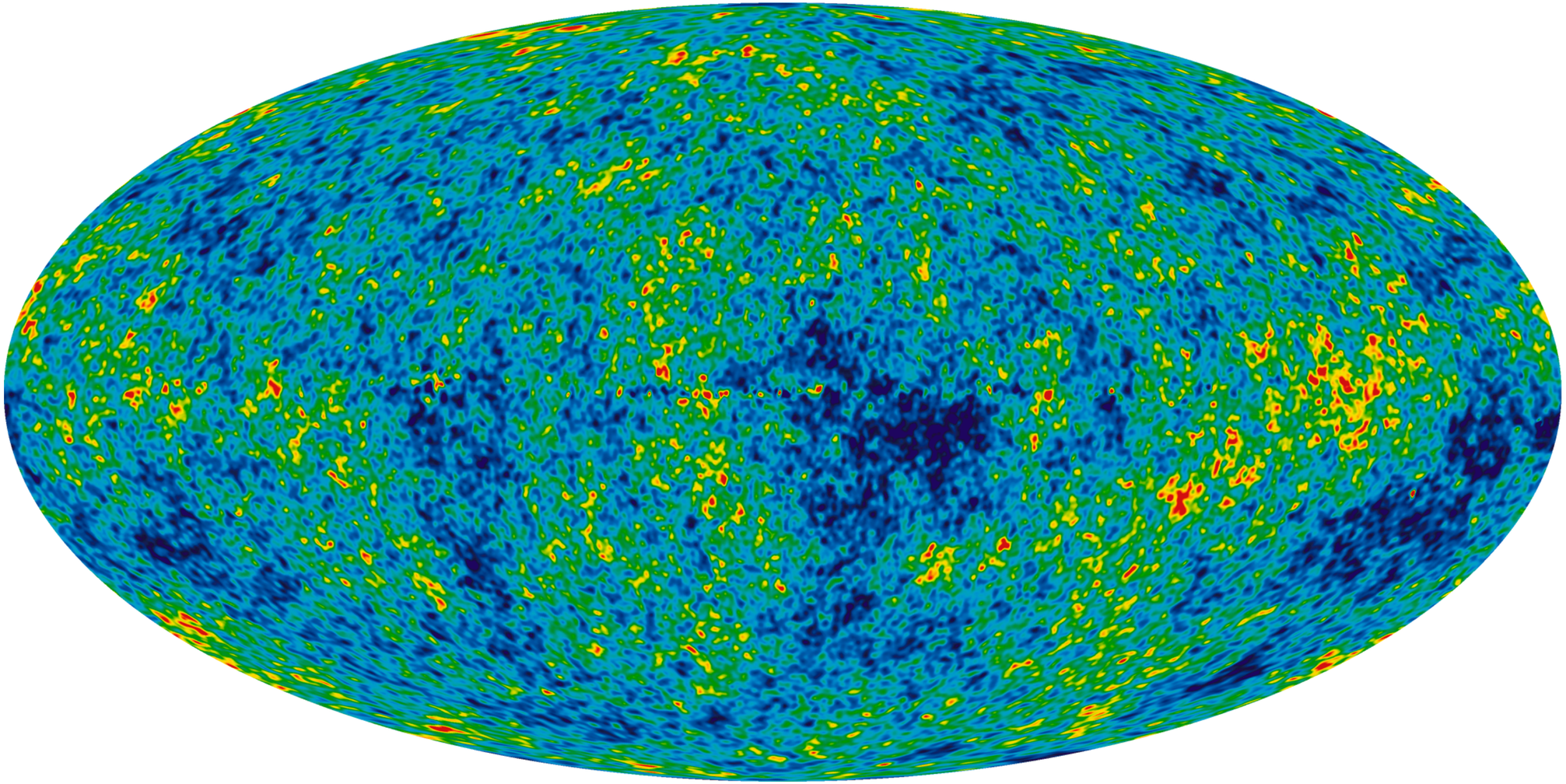




- Without this anisotropy, the scattered light from different directions cancels out, but with a quadrupole pattern, the asymmetry leaves a residual, **net polarization.**

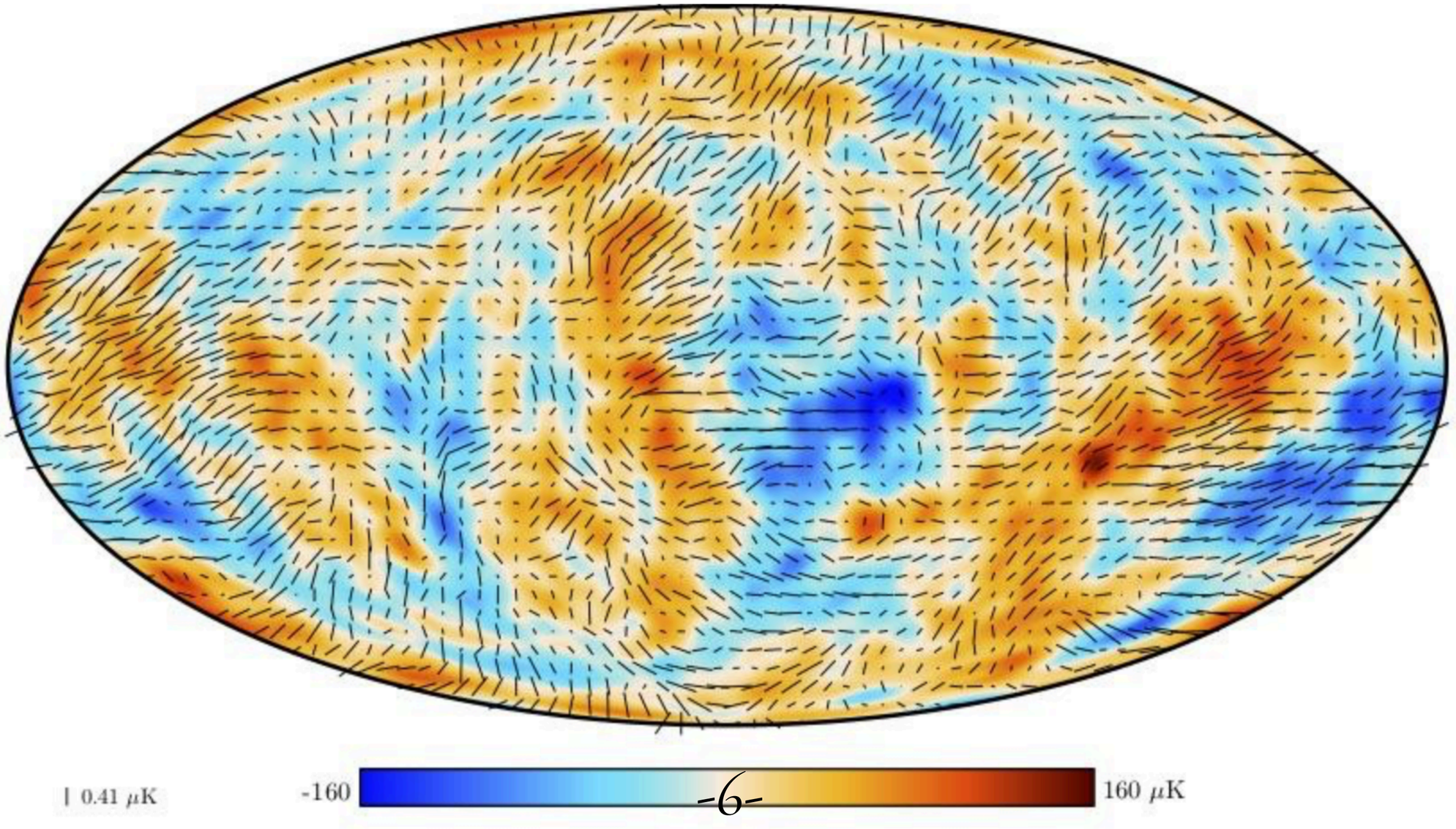
DERIVED FROM ESA/PLANCK AND THE DOE/NASA/ NSF INTERAGENCY TASK FORCE ON CMB RESEARCH

INFLATION AND CMB



By NASA / WMAP Science Team

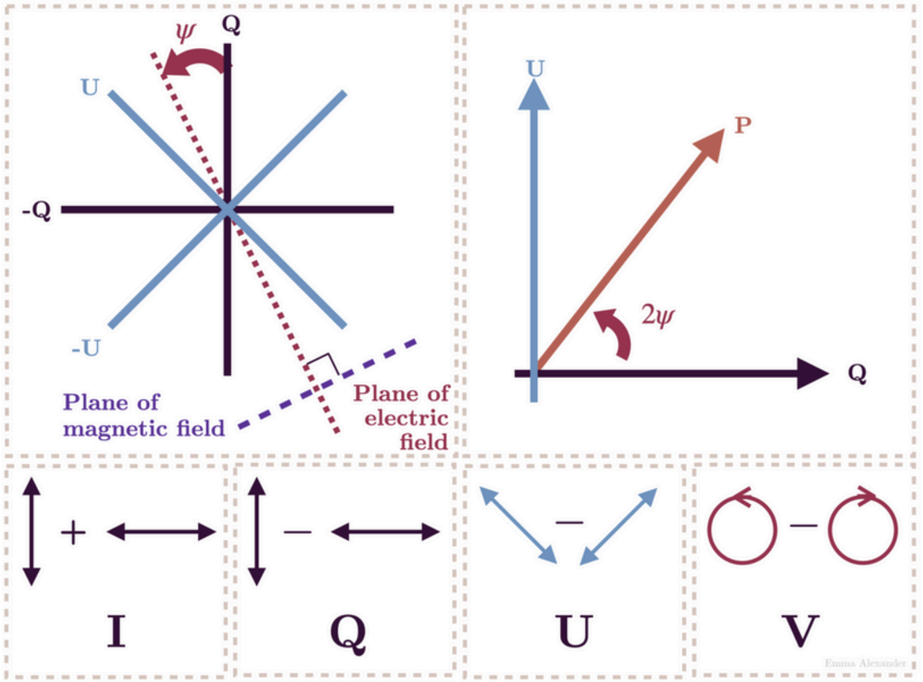
INFLATION AND CMB



By ESA

STOKES PARAMETERS

- Set of values that describe the polarization state of electromagnetic radiation.



Emma Alexander

- We can construct two quantities from the Stokes Q and U parameters that have a **definite value of spin** and **transform under rotation** by an angle ψ as

$$(Q \pm iU)'(\hat{n}) = e^{\mp 2i\psi}\,(Q \pm iU)(\hat{n})$$

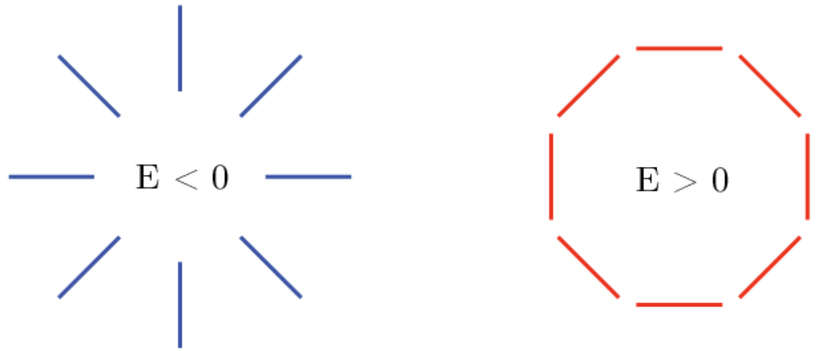
ZALDARRIAGA, M., 2001. AN ALL-SKY ANALYSIS ON PARITY VIOLATION, PHYS. REV. D 64, 103001.

E AND B-MODES

- Creating **rotationally invariant quantities** (spin 0)

$$\tilde{E}(\hat{n}) \equiv -\frac{1}{2}\left[\eth'^2(Q+iU)+\bar{\eth}'^2(Q-iU)\right]$$

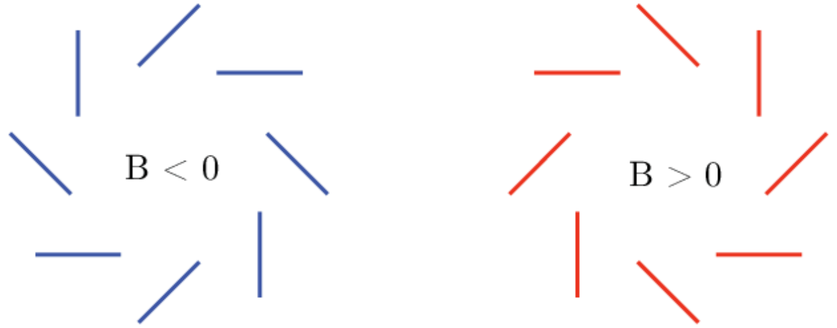
E-modes



- Unchanged under reflection (**parity even**)

$$\tilde{B}(\hat{n}) \equiv \frac{i}{2}\left[\eth'^2(Q+iU)-\bar{\eth}'^2(Q-iU)\right]$$

B-modes



- Interchanged under reflection (**parity odd**)

Probing Inflation with CMB Polarization - Scientific Figure on ResearchGate.

E AND B-MODES

- Creating rotationally invariant quantities

$$\tilde{E}(\hat{n}) = \sum_{lm} \sqrt{\frac{(l+2)!}{(l-2)!}}\, a_{E,lm}\, Y_{lm}(\hat{n})$$

$$\tilde{B}(\hat{n}) = \sum_{lm} \sqrt{\frac{(l+2)!}{(l-2)!}}\, a_{B,lm}\, Y_{lm}(\hat{n})$$

- In a statistically isotropic universe, the expected value of a_{lm} is zero:

$$\langle a_{lm} \rangle = 0$$

but its variance is non-zero and is related to the angular power spectrum:

$$\begin{aligned}
\langle a^*_{E,l'm'} a_{E,lm} \rangle &= C_{El}\, \delta_{l'l}\, \delta_{m'm}, \\
\langle a^*_{B,l'm'} a_{B,lm} \rangle &= C_{Bl}\, \delta_{l'l}\, \delta_{m'm}, \\
\langle a^*_{T,l'm'} a_{E,lm} \rangle &= C_{Cl}\, \delta_{l'l}\, \delta_{m'm},
\end{aligned}$$

ZALDARRIAGA, M., 2001. AN ALL-SKY ANALYSIS ON PARITY VIOLATION, PHYS. REV. D 64, 103001.

E AND B-MODES

- E and B modes are transformed differently under the parity transformation. Therefore, the product of the two, the “EB correlation”, is a pseudoscalar, ie, it changes sign under parity transformation.

- The full-sky average of the **EB correlation must vanish** (to within the measurement uncertainty), **if there is no parity violation!**

$$\langle a^*_{B,l'm'} a_{E,lm} \rangle = \langle a^*_{B,l'm'} a_{T,lm} \rangle = 0$$

E AND B-MODE CORRELATION

- E and B modes are transformed differently under the parity transformation. Therefore, the product of the two, the “EB correlation”, is a pseudoscalar, ie, it changes sign under parity transformation.

- The full-sky average of the **EB correlation must vanish** (to within the measurement uncertainty), **if there is no parity violation!**

$$\langle a^*_{B,l'm'} a_{E,lm} \rangle = \langle a^*_{B,l'm'} a_{T,lm} \rangle = 0$$

- But, in reality

$$\langle a^*_{B,l'm'} a_{E,lm} \rangle \neq 0$$

E AND B-MODE CORRELATION

- E and B modes are transformed differently under the parity transformation. Therefore, the product of the two, the “EB correlation”, is a pseudoscalar, ie, it changes sign under parity transformation.

- The full-sky average of the **EB correlation must vanish** (to within the measurement uncertainty), **if there is no parity violation!**

$$\langle a^*_{B,l'm'} a_{E,lm} \rangle = \langle a^*_{B,l'm'} a_{T,lm} \rangle = 0$$

- But, in reality

$$\langle a^*_{B,l'm'} a_{E,lm} \rangle \neq 0$$

How is that obtained?

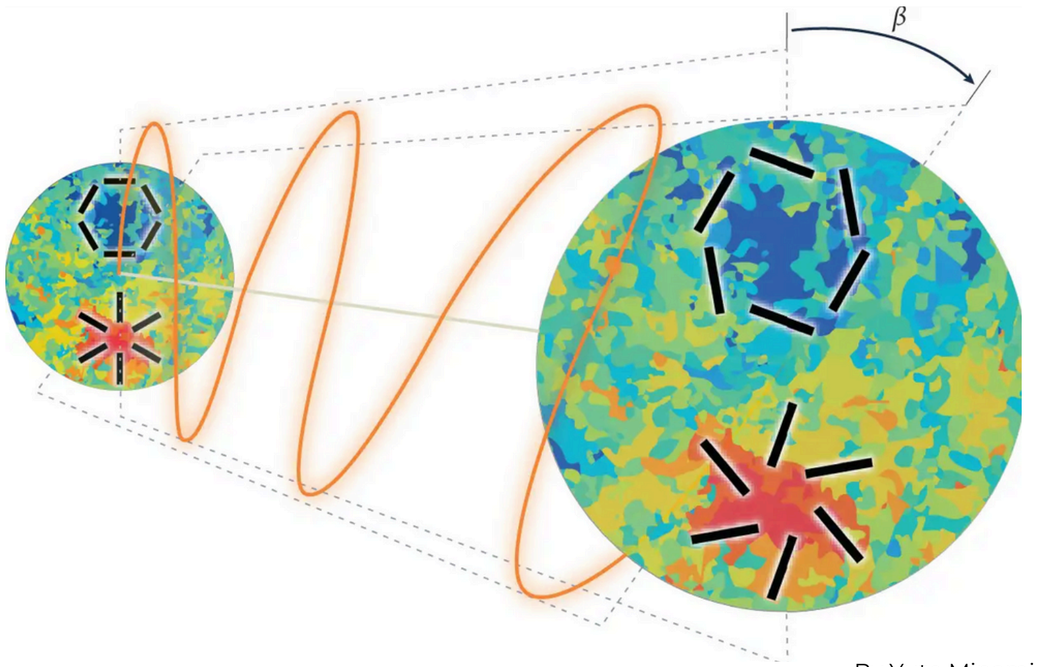
POSSIBLE MODEL: COSMIC BIREFRINGENCE

- The rotation of the plane of linear polarization β, known as **cosmic birefringence**, can occur if light interacts with dark matter as it travels across the universe.

- The polarization rotation angle is found to be $\beta = 0.35 \pm 0.14\ \mathrm{deg.}$

- If these interactions violate parity symmetry, their signature could appear in the CMB polarization data as

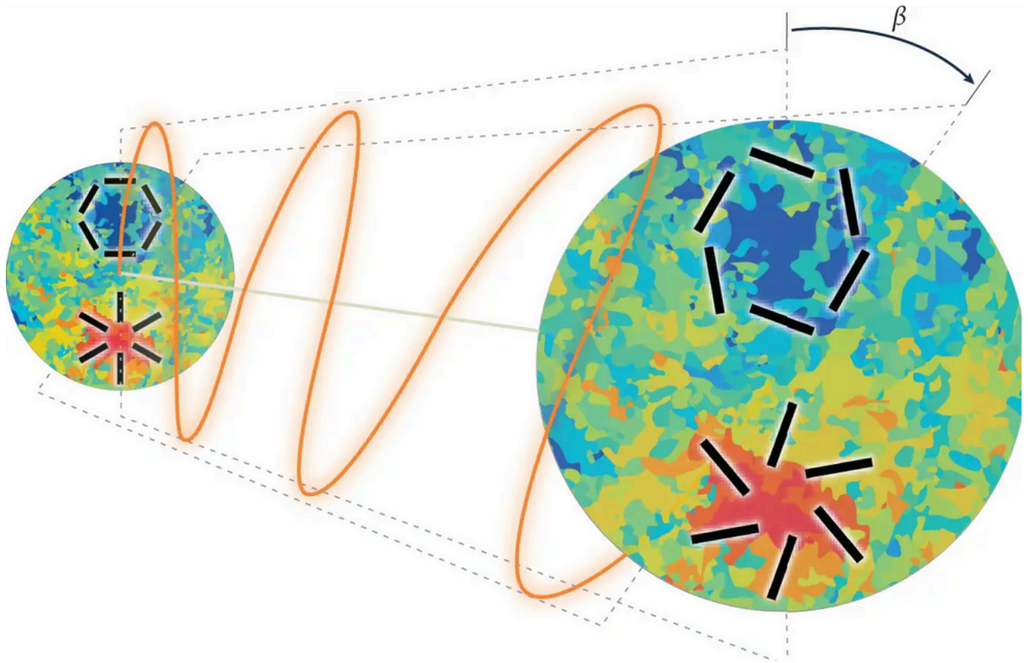
$$\langle a^*_{B,l'm'} a_{E,lm} \rangle \neq 0$$



By Yuto Minami

MINAMI, Y., & KOMATSU, E. (2020). NEW EXTRACTION OF THE COSMIC BIREFRINGENCE FROM THE PLANCK 2018 POLARIZATION DATA. HTTPS://DOI.ORG/10.1103/PHYSREVLETT.125.221301

POSSIBLE MODEL: COSMIC BIREFRINGENCE



By Yuto Minami

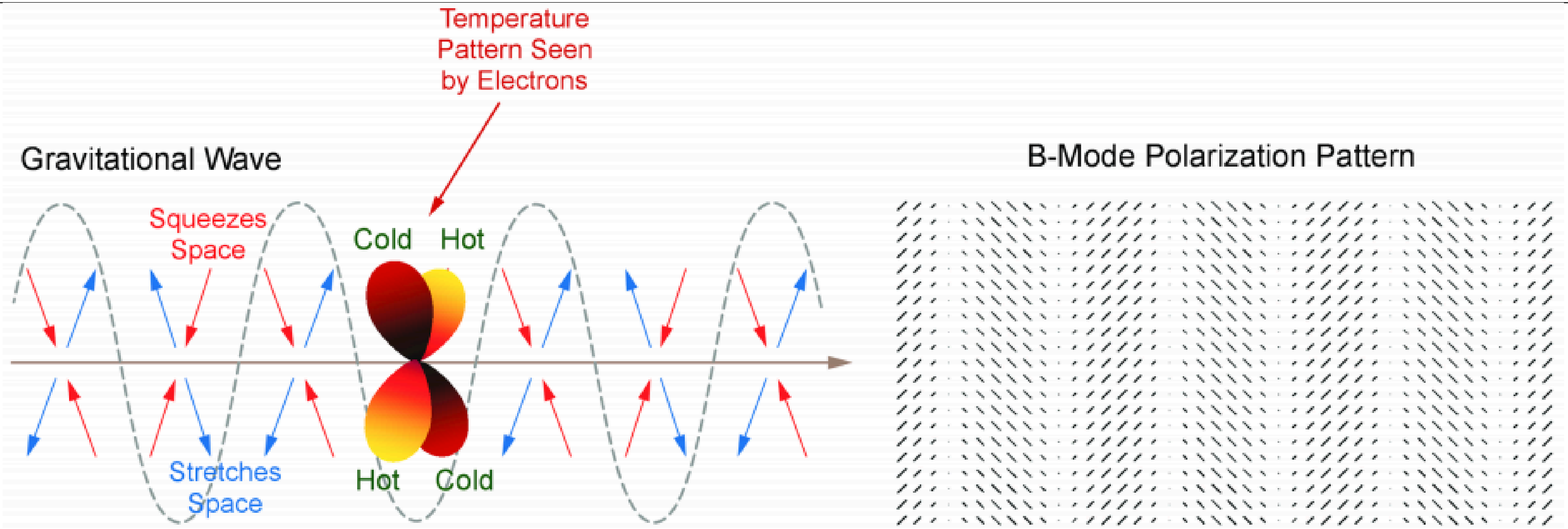
- Theoretical models:
  Chern-Simons coupling term

$$\mathcal{L}_{int} = g(\chi) F_{\mu\nu} \tilde{F}^{\mu\nu}$$

- Pseudo-scalar:

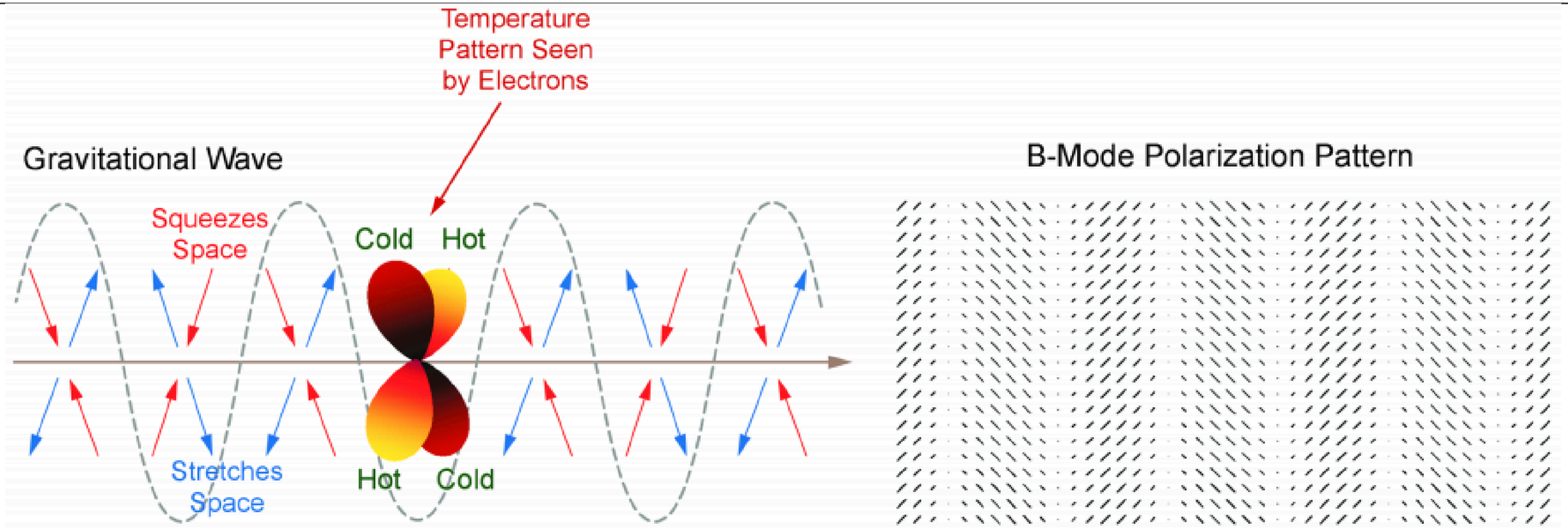
behaves like a scalar, except that it changes sign under a parity inversion.

POSSIBLE MODEL: PRIMORDIAL GW



- Anisotropies in the + and × gravitational-wave helicities alter the E- and B-mode polarization patterns.

RECENT PROGRESS: NON-PARITY VIOLATING GW



- The quadratic action for tensor perturbations for each polarization:

$$S_\gamma = \frac{m_{\rm Pl}^2}{8} \sum_a \int d^3x \int d\tau\, a^2(\tau) \left[(\gamma_a')^2 - (\nabla \gamma_a)^2 \right].$$

- Performing a field redefinition

$$u_a = \frac{m_{\rm Pl}}{2}\, a(\tau)\, \gamma_a.$$

RECENT PROGRESS

Solution of the equation of motion for PGW

- Action for Inflation

  $a(t) = e^{Ht}$ $\longrightarrow$ $S_\gamma = \frac{1}{2}\sum_a \int d^3x \int d\tau \left[(u_a')^2 - (\nabla u_a)^2 + \frac{1}{\tau^2}(2+3\epsilon)\, u_a^2\right].$

  - Solution $u_k(\tau) = \sqrt{\frac{\pi}{2k}}\,(-k\tau)^{1/2}\, e^{\,i\pi(\nu/2+1/4)} H_\nu^{(1)}(-k\tau).$ Hankel functions

    ✳ $\nu = \sqrt{9/4 + 3\epsilon}$

- Action for RDE

  $a(t) \propto t^{1/2}$ $\longrightarrow$ $S_\gamma = \frac{1}{2}\sum_a \int d^3x \int d\tau \left[(u_a')^2 - (\nabla u_a)^2\right].$

  - Solution $u_k(\tau) = \sqrt{\frac{1}{2k}}\, e^{-ik\tau}$

RECENT PROGRESS

- Action for MDE

  $a(t) = t^{2/3}$ $\longrightarrow$ $S_\gamma = \frac{1}{2}\sum_a \int d^3x \int d\tau \left[(u_a')^2 - (\nabla u_a)^2 + \frac{2}{\tau^2}\, u_a^2\right].$

  - Solution

    $u_k(\tau) = \sqrt{\frac{\pi}{2k}}\,(-k\tau)^{1/2}\, e^{\,i\pi(\nu/2+1/4)}\, H_\nu^{(1)}(-k\tau).$ $\ast$ $\nu = 3/2$

- Action for both components

  $a(\tau) = a_{eq}\left([\tau C + 1]^2 - 1\right)$ $\longrightarrow$ $S_\gamma = \frac{1}{2}\sum_a \int d^3x \int d\tau \left[(u_a')^2 - (\nabla u_a)^2 + \frac{2C}{\tau^2 C + 2\tau}\, u_a^2\right].$

  - Numerical solution

POSSIBLE MODEL: PRIMORDIAL GW

Objectives

- Solve the equation of motion of primordial GW **with a parity-violating source term** during the radiation-dominated era, the matter-dominated era, and the intermediate period in which both components contribute.

- Theoretical models:
  Chern-Simons coupling term

$$\mathcal{L}_{int} = f(\Phi) R^{\lambda}{}_{\sigma\mu\nu} \tilde{R}_{\lambda}{}^{\sigma\mu\nu}$$

- The tensor perturbations equation of motion with a source term is

$$M_P^2 \Box h_{\alpha\beta} = 2f''\dot{\Phi}^2 \epsilon^{ijk} \eta_{i\alpha} (\partial_\beta \partial_j h_{0k} + \partial_0 \partial_k h_{\beta j}) + 2f'\dot{\Phi} \epsilon^{ijk} \eta_{i\alpha} \partial_j \Box h_{\beta k} + (\alpha \leftrightarrow \beta),$$

A. LUE, L. WANG, AND M. KAMIONKOWSKI, COSMOLOGICAL SIGNATURE OF NEW PARITY-VIOLATING INTERACTIONS, PHYS. REV. LETT. 83, 1506 (1999), ARXIV:ASTRO-PH/9812088.

POSSIBLE MODEL: PRIMORDIAL GW

Objectives

- Determine how the resulting tensor-mode evolution modifies the polarization of the CMB.

The tensor contribution to the angular power spectrum to the CMB anisotropies is given by

$$\frac{\Delta T}{T}(\hat{n}) = -\frac{1}{2}\int_{\mathbf{k}} e^{+i\mathbf{k}\cdot\mathbf{x}_0} \sum_{\lambda} \int_{t_L}^{t_0} dt' e^{i\hat{n}\cdot\mathbf{k}r(t')} \mathcal{T}_{\lambda}(k,t') \tilde{\gamma}^{0}_{\lambda}(\mathbf{k}) \hat{e}^{\lambda}_{ij}(\hat{k}) \hat{n}^i \hat{n}^j .$$

How do these solutions for the gravitational-wave modes affect the Stokes parameters Q, U and V?

CONCLUSION

- This work explored how parity violation could leave observable signatures in the CMB polarization, particularly through non-vanishing EB correlations, which would signal a breakdown of parity symmetry.

- We discussed two theoretical sources of parity violation:
  - **Cosmic birefringence**, arising from Chern–Simons–type couplings or pseudoscalar fields.
  - **Chiral primordial gravitational waves**, whose evolution across radiation, matter, and transitional eras can be studied through parity-violating tensor equations of motion. We reviewed how primordial gravitational waves generate E- and B-mode patterns, and how an asymmetry between the + and × helicities can modify these signals.

- Overall, these mechanisms offer promising avenues to probe new physics through CMB polarization.

REFERENCES

- Zaldarriaga, M., 2001. An All-Sky Analysis on Parity Violation. Phys. Rev. D 64, 103001.
- Jamieson, D., 2022. Cosmological Parity Violation, lecture notes.
- Weinberg, S., 2008. Cosmology, Oxford University Press.
- Fujita, T., Minami, Y., Shiraishi, M., Yokoyama, S., 2022. Can Primordial Parity Violation Explain the Observed Cosmic Birefringence?, arXiv:2208.08101 [astro-ph.CO].
- Komatsu, E., 2023. Parity Violation in Cosmology, JCAP Colloquium, Max Planck Institute for Astrophysics.
- Minami, Y., & Komatsu, E. (2020). New extraction of the cosmic birefringence from the Planck 2018 polarization data. https://doi.org/10.1103/PhysRevLett.125.221301
- A. Lue, L. Wang, and M. Kamionkowski, Cosmological Signature of New Parity-Violating Interactions, Phys. Rev. Lett. 83, 1506 (1999), arXiv:astro-ph/9812088.

STATE OF THE ART

- “We carefully investigate the possibility of explaining the observed EB correlation by the primordial chiral gravitational waves (CGWs), which can be generated in the parity-violating theories in the primordial Universe. We found that the CGWs scenario does not work due to the overproduction of the BB auto-correlation which far exceeds the observed one by SPTPol and POLARBEAR.”

FUJITA ET AL., “*CAN PRIMORDIAL PARITY VIOLATION EXPLAIN THE OBSERVED COSMIC BIREFRINGENCE?*” ARXIV:2208.08101 (2022)