PRESENTATION

宇宙の複屈折

How our Universe violates left-right symmetry

Tomohiro Fujita
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TF, Murai, Nakatsuka & Tsujikawa PRD**103,**043509(2021)
TF, Minami, Murai & Nakatsuka PRD**103,**063508(2020)

早稲田大学高等研究所
Waseda Institute for Advanced Study

27th. Mar. 2023 @統計物理懇談会

JPS Journal (物理学会誌)

- Contributed article

  Dr. Yuto Minami and I wrote an introductory article of this topic “cosmic birefringence”.
  Find it in Sep. volume of JPS journal.

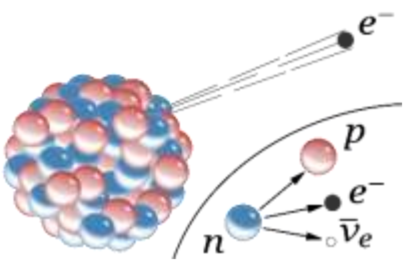
- It appeared on cover!

Left-right Symmetry

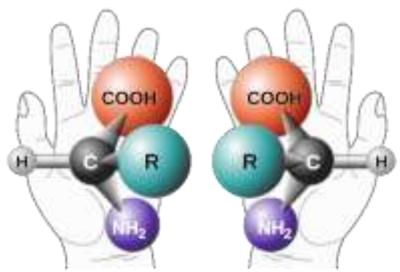
- Symmetry is crucially important in modern physics.
- **Parity sym.** = left-right sym. = reflectional sym.
- Classical dynamics, Electromagnetism, etc. respect this symmetry.

Violation of Parity Sym.

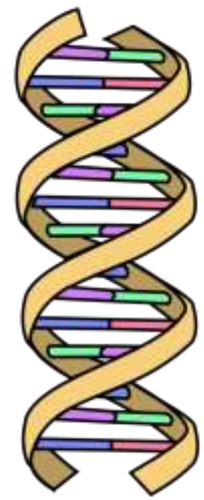
- In reality, however, parity sym. is often **broken**.



Weak nuclear force



Chiral molecule (enantiomer)



DNA

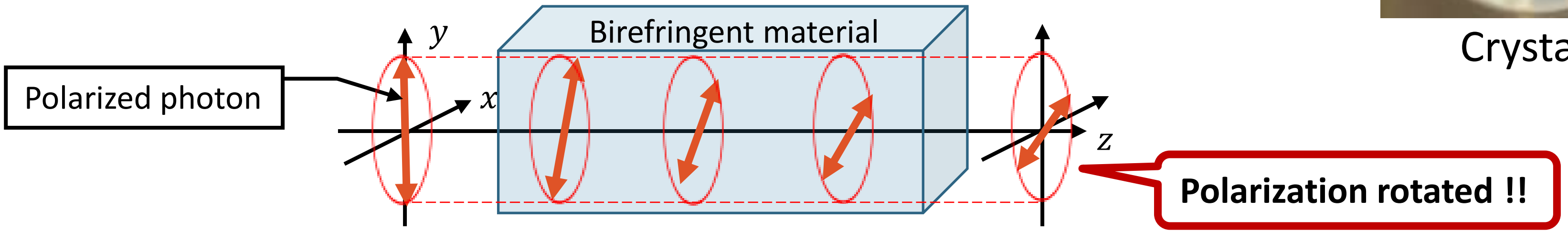
Right-left handed people

- Is this symmetry preserved on the largest scale??

Birefringence

Crystal

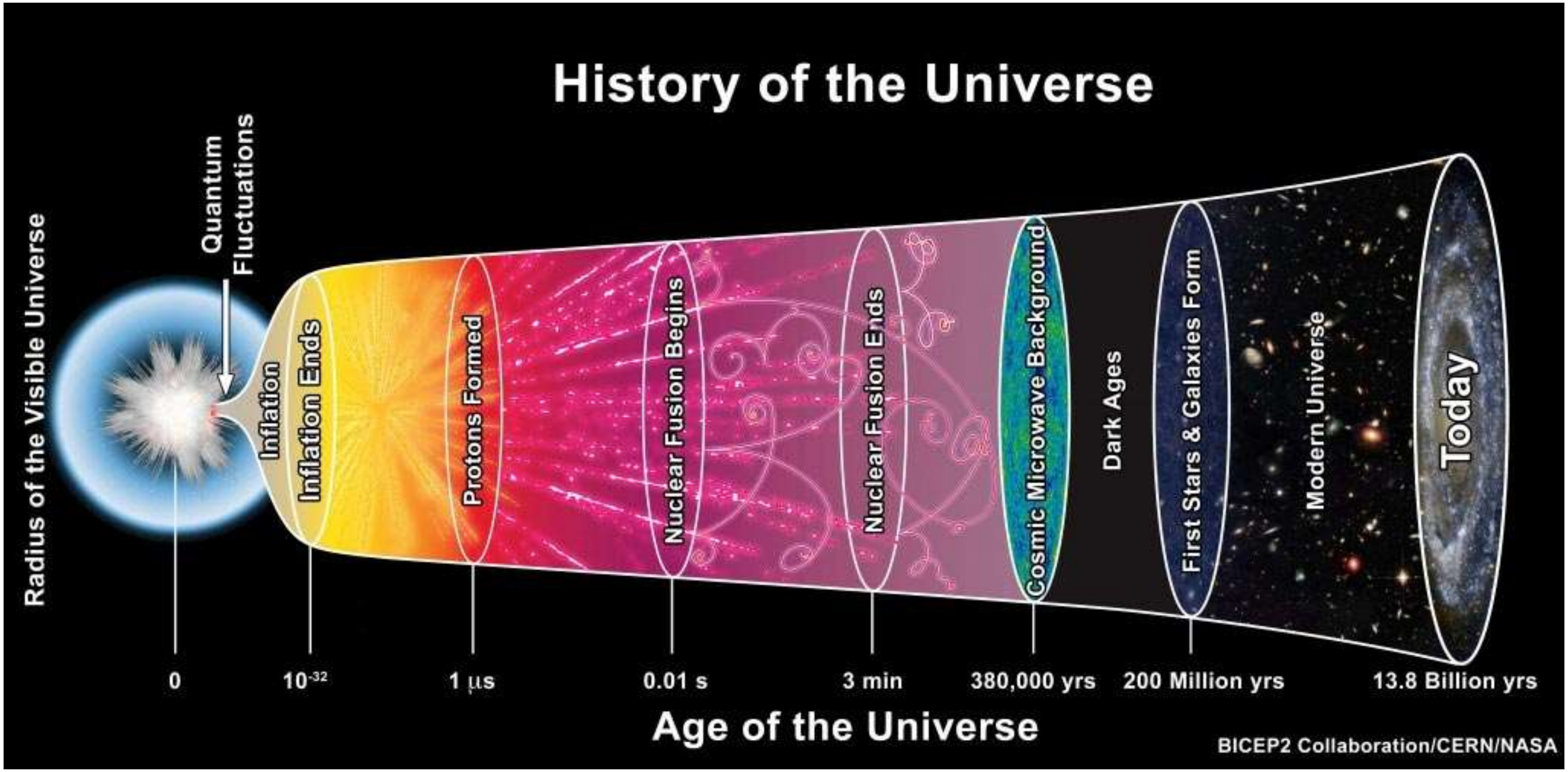
- Birefringent material rotates linear polarization plane



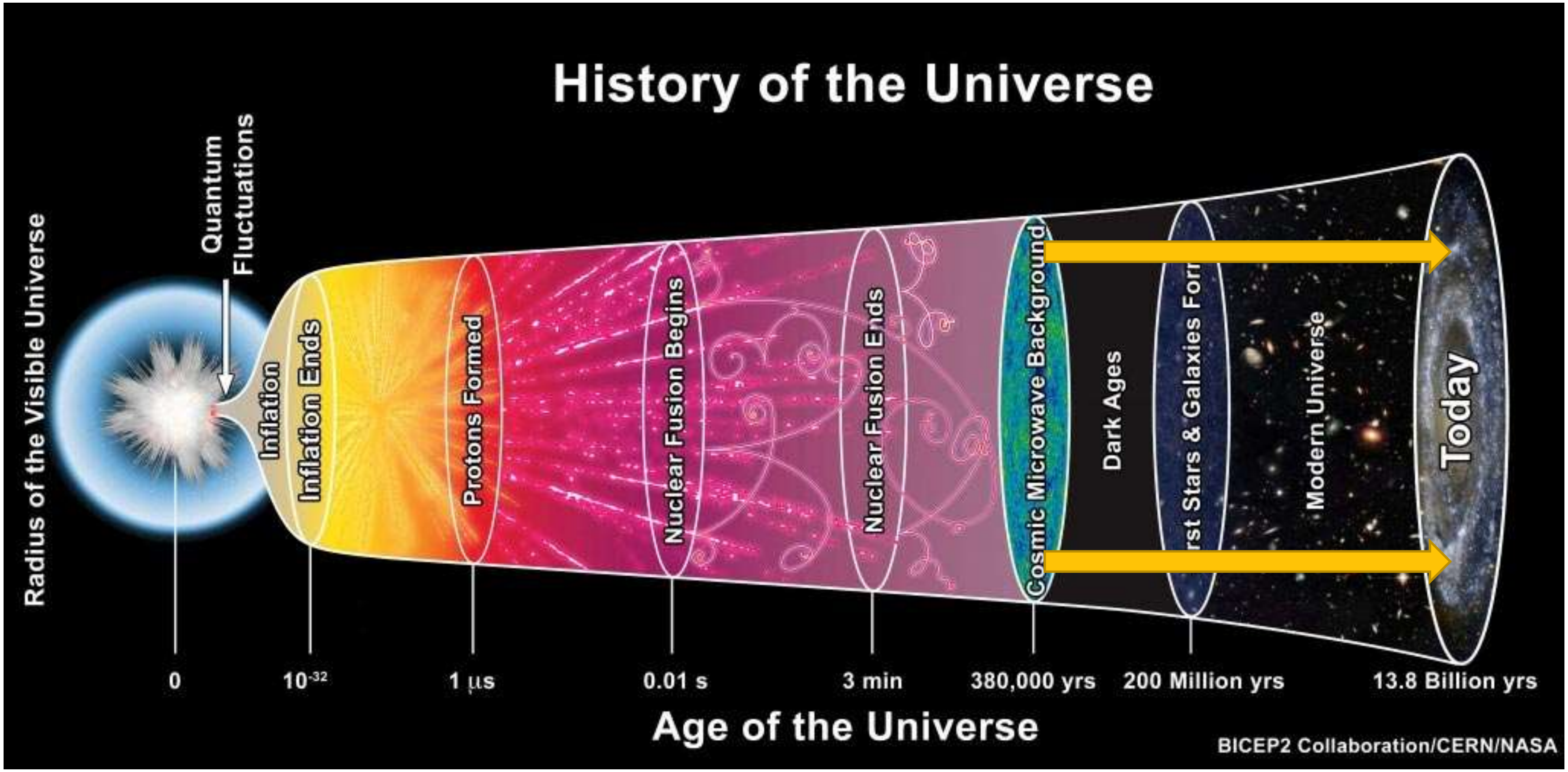
- The rotation can be clock-wise and counter-clock wise.
  Material structure determines either of them happens.
  ⇒ Parity symmetry is violated (by the structure).

- We found cosmic birefringence (= birefringence in vacuum space)
  in the big bang light.

Cosmology


History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 μs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8 Billion yrs
Age of the Universe
BICEP2 Collaboration/CERN/NASA

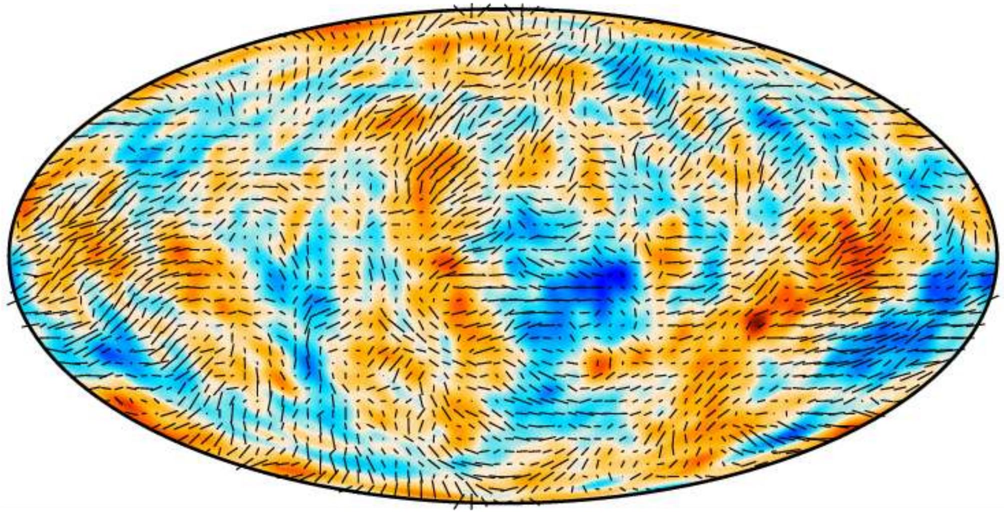
Cosmology



- The photons propagating from hot big bang are observed today!

Planck Satellite

Cosmic birefringence



- Planck gave us detailed polarization map of big bang light.
- Minami&Komatu(2020) found its optical rotation about 0.3 deg.
- What can cause such “cosmic birefringence”?

Outline of Talk

1. Cosmic Birefringence

2. ALP Dark Energy

3. Early Dark Energy

4. Summary

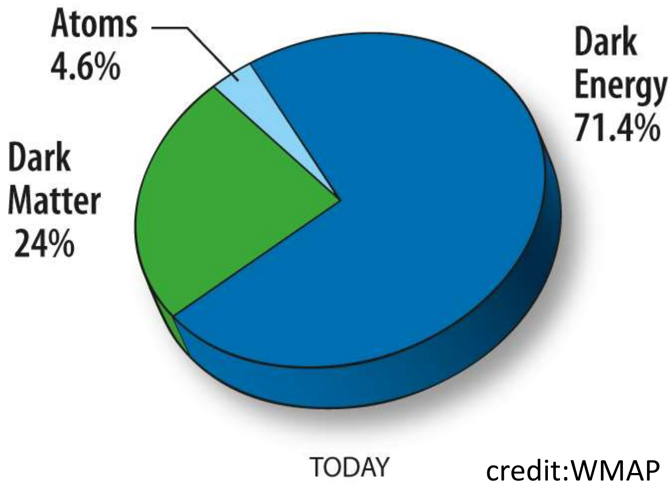
The standard cosmology

宇宙論には理論・観測両面で確立した**標準モデル**がある。それから外れるシグナルは大発見の可能性あり。

ΛCDM Paradigm

- All the cosmological observations are explained by the DE+DM universe. (but the Hubble tension…)

Energy component of current universe



credit:WMAP

Dark Energy (DE)

- Measuring the current Hubble parameter indicates the accelerated expansion.
- Dynamics : constant or scalar potential $V(\phi)$ which slowly rolling

$$w \equiv \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}, \quad -1 \le w < -0.95 \text{ (95\% C.L.)}$$

, [Planck2018]

Review of Cosmic Birefringence

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

Yuto Minami and Eiichiro Komatsu

Phys. Rev. Lett. **125**, 221301 – Published 23 November 2020

ABSTRACT

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 β. 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 β 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 2.4σ.

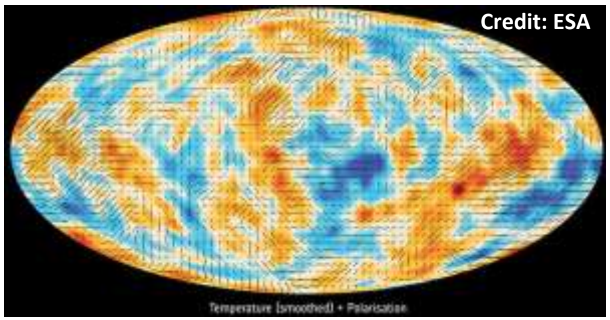
"cosmic birefringence angle β"
New signal?

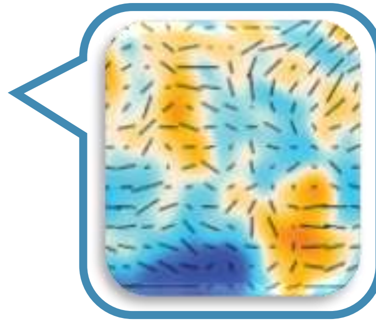
"finding β = 0.35 ± 0.14 deg (68% C.L.), which excludes β = 0 at **99.2% C.L.**
This corresponds to the statistical significance of **2.4σ**."

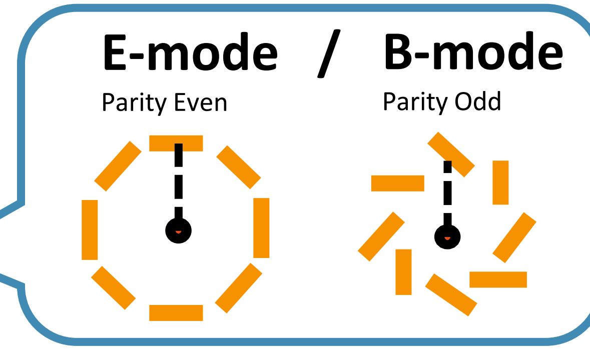
What is Cosmic Birefringence ?

Review of Cosmic Birefringence

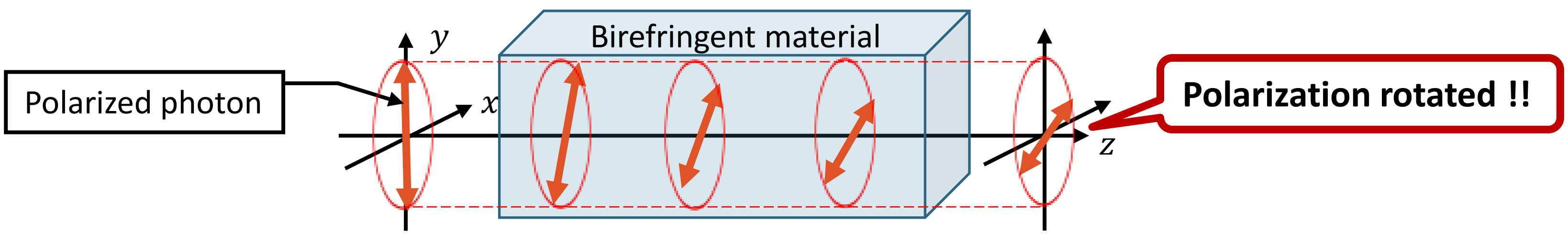
- Polarization signal in Cosmic Microwave Background (CMB)







- Birefringent material rotates direction of polarization



cosmic birefringence = polarization rotation signal

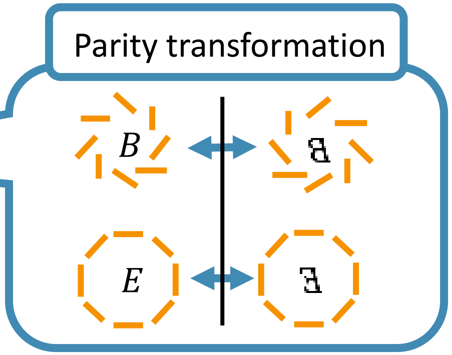
How to measure ?

Review of Cosmic Birefringence

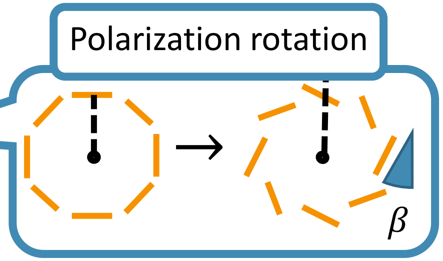
標準宇宙論ではE,B-modeの自己相関はあるが、相互相関はゼロ。なぜなら、相互相関があるとパリティを破ってしまう。

- W/o cosmic birefringence, *parity* is conserved,
  - Parity of $\begin{cases} \text{B-mode:} & P(B) = -B \\ \text{E-mode:} & P(E) = +E \end{cases}$
  - $P(\langle E_l B_{l'} \rangle) = -\langle E_l B_{l'} \rangle$, so when parity is conserved,

$$\langle E_l B_{l'} \rangle = P(\langle E_l B_{l'} \rangle) = 0$$



- With Cosmic Birefringence,
  - Mixing E-mode to B-mode

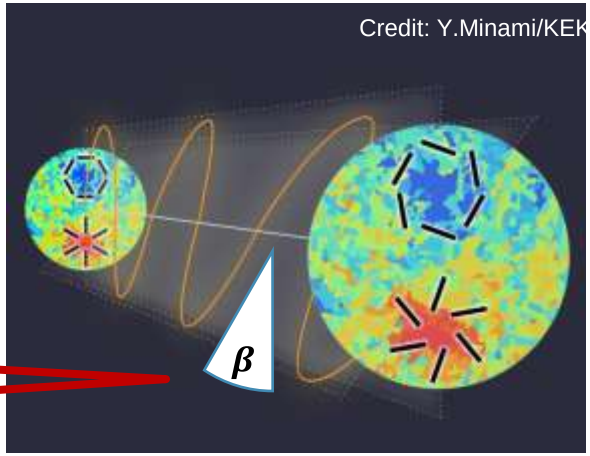


  - Parity violating $\langle E_l B_{l'} \rangle$ is produced

$$\langle E_l B_l \rangle = \frac{1}{2}(\langle E_l E_l \rangle - \langle B_l B_l \rangle)\sin(4\beta)$$

Minami&Komatsu reported **isotropic** rotation

β = 0.35 ± 0.14 deg



Follow-up paper 1

Cosmic Birefringence from the *Planck* Data Release 4

P. Diego-Palazuelos, J. R. Eskilt, Y. Minami, M. Tristram, R. M. Sullivan, A. J. Banday, R. B. Barreiro, H. K. Eriksen, K. M. Górski, R. Keskitalo, E. Komatsu, E. Martínez-González, D. Scott, P. Vielva, and I. K. Wehus

Phys. Rev. Lett. **128**, 091302 – Published 1 March 2022

ABSTRACT

We search for the signature of parity-violating physics in the cosmic microwave background, called cosmic birefringence, using the *Planck* data release 4. We initially find a birefringence angle of $\beta = 0.30^\circ \pm 0.11^\circ$ (68% C.L.) for nearly full-sky data. The values of β decrease as we enlarge the Galactic mask, which can be interpreted as the effect of polarized foreground emission. Two independent ways to model this effect are used to mitigate the systematic impact on β for different sky fractions. We choose not to assign cosmological significance to the measured value of β until we improve our knowledge of the foreground polarization.

Follow-up paper 1

Cosmic Birefringence from the *Planck* Data Release 4

A. J. Banday, R. B. Barreiro, H. K. Eriksen,
P. Vielva, and I. K. Wehus

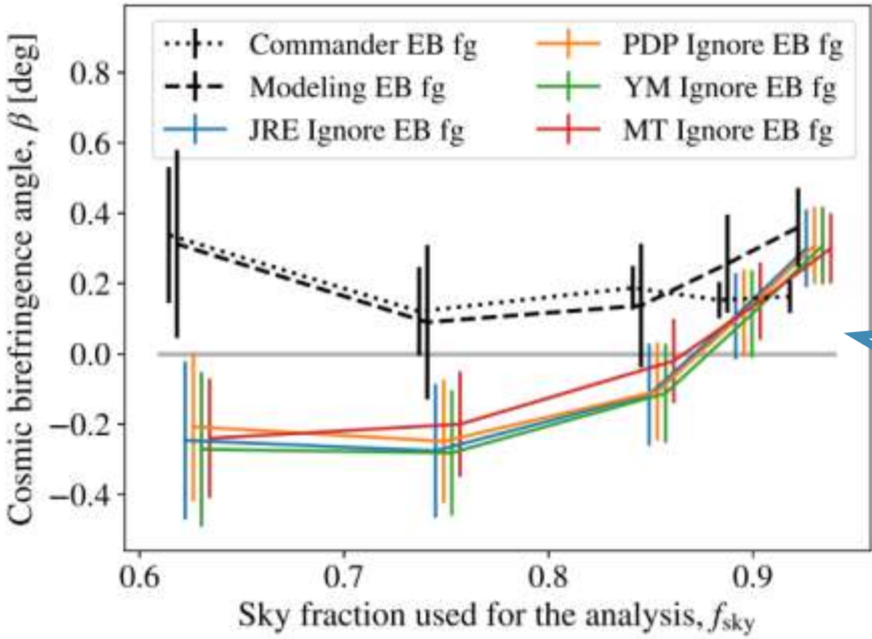


FIG. 1. Constraints on β for various values of $f_{\rm sky}$ with and without accounting for the foreground EB correlations. For the former, the dashed and dotted lines show corrections using the filament model [Eq. (2)] and the COMMANDER sky model, respectively. For the latter, the results of four pipelines (JRE, PDP, YM, MT) are shown.

The sign of β flips if $f_{\rm sky}$ is reduced.

A foreground EB model makes β stable.

Follow-up paper 2

arXiv > astro-ph > arXiv:2205.13962

Search...

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 27 May 2022]

Improved Constraints on Cosmic Birefringence from the WMAP and Planck Cosmic Microwave Background Polarization Data

Johannes R. Eskilt, Eiichiro Komatsu

The observed pattern of linear polarization of the cosmic microwave background (CMB) photons is a sensitive probe of physics violating parity symmetry under inversion of spatial coordinates. A new parity-violating interaction might have rotated the plane of linear polarization by an angle β as the CMB photons have been traveling for more than 13 billion years. This effect is known as "cosmic birefringence." In this paper, we present new measurements of cosmic birefringence from a joint analysis of polarization data from two space missions, Planck and WMAP. This dataset covers a wide range of frequencies from 23 to 353 GHz. We measure $\beta = 0.342^\circ {}^{+0.094^\circ}_{-0.091^\circ}$ (68% C.L.) for nearly full-sky data, which excludes $\beta = 0$ at 99.987% C.L. This corresponds to the statistical significance of 3.6σ. There is no evidence for frequency dependence of β. We find a similar result, albeit with a larger uncertainty, when removing the Galactic plane from the analysis.

CMB Birefringence

OK, we found something, maybe either of

(i) Cosmic birefringence

(ii) New galactic signal

Here let's assume (i) and consider what can cause it!

Outline of Talk

1. Cosmic Birefringence
2. ALP Dark Energy
3. Early Dark Energy
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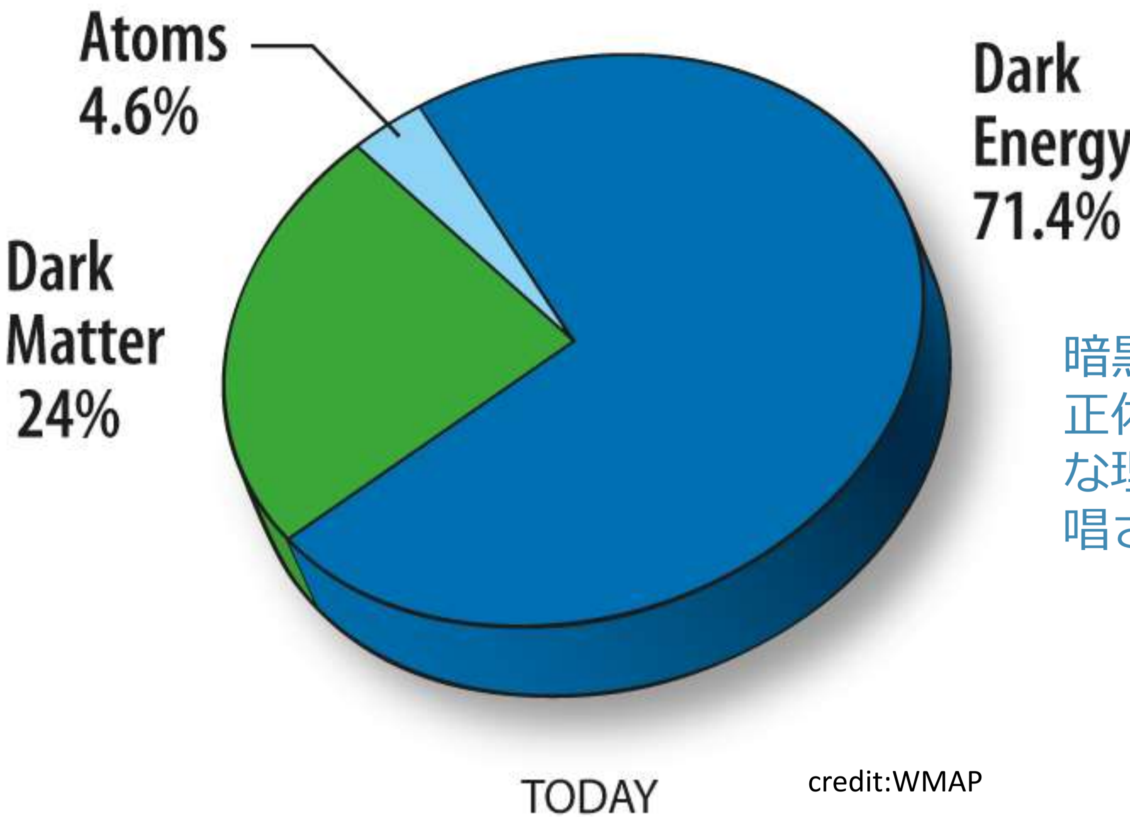
The standard cosmology

Energy component of current universe



credit:WMAP

暗黒エネルギーの正体は不明。色々な理論モデルが提唱されている。

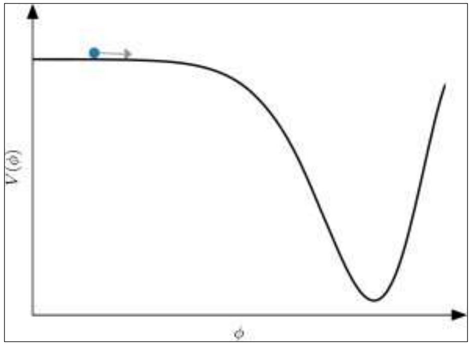
Dark Energy models

- In the standard model of cosmology,
  Dark Energy = Cosmological constant Λ

- However, a slow-rolling scalar field is another candidate,
  if it has a flat potential and homogeneously filles up the universe .

- Because its energy density behaves just like Λ

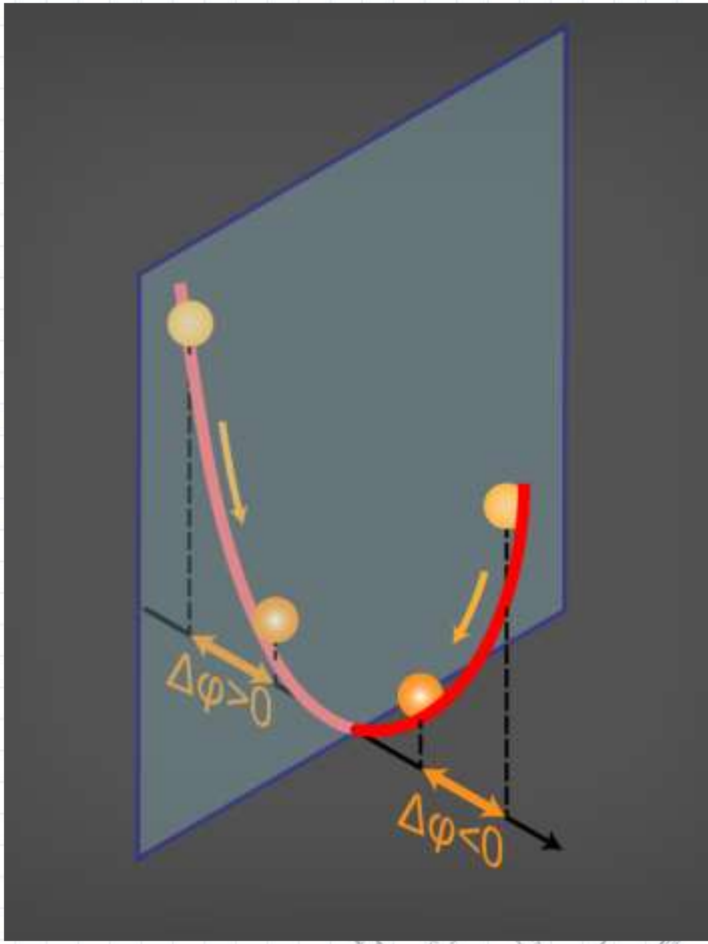
$$\rho(t) = \frac{1}{2}\dot{\phi}^2(t) + V(\phi) \xrightarrow{\text{Small } \dot{\phi}} \rho \simeq V \simeq \text{const.}$$



Which scalar field is suitable?

ALP DE model in a nutshell

- ALP is a field $\varphi(t, \boldsymbol{x})$ filling up our universe and slowly rolling down its potential.
- ALP rotates photon pol. plane by $\theta = -g\Delta\varphi/2$
- Sign of ALP displacement $\Delta\varphi \lesseqgtr 0$ violates parity sym as spontaneous sym breaking.



(Conventional) motivation of ALPs

- QCD axion
  - Strong CP problem:

Baker, et al. (2006)

$$\mathcal{L}_{\theta_{QCD}} = \frac{\theta_{QCD}}{32\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \theta_{QCD} \lesssim 10^{-10}$$

by the electric dipole moment of neutron

  - One of the solutions is QCD axion:

$$\mathcal{L}_{\theta_{QCD}} \to \left(\theta_{QCD} + \frac{\phi}{f}\right)\frac{1}{32\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

Peccei&Quinn. (1977)
Winberg(1978),Wilczek (1978)

- Axion-like particles by String Axiverse

"*String theory predicts many ultralight axions*"

Arvanitaki+ (2009)

  - ALPs have mass nonperturbatively, which is exponentially suppressed:

$$m_\phi^2 \propto \left(\frac{\mu^4}{f^2}\right)e^{-S_{\mathrm{inst}}}$$

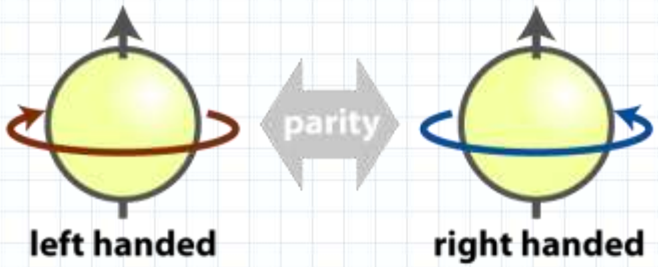
Marsh (2015)

  - ALP as Dark Matter: $10^{-22}\mathrm{eV} \lesssim m_\phi$
  - ALP as Dark Energy: $m_\phi \lesssim H_0 \sim 10^{-33}\mathrm{eV}$

Observational hints motivate the studies of ALP!

What characterizes ALPs?

- ALP can be very light ($m \lll 1\mathrm{eV}$) by its shift sym.
- ALP breaks parity



- ALP may be coupled to photon!!

Turner & Widrow (1988); Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)…

$\tilde{F}^{\mu\nu} \equiv \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}/2\sqrt{-g}$

Axion-Photon Coupling

- Interaction term: $\mathcal{L}_{\phi\gamma} = \frac{1}{4} g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$

Turner & Widrow (1988); Carroll, Field & Jackiw (1990);
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Axion-Photon Coupling

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Photon: $\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\dot{\phi}\boldsymbol{\nabla} \times \boldsymbol{A}$

Axion: $\left[\partial_t^2 - \partial_i^2 + m^2\right]\phi = -g\dot{\boldsymbol{A}} \cdot \boldsymbol{\nabla} \times \boldsymbol{A}$

Turner & Widrow (1988); Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)…

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Axion: $$[\partial_t^2 - \partial_i^2 + m^2]\phi = -g\dot{\boldsymbol{A}}\cdot\boldsymbol{\nabla}\times\boldsymbol{A}$$

New terms!

What if this axion is dark energy?

[Harari & Sikivie, Phys. Lett. B 289, 67 (1992)]

Birefringence

- Assume background DE axion

$\dot{\phi} \simeq \dot{\phi}_0 \approx \text{const.}$

Photon EoM: $\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\dot{\phi}\boldsymbol{\nabla} \times \boldsymbol{A}$

[Harari & Sikivie, Phys. Lett. B 289, 67 (1992)]

Birefringence

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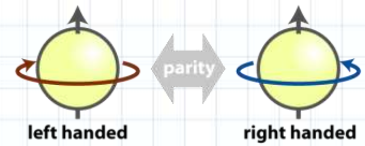
Photon EoM: $\left[\partial_t^2 - \partial_i^2\right]\boldsymbol{A} = -g\dot{\phi}\boldsymbol{\nabla} \times \boldsymbol{A}$

$i\hat{\boldsymbol{k}} \times \boldsymbol{e}_{L,R} = \pm\, \boldsymbol{e}_{L,R}$

⇨ Dispersion relations of Left/Right Pol. are modified

$$\omega_{L,R}^2 = k^2 \left[1 \pm \frac{g}{k}\dot{\phi}_0\right]$$



Speed of light changes depending on polarization!

Birefringence

- Another consequence: Rotation of liner pol. Plane

Linear pol. Photon can be decomposed into circular pol.

$$\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 \\ i \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 1 \\ -i \end{pmatrix},$$

$t \longrightarrow t + T$

With ADE BG phase velocity are different,
⇨ polarization plane rotates

$$\frac{e^{ikT}}{2}\left[e^{i\int_t^{t+T}\delta\omega \mathrm{d}t}\begin{pmatrix} 1 \\ i \end{pmatrix} + e^{-i\int_t^{t+T}\delta\omega \mathrm{d}t}\begin{pmatrix} 1 \\ -i \end{pmatrix}\right]$$

$$= e^{ikT}\begin{pmatrix} \cos(\int_t^{t+T}\delta\omega\,\mathrm{d}t) \\ -\sin(\int_t^{t+T}\delta\omega\,\mathrm{d}t) \end{pmatrix}.$$

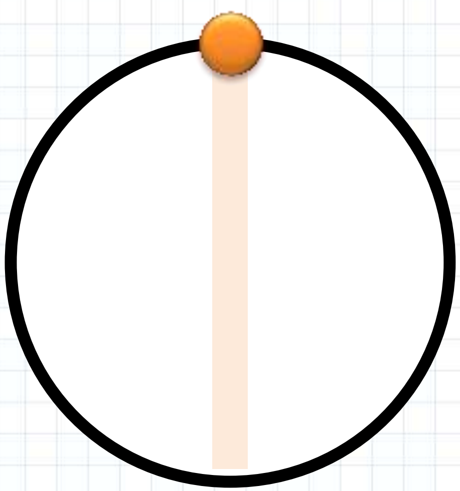
Birefringence

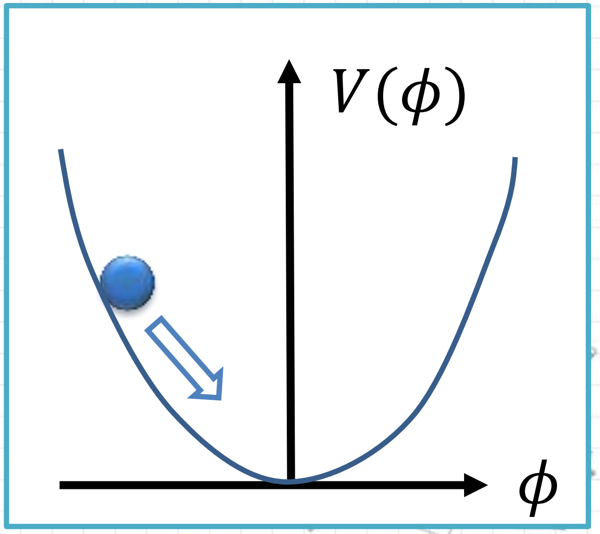
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\nabla\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- Rotation angle synchronizes with Axion

$$\theta(t,T) = \int_t^{t+T} \delta\omega(t)\,\mathrm{d}t = -\frac{g_{a\gamma}}{2}\left[\phi(t+T) - \phi(t)\right],$$

- Motion of the linear polarization plane





Birefringence

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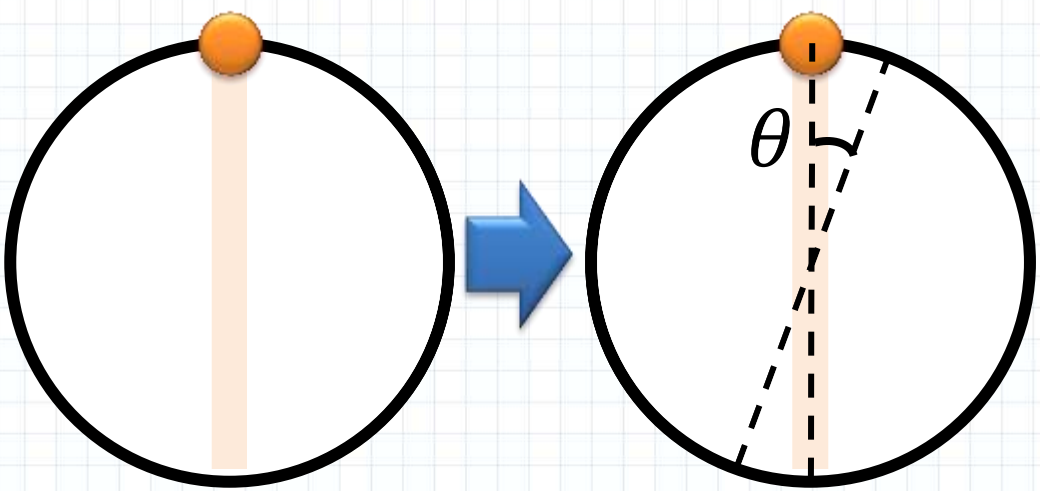
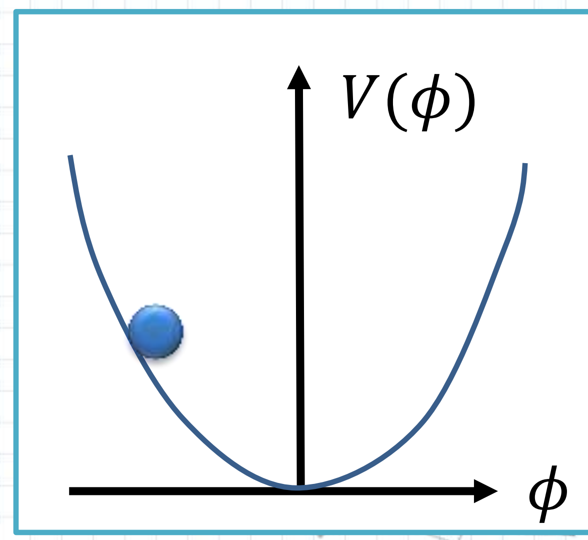




Axion causes CMB Biref.

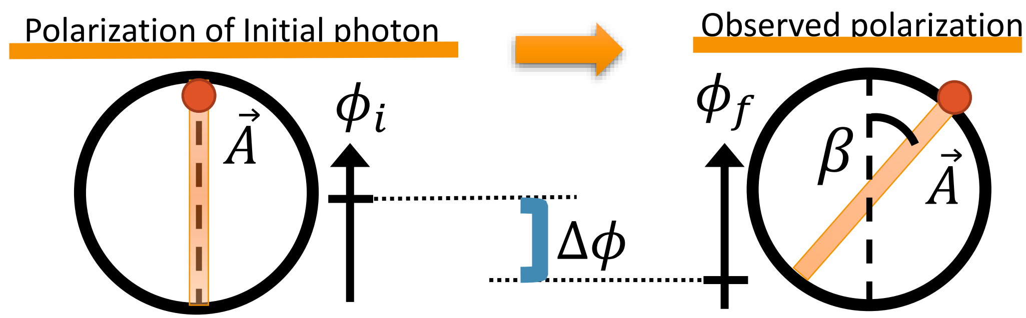
- Axion-Photon coupling

$$\mathcal{L} = -\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Polarization rotation angle

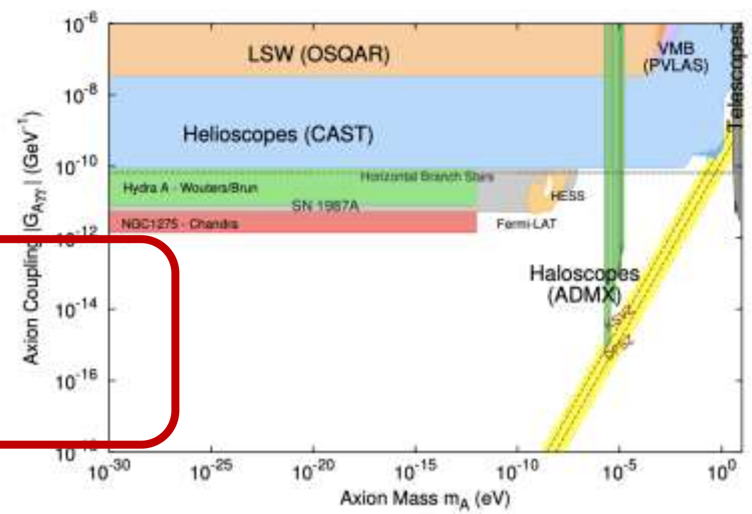
$$\beta = \frac{g}{2}\int \mathrm{d}\eta \frac{\mathrm{d}\phi}{\mathrm{d}\,\eta} = \frac{g}{2}(\phi_f - \phi_i)$$

Harari&Sikivie (1992)



- Different mass range

What kind of axion can reproduce the observed β?



Lighter Axion

Axion causes CMB Biref.

How to calculate Cosmic Birefringence:

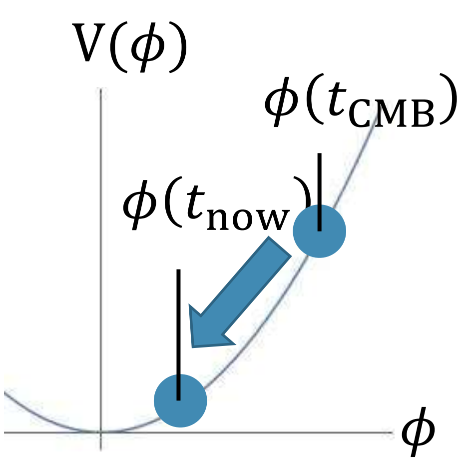
- In this talk, focus on background motion.

$$\phi(t,x) = \bar{\phi}(t) + \delta\phi(t,x)$$

(perturbations $\delta\phi$ result in anisotropic birefringence signal: Pospelov, et.al., (2008), Caldwell, et.al., (2011))

- If $V(\phi) = m^2\phi^2/2$, background field dynamics is governed by axion mass m

$$\ddot{\bar{\phi}} + 3H\dot{\bar{\phi}} + m^2\bar{\phi} = 0$$, H: Hubble expansion rate

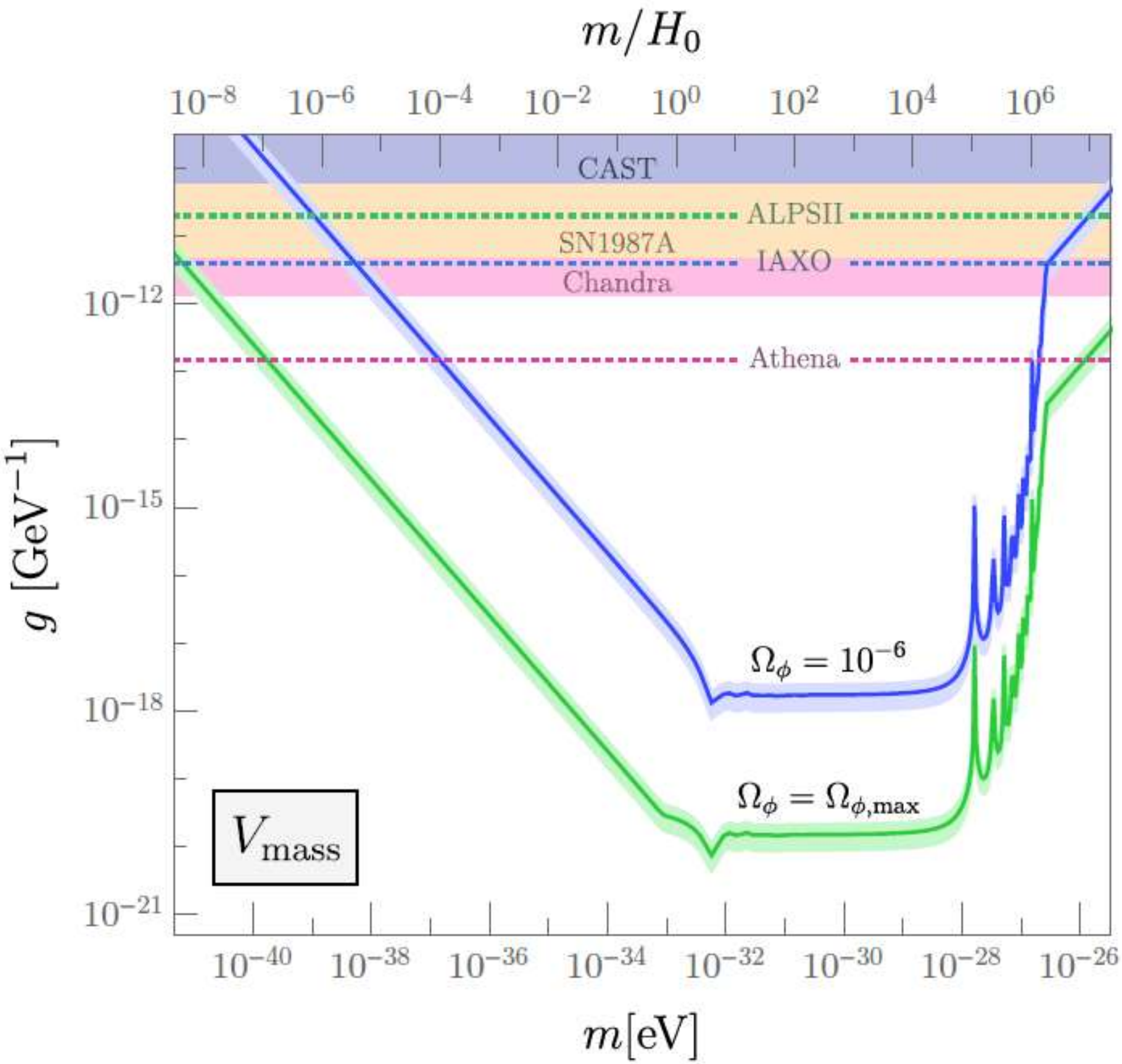


- Axion-photon coupling

$$g = 2\,\beta(\,\bar{\phi}(t_{\rm now}) - \bar{\phi}(t_{\rm CMB})\,)^{-1}$$, β = 0.35 deg

Determine axion-photon coupling g for a given m

Axion causes CMB Biref.



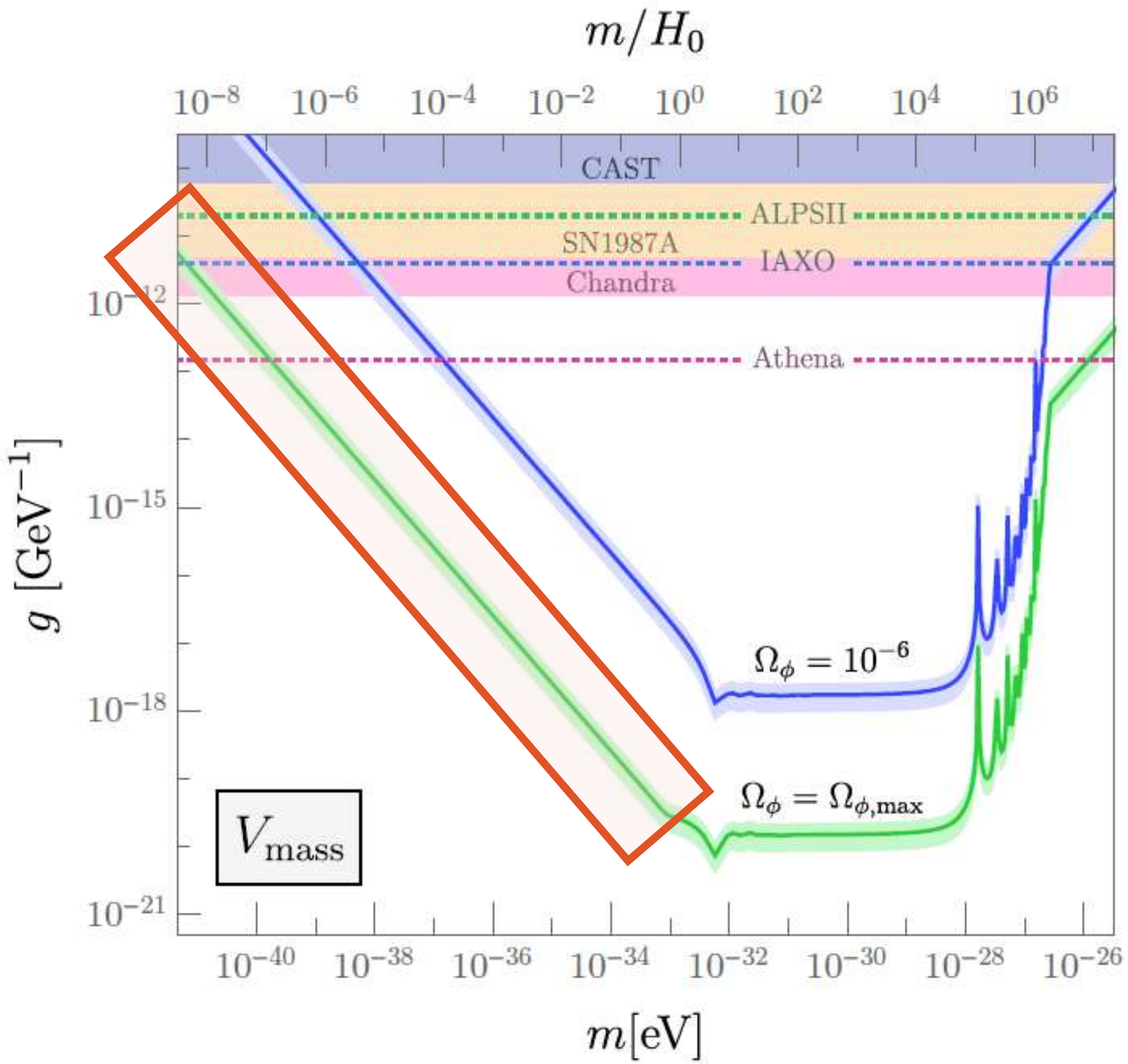
- Model: $V = m^2\phi^2/2$

  m : axion mass

  Ω_ϕ: present energy fraction

  On the lines, the rolling axion explains the observed β!!

Axion causes CMB Biref.



- Model: $V = m^2\phi^2/2$

  m : axion mass

  Ω_ϕ: present energy fraction

  On the lines, the rolling axion explains the observed β!!

- Axion dark energy

  For $m < 10^{-33}$eV,
  we find $\Omega_{\phi,\max} = \Omega_\Lambda$.

  The axion explains the current accelerated expansion, too!

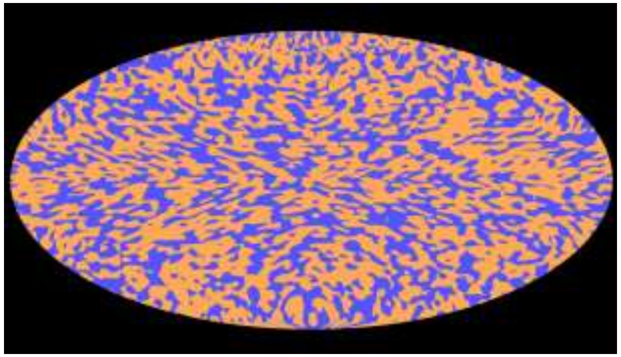
- We also study cos potential

$$V_{\cos}(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

Other proposals

■ Axion domain walls

[Takahashi&Yin(arXiv:2012.11576)]

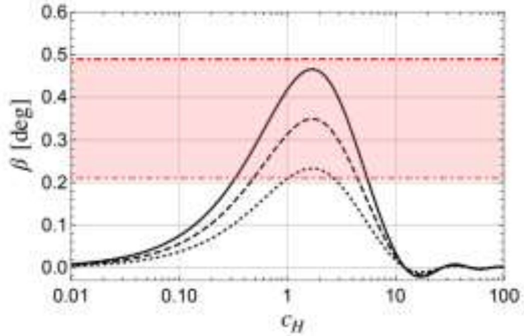


■ Axion coupled to Dark matter

[Nakagawa, Takahashi&Yamada(arXiv:2103.08153)]

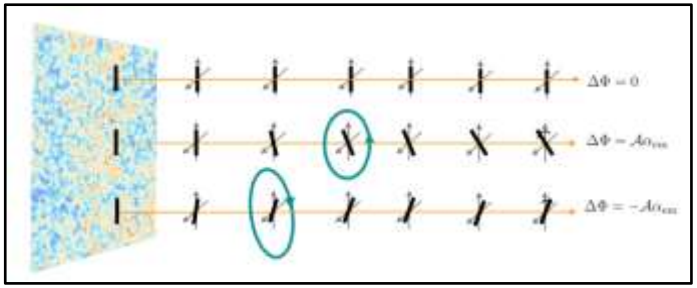
■ Electroweak axion quintessence

[Choi, Lin, Visinelli&Yanagida(arXiv:2106.12602)]



■ Axion Strings

[Jain, Long, & Amin(arXiv:2103.10962)]



Any other ideas?

Outline of Talk

1. Cosmic Birefringence
2. ALP Dark Energy
3. Early Dark Energy
4. Summary

Summary

- CMB may find cosmic birefringence $\beta = 0.34^\circ \pm 0.1^\circ$.
  It'd indicates parity violation in our universe.

- ALPs are a well-motivated DM/DE candidate
  Its coupling to photon causes Birefringence

- Simple models of slowly-rolling Axion can explain both
  dark energy and cosmic birefringence

- Early Dark Energy which alleviates Hubble tension
  can also explain cosmic birefringence if $g_{a\gamma} \sim M_{\rm Pl}^{-1}$

- Anisotropic birefringence will be tested by future CMB obs.

Thank you ！