PRESENTATION

Cosmic Birefringence

How our Universe violates left-right symmetry

Tomohiro Fujita
(Waseda Inst. Adv. Study & RESCEU Tokyo U.)

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

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

RESEARCH CENTER FOR THE EARLY UNIVERSE
THE UNIVERSITY OF TOKYO
RESCEU

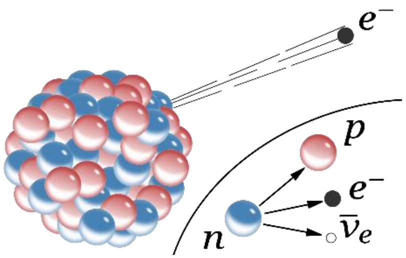
Jul. 2023 @Cosmology from Home

Left-right Symmetry

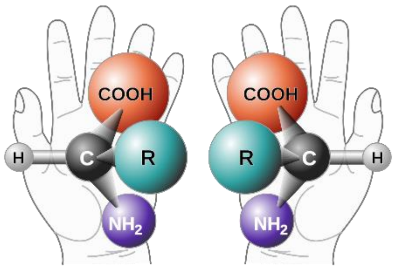
- Symmetry is crucially important in modern physics.
- **Parity sym.** = left-right sym. = reflectional sym.
- Classical dynamics, Electromagnetism, etc. respect this symmetry.

Violation of Parity Sym.

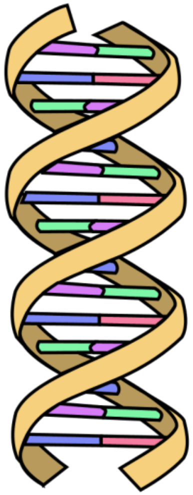
- In reality, however, parity sym. is often **broken**.



Weak nuclear force



Chiral molecule (enantiomer)



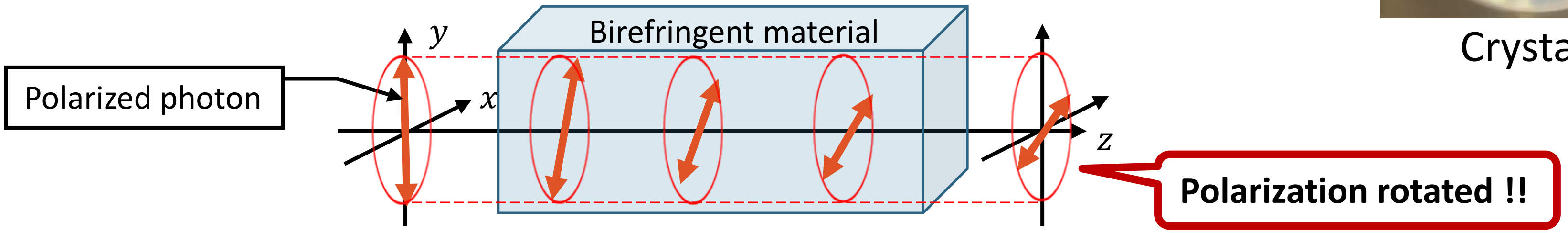
DNA

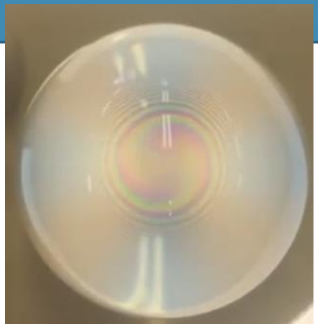
Right-left handed people

- Is this symmetry preserved on the largest scale??

Birefringence

- Birefringent material rotates linear polarization plane

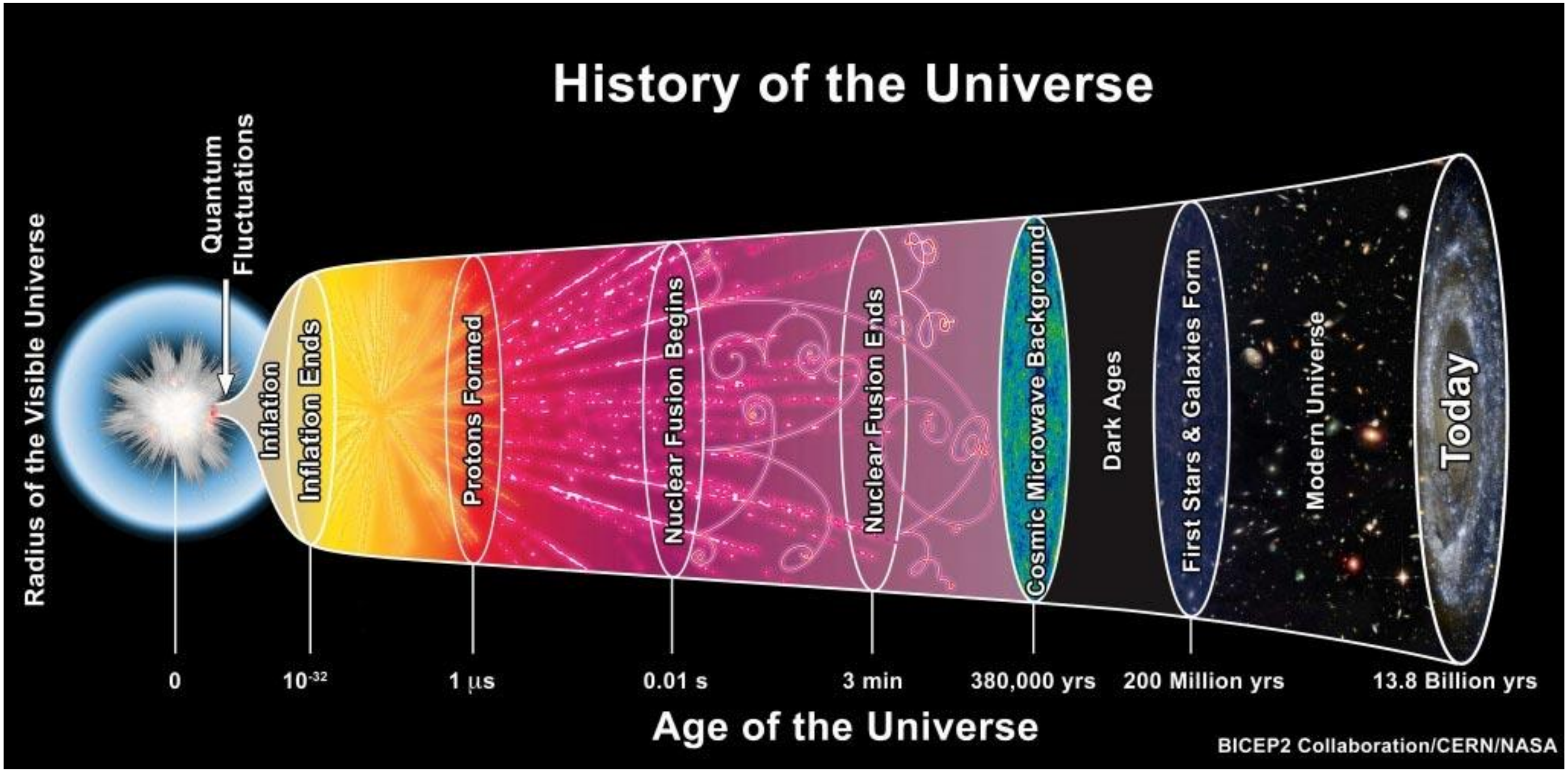



Crystal

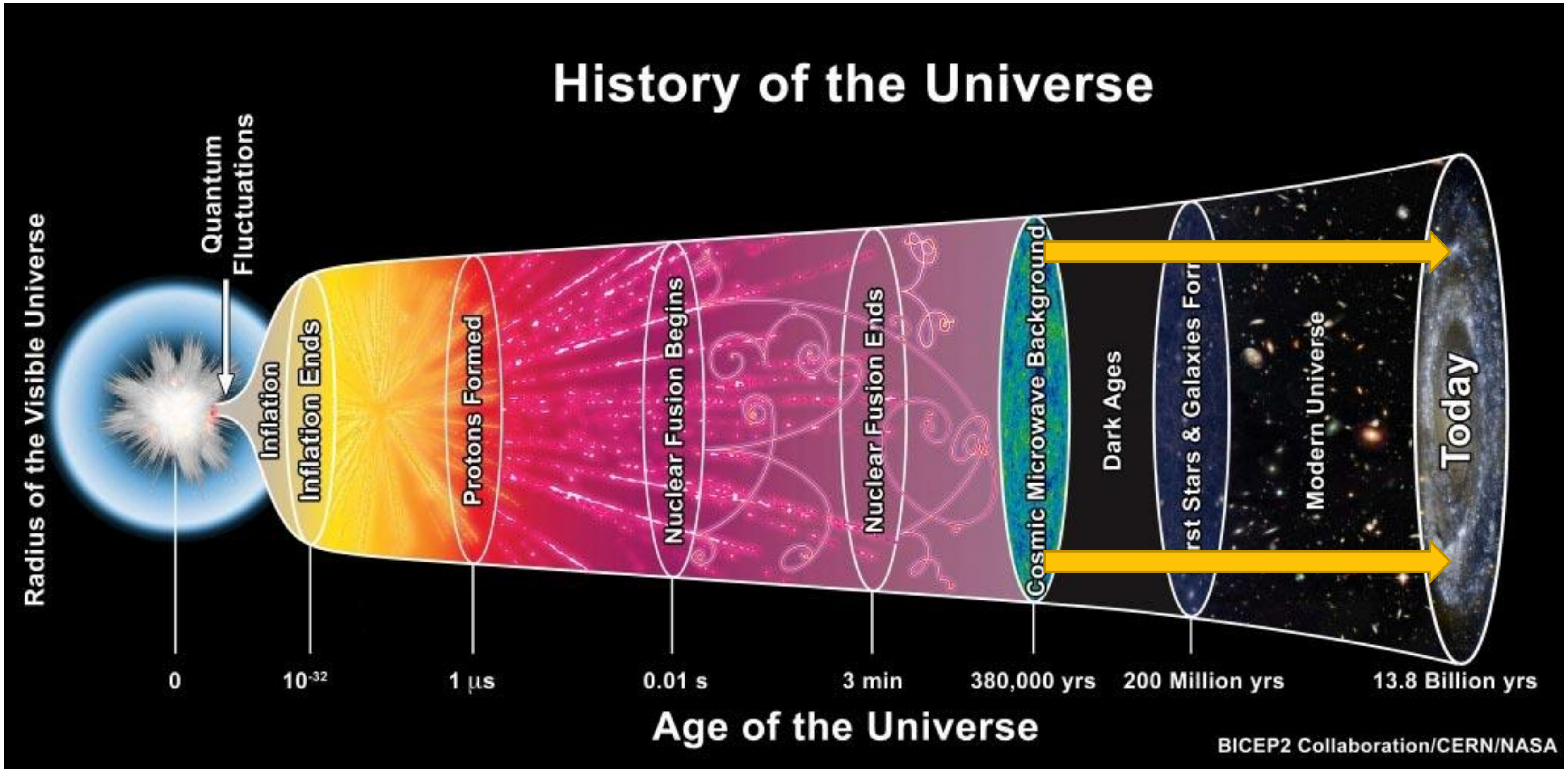
- The rotation can be clock-wise and counter-clock wise.
  Material structure determines either of them happens.
  ⇒ Parity symmetry is violated (by the structure).

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

Cosmology

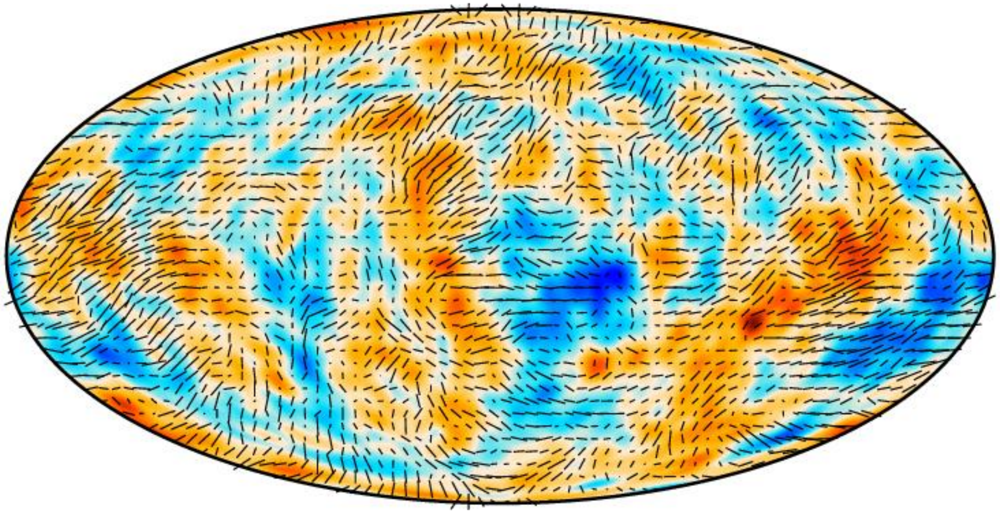

History of the Universe
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0
10-32
1 µs
0.01 s
3 min
380,000 yrs
200 Million yrs
13.8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

Cosmology



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

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

ΛCDM Paradigm

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

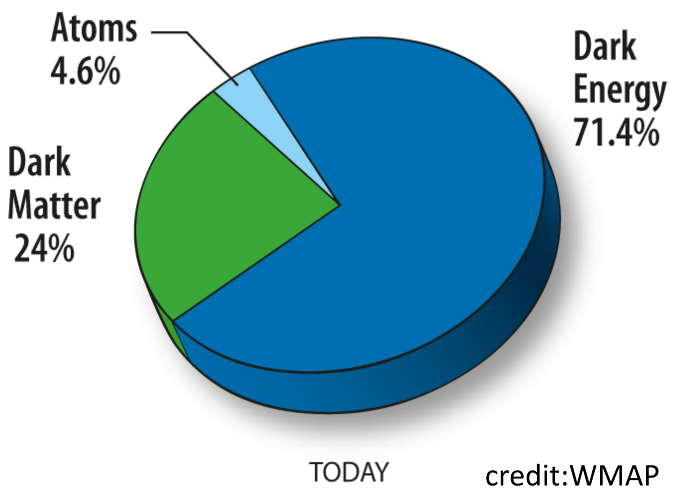
Dark Energy (DE)

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

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

, [Planck2018]

Energy component of current universe



credit:WMAP

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.

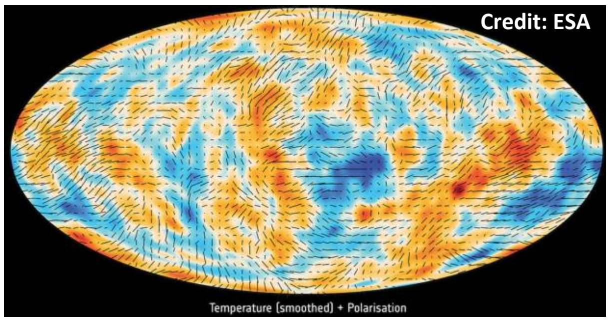
“cosmic birefringence angle β”
New signal?

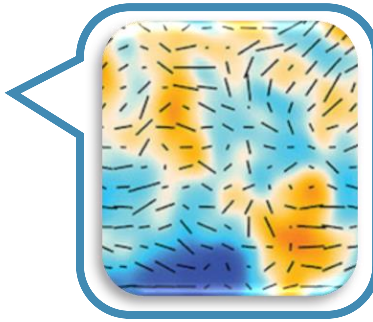
“finding β = 0.35 ± 0.14 deg (68% C.L.), which excludes β = 0 at **99.2% C.L.**
This corresponds to the statistical significance of **2.4σ**.”

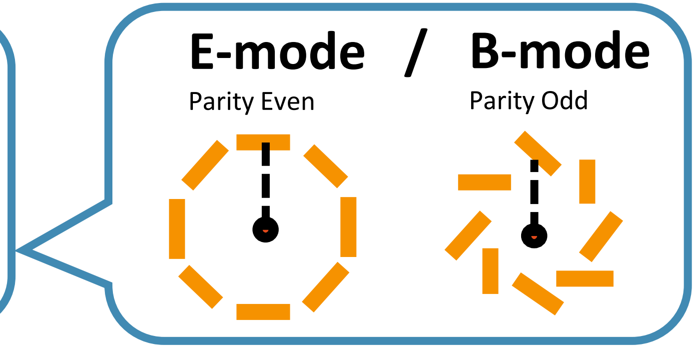
What is Cosmic Birefringence ?

Review of Cosmic Birefringence

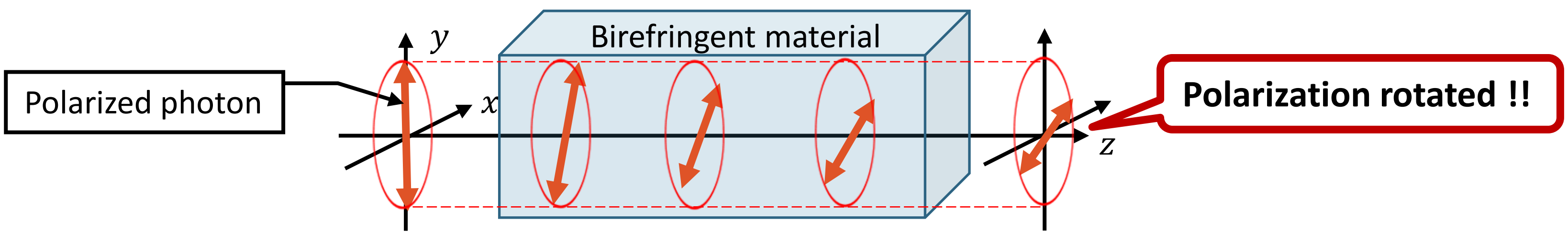
- Polarization signal in Cosmic Microwave Background (CMB)







- Birefringent material rotates direction of polarization

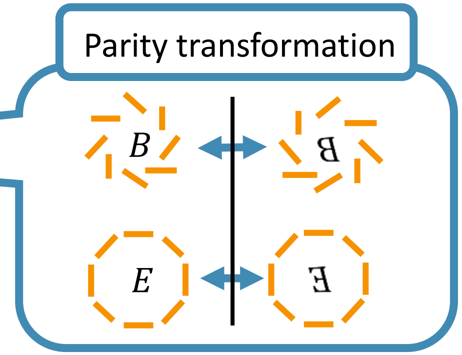


cosmic birefringence = polarization rotation signal

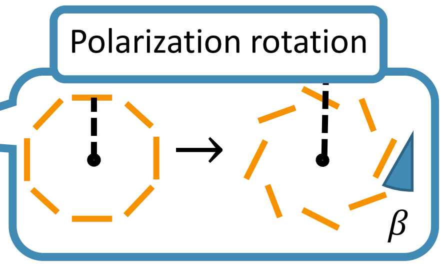
How to measure ?

Review of Cosmic Birefringence

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



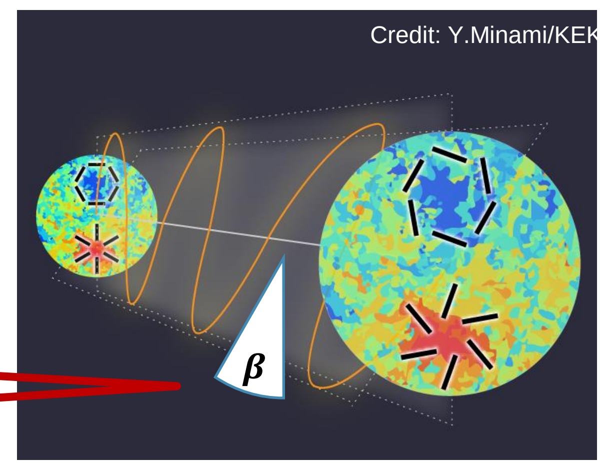
- With Cosmic Birefringence,
  - Mixing E-mode to B-mode



  - 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 $\pm$ 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 2

arXiv > astro-ph > arXiv:2205.13962

Search...

Help | Advance

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.

Follow-up paper 3

arXiv > astro-ph > arXiv:2210.07655

Search...

Help | Advance

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 14 Oct 2022 (v1), last revised 10 Jan 2023 (this version, v2)]

Robustness of cosmic birefringence measurement against Galactic foreground emission and instrumental systematics

P. Diego-Palazuelos, E. Martínez-González, P. Vielva, R. B. Barreiro, M. Tristram, E. de la Hoz, J. R. Eskilt, Y. Minami, R. M. Sullivan, A. J. Banday, K. M. Górski, R. Keskitalo, E. Komatsu, D. Scott

The polarization of the cosmic microwave background (CMB) can be used to search for parity-violating processes like that predicted by a Chern-Simons coupling to a light pseudoscalar field. Such an interaction rotates E modes into B modes in the observed CMB signal by an effect known as cosmic birefringence. Even though isotropic birefringence can be confused with the rotation produced by a miscalibration of the detectors' polarization angles the degeneracy between both effects is broken when Galactic foreground emission is used as a calibrator. In this work, we use realistic simulations of the High-Frequency Instrument of the Planck mission to test the impact that Galactic foreground emission and instrumental systematics have on the recent birefringence measurements obtained through this technique. Our results demonstrate the robustness of the methodology against the miscalibration of polarization angles and other systematic effects, like intensity-to-polarization leakage, beam leakage, or cross-polarization effects. However, our estimator is sensitive to the EB correlation of polarized foreground emission. Here we propose to correct the bias induced by dust EB by modeling the foreground signal

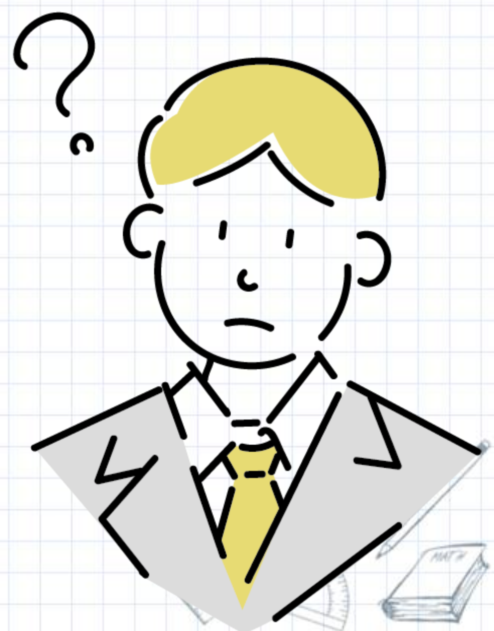
CMB Birefringence

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!

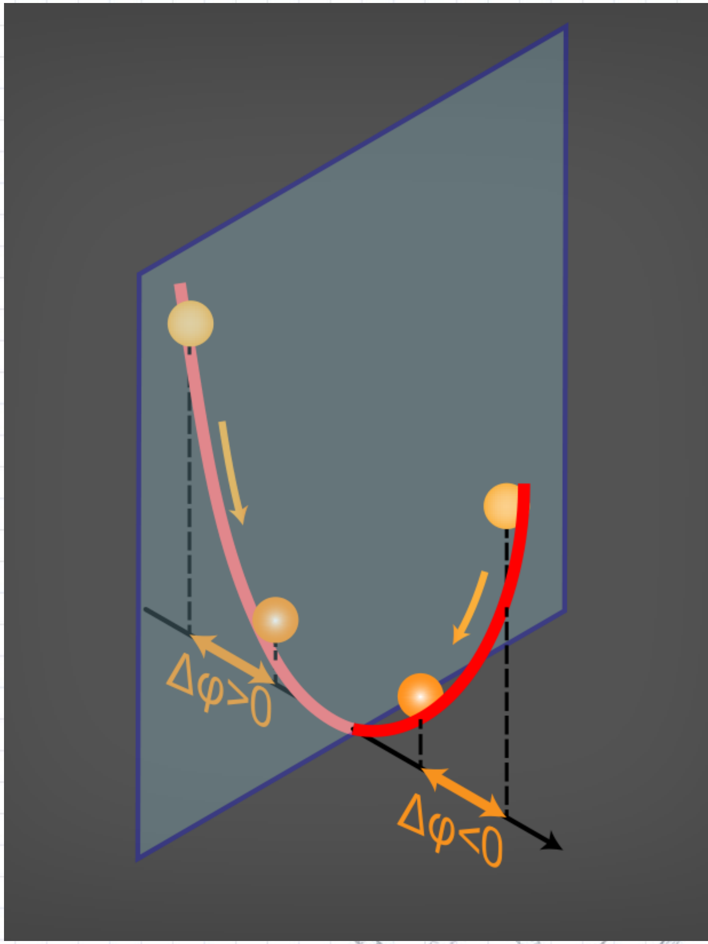


Outline of Talk

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

ALP DE model in a nutshell

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



(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)

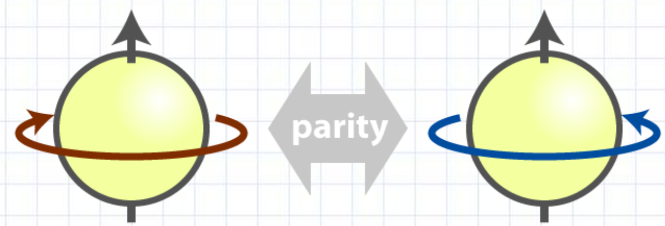
  - ALP as Dark Matter: $10^{-22}\mathrm{eV} \lesssim m_\phi$
  - ALP as Dark Energy: $m_\phi \lesssim H_0 \sim 10^{-33}\mathrm{eV}$

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)…

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); Carroll & Field (1991); Harari & Sikivie (1992)…

Axion-Photon Coupling

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

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)…

Axion-Photon Coupling

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

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

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

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

- Assume background DE axion

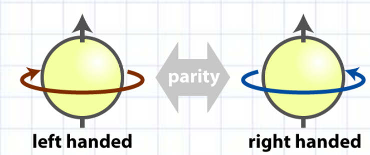
$$\dot{\phi} \simeq \dot{\phi}_0 \approx \text{const.}$$

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

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

⇒ 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

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

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

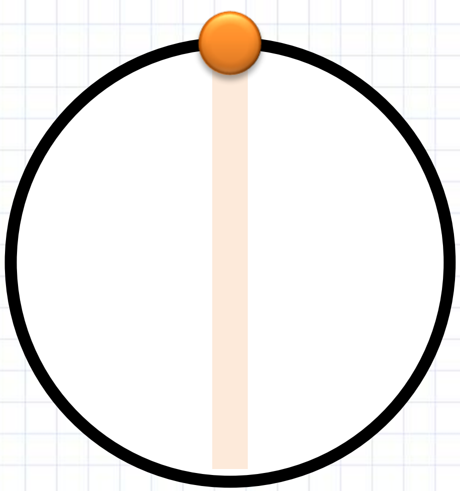
Birefringence

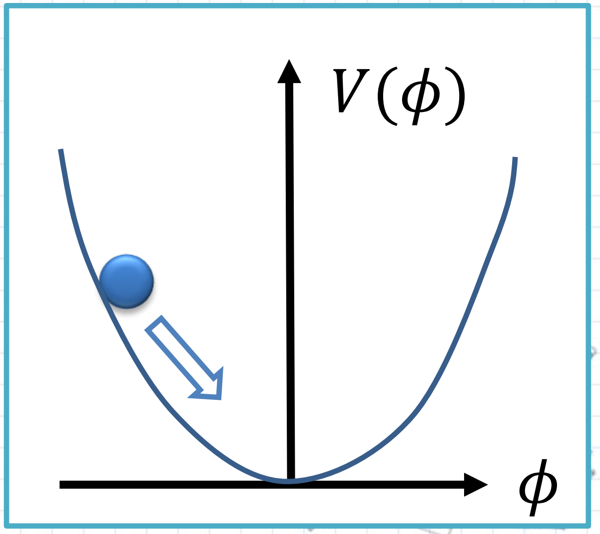
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla}\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- 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





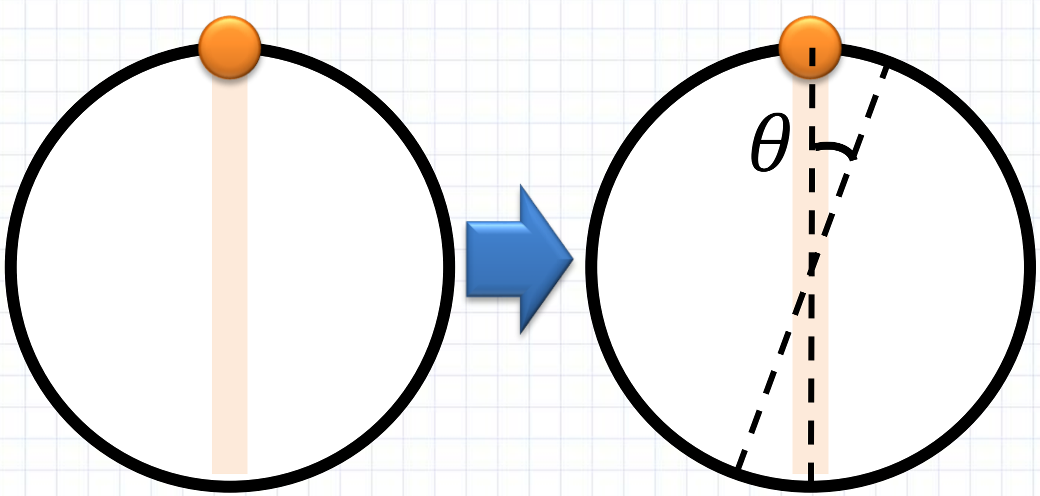
Birefringence

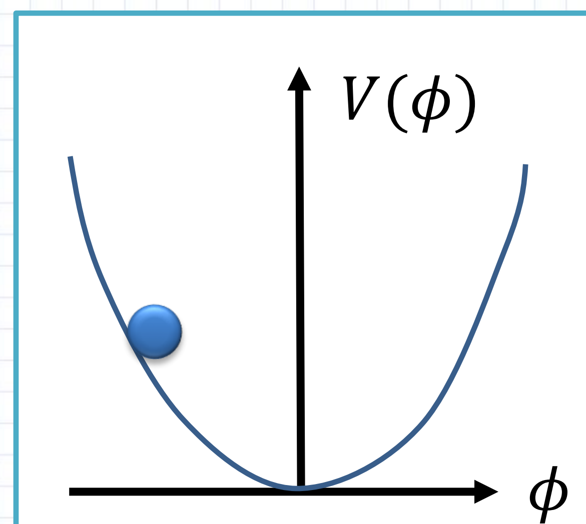
$$\delta\omega = -\frac{g_{a\gamma}}{2}\left[\dot{\phi} + \hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla}\phi\right] = -\frac{g_{a\gamma}}{2}\frac{\mathrm{d}\phi}{\mathrm{d}t}$$

- 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





Axion causes CMB Biref.

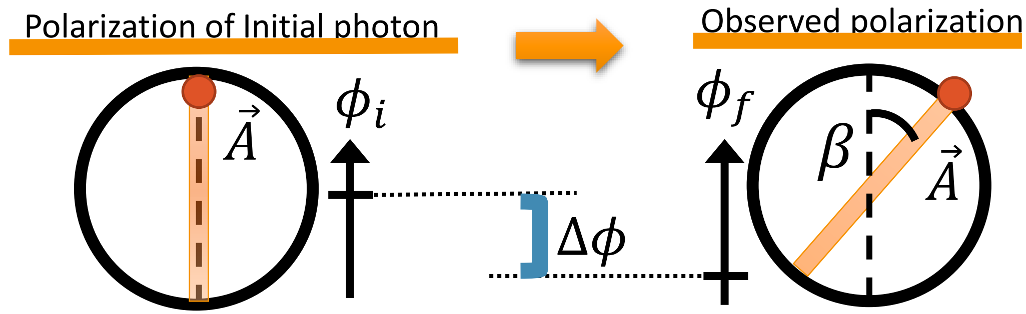
- Axion-Photon coupling

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

Polarization rotation angle

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

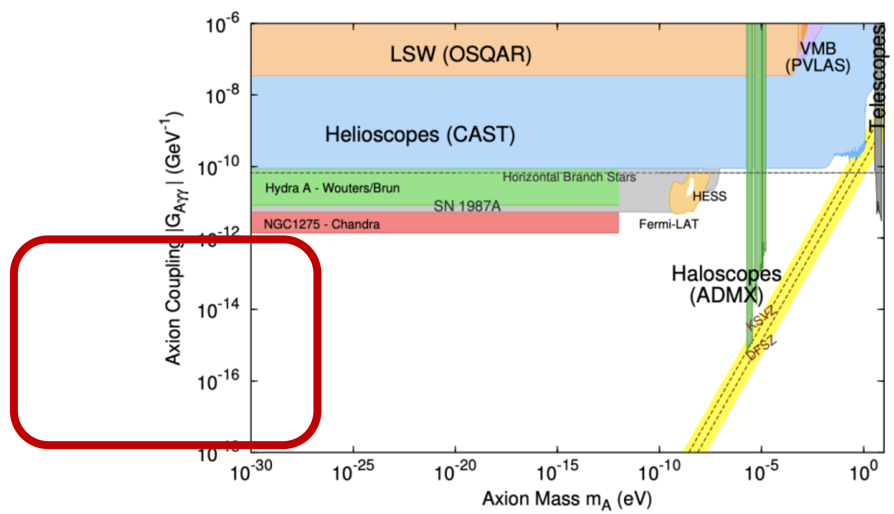
Harari&Sikivie (1992)



- Different mass range

What kind of axion can reproduce the observed β?

Lighter Axion



Axion causes CMB Biref.

How to calculate Cosmic Birefringence:

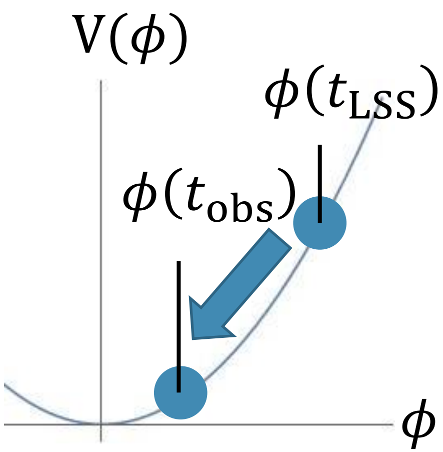
- In this talk, focus on background motion.

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

(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



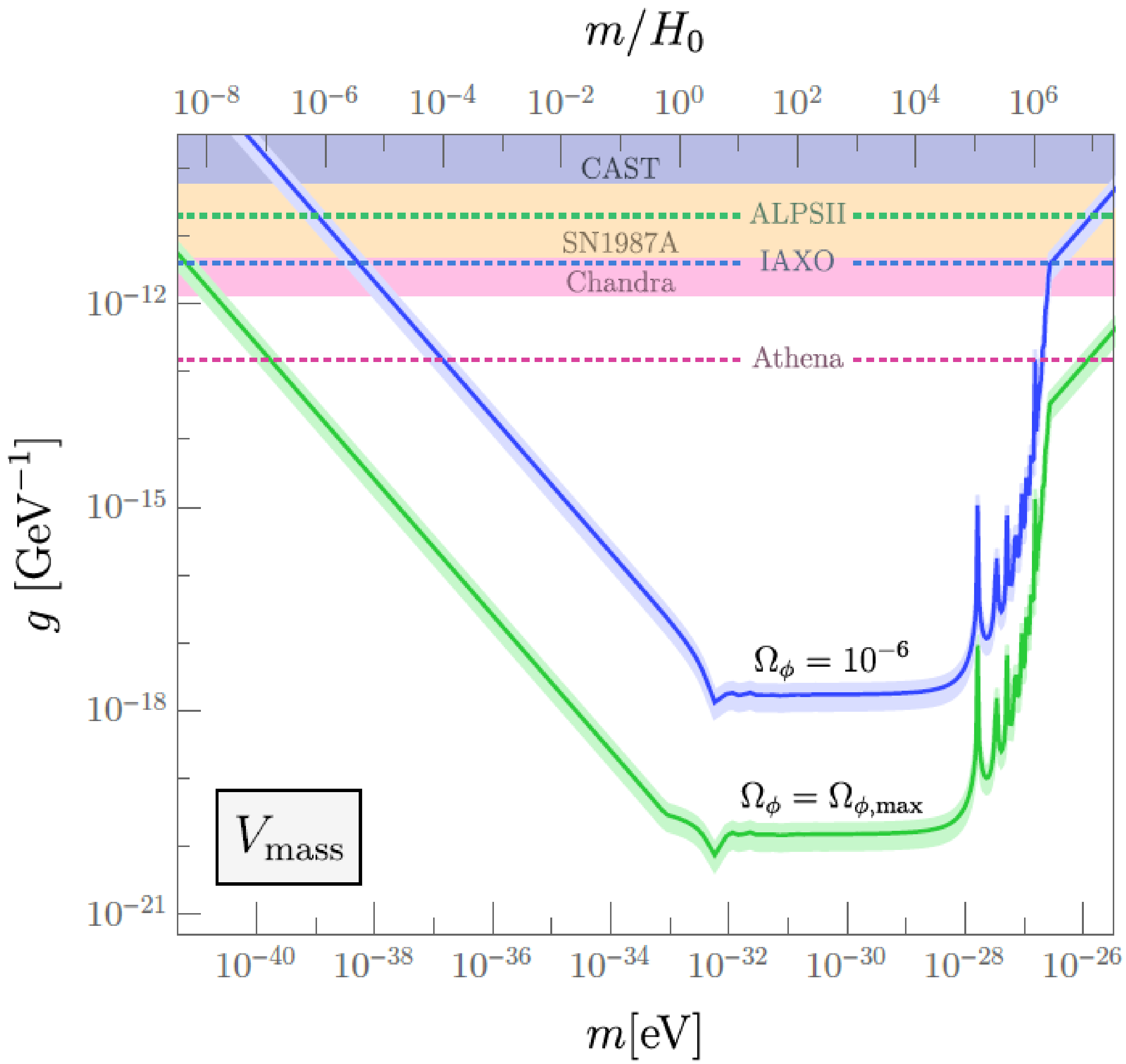
- Axion-photon coupling

$$g = 2\,\beta(\,\bar{\phi}(t_0) - \bar{\phi}(t_{LSS})\,)^{-1}$$, β = 0.35 deg

Hereafter, we write $\bar{\phi}$ as ϕ.

Determine axion-photon coupling g for a given m

Axion causes CMB Biref.



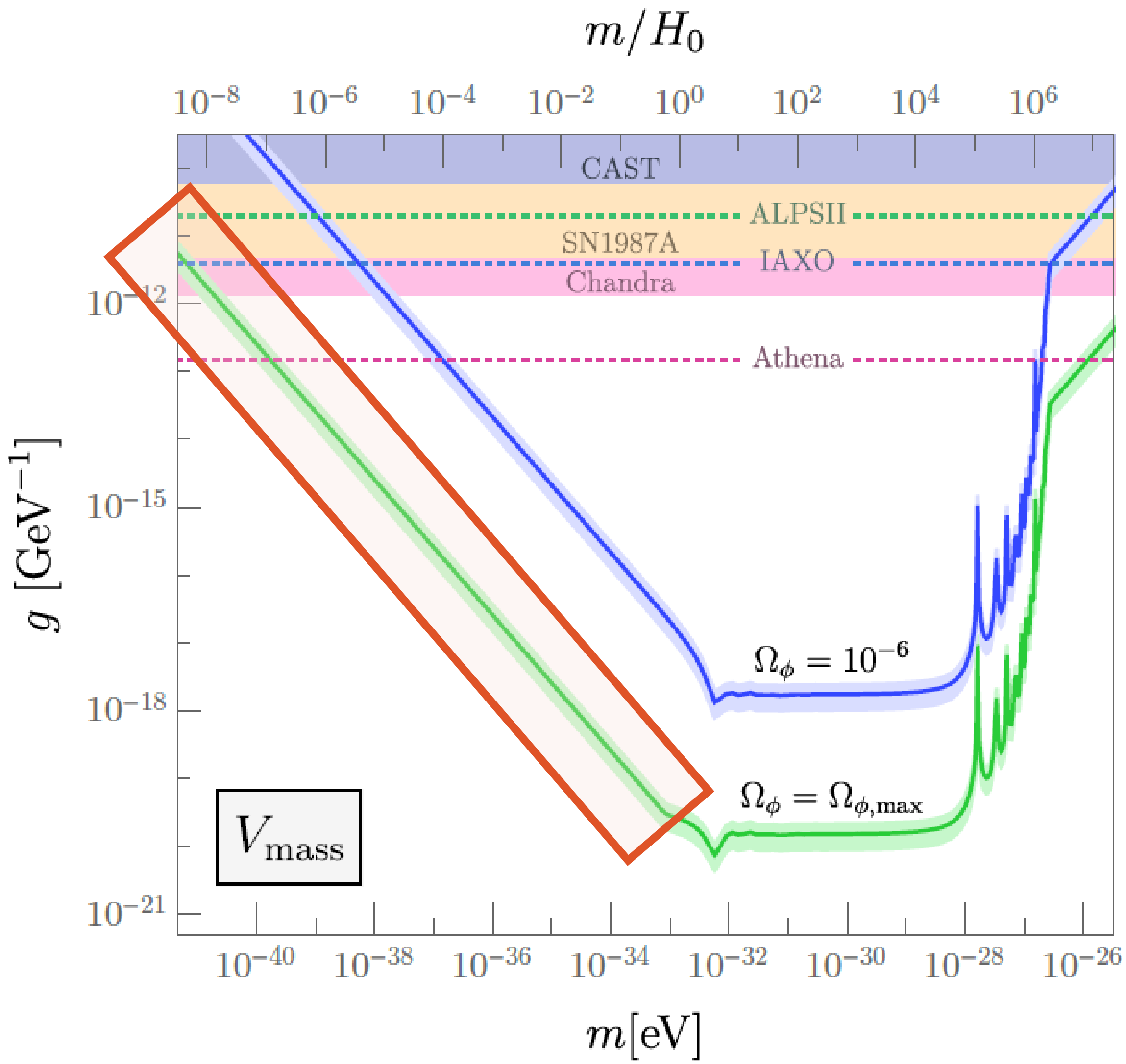
- Model: $V = m^2\phi^2/2$

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

  The axion explains the current accelerated expansion, too!

- We also study cos potential

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

Outline of Talk

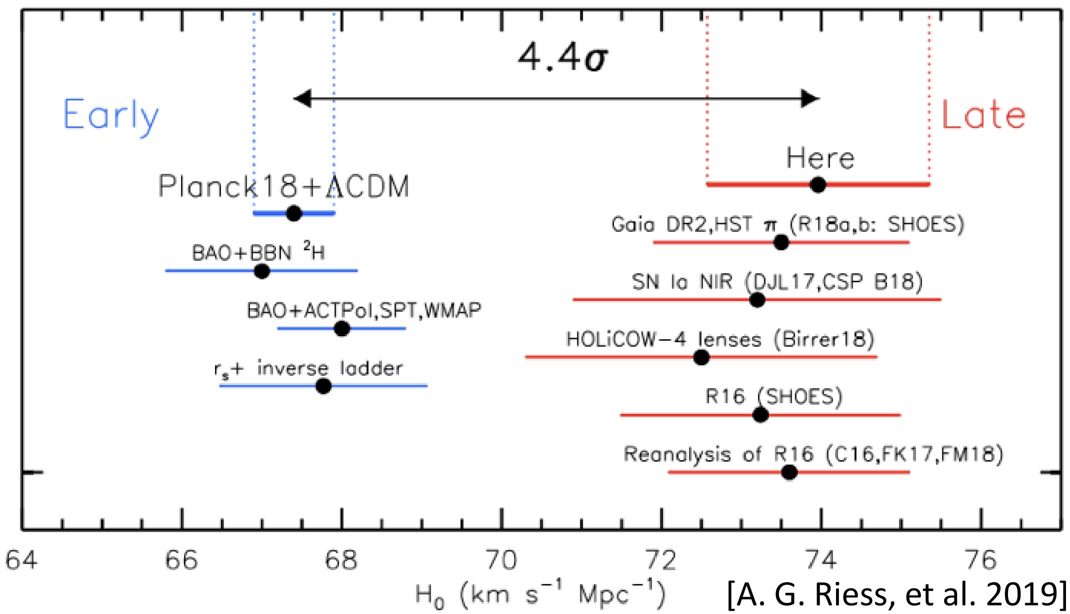
1. Cosmic Birefringence
2. ALP Dark Energy
3. Early Dark Energy
4. Summary

Hubble tension

Early Dark Energy (EDE) is scheme to alleviate “Hubble tension” problem.

■ Discrepancy between:

- local astrophysical measurements at low redshifts (cosmic distance ladder)
- CMB and large scale structures



[A. G. Riess, et al. 2019]

Hubble Space Telescope

$74.03 \pm 1.42\,\mathrm{km/s/Mpc}$

Planck 2018

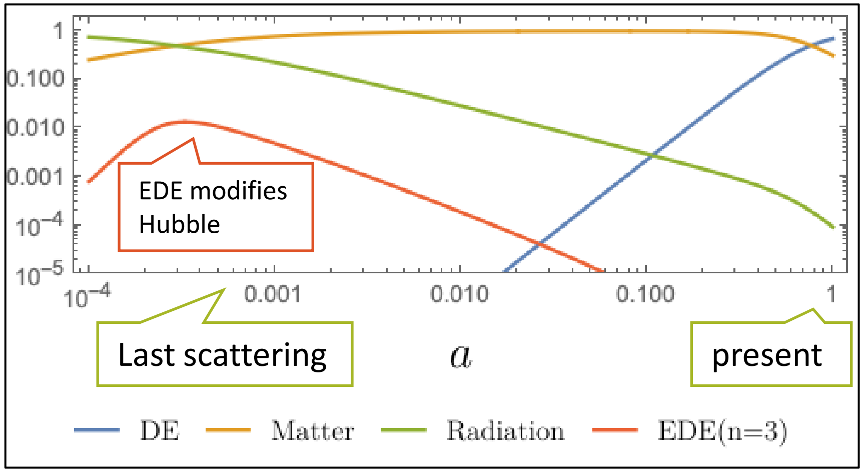
$67.4 \pm 0.5\,\mathrm{km/s/Mpc}$

How does EDE work?

Early dark energy alleviates H_0 tension

- EDE modify cosmology around last scattering.
  - Reduce sound horizon at last scattering.
  - Increase H_0 estimated by CMB observation $H_0 \sim\ 68 \to (70-72)[\mathrm{km \cdot s/Mpc}]$

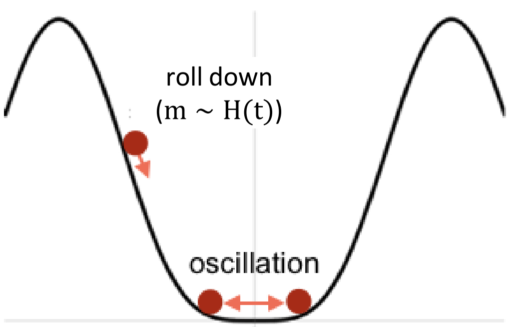
Energy fraction of each component Ω_X



- How to achieve the above dynamics?

$$V_{\cos}^{(n)} \equiv m^2 f^2 \left[1-\cos\left(\frac{\phi}{f}\right)\right]^n, \quad n \geq 2$$ [Poulin+ 2018]

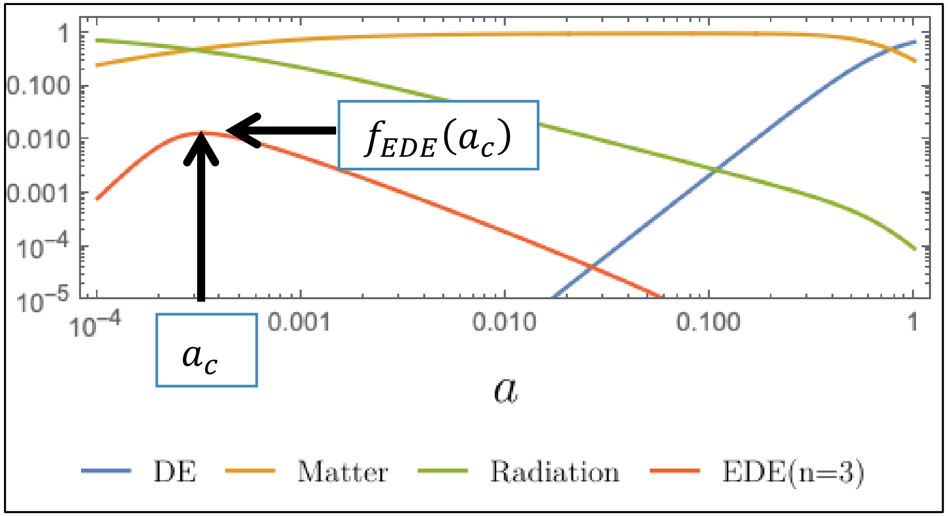
$$V_{\mathrm{RnR}}^{(n)}(\phi) = V_0 \left(\frac{\phi}{M_{\mathrm{Pl}}}\right)^{2n}$$ nt Ω_X [Agrawal+ 2019]



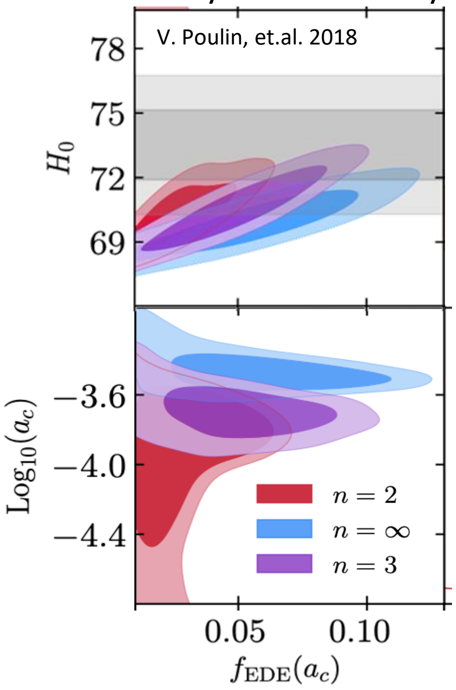
- Before oscillation, V is almost constant
- After oscillation, V decreases like or faster than radiation for $n \geq 2$.

Early dark energy alleviates tension

- Required abundance of EDE V. Poulin, et.al. (2018)
  - a_c: scale factor to start oscillation
  - $f_{EDE}(a_c) \equiv \rho_\phi(a_c)/\rho_{\rm tot}(a_c)$: energy fraction at a_c



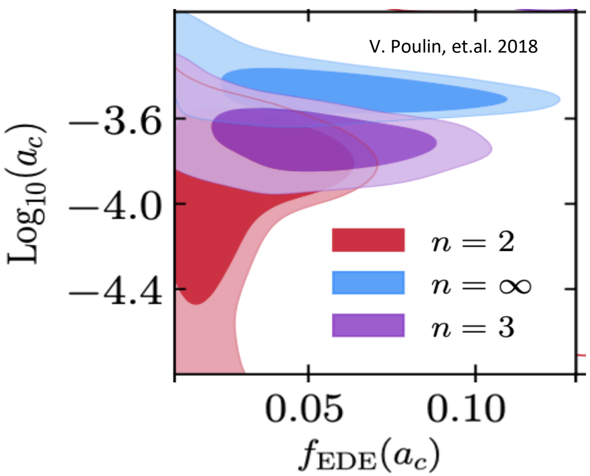
Probability distribution by MCMC

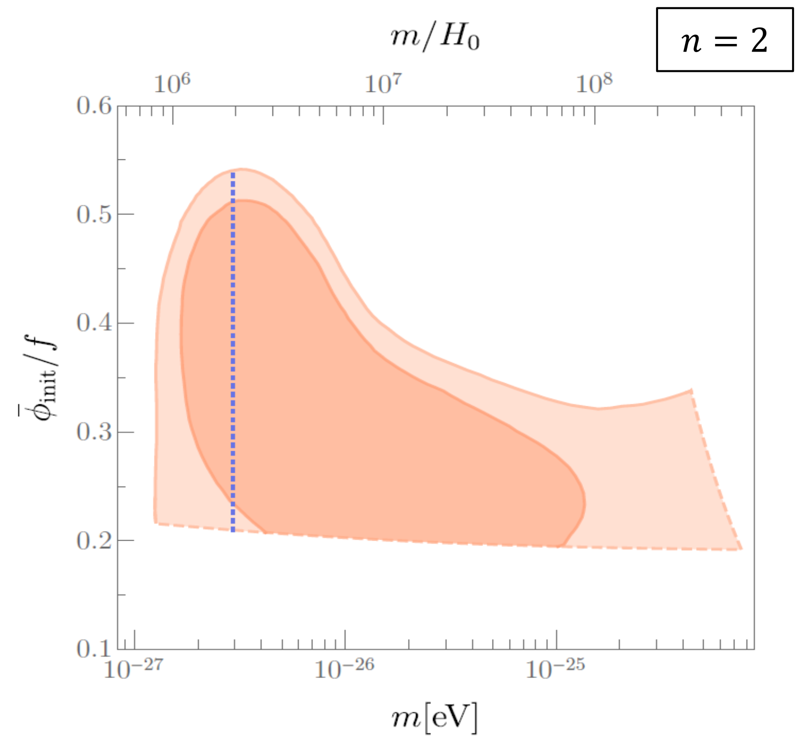


Does EDE produce cosmic birefringence?

Does EDE reproduce CMB Biref.?

- Cosmic birefringence of EDE
  - Let ϕ have the CS coupling to photon
  - Convert (f_{EDE}, a_c) into (ϕ_i, m_ϕ) by assuming $f = M_{pl}$

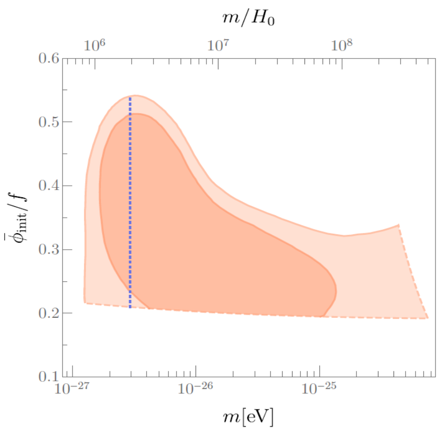




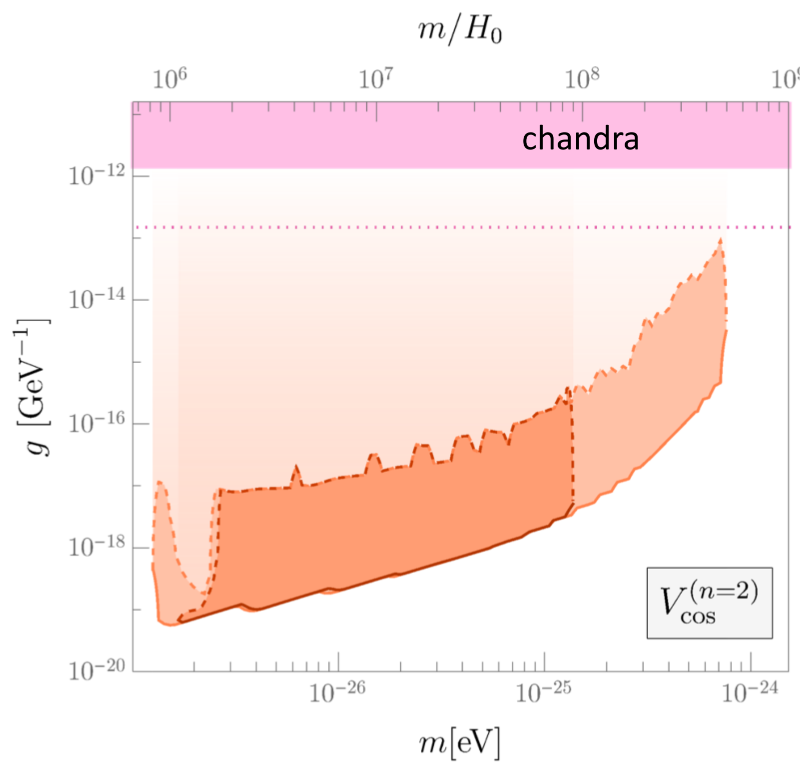
Allowed mass range is limited for EDE.

Does EDE reproduce CMB Biref.?

(ϕ_i, m)



(g, m)



The observed CMB birefringence

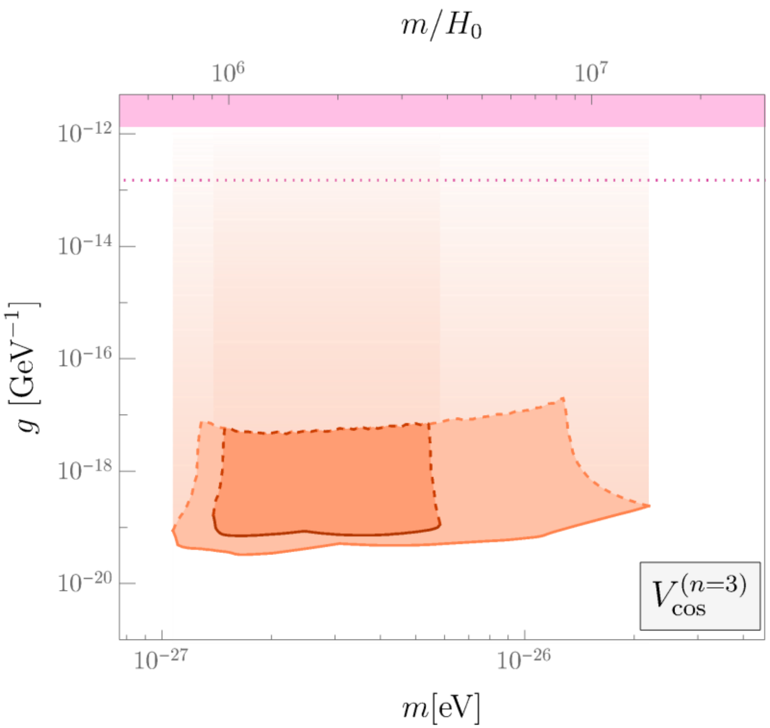
$$g = 2\,\beta(\,\phi(t_0) - \langle\phi\rangle_{LSS}\,)^{-1}$$

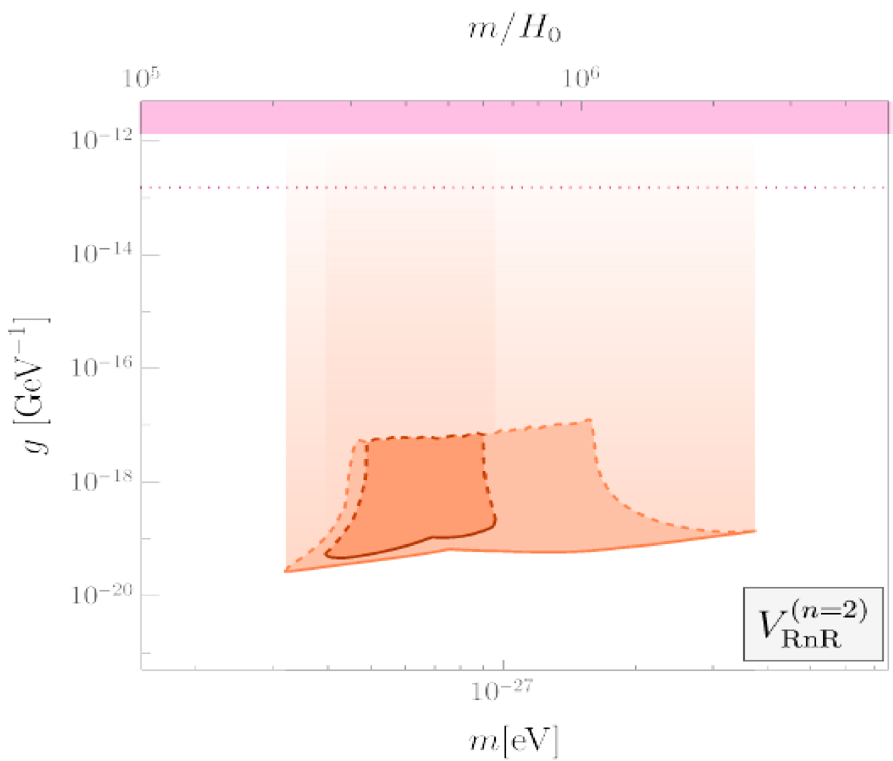
β = 0.35 deg

Does EDE reproduce CMB Biref.?

- Other models

n=2 case : $V_{\rm RnR}^{(n)}(\phi) = V_0\left(\frac{\phi}{M_{\rm Pl}}\right)^{2n}$





n=3 case : $V_{\cos}^{(n)} \equiv m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$

EDE models typically constrained
$g \sim (10^{-20} - 10^{-17})\ \mathrm{GeV}^{-1}$

Summary of EDE as ALP

- EDE model is expected to alleviate "Hubble tension problem".

- ALP as EDE can explain reported rotation angle

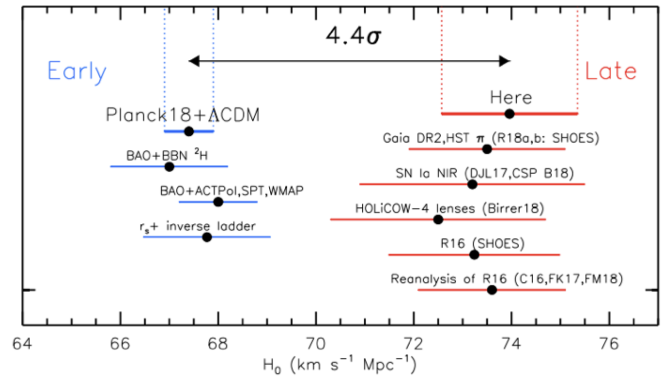
$$\beta \sim 0.35 \text{ deg.}$$

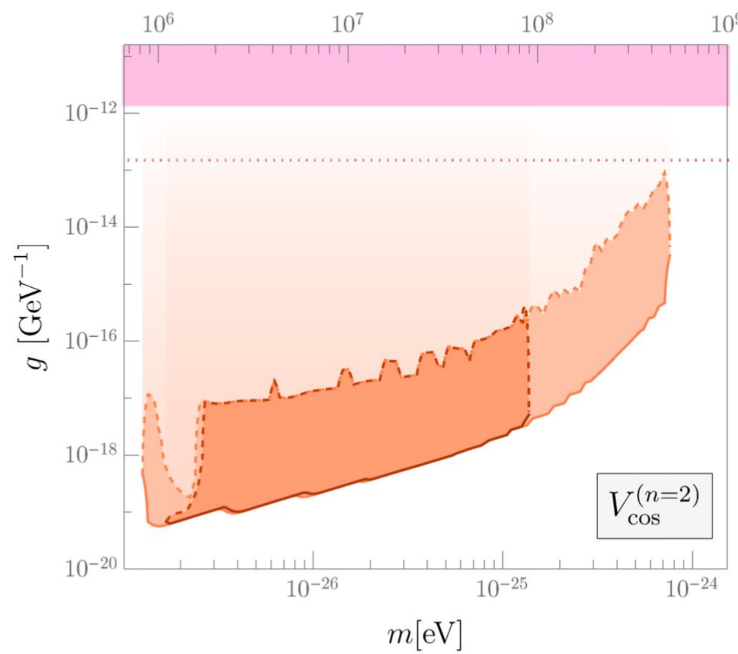
- Typical coupling constant is expected to be

$$g \sim (10^{-20} - 10^{-17})\ \mathrm{GeV}^{-1},$$

which means following nontrivial relation:

$$g \sim M_{Pl}^{-1}.$$





$$V_{\cos}^{(n)} \equiv m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n, \quad n \geq 2$$

Future Prospect of ALP EDE

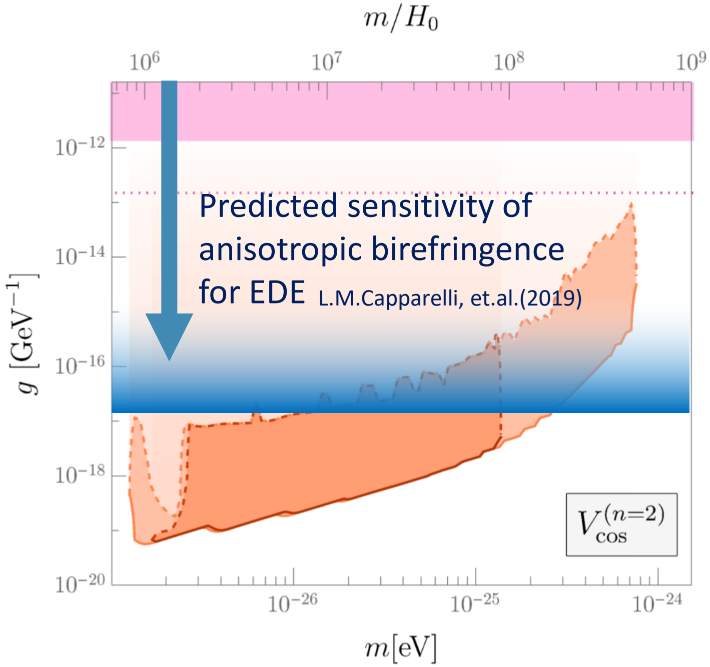
In this talk, I focused on the background ϕ(t).

- fluctuation modes $\delta\phi(x,t)$
  - Hubble fluctuation during inflation
  - gravitational growth of adiabatic perturbation

- $\delta\phi_{obs}$: another source of isotropic rotation angle
- $\delta\phi_{LSS}$: direction dependent rotation angle (anisotropic cosmic birefringence)

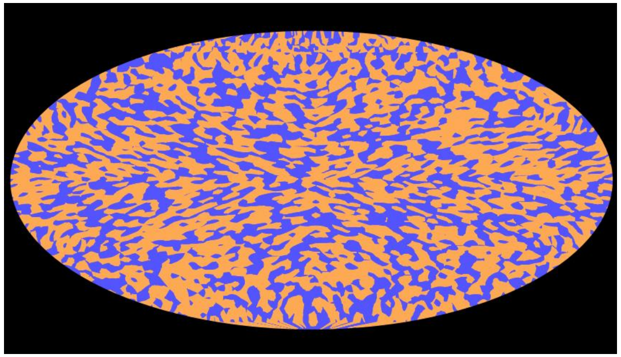
Pospelov, et.al., (2008), Caldwell, et.al., (2011)

$$\delta\beta(\hat{n}) = \frac{g}{2}(-\delta\phi_{LSS}(\hat{n}))$$

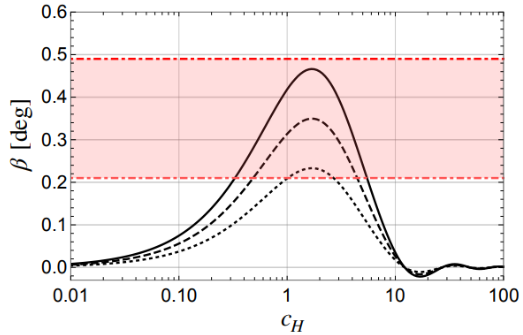


Anisotropic cosmic birefringence is useful tool to investigate axion-photon coupling.

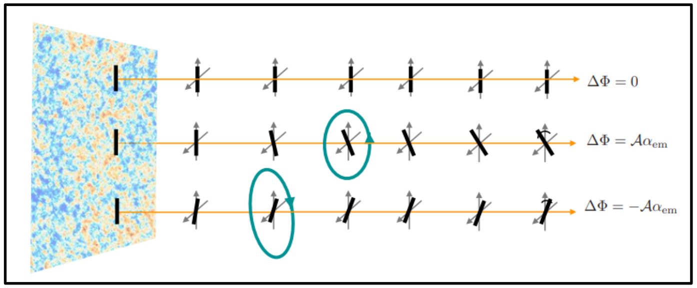
Other proposals



- **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 $\beta = 0.34° \pm 0.1°$.
  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 $g_{a\gamma} \sim M_{\mathrm{Pl}}^{-1}$

- Anisotropic birefringence will be tested by future CMB obs.

THE THEME
OF CHAPTER IS...

Thank you ！

Current constraint