Cosmic Birefringence Measurement

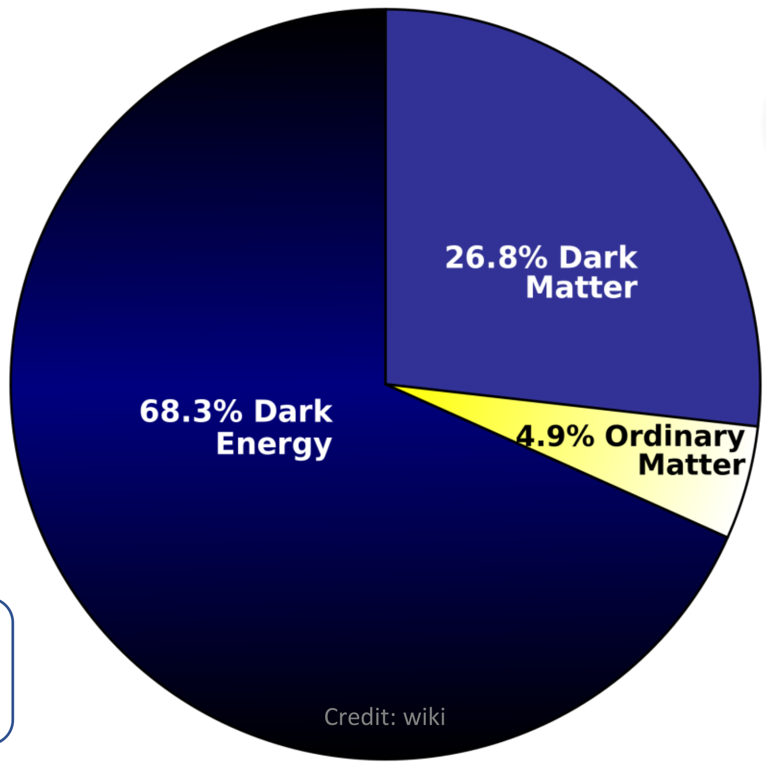
-Implications for the axion search-

Ippei Obata (Max-Planck-Institute for Astrophysics, JSPS fellow)

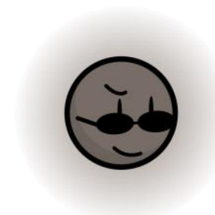
Reference
arXiv: 2108.02150

19.10.2021 SYRTE-UTokyo seminar

Dark sectors in our universe



(standard model)



Credit: higgstan.com

WIMP?
Axion?
MACHO?
PBHs?

Credit: higgstan.com

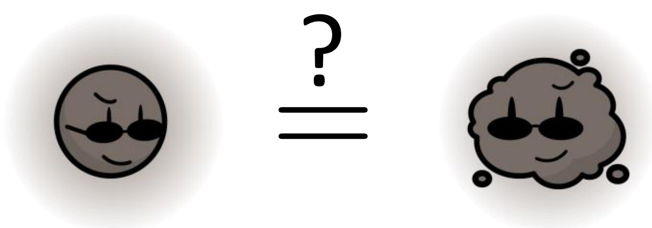
Cosmological Constant?
Quintessence?

We know only 5 % in our universe!

Question

Are these sectors independent components?

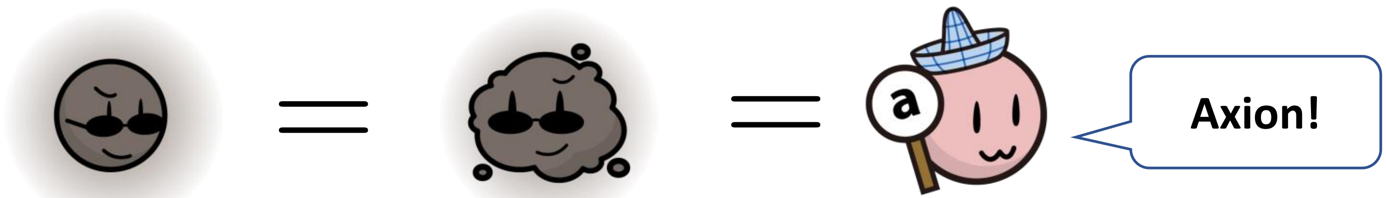
What if they are related by a common origin?



Unified models for dark matter and dark energy have been developed

- **Generalized Chaplygin gas:** *Bento, Bertolami & Sen (2002); Makler, Oliveira, Waga (2003); …*
- **k-essence:** *Scherrer (2004); Giannakis & Hu (2005); …*
- **Fast transition models:** *Bruni, Lazkoz & Fernandez (2013); Leanizbarrutia, Fernandez & Tereno (2017); …*
- **…**

Overview of this talk



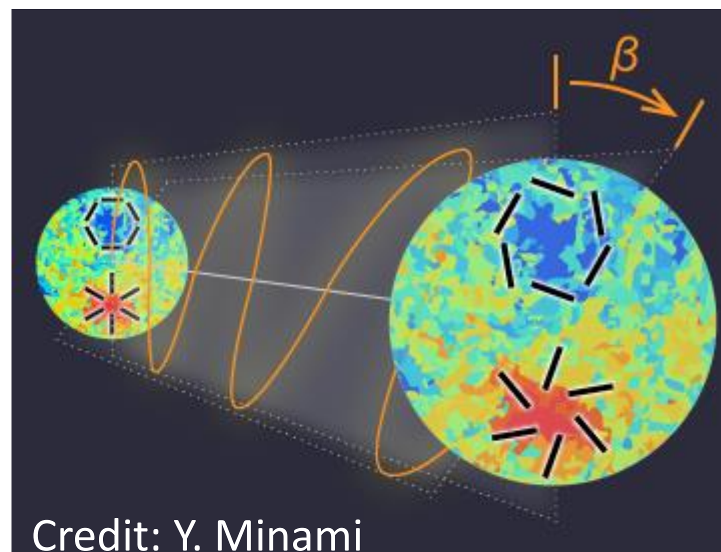
Credit: higgstan.com

➢ Axion can be a candidate for both dark matter and dark energy

Motivation

✓ The constraints on this scenario are potentially connected by the measurement of cosmic birefringence effect in CMB!

✓ We can do a comprementary search between CMB observations (axion dark energy) and resonant cavity experiments (axion dark matter)



Credit: Y. Minami

Cosmic birefringence

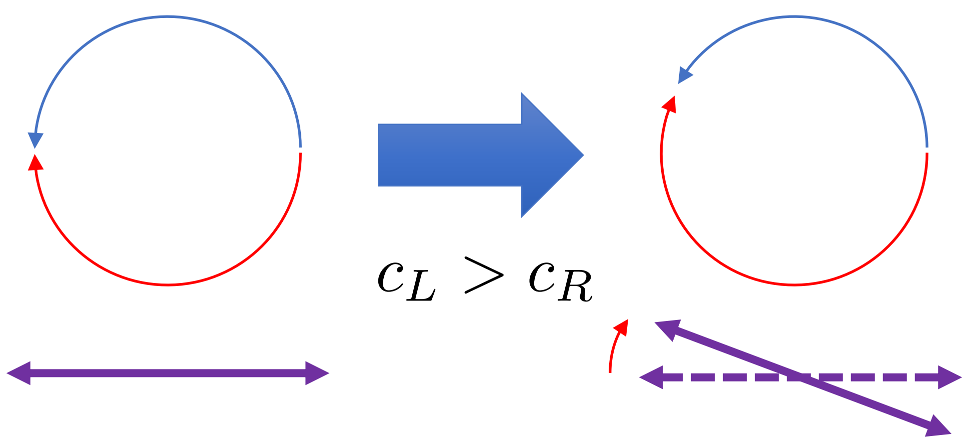
Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); …

Axion behaves as a birefringent material in our universe

- Via the axion-photon coupling, axion differentiates the phase velocities of circular-polarized photon

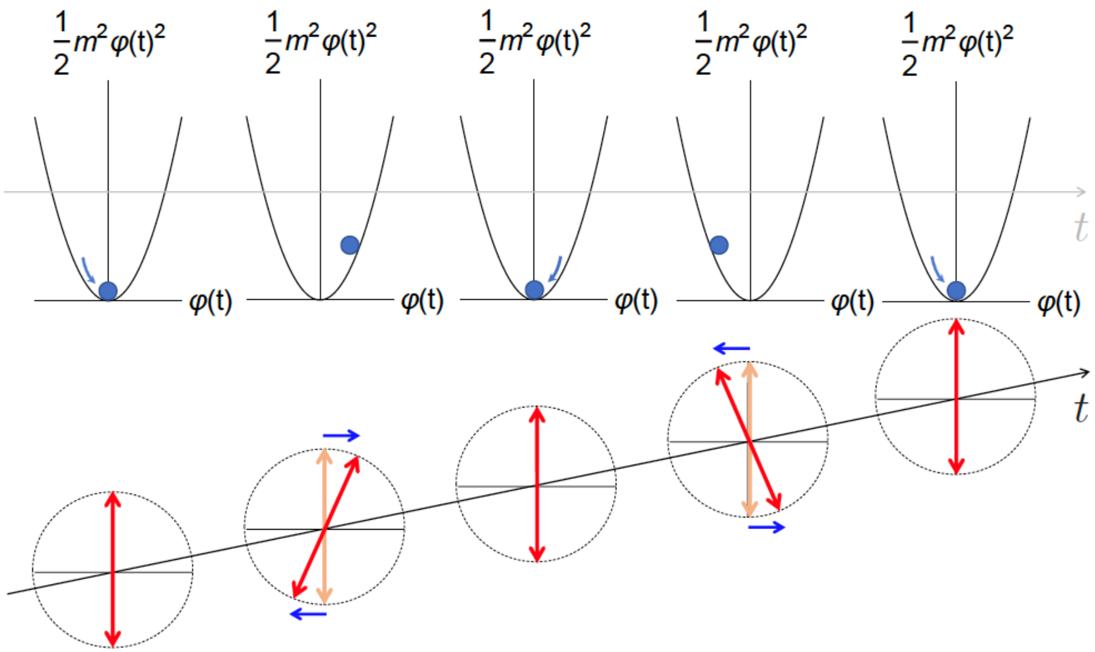
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu} \ , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Dispersion relation: $\ddot{A}_k^{\mathrm{L/R}} + \omega_{\mathrm{L/R}}^2 A_k^{\mathrm{L/R}} = 0, \quad c_{\mathrm{L/R}} \equiv \frac{\omega_{\mathrm{L/R}}}{k} = \sqrt{1 \pm \frac{g_{a\gamma}\dot{\varphi}}{k}}$



→ leading to the rotation of linear-polarization direction

Birefringence by axion DM



- Axion DM induces the polarization rotation oscillating in time with a frequency of axion mass:

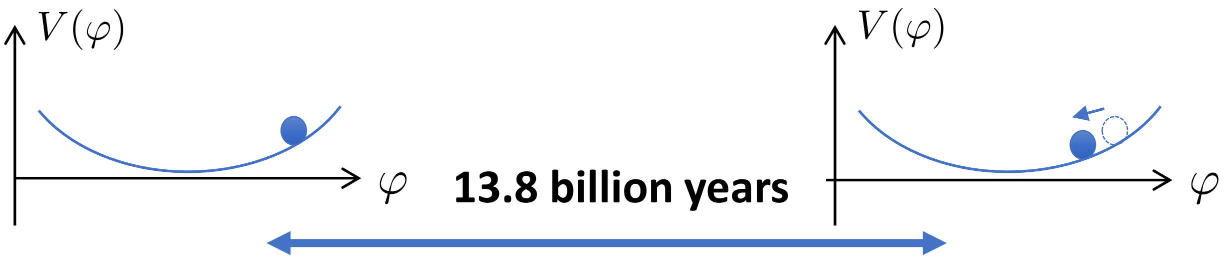
$$f_c = \frac{m_a}{2\pi} \simeq 2.4\text{Hz}\left(\frac{m_a}{10^{-14}\text{eV}}\right)$$

- Possible to observe by…
  - **Resonant cavities:** *Melissinos (2009); DeRocco & Hook (2018); Obata, Fujita & Michimura (2018); Nagano+ (2019,2021); DANCE (2020); …*
  - **Astrophysical polarimetric surveys:** *Fujita, Tazaki & Toma (2019); Chen+ (2020,2021); …*
  - **CMB:** *Finelli & Garaverni (2009); Lee, Liu & Ng (2014); …*

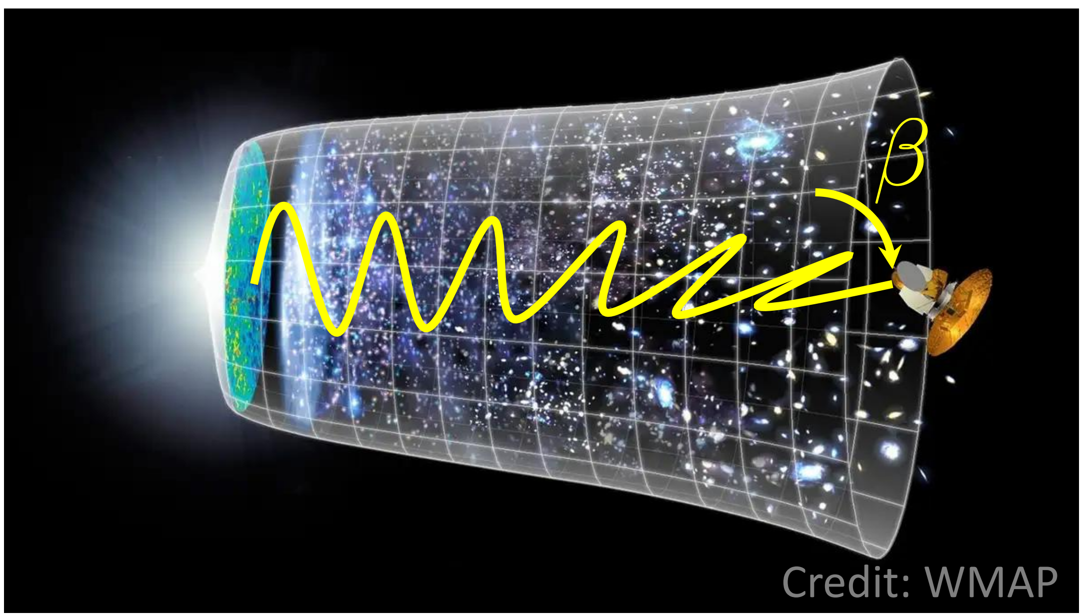
Birefringence by axion quintessence

(*Fukugita & Yanagida (1994); Friemann+ 1995; J.E.Kim 1999+; …*)

- Axion with mass smaller than current Hubble scale behaves as a quintessence



$$m_a \lesssim H_0 \sim 10^{-33}\mathrm{eV}$$

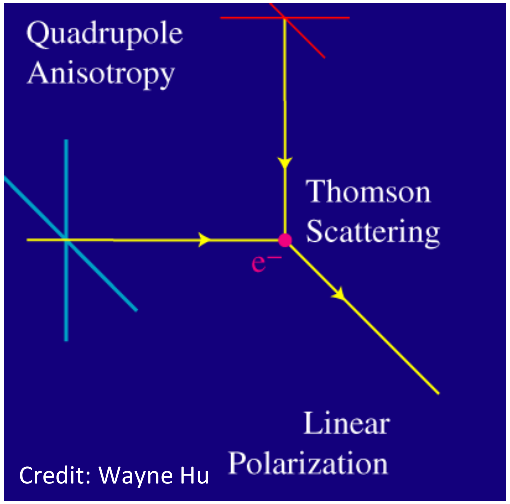


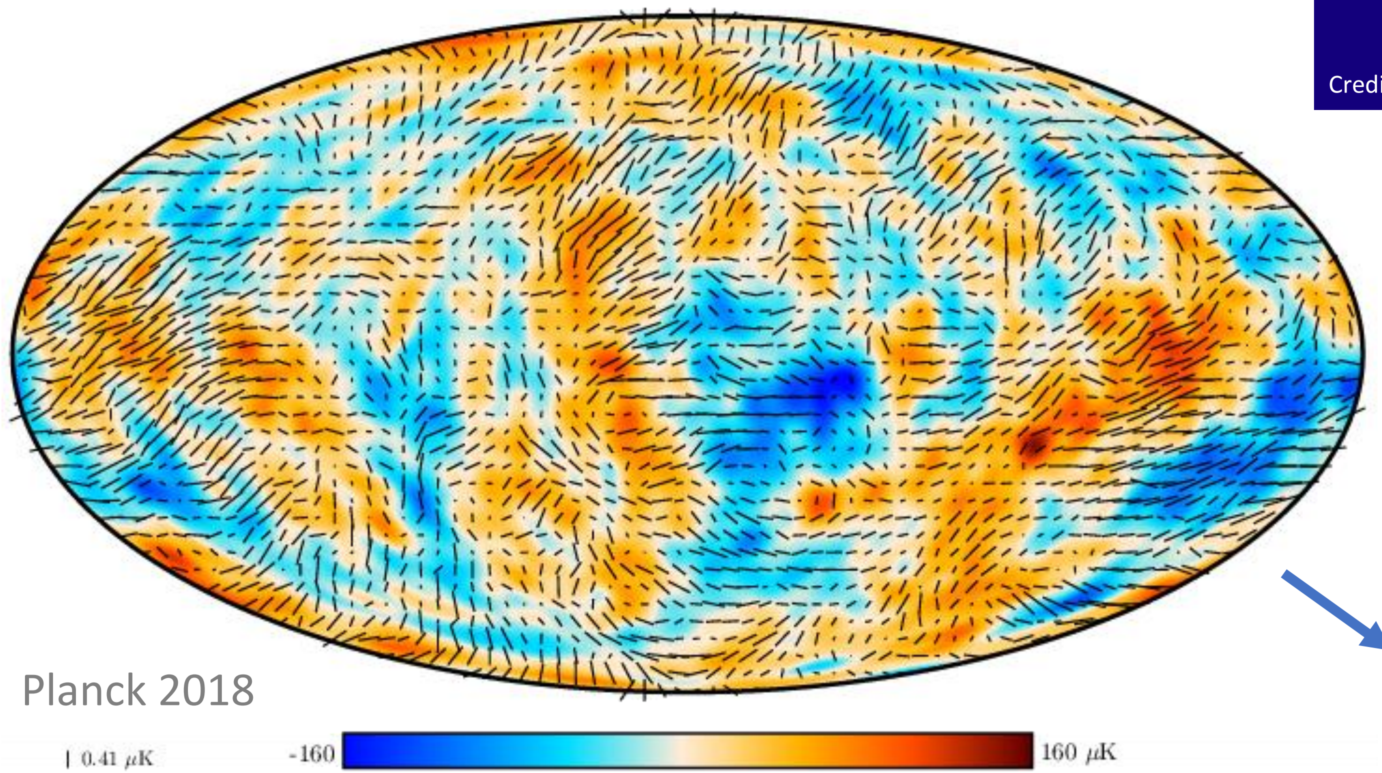
- If axion is responsible for dark energy, it makes the polarization plane of CMB rotate from the last-scattering-surface

Rotation angle:

$$\beta = \frac{g_{\phi\gamma}}{2}\Delta\phi \equiv \frac{g_{\phi\gamma}}{2}(\phi_0 - \langle\phi_{\rm LSS}\rangle)$$

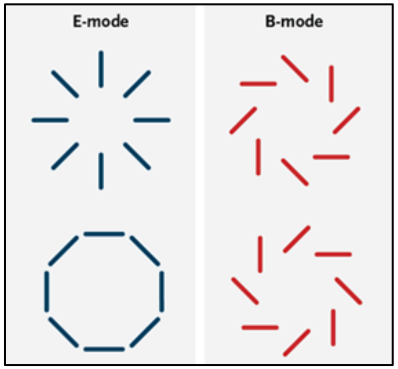
CMB polarization map





Planck 2018

E-mode v.s. B-mode

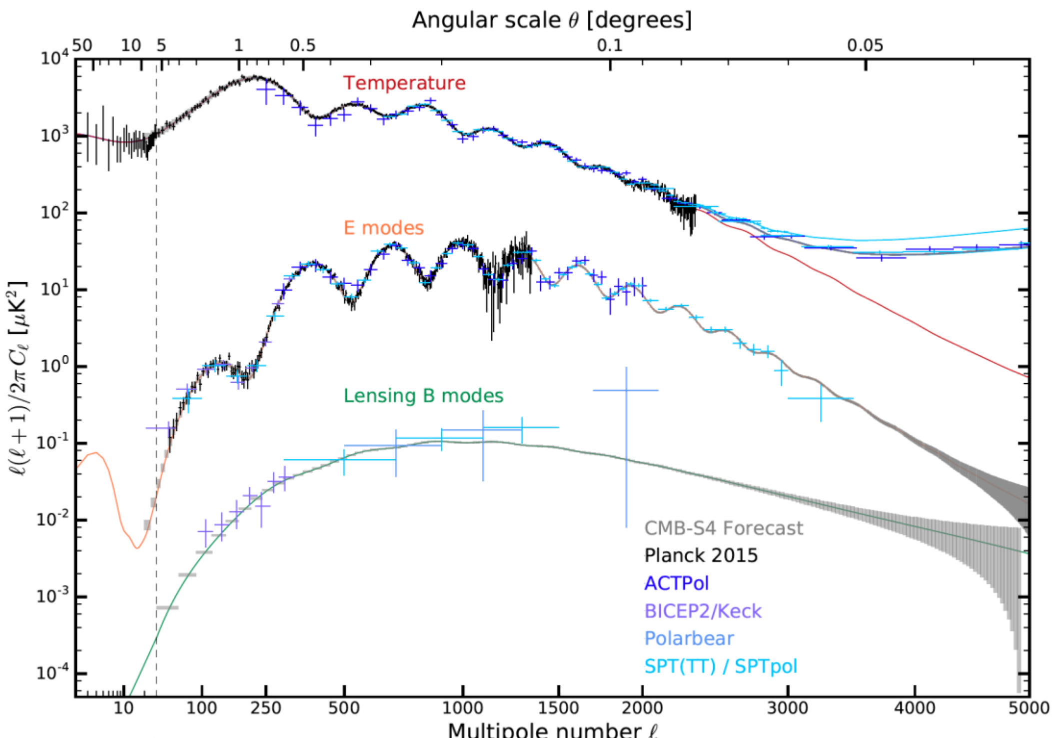


Angular power spectra

$$\langle T(\boldsymbol{\ell})T^*(\boldsymbol{\ell}')\rangle = (2\pi)^2\delta^{(2)}(\boldsymbol{\ell}-\boldsymbol{\ell}')C_\ell^{TT}$$

$$\langle E(\boldsymbol{\ell})E^*(\boldsymbol{\ell}')\rangle = (2\pi)^2\delta^{(2)}(\boldsymbol{\ell}-\boldsymbol{\ell}')C_\ell^{EE}$$

$$\langle B(\boldsymbol{\ell})B^*(\boldsymbol{\ell}')\rangle = (2\pi)^2\delta^{(2)}(\boldsymbol{\ell}-\boldsymbol{\ell}')C_\ell^{BB}$$



Credit: CMB-S4

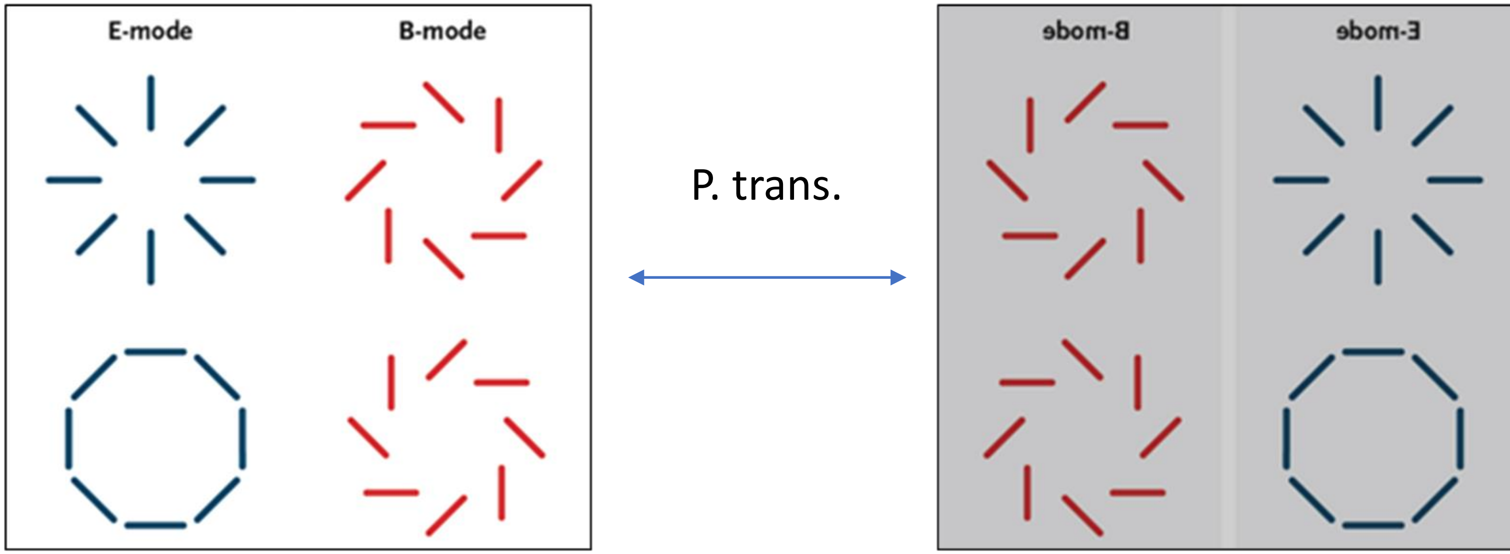
- Power spectra of T and E-mode have been precisely measured
- B-mode is still dominated by instrumental noises

  (especially for the inflationary B-mode)

→ **More to come** in next decade!

Simons Observatory
CMB-S4
LiteBIRD…

Parity flip in polarization pattern

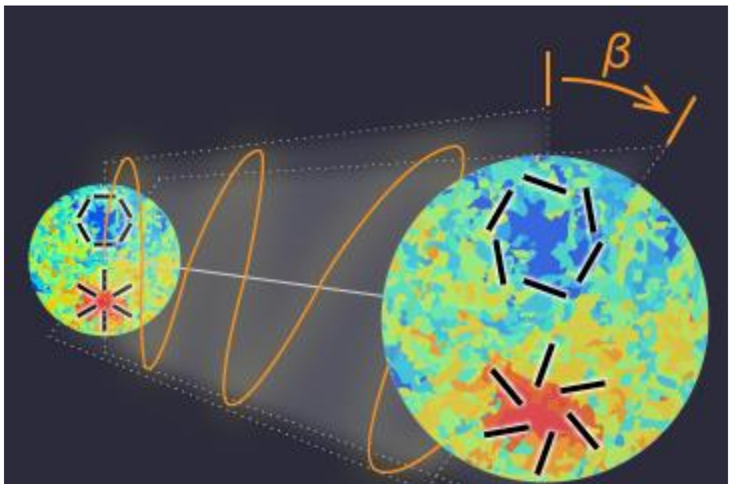


Parity-even: $C_\ell^{TT},\ C_\ell^{EE},\ C_\ell^{BB},\ C_\ell^{TE}$ (parity-invariant theory, well measured)

Parity-odd: $C_\ell^{TB},\ C_\ell^{EB}$ → **parity-violating physics, not well measured**

<EB> from cosmic birefringence

Lue, Wang & Kamionkowski (1999); Feng+ (2005,2006); Liu, Lee & Ng (2006); …



Credit: Y. Minami

Parity-violating interaction

e.g. $$\mathcal{L}_{\rm int} = \frac{1}{4} g_{a\gamma} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

produces the parity-odd EB correlation

$$C_\ell^{EB,o} = \frac{1}{2}\sin(4\beta)\left(C_\ell^{EE,{\rm CMB}} - C_\ell^{BB,{\rm CMB}}\right) + \cos(4\beta) C_\ell^{EB,{\rm CMB}}$$

↑ measured value

↑usually assume 0

History of measurements (WMAP, Planck, ACT,…)

Non-zero <EB> has been detected.
But, not reliable estimates due to the systematic uncertainty.

<EB> from instrumental effect

Wu (2008); Miller (2009); Komatsu (2010); …

Credit: Minami & Komatsu

- Miscalibration of the polarization angle α also contributes to the birefringent signal

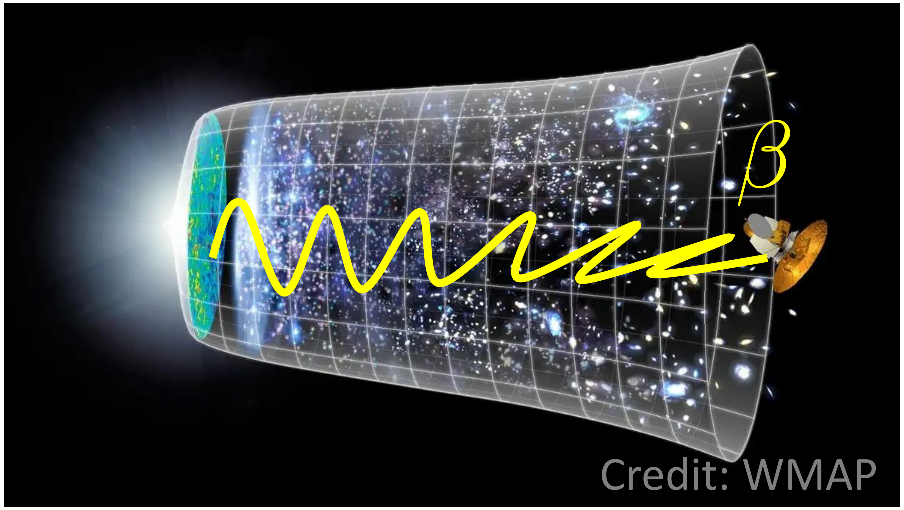
- The past measurements have detected the angle $\theta = \alpha + \beta$

How to break degeneracy of α & β

Minami+ (2019); …

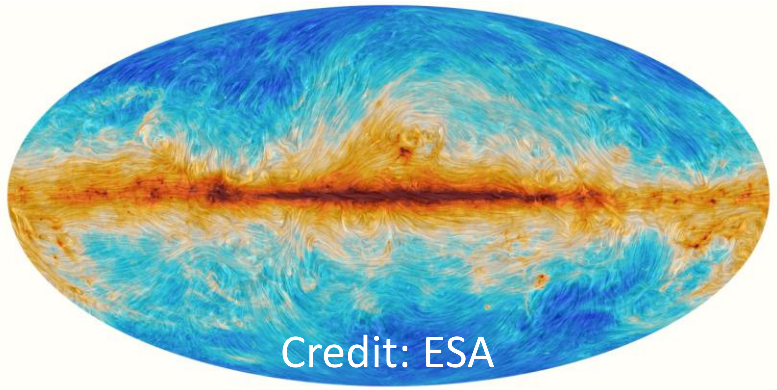
Point: Intrinsic birefringence angle β is **proportional to the path length of photon**

(note: axion is assumed to be quintessence)



Birefringence angle from LSS (z ~ 1100):

$$\theta_{\rm CMB} = \alpha + \beta$$



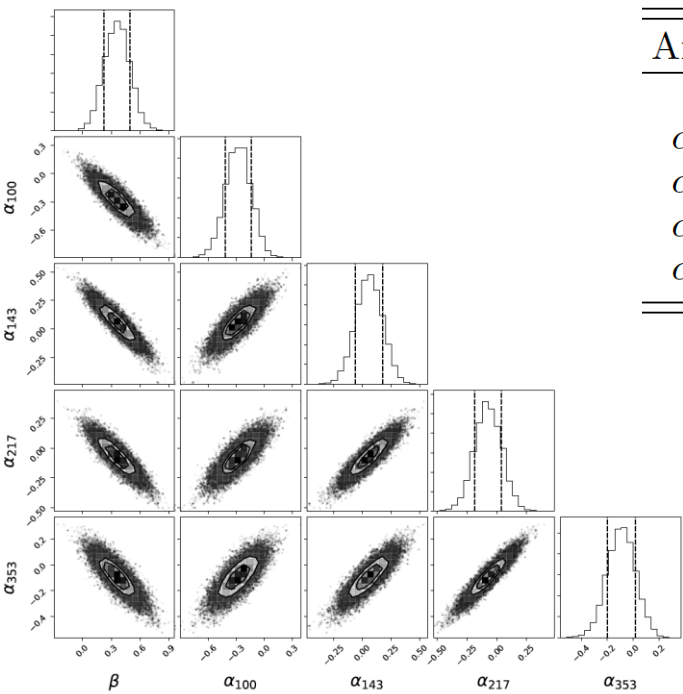
Birefringence angle from galactic foregrounds:

$$\theta_{\rm fg} = \alpha \text{ only}$$

Foreground-based α-calibration

Minami & Komatsu (2020);

calibrate α by using the polarized emission from the galactic foregrounds
and measures the intrinsic birefringence angle β by Planck 2018 polarization data



Angles	Results (deg)
β	0.35 ± 0.14
α_{100}	-0.28 ± 0.13
α_{143}	0.07 ± 0.12
α_{217}	-0.07 ± 0.11
α_{353}	-0.09 ± 0.11

$$\beta = 0.35 \pm 0.14 \text{ deg } (68\% \text{ C.L.})$$

(excludes the null result at 99.2% C.L.)

Tantalizing hint of new physics!

Implication for the axion search

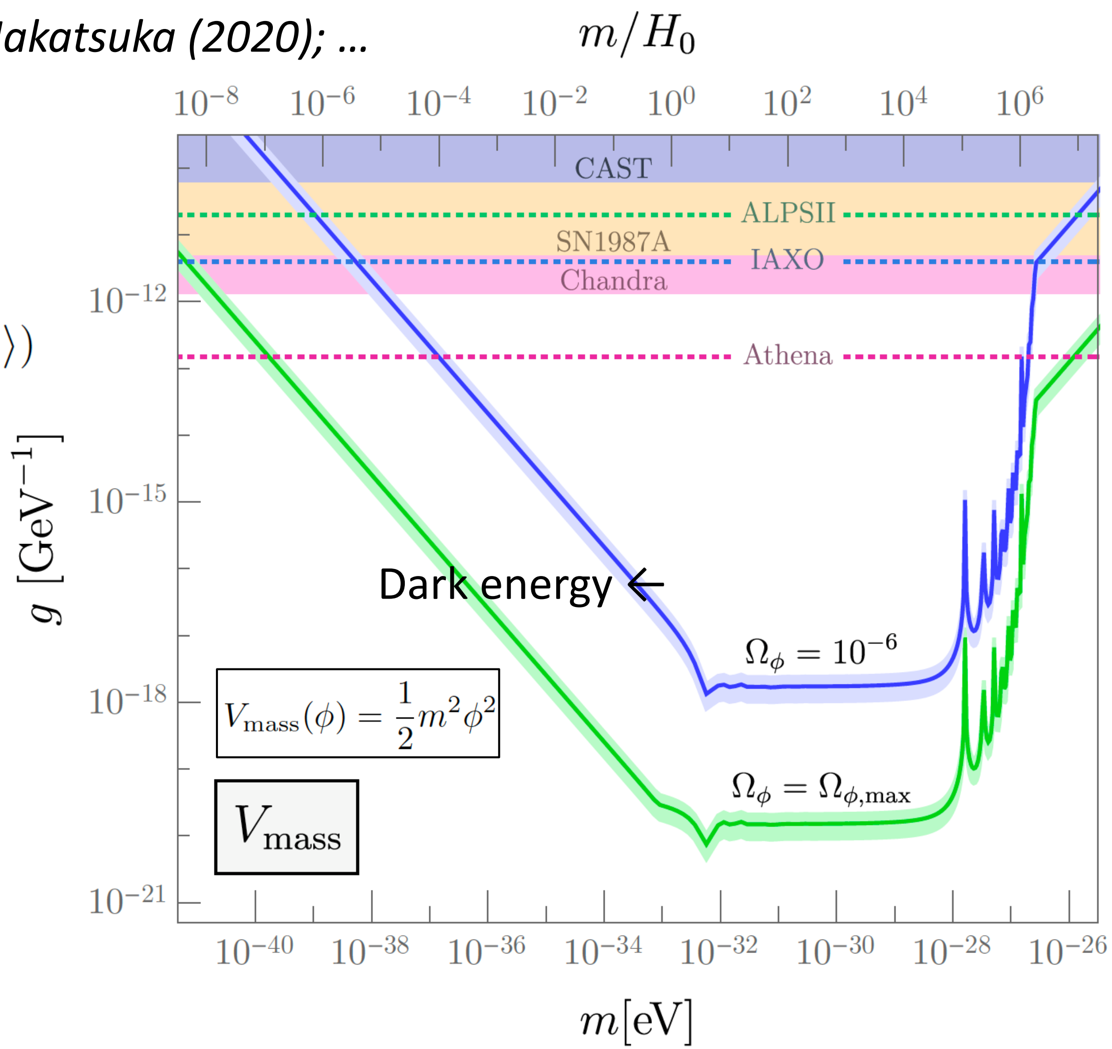
Fujita, Minami, Murai & Nakatsuka (2020); …

- From this relationship

$$\beta = \frac{g_{\phi\gamma}}{2}\Delta\phi \equiv \frac{g_{\phi\gamma}}{2}(\phi_0 - \langle\phi_{\rm LSS}\rangle)$$

we can constrain the parameter space of axion-photon coupling w.r.t. axion mass

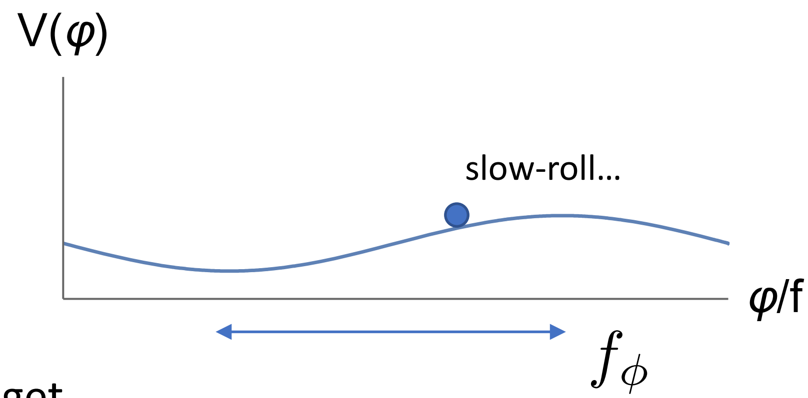
- Support the presence of axion as dark energy



Credit: Fujita, Murai, Nakatsuka & Tsujikawa (2020)

Reconsidering single-field model…

Friemann+ (1995); …



- Consider a **nearly flat** axion cosine potential

$$V(\phi) = m_\phi^2 f_\phi^2 \left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$$

- To satisfy the constraint on EoS parameter, we get

$$f_\phi \simeq 14 M_{\rm Pl} \left(\frac{\Omega_\phi}{0.69}\right)^{1/2} \left(\frac{m_\phi/H_0}{0.1}\right)^{-1} > M_{\rm Pl}$$

requires a **super-Planckian** decay constant or a fine-tuning of initial axion displacement

- To get the measured β, a **large anomaly coefficient** is required

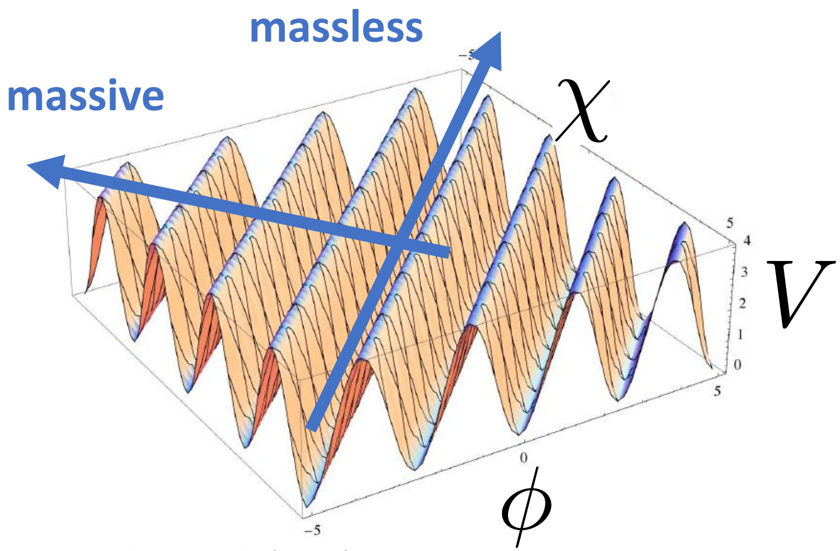
$$g_{\phi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\phi\gamma}}{f_\phi}$$

$$|c_{\phi\gamma}| \simeq 2.3 \times 10^3 \left(\frac{\beta}{0.35\mathrm{deg}}\right) \left(\frac{m_\phi/H_0}{0.1}\right)^{-2} \gg 1$$

Our study

Multiple axion model

Quintessence: ***Kim (1999)(2000), …*** Inflation: ***Kim, Nilles & Peloso (2005), …***



Credit: Kappl+ (2014)

- Flat direction can be realized by an alignment of the potentials from **multiple axions**:

e.g.)

$$V(\phi,\chi) = \Lambda_1^4\left[1-\cos\left(\frac{\phi}{F_{\phi 1}}+\frac{\chi}{F_{\chi 1}}\right)\right] + \Lambda_2^4\left[1-\cos\left(\frac{\phi}{F_{\phi 2}}+\frac{\chi}{F_{\chi 2}}\right)\right]$$

with $\frac{F_{\chi 1}}{F_{\phi 1}} = \frac{F_{\chi 2}}{F_{\phi 2}}$ (exactly flat) $(F_i < M_{\rm Pl})$

- The misalignment can be characterized by the deviation from the above condition

- Linear combinations of two-fields provide two (nearly) massless & massive direction

Dark energy **Dark matter**

Alignment axion model (1)

arXiv: 2108.02150

- Consider the aligned cosine potentials:

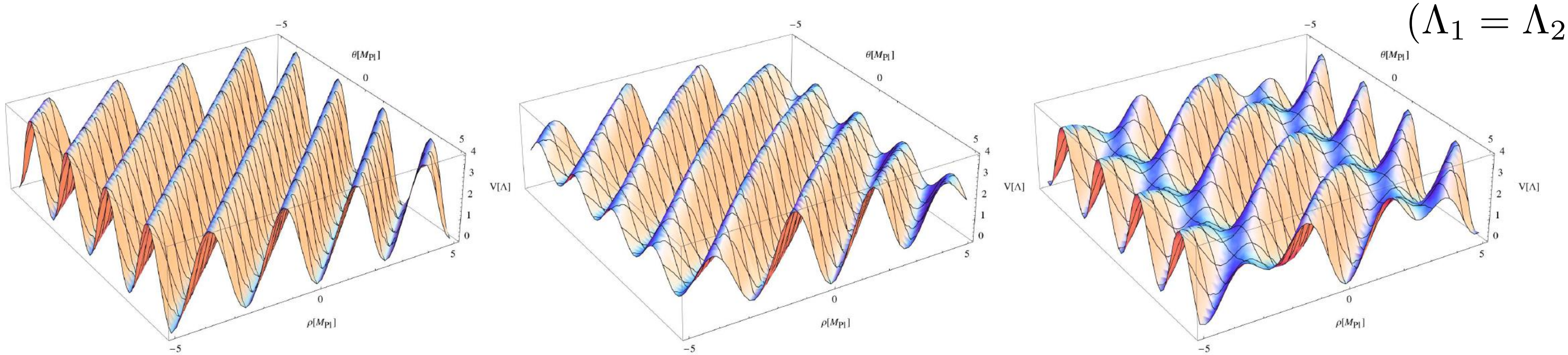
$$V(\phi,\chi) = \Lambda_1^4\left[1-\cos\left(\frac{\phi}{F_{\phi 1}}+\frac{\chi}{F_{\chi 1}}\right)\right]+\Lambda_2^4\left[1-\cos\left(\frac{\phi}{F_{\phi 2}}+\frac{\chi}{F_{\chi 2}}\right)\right]$$

For simplicity, we assume $F_{\phi 1} = F_{\phi 1} \equiv F_\phi,\ F_{\chi 2} = F_{\chi 1}(1+\epsilon)$

- The misalignment of the potential is characterized by $\epsilon \ll 1$

→nearly flatness

$(\Lambda_1 = \Lambda_2)$

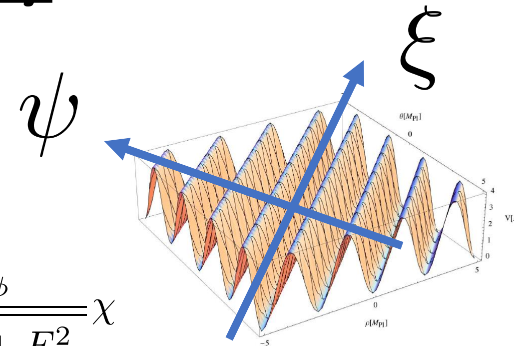


$\epsilon = 0$ $\epsilon = 0.1$ $\epsilon = 0.3$

Credit: Kappl+ (2014)

Alignment axion model (2)

arXiv: 2108.02150



- Then, two mass eigen bases can be found:

$$\xi = \frac{F_\phi}{\sqrt{F_\phi^2 + F_{\chi 1}^2}}\phi - \frac{F_{\chi 1}}{\sqrt{F_\phi^2 + F_{\chi 1}^2}}\chi \,, \quad \psi = -\frac{F_{\chi 1}}{\sqrt{F_\phi^2 + F_{\chi 1}^2}}\phi - \frac{F_\phi}{\sqrt{F_\phi^2 + F_{\chi 1}^2}}\chi$$

with mass

$$m_\xi^2 \simeq \frac{\Lambda_2^4}{F_\phi^2 + F_{\chi 1}^2}\epsilon^2 \,, \qquad m_\psi^2 \simeq \frac{F_\phi^2 + F_{\chi 1}^2}{F_\phi^2 F_{\chi 1}^2}\Lambda_1^4 \qquad \frac{m_\psi}{m_\xi} \simeq \frac{1}{\epsilon}\frac{\Lambda_1^2}{\Lambda_2^2}\frac{F_\phi^2 + F_{\chi 1}^2}{F_\phi F_{\chi 1}} \gg 1$$

$(\text{assuming that } \Lambda_1 \gg \Lambda_2)$

- In terms of (ξ, ψ), the cosine potential can be rewritten as

$$V(\psi,\ \xi) \simeq \Lambda_1^4\left[1 - \cos\left(\frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{F_\phi F_{\chi 1}}\psi\right)\right] + \Lambda_2^4\left[1 - \cos\left(\frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{F_\phi F_{\chi 1}}\psi - \frac{\epsilon}{\sqrt{F_\phi^2 + F_{\chi 1}^2}}\xi\right)\right]$$

Alignment axion model (3)

arXiv: 2108.02150

$$V(\psi,\ \xi) \simeq \Lambda_1^4 \left[1 - \cos\left(\underbrace{\frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{F_\phi F_{\chi 1}}}_{\equiv \tilde{F}_\psi^{-1}} \psi\right)\right] + \Lambda_2^4 \left[1 - \cos\left(\underbrace{\frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{F_\phi F_{\chi 1}}}_{\equiv \tilde{F}_\psi^{-1}} \psi - \underbrace{\frac{\epsilon}{\sqrt{F_\phi^2 + F_{\chi 1}^2}}}_{\equiv \tilde{F}_\xi^{-1}} \xi\right)\right]$$

➢ The effective field ranges (decay constants) of axions are obtained:

$$\tilde{F}_\xi \simeq \frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{\epsilon}\,, \qquad \tilde{F}_\psi \simeq \frac{F_\phi F_{\chi 1}}{\sqrt{F_\phi^2 + F_{\chi 1}^2}}$$

➢ Even if the original axion decay constants are sub-Planckian $(F_i < M_{\rm Pl})$,

$$\tilde{F}_\xi \gg M_{\rm Pl} \text{ as } \epsilon \to 0$$

(ξ can act as dark energy!)

Axion-photon couplings

arXiv: 2108.02150

- The interactions of photon to the (original) axion fields are given by

$$\mathcal{L} \supset \frac{\alpha}{8\pi}\left(\frac{\phi}{F_{\phi\gamma}} + \frac{\chi}{F_{\chi\gamma}}\right) F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- In terms of (ψ, ξ), the effective coupling constants are obtained:

$$g_{\xi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\xi\gamma}}{\tilde{F}_\xi}\,, \quad c_{\xi\gamma} \equiv \frac{1}{\epsilon}\left(\frac{F_\phi}{F_{\phi\gamma}} - \frac{F_{\chi 1}}{F_{\chi\gamma}}\right)\,,$$

$$g_{\psi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\psi\gamma}}{\tilde{F}_\psi}\,, \quad c_{\psi\gamma} \equiv -\left(\frac{F_\phi}{F_{\chi\gamma}} + \frac{F_{\chi 1}}{F_{\phi\gamma}}\right)\frac{F_\phi F_{\chi 1}}{F_\phi^2 + F_{\chi 1}^2}$$

- g_ξγ is fixed by the measured birefringence angle β = 0.35 $\pm$0.14

  → also constrain the parameter space of g_ψγ as axion DM

Parameter Search (1)

arXiv: 2108.02150

- (Effective) axion quintessence field range: $\tilde{F}_\xi \simeq 14 M_{\rm Pl} \left(\frac{\Omega_\phi}{0.69}\right)^{1/2} \left(\frac{m_\phi/H_0}{0.1}\right)^{-1}$

  leads to the tuning of the small misalignment parameter:

$$\epsilon \simeq 7.0 \times 10^{-2} \frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{M_{\rm Pl}} \left(\frac{\Omega_\xi}{0.69}\right)^{-1/2} \left(\frac{m_\xi/H_0}{0.1}\right)$$

- Birefringence condition: $|c_{\xi\gamma}| \simeq 2.3 \times 10^3 \left(\frac{\beta}{0.35 \rm deg}\right) \left(\frac{m_\xi/H_0}{0.1}\right)^{-2}$

  leads to the condition of the ratio of decay constants:

$$\left|\frac{F_\phi}{F_{\phi\gamma}} - \frac{F_{\chi 1}}{F_{\chi\gamma}}\right| \simeq 1.6 \times 10^2 \frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{M_{\rm Pl}} \left(\frac{\beta}{0.35 \rm deg}\right) \left(\frac{\Omega_\xi}{0.69}\right)^{-1/2} \left(\frac{m_\xi/H_0}{0.1}\right)^{-1}$$

Parameter Search (2)

arXiv: 2108.02150

- Axion DM abundance by misalignment production: $\Omega_\psi \simeq \frac{1}{6}\left(\frac{\tilde{F}_\psi}{M_{\rm Pl}}\right)^2 (9\Omega_r)^{3/4}\left(\frac{m_\psi}{H_0}\right)^{1/2}$

  leads to the condition of axion DM decay constant: *Marsh & Ferreira (2010);*

$$\tilde{F}_\psi \simeq 3.8\times 10^{-2} M_{\rm Pl}\left(\frac{\Omega_\psi}{0.31}\right)^{1/2}\left(\frac{m_\psi}{10^{-22}{\rm eV}}\right)^{-1/4}$$

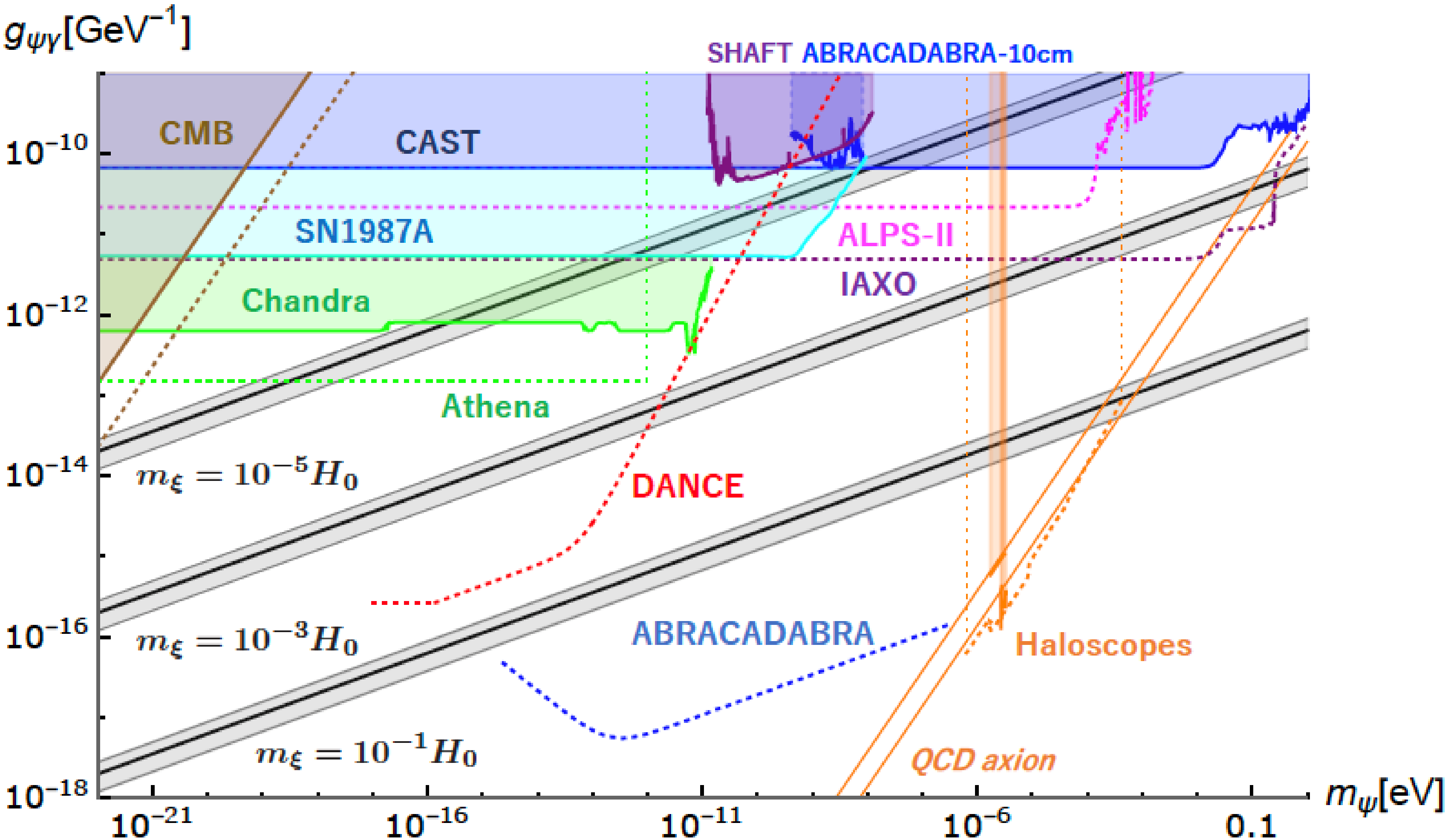
- The axion DM-photon coupling constant is obtained by:

$$g_{\psi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\psi\gamma}}{\tilde{F}_\psi}\ , \quad c_{\psi\gamma} \equiv -\left(\frac{F_\phi}{F_{\chi\gamma}} + \frac{F_{\chi 1}}{F_{\phi\gamma}}\right)\frac{F_\phi F_{\chi 1}}{F_\phi^2 + F_{\chi 1}^2}$$

$$|g_{\psi\gamma}| \simeq 2.0\times 10^{-18}\ {\rm GeV}^{-1}\,\frac{F_{\chi 1}}{M_{\rm Pl}}\left(\frac{\Omega_\xi}{0.69}\right)^{-1/2}\left(\frac{\Omega_\psi}{0.31}\right)^{-1/2} \times\left(\frac{\beta}{0.35{\rm deg}}\right)\left(\frac{m_\xi/H_0}{0.1}\right)^{-1}\left(\frac{m_\psi}{10^{-22}{\rm eV}}\right)^{1/4}\ .$$

(assuming the region $F_\phi \ll F_{\chi 1}, F_{\chi 1} \ll F_{\chi\gamma}$)

Parameter space of axion DM



Summary & Outlook

- We show that a recent constraint on the cosmic birefringence effect can connect the constraints on axion as dark energy and dark matter, respectively.
- The resultant parameter space of axion DM is potentially testable with future axion DM experimental searches.
- The extension of this scenario to other multiple axion models? The compatibility with the swampland criteria in string theory?