Probing axions with the measurements of photon's birefringence

Ippei Obata (Kavli IPMU, University of Tokyo)

科研費
KAKENHI

ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
What is dark matter? - Comprehensive study of the huge discovery space in dark matter

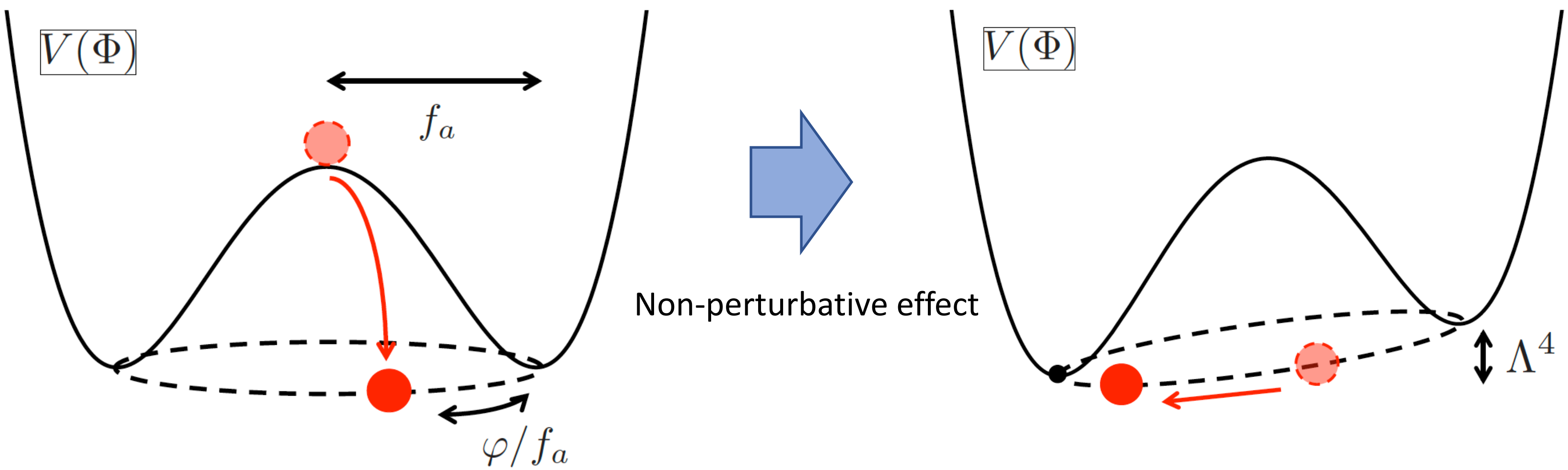
文部科学省
科学研究費助成事業
学術変革領域研究
(2020–2024)

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

2023.2.21 @Kagoshima workshop on particles, fields and strings

What is axion?

A (pseudo) Nambu-Goldstone boson of global *U(1)* symmetry



$$V(\varphi) = \Lambda^4 \left[1 - \cos\left(\varphi/f_a\right)\right]$$

Two characteristic scales:

f_a : decay constant $\qquad m_a = \Lambda^2/f_a$: mass

When people say axion…

QCD axion ***Peccei & Quinn (1977); Weinberg, Wilczek (1978); …***

- Suggested to solve strong CP problem
- Mass & decay constant are related to each other in QCD energy scale

$$m_a = \frac{\Lambda_{\rm QCD}^2}{f_a} \simeq 6\ \mu{\rm eV} \left(\frac{10^{12}{\rm GeV}}{f_a}\right)$$

(typical) QCD axion window

$$10^9\ {\rm GeV} \lesssim f_a \lesssim 10^{12}{\rm GeV}$$

Axion-like particle (ALP) ***Svrcek & Witten (2006); Arvanitaki+ (2010); …***

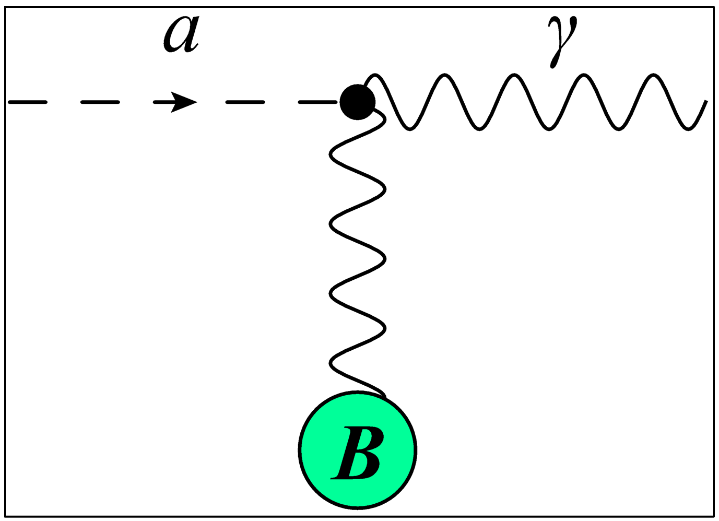
- Predicted by theories beyond the standard model (e.g. string theory)
- Mass & decay constant are treated as independent parameters

↑Main focus of this talk

Conventional axion search

- Axion generically couples to photon via the topological term

$$\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$



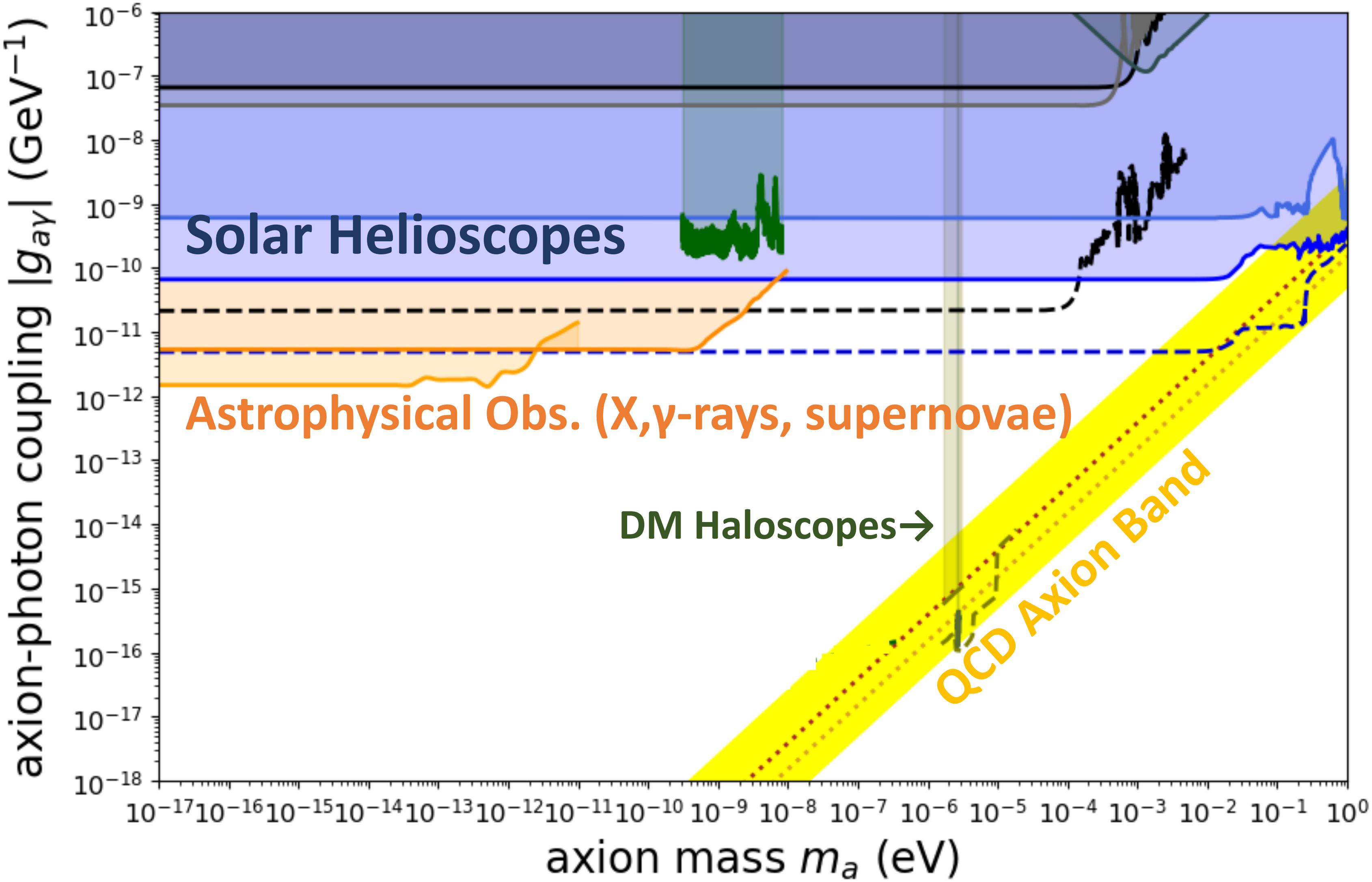
a : axion

γ : photon

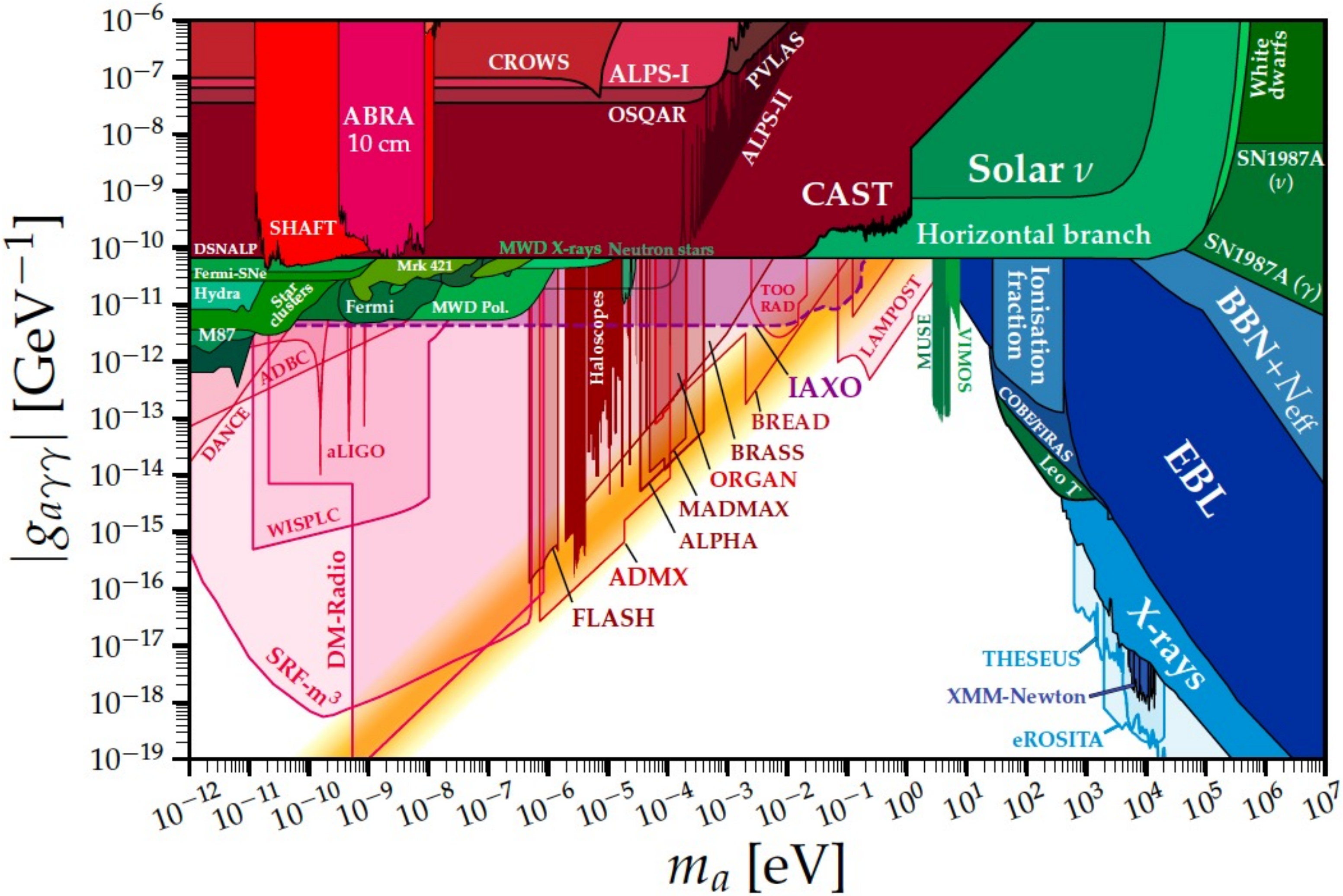
B : magnetic field

- **Axion is converted into photon under the background magnetic field (“axion-photon conversion” or “Primakoff effect”)**

Overview of target space



Overview of target space (more)

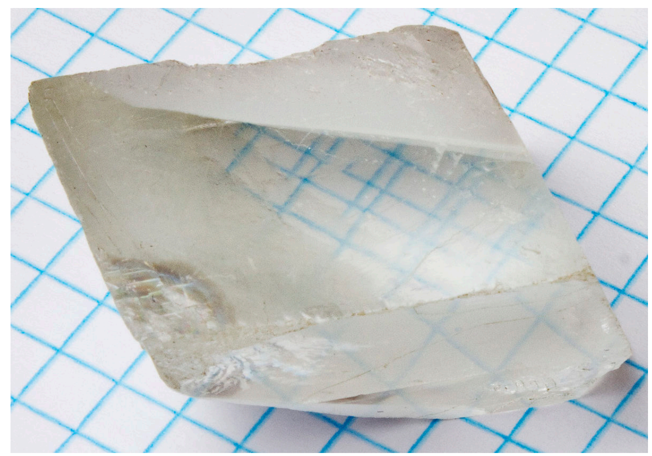


Ciaran O'Hare, AxionLimits: https://cajohare.github.io/AxionLimits/

New search methods for axions
-Photon's birefringence effect-

Credit: higgstan.com

Axion as a birefringent material



Photon’s birefringence by axion

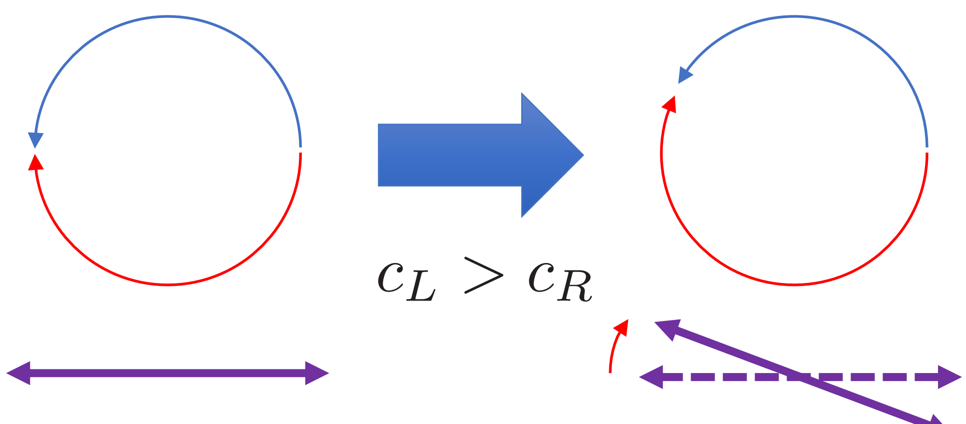
Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); …

Axion behaves as a birefringent material in our universe

- Axion differentiates the phase velocities of circular-polarized photon

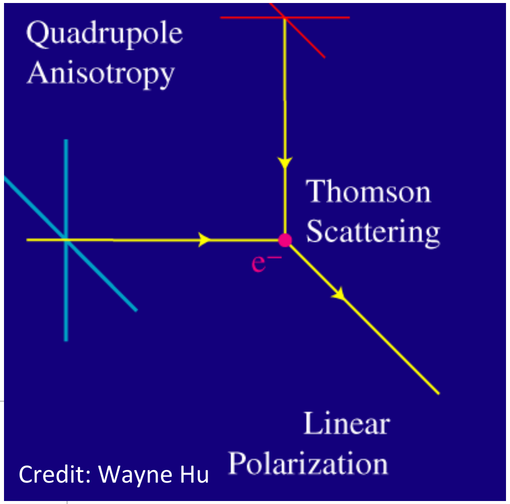
$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \ , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

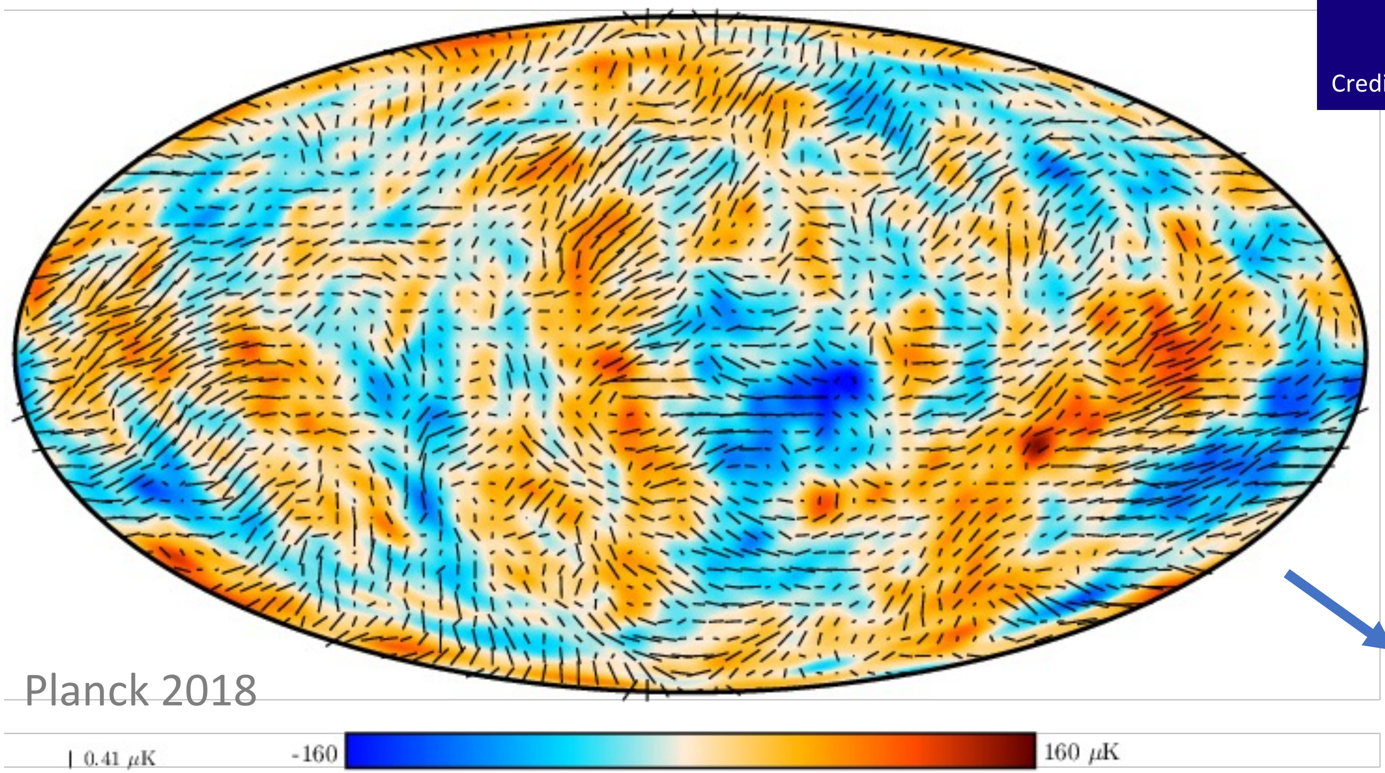
Dispersion relation: $\ddot{A}_k^{\mathrm{L/R}} + \omega_{\mathrm{L/R}}^2 A_k^{\mathrm{L/R}} = 0, \quad c_{\mathrm{L/R}} \equiv \frac{\omega_{\mathrm{L/R}}}{k} = \sqrt{1 \pm \frac{g_{\phi\gamma}\dot{\phi}}{k}}$



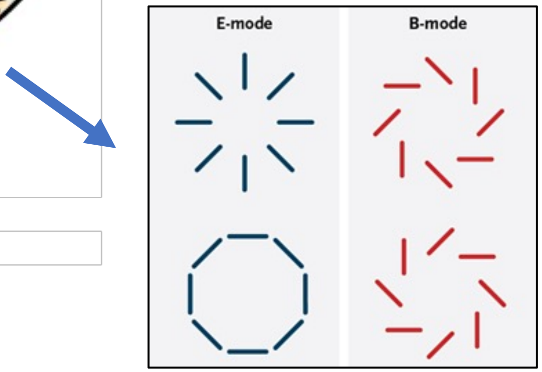
→ leading to the rotation of linear-polarization direction!

CMB is polarized



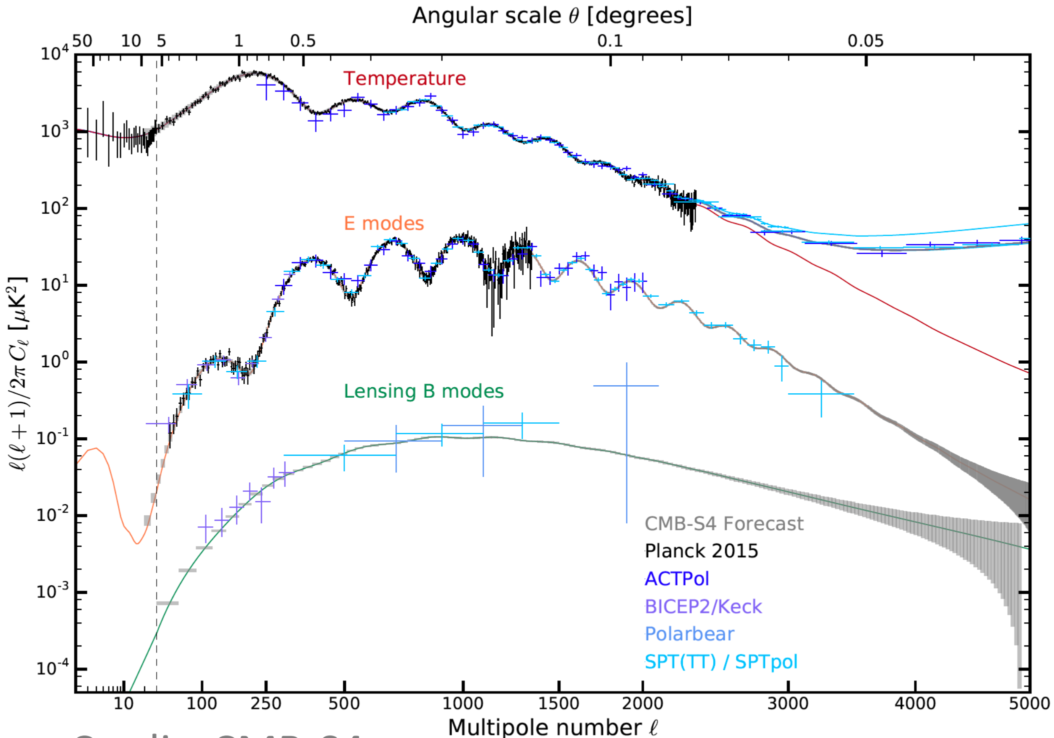


E-mode v.s. B-mode



CMB 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

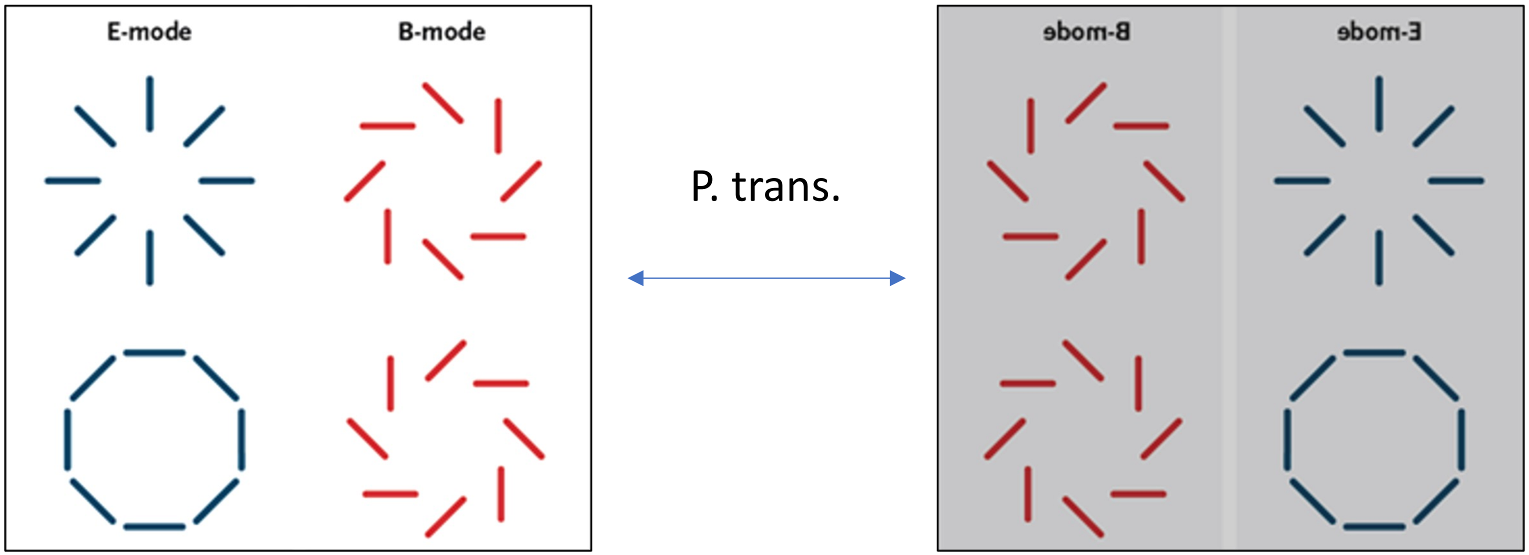
- Power spectra of T and E-mode have been precisely measured
- B-mode is still dominated by instrumental noises.

  (especially for the inflationary B-mode)

→ **More to come** in next decade!

Simons Observatory
CMB-S4
LiteBIRD…

Parity flip in polarization pattern

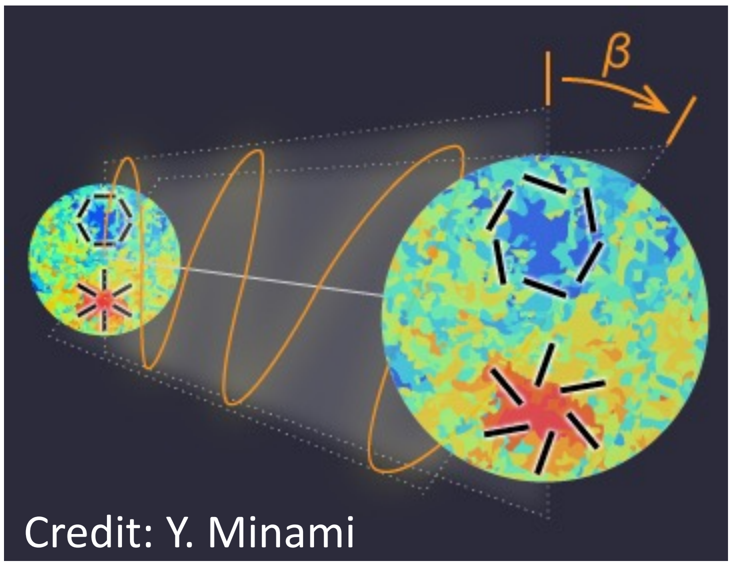


Parity-even: $C_\ell^{TT},\ C_\ell^{EE},\ C_\ell^{BB},\ C_\ell^{TE}$ (parity-invariant theory, well measured)

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

Generation EB correlation function

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



Parity-violating interaction

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

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 miscalibration of instrumental angle “α” .

<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

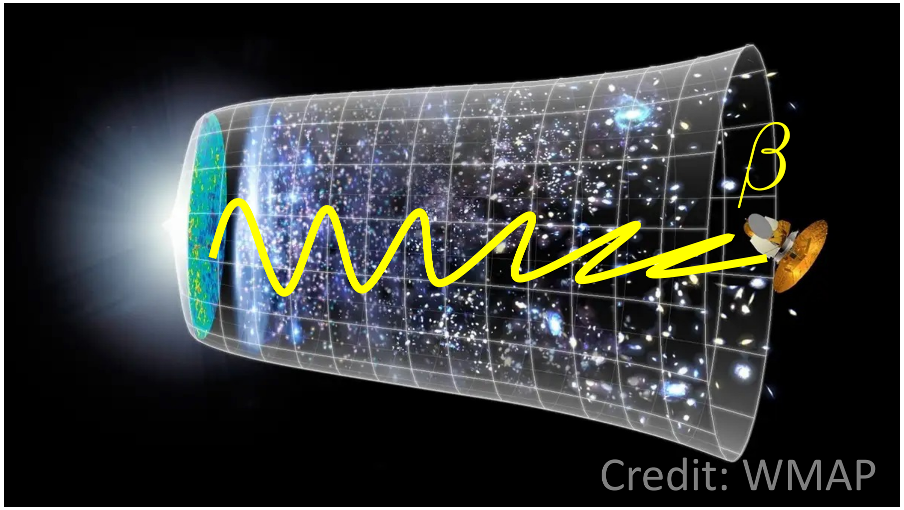
- The past measurements have detected the angle $\theta = \beta + \alpha$

How to break degeneracy of α & β

Minami+ (2019); …

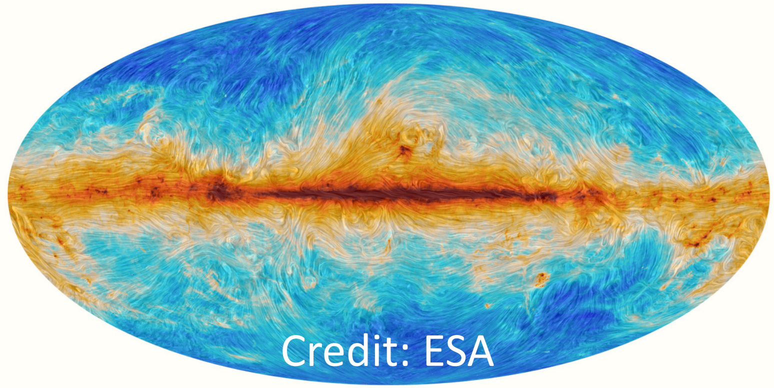
Point: Intrinsic birefringence angle β is **proportional to the path length of photon**

(note: axion is assumed to be quintessence)



Birefringence angle from LSS (z ~ 1e3):

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



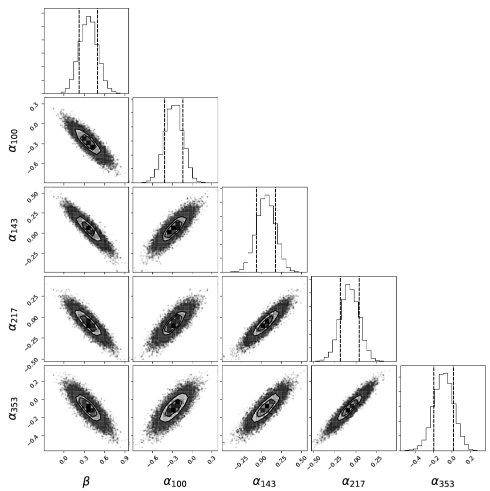
Birefringence angle from galactic foregrounds:

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

Foreground-based 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 PR3 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

$$\beta = 0.35 \pm 0.14 \text{ deg } (2.4\sigma)$$

Diego-Palazuelos+ (2022.1)

Upgrade! (with Planck PR4 data):

$$\beta = 0.36 \pm 0.11 \text{ deg } (3.3\sigma)$$

Eskilt & Komatsu (2022.5)

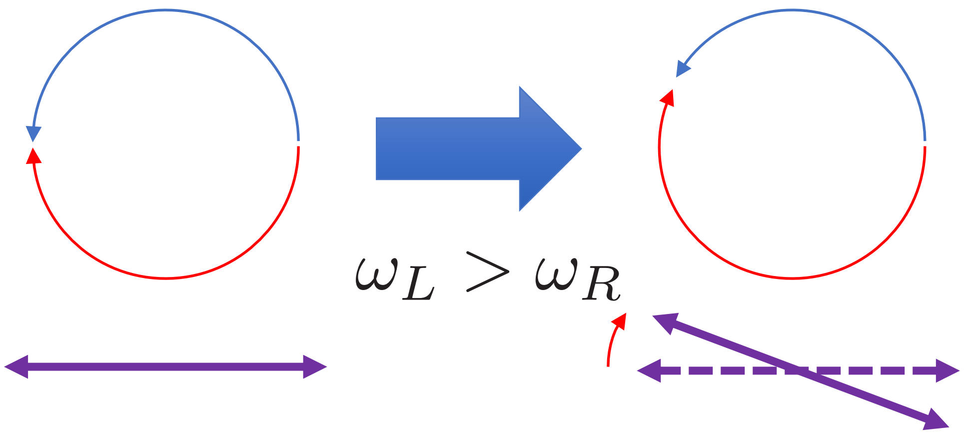
Upgrade! (with Planck + WMAP data):

$$\beta = 0.34 \pm 0.09 \text{ deg } (3.6\sigma)$$

How is β given by the axion field?

$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \rightarrow \quad \omega_{\rm L/R} = k\sqrt{1 \pm \frac{g_{\phi\gamma}\dot{\phi}}{k}} \simeq k \pm \frac{g_{\phi\gamma}}{2}\dot{\phi}$$

(Dispersion relation)



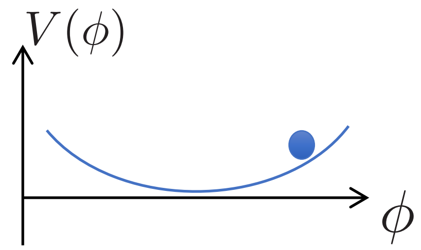
→ the net phase shift is given by the time integration of angular velocity difference from emission to observed point!

$$\beta = \frac{1}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} dt(\omega_L - \omega_R) = \frac{g_{\phi\gamma}}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} dt\dot{\phi} = \frac{g_{\phi\gamma}}{2}\left[\phi(t_{\rm obs}) - \phi(t_{\rm emit})\right]$$

Cosmological axion evolution

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

(background evolution)



- In early universe (m < H), $\phi \simeq \text{const.}$ (frozen due to the Hubble friction)
- In late universe (m > H), $\phi \simeq a^{-3/2}\phi_0 \cos(mt)$ (start to oscillate)

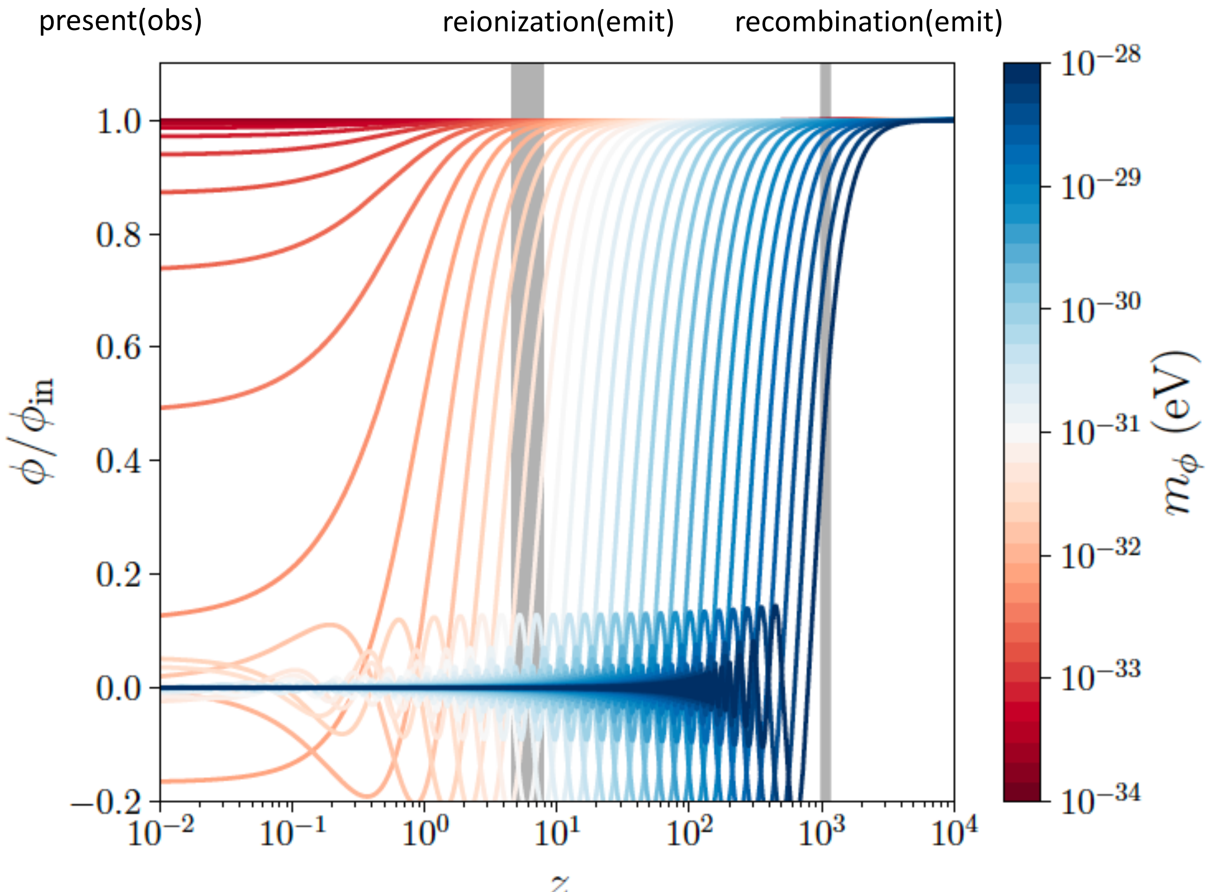
- After oscillation begins, axion behaves as a pressureless matter fluid

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 \simeq \frac{\rho_0}{a^3}$$
$$P = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2 \simeq \frac{P_0}{a^3}\sin(2mt) \sim 0$$

(pressure) < (gravity)
→ could behave as dark matter

- If $m \lesssim H_0 \sim 10^{-33}$ eV → could behave as dark energy (quintessence)

Time evolution with different mass



Lee, Hotinli, Kamionkowski (2022)

$$\beta = \frac{g_{\phi\gamma}}{2}(\phi_{\rm obs} - \phi_{\rm emit})$$

→ once we fix the angle as $\beta = 0.34 \pm 0.09$ deg (3.6σ),

the axion-photon coupling is constrained w.r.t. mass scale

Constraint on axion with light mass

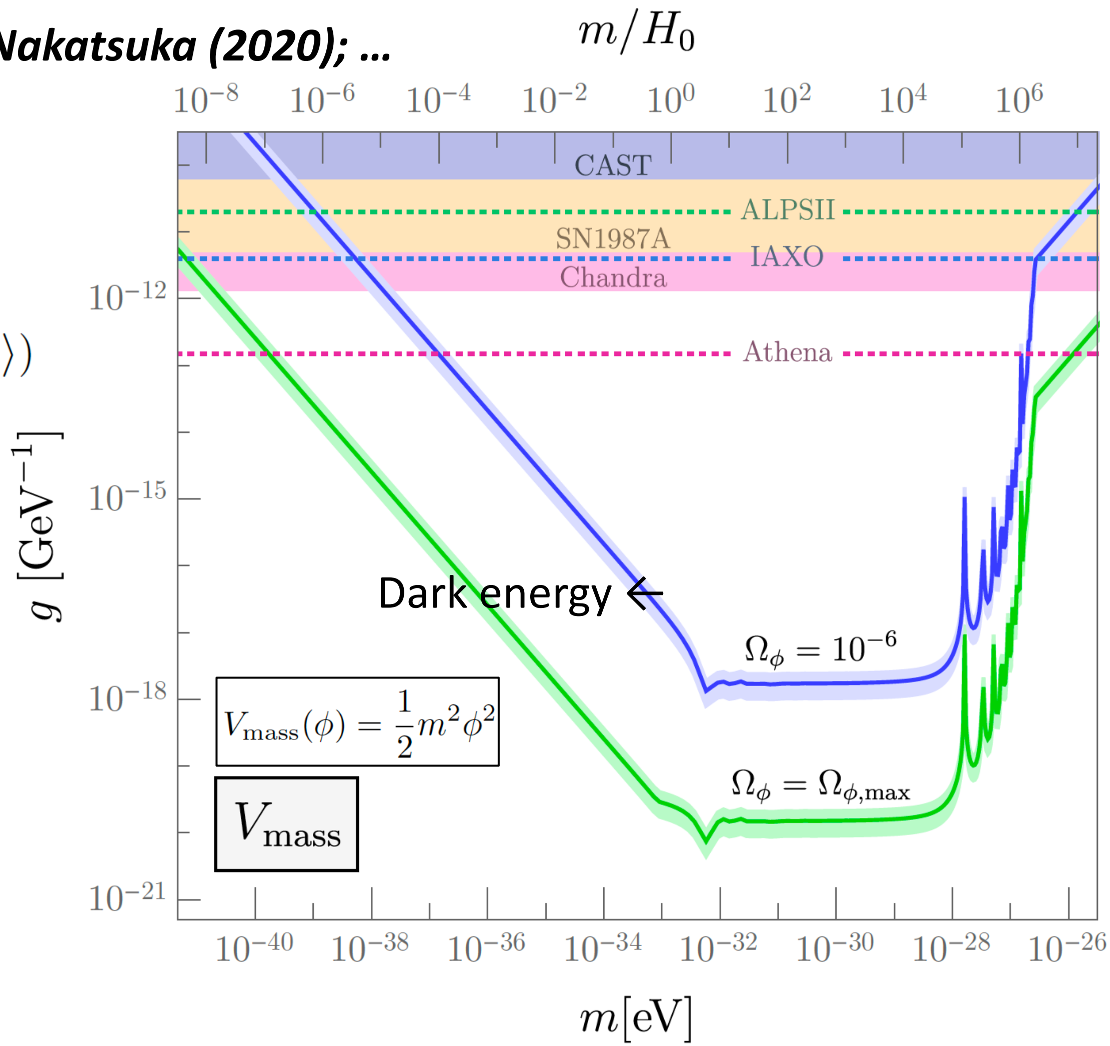
Fujita, Minami, Murai & Nakatsuka (2020); …

- 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



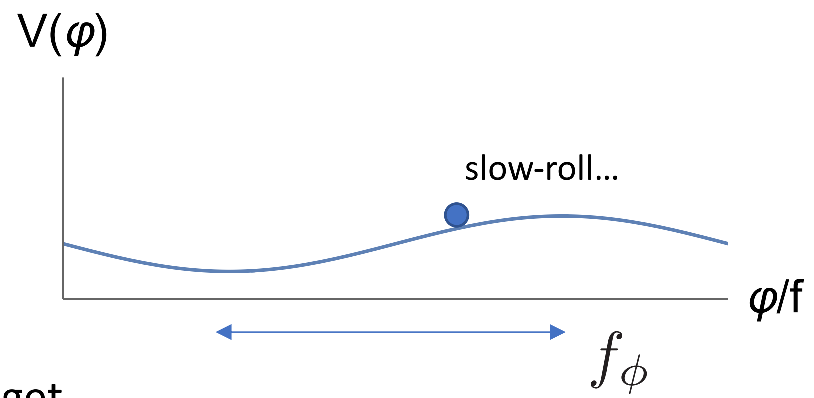
Fujita, Murai, Nakatsuka & Tsujikawa (2020)

Some issues of 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

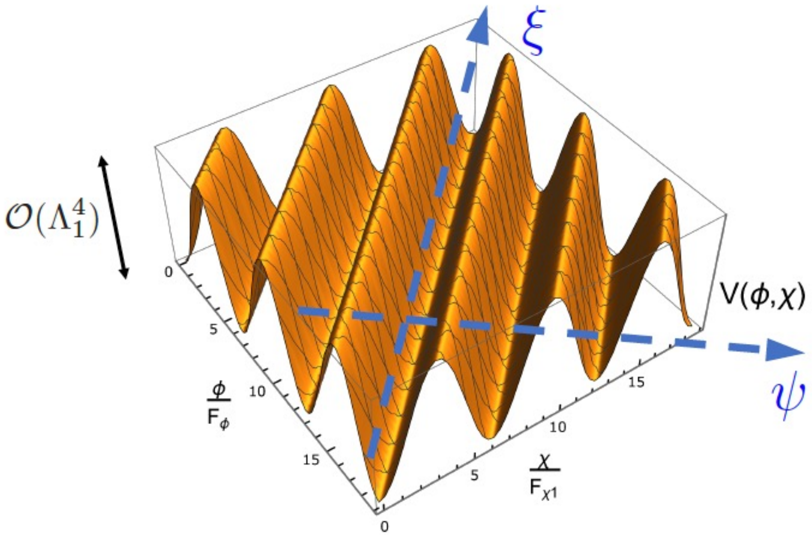
- To get the measured β, a **large anomaly coefficient** is required

$$g_{\phi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\phi\gamma}}{f_\phi} \qquad |c_{\phi\gamma}| \simeq 7.5\times 10^3 \left(\frac{\beta}{0.35\mathrm{deg}}\right)\left(\frac{m_\phi/H_0}{0.1}\right)^{-2} \gg 1$$

Two-fields axion model

Kim (1999)(2000), …

Kim, Nilles & Peloso (2005), …



Potential

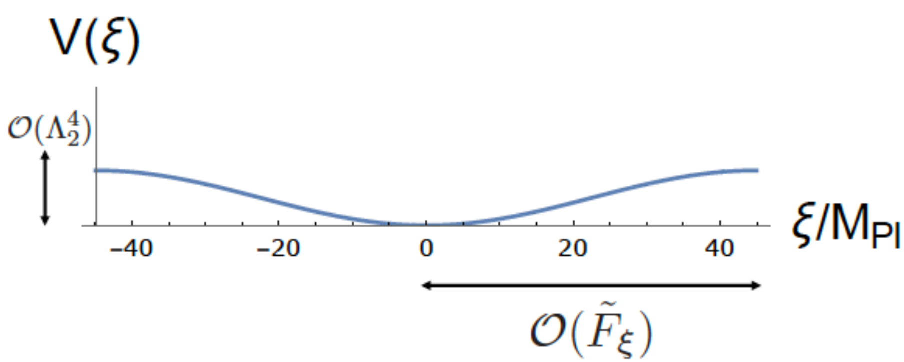
$$V(\phi,\chi) = \Lambda_1^4\left[1-\cos\left(\frac{\phi}{F_{\phi 1}}+\frac{\chi}{F_{\chi 1}}\right)\right] + \Lambda_2^4\left[1-\cos\left(\frac{\phi}{F_{\phi 2}}+\frac{\chi}{F_{\chi 2}}\right)\right]$$

$$(\Lambda_1^4 \gg \Lambda_2^4,\ F_i < M_{\rm Pl})$$

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

- Nearly-flat direction can be realized by an alignment of the **multiple axion potentials**:

$$F_{\phi 1} = F_{\phi 1} \equiv F_\phi,\ F_{\chi 2} = F_{\chi 1}(1+\epsilon)$$ $$\epsilon \ll 1$$: misalignment parameter

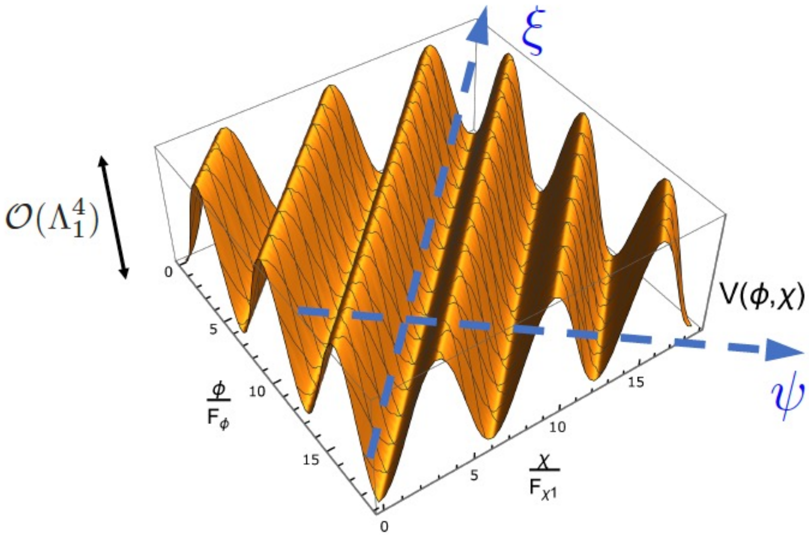


Effective field range of axion

$$\tilde{F}_\xi = \frac{\sqrt{F_\phi^2+F_{\chi 1}^2}}{\epsilon} \gg M_{\rm Pl}$$

Two-fields axion model

Kim (1999)(2000), …
Kim, Nilles & Peloso (2005), …



Potential

$$V(\phi,\chi) = \Lambda_1^4\left[1-\cos\left(\frac{\phi}{F_{\phi1}}+\frac{\chi}{F_{\chi1}}\right)\right] + \Lambda_2^4\left[1-\cos\left(\frac{\phi}{F_{\phi2}}+\frac{\chi}{F_{\chi2}}\right)\right]$$

$$(\Lambda_1^4 \gg \Lambda_2^4,\ F_i < M_{\rm Pl})$$

$$\xi = \frac{F_\phi}{\sqrt{F_\phi^2+F_{\chi1}^2}}\phi - \frac{F_{\chi1}}{\sqrt{F_\phi^2+F_{\chi1}^2}}\chi\ ,\quad \psi = -\frac{F_{\chi1}}{\sqrt{F_\phi^2+F_{\chi1}^2}}\phi - \frac{F_\phi}{\sqrt{F_\phi^2+F_{\chi1}^2}}\chi$$

- Nearly-flat direction can be realized by an alignment of the **multiple axion potentials**:

$$F_{\phi1} = F_{\phi1} \equiv F_\phi,\ F_{\chi2} = F_{\chi1}(1+\epsilon) \qquad \epsilon \ll 1$$: misalignment parameter

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

Dark energy ξ

Dark matter ψ

Introduce axion-photon couplings

IO (2021);

- 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:

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

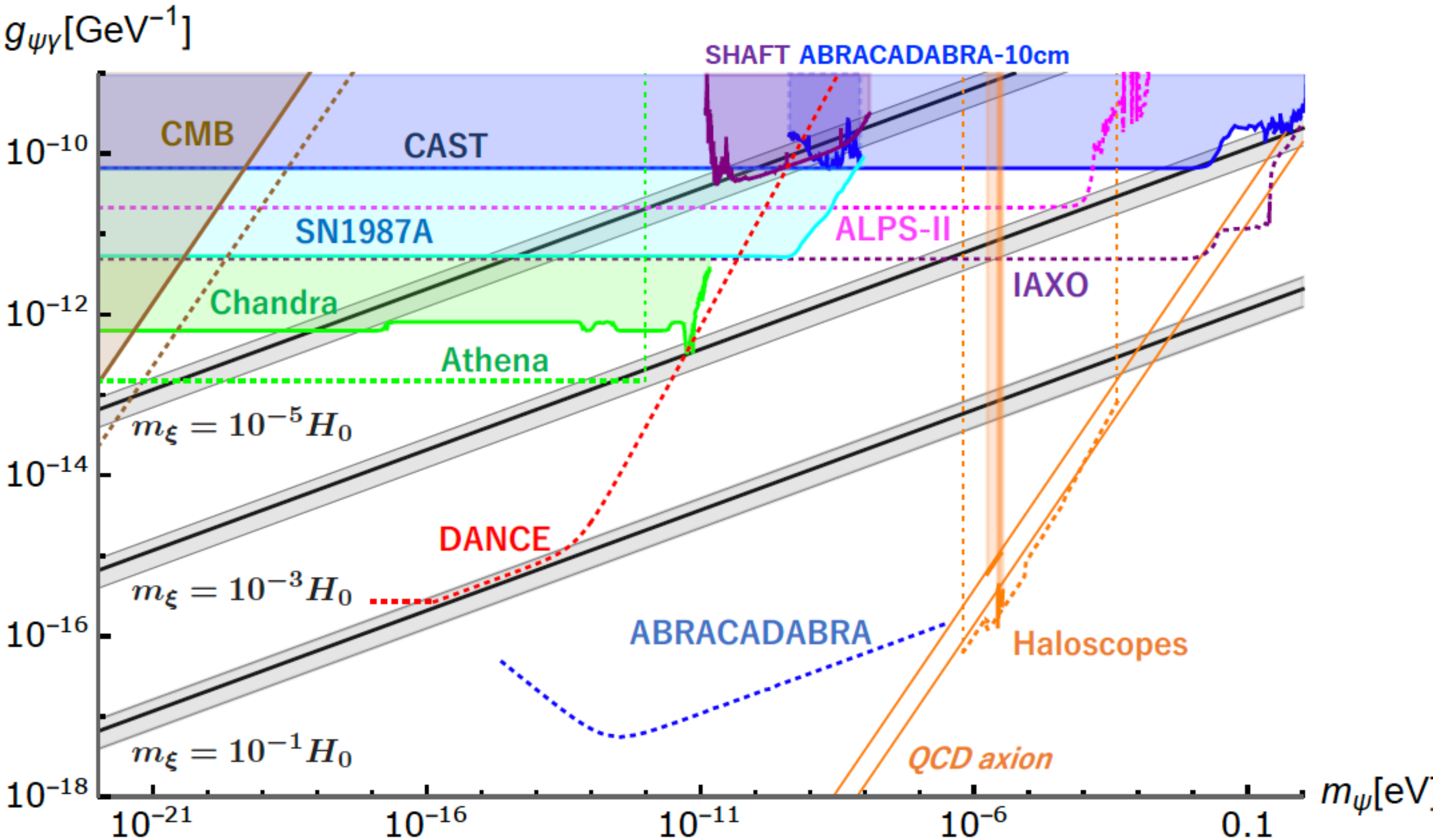
$$g_{\psi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\psi\gamma}}{\tilde{F}_\psi}, \quad c_{\psi\gamma} \equiv -\left(\frac{F_\phi}{F_{\chi\gamma}} + \frac{F_{\chi 1}}{F_{\phi\gamma}}\right)\frac{F_\phi F_{\chi 1}}{F_\phi^2 + F_{\chi 1}^2}$$

(release 3)

- $g_{\xi\gamma}$ (dark energy) is fixed by the measured birefringence angle β = 0.35 ± 0.14

→ the parameter space of $g_{\psi\gamma}$ (dark matter) is also constrained

Parameter space of axion DM



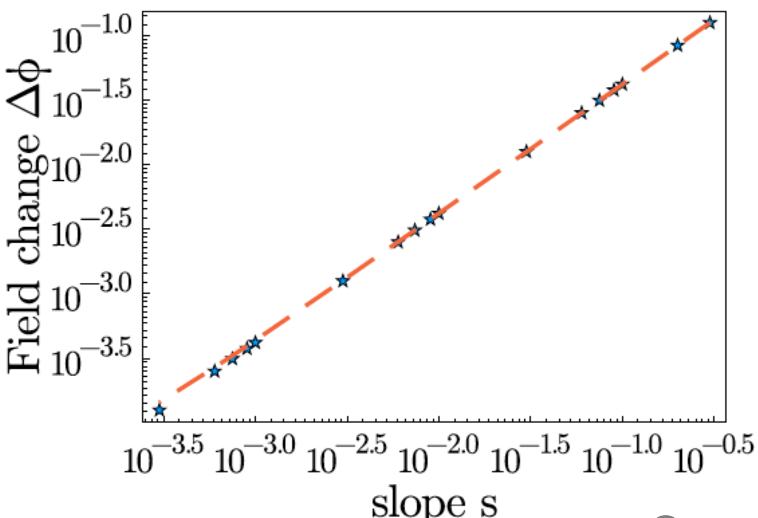
Birefringence from axion monodromy

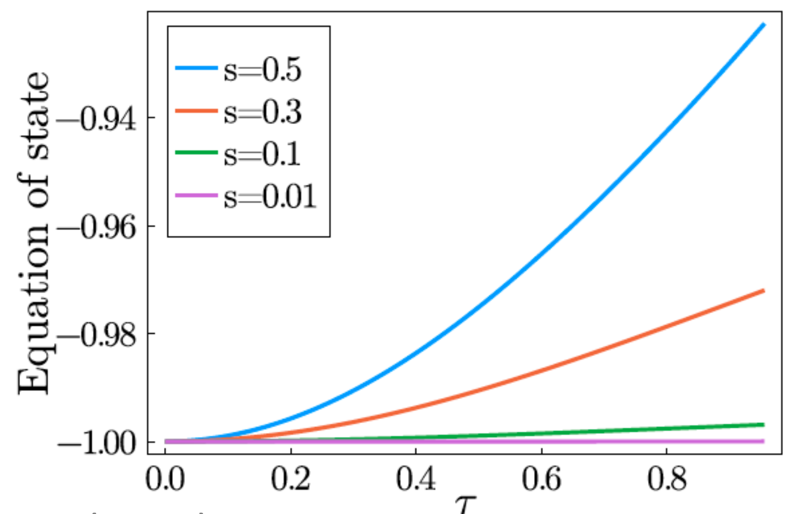
Panda, Sumitomo, Trivedi (2010); Gasparotto, IO (2022);

- Axion shift symmetry is also broken by monodromy mechanism:

Ex) $V = \mu^4 \frac{\phi}{f_a}$ $\qquad s = \frac{1}{3M_{Pl}^2 H_0^2}\frac{\mathrm{d}V}{\mathrm{d}\phi} = \frac{\mu^4/f_a}{3M_{Pl}H_0^2}$

EOM: $\phi_n'' + 3\mathcal{H}\phi_n' + 3s = 0$ $\qquad \mathcal{H} = H/H_0$ $\qquad \phi_n = \phi/M_{Pl}$

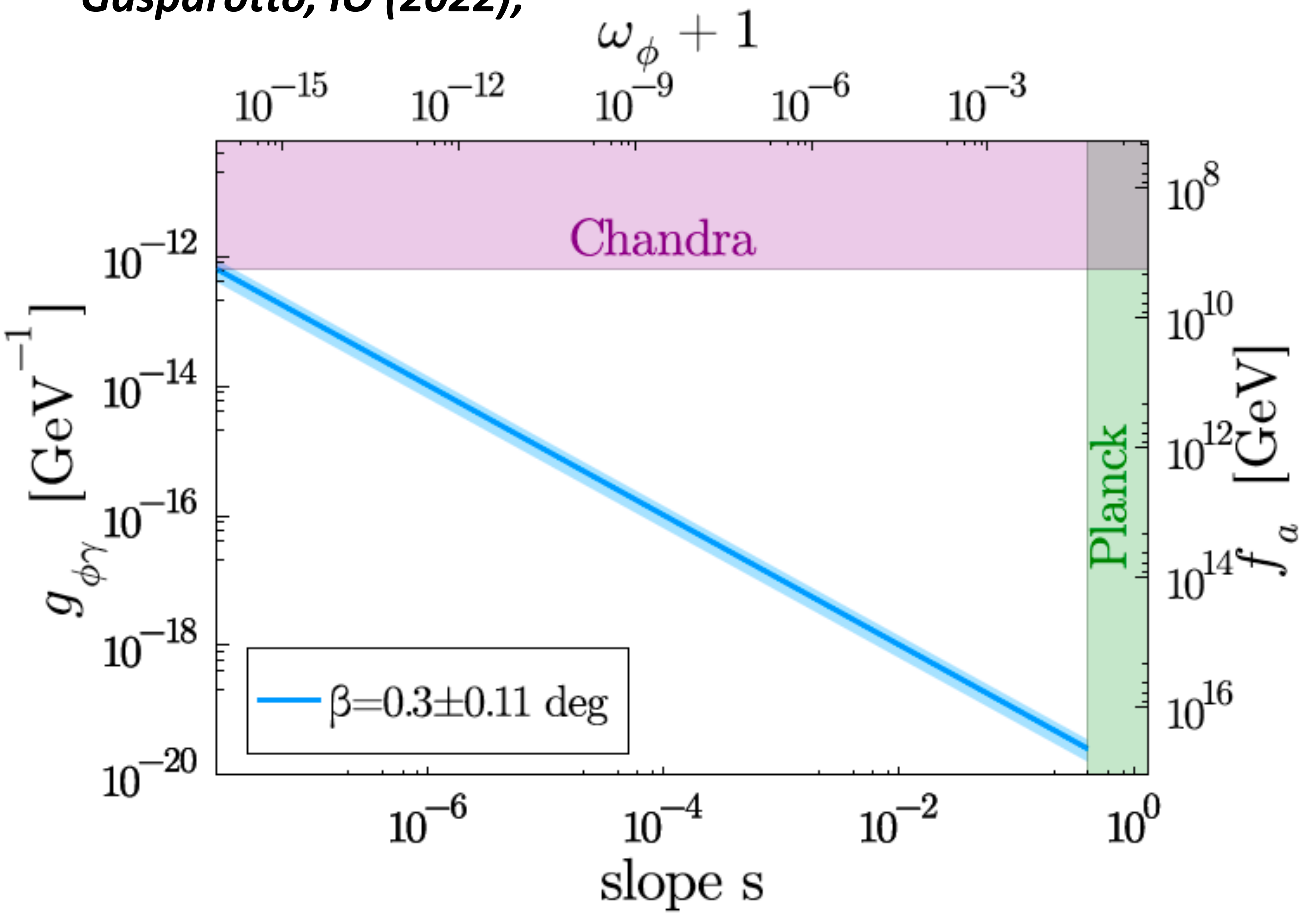




Gasparotto, IO (2022)

Constraint on the parameter space

Gasparotto, IO (2022);



$$g_{\phi\gamma} = \frac{\alpha_{em} c_{\gamma\phi}}{2\pi f_a}$$

$$\frac{f_a}{c_{\gamma\phi}} = 4.52 \times 10^{16}\mathrm{GeV}\left(\frac{0.30\mathrm{deg}}{|\beta|}\right)\left(\frac{s}{0.4}\right)$$

← sub-Planckian (GUT) scale!

Summary & Outlook

- Axions are the promising candidate for the dark sector of our universe. Up to now, a variety of astrophysical/experimental methods has been proposed by using axion-photon conversions.

- Photon's birefringence measurements potentially develop a new frontier of the axion search! A recent measurement of CMB birefringence gives us a tantalizing hint for the axion physics, especially axion as a dark energy.

- Based on a multiple axion scenario, this observable potentially connect the constraints on axion as dark energy and dark matter. Axions in string theory such as the monodromy mechanism would also give some implications on the cosmic birefringence measuement.

- More exciting discovery to come in next decades!?

International workshop on Very Light Dark Matter 2023 (3.28-30)

https://indico.ipmu.jp/event/416/overview

会場：マリオローヤル会館（長野県茅野市）, ハイブリッド形式
お問い合わせ：vldm2023-group_at_g.ecc.u-tokyo.ac.jp (_at_を@に)
講演締め切り：２月２８日

- Axion and axion like particles
- Dark photon and other light dark matter
- Light dark matter search experiments
- Black hole superradiance
- Cosmic birefringence
- Structure formation
- Weak gravity conjecture

ありがとうございました！