Probing axions with the measurements of photon's birefringence

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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

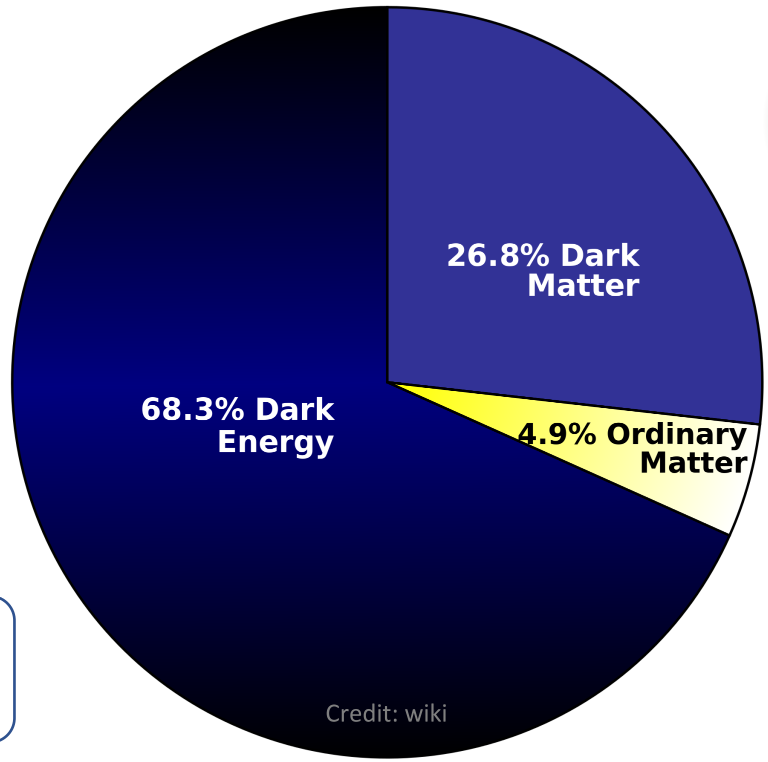
文部科学省
科学研究費助成事業
学術変革領域研究
(2020–2024)

科研費 KAKENHI

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

2022.11.28 The 7th IBS-ICTP-MultiDark Workshop (Daejeon)

Dark sectors in our universe



(standard model)

Credit: higgstan.com

WIMP?
Axion?
MACHO?
PBHs?

Credit: higgstan.com

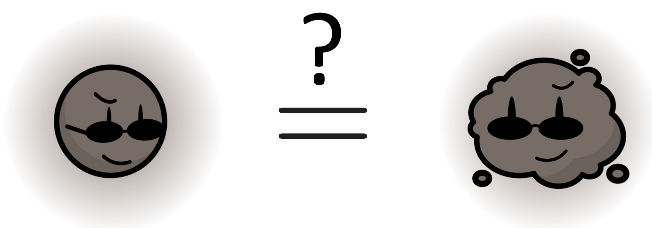
Cosmological Constant?
Quintessence?

We know only 5 % in our universe!

Question

Are these sectors independent components?

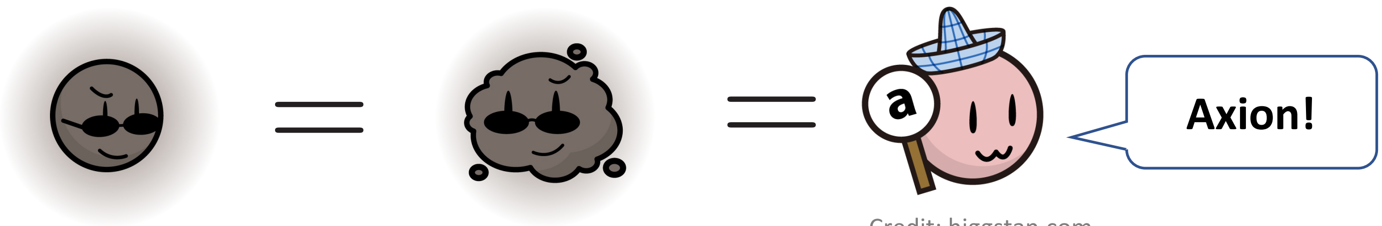
What if they are related by a common origin?



<u>Unified models for dark matter and dark energy have been developed</u>

- **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); …*
- …

Motivation



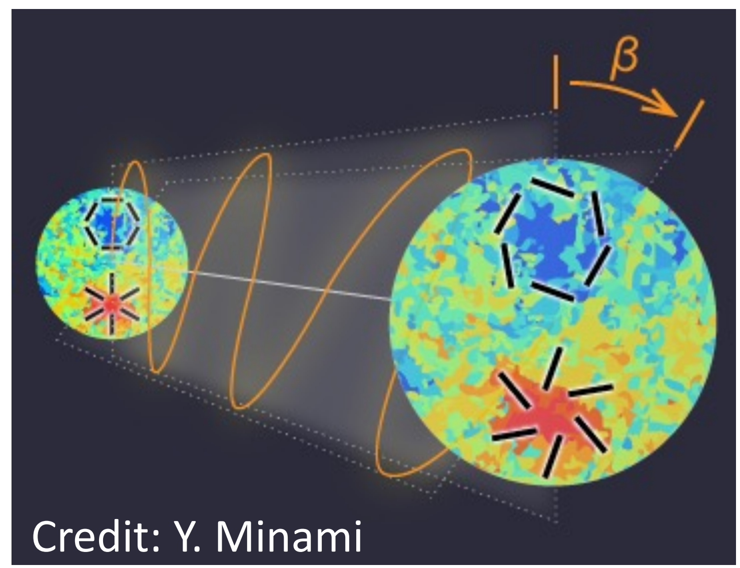
Credit: higgstan.com

Axion could be a candidate for both dark sectors!

Overview of talk

Background
Introduce what is axion? how to search for it?, mainly focusing on the search for **axion-photon conversions**

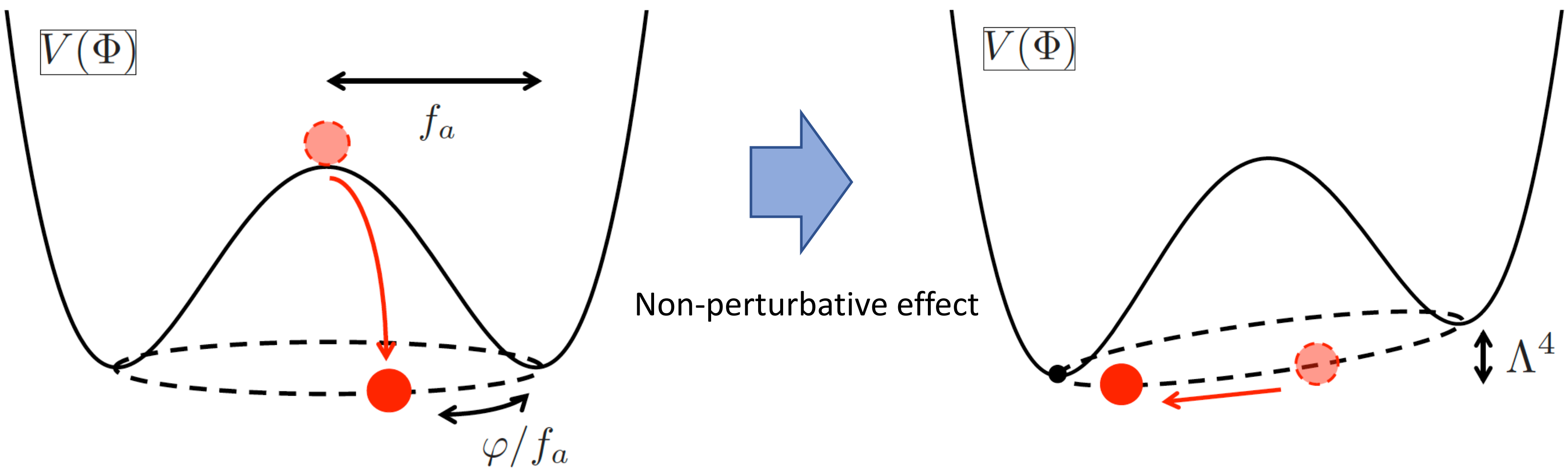
Our study
Introduce a new search method using the **photon's birefringence effect** and corresponding observational progress



Credit: Y. Minami

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:

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

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

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

(typical) QCD axion window

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

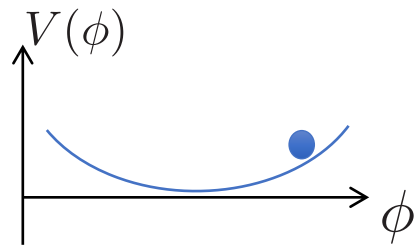
Axion-like particle (ALP) *Svrcek & Witten (2006); Arvanitaki+ (2010); …*

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

↑Main focus of this talk

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

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

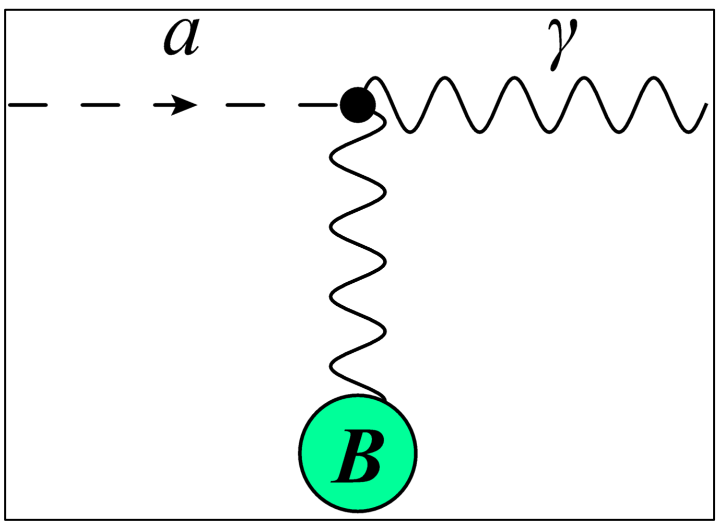
(pressure) < (gravity)
→ could behave as dark matter

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

Conventional Axion Search

- Axion generically couples to photon via the topological term

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



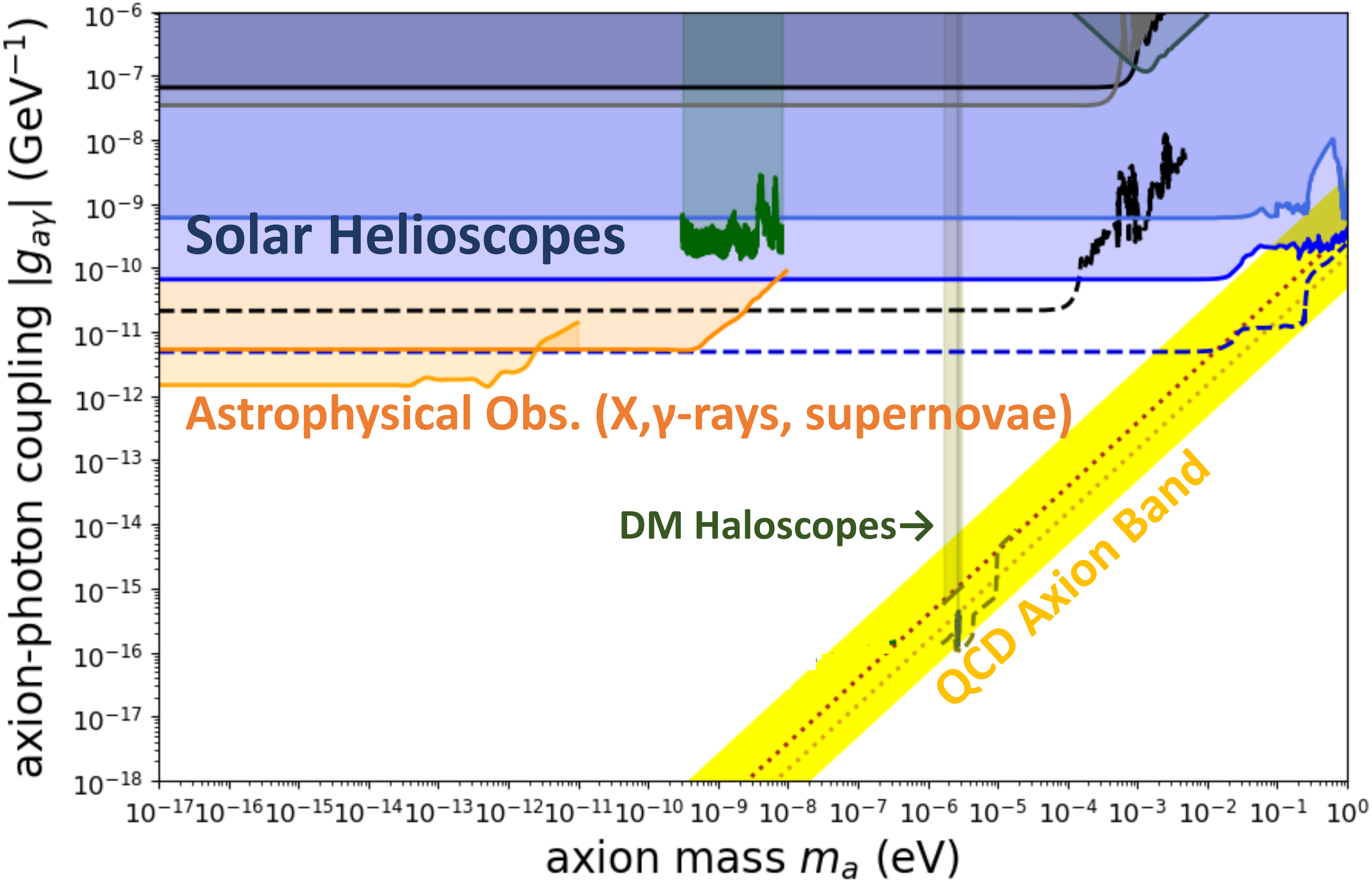
a : axion

γ : photon

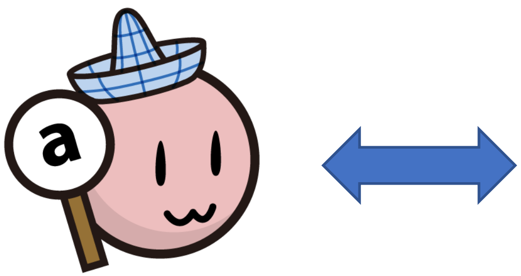
B : magnetic field

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

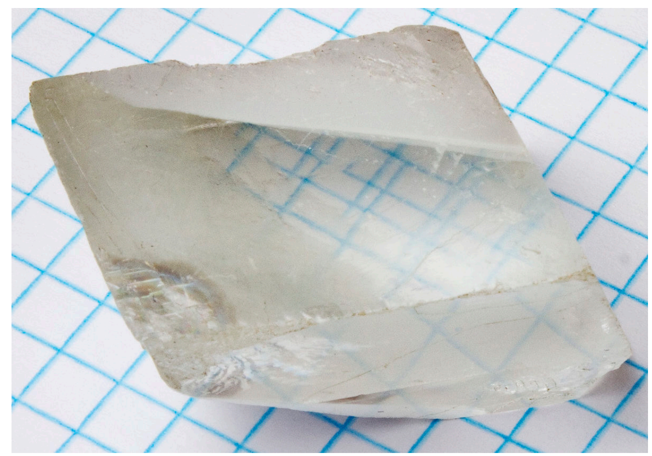
Overview of Target Spaces



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



Axion as a birefringent material



Photon's birefringence by axion

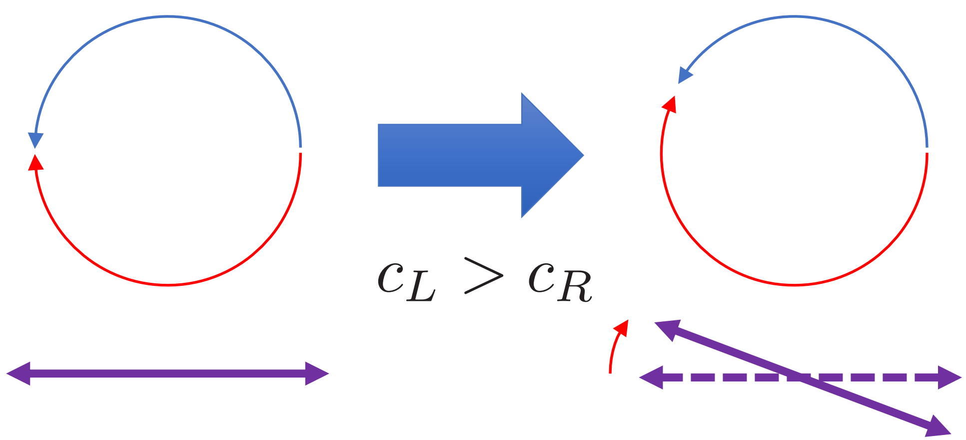
Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); …

Axion behaves as a birefringent material in our universe

- Axion differentiates the phase velocities of circular-polarized photon

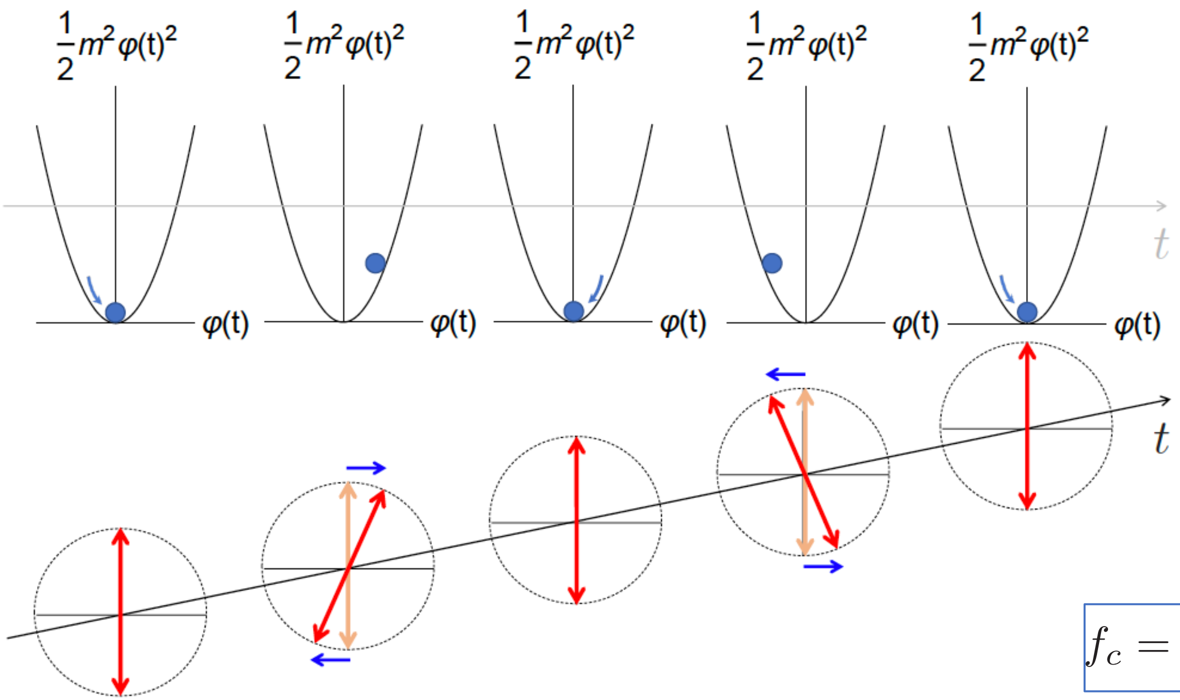
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu} \ , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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



→ leading to the rotation of linear-polarization direction

Birefringence by axion DM

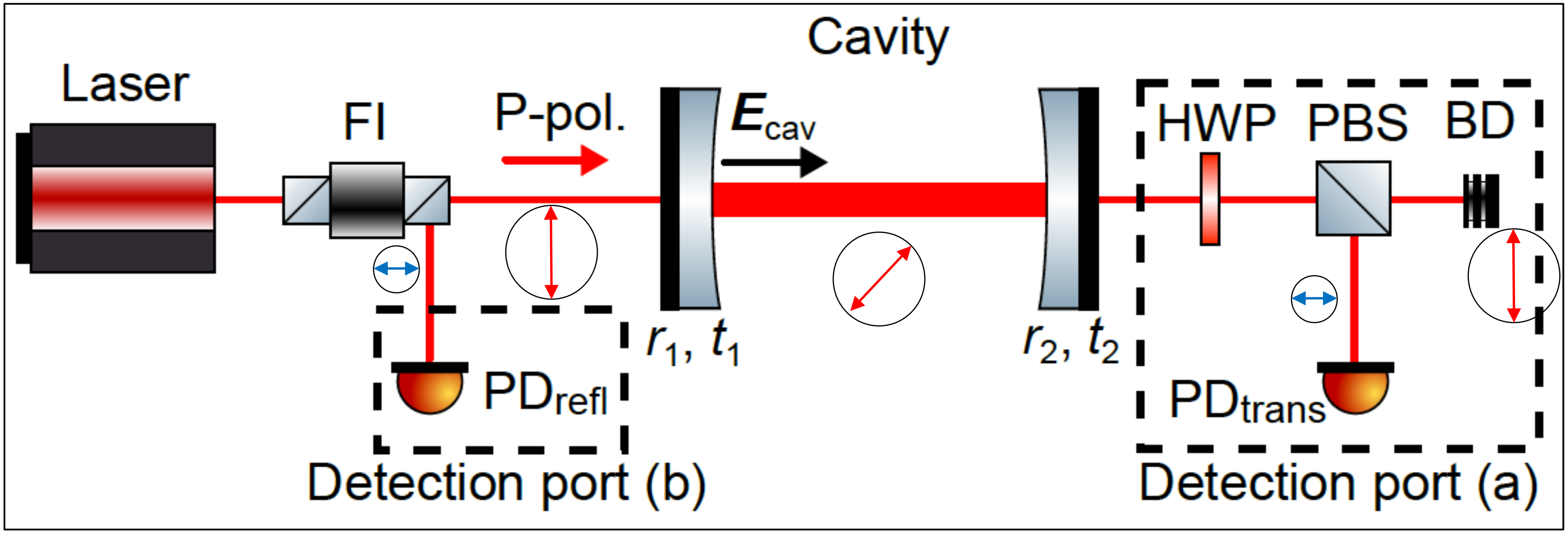


$$f_c = \frac{m_a}{2\pi} \simeq 2.4\mathrm{Hz}\left(\frac{m_a}{10^{-14}\mathrm{eV}}\right)$$

- Axion DM induces the polarization rotation oscillating in time with a frequency of axion mass:
- Possible to observe by several experimental/astrophysical approaches!

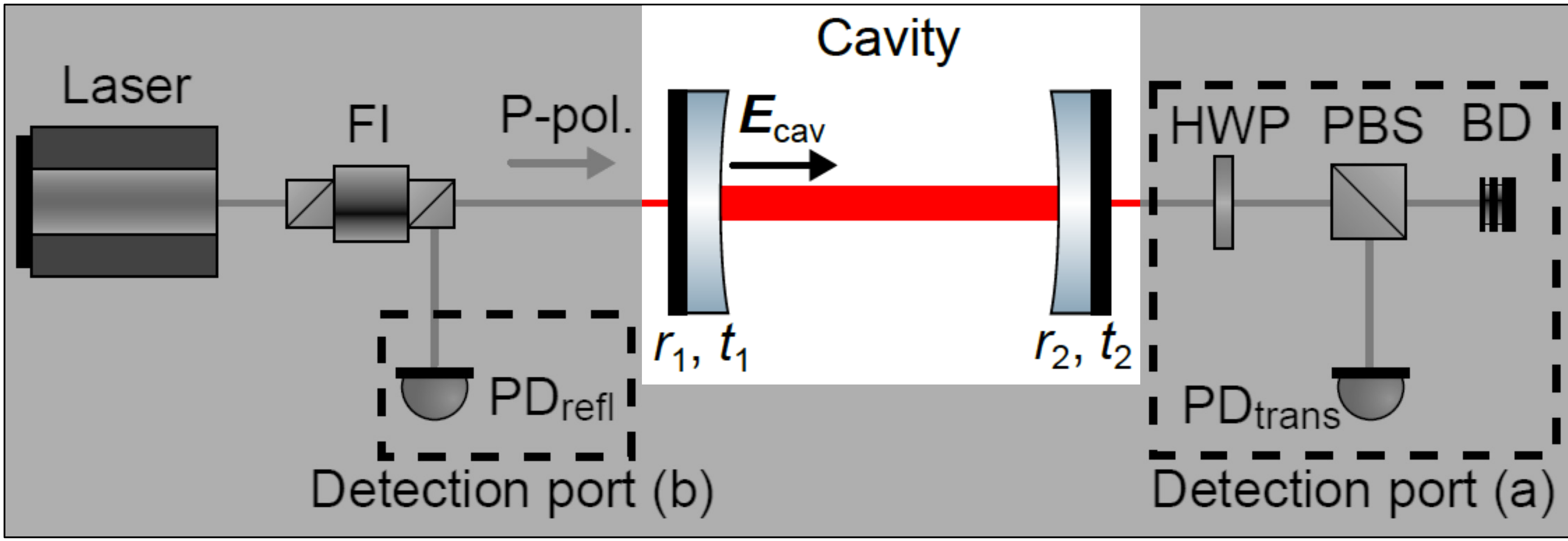
Birefringence in Resonant Cavity

Nagano, Fujita, Michimura, IO (2019);...



- **As a carrier wave, we input the linearly-polarized monochromatic laser light.**
- **The linear cavity consists of front and end mirrors. The cavity is kept to resonate with a phase measurement.**
- **The signal is detected in detection port (a) or (b) as polarization modulation.**

Inside Cavity



- **When the resonant condition is met, the beam is accumulated inside cavity:**

$$\boldsymbol{E}_{\text{cav}}(t) = \frac{t_1 E_0 e^{ikt}}{1 - r_1 r_2} \begin{pmatrix} \boldsymbol{e}^{\text{L}} & \boldsymbol{e}^{\text{R}} \end{pmatrix} \begin{pmatrix} 1 + i\delta\phi(t) & 0 \\ 0 & 1 - i\delta\phi(t) \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

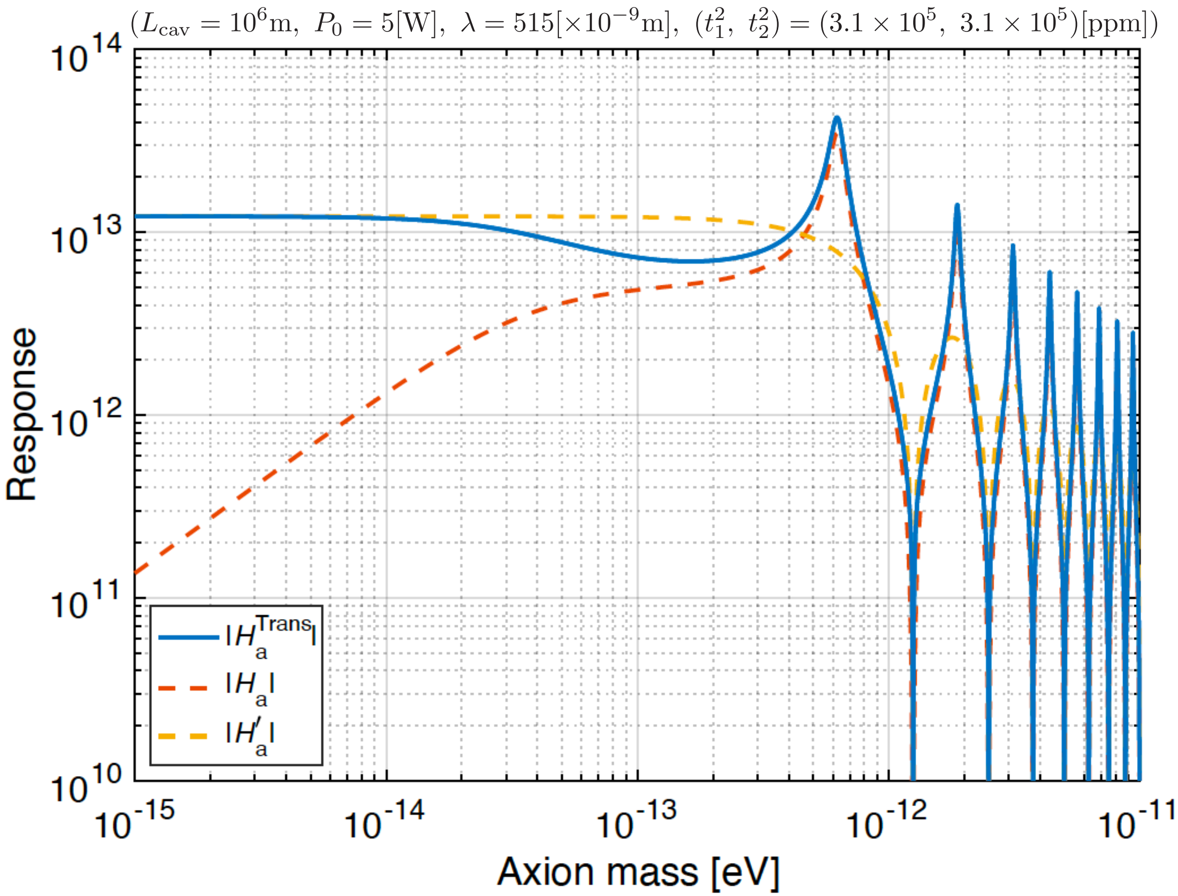
$$= \frac{t_1}{1 - r_1 r_2} [\boldsymbol{E}^{\text{p}}(t) - \delta\phi \boldsymbol{E}^{\text{s}}(t)] \quad (2kL = 2\pi\mathbb{N})$$

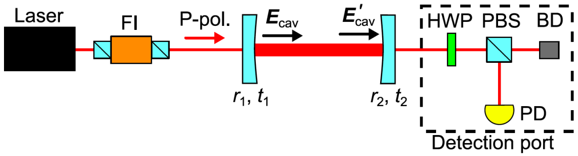
$$\gg 1 \quad (\because r_i \simeq 1)$$

$$r_i^2 + t_i^2 = 1$$

Frequency response in signal

$$\delta\phi(t) = \int_{-\infty}^{\infty} \delta c(m) H_a(m) e^{imt} \frac{dm}{2\pi} \qquad H_a(m): \ \text{response function}$$





Longer cavity length

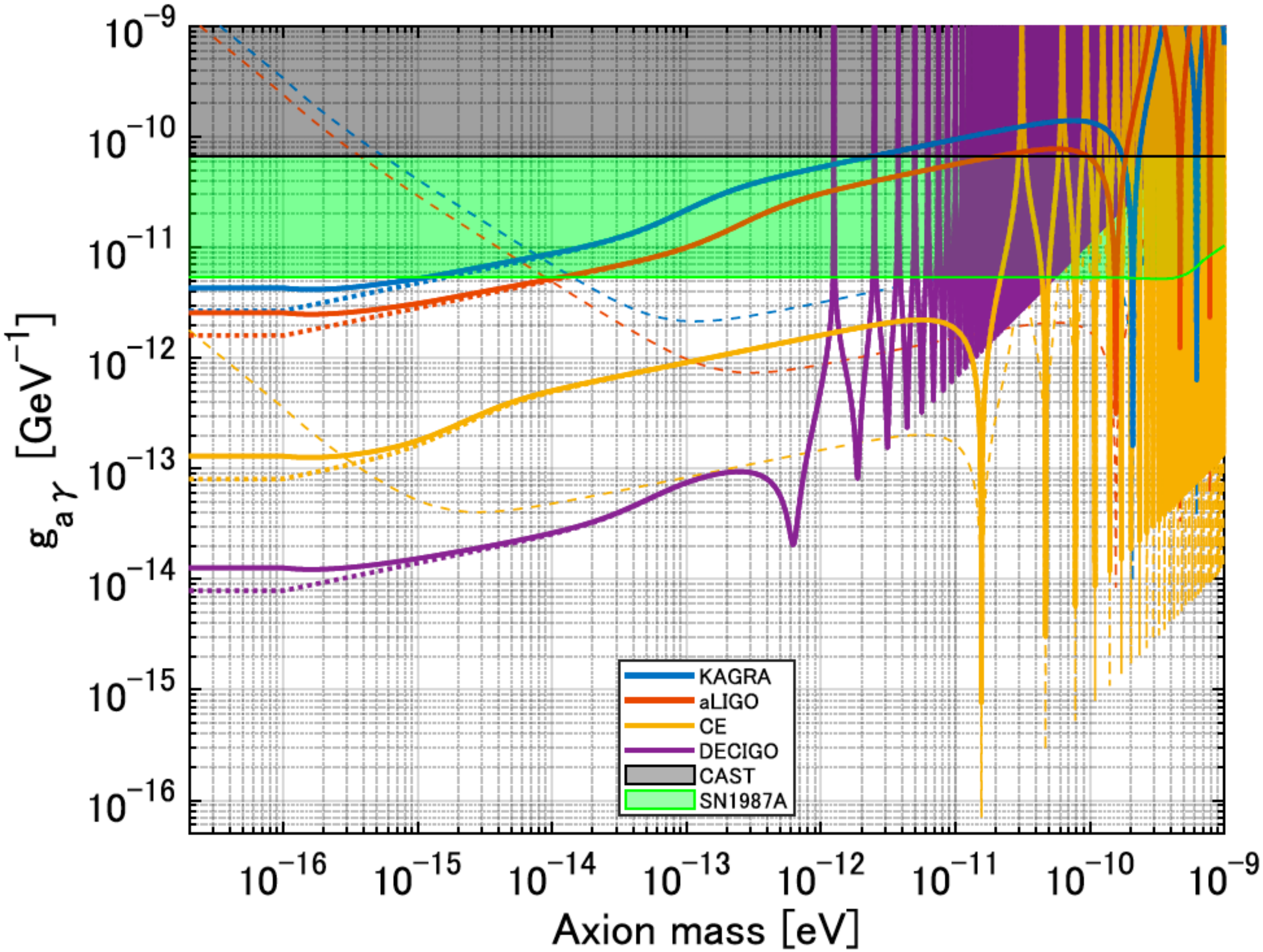
&

Higher mirror quality is better

→ GW detector!

Nagano, Nakatsuka, Morisaki, Fujita, Michimura, IO (2021)

Axion DM search with GW detector



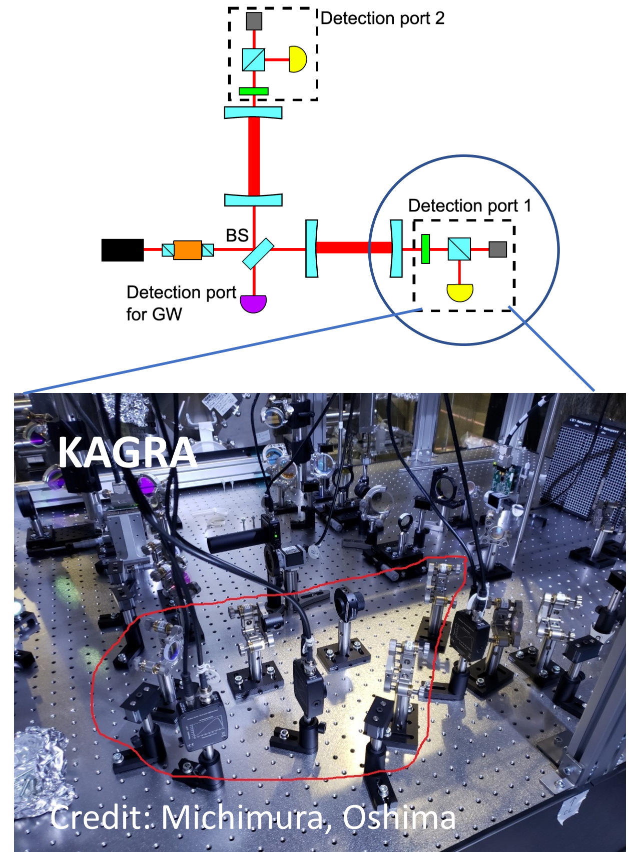
Nagano, Nakatsuka, Morisaki, Fujita, Michimura, IO (2021)

- Assuming
  - Axion is 100% in DM
  - 1-year observation
  - shot noise is primary
- sensitive to

$$10^{-17}\mathrm{eV} \lesssim m_a \lesssim 10^{-11}\mathrm{eV}$$

(~mHz) (~kHz)

Axion DM search with KAGRA



- The polarization optics have been installed at 3-km arm cavity transmission of KAGRA.
- We can search not only for GWs but also for axion DM!

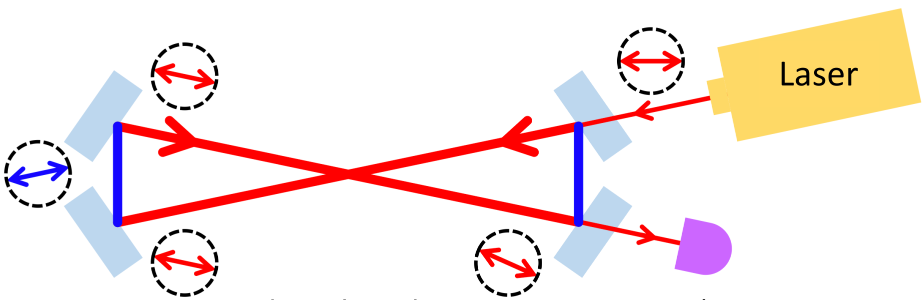
Optical cavity experiment

DANCE: Dark matter Axion search with riNg Cavity Experiment

Ando, Fujimoto, Fujita, Kume, Michimura, Morisaki, Nagano, Nishizawa, IO, Oshima, Wang

@Ando Lab. (Hongo Campus)

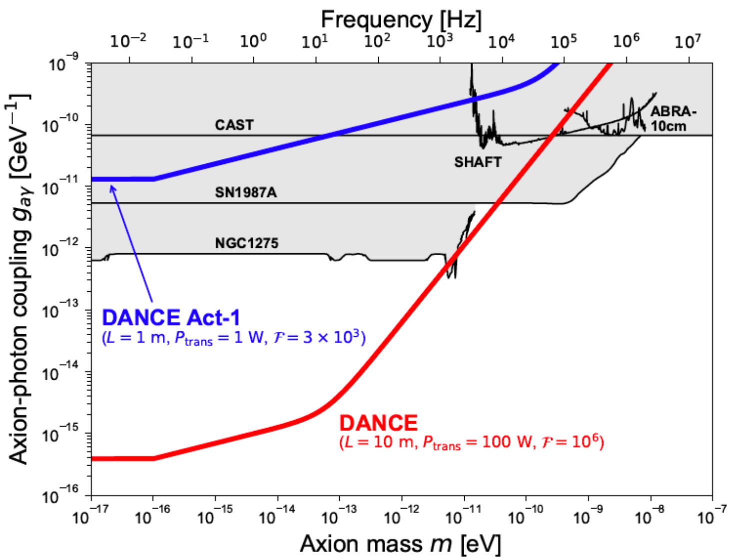
IO, Fujita, Michimura (2018);…



Credit: Yuka Oshima

- A bowtie-like mirror configuration can sustain the rotational orientation of photon polarization

Goal of sensitivity curves



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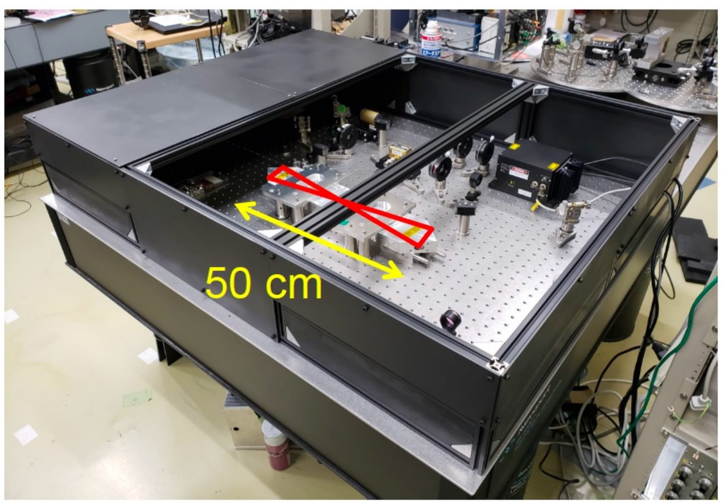
DANCE Act-1 (prototype experiment)

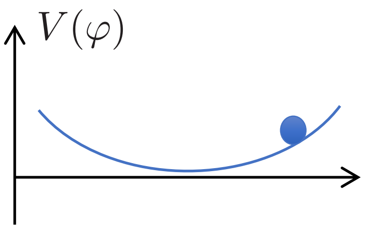


- ✓ First observation in May 2021
- ✓ Constructing further data analysis environment

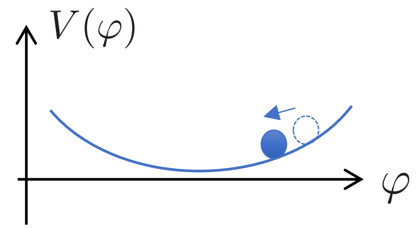
CMB Birefringence by axion DE

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

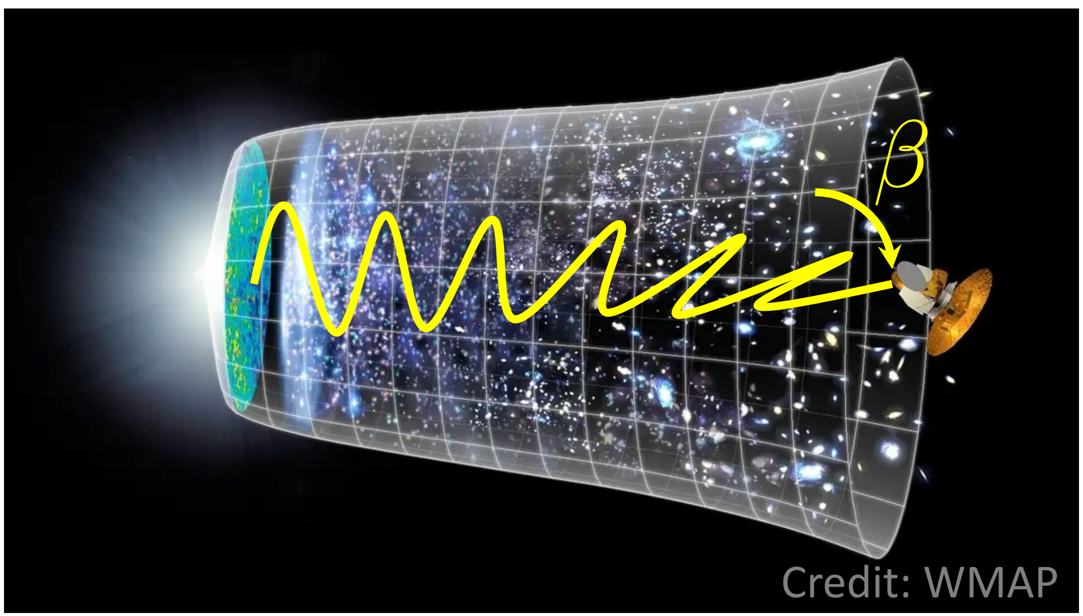
- Axion with mass smaller than current Hubble scale behaves as a dark energy



13.8 billion years



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



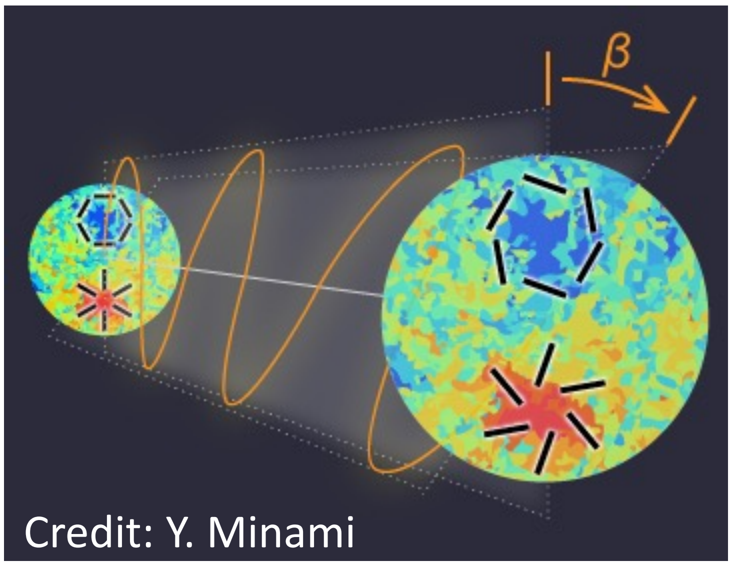
- If axion is responsible for dark energy, it makes the polarization plane of CMB rotate from the last-scattering-surface

Rotation angle:

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

Generation EB correlation function

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



Parity-violating interaction

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

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

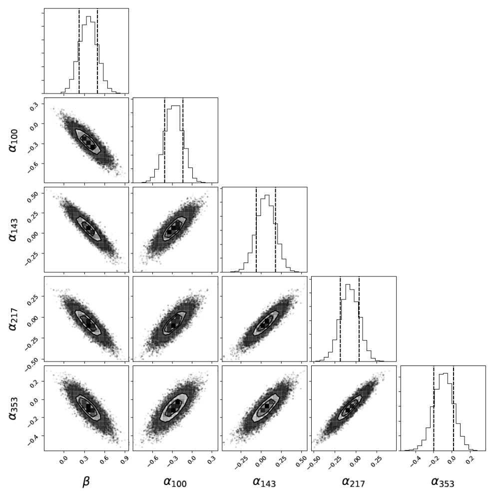
History of measurements (WMAP, Planck, ACT,…)

Non-zero <EB> has been detected.
But, not reliable estimates due to the miscalibration of instrumental angle "α" .

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):

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

CMB Birefringence by axion DE

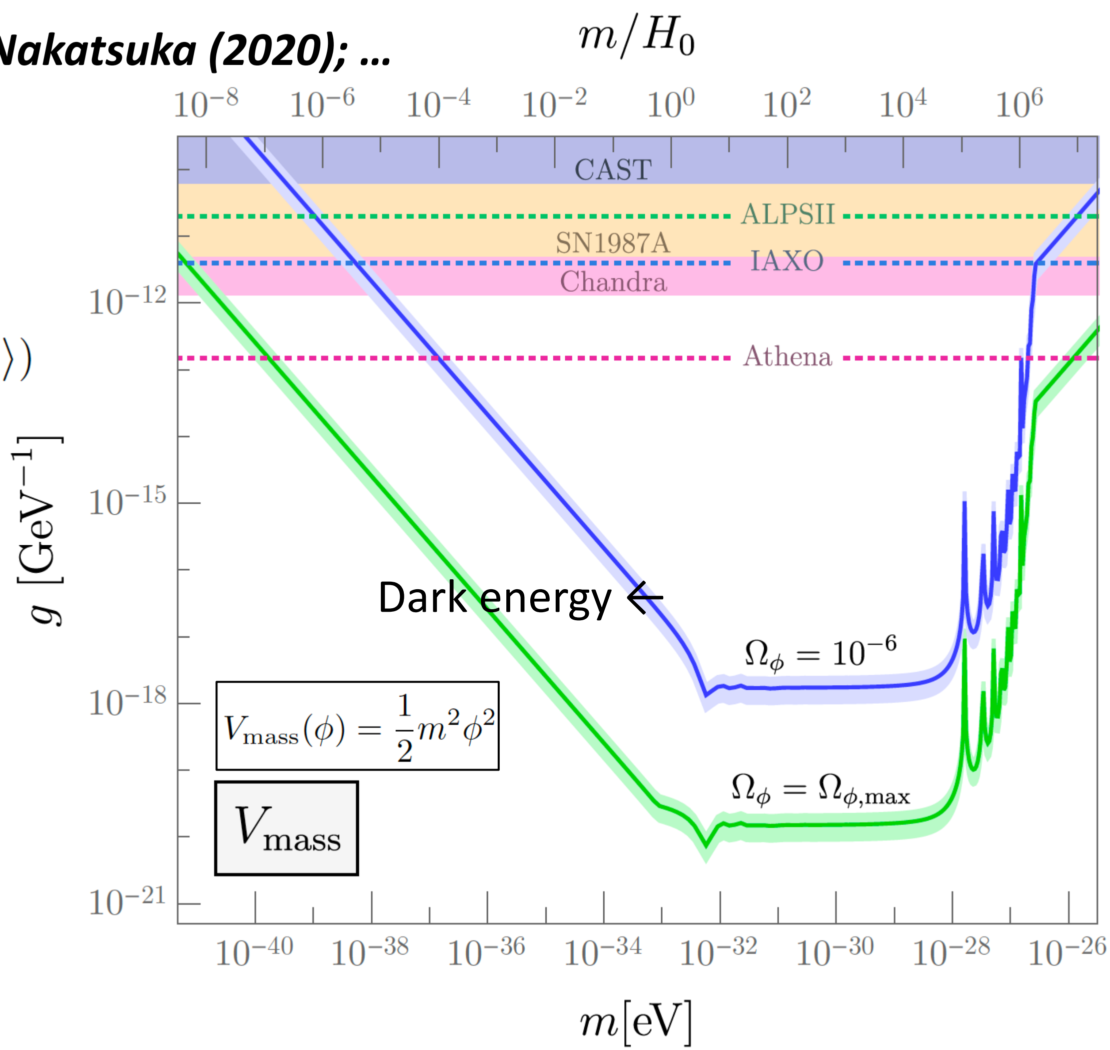
Fujita, Minami, Murai & Nakatsuka (2020); …

- 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

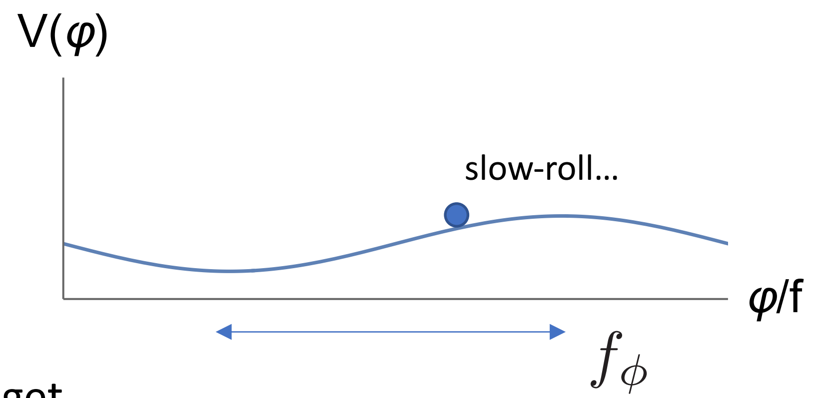
- Support the presence of axion as dark energy



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

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

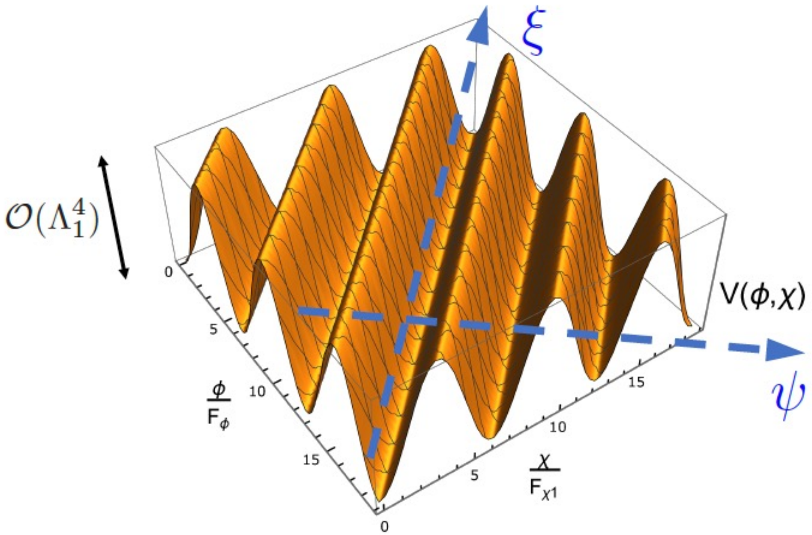
- To get the measured β, a **large anomaly coefficient** is required

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

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

Two-fields axion model

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



Potential

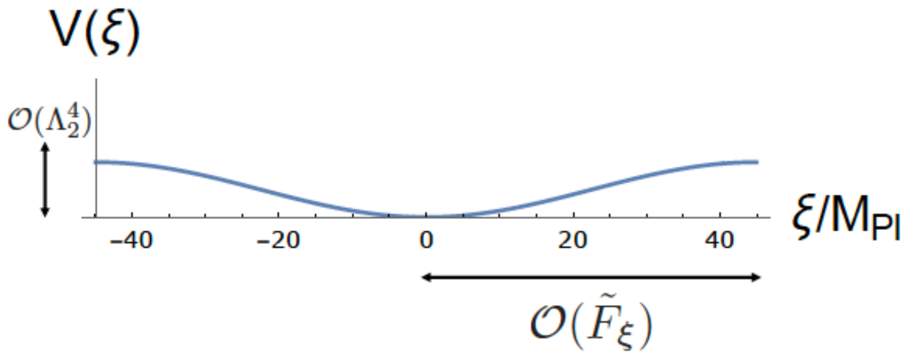
$$V(\phi,\chi) = \Lambda_1^4\left[1-\cos\left(\frac{\phi}{F_{\phi 1}}+\frac{\chi}{F_{\chi 1}}\right)\right] + \Lambda_2^4\left[1-\cos\left(\frac{\phi}{F_{\phi 2}}+\frac{\chi}{F_{\chi 2}}\right)\right]$$

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

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

- 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

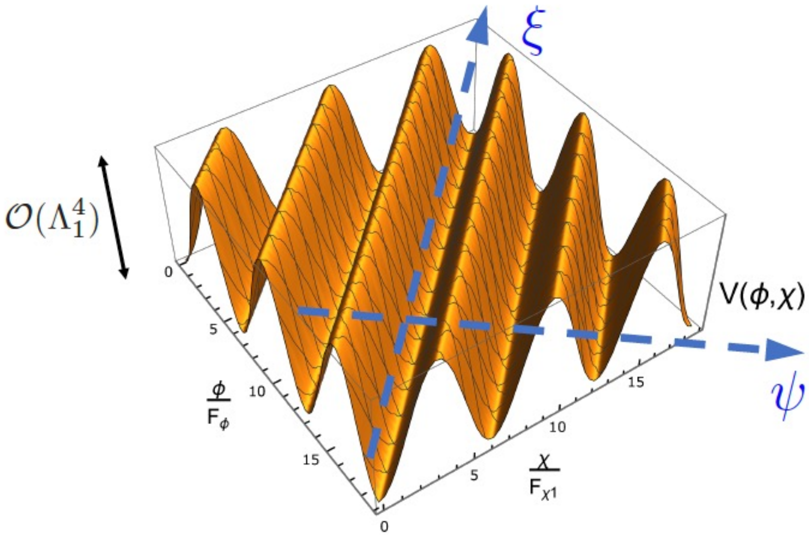


Effective field range of axion

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

Two-fields axion model

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



Potential

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

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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:

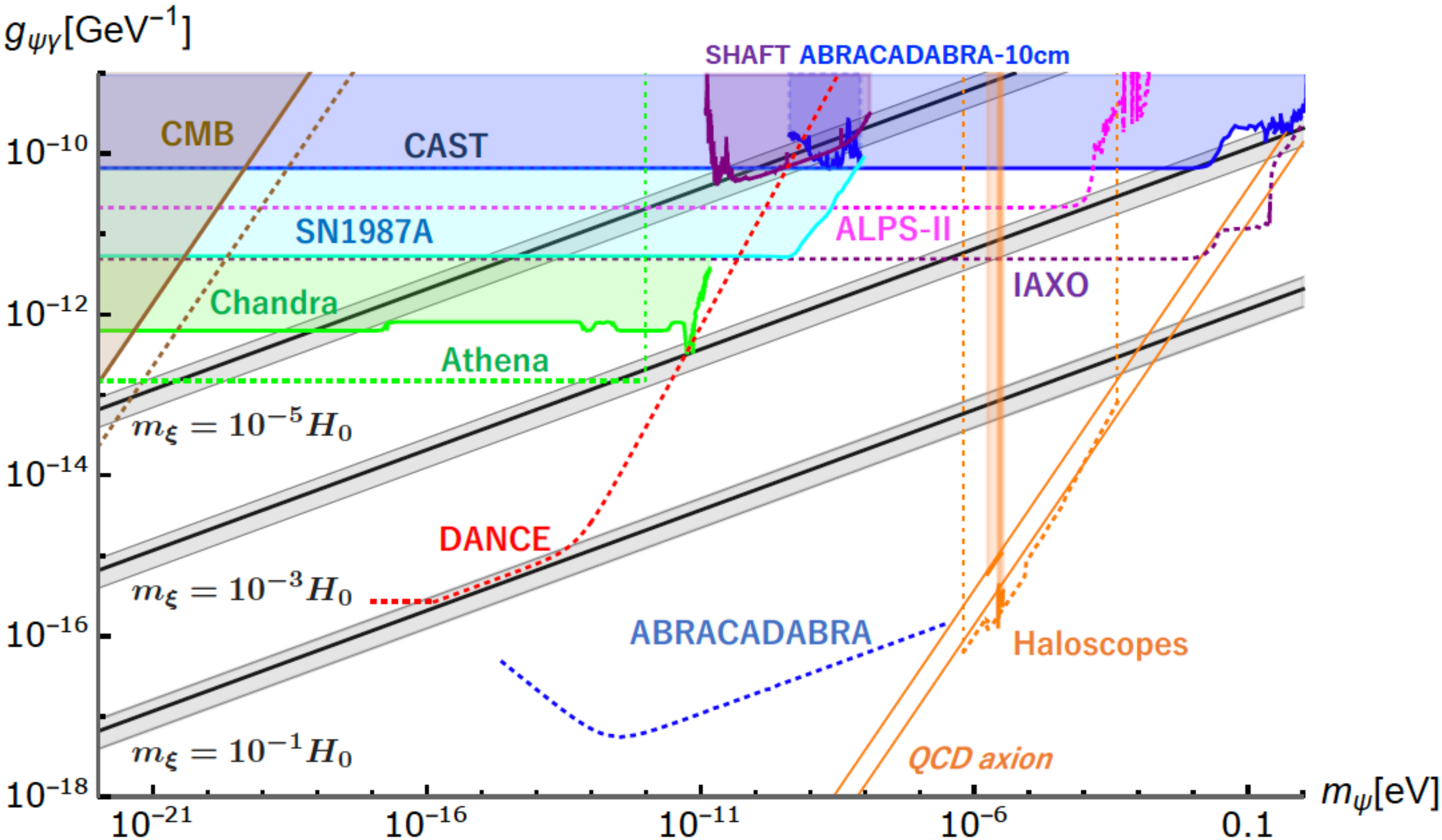
$$g_{\xi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\xi\gamma}}{\tilde{F}_\xi}\,, \quad c_{\xi\gamma} \equiv \frac{1}{\epsilon}\left(\frac{F_\phi}{F_{\phi\gamma}} - \frac{F_{\chi 1}}{F_{\chi\gamma}}\right)\,,$$
$$g_{\psi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\psi\gamma}}{\tilde{F}_\psi}\,, \quad c_{\psi\gamma}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

(release 3)

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

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

Parameter space of axion DM



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! We have suggested an experimental scheme to search for axion dark matter with optical cavities used in such as gravitational wave detectors.
- 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 can connect the constraints on axion as dark energy and dark matter.
- More exciting discovery to come in next decades!?

감사드립니다