Implications of the cosmic birefringence measurement for the axion dark matter search

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

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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
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MAX-PLANCK-INSTITUT
FÜR ASTROPHYSIK

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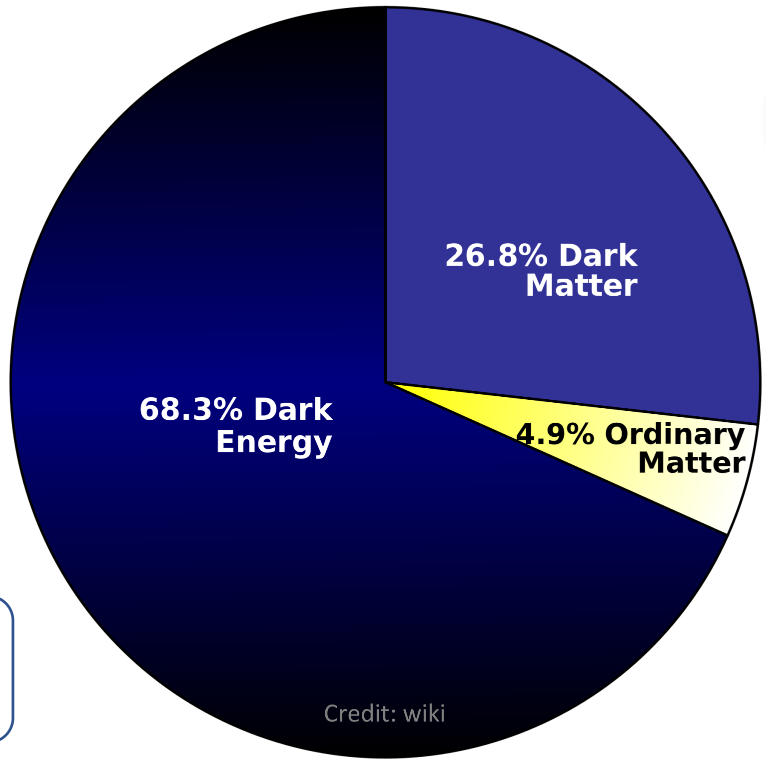
Dark sectors in our universe



(standard model)

Credit: higgstan.com

WIMP?
Axion?
MACHO?
PBHs?

Credit: higgstan.com

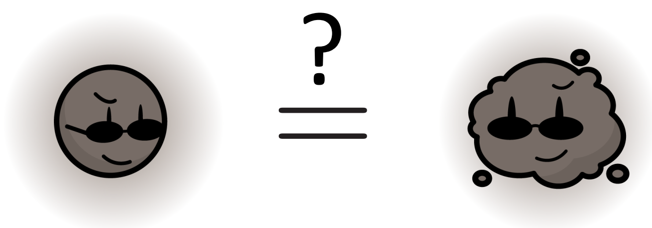
Cosmological Constant?
Quintessence?

We know only 5 % in our universe!

Question

Are these sectors independent components?

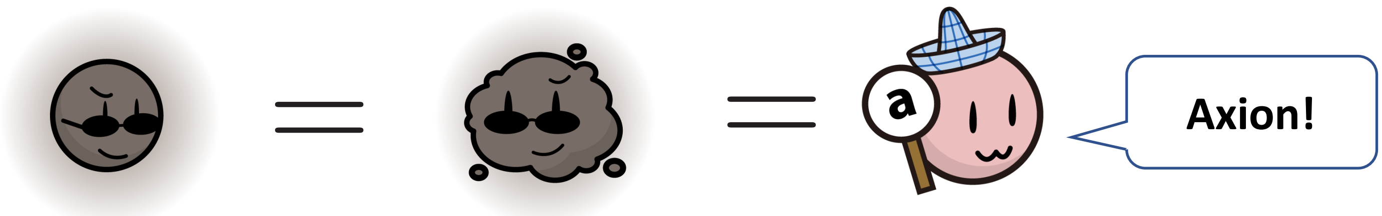
What if they are related by a common origin?



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

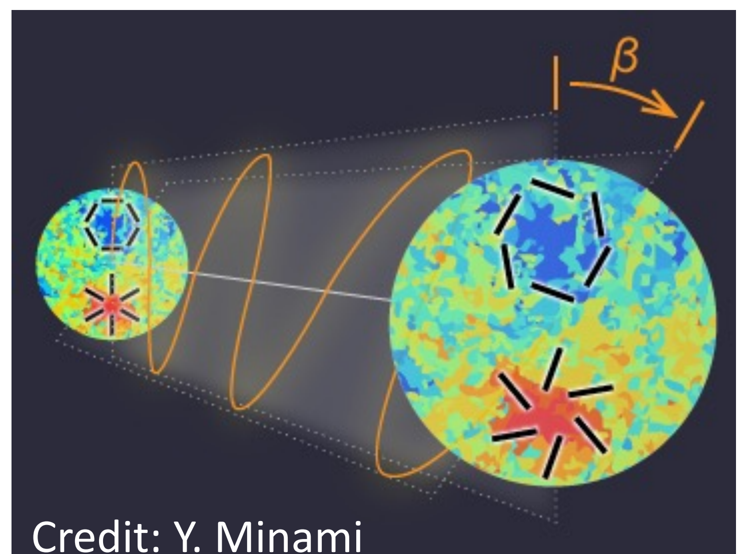


Credit: higgstan.com

- 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 complementary search between CMB observations (axion dark energy) and resonant cavity experiments (axion dark matter)



Credit: Y. Minami

Photon’s birefringence by axion

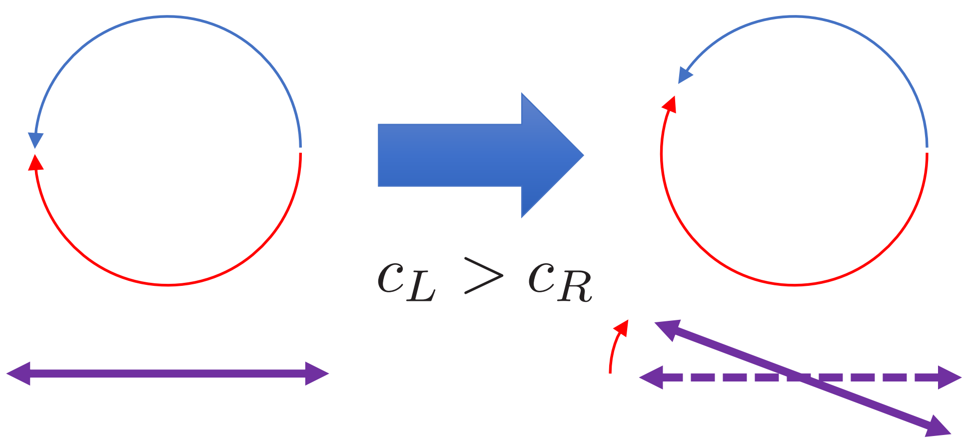
Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); …

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

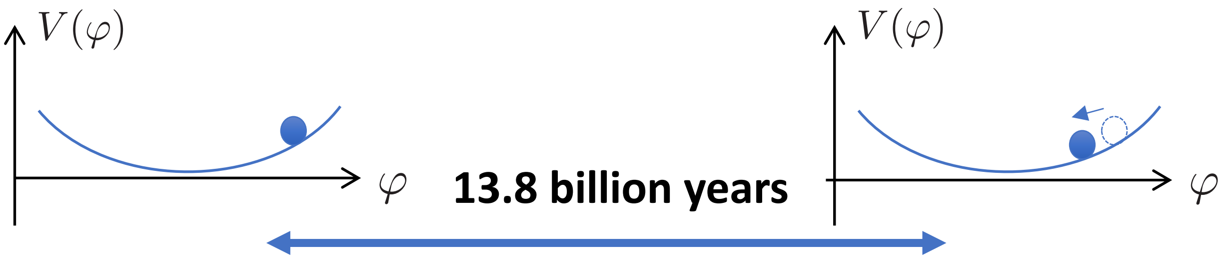


→ leading to the rotation of linear-polarization direction

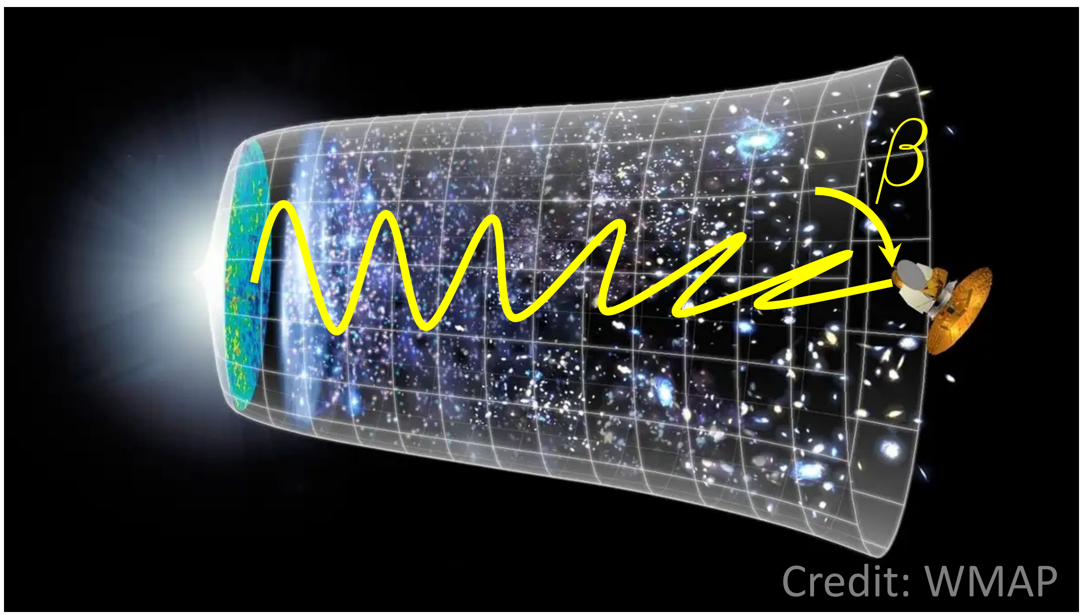
CMB Birefringence by axion DE

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

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



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



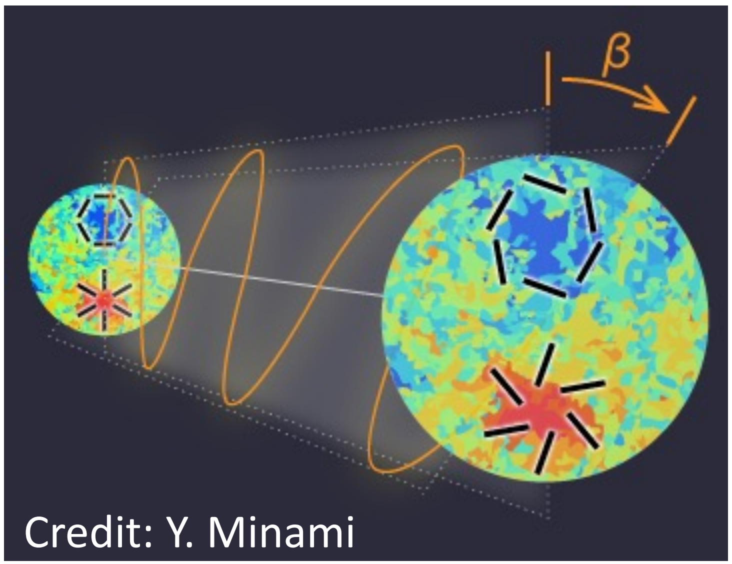
- If axion is responsible for dark energy, it makes the polarization plane of CMB rotate from the last-scattering-surface

Rotation angle:

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

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

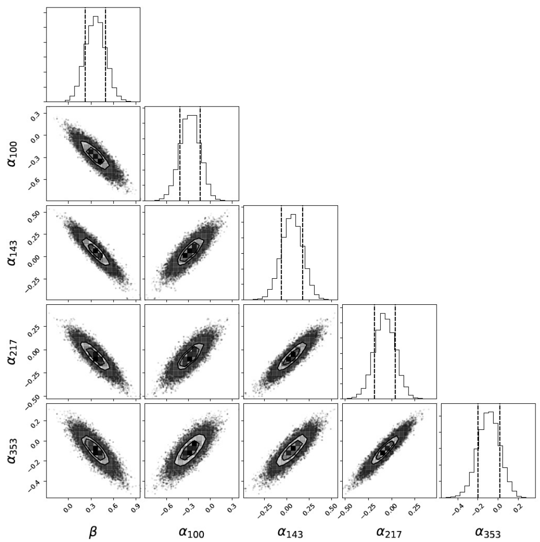
History of measurements (WMAP, Planck, ACT,…)

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)

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

Update! (PR4 data):

Implication for the axion search

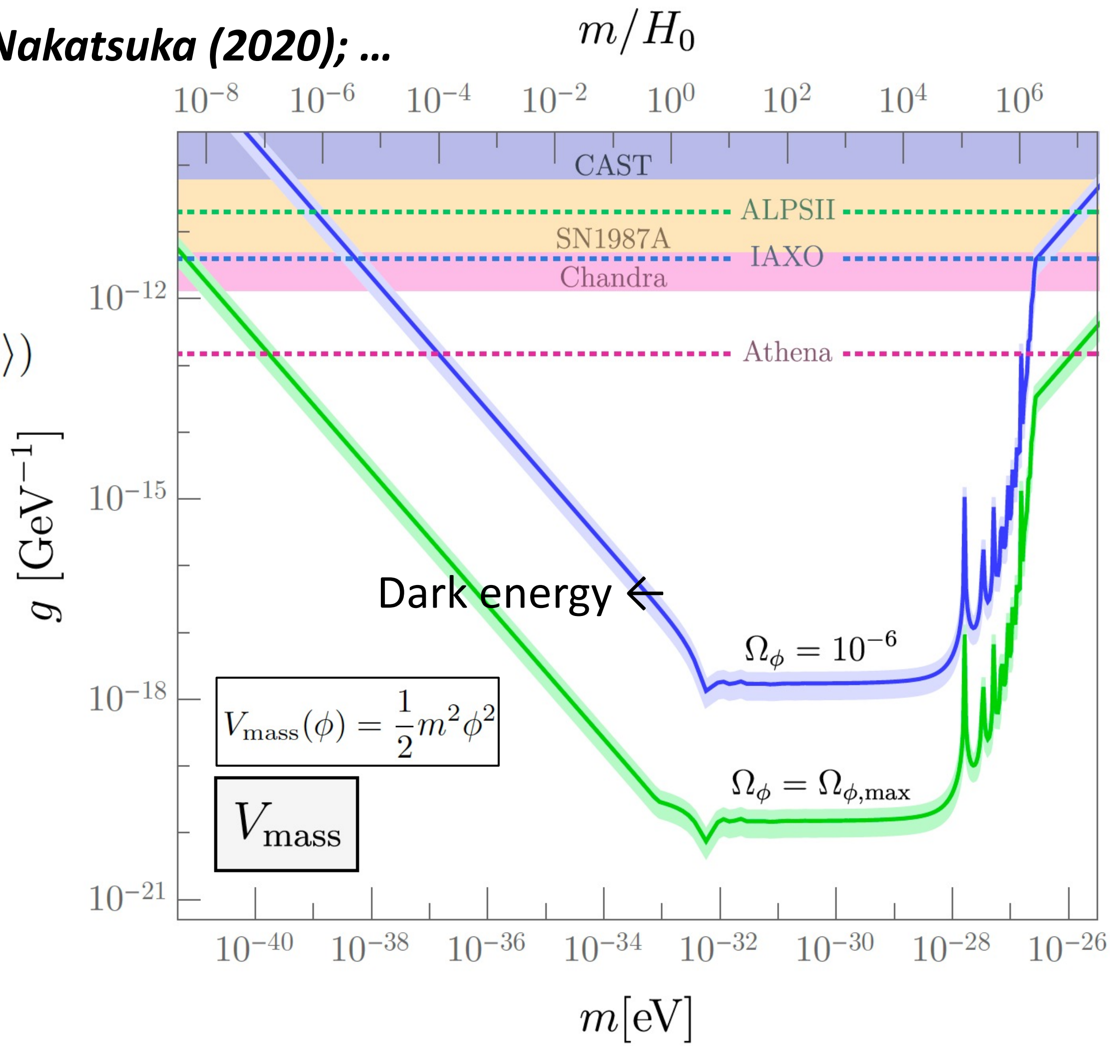
Fujita, Minami, Murai & Nakatsuka (2020); …

- 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

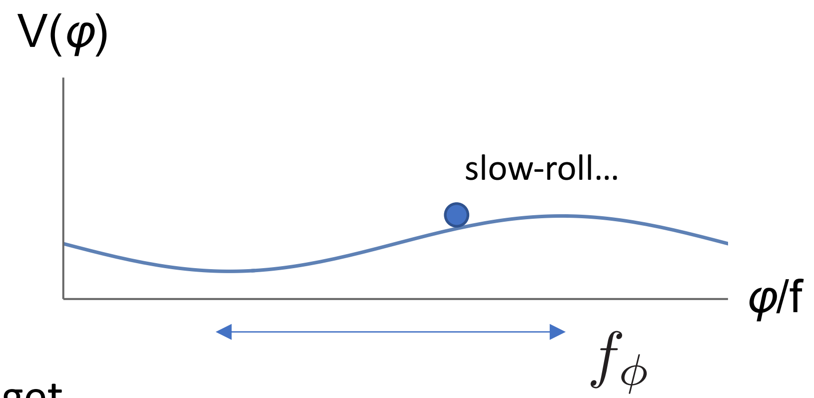
- Support the presence of axion as dark energy



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

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

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

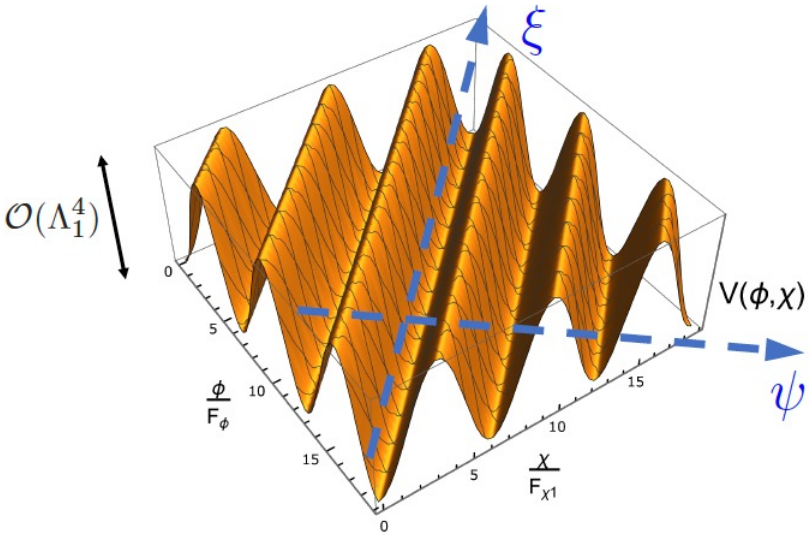
requires a **super-Planckian** decay constant or a fine-tuning of initial axion displacement

- 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

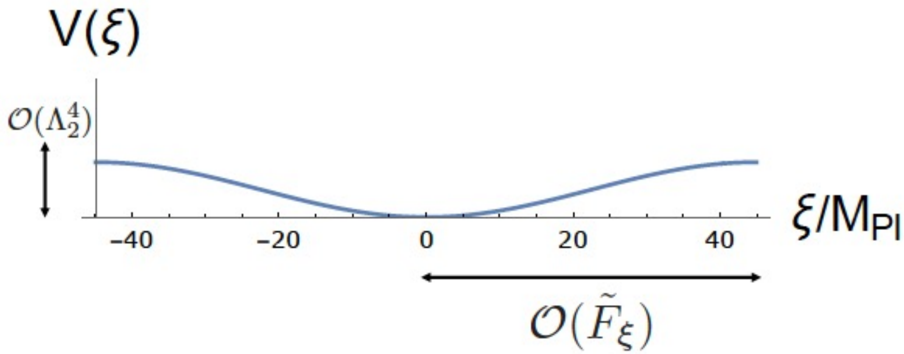
$$V(\phi,\chi) = \Lambda_1^4\left[1-\cos\left(\frac{\phi}{F_{\phi 1}}+\frac{\chi}{F_{\chi 1}}\right)\right] + \Lambda_2^4\left[1-\cos\left(\frac{\phi}{F_{\phi 2}}+\frac{\chi}{F_{\chi 2}}\right)\right]$$

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

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

- 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

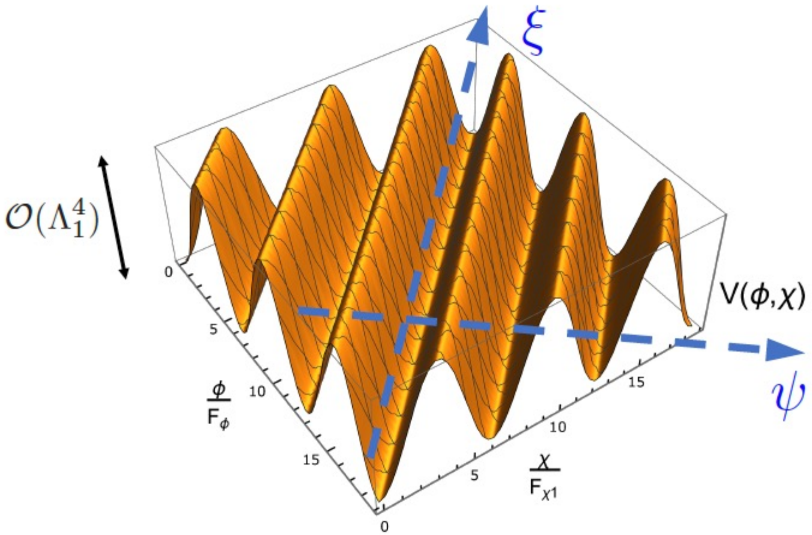


Effective field range of axion

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

Two-fields axion model

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



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: misalignment parameter

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

Dark energy ξ **Dark matter** ψ

Introduce axion-photon couplings

Obata (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 Search (1)

- (Effective) axion DE 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: $|c_{\xi\gamma}| \simeq 7.5 \times 10^3 \left(\frac{\beta}{0.35 \rm deg}\right) \left(\frac{m_\xi/H_0}{0.1}\right)^{-2}$

  leads to the condition of the ratio of decay constants:

$$\left|\frac{F_\phi}{F_{\phi\gamma}} - \frac{F_{\chi 1}}{F_{\chi\gamma}}\right| \simeq 5.2 \times 10^2 \frac{\sqrt{F_\phi^2 + F_{\chi 1}^2}}{M_{\rm Pl}} \left(\frac{\beta}{0.35 \rm deg}\right) \left(\frac{\Omega_\xi}{0.69}\right)^{-1/2} \left(\frac{m_\xi/H_0}{0.1}\right)^{-1}$$

Parameter Search (2)

- 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);

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

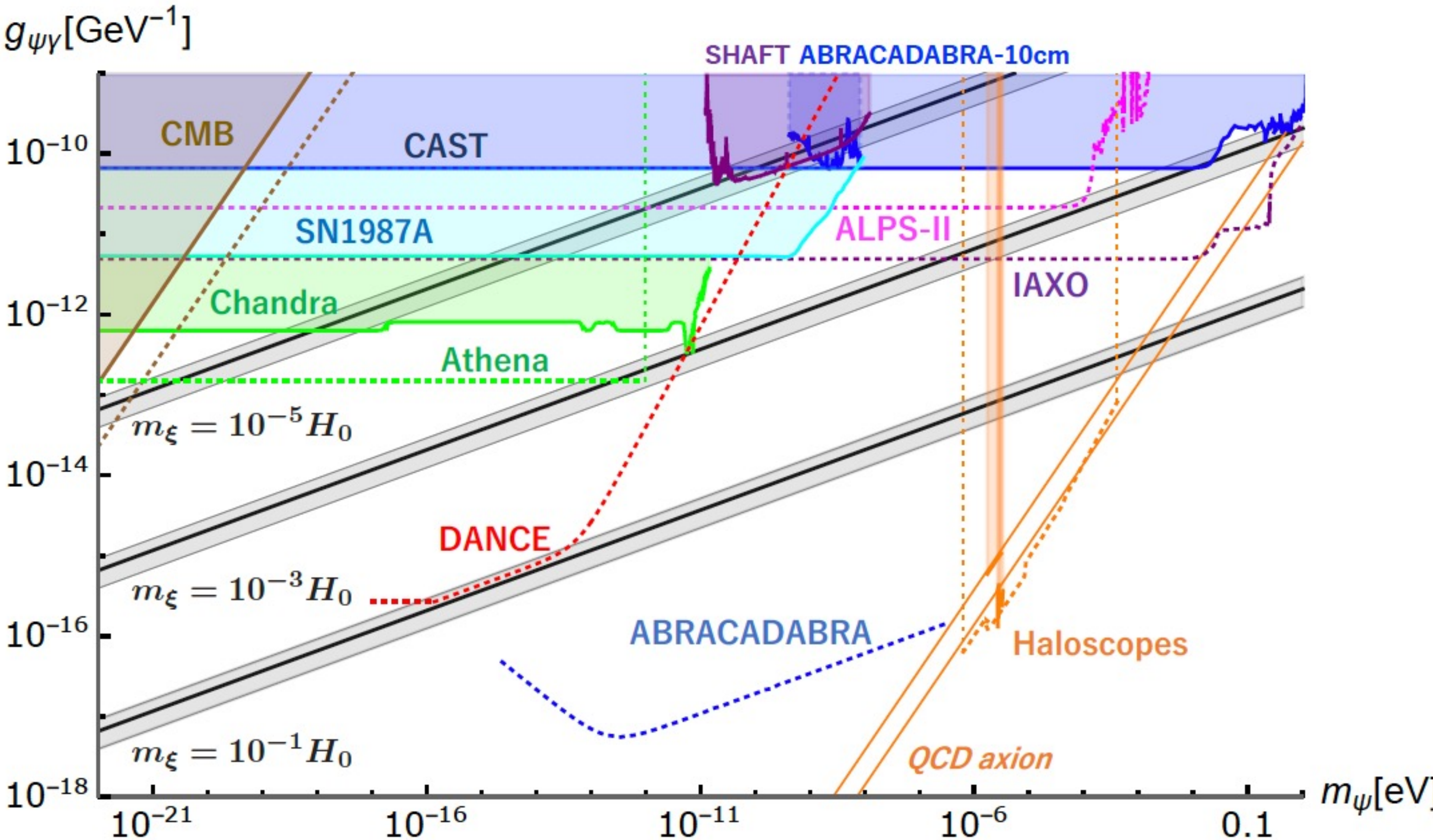
- The axion DM-photon coupling constant is obtained by:

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

$$|g_{\psi\gamma}| \simeq 6.6\times 10^{-18}\ {\rm GeV}^{-1}\frac{F_{\chi 1}}{M_{\rm Pl}}\left(\frac{\Omega_\xi}{0.69}\right)^{-1/2}\left(\frac{\Omega_\psi}{0.31}\right)^{-1/2} \times\left(\frac{\beta}{0.35{\rm deg}}\right)\left(\frac{m_\xi/H_0}{0.1}\right)^{-1}\left(\frac{m_\psi}{10^{-22}{\rm eV}}\right)^{1/4} .$$

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

Parameter space of axion DM



Summary & Outlook

- Axion is one of the promising candidates for the dark sector of our universe.

- Photon's birefringence measurements potentially develop a new frontier of the axion search! (b01, b06)

- A recent measurement of CMB birefringence gives us a tantalizing hint for the axion physics, especially for the axion as dark energy.

- Based on a multiple axion scenario, this observable can connect the constraints on axion as dark energy and dark matter.

- Extensions of this scenario to more generic ones? (e.g. N-field, kinetic mixings, …)