On the recent progress of axion cosmology

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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

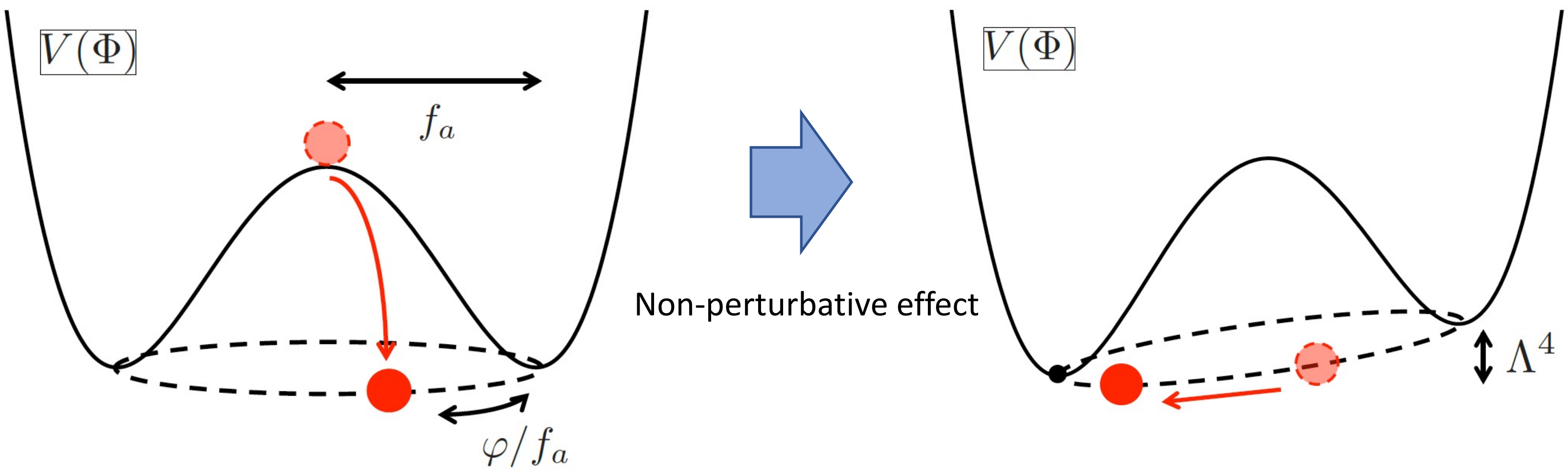
文部科学省
科学研究費助成事業
学術変革領域研究
（2020–2024）

Max-Planck-Institut
für Astrophysik

２０２１年１１月１７日　第１０回観測的宇宙論ワークショップ

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 QCD energy scale

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

QCD axion window (ざっくり)

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

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

↑本発表ではこちらに注目

Features of axion

1. Small mass (compared with WIMP)

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

2. Weakly coupled to the standard model (respecting shift-sym.)

$$\mathcal{L}_{\rm int} = \frac{g_{a\gamma}}{4}\varphi F_{\mu\nu}\tilde{F}^{\mu\nu}$$ Axion-photon (most popular)

$$+ i g_{aN}\partial_\mu\varphi(\bar{N}\gamma^\mu\gamma_5 N)$$ Axion-nucleon

$$+ i g_{ae}\partial_\mu\varphi(\bar{e}\gamma^\mu\gamma_5 e)$$ Axion-electron

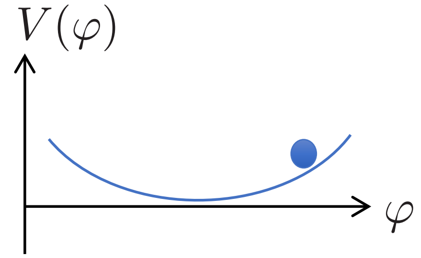
$$+ \frac{i}{2} g_d\varphi\bar{N}\sigma_{\mu\nu}\gamma_5 N F^{\mu\nu}$$ Axion-nucleon EDM

$$\text{coupling strength} : g \propto 1/f_a \ll (\sqrt{2}G_F)^{1/2} \sim 10^{-3}{\rm GeV}^{-1}$$

Fermi coupling constant

Features of axion

3. Scalar dark matter, quintessence



Evolution: $\ddot{\varphi} + 3H\dot{\varphi} + m_a^2\varphi = 0$

$m_a \gg H$

$$\varphi \simeq a^{-3/2}\varphi_i \cos(m_a t) \;\rightarrow\; \rho_a \propto a^{-3},\; P_a \propto \sin(2m_a t) \sim 0$$

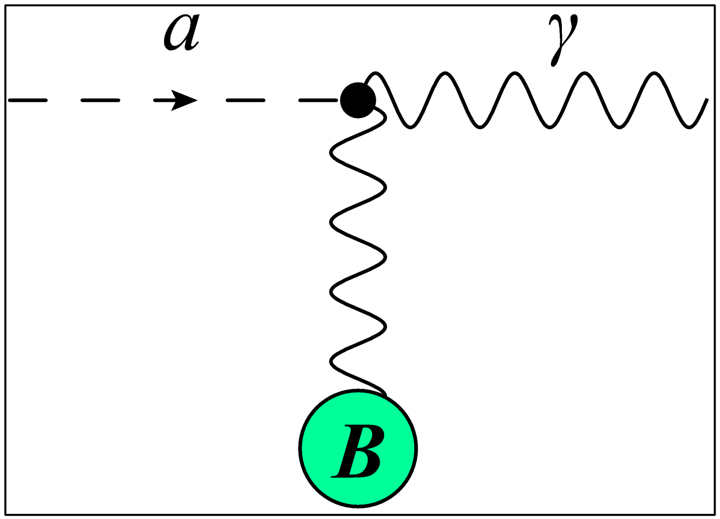
Axion DM mass window (ざっくり): $10^{-22}\mathrm{eV} \lesssim m_a \lesssim \mathrm{eV}$

Note: behaves as a classical field (different from the particle DM such as WIMP)

$m_a \ll H$

$\varphi \simeq \mathrm{const.}$ **Axion quintessence:** $m_a \lesssim H_0 \sim 10^{-33}\mathrm{eV}$

Conventional Axion Search



Axion-photon conversion (Primakoff effect)

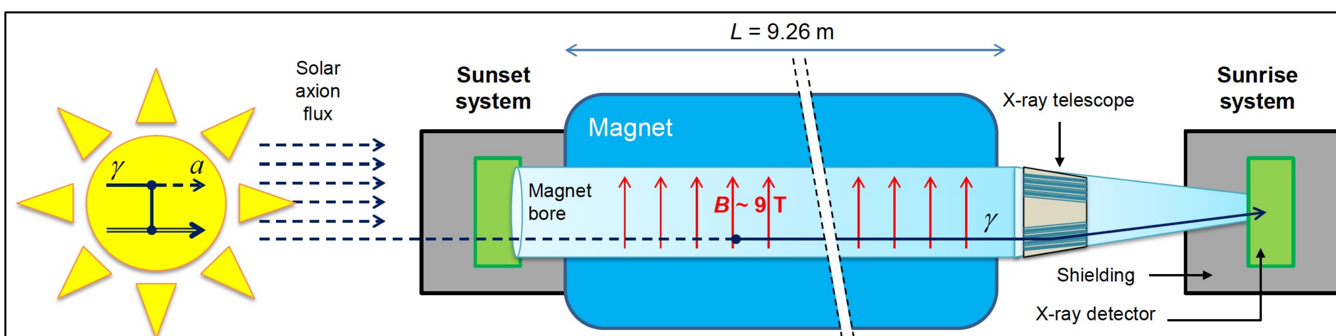
a : axion

γ : photon

B : magnetic field

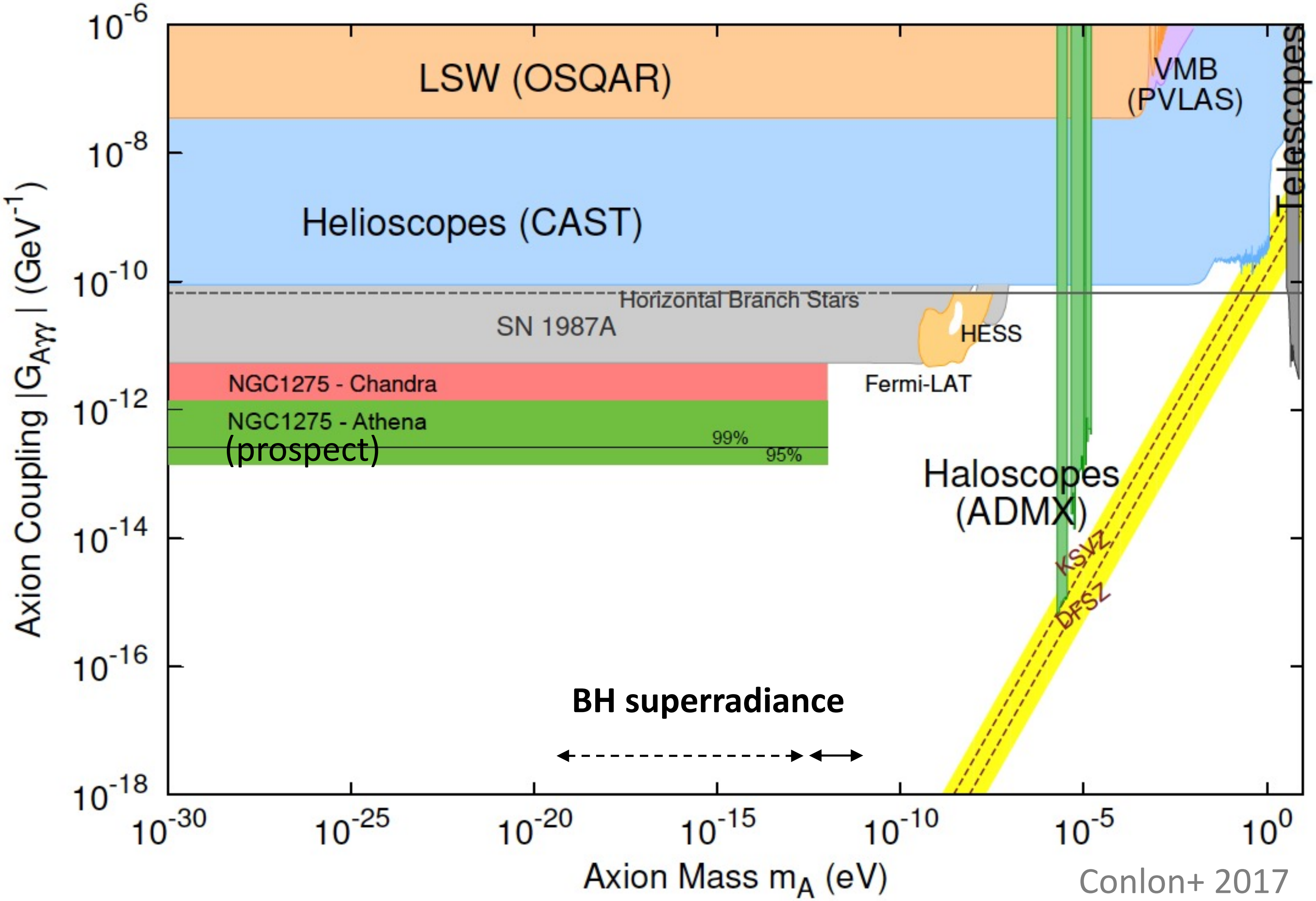
Axion is converted into photon under the background magnetic field

Ex)
Axion helioscope



Credit: CERN Axion Solar Telescope (CAST)

Overview of Target Spaces



Conlon+ 2017

New search methods for axion dark matter

(without using background magnet)

Cosmic birefringence

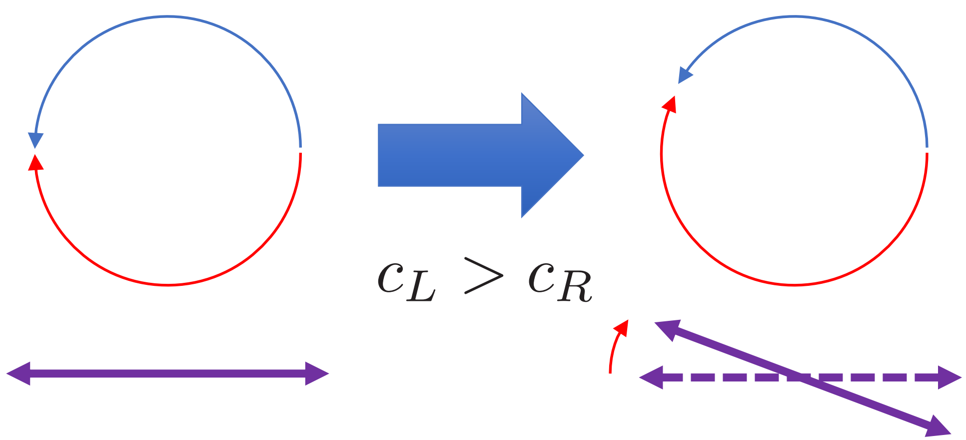
Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); …

Axion behaves as a birefringent material in our universe

- Axion differentiates the phase velocities of circular-polarized photon

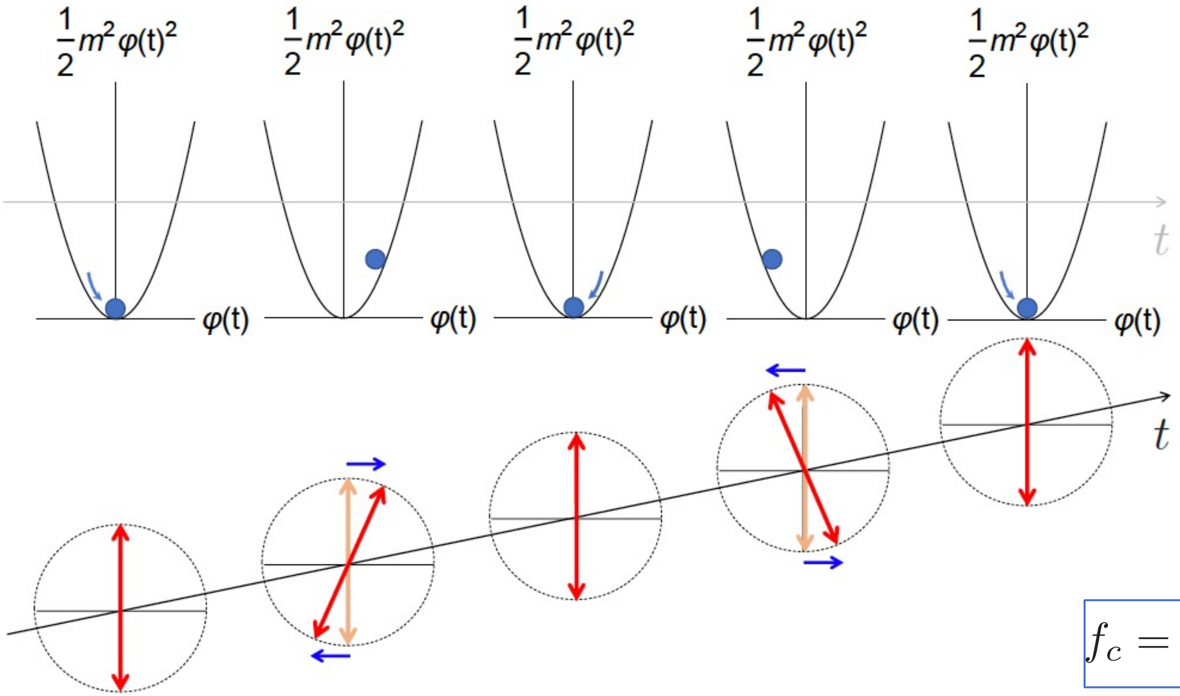
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu} \ , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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

Birefringence by axion DM

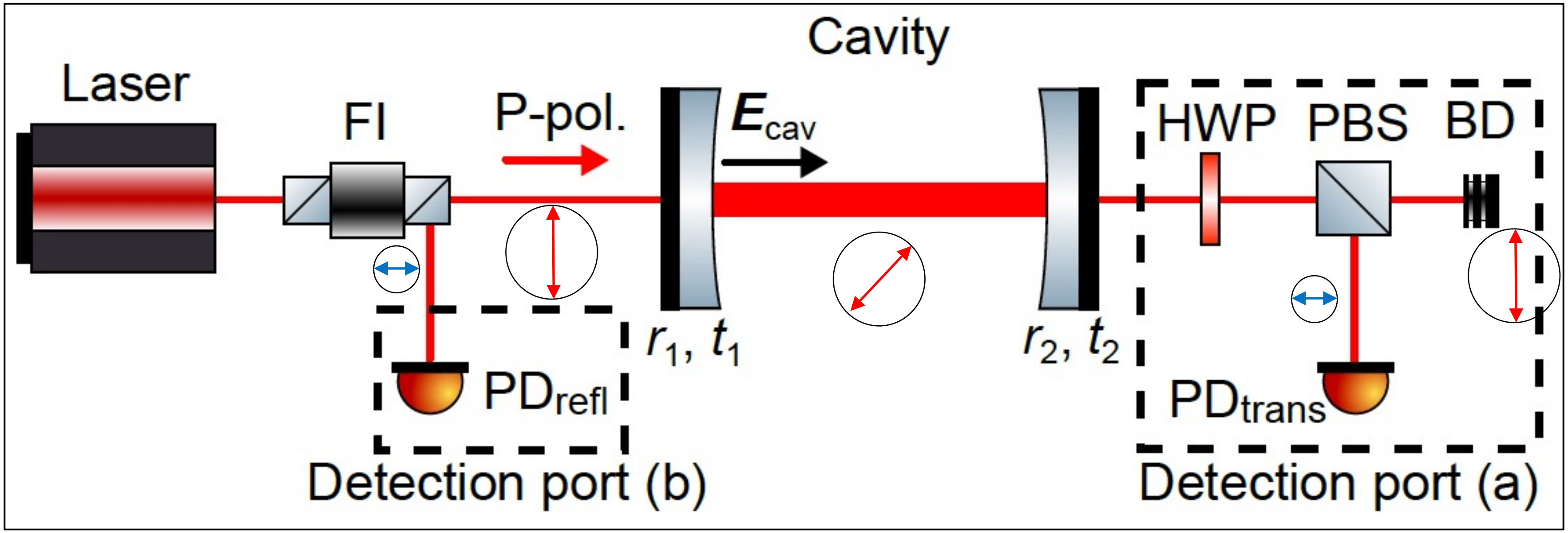


$$f_c = \frac{m_a}{2\pi} \simeq 2.4\mathrm{Hz}\left(\frac{m_a}{10^{-14}\mathrm{eV}}\right)$$

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

(1) Resonant cavity experiments

IO, Fujita & Michimura (2018); Nagano, Fujita, Michimura & IO (2019); …

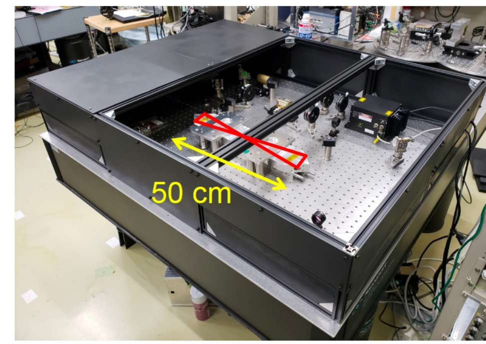


- The presence of axion dark matter acts on the laser in the resonator, creating a new polarization state.
- By separating the polarized state of the light that comes out, we can explore the ALP dark matter!

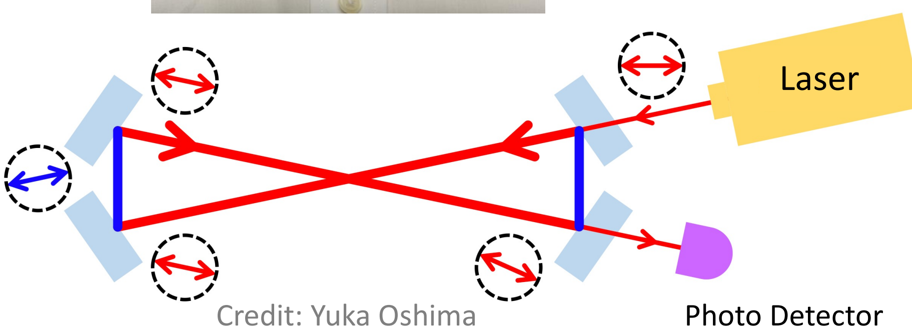
(1) Resonant cavity experiments

DANCE: Dark matter Axion search with riNg Cavity Experiment

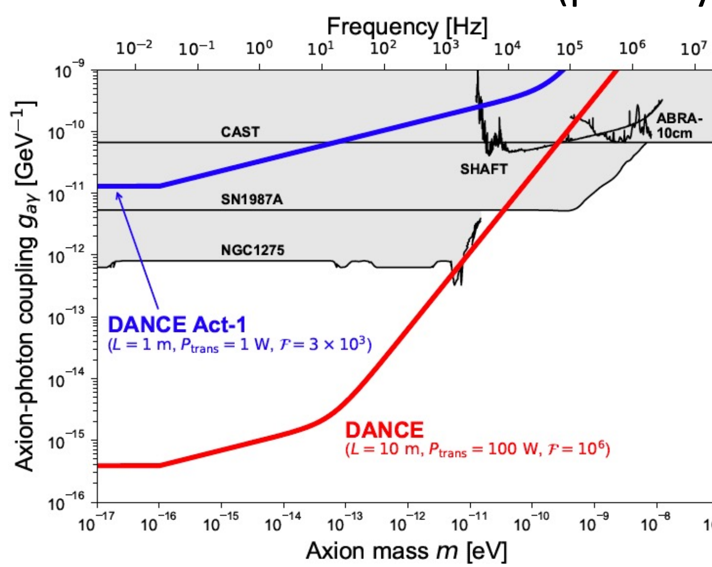
Y. Oshima, H. Fujimoto, H. Wang, Y. Michimura, M. Ando
T. Fujita, J. Kume, K. Nagano, H. Nakatsuka, A. Nishizawa, S. Morisaki, IO



DANCE Act-1 (prototype)



Credit: Yuka Oshima



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

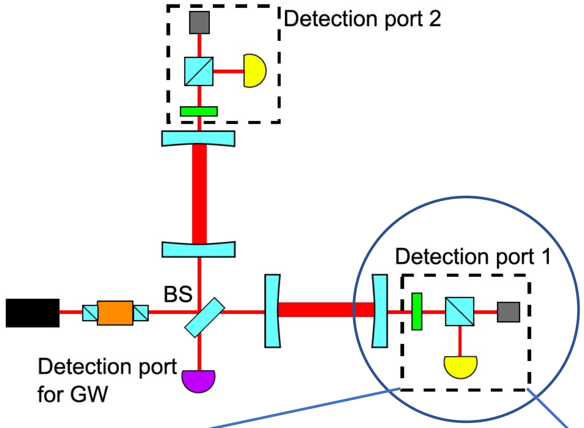
(1) Resonant cavity experiment

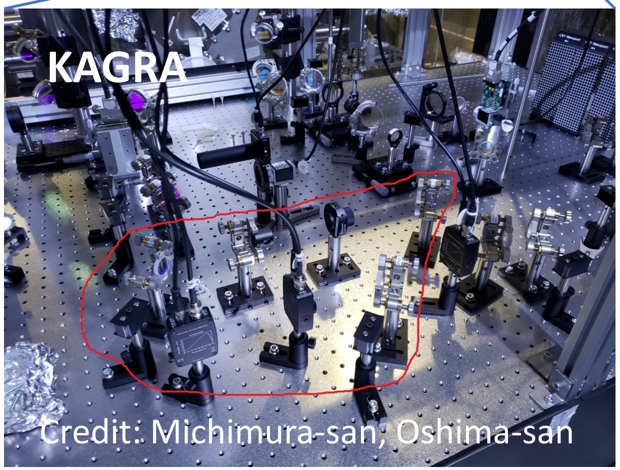
We are up for axion DM search by real GW detectors!!!

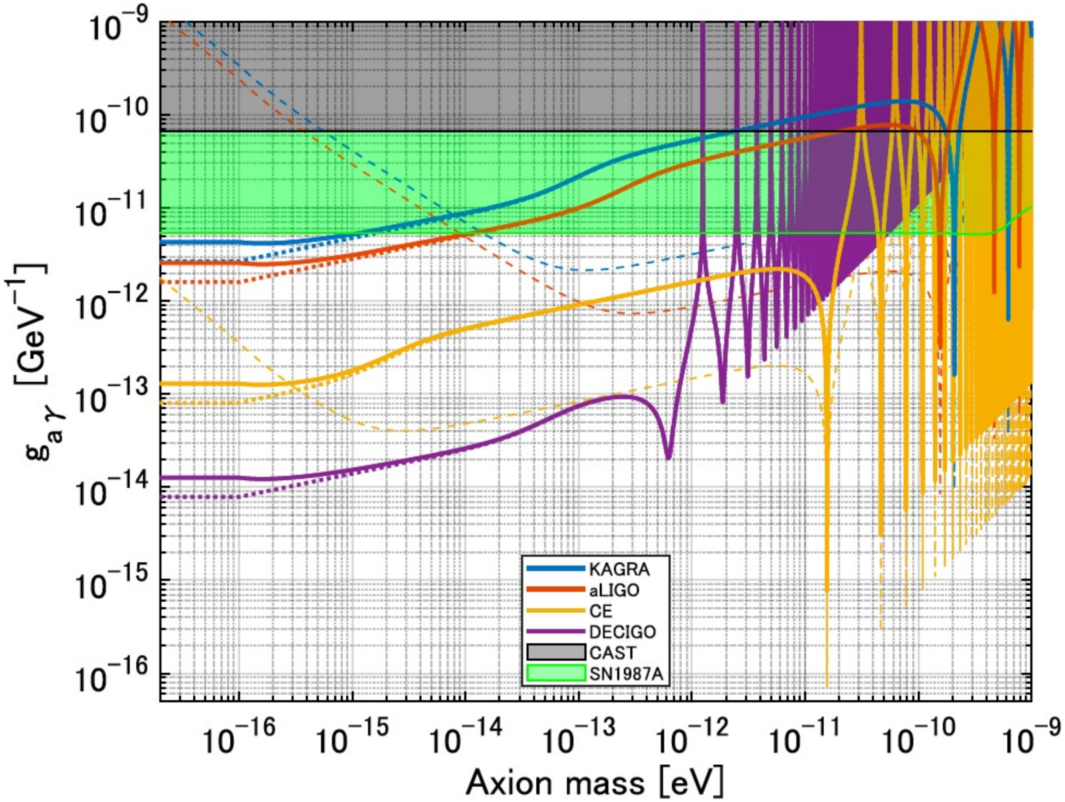
(~mHz) (~kHz)

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

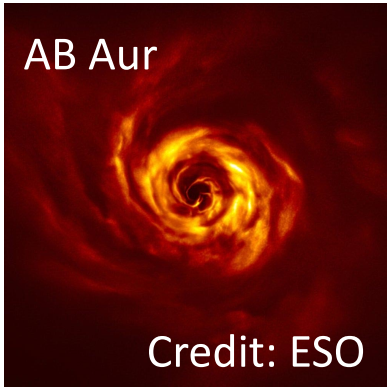
Nagano, Nakatsuka, Morisaki, Fujita, Michimura, IO (2021)





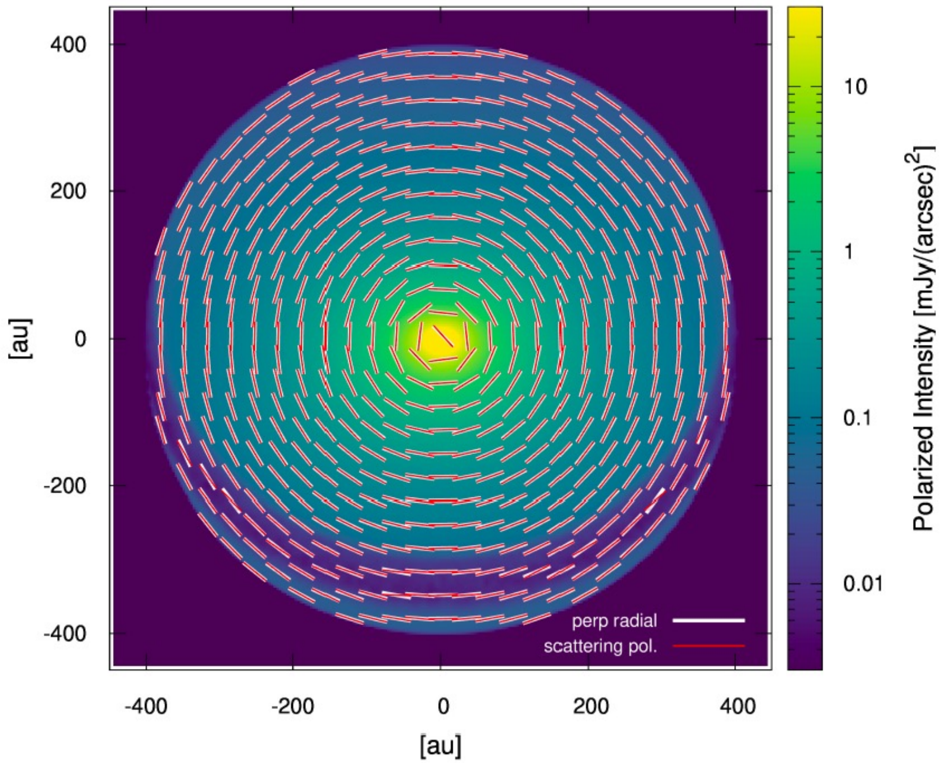


(2) Photoplanetary disk



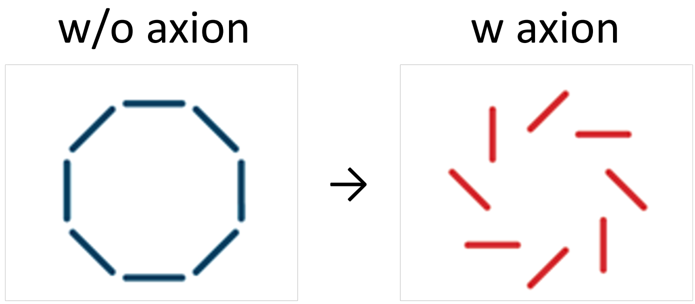
Fujita, Tazaki & Toma (2019);

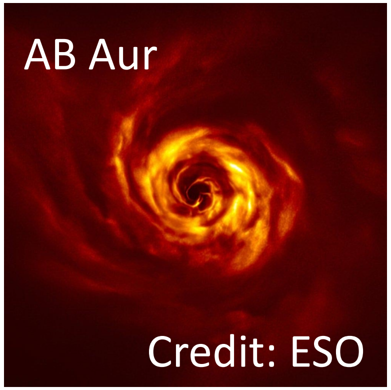
Observations of scattered lights from PPD are useful to search for ultralight axion DM



(simulation without axion DM)

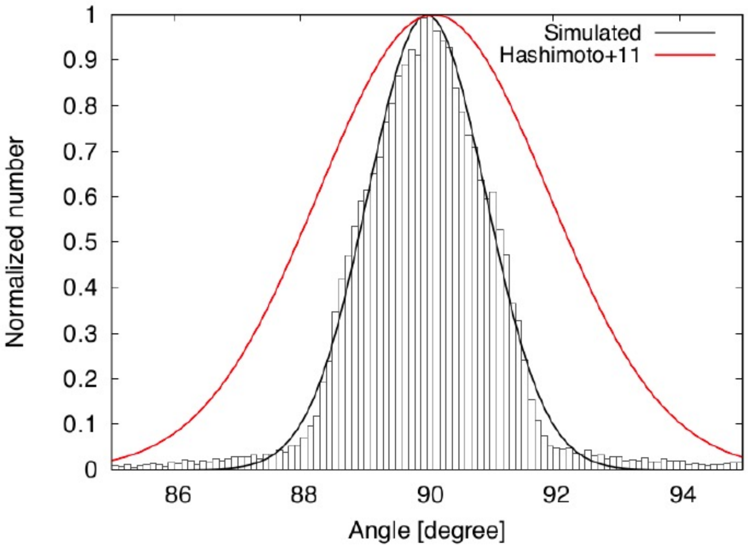
Axion DM rotate polarizations





(2) Photoplanetary disk

Fujita, Tazaki & Toma (2019);

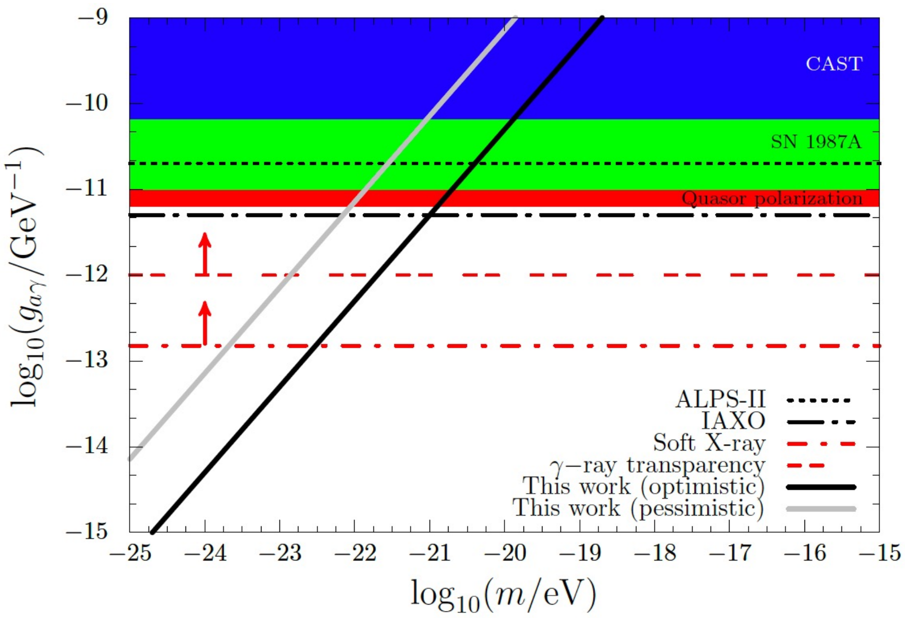


Observational data:

$$\theta = 90.1 \pm 0.2 \text{ deg}$$

$$\rightarrow |\delta\theta| < 5 \times 10^{-3} \text{ rad}$$

sensitive to $m_a \lesssim 10^{-22}\text{eV}$



Target axion DM mass ranges

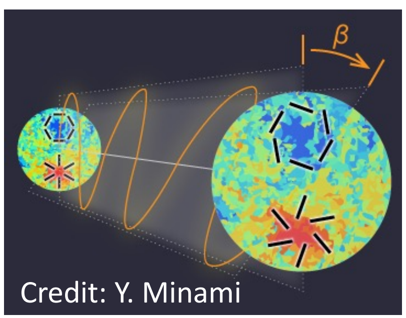
Quintessence | Fuzzy DM | QCD axion DM

m_a[eV]: 10^{-33} — 10^{-22} — 10^{-6}

CMB

Superradiance

CMB polarization



(Recent discovery)

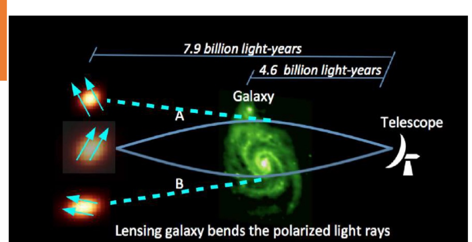
Photoplanetary disk

Resonant cavity experiments (DANCE, GW detector)

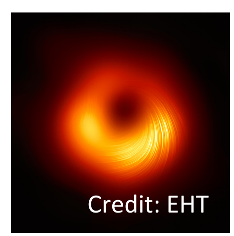
BH Event Horizon Telescope *Chen+ (2020,2021);*

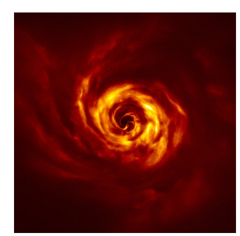
Gravitational strong lensing *Basu+ (2021);*

CMB *Finelli & Garaverni (2009); Lee, Liu & Ng (2014); ...*



Credit: Y. Urakawa

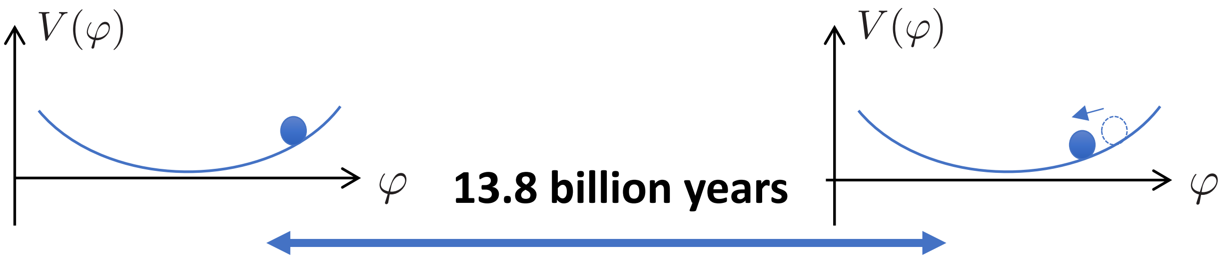




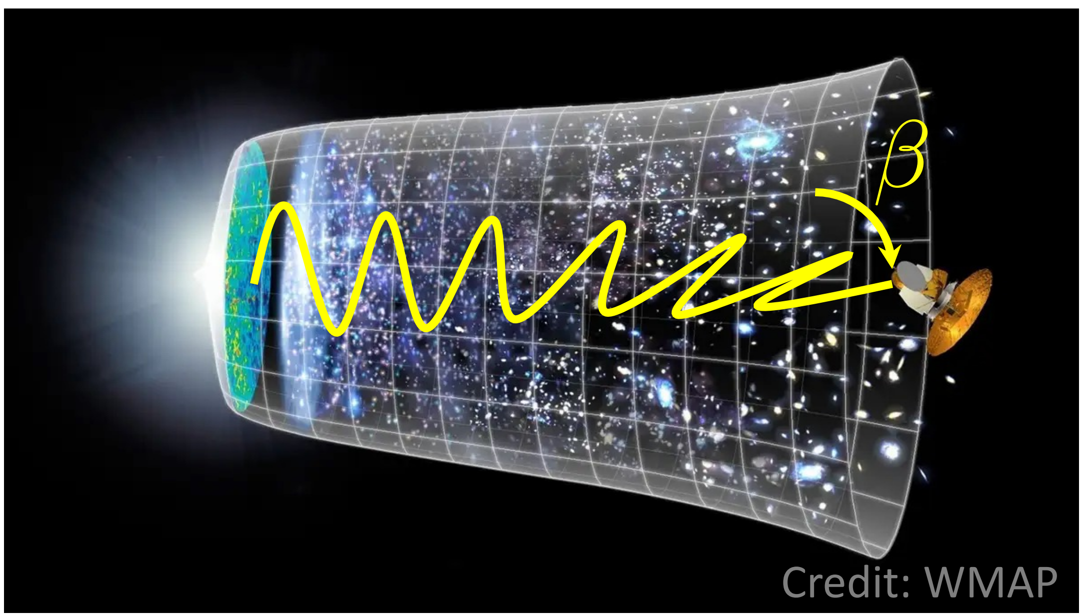
Birefringence by axion quintessence

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

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



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

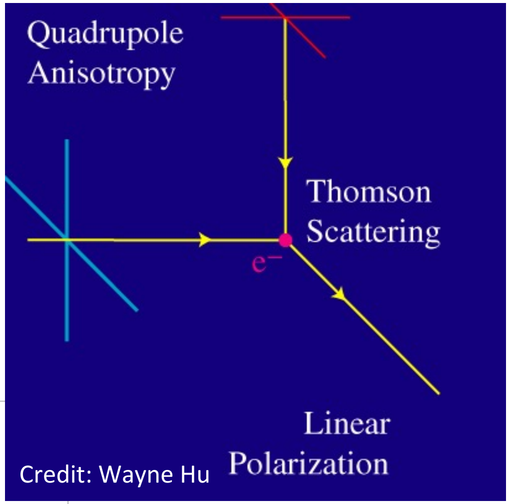


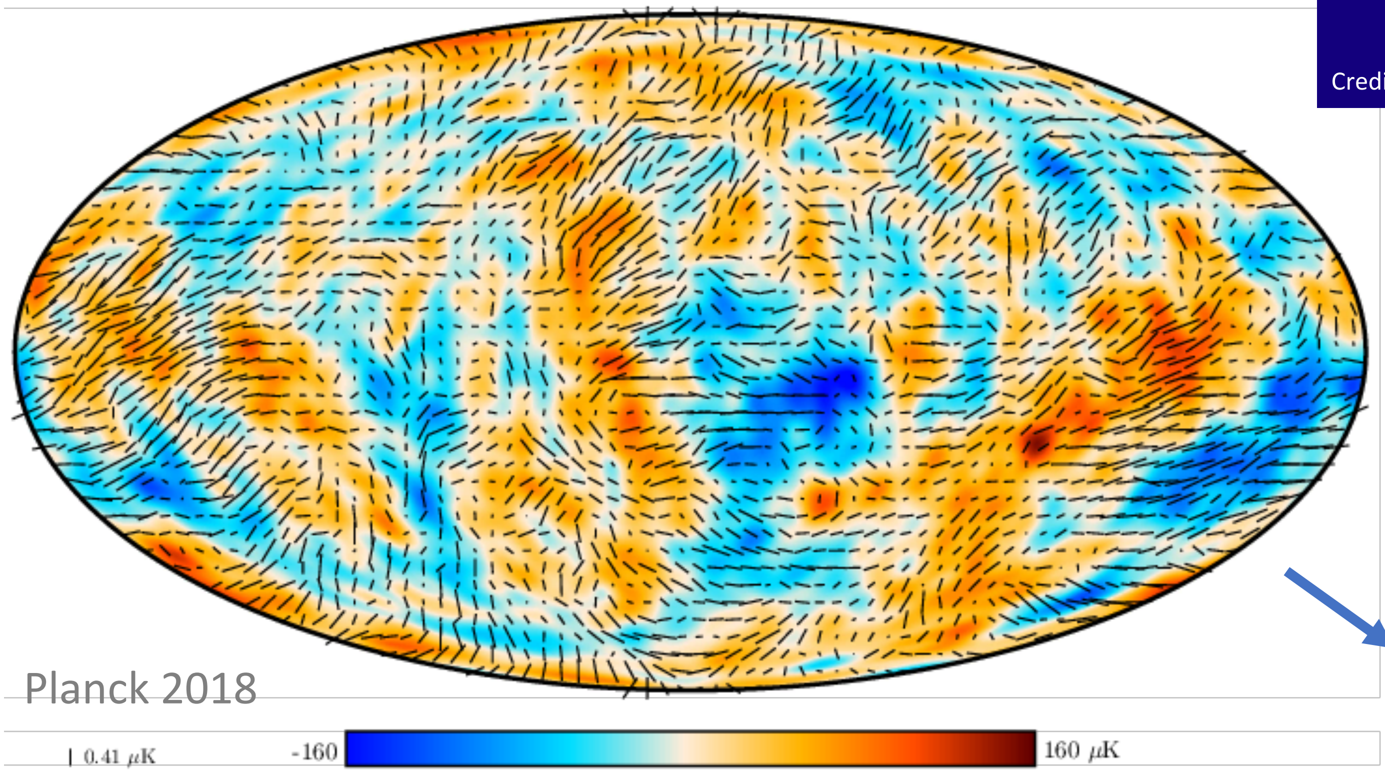
- If axion is responsible for dark energy, it makes the polarization plane of CMB rotate from the last-scattering-surface

Rotation angle:

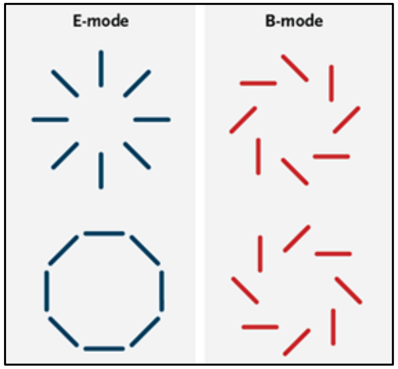
$$\beta = \frac{g_{\phi\gamma}}{2}\Delta\phi \equiv \frac{g_{\phi\gamma}}{2}(\phi_0 - \langle\phi_{\mathrm{LSS}}\rangle)$$

CMB polarization map

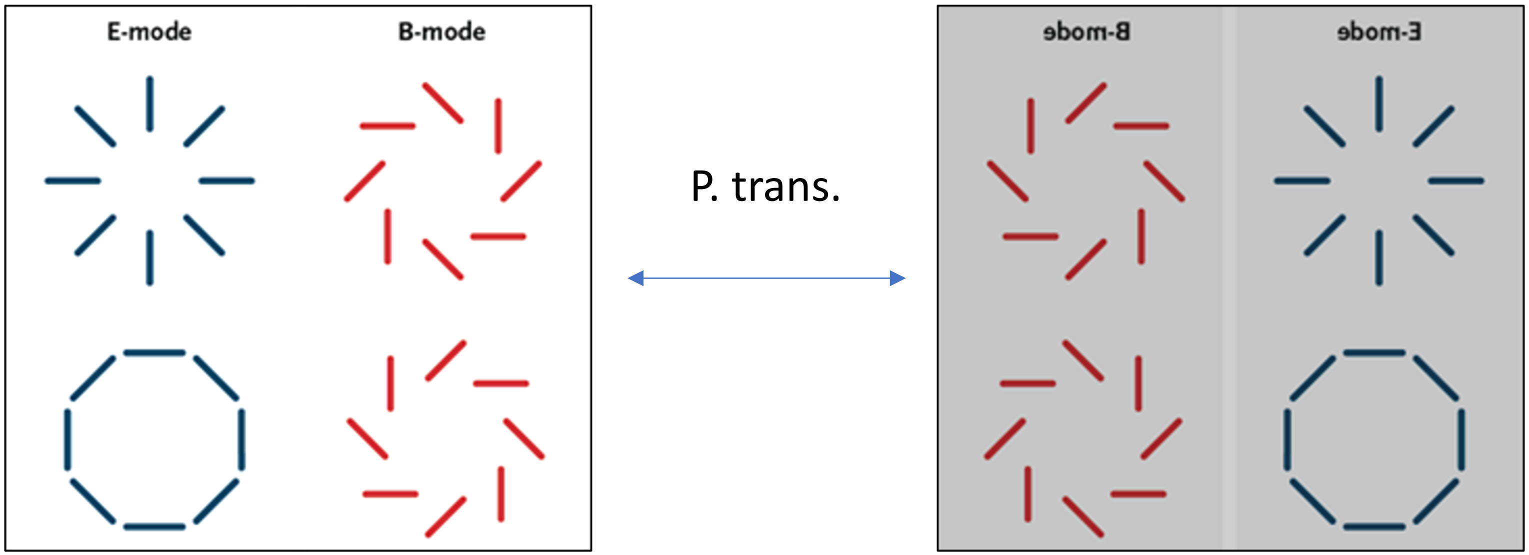




E-mode v.s. B-mode



Parity flip in polarization pattern



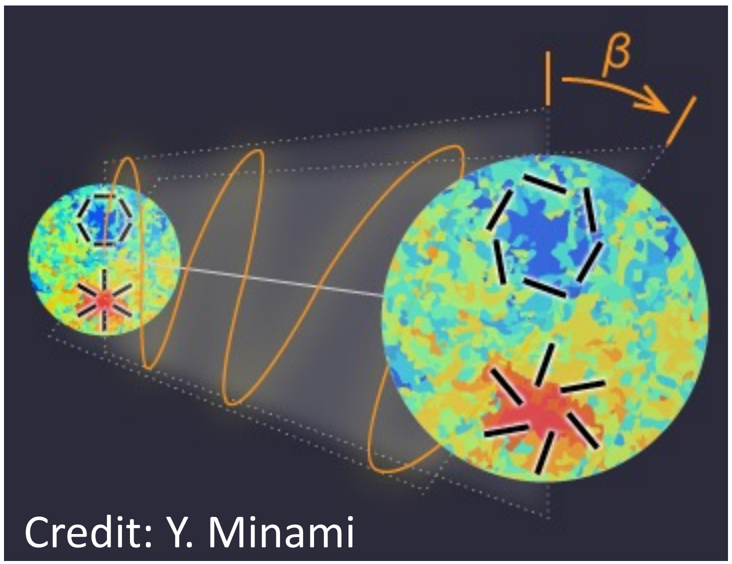
Angular power spectra

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

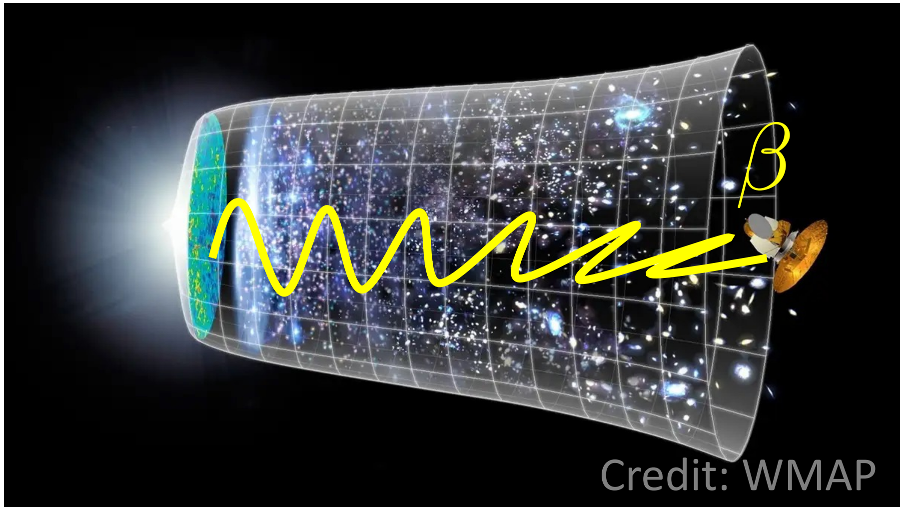
- The past measurements have detected the angle $\theta = \alpha + \beta$

How to break degeneracy of α & β

Minami+ (2019); …

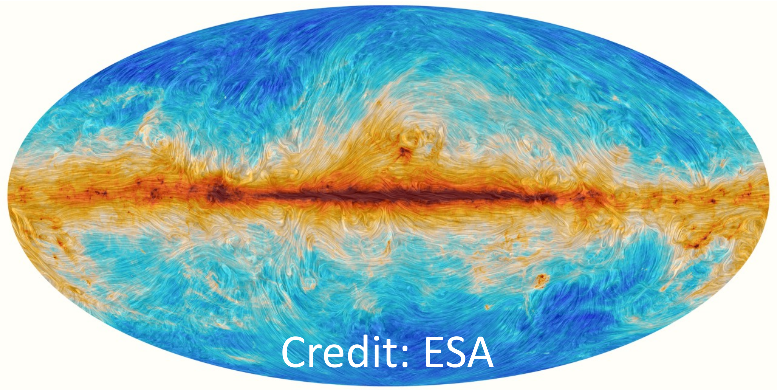
Point: Intrinsic birefringence angle β is **proportional to the path length of photon**

(note: axion is assumed to be quintessence)



Birefringence angle from LSS (z ~ 1100):

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



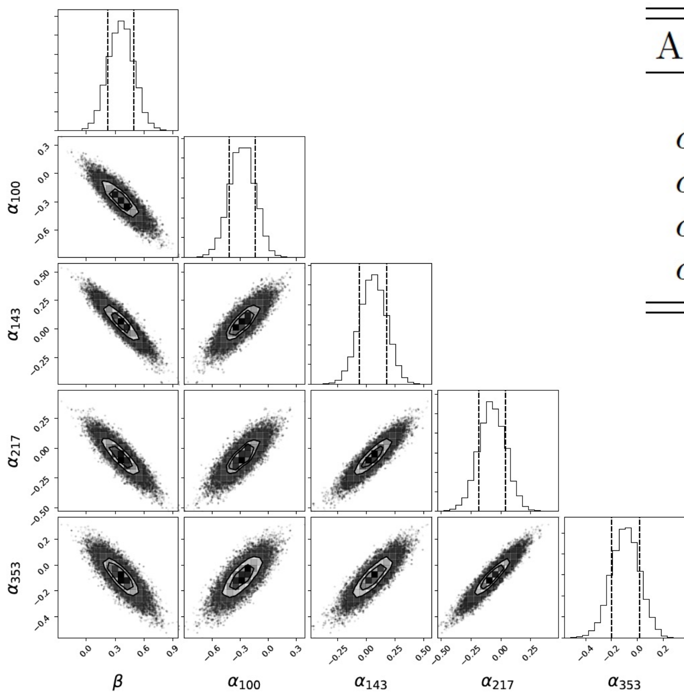
Birefringence angle from galactic foregrounds:

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

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

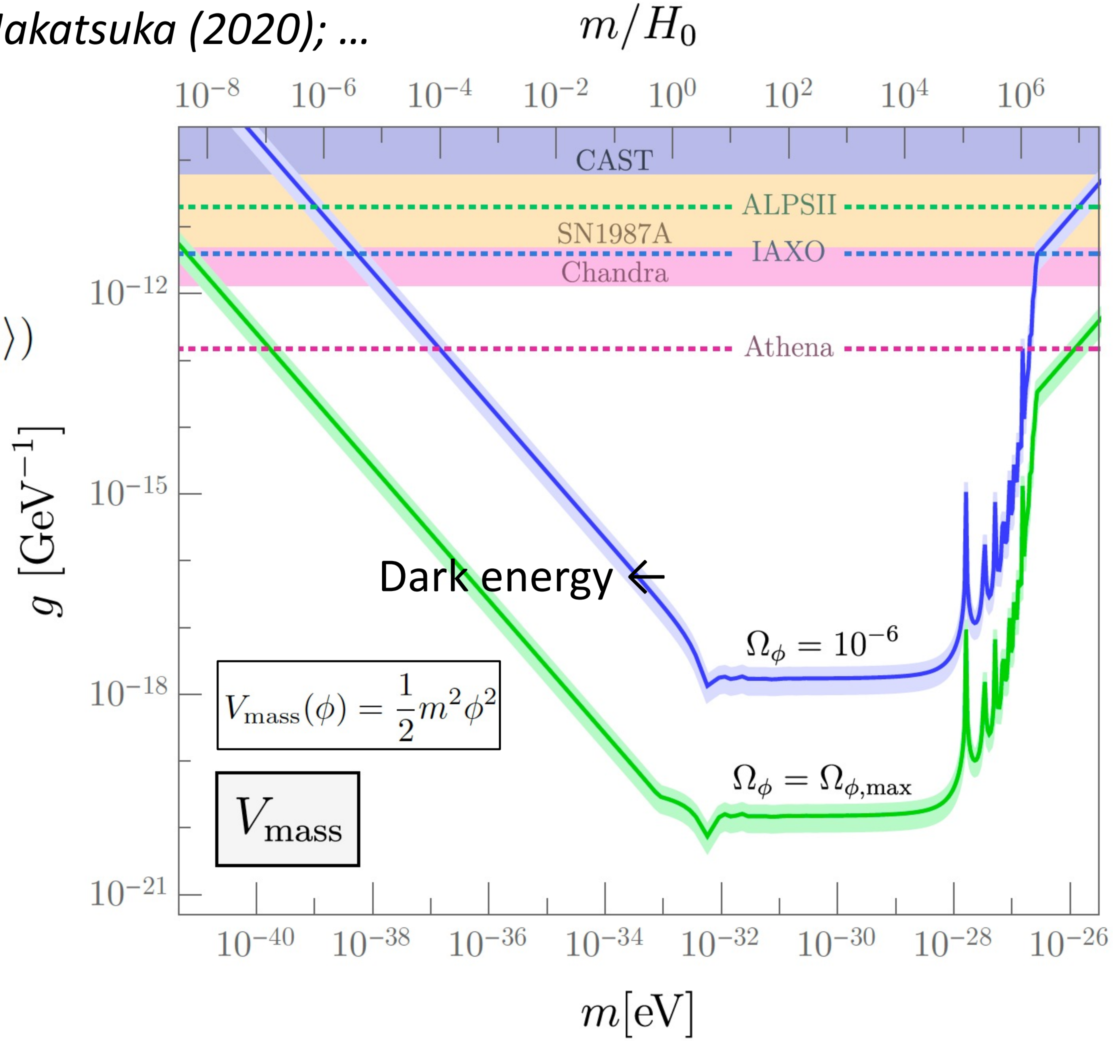
Fujita, Minami, Murai & Nakatsuka (2020); …

- 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)

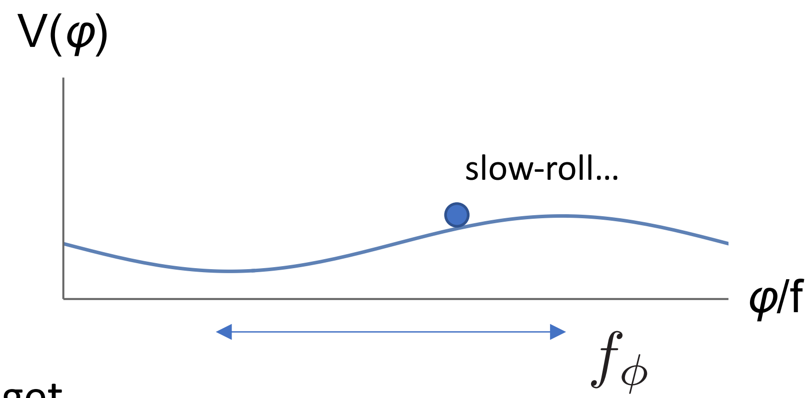
Our study

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

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

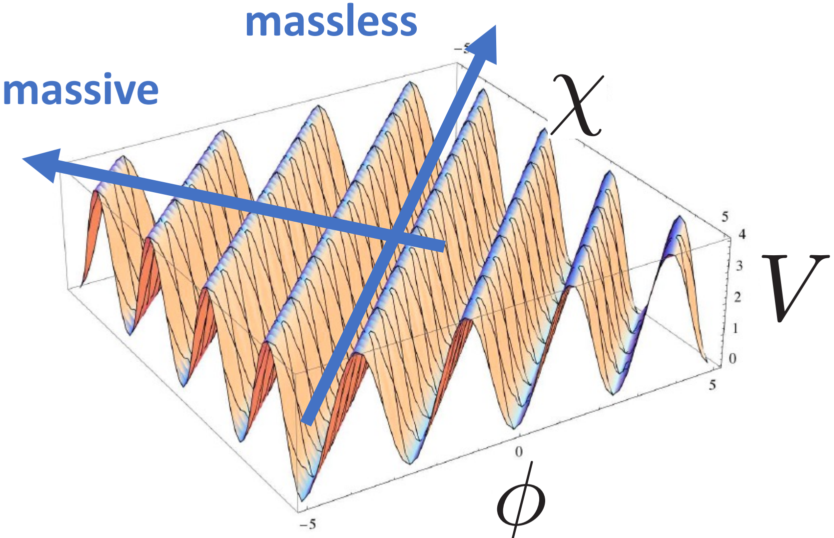
requires a **super-Planckian** decay constant or a fine-tuning of initial axion displacement

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

$$g_{\phi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\phi\gamma}}{f_\phi} \qquad |c_{\phi\gamma}| \simeq 2.3 \times 10^3 \left(\frac{\beta}{0.35\rm deg}\right)\left(\frac{m_\phi/H_0}{0.1}\right)^{-2} \gg 1$$

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:

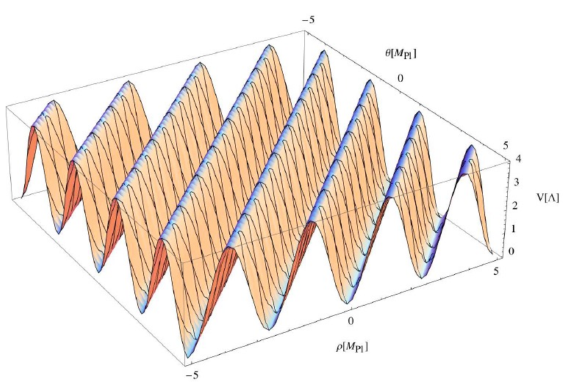
$$V(\phi,\chi)=\Lambda_1^4\left[1-\cos\left(\frac{\phi}{F_{\phi1}}+\frac{\chi}{F_{\chi1}}\right)\right]+\Lambda_2^4\left[1-\cos\left(\frac{\phi}{F_{\phi2}}+\frac{\chi}{F_{\chi2}}\right)\right]$$

For simplicity, we assume $F_{\phi1}=F_{\phi1}\equiv F_\phi,\ F_{\chi2}=F_{\chi1}(1+\epsilon)$

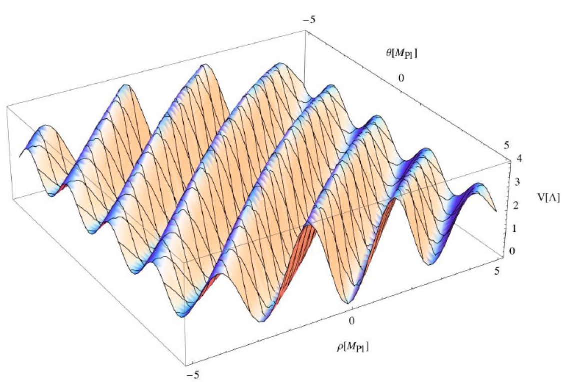
- The misalignment of the potential is characterized by $\epsilon \ll 1$

→nearly flatness

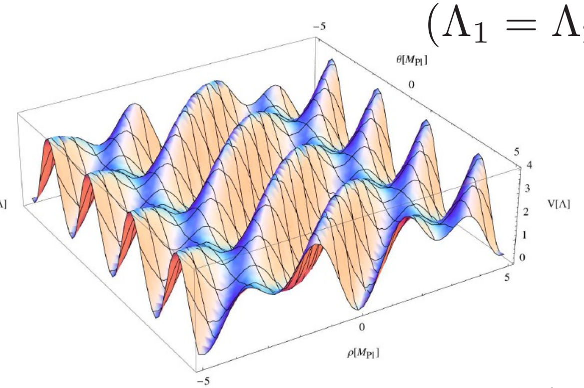
$(\Lambda_1=\Lambda_2)$



$\epsilon=0$



$\epsilon=0.1$

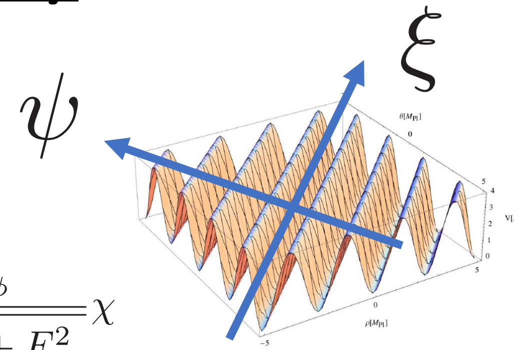


$\epsilon=0.3$

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

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

(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

$$V(\psi,\ \xi) \simeq \Lambda_1^4\left[1-\cos\left(\frac{\sqrt{F_\phi^2+F_{\chi1}^2}}{F_\phi F_{\chi1}}\psi\right)\right]+\Lambda_2^4\left[1-\cos\left(\frac{\sqrt{F_\phi^2+F_{\chi1}^2}}{F_\phi F_{\chi1}}\psi-\frac{\epsilon}{\sqrt{F_\phi^2+F_{\chi1}^2}}\xi\right)\right]$$

$\equiv \tilde{F}_\psi^{-1}$ $\equiv \tilde{F}_\psi^{-1}$ $\equiv \tilde{F}_\xi^{-1}$

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

$$\tilde{F}_\xi \simeq \frac{\sqrt{F_\phi^2+F_{\chi1}^2}}{\epsilon}\,, \qquad \tilde{F}_\psi \simeq \frac{F_\phi F_{\chi1}}{\sqrt{F_\phi^2+F_{\chi1}^2}}$$

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

$\tilde{F}_\xi \gg M_{\rm Pl}$ 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:

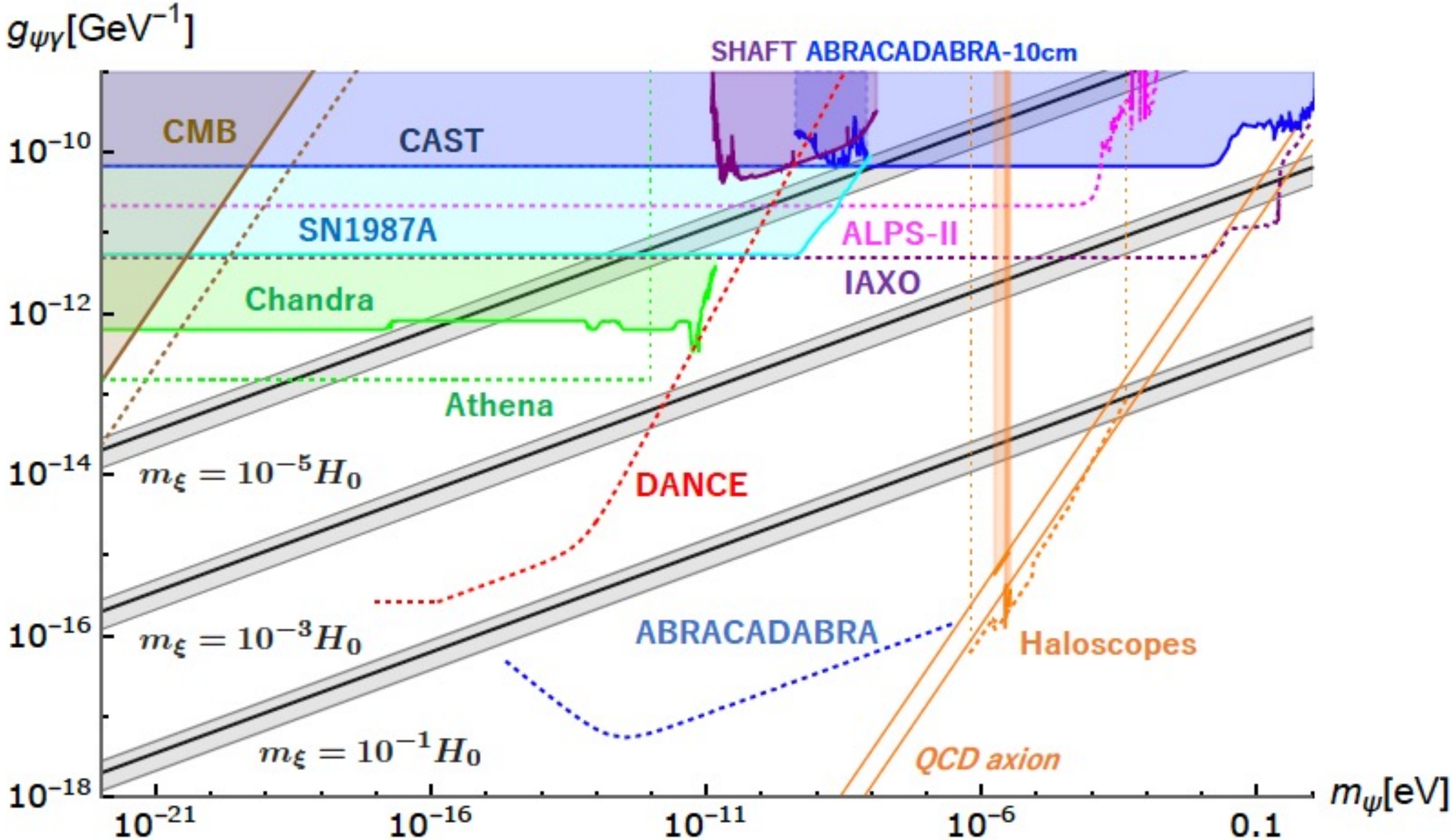
$$g_{\xi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\xi\gamma}}{\tilde{F}_\xi}\,, \quad c_{\xi\gamma} \equiv \frac{1}{\epsilon}\left(\frac{F_\phi}{F_{\phi\gamma}} - \frac{F_{\chi1}}{F_{\chi\gamma}}\right)\,,$$

$$g_{\psi\gamma} = \frac{\alpha}{2\pi}\frac{c_{\psi\gamma}}{\tilde{F}_\psi}\,, \quad c_{\psi\gamma} \equiv -\left(\frac{F_\phi}{F_{\chi\gamma}} + \frac{F_{\chi1}}{F_{\phi\gamma}}\right)\frac{F_\phi F_{\chi1}}{F_\phi^2 + F_{\chi1}^2}$$

- g_ξγ is fixed by the measured birefringence angle β = 0.35 ±0.14

→ also constrain the parameter space of g_ψγ as axion DM

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!
- A recent measurement of CMB birefringence gives us a tantalizing hint of the axion physics, especially axion as a quintessence.
- Based on a multiple axion scenario, this observable can connect the constraints on axion as dark energy and dark matter.