Axion search with the observations of photon's birefringence effect

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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)

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

2024.3.13 Berkeley Week (Hongo Campus, University of Tokyo)

What is 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

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

(typical) QCD axion window

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

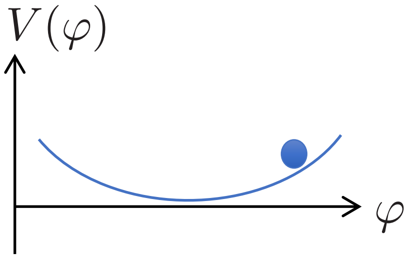
Axion-like particle (ALP) ***Svrcek & Witten (2006); Arvanitaki+ (2010); …***

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

↑Main focus of this talk

Axion as dark matter, dark energy

Cosmological axion background



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

$$m_a \gg H$$

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

Ultralight axion DM mass (roughly): $\boxed{10^{-22}\mathrm{eV} \lesssim m_a \lesssim \mathrm{eV}}$

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

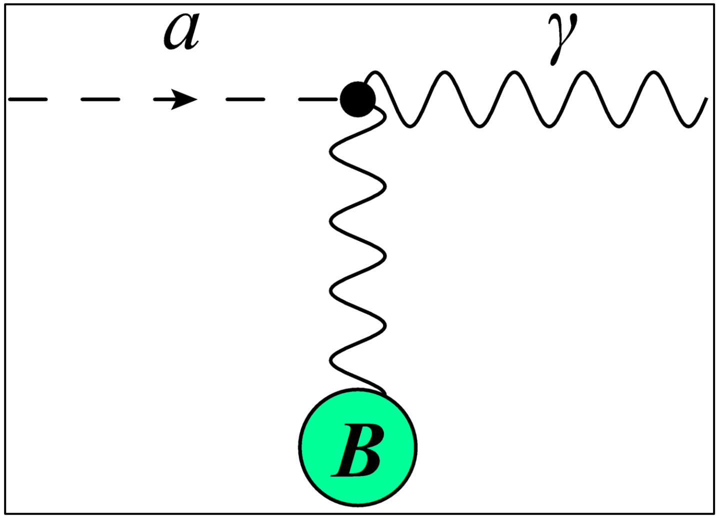
$$m_a \ll H$$

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

Conventional Axion Search

- Axion generically couples to photon via the topological term

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



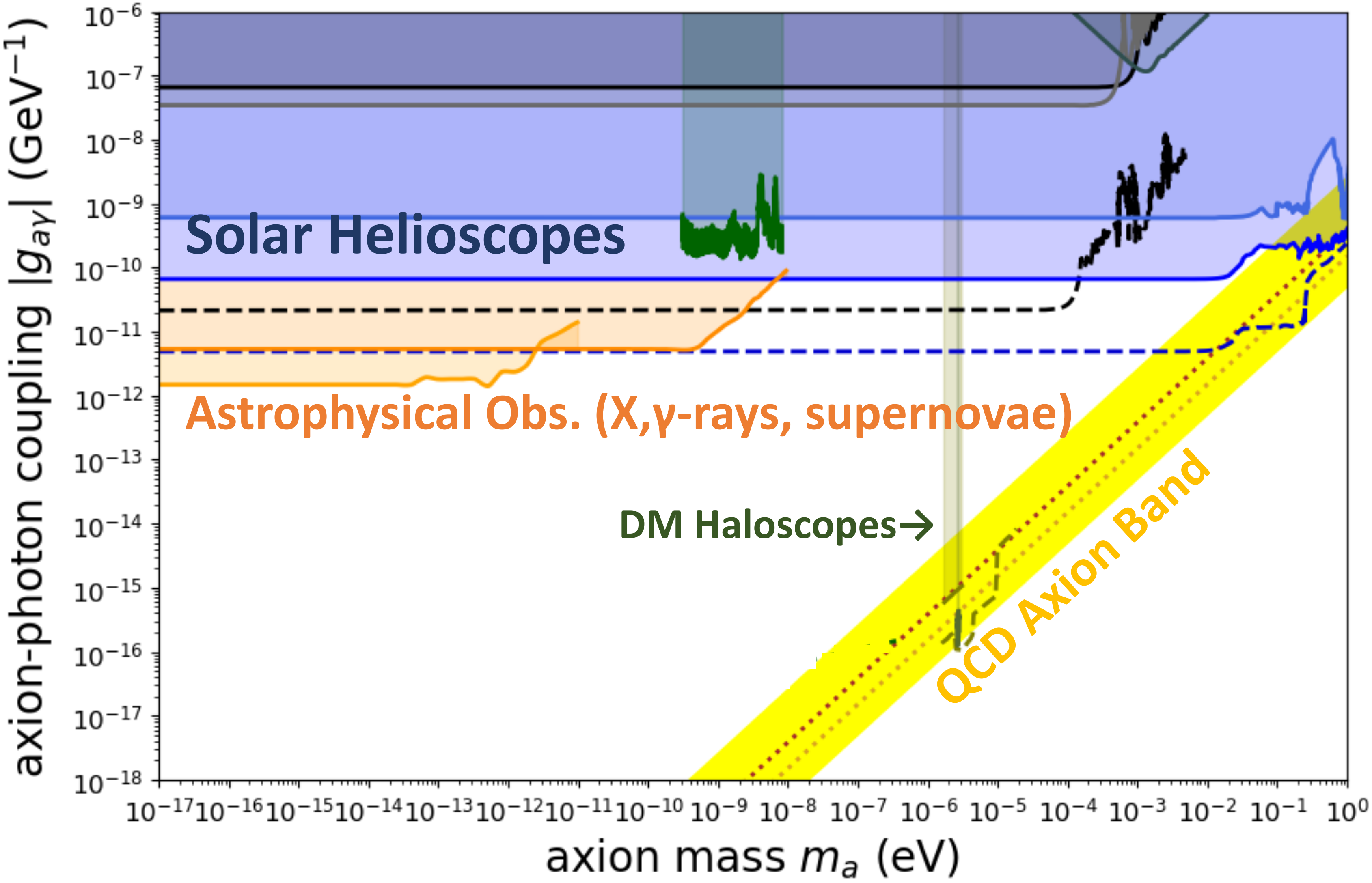
a : axion

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

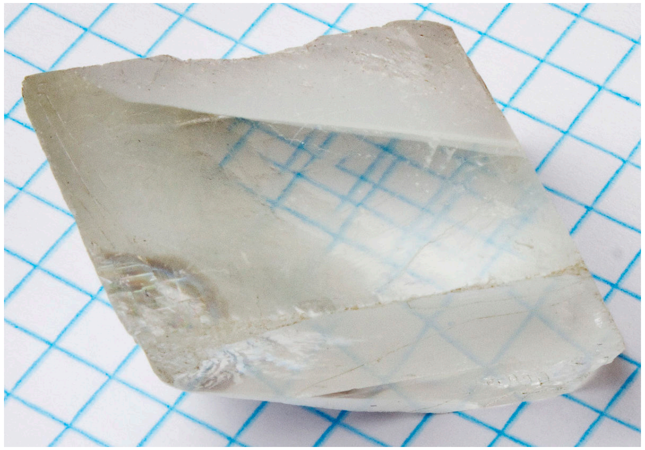


New search methods for axions without using external magnetic field

-Photon’s birefringence effect-

Credit: higgstan.com

Axion as a birefringent material



Photon’s birefringence by axion

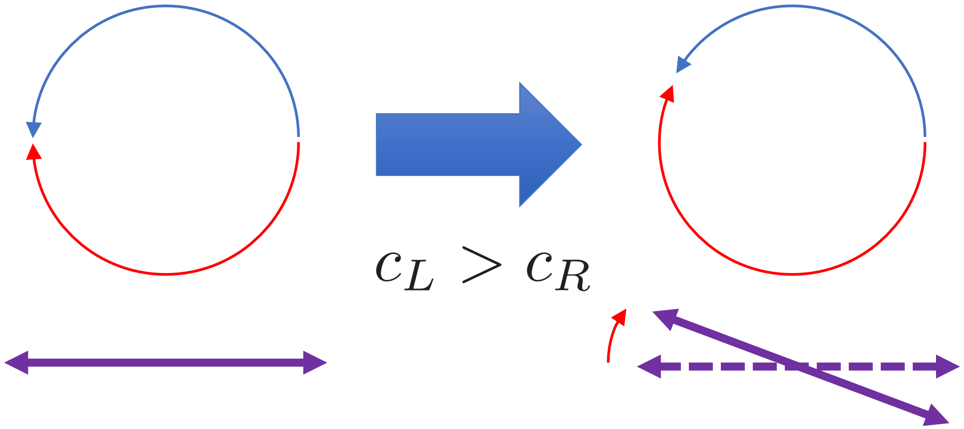
Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); …

Axion behaves as a birefringent material in our universe

- Axion differentiates the phase velocities of circular-polarized photon

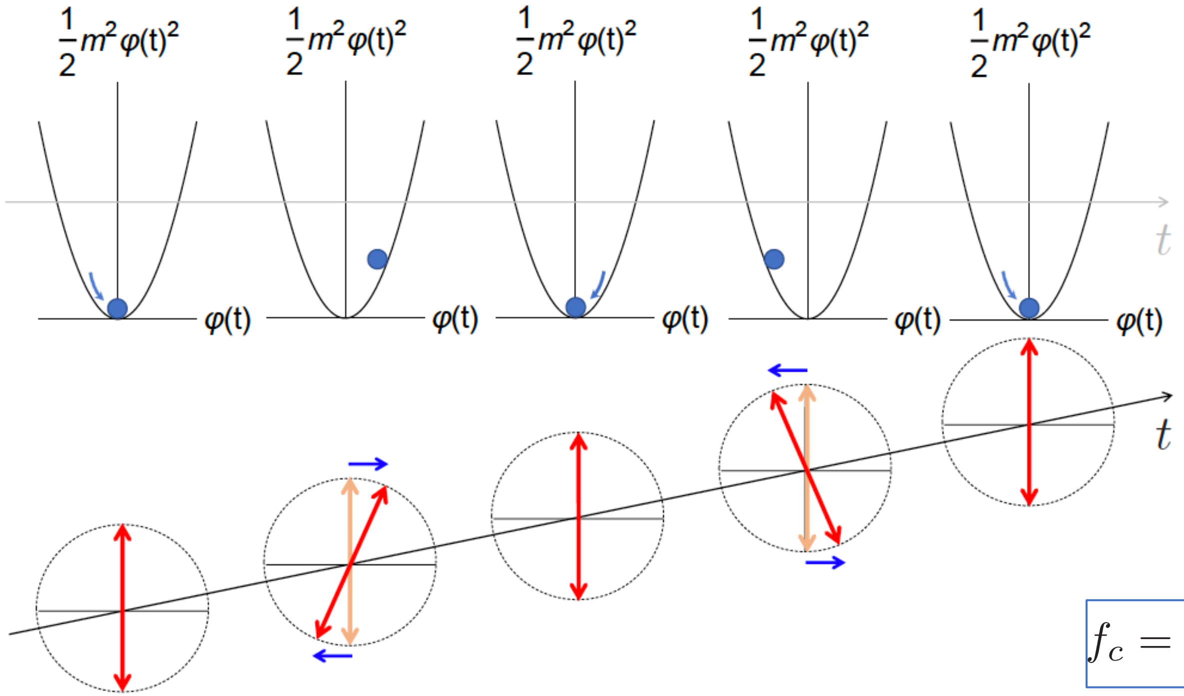
$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu} \ , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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



→ leading to the rotation of linear-polarization direction

Photon’s birefringence by axion DM

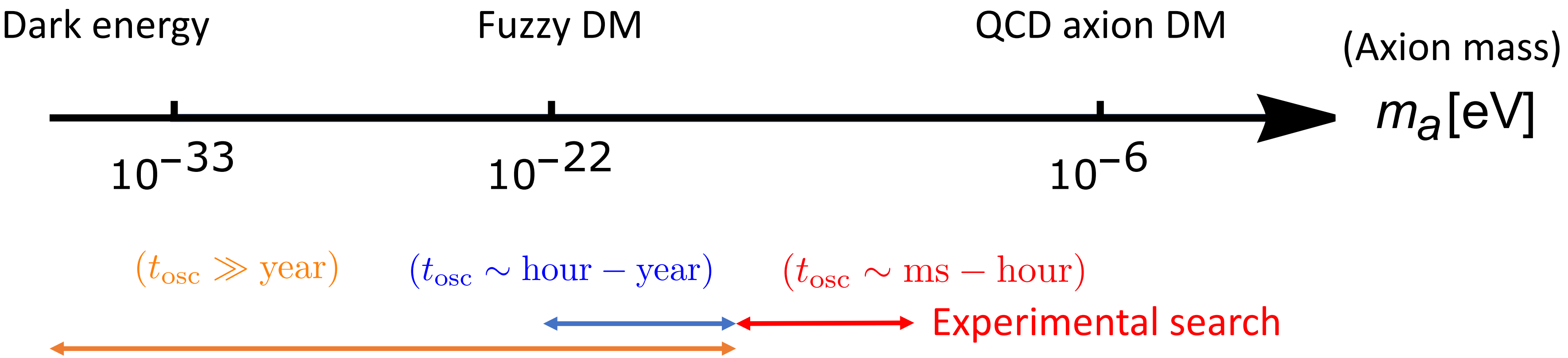


$$\boxed{f_c = \frac{m_a}{2\pi} \simeq 2.4\mathrm{Hz}\left(\frac{m_a}{10^{-14}\mathrm{eV}}\right)}$$

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

- Possible to observe by several experimental/astrophysical approaches!

Probing axions with birefringence



Dark energy

Fuzzy DM

QCD axion DM

(Axion mass)

m_a[eV]

10^{-33}

10^{-22}

10^{-6}

$(t_{\rm osc} \gg {\rm year})$

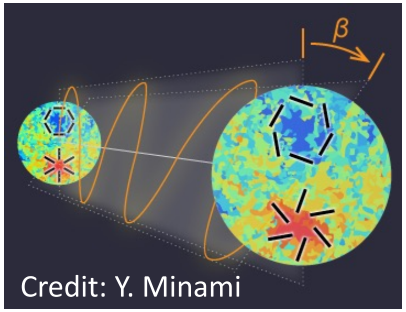
$(t_{\rm osc} \sim {\rm hour} - {\rm year})$

$(t_{\rm osc} \sim {\rm ms} - {\rm hour})$

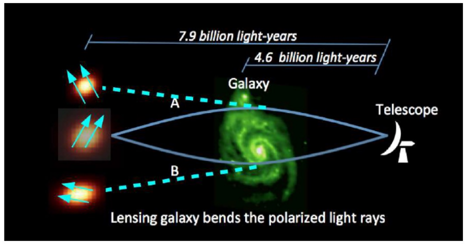
Experimental search

CMB search

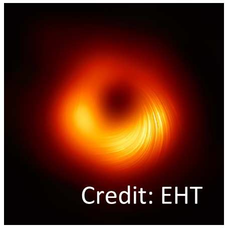
Astrophysical search



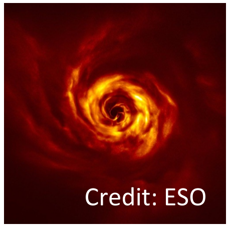
Credit: Y. Minami



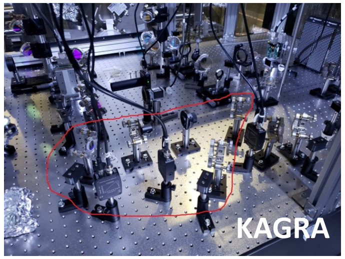
Credit: Y. Urakawa



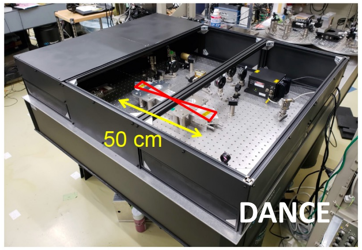
Credit: EHT



Credit: ESO



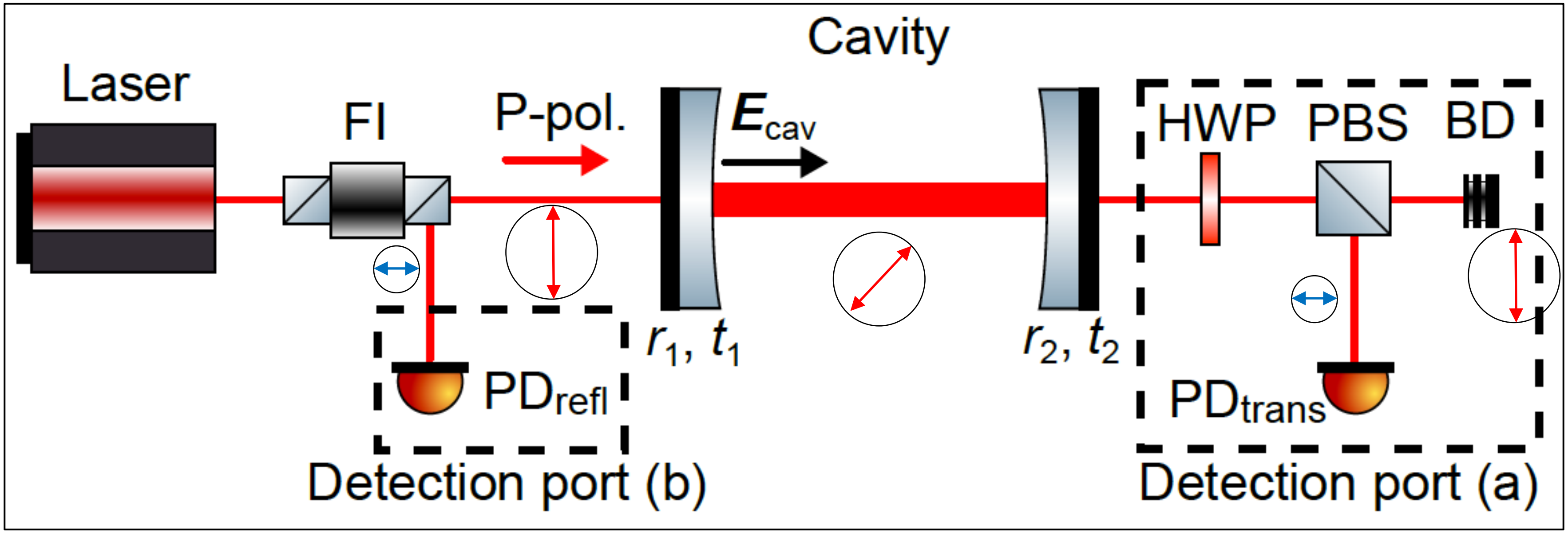
KAGRA



DANCE

Experimental birefringence search

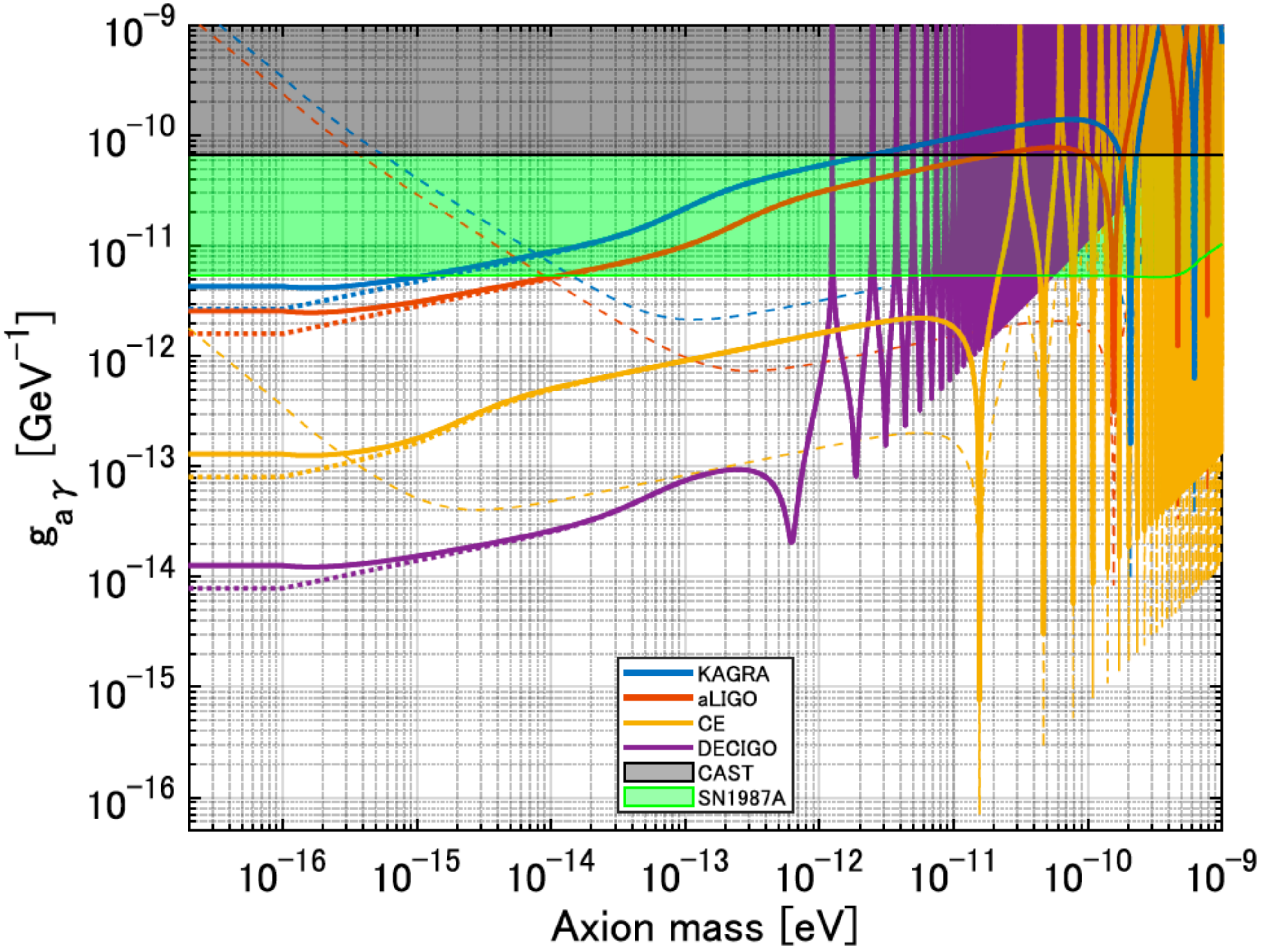
Resonant cavity experiment



- 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!

Axion DM search with GW detectors

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



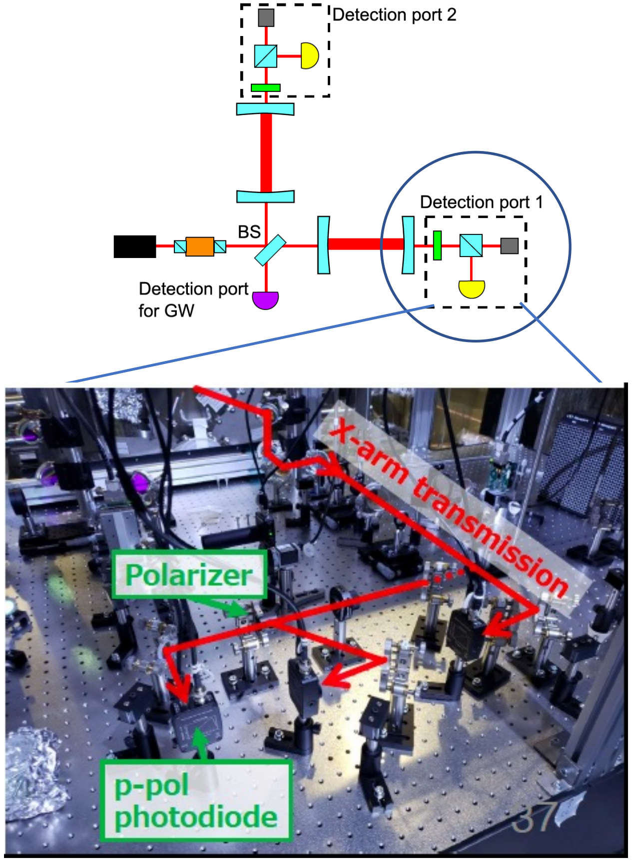
Nagano, Nakatsuka, Morisaki, Fujita, Michimura, IO (2021)

- Complemental search by installing polarization optics at different ports
- 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

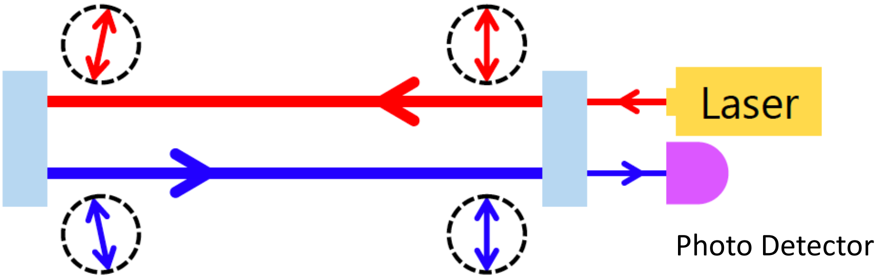


- The polarization optics have been installed at 3-km arm cavity transmission of KAGRA.

- Ready for first data taking in O4 run (starting in May 2023)

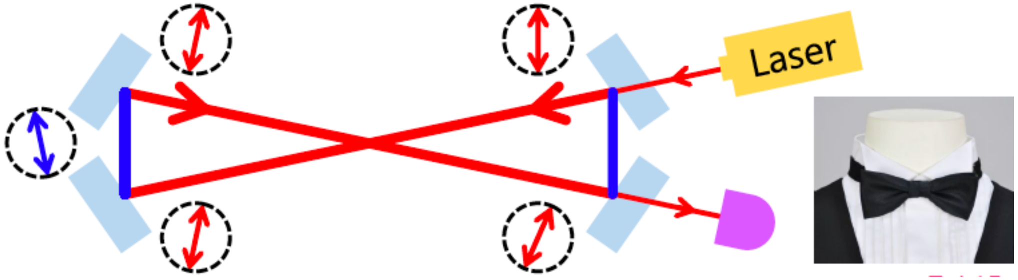
Bowtie ring cavity method

In the case of GW laser-interferometers…



- As a demerit of linear cavity, the sensitivity is lost by a **parity-flipping effect** on the reflection of mirror

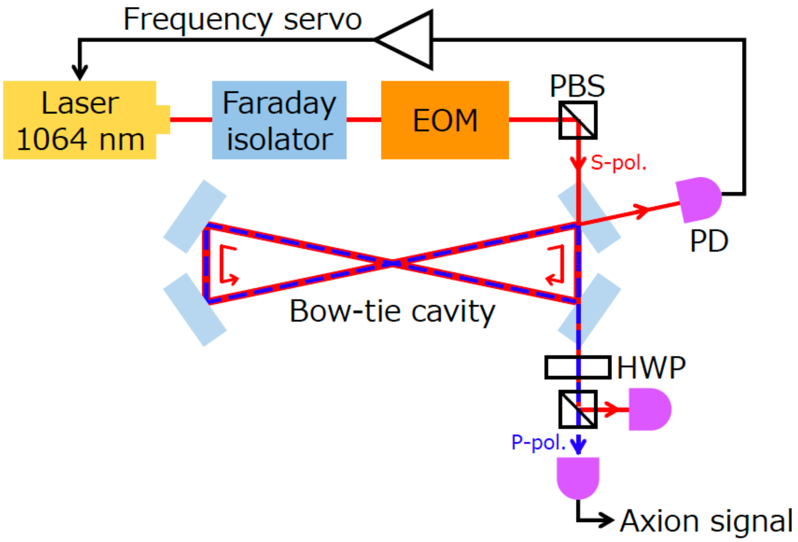
IO, Fujita, Michimura (2018);…



- A bowtie-like mirror configuration can prevent the linear polarization from flipping

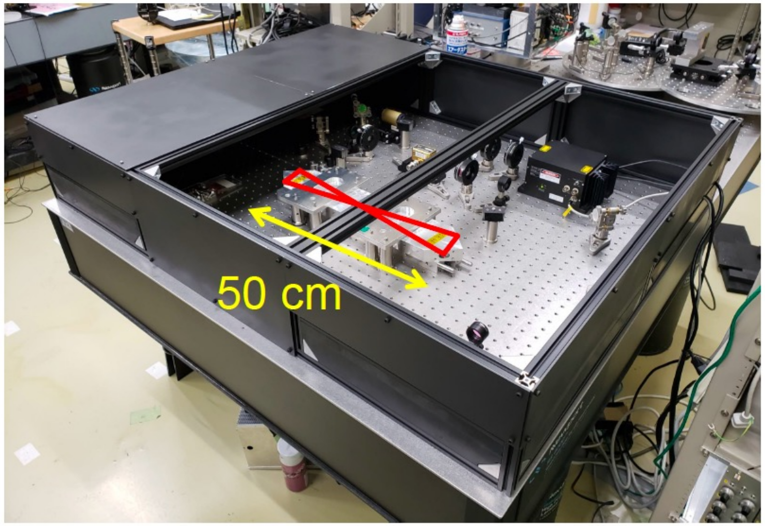
Credit: Yuka Oshima

DANCE: Dark matter Axion search with riNg Cavity Experiment



Michimura+ (2019);…

- New table-top experimental project to search for axion DM with an optical ring (bowtie-like) cavity



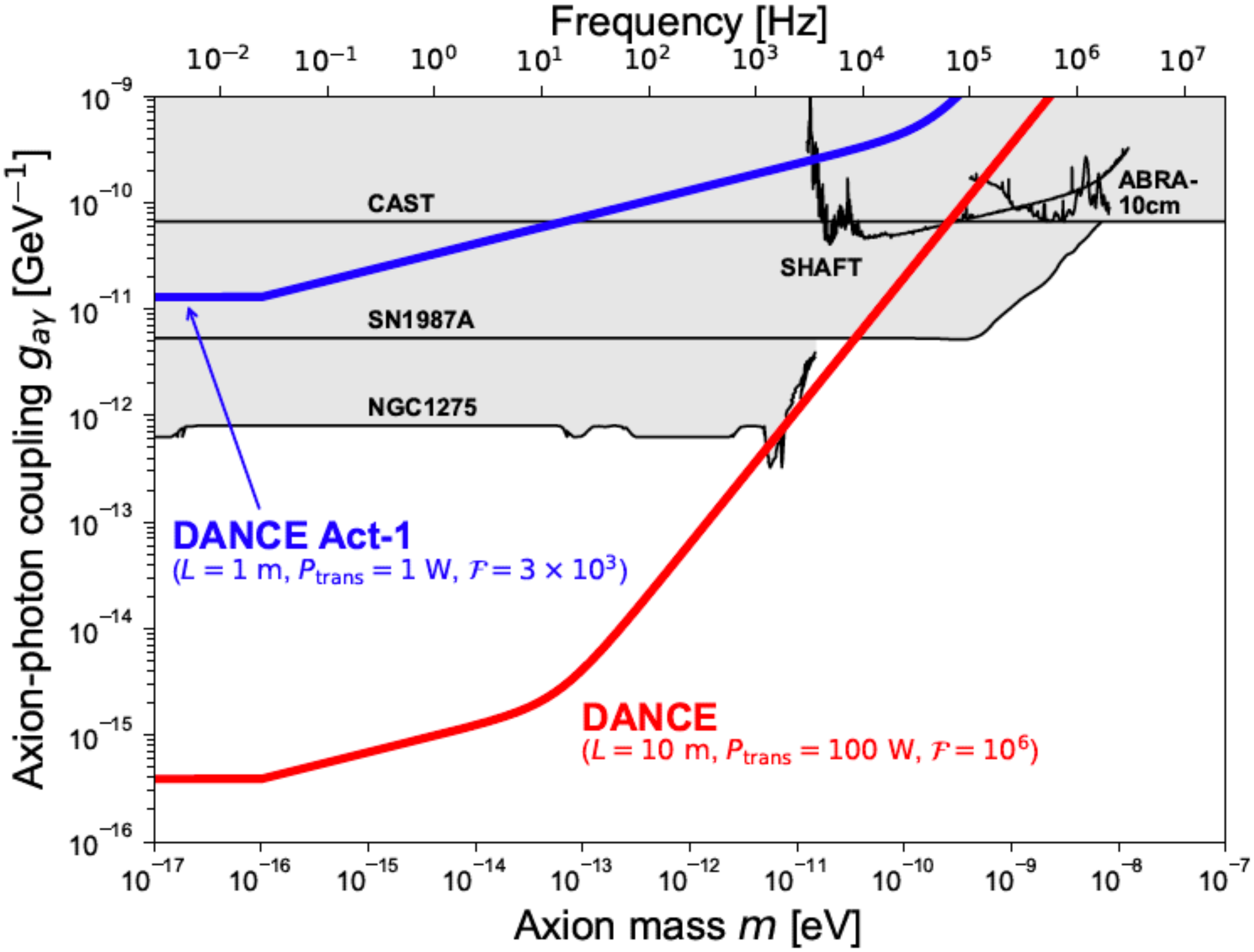
Dance Act-1 (Tokyo University)

- First-step prototype experiment

Design goal

Round-trip: 1m
Laser power: 1W
Finesse: 3000

Design sensitivity of DANCE



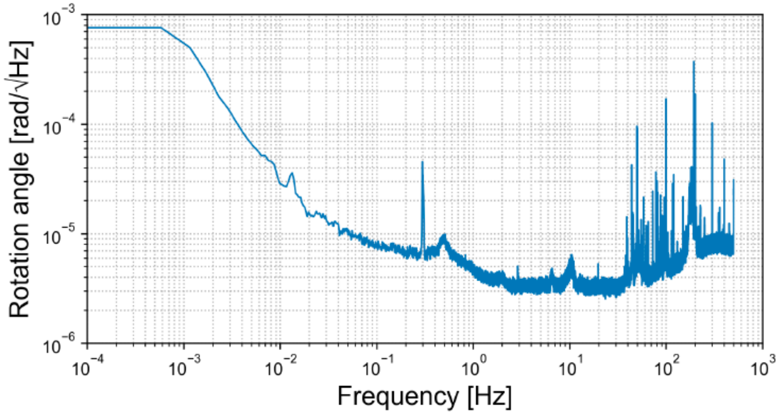
Oshima+ (2021)

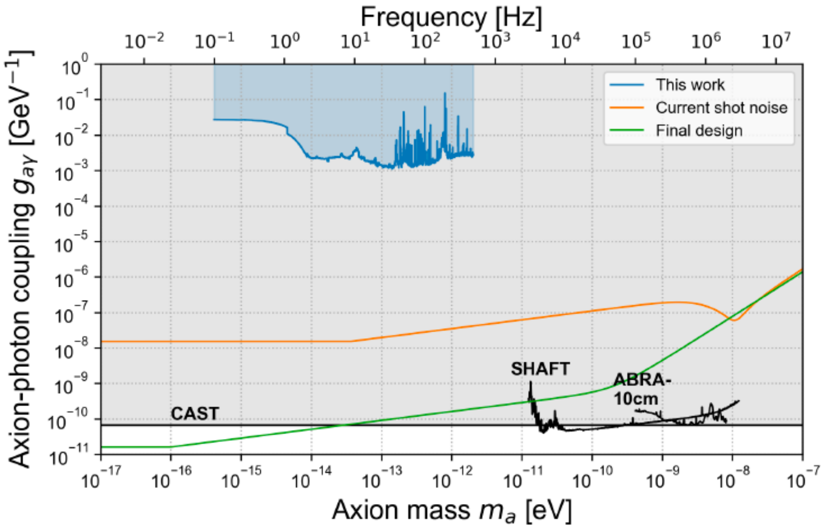
Assuming…

- ✓ quantum shot noise
- ✓ 1-year observation
- ✓ Axion is 100% in DM

First results of DANCE (May, 2021)

Oshima, Fujimoto, Kume, Morisaki, Nagano, Fujita, IO, Nishizawa, Michimura, Ando (2023)





- Rotation angle of linear polarization:

$$\phi(t) = \sqrt{\frac{P_{\mathrm{p}}(t)}{P_{\mathrm{s}}(t)+P_{\mathrm{p}}(t)}} - 2\theta_{\mathrm{HWP}}$$

- Observed for 2 weeks, and analyzed two sets of continuous 24-hour data

We need to…

- ✓ reduce classical noises
- ✓ Improve the experimental parameters

Laser power: 0.2 W → 1 W
Observation time: 24 hour → 1 year
Resonant freq. difference: 3MHz → 0 Hz

Takidera+, in progress

Astrophysical birefringence search

- A couple of axion DM searches with birefringence:
  - **Protoplanetary disk**

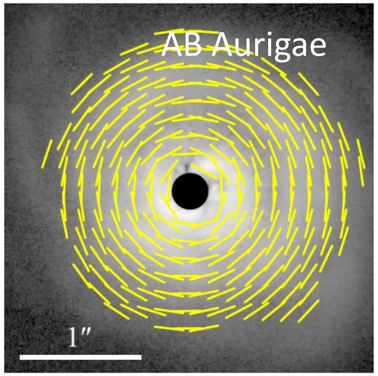
    Fujita, Tazaki, Toma (2019);
  - **Strong gravitational lenses**

    Basu, Goswami, Schwarz, Urakawa (2021);
  - **Pulsar polarimetry**

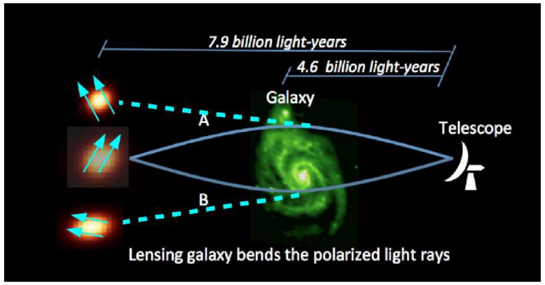
    Castillo+ (2022);
  - **Event Horizon Telescope**

    Chen+ (2020,2021);

    (Note: search for axion cloud around spinning BH)



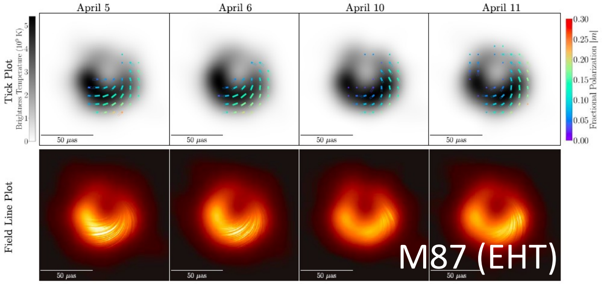
Hashimomtto+ (2011)



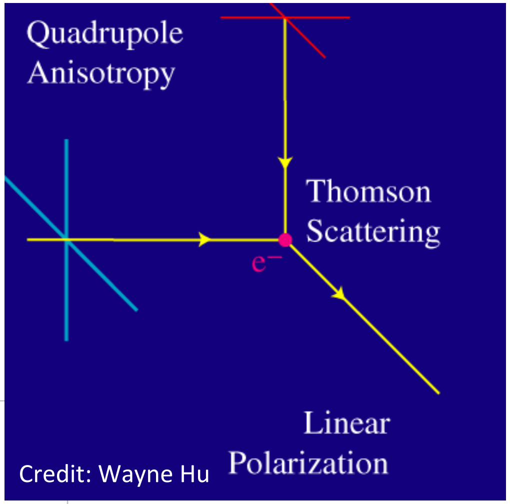
Credit: Y. Urakawa

- Sensitive to $\boxed{10^{-22}\mathrm{eV} \lesssim m_a \lesssim 10^{-18}\mathrm{eV}}$

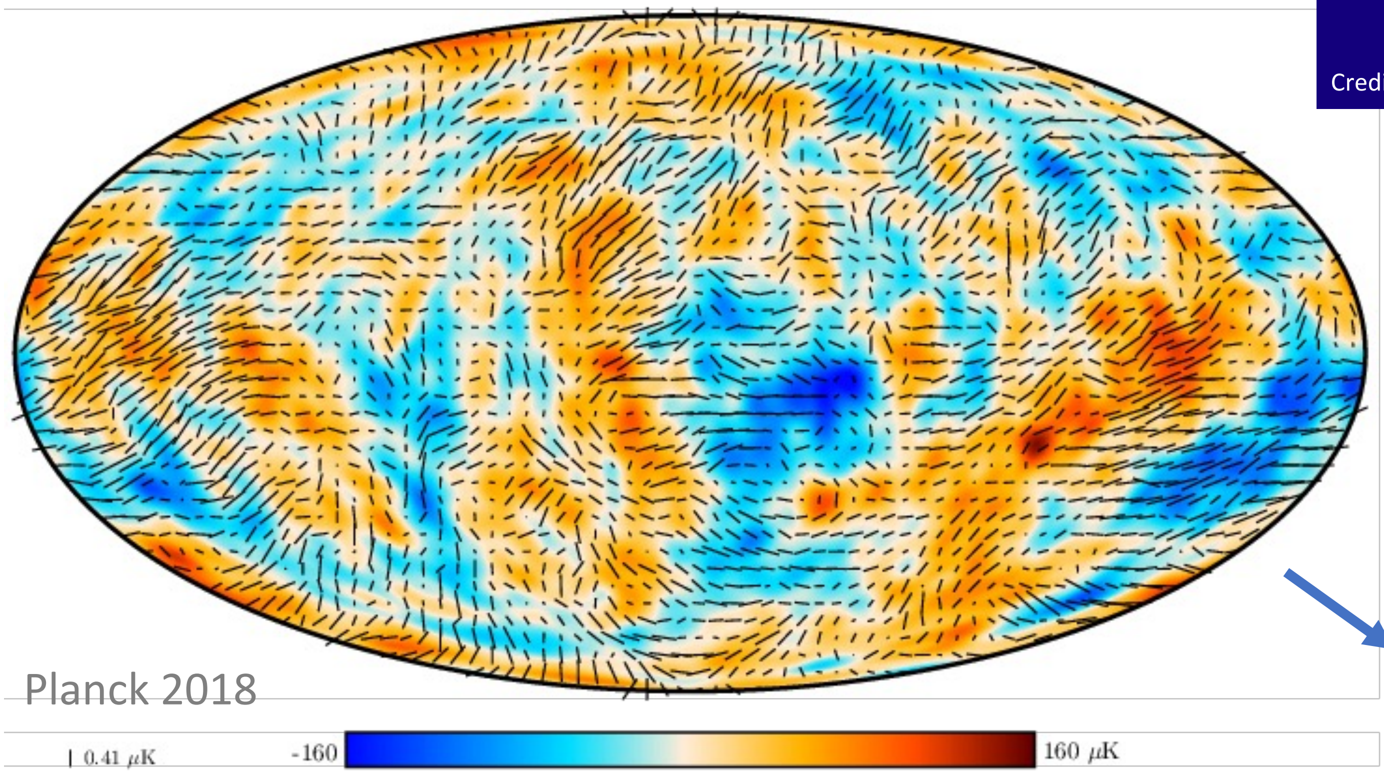
  (~years) (~hours)



Birefringence in CMB

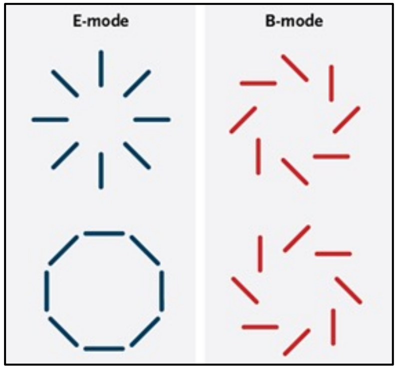


Credit: Wayne Hu



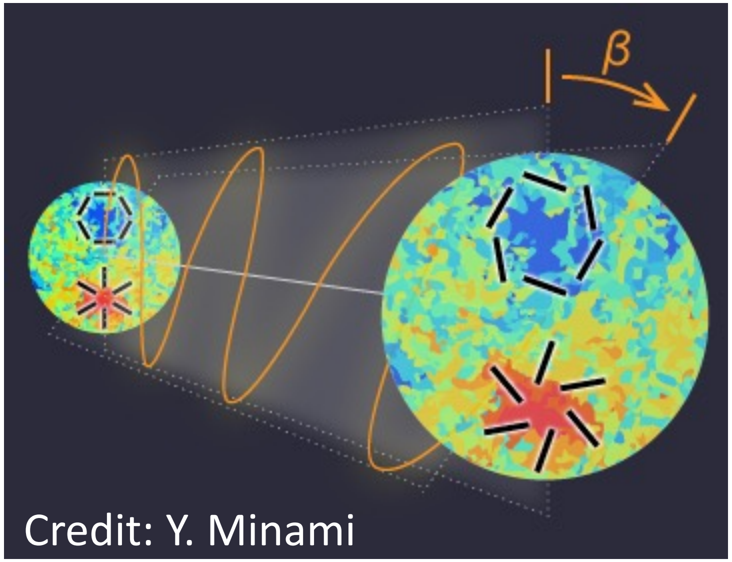
Planck 2018

E-mode v.s. B-mode



Generation EB correlation function

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

(β is assumed to be constant)

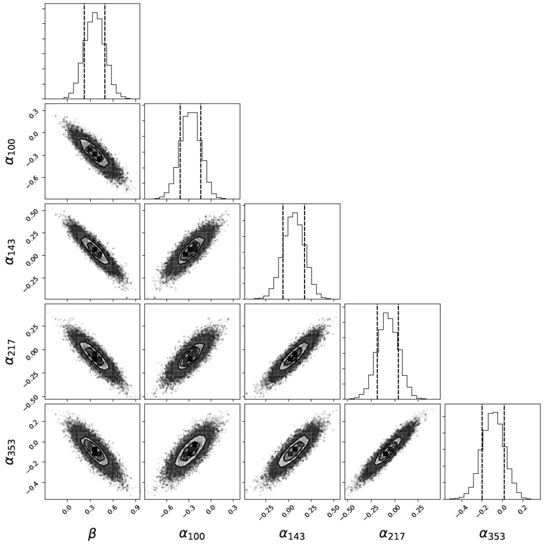
History of measurements (WMAP, Planck, ACT,…)

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

Isotropic cosmic birefringence (ICB)

Minami, Komatsu (2020); (*Planck* PR3)

calibrate the systematic angle by using the polarizations from the galactic foregrounds:



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

(upgrade!)

Eskilt & Komatsu (2022); (*Planck*/WMAP)

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

- Linear polarization rotation is potentially caused by the axion-photon interaction

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

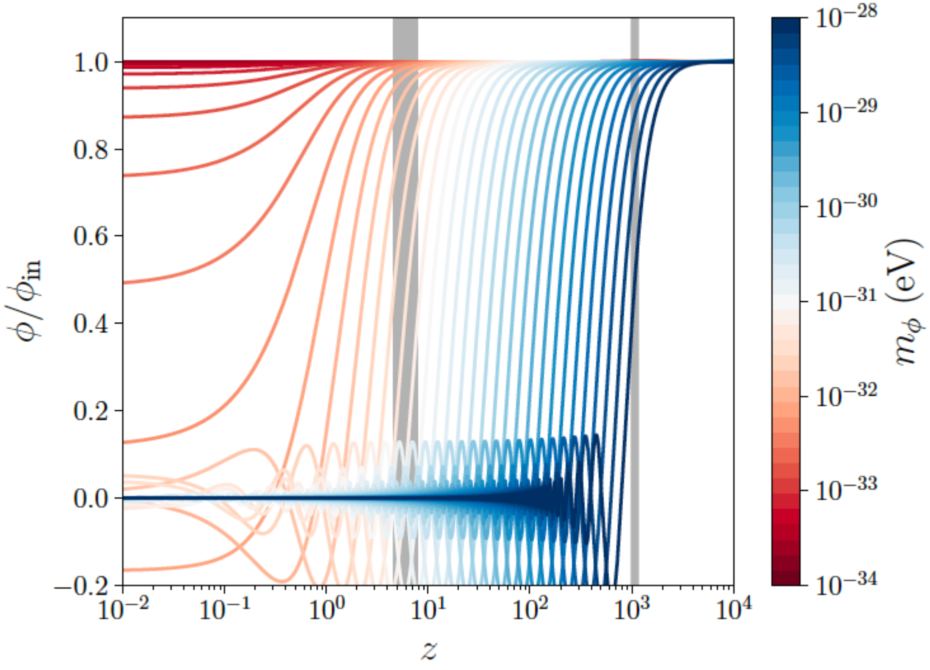
$$\beta = \frac{1}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} dt(\omega_L - \omega_R) = \frac{g_{\phi\gamma}}{2}\int_{t_{\rm emit}}^{t_{\rm obs}} dt\dot{\phi} = \frac{g_{\phi\gamma}}{2}\left[\phi(t_{\rm obs}) - \phi(t_{\rm emit})\right]$$

ICB from cosmological axion background

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

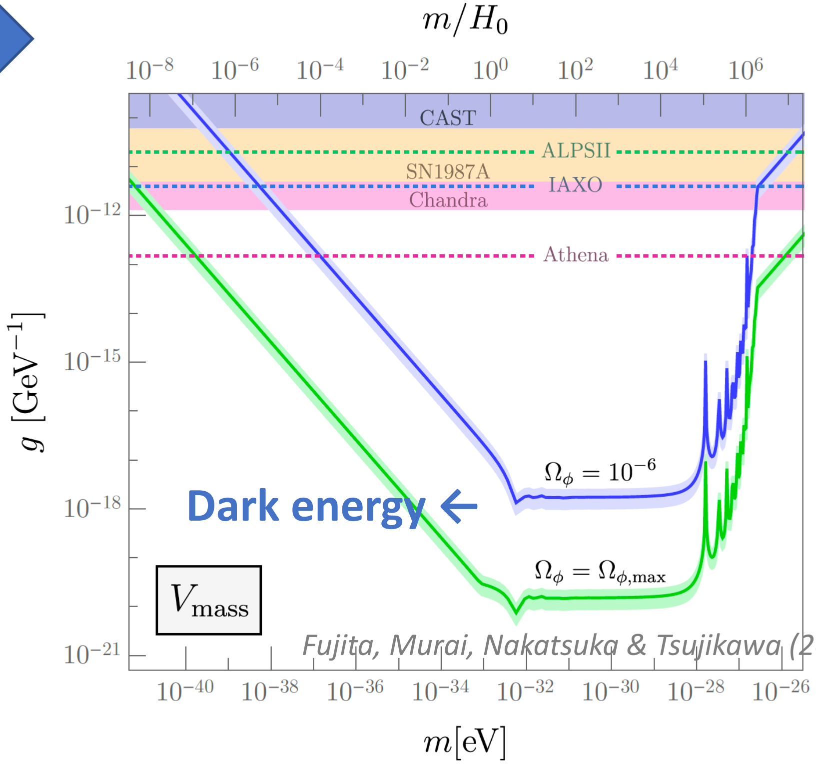
$$\boxed{\beta = \frac{g_{a\phi}}{2}\Delta\phi}$$

Time evolution of axion with different mass



Lee, Hotinli, Kamionkowski (2022)

Constraints on the axion-photon coupling



Dark energy ←

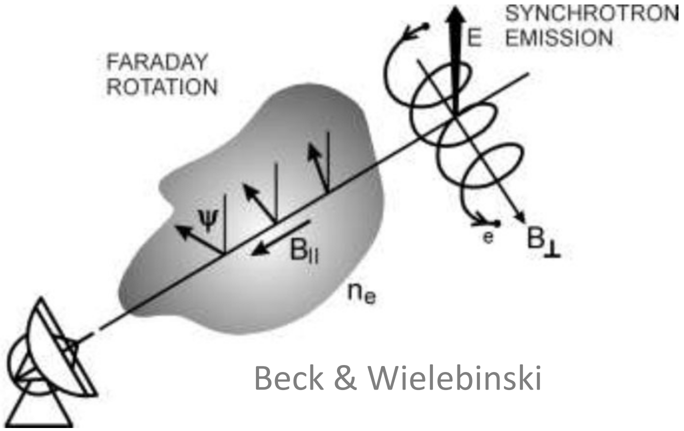
Fujita, Murai, Nakatsuka & Tsujikawa (2020);…

$$\Omega_{\phi,\rm max} \simeq \begin{cases} 0.69 \quad (m \lesssim 10^{-33}\mathrm{eV}) \\ 6\times10^{-3}h^{-2} \quad (10^{-32}\mathrm{eV} \lesssim m \lesssim 10^{-25}\mathrm{eV}) \end{cases}$$

Hlozek+ (2015)

Any other explanations on ICB?

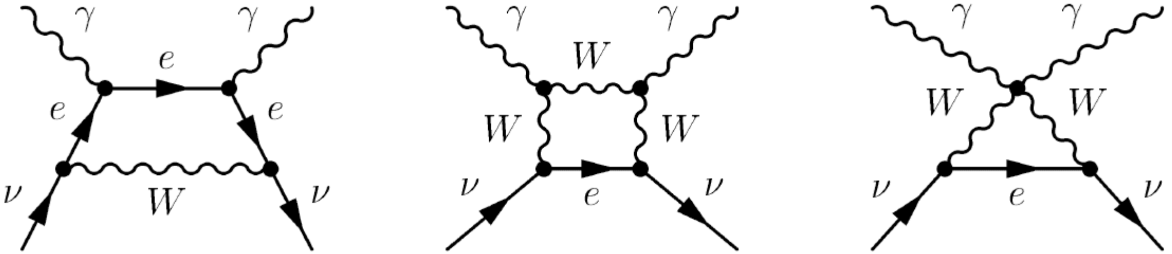
- Faraday rotation due to (cosmological) magnetic field and free electron:



Beck & Wielebinski

$$\beta = \mathrm{RM}\ \lambda^2$$

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 c^4} \int_0^d ds\ n_e(s) B_{\|}(s)$$



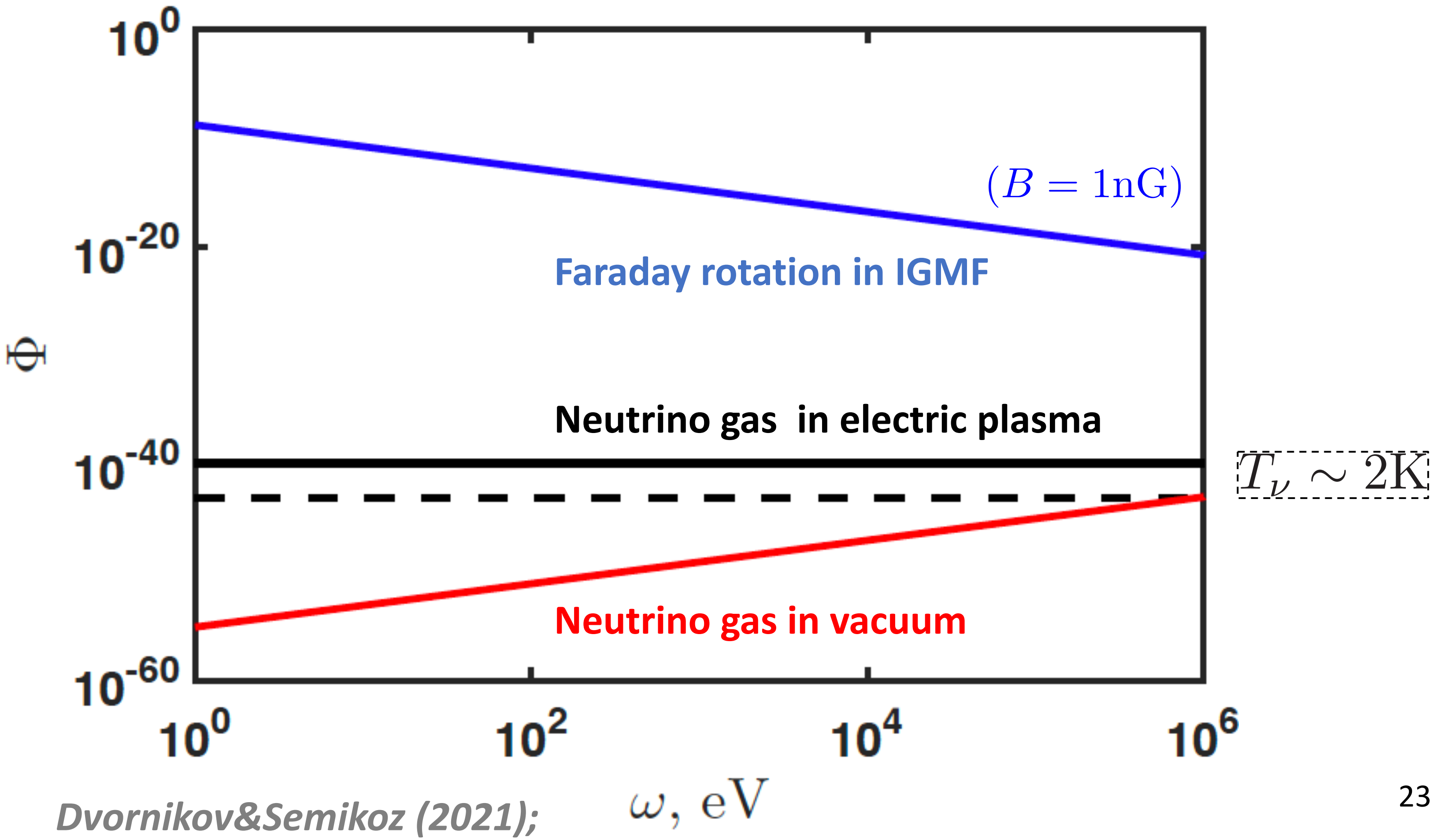
Karl & Novikov (2004);

- Via loop-interactions, neutrino-antineutrino background asymmetry could provide a difference of photon's propagation between two helicities.

Rotation angle at horizon size

$\Phi = \phi/(\ell/\ell_H) \quad \ell_H = H_0^{-1}$

Planck/WMAP: $\beta \simeq 0.005[\mathrm{rad}]$



Dvornikov&Semikoz (2021);

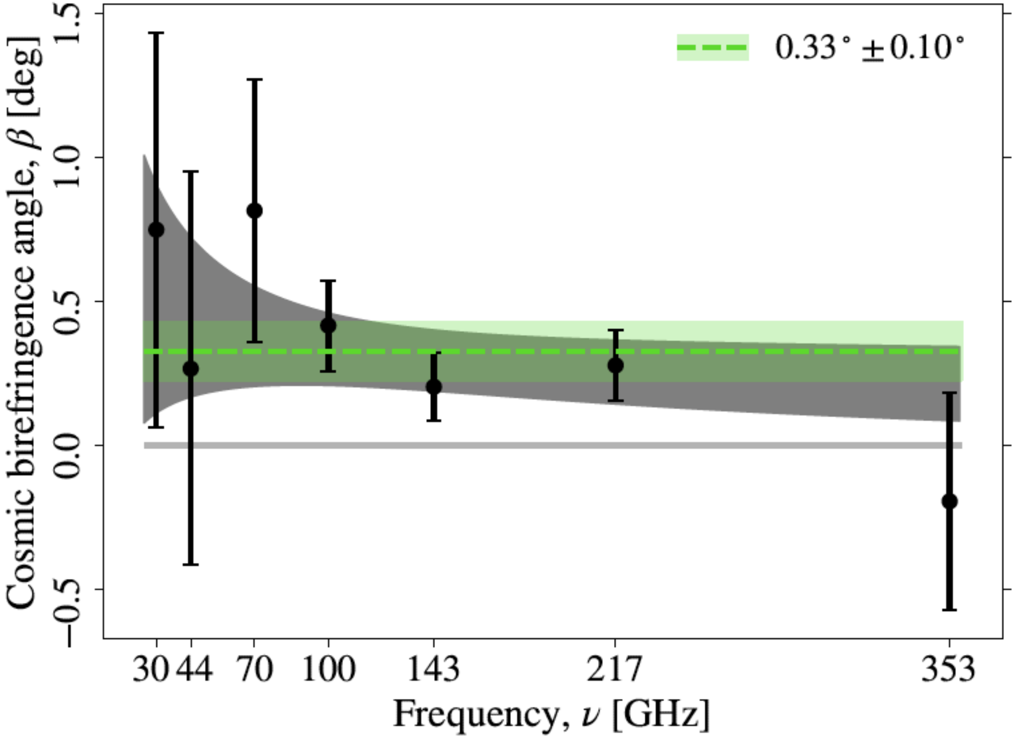
Another important observational fact

Eskilt (2022);

- Constraint on a frequency-dependence of the birefringence angle β:

$$\beta_\nu = \beta_0 \left(\frac{\nu}{\nu_0 = 150\mathrm{GHz}} \right)^n$$

(Planck DR4 polarization maps)



- For a nearly full-sky measurement,

$$\boxed{\begin{aligned} \beta_0 &= 0.29^{\circ}{}^{+0.10^\circ}_{-0.11^\circ} \\ n &= -0.35^{+0.48}_{-0.47} \end{aligned}}$$

- **Consistent with frequency-independent**

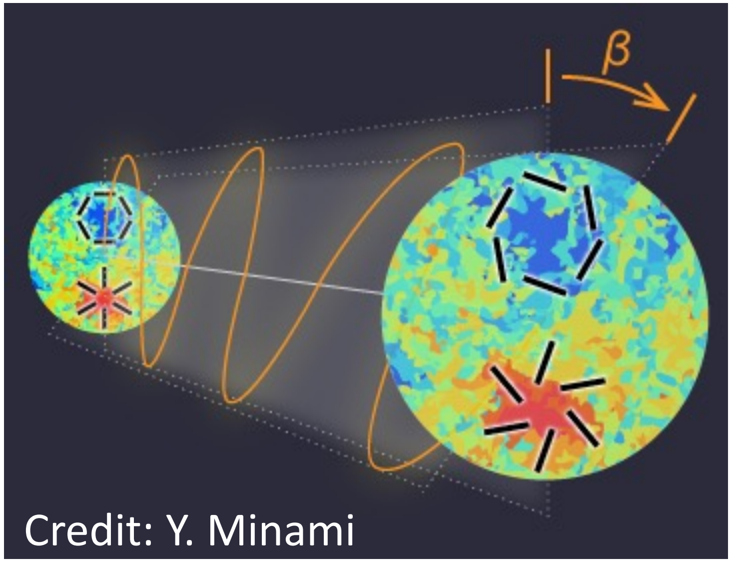
ICB from effective Lagrangian approach

- To explain this, we need to consider:

$$\mathcal{L} = -\frac{1}{4}FF - \frac{1}{4}F\tilde{\mathcal{O}}\tilde{F}$$

- On a cosmological background

$$\phi_{\tilde{\mathcal{O}}} \equiv \langle \tilde{\mathcal{O}} \rangle,$$



Credit: Y. Minami

the rotation angle is given by **its field displacement**

$$\beta = \frac{1}{2}\int_{t_{\rm LSS}}^{t_0} dt\,\frac{\partial \phi_{\tilde{\mathcal{O}}}}{\partial t} = \frac{1}{2}\left[\phi_{\tilde{\mathcal{O}}}(t_0) - \phi_{\tilde{\mathcal{O}}}(t_{\rm LSS})\right]$$

(present) (last scattering surface)

- If $\tilde{\mathcal{O}} = \tilde{\mathcal{O}}(\partial) \to \tilde{\mathcal{O}}(\omega)$, it leads to a frequency-dependent birefringence

Why axion is necessary to explain ICB?

Nakai, Namba, IO, Qiu, Saito (2023);

Chern Simons-type effective operator: $\mathcal{L}_{\rm CS} = \frac{\alpha}{8\pi}\sum_a \frac{\tilde{\mathcal{O}}_a}{\Lambda_a^n} F_{\mu\nu}\tilde{F}^{\mu\nu}$

is possible to explain measured ICB angle in the EFT of Standard Model (SMEFT)?

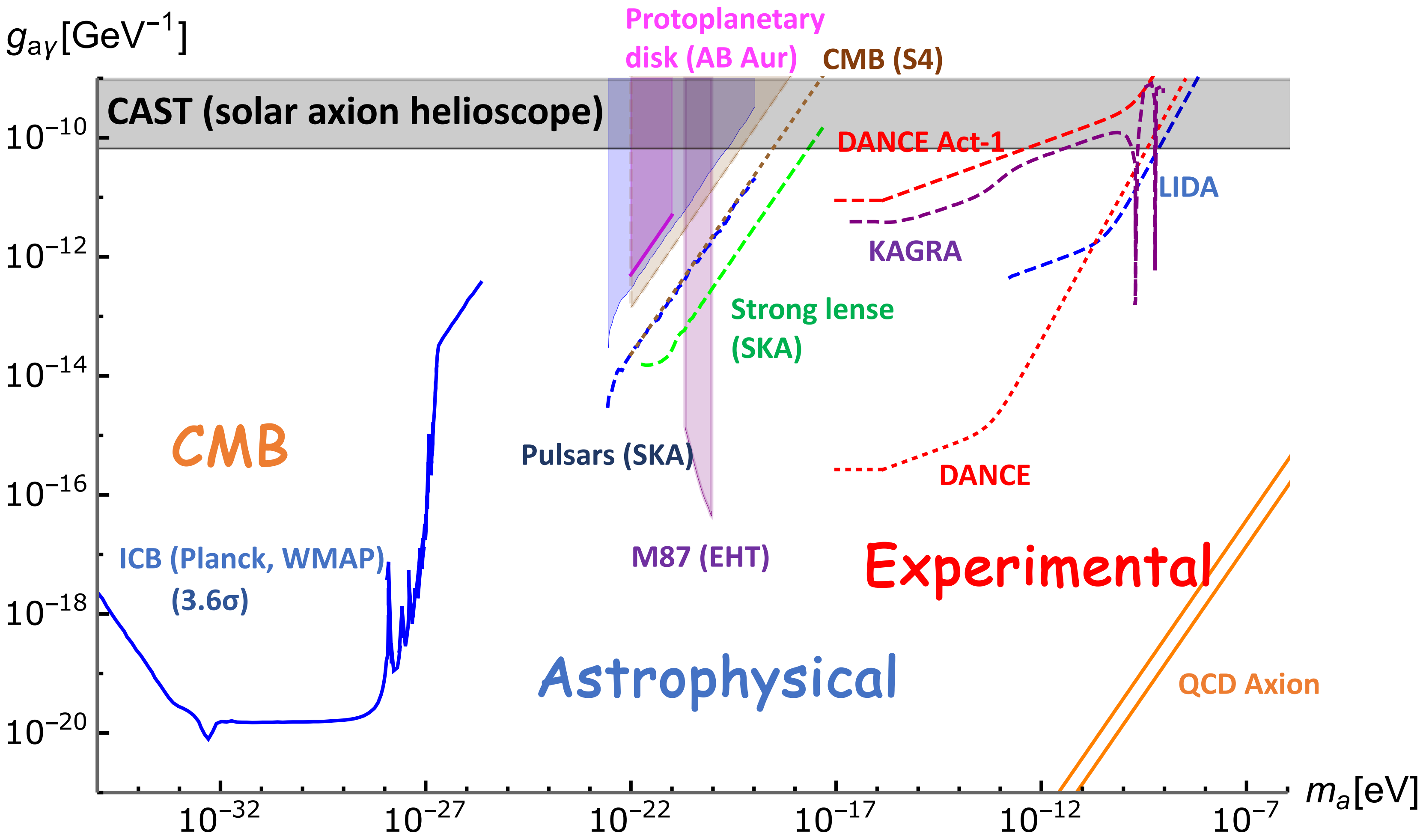
- Homogeneous & neutral background: Higgs, quark/gluons, neutrino
  - ✓ Higgs vev, quark/gluon condensates: time-independent in CMB epoch → no ICB
  - ✓ How about cosmic neutrino background?

$$\boxed{\beta \simeq -0.008^\circ \frac{\alpha}{137^{-1}} \sum_i \frac{m_i}{T_{\rm LSS}} (\tilde{\mathcal{C}}_\nu + \tilde{\mathcal{C}}_\nu^\dagger)^{ii} \frac{N^i + \bar{N}^i}{\Lambda_\nu^3}}$$

(too small)

SMEFT is hard to explain ICB → Need for a new (light) particle

Summary Overview



Thank you very much!