Can gravitational wave detectors meet the Majoron?

Ippei Obata

(Kavli Institute for the Physics and Mathematics of the Universe)

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

2024.10.11 The 4th AEI workshop for BSM @TDL Institute (Shanghai)

Motivation: two important & old problems

1. Neutrino

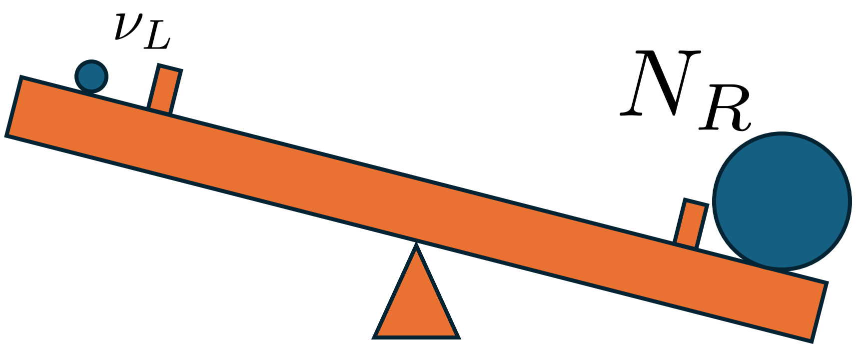
- Nonzero, but tiny mass.
- Only left-handed neutrinos have been measured

2. Matter-antimatter (baryon-number) asymmetry

- How was it produced in early Universe?

Seesaw mechanism

Minkowski (1977); Yanagida (1979);…



$$m_{\nu_L} M_{N_R} = m_D^2$$

$$(m_{\nu_L} \ll M_{N_R})$$

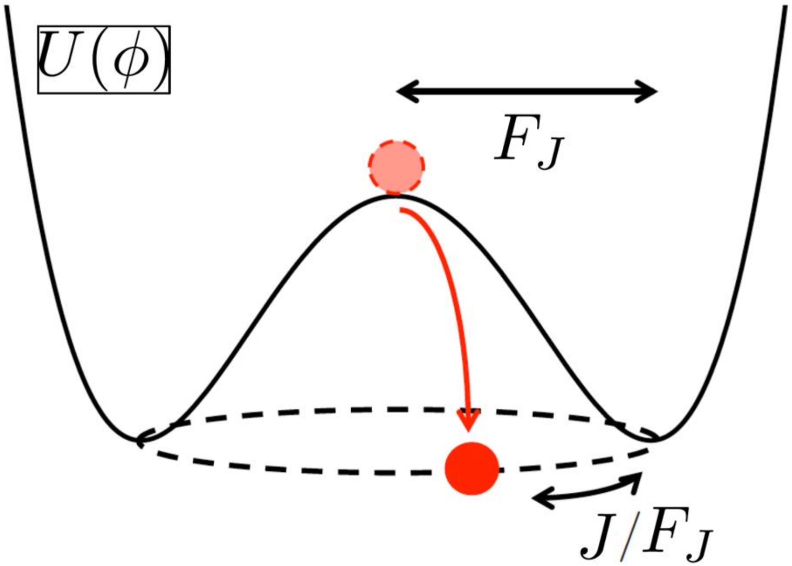
- Light (left-handed) neutrino masses are explained by heavy Majorana (right-handed) neutrino masses.
- Majorana neutrinos do not conserve the fermion number (Lepton number)

  →produces baryon number asymmetry via a leptogenesis mechanism

But… how to produce (heavy) Majorana mass?

Spontaneous breaking of lepton number

Chikashige, Mohapatra, and Peccei (1980);...



- Spontaneous symmetry breaking of a lepton number induces heavy Majorana neutrino masses

$$\phi = \frac{F_J}{\sqrt{2}} \exp(iJ/F_J)$$

- A (pseudo) Nambu-Goldstone boson (**Majoron**) arises

Standard Majoron model

Chikashige, Mohapatra, and Peccei (1980);...

$$\mathcal{L} \supset \bar{\ell}_L Y_e e_R H + \bar{\ell}_L Y_D N_R \tilde{H} + \frac{1}{2} \bar{N}_R^c Y_N N_R \phi^* + \text{h.c.}$$

Yukawa interaction　Dirac mass term　Majorana mass term $(M_N = Y_N \langle \phi \rangle = Y_N v_\phi / \sqrt{2})$

$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$: lepton doublet　H : Higgs field　N_R : right-handed neutrino

e_R : electron singlet　Y_i : Yukawa coupling constant

- Lepton charge assignment:

$$\mathcal{X}_N = \boxed{\mathcal{X}_\ell = \mathcal{X}_e = +1/2}, \ \mathcal{X}_\phi = +1,$$

This assignment is not anomalous in quantum electrodynamics (QED)

A new type of Majoron model

Liang, Diaz, Yanagida (2024);

$$\mathcal{L} \supset \bar{\ell}_L Y_e e_R H_2 + \bar{\ell}_L Y_D N_R \tilde{H}_1 + \frac{1}{2} \bar{N}_R^c Y_N N_R \phi^* + \mu_\phi H_2^\dagger H_1 \phi + \text{h.c.}$$

- Introduce a second Higgs field with lepton charge:

$$\mathcal{X}_1 = 0, \;\; \mathcal{X}_2 = \mathcal{X}_\phi = +1$$

- Lepton charge of right-handed electron and left-handed lepton doublet could be different:

$$\mathcal{X}_N = \mathcal{X}_\ell = -\mathcal{X}_e = +1/2$$

$$\rightarrow \mathcal{L}_{\text{anom}} = 3(\mathcal{X}_\ell - \mathcal{X}_e) \frac{\alpha_{\text{em}}}{4\pi} \frac{J}{F_J} F_{\mu\nu} \tilde{F}^{\mu\nu} \equiv \frac{g_{J\gamma}}{4} J F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Majoron obtains QED anomaly → testable with axion experiments!

Parameter region of Majoron as DM

- Potential energy of Majoron DM:

$$V(J) = \frac{1}{2} m_J^2 J^2 \ , \qquad J_i = F_J \theta_J^i$$ (initial value of Majoron DM)

- DM abundance:

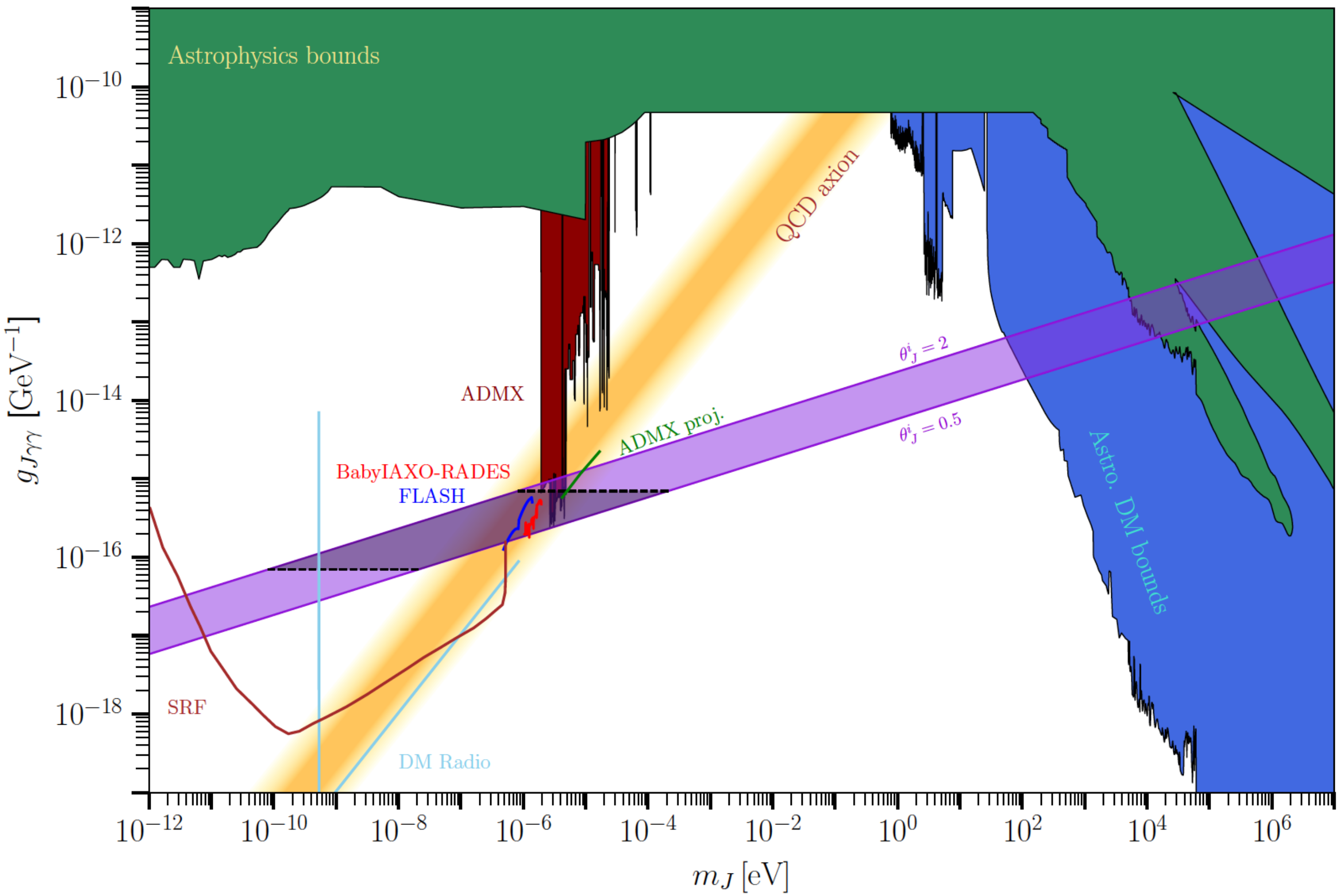
$$\Omega_J h^2 \simeq 0.12 \left(\frac{m_J}{10^{-10}\mathrm{eV}} \right)^{1/2} \left(\frac{F_J \theta_J^i}{1.9 \times 10^{14}\mathrm{GeV}} \right)^2$$

- Majoron DM-photon coupling: $g_{J\gamma} = \frac{3\alpha_{\mathrm{em}}}{\pi F_J}$

$$\rightarrow g_{J\gamma} \simeq 3.7\theta_J^i \times 10^{-17}\mathrm{GeV}^{-1} \left(\frac{m_J}{10^{-10}\mathrm{eV}} \right)^{1/4} \left(\frac{\Omega_J h^2}{0.12} \right)^{-1/2}$$

Majoron can meet QCD axion experiment

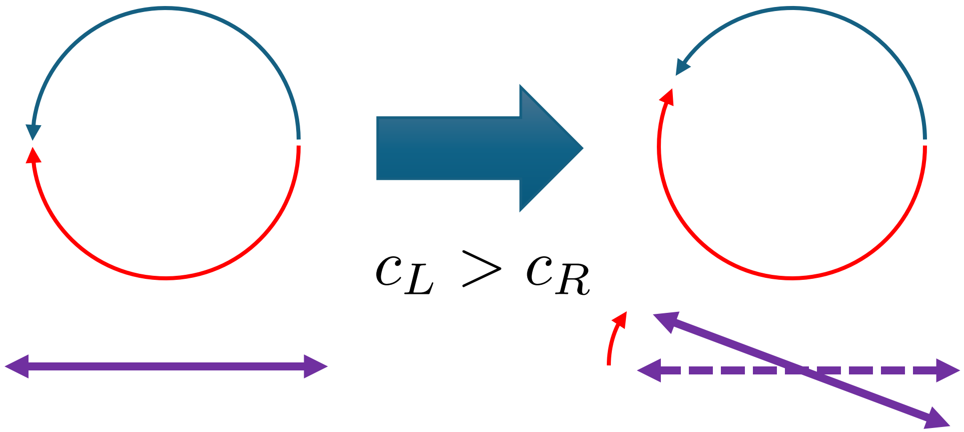
Liang, Diaz, Yanagida (2024);



(another) Majoron-photon interaction

- Majoron background evolution differentiates the phase velocities of circularly-polarized photons:

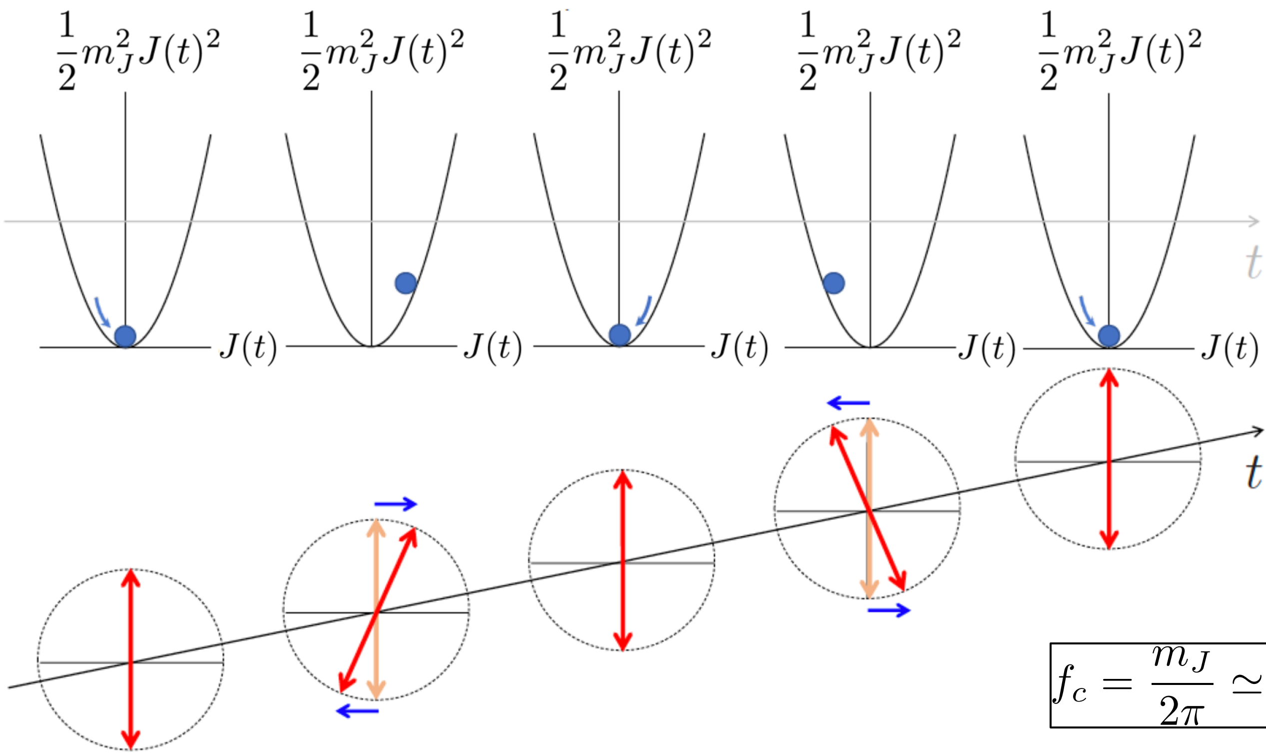
$$\ddot{A}_k^{\mathrm{L/R}} + \omega_{\mathrm{L/R}}^2 A_k^{\mathrm{L/R}} = 0, \quad c_{\mathrm{L/R}} \equiv \frac{\omega_{\mathrm{L/R}}}{k} = \sqrt{1 \pm \frac{g_{J\gamma}\dot{J}}{k}}$$



- Leads to a polarization rotation effect

Majoron (axion) background behaves as a birefringent material!

Birefringence by Majoron dark matter

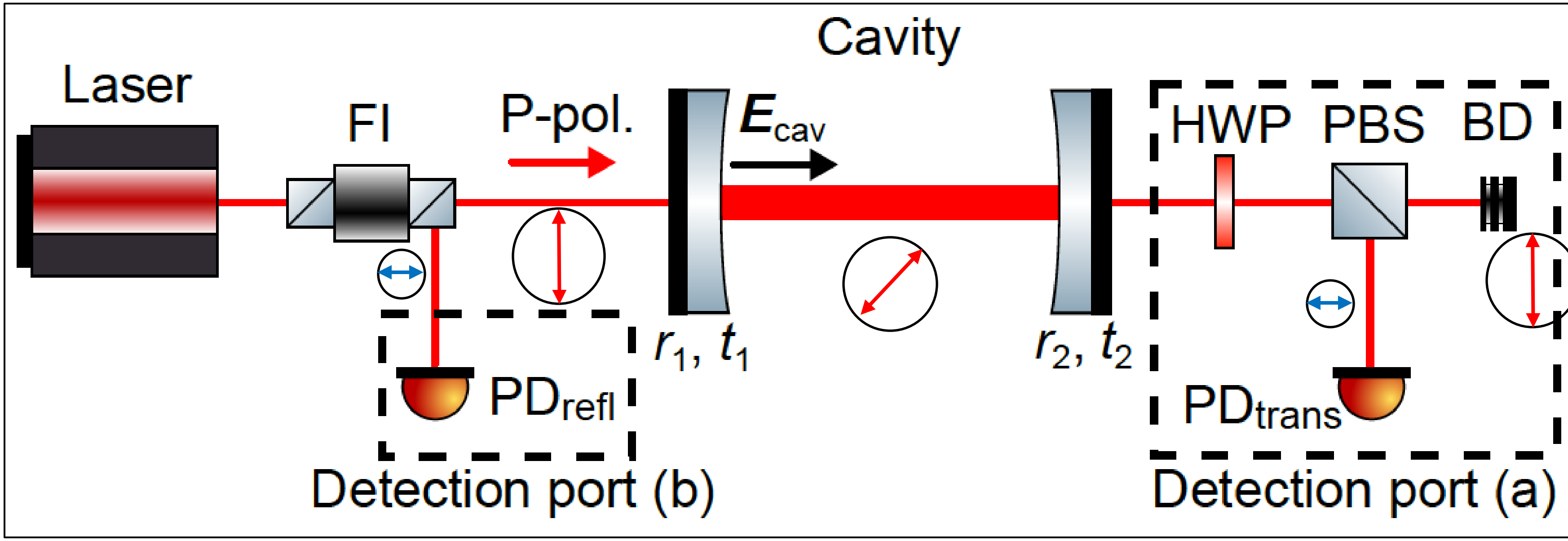


$$f_c = \frac{m_J}{2\pi} \simeq 2.4\mathrm{Hz}\left(\frac{m_J}{10^{-14}\mathrm{eV}}\right)$$

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

Dark matter search with resonant cavity

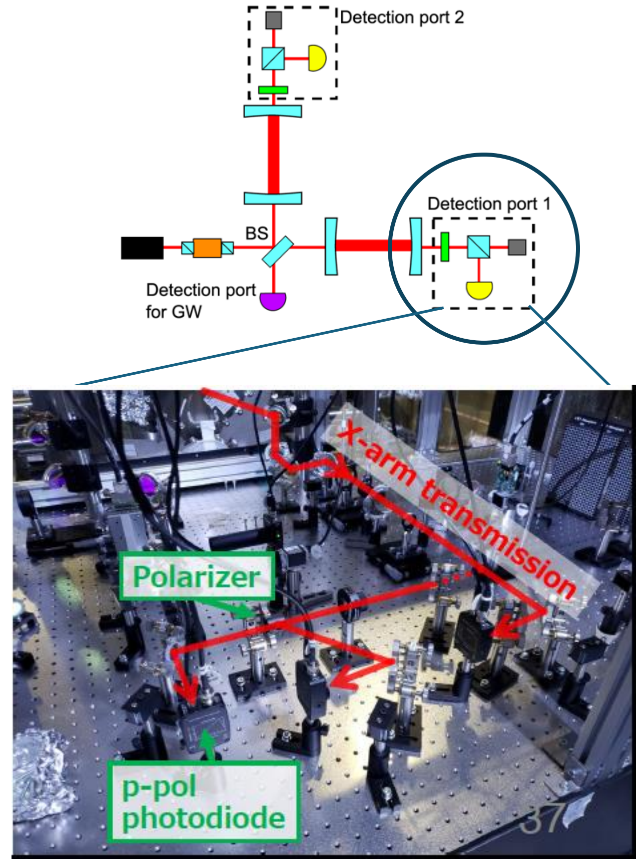
Nagano, Fujita, Michimura, IO, PRL (2019);



- Majoron DM acts on the laser in the resonator, creating a new polarization state:

$$\boldsymbol{E}_{\rm cav} \simeq \frac{t_1}{1 - r_1 r_2}\left[\boldsymbol{E}^p(t) - \delta\phi(t)\boldsymbol{E}^s(t)\right]$$

DM search with GW detector

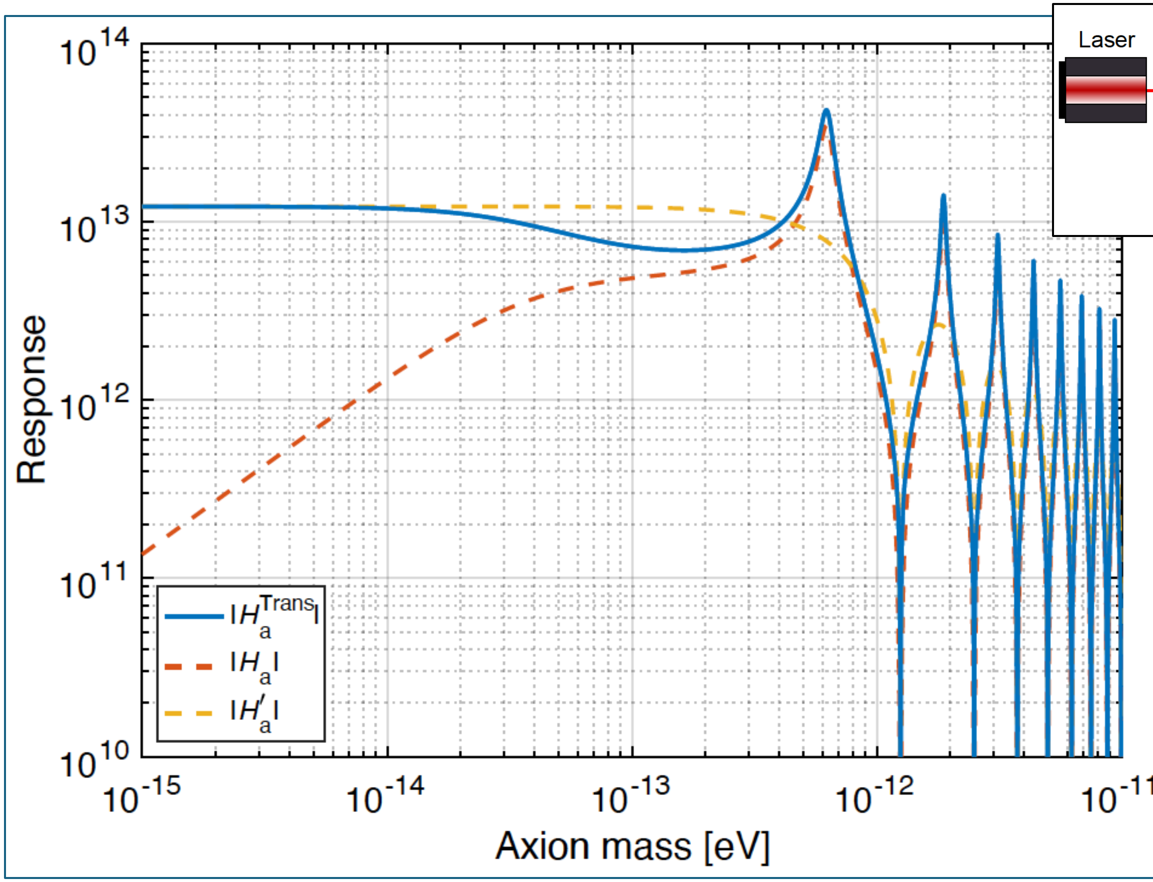


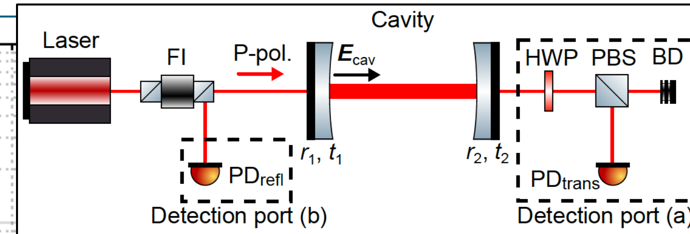
- The polarization optics have been installed at 3-km arm cavity transmission of KAGRA.
- Ready for first data taking in O4 run (starting in 2025)

Response function

$$\delta\phi(t) \equiv \int_{-\infty}^{\infty} \tilde{\delta c}(m) H_{\mathrm{a}}(m) e^{imt} \frac{dm}{2\pi}$$

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





: detection port (a)

: detection port (b)

$$H_{\mathrm{a}}(m) \equiv i \frac{k}{m} \frac{4 r_1 r_2 \sin^2\left(\frac{m L_{\mathrm{cav}}}{2}\right)}{1 - r_1 r_2 e^{-i 2 m L_{\mathrm{cav}}}} \left(-e^{-i m L_{\mathrm{cav}}}\right)$$

$$H_{\mathrm{a}}'(m) = \frac{2k}{m} e^{i \frac{m L_{\mathrm{cav}}}{2}} \sin\left(\frac{m L_{\mathrm{cav}}}{2}\right)$$

Experimental sensitivity

- Quantum shot noise is assumed to be a primal noise:

$$\sqrt{S_{\rm shot}(m)} = \frac{1}{\frac{t_1 t_2}{1-r_1 r_2} H_a^{\rm Trans}(m) \sqrt{\frac{2P_0}{k}}}$$

- The signal-to-noise ratio reads

$$\mathrm{SNR} = \begin{cases} \frac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 & (T_{\rm obs} \lesssim \tau) \\ \frac{(T_{\rm obs}\tau)^{1/4}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 & (T_{\rm obs} \gtrsim \tau) \end{cases}$$

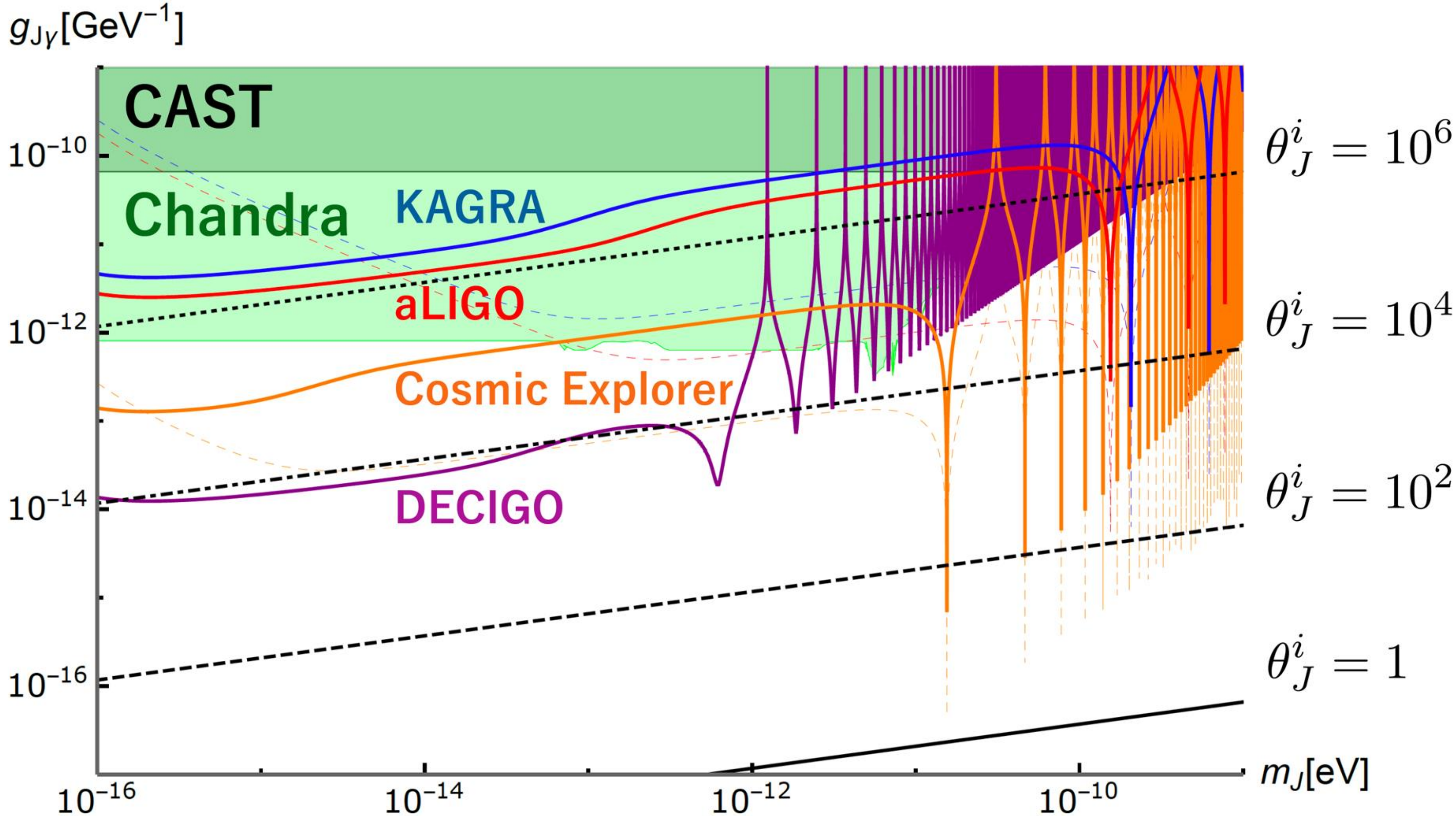
$$\delta c_0 = \frac{g_{J\gamma}}{k}\sqrt{\frac{\rho_{\rm DM}}{2}}$$

$$\tau \equiv 2\pi/(m_J v^2)$$ (DM coherent time)

- Sensitivity of DM-photon coupling with two detection ports:

$$g_{J\gamma}(m) \simeq 1.3 \times 10^{12}\,\mathrm{GeV}^{-1}\left(\frac{1064\mathrm{nm}}{\lambda}\right)\begin{cases} \sqrt{\frac{S_{\rm shot}(m)}{T_{\rm obs}}} & (T_{\rm obs} \lesssim \tau) \\ \frac{\sqrt{S_{\rm shot}(m)}}{(T_{\rm obs}\tau)^{1/4}} & (T_{\rm obs} \gtrsim \tau) \end{cases}$$

Constraints on the parameter regions



- 1-year observation
- Majoron as 100% dark matter

θ_J^i : initial angle of Majoron DM

Summary & Outlook

- Majoron is a NG-boson from lepton-number symmetry breaking and can behave as DM, couples to QED anomaly.
- Its oscillatory behavior is potentially testable with the polarization modulation of laser light in GW detector.
- Predicted parameter region is tiny and challenging to search for it.
- If there exists a scenario of generating Majoron DM with large field excursion

$$J \gg F_J \ \left(|\theta_J^i| \gg 1\right)$$

we may search for it with current or ongoing GW detectors

谢谢大家的关注！