Probing Majoron Dark Matter with Optical Interferometry

Ippei Obata

(Institute of Particle and Nuclear Studies, KEK)





What is dark matter? - Comprehensive study of the huge discovery space in dark matter (2020-2024)

2025.7.21 PASCOS (the 30th) @Durham University

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);...



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 $(M_N=Y_N\langle\phi
angle=Y_Nv_\phi/\sqrt{2})$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$
: lepton doublet H : Higgs field N_R : right-handed neutrino e_R : electron singlet Y_i : Yukawa coupling constant

Lepton charge assignment:

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

This assignment is not anomalous in quantum electrodynamics (QED)

A new type of Majoron model

Liang, Diaz, Yanagida, PRL (2024); Lu, Picker, Kusenko, Yanagida (2025)

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

Introduce a second Higgs field with lepton charge:

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

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

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

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

Majoron obtains QED anomaly → testable with axion experiments!

Majoron-photon interaction

Majoron background evolution differentiates the phase velocities of circularlypolarized 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



- 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:

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

DM search with GW detector



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

First data taking in O4 run was started! (June 2025)

Response function



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



Experimental sensitivity

Quantum shot noise is assumed to be a primal noise:

$$\sqrt{S_{\text{shot}}(m)} = \frac{1}{\frac{t_1 t_i}{1 - r_1 r_2} |H(m)| \sqrt{\frac{2P_0}{k}}}$$

The signal-to-noise ratio reads

$$(r_i, t_i : \text{reflectivity, transmittivity})$$

 $(P_0 : \text{indicend laser power})$
 $(k : \text{wave number of laser light})$

$$\mathrm{SNR} = \begin{cases} \frac{\sqrt{T_{\mathrm{obs}}}}{2\sqrt{S_{\mathrm{shot}}(m)}} \delta c_0 & (T_{\mathrm{obs}} \lesssim \tau) \\ \frac{(T_{\mathrm{obs}}\tau)^{1/4}}{2\sqrt{S_{\mathrm{shot}}(m)}} \delta c_0 & (T_{\mathrm{obs}} \gtrsim \tau) \end{cases} & \delta c_0 = \frac{g_{J\gamma}}{k} \sqrt{\frac{\rho_{\mathrm{DM}}}{2}} \\ \tau \equiv 2\pi/(m_J v^2) & (\mathrm{DM \ coherent \ time}) \end{cases}$$

Sensitivity of DM-photon coupling with two detection ports:

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

Parameter region of Majoron as DM

Potential energy of Majoron DM:

■ Initial value of Majoron field:

$$V(J) = m_J^2 F_J^2 \left[1 - \cos\left(\frac{J}{F_J}\right) \right] \qquad J_i = F_J \theta_J^i$$

DM abundance:

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

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

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



Summary & Outlook

- Majoron is a (pseudo) Nambu Gold-boson from a global Lepton symmetry breaking and can be a viable candidate for dark matter in our universe.
- Although the original Majoron model did not include couplings to photons, a recent variant model has shown that Majoron can indeed couple to photons via a chiral anomaly.
- Such Majoron dark matter differentiates the phase velocities of circularpolarized photons and inducing an oscillatory rotation of the polarization direction, opening up the possibility of detecting signal as a time-varying interference pattern with optical interferometry.
- The predicted parameter region for Majoron dark matter is challenging to probe, but potentially testable with certain frequency bands of current and future GW experiments.

Thank you very much!