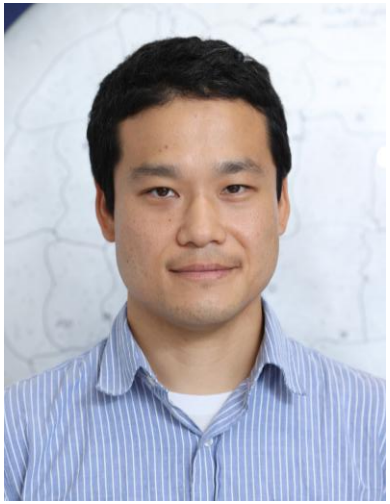
DANCE: Dark matter Axion search with riNg Cavity Experiment



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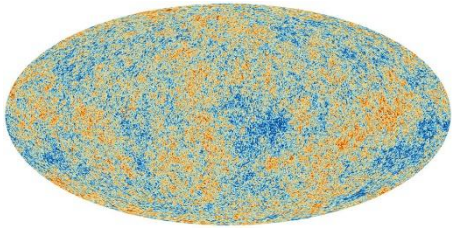
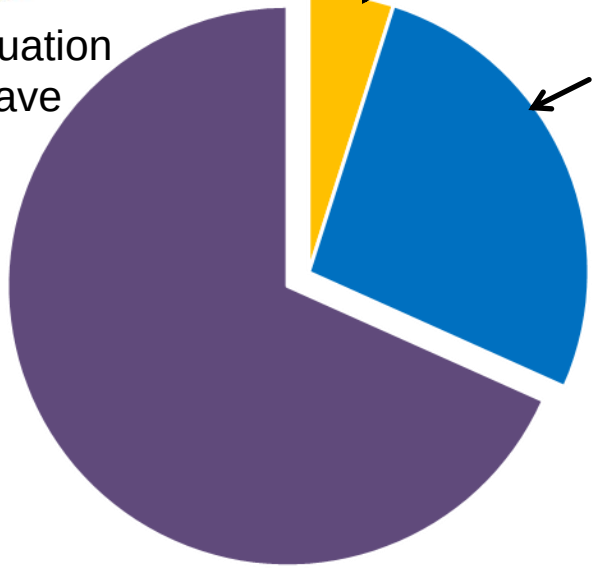
Dark Matter Mystery

- Suggested in 1930s from galaxy rotation curves
- Accounts for ~80% of all the matter of the universe
- The nature remains mystery



Temperature fluctuation of cosmic microwave background

Derive energy



Ordinary matter (~5%)
can be explained by the standard model of particle physics

Dark matter (~27%)
not included in the standard model of particle physics

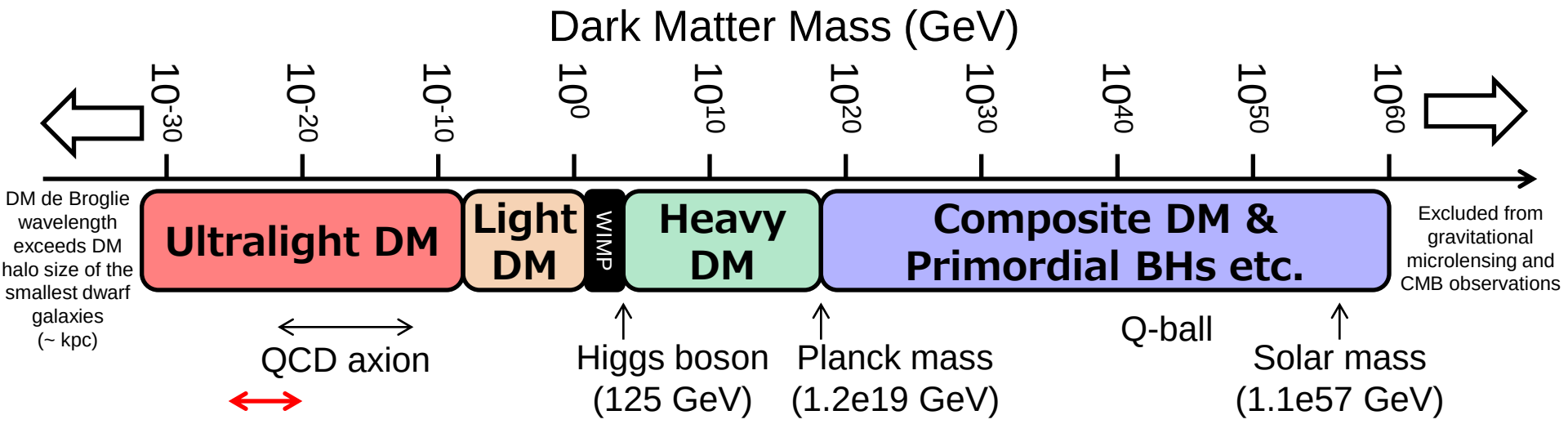
All the matter

This standard model of cosmology is amazingly consistent with various observations

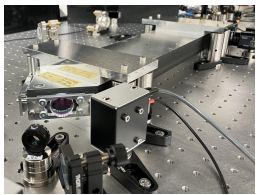
Dark energy (~68%)
drives an acceleration of the expansion of the universe

Dark Matter Models

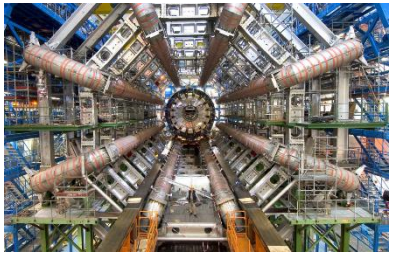
- ~90 orders of magnitude
- Searches focused on WIMPs, but not detected yet
- Motivates new searches for other candidates



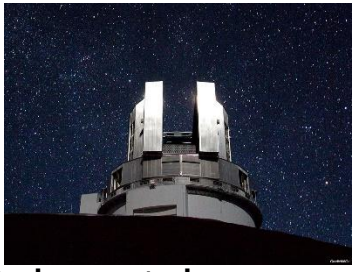
2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)
Laser Interferometry



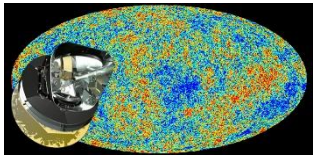
Underground experiments (XENON etc.)



LHC



Subaru telescope etc.



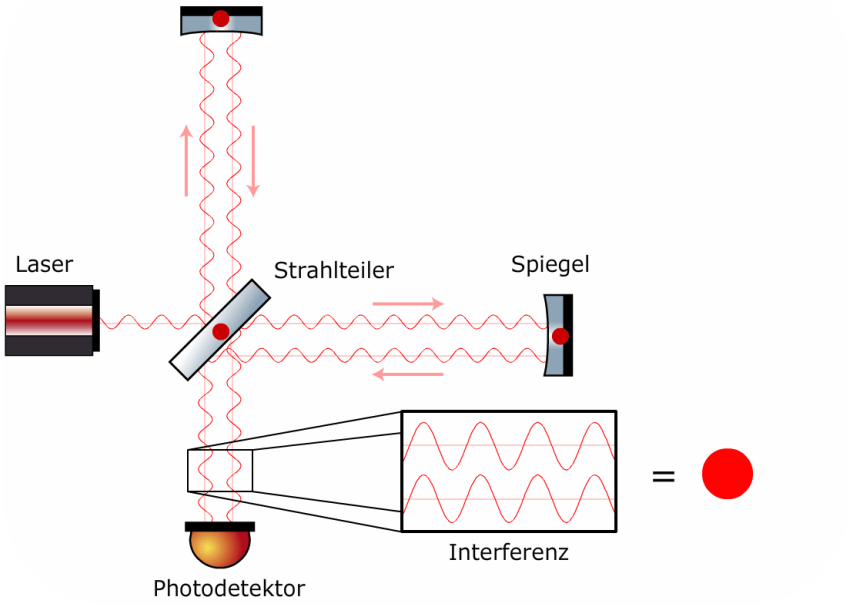
Cosmic microwave background

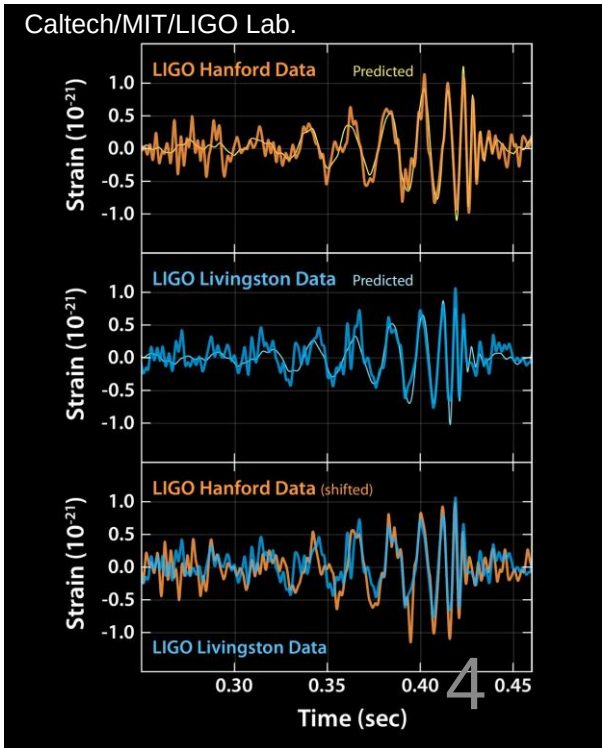
Ultralight DM with Interferometers

- Bosonic ultralight field (<~1 eV) are well-motivated from cosmology
- Behaves as classical waves

$$f = 242\ \mathrm{Hz} \left(\frac{m_{\mathrm{DM}}}{10^{-12}\ \mathrm{eV}} \right)$$

- Laser interferometers are sensitive to such oscillating changes





Various Searches Possible

Tiny forces from vector DM

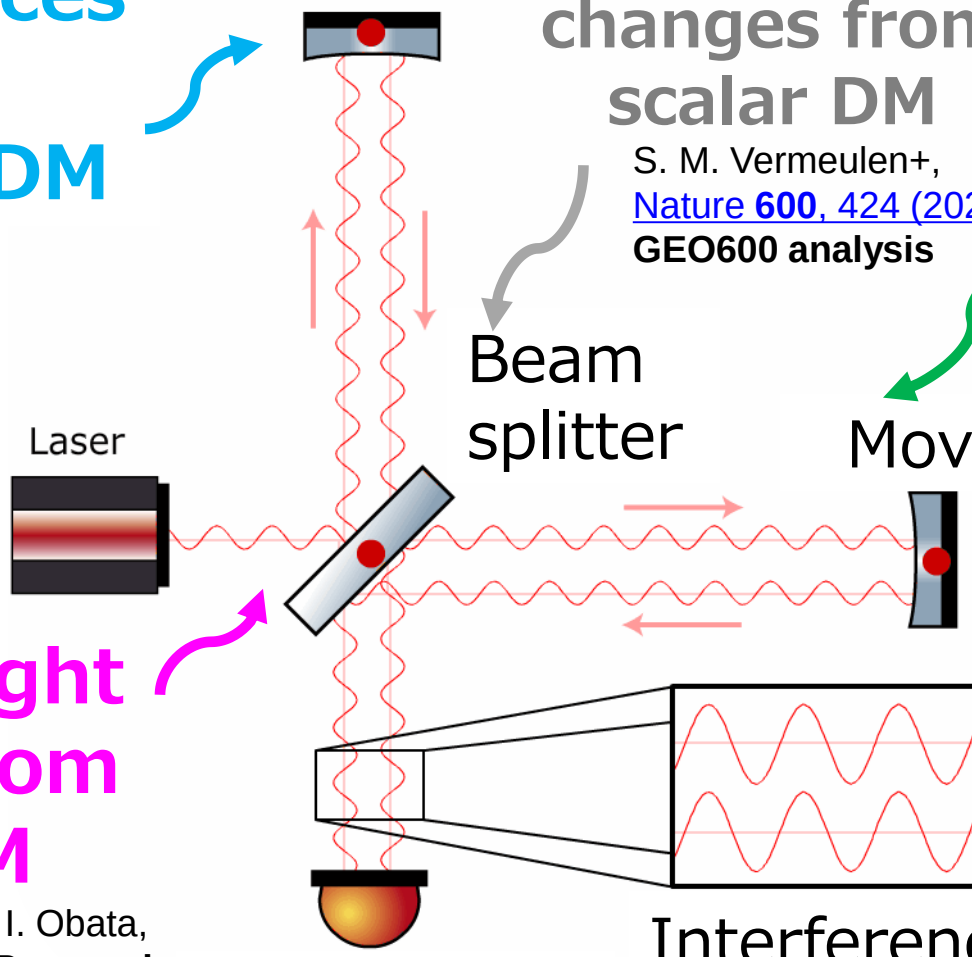
LIGO-Virgo-KAGRA,
PRD **105**, 063030 (2022)
LIGO/Virgo O3 analysis
LIGO-Virgo-KAGRA,
PRD 110, 042001 (2024)
KAGRA O3GK analysis

Mirror thickness changes from scalar DM

S. M. Vermeulen+,
Nature **600**, 424 (2021)
GEO600 analysis

Metric changes from spin-2 DM

Y. Manita+,
PRD **107**, 104007 (2023)



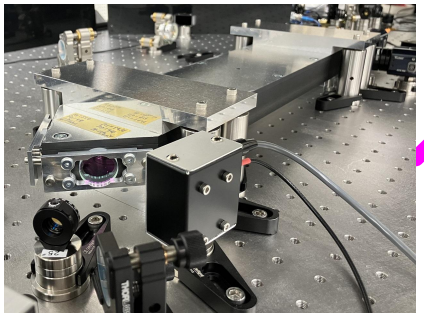
Speed of light changes from axion DM

K. Nagano, T. Fujita, YM, I. Obata,
PRL **123**, 111301 (2019) **Proposal**
Y. Oshima+, PRD **108**, 072005 (2023)
Table-top experiment DANCE analysis

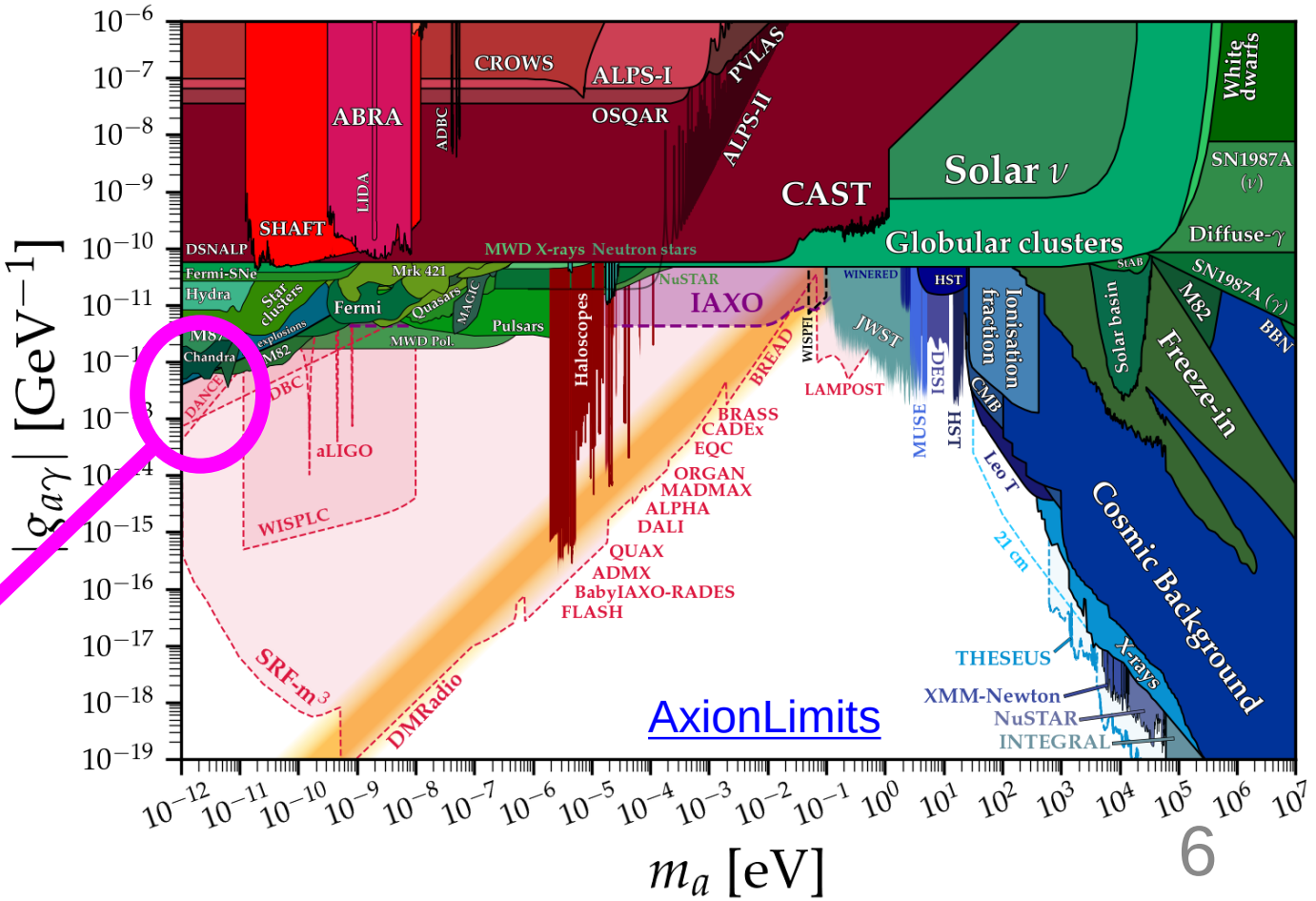
= Fringe change

Axion Dark Matter

- Many experiments to search for ALPs through axion-photon coupling, especially by using magnetic fields (but **ours don't**)



DANCE



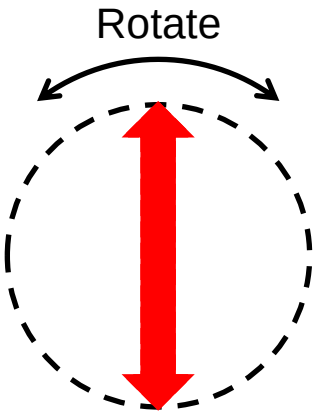
Polarization Modulation from Axions

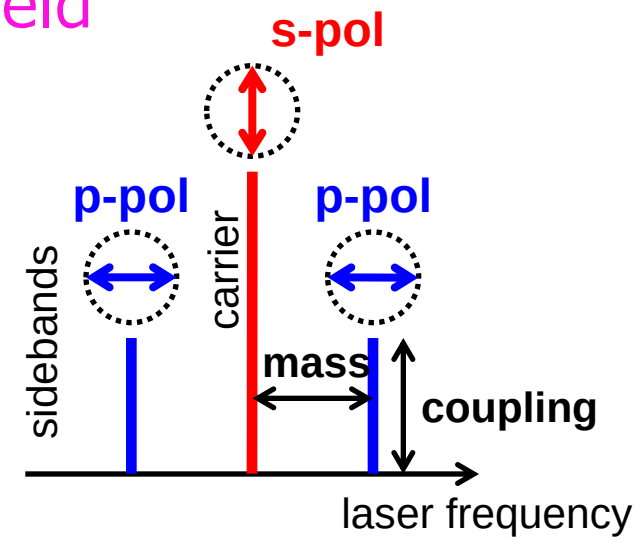
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

coupling constant　axion field　axion mass

- Linear polarization will be modulated
  - p-pol sidebands will be generated from s-pol
- Search can be done without magnetic field

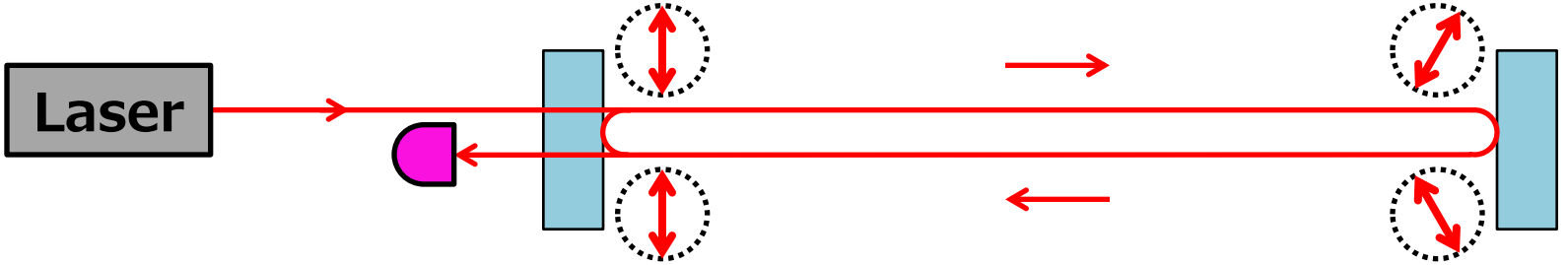




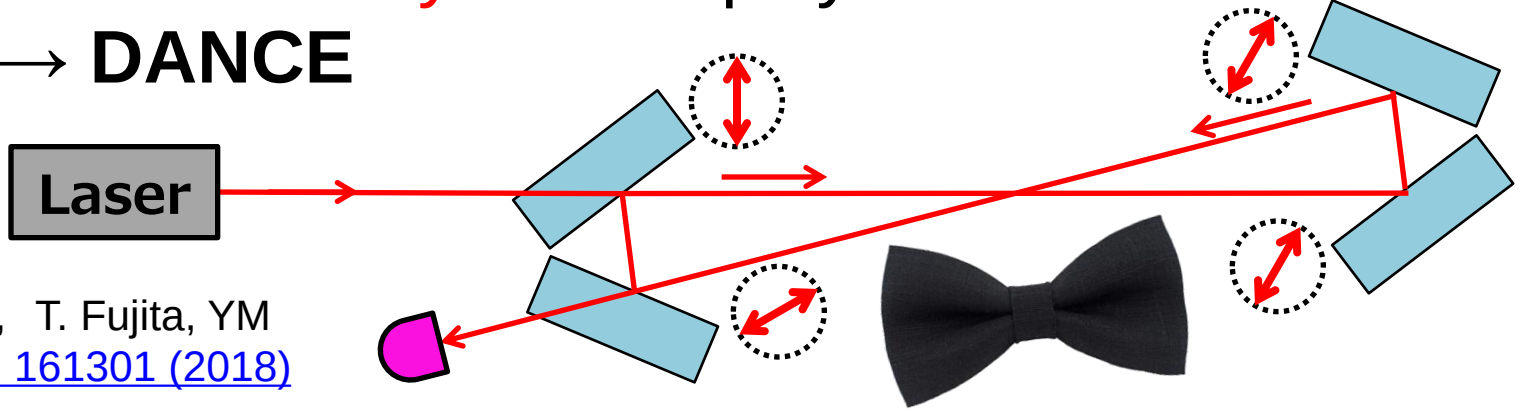
Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

- Optical cavities can increase the optical path, but the polarization is flipped by mirror reflections



- Bow-tie cavity can amplify the rotation
  → **DANCE**

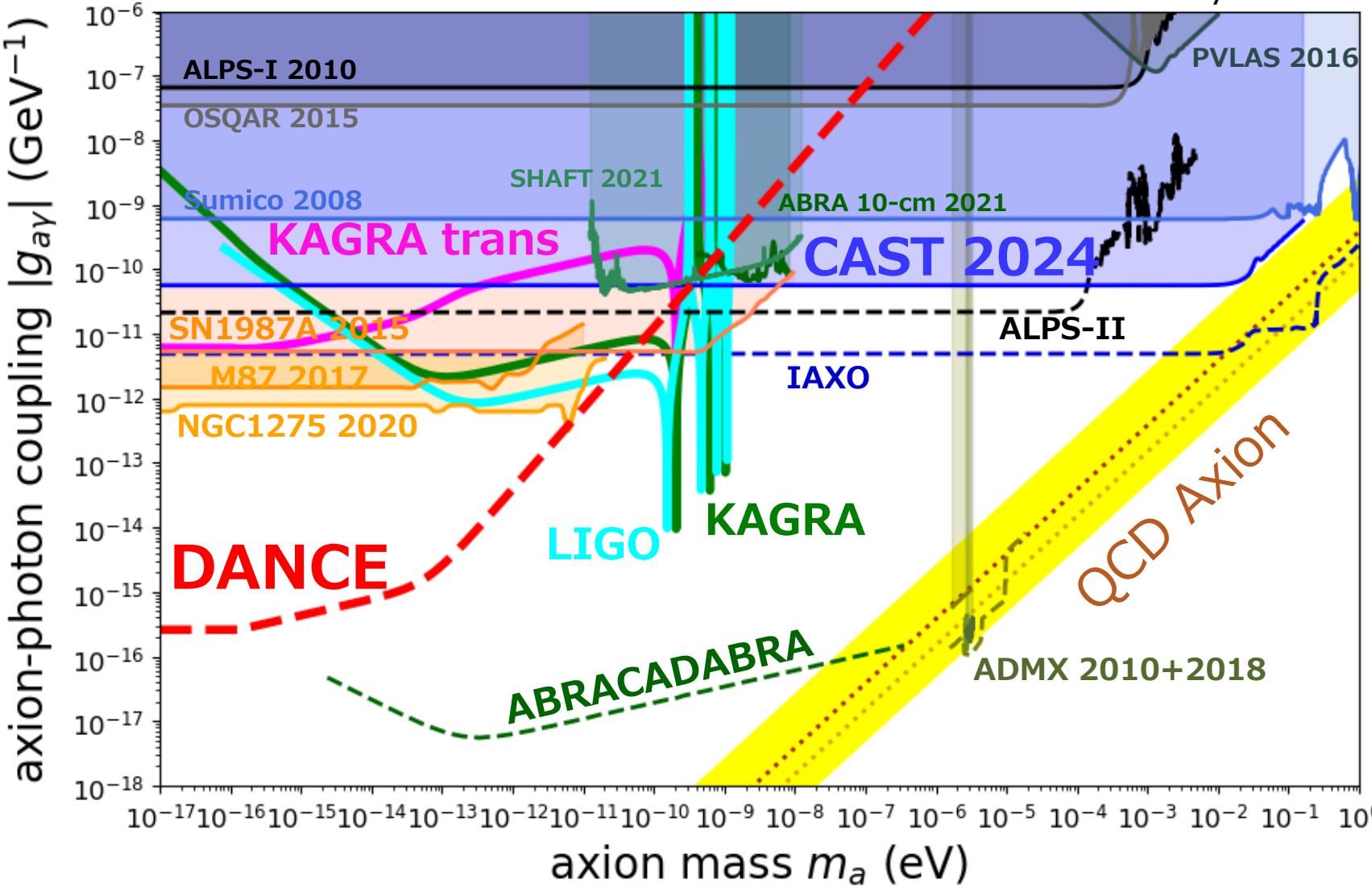


I. Obata, T. Fujita, YM
PRL **121**, 161301 (2018)

Estimated Reach

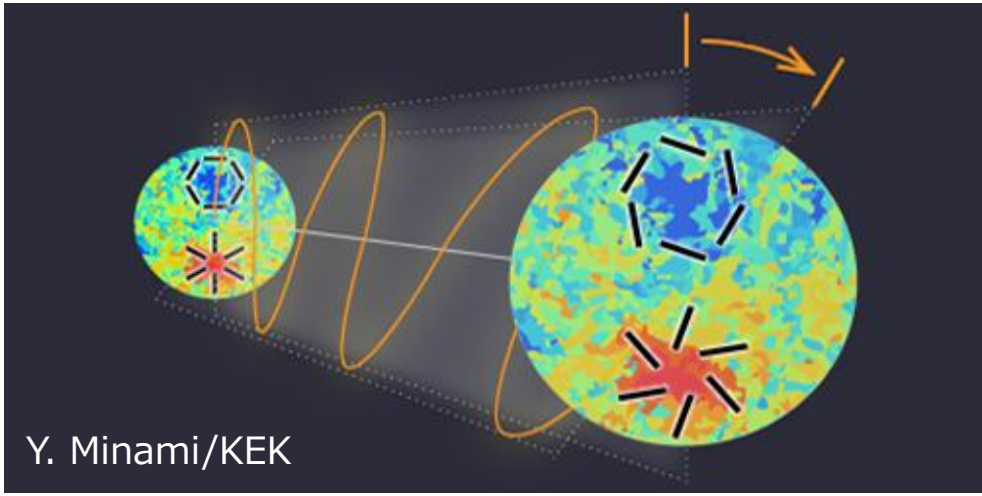
- Better than CAST below 10^{-10} eV

* Shot noise limited,
1-year observation

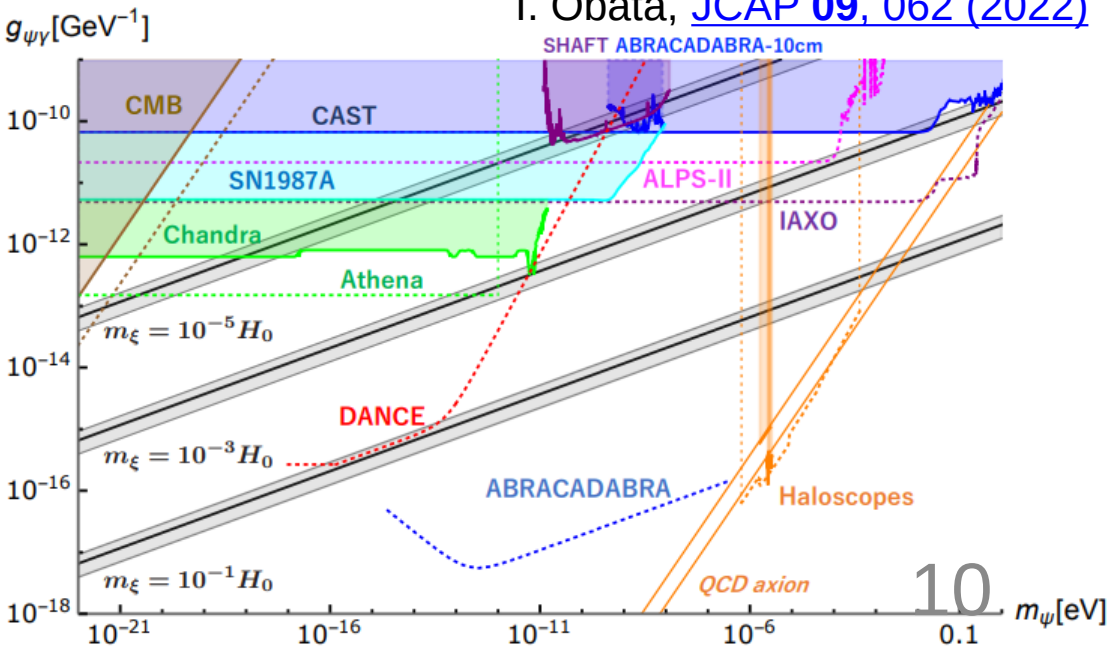


Cosmic Birefringence and DANCE

- Same principle
- Two-axion model can explain both cosmic birefringence and dark matter in the mass range of DANCE and GW detectors
- Dynamical Dark Energy can also be explained by axions

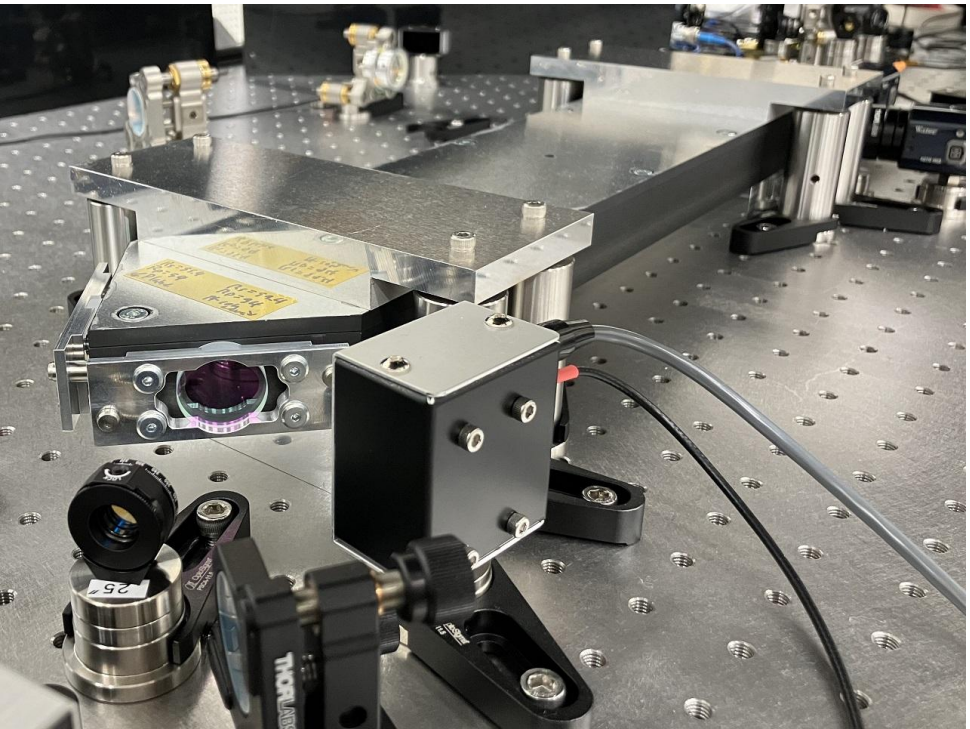


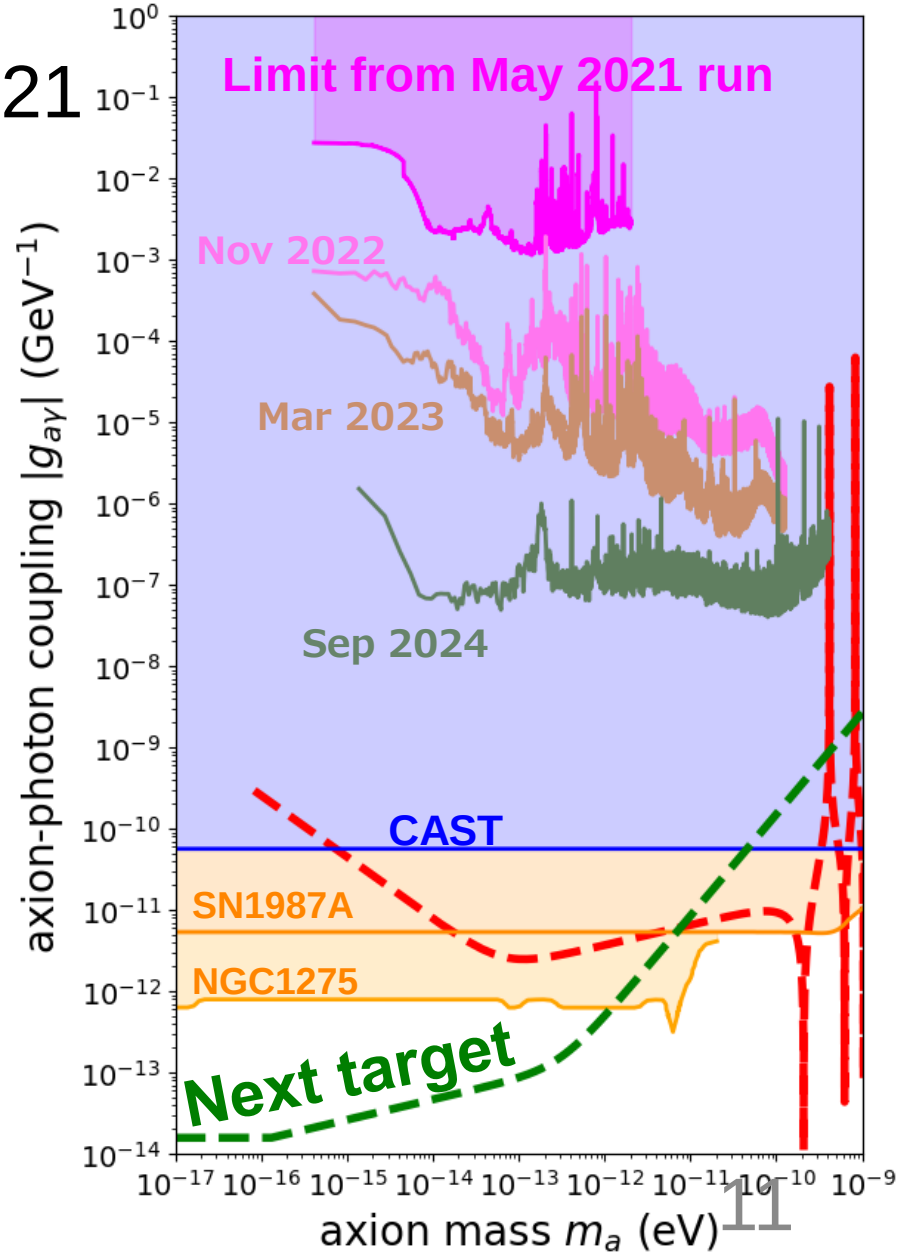
I. Obata, JCAP **09**, 062 (2022)



Status of DANCE

- First demonstration in 2021
  Y. Oshima+,
  PRD **108**, 072005 (2023)
- 4 orders of magnitude improvement over the past years

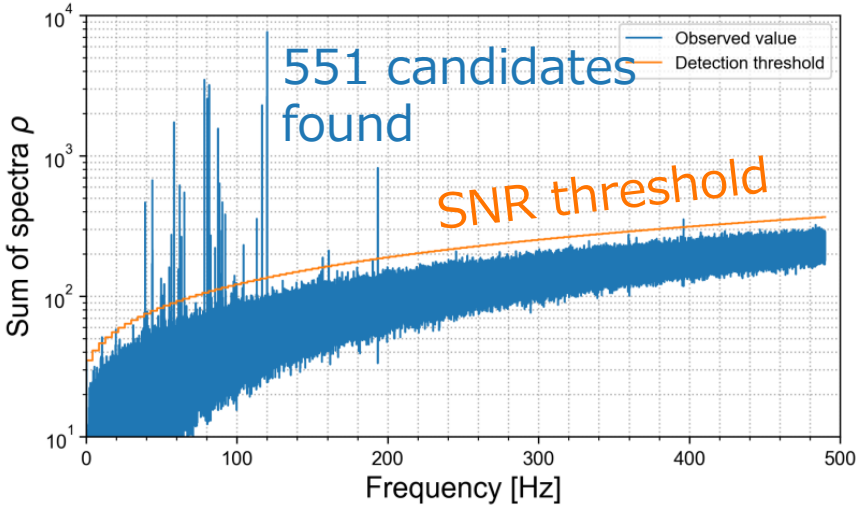


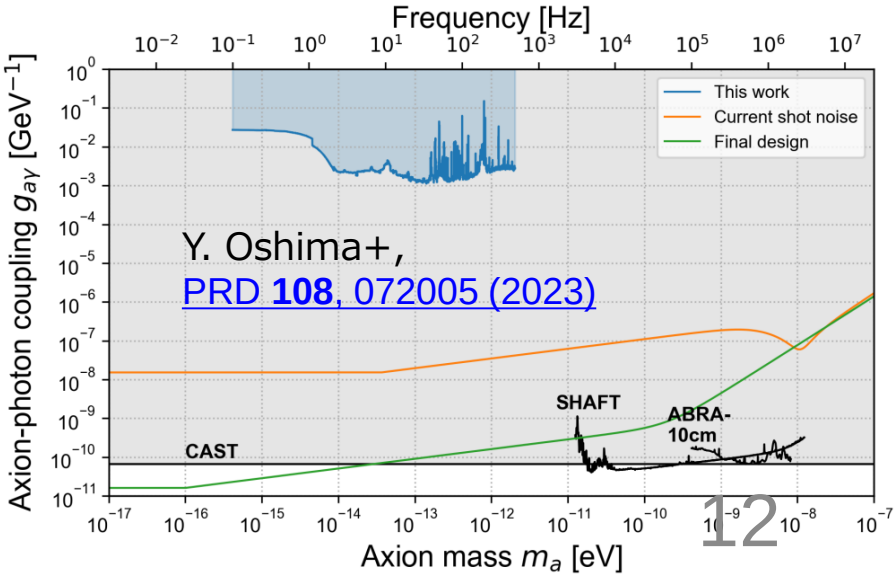


First Data Analysis Results

- Used 24-hour data from 12-day run in May 2021
- 551 candidates found from initial analysis

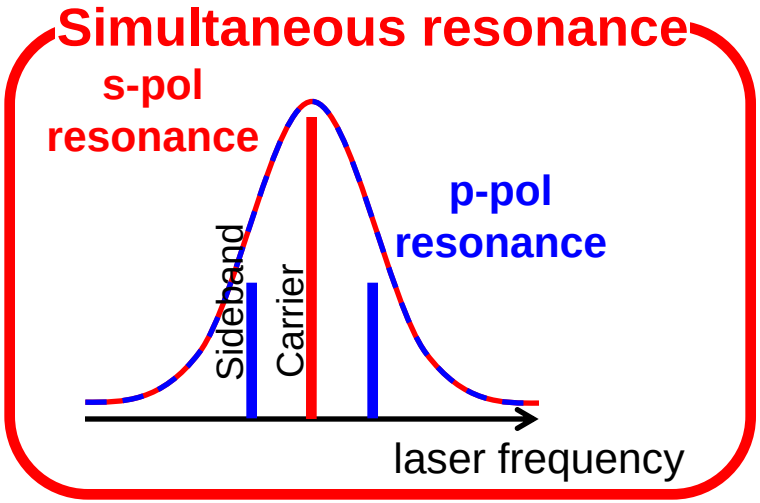
  H. Nakatsuka+,
  PRD **108**, 092010 (2023)
- Veto analysis
  - Consistency veto
    (Frequency should be the same for different set of 24-hour data)
  - Q-factor veto
    (DM signal must have Q of 10^6)
  - Remaining 7 candidates (all multiples of ~40 Hz) are also found in laser frequency control, and thus rejected
- Placed upper limits

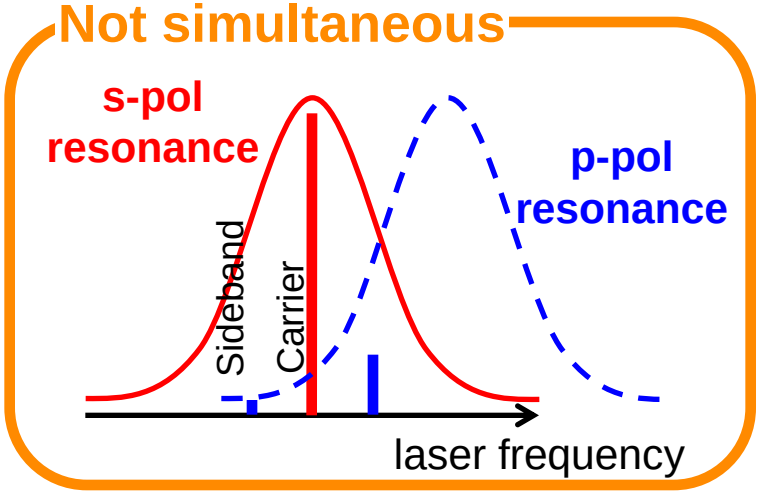


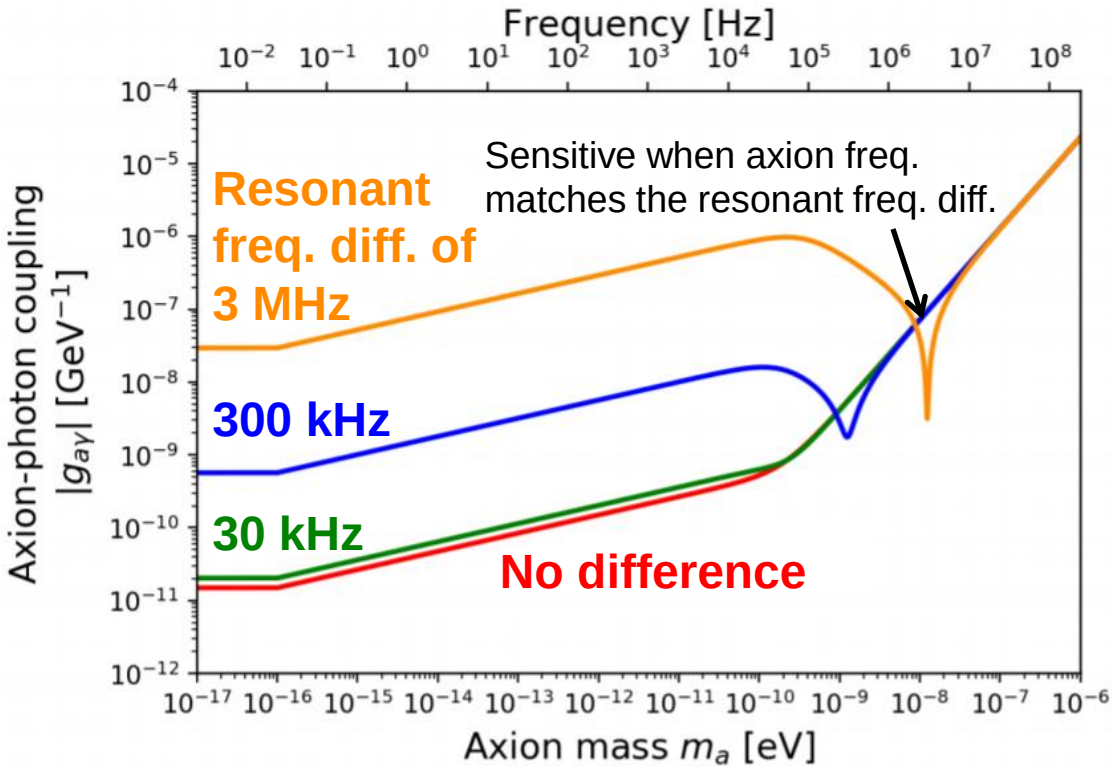


Simultaneous Resonance

- Carrier pol and sideband pol needs to be enhanced simultaneously for improving the sensitivity





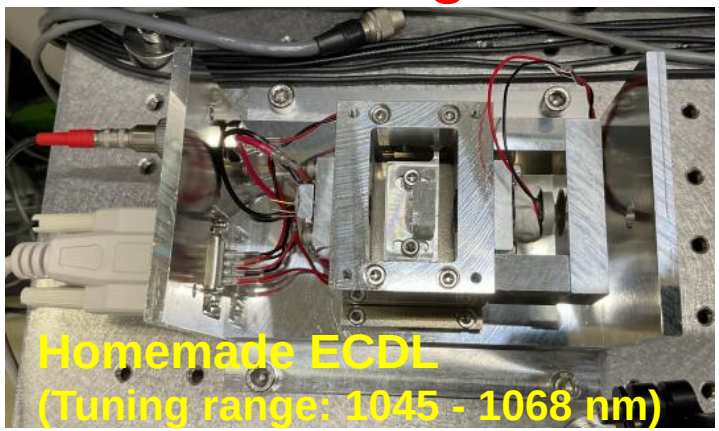


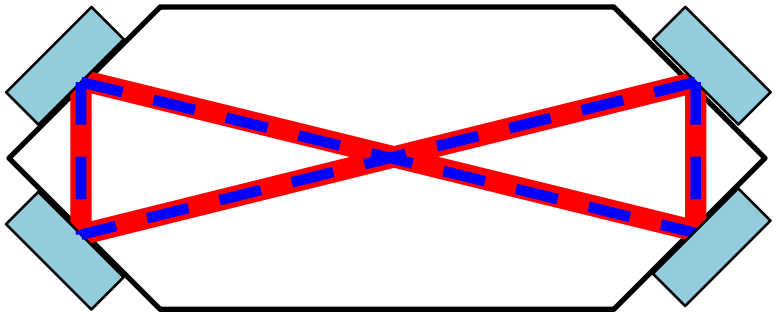
Plot by Y. Oshima & H. Fujimoto

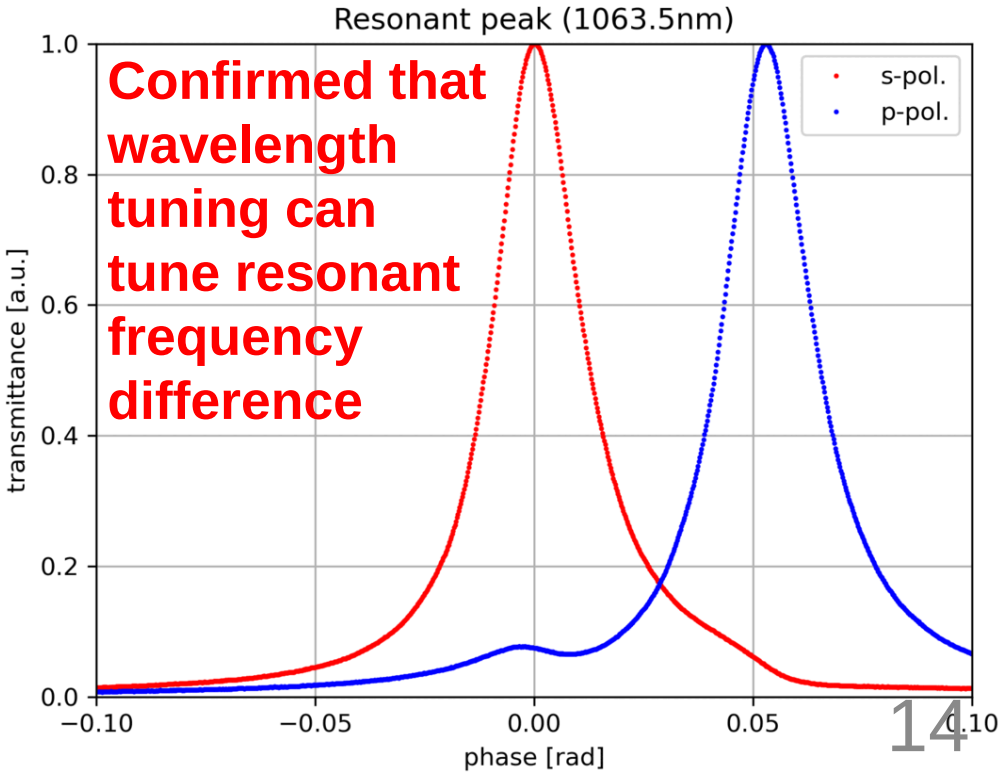
Cavity Birefringence Tuning

- Near 45 deg incidence on cavity mirrors create reflection phase difference, which leads to non-simultaneous resonance
- Reflection phase can be tuned by tuning laser wavelength

H. Takidera+, arXiv:2505.06770

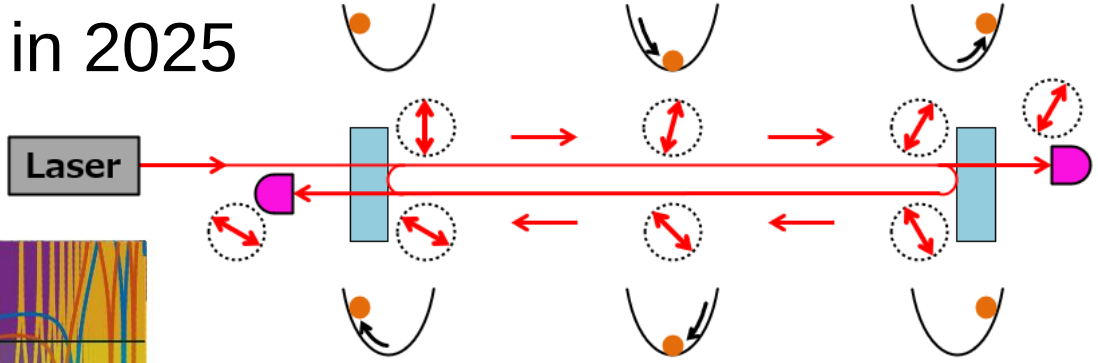


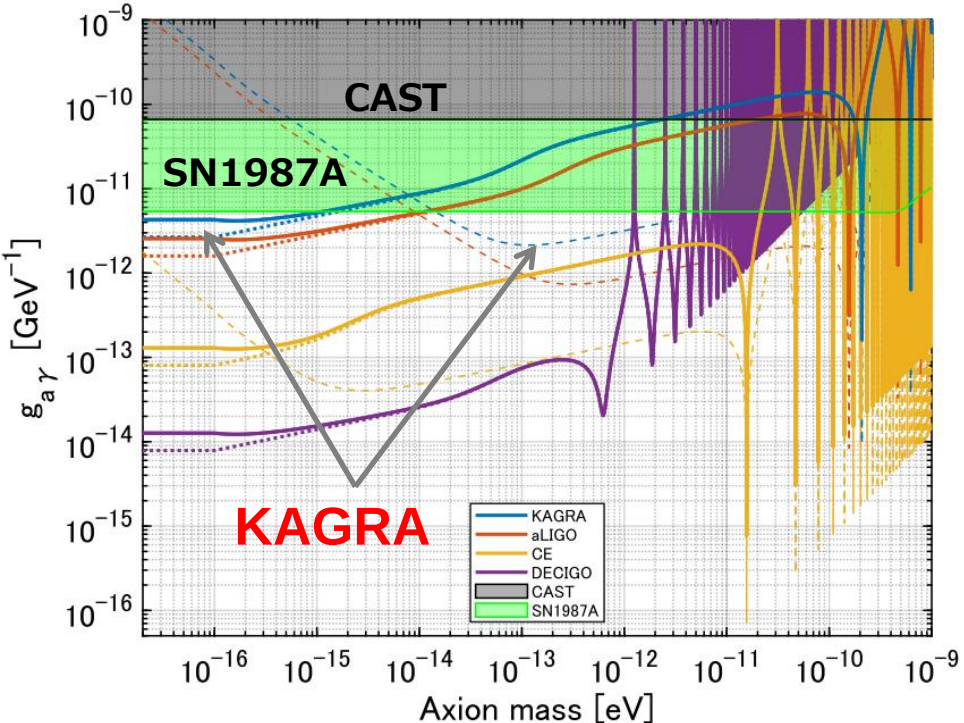


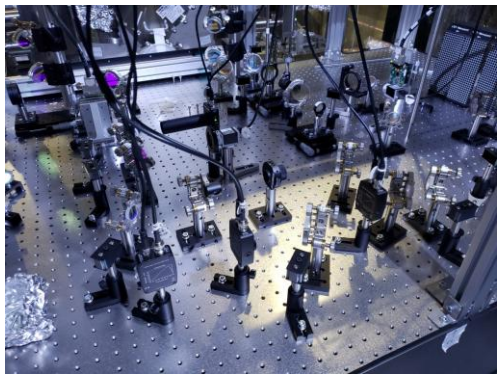


Axion DM Search with KAGRA

- Linear cavities can be sensitive when the round-trip time equals odd-multiples of axion oscillation period
- Polarization optics installed in KAGRA
- First data expected in 2025







K. Nagano, T. Fujita, Y. Michimura, I. Obata,
PRL **123**, 111301 (2019)
K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita,
Y. Michimura, I. Obata,
PRD **104**, 062008 (2021)

Summary

- Laser interferometers open up new possibilities for dark matter search
- Axion-like particles can be searched with DANCE to search for polarization modulation of light with optical ring cavity (without magnets!)
- Prototype experiment DANCE Act-1 is underway
- First result from 24-hour data released
  Y. Oshima+, PRD **108**, 072005 (2023)
- Further sensitivity improvement underway with wavelength tunable laser
  H. Takidera+, arXiv:2505.06770