Axion Dark Matter Search with Optical Interferometers

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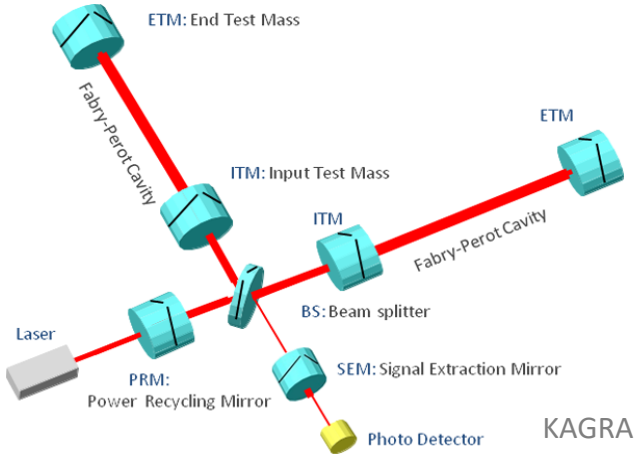
Overview

Axion

- Important old problem
- Candidate for dark matter

Apply!



Optical Interferometry

- Most recent technological innovation such as gravitational wave detectors
- Possible to test a tiny tiny signal of phase modulation

→ Pioneering a new phase of axion search!

What is Axion?

QCD Axion (Peccei & Quinn, 1977, …)

A pseudo NG boson of PQ mechanism in order to solve the strong CP problem in QCD physics

$$\mathcal{L}_{\rm QCD} \supset \theta G\tilde{G}, \quad |\theta| \lesssim 10^{-10}$$
$$\theta \to \theta_{\rm eff} = \theta + \phi/f \ll 1$$

Axion-like particles (ALPs, string axion) (Witten 1984, …)

A plentitude of axion-like particles provided by the compactifications of extra dimensions

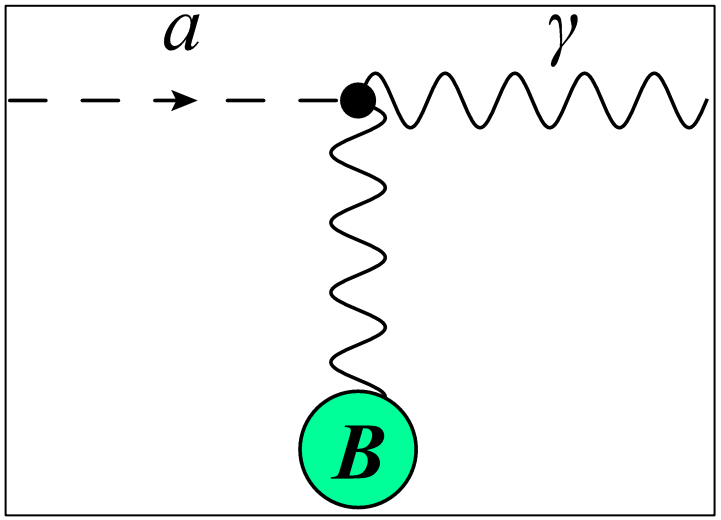
- **A scalar field with small mass, tiny interactions**

→ candidate for **cold dark matter**

Conventional Way for 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

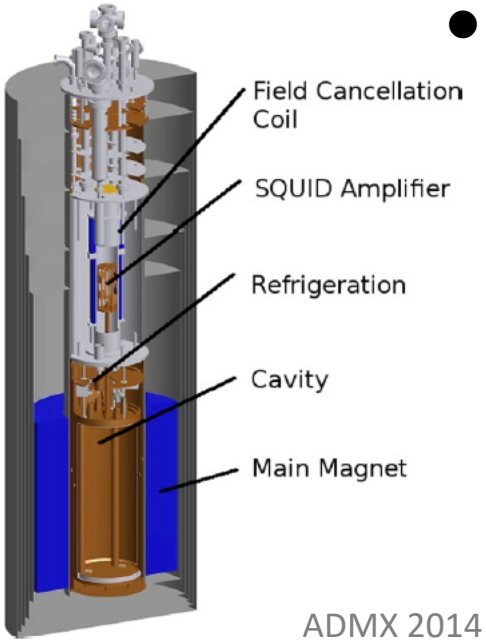
B : magnetic field

- **Axion is converted into photon under the background magnetic field (“axion-photon conversion”)**

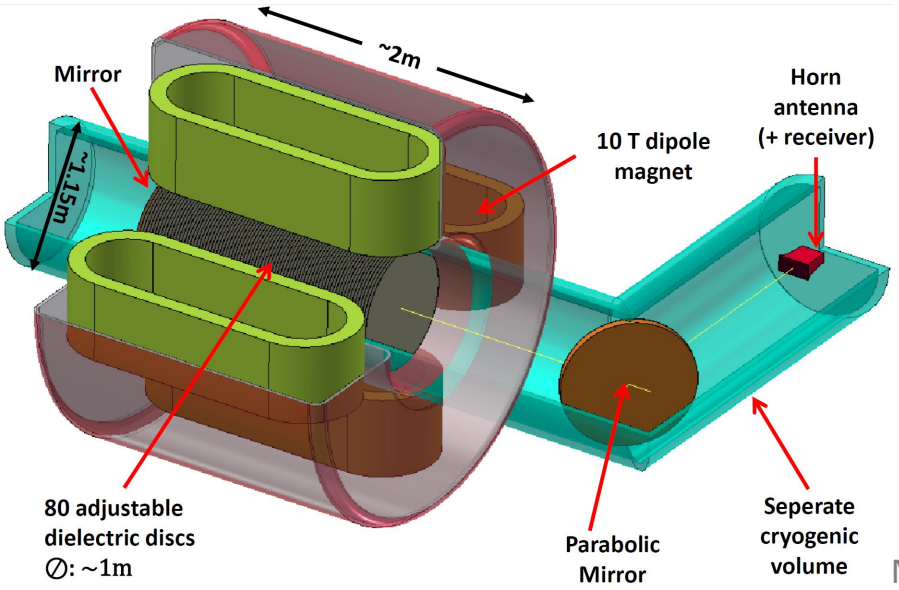
Axion-photon Conversion Experiments (1)

Axion Haloscope

- **ADMX (Axion Dark Matter eXperiment), HAYSTAC**
- **MADMAX (MAgnetized Disc and Mirror Axion eXperiment)**
- **…**



ADMX 2014

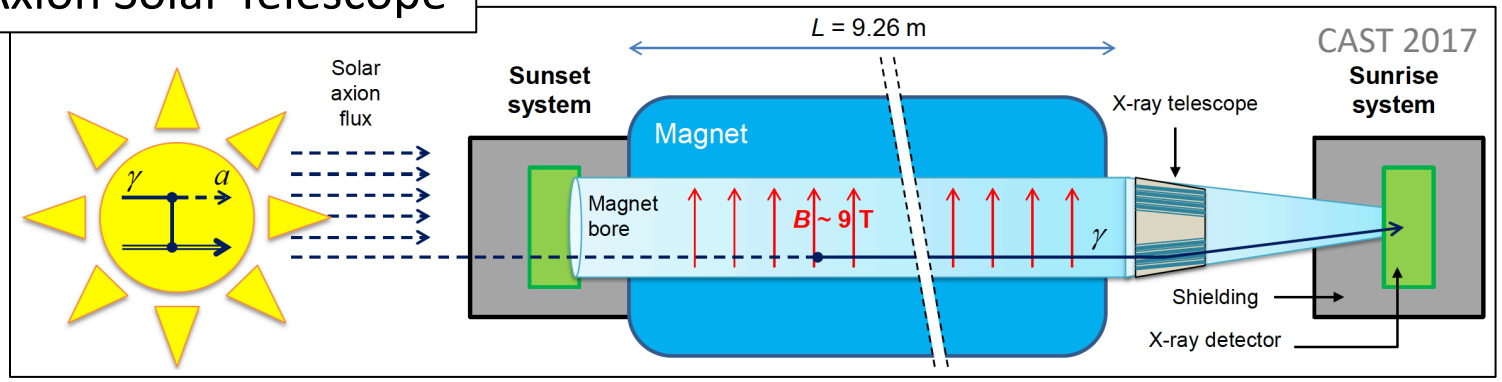


MADMAX

- A resonant haloscope using a strong magnet.
- It can probe the power signal of QCD axion dark matter with mass around μeV ~ meV.

Axion-photon Conversion Experiments (2)

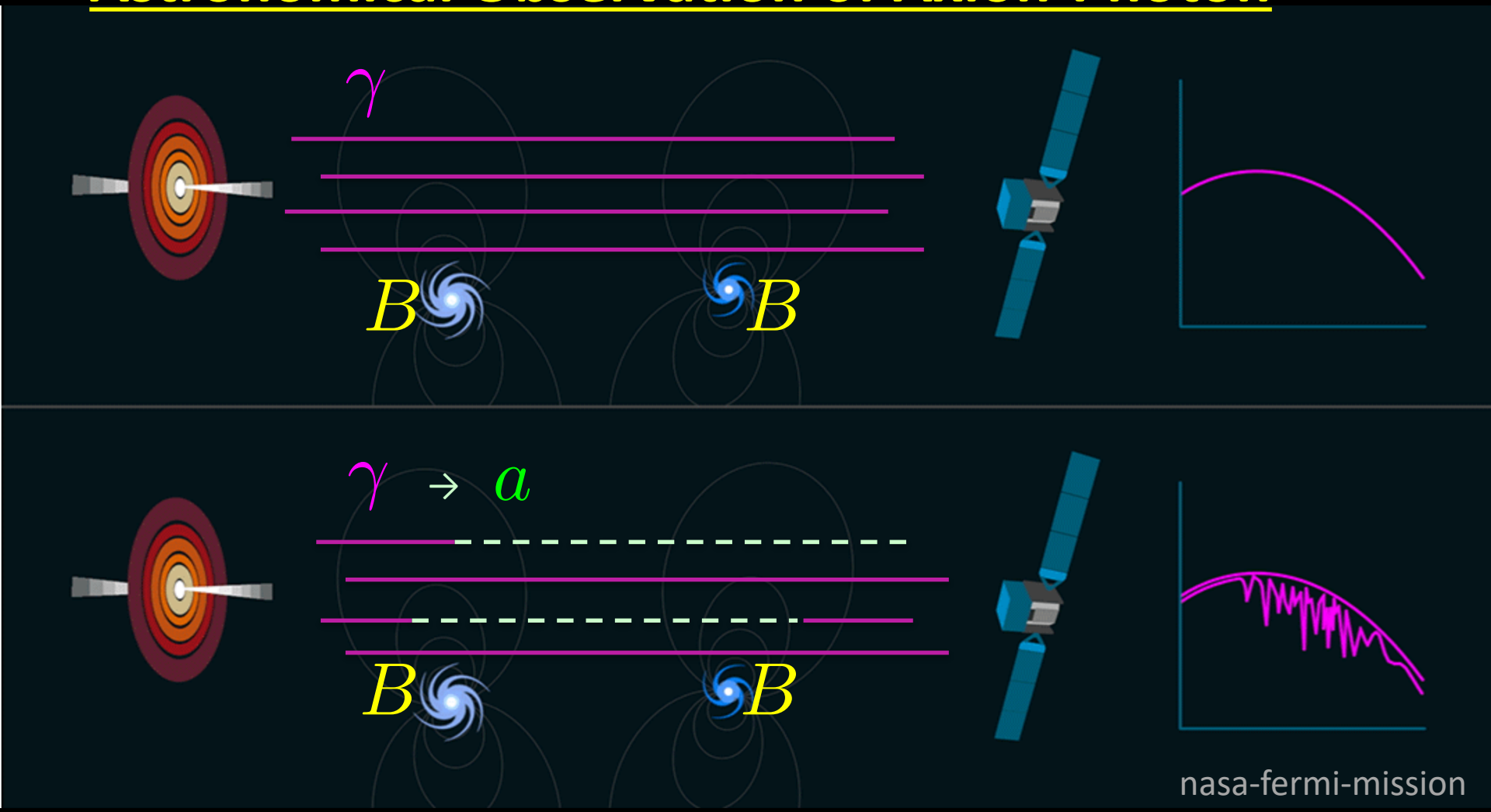
Axion Solar Telescope



- **CAST (CERN Axion Solar Telescope)**
- **IAXO (International Axion Observatory) : Next generation of CAST**

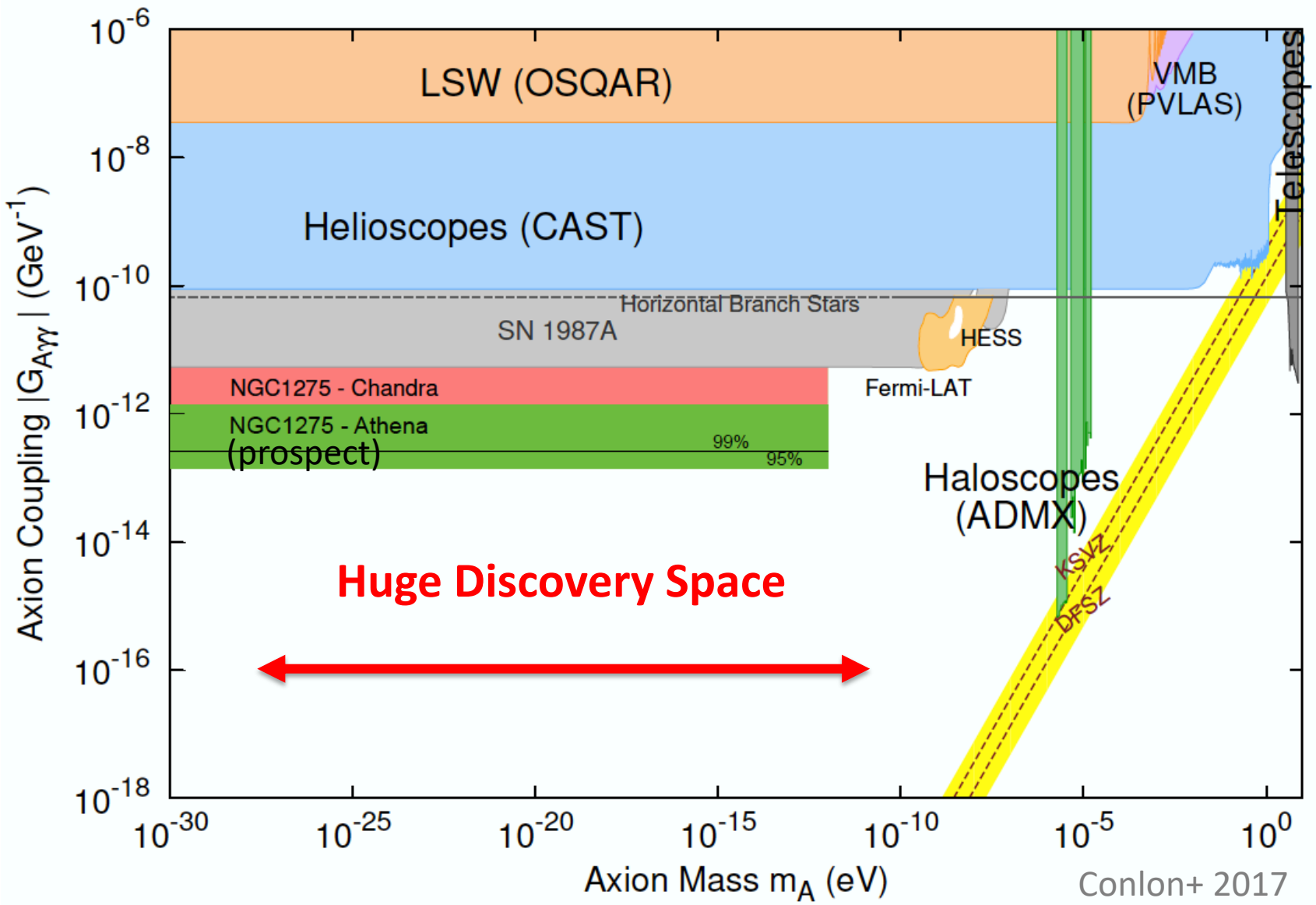
- A telescope to search for axion particles thermally produced in the Sun.
- The strong magnet converts the solar axion flux into X-rays.
- Possible to probe the axion-photon coupling with broad mass range.

Astronomical Observation of Axion-Photon



- Axion-photon conversion will modify the spectrum of cosmic rays.
- The prediction depends on the uncertainty of magnetic field in the cluster background.

Overview of Target Spaces



Conlon+ 2017

The problem is…

- In order to get better sensitivity, the more powerful superconducting magnets would be needed.

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

- In parallel with these experiments, we might as well suggest another (perhaps more economical?) experimental approach to axion DM.

Axion DM Search
without the external magnetic field

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

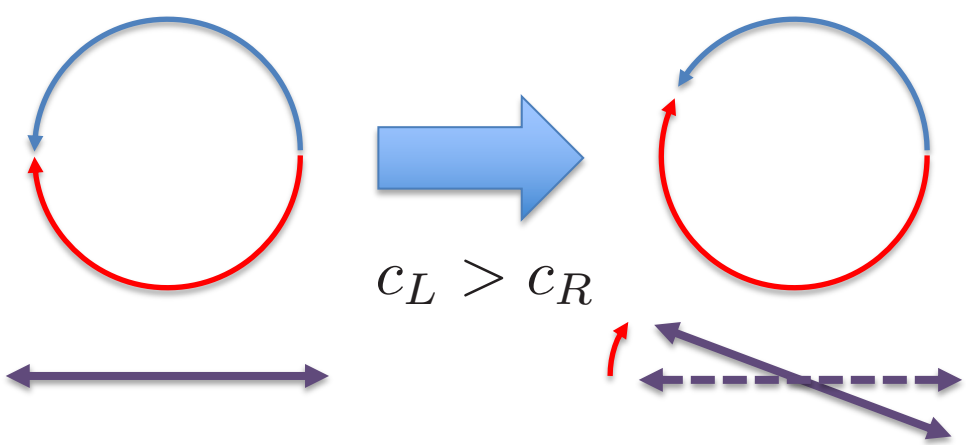
$$a(t) = a_0 \cos(mt + \delta_\tau)$$

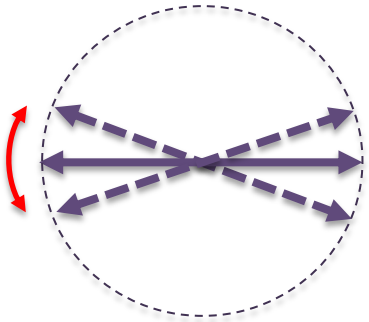
Modulation of Photon Polarization

- Axion dark matter differentiates the phase velocities of the **circular-polarized** photons

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

- This velocity difference provides the rotation of **linear-polarized** photon

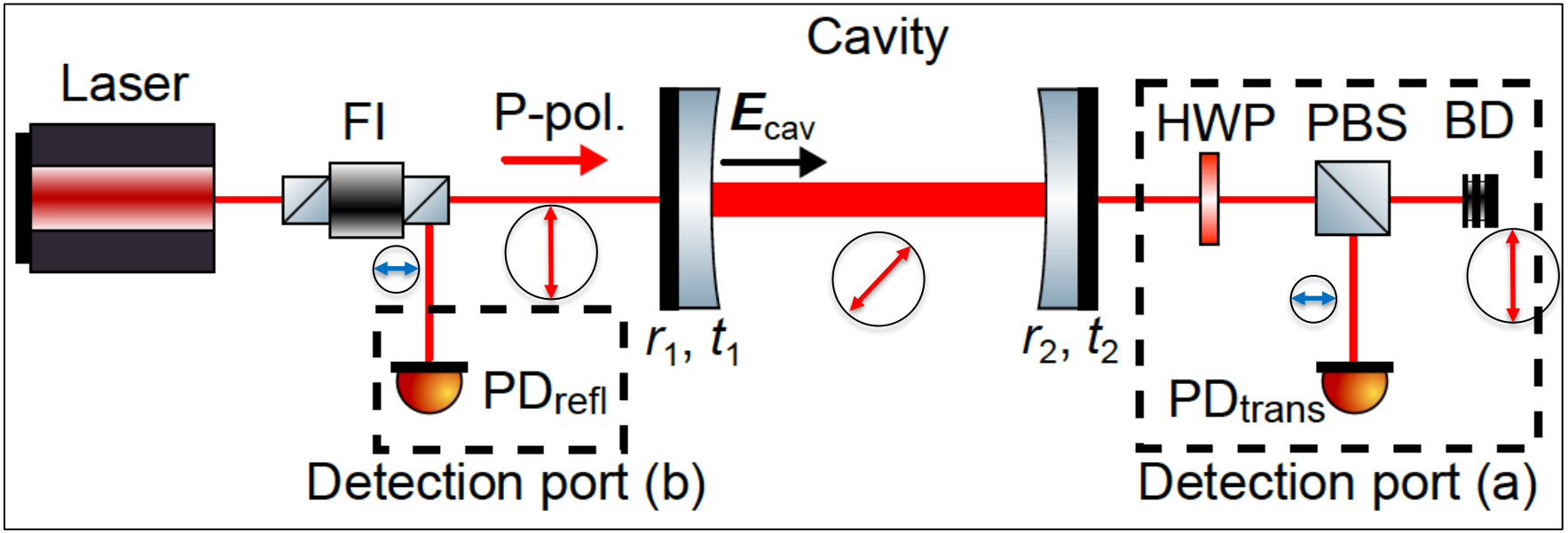




slightly oscillates!

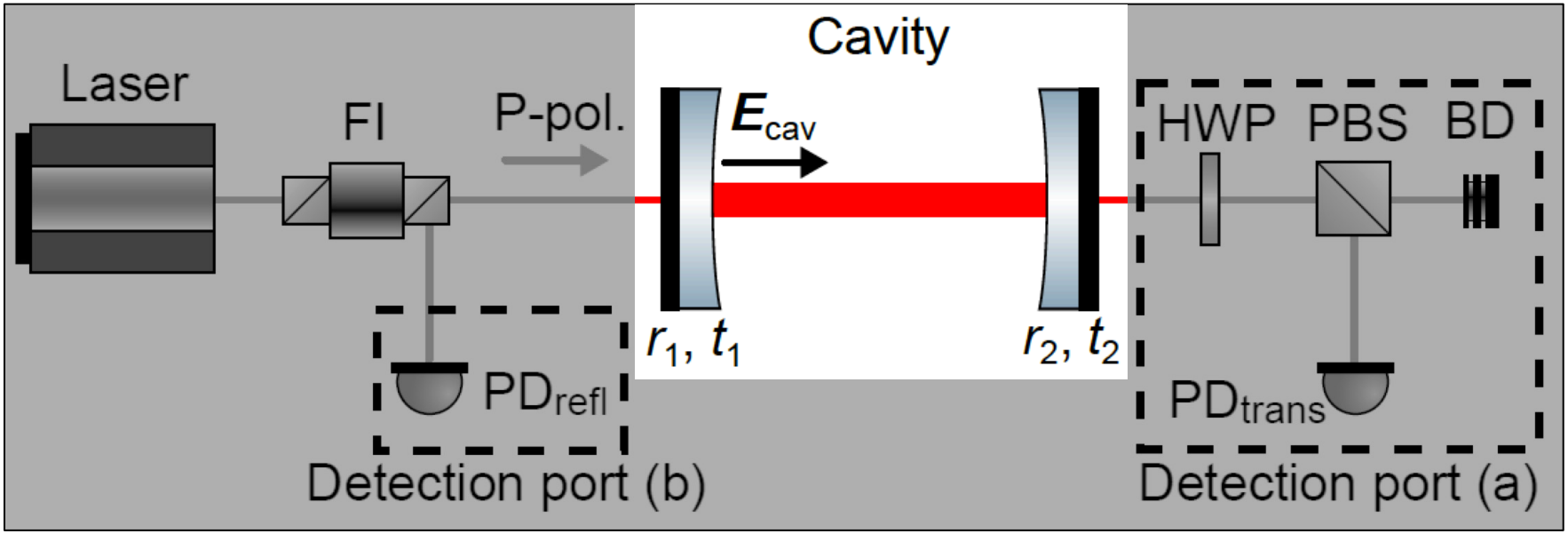
Axion Search with Resonant Cavity

K.Nagano, T.Fujita, Y.Michimura, IO



- As a carrier wave, we input the linearly-polarized monochromatic laser light.
- The linear cavity consists of front and end mirrors. The cavity is kept to resonate with a phase measurement.
- The signal is detected in detection port (a) or (b) as polarization modulation.

Inside Cavity



- **Electric vector inside cavity is represented as the superposition of reflected beams:**

$$\boldsymbol{E}_{\mathrm{cav}}(t) = t_1 E_0 e^{ikt} \left(\boldsymbol{e}^{\mathrm{L}}\ \boldsymbol{e}^{\mathrm{R}}\right) \sum_{n=1}^{\infty} A_n(t) \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} ,$$

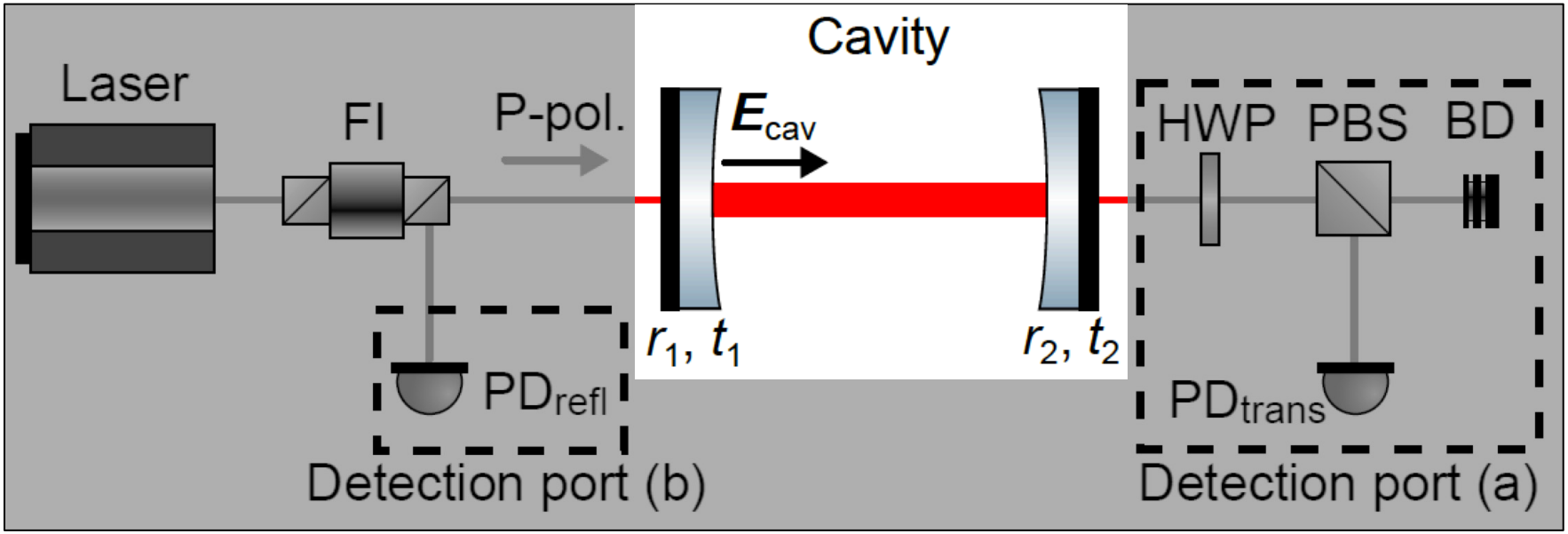
$$\begin{cases} A_{n+1}(t) \equiv A_n(t) R_1 T(t - 2L(n-1)) \\ \qquad\qquad \times R_2 T(t - 2L(n-1/2)) \quad (n \geq 1) \\ A_1 = 1 \end{cases}$$

$$R_i \equiv \begin{pmatrix} 0 & -r_i \\ -r_i & 0 \end{pmatrix} \quad (i = 1, 2) ,$$

$$T(t) \equiv \begin{pmatrix} e^{-i\phi^L(t)} & 0 \\ 0 & e^{-i\phi^R(t)} \end{pmatrix} ,$$

$$\phi^{L/R}(t) \equiv kL \mp k \int_{t-L}^{t} \delta c(t')dt'$$

Inside Cavity



- **When the resonant condition is met, the beam is accumulated inside cavity:**

$$\boldsymbol{E}_{\mathrm{cav}}(t) = \frac{t_1 E_0 e^{ikt}}{1 - r_1 r_2} \begin{pmatrix} \boldsymbol{e}^{\mathrm{L}} & \boldsymbol{e}^{\mathrm{R}} \end{pmatrix} \begin{pmatrix} 1 + i\delta\phi(t) & 0 \\ 0 & 1 - i\delta\phi(t) \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$= \frac{t_1}{1 - r_1 r_2} [\boldsymbol{E}^{\mathrm{p}}(t) - \delta\phi \boldsymbol{E}^{\mathrm{s}}(t)] \quad (2kL = 2\pi\mathbb{N})$$

$$\gg 1 \quad (\because r_i \simeq 1)$$

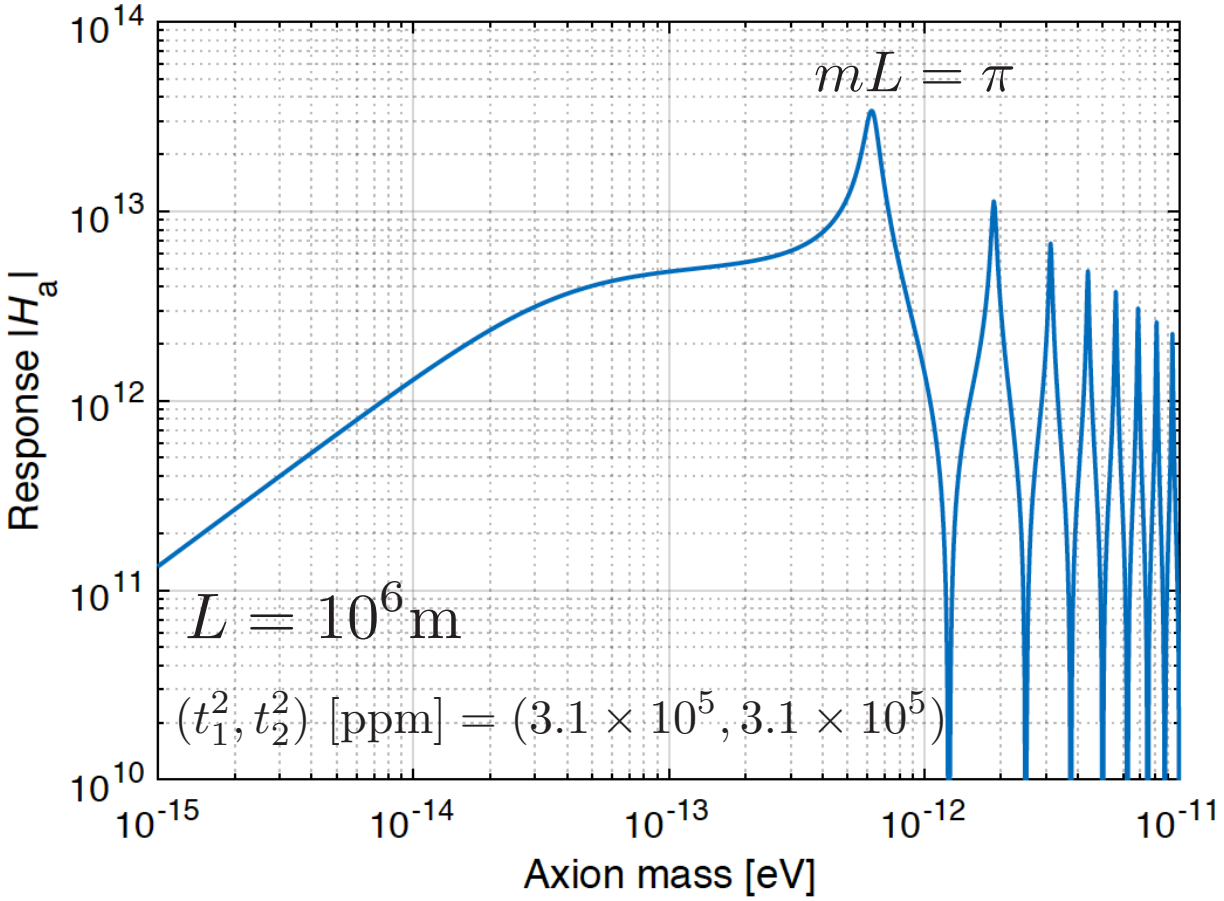
$$r_i^2 + t_i^2 = 1$$

Frequency Response in Signal

$$\delta\phi(t) = \int_{-\infty}^{\infty} \delta c(m) H_a(m) e^{imt} \frac{dm}{2\pi}$$

$$H_a(m) = i\frac{k}{m}\frac{4r_1 r_2 \sin^2(\frac{mL}{2})}{1 - r_1 r_2 e^{-i2mL}}(-e^{-imL})$$

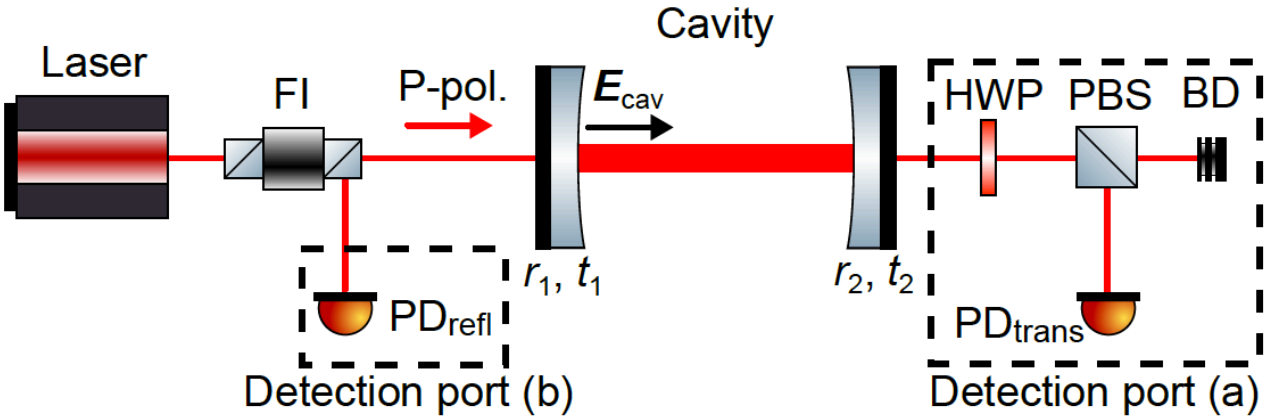
Response function of signal



Longer length
&
Higher finesse is better

→GW detectors!

SN Ratio



- **We assume the sensitivity is determined by the quantum shot noise**

Kimble+ 2001

$$\sqrt{\mathcal{T}_i}\delta\phi_{\rm shot} \sim \frac{\delta E_{\rm vac}}{E_0} \quad \longrightarrow \quad \sqrt{S_{\rm shot}(m)} = \frac{\sqrt{\frac{k}{2P_0}}}{\sqrt{\mathcal{T}_i}|H_{\rm a}(m)|}$$

$$\sqrt{\mathcal{T}_i} \equiv \frac{t_1 t_i}{1 - r_1 r_2} \quad (i = 1, 2)$$

- **The SNR for axion DM is improved with the measurement time**

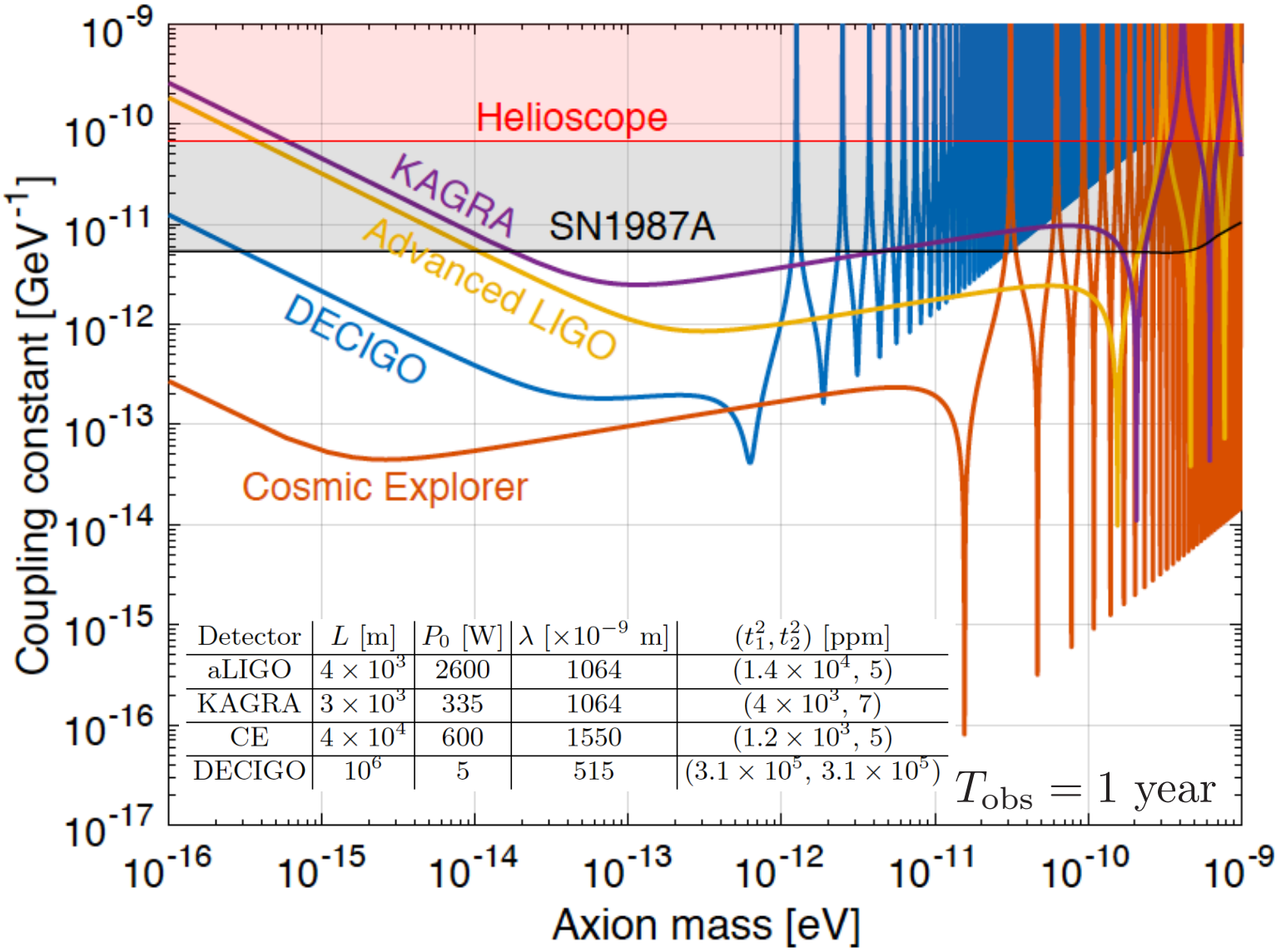
$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 \ \ (T_{\rm obs} \lesssim \tau) \\ \dfrac{(T_{\rm obs}\tau)^{1/4}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 \ \ (T_{\rm obs} \gtrsim \tau) \end{cases}$$

$$a(t) = a_0 \cos(mt + \delta_\tau)$$

(coherent time of axion DM)

$$\tau = \frac{2\pi}{mv^2} \sim 1\mathrm{yr}(10^{-16}\mathrm{eV}/m)$$

Potential Sensitivity Curves



Detector	L [m]	P_0 [W]	λ [$\times 10^{-9}$ m]	(t_1^2, t_2^2) [ppm]
aLIGO	4×10^3	2600	1064	$(1.4 \times 10^4, 5)$
KAGRA	3×10^3	335	1064	$(4 \times 10^3, 7)$
CE	4×10^4	600	1550	$(1.2 \times 10^3, 5)$
DECIGO	10^6	5	515	$(3.1 \times 10^5, 3.1 \times 10^5)$

$T_{\rm obs} = 1$ year

The problem is…

- In order to apply our method to the real GW detector, some optics need to be added for detection port.

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

the rotation signal is not so accumulated…

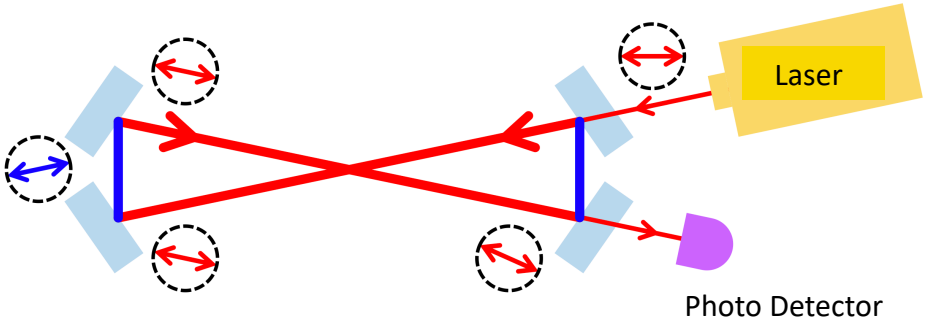
In case $m \sim L^{-1}$,

the rotation signal is most accumulated since the oscillatory turning point matches with the reflection-timing.

Axion DM Tabletop Experiment

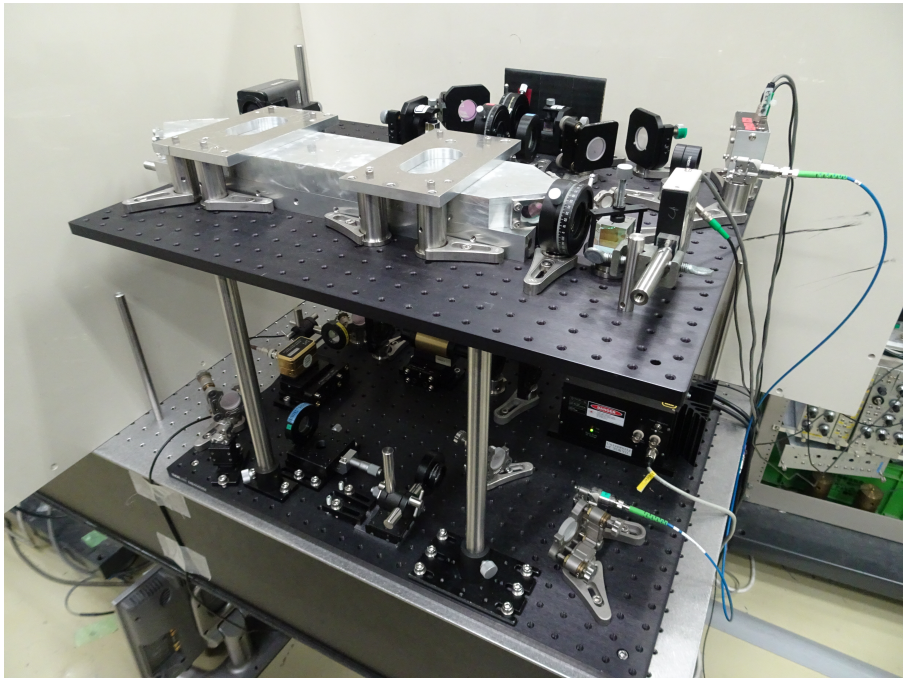
with Y.Oshima, T.Watanabe, Y.Michimra, K.Nagano, IO, T.Fujita, M.Ando **@Tokyo University**

DANCE: Dark matter Axion search with riNg Cavity Experiment

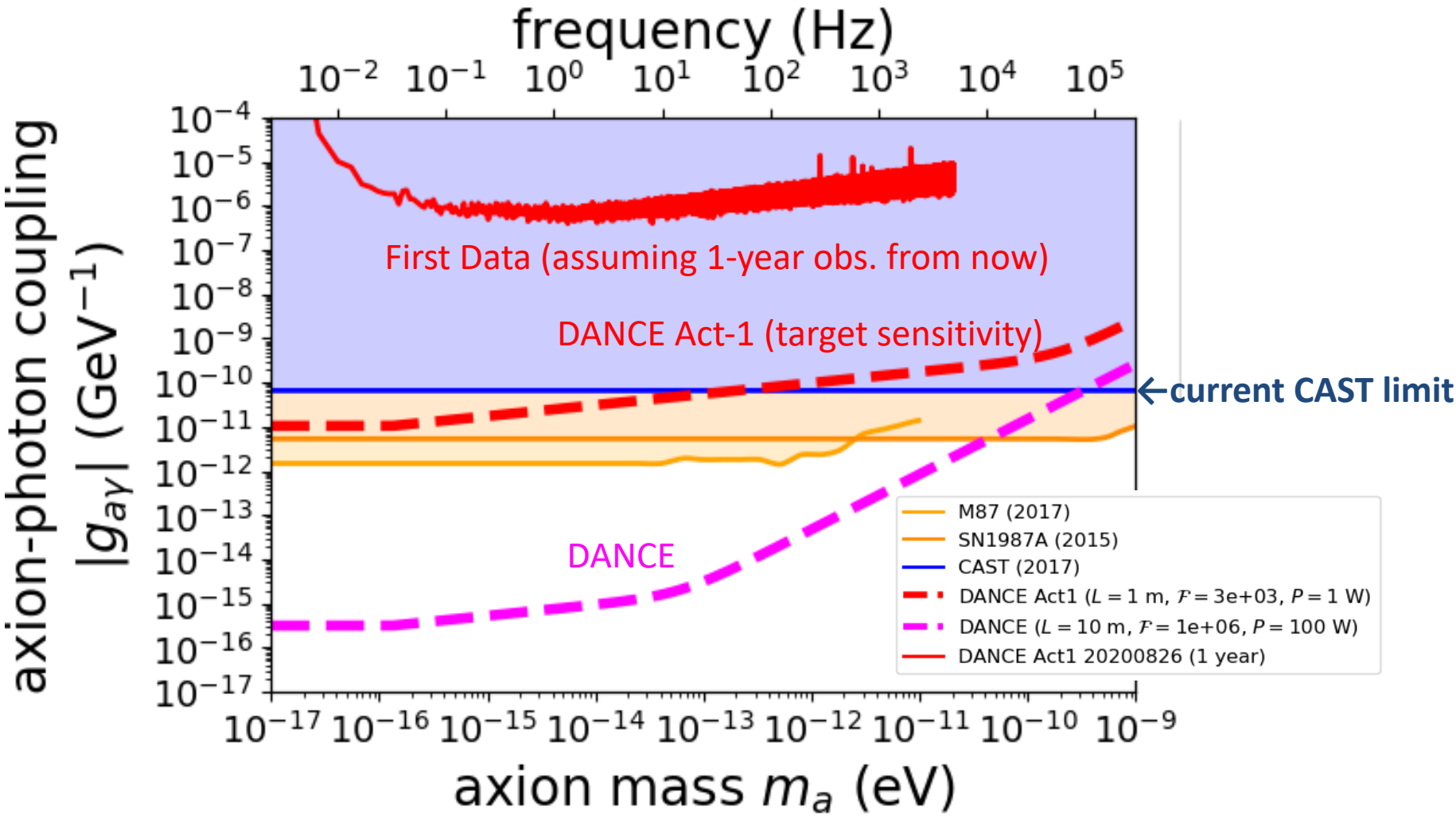


- A bowtie-like mirror configuration can sustain the rotational orientation of photon polarization

(DANCE Act-1: Proto-type experiment)



First Data of DANCE Act-1 (2020.8)



Summary & Outlook

- We suggest an experimental scheme to search for axion dark matter with the linear optical cavity used in gravitational wave detectors.
- We found that these sensitivities can reach beyond the current limit with a wide range of axion mass and our new scheme can coexist with the observation run for gravitational waves.
- We also suggest a tabletop experiment to search for axion DM.
- Achieving the target sensitivity of DANCE is still ongoing…

Summary & Outlook

- Possible to probe QCD axion DM by interferometers?
- Application of our scheme to other projectable axion experiments? (e.g. LSW experiment)
- Constraining axion DM birefringence from astrophysical or cosmological measurements? (e.g. CMB)
- Vector dark matter search with optical interferometers