Axion Dark Matter Search with Interferometric Detectors

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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

$$\mathcal{L}_{\rm QCD} \supset \theta G\tilde{G}, \quad |\theta| \lesssim 10^{-10}$$

$$\theta \to \theta_{\rm eff} = \theta + \phi/f \ll 1$$

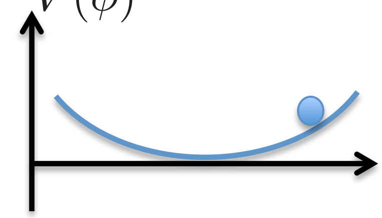
Axion-like particles (ALPs, string axion) (Witten 1984, …)

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

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

→ candidate for **dark matter**

Axion as Dark Matter (misalignment mechanism)



$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$ (background evolution)

- In early universe (m < H), $\phi \simeq \text{const.}$ (frozen due to the Hubble friction)
- In late universe (m > H), $\phi \simeq a^{-3/2}\phi_0 \cos(mt)$ (start to oscillate)
- After oscillation begins, axion behaves as a pressureless matter fluid

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 \simeq \frac{\rho_0}{a^3}$$

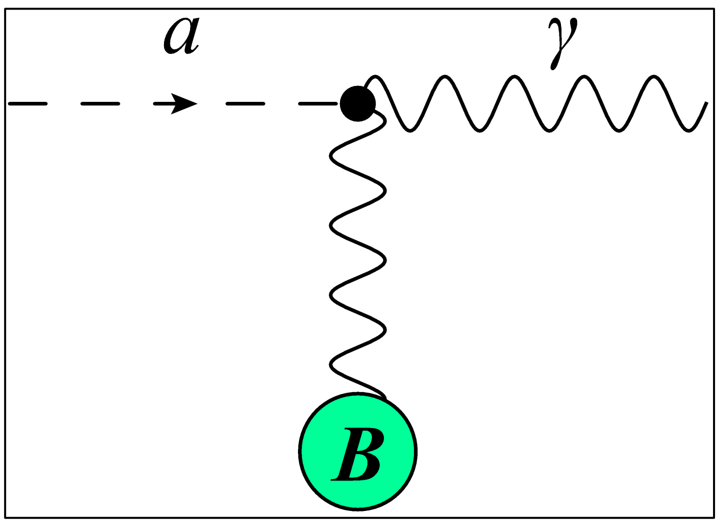
$$P = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2 \simeq \frac{P_0}{a^3}\sin(2mt) \sim 0$$

(Pressure) < (Gravity)
→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

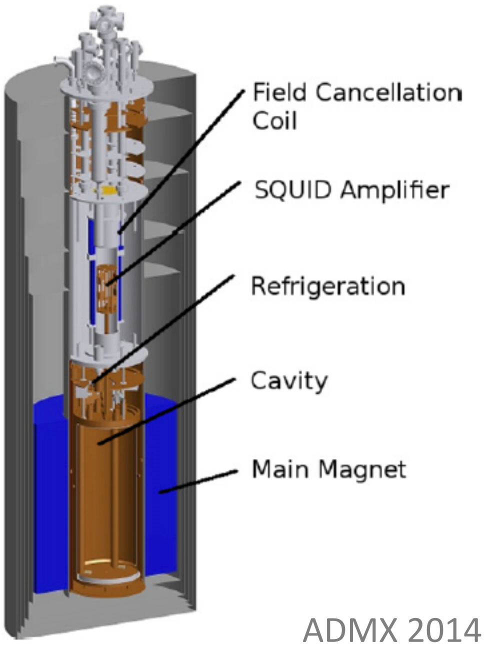
B : magnetic field

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

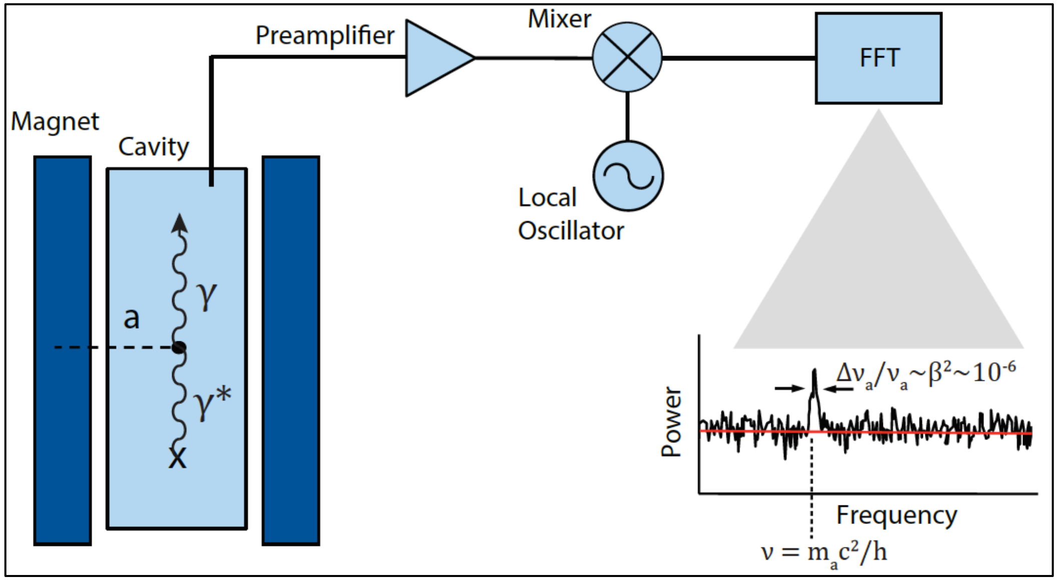
Axion-photon Conversion Experiments (1)

Axion Haloscope

- **ADMX (Axion Dark Matter eXperiment)**



ADMX 2014

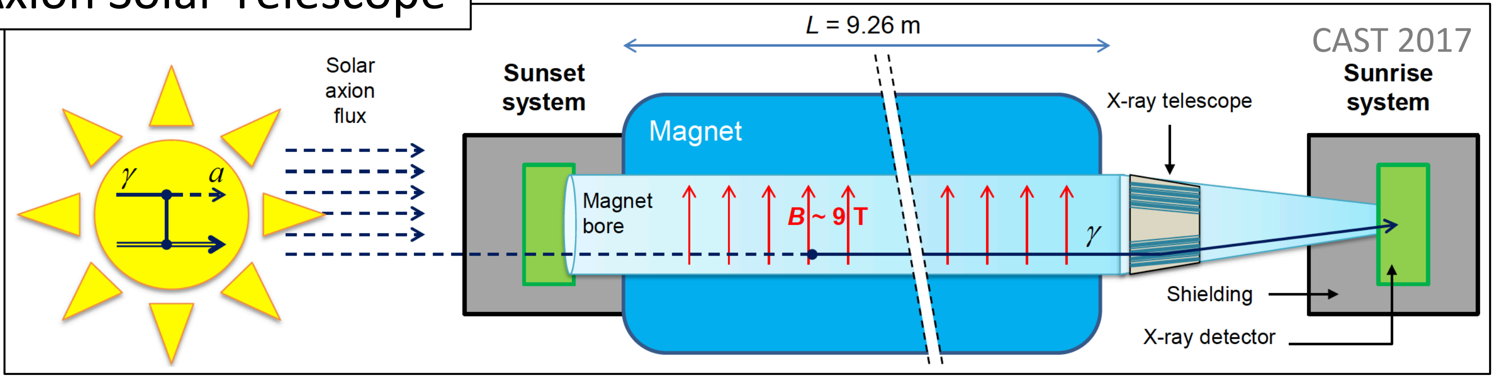


ADMX Patras 2016

- A microwave resonant cavity using a superconducting magnet B ~ 8T.
- It can probe the power signal of QCD axion dark matter m ~ μeV (narrow mass region).

Axion-photon Conversion Experiments (2)

Axion Solar Telescope



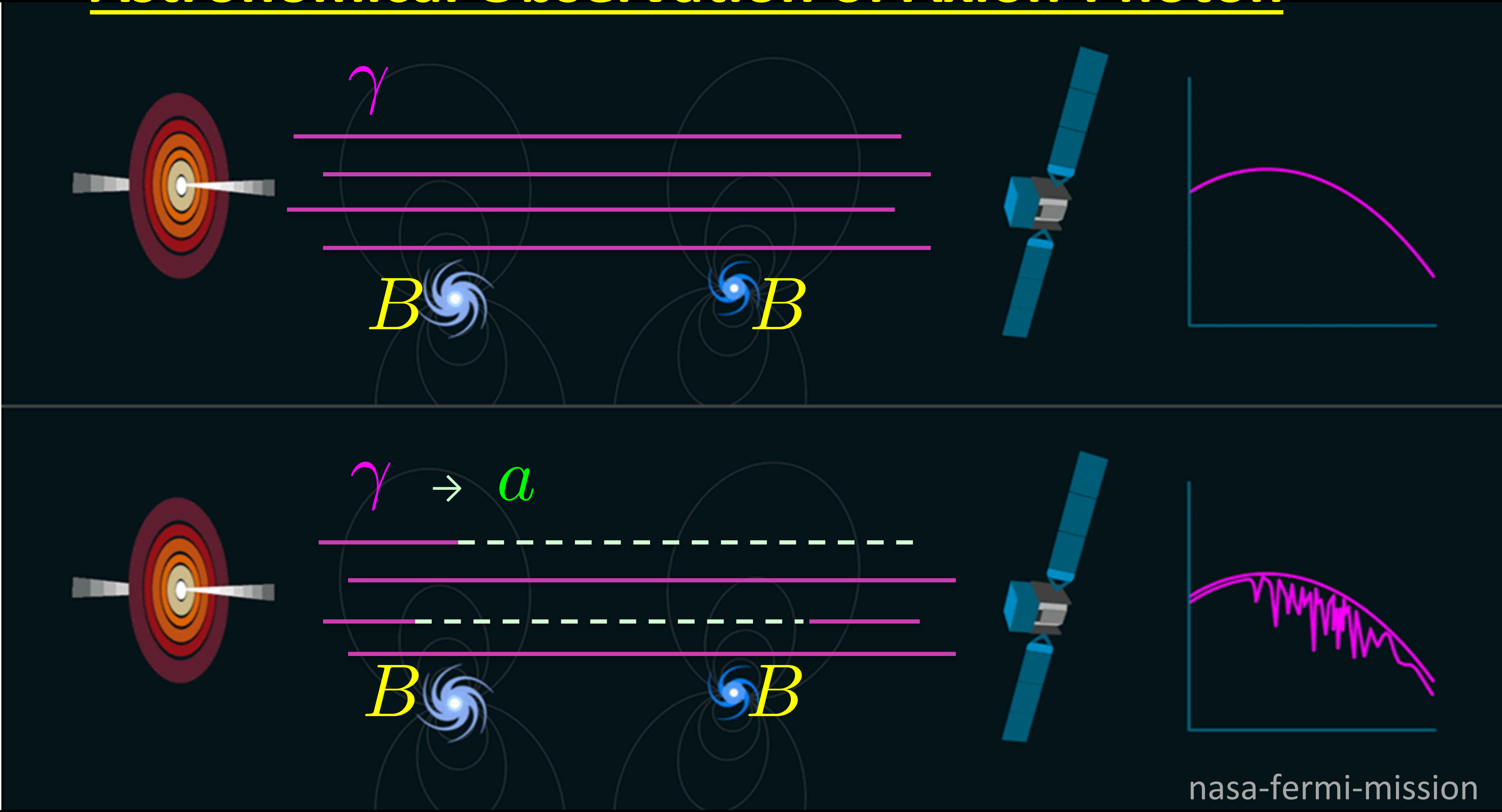
- **CAST (CERN Axion Solar Telescope)**
- **IAXO (International Axion Observatory) : Next generation**

■ A telescope to search for axion particles thermally produced in the Sun.

■ The strong magnet converts the solar axion flux into X-rays.

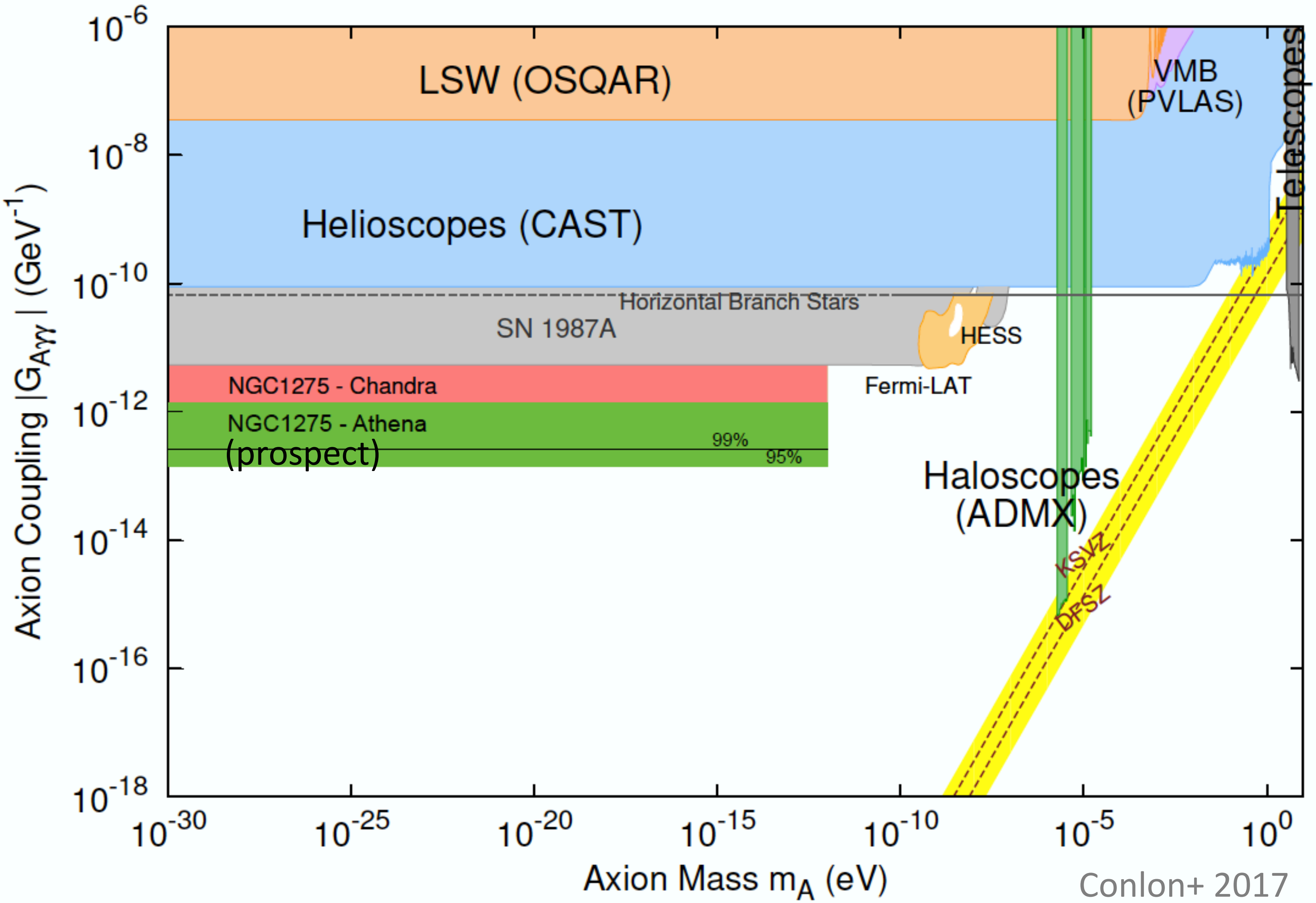
■ Possible to probe the axion-photon coupling with broad mass range.

Astronomical Observation of Axion-Photon



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

Overview of Target Spaces



Conlon+ 2017

Axion DM – Photon Interaction

(without using a background magnetic field)

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\dot{a}A_i\epsilon_{ijk}\partial_j A_k + (\text{total derivative})$$

EOM for photon : $\ddot{A}_i - \nabla^2 A_i + g_{a\gamma}\dot{a}\epsilon_{ijk}\partial_j A_k = 0,$

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

- Decomposing two circular polarized photons, we get

$$\ddot{A}_k^{\mathrm{L/R}} + \omega_{\mathrm{L/R}}^2 A_k^{\mathrm{L/R}} = 0,$$

$$\omega_{\mathrm{L/R}}^2 \equiv k^2 \left(1 \pm \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau)\right)$$

Axion DM – Photon Interaction

- The phase velocity of each polarized photon is given by

$$c_{\mathrm{L/R}} \equiv \frac{\omega_{\mathrm{L/R}}}{k} = \left(1 \pm \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau)\right)^{1/2}$$

- The difference of phase velocities between two modes:

$$c_{\mathrm{L/R}}(t) \simeq 1 \pm \delta c(t) \equiv 1 \pm \delta c_0 \sin(mt + \delta_\tau(t))$$

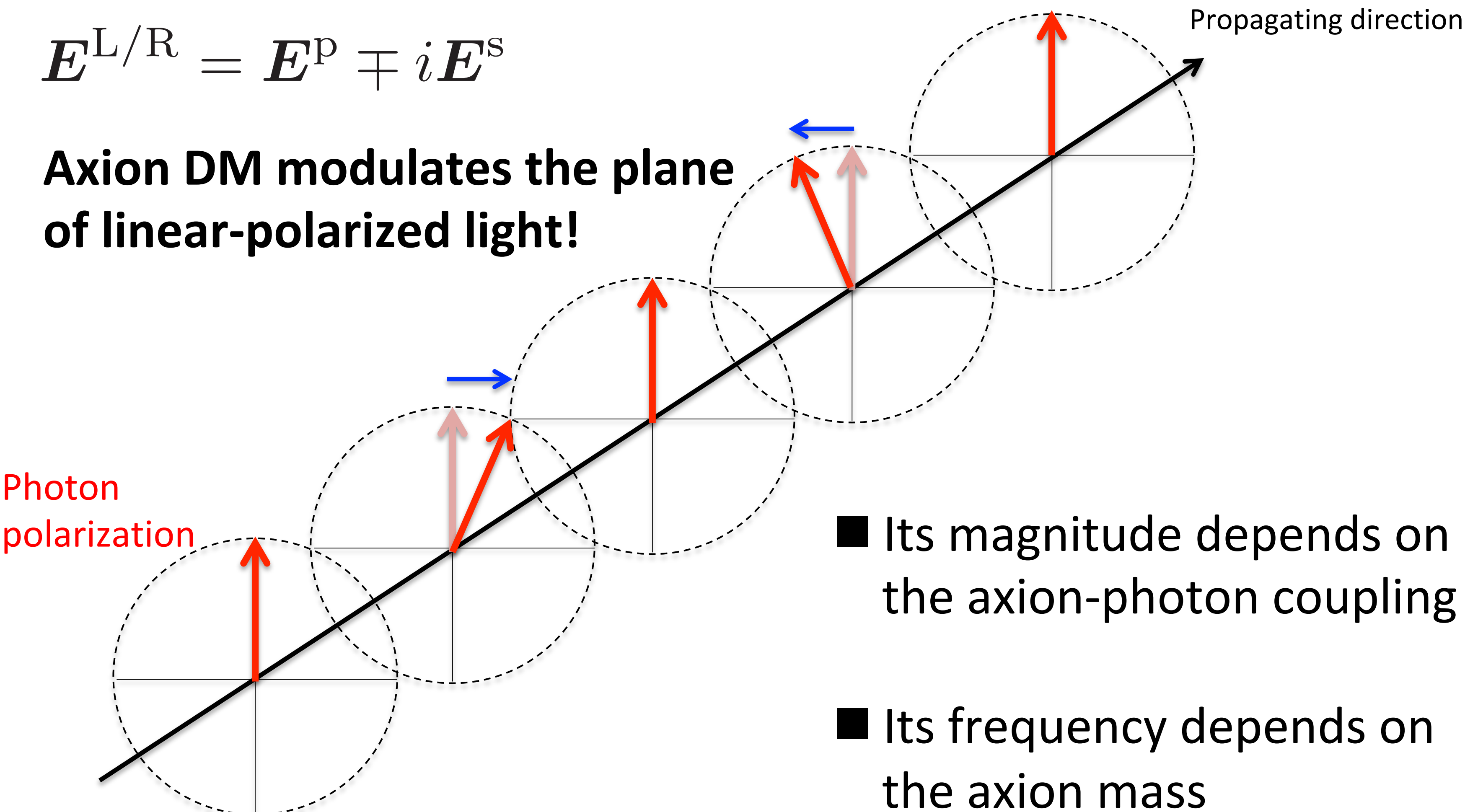
$$\frac{\delta c_0}{c} \simeq 1.3 \times 10^{-24} \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right) \left(\frac{\lambda}{1550\ \mathrm{nm}}\right) \left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm^3}}\right)^{1/2}$$

How to measure this phase modulation?

Modulation of Linear Polarization

$$\boldsymbol{E}^{\mathrm{L/R}} = \boldsymbol{E}^{\mathrm{p}} \mp i\boldsymbol{E}^{\mathrm{s}}$$

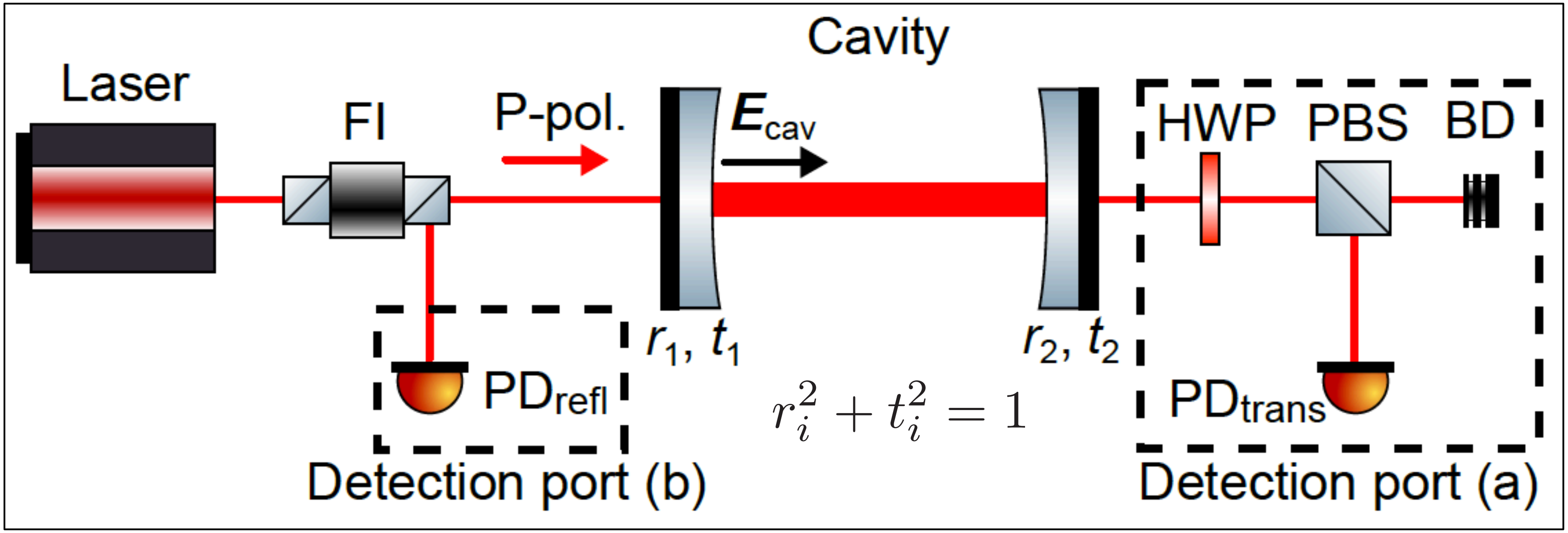
Axion DM modulates the plane of linear-polarized light!



- Its magnitude depends on the axion-photon coupling
- Its frequency depends on the axion mass

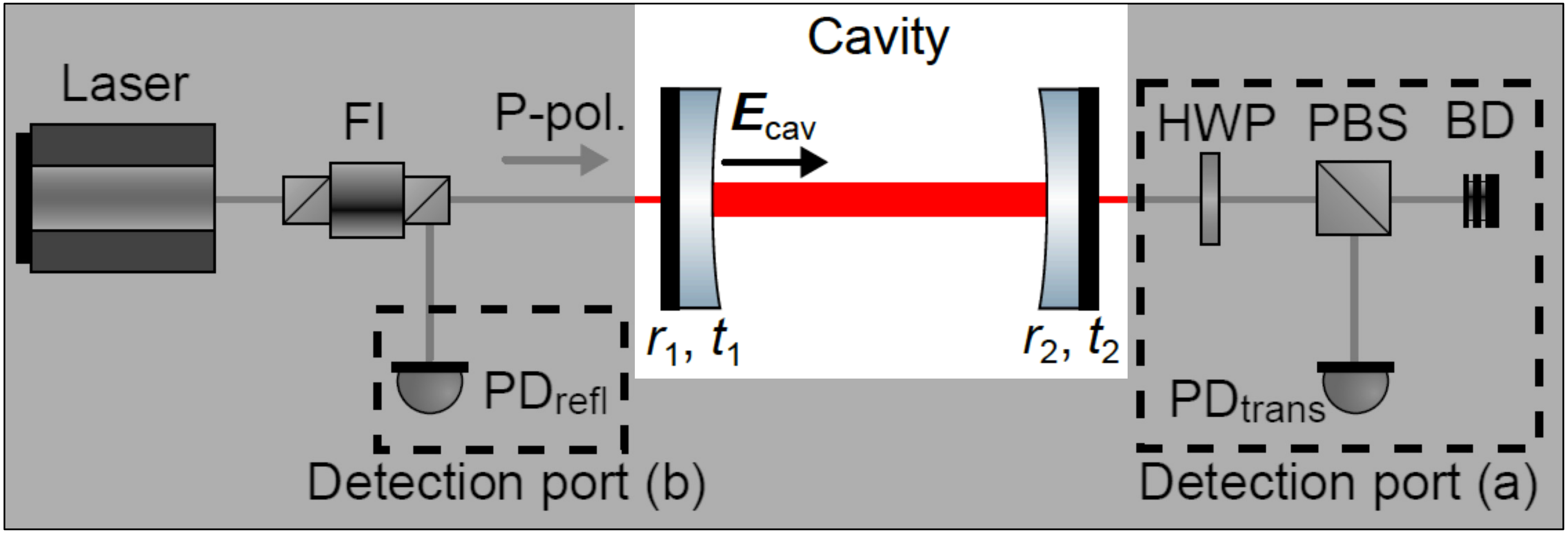
Experimental Setup

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



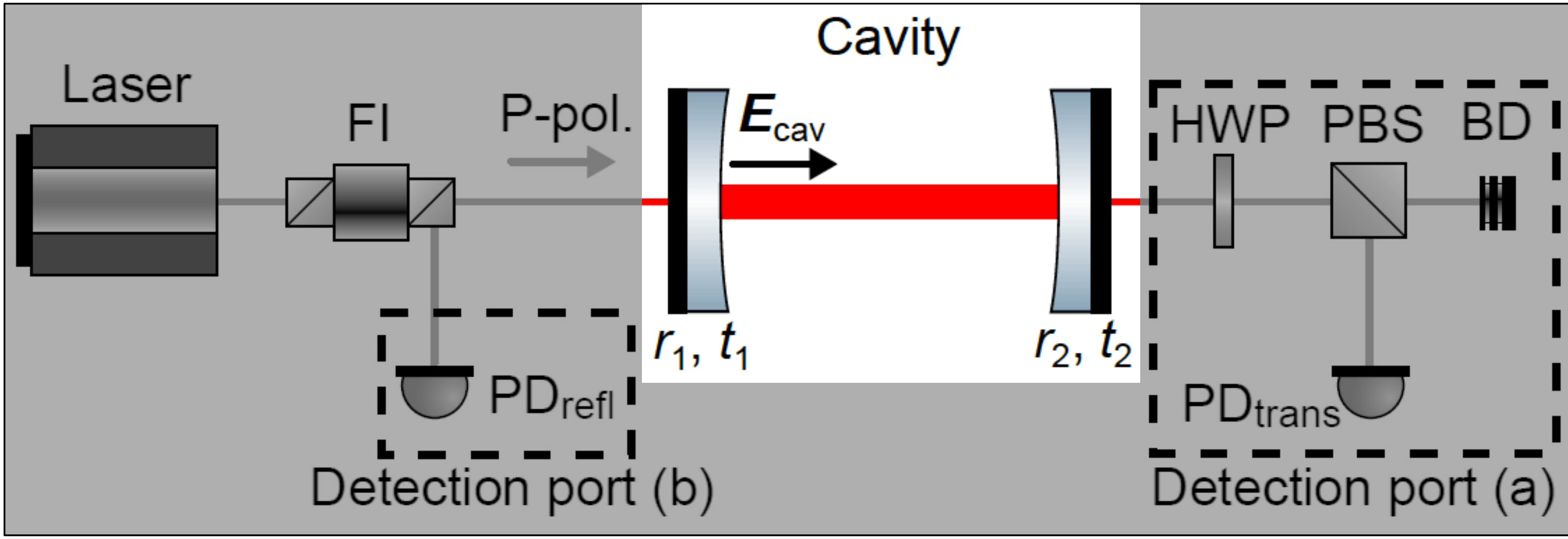
- **Electric vector inside cavity is represented as the superposition of reflected beams:**

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

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

R_i : reflection matrix
$T(t)$: transfer matrix for one way
L : cavity length

Inside Cavity



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

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

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

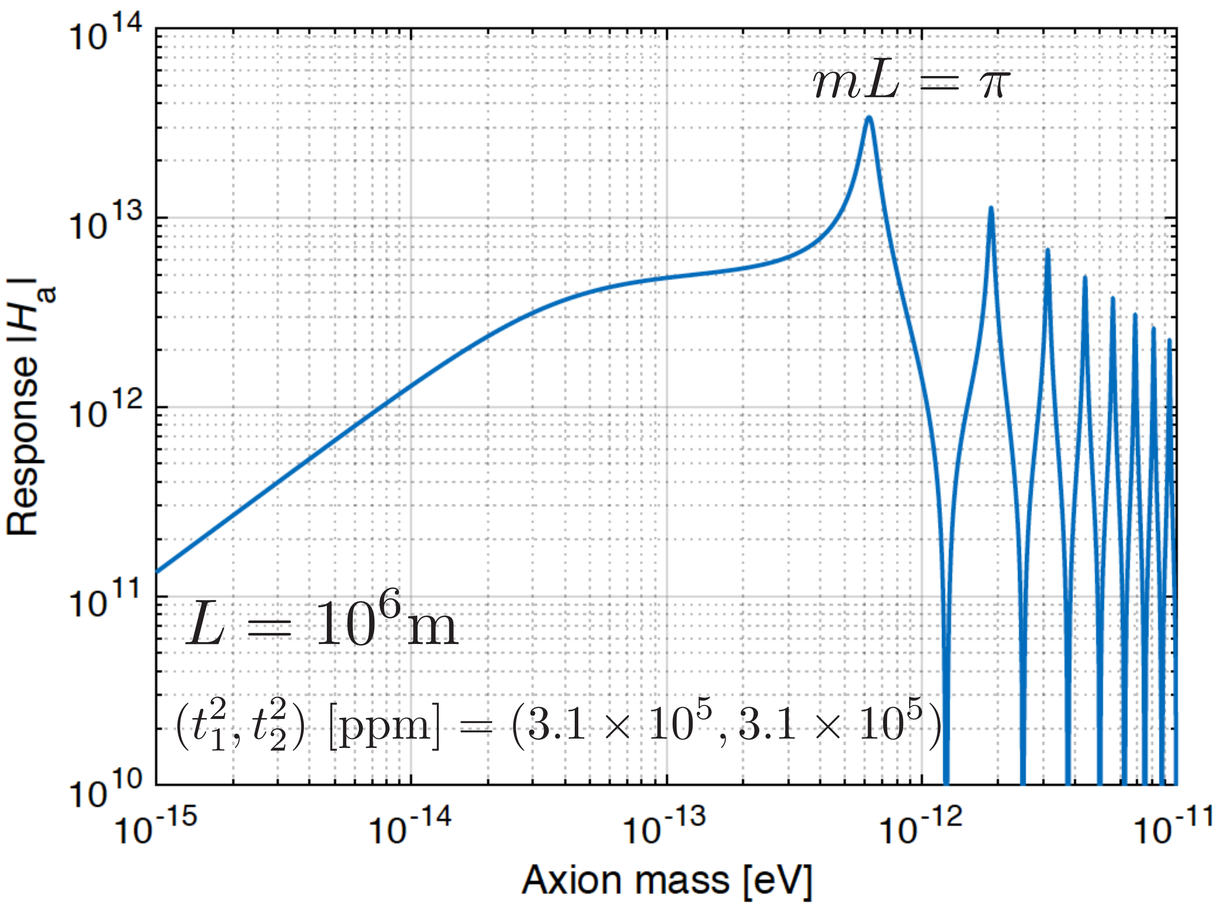
$$\gg 1 \quad (\because r_i \simeq 1)$$

Frequency Response in Signal

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

$$H_{\rm a}(m) = i\frac{k}{m}\frac{4r_1r_2\sin^2(\frac{mL}{2})}{1-r_1r_2e^{-i2mL}}(-e^{-imL})$$

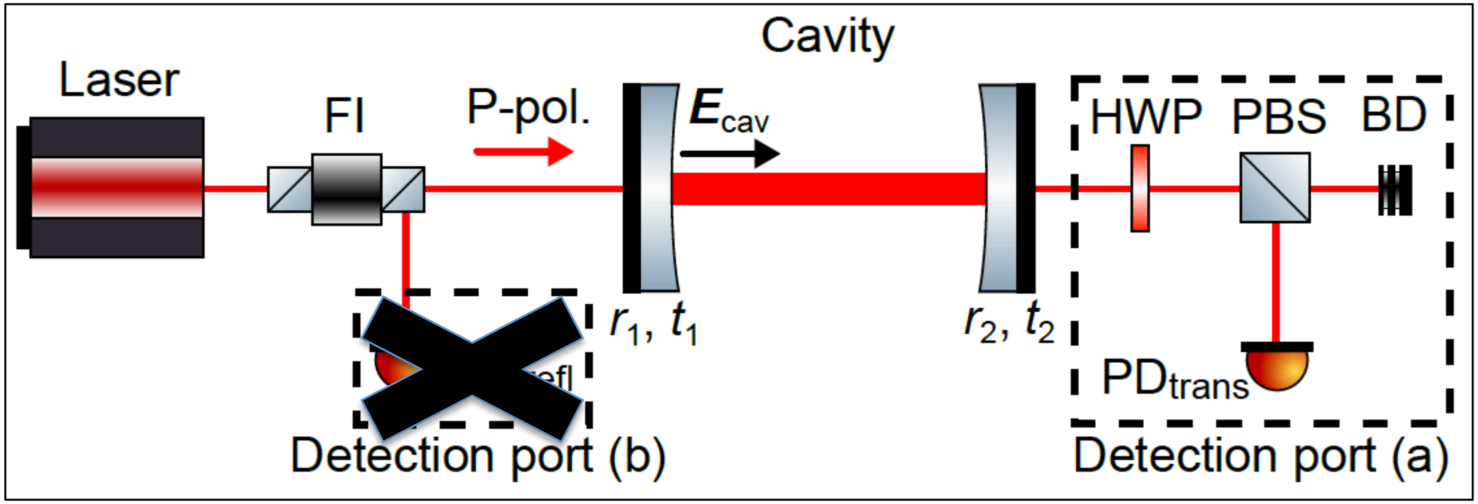
Response function of signal



Longer length
&
Higher finesse is better

→GW detectors!

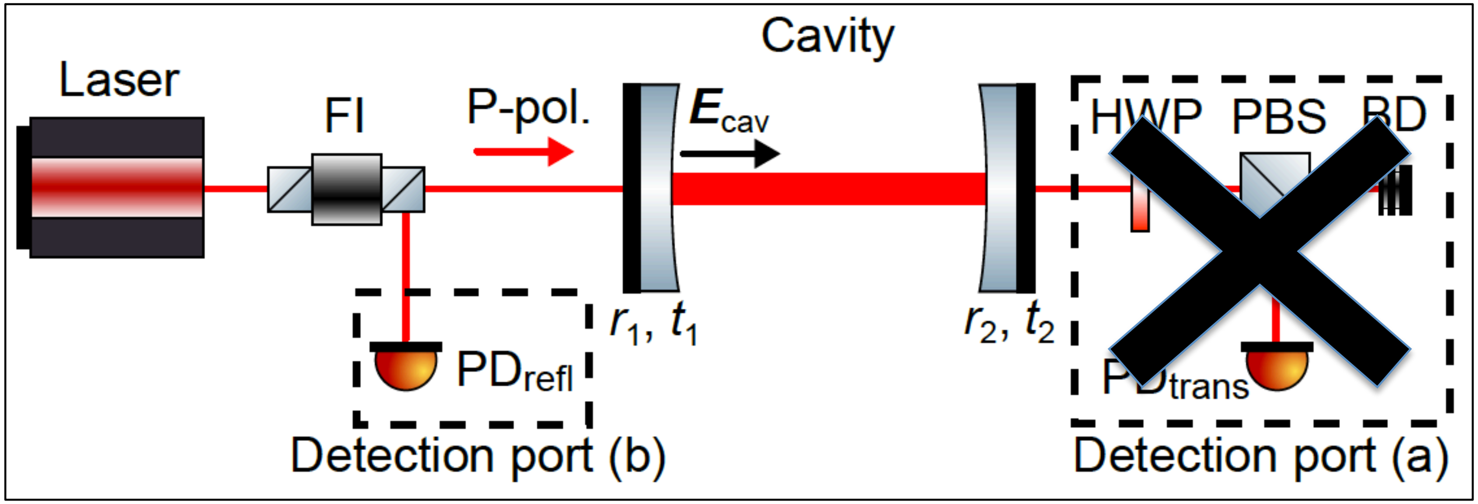
Detectability (Detection Port (a))



- **The polarization of transmitted light from the cavity is slightly rotated by the half wave plate.**
- **The PD receives the s-polarized light as a beatnote with faint carrier wave.**
- **The interferometer with large t2 mirror is available (DECIGO).**

Note : We would not apply this scheme to LISA interferometer (LISA is not resonant cavity)

Detectability (Detection Port (b))

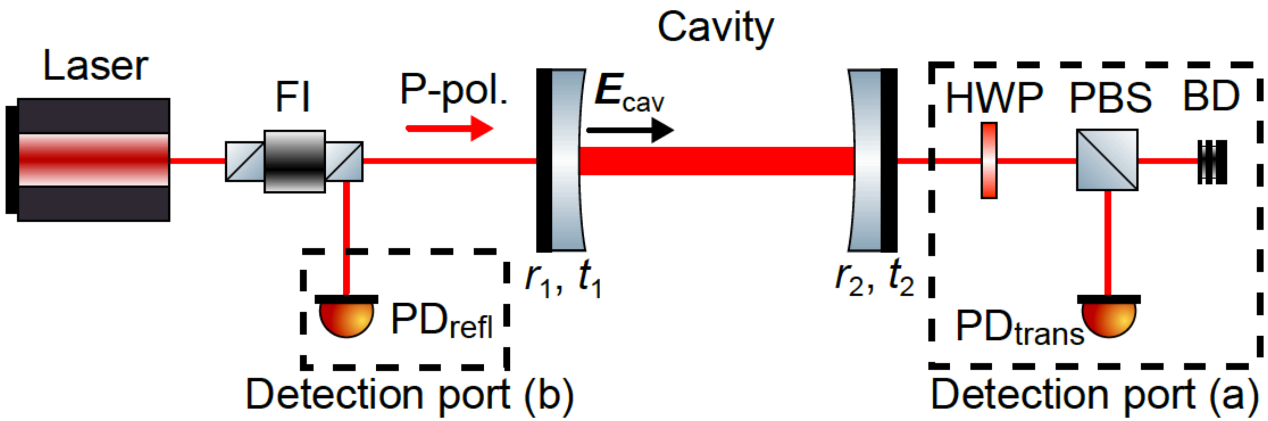


- The PD receives the signal reflected by the FI as a beatnote with faint carrier wave again.

- The mixed carrier wave would be generated by the non-ideal birefringence between FI and cavity (there have been equipped several apparatuses in a real detector).

- The interferometer with small t2 mirror is available (aLIGO, KAGRA, CE).

SN Ratio



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

$$\boldsymbol{E}_{\rm PD}(t) = \left[\sqrt{\mathcal{T}_i}(\alpha - \delta\phi(t)) + \frac{E_{\rm vac}(t)}{E_0}\right]\boldsymbol{E}^{\rm s}(t),\ \ \sqrt{\mathcal{T}_i} \equiv \frac{t_1 t_i}{1 - r_1 r_2}\ \ (i = 1, 2)$$

$$P_{\rm PD}(t) \propto |\boldsymbol{E}_{\rm PD}(t)|^2 \longrightarrow \sqrt{S_{\rm shot}(m)} = \frac{\sqrt{\frac{k}{2P_0}}}{\sqrt{\mathcal{T}_i}|H_{\rm a}(m)|}$$

Kimble+ 2001

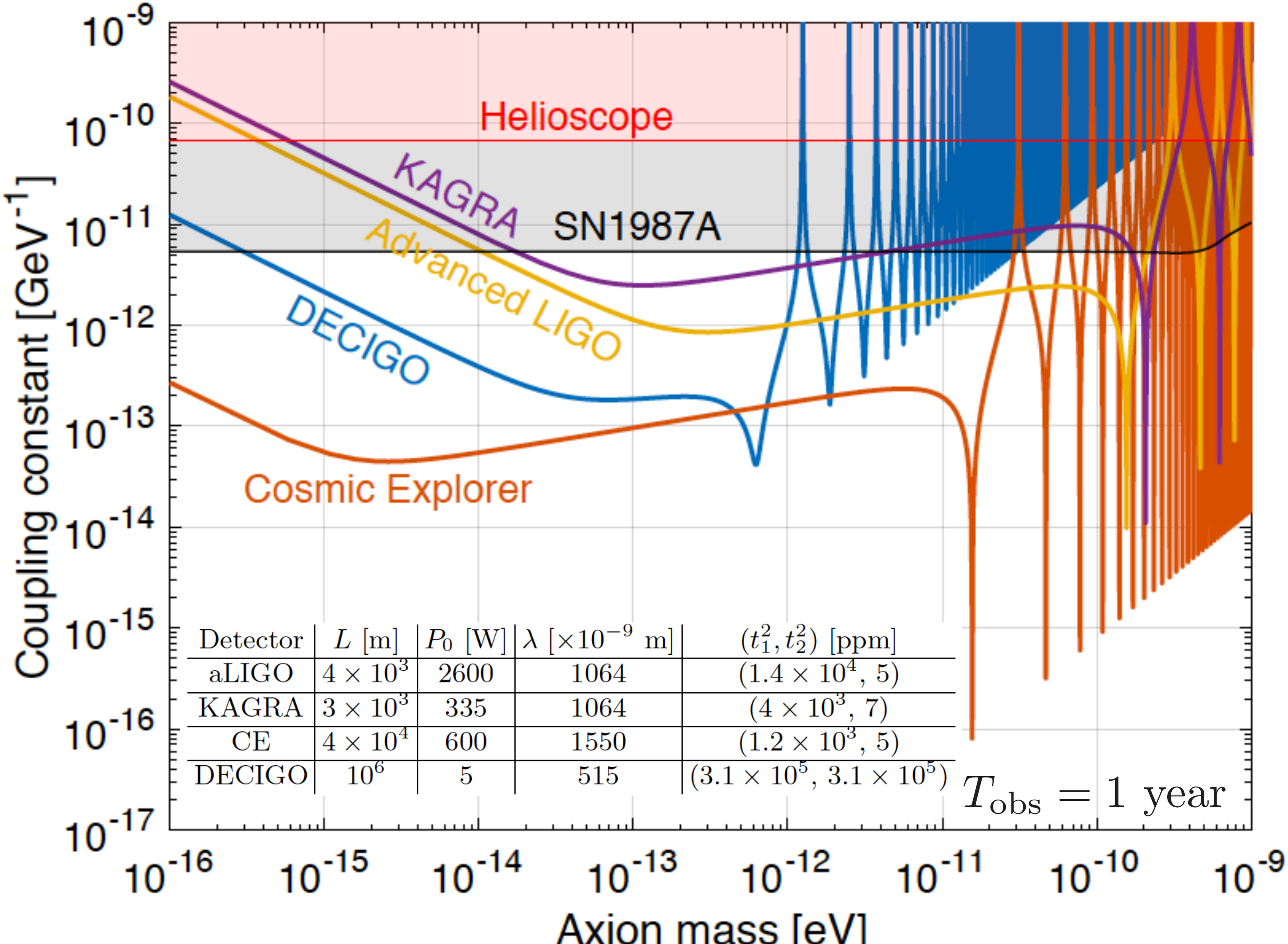
$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 & (T_{\rm obs} \lesssim \tau) \\ \dfrac{(T_{\rm obs}\tau)^{1/4}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 & (T_{\rm obs} \gtrsim \tau) \end{cases}$$

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

(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	$(3.1 \times 10^5,\ 3.1 \times 10^5)$

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.

- Which detection port (a) or (b) can be constructed depends on the gravitational wave detectors.

- As a first step, we want to apply our scheme to KAGRA.