Axion Dark Matter Search with Interferometric Gravitational Wave Detectors

Ippei Obata (theory group, ICRR, University of Tokyo)

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Collaborators：
Koji Nagano (ICRR)
Tomohiro Fujita (Kyoto University)
Yuta Michimura (University of Tokyo)

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What is Axion?

QCD Axion (Peccei & Quinn, 1977)

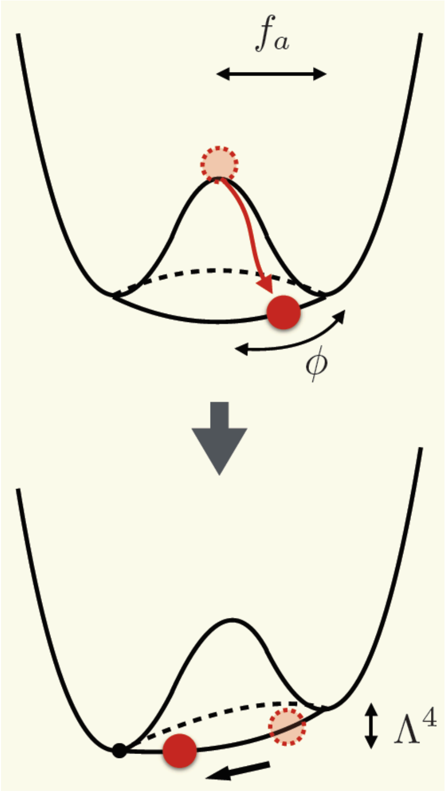
A pseudo NG boson of PQ mechanism in order to solve the strong CP problem in QCD physics

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

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

Axion-like particles (ALPs, string axion) (Svrcek & Witten 2006)

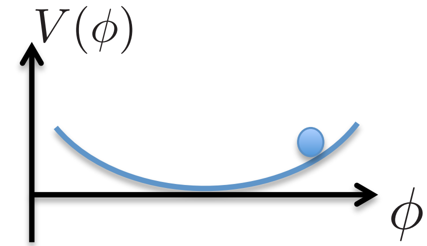
A plentitude of axion-like particles provided by the compactifications of extra dimensions



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

→ candidate for **dark matter**

Axion as Dark Matter (misalignment production)



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

- In early universe (m < H), $\phi \simeq \mathrm{const.}$ (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

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

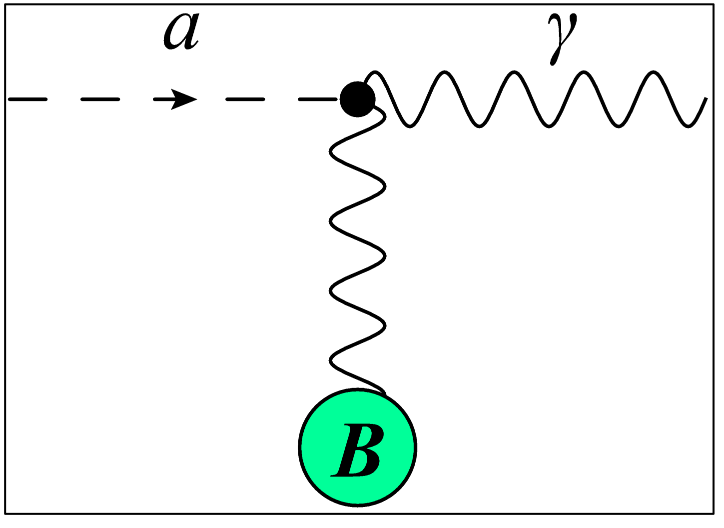
$$P = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2 \simeq \frac{P_0}{a^3}\sin(2mt) \sim 0$$

(Pressure) < (Gravity)
→Dark Matter!

Search for Axion (DM) via Photon

- Axion generically couples to photon via the topological term

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



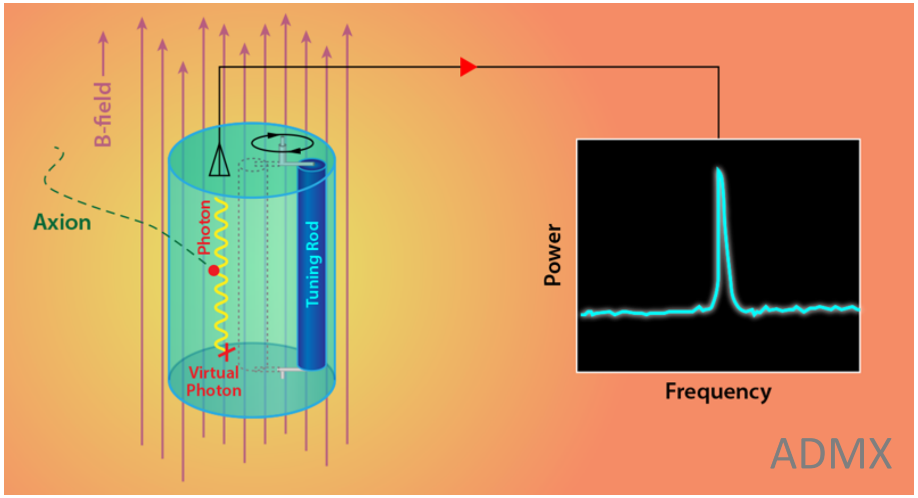
a : axion

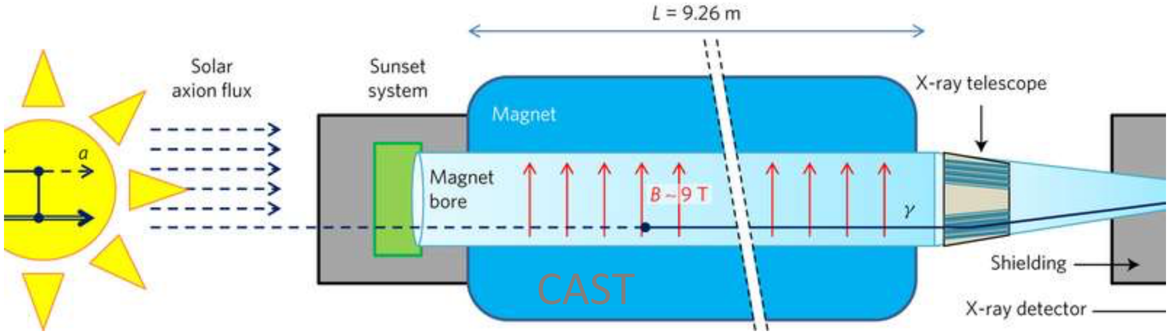
γ : photon

B : magnetic field

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

Search for Axion (DM) via Photon





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 the following dispersion relation

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

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

Axion DM – Photon Interaction

- The phase velocity of each polarized photon is given by

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

- Therefore, we get the difference of phase velocities between two modes

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

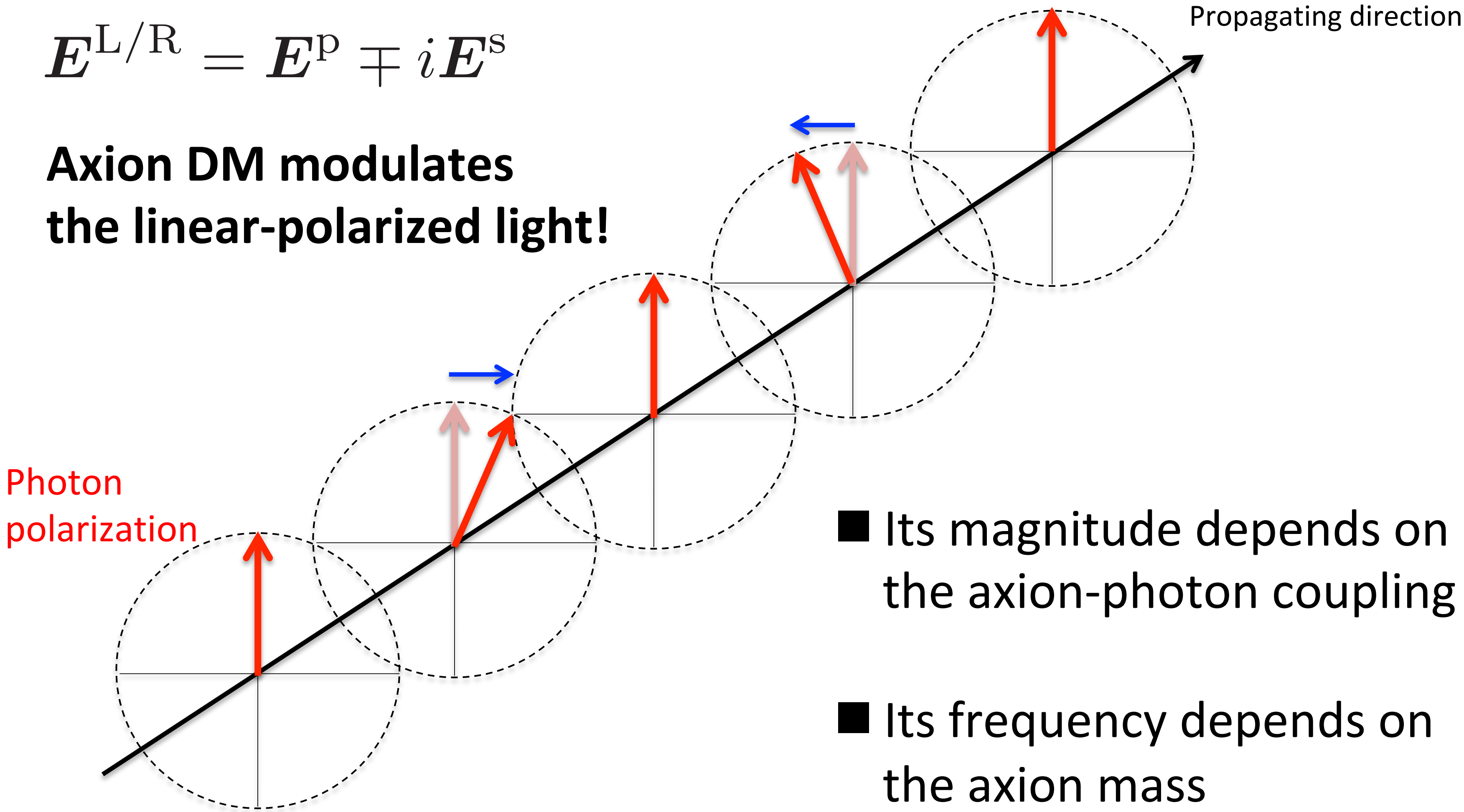
$$\frac{\delta c_0}{c} \simeq 1.3 \times 10^{-24} \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)\left(\frac{\lambda}{1550\ \mathrm{nm}}\right)\left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm^3}}\right)^{1/2}$$

Is it possible to test this tiny phase difference?

Modulation of photon polarization

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

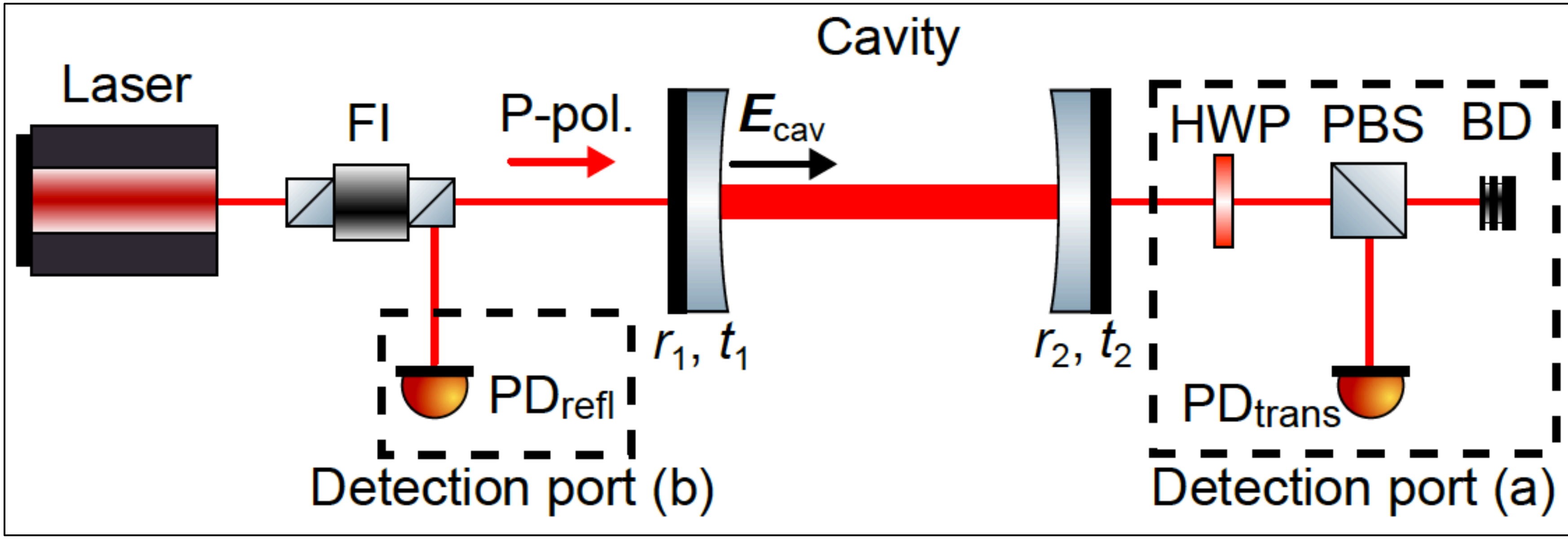
Axion DM modulates the linear-polarized light!



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

Experimental Setup

K.Nagano, T.Fujita, Y.Michimura, IO
1903.02017



FI: Faraday isolator
HWP: half wave plate
PBS: polarizing beam splitter
BD: beam dump

(r_i, t_i) $\quad r_i^2 + t_i^2 = 1$

reflectivity and transmissivity of cavity mirrors

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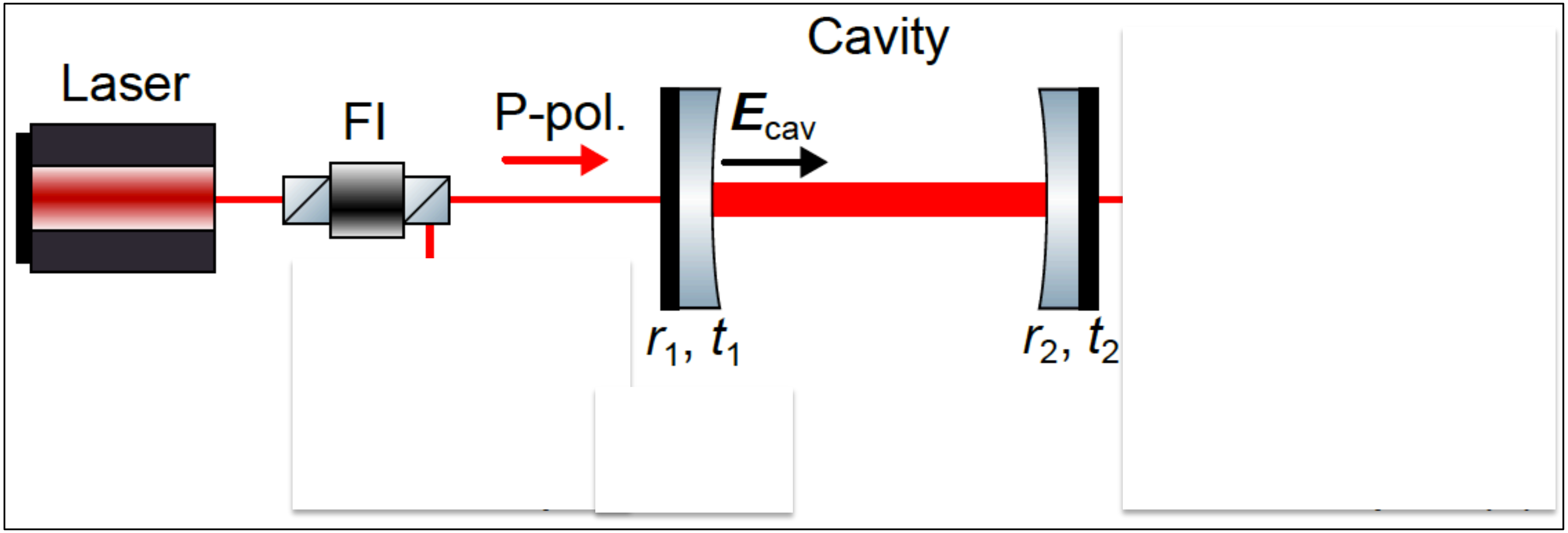

Electric vector inside cavity:

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

(superposition of reflected beams)

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

L : cavity length

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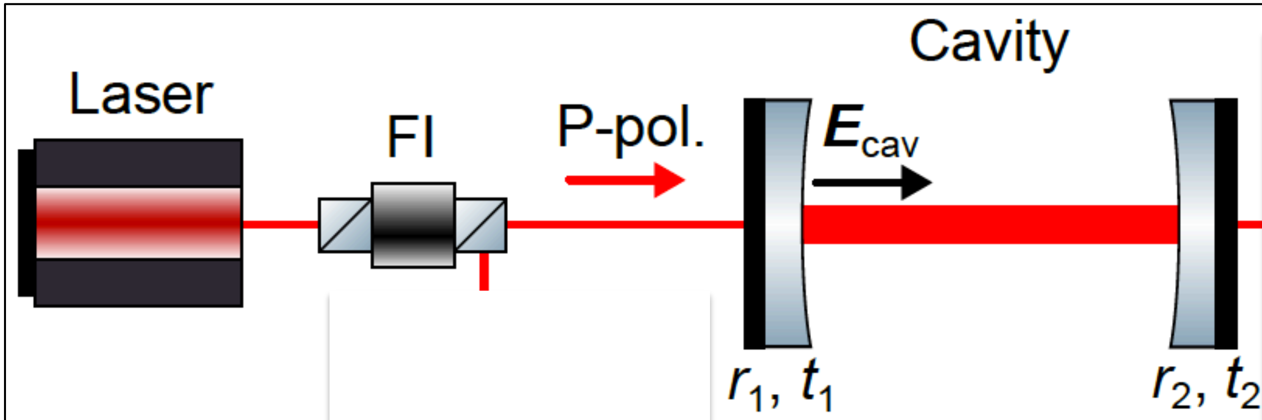

Transfer matrix

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

Reflection matrix

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

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

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

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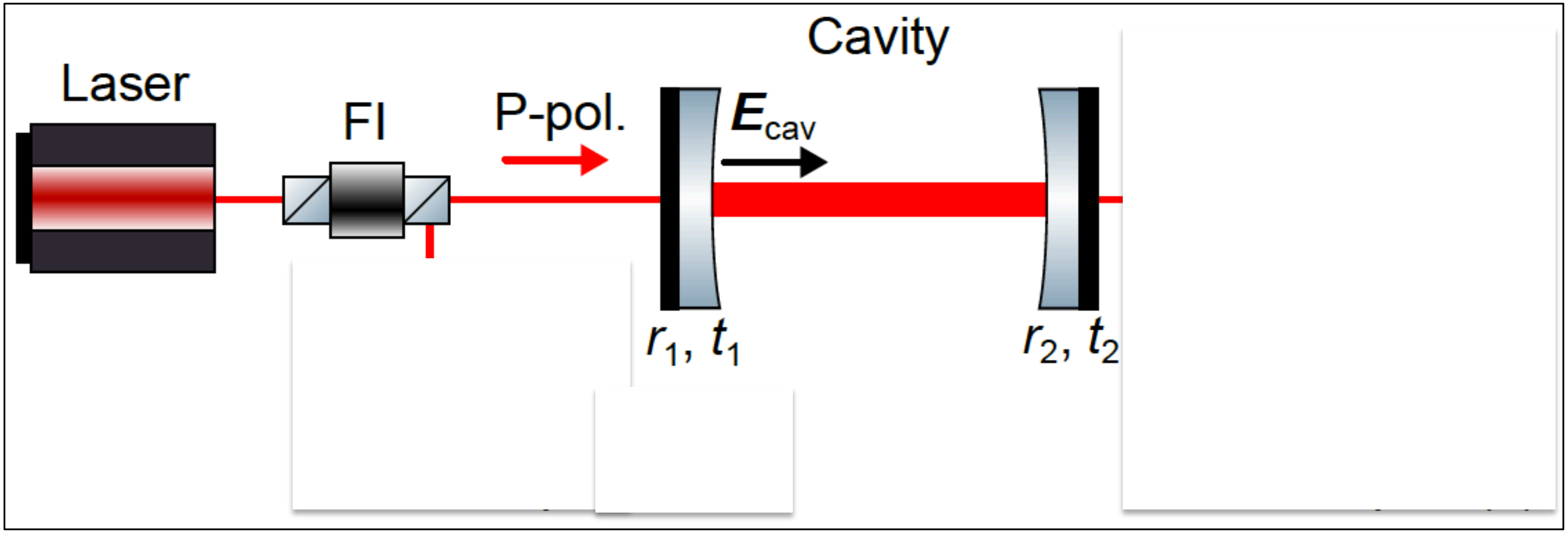

$$\boldsymbol{E}_{\rm cav}(t) = \frac{t_1 E_0 e^{ikt}}{1 - r_1 r_2} \begin{pmatrix} \boldsymbol{e}^{\rm L} & \boldsymbol{e}^{\rm R} \end{pmatrix} \begin{pmatrix} 1 + i\delta\phi(t) & 0 \\ 0 & 1 - i\delta\phi(t) \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

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

The signal is enhanced inside the cavity

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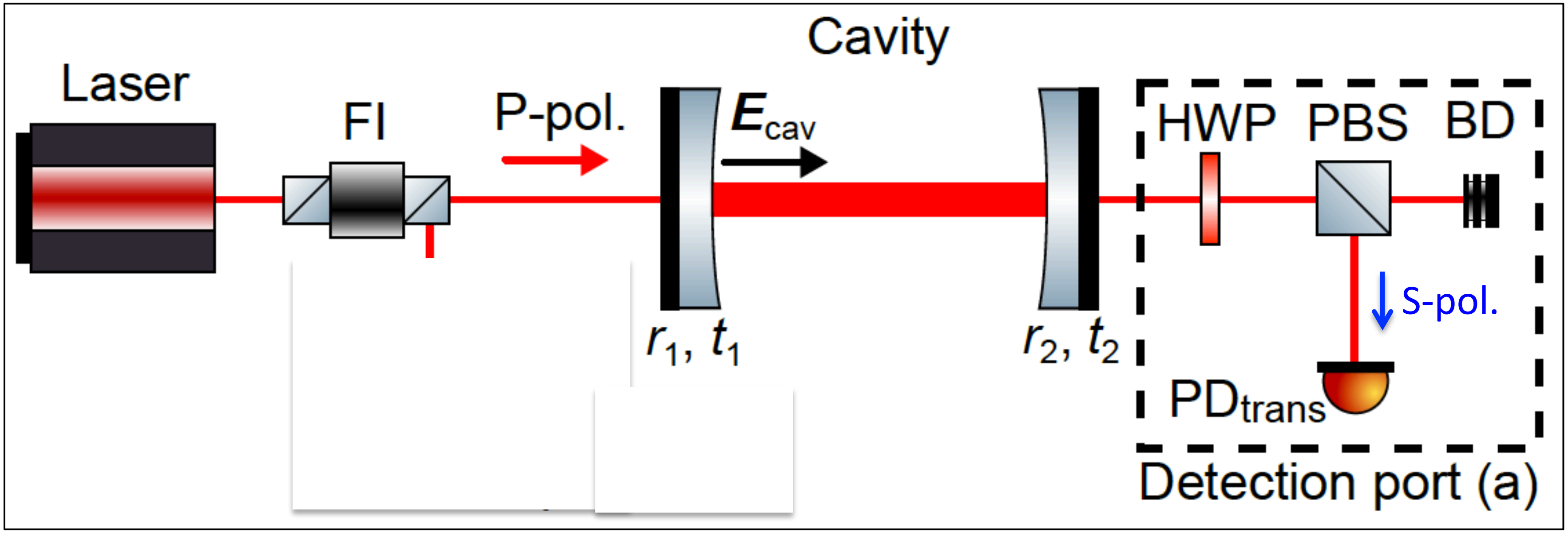

$$\boldsymbol{E}_{\mathrm{PD}}(t) = \frac{t_1 t_2}{1 - r_1 r_2}(\alpha - \delta\phi)\boldsymbol{E}^{\mathrm{s}}(t) \quad \alpha \ll 1 : \text{mixing angle}$$

Available for the detector of large t2 (t1=t2)

Experimental Setup

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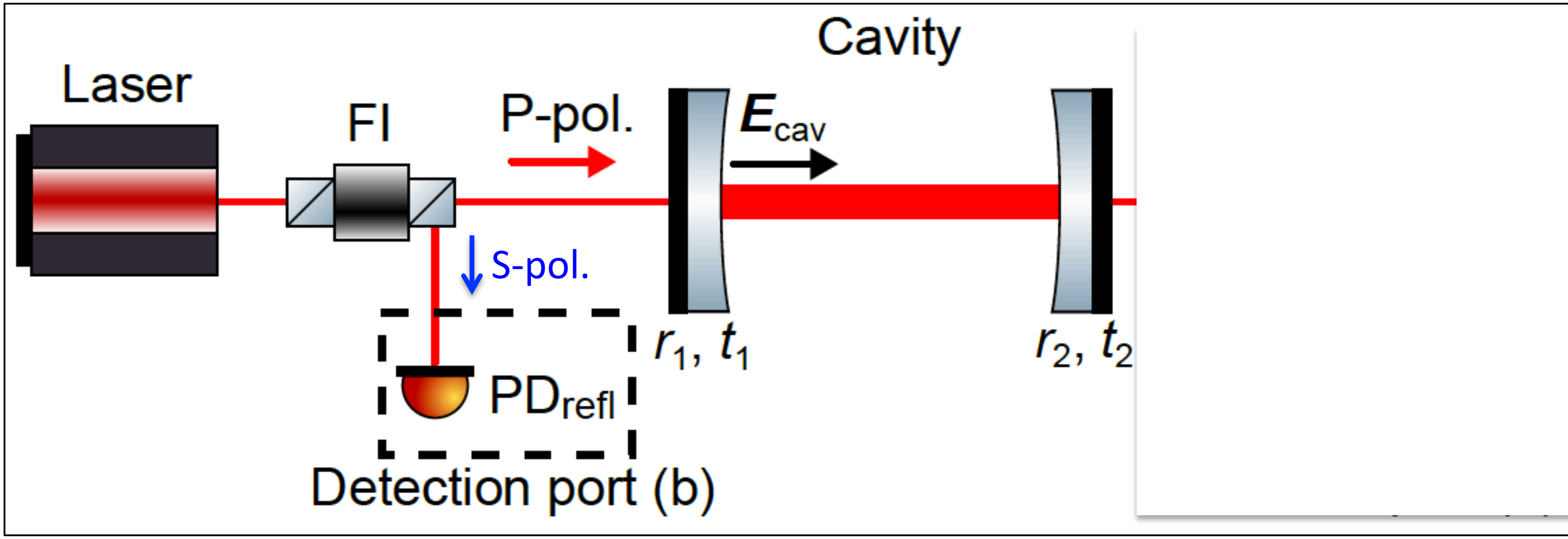


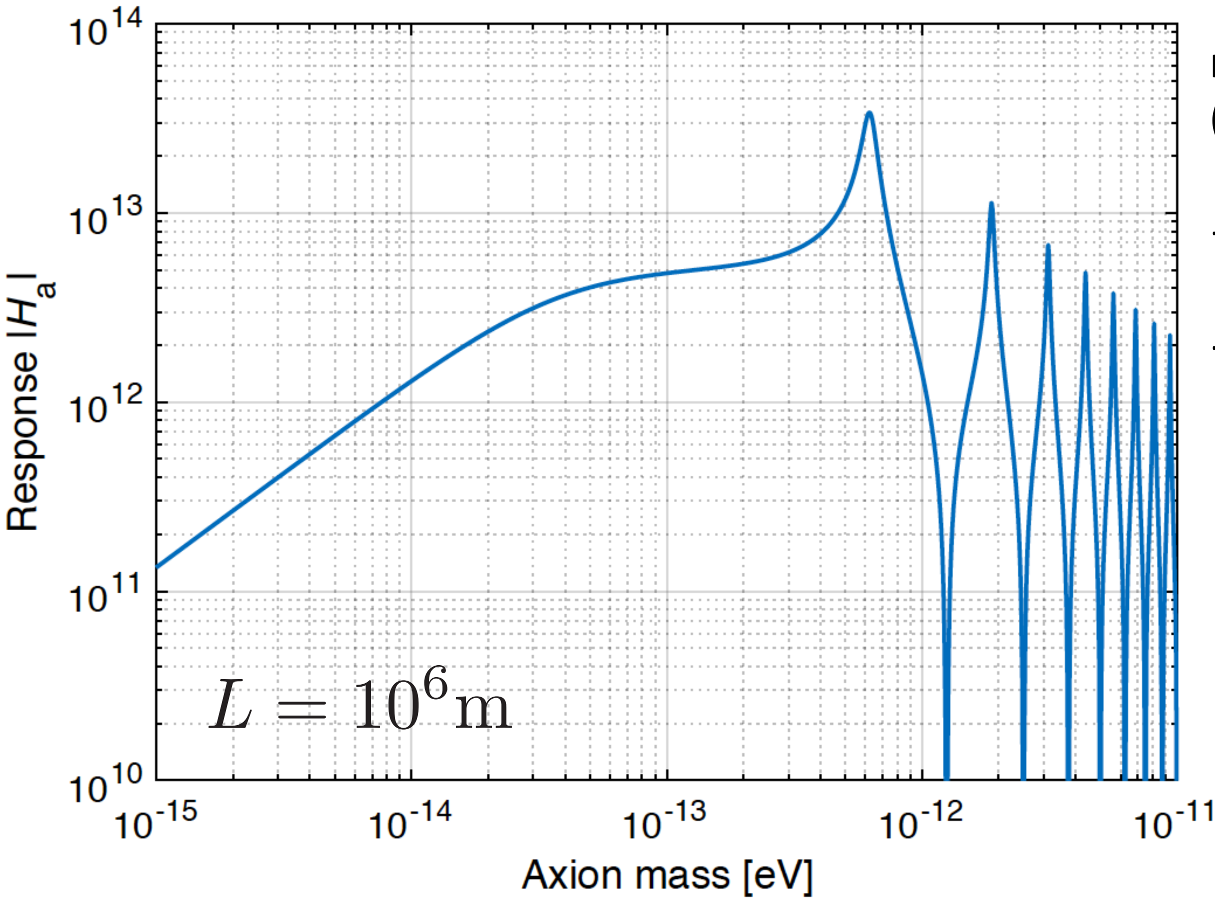
$$\boldsymbol{E}_{\rm PD}(t) = \frac{t_1 t_1}{1 - r_1 r_2}(\alpha - \delta\phi)\boldsymbol{E}^{\rm s}(t) \quad \alpha \ll 1 : \text{mixing angle}$$

Available for the detector of small t2 (t1 > t2)

Response function

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

$$H_{\mathrm{a}}(m) \equiv i \frac{\Omega}{m} \frac{4 r_1 r_2 \sin^2\left(\frac{mL}{2}\right)}{1 - r_1 r_2 e^{-i2mL}} \left(-e^{-imL}\right)$$

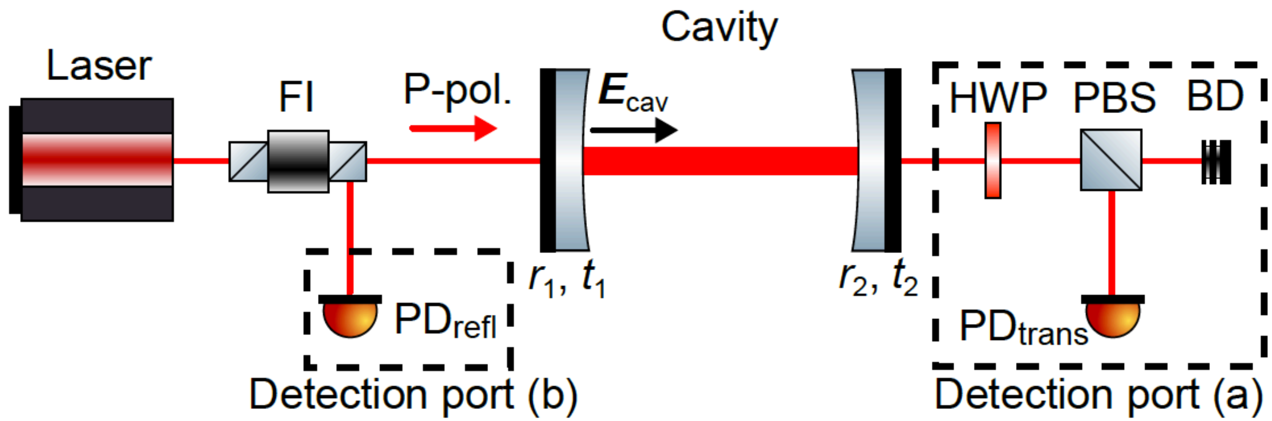


m L ~ 1 is best sensitivity (proportional to 1/m)

→longer cavity length is better

→GW detectors!

SN ratio



The sensitivity is determined by quantum shot noise

$$\boldsymbol{E}_{\rm PD}(t) = \left[\sqrt{\mathcal{T}_i}(\alpha - \delta\phi(t)) + \frac{\epsilon_0(t)}{E_0}\right] \boldsymbol{E}^{\rm s}(t), \;\; \sqrt{\mathcal{T}_i} \equiv \frac{t_1 t_i}{1 - r_1 r_2} \;\; (i = 1, 2)$$

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

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

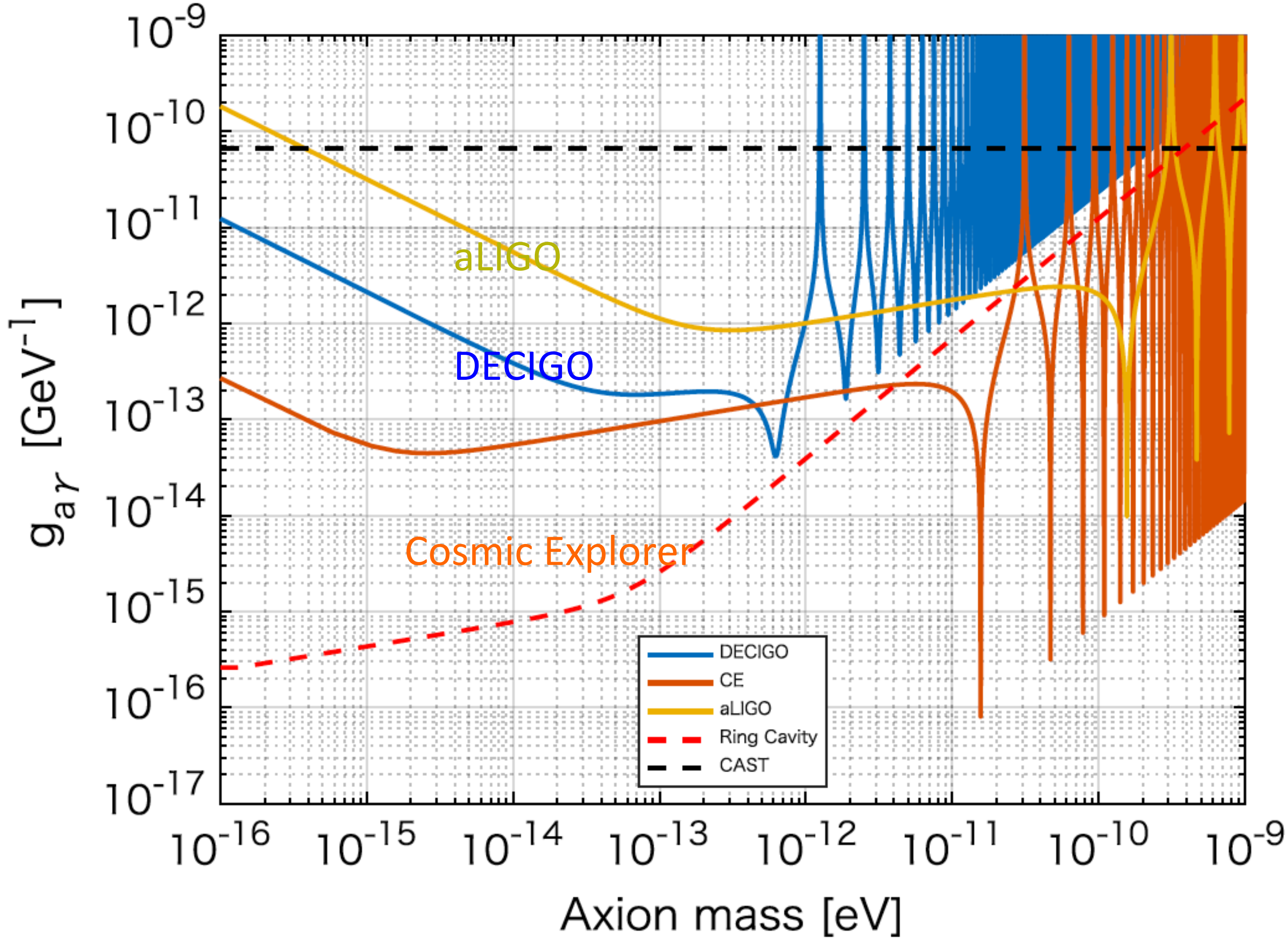
$$a(t) = a_0 \cos(mt + \delta_\tau)$$

(coherent time of axion DM)

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

Sensitivity curves

Similar detector	L [m]	P_0 [W]	λ [$\times 10^{-9}$ m]	(t_1^2, t_2^2) [ppm]
DECIGO [33]	10^6	5	515	$(3.1 \times 10^5, 3.1 \times 10^5)$
CE [32]	4×10^4	600	1550	$(1.2 \times 10^3, 5)$
aLIGO [26]	4×10^3	2600	1064	$(1.4 \times 10^4, 5)$

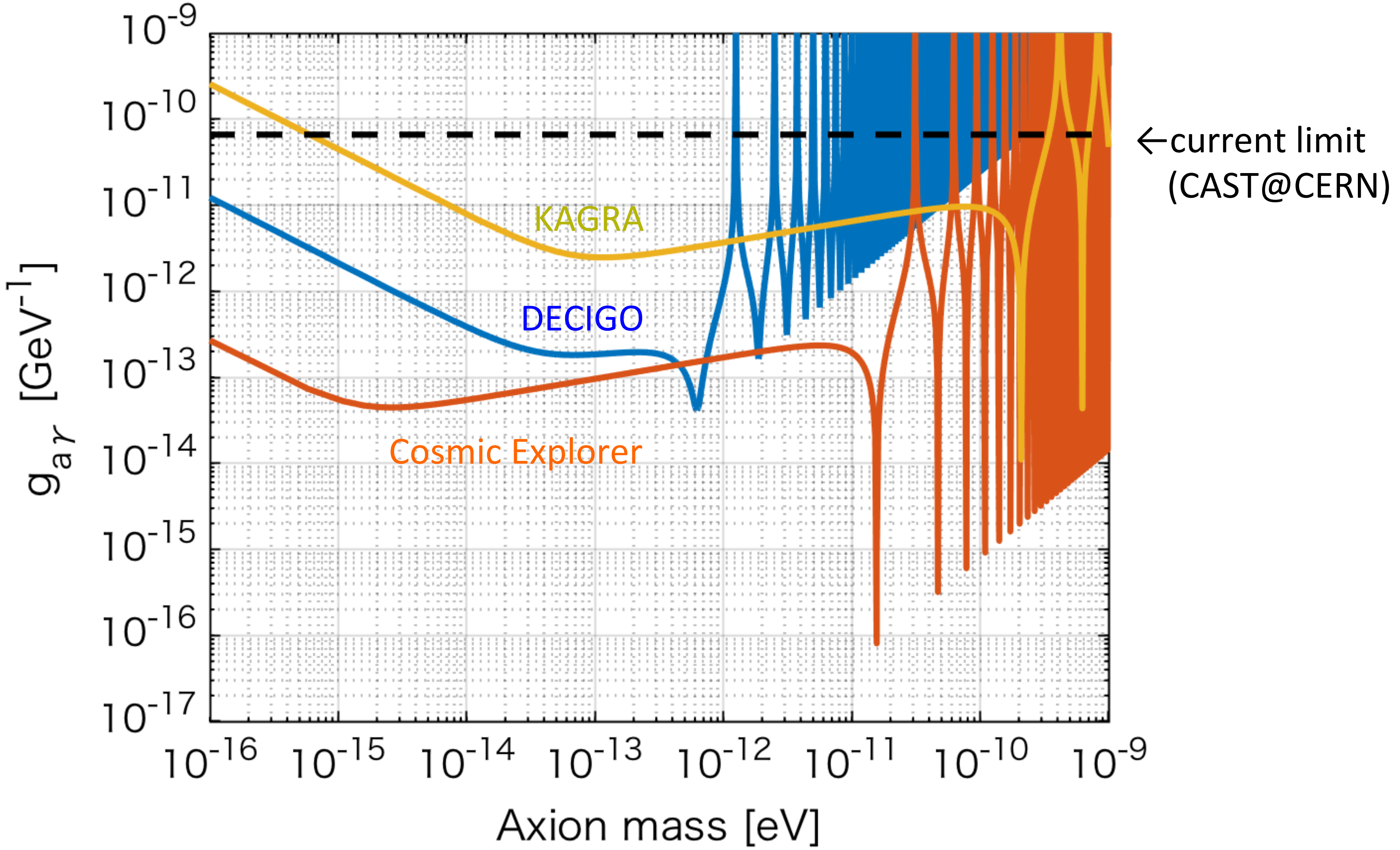


←current limit
(CAST@CERN)

Sensitivity curves

KAGRA

$L = 3 \times 10^3 [\mathrm{m}],\ P = 335 [\mathrm{W}],$
$\lambda = 1064 [\mathrm{nm}],\ (t_1^2, t_2^2\ [\mathrm{ppm}]) = (4 \times 10^3, 7)$



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.

- We hope that our scheme is applied to KAGRA,DECIGO, ….