Axion-Like Particle Search in Birefringent Cavity

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Keywords Related to Research

Cryptanalysis, Quantum Algorithm, Information Security

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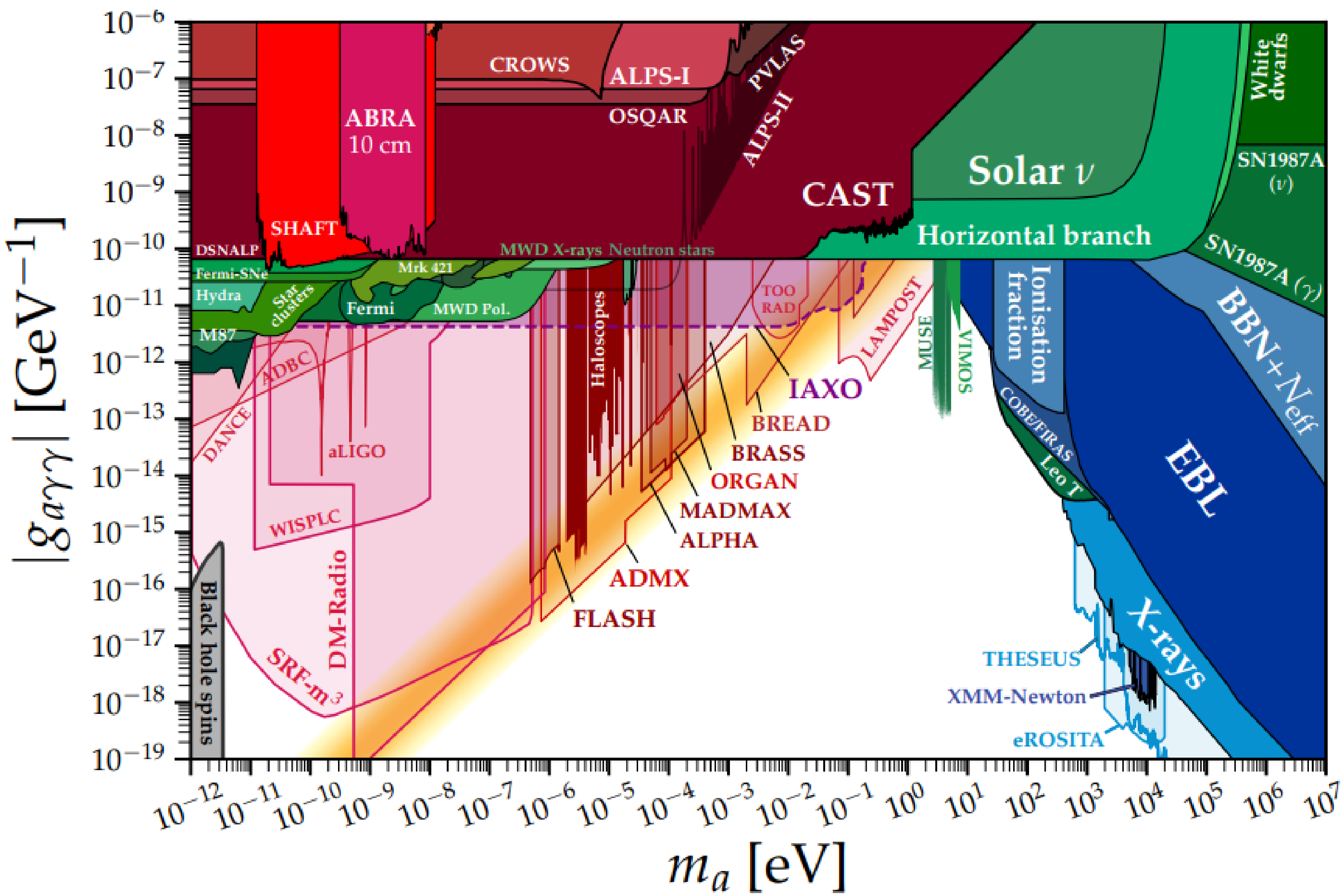
Keywords Related to Research

Semiconductor qubit, Quantum network, Non-equilibrium statistical physics

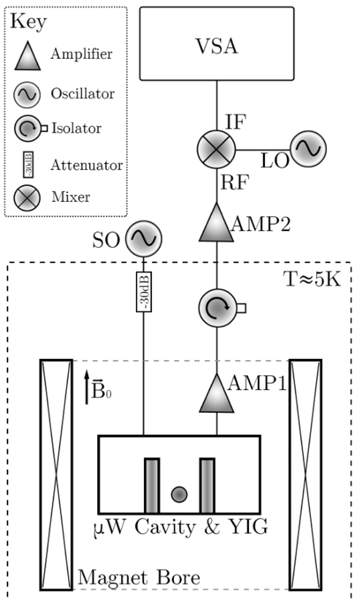
Website

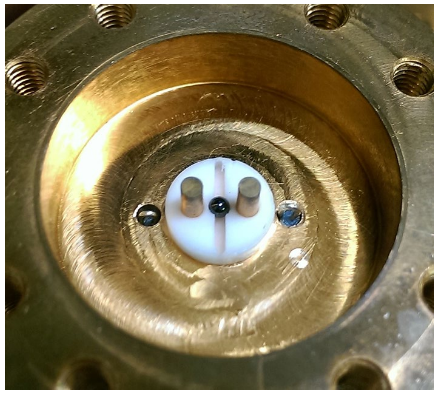
Axion-like particle (ALP) search

ALP is one of the candidates of the cold dark matter.
ALP is assumed to be the same interaction to the axion.
Quantum sensing technique is one the candidates of the detection.

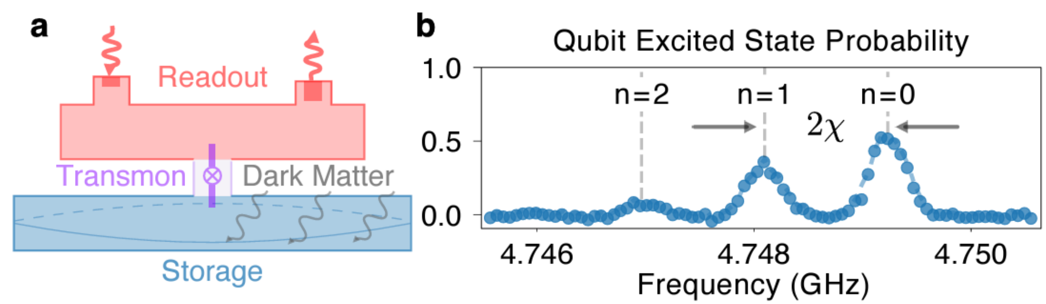


ALP search
w/ quantum sensors (microwave region)

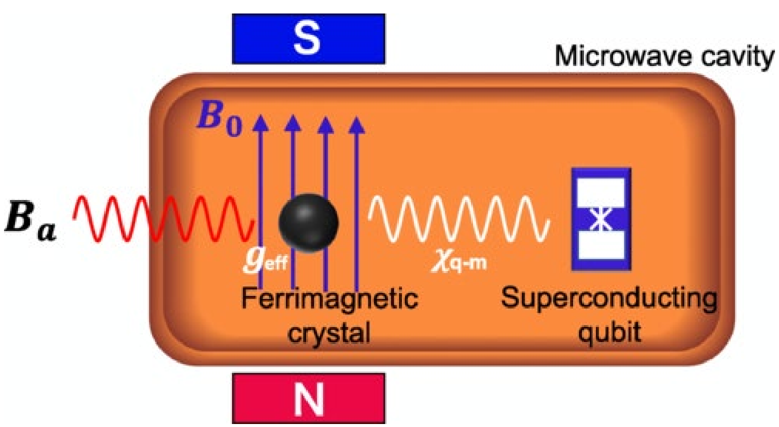




Flower+ Physics of the Dark Universe 2019 (Michael E. Tobar G)

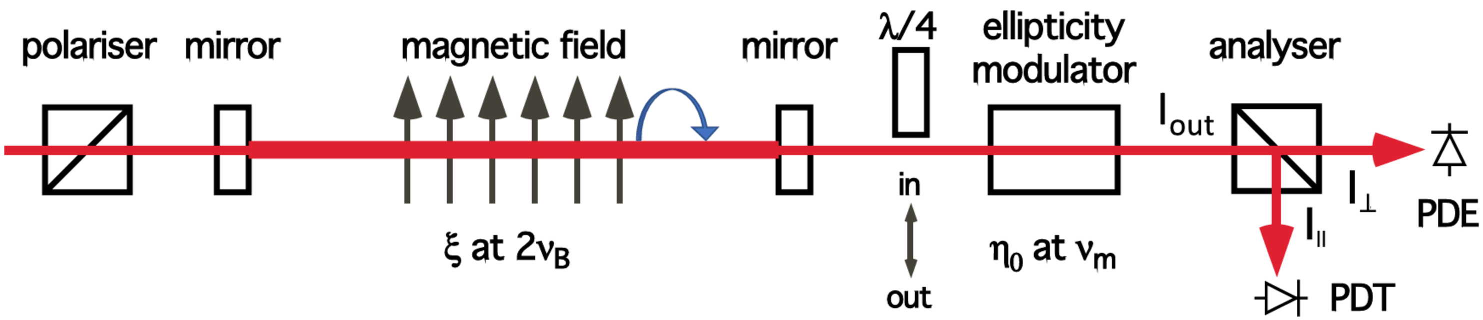


Dixit+ PRL 2021 (Chicago)



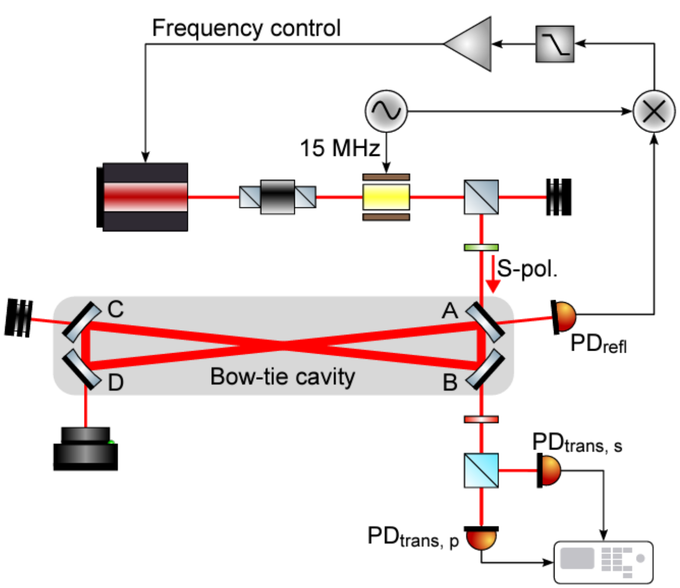
Ikeda, <u>YS</u>+ PRD 2022

ALP search w/ polarized light

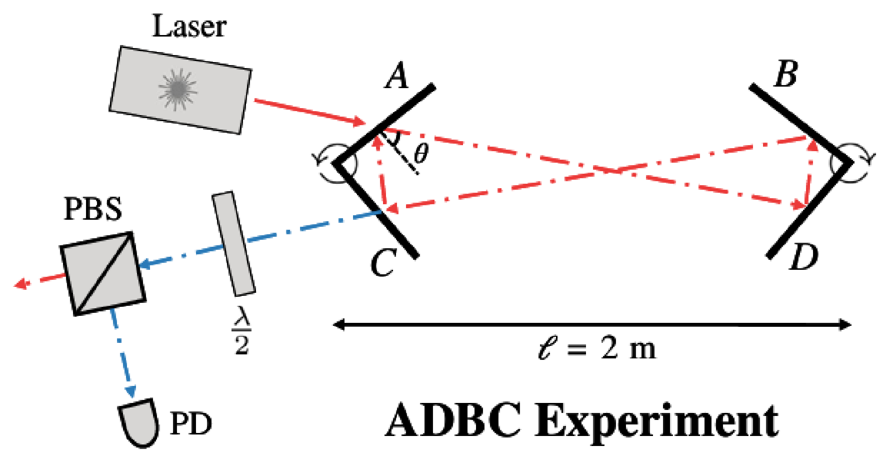


PVLAS experiment @ Ferrara, Italy

DANCE Experiment



Oshima+ PRD 2023

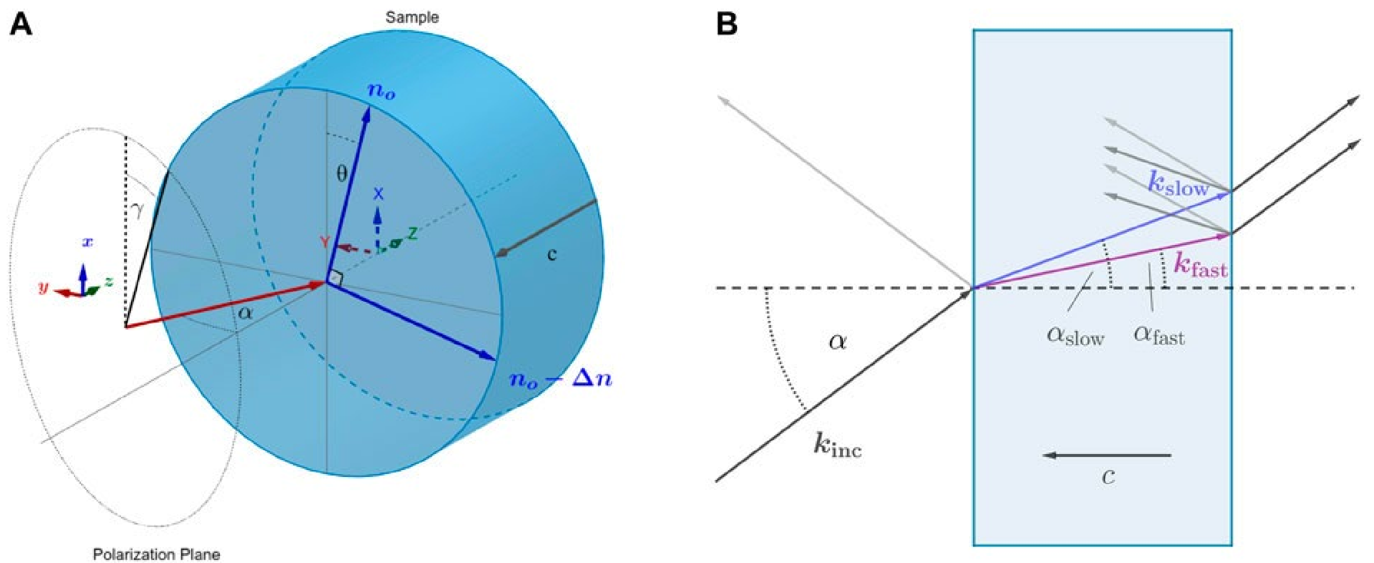


ADBC Experiment

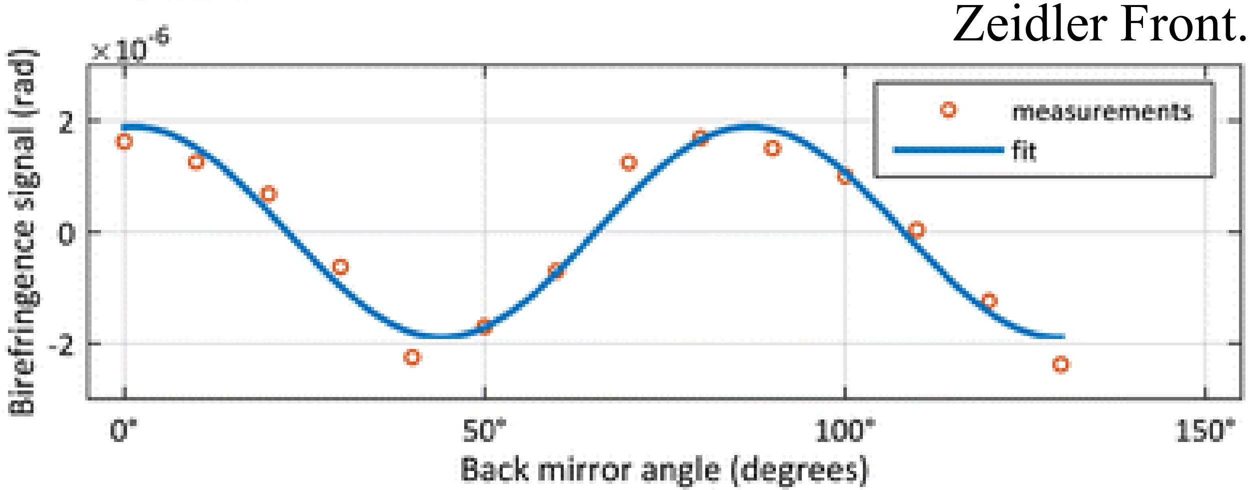
Liu+ PRD 2019

Problem on polarization

(Alignment mismatched) Mirror-induced birefringence

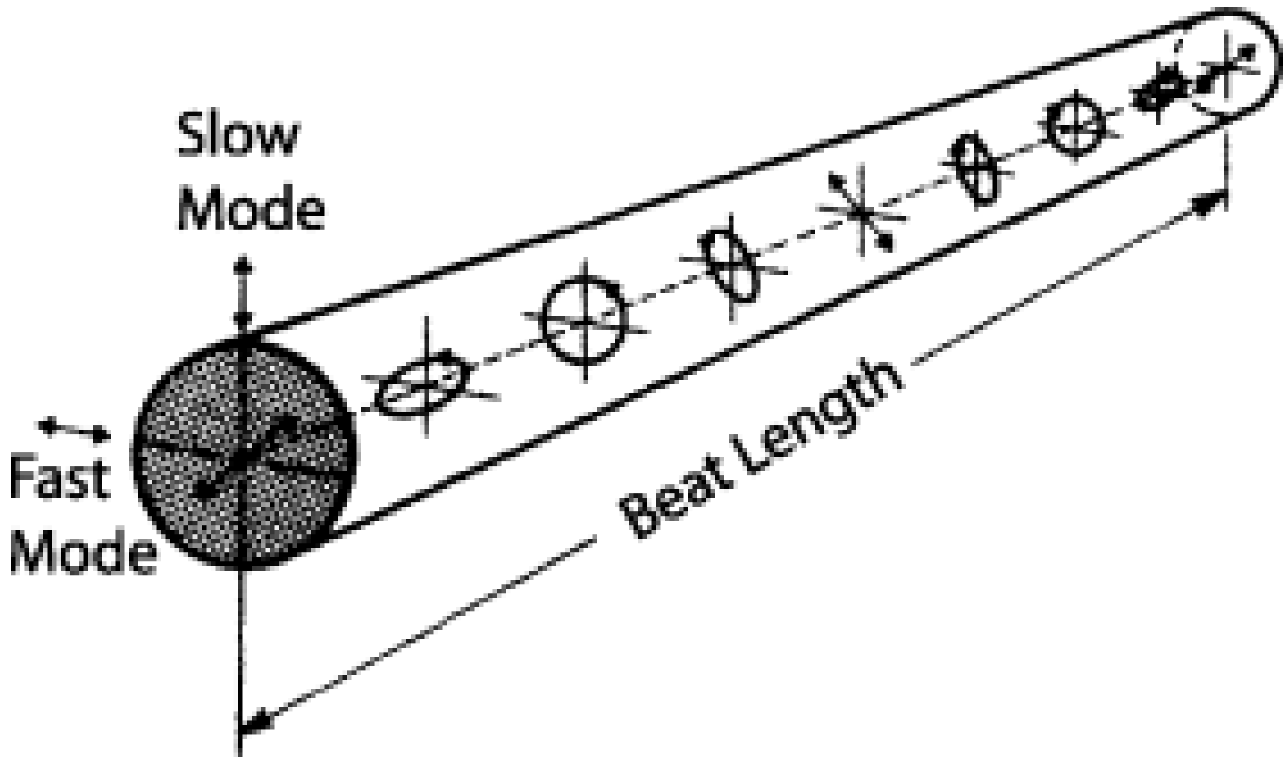


Zeidler Front. Astron. Space Sci. 2022



Westberg+ APB 2017

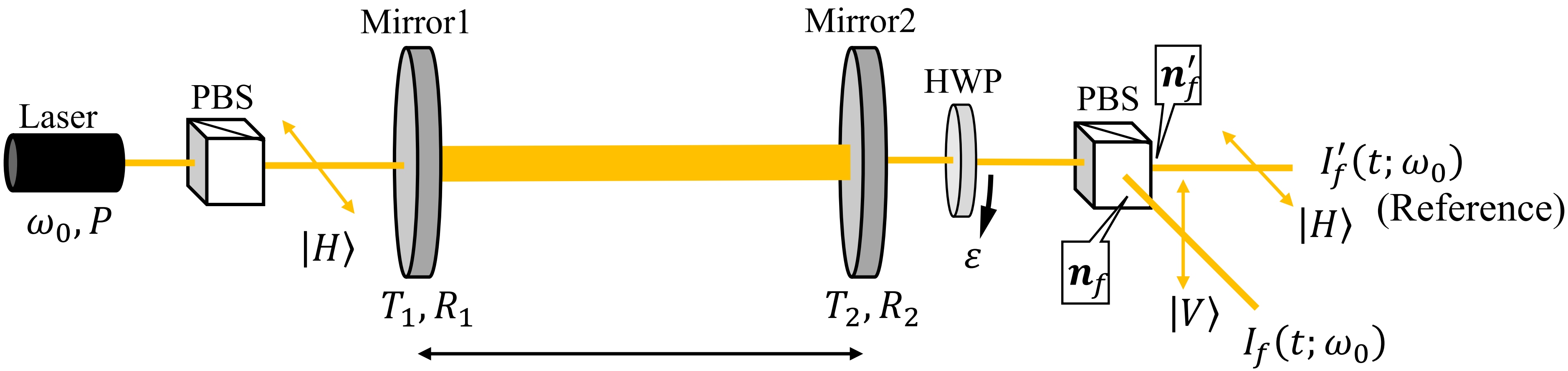
Birefringence through material



Fast mode / axis: relatively low refractive index
Slow mode / axis: relatively high refractive index

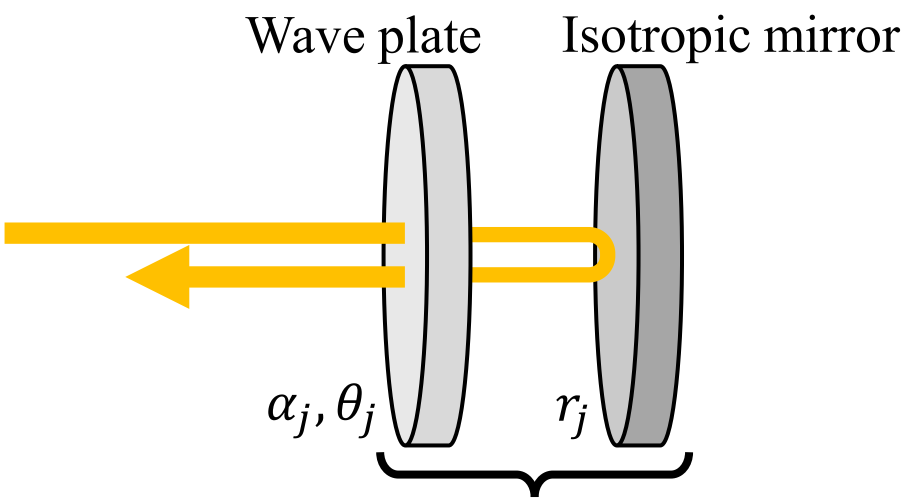
The polarization is slightly changed due to the material transmitting.

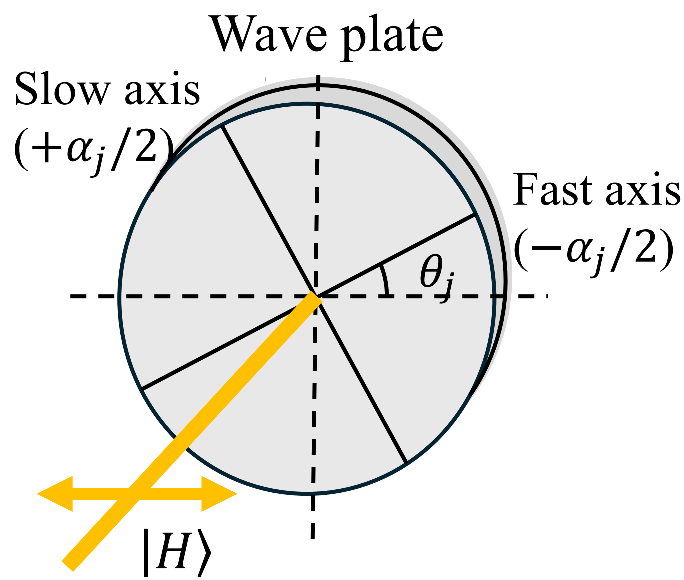
Fabry-Perot type cavity w/ Birefringence



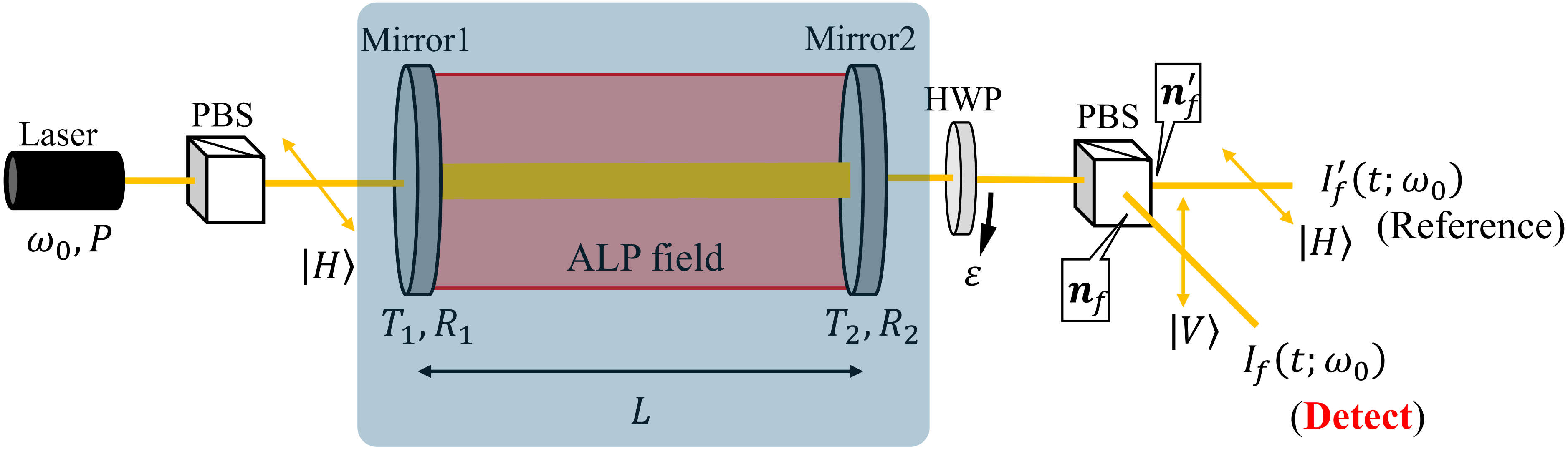
Description of birefringent mirror

Brandi+ APB 1997

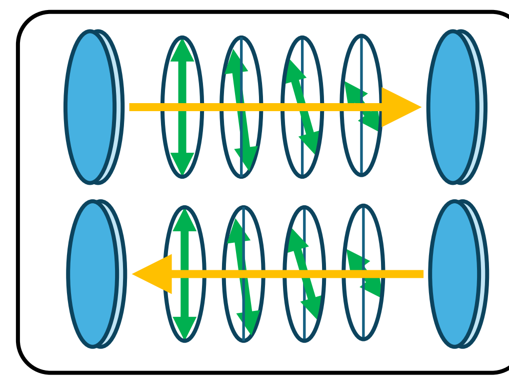




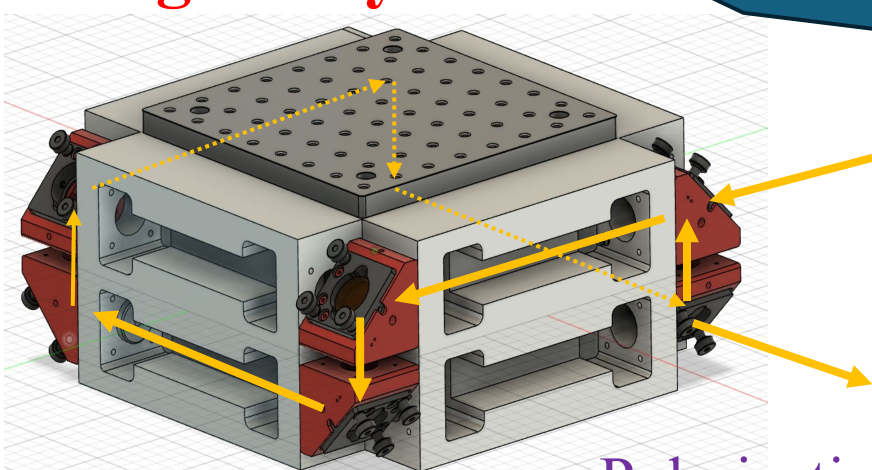
Our proposed setup

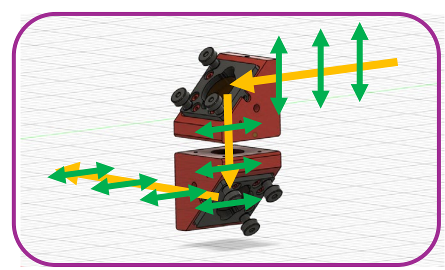


In FB-type cavity, the polarized effect due to ALP field is cancelled.



Ring cavity





Polarization-dependent path cavity

Signal-to-Noise Ratio (SNR)

$$\mathrm{SNR} = \frac{\sqrt{2}}{\left|C_f^{(0)}\right|}\left|C_f^{(0)*}C_f^{(+)} + C_f^{(0)}C_f^{(-)*}\right|\sqrt{\frac{P\mathcal{T}_{\mathrm{obs}}}{\hbar\omega_0}}$$

$$\boldsymbol{C}_f^{(0)} = e^{i\omega_0 L}e^{-i\theta\boldsymbol{n}\cdot\boldsymbol{\sigma}} \times \begin{pmatrix} \frac{1}{1-r_1r_2e^{2i\omega_0L}e^{-i\alpha}} & 0 \\ 0 & \frac{1}{1-r_1r_2e^{2i\omega_0L}e^{i\alpha}} \end{pmatrix} \times e^{i\theta\boldsymbol{n}\cdot\boldsymbol{\sigma}}T_1\begin{pmatrix}1\\0\end{pmatrix}.$$

$$\boldsymbol{C}_f^{(\pm)} = \frac{1}{2}ge^{i\omega_0L}\left(1-e^{\pm im_aL}\right)\times\left\{\frac{\boldsymbol{u}_F^{(\pm)}}{1-r_1r_2e^{2i(\omega_0\pm m_a)L}e^{-i\alpha}} + \frac{\boldsymbol{u}_S^{(\pm)}}{1-r_1r_2e^{2i(\omega_0\pm m_a)L}e^{i\alpha}} + \frac{\boldsymbol{v}_F^{(\pm)}}{1-r_1r_2e^{2i\omega_0L}e^{-i\alpha}} + \frac{\boldsymbol{v}_S^{(\pm)}}{1-r_1r_2e^{2i\omega_0L}e^{i\alpha}}\right\}$$

$$\boldsymbol{u}_F^{(\pm)} := \boldsymbol{b}_F + \frac{i\Xi_\pm - \Sigma_\pm}{1-e^{\pm 2im_aL}}\boldsymbol{a}_F - \frac{\Sigma_\pm}{1-e^{\pm 2im_aL}e^{-2i\alpha}}\boldsymbol{a}_S,$$

$$\boldsymbol{u}_S^{(\pm)} := \boldsymbol{b}_S + \frac{i\Xi_\pm + \Sigma_\pm}{1-e^{\pm 2im_aL}}\boldsymbol{a}_S + \frac{\Sigma_\pm}{1-e^{\pm 2im_aL}e^{2i\alpha}}\boldsymbol{a}_F,$$

$$\boldsymbol{v}_F^{(\pm)} := \frac{-1}{1-e^{\pm 2im_aL}}\left[i\Xi_\pm + \frac{e^{2im_aL}\left(e^{2i\alpha}-1\right)}{1-e^{\pm 2im_aL}e^{2i\alpha}}\Sigma_\pm\right]\boldsymbol{a}_F,$$

$$\boldsymbol{v}_S^{(\pm)} := \frac{-1}{1-e^{\pm 2im_aL}}\left[i\Xi_\pm - \frac{e^{2im_aL}\left(e^{-2i\alpha}-1\right)}{1-e^{\pm 2im_aL}e^{-2i\alpha}}\Sigma_\pm\right]\boldsymbol{a}_S$$

$$\Xi_\pm := \sigma_y + e^{\pm im_aL}R_1\sigma_yR_1^{-1},$$

$$\Sigma_\pm := \frac{1}{2}\left[\left(\frac{\partial}{\partial\alpha}\Gamma\right)_{\alpha=0}, \Xi_\pm\right],$$

$$\boldsymbol{a}_{F/S} := e^{-i\theta\boldsymbol{n}\cdot\boldsymbol{\sigma}}\frac{1\pm\sigma_z}{2}e^{i\theta\boldsymbol{n}\cdot\boldsymbol{\sigma}}T_1\begin{pmatrix}1\\0\end{pmatrix},$$

$$\boldsymbol{b}_{F/S} := e^{-i\theta\boldsymbol{n}\cdot\boldsymbol{\sigma}}\frac{1\pm\sigma_z}{2}e^{i\theta\boldsymbol{n}\cdot\boldsymbol{\sigma}}\left(-i\sigma_y\right)T_1\begin{pmatrix}1\\0\end{pmatrix}$$

$$\mathcal{T}_{\mathrm{obs}} = \begin{cases} T_{\mathrm{obs}} & (T_{\mathrm{obs}} \lesssim \tau) \\ (T_{\mathrm{obs}}\tau)^{1/2} & (T_{\mathrm{obs}} \gtrsim \tau) \end{cases}.$$

Axion coherence time

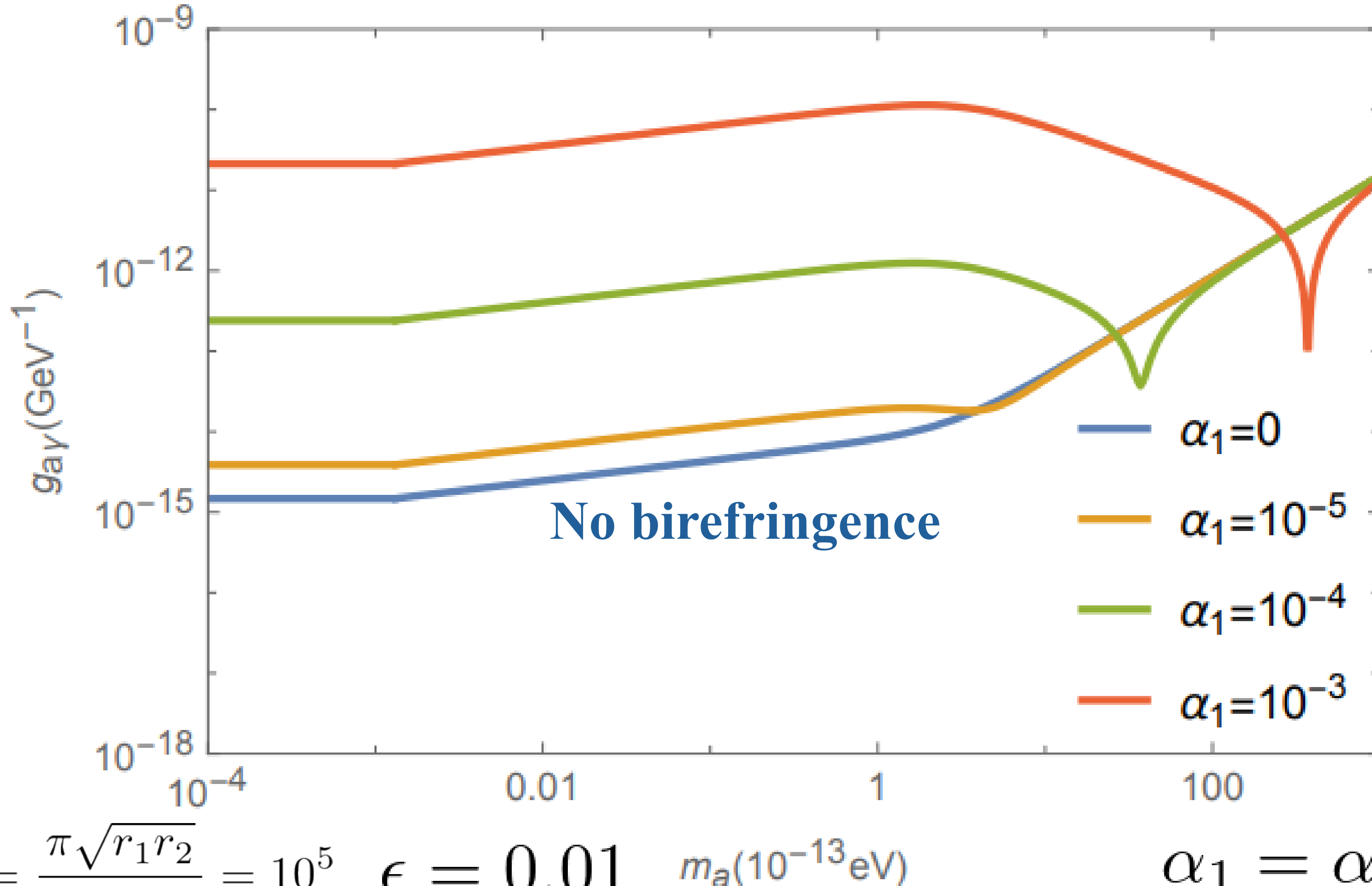
$$\tau = 10^6\frac{2\pi}{m_a}$$

Common parameters

$L = 10.64\ \mathrm{m}, \lambda = 1064\ \mathrm{nm},$

$P = 100\ \mathrm{W}, T_{\mathrm{obs}} = 1\ \mathrm{yr}$

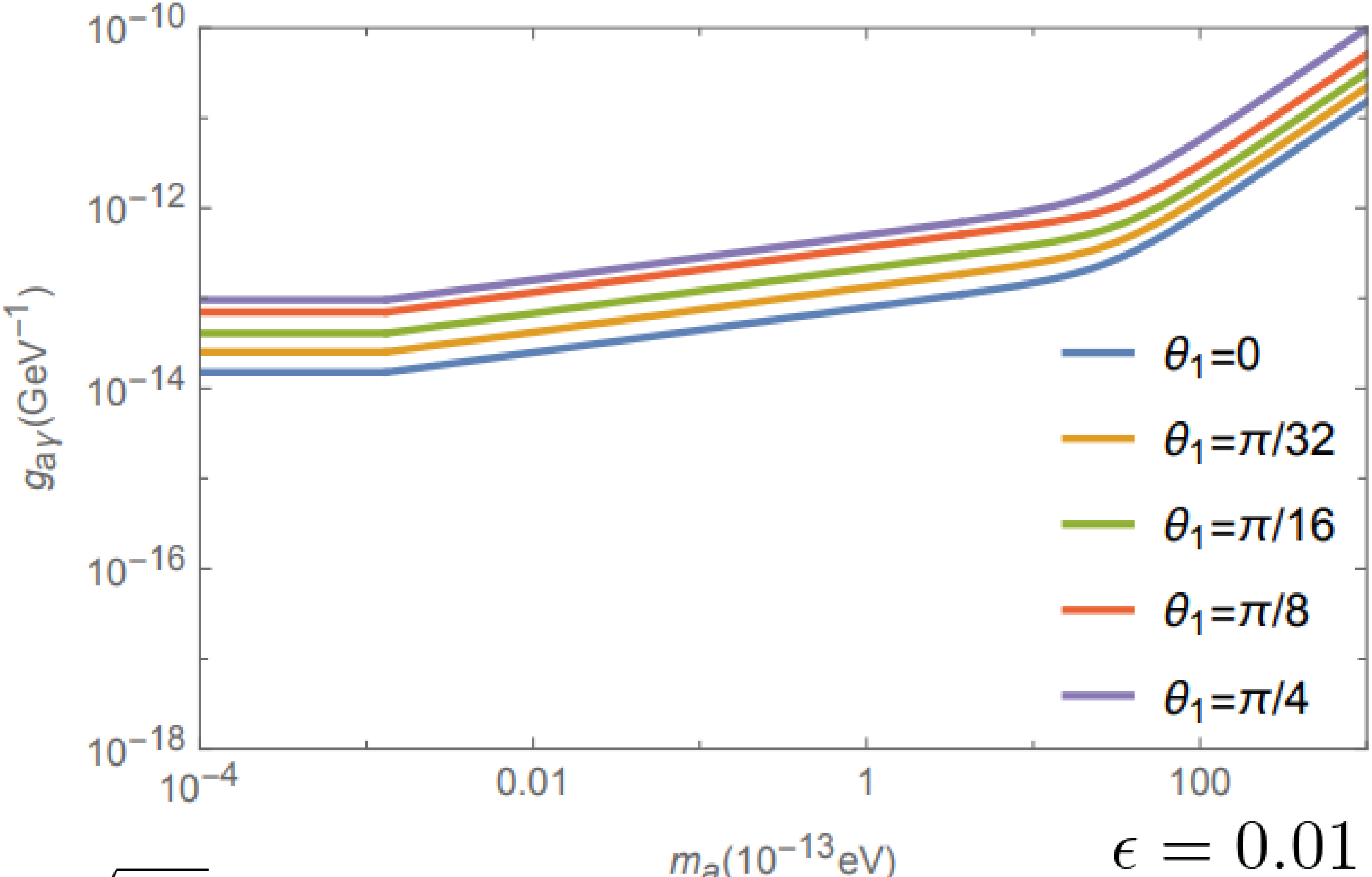
Sensitivity in birefringent cavity (In the case of the perfect alignment)



$\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2} = 10^5$ $\epsilon = 0.01$ $\alpha_1 = \alpha_2$

The resonance effect to detect the ALP with polarized light is observed.

Sensitivity with birefringence (In the case of the imperfect alignment)



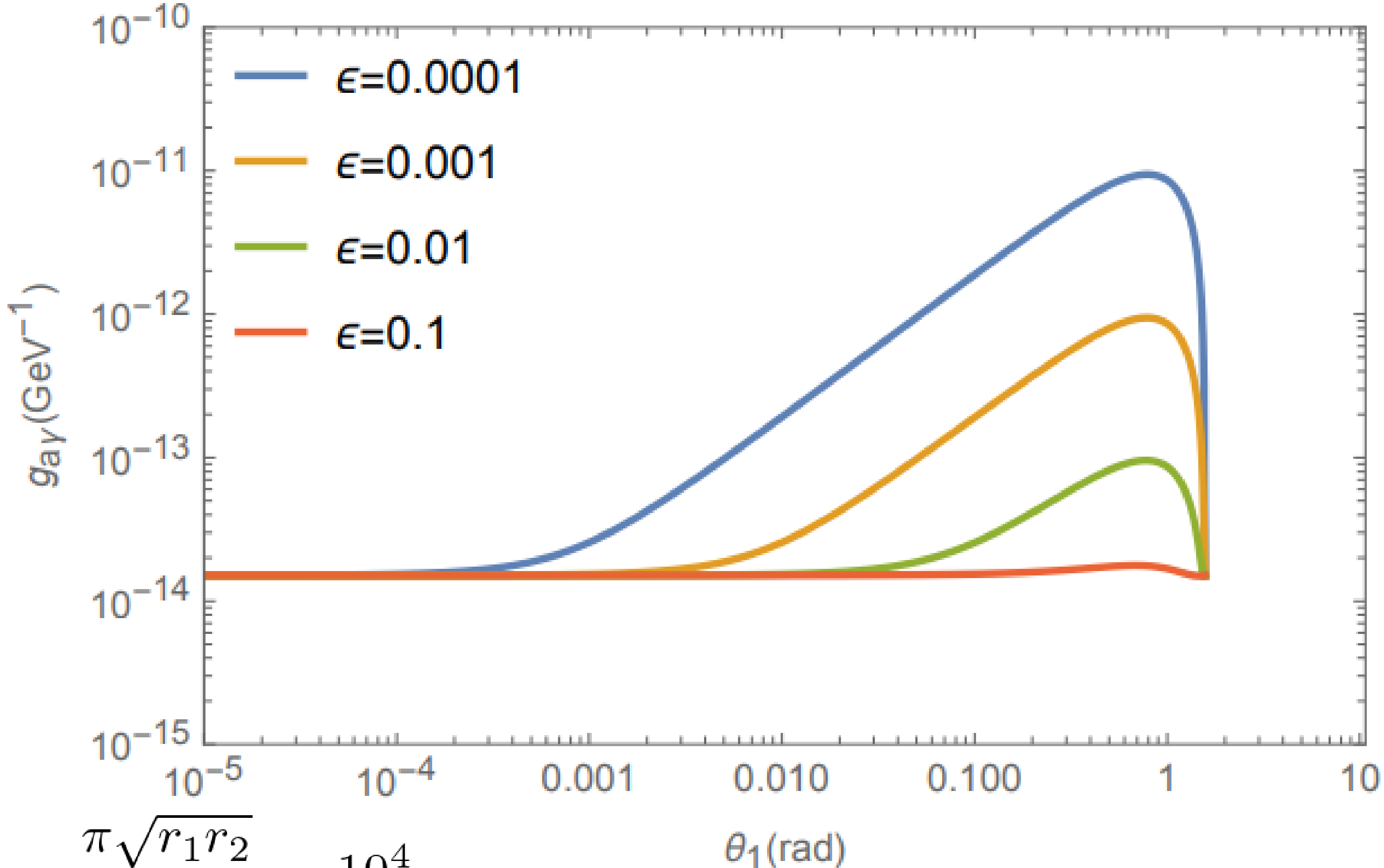
$\epsilon = 0.01$

$$\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2} = 10^4$$

$$\alpha_1 = \alpha_2 = 10^{-5}$$

$$\theta_1 = \theta_2$$

Sensitivity with birefringence
Post-selection angle dependence



$$\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2} = 10^4$$

$$m_a = 10^{-16}\ \text{eV} \qquad \alpha_1 = \alpha_2 = 10^{-5} \quad \theta_1 = \theta_2$$

Conclusion

T. Kuramoto et al., in preparation.

1. Axion-like particle detection with polarized light plus ring cavity was proposed.
2. We study the birefringence effect in this situation.
   - Post-selection angle tuning will cover the sensitivity against to the birefringence.

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