KIW 2026

Impact of ITM Birefringence on Future Squeezed-Light Operation in KAGRA

May 15, 2026

Yuheng Ye (Yoko Yo)
The University of Tokyo, Japan

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1. Motivation

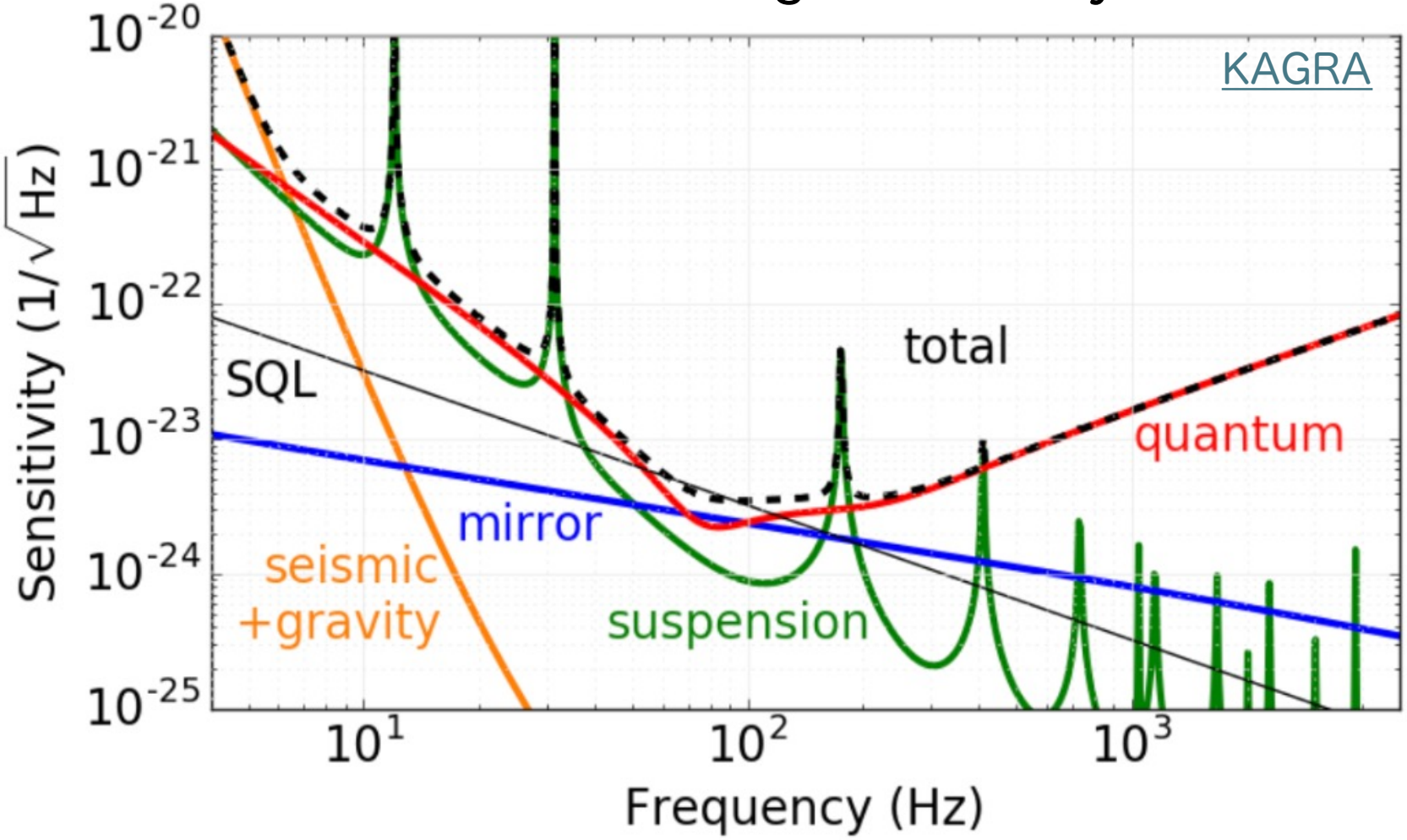
2. My Works:
   SQZ & anti-SQZ mixing

3. Conclusion / Future Work

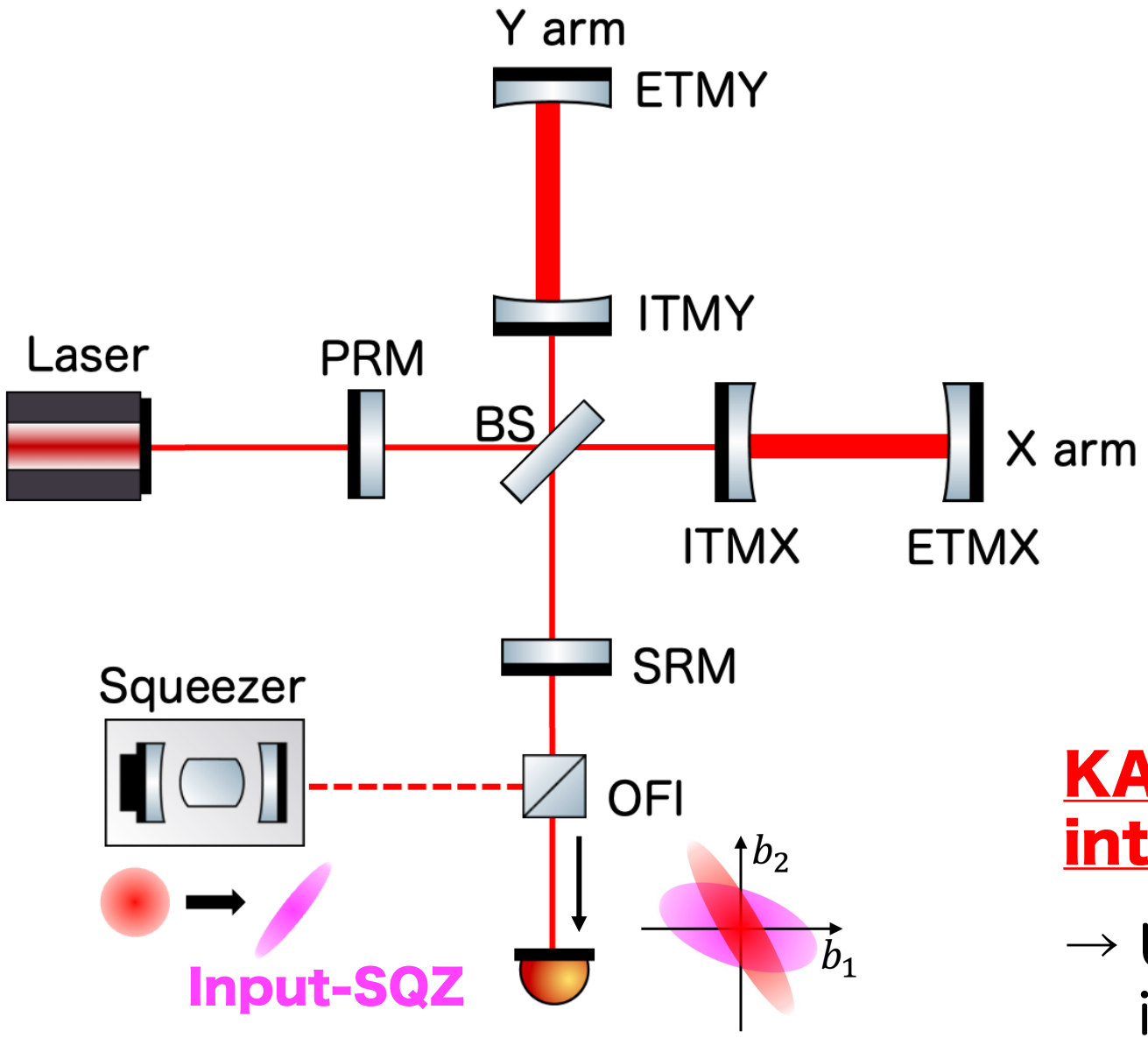
1. Sensitivity of GW Detectors

➢ Main noise sources in GW Detectors

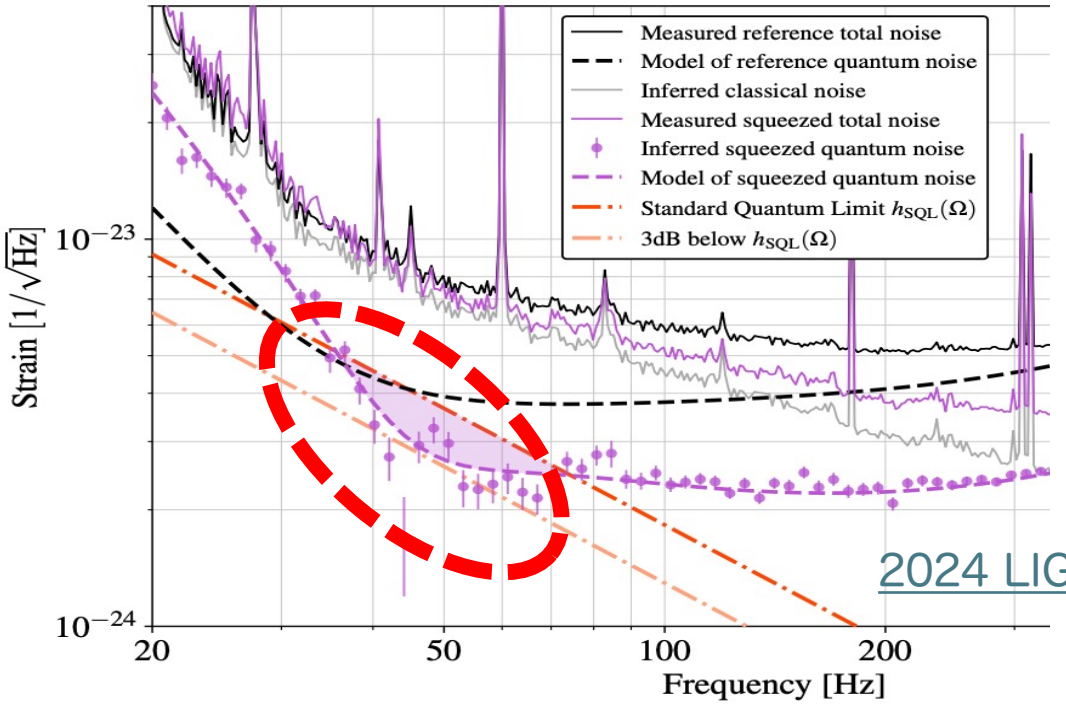
KAGRA design sensitivity



1. Quantum noise reduction with input-SQZ



LIGO surpassed the SQL
by 3dB with input-SQZ



2024 LIGO

KAGRA is planning to introduce SQZ from O6

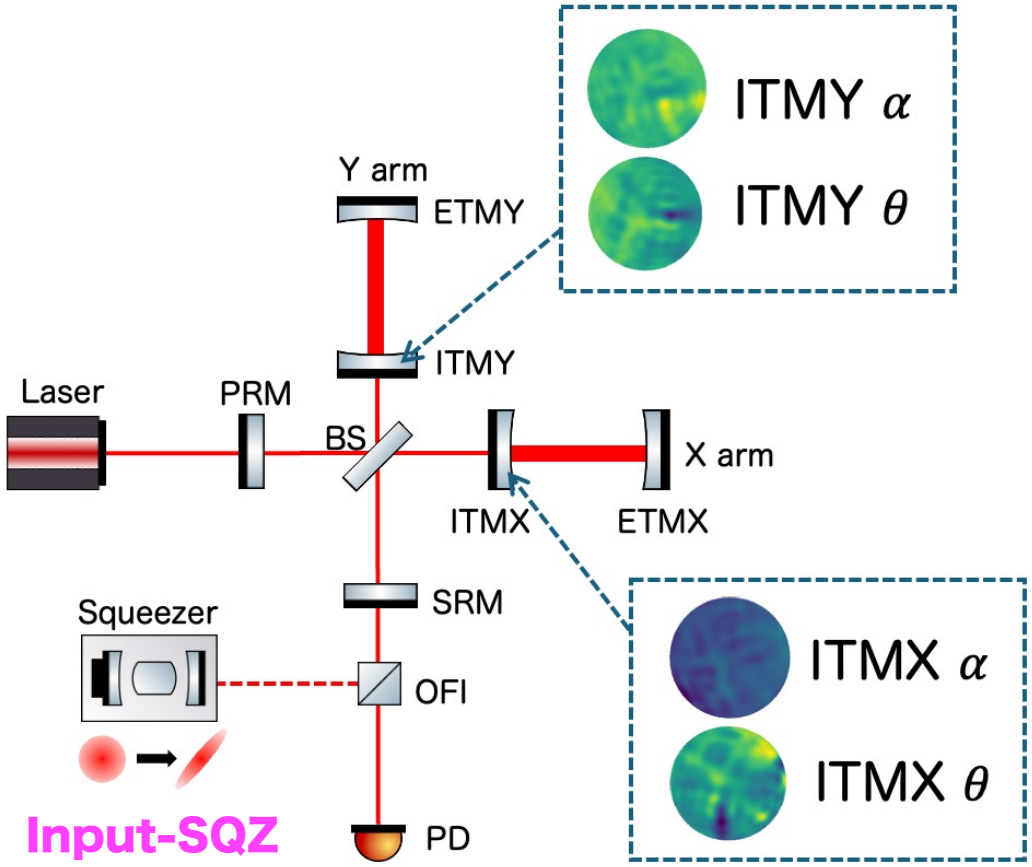
→ Understanding **SQZ degradation** is essential to fully benefit from SQZ

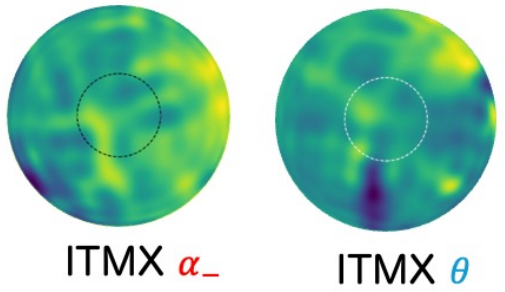
1. KAGRA-specific issue: ITM birefringence

➢ Birefringence of KAGRA ITM

KAGRA ITM: anisotropic sapphire

→ **birefringence matters!**





α_- : birefringent phase retardation

θ : polarization–crystal misalignment

① S-pol / P-pol splitting

$$\begin{pmatrix} S_{\rm in} \\ P_{\rm in}=0 \end{pmatrix} \rightarrow \begin{pmatrix} A & B \\ B & D \end{pmatrix} \rightarrow \begin{pmatrix} S_{\rm out} \\ P_{\rm out}\neq 0 \end{pmatrix}$$

Biref. Jones matrix

$$A = \cos^2\theta\, e^{i\alpha_-} + \sin^2\theta\, e^{-i\alpha_-},$$
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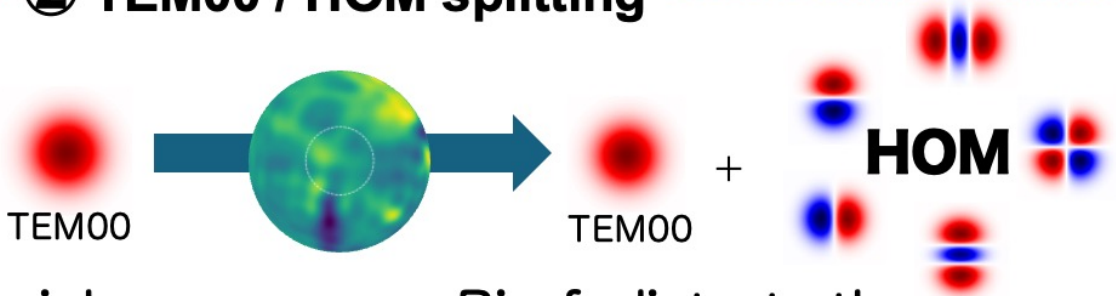
even if $P_{\rm in} = 0$, $P_{\rm out}$ can be non-zero

② TEM00 / HOM splitting



inhomogeneous Biref. distorts the wavefront, and generates HOM

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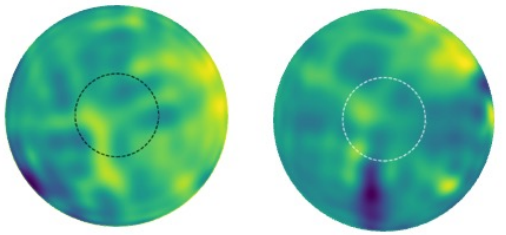

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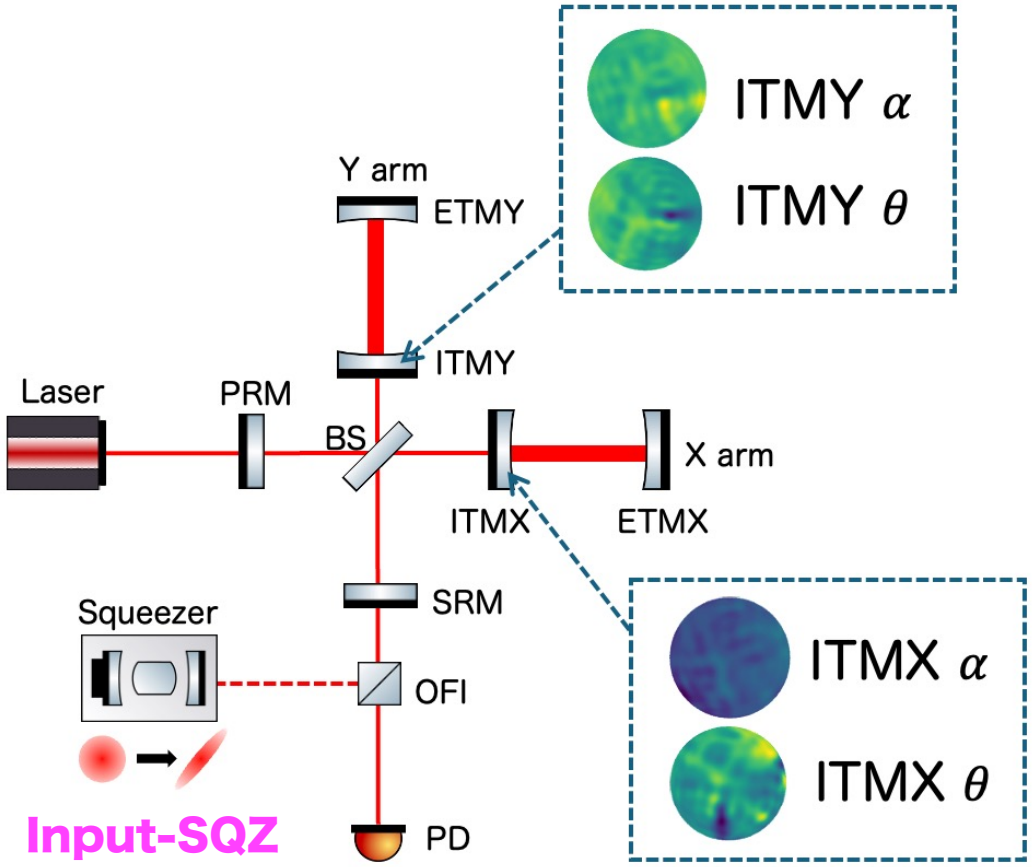

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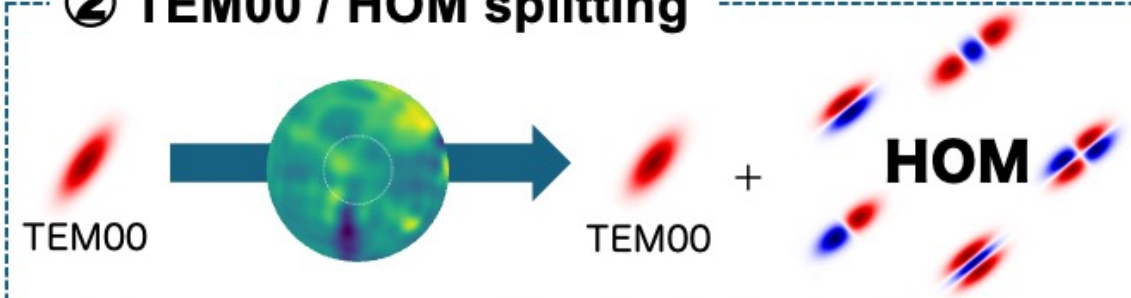

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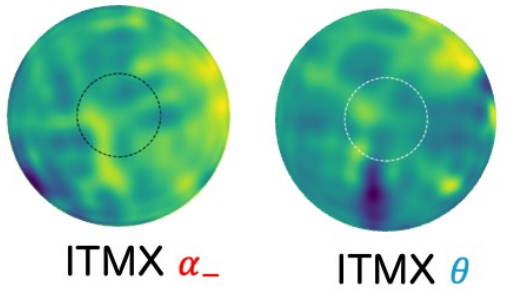

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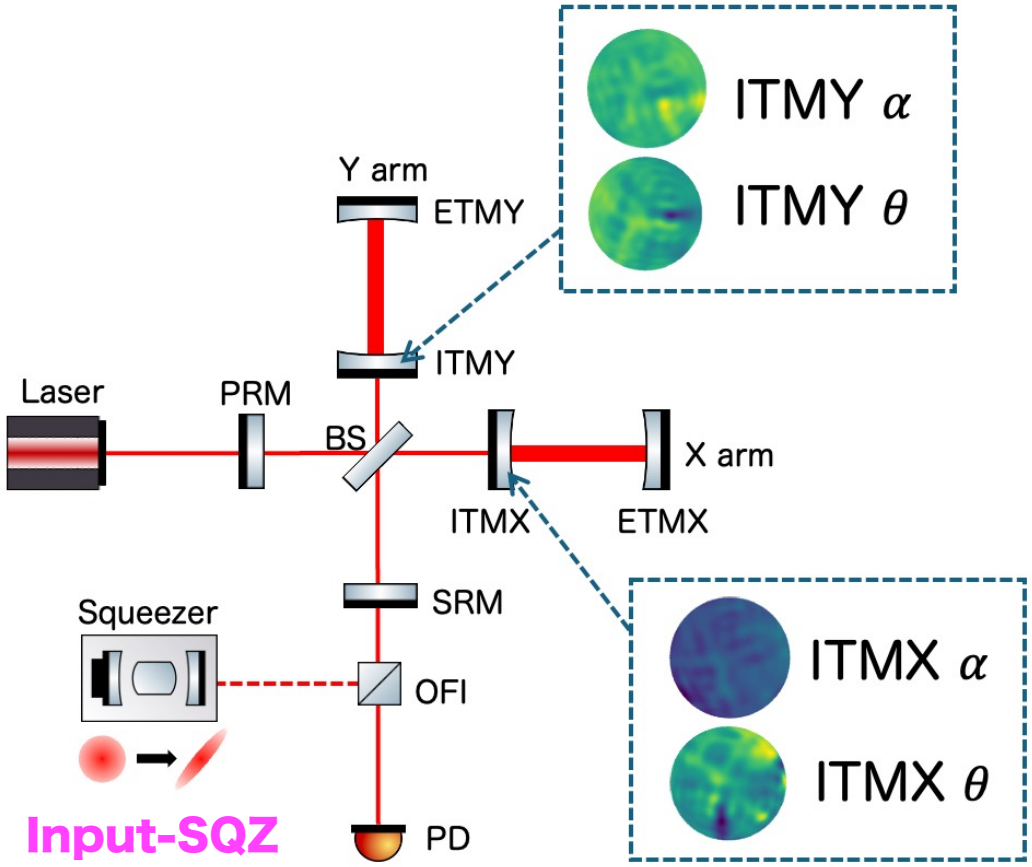

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How Birefringence affects input-SQZ?

② TEM00 / HOM splitting

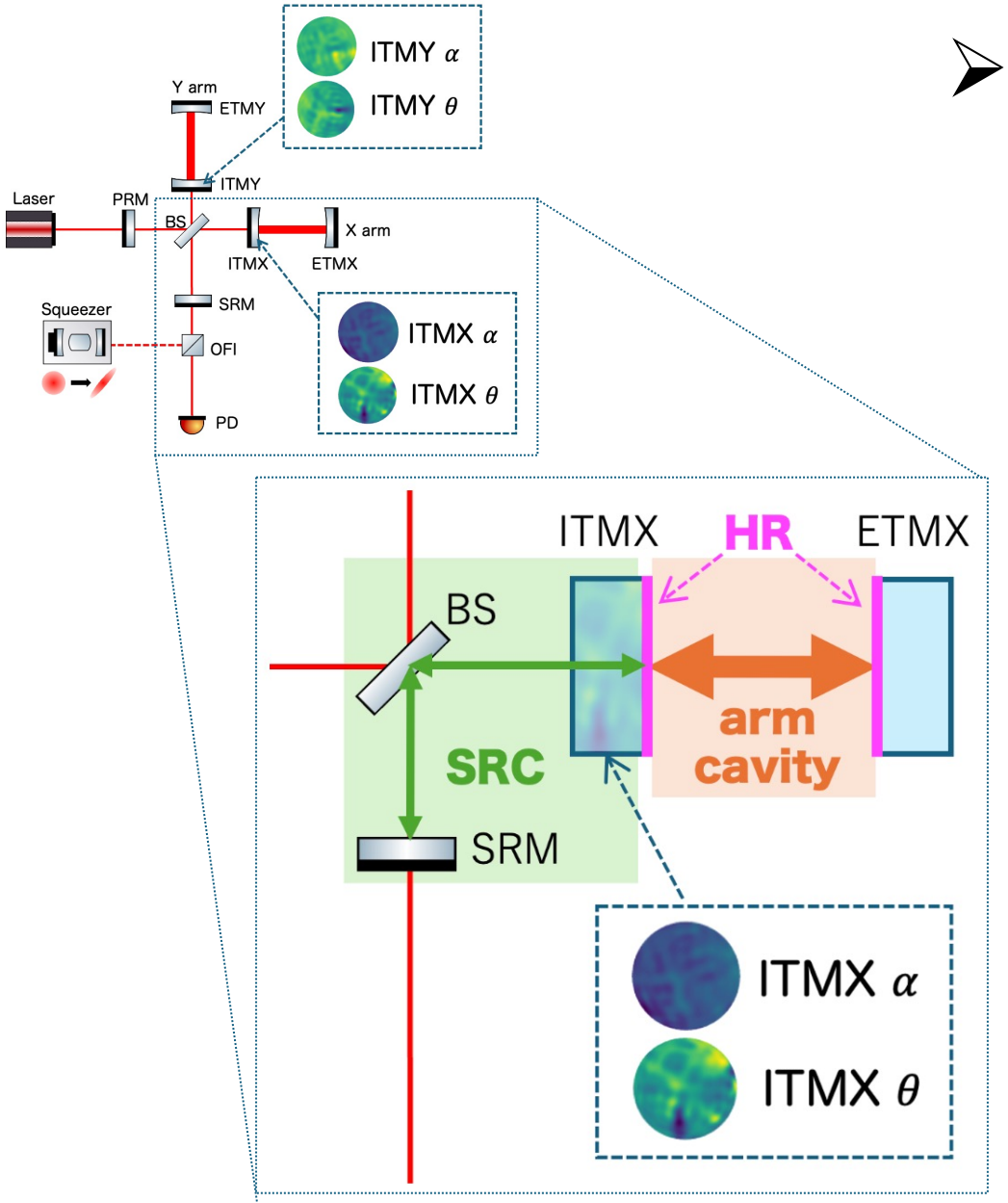
inhomogeneous Biref. distorts the wavefront, and generates HOM

1. Motivation

2. My Works:
   SQZ & anti-SQZ mixing

3. Conclusion / Future Work

2. KAGRA-specific issue: ITM birefringence



➢ Birefringence effects

① S-pol / P-pol splitting

$$\begin{pmatrix} S_{\mathrm{in}} \\ P_{\mathrm{in}} = 0 \end{pmatrix} \rightarrow \begin{pmatrix} A & B \\ B & D \end{pmatrix} \rightarrow \begin{pmatrix} S_{\mathrm{out}} \\ P_{\mathrm{out}} \neq 0 \end{pmatrix}$$

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pure loss?

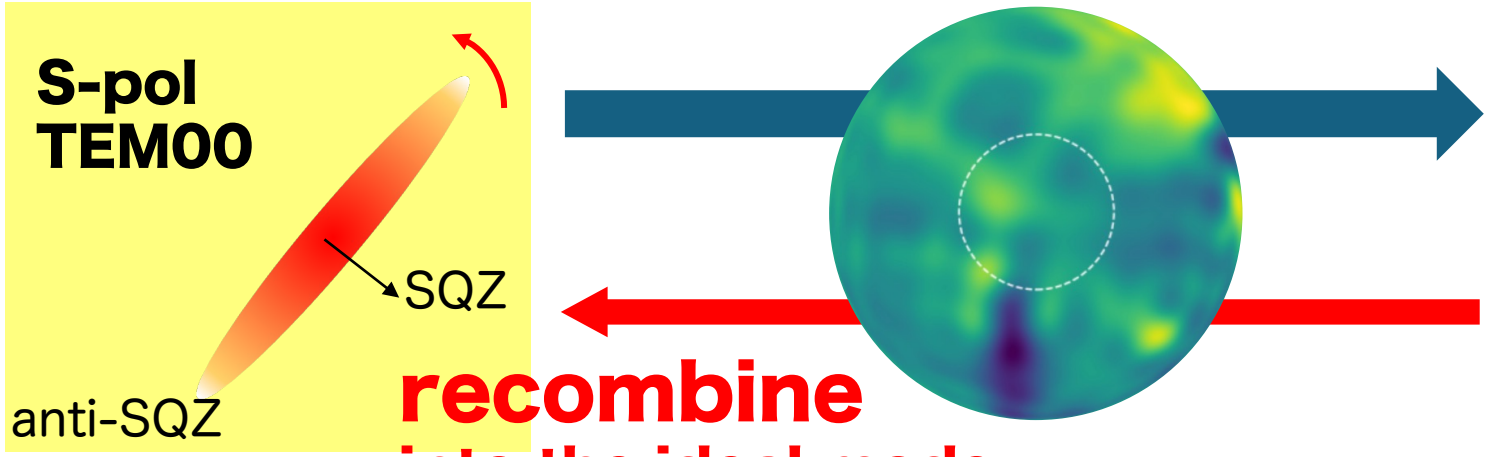
② TEM00 / HOM splitting

TEM00 → TEM00 + HOM

inhomogeneous Biref. distorts the wavefront, and generates HOM

2. Concern: SQZ & anti-SQZ mixing

Ideal mode



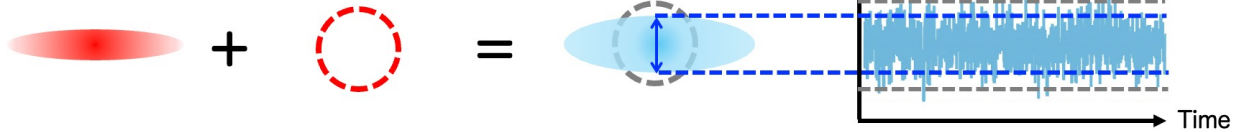
Bad mode

Bad modes experience
a different SQZ rotation
than IFO mode

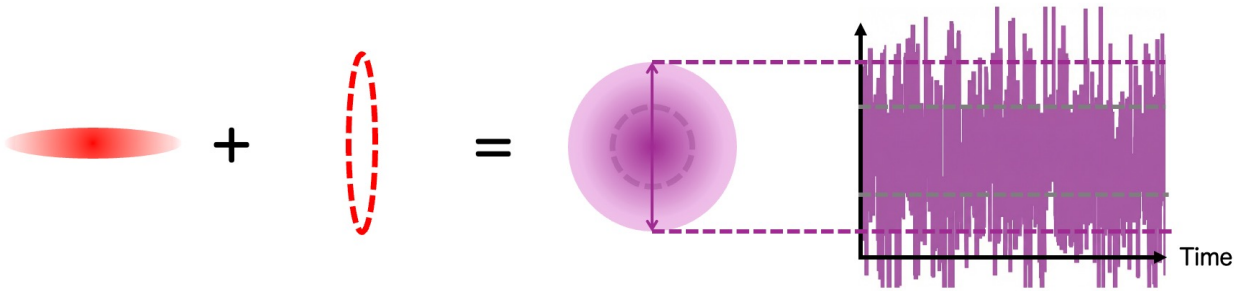
||

P-pol: BS reflection
HOM: Gouy phase

pure loss



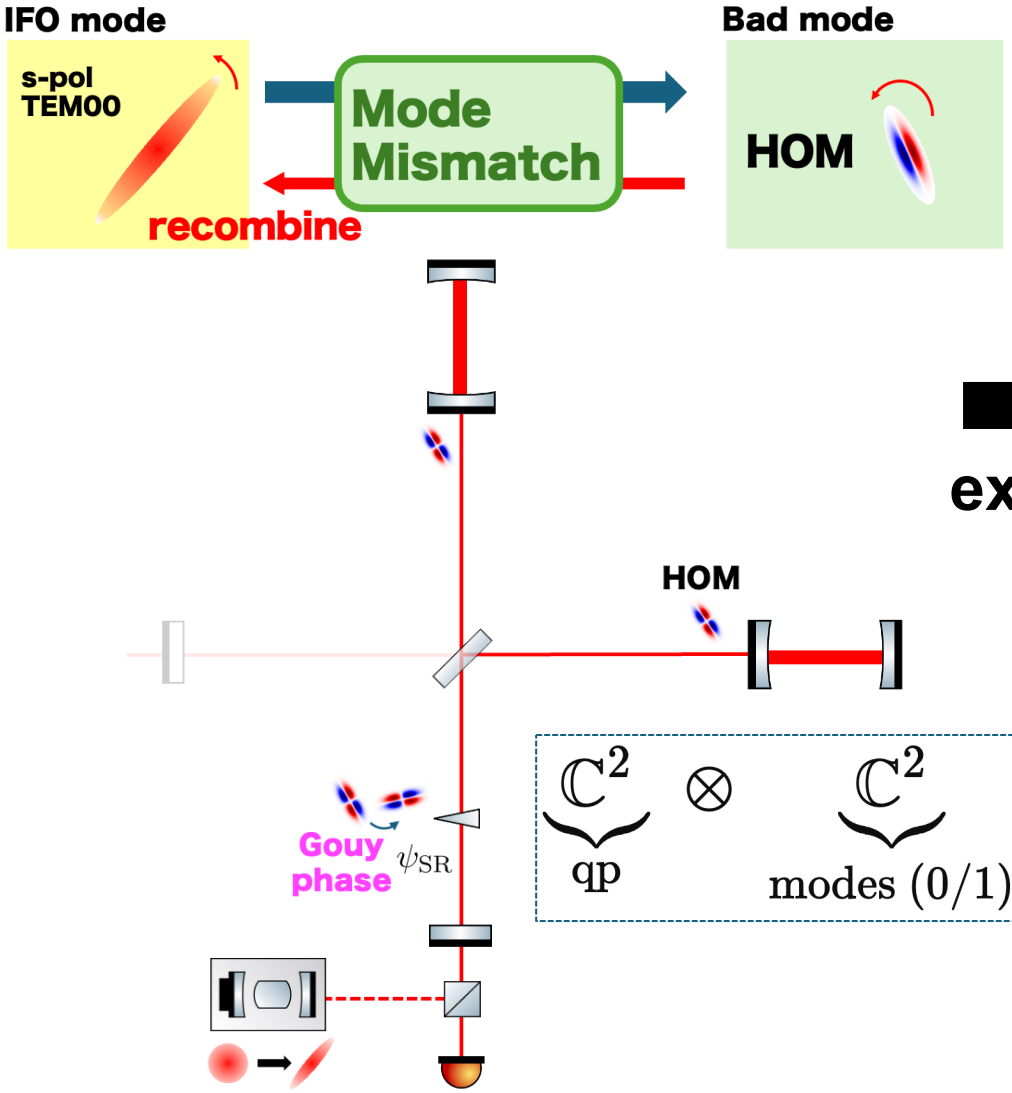
SQZ & anti-SQZ mixing



This effect must be considered !

2. Mixing model (Extension of McCuller+ model)

McCuller+ model



extend

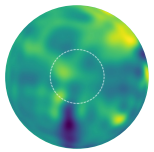
Mixing model (Our model)

① Adding polarization & port space

$$\underbrace{\mathbb{C}^2}_{\text{qp}} \otimes \underbrace{\mathbb{C}^2}_{\text{pol}} \otimes \underbrace{\mathbb{C}^{(M+1)}}_{\text{modes}} \otimes \underbrace{\mathbb{C}^2}_{\text{ports}}$$

② Adding birefringence effect

$$\left[\mathbf{T}_j^{(\text{pol}\times\text{mode})}\right]_{\sigma' m' \to \sigma m} = \iint d^2\mathbf{r}\, u_m^*(x,y) \underbrace{\left[\mathbf{J}_j(x,y)\right]_{\sigma,\sigma'}}_{\text{Biref. Jones matrix}} u_{m'}(x,y)$$



③ Adding BS reflection phase shift for P-pol

$$\mathbf{B}_{\text{out}}^{(\text{cplx})} = \mathbf{I}_{\text{modes}} \otimes \left(|\text{s}\rangle\langle\text{s}| \otimes \begin{bmatrix} t_\text{s} & r_\text{s} \\ -r_\text{s}^* & t_\text{s}^* \end{bmatrix} + |\text{p}\rangle\langle\text{p}| \otimes \begin{bmatrix} t_\text{p} & r_\text{p} \\ -r_\text{p}^* & t_\text{p}^* \end{bmatrix} \right) \qquad \mathbf{B}_{\text{out}} = \begin{bmatrix} \Re\mathbf{B}_{\text{out}}^{(\text{cplx})} & -\Im\mathbf{B}_{\text{out}}^{(\text{cplx})} \\ \Im\mathbf{B}_{\text{out}}^{(\text{cplx})} & \Re\mathbf{B}_{\text{out}}^{(\text{cplx})} \end{bmatrix}$$

④ Combining X/Y arm reflectivities, adding PRC

$$\mathbf{r}_A^{(\text{cmb})} = \mathbf{B}_{\text{out}} \begin{bmatrix} \mathbf{r}_A^{(X)} & 0 \\ 0 & \mathbf{r}_A^{(Y)} \end{bmatrix} \mathbf{B}_{\text{in}} \qquad \tilde{\mathbf{r}}_{\text{IFO}} = \mathbf{r}_s + \mathbf{t}_s \mathbf{L}_s \eta_s \left[r_{dd} + BC \right] P^{-1} \mathbf{L}_s \mathbf{t}_s$$

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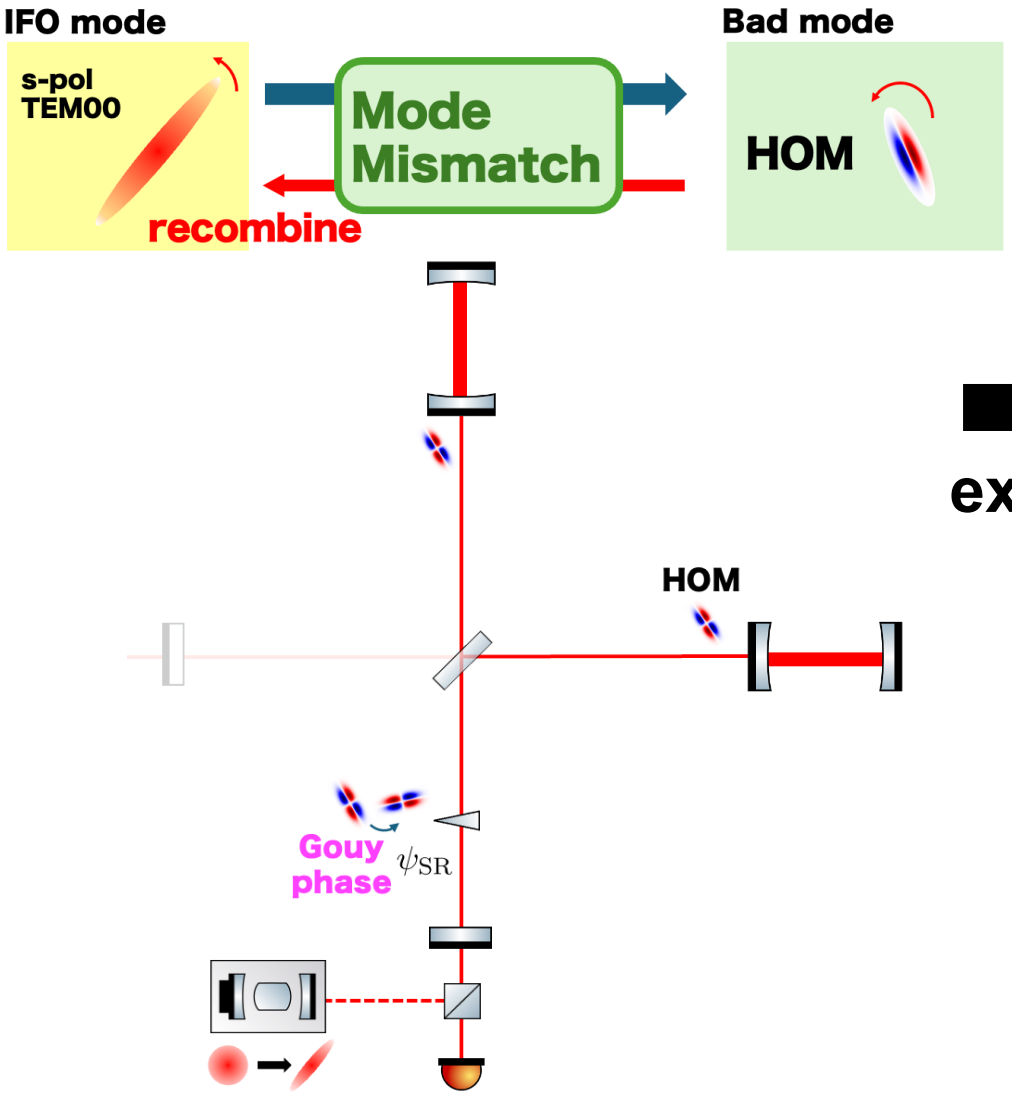
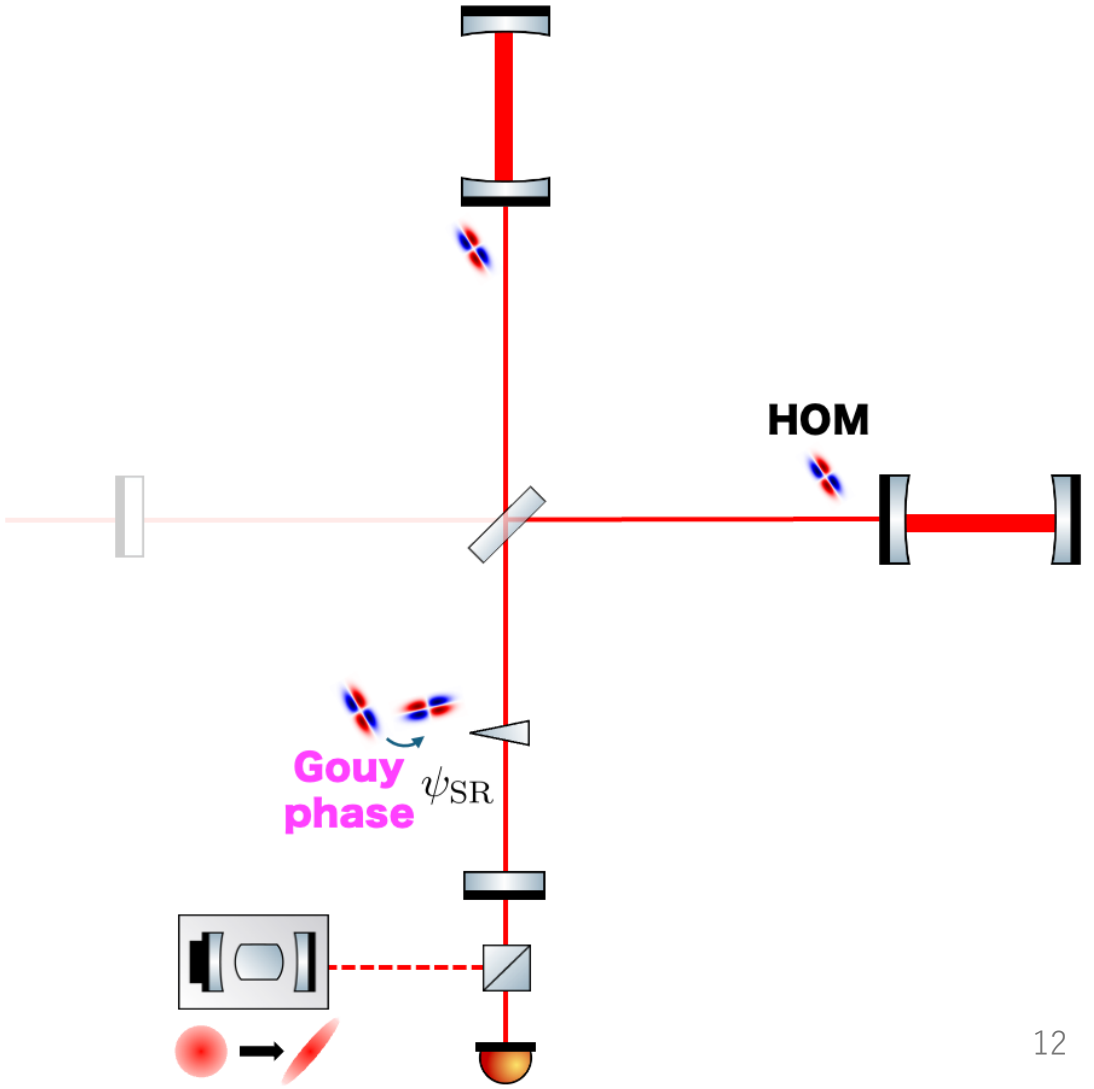
McCuller+ model



extend

Extension Step 0 (Our model)



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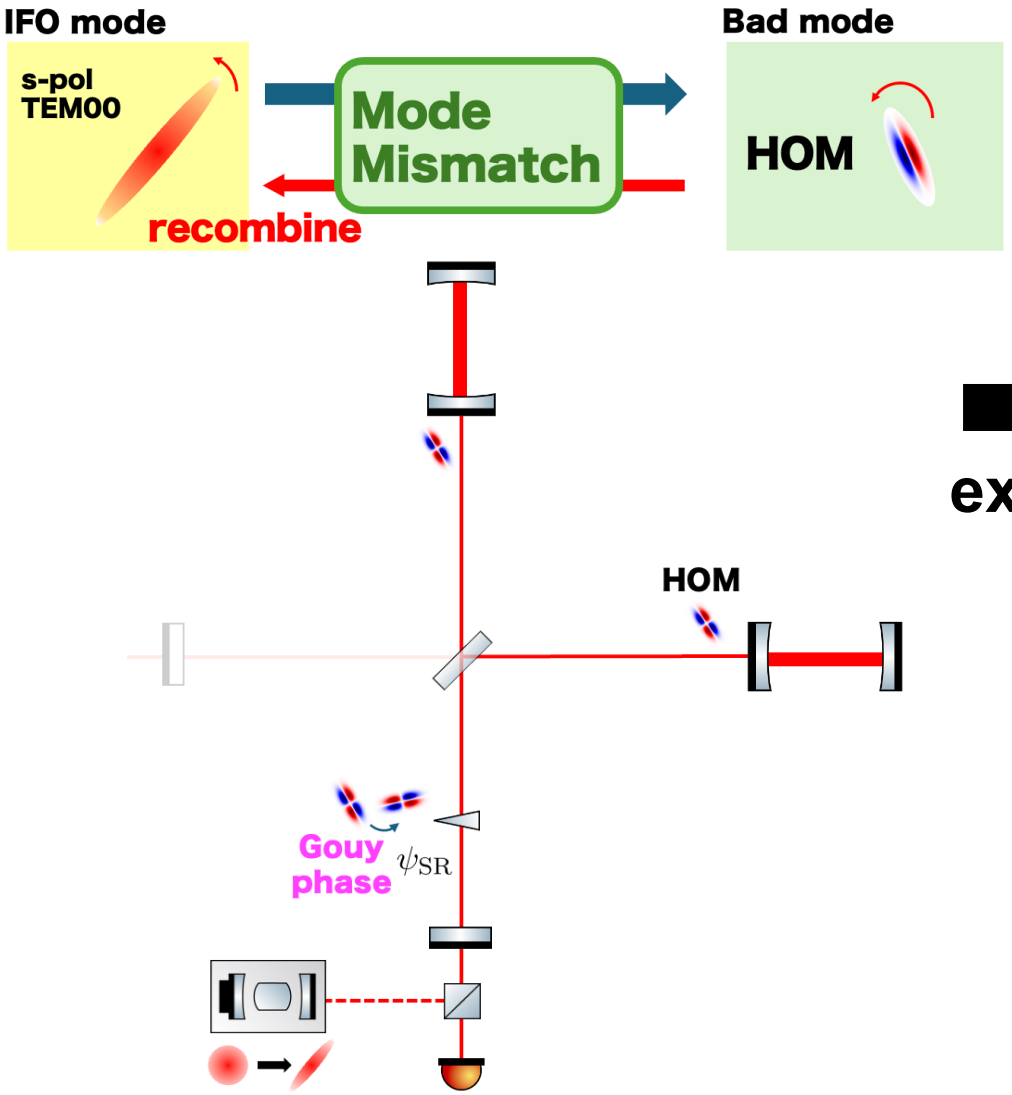
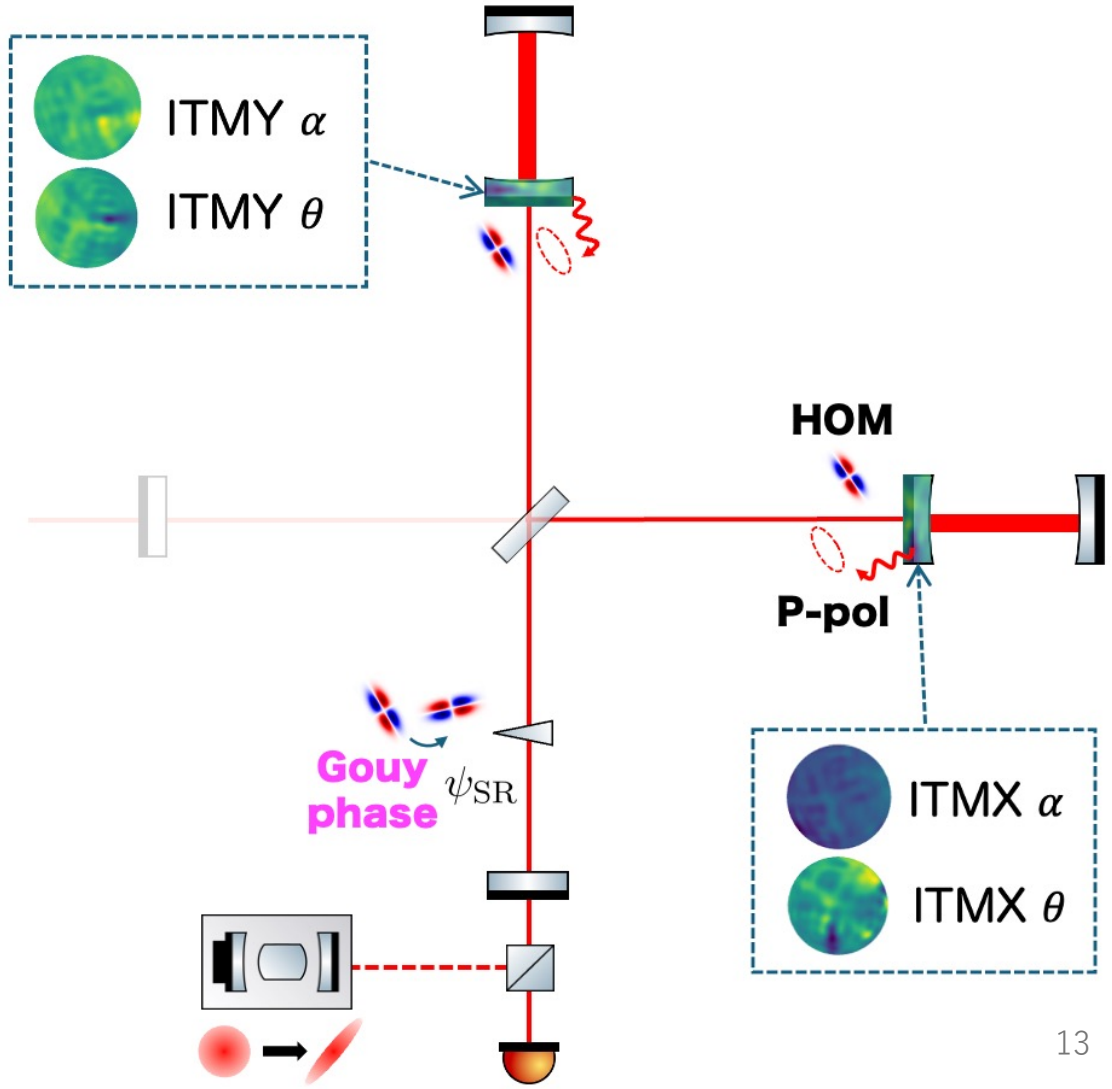


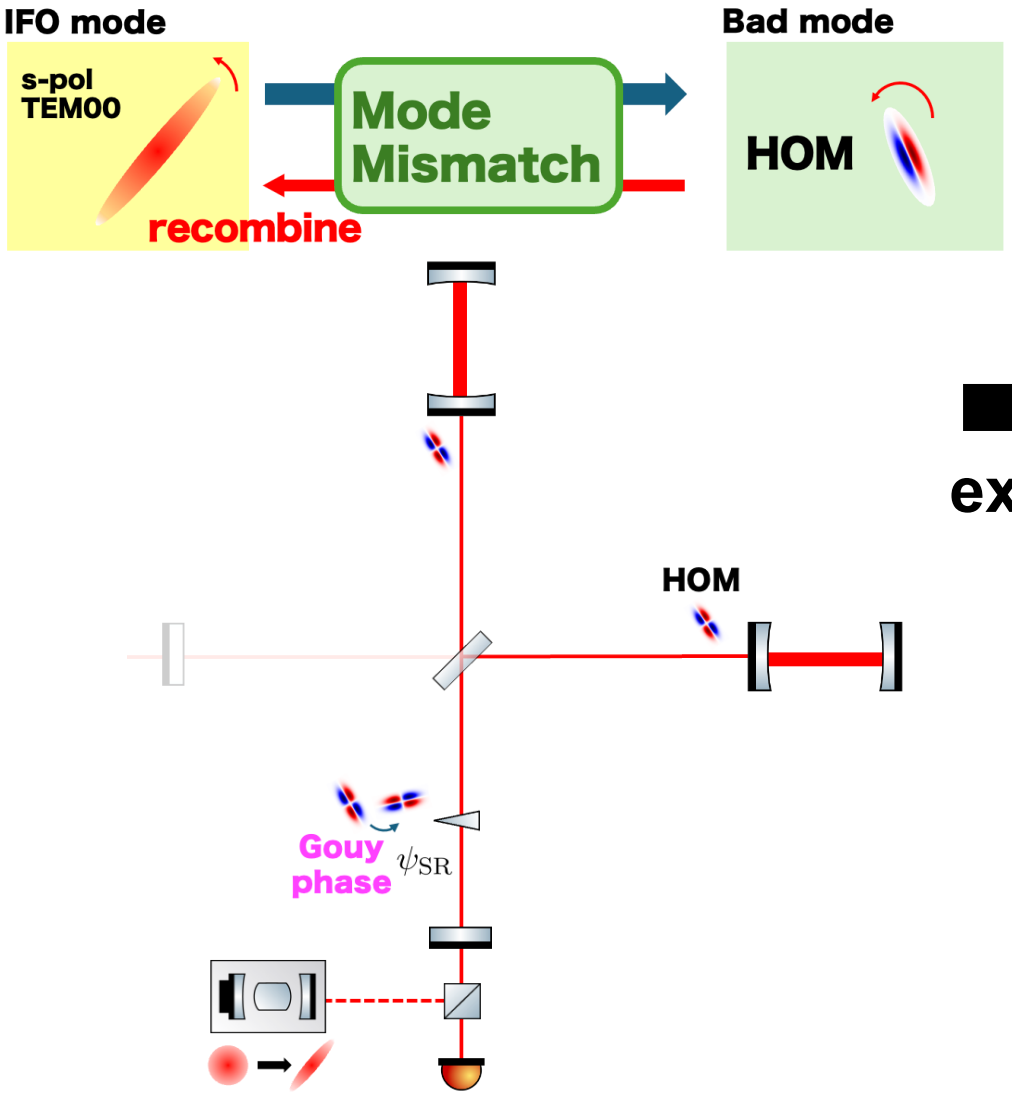
extend

Extension Step 1 (Our model)



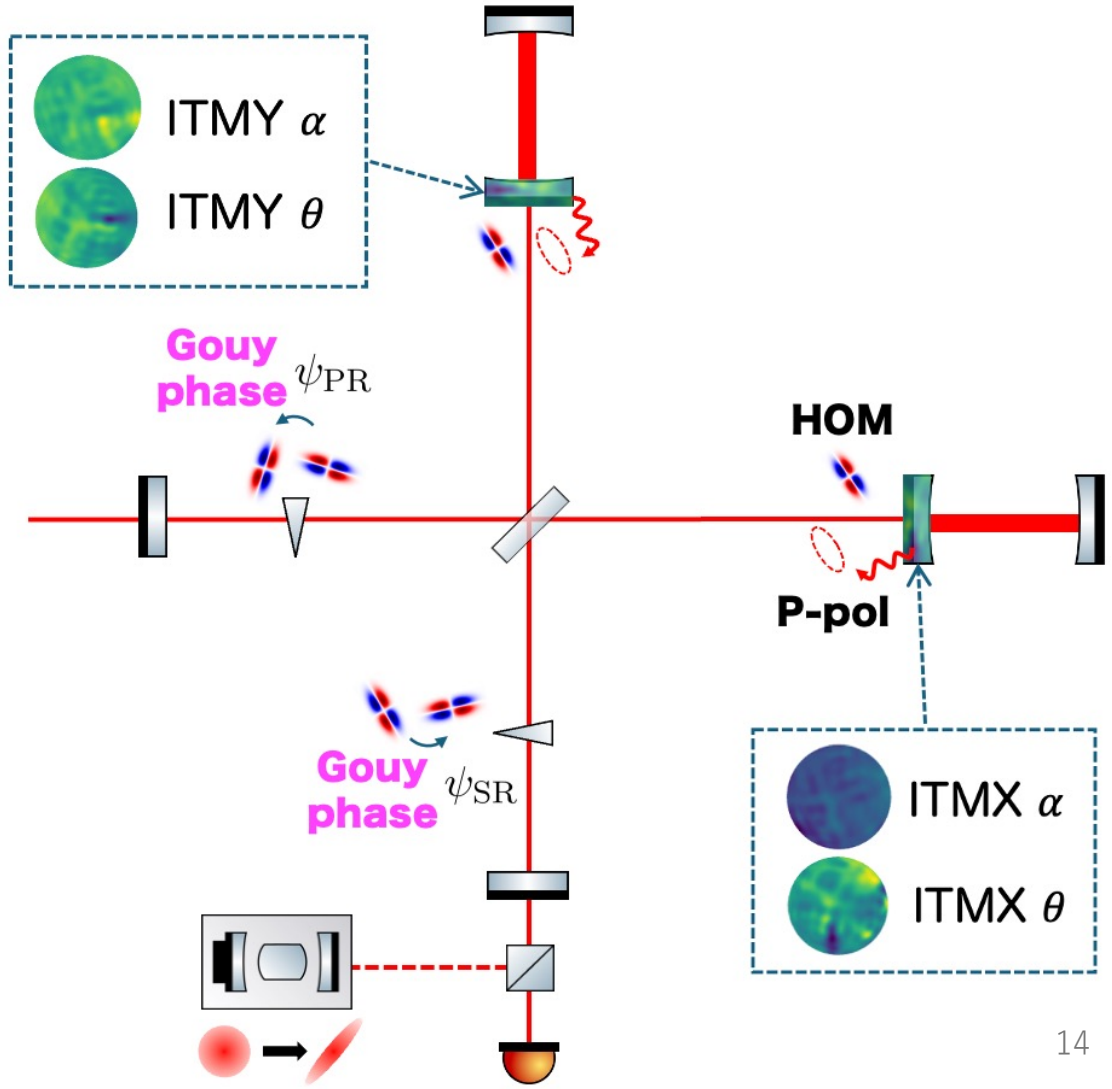
2. Mixing model (Extension of McCuller+ model)

McCuller+ model



extend

Extension Step 2 (Our model)



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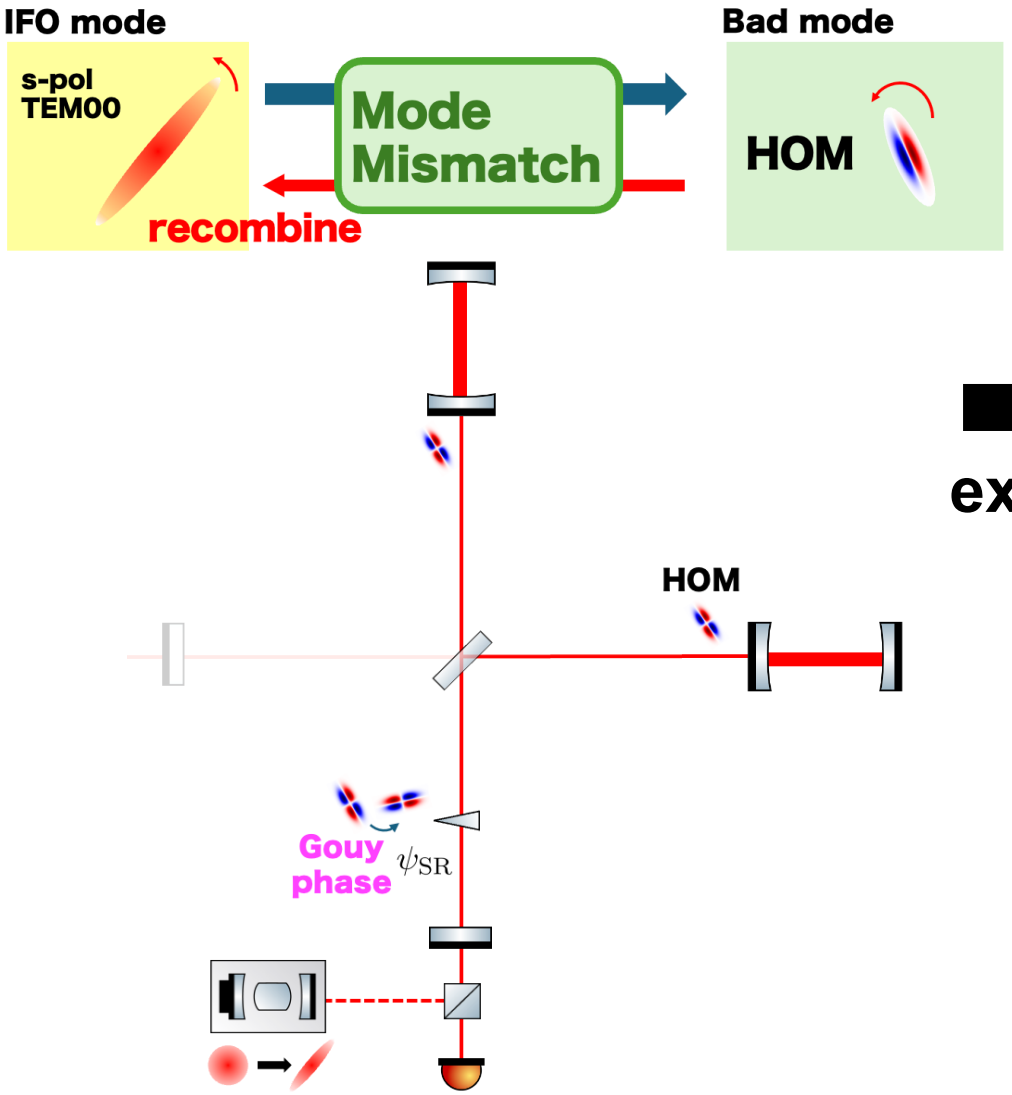
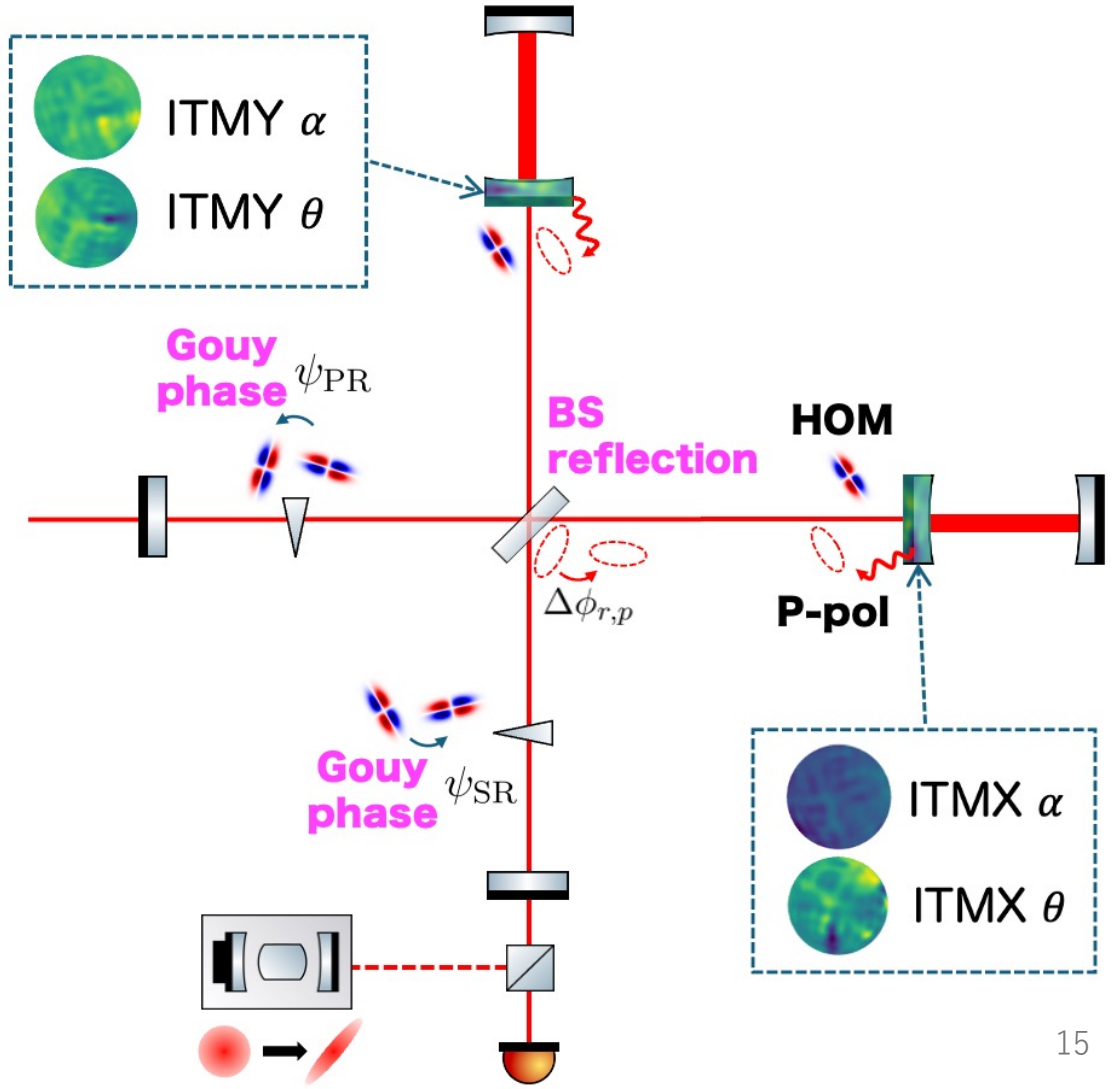


extend

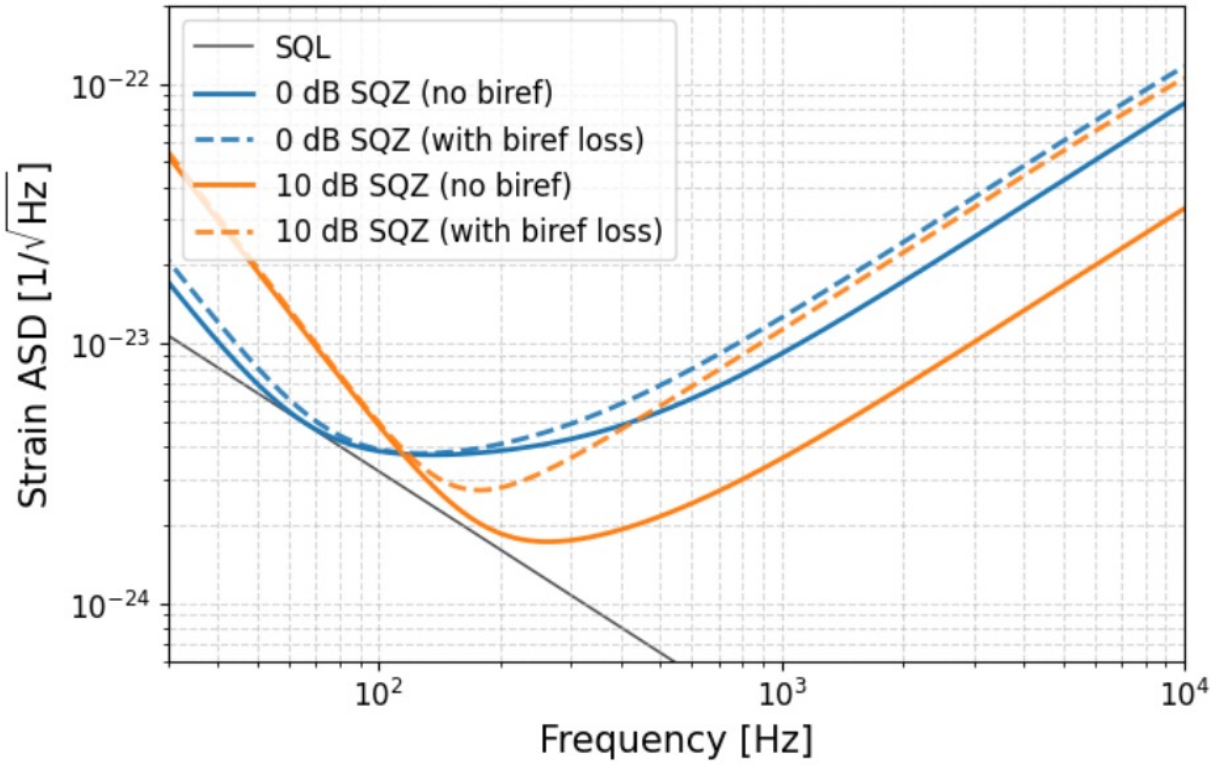
This is Mixing model!



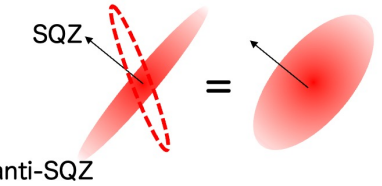
2. Mixing model (Extension of McCuller+ model)

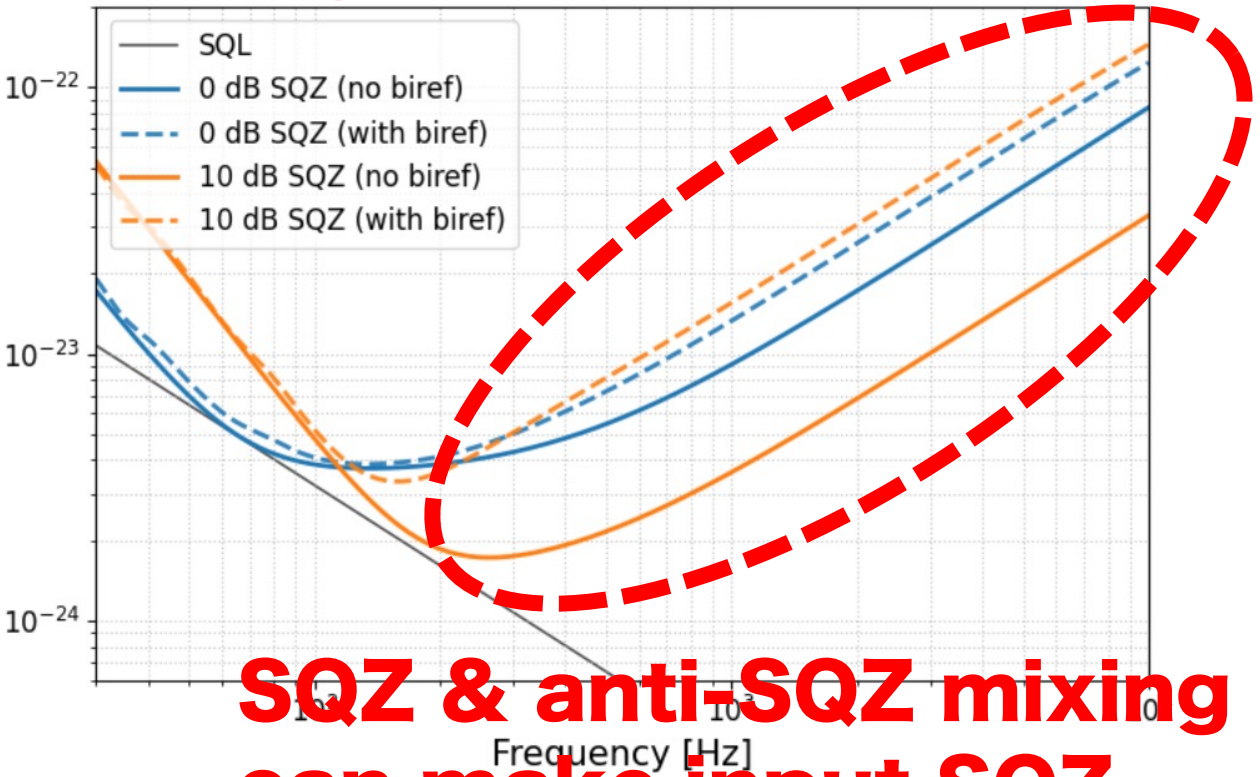
➢ Result of mixing model

Biref. = pure loss



Mixing model



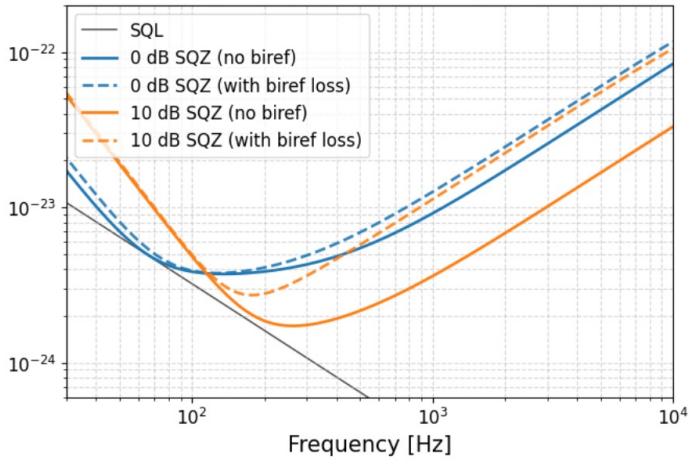


SQZ & anti-SQZ mixing can make input SQZ worse than no SQZ 😱

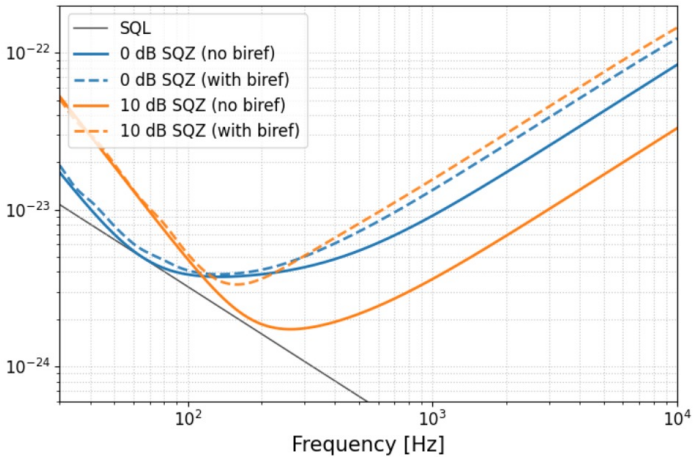
2: Mixing model (Extension of McCuller+ model)

➢ Result of mixing model

Pure loss model

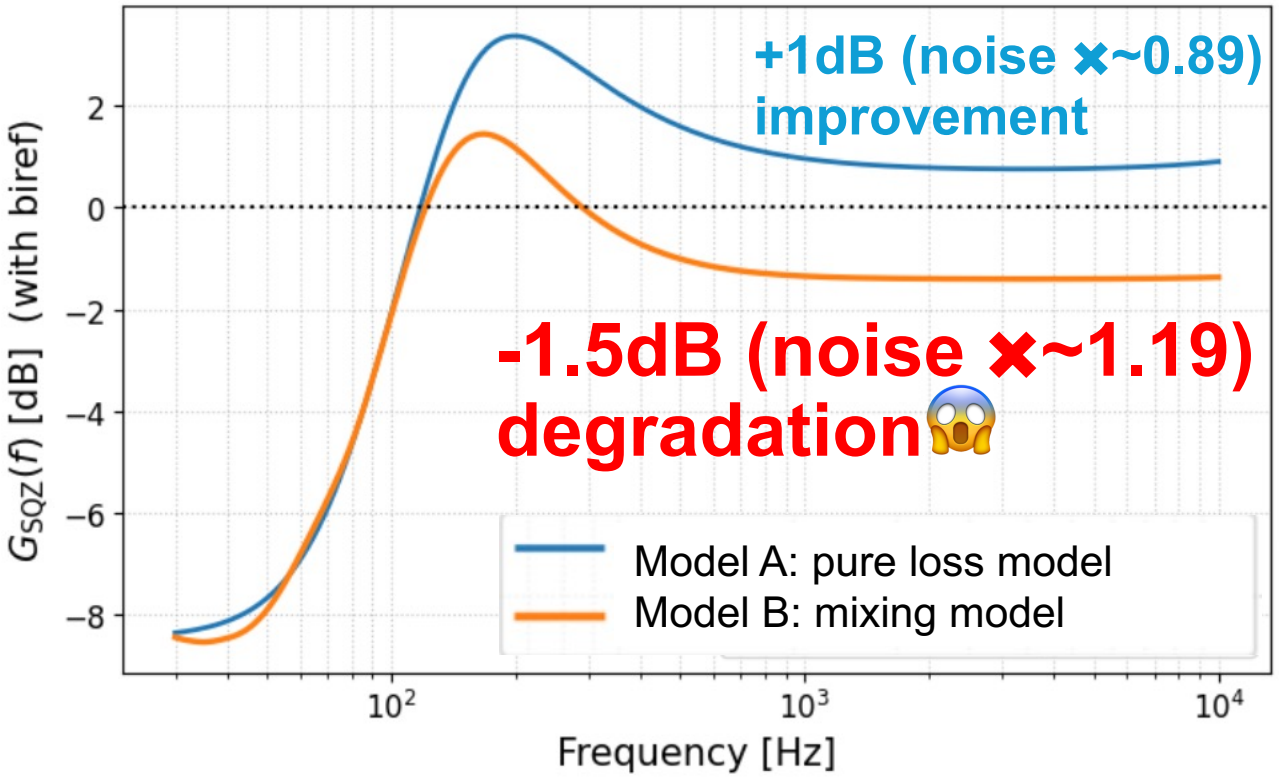


Mixing model



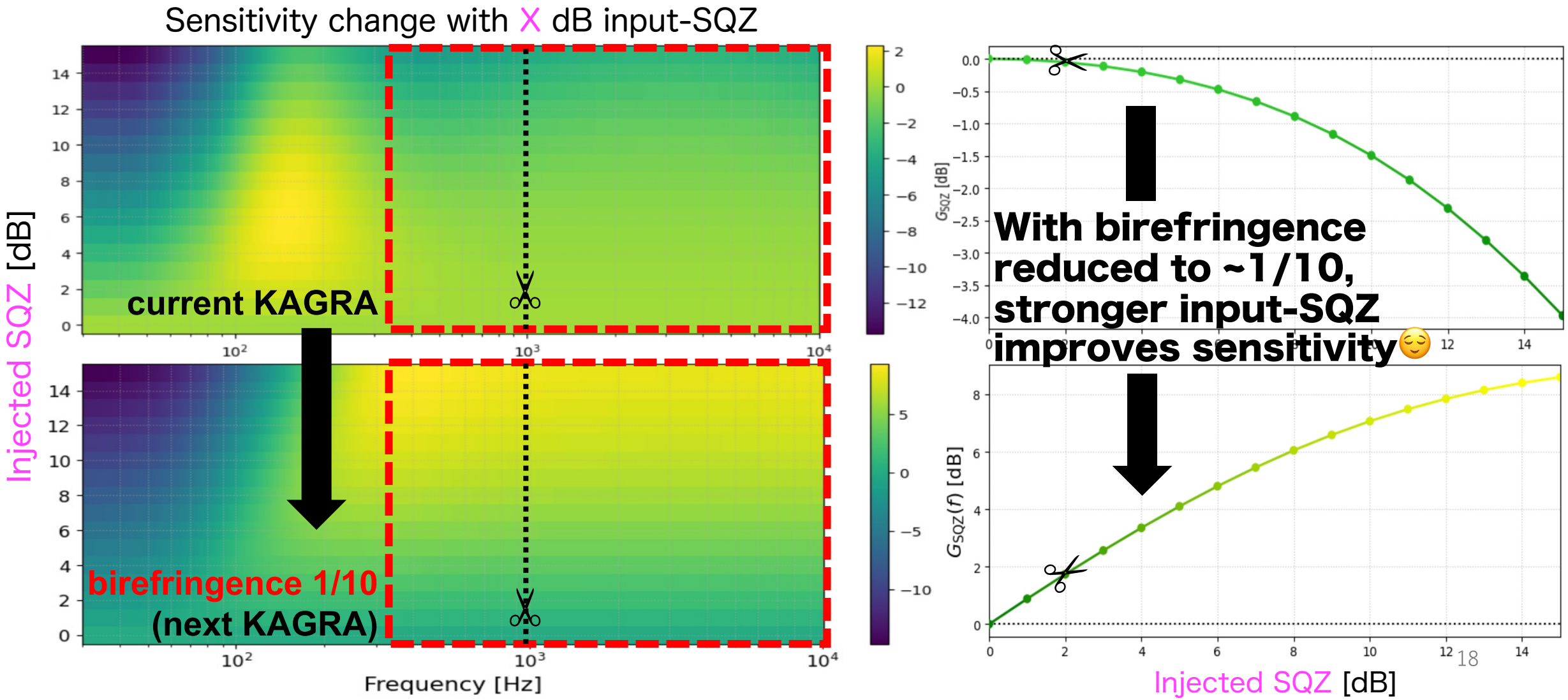
difference

Sensitivity change with
10 dB input-SQZ



2. Mixing model (Extension of McCuller+ model)

➢ Changing birefringence & input-SQZ level



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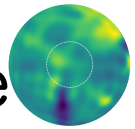
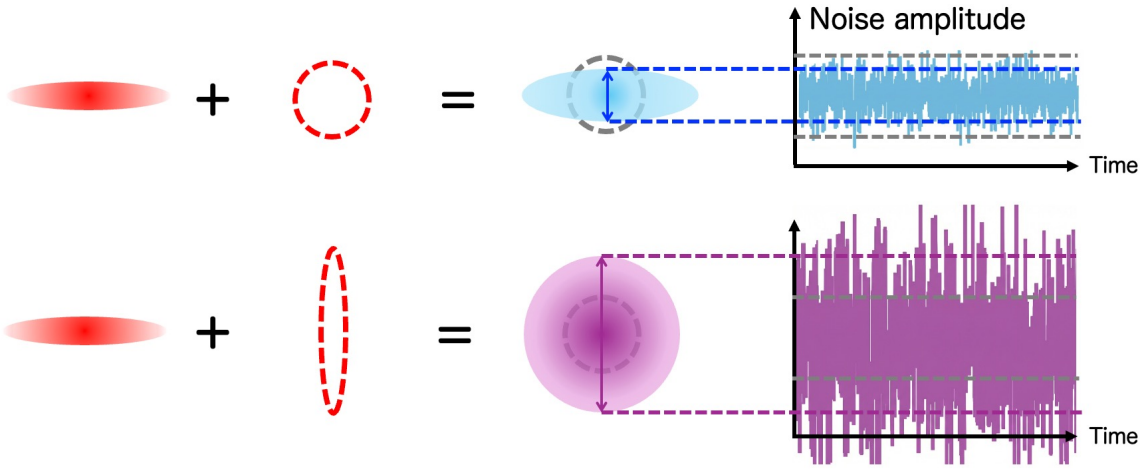
① In KAGRA, ITM birefringence  may degrade the input-SQZ noise reduction



My Works

② We built the mixing model focusing on **SQZ & anti-SQZ mixing** caused by birefringence

③ The mixing model shows that input-SQZ can worsen sensitivity compared to no-SQZ 😱

④ Input-SQZ becomes effective when birefringence is reduced to ~1/10 😌

This work clarifies when input-SQZ helps
(quantum noise reduction)
— and when it hurts — in KAGRA