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Noise from birefringence fluctuations in laser interferometric gravitational wave detectors

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Overview

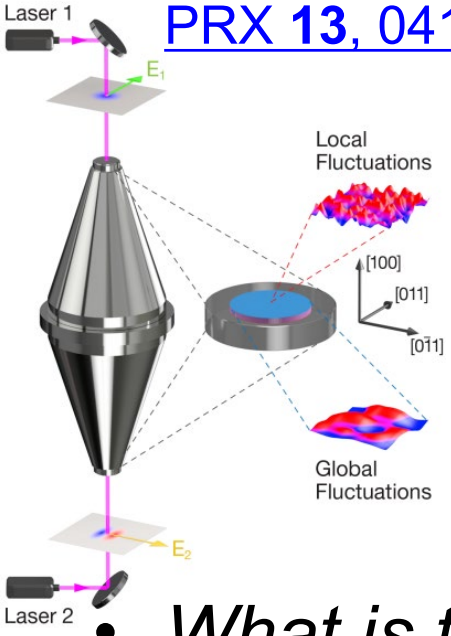
- Fluctuations in mirror birefringence will be phase noises for GW detectors
- This can be avoided by aligning input polarization axis and mirror crystal axes
- Requirements at 100 Hz will be
  - $\Delta\varphi<\sim10^{-8}$ rad/$\sqrt{\text{Hz}}$ (or $\Delta n<\sim10^{-14}/\sqrt{\text{Hz}}$) for substrate
  - $\Delta\varphi<\sim10^{-10}$ rad/$\sqrt{\text{Hz}}$ for coating

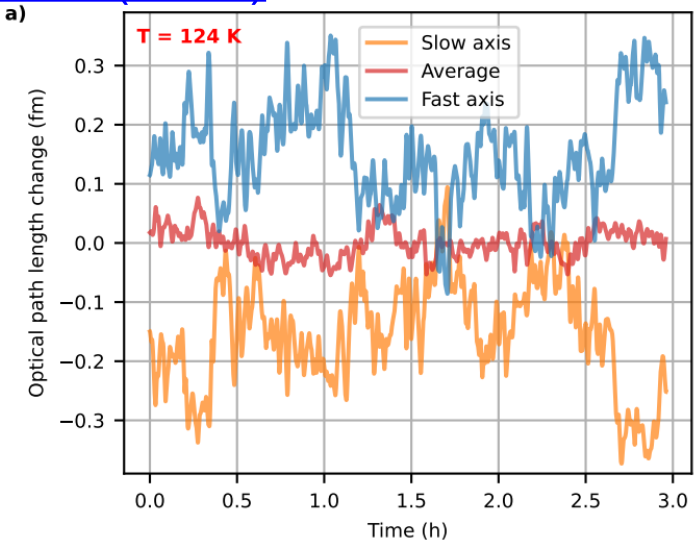
- Measurements and simulation work are necessary for further study

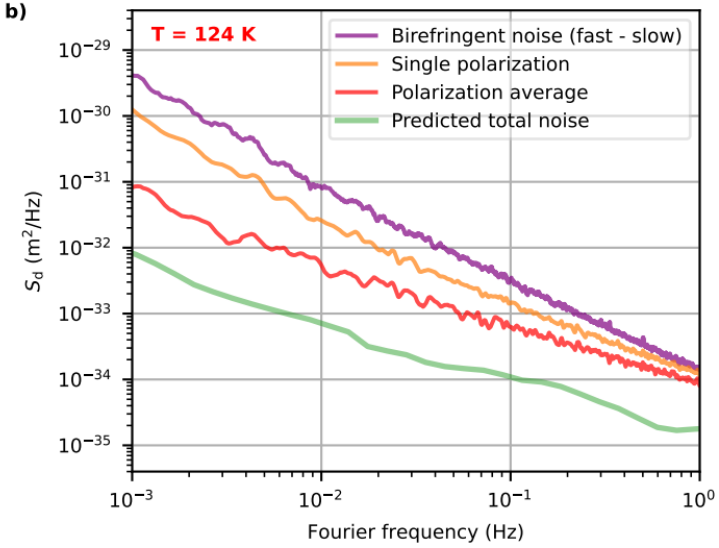
Y. Michimura, H. Wang, F. Salces-Carcoba, C. Wipf, A. Brooks, K. Arai, R. X. Adhikari, arXiv:2308.00150 (to appear in PRD)

Birefringence Noise

- Crystalline materials (Silicon, Sapphire, AlGaAs etc.) are promising, but has birefringence
- Static birefringence is (probably) small enough
  e.g., CQG **33**, 015012 (2015), APL **122**, 064101 (2023)
- JILA found "birefringent noise" in AlGaAs
  PRX **13**, 041002 (2023)





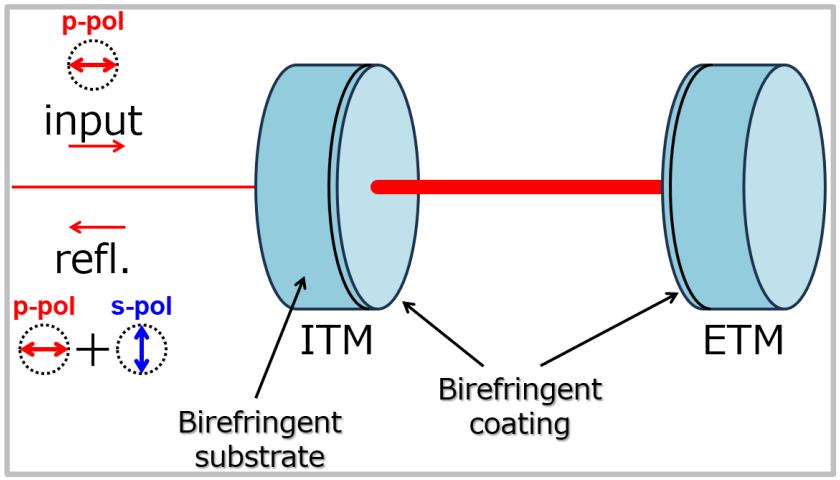


- *What is the requirement for mirror birefringence fluctuations for GW detectors?*

Birefringent FP Cavity ≒ FPMI

- Fabry-Pérot cavity with birefringent mirror can be understood as unbalanced Fabry-Pérot Michelson

Birefringent FP Cavity



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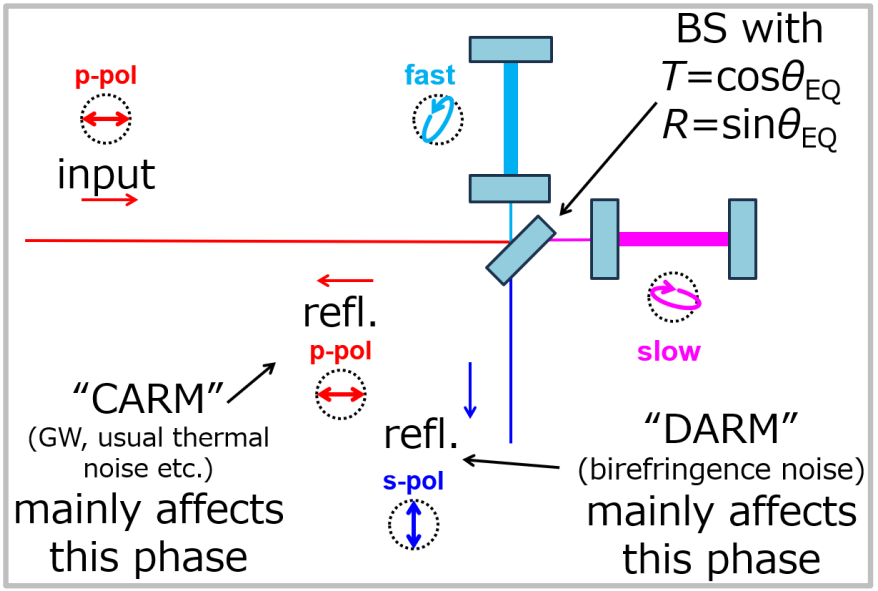
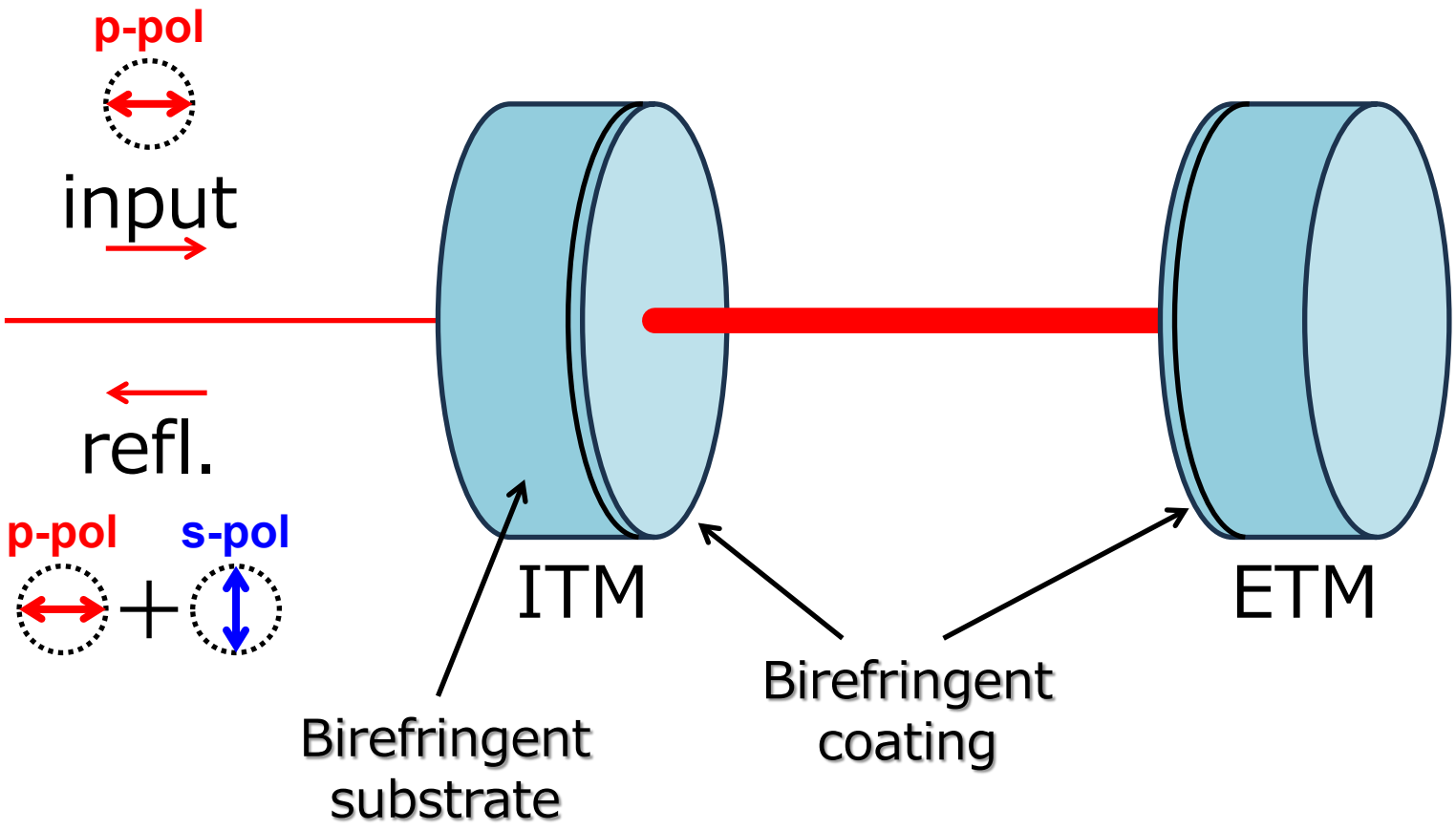
Unbalanced FPMI



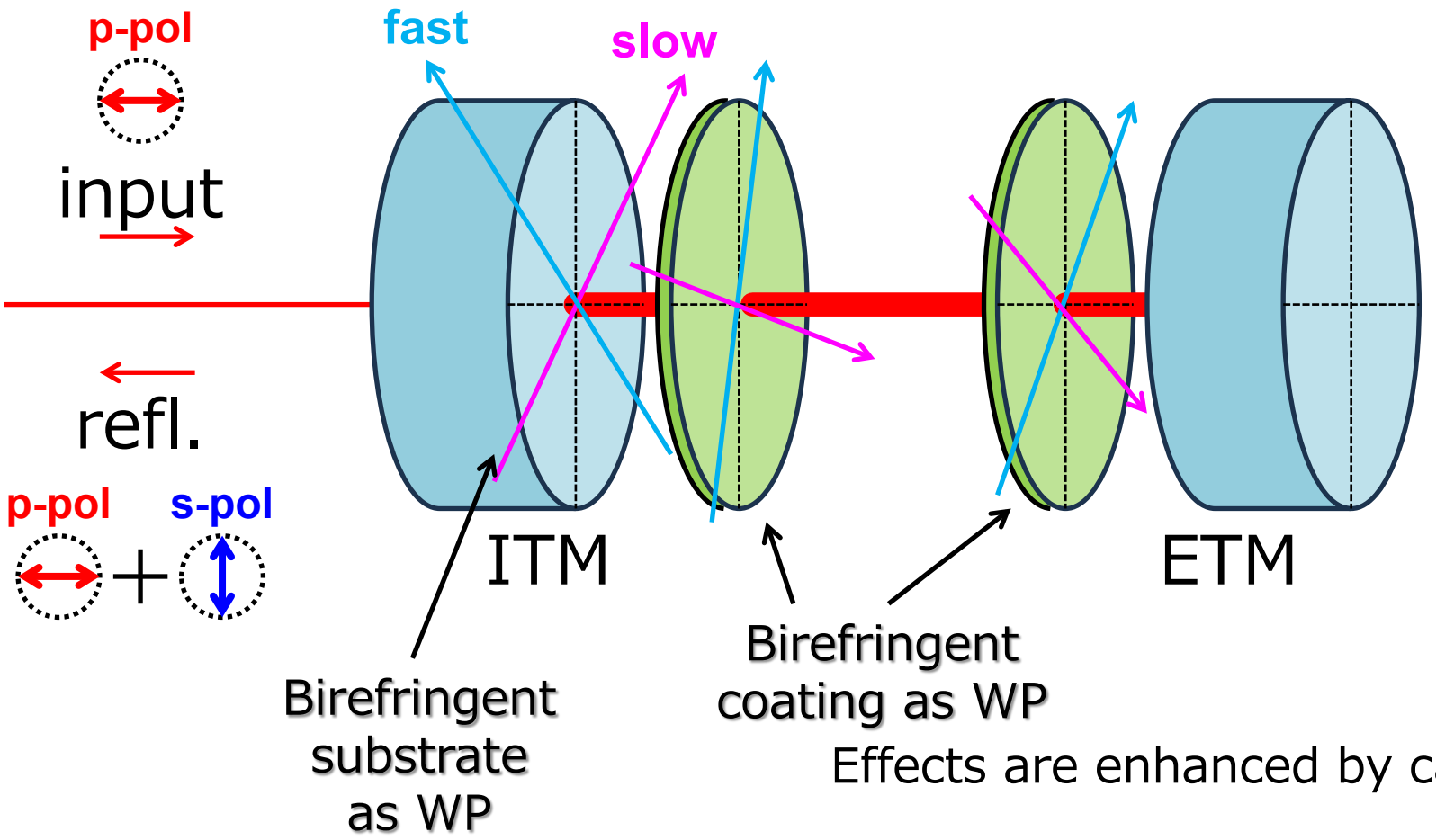
Birefringent FP Cavity

- Consider a FP cavity with mirrors that have substrate and coating birefringence



Birefringent FP Cavity

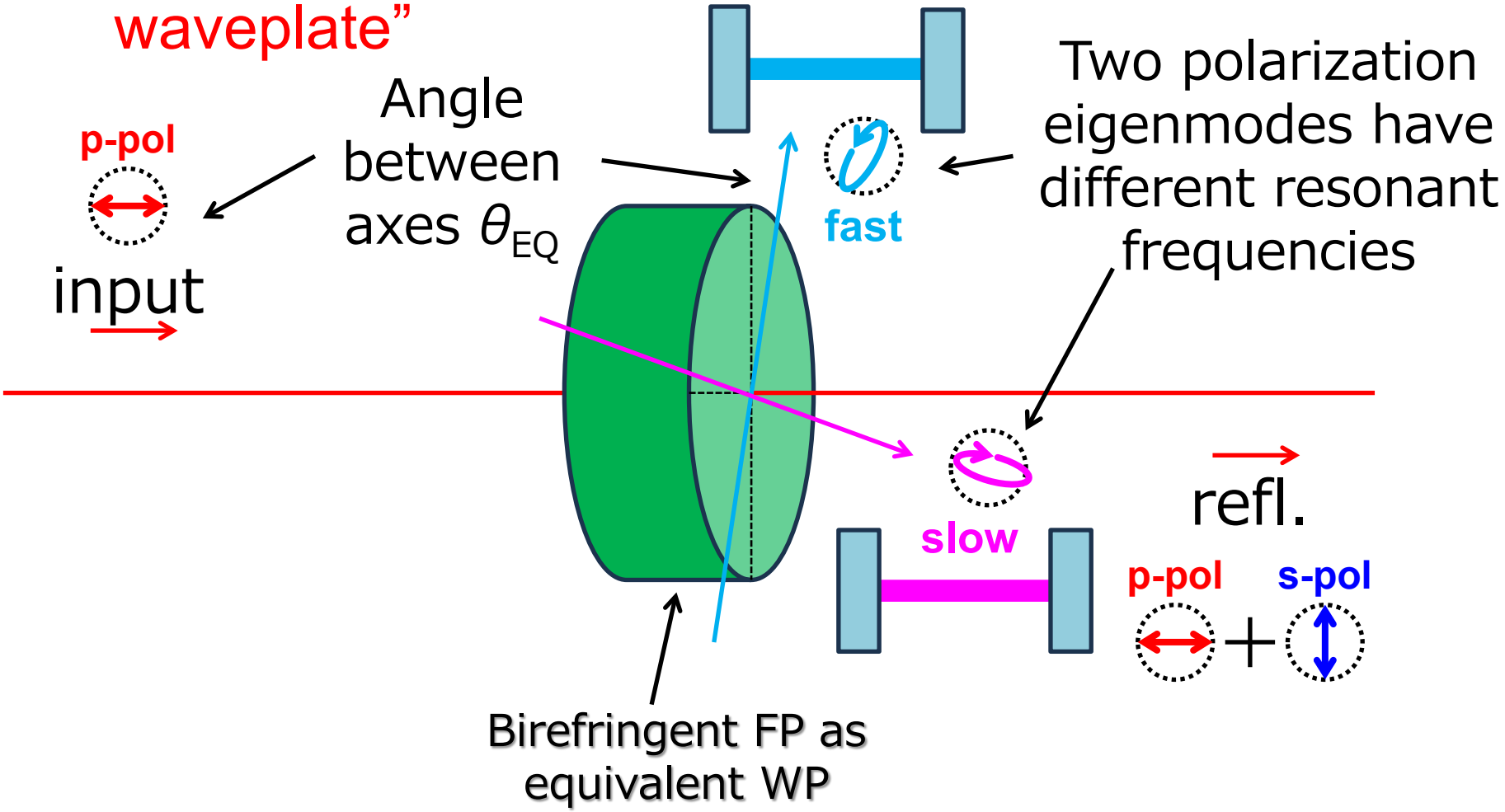
- This is equivalent to FP cavity with waveplates



Effects are enhanced by cavity

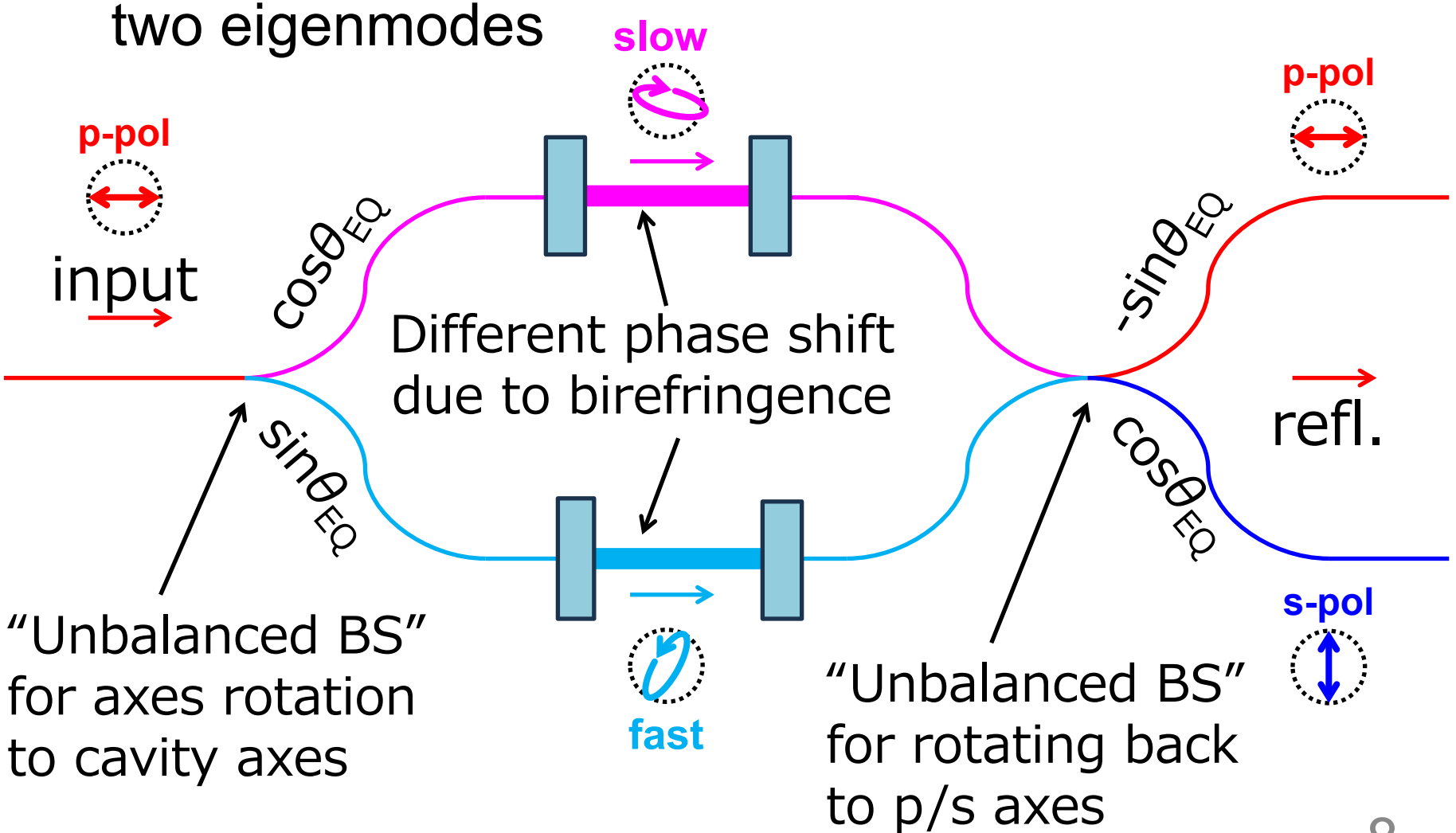
Birefringent FP Cavity

- FP cavity can be reduced to single "equivalent waveplate"



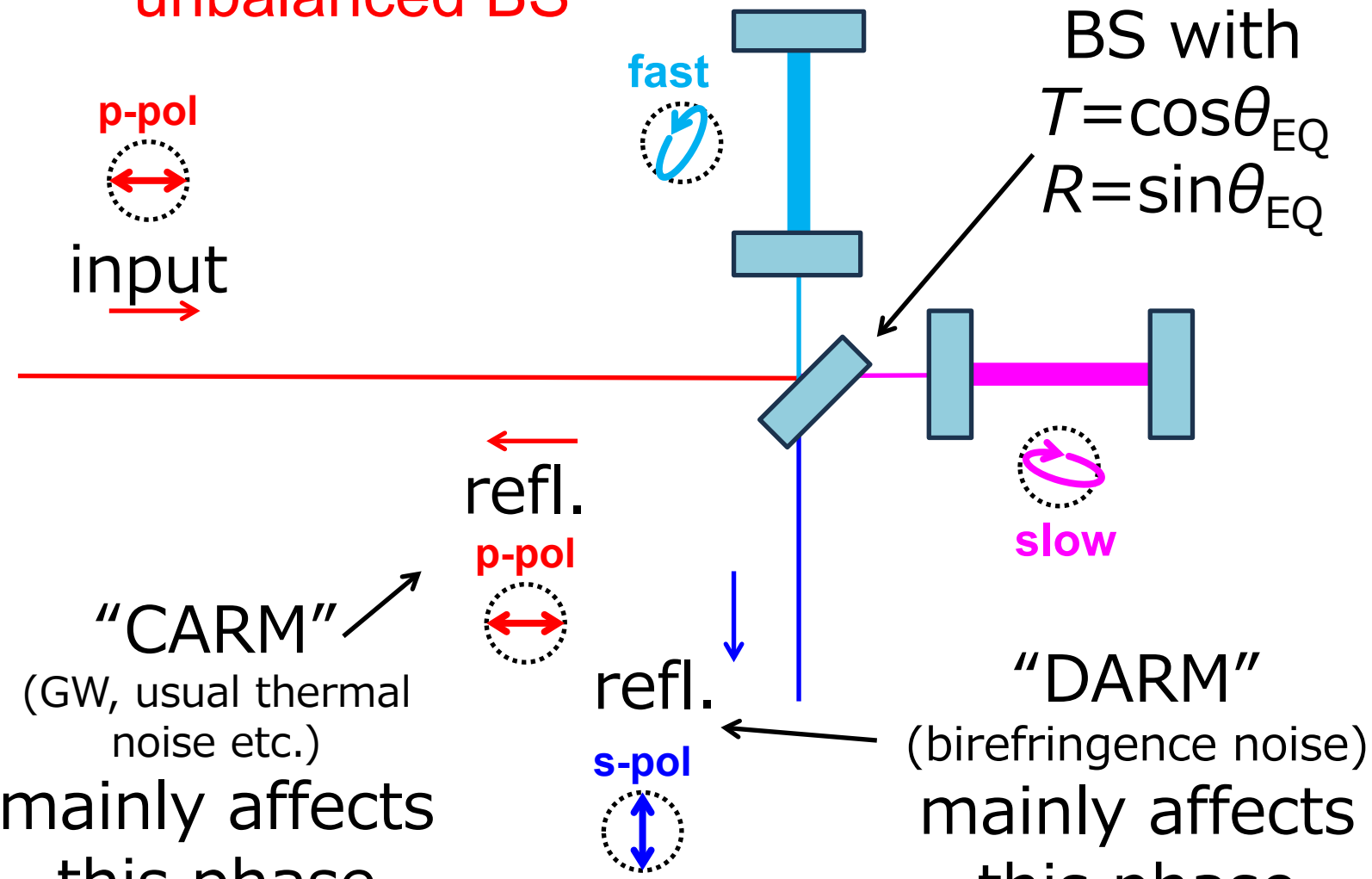
Birefringent FP Cavity

- "Equivalent waveplate" splits input polarization into two eigenmodes



Birefringent FP Cavity

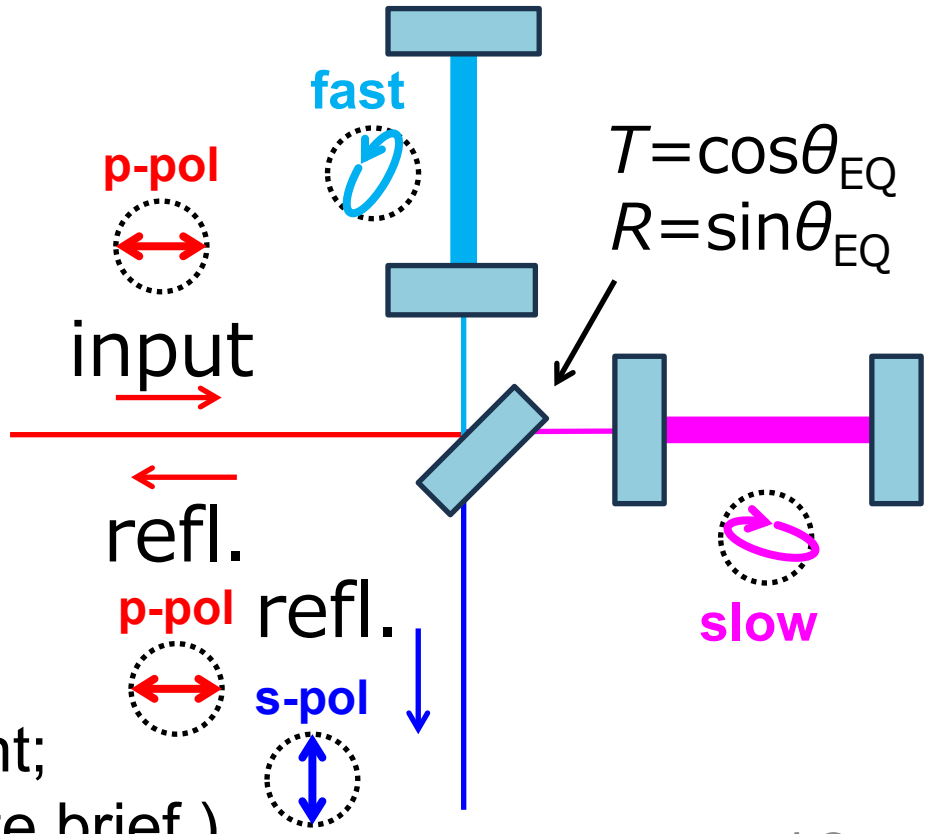
- So, birefringent FP cavity is equivalent to FPMI with unbalanced BS



Avoiding Birefringence Noise

- "CARM" (GW, usual thermal noise etc.) and "DARM" (birefringence noise) are mixed due to unbalanced BS, and therefore birefringence noise couples to GW signal

- How to avoid?
  - Align polarization axis and mirror axes (make θ_{EQ}=0)
  - Make coating brief. large (make only one of the eigenmodes resonant; would not work for substrate brief.)



Requirements for Birefringence

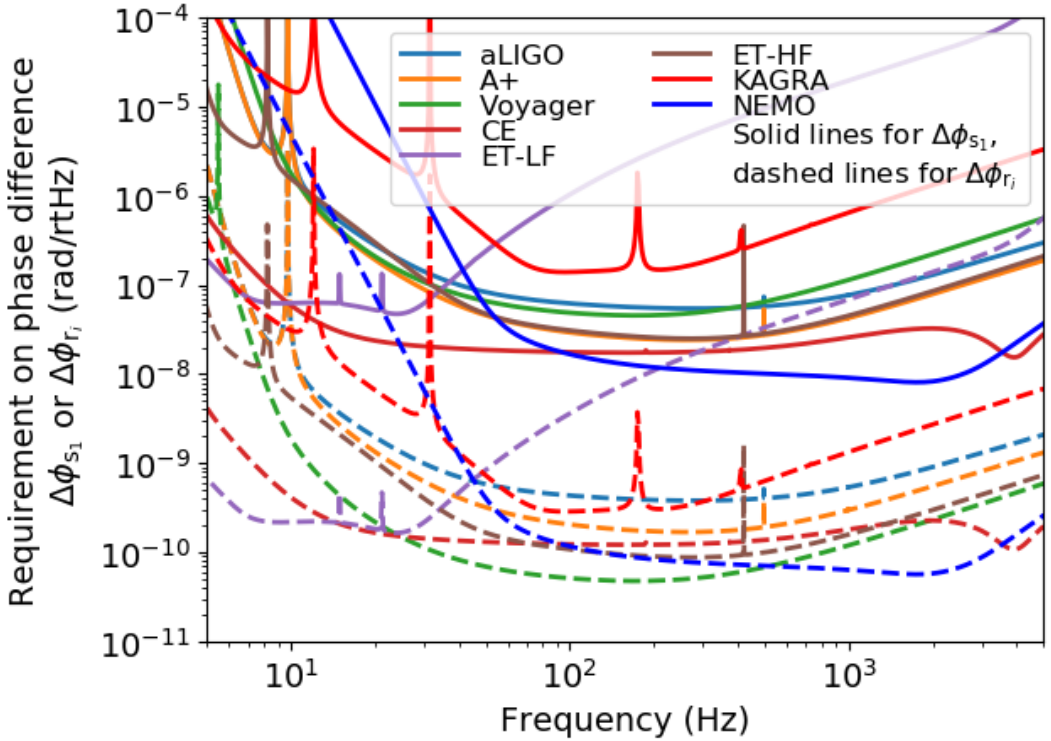
- Displacement noise coupling

$$\frac{\delta L}{\delta(\Delta\phi)} = \frac{\lambda}{4\pi}\sin^2\theta \times \frac{\pi}{\mathcal{F}}$$

Factor only for substrate birefringence

Angle between polarization axis and cavity axes

Phase difference between axes



Requirements on Δφ

assuming θ~1 deg

For substrate

Δφ<~10^{-8} rad/√Hz

(or Δn<~10^{-14}/√Hz)

For coating

Δφ<~10^{-10} rad/√Hz

Requirements for Axis Rotation

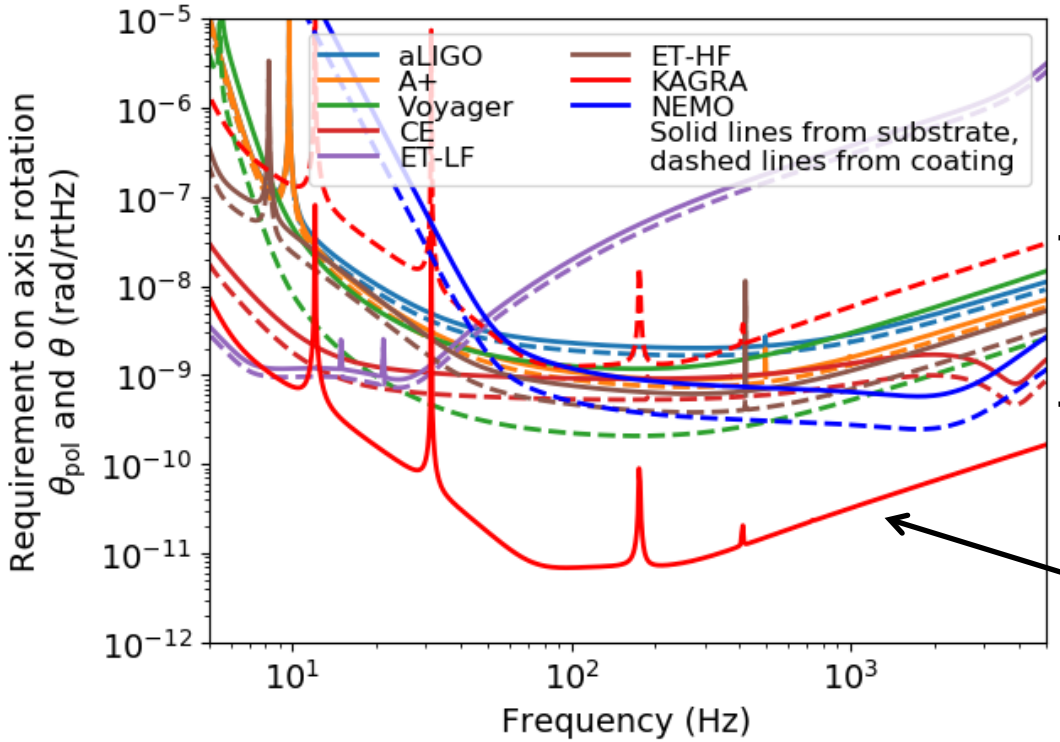
- Displacement noise coupling

$$\frac{\delta L}{\delta \theta} = \frac{\lambda}{4\pi} \Delta\phi \sin 2\theta \times \frac{\pi}{\mathcal{F}}$$

Factor only for substrate birefringence

Phase difference between axes

Angle between polarization axis and cavity axes



Requirements on θ

assuming Δn~10^{-7} or 10^{-4} for substrate, $\Delta\varphi$~1 mrad for coating

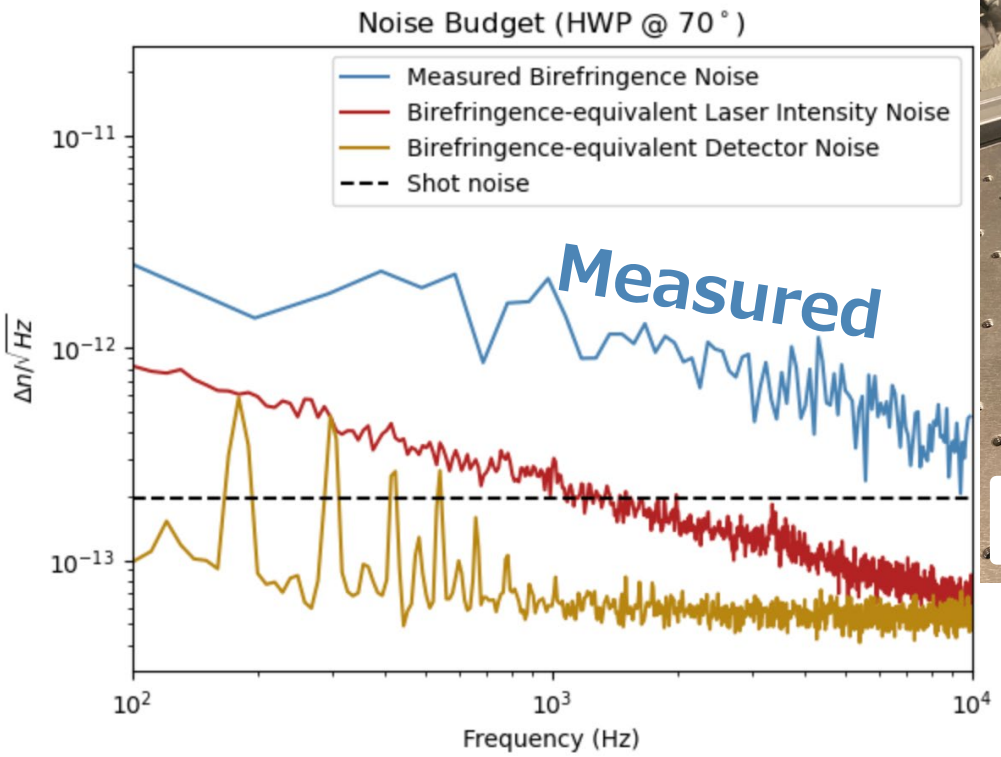
For substrate/coating

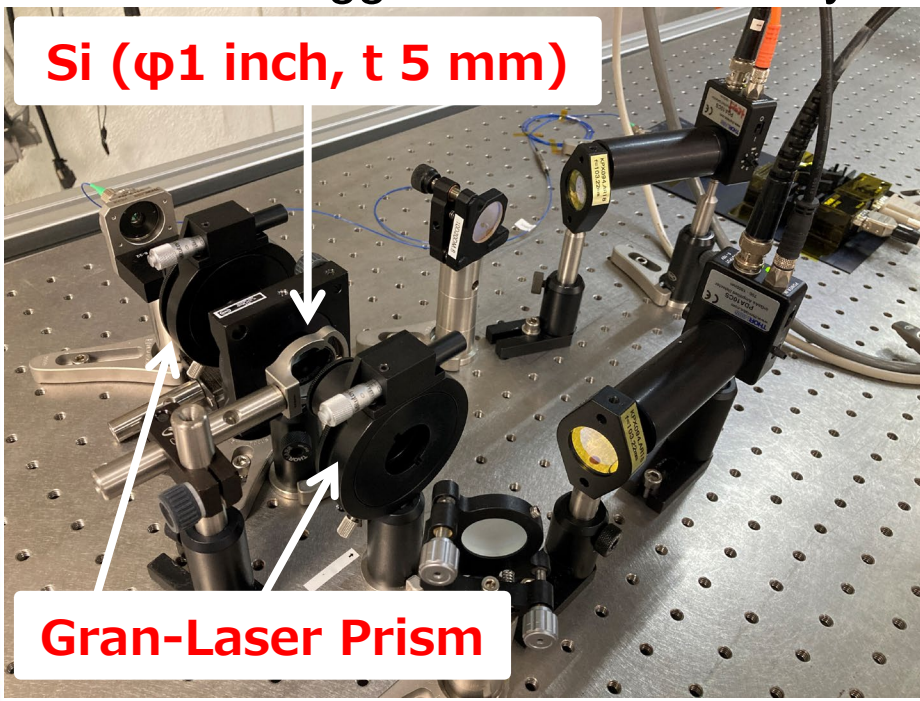
θ<~10^{-10} rad/√Hz

Strict requirement for KAGRA if Δn~10^{-4} (sapphire)
For others, assumed Δn~10^{-7} (e.g. silicon)

Measurement at Caltech

- Silicon birefringence measurements started
- Sensitivity to Δn of 2×10^{-12} /rtHz @ 100 Hz achieved with Silicon @ 1550 nm, room temp.
  - Measurement at different input polarization suggest this is limited by noise not from silicon





Measurement and plot by Kushal Jain

Summary and Outlook

- Fluctuations in mirror birefringence will be phase noises for GW detectors

YM+, arXiv:2308.00150

- Measurements of birefringence fluctuations in Silicon, Sapphire, AlGaAs etc. are necessary to see if they meet the requirement

- Further simulation studies necessary for
  - Investigating PRC/SRC effects (unbalanced BS, ITM birefringence)
  - Noise from inhomogeneous birefringence x beam spot motion
  - Investigating effects for squeezing
  - Classical radiation pressure noise from orthogonal pol.