Birefringence measurements on crystalline silicon

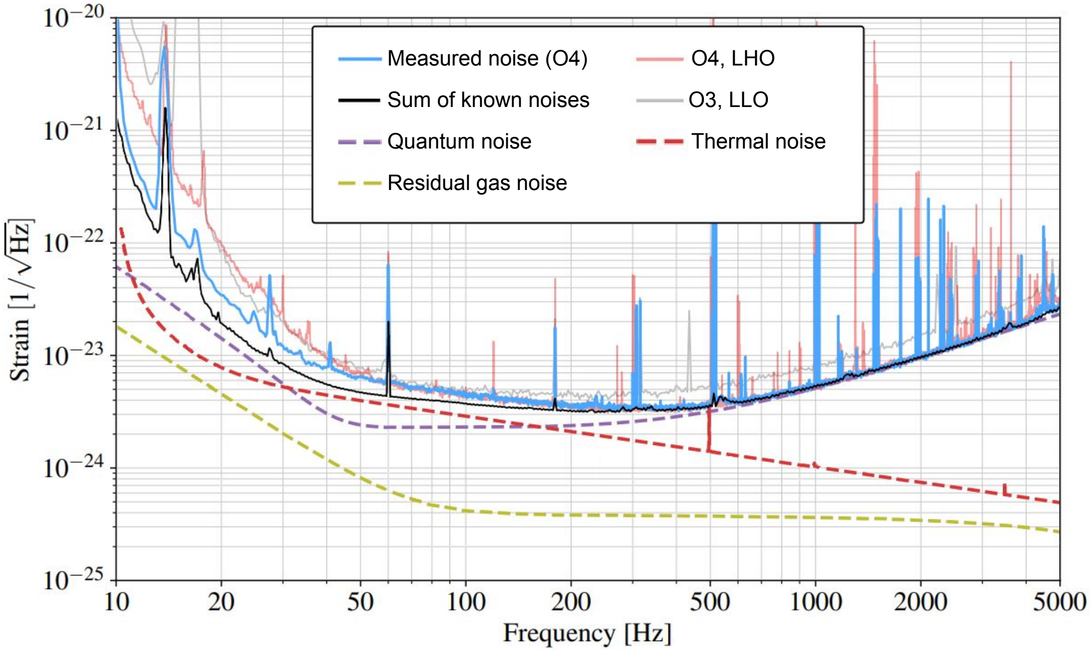
Luca Craighero

16 March 2026

Topics of the presentation:

- Cryogenic detectors
- Effect of birefringence on gravitational interferometers
- Properties of crystalline silicon at cryogenic temperatures
- Birefringence experiment: objectives, working principle and present state

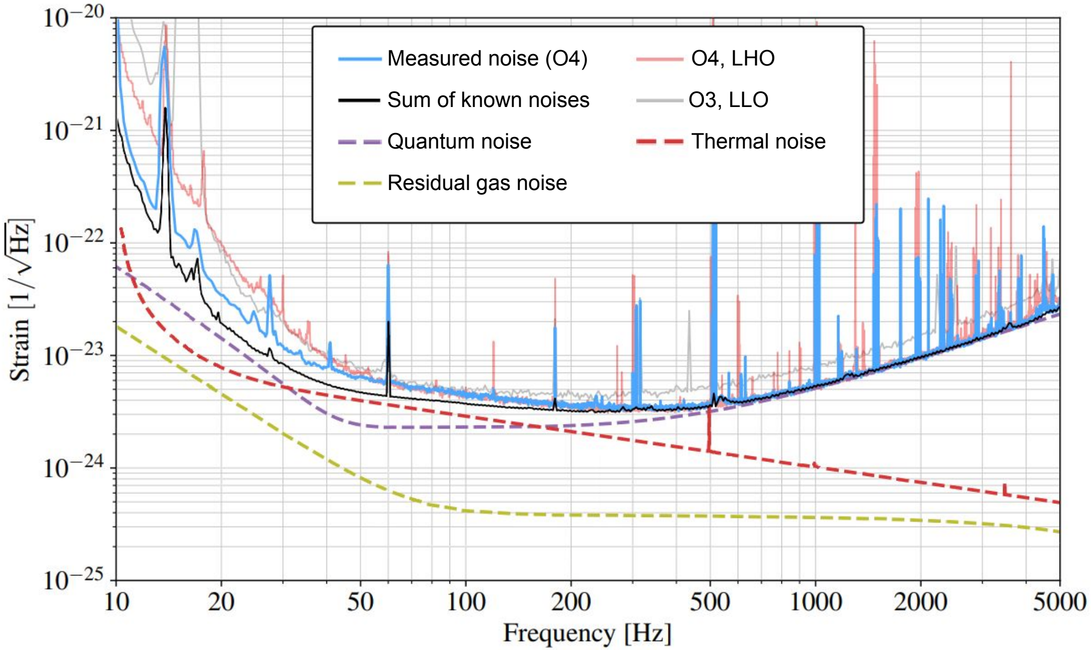
Why do we need cryogenics?



Noise budget for the LIGO Livingston Observatory, as of October 2023.

Capote, E., et al. "Advanced LIGO detector performance in the fourth observing run." *Physical Review D* 111.6 (2025): 062002.

Why do we need cryogenics?



Noise budget for the LIGO Livingston Observatory, as of October 2023.

Capote, E., et al. "Advanced LIGO detector performance in the fourth observing run." *Physical Review D* 111.6 (2025): 062002.

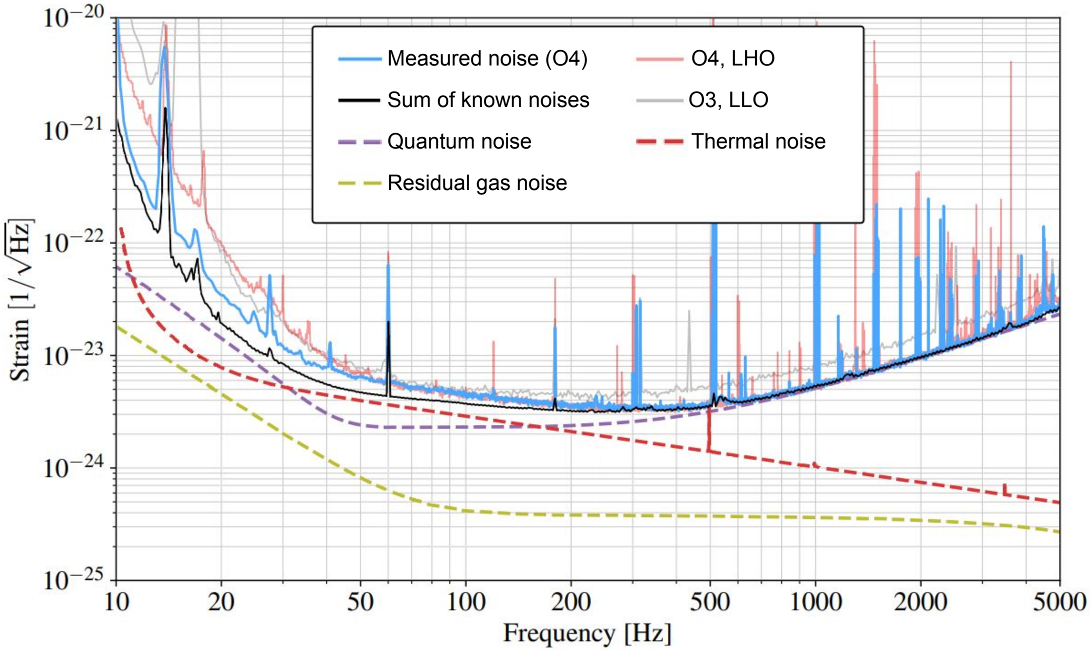
Cryogenics detectors in the future

KAGRA

ET-Low Frequency

LIGO Voyager

Why do we need cryogenics?



Noise budget for the LIGO Livingston Observatory, as of October 2023.

Capote, E., et al. "Advanced LIGO detector performance in the fourth observing run." *Physical Review D* 111.6 (2025): 062002.

Cryogenics detectors in the future

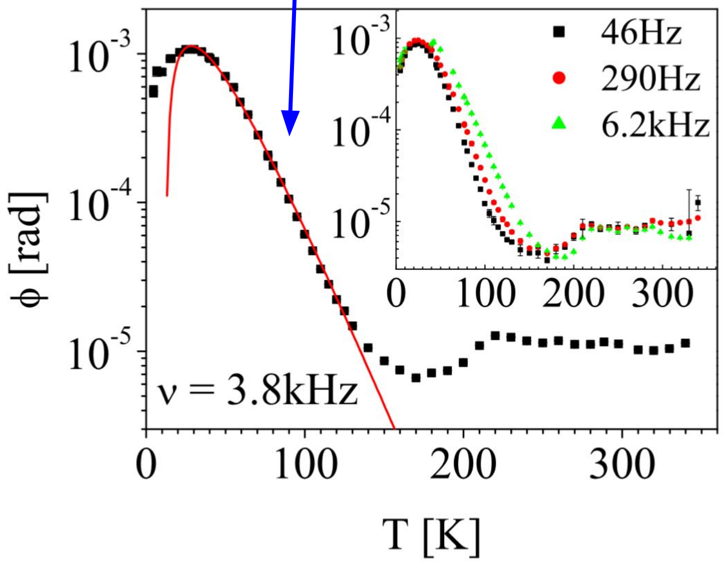
KAGRA

ET-Low Frequency

LIGO Voyager

Problem of fused silica in cryogenic detectors

Fused silica has high mechanical loss at low temperature



Ligo/Virgo → Fused Silica

Cryogenic detectors → Sapphire

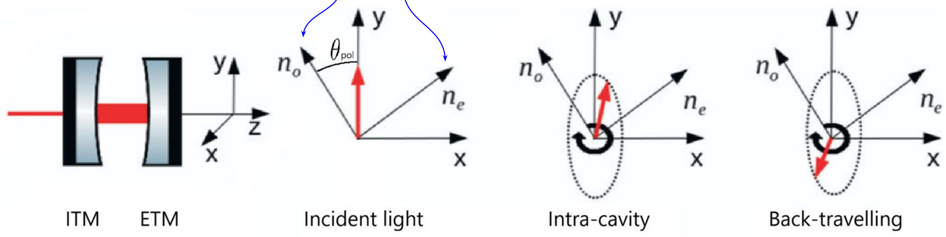
Cryogenic detectors → Crystalline Silicon

Travasso, Flavio, et al. "Low-frequency internal friction in silica glass."
EPL (Europhysics Letters) 80.5 (2007): 50008.

Effect of birefringence on an interferometer

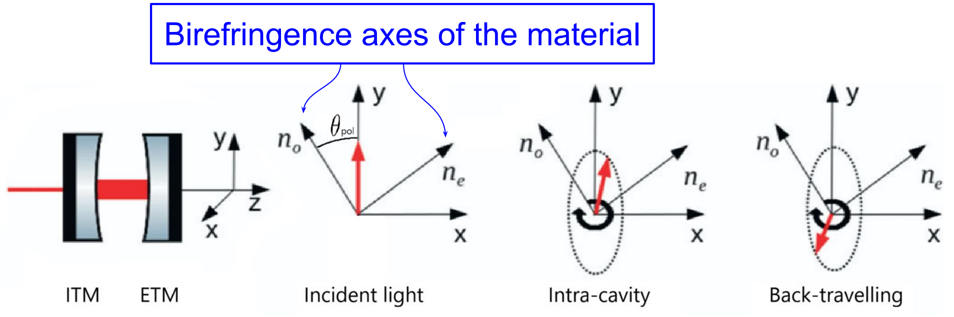
Birefringence: $\Delta n = n_e - n_o$

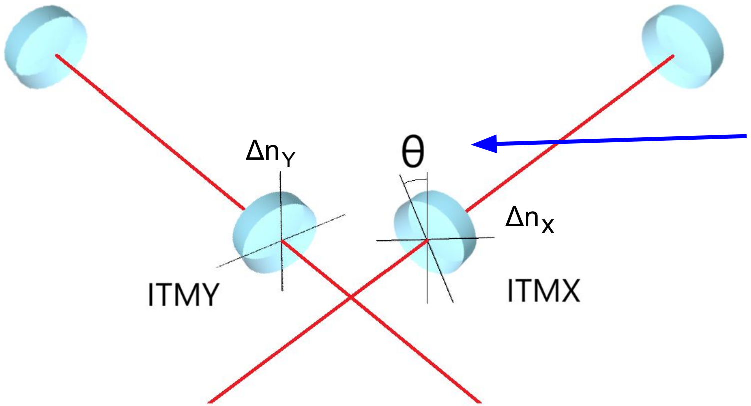
Birefringence axes of the material



Effect of birefringence on an interferometer

Birefringence: $\Delta n = n_e - n_o$





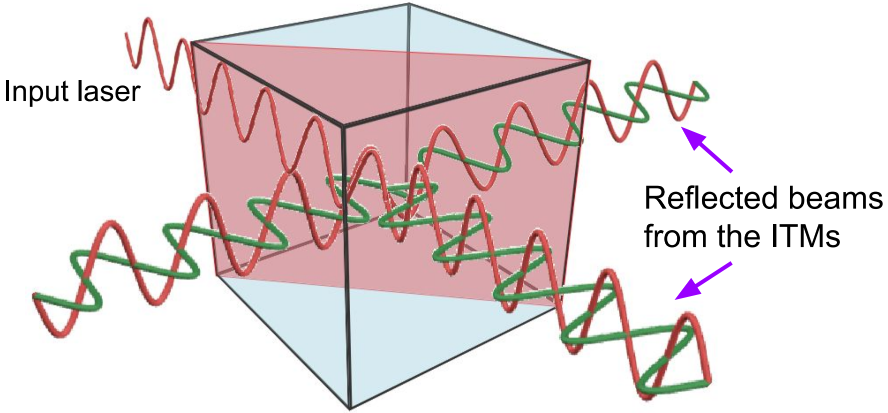
The angle between the two ITMs axes also influences the interferometer

In ET-LF both θ and (θ + θ_{pol}) should be kept smaller than 1.8° in order to have birefringence losses of up to 0.1%

Michimura, Yuta, et al. "Effects of mirror birefringence and its fluctuations to laser interferometric gravitational wave detectors." *Physical Review D* 109.2 (2024): 022009.

Birefringence noises and sources

KAGRA's beam-splitter is not symmetric for the two polarizations:

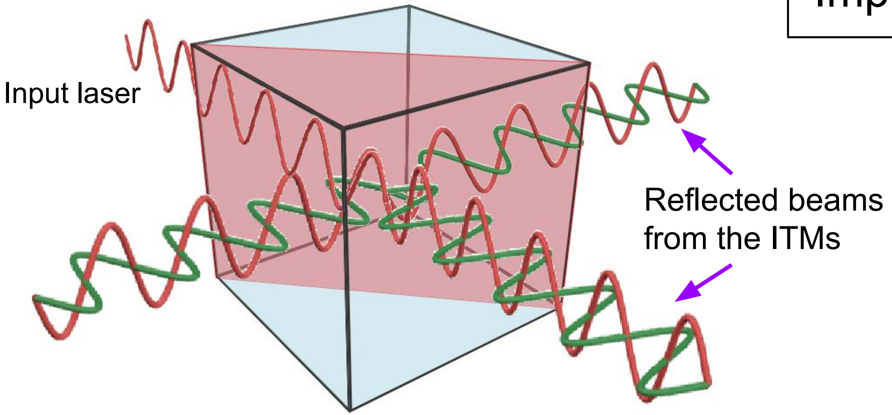


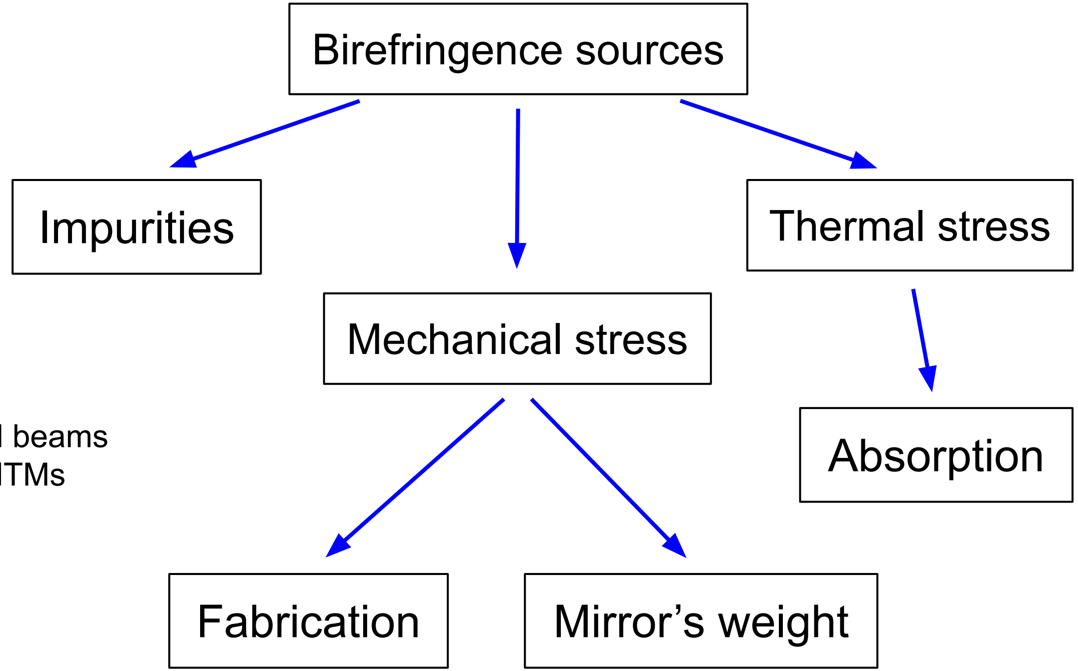
s-polarization ➞ R:T = 50%:50%

p-polarization ➞ R:T = 20%:80% ⟶ This will lead to non optimal interference

Birefringence noises and sources

KAGRA's beam-splitter is not symmetric for the two polarizations:

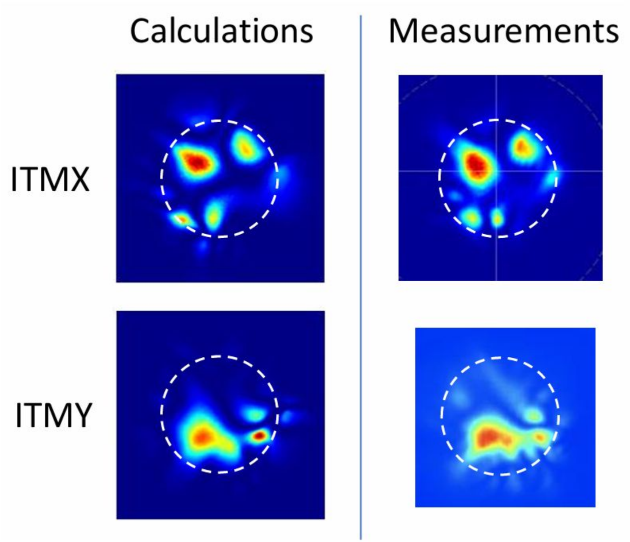




s-polarization → R:T = 50%:50%

p-polarization → R:T = 20%:80% ⟶ This will lead to non optimal interference

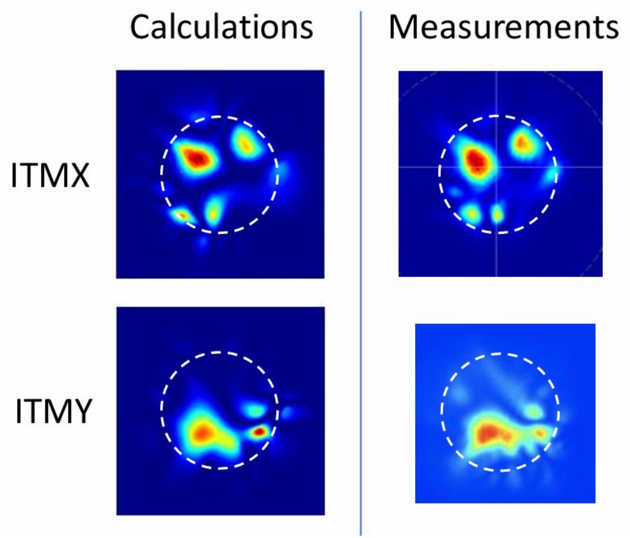
Birefringence inhomogeneities in KAGRA’s mirrors

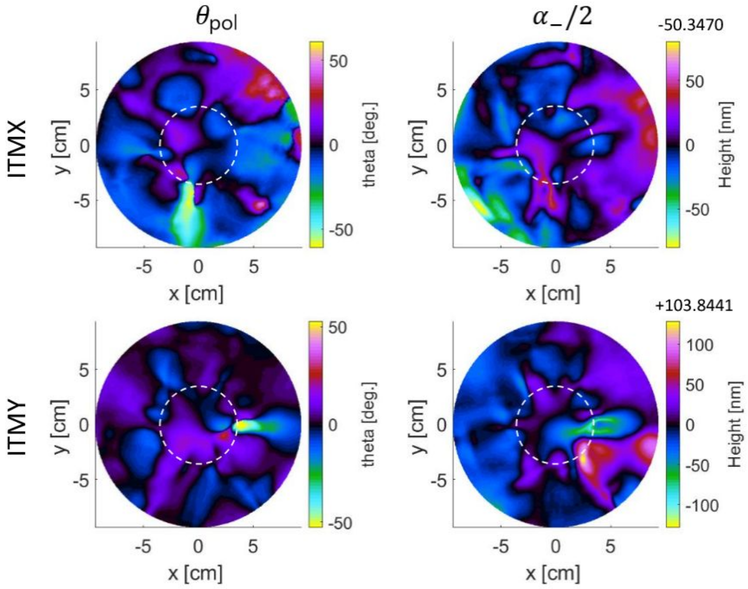


Shape of the reflected p-polarization

Wang, Haoyu, et al. "Characterization of birefringence inhomogeneity of kagra sapphire mirrors from transmitted wavefront error measurements." *Physical Review D* 110.8 (2024): 082007.

Birefringence inhomogeneities in KAGRA's mirrors





Shape of the reflected p-polarization

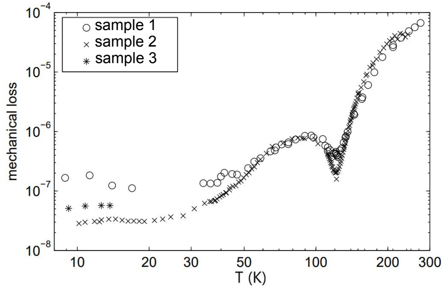
- Maximum spatial variation of θ : ± 50°
- Maximum spatial variation of birefringence : $\Delta n \simeq 7 \cdot 10^{-7}$

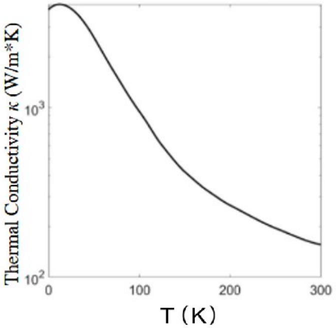
Wang, Haoyu, et al. "Characterization of birefringence inhomogeneity of kagra sapphire mirrors from transmitted wavefront error measurements." *Physical Review D* 110.8 (2024): 082007.

Crystalline Silicon at cryogenic temperatures

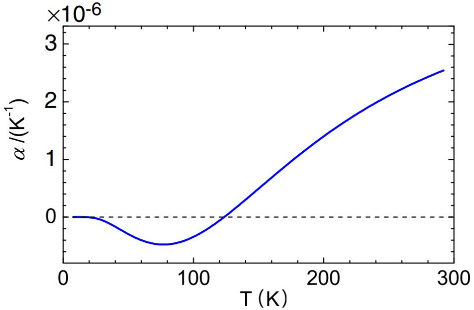
Great mechanical and thermal properties at low temperatures:

Low mechanical loss





High thermal conductivity



Low thermal expansion

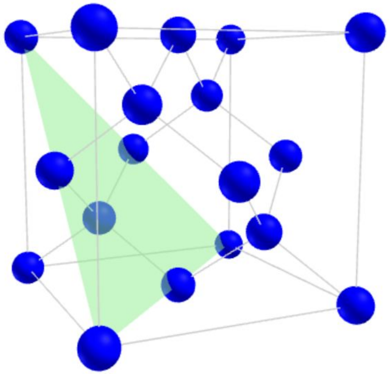
Nawrodt, Ronny, et al. "Investigation of mechanical losses of thin silicon flexures at low temperatures." *Classical and Quantum Gravity* 30.11 (2013): 115008.

Glassbrenner, C. Jo, and Glen A. Slack. "Thermal conductivity of silicon and germanium from 3 K to the melting point." *Physical review* 134.4A (1964): A1058.

Middelmann, Thomas, et al. "Thermal expansion coefficient of single-crystal silicon from 7 K to 293 K." *Physical Review B* 92.17 (2015): 174113.

Birefringence of cSi at 1550 nm and room temperature

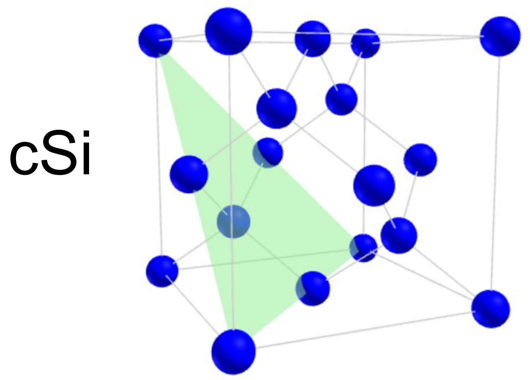
cSi



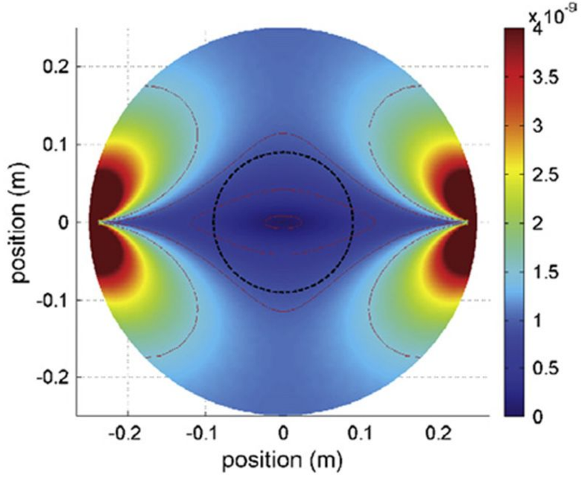
Crystalline silicon structure and measured plane <111>

Measured birefringence: $\Delta n \simeq 10^{-7}$

Birefringence of cSi at 1550 nm and room temperature



Crystalline silicon structure and measured plane <111>



Krüger, Christoph, et al. "Birefringence measurements on crystalline silicon." *Classical and quantum gravity* 33.1 (2016): 015012.

Measured birefringence: $\Delta n \simeq 10^{-7}$

Calculated birefringence due to gravity stresses in ET-LF: $\Delta n \simeq 10^{-9}$

Objectives of the experiment

Measuring birefringence of a cSi sample at room temperature

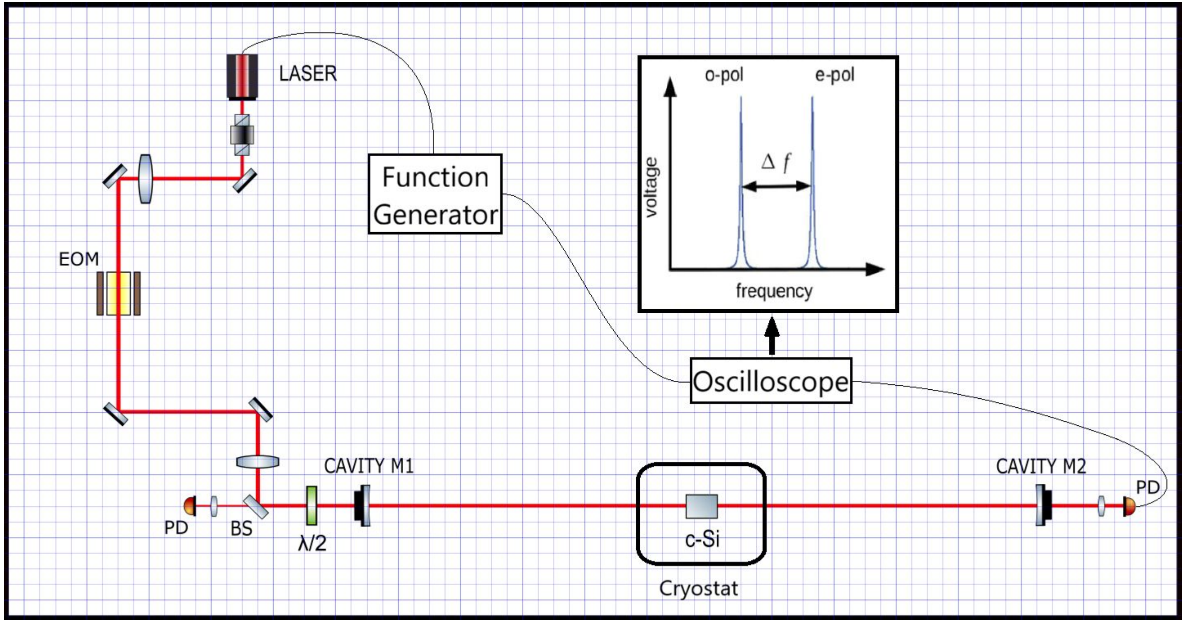
↓

Mapping the birefringence of the sample

↓

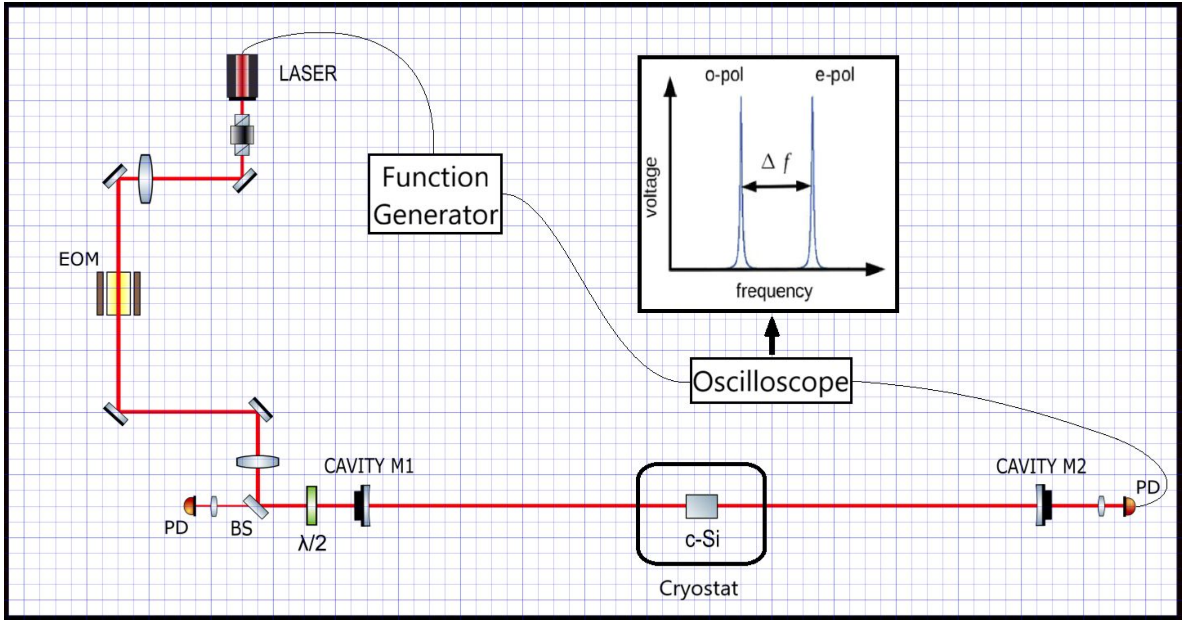
Measure birefringence at cryogenic temperatures

How does the experiment work



It’s a Fabry-Perot cavity based experiment

How does the experiment work



It's a Fabry-Perot cavity based experiment

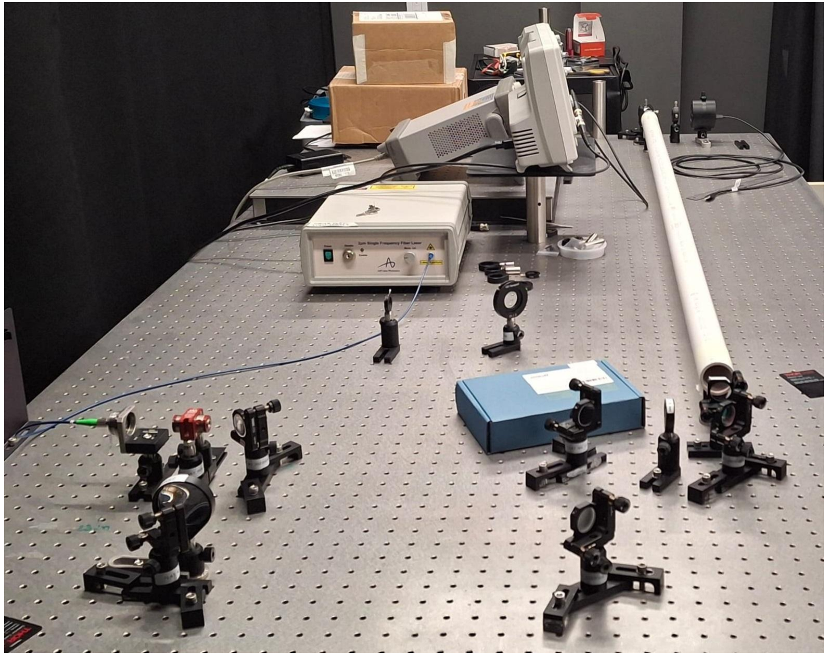
Equation for birefringence:

$$\Delta n = \frac{\frac{L}{d} + n_o - 1}{\nu_e} \Delta f \; + \; \frac{c}{2d} \frac{1}{\nu_o} \Delta N$$

With $\Delta n \simeq 10^{-7}$ and d = 10 cm → $\Delta f \simeq 700$ kHz

Resolvable with the current setup

State of the experiment and possible outcomes



- We are currently setting up the cavity

- Expected resolution: less than 1mm

- Measurements down to 4 K

Thank you!