Introduction to Gravitational Wave Detector Development in Korea

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2026 Summer School on Numerical Relativity and Gravitational Waves

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RESEARCH IDENTITY

Instrumentation and observation techniques for improving accuracy and efficiency of astronomical data

Off-axis reflective system, Spectrophotometric calibration

INTERESTS

Planetary nebula
→ Astronomical data processing
→ Telescope system
→ GWD

GRAVITATIONAL-WAVE OPTICS

(Active) mode-matching: Virgo EPR-SIPS, KAGRA, ET

Faraday isolator: KAGRA

Generated using ChatGPT

Take-home message?!

1. GWDs are consisted of lots of components to enhance and protect signals.
2. Korean researchers are working hard to reduce noise of GWDs.
3.

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2. Korean researchers are working hard to reduce noise of GWDs.
3.

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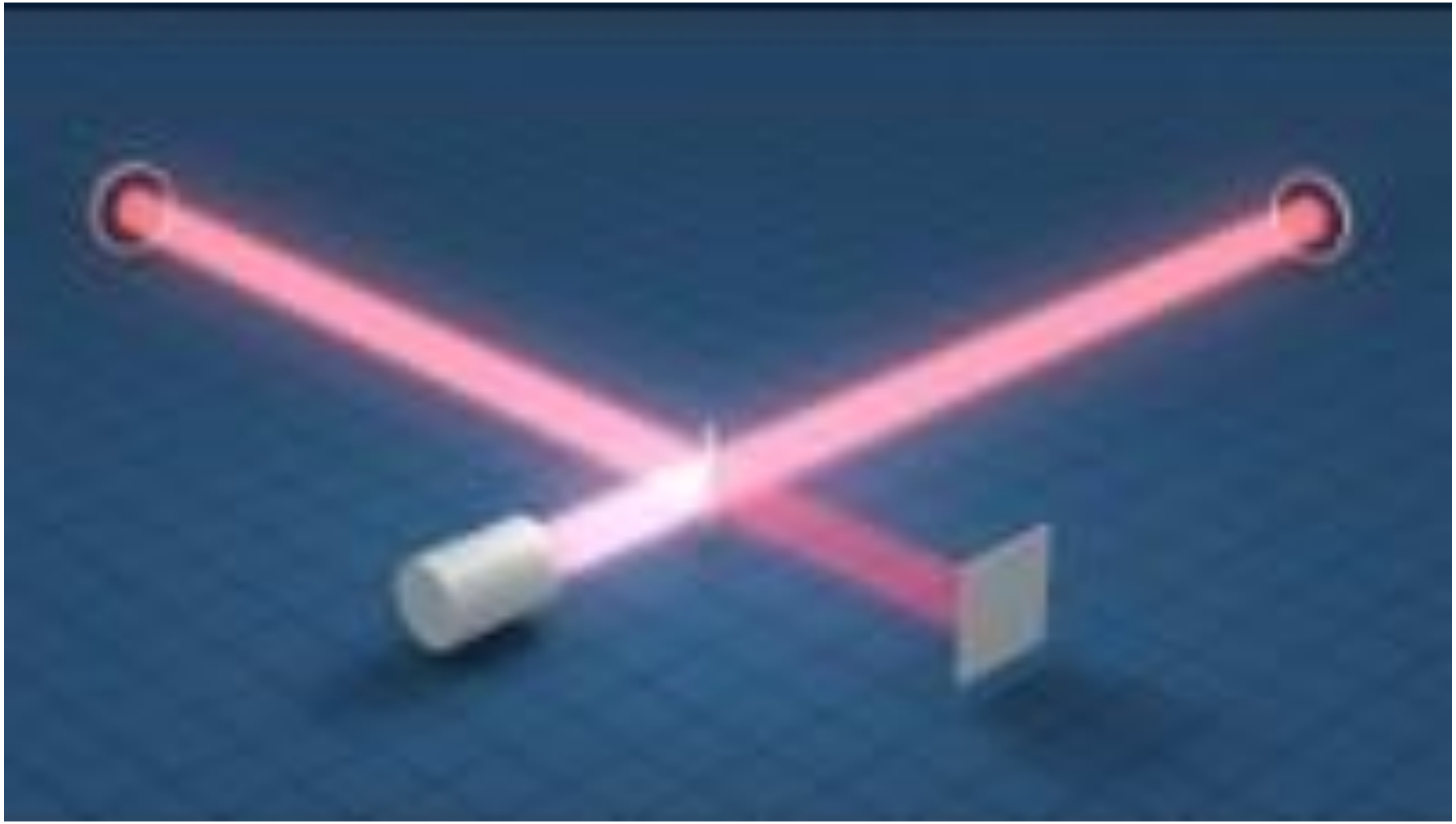
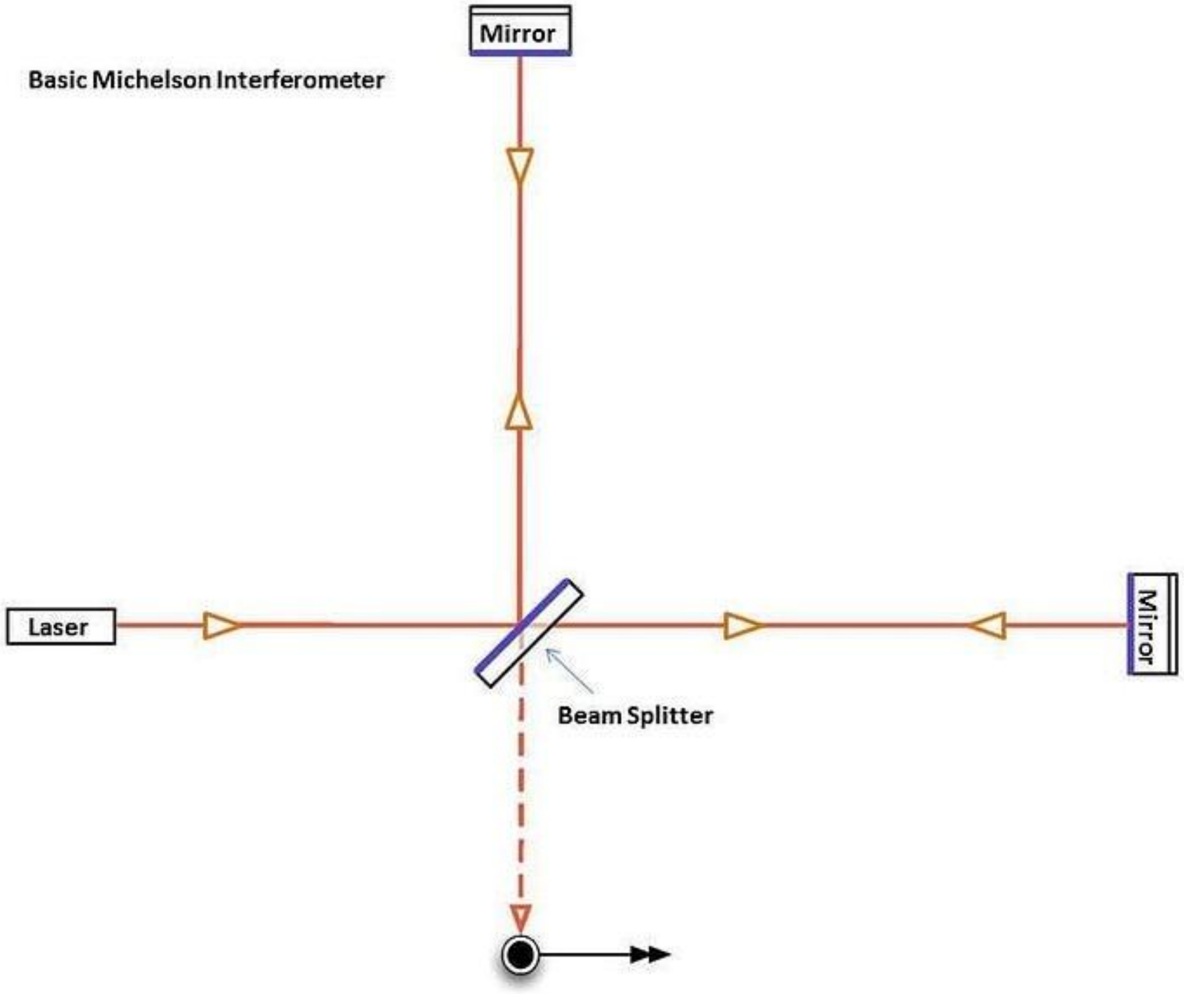
Gravitational wave detector



https://www.youtube.com/watch?v=tQ_teIUb3tE

Gravitational wave detector

Is it enough? Really?



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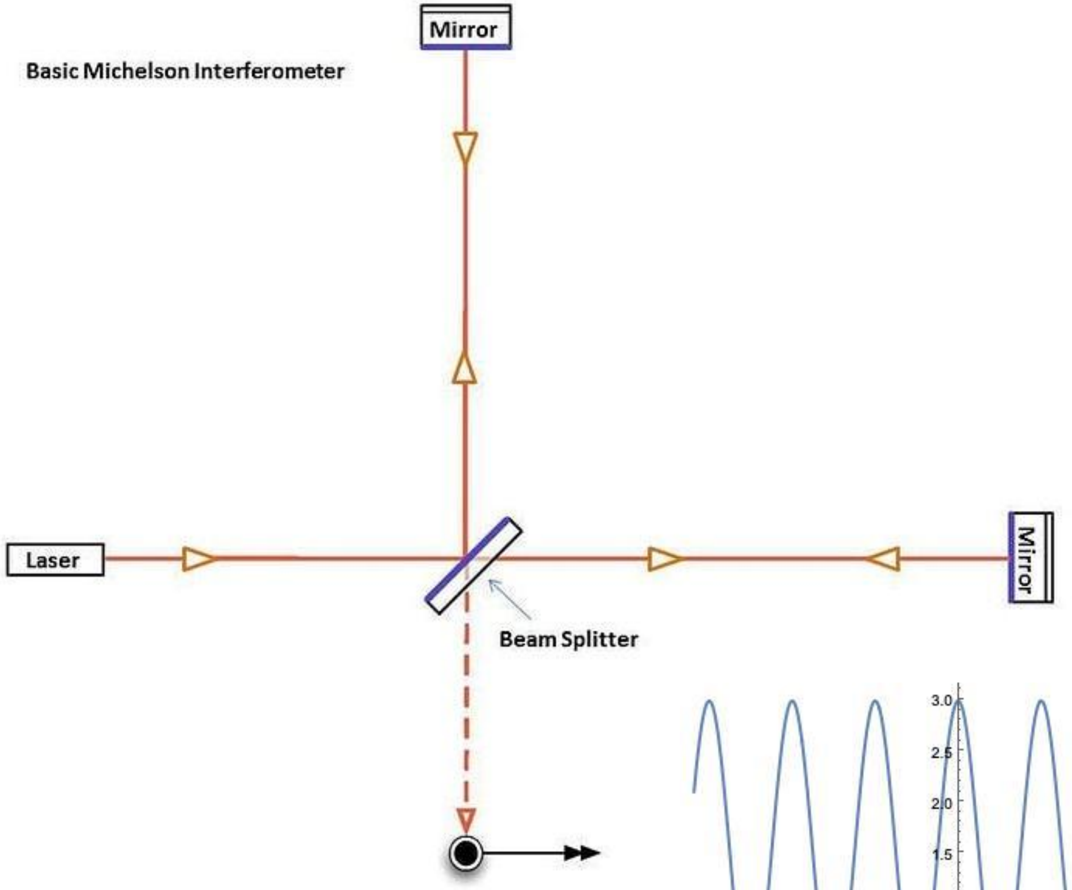
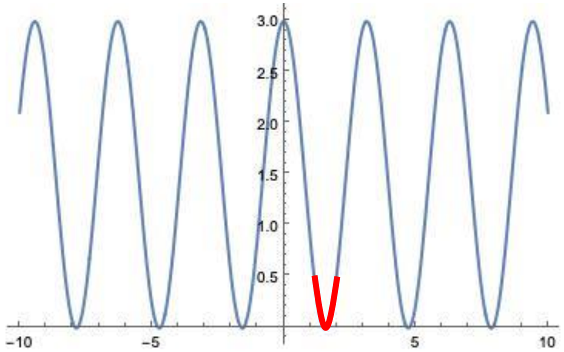
Gravitational wave detector

- Gravitational wave (strain)
- ΔL
- $\Delta\varphi$
- P_{out}





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Gravitational wave detector

- Gravitational wave (strain) ~ 10^{-21}
- ΔL
- $\Delta\varphi$
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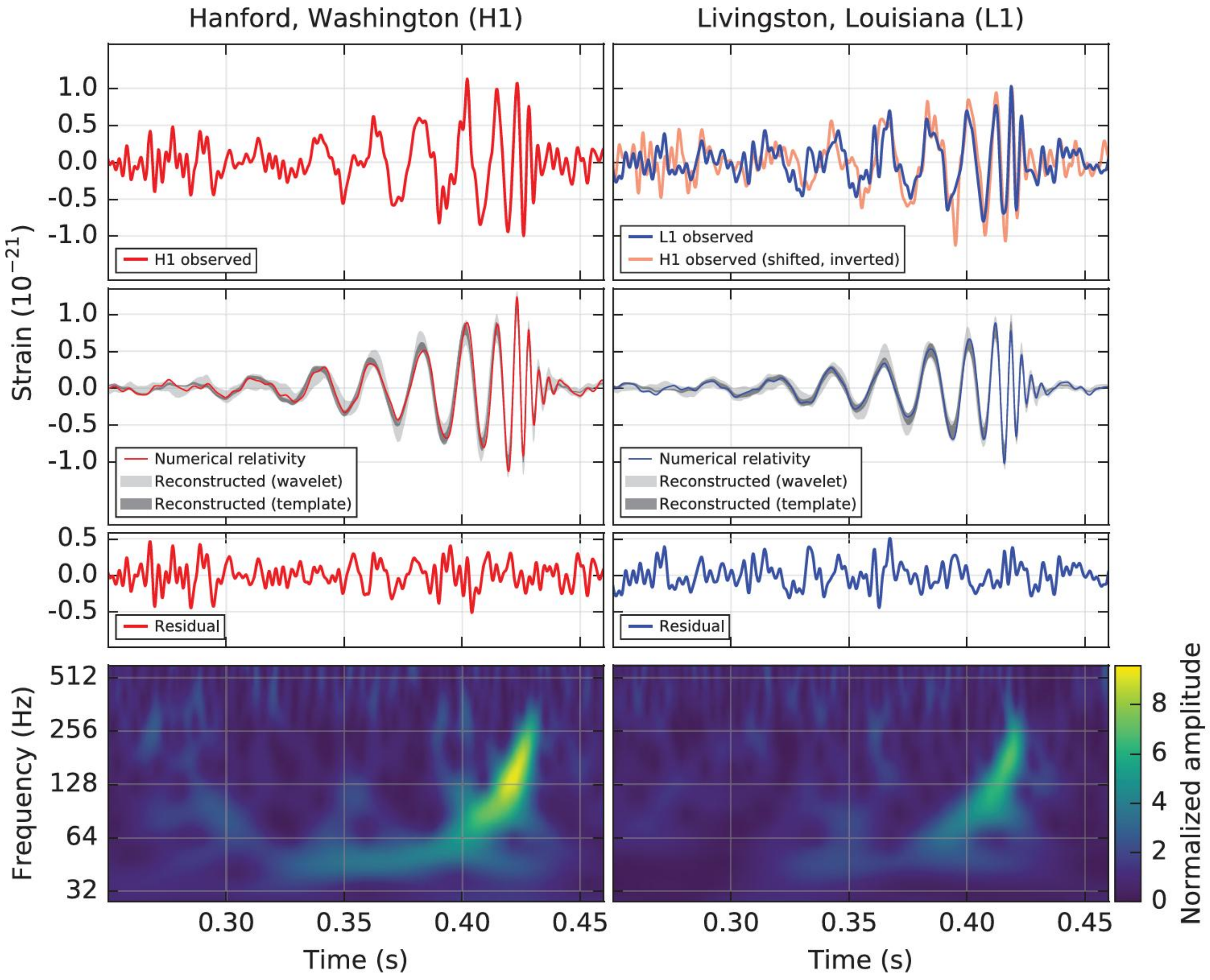
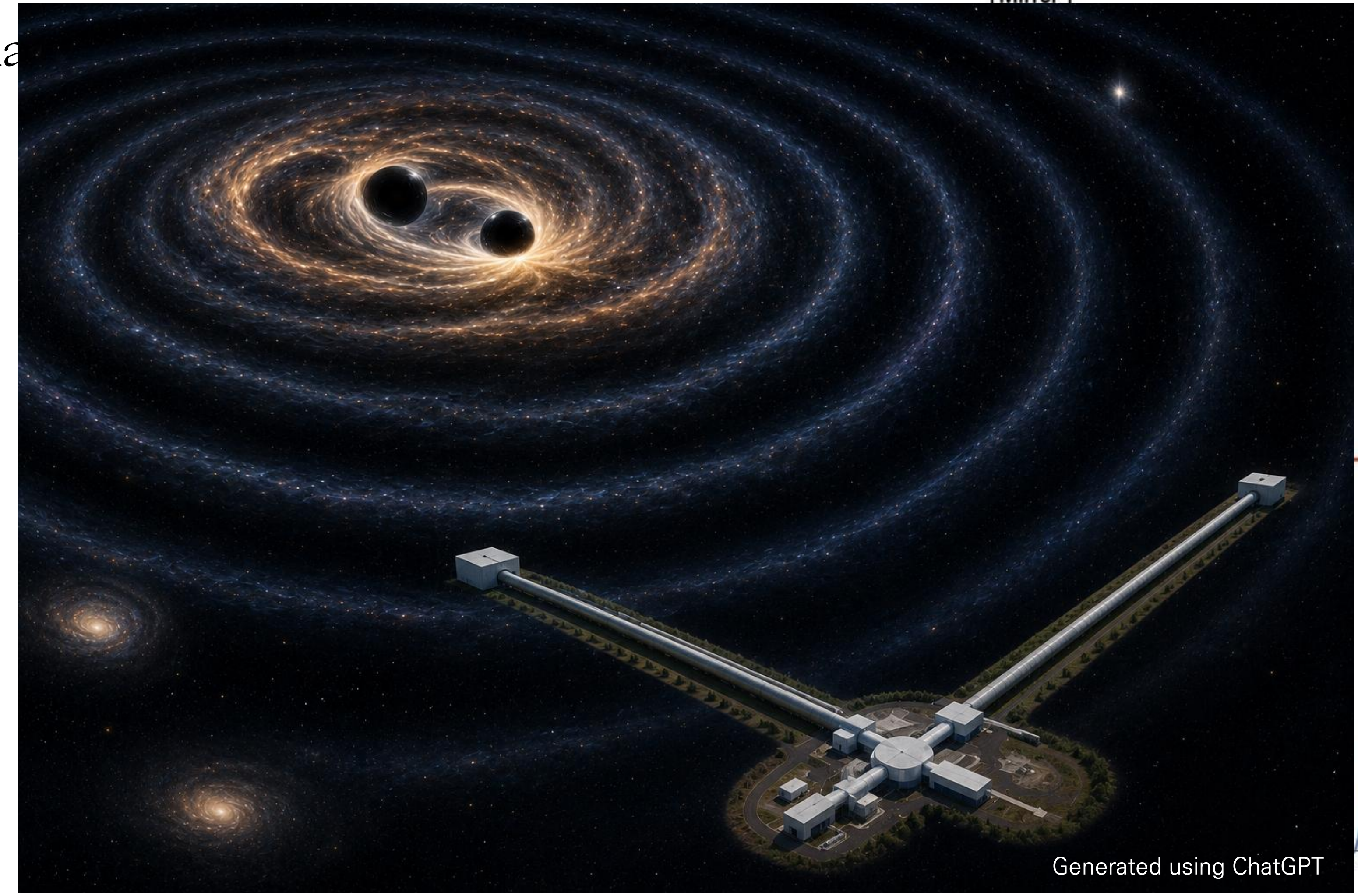


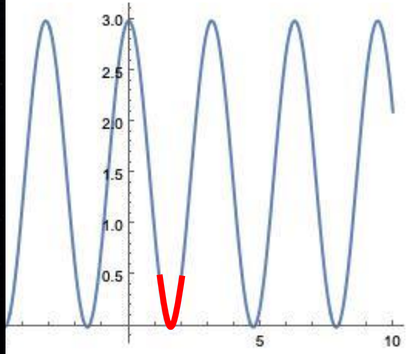
(LV Collaboration+16)

Gravitational wave detector

- Gravitationa
- ΔL
- $\Delta\varphi$
- P_{out}

Mirror





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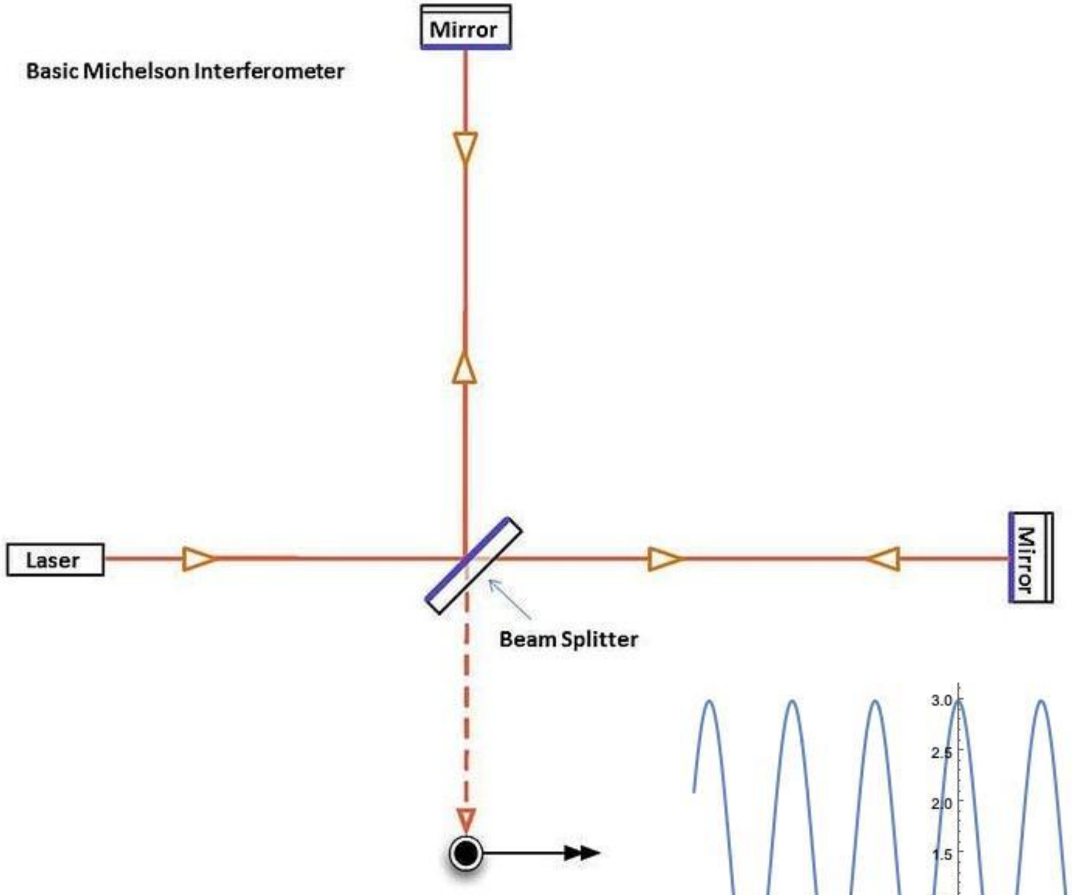
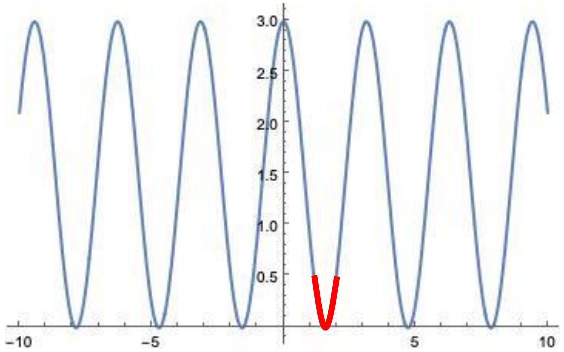
Gravitational wave detector

- Gravitational wave (strain, h) ~ 10^{-21}
- $\Delta L \sim hL$
- $\Delta\varphi$
- P_{out}





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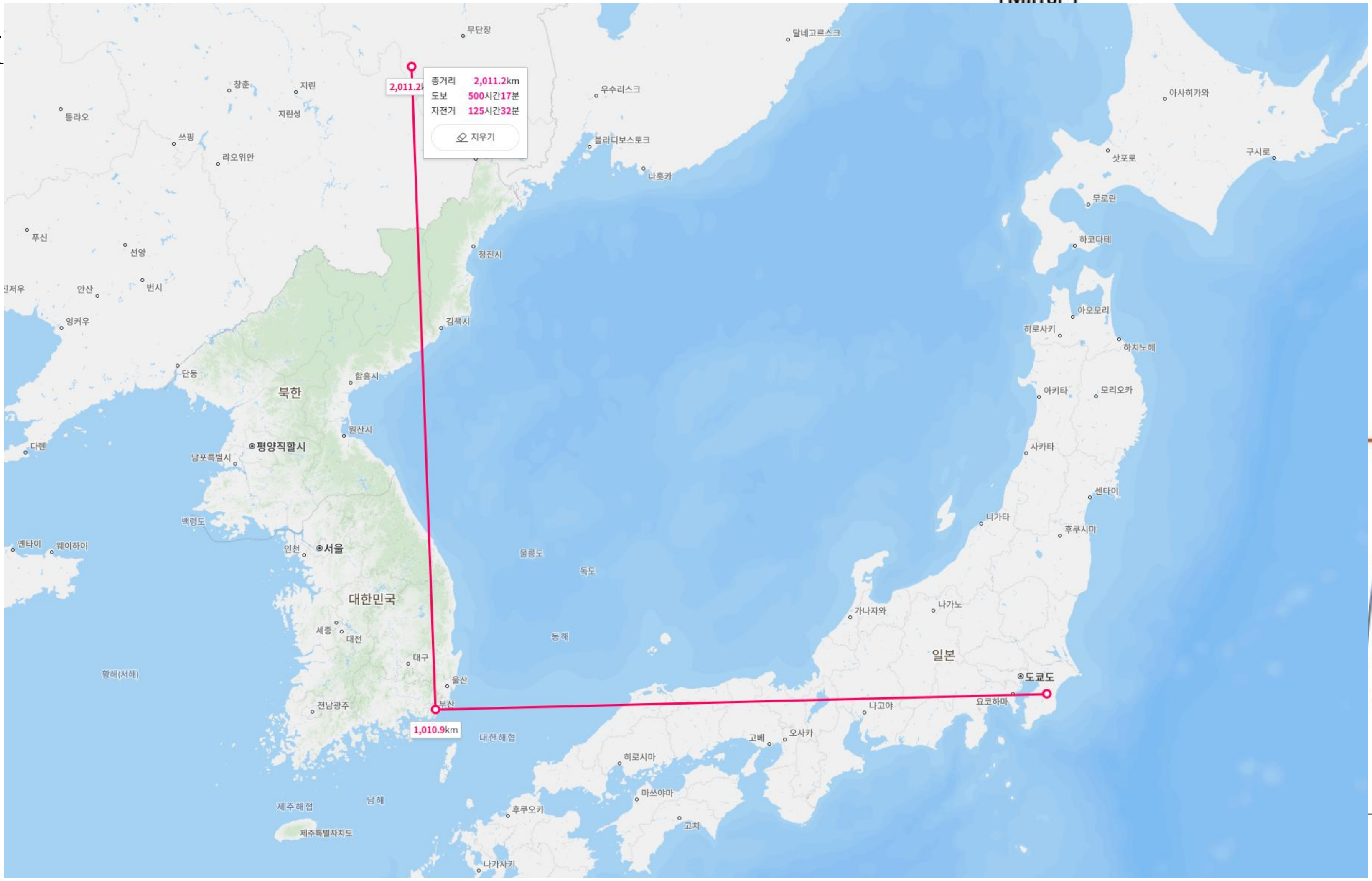

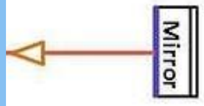

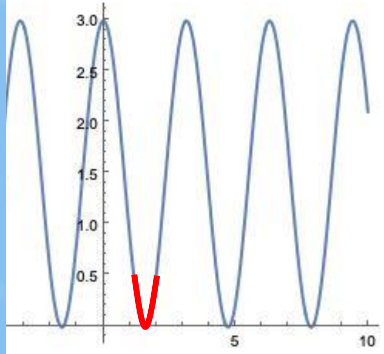

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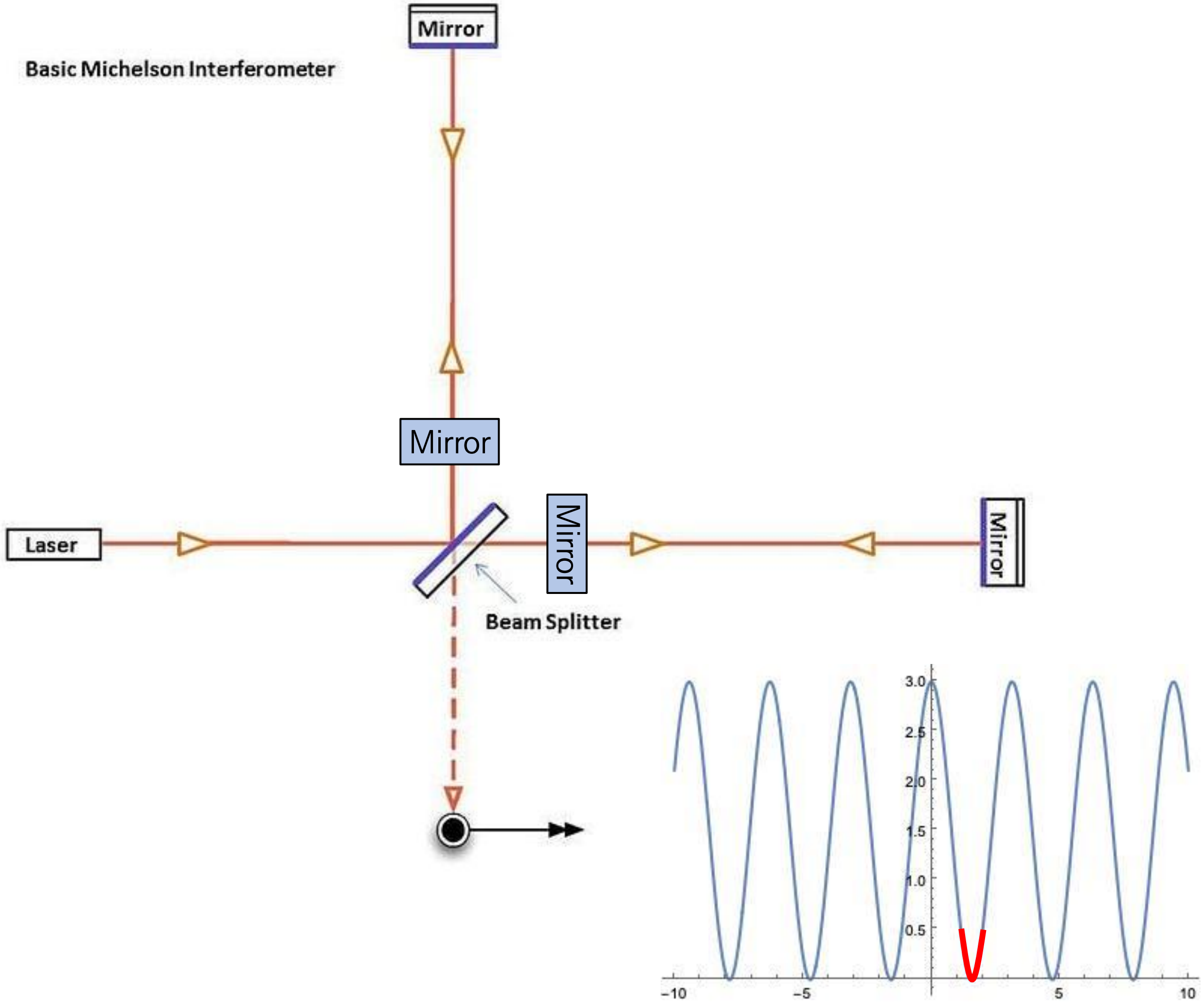
Cavity

- Gravitational wave (strain) ~ 10^{-21}
- $\Delta L \sim hL$
- $\Delta\varphi$
- P_{out}



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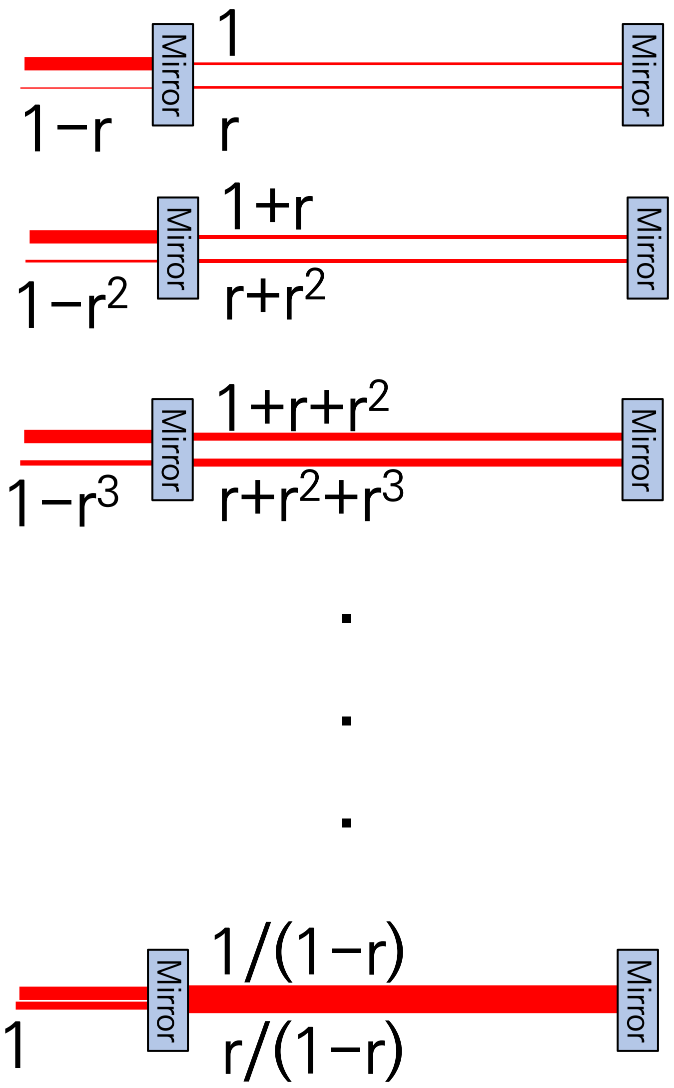
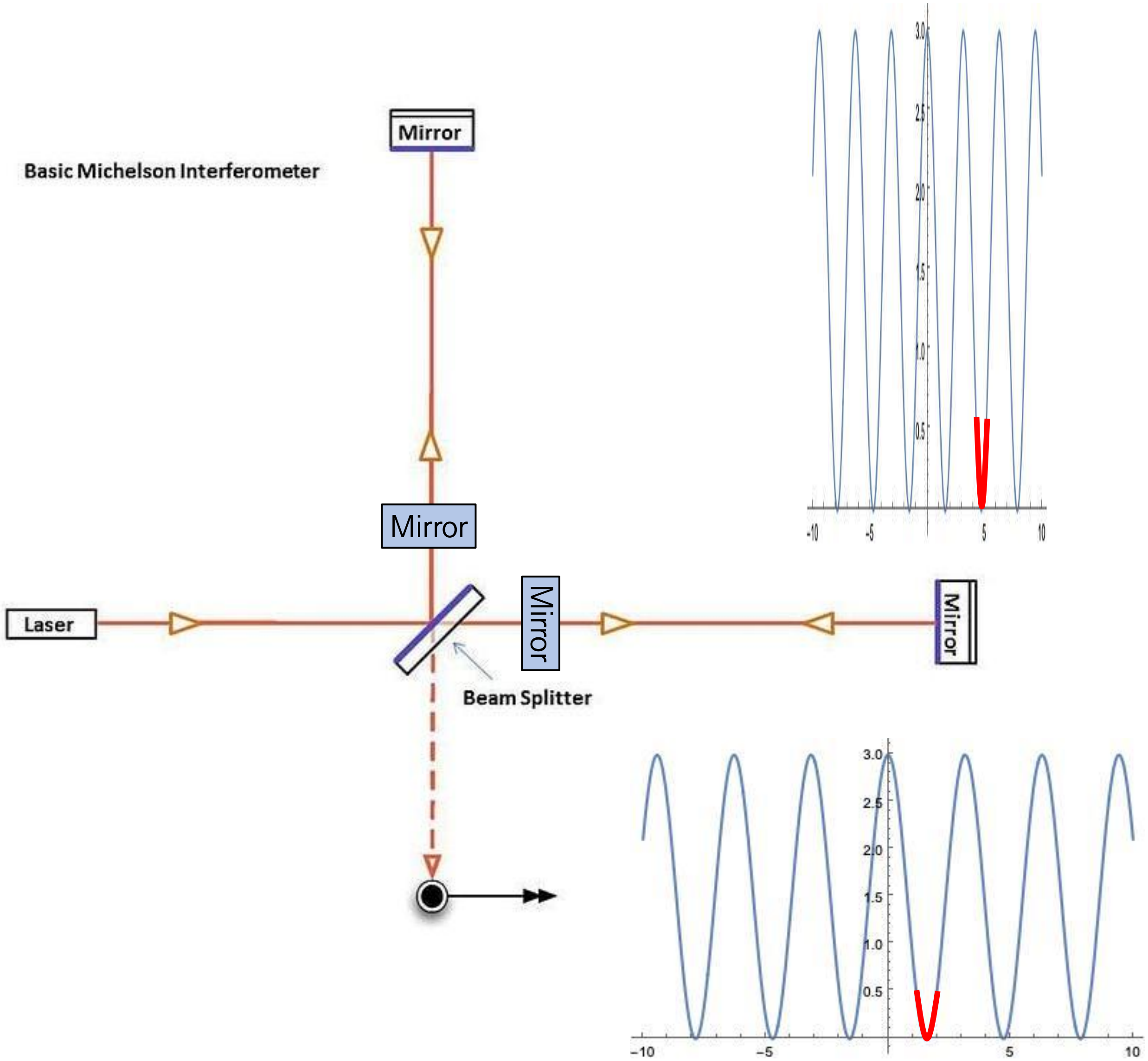


Cavity

- Gravitational wave (strain) ~ 10^{-21}
- ΔL : Cavity (4 km → 1200 km)
- $\Delta\varphi = \Delta L/\lambda$: Wavelength?
- $P_{\text{out}} = P_0 \cos^2(\Delta\varphi/2)$: Power?



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01 Introduction

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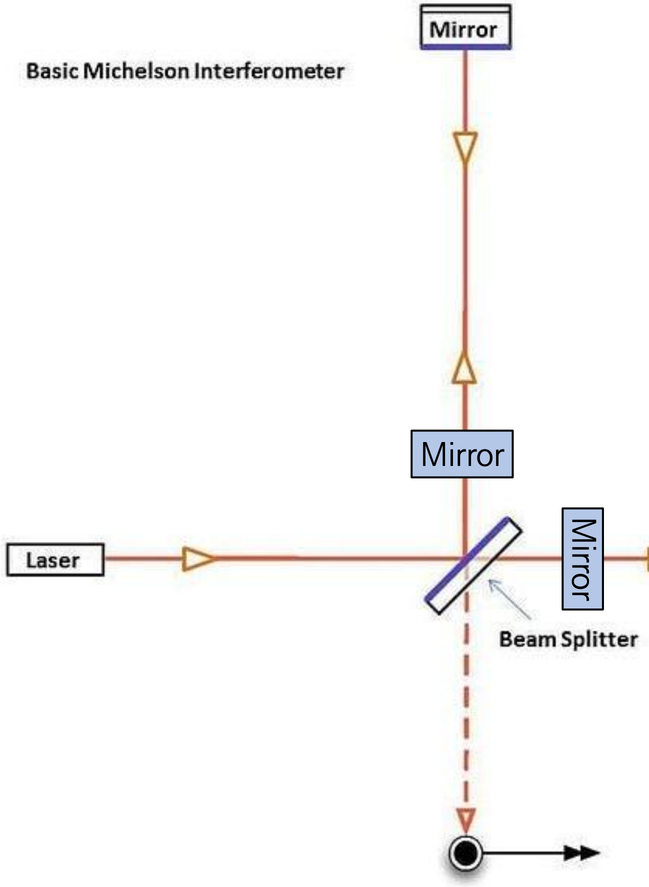

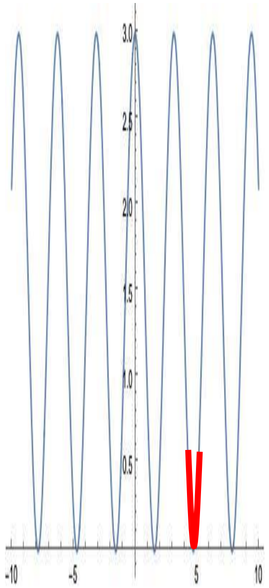

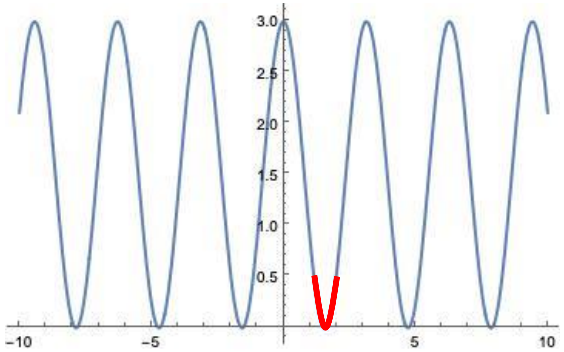

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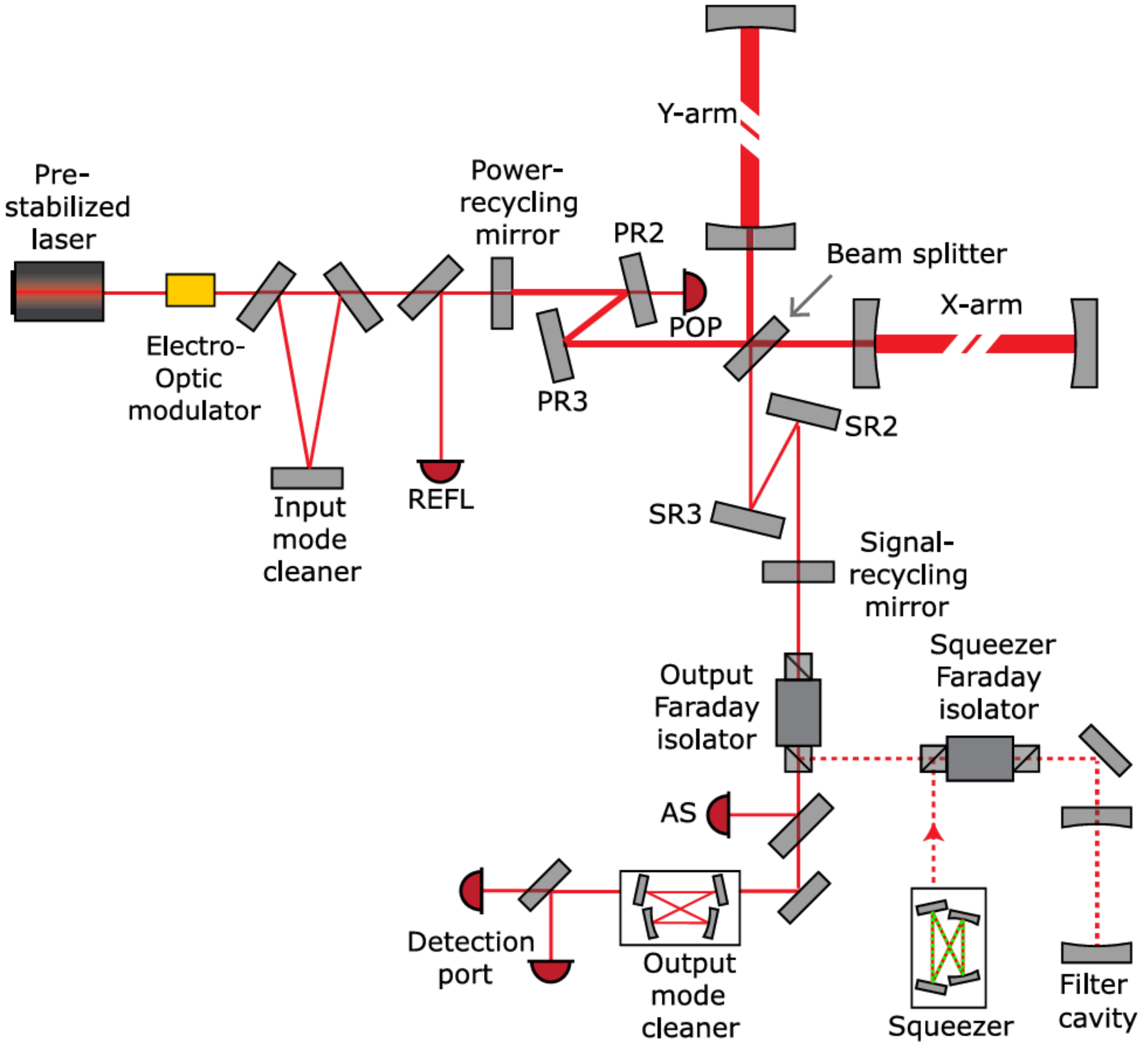
Gravitational wave detector

- So many other factors make the situation confusing…

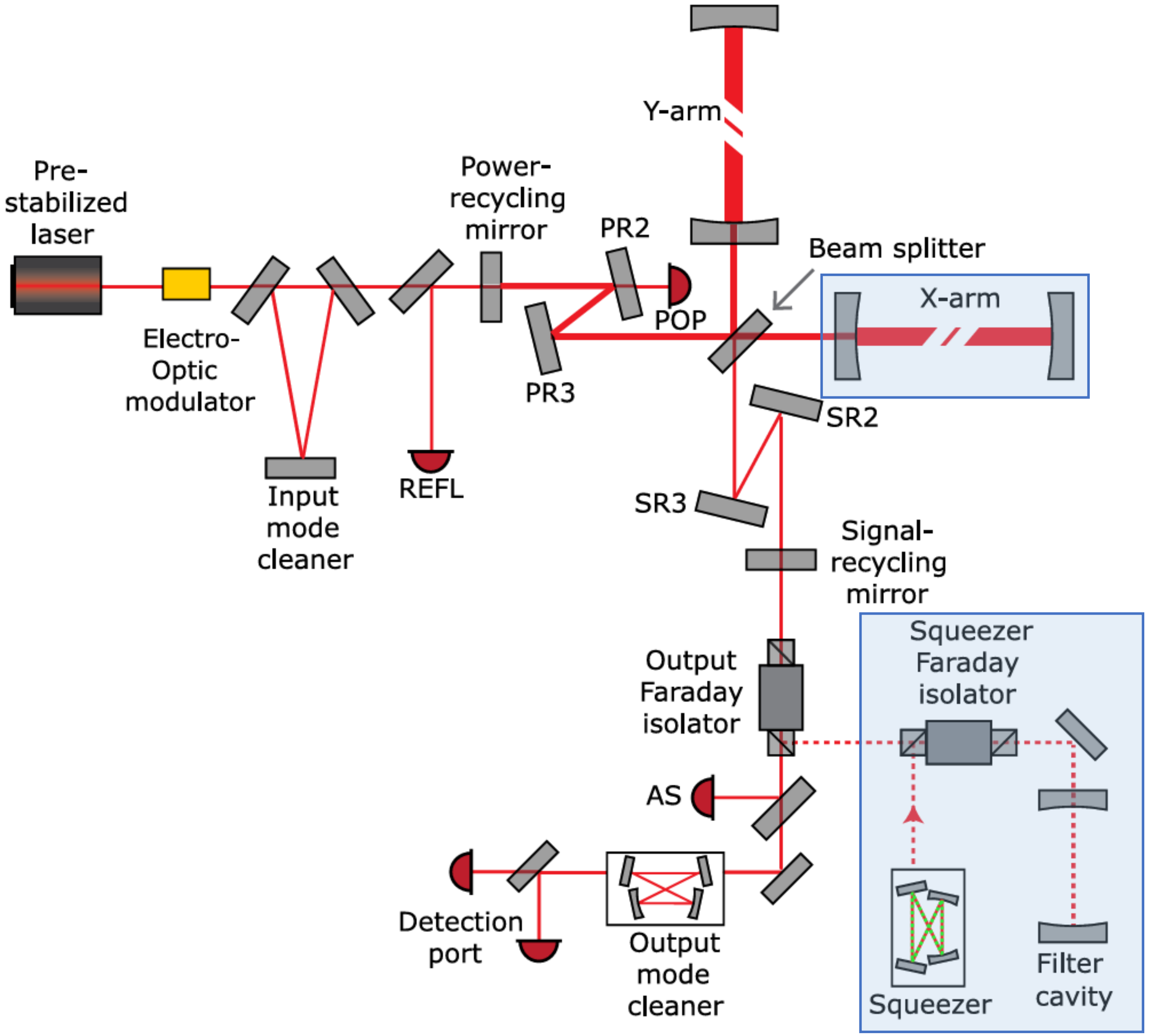
- Earthquake
- Laser power and frequency fluctuation
- Beam jitter
- Stray light
- Thermal lensing
- …



(Capote+25)

Gravitational wave detector

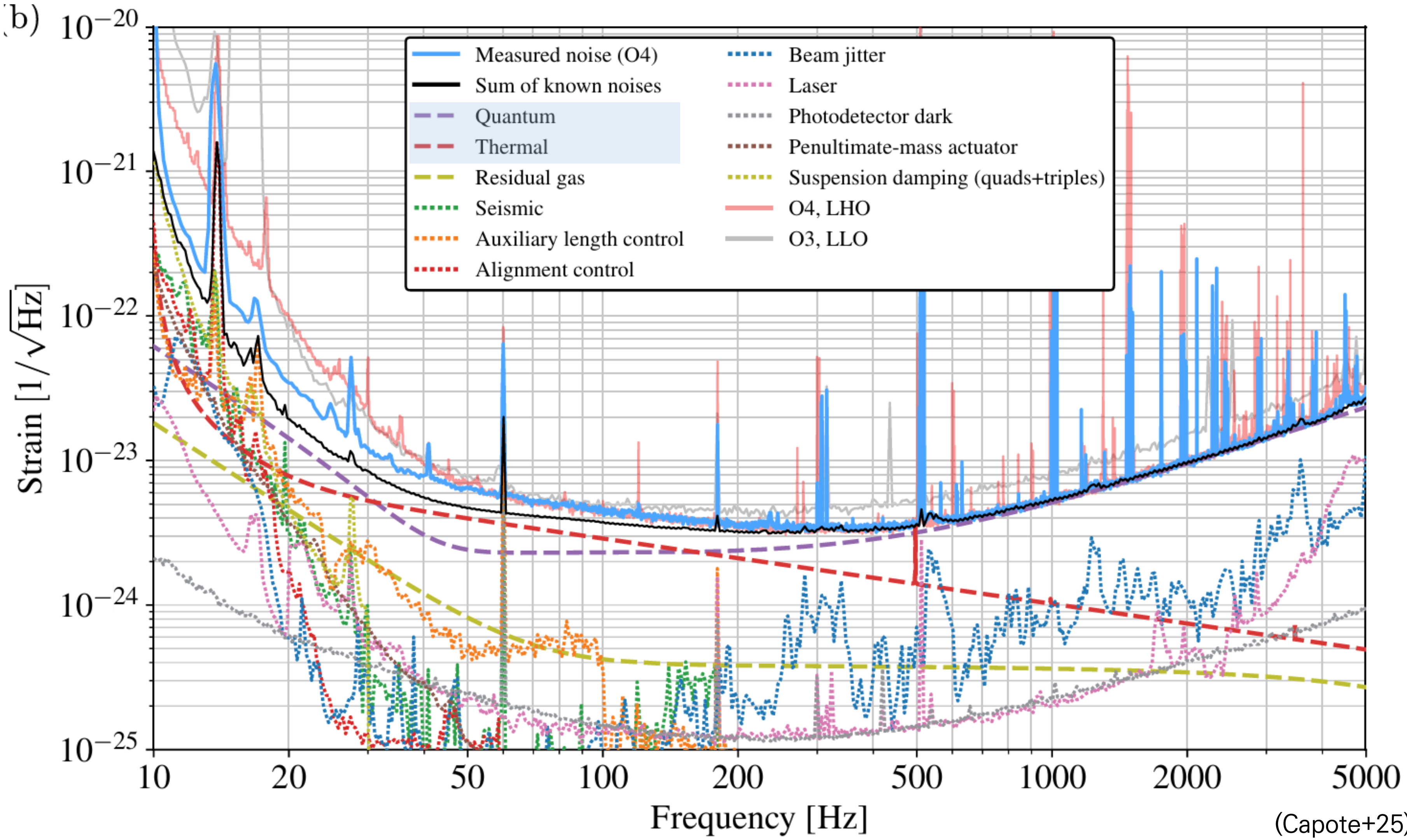
- We are still upgrade the detector to reduce noise and improve sensitivity.
- Especially, Korean researchers are focusing on …
  - Squeezing (KASI, Yonsei, KHU, KAIST)
  - Test mass (SKKU, Yonsei, KASI)
  - Data reduction/denoising (NIMS, UNIST, KASI, CNU)



(Capote+25)

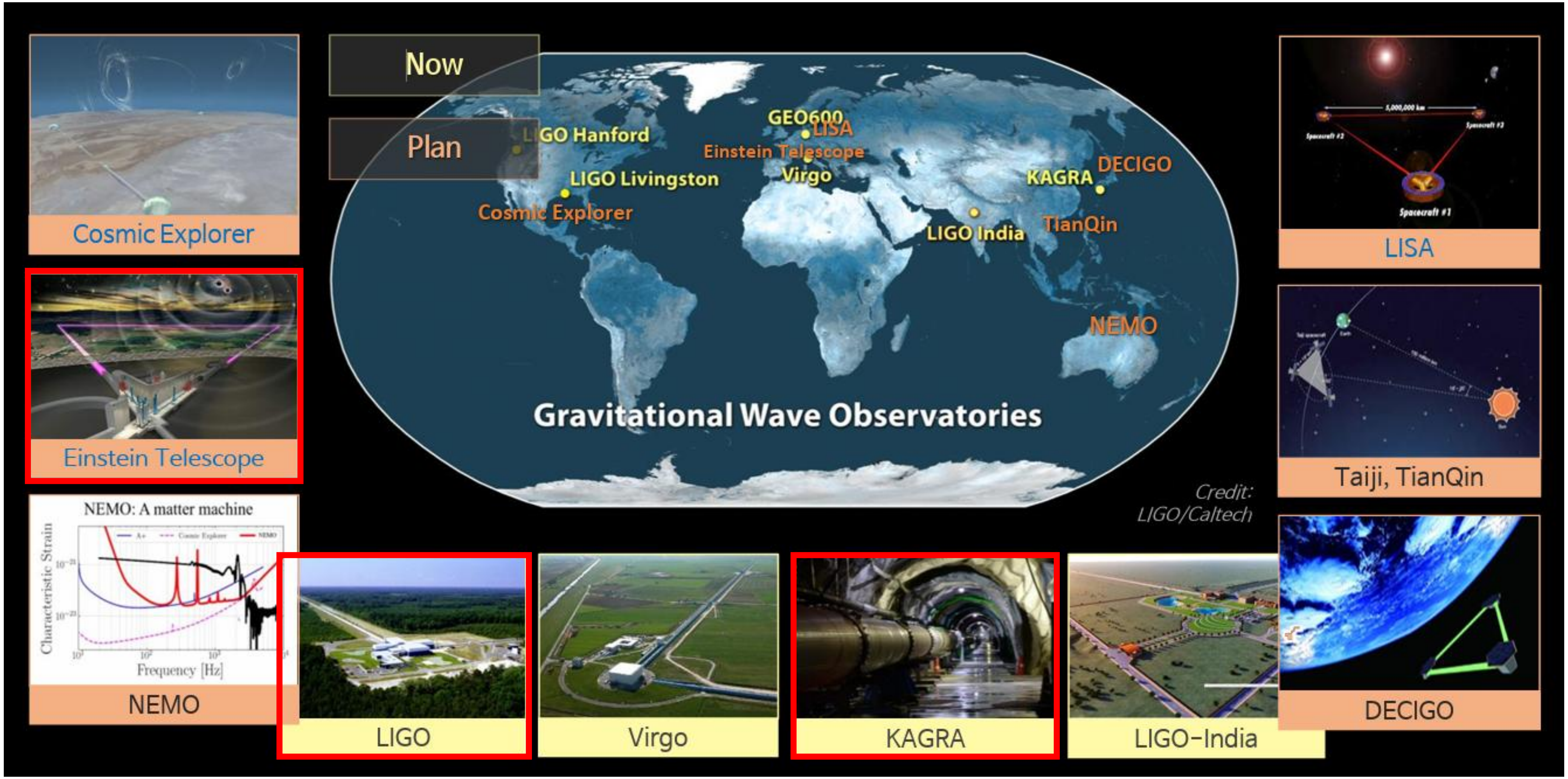
Noise of GWD (LLO, O4)

- Quantum noise → squeezing
- Thermal noise → Test mass coating



(Capote+25)

Worldwide GWDs



02

Quantum noise reduction

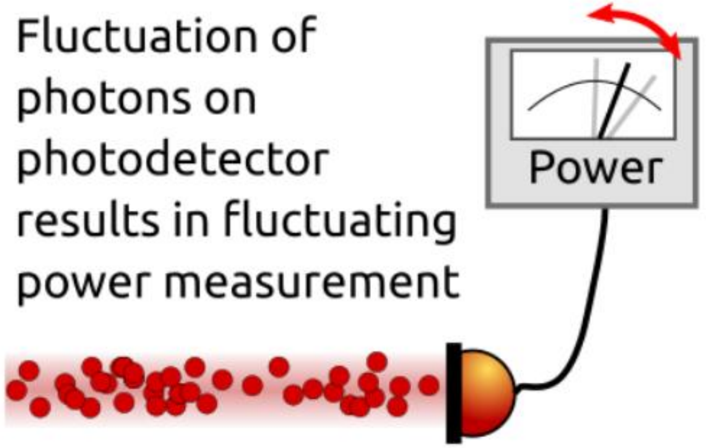
Shot noise

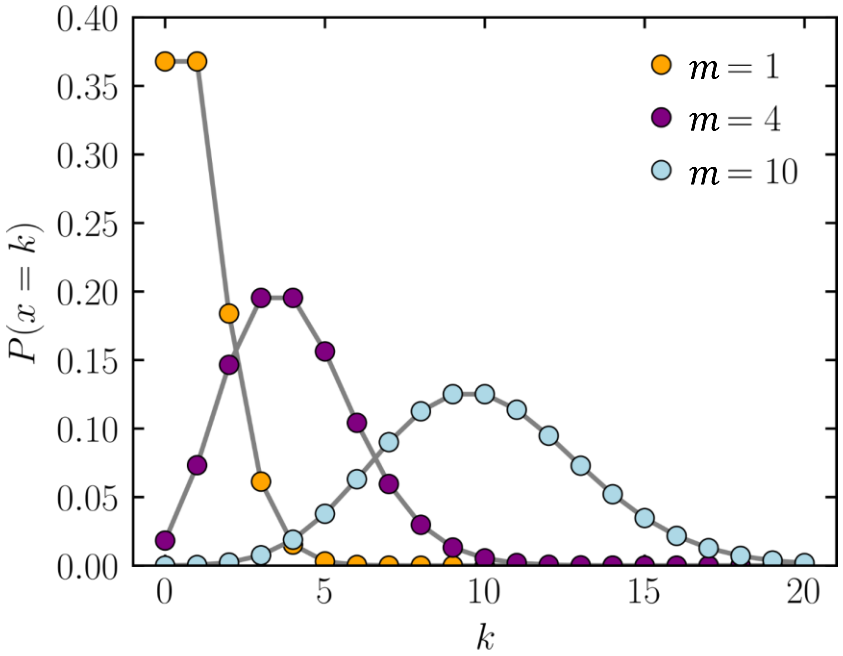
- The arrival time of a photon is characterized by the Poisson probability distribution:

$$p(k) = \frac{m^k e^{-m}}{k!}$$

- For GWD,

$$h_{shot} \propto \frac{1}{L}\sqrt{\frac{1}{P_{in}}}$$





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https://en.wikipedia.org/wiki/Poisson_distribution

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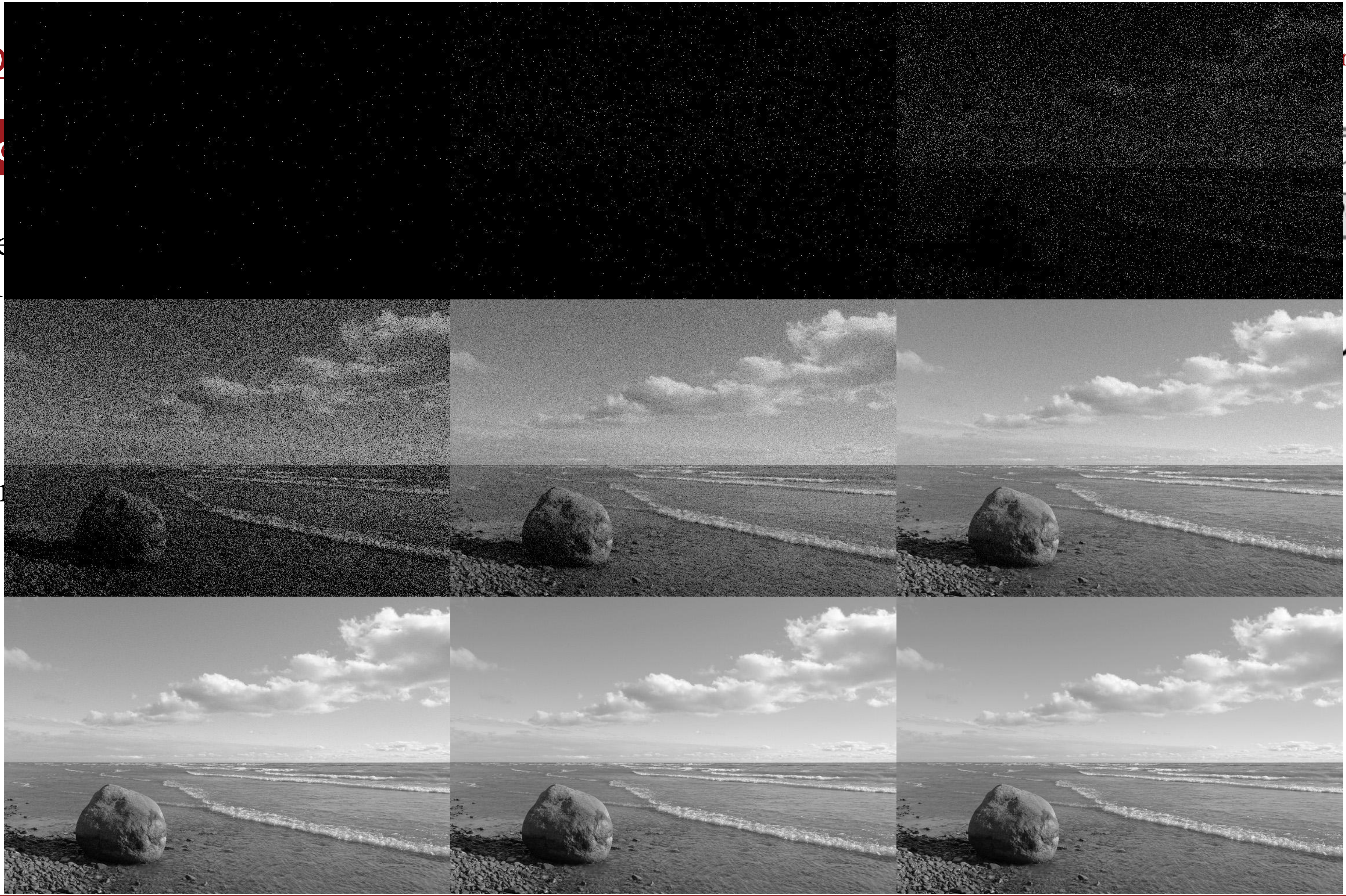

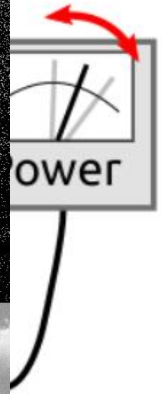

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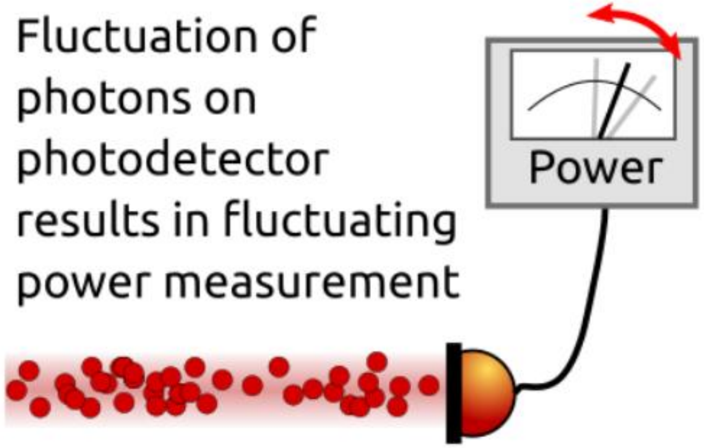
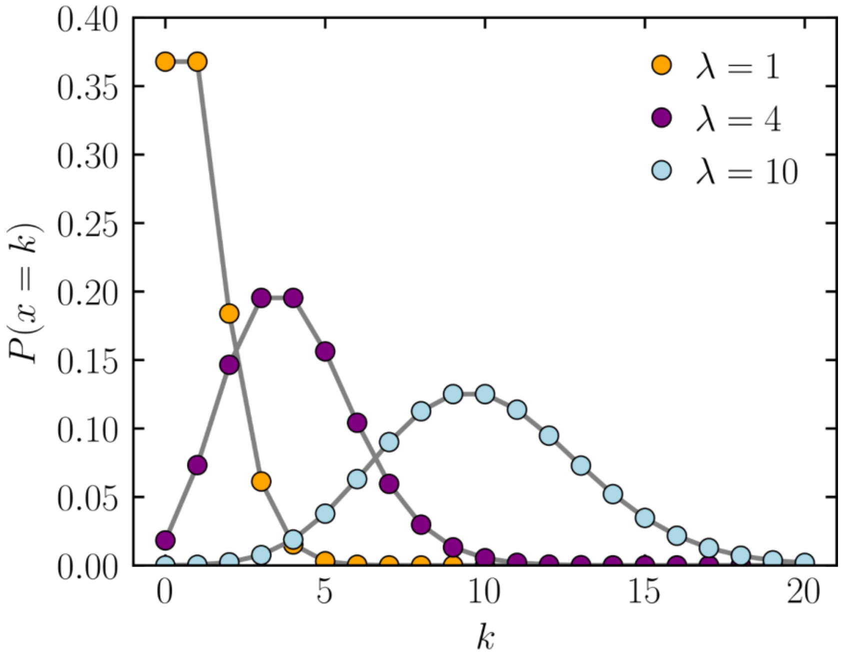




https://10m.aei.mpg.de/standard-quantum-limit-sql/
https://en.wikipedia.org/wiki/Poisson_distribution

Radiation pressure noise

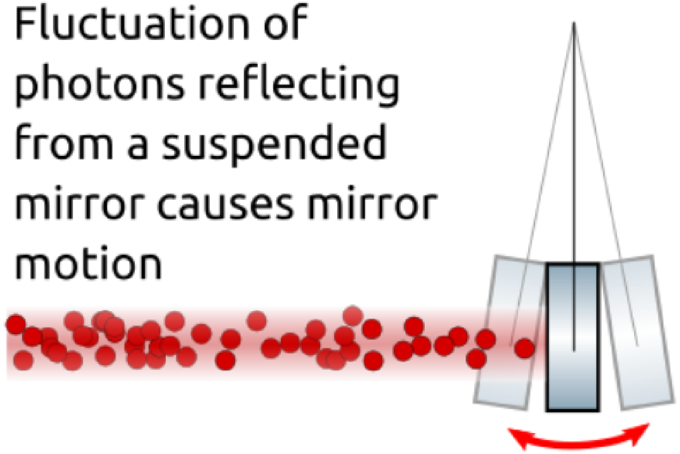
- Laser (photon) exerts force to test mass via momentum transfer.

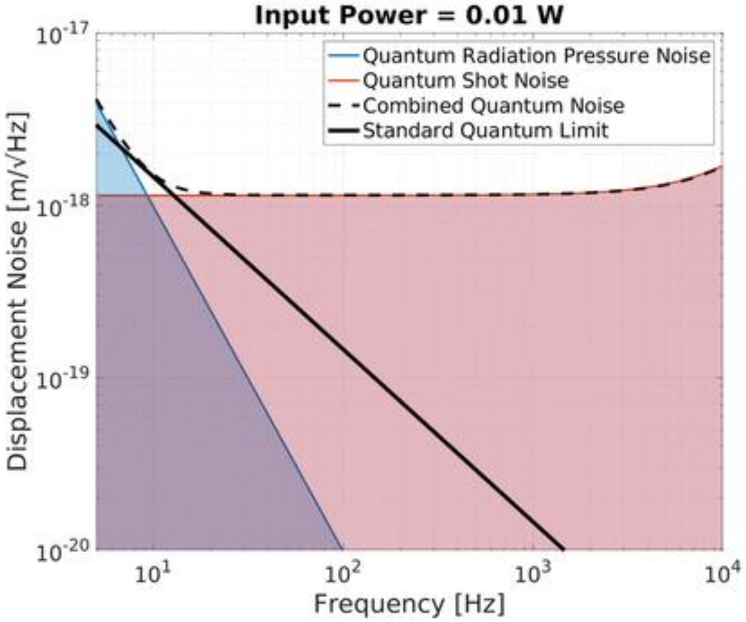
$$F = \sqrt{\frac{2\pi\hbar P_{in}}{c\lambda}}$$

- For GWD,

$$h_{rp} \propto \frac{1}{Mf^2L}\sqrt{\frac{P_{in}}{\lambda}}$$

Fluctuation of photons reflecting from a suspended mirror causes mirror motion





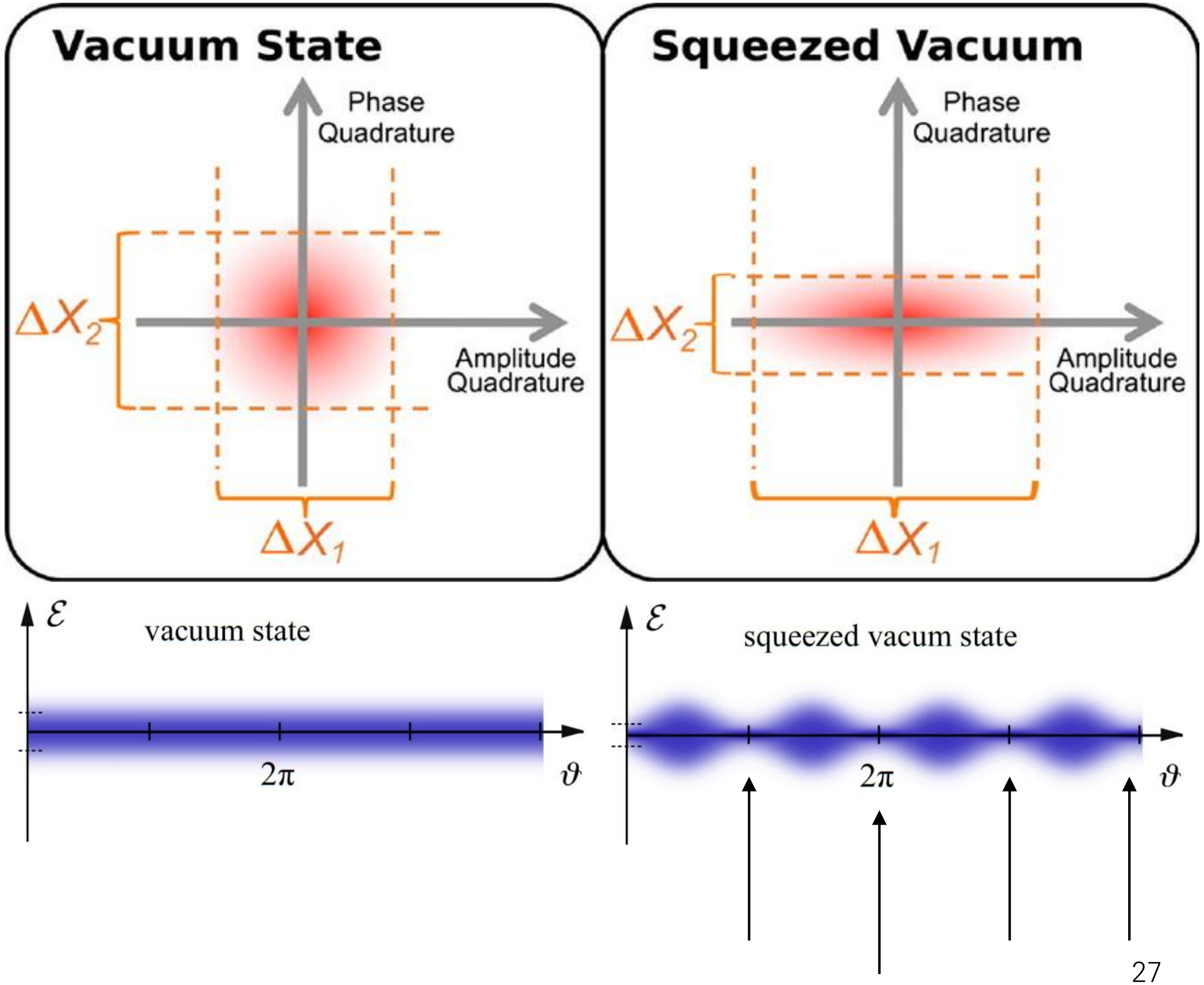
https://10m.aei.mpg.de/standard-quantum-limit-sql/

Squeezing

- Field is described by amplitude & phase.

- By uncertainty principle,
$$\Delta^2 A\, \Delta^2 \varphi \geq 1/16$$

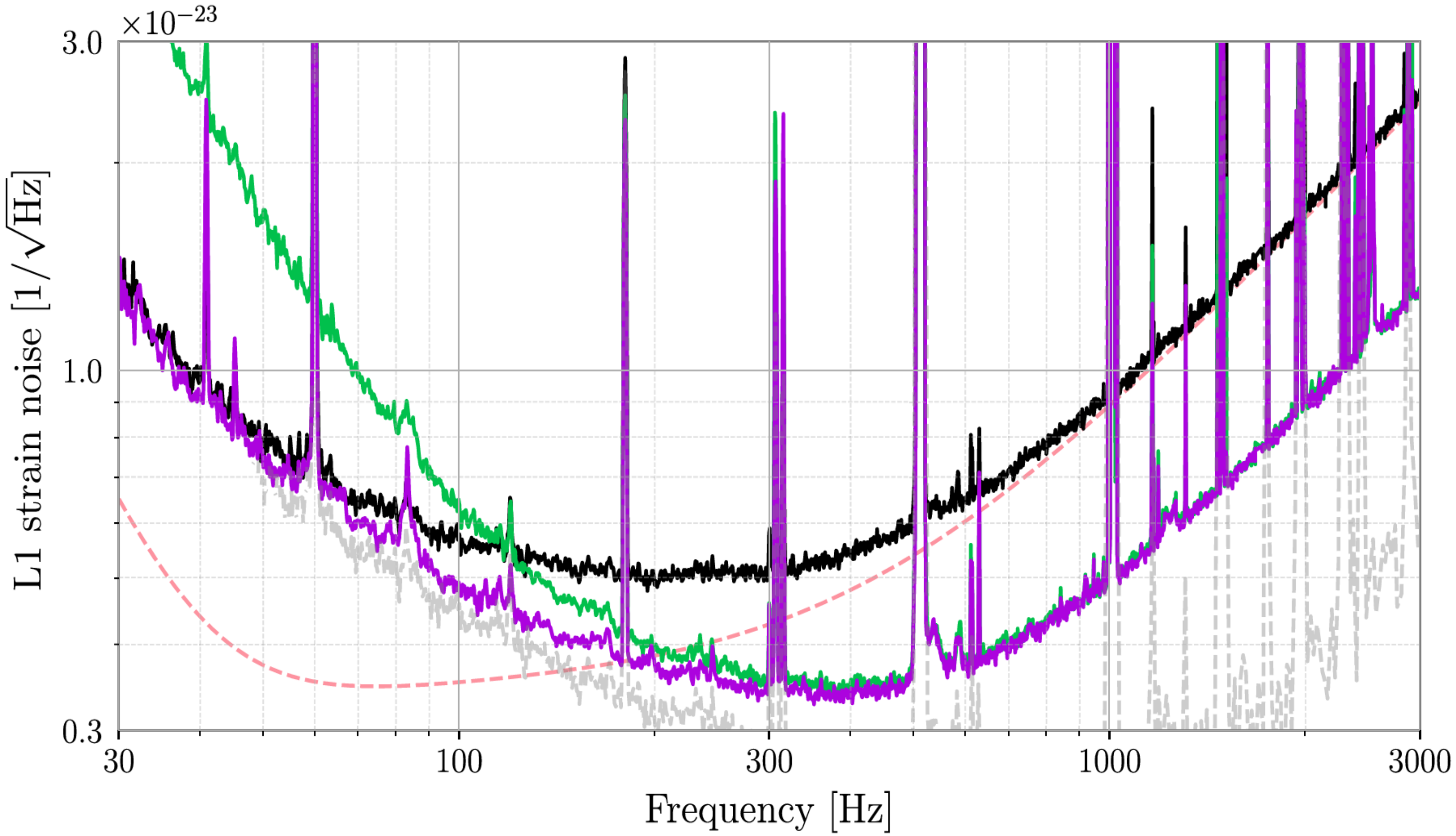
- For classical vacuum state,
$$\Delta^2 A = \Delta^2 \varphi = 1/4$$



https://en.wikipedia.org/wiki/Squeezed_states_of_light

Squeezing

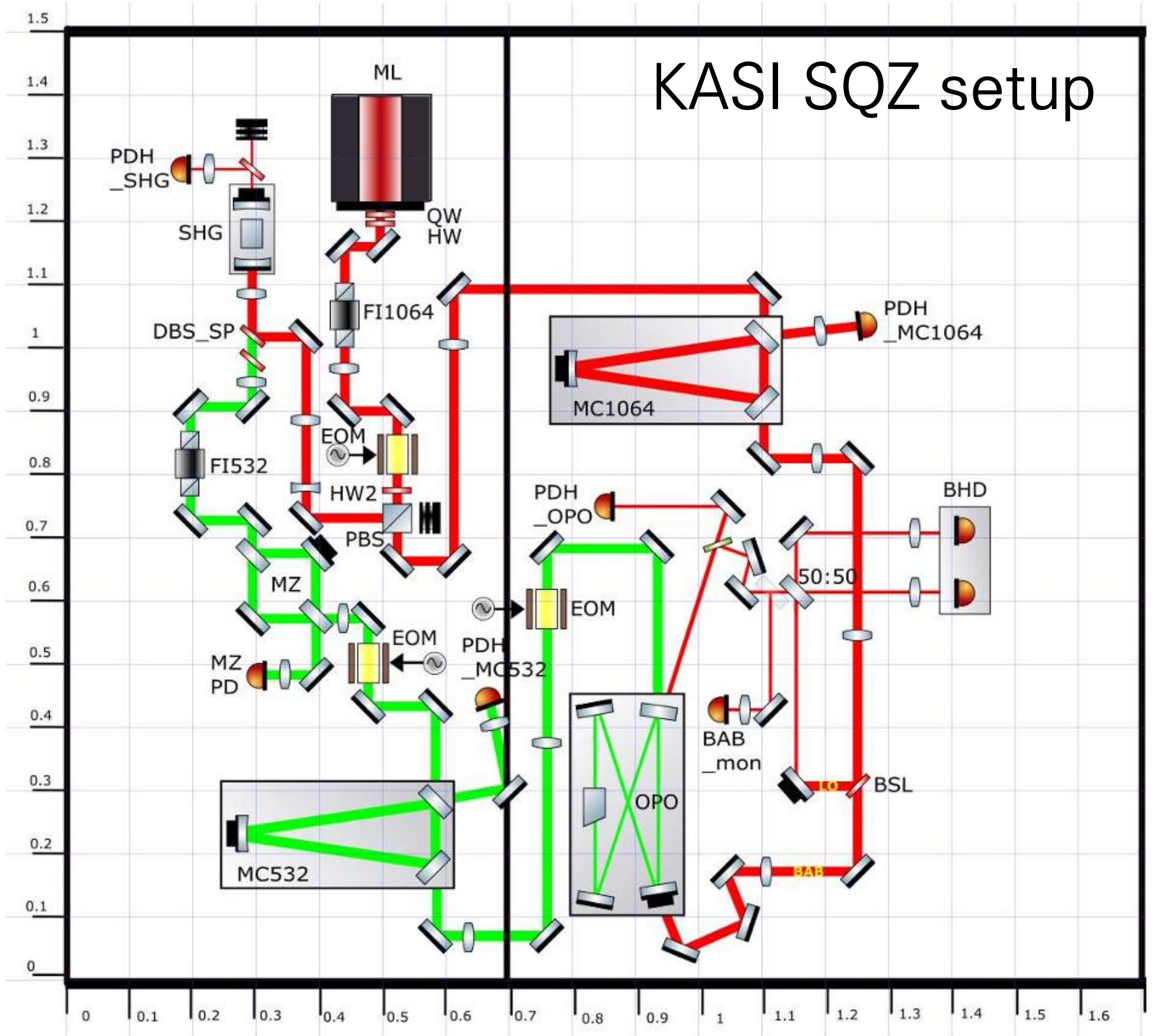
- Successfully implemented in the detectors!

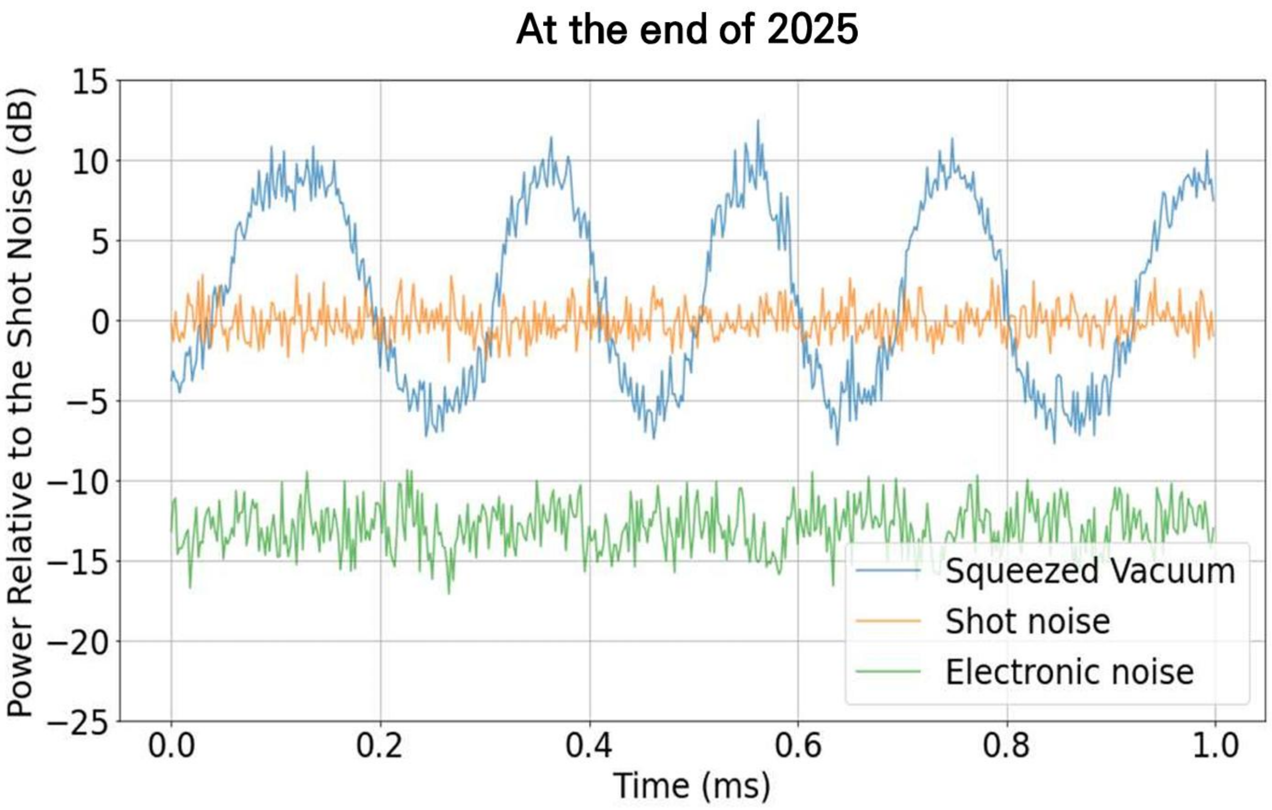


(Ganapathy+23)

02 Quantum noise reduction

1064nm/1550nm Squeezer



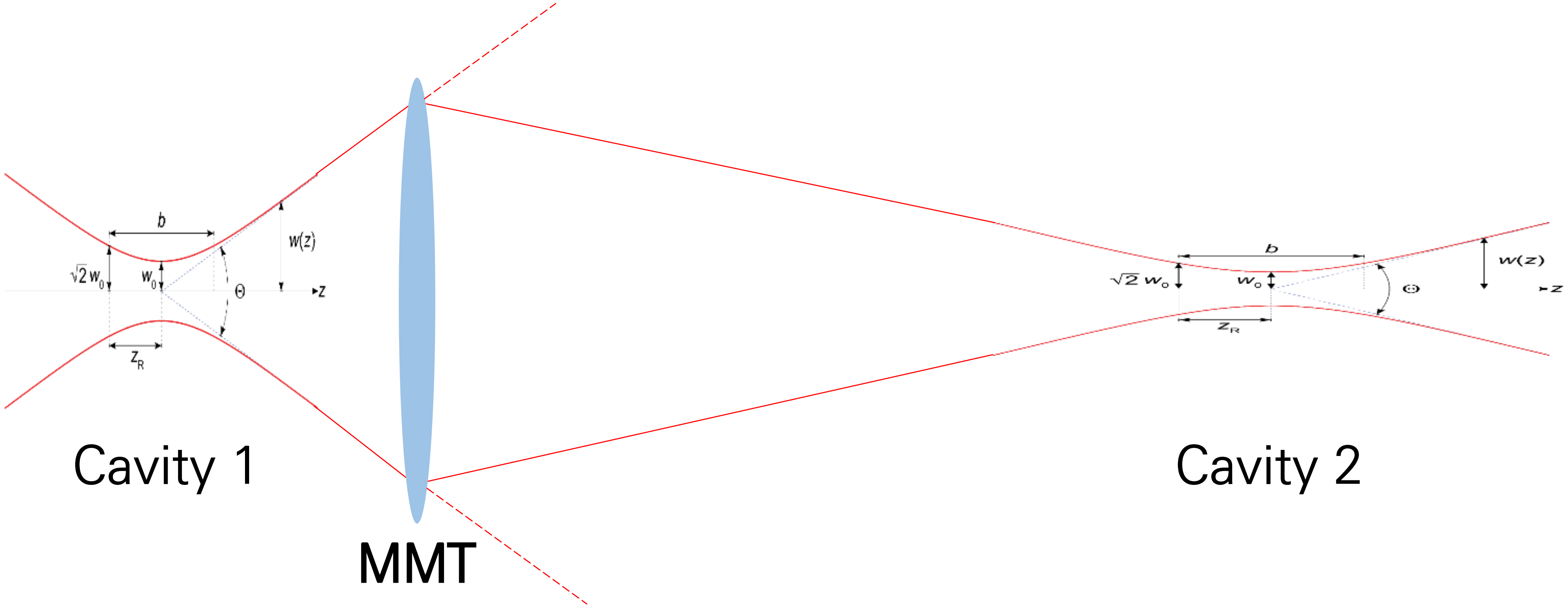


6.2 dB (0.25 in linear scale) squeezing!

Mode-matching telescope

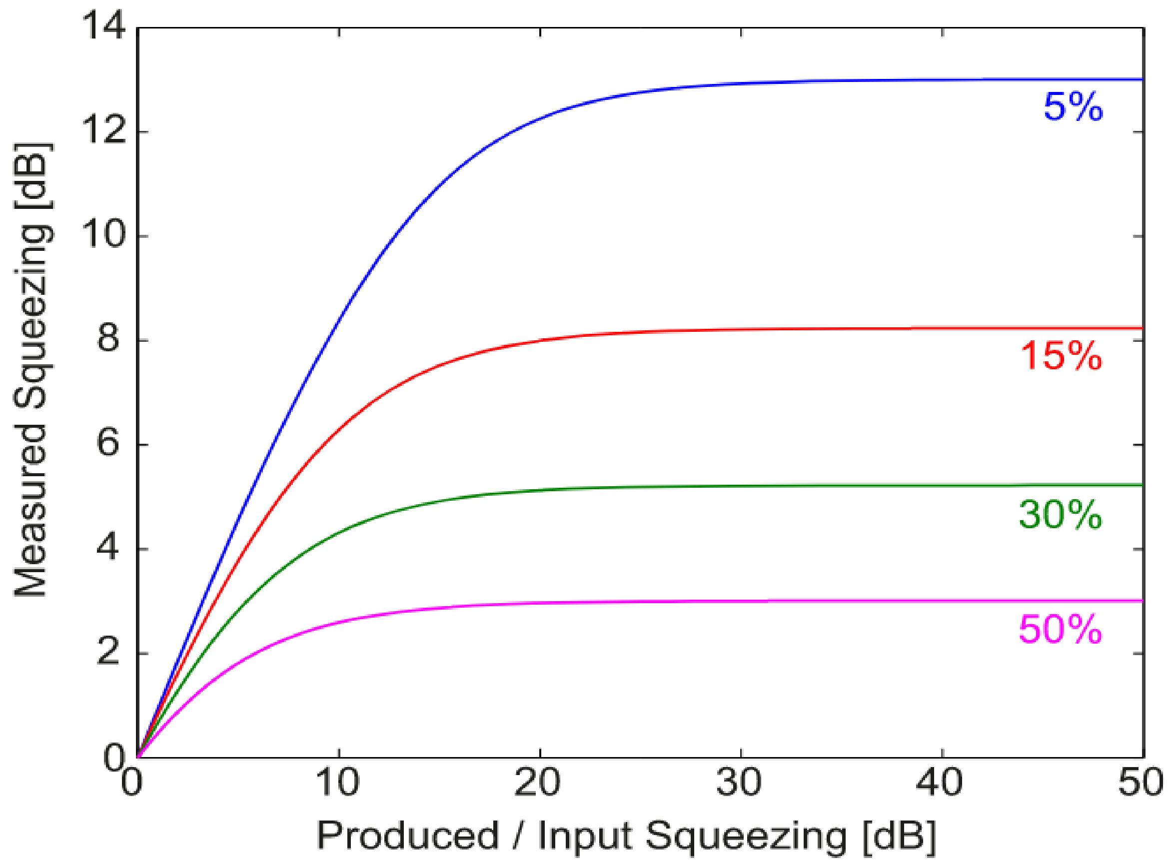
GWD comprises many optical cavities which have different eigenmodes.

Mode-matching telescope (MMT) converts the modes from one cavity to another cavity.



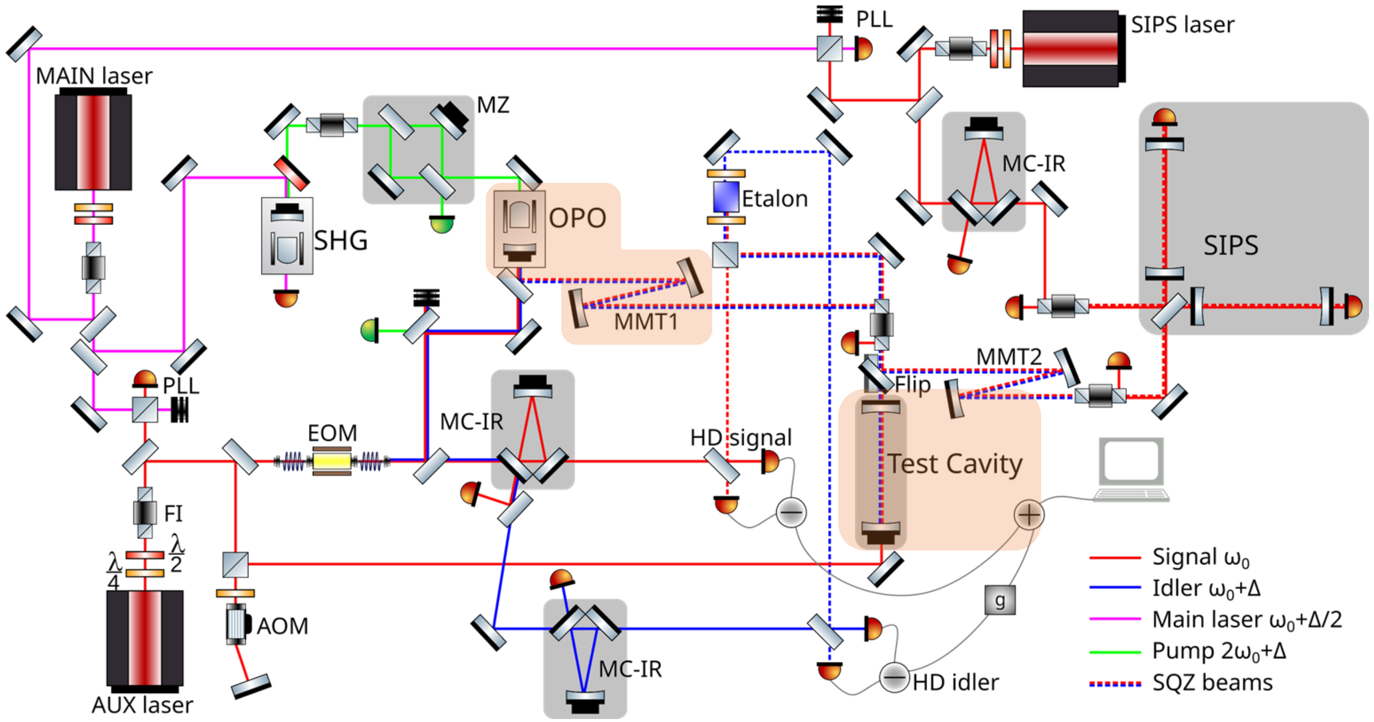
Sensitivity of GWD

- Quantum squeezed state is sensitive to mode mismatch, thus mode-matching become more important to 2nd and 3rd generation GWDs.

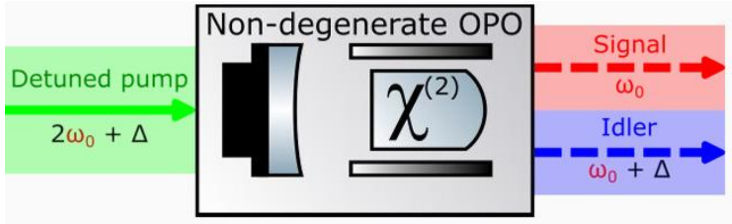


(Chua+14)

EPR-SIPS experiment



1. Signal and idler are squeezed vacuum, EPR-entangled and detuned by Δ.

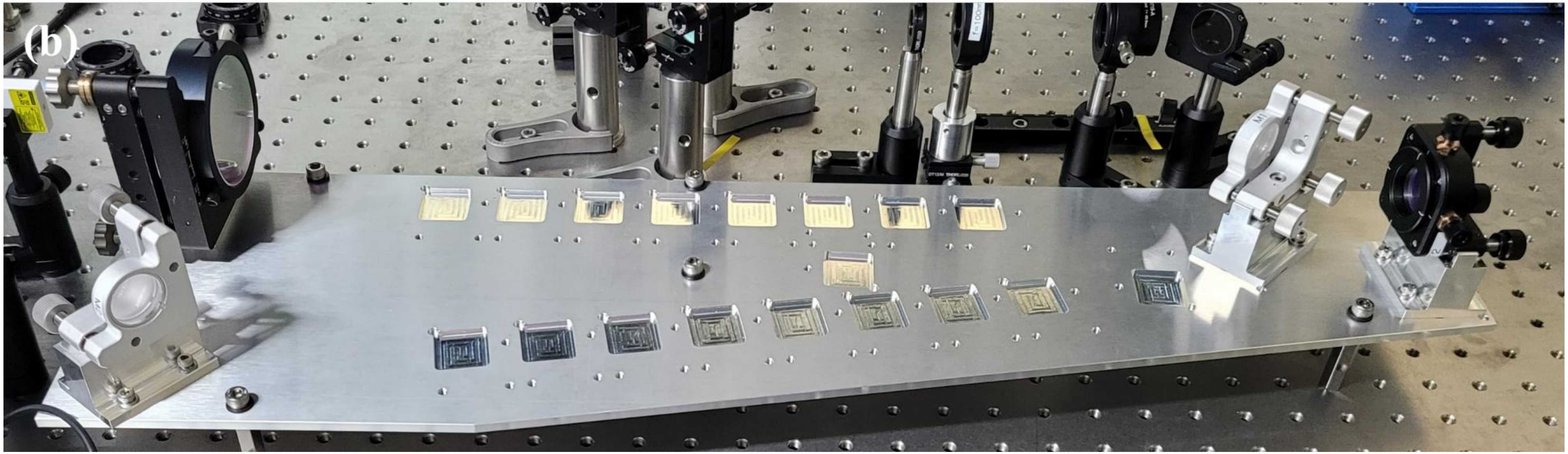


2. The idler sees the interferometer as a filter cavity and acquires frequency-dependence.

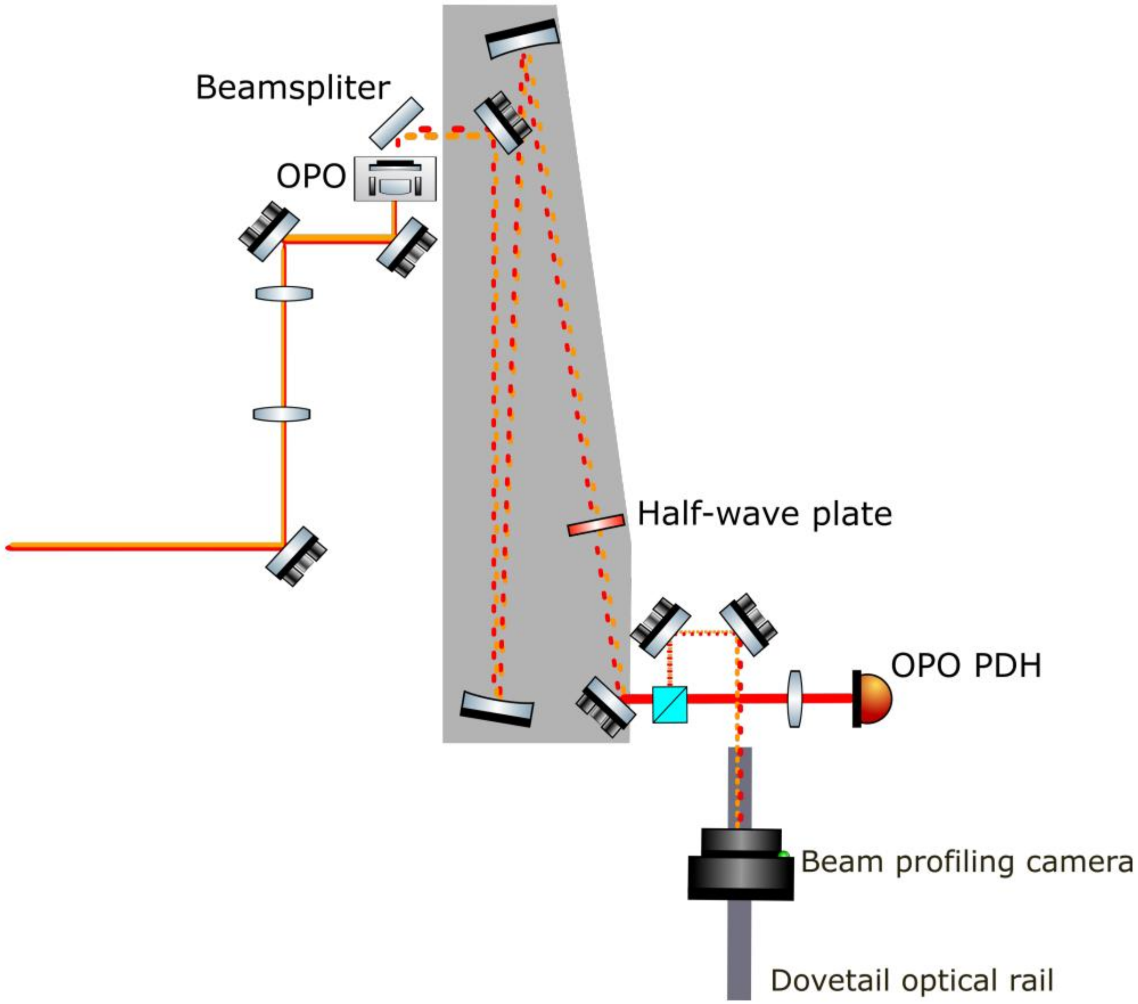
3. Combined measurement transfers the frequency dependent transfers the frequency dependence to the signal via EPR entanglement.

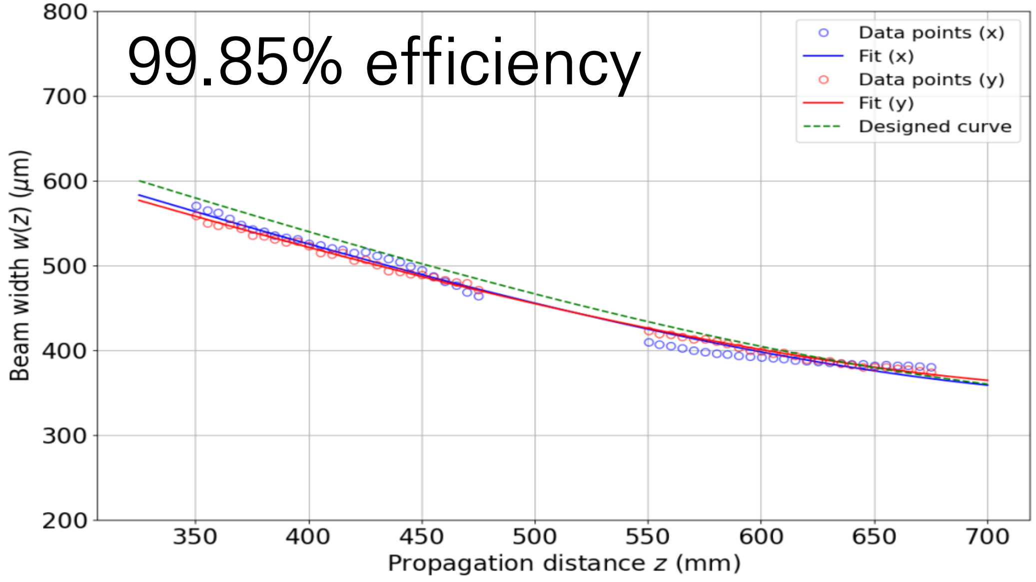
MMT-1 (OPO ↔ TC)

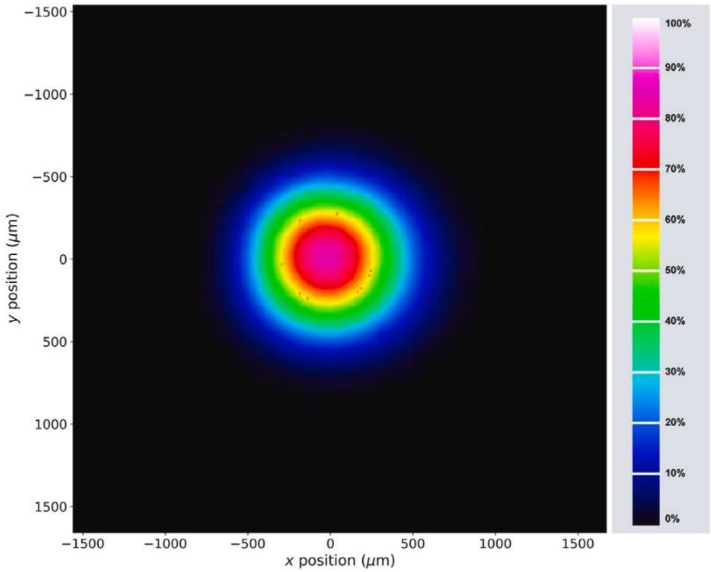
- $W_{0,in}$ = 36 micron, $w_{0,out}$ = 407 um → Magnification = 11.3
- Fast and robust alignment using kinematic mounting



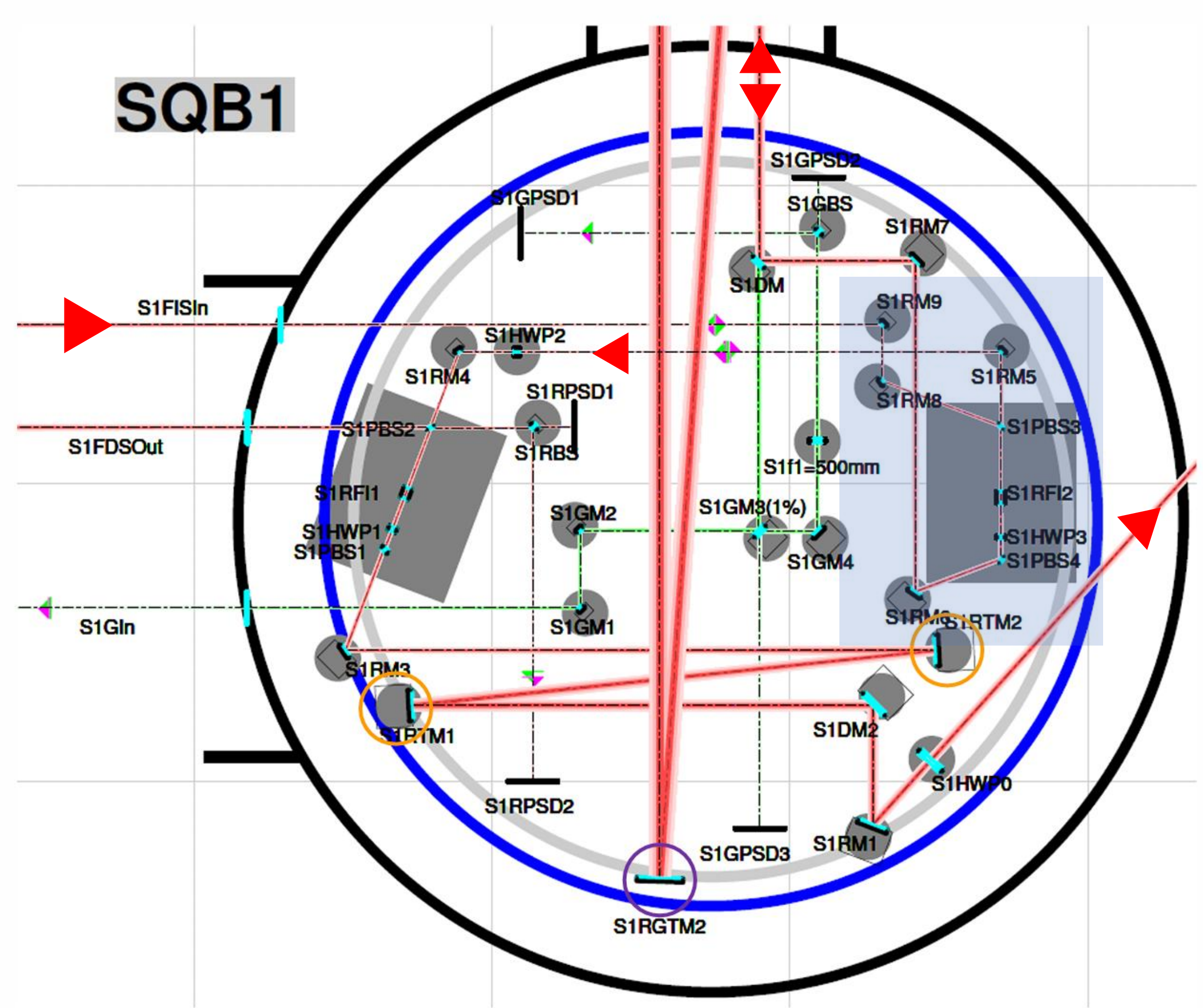
Performance test

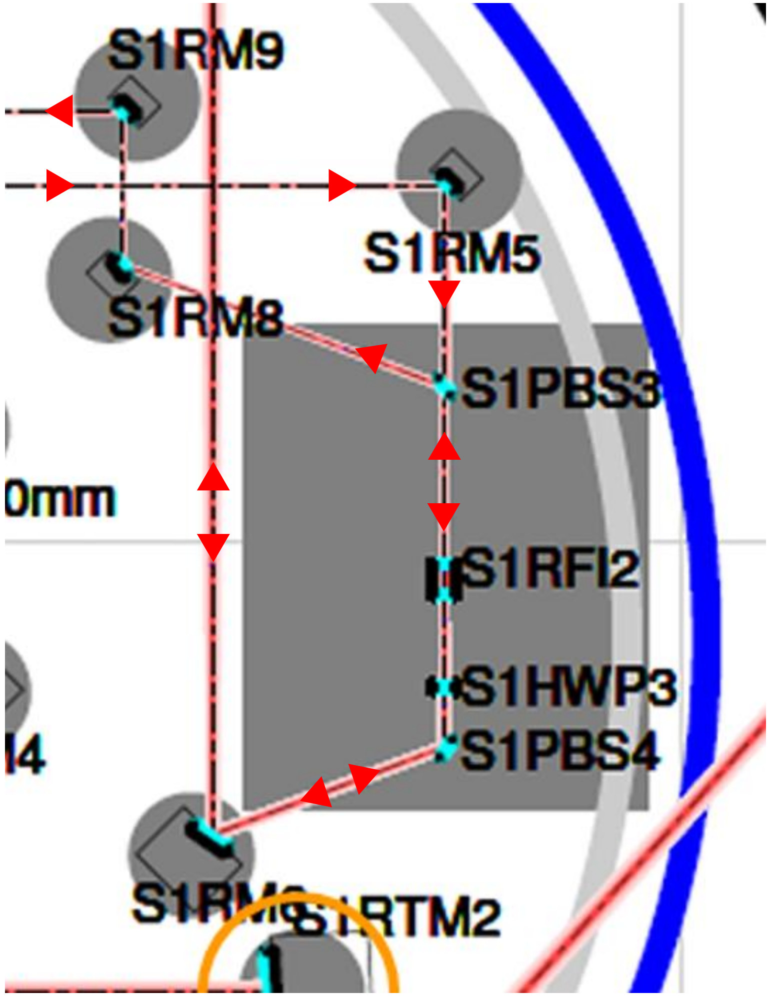






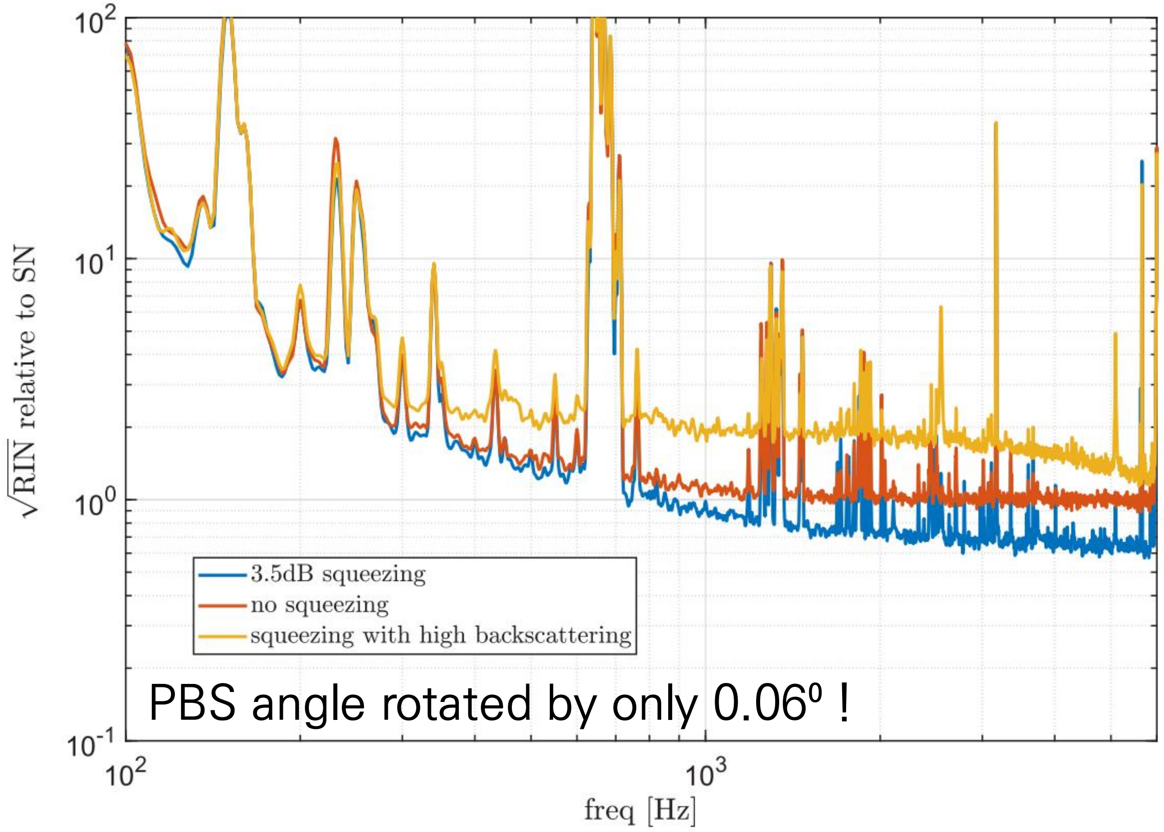
Faraday isolator





Faraday isolator

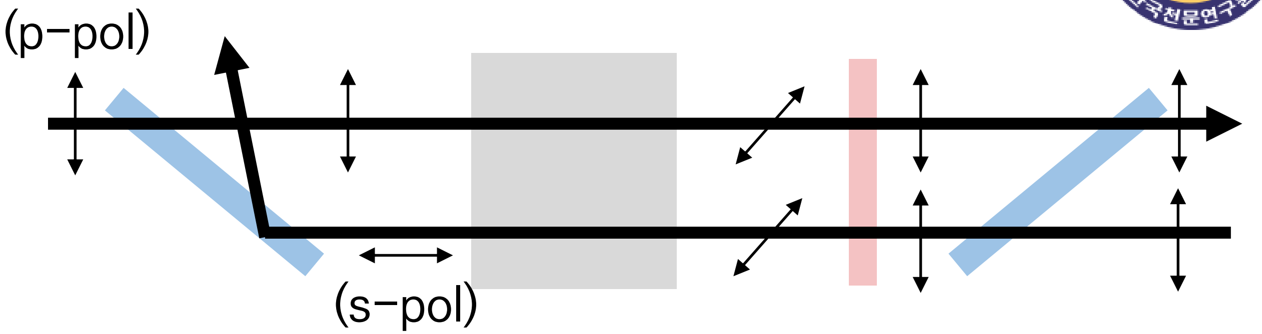
- Faraday isolator allows light to travel in one direction.
- Isolators are used to protect a source from back reflections or signals that may occur after the isolator.
- Mitigation of back-reflection is especially important in squeezing experiment.



(Bergamin+23)

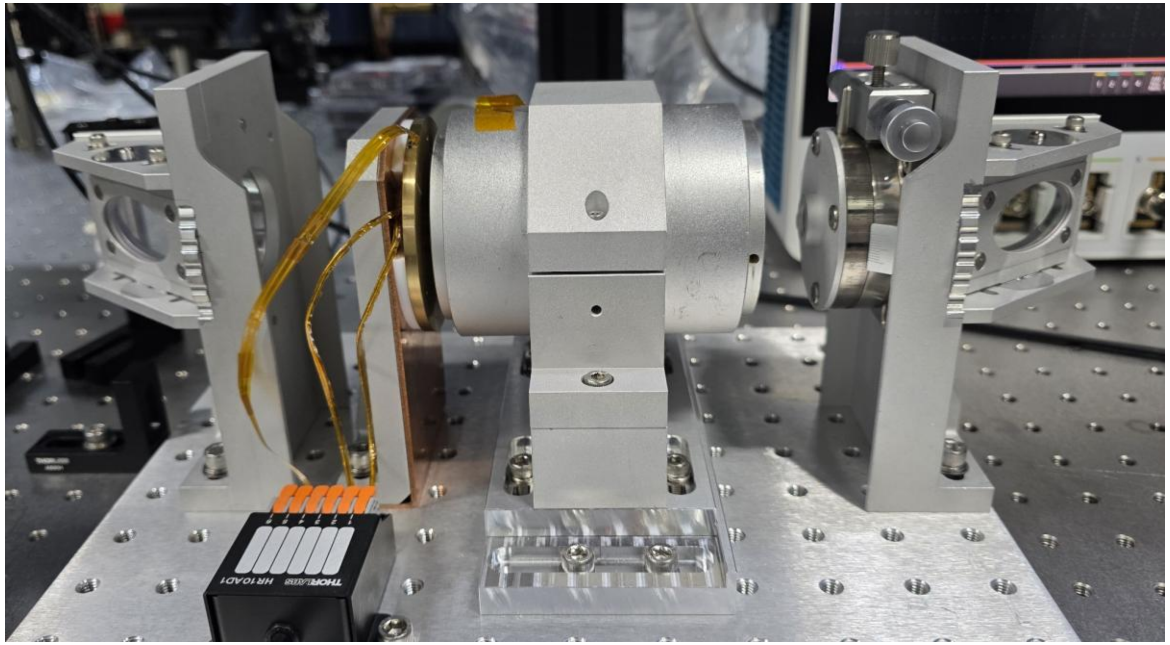
Faraday isolator

KASI is developing a Faraday isolator whose Faraday rotation angle of a TGG crystal can be precisely tuned by temperature control.



KASI Faraday isolator has

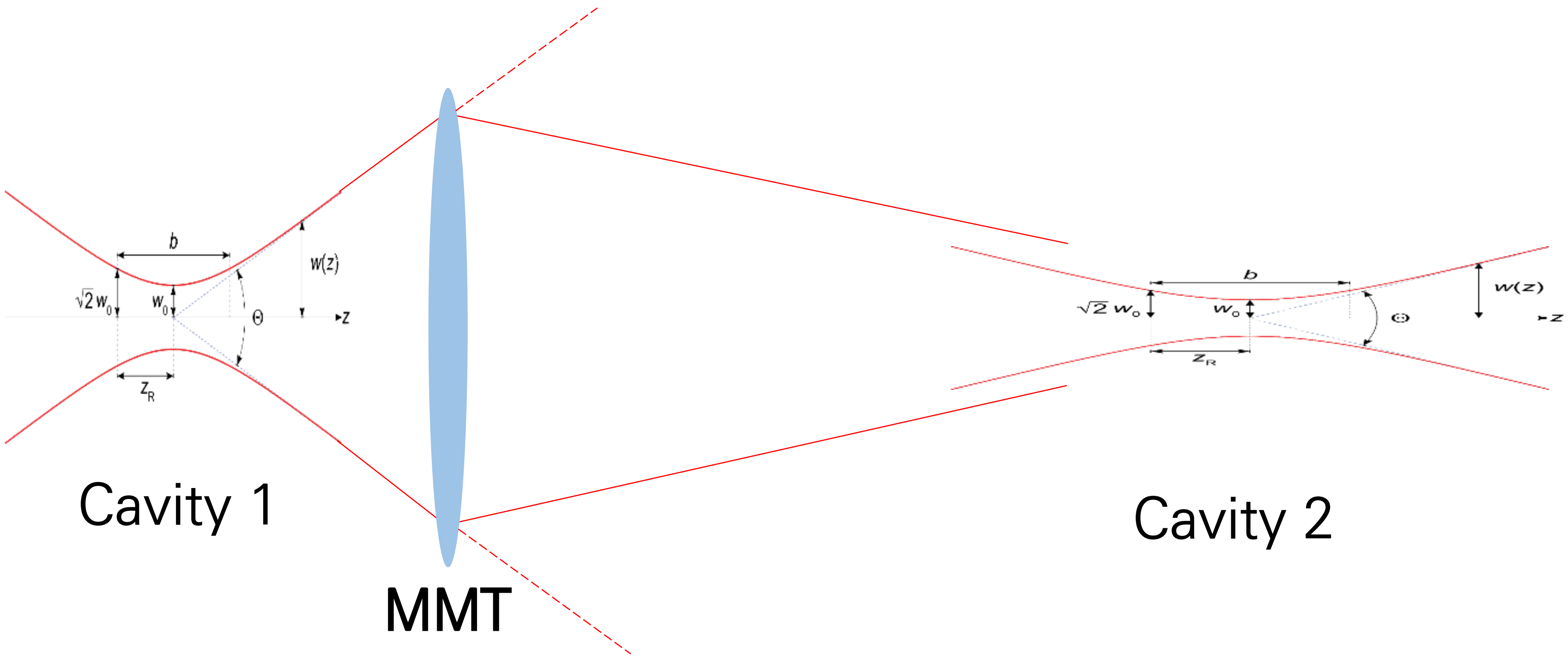
1. Low loss (1.3%, 1% goal)
2. High isolation (41 dB, 35 dB requirement)
3. Zero beam shift
4. Low outgassing



Active mode-matching

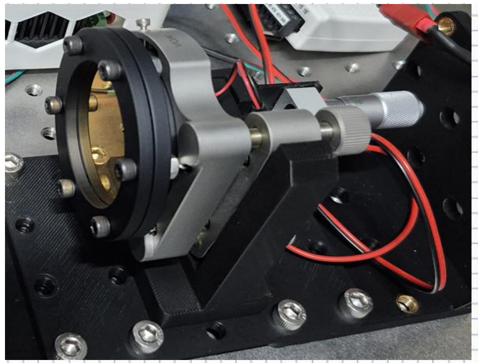
When the cavity is locked, locked state slightly changes from previous state.

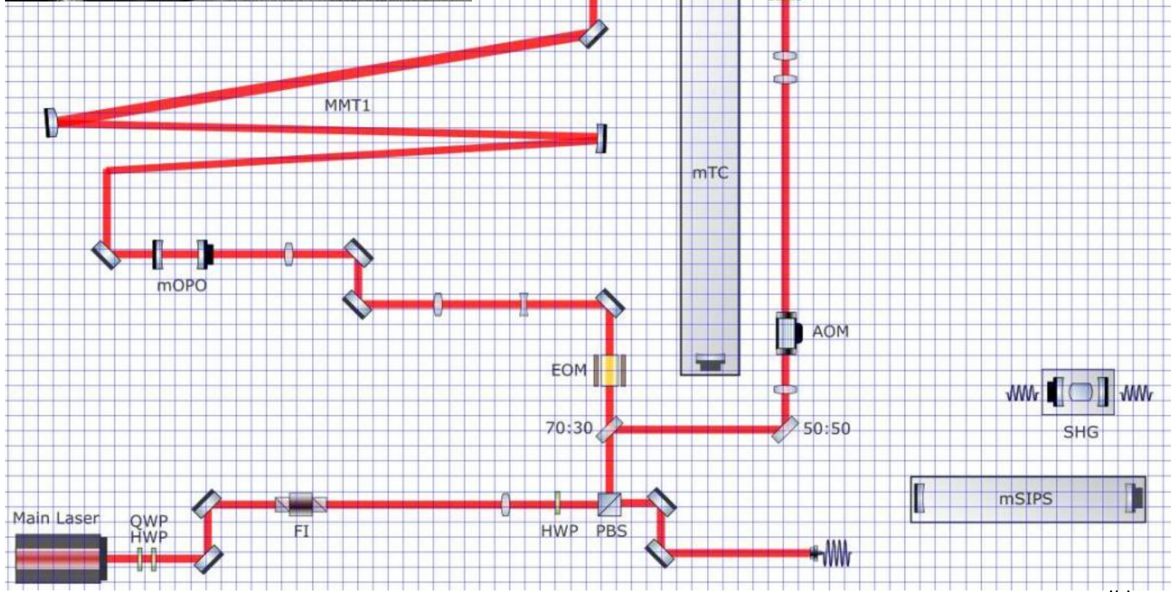
Active mode-matching compensates this effect.



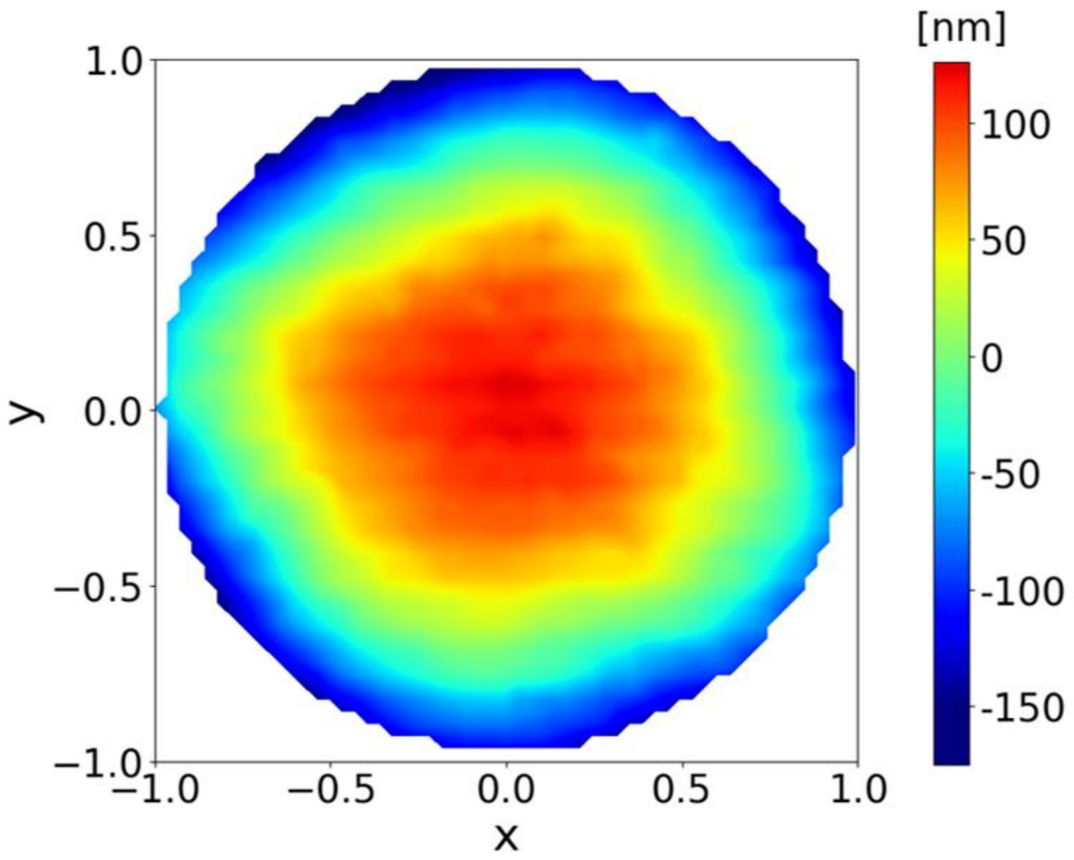
Active mode-matching

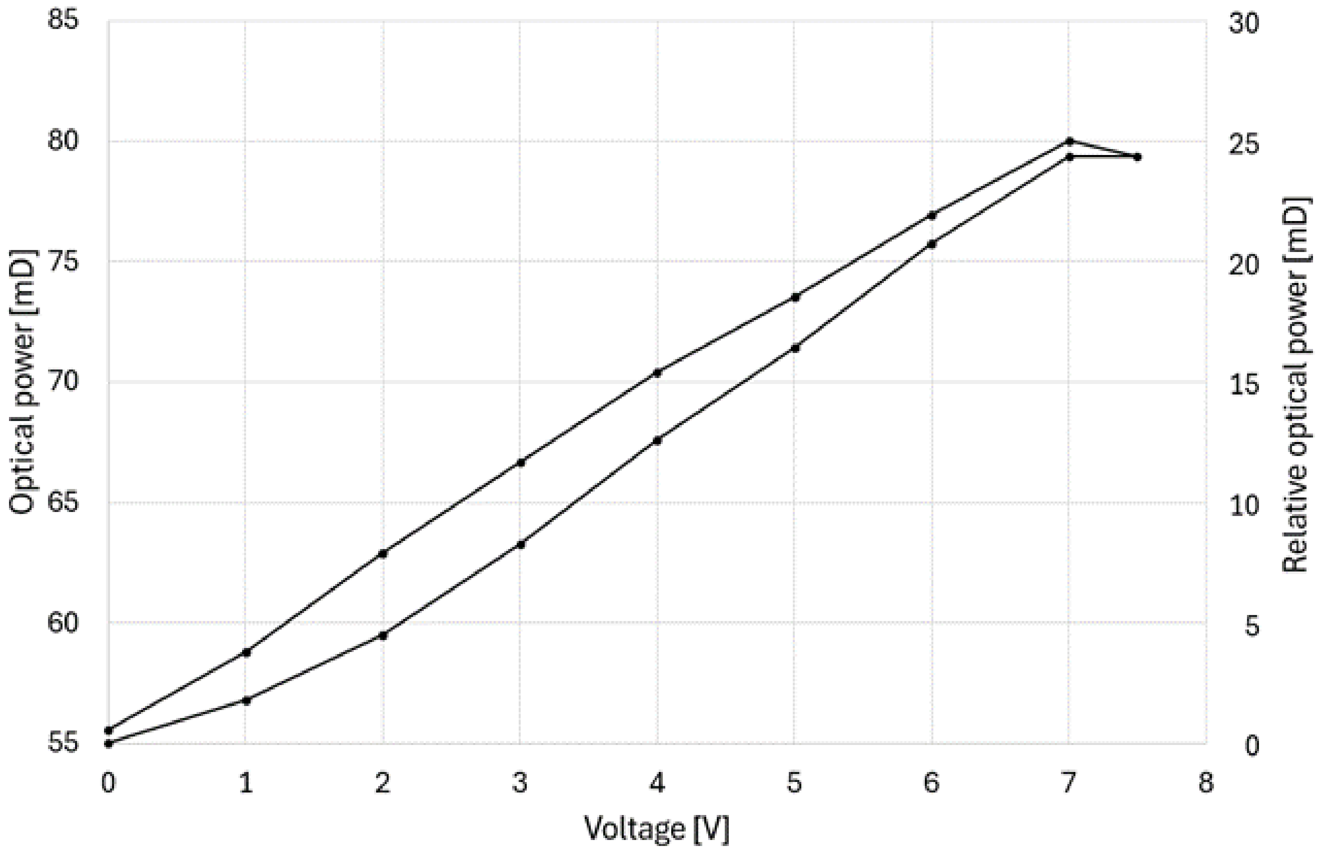
- KASI, Yonsei U., and KHU are collaborating to develop active mode-matching technology.
- This technology will be applied to the KAGRA and ET squeezing system.





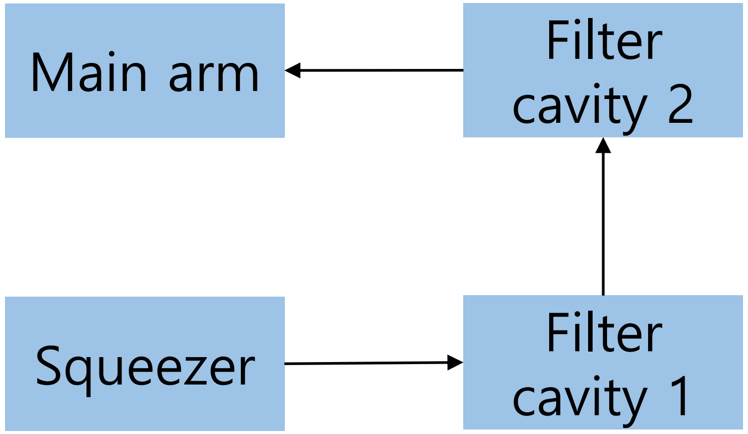
Active mode-matching

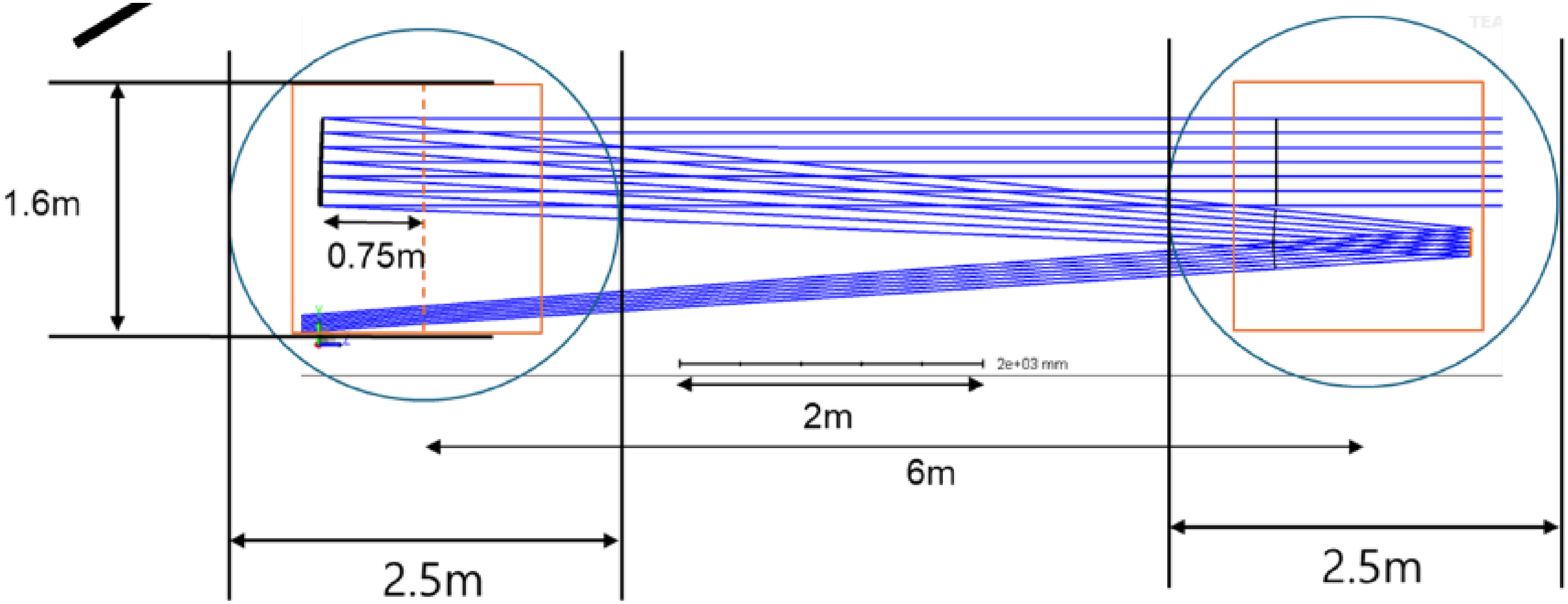




ET & KAGRA SQZ MMT

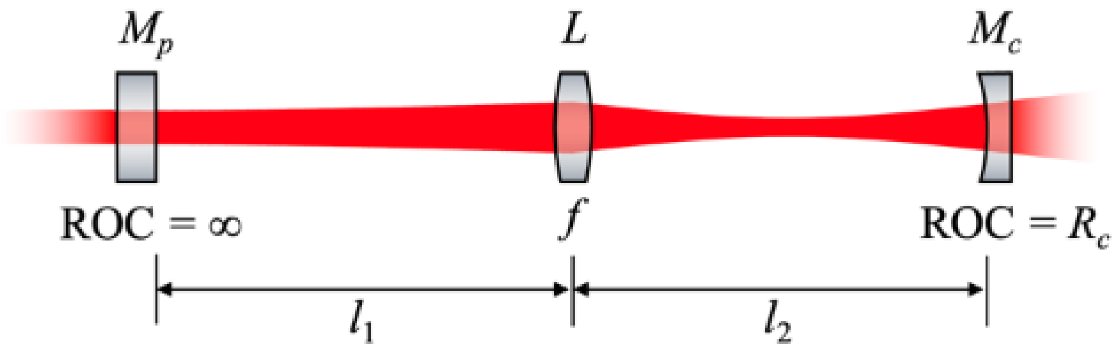
(3 arms) X (2.5 MMTs) X (2 configurations) = 15 MMTs in total!





Self-imaging cavity

It can be simultaneously resonant for all spatial modes.



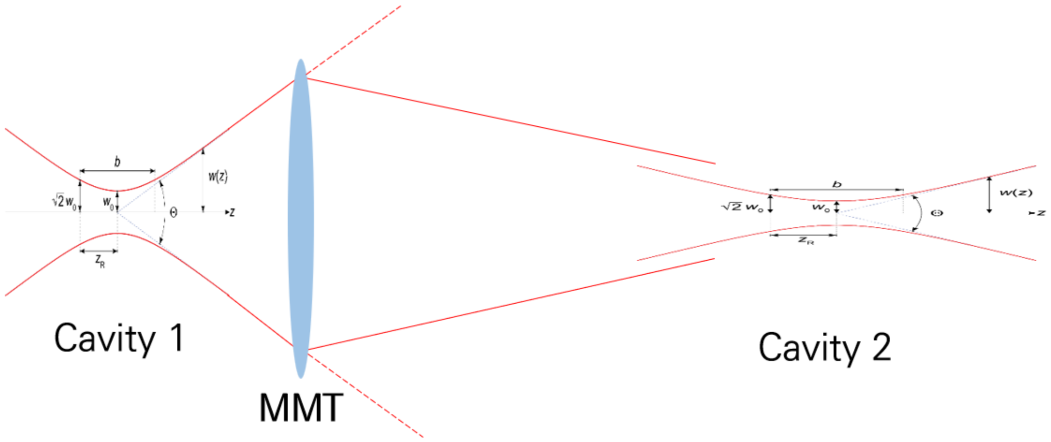
$$l_1 = f + f^2/R_c$$
$$l_2 = f + R_c$$

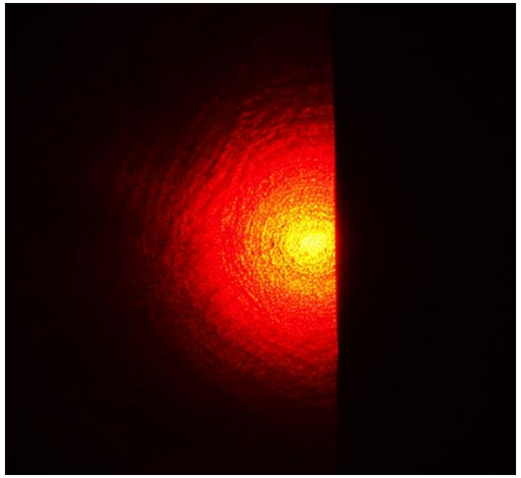
⇒

$$M_{\text{round-trip}} = \mathbb{1}_{2\times 2}$$
$$\theta_{\text{Gouy}} = 0$$

The self-imaging cavity is robust to mode-mismatch!

(Credit: Byeong-Yoon Go)



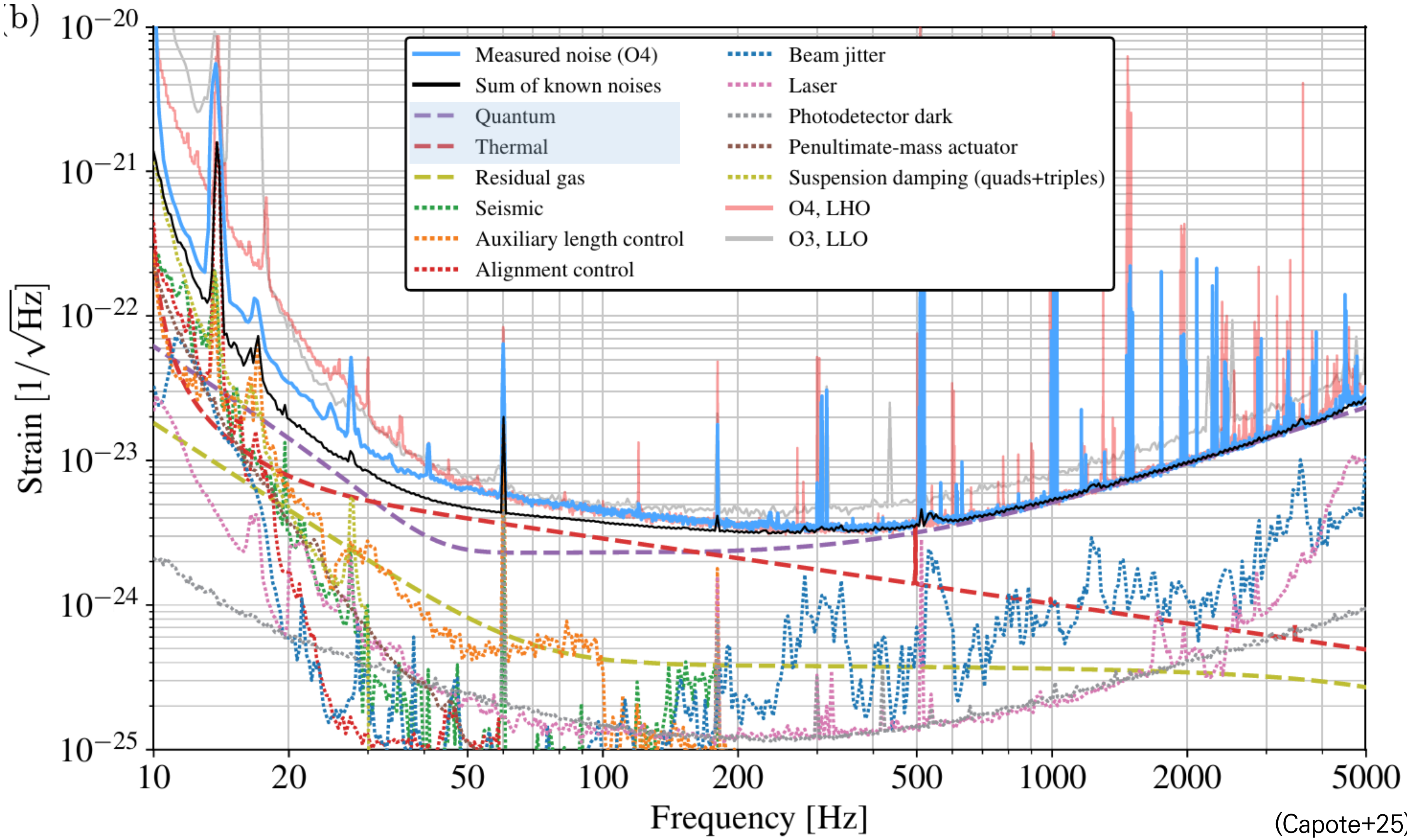


(Generated using ChatGPT)

03

Test mass

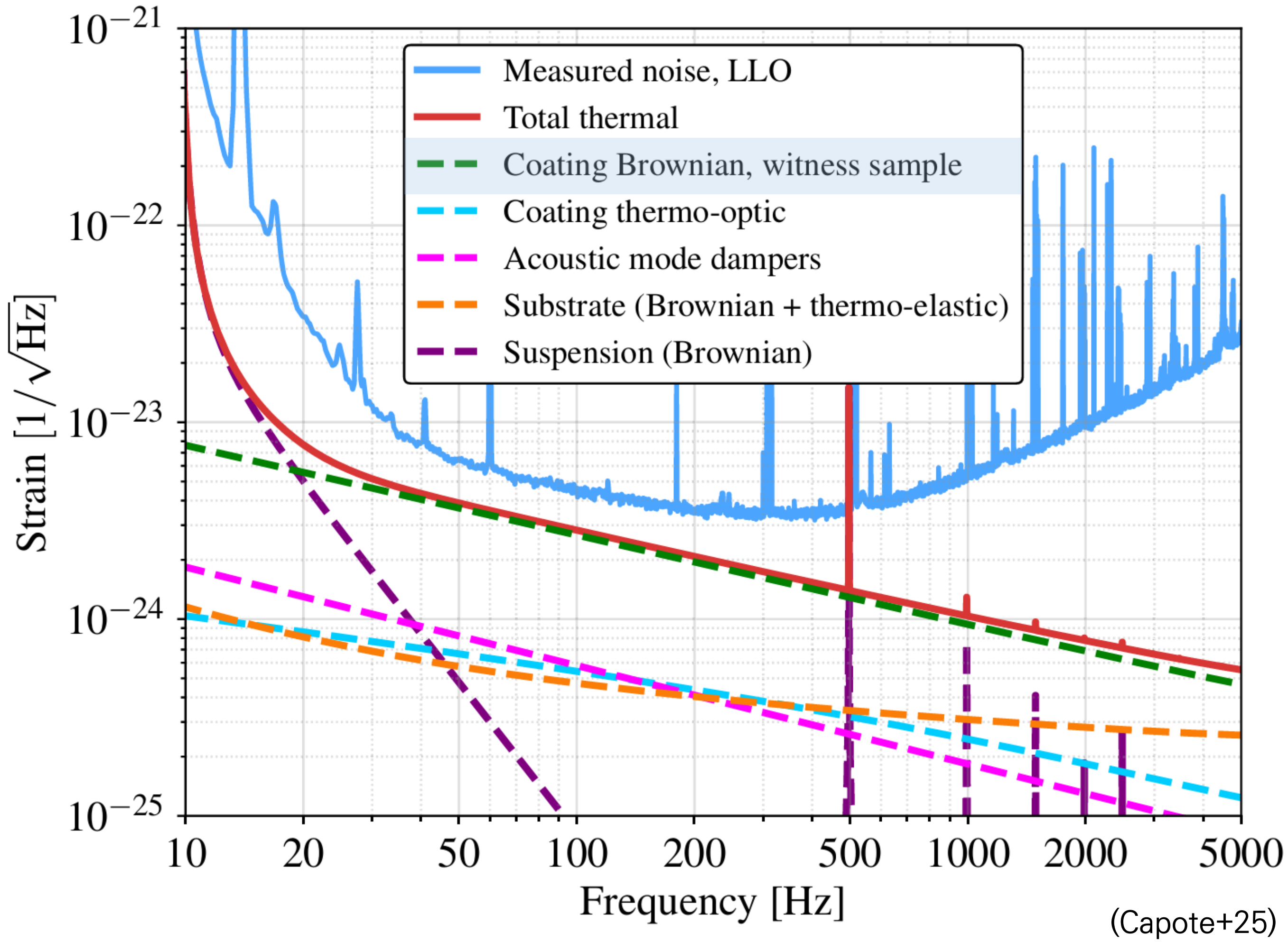
Noise of GWD (LLO, O4)



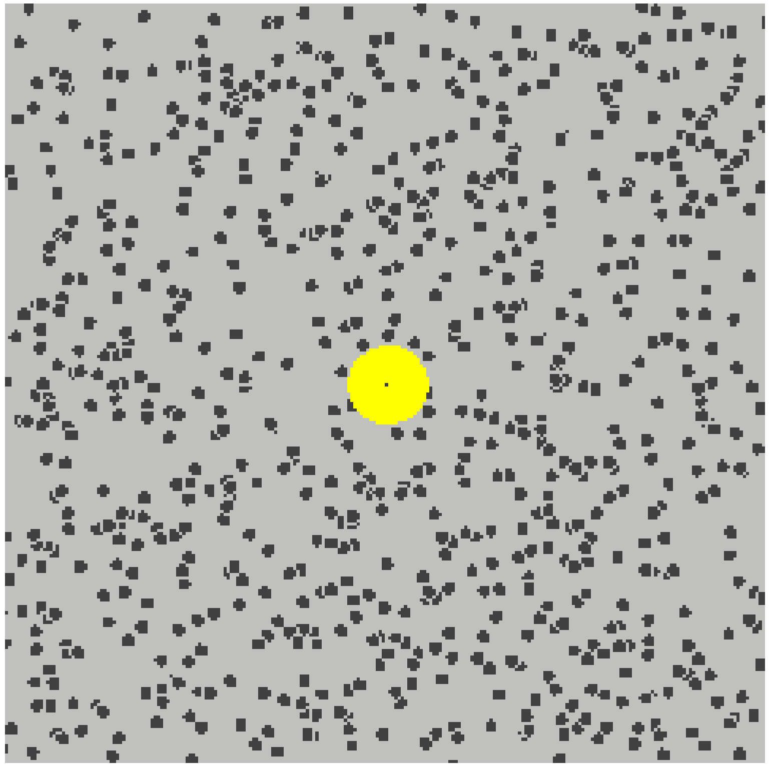
(Capote+25)

Thermal noise

Brownian motion: Random motion of particles suspended in a medium.



(Capote+25)

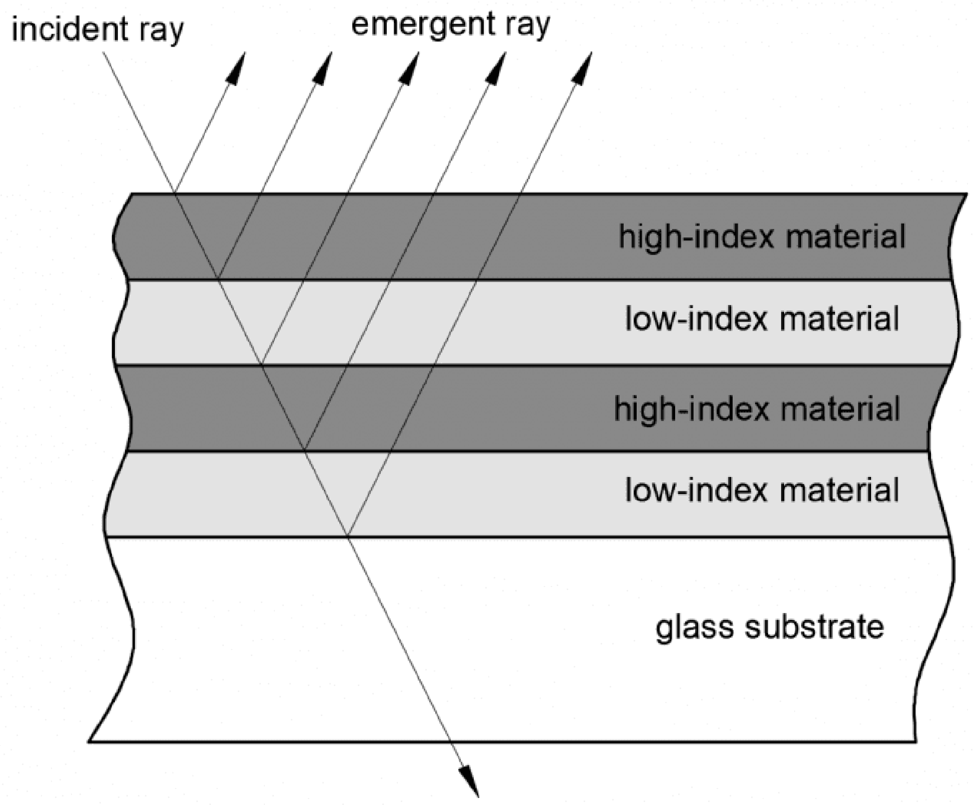


https://en.wikipedia.org/wiki/Brownian_motion

HR coating for test mass

LIGO End Test Mass has 99.996% reflectivity.

High reflective coating consists of alternating layers of low- and high-refractive index materials.
For LIGO, SiO_2 (n=1.4) and Ti:Ta_2O_5 (n=2.1) have been used.



Coating Brownian noise $\propto Td\Phi$

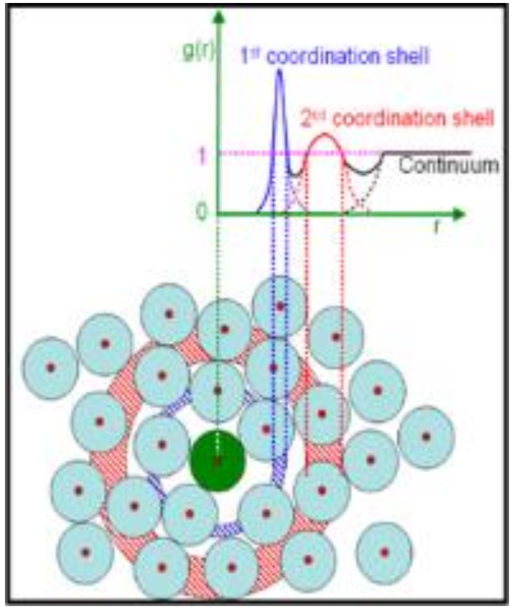
1) Cryogenic temperature (not for LIGO)
2) **High refractive index**
3) **Low mechanical loss**

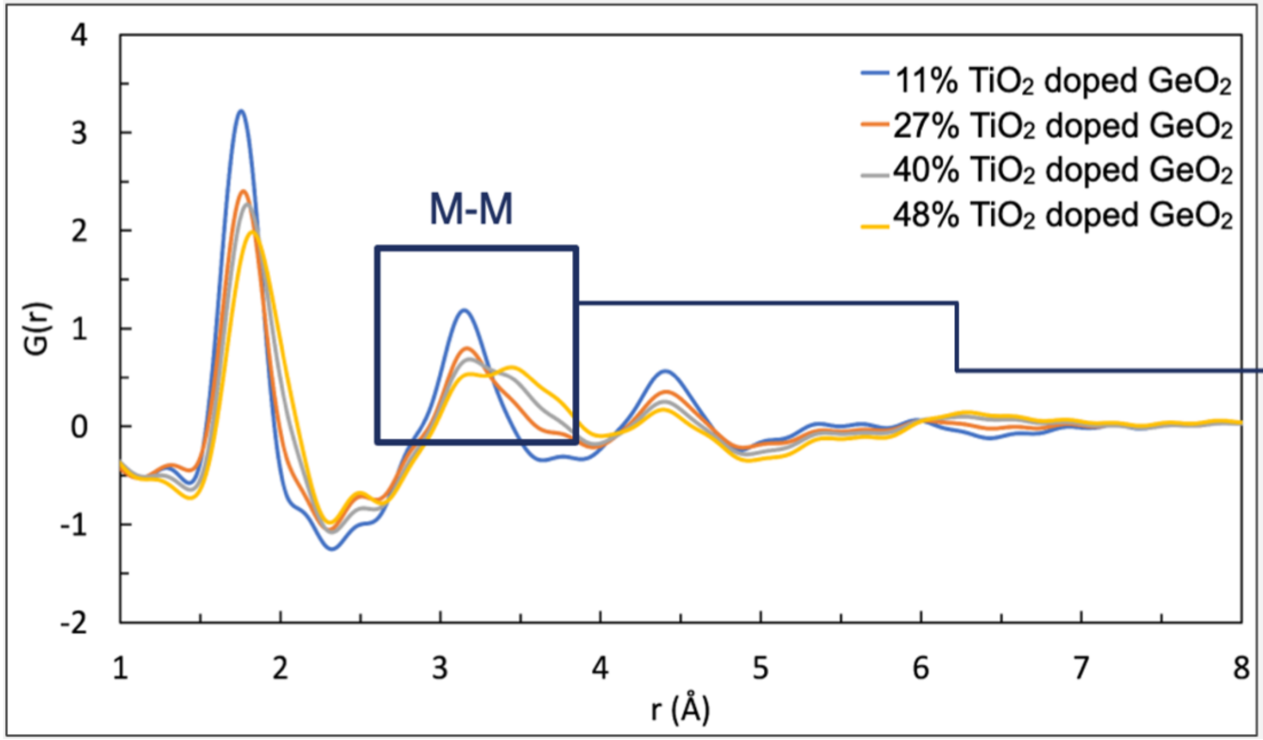
ePDF

Electron Pair Distribution Function

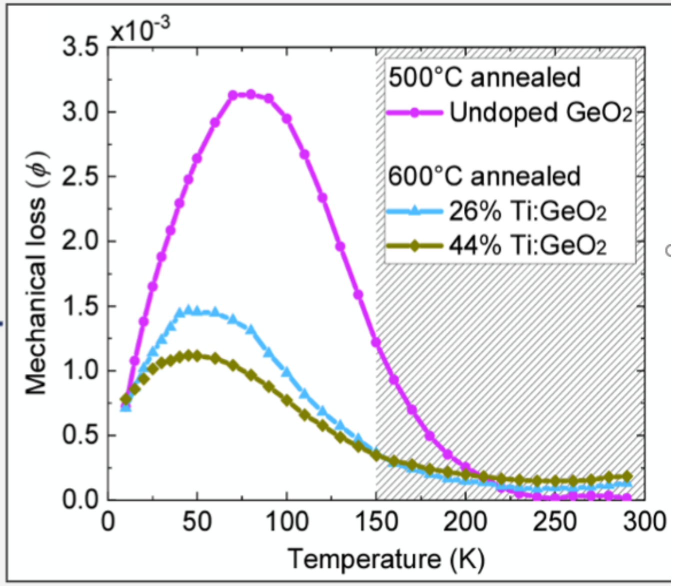
Angstrom-scale atomic structure such as bonding distance

Amorphous!





Unpublished, Sudi & Ashot

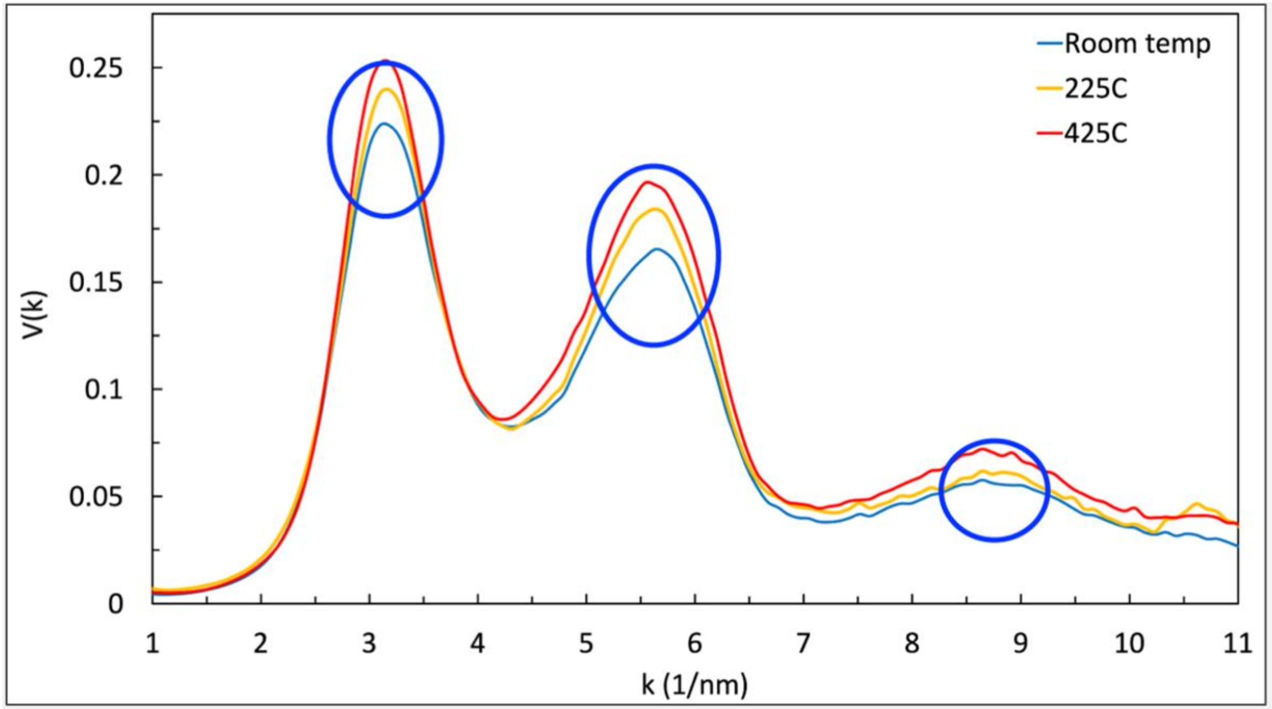


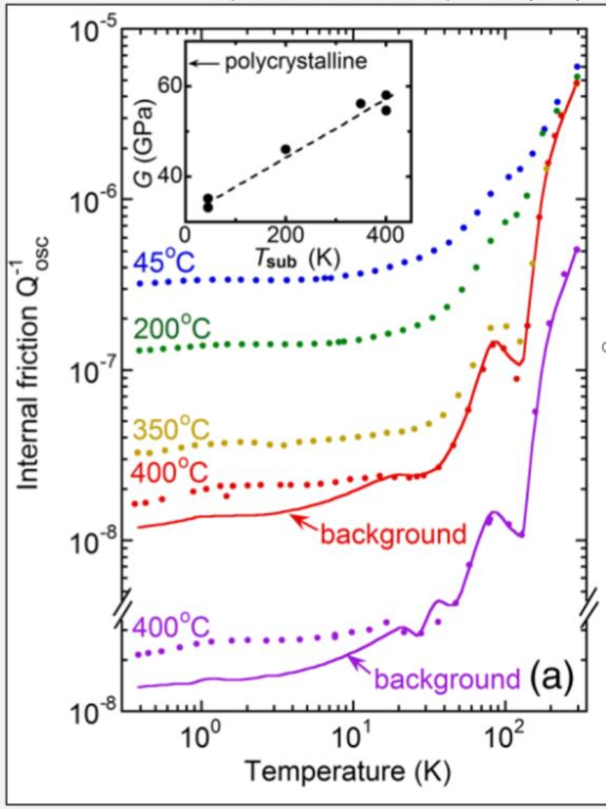
(Credit: Kyung-ha Lee)

FEM

Fluctuation Electron Microscopy

Nanometer-scale atomic structures also affect the mechanical loss.





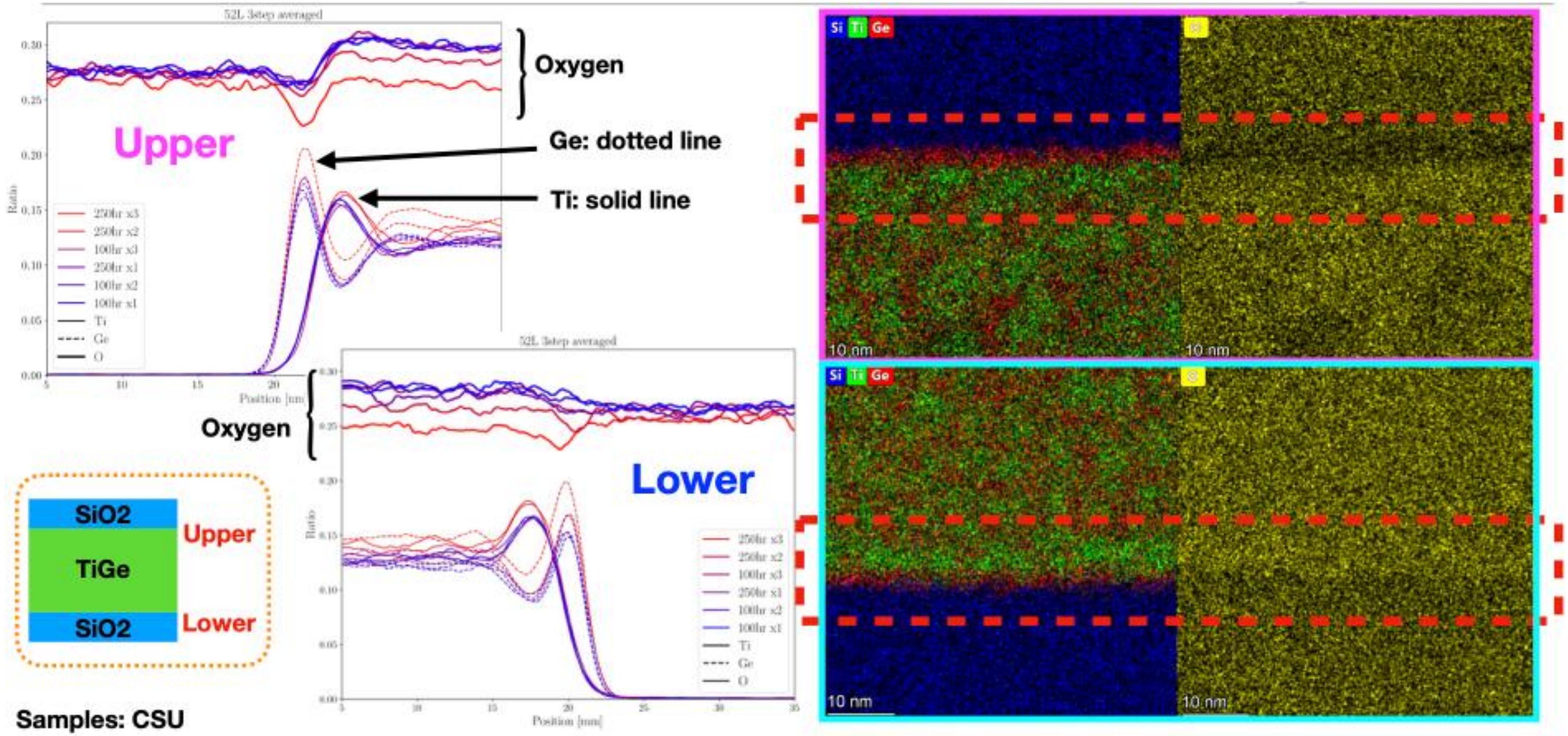
- Mechanical loss measurement data also shows a systematic change
  - ✓ Higher deposition temperature = more rearrangement to achieve low energy configuration = Lower mechanical loss

(Credit: Kyung-ha Lee)

EDS

Energy Dispersive Spectroscopy

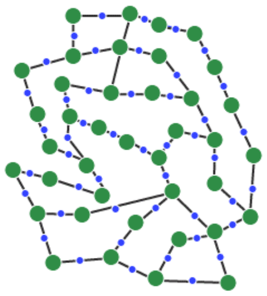
Multi-layer coating analysis



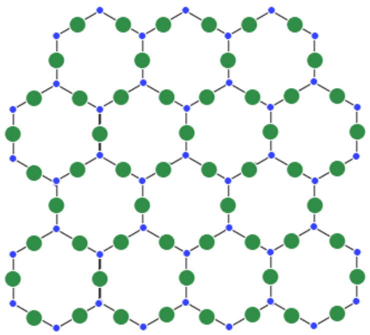
Samples: CSU

(Credit: Kyung-ha Lee)

Birefringence



Amorphous Solids



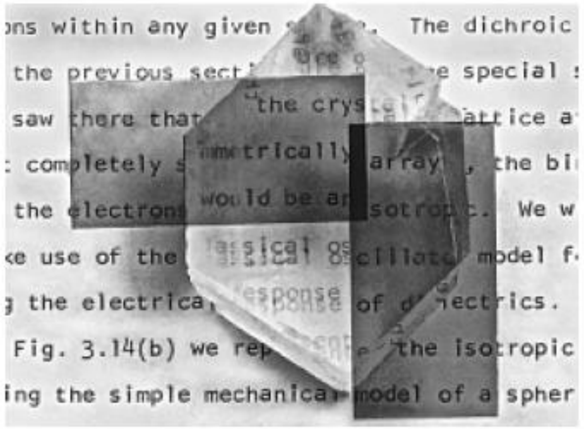
Crystalline Solids

Fused Silica

Sapphire (KAGRA)

Silicon (ET ?)

Birefringence



- Polarization-dependent refractive index

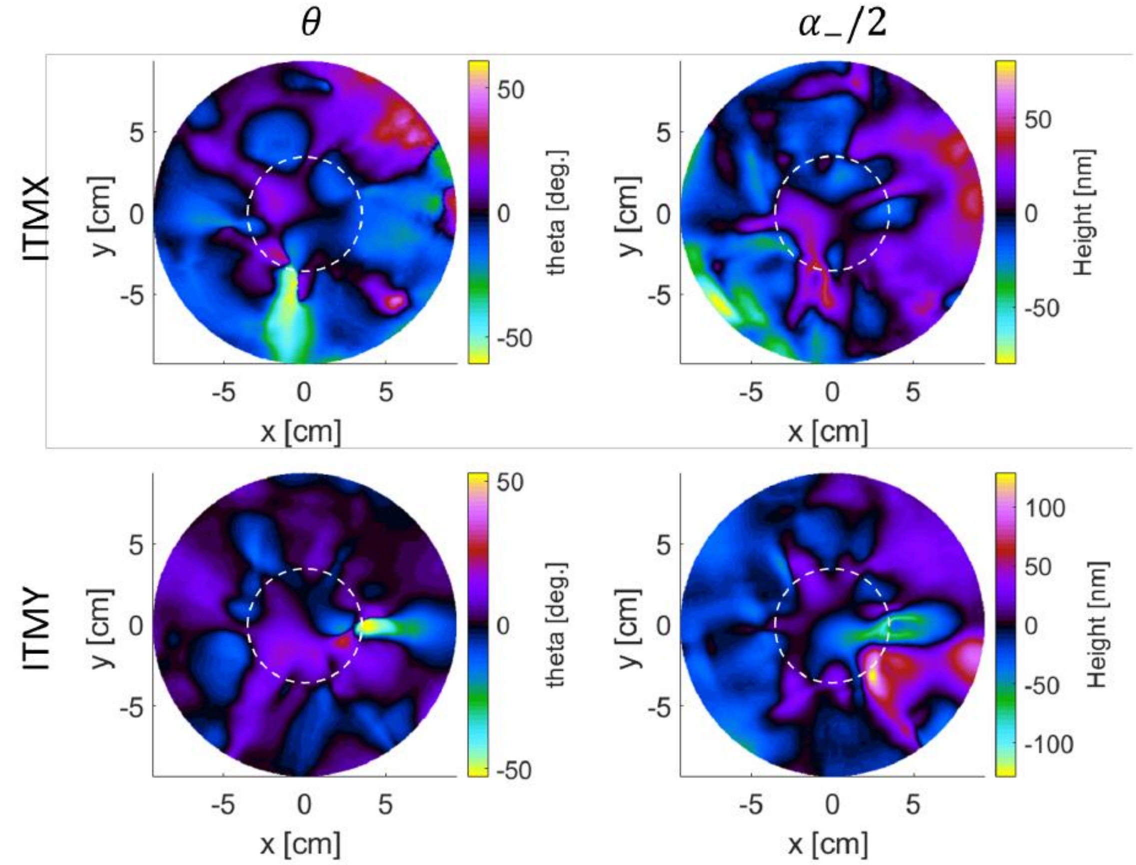
- If a single polarized beam is aligned with the birefringence axis, birefringence is not an issue by itself.

(https://www.geeksforgeeks.org/chemistry/difference-between-crystalline-and-amorphous-solids/)

Birefringence

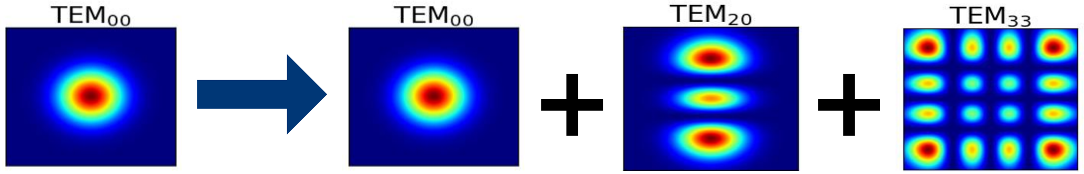
However, it is not uniform…

Sapphire Test Mass (KAGRA)

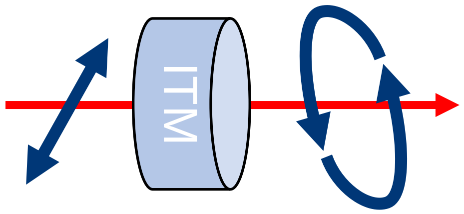


(Wang+24)

(a) Higher-order mode excitation



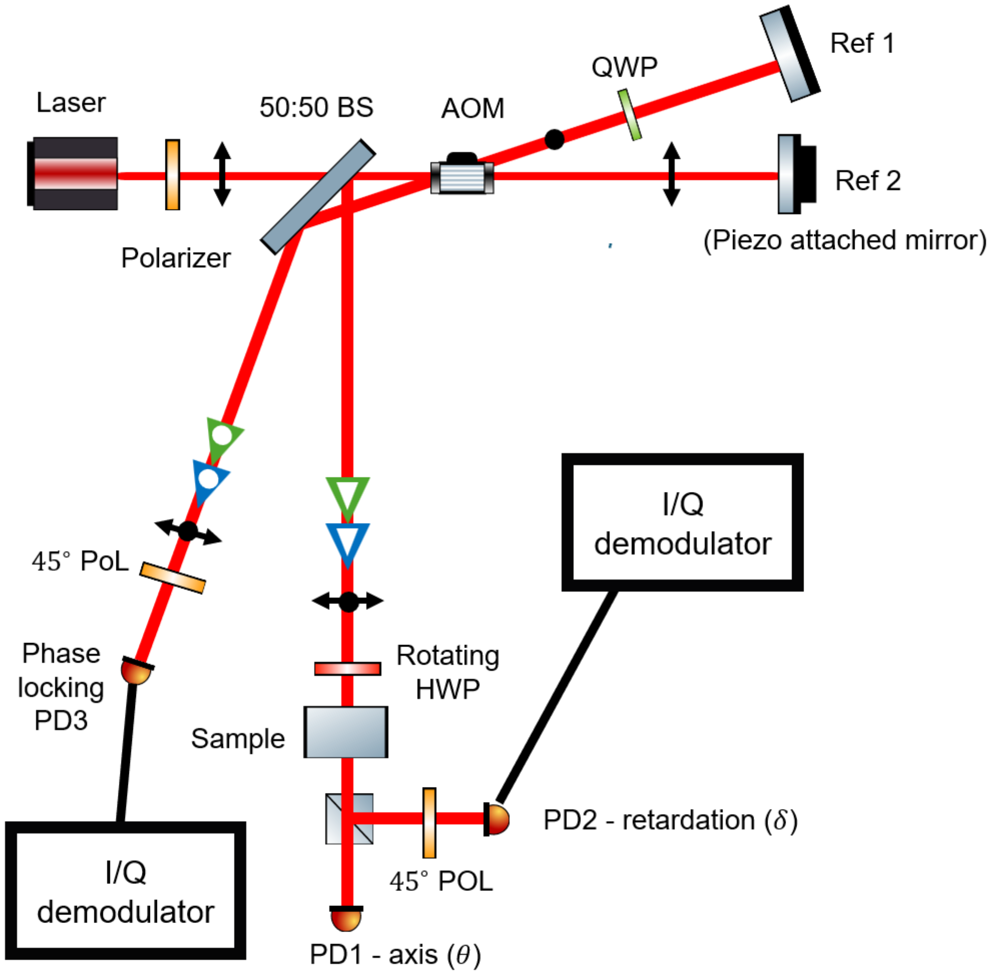
(b) Depolarization

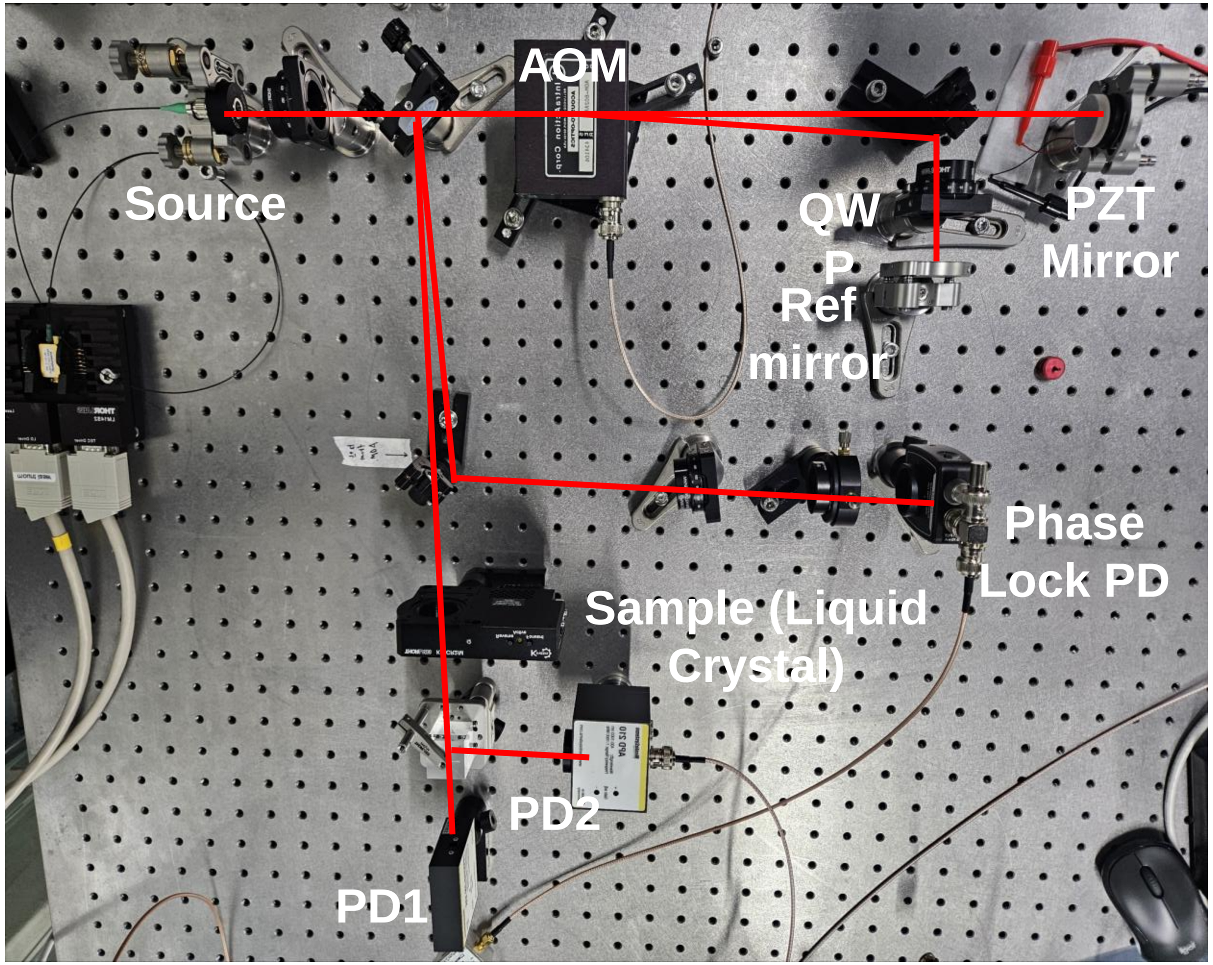


(c) Degradation of dark-port visibility

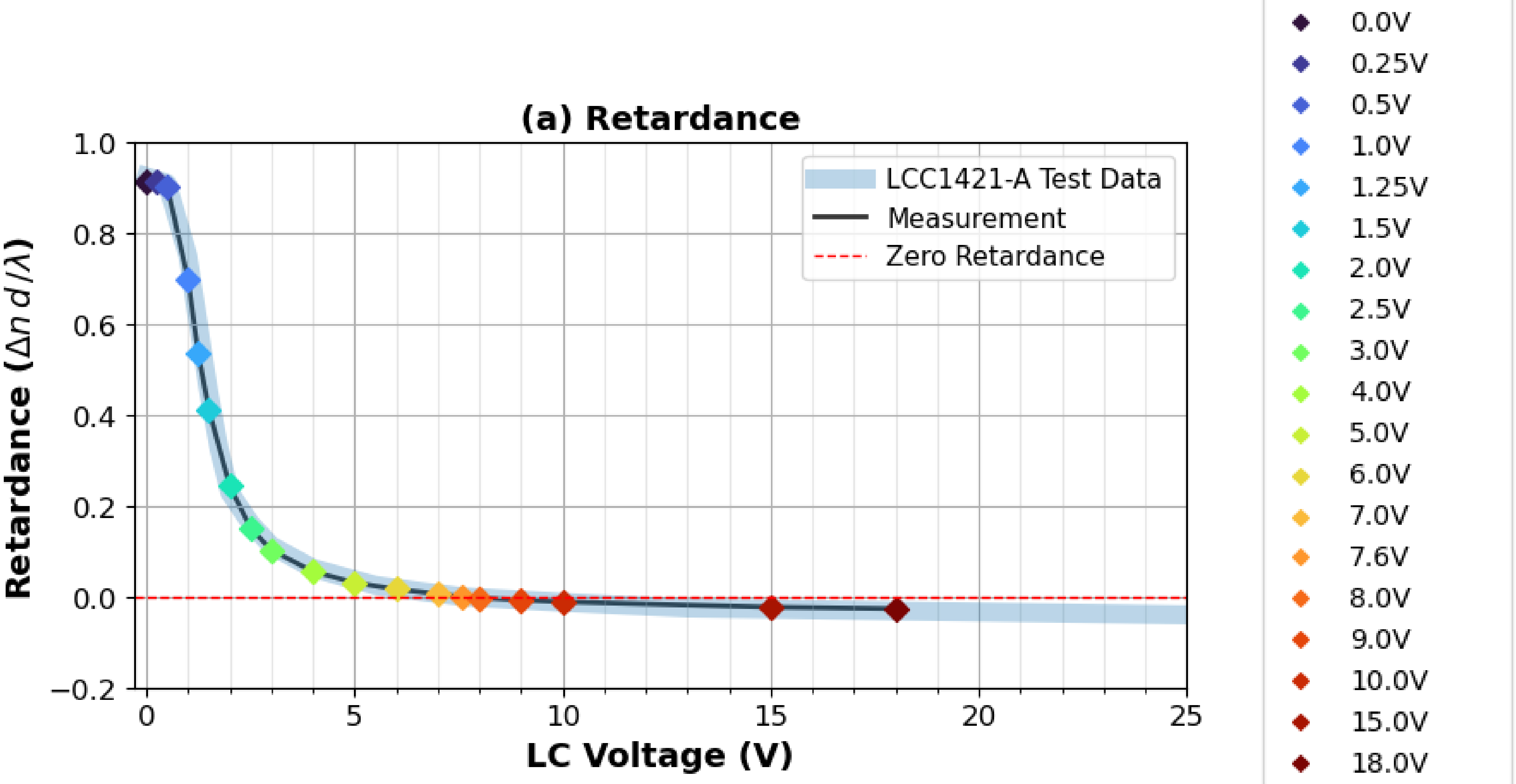
(Credit: Gyoik Kim)

Test setup


Laser
50:50 BS
AOM
QWP
Ref 1
Ref 2
(Piezo attached mirror)
Polarizer
45° PoL
Phase
locking
PD3
I/Q
demodulator
Rotating
HWP
Sample
PD2 - retardation (δ)
45° POL
PD1 - axis (θ)
I/Q
demodulator


AOM
Source
QW
P
PZT
Mirror
Ref
mirror
Phase
Lock PD
Sample (Liquid
Crystal)
PD2
PD1

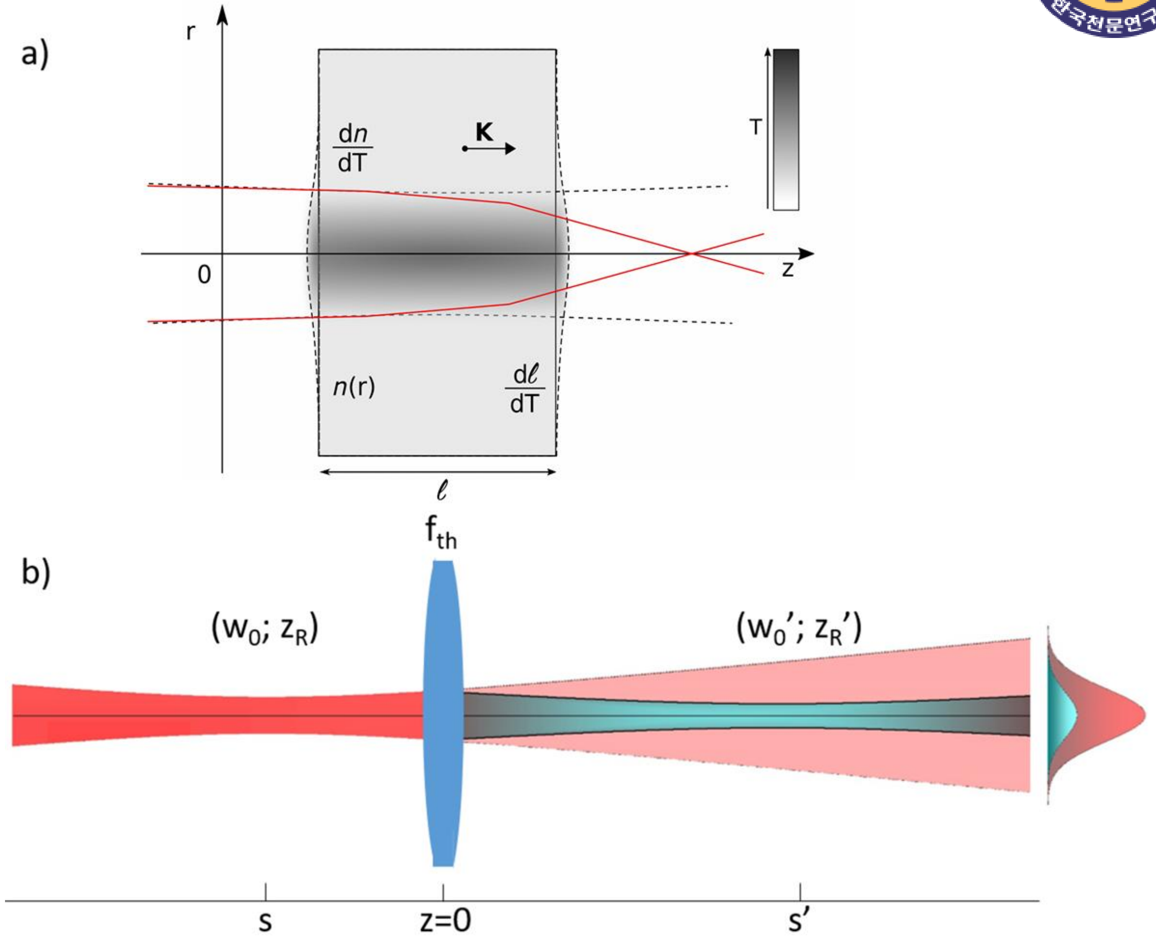
Test result: liquid crystal



Absorption

- Thermal lensing effect degrades mode-matching efficiency.

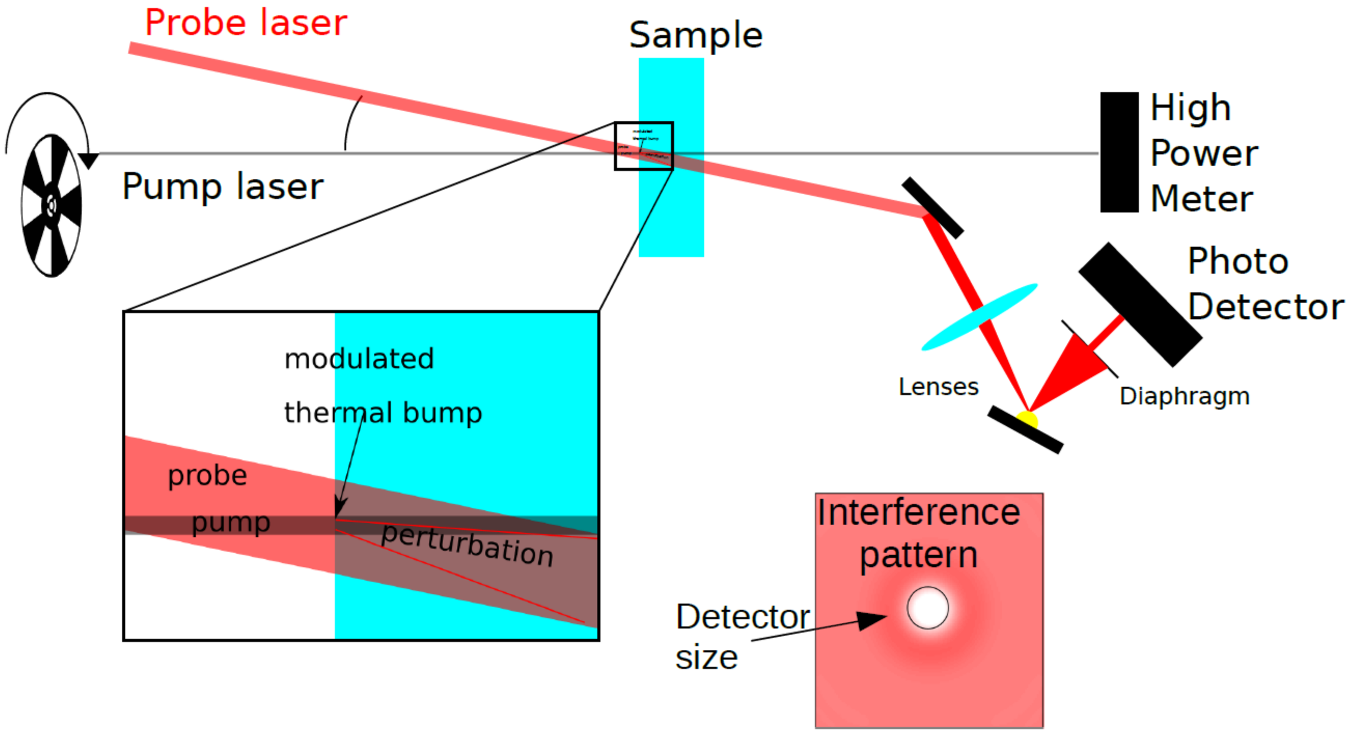
- In cryogenic environment, thermal absorption yields thermal load to the suspension fibers.

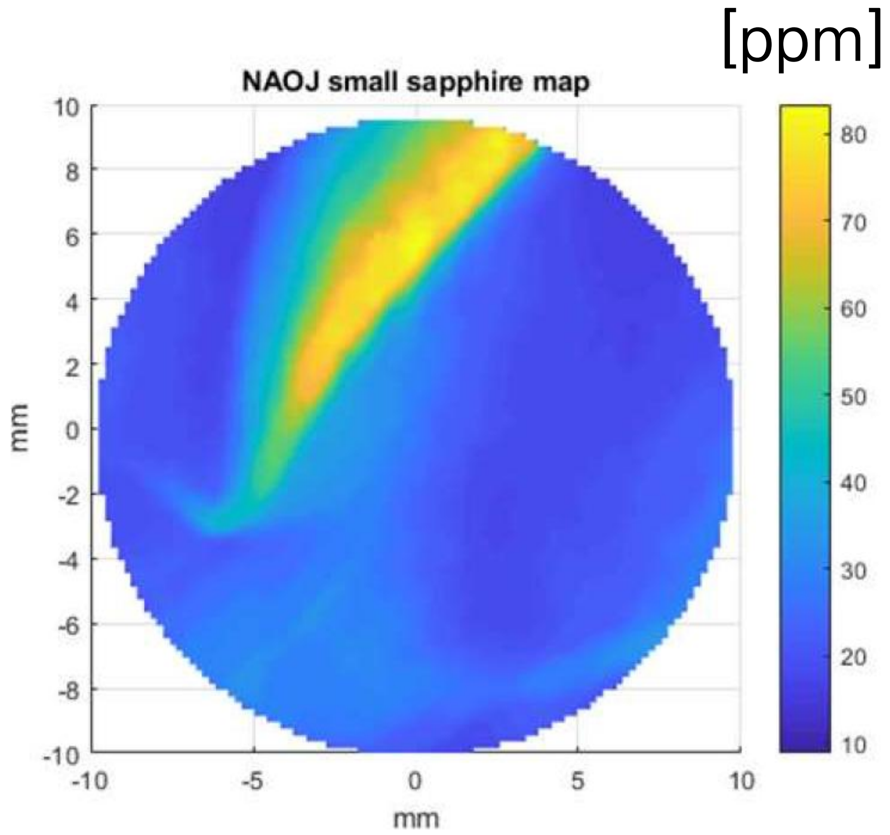


(Simonelli+19)

PCI

Photothermal Common-path Interferometry





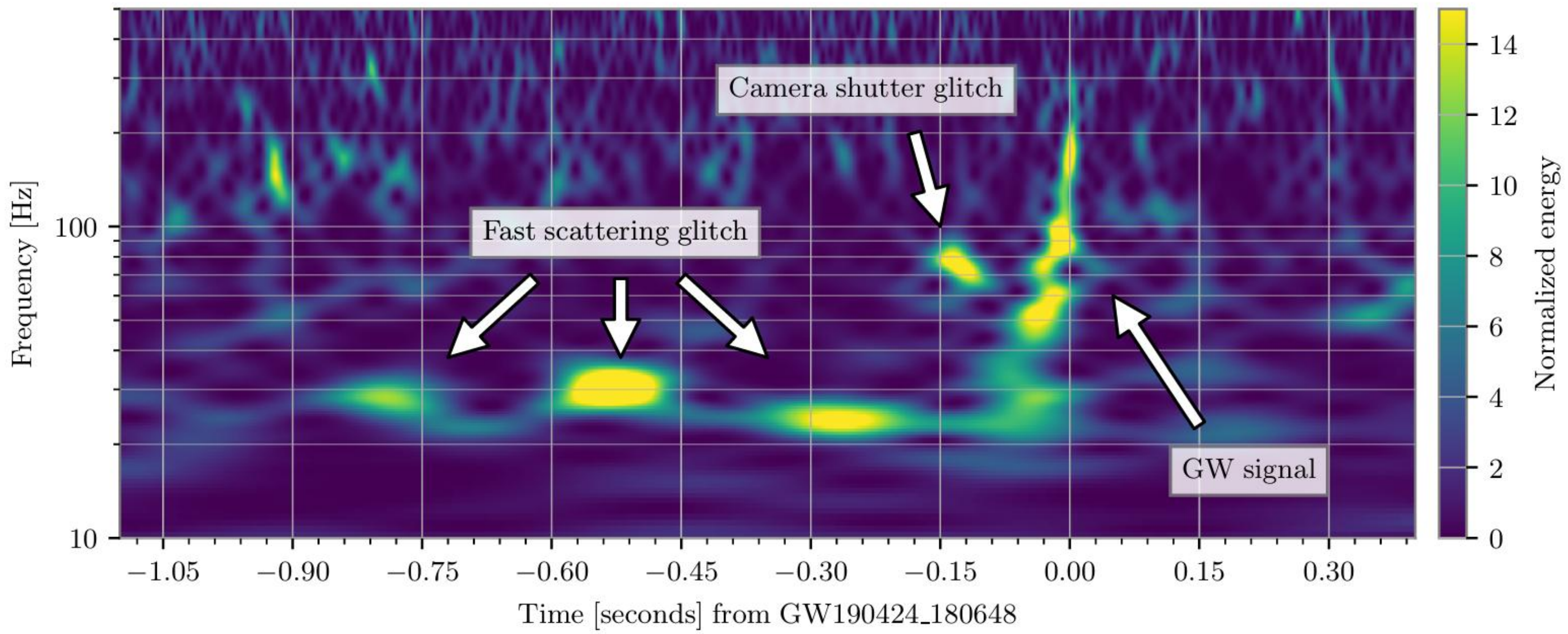
- $\Delta T \rightarrow \Delta n \rightarrow \Delta L \rightarrow \Delta\varphi \rightarrow$ Self-interference!

(Manuel, PhD thesis)

04

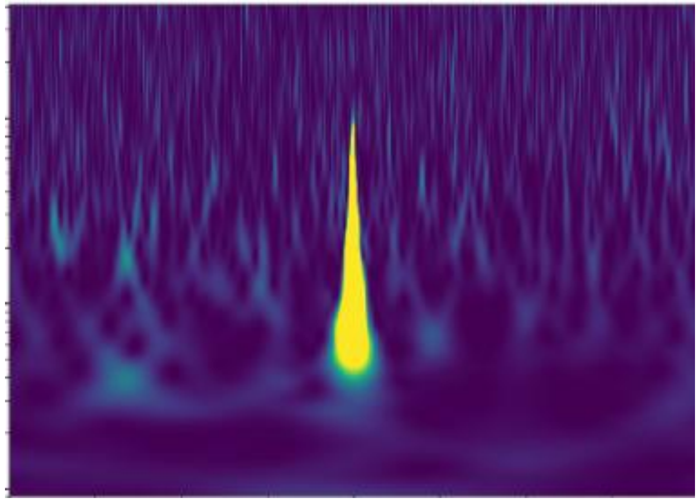
Data reduction/denoising

DetChar



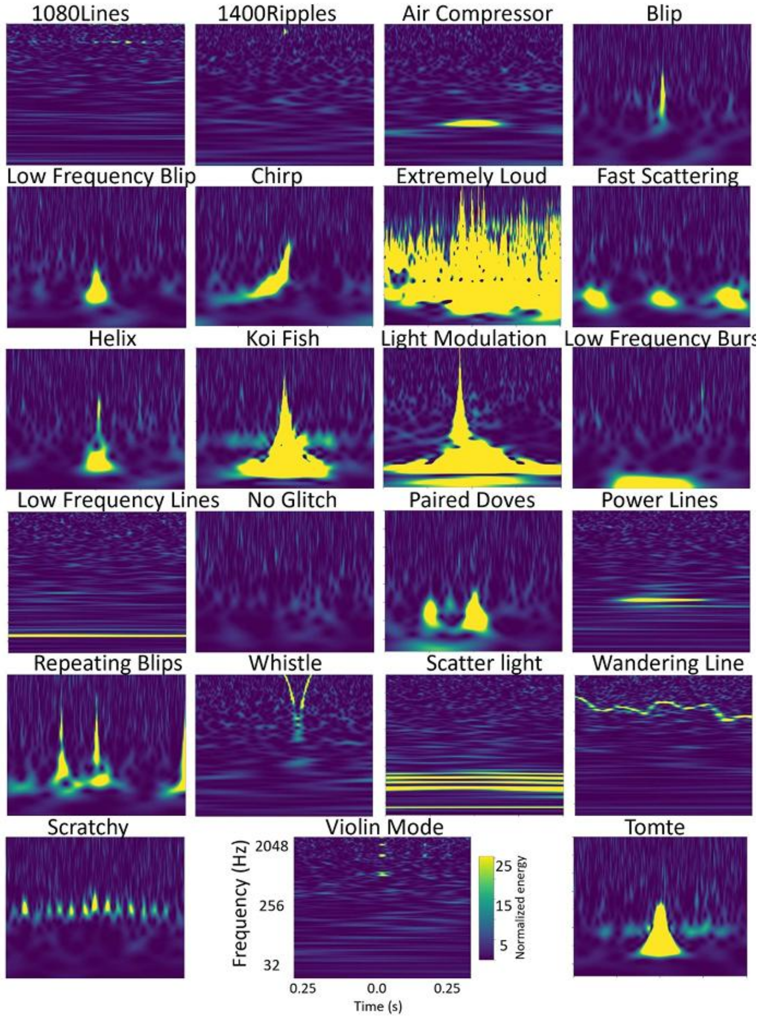
(Davis&Walker22)

Blip-type glitch

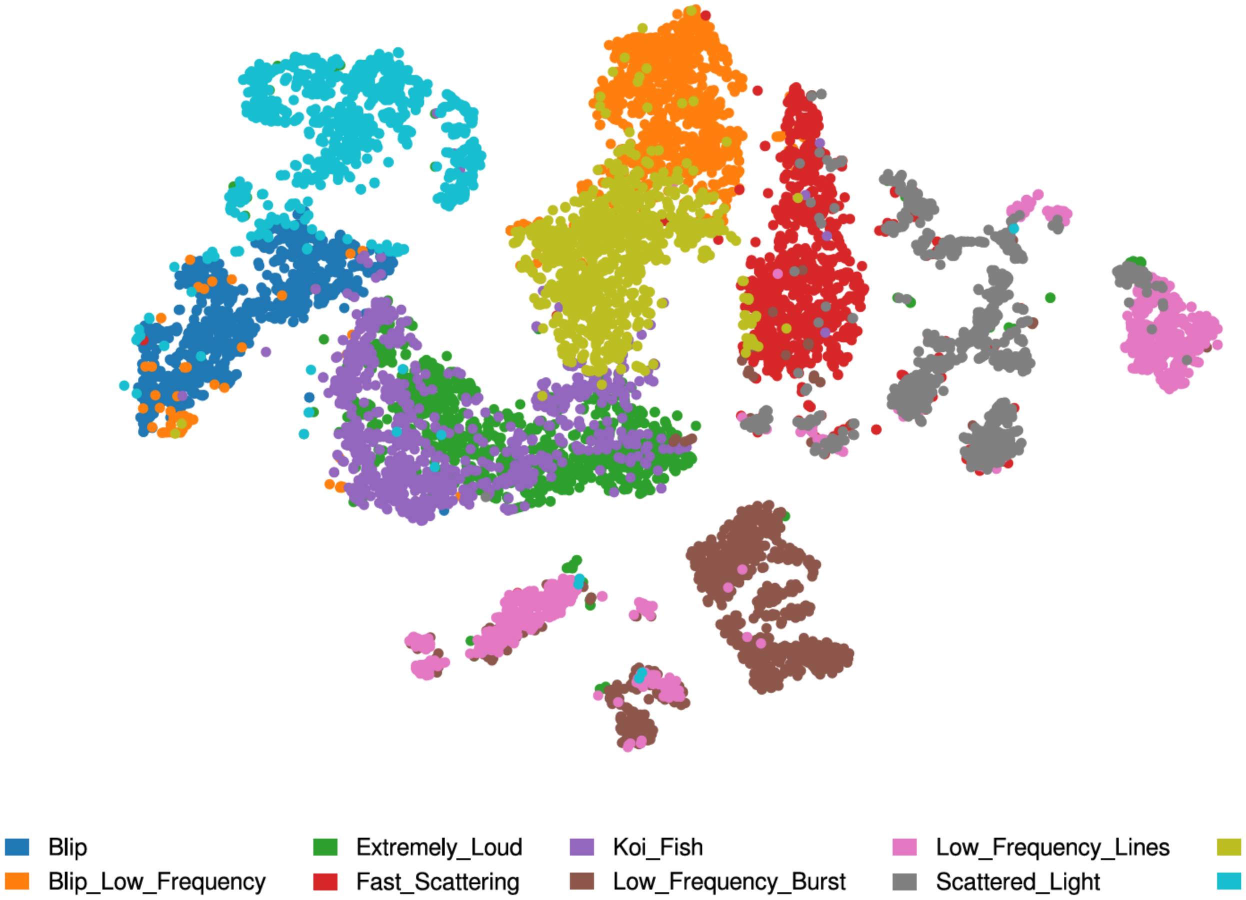


(Ferreira&Gonzales25)

DetChar

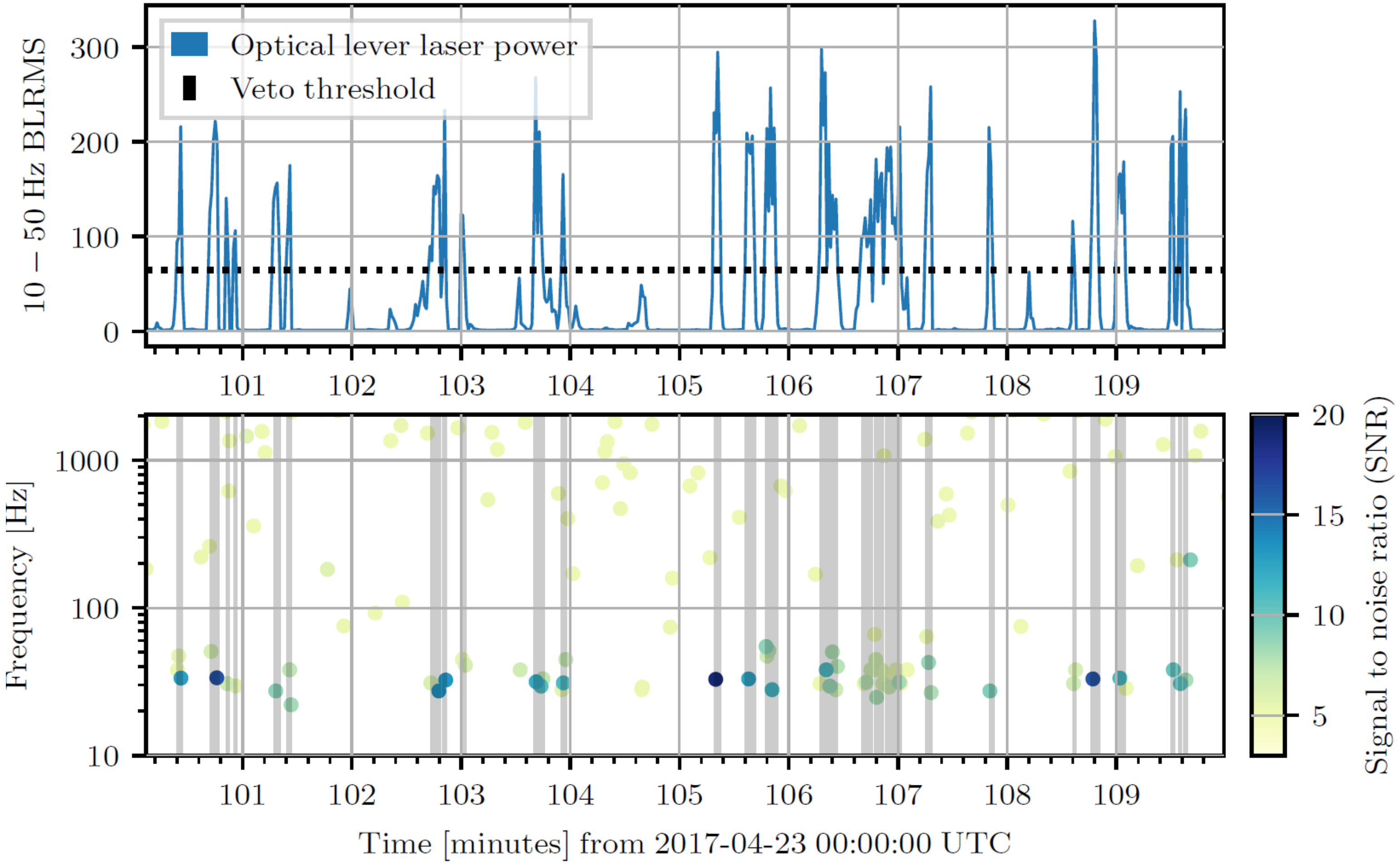


(Wu+25)



(Ferreira&Gonzales25)

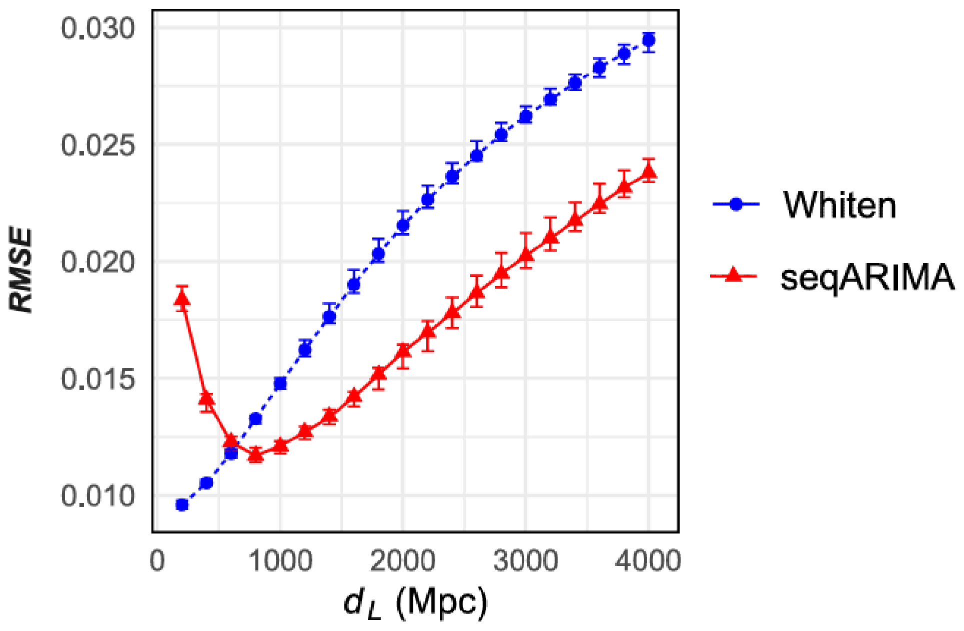
hveto

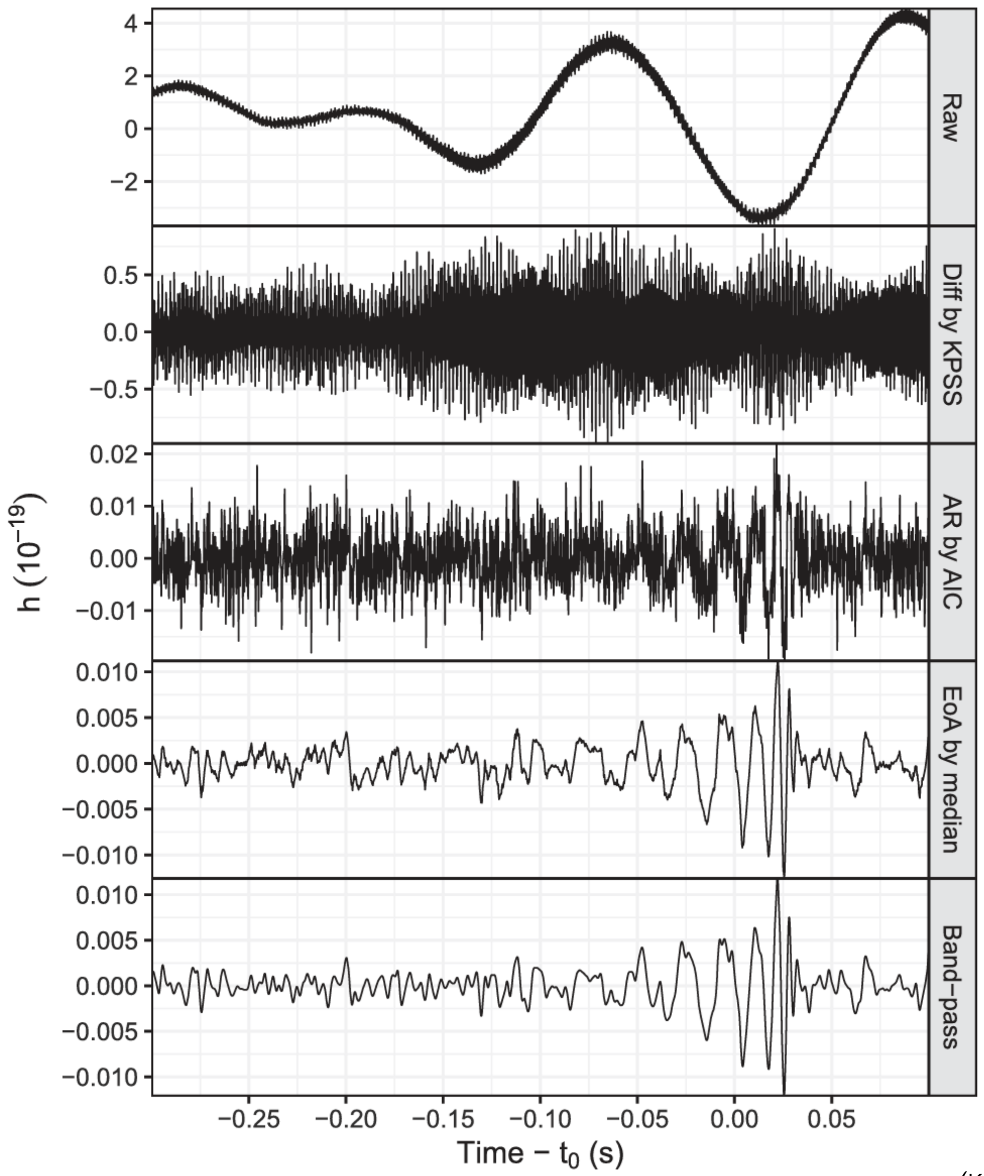


(Davis+21)

Data denoising

- GW signal is still too weak and hidden.





(Kim+24)

Summary

1. GWDs are consisted of lots of components to enhance and protect signals.
2. Korean researchers are working hard to reduce noise of GWDs.

Large categories	Small categories	Institute
Quantum noise reduction	Squeezer	KASI, KAIST
	Mode-matching	KASI, KHU, Yonsei, KAIST
	Active mode-matching	KASI (System) KHU (DM) Yonsei (Control)
Test mass	Coating	SKKU
	Birefringence	Yonsei
	Absorption	KASI
Data processing	DetChar	UNIST, KASI, NIMS
	Denoising	CNU

Thank you

Thank you for listening to my presentation

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