Optical loss study of cryogenic molecular layer

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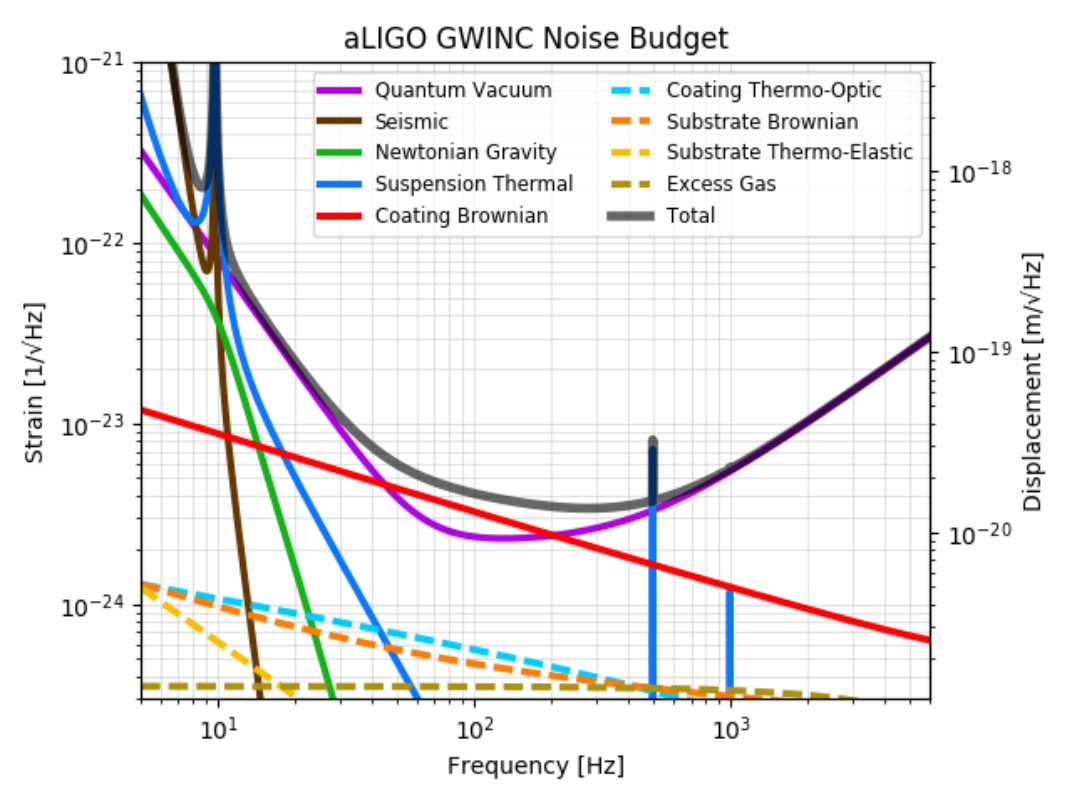
Abstract

- Future gravitational-wave detectors (GWDs) will employ cryogenically cooled test masses to improve the sensitivity.
- A cryogenic mirror in the GWD can suffer from the formation of the molecular layer on its surface.
- The optical loss induced by the molecular layer can prevent the cryogenic operation of a cryogenic GWD.

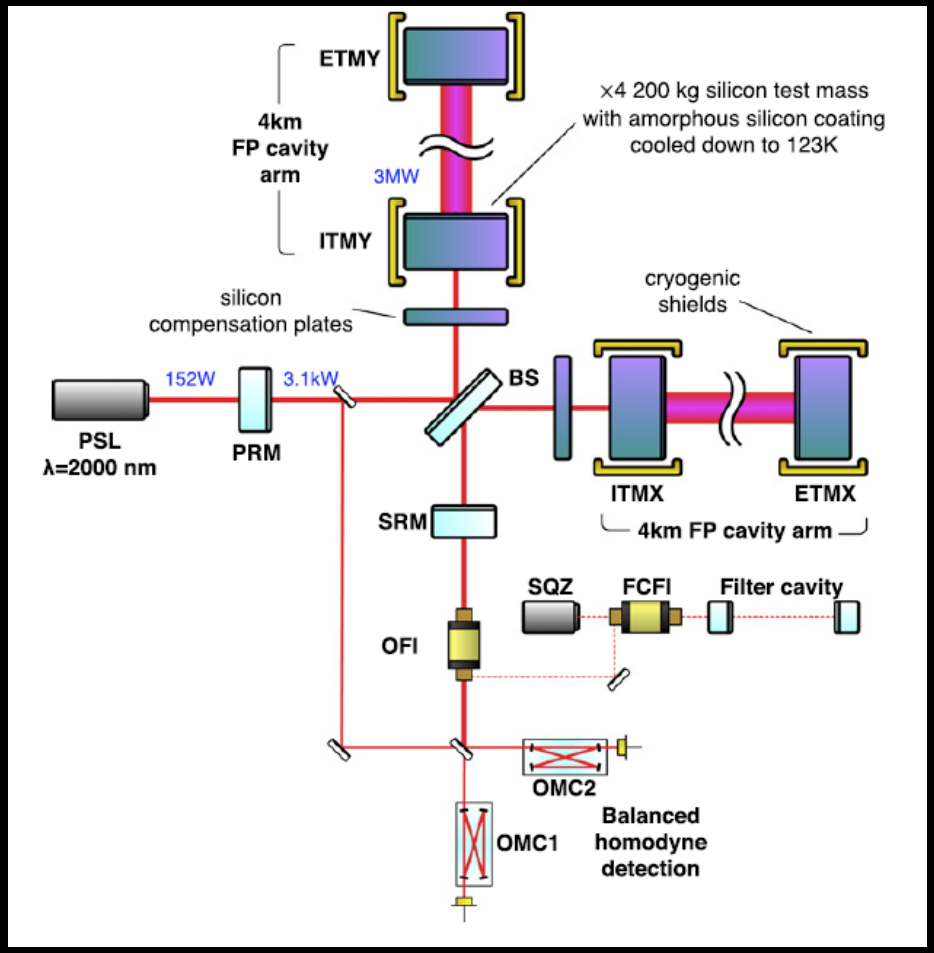
Sensitivity of current GWD



- Thermal noise is a limiting noise source.
- Future GWDs will employ cryogenic mirrors.
  -> thermal noise reduction

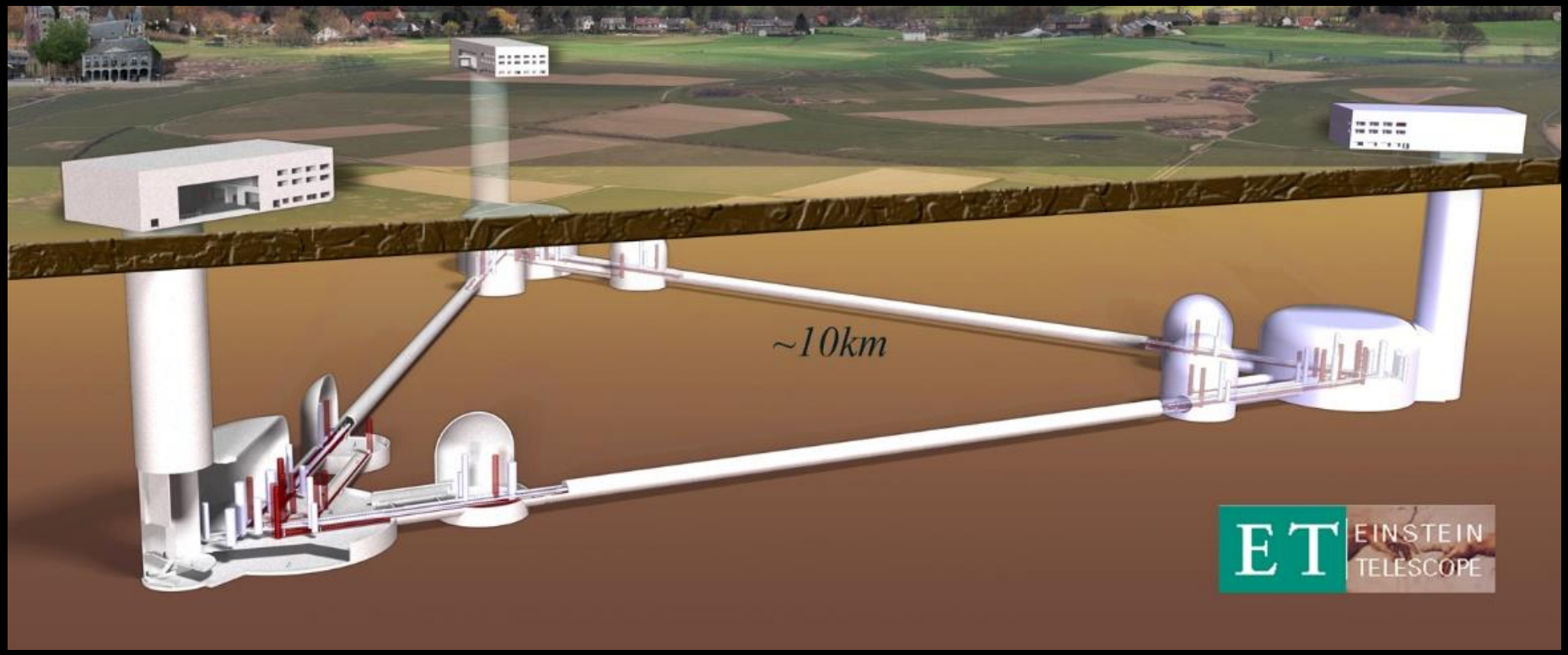
LIGO Voyager

- ✓123 K cryogenic silicon mirror
- ✓2 um laser



R. Adhikari+ 2020

The Einstein Telescope (ET)



- ✓ 10 K cryogenic mirror
- ✓ 1.5 um laser

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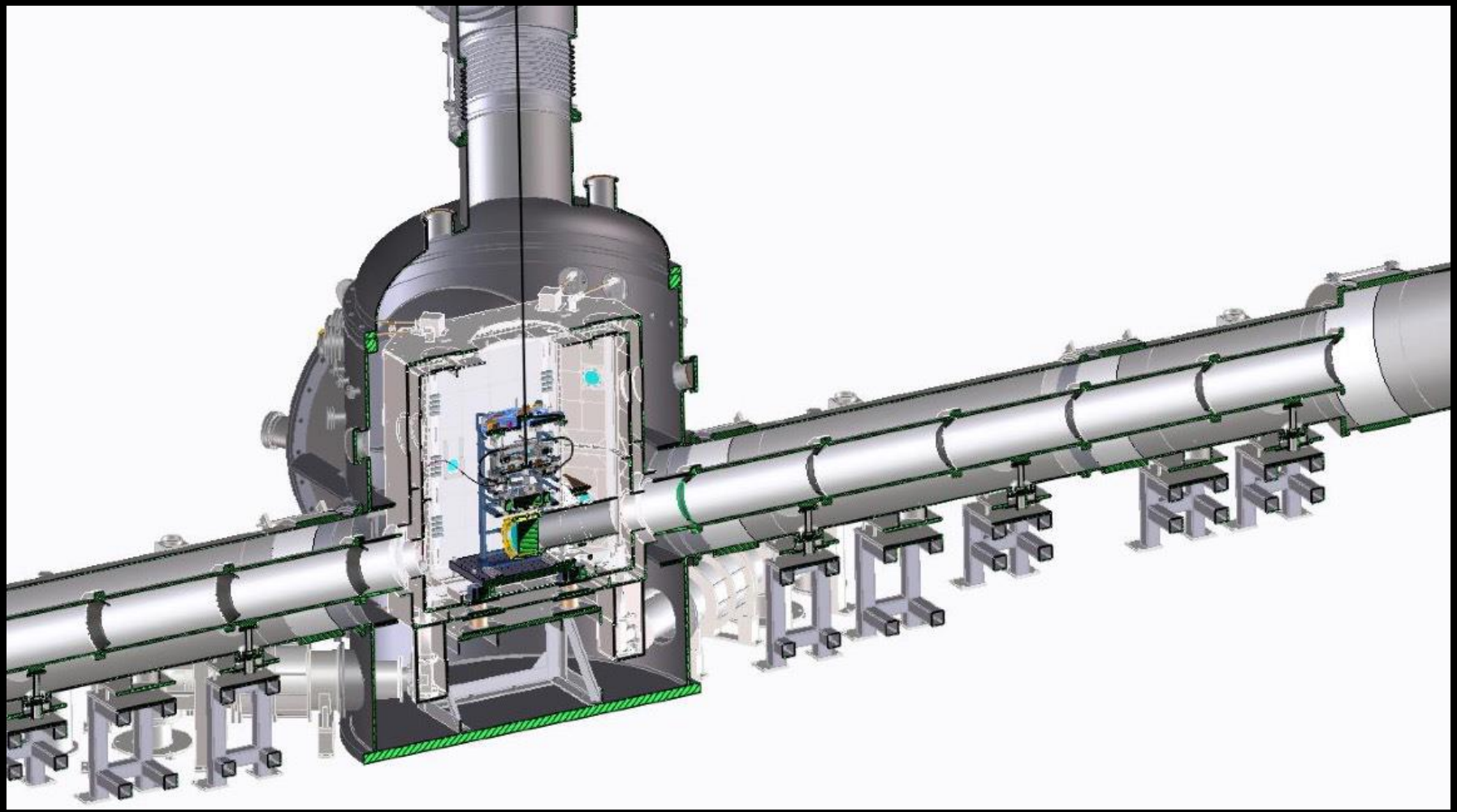
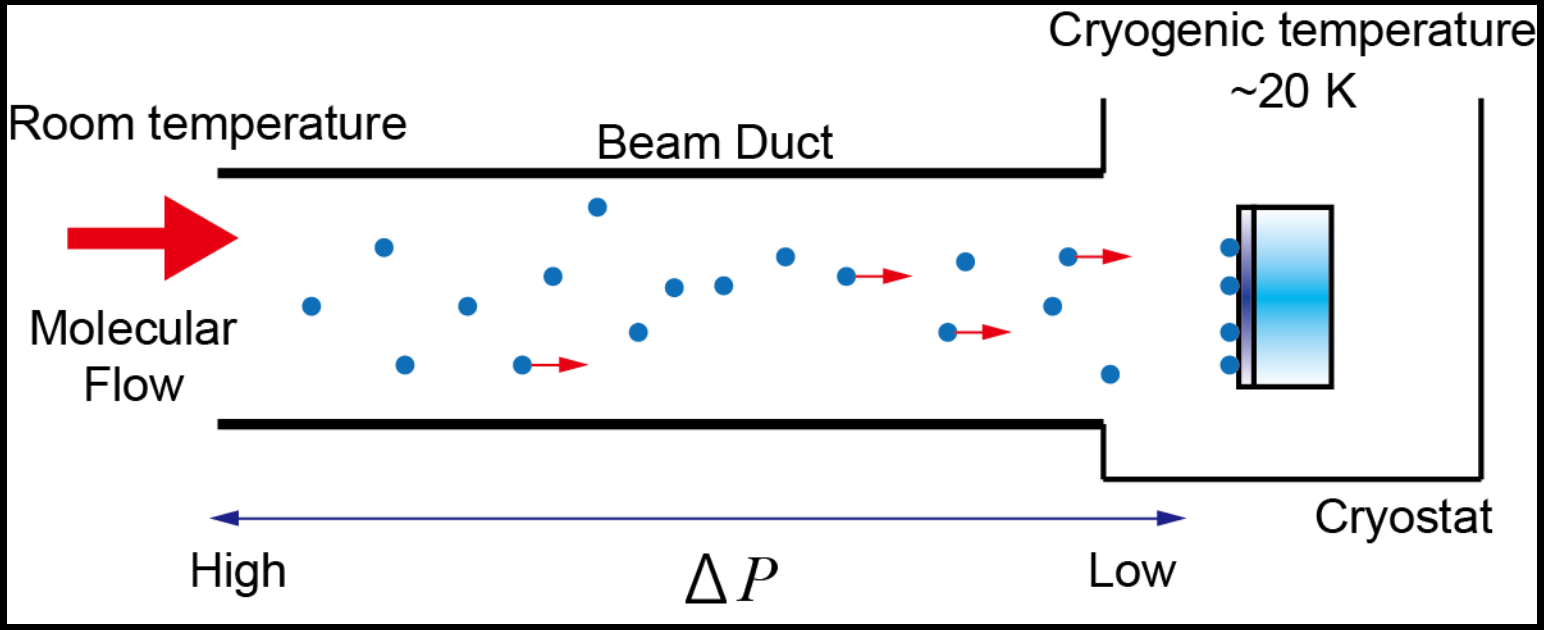
- ✓underground
- ✓cryogenic

Cryogenic system of KAGRA



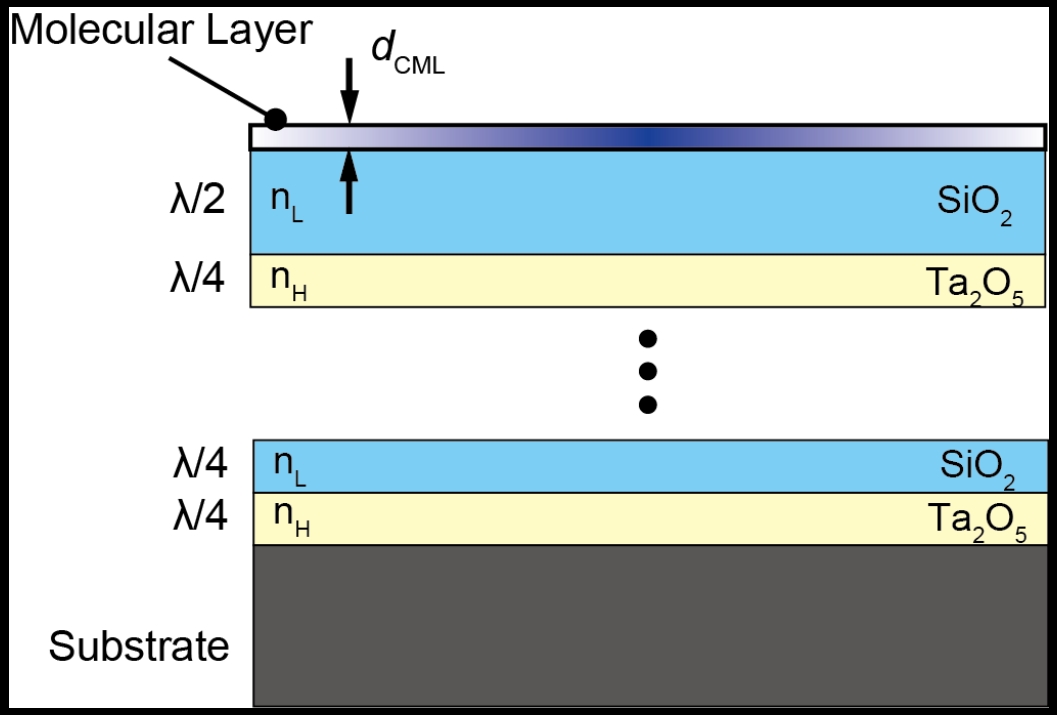
Molecular flow to the mirror



- ✓ Cryogenic mirror is exposed to the room temperature vacuum.
  -> molecules are adsorbed onto the mirror
  cryopumping

Hasegawa+ PRD (2019)

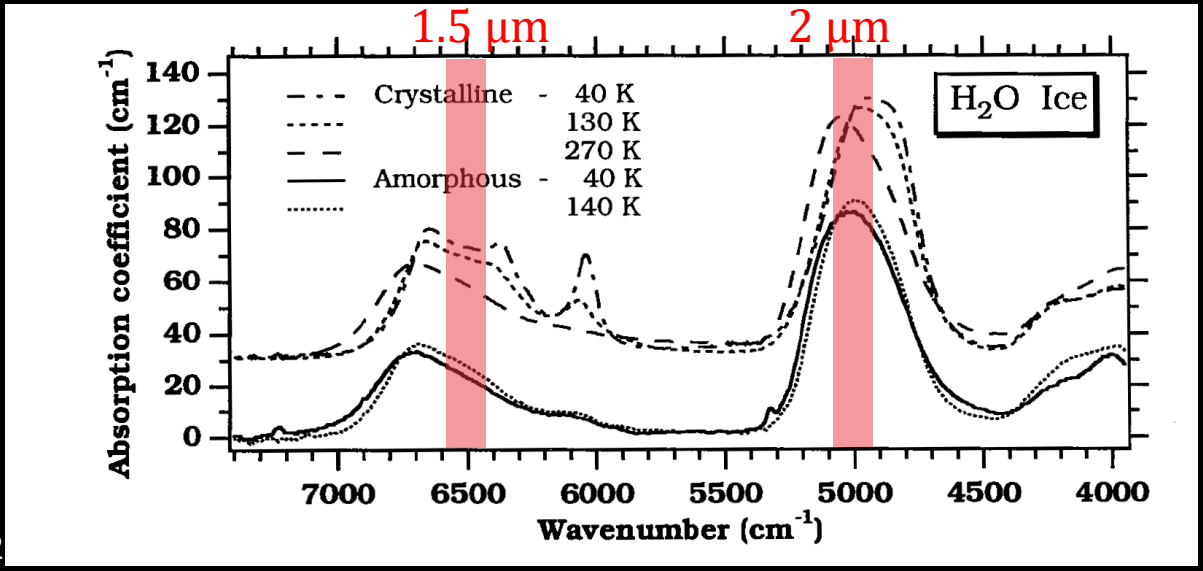
Cryogenic molecular layer (CML)



- ✓ Continuous molecular flow leads to the formation of cryogenic molecular layers (CMLs).
- ✓ Water molecules are main components.
  -> amorphous ice

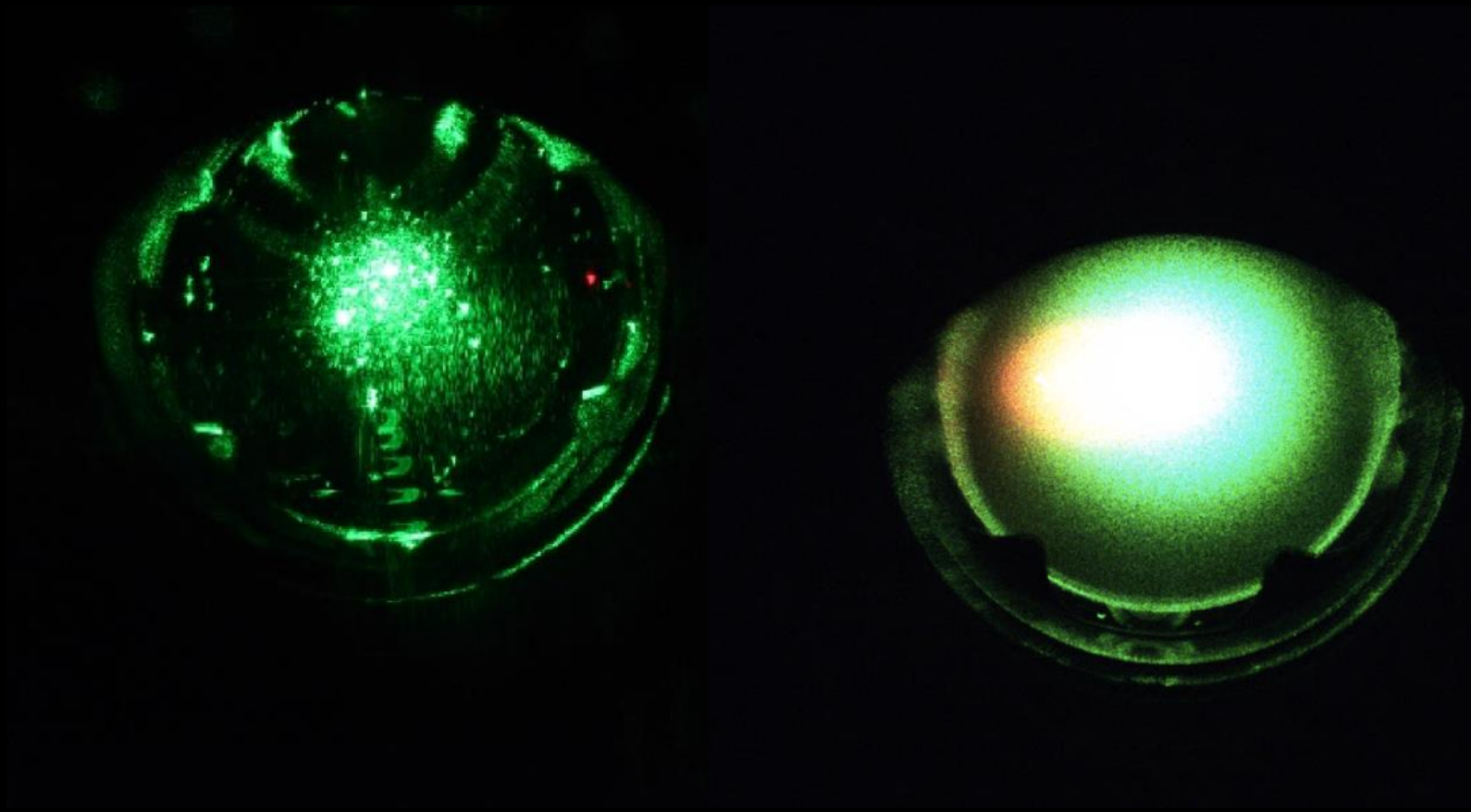
Absorption of amorphous ice

- ✓Future GWDs will use longer wavelength laser (1.5 um, 2 um).
- ✓Amorphous ice has large absorption.
  ~ 2 ppm/nm @ 1.5 um
  ~ 8 ppm/nm @ 2.0 um
  -> large optical loss
- ✓This effect has not been taken into account.



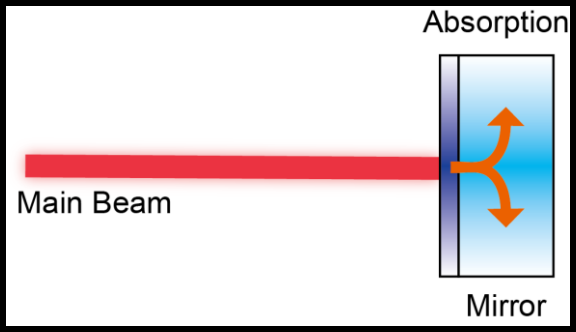
Schmitt+ "Optical Properties of Ices From UV to Infrared", Springer (1998)

CML formation on KAGRA test mass

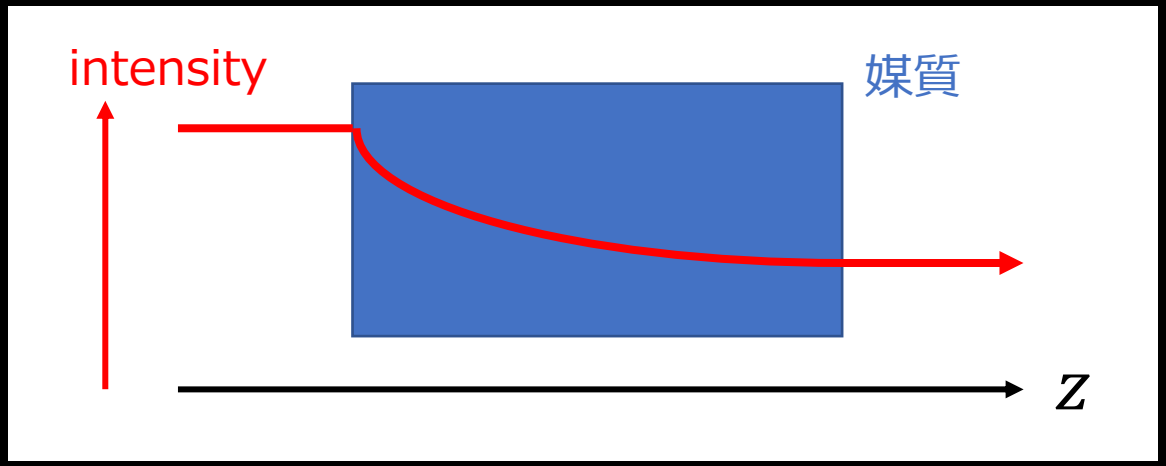


http://klog.icrr.u-tokyo.ac.jp/osl/?r=9377

Optical absorption

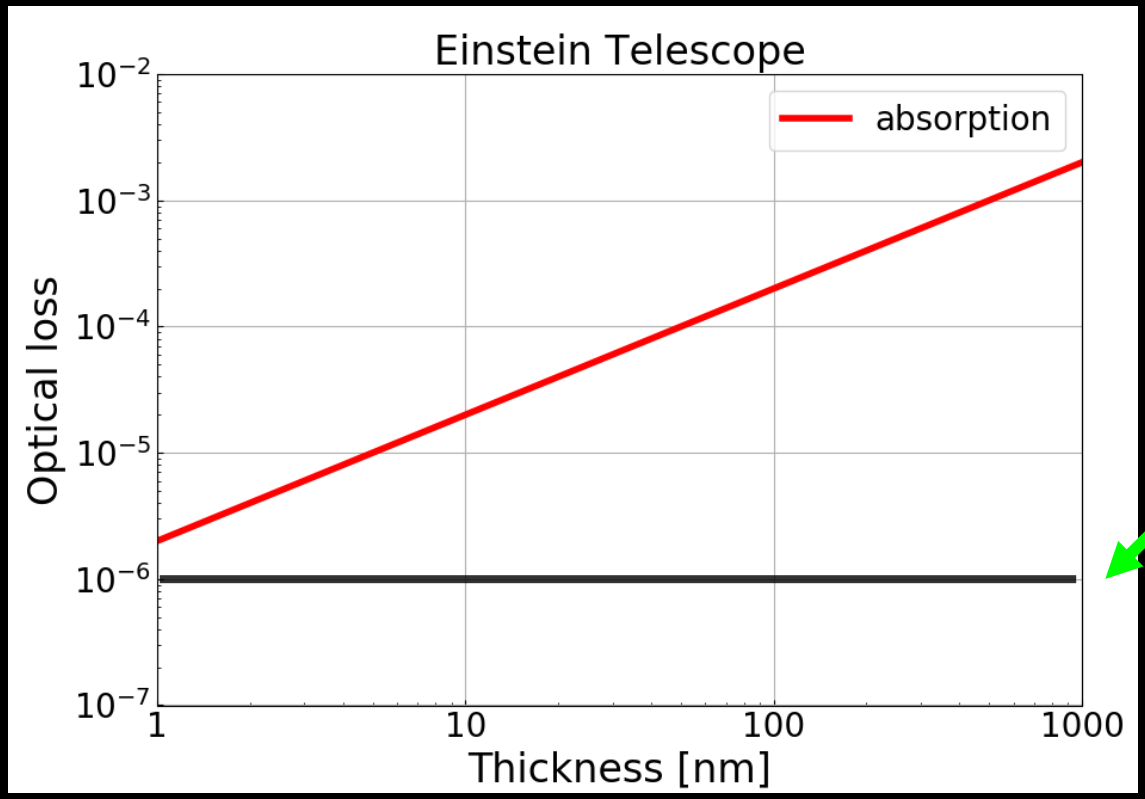


- ✓Lambert-Beer's law
- ✓Intensity $I(z) = I_0 \exp(-\alpha z)$
  - α: absorption coefficient



$$A_{\mathrm{CML}} = P_{\mathrm{CML}}[1 - \exp(-\alpha_{\mathrm{CML}} d_{\mathrm{CML}})],$$

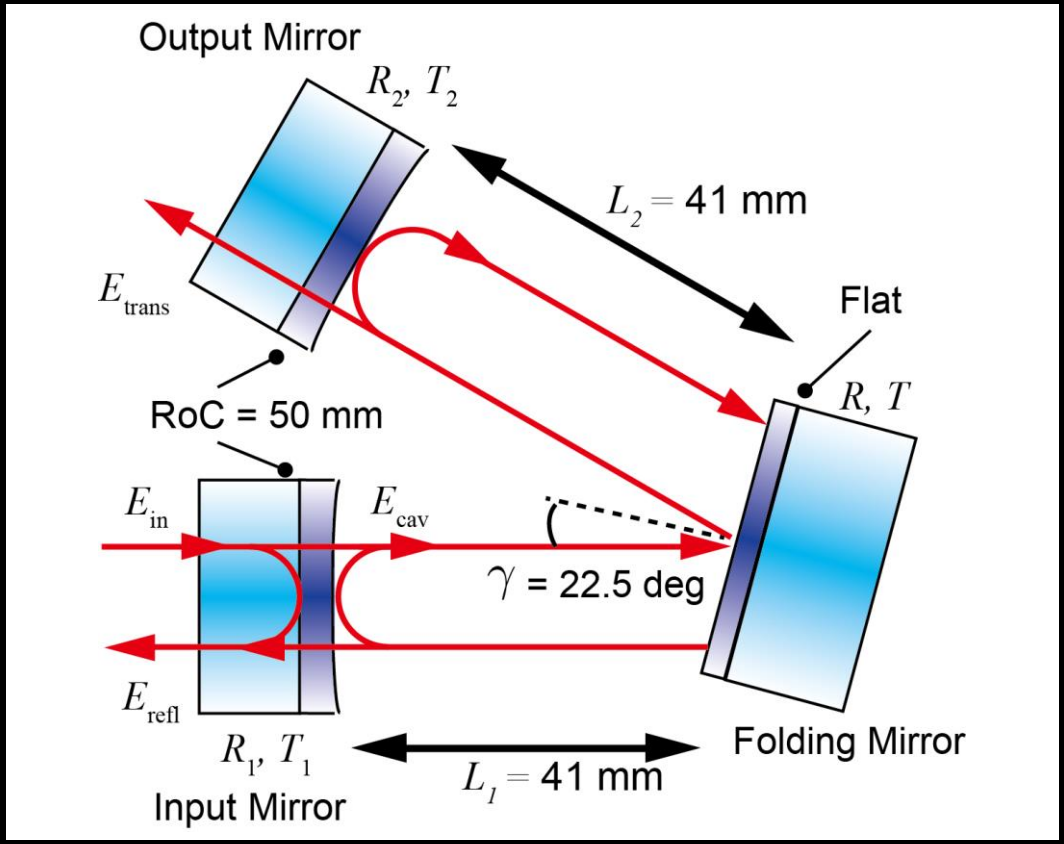
For the case of the ET



requirements on coating absorption

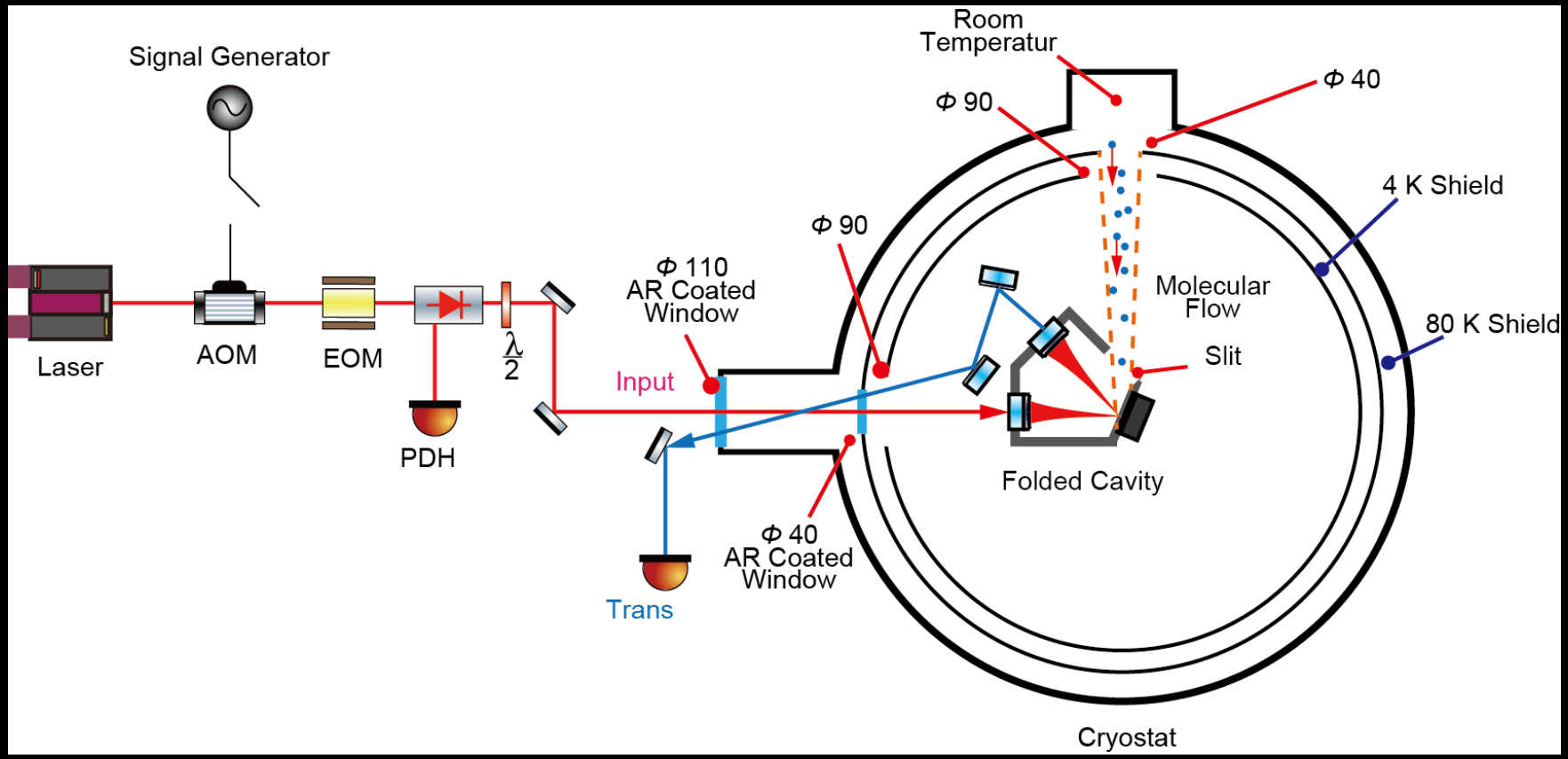
- ✓ Optical absorption by CML can become ppm order.
- ✓ Excess heat load can be introduced by this absorption.
  -> cannot be cooled down to target temperature?

Folded Cavity



- ✓ Composed by 3 mirrors.
- ✓ Finesse is $\sim 2 \times 10^4$.
- ✓ 1550 nm wavelength laser.

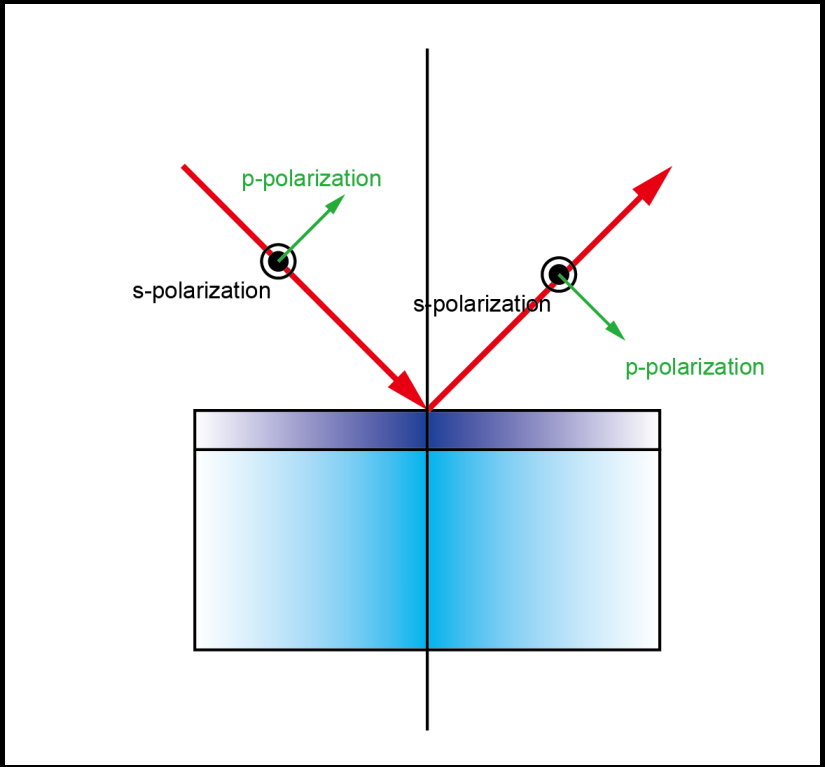
Overview of the setup

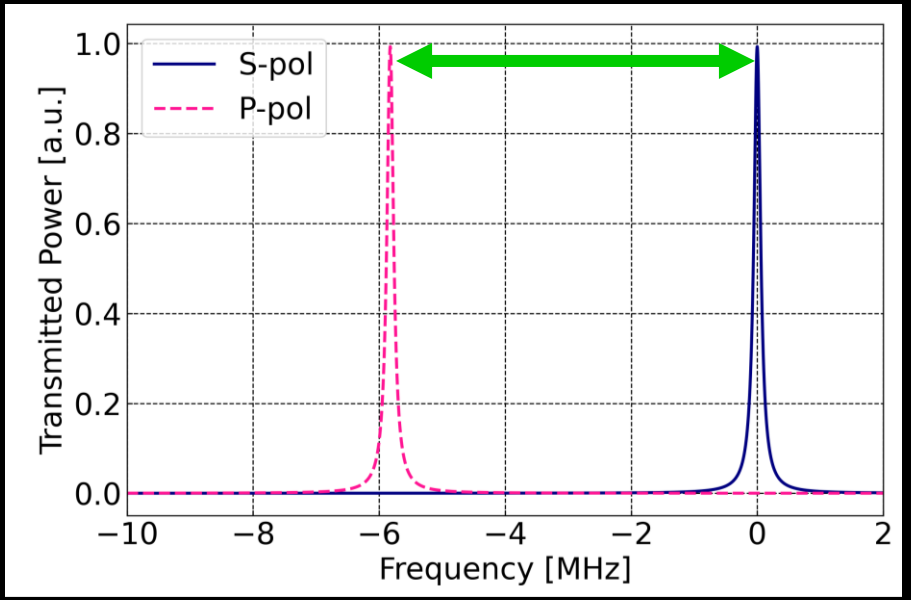


- ✓ The cavity is cooled down to 10 K.
- ✓ A folding mirror is exposed to the room temperature vacuum.
  -> CML formation

Cavity enhanced ellipsometry

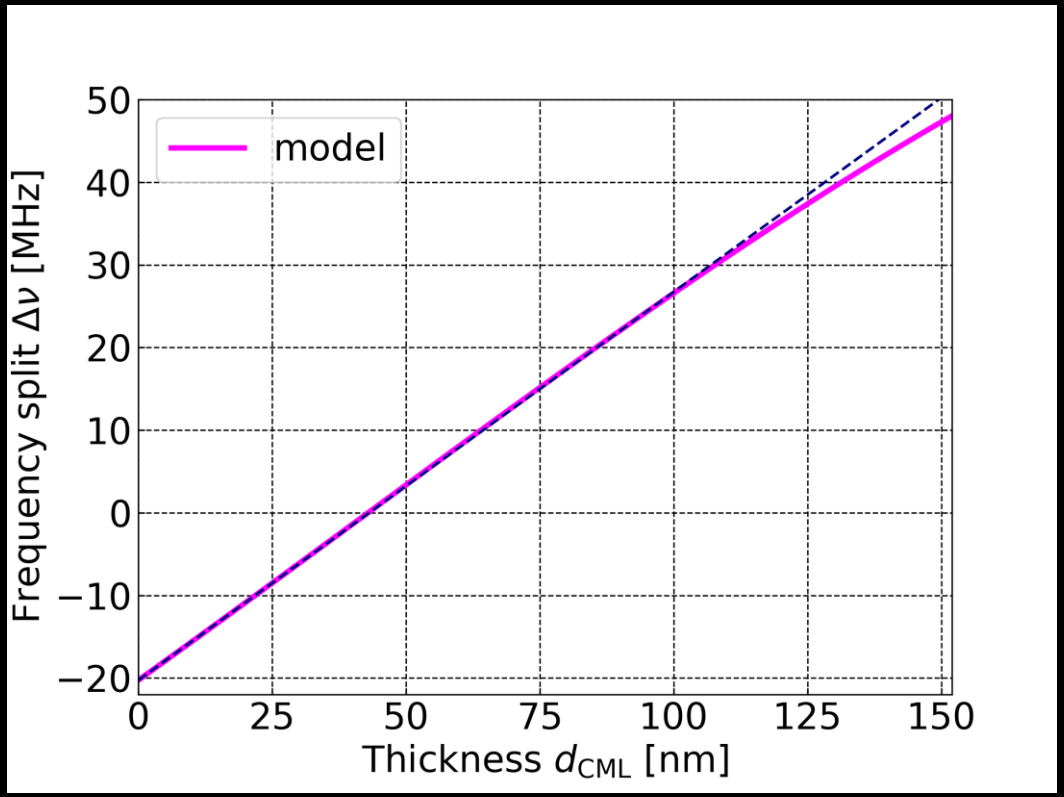
- ✓A folding mirror introduces a phase shift between P- and S-polarization
  -> resonant frequency split





Cavity enhanced ellipsometry

- The resonant frequency split drifts as the CML thickness increases.



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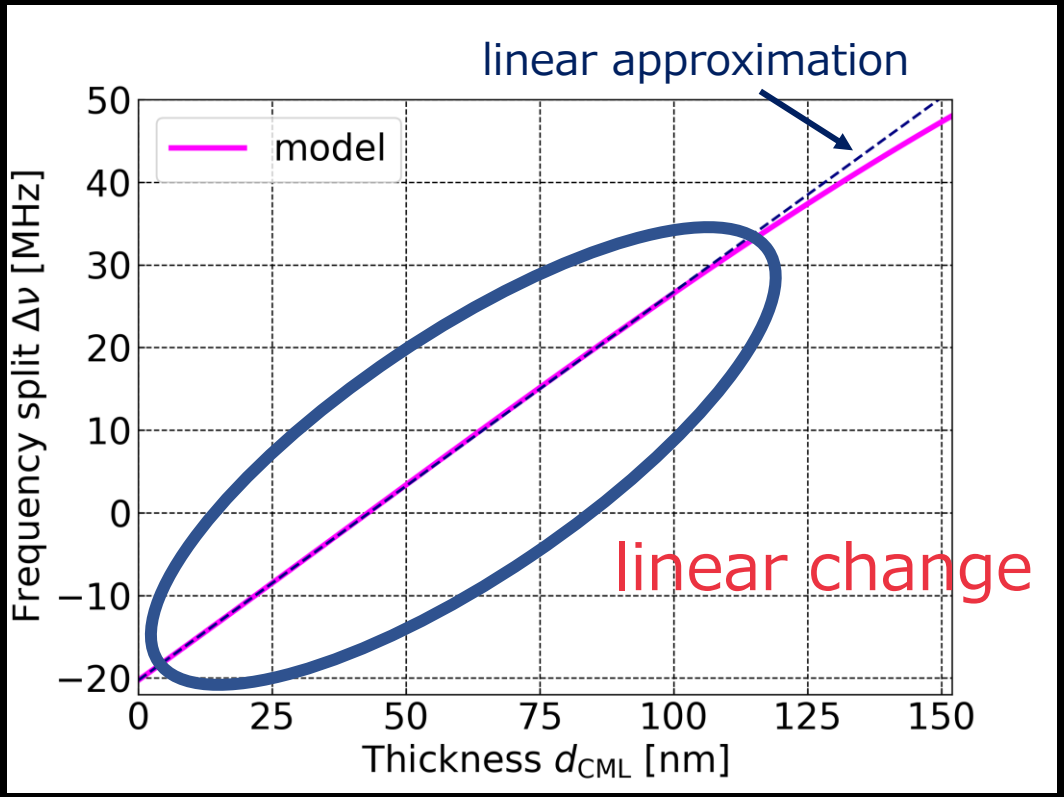
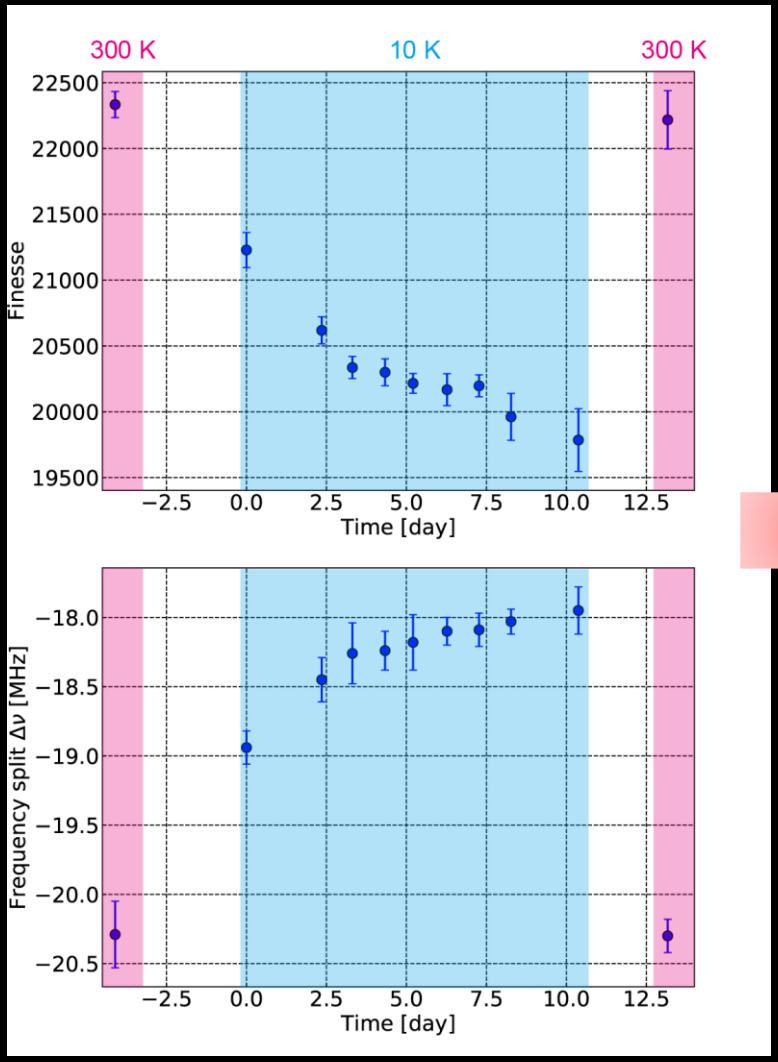
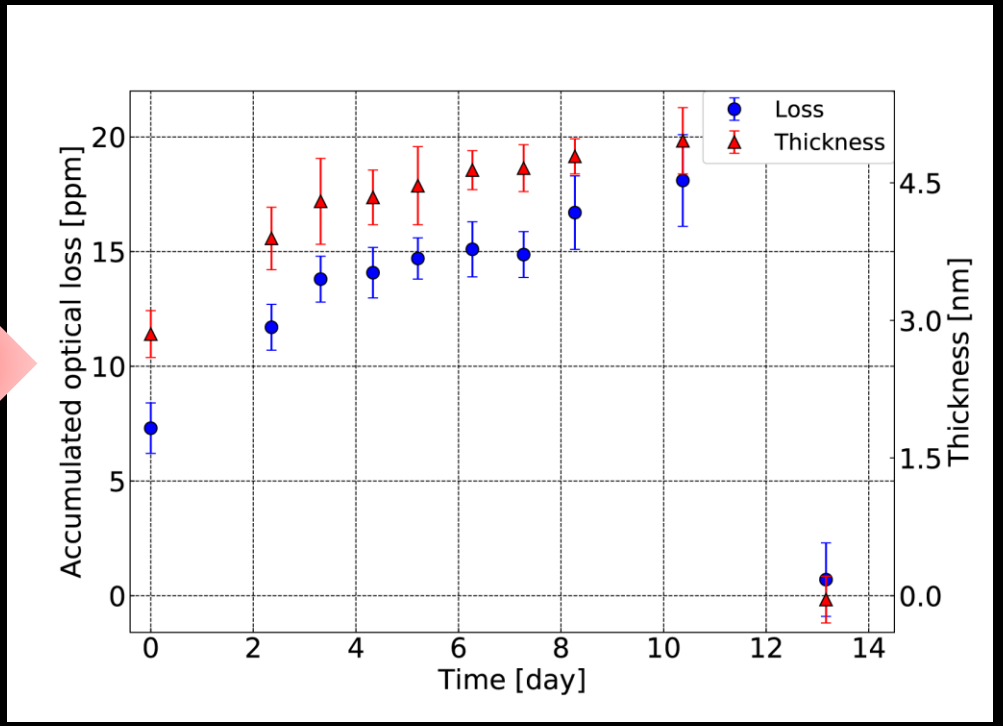
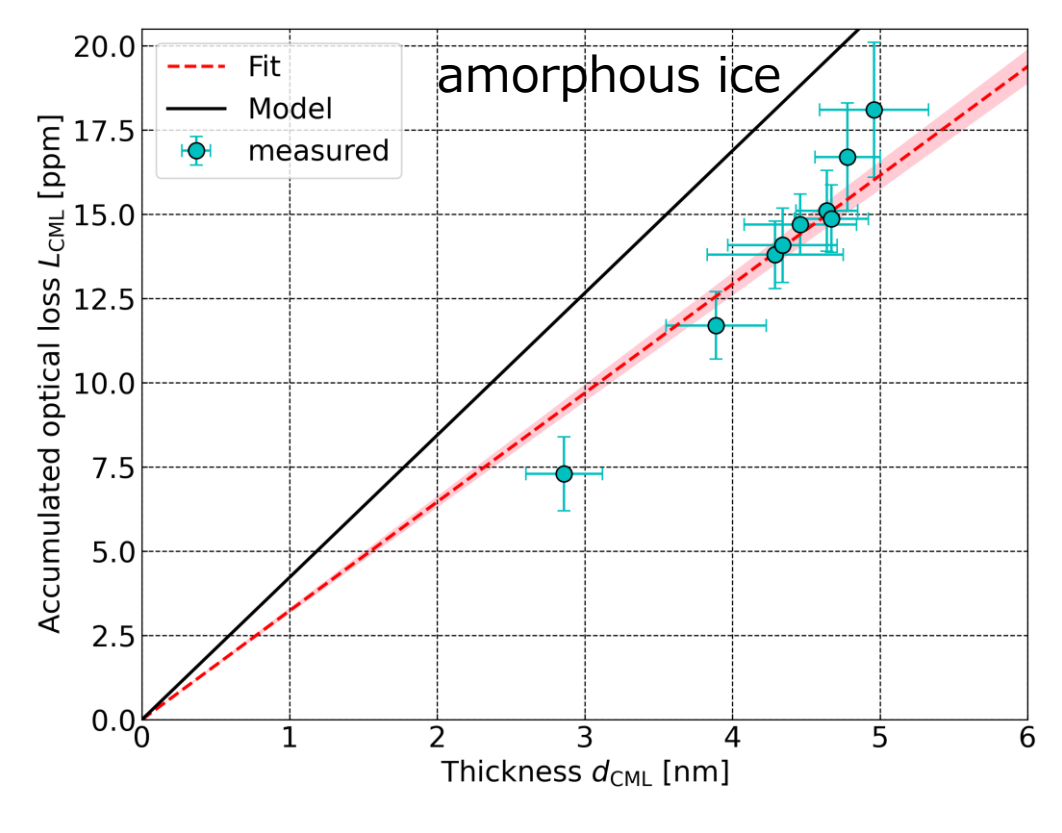


Finesse and CEE trends





Comparison to the amorphous ice model



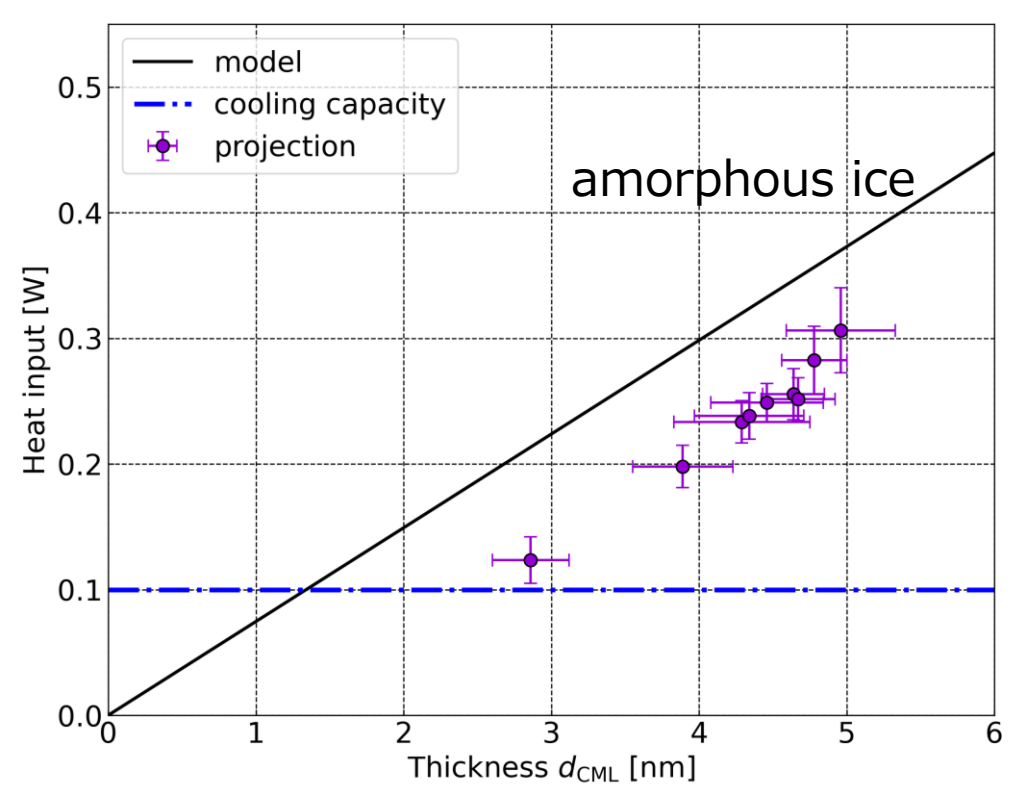
Lambert-Beer Law is assumed

$$L_{\mathrm{CML}} = 2\alpha d_{\mathrm{CML}}$$

α: absorption coefficient

✓ Assumed that the scattering is negligible.
✓ Smaller than compared to the amorphous ice model.

Implication to the ET

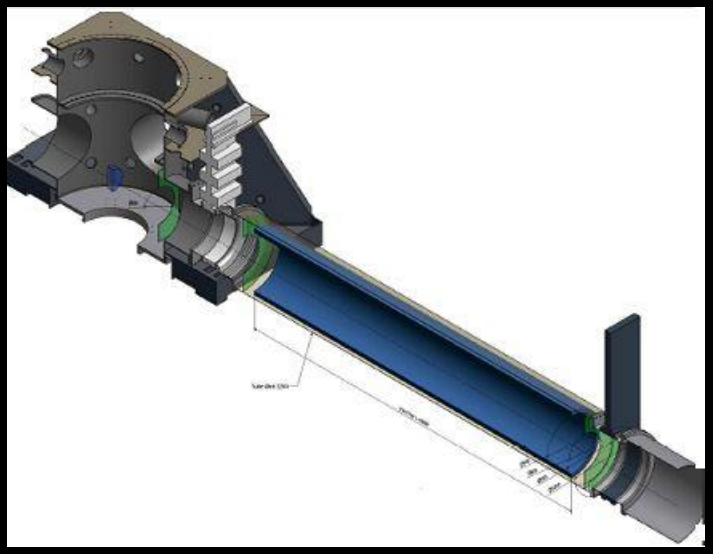


18 kW intra-cavity power

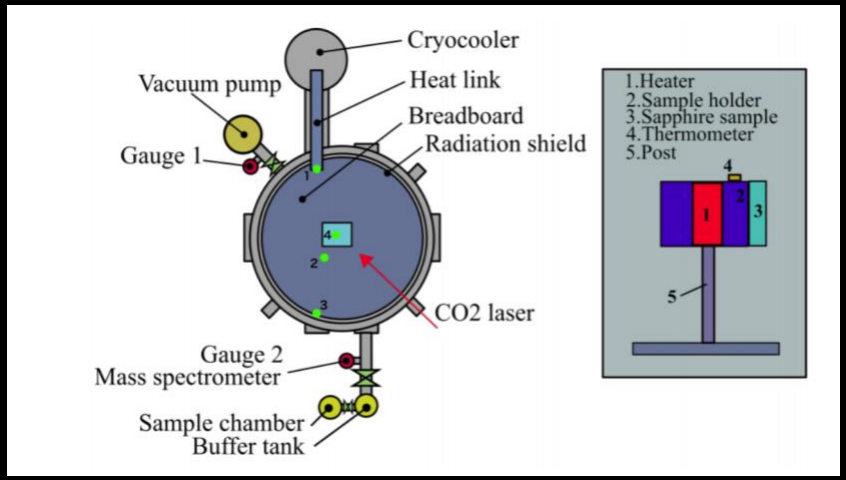
- ✓ The heat input induced by the CML can exceed the cooling capacity even a few nanometer thickness.

How to solve?

- ✓Passive way
  - ✓better vacuum level
  - ✓longer cryotrap
- ✓Active way
  - ✓heating up the mirror
    - ✓utilize CO_2 laser



http://www.et-gw.eu/images/ET_Image_Gallery/vac6.jpg



K. Hasegawa, Ph.D Thesis (2020)

Summary

- ✓Molecular layers formed on a cryogenic mirror surfaces induce optical loss.
- ✓Optical absorption by the CML can be a crucial problem in the future cryogenic GWDs.
  - ✓even if a few nm thickness
- ✓Further studies are important for future cryogenic GWDs.
  - ✓mitigate the formation of CML
  - ✓remove the CML