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# Molecular layer formation on cooled sapphire mirrors in KAGRA Japanese gravitational wave observatory

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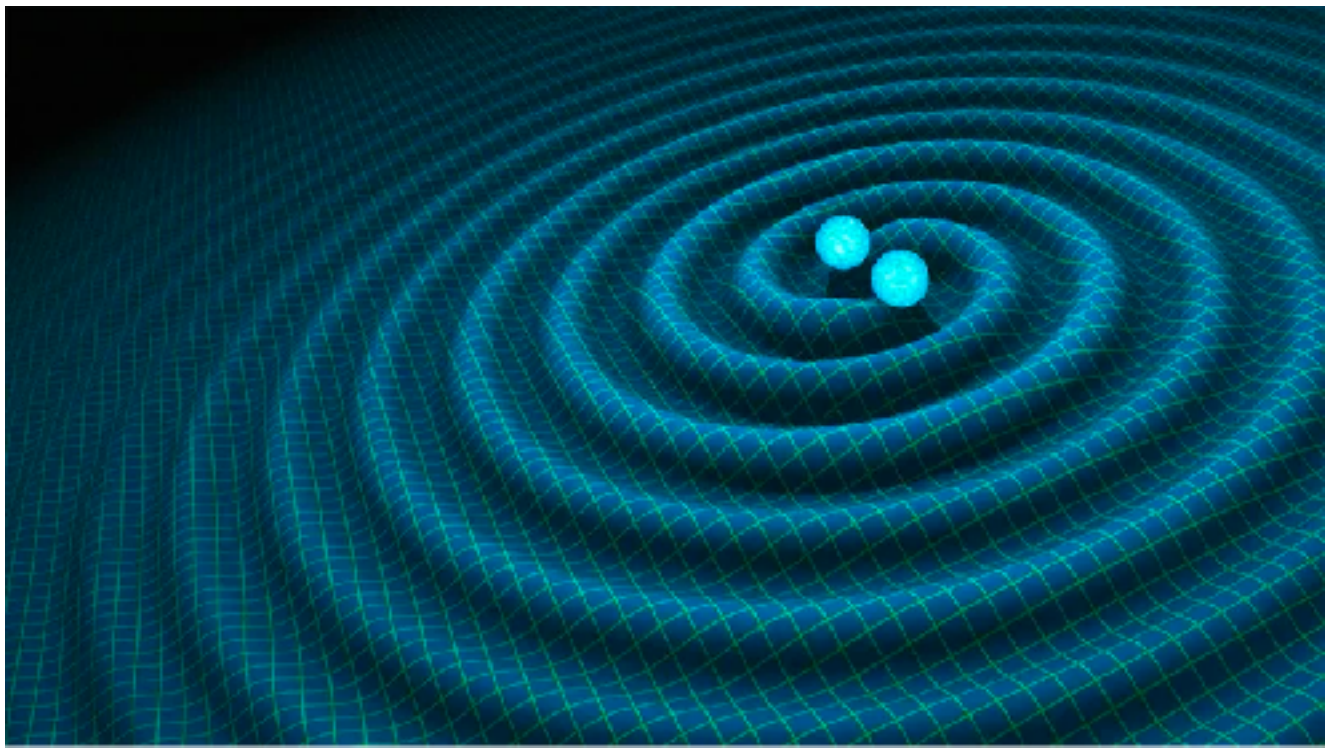
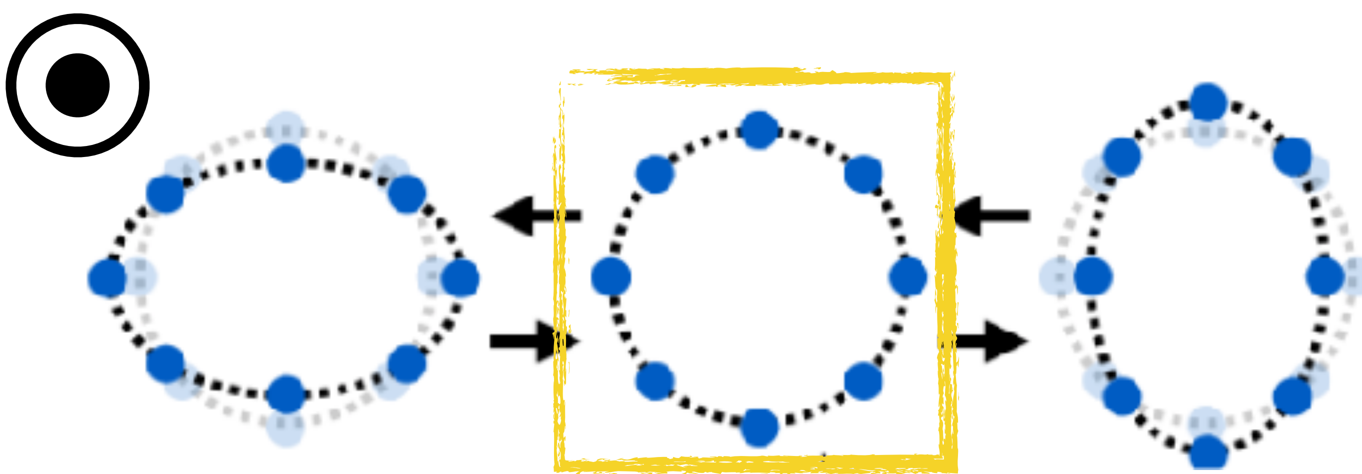
# Contents

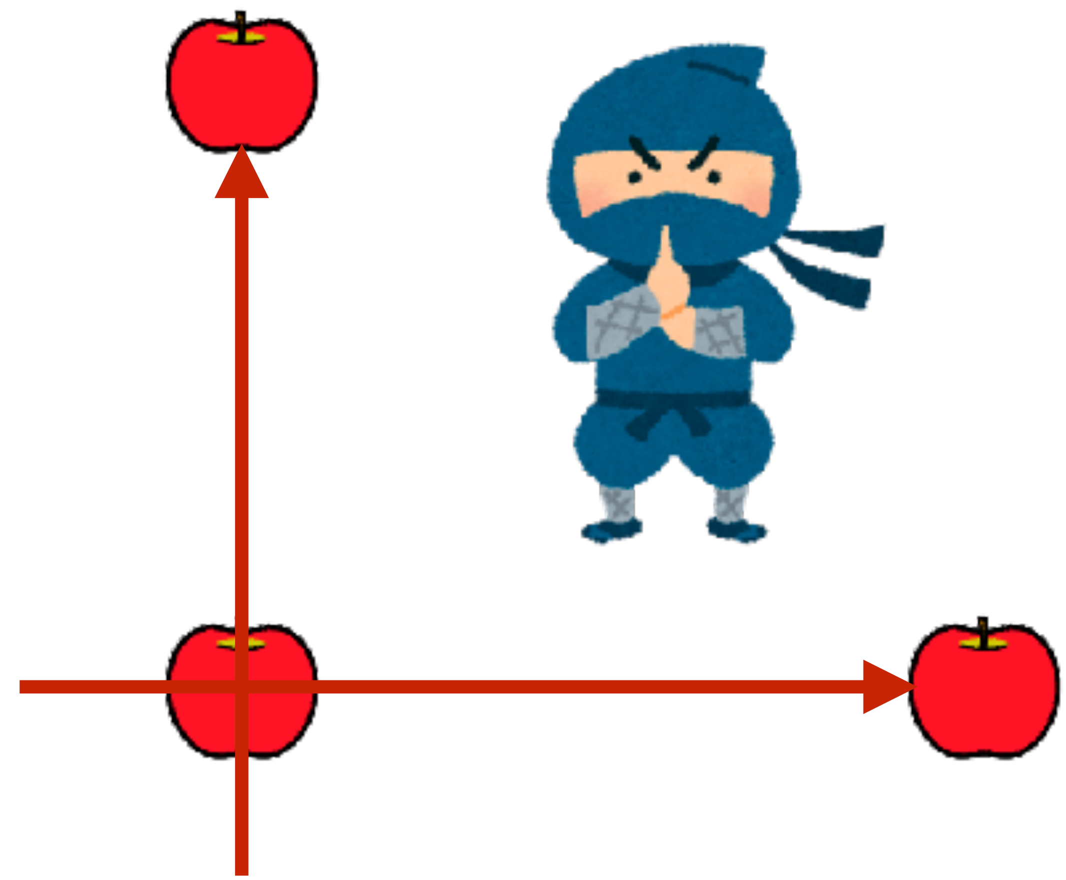
- KAGRA - Japanese gravitational wave telescope
- Overview of the KAGRA vacuum and cryogenic systems
- Molecular adsorption on cryogenic objects
- Experiment and results
- Impact for GW detectors
- How can we tackle adlayer
- Summary & Future prospects

# Gravitational wave and its detection



Gravitational wave (GW) is the wave of space time.
It can change the distance between two objects.





GWs can be detected by the laser interferometer.

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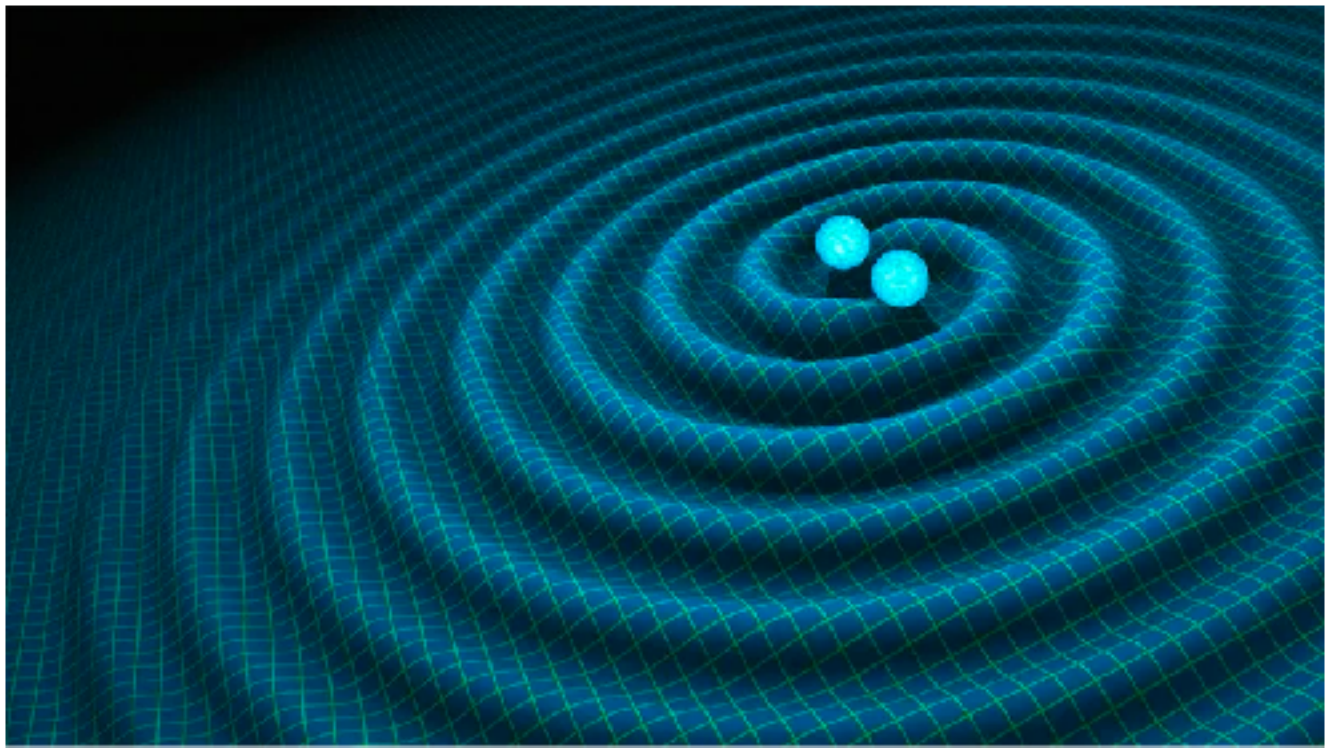

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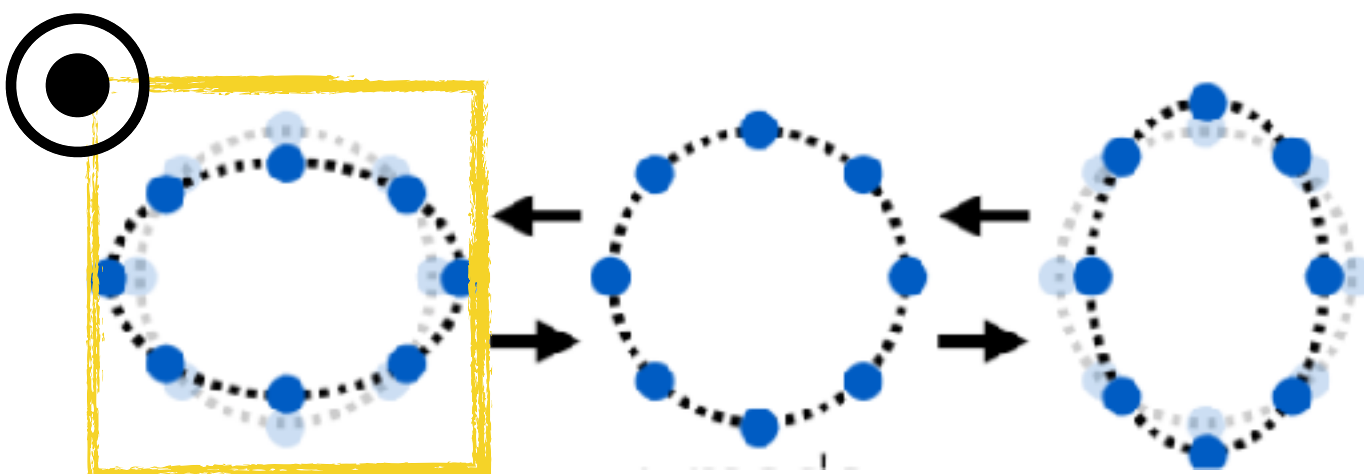

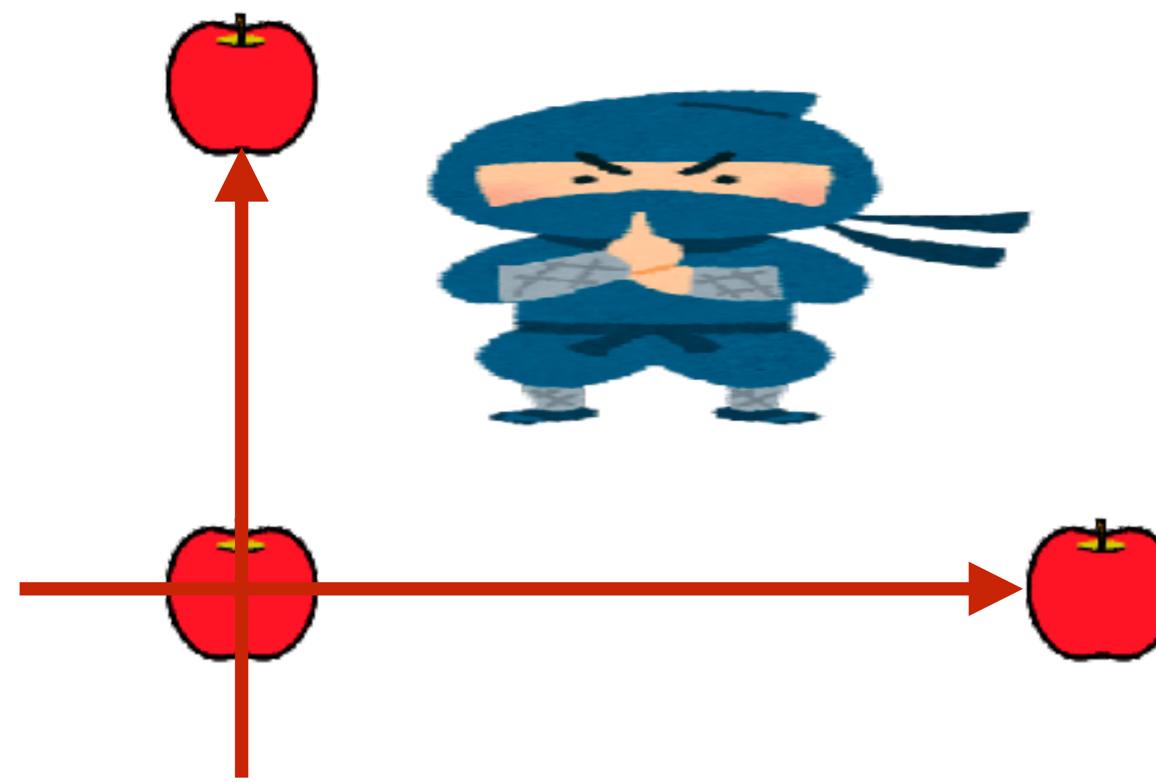

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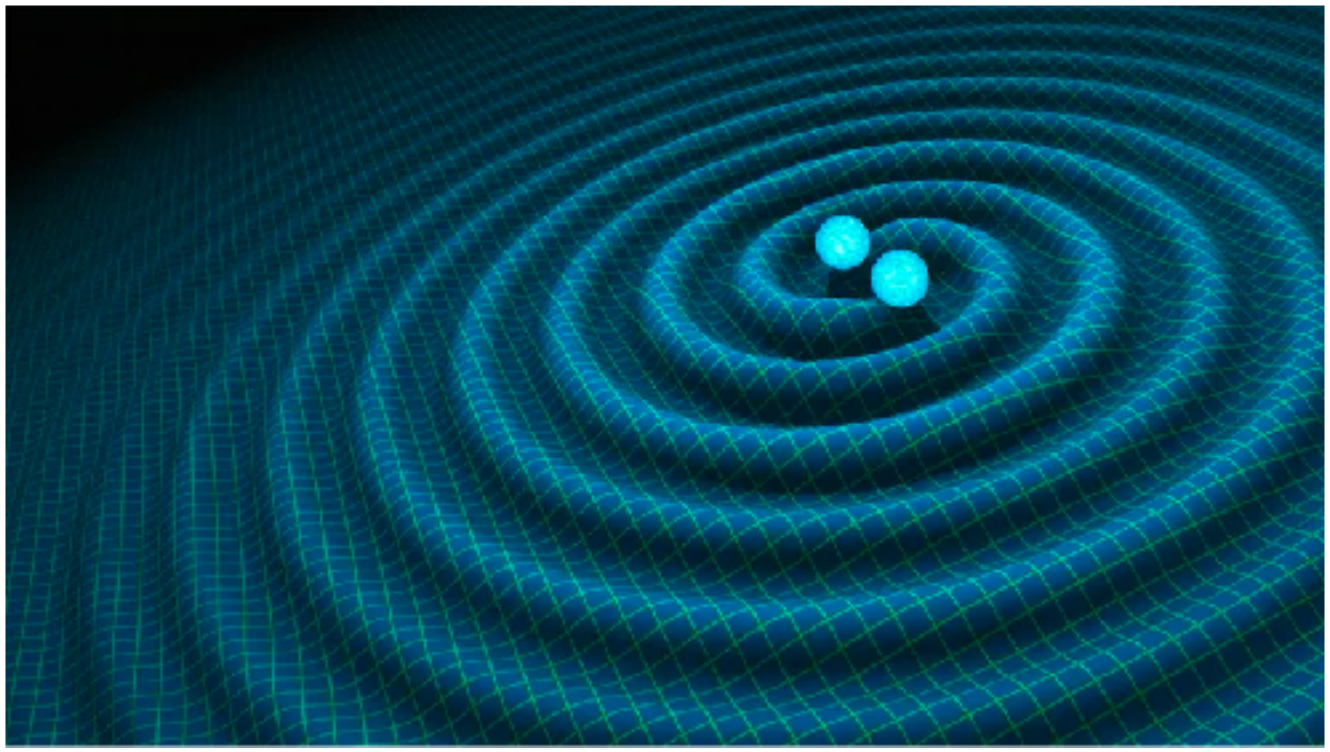

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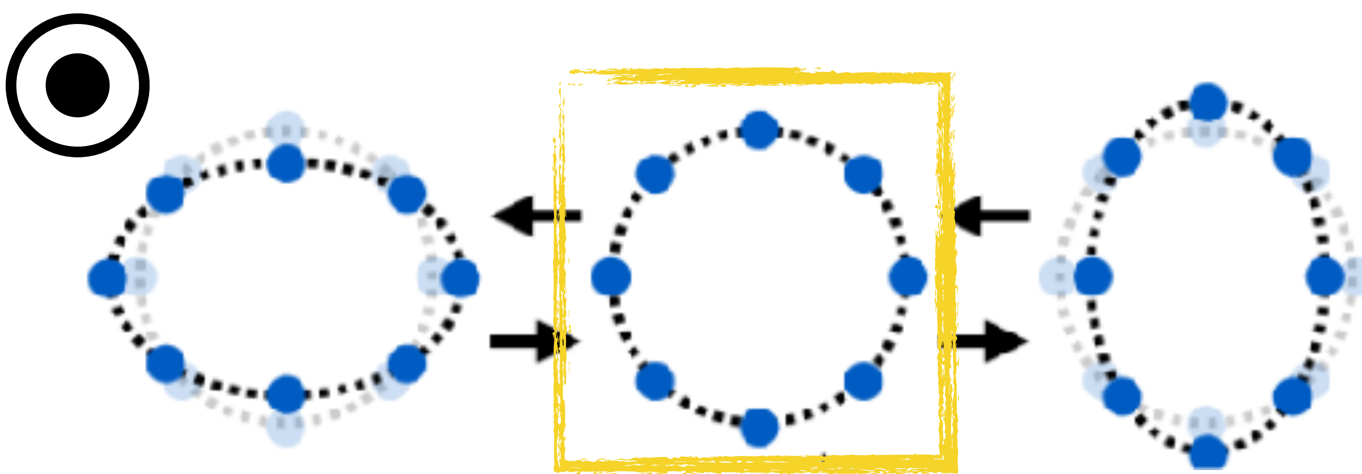

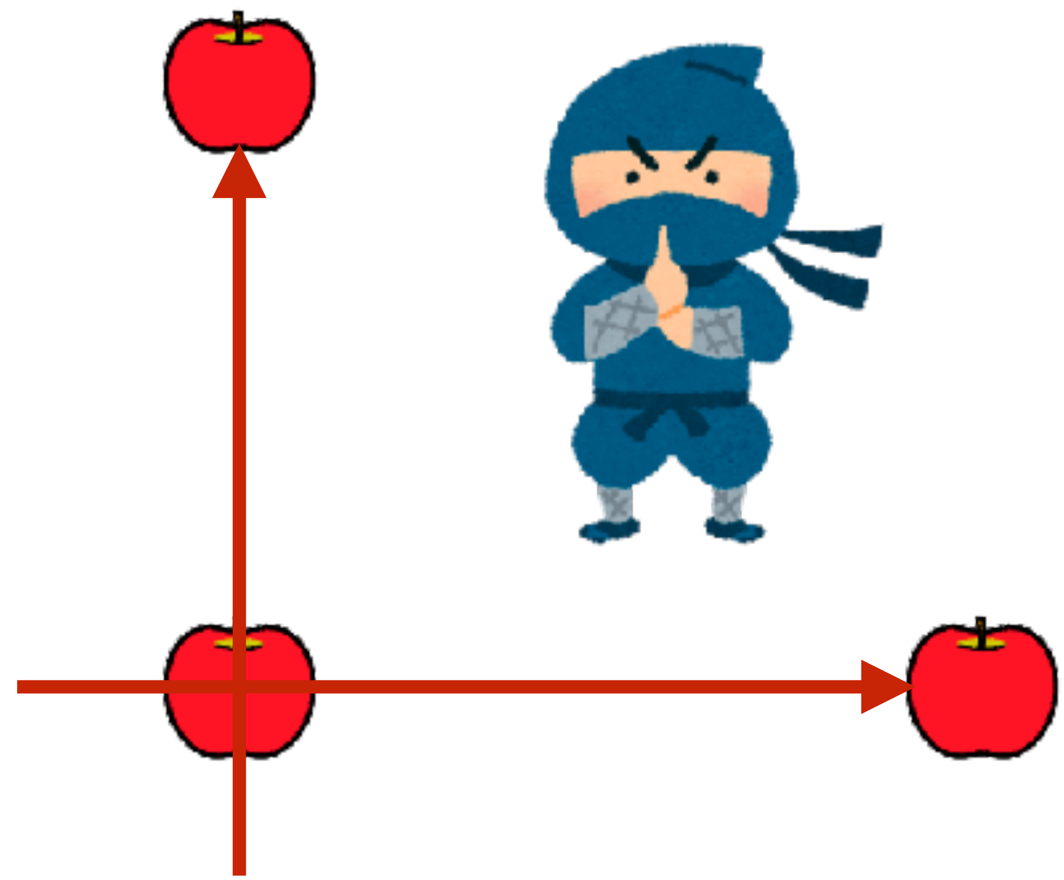

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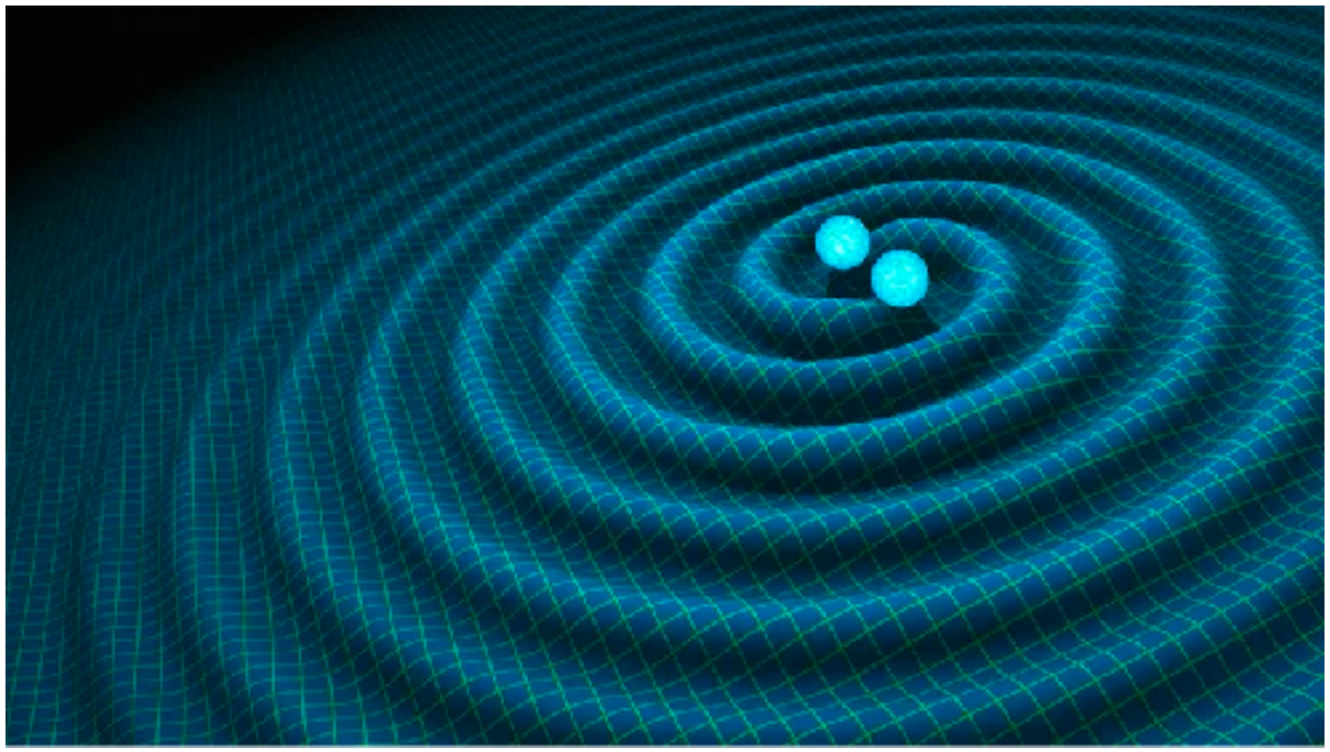

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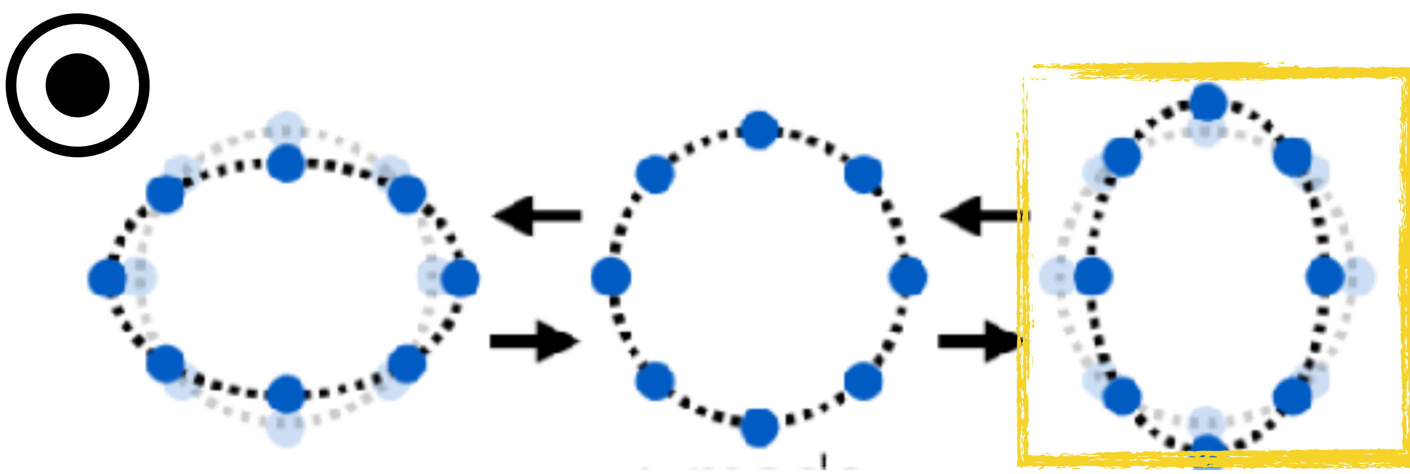

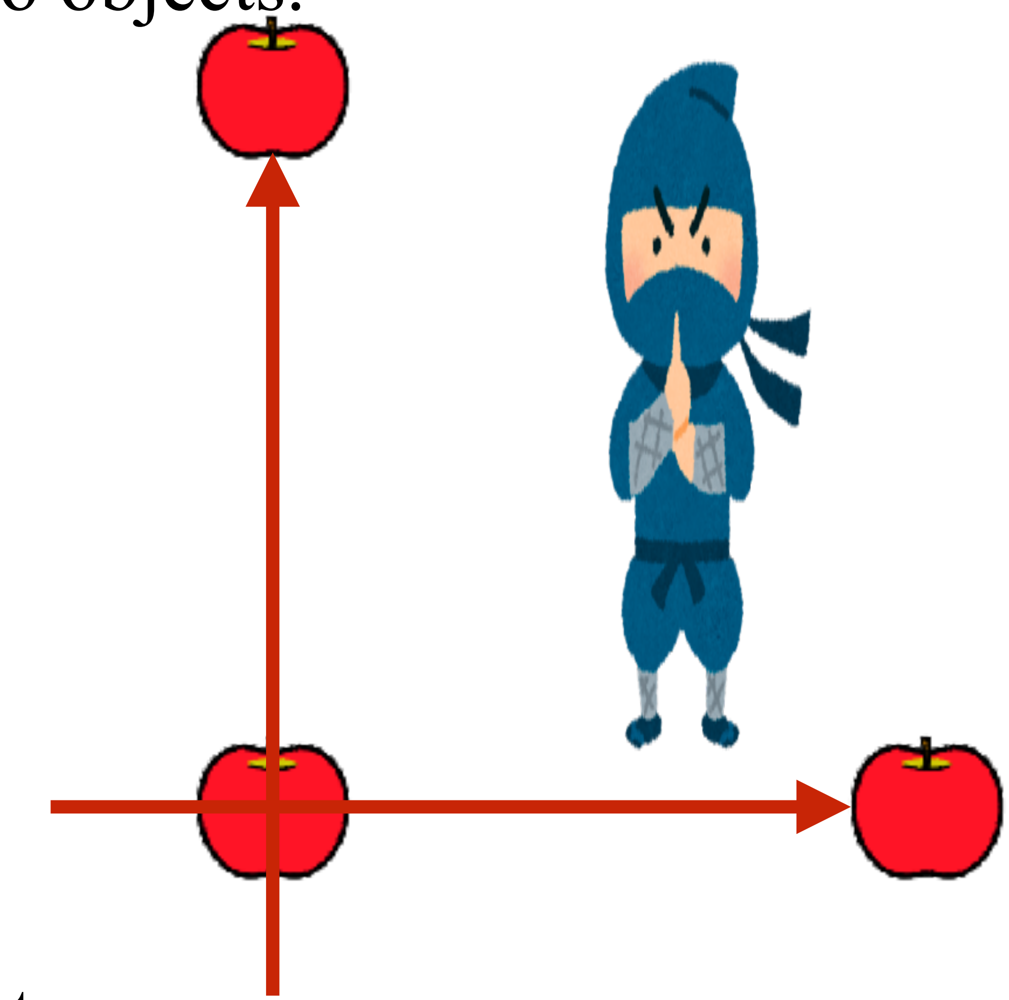

GWs can be detected by the laser interferometer.

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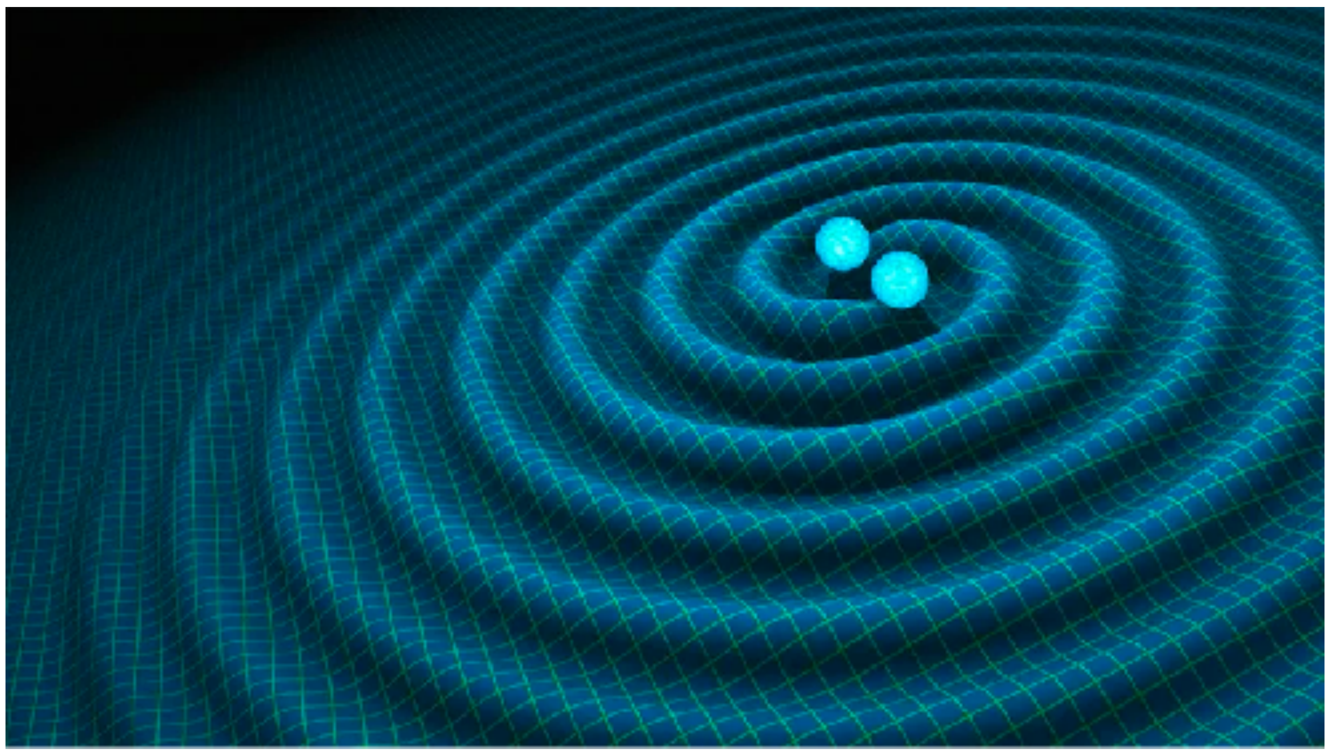

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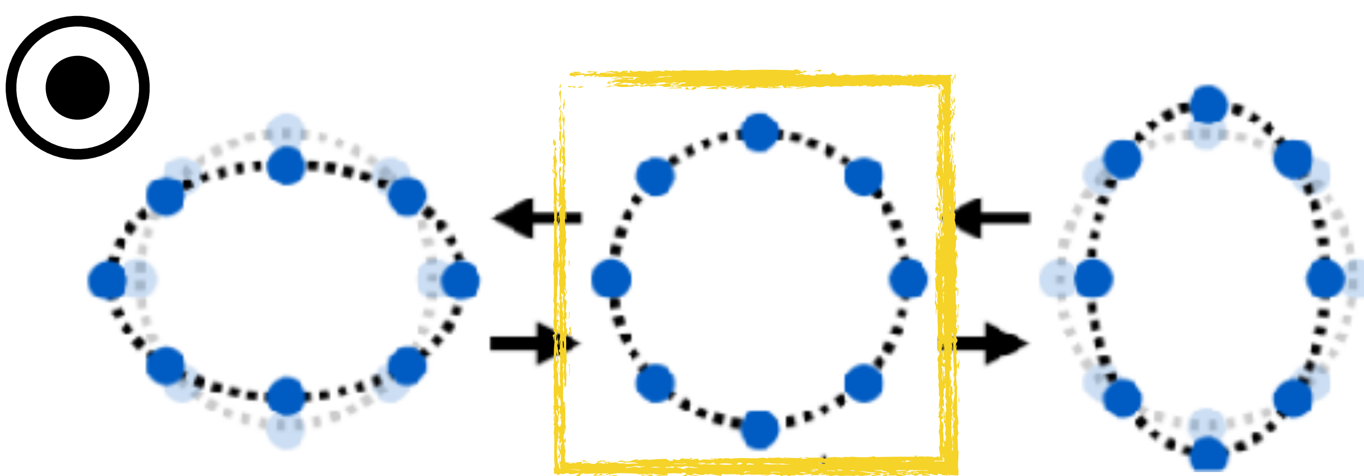
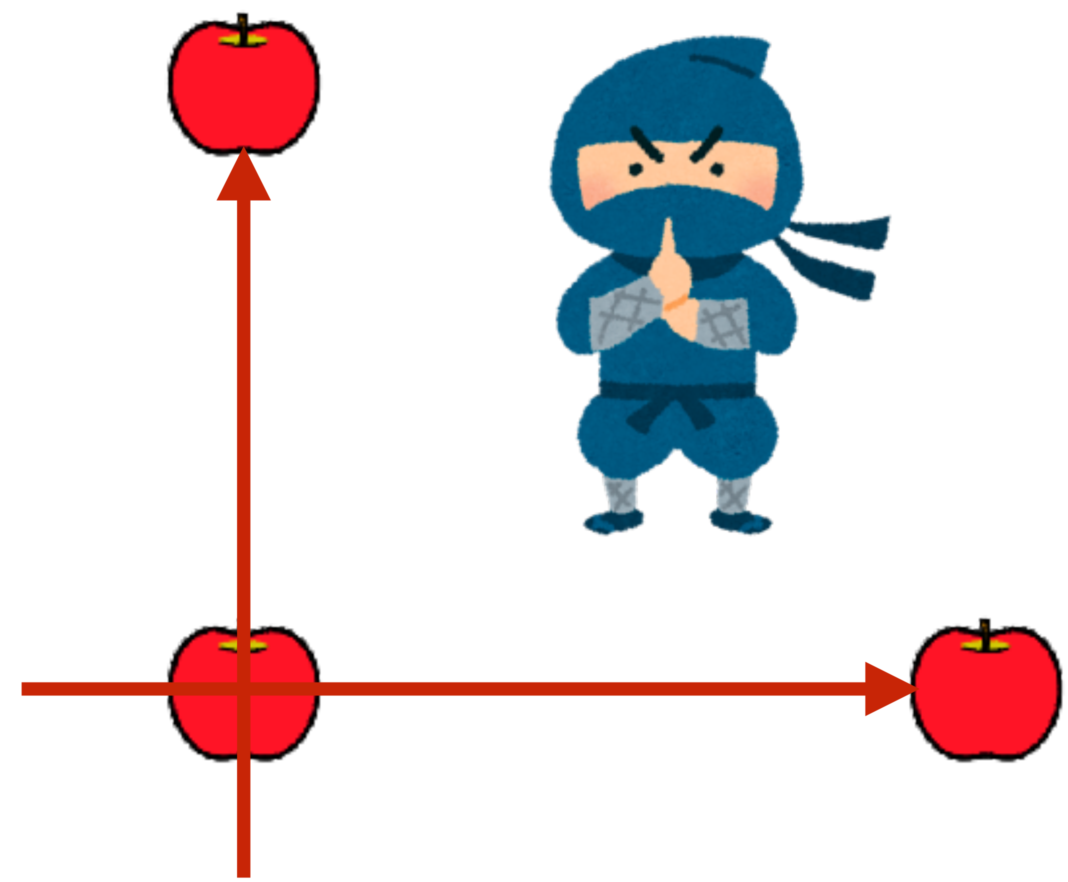




GWs can be detected by the laser interferometer.

# KAGRA - Japanese GW telescope -

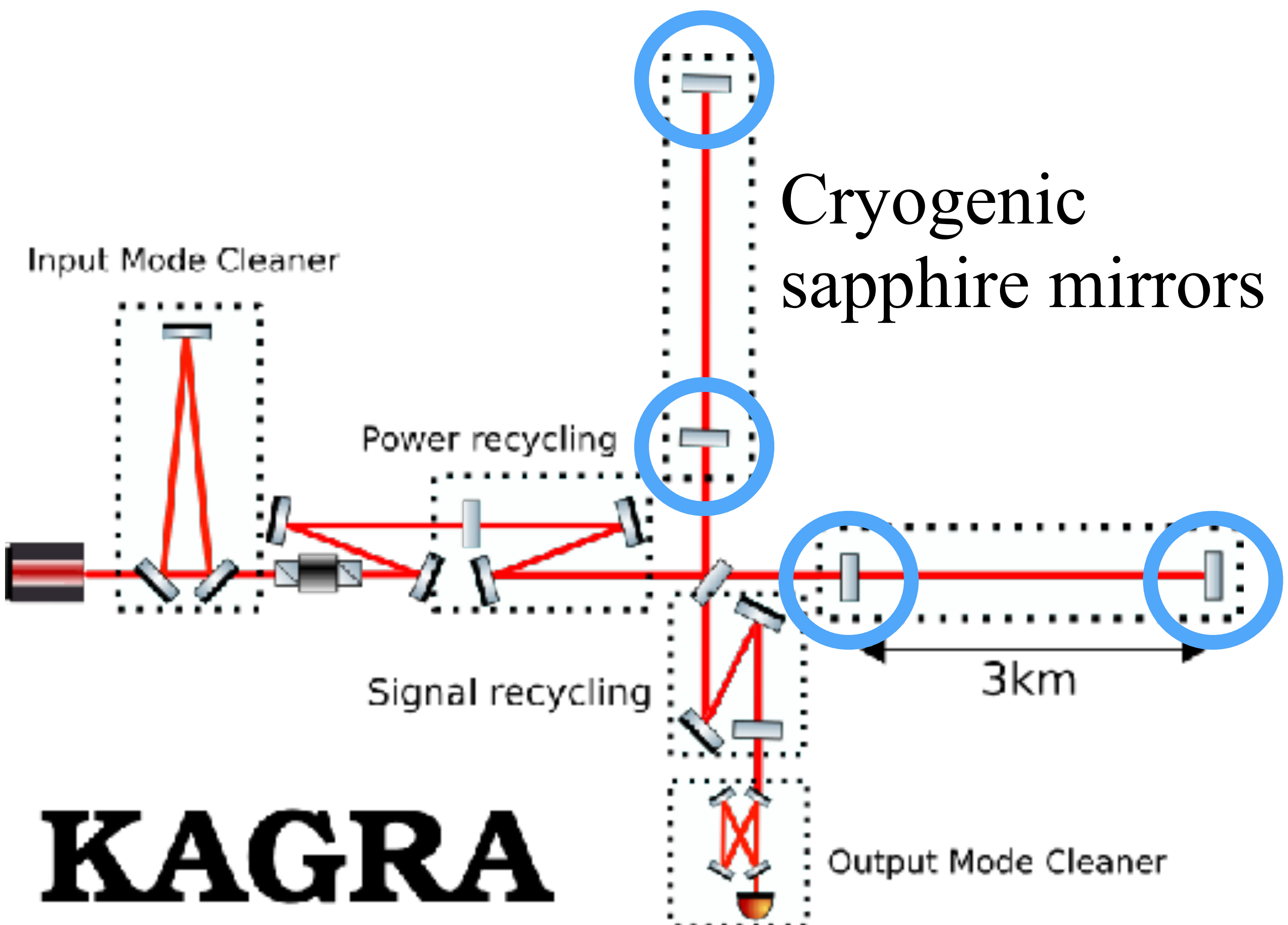
KAGRA

・3 km DRFP Michelson Interferometer

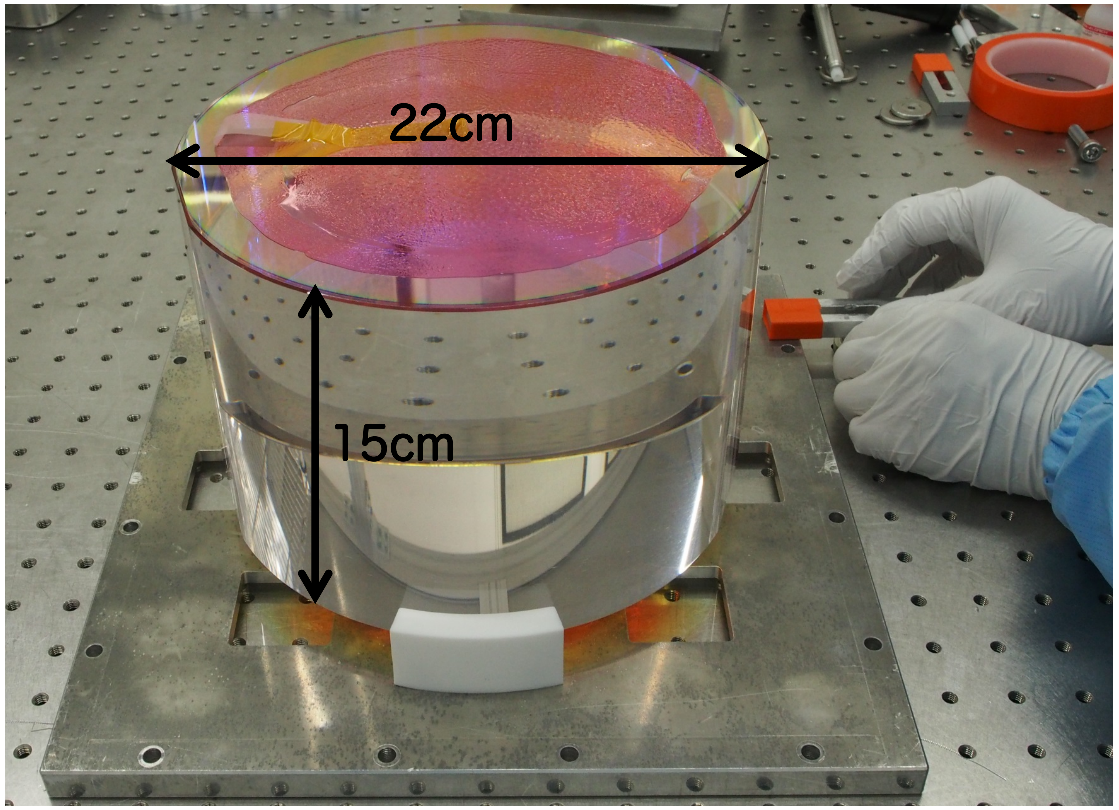
Key features :

・Underground - To reduce the seismic motion

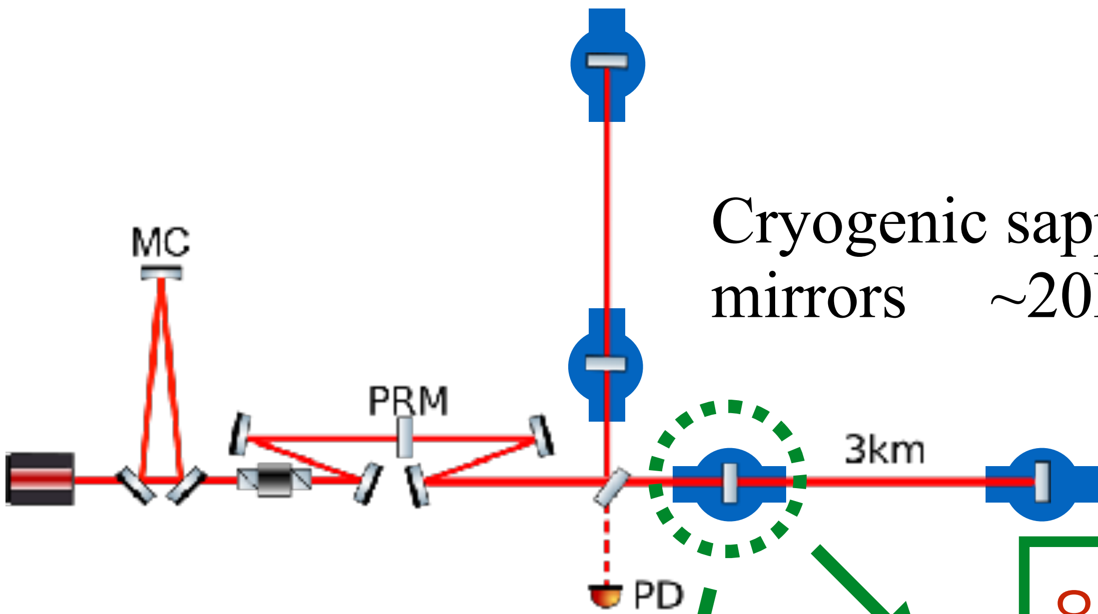
・Cryogenic sapphire mirrors - To reduce the thermal fluctuation of the mirrors




KAGRA

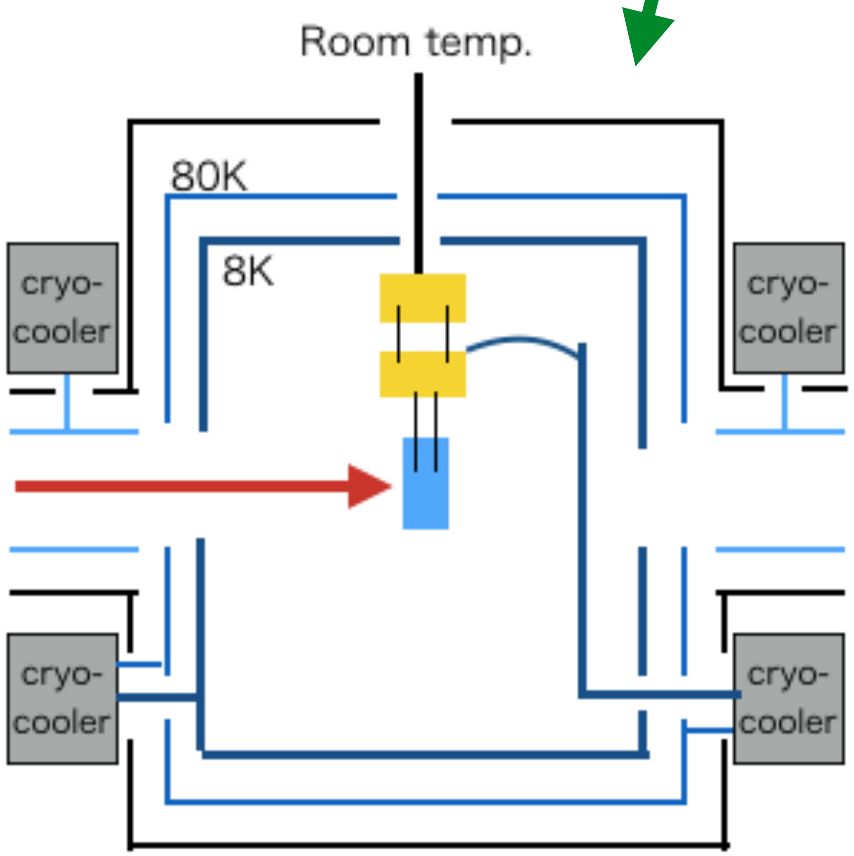


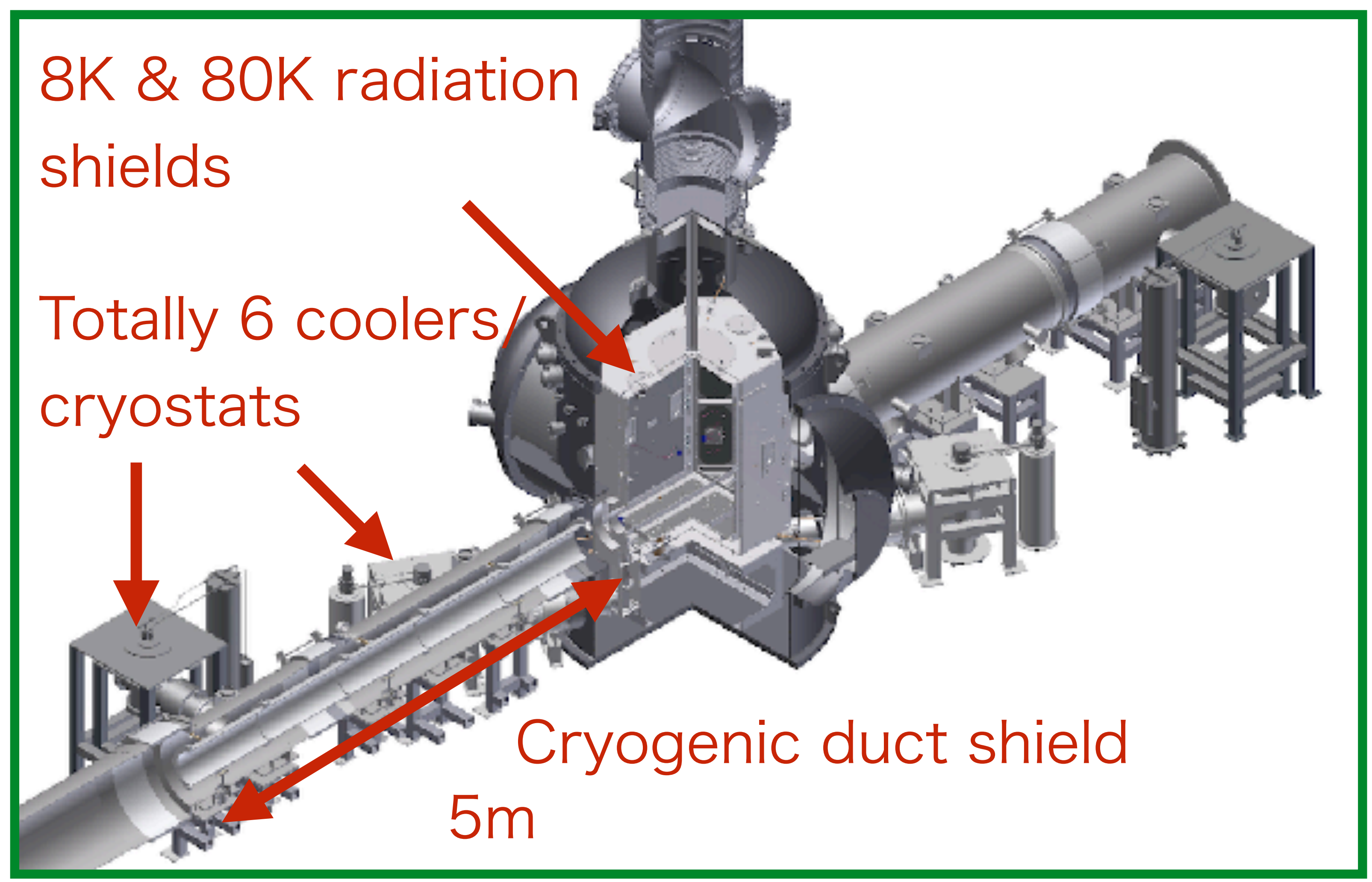
# Overview of the KAGRA cryogenic system




Cryogenic sapphire mirrors ~20K

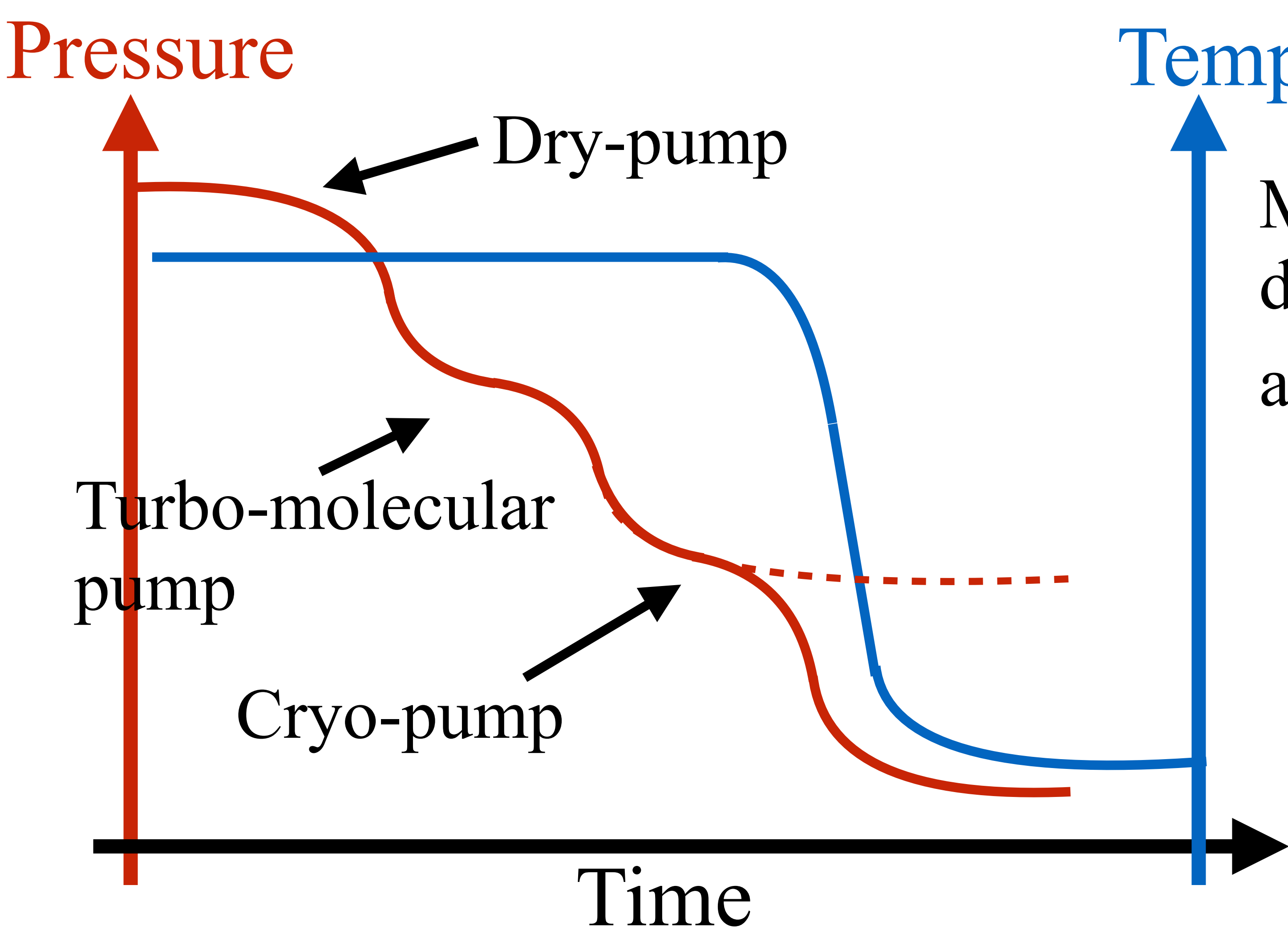
Credit : D.Chen Ph.D-thesis(2015)



# Cryo-pumping effects

The vacuum residual gases are collected by cryogenic surfaces.
->The KAGRA cryogenic system works as a cryogenic pump.
Cryogenic is a good technique for better vacuum condition.

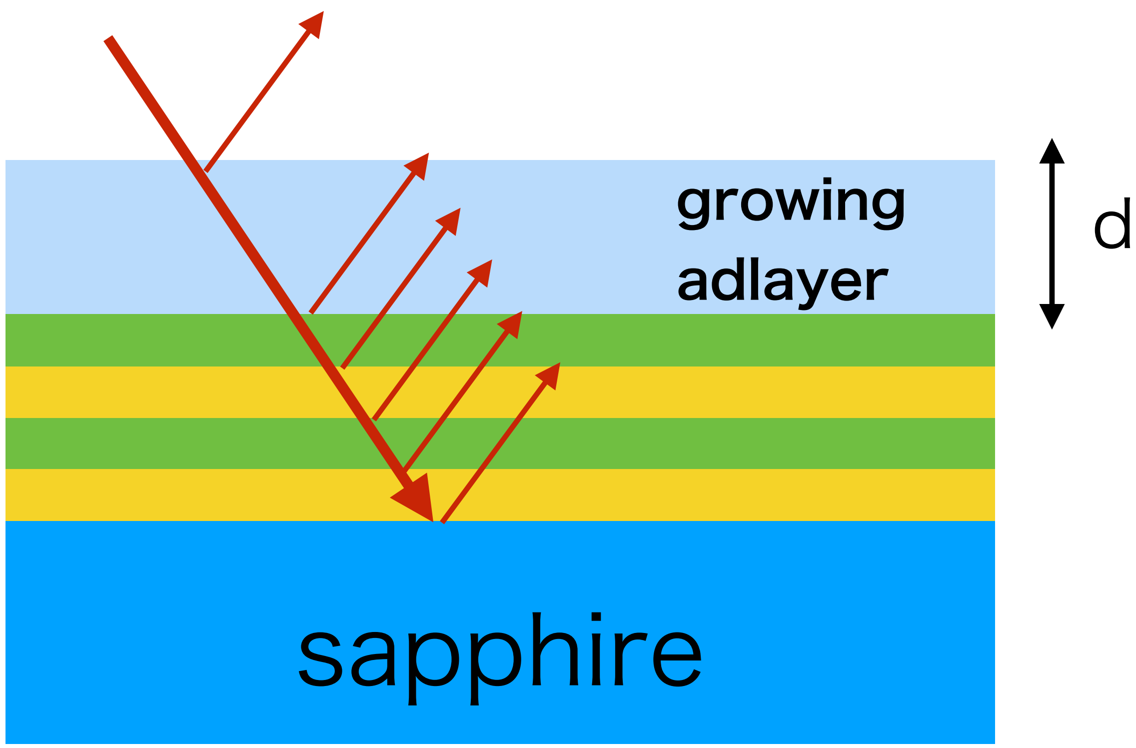



Molecules are collected by cryogenic ducts, radiation shields…
and **MIRRORS.**

A number of adsorbed molecules make an adlayer on cooled mirror surfaces.

# A growing adlayer and reflectance

## What is happen if there is a growing adlayer?




(1)d=0 :high reflectivity (Original)

(2)d=$\lambda$/8 : low reflectivity (Destructive)

(3)d=$\lambda$/4 : high reflectivity (Constructive)

(2) and (3) are repeated.

Optical thickness : $d = n \times l$

n : Refractive index

l : Thickness of a adlayer

**Reflectance of a mirror changes depending on the adlayer thickness**

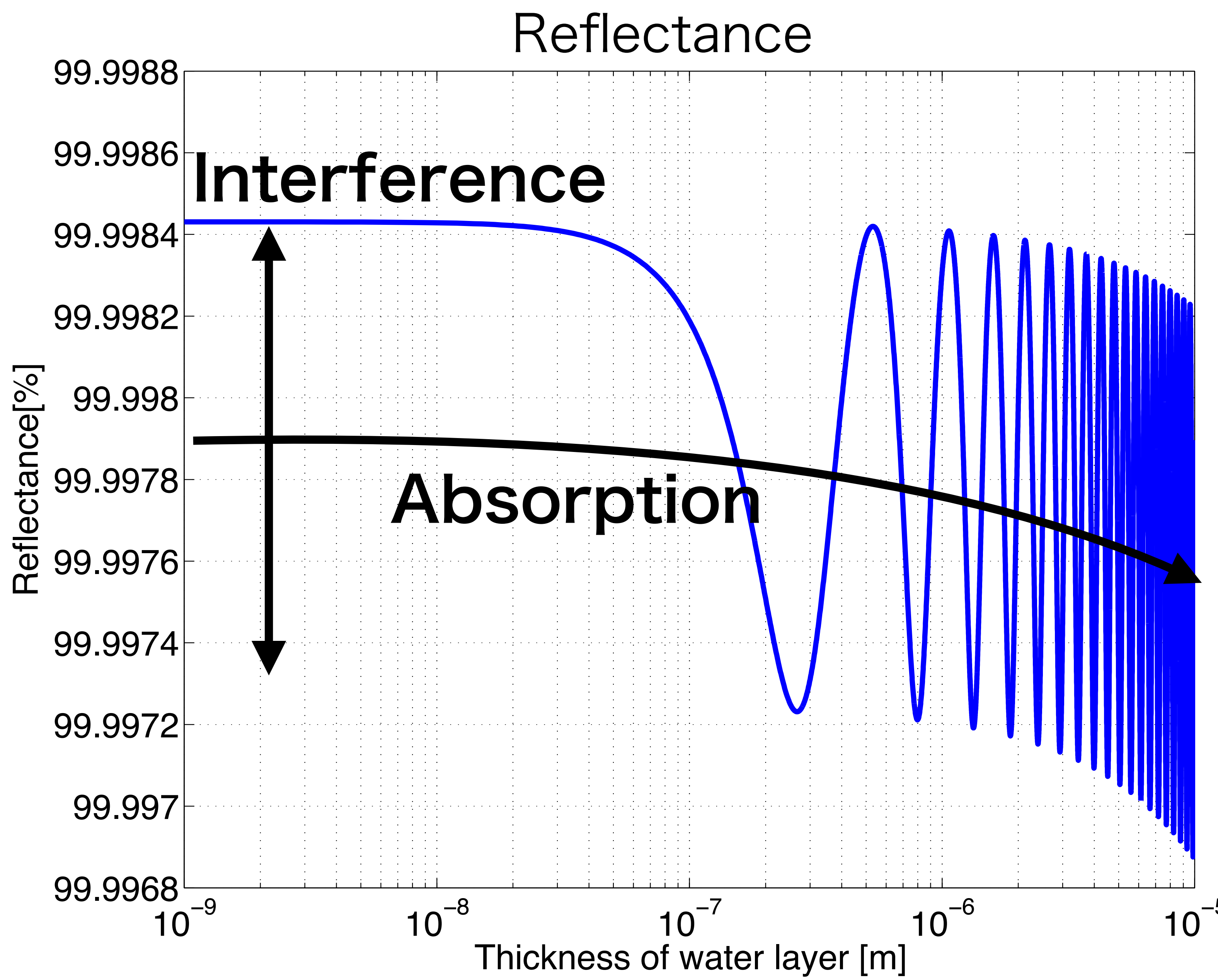
# Adlayer coating effects

Total Fresnel coefficient

$$\rho=\frac{\rho_0+\rho_1 e^{-2i\delta}}{1+\rho_0\rho_1 e^{-2i\delta}}$$

$\delta$: optical phase shift

$$\delta=\frac{2\pi N d}{\lambda_0}$$



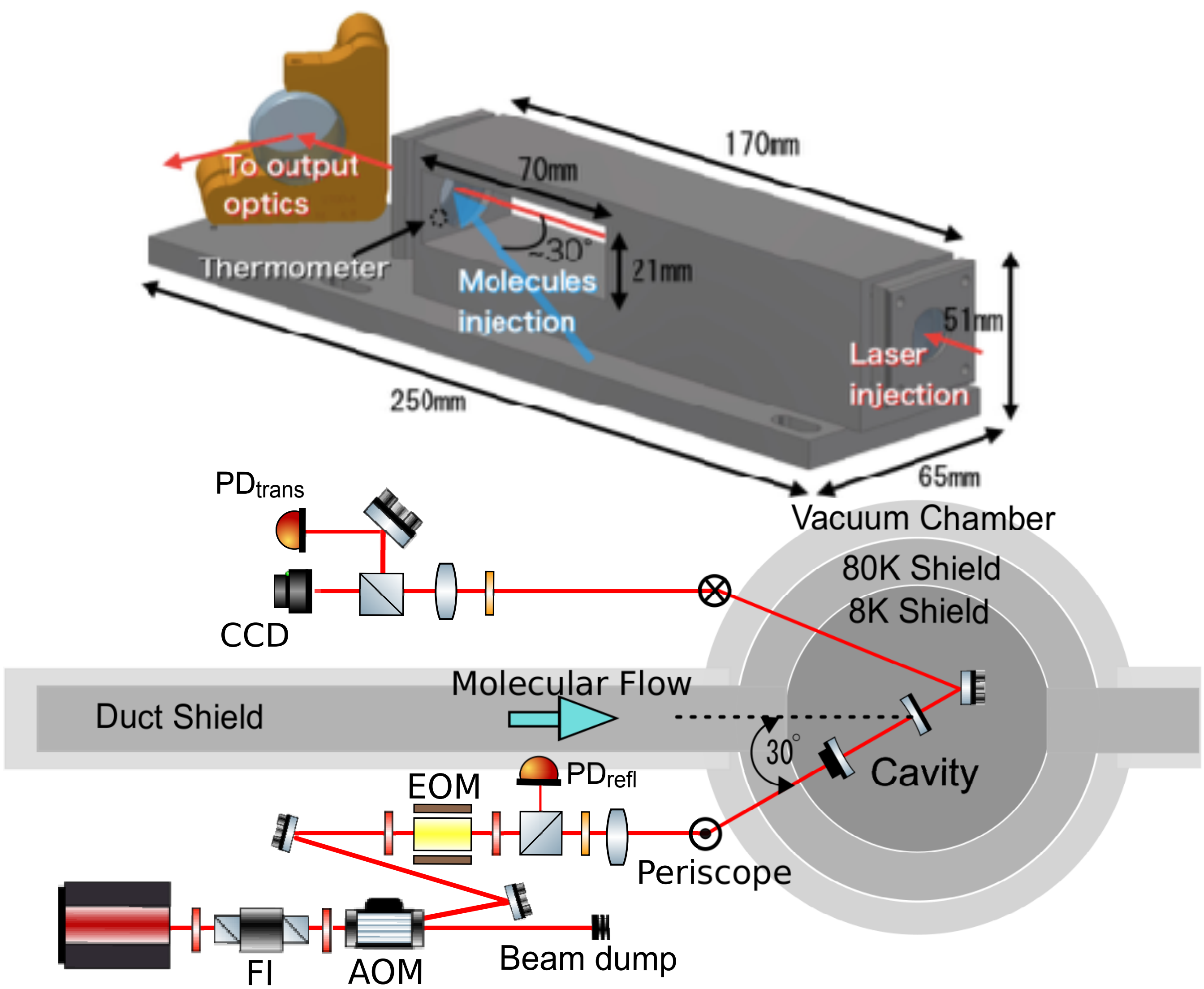

N: Complex refractive index
d: Thickness of a adlayer
$\lambda_0$: Wavelength
$\rho_0$: Fresnel coefficient of a adlayer
$\rho_1$: Fresnel coefficient of a HR coating

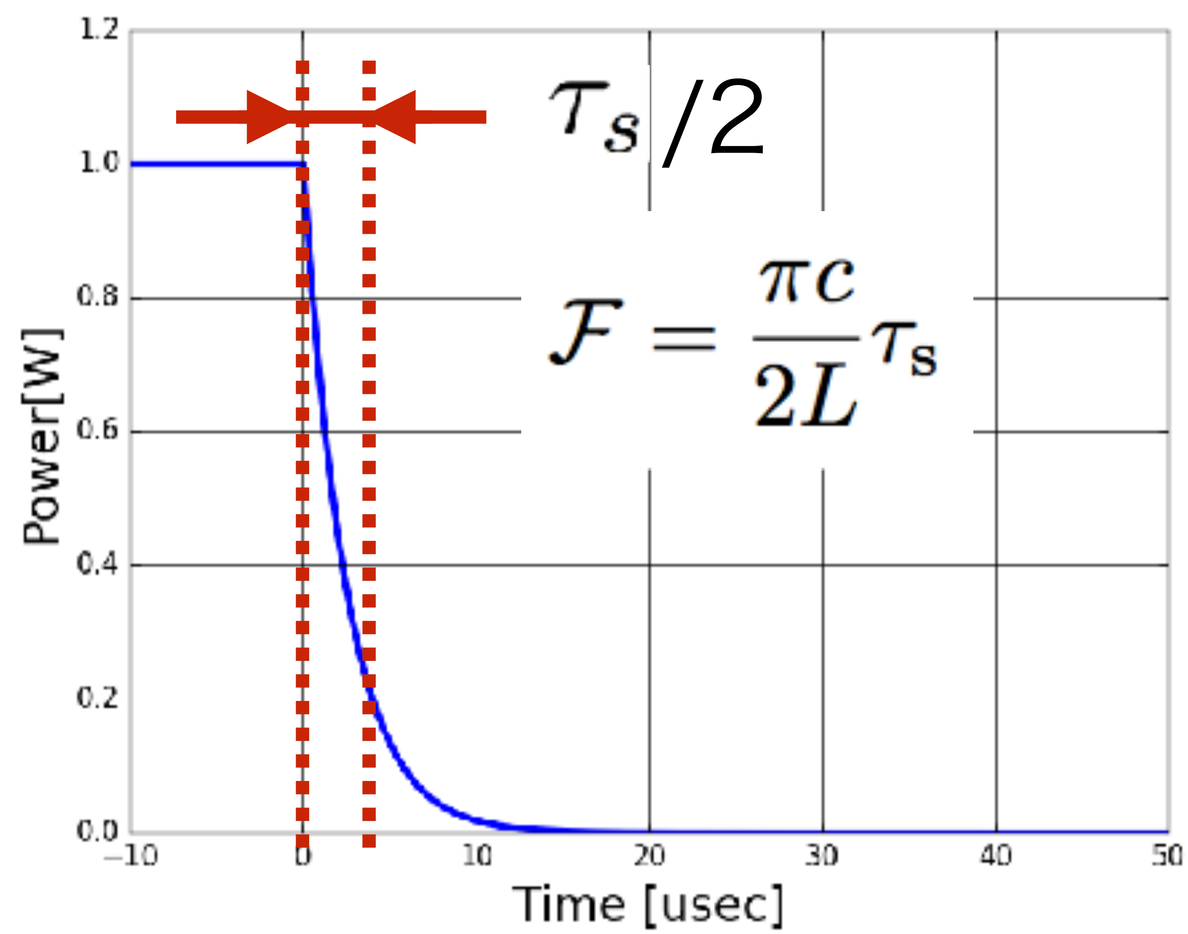
# Measurement of an adlayer formation on a cooled mirror

- The rigid FP cavity was set into the KAGRA cryostat.
- To evaluate the finesse of FP cavity, the transient response of FP

cavity was monitored for 35 days.

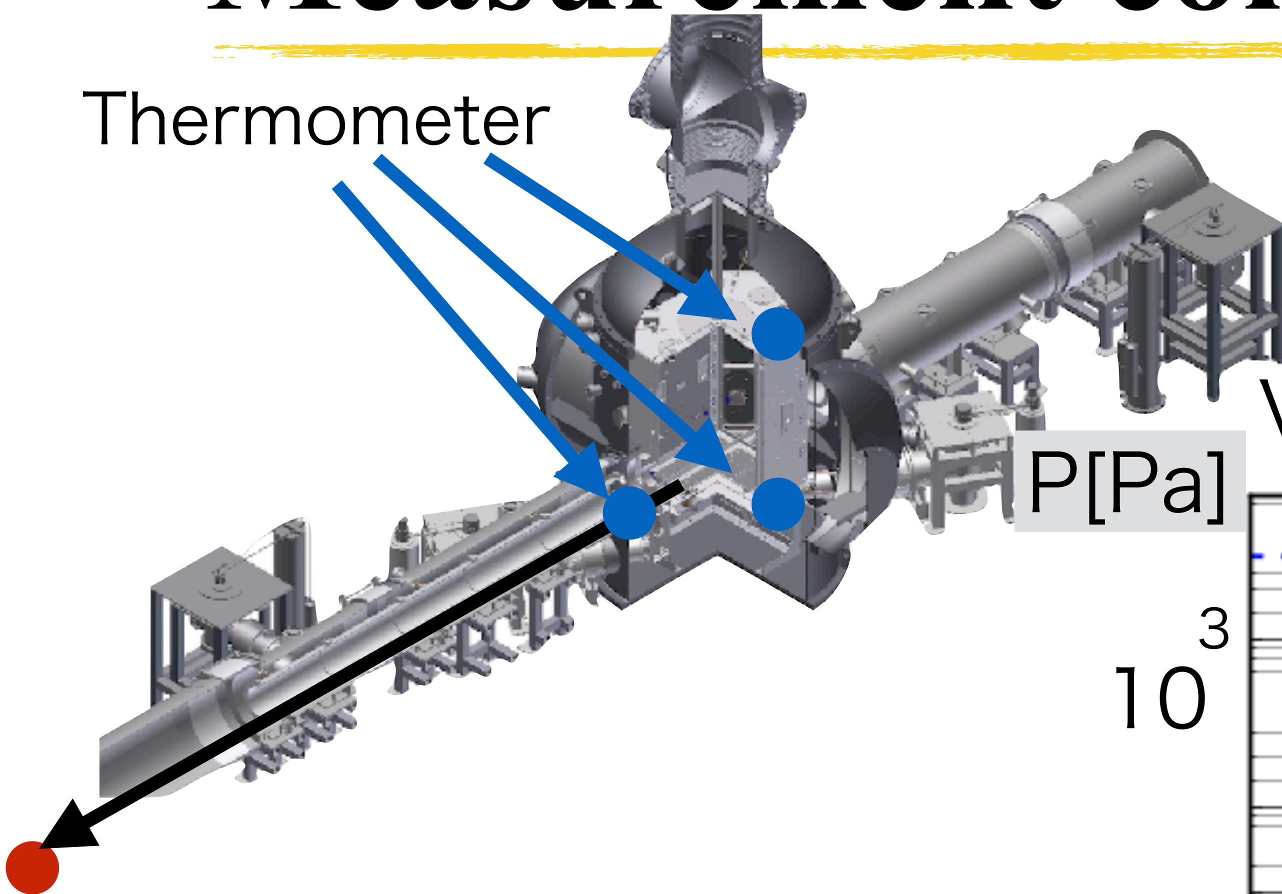
*Finesse : The sharpness of the resonance of optical cavities



KAGRA

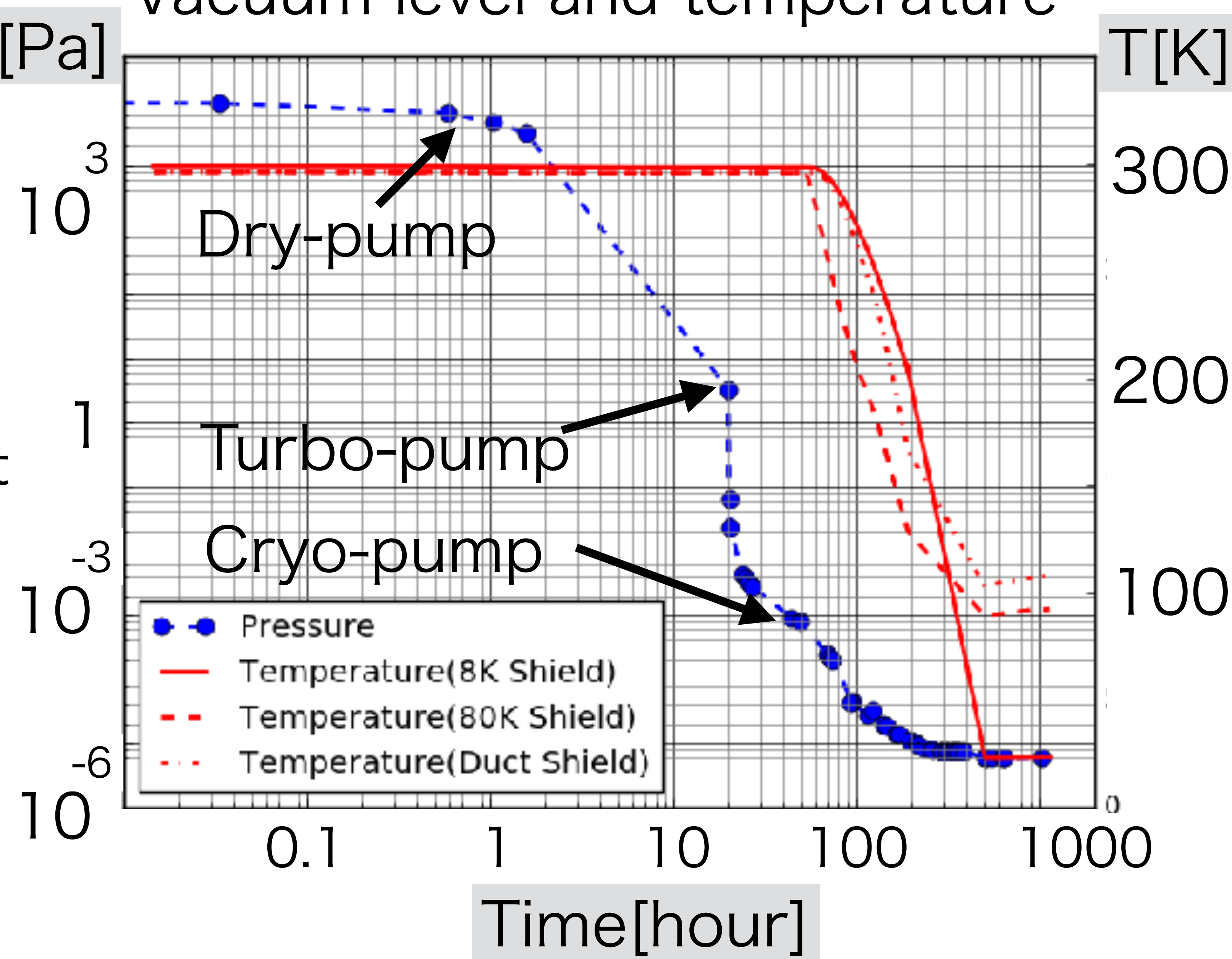
# Measurement conditions



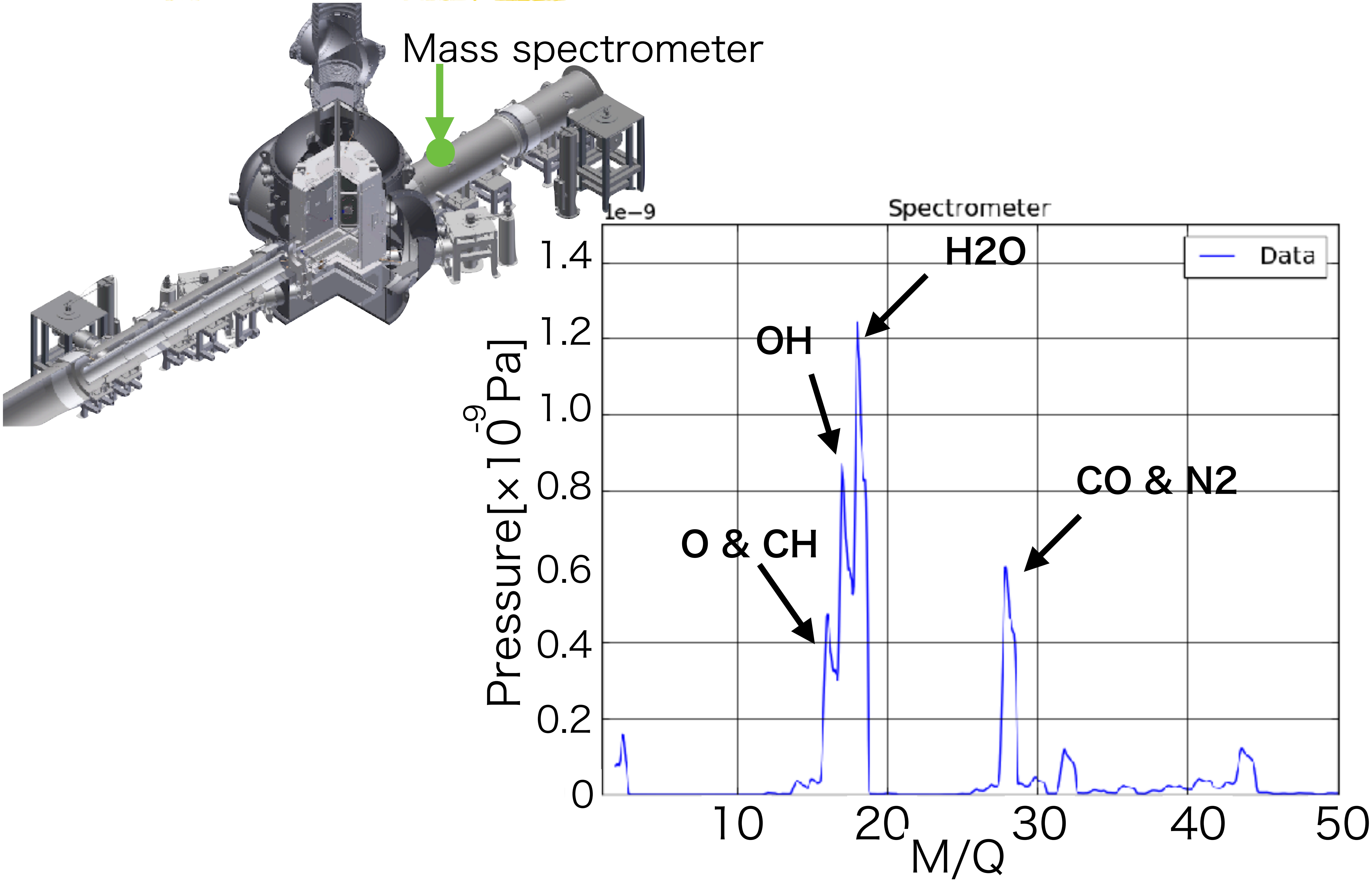

A Pressure gauge :
11m away from the cryostat

Vac. Pressure:$6\times10^{-6}$[Pa]
8K shield : 25 [K]
80K shield : 90 [K]
Duct shield : 110[K]
FP cavity : 47 [K]

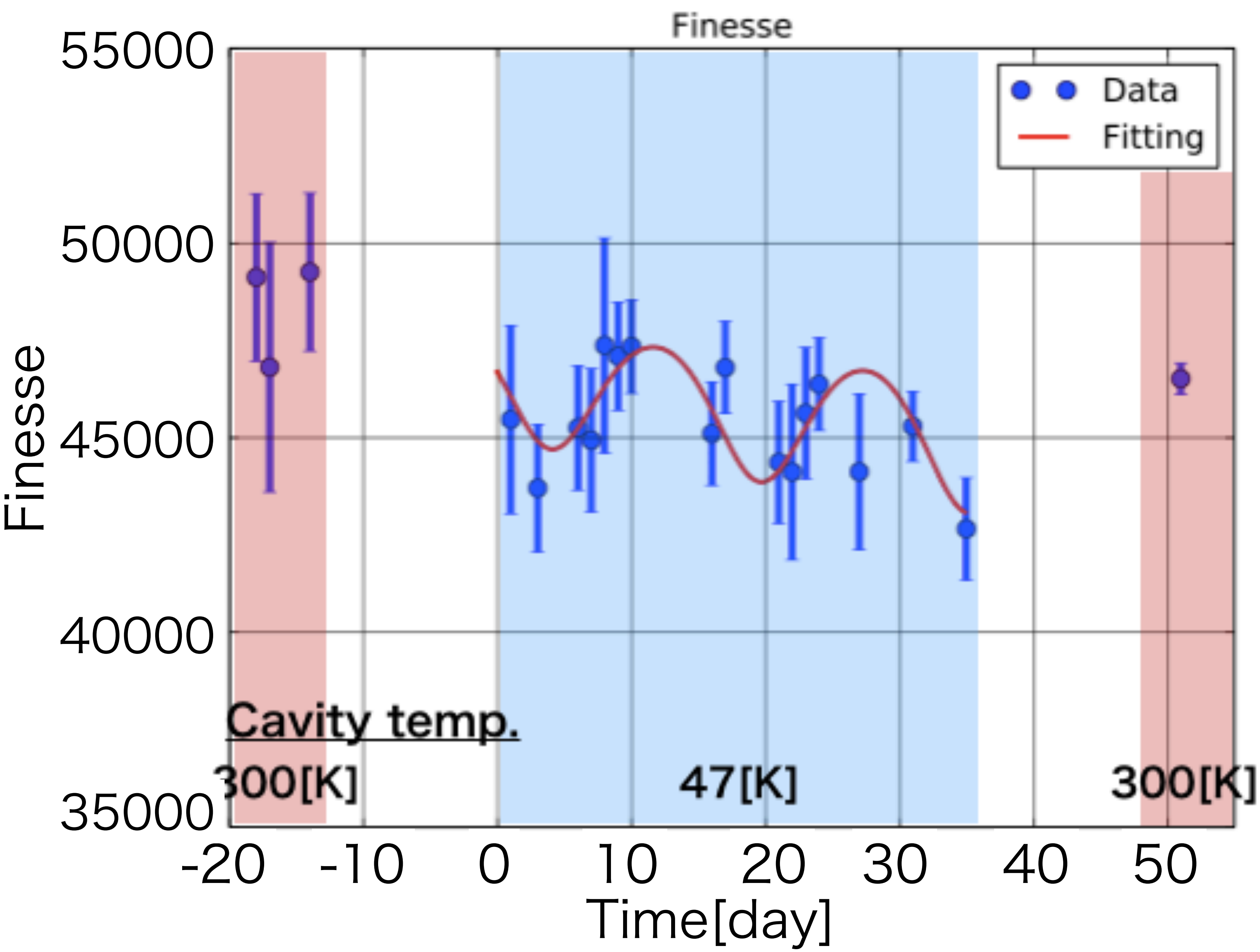
Vacuum level and temperature



# The species of residual gas



# The result of finesse measurement




**Fitting results**

- The layer forming rate is

  27.1 ± 1.9 [nm/day]

- The mean of the real part of refractive index is 1.26 ± 0.073

- The mean of the imag. part of refractive index is

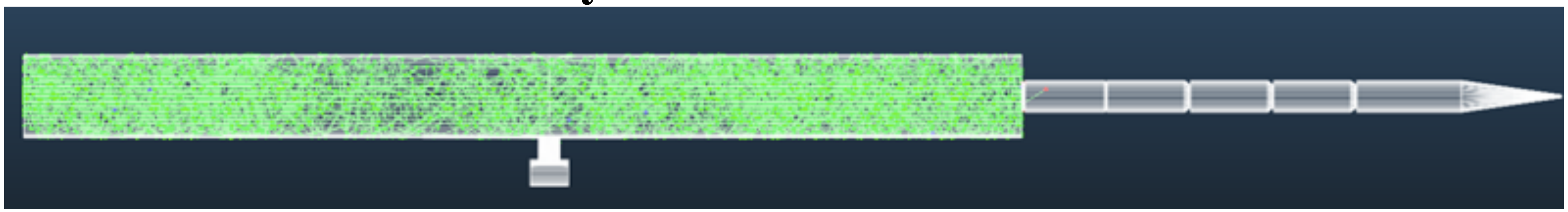
  $2.2\times10^{-7} \pm 1.26\times 10^{-7}$.

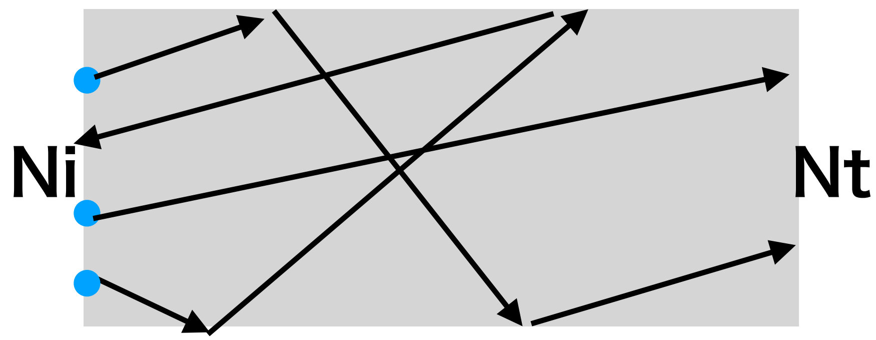
This value corresponds to 2.6 ± 1.5 [1/m] of the absorption coefficient.

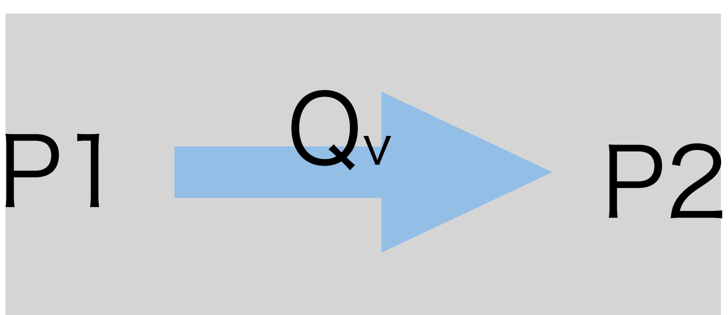
*Finesse : The sharpness of the resonance of optical cavities

# The simulation

Monte Carlo simulation by Molflow+






Ni : Number of particles injected to a duct

Nt : Number of particles coming through a duct

P=Nt/Ni

Conductance and trans probability

$C=C_0P$ : Conductance

$Q_v=C(P_1-P_2)$ [Pa m3/s]

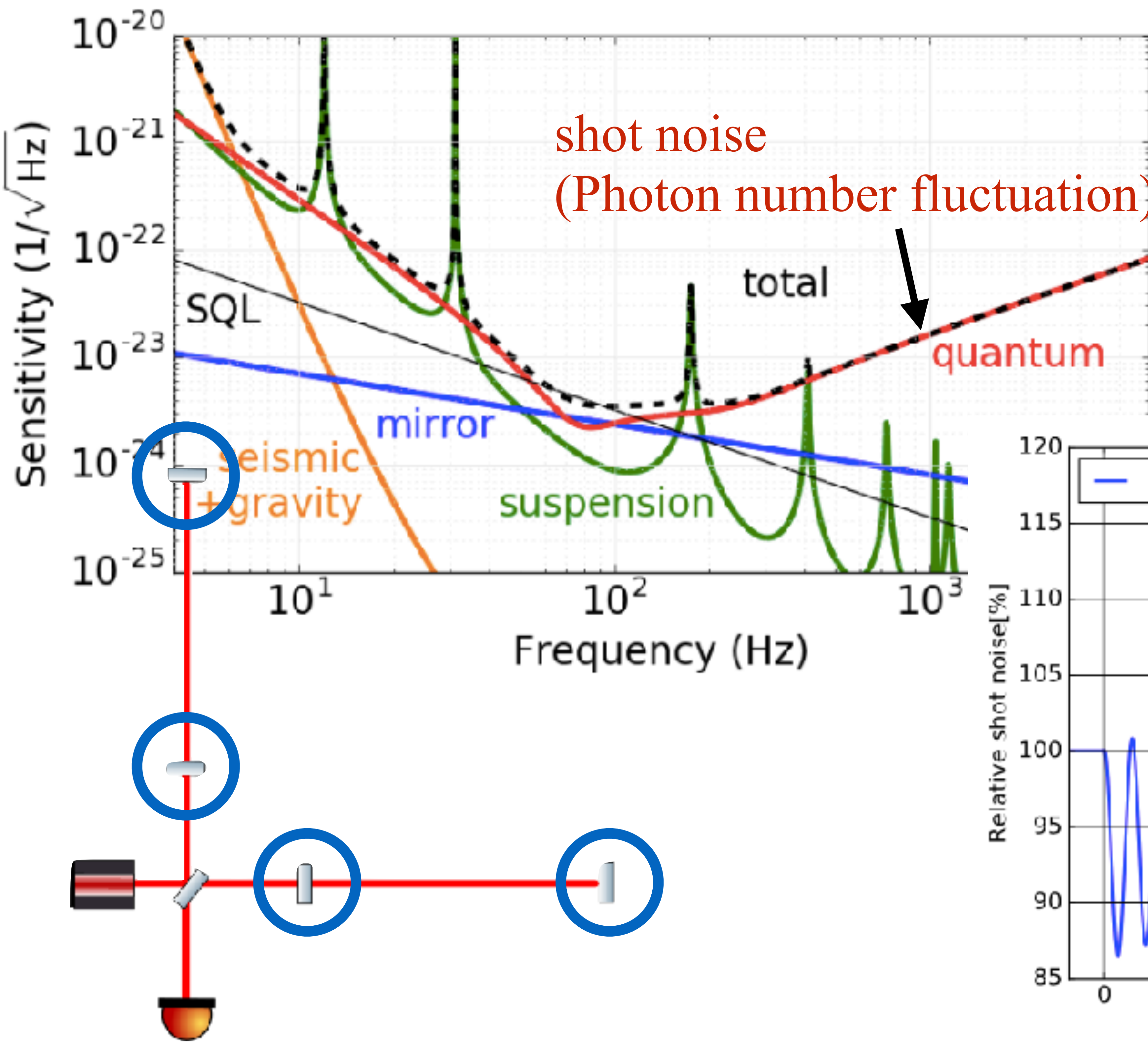
$Q=Q_v/k_BT$ [1/s]

| Cond. [m3/s] | ΔP [Pa] | Dep. rate | Eep. Result |
|---|---|---|---|
| 0.162 | $1.26\times10^{-5}$ | 19.2 nm/day | 27.1nm/day |

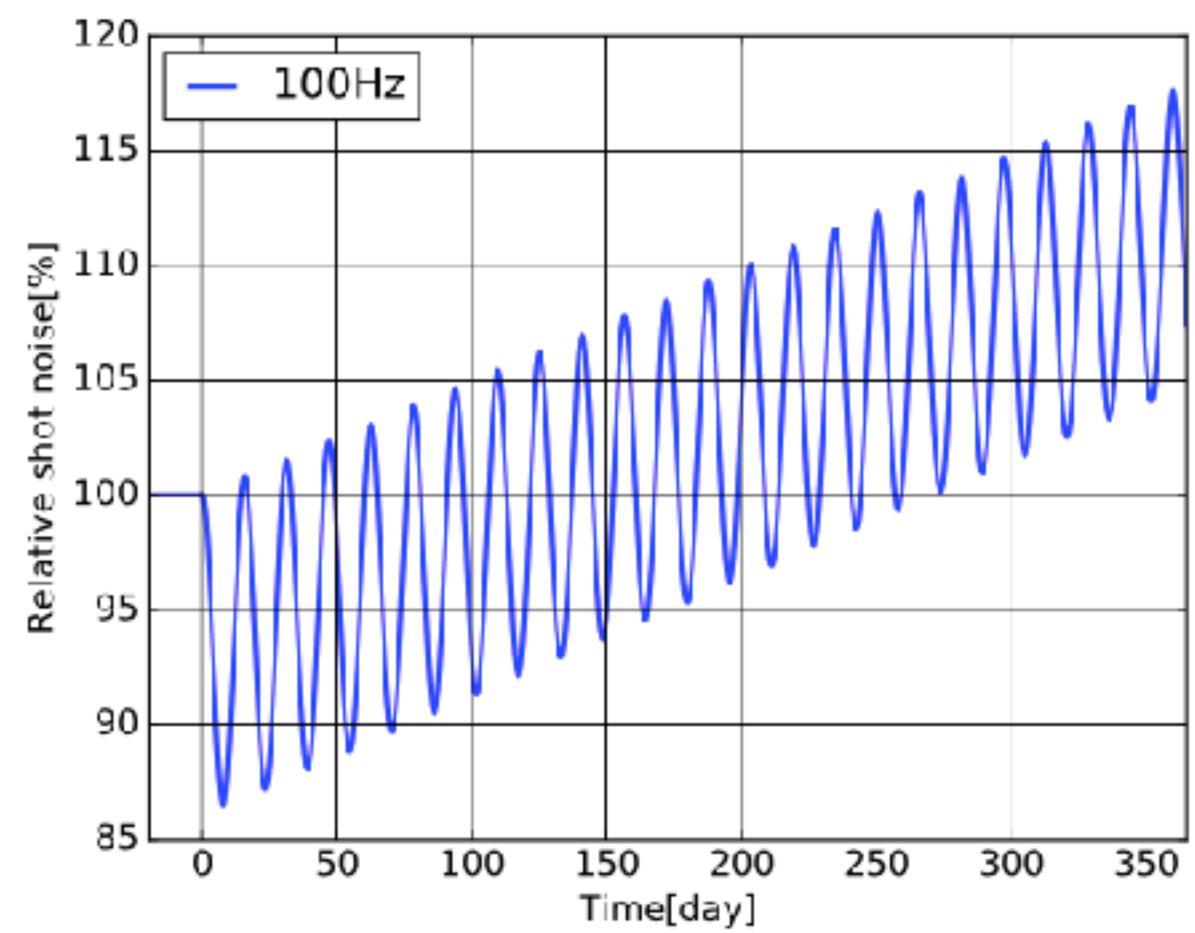
Pumping speed：~2700[l/s](H2O)

The adsorption probability at cryogenic region:100%

# The sensitivity of KAGRA




Finally, the sensitivity of KAGRA will be limited by the quantum noise.



# How can we tackle adlayer?

**(1)Higher vacuum**

—Higher vacuum (lower pressure) lead to less number of molecules inside the vacuum chamber.
In order to decrease the number of oscillation, $10^{-8}$ [Pa] of vacuum pressure at the beam duct is required.

**(2)Longer and lower temp. cryo-duct**

—Effective conductance will be smaller. There is a possibility that current temperature of the cryo-duct makes it easy to adhere the molecules to cooled mirror surfaces.

**(3)Forced desorption**

—Several forced desorption methods will be tested.

# Summary & Future prospects

・Cooled mirrors suffer from the contamination of vacuum residual gases.
・As a result of contamination, the reflectance of a mirror is expected to change and decrease depending on the thickness of an adlayer.

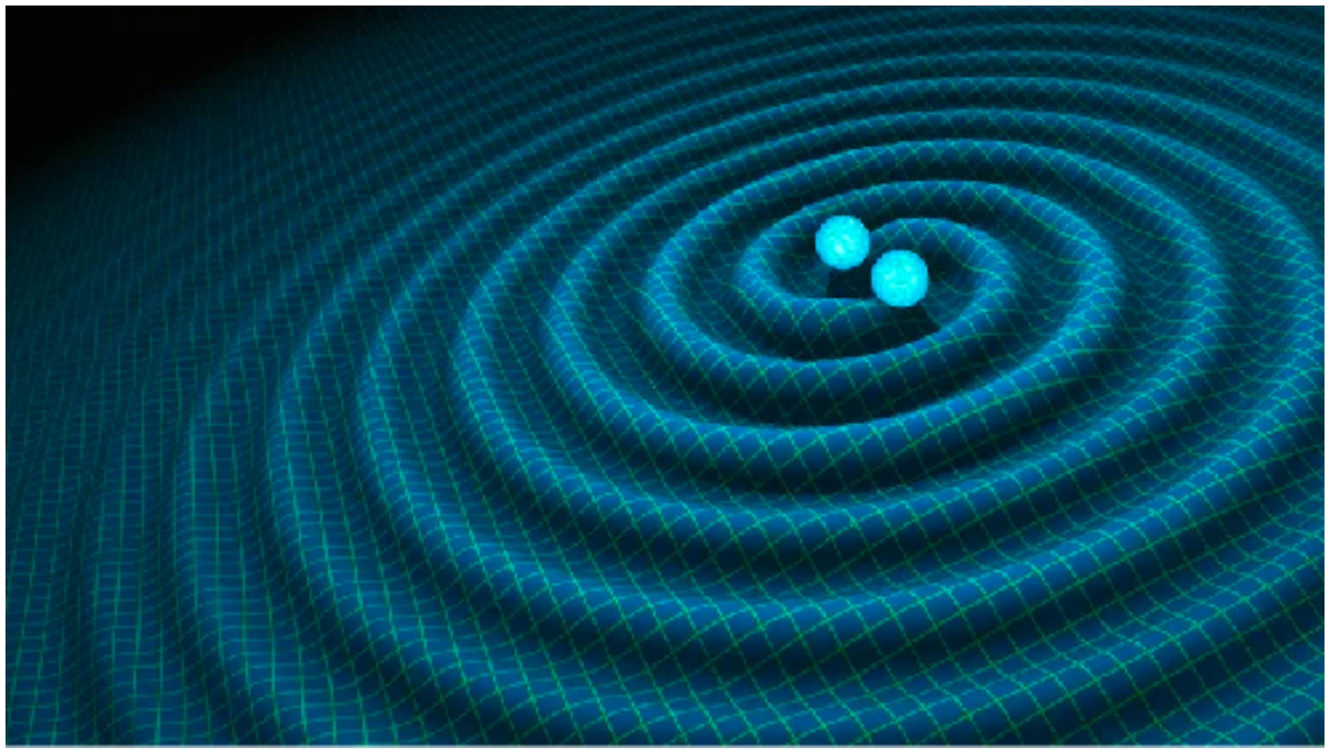
・To measure the adlayer effect, the rigid FP cavity was introduced to KAGRA cryostat and its finesse was monitored for 35 days.
・Measured accumulating speed in the KAGRA system is 27±1.9[nm/day] and it's likely due to water molecules.

・An adlayer largely affects the sensitivity of GW detectors.
・Further discussion is necessary from the point of view of noise, controls of GW detectors etc….
・Several forced desorption methods will be tested.

Thank you for your attention.

# Back up slides

# Gravitational wave and its detection



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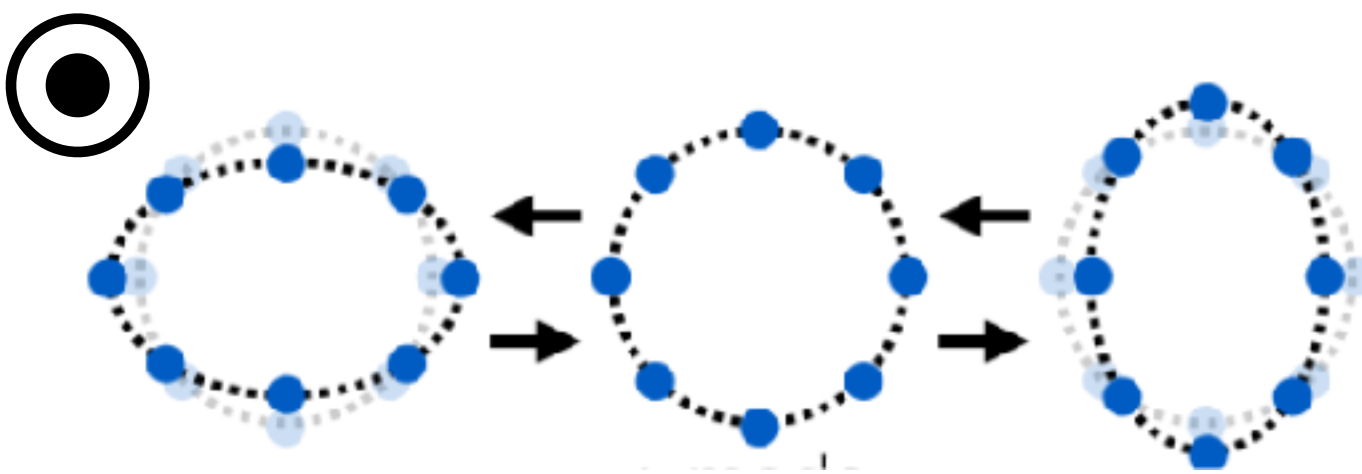
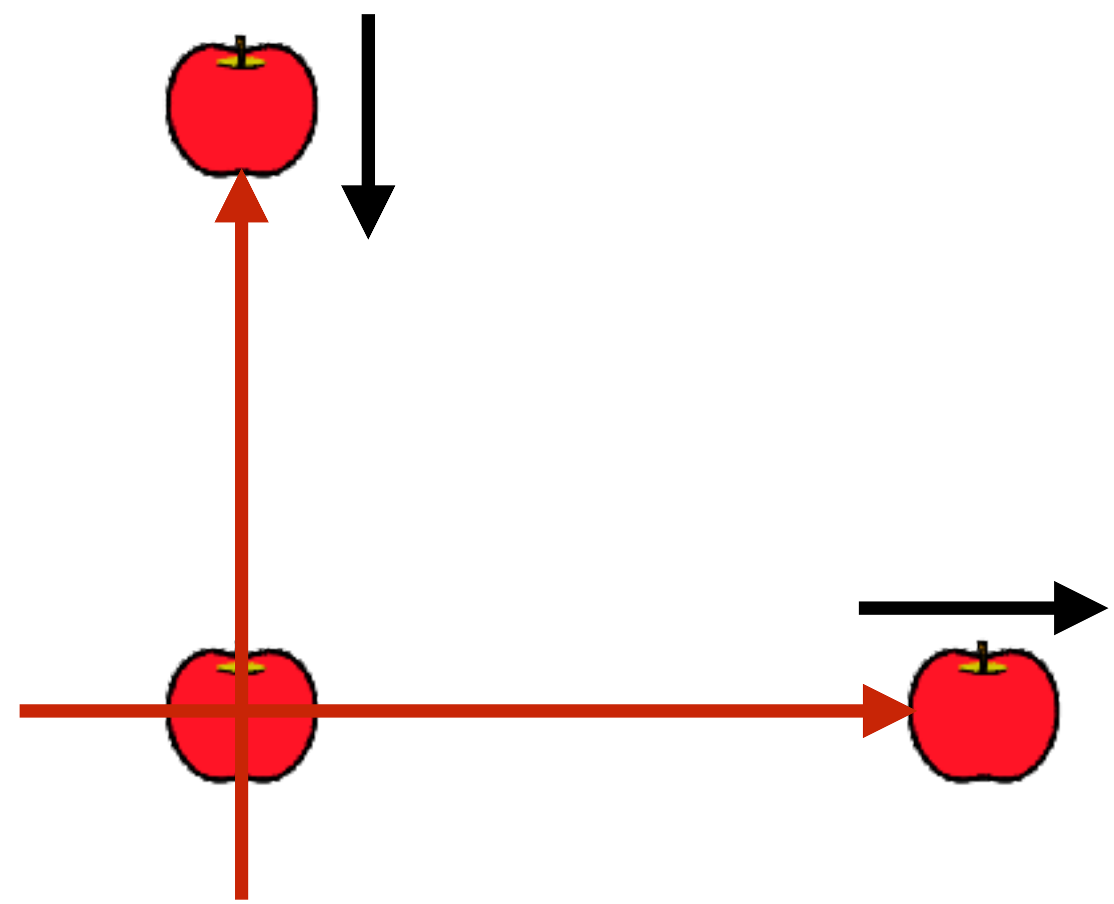
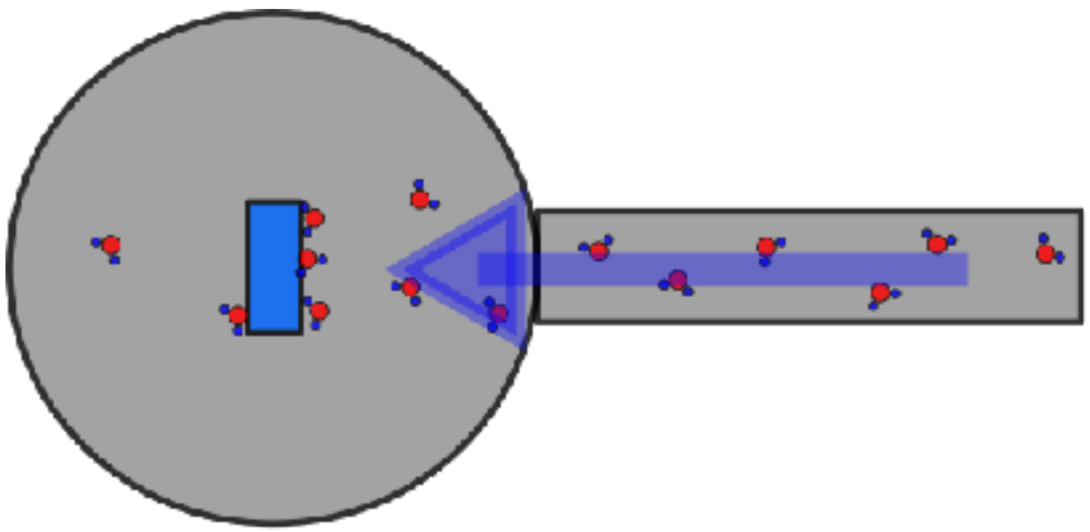




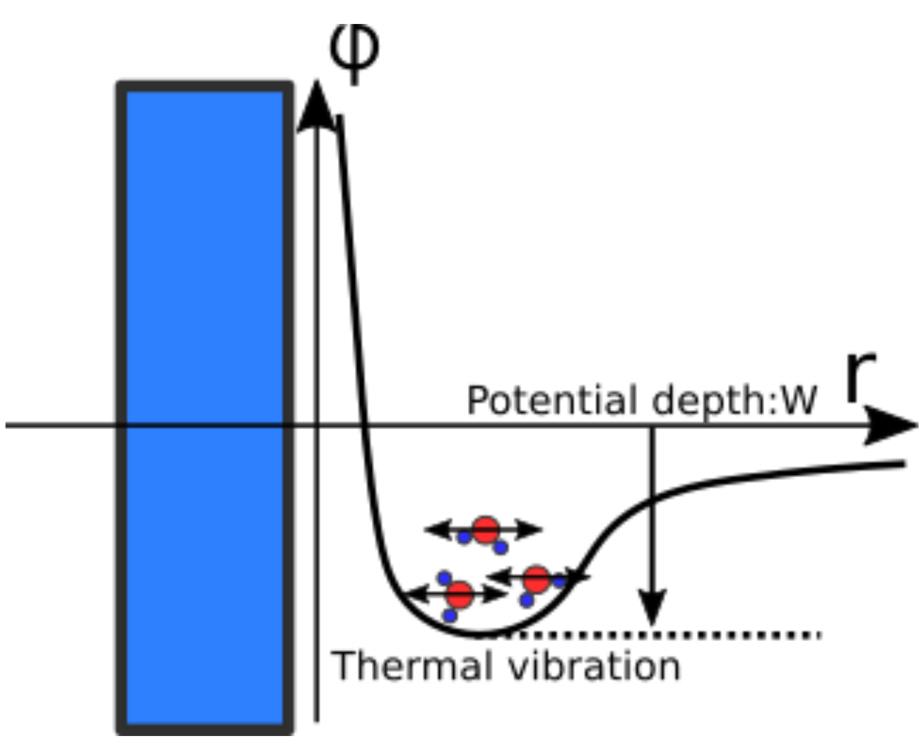
GWs can be detected by the laser interferometer.

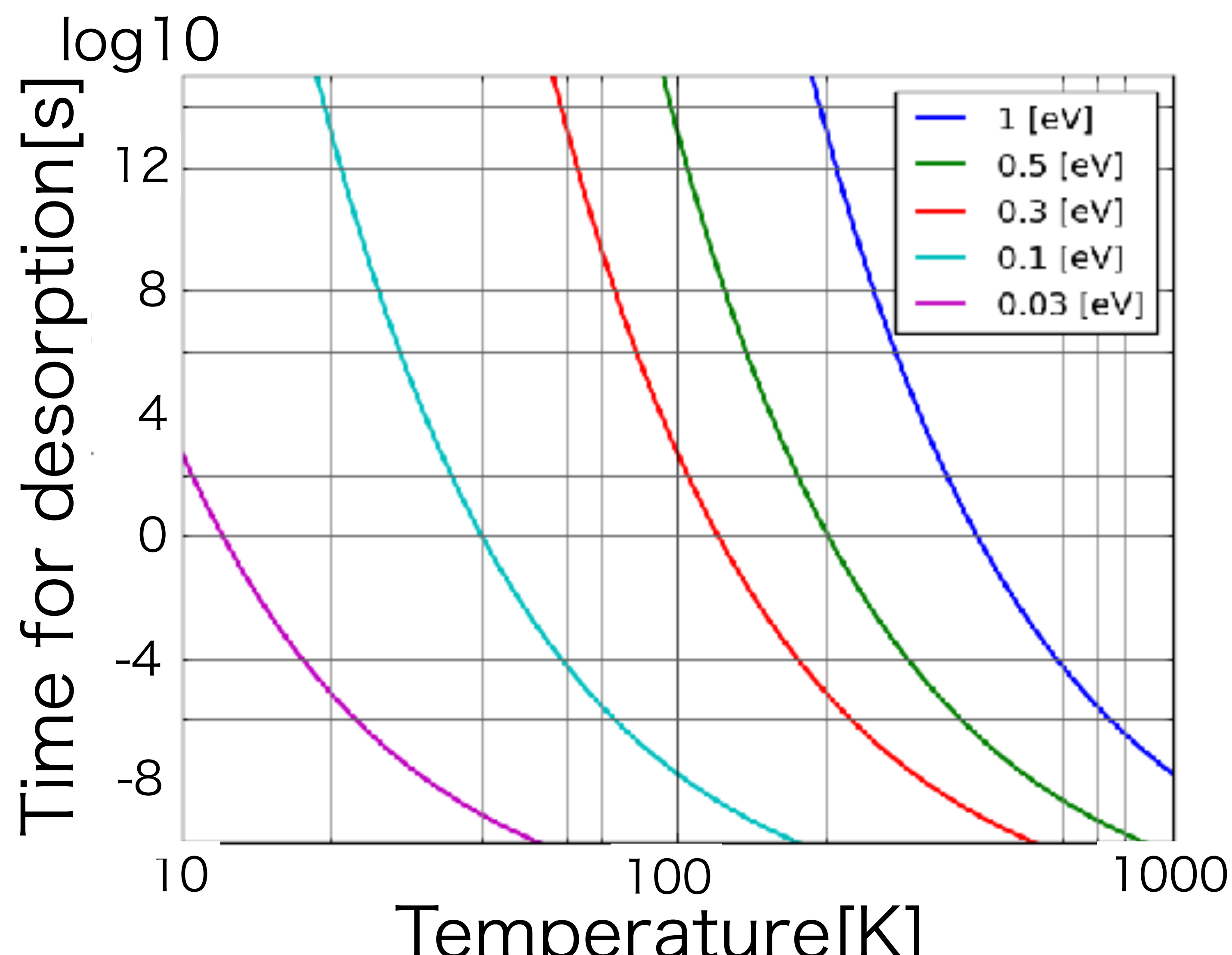
# Cryo-pumping on cooled mirror surfaces



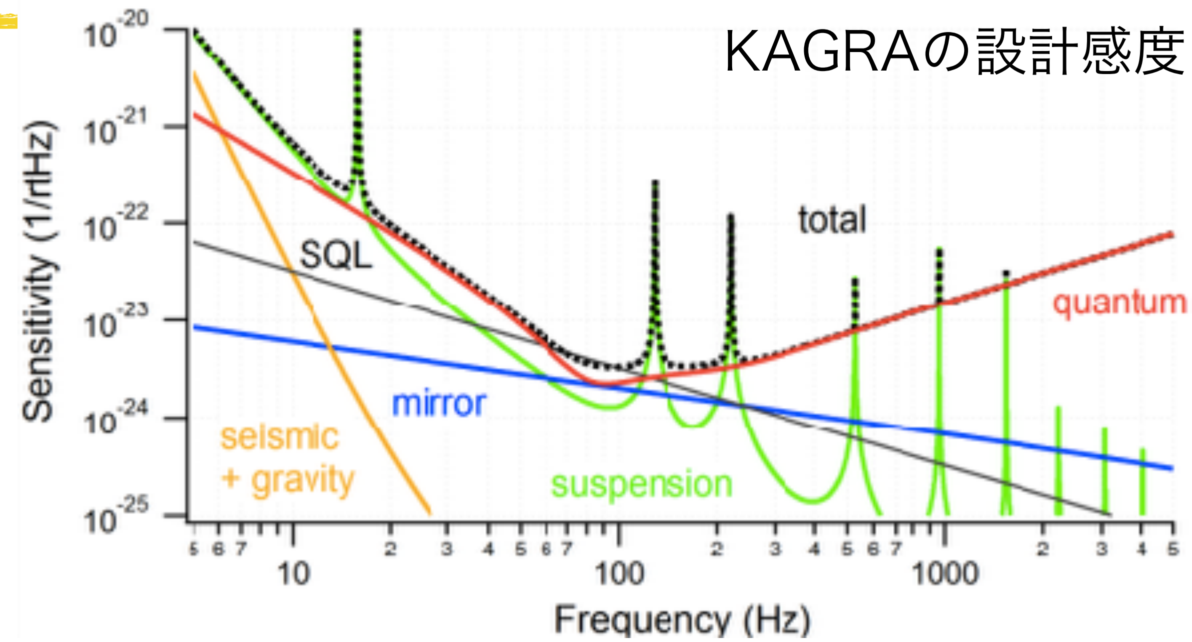
Vacuum pressure inside a cryostat becomes quite good, but still there are many molecules in a beam duct and they move to the cryostat.

The number density of vacuum residual molecules : ~$2.5\times10^{14}$ [$1/m^3$] @ $P=1.0\times10^{-6}$ [Pa]



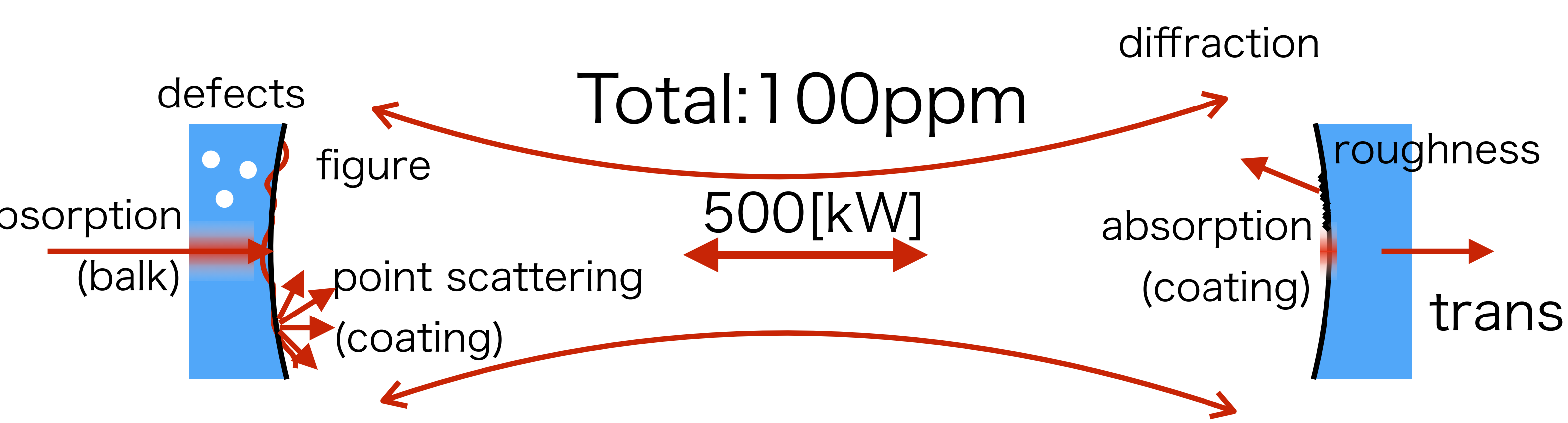
# KAGRA sensitivity & contamination




## KAGRA sensitivity

Quntum noise will limit the KAGRA sensitivity for almost all frequency. To archieve the final sensitivity, reduction of optical loss inside the arm cavity is important.

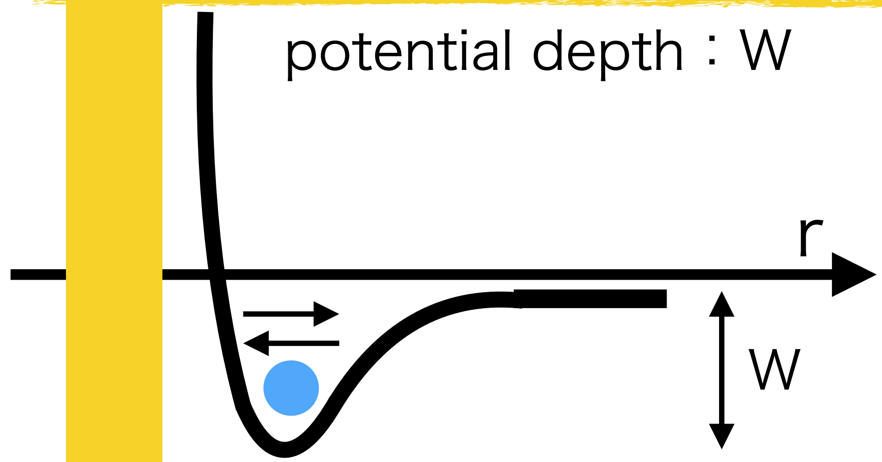
Requirement for KAGRA arm cavity is …



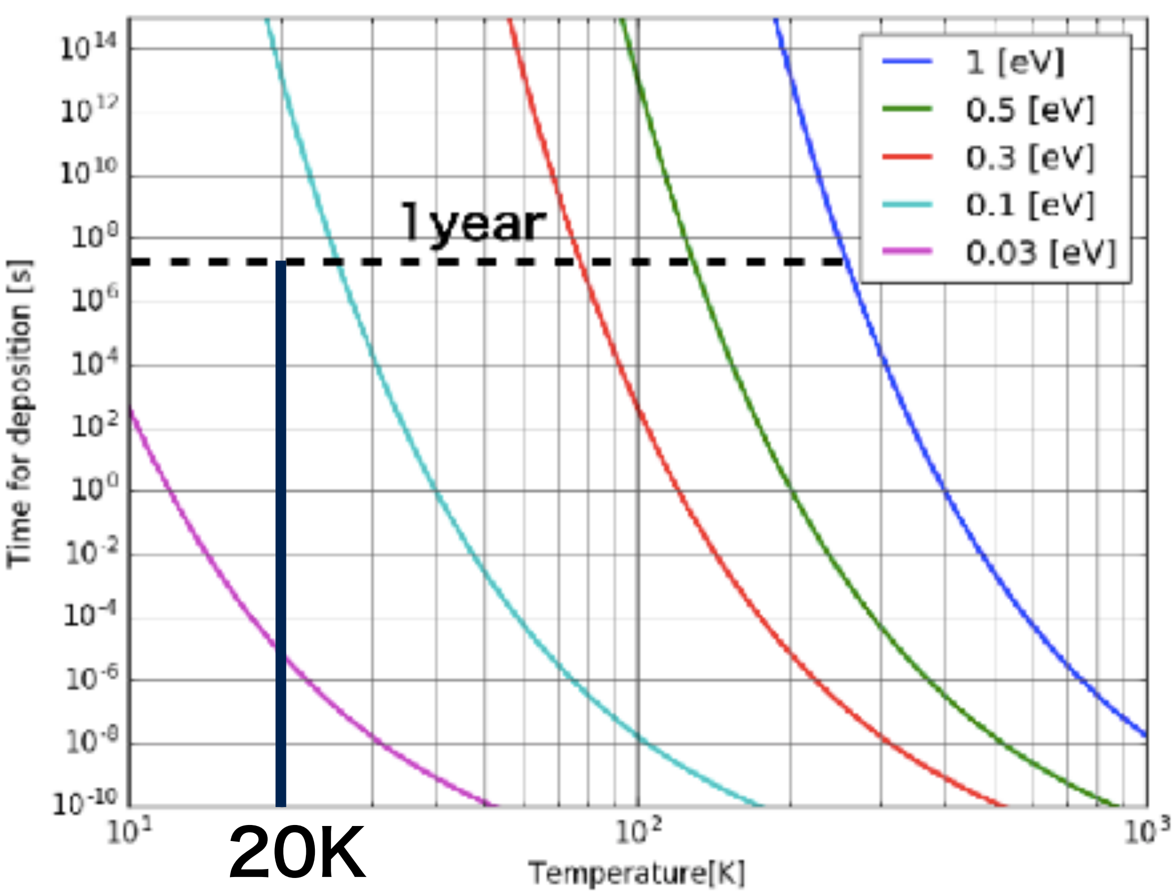

→The loss margine for requirement will be few~10ppm

Furthermore, optical loss due to contamination will be added. A study of cantamination in GWD is essential to archieve final sensitivity and characterize well.

# Adsorption of molecules




When molecules hit to the cryogenic matter surface, molecule will decrease its enegy and be trapped by surface potential.




Actual potential depth is hard to know, but it may be about 100kJ/mol.
Calcultion for various potential depth.

$$\tau = \tau_0 \exp(-W/k_B T) \quad [1]$$

$$\tau_0 \sim 10^{13} \quad [s]$$

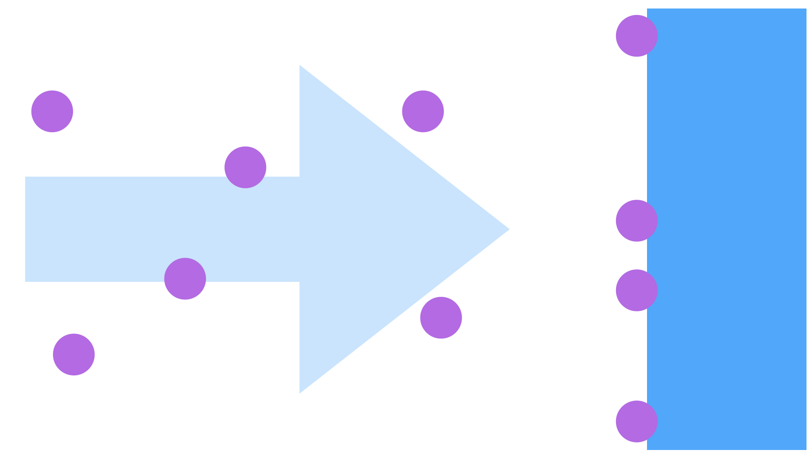
Even if it is 0.1eV, at 20K ,it will takes more than 1 year to release from the surface potential.
These adsorped molecules will form layer.

[1] https://www.jstage.jst.go.jp/article/jvsj2/56/6/56_13-LC-018/_pdf

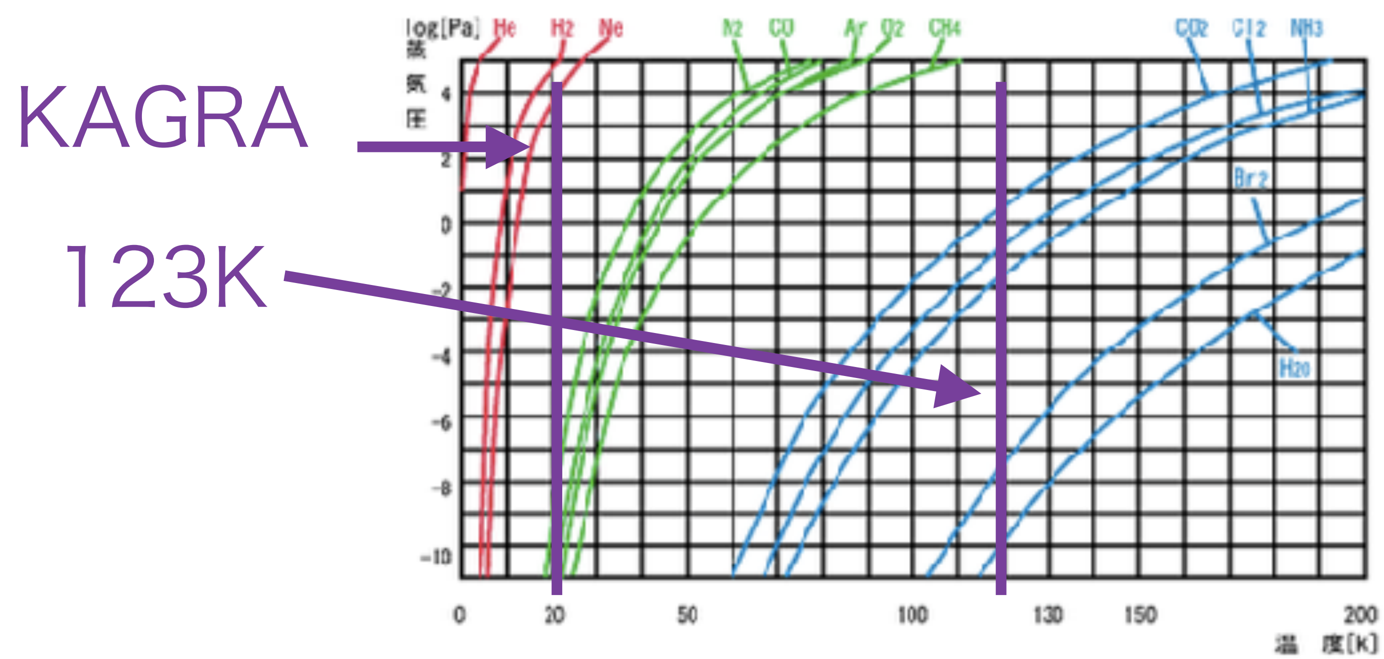
# What is the cryo adsorption??

**Cryo adsorption(cryo pumping effect)**

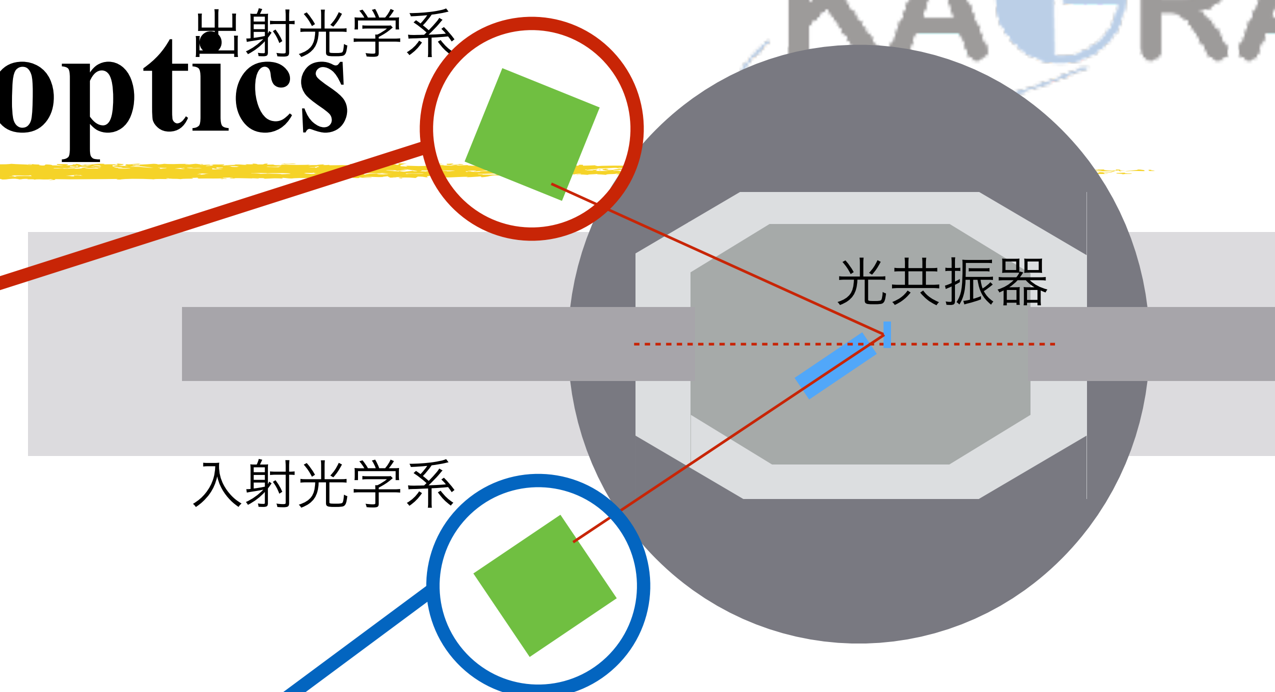
- When molecules hit a cryogenic matter, molecules lost these energy and catched by surface potential.
- One of the famous tequniques to archieve ultra high vacuum.

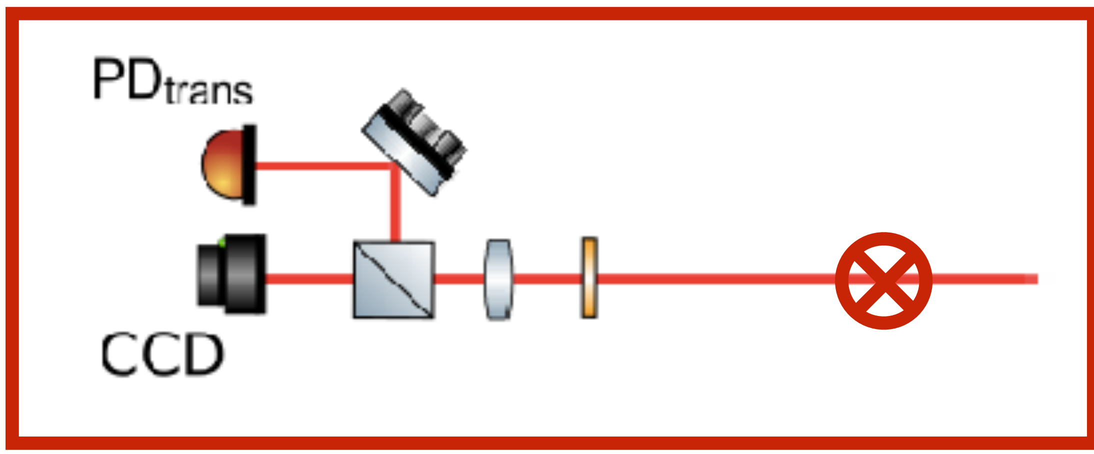


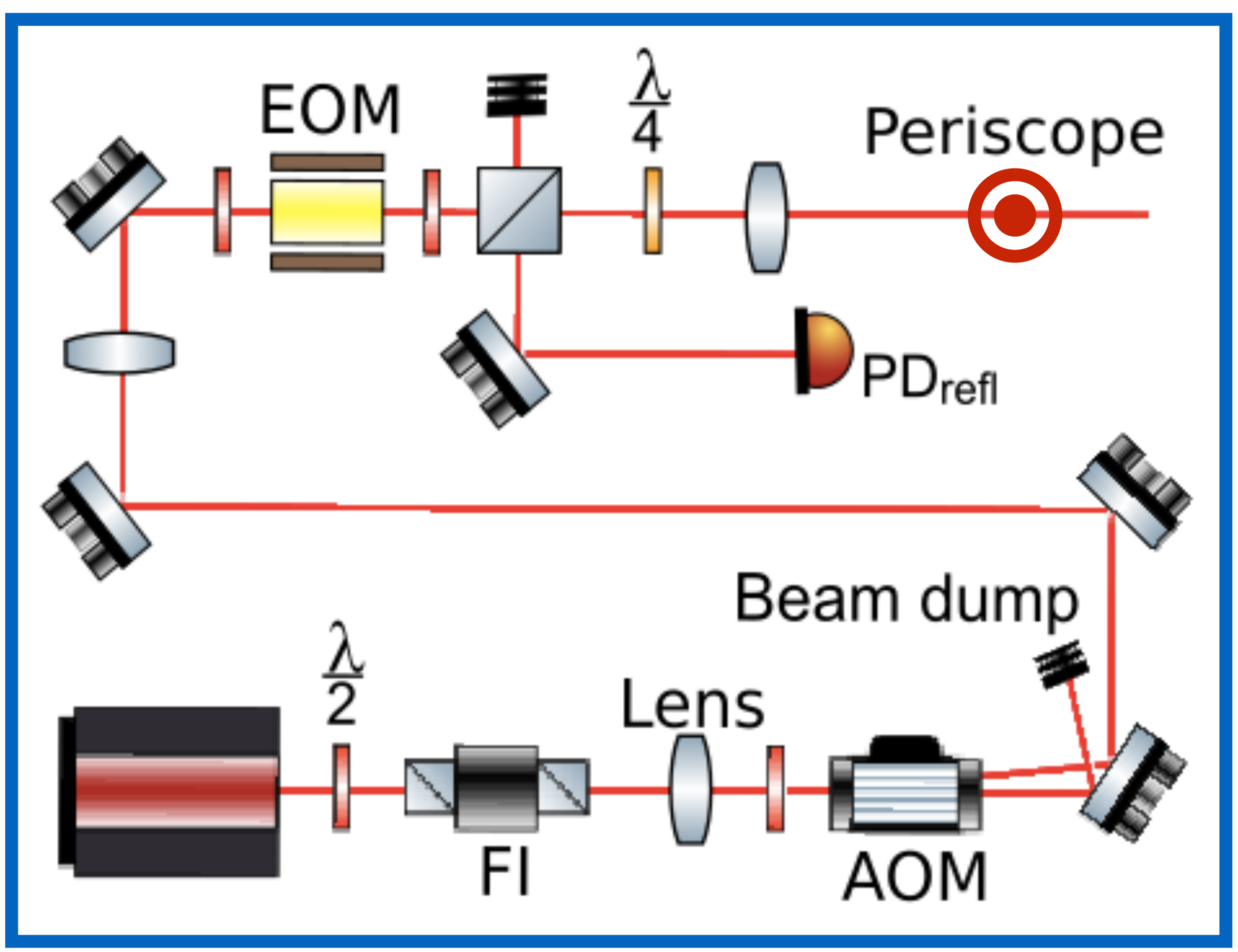
KAGRA & next generation GWD will use cryogenic mirrors. Vacuum residual gas will adhere to mirrors surface and cause refractivity change.



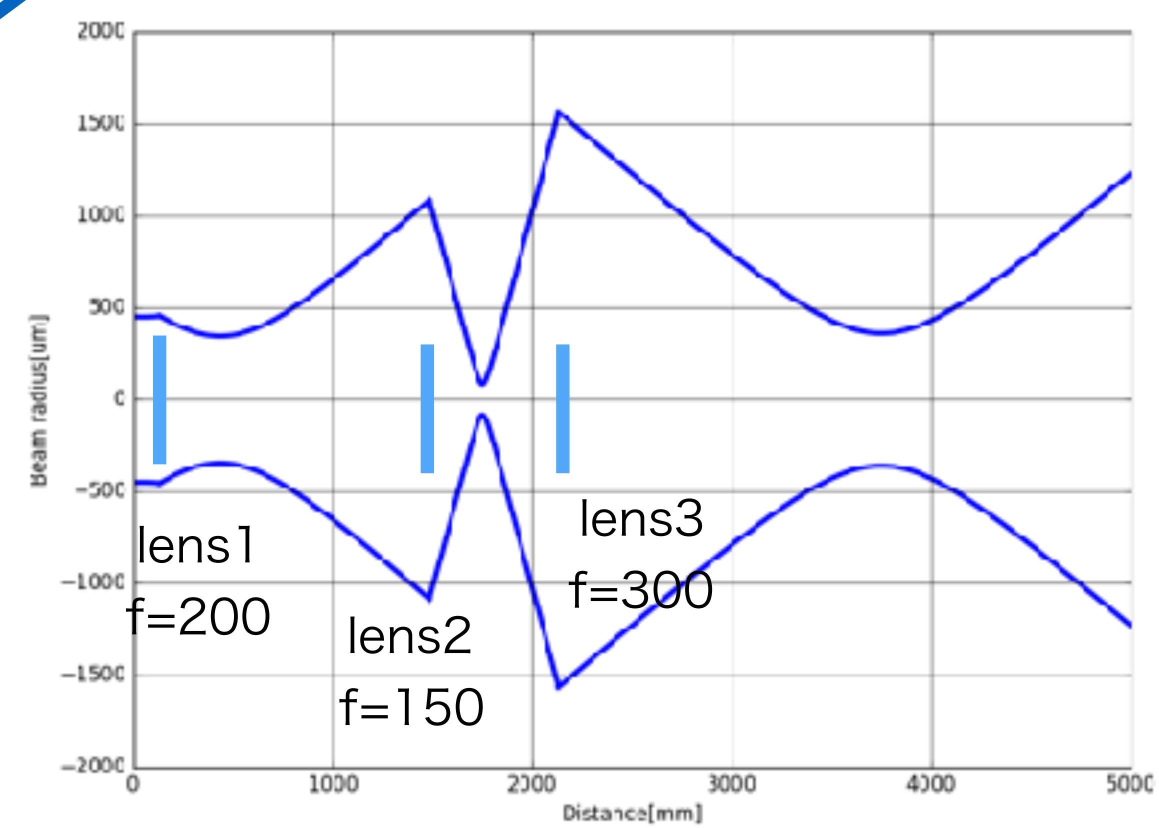
# Input and output optics




beam profile

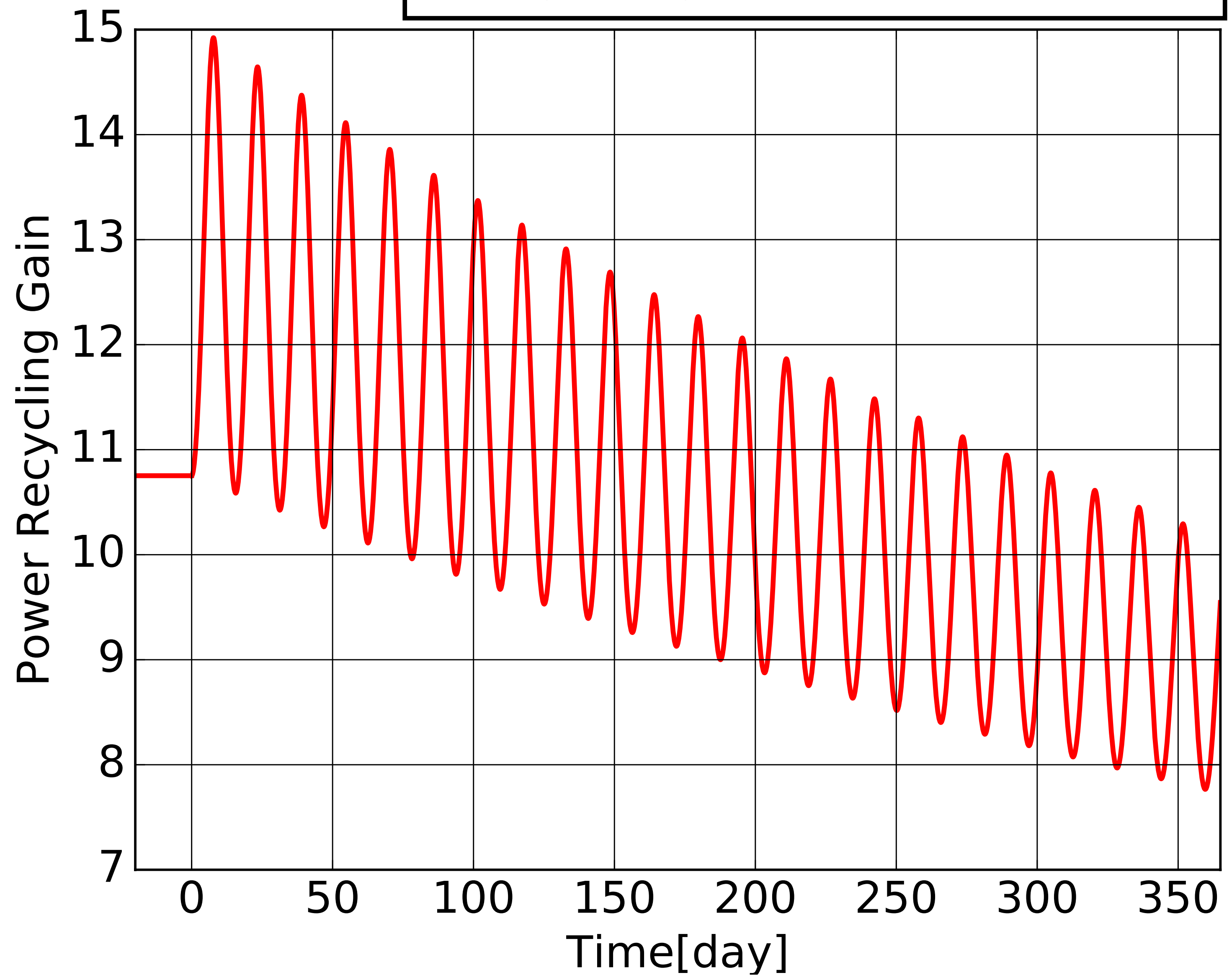



target : 360[um]@z=3800[mm]

# Influence for the GWs detector

A molecular adlayer changes the reflectance of a FP cavity depending on its thickness.
->How power recycling gain changes?

contamination starts at the same time for ITM and ETM



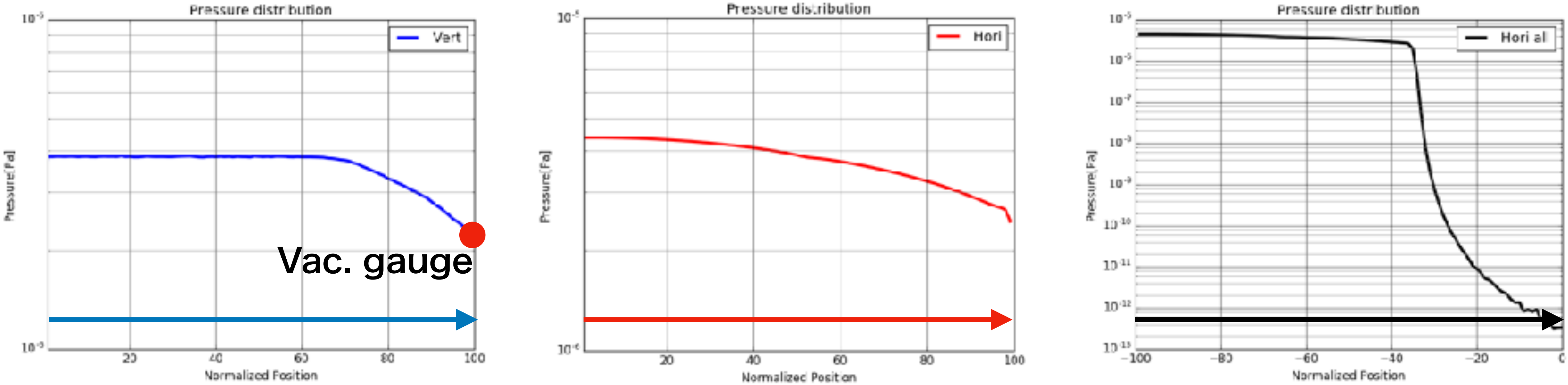

**Power recycling gain**

$$G = \left( \frac{t_{\mathrm{prm}}}{1 - \frac{1}{2} r_{\mathrm{prm}} \left( r_{\mathrm{fpx}} + r_{\mathrm{fpy}} \right)} \right)^2$$

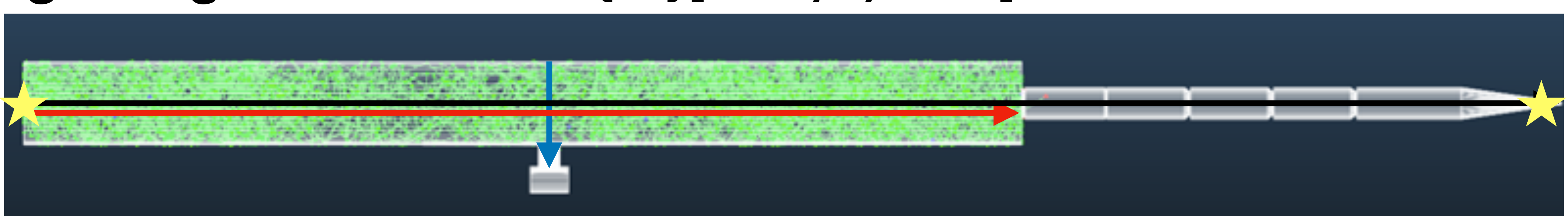
$t_{prm}$ : Transmittance of power recycling mirror

$r_{prm}$ : Reflectance of power recycling mirror

# Pressure distribution




Outgassing rate：1.5×10^{-6}[Pa l /s/cm2]

P1  P2

排気速度：~2700[l/s](H2O)

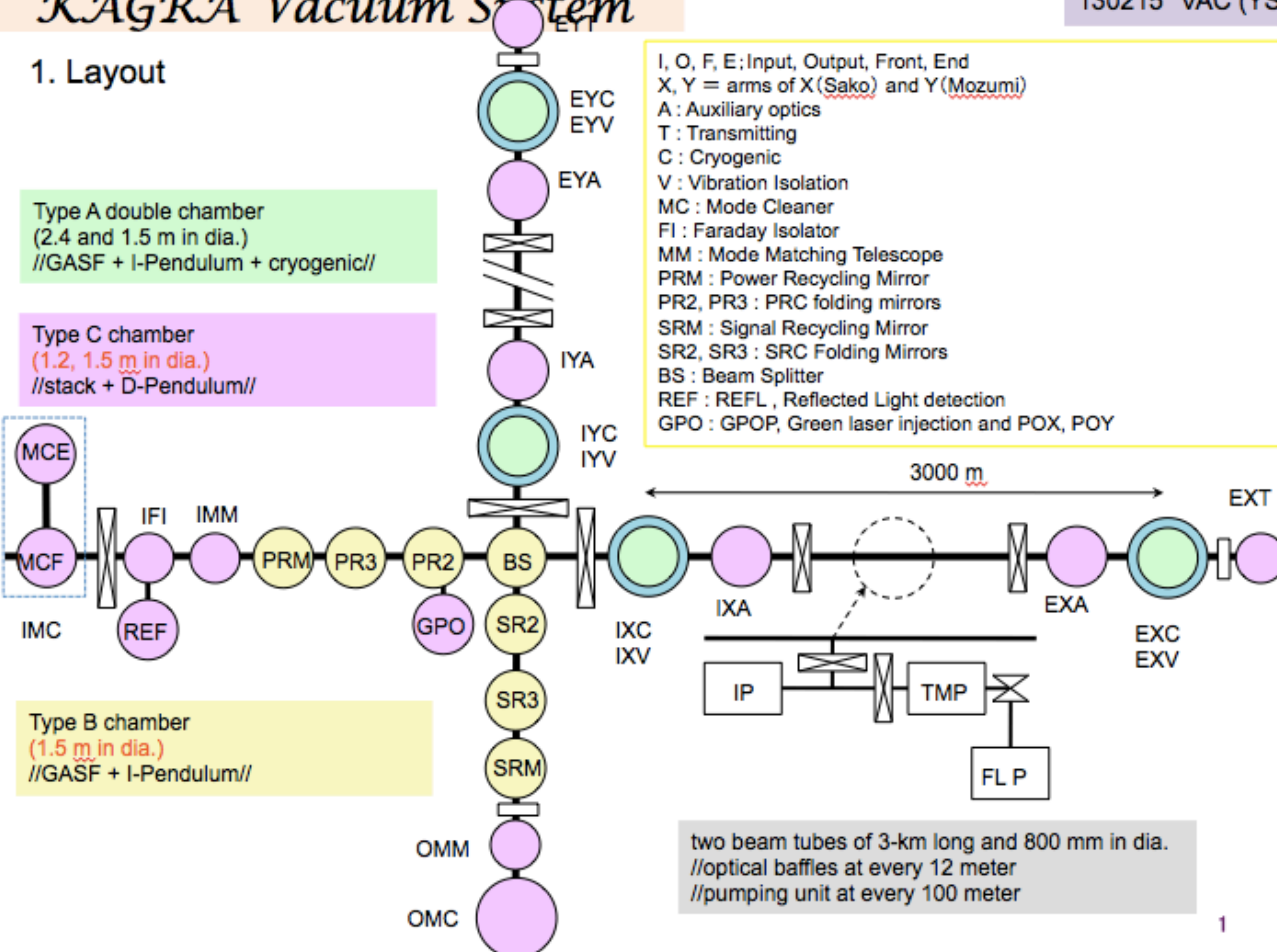
Estimated pressure

P1~1.26×10^{-5}[Pa]

P2~8.75*10^{-13}[Pa]

# KAGRA Vacuum System

## 1. Layout




Type A double chamber
(2.4 and 1.5 m in dia.)
//GASF + I-Pendulum + cryogenic//

Type C chamber
(1.2, 1.5 m in dia.)
//stack + D-Pendulum//

Type B chamber
(1.5 m in dia.)
//GASF + I-Pendulum//

I, O, F, E : Input, Output, Front, End
X, Y = arms of X (Sako) and Y (Mozumi)
A : Auxiliary optics
T : Transmitting
C : Cryogenic
V : Vibration Isolation
MC : Mode Cleaner
FI : Faraday Isolator
MM : Mode Matching Telescope
PRM : Power Recycling Mirror
PR2, PR3 : PRC folding mirrors
SRM : Signal Recycling Mirror
SR2, SR3 : SRC Folding Mirrors
BS : Beam Splitter
REF : REFL , Reflected Light detection
GPO : GPOP, Green laser injection and POX, POY

two beam tubes of 3-km long and 800 mm in dia.
//optical baffles at every 12 meter
//pumping unit at every 100 meter

# Reflectance of the mirrors and the arm cavity

Depending on the thickness of an adlayer on ITM and ETM HR coating, the reflectance of FP changes.