Cryogenics in Interferometric Gravitational Wave Detector

15/Feb/2007 KEK-Saclay Workshop

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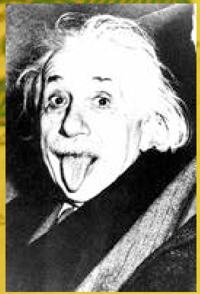
Contents



1. Cryogenic Interferometric Gravitational Wave Detector

1.1. GW detctors

Gravitational Wave Detection → Important to verify general relativity and to open new astronomy

Major detector type

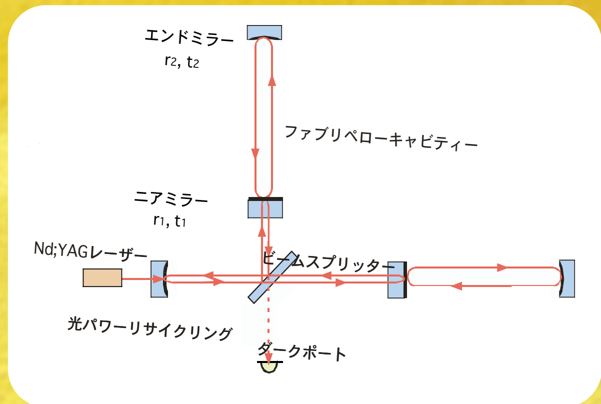
Resonant mass detector

EXPLORER at CERN

A few tons mass class
A few kelvin temperature

- **Narrow observation band**

Interferometer



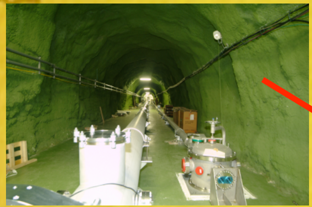
Fabry-Perot Michelson

km scale

- **Wide observation band**

Present GWD Global Network

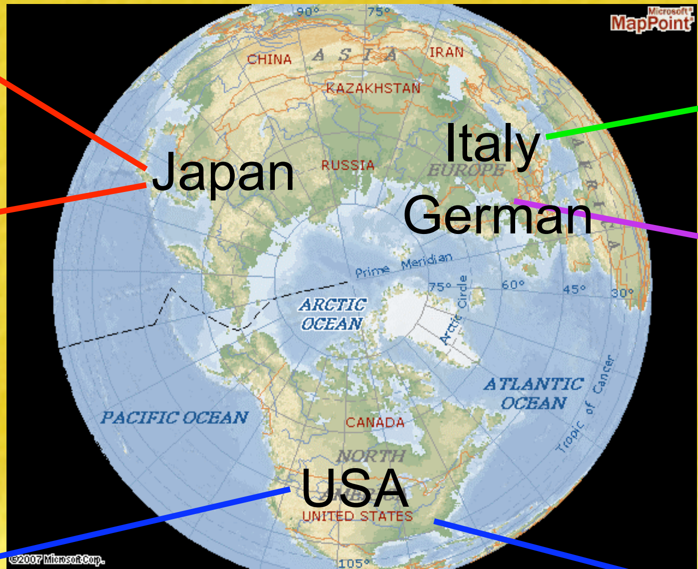
CLIO 100m



TAMA300 300m

LIGO (Hanford)

4km, 2km



VIRGO 3km

GEO600 600m

LIGO (Livingston)

4km

NS-NS binary coalescence

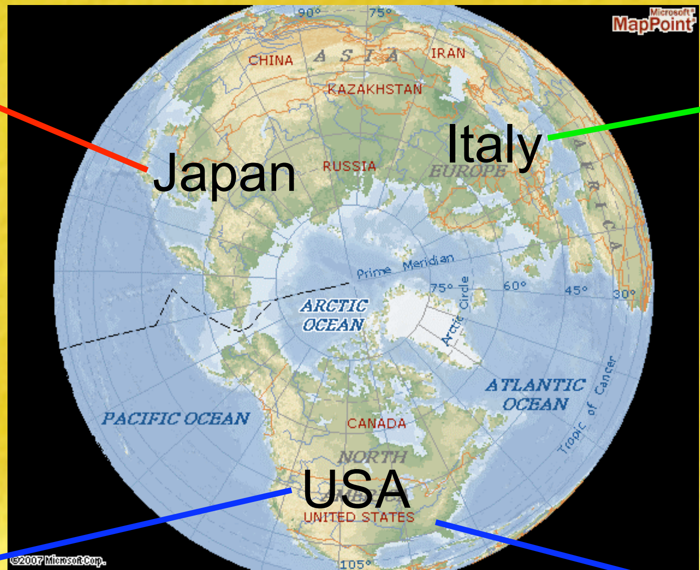
Event Rate: 1 / 10^6 yr

CLIO, TAMA, VIRGO, GEO LIGO

Next Generation GW Detectors

LCGT

Adv. VIRGO



Adv. LIGO
(Hanford)

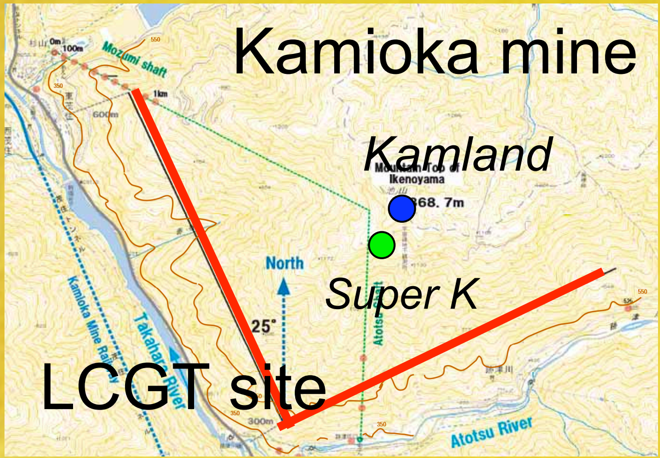
Adv. LIGO (Livingston)

NS-NS binary coalescence

Event Rate: 10 / yr

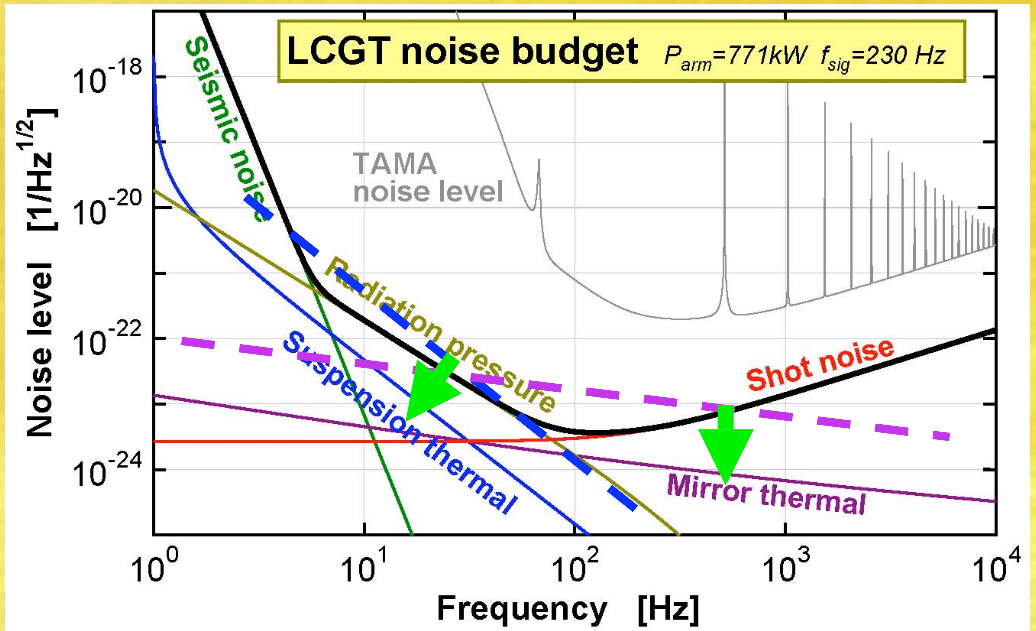
LCGT, Adv. LIGO, Adv. VIRGO

1.2. LCGT (Large-scale Cryogenic Gravitational wave Telescope) Project



Key Word

- Underground → Small seismic noise
- **Cryogenic Mirror & Suspension**
  → < 20 K,
  Reduction of Thermal Noises

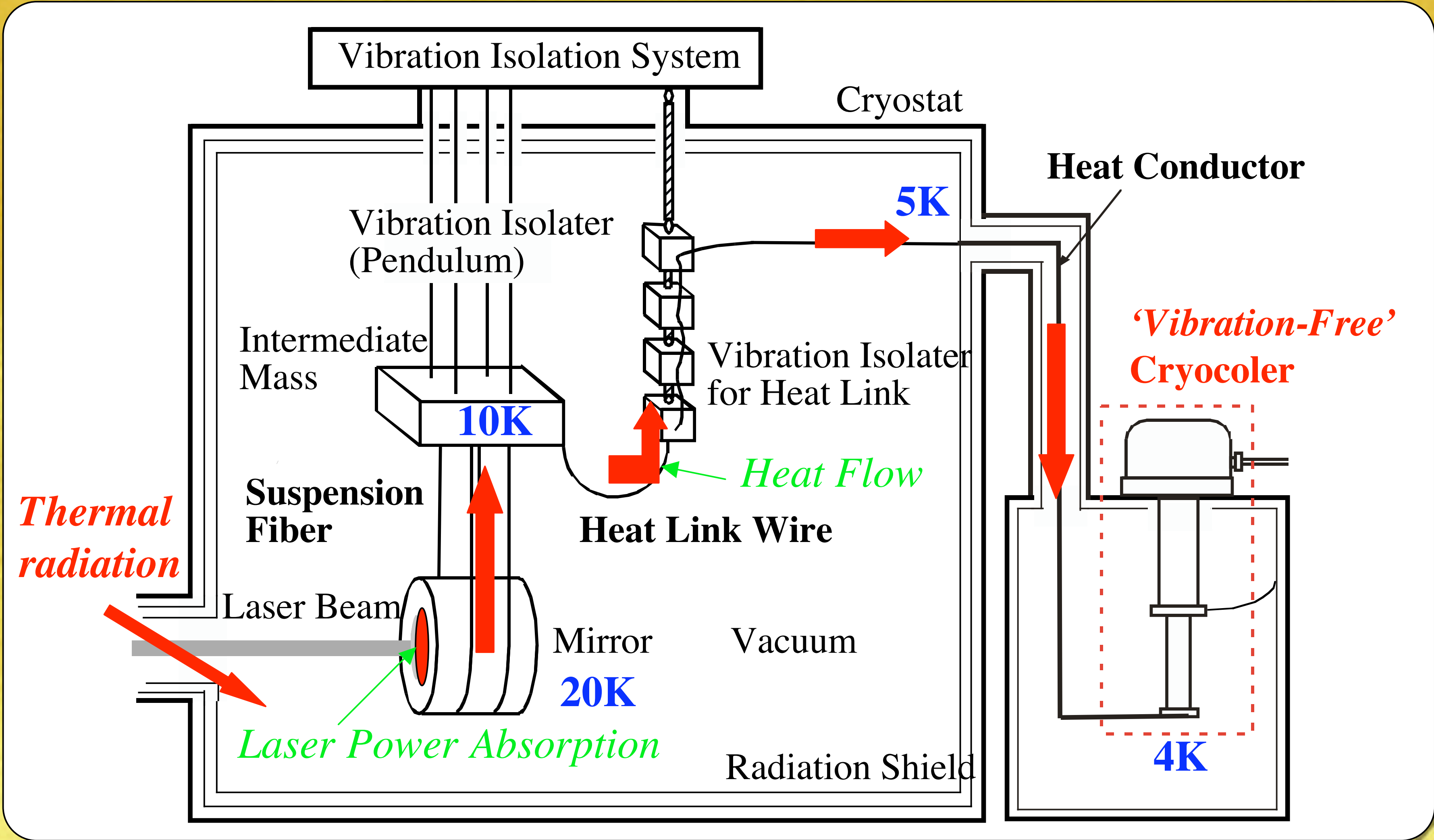


Technical Issue

How do we achieve cooling mirrors & suspensions with keeping their vibration isolation?

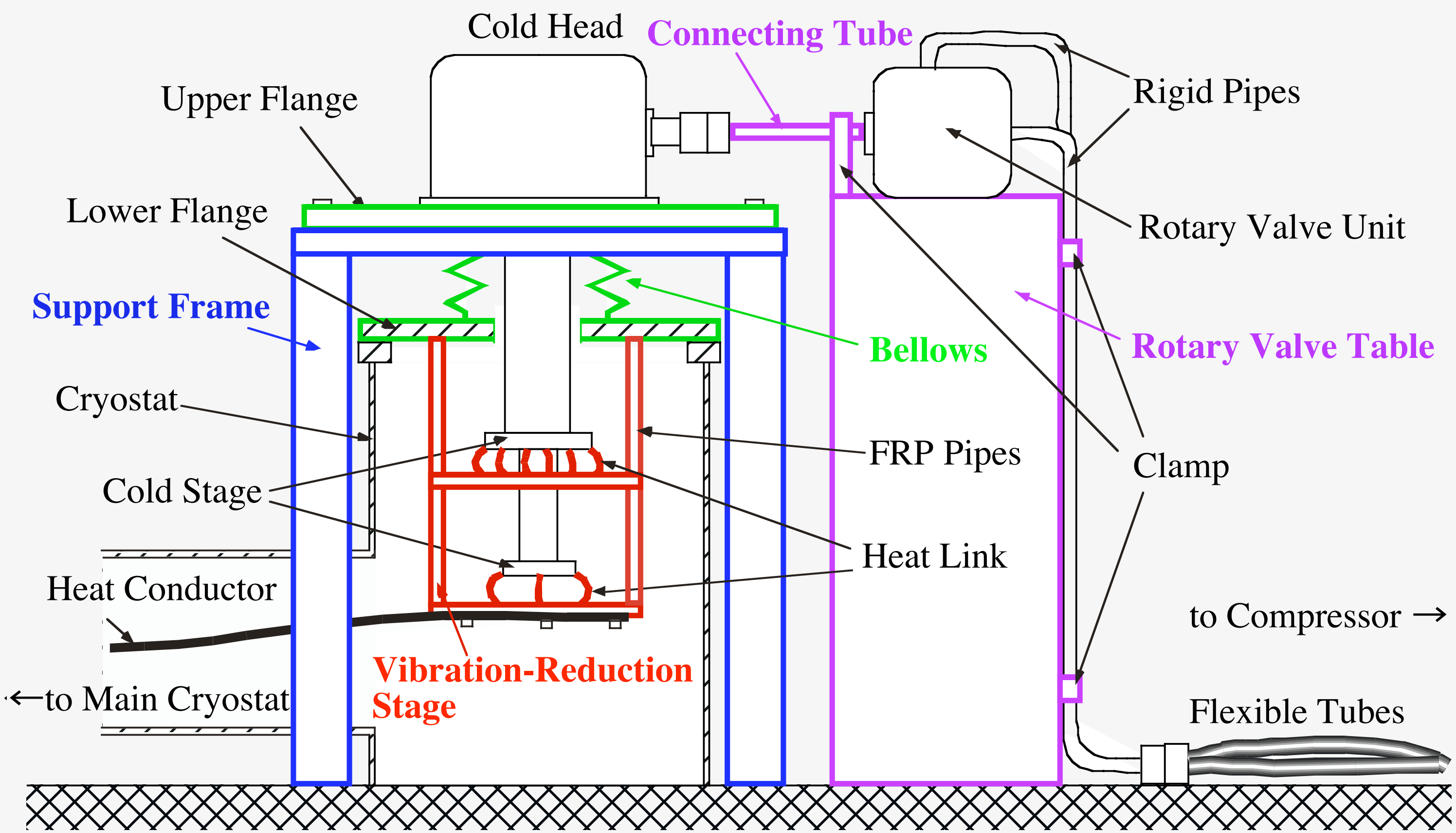
Cooling System in Cryogenic Interferometer

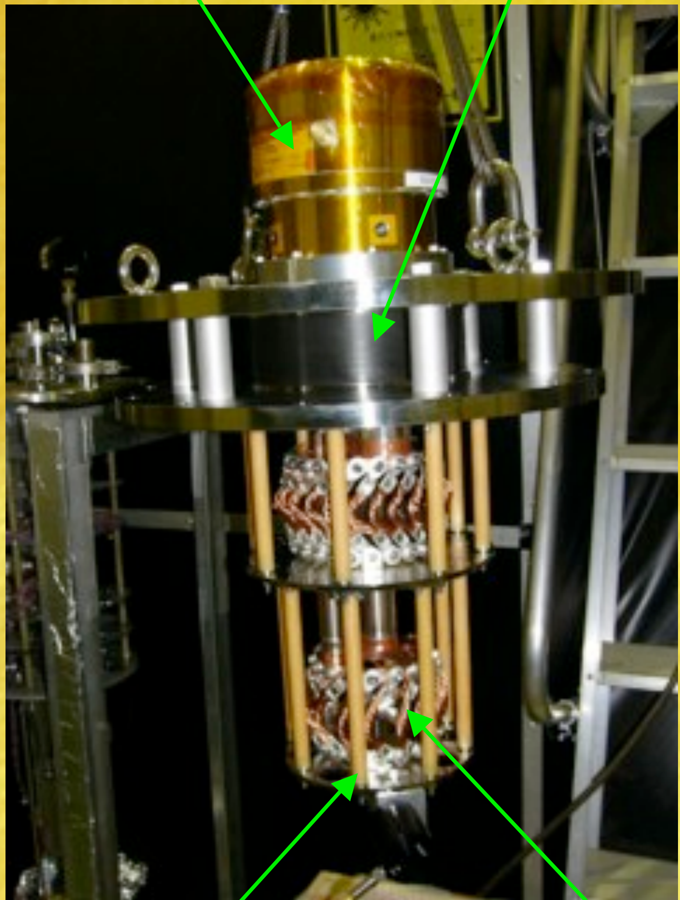
Requirement
- Vibration-free cooling
- Extreamly small heat load

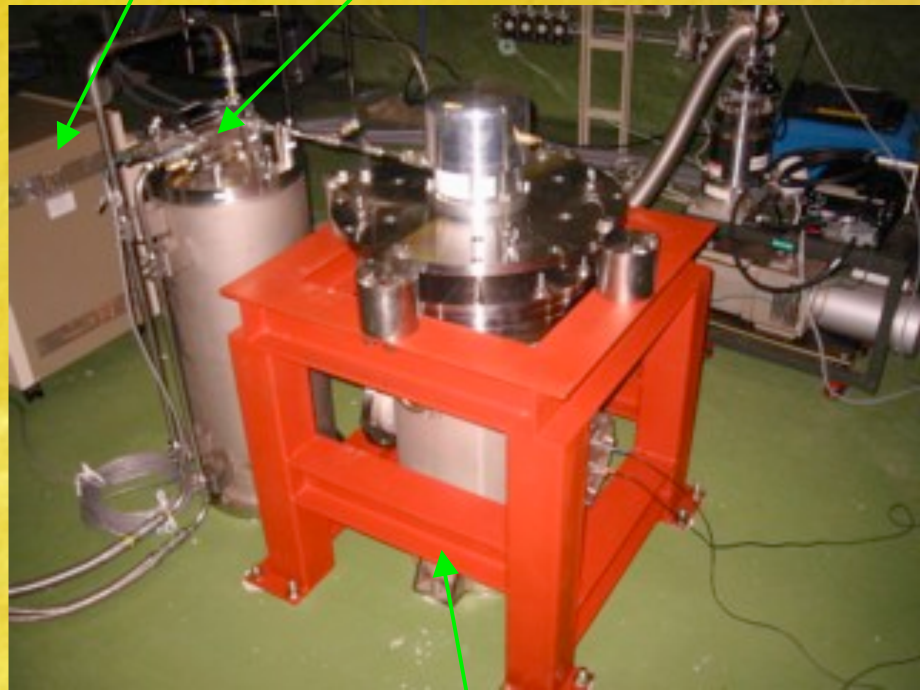


1.3. “Quiet” Cooling Technology

Vibration-free cryocooler system



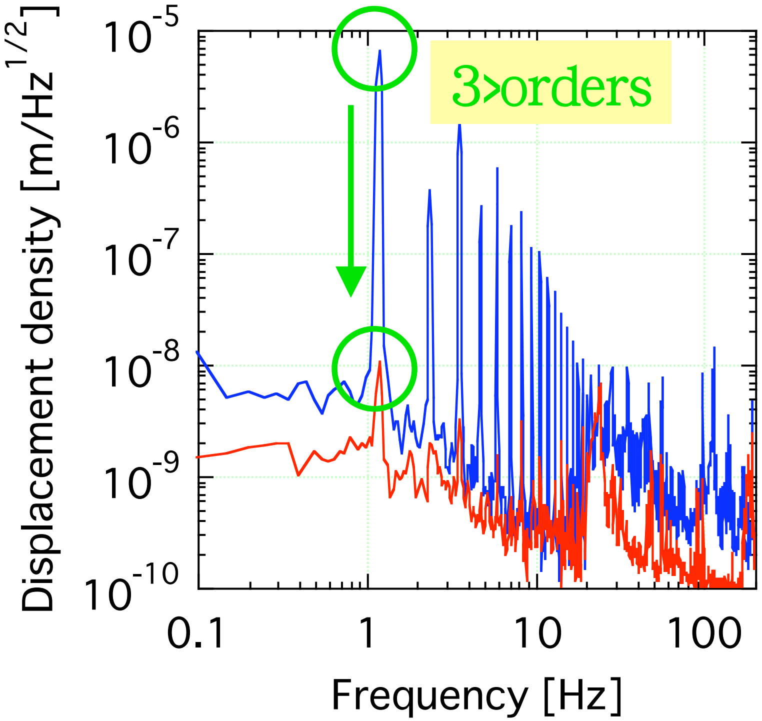

Cold Head
Bellows
Vibration-reduction stage
“Soft” heat links


Compressor
Rotary valve unit
Support frame

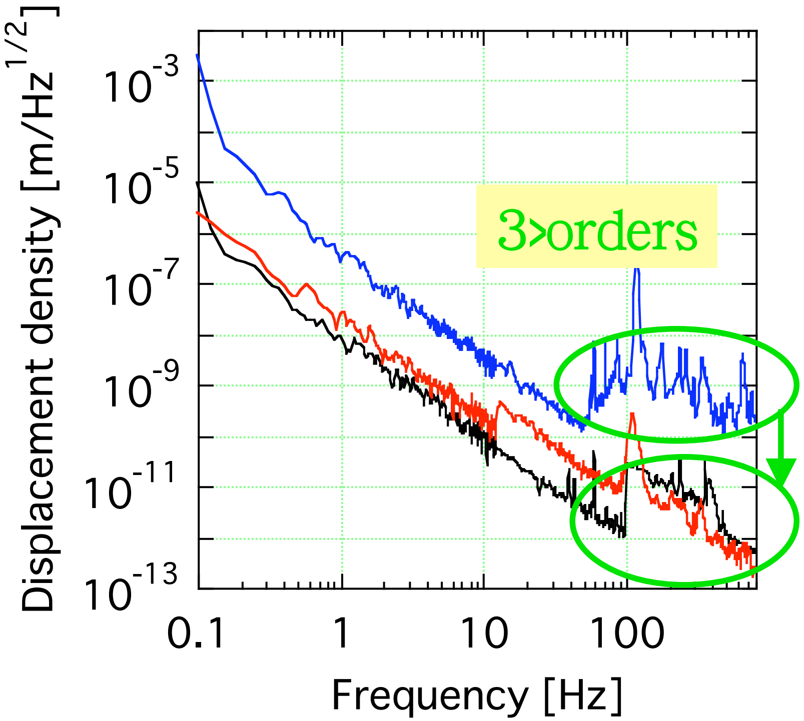
Measured Results

測定結果>(鉛直方向)

Seismic Vibration in Kamioka Mine
Without vibration reduction system
With vibration reduction system



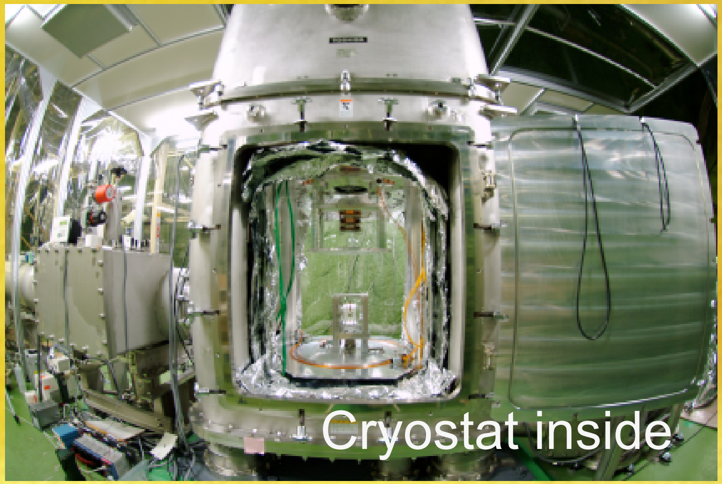
Cold Stage

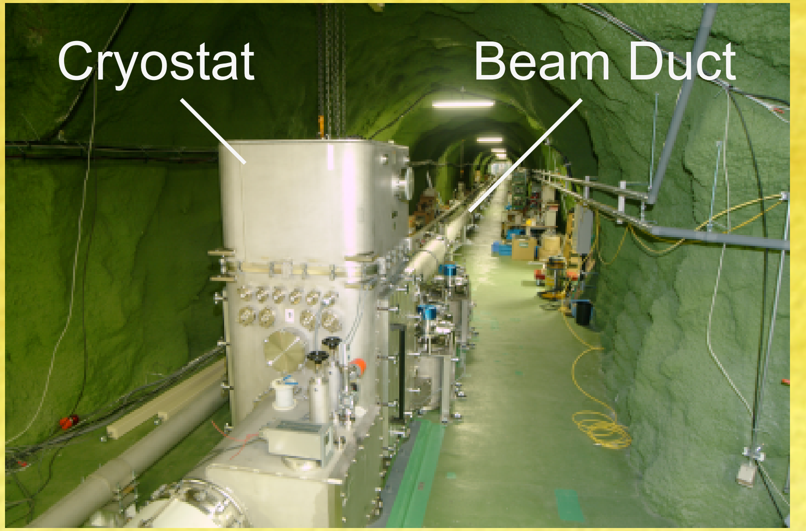


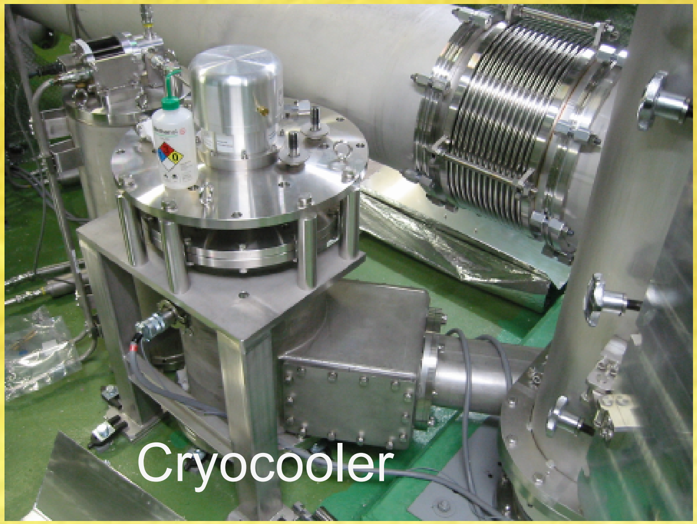
Cold Head

Prototype Cryogenic Interferometric Gravitational Wave Detector: *CLIO*

- 100m arm length cryogenic interferometer in Kamioka mine
- 4 cryostats, 6 radiation shield pipes, 2 beam ducts at 300K
- 10 vibration-free crycooler systems are used.
- $h = 5 \times 10^{-19}$ m/$\sqrt{\text{Hz}}$ sensitivity @ 300K
- Under trying to operate it @ cryogenic temp.

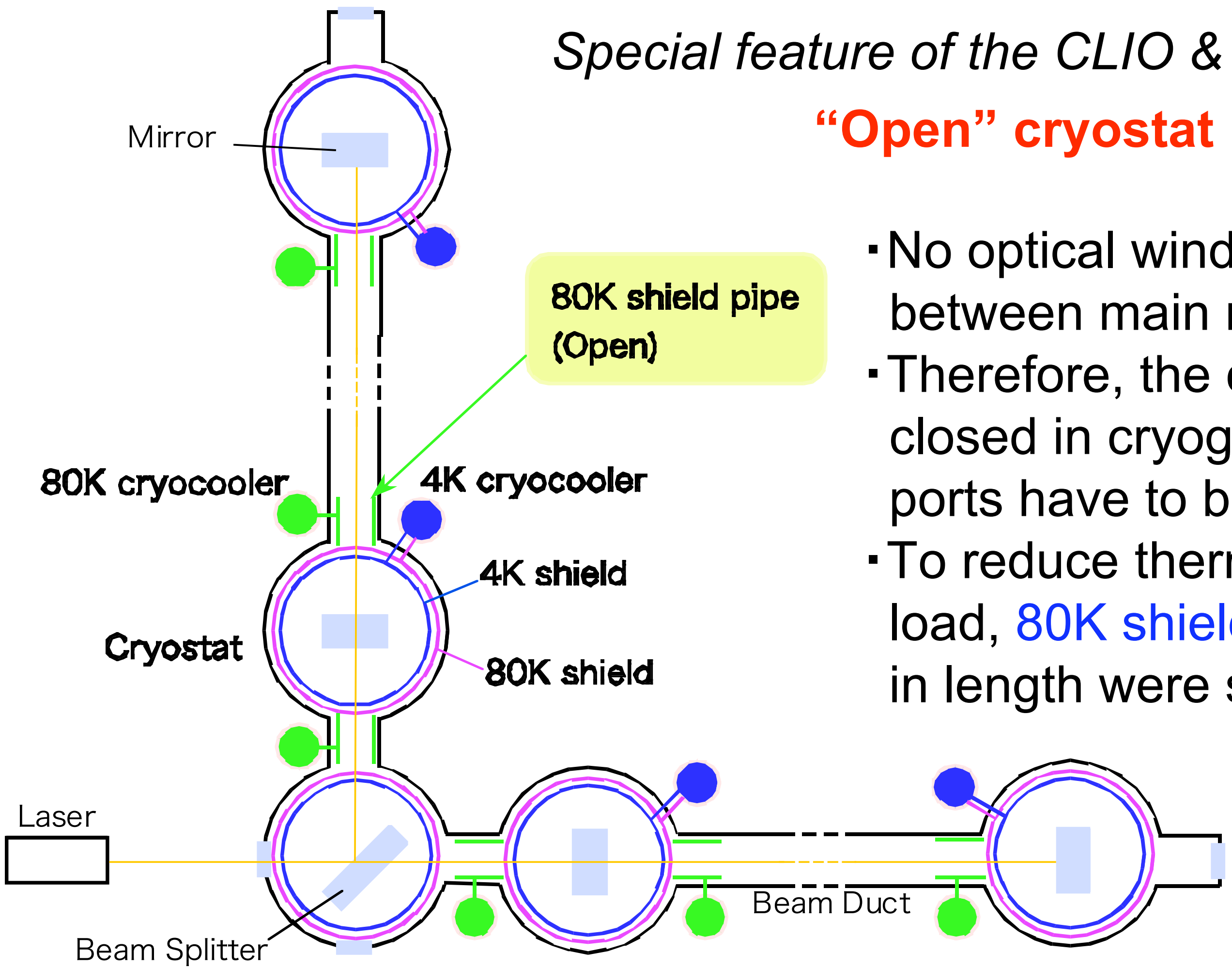






2. Minimizing Radiation Heat Load

2.1 Conduction effect of thermal radiation in a cryogenic pipe



Special feature of the CLIO & LCGT cryostat

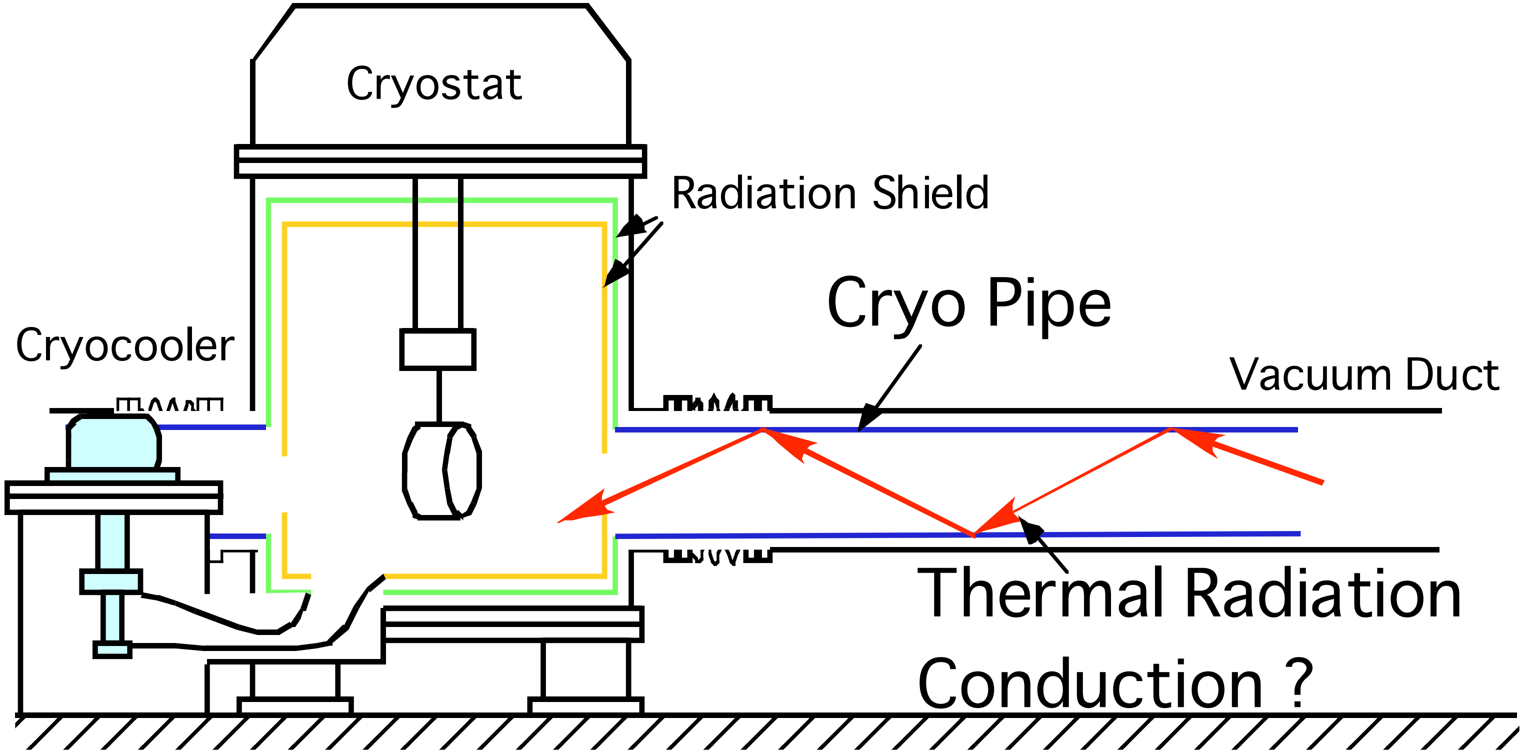
"Open" cryostat

- No optical windows can put between main mirrors.
- Therefore, the cryostats can not closed in cryogenic wall, and large ports have to be opened to 300K.
- To reduce thermal radiation heat load, 80K shield pipes with 5m in length were set in beam ducts.

In these cryostats with open ports, large heat load was observed.

Initial cooling test: 12.6 K @ 4K shield → Estimated heat load > 3W
Designed heat load ~ a few mW (cryocooler power ~ 0.5 W)

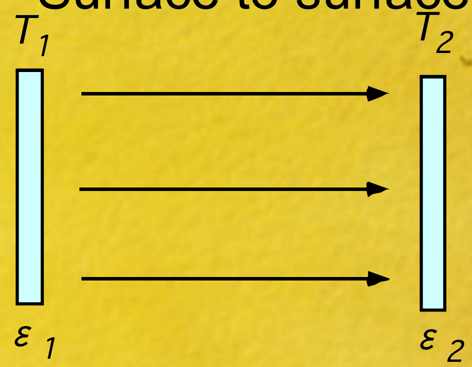
→ ・When cryo-pipe was closed, cryostat reached design temperature.
・When two baffles were set in a cryo-pipe, heat load reduced to 100mW level.



In general thermal radiation calculation:

$$P = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \sigma \left(T_2^2 - T_1^2 \right) A \frac{\Omega}{2\pi}$$

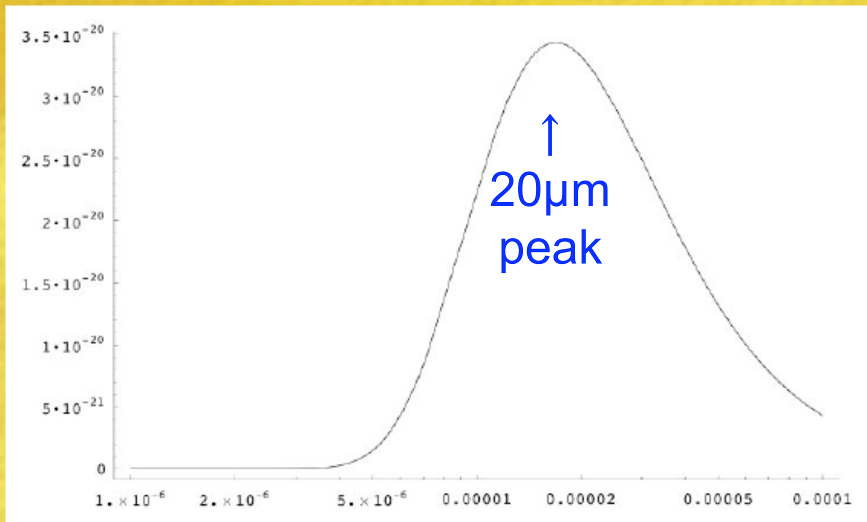
Surface to surface



In other view point :

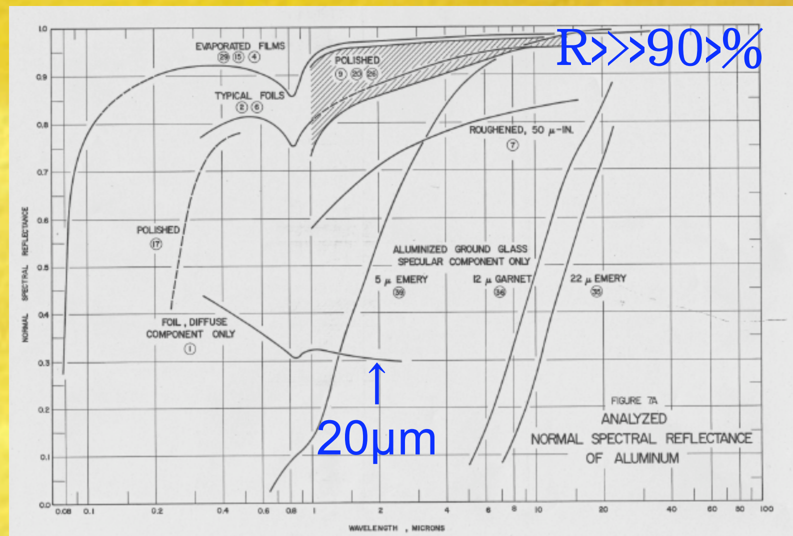
Thermal radiation consists of IR

Black body radiation: $u(\omega) = \frac{\hbar}{\pi^2 c^3} \frac{\omega^3}{\exp(\hbar\omega/kT) - 1}$



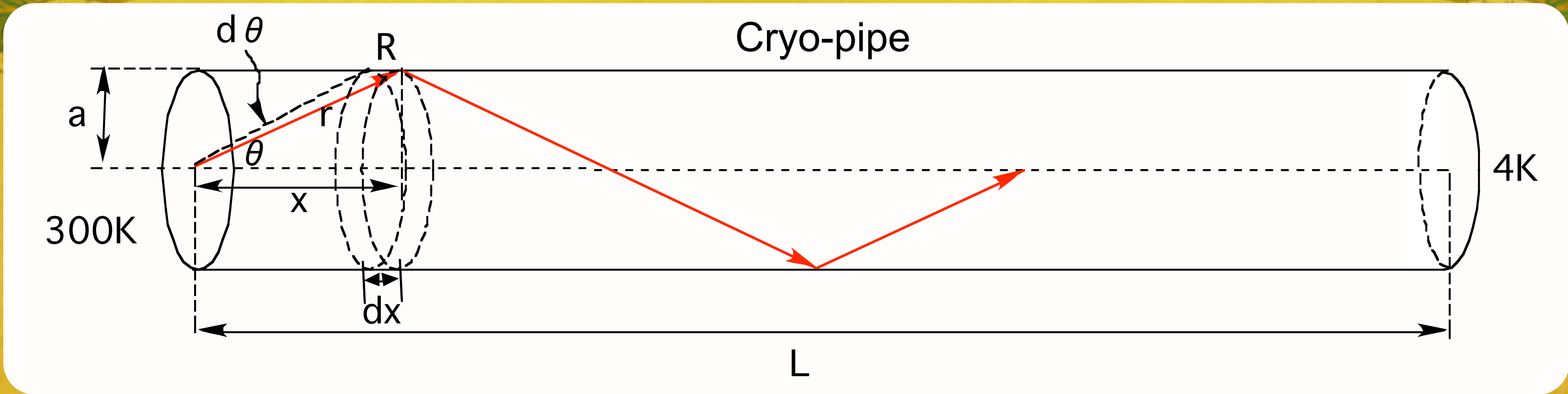
This function shows that 300K thermal radiation consists of infrared light with between 10μm and 100μm in wavelength.

Additionally…



Reflective spectrum aluminum

2.1.1. Simulation: *Ray trace model*



Solid angle of *dx* area, position *x* from 300K, inside the cryo-pipe

$$d\Omega = \frac{2\pi r \sin\theta \, dx \cos(\pi/2 - \theta)}{r^2} = \frac{2\pi a^2 \, dx}{(x^2 + a^2)^{3/2}}$$

Number of reflection of infrared beam at cryo-pipe wall between *x=0* and *x=L*

$$N(x) = 1 + n\left(\frac{L - x}{2x}\right)$$

↓

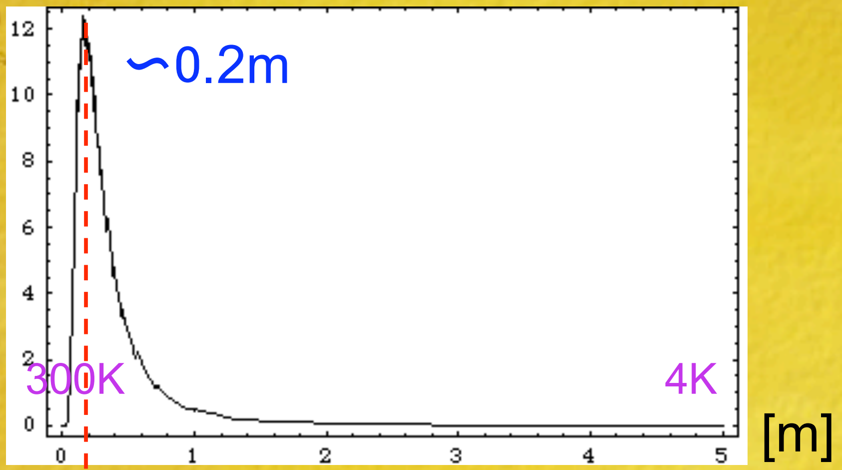
IR power component of thermal radiation reached to 4K region by reflection

$$P_{ref} = P_0 \int_0^L R^{N(x)} \frac{d\Omega}{2\pi} = P_0 \int_0^L R^{N(x)} \frac{a^2}{(x^2 + a^2)^{3/2}} dx$$

Power of thermal radiation, directly reached to 4K region

$$P_{th} = P_0 \frac{d\Omega_{th}}{2\pi} = P_0 \frac{a^2}{2L^2}$$

Calculation result in the case of CLIO



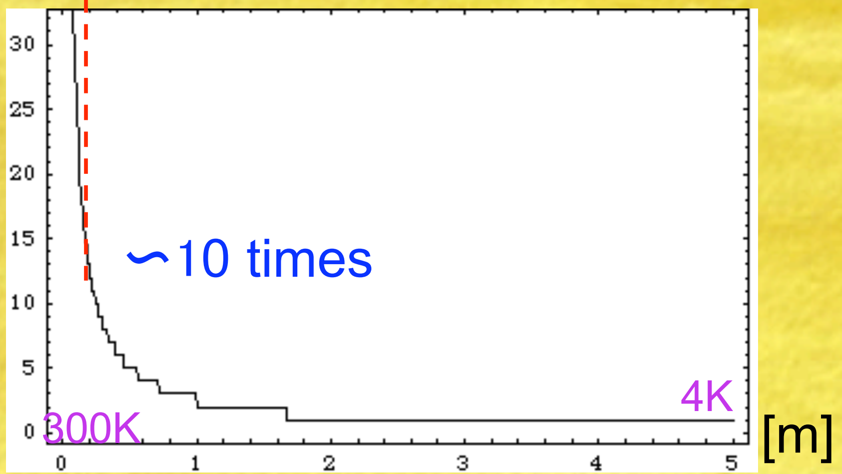
Plot of $P_{ref}(x)$ as a function of *x*

L=5m, 2a=0.3m

$$P_{ref}(x) = P_0 R^{N(x)} \frac{a^2}{(x^2+a^2)^{3/2}}$$

Assumption: R=0.90 (constant)

Almost power reached to 4K area by reflections is within 1m incident components.



Number of reflection

Corresponding number of reflection is about 10 times.

Assumption:

Thermal radiation source → Vacuum duct consist of stainless steel
$\varepsilon = 0.1 @ 300K$

Absorbed power in cryostat → 100% (black body)

⇩

Calculation result including reflection effect

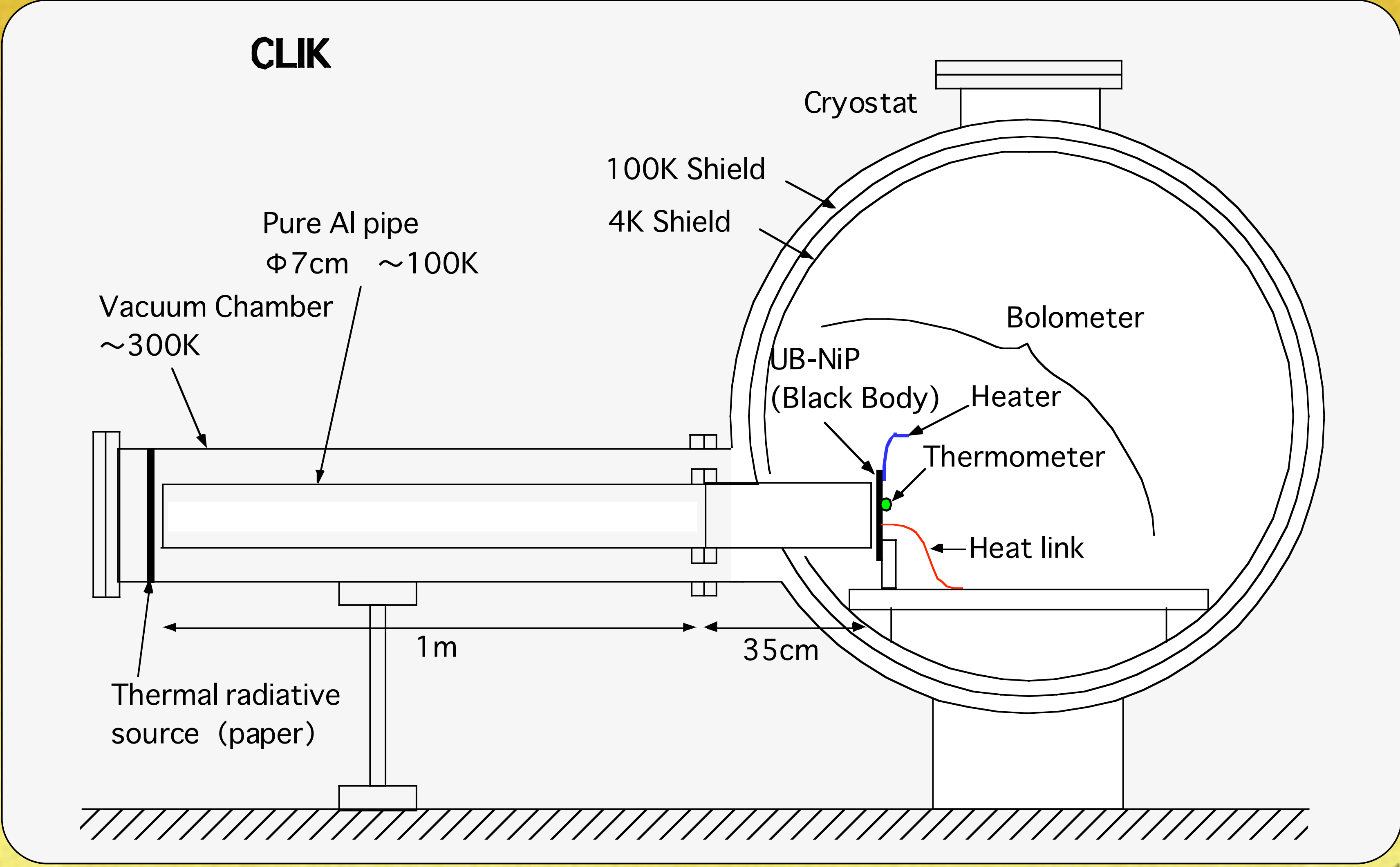
	$R = 0.90$	$R = 0.95$	$R = 0.97$
$\left(P_{ref} + P_{dir}\right)/P_{dir}$	307	622	898
P_{ref}/P_0	14%	28%	40%

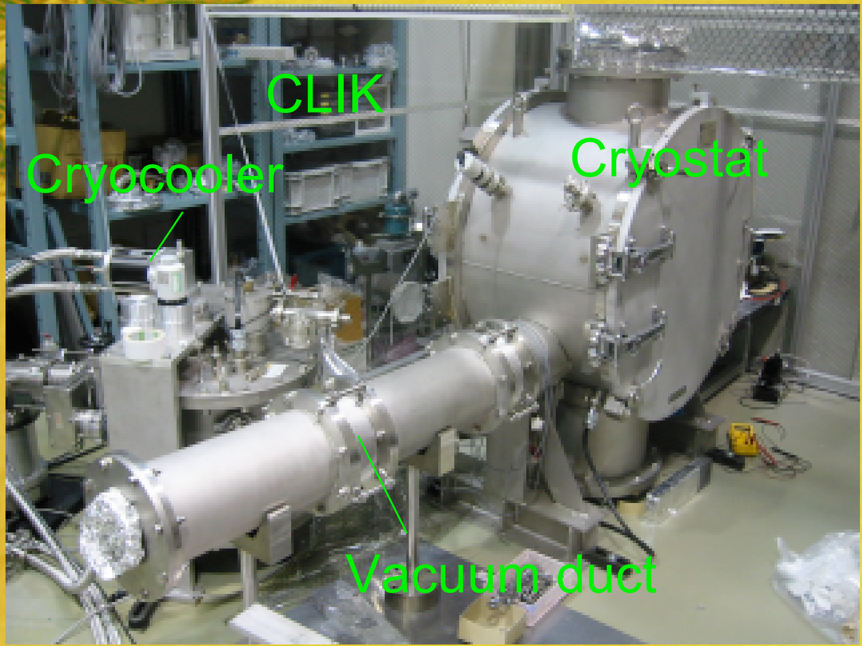
Calculated direct incident component: P_{dir} = 1.5mW
(0.045% for total thermal radiation from 300K half plane)

It is possible to increase thermal radiation heat load by 100 times order by its conduction in the cryo-pipe.

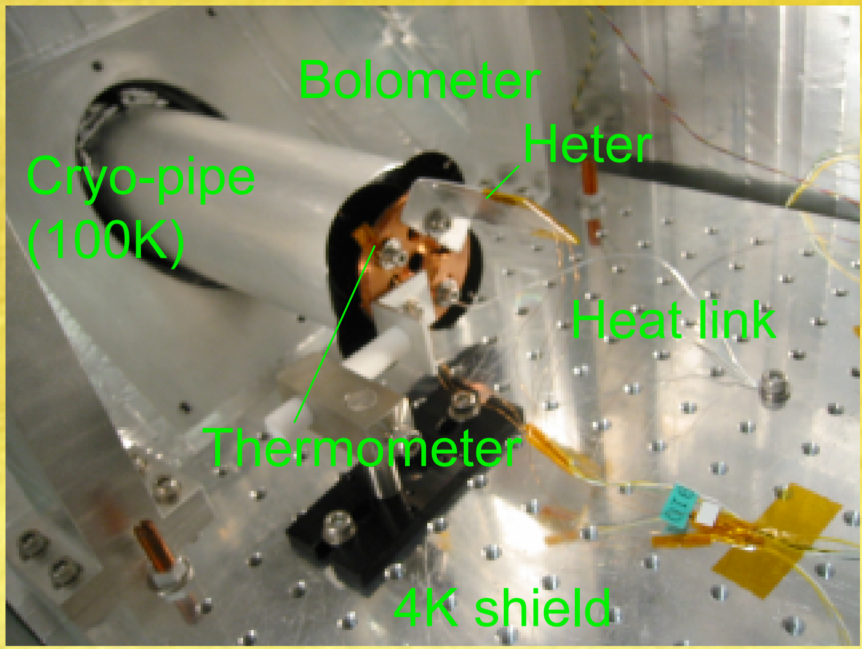
2.1.2. Experiment

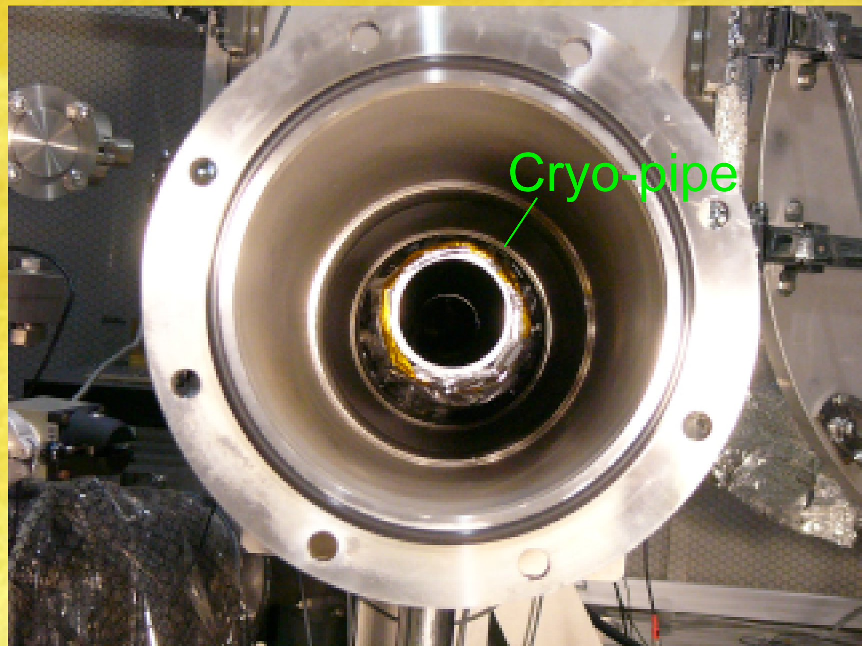
Experimental verification by a prototype cryogenic interferometer (CLIK) at ICRR.
CLIK has similar configuration to the CLIO.




CLIK
Cryocooler
Cryostat
Vacuum duct


Cryo-pipe


Bolometer
Heter
Cryo-pipe
(100K)
Heat link
Thermometer
4K shield


Cryo-pipe

Experimental result

Twice measurement to check reappearance

Ex. 1: $T_{bolo} = 14.13\text{K}$

Ex. 2: $T_{bolo} = 14.28\text{K}$

When

Absorption rate of bolometer: ~0.8

emissivity of paper: ~0.9

⇩

Average: $P_{meas} = 350mW$

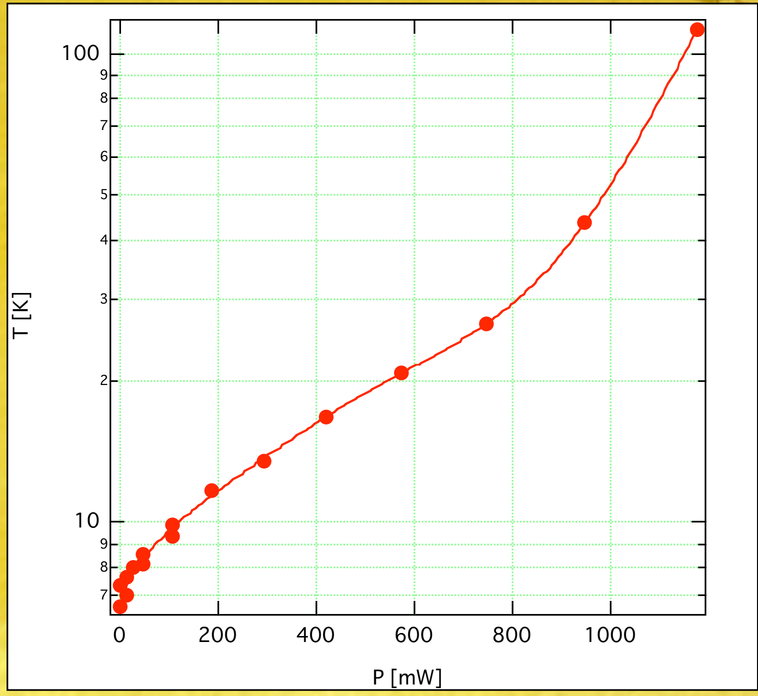
Heat load without reflection:

$P_{dir} = 0.53mW$

⇩

$P_{meas} / P_{dir} = 743$

Calibration curve of bolometer



$T\ [K] = K0 + K1 \times P + K2 \times P^2 + K3 \times P^3 + K4 \times P^4 + K5 \times P^5$

Estimated reflectivity of thermal radiation inside the cryo-pipe is 0.943.

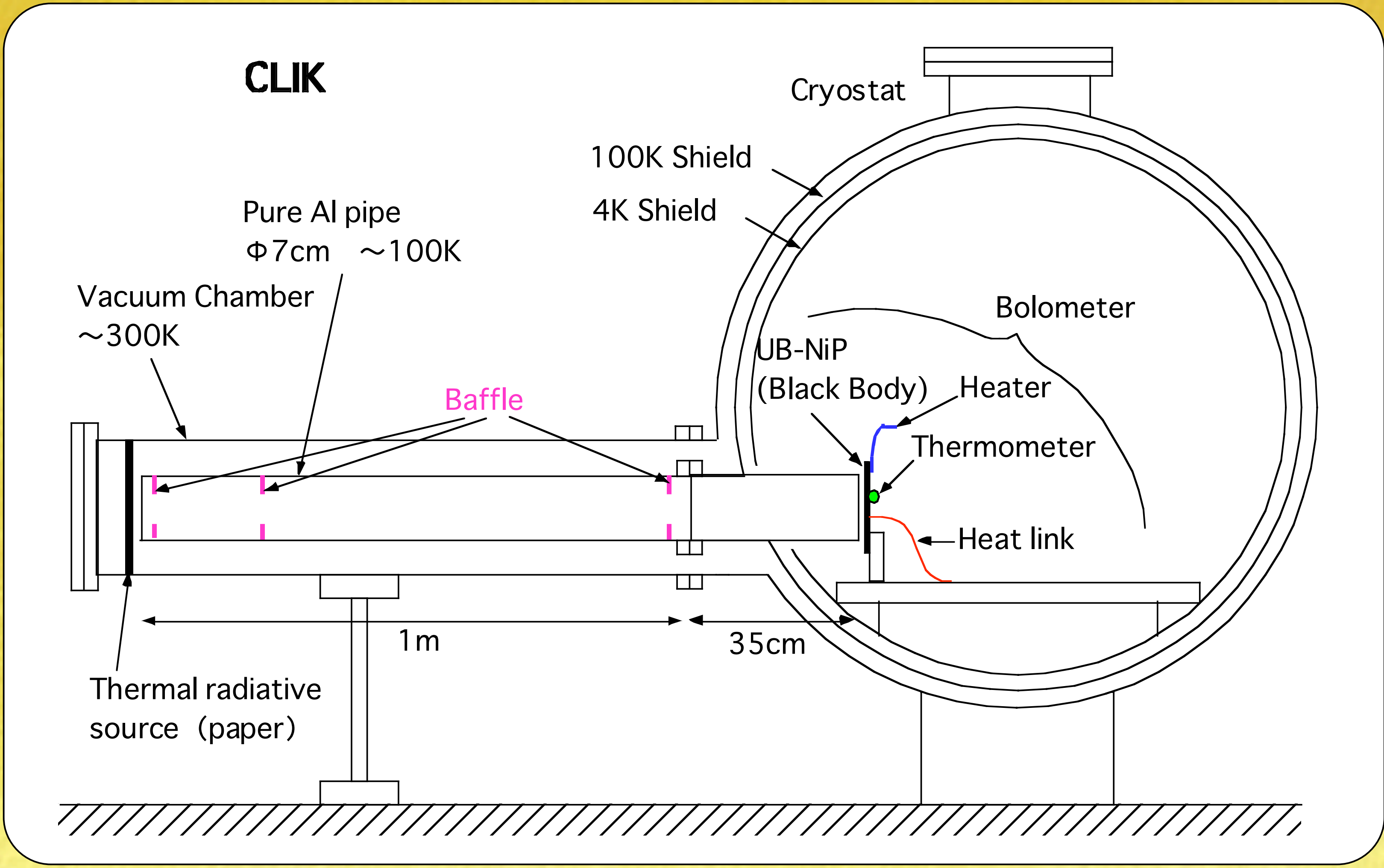
⇩

Simulation and experiments are almost consistent.

Thermal radiation conduction effect was verified.

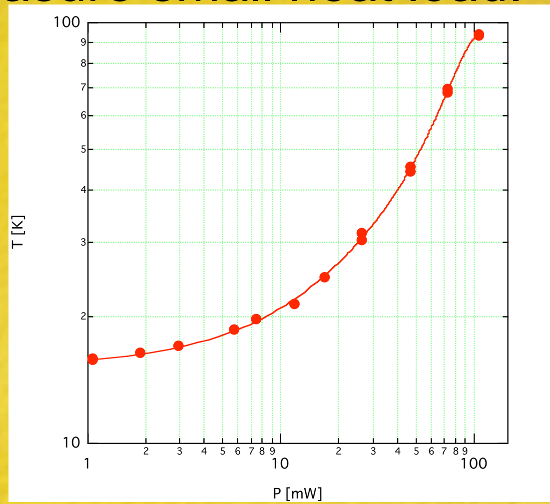
2.2 Reduction of thermal radiation conduction effect

Hit thermal radiation back by baffles



Al baffles with a center hole of 1/3 of cryo-pipe diameter

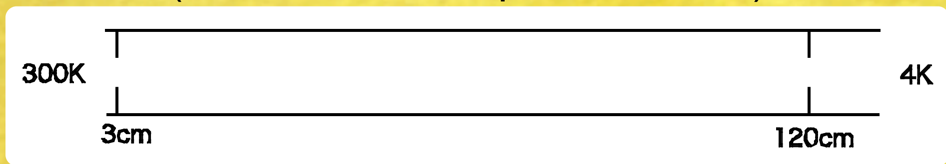
Recalibration by exchanging heat link to Φ0.5mm in diameter wire to measure small heat load.



$$T\,[K] = K0 + K1 \times P + K2 \times P^2 + K3 \times P^3 + K4 \times P^4 + K5 \times P^5$$

2 baffle experiment

(Almost same as present CLIO)



$\alpha_{bolo} = 0.8,\ \varepsilon_{paper} = 0.9$

⇩

Results

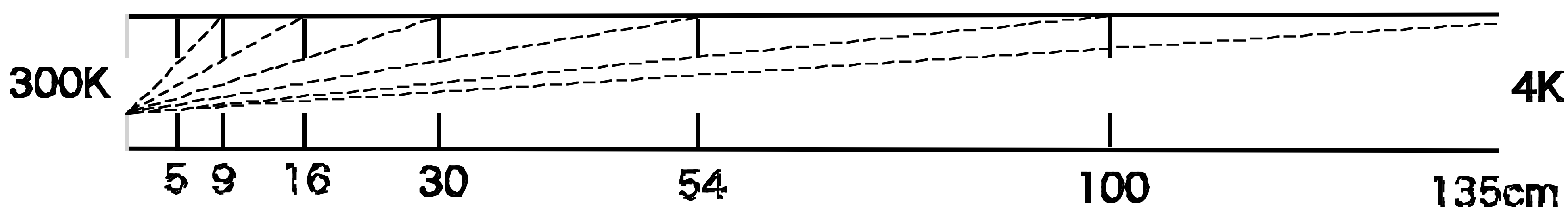
Exp.1: 18.28K
Exp.2: 19.35K ⇨ Ave. $P_{2baffle} = 6.3mW$ ⇨

$$P_{2baffle} / P_{dir} = 15$$

$$P_{2baffle} / P_{nobaffle} = 0.02$$

6 baffles experiment

set at positions that baffle shadows cover the inside wall of the cryo-pipe



Results

T_{bolo} = *14.31 K* ⇨ Heat load: *unmeasurable level*

⇩

Baffles are very effective to reduce thermal radiation conduction effect.

3. Summary

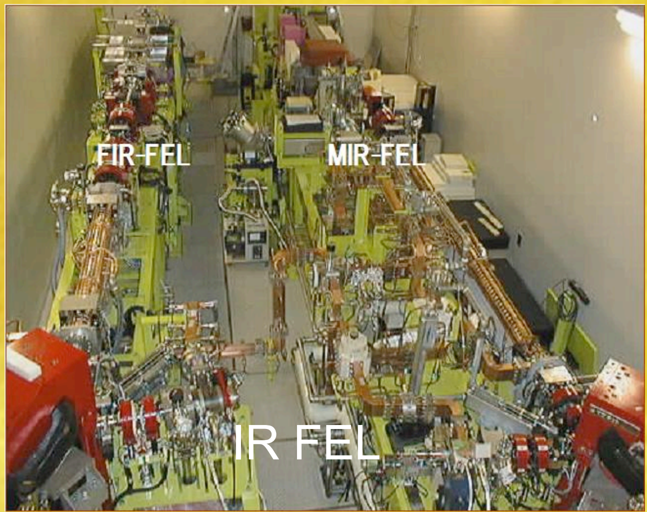
- In cryogenic interferometric GW detector, advanced cryogenic technologies, such as quiet cooling system, were used.
  CLIO will demonstrate at cryogenic temperature soon.
- Large heat load excess related to thermal radiation was observed in CLIO cryostat.
- Thermal radiation conduction effect in cryo-pipe was confirmed by CLIK experiment.
- Introduction of baffles was effective to reduce thermal radiation conduction effect.

Next step

- Test of baffles with large center hole to achieve suitable baffle design for the CLIO.

Appendix. Infrared reflectivity measurement

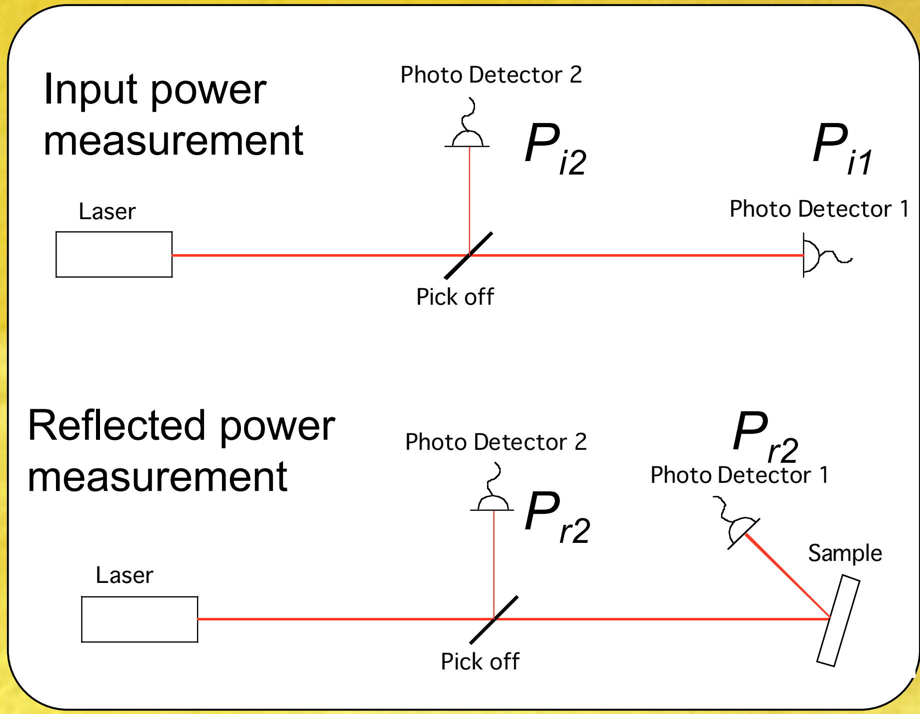
IR reflectivity of several key materials for GW detector, such as Al cryo-pipe, were measured by using IR FEL at IR FEL Research Center in Tokyo University of Science.



5 < λ < 13 μm
Beam Dia. 8mm at focus point

Detector: calorimeter (5cm×5cm)

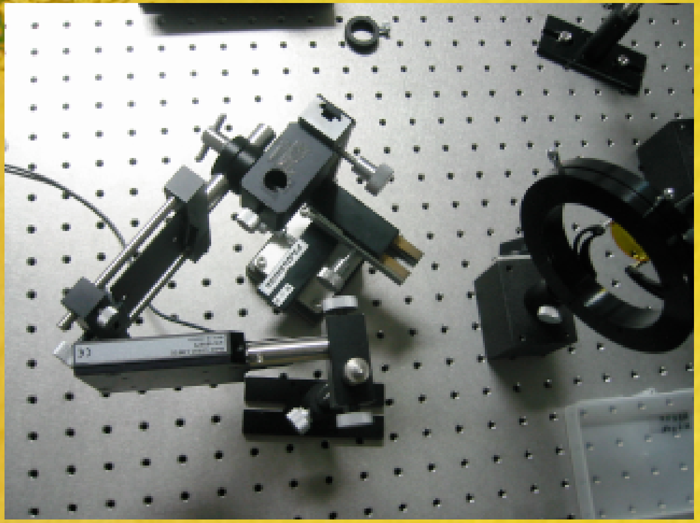
Method: Regular reflection measurement



Since each FEL pulse power flucuate about % order, to cancel it, pick off power was monitored. →

$$R = \frac{P_{r1}}{P_{r2}} \Big/ \frac{P_{i1}}{P_{i2}}$$

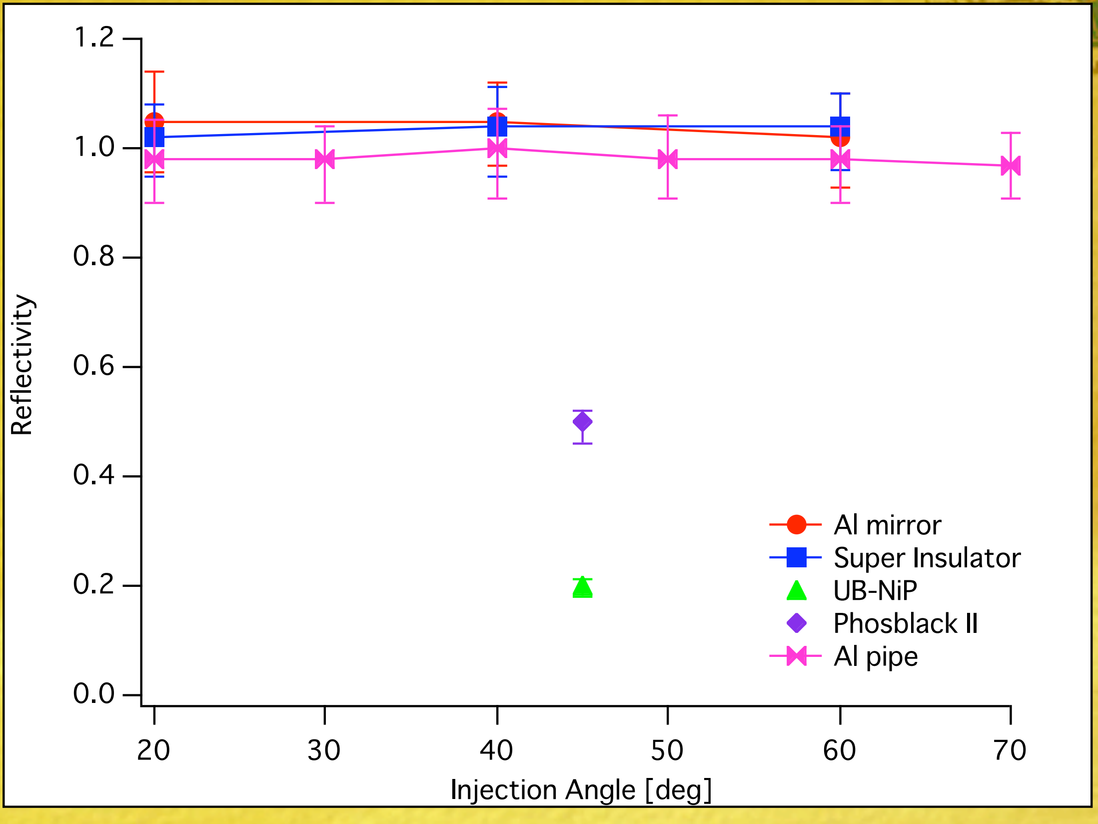
Measured results



Large error bar

↑

Detector precision



λ = 8.33 μm
T = 300 K

Al pipe (Al1070) had over 90% reflectivity at 8.33μm IR
And did not had large dependence of laser injection angle.
UB-NiP had 80% absorption coefficient.

Measured results *(Mirror materials)*

@ λ = 8.33 μm

\# Sapphire has absorption peak around 8μm

Sample	Reflectivity %	Transmittance %	Absorption %
Fused silica (20 deg)	37.1	0.7	62.2
Sapphire (20 deg)	2.1	1	96.9
SiO_2/Ta_2O_5 + fused silica substrate	2.5	0.2	97.3
SiO_2/Ta_2O_5 + sapphire substrate	1.1	0.9	98

@ λ = 12.5 μm

Sample	Reflectivity %	Transmittance %	Absorption %
Sapphie (20 deg)	89.1	1.8	9.1
SiO_2/Ta_2O_5 + Sapphire substrate	11.4	1.5	87.1

Dielectric multi-layer coating has large absorption for IR.