KAGRA Large-scale Cryogenic Gravitational wave Telescope Project in Japan

KAGRA Collaborators

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National Astronomical Observatory of Japan,
High Energy Accelerator Research Organization,
Phys.S. Univ. of Tokyo,
GSFS Univ. of Tokyo,
F.Eng. Univ of Tokyo,
Tokyo Institute of Technology,
Osaka City Univ.,
Phys.S. Kyoto Univ.,
Electro Communication Univ.,
ERI. Univ of Tokyo,
Astro. Univ. of Tokyo,
Hosei Univ., AIST, NICT,
Phys.S. Osaka Univ.,
YITP Kyoto Univ.,
Phys.S. Ochanomizu Univ.,
ARISH Nihon Univ.,
S.Niigata Univ.,
Yamanashi-Eiwa Univ.,
CIT Nihon Univ.,
FST Hirosaki Univ.,
S. Tohoku Univ.,
S. Rikkyo Univ.,
S. Hiroshima Univ.,
S. Ryukyu Univ.,
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KAGRACollaborators

Phys.S. Univ. of Western Australia,
Louisiana State Univ.,
CCRG Rochester Institute of Technology,
Beijing Normal Univ.,
Inter-University Center for Astronomy and Astrophysics, Moscow Univ.,
LATMOS/CNRS,
Univ. of Science and Technology of China,
Inst. for High Energy Physics of Chinese Academy of Sciences,
Peking Univ.,
CMS ITR Taiwan,
Maryland Univ.,
Columbia Univ.,
Glasgow Univ.,
Sannio Univ.,
Shanghai Normal Univ.,
National Tsing Hua Univ.,
Korea Univ., KIAS,
Inje Univ., Korea Univ.,
Yongji Univ.,
Seoul National Univ.,
Korea Atomic Energy Research Institute ,
Hanyang Univ.,
Pusan National Univ.,
KISTI , Korea NIMS,
Kyungpook National Univ.,
Kunsan National Univ.,
KIAS , IISER-TVM,

Purposes of GW Direct Detection

GWs have not been directly detected. Its direct detection is expected to open a new window of Physics and Astronomy.

(1) Test of General Relativity.

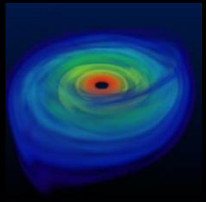
(2) GW Astronomy and Physics about Black Holes, Neutron Stars and Supernovae in the extremely strong gravity field.

(3) Cosmology (in the future) cosmic background radiation of **GWs to see the beginning of the Universe that cannot be observed by EMWs.**

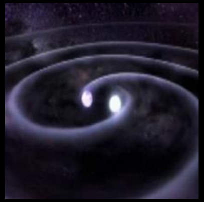
Supernovae

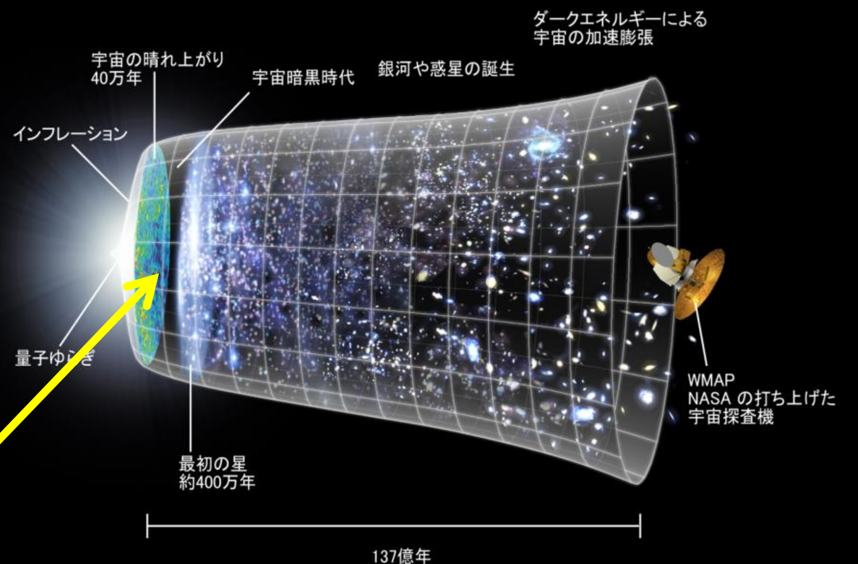
Pulsar

Black Hole



NS-NS

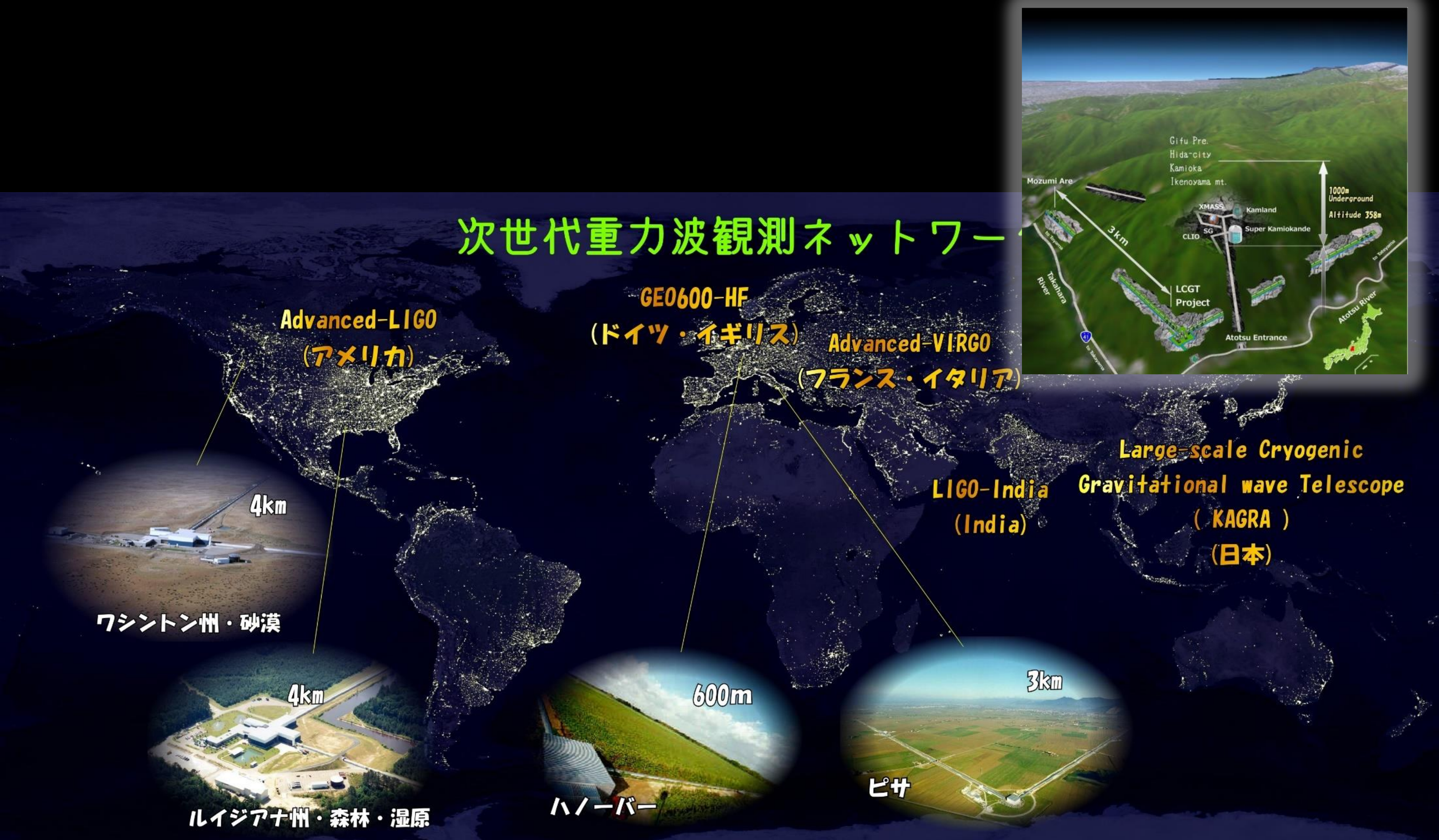




Evolution of the Universe

NASA/WMAP Science Team

Network Detection



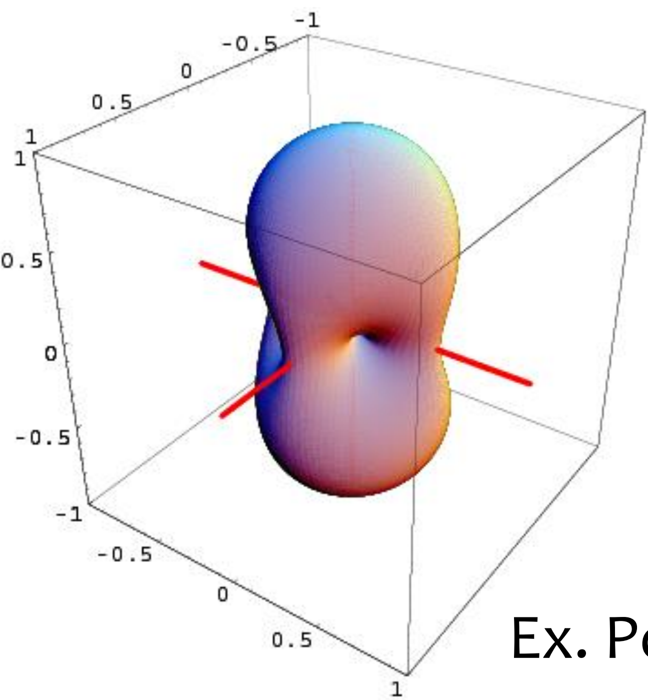
Merits of GW network detection

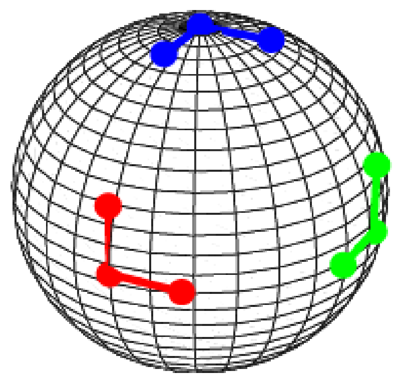
- **Convincing detections**
  - By coincidence of independent detectors.
- **Determination of**
  - Arrival time,
  - Polarization of GWs,
  - (in case of inspiral binary,) absolute amplitude and inclination angle of orbit.
- **Enhancing the duty time of observation**
  - More GW events,
  - Chance of follow up observation.
- **Sky coverage enhancement**

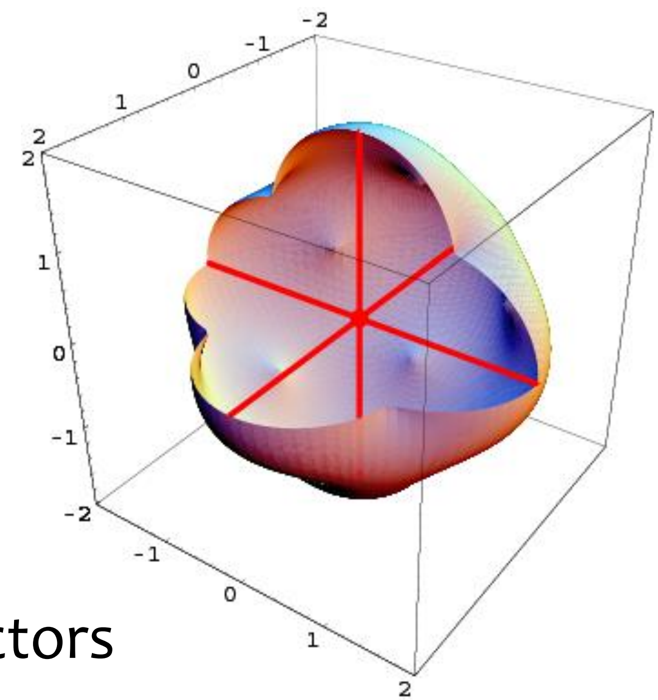
Why Network Detection

- **Cover the dead angles with each other**

GW Interferometer Directivity



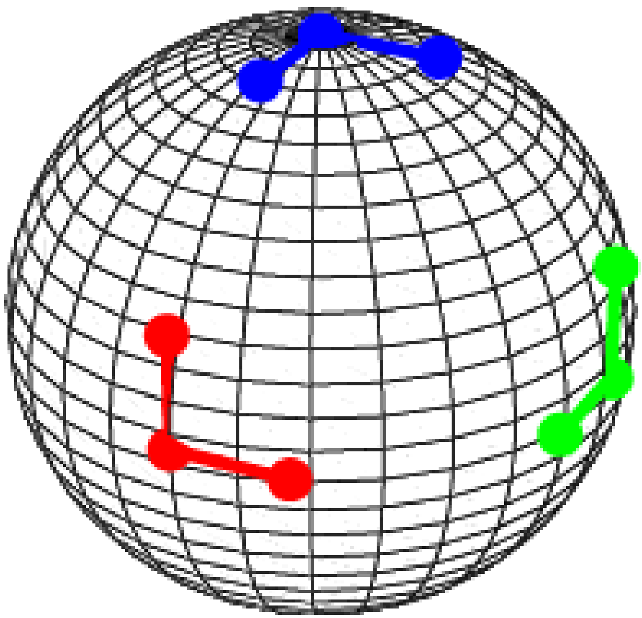




Ex. Positions of three detectors

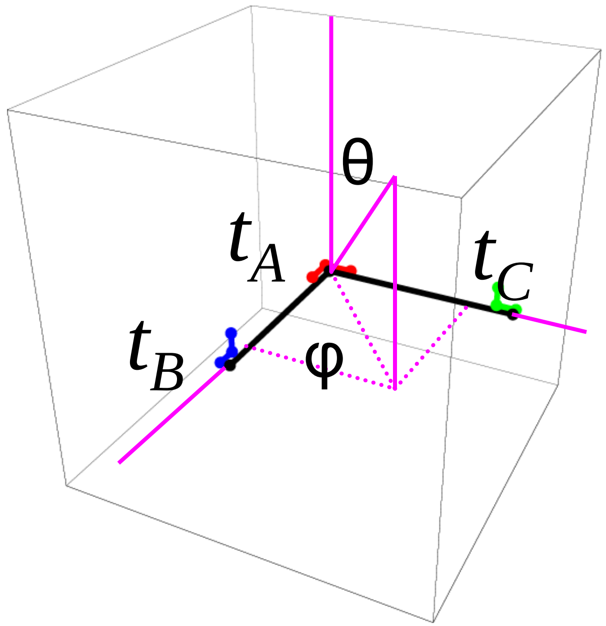
Why Network Detection

- identification of GW source position by three detectors



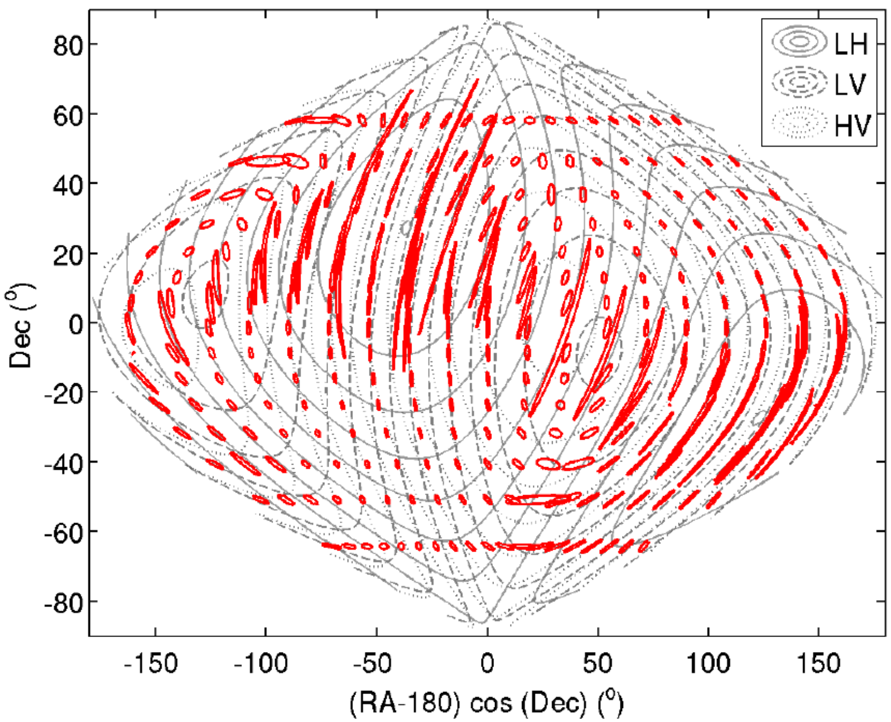
$$\tan\phi = \frac{t_C - t_A}{t_B - t_A}$$

$$\sin\theta = \frac{c}{L}\sqrt{(t_C - t_A)^2 + (t_B - t_A)^2}$$

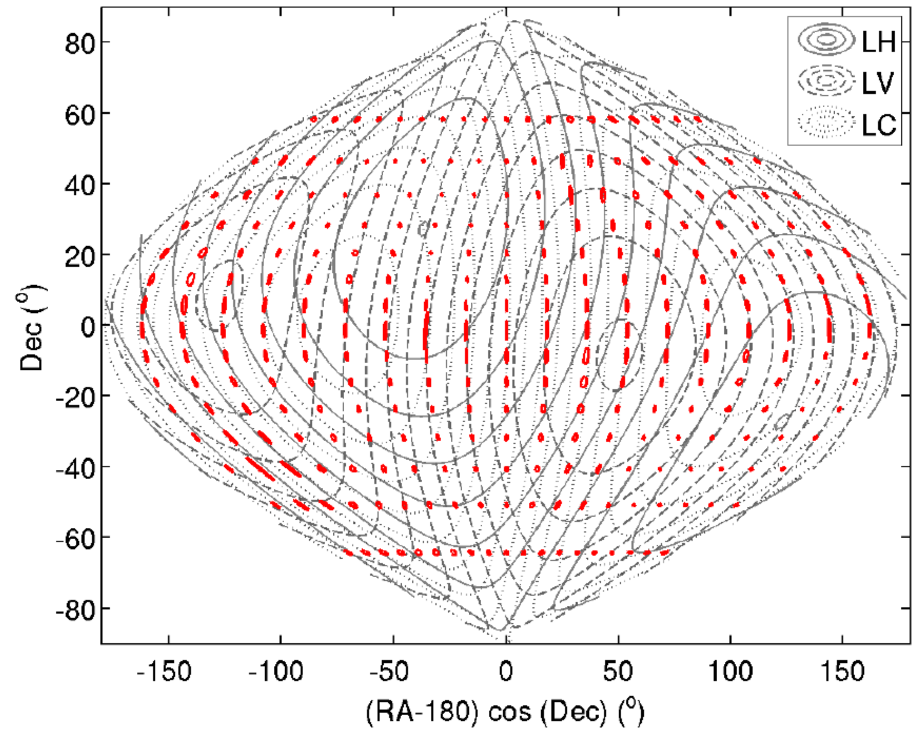


Why Network Detection

- Enhance the precision by three and more detectors



LIGO (L+H) + VIRGO



LIGO (L+H) + VIRGO + KAGRA

Better with LIGO-INDIA

Wen and Chen, arXiv : 1003:2504

KAGRA Highlights

KAGRA highlights that are different from other GWDs such as aLIGO,a VIRGO are …

(1) Underground
→ Stable Operation owing to low seismic noise.

(2) Usage of Cryogenic Mirrors and suspensions
→ Reduce Thermal Noises

(3) Collaboration with Geophysical Laser Strain-meter

KAGRA Collaboration 1

- **With LIGO group**
  - Some members visits and help, LIGO mirror rent, Design tool for IFO, Digital Control system, DCC access.
- **With VIRGO group**
  - ICRR-VIRGO meeting, Exchange of academic agreement (Pro. Fidecaro, Pro. Flaminio, Pro Mours, Pro Ricci).
  - Italy-Japan conference was held in October in Tokyo.
- **With GEO group**
  - MOU with Glasgow Univ., (Pro.Hough) AEI., Collaboration on some R&Ds about suspension and optical coating mechanical loss.
- **With University of Sannio (Italy)**
  - Academic agreement, Researcher exchange, and so on (Pro. De Salvo).
- **With SUCA**
  - Academic agreement, Collaboration on advanced IFO and data analysis (Pro. Ni).
- **With NIKHEF**
  - Collaboration on SAS system (Pro. Jo van den Brand).
- **With India Group**

KAGRA Collaboration 2

- **With some USA groups**
  - Collaboration on 3rd generation detector in USA (Pro. W. Johnson).
- **With ET project in Europe**
  - IRSES program between EU and Japan might be approved in 2012-2015?
  - Collaboration on Cryogenic, Super Attenuator System and suspension system.
- **With Korean Group**
  - Collaboration on laser and optics, data analysis and so on (Pro.Yoon).
- **With Toyama Univ. in Japan**
- **With Hanoi National University for Education in Vietnam.**

KAGRA in Taiwan

- National Tsing Hua University (NTHU)
- Industrial Technology Research Institute (ITRI)
- Academia Sinica, Institute of Physics (AS IoP)
- National Center for High-performance Computing (NCHC)

GW activity of Academia Sinica

Academia Sinica joined KAGRA in 2016
and giving contributions on:

- Tier1 GW Data Mirroring
- Cryogenics Development
- Calibration

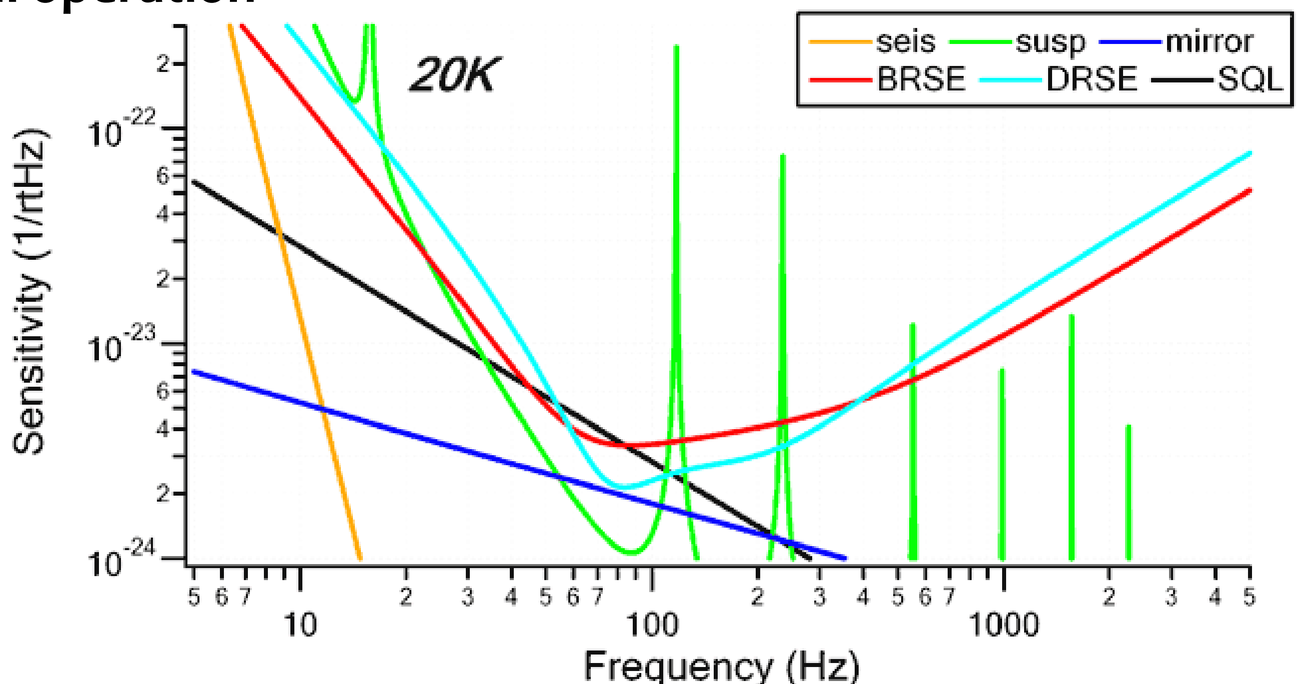
initial-KAGRA (2010~2016.4)

- Construction Phase.
  - Tunnel
  - Vacuum
  - Facility
- Interferometer component design.
- 3km arm Michelson Interferometer construction.
  - Mirrors and suspension are set at 300K.
  - SiO_2 Mirrors.
  - 2W level laser sources
  - Simple Mirror Suspension
- 1.5 manths Operation (for engineering)

initial-KAGRA (2016.3~2016.4)

baseline-KAGRA (2016,5~2017,18)

- **Toward the Targeted Sensitivity ~ 200Mpc**
  - Phase I -> II -> III
  - Cryogenic mirrors and suspensions (sapphire)
  - 200W~ 25W Laser (Mitsubishi-Amp or Fiber-Amp)
  - RSE technique (Broadband or Detuned in Variable RSE)
  - DC readout technique
  - Output Mode Cleaner
  - SAS full operation



Phase I

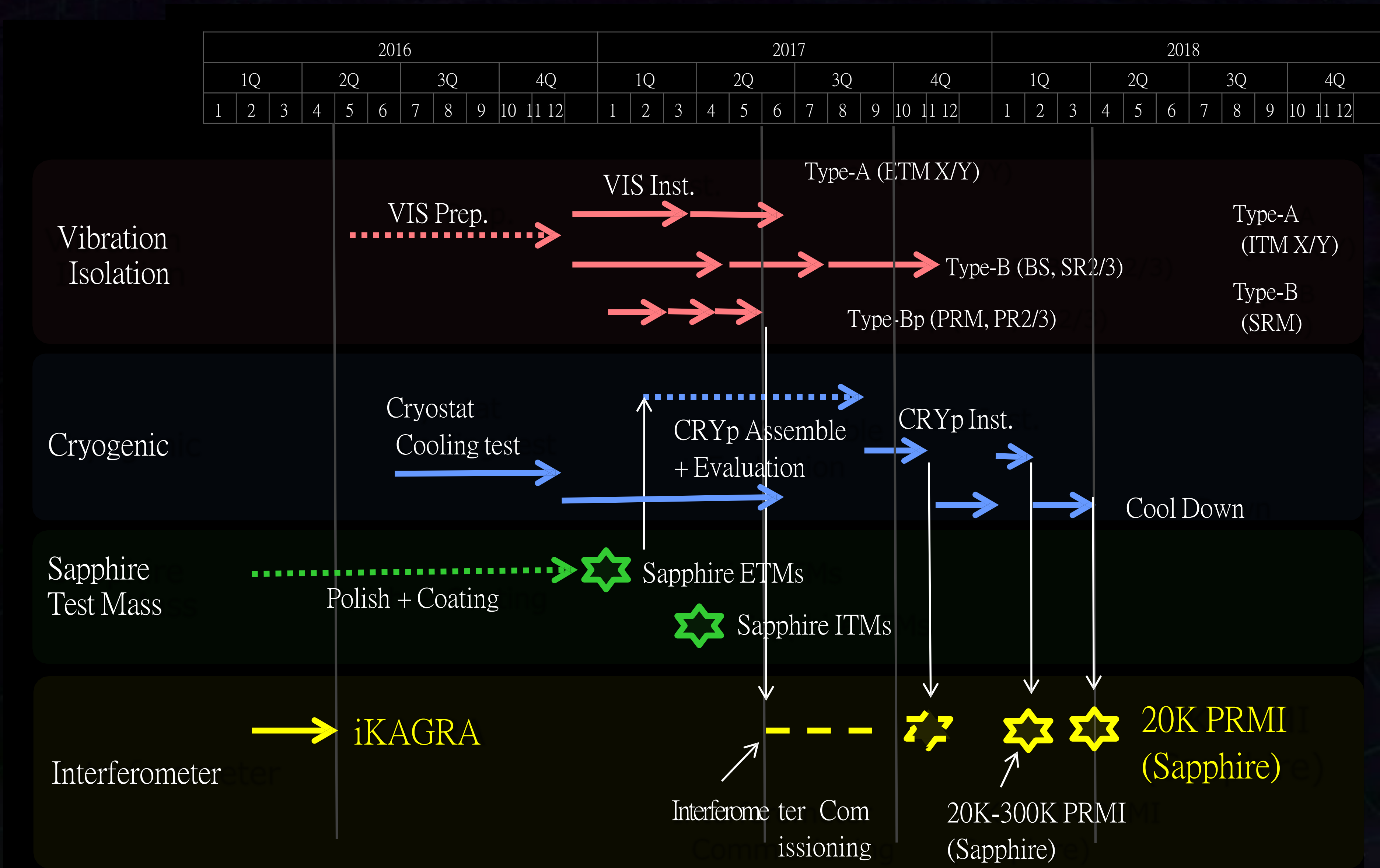
- Promise to the government:

  Operation of the KAGRA cryogenic interferometer
  by the end of FY2017 (2018.3).

  Constraint for Phase-1 goal.

- Positive Interpretation:
  - Cryogenic operation is an indispensable step for KAGRA. We will realize it anyway.
  - Almost no delay on schedule because of this constraint, by minimizing the additional tasks only for this step.

Plan for bKAGRA Phase-I

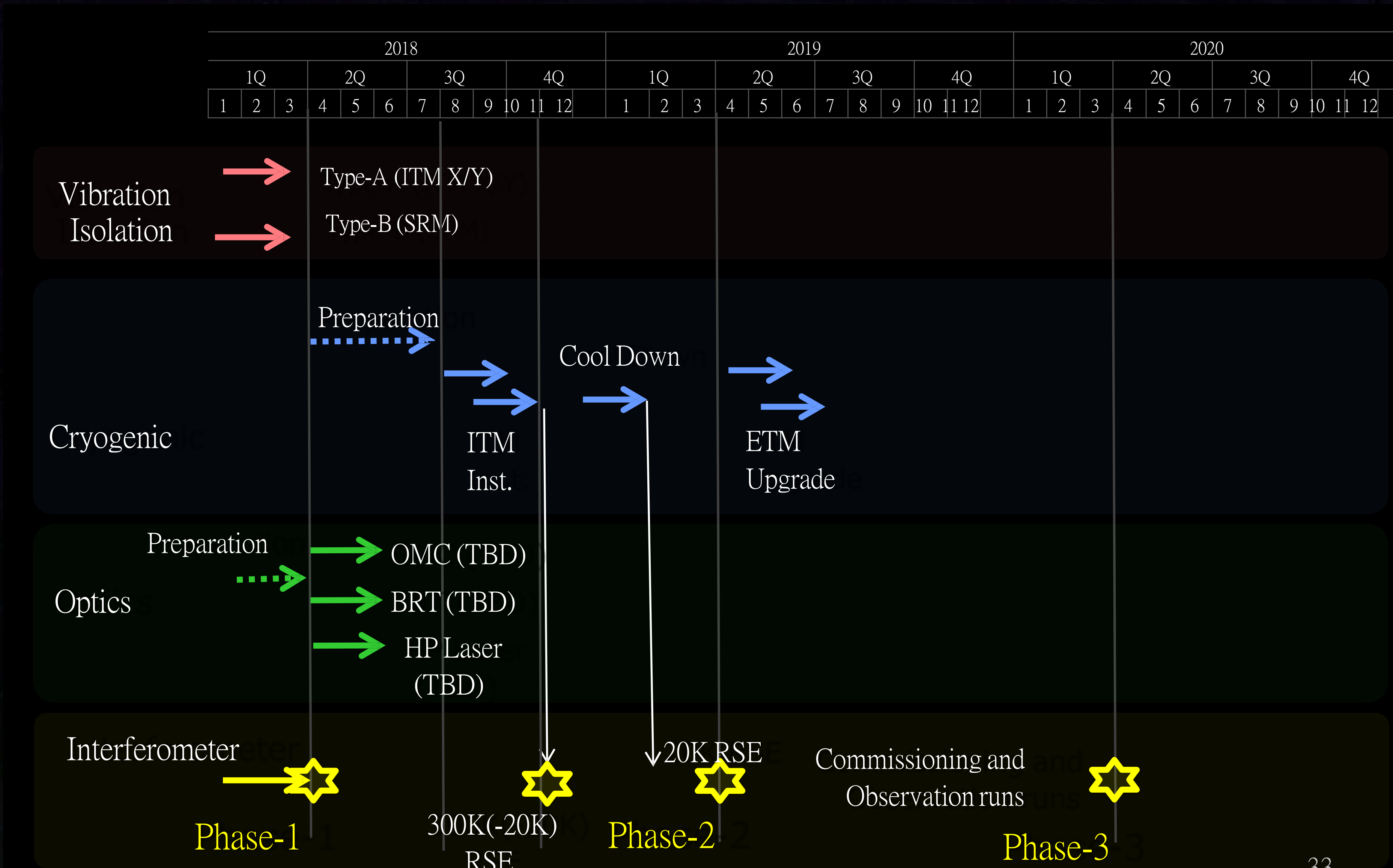


Phase II, III

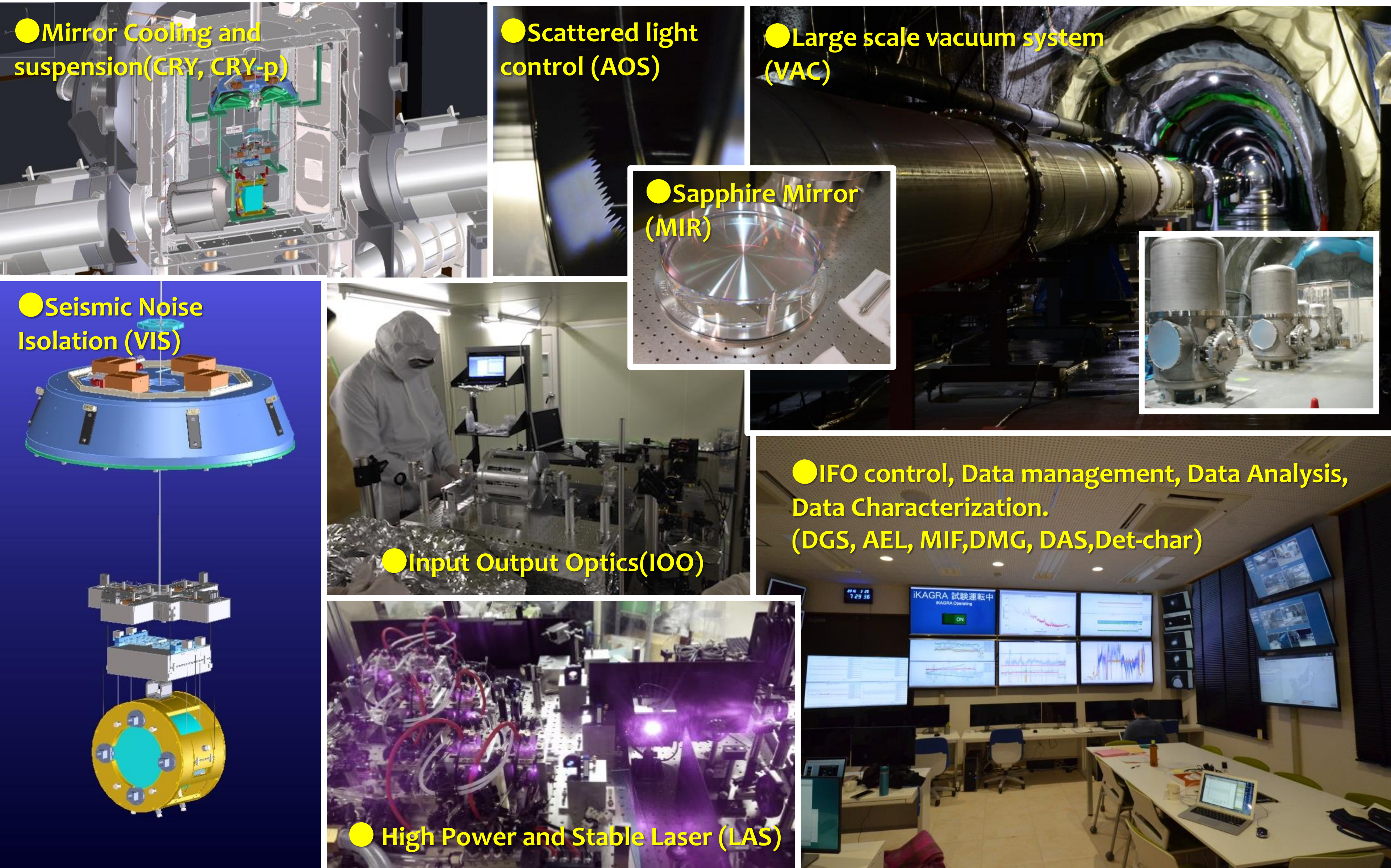
- Operation of a 3-km Full Cryogenic Interferometer
  by 2019.3 (???).
  Full lock of the RSE interferometer will be
  a main issue. We cannot seriously discuss about the
  sensitivity in this phase.

  * A few new items :
    - 2 cryogenic ITM (Type-A + CRYp)
    - SRM (Type-B) can be installed in Phase-1
    - Green-lock system,...
  * There will be an upgrade of cryogenic payload.

Plan for bKAGRA Phase-II/III



Construction Status of KAGRA



Merits (& demerits) of Underground

- **Out-band frequency range seismic noise at low frequency has nonlinear effect on in-band frequency range sensitivity in GWD. So lower seismic noise in out-band is desirable.**

  →Smaller low-frequency motion of mirror

  → Lower gain of control system necessary

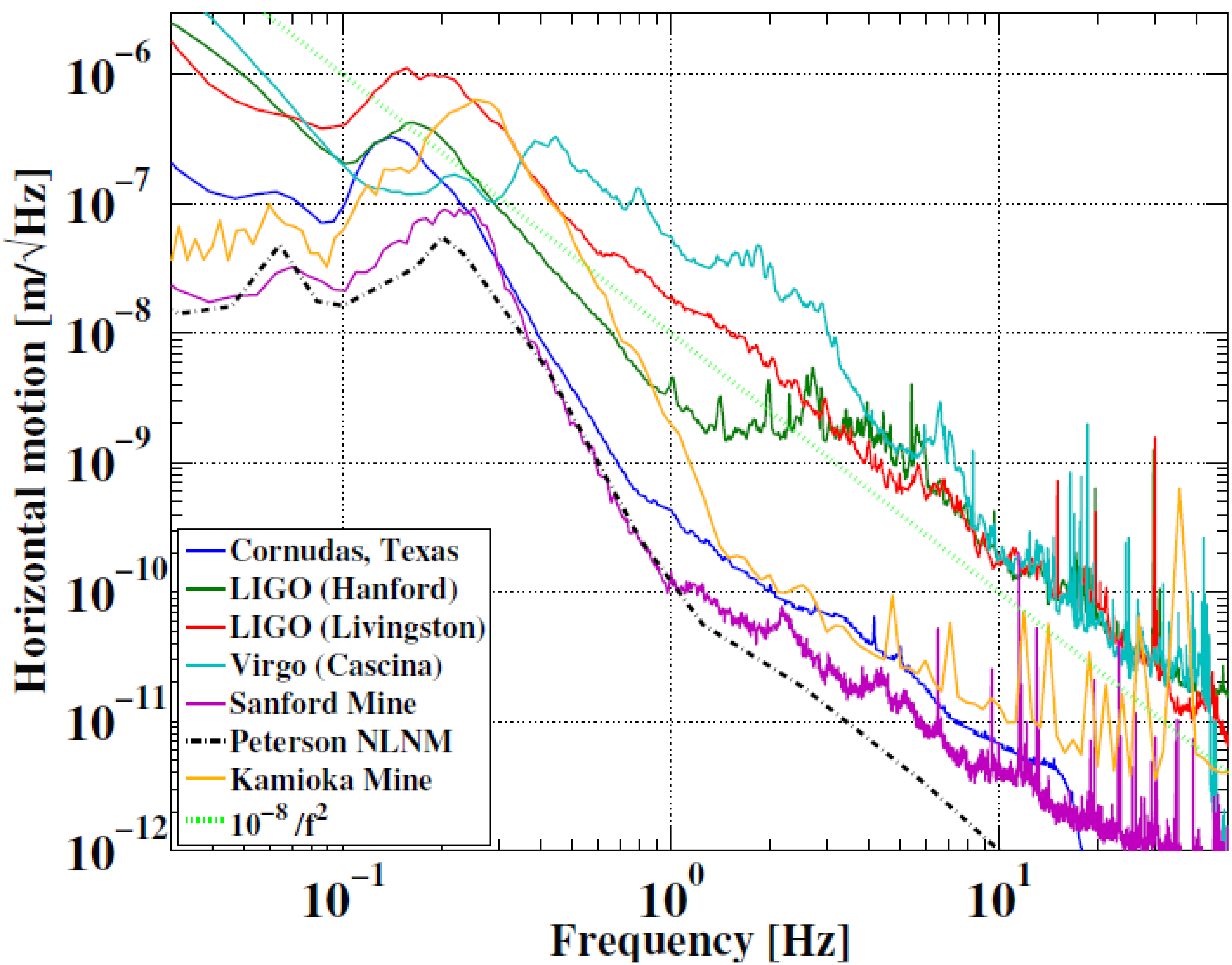
  →Lower in-band noise imposed by control system

- **Low Gravity Gradient Noise**

on the other hand,

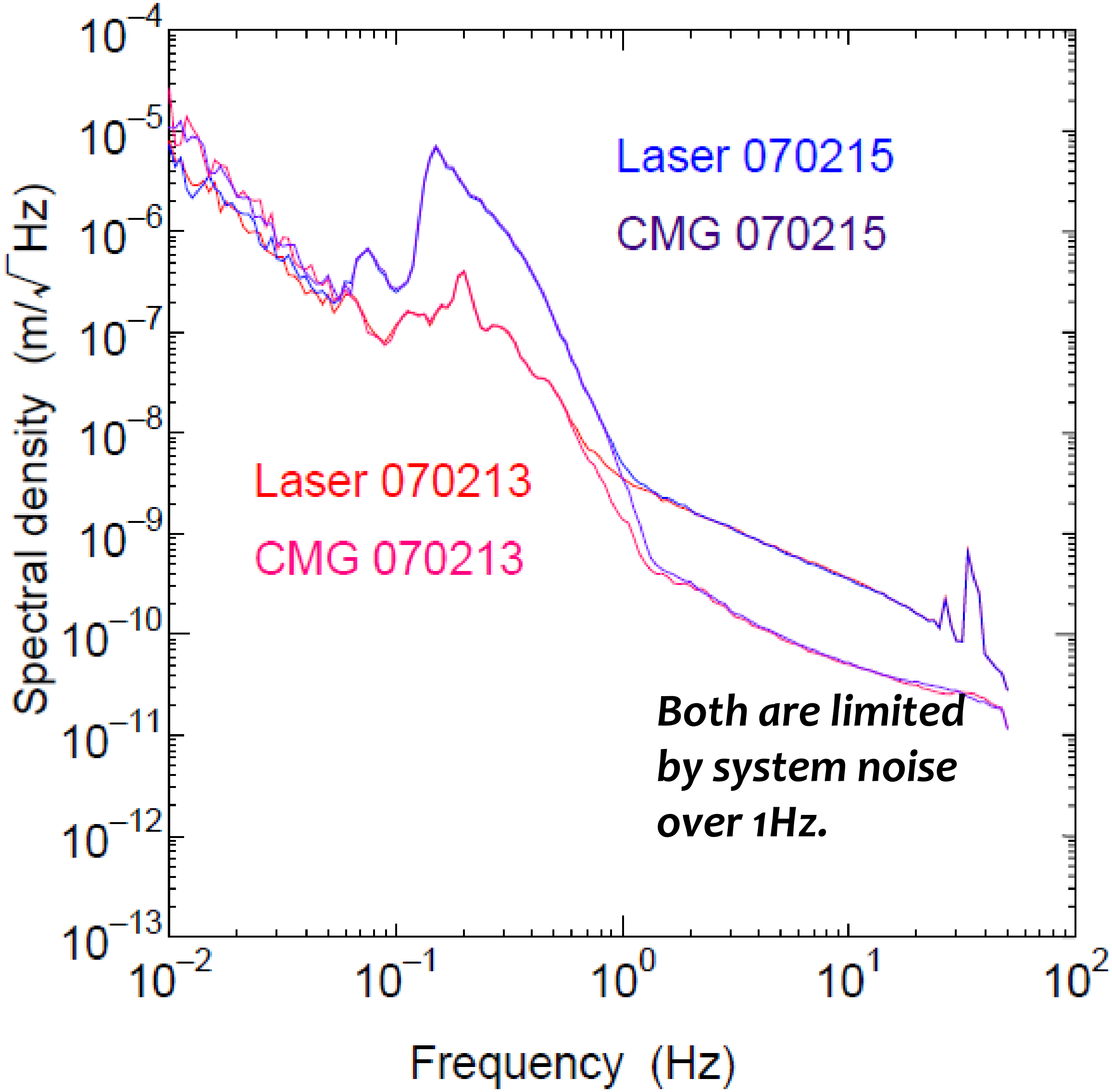
- **We found the “water” in the mountain is annoying source in many practical aspects.**
- **We should check the “Gravity Gradient Noise” due to water flow near mirrors**

Low Seismic noise Underground



By Rana (LIGO)

Kamioka Seismic Noise



Strain Meter Data (< 20Hz)

070215 : Stormy day

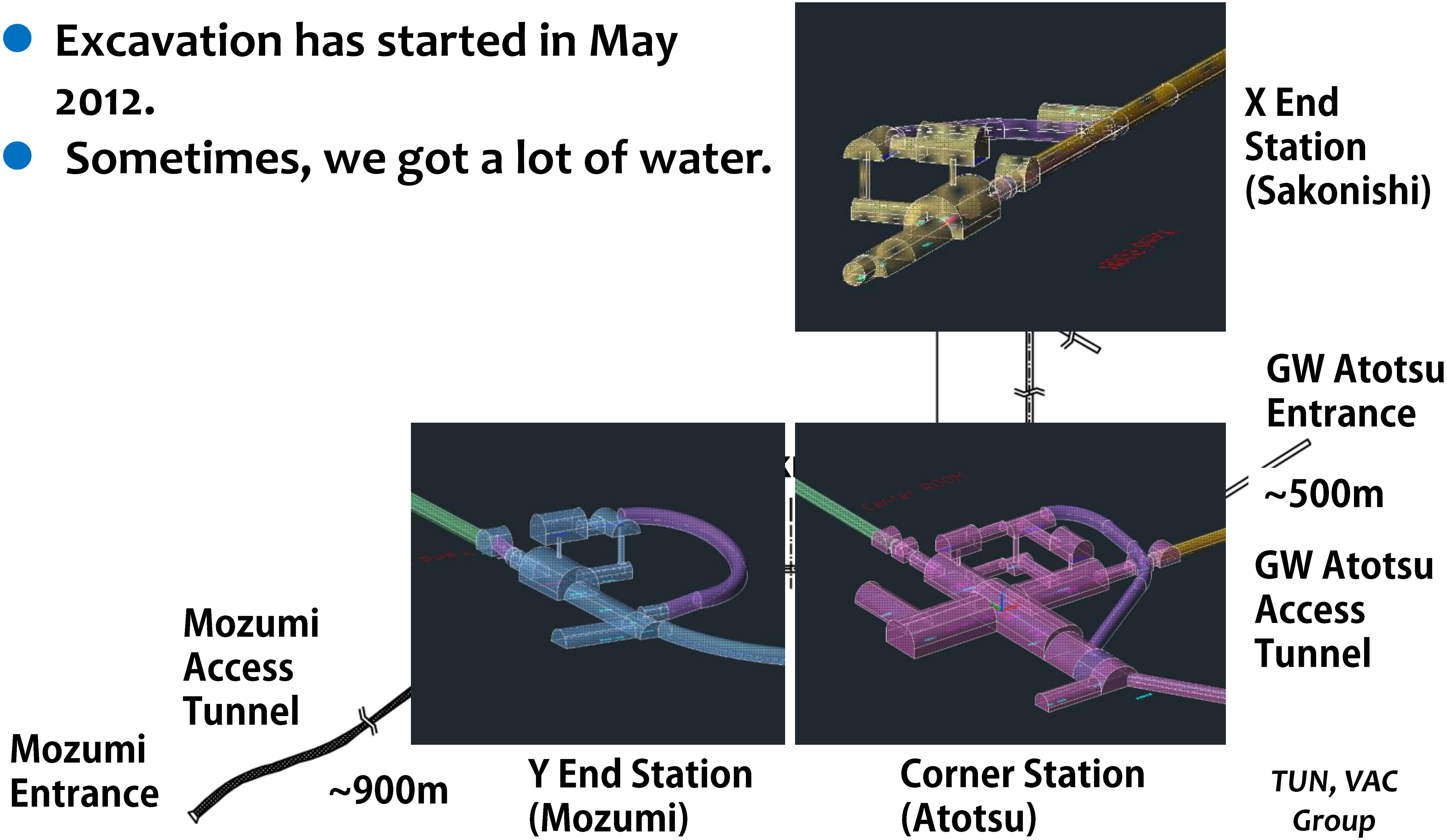
070213 : fine day

10 times enhancement of micro seismic noise due to ocean waves can be observed.

Tunnel Excavation

- Tunnel Design -

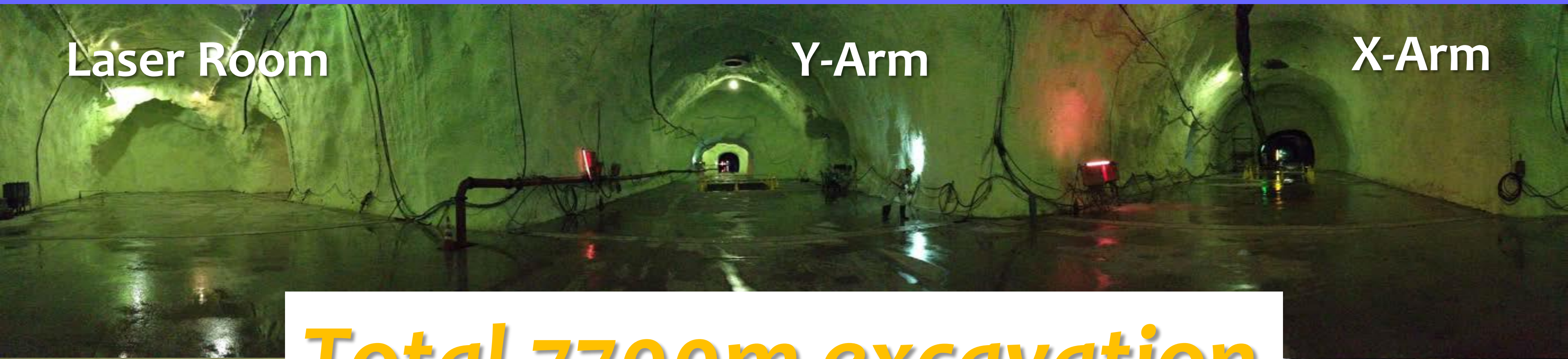
- Excavation has started in May 2012.
- Sometimes, we got a lot of water.



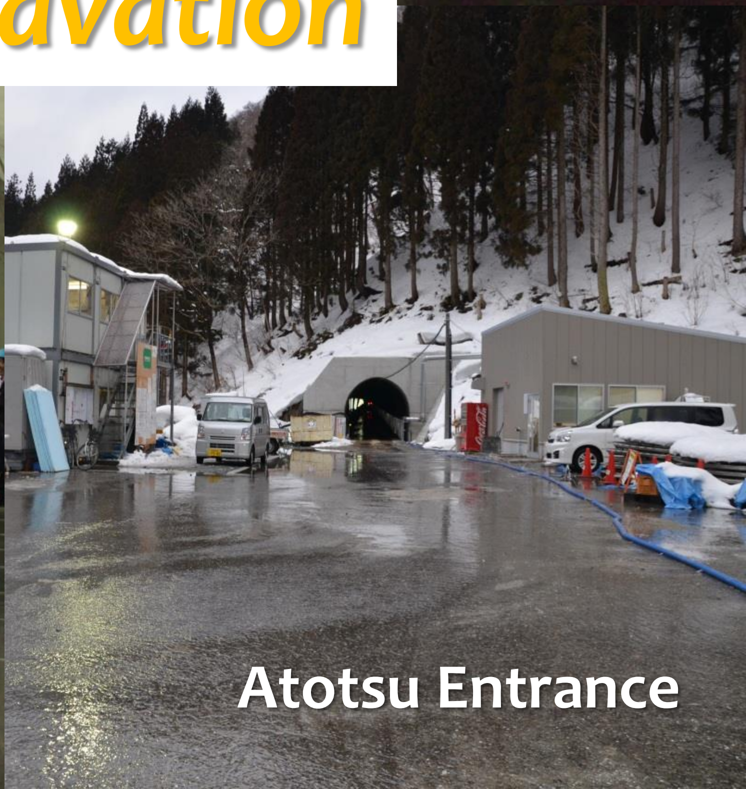
TUN, VAC Group

Tunnel Group

Tunnel Completed in March 2014

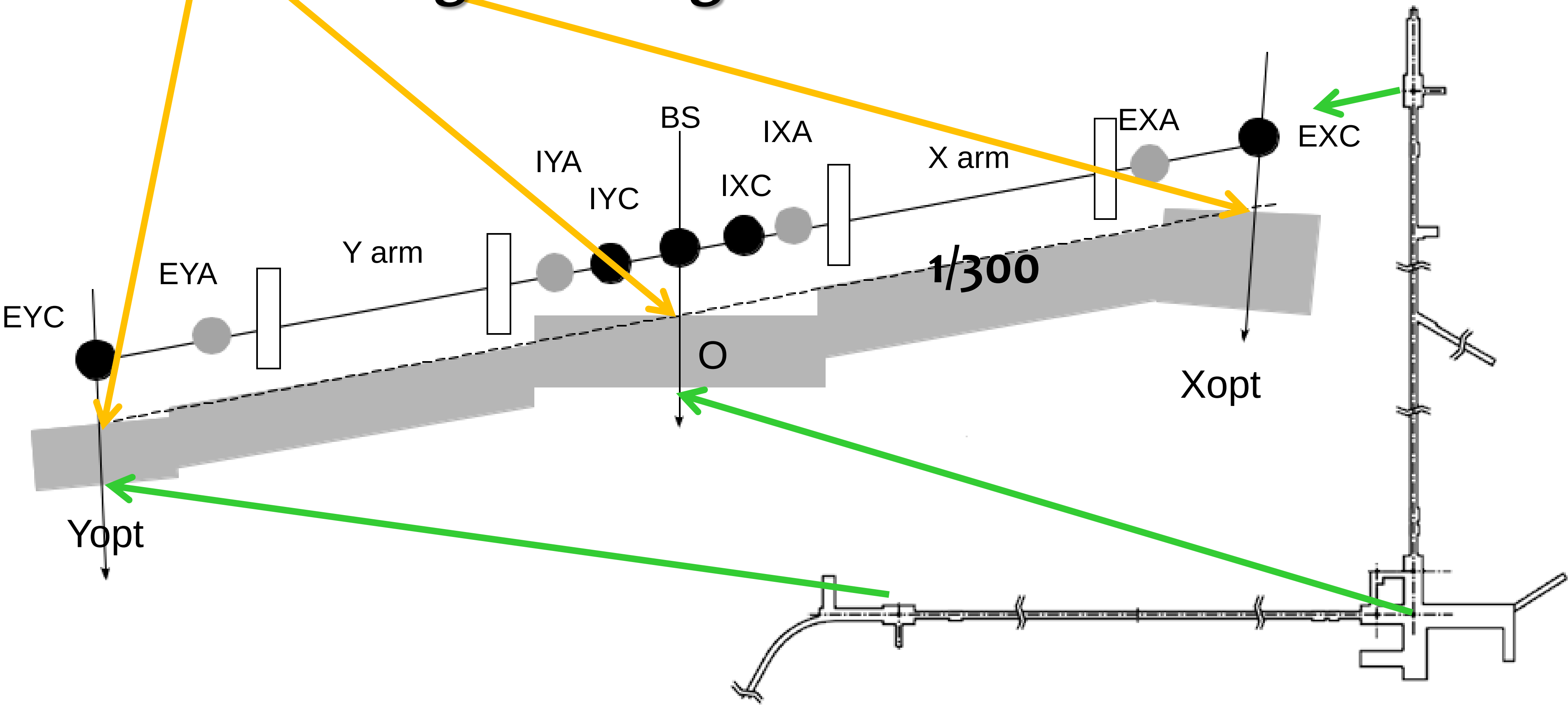


Total 7700m excavation



Tunnel Design

- Slope of 1/300 was selected to drain the water to rivers.
- Horizontal planes for each station are prepared for easiness during installing vacuum tanks

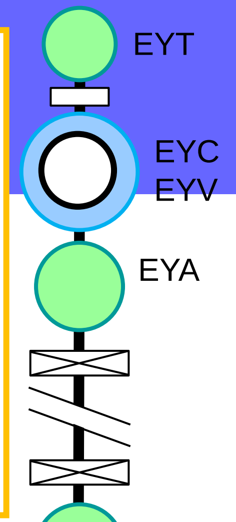


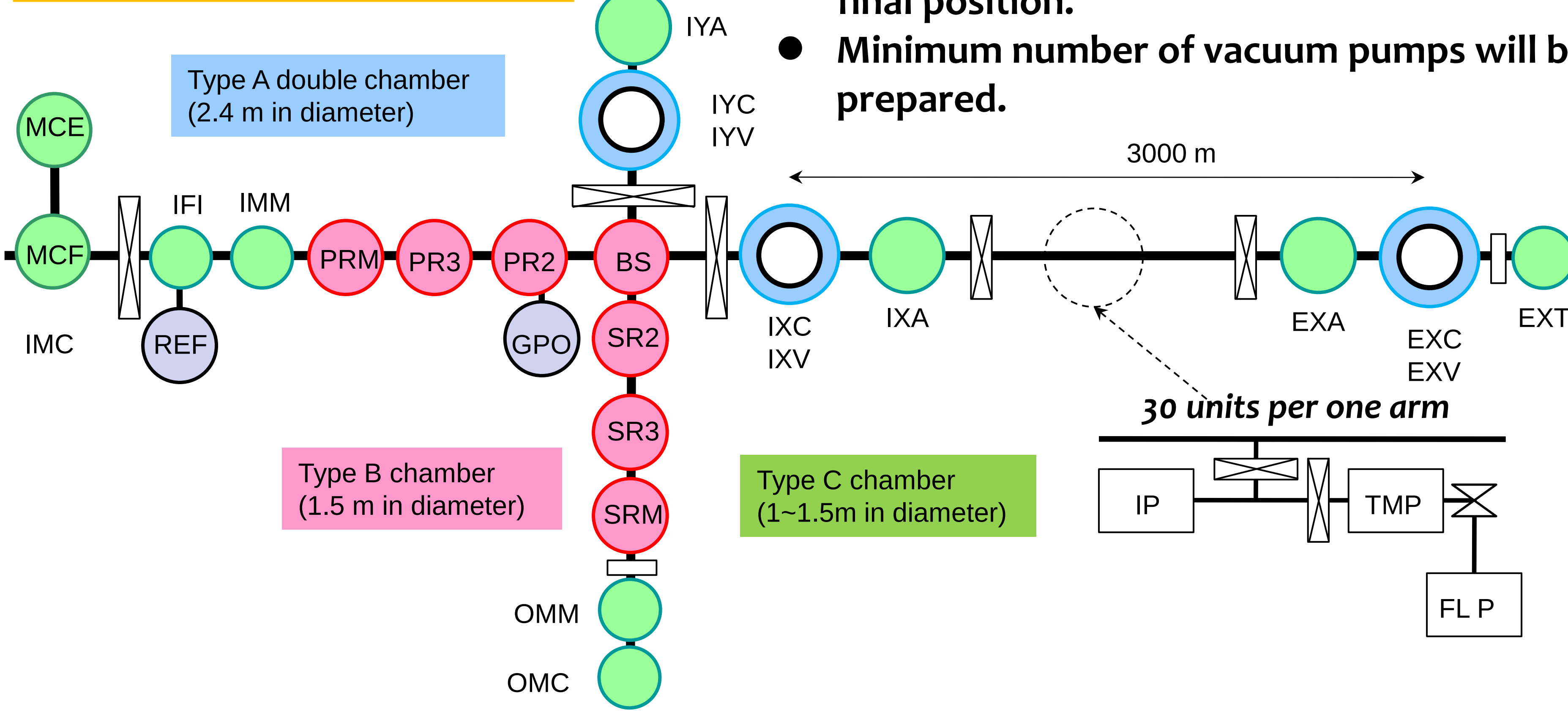
New Building for KAGRA

Vacuum System

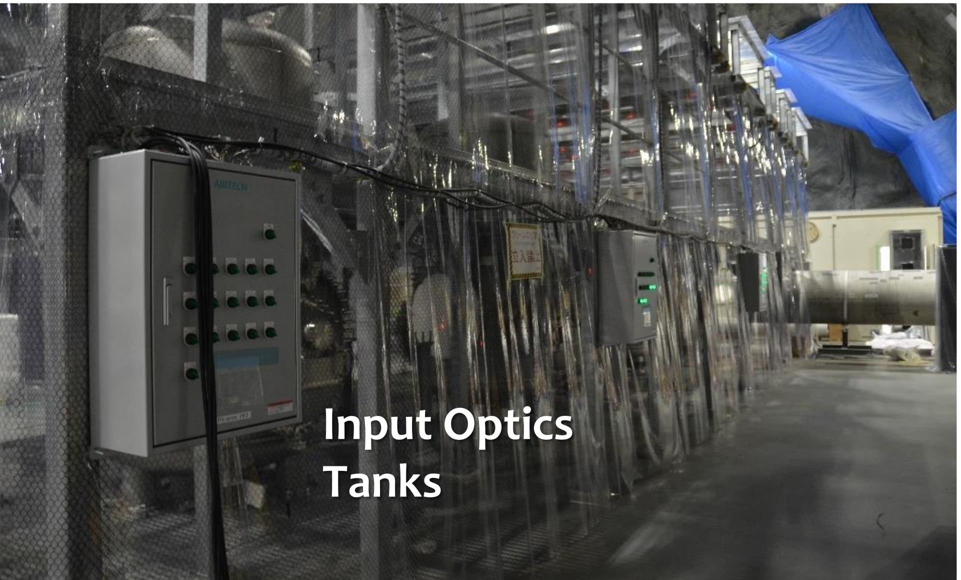
MC : Mode Cleaner
I, O, F, E : Input, Output, Front, End
FI : Faraday Isolator
MM : Mode Matching Telescope
PRM : Power Recycling Mirror
PR2, PR3 : PRC folding mirrors
SRM : Signal Recycling Mirror
SR2, SR3 : SRC Folding Mirrors
BS : Beam Splitter
X, Y : X and Y arm
A : AOX
T : Transmitting
C : Cryogenic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

- **~250 vacuum duct units (L=12m, d=0.8m) formed 3km arm, using metal gaskets. No leak was found. No baked, but ECB was adopted inside to minimize outgas.**
- **Almost vacuum tanks have been set at their final position.**
- **Minimum number of vacuum pumps will be prepared.**



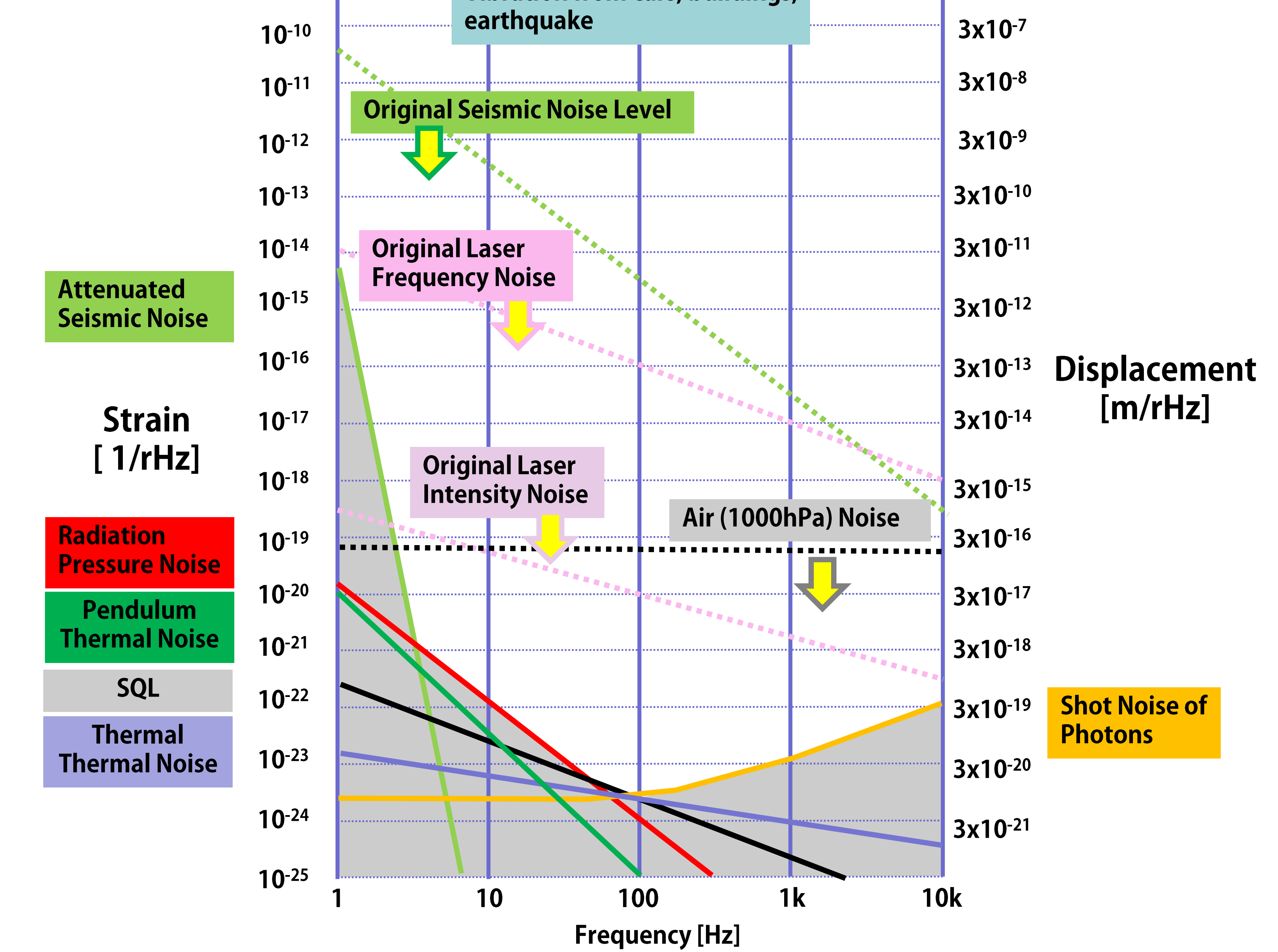


Vacuum Ducts and Chambers Set in FY2014



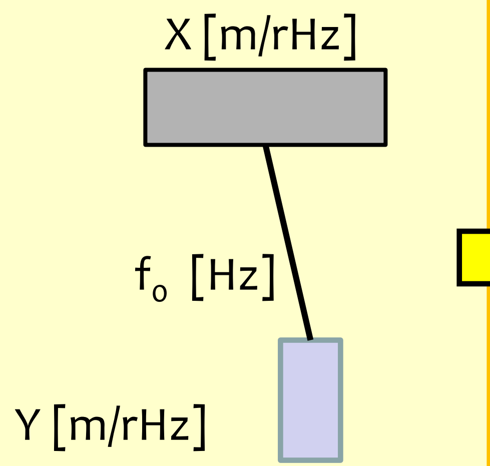
Vibration Isolation System

- Seismic noise attenuation is essential even underground.
- Not only the observation frequency band, but also the lower frequency band seismic noise (active an/or passive) attenuation is necessary for stable operation and for less up-conversion noise.
- Seismic Noise attenuation techniques using a pendulum are applied,
  - Multi-Stage Pendulum.
  - Pendulum with lower resonance frequency.
  - Highest performance SAS for the main four sapphire mirrors (type-A).
  - Less performance isolators than Type-A for silica mirrors that form main parts of IFO (Type-B, Type-Bp, Type-Bp').
  - Simple isolators for MC mirrors and small optics. (Type-C)

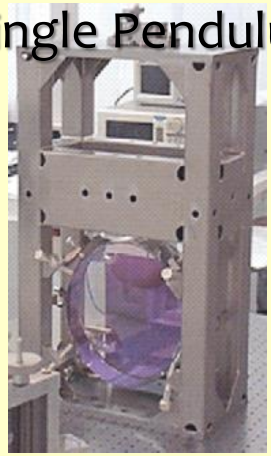

earthquake
Original Seismic Noise Level
Original Laser
Frequency Noise
Original Laser
Intensity Noise
Air (1000hPa) Noise
Attenuated
Seismic Noise
Strain
[1/rHz]
Radiation
Pressure Noise
Pendulum
Thermal Noise
SQL
Thermal
Thermal Noise
Displacement
[m/rHz]
Shot Noise of
Photons
10-10
10-11
10-12
10-13
10-14
10-15
10-16
10-17
10-18
10-19
10-20
10-21
10-22
10-23
10-24
10-25
3x10-7
3x10-8
3x10-9
3x10-10
3x10-11
3x10-12
3x10-13
3x10-14
3x10-15
3x10-16
3x10-17
3x10-18
3x10-19
3x10-20
3x10-21
1
10
100
1k
10k
Frequency [Hz]

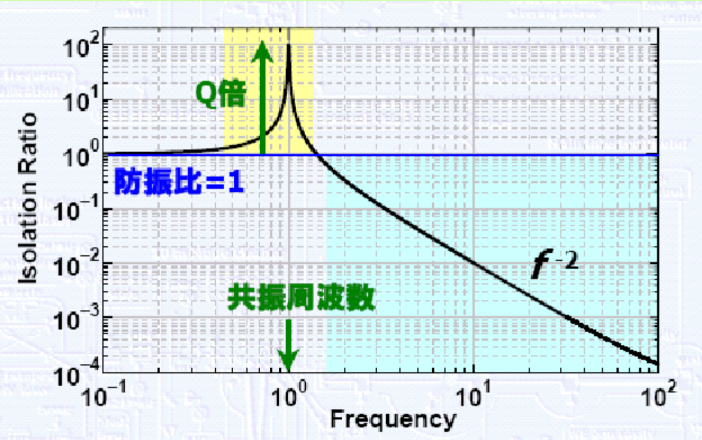
Attenuation using a Pendulum

- Mirrors are suspended like a pendulum on the Earth as free mass



Single Pendulum





Transfer Function (TF)

$$\frac{Y}{X} = \left(\frac{f_0}{f}\right)^2$$

$$\frac{Y}{X} = \left(\frac{f_0}{f}\right)^{2N}$$

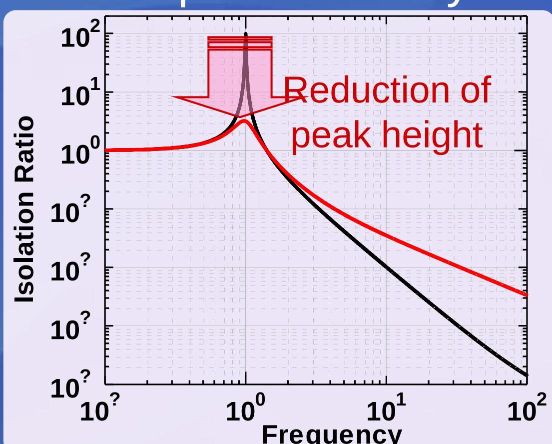
- A mirror is inevitably excited by seismic noise through the pendulum transfer function (TF).
- TF has isolation effect for seismic noise !
- For more isolation…
  - Multi-stage
  - Lower pendulum resonance frequency
- Trade-off : Many resonance mode (excited by Q) damping is necessary.

For More Attenuation

- For more isolation…
  - Multi-stage
  - Lower pendulum resonance frequency

Damping

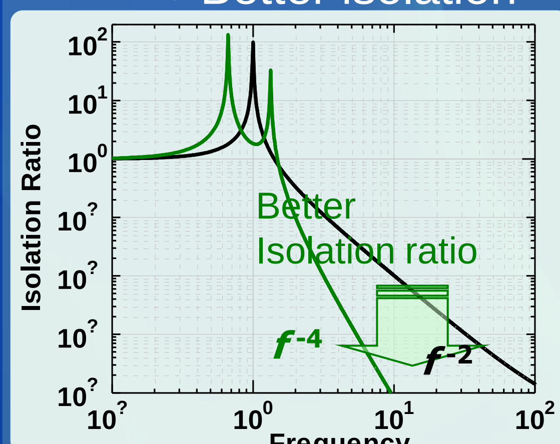
Reduce Q-value
→ improve stability



Degraded isolation

Multi stage

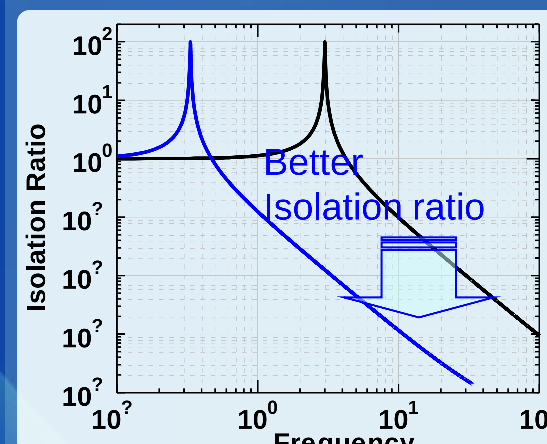
More steep reduction
→ Better isolation



Resonant peaks

Low reso. freq.

Low-freq. cut-off
→ Better isolation

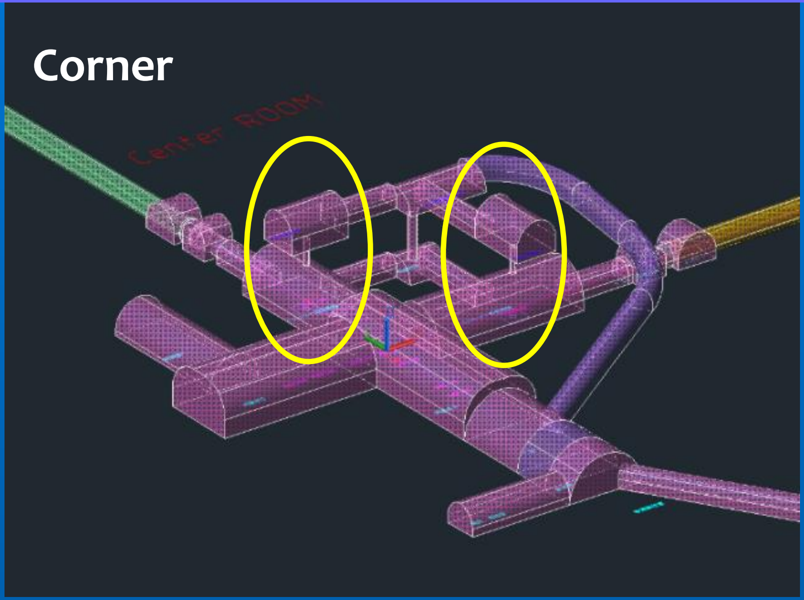


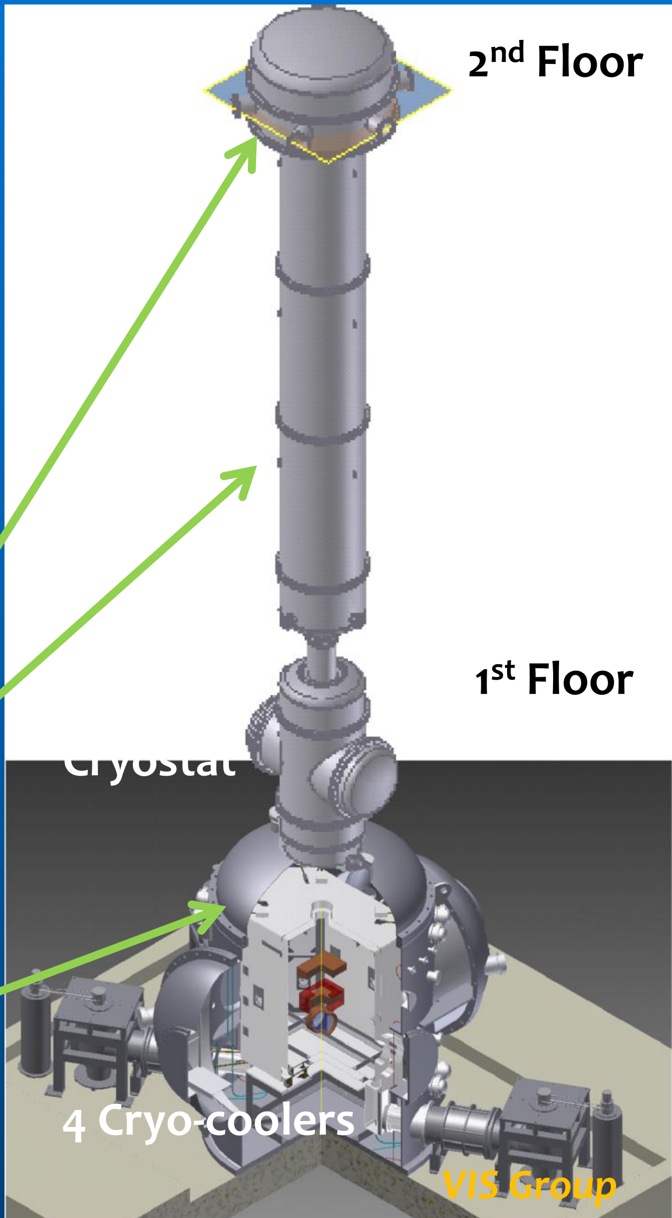
Drift by environment

Ando’s (U Tokyo) View Graph

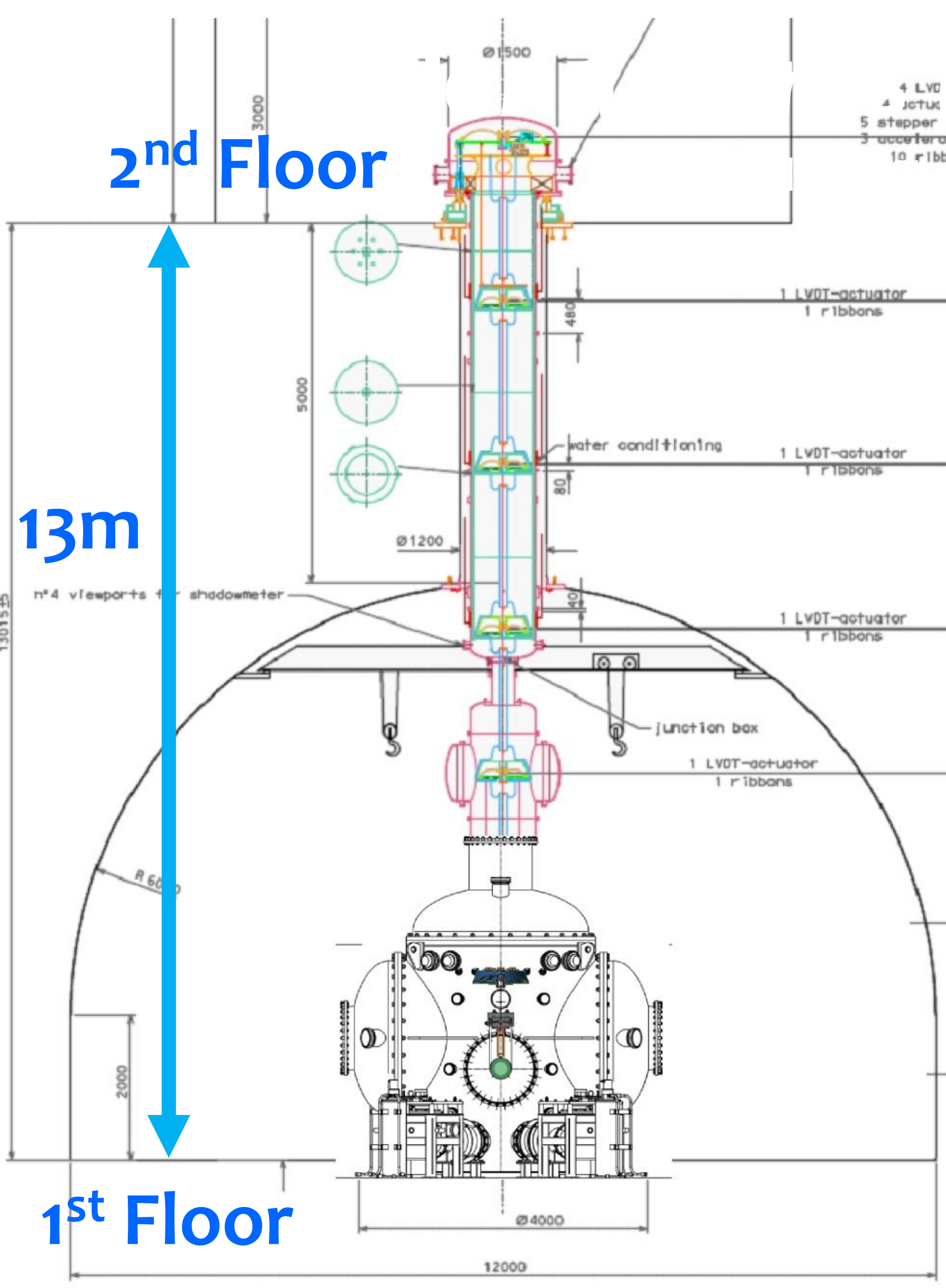
Super Attenuation System (Type-A)

- for sapphire mirrors -

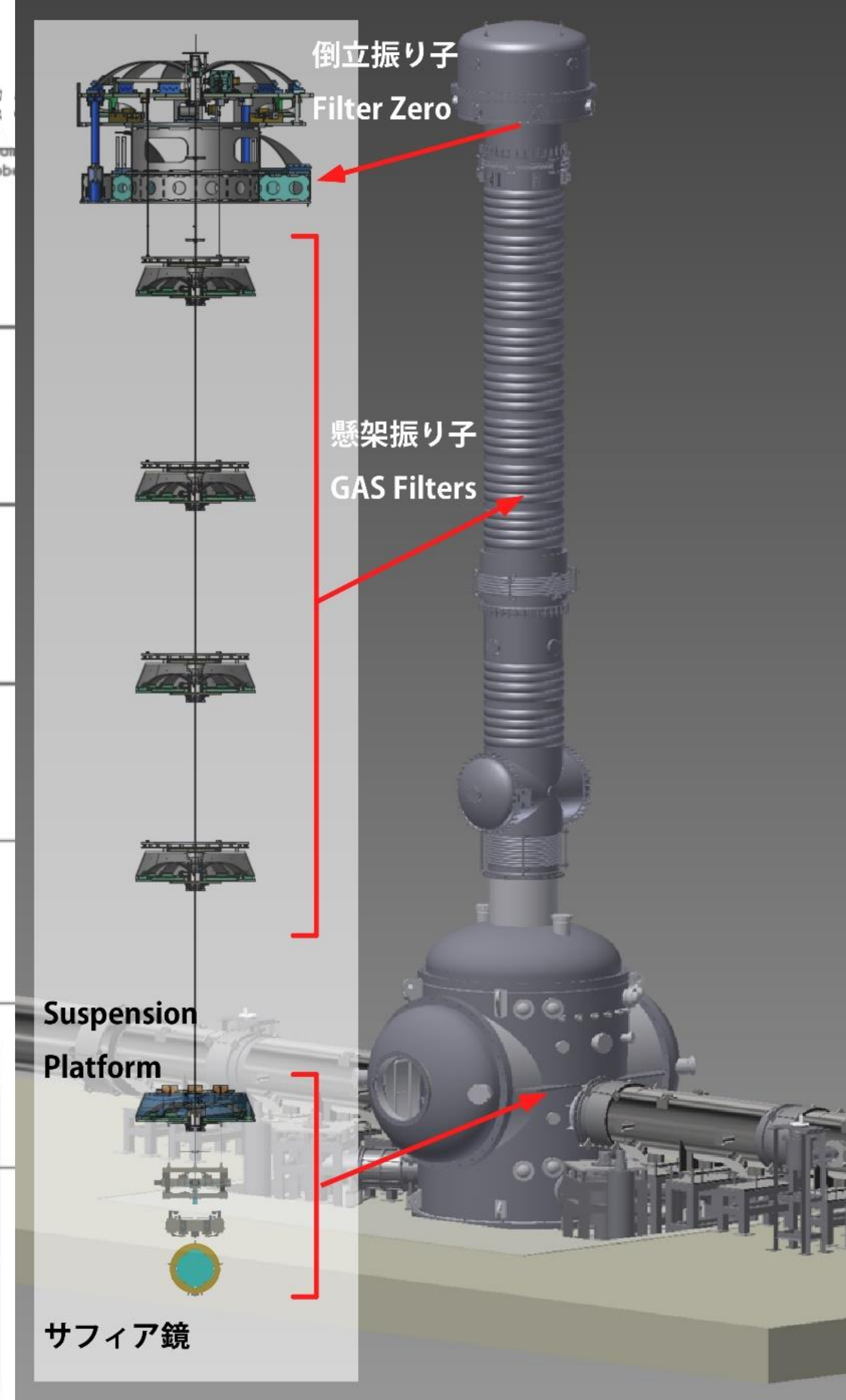




- Upper tunnel containing pre-isolator (short IP and top filter)
- 1.2m diameter 5m tall borehole containing standard filter chain
- Lower tunnel containing cryostat and payload

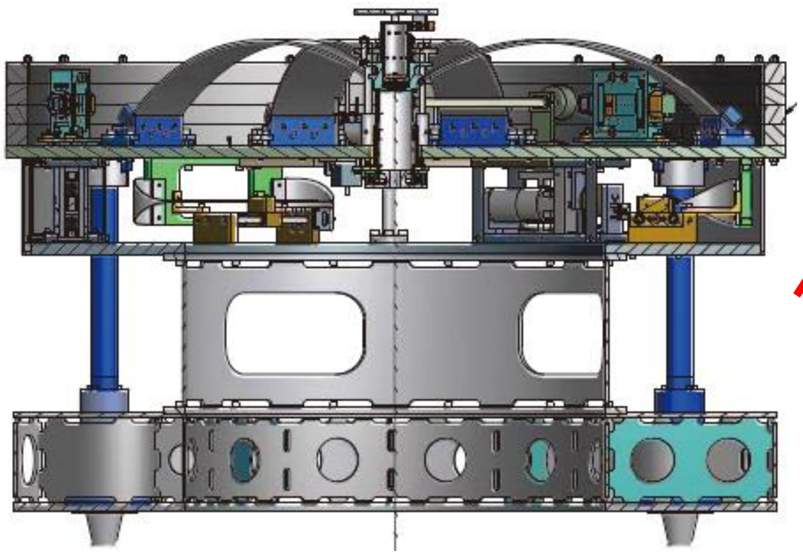


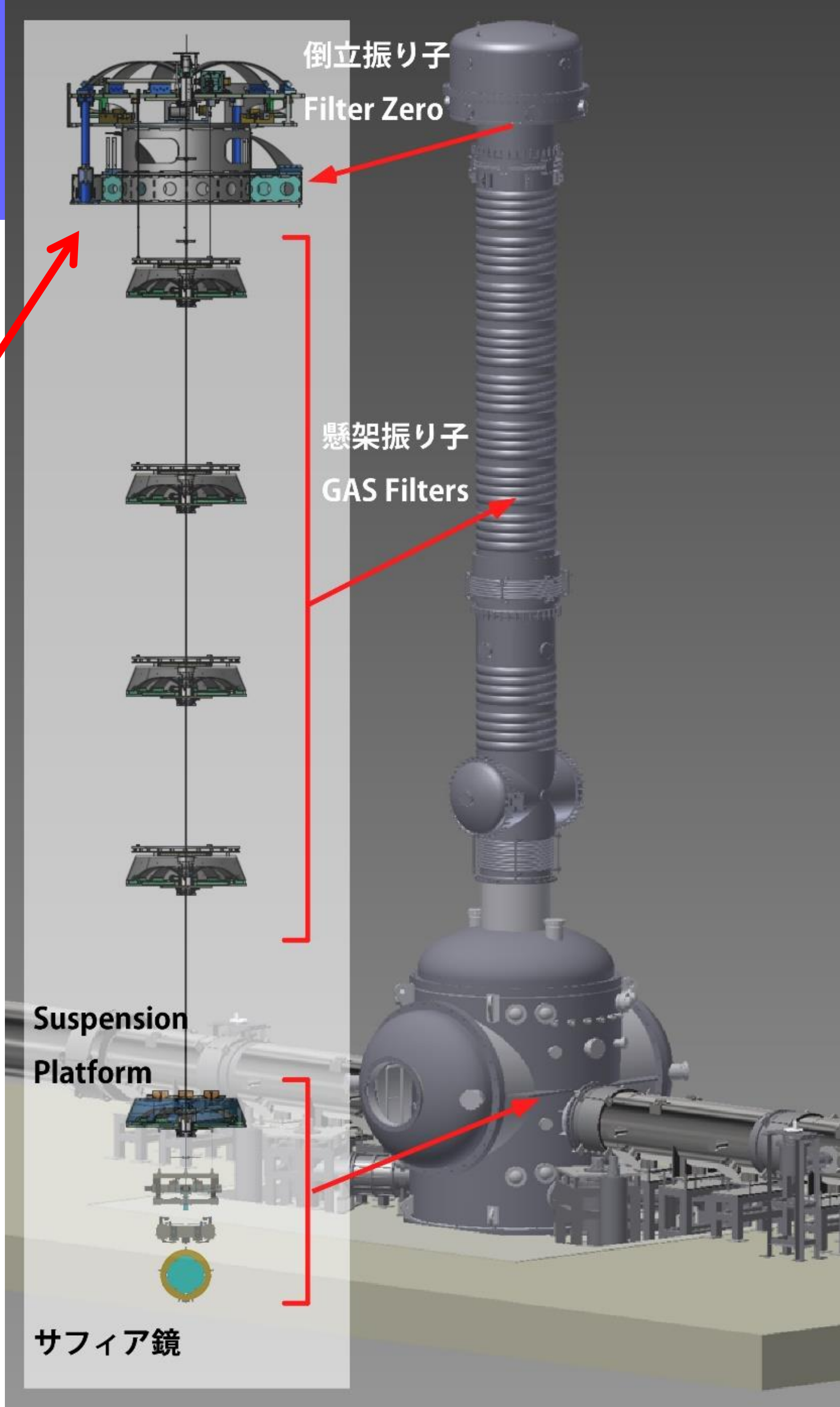
2nd Floor
13m
1st Floor
Ø1500
5 stepper
1 LVDT-actuator
1 ribbons
water conditioning
Ø1200
n°4 viewports for shadowmeter
junction box
3000
5000
2000
Ø4000
12000



倒立振り子
Filter Zero
懸架振り子
GAS Filters
Suspension
Platform
サファイア鏡

Filter Zero
In SAS





Horizontal Isolation

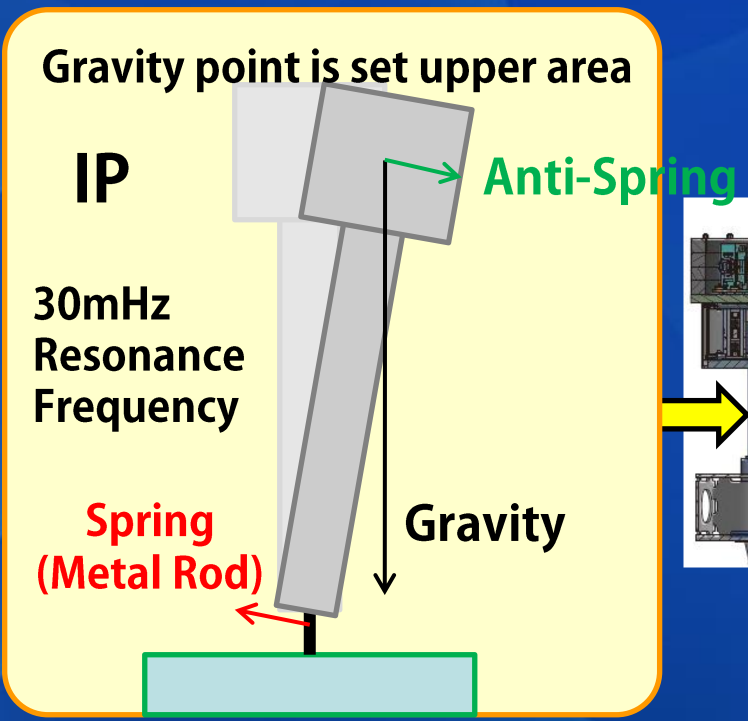
Inverted Pendulum : freso < ~ 0.01 Hz

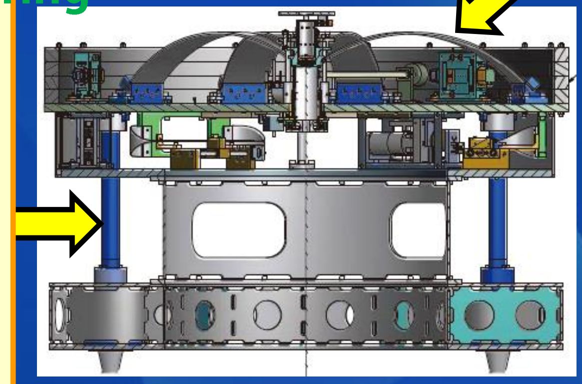
Vertical Isolation

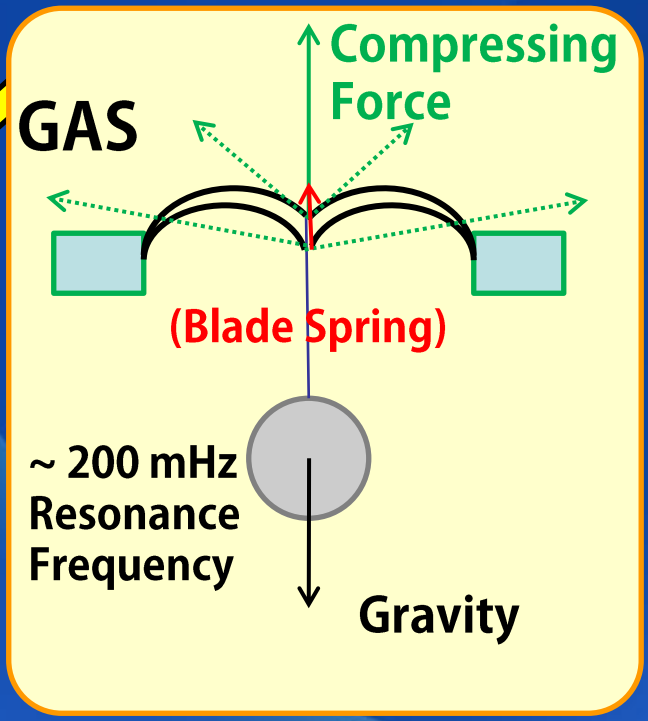
Filter Zero: Geometrical Anti Springを利用
(freso < ~ 0.1Hz)

Principle of an IP and GAS

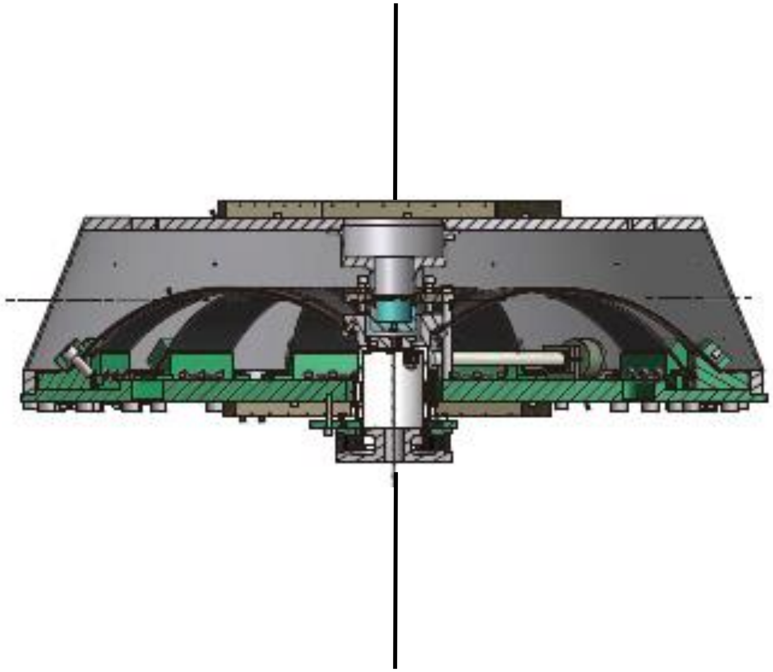
- **Principle to obtain low resonance frequency :**
  Set the residual spring constant to be small with combination of spring and anti-spring.
- **Problem and Trade-off :**
  1. Spring constant sensitive to temperature → Balanced position change.
  2. Internal buckling results in instability.
  3. Isolation effect lost at ~100 times resonance frequency because of percussive effect.







GAS Filters In SAS

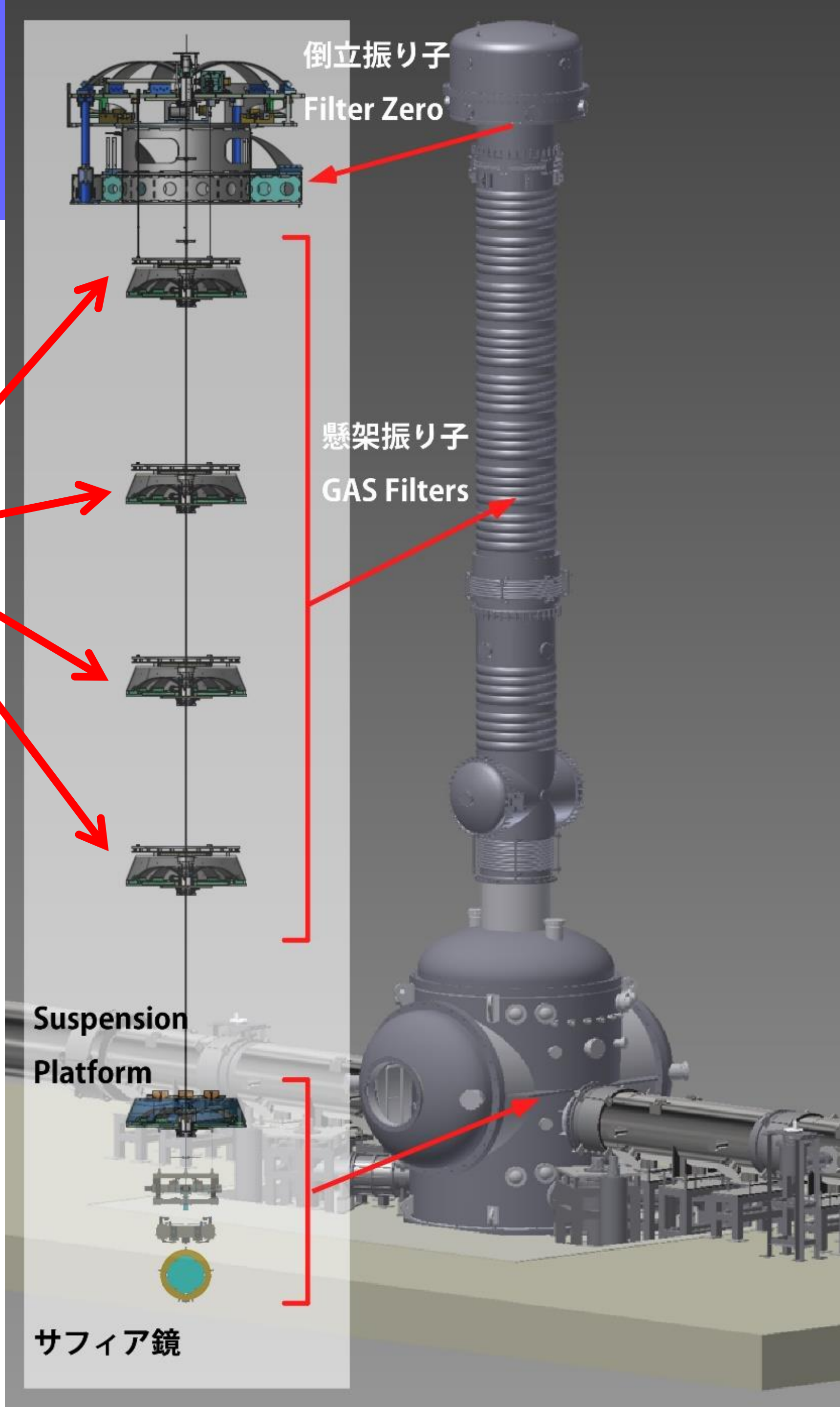


Horizontal Isolation

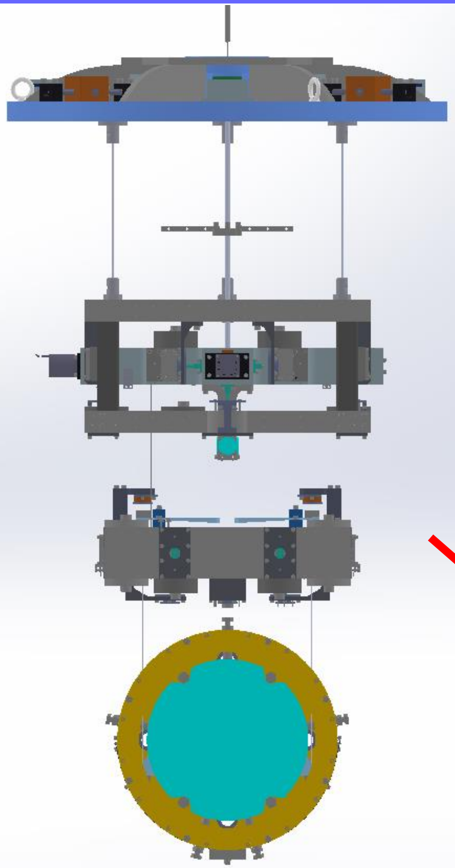
Single Wire Suspension : freso < ~ 0.5 Hz

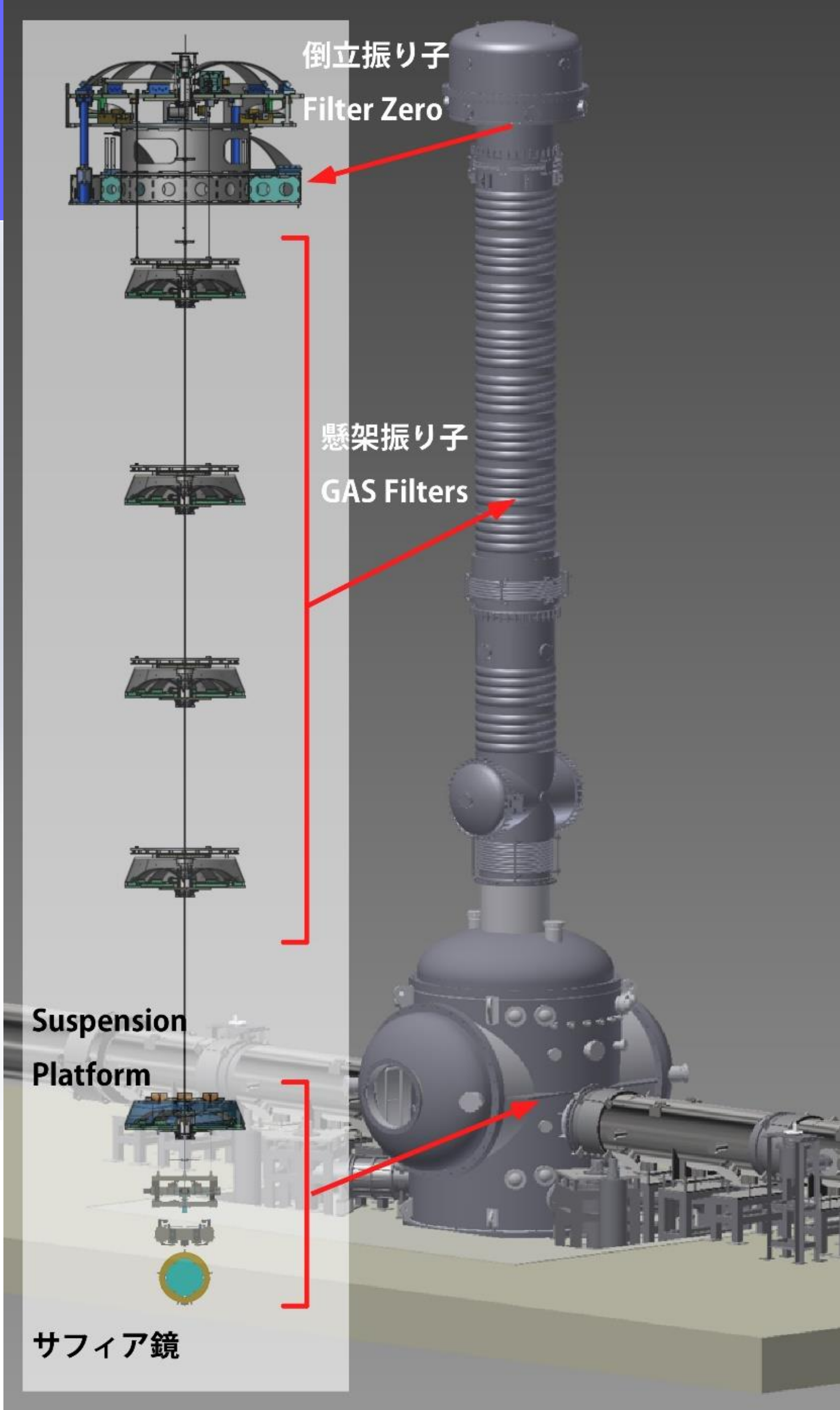
Vertical Isolation

Filter Zero: Geometrical Anti Springを利用
(freso < ~ 0.1Hz)



GAS Filters In SAS





Sapphire Mirror will be cooled by using heat conduction through its sapphire suspension fibers.

Pendulums (Type-B)

- Simplified Type-A -

Pre-isolator

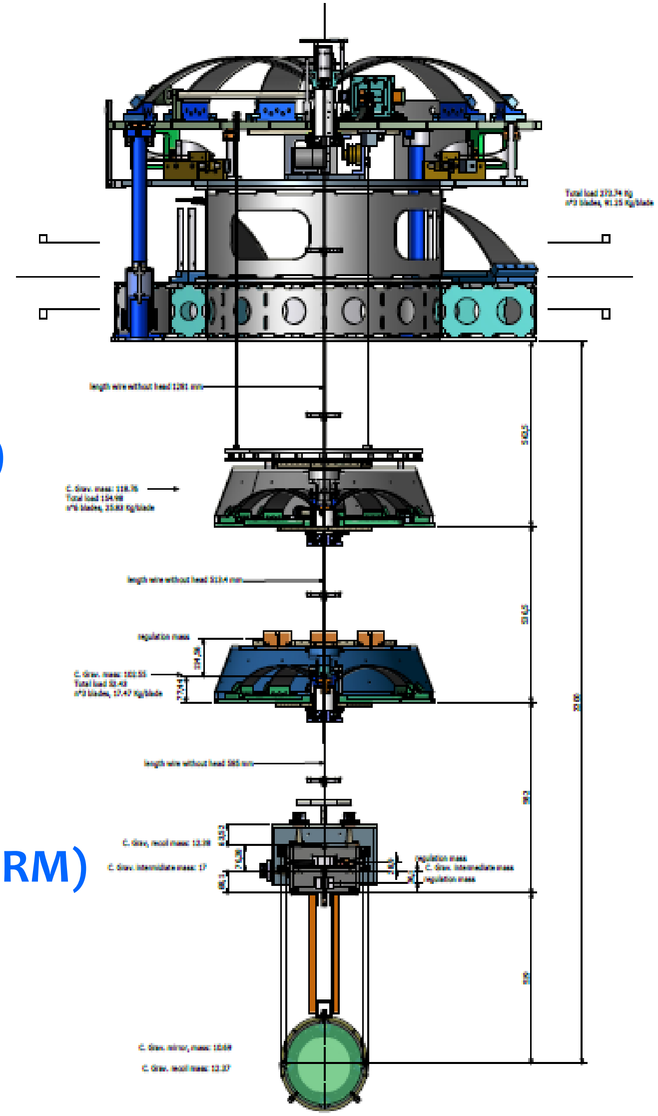
- Top filter [Filter0]
- Inverted Pendulum (IP)

Filter chain

- Geometric Anti-Spring (GAS)
- Filter1 (Filter1~3 in Type-A)

Payload

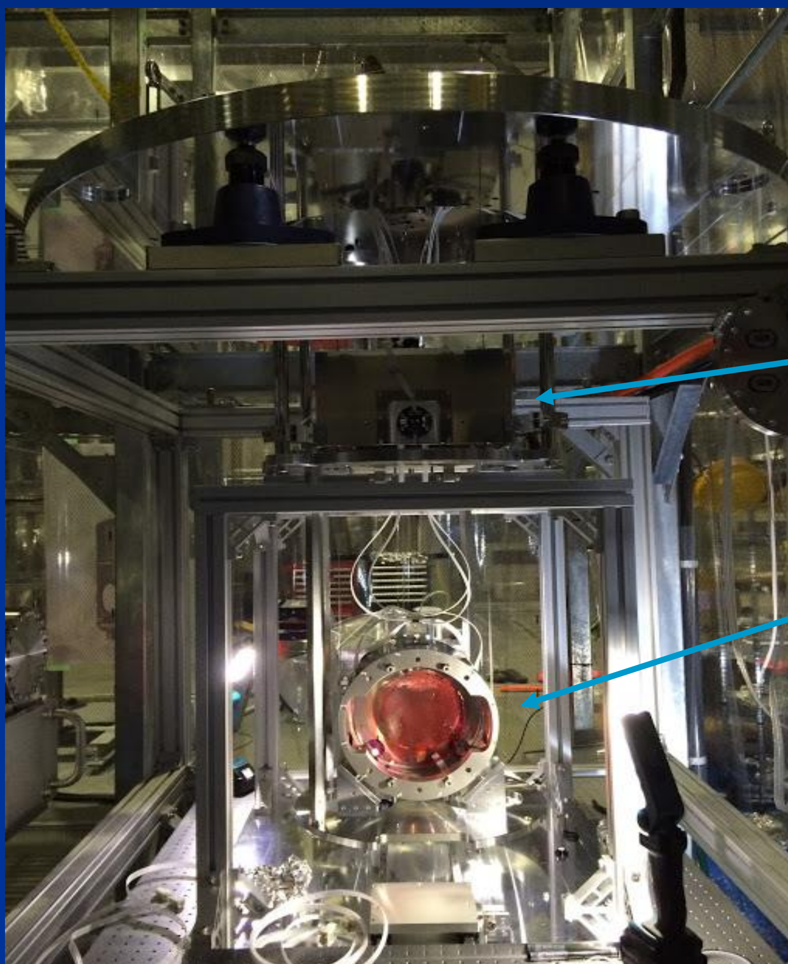
- Bottom Filter (BF)
- Intermediate Mass (IM)
- Intermediate Recoil Mass (IRM)
- Test Mass (TM)
- Recoil Mass (RM)



VIS Group

Configuration for iKAGRA

Type-Bp' system was used for only PR3 in iKAGRA.



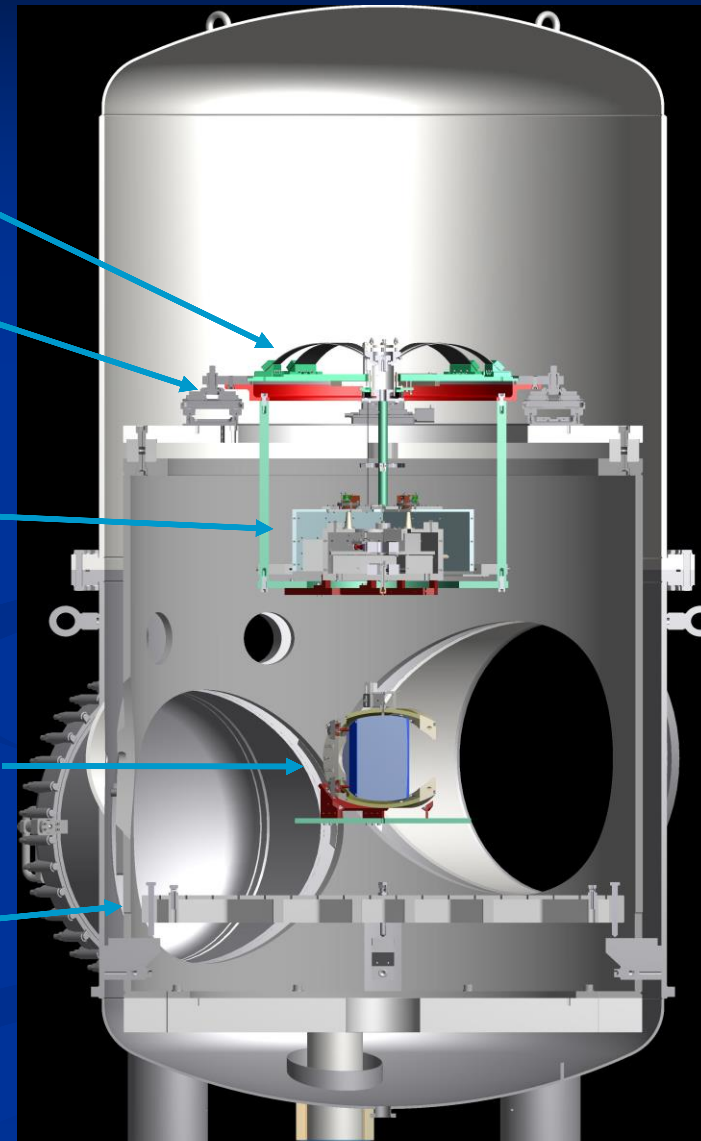
Bottom filter

Traverser

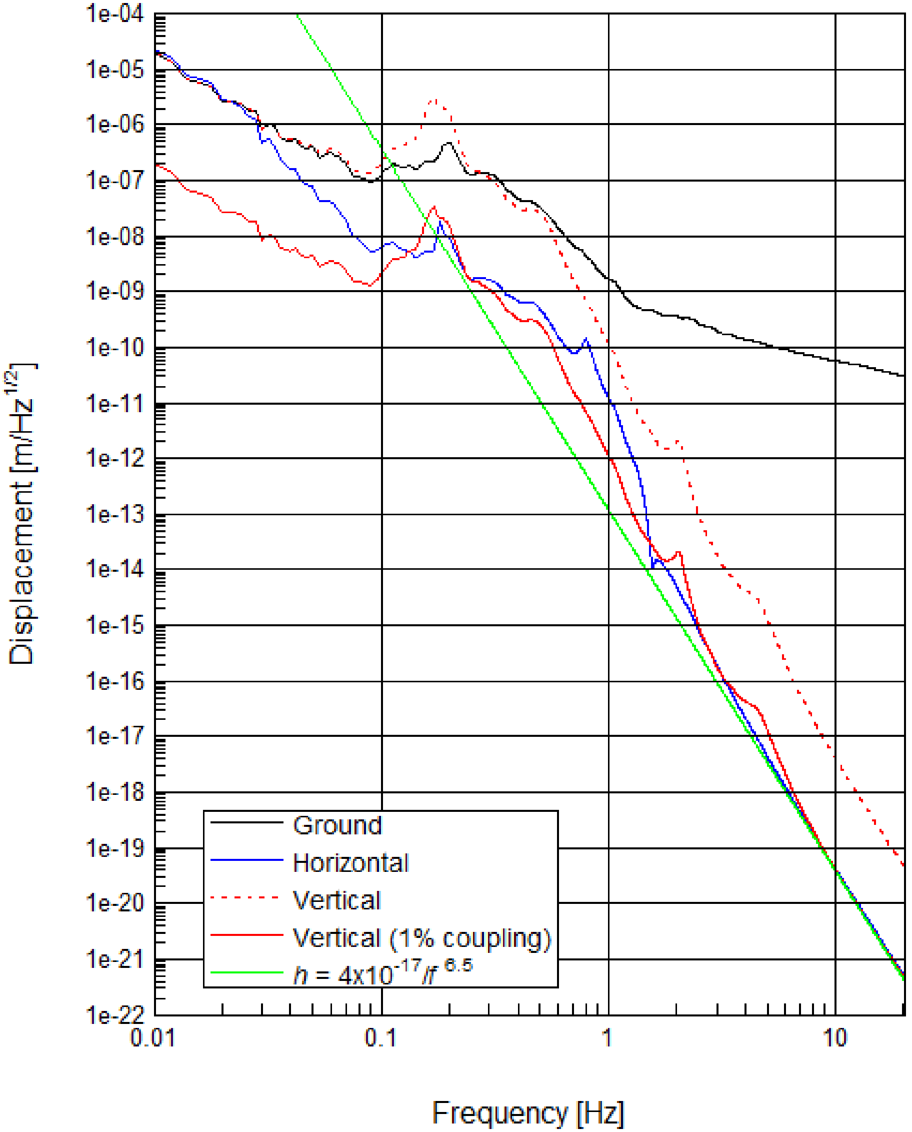
Intermediate Mass & Intermediate Recoil Mass

Test Mass & Recoil Mass

Bread Board



Isolation Performance (Type-A)

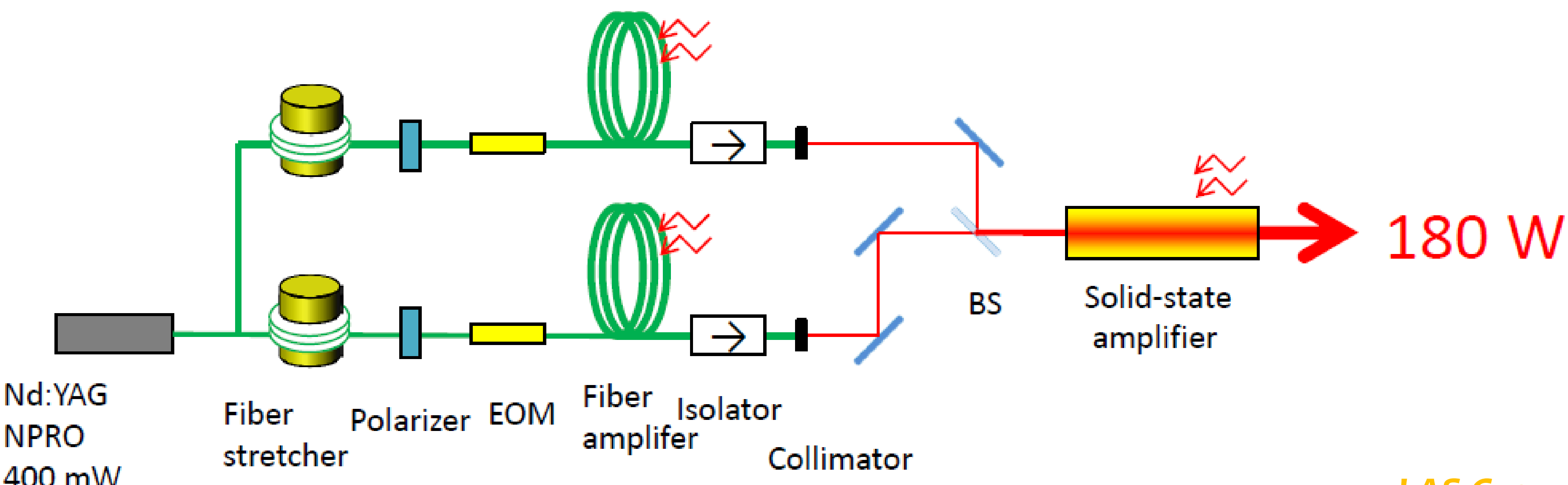


- The isolation above 3Hz is due to a heat link of 0.03Hz.
- The 1% coupling from vertical displacement is comparable with the horizontal one.
- Predicted displacements are consistent with the IFO requirement above 5Hz.

Laser Source for bKAGRA

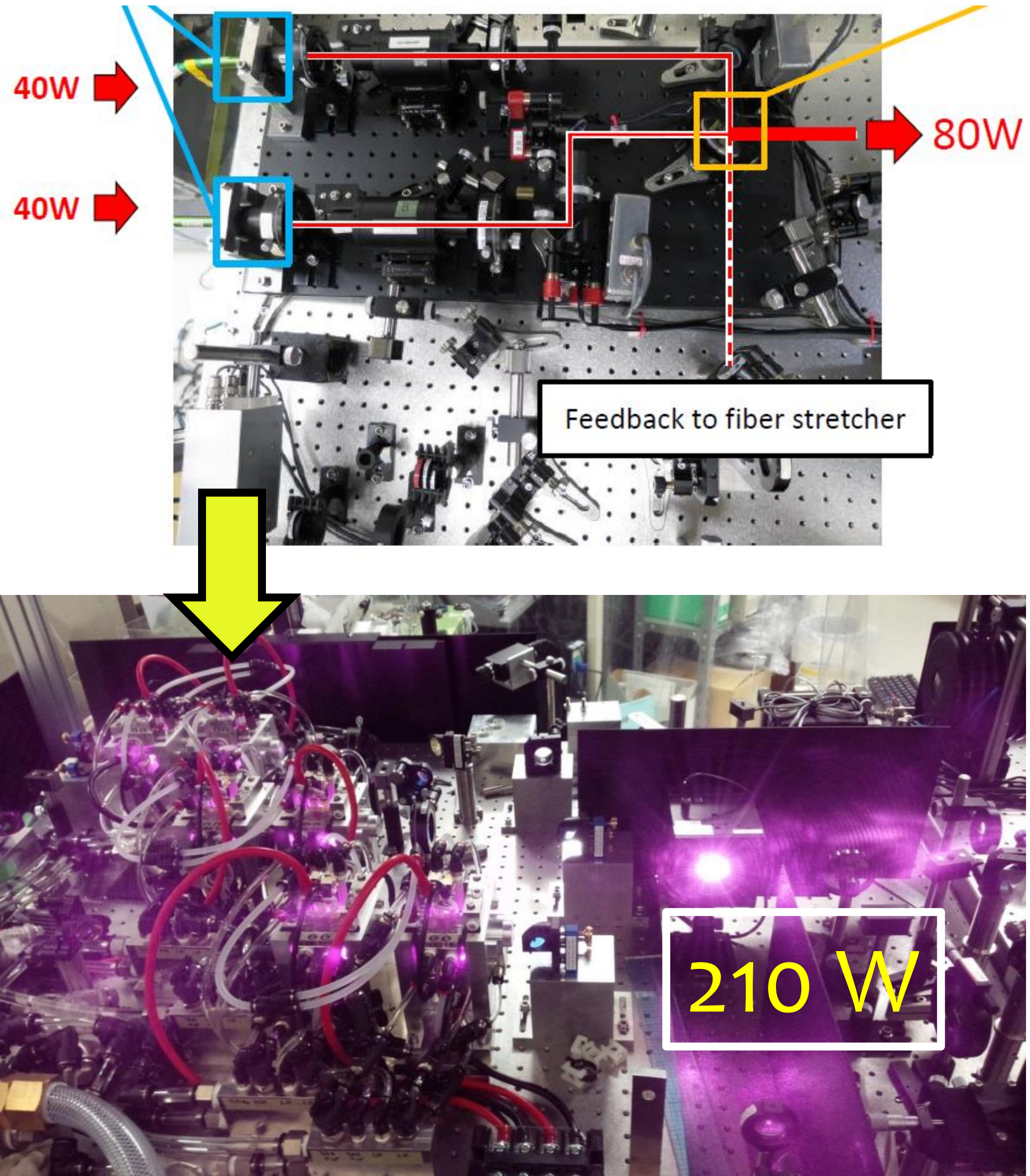
Laser should has...

- Power > 180 W
- Single frequency of 1064nm
- Low frequency noise
- Stable linear polarization
- Stable single transverse mode (TEM00)
- Low intensity noise
- Wide-band control for stabilization systems
  - About 1MHz for frequency control
  - About 100kHz for intensity control



LAS Group

Preliminary Result of Laser



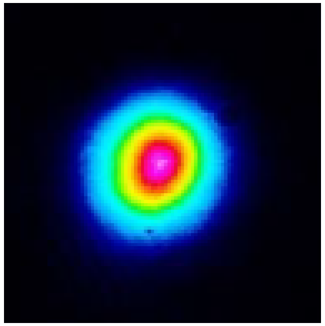
- 78.9 W was achieved by coherent addition
- 210 W was achieved by solid-state amplifiers
- Coherent addition was maintained for 8 hours
- Output power changed in time
- Atmosphere temperature changed in time
- Noise peak in Intensity & phase noise–18 kHz

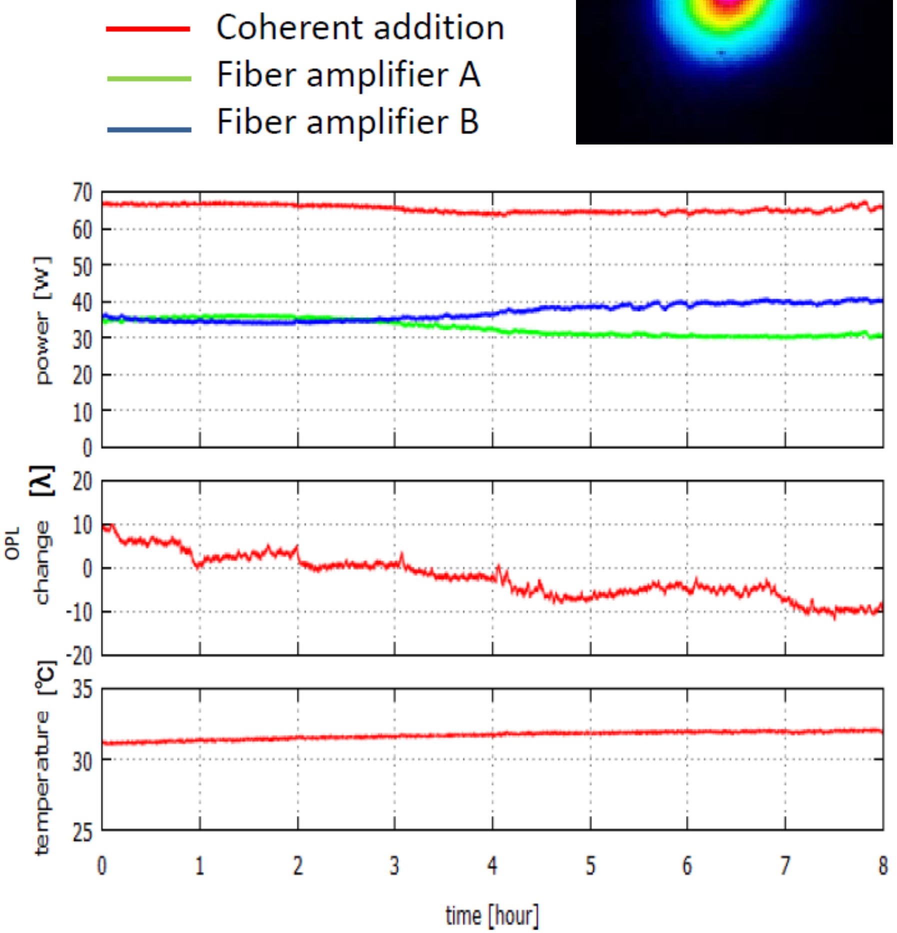
- Stabilize output power–Stabilize temperature?
- Evaluate the noise of the 210-W beam
- Beam quality is ugly.
- Diminish the 18 kHz noise peak–Change fiber stretchers?

LAS Group

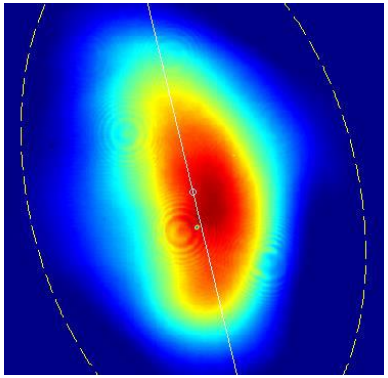
Laser Quality

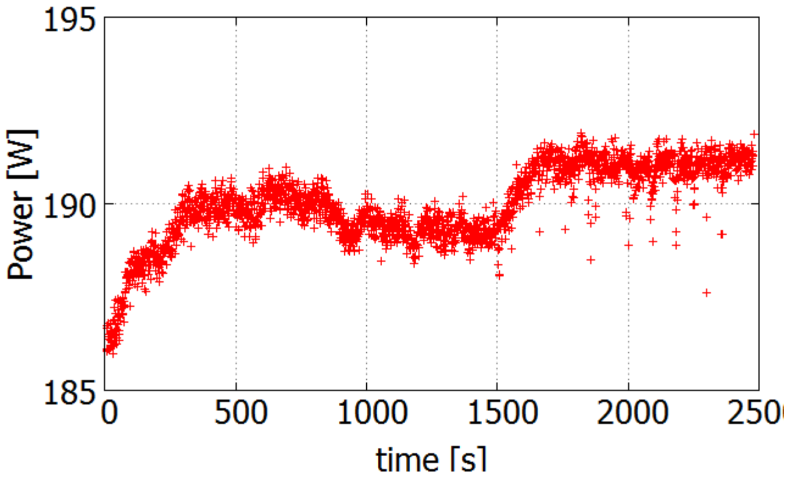
- 78.9 W Coherent Addition Laser





- 190 W amplified and mode improved Laser (210 W -> 190W because of realignment of the Amplifiers)





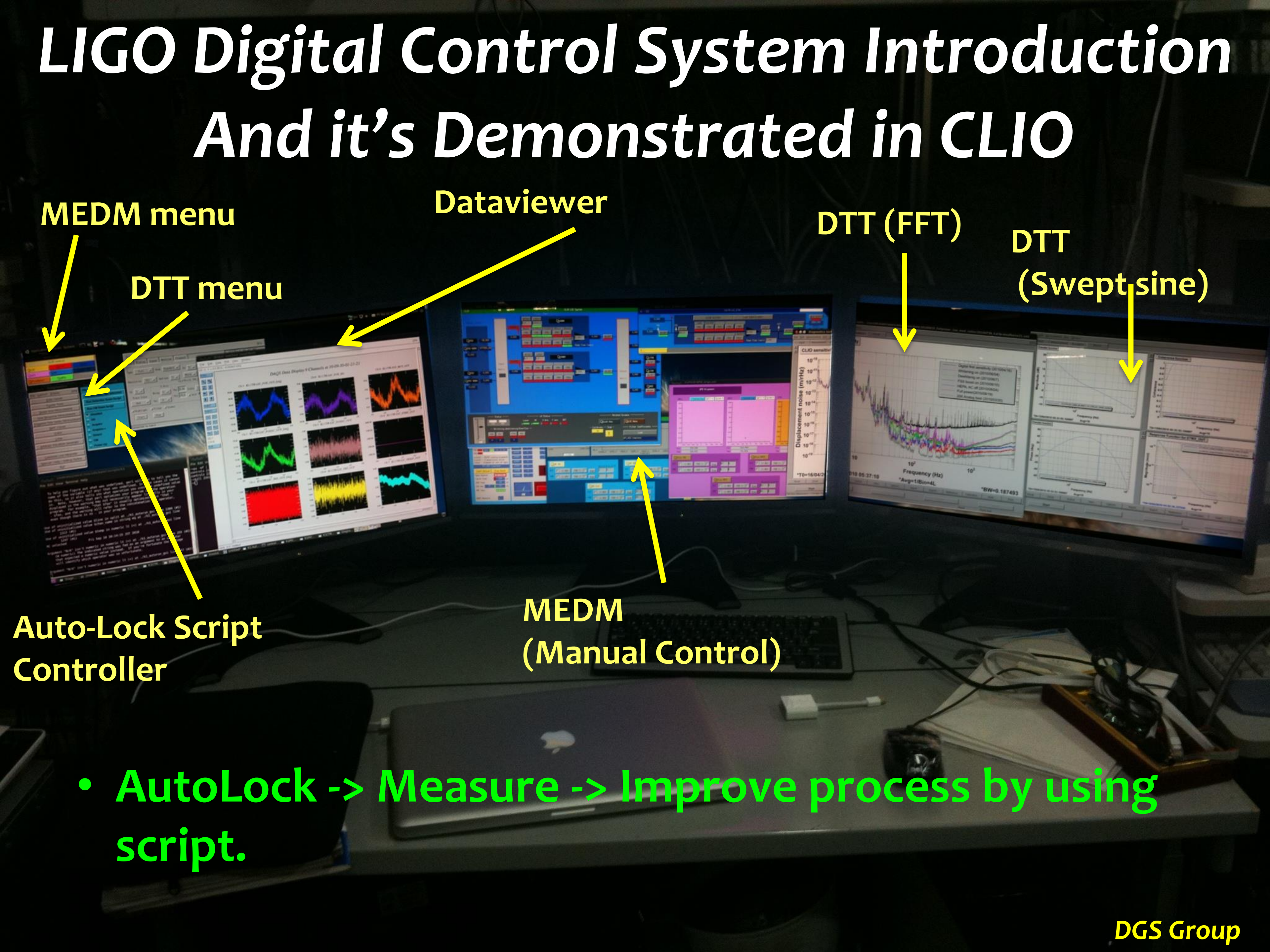
Digital Control System

DGS is indispensable for GWD control including many of freedoms, quick trouble shooting, quick trial and error, data storage, GW signal analysis and GW signal evaluation.

- **KAGRA DGS is based on aLIGO system.**
- **It is applied to the real time control of SAS, IFO length and alignment, pre-stabilized laser using reflective memory, and to the sequence control of an interlock system.**
- **It covers data taking and storage of IFO output (= GW signals) and many detector characterization data in IFO,**
- **Timing control.**
- **For Mainly signals less than ~ 10kHz management.**

DGS Group

LIGO Digital Control System Introduction And it's Demonstrated in CLIO



- AutoLock -> Measure -> Improve process by using script.

Remote Control Room in DAB

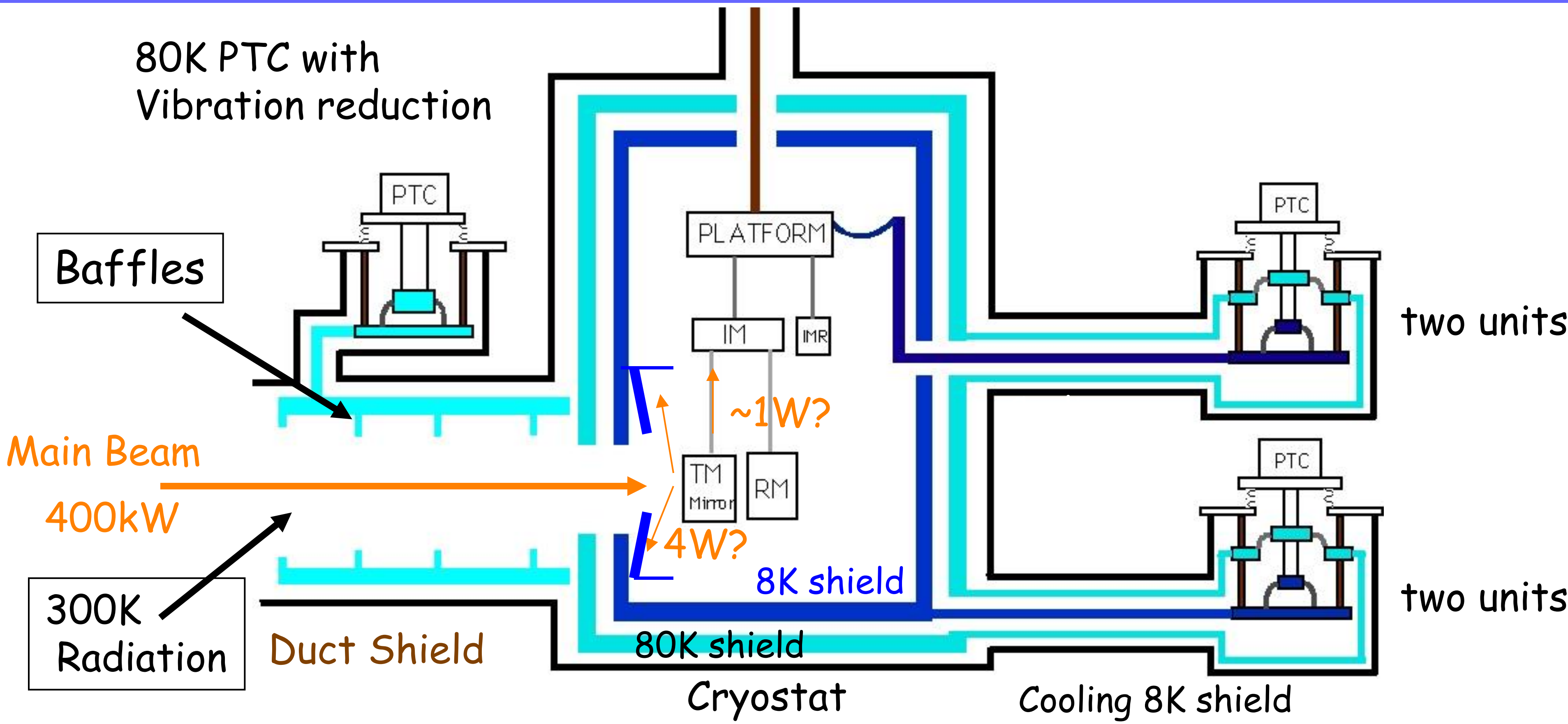
DGS Group

Cryostats

Cryostat for mirror cooling is essential in KAGRA.
Requirement for cryostats are …

- Temperature of the test mass/mirror < 20 K.
- Inner radiation shield have to be cooled < 8 K.
- The mirror have to be cooled without introducing excess noise, especially vibration from the cryo-coolers.
- Accessibility and enough volume for the installation work around the mirror.
- Satisfy ultra high vacuum specification < 10^{-7} Pa.

Conceptual Cooling System

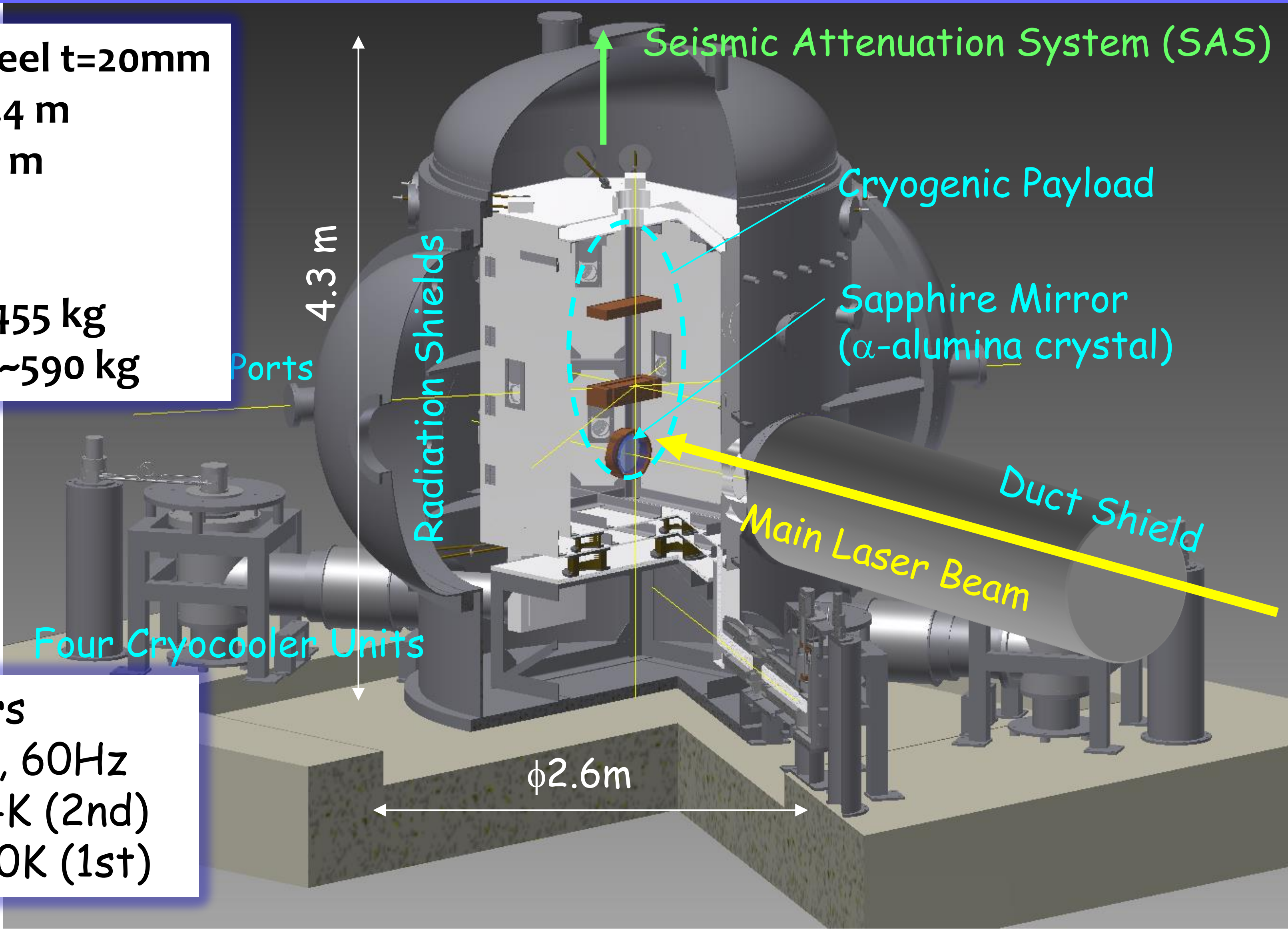


- Four 4K cryocooler units per one cryostat
- Baffles against wide scattering is cooled via 8K shield.

2 units for cool cryo-payload
2 units cool for 8K shield
4 units cool for 80K shield

Structure of Cryostats

Stainless steel t=20mm
Diameter 2.4 m
Height ~4.3 m
M ~ 12 ton
Cold Mass:
8K shield ~455 kg
80 K shield ~590 kg

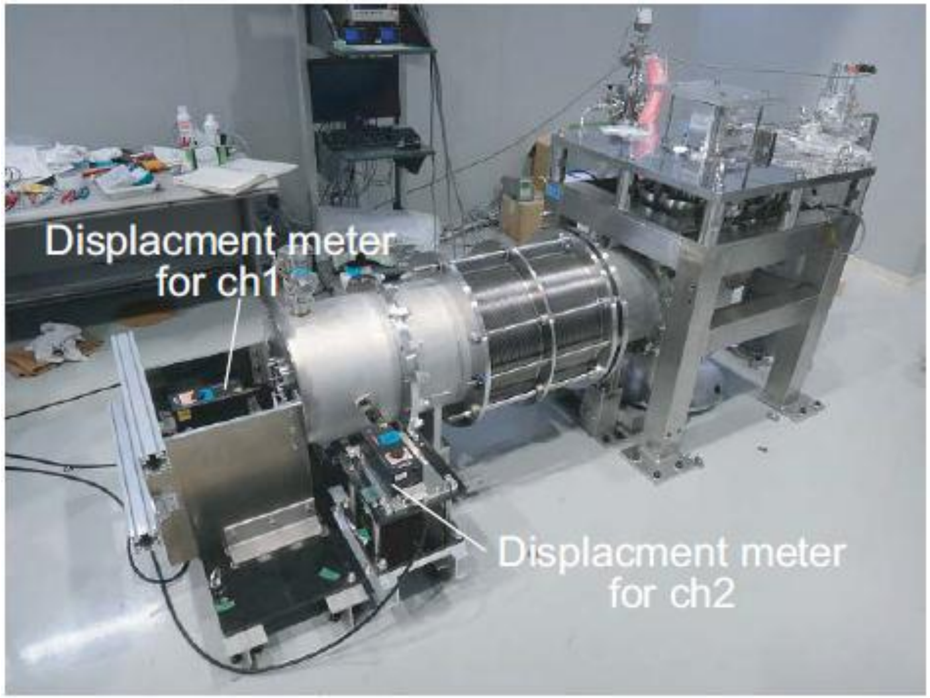


Cryocoolers
Pulse tube, 60Hz
0.9 W at 4K (2nd)
36 W at 50K (1st)

CRY Group

Low Vibration Cryo-cooler Unit

Photo: Performance test at ICRR



Base on CLIO type Cryo-cooler with low vibration mount for KAGRA, but cooling power is lager than CLIO

Cooling Power

・> 2.5W@9K

(@ connection part of 8 K conduction bar)

・> 35W@70K

(@ connection part of 80 K conduction bar)

Vibration Characteristics

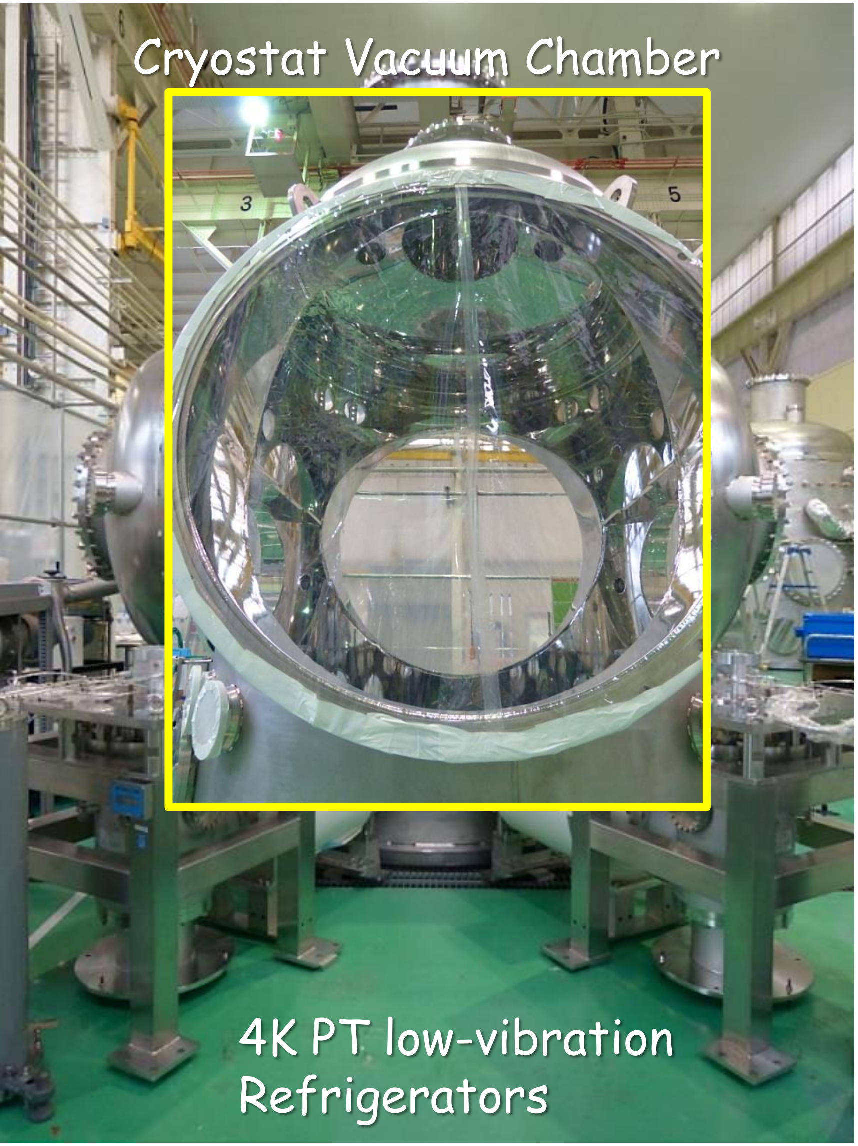
・< $\pm 100 \times 10^{-9}$ m

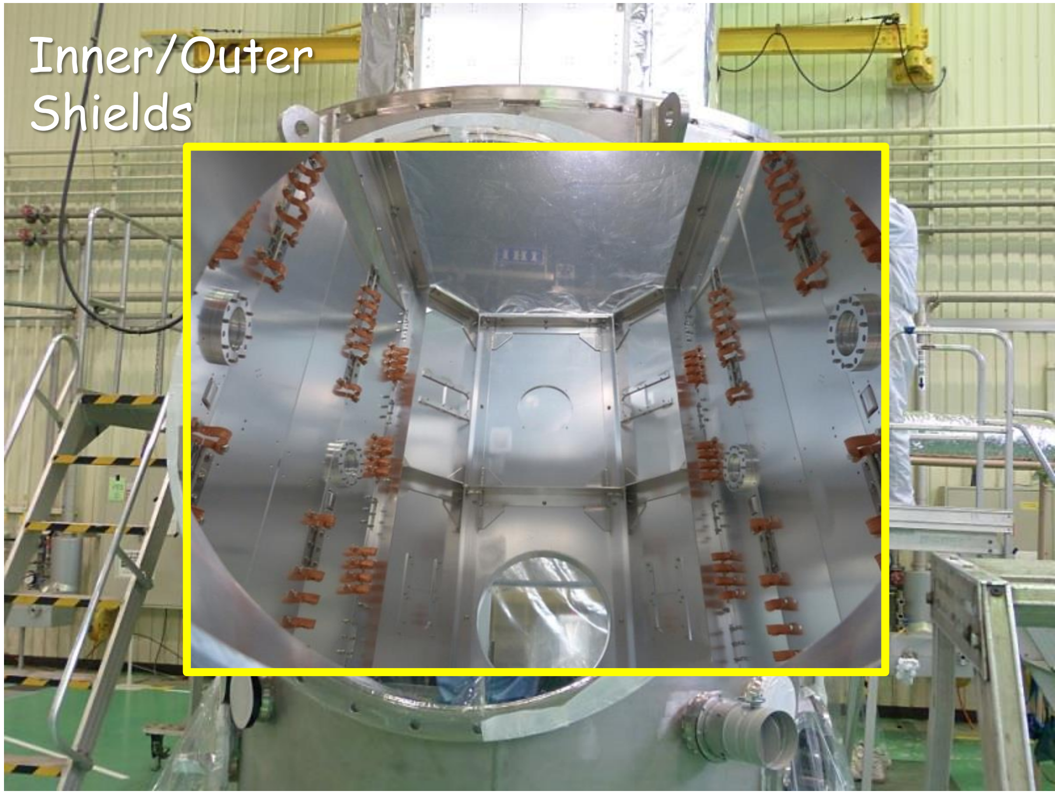
(@ connection part of 8 K conduction bar)

・< $\pm 100 \times 10^{-9}$ m

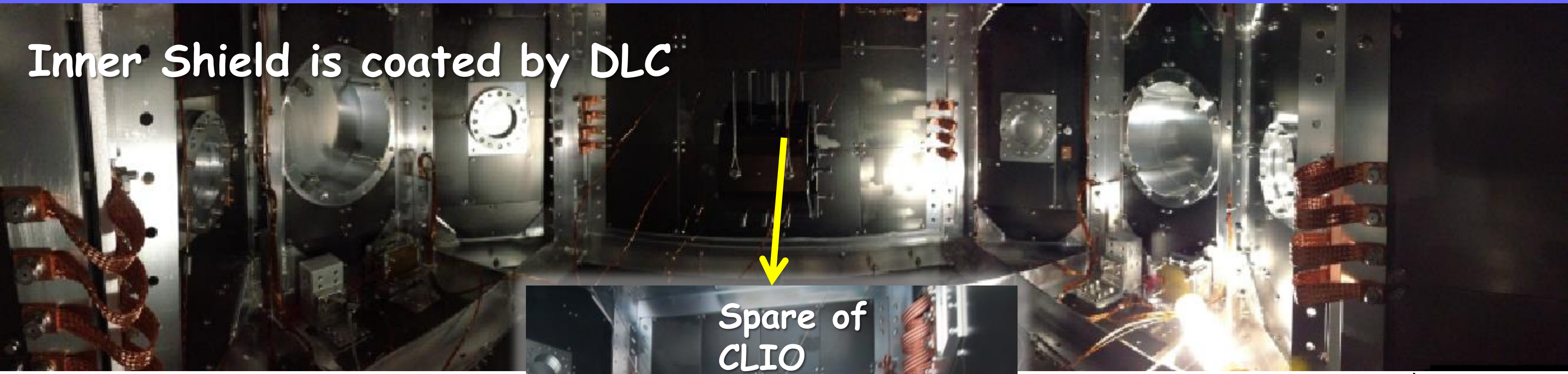
(@ connection part of 80 K conduction bar)

Cryostats Manufacturing in Toshiba

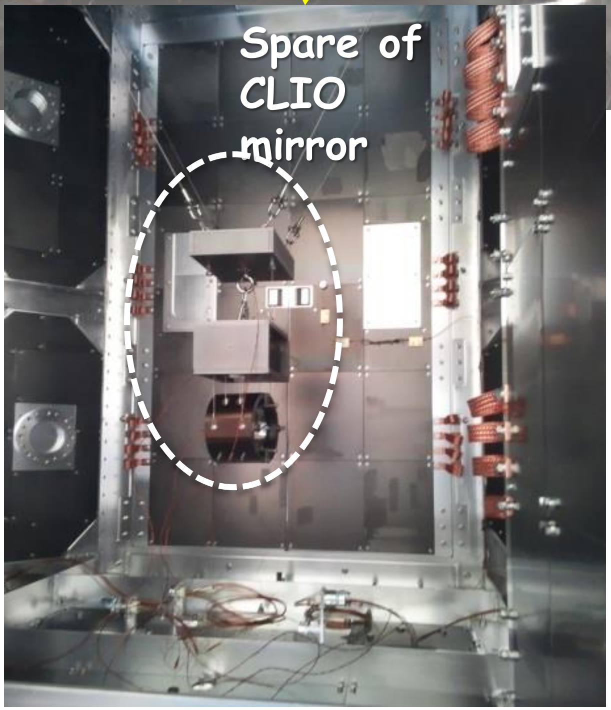


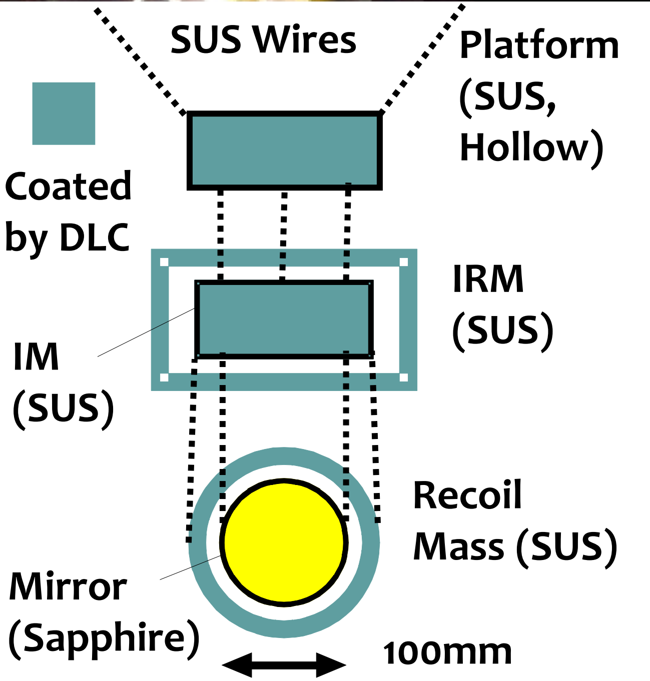


Half Size Dummy Cryo-payload Test



- **1/2 size dummy payload was suspended inside cryostat No.3**
- **Thermal radiation was examined (without any heat links) Cooling from room temperature**

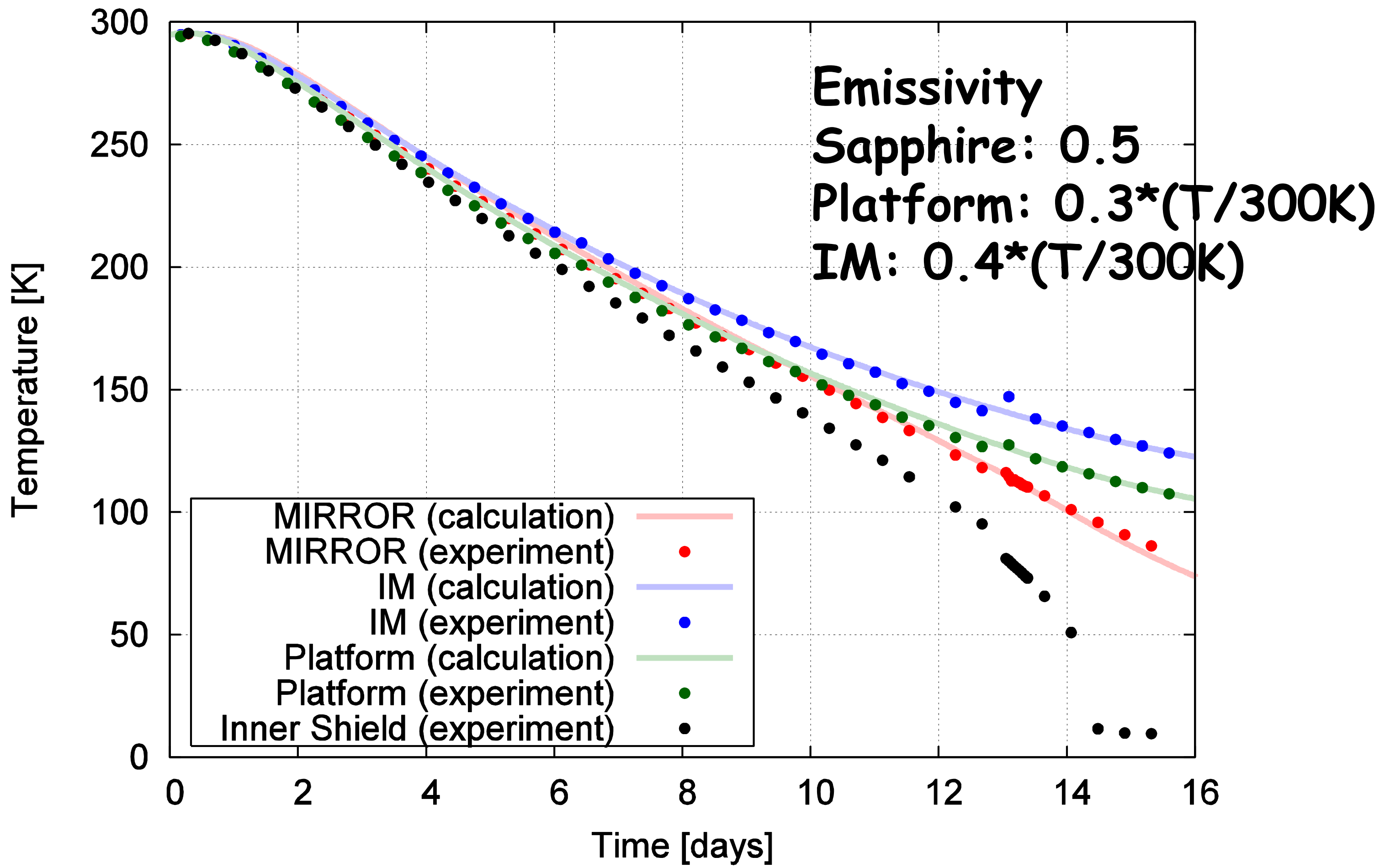




½ Dummy Payloads designed and made by R. Kobayashi, S. Koike (KEK)

Half Size Dummy Cryo-payload Test

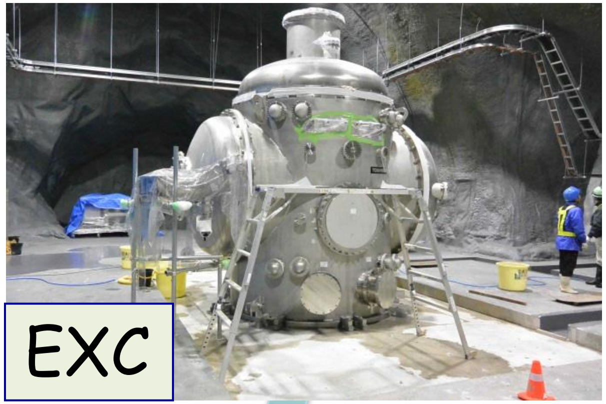
- Effect of High Emissivity Coating for Cooling Time is Confirmed.
- It was consistent with the estimation!

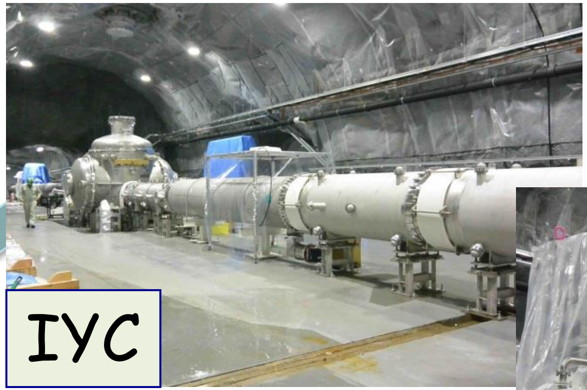


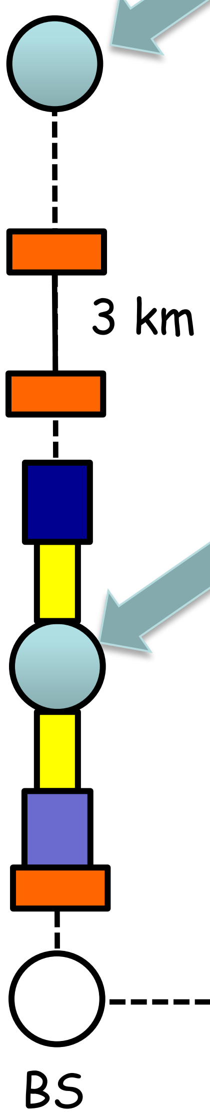
CRY Group

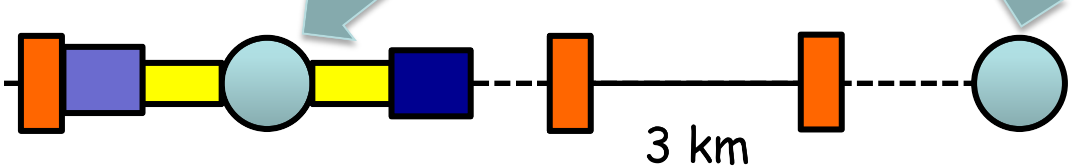
Cryostat Installation in KAGRA

Assembled Cryostat Photos





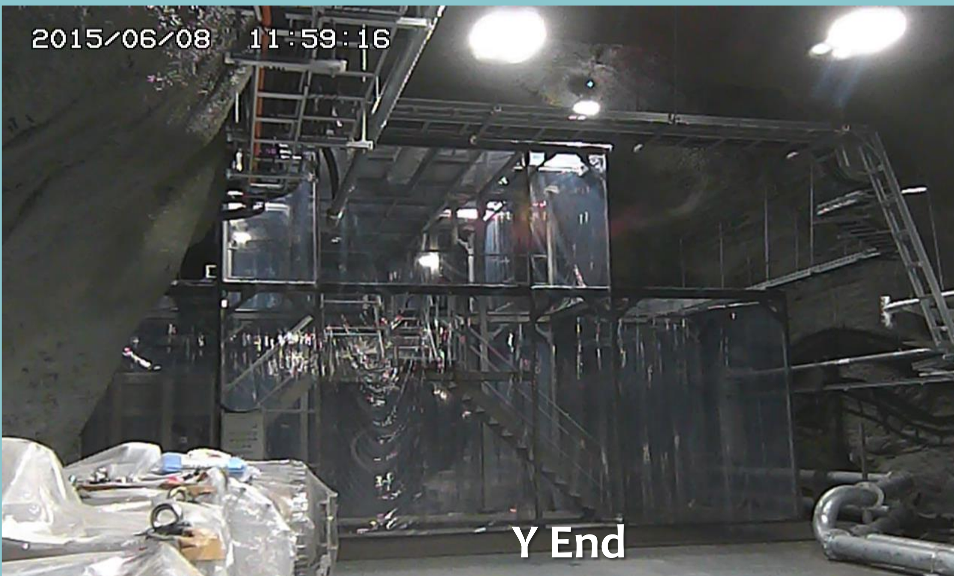


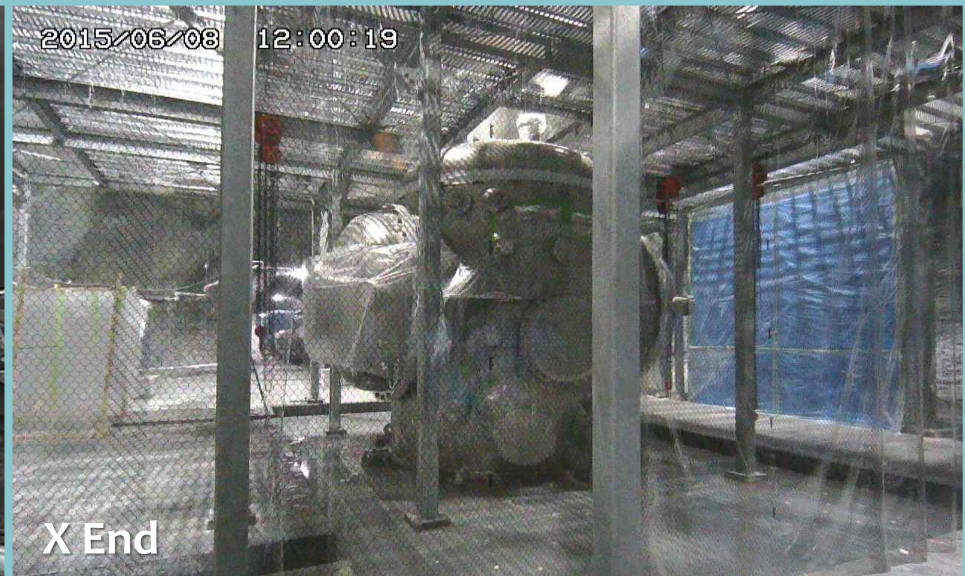


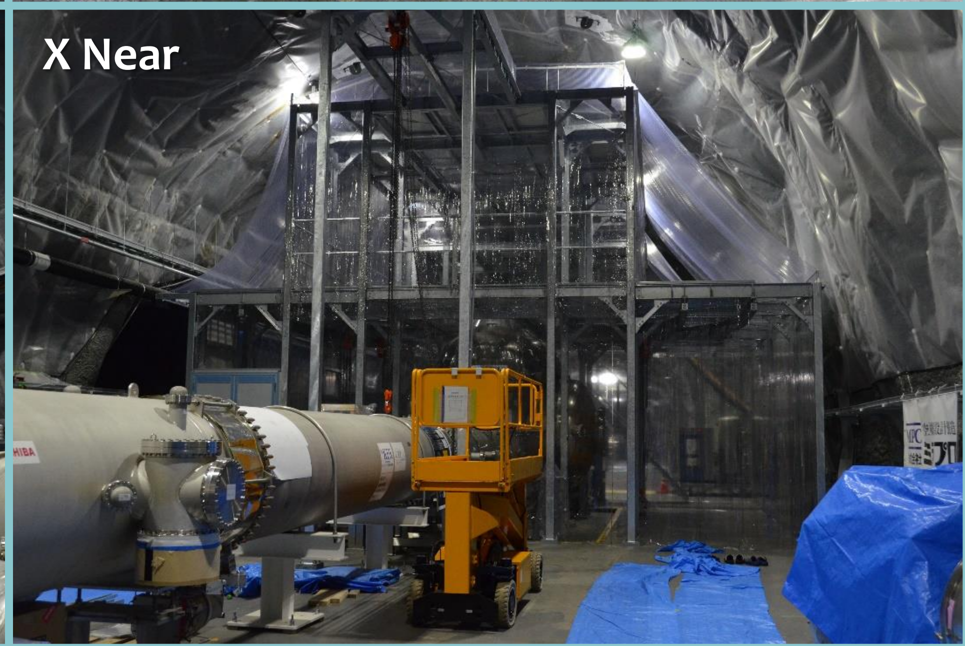
Reached pressure
in the Y-front cryostat
3.7×10^{-7} kPa

CRY Group

Cryostat and Clean Booths







Cryogenic payload system

<u>*Key facts*</u>

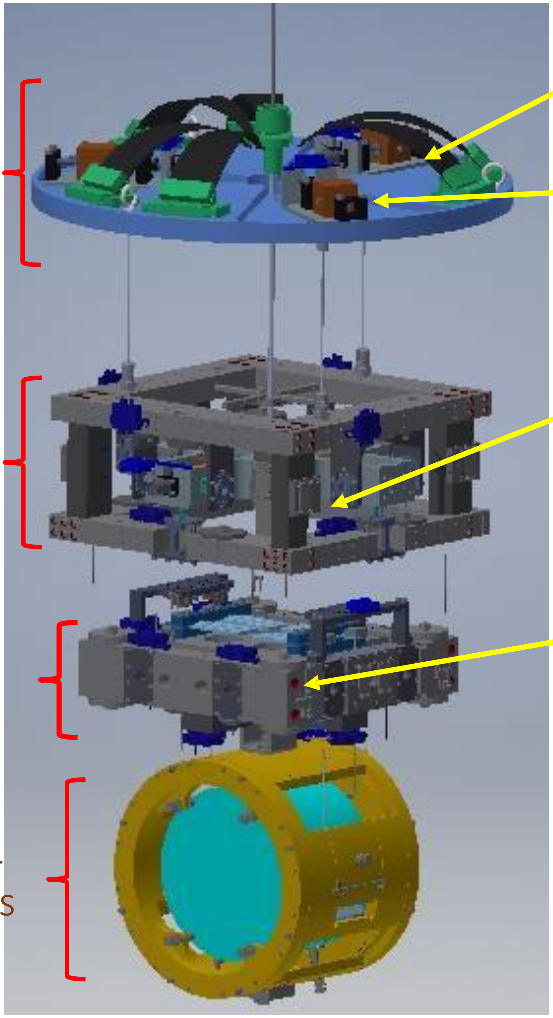
Total mass - 200 kg

Height - 2 m

Suspended from Room temp.

Type A (NAOJ) system

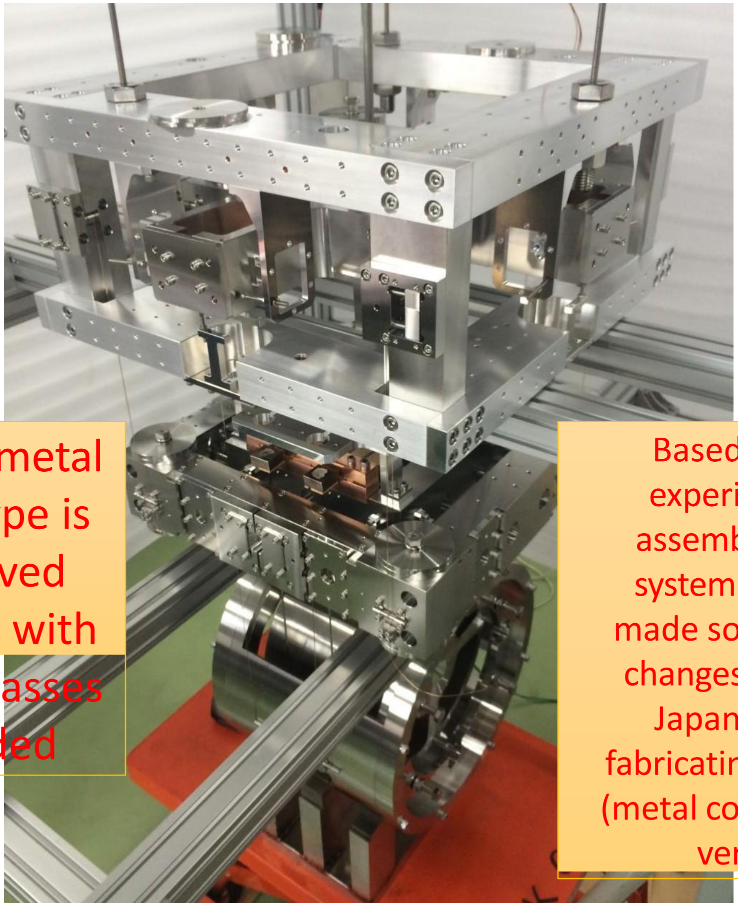
Total height 14 m



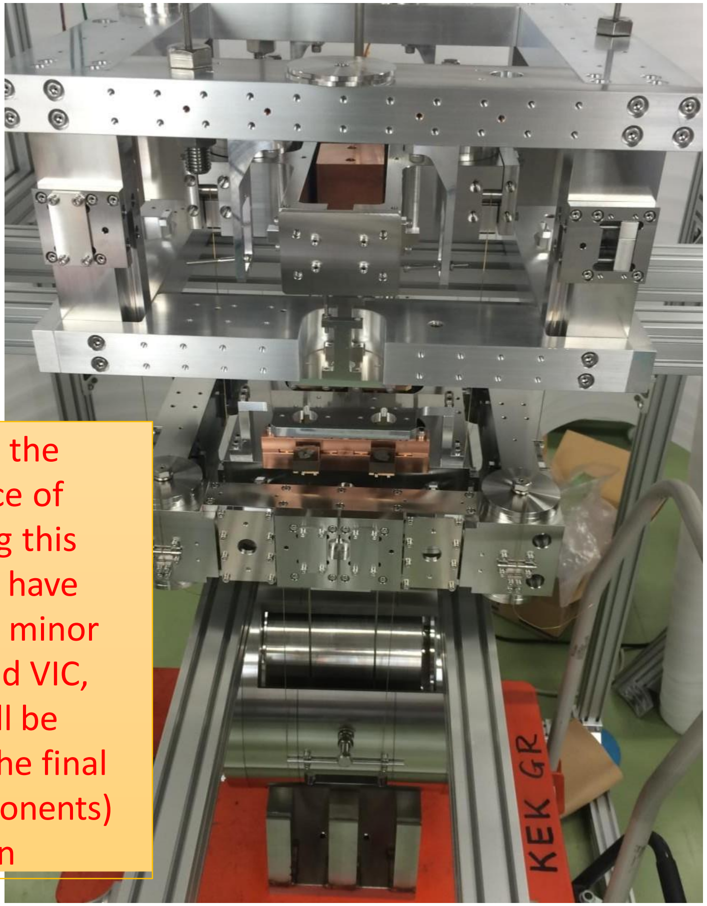
* Heat links not shown

Cryogenic payload system

2nd Metal prototype of the suspensions system fabricated at KEK



The 2nd metal prototype is improved version with recoil masses included



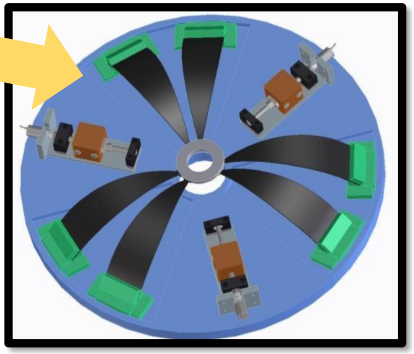
Based on the experience of assembling this system we have made some minor changes and VIC, Japan will be fabricating the final (metal components) version

Takahiro Miyamoto (PhD student) working on developing/testing control systems (coil magnet actuators, PD, LED etc.)

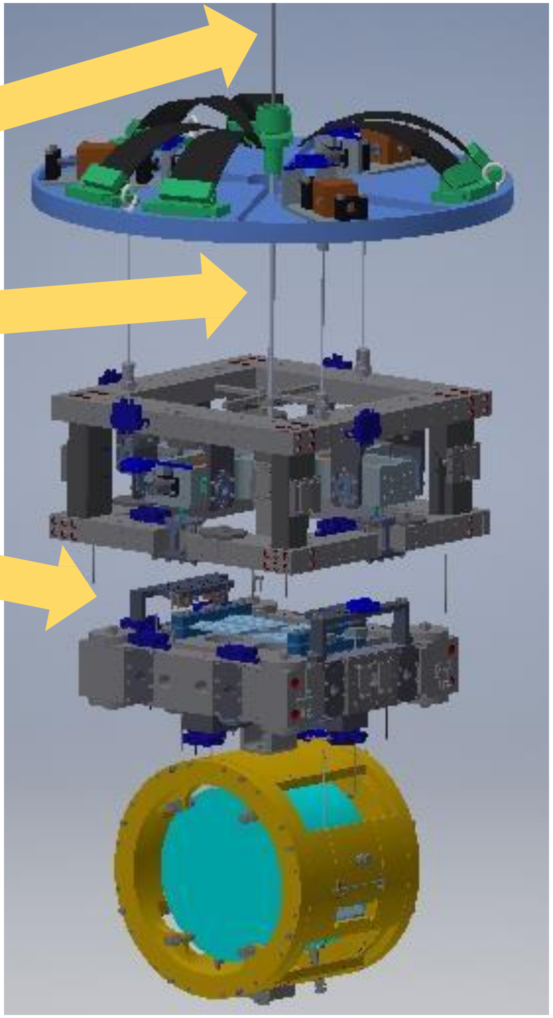
Cryogenic payload system

Materials research at cryogenic temp.

- ✓Connecting rod:-
  - ✓VIS (300 K) to cryo-payload (20 K)
  - ✓Platform to Marionette (20 K)
    - ✓ Maraging steel/Titanium alloy
    - ✓ Strength, bending length and thermal conductivity
- ✓Platform stage blade springs/wire suspending IM(20K)
  - ✓Beryllium copper (BeCu)
    - ✓Strength
    - ✓Young's modulus
    - ✓Q factor (Mechanical loss)
- ✓Wide angle baffles (WAB)
  - ✓Material BeCu



Platform stage blade springs



Cryogenic strength test

Beryllium copper (alloy 25)

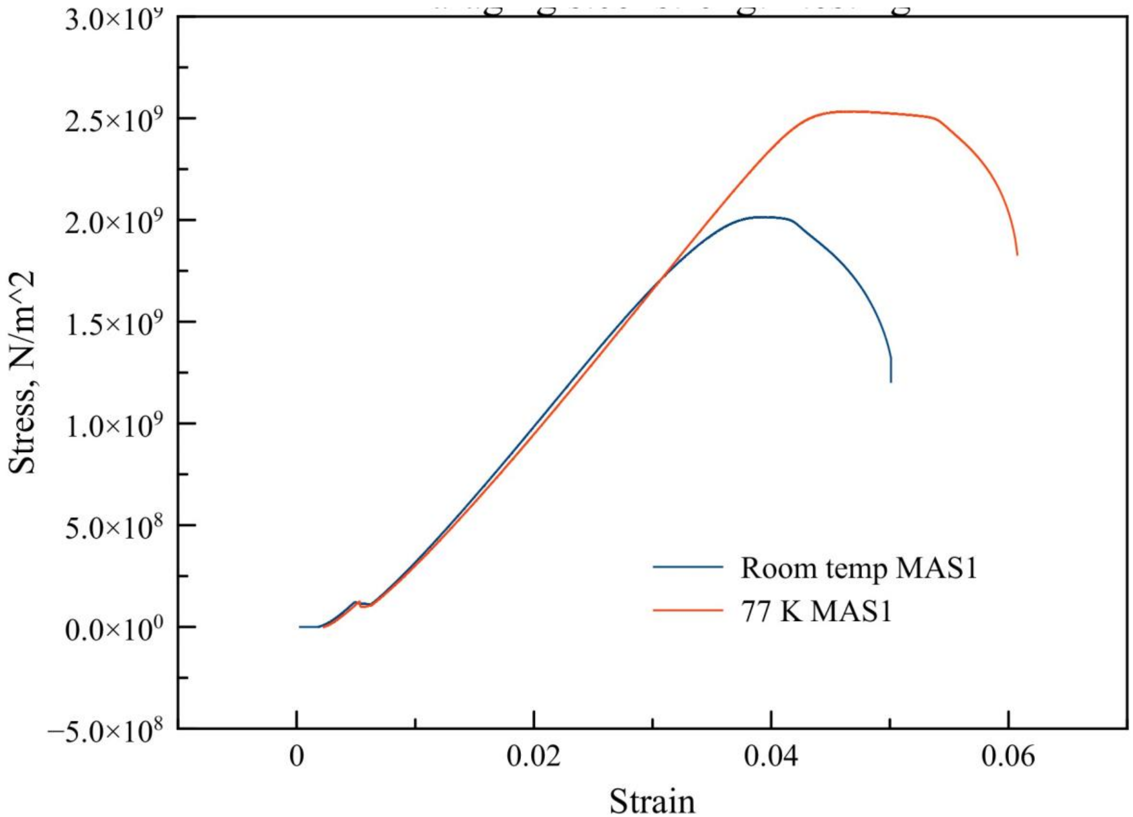
Ti 6Al-4V (Titanium alloy)

Maraging steel MAS1

Specimen in liquid nitrogen bath

Cryogenic strength test

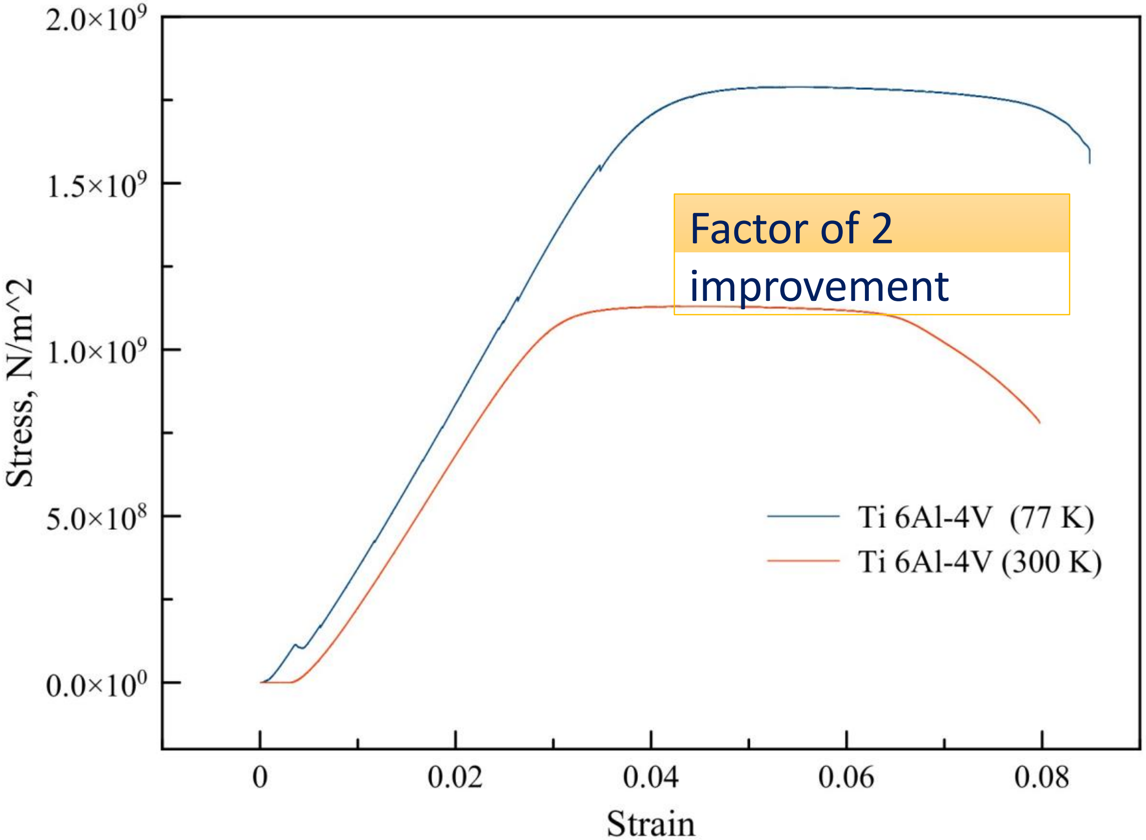
Maraging steel (MAS 1)

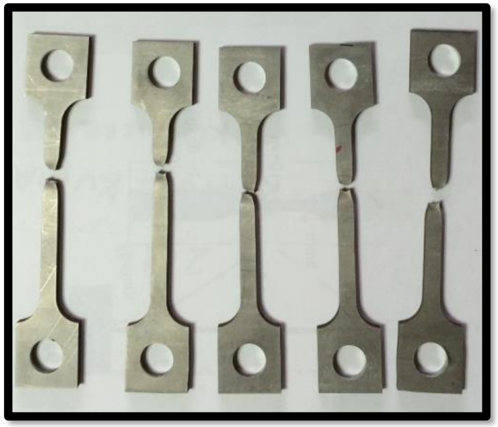


Temp.	Ultimate strength	Breaking stress
300 K	2.0 GPa	1.32 GPa
77 K	2.5 GPa	1.84 GPa

Cryogenic strength test

Titanium alloy (Ti 6Al-4V)

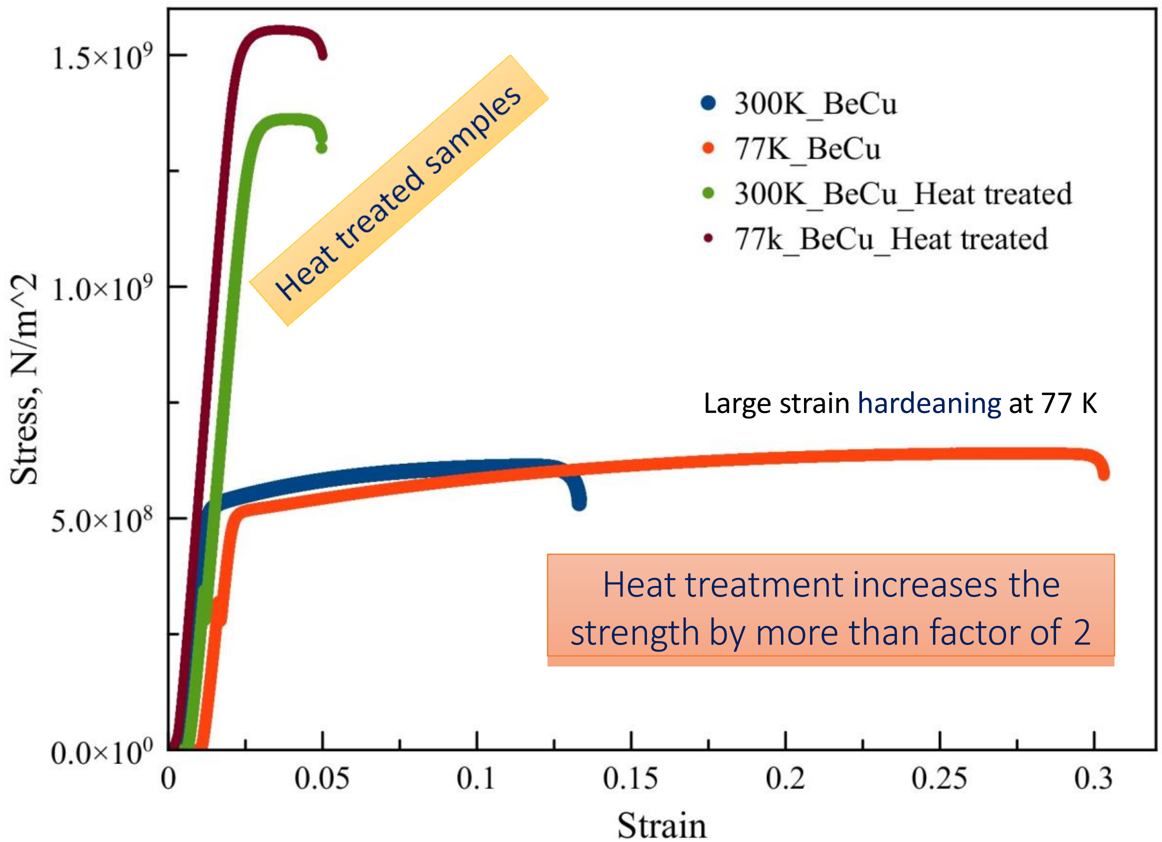


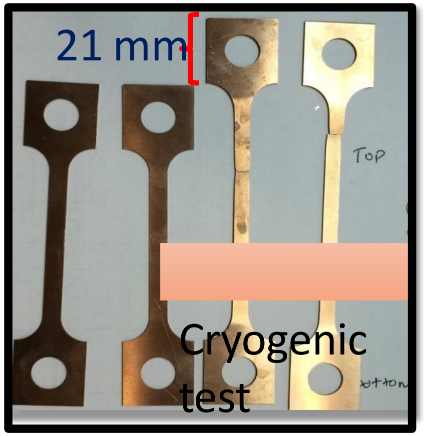


Temp.	Ultimate strength	Breaking stress
300 K	1.13±0.02 GPa	785±14.2 MPa
77 K	1.78±0.014 GPa	1.62±0.05 GPa

Cryogenic strength test

Beryllium copper
(platform stage blade springs)





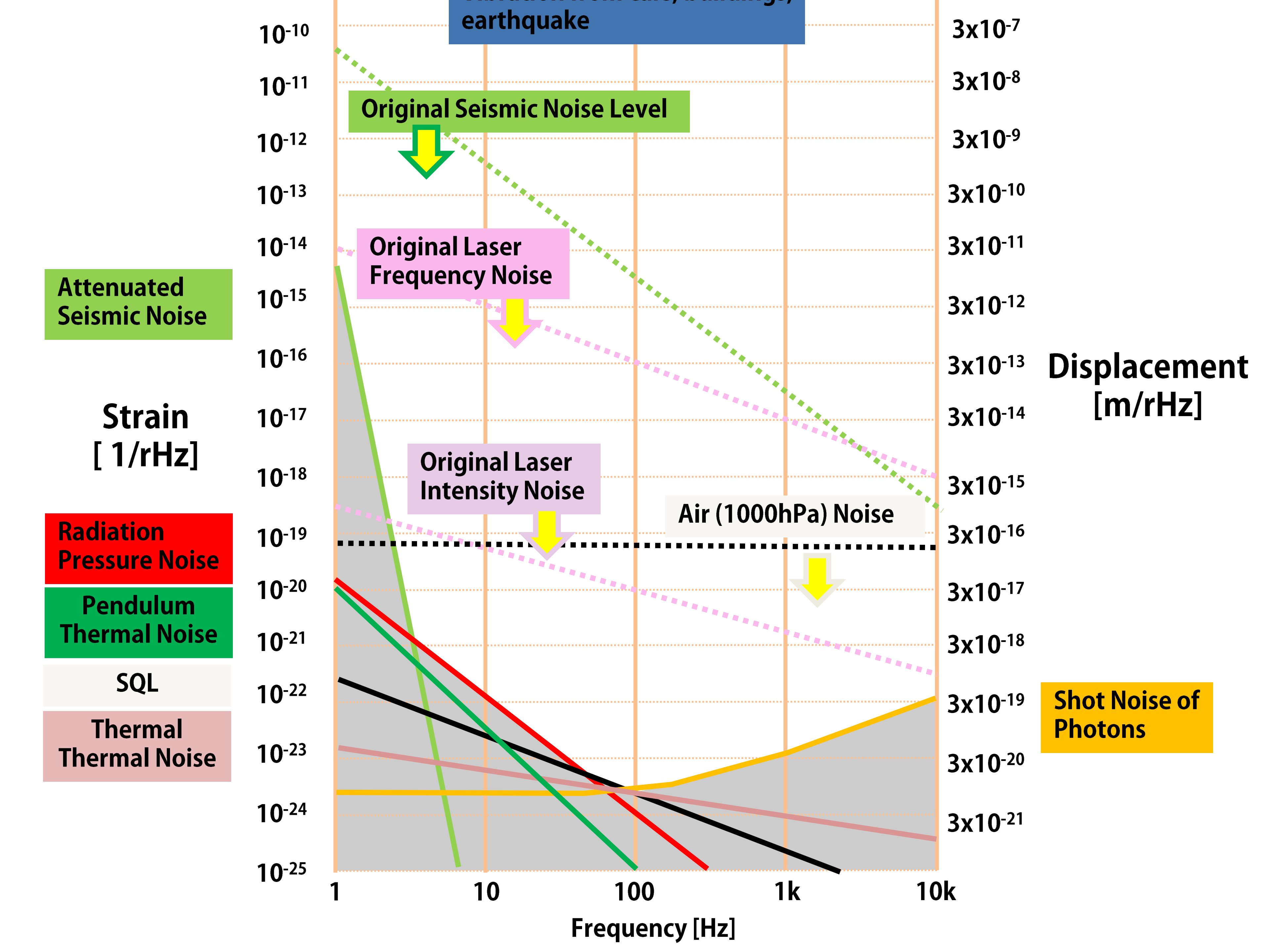
Thermal Noise Reduction

- **Mirror thermal noise and mirror suspension thermal noise are final barrier to reach and enhance the targeted sensitivity of many 2nd and 3rd generation GW detectors.**

- **Several methods were proposed to reduce them.**

- **In the case of KAGRA, cooling technology is applied for this purpose, while coating loss reduction is applied in aLIGO and aVIRGO.**

- **For cooling mirrors and their pendulums, their substrate should be "sapphire ".**


earthquake
Original Seismic Noise Level
Original Laser Frequency Noise
Attenuated Seismic Noise
Original Laser Intensity Noise
Air (1000hPa) Noise
Strain [1/rHz]
Displacement [m/rHz]
Radiation Pressure Noise
Pendulum Thermal Noise
SQL
Thermal Thermal Noise
Shot Noise of Photons
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
$3x10^{-7}$
$3x10^{-8}$
$3x10^{-9}$
$3x10^{-10}$
$3x10^{-11}$
$3x10^{-12}$
$3x10^{-13}$
$3x10^{-14}$
$3x10^{-15}$
$3x10^{-16}$
$3x10^{-17}$
$3x10^{-18}$
$3x10^{-19}$
$3x10^{-20}$
$3x10^{-21}$
1
10
100
1k
10k
Frequency [Hz]

Mirror Substrate

- Sapphire for b.KAGRA (= KAGRA)
  - A-axis crystal (ϕ22 cm x t15 cm) has been obtained.
  - Max size of C-axis crystal is now ϕ22cm x t15cm; this size is limited by the height of the boules of a machine in Crystal Systems LAOS Inc.
  - 20ppm/cm absorption is required, but … not so easy.
  - Several C-axis crystals are now on polishing.
  - Shinkosha (Japanese Company) might be able to large size low loss sapphire substrate. Shinkosya can make C-axis growing crystal.

Mirror Polishing

- **Polishing of Sapphire substrate**
  - Sapphire is the secondly hardest material, so it is not easy to be polished smoothly. It requires longer time and high technology to polish it.
  - 1.9km radius of curvature for the sapphire mirrors is required for arm FP cavity mirrors with …
    - ✓ < λ/100 waviness (-> refraction loss)
    - ✓ < 5 A micro roughness (scattering loss)
  - Uniformity of these qualities is required for the whole mirror surface (diameter ~ 22cm)
  - ZYGO inc. is now trying to polish them.

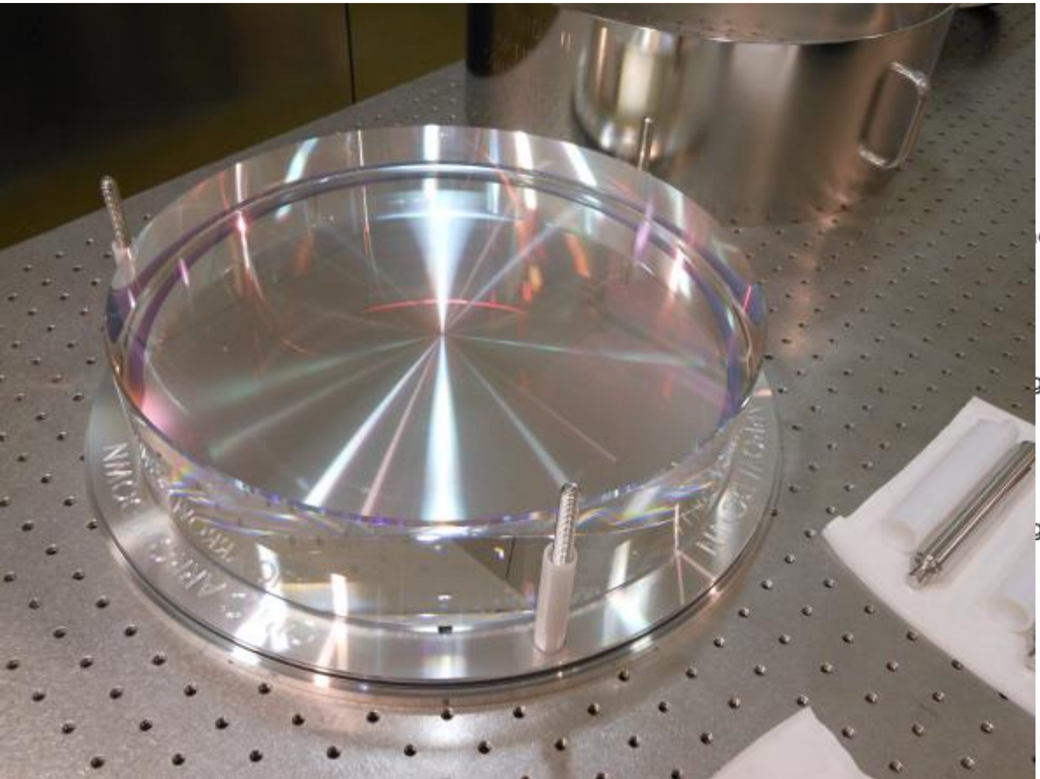
Mirror Coating

- Multi-layered coating films (Ta_2O_5/SiO_2) for 1064nm wavelength is required with…
  - Absorption loss : < 0.5 ppm/films => Heating problem
  - Scattering due to defects in films : < 30ppm
- Mechanical loss of Ta_2O_5 is the source of thermal noise which limits the GW detectors' sensitivity. So huge efforts have been done to reduce its mechanical loss, to find alternative materials and to develop crystalline coating. It is proceeding gradually.
- In the case of KAGRA, the mirror cooling technique was selected for this purpose.

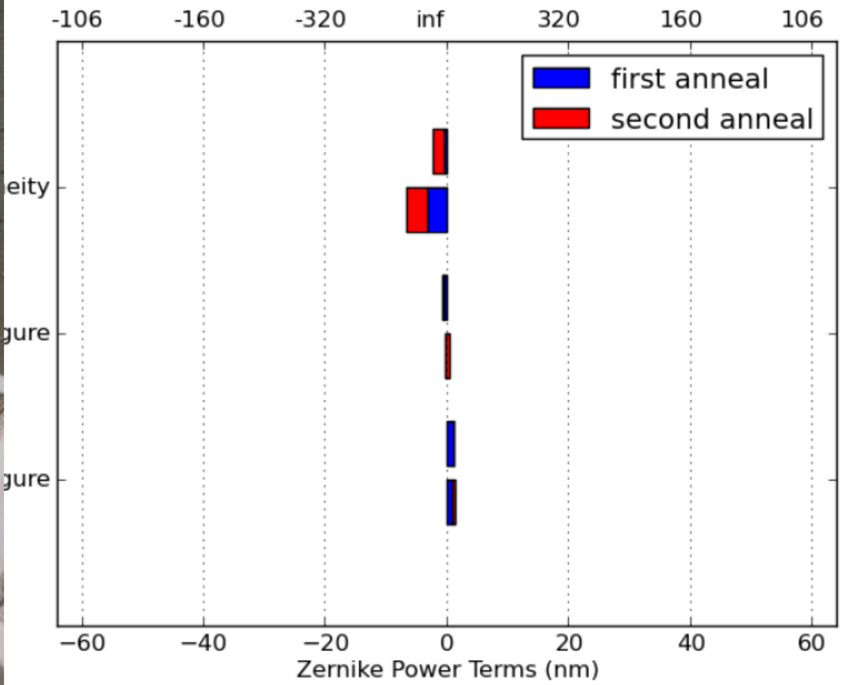
Sapphire Mirror Substrate

Beam Splitter

- AQ2of ASAHI Glass Inc.
- Diameter:38cm, Thickness:8cm
- Two BSs were ready



Flat Polishing



Sapphire Mirror Suspension

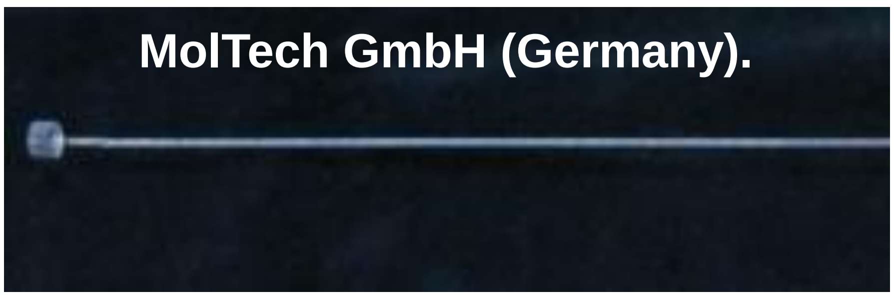
Sapphire mirror suspension is essential in KAGRA.
Requirement for sapphire mirror suspension (wires) are …

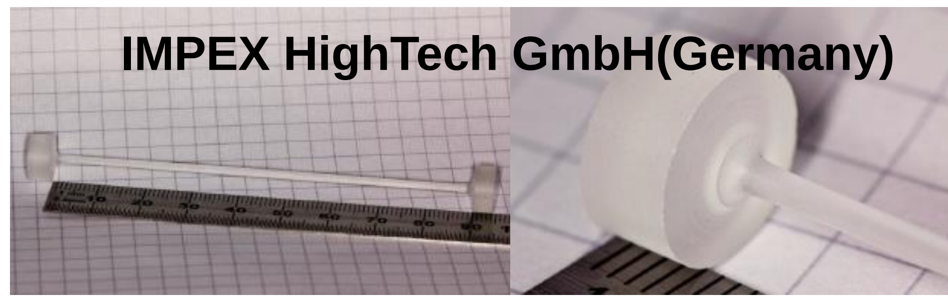
- High tolerance for tension to suspend 30kg sapphire mirror.
- High thermal conductivity to extract heat from the mirror.
- Low mechanical loss of fibers (wires) and their fixing on mirrors ($< 10^{-8}$).
- Easy assembly.
- Satisfy ultra high vacuum specification $< 10^{-7}$ Pa.

The solution is to use sapphire fibers (almost rods)

Mirror Suspension using Sapphire Fibers

- KAGRA Sapphire mirrors are designed to be suspended by sapphire fibers to obtain heat drain path and to reduce suspension thermal noise.
- Because bonding attachment is hopeless for sapphire fibers, nail heads shape is desired to huck sapphire mirrors.





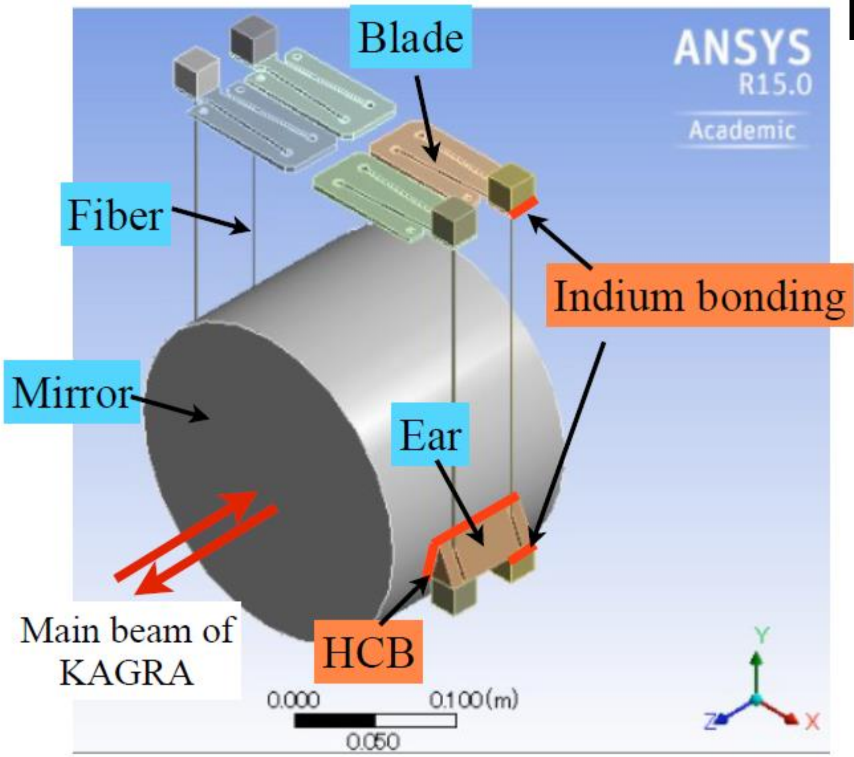
Property Checks are required about ...

- Mechanical Loss
- Thermal Conductivity
- Strength (bending, sheer, tensile)

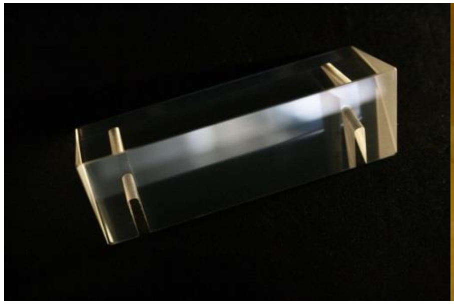
in Univ. of Tokyo, Jena Univ. and Roma Univ.

Mirror Suspension using Sapphire Fibers

(1) Sapphire lop-eared suspension
- A part of cryo-payload
- Main sapphire mirrors are included.
- All parts are made from sapphire.

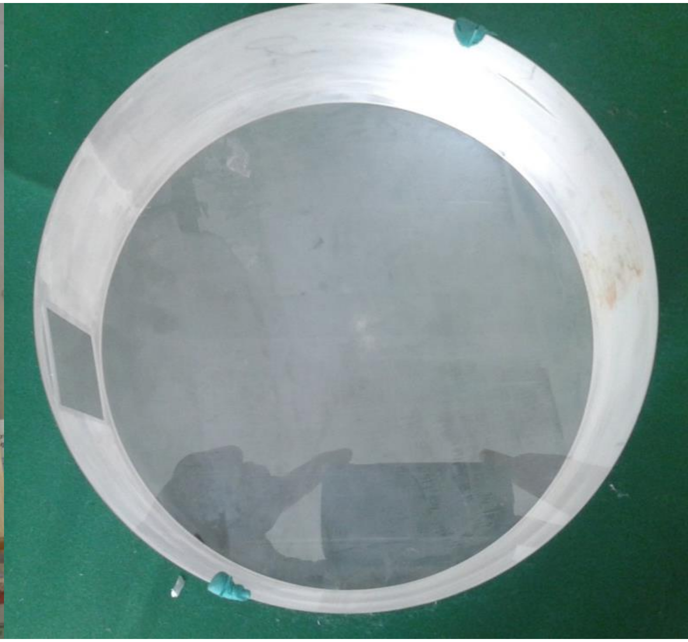


Sapphire Ear



Sapphire Blade

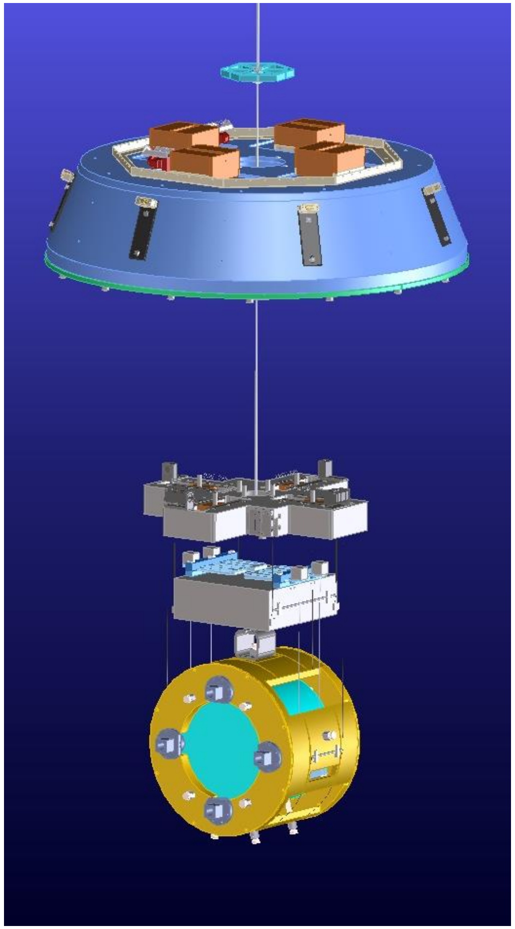
Sapphire rod

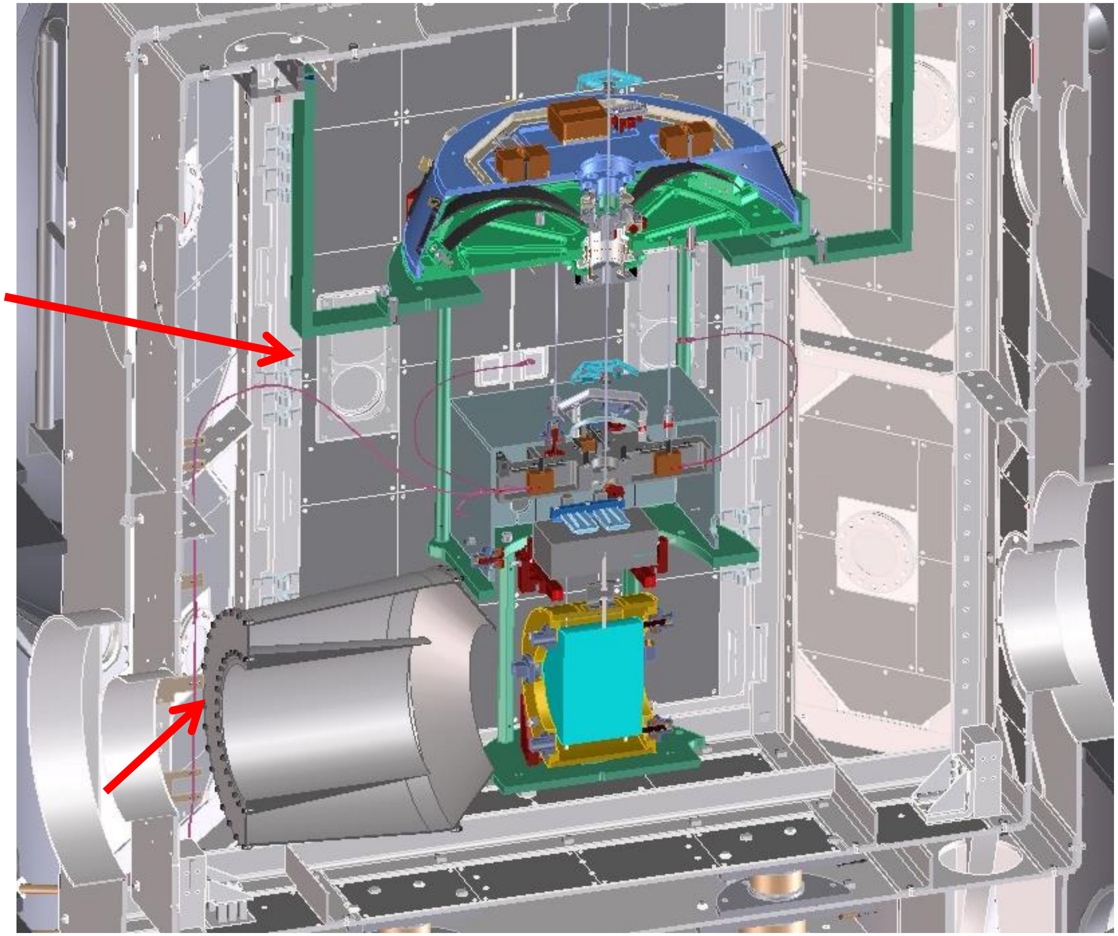


Sapphire Mirror Substrate

Mirror Suspension using Sapphire Fibers

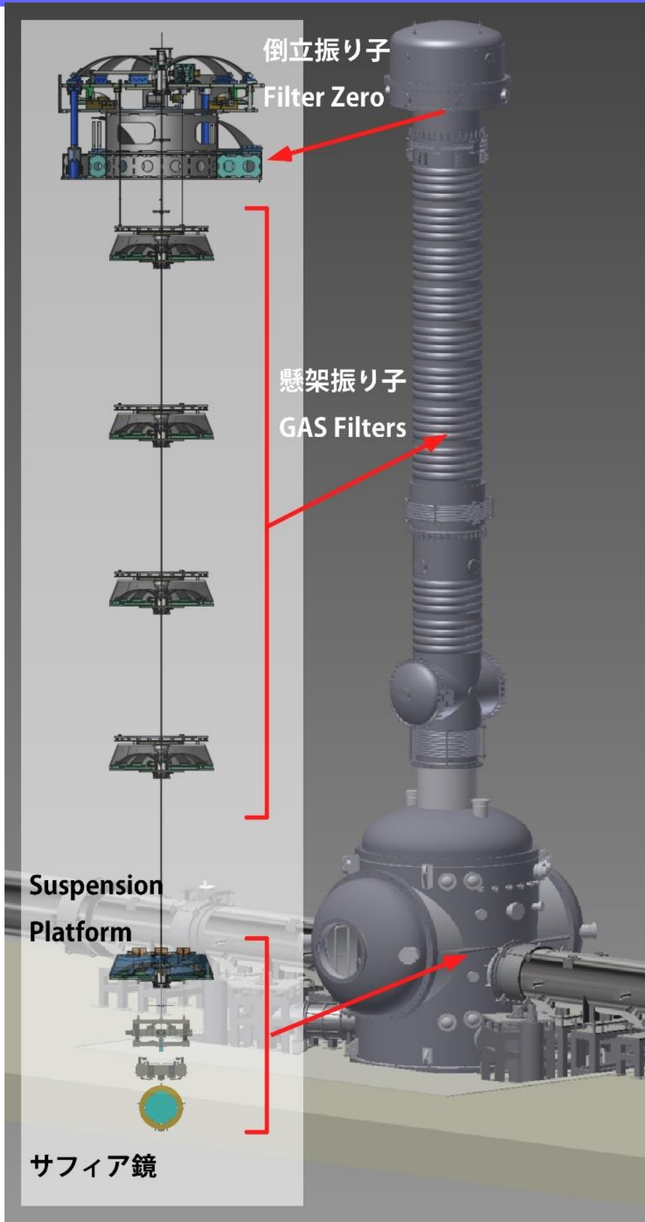
(2) Cryo-payload with dummy sapphire suspension
This is almost same as the actual cryo-payload. Parts of "sapphire" suspension is a dummy (made from metal).





Geophysical Strain Meter in KAGRA

- Mirrors in GWD will move about 60 um because of the tidal and local geophysical motion.
- The compensation for this large displacement is necessary for the continuous GWD operation.
- However, the direct mirror position control using a large mirror actuating force for mirrors will spoil the GWD sensitivity with its electrical noise.
- So, the large dynamic range should be not in mirrors but in their suspension points.
- The tidal motion, at present, can be predicted, but local one cannot be.



Ground motion compensation

Countermeasure

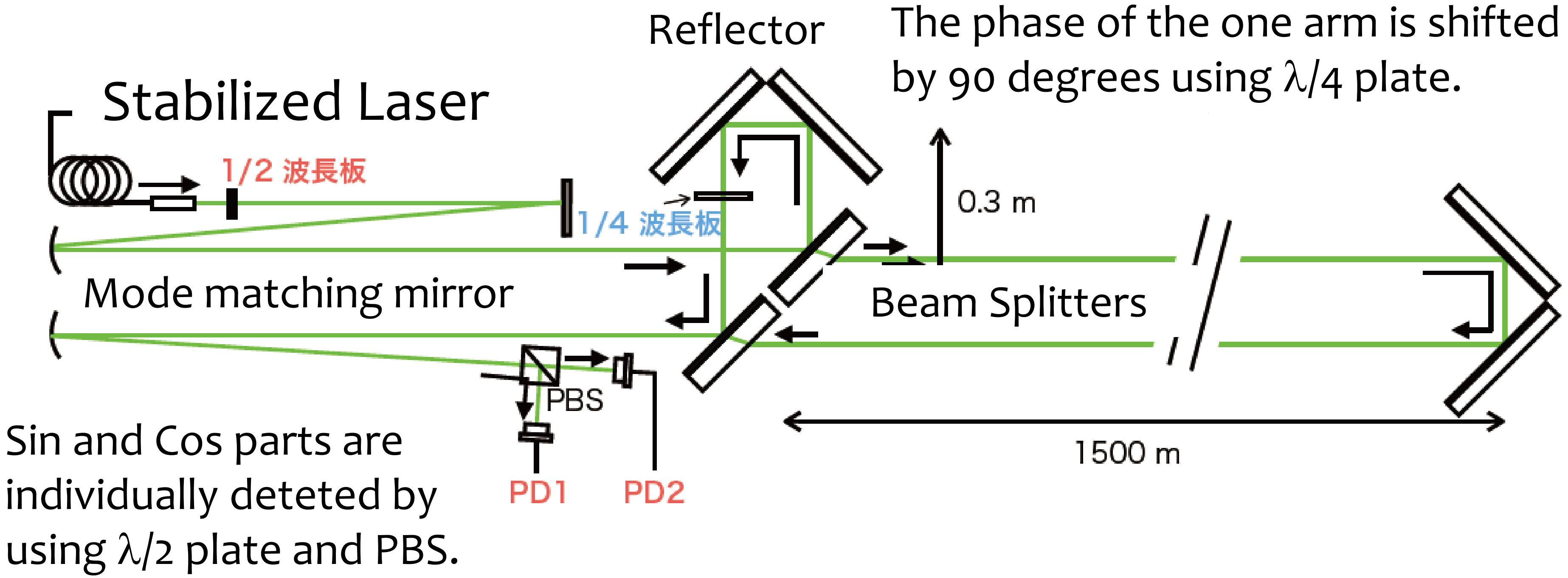
- Feedforward system introduction using a theoretical tidal motion model simulation.

- In KAGRA, two geophysical strain meters will be constructed to know the precise ground motion due to the tidal motion, air pressure, temperature, water pressure and so on.

Two STs in KAGRA tunnel

- Each ST in X and Y arm.
- 1500m laser ST is longest in the world

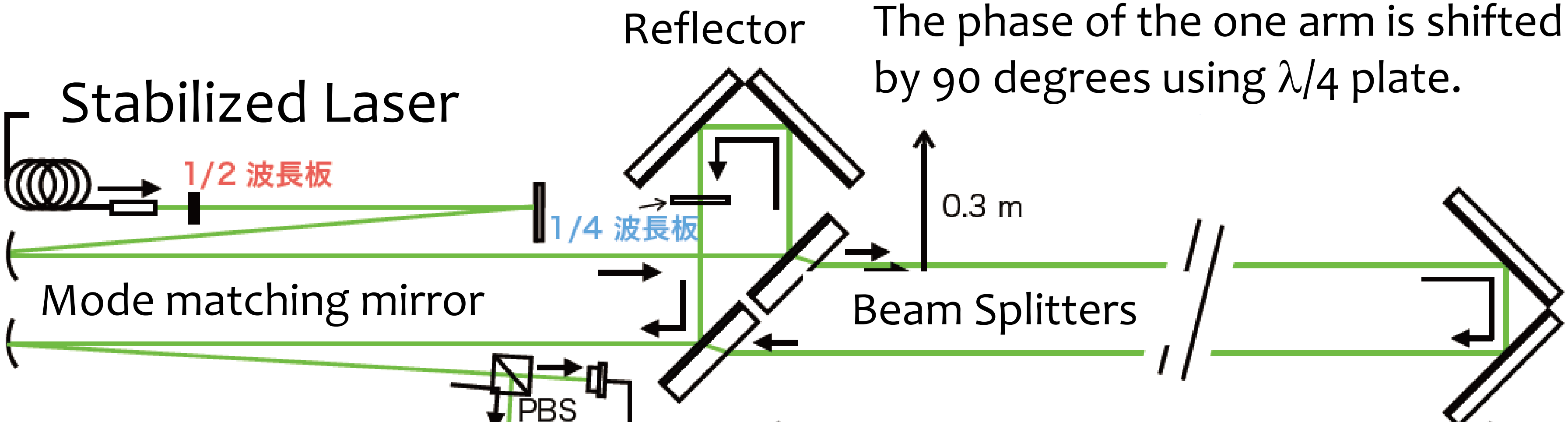
Principle of the ST (unbalanced MI)

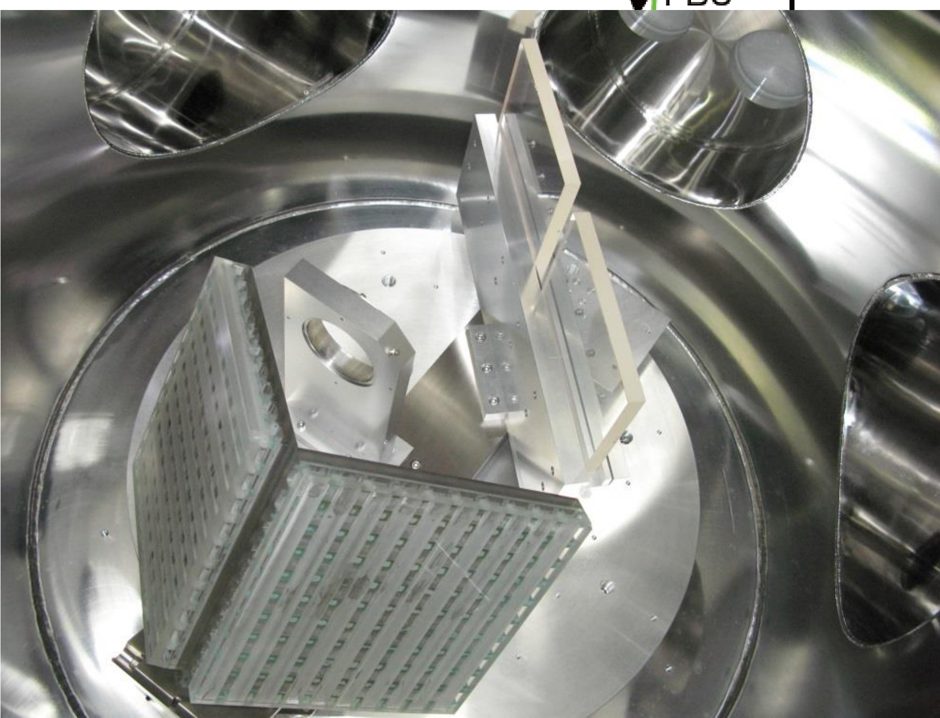


- Unbalanced-michelson interferometer is used.
- 532 nm wavelength is used with a frequency stabilization system using an absorption saturation technique in Iodine
- The SIN and COS part detection (quadrature detection) enables us a wide range length measurement.

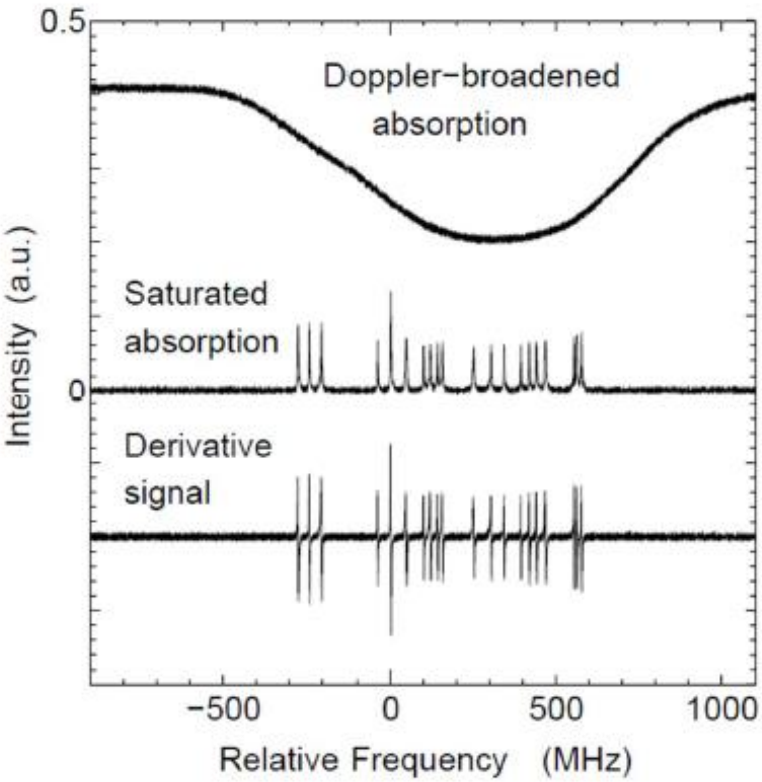
Optics of STM

The phase of the one arm is shifted by 90 degrees using $\lambda/4$ plate.

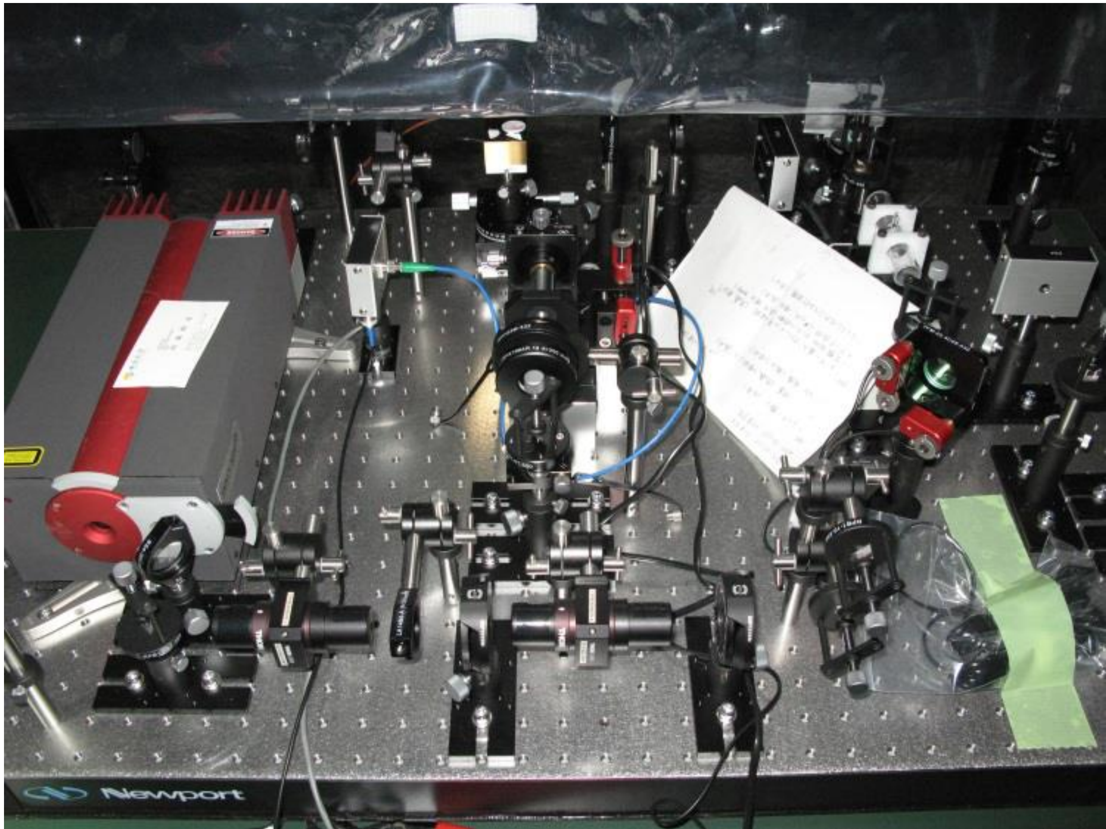




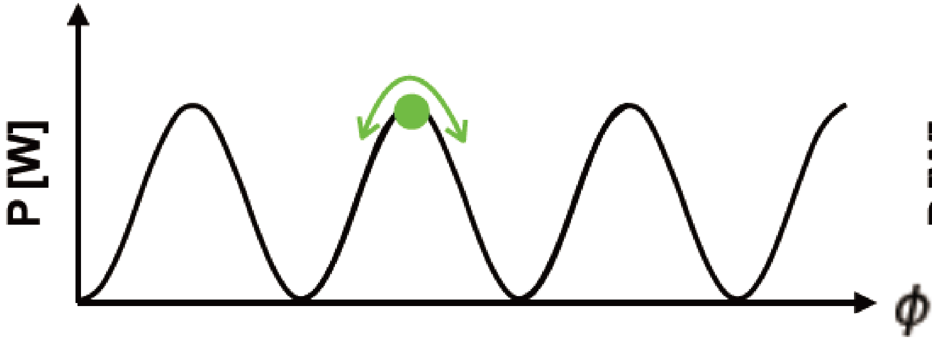
Frequency Stabilization using I2 Gas



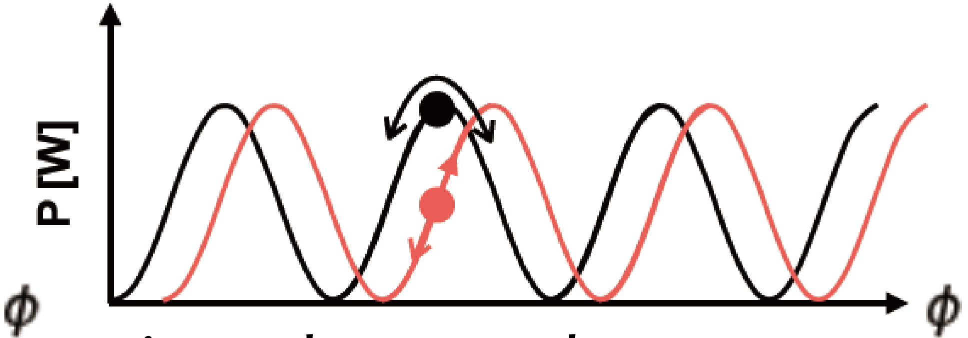
- 532nm laser's frequency is locked to an inter-orbit transition energy of Iodine gas.
- $d\nu/\nu=10^{-13}$ stability is expected.



ST signals



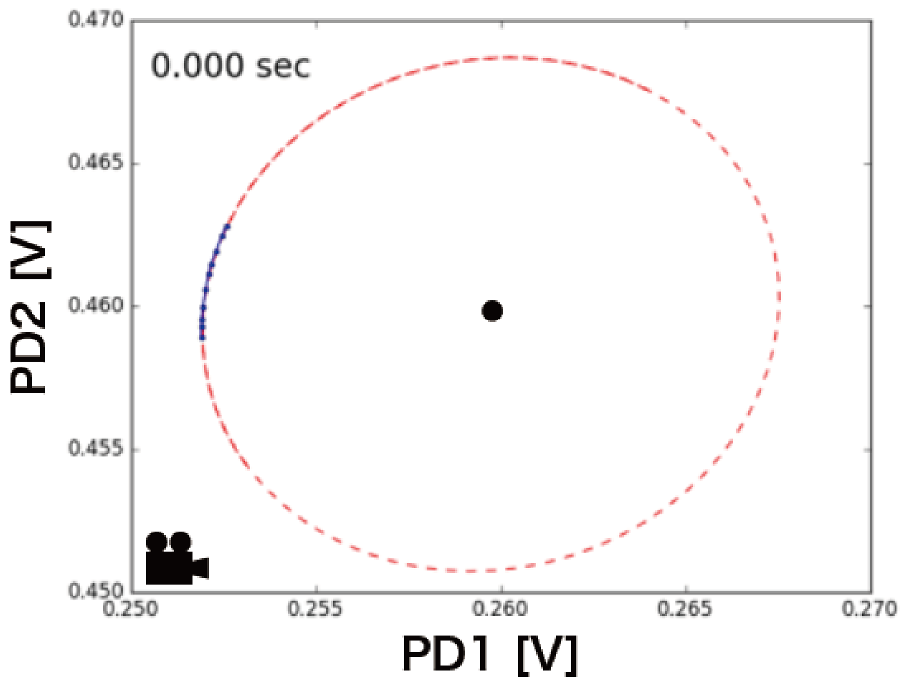
Only sin and cos mode



sin and cos mode

リサージュプロット

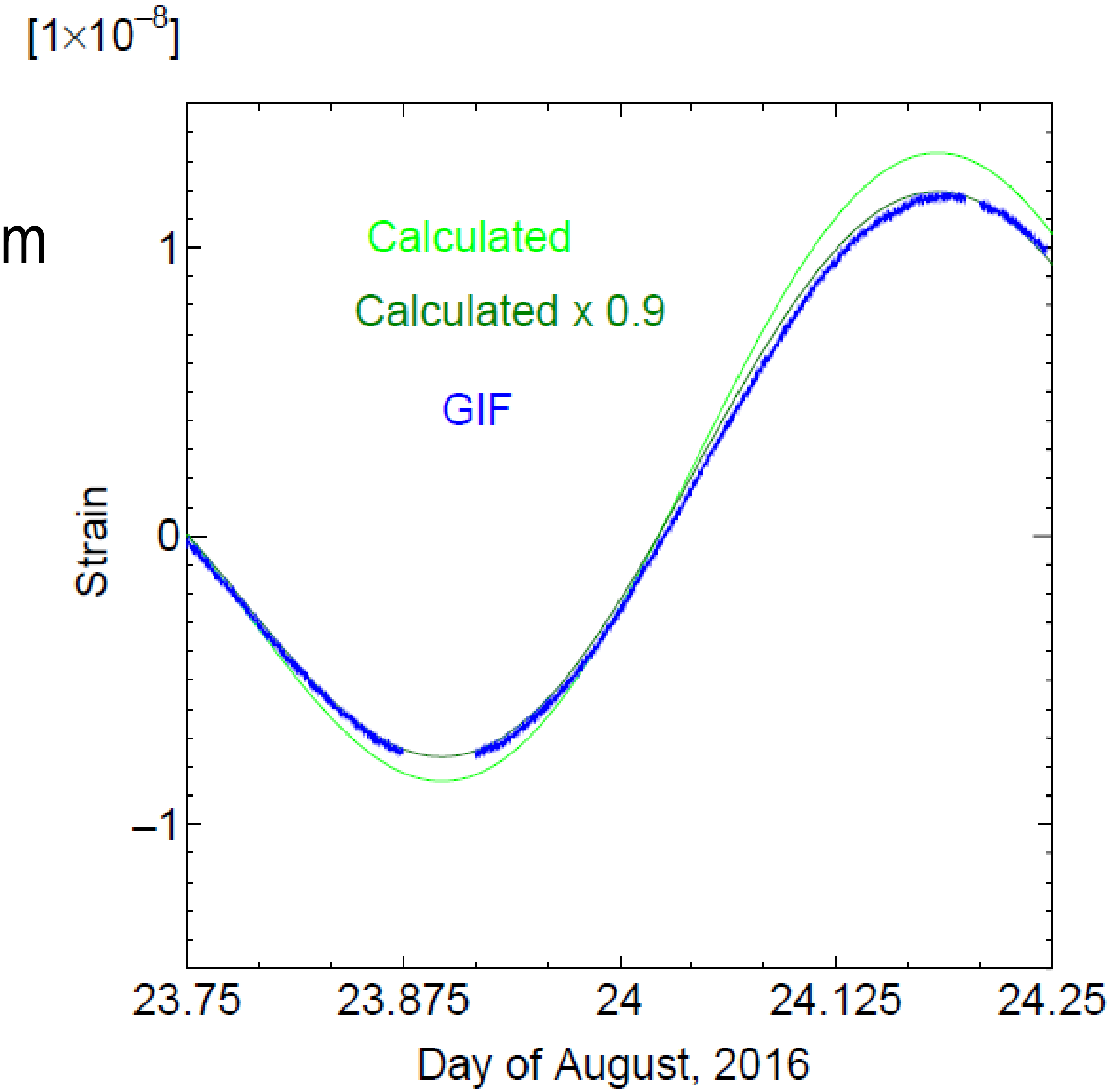
Lissajous Plot



STM interfered beam

One ST operation started in Oct 2016

～30μm



Summary

- ***Fundamental techniques for KAGRA have been prepared by TAMA and CLIO and KAGRA Collaborators.***
- ***KAGRA started in 2010.***
- ***The iKAGRA has finished in April 2016.***
- ***The bKAGRA has started after iKAGRA short engineering run.***
- ***Although there are many to do in the future tasks and problems in the finished tasks, we keep proceedings and improving them step by step.***