
# KAGRA status and Future(O5)

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**For NSF, The USA**

# History of IFO GW detector development in Japan

2023 (O4)

2020 (O3GK)

2015 LIGO GW Detection

2010 KAGRA Start

2002

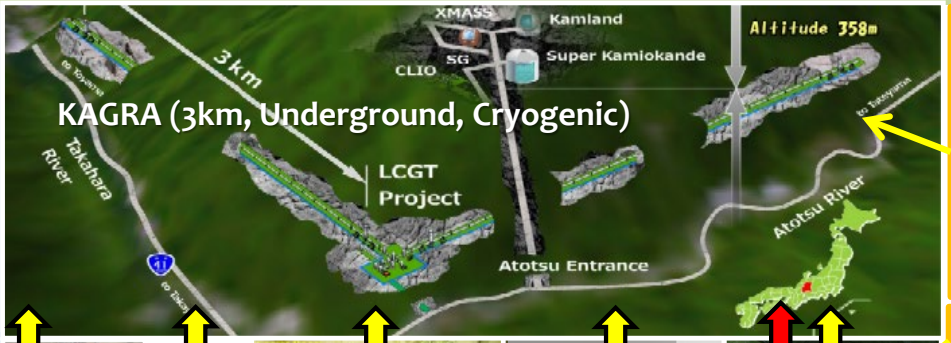
1996

1993 Virgo Start

1990 LIGO Start

1991

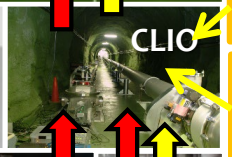
1980's





RSE


High Power Laser

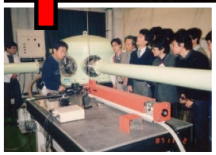












10m Delay-Line in ISAS supported by MPQ, Germany

**From O3 to O4 to O5**

2010: KAGRA approval
2014 ~ 2016 March: iKAGRA
2016 April ~ 2019 April: bKAGRA
2019 May ~ 2020 April: Prep. O3
2020 April: O3GK with GEO600
2020 May ~ 2023 May: Prep. for O4
2023 May: O4 started with LH

Thermal noise reduction in CLIO

100-m Cryogenic Laser Interferometer (CLIO) development for the km scale GW detector

TAMA-LISM GW Observation

Cryogenic FP Development (CLIK)

TAMA 300 Construction

LISM @ Kamioka

FP type Or DL type?

Development of the ultra low-loss mirrors in Japan

# KAGRA Collaboration

Collaborators (~450)

Author List Members (~ 170)

Universities, Institutes (~100)

# 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.

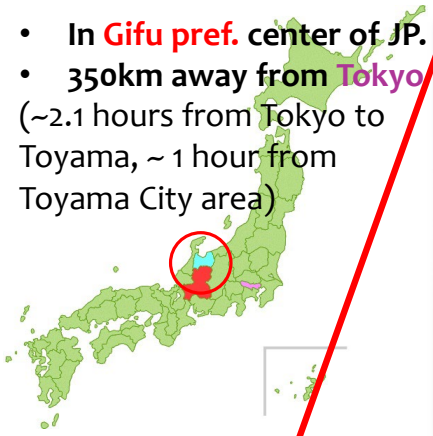
(2) **Usage of Cryogenic Mirrors and suspensions**
→ Reduce Thermal Noises

(3) **Collaboration with Geophysical Laser Strain-meter**

# KAGRA Site

- **In Gifu pref. center of JP.**
- **350km away from Tokyo**

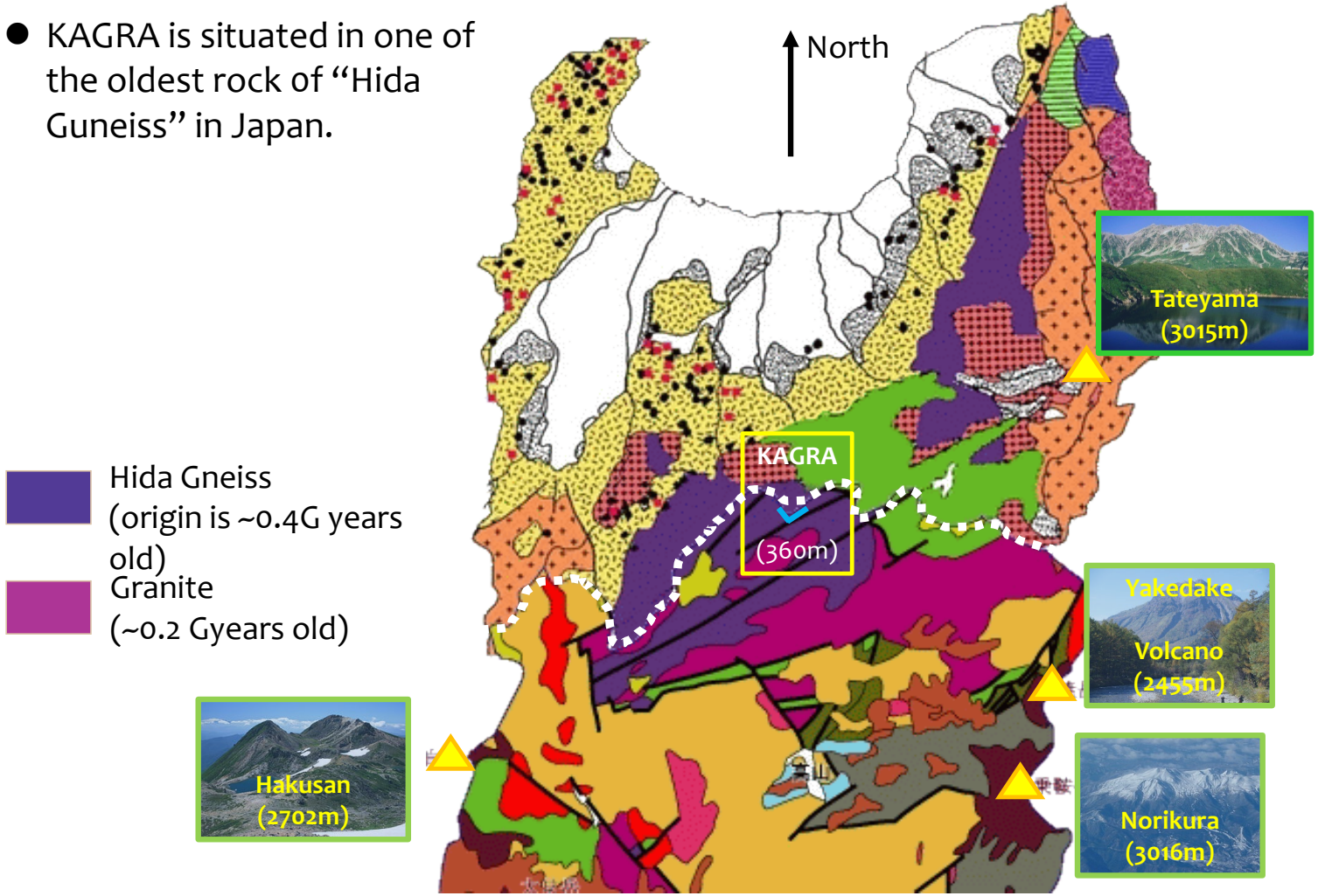
(~2.1 hours from Tokyo to Toyama, ~ 1 hour from Toyama City area)



The border area between Gifu and Toyama


# KAGRA in “Hida” Gneiss

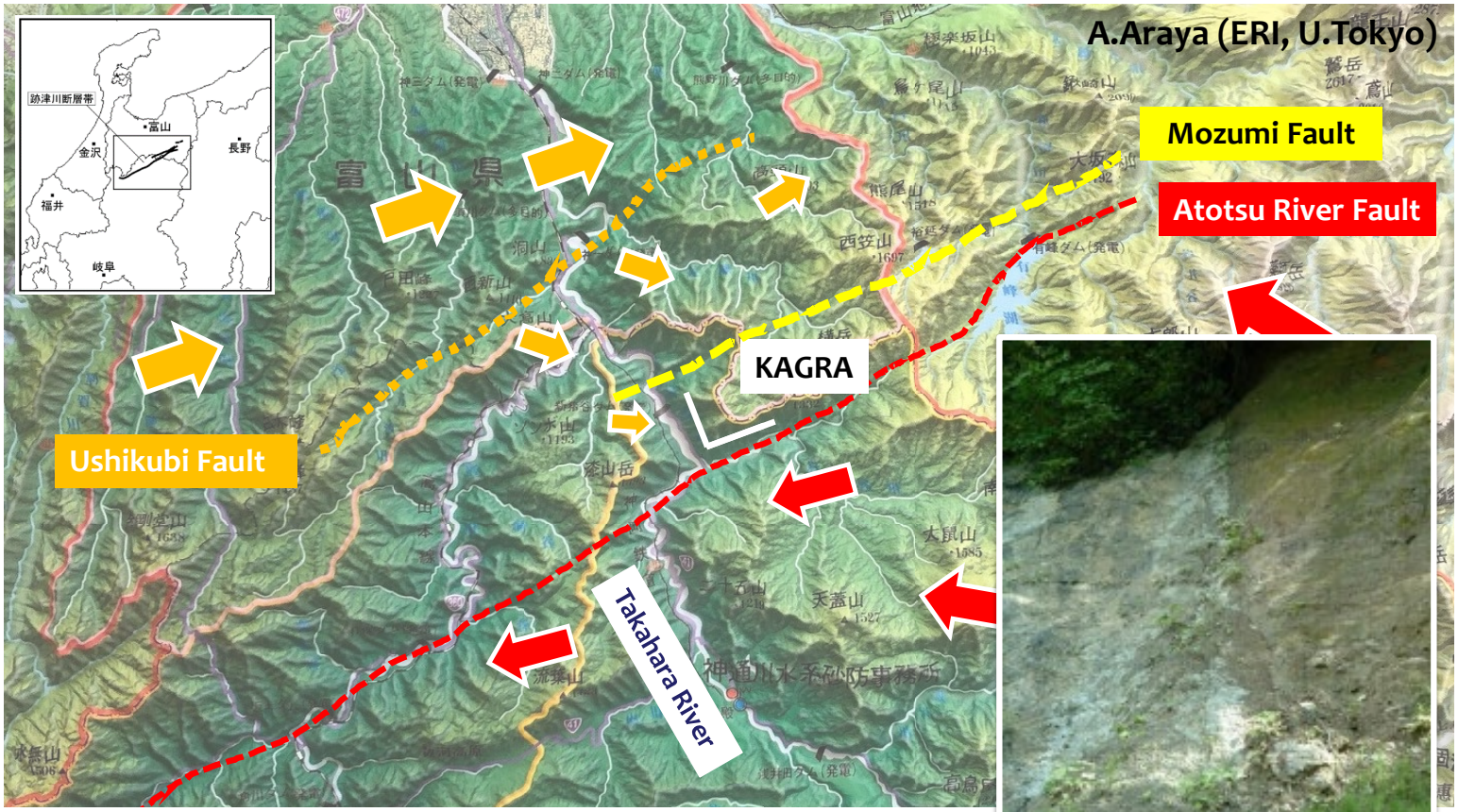
- KAGRA is situated in one of the oldest rock of “Hida Guneiss” in Japan.




Hida Gneiss
(origin is ~0.4G years old)

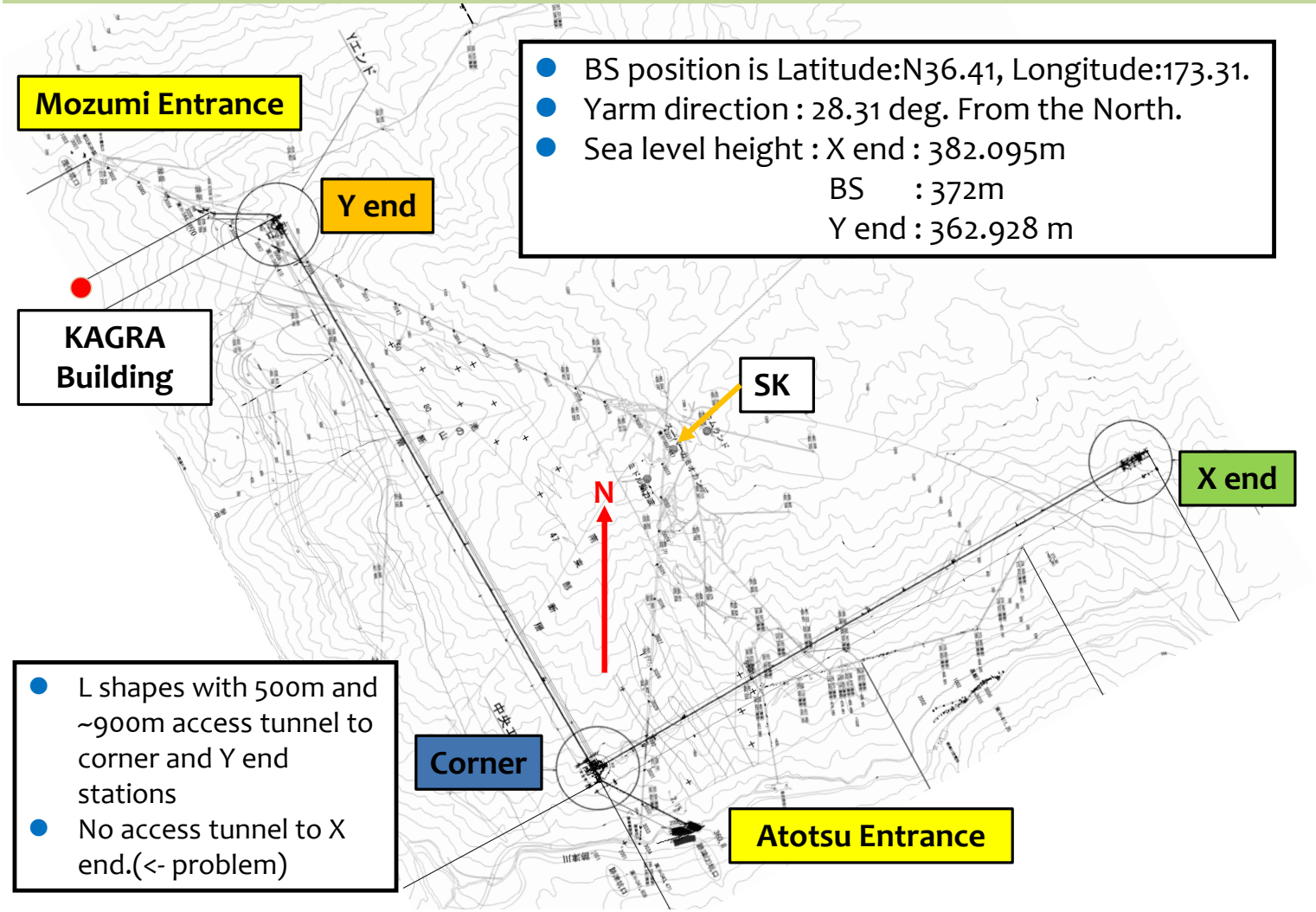
Granite
(~0.2 Gyears old)

# KAGRA between Two Faults




- 1 mm /year slip or creep for 3 million years.
- It made crank shape of “Takahara” river near KAGRA.

# Tunnel Position and Alignment

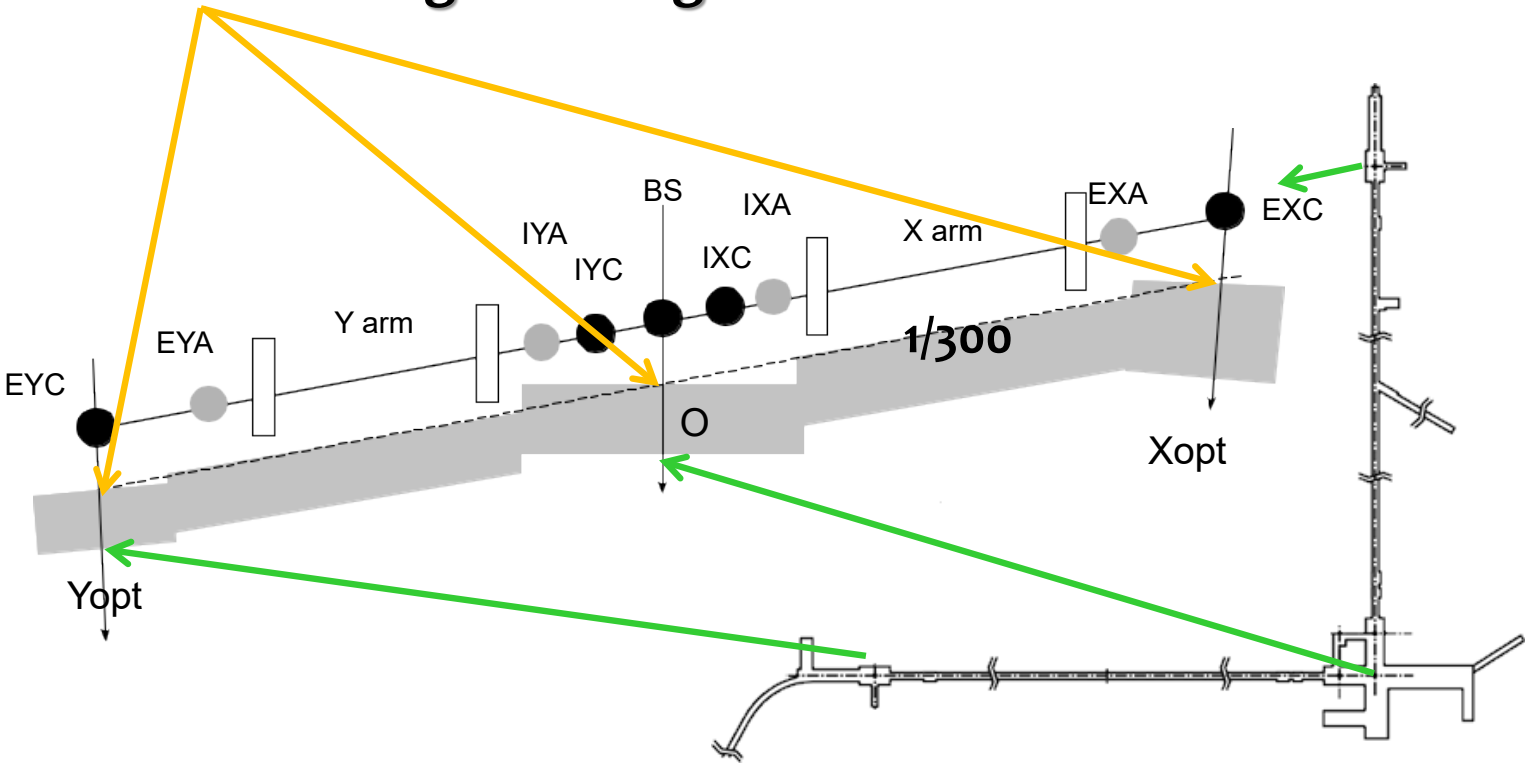



- BS position is Latitude:N36.41, Longitude:173.31.
- Yarm direction : 28.31 deg. From the North.
- Sea level height : X end : 382.095m
  BS : 372m
  Y end : 362.928 m

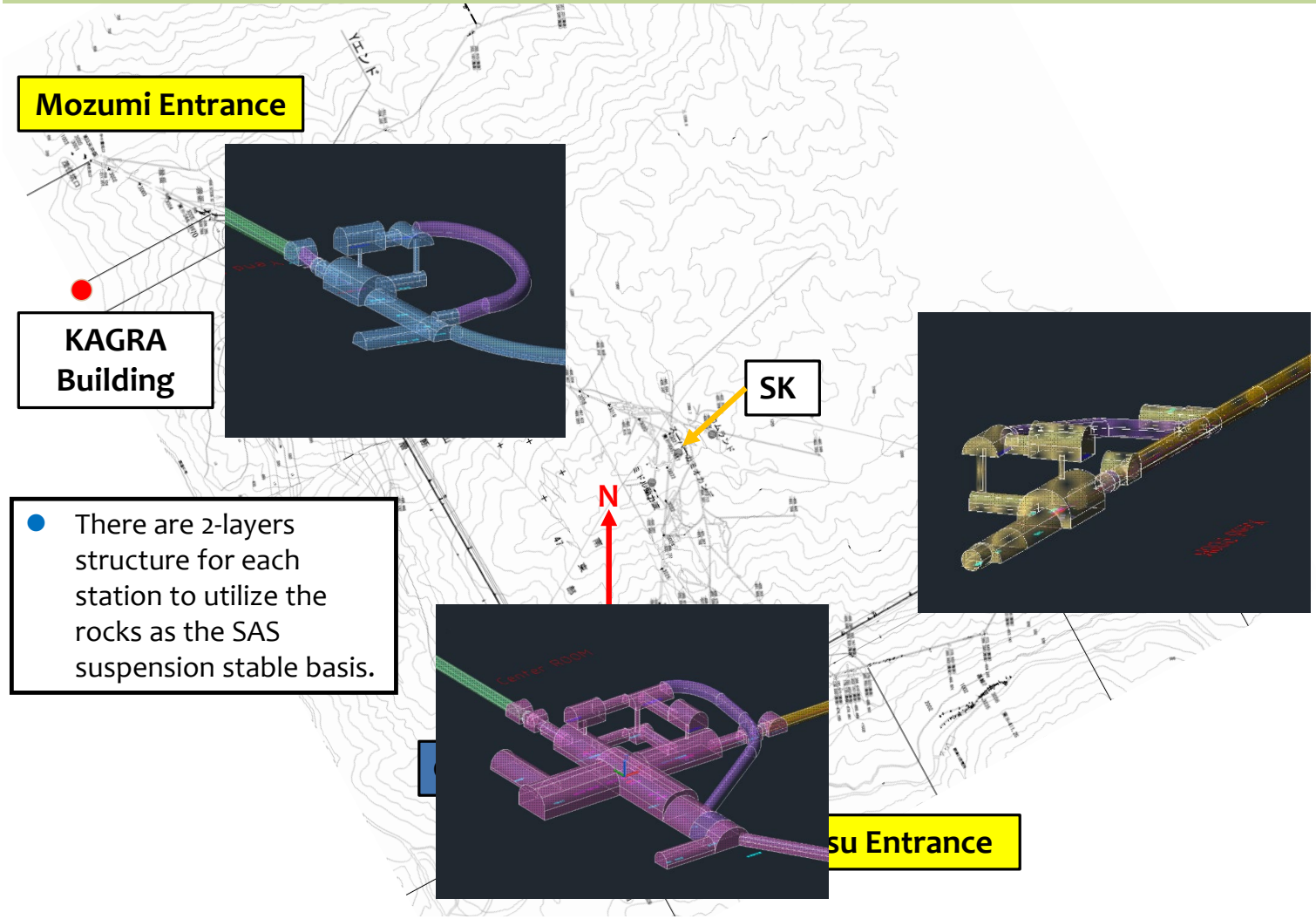
- L shapes with 500m and ~900m access tunnel to corner and Y end stations
- No access tunnel to X end.(<- problem)

# 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

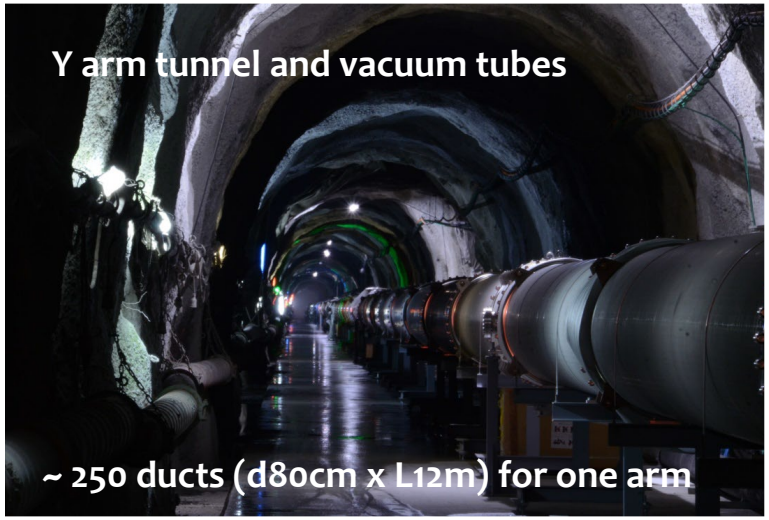


# Tunnel Position and Alignment

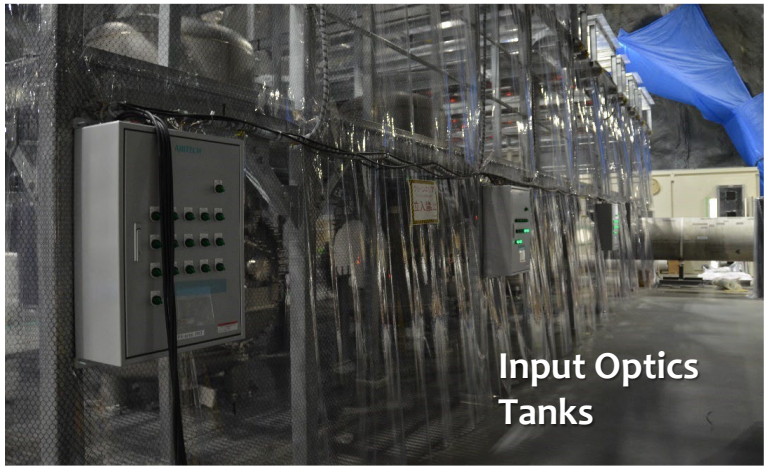



- There are 2-layers structure for each station to utilize the rocks as the SAS suspension stable basis.

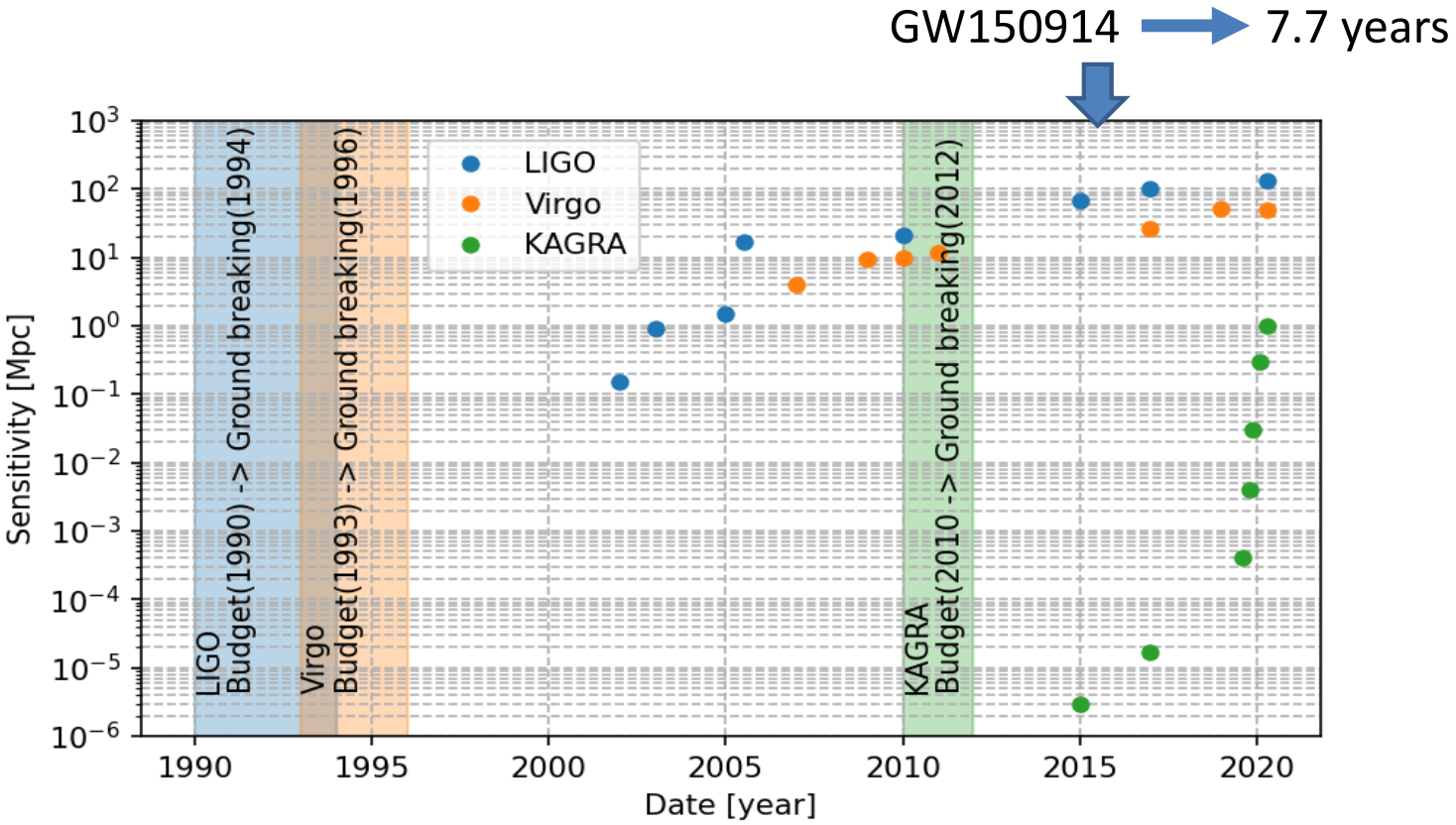
# Vacuum Ducts in arms and Chambers Set in FY2014



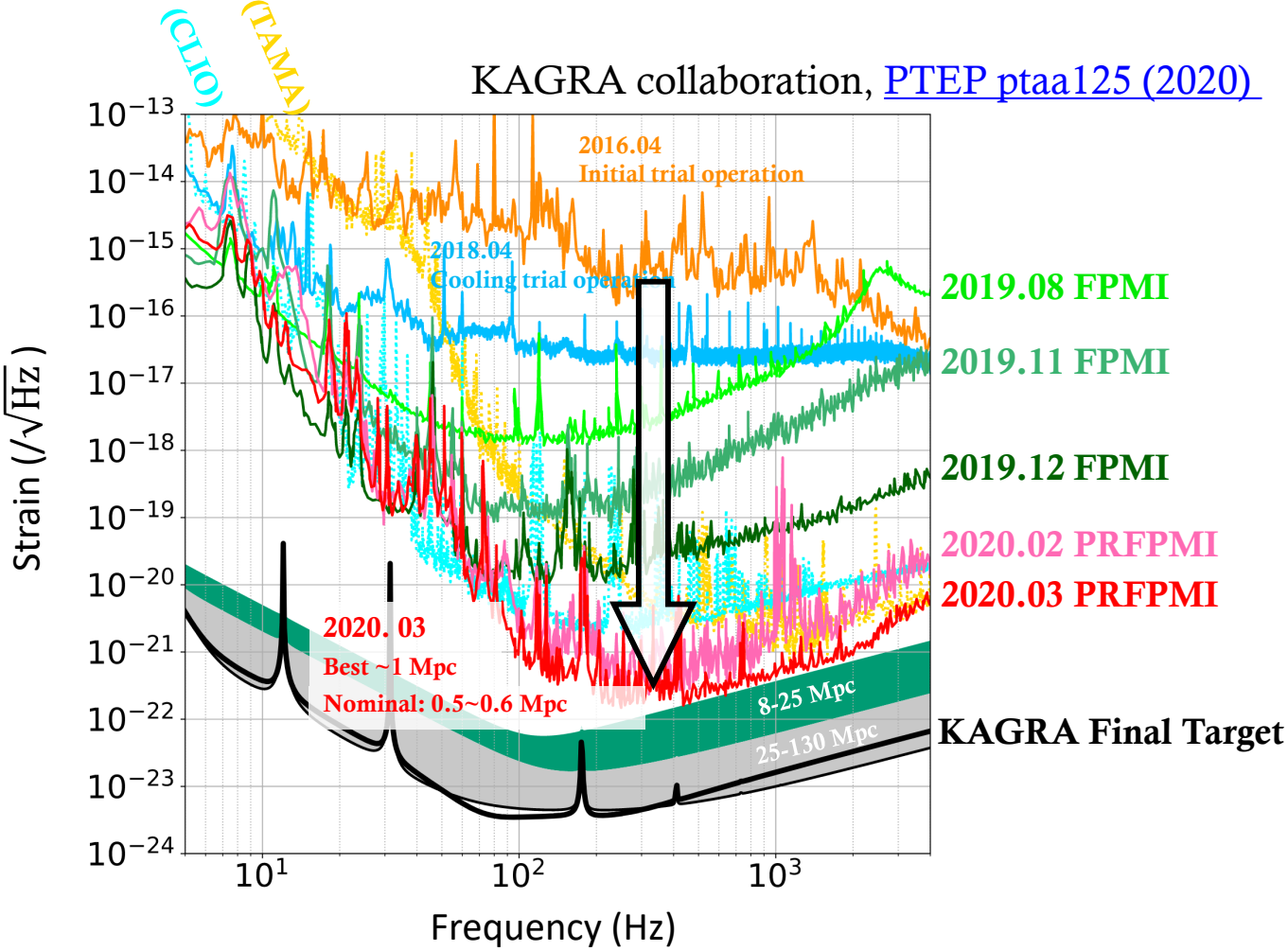




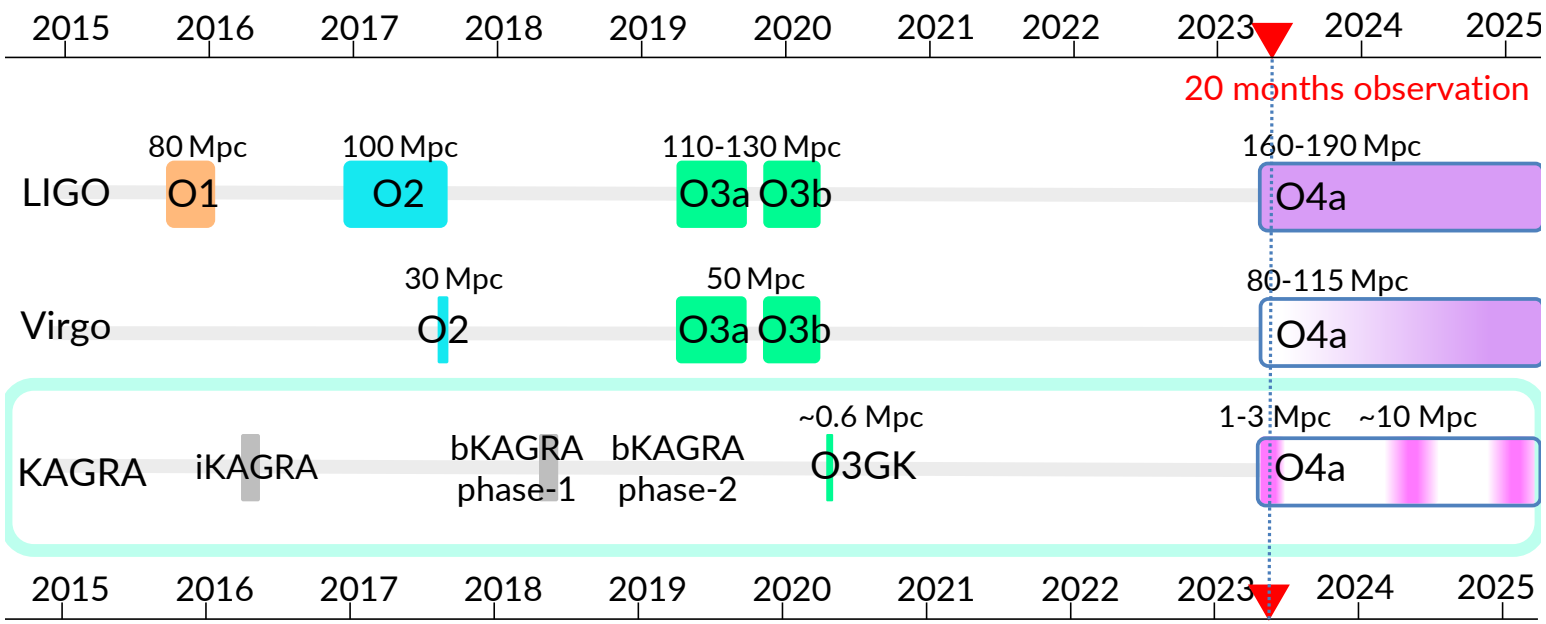

# Evolution of KAGRA BNS range until O3GK



# Evolution of KAGRA sensitivity to O3GK (2019-20)



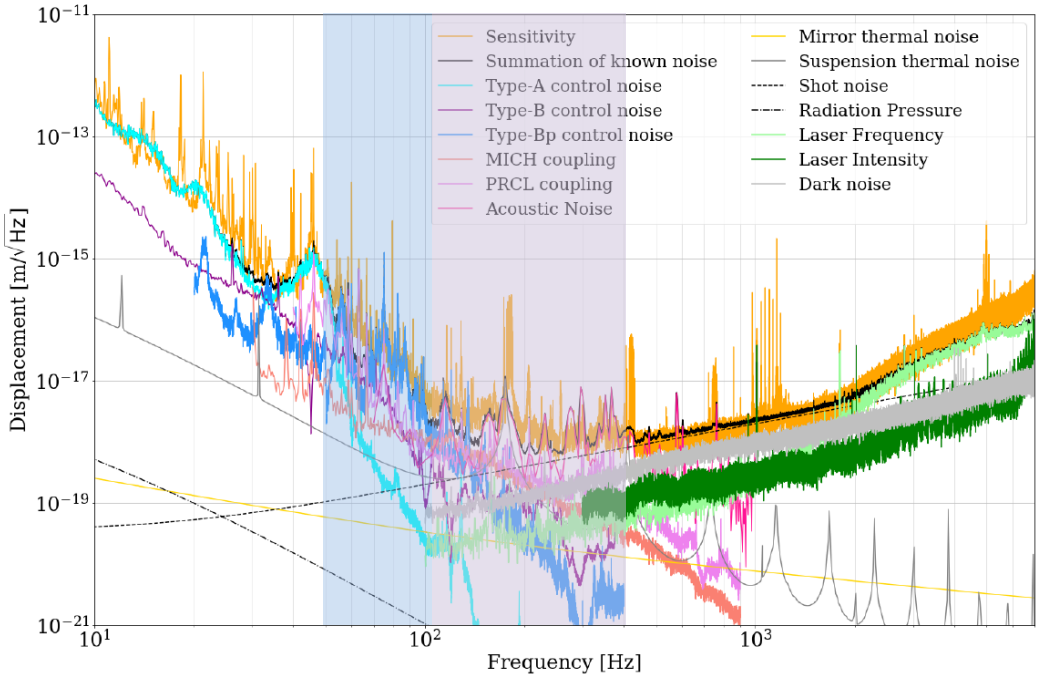
# LVK GW Observation Status




- iKAGRA - Michelson interferometer at room temperature.
- bKAGRA phase-1 - Michelson interferometer with cryogenic operation.
- bKAGRA phase-2 - All elements have been installed.
- O3GK - Power-Recycling Fabry-Perot Michelson interferometer (no cryogenic).
- O4 start delays to January, July, December 2022, March 2023, and 24th May 2023.
- O4 by LH will be done for 20 months including two months breaks.
- O4 by Virgo will join from summer/autumn? 2023.
- O4 by KAGRA is separated: from May 24th to June 21st, and 3 months from March/April 2024.
  - 87K at ETMX mirror, ~250K at ITMX, ITMY and ETMY -> at least ~ 100K for all mirrors

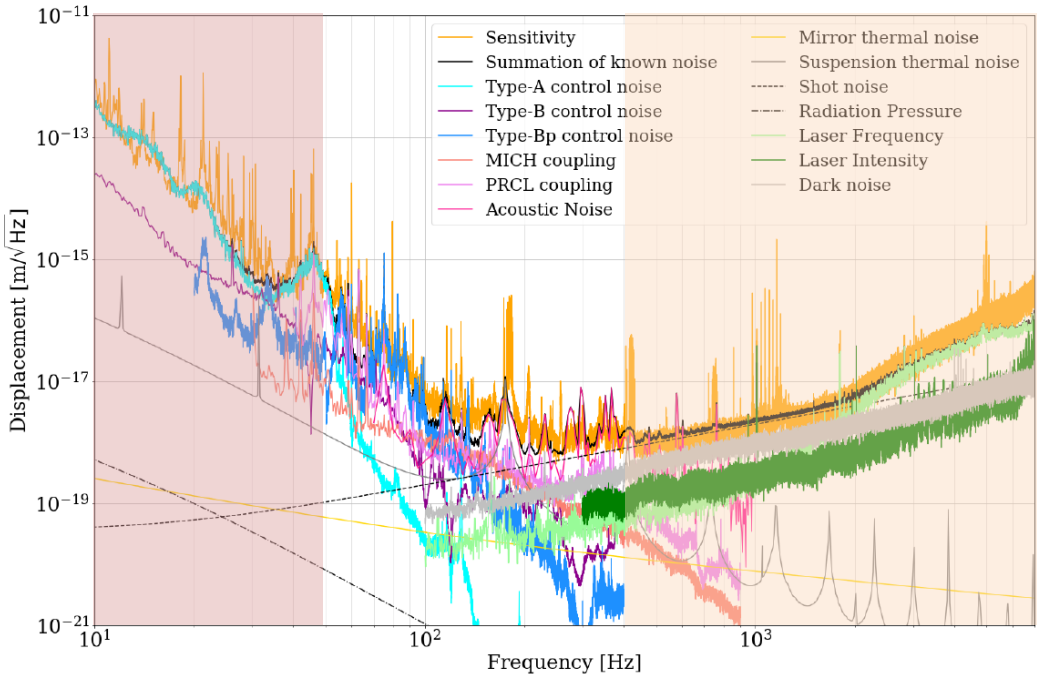
# Expected stories to enhance the Sensitivity from O3GK to O4a

- **Expected improvement in sensitivities by upgrades**
  - 100Hz ~ 400 Hz : Acoustic Noise reduction by baffles in MICH area
    MICH/PARCL noise by control scheme ?? or PY2L coupling ??
  - 50Hz ~ 100Hz : Control noise reduction of Type-B/Bp
    Suspension thermal noise by cooling after reduction of misc noises.



# Expected stories to enhance the Sensitivity from O3GK to O4a

- **Expected improvement in sensitivities by upgrades**
  - **< ~ 50Hz : Control noise reduction of Type-A**
  - **> ~ 400Hz : More laser power by O%SRM and high-power laser if possible**
    **Less optical power loss in OMC and repaired PD**
    **Less frequency noise and Less intensity noise**



# Expected Sensitivity Enhancement Story

- **Expected BNS range sensitivity**

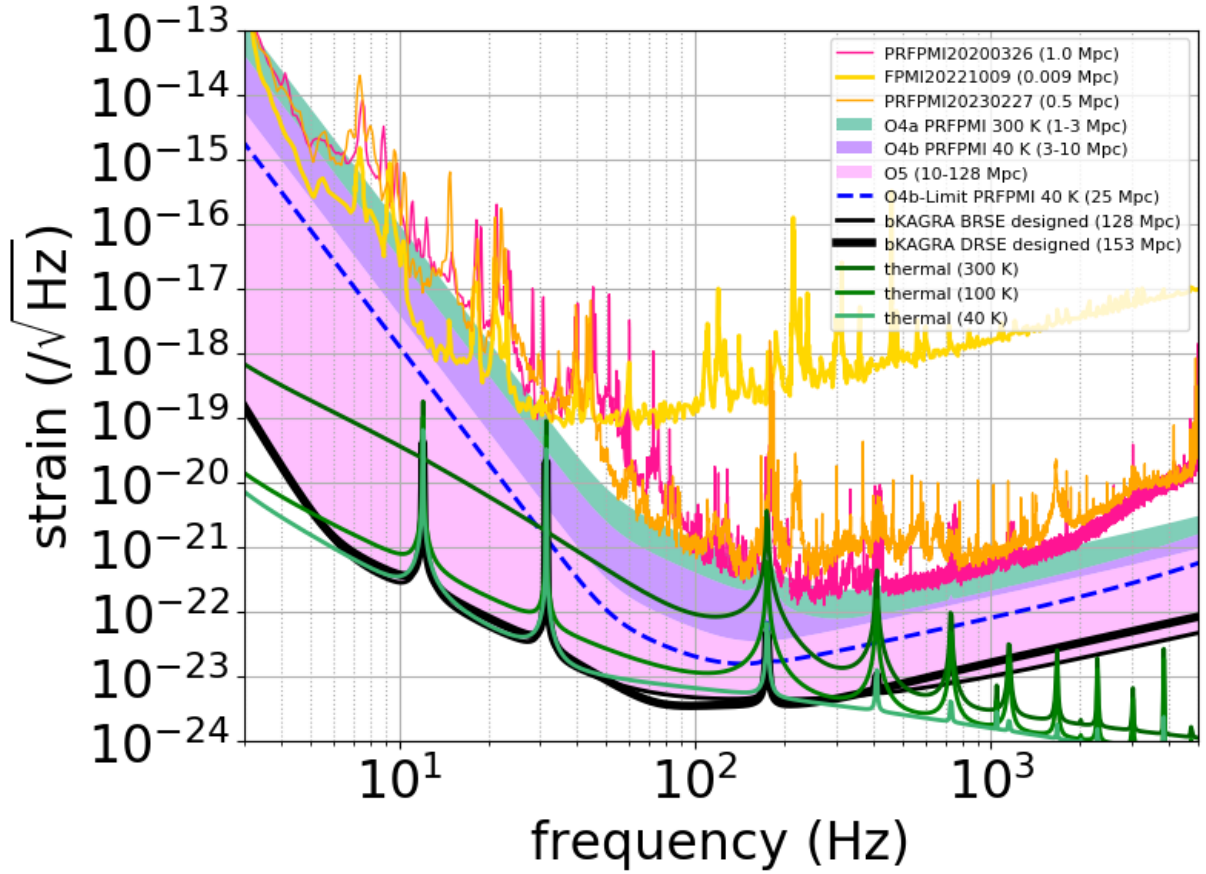
| | Mirror temp. | Power at BS | SRM reflectivity | BNS Range | Excess noises & assumed reduction factors |
|---|---|---|---|---|---|
| **O3GK best** | ~250 K | 30-50 W | 70 % tilted | ~ 1Mpc | Low Freq. noise<br>Pessimistic laser noise |
| **O4a low** | 300 K | 50 W | 70 % tilted → 0% | > 1 Mpc | Low Freq. noise<br>Pessimistic laser noise |
| **O4a high / O4b low** | 300 K | 50 W | 0 % | 3Mpc | **0.3***Low Freq. noise<br>Feasible laser noise |
| **O4b high** / O5 low | 40 K | 30 W | 0 % | 10Mpc | **0.04***Low Freq. noise<br>Feasible laser noise |
| O4b high / O5 low | 40 K | 300 W (High Power LAS) | 0 % | 25Mpc | **0.013***Low Freq. noise<br>Feasible laser noise |
| O5 limited | ~33 K | ~150 W (High Power LAS) | 85 % | ~85 Mpc (JGW-T2011662-v13) | no excess<br>Thermal resistance at suspensions |
| O5 high | 22 K | 673 W (High Power LAS) | 85 % | 128Mpc | no excess |

- **PRFPMI style will be taken during O4 using an AR-coated (~0% Ref) SRM**

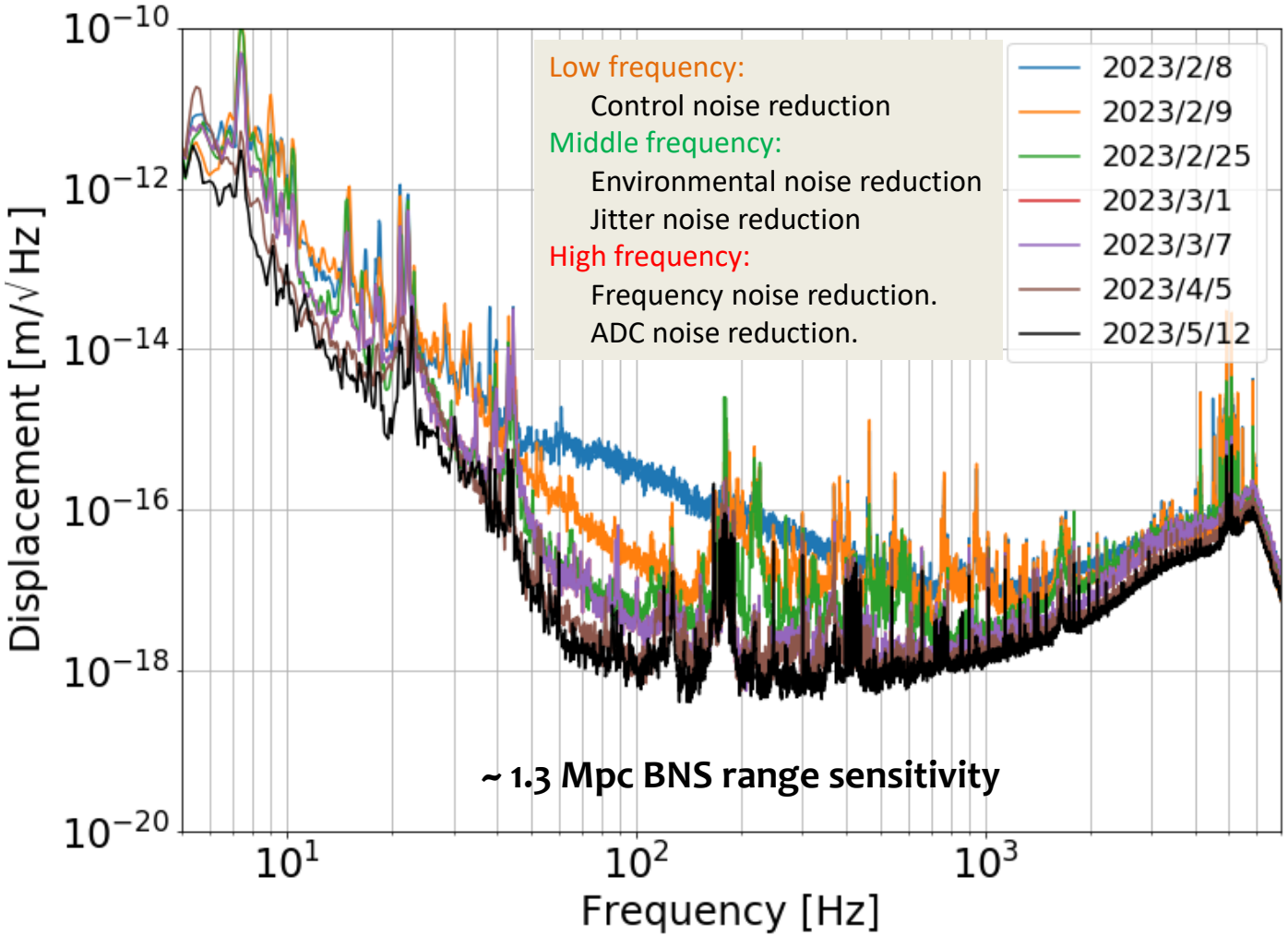
# O4a/b Targets

O3GK best sensitivity

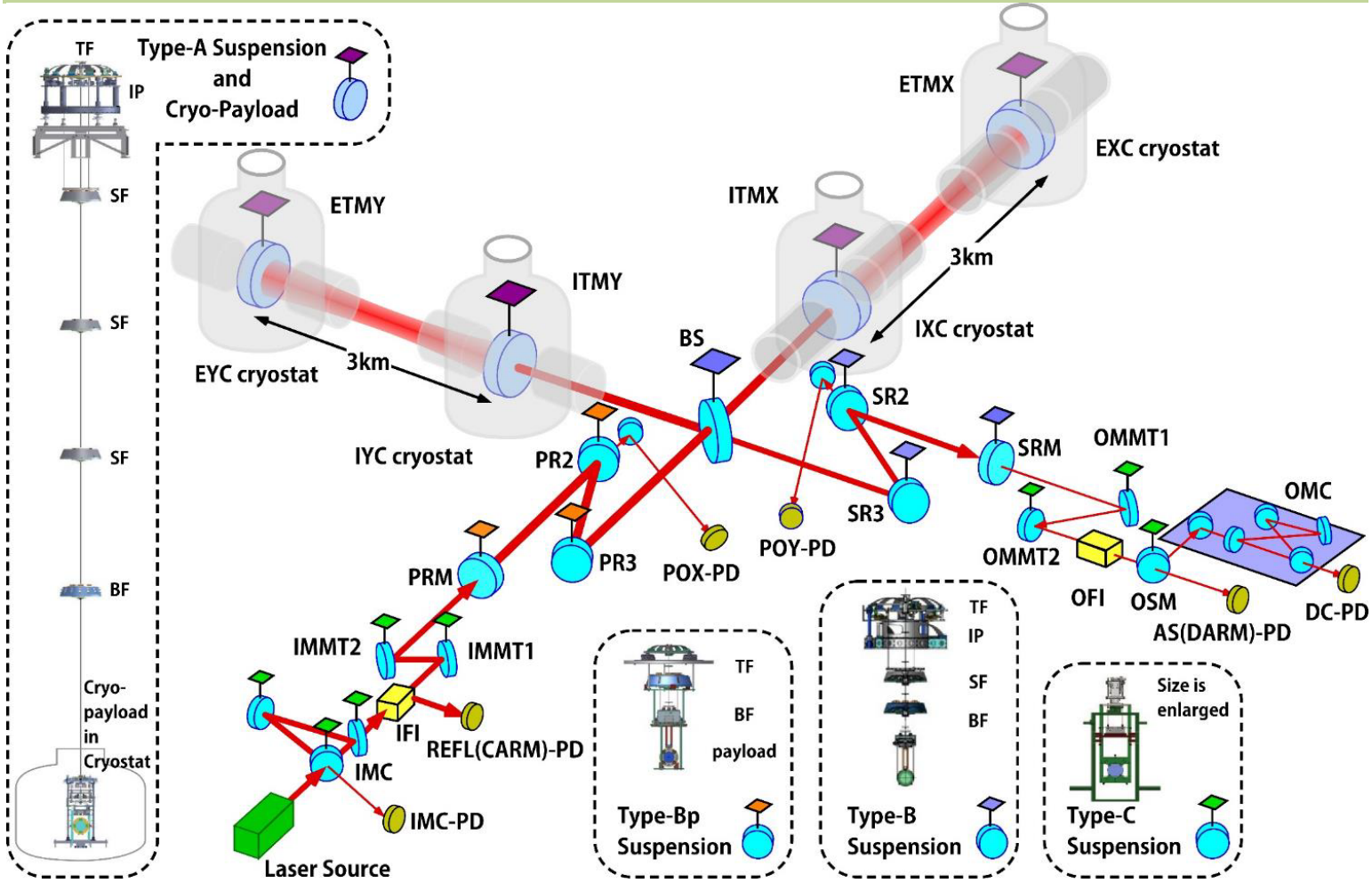
FPMI PRFPMI



# KAGRA sensitivity at the start of O4a (2020~23)



# KAGRA Optical Configuration (PRFPMI for O4)



# What were Done until FY2022

- **Type-A suspension finalization. ->** All health checks were completed. We finally verified that no unwanted contacts inside suspensions and disorders, except for one GAS filter.
  - We found some faults in all suspensions after O3GK, and their repair took huge amount of time (~ 2 years).
- **Temperature control system operation for stabilize GASs in suspensions were verified.**

- **Type-A/B/Bp control noise reduction** -> Succeed to reduce at very lower level except for ETMX in Type-A. We also did for some of Type-B/Bps.

- **Mid-size baffle installation in MICH area and optical dumpers installation in IFI/IMMT/OMC/OMMT tanks for the scattered/stray light mitigation** -> Installation itself was completed. The efficiency should be checked in the sensitivity.

- **Cryostat and Sapphire mirrors cooling -> Smooth operation**, except for one cryocooler restarting. The continuous operation time is over one year at EXC. The only ETMX was cooled around 80K, others are at 250K by just radiation cooling.

- **Mirror height monitoring system** -> was newly made.

# What were Done until FY2022

- **Vacuum closing in the MICH area. Vacuum system modification around SRM and PRM (installing GVs to segment the MICH area). Ion pump operation for all vacuum system** -> 10^-10 [Pa m^3 sec] level leak was realized, although two serious leaks at the hermetic pins at BS and EY. In addition, these additional GVs actually saved the time for the repair in the IFI and OMC vacuum tank.

- **OMC was repaired ->** The lower loss was realized. Some scattering light might be necessary to be improved.

- **Laser Intensity Stabilization System improvements** -> RIN ~ 10^-8 was realized. We need more stability.

- **High power laser preparation ->** HPL can be operated with IMC.

- **Optical simulation of the interferometer including Sapphire birefringence ->** FPMI case could be simulate.

- **CAL system improvements** -> Reliability was recovered for YPcal.

# What were Done until FY2022

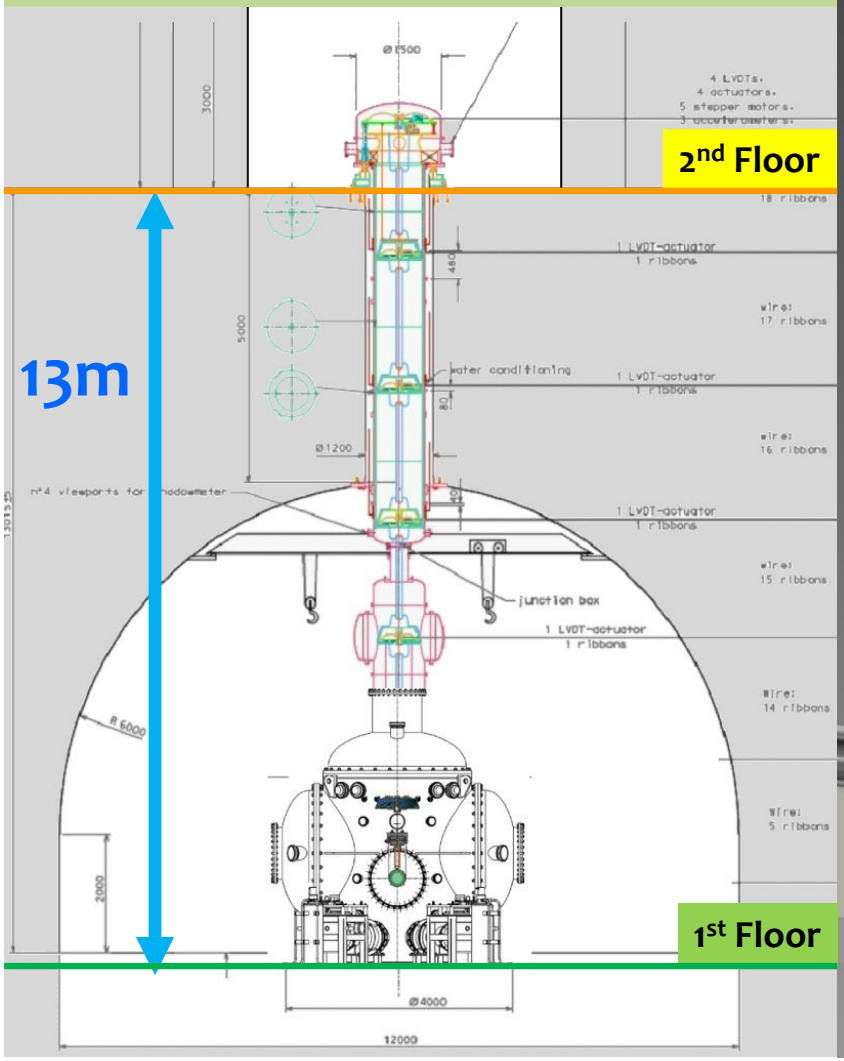
- **PEM instruments such as a Water flow meter around EY area for monitoring the water flow effect on the sensitivity and an Infrasound monitor system for checking the effect of sound on sensitivity**

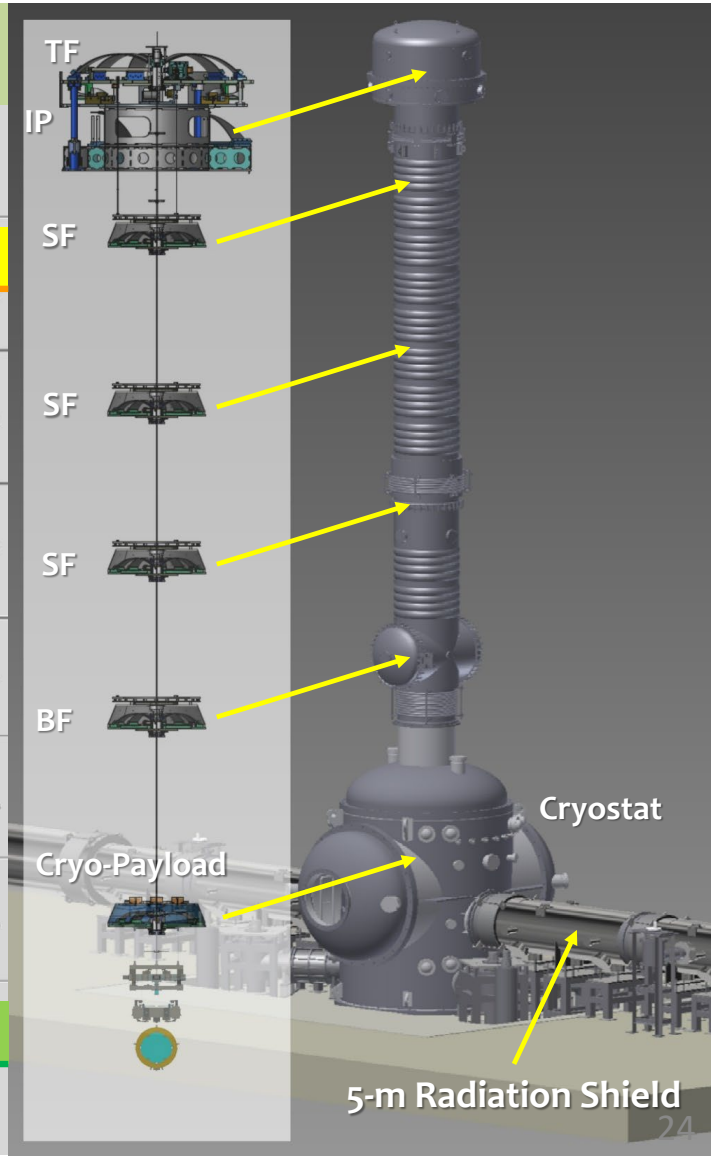
- **DGS / AEL upgrade works mainly for O5 are ongoing.**

- **Interlock system construction has finally start for more reliable system monitoring.**

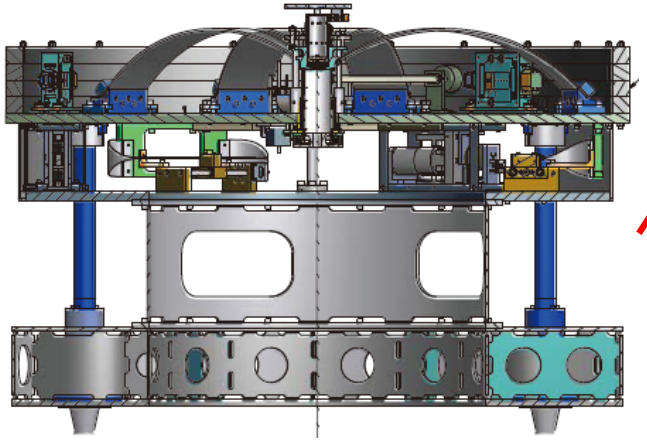
- **FPMI / PRFPMI Length and Alignment controls -> The length control of PRFPMI was realized. MICH/PRCL feedforward was also improved. ASC except for PR3 was implemented.**

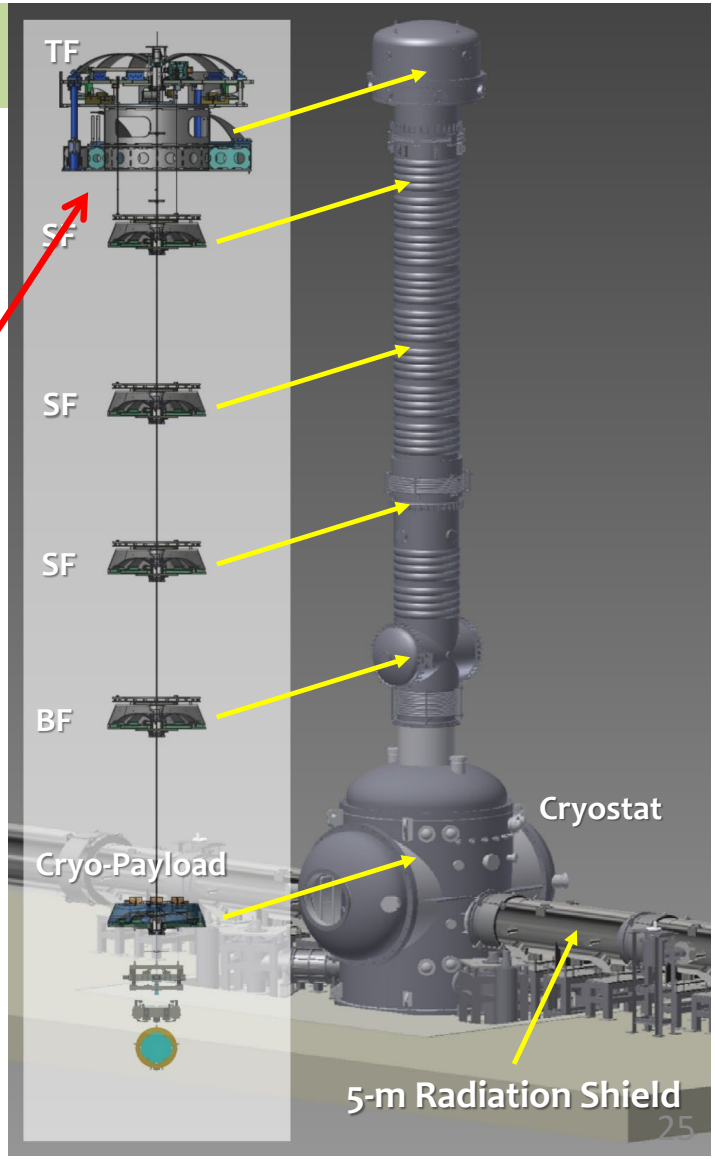
# Type-A Seismic Noise Isolator



# Top Filter (IP/Fzero) In Type-A





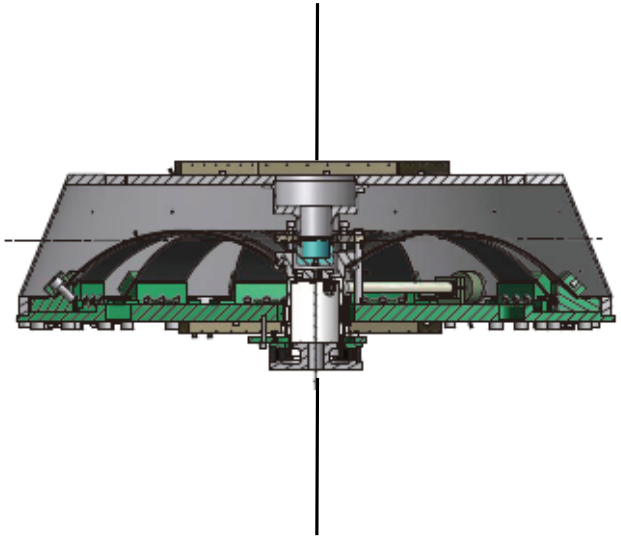

## Horizontal Isolation

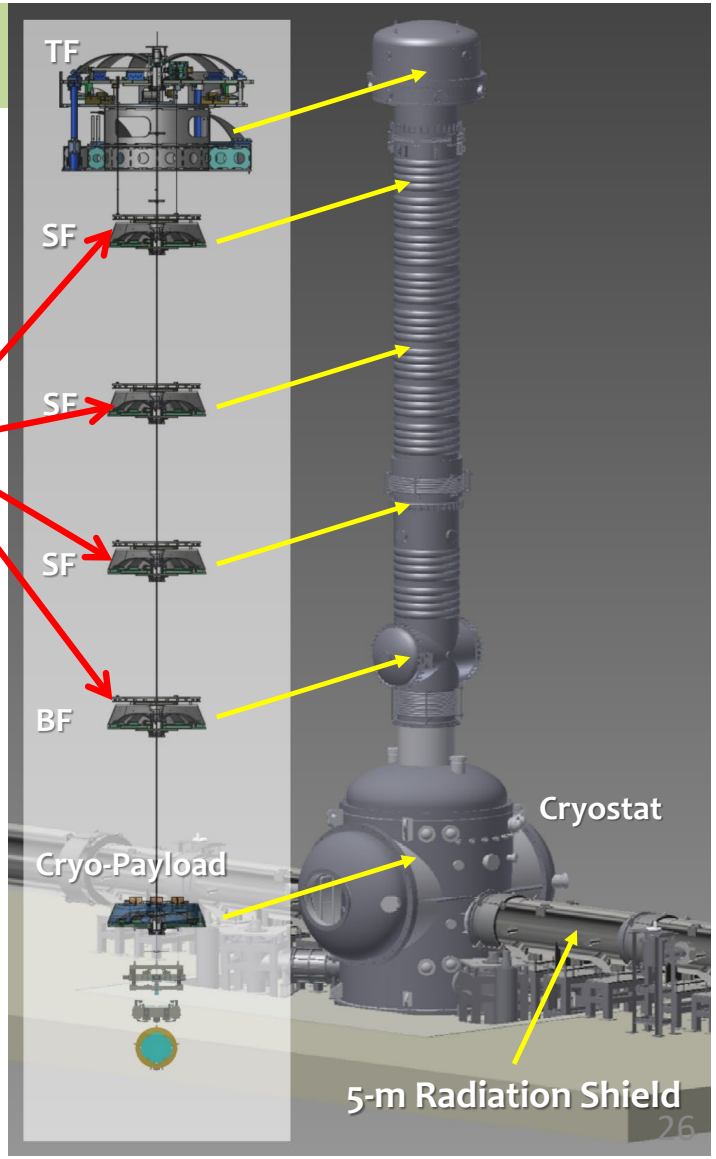
**Inverted Pendulum : freso < ~ 0.03 Hz**

## Vertical Isolation

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

# GAS Filters (SF/BF) In Type-A





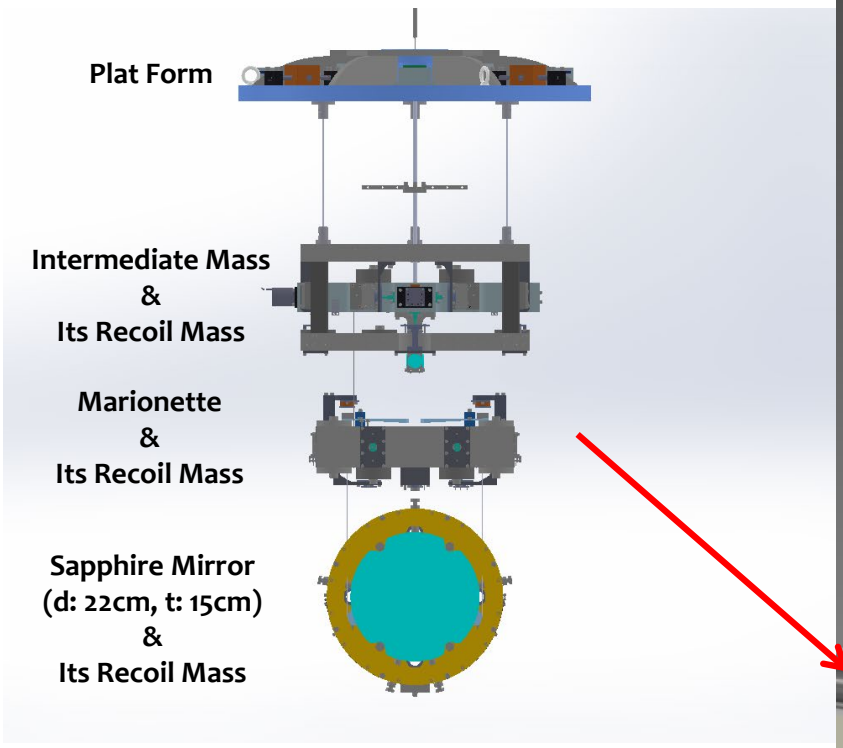

## Horizontal Isolation

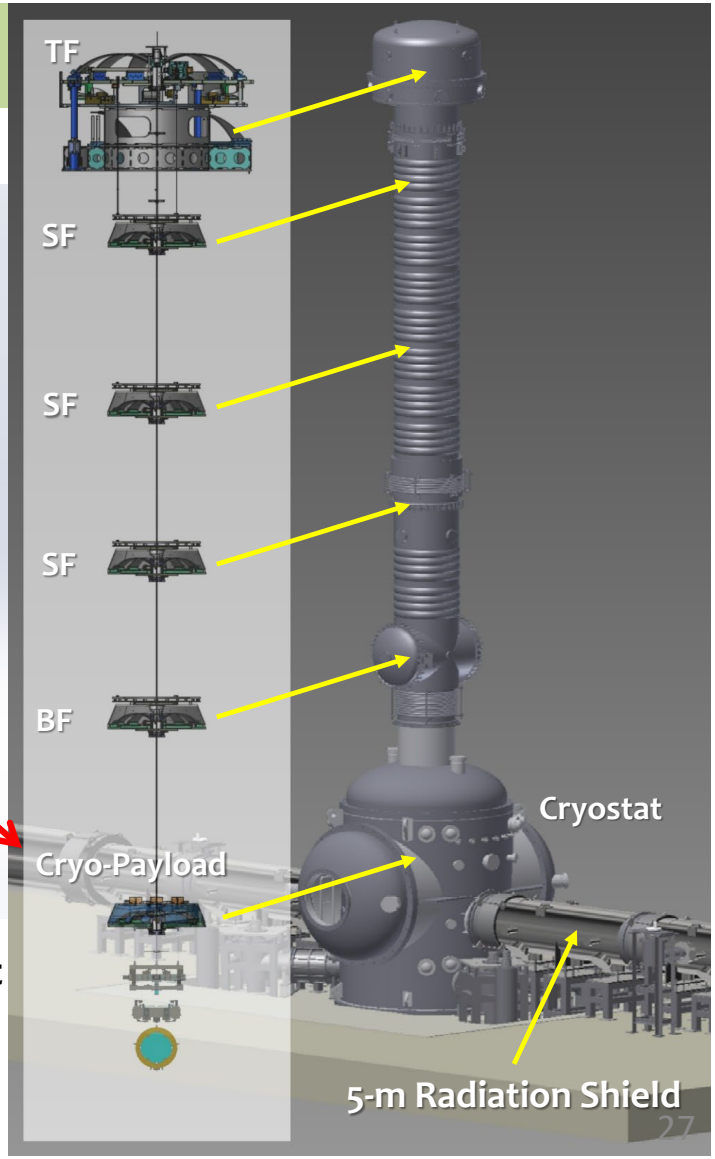
**Single Wire Suspension : freso < ~ 0.5 Hz**

## Vertical Isolation

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

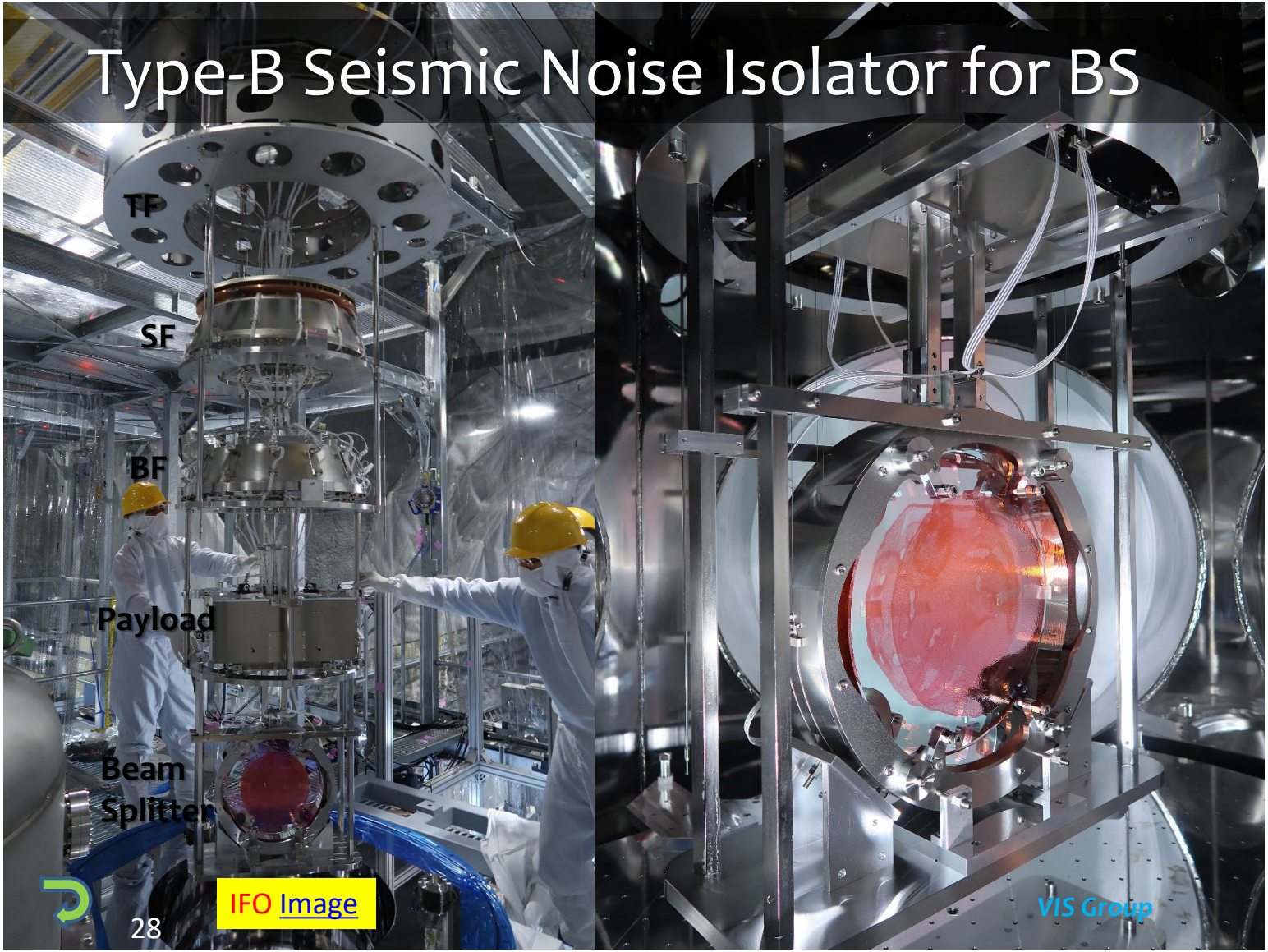
# Cryo-Payload In Type-A




**Sapphire Mirror will be cooled by using heat conduction through its sapphire suspension fibers. (Explained Later)**

# Type-B Seismic Noise Isolator for BS



# Suspension Repairs and Improvements

- **Some of GAS filters at type-A lost their isolation function.**
  → Progress: Repair and reconstruction of the tower and cryo-payload was done. Health check were done in air/vacuum.

- **LVDT suffered from too much noises.**
  → Progress: Low noise LVDTs have been prepared for all of IX, EX, IY, and EY. The control scheme will be refined with these new LVDTs.

- **Lack of temperature control for GAS in Type-A/B/Bp.**
  → Progress: Ribbon heaters were installed. Tests will be done in vacuum.

- **Unstable performance of PR2 and PR3.**
  → Progress: PR2 was fixed. PR3 remains to be fixed. The jumping amount has reduced, although still remaining.

- **Traverser control software for PRM/2/3 suspension had bugs resulting in runaway.**
  → Progress: The bugs were fixed and a limit switch was installed to avoid runaway.

IFO Image

Takahashi, Lucia, Fabian, Hirata, Sato, VIS

# Health check for Type-A, B, Bp and C

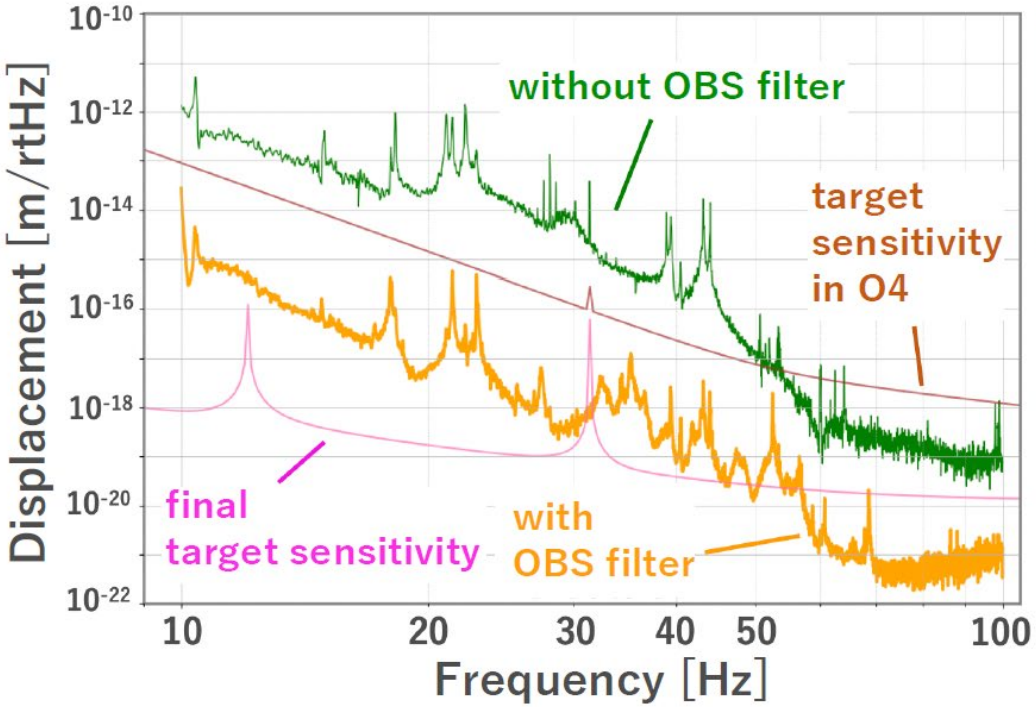
- **Background**
  - Just before O3 commissioning, all suspensions were just mechanically constructed.
  - During O3 commissioning, their performance were not systematically investigated at all. Ideally, the following should be checked before using a mirror actuator for IFO LSC/ASC/ALS.
    - ✓ sensor spectrum,
    - ✓ transfer functions,
    - ✓ actuator performance and balance,
    - ✓ low actuator coupling,
    - ✓ enough gap between instruments/sensors,
    - ✓ proper default positions and so on.
  - Their resonance damping system also varied in Type-A/B/Bp and C.
- **Measures**
  - We decided to perform all check items as an acceptance check before pumping the vacuum tank that house these suspensions.

  → **Progress:** All suspension health checks have been finished.

IFO Image

Takahashi, Ushiba, Tamaki, Lucia, Fabian, Hirata, Sato, VIS

# Suspension Control Noise Contribution




**Result**

**Control noise was reduced by 2~3 order of magnitde**

- We could achieve the target sensitivity in O4 with OBS filter
- Improvements are needed to reach the final target sensitivity

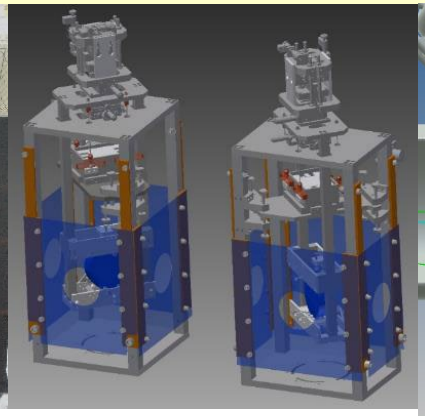
IFO Image

Tamaki, Ushiba

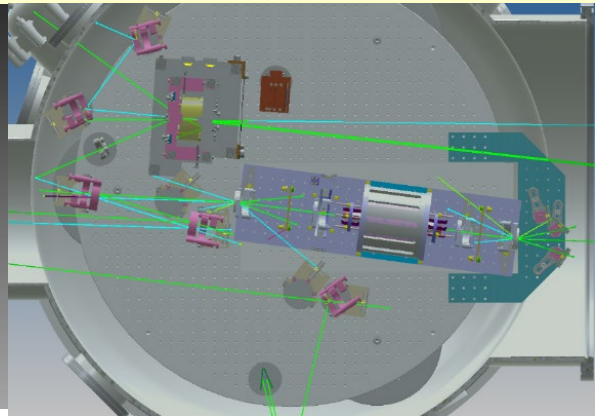
# Mid-size baffle installation in the MICH area

- **Stray light mitigation is key issue to clean the sensitivity curve and enhance the data quality by removing non-stational noise**
  - → **Progress:**
    (1) Preparation of mid-size baffles in 2019. We have a plan to install them according to the well aligned optical axis of PRFPMI configuration.
    (2) Installation of Baffles for IMC suspensions was completed.
    (3) Installation of Mid-size baffles for PRM/2/3, BS and SRM/2/3 have been completed!

**Mid-size baffles**



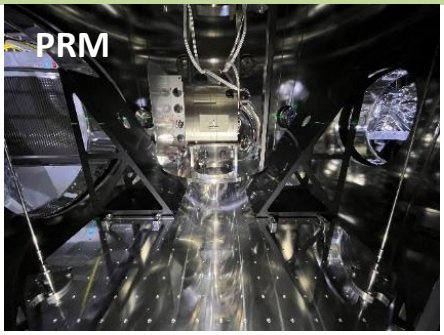
**IMC baffles**

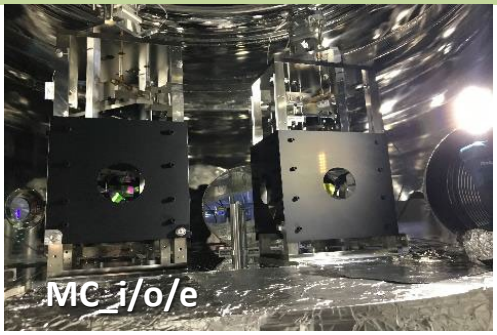


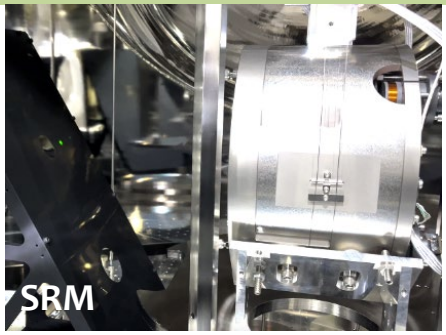
**Optical components Position in IFI**

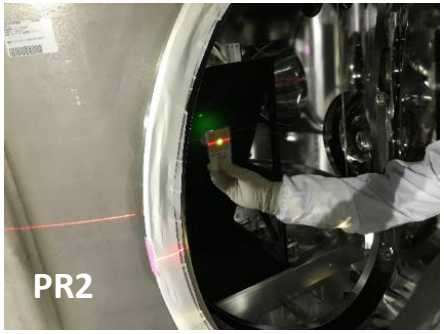
IFO Image

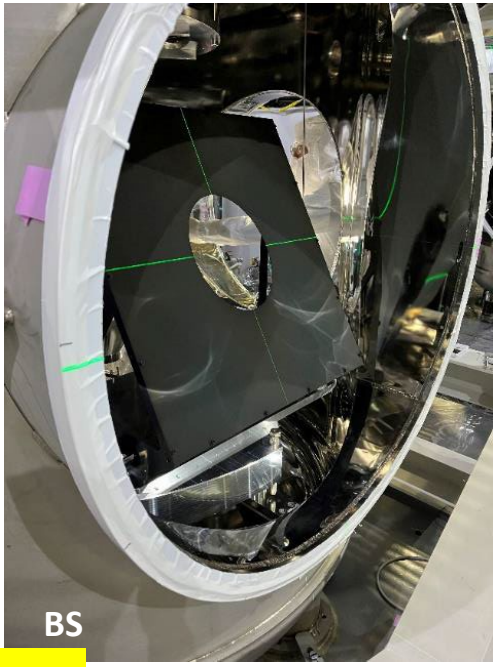
# Baffles for MCi/o/e, PRM/2/3, BS, SRM/2/3



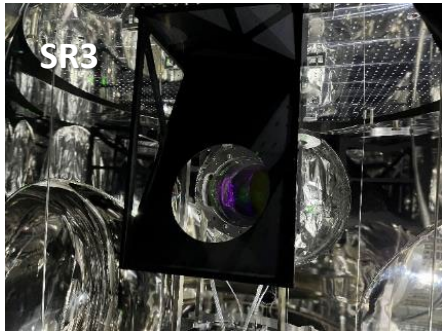





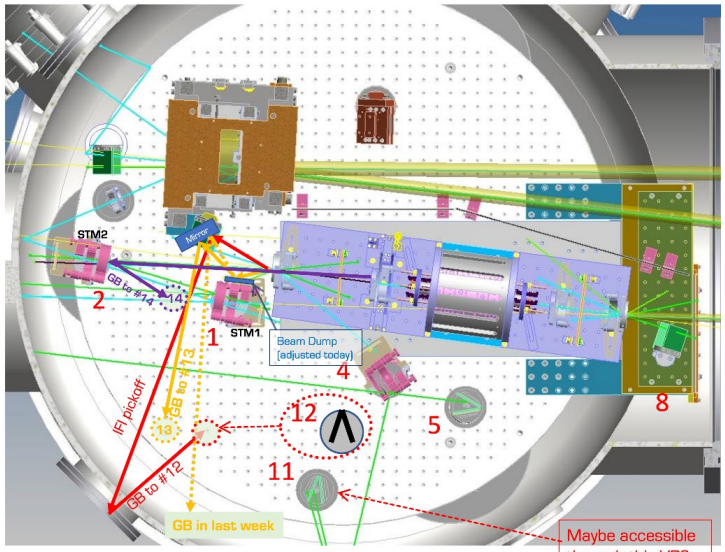




IFO Image

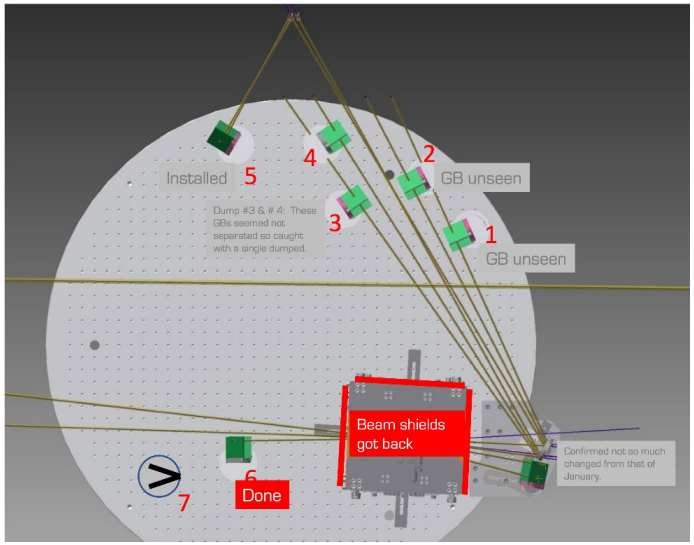
# Optical Dumper installation in IFI, OMC

- **Stray light mitigation is key issue to clean the sensitivity curve and enhance the data quality by removing non-stational noise**
  - → **Progress:**
    - (1) All mid-size baffles were installed.
    - **(2) All necessary optical dumpers were installed for IFI-IMM and OMC-OMM tank.**

**IFI tank**



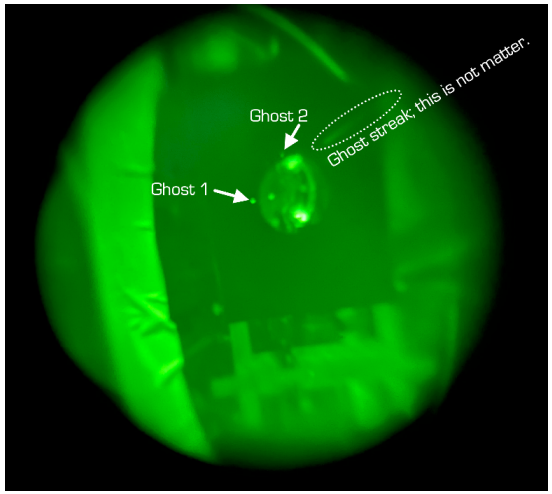

**IMM tank**

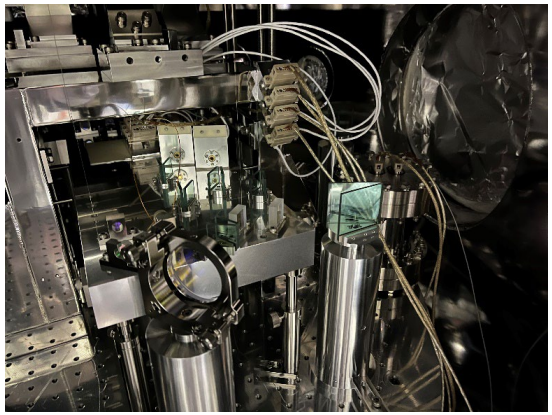



IFO Image

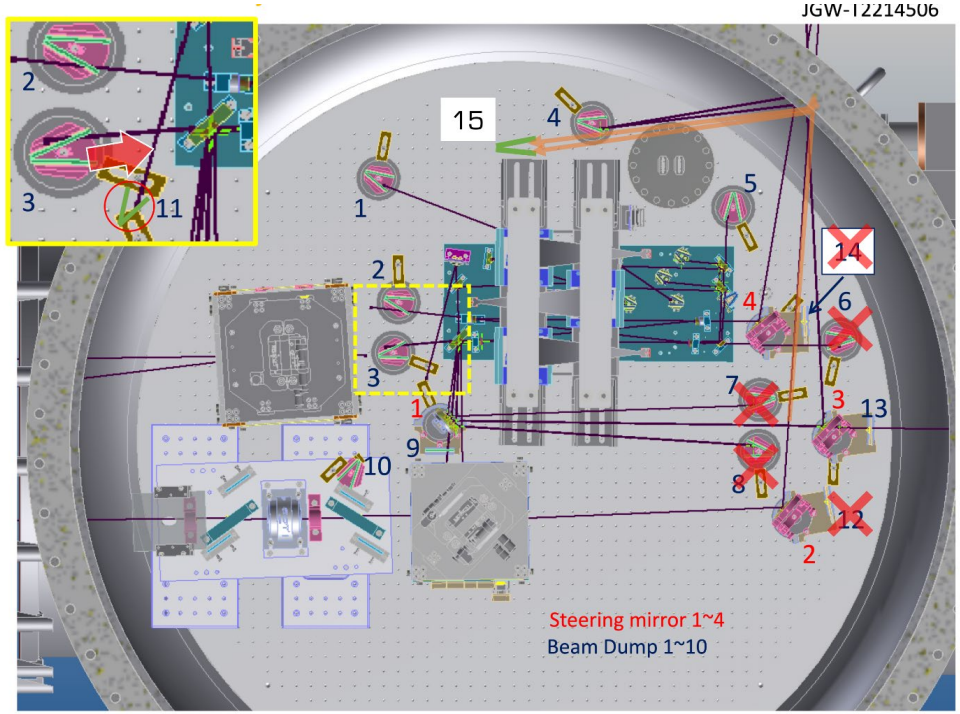
Akutsu, Sato, Hirata

# Optical Dumpers for OMC-OMM



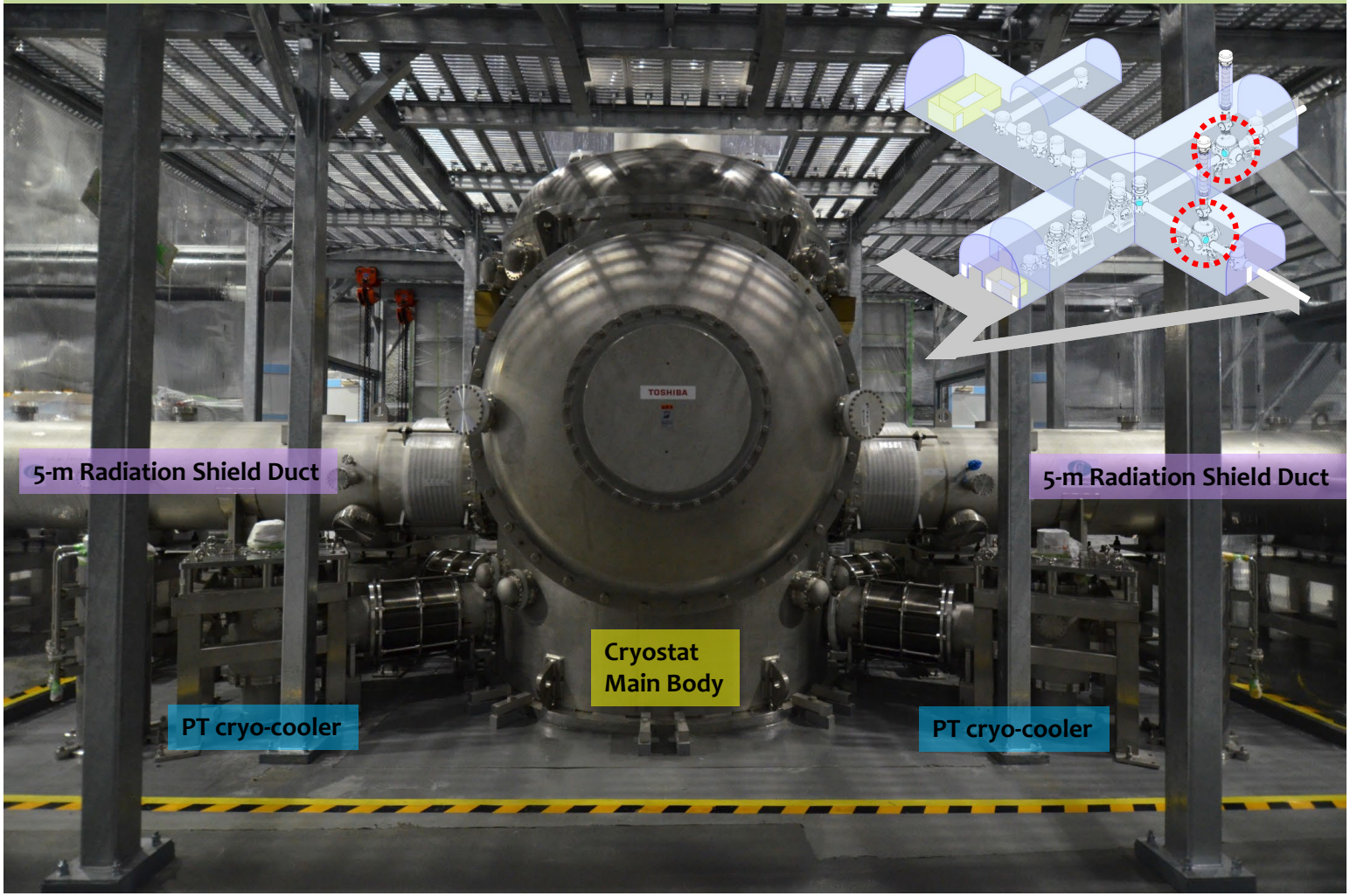
**OMC tank**




IFO Image

Akutsu, Sato, Hirata

# KAGRA Cryogenic System Outlook



# KAGRA Cryogenic System

Cryostat Char
Diameter: 2.4
I/O shields Ma

ube type
(2nd)
K (1st)

1st cooling stage
(~ 40K)

1st vibration
reduction stage

2nd cooling stage
(~ 4.2K)

2nd vibration
reduction stage

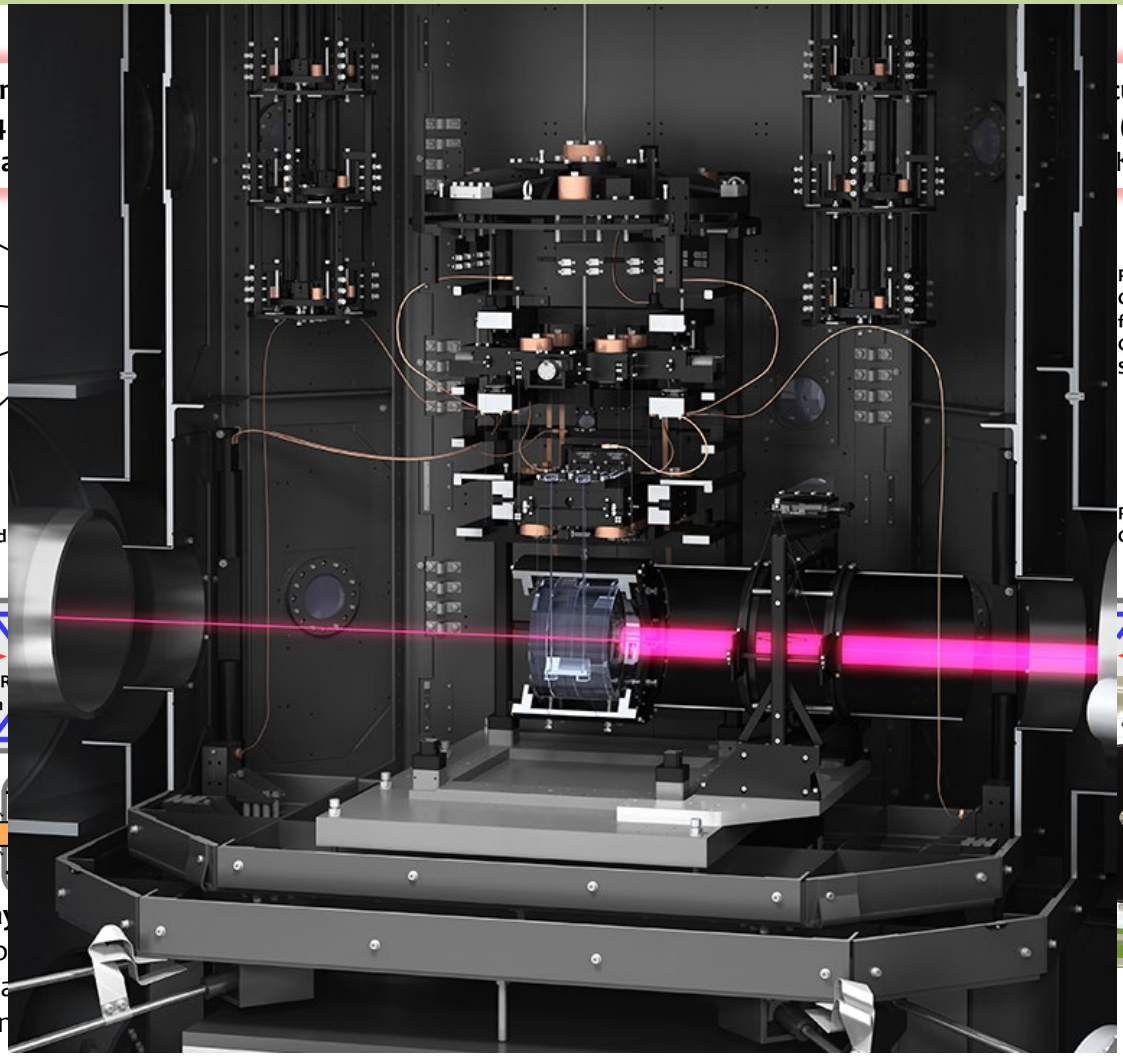
PTC for
Cryo-Payload

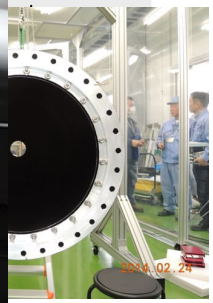
Pulse Tube type
Cryocooler (PTC)
for
Cryostat Radiation
Shields

PTC for
Cryo-Payload

5-m R
with

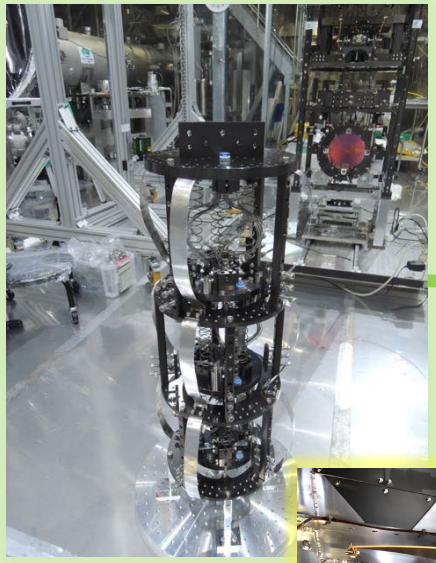
PTC for
5-m Radiation
Shield Duct



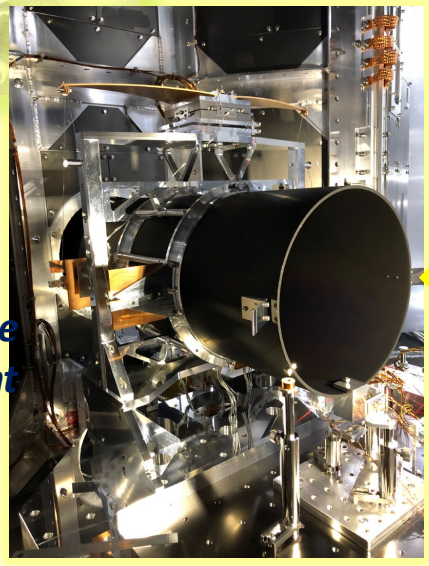


Cryogenic pay
SOLBLACK co
low cost, ca
some magn

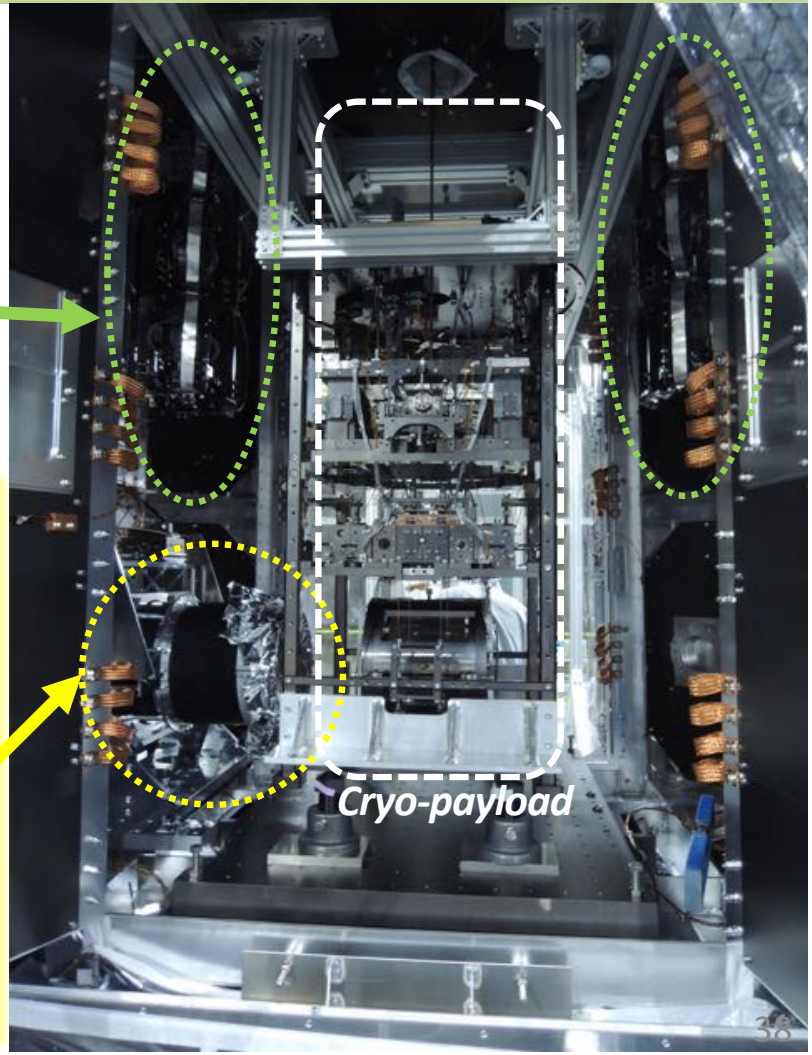
# Heat Link Vibration Isolation



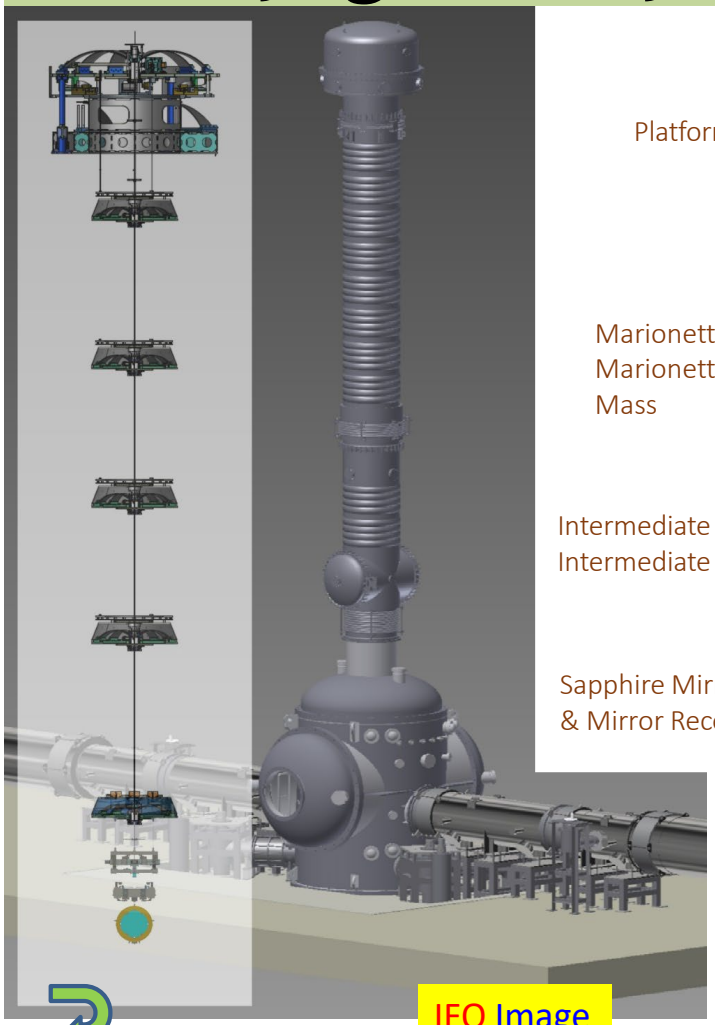
*Heatlink Vibration Isolation Towers*



*Wide Angle Baffle For scattered light mitigation (done by AOS)*



# Cryogenic Payload inside Cryostat



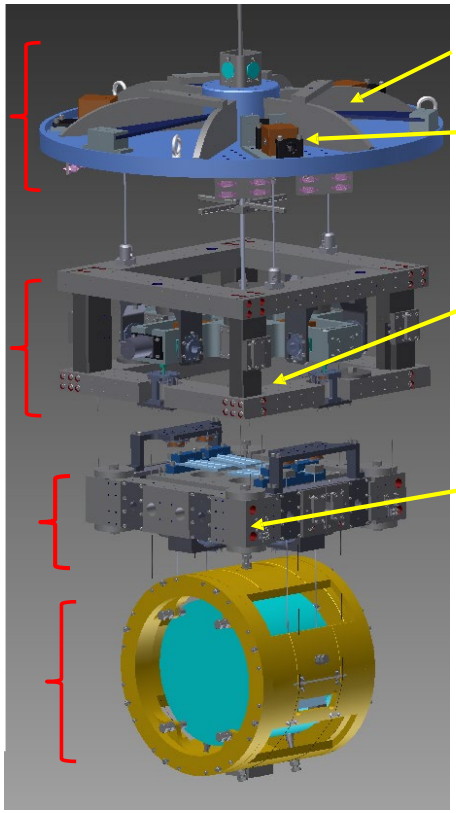
IFO Image

Platform stage

Marionette & Marionette Recoil Mass

Intermediate Mass & Intermediate Recoil

Sapphire Mirror & Mirror Recoil Mass



*BeCu blade springs*

*Moving mass*

*Coil-Magnet actuators w/ optical sensors*

*Coil-Magnet actuators w/ optical sensors*

*Total mass - 200 kg*

*Height - 2 m*

* Heat links not shown

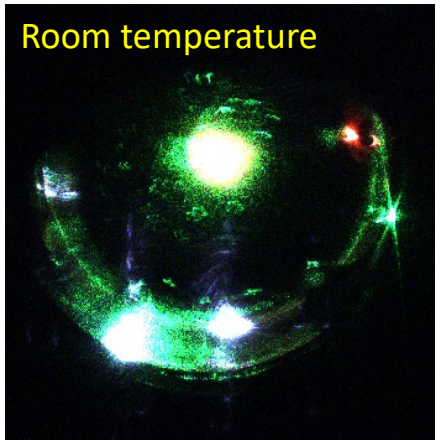
# Cryo-part Improvements

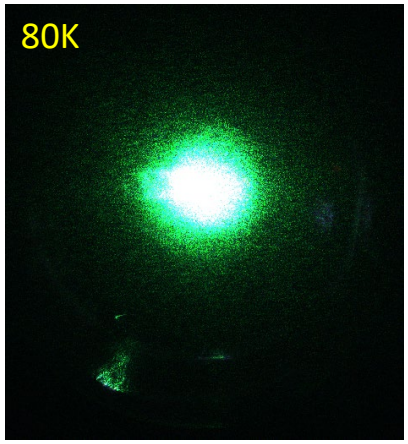
- **Frosting on Mirrors → Super-low finesse, super-low sensitivity**
  - → **Progress:**
    - ✓ We set a new regulation on acceptable vacuum leak level from 10^-9 Pa m3/sec to 10^-10 Pa m3/sec.
    - ✓ Mass spectrometers were set in each cryostat for monitoring N2. O2, H2O.
    - ✓ We established the cooling orders.
    - ✓ Heaters were installed on Intermediate mass to enhance the speed of heat up for the emergency cases
  - → **Present status:**
    - ✓ ETMX was cooled around 87K from July 2022. While 250K at ITMX.
      - No serious finesse reduction of 1420 for X-arm FP cavity until now.
    - ✓ ITMY and ETMY were cooled around 250K.
      - No serious finesse reduction of 1350 for Y-arm FP cavity until now.

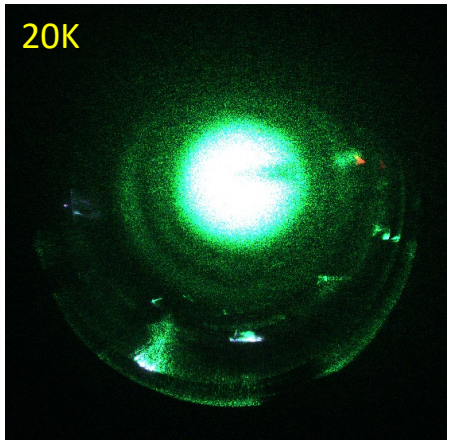
- **Frosting on windows where the oplev light pass through → Unreliable mirror alignment information, no P/Y damping control for mirrors, No operation of IFO**
  - → **Progress:** Heater were installed around windows on the inner and outer radiation shields.
  - → **Present status:**
    - ✓ No serious frosting at EXC. So no test of heating up was done.
    - ✓ We should monitor when the inner/outer radiation shields will be cooler at 10K/40K level by operating cryocoolers for them.

Kimura, CRY

# Frosting on Mirrors before O3GK




- When we cooled the sapphire mirrors, scattered light of green laser can be observed in the camera image.
- This scattered light observed when the mirrors reached below 100 K or 30 K.
- So, it might be due to the residual gas contamination due to the cryogenic pumping effect of mirrors.
- So we gave up cool sapphire mirrors for O3(GK) in 2019.

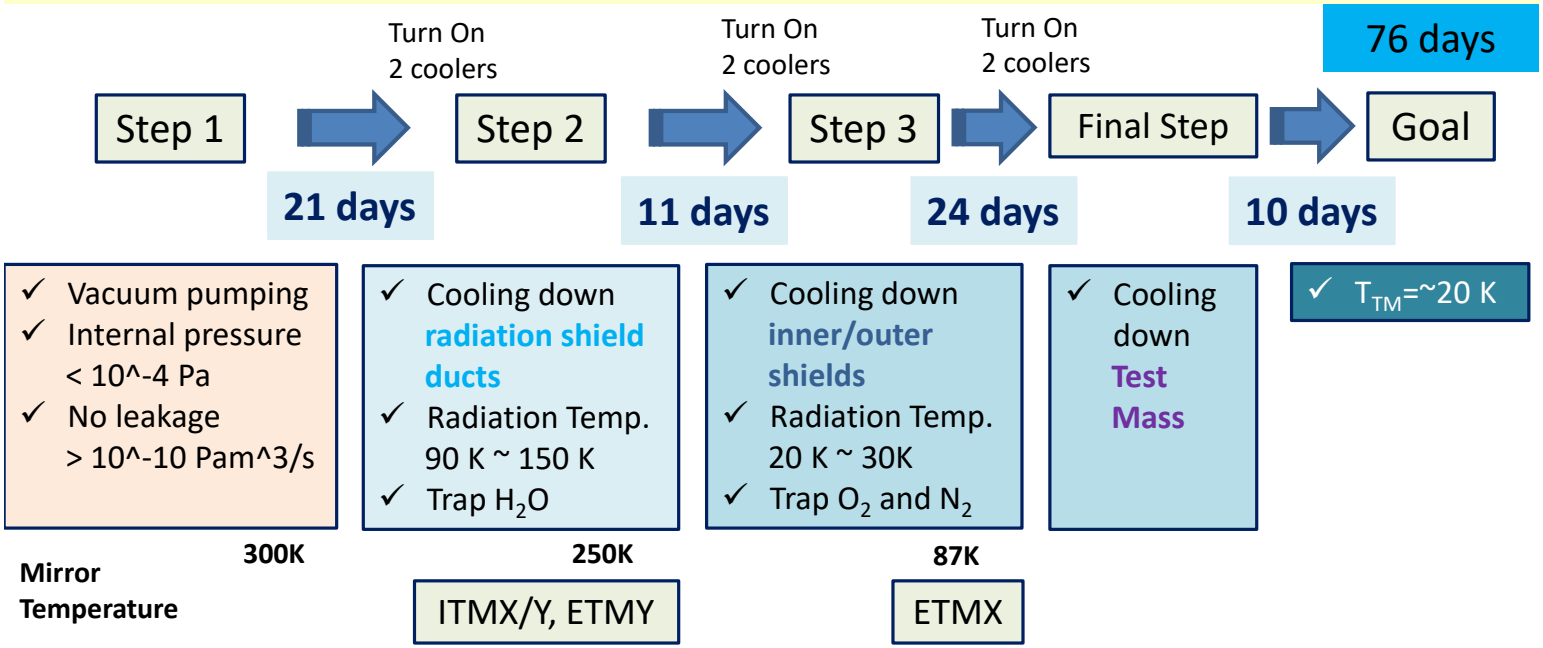
# More Cryo-part Improvements

- **Short-lifetime cryocoolers for the Radiation shield Ducts → frosting triggers, time wasting**
  - → **Progress:** all nasty coolers were replaced with two stage type PT-coolers. The only first stage(~ 40K) is used for cooling the radiation shield duct.
- **Stuck of a moving mass for the rough alignment for mirrors at cryogenic temp → unenabled us to align test masses**
  - → **Progress:** New designed moving mass system were installed.

IFO Image

# Cooling strategy to minimize frosting works WELL !

- **Measures and Progress**
  - We made a sophisticated cooling process to avoid frosting.




- We prepared mass-spectrometer to know the residual components for each cryostat.
- We also learned that too long step 3 in EXC showed O2/N2 adsorption and vaporization cycle because the temperature at the “uncooled” refrigerators’ structure inside the cryostat.

IFO Image

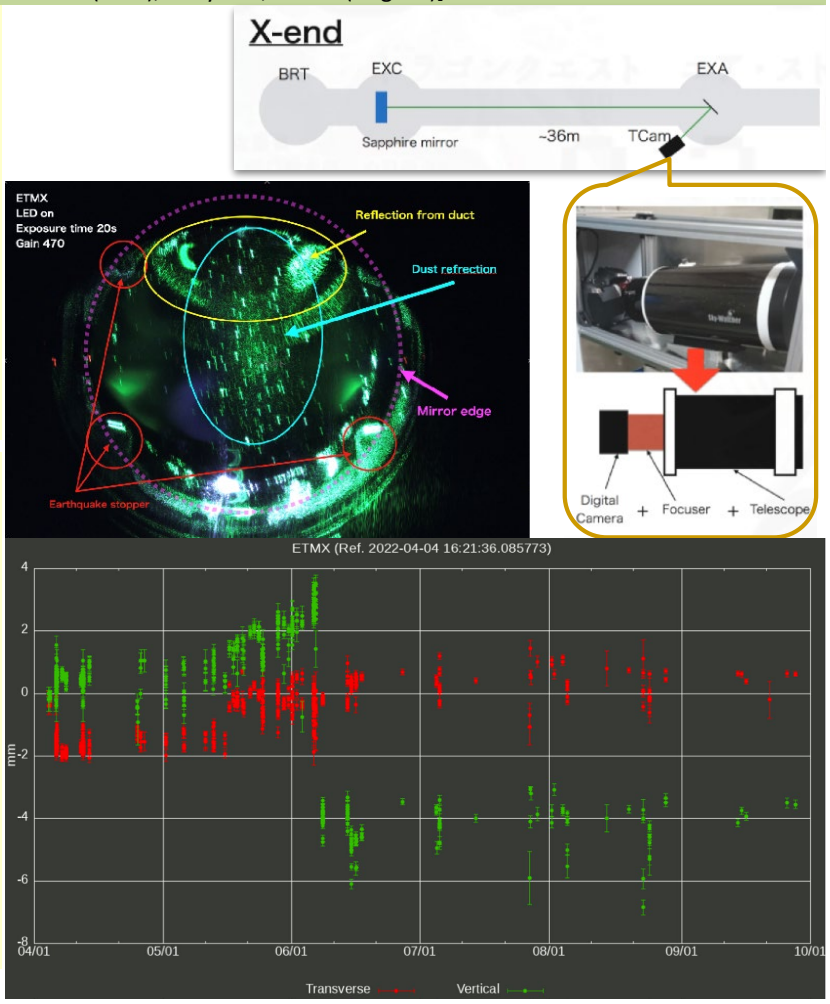
Kimura, CRY

# Mirror Height Estimation System

[Yuzurihara, Yokozawa, Yamamoto(ICRR), Toriyama, Shiota (Aogaku)]

- **Background**
  - Mirror Position can be up when the cryo-payload is cooled due to physical stiffness enhancement at the cryogenic temperature.
  - We need to keep the position of the mirror at the targeted position for the IFO alignment.
  - We need a system to judge the height change of the mirror.

- **Measures and Progress**
  - We prepared the mirror height measuring system using Tcam.
  - TCam : Monitoring mirror position / main, green, pcal beam position / surface of mirror.
  - Procedure of automatic system
    - Take Tcam photo.
    - Crop necessary regions and fit them.
    - TCam photo overlaying mirror circle is uploaded on web server.

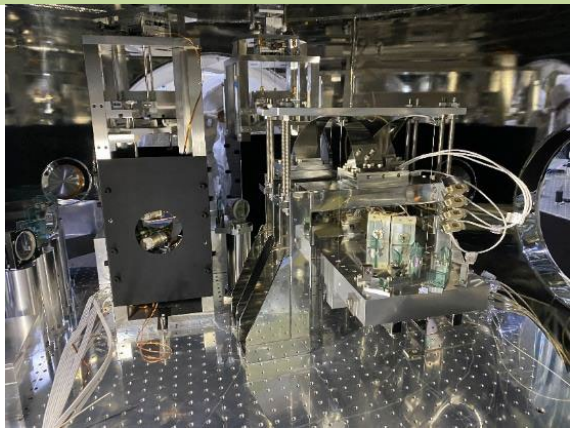



IFO Image

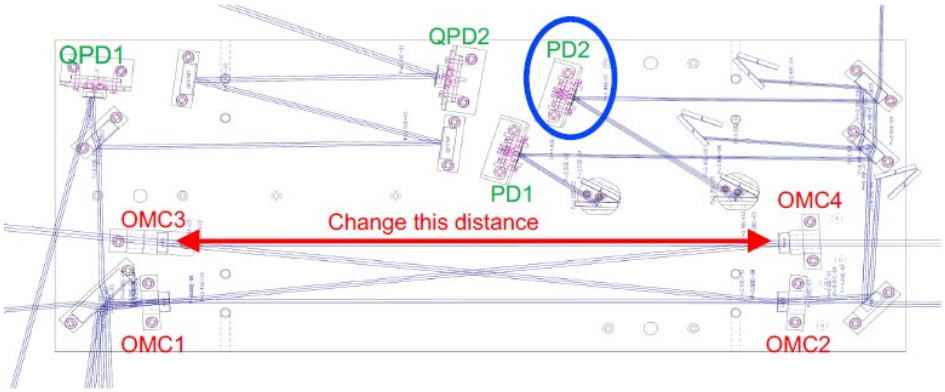
# Output Mode Cleaner Improvement

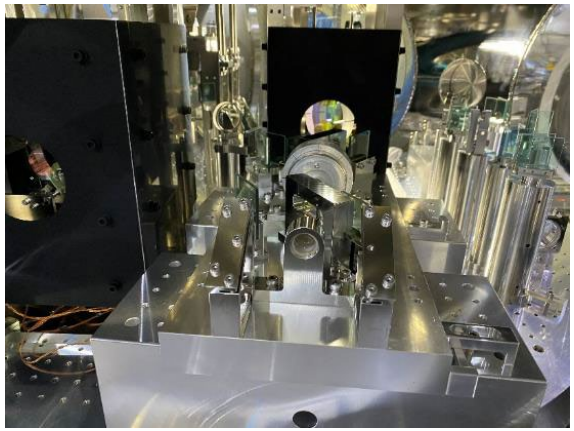
- **Background**
  - Mirror loss for OMC was larger than designed value. → Less shot noise.
  - One of PD for DC readout was broken. → Less shot noise.

- **Measures and Progress**
  - We prepared higher quality mirrors for OMC. 80% → 95% transmittance.
  - We fixed the DCPD.
  - OFI transmittance performance was checked to be OK.



OMC Setting



OFI Setting

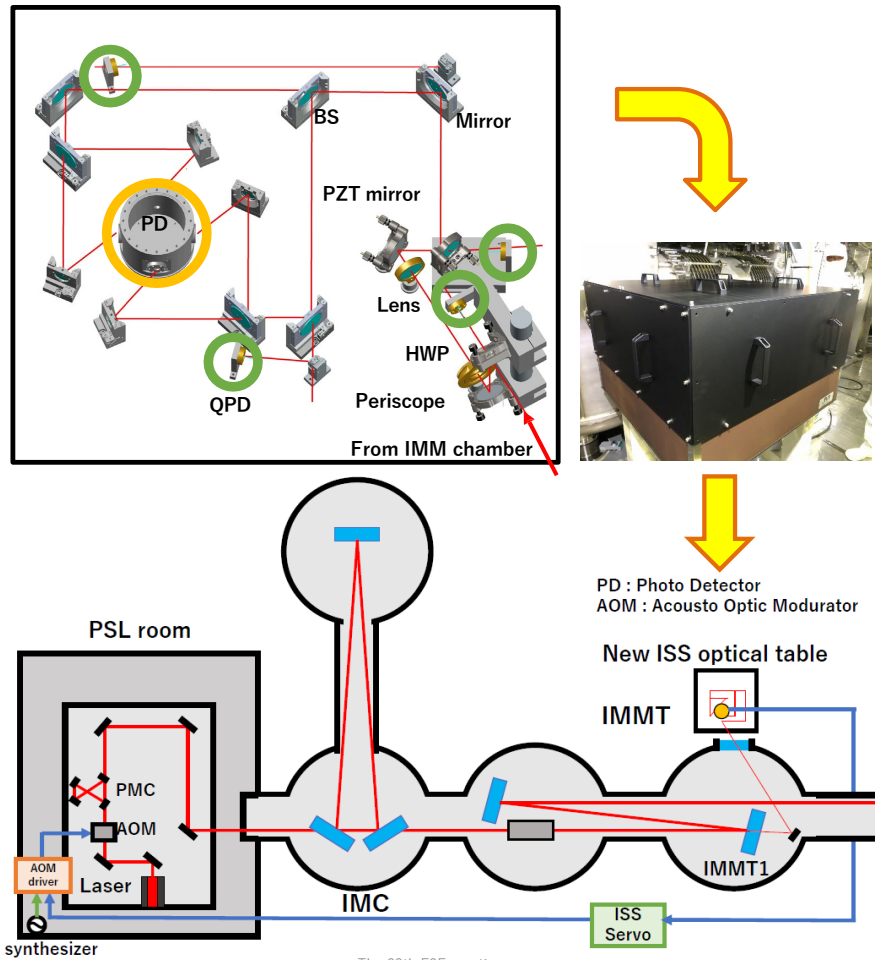
IFO Image

Aso, Nishino, Akutsu, Tanaka

# New Laser Intensity Stabilization

- **Background**
  - O4 requirement is 10^-8, while 10^-7 for O3.
- **Measures**
  - We prepared a new intensity stabilization system.
  - **Four PDs** are provided to support higher laser power for O5, which is a maximum of 200 W with a light source.
  - **Two QPDs** detect vertical and horizontal optical axis misalignment. In addition, it is possible to search for a position that has a small effect when the optical axis fluctuation on the PD is generated using the PZT mirror, and to control to that position.
  - **A cover** will be prepared to mitigate the air flow effect.
- **Progress**
  - Very smooth stabilization was achieved.

IFO Image

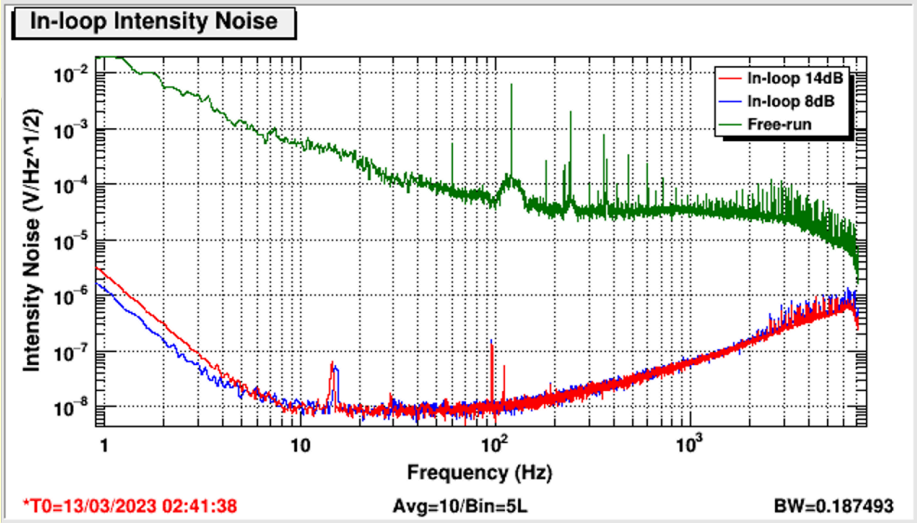


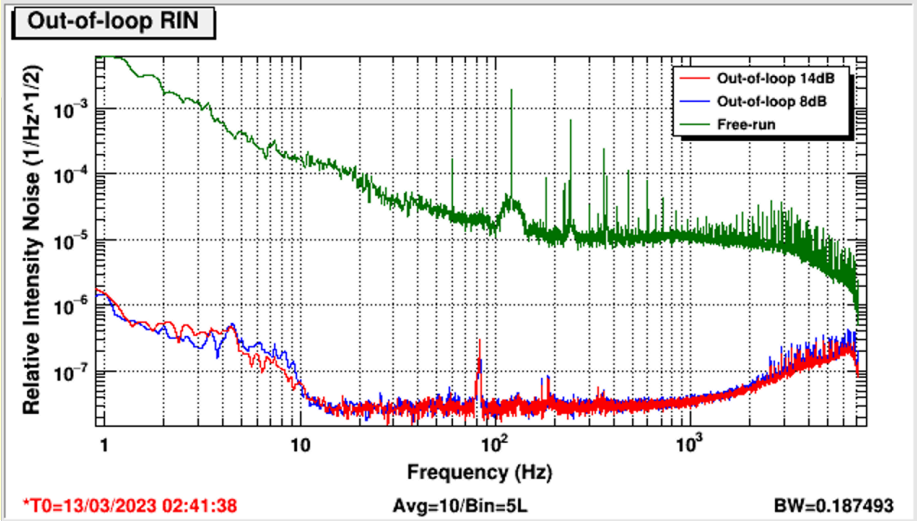

Miyakawa, Sako, Kato, Maeda, Mio, Moriwaki

# New Laser Intensity Stabilization

- O4 requirement is 10^-8, while 10^-7 for O3.
- The requirement was satisfied.

- ISS stability should be checked now.

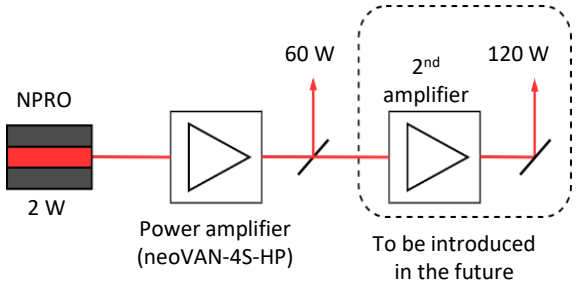


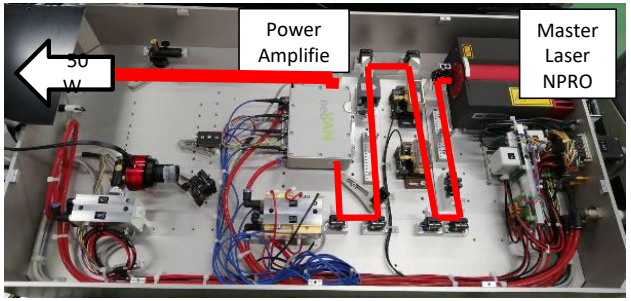




IFO Image

# High-Power Laser Preparation

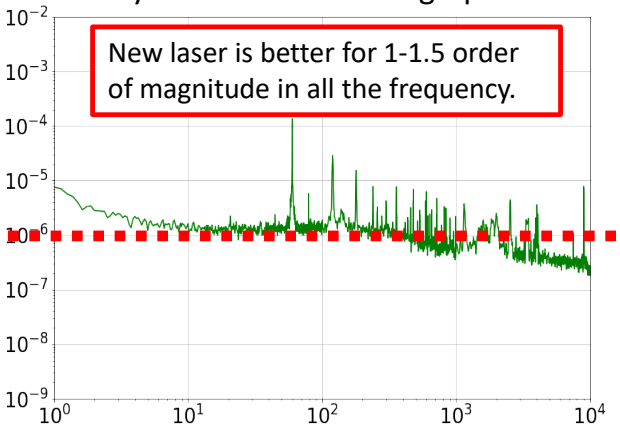
- Maximum power: 60 W (120 W in the future) .
- It was installed in the PSL room KAGRA.
- IMC lock using HPL was realized.




Intensity noise of current KAGRA laser

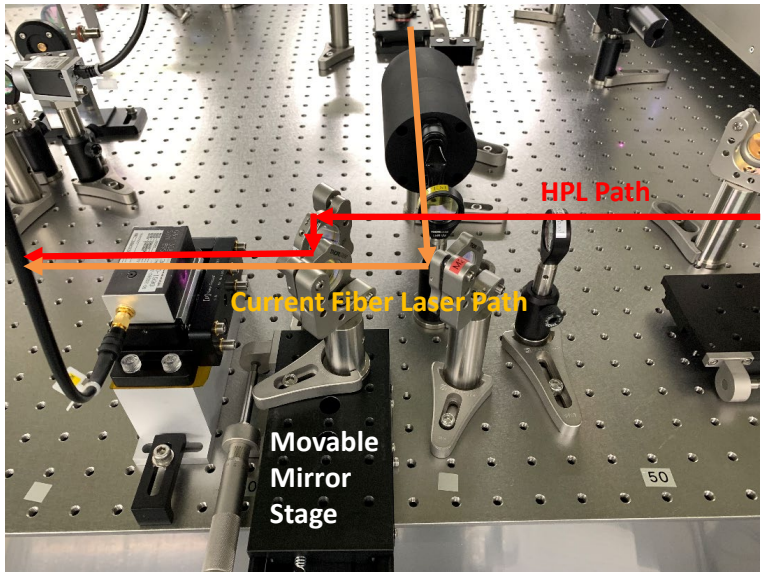

Intensity noise of the new high-power laser

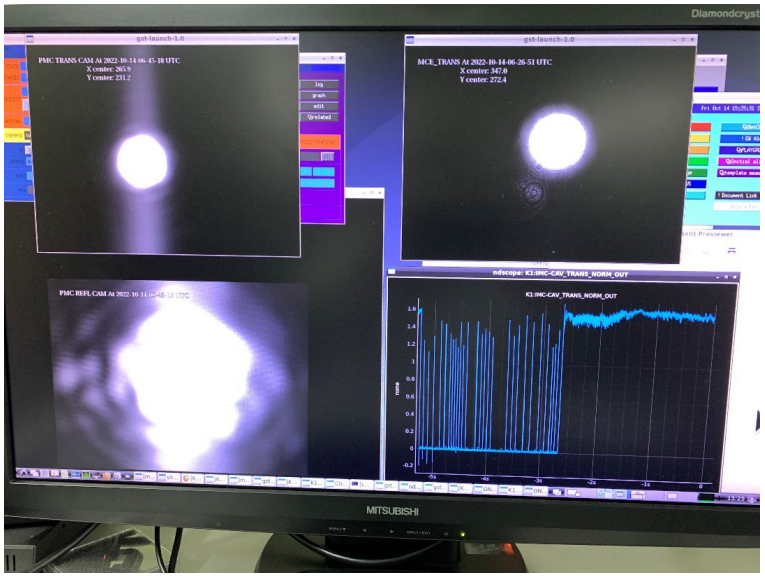



IFO Image

# High-Power Laser Preparation

- Optical Path separation between the present fiber laser and HPL
- IMC lock using HPL was realized. More control tuning is necessary.



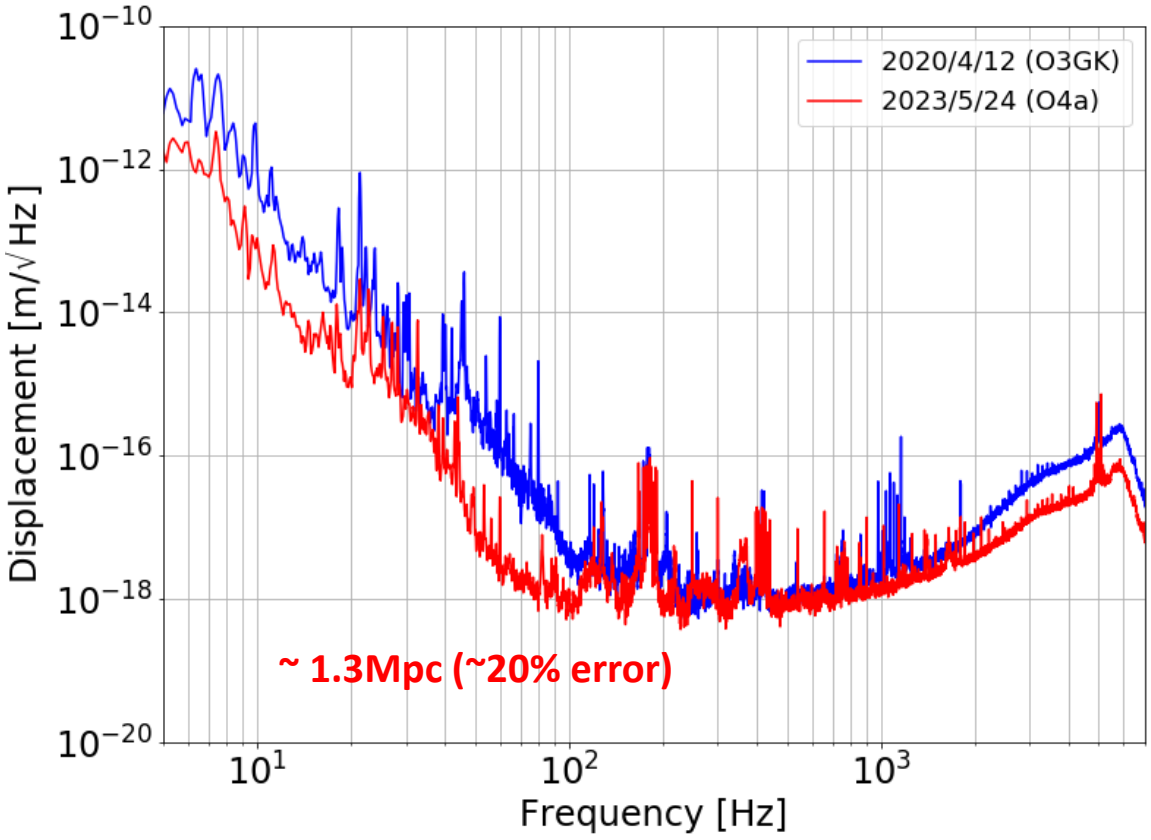




IFO Image

Miyakawa, Sako, Kato, Maeda, Uehara, Mio, Moriwaki

# IFO preparation status

- PRFPMI with DC-readout configuration is realized.
- A part of the Alignment Sensing Control(ASC) is now being accompanied with PRFPMI+DC-readout to enhance the IFO stability and sensitivity stability.



# What are the biggest problems at present

- **We are now suffering from**
  - PR3 ASC was not applied because of time-up before O4a
    - So, we need to adjust PR3 alignment manually every day. It loses ~ 2 hours observation time during O4a.
  - Scattered light in the OMC tank
    - We forgot to mitigate one of stray light in the OMC tank, and it seems to hit on something and it generates the scattered light noise around 100Hz.
  - Type-C suspensions cannot isolate 3~10Hz seismic noise effectively. Because of the seimic noise shock due to even the small scale swarm earthquake near the KAGRA site could down not the FP am control, but the IMC control.

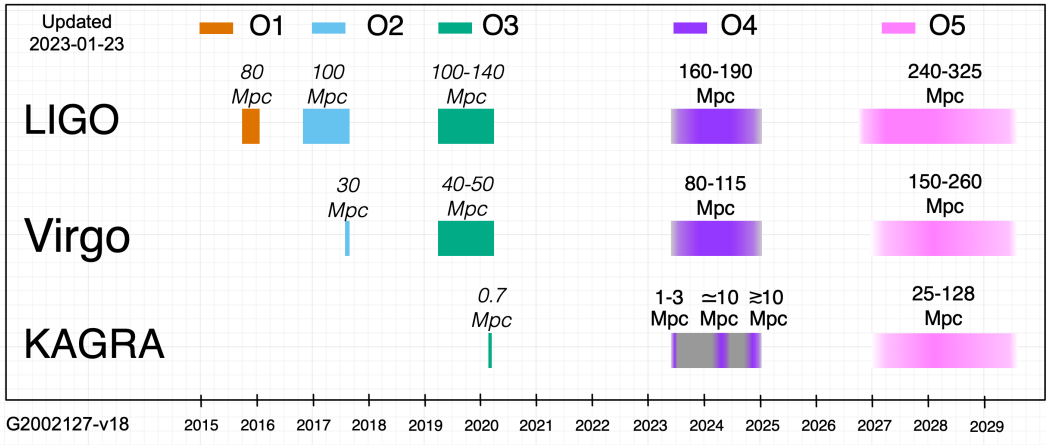
# O4b(c) plan

- We resume commissioning, including cooling the mirrors from July 3rd.
  - Switch to high power laser from a fiber laser and more laser power injection.
  - Cryocooler regeneration and all mirror cooling below 100K.
  - Scattered light mitigation in OMC.
  - ASC for PR3 and ITMs.
  - MICH/PRCL control noise reduction.
  - Suspension control noise reduction.

- KAGRA will rejoin O4 again for three months from around spring 2024 with the sensitivity of 10Mpc.
- We would like to enhance the sensitivity more than 10Mpc for maybe the last three months of O4.
- RSE is one of possibilities for O4c.

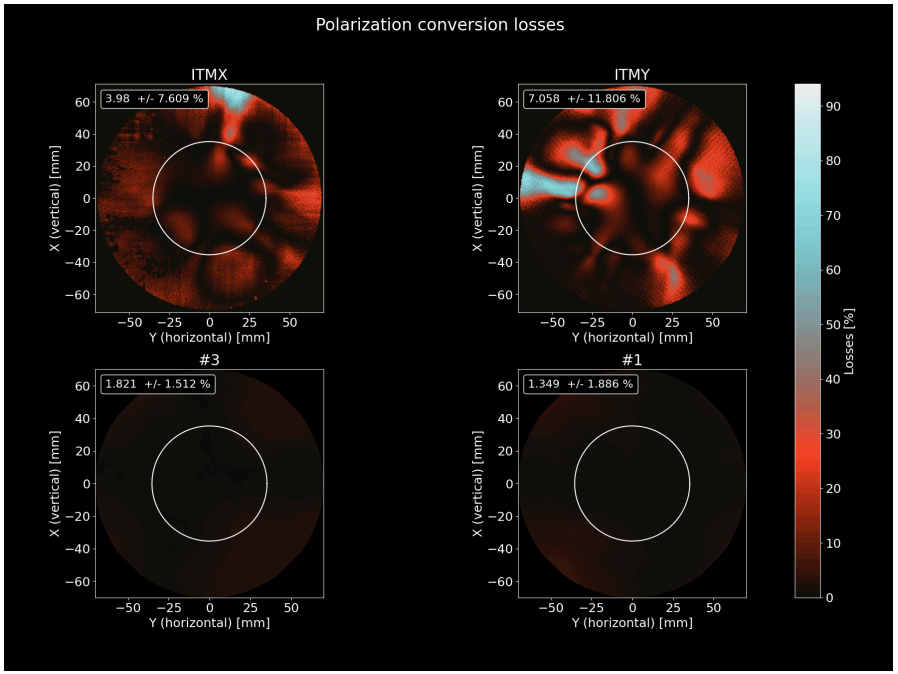
# O5 plan

- **Some suspensions should be improved in their mechanical performance.**
  - PR3, Type-C suspensions, Seismic noise isolation for OMC/IFI area.
- **Control noise reduction for Type-A/B suspensions for the lower frequency range.**
- **RSE introduction**
- **The introduction of Frequency independent/dependent squeezing.**
  - However, it requires the large scale KAKENHI.
- **New sapphire input test mass introduction**
  - To mitigate birefringence -> smooth IFO response as we expect
  - To obtain the same reflectivity -> less contribution of common mode noises such as frequency noise..



# Birefringence of Sapphire Substrate

- Birefringence in the sapphire crystals will be a problem in future.
  - However, no serious effects were identified in WFS control.
  - On the other hand, the best sensitivity tends to select off-enter axis on ITMs for the arm FP.
- Search for better crystals was carried out.
- Crystals from a Korean company have better birefringence homogeneity compared to the currently installed TMs and comparable absorption.

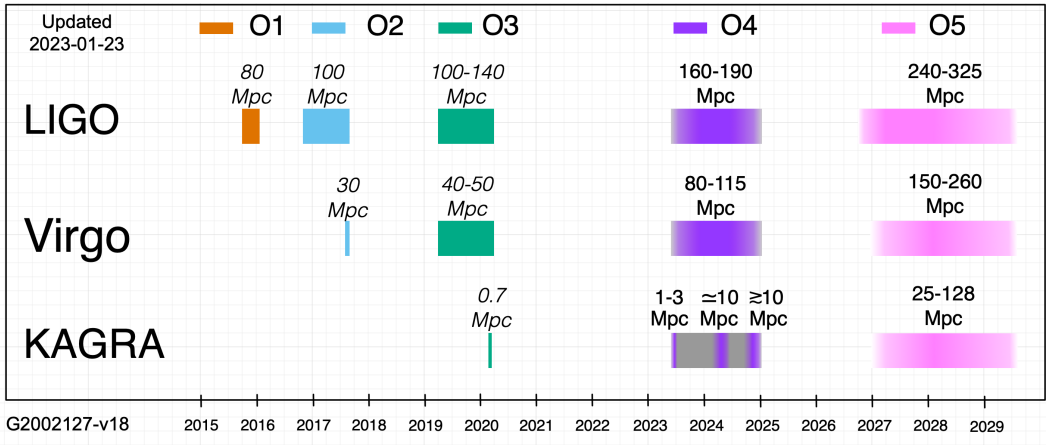



- We are in a process of making new ITMs with crystals from this company.
- Hopefully, we can install a new set of ITMs before O5.

**Leonardi**

# O5 plan

- **More stray light mitigation around OMC**
  - To mitigate some noises around 100Hz
- **Full and multi High Power Laser preparation**
  - We have 40W FL and 60W LIGO type laser. 120W should be prepared for the future.
  - Two lasers are always necessary for redundancy at KAGRA.
- **In-vac PD for REFL, etc.**
  - To mitigate acoustic noises around 100Hz according to LV experiences.



# Thank you