Status of KAGRA Large-scale Cryogenic Gravitational Wave Telescope

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KAGRA Observatory

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TAUP2025@ 西昌市, 四川省, 中国

KAGRA Highlights as 2.5 Gen GW Telescope

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

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

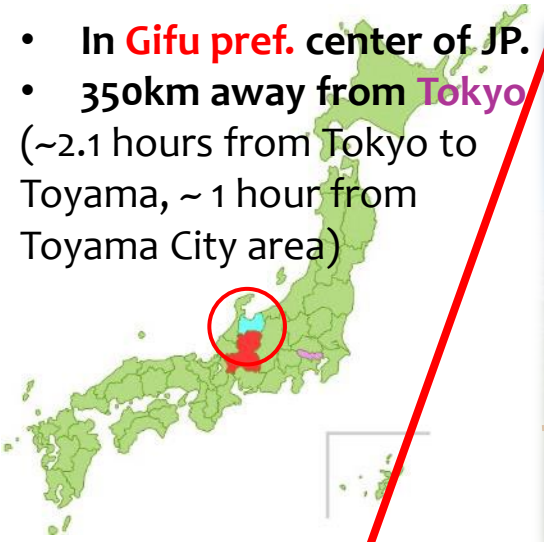
(2) **Usage of Cryogenic Mirrors and suspensions**
→ Reduce Thermal Noises

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

KAGRA Site

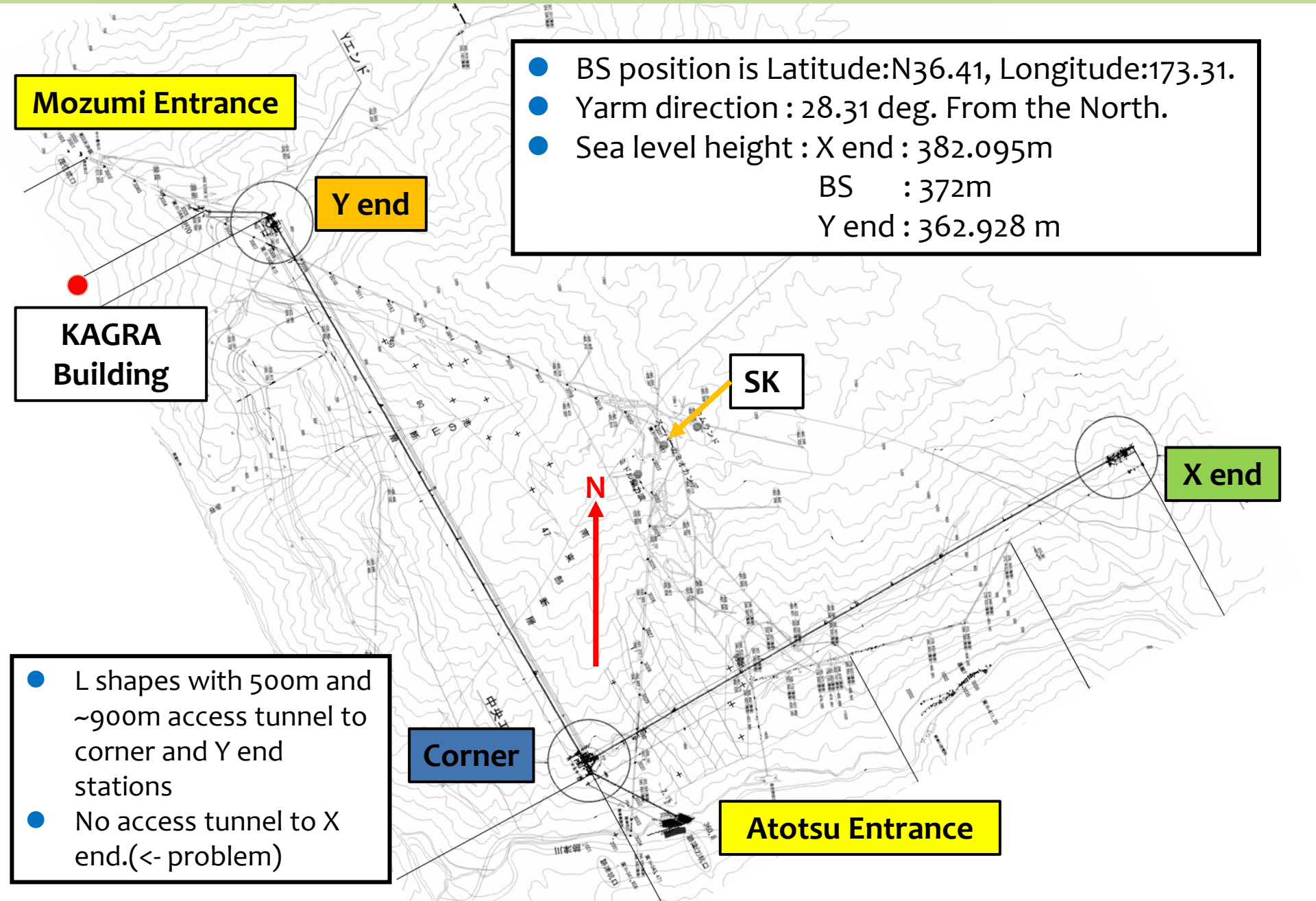
- In Gifu pref. center of JP.
- 350km away from Tokyo

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



The border area between Gifu and Toyama

Tunnel Position and Alignment

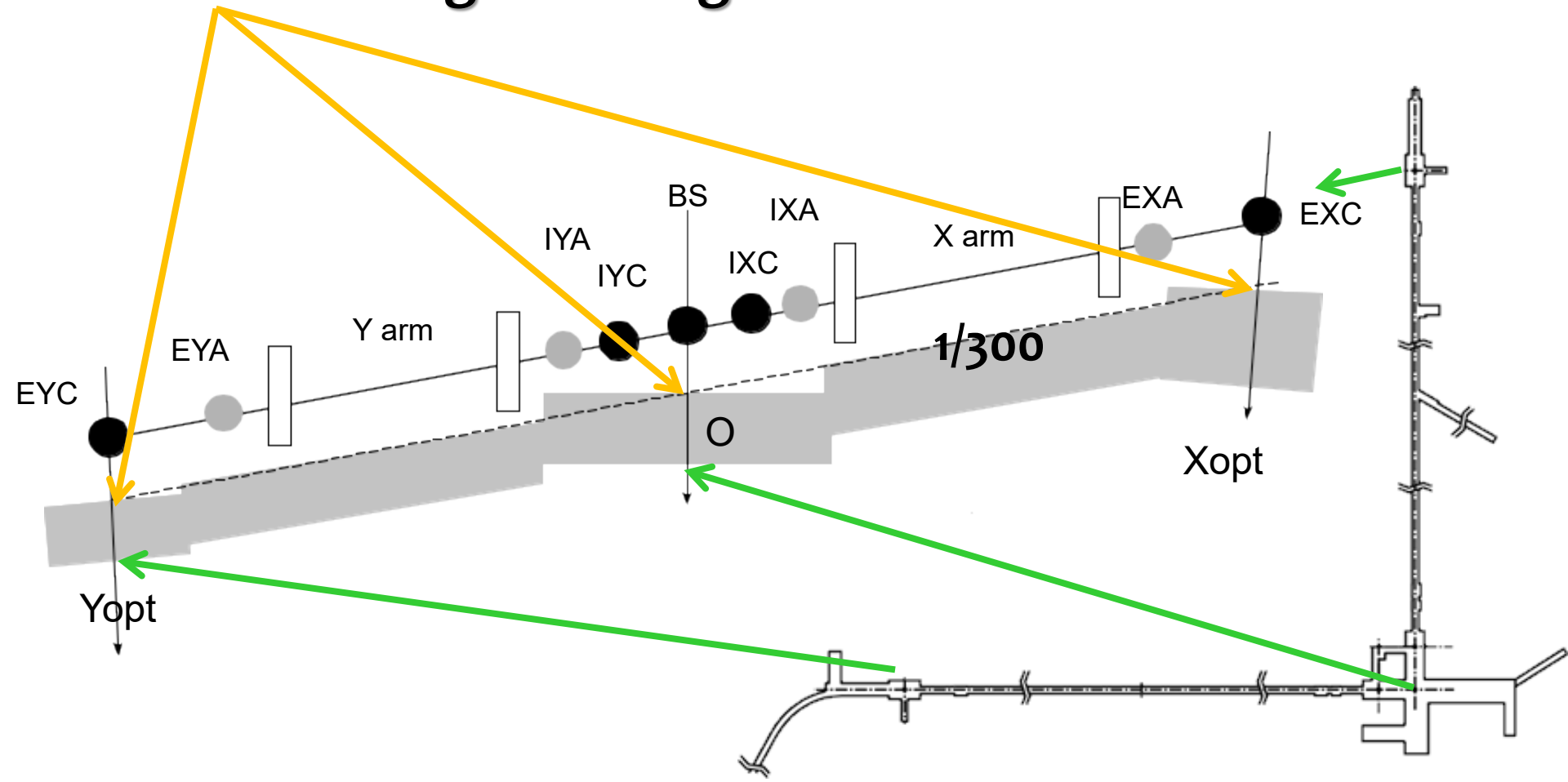


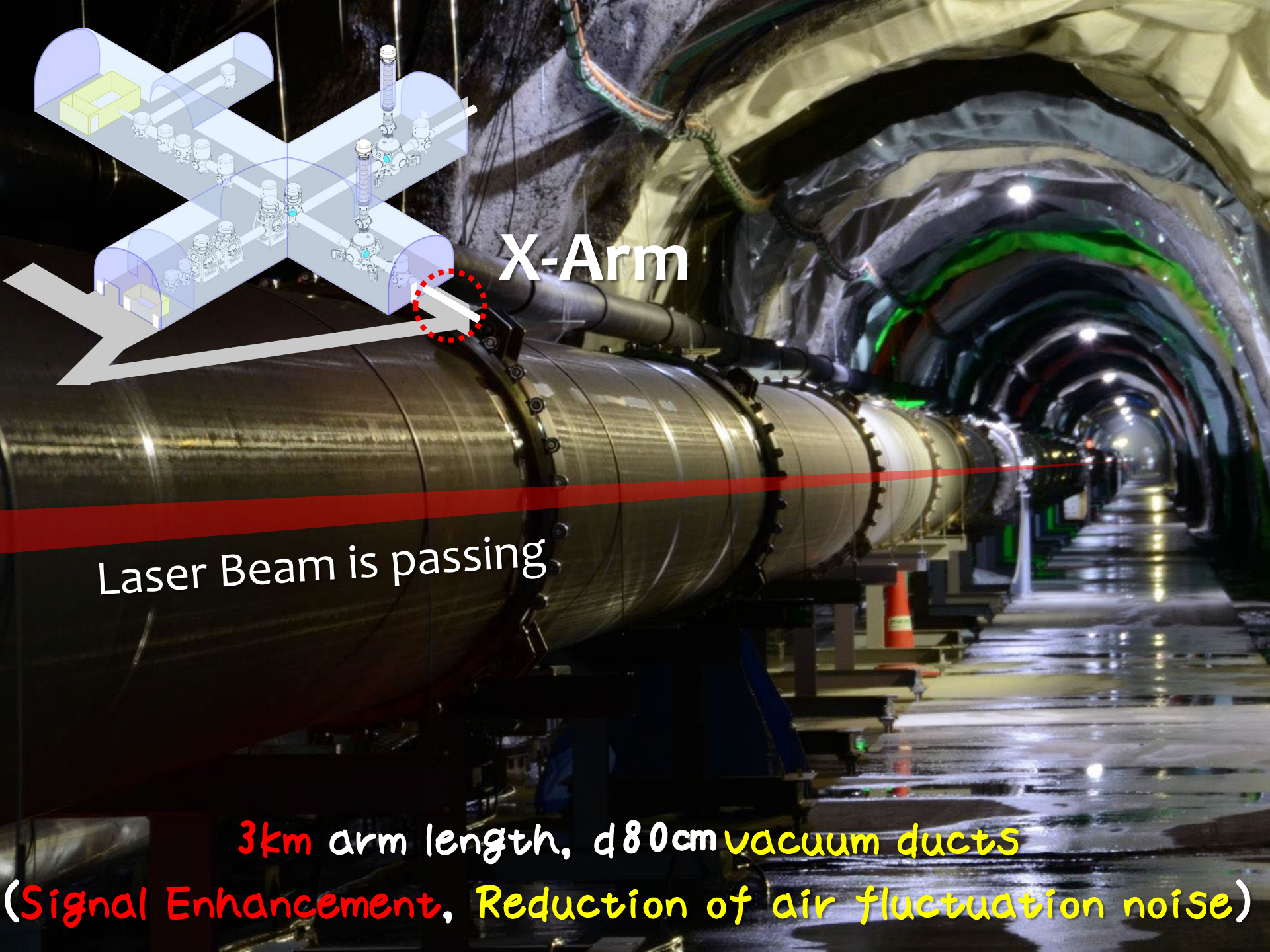
- BS position is Latitude:N36.41, Longitude:173.31.
- Yarm direction : 28.31 deg. From the North.
- Sea level height : X end : 382.095m
  BS : 372m
  Y end : 362.928 m

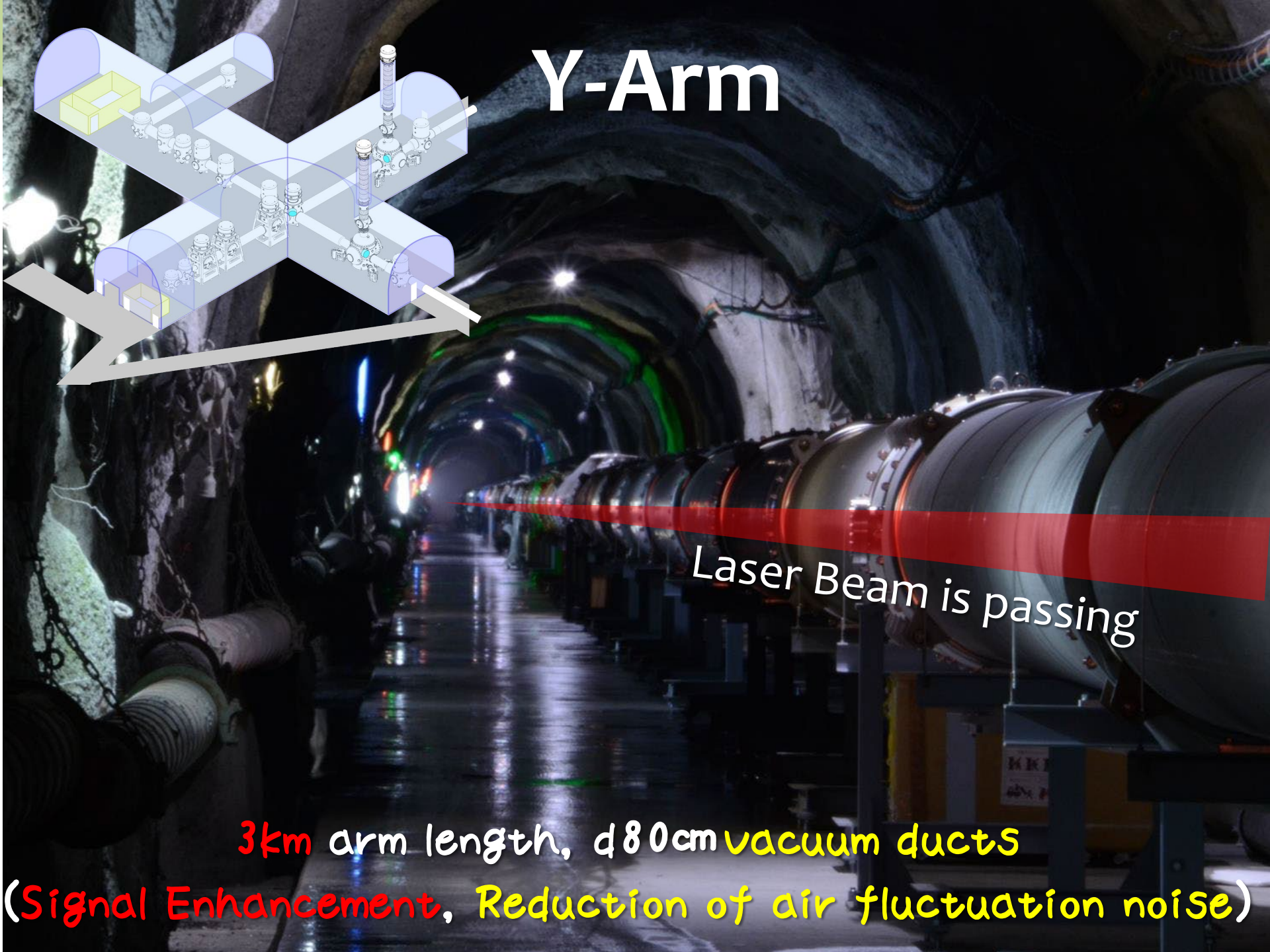
- L shapes with 500m and ~900m access tunnel to corner and Y end stations
- No access tunnel to X end.(<- problem)

Tunnel Design

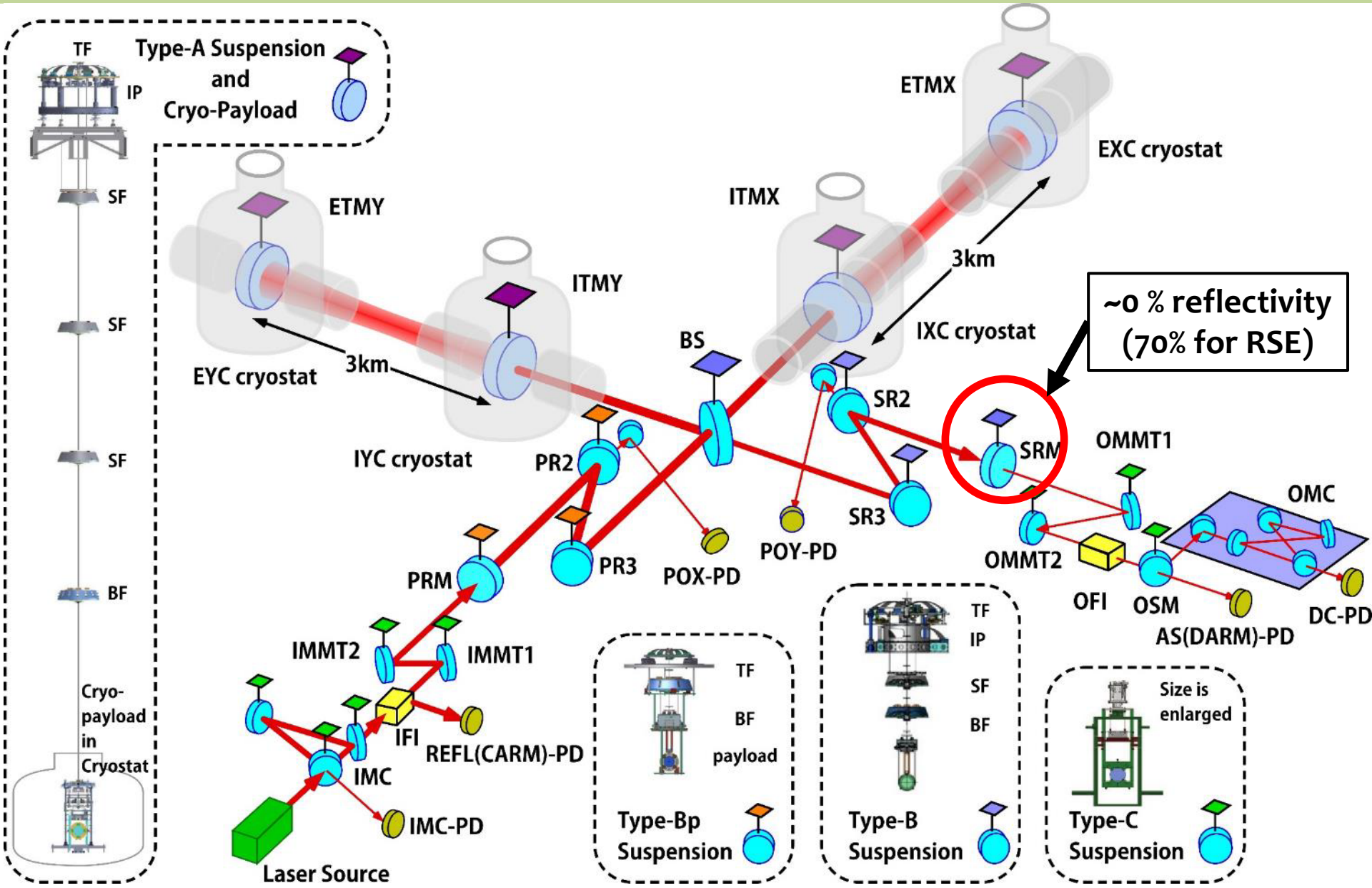
- **Slope of 1/300** was selected to drain the water to rivers.
- **Horizontal planes** for each station are prepared for easiness during installing vacuum tanks



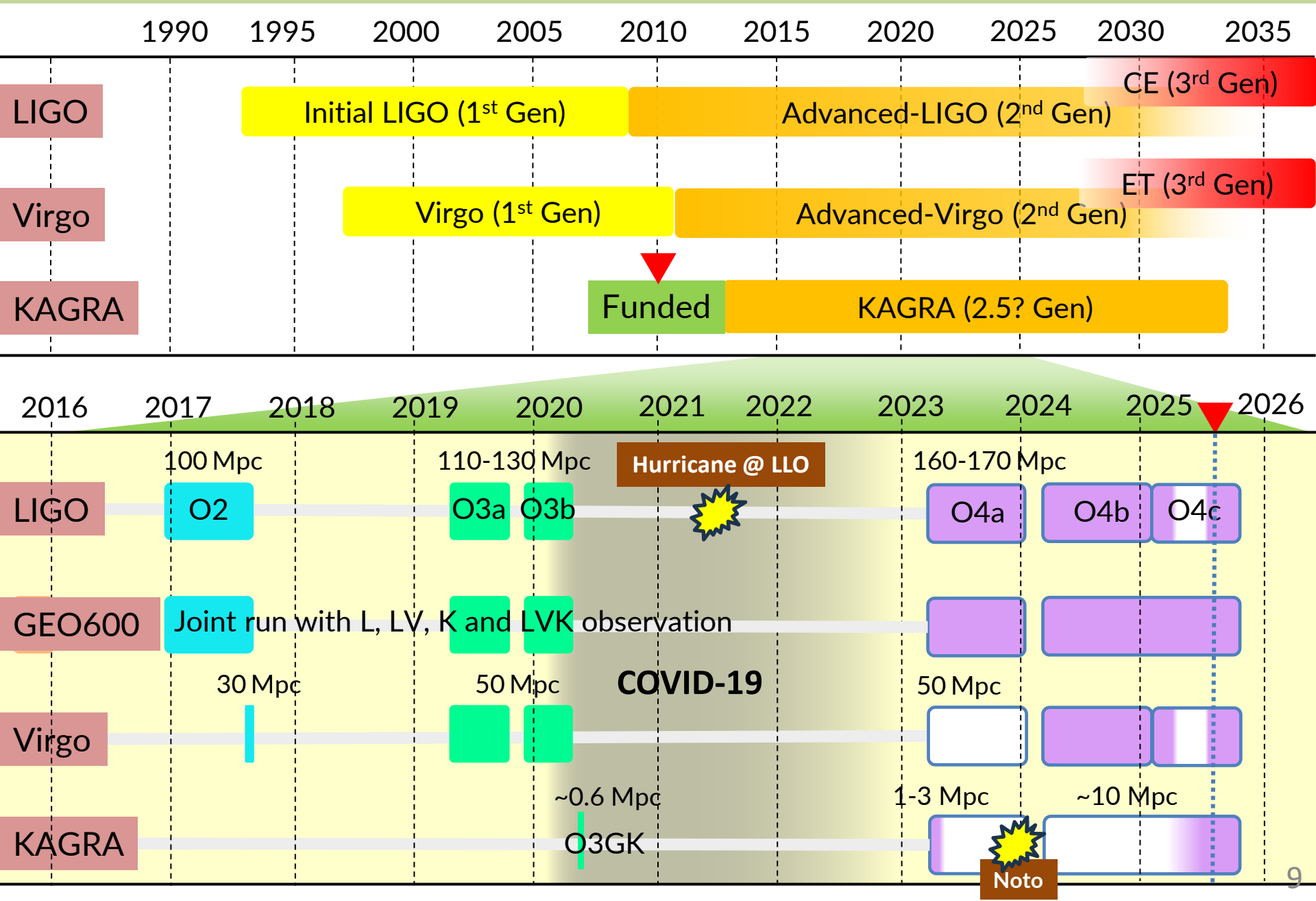

X-Arm
Laser Beam is passing
3km arm length, d80cm vacuum ducts
(Signal Enhancement, Reduction of air fluctuation noise)


Y-Arm
Laser Beam is passing
3km arm length, d80cm vacuum ducts
(Signal Enhancement, Reduction of air fluctuation noise)

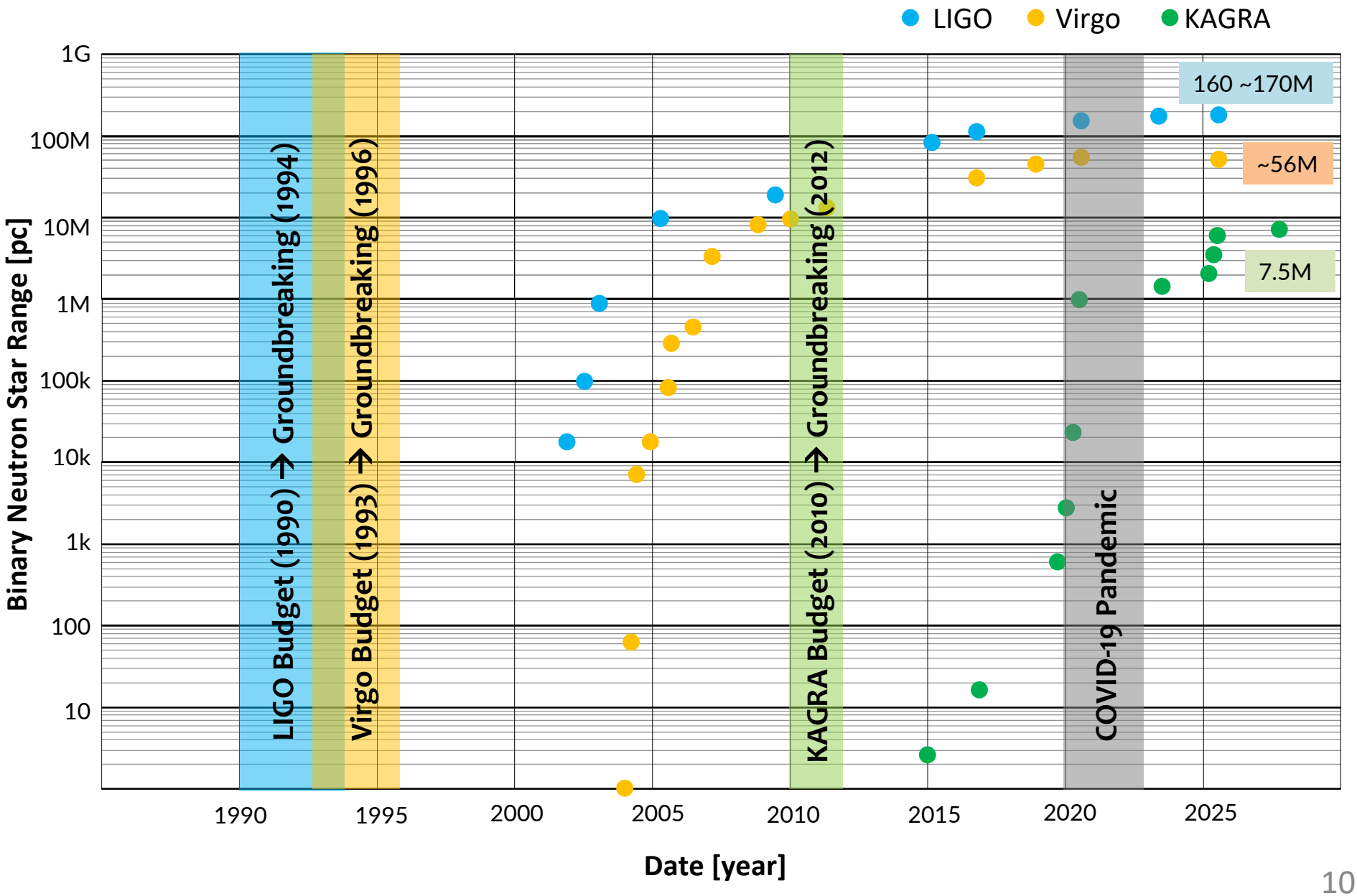
KAGRA Optical Configuration (PRFPMI for O4)



GW Telescopes Generation and LVK Observations



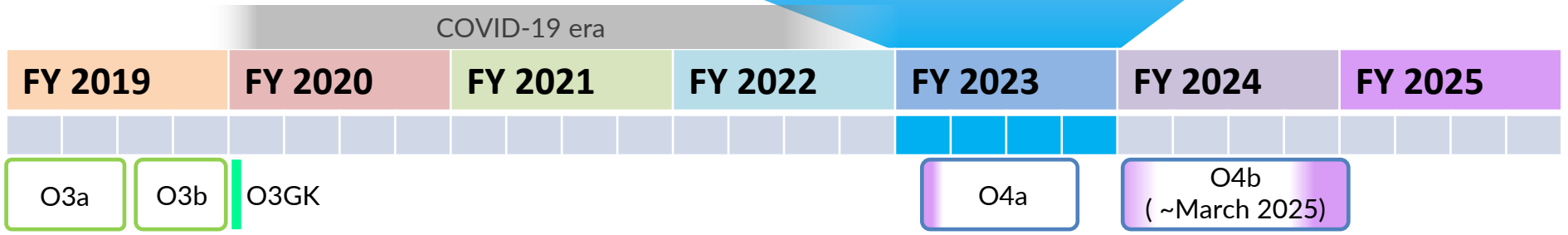
LIGO-Virgo-KAGRA Binary Neutron Star Range History



O4a Observation for one month

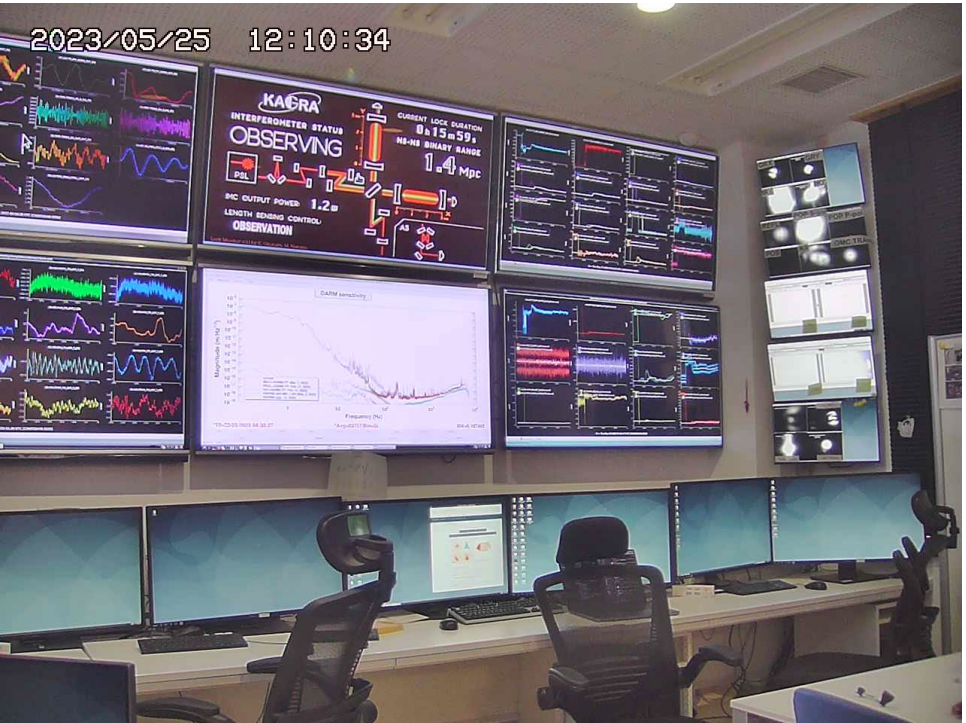
Target BNS: 1 ~ 3 Mpc

(May 2023 ~ June 2023)



KAGRA O4a: Operation Summary

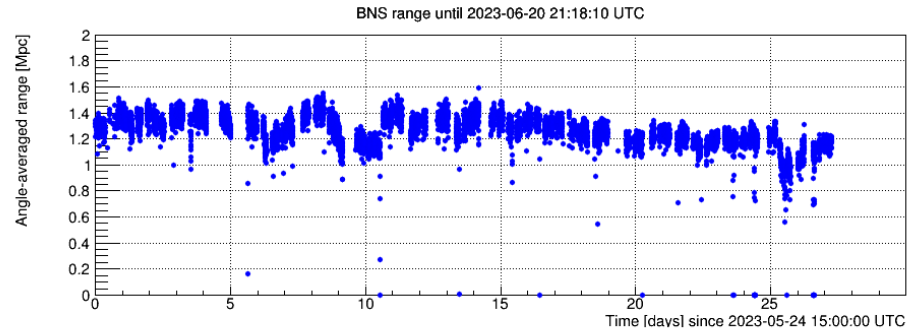
- **O4a summary is here** (https://gwdet.icrr.u-tokyo.ac.jp/~controls/misc/html/)
- **Calibration/Detector Characterization days, night Engineering Run, Start, End and CAL/Det days as follows**
  - CAL/Det & ER : 17th May --- 24th May 08:00 (JST) for KAGRA. (LV approved)
  - O4a : 24th May 08:00 (JST) --- 21st June 08:00 (JST). LIGO started from May 24th 24:00 (JST).
  - 3 operator shifts: noon, night, mid-night
  - CAL/DET: 21st June --- 28th June after KAGRA O4a.

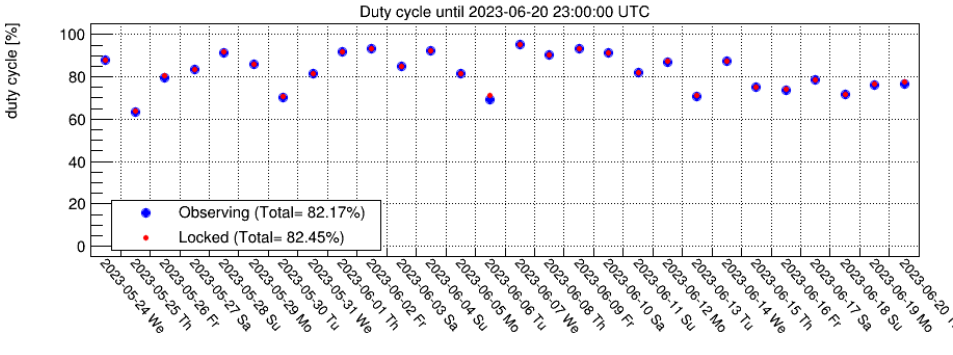


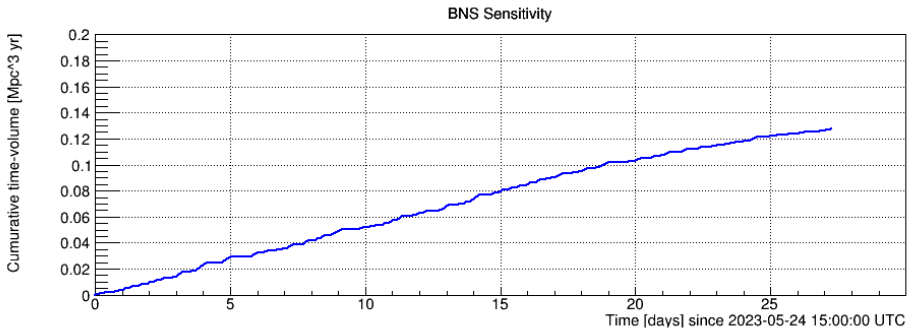
Events	data & time	24:00~8:00	8:00 ~ 16:00	16:00 ~ 24:00	メンテメンバー 坑口スタッフ
Fixed Plan					
GWADW(Elba)	5/24	non	池田	安居	
	水	non	譲原	中垣	
GWADW(Elba)	5/25	佐藤	池田	安居	
	木	田中	譲原	中垣	
GWADW(Elba)	5/26	佐藤	池田	安居	
	金	田中	R麻生	中垣	
GWADW(Elba)	5/27	佐藤	押野	青海	高橋正
BGWT(CERN)	土	田中	横澤	平田	山口
	5/28	佐藤	譲原	青海	吉村
BGWT(CERN)	日	田中	横澤	平田	大前
KIW(Taiwan)	5/29	安居	池田	青海	
BGWT(CERN)	月	中垣	譲原	平田	
KIW(Taiwan)	5/30	安居	池田	青海	山本
	火	中垣	譲原	平田	池田、譲原
	5/31	安居	池田	平田	
	水	中垣	譲原	田中	
	6/1	安居	non	佐藤	
	木	中垣	non	田中	

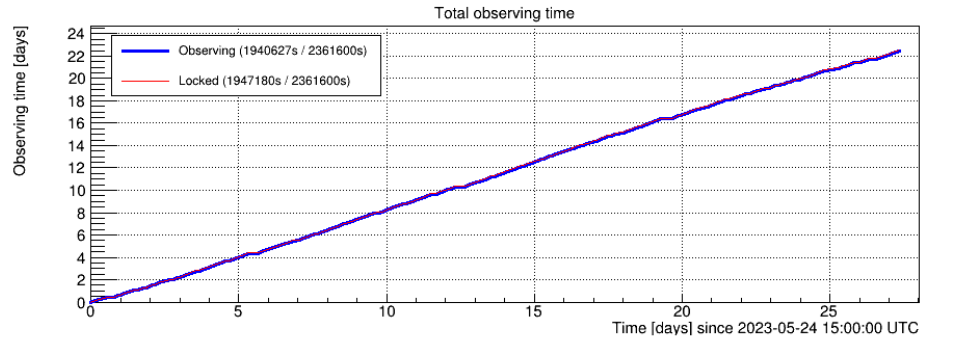
KAGRA O4a: BNS Sensitivity

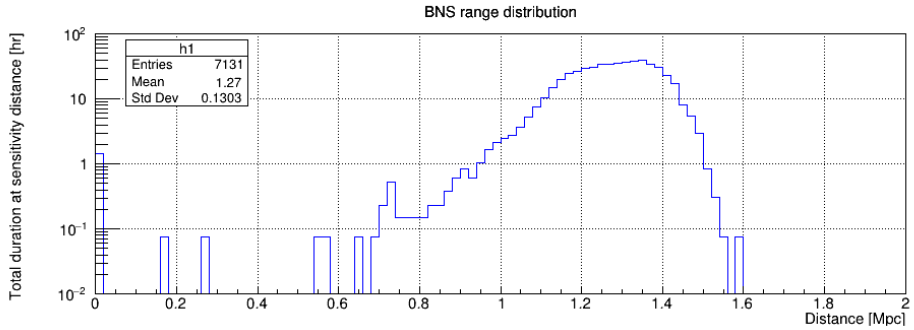
- Started with 1.3Mpc.
- The average is ~1.3Mpc. (~ 0.7Mpc in O3GK)
- ~ 80% including the Tuesday maintenance day. (53.2% in O3GK)

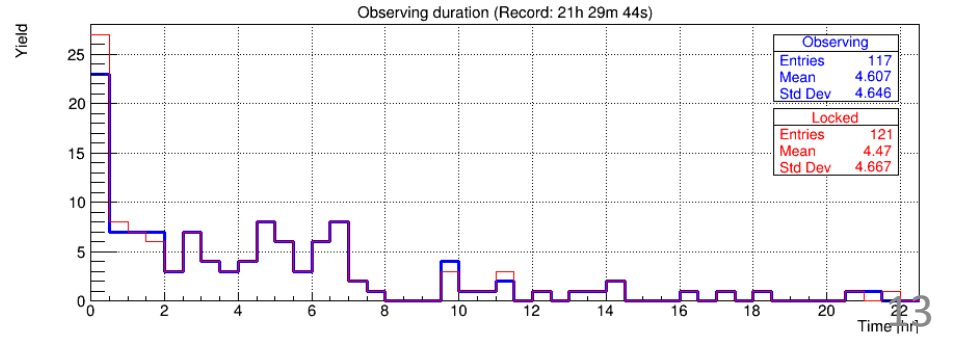












KAGRA O4a: Lock-Loss Sources

- **Main sources are earthquakes**

EQ: Earthquake
1Hz: Earthquake only in human band
OVF: ADC/DAC saturation
REQ: Human request

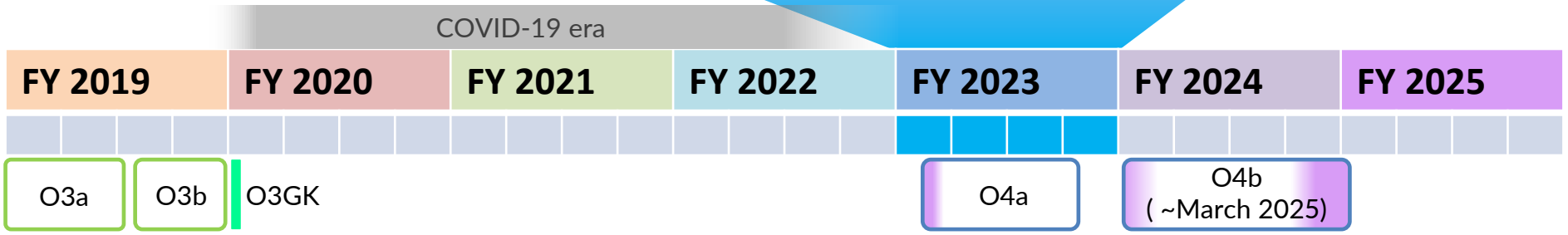
ID	lockloss GPS	JST	Segment	duration	label
110	1371156938	2023-06-19 05:55:20 JST	1371145184,1371156938	11754	EQ
111	1371175429	2023-06-19 11:03:31 JST	1371164008,1371175429	11421	EQ
112	1371185798	2023-06-19 13:56:20 JST	1371177756,1371185798	8042	EQ
113	1371209557	2023-06-19 20:32:19 JST	1371187521,1371209557	22036	EQ
114	1371232565	2023-06-20 02:55:47 JST	1371221849,1371232565	10716	EQ
115	1371250840	2023-06-20 08:00:22 JST	1371233317,1371250840	17523	REQ
116	1371287335	2023-06-20 18:08:37 JST	1371269717,1371287335	17618	EQ
117	1371294661	2023-06-20 20:10:43 JST	1371289414,1371294661	5247	1Hz
118	1371331109	2023-06-21 06:18:11 JST	1371296488,1371331109	34621	OVF,1Hz
119	1371337218	2023-06-21 08:00:00 JST	1371331143,1371337218	6075	REQ

O4a End

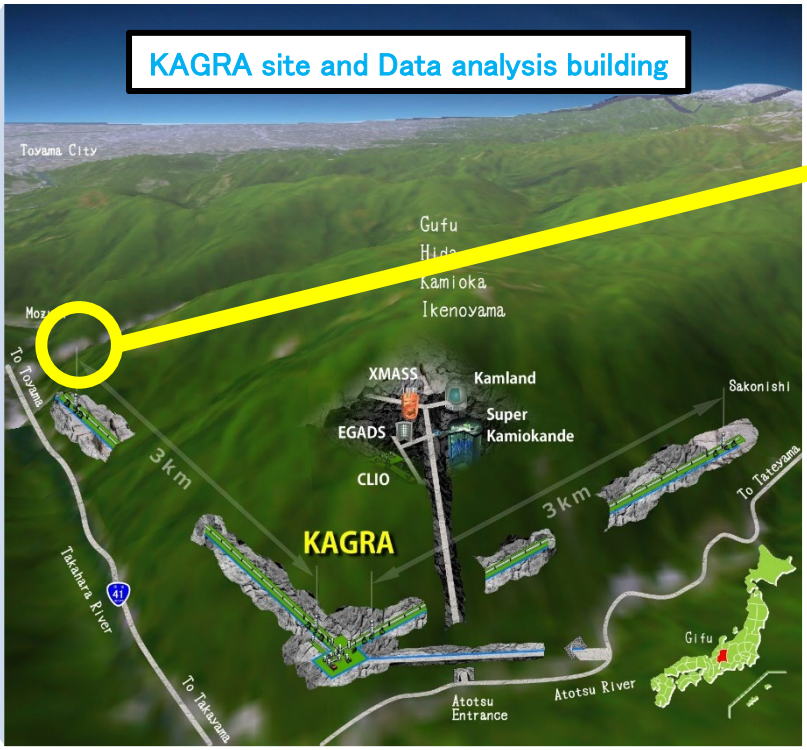
Commissioning for O4b/c

Target BNS: ~10 Mpc

(June 2023 ~ December 2023)



Noto-Earthquakes damaged KAGRA on Jan 1, 2024



- List of Large Earthquakes in the past 100 years
  - 1909 Aug 14, M6.8【Anegawa 】Lv.3
  - 1944 Dec 7, M7.9【Tounankai】Lv.4
  - 2011 Feb 17, M5.5【Hida area】Lv.3～4
  - 2023 May 5, M6.5【 Noto Peninsula】LV.2～3
  - 2024 Jan 1, M7.6【 Reiwa 6 Noto Peninsula】LV 5- (Red color means KAGRA was operated.)

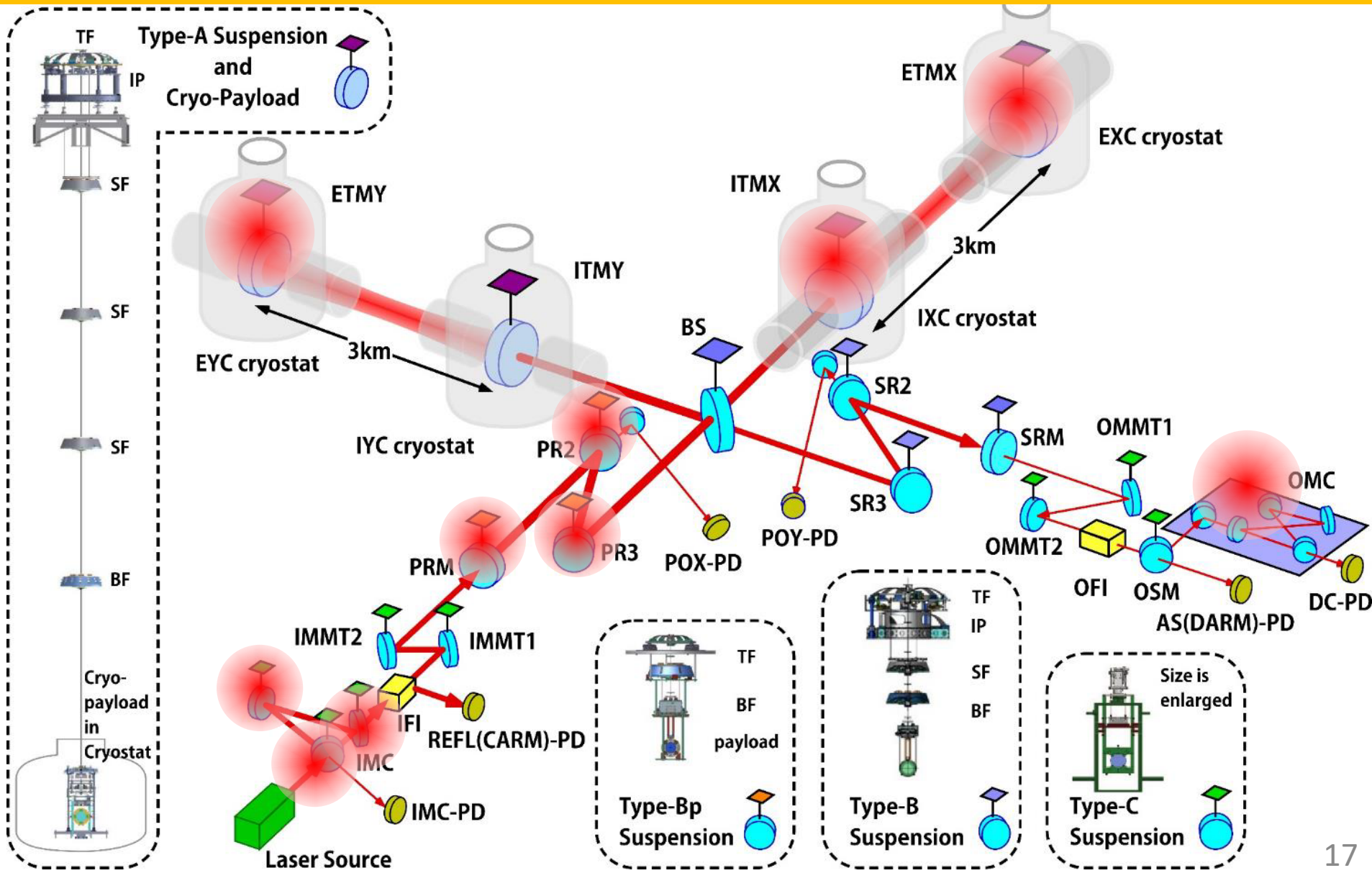
  Lv.5- was the largest earthquake at least in the last 100 years.

- 4m elevation at the seashore area. One per 6000 years!

- According to GIAJ (Geophysical information Authority of Japan, 国土地理院), the mountain housing KAGRA moved 2~3cm in the direction of Y-arm（ https://www.gsi.go.jp/common/000254115.pdf ）。

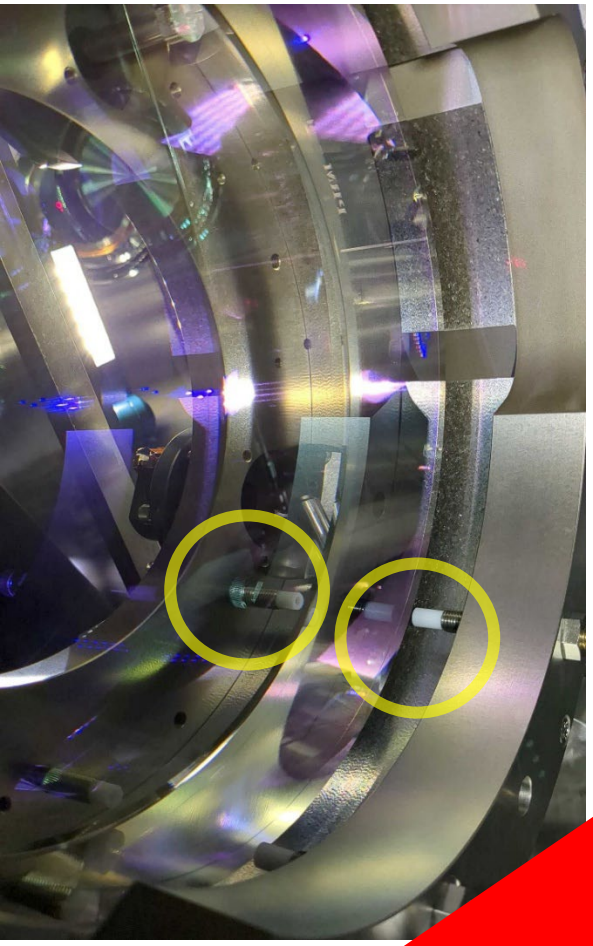
10 of 20 Mirror Suspensions were Damaged

All are housed in the vacuum area except for PDs and Lasers.

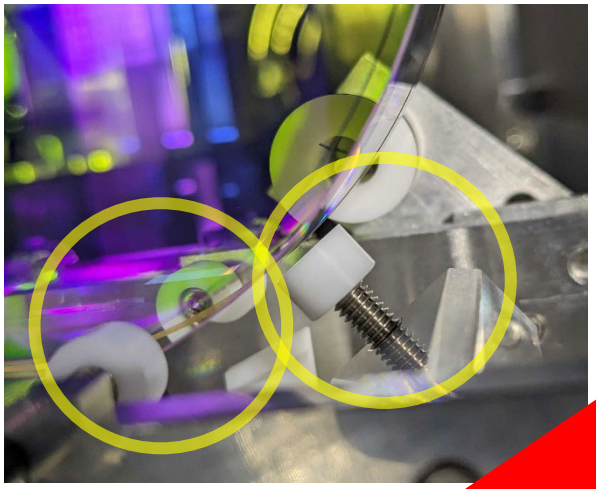


We had EQ Stoppers for Mirror Protection, but …

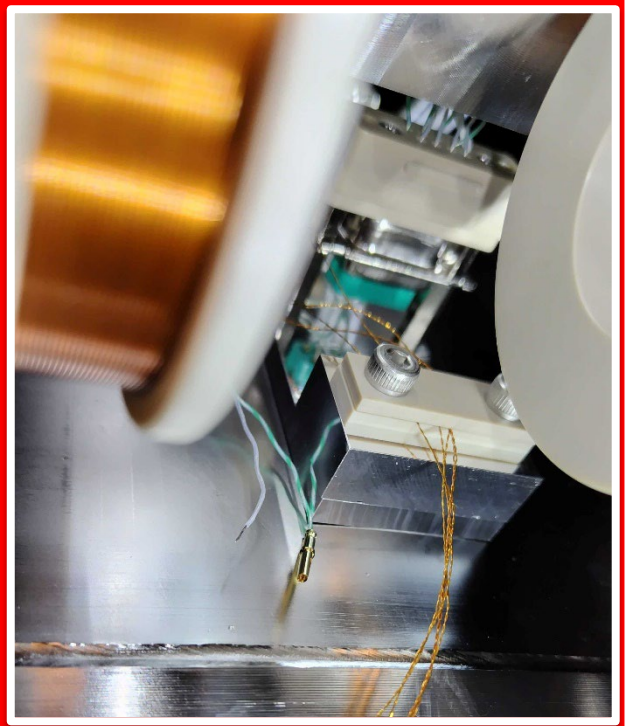
Type-Bp EQ Stopper



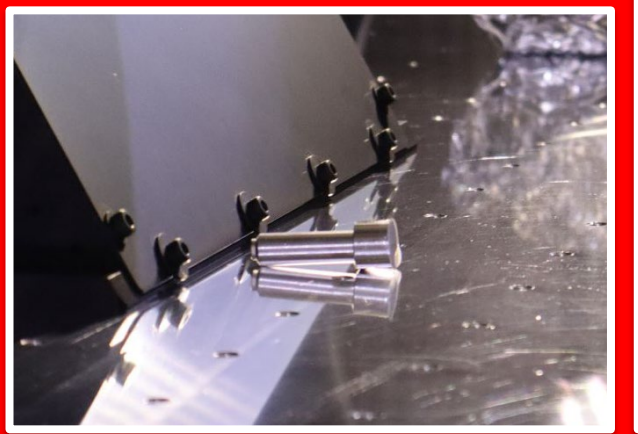
Type-C EQ Stopper



Signal Wire Cut because they were sandwiched by suspension components

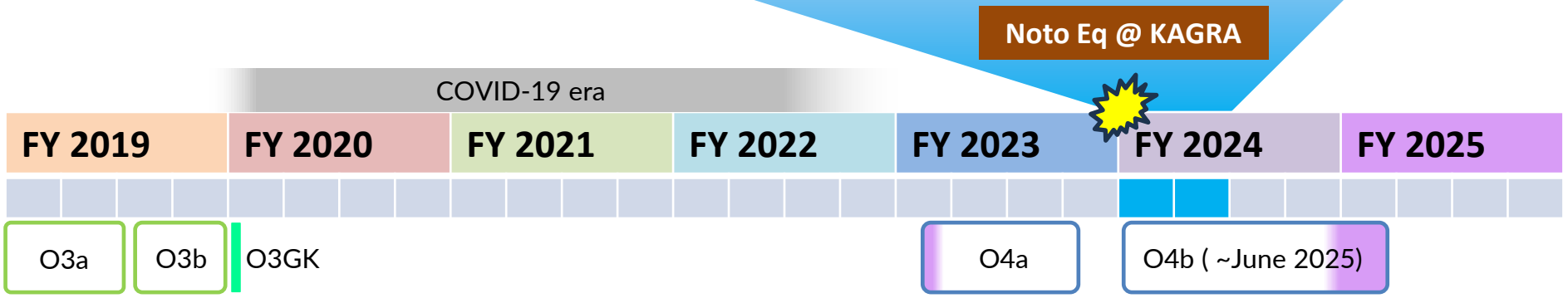


Magnet Dropoff because of hitting on facing coil body



Recovery of KAGRA

(January 2024 ~ July 2024)



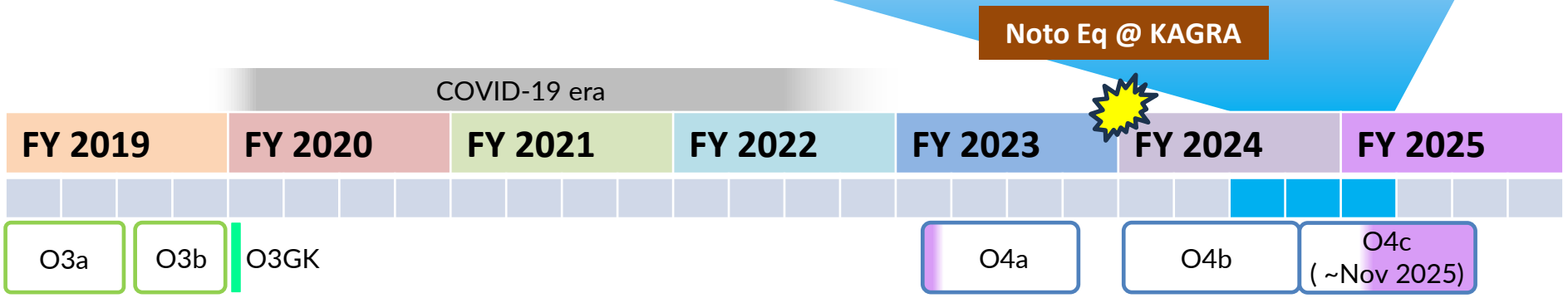
Heartful Messages

- **Many citizens of Hida-city gave us so many heartful messages for the KAGRA recovery.**

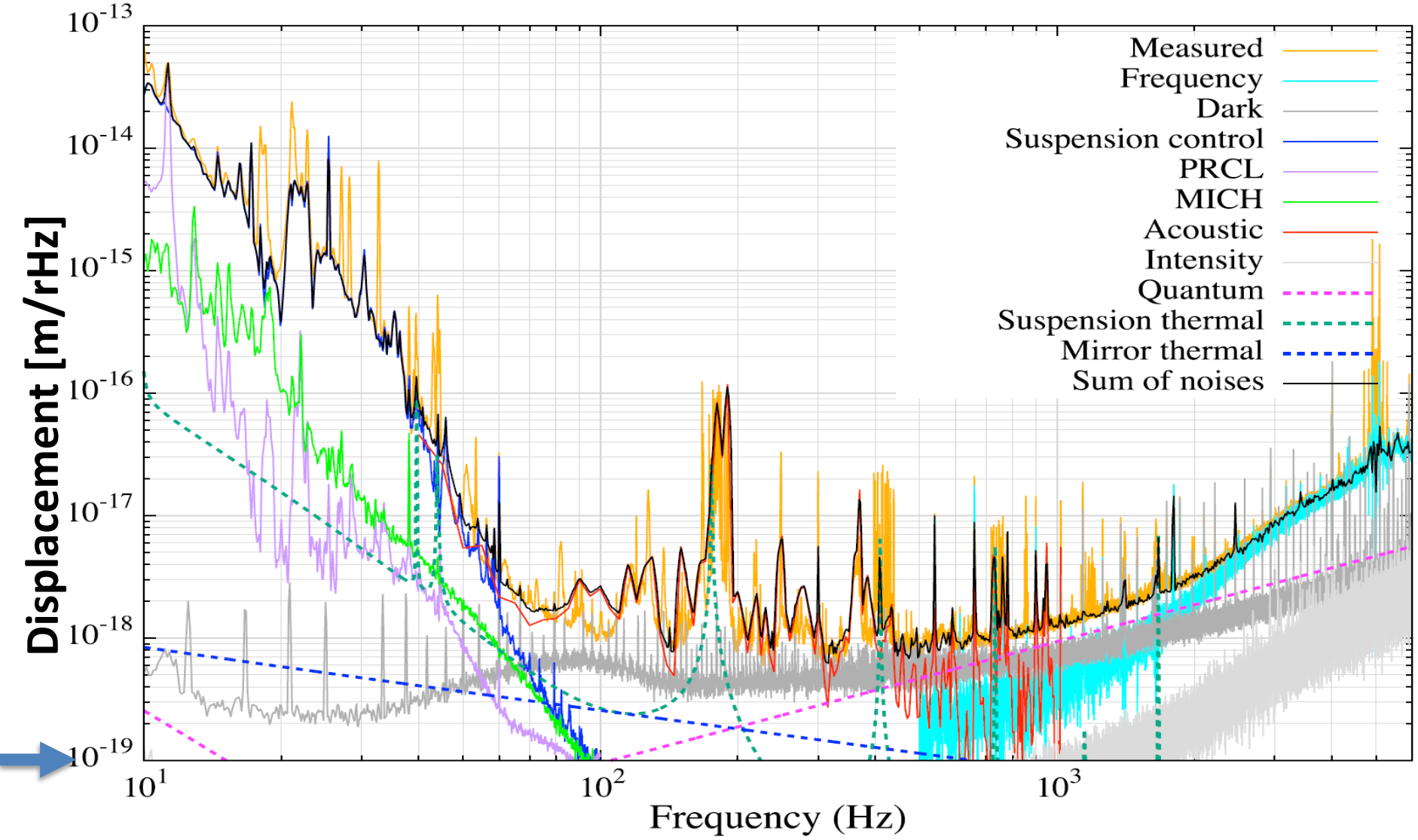
Commissioning Restart for O4c

Target BNS: ~10 Mpc

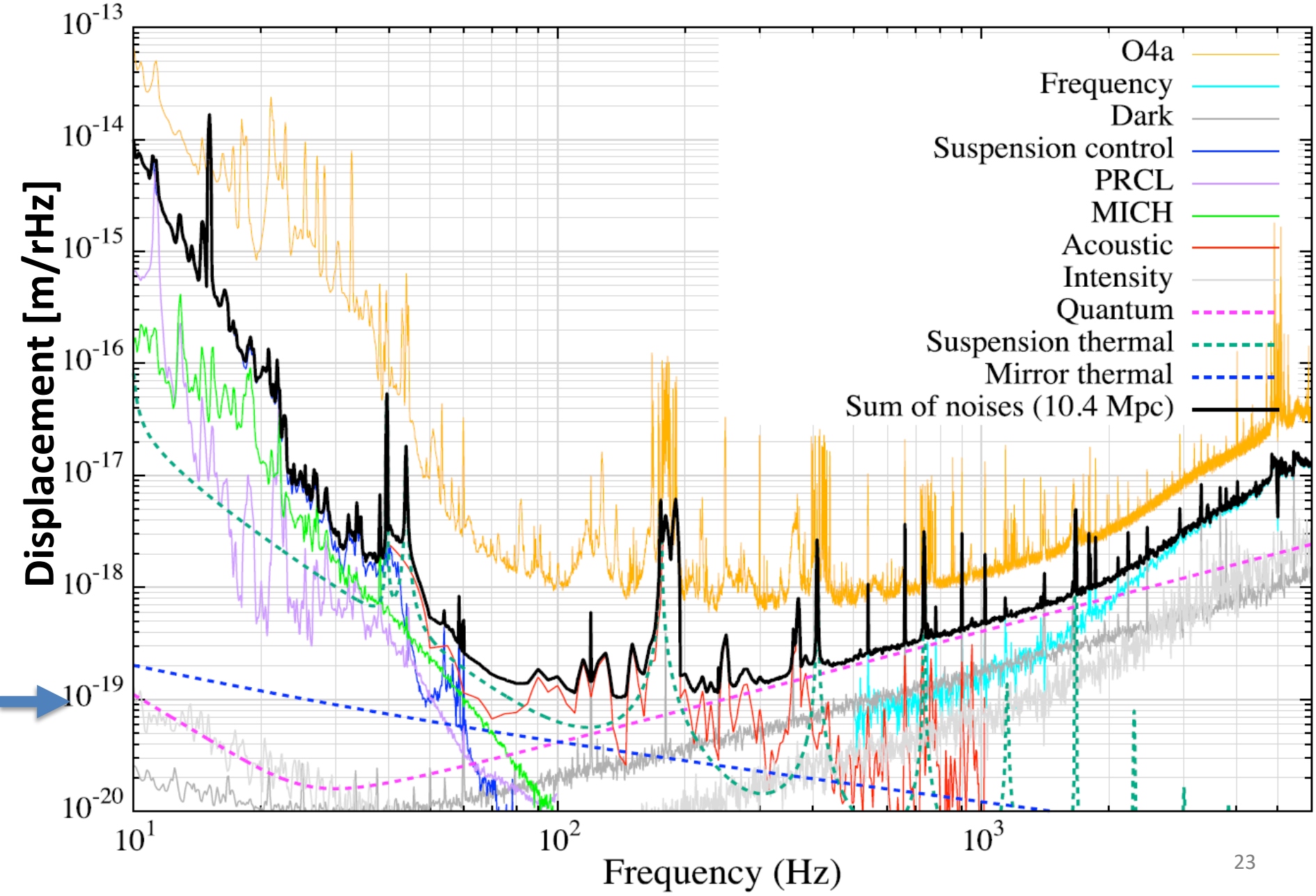
(July 2024 ~ June 2025)



O4a (2023 May ~ June) Noise Budget



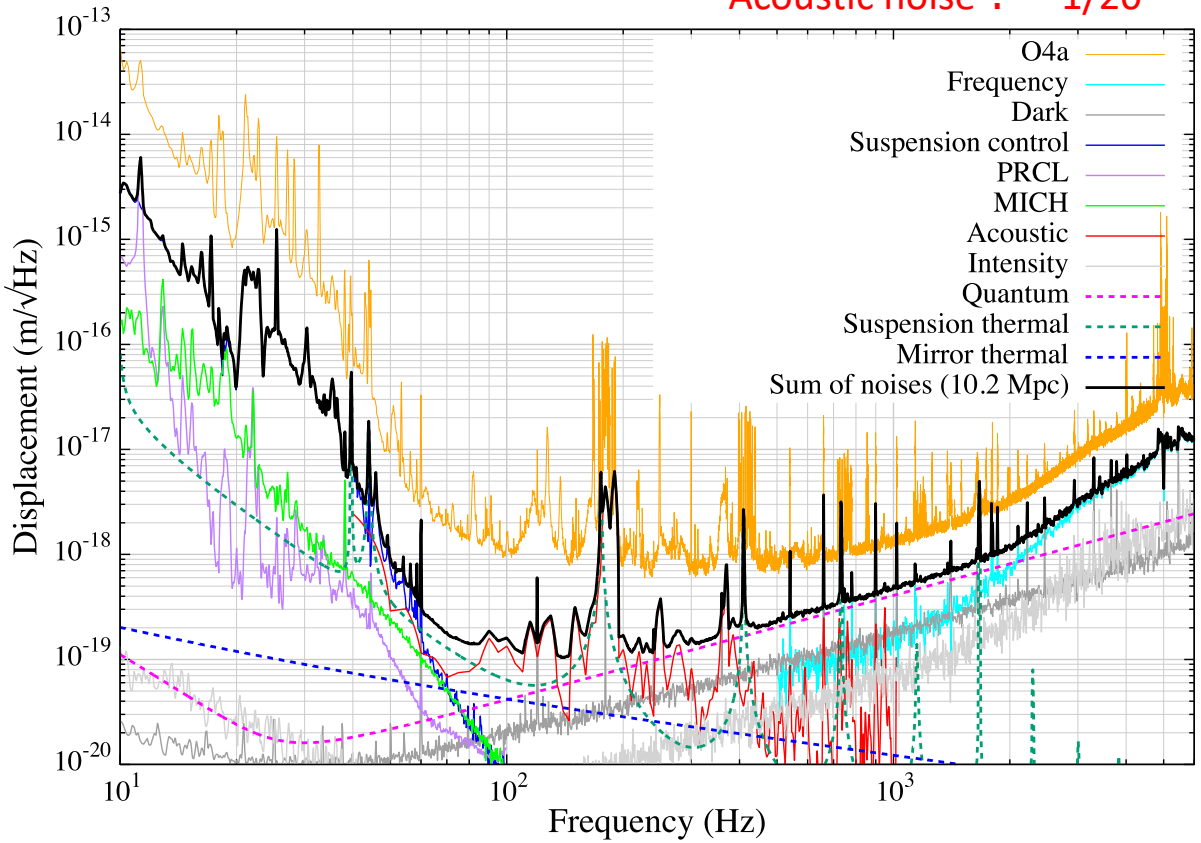
Expected Sensitivity Curve and its Noise budgets for O4c



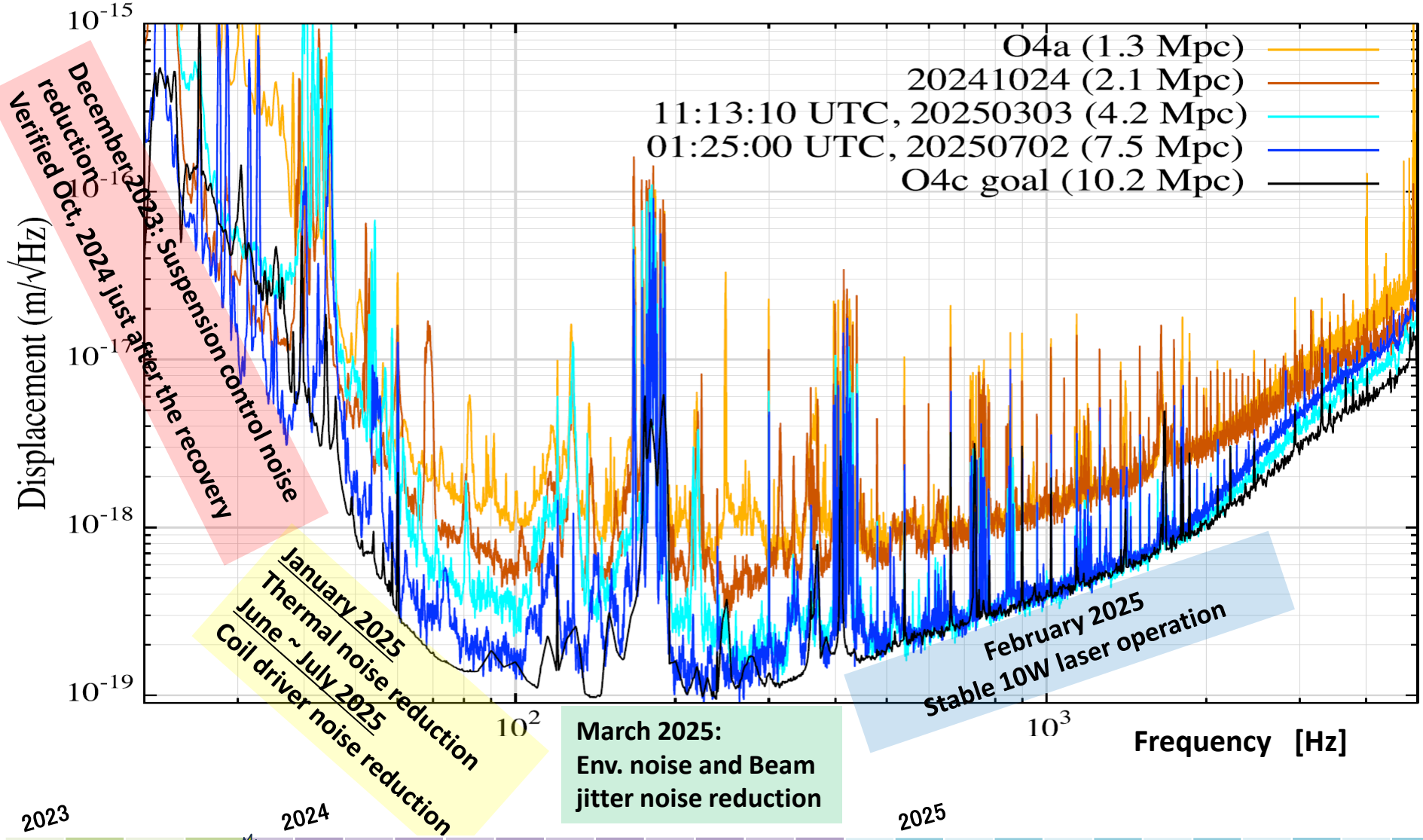
Strategies to Realize 10Mpc

1. **Already reduced noise before Noto Earthquake(Jan 2024)：**
   - Suspension control noise：1/10
   - Interferometer (IFO) control noise reduction：1/10
   - PD dark noise reduction

2. **Noise reduction Plan after Recovery (Oct 2024)**
   - **High power operation：10W done Feb 2025**
     - PRCL, MICH control noise：1/10
     - Quantum shot noise：1/3
   - **Cooling：~ 100K → Done Jan 2025**
     - Thermal noise：1/5
   - **Control/hardware update：done in March 2025**
     - Frequency noise：～1/2
     - Acoustic noise：～1/20



Recovery from Disaster and Commissioning [1.3Mpc(O4a) → 6.9Mpc (Now)]

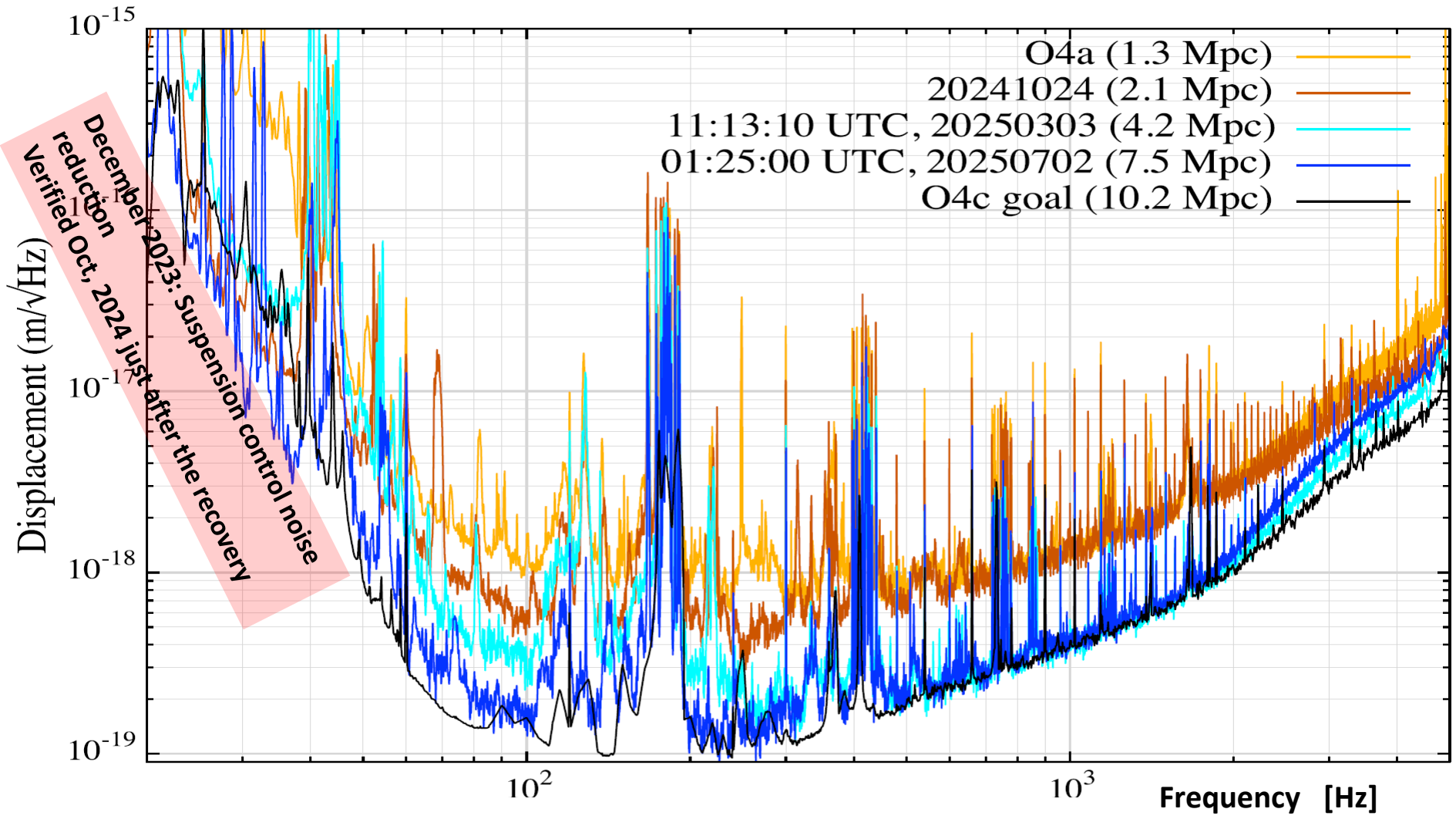


2023 2024 2025

9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12

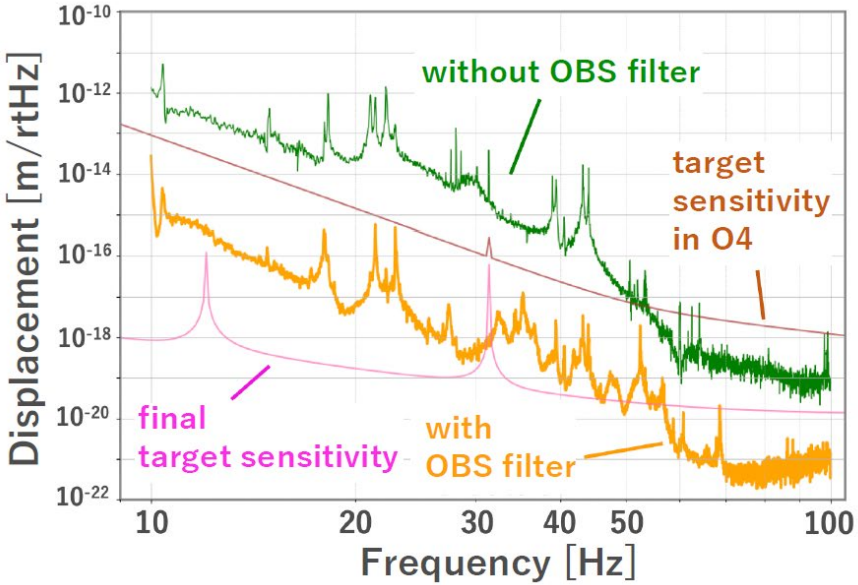
Suspension control noise reduction, etc.	Recovery mainly for 10 suspensions and vacuum system OMC Stack Recovery	Recovery of Optical Control (FPMI → PRFPMI+RF → PRFPMI+DC) Suspension optimization	Thermal noise reduction by cooling (with serious troubles in one cryocooler at EX) 10W laser operation Beam jitter Noise Reduction Mirror control noise red.	O4c with LIGO Virgo	Up – Grade For O5

Suspension control noise reduction



Suspension control noise reduction

- **Drastic reduction of the suspension control noise**
  - We changed the local damping control scheme, especially for sapphire mirror suspensions, to reduce the control noise at low frequency. In fact, 100 times reduction of local control feedback signals of sapphire mirror suspensions was already achieved in the end of last year, but we have no chance to check it with the interferometer due to the Noto earthquake on January 1, 2024.



Result

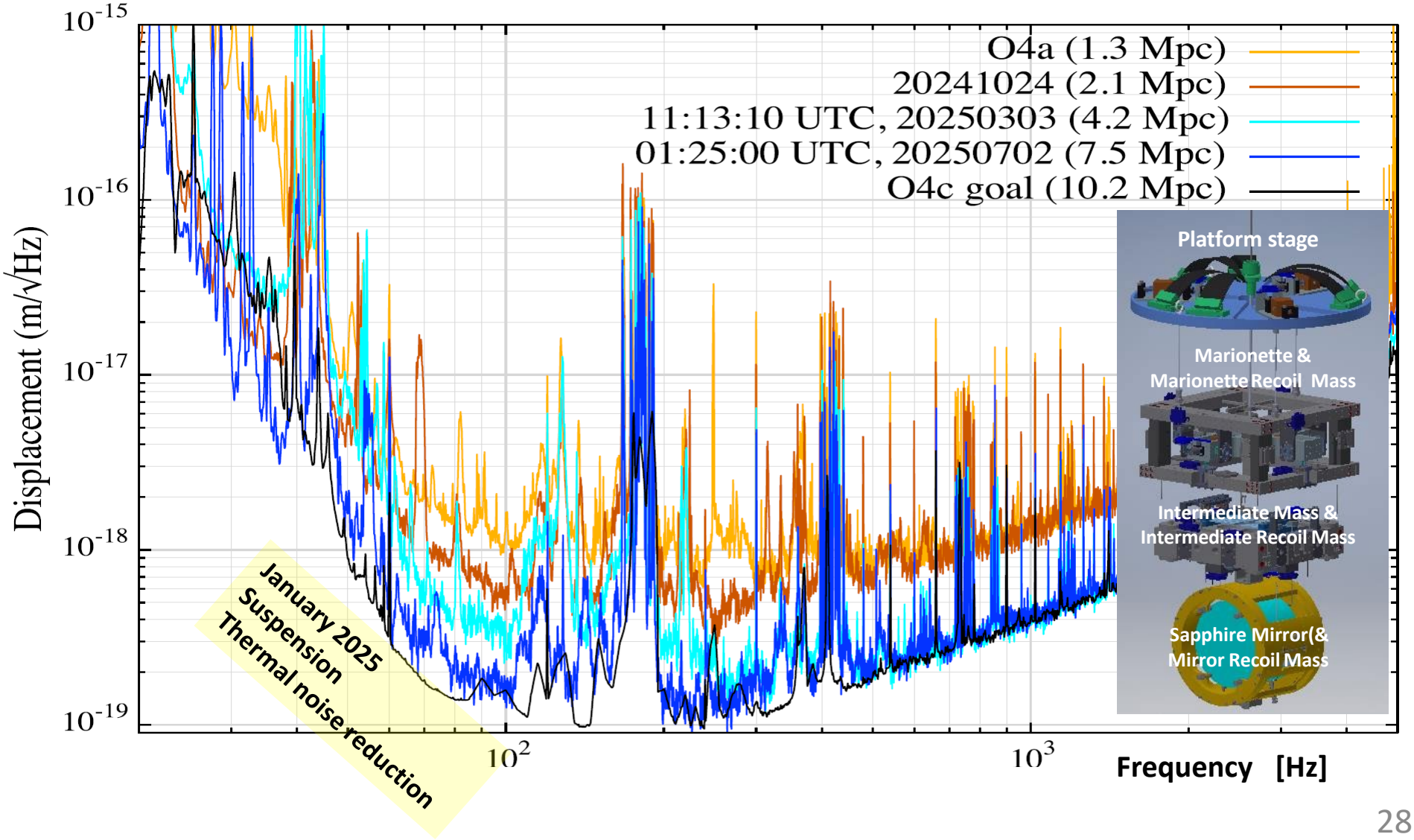
Control noise was reduced by 2~3 order of magnitde

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

  - The slight improvement between 30-60 Hz comes from local control update of the other suspension such as BS, SRs, and PRs because the sensitivity during O4a was limited by local control noise of these suspensions up to 60 Hz.

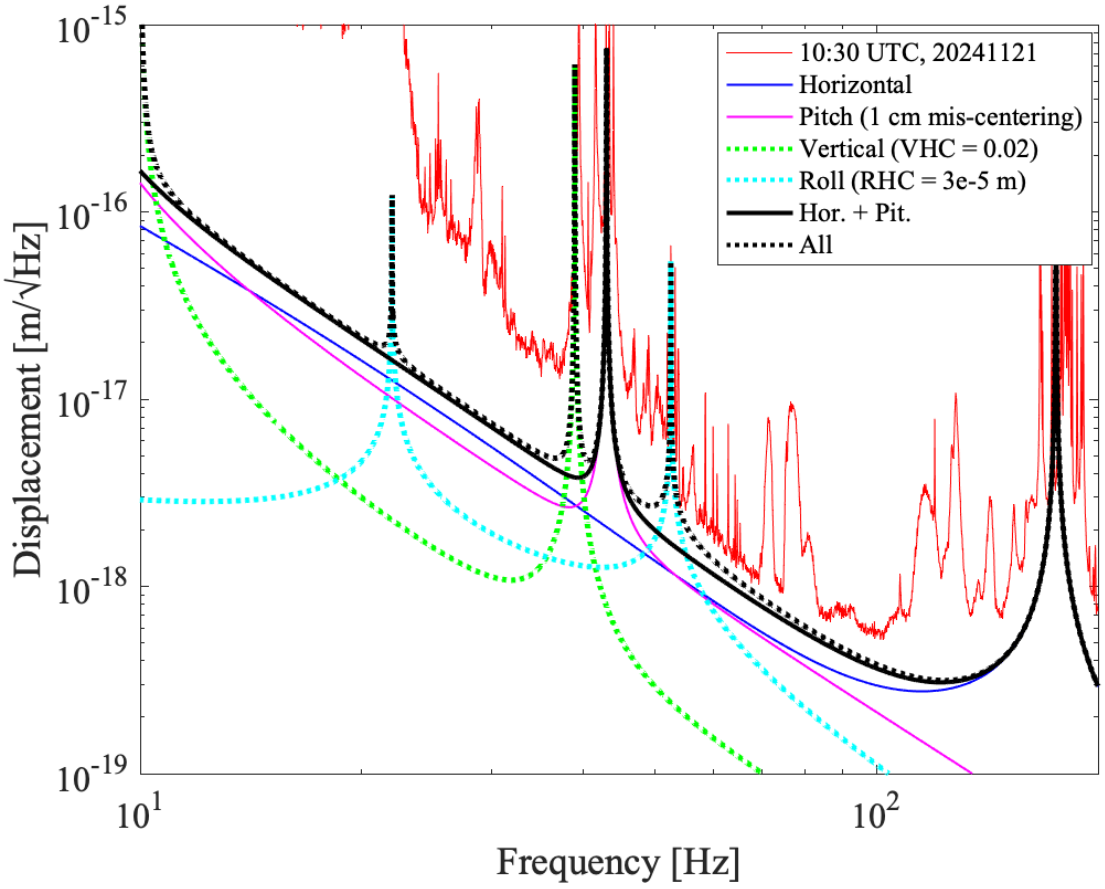
Suspension Thermal Noise Reduction

- Several Noise sources
  - Suspension Thermal noise (length and Pitch to Length coupling of ITMY(X))
  - High power coil driver noise for Test Mass, Intermediate Mass, Marionette Stage in the cryopayload.



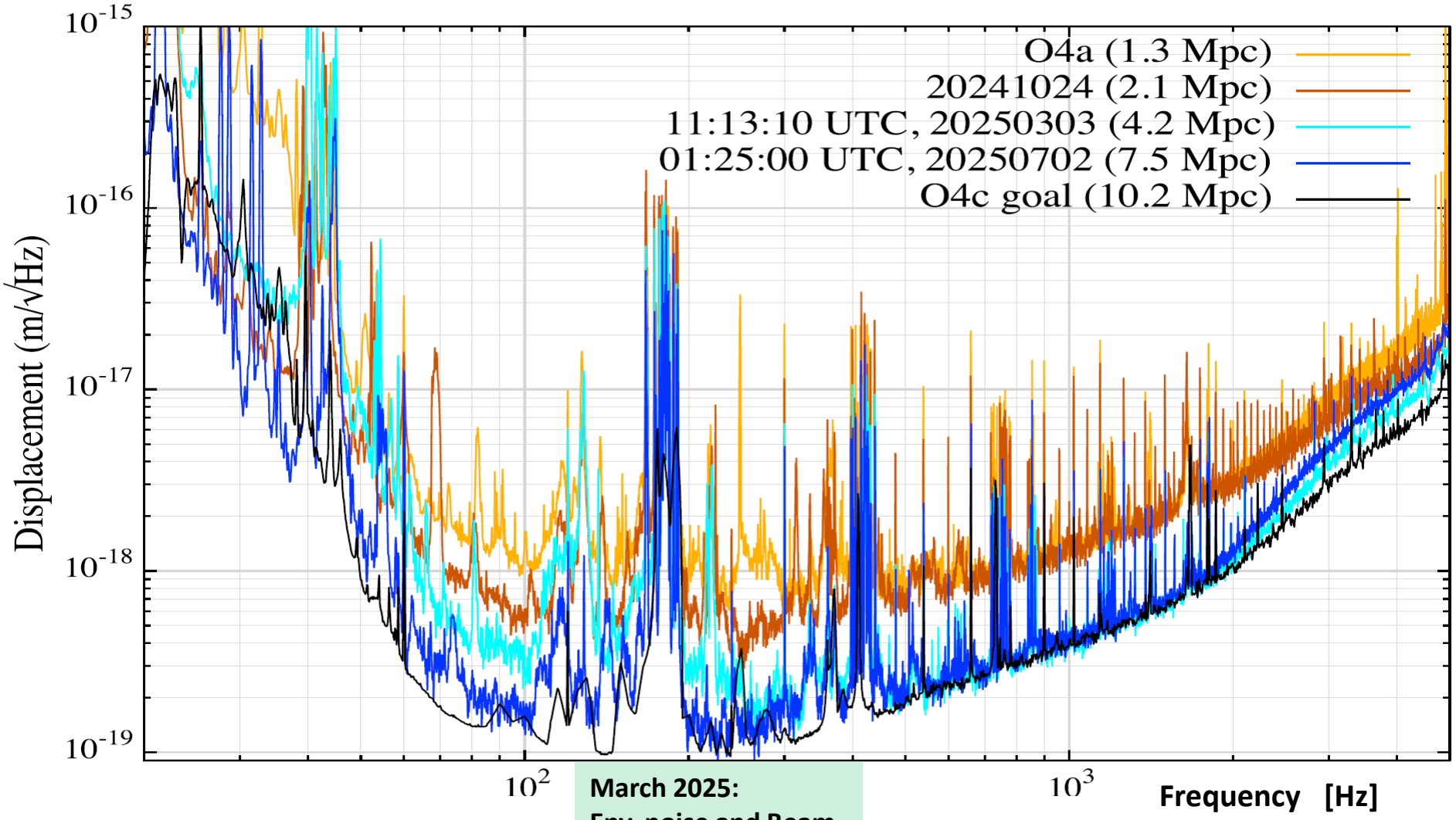
“Pitch” thermal noise to “Length” coupling of ITMY

- Why such coupling happened?
  - In KAGRA, the better IFO condition seemed to favor the off-center beam spot at ITMY(X) (~ upper position by 1cm or so).
  - One possibility is the birefringence in ITMY(X). Beam jitter may couple with the optical property condition changes at each ITM because of the variation of birefringence.
- Anyway, we started cooling sapphire mirrors from October 2024 and completed around the end of January 2025. Sapphire mirror temps were ~ 85K.



Recovery of Stack Isolation for Output Mode Cleaner

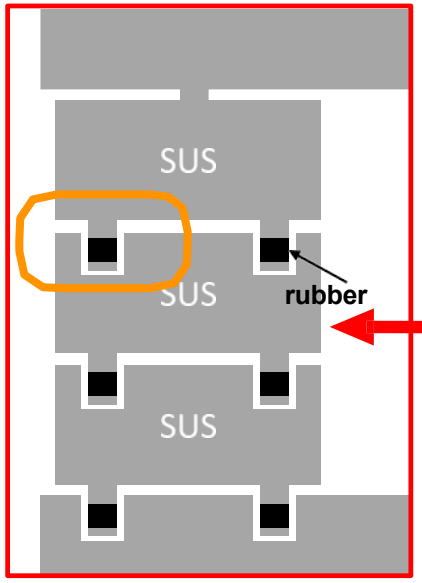
- Ground motion invasion due to stack structure malfunction.
- Insufficient resonance motion damping of Output Mode Cleaner (OMC) structure.
- Insufficient mirror mount fixing generated large beam jitter noise.

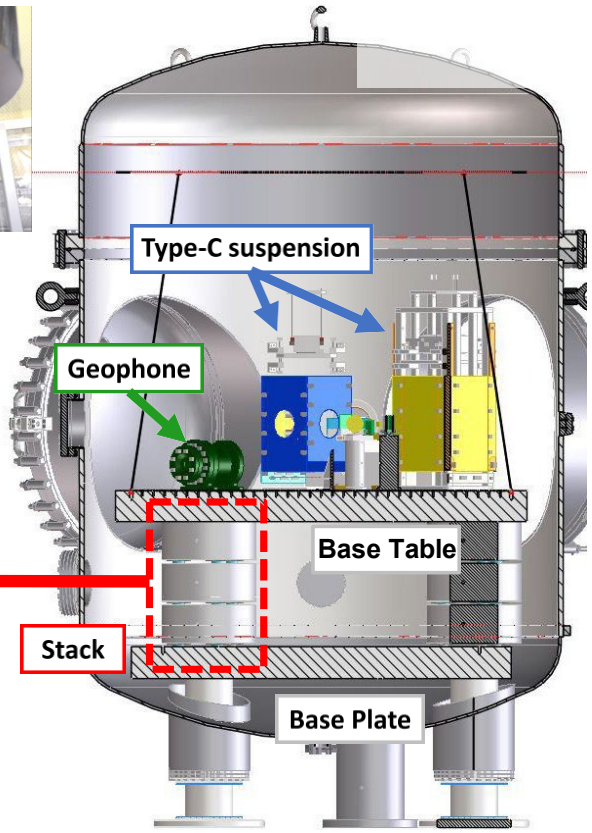


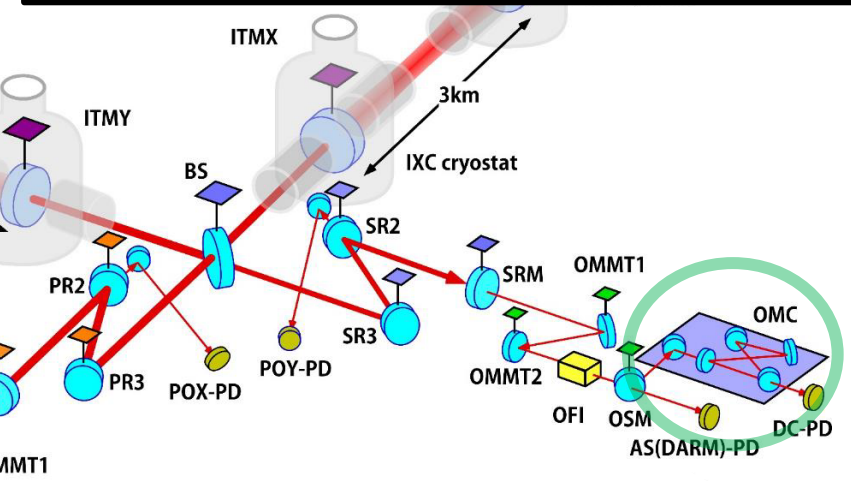
March 2025:
Env. noise and Beam jitter noise reduction

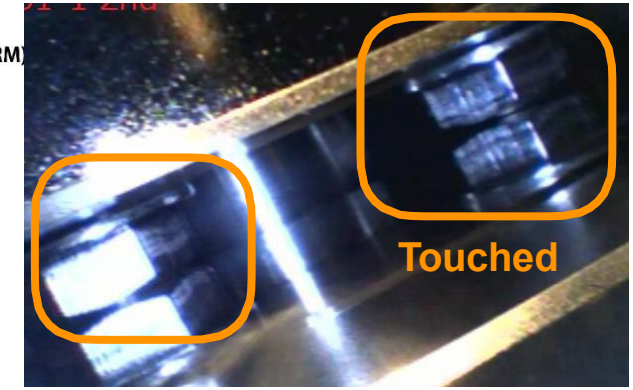
Recovery of Stack Isolation for Output Mode Cleaner

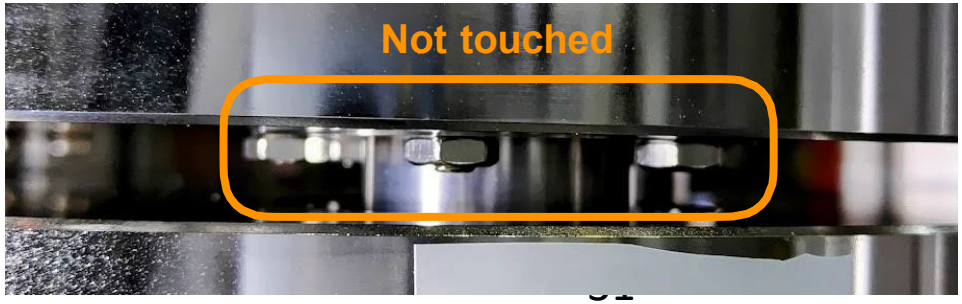
- We found that OMC stack structure was damaged, and it lost seismic noise isolation function because the neighboring SAS blocks contacted with each other.
- We decided to remove all optics inside the OMC vacuum tank and reconstruct the stack structure.



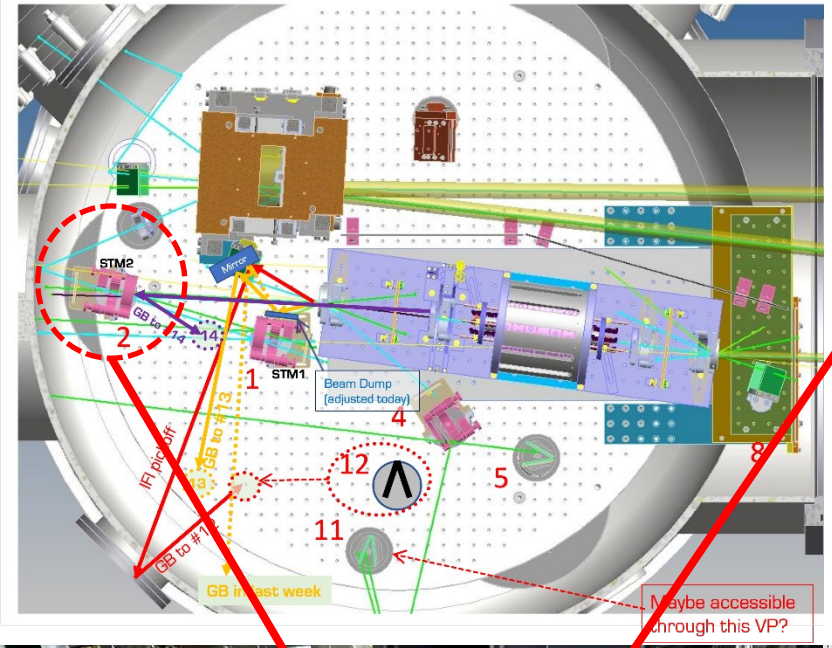




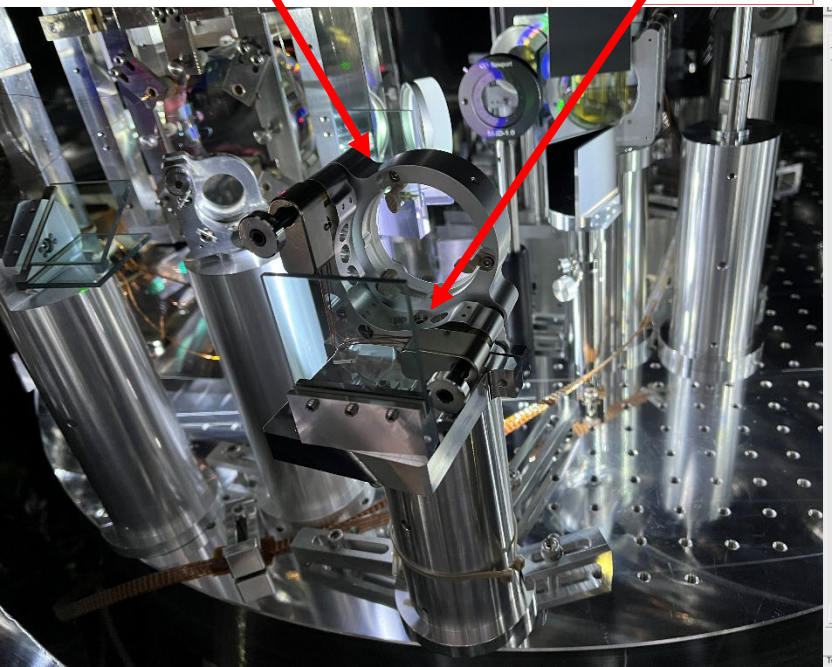


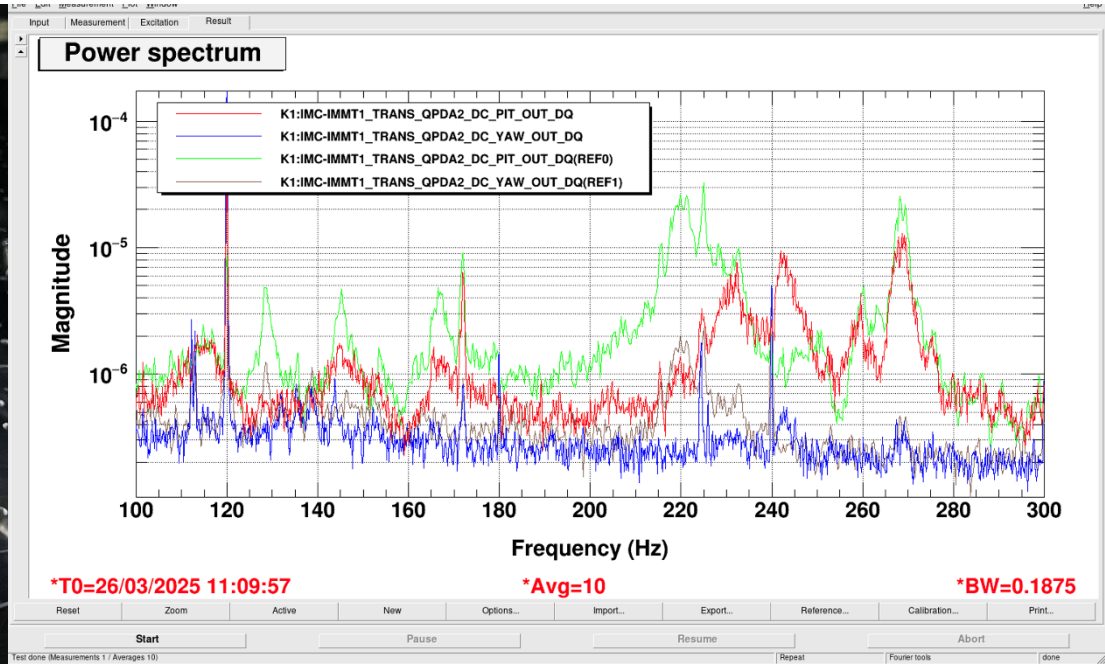


Tight Fixing of STM2 Mirror in IFI Tank



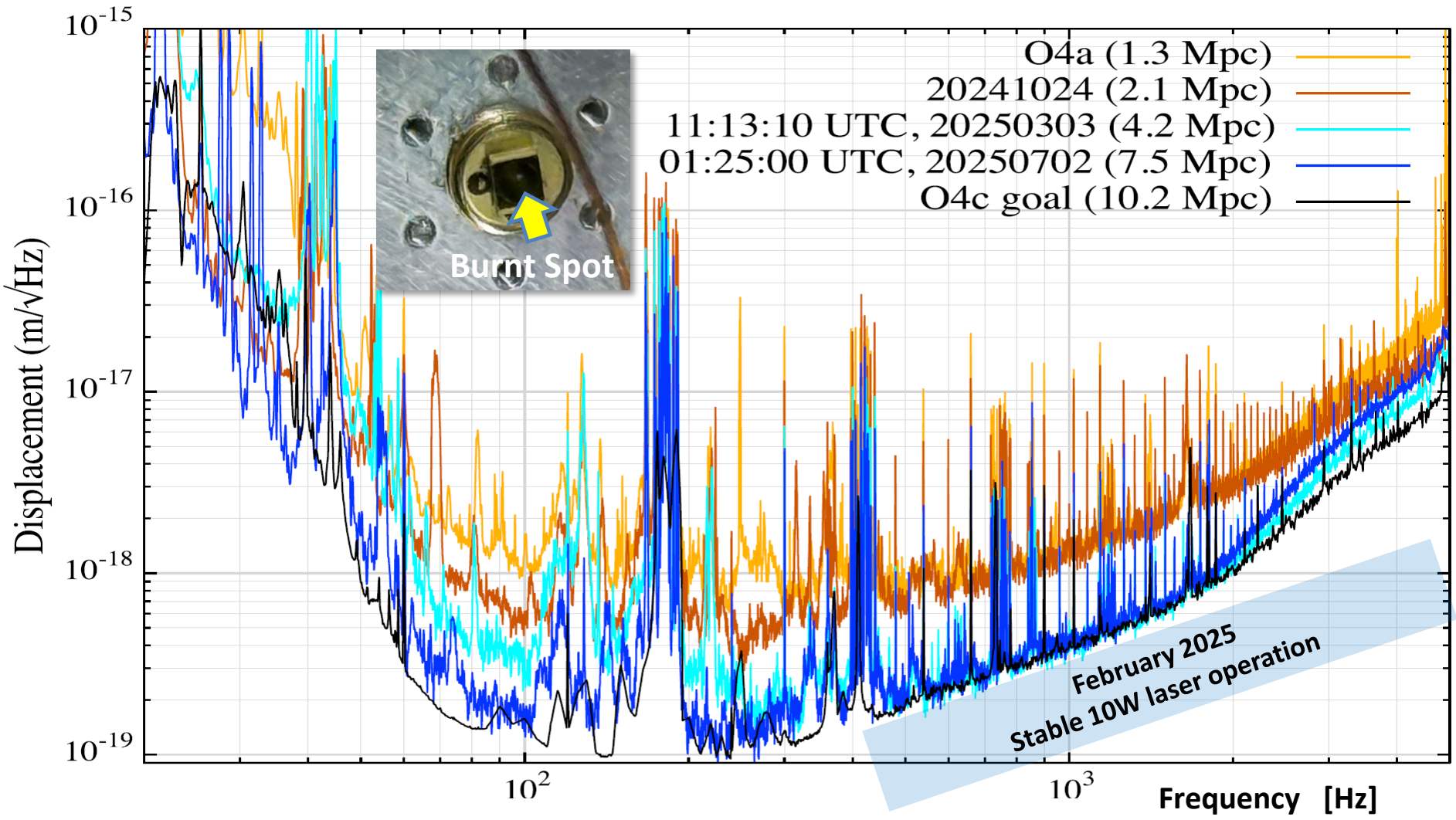
- **We have suspected the beam jitter noise around 120Hz from STM2 mirror which is put on the IFI stack as photo.**
  - We found the M4 cap screw for the mirror mount was not so tight.
  - After fixing tightly it, the vibration of STM2 mirror was improved from “Green” to “Red”.
  - The higher frequency vibrations and peaks could be isolated by the IFI stack because it has sharp reduction ratio from these frequency ranges.
  - We also verified its improvement in the KAGRA sensitivity curves.



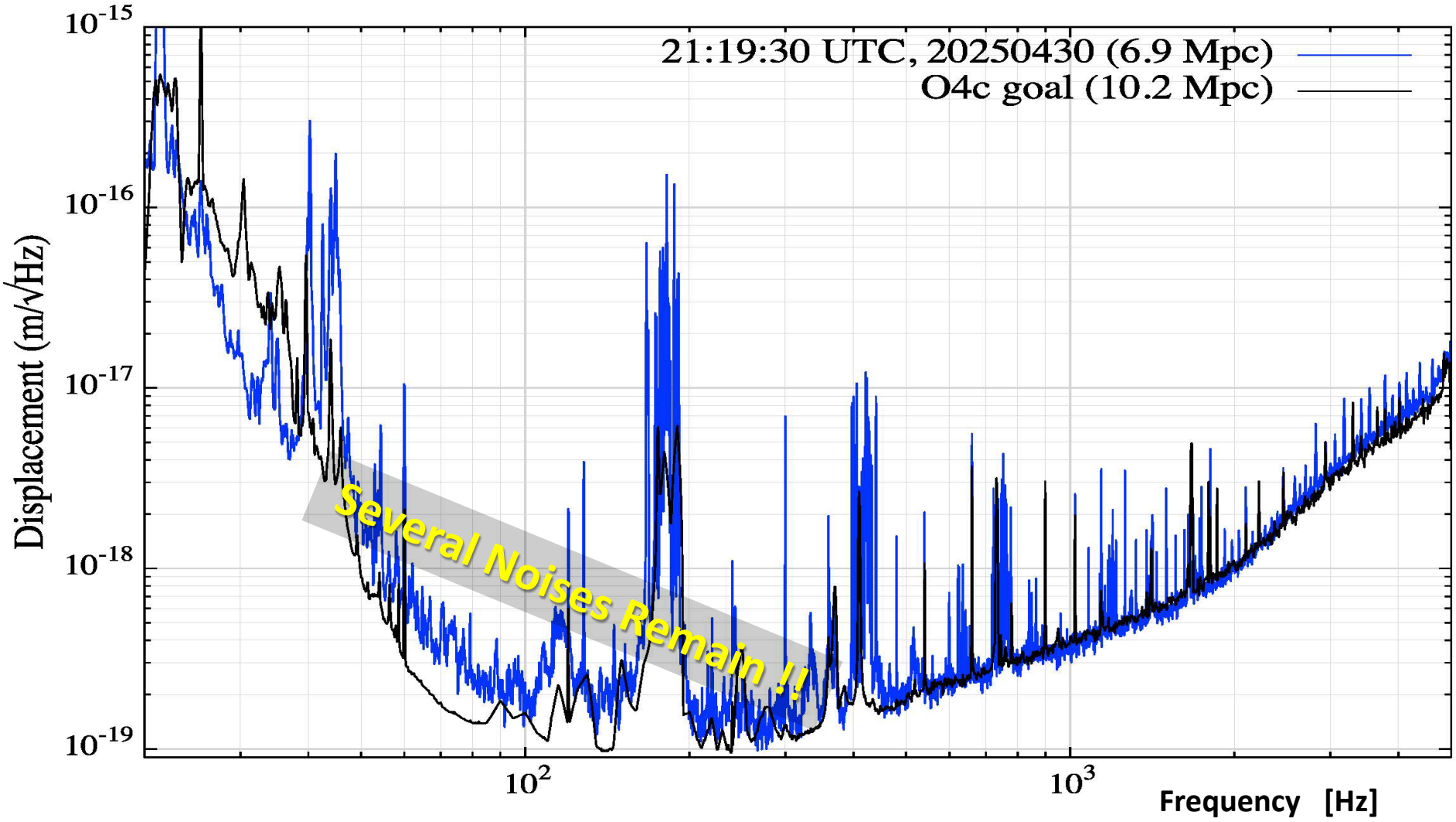


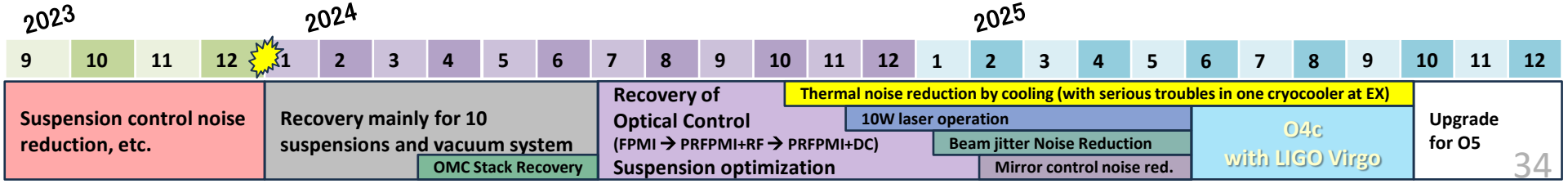
10W Laser Operation (← 1.3W)

- Stable 10W laser operation without PD burning. Shot noise enhancement was as the theory.
- This meant that “No curvature deformation” in sapphire mirrors at ~ 85K with 13x10x1000/2=65kW [W] intracavity power.



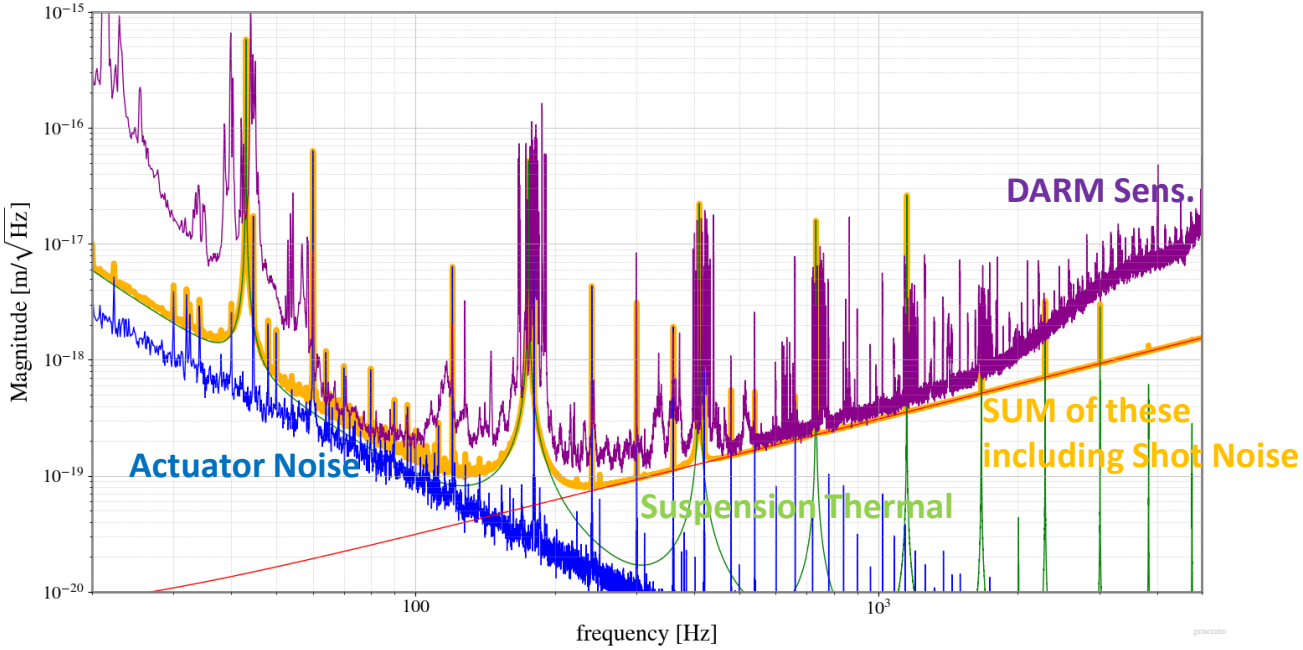
Last “one mile” from 6.9Mpc to 10Mpc BNS sensitivity

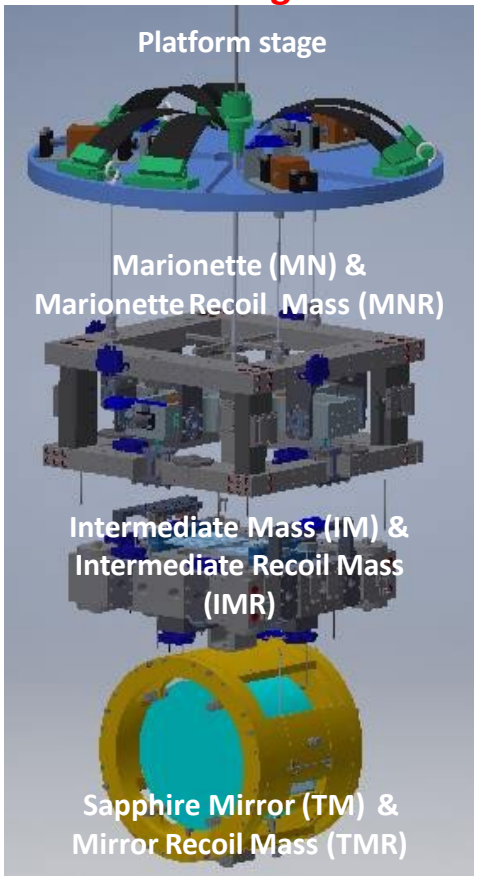




Final one mile (3.1Mpc): Coild Driver Noise should be minimized

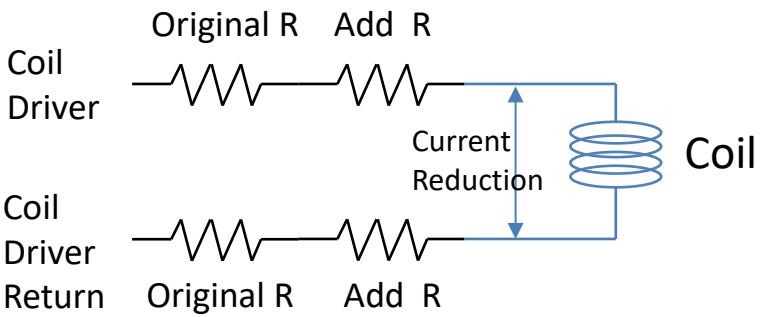
- **Coil Driver noise partially dominates the sensitivity around 100Hz because we still use "high power coil driver(HPCD)" whose electrical noise can drive TMs, IMs, MNs a lot.**
  - We need to use "Low power coil driver (LPCD)" in the "**hierarchical length control chain**" after the PRFPMI+DC with HPCD.
    - The switcher and LPCD were ready.
    - We need to reduce the RMS value to the LPCD by a factor of 1/4 with the hierarchical TM-IM-MN actuation to use LPCD.
  - **However, the hierarchical length control failed because of the existence of the "negative-Zero" around 2 Hz in the suspension system.**
  - Mode shape of the oscillation mode around 2.1Hz has common motion at IM and MN stages: When IM/MN stage moves +x direction, IMR/MNR also moves +x direction.

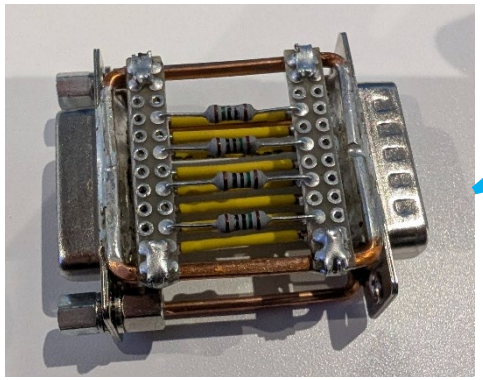




Final one mile (3.1Mpc): Coild Driver Noise, Thermal Noise, etc.

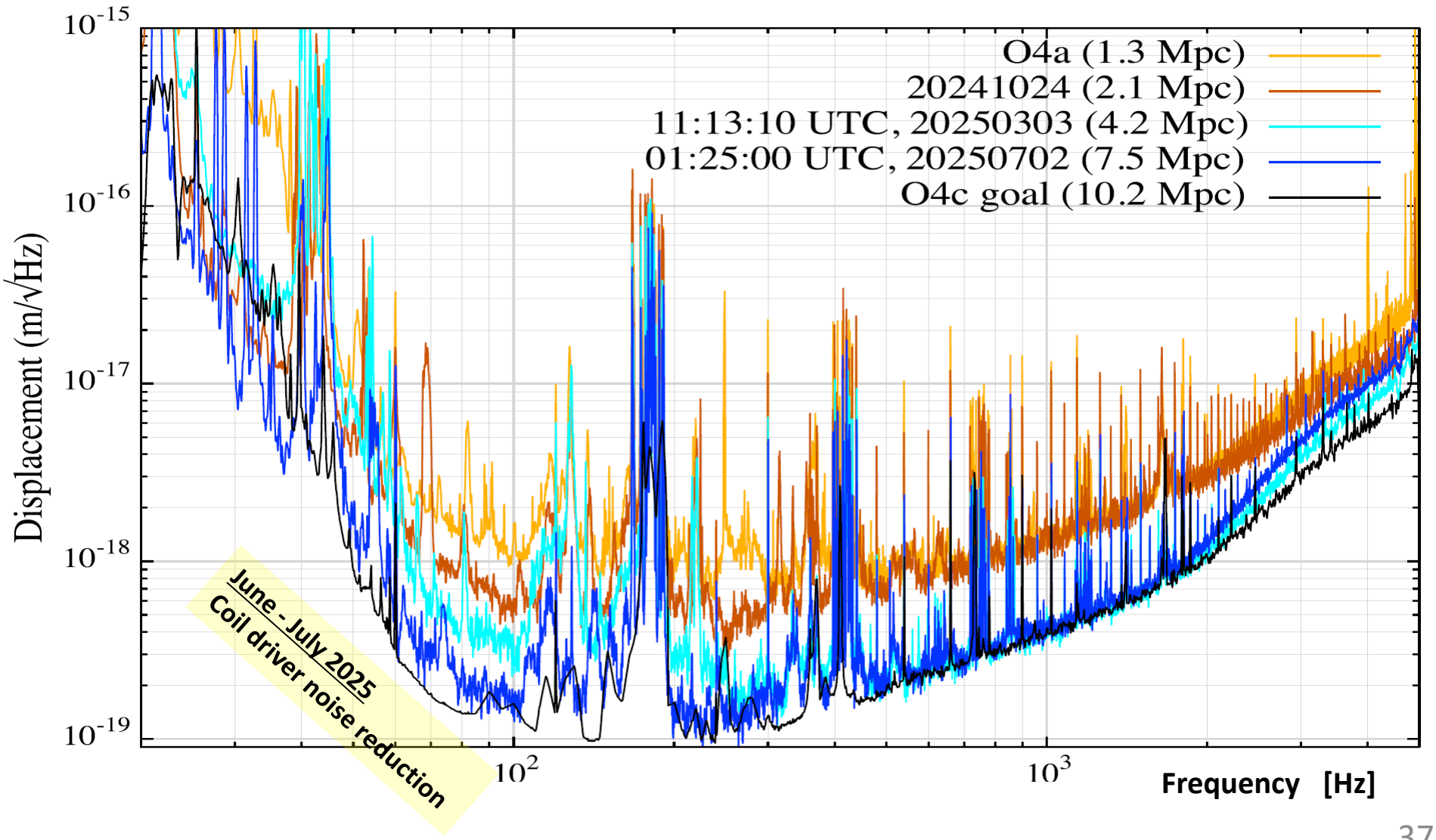
- Coil driver noise is now mitigated **by reducing the actuation efficiency with resistances inserted between the coils and the coil drivers** for TM, IM and RM.





- **Suspension thermal noise assuming 90K is still comparable with the current noise level.**
  - Especially, ITMY pitch to Length coupling because of off-centering by ~ 1cm at ITMY(X).
  - No way, except for cooling more. The target is ~40K to avoid Nitrogen frosting.
    - Strictly speaking, CO2 frosting will happen around 82K. Because of CO2 ration in air is so small, CO2 frosting does not become serious problem soon.)
- **Individual beam spot adjustment in Type-A suspensions for ITMY and ITMX**
  - **Now:** beam spots on ITMX/Y are adjusted simultaneously. So the spot on ITMX should be backed to center for the better IFO condition.
  - **Trial:** Adjust the vertical ITMX/Y position by using the mechanics in Type-A suspensions, individually to find best beam spot on each mirror.

Last “one mile” from 6.9Mpc to 7.5 Mpc BNS sensitivity



O4c started from 24:00 on June 11th to November 18th

- O4c start was delayed from 7th to 11th . However, KAGRA was ready on June 6th.
- O4c has started with LIGO, Virgo, GEO600 and KAGRA.

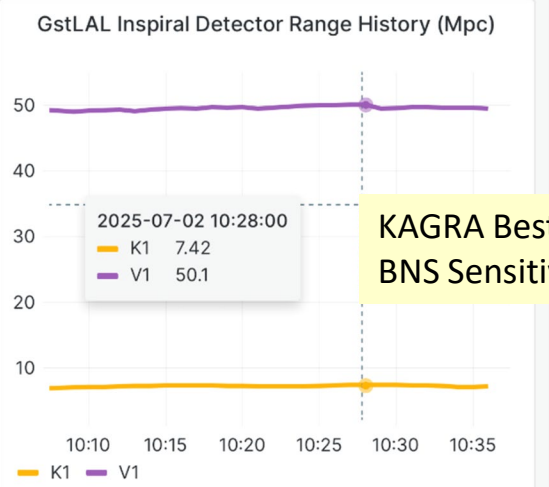
- **Observation status**
  - Longest lock was over 18 hours.
  - Best BNS sensitivity of 7.5 Mpc on July 2nd.
  - Influence of swarm earthquakes of Tokara Islands in Japan (Mid of July)
  - Aftershocks of Kamchatka Peninsula in Russia (from July 30th to Now) resulted in 1 week down of KAGRA.
  - Mirror frosting seemed to continue, judging from the finesse reduction.

O4c start

Gravitational Wave Detector Network

Operational Snapshot as of Jun. 11, 2025 15:16:56 UTC

Detector	Status	Duration [hh:mm]	Latency [s]
GEO600	Observing	00:17	36
LIGO Hanford	Observing	00:19	18
LIGO Livingston	Calib not ready	20:52	62
Virgo	Down	07:43	29
KAGRA	Observing	02:10	37



KAGRA Best BNS Sensitivity

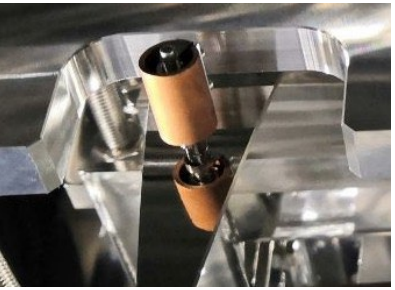
Summary

- KAGRA site members and site working collaborators are increasing.
- Commissioning to reach the 10Mpc BNS range sensitivity was done.
- The effect of suspension control modification, OMC stack recovery, cooling of sapphire mirrors and suspensions at ~ 85K, 10W laser operation, and beam jitter noise removal were verified in the sensitivity enhancement.
- KAGRA BNS sensitivity reached 7.5Mpc during O4c.
- We rejoined O4c from June 11th.
- 5 and 10-year plans are under discussion mainly among the young generations.

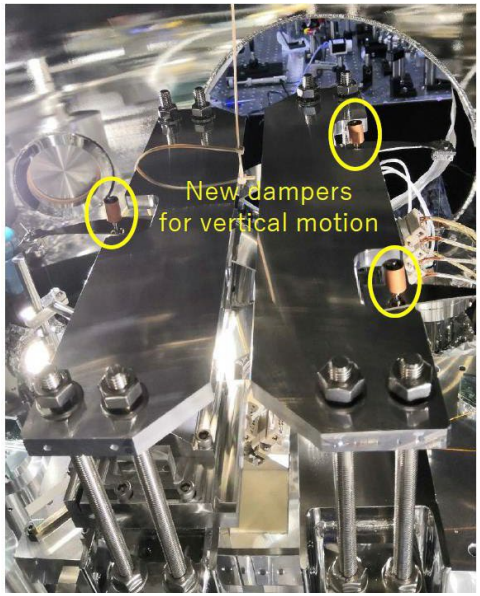
Appendix

Reinforcement of OMC Suspension Damping

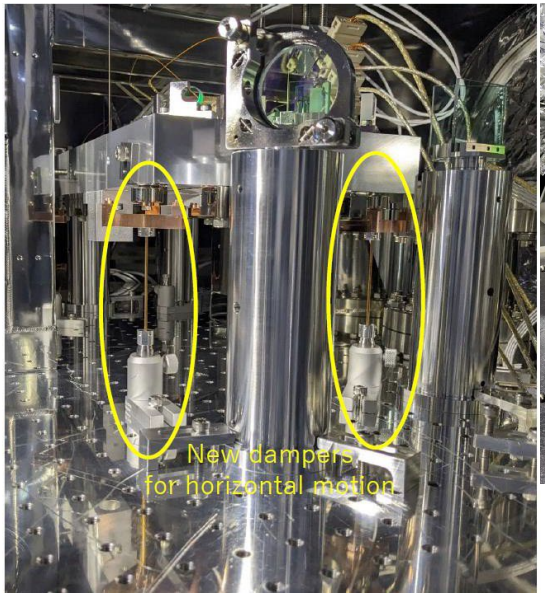
- **About the noise reduction between 60-300 Hz, we think it is thanks to some improvements around OMC suspensions.**
  - One is improving the passive damping performance of OMC suspension resonances to install new magnet dampers on blade springs and below OMC breadboard.
  - Another is to repair the contacted OMC stacks as already explained.
  - The other is reduction of AC power line noise injected to OMC PZT, which really shakes OMC length.
  - These activities reduce the RMS of OMC length fluctuations, and square coupling from the residual OMC length fluctuation to OMC transmission power becomes smaller.



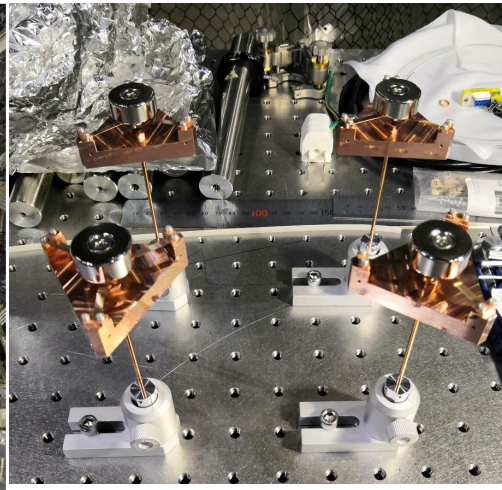
Dumper for blades



Top view of
OMC suspension blades with dumpers



Side view of OMC Plate with Dumpers



Dumper for OMC plate

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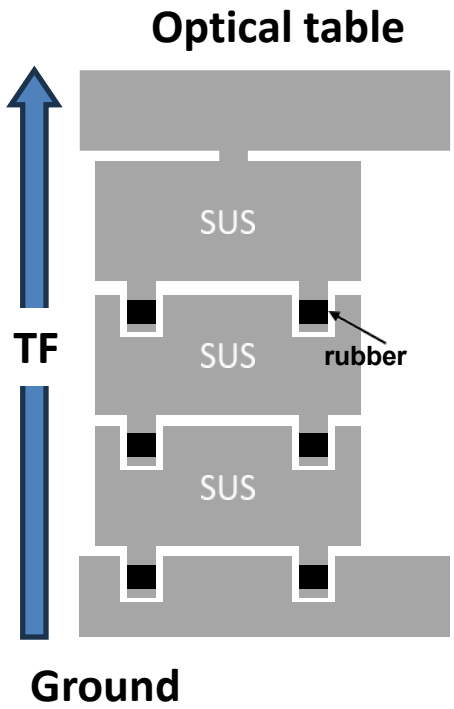
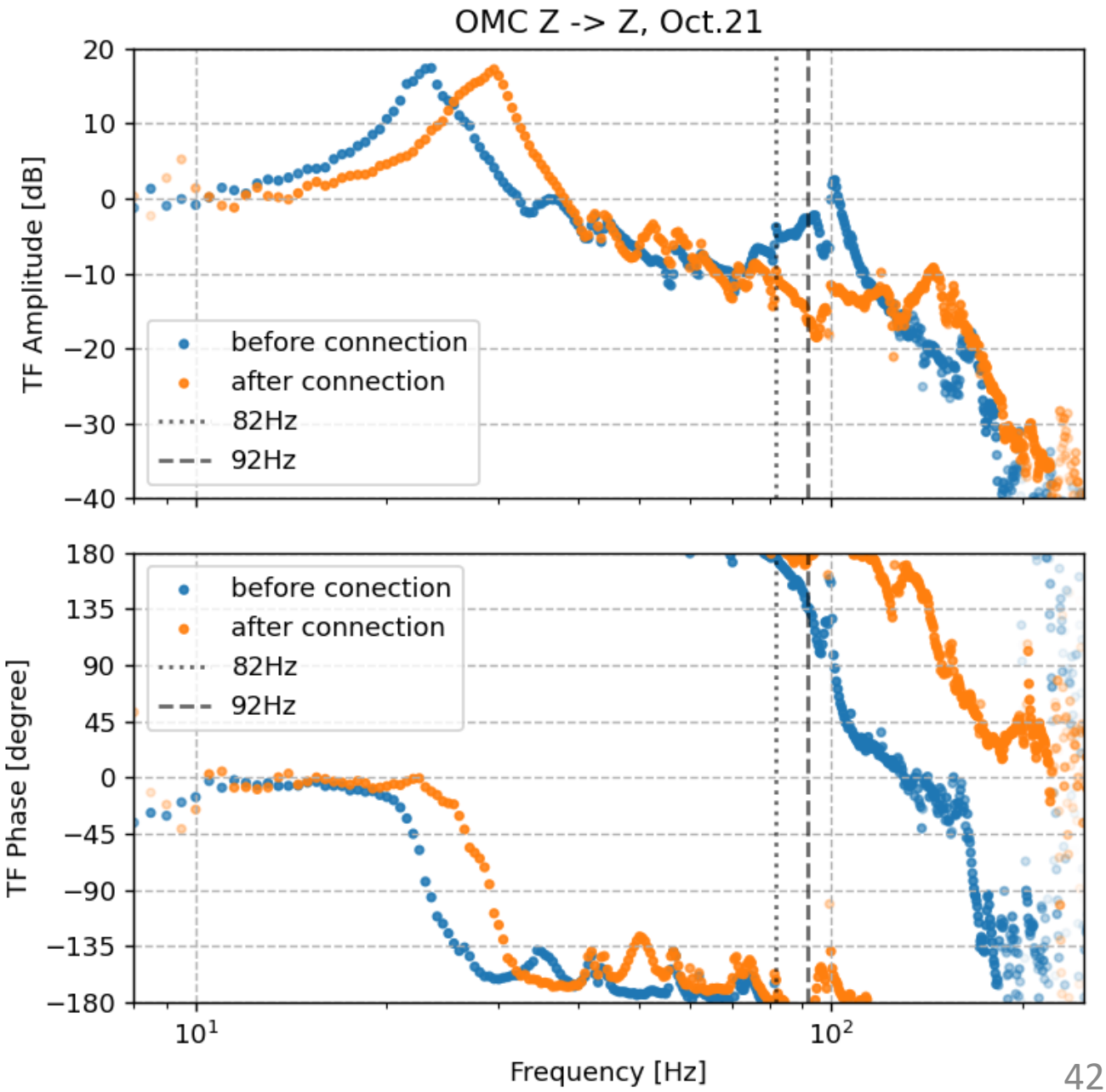
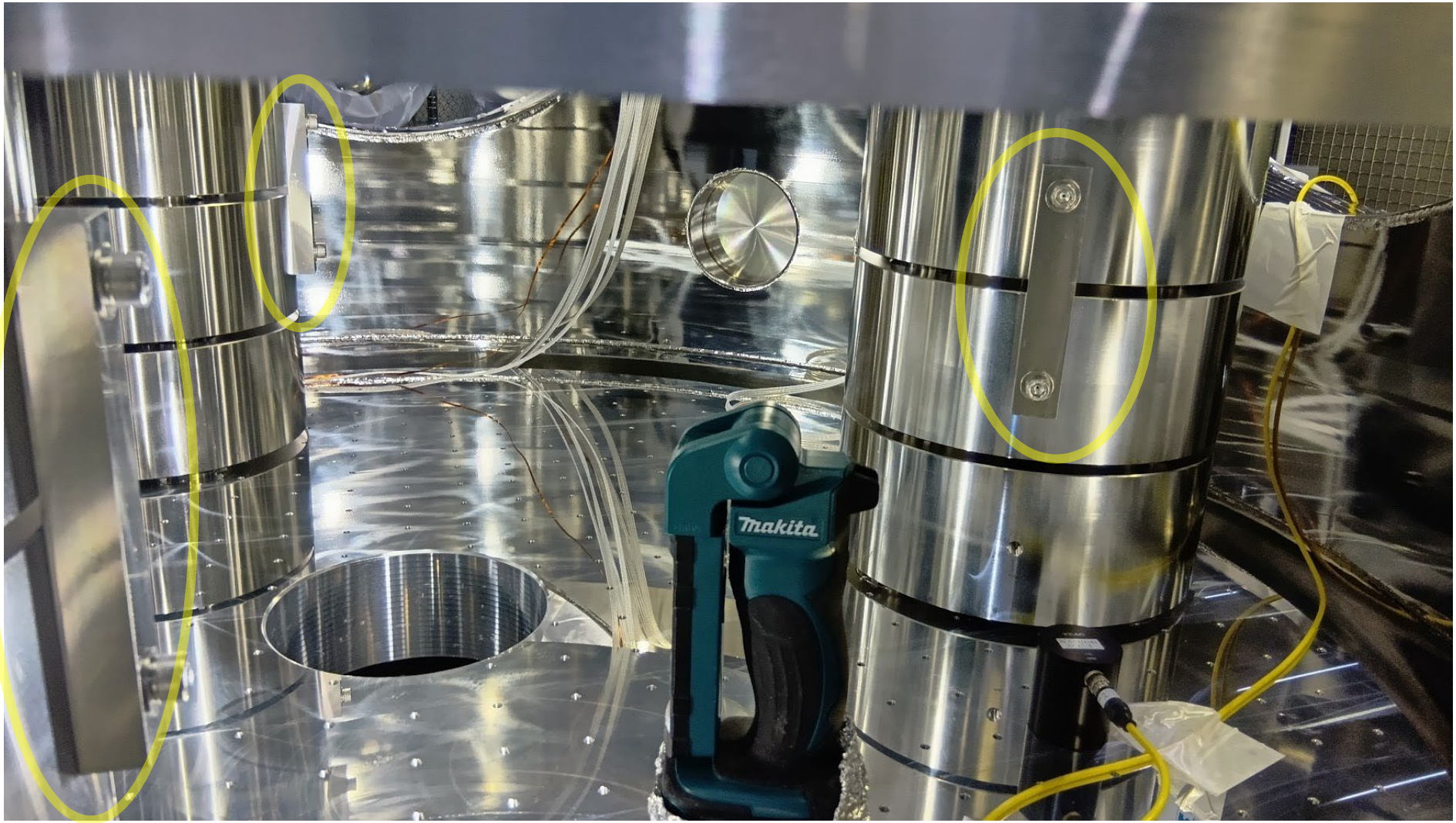
Shift of OMC Stack Resonance by Reducing Stages



- An annoying resonance peak was around 100Hz!!
- We decided to reduce the stack stage number from three to two.

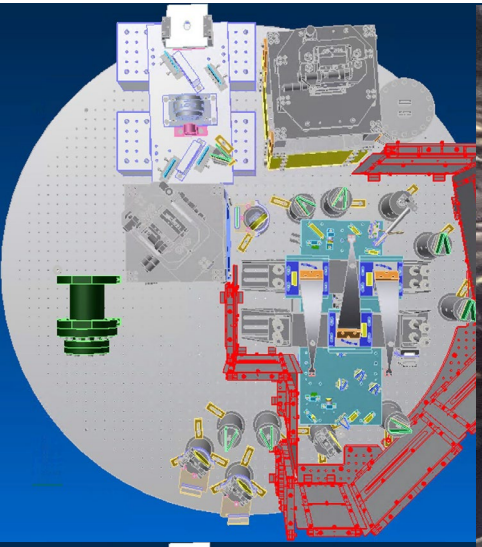


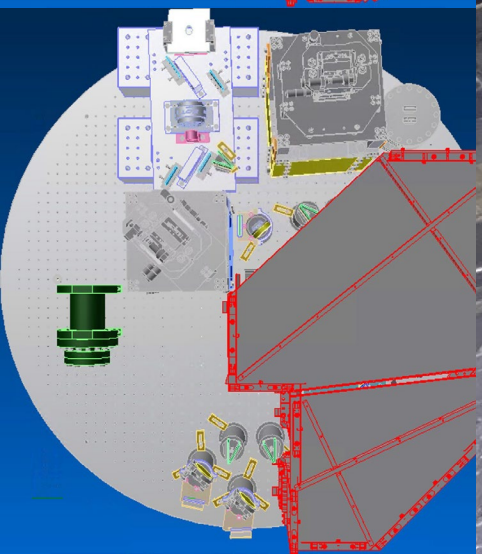
Shift of OMC Stack Resonance by Reducing Stages using Bars



Stray Light Mitigation Around OMC

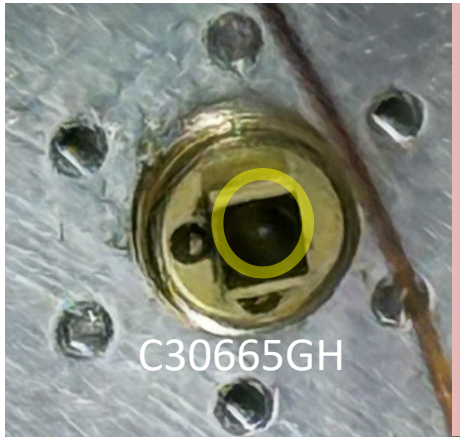
Shrouds (not coated in black) around OMC was set.





Many Serious Troubles were Scarcely Overcame

- **DC PDs Burning Again and Again during 10W operation**
  - By improper-selection of trigger PD and improper logic. → Improved. Shutter, please.



If no stock of PDs, Joining O4 could be impossible. 4 of 6 stock were used.

At present, the stock became 10. The lead time was 4 months!

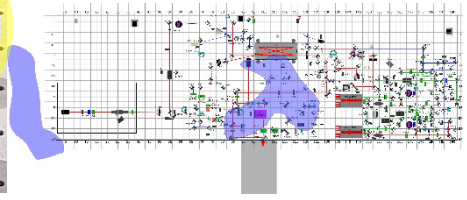
- **Water Supply System trouble**
  - By aging and no maintenance.

If water stopped, Joining O4 could be impossible because we could not keep stable temp in the corner station, PSL room, and operate cryocoolers.

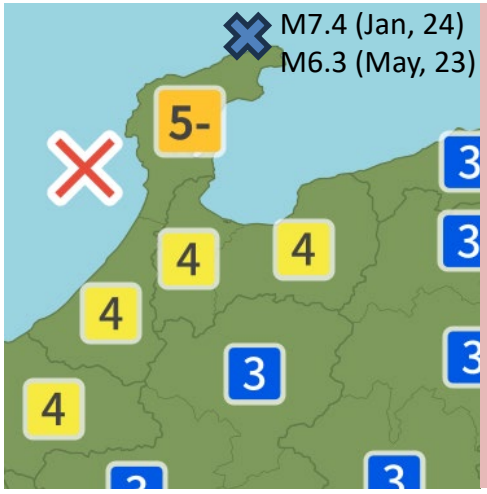
Urgent maintenance done for all stations

- **Water Leak from Beam Damper in PSL**
  - By mis-selection of tube sleeve.

If FB/NeoLase were damaged, commissioning could encounter long delay.



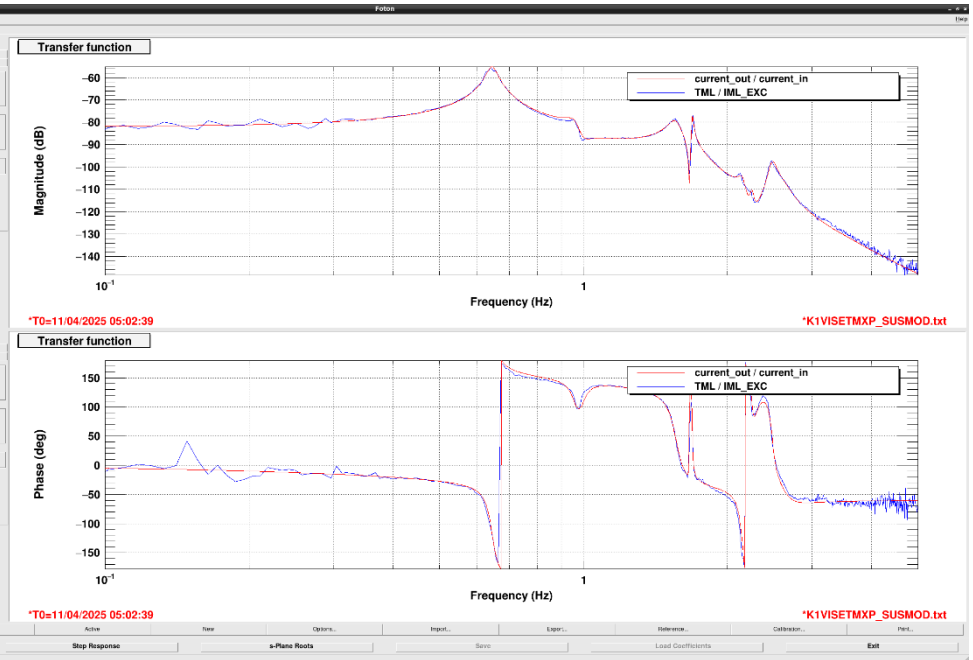
- **M6.4 Earthquake near Noto Peninsula Again (27th Nov. 2024)**

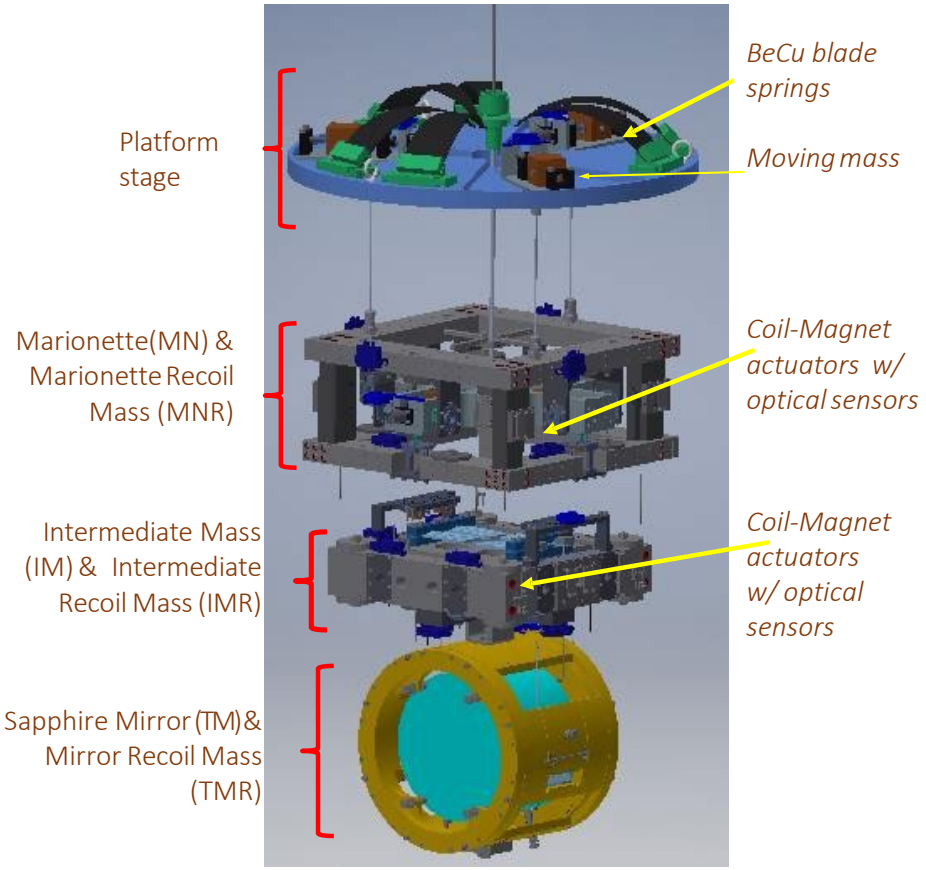


There seemed to be a critical Magnitude between 6.4 and 7.4 for the KAGRA survival.
In the KAGRA site
- Shindo:0.5 for M6.4 with **short** shaking,
- Shindo:3 for M7.4 with **longer** shaking.

KAGRA Cryo-Payload

- Mode shape of the oscillation mode around 2Hz has common motion at IM and MN stages: When IM/MN stage moves +x direction, IMR/MNR also moves +x direction.(klog#33338)
- Naively thinking, if feedback signals applies the force to IM/MN to stop the suspension motion, the force to IMR/MNR applies to the opposite direction, which enhances the motion of IMR/MNR.
- Assuming negative-zero around 2Hz, the TF can be well explained, especially in the phase changes.

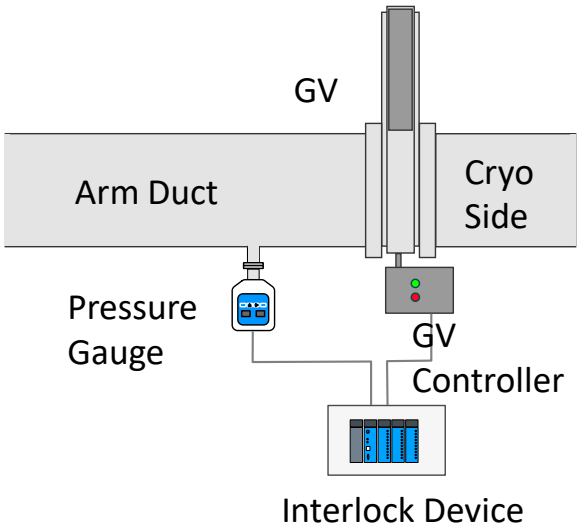




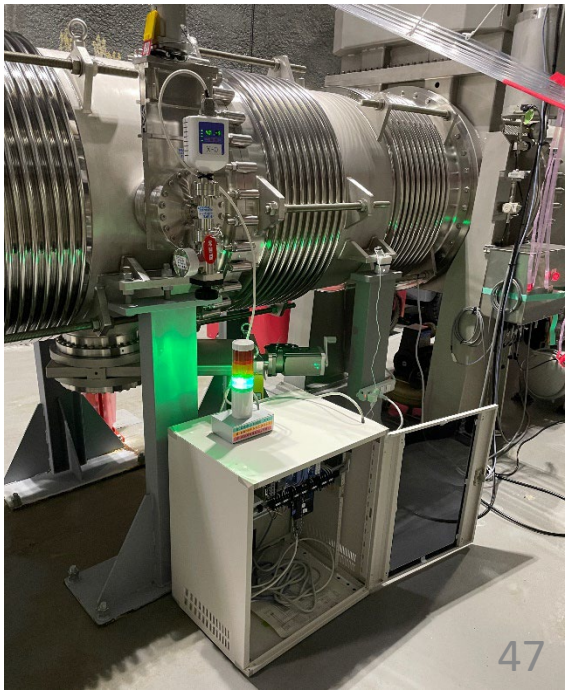
For Reliable Vacuum System

- **What we learn during commissioning before/after O4a?**
  - Vacuum leak at High voltage connectors in ion pumps in arms happened because of high humid environment.→ **Frosting on mirrors.**
  - Vacuum level degradation in arms happened because of air flow from the working dry pumps through the TMP that stopped due to some troubles. → **Frosting on mirrors**.
  - Although we set a mail alert system triggered by the high vacuum level from each sensor, we could not close GVs immediately before.

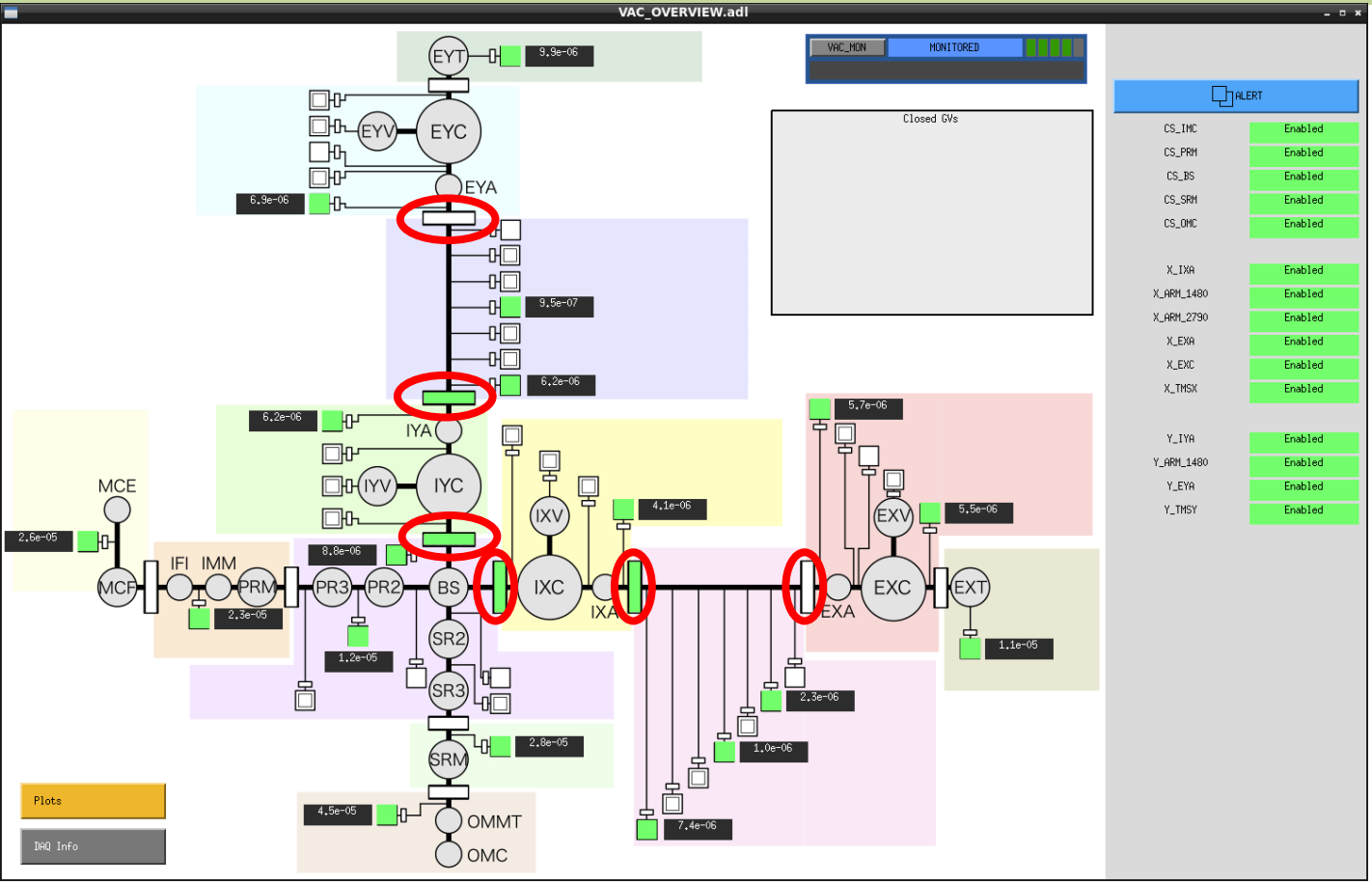
Interlock configuration diagram



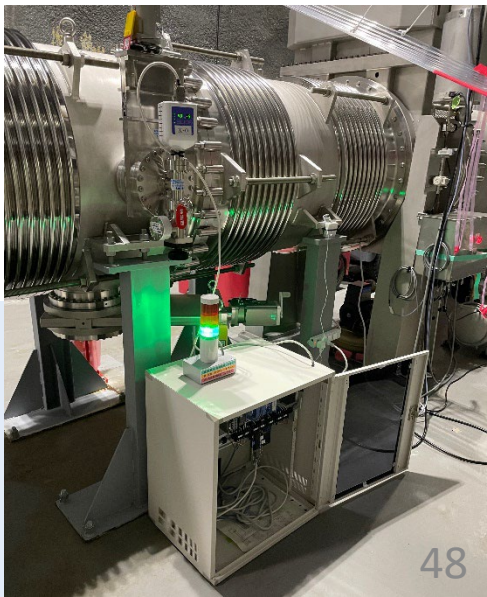
- **What is counter measure?**
  - Interlock system for TMPs were prepared in arm.
    - Enables closing EM-valves between the dry pump and TMP automatically.
  - Automatic Gate Valve closing system between IEXYA and arms, & BS.
    - Senses the vacuum level near IEXYA tanks
    - If high vacuum level (10^-4 Pa)is sensed, GVs between IEXYA and arms/BS will be closed automatically.
    - The interlock device only closes the gate valve.
    - The gate valve is opened by a person on site after the cause of the closed valve has been identified and corrected.
  - GV's status can be monitored in the MEDM system.
  - Remote closing is also available by using Switch Bots.



For Reliable Vacuum System



- Interlock devices have been or will be installed on gate valves circled in red.
- Plans install interlock devices on 6 gate valves.
- Interlock devices installed on 4 gate valves by 2024/Dec./7.
- Completed installation of gate valve interlock devices by 2024/Dec./18.



Captured from the display screen of the monitor in the control room

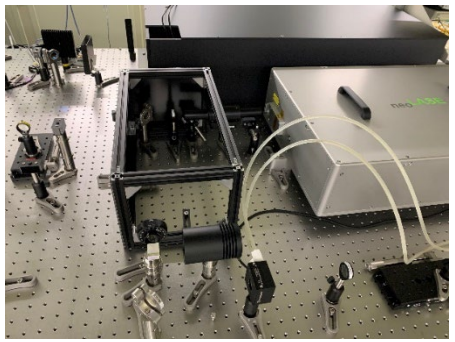
- Gate valve display status

→ **Open** → Installation and adjustment in progress

→ **Close**

Fiber Laser(20W) to High Power Laser(60W->120W)

- **Status and plan**
  - The previous FB is still used because the max laser power is still enough to reach 10Mpc sensitivity. In addition, the ISS reached the shot noise level even if the intensity noise got worse.
    - 1st neoLASE laser was installed to KAGRA on 2022/8 and it has been locked to PMC, IMC and PRFPMI in RF, but died by burning fiber cables.
      - It was repaired and was backed to the Toyama University.
      - Interlock system was installed not to repeat the same trouble.
    - 2nd neoLASE laser was set in the PSL room.
      - We performed the test a high-power operation.
      - IMC lock was realized.
      - PLL lock was verified.
      - Almost ready for swapping for an emergency case.



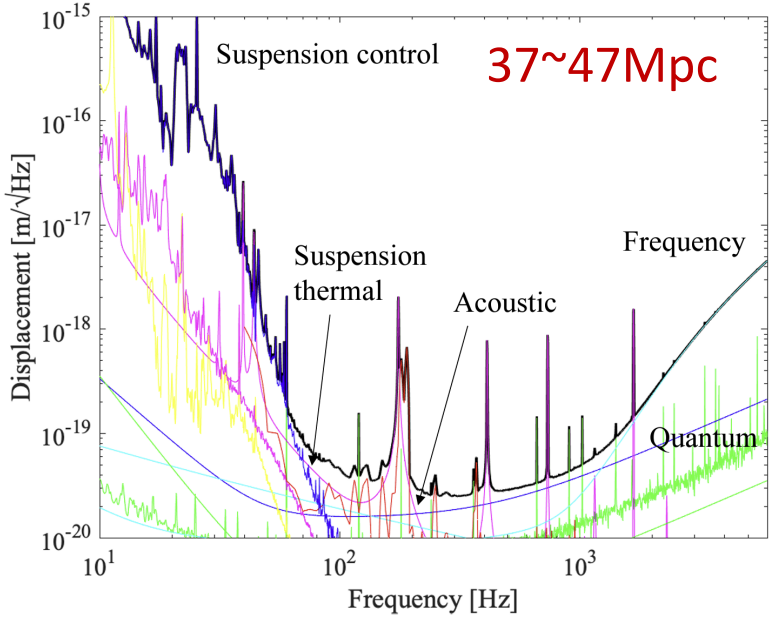
  - We will wait for swap lasers for a while.
    - The biggest difference between current/new lasers is the efficiencies of wideband EOM. We used RF high voltage amplifiers for the new EOM and the new laser has been locked IMC and PRFPMI stably.

Plans for O5 (~ 5 Years Plan) led by Y.Aso (NAOJ)

- The younger generation is now leading future plans (5 and 10 years plan for KAGRA)
- Sensitivity Estimation for O5 (Under discussion level)

Assumptions

- Laser power: 30W (150kW in arm)
  - Better PRCL/MICH noises
  - Better CARM shot noise
  - RIN ~ 10^{-8}
- RSE
  - SRM: 85%
- 22K
- Bad Q factors
- Better ITMs
  - Better CMRR



Things to be done for sensitivity improvement (almost certainly)

New ITMs
- CMRR improvement (laser noises)
- Better contrast at AS (reduction of DARM offset)
- Better ASC

High Power Laser (30W)
- Shot noise reduction
- MICH/PRCL noise reduction
- Less dark noise

RSE with 85% SRM
- Shot noise reduction
- SRM reflectivity is a matter of discussion

In-vac RFPDs
- Scattered light noise reduction

Better OMC VIS
- Acoustic noise reduction

In-vac TMS optics
- Scattered light mitigation

Input beam jitter mitigation
- Need more investigation

Type-B yaw damping
Suspension Q-factor improvement
Mirror Q-factor improvement
Other acoustic noise mitigations
- OFI beam dump
- Soundproofing the optical tables

CRY upgrades
- Cooler unit maintenance
- Cooler operation parameter optimization

Facility
- Increasing the power supply capacity

Calibration
- Pcal upgrade
- Gcal test

Fast Beam Shutter
- Protect the OMC PDs
- Will purchase from LIGO

DGS upgrade
- Large scale upgrade will be postponed after O5

Vacuum upgrades
- More ion-pumps
- UPS
- Remote monitoring

10 Years Plan Led by T.Kajita(ICRR) and K.Komori(UT. Phys)

- The younger generation is now leading future plans (5 and 10 years plan for KAGRA)

- **Strategy to contribute to the LVK GW observation with LIGO A# and Virgo nEXT plans**
  - Scientific contribution to the LVK /EM communities with KAGRA's limited human resources
  - Better sensitivity for the higher frequencies than L-A# and V-nEXT to offer better SN GW signals.
  - Collaboration with NEMO project with Australia.

- **Outlook for KAGRA with better sensitivity for the high frequency ranges**
  - Shot noise for the higher frequencies is rather easy to reduce compared with "technical noises" with frequency dependent squeezing.
  - Higher power intracavity by using cryogenic sapphire mirrors (high thermal conductivity and low thermal expansion ratio)

- **Two strategies**
  - High Frequency Type, assuming
    - High quality suspension
    - Long Signal Recycling Cavity targeting 2KHz or 3kHz dip in the sensitivity
    - Frequency independent/dependent squeezing
  - Broadband Type, assuming
    - Sapphire mirror mass of 23kg or 40kg
    - Larger beam size
    - Low loss coating