大型低温重力波望遠鏡に関する研究（XIV）

三代木 伸二, on behalf of KAGRA Collaboration

30th January, 2025

共同利用研究成果発表会
東京大学宇宙線研究所

共同利用研究採択課題（国内）

整理番号	所属機関	研究代表者	研究課題	2024査定額（単位：円）		
				物件費	旅費	計
G1	東京大学	大橋 正健	大型低温重力波望遠鏡に関する研究（ＸⅣ）	0	400,000	400,000
G2	東京大学	大橋 正健	低温レーザー干渉計CLIOによる重力波研究（Ⅷ）	0	50,000	50,000
G3	国立天文台	都丸 隆行	KAGRAモニター&インターロックシステムの開発	300,000	300,000	600,000
G4	富山大学	山元 一広	大型低温重力波望遠鏡（KAGRA）の低温懸架系の研究	180,000	148,000	328,000
G5	富山大学	森脇 喜紀	KAGRAにおけるレーザー強度安定化のためのR&D	301,000	29,000	330,000
G6	新潟大学	大河 正志	重力波望遠鏡KAGRAの測定感度向上に資する雑音低減および極微小散乱光計測技術の開発V	0	400,000	400,000
G7	NICT	井戸 哲也	超狭線幅光源のための光共振器の開発	0	100,000	100,000
G8	国立天文台	鷲見 貴生	KAGRAにおける環境由来のノイズ削減に関する研究	0	400,000	400,000
G9	東京大学	横澤 孝章	KAGRA検出器における注入試験による環境雑音評価手法の研究	100,000	150,000	250,000
G10	東京都市大	高橋 弘毅	機械学習・深層学習を用いたノイズ特徴の分析と干渉計診断への応用 (IV)	0	350,000	350,000
G11	東京大学	押野 翔一	重力波検出の信頼性向上のための突発性雑音データ解析システムの構築	200,000	0	200,000
G12	東京大学	内山 隆	KAGRAにおける非定常雑音の低減 (II)	0	150,000	150,000
G13	東京大学	譲原 浩貴	KAGRA望遠鏡の高感度化のための雑音源同定ツール開発	0	200,000	200,000
G14	東京大学	三代木 伸二	重力波望遠鏡における電磁波散乱・伝搬シミュレーション XII	0	100,000	100,000
G15	東京大学	牛場 崇文	高性能サファイア鏡懸架系の開発	150,000	200,000	350,000
G16	東京大学	宮川 治	KAGRAの制御と自動運転	150,000	150,000	300,000
G17	大阪公立大	神田 展行	KAGRAデータ転送・保管系の構築 (10)	0	350,000	350,000
G18	東京大学	澤田 崇広	KAGRAデータを低遅延国際重力波探索網へ組み込むための共同研究推進（4）	100,000	100,000	200,000
G19	東京大学	山本 尚弘	重力波探索のための望遠鏡診断システムの構築(IV)	0	250,000	250,000
G20	東京大学	新谷 昌人	神岡坑内における精密地球物理観測と地殻活動のモデリング	0	200,000	200,000
G21	東京大学	田越 秀行	重力波データ解析の研究	150,000	200,000	350,000
G22	国立天文台	E. Marc	KAGRAアップグレードのために、サファイアの不純物と吸収、複屈折の関係調査	200,000	0	200,000
G23	国立天文台	陳 たん	グローバルネットワークによる重力波望遠鏡較正の改善	200,000	0	200,000
G24	KEK	山田 智宏	KAGRA極低温鏡懸架装置のための新しい制御手法および高感度低温センサーの開発	150,000	200,000	350,000

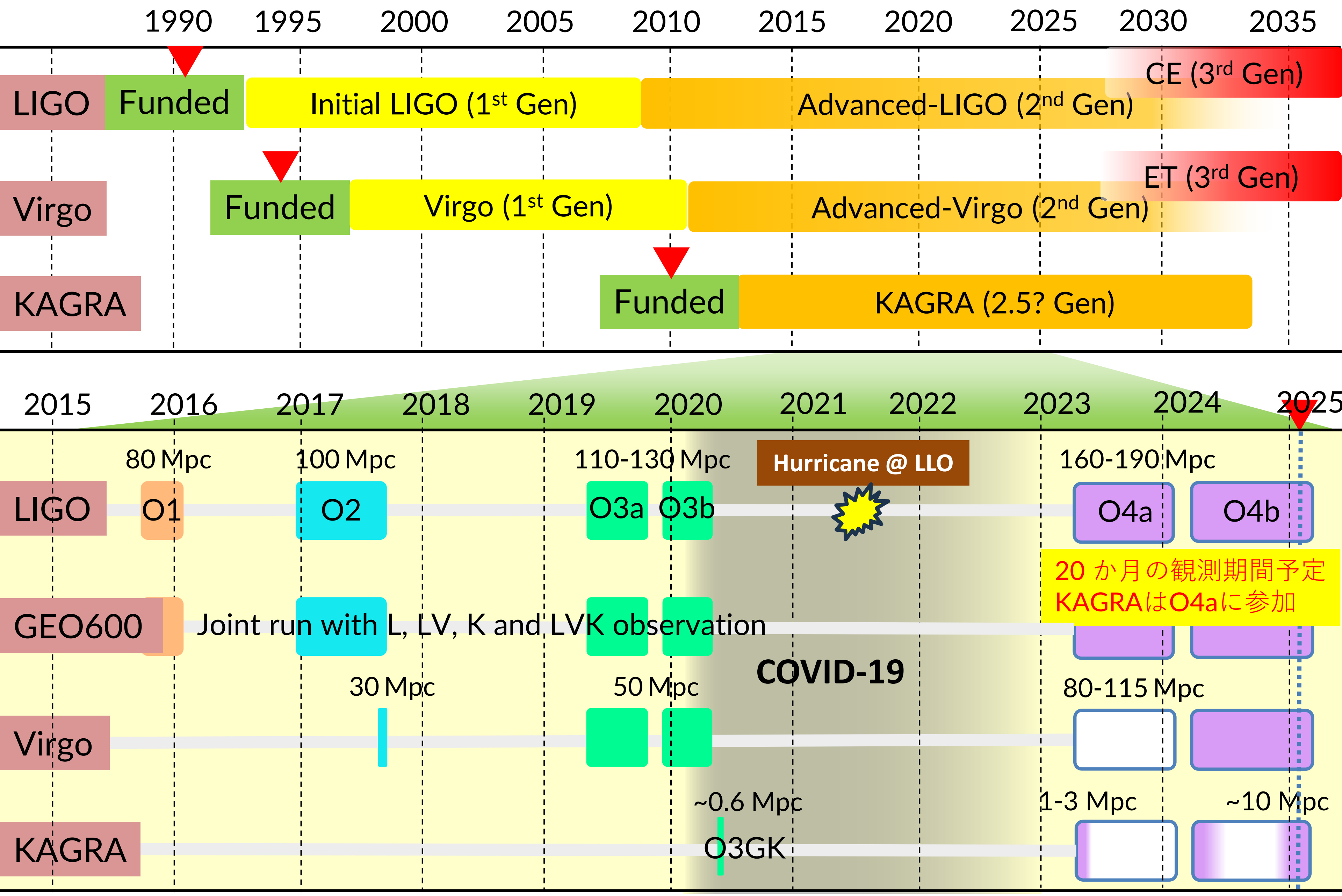
6,608,000

共同利用研究採択課題(国外)

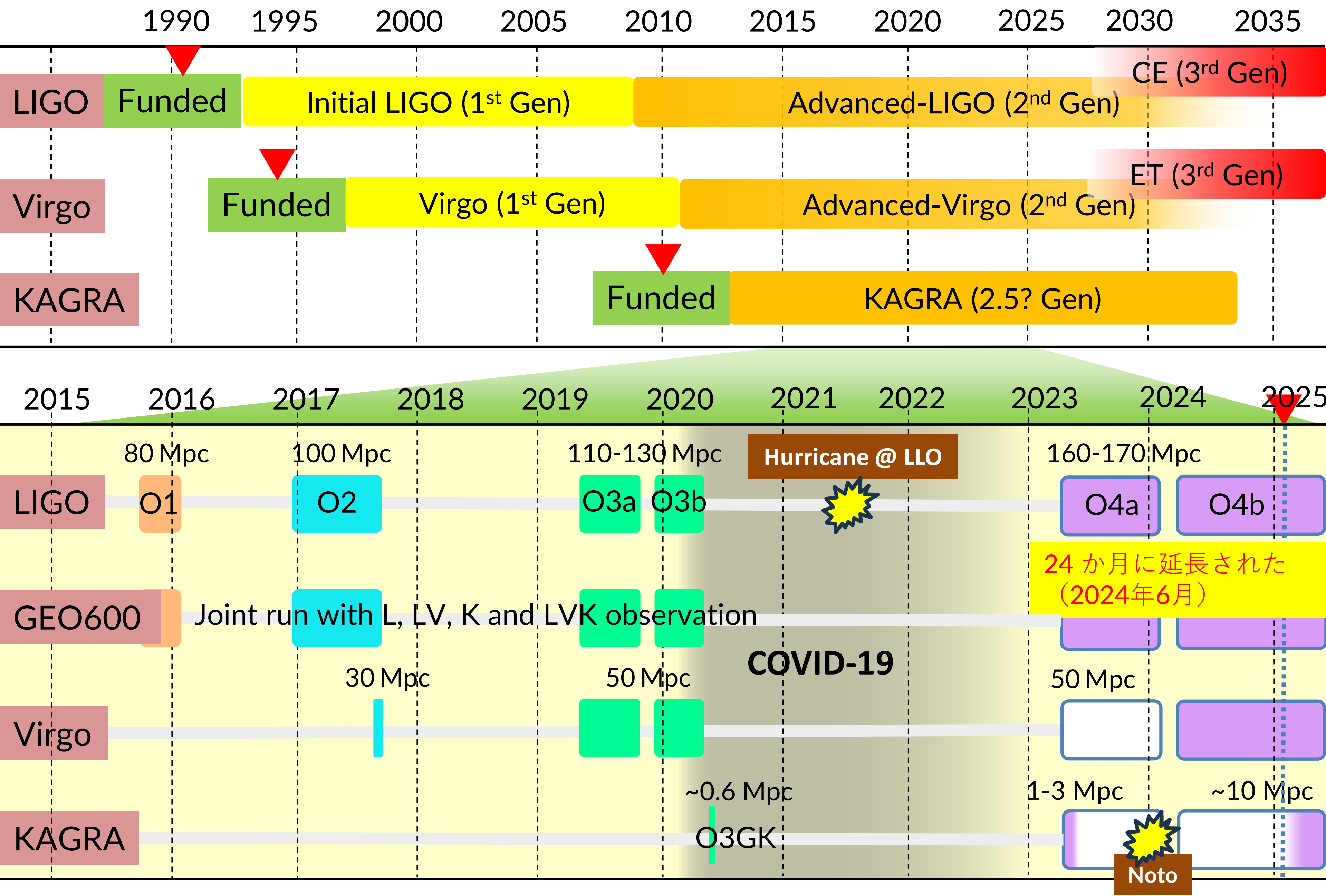
整理番号	所属機関	研究代表者	研究課題	2024査定額（単位：円）		
				物件費	旅費	計
G1	National Tsing Hua University	Lee Ray-Kuang	Filter cavity experiments for the frequency dependent squeezed light for KAGRA	0	291,000	291,000
G2	University of Notre Dame	Nguyen Lan	Self interacting dark matter and gravitational waves	200,000	83,000	283,000
G3	University of Perugia	Bawaj Mateusz	Position control system for silicon monolithic suspension in cryogenic gravitational waves detectors.	350,000	0	350,000
G4	National Tsing Hua University	Kong Albert	Implementing Sophisticated Data Analysis Methods on KAGRA Data	0	350,000	350,000
G5	National Yang Ming Chiao Tung University	Yang Yi	Applications of machine learning technique on gravitational wave detection	0	323,000	323,000
G6	Tamkang University	Liu Guo Chin	Test Run Analysis of KAGRA O4 data for Stochastic Gravitational- Wave Background Search	0	322,000	322,000
G7	Inje University	Lee Hyung Won	Implementing parameter estimation for CBC sources using particle swarm optimization	0	0	0
						1,919,000

- 特に、イタリアとの国際共同利用研究は、2024年6月14日：日伊アクションプラン、
(https://www.mofa.go.jp/mofaj/erp/we/it/pageit_000001_00742.html)
に基づき、6月27日に発表された、
（https://www.mext.go.jp/b_menu/activity/detail/2024/20240627_2.html）
「イタリアの大学・研究省と日本の文部科学省の間で昨年署名した科学技術・研究分野での協力に関する覚書に基づき、今回、**新たに「重力波」**及び「蓄電池」の分野での協力を行うことに関する声明」の具現形態の一つである、イタリアのINFNとKAGRAの間で締結された研究協定（2024年6月）の中で求められている、日本側のマッチングファンドとしても認定。

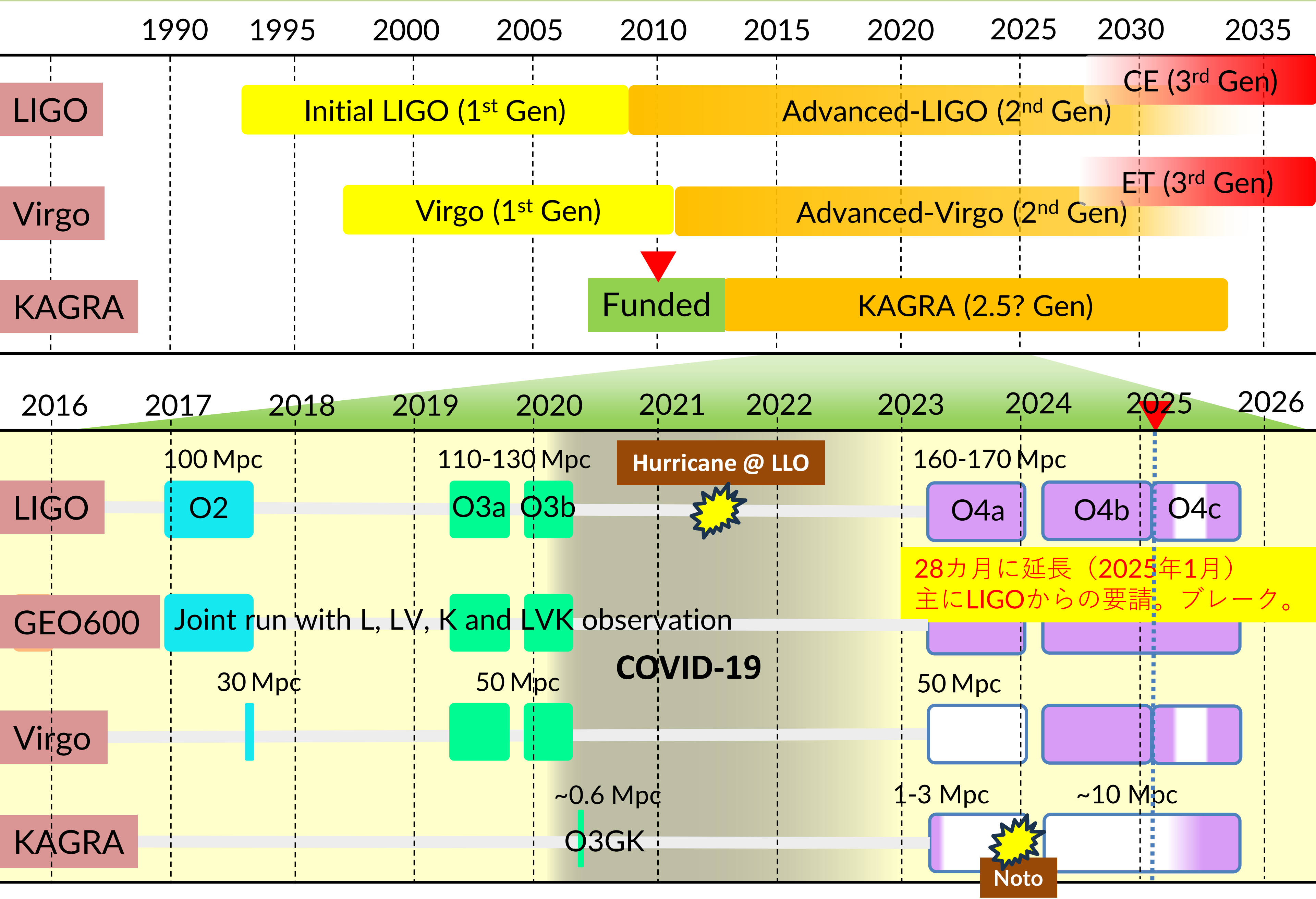
GW Telescopes Generation and LVK Observations



GW Telescopes Generation and LVK Observations



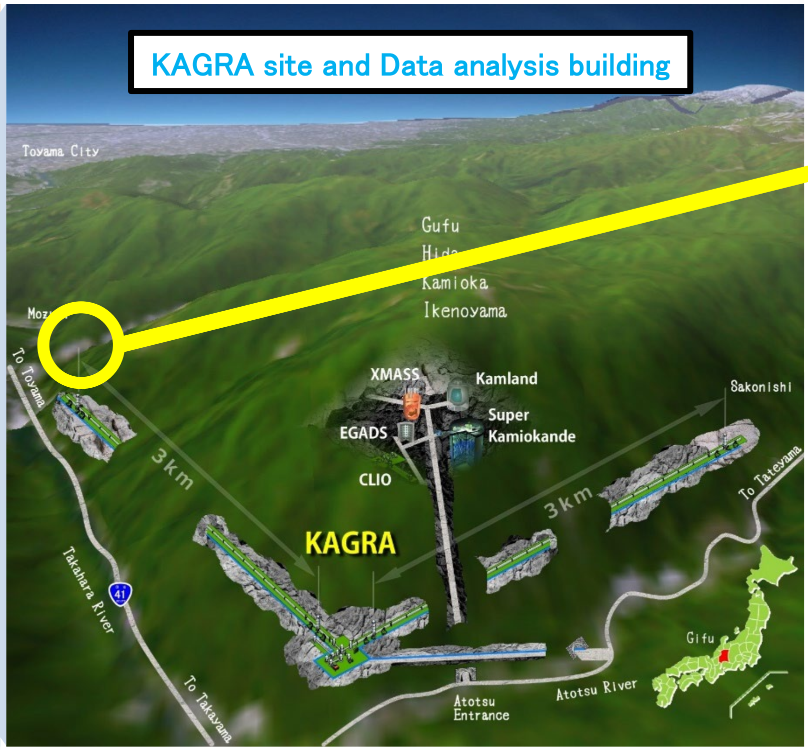
GW Telescopes Generation and LVK Observations



Recovery of KAGRA (January ~ July)

能登半島地震の影響

地表最大震度は5強、KAGRA坑内は震度3



- 飛騨地方の過去100年間の大きな地震
  - 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.)

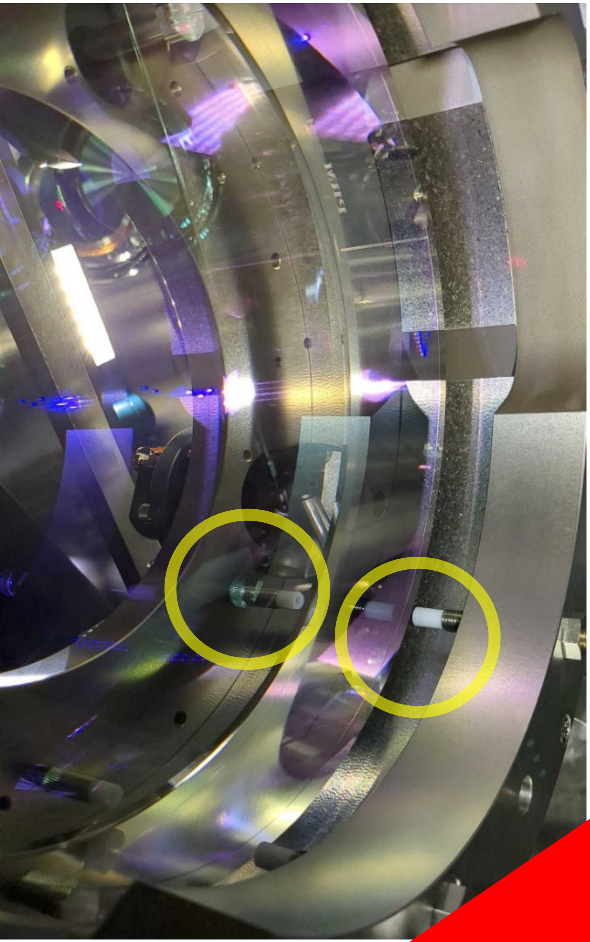
  Lv.5- was the largest earthquake at least in the last 100 years.

- 海岸地域では4mの隆起を観測
- このような現象は6000年に1回などと報道

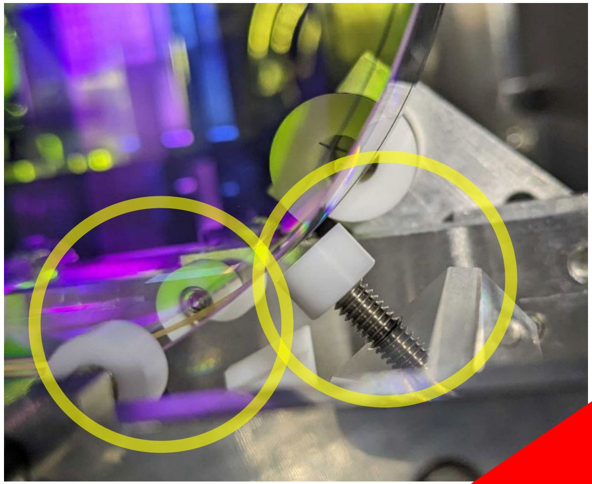
- According to GIAJ (Geophysical information Authority of Japan, 国土地理院), the mountain housing KAGRA moved 2~3cm in the direction of Y-arm（ https://www.gsi.go.jp/common/000254115.pdf ）。

We had EQ Stoppers for Mirror Protection, but …

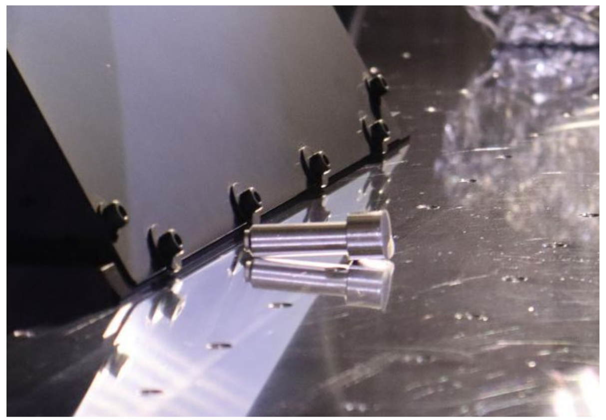
Type-Bp EQ Stopper



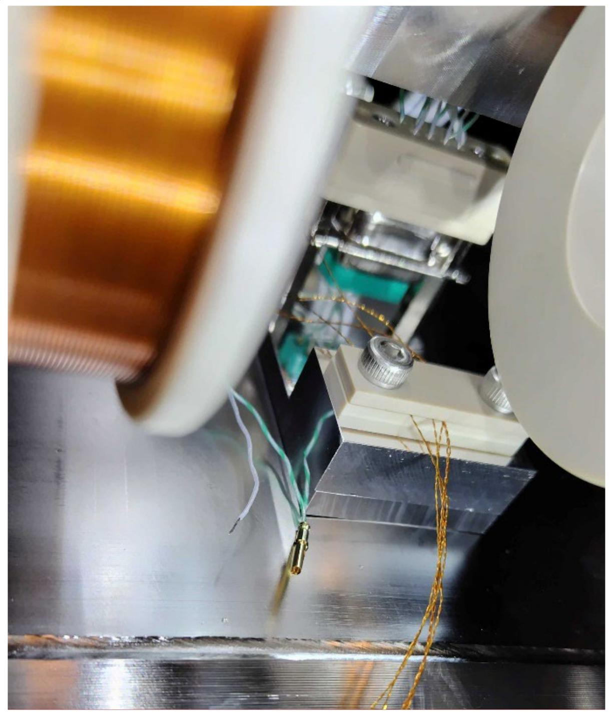
Type-C EQ Stopper



Magnet Dropoff because of hitting on facing coil body

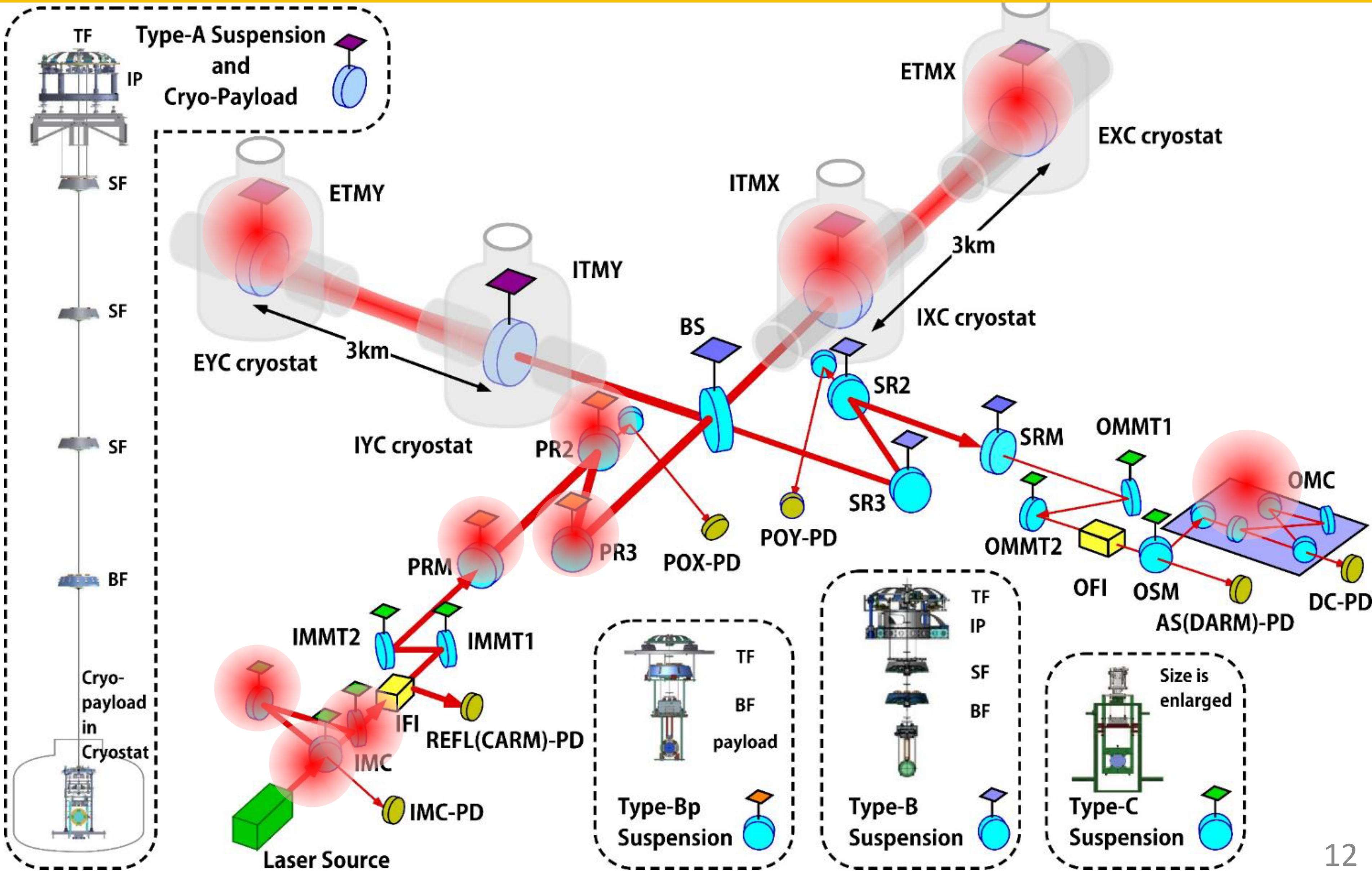


Signal Wire Cut because they were sandwiched by suspension components



10 of 20 Mirror Suspensions were Damaged

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



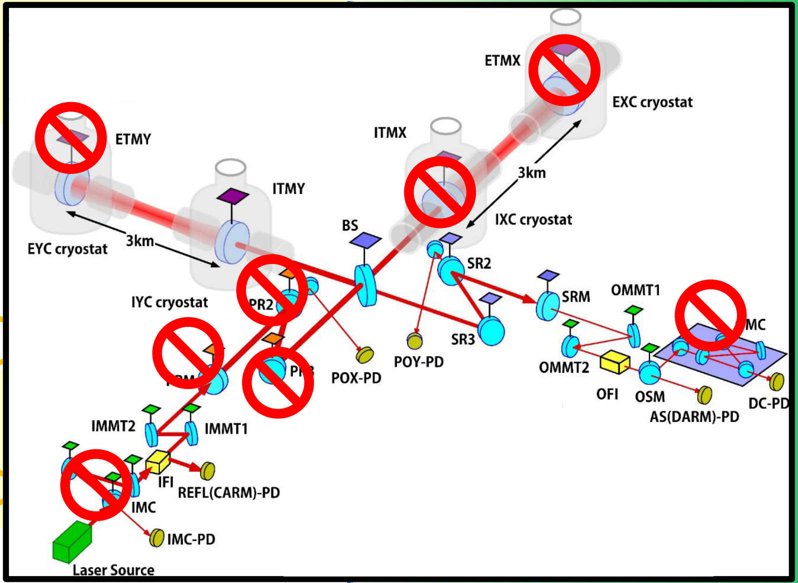
Heartful Messages

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

Recovery Status (started from Jan 2024)

March	April	May	June	July

- **IMC(MCi, MCo, MCe)**
  - Recovered InVac
- **IFI-PRM(Type-Bp)**
  - Suspension Recovered inAir
  - Finalization
  - Pumping
  - Recovered InVac
- **ETMX(Type-A)**
  - Suspension Recovered inAir
  - Pumping/No Leak
  - Recovered InVac
- **ITMX(Type-A)**
  - Suspension Recovered inAir
  - Pumping/Leak Repair
  - Recovered InVac
- **ITMY(Type-A)**
  - Suspension Recovered inAir
  - Pumping/No leak
  - Recovered InVac
- **PR2,3(Type-Bp)**
  - Suspension Recovered inAir
  - Finalization
  - Recovered InVac
- **SRM/2/3(Type-B)**
  - No damages as suspensions
  - Pumping/Leak Repair
  - Optical Axis Check
  - Recovered InVac

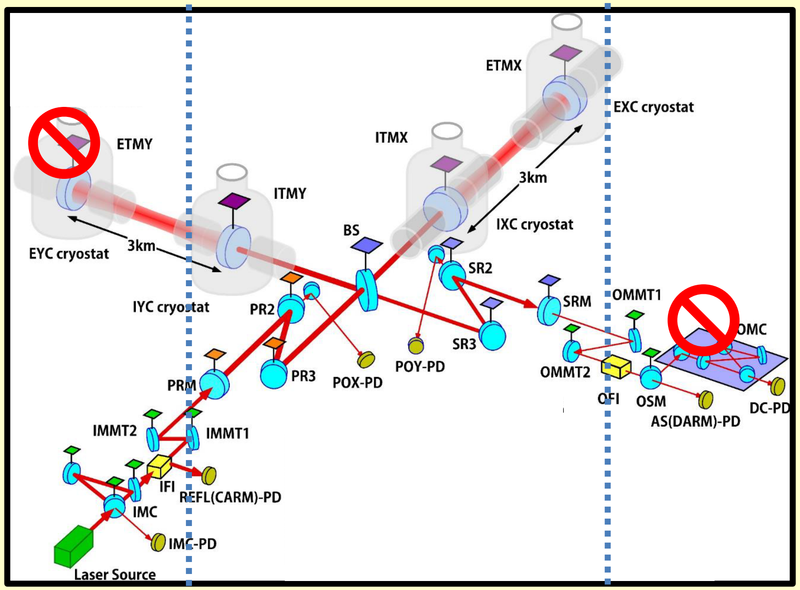


FPMI Commissioning and Suspension control mitigation

Recovery Status (started from Jan 2024)

March	April	May	June	July

- ETMY(Type-A)
  - Oily Material found in EYA
    - Material Component Analysis (4 individual places)
      - Start EYA Cleaning lead by Uchiyama-kun (ICRR)
        - Cleaning Finish
  - Repair in EY Tower
    - Pumping/**small leak was found (repair in September)**
      - Recovered InVac



FPMI Commissioning and Suspension control mitigation

- OMC
  - OMC stack function check
    - OMC was confirmed to have troubles in its isolation function
      - We confirmed its malfunction visually
        - Start of recovery
  - Recovered InVac
    - Check Isolation

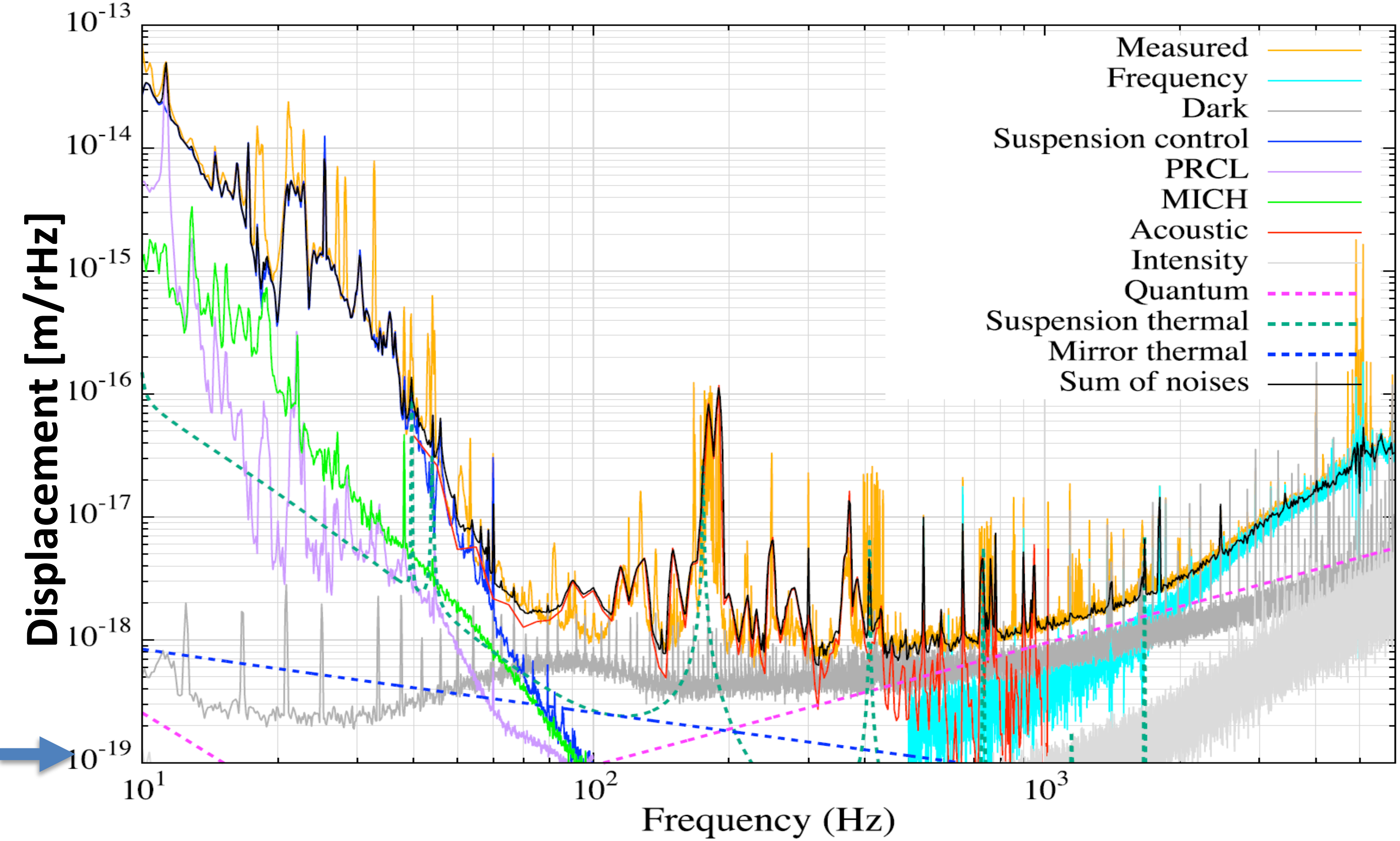
2024年12月　令和6年度文部科学省補正予算（案）
【東京大学関係】＜国民の安心・安全の確保＞学校施設の災害復旧等：
◆大型低温重力波望遠鏡（KAGRA）（宇宙線研究所）で復旧費が認められた。

Commissioning of KAGRA
(July ~ now)

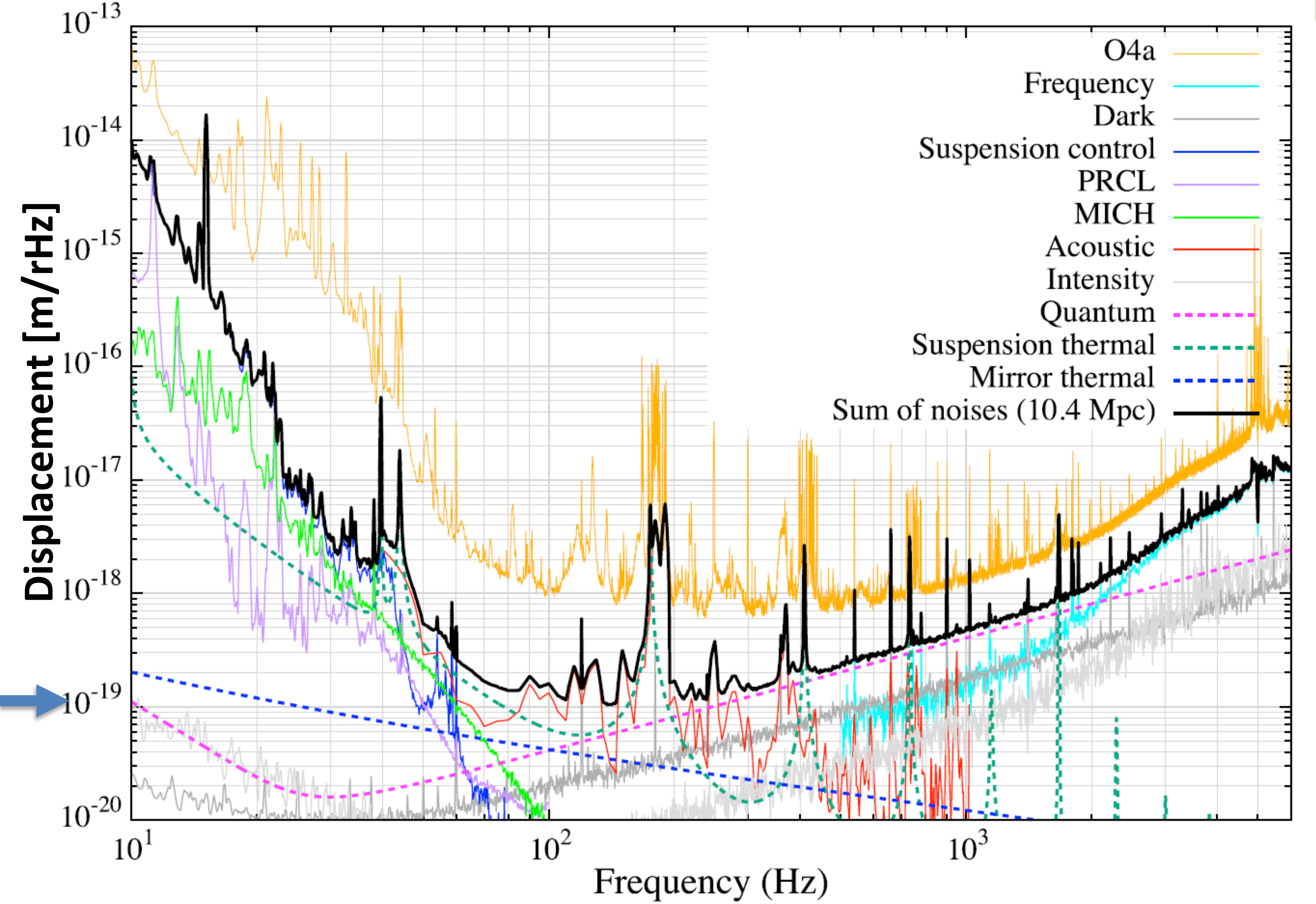
Overview of Commissioning Works after July 2024

- From July 2023, Commissioning Restarted for the sensitivity enhancement
- On Jan 1st, M7.6 earthquakes at Noto Peninsula destroyed KAGRA
- O4b start by KAGRA from this Spring became impossible. We started recovery work until July.
- July 2024: Commissioning Restart.
- **August:** FPMI was realized. Water supply system repaired at the corner station.
- **September**:
    - ASC with WFS, BPC and ADS was almost completed.
    - PRFPMI+RF was recovered.
- **October:**
    - OMC stack modification was done, and more isolation was confirmed.
    - RF→AM conversion reduction in the modulation for the laser was successfully mitigated.
    - PRFPMI+DC was realized with Better BNS range sensitivity (Preliminary ~ 2Mpc (1.3Mpc in O4a)).
    - PEM Injection test started.
    - Start duct shield cooling (, and 255K temp of all mirrors were realized in December).
    - <<< PAB follow up meeting >>>.
- **November:**
    - Some troubles (DC PD burning, Water leak from the Beam Damper in PSL) that delayed the schedule by several days for each. Improved protection for PD burning was applied.
    - Repair for the water supply system for X/Y ends.
    - Another **M6.4 earthquake happened near the Noto Peninsula** and destroyed KAGRA alignment. 1 week health checks and recovery work.
    - PEM injection test restarted. Noise budgeting activities was ongoing.
    - <<< MEXT review meeting >>>.
- **December:**
    - Tapping test started by PEM.

O4a (2023 May ~ June) Noise Budget



Expected Sensitivity Curve and its Noise budgets for O4c

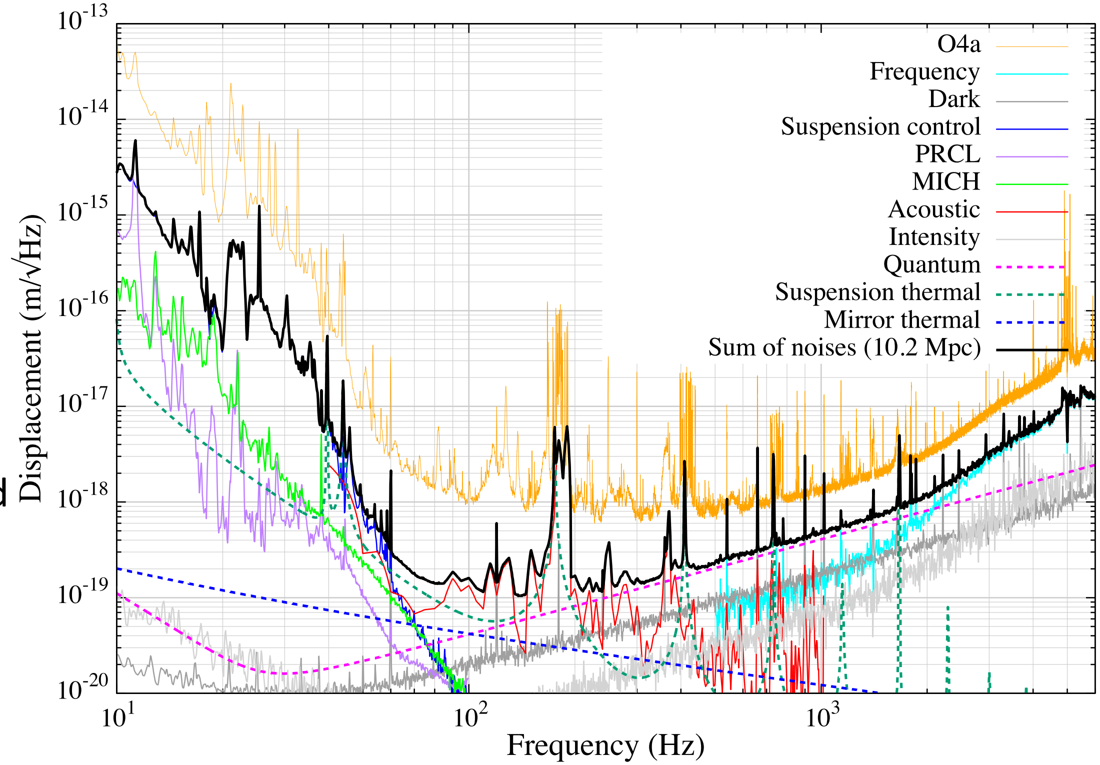


Strategies to Realize 10Mpc

- **Already reduced noise：**
  - Susp local control noise：1/10
  - PD dark noise : below shot noise (improved)

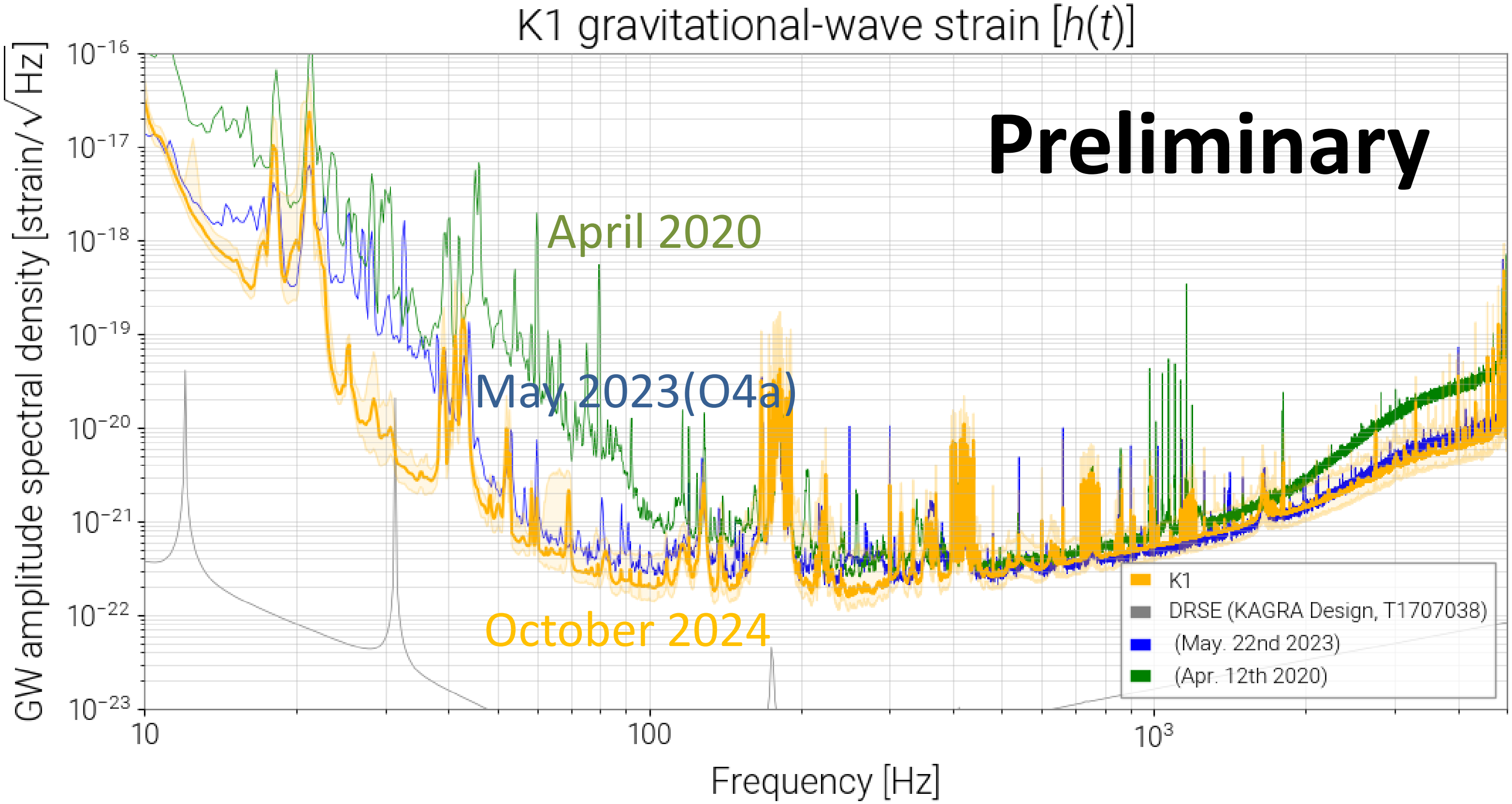
- **But Noto EQ Disaster and Recovery**

- **Noise reduction Plan：**
  - ➢ **High power operation：10W (5W was done)**
  - Auxiliary control noise：1/10 (done in FY2023)
  - Quantum shot noise：1/3 (was tried in FY2024)
  - ➢ **Cooling：~ 100K → Done Jan 2025**
  - Thermal noise：1/5
  - ➢ **Control/hardware update：**
  - Frequency noise：～1/2
  - Acoustic noise：～1/20 (partially done)



Improved Sensitivity(1) (Preliminary)

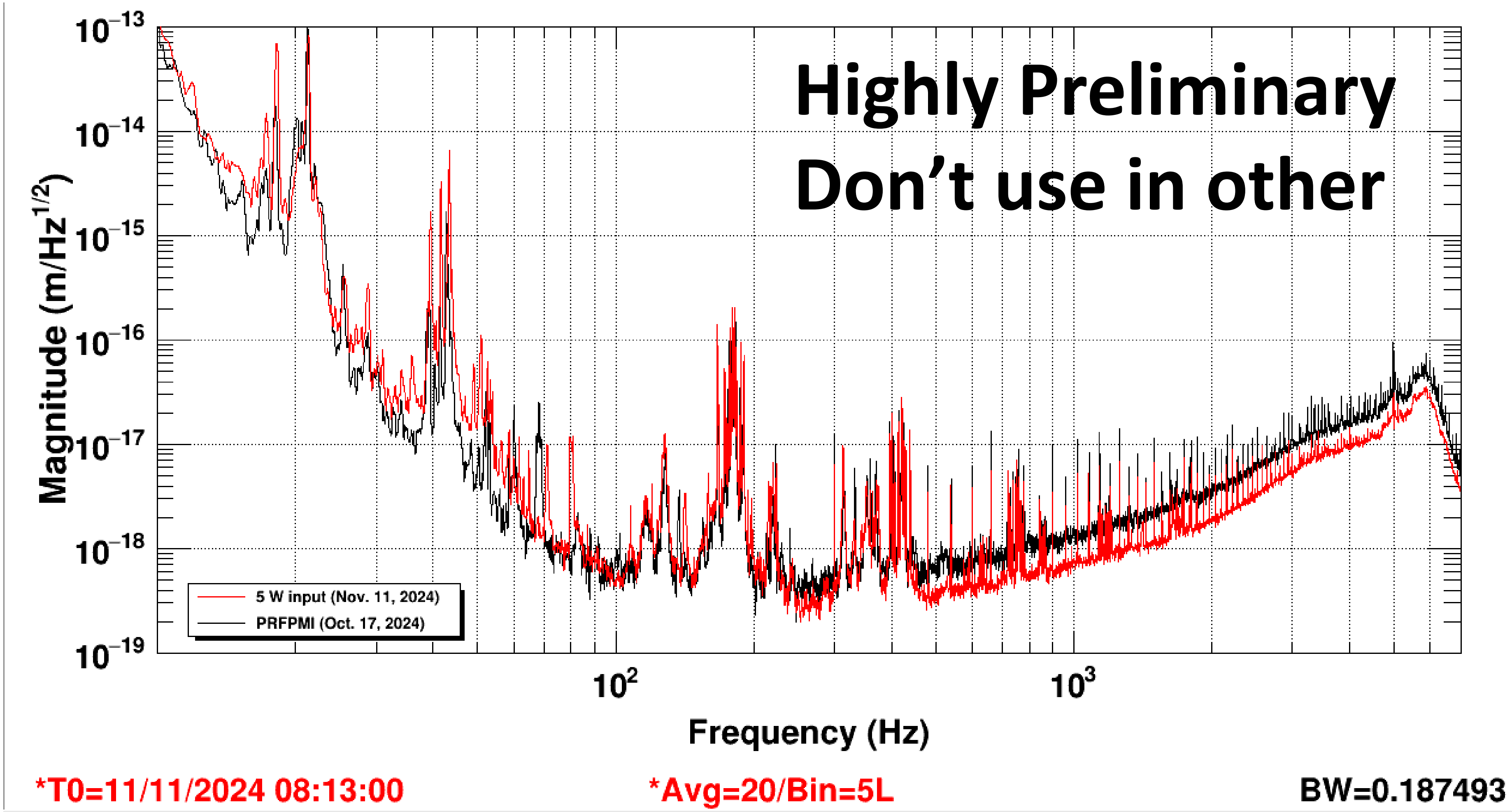
- **KAGRA sensitivity was improved to be ~ 2Mpc owing to several improvements with 1.3W.**
  - Suspension control noise reduction with well designed filters. → Shaking mirrors by the higher noise electrical noises could be reduced a lot.
  - OMC stack structure recovery. → The seismic/acoustic noise invasion to the OMC cavity was reduced.
  - Better alignment by using the full mirror Alignment Sensing Control using WFS, BPC and ADS.→ Darker AS port.



Configuration: Room-temperature PRFPMI with 1.3W injection

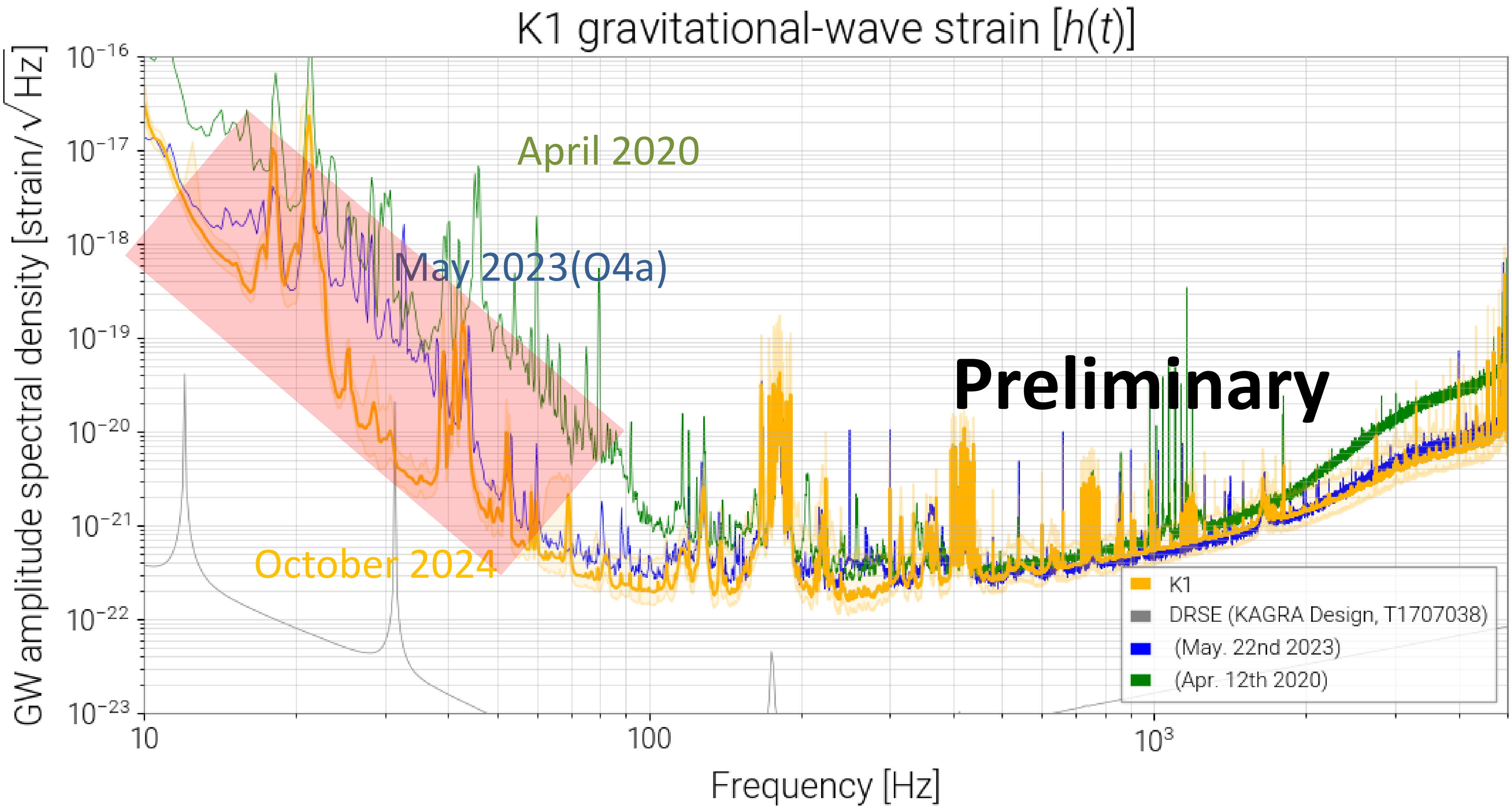
Improved Sensitivity(2) (Highly Preliminary)

- KAGRA sensitivity was improved for high frequency range owing to 5W laser power



Configuration: Room-temperature PRFPMI with 5W injection

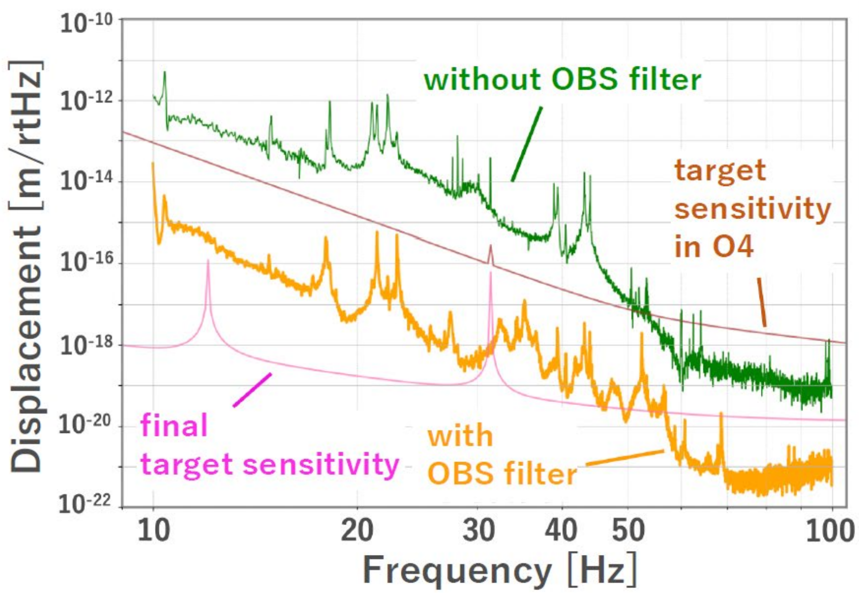
Improved Sensitivity



Configuration: Room-temperature PRFPMI with 1.3W injection

Sensitivity enhanced by better damping control scheme

- **Almost a factor of 10 improvement between 20 and 30Hz**
  - We changed the local damping control scheme, especially for sapphire mirror suspensions, to reduce the control noise at low frequency. In fact, 10 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.



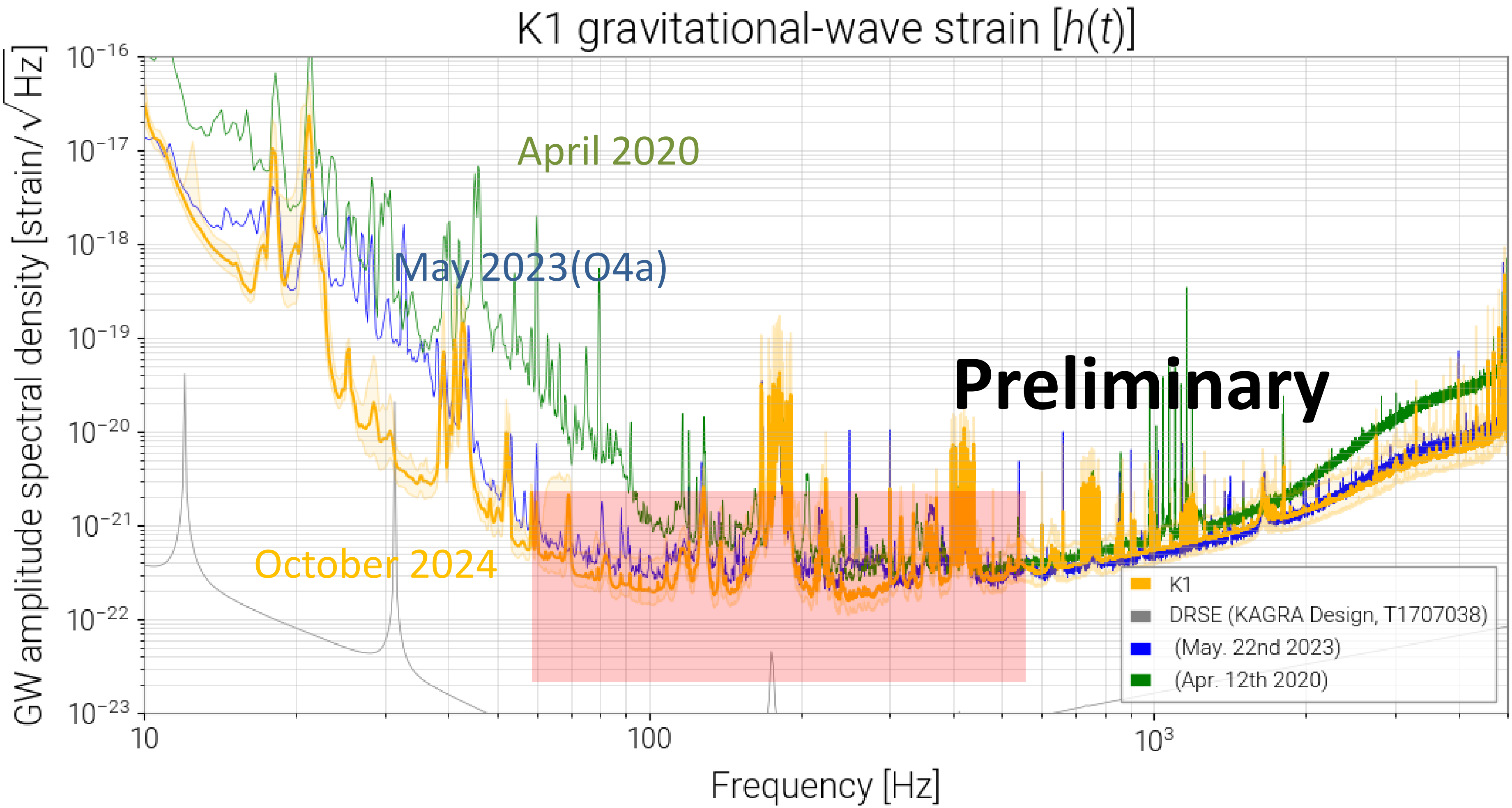
Result

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.

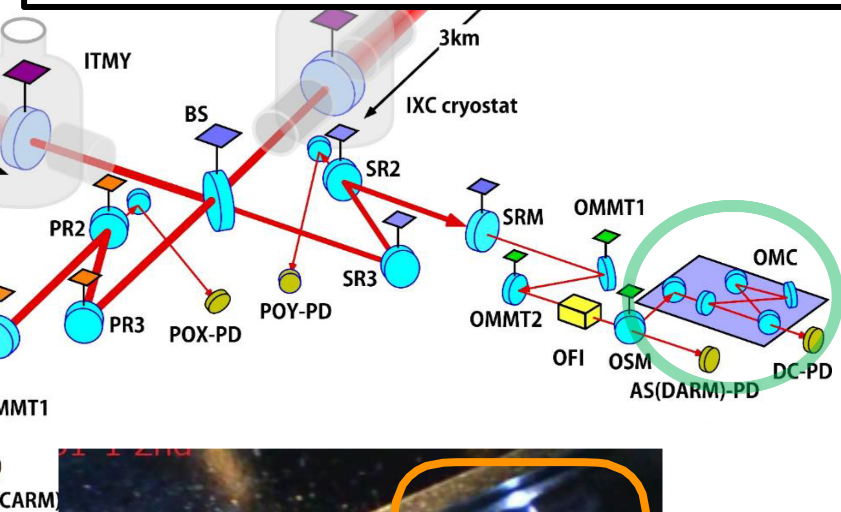
Improved Sensitivity

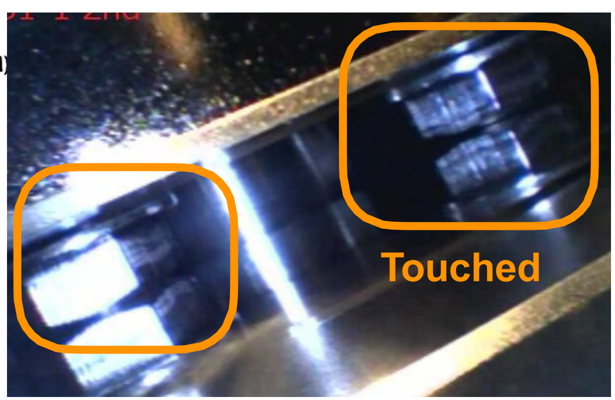


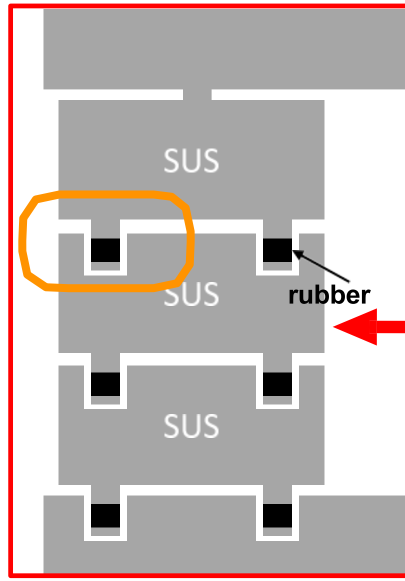
Configuration: Room-temperature PRFPMI with 1.3W injection

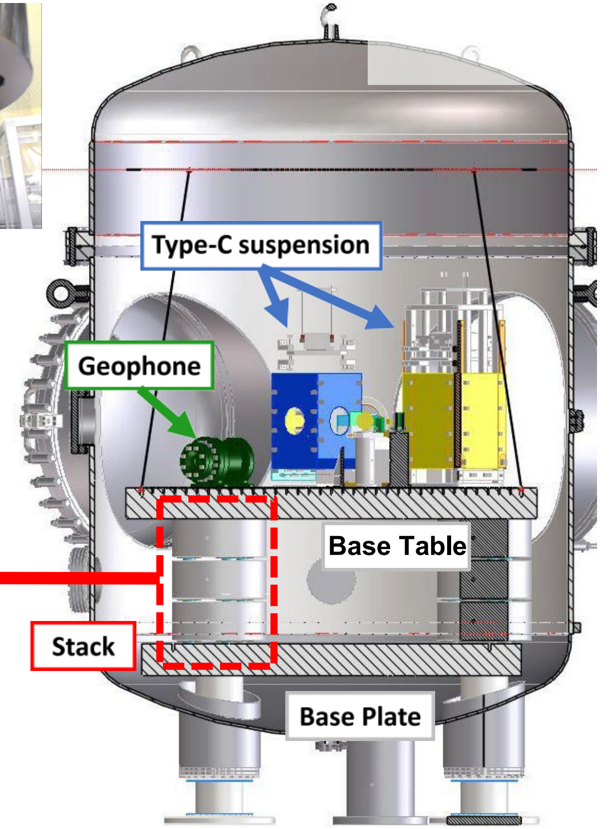
OMC Stack Isolation Recovery (in July)

- 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.



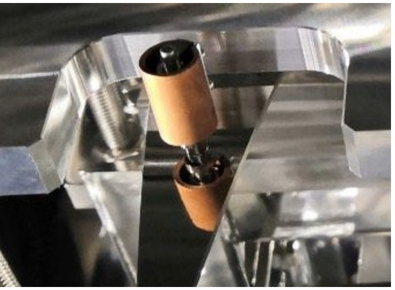




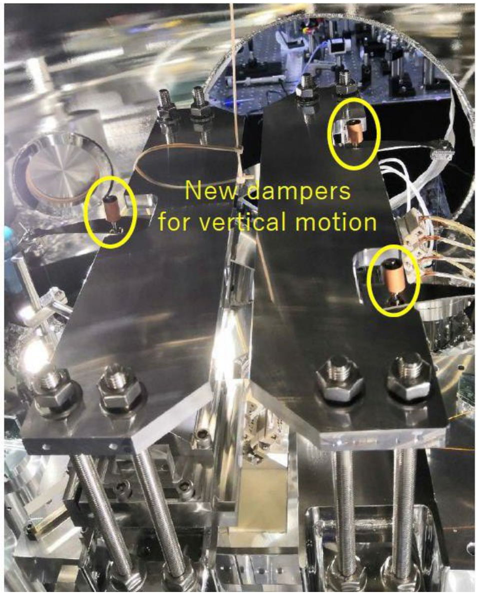


Sensitivity enhanced by OMC Suspension Damping

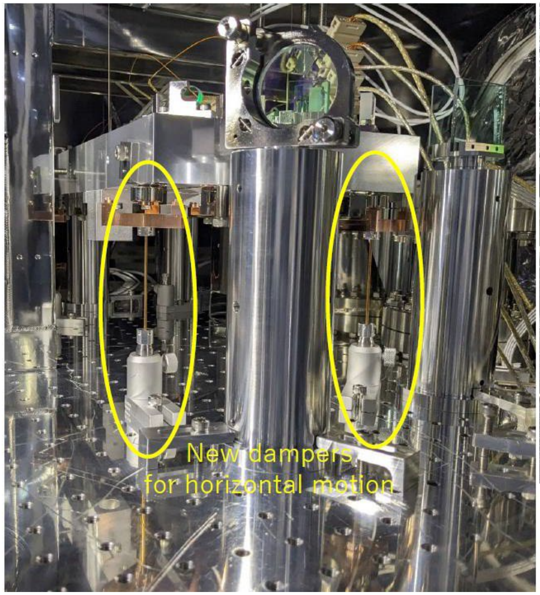
- **About the noise reduction between 60-300 Hz, we think it is thanks to some improvements around OMC suspensions.**
  - One is improving the passive damping performance of OMC suspension resonances to install new magnet dampers on blade springs and below OMC breadboard.
  - Another is to repair the 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.



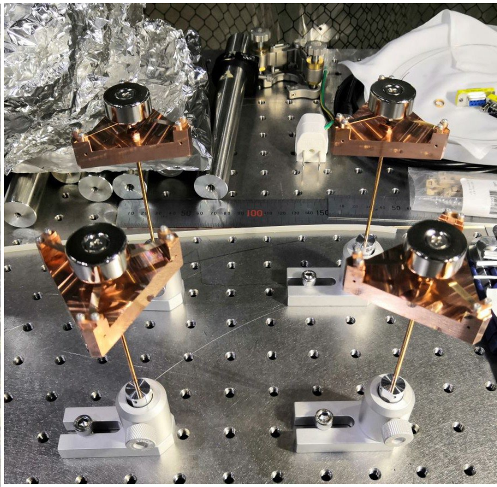
Dumper for blades



Top view of
OMC suspension blades with dumpers



Side view of OMC Plate with Dumpers

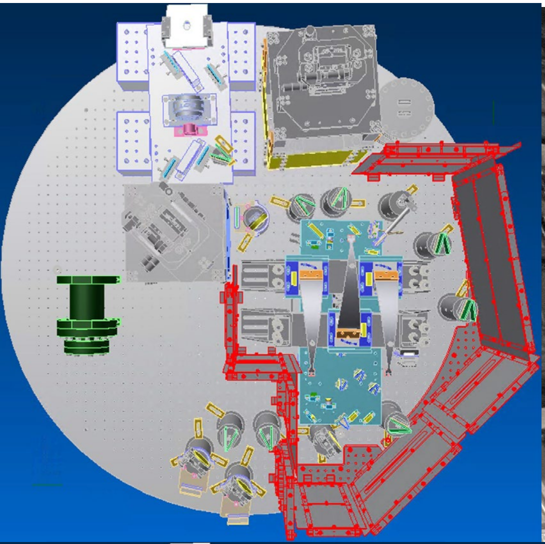


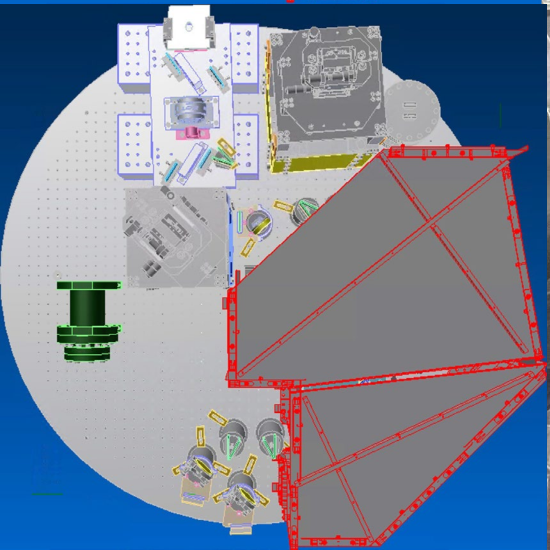
Dumper for OMC plate

29

Stray Light Mitigation Around OMC

Shrouds (not coated in black) around OMC for fit check. They was already removed again and will be coated in black.

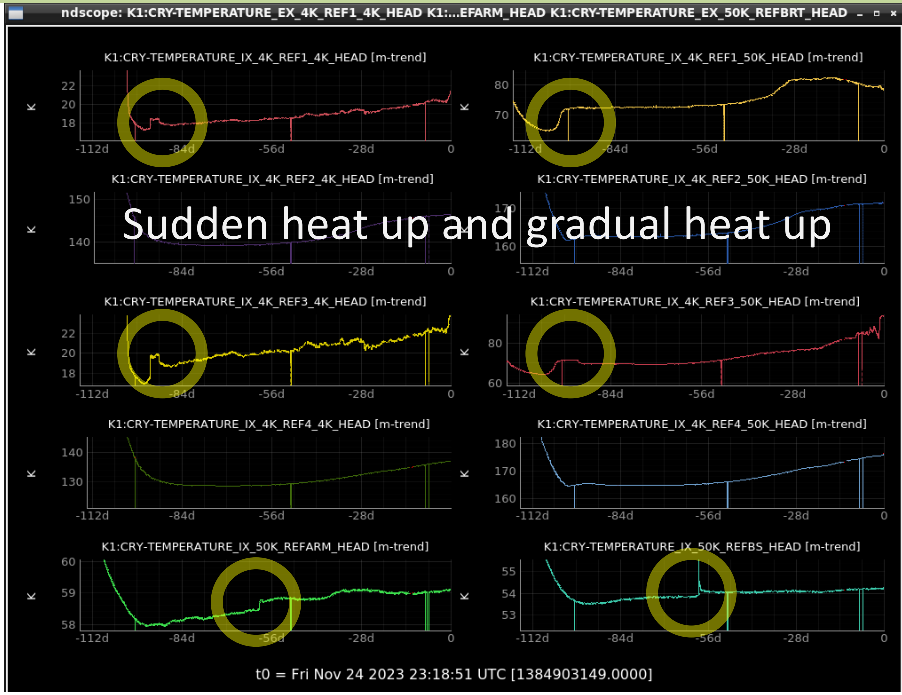


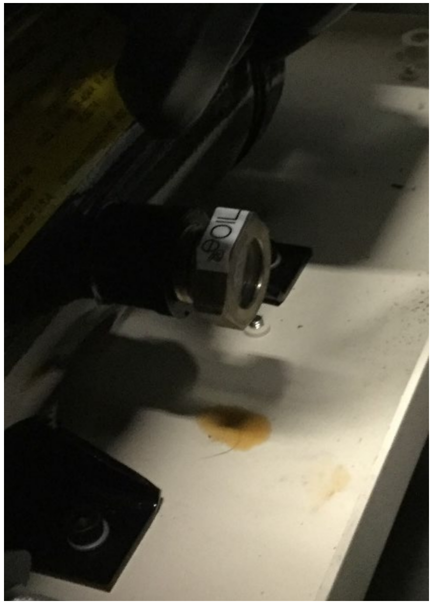


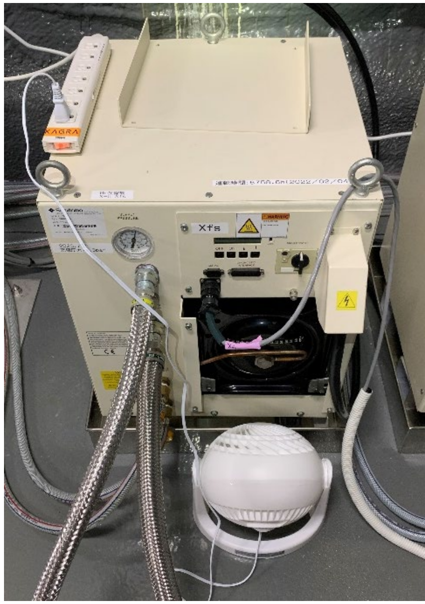
Cryo-cooler Compressor Maintenance

- **What we learn during commissioning before/after O4a?**
  - Unstable cooling performance happened. It resulted the temp enhance of duct /radiation shields and H2O gas release → Frosting of mirrors → **Warm up for 2 weeks for recovery. Huge time loss.**
  - Oil leak in the compressor He gas cooling system. It could result in the cooling performance reduction.
    - High temperature (~ 80C) in the He gas cooling system.
  - He gas leak at the connector of the flexible tube.

- **What is counter measure?**
  - Maintenance and Repair works.
    - Cleaning in the water cooling system in the compressor.
  - Weekly Temp monitor (done every week) of the compressor He gas tank and its data taking (under preparation) for the remote monitoring to find problems in the early stages.

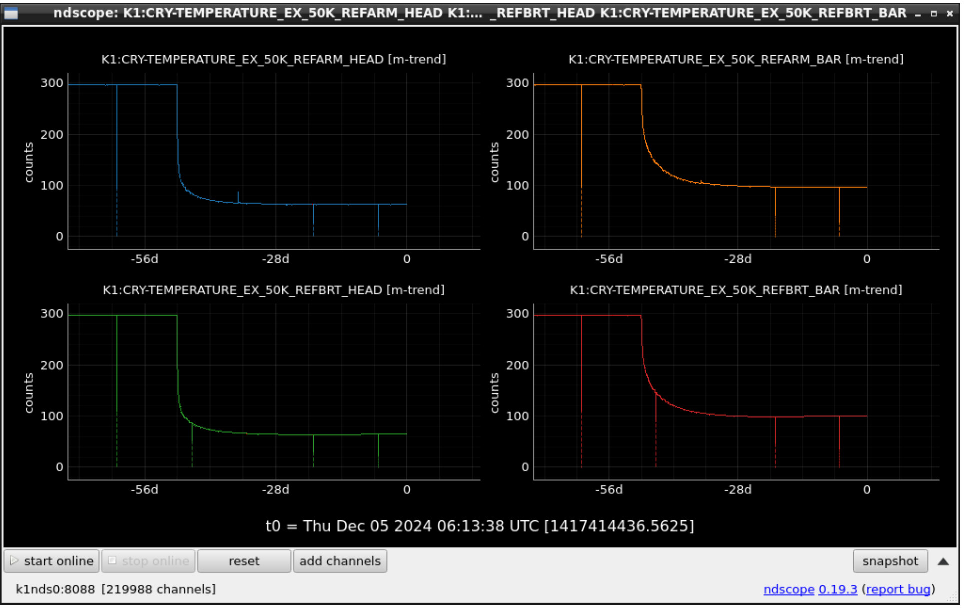




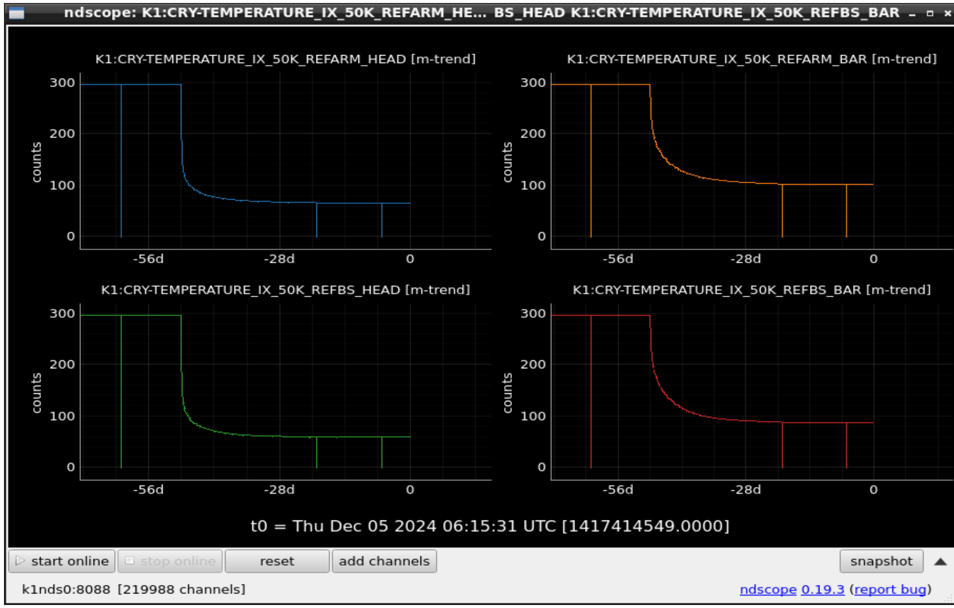


Steady Duct Shield Cooling after Maintenance

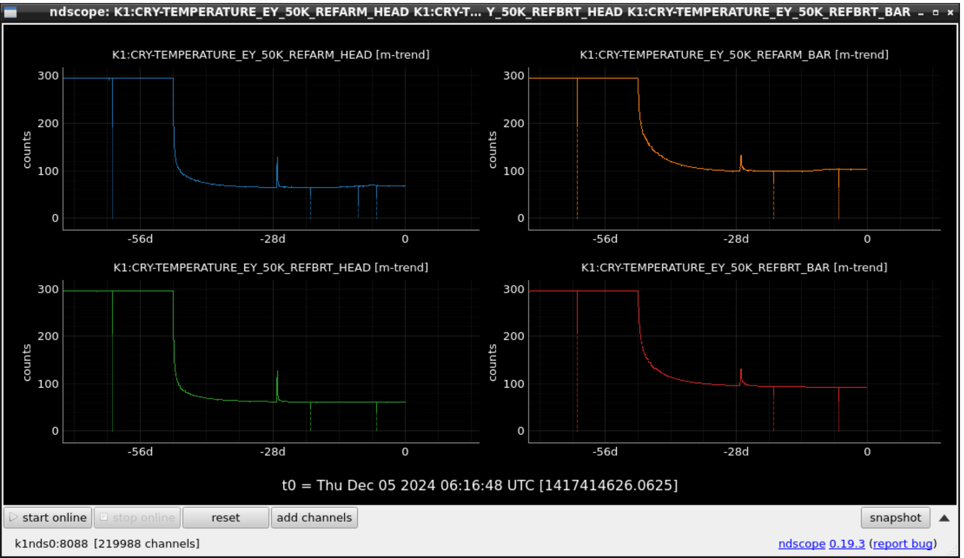
EXC



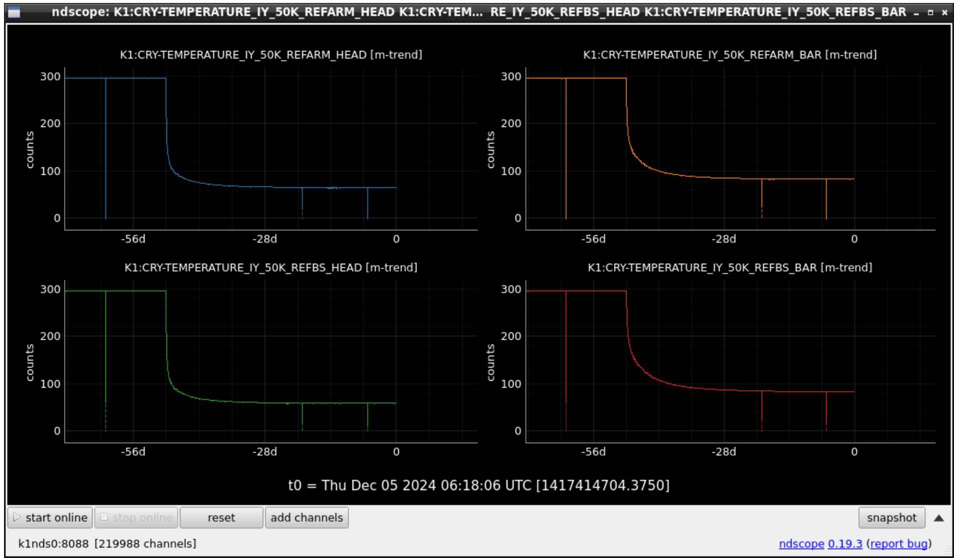
IXC



EYC



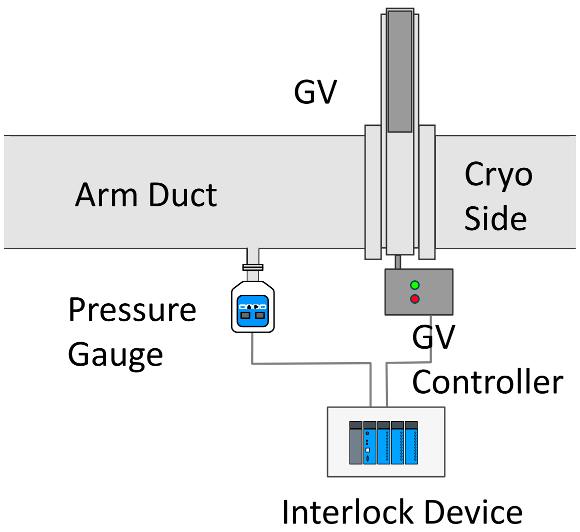
IYC



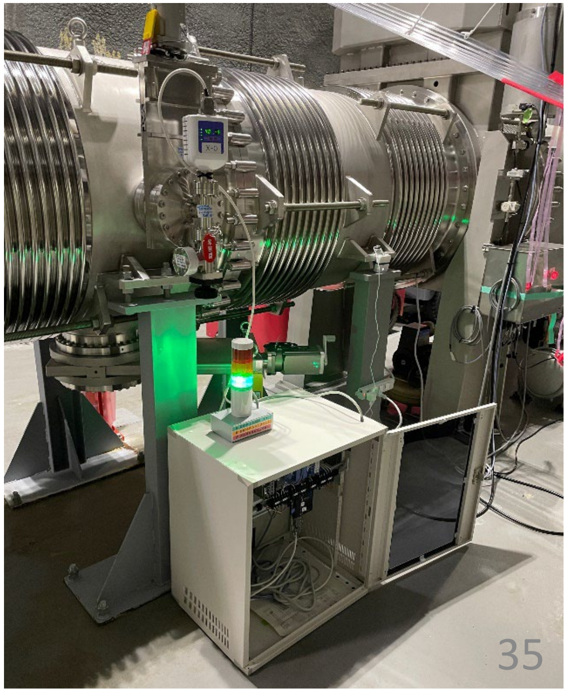
For Reliable Vacuum System

- **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.

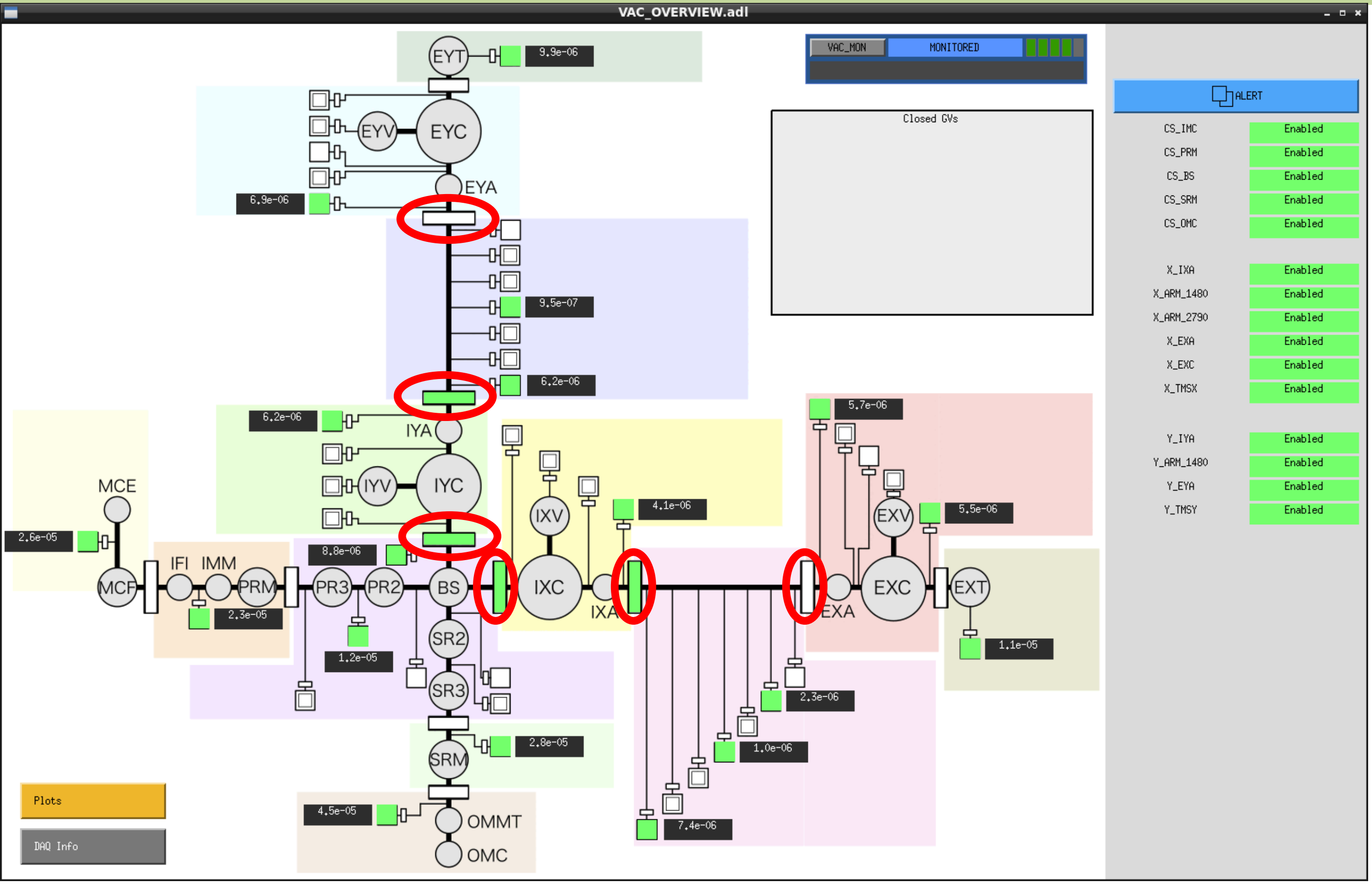
Interlock configuration diagram



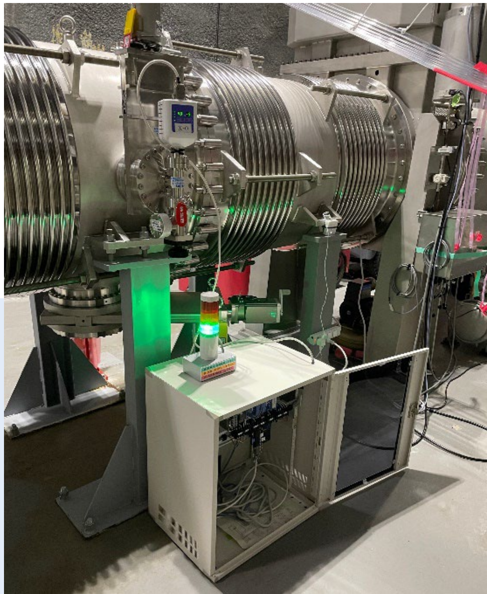
- **What is counter measure?**
  - Interlock system for TMPs were prepared in arm.
    - Enables closing EM-valves between the dry pump and TMP automatically.
  - Automatic Gate Valve closing system between IEXYA and arms, & BS.
    - Senses the vacuum level near IEXYA tanks
    - If high vacuum level (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

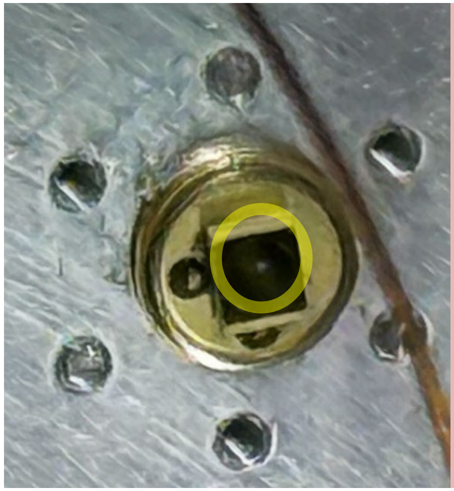
- Gate valve display status

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

→ **Close**

Many Serious Troubles were Scarcely Overcame

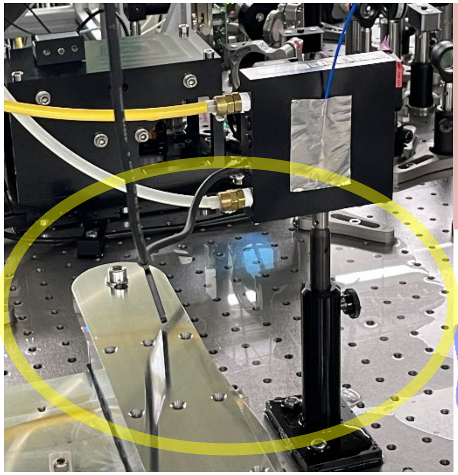
- **DC PDs Burning Again**
  - By improper-selection of trigger PD and improper logic. → Improved. Shutter, please.



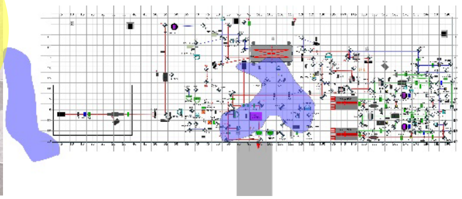
If no stock of PDs, Joining O4 could be impossible. We found 6 stock in MIF(1), ISS(3), CAL(2).

However, the supply of the productor itself seemed to be hard?

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



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

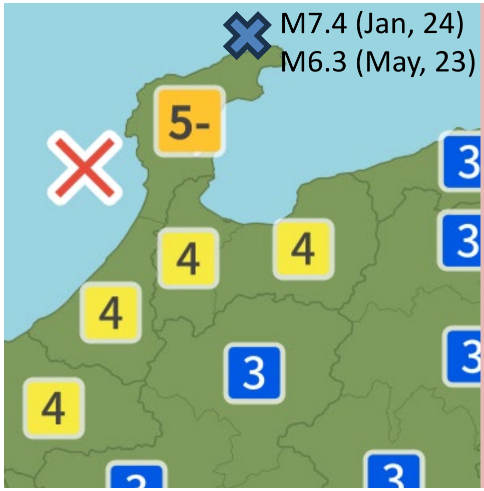


- **Water Supply System trouble**
  - By aging and no maintenance.

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

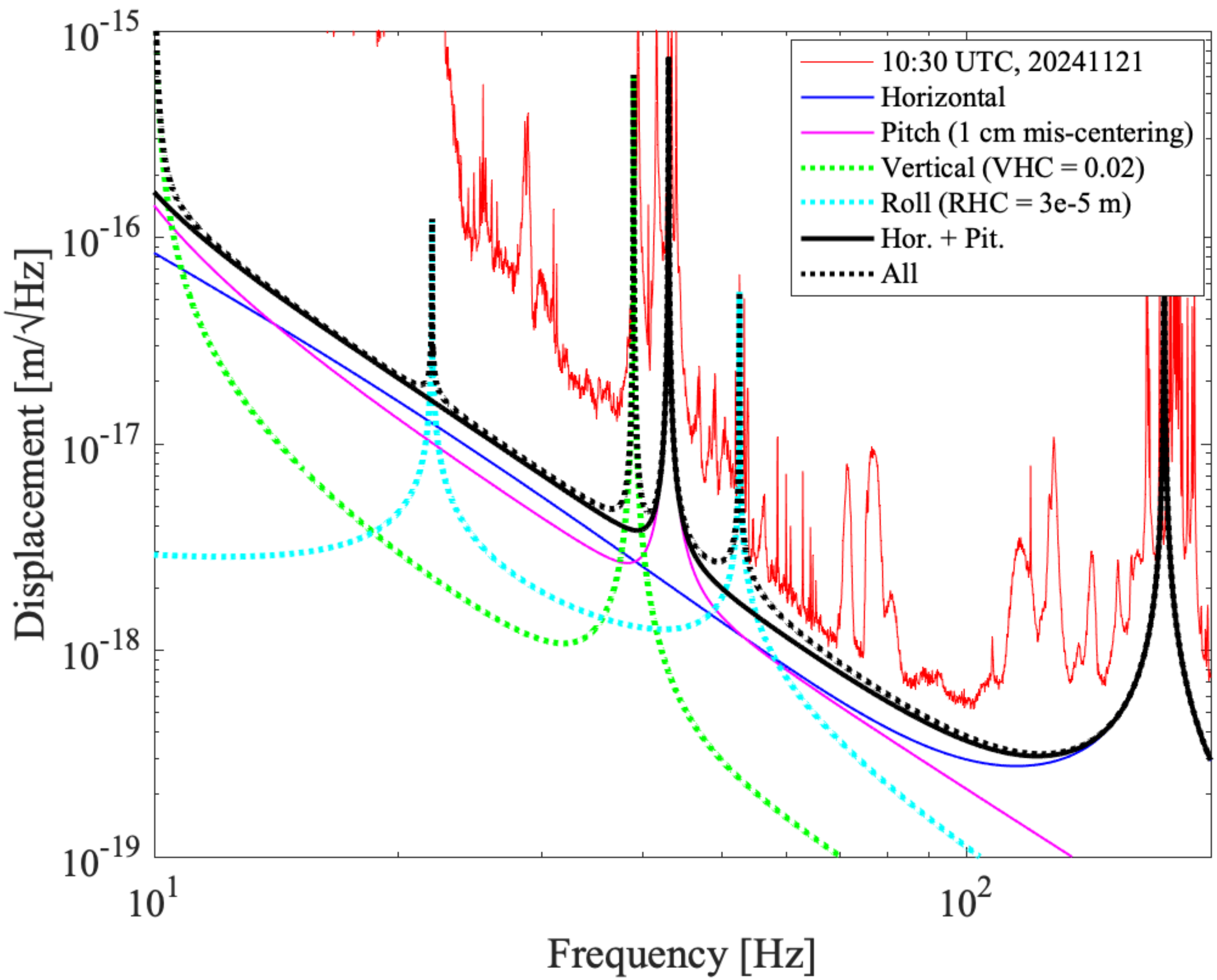
- **M6.4 Earthquake near Noto Peninsula Again (27th Nov. 2024)**



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.

Thermal Noises are Visible ?

- The P → L coupling thermal noise and suspension thermal noise seem to dominate the sensitivity around 50 ~ 100Hz . → Should we decided to cool cryo-payloads?



Summary of LIGO-Virgo observing runs by O3

O1: from September 2015 to January 2016, LIGO only
First observation, GW150914, 3 confident events

O2: from November 2016 to August 2017, LIGO only (+ Virgo in August 2017)
First observation of BNS, GW170817, 8 confident events

O3: from April 2019 to March 2020, LIGO and Virgo
First confident observation of BHNS, GW200115_042309, 79 confident events

Total 90 confident events

Binary Black Holes (BBH): about 84-87
Binary Neutron stars (BNS): 2 confident events GW170817, GW190425
Black hole–Neutron star binaries (BH–NS): 1 confident event GW200115_042309

GW190814: either BBH or BHNS (23.3 2.6) Msun
GW200210_092254: either BBH or BHNS (24.1, 2.83) Msun
GW191219_163120: less confident event
(GW200105_162426: sub–threshold event)

Catalog papers

GWTC-1: O1, O2
PRX 9, 031040 (2019)
arXiv:1811.12907

GWTC-2: O1, O2, O3a
PRX 11, 021053 (2021)
arXiv:2010.14527

GWTC-2.1: Update of GWTC-2
PRD 109, 022001 (2024)
arXiv:2108.01045

GWTC-3: O1, O2, O3a, O3b
PRX 13, 041039 (2023)
arXiv: 2111.03606

O4 run

O4: from May 24 2023 to October 7, 2025

- O4a: 2023-05-24 to 2024-01-16
- O4b: 2024-04-10 to 2025-01-28 17:00 UTC
- O4c: 2025-01-28 17:00 UTC to 2025-10-7 17:00 UTC

O4 public alerts (as of Jan. 28, 2025)   https://gracedb.ligo.org/superevents/public/O4/

- O4 Significant Detection Candidates:186
  - O4b Significant Detection Candidates: 105
  - O4a Significant Detection Candidates: 81

データ解析は進行中で詳細はまだ非公表だが、
今日までに3つの論文を発表

これまでに発表された論文

1. 中性子星+低い質量のmass gapブラックホール合体 ApJL 970, L34 (2024), arXiv:2404.04248

m_1: 3.6 (+0.8 -1.2) Msun

m_2: 1.4 (+0.6 -0.2) Msun

2. 超新星SN2023ixfからの重力波の探索 arXiv:2410.16565

ホスト銀河M101, ~6.4 Mpc,SN2023ixfは過去数十年で観測された中で最も近傍で発生した重力崩壊型超新星爆発

重力波は未検出

3. O4aデータを用いた、知られている45個のパルサーからの重力波の探索

重力波は未検出 arXiv:2501.01495

Summary

- Commissioning to reach the 10Mpc BNS range sensitivity is ongoing.
- The effect of suspension control modification and OMC stack recovery was verified in sensitivity.
- Full ASC enabled stable commissioning work, PEM and noise budgeting activities.
- We still encountered several troubles that delayed the schedule.
- We would like to rejoin O4 around Spring.
- O4 has reported 186 significant detection candidates.
- 3 papers about O4 events have been published.