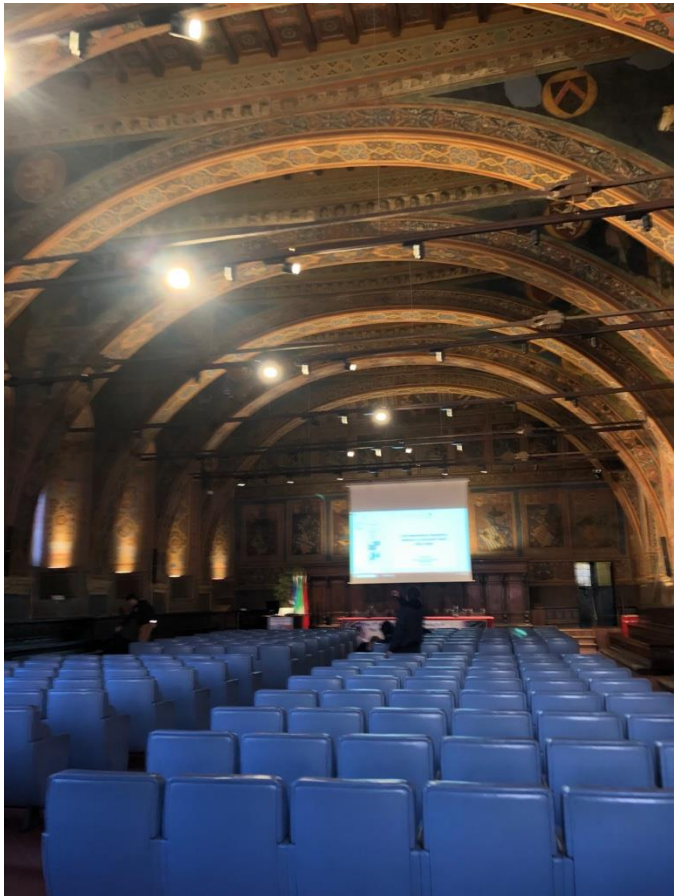
Status and Plans of KAGRA Squeezing subsystem

Ray-Kuang Lee
National Tsing Hua University (NTHU), Taiwan
on behalf of the KAGRA SQZ subsystem

The 14th KAGRA International Workshop (KIW) in Perugia

JGW-G2617357

The 5th KIW in Perugia, Feb. 2019
The 1st KAGRA-Virgo-3D Detectors Workshop



from Project R&D: KFC, to SQZ Subsystem

- **KAGRA Filter Cavity (KFC) Project [2021-2025]**
- Goal
- Improving the sensitivity of KAGRA by injecting Frequency Dependent Squeezing (FDS)

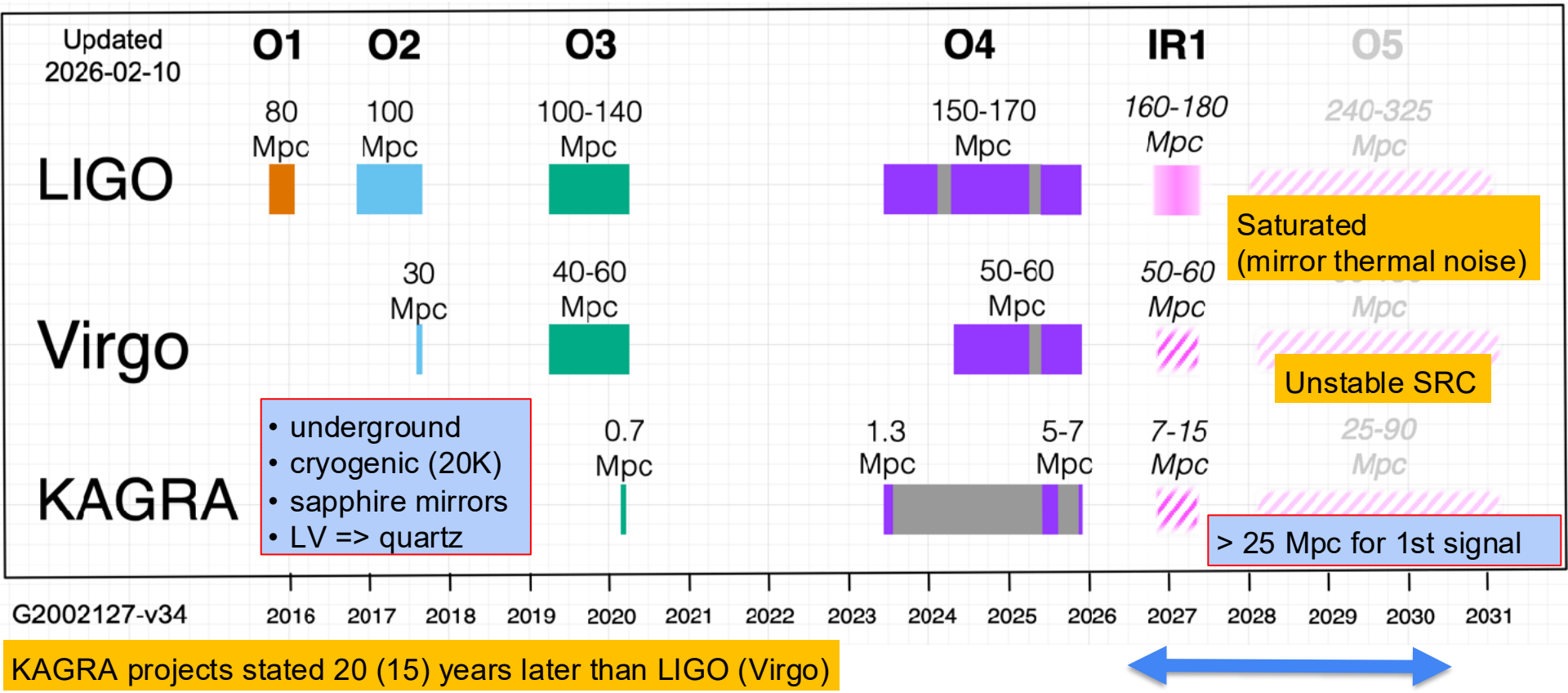
- Kick-off meeting Jan. 20 2021

- Members
- 34 people subscribed to the [KAGRA-filter-cavity] mailing list

- Bi-weekly meetings on Tuesday 4PM (JST)

- Thank Yoichi Aso for his leadership in the KFC project

Observation Timeline



KAGRA projects stated 20 (15) years later than LIGO (Virgo)

KAGRA SQZ Subsystem:

- Alignment with the KAGRA Upgrade Plan
- Most of the upgrade options in the 10yr white paper use squeezing

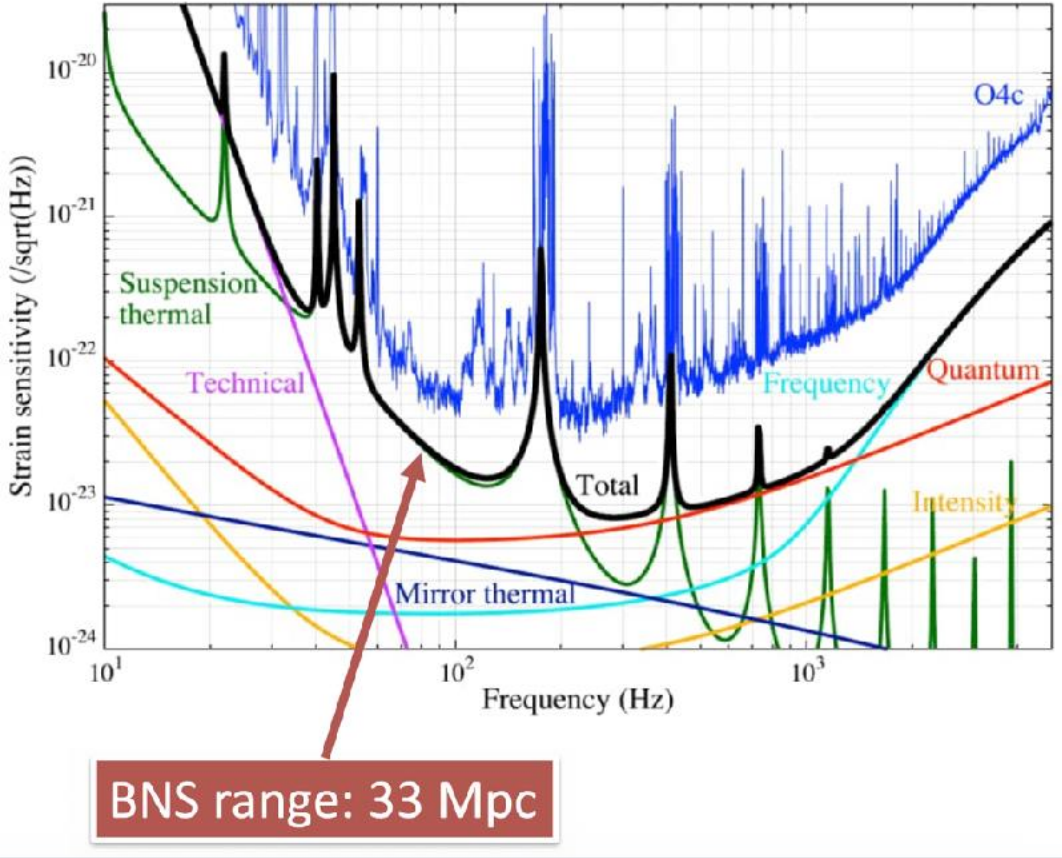
https://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=16701

- **KAGRA 10-year planning**
  - **Broadband Upgrade**
    - Filter Cavity is Necessary
  - **High-Frequency Upgrade**
    - Frequency Independent Squeezing is enough for kHz region
    - FDS is necessary to expand the binary range

- **Our Strategy**
  - Focus on the development of **squeezer**
    - This is necessary for any type of upgrade
    - Conceptual design of the filter cavity is basically done
      - We can resume this work if necessary (and resource is available)

KAGRA in O5

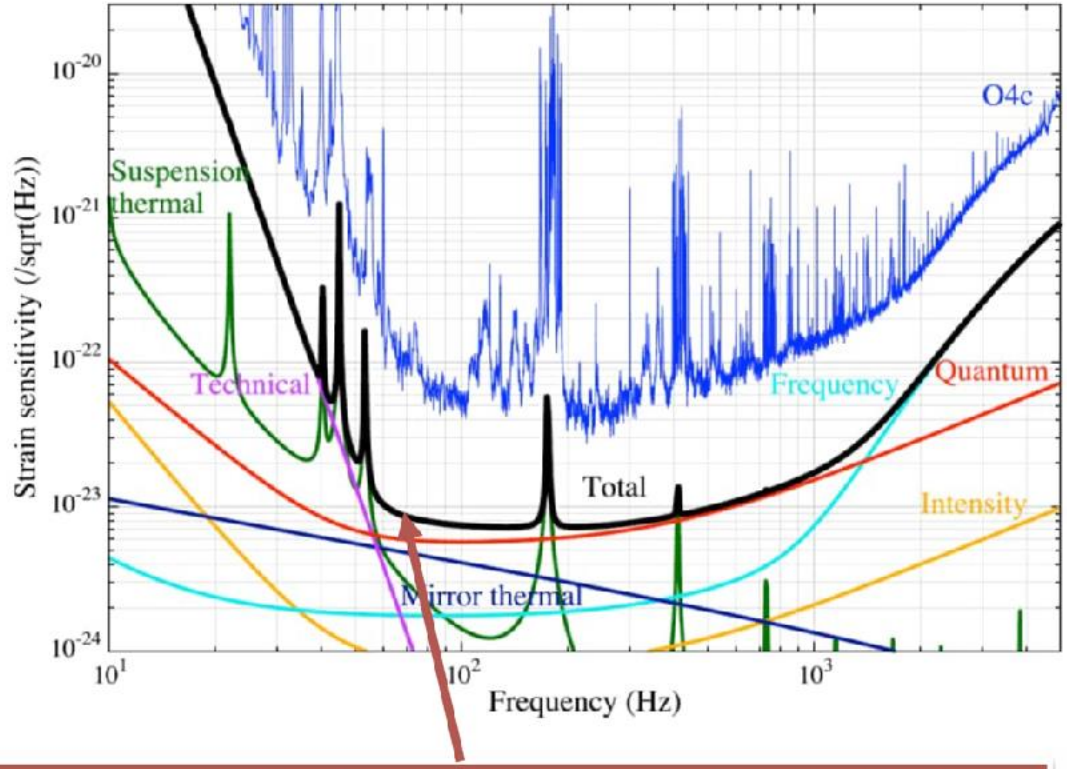
- Joining O4c with BNS range ~7.5 Mpc
- New ITMs for O5 (better symmetry and birefringence)
- Joining O5 with > 25 Mpc
- How shall we achieve this sensitivity?
  - Better ITMs
  - Signal recycling technology
  - Higher laser power
  - Reduction of control noises
  - Reduction of various other noises
  - ….



"Decadal upgrade strategy for KAGRA toward post-O5 gravitational-wave astronomy," arXiv: 2508.03392v1 (2025).

KAGRA in O5 (optimistic)

- One of the factors that limit the current KAGRA sensitivity is the lower-than-expected Q value of the sapphire suspension fibers
- better sapphire suspension fibers
- Other possibilities of improvements exist

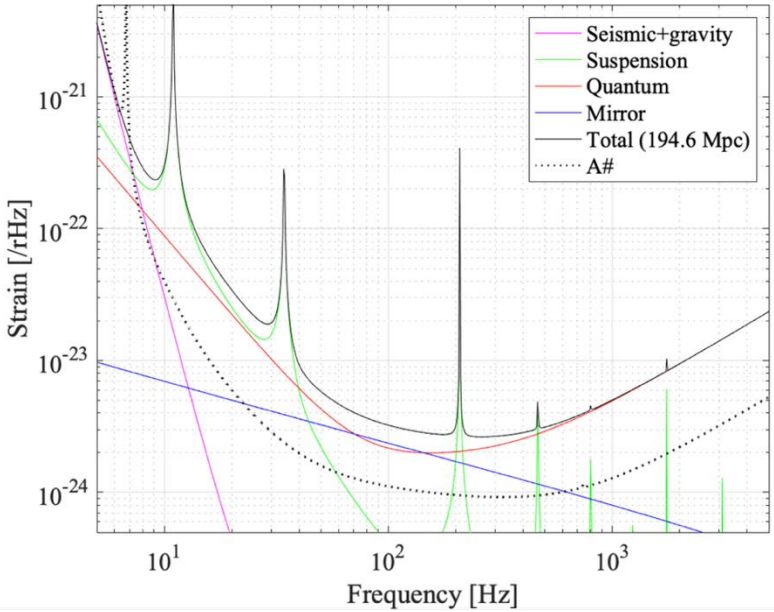


"Decadal upgrade strategy for KAGRA toward post-O5 gravitational-wave astronomy," arXiv: 2508.03392v1 (2025).

BNS range could be further improved upto 74 Mpc

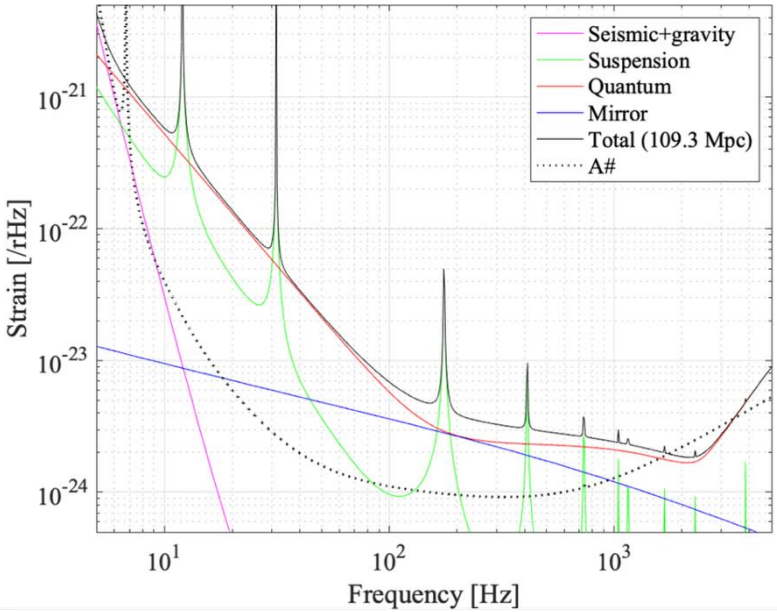
KAGRA Upgrade Plans:

BB40FDS-HQS
Broadband + 40kg Test Mirror +FDS



Suspension loss	2x 10^{-7}
Squeezing	6dB FDS
Larger mirrors	40kg

HF2KFIS-HQS
High-Freq. @ 2 KHz +FIS



Suspension loss	2x 10^{-7}
Squeezing	10dB non-FDS
Higher ITM reflectivity	99.6%-> 99.8%

High-Frequency Specialized Upgrade: KAGRA-HF

KAGRA 10-Year White paper: http://arxiv.org/abs/2508.03392

- Among various upgrade options, selected a high-frequency (kHz) specialized upgrade

Why High Frequency?

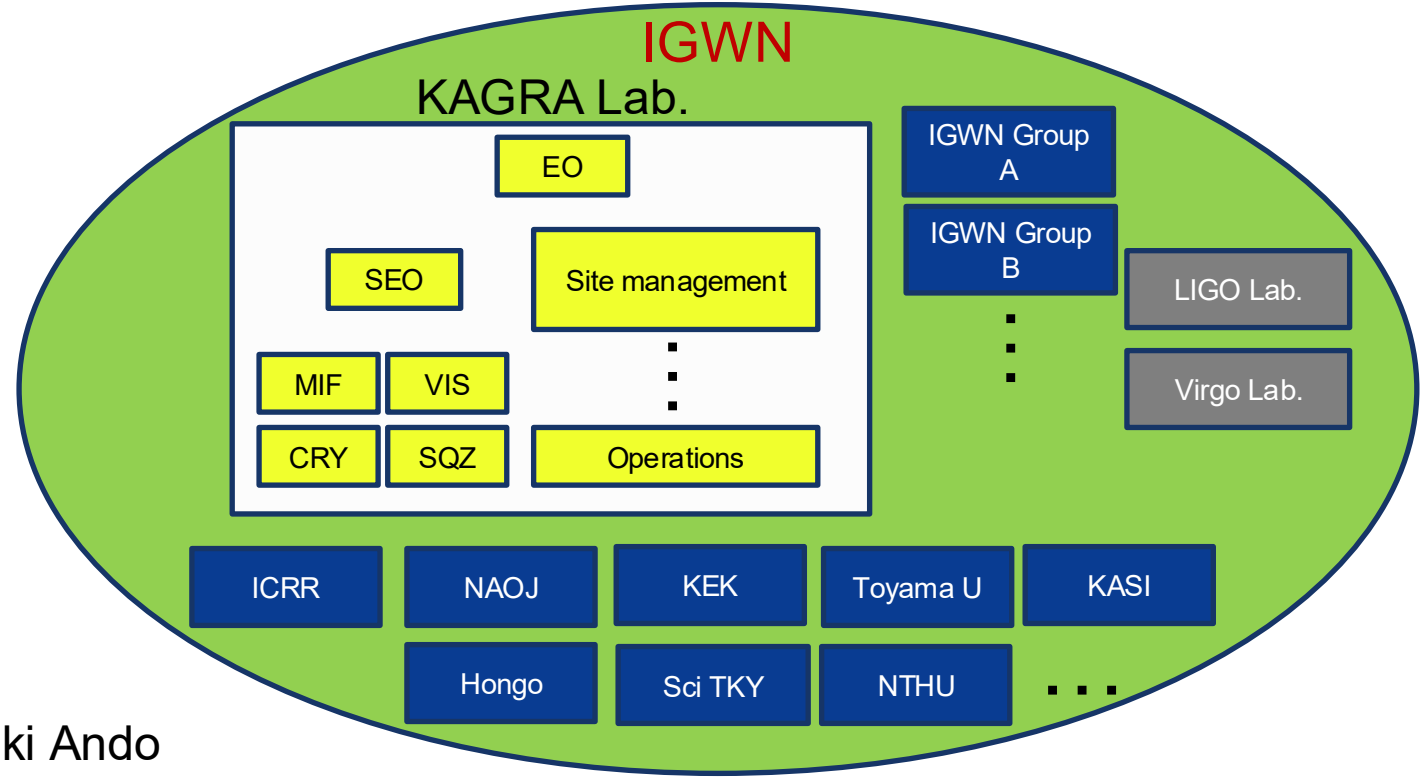
- In O6, LIGO, Virgo, and LIGO India will be operational: 4 broadband (BB) detectors in total
- Adding KAGRA as a 5th BB detector offers limited additional science merit
- Upgrading as a BB detector is costly
- LIGO and Virgo cannot sacrifice low-frequency sensitivity (BBH mergers)
- By specializing in high frequency, KAGRA can deliver unique science impact

Niches:

- Cryogenic systems => High-Pump Power operation
- No mysterious noises in HF => Only limited by Shot-Noise (Quantum Noise)
- Squeezing is the Must-Needed => KAGRA SQZ Subsystem

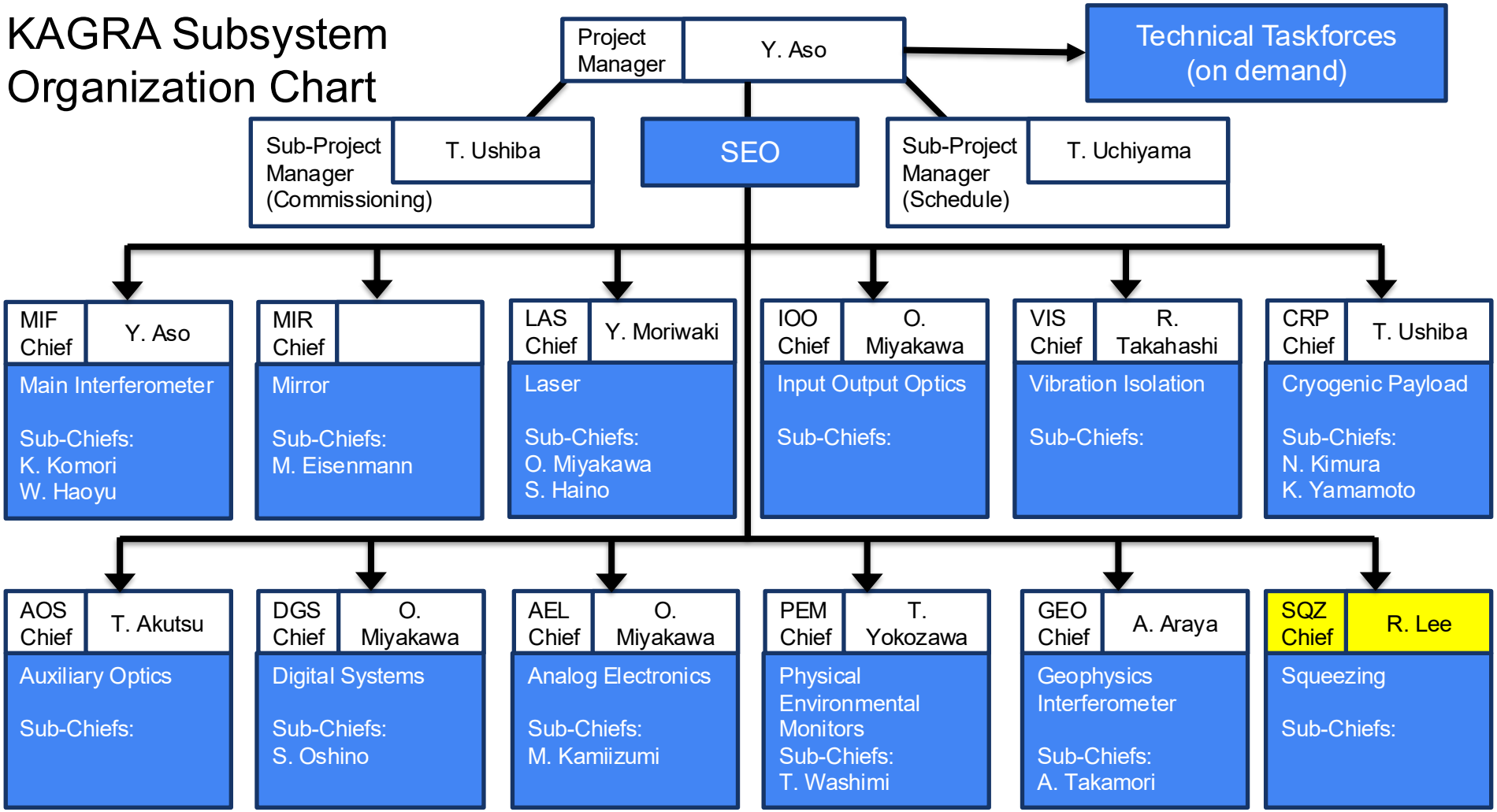
The era of IGWN: KAGRA Lab. (proposal)

- Similar to LIGO Lab. And Virgo Lab., a new KAGRA Lab. will be organized.
- Dark blue boxes represent IGWN groups



Courtesy:
Yoichi Aso and Masaki Ando

KAGRA Subsystem Organization Chart



KAGRA SQZ Subsystem:

Chief: Ray-Kuang Lee

- **VOPO test:** NAOJ, **NTHU**
- **Squeezer design:** NAOJ, U Tokyo
- **Filter Cavity design:** NAOJ
- **Vacuum and Cryogenic Systems:** NAOJ, KEK
- **Faraday Isolator:** KASI
- **Small Suspension:** ICRR
- **Interface & Mode Match Optics:** **NTHU**, KASI, Yonsei, Kyung Hee, Myungji
- **Auto-alignment Control:** HAS , KASI
- **Noise budget curve Simulation:** RESCEU, NAOJ, **NTHU**

also with Science Tokyo, KAIST, APC (France), U. Trento (Italy), ANU, AEI, Nikhef, Henan AS

Scope of Squeezing Subsystem (SQZ)

Name: Squeezing Subsystem
Acronym: SQZ
Purpose and scope

- Design, fabrication, test and installation of a squeezer for KAGRA
- “Squeezer” includes, a squeezed vacuum source, interface optics and control electronics.
- If KAGRA decides to use a filter cavity, SQZ will take charge of the development of the FC.
- SQZ is mainly responsible for the optical systems.
- SQZ works closely with VIS, VAC, AEL and other subsystems to develop related components, such as,
  - Vacuum chambers to house OPO, interface optics, etc
  - Vibration isolation systems for the breadboard inside the chambers
  - Suspension systems for the FC mirrors
  - Control electronics necessary to operate the squeezer

Subsystem Chief: Ray-Kuang Lee (NTHU)

SQZ: Tasks

Current Task assignment:

- VOPO test: Michael, Ye (NAOJ)
- Squeezer design: Michael, Ye, Aritomi (NAOJ, U.Tokyo)
- FC design: Marc (NAOJ)
- Interface Optics and Mode Matching Telescope : Hua Li (NTHU)
- OPO: Chien-Ming Wu and Hsun-Chung Wu (NTHU)
- Control system: Yuhang, Chang Hee, Gyoik (HAS, KASI, Yonsei)
- Faraday Isolator: Sungho (KASI)
- Small Suspension: Aso (ICRR)
- Noise budget curve simulation: Komori, Michael, Musfar (NAOJ, NTHU)

- Kick-off meeting Sept. 30 2025
  minute: https://docs.google.com/document/d/1L6CKvRKwJl9rRhNqb-iMmUe8xGN2YFSMci8CoI3Duek/edit?tab=t.0

- Members
- Currently 38 people subscribed to the [new **KAGRA-SQZ**] mailing list, and Nortion page

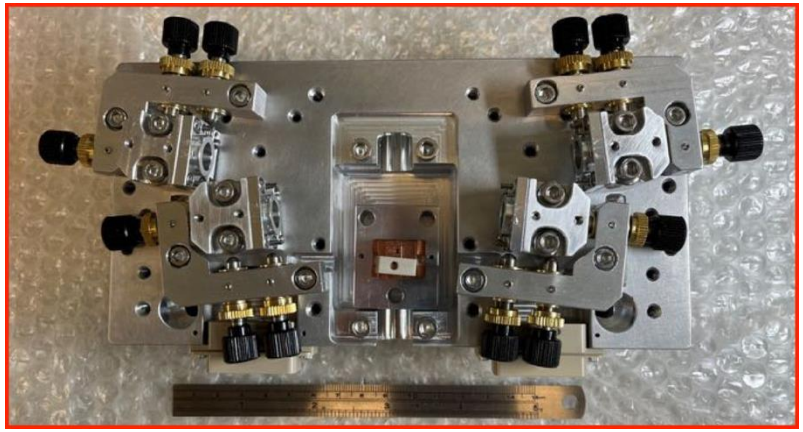
- SQZ Bi-weekly meetings on Tuesday 4PM (JST), hosted by Ray-Kuang
- TAMA Filter-Cavity Bi-weekly meetings on Tuesday 4PM (JST), hosted by Michael Page

- Please contact Ray-Kuang Lee if you are interested in joining the team

Test on the vOPO for the quantum noise reduction in the advanced gravitational wave detectors [P1-OP-059- OP]

Test Results of the VOPO squeezer for KAGRA

JGW-G2516848



VOPO :Vacuum-compatible Optical Parametric Oscillator based on the aLIGO design.

kHz BHD: Balanced Homodyne Detector for detection below 100 kHz.

Hua Li Chen, Hsun-Chung Wu, Yang-Yi Lee, Heng-Yi Lee, Te-Hwei Suen, Chien-Ming Wu and Ray-Kuang Lee (NTHU)

Michael Page, Yuheng Ye, Yoichi Aso, Takayuki Tomaru (NAOJ), and KAGRA Filter Cavity (KFC) Team

国立天文台 NAOJ National Astronomical Observatory of Japan

國立清華大學 NATIONAL TSING HUA UNIVERSITY

KAGRA

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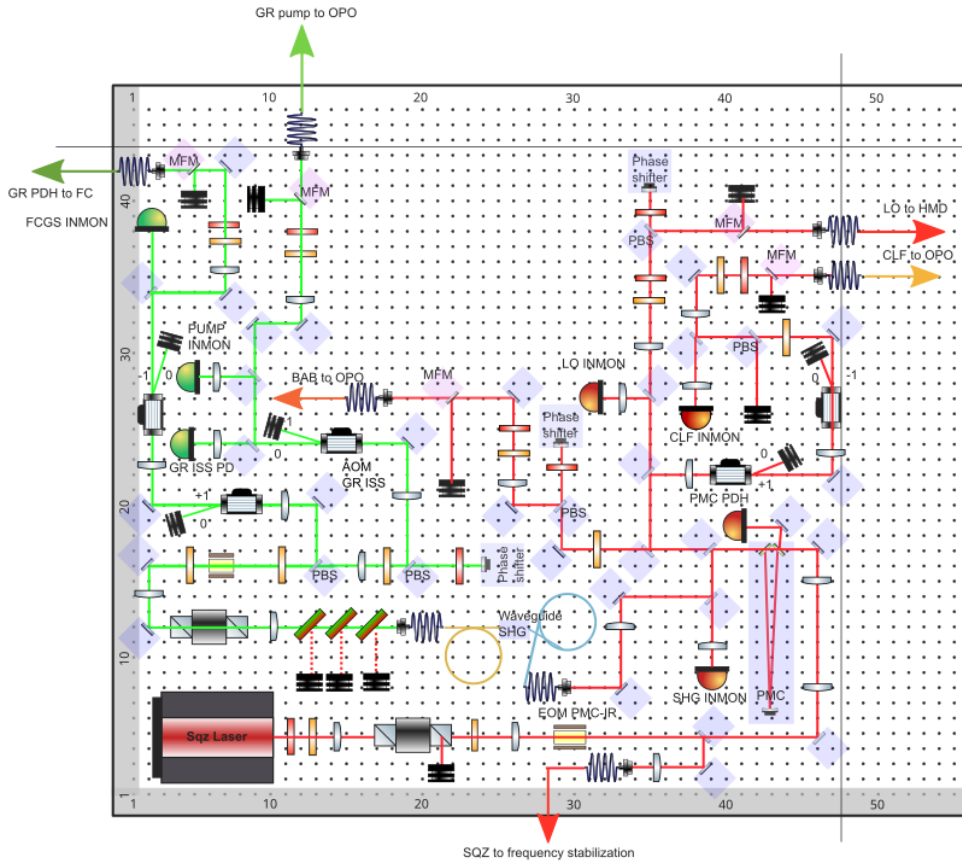

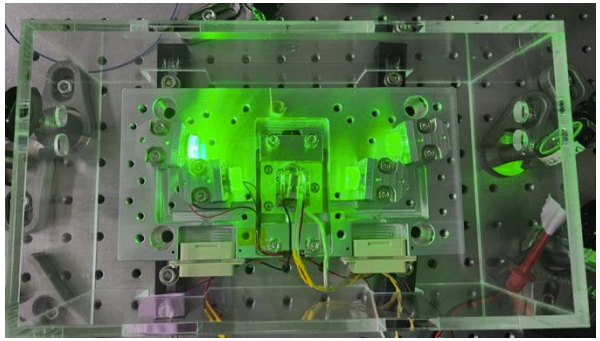

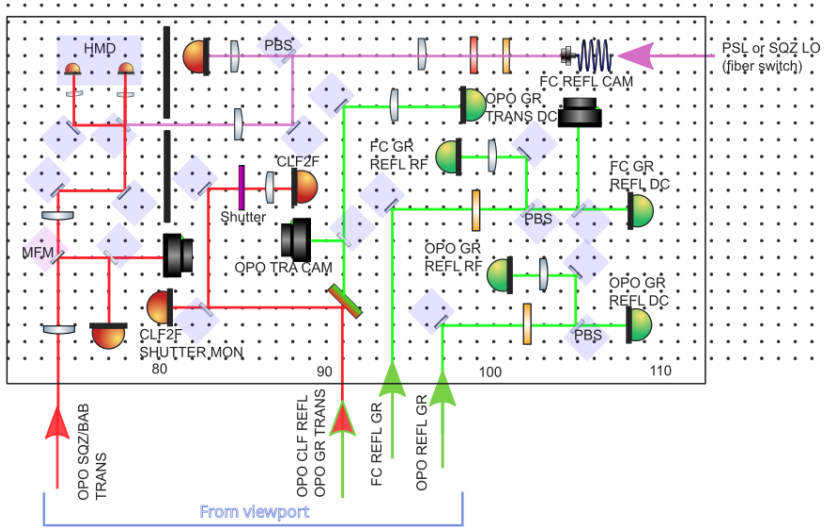

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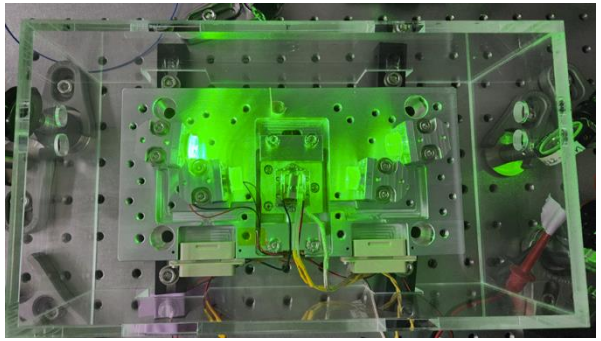

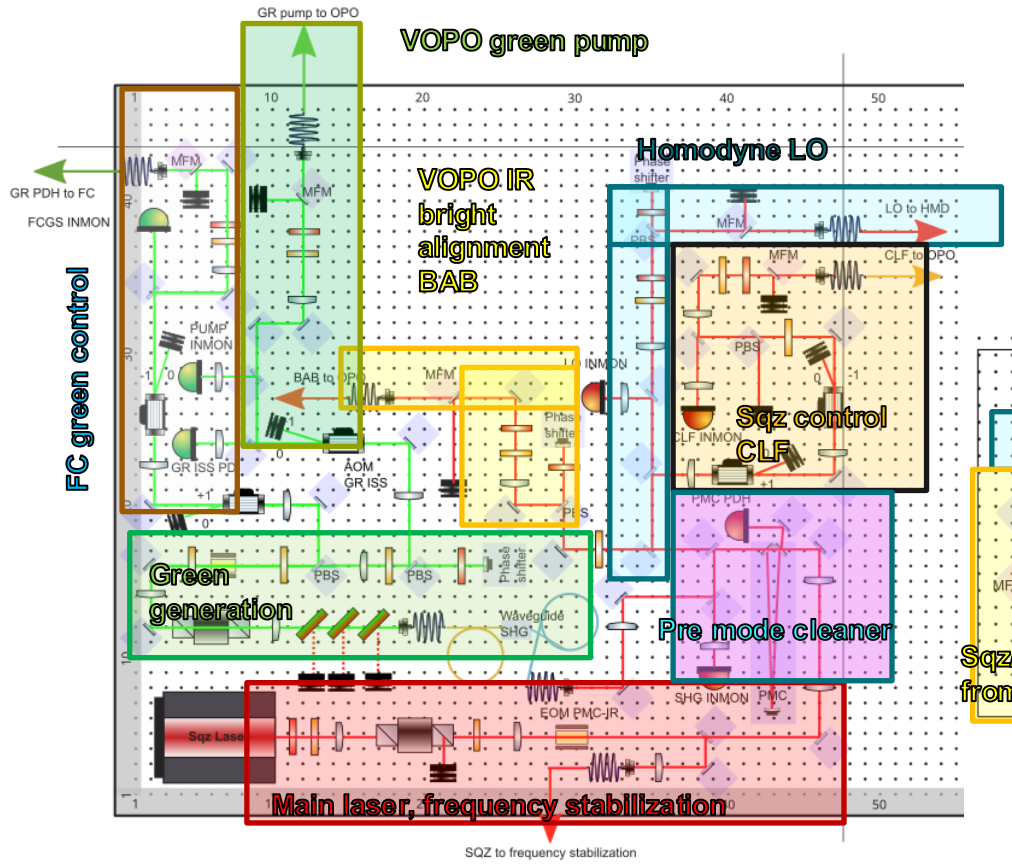

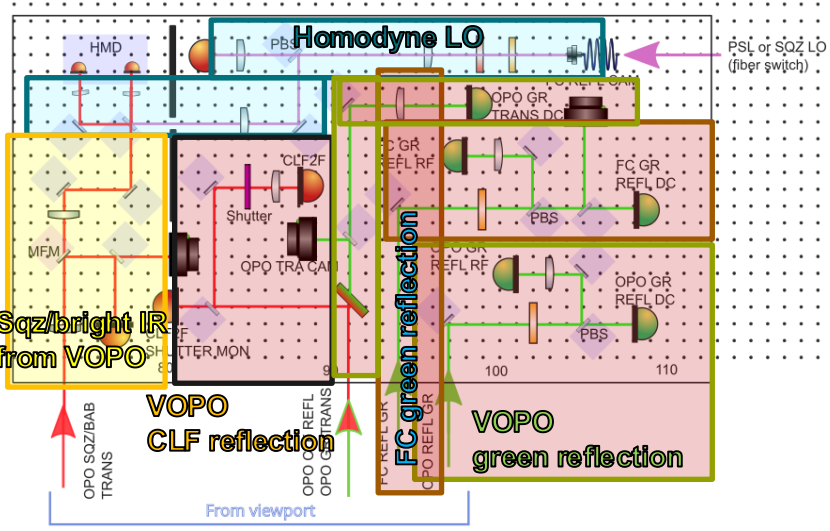


CLIO300


Frequency dependent squeezing experiment
フリクエンシー　ディペンデント　スクィージング　エクスペリメント

VOPO's parameter

Cavity Parameter	Symbol	Value				Unit
		Our VOPO			LIGO VOPO data	
		2024 NTHU measurement	2025 NAOJ measurement	Calculated from component specs		
Input/Output Coupler Fundamental Reflectivity	$R_{in/out}^{1064}$	0.875	0.875	0.875	0.875	-
Input/Output Coupler Pump Reflectivity	$R_{in/out}^{532}$	0.875	0.875	0.875	0.875	-
Total Intra-Cavity Loss for Fundamental	T_l^{1064}	0.016	0.0078	0.0039	0.0027	-
Total Intra-Cavity Loss for Pump	T_l^{532}	0.0477	0.0474	0.0105	0.0459	-
Finesse at Fundamental	F_1	42.0	45.8	45.7	46.1	-
Finesse at Pump	F_3	34.4	35.4	43.6	34.8	-
Linewidth at Fundamental	$\Delta\nu_1$	20.7203	18.96	19.02	18.5	MHz
Linewidth at Pump	$\Delta\nu_3$	25.2505	24.55	19.94	24.5	MHz
Free spectral range	FSR	869.56	869	869.56	853.45	MHz
Optical Path Length	L	0.345	0.345	0.345	0.343	m
Threshold Power	$P_{threshold}$	54	67.95	-	-	mW
Escape Efficiency	η_{esc}	0.892094	0.943	0.971604	0.979916	-
Non-linear Coupling Strength	g	1259.82	1016	-	-	$s^{-\frac{1}{2}}$

KAGRA SQZ timeline:

At this moment, we have preliminarily observed nearly **7 dB Squeezing (at 2.5 MHz)** and nearly **8 dB SQZ (at 100 kHz)** at the ATC clean booth in NAOJ.

The target Squeezing level is **10 dB Squeezing**!

Timeline for deliverables:

- In-air test of the OPO in ATC NAOJ (in **FY2026**)
  - Confirmation of the basic squeezing operation
- Finalizing the design of the KAGRA squeezer system (in **FY2026**)
  - Fix the specifications of custom optical components
- Procurement of optical components for KAGRA squeezer prototype (in **FY2026**)
- Assembly and in-air test of the KAGRA squeezer prototype (in **FY2026**)
- In-vac OPO test using TAMA 300 (in **FY2027**)
- Coupling In-vac OPO to TAMA 300 (in **FY2028**)
- Ready to be installed into KAGRA (in **FY2029**)

Target: Late O5 (2030) or post O5 (2031) Installation in KAGRA with Squeezing.

Our SQZ also provides a platform to implement new Quantum Technologies: EPR-SQZ, Teleportation, SU(1,1), non-Gaussian, Quantum Interferometry.