Technology Developments in Korea for GW Detectors

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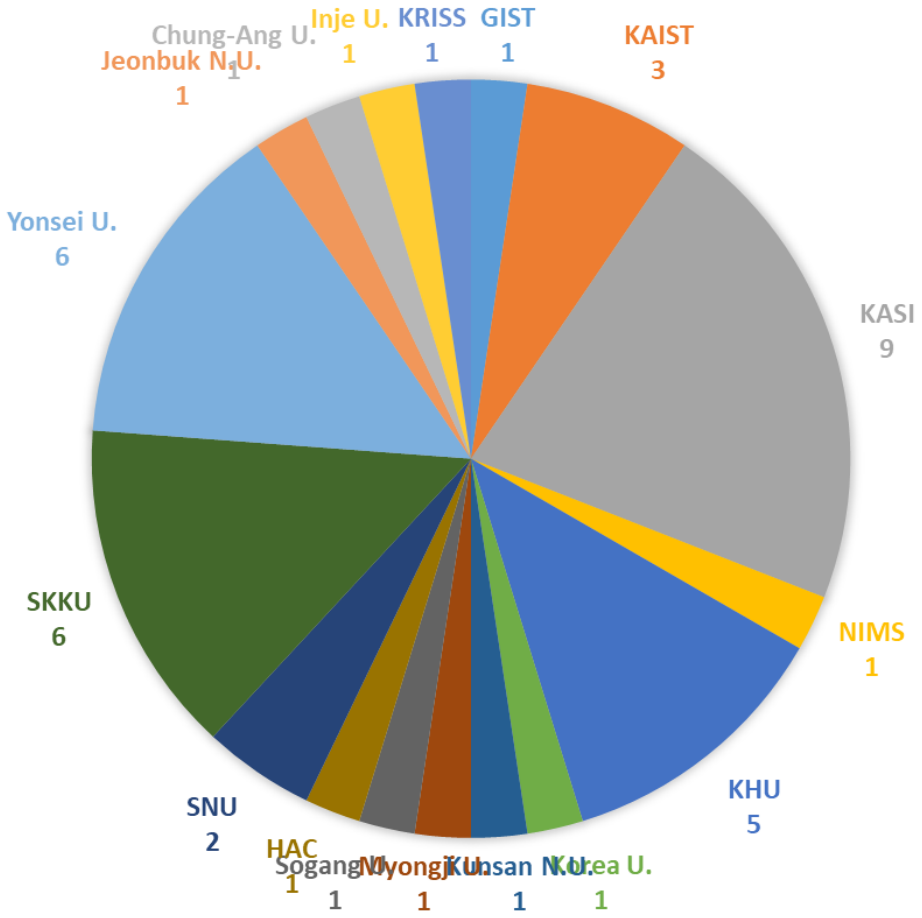
Credit: Einstein Telescope, KAGRA, LIGO, & ChatGPT

KGWG Experiment Division

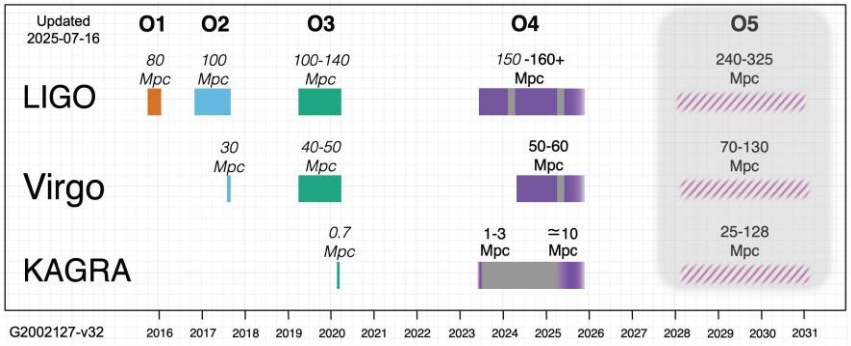
- 42 members from 17 institutions
- 42% of 101 KGWG members

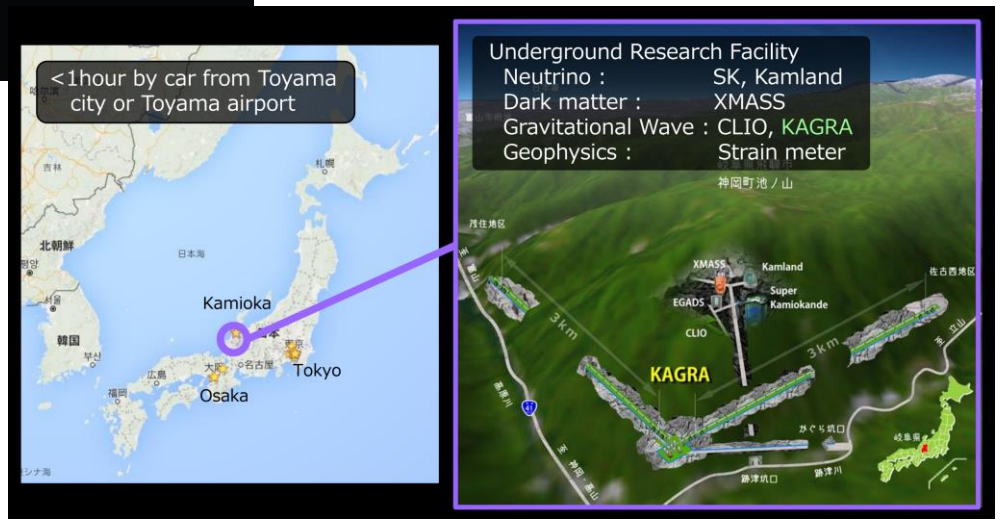


- Accelerated growth over the past 5 years

KAGRA Collaboration

- Baseline: 3 km
- Mirror temperature: 20 K
- Underground site





KAGRA – Early Contributions (2011-2012)

Atom interferometry using ultracold atoms and its applications to monitor seismic noise in a large scale gravitational wave detector

Jaewan Kim
Department of Physics
Myongji University

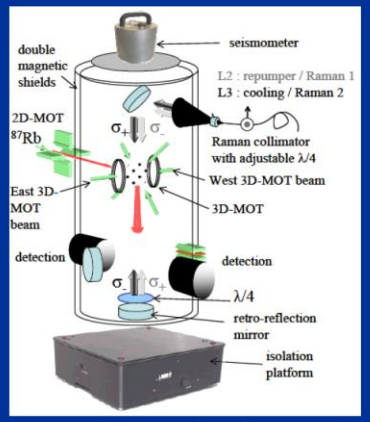
Feed-forward vibration isolation and reduction of Newtonian noise

Ryutaro Takahashi
(Institute for Cosmic Ray Research, Univ. of Tokyo)

Collaboration with Jaewan Kim (Myongji University)

1. **Newtonian noise**
2. **Feed-forward (FF) control**
3. **Some demonstrations of FF vibration isolation**
4. **Our plan**

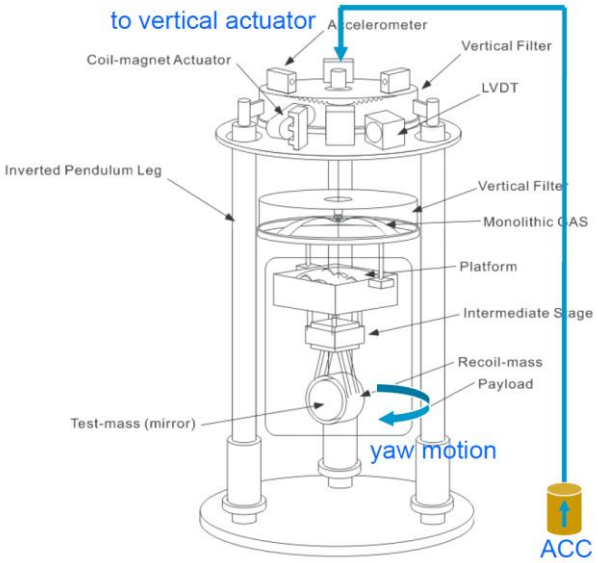
2nd Korea-Japan Workshop on KAGRA
(28 May 2012)



Atom gravimeter by Jaewan Kim

x2 ⇒ Gradiometer

R&D
- Establishment of FF algorithm
- Improvement of repetition cycle of gravity measurements



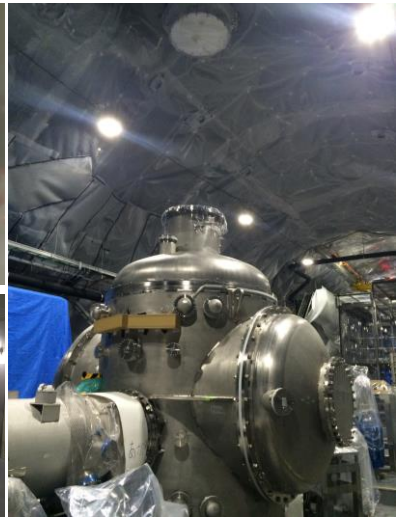
KAGRA – Early Contributions (2014-2019)

- Installing Suspensions (2014)

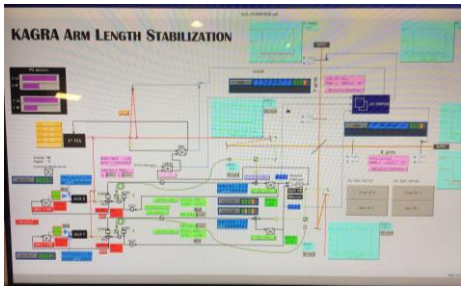


- Comissioning (2016, 2019)

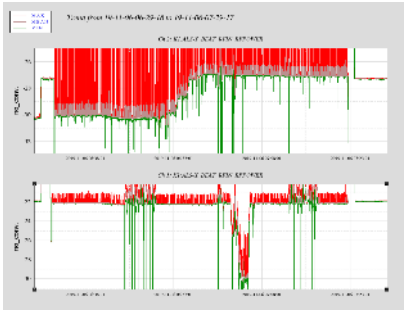


Mirror suspension and alignment

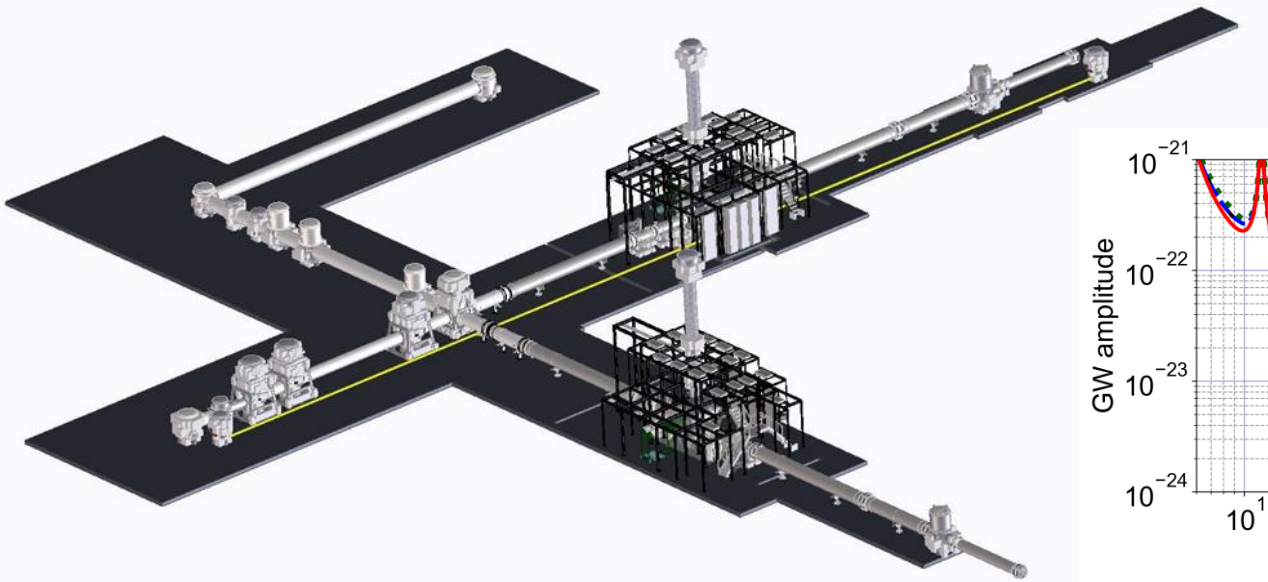


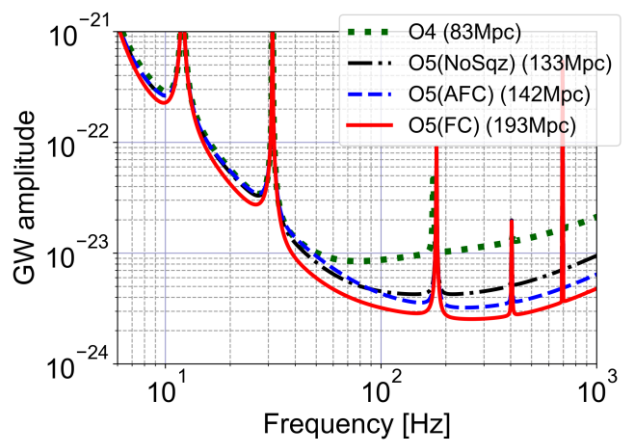
Arm Length Stabilization (ALS)

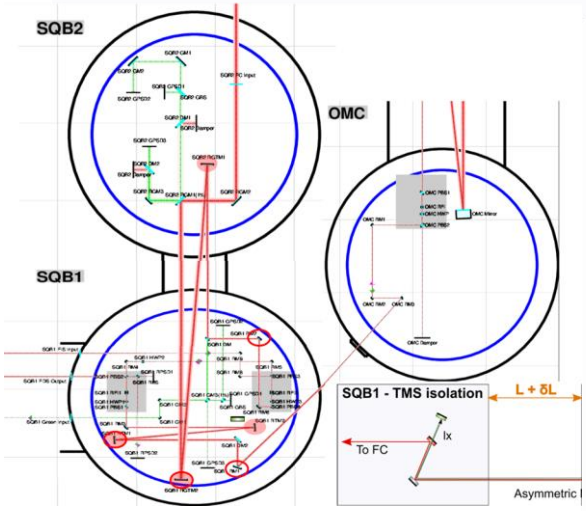


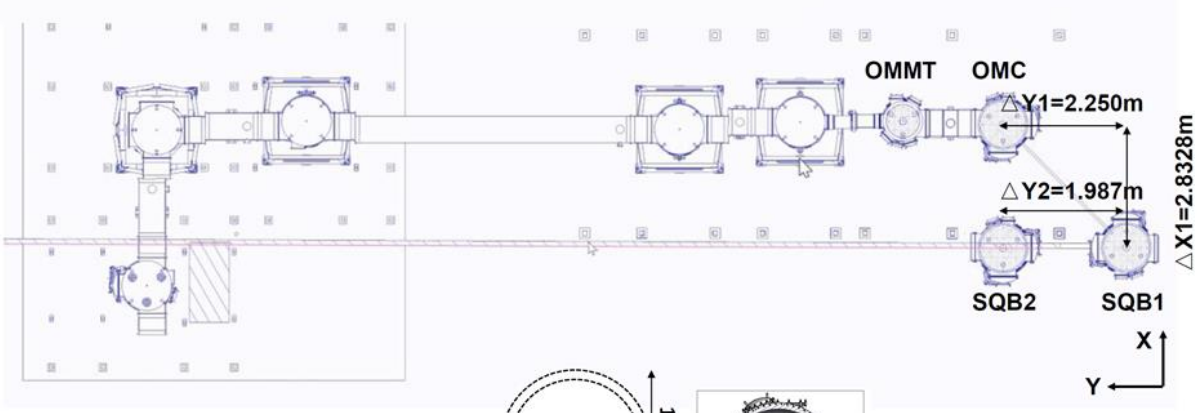
Physical Environmental Monitoring (PEM)

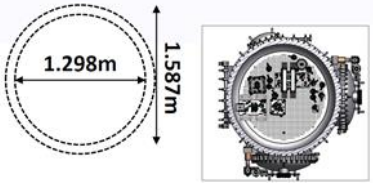
KAGRA – Squeezing System (2021~)



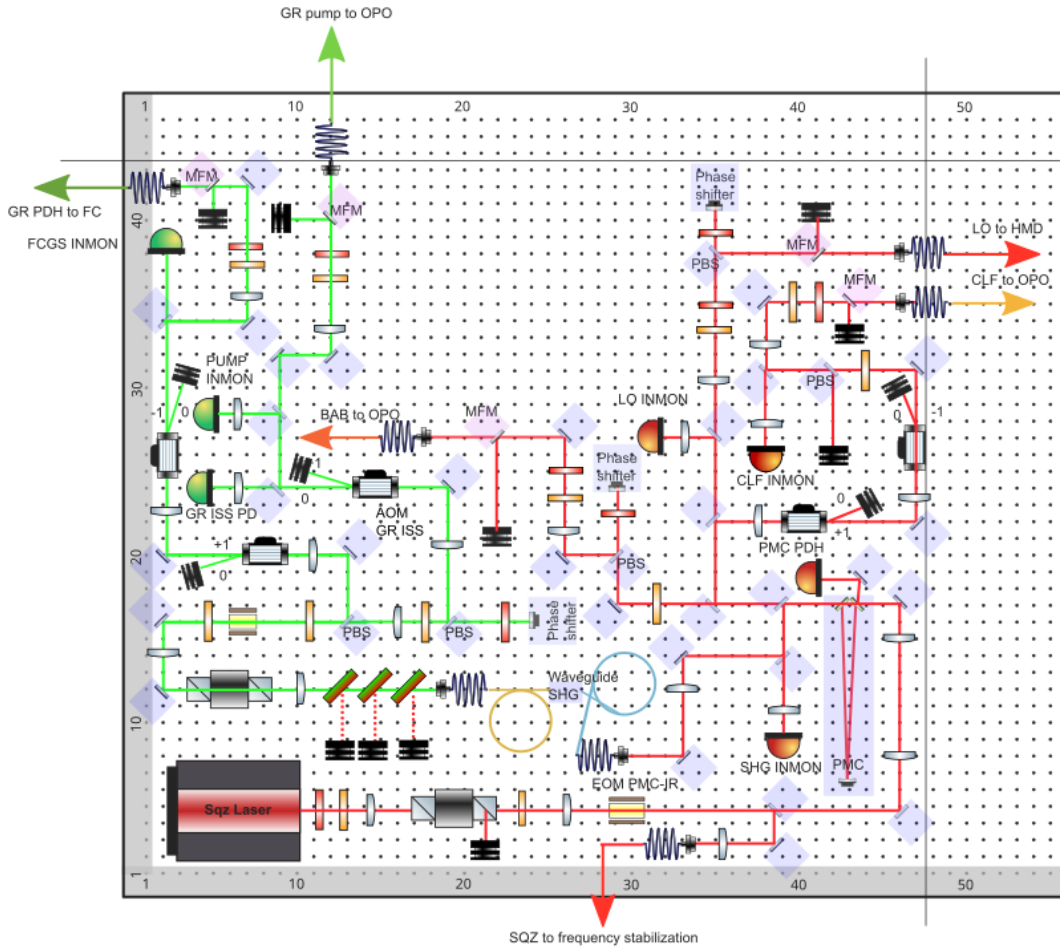


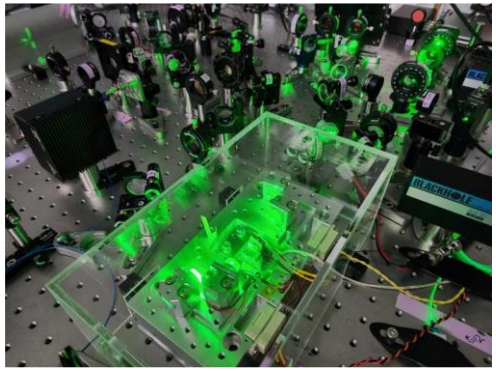


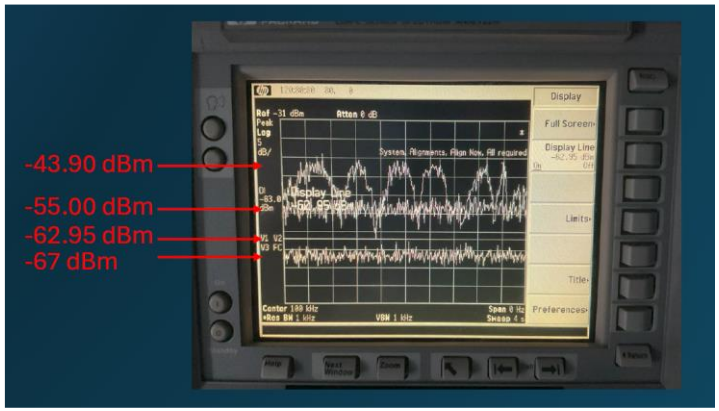


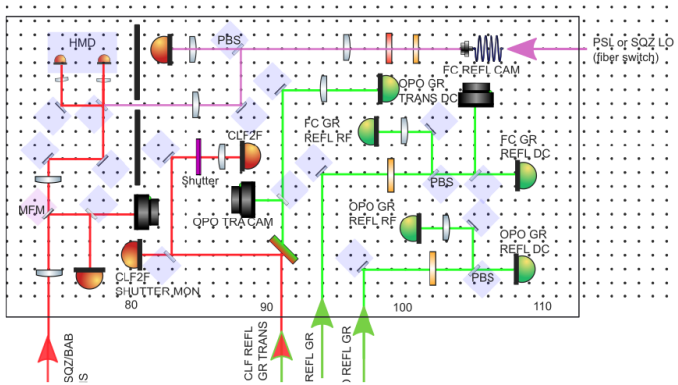


KAGRA – Squeezing System (2021~)



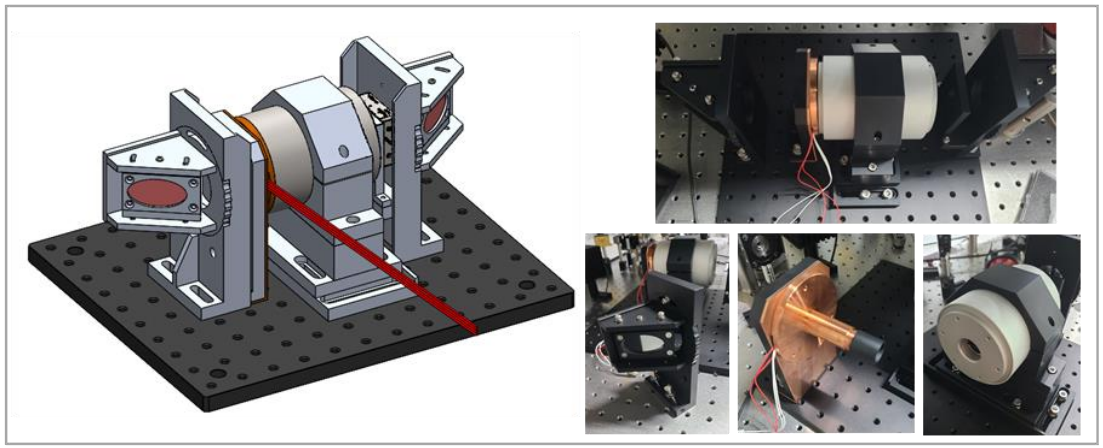


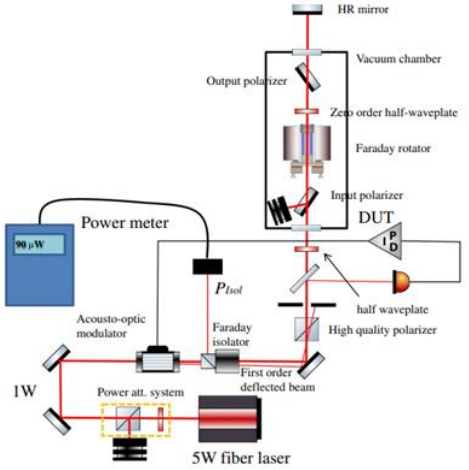


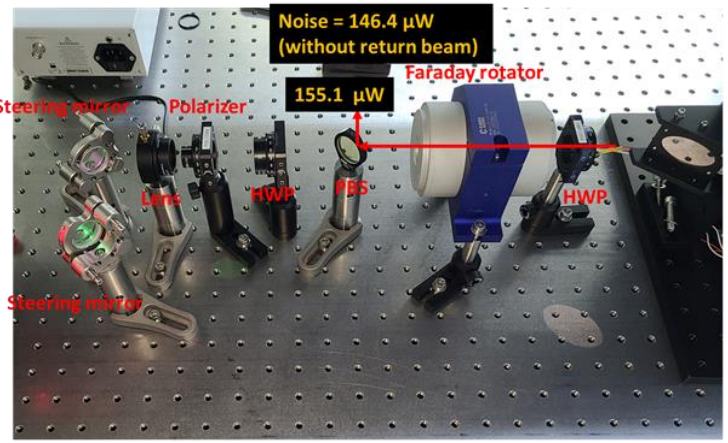


KAGRA – Squeezing System (2021~)

Development of Faraday Isolator for minimizing squeezing loss

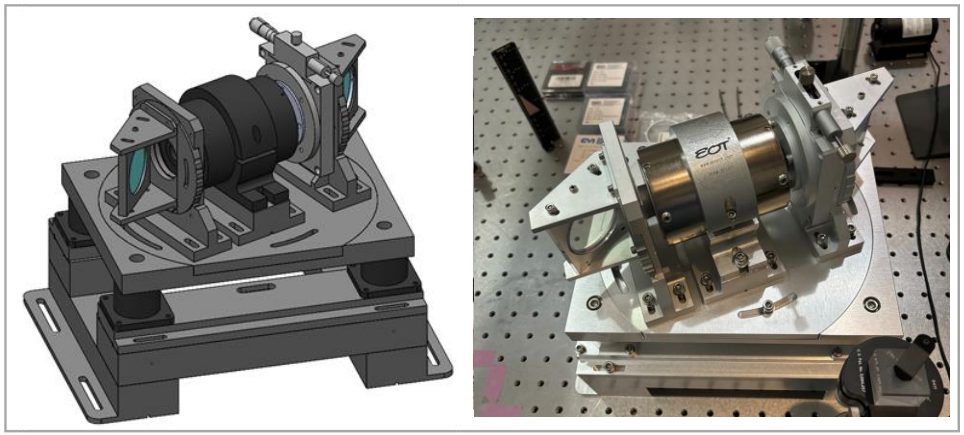






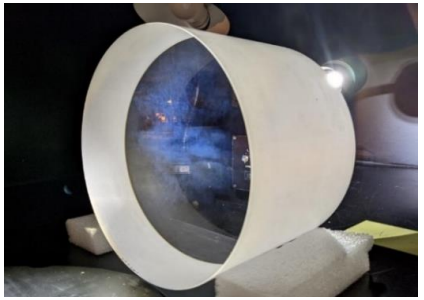
Return beam power : 155.1 μW - 146.4 μW = 8.7 μW Isolation = -41.75 dB

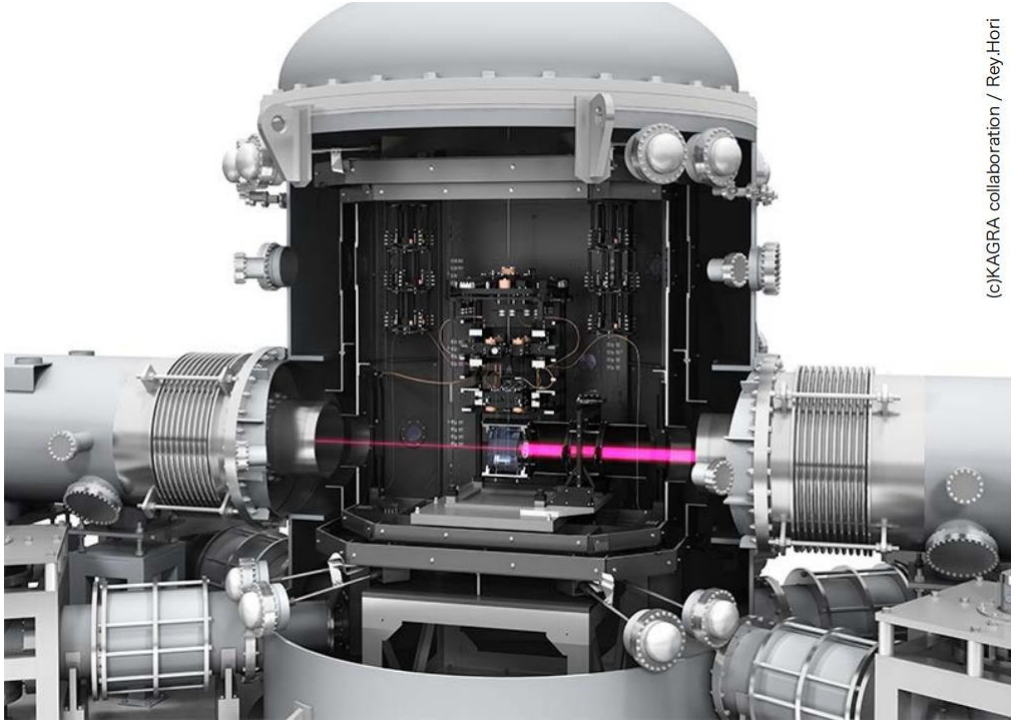
Faraday isolator for TAMA experiment at NAOJ



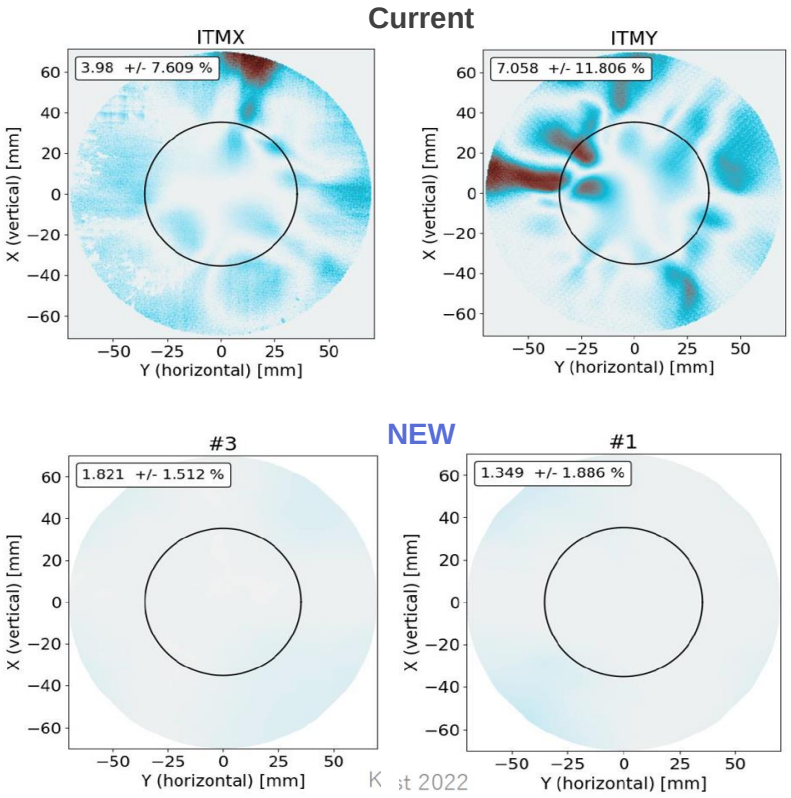
KAGRA – Test Mass Materials (2020~)

- Birefringence issue of the sapphire Input Test Masses (ITM)
- Collaboration with NAOJ and a Korean crystal maker (AZTEC)
- Successful development of substrates to replace the current ITMs
- In the process of fine polishing now, for O5 operation



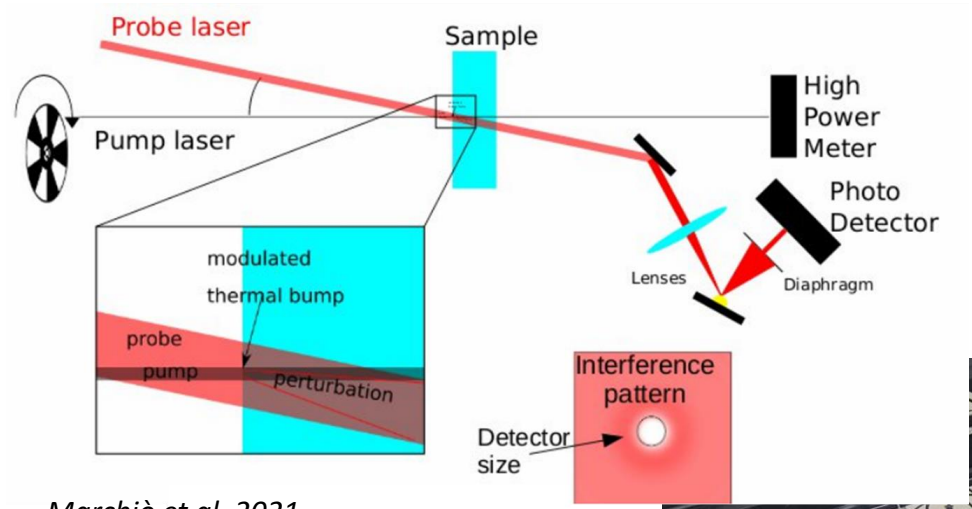


(c)KAGRA collaboration / Rey.Hori

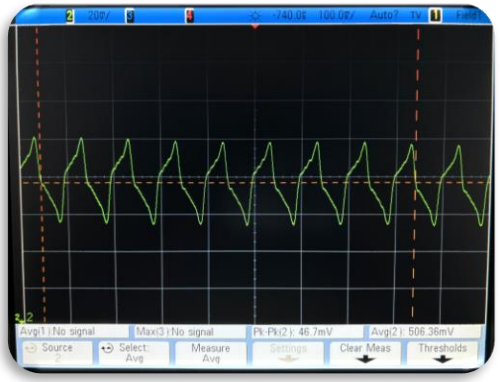


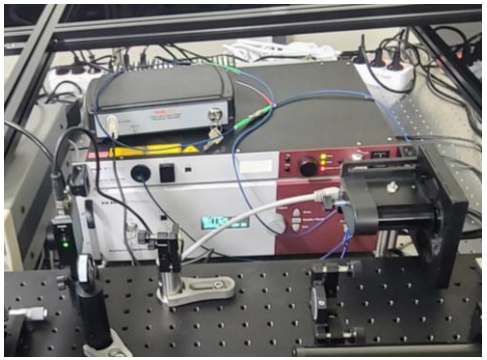
KAGRA – Test Mass Materials (2020~)

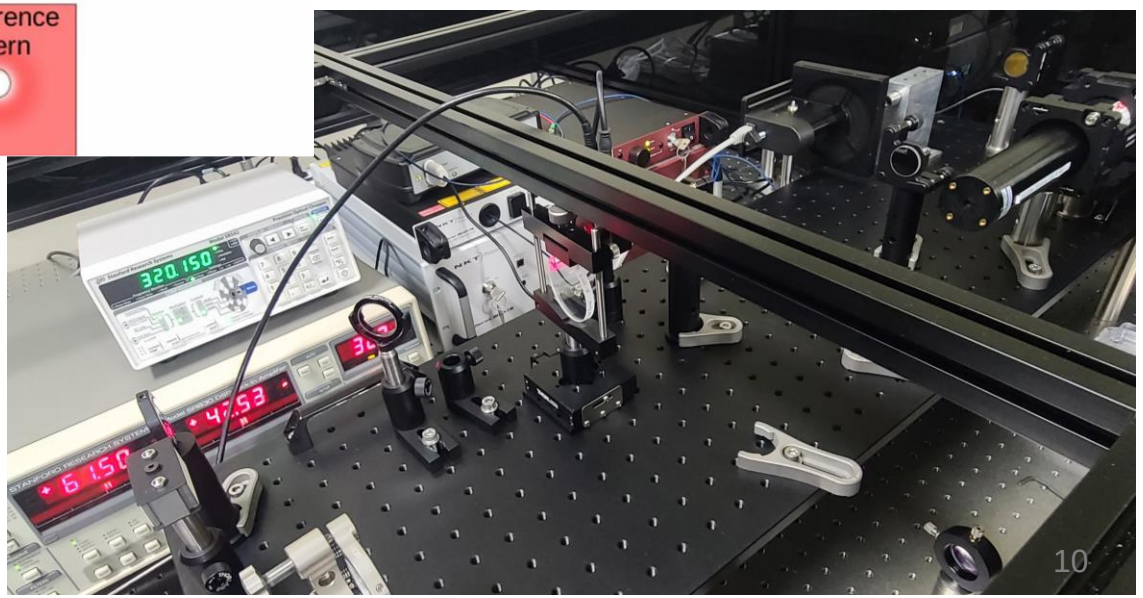
- Development of a metrology setup at KASI for substrate evaluation
- Absorption measurement by Photothermal common path interferometry (PCI)
- 1550 nm setup for synergy with the 1064 nm setup at NAOJ



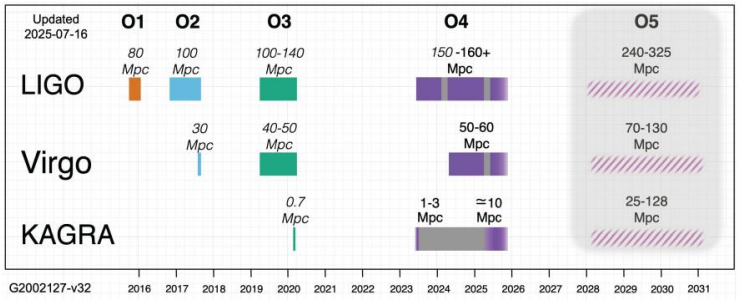
Marchiò et al. 2021





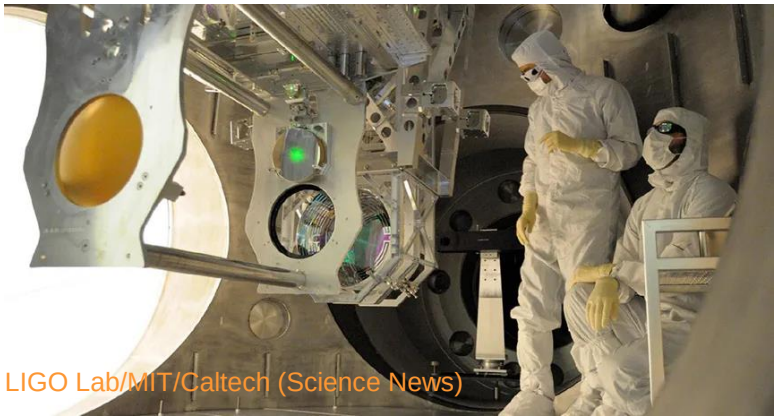


LIGO Collaboration




LIGO Livingston


LIGO Hanford


LIGO Lab/MIT/Caltech (Science News)

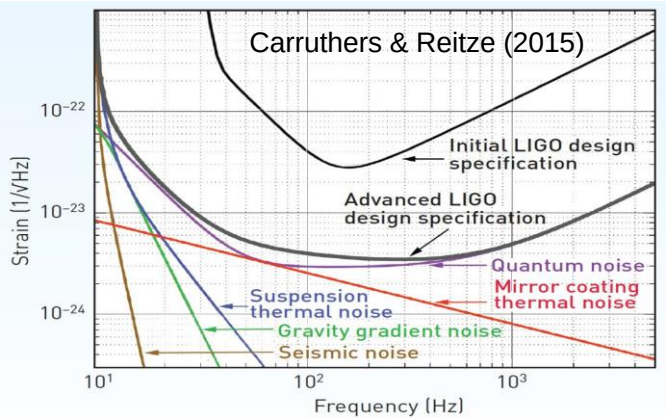
LIGO – Coating Materials (2021~)

- Atomic structure characterization
  - Amorphous oxide (TiGe, a-Si and beyond)
  - Mainly using electron probe measurement to see localized atomic structure

Transmission Electron Microscope (TEM) based analysis

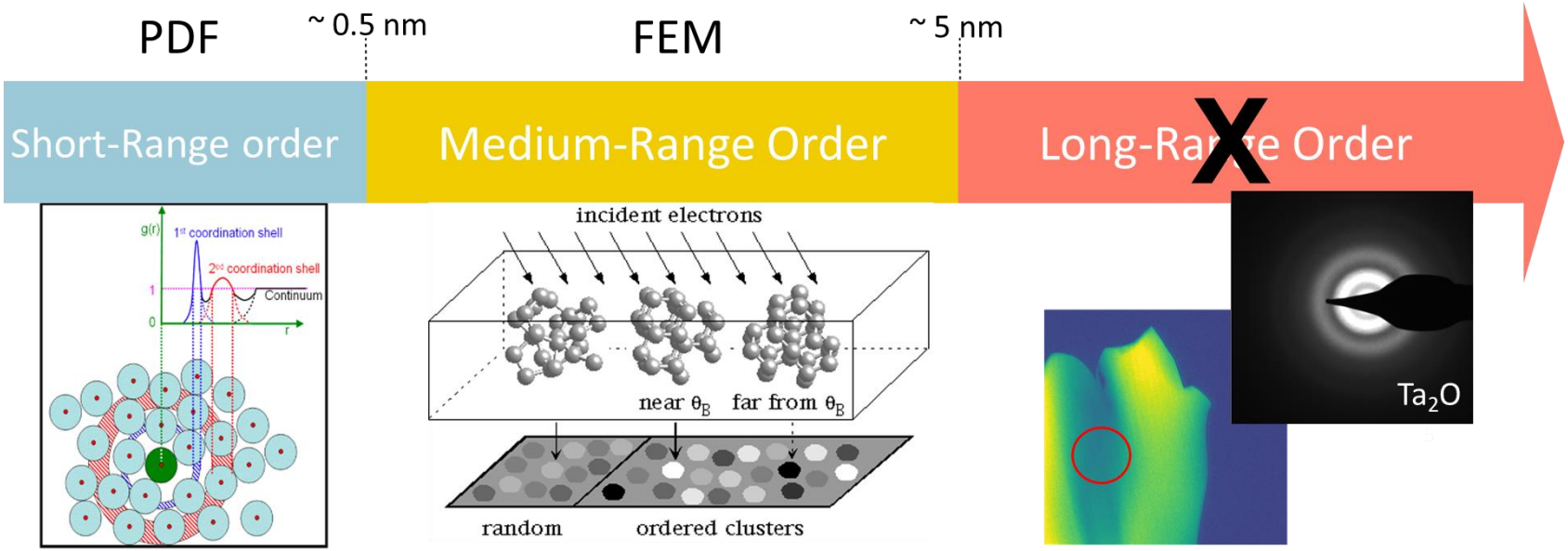
- Electron Pair Distribution Function (ePDF)
- Fluctuation Electron Microscopy (FEM)
- Energy Dispersion Spectroscopy (EDS) for Multilayer coating interface study

→ SKKU was the only group who could find the defect from the A+ Pathfinder coating with high absorption.



LIGO – Coating Materials (2021~)

Atomic structure characterization



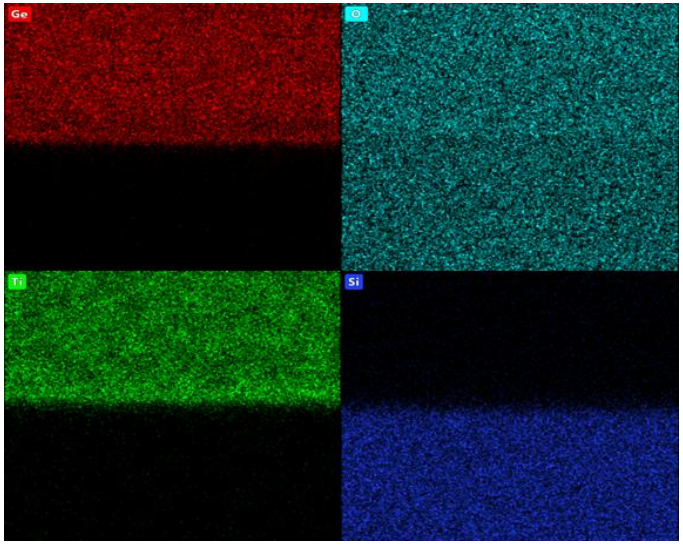
- Investigating the correlation between optical/physical properties of the coating material and its atomic structures.

  → Learned about the key correlation between low room temperature mechanical loss & corner-sharing (CS) structure

  → **Key contribution to finding materials with low mechanical loss**

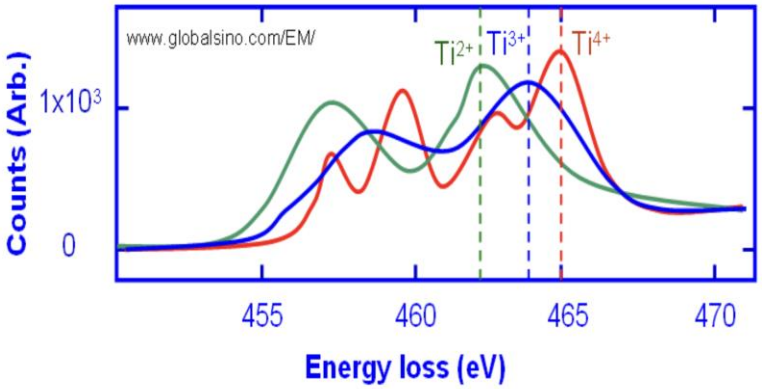
LIGO – Coating Materials (2021~)

Spectroscopy (EDS/EELS)



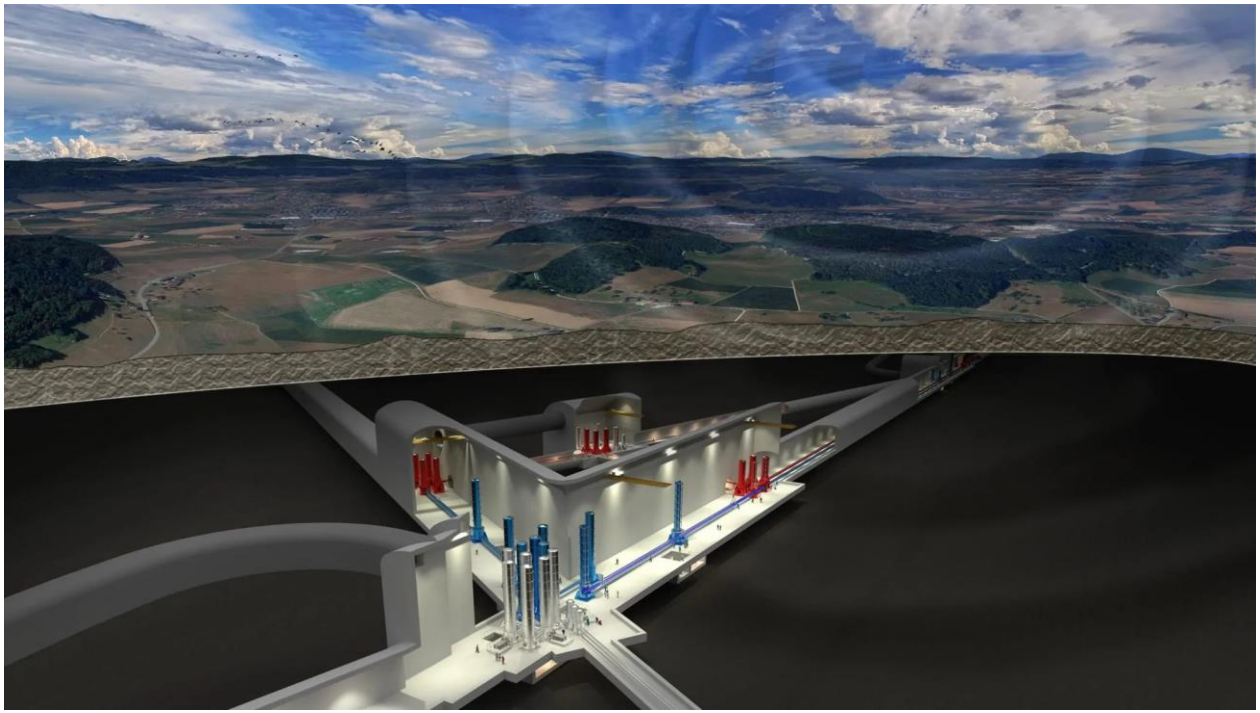
- Energy Dispersion Spectroscopy (EDS)
  - EDS spectrum showed interface diffusion might be the origin of discrepancy of mechanical loss property.
  - Could detect very early sign of crystalline structure formation & perform composition studies & investigate interface effects

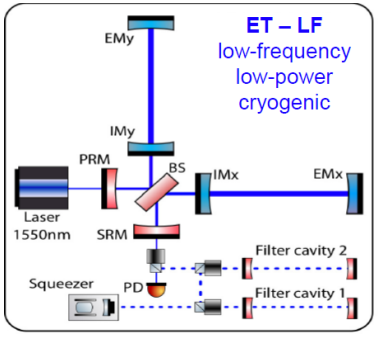
  → Interface effect in multi-layer samples was first confirmed by SKKU

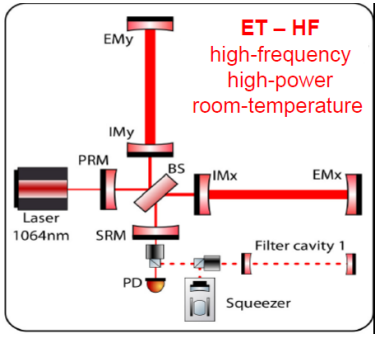


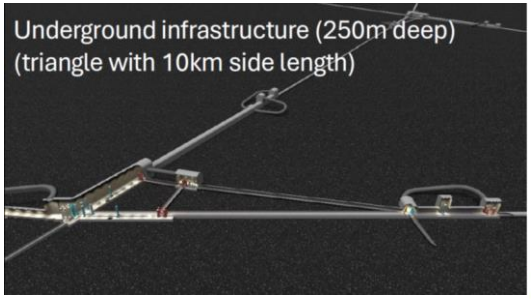
- Electron Energy Loss Spectroscopy (EELS)
  - EELS can provide the band gap strcture of the material.
  - Absorption rate of the material depends on the band gap structure.

Einstein Telescope Collaboration





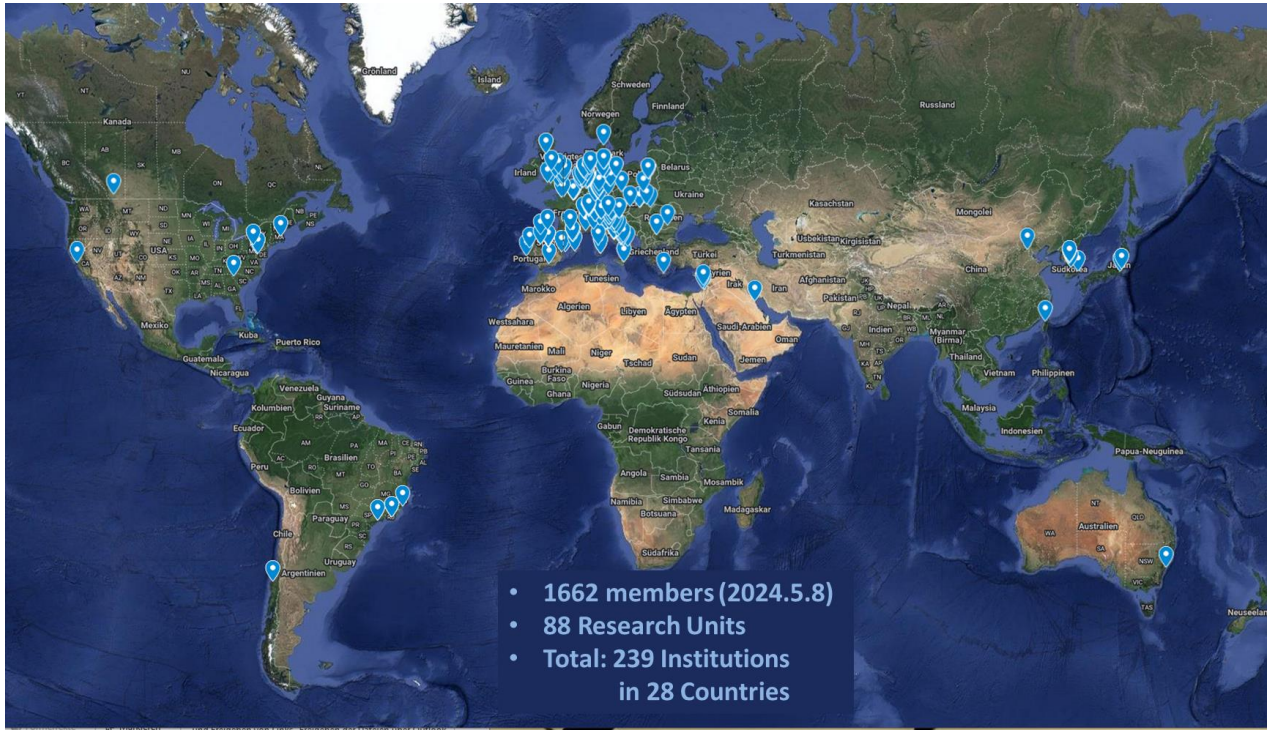




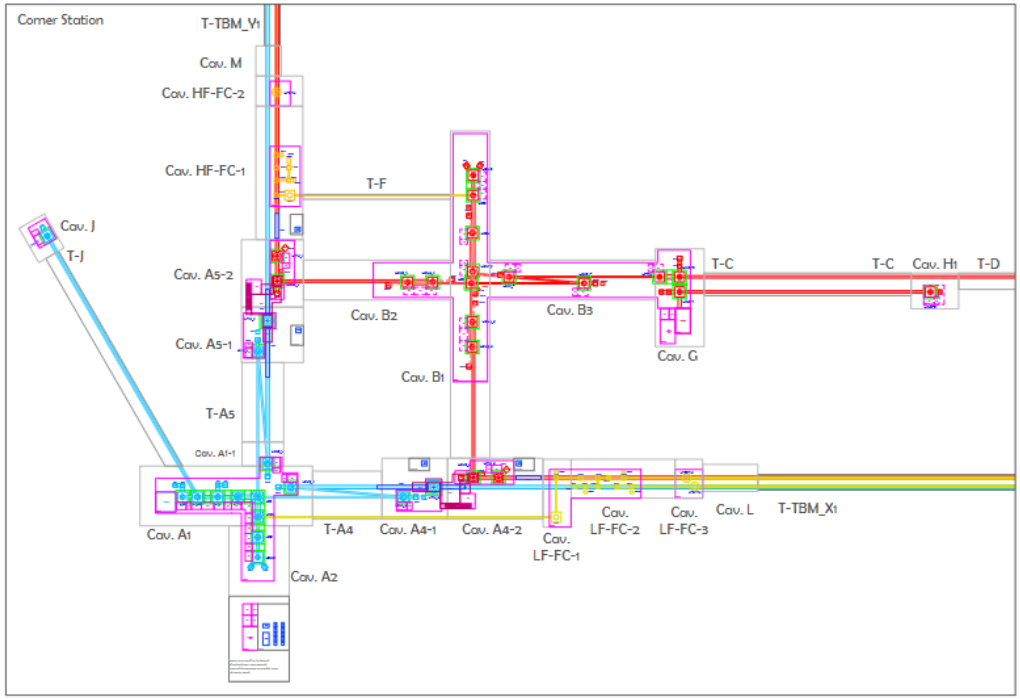
Einstein Telescope Collaboration

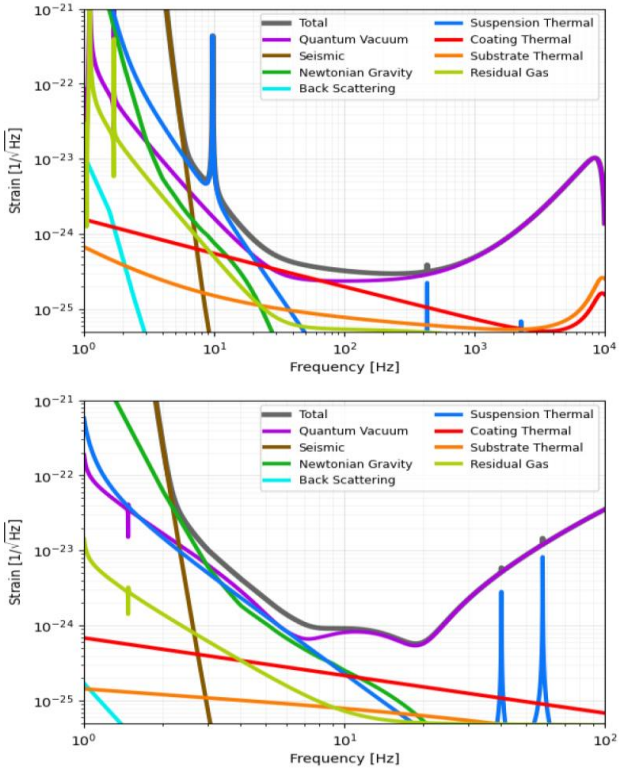
Korean Research Unit

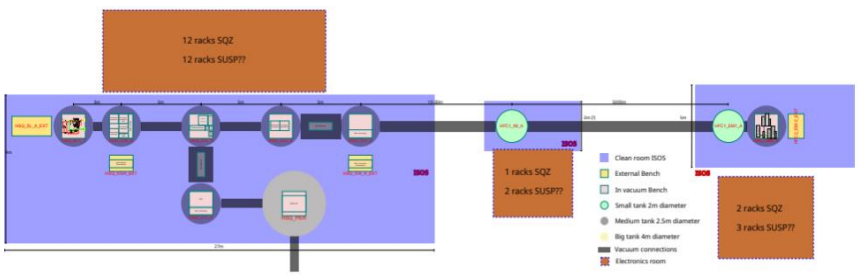
- 29 members @ 8 institutions (KASI, KAIST, KHU, UNIST, EWU, SKKU, Yonsei U., NIMS)
- ISB → Optics division → SQZ, Core Optics
- ISB → Interferometer division → Noise Characterization
- ISB → Active Noise Mitigation division → Newtonian Noise
- OSB → Fundamental Physics, Population studies, Stellar collapse & isolated neutron stars, Data analysis platform



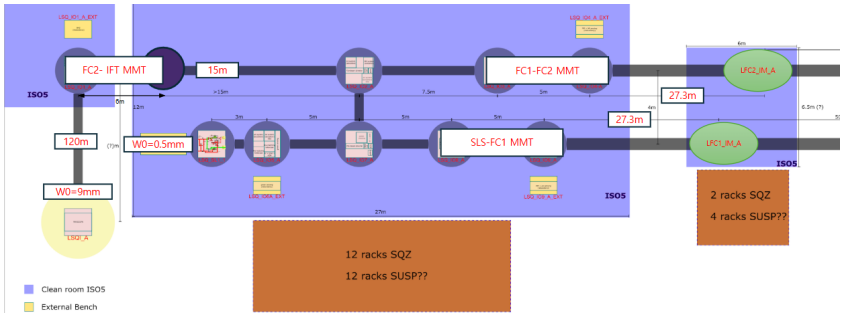
Einstein Telescope – Squeezing System







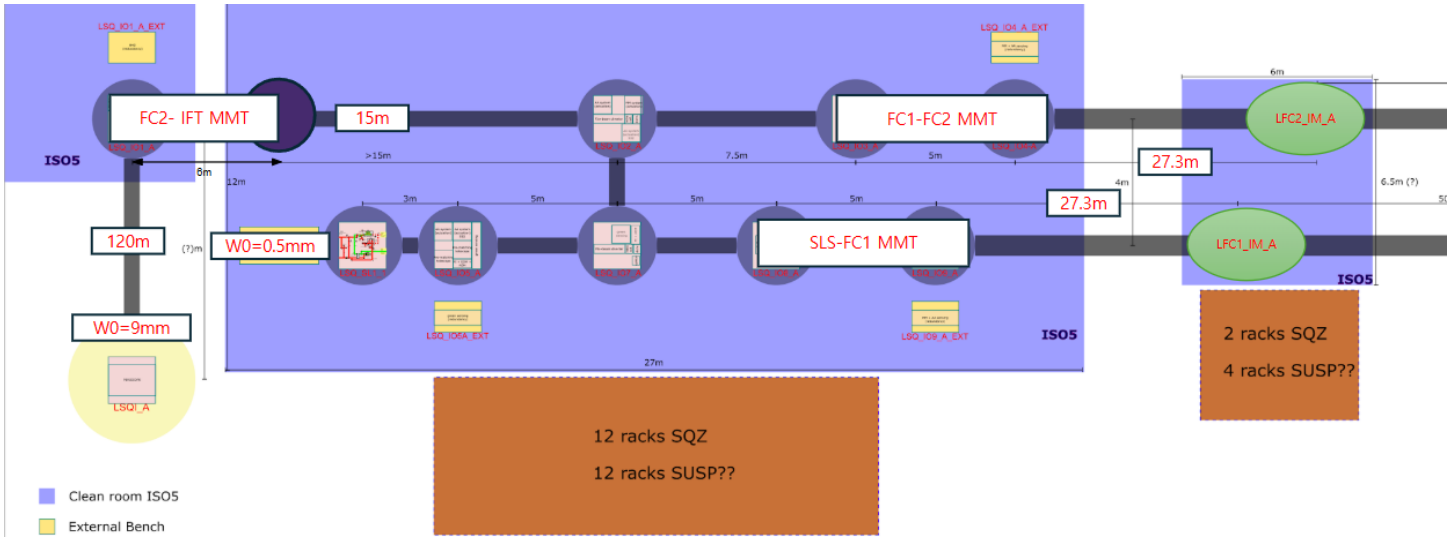
Quantum Noise Reduction System for ET-HF

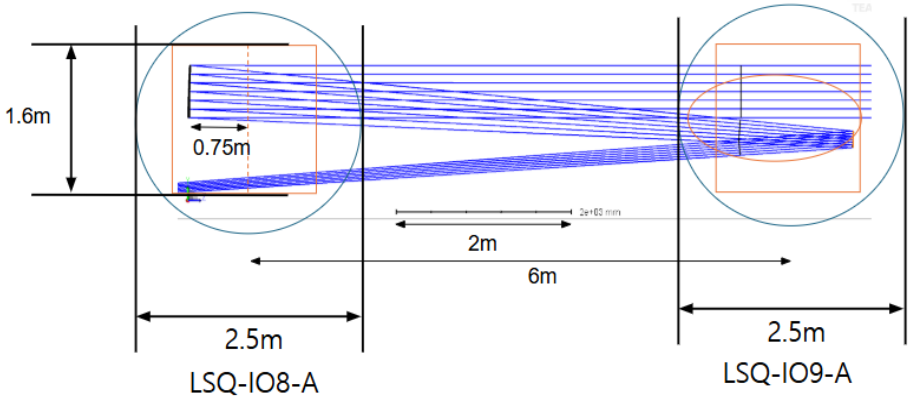


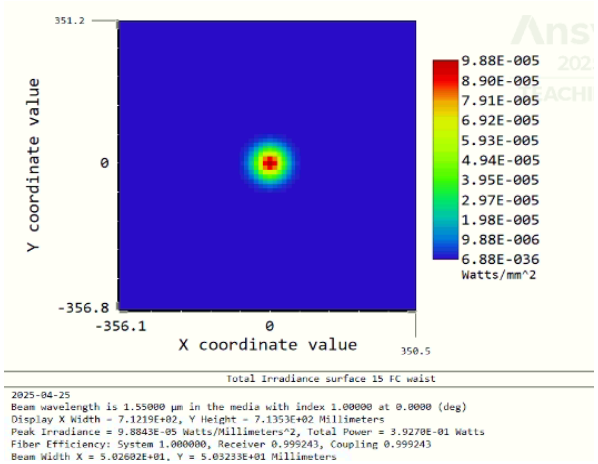
Quantum Noise Reduction System for ET-LF

Einstein Telescope – Squeezing System

Mode Matching Telescopes



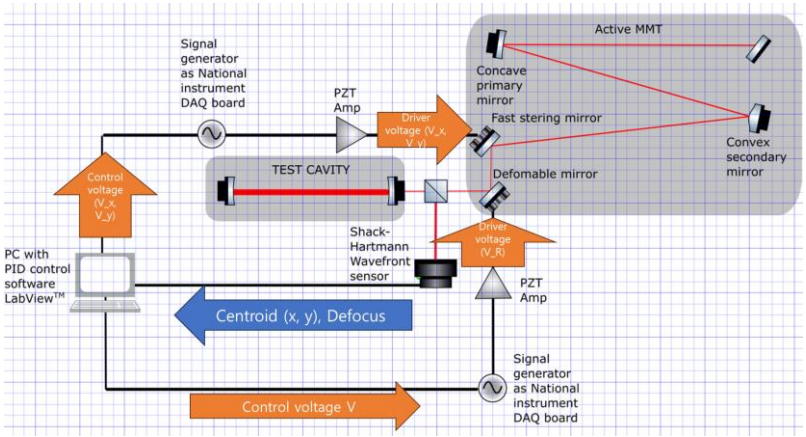


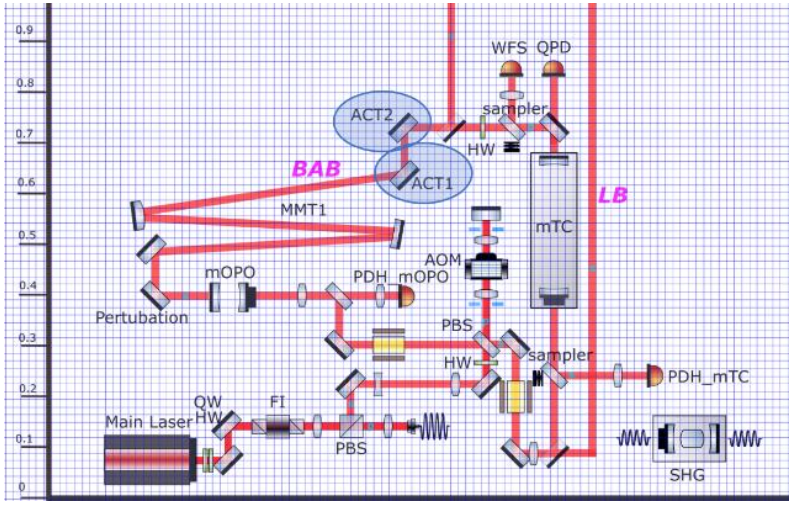


Optical design of one of 14 MMTs for the ET SQZ systems

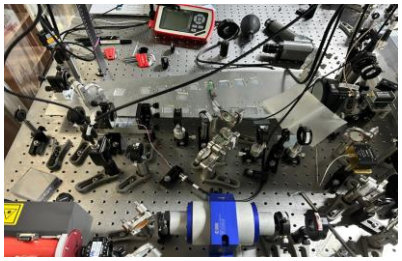
Einstein Telescope – Squeezing System

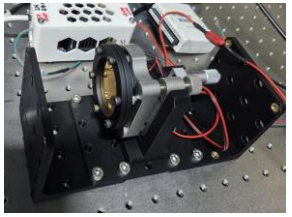
Active Mode Matching Control

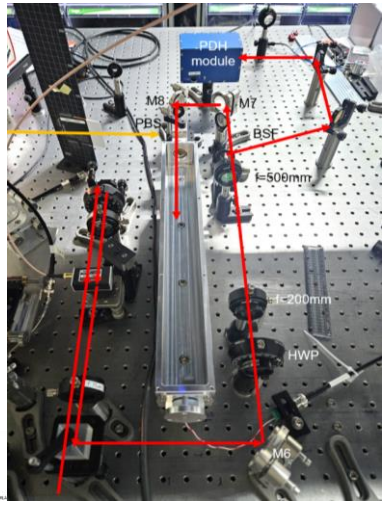


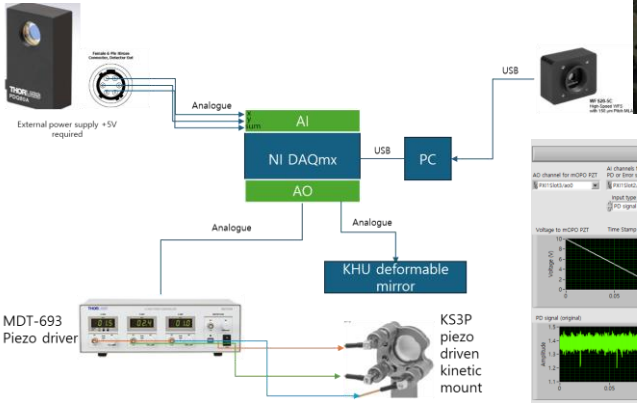


Active MMT experiment at KASI



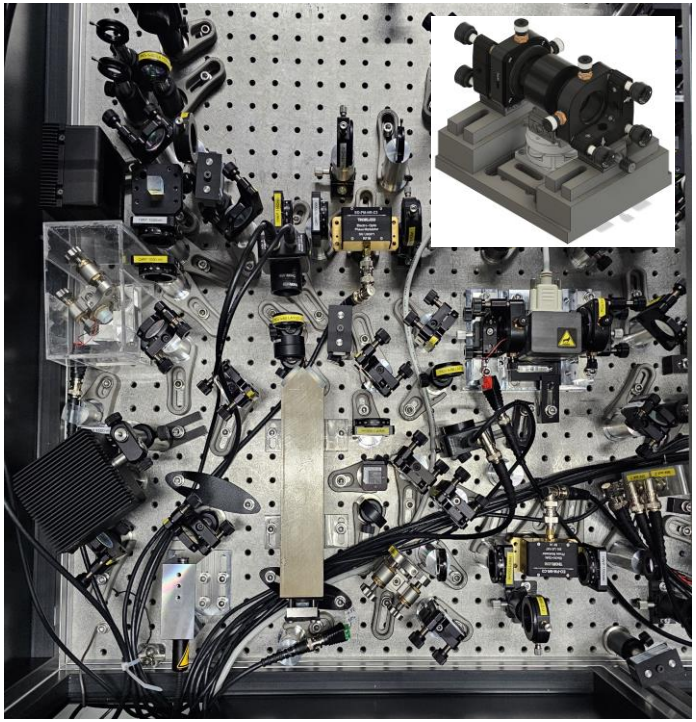


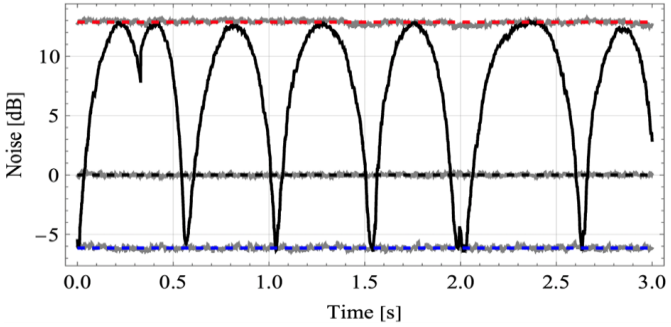




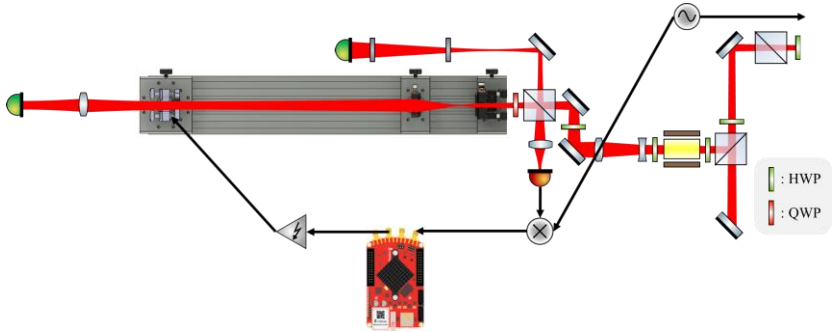
Einstein Telescope – Squeezing System

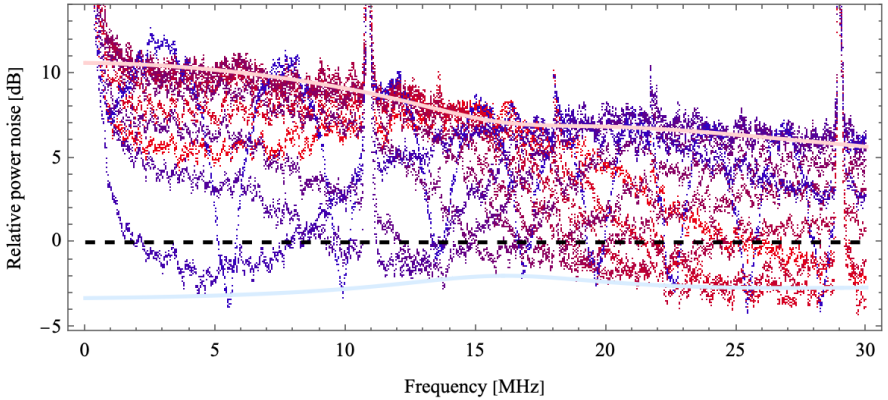
Squeezed Vacuum Source (KAIST)

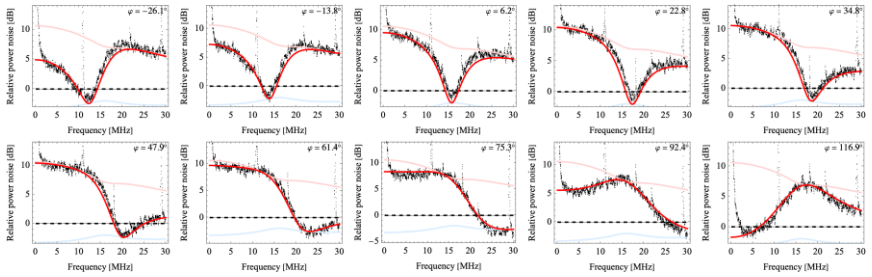




1550 nm Squeezer at KAIST (-6.1 dB)



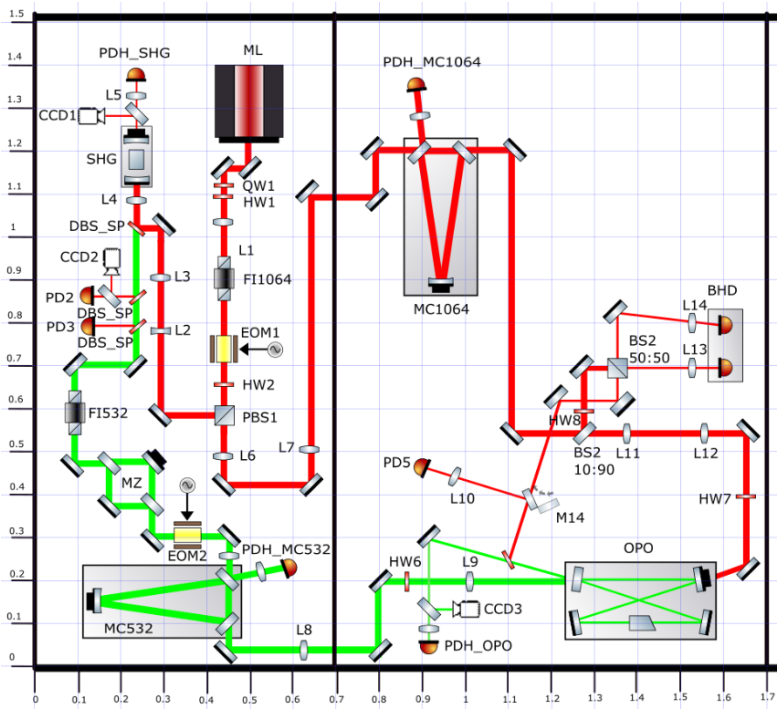


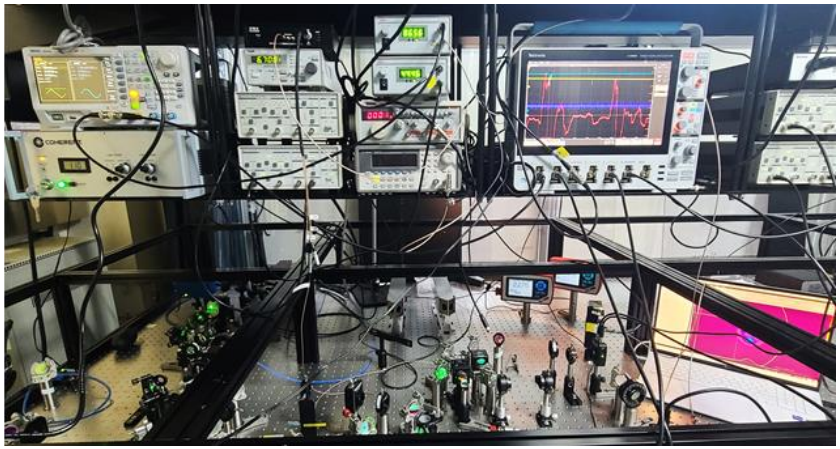


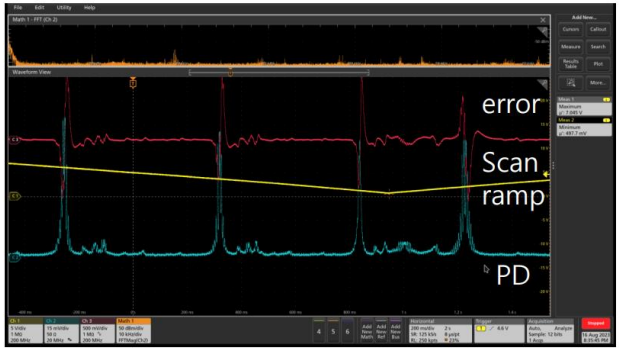
Frequency-dependent squeezing

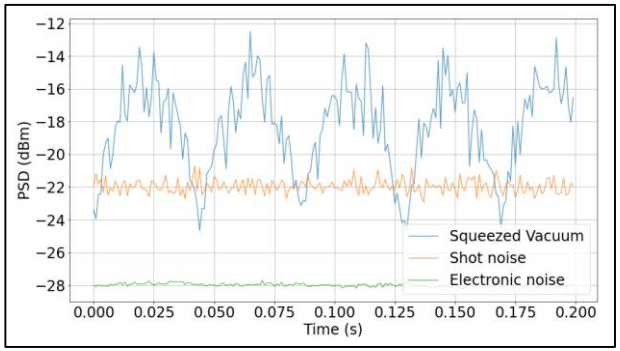
Einstein Telescope – Squeezing System

Squeezed Vacuum Source (KASI)





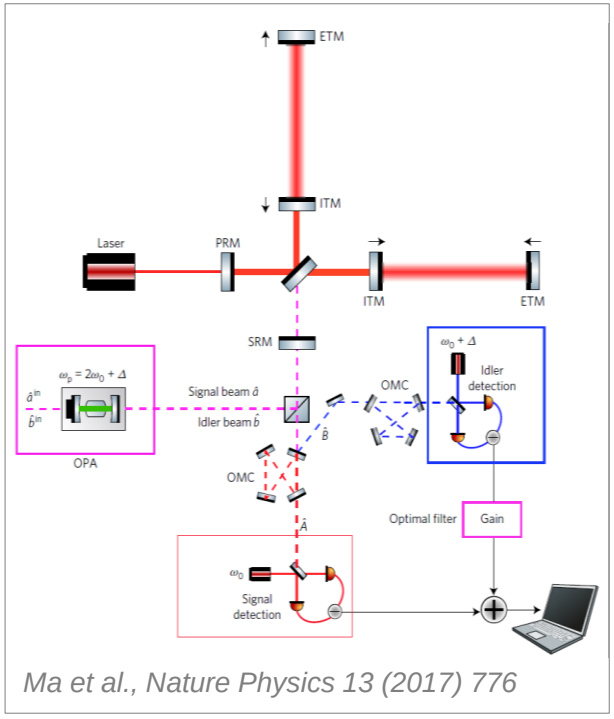




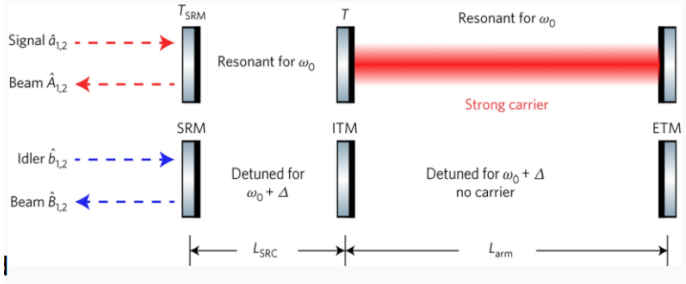
1064 nm Squeezer at KASI (-2.2 dB)

Einstein Telescope – Squeezing System

EPR (Einstein-Podolsky-Rosen) squeezing:
Next-generation FDS technology w/o filter cavity



Ma et al., Nature Physics 13 (2017) 776

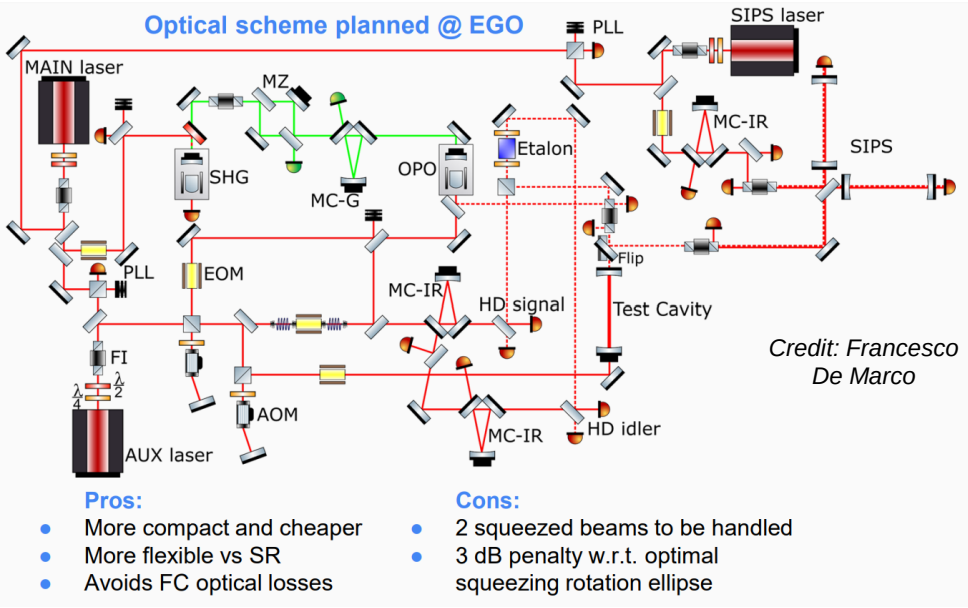


Istituto Nazionale di Fisica Nucleare

Università degli Studi di Napoli Federico II

Sapienza Università di Roma

Università degli Studi di Perugia



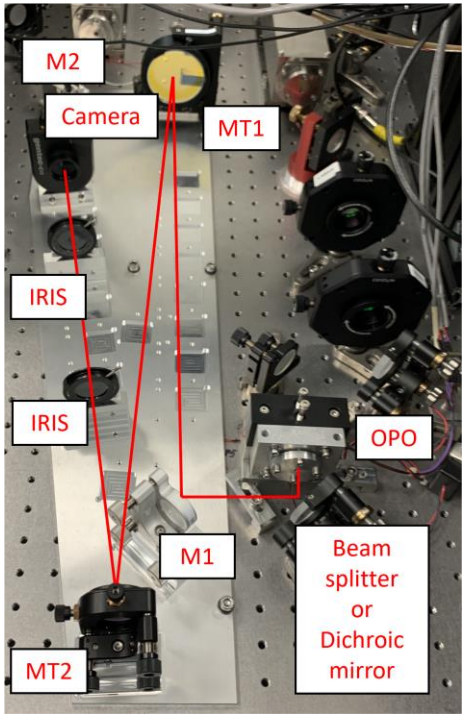
Credit: Francesco De Marco

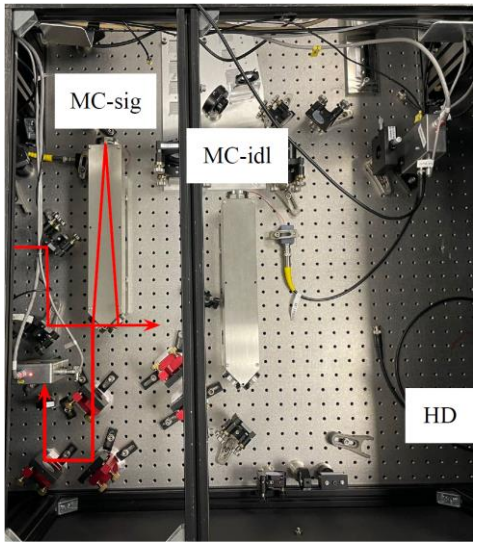
Pros:
- More compact and cheaper
- More flexible vs SR
- Avoids FC optical losses

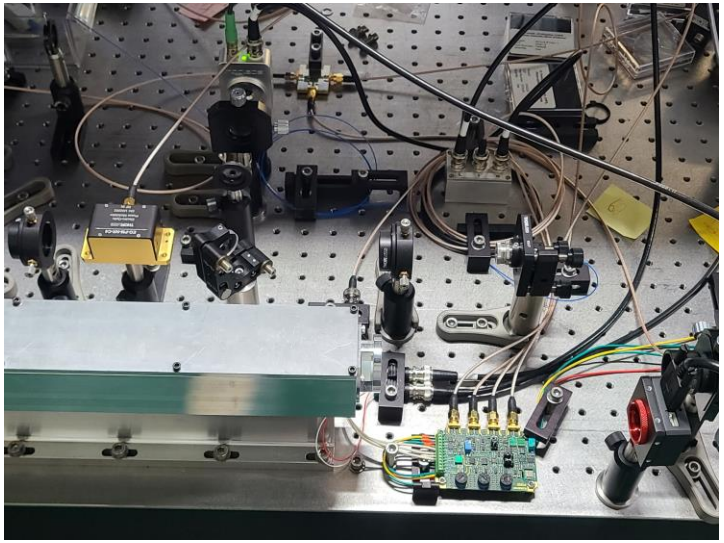
Cons:
- 2 squeezed beams to be handled
- 3 dB penalty w.r.t. optimal squeezing rotation ellipse

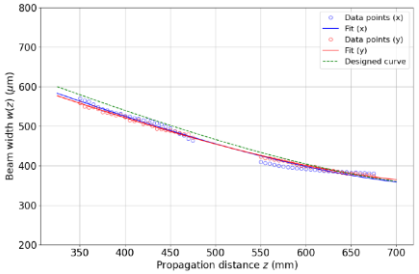
Einstein Telescope – Squeezing System

EPR Squeezing

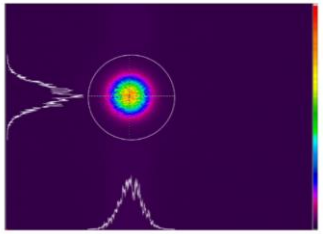


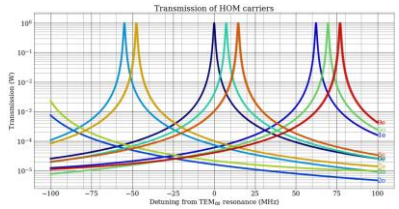




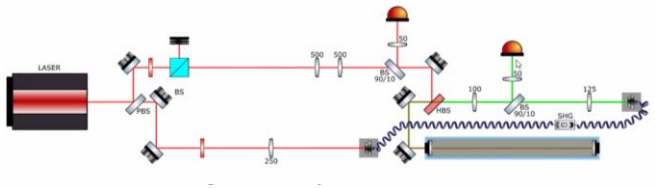


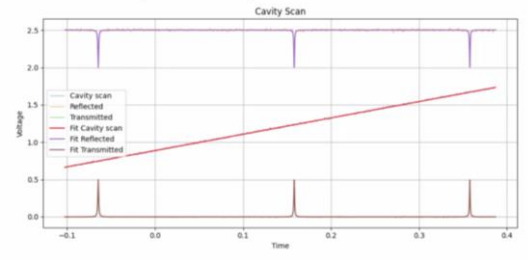
Mode matching telescope for OPO-TC





Infrared mode cleaners

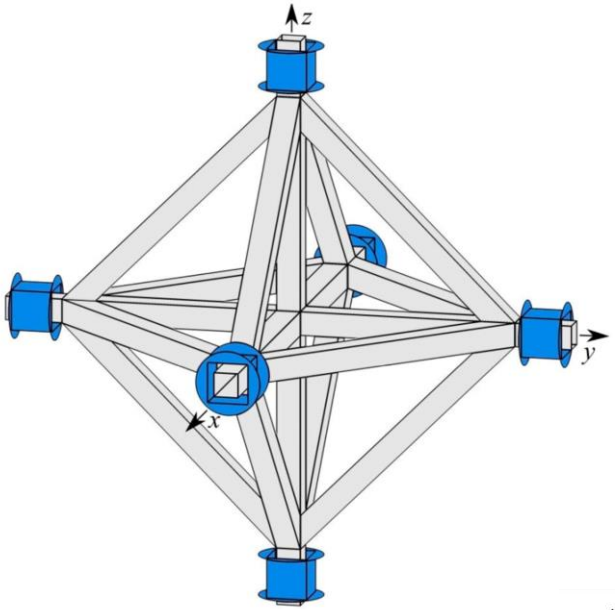




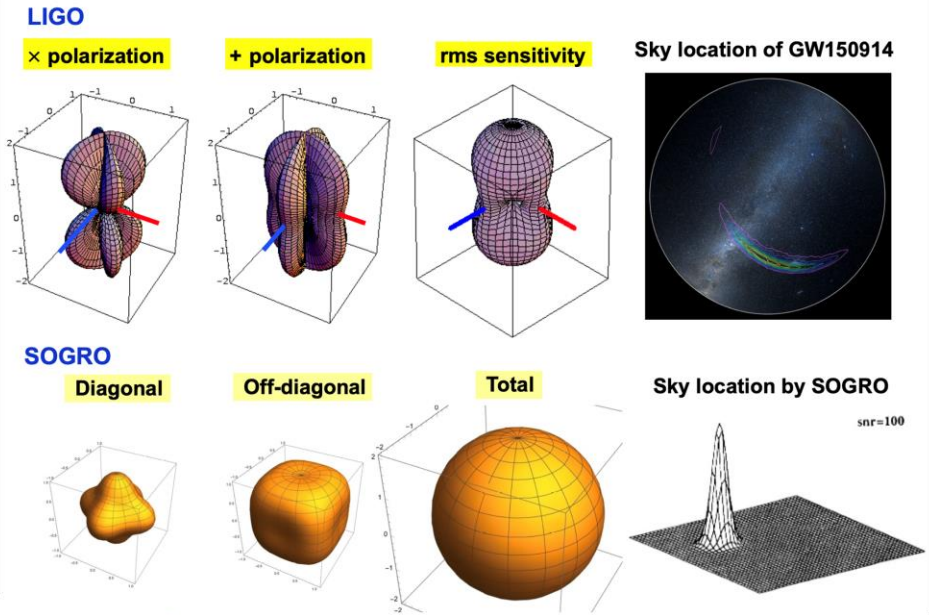
High finess (23,000) cavity control experiment

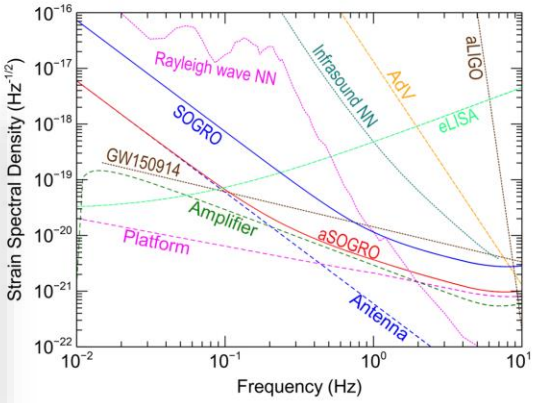
New Detectors – SOGRO & mSOGRO

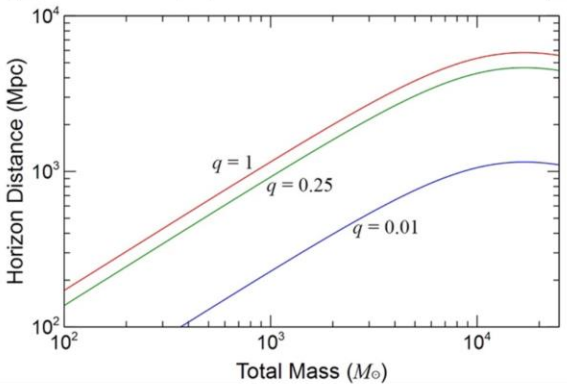
SOGRO: Superconducting Omni-directional Gravitational Radiation Observatory



Paik et al., CQG33, 075003 (2016)







PTEP

Prog. Theor. Exp. Phys. 2024 053E01 (26 pages)
DOI: 10.1093/ptep/ptae045

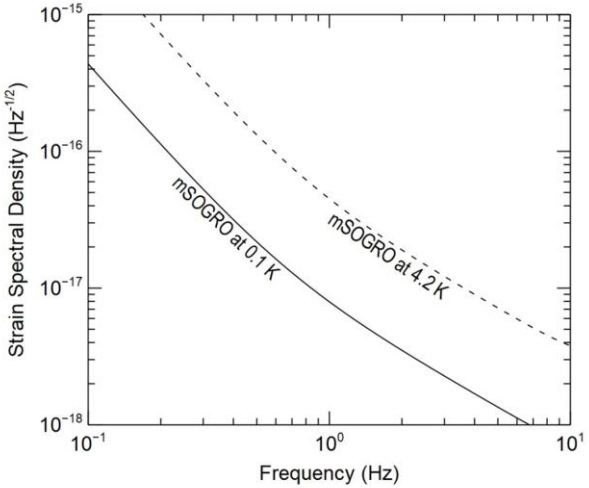
A Superconducting Tensor Detector for Mid-Frequency Gravitational Waves: Its Multichannel Nature and Main Astrophysical Targets

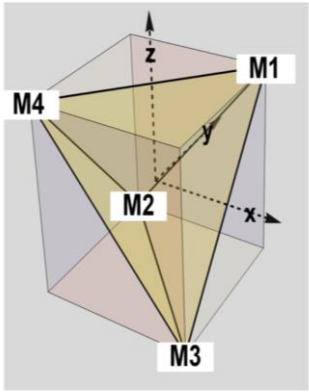
Yeong-Bok Bae[1,2,†], Chan Park[2,3,†], Edwin J. Son[4,†], Sang-Hyeon Ahn[5], Minjoong Jeong[6], Gungwon Kang[1], Chunglee Kim[7], Dong Lak Kim[8], Jaewan Kim[9], Whansun Kim[4], Hyung Mok Lee[3], Yong-Ho Lee[10], Ronald S. Norton[11], John J. Oh[4], Sang Hoon Oh[4], and Ho Jung Paik[11]

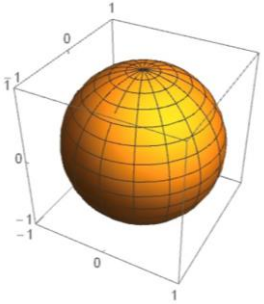
New Detectors – SOGRO & mSOGRO

mSOGRO (SEED): Tetrahedral design

Z. Metzler, C. J. Collins, H. J. Paik and P. S. Shawhan, Class. Quantum Grav. 39, 225012 (2022)







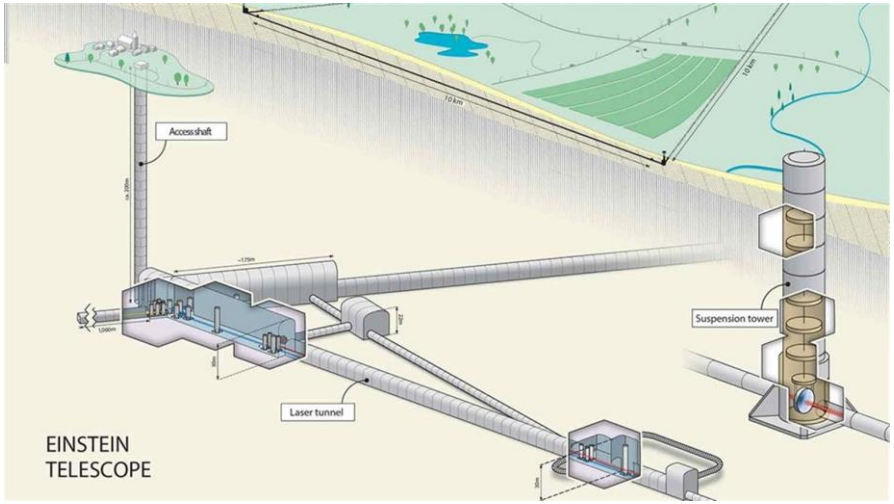
Parameter	Prototype SEED	2nd-stage SEED
Each test mass M	10 kg	10 kg
Arm-length L	0.40 m	0.40 m
Temperature T	4.2 K	0.1 K
DM frequency f_D	0.03 Hz	0.01 Hz
DM quality factor Q_D	10^7	10^7
Pump frequency f_p	4 MHz	4 MHz
Amplifier noise no. n	280	10
Detector noise $S_{h,\Sigma}^{1/2}(f)$	4.9×10^{-15} Hz$^{-1/2}$	4.4×10^{-16} Hz$^{-1/2}$

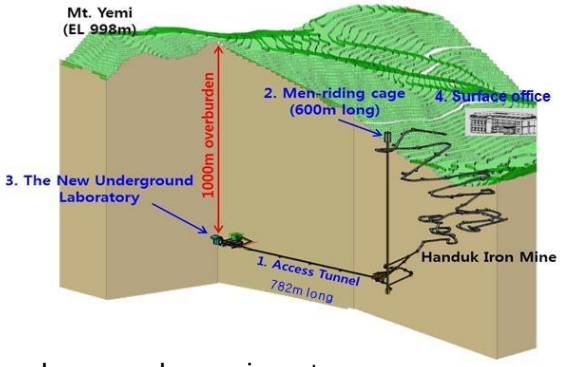
($f = 0.1$ Hz)

New Detectors – SOGRO & mSOGRO

Applications

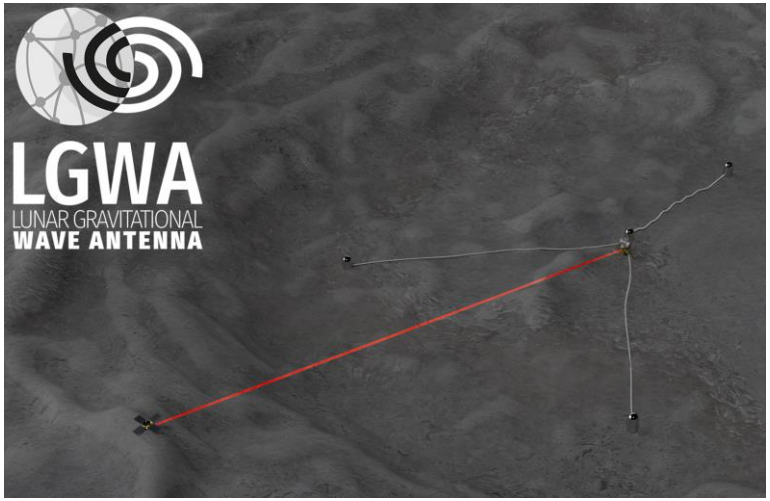
Newtonian noise mitigation for Einstein Telescope

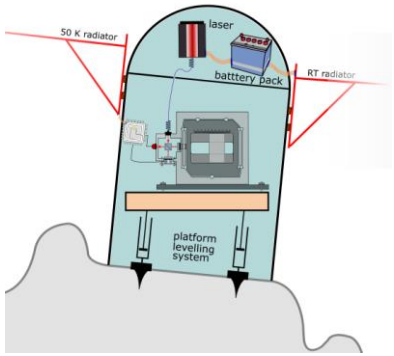




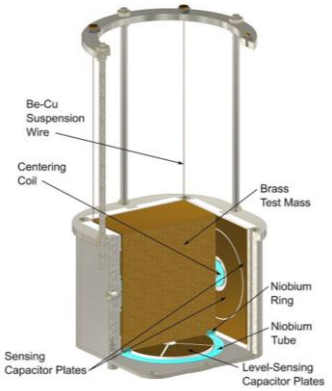
Yemilab underground experiments

Lunar GW detectors





Payload concept of LGWA
(Lunar Gravtiational-wave Antenna)



LANGO (Lunar Accelerator Network
for Gravtiational-wave Observatory)

Summary & Future Prospects

2010

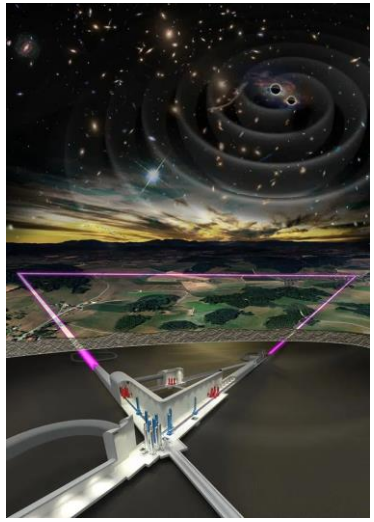
- KAGRA Newtonian noise
- KAGRA commissioning

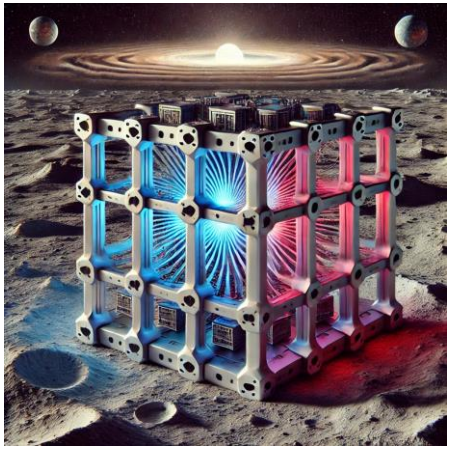
2020

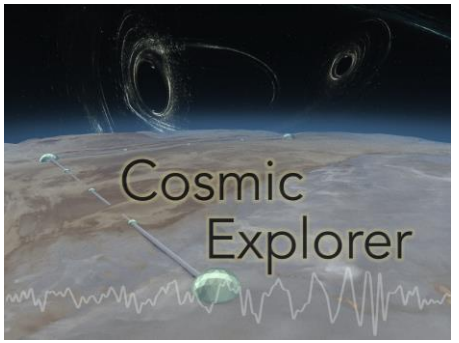
- KAGRA squeezing
- KAGRA TM material
- LIGO TM coating
- ET squeezing

2030

- KAGRA, LIGO
- ET squeezing
- ET, CE TM coating
- ET Newtonian noise
- Lunar GW detectors





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Instrumentation for
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중력파 검출기술 워크숍(GW Detector R&D Workshop)
2023 중력파 공동연구팀 중간점검 워크샵

Thank you