Parameter Estimation of Compact Binary Gravitational Wave Sources with Mid-Band Detectors and Cosmological Applications

SURVEY SCIENCE WORKSHOP

Jan. 29-31, 2024

Hyung Mok Lee (Seoul National University)

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Gravitational-wave research in Korea
+ Present and Future Detectors of the Gravitational-Waves

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Summary

- Korean GW Group (KGWG) was founded in Nov. 2003 as a voluntary study group and has grown to a ~100 member group
- KGWG members are now actively taking part in LIGO, KAGRA, ET and PTA projects.
  - No LISA member yet
- Initially most people worked on data analyses, but now the scope has increased to include experiments
  - Characterization and search for coating material (LIGO)
  - Squeezing of light source to overcome quantum limit (KAGRA, ET)
- GW astronomy just has begun, and more exciting sciences can be done with future detectors at lower frequencies than the current generation of ground-based detectors
  - Mid-band detectors are able to localize some of the GW sources in 3-dimensional volume smaller than the occupation volume of typical galaxies: identification of host galaxies without the aid of the EM telescope.
    - Precision cosmology, independent of other means (SN, LSS, etc.)

Topics

- Overview of the Korean Gravitational-Wave Group (KGWG)
- Short Summary of GW Observations so far
- Third generation detectors
- GWs over wide frequencies
- Mid-band detectors: SOGRO and LGWA

How did I get involved in the Gravitational-Wave



Korean Gravitational-Wave Group

- Started as a voluntary study group composed of ~ 20 members
  - Kick-off meeting of working group was held on: November 21, 2003 (no photo exists)
    - Among participants, Matt Chaptuik (UBC), M. van Putten (MIT)
- Supercomputer Center at KISTI immediately began to support by providing small funds for meetings, and opened a position.
  - Numerical Relativity Sub-Group led by Gungwon Kang (KISTI, Currently at ChungAng Univ.)
    - Organized a series of summer school on numerical relativity and gravitational waves since 2005
  - Sept. 2009 : Presentation in LSC meeting at Budapest. LSC Council approved our proposal
- MOU signed during the LSC Meeting in March 2010
- 2011: KAGRA participation
- 2017: Successful observations of the optical counterpart of GW170817
- 2018: Inauguration of the experimental group at KASI



Summer School 2008


Signing of the first MOU in 2009 (Dave Reitz & Jay Marx)

Meetings Organized by the KGWG

- **Gravitational Waves: New Frontier**
  - Jan. 16-18, 2013 at Seoul National University
  - Supported by the Korean Academy of Science and Technology (KAST)
  - ~100 participants
- **The 11th Edoardo Amaldi Conference**
  - June 21-26, 2015 at Gwangju
  - Last Amaldi Conference before the first detection of the GW
  - ~140 participants
  - Public lecture by Bernard Schutz





Participation in KAGRA

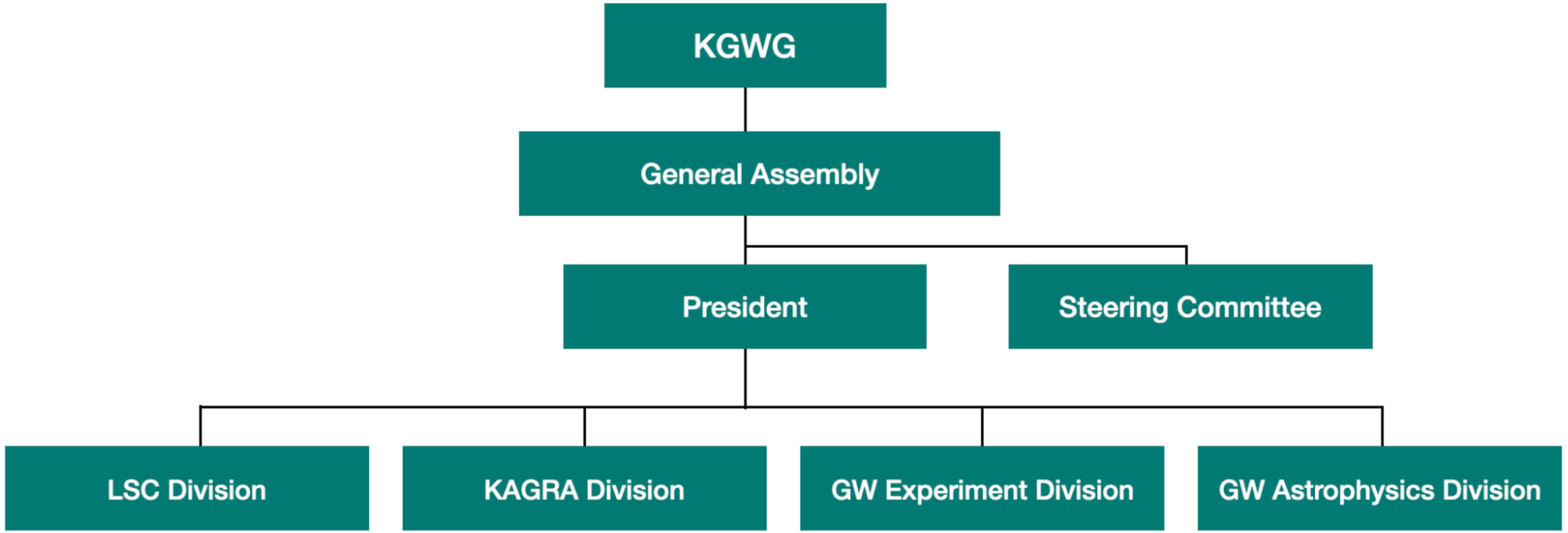
- KGWG joined in LCGT Project (later renamed to KAGRA) at the KGWG-LCGT Joint Workshop held on Jan 21, 2011 at SNU
  - 12 members are admitted to LCGT collaboration at the Face-to-Face meeting in August 2011
  - Currently, there are more than 20 KAGRA members from Korea
- Eight Korea-Japan joint workshops have been held from 2012 to 2015
- As KAGRA collaboration grows, KJ workshop was transformed to KAGRA International Workshop (KIW) Series.
  - First KIW was held at KISTI on June 23-25, 2016.
  - The latest KIW was KIW10 at National Tsinghua University , Taiwan (hybrid) on May 29-30, 2023



The 3rd Korea-Japan Workshop on Dec. 21, 2012@Sogang Univ.

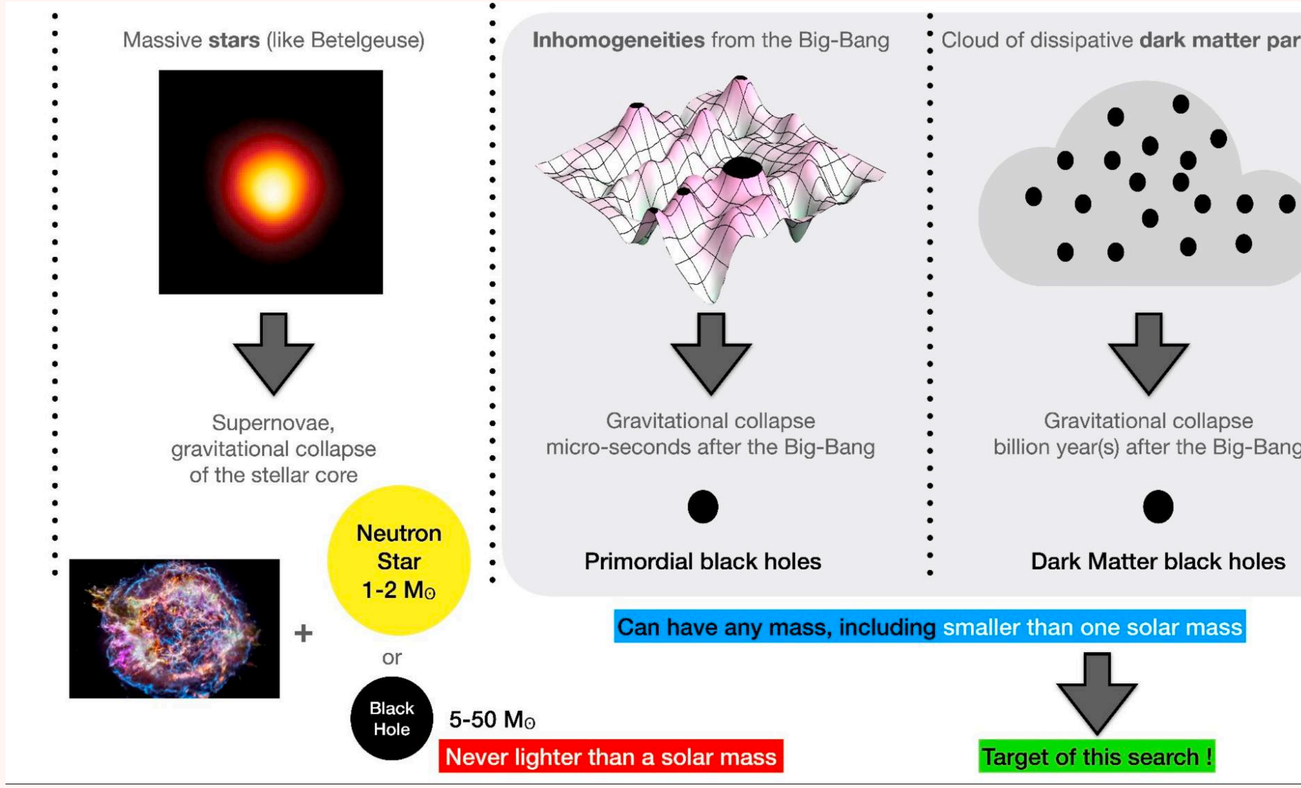


Current Structure of the KGWG



Search for subsolar-mass black hole binaries in the second part of Advanced LIGO's and Advanced Virgo's O3 (arXiv:2212.01477, MNRAS, 523, 6234 [2023], LVK authors + Donghui Jeong)

- Stellar evolution theory predicts of the remnant masses
  - NS: 1 ~ 2 $M_\odot$, BH: 5 ~ 50 $M_\odot$
- Other scenarios for the sub solar mass BH formation
  - Primordial, Dark Matter:
- LVK Pipelines assume 1 - 100 $M_\odot$ for BH
- Search for sub solar mass BH
  - $m_1 = 0.2 \sim 1\ M_\odot$, $m_2 = 1 \sim 10\ M_\odot$
  - Longer signal duration
    - e.g. $m_1 = m_2 = M_\odot$: 280 seconds
- **Search for O3b data**
  - No candidate is significant enough to be considered a discovery
  - The best one has a FAR of 1 per 5 years.
  - PBH: cannot be ruled out as a candidate of DM
  - DBH: $f_{DBH} < 10^{-5}$

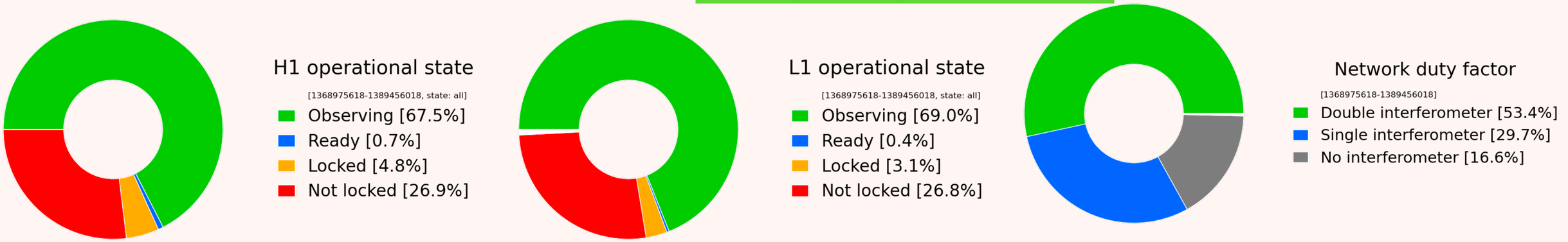


Summary of O4

- O4 Started on May 24, 2023 and stopped observation on Jan. 16, 2024 for commissioning break
- General public can monitor the status through Gravitational Wave Open Science Center at https://gwosc.org
  - KAGRA observed for one month, and rejoin later in the run after some upgrades.
  - Virgo will join O4b, in mid-March, 2024
- **LIGO/Virgo/KAGRA alerts are public via**
  - GCN: https://gcn.nasa.gov (subscribe to GCN circulars)
  - Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics (SCiMMA, https://scimma.org).
- Types of alerts:
  - Human-readable GCN Circulars
  - Machine-readable Notices.

Operational states of Individual detectors During O4 (24/05/2023 - 16/01/2024)

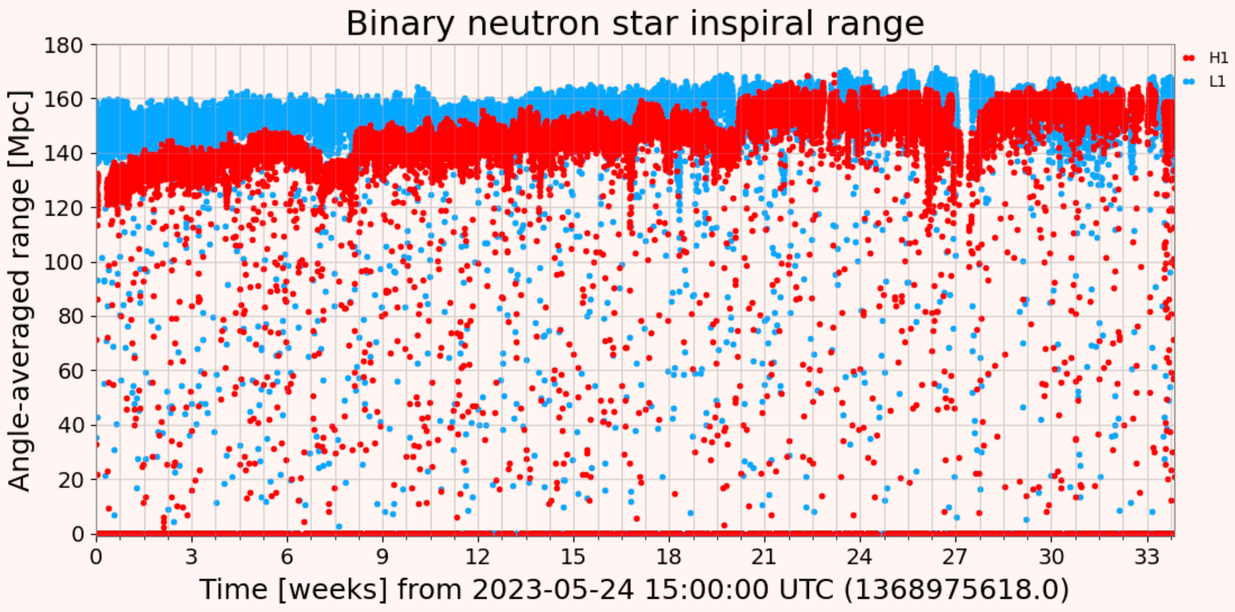
https://gwosc.org/detector_status/

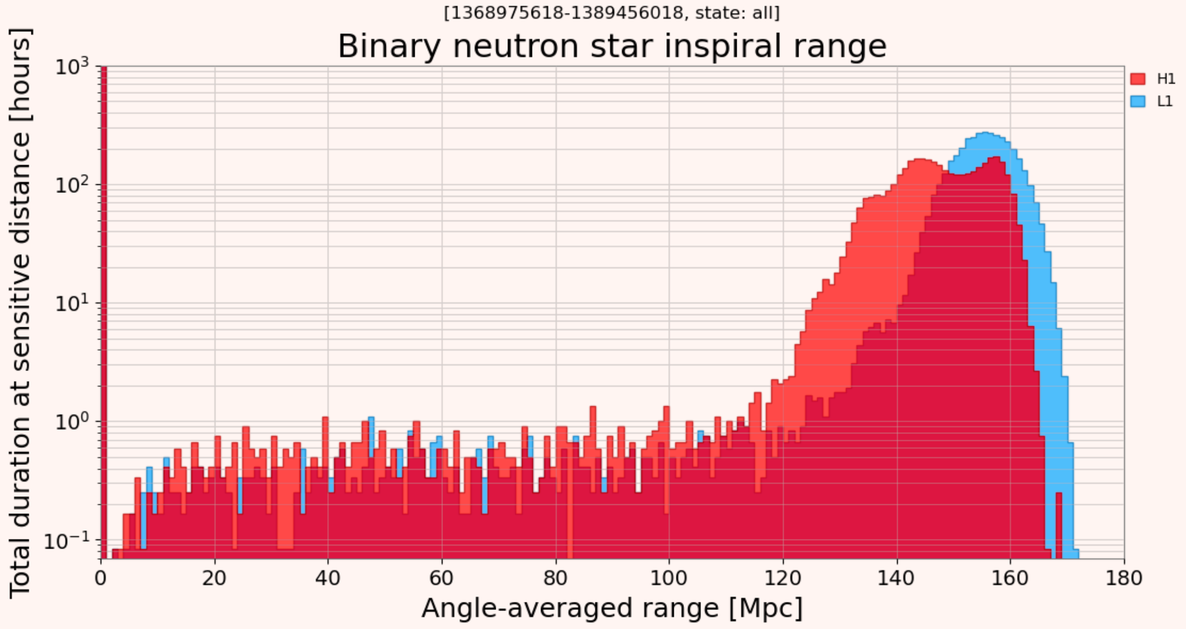


- Anybody has access to real time detector status including BNS range through https://gwosc.org/detector_status/
- Typical operation time is ~70 % for Hanford (H1) and Livingston (L1)
- Virgo was still on commissional stage

BNS Range of LIGO Detectors (until Nov. 22)

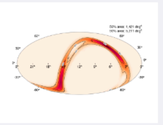
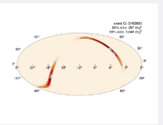
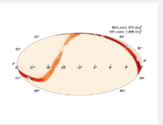
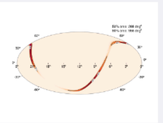
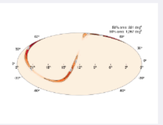
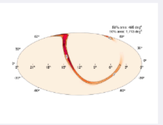
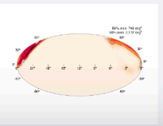
https://gwosc.org/detector_status/





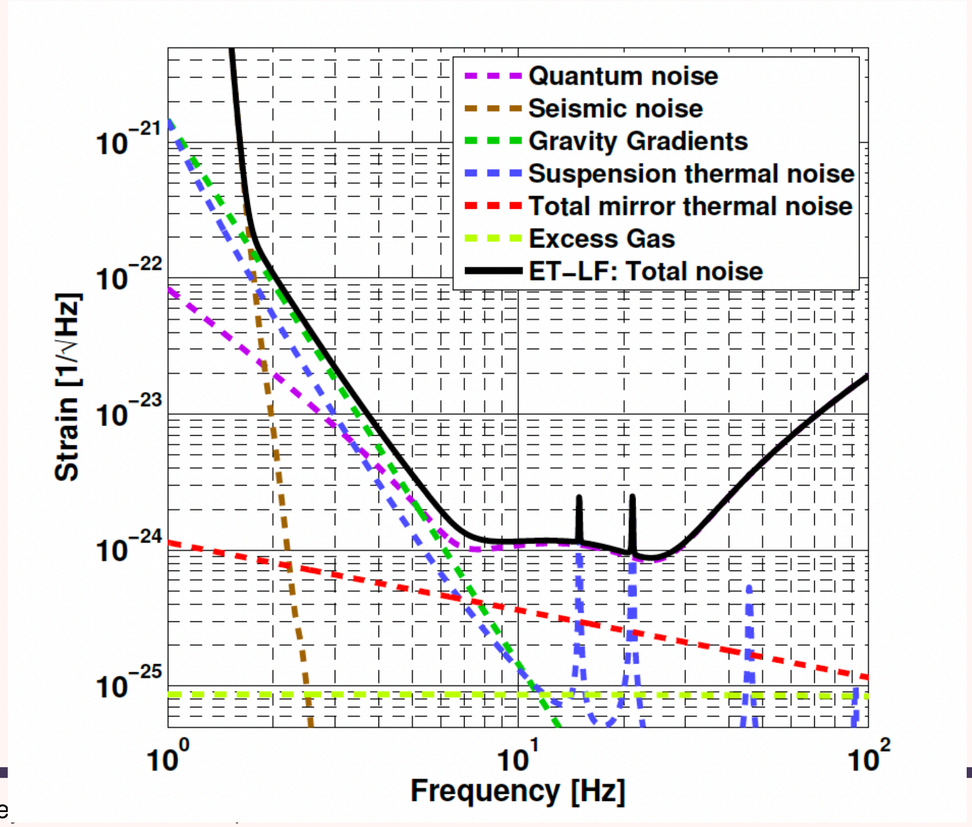
Real Time Detections (As of Jan. 26, 2024)

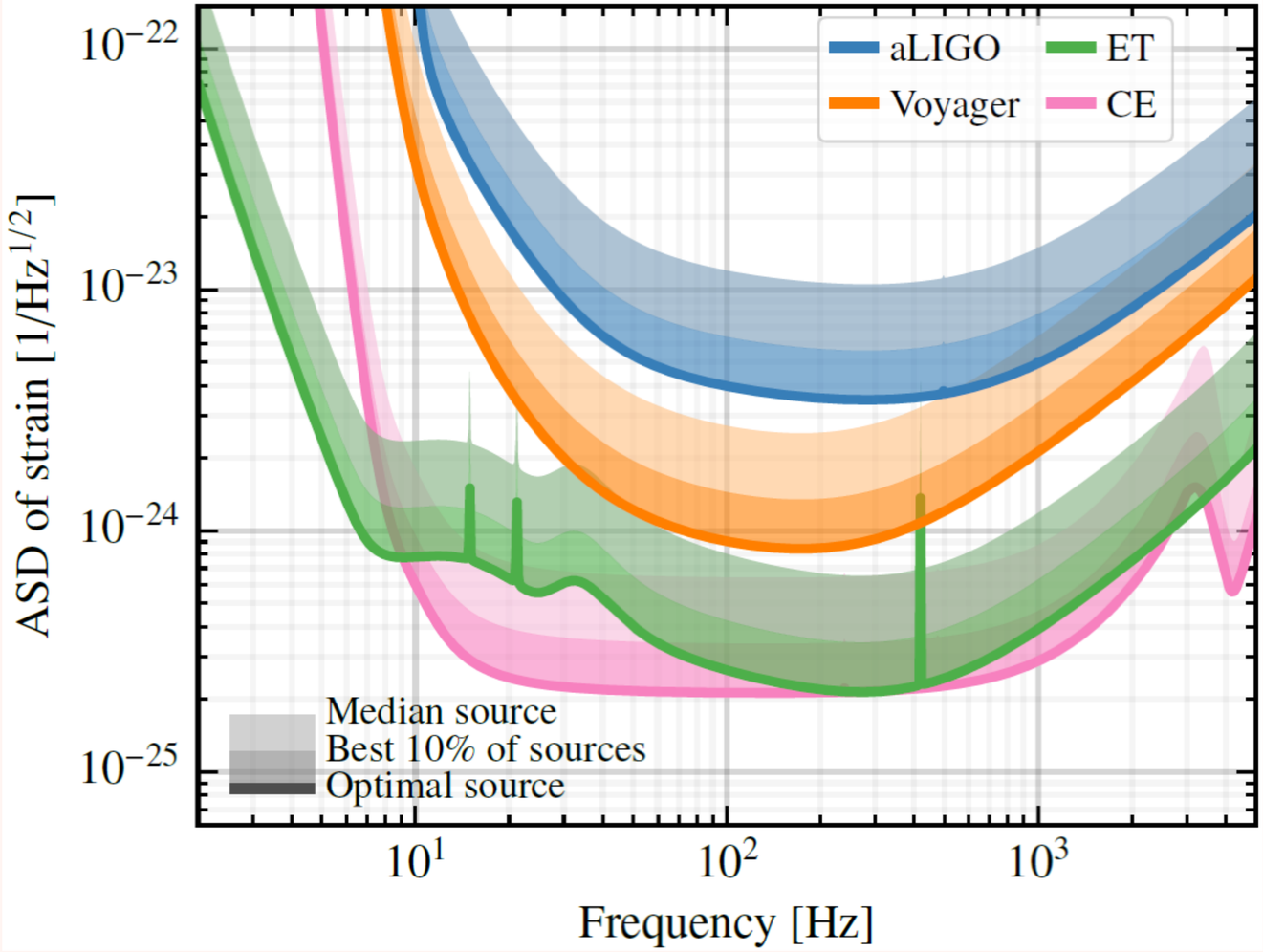
- All public alerts during the O4 can be seen at https://gracedb.ligo.org/superevents/public/O4/.
  - 92 Significant Detection Candidates (11 retraction) -81 remain
    - Most of them are BBH
    - Exceptions:
  - Low Significance Detection Candidates: 1610

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S231119u	BBH (95%), Terrestrial (5%)	Yes	Nov. 19, 2023 07:52:48 UTC	GCN Circular Query Notices | VOE		2.345 per year	
S231118an	BBH (74%), Terrestrial (24%), NSBH (1%)	Yes	Nov. 18, 2023 09:06:02 UTC	GCN Circular Query Notices | VOE		2.3593 per year	
S231118ab	BBH (99%), Terrestrial (1%)	Yes	Nov. 18, 2023 07:14:02 UTC	GCN Circular Query Notices | VOE		1 per 1.672 years	
S231118d	BBH (>99%)	Yes	Nov. 18, 2023 00:56:26 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	
S231114n	BBH (>99%)	Yes	Nov. 14, 2023 04:32:11 UTC	GCN Circular Query Notices | VOE		1 per 100.04 years	
S231113bw	BBH (96%), Terrestrial (4%)	Yes	Nov. 13, 2023 20:04:17 UTC	GCN Circular Query Notices | VOE		1 per 2.3265 years	
S231113bb	BBH (96%), Terrestrial (4%)	Yes	Nov. 13, 2023 12:26:23 UTC	GCN Circular Query Notices | VOE		1.7663 per year	

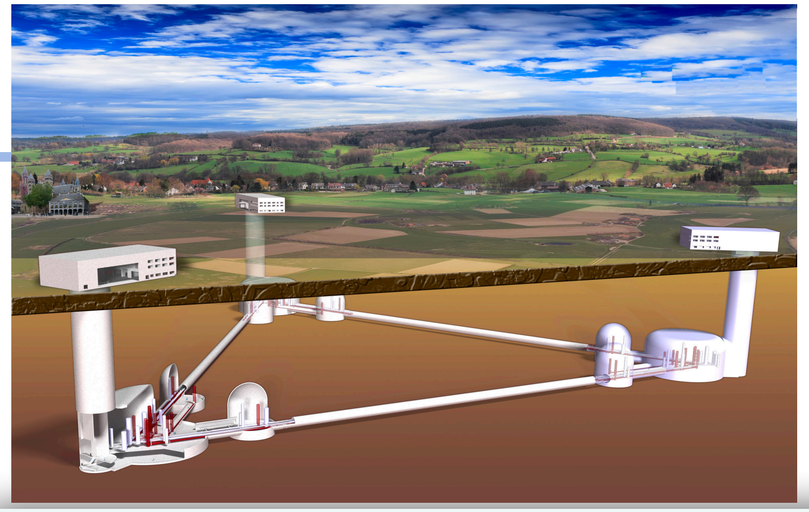
3G Ground based detectors

Laser interferometers similar to LIGO/ Virgo covers frequencies higher than 10 Hz (except for ET which will be located underground)





ET Collaboration & Korean Research Unit

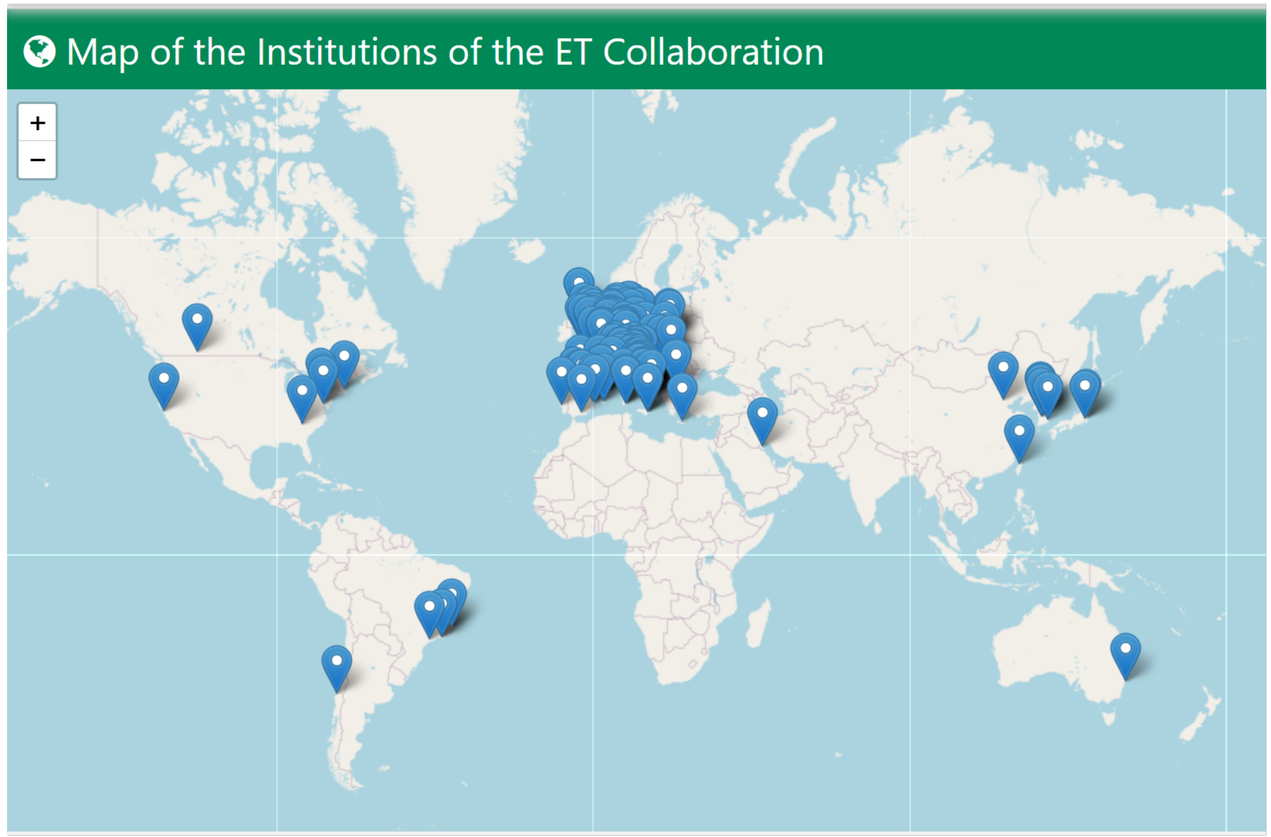


ET Collaboration

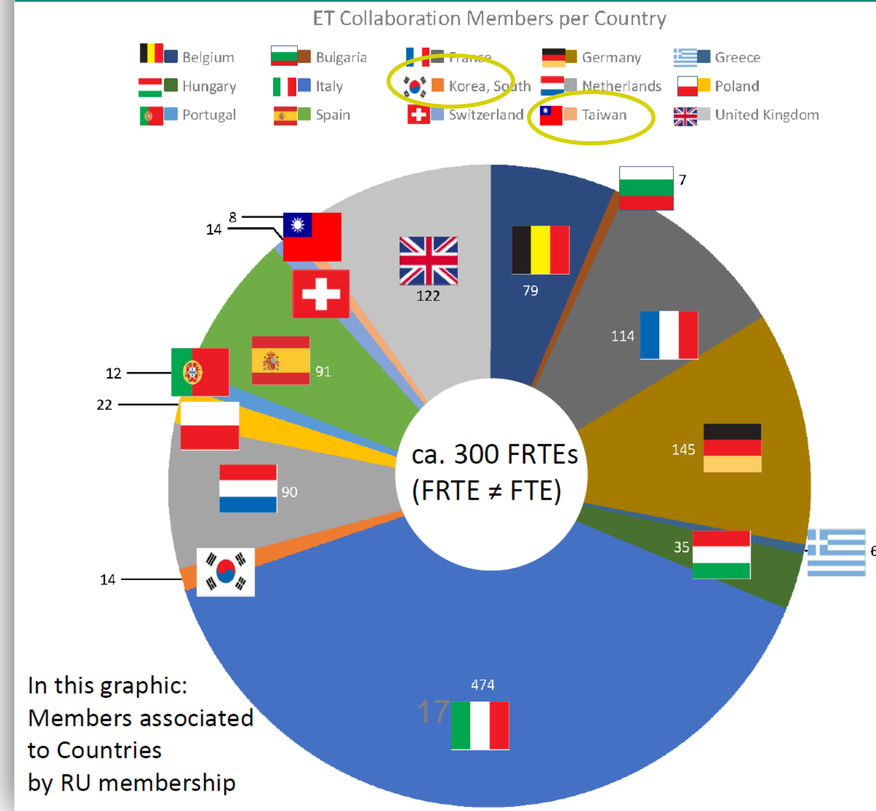
- ✓ Officially launched in June 2022
- ✓ 25 countries, 87 Research Units, 1,611 members

Korean Research Unit

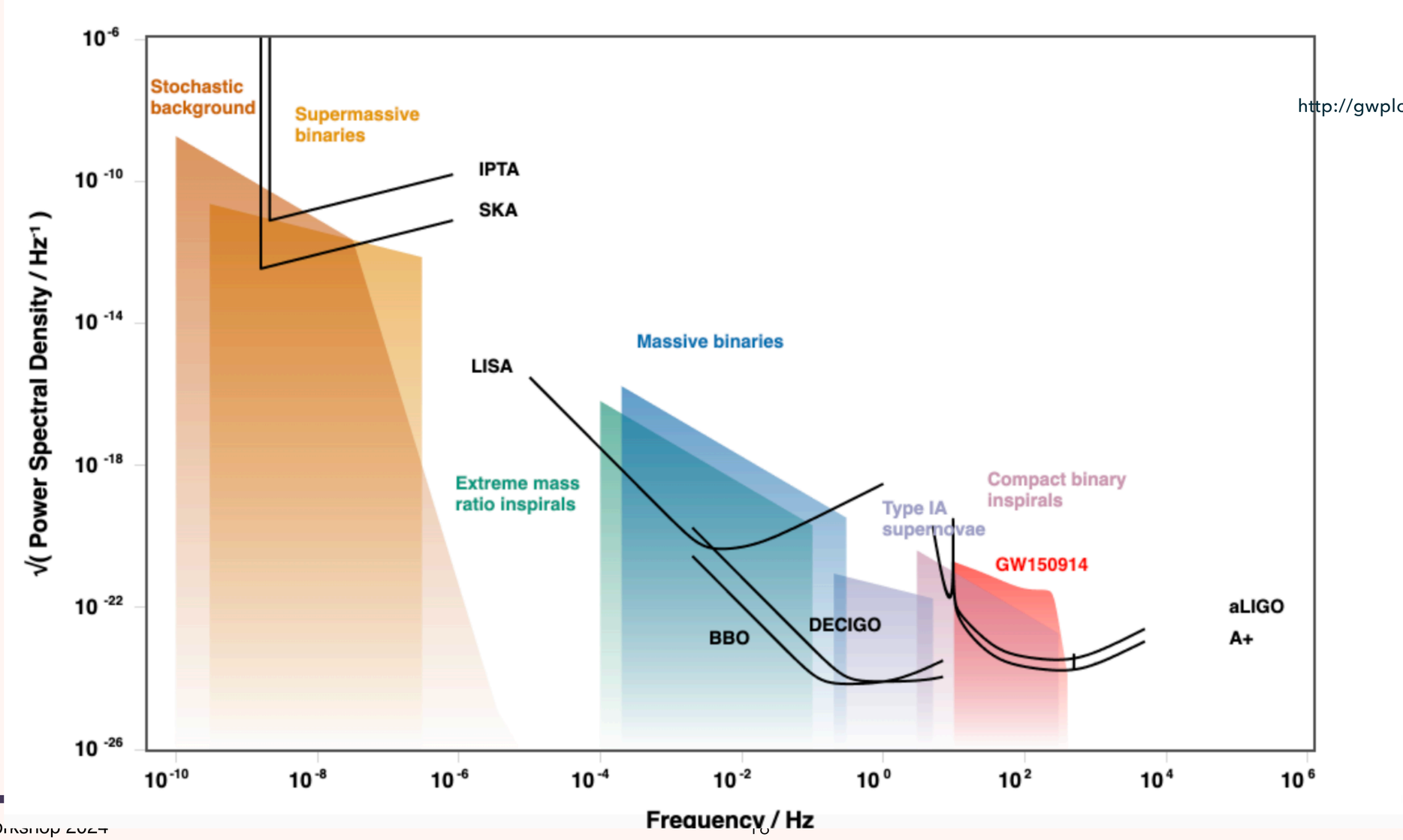
- ✓ 19 members @ 7 institutions (KASI, KAIST, KHU, UNIST, EWU, SKKU, Yonsei U.)
- ✓ Research Unit leader: Sungho Lee (KASI) → ET Collaboration Board member
- ✓ National Representative: Chunglee Kim (EWU) → ET Forum of National Representative



ET Membership



Current and future Detectors in all frequency bands

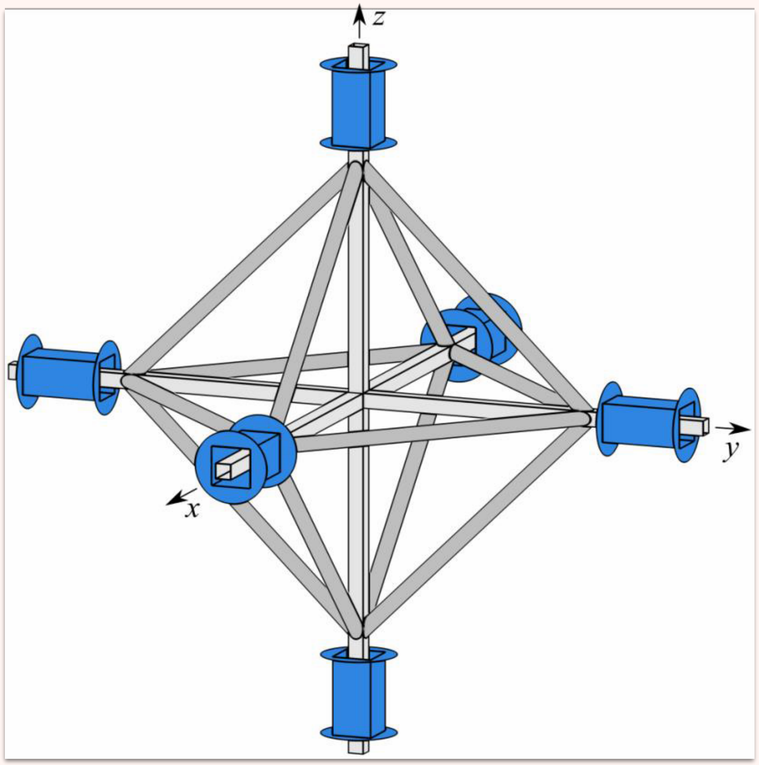


http://gwplotter.com/

Benefits of low to mid-frequency Detectors

- Exploration of the space-time structure of around the (spinning) massive black holes
- Population of compact stars in the central parts of the galaxies
- Horizon distances are much larger than those of high-frequency sources
- Origin of the intermediate mass black holes
- Growth of the massive black holes
- Early warning to the higher frequency detectors
- Determination of 3-D positions with high precision: identification of host galaxies with GW data only (Yang et al. 2022, 2023…)

SOGRO - a ground based detector in mid band ($f \gtrsim 0.1$ Hz)



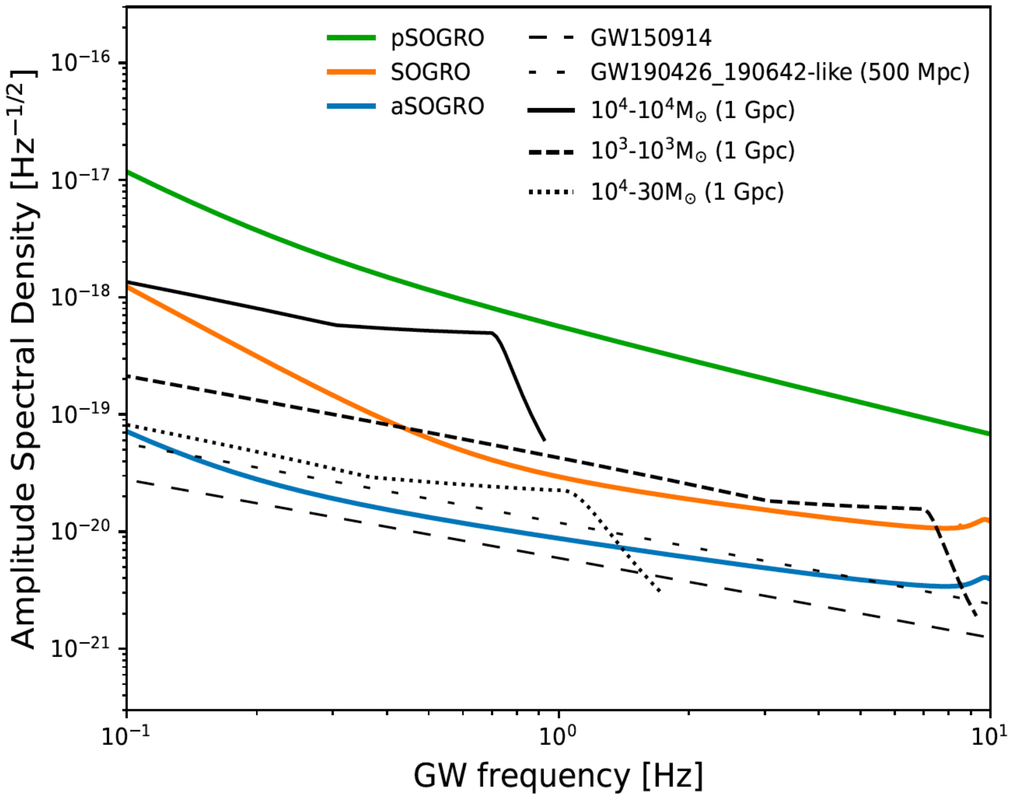
Paik et al., 2015

- Superconducting Omni-directional Gravitational Radiation Observatory (SOGRO)
- Detector motion of the magnetically levitated test masses due to gravity gradient tensor using SQUID

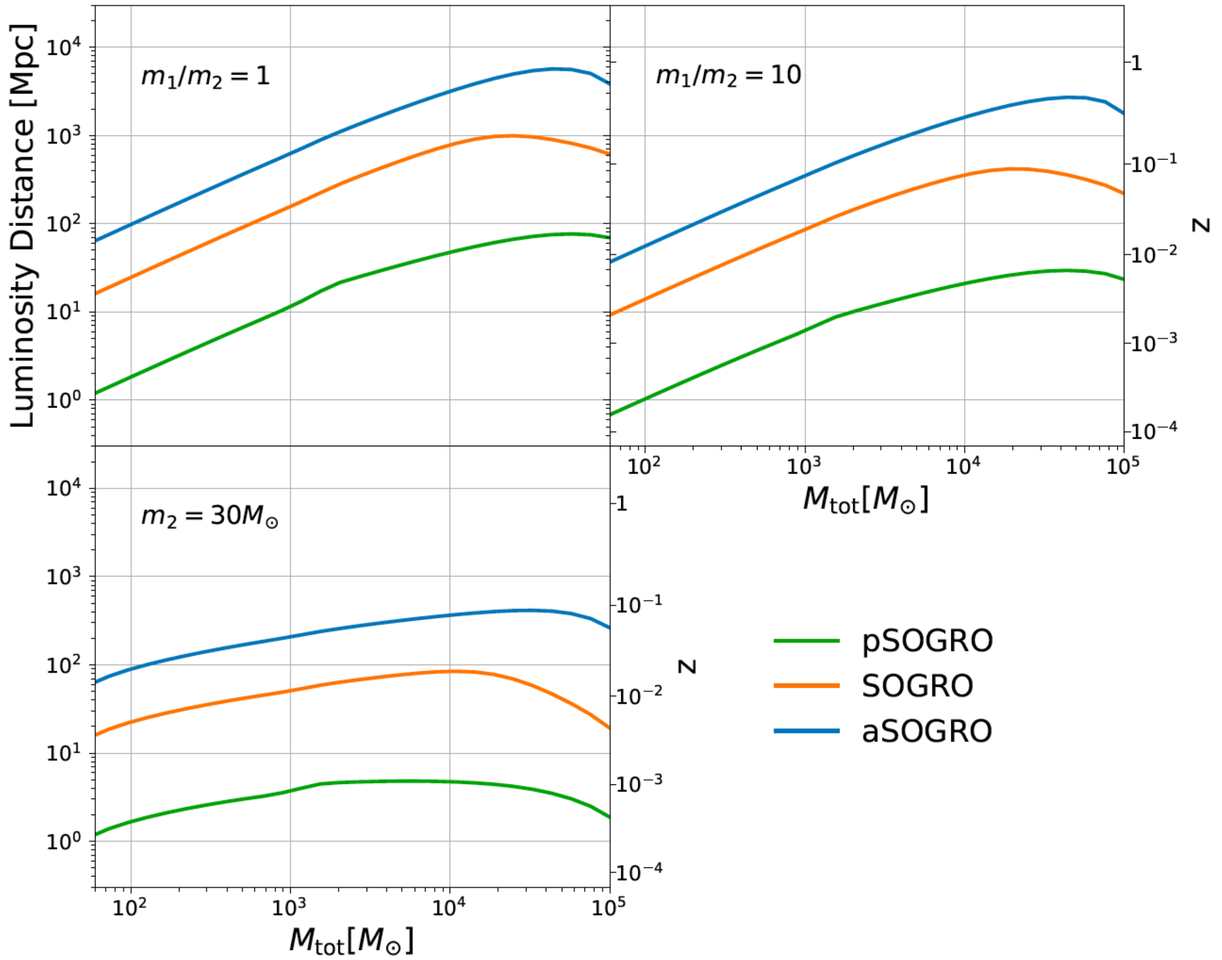
$$h_{ij} = \frac{1}{\omega^2}\frac{\partial^2 \Phi}{\partial x^i \partial x^j}$$

- By detecting all six components of Riemann tensor, the source direction and the polarization can be determined
- To be installed deep underground in order to minimize seismic and gravity gradient (Newtonian) noises
  - Mitigation of Newtonian noise using extra components of the test mass motions
- Development roadmap: pSOGRO, SOGRO, aSOGRO

SOGRO Sensitivity and Target Sources

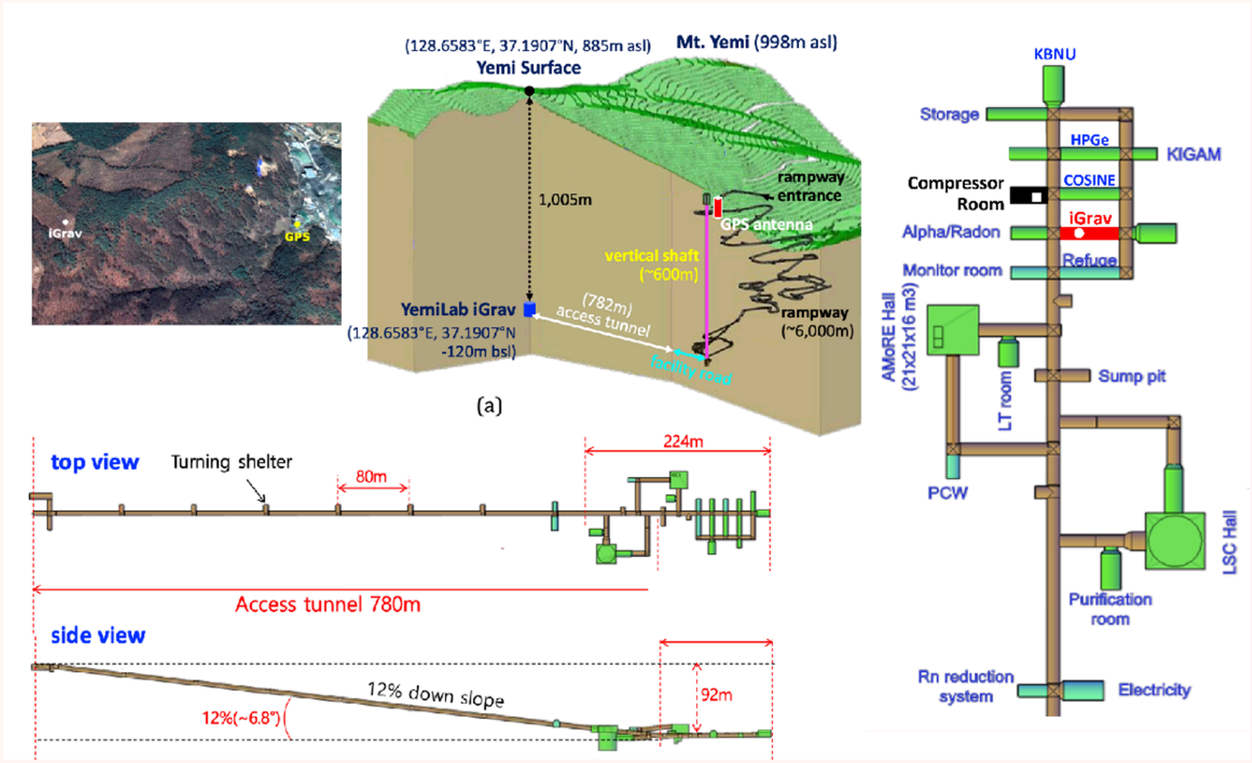


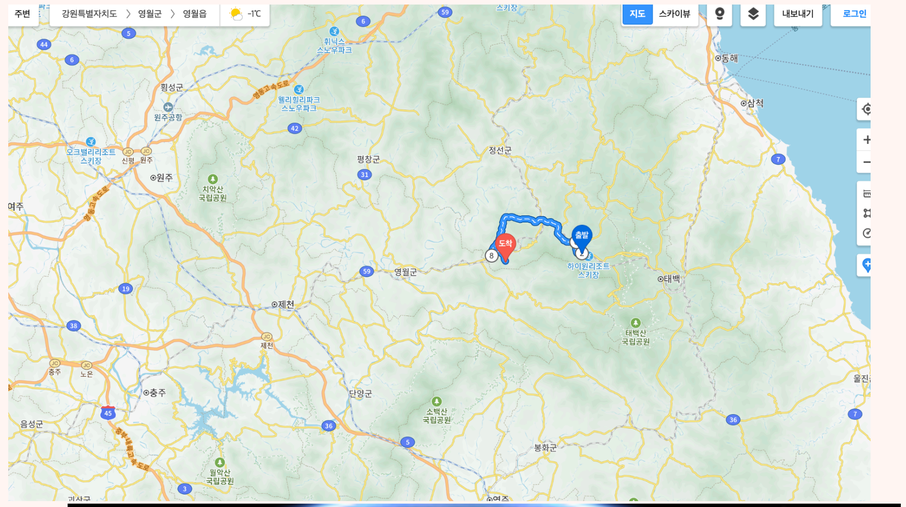
Bae et al.2024, arXiv:2311.17639

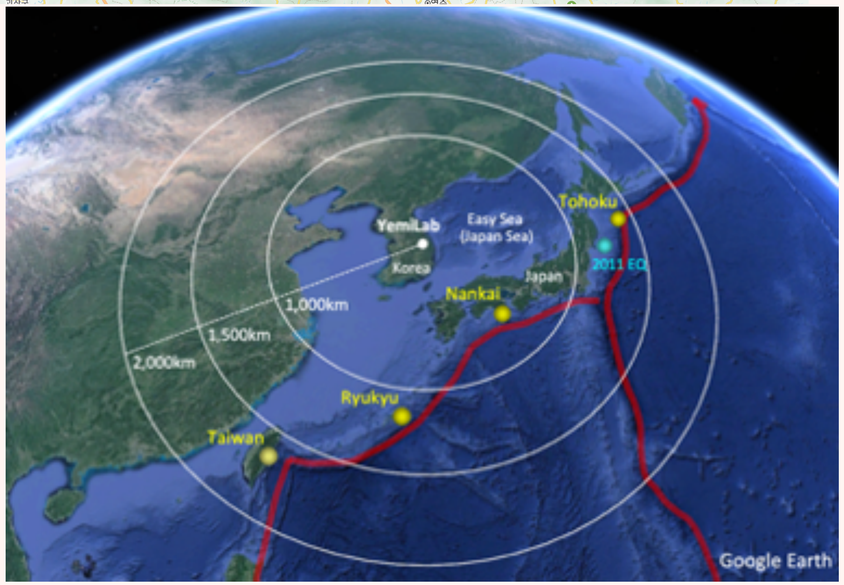


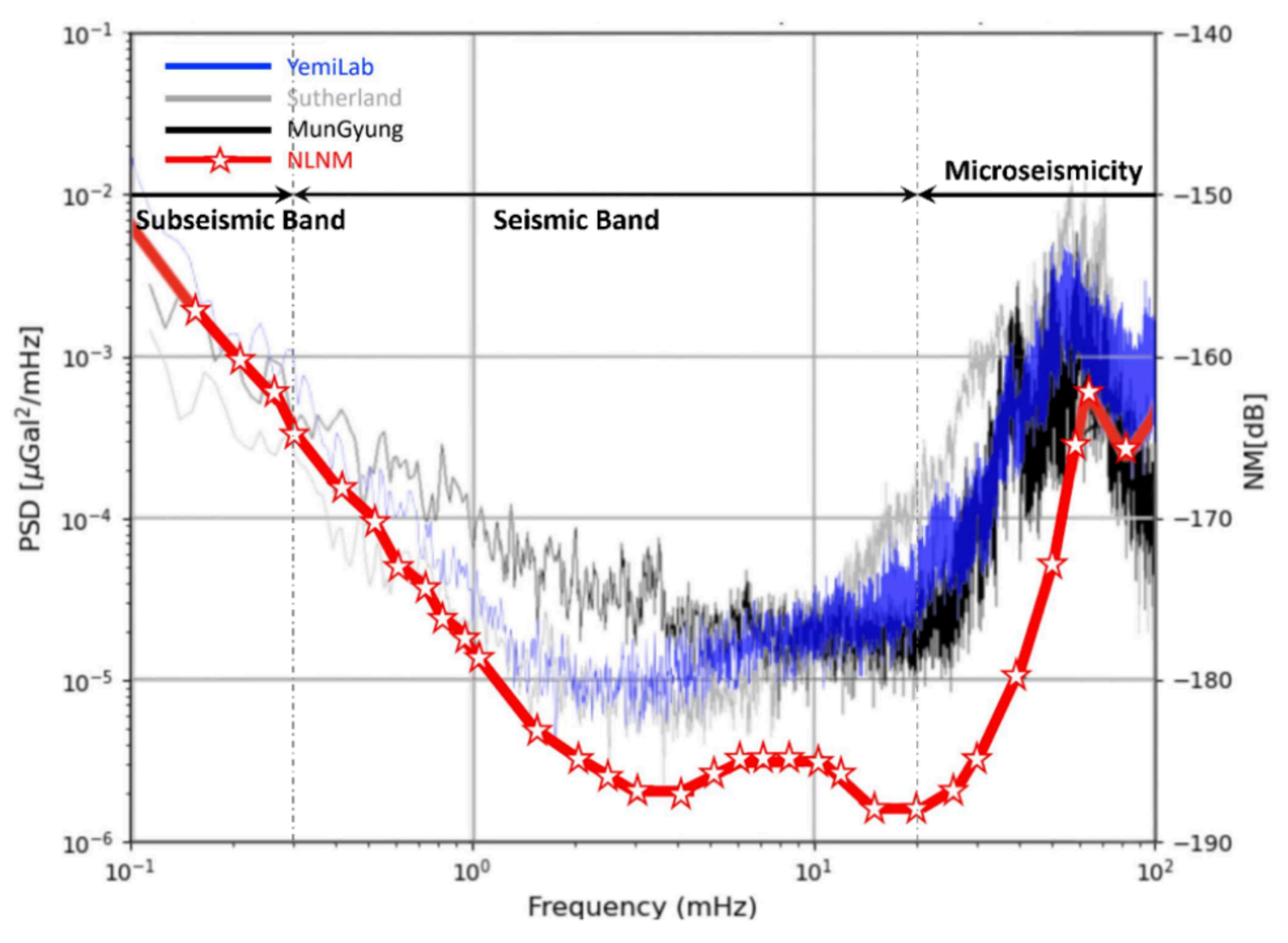
Yemi Underground Laboratory

- We have to understand the Newtonian noise and its dependence on the environmental parameters
- IBS CUP constructed YemiLab, Jeongsun for underground experiments (Shindong-eup Yemi-ri (Yemi AMORE II, COSINE experiments and more space for other experiments
- Yemilab is ~1000 meters from the top of the mountain peak
- The gravity group at NIMS installed sensitive gravimeter in Yemilab to carry out microgravity studies for geophysical research (early warning of Earthquake, motion of the surfaces, etc.)








YemiLab
Sutherland
MunGyung
NLNM
Microseismicity
Subseismic Band
Seismic Band
PSD [μGal²/mHz]
NM[dB]
Frequency (mHz)
10⁻¹
10⁰
10¹
10²
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
−140
−150
−160
−170
−180
−190

Lunar Gravitational-wave Antenna

- Moon is seismically quiet and we can use moon as a resonant body that responds to the Gravitational-waves, as seismic motion
- The resonant response can be detected with sensitive seismometers

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Lunar Gravitational-wave Antenna

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[1] Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy; jan.harms@gssi.it

Three main criteria

- How strongly does the body respond to GWs?

$$\xi(f) = \frac{1}{2} h(f) \sum_{n=0}^{\infty} L_n \frac{-f^2}{f_n^2 - f^2 + i f_n^2 / Q_n},$$

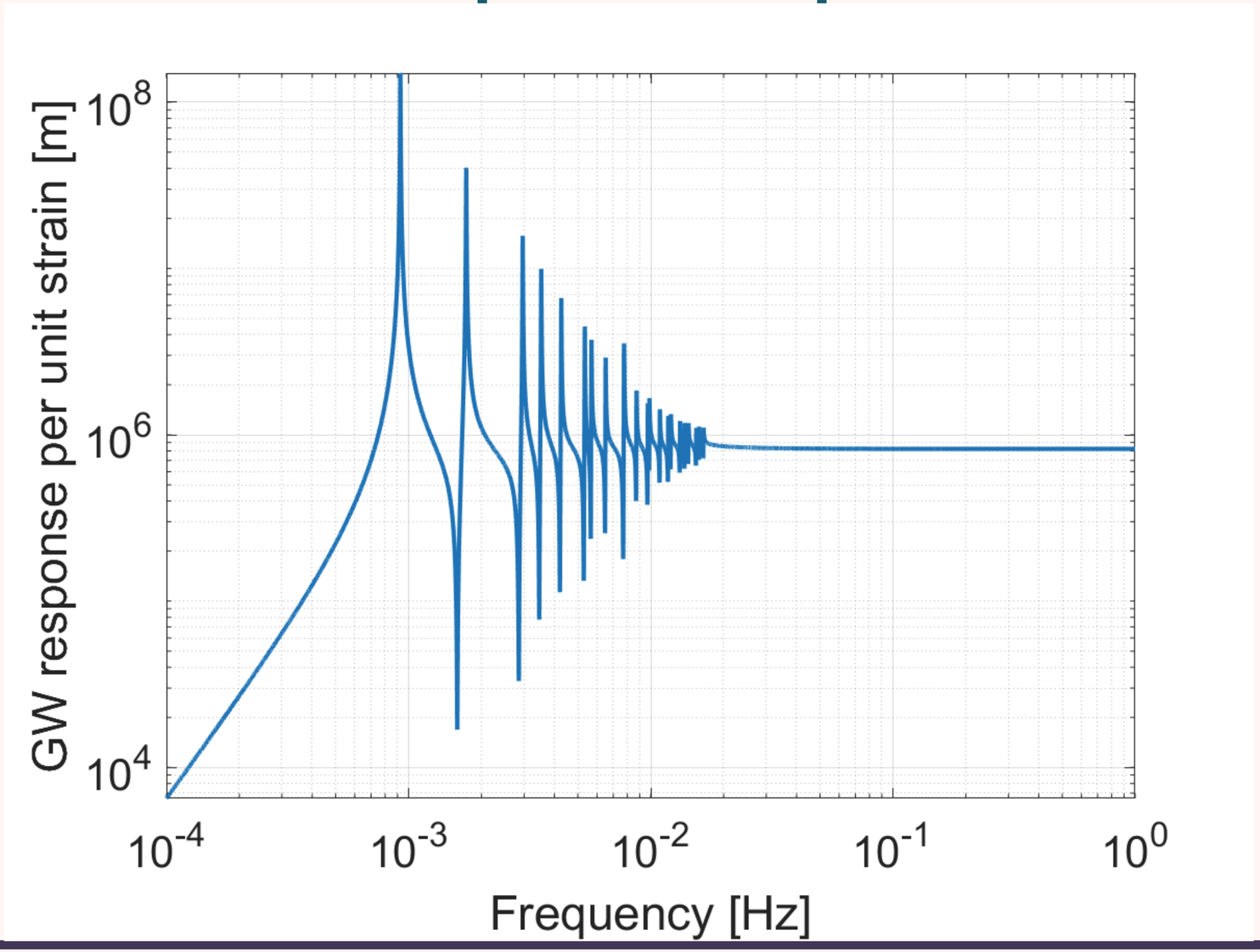
where f_n: frequency of the vibrational quadrupole mode of order n,

Q_n: quality factor (~200)

and L_n: effective baseline (~R)

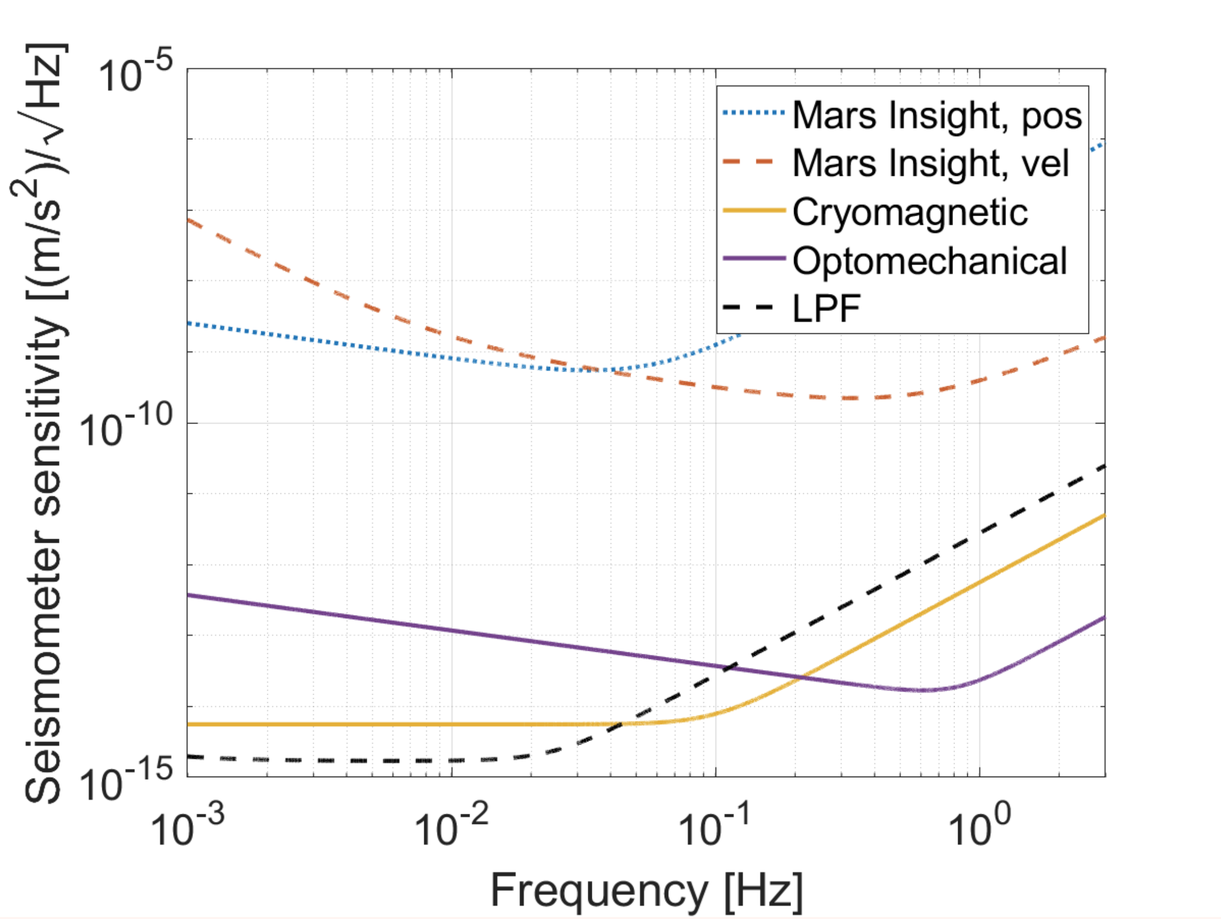
- How sensitive is the readout system to changes in the response body affected by GWs?
- What is the level of environmental or intrinsic random excitation of the response body?

Simple Model up to n=22



Readout

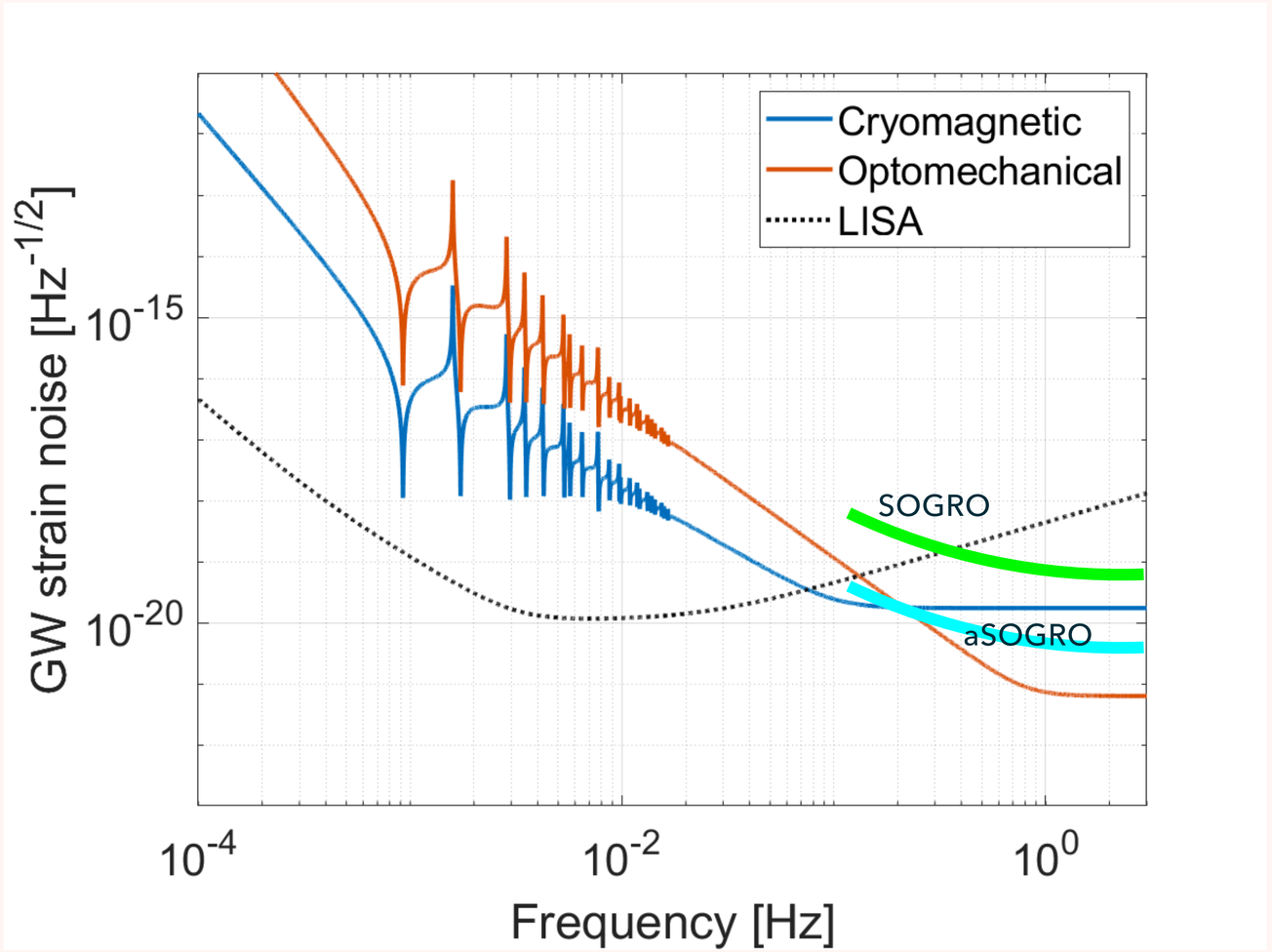
- Quality of the seismometer system:



Intrinsic Noise

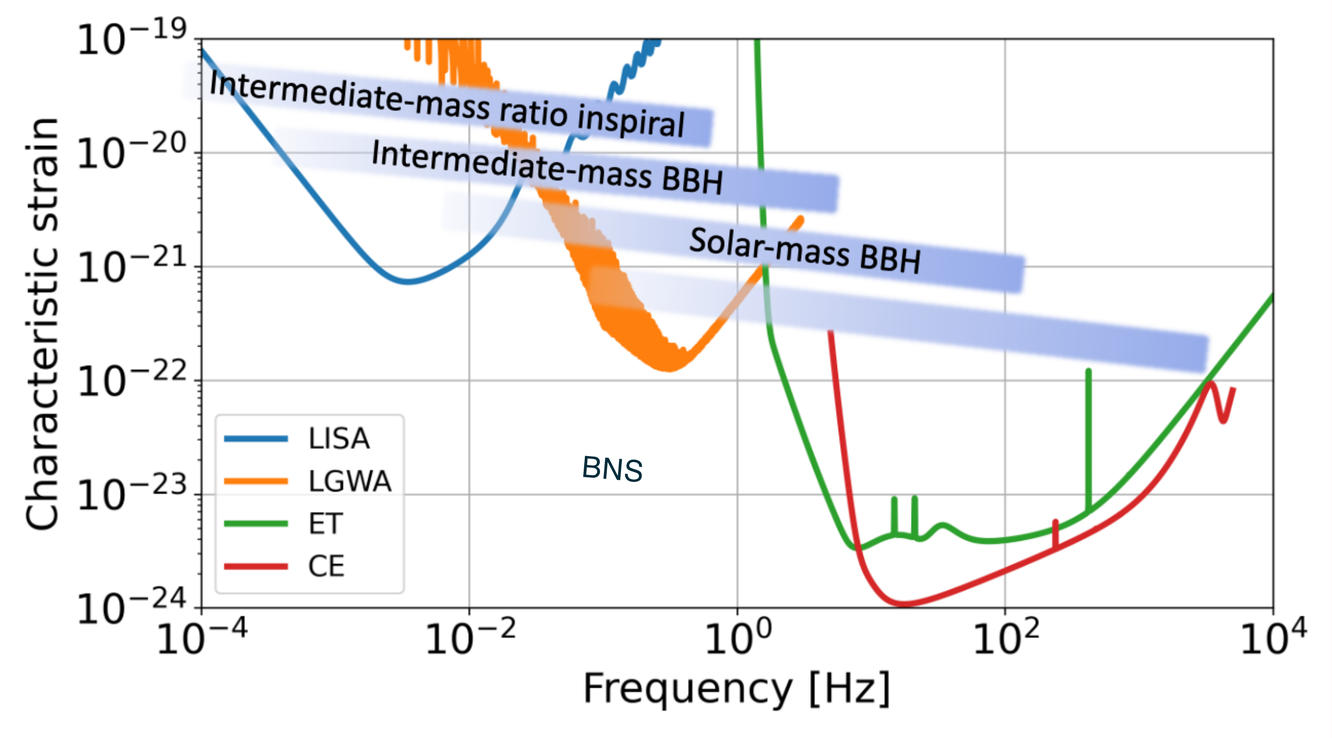
- Absence of the ocean: background noise is very low
- Natural seismic events on the moon
  - Deep Moonquakes probably produced by tides
  - Shallow Moonquakes a few tens km below surface
  - Thermal quakes
  - Meteoroid impact
- Dominant noise background is produced by the impact of meteoroids
- However, even the meteoroid background noise is estimated to lie below the targeted sensitivity over the entire observation band: readout noise dominated

LGWA Sensitivity



Science Cases

- Binaries
  - Multiband observations can give more precise information on source parameters
  - Early warning of binary neutron star merger
- Fundamental Physics
- Lunar Science



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- GW astronomy just gas begun, and more exciting sciences can be done with future detectors at lower frequencies than the current generation of ground-based detectors
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