# Gravitational Wave Detectors on the Moon

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# Abstract

- Four proposals to detect GWs in 1 mHz – 10 Hz on the Moon (I found, perhaps more)
- I will introduce one of them in detail and the other three quickly

Main LGWA: Lunar Gravitational-Wave Antenna

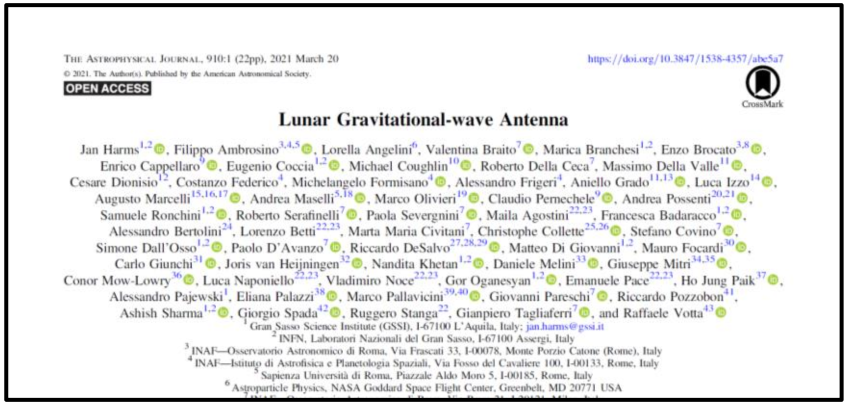
GLOC: Gravitational-wave Lunar Observatory for Cosmology

LION: Laser Interferometer On the mooN

LSGA: Lunar Seismic and Gravitational Antenna

# Today’s papers

J. Harms+, ApJ 910, 1 (2021)


The Astrophysical Journal, 910:1 (22pp), 2021 March 20 https://doi.org/10.3847/1538-4357/abe5a7
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**Lunar Gravitational-wave Antenna**

Jan Harms[1,2], Filippo Ambrosino[3,4,5], Lorella Angelini[6], Valentina Braito[7], Marica Branchesi[1,2], Enzo Brocato[3,8], Enrico Cappellaro[9], Eugenio Coccia[1,2], Michael Coughlin[10], Roberto Della Ceca[7], Massimo Della Valle[11], Cesare Dionisio[12], Costanzo Federico[4], Michelangelo Formisano[4], Alessandro Frigeri[4], Aniello Grado[11,13], Luca Izzo[14], Augusto Marcelli[15,16,17], Andrea Maselli[5,18], Marco Olivieri[19], Claudio Pernechele[9], Andrea Possenti[20,21], Samuele Ronchini[1,2], Roberto Serafinelli[7], Paola Severgnini[7], Maila Agostini[22,23], Francesca Badaracco[1,2], Alessandro Bertolini[24], Lorenzo Betti[22,23], Marta Maria Civitani[7], Christophe Collette[25,26], Stefano Covino[7], Simone Dall’Osso[1,2], Paolo D’Avanzo[7], Riccardo DeSalvo[27,28,29], Matteo Di Giovanni[1,2], Mauro Focardi[30], Carlo Giunchi[31], Joris van Heijningen[32], Nandita Khetan[1,2], Daniele Melini[33], Giuseppe Mitri[34,35], Conor Mow-Lowry[36], Luca Naponiello[22,23], Vladimiro Noce[22,23], Gor Oganesyan[1,2], Emanuele Pace[22,23], Ho Jung Paik[37], Alessandro Pajewski[1], Eliana Palazzi[38], Marco Pallavicini[39,40], Giovanni Pareschi[7], Riccardo Pozzobon[41], Ashish Sharma[1,2], Giorgio Spada[42], Ruggero Stanga[22], Gianpiero Tagliaferri[7], and Raffaele Votta[43]
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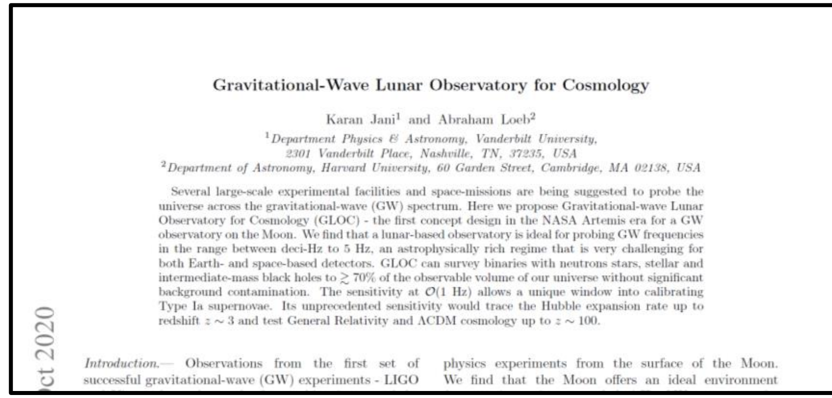
[5] Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185, Rome, Italy
[6] Astroparticle Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA

K. Jani & A. Loeb, arXiv:2007.08550 (2020)


**Gravitational-Wave Lunar Observatory for Cosmology**

Karan Jani[1] and Abraham Loeb[2]
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[2] *Department of Astronomy, Harvard University, 60 Garden Street, Cambridge, MA 02138, USA*

Several large-scale experimental facilities and space-missions are being suggested to probe the universe across the gravitational-wave (GW) spectrum. Here we propose Gravitational-wave Lunar Observatory for Cosmology (GLOC) - the first concept design in the NASA Artemis era for a GW observatory on the Moon. We find that a lunar-based observatory is ideal for probing GW frequencies in the range between deci-Hz to 5 Hz, an astrophysically rich regime that is very challenging for both Earth- and space-based detectors. GLOC can survey binaries with neutrons stars, stellar and intermediate-mass black holes to $\gtrsim 70\%$ of the observable volume of our universe without significant background contamination. The sensitivity at $\mathcal{O}(1\ \mathrm{Hz})$ allows a unique window into calibrating Type Ia supernovae. Its unprecedented sensitivity would trace the Hubble expansion rate up to redshift $z \sim 3$ and test General Relativity and ΛCDM cosmology up to $z \sim 100$.

ct 2020

*Introduction.*— Observations from the first set of successful gravitational-wave (GW) experiments - LIGO … physics experiments from the surface of the Moon. We find that the Moon offers an ideal environment

P. Amaro-Seoane+, Class. Quantum Grav. 38, 125008 (2021)


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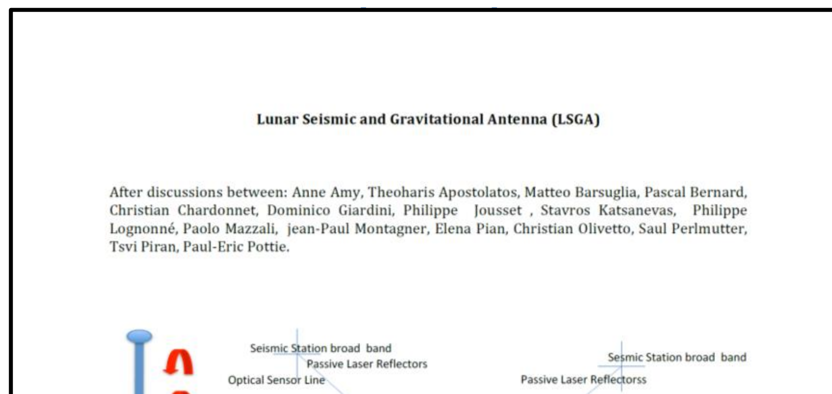
**IOP** Publishing Classical and Quantum Gravity
Class. Quantum Grav. **38** (2021) 125008 (24pp) https://doi.org/10.1088/1361-6382/abf441

**LION: laser interferometer on the moon**

**Pau Amaro-Seoane[1,2,3,4,5,8], Lea Bischof[6,7,8], Jonathan J. Carter[6,7,8,*], Marie-Sophie Hartig[6,7,8] and Dennis Wilken[6,7,8]**
[1] Universitat Politècnica de València, IGIC, Spain
[2] DESY, Zeuthen, Germany
[3] Kavli Institute for Astronomy and Astrophysics, People’s Republic of China
[4] Institute of Applied Mathematics, Academy of Mathematics and Systems Science, People’s Republic of China

S. Katsanevas+, Ideas for exploring the Moon with a large European lander


**Lunar Seismic and Gravitational Antenna (LSGA)**

After discussions between: Anne Amy, Theoharis Apostolatos, Matteo Barsuglia, Pascal Bernard, Christian Chardonnet, Dominico Giardini, Philippe Jousset , Stavros Katsanevas, Philippe Lognonné, Paolo Mazzali, jean-Paul Montagner, Elena Pian, Christian Olivetto, Saul Perlmutter, Tsvi Piran, Paul-Eric Pottie.

# Why did I choose this topic?

→ Because this is a hot topic for me these days

- Jan Harms: the author of LGWA
  - A professional of Newtonian noise
  - The author of earthquake alert with GW detectors
  - I found out about him when I was writing the DC1 application
  - I also watched his record talk about LGWA in GWADW2021

Geophys. J. Int. 201, 1416 (2015)


Geophysical Journal International

Geophys. J. Int. (2015) 201, 1416–1425 doi: 10.1093/gji/ggv090

GJI Gravity, geodesy and tides


**Transient gravity perturbations induced by earthquake rupture**


J. Harms,[1,2,*] J.-P. Ampuero,[3] M. Barsuglia,[4] E. Chassande-Mottin,[4] J.-P. Montagner,[5] S. N. Somala[3] and B. F. Whiting[4,6]

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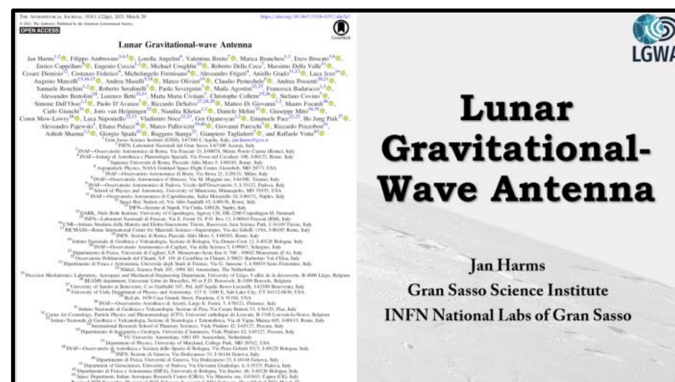
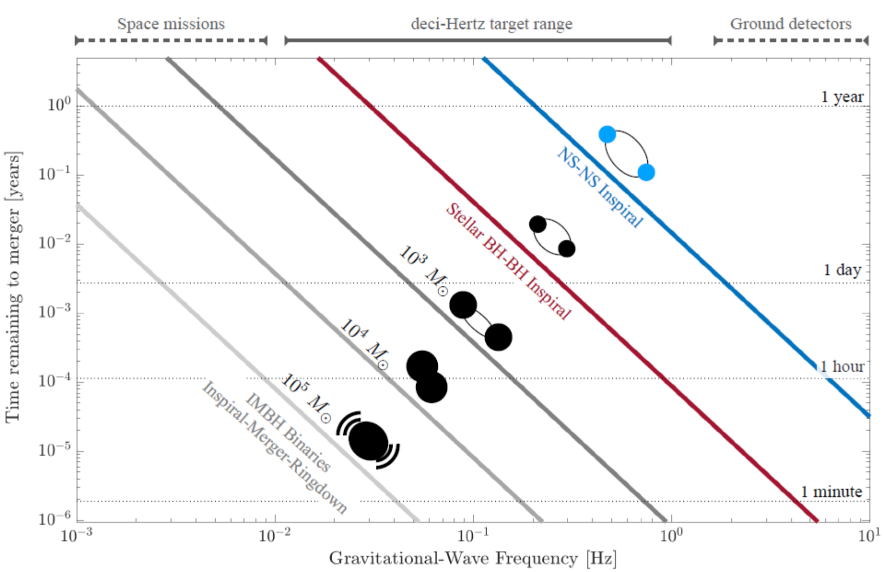
From Harms's slide in GWADW

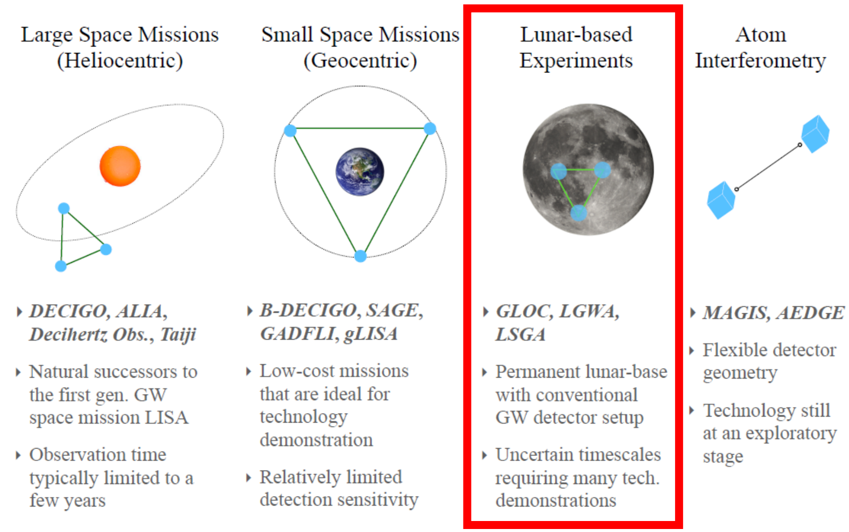


# Low freq. GW detectors on the Moon

- Binary mergers with massive and intermediate-mass black holes would undergo within in 1 mHz – 10 Hz

- GW detector on the Moon is one of the candidates



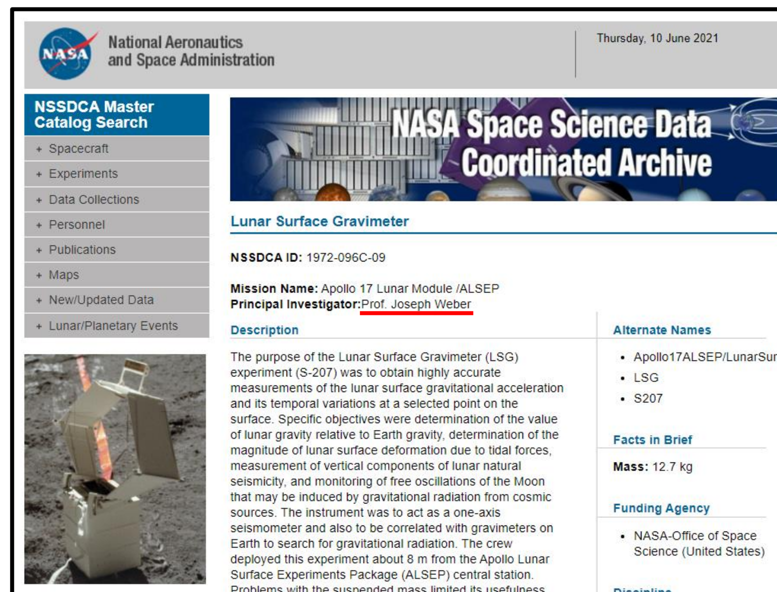

K. Izumi & K. Jani, arXiv:2105.06069 (2021)

# LGWA:
## Lunar Gravitational-Wave Antenna

# Moon as Weber bar

- Weber's idea: monitor vibrational eigenmodes
  of an elastic body excited by GWs
- He developed the first resonant bar detector
  at a laboratory in 1960s (range: kHz)
- He also pointed out that we can detect GWs in mHz band
  by monitoring vibrations of the Earth or Moon
- His Lunar Surface Gravimeter experiment by Apollo 17
  had a technical failure

sciencemag.org



National Aeronautics
and Space Administration

Thursday, 10 June 2021

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NASA Space Science Data Coordinated Archive

Lunar Surface Gravimeter

**NSSDCA ID:** 1972-096C-09

**Mission Name:** Apollo 17 Lunar Module /ALSEP
**Principal Investigator:** Prof. Joseph Weber

**Description**

The purpose of the Lunar Surface Gravimeter (LSG) experiment (S-207) was to obtain highly accurate measurements of the lunar surface gravitational acceleration and its temporal variations at a selected point on the surface. Specific objectives were determination of the value of lunar gravity relative to Earth gravity, determination of the magnitude of lunar surface deformation due to tidal forces, measurement of vertical components of lunar natural seismicity, and monitoring of free oscillations of the Moon that may be induced by gravitational radiation from cosmic sources. The instrument was to act as a one-axis seismometer and also to be correlated with gravimeters on Earth to search for gravitational radiation. The crew deployed this experiment about 8 m from the Apollo Lunar Surface Experiments Package (ALSEP) central station. Problems with the suspended mass limited its usefulness.

**Alternate Names**

- Apollo17ALSEP/LunarSurfa
- LSG
- S207

**Facts in Brief**

**Mass:** 12.7 kg

**Funding Agency**

- NASA-Office of Space Science (United States)

**Discipline**

Lunar Surface Gravimeter

# Evaluation of GW detectors

- It is useful to divide the detector into a response body and a readout system in order to assess the quality of GW detectors

**GW detectors**

**Response body**
: affected by a passing GW

e.g.) a laser beam, suspended test masses, an elastic body

→ How strongly does the body respond to GWs?

**Readout system**
: translate the GW signal into a human-readable form

e.g.) photo detectors, seismometers

→ How sensitive is the readout system to changes in the response body?

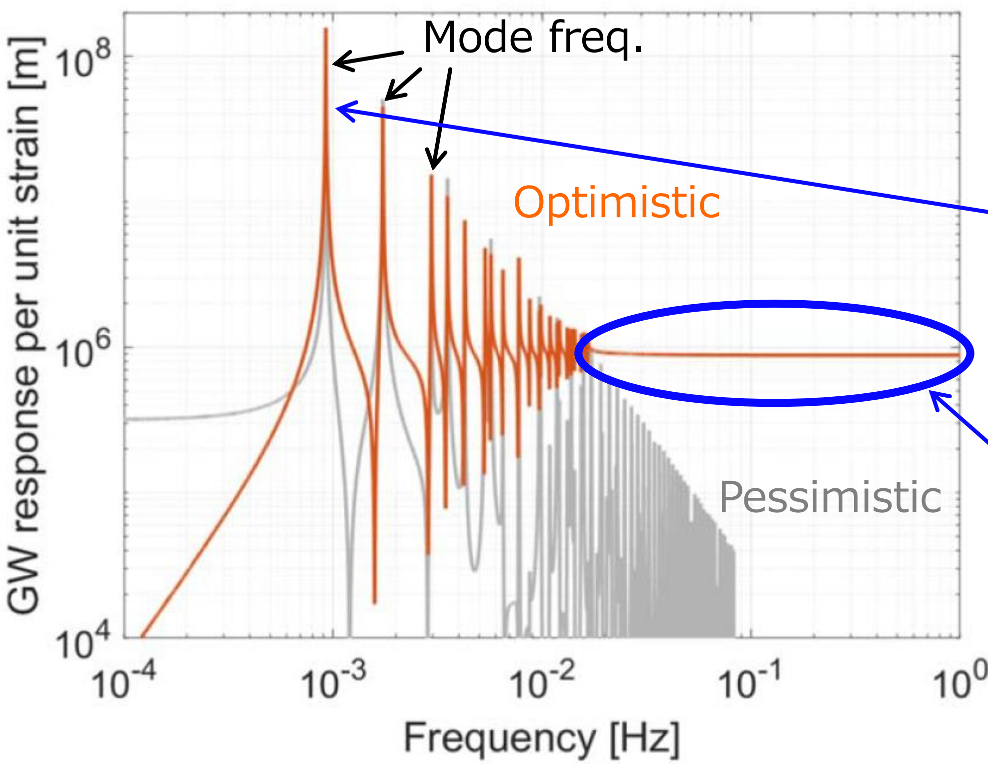
# Response of the Moon

GW strain amplitude — Effective baseline

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

Seismometer displacement signal — Mode freq. — Quality factor

Note:
- $\xi$ is not the surface displacement, but the difference of surface displacement and direct seismometer test mass displacement
- $L_n, f_n, Q_n$ depend strongly on the internal structure of the Moon

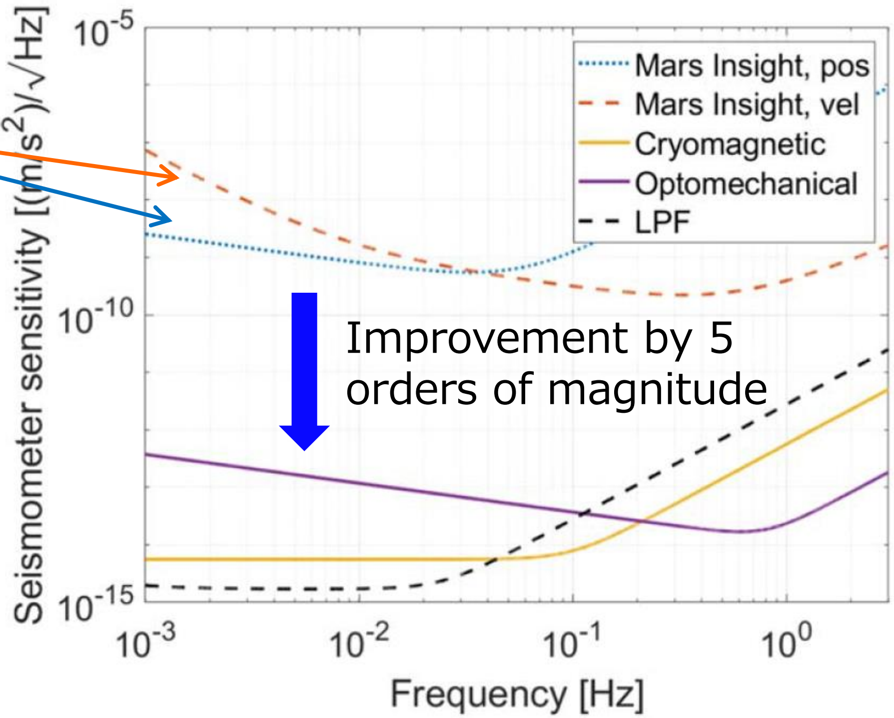



$\xi = 10^{-13}$ m
when $h = 10^{-21}, L_n = 10^6$ m$, Q_n = 200$
(Similar to LISA with $L = 10^9$ m)

The Moon becomes softer to tidal forces with increasing freq.
→ The differential motion of the Moon reduces at high freq.

# Seismometers

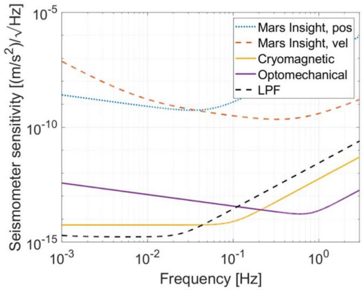
SEIS experiment of the Mars Insight mission: the best seismic sensor outside the Earth




- Atmospheric disturbances and thermal noise can be reduced by 10 times on the Moon
- Do not need to monitor vertical displacement
  → The stiffness of the mass suspensions can be reduced, leading to lower suspension resonance frequency
- Change capacitive readout to optomechanical or cryomagnetic readout

# Sensitivity

Readout noise

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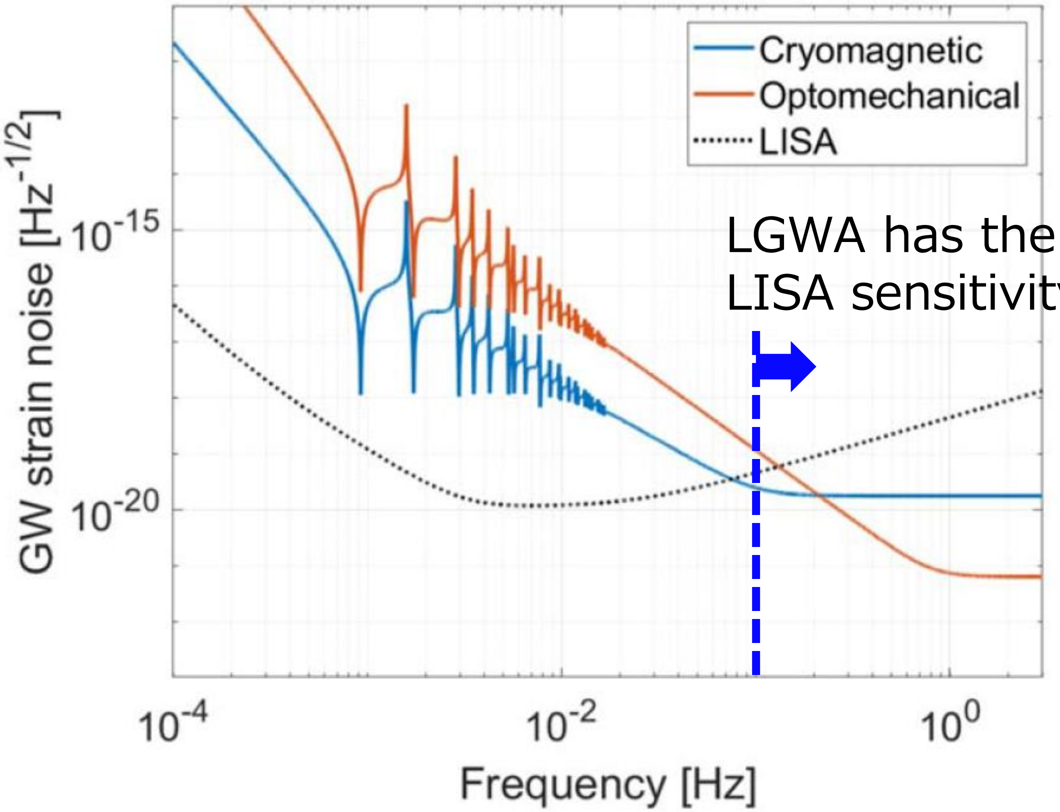
Response to GWs

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

=

LGWA noise spectral density



# Characteristics of the Moon

Merits:

- Very large
- Lacks an atmosphere, natural vacuum chambers
- Much lower seismic activity than on the Earth (later)
- Natural cryostats (later)

Difficulties:

- Dust called regolith
- The closet object to the Earth, but need to launch detectors (later)

# Small seismic vibration

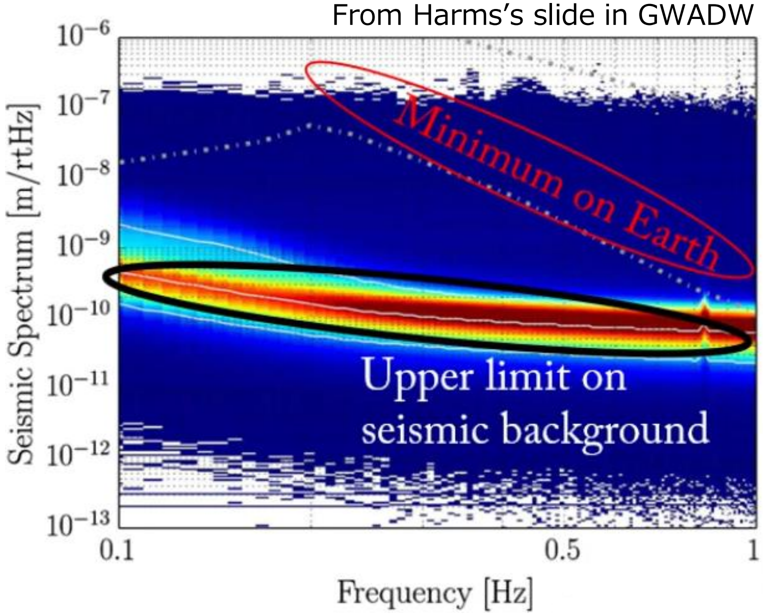
Four natural seismic events on the Moon

- Deep moonquakes produced by tides
- Shallow moonquakes
- Thermal quakes
- Meteoroid impact (dominant)

12,500 such events in 9 years

Seismic energy is smaller than on the Earth by $10^{-4}$ – $10^{-8}$

From Harms's slide in GWADW



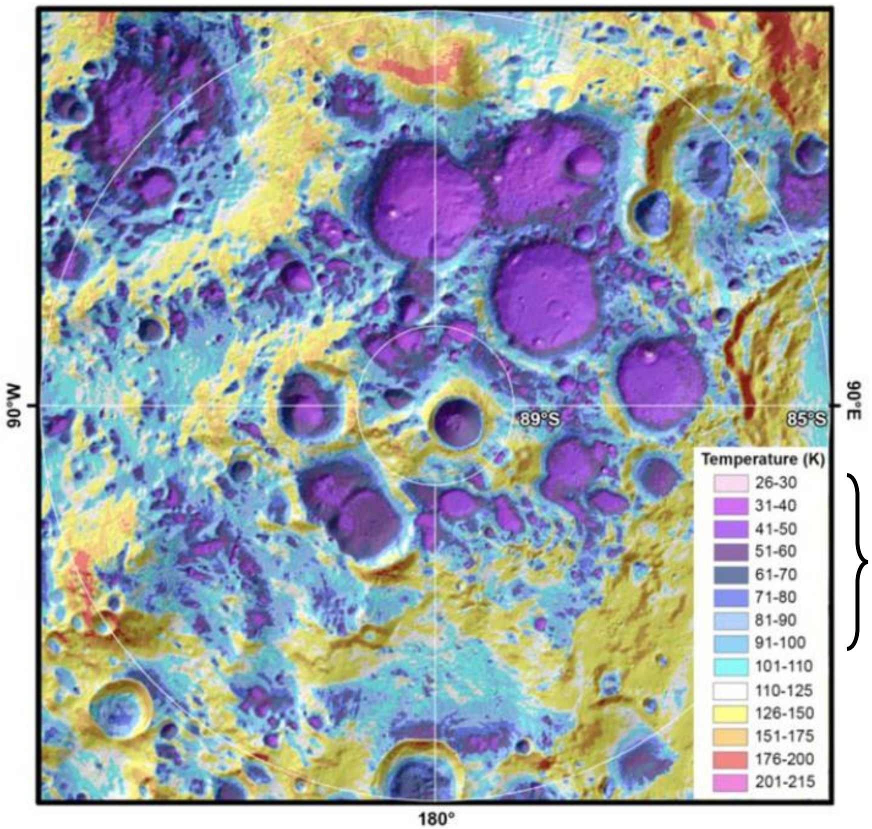

Constant seismic noise on the Moon is three orders of magnitude lower than on the Earth

# Natural cryostats

- Permanently shadowed regions at the south pole of the Moon

  → Can be used as natural cryostats for seismometers

Average surface temperatures
at the lunar south pole




Below 100 K

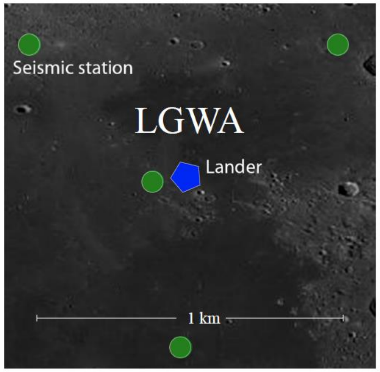
Note:
- 400 K during lunar days
- -50 ℃ at south pole on the Earth

# Proposed NASA missions

- Artemis program: to land humans to the Moon, specifically the lunar south pole region in 2024
- Lunar Geophysical Network: to deploy a global network of instruments on the Moon to understand the internal structure
- Commercial Lunar Payload Services: allows rapid lunar delivery services from American companies

# Phase 1 & 2

- Plans of LGWA are divided into phase 1 and 2





Phase 1:

- Four seismometers to form a kilometer-scale array
- To identify seismic events and subtract them from the data (similar technique to Newtonian-noise cancellation)

Phase 2:

- Additional seismometers on the opposite side of the Moon
- Seismic correlations would be minimal and GW correlations would be maximal between phase 1 and 2 seismometers

→ To observe stochastic GW backgrounds

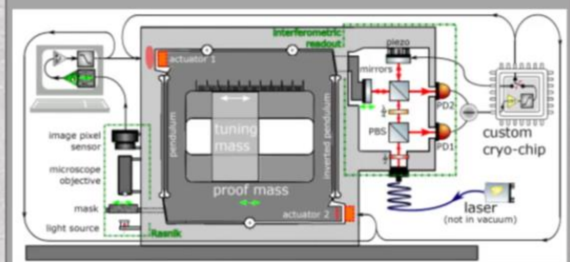
# Recent development

From Harms's slide in GWADW

## Test Facility at LNGS

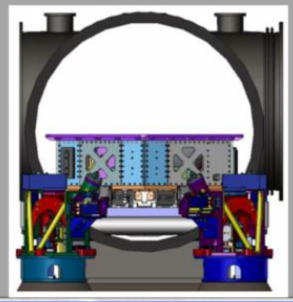
LGWA

**LGWA seismometer**
- Similar to cryo-concept by J van Heijningen




**Seismic platform**
- Test LGWA seismometer on Earth
- Mechanics similar to LIGO HAM ISI

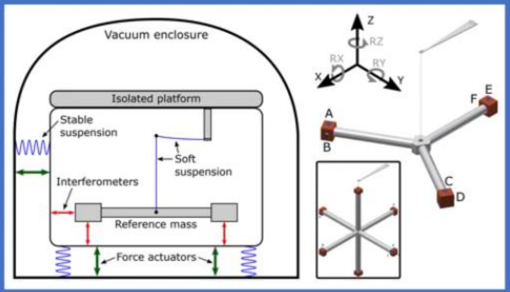
**Vacuum chamber**



**Inertial reference**

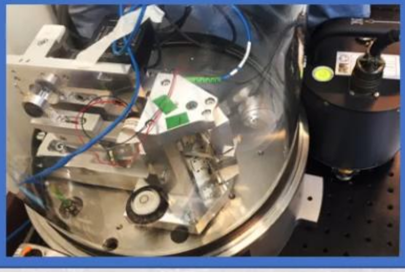
**Inertial reference system for seismic platform**

Option (A): 6D inertial reference concept by C Mow-Lowry

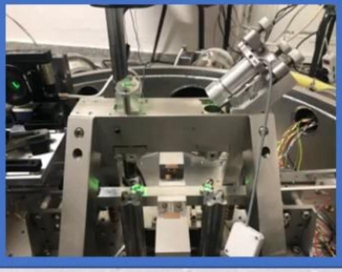



Option (B): Suite of 1D inertial references

Seismometers, e.g., concept by C Collette



Tiltmeters, e.g., concept by E Calloni



May 17, 2021 GWADW 2021; J Harms 6

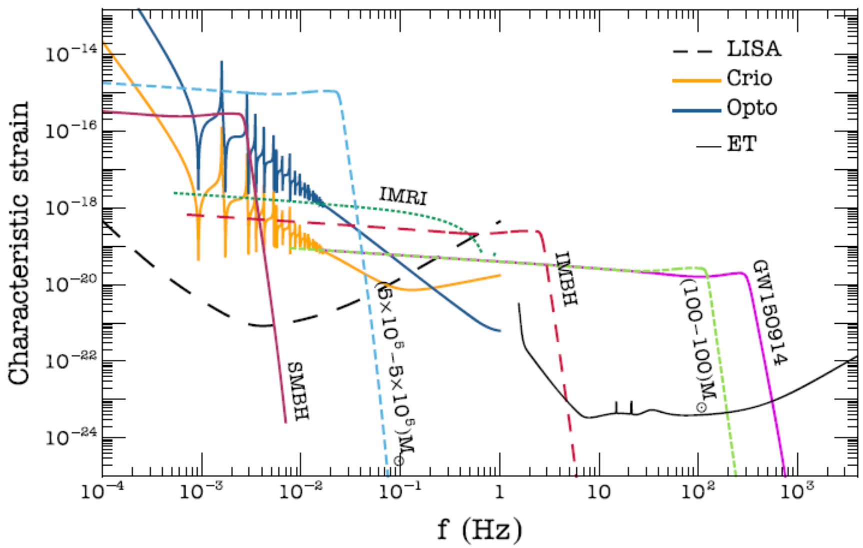
# Science goals

- Massive black holes (later)
- Galactic binaries (later)
- Lunar geophysics (later)
- Test of general relativity

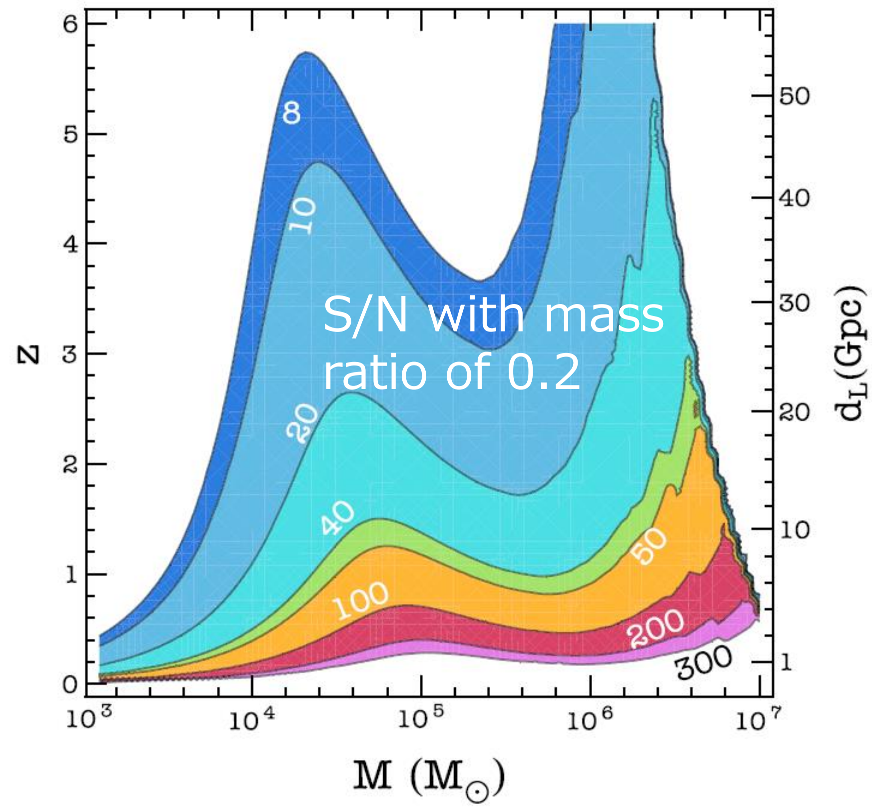
Note: a unique temporal evolution of its antenna pattern due to the Moon's rotation with a period of 27.3 days

# Massive black holes

Reference inspiral spectra




Detection range

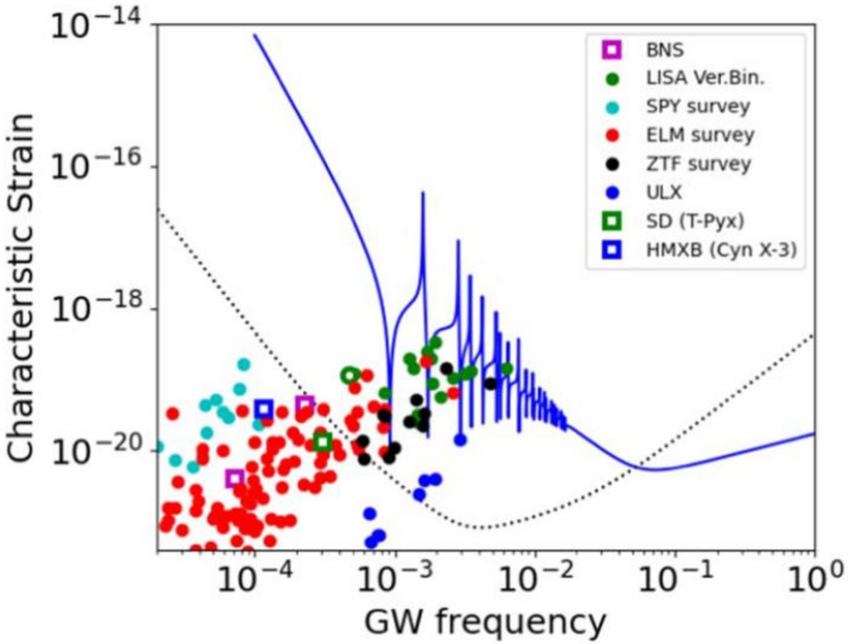



Total source-frame mass

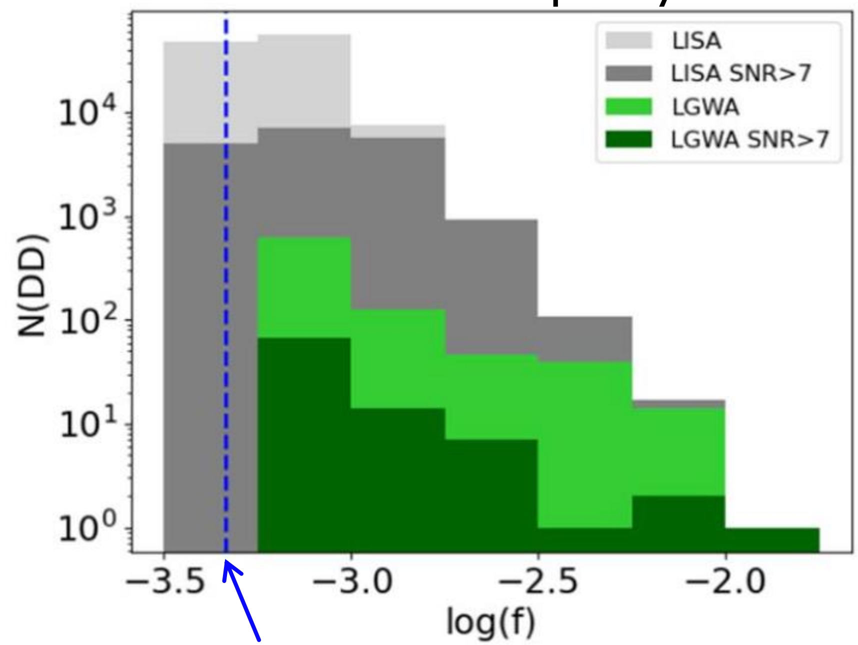
- Massive black hole binary mergers can be detectable
- Multi-messenger observation is possible if binary massive black holes interact with accretion disks

# Galactic binaries

Estimated GW amplitude from known short-period binaries in the Galaxy




Predicted detection number of double white dwarfs per year



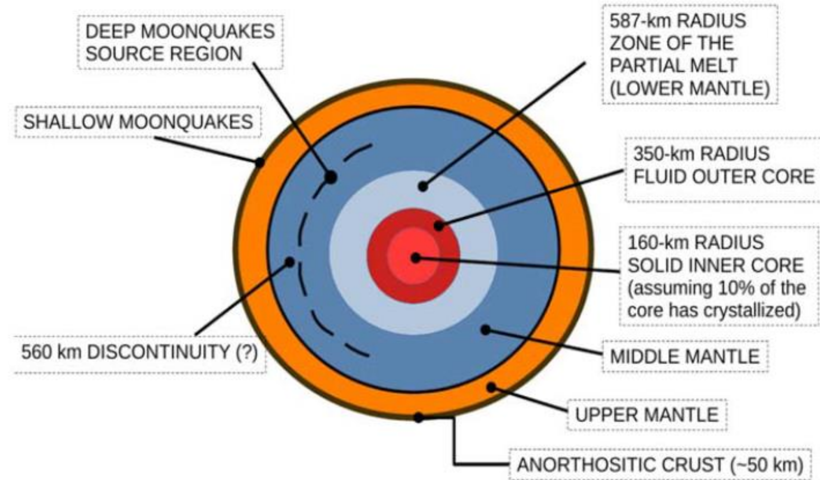

Expected maximum GW freq.

- Probability of coincident detection with SN Ia is low
- But it would be useful for SN Ia progenitor identification

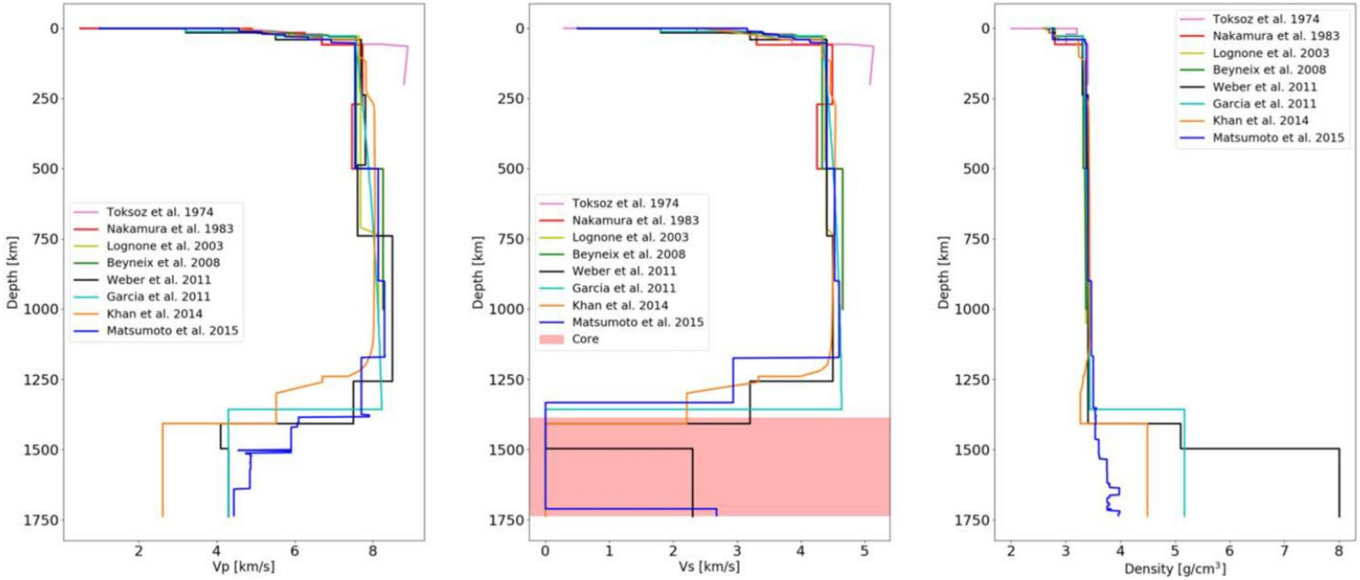
# Lunar geophysics

Targets:

- Seismic background from meteoroid impact
- Origin of thermal moonquakes
- Moon's internal structure →




Comparison of several seismic velocity models



# GLOC:

## Gravitational-wave Lunar Observatory for Cosmology

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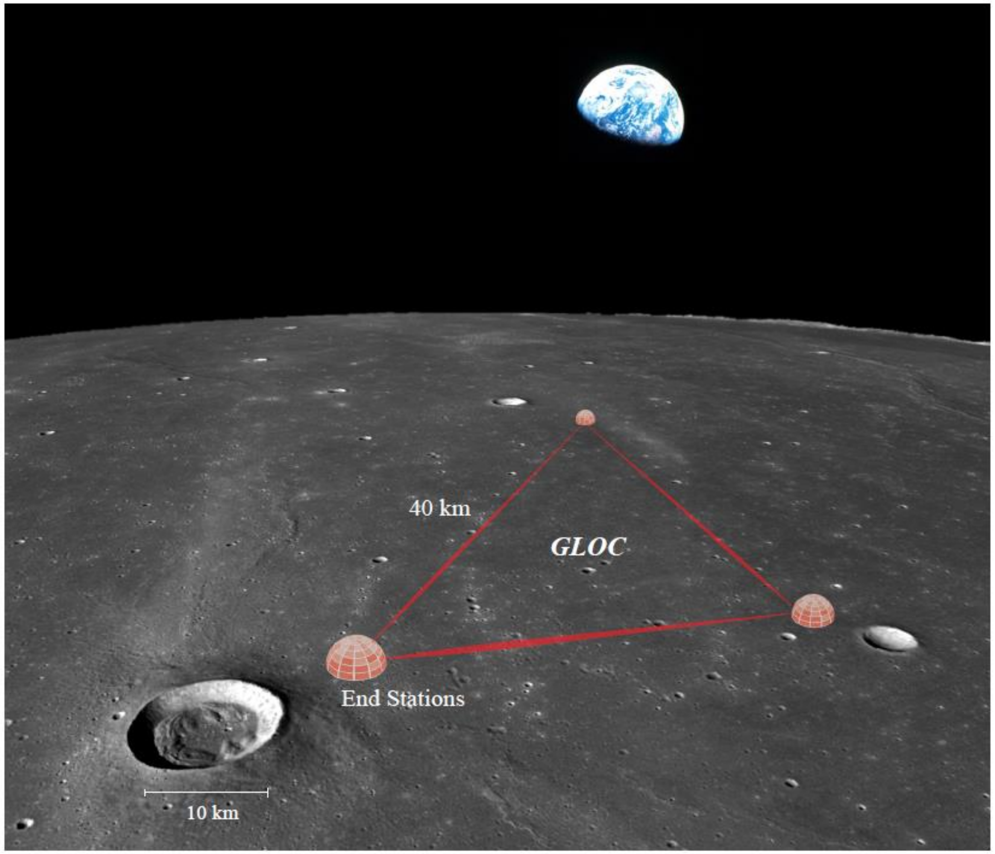
# LION:

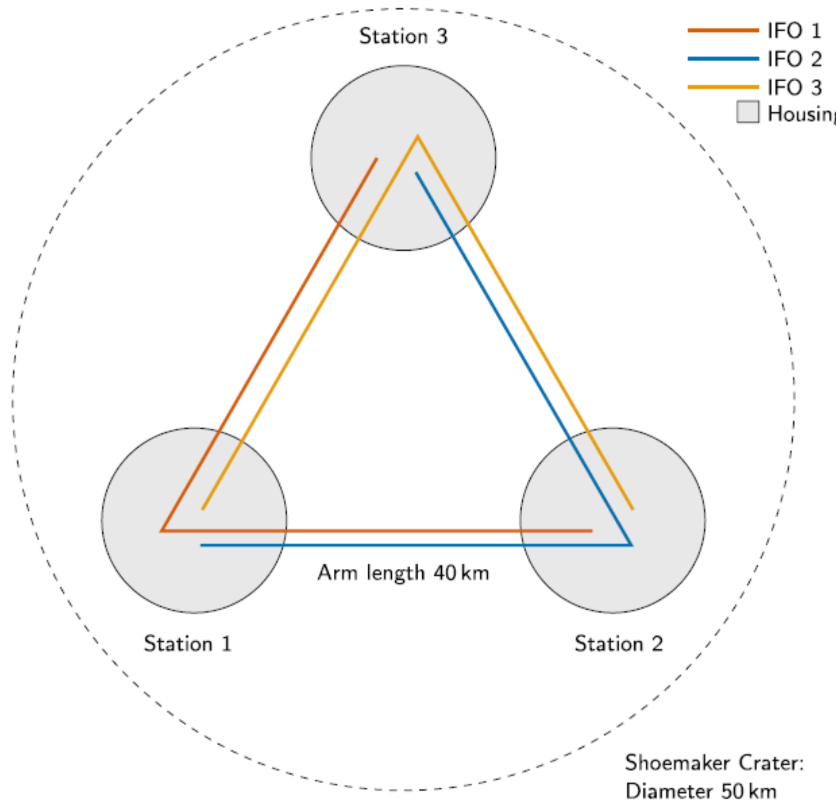
## Laser Interferometer On the mooN

# Triangle interferometer

GLOC LION

- Both detectors consist of a triangular interferometer with arm length of 40 km



# LION: parameters

LION

- The author of LION made a table about interferometer parameters

How is the mirror delivered to the Moon?

| Parameter | Value |
|---|---|
| Laser power | 50 W |
| Wavelength | 2000 nm |
| Arm length | 40 km |
| Seismic | Earth surface/1000 |
| Test mass | 1267/1267/698/707 kg |
| ITM radius of curvature | 34 km |
| ETM radius of curvature | 36 km |
| Suspension length | 3.54/2.05/1.66/2.50 m |
| Temperature | 70 K |
| Signal recycling cavity length | 55 m |
| **Squeezing** | |
| Initial squeezing level | 15 dB |
| Filter cavity length | 8.94 km |
| Filter cavity detuning | −2.3 Hz |
| **Mirror transmittance** | |
| End test mass | 5 ppm |
| Input test mass | 1.2% |
| Power recycling mirror | 3% |
| Signal recycling mirror | 2% |
| Filter cavity input mirror | 0.17% |
| Filter cavity end mirror | 5 ppm |

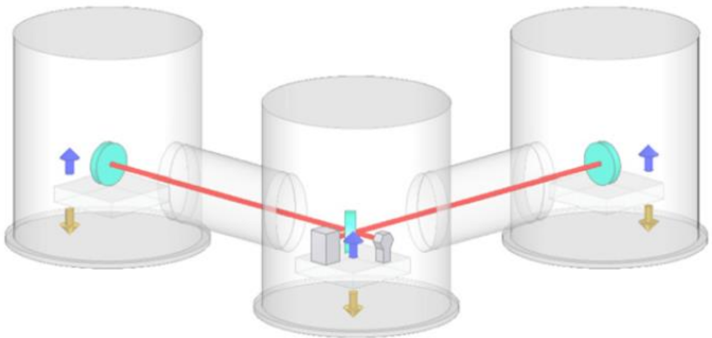
# Juggled interferometer

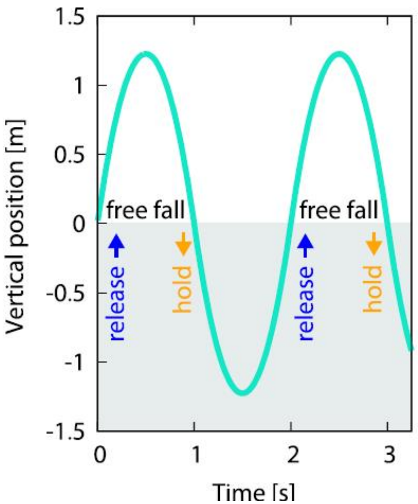
GLOC LION

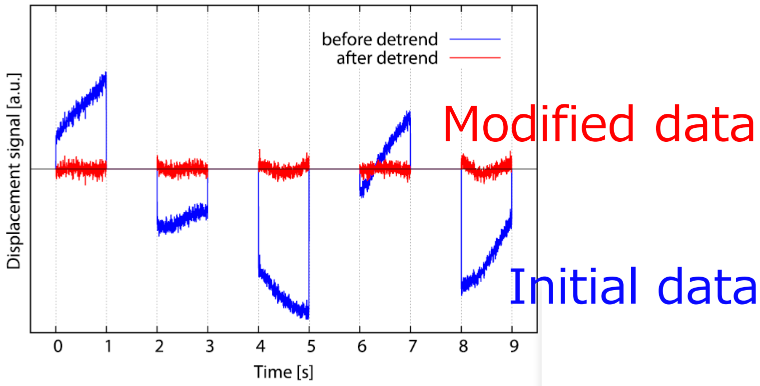
- Test masses can avoid seismic noise and suspension thermal noise by repeatedly free falling, “juggling”

D. Friedrich+, Class. Quantum Grav. 31, 245006 (2014)

→ Sensitivity would be limited by shot noise and Newtonian noise





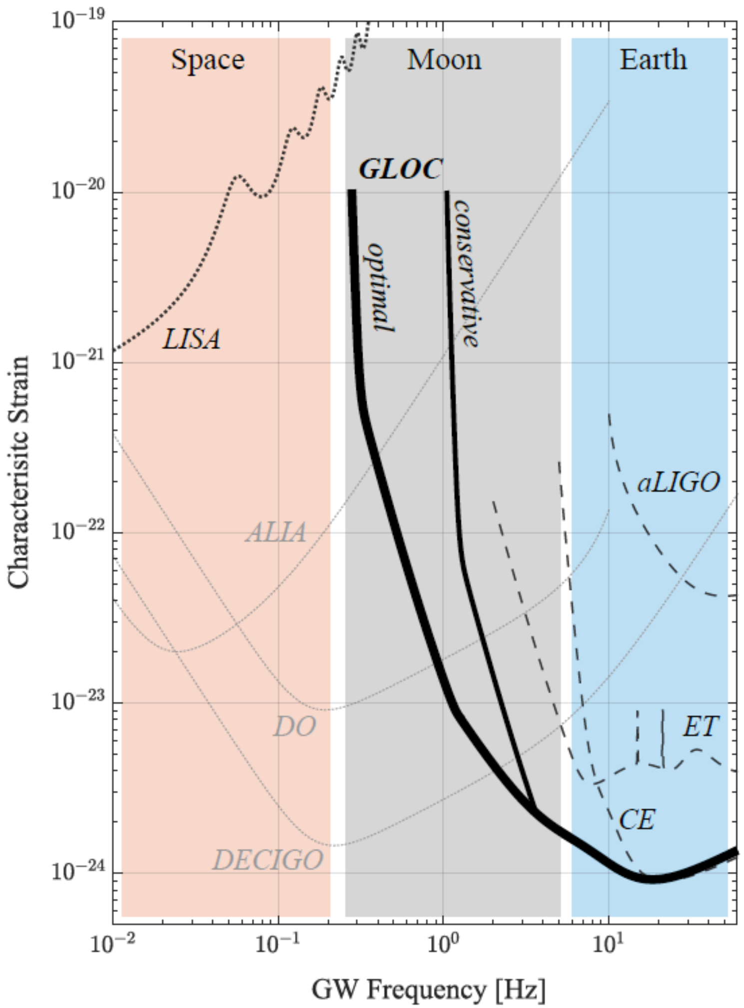

Future work:

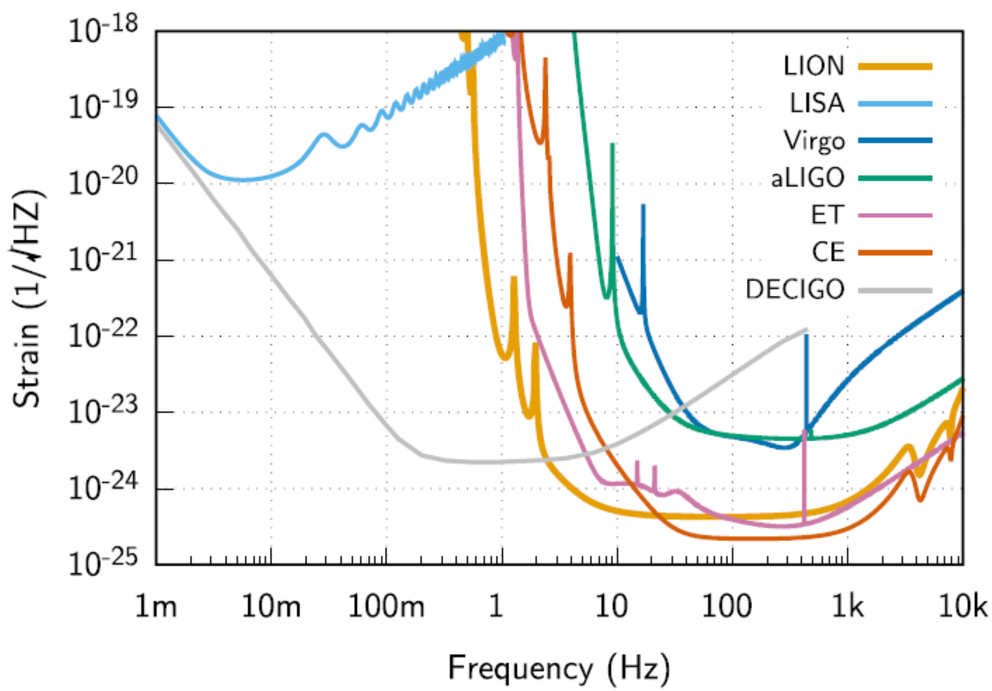
- To keep alignment of test masses
- To detect continuous signals in the initially discontinuous data

# Strain sensitivity

GLOC LION

- Both detectors have the sensitivity of $10^{-23}$ /√Hz at 1 Hz and $10^{-24}$ /√Hz at 10 Hz

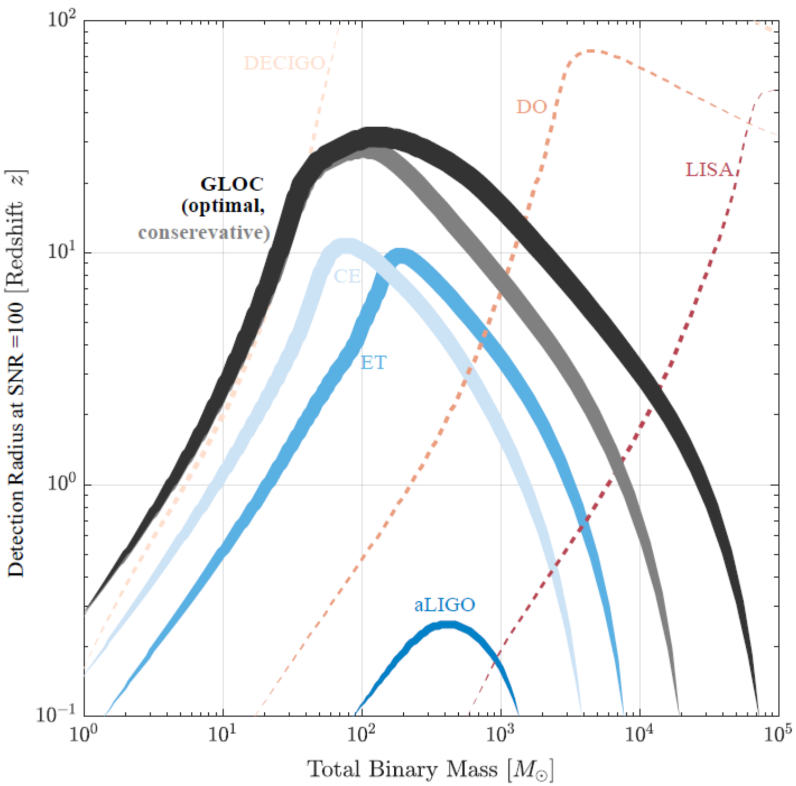


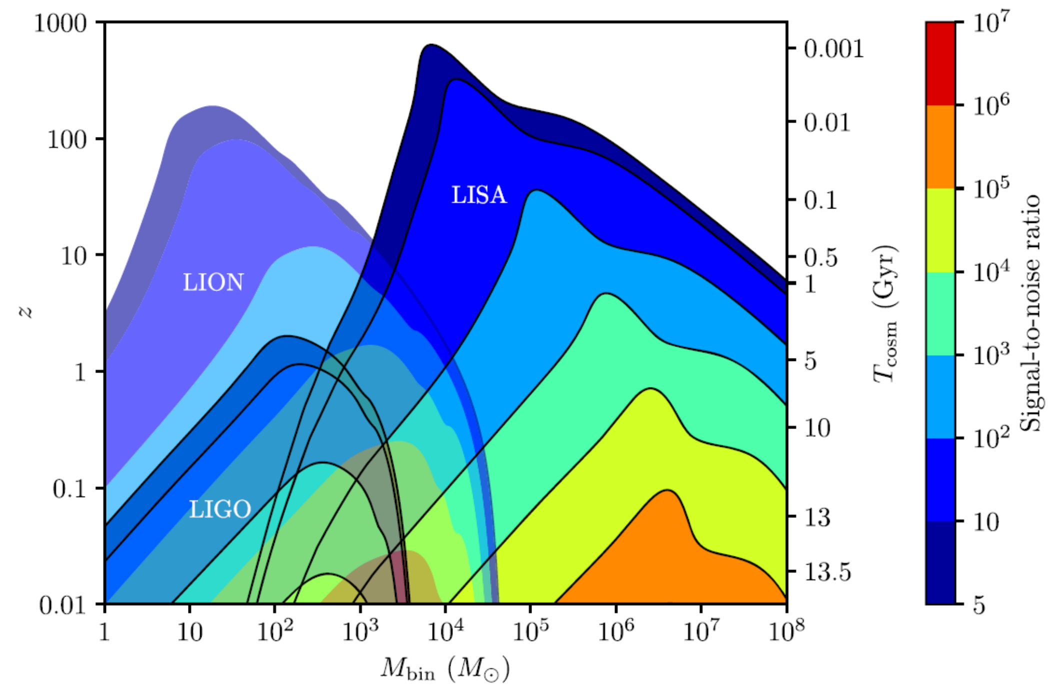



# Detection range

GLOC LION

- Both detectors have the detection range within red shift ~100

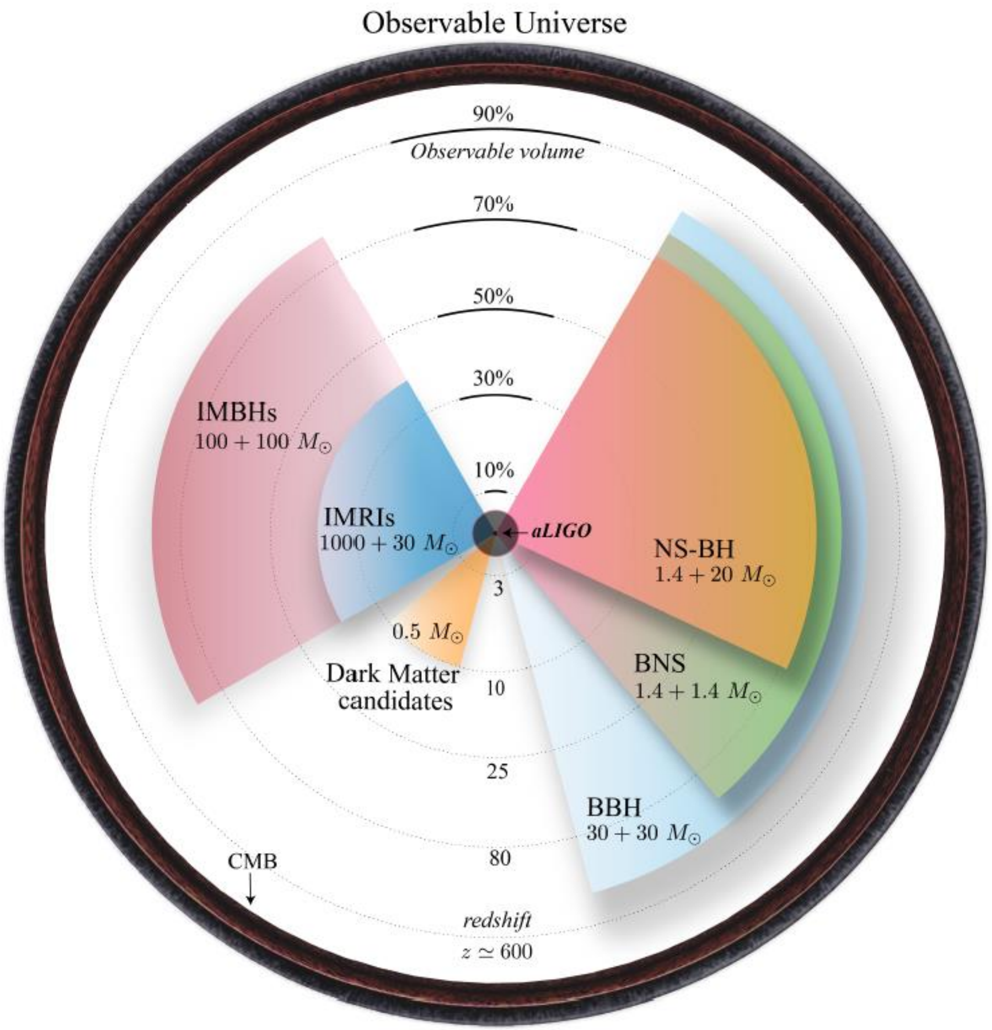


# GLOC: cosmological reach



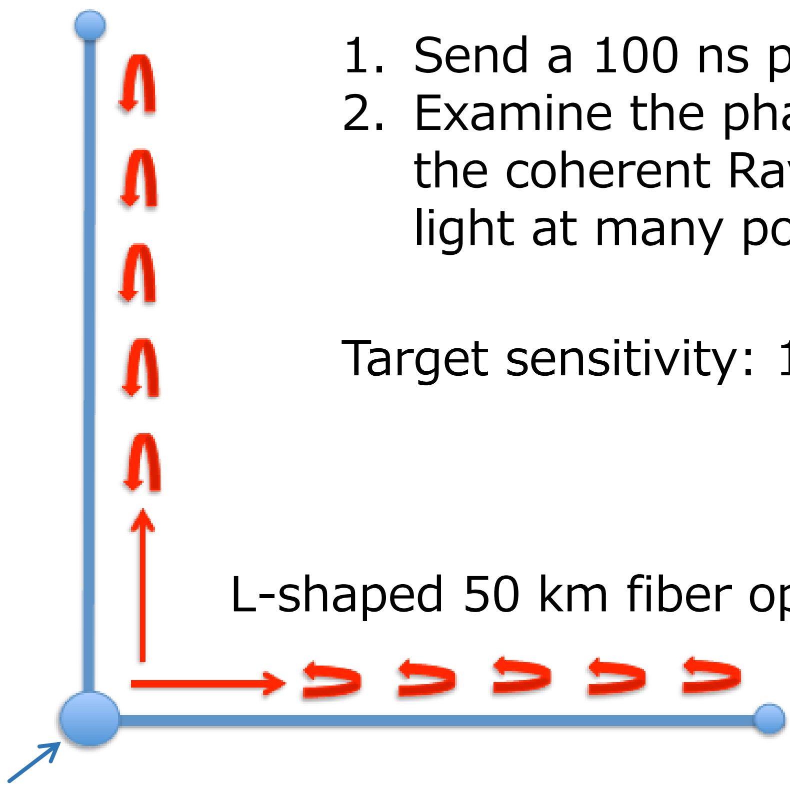
- GLOC can survey 70 % of the observable volume of our universe



# LSGA:
## Lunar Seismic and Gravitational Antenna

# Plan 1: Weber bar

- Use the Moon as Weber bar
- Measure the displacement with two 50 km long fiber optics cables



1. Send a 100 ns pulse laser with 2 kHz
2. Examine the phase and amplitude of the coherent Rayleigh backscattered light at many point of cables

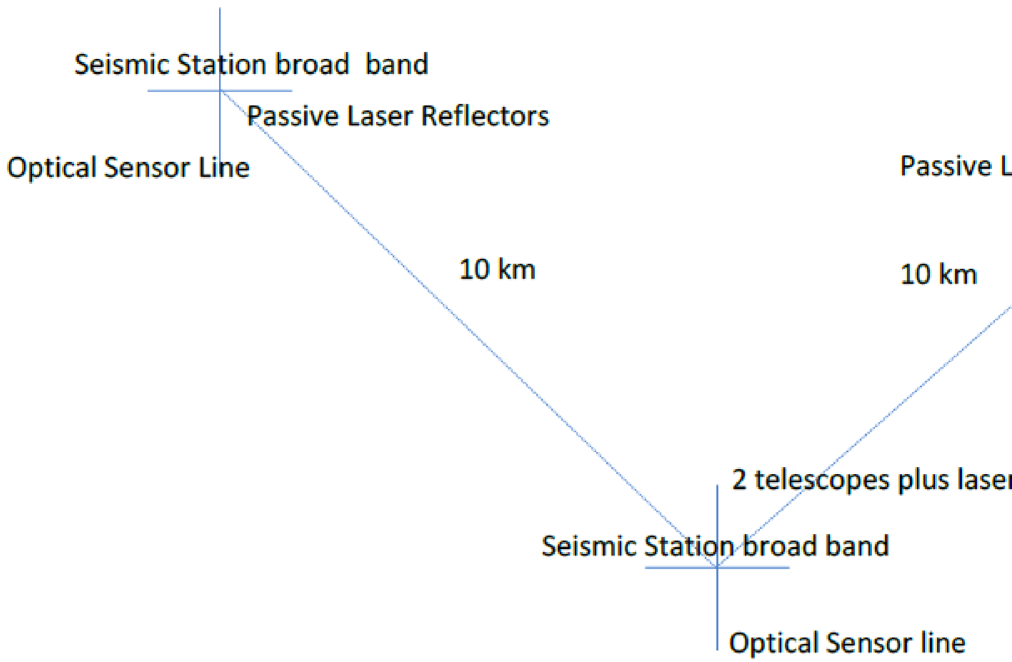
Target sensitivity: $10^{-20}$ /√Hz @1 Hz

L-shaped 50 km fiber optics cables

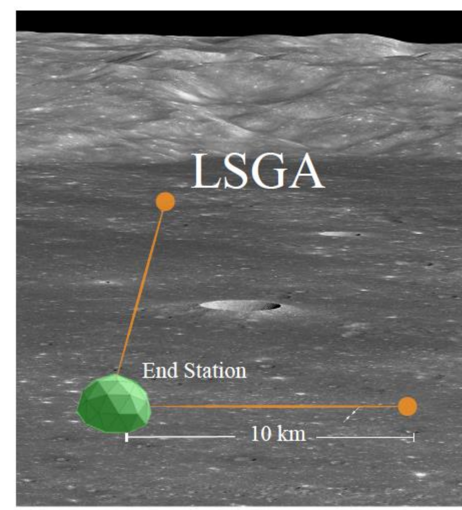
Central interrogator unit

# Plan 2: Michelson interferometer

- Michelson interferometer with 10 km arms
- The author pointed out natural cryostats and vacuum chambers as advantages and dust as a disadvantage




Laser: 1 μm, 10 W




Target sensitivity: $10^{-16}$ m/√Hz, $10^{-21}$ /√Hz

# Summary

- I introduce four proposals to detect GWs in 1 mHz – 10 Hz on the Moon
- They have interesting characteristics and sciences, but of course we have many items to be developed

| Detector's name | Principle | Sensitivity | My comments |
|---|---|---|---|
| LGWA:<br>Lunar Gravitational-Wave Antenna | Moon as Weber bar<br>and seismometers | $10^{-20}$ /√Hz<br>@1 Hz | Most feasible<br>and interesting |
| GLOC:<br>Gravitational-wave Lunar Observatory for Cosmology | Triangular interferometer | $10^{-24}$ /√Hz<br>@ 10 Hz | Almost the<br>same |
| LION:<br>Laser Interferometer<br>On the mooN | Triangular interferometer | $10^{-24}$ /√Hz<br>@ 10 Hz | |
| LSGA:<br>Lunar Seismic and<br>Gravitational Antenna | Moon as Weber bar<br>and fiber optics,<br>or Michelson interferometer | $10^{-20}$ /√Hz<br>@ 1 Hz | Plans are not<br>concrete yet |