Gravitational Wave Detector Technologies for the Moon

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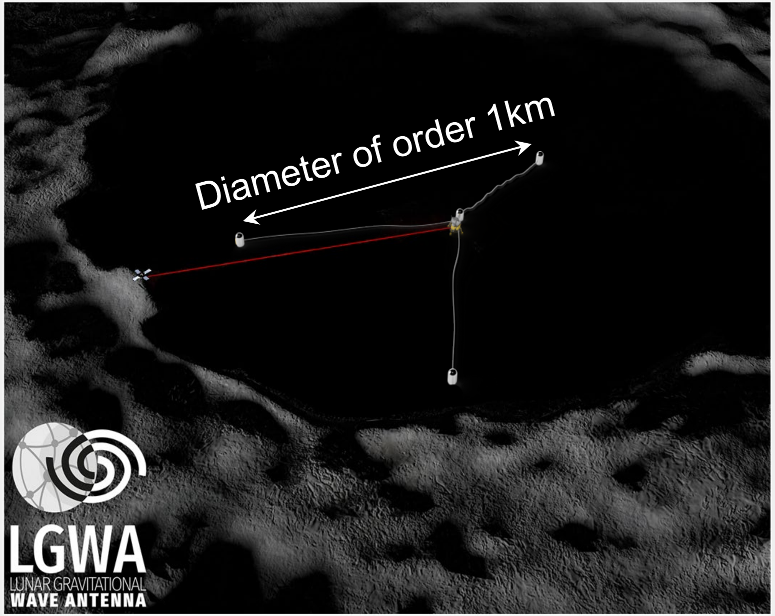
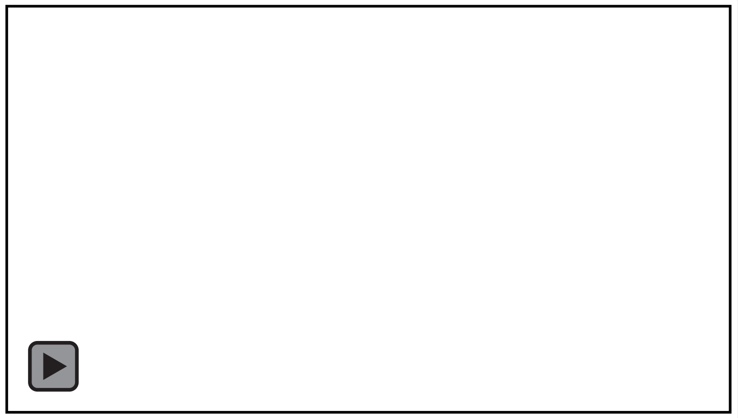
LGWA Mission Concept

LGWA is an evolution of the Lunar Surface Gravimeter deployed on the Moon with Apollo 17 in 1972

Deployment of sensor array inside a permanently shadowed region (PSR)



Measure oscillations of the Moon caused by GWs

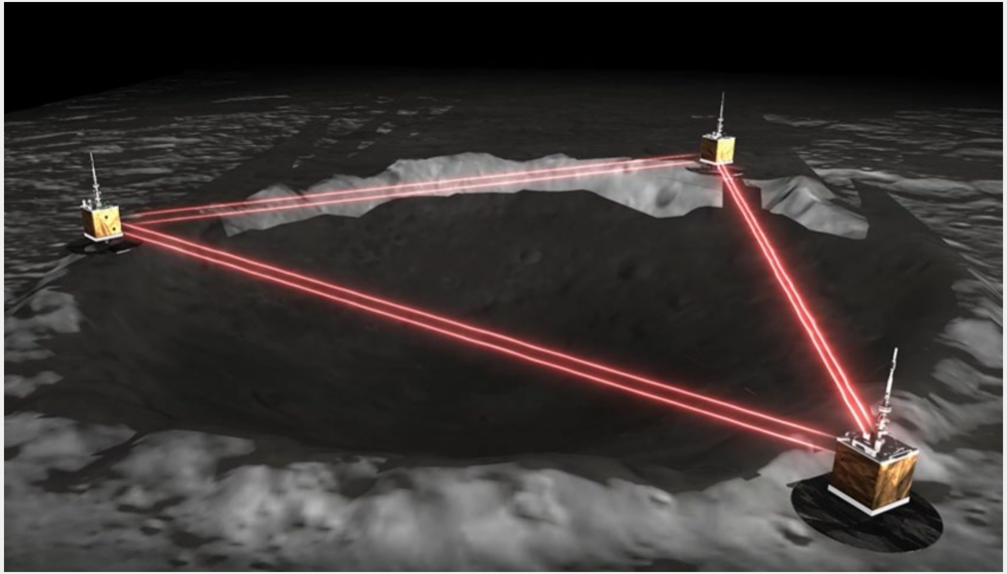


GSSI

Key LGWA Mission Features

- Femtometer precise ground-vibration measurement to observe the lunar response to gravitational waves (GWs)
- Exploiting the extremely low seismic background on the Moon
- Exploiting the extremely low temperature and high temperature stability inside permanently shadowed regions at the lunar poles
- Station array to mitigate the noise from the seismic background in post-processing
- **Longevity of stations (target: 10yr+) enables extension to global sensor array**

Laser Interferometer Lunar Antenna (LILA)



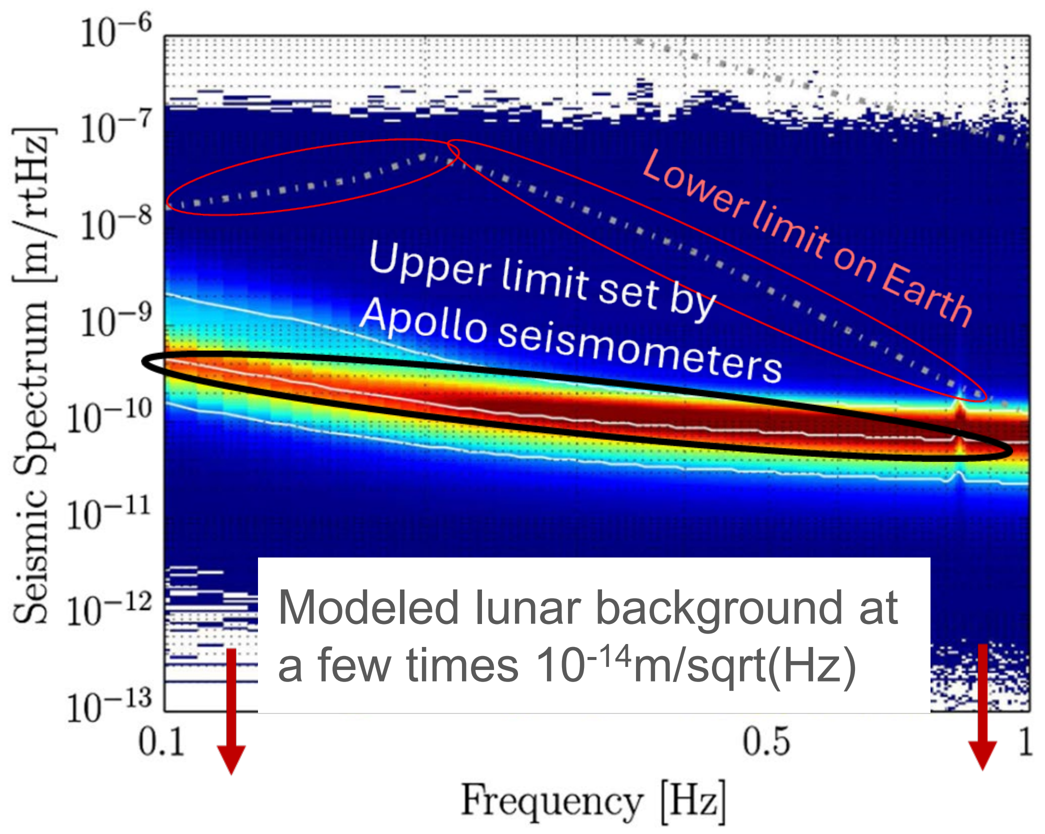
https://arxiv.org/abs/2508.11631

Key differences to LGWA:

- Long-baseline laser interferometry
- Peak sensitivity of LILA will not be in the dHz band (complementarity with LGWA); could however beat LGWA sensitivity at lower and higher frequencies

Can be realized with (high-f concept) and without (low-f concept) suspended optics.

Extremely Weak Seismic Background



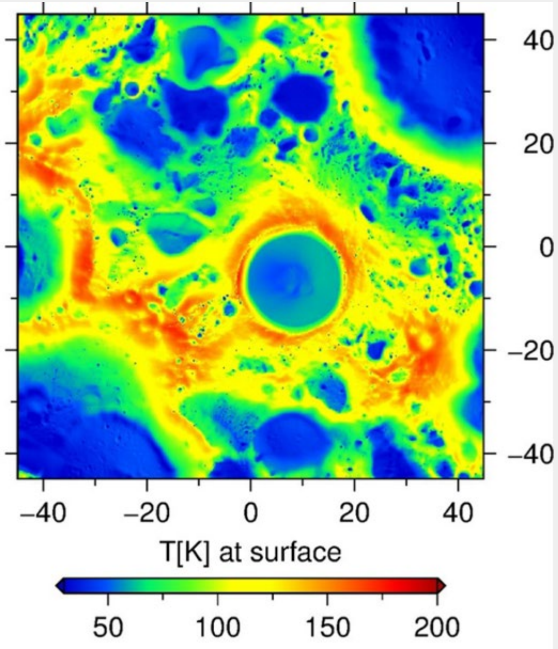
The Moon might be the seismically quietest planetary body in the solar system:

- Absence of atmosphere
- Relatively small temporal variations of tidal forces
- No active tectonics as far as we know

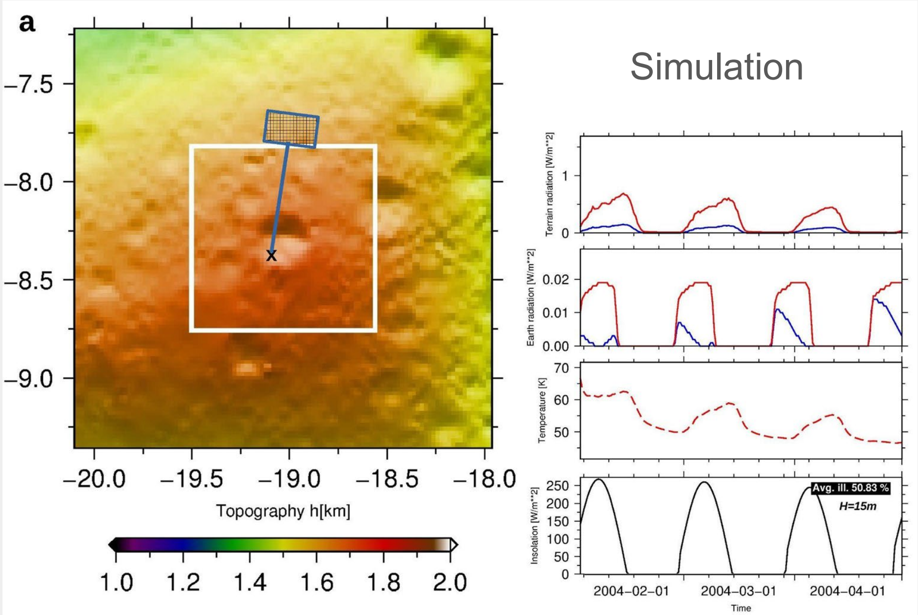
What causes the dominant background? Meteoroid impacts? Deep moonquakes? Future human activity?

High Temperature Stability and Uniformity

The surface temperature inside PSRs at the lunar poles is very low (can be continuously below 50K).



Even a small temperature fluctuations inside PSRs might cause an important thermal response of ground, lander, payload, leading to excess noise in the LGWA measurement.



	Soundcheck* (PSR geophysical explorer)	**LGWA** (GW observatory)
Number of seismic stations	1 seismic station (two horizontal channels) deployed on ground	4 seismic stations (each with two horizontal channels) deployed on ground and forming a kilometer-scale array
Displacement sensitivity	<1pm/Hz$^{1/2}$ between 0.1-1Hz	<1pm/Hz$^{1/2}$ at 0.1Hz, <fm/Hz$^{1/2}$ at 1Hz
Deployment site	Inside any PSR (<100K)	Inside PSR with T<40K
Proof-mass material	Niobium	Niobium or silicon
Proof-mass temperature	Ambient PSR temperature (<100K)	Cooled to 4K with low-vibration cryocooler
Readout	Laser interferometric	Laser interferometric or through superconducting coils and SQUIDs
Targeted mission lifetime	2 months	10 years

*selected by ESA into the lunar reserve pool; ASI funding starts in 2025

Science Case

GW Astronomy and Lunar Science

LGWA Science White Paper

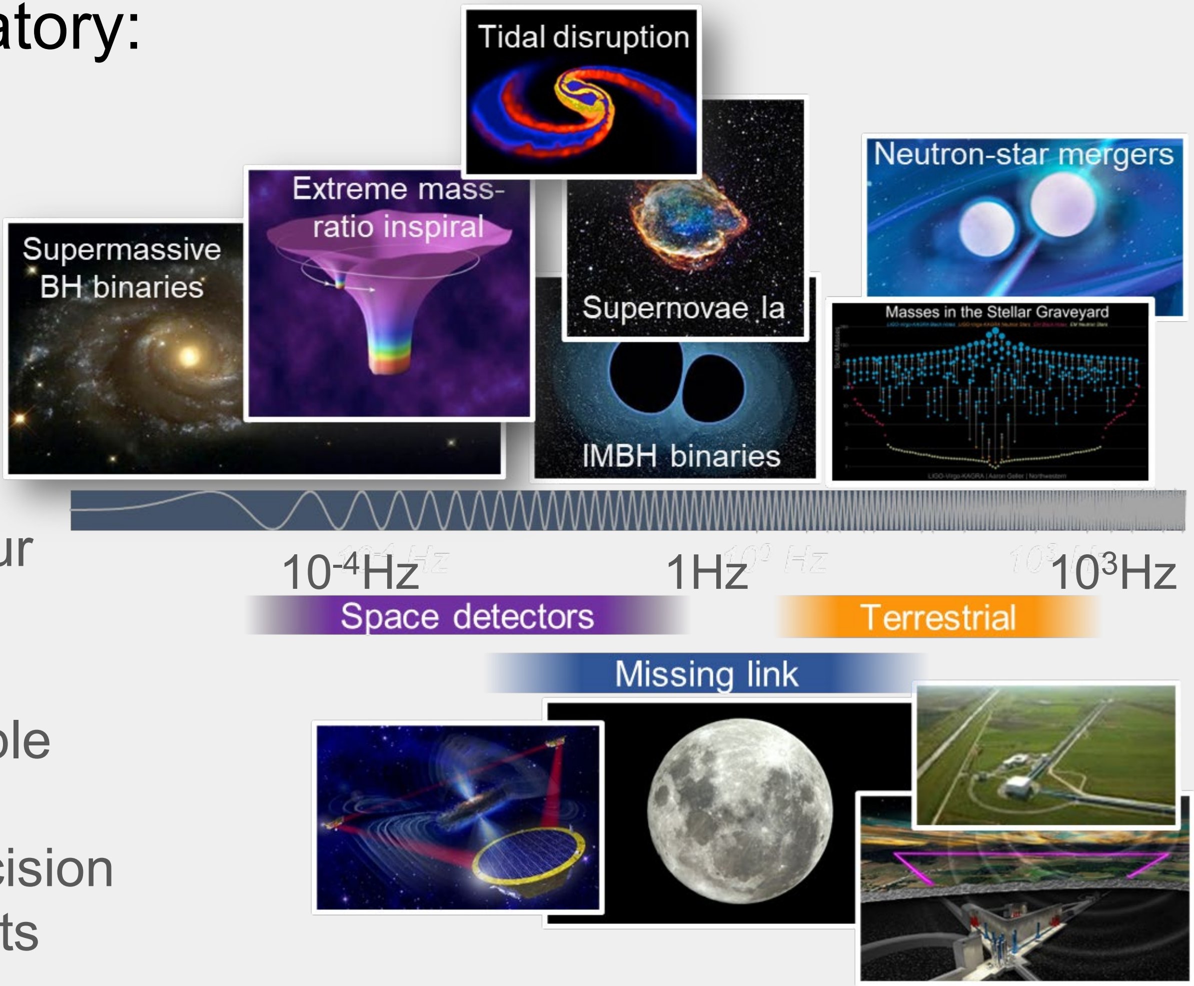
Decadal Survey on Planetary Science and Astrobiology

Decadal Survey on Biological and Physical Sciences Research in Space

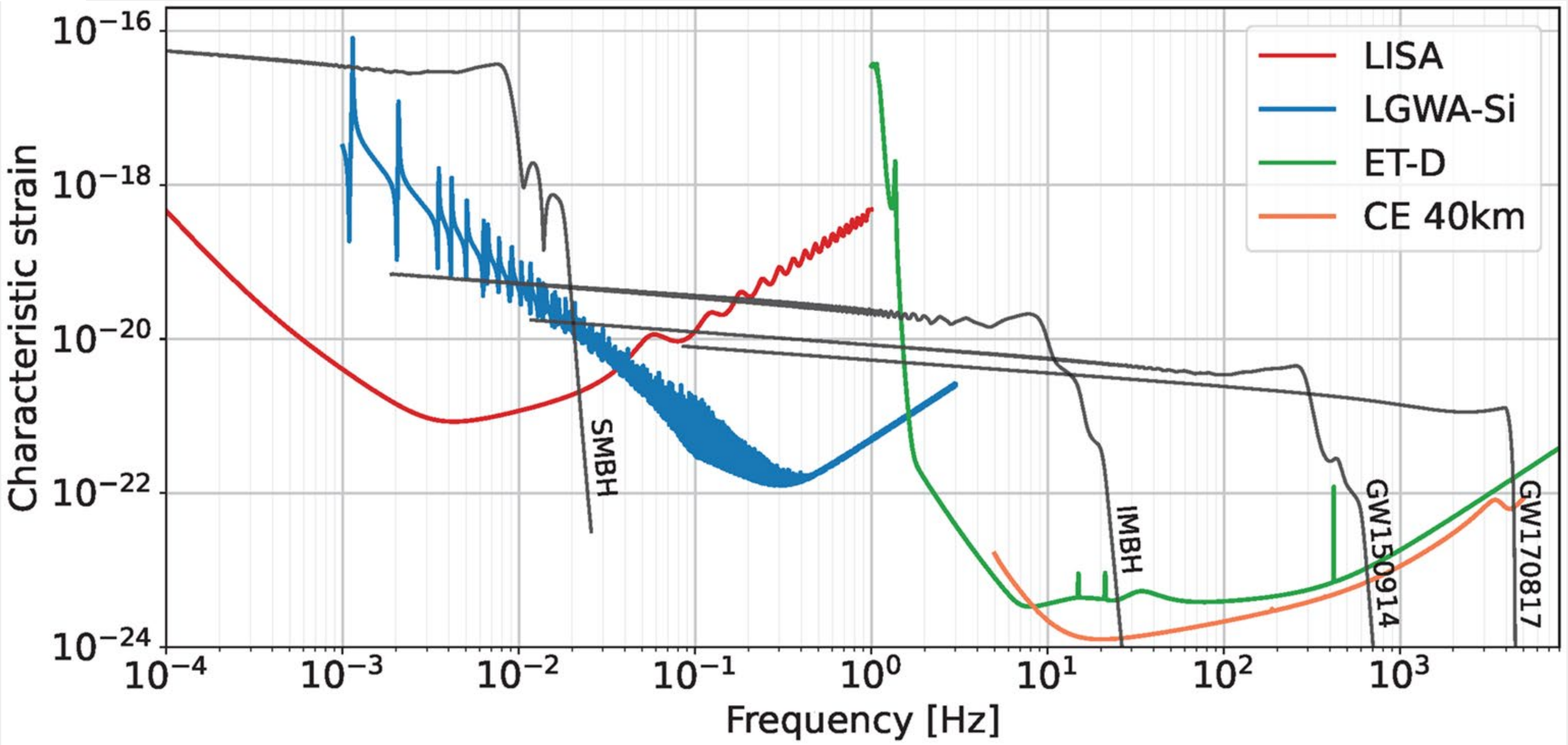
ESA SciSpacE White Papers

Decihertz Observatory: The Missing Link

- Astrophysical explosions and disruptions
- Black-hole populations and their role for the structure formation in our Universe
- Hubble constant measurement with double white dwarfs
- Enabling ultra-high precision waveform measurements

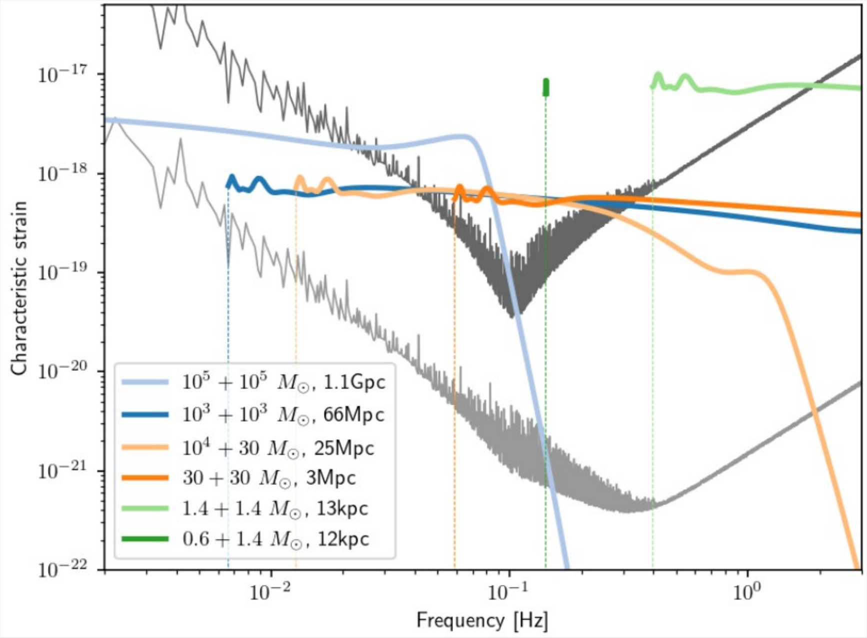


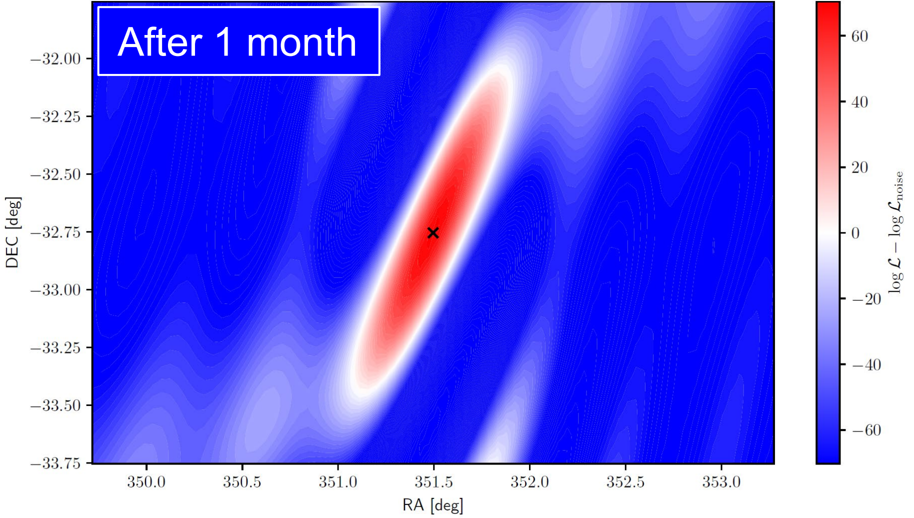
Multiband: One Source, Multiple Observation Bands

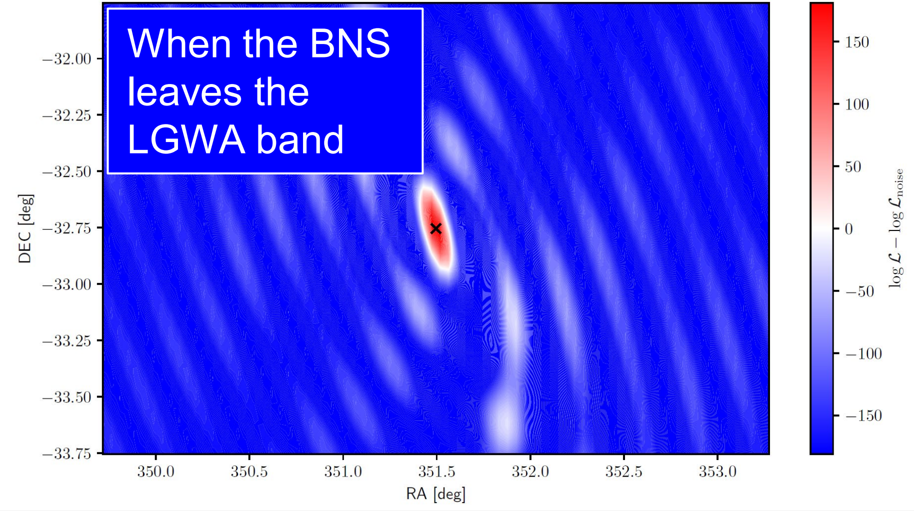


Sky Localization

Sub deg^2 sky-localization of binary neutron stars for merger early warning

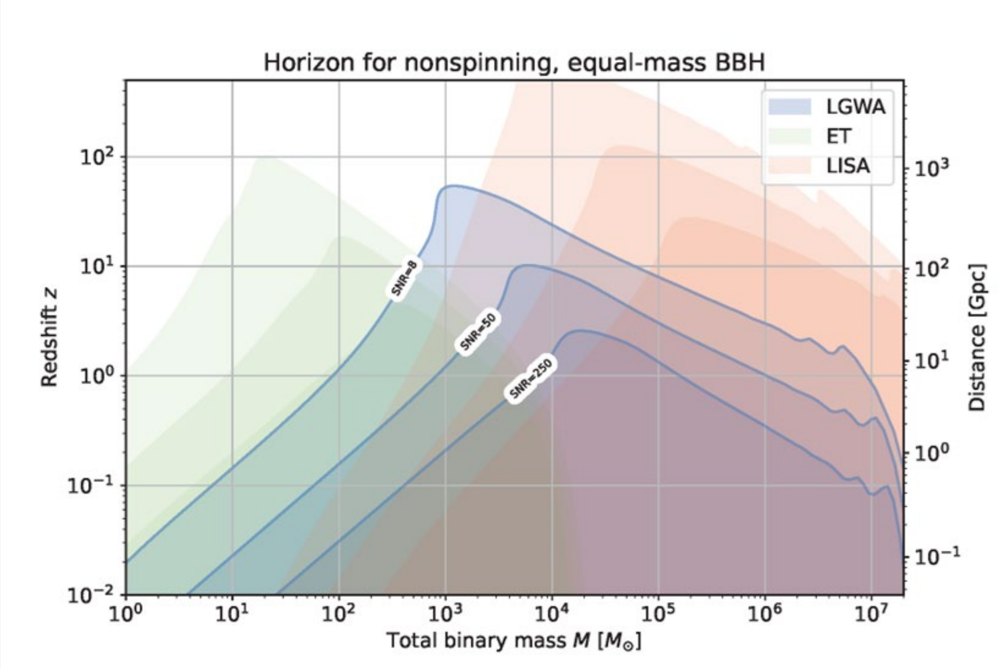


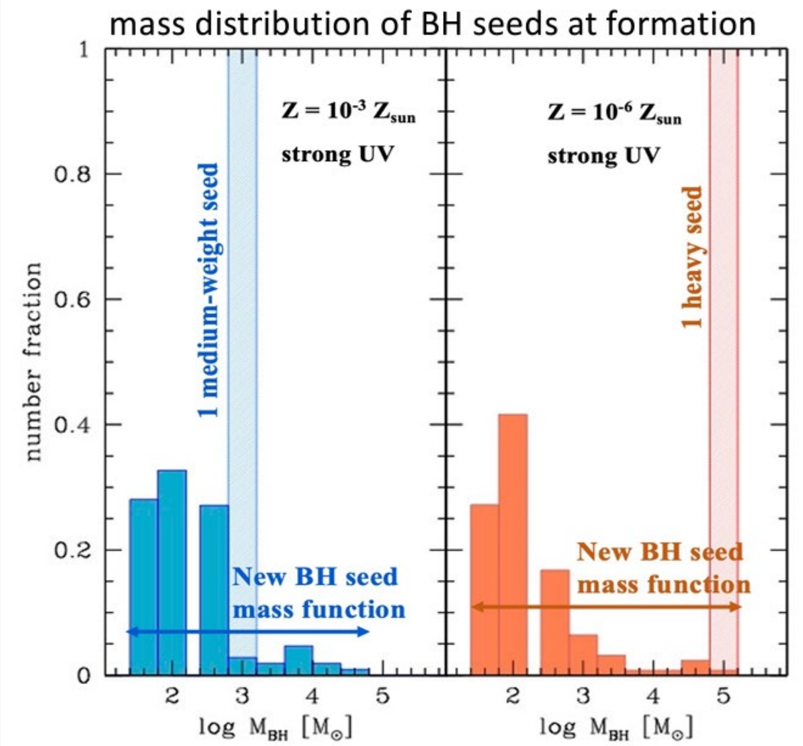




Exploring Black-hole Populations

Binary black holes (BBHs) can be observed out to high redshift complementing the mass ranges to be observed with LISA and Einstein Telescope.



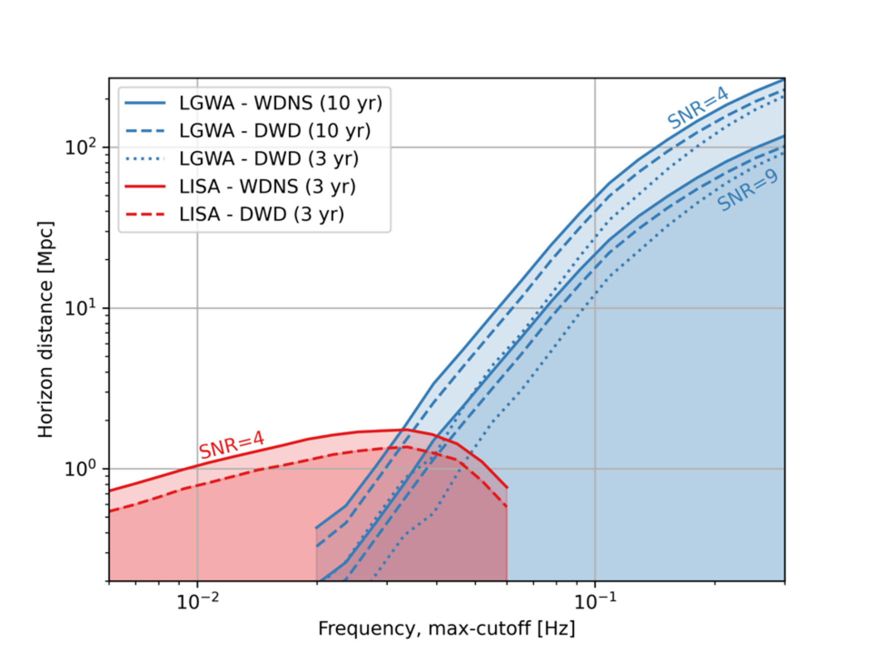


R Schneider

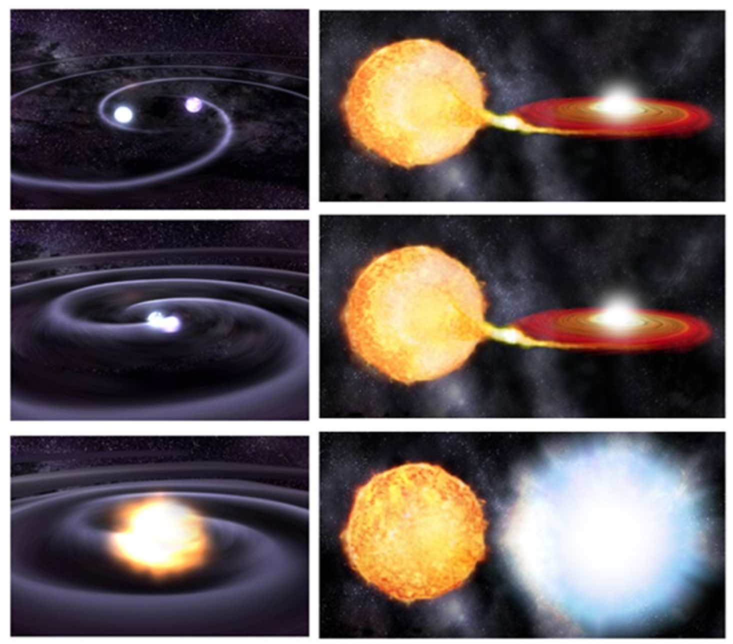
This will allow us to study the early population of seed black holes of today’s supermassive BHs.

What are the progenitors of Supernovae Type Ia?

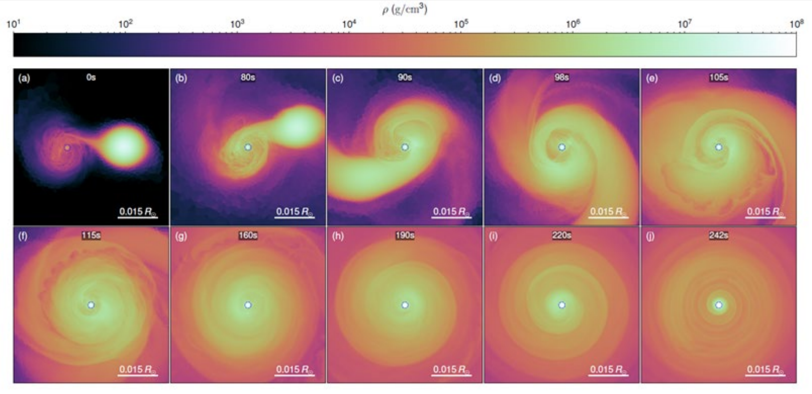
Double-white dwarfs can be observed out to a few 10Mpc.
Tens of mergers per year expected to be observed with LGWA.



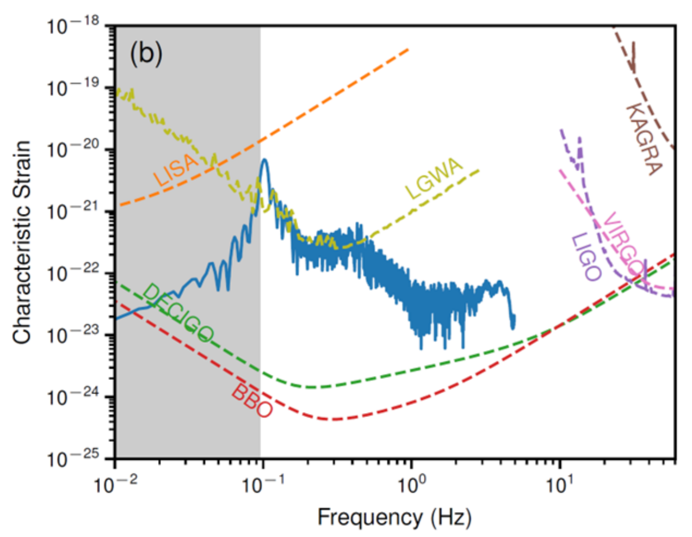
Double degenerate   Single degenerate



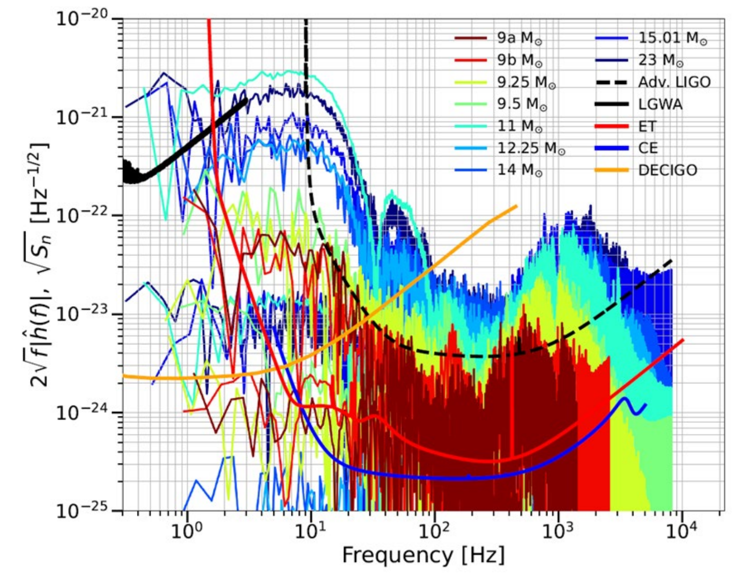
Stellar Disruptions and Explosions



Asymmetric mass ejection and associated neutrino emission in core-collapse SNe produce GW memory effect detectable by LGWA



Observation of the final phase of white-dwarf - neutron-star mergers

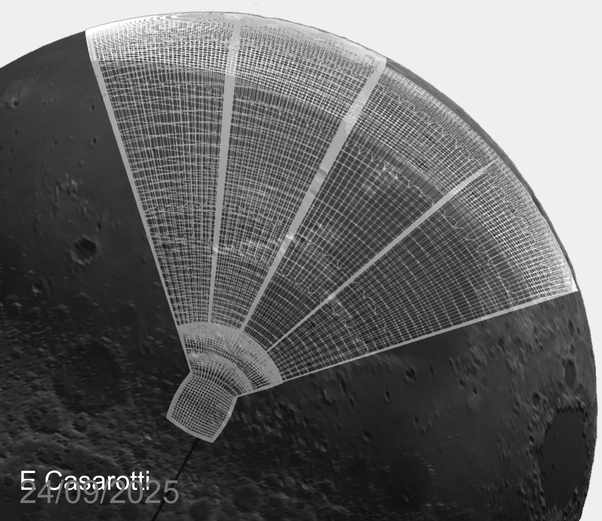


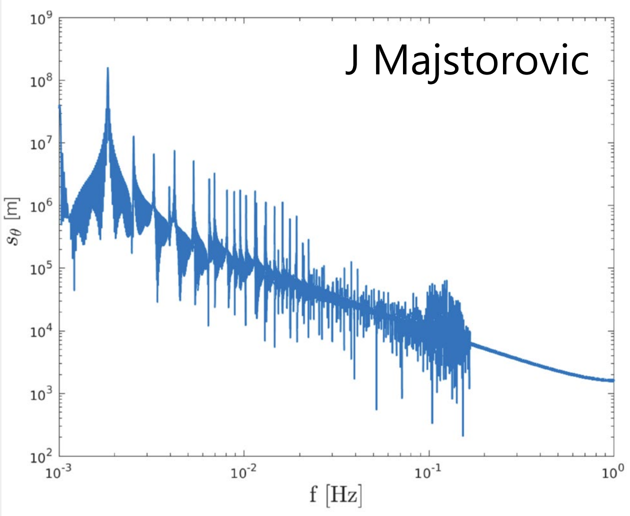
Lunar Internal Structure and Formation History

The internal structure of the Moon needs to be understood accurately to model its response to GWs.

Learning about the Moon's internal structure and geology means to learn about its formation history.

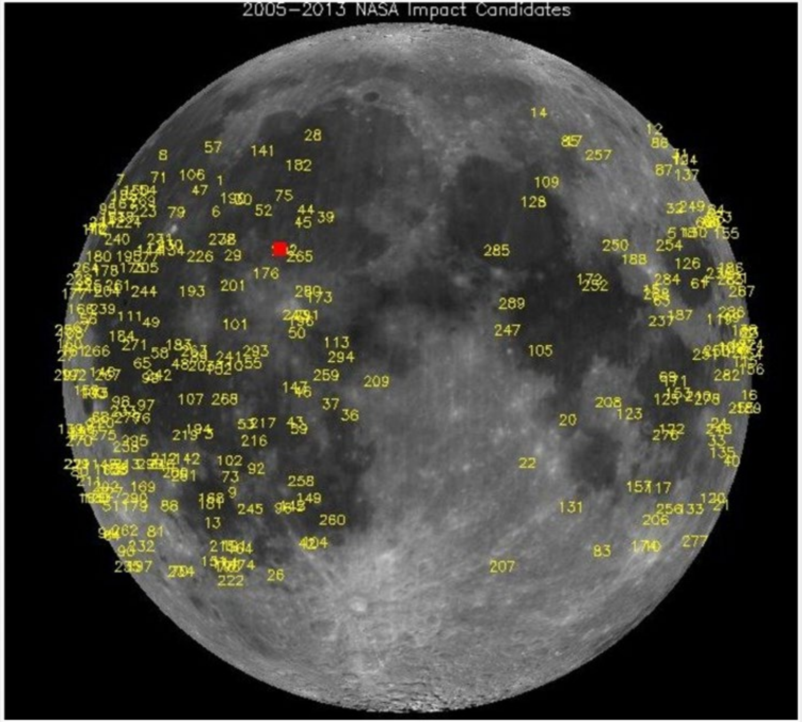
Accurate simulations of the lunar GW response are imperative (Digital Twin?).



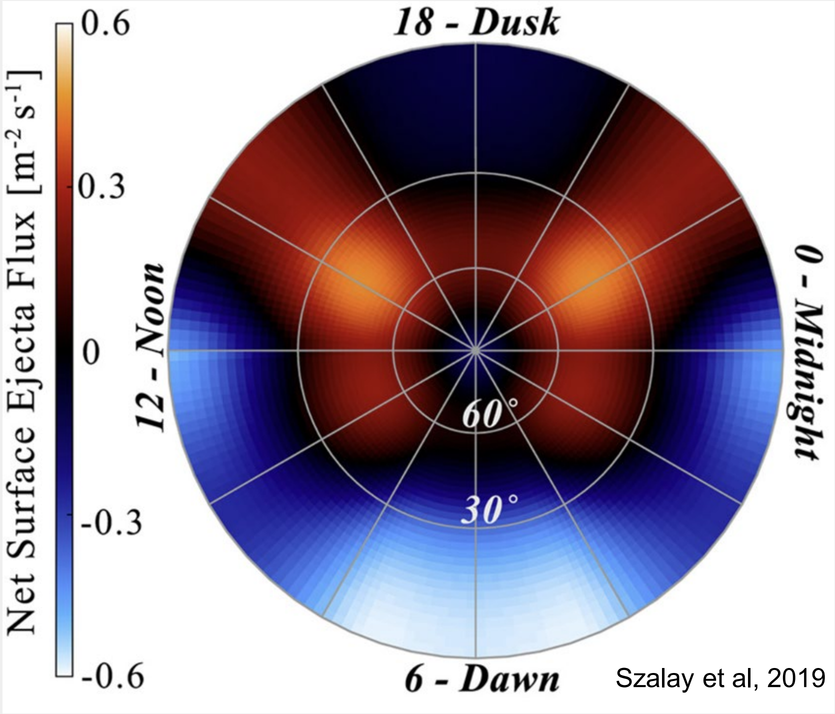


Studying the Spatial Distribution of Meteoroid Impacts

Meteoroid impacts observed with NASA's lunar monitoring program



Weak impact ejecta flux at the poles (simulation)

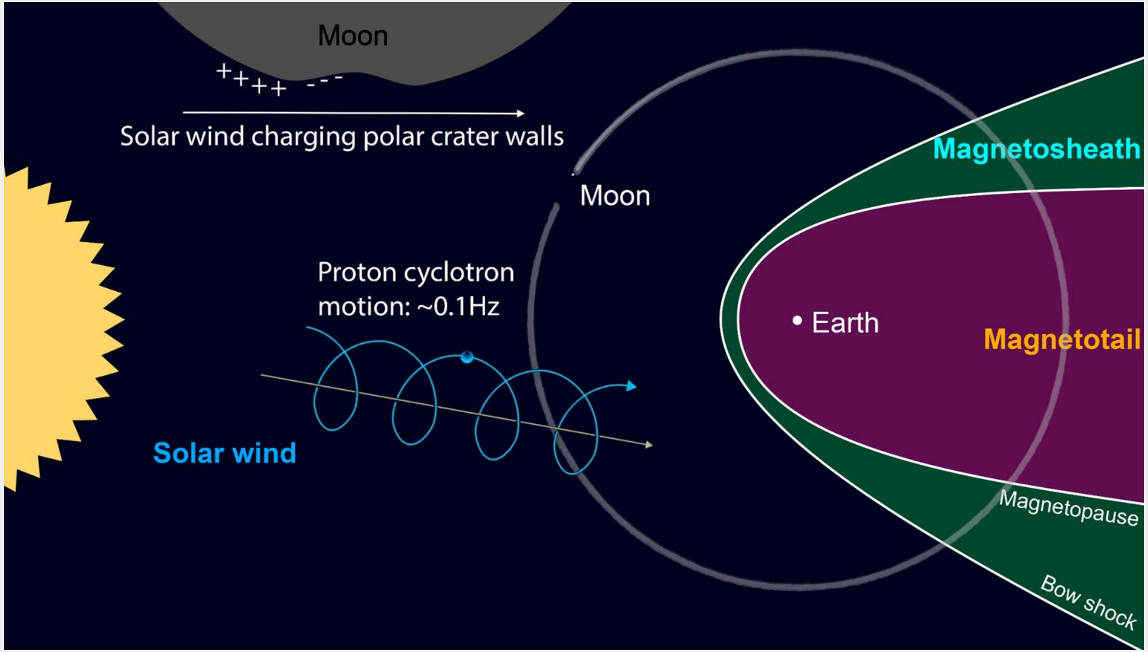


High Precision Tomography of the Moon with GWs

Same binary black hole observed with LGWA and ground-based detectors

Use calibrated GW signals for lunar tomography (and to calibrate LGWA) ← Estimate GW strain amplitude with 0.1% precision/accuracy

Magnetic Fluctuations at Lunar Surface



Charged crater walls, the Earth' magnetotail, and proton cyclotron motion are among the relevant electromagnetic effects at the LGWA site.

These effects need to be studied due to the accelerometers' susceptibility to electromagnetic fields and charges.

GS
SI

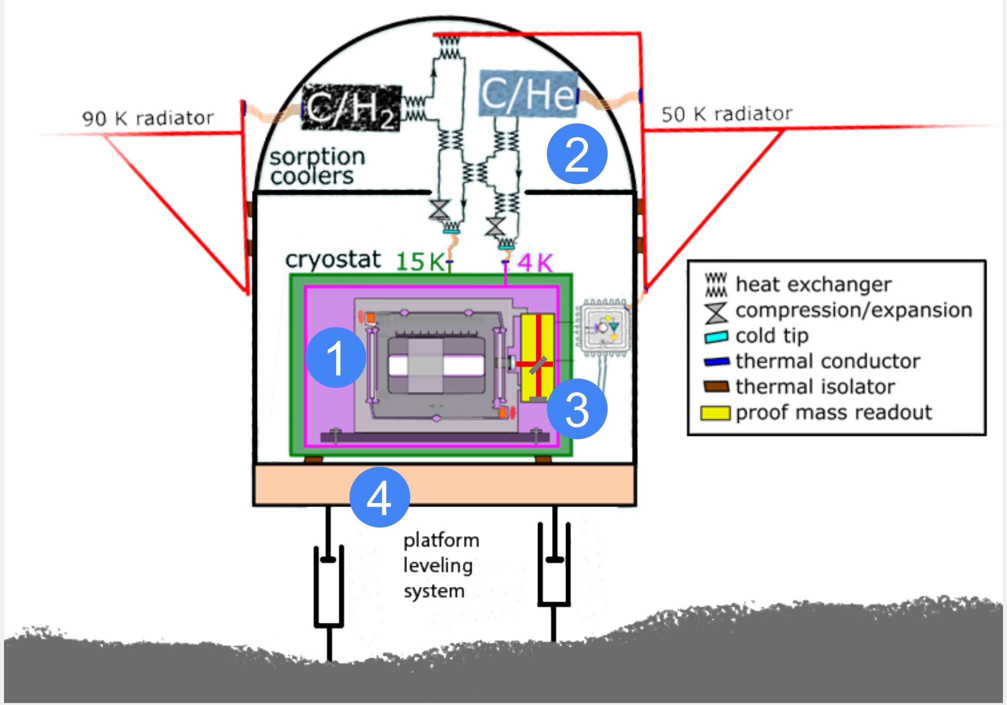
Synergies and Missions of Interest

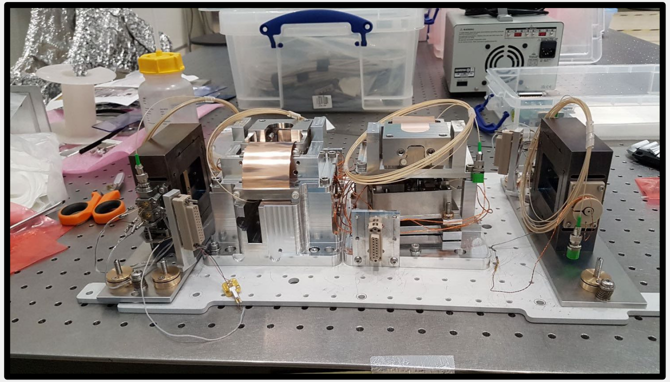
Type of Synergy	Targets	Instruments together with LGWA
Multi-messenger observations and science	Tidal disruption, supernovae, jets, black-hole binaries	EM observatories: X-ray, optical, radio (like ELT, Athena, VRO, SKA)
Multiband observations and science	Compact binaries with black holes and neutron stars	Terrestrial and space-based GW detectors (like LISA, Einstein Telescope, Cosmic Explorer)
Studies of the lunar interior and seismicity	Moonquakes	Lunar geophysical stations (like Lunar Geophysical Network, Farside Seismic Suite, Chang'e 7 seismograph)
Studies of the lunar surface environment	Meteoroid impacts, magnetic fields, temperature, lunar regolith	LUMIO, LUNA Analog Facility

LGWA Payload Concept

The LGWA Payload Concept

J Appl Phys 131, 244501, 2023





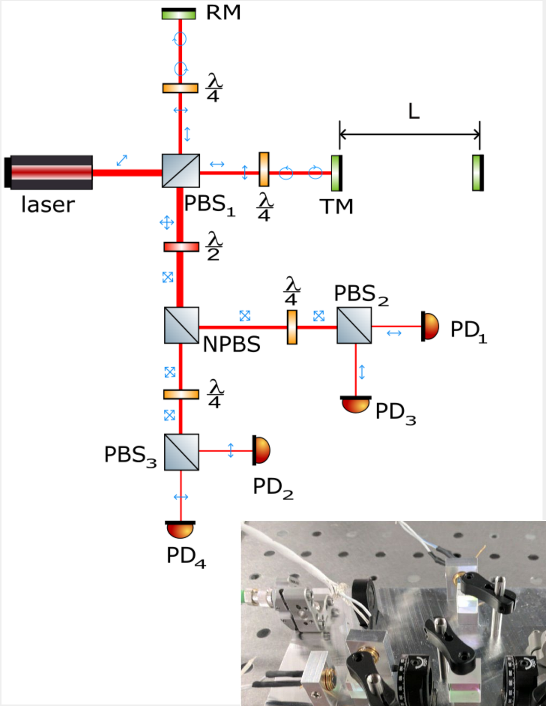
J van Heijningen, VU Amsterdam

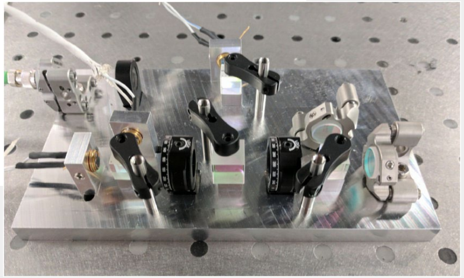
1. Ultra-high quality mechanical structure
2. Vibration free sorption cooling
3. Quantum limited readout
4. Microradian precision leveling at cryo-temperatures

GSSI

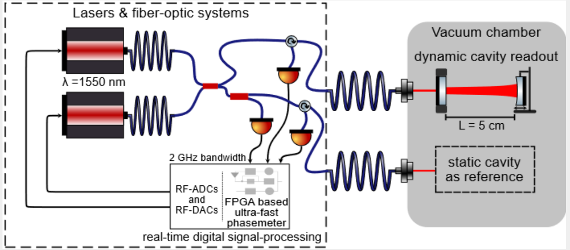
Compact Interferometric Displacement Sensor

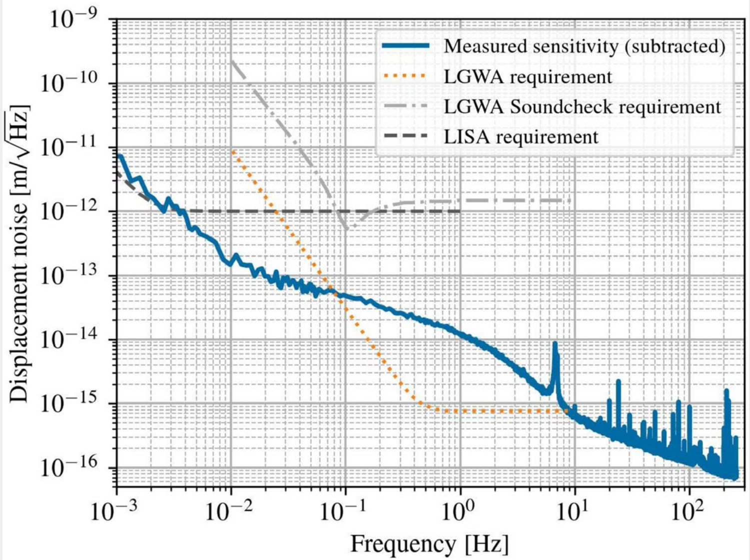
Homodyne quadrature (Soundcheck candidate)





Heterodyne cavity tracking (LGWA candidate)





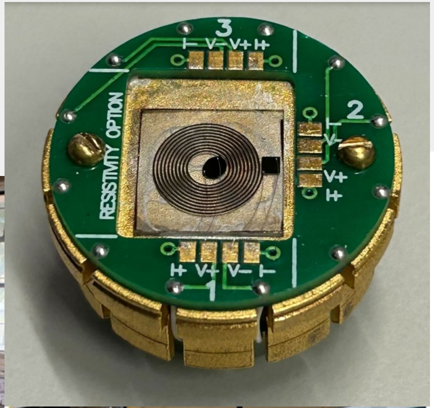
University of Hamburg, O Gerberding et al

Superconducting Actuator Coils

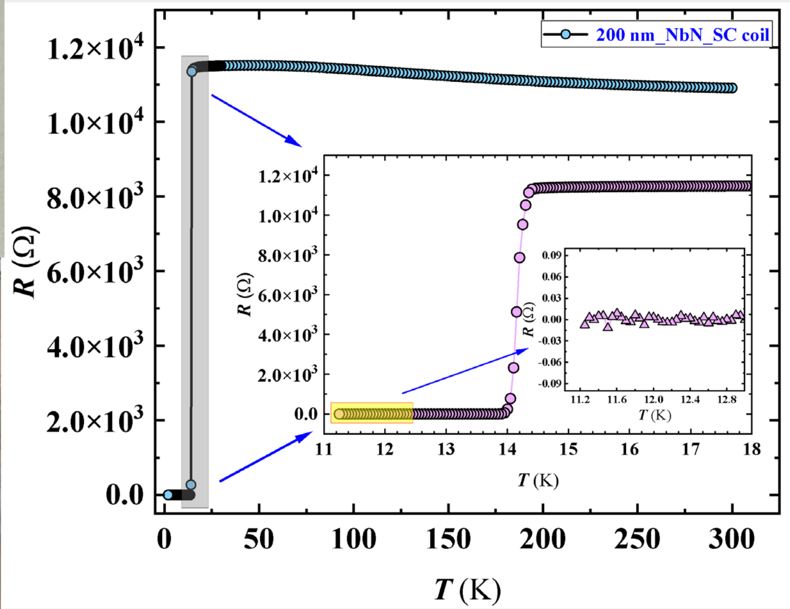
CSIR – NPL, India
University of Camerino, Italy
Max-Planck-Institute CPFS, Germany

Deposition of superconducting NbN thin film at NPL

DC Magnetron Sputtering



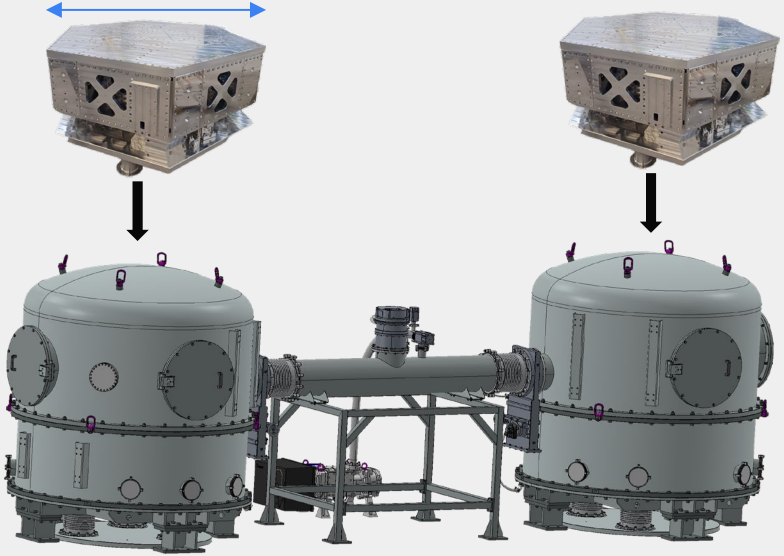
Transition to the superconducting state demonstrated in October 2024



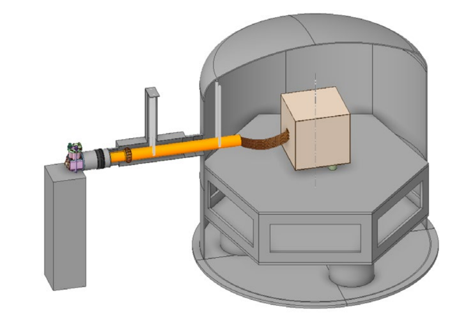
GEMINI: Moon Emulator

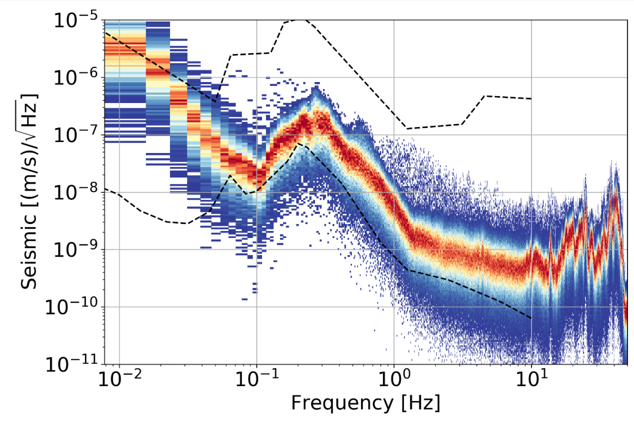
GEMINI site is 1.4km underground

A pair of suspended platforms under vacuum



40K cryo-box will be deployed on one of the platforms



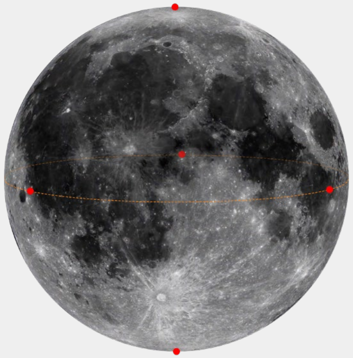


LGWA White Papers

- White paper submitted to Ideas for exploring the Moon with a large European lander (ESA, 2020)
- Artemis Science White Papers (NASA, 2020)
- Topical Paper and Research Campaign: Decadal Survey on Biological and Physical Sciences Research in Space (National Academies of Sciences, 2021)
- Presentation to the GW Space working group of ESA's Voyage 2050 (2024)
- White paper to **Key Non-Polar Destinations Across the Moon to Address Decadal-level Science Objectives with Human Explorers** (National Academies of Sciences, 2025)

Global Configurations of the Lunar Gravitational-wave Antenna

Jan Harms[1,2,*] Stefano Benetti,[3] Emanuele Berti,[4] Xing Bian,[5] Alessandro Bonforte,[6] Marica Branchesi,[1,2] Roberto Della Ceca,[7] Christophe Collette,[8,9] Alessandra Corsi,[4] Michael W. Coughlin,[10] Suresh Doravari,[11] Alessandro Frigeri,[12] Kiranjyot Gill,[13] Oliver Gerberding,[14] Joris van Heijningen,[15,16] Francesco Iacovelli,[4] Augusto Marcelli,[17] Andrea Maselli,[1,2] Marco Olivieri,[18,12] Ferdinando Patat,[19] Andrea Perali,[20,21] Gianluca Di Rico,[22] Roberto Serafinelli,[23,24] Paola Severgnini,[7] Angela Stallone,[18] Morgane Zeoli,[8,25] and Aayushi Doshi[26]

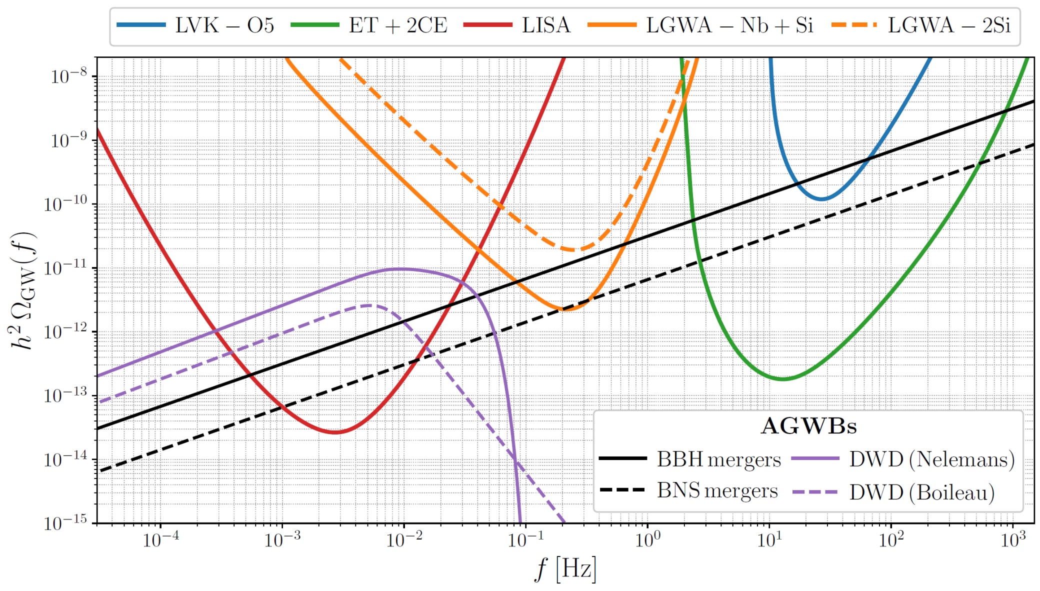


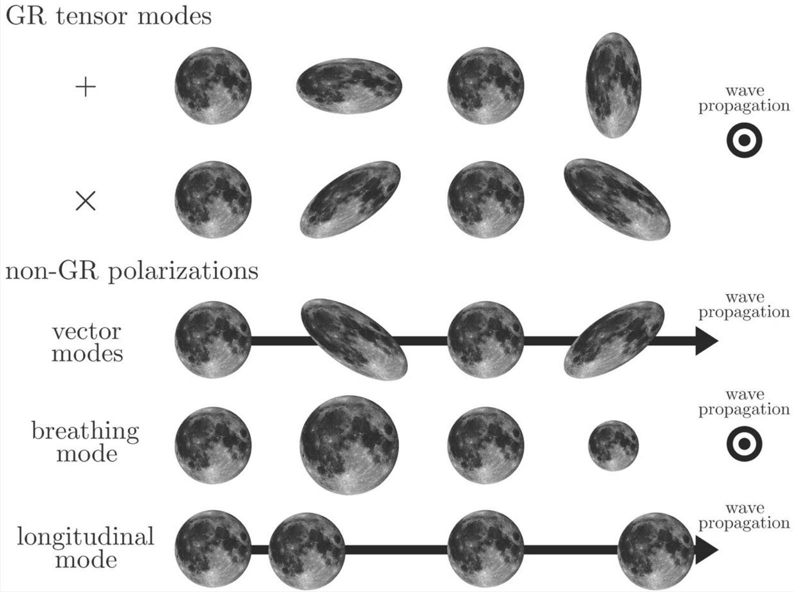
Global Network: Augmenting the LGWA Science Case

Cosmology:
Measurement of a primordial GW background

Voted most exciting LGWA science at last week's annual meeting!

Fundamental physics:
Measurement of GW polarizations





PHYSICAL REVIEW D **90**, 042005 (2014)

Constraining the gravitational wave energy density of the Universe using Earth's ring

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(Received 5 June 2014; published 25 August 2014)

PHYSICAL REVIEW D **73**, 042001 (2006)

Big Bang Observer and the neutron-star-binary subtraction problem

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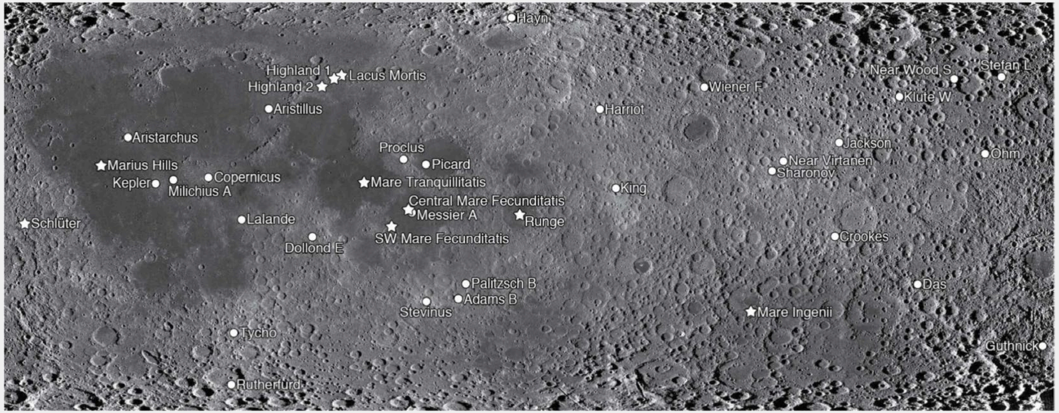
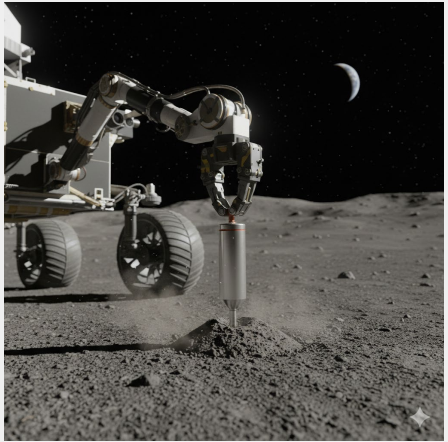
(Received 16 November 2005; published 8 February 2006)

Non-polar Deployment Sites

Lunar pits and lava tubes



Bury LGWA station into regolith



Key parameters for site selection:

- Access; deployment by astronauts could potentially greatly reduce risks compared to robotic deployments
- High temperature stability
- Low seismic background
- Distribution at equator and north pole (in addition to the south-pole PSR array)
- Any prior high-precision seismic experiment inside the PSR (Soundcheck) and at non-polar sites will be of high value to LGWA

Conceivable Timeline