The Lunar GW Antenna

Opening the decihertz band to GW detection

Jan Harms

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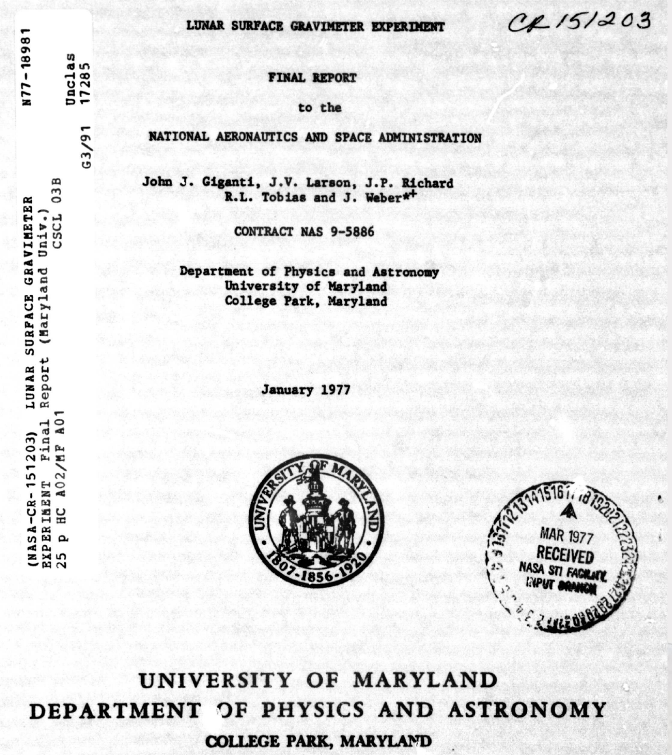
https://iopscience.iop.org/article/10.3847/1538-4357/abe5a7

Quadrupolar vibration induced by a GW
(here showing spheroidal mode)

Apollo 17: Lunar Surface Gravimeter

NASA, Apollo 17 (1972)



(NASA-CR-151203) LUNAR SURFACE GRAVIMETER EXPERIMENT Final Report (Maryland Univ.) 25 p HC A02/MF A01 CSCL 03B N77-18981 Unclas G3/91 17285

LUNAR SURFACE GRAVIMETER EXPERIMENT CR 151203

FINAL REPORT

to the

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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R.L. Tobias and J. Weber*+

CONTRACT NAS 9-5886

Department of Physics and Astronomy
University of Maryland
College Park, Maryland

January 1977

UNIVERSITY OF MARYLAND 1807-1856-1920

MAR 1977 RECEIVED NASA STI FACILITY INPUT BRANCH

UNIVERSITY OF MARYLAND
DEPARTMENT OF PHYSICS AND ASTRONOMY
COLLEGE PARK, MARYLAND

The LSG would have set the most stringent limits on the energy of a GW background at that time, but it had greatly reduced sensitivity to due a design flaw.

It was then determined that an error in arithmetic made by La Coste and Romberg, and known to the firm's highest officials, had not been corrected by La Coste and Romberg. This led to an instrument which had excellent performance in earth g and was just barely outside of the tolerances for variations of lunar site g. This error resulted in the

Searches on Earth

Data from N.32°W. Benioff strain seismograph at Isabella, CA

No. 4763 February 11, 1961 NATURE

LETTERS TO THE EDITORS

GEOPHYSICS

Upper Limit for Interstellar Millicycle Gravitational Radiation

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David Zipoy
J. Weber

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Stewart Smith
Hugo Benioff

Seismological Laboratory, California Institute of Technology, Pasadena, California.

$$\overline{\varepsilon(t)^2} \approx \frac{4c^4 Q}{\pi^2 \omega^3} R^2_{iojo}(\omega) = \frac{60GQ}{c^3\omega} t_{or}(\omega) \quad (2)$$

In equation (2), $R^2_{iojo}(\omega)$ is the power spectrum of the Riemann tensor, G is the constant of gravitation

Upper limits on Riemann-tensor power spectrum

Table 1

Fundamental mode	Period (min.)	Q (est.)	Strain² (av.)	$R^2_{iojo}(\omega)$ $\left[\frac{1}{\text{cm.}^4 \text{ (rad./sec.)}}\right]$	$t_{or}(\omega)$ $\left[\frac{\text{watts}}{\text{cm.}^2 \text{ (rad./sec.)}}\right]$
S_2	54·0	400	80×10^{-25}	$< 0·5 \times 10^{-75}$	< 20
S_4	25·8	350	20	2	20
S_6	16·0	300	8	3	10
S_8	11·81	250	4	5	10
S_{10}	9·66	210	2·5	7	10
S_{14}	7·47	180	1·2	10	10
S_{20}	5·78	160	1	20	10
S_{30}	4·37	120	0·6	30	10
S_{38}	3·66	100	0·6	60	10

Multiply with $8 \cdot 10^{49} \cdot (1\text{mHz}/f)^4$ to get GW strain PSD

GRG Vol.4, No.4 (1973), pp. 279 - 287.

A SEARCH FOR GRAVITY WAVES BY MEANS OF THE EARTH EIGEN VIBRATIONS†

V.S. TUMAN

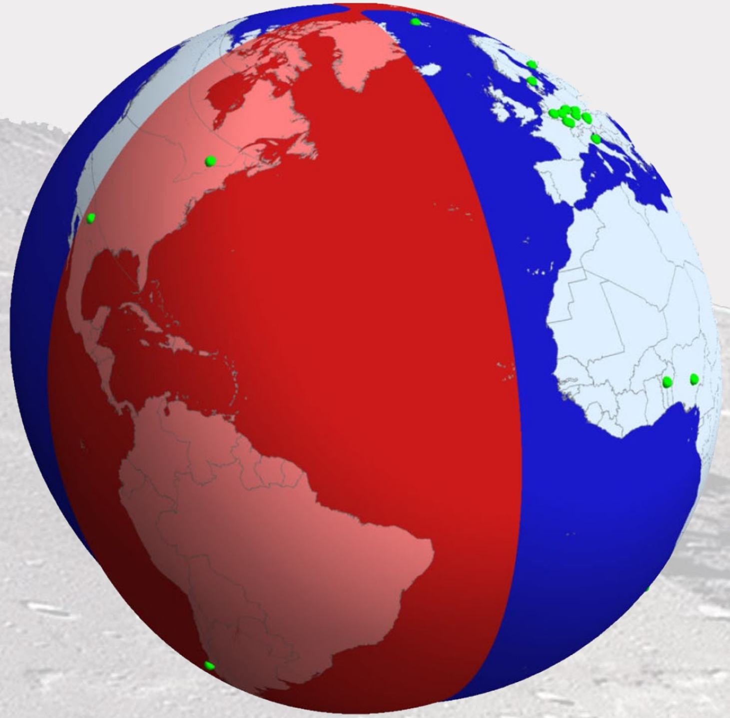
Stanislaus State College, Turlock, California 95380

Received 28 *July* 1971

- Data from a cryogenic gravity meter (magnetically levitated Nb ball with SQUID readout)
- Energy differential of odd and even modes between two sites (100km distance) used to set upper limit on GW energy

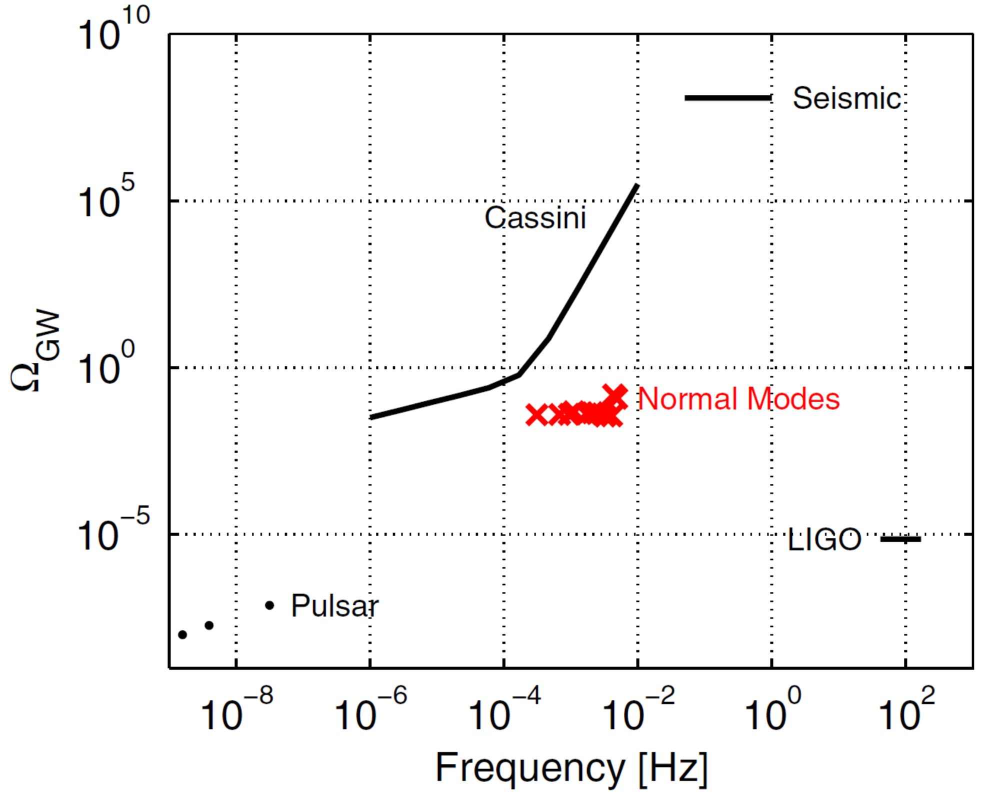
17 hours). Since it is difficult to explain this parity effect as being due to an internal source, it is speculated that the effect is caused by intense gravitational radiation. In order to maintain

Earth: 0.3mHz – 5mHz



Monitoring ℓ=2 normal modes with GGP network of superconducting gravimeters.

Requires gravity-noise cancellation from atmosphere.



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

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

Michael Coughlin[1] and Jan Harms[2]

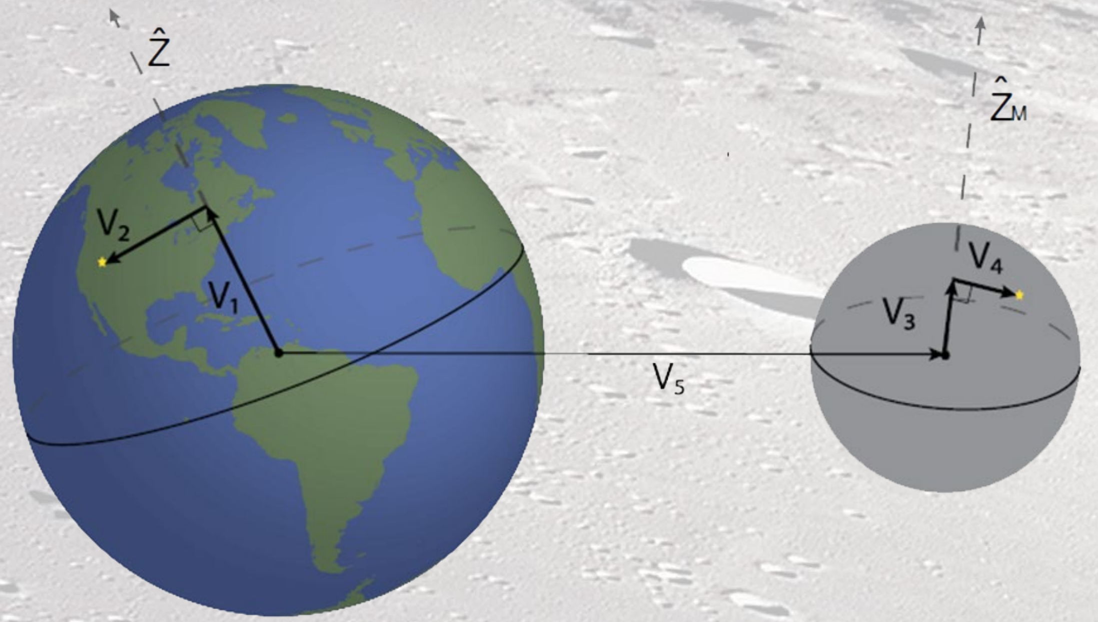
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*INFN, Sezione di Firenze, Sesto Fiorentino 50019, Italy*

(Received 5 June 2014; published 25 August 2014)

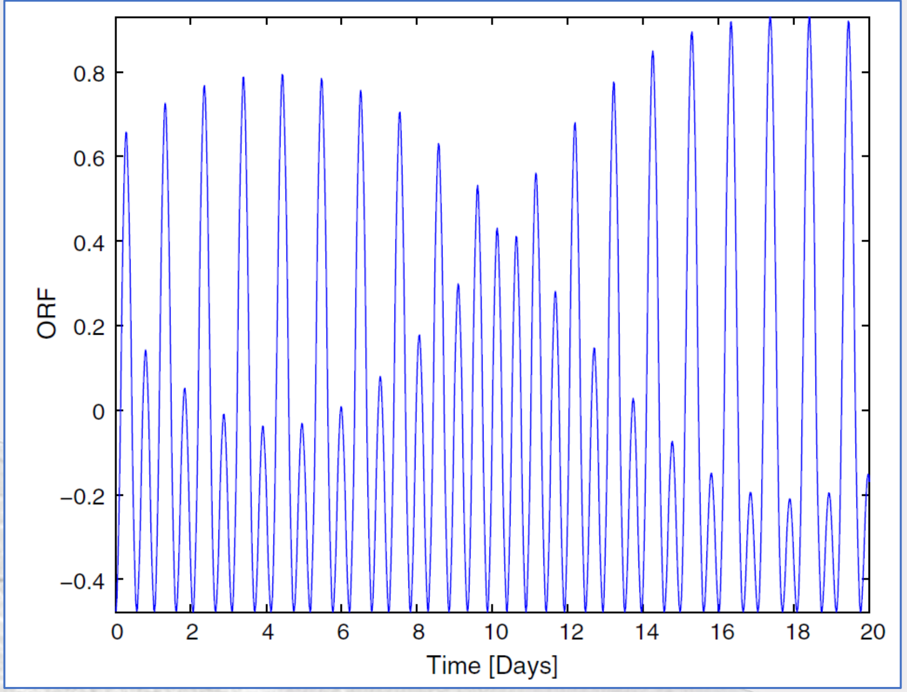
Moon-Earth: 0.1Hz – 1Hz

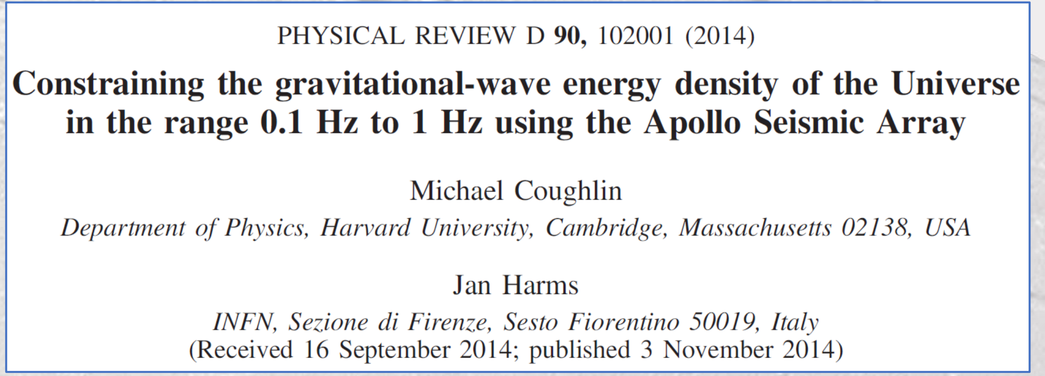
Correlations between Moon and Earth from a stochastic GW background are potentially measurable in the 0.1Hz to 1Hz band.

The analysis needs to consider Earth rotation as well as Moon libration (elliptic orbit and angle between Moon rotation axis and orbital plane).



GW correlation strength (Albuquerque, S12)





PHYSICAL REVIEW D **90**, 102001 (2014)

Constraining the gravitational-wave energy density of the Universe in the range 0.1 Hz to 1 Hz using the Apollo Seismic Array

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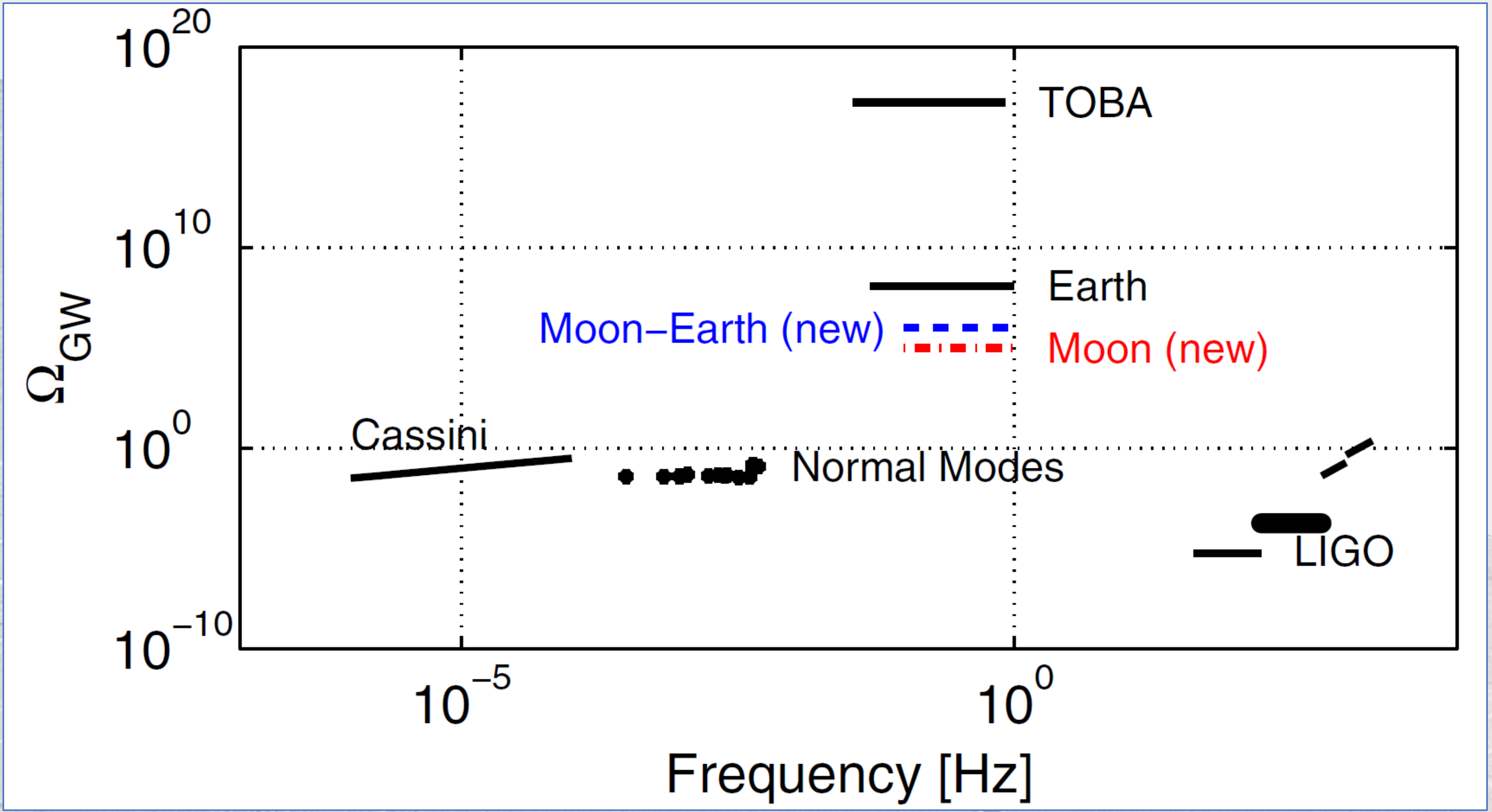
(Received 16 September 2014; published 3 November 2014)

Three Studies of 2014



Lunar GW Detection

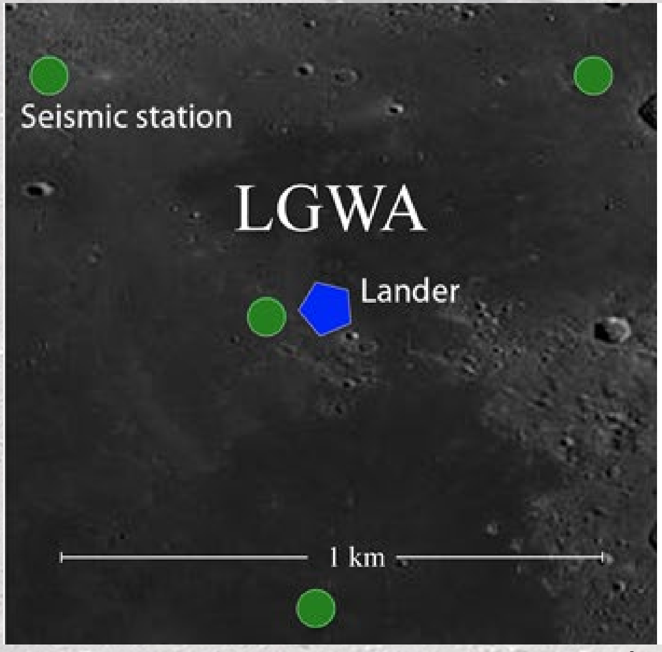
Gravitational-wave Lunar Observatory for Cosmology
(Jani/Loeb; 2020)

Laser interferometer with seismically isolated test masses.

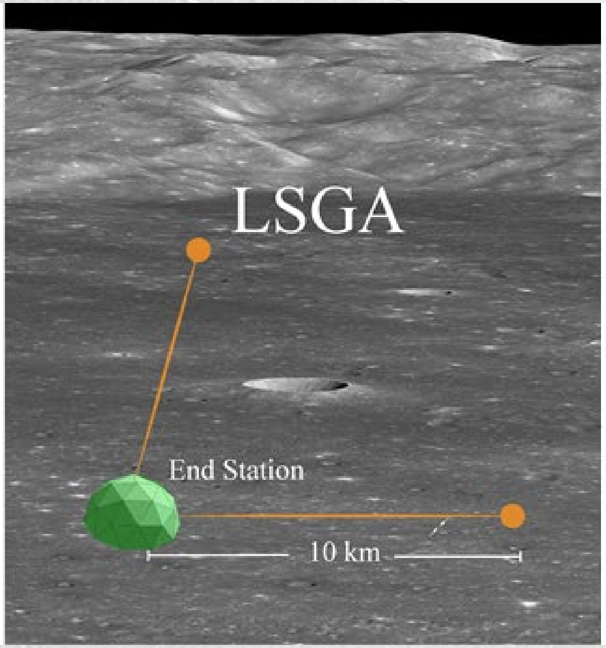
Lunar Seismic and Gravitational Antenna
(Stavros Katsanevas et al; 2020)

Laser-interferometric seismic strainmeter.

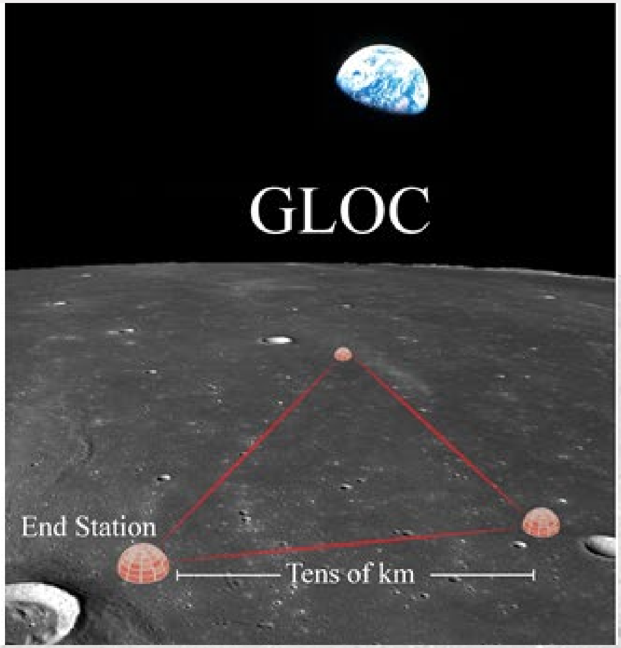
Time →



Harms et al



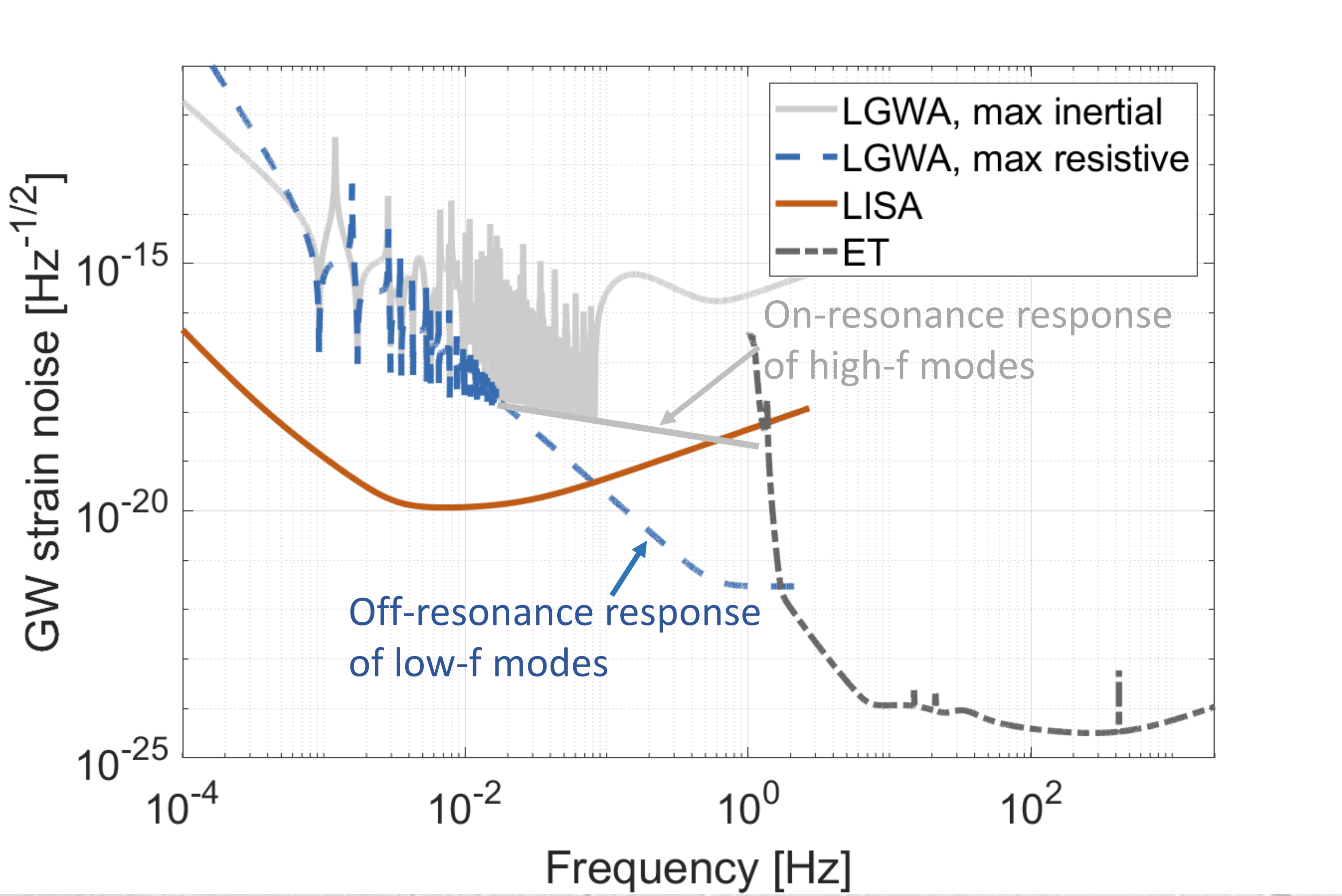
Katsanevas et al



Jani/Loeb

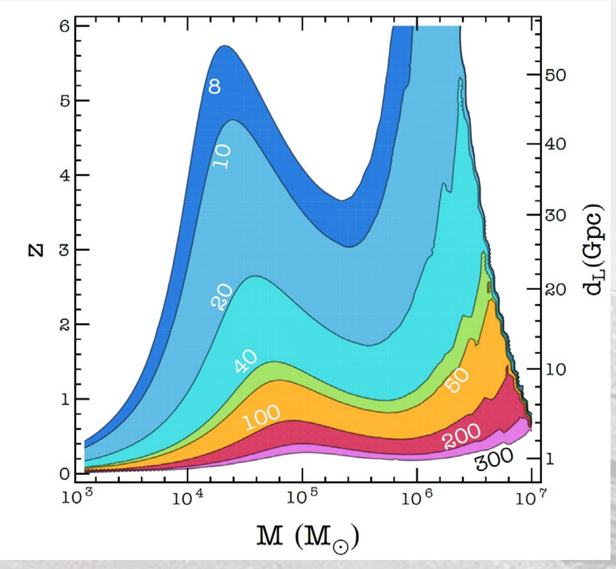
LGWA Sensitivity Target

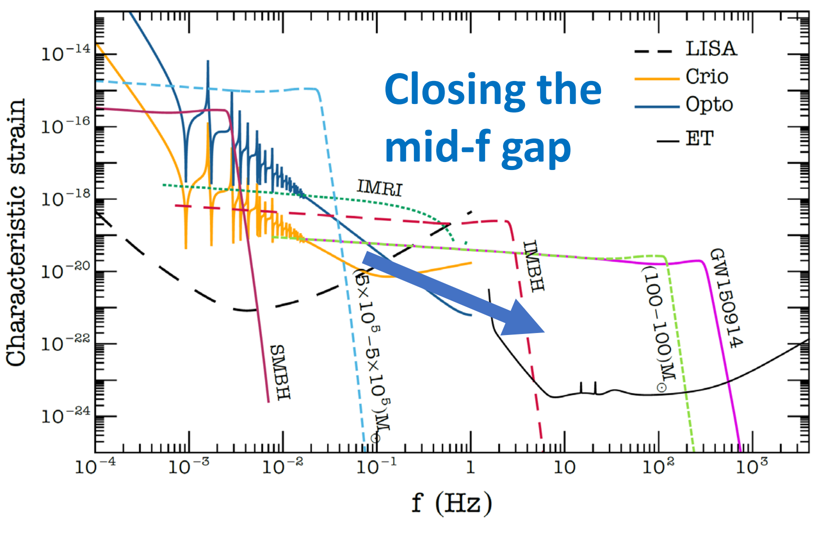
1mHz to few Hz



- LGWA will deliver first GW detections at deciHz
- Synergy with ET/CE on IMBH, solar-mass BBH and BNS
- Potential synergy with LISA (depending on when LGWA will be deployed) on double white dwarfs and massive BBHs

Extragalactic Compact Binaries





Possible detections

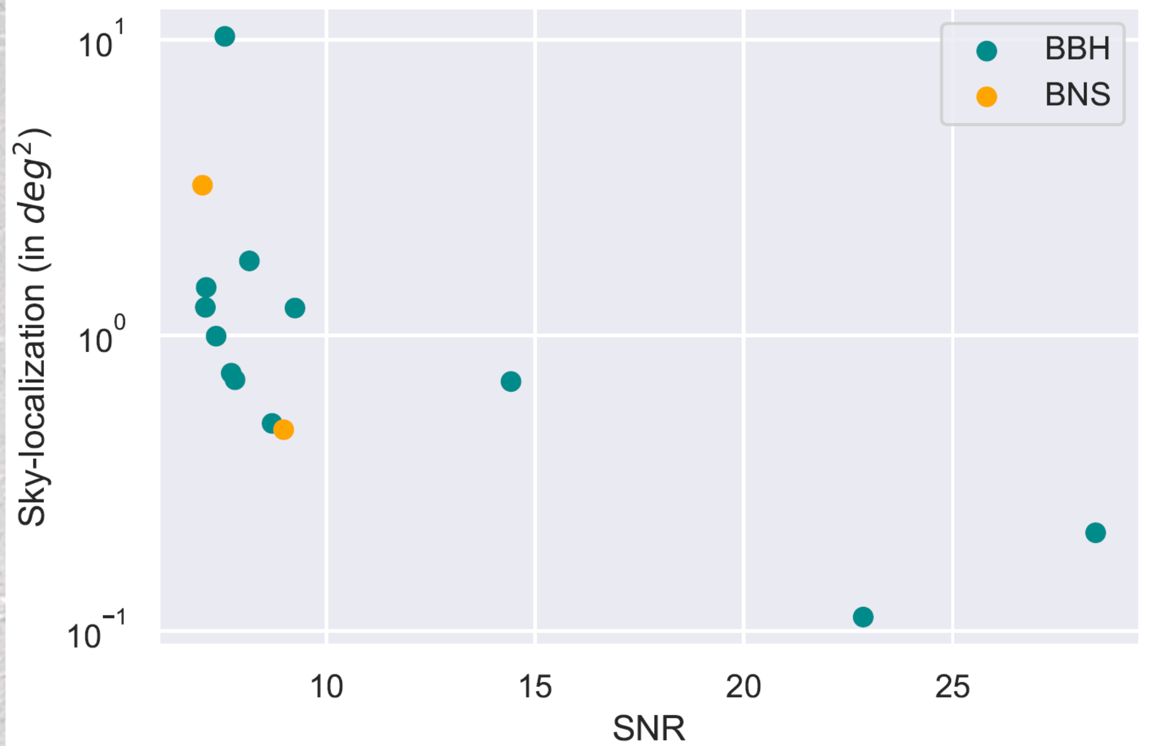
- (Super)massive and intermediate mass BBHs (majority of mergers would be detected)
- Solar-mass BBHs and BNS (few inspirals would be detected)

Impact on science (under study by LGWA WG)

- Early warning for BNS mergers to be observed in multi-messenger campaigns with ET/CE and EM facilities
- Together with ET, confidently detect IMBH mergers for population studies
- Improved sky-localization of massive BBHs compared to LISA

Solar-mass Compact Binaries

BNS and solar-mass BBH detections and sky localization (only those merging within 10 years)



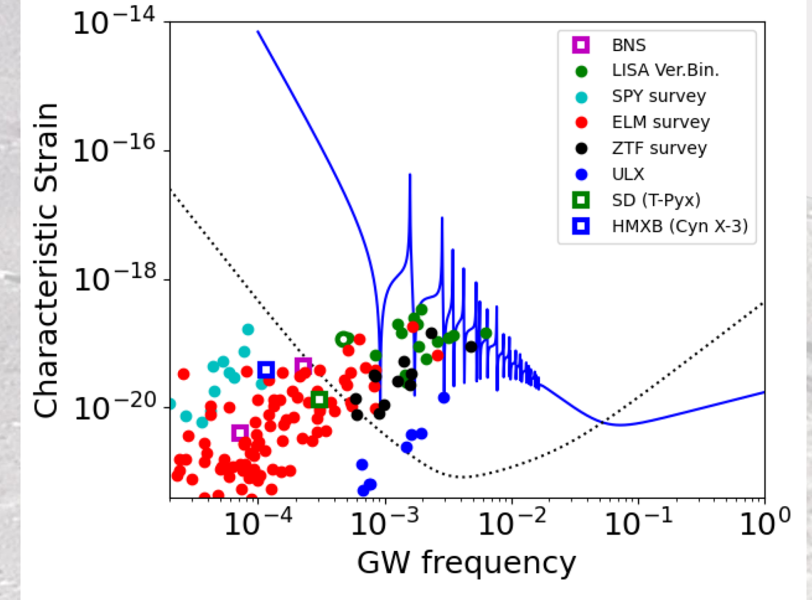
A Oliveira (2021)

Rotation (and orbital motion) of the Moon leads to modulations of GW phase and amplitude over the course of the LGWA lifetime (assumed to be 10 years), which gives LGWA the capability to localize lasting GW sources.

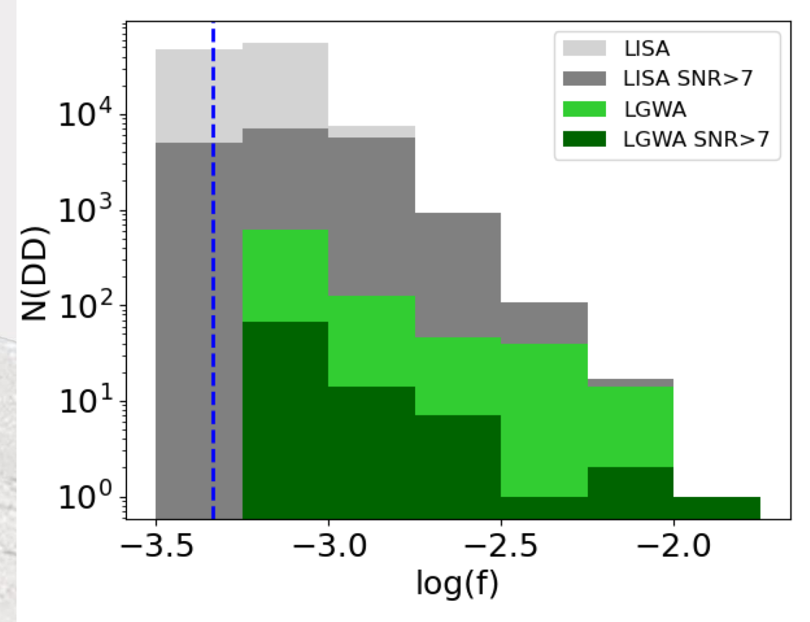
A few BNS could be detected each year with more than a day of warning time of an imminent merger.

Galactic Binaries

Estimated GW amplitudes from known short-period binaries in the Galaxy.

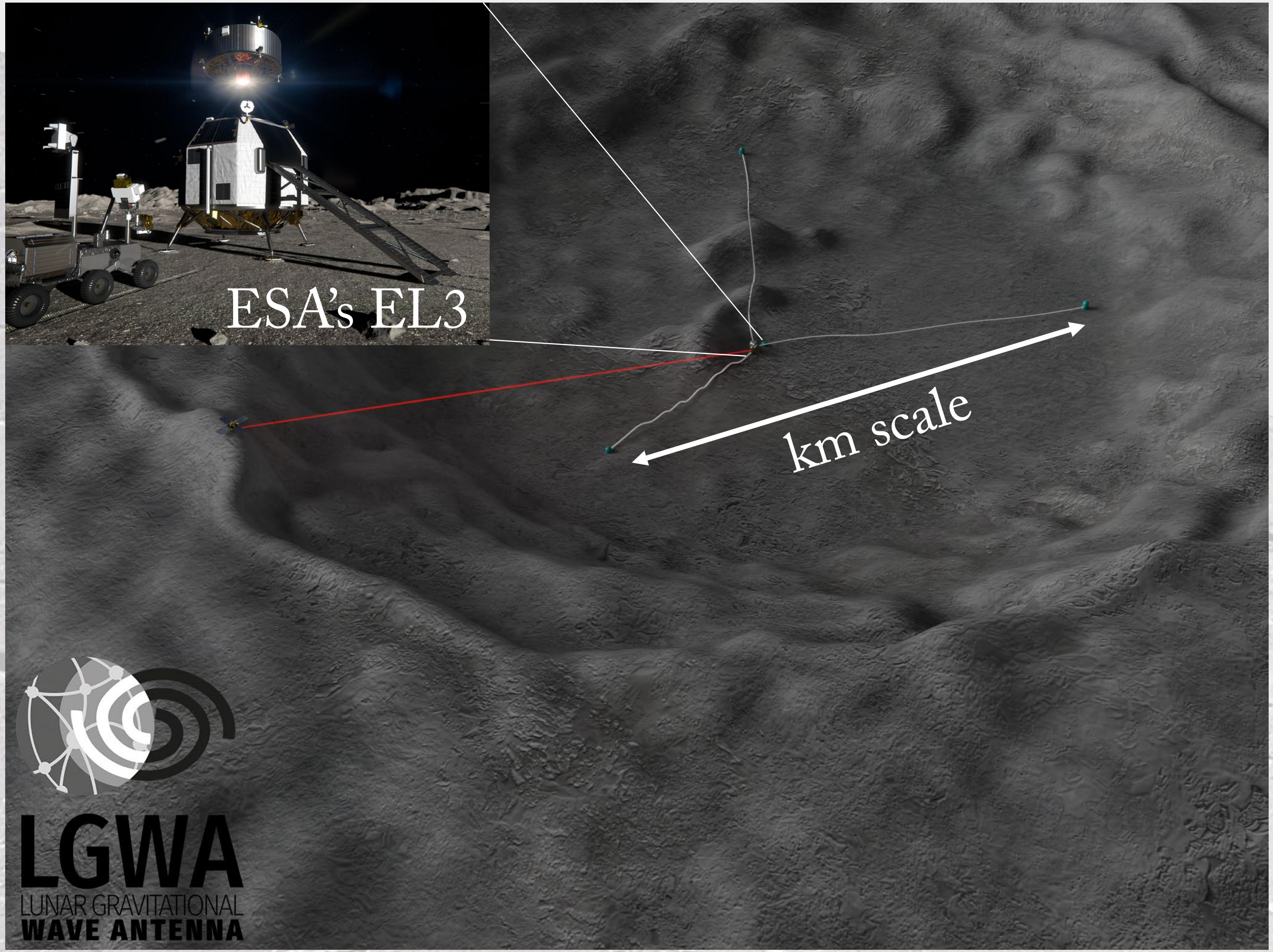


Predicted number of detections per year

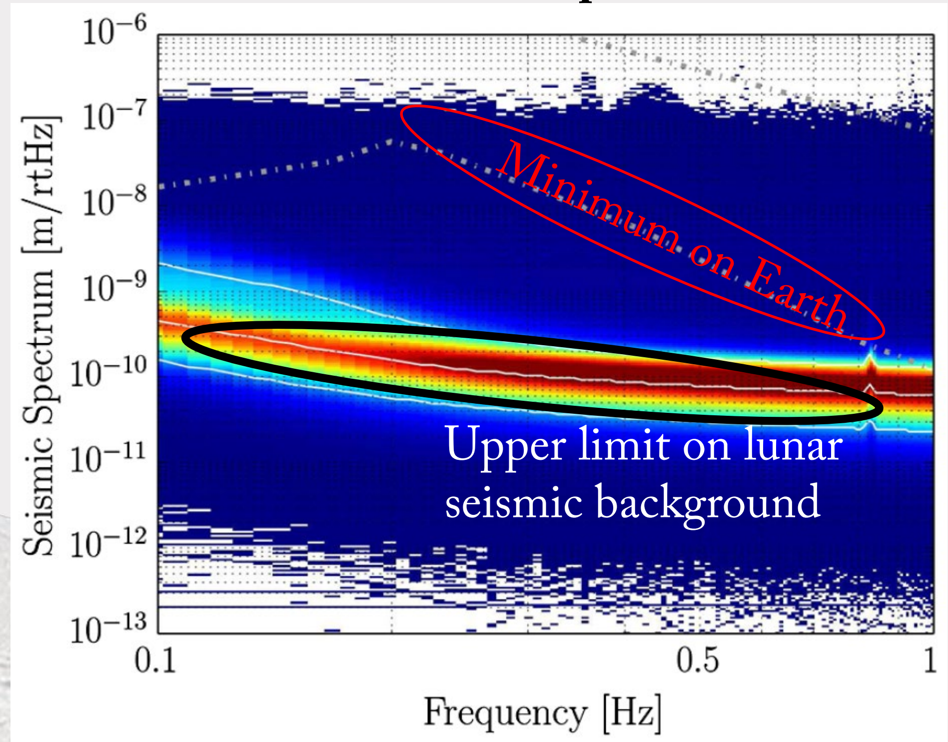


Probability of coincident detection with SN Ia is low, but it would be decisive for SN Ia progenitor identification, and the long lifetime of the LGWA mission is a great benefit.

LGWA Concept

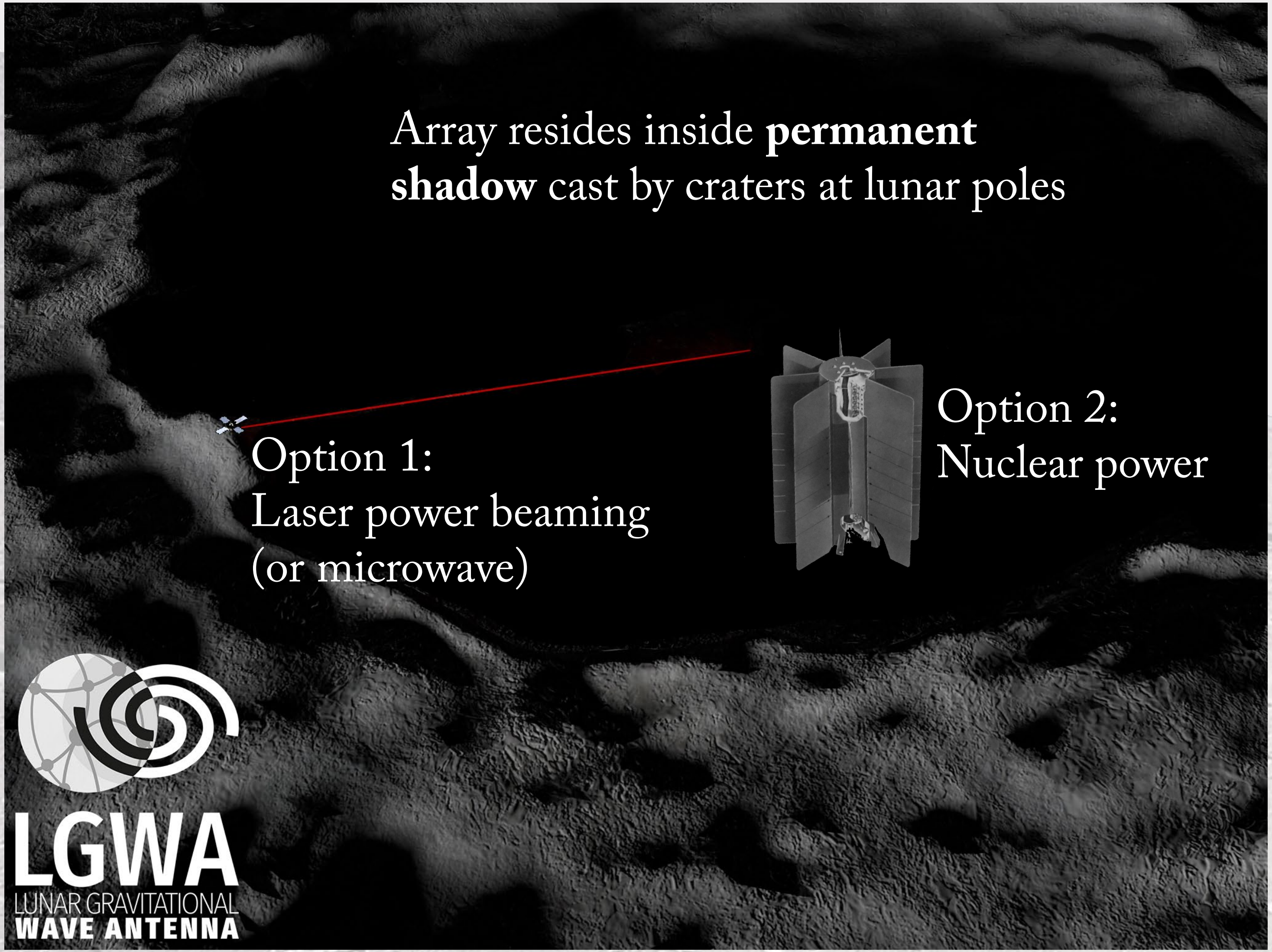


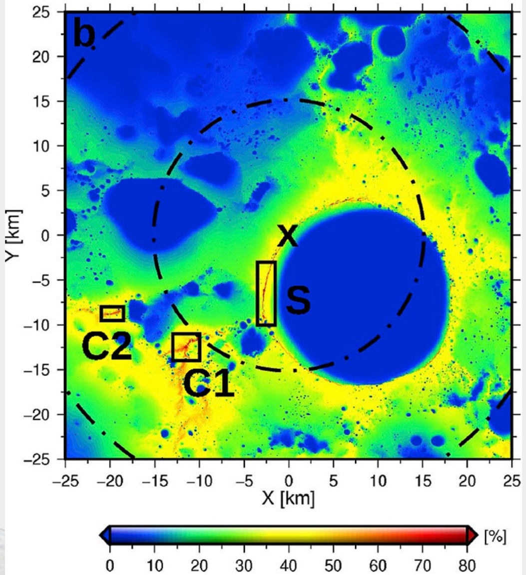
Lunar seismic spectra



- Extremely weak seismic background
- Data stretches with moonquakes, meteoroid impacts etc can be ignored or cleaned using coherent noise cancellation

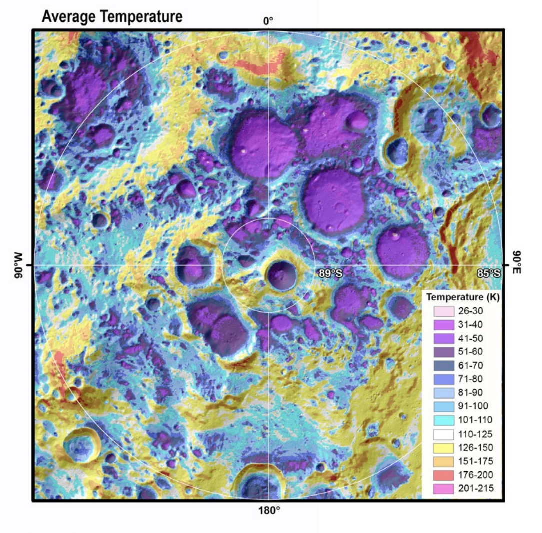
Powering





Gläser et al, 2018

Sunshine illumination near south pole



Temperature <40K in some permanent shadows of the lunar north and south poles.

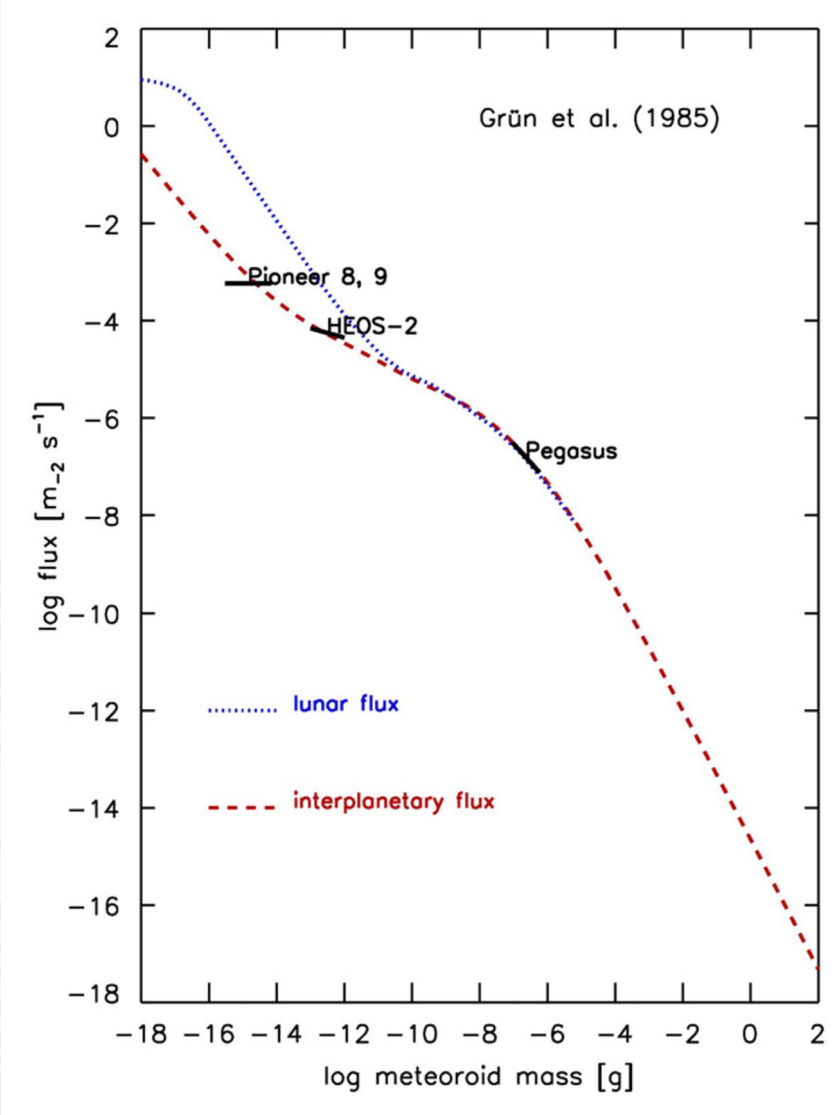
Seismic Background

Seismic background

- Predicted to be formed by meteoroid impacts
- Background estimation requires meteoroid mass and velocity distributions, and accurate Moon response model
- Might be relevant >0.1Hz (Lognonné et al., 2009)

Noise-cancellation techniques

- Limited by number of seismometers on the Moon
- Several orders of magnitude reduction possible, but with only 4 sensors, the reduction will greatly depend on properties of the seismic field

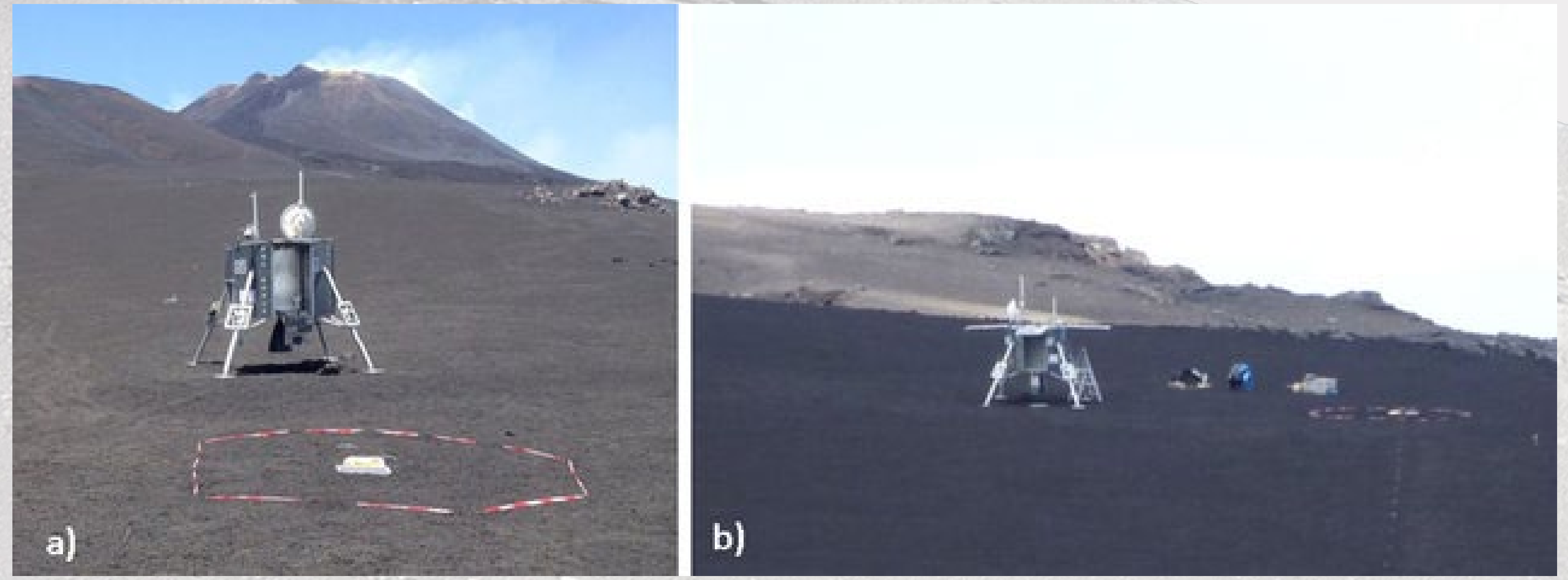


Testing Array Function

Mt Etna as test ground for array measurements

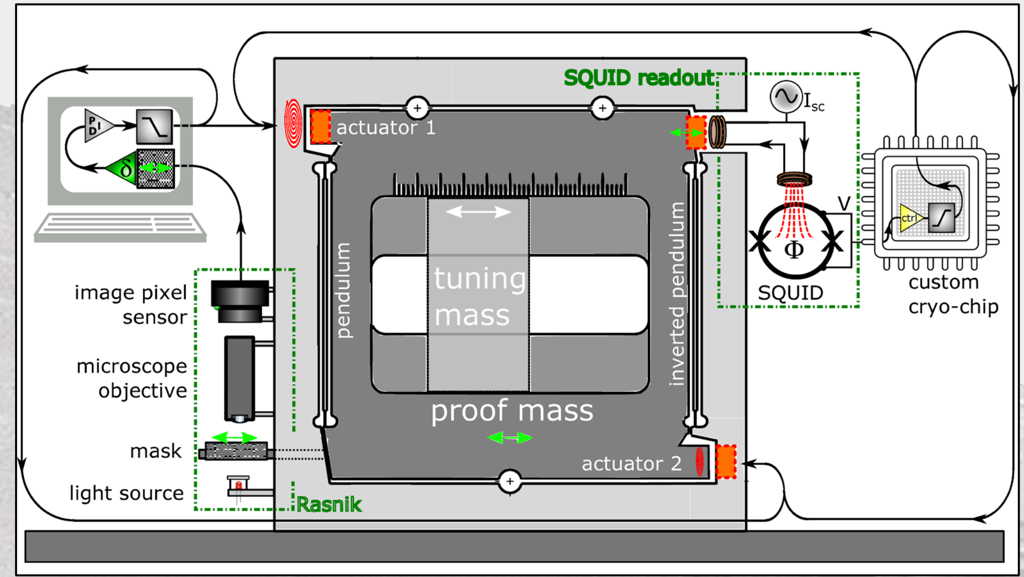
- Conditions at Mt Etna similar to the lunar regolith
- Characterize the seismic field in the LGWA observation band (1mHz – few Hz)
- Test noise cancellation for LGWA
- INGV members of LGWA are currently preparing data sets for these analyses and assess whether new dedicated measurements are required.

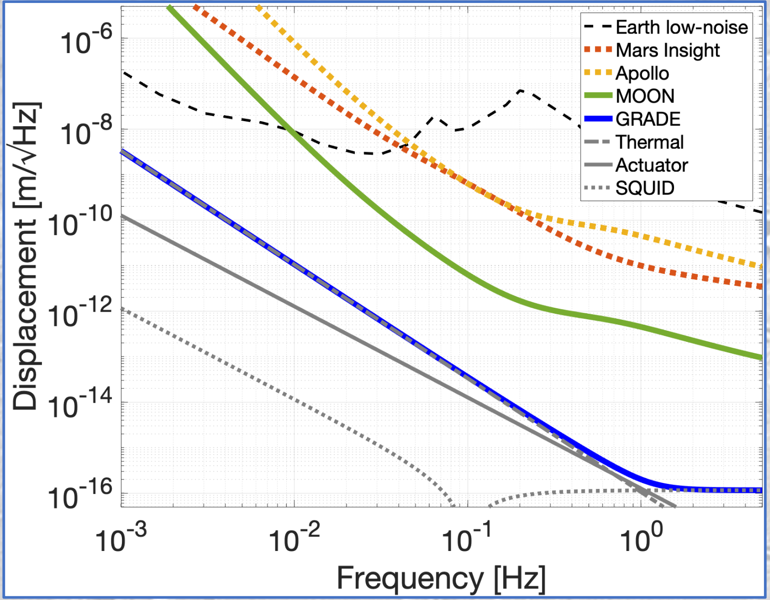
ROBEX lander with seismic station at Mt Etna



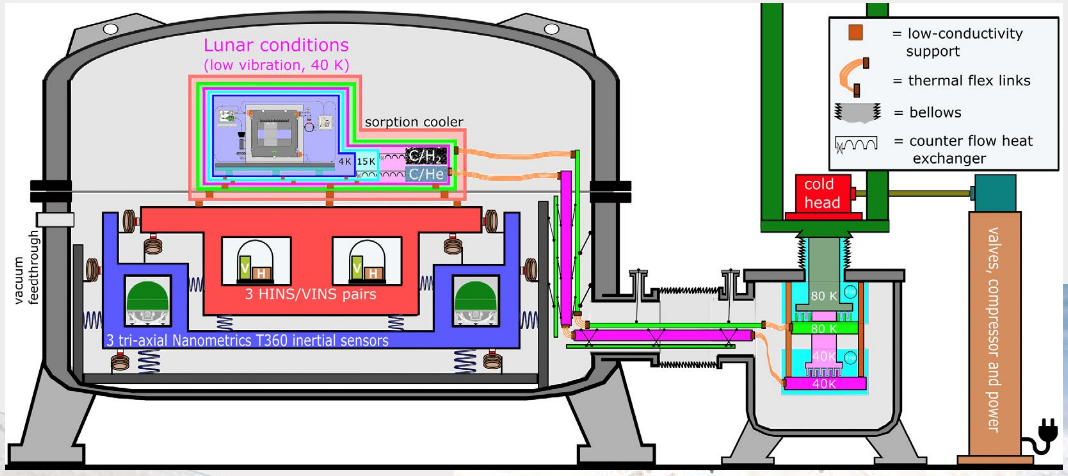
LGWA Payload

LGWA inertial sensor





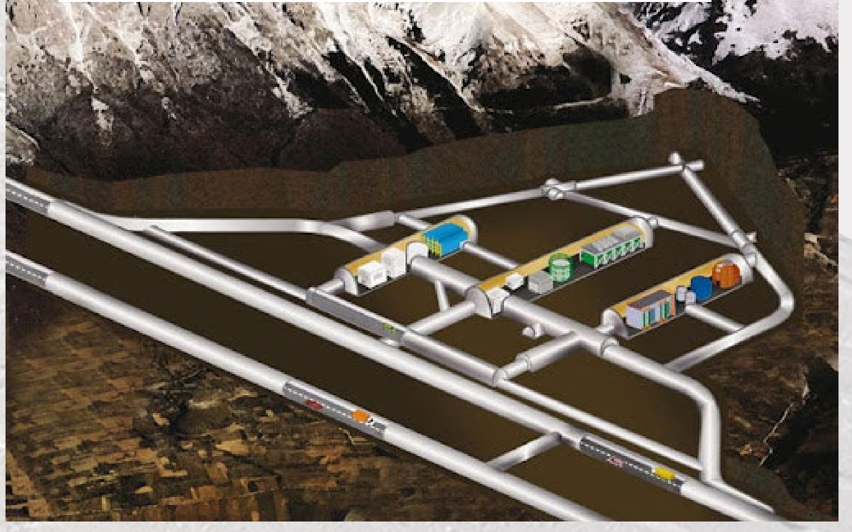
Underground seismic isolation platform



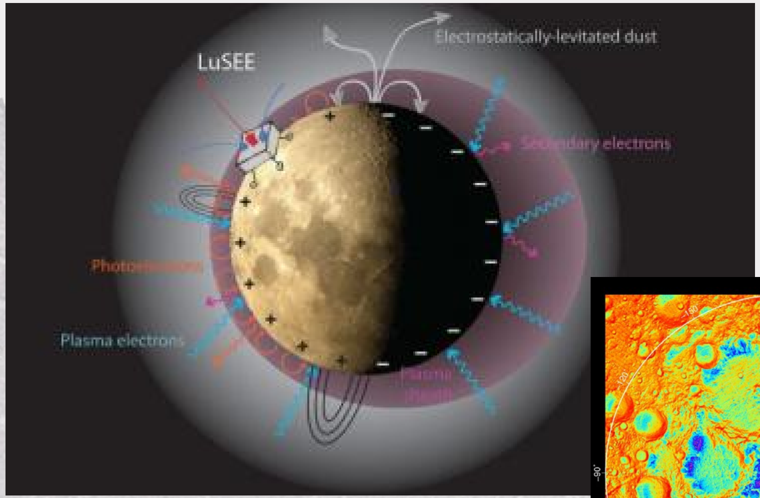
There is no natural environment on Earth where LGWA seismometers can be operated.

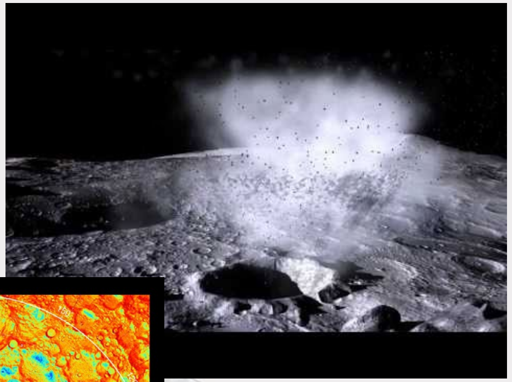
Emulator of lunar seismic and thermal environment will be realized underground at LNGS.

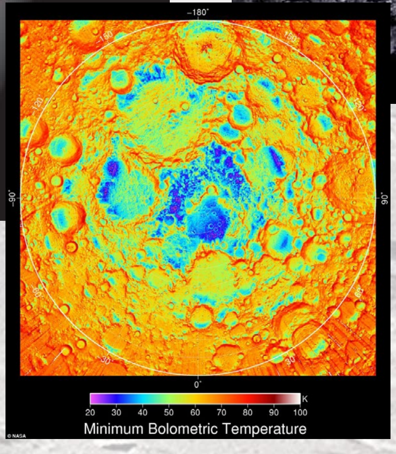
INFN LNGS near L'Aquila

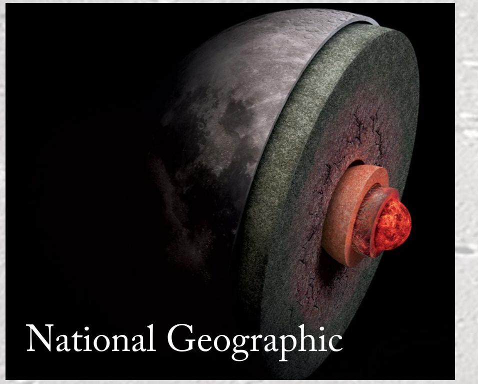


LGWA's Physical Environment








National Geographic

Moon as a spherical detector

- Seismic background
- Moon's internal structure

Important environmental factors

- Electromagnetic fields and charges
- Temperatures and thermal fluctuations
- Radiation
- Dust

Technologies

Technology	Function
Power system (power beaming or nuclear)	**Apollo technology would be sufficent**. At lunar poles, laser/microwave power beaming is a possible solution. The **Lunar Geophysical Network (deployment early 2030s)** has a similar problem to solve, however, nuclear power systems being the only solution.
Heat management	Radiator panels must remove a few Watts of heat to keep seismometer at 4K.
Rovers	Deploy seismic stations in star formation around central lander. Leave cable/fiber connection. Separate landings are an alternative, but it would probably require separate power systems for each LGWA station (as for LGN).
Drill	Drill 1m – 2m into regolith for seismometer mount. Might already be used for the **Farside Seismic Suite (deployment in 2024)**.
Communication	Satellite(s) in orbit around Moon (not necessarily a cost for LGWA).
Platform control	Slow tidal deformations of the Moon lead to ground tilt, which must be compensated with a leveling system for horizontal seismic sensing.