The Lunar GW Antenna

Opening the decihertz band to GW detection

Jan Harms

Gran Sasso Science Institute

INFN National Labs of Gran Sasso

More information on lgwa.unicam.it

LGWA Collaborating Institutions

GSSI

LGWA

UNIVERSITY OF TWENTE.

Università degli Studi di Padova

IFCA Instituto de Física de Cantabria

INAF ISTITUTO NAZIONALE DI ASTROFISICA

POLITECNICO MILANO 1863

Columbia University in the City of New York

University of Copenhagen

UCLouvain

INFN Istituto Nazionale di Fisica Nucleare

University of Minnesota Driven to Discover

Université de Genève

Nikhef

INGV

Alma Mater Studiorum Università di Bologna A.D. 1088

Liège université

OPC Osservatorio Polifunzionale Del Chianti

Università degli Studi Firenze

NASA

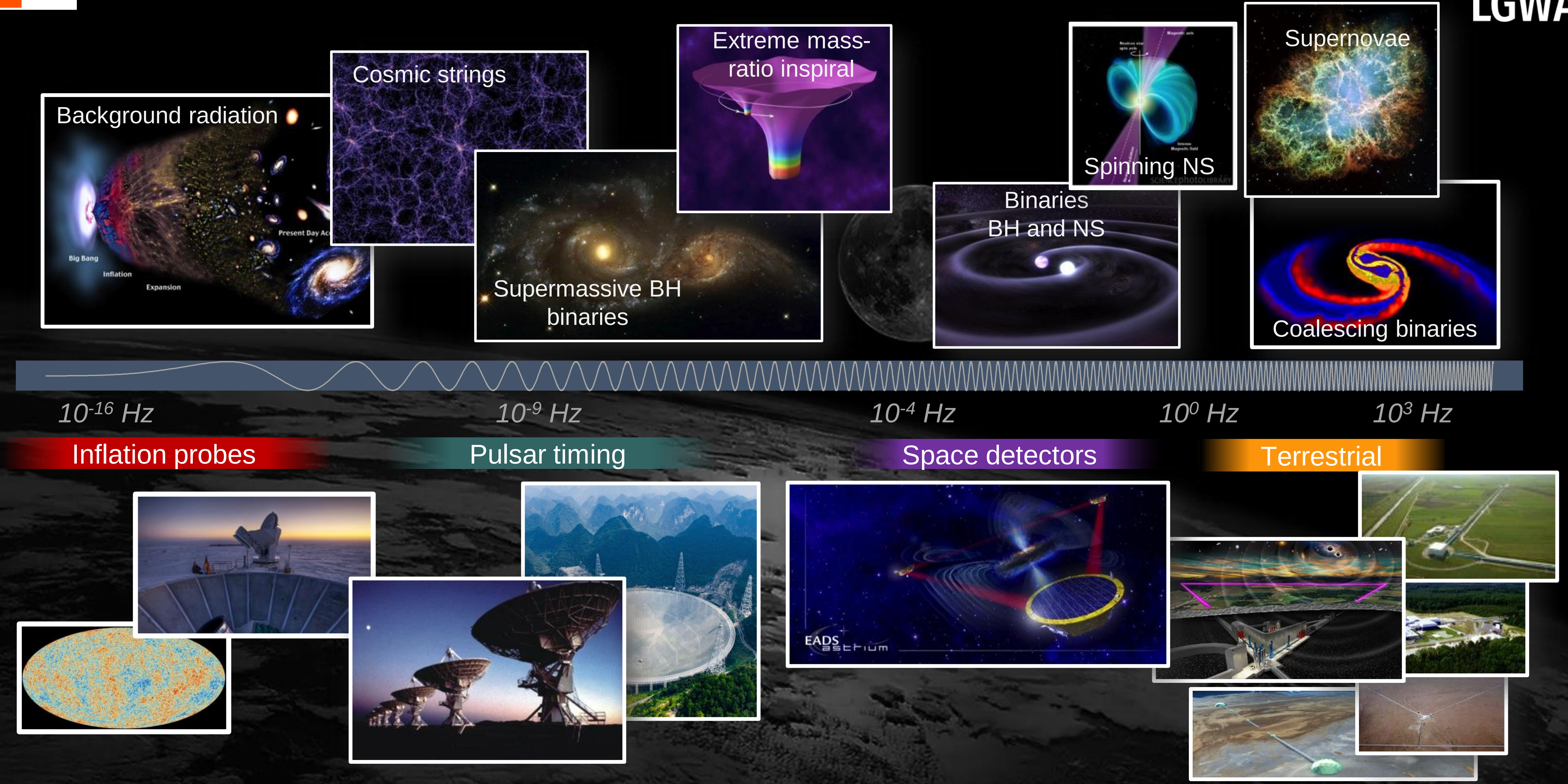
UNICAM Università di Camerino 1336

IPC Technical Institute of Physics and Chemistry, CAS

University of Birmingham

Osservatorio Astronomico della Regione Autonoma Valle d'Aosta
Observatoire Astronomique de la Région Autonome Vallée d'Aoste

GW Observations



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

A Brief History Lesson

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

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

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

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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

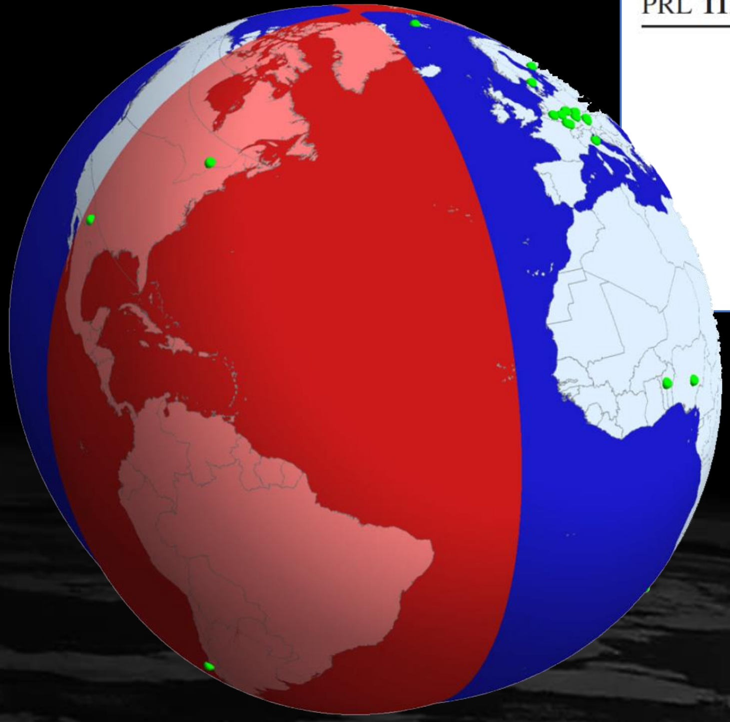
Multiply with $8\cdot10^{49}\cdot(1\text{mHz}/f)^4$ to get GW strain PSD

NASA, Apollo 17 (1972)

The **Lunar Surface Gravimeter** 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

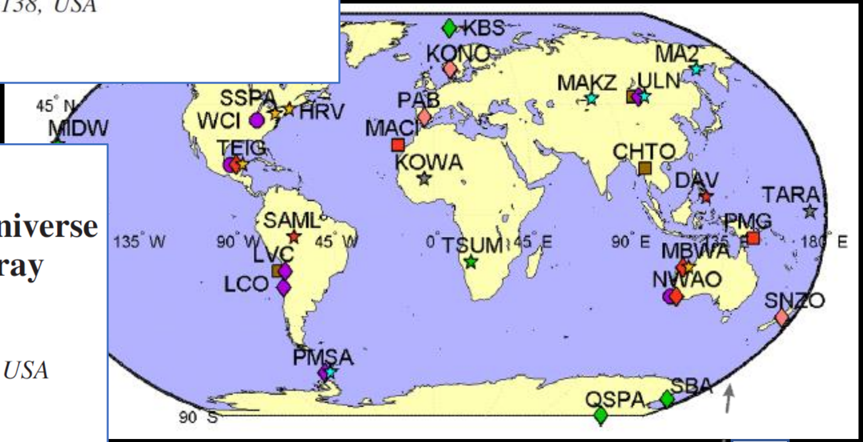
Studies of 2014



PRL 112, 101102 (2014) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2014

Upper Limit on a Stochastic Background of Gravitational Waves from Seismic Measurements in the Range 0.05–1 Hz

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 13 January 2014; published 13 March 2014)



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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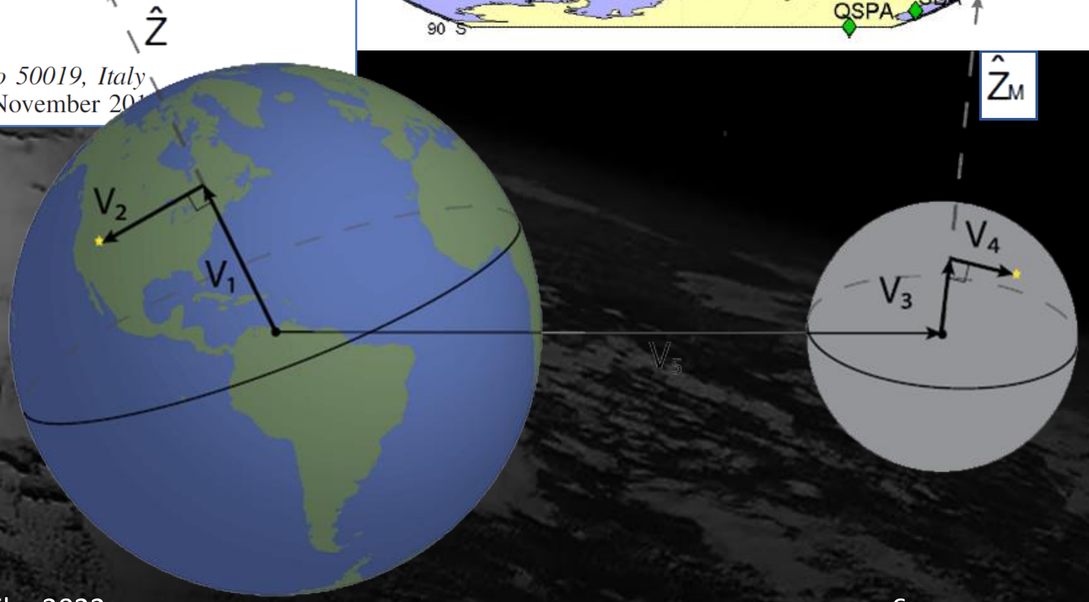
(Received 16 September 2014; published 3 November 20



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]
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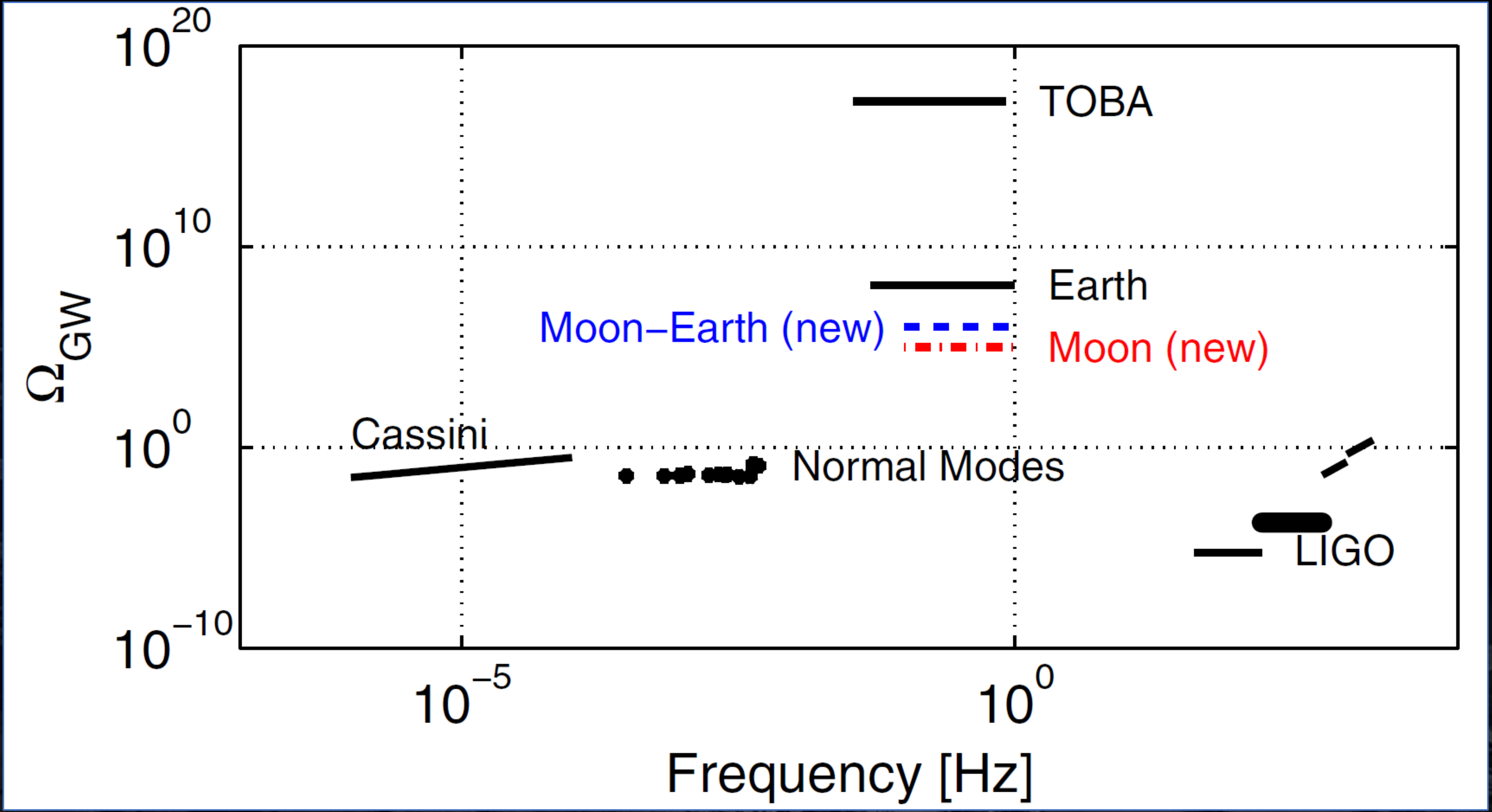
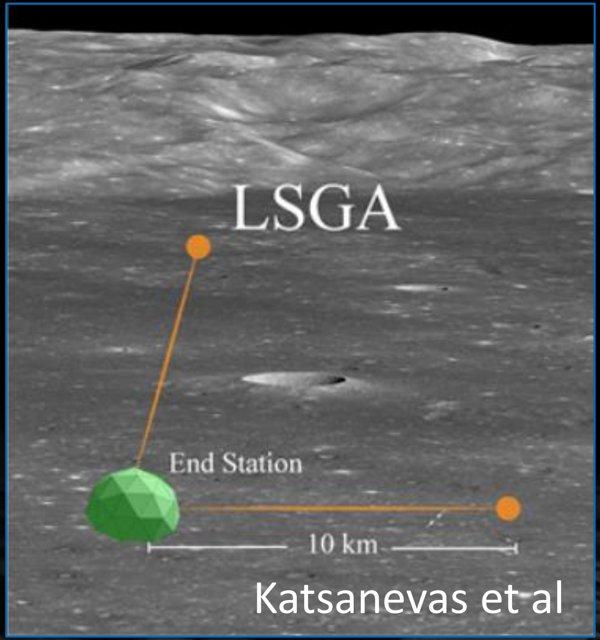
(Received 5 June 2014; published 25 August 2014)

Results of 2014 Studies

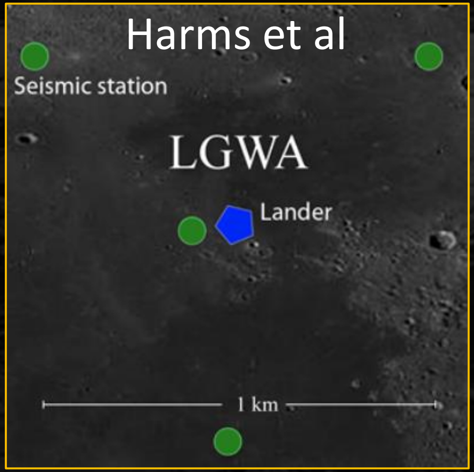


Lunar GW Detection, 2020



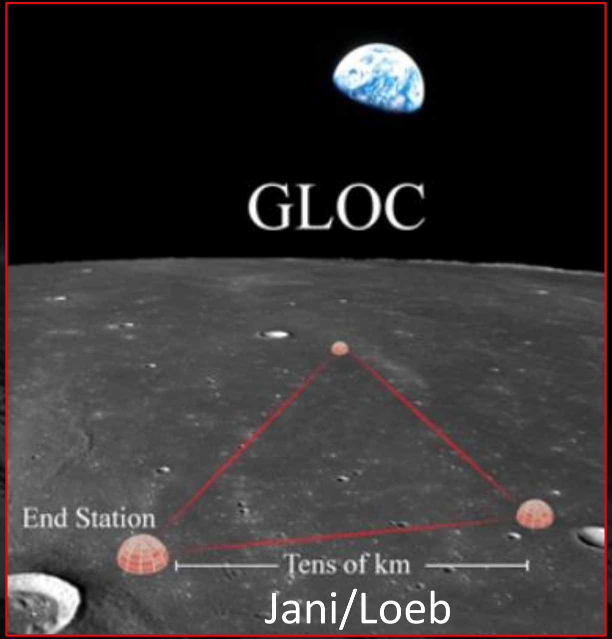
LSGA (my projection: < 50mHz)

- Laser-interferometric seismic strainmeter
- Is necessarily inferior to LGWA at frequencies where the (random) seismic background dominates
- Relies mostly on known technologies

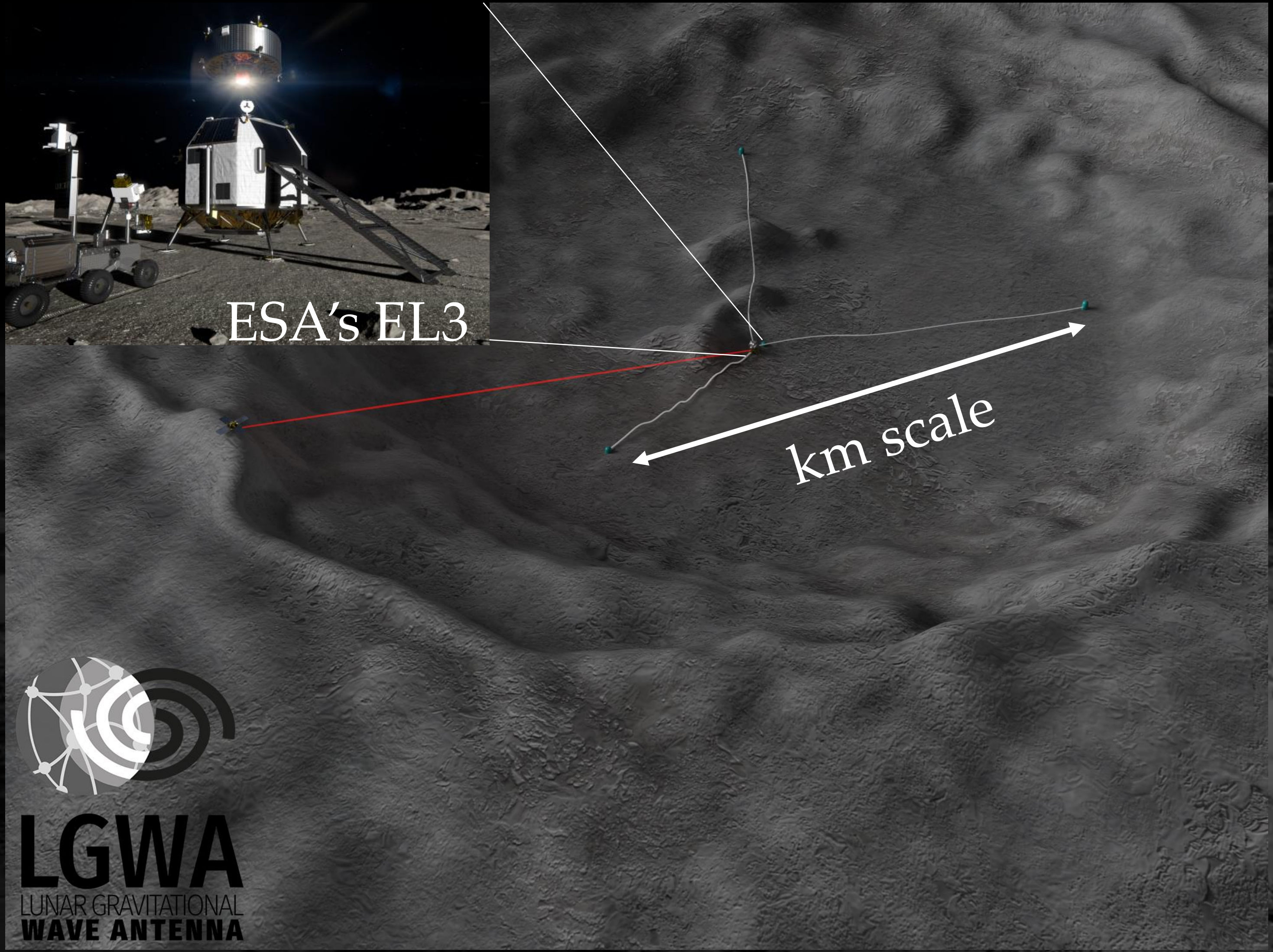


GLOC (my projection: 0.1Hz – 10Hz)

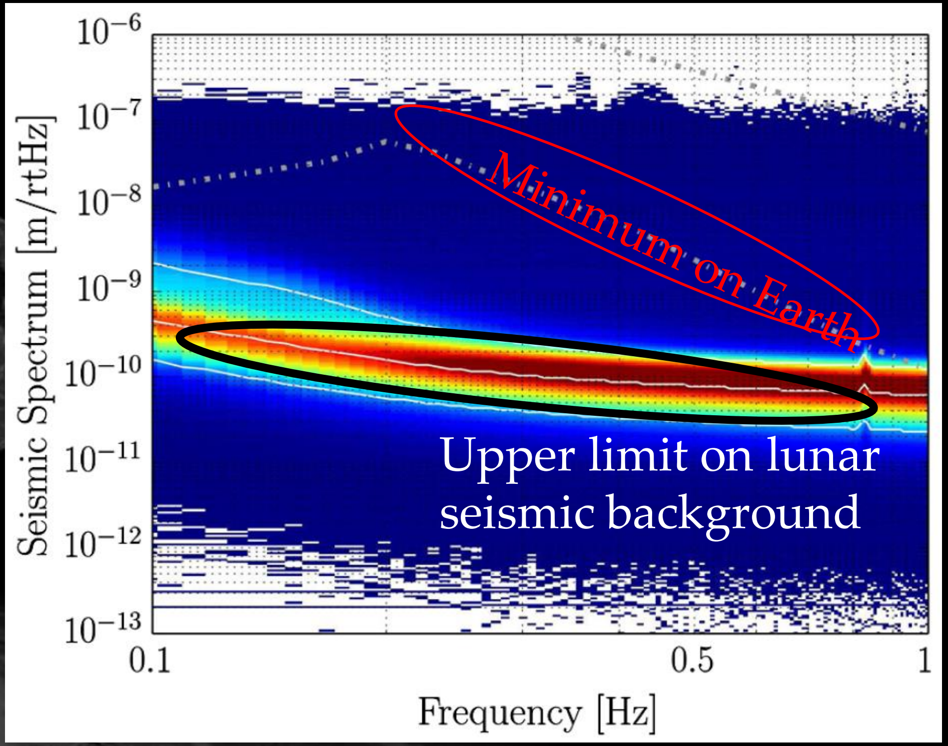
- Laser-interferometric gravitational strainmeter
- It can beat LGWA sensitivity at frequencies where the background reduction method used in LGWA meets its limits
- Requires several new technologies



LGWA Concept

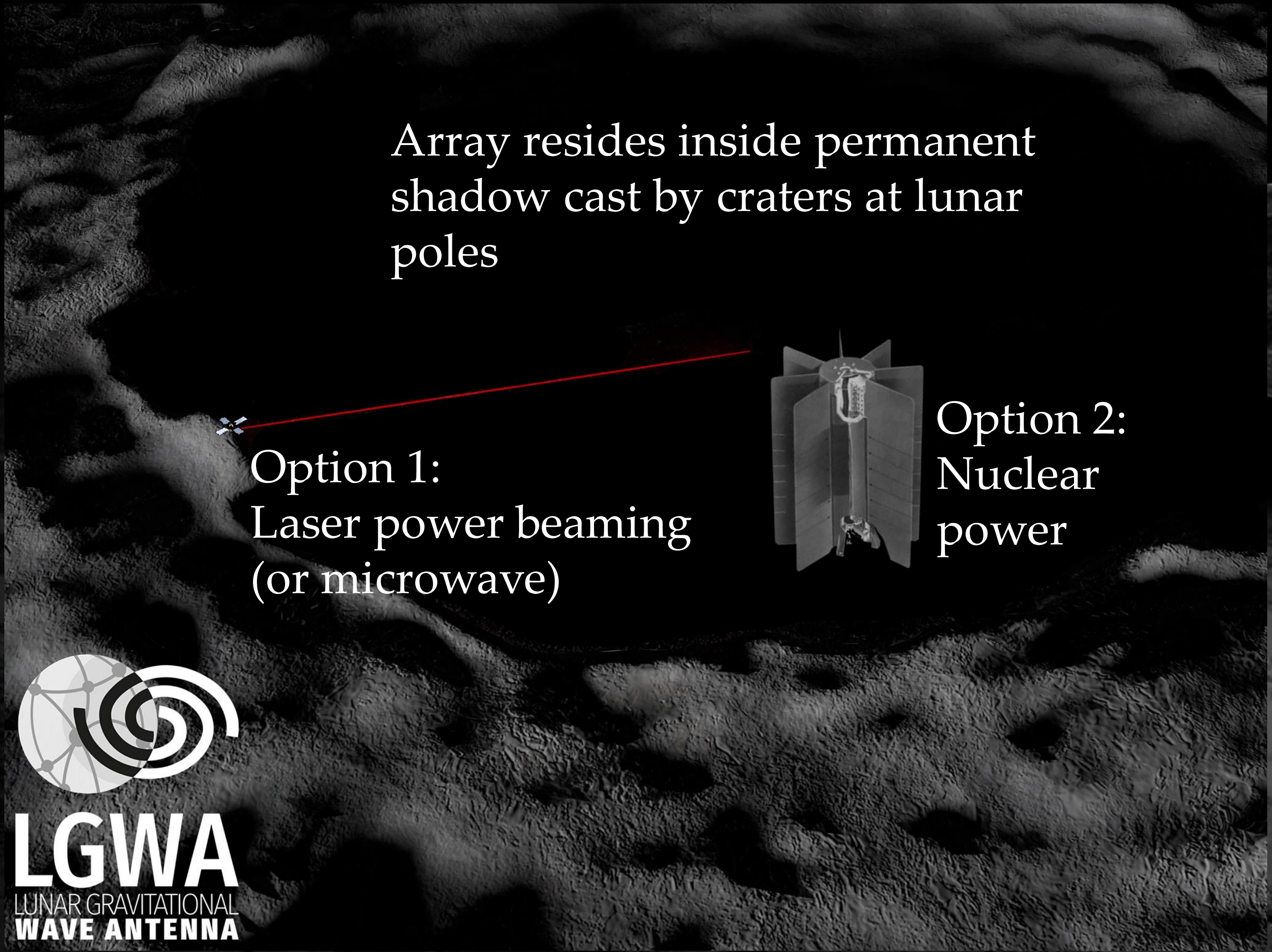


Lunar seismic spectra



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

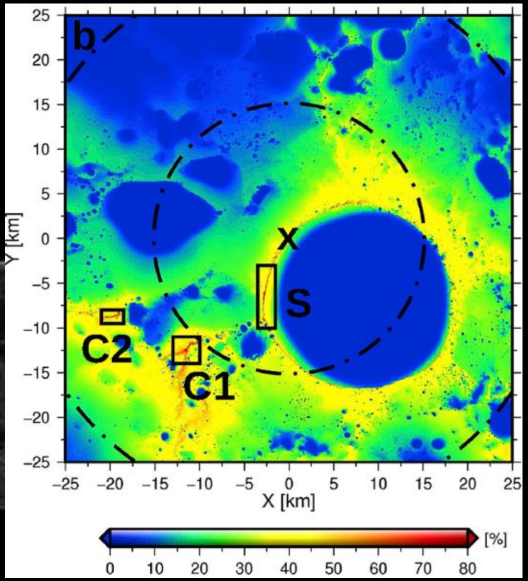
Powering



Array resides inside permanent shadow cast by craters at lunar poles

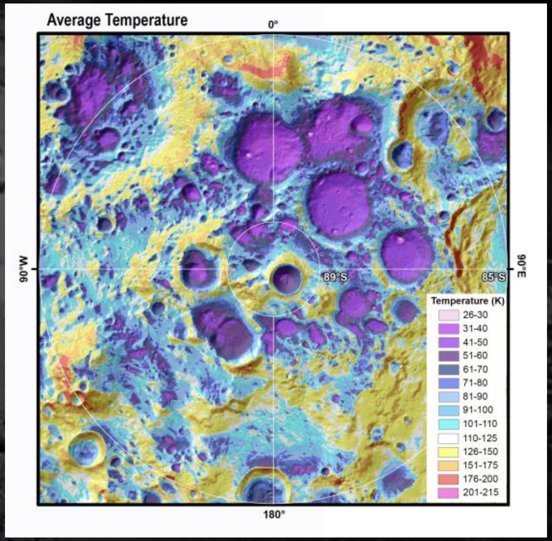
Option 1:
Laser power beaming
(or microwave)

Option 2:
Nuclear
power



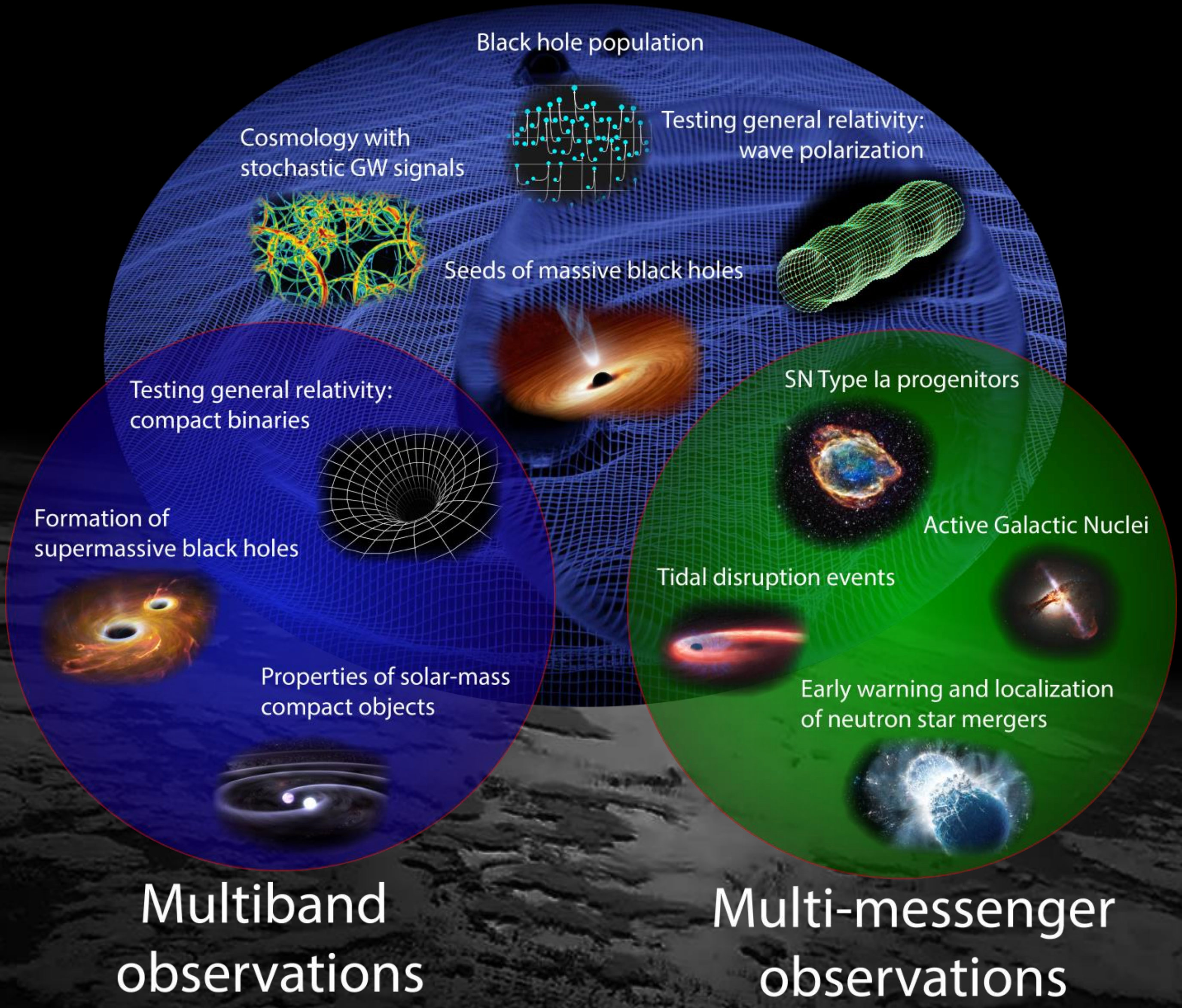
Gläser et al, 2018

Sunshine illumination near south pole



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

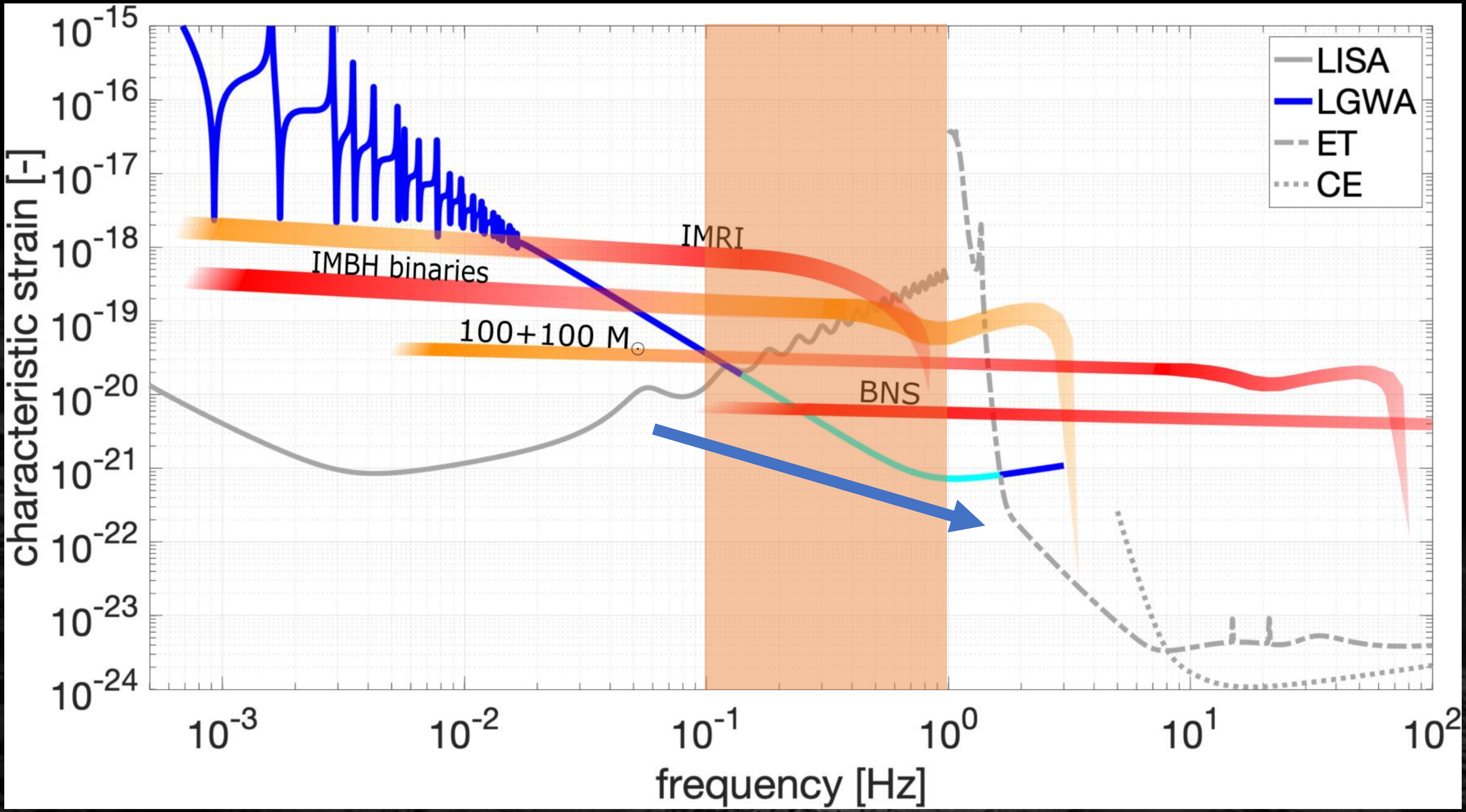
LGWA Science



Multiband GW Observations

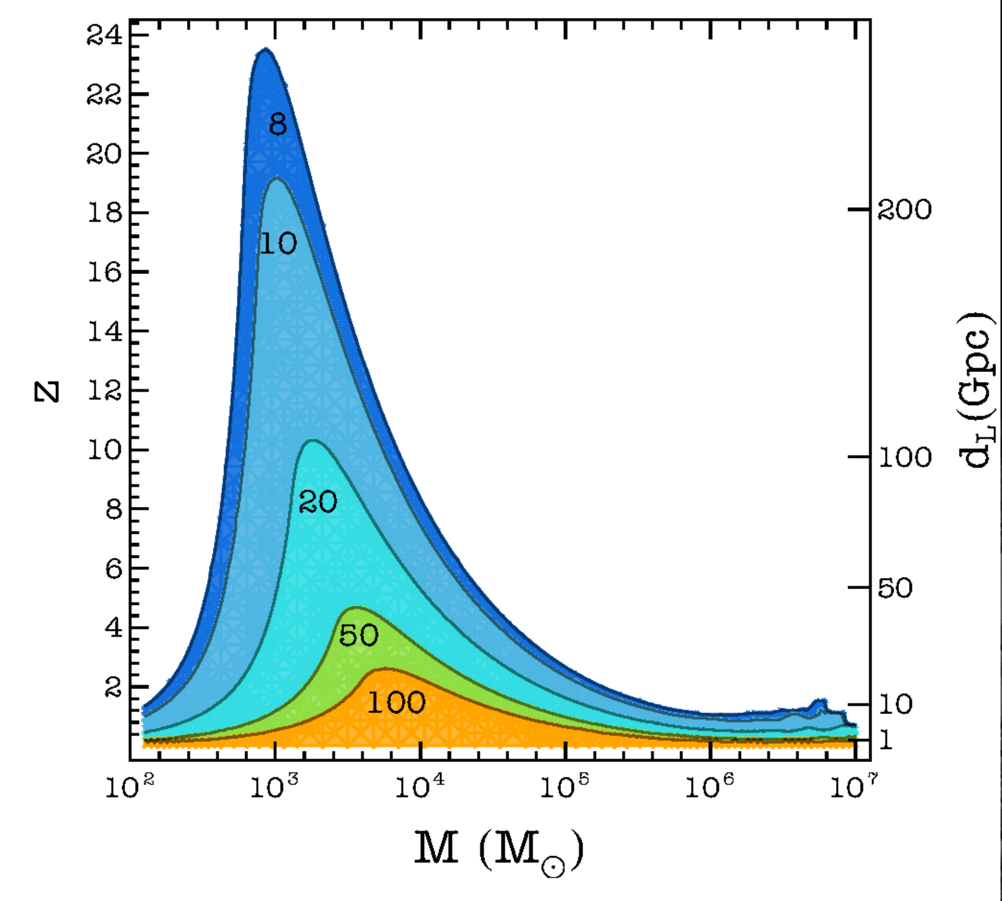
LGWA

Common GW signals with
LISA and ET/CE



A Oliveira (2021)

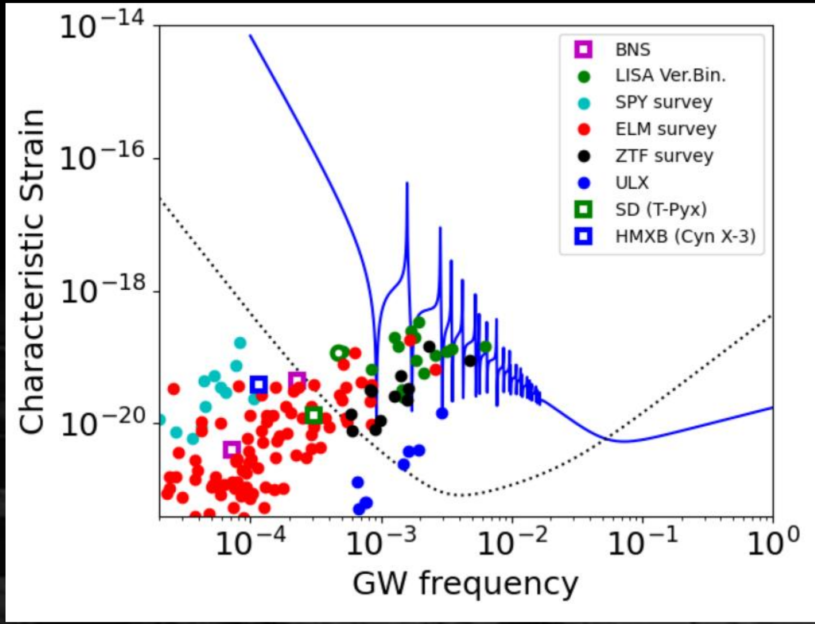
Intermediate to (Super)Massive Black-Hole Binaries



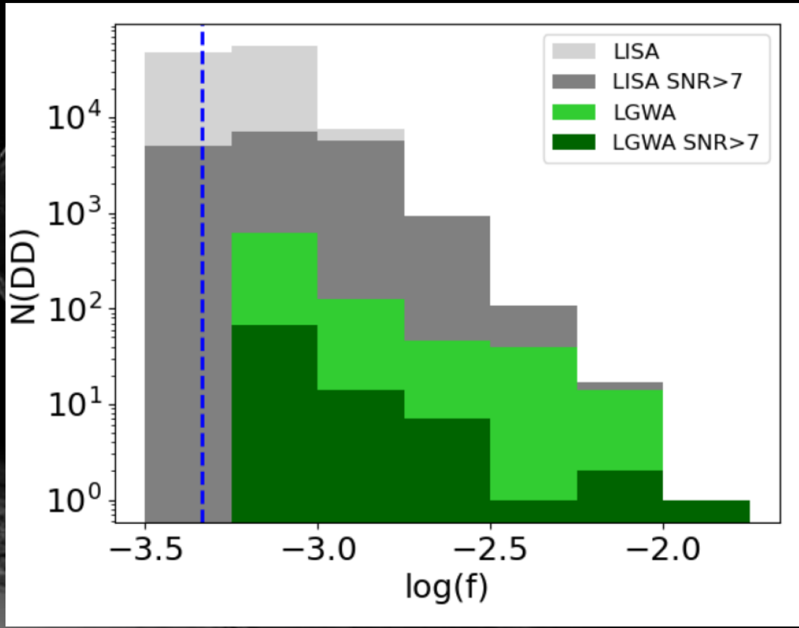
- Detection range peaks for 10^3 solar masses
- Exploration of the full range of intermediate-mass BH binaries
- Together with LISA and 3G, explore the full black-hole hierarchy, seeds of massive BHs in the early universe
- Connects to ongoing AGN studies to reveal the presence of massive BH binaries in the nearby universe

Galactic Binaries

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

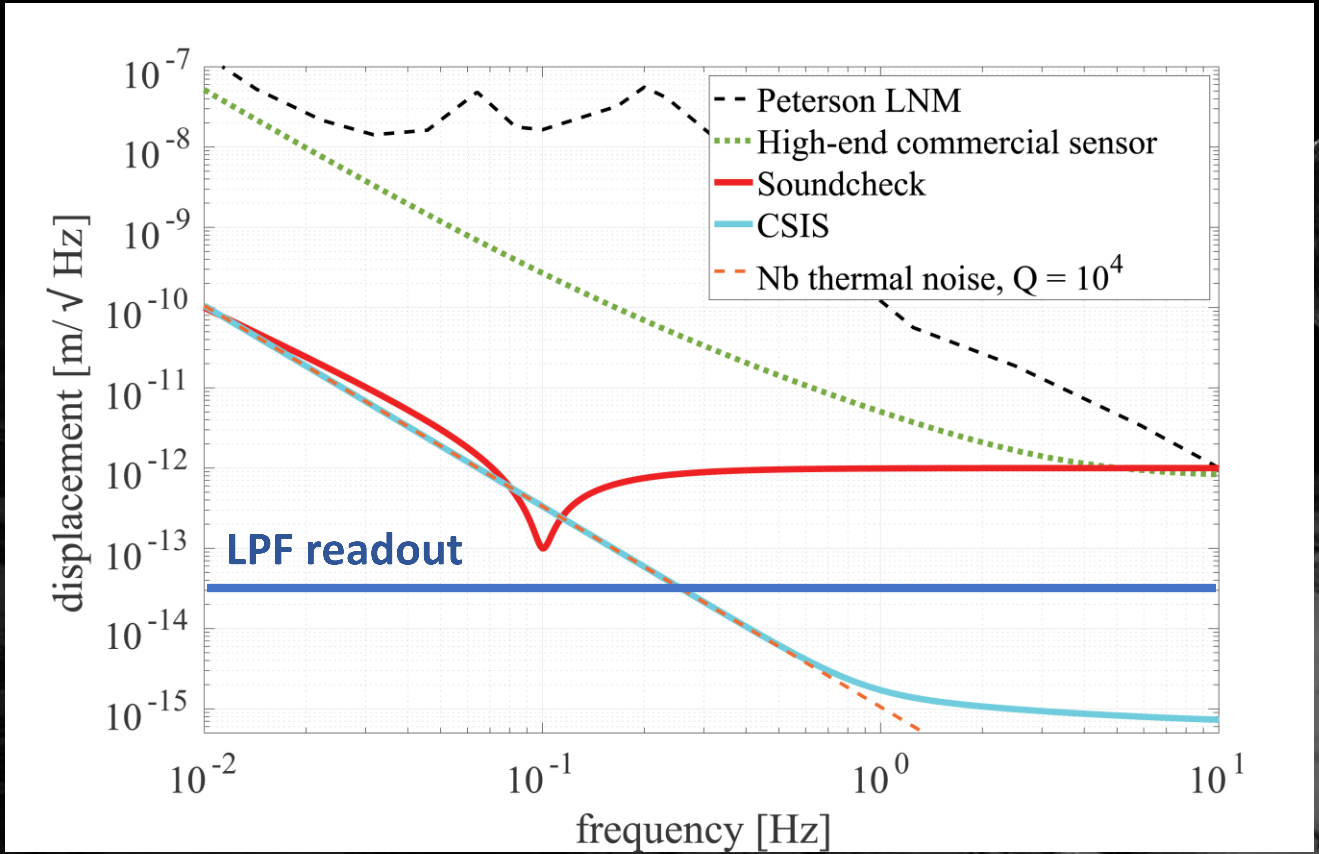


Predicted number of detections (one year observation time)



Probability of galactic WD/WD merger is low, but it would be decisive for SN Ia progenitor identification, and the long lifetime of the LGWA mission is important for this study.

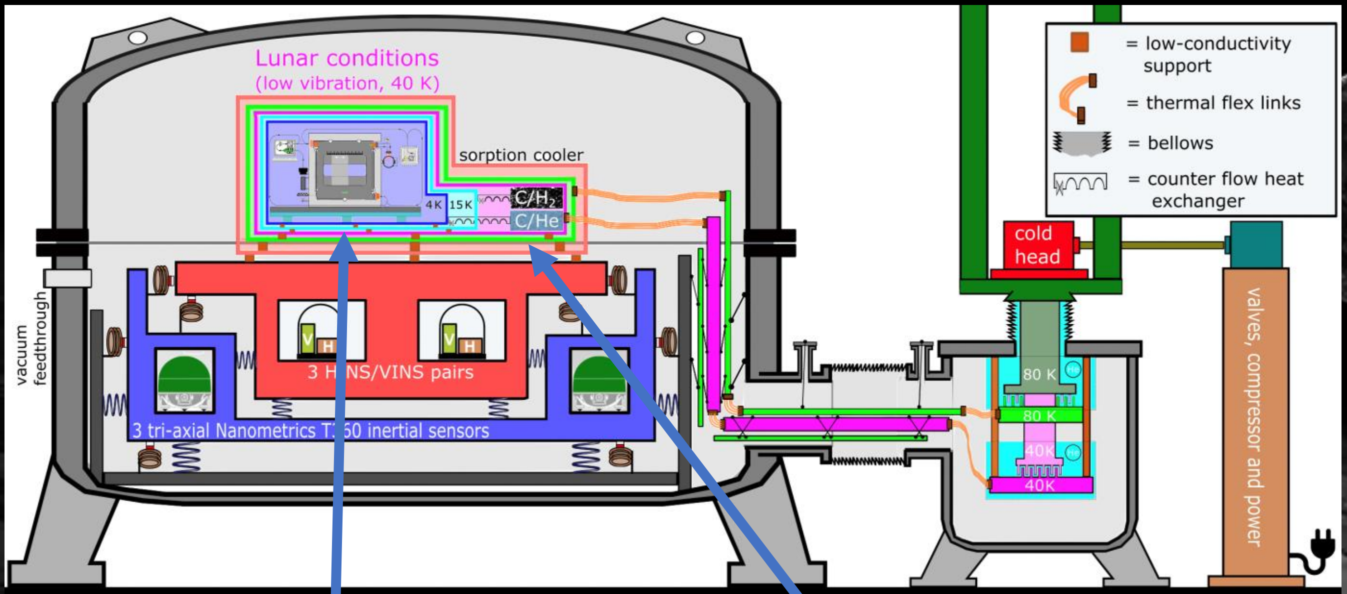
Sensor Noise Targets



- LGWA Soundcheck is a pathfinder mission to characterize the seismic background inside a PSR
- LGWA readout is less complex than the LPF interferometer
- Straight-forward measures will lead to sensitivities that meet LGWA requirement

Planned LGWA Facility

Moon Emulator & LGWA sensor



Cryogenic niobium Watt's linkage

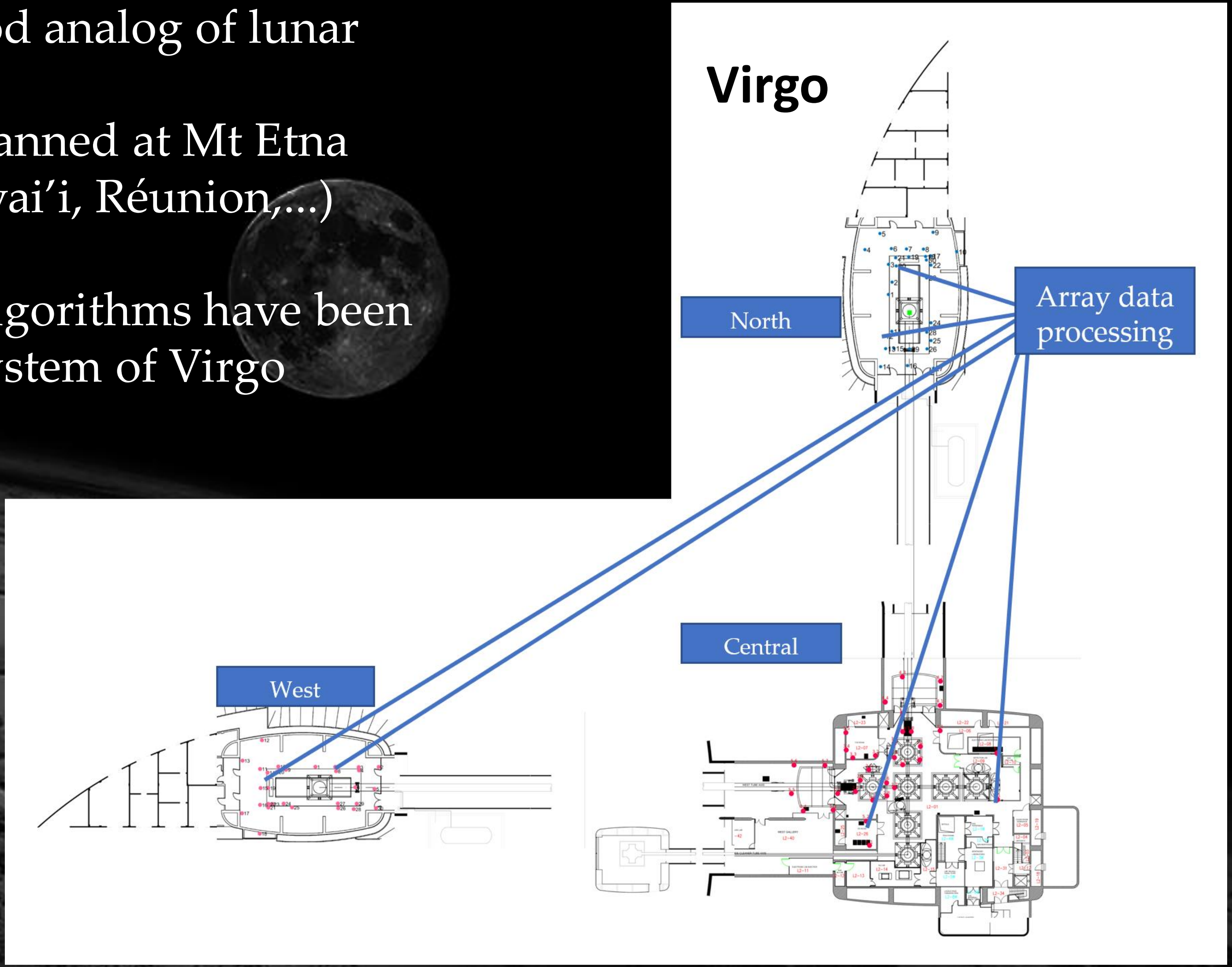
Ultra-low vibration 4K He/H sorption cryocooler

For LGWA payload testing, ultra-quiet seismic environment is required → **underground inertial platform**

Array Processing

- Volcanic landscapes can be a good analog of lunar regolith
- Background cancellation tests planned at Mt Etna (could also be carried out at Hawai’i, Réunion,…)
- Collaboration with INGV
- Optimal array-data processing algorithms have been developed for noise-reduction system of Virgo

Space missions at Mt Etna
(image: ROBEX)

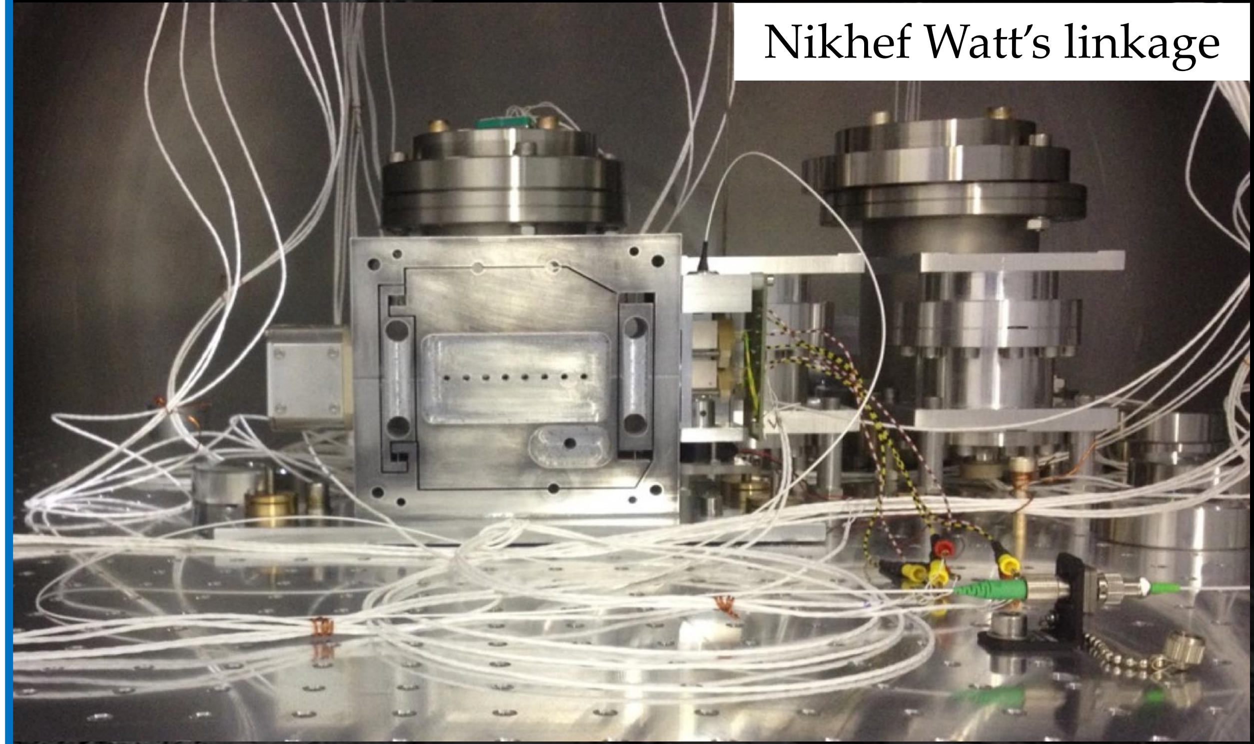


LGWA Soundcheck

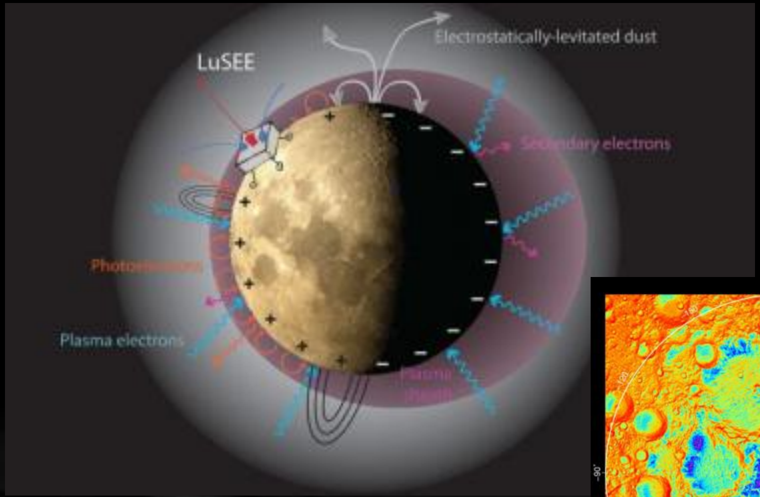
Purpose:
- Characterization of the seismic environment inside a permament shadow (where thermal disturbances are absent)
- Technology demonstration

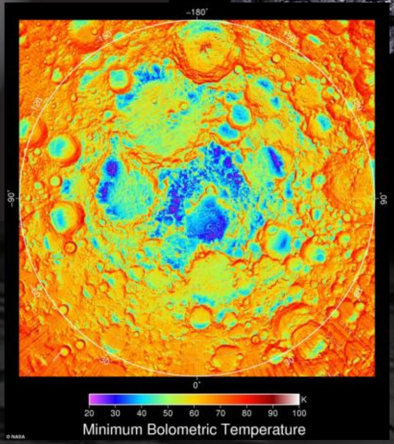
Concept
- Short lifetime (few weeks) battery powered
- Compatible with CLPS-PRISM, e.g., ground deployment of the sensor is not required
- Sub-pm/sqrt(Hz) sensitivity throughout the decihertz band
- Laser-interferometric readout and Watt's linkage as mechanical system
- No cryocooler

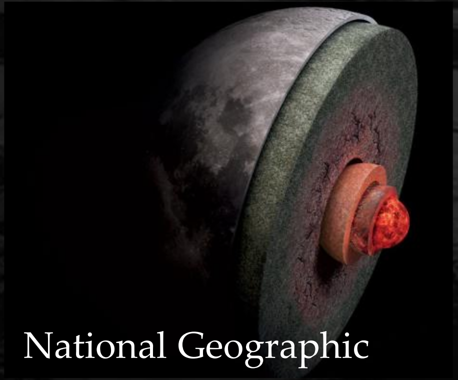
- Inertial platforms for performance measurements are already available (room temperature) or under construction (cryogenic)
- Niobium Watt's linkage under development


Nikhef Watt's linkage

LGWA and Lunar Exploration






National Geographic

Future lunar geophysical missions

- Farside Seismic Suite (approved, 2024/25)
- Lunar Geophysical Network (proposed, early 2030s)

Moon as a spherical detector

- Seismic background
- Moon's internal structure

Important environmental factors

- Local geology
- Temperature and thermal fluctuations
- Radiation (much less inside a PSR)
- Dust
- Electromagnetic fields and charges

Preliminary Target for the Timeline