Lunar Gravitational-Wave Antenna

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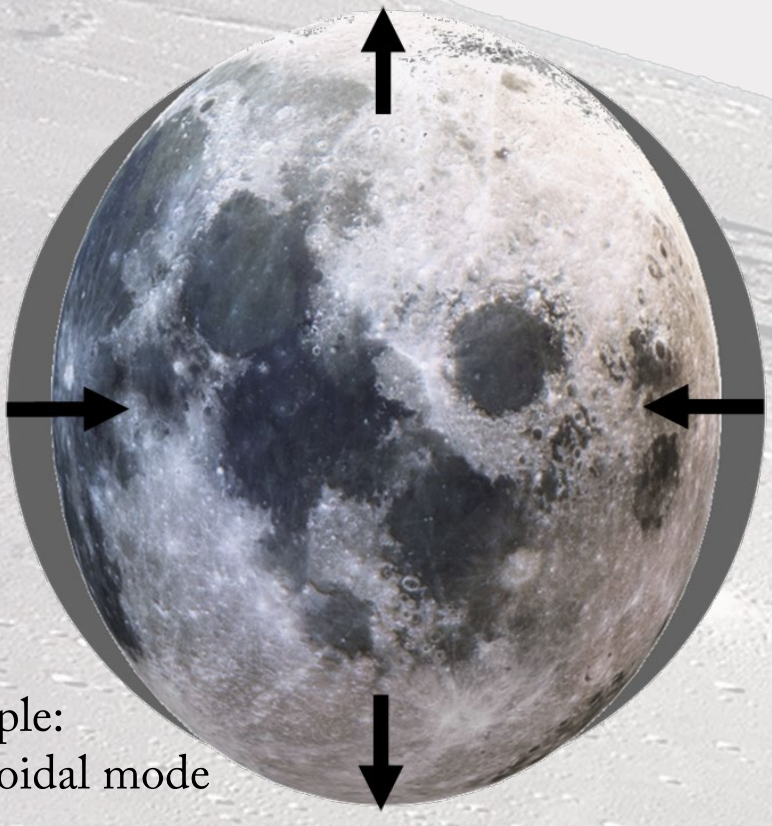
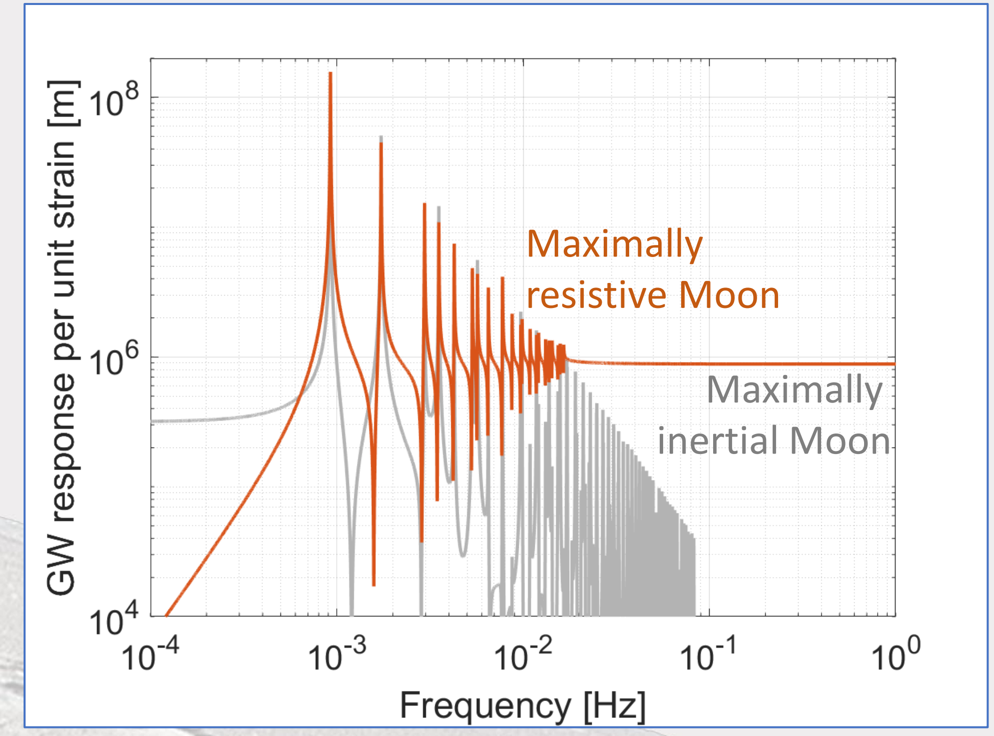
Measurement Principle

GWs excite quadrupolar, spheroidal and toroidal vibrations of a planet, which can be monitored by inertial sensors



Example:
Spheroidal mode



On-resonance GW observations

- Exploit the resonant enhancement of the Moon's response

Off-resonance GW observations

- Since inertial sensors are used for the vibration monitoring, the less the Moon responds to GWs the better.

Historical Context

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

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

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

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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

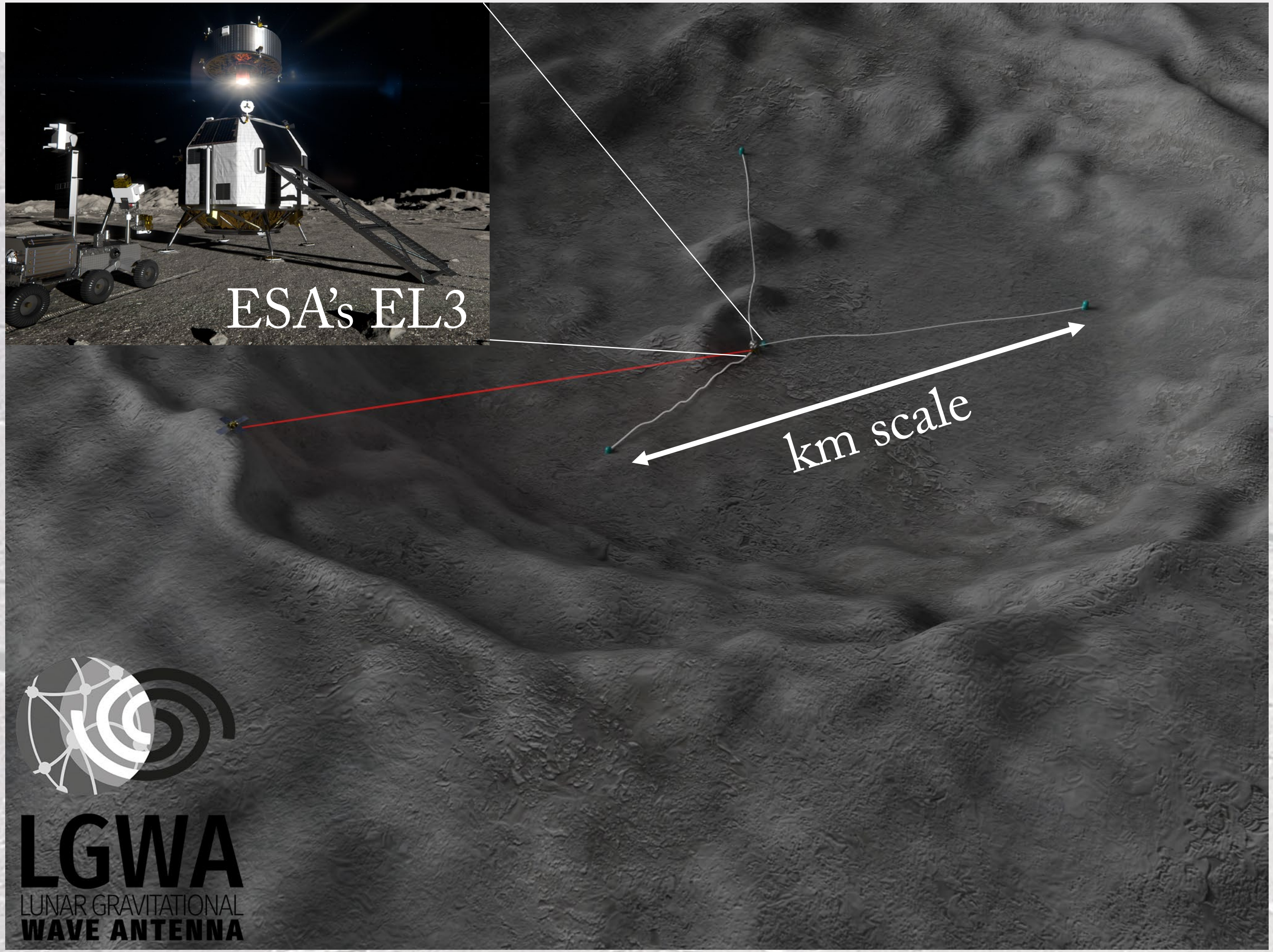
Multiply with $8\cdot10^{49}\cdot(1\text{mHz}/f)^4$ to get GW strain PSD

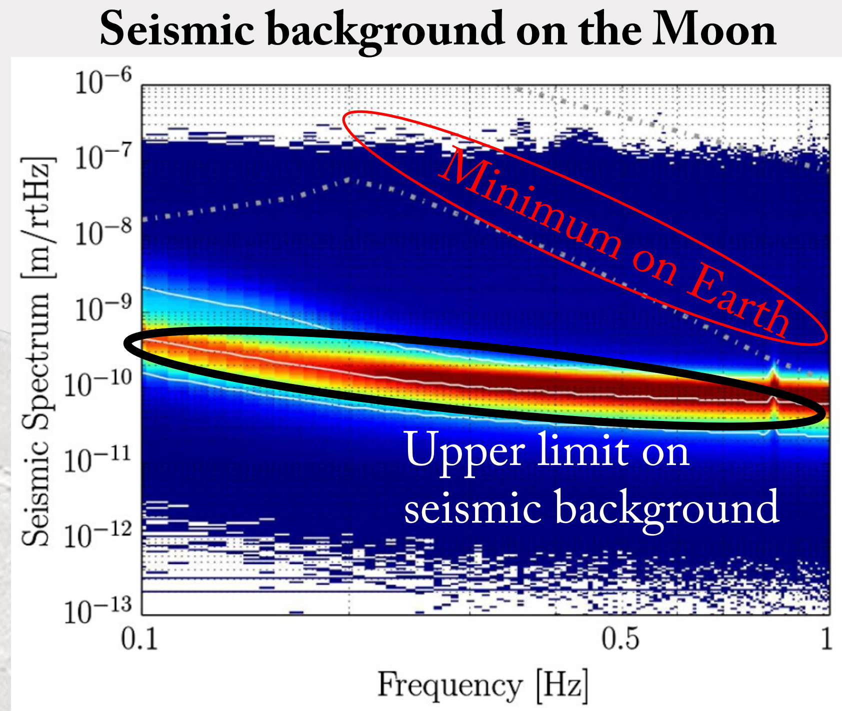
Lunar Surface Gravimeter

NASA, Apollo 17 (1972)

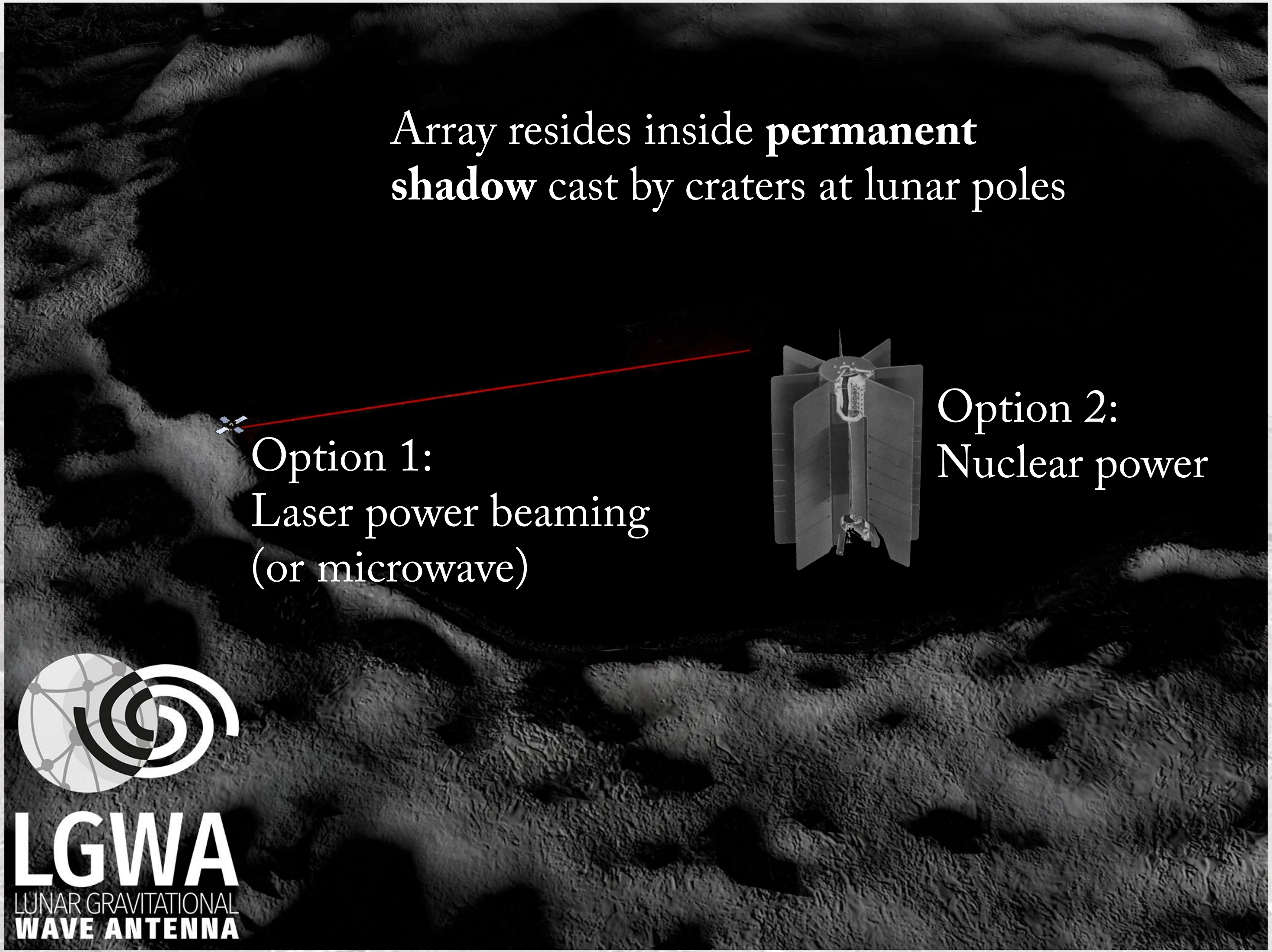
It was then determined that an error in arithmetic made by La Coste and Romberg, and known to the firm's highest officials, had not been corrected by La Coste and Romberg. This led to an instrument which had excellent performance in earth g and was just barely outside of the tolerances for variations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

LGWA Concept





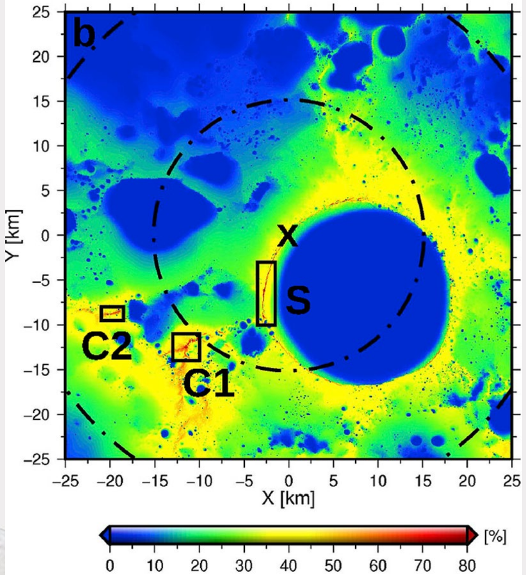
Powering



Array resides inside **permanent shadow** cast by craters at lunar poles

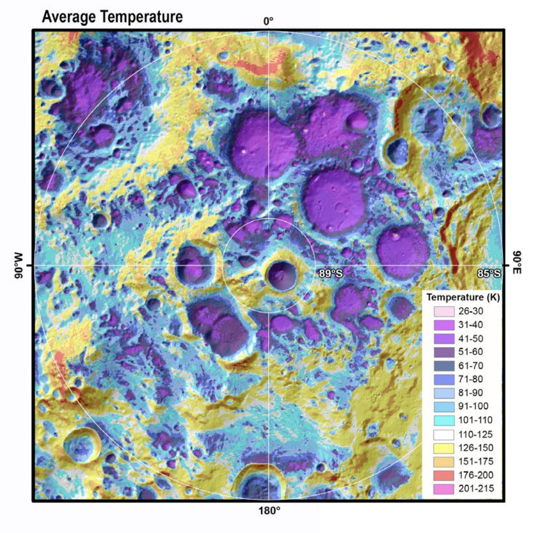
Option 1:
Laser power beaming
(or microwave)

Option 2:
Nuclear power



Gläser et al, 2018

Sunshine illumination near south pole

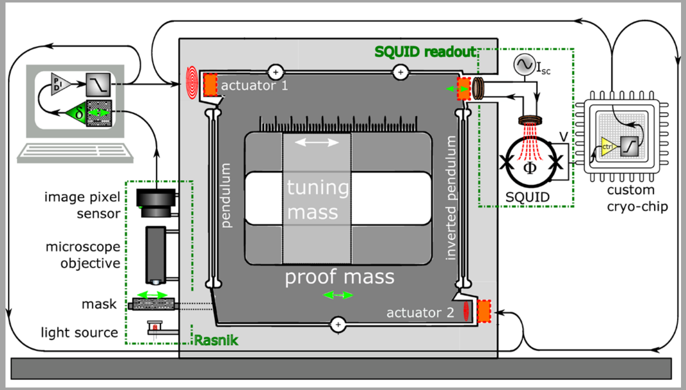


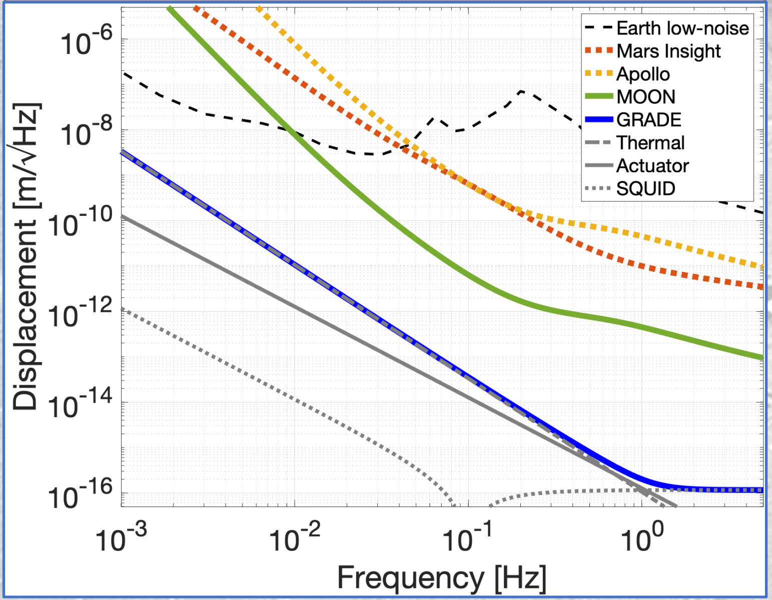
Temperature <40K in some permanent shadows of the lunar north and south poles.

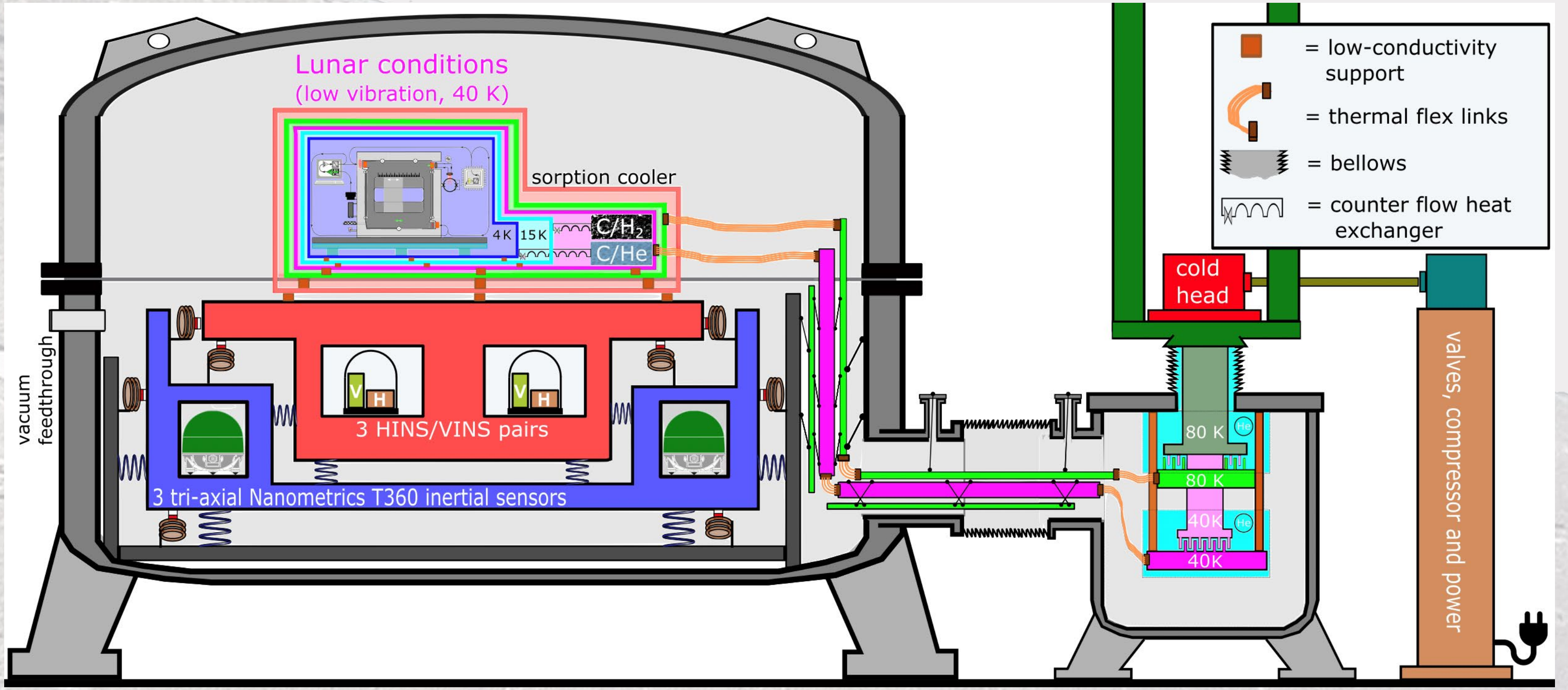
LGWA Payload

Groups involved in proof-of-concept:
University of Twente (low-vibration cryocooling)
Nikhef (mechanical designs)
University of Camerino, TIPC Beijing (superconductors, SQUIDs)
GSSI (noise cancellation, control)
University of Liège (active seismic isolation)
UCLouvain (sensor assembly)

LGWA inertial sensor







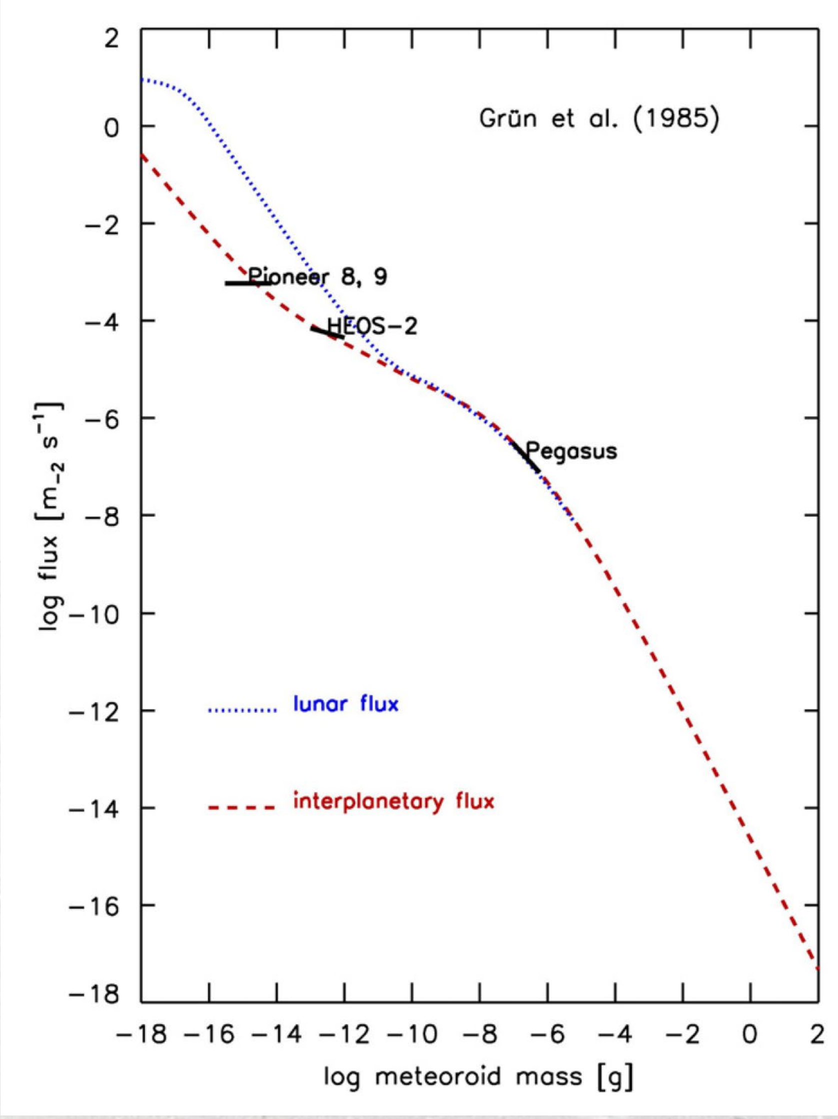
Seismic Background

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

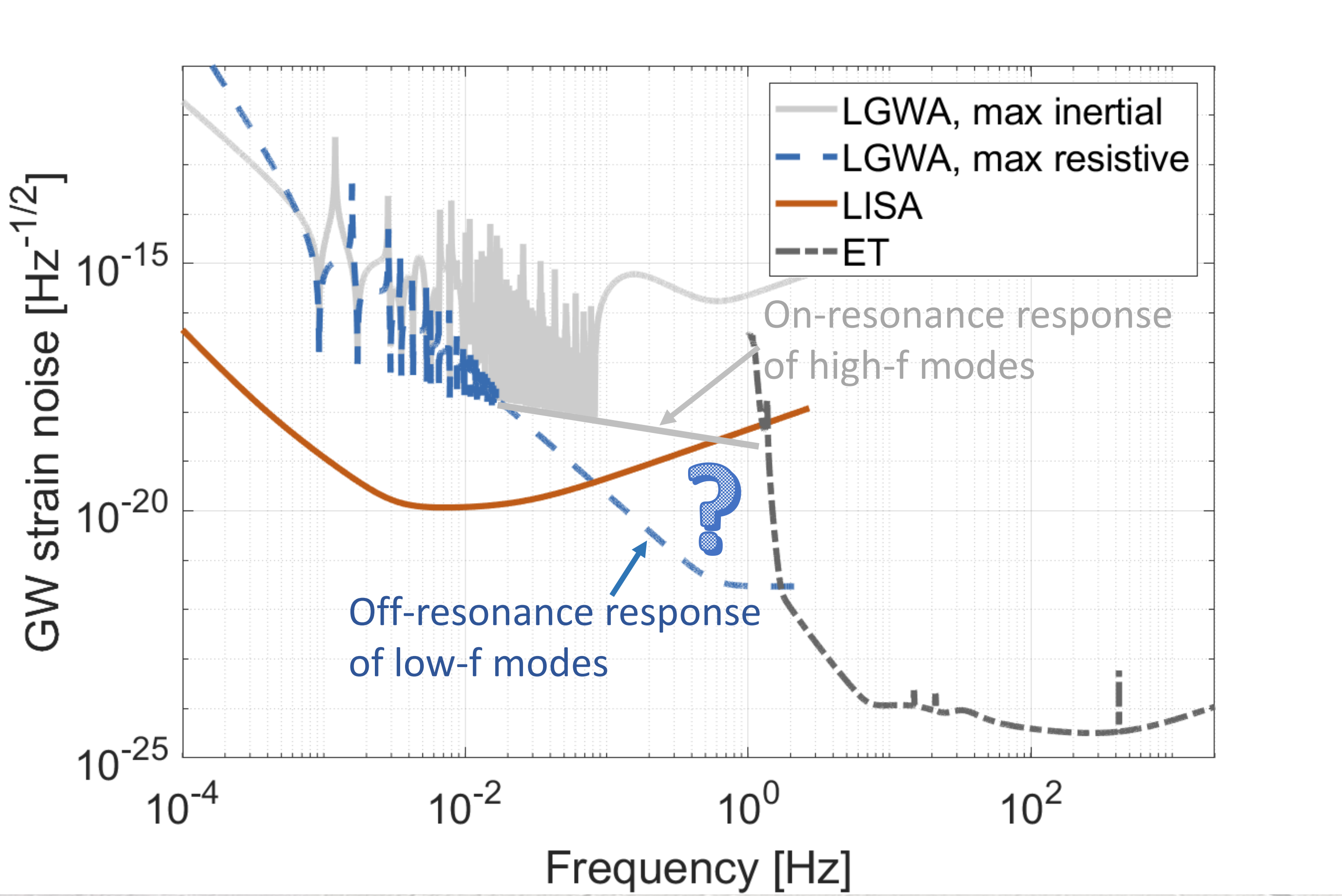
- Limited by number of seismometers on the Moon
- Several orders of magnitude reduction possible, but with only 4 sensors, the reduction will greatly depend on properties of the seismic field



Grün et al, 2011

LGWA Sensitivity

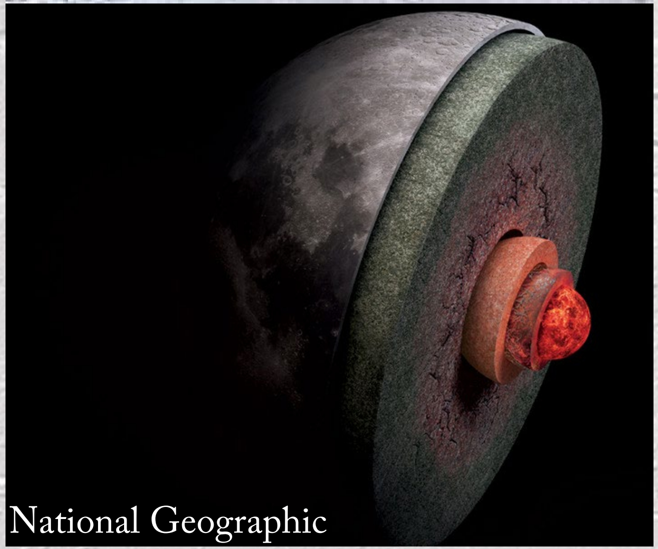
1mHz to few Hz



- Synergy with LISA: common observation of sources for better understanding of the sources
- Synergy with Einstein Telescope: warnings of binary neutron-star mergers, better PE with common observations
- Multi-messenger astronomy (e.g., with SN Ia)
- Compact binaries from Supermassive BH to WDs

Geophysical Observations

Lunette: robotic lander concept for lunar geophysical stations



National Geographic

Lunar Geophysical Network (prioritized by the Planetary Decadal Survey) might be deployed by the end of this decade.

Farside Seismic Suite (FSS) recently selected as NASA CLPS mission. Deployment foreseen in 2023/24.

Europe is getting organized with newly formed ESA **Geophysics Topical Team**.

Targets important to LGWA

- Seismic background from meteoroid impact
- Origin of thermal moonquakes
- Moon's internal structure
- Magnetic fluctuations
- Temperatures and thermal fluctuations

Working groups will be forming after this summer.

WG 1: GW Science and Multi-messenger Astronomy
WG 2: Lunar Science and Exploration
WG 3: Payload
WG 4: Deployment and Operation

Join us!