The Moon: the new frontier for Gravitational Waves astrophysics with LGWA

Lunar Gravitational Wave Antenna

Francesca Badaracco on behalf of LGWA collaboration

INFN GENOVA

LGWA Collaborating institutes

INAF ISTITUTO NAZIONALE DI ASTROFISICA

TU berlin

UNIVERSITY OF TWENTE.

UNIVERSITÀ DEGLI STUDI DI PADOVA

IFCA Instituto de Física de Cantabria

UNIVERSITY OF COPENHAGEN

UCLouvain

INFN Istituto Nazionale di Fisica Nucleare

POLITECNICO MILANO 1863

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

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

GSSI

UNIVERSITY OF BIRMINGHAM

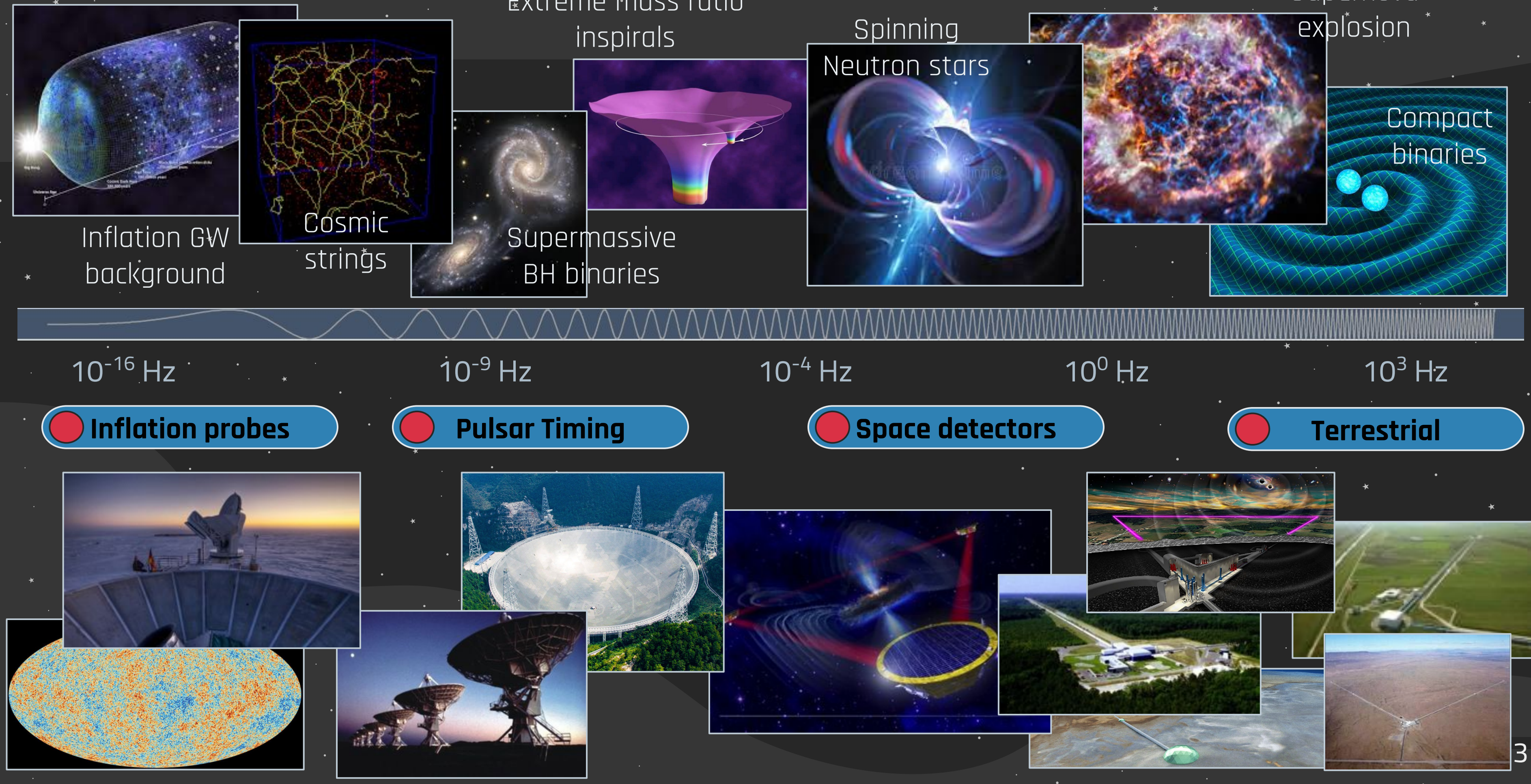
Osservatorio Astronomico della Regione Autonoma Valle d'Aosta
Observatoire Astronomique de la Règion Autonome Vallée d'Aoste

UNICAM Università di Camerino 1336

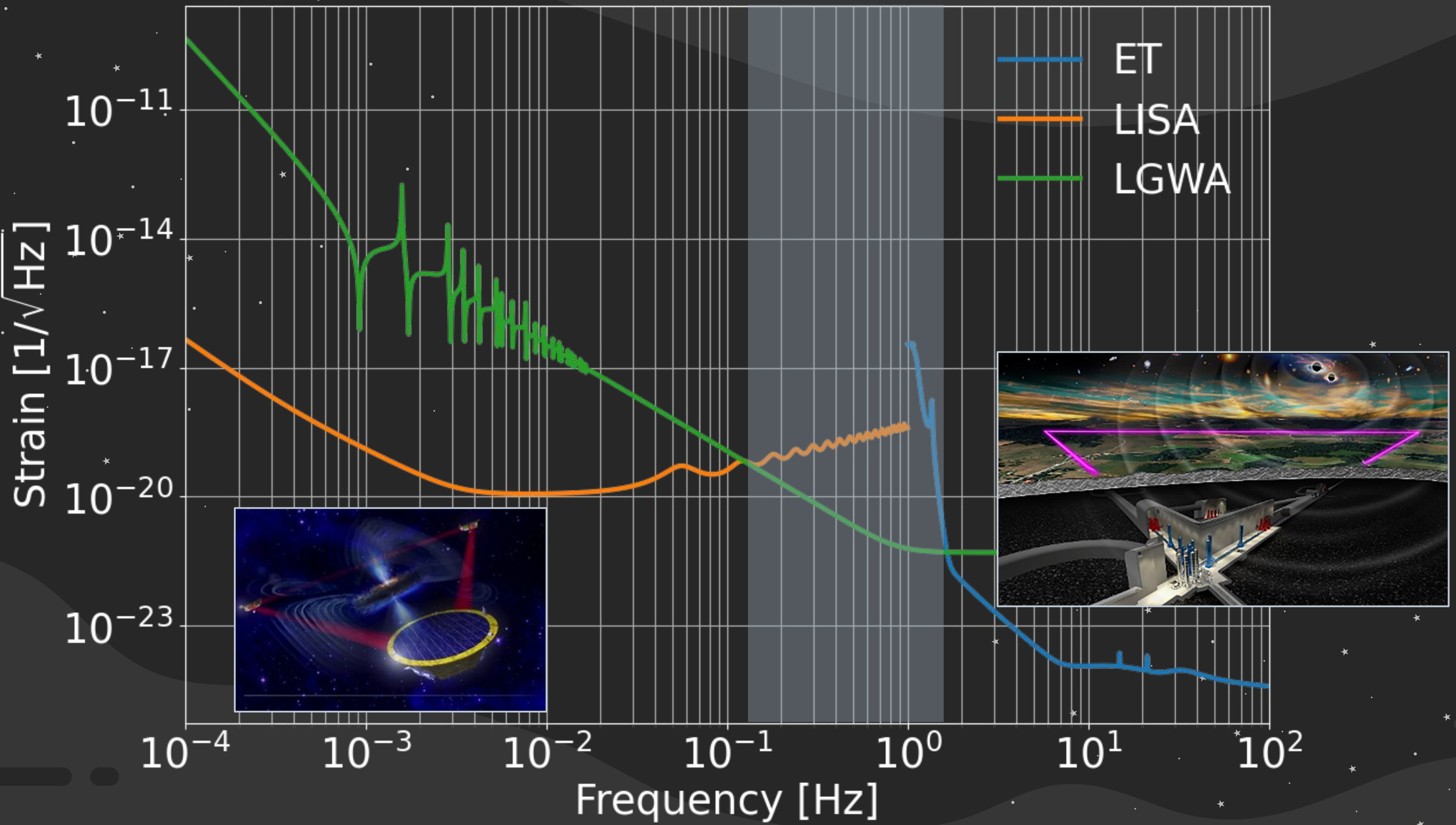
IPC Technical Institute of Physics and Chemistry, CAS

GW observations and its spectrum

Slide credits: Matt Evans

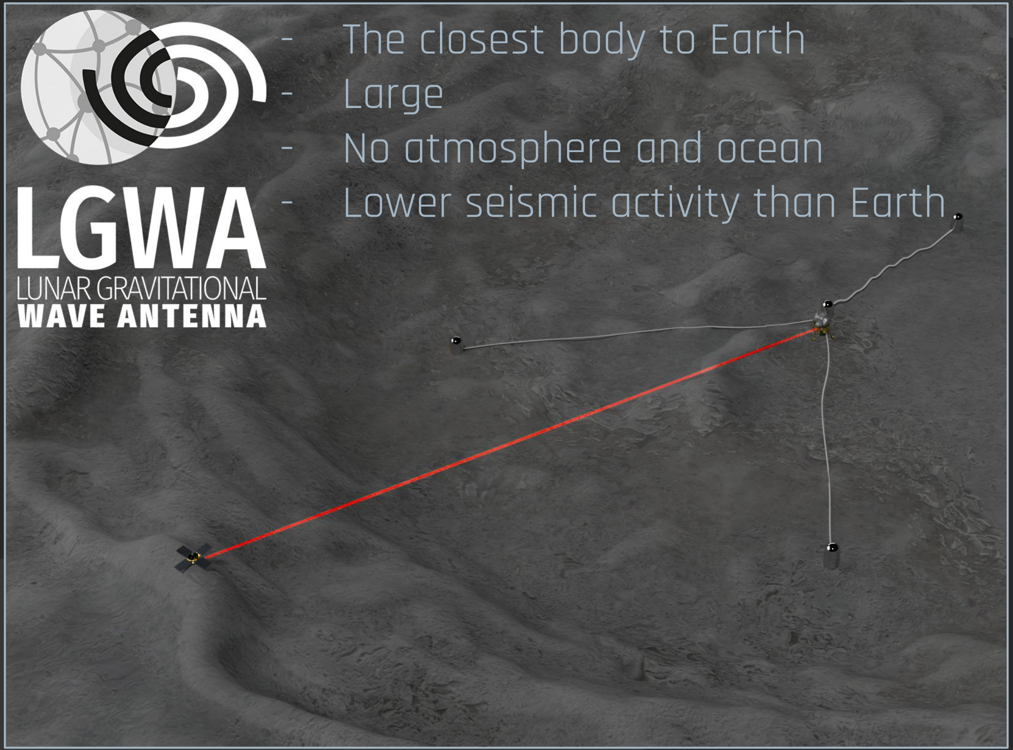


LGWA sensitivity comparison

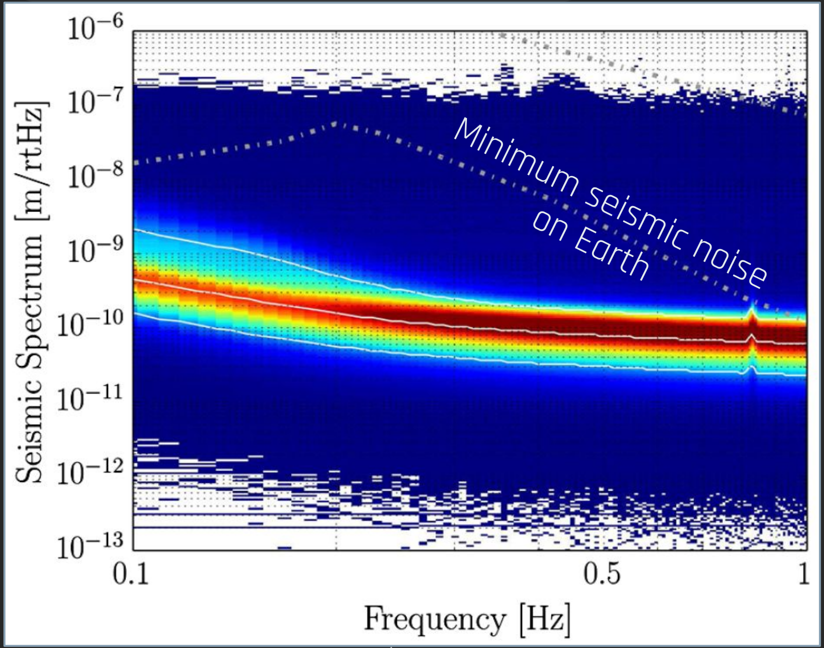


Concept & Working principle

- The closest body to Earth
- Large
- No atmosphere and ocean
- Lower seismic activity than Earth



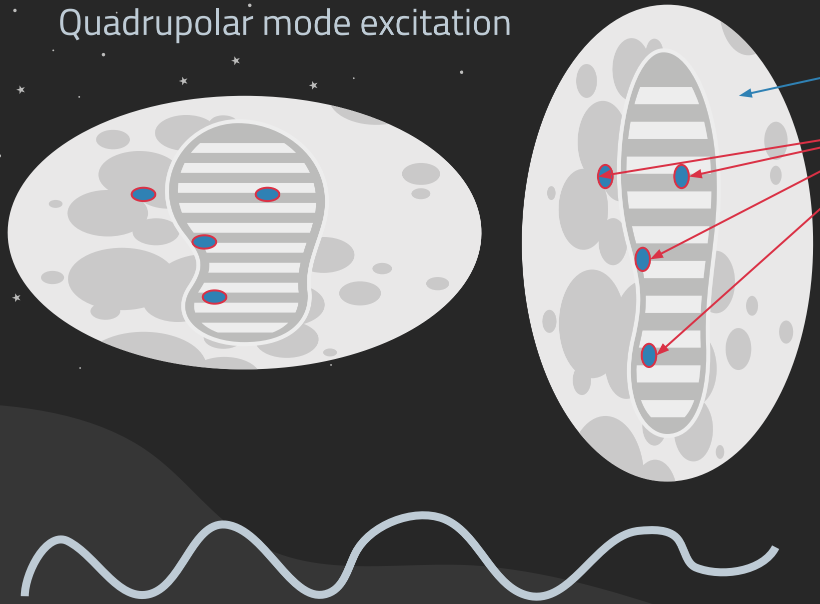
Moon's seismic noise



Michael Coughlin and Jan Harms Phys. Rev. D 90, 102001

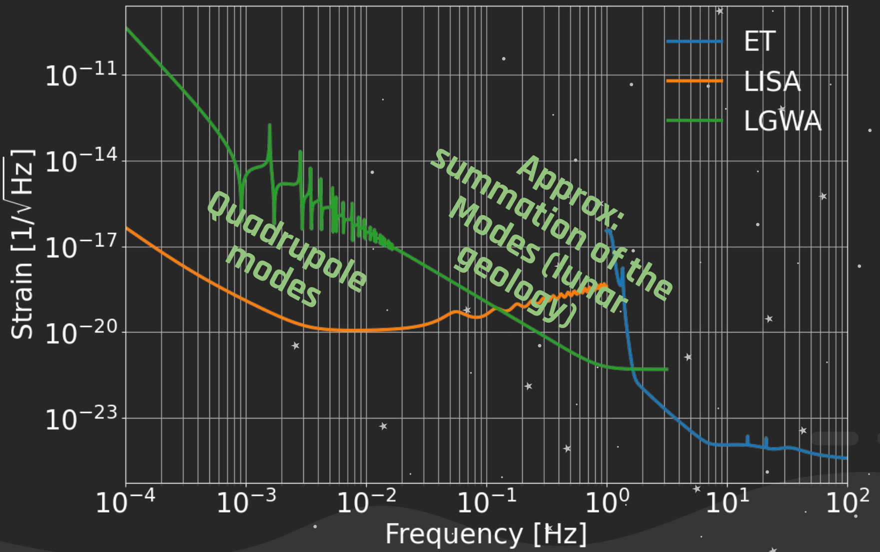
Concept & Working principle

A **GW** sweeping over the Moon will excite its **quadrupole modes** of vibration, since the driving **forces** in the wave have **quadrupolar spatial distributions**.



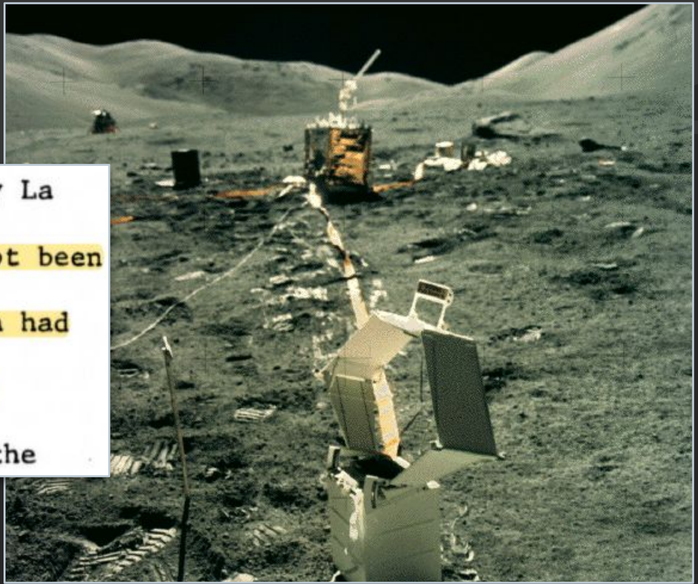
Moon = Detector

Seismic sensor = Detector readout



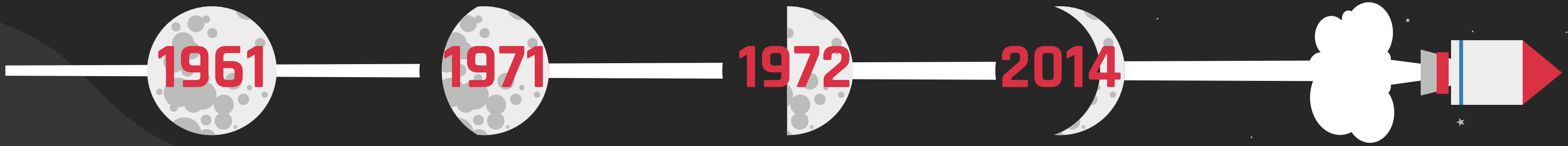
A bit of history…

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



FORWARD, R. et al. Upper Limit for Interstellar Millicycle Gravitational Radiation. Nature 189, 473

Apollo 17: **Lunar Surface gravimeter** experiment

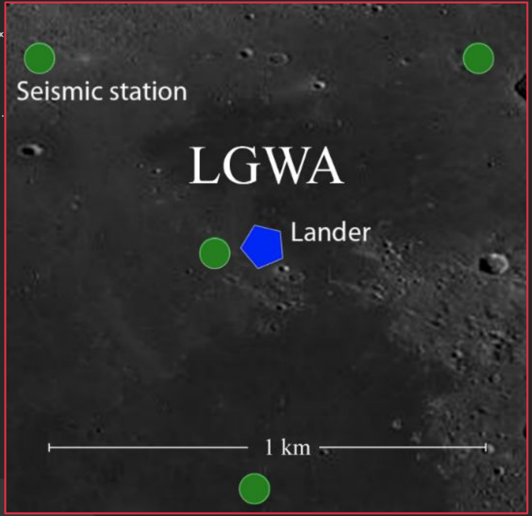


CLAIM!!!

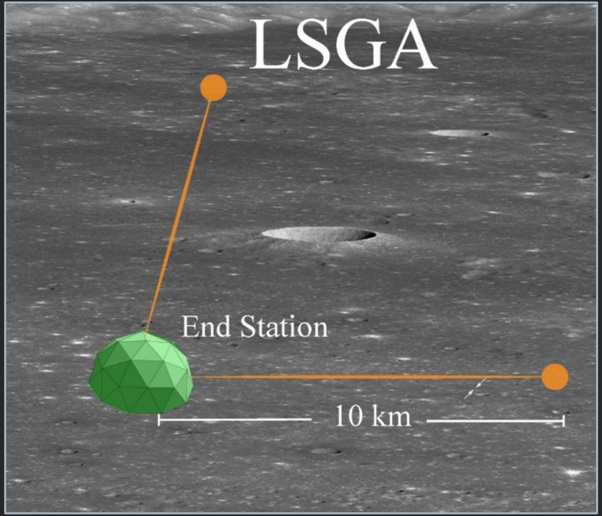
TUMAN, V. Observation of Earth Eigen Vibrations Possibly Excited by Gravity Waves. Nature Physical Science 230, 101–106

A series of works from Caughling M & Harms J to constrain the **GW energy density** using **Earth's and Moon's** (Apollo missions) seismic data

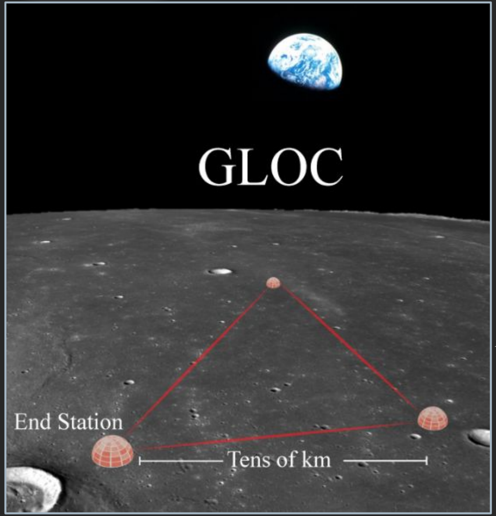
Concepts for Lunar GW detectors...



Harms et al., Lunar Gravitational Wave Antenna



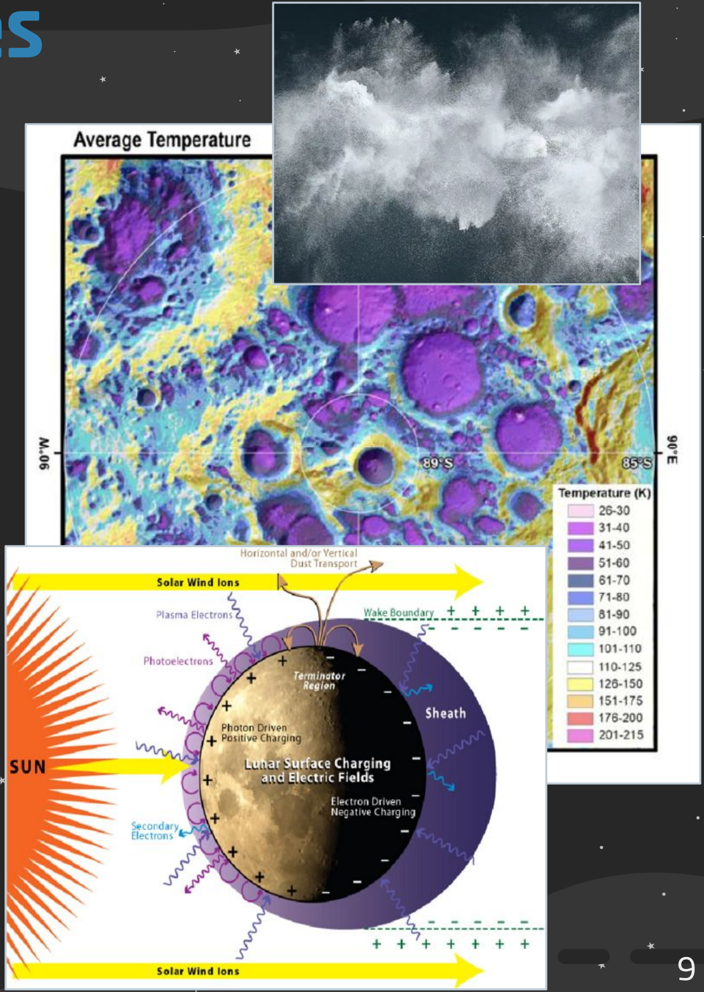
Katsanevas et al., Lunar Seismic and Gravitational Antenna (LSGA)



Jani & Loeb, Gravitational-Wave Lunar Observatory for Cosmology (GLOC)

Environmental challenges

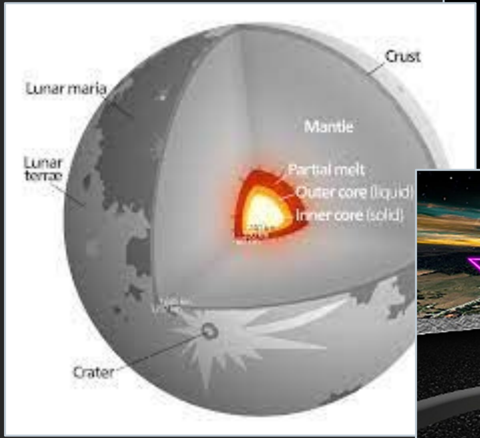
- **Lunar Dust** (overheating of the Apollo 11 seismometer was attributed to dust deposition)
- **Surface temperatures** during lunar nights can fall close to 100 K and rise up to 400 K during lunar days (--> Permanent shadow regions)
- Radiation, for example, in the form of galactic **cosmic rays**, can damage electronics
- In addition, cosmic rays can lead to continuous **charging of the lunar regolith**, which can develop significant **electric field** strengths

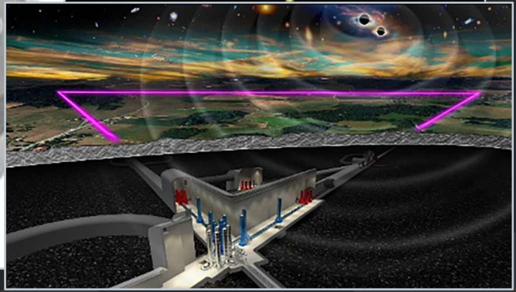
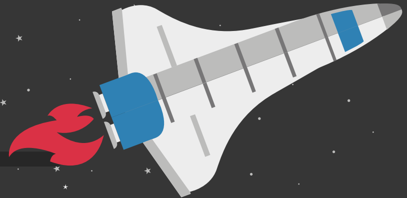


LGWA observational capabilities

- **Massive BBH** (10^5 - 10^{10} solar masses)
- Double **White Dwarfs** mergers (**Supernovae** 1a mechanism?)
- **Dark matter** (Dark photon & strange nuggets
- Deviations from GR observing binaries **inspiralling** and **Quasi-normal modes** of the BH merging or deviations from **polarized states** of GW
- Moon Geology (**Seleno-logy**?) and its origin
- Synergies with other GW (**multiband observation** and **parameter estimation** improvement) or EM facilities

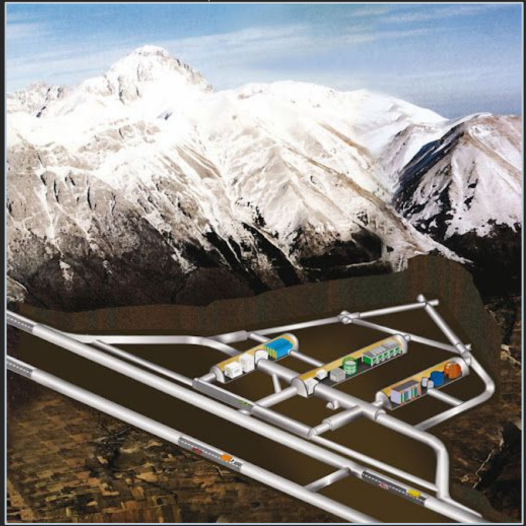


What's next?

INFN LNGS: LGWA payload testing, ultra-quiet seismic environment, underground inertial platform



Background cancellation tests at Mount Etna

LGWA
Soundcheck (ESA proposal)

Test facilities in Belgium
(E-TEST, SILENT)

Thank you for listening!!!

If you want to join us, please contact me:

francesca.badaracco92@gmail.com

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Normal modes

Displacements are produced in the **vertical direction** (by **spheroidal** modes) and in the **horizontal** (by **both spheroidal and toroidal** modes).

The **excitation of toroidal modes by GWs is strongly suppressed**, i.e., toroidal modes cannot be excited at all by GWs in a **homogeneous body.**

The seismic displacement is not (necessarily) the surface displacement
induced by GWs, but the **difference of surface displacement and direct seismometer test mass displacement** caused by gravitational fluctuations.

Normal modes

- **Dyson, Vol. 156, May 1969:**
    - **Flat stationary Earth**:
        - Gws are absorbed by irregularities in the **shear modulus**: a uniform flat model **do not absorbs GWs** (Earth has 2 major discontinuities: mantle-core and surface-atmosphere)
        - Seismic sensors at the surface: **surface discontinuity** is the dominant contribution
        - Elastic waves propagate perpendicularly to the surface to a very good approximation.
        - In this approximation all points on the surface move together in phase. Thus all the
        - instruments in a **seismic array** should respond **coherently** to a gravitational wave

Normal modes

- **Dyson, Vol. 156, May 1969:**
  - **Spherical Rotating Earth + local dynamics described by flat model**:
    - Consider kinematical effects of sphericity and rotation, produced by the **motion of the source relative to an Earth-bound detector**.
    - **Doppler effect** produced by the motion of the detector relative to the distant source ⟶ The incident GW of frequency f is split in f, f +- F, f+-2F and so on...
    - **Apparent motion** of the source in the sky (independent by the Doppler effect)

Lunar surface environment

- **Lunar Dust** (overheating of the Apollo 11 seismometer was attributed to dust deposition)
- **Surface temperatures** during lunar nights can fall close to 100 K and rise up to 400 K during lunar days (--> Permanent shadow regions)
- Radiation, for example, in the form of galactic **cosmic rays**, can damage electronics
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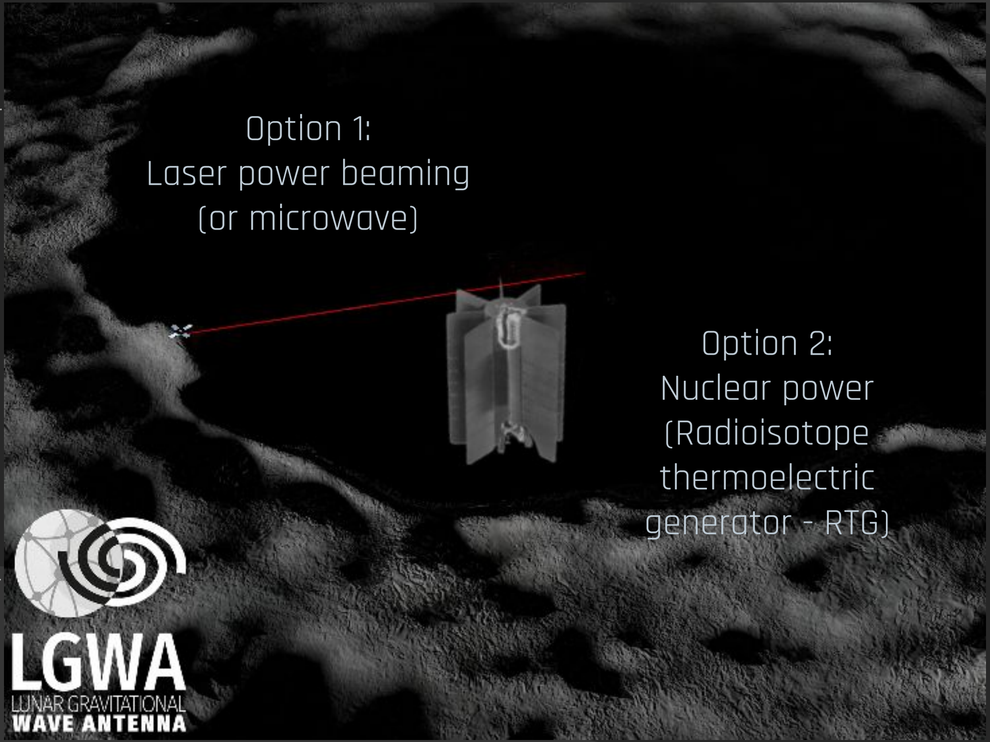
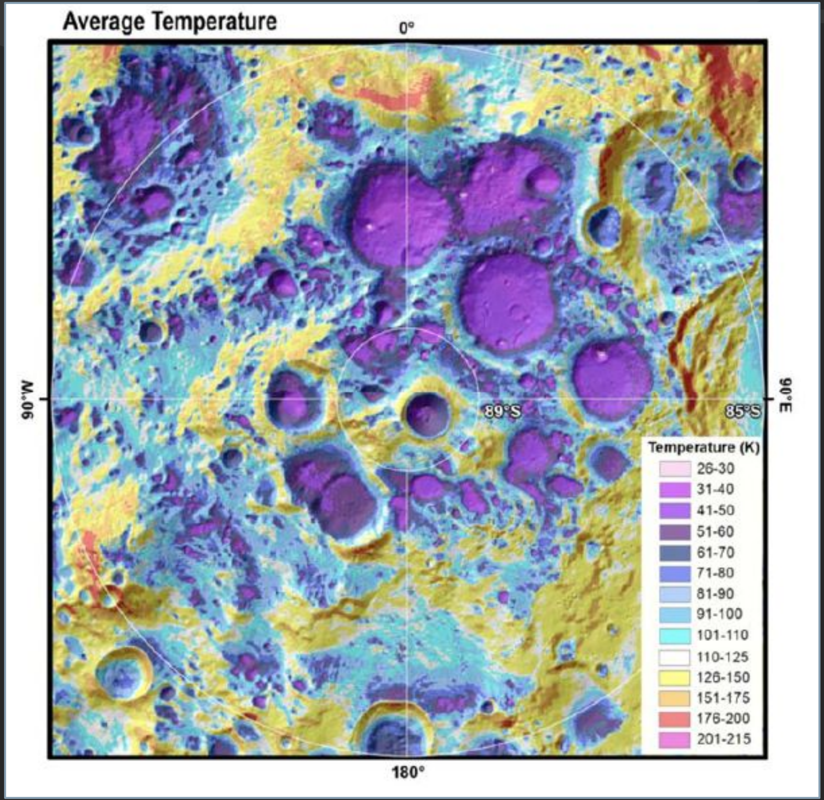
Concept & Working principle





Credits: Digital Repositoory Unimib link

Lunar Surface Gravimeter

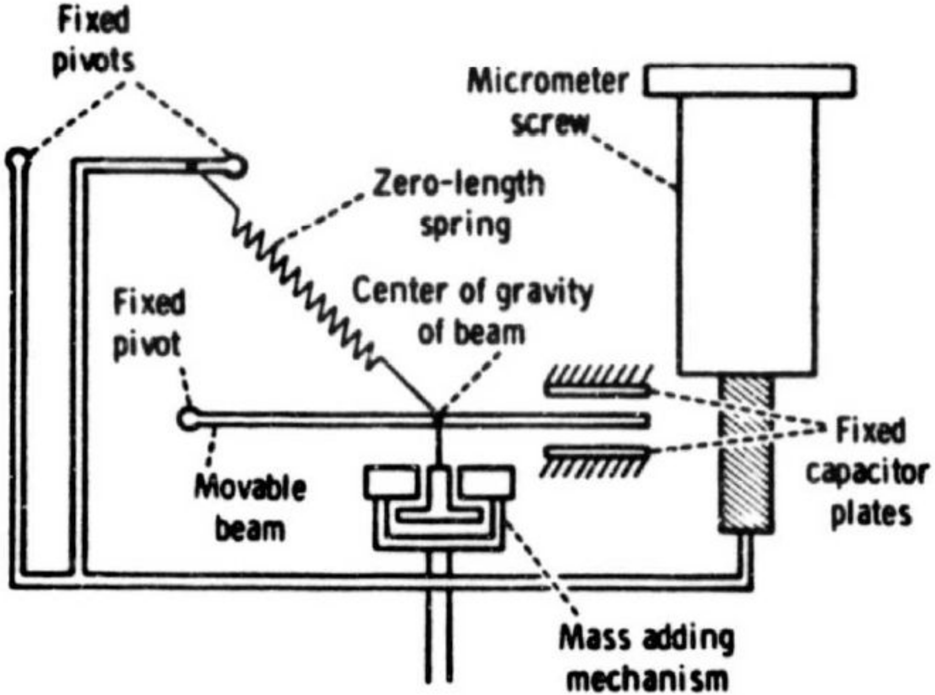
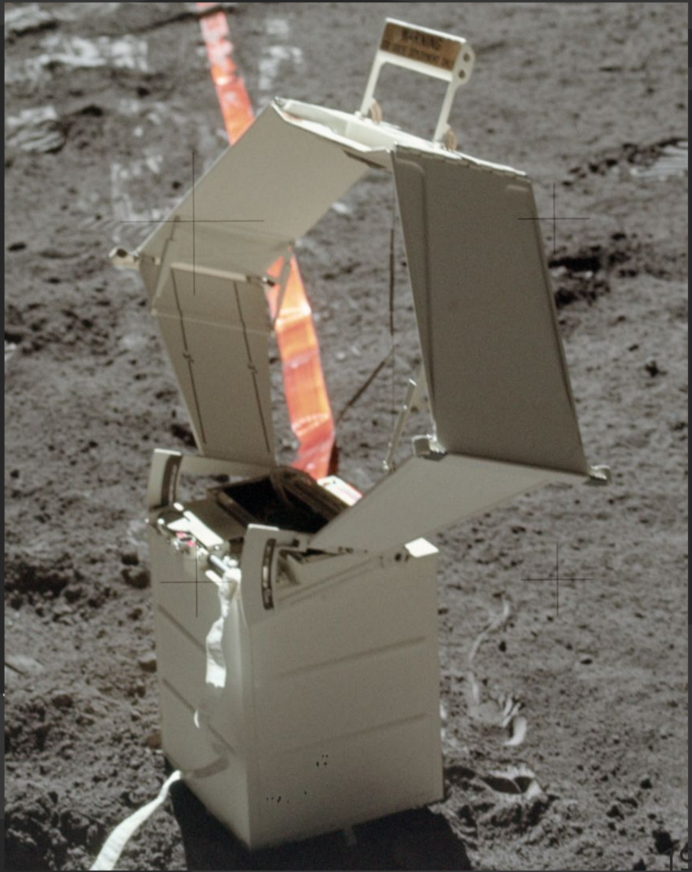
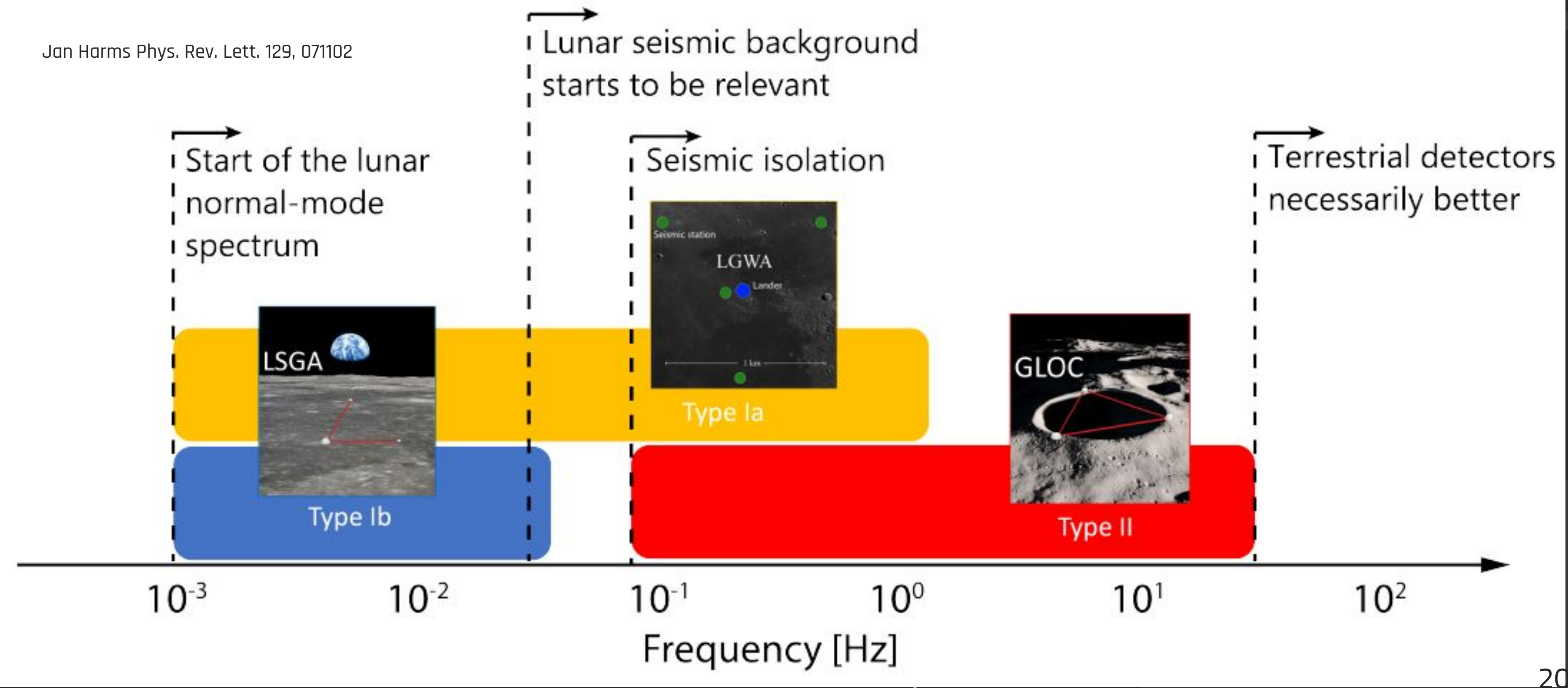


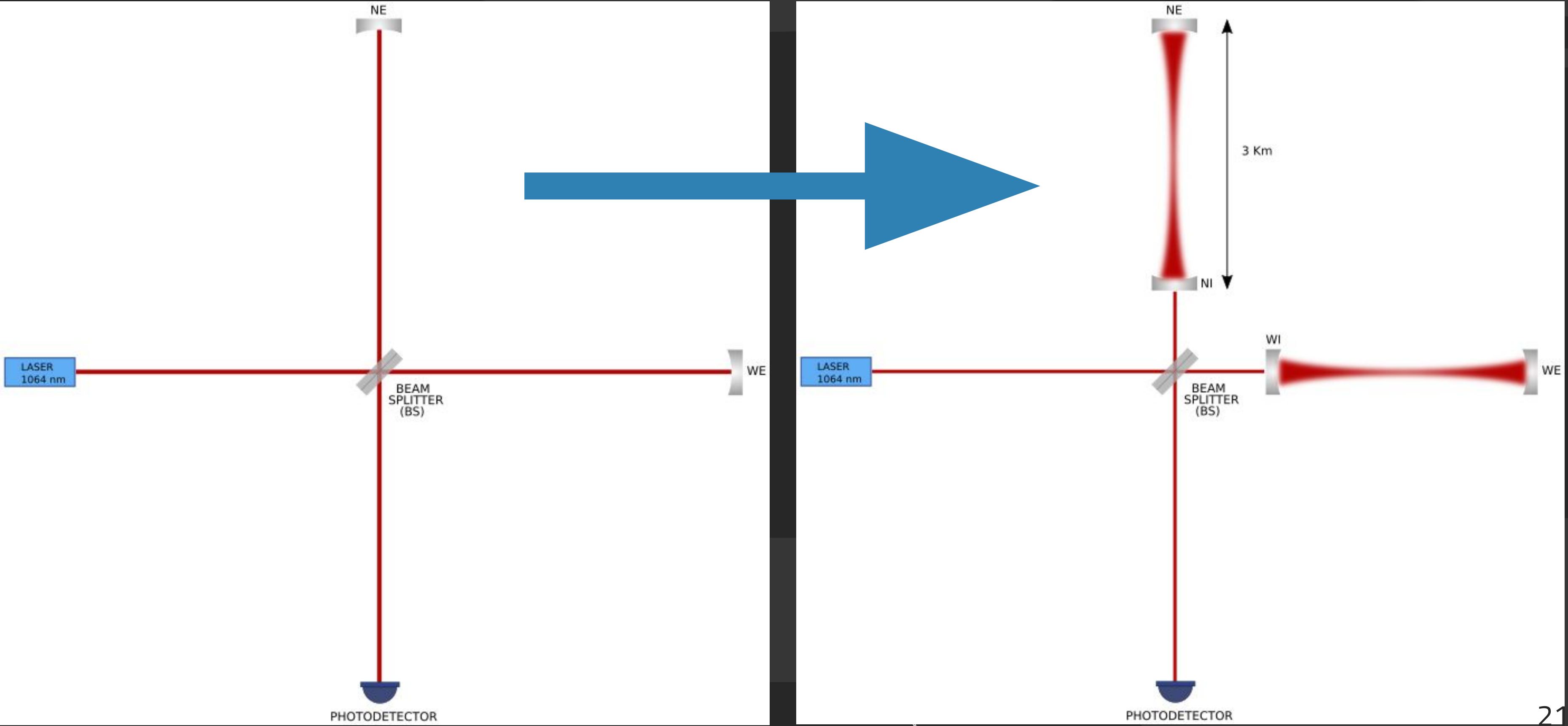
FIGURE 2.–Schematic diagram of the lunar gravity sensor.



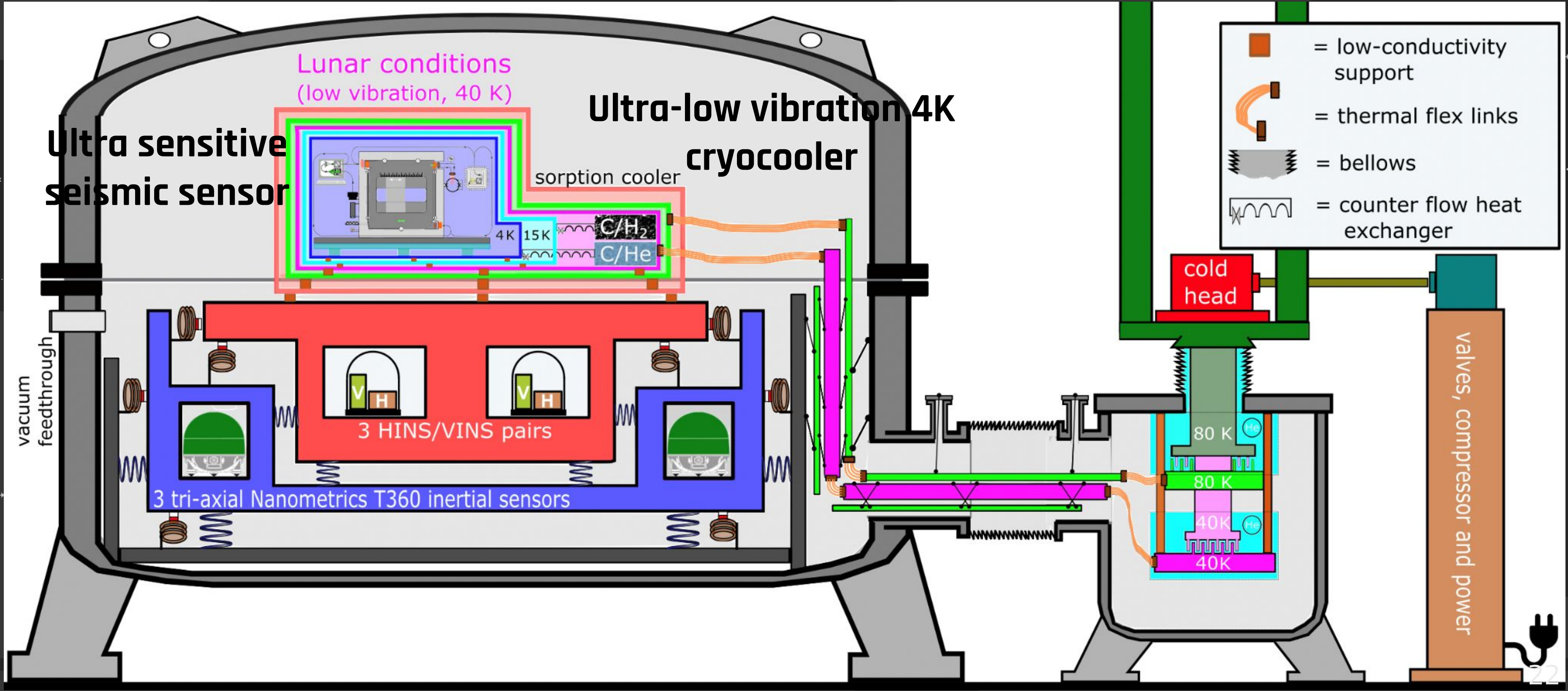
Observation bands of recently proposed lunar GW detector concepts



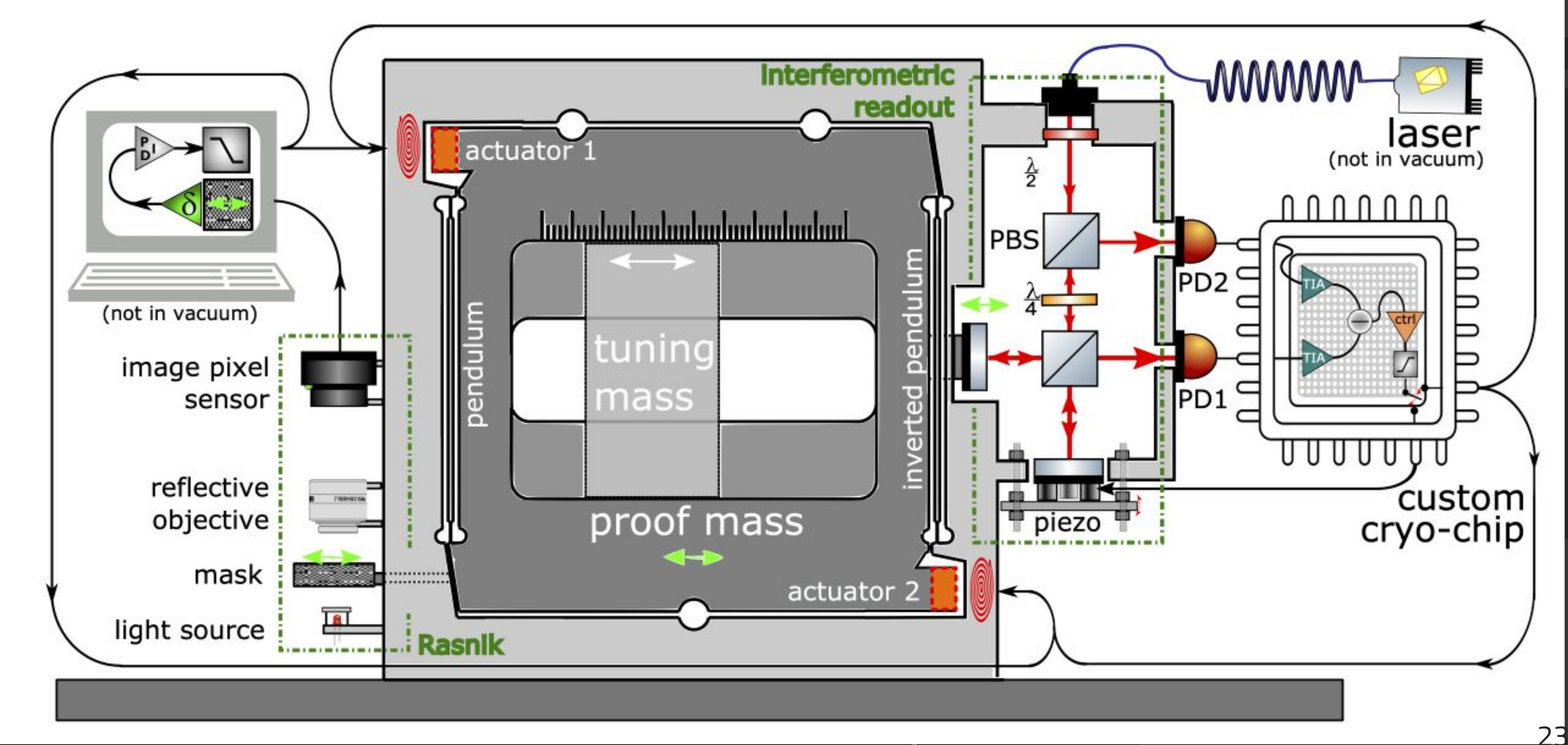
Interferometric GW detector



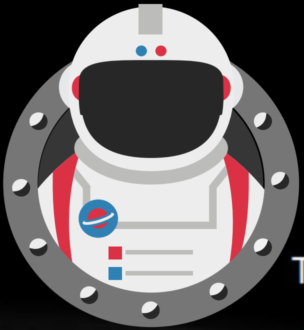
Moon Emulator & LGWA payload proof-of-concept



CSIS: Cryogenic Superconductive Inertial Sensor



Preliminary Target for the Timeline



Deployment of LGWA Soundcheck (e.g., CLPS-PRISM)

TRL6 for LGWA Soundcheck

TRL6 for LGWA

Deployment of LGWA (large mission)

2022 2024 2026 2028 2030 2032 2034 2036 2038

Farside Seismic Suite (CLPS-PRISM)

Lunar Geophysical Network (not approved and deployment not expected before the early 2030s)

Slide credits: Jan Harms

GW Response

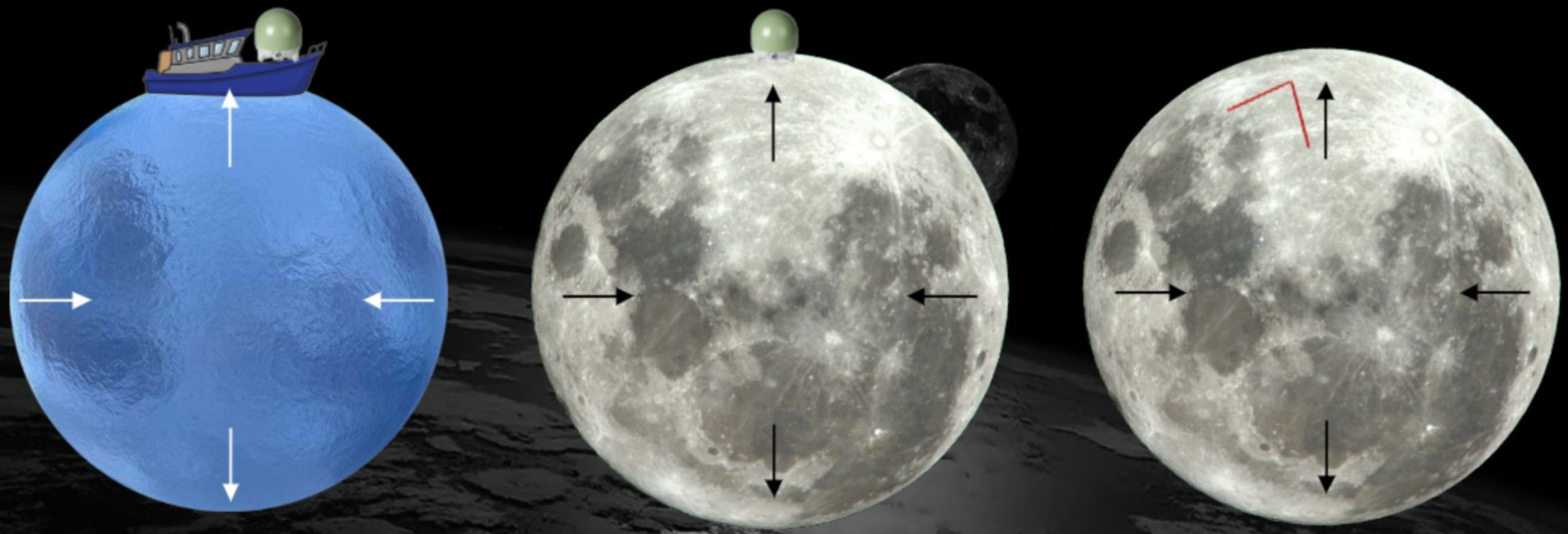
Slide credits: Jan Harms

LGWA

Case 1: Inertial measurement on liquid planet

Case 2: Inertial measurement on solid planet

Case 3: Deformation measurement on solid planet



No GW signal

GW signal is differential between free fall and elastic response

GW signal is elastic response