Gravitational wave detectors on the Moon

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Content provided by
many members of GW community

Meeting:
Key Non-Polar Destinations Across the Moon
to Address Decadal-level Science Objectives with Human Explorers:
Panel on Heliophysics, Physics, and Physical Science
June 10–12, 2025, Keck Center of the National Academies, Washington, D.C

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Outline

- Overview GW detectors
- Why 1mHz to 1 Hz frequency GWs are of interest?
  - Interesting GW range with lots of astrophysical relevance!
- Why going to the moon?
  - Environmental advantages/disadvantages
  - Human interaction for setup, maintenance and upgrades.
- Development in stages
  - LILA
    Feasible and nearly shovel ready
    Access to interesting science
  - LILA+
    Larger scope/footprint
    Deep access to new astrophysical science

Complexity of LIGO/Virgo-like Key Interferometer Features

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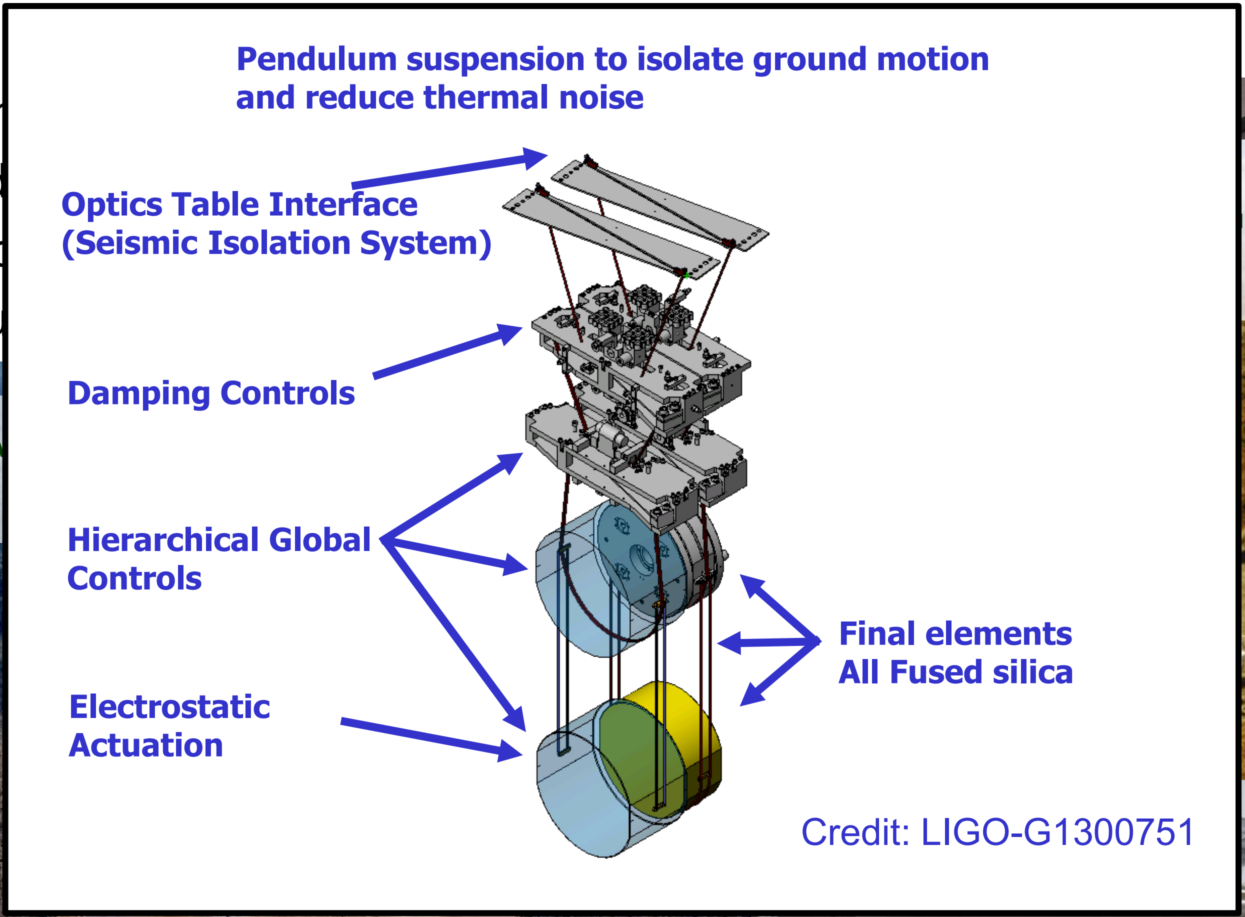
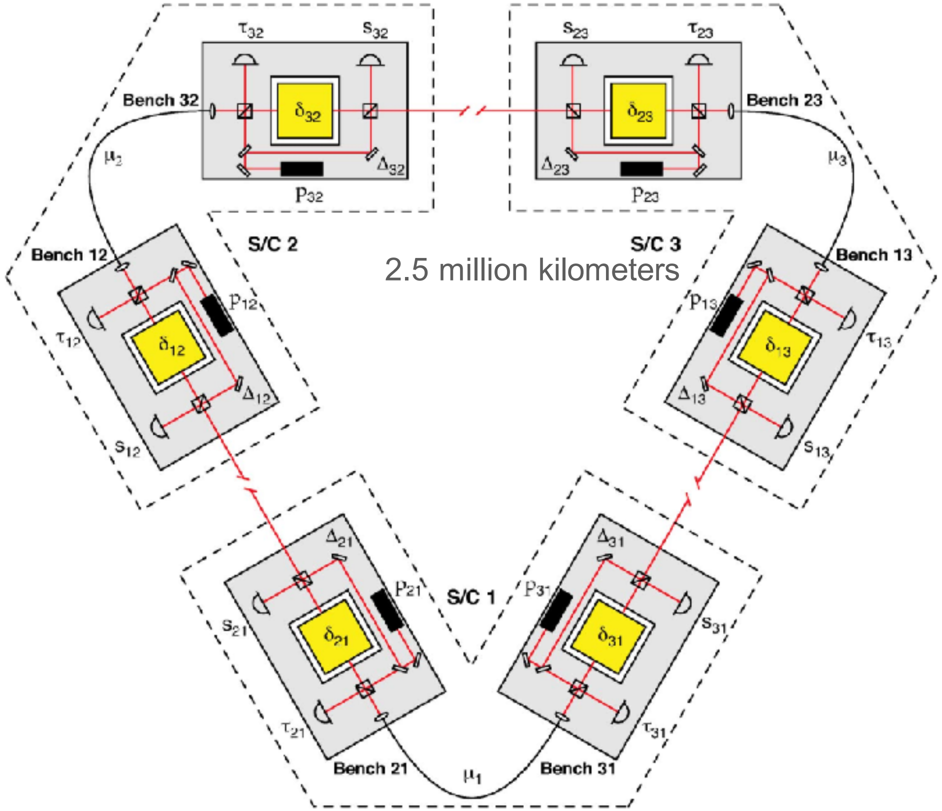
- Seismic isolati
- Active mode m
- Low loss farad
- Output mode c
- 4km long vacu

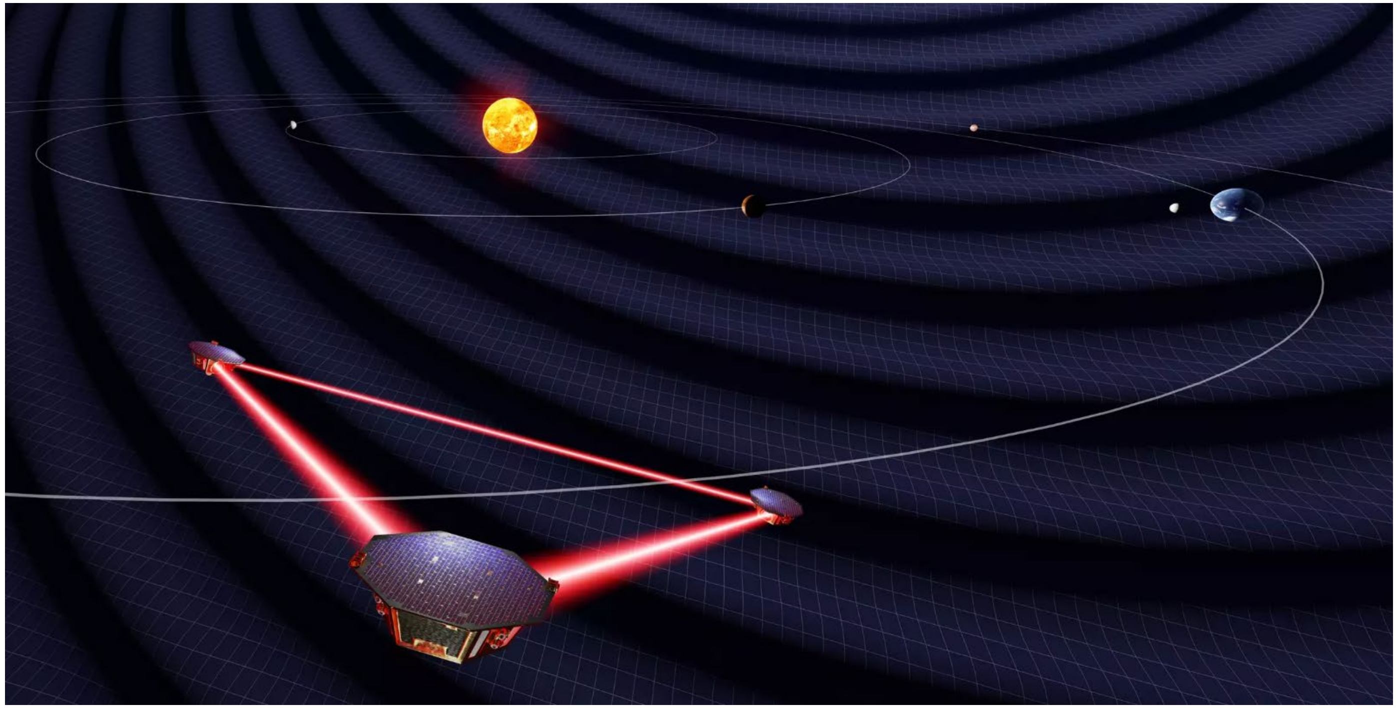
LIGO G2200736



LISA



D. Shaddock, 2004 Phys. Rev. D 69, 022001



Science measurement is made using a series of Heterodyne measurements where the phase is tracked using a phasemeter

Picture credit: University of Florida / Simon Barke

LGWA

- A kilometer-scale array equipped with cryogenic inertial sensors.
- The LGWA deployment site is one of the permanently shadowed regions (PSRs) inside a crater at the lunar north or south pole.

- Two components:
  - A cryogenic inertial sensor concept for the measurement of horizontal ground displacements reaching femtometer sensitivity at 1Hz;
  - Deployment of a kilometer-scale array of at least four inertial sensors for the reduction of seismic background noise in the decihertz band.
  - Additionally, a laser-power beaming system is shown as a possible power system for LGWA.

Credit: http://lgwa.unicam.it

LILA / LILA+

Multi-band GW Observatory on the Moon

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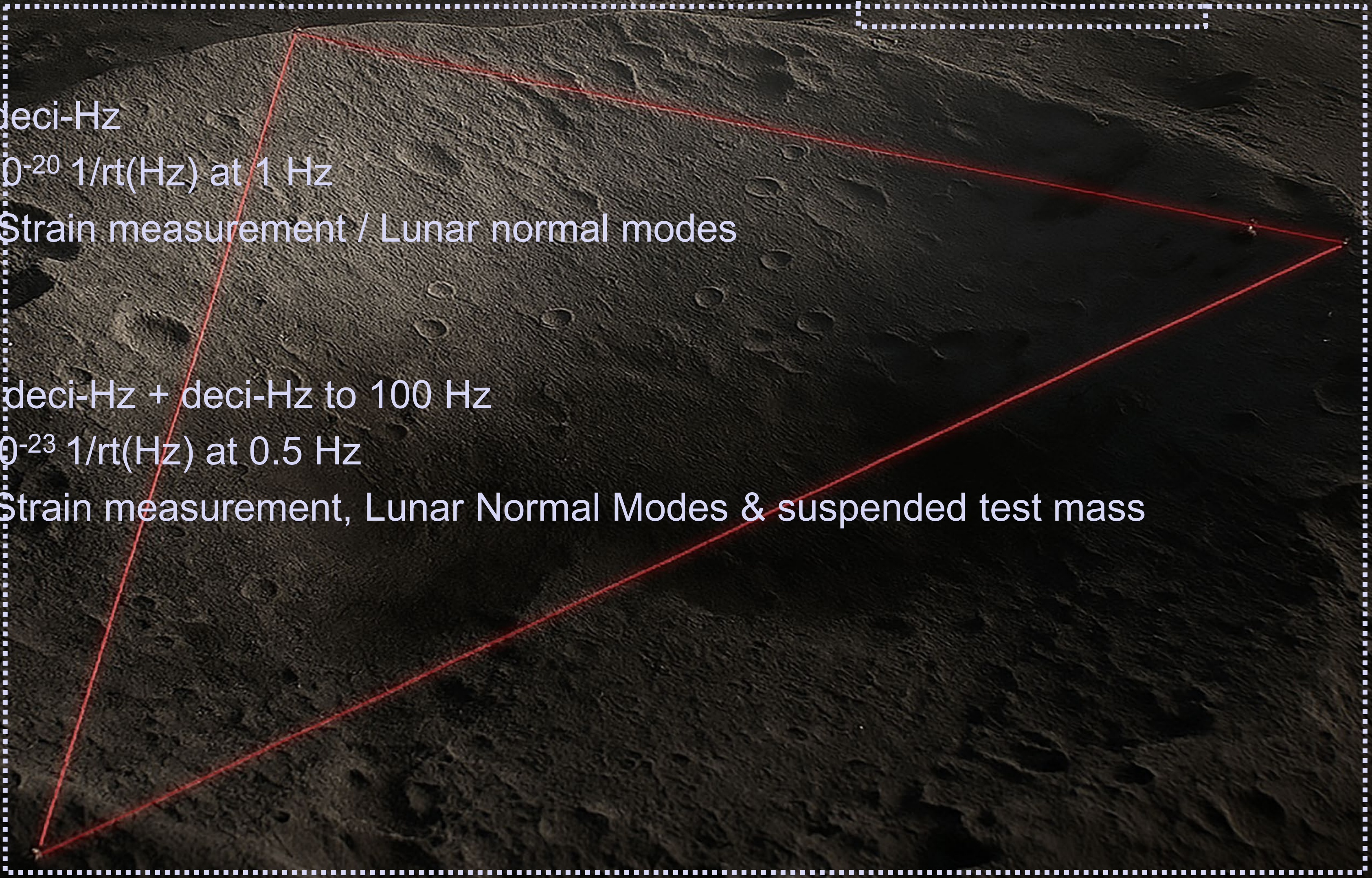

LILA Detector

- GW band: mHz to deci-Hz
- GW Sensitivity: $2*10^{-20}$ 1/rt(Hz) at 1 Hz
- Detection Method: Strain measurement / Lunar normal modes

LILA+ Detector

- GW bands: mHz to deci-Hz + deci-Hz to 100 Hz
- GW Sensitivity: $2*10^{-23}$ 1/rt(Hz) at 0.5 Hz
- Detection Method: Strain measurement, Lunar Normal Modes & suspended test mass

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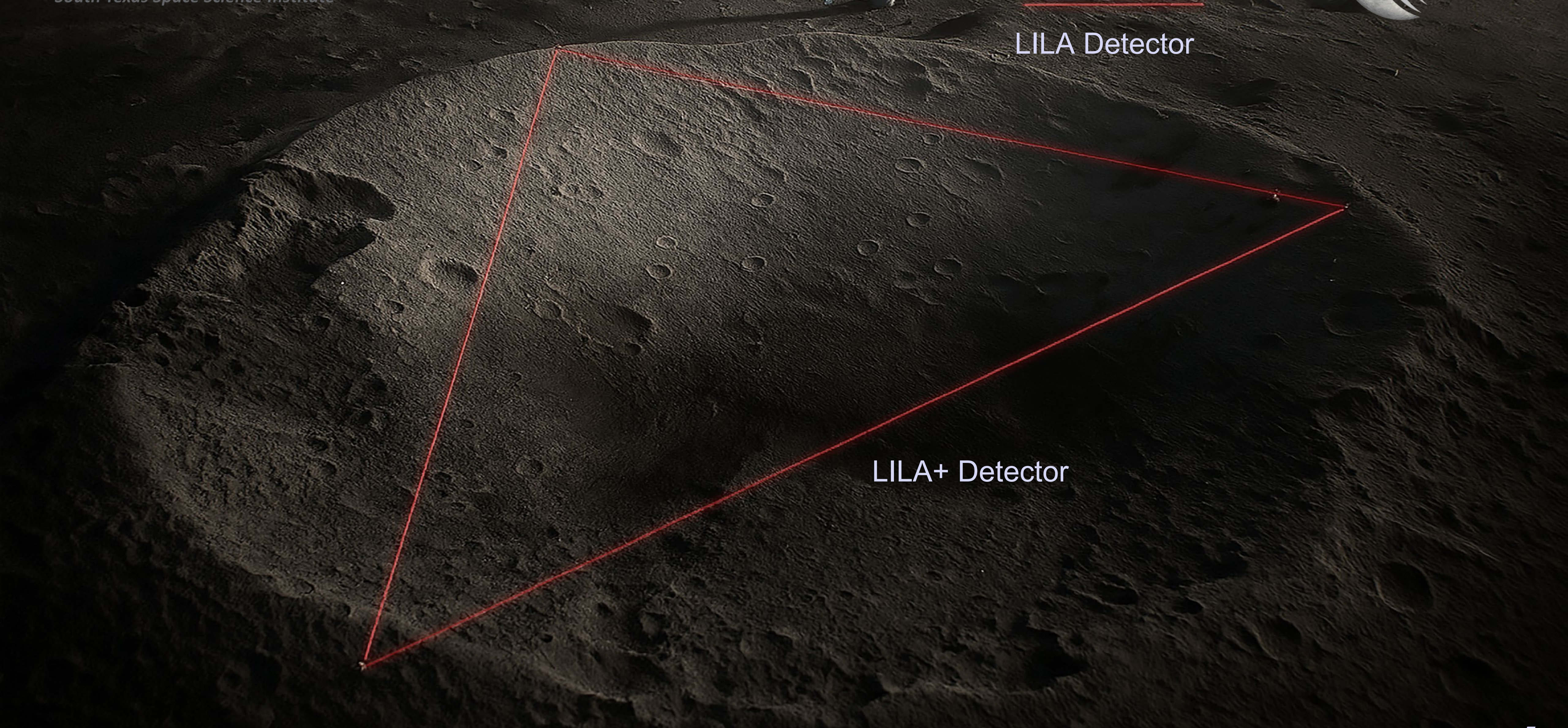
LILA / LILA+
Multi-band GW Observatory on the Moon



Gravitational waves from mHz to kHz

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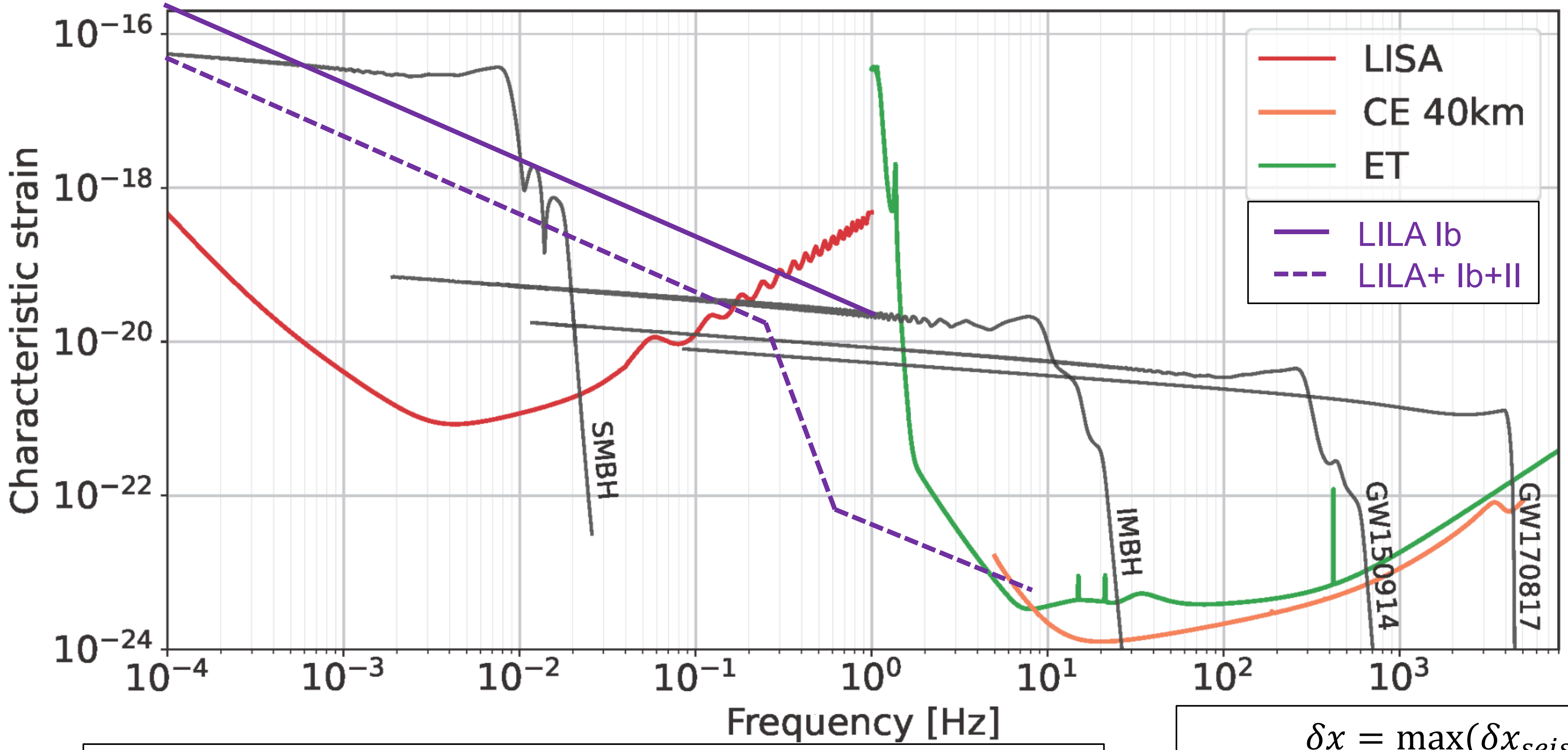
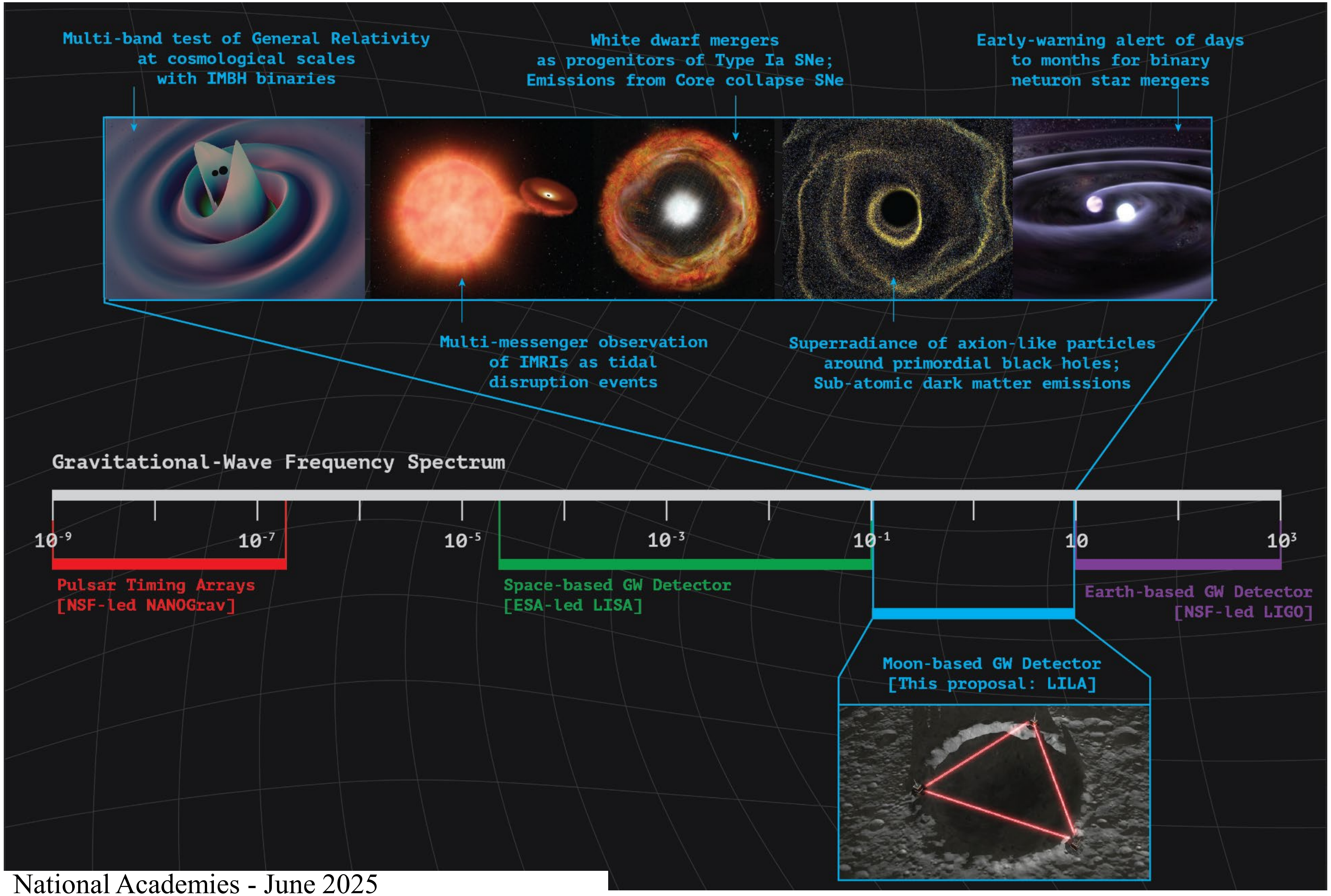
LILA



Moon as Weber bar – GW excites moon normal modes
Type (Ia) - see: J. Harms, Phys Rev D 2022.
For Ia sensitivity prediction: P. Ajith et al JCAP01(2025)

$$\delta x = \max(\delta x_{seis,}\delta x_{sens})$$
$$h_{Ia} = \delta x / Q_{eff}\, L_{eff}$$
$$h_{Ib} = \delta x / L$$
$$h_{II} = \max(H \otimes \delta x_{seis}/L\,, \delta x_{sens}/L)$$

LILA Science: New Multi-Messenger Astrophysics Landscape

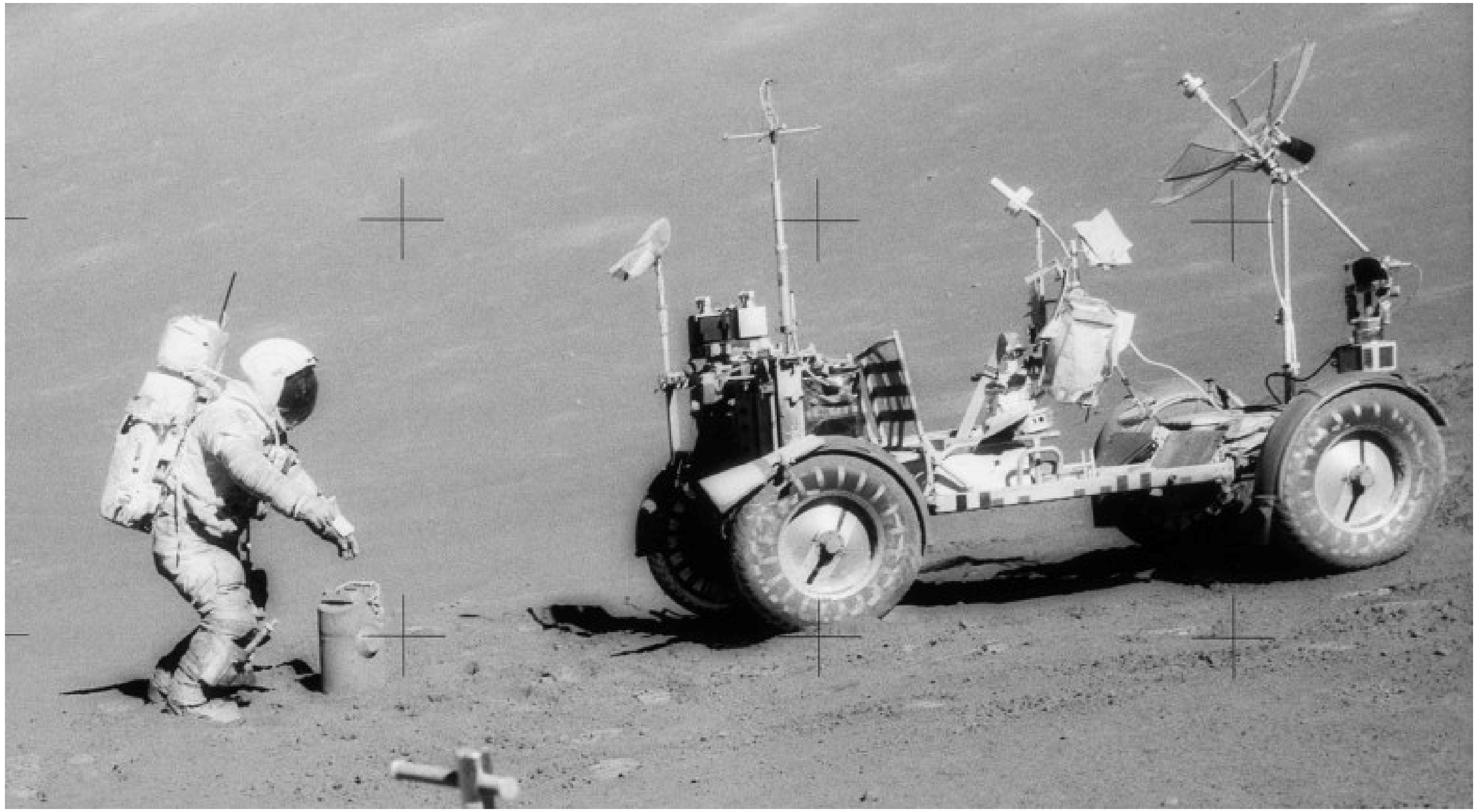


- Early-warning of binary neutron star mergers:
  LILA: weeks
  (LIGO: ~1 minute)
- Sky-localization:
  LILA: arc-min^2
  (LIGO: 10s deg^2)
- New MMA sources:
  - Tidal disruption of white dwarfs around IMBHs
  - White dwarf mergers as progenitors of Type Ia SNe
- New tests for GR test:
  - multi-band measurements of black holes between LILA-LISA and LILA-LIGO

How LILA satisfies decadal 2020 targets

Astro 2020 reference (chapter § / appendix)	Why the 0.1 – 10 Hz GW band matters	How LILA addresses the need
§1.1.2 – Priority Science Area: "New Windows on the Dynamic Universe"	Binary-neutron-star & stellar-mass BH mergers linger here for hours–days, supplying early-warning and high S/N. Phase-transition & cosmic-string backgrounds peak near 1 Hz. Long baselines enable precision GR tests & dark-sector searches.	Fills the LISA – LIGO/CE desert with lunar baselines (10–40 km). 4–12 h alerts at ≤ 10 deg² for kilonova capture. Lunar seismic quiet lets LILA probe extra GW polarizations to 10^{-8}.
§7.5.3.1 – Time-Domain & Multi-Messenger Follow-Up Program (highest-priority sustaining activity)	Early GW detection before EM flash is only possible in the decihertz band; this currently not covered.	Real-time trigger engine: LILA streams sub-minute alerts to the TDAMM fleet, fulfilling the decadal call for a dedicated follow-up pipeline.
§1.1.3 – Priority Science Area: "Unveiling the Hidden Drivers of Galaxy Growth"	IMBH mergers (10^3–10^5 M☉) radiate strongest at 0.1–3 Hz, beyond LISA/CE reach. WD–IMBH tidal disruptions emit week-long GW tones around 1 Hz.	IMBH census: horizon z ≈ 0.8 for 10^4 M☉ binaries; measures merger-rate density. • Allows coordinated ALMA/ngVLA studies of AGN-disk feedback during mergers.
§1.5.4 – Technology Development for Future GW Observatories (Ground)	Opening the decihertz window is singled out as the next frontier, demanding novel low-f isolation and lunar-qualified optics.	Pathfinder lab: staged LILA demonstrators (Artemis lander → 10 km array) de-risk low-g optics, cryo-SiC suspensions, and dust-hard coatings.
Appendix L (Panel on Particle Astrophysics & Gravitation) – New Physics & Cosmic Origins	Primordial GW backgrounds from TeV–PeV physics and cosmic strings peak inside 0.1–10 Hz—unreachable by CMB or mHz detectors.	Ultra-low lunar noise: multi-year LILA integration targets $\Omega_{GW} \approx 10^{-15}$ at 1 Hz, complementing PTA and CMB-S4 limits, and combining with CE to disentangle cosmological backgrounds.

Environmental Advantages

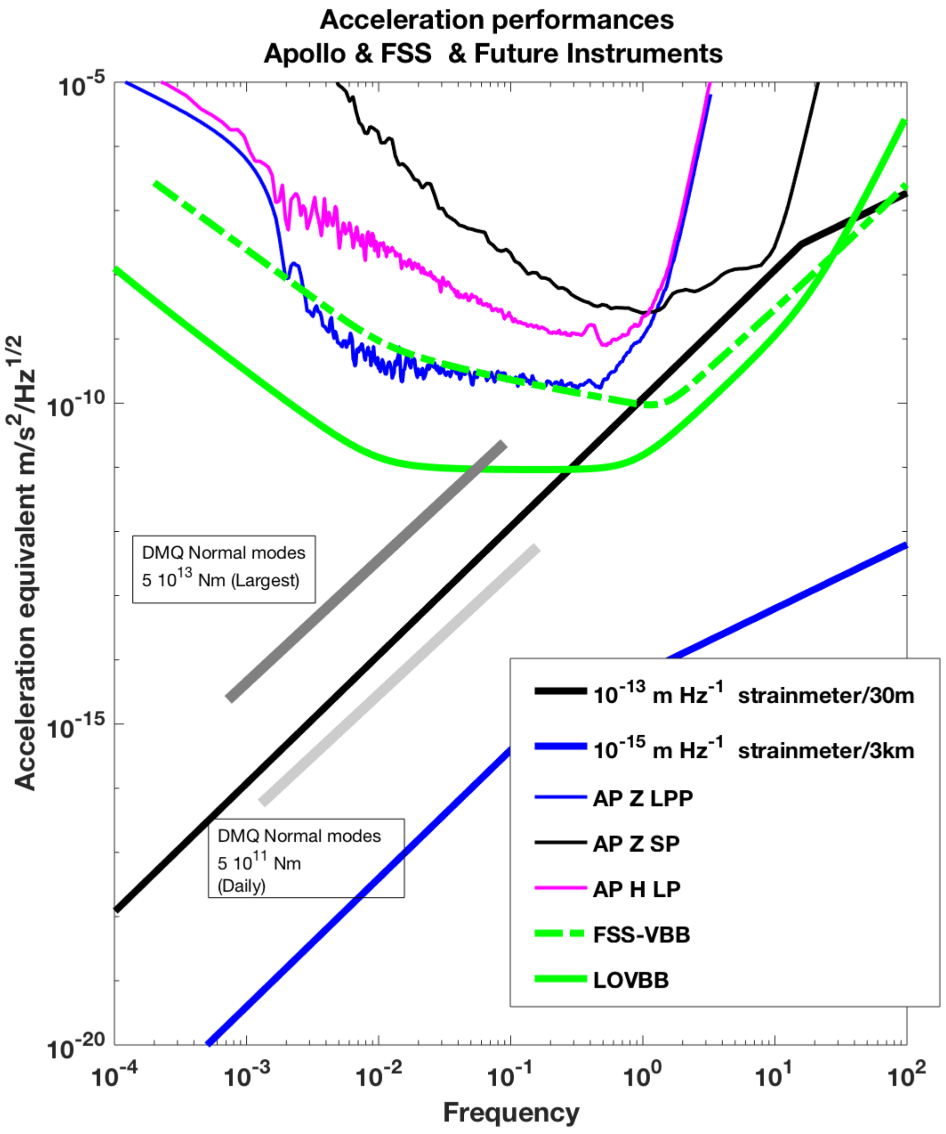


Our Moon is many orders of magnitude quieter than Earth at low frequencies.

Natural vacuum on the lunar surface is >100x better than ultra-high vacuum of LIGO

Ongoing area of interest, see below.

Planetary science comparison and synergy

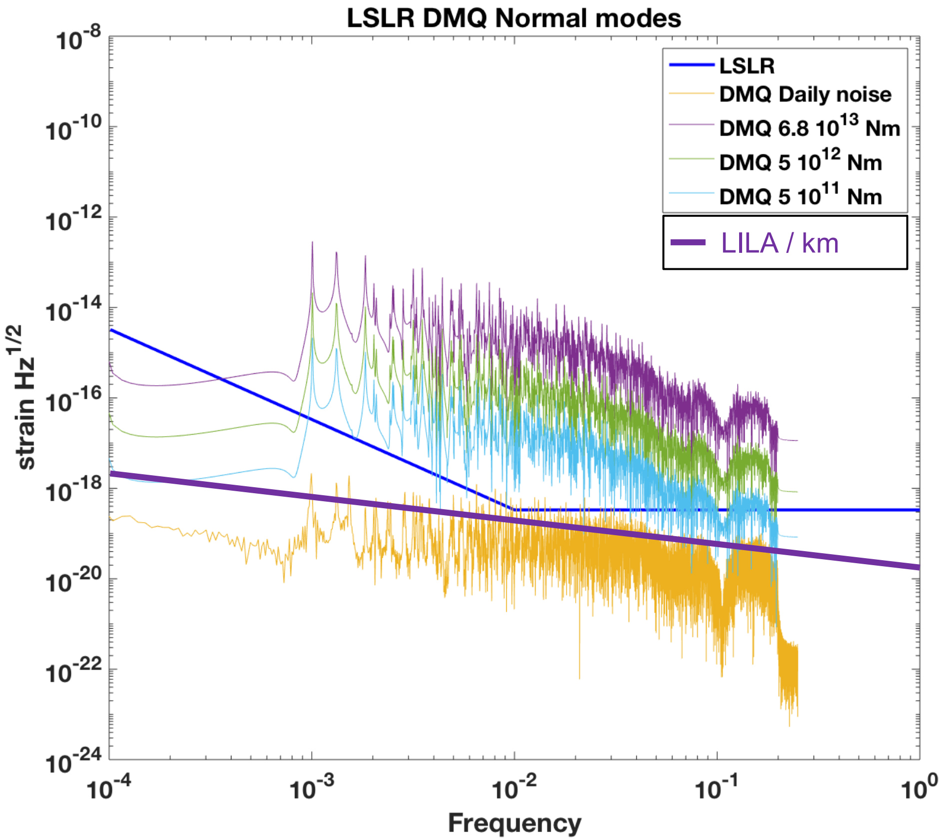


The FarSide Seismic suite (FSS) mission and more advanced seismometers (OVBB) are unable to match a LILA strain meter. **LILA is more sensitive AND can observe GWs.**

- Upper limit (Apollo) 10^{-11} m/rt(Hz)
- Farside Seismic Suite (Lognonné, Panning) will have higher sensitivity
- Indication that the moon seismic is “burst” driven, but generally better. (see next slide)

Expected seismic activity
lessons from the geophysics side

LSLR arm length = 3000m => noise 10^{-15} m/Hz$^{1/2}$ at 0.01 Hz



LILA is a Laser strain Laser Ranging device, with better sensitivity – at 5 km baseline.

- A Lunar Laser strain Laser Ranging (LSLR) due to its extreme sensitivity will target the detection of Normal modes of the Moon excited by the Lunar Deep Moonquakes (DMQ) occurring with weekly frequency
- **During the absence of seismic activity – see “daily noise” LILA will be able to detect GWs down to the seismic floor of about 10^{-20}/rt(f) [1/rt(Hz)]**

Credit: Lognonné, P., et al. "Deploying Extreme Sensitive Laser Strainmeter and Distributed Accoustic Sensing on Future Artemis Opportunities: Geophysical Goals and Challenges." LPI Contributions 3063 (2024): 5042.

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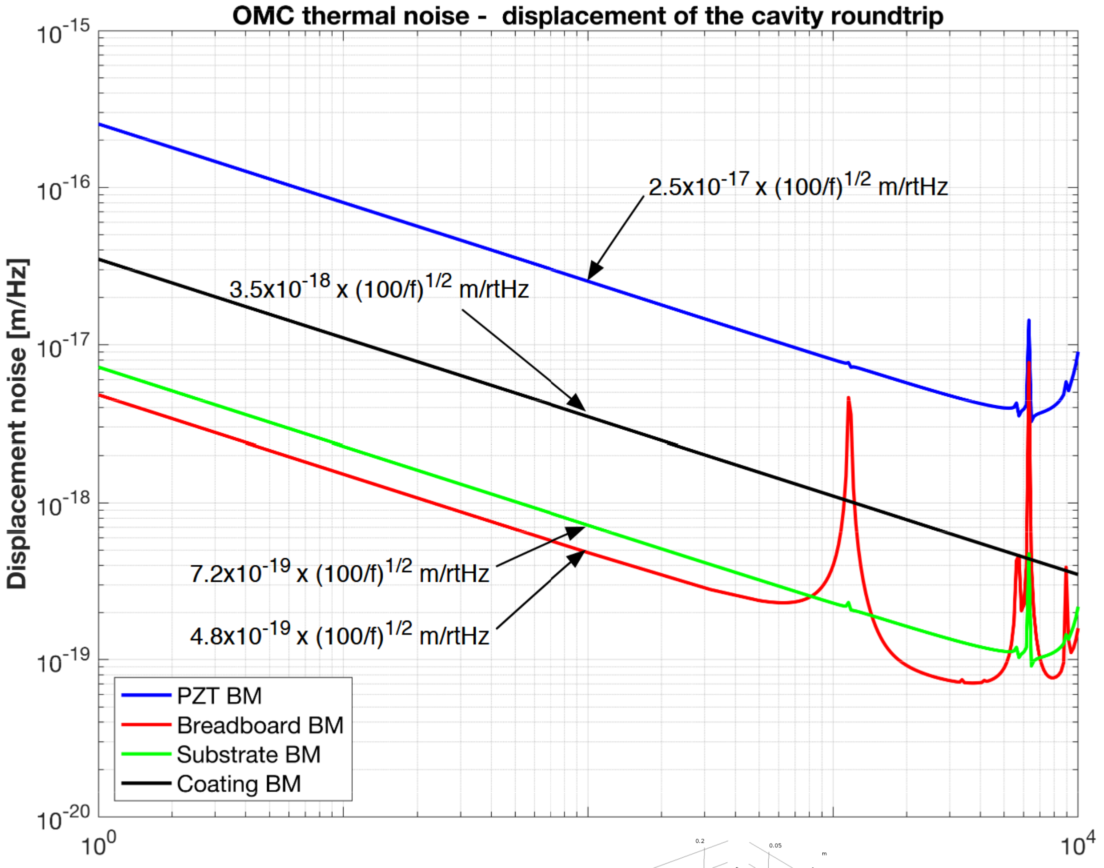
Environmental advantages/disadvantages

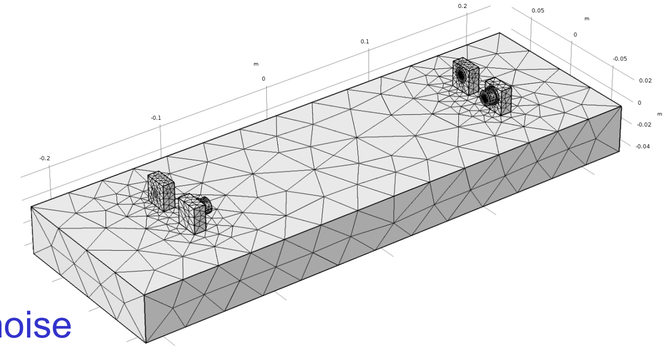
LILA

- Advantages
  - Good vacuum, but avoid dust
- Disadvantages:
  - Temperature swings between 120°C to -130°C. Precise temperature control is needed.
  - Energy need is complicated. Solar only works for daytime, battery storage, isotope batteries or nuclear reactors for nighttime operation (14 days). Possibly provided from lunar “economy”
  - Radiation – the detector needs to be carefully designed/screened for radiation hardening.
- Complexity and modular nature of the system requires Astronauts for setup, commission, mitigation and for upgrades.
- A lunar economy enables:
  - Access through astronauts will allow incremental testing and upgrades.
  - Future missions can share power and other resources.
  - Mitigation and improvement are possible after mission start.
    As opposed to other space missions, LILA’s design does not need to be final
    Incremental upgrades, mitigation is possible through astronauts
- LILA is location agnostic – but please, avoid too many neighbors.

LILA - IFO readout and noise limits

- No cavities
- No recycling technology, no quantum techniques
- Limitation to technical noise and thermal noise
  - With 100mW detected and 5km arms
    h = 10^{-20} 1/sqrt(Hz) is given by the shot noise limit.
- No suspension/isolation needed
- Fundamental readout limit is thermal noise of the optical bench (LISA, Grace follow on, LIGO OMC, frequency stabilization cavities)
  - OMC noise coating noise limited and reaches 10^-16 m/rt(Hz) at 1 Hz
  - Falls with 1/rt(f)
  - This is challenging, but pre-cursor technology exists.

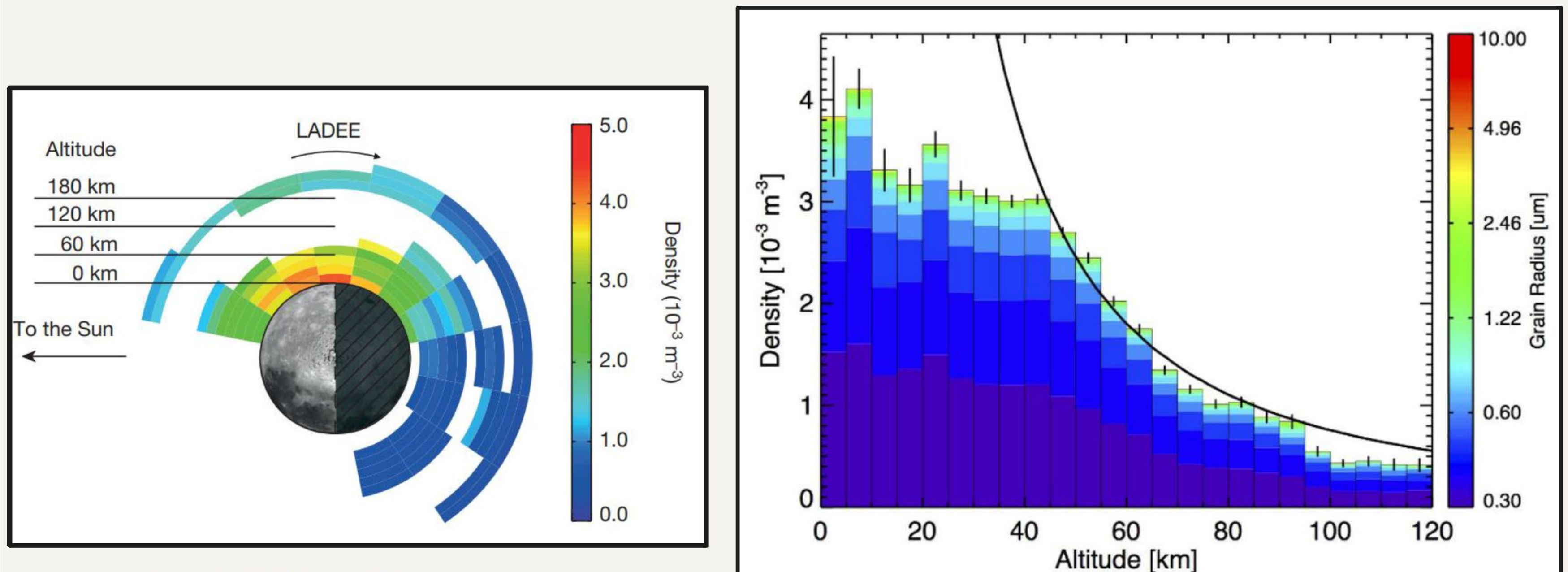




Credit:
LIGO DCC G1800149_OMC_thermal_noise

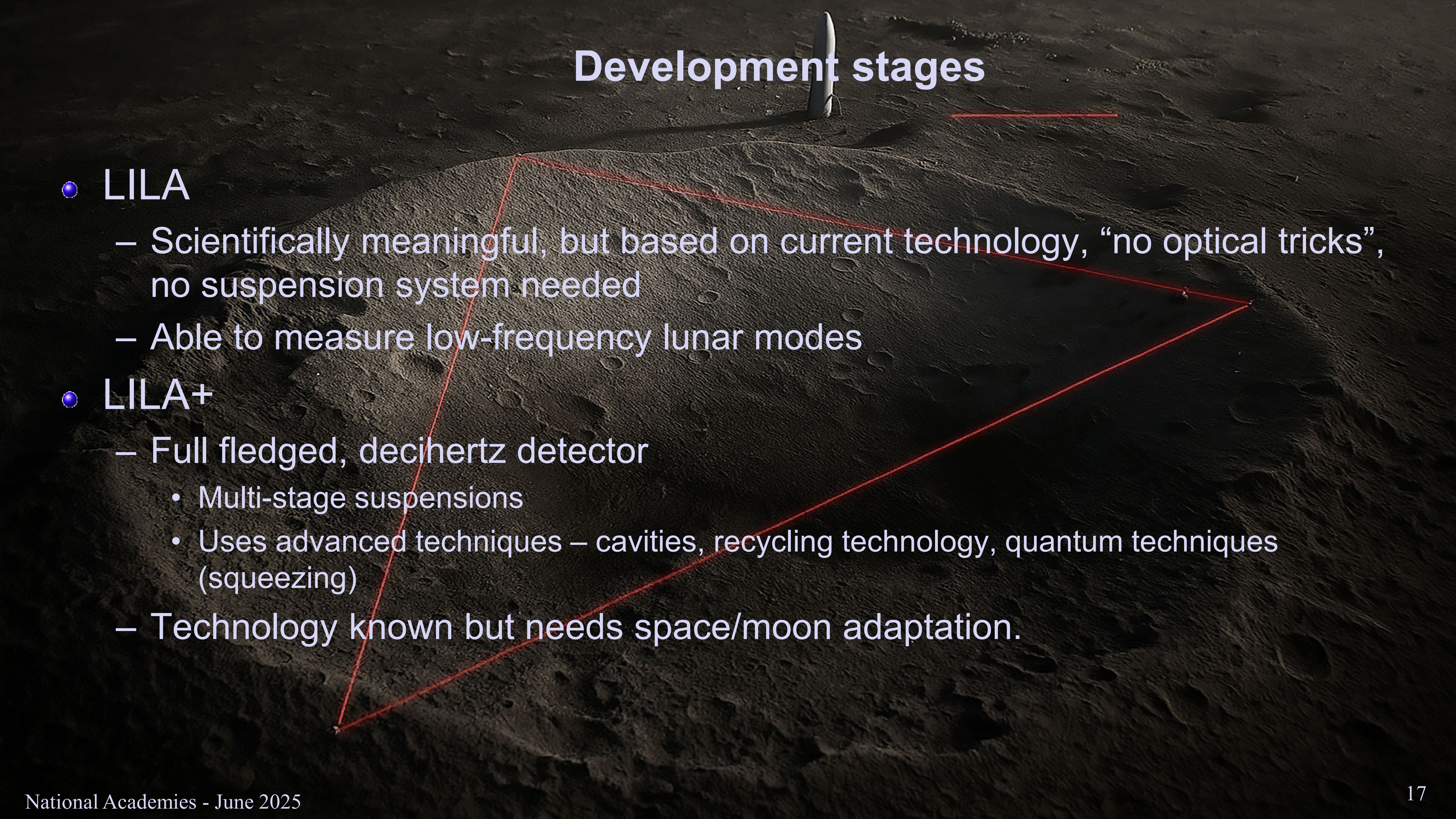
Dust mitigation

- Density of lunar dust as a function of altitude, radius & mass from the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission



https://doi.org/10.1038/nature14479

- Noise estimates to (Rubanu, CQG, 2009, Cozzumbo, PTA, 2023) < 2×10^{-22} 1/rt(Hz). Good for LILA, LILA+ might need elevation/mitigation.



Development stages

- LILA
  - Scientifically meaningful, but based on current technology, “no optical tricks”, no suspension system needed
  - Able to measure low-frequency lunar modes
- LILA+
  - Full fledged, decihertz detector
    - Multi-stage suspensions
    - Uses advanced techniques – cavities, recycling technology, quantum techniques (squeezing)
  - Technology known but needs space/moon adaptation.

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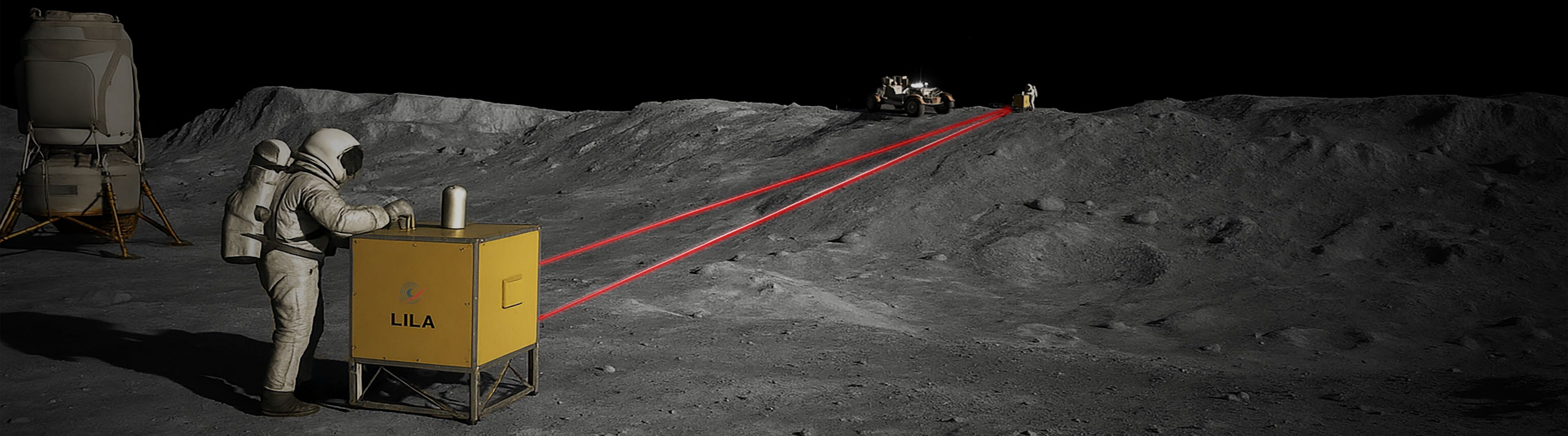
LILA mission concept

LILA



- Primary Payload (active): 100 kg
- Secondary Payload (passive): 20 kg
- Separation between payloads: 5 km

- Role of Human Explorers: Modular assembly and placement
- Location Requirements: Line of sight of 5 km
- Additional Resources: LTV, operations power (5W), comms (0.1 mpbs), heating power (50W)

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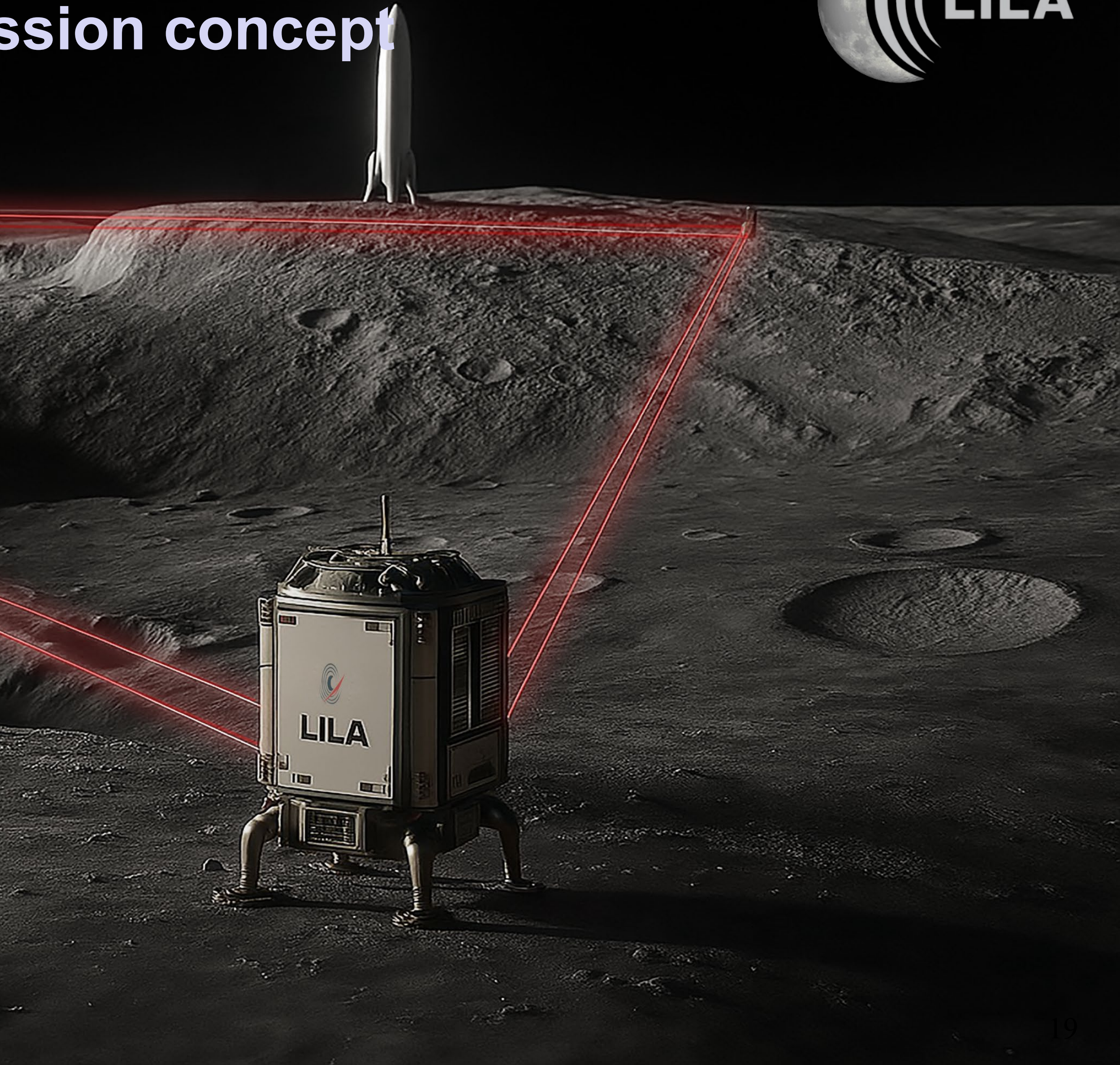
LILA+ mission concept

LILA

- Payloads: 3 stations – about 1000 kg each
- Separation between stations: 40 km
- Role of Human Explorers: Modular integration of station, commissioning, alignment, maintenance, upgrades
- Multi-stage suspensions
- Needs advanced techniques – cavities, recycling technology, quantum techniques (squeezing)

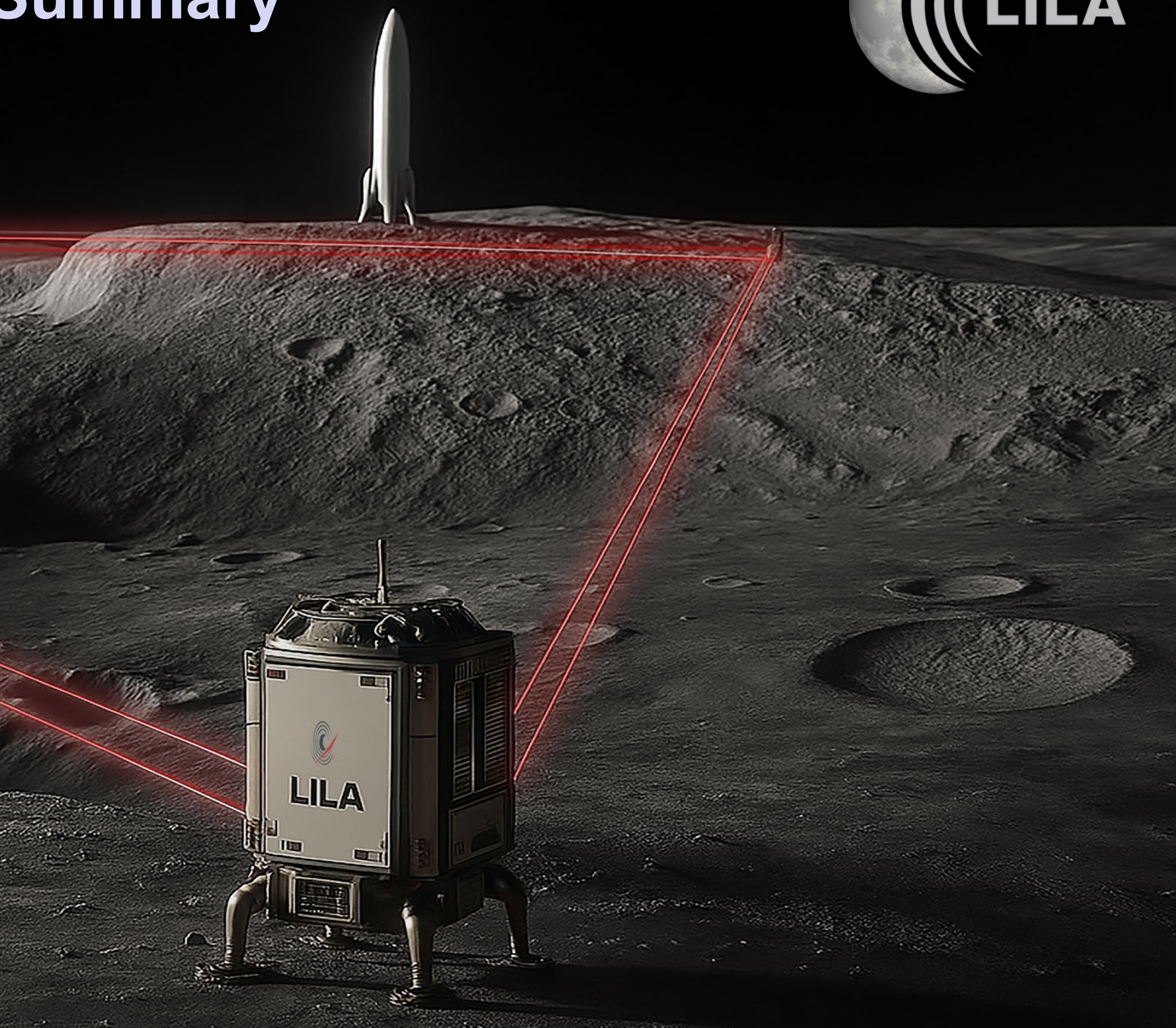
- Location Requirements: Line of sight of 40 km, limited launches in 100 km radius
- Additional Resources: LTV, operation power (50 W each), Comms (10 mbps), heating power (500 W), thermal shielding



Summary

- The moon provides an environment that will allow to extend the scientific reach of earth-bound GW detectors to the deci-hertz range with “shovel” ready techniques.
- Astronauts will enable modular setup, commissioning, mitigation and upgrades.
- A lunar economy will be advantageous for project deployment

- Stebbins, R. T., et al. "Gravitational radiation observations on the moon." AIP Conference Proceedings. Vol. 207. 1990 proposed an interferometer on the moon. The Artemis program can make this finally happen.



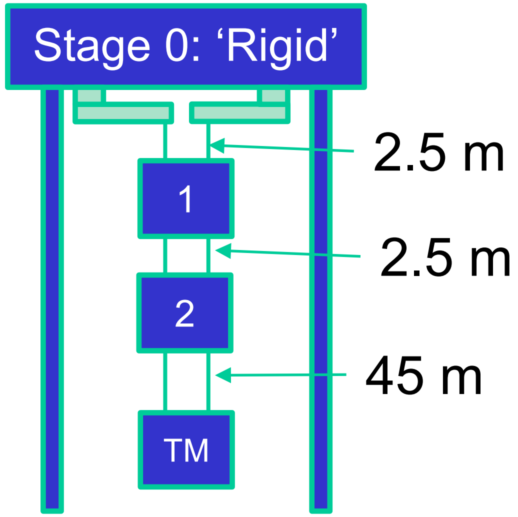
Additional material

- On the following slides …

Example Suspension for LILA+

- Lower performance, but very large, though no IP needed
- Dominated by vertical thermal noise of metal blades
- First simulations, further improvements realistic

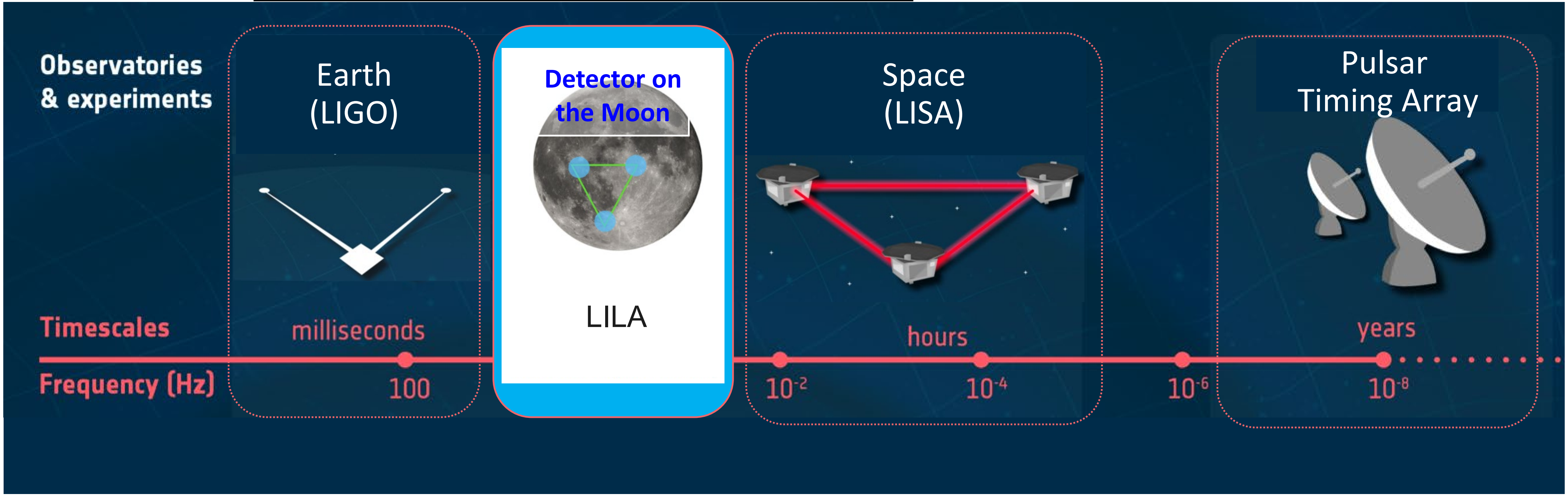
'Standard' non-IP suspension

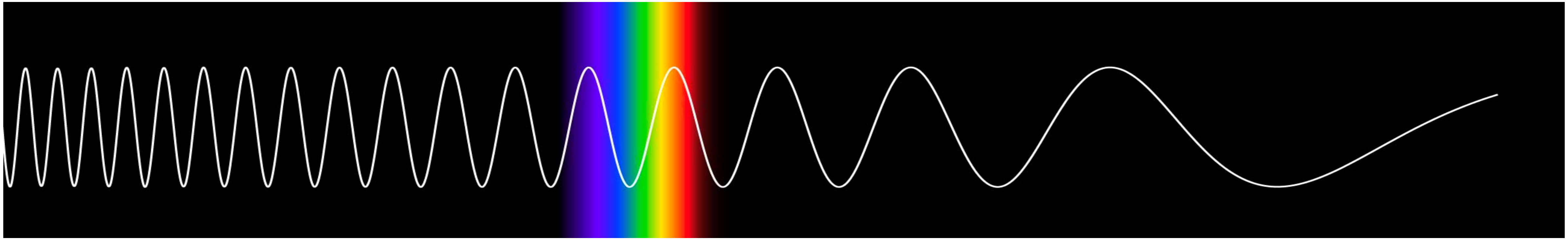


- silica fiber stress = 1.6 Gpa
- L = 2.5 + 2.5 + 45 m = 50 m
- Total mass = 1000 kg
- Test mass = 100 kg
- anti-spring res freq = 0.05 Hz
- room temperature

Credit: Brett Shapiro, APL, 2025

Spectrum of gravitational waves





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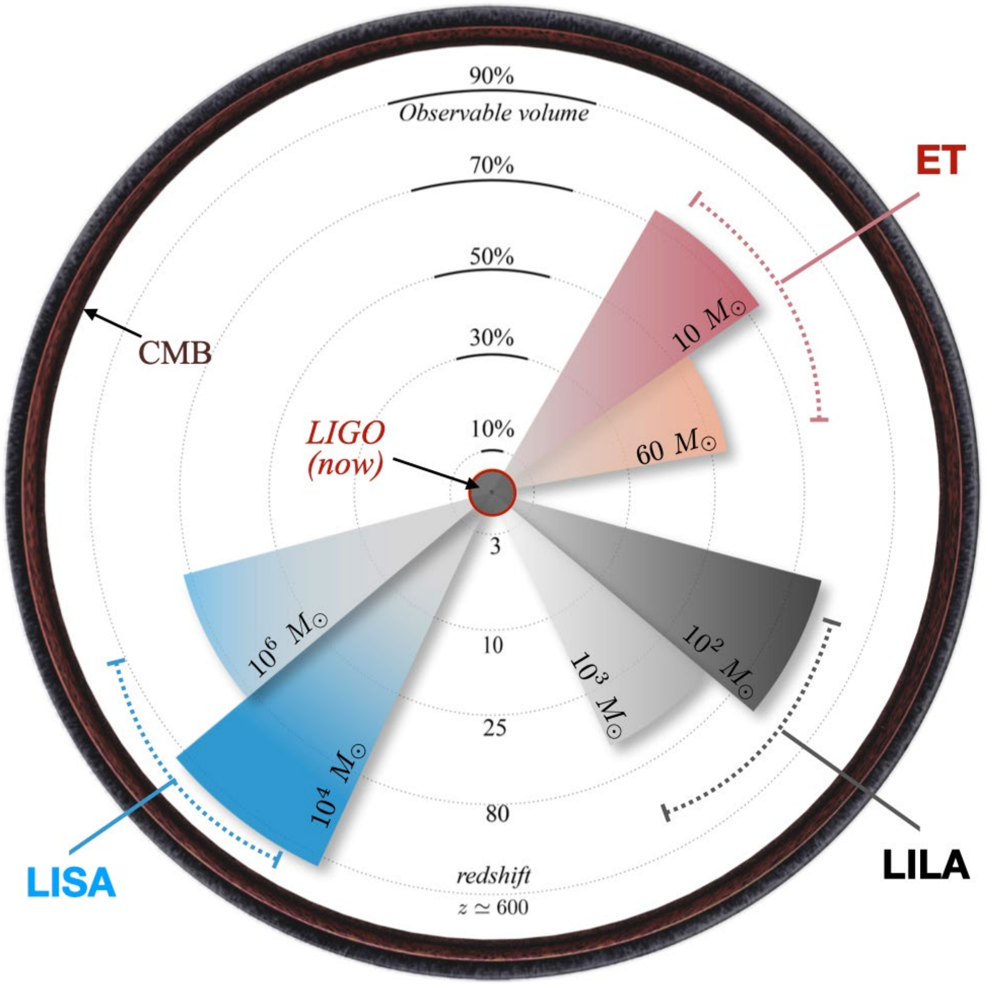
LILA Science: Cosmological Survey & BSM Physics

LILA

- **Early universe:** LILA can survey primordial black holes and seed formation of intermediate-mass black holes across the observable universe!
- **Dark Matter:** LILA can probe beyond-standard model particles for dark matter candidates to z>3 such as low frequency bosonic fields scattering off rotating black holes and sub-solar mass collisions.
- **Dark Energy:** LILA will measure four independent "standard candles" of cosmic expansion rate: WD mergers as progenitors of Type Ia SNe, single-degenerate channel of Type Ia SNe, binary neutron star (EM follow) and binary black holes (galaxy catalogs).



Observable Universe