LILA Observatory: A Lunar-Surface Mid-Band Gravitational-Wave Observatory

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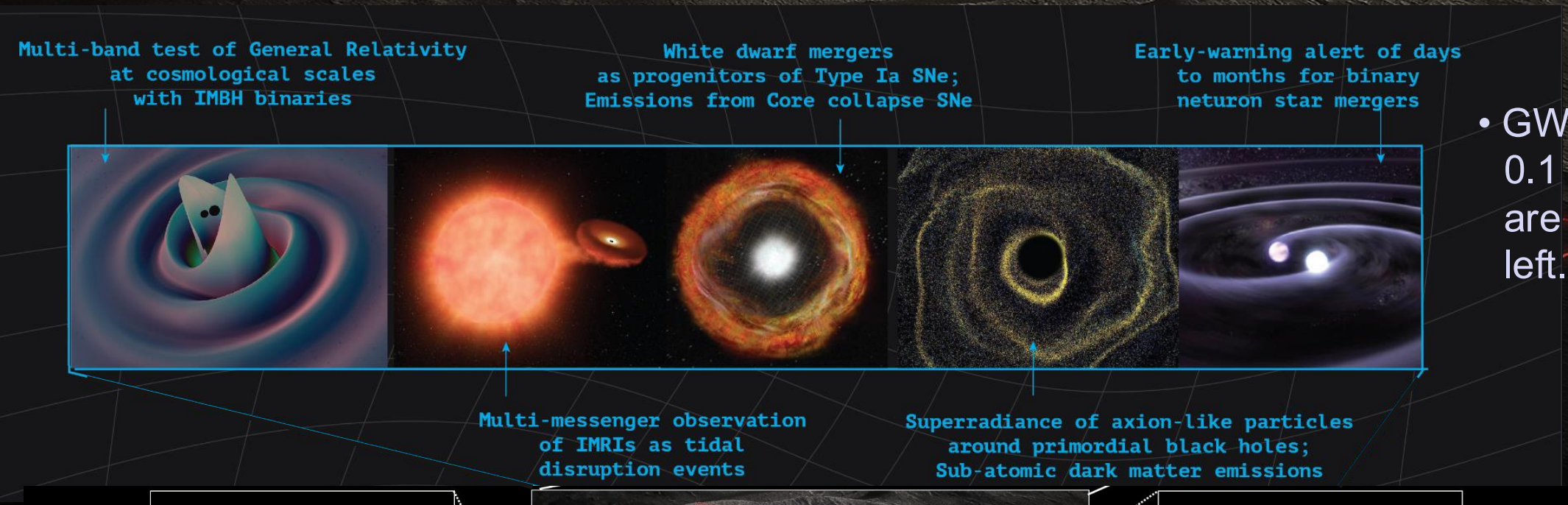
For the LILA collaboration

Meeting: Community Science (Ad ASTRA) Workshop
Session: Day 2, Gravitational Waves & Fundamental Physics
https://science.nasa.gov/astrophysics/programs/physics-of-the-cosmos/community/ad-astra/

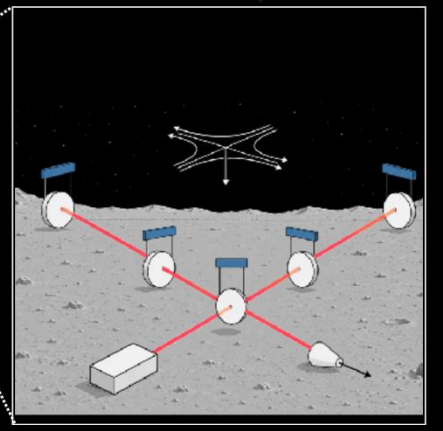
LILA Science: deciHz Astrophysics Landscape



- GW events in the 0.1 to 10 Hz range are shown on the left.

Lunar Deformation Channel (LDC)
[Using the Moon's resonant deformation]

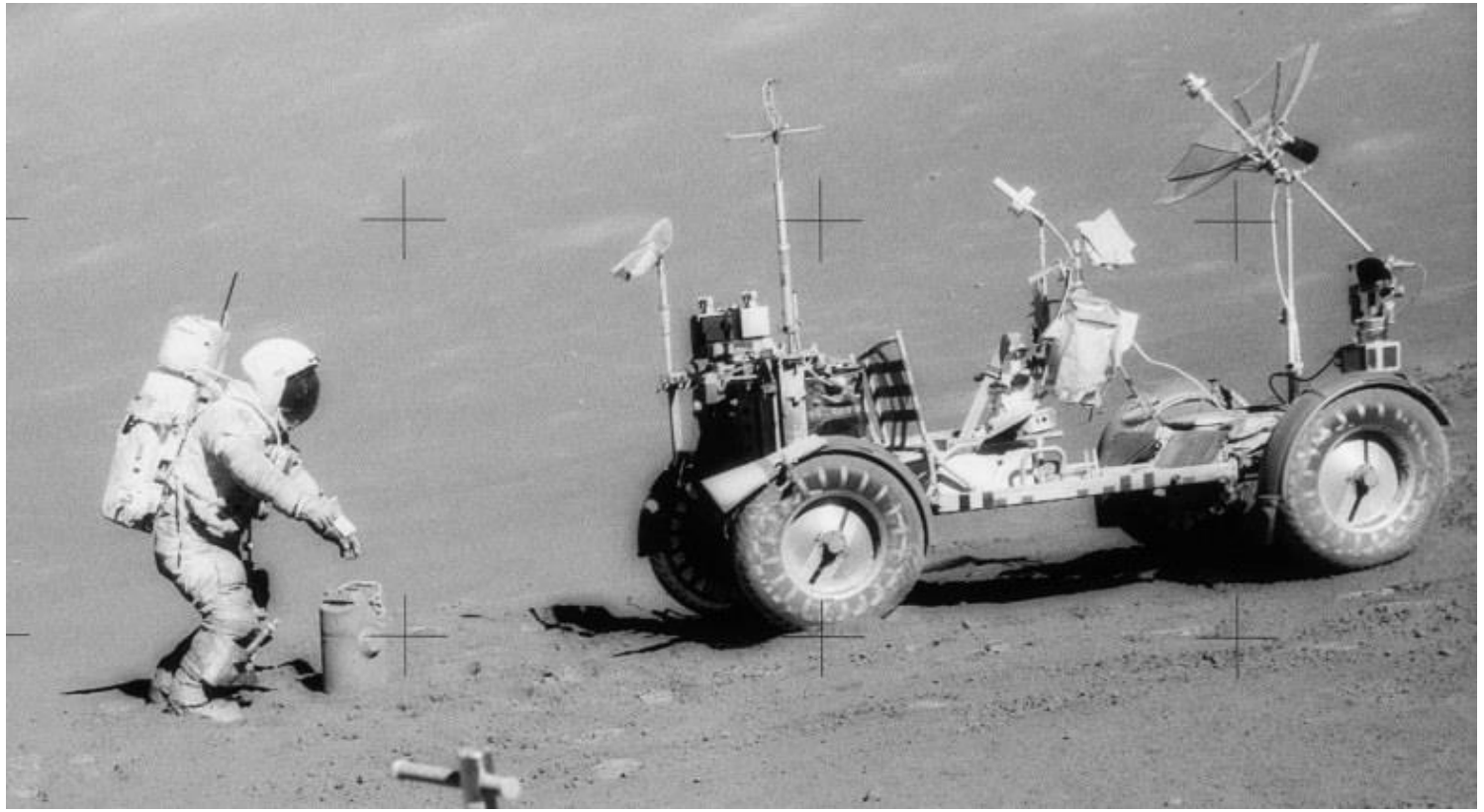
LILA Observatory
[Two GW measurement channels]



Geodesic Displacement Channel (GDC)
[Using suspended test masses]

- LILA is designed to open the mid-band between the Earth-based and space-based detectors.

Environmental Advantages

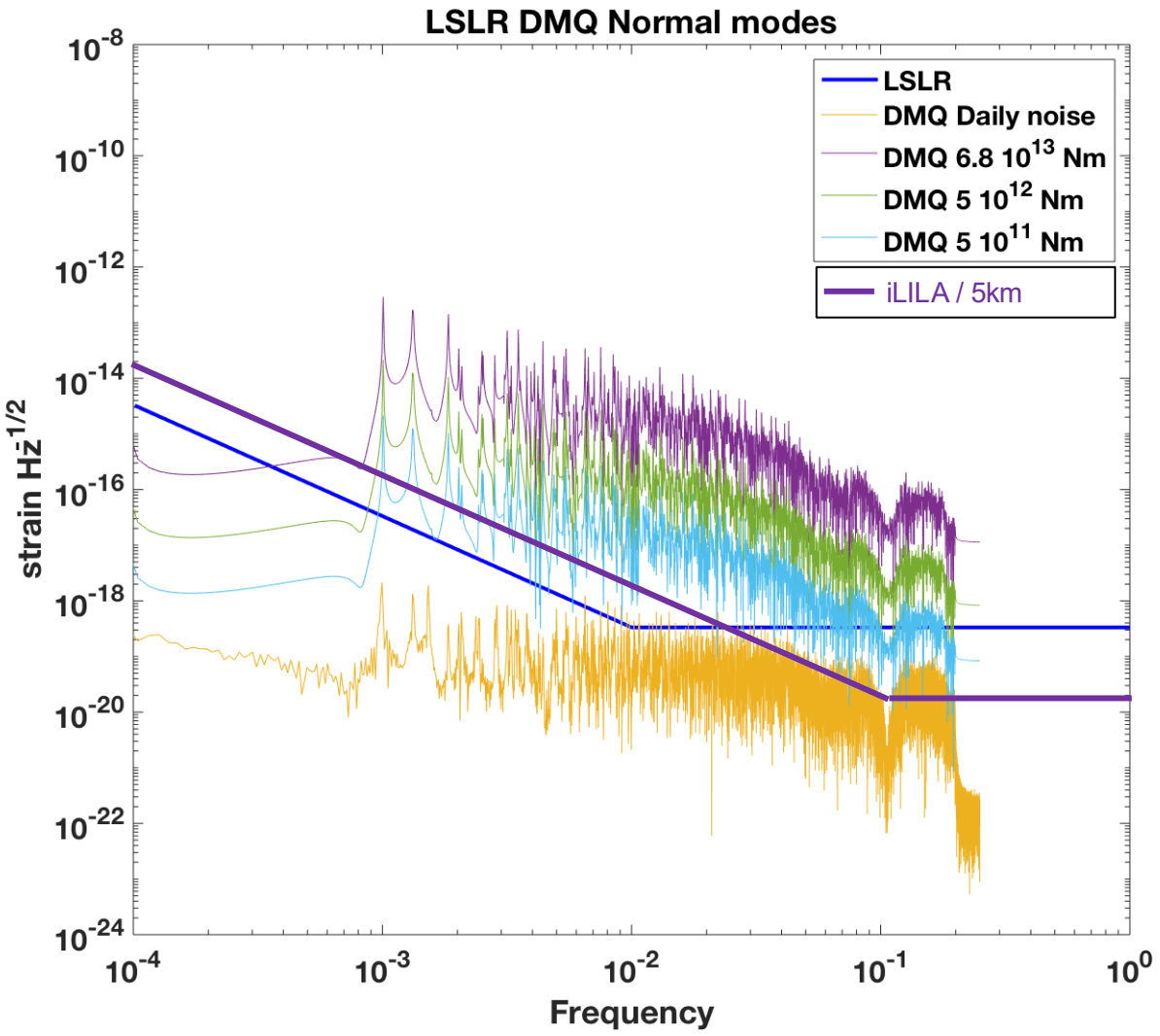


Our Moon is many orders of magnitude quieter than Earth at low frequencies.

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

Ongoing area of interest, see next slide.

Expected seismic activity: resulting strain



- But currently we don't know how low the seismic background is.
- The last measurements were done by the Apollo missions.
  Upper limit: 10^{-11} m/rt(Hz)
- The modeled daily noise – no moon quake activity – is very low
- Daily strain noise: ~ 10^{-20} 1/rt(Hz) noise
- Plot shows a lunar strain laser ranging (LSLR) strainmeter with arm length = 3km (older model with 10^{-15} m/Hz$^{1/2}$)
- The model shows the moon seismic is "burst" driven.
- iLILA curve added
- An LSLR will enable geophysics and GW detection
- The moon seismic becomes the signal!

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.

Environmental advantages/disadvantages summary

- 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.

- LILA is location agnostic – but please, avoid too many neighbors.

Lunar and Instrumental Response

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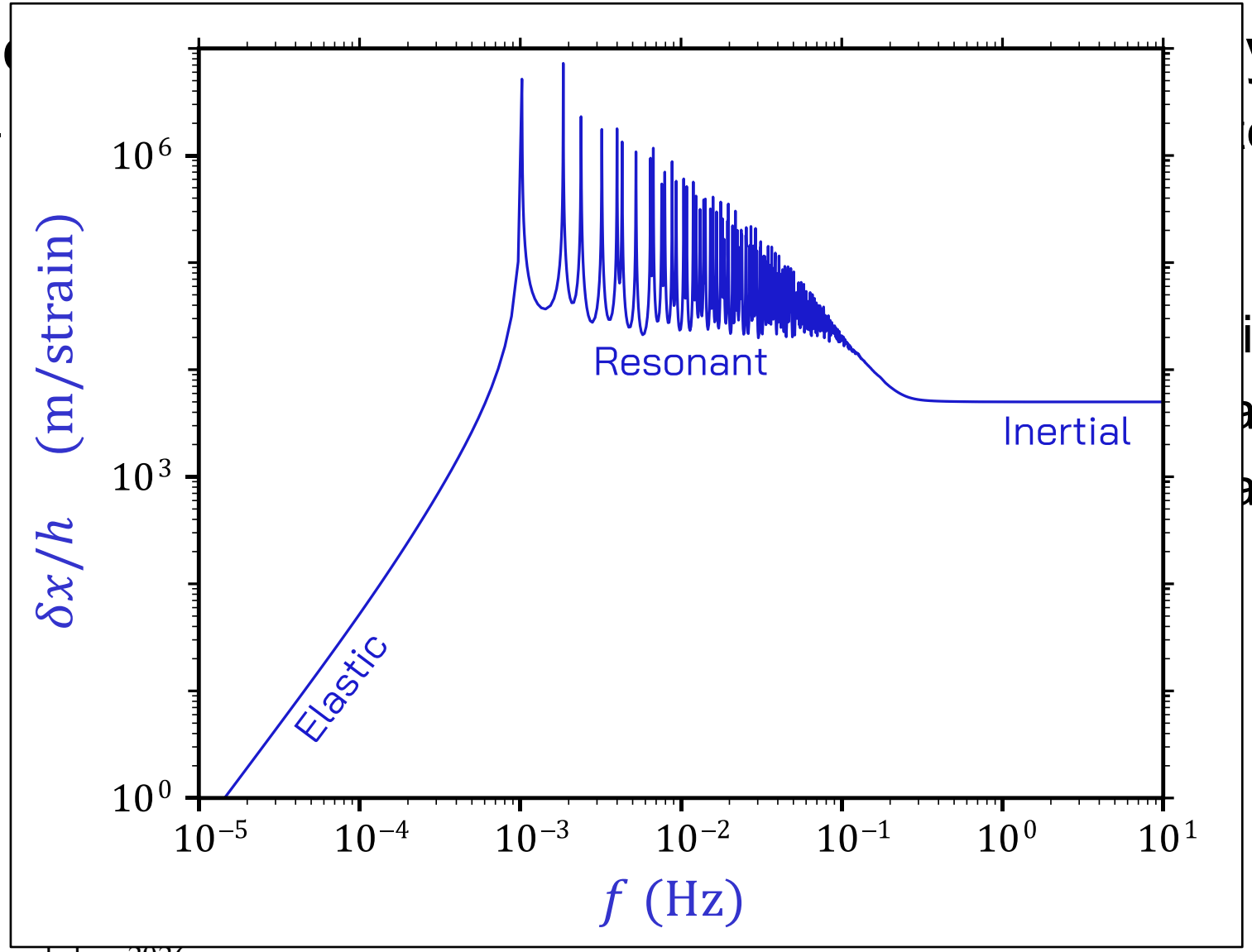
id – suspended mirrors

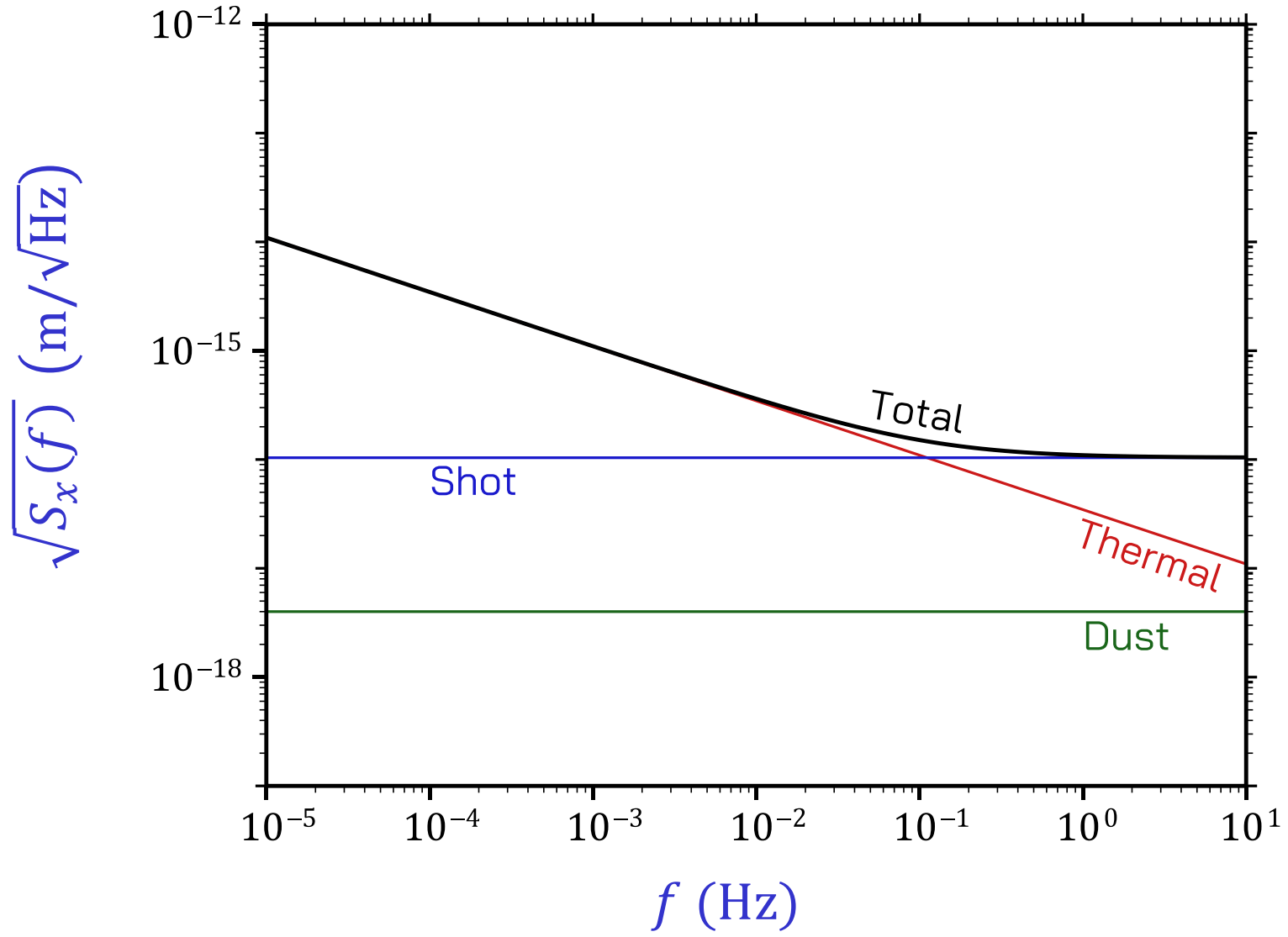
as resonator – strainmeter

astic solid – not used



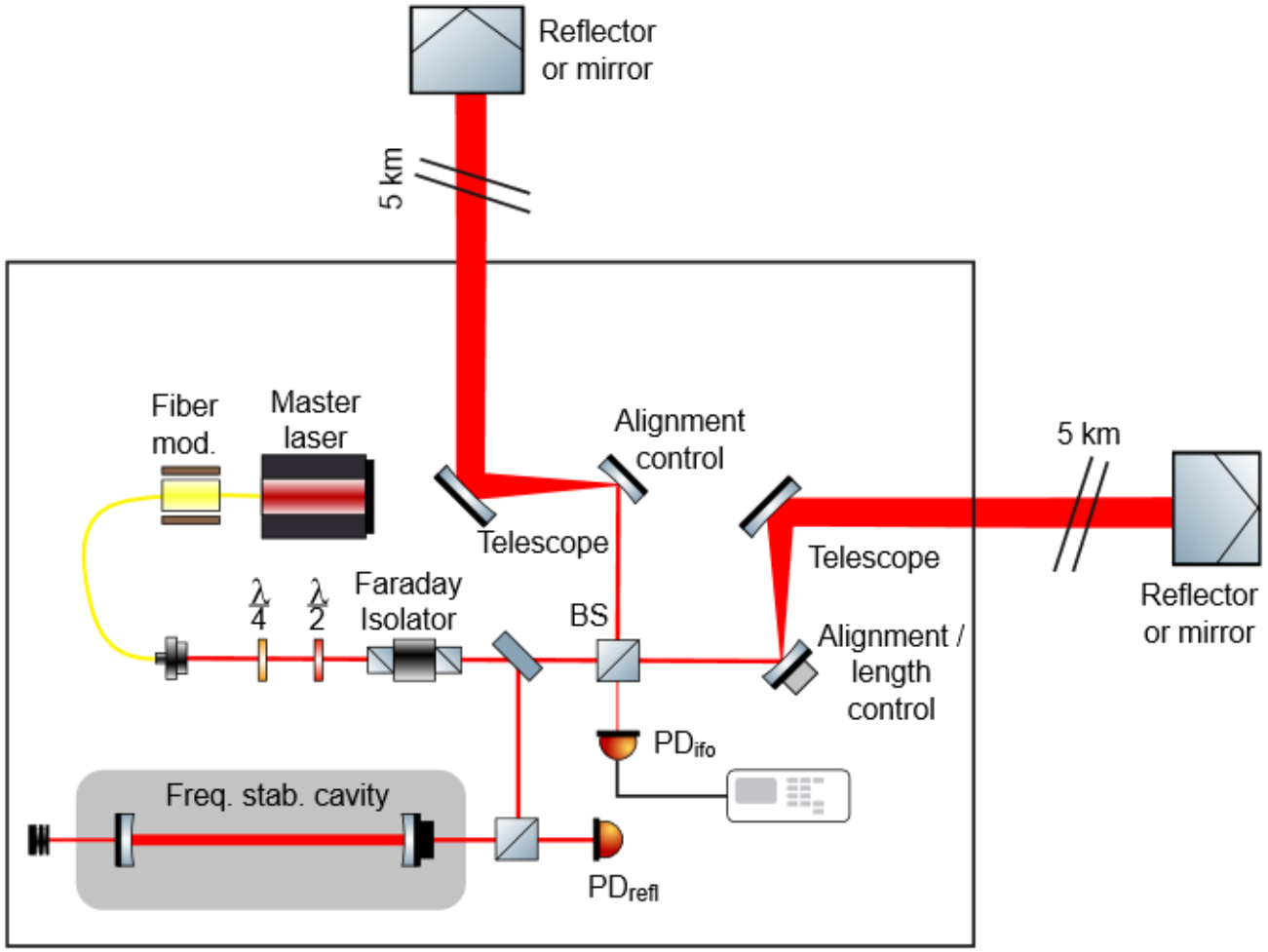
Credit: Creighton, T., et al. arXiv:2508.18437; Panning, M. P., et al. Classical and Quantum Gravity, 43(12), 127001.

Fundamental Noise Sources



iLILA Detector Development

- Readout scheme
  - Basic IFO, active corner, passive retroreflectors at the ends
- Technical challenges
  - Optical system design, surface and coating specifications. (especially for 30cm optics)
  - Thermal expansion and impact. Breadboard and telescope. Shielding the space craft.
  - Beam control and noise (telescope).
  - Retroreflectors (30 cm aperture?)
  - Operational on the Moon
  - Response to radiation
  - Maintenance



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The plan:
Laser Interferometer Lunar Antenna (LILA)

Multi-band GW Observatory on the Moon

LILA

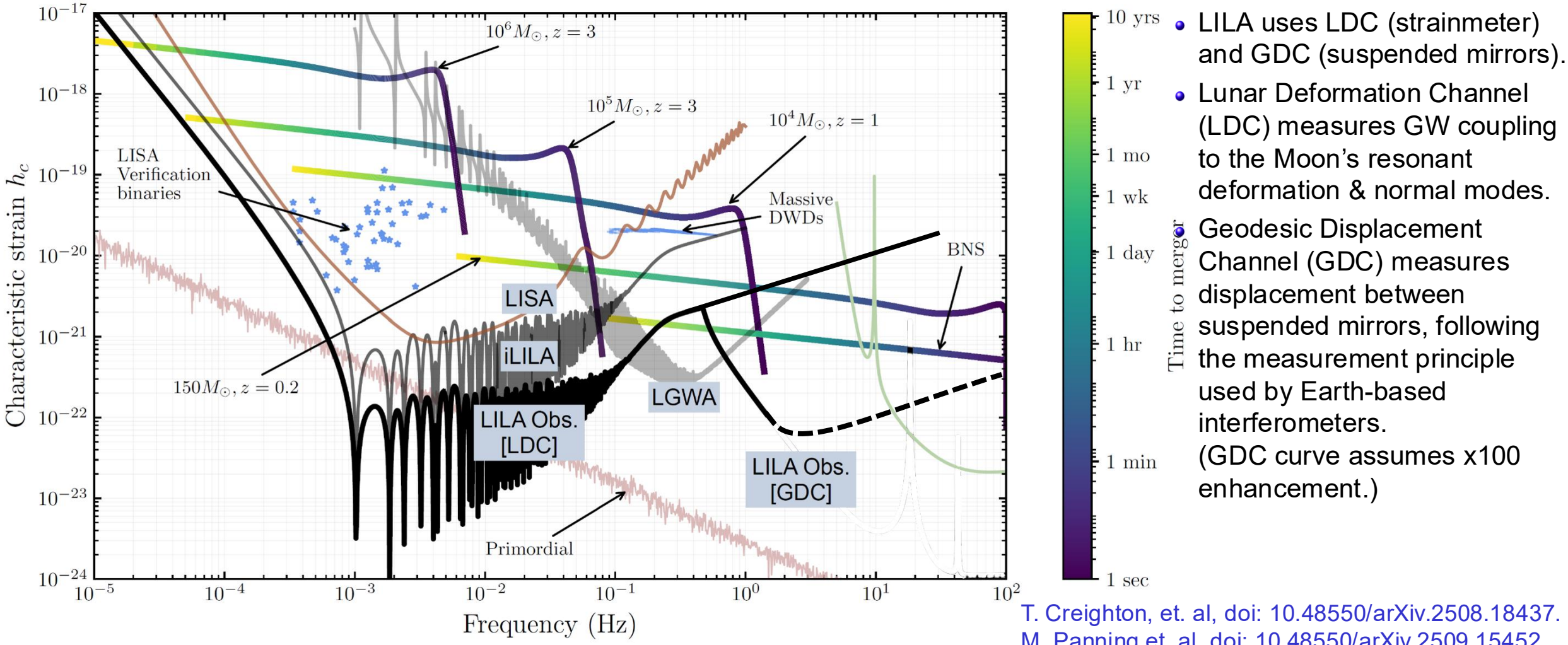
iLILA

- GW band: 1 Hz to and below
- 5 km armlength Michelson interferometer
- Targeted GW Sensitivity: $2*10^{-20}$ 1/rt(Hz) at 1 Hz
- Detection Method: Strain measurement / Lunar normal modes
- Scientifically meaningful, but based on current technology, "no optical tricks", no suspension system needed

Full LILA Observatory

- GW bands: mHz to deci-Hz + deci-Hz to 100 Hz
- 40 km armlength Michelson interferometer
- Targeted GW Sensitivity: $5*10^{-21}$ 1/rt(Hz) Strainmeter at 1 Hz
  $2*10^{-22}$ 1/rt(Hz) suspended at 1 Hz
- Detection Method: Strain measurement, Lunar Normal Modes & (multi-stage suspended test masses)
- Will need advanced techniques – cavities, recycling technology, quantum techniques (squeezing)

Targeted sensitivity for iLILA and LILA
Comparison to sources



- iLILA uses LDC (strainmeter)
- LILA uses LDC (strainmeter) and GDC (suspended mirrors).
- Lunar Deformation Channel (LDC) measures GW coupling to the Moon's resonant deformation & normal modes.
- Geodesic Displacement Channel (GDC) measures displacement between suspended mirrors, following the measurement principle used by Earth-based interferometers.
  (GDC curve assumes x100 enhancement.)

T. Creighton, et. al, doi: 10.48550/arXiv.2508.18437.
M. Panning et. al, doi: 10.48550/arXiv.2509.15452.
J. Harms, doi: 10.1103/PhysRevLett.129.071102
B.N. Shapiro, doi: 10.48550 *arXiv:2512.11268*.

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iLILA
artist version

LILA

- Primary Payload (active): about 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