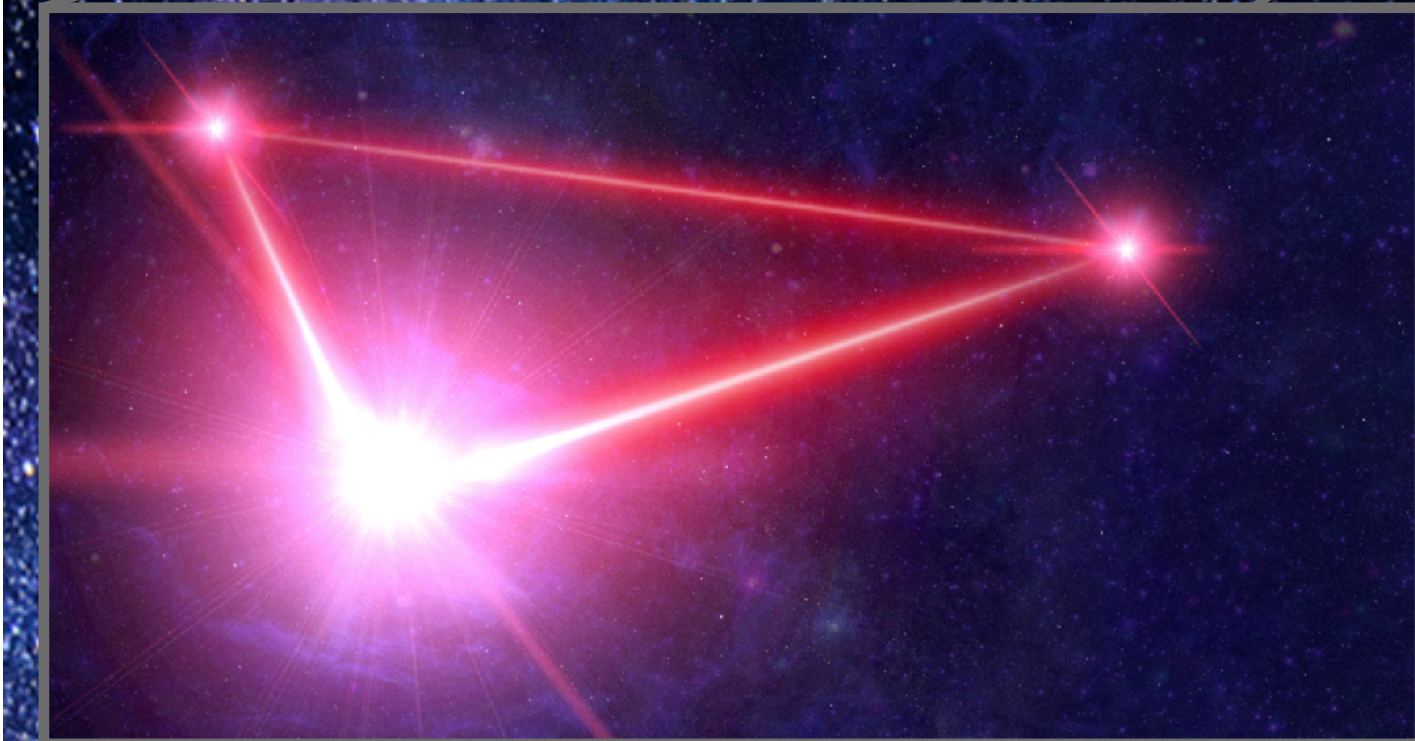
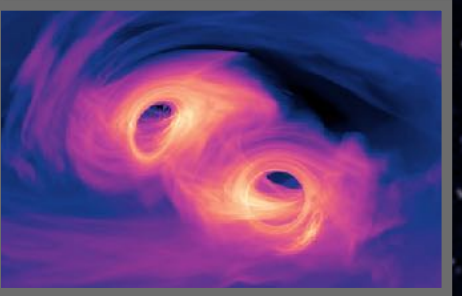
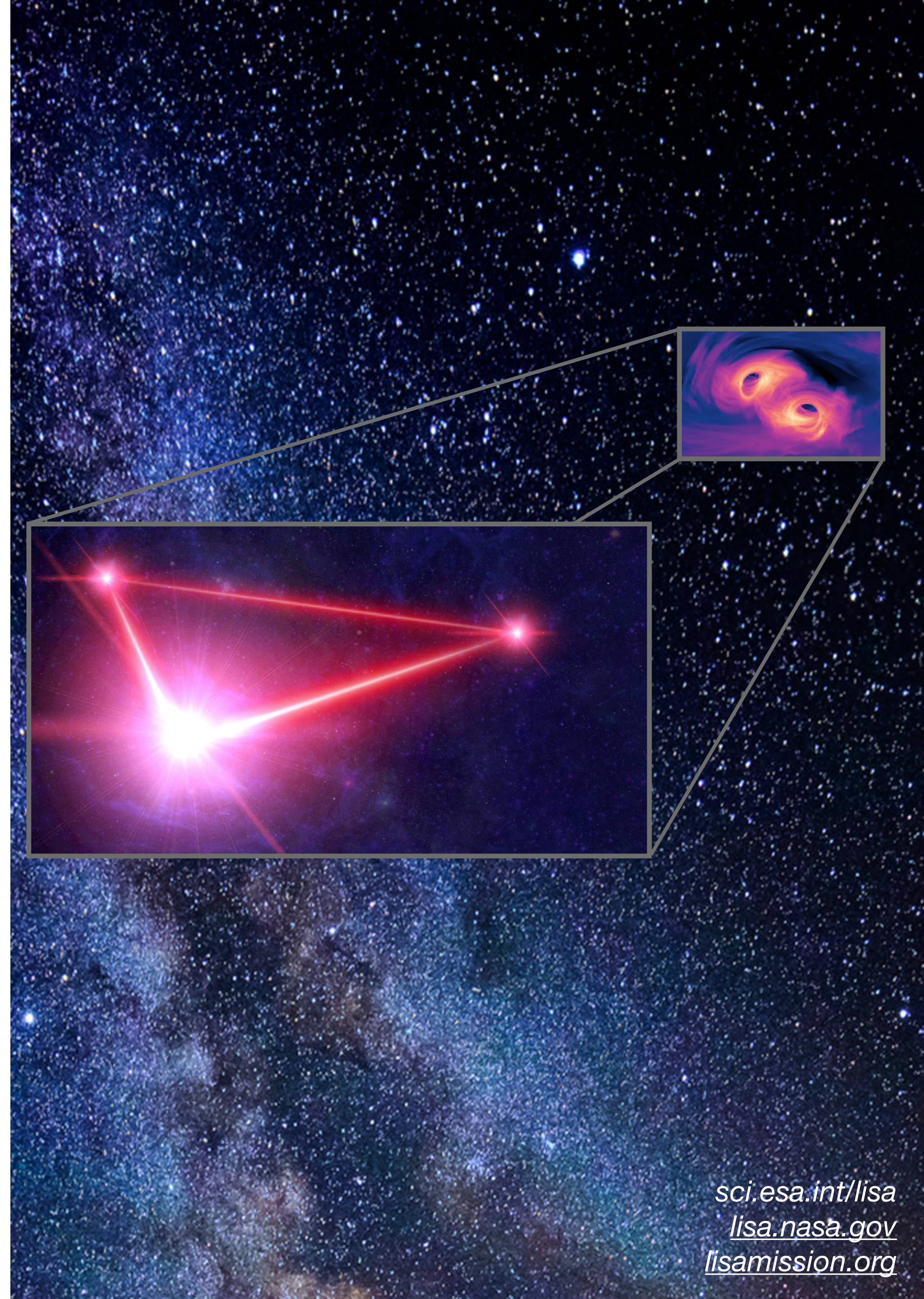


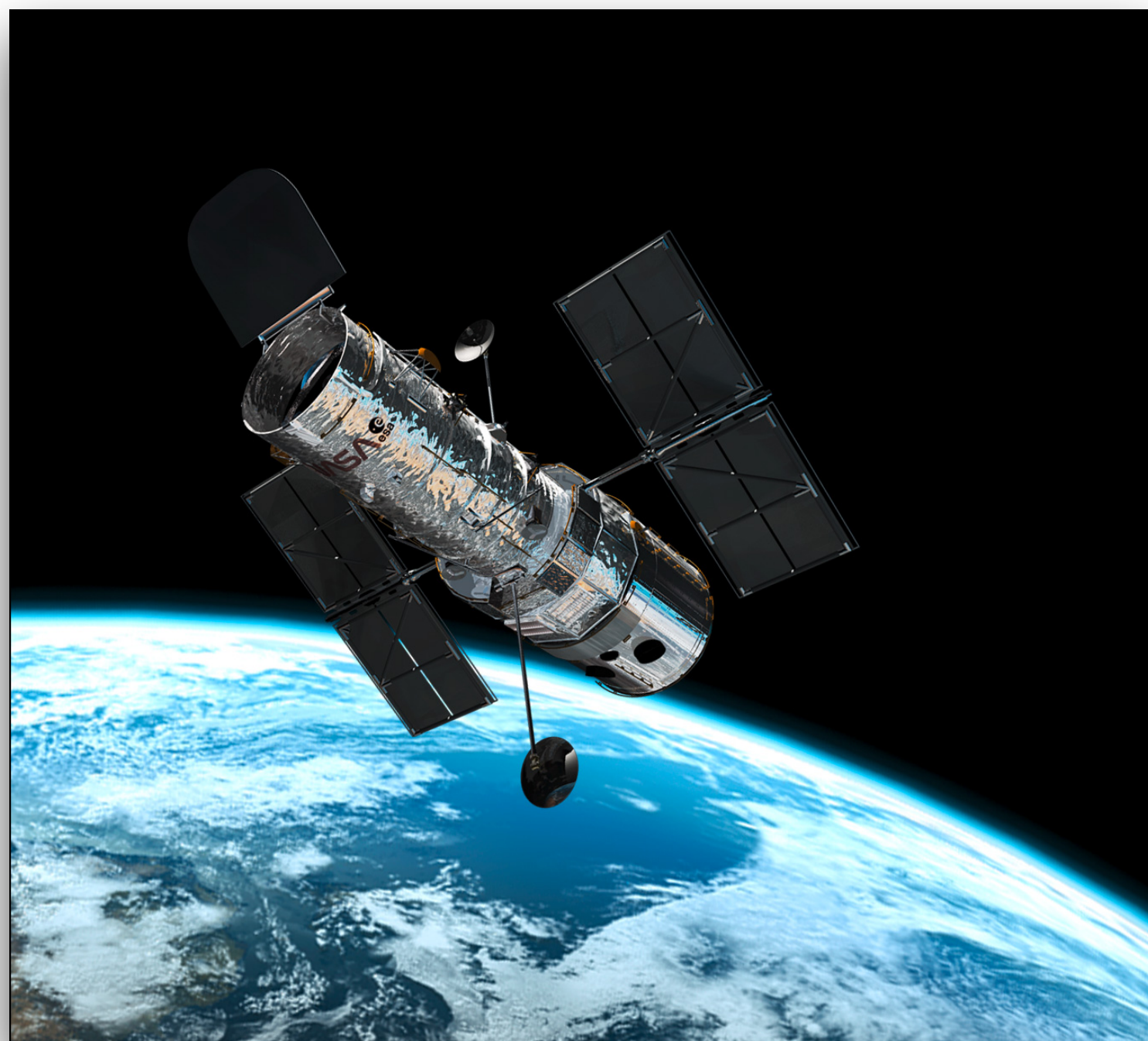
# The Laser Interferometer Space Antenna: Bringing the Gravitational-wave Revolution to Space

Ira Thorpe, NASA LISA Study Scientist  
On behalf of the worldwide LISA Team



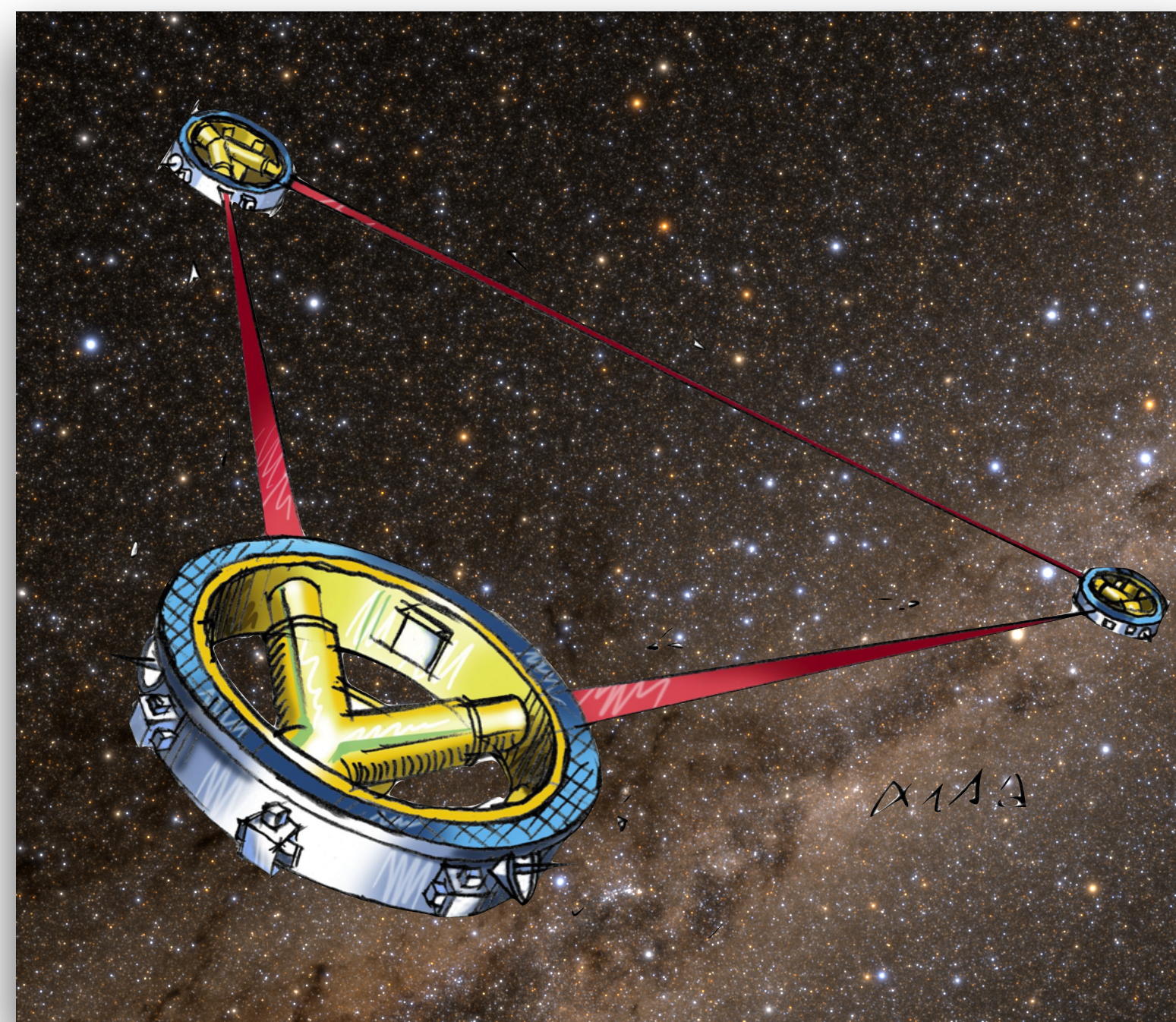
*Gravitational Wave Astronomy Pacific Northwest (GWPNW)*  
*June 29, 2021*





NASA/STScI

- Avoid terrestrial disturbances
- Access new spectral bands



Credit: ESA-C. Vijoux

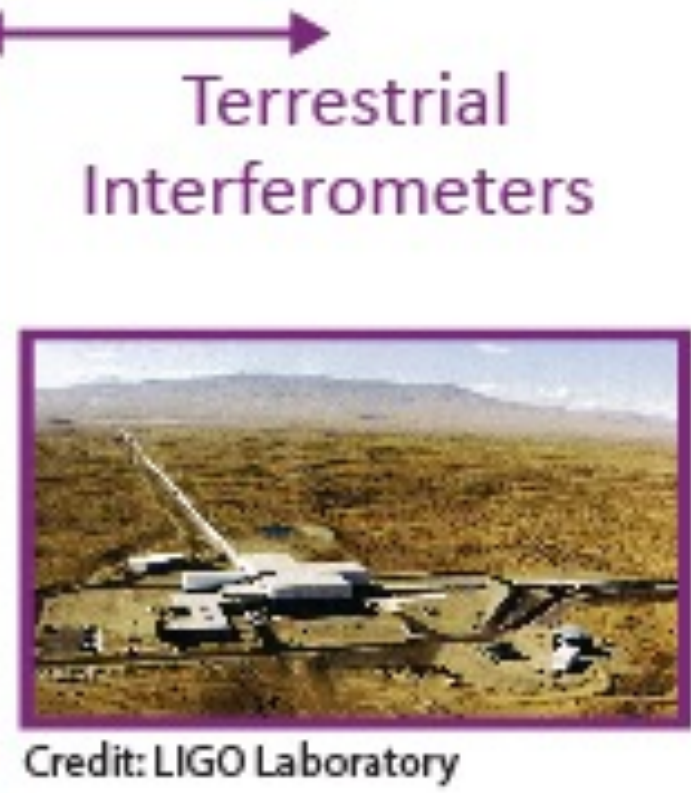
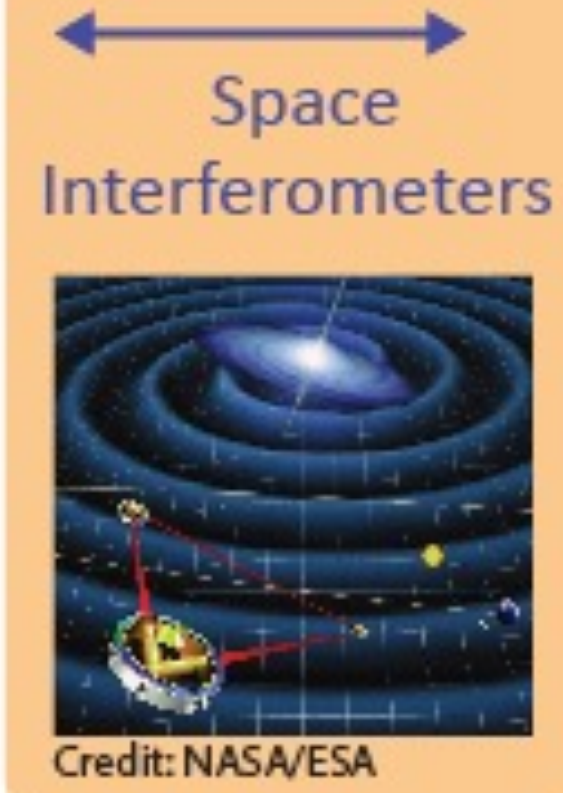
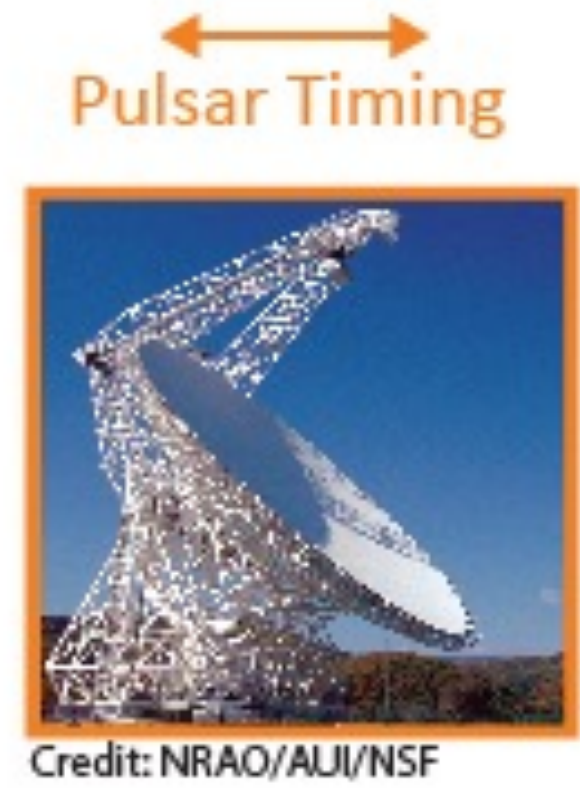
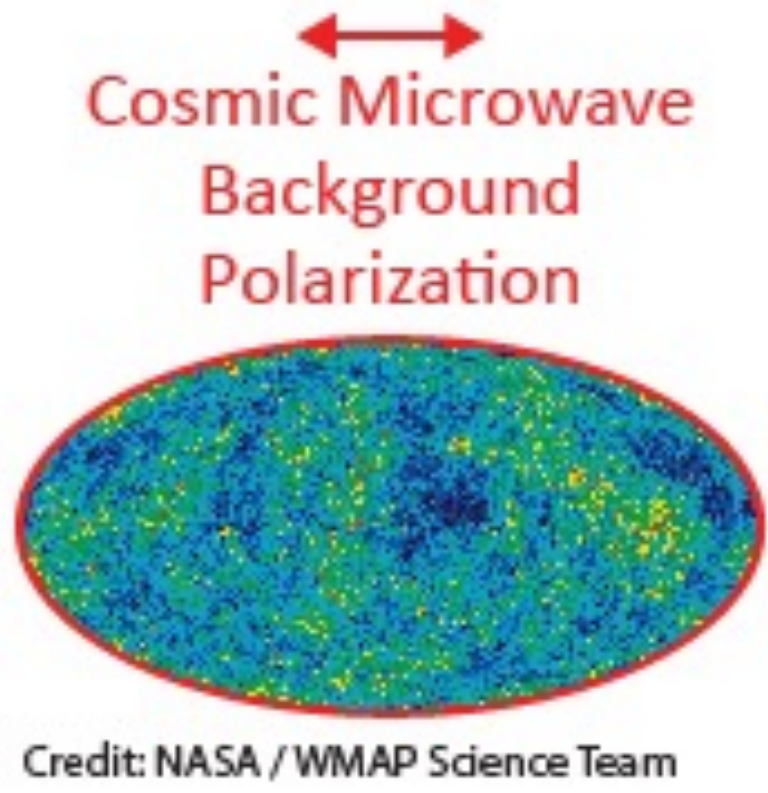
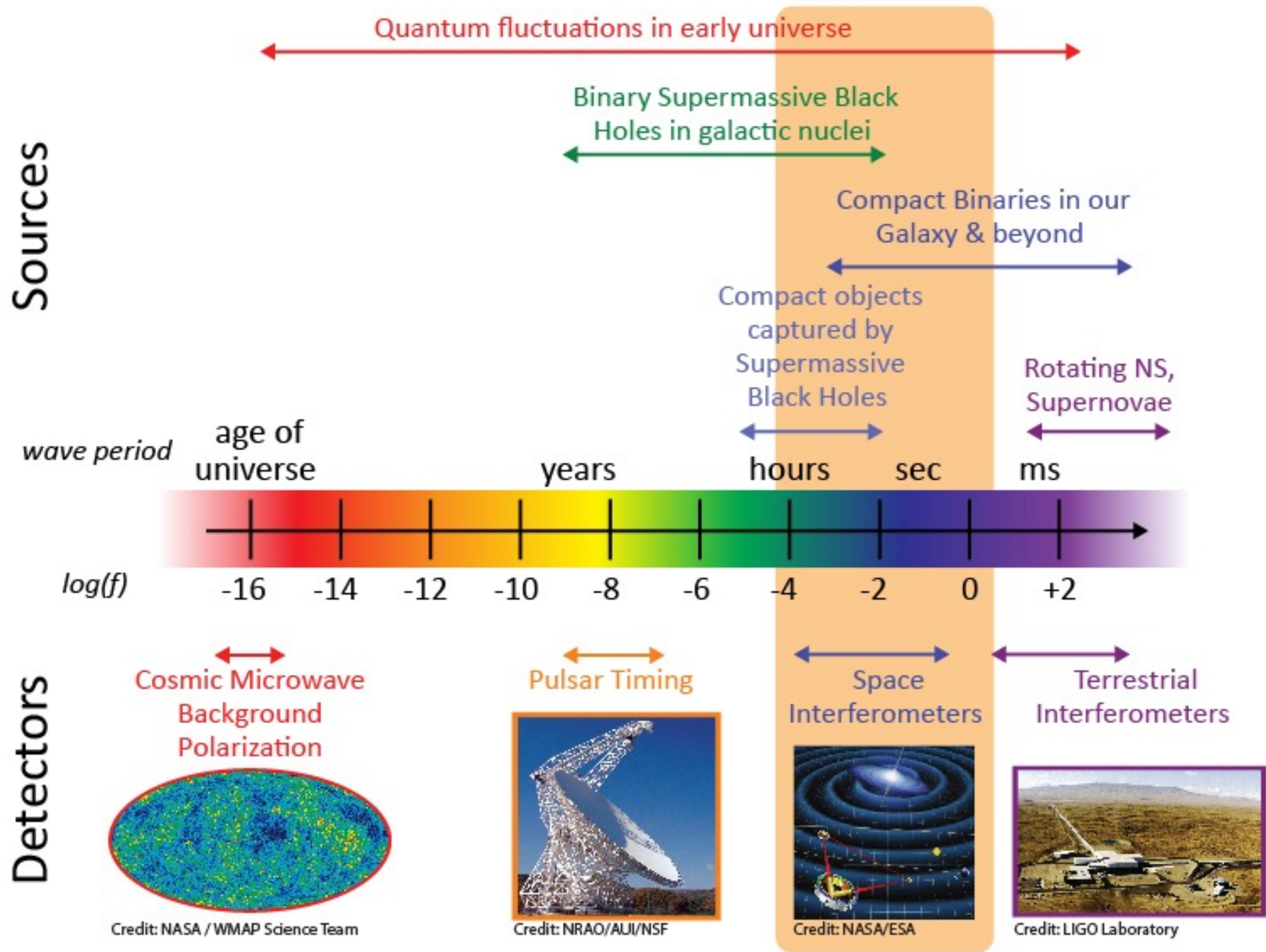
- Avoid terrestrial disturbances
- Access new spectral bands

# Why go to space?

Same reasons as for EM telescopes



# The Gravitational Wave Spectrum





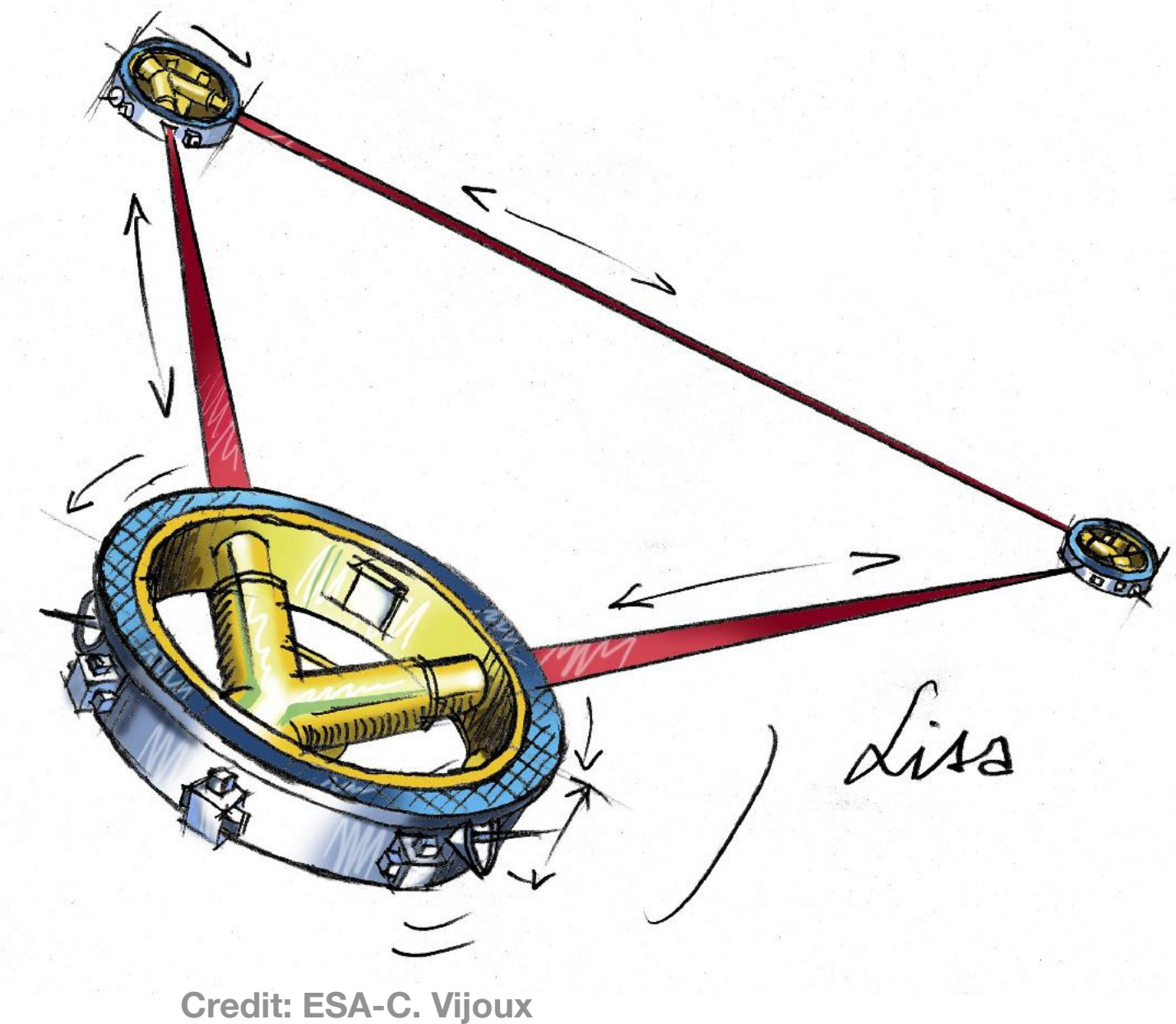
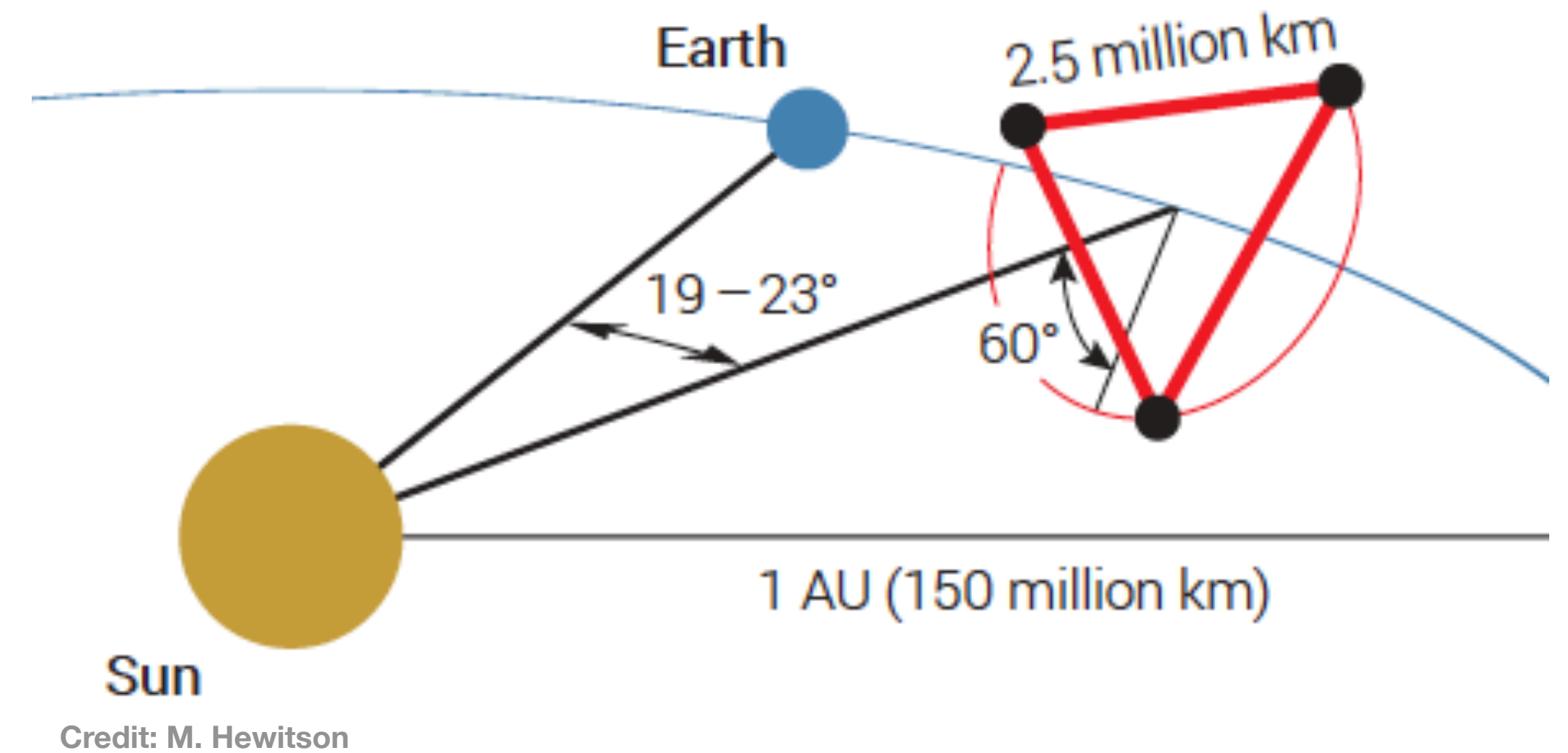
# The LISA concept

## • History

- 1974: Weiss and Bender
- 1980s-1990s: US and European academia
- 2001-2011: joint NASA/ESA project
- 2017+: ESA-led international project

## • Concept

- million-kilometer scale triangular observatory
- drag-free test masses as inertial references
- laser interferometry monitors distances for picometer-scale GW perturbations
- matched filtering used to disentangle thousands of overlapping sources

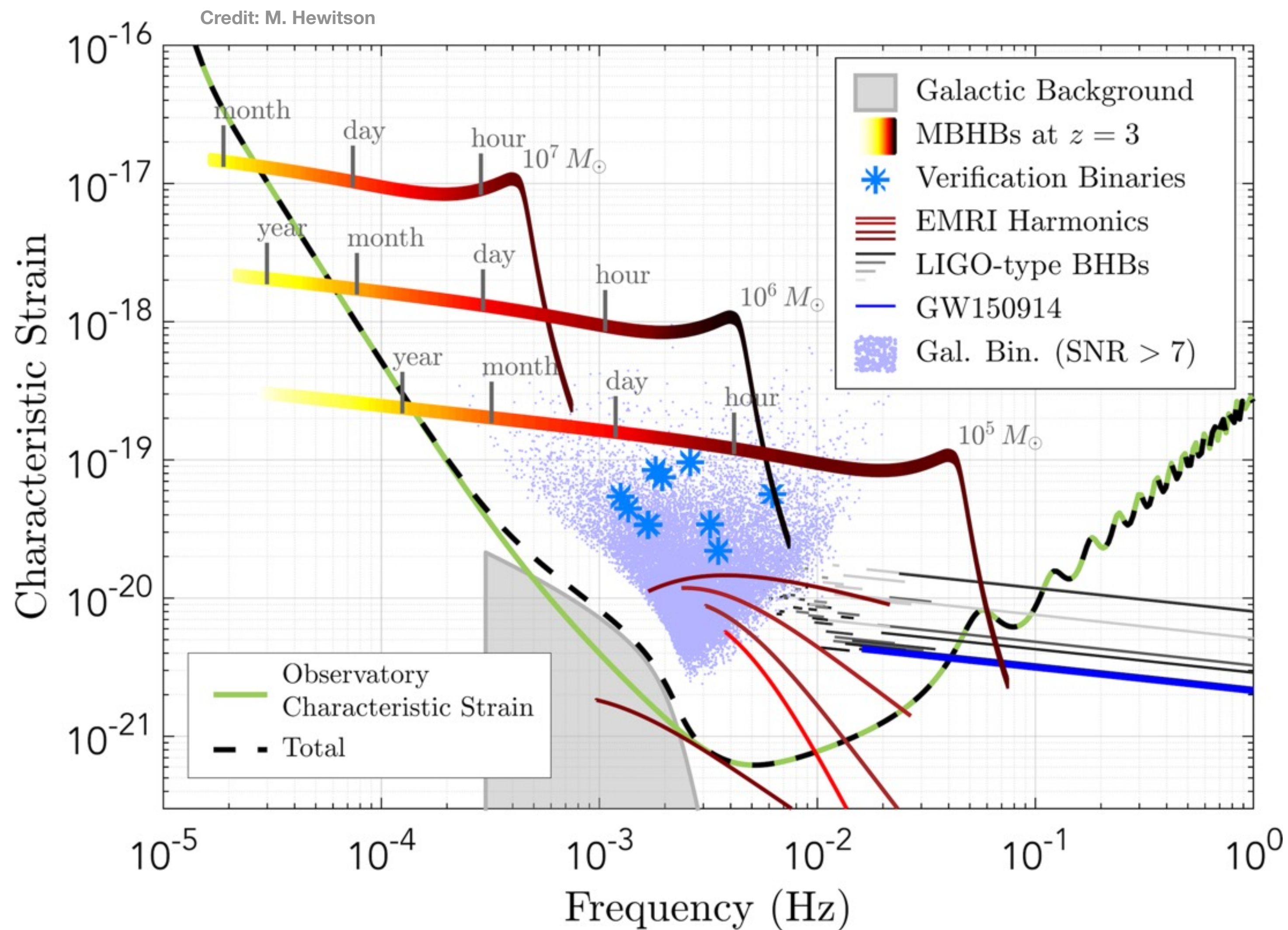


# Science



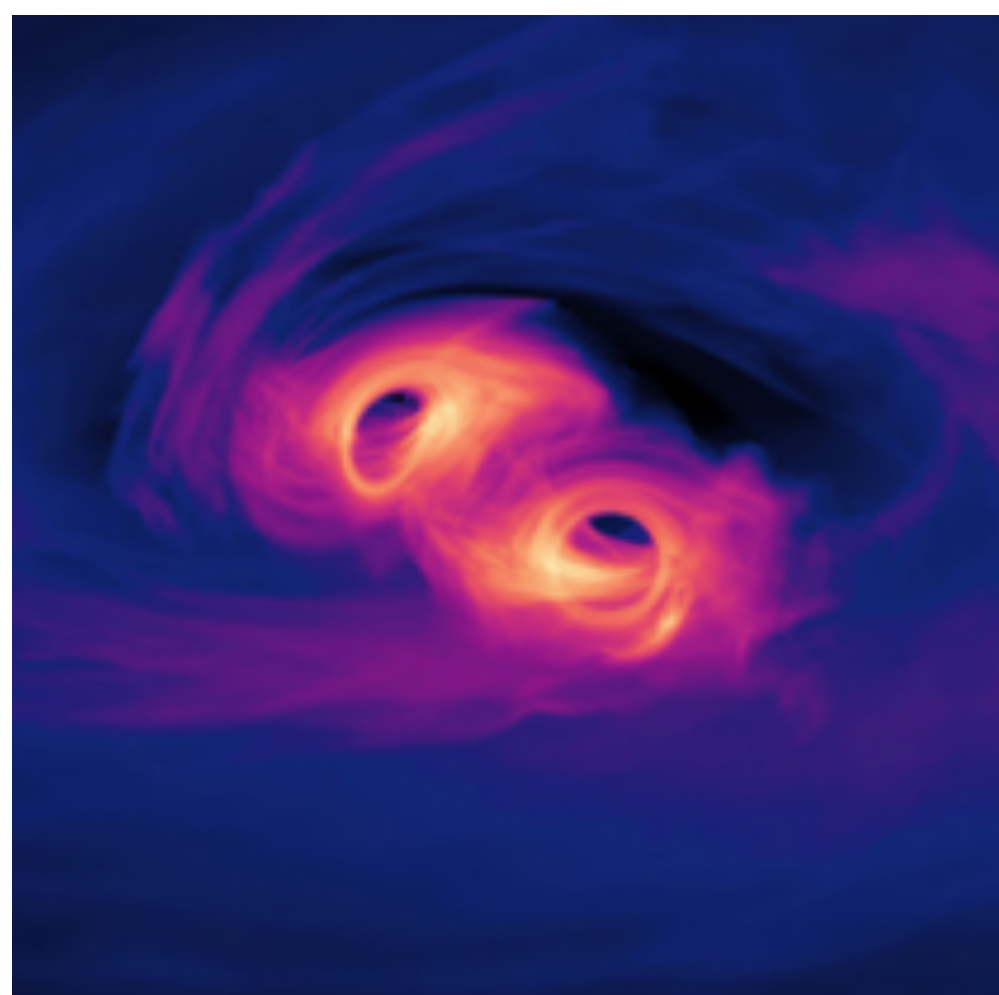
# Rich and complex data set

- Several different source types
- persistent and transient sources
- unresolved galactic “foreground”
- $>10^4$  sources simultaneously in band
- Global fit!



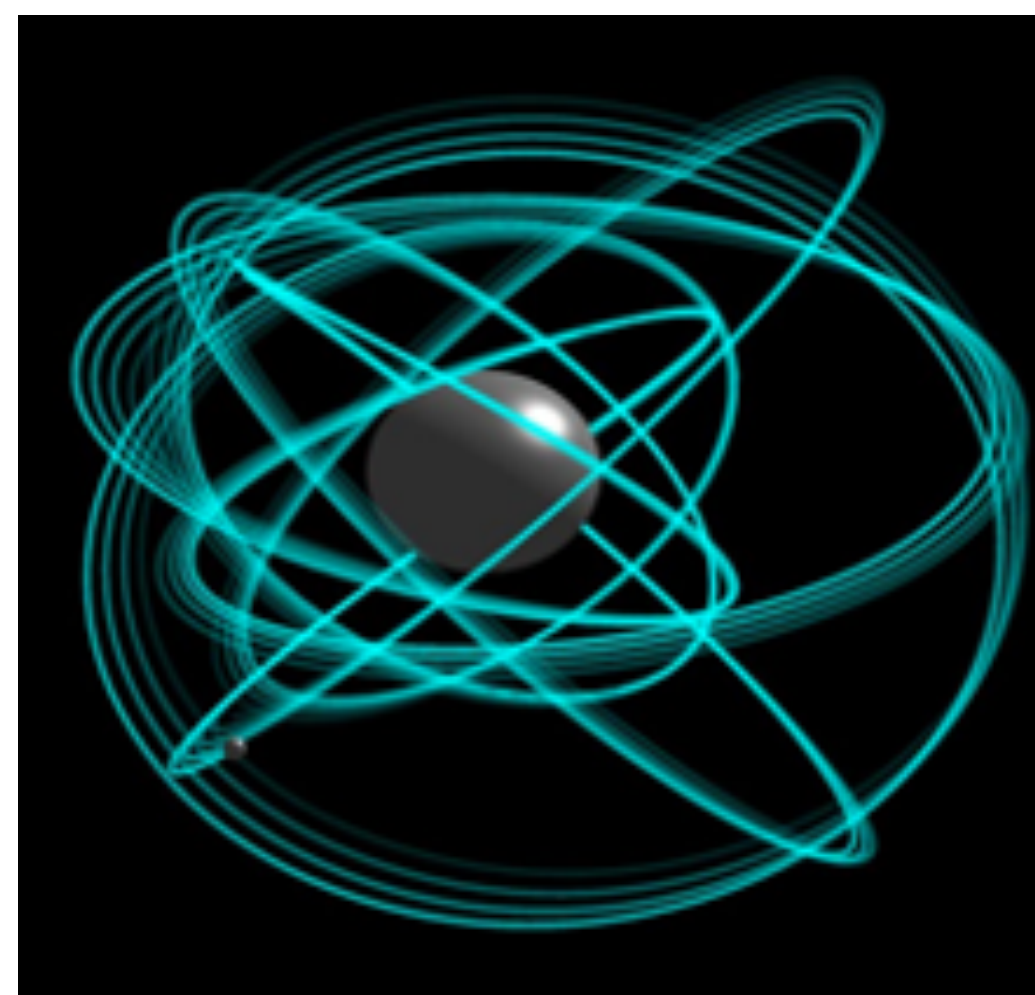
# Science Highlights

## Mergers of Massive BHs



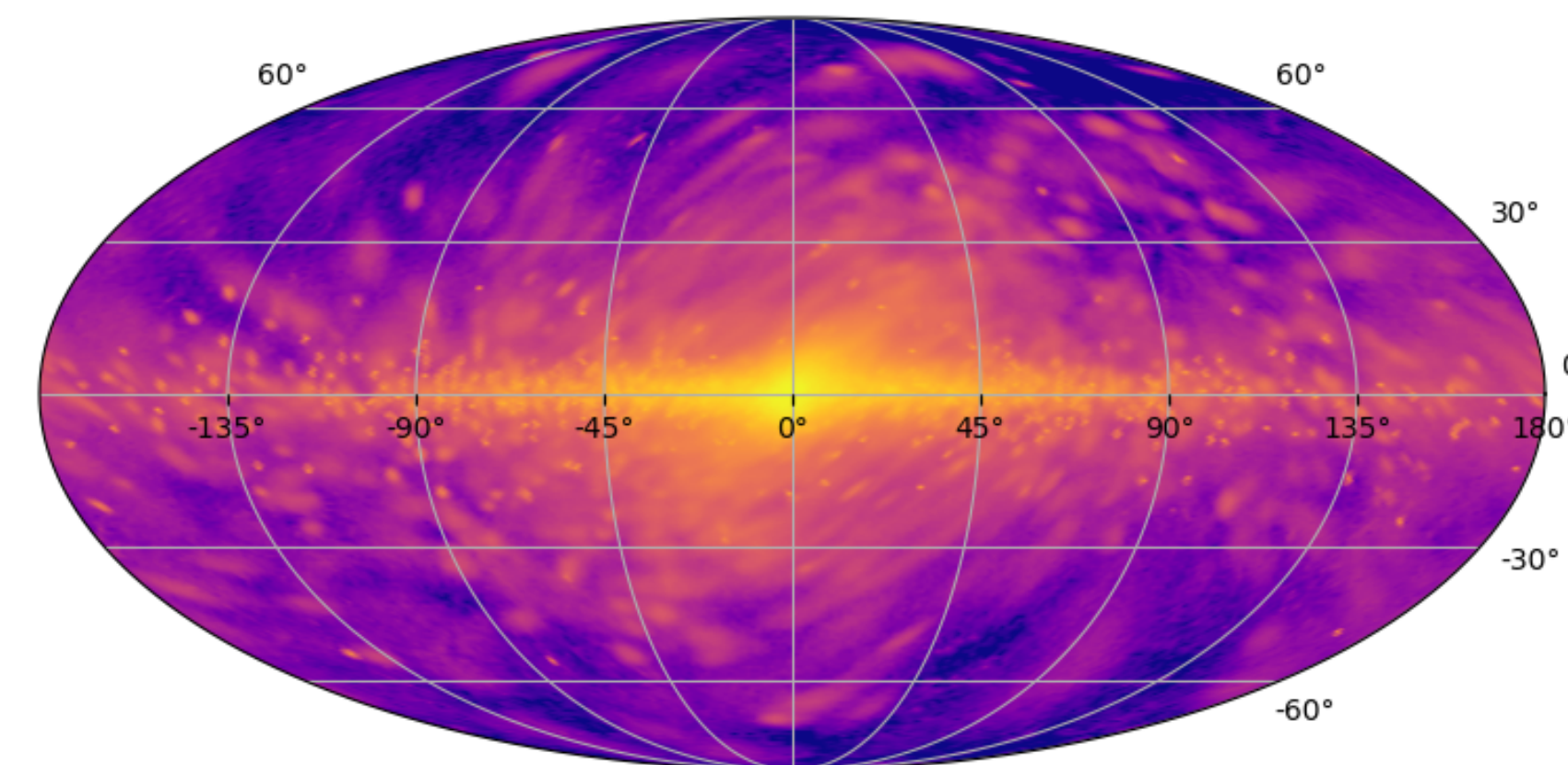
- $10^3 M_{\odot} \sim 10^8 M_{\odot}$
- $1 \lesssim z \lesssim 20+$
- $D, M, m, \chi$ , etc. at % level
- MBH formation and co-evolution with galaxies
- Potential EM counterparts?

## Extreme Mass-ratio Inspirals



- BH analog of a TDE
- Extreme probe of strong gravity
- Probe high-mass demographics and dynamics of nuclear clusters

## Ultra-compact binaries



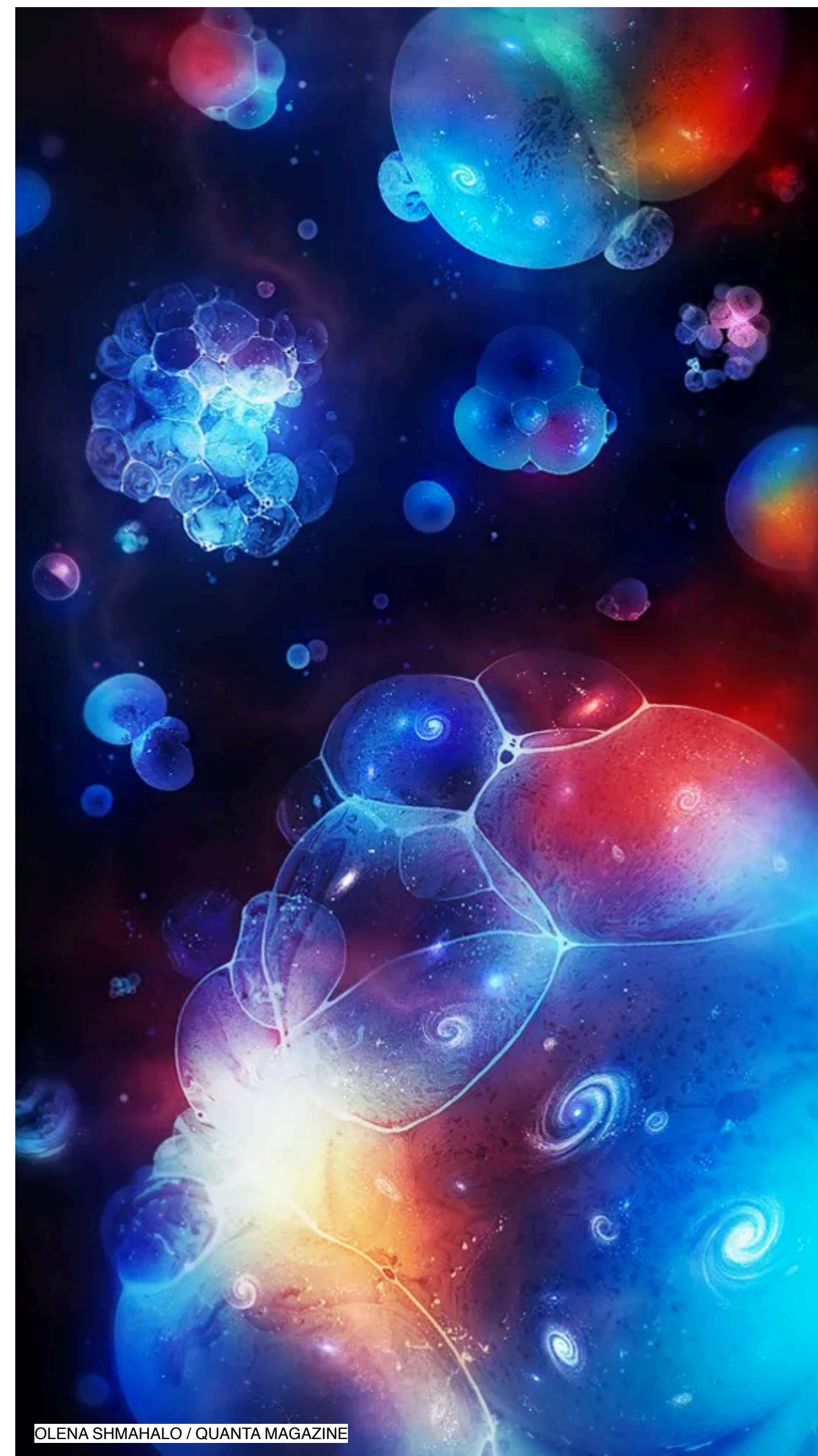
- $\sim 10^4$  resolved binaries (WD-WD, WD-NS, etc.)
- Unresolved galactic foreground
- Guaranteed multi-messenger sources
- End states of stellar + binary evolution, tracer of Milky Way formation history, binary astrophysics, etc.



# Backgrounds / Discovery Space

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- “Unknowns, both known and unknown”
- Astrophysical
  - Intermediate mass black holes
- Physics
  - Inflationary GWs
  - Cosmic string cusps
  - vacuum transitions



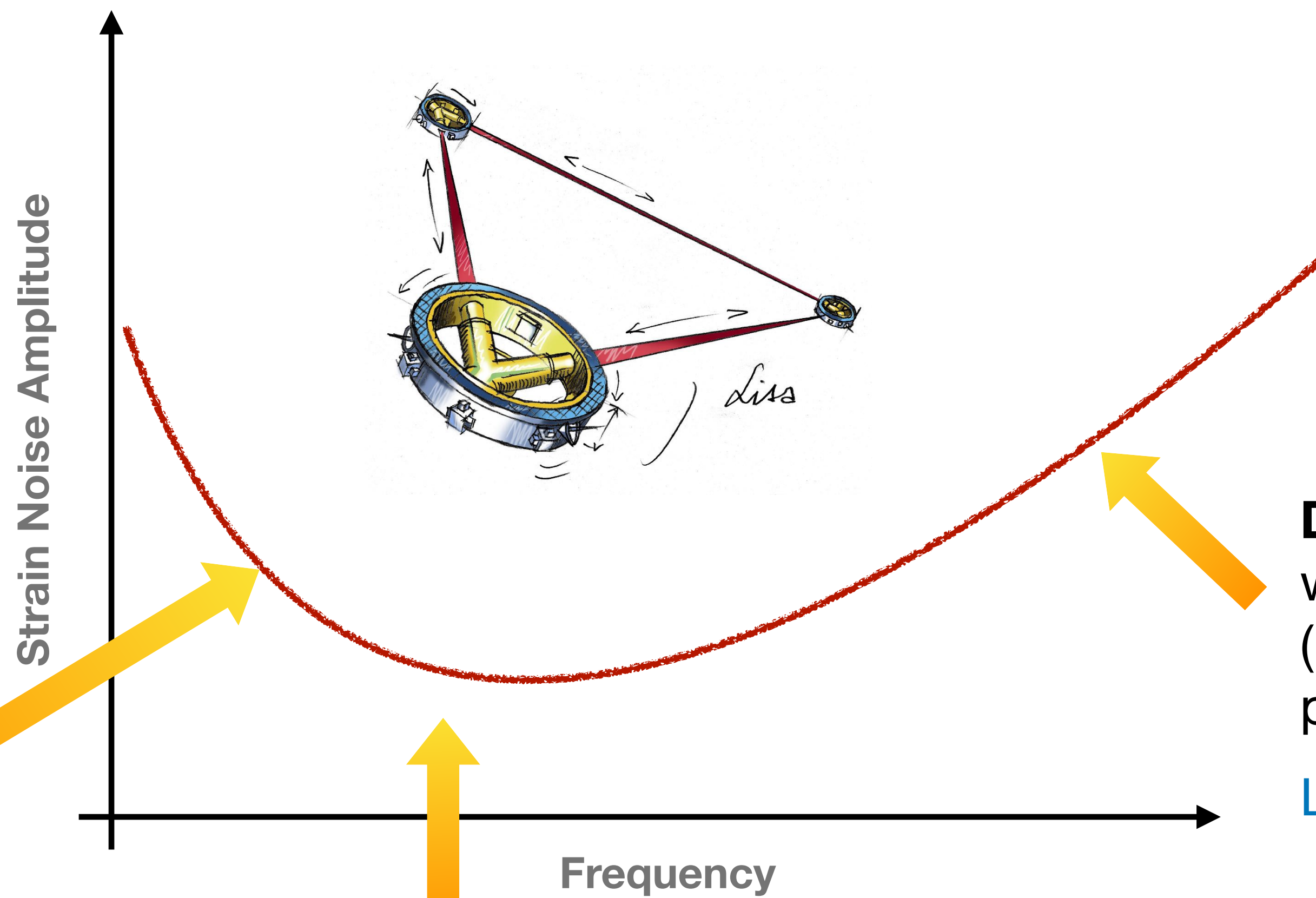
OLENA SHMAHALO / QUANTA MAGAZINE



# Technology



# Fundamentals of GW Interferometers



**Acceleration noise:** how stable are your fiducial test particles?

LISA ~ femto-g/Hz<sup>1/2</sup>

**Arm length:** Sets overall sensitivity scale *and* frequency of peak sensitivity

LISA ~2.5 Mkm

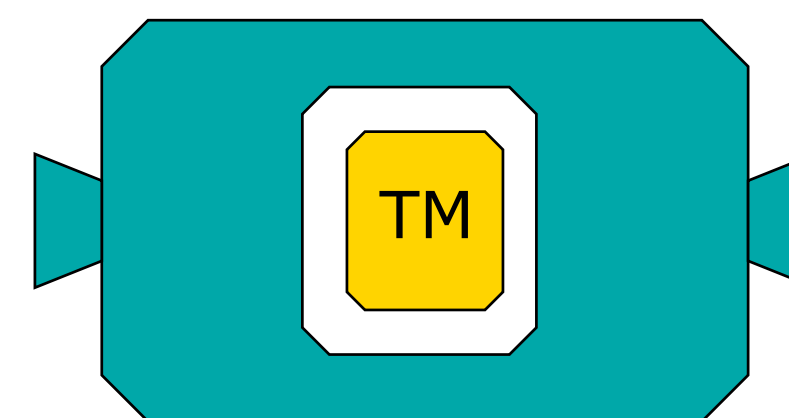
**Displacement noise:** how well can you measure (proper) distance between pairs of test particles?

LISA ~ picometer/Hz<sup>1/2</sup>

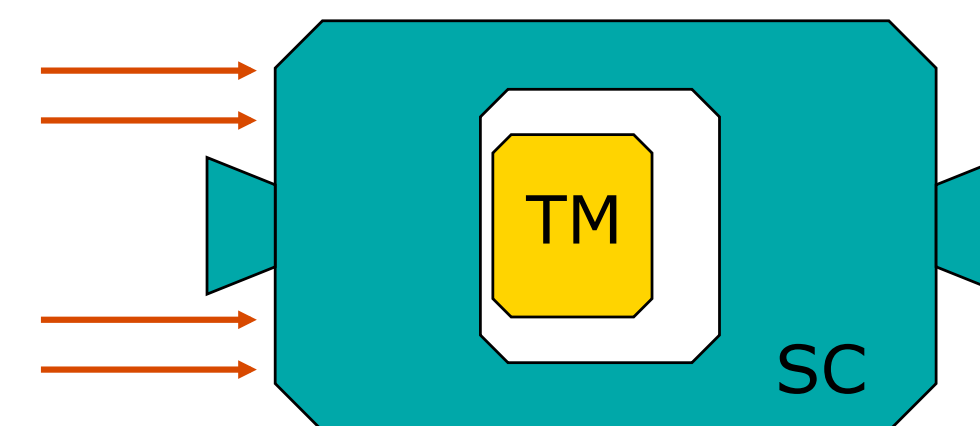


# Acceleration Noise

- Goal: test masses in “perfect” free-fall
  - $\sim \text{femto-g/Hz}^{1/2}$
- Drag-free control to suppress external disturbances
  - solar radiation pressure
  - micrometeoroids
- Careful engineering to suppress local disturbances
  - electric charge control
  - good vacuum
  - careful thermal design



TM and SC in free-fall



External disturbance

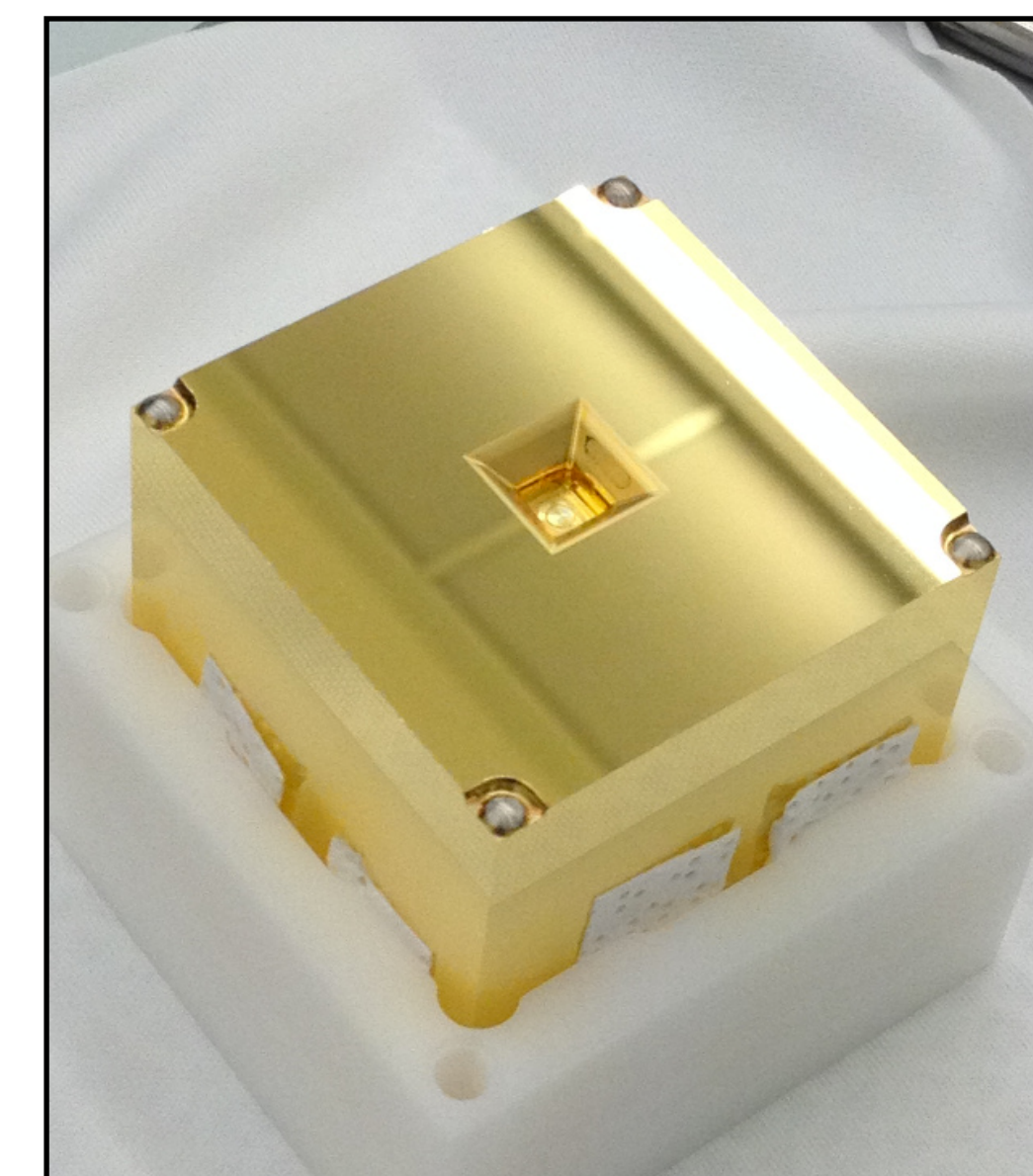
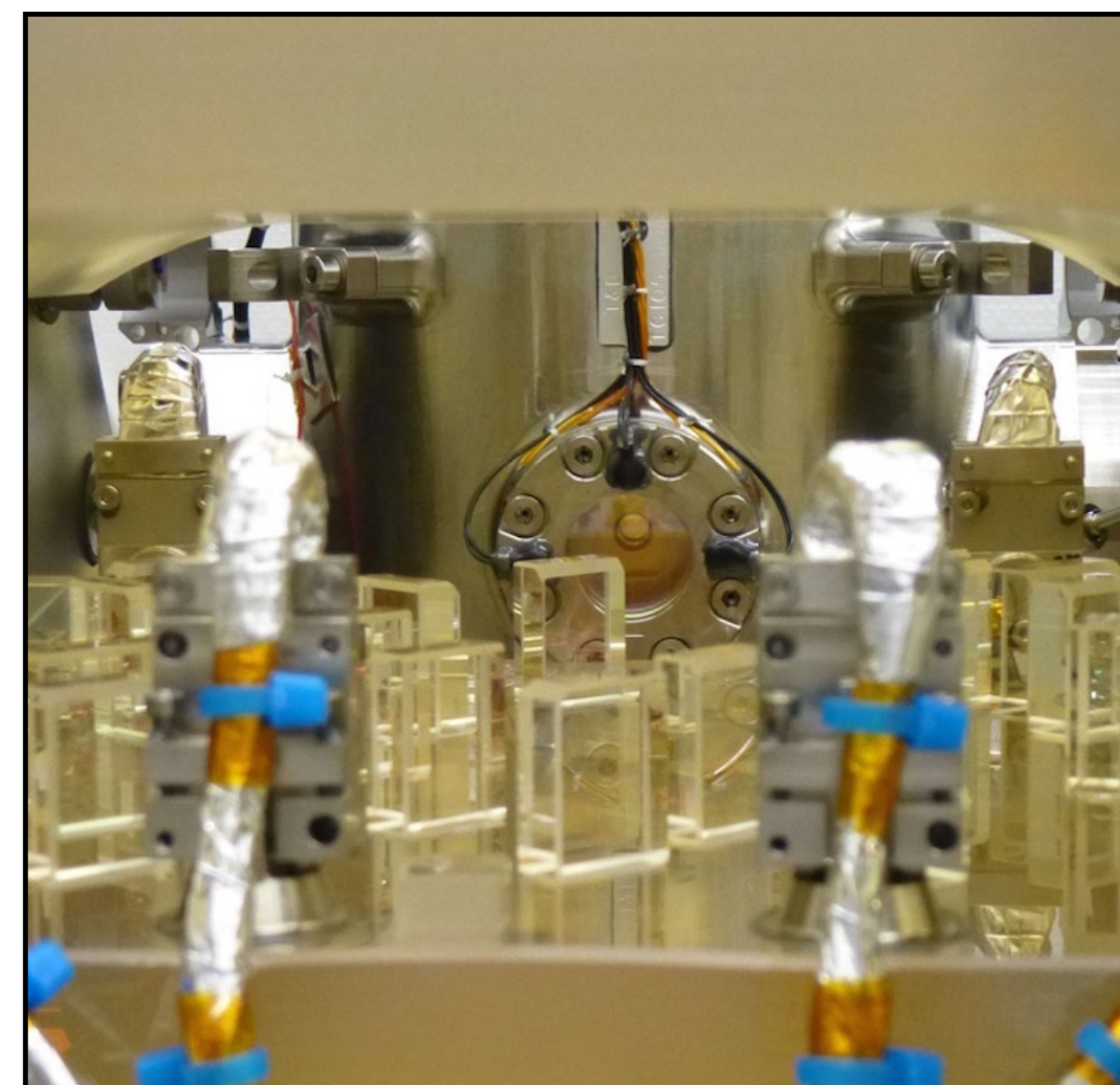
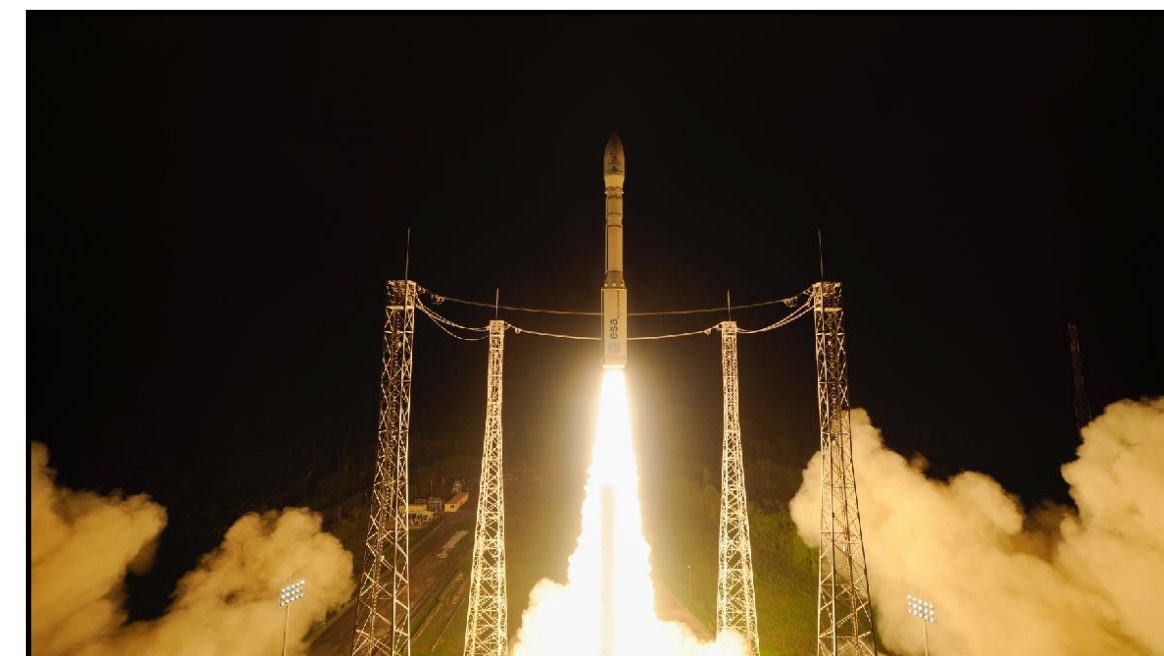


Control system corrects



# LISA Pathfinder

- ESA-led technology demonstrator w/ participation from NASA & European Member States
- Demonstrated drag-free control as technique to realize inertial reference
  - acceleration noise
  - displacement noise for *local* interferometry
- Launched December 2015, operated at Earth-Sun L1 from March 2016 - July 2017
- Also a pathfinder for how to do precision measurement in space *and* through international collaborations



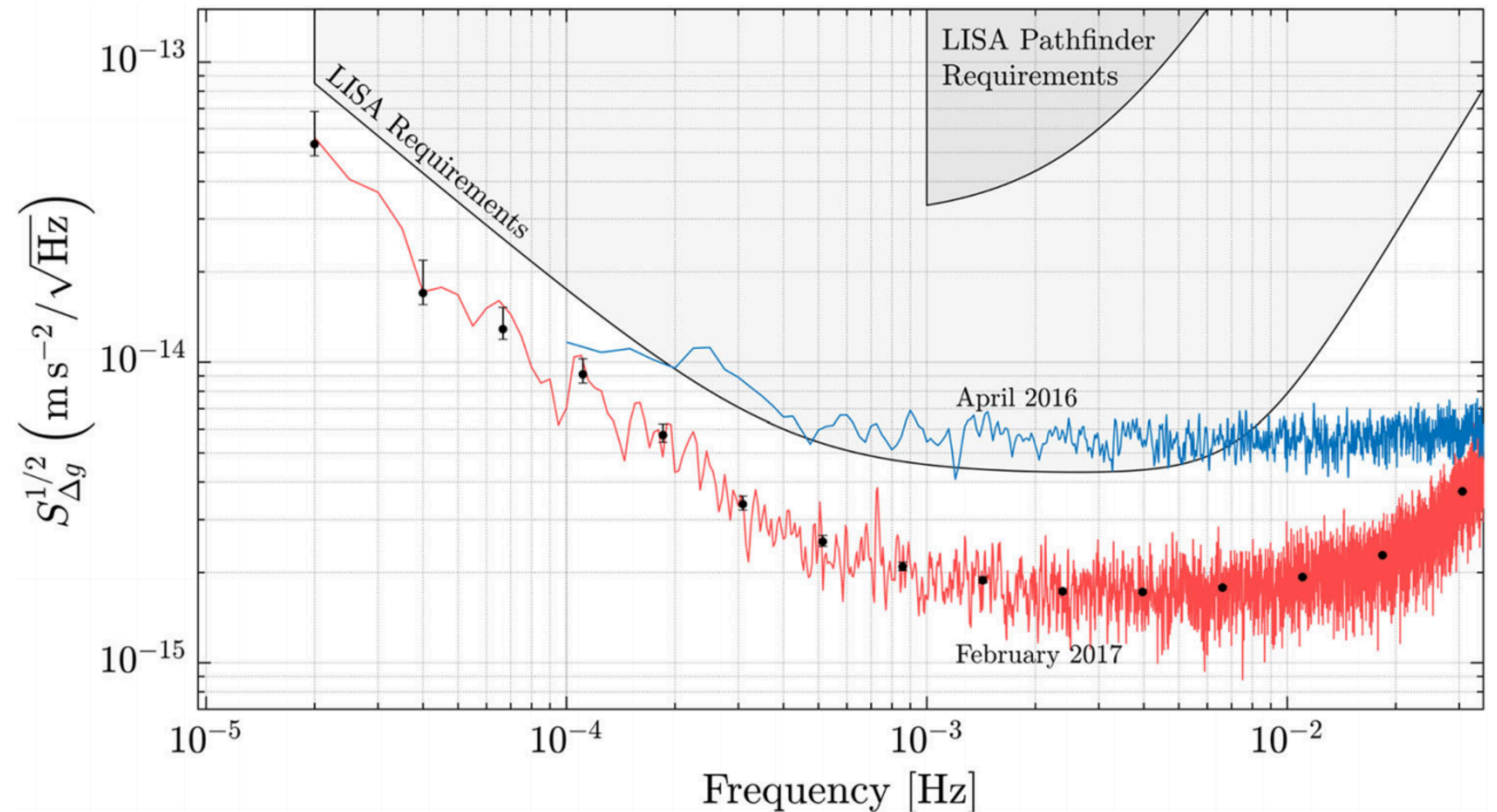
**top left:** LISA Pathfinder launches from Kourou, French Guiana on Dec 3rd, 2015. **top right:** technical assembling the LISA technology package (LTP) payload. **bottom left:** a view of the LTP optical bench during integration. **bottom right:** the gold-platinum LTP test mass

Credit: ESA / LISA Pathfinder Collaboration / CGS



# LISA Pathfinder Results

- Differential acceleration:
  - significantly exceeded LPF requirements (deliberately relaxed from LISA)
  - Met LISA requirements
- Other benefits
  - sub-picometer optical metrology in space (over short distances)
  - measuring and controlling electric charge
  - control of multi-body 3D kinematic system
  - precision microthrusters x 2
  - general experience flying precision measurement hardware in space

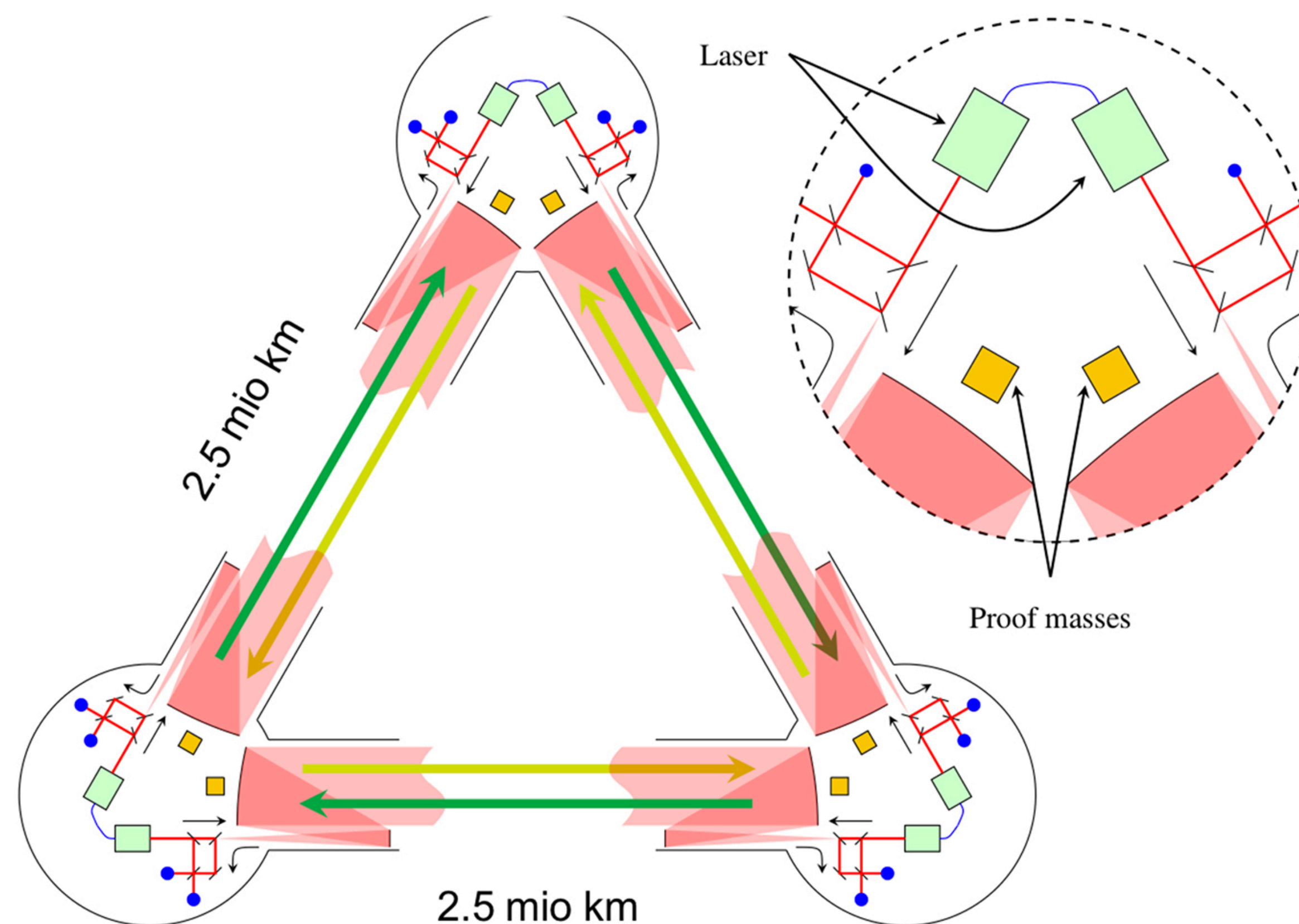


*Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 $\mu$ Hz*  
Phys. Rev. Lett. **120**, 061101



# Displacement Noise

- heterodyne interferometry with  $\sim 1\mu\text{m}$  light
- Six “one-way” measurements between pairs of spacecraft
- Telescopes reduce diffraction loss, still only receive about  $10^{-10}$  of the transmitted power.
- Passively stable orbits maintain arm lengths to  $\sim 0.5\%$  ( $10^5$  km)
- On ground “Time Delay Interferometry” processing surpasses residual laser frequency noise.

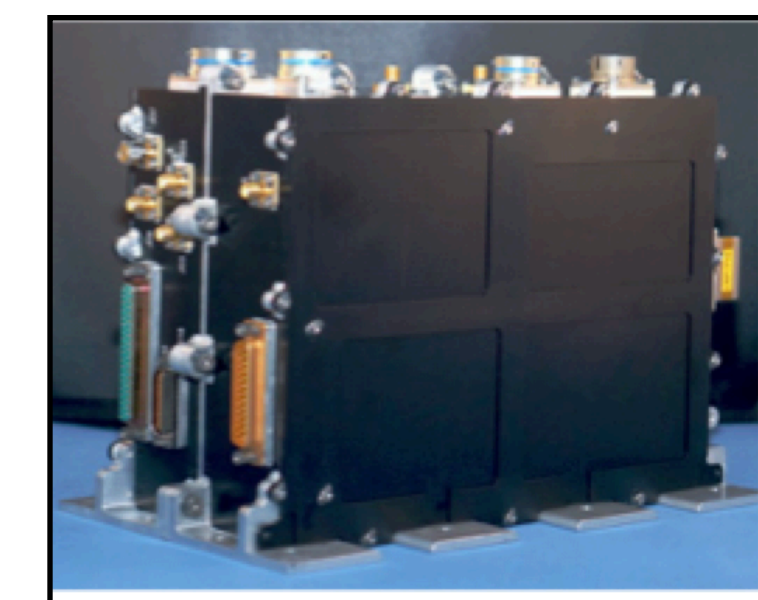
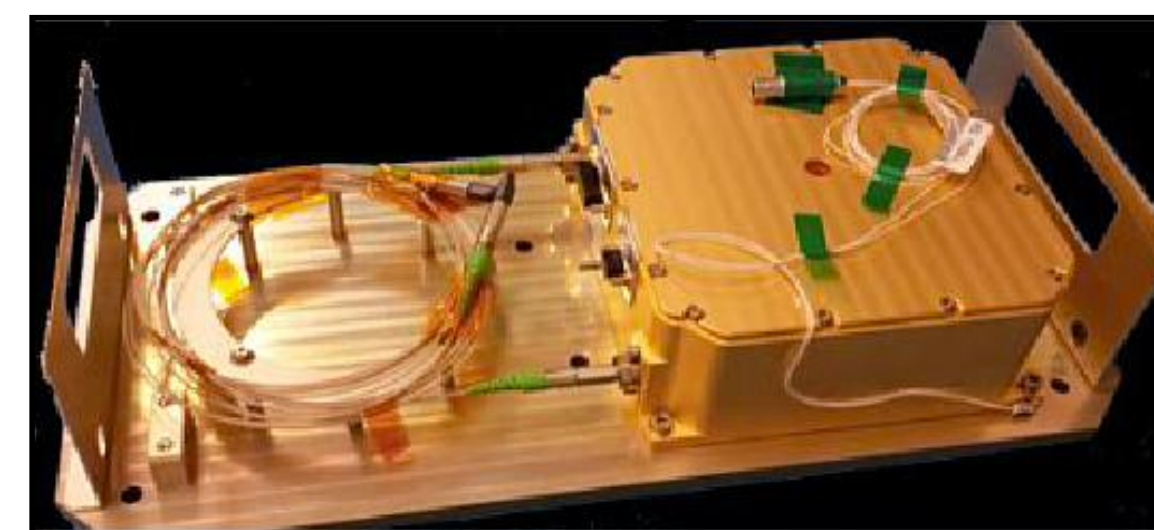
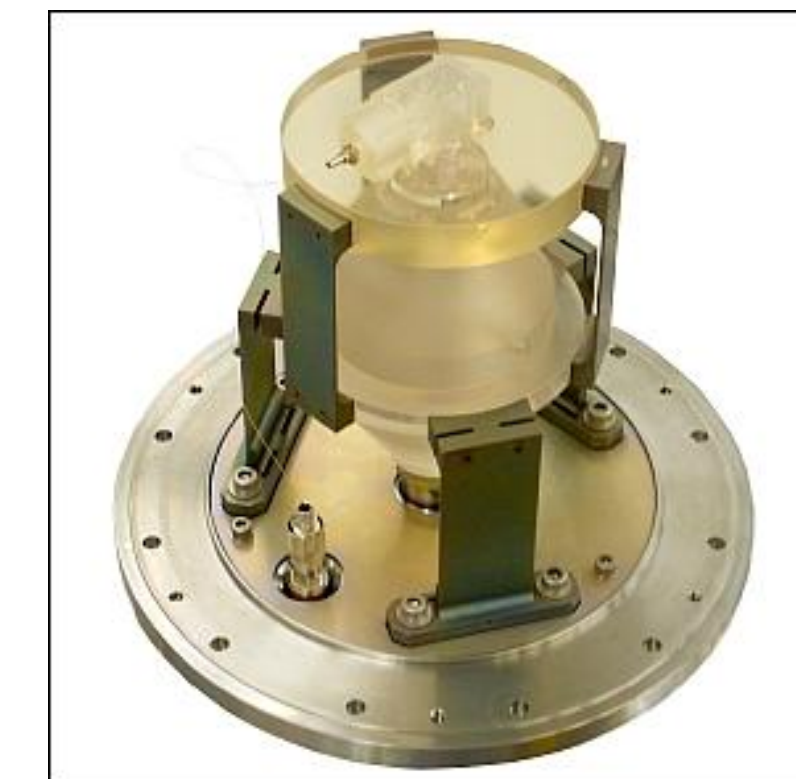
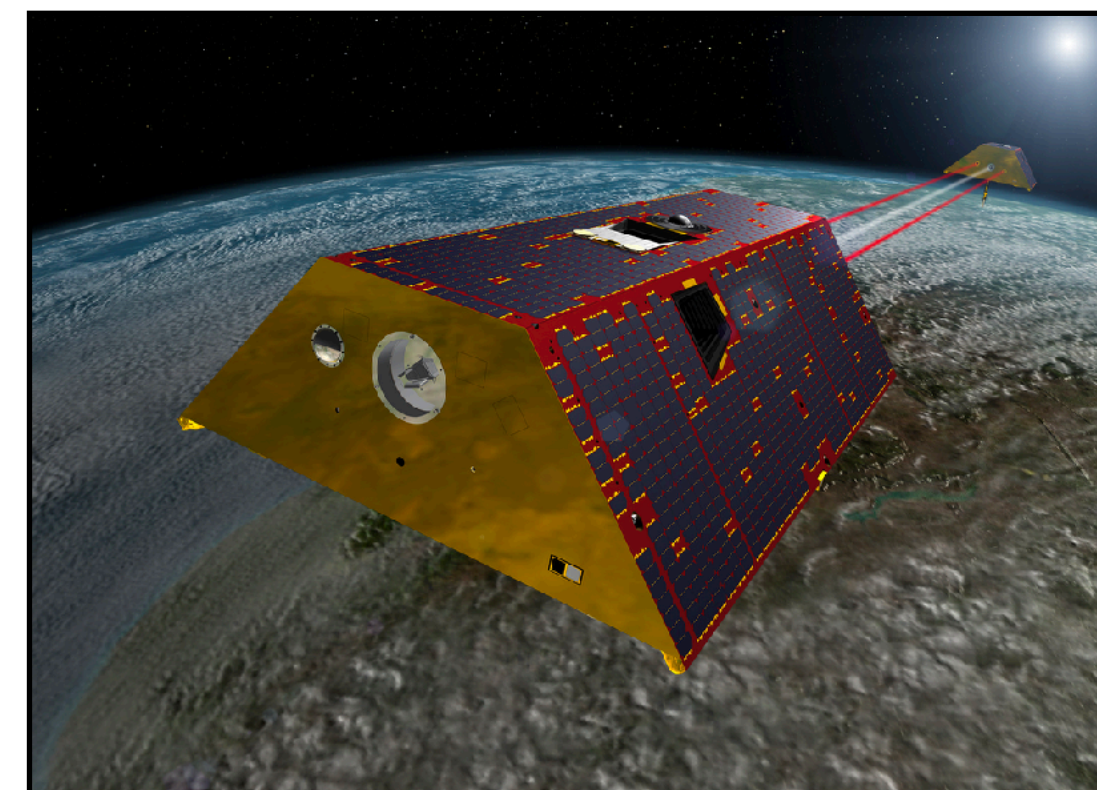


*Schematic of the LISA interferometric measurement (T. Schuldt)*



# GRACE-FO

- US-German collaboration to provide data-continuity for the original GRACE mission (2002-2017)
  - measurements of Earth's gravitational potential with applications to hydrology, glaciology, geophysics, etc...
- Two spacecraft in a low-altitude, near-polar orbit separated by ~300km
  - accelerometers measure atmospheric drag
  - microwave instrument measures relative range
  - **laser ranging instrument (LRI) tech. demo**
- Launched in May 2018, operations ongoing.



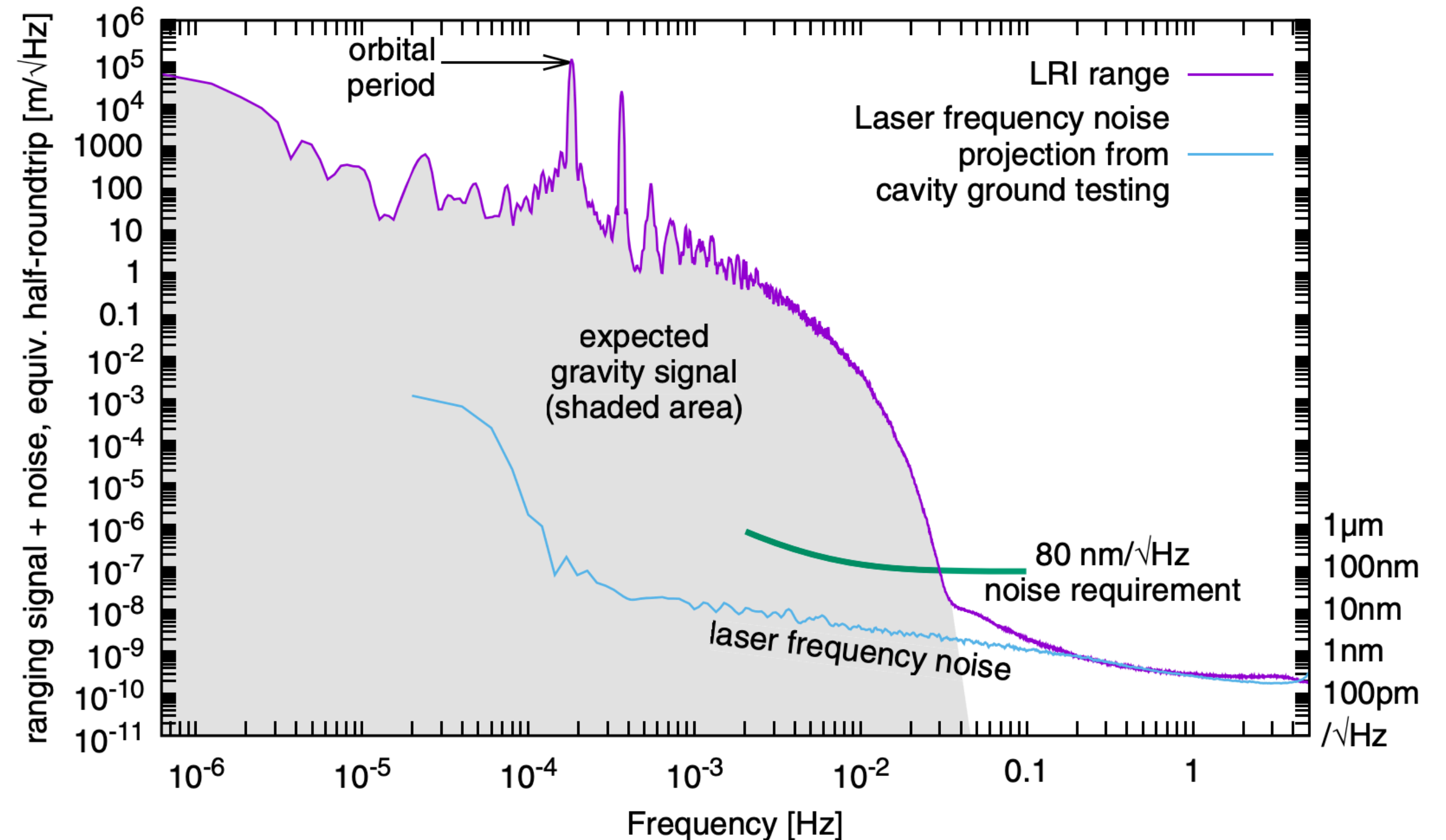
**top left:** Artist rendering of GRACE-FO spacecraft. **top right:** optical frequency reference for LRI. **bottom left:** LRI laser assembly **bottom right:** laser ranging processor (measurement and control)

Credit: NASA / GFZ / Ball Aerospace / TESAT



# GRACE-FO LRI Results

- Ranging precision
  - most of measurement band is signal-dominated.
  - high-frequency displacement noise beats requirements and is consistent with coupling of laser frequency noise (*GRACE-FO only has one measurement arm*)
- Ancillary benefits relevant to LISA
  - Similar laser system (but lower power)
  - Similar heterodyne receiver (but lower channel count)
  - Experience with operations like link acquisition



*In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer*

Phys. Rev. Lett. **123**, 031101

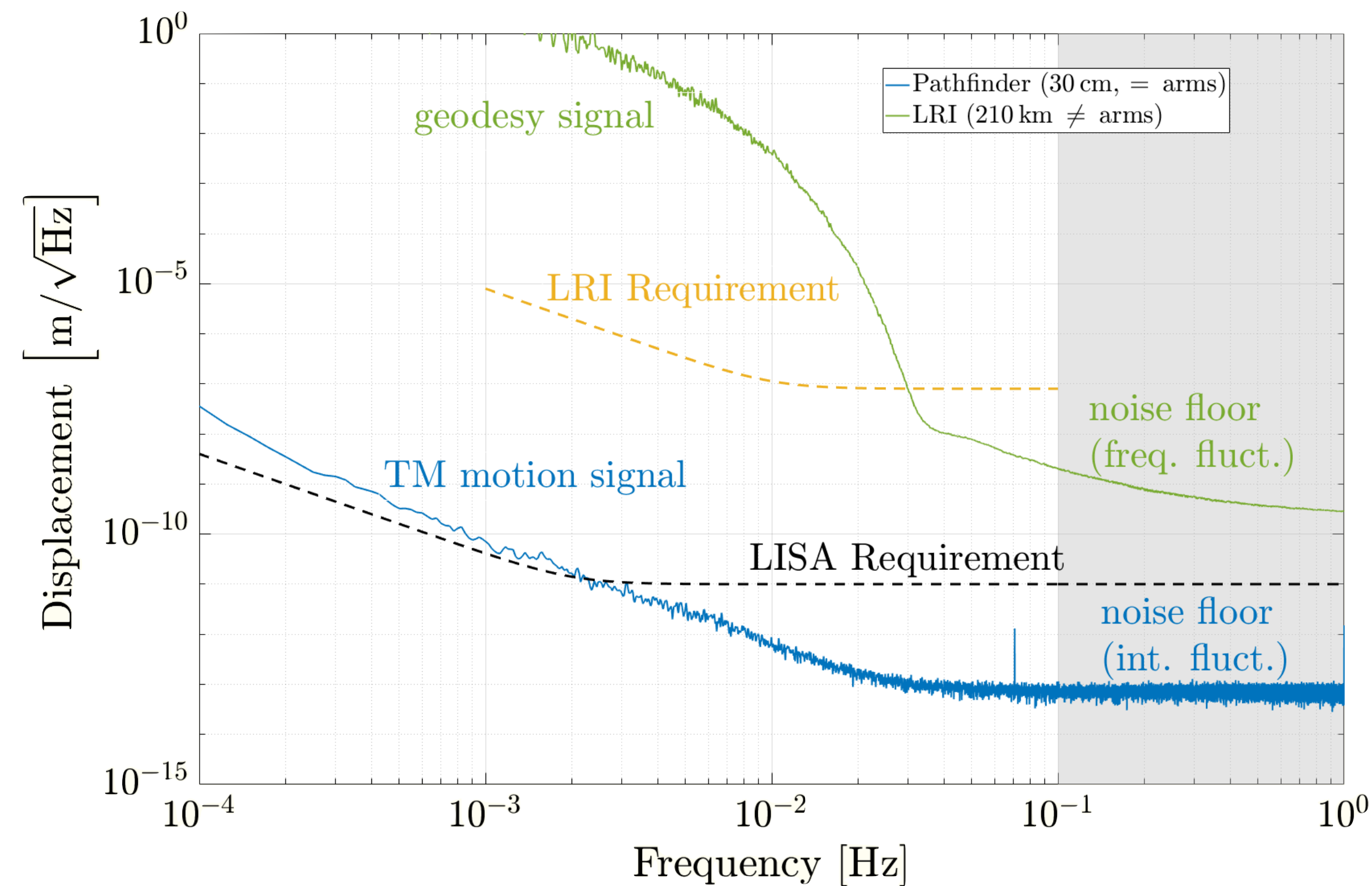
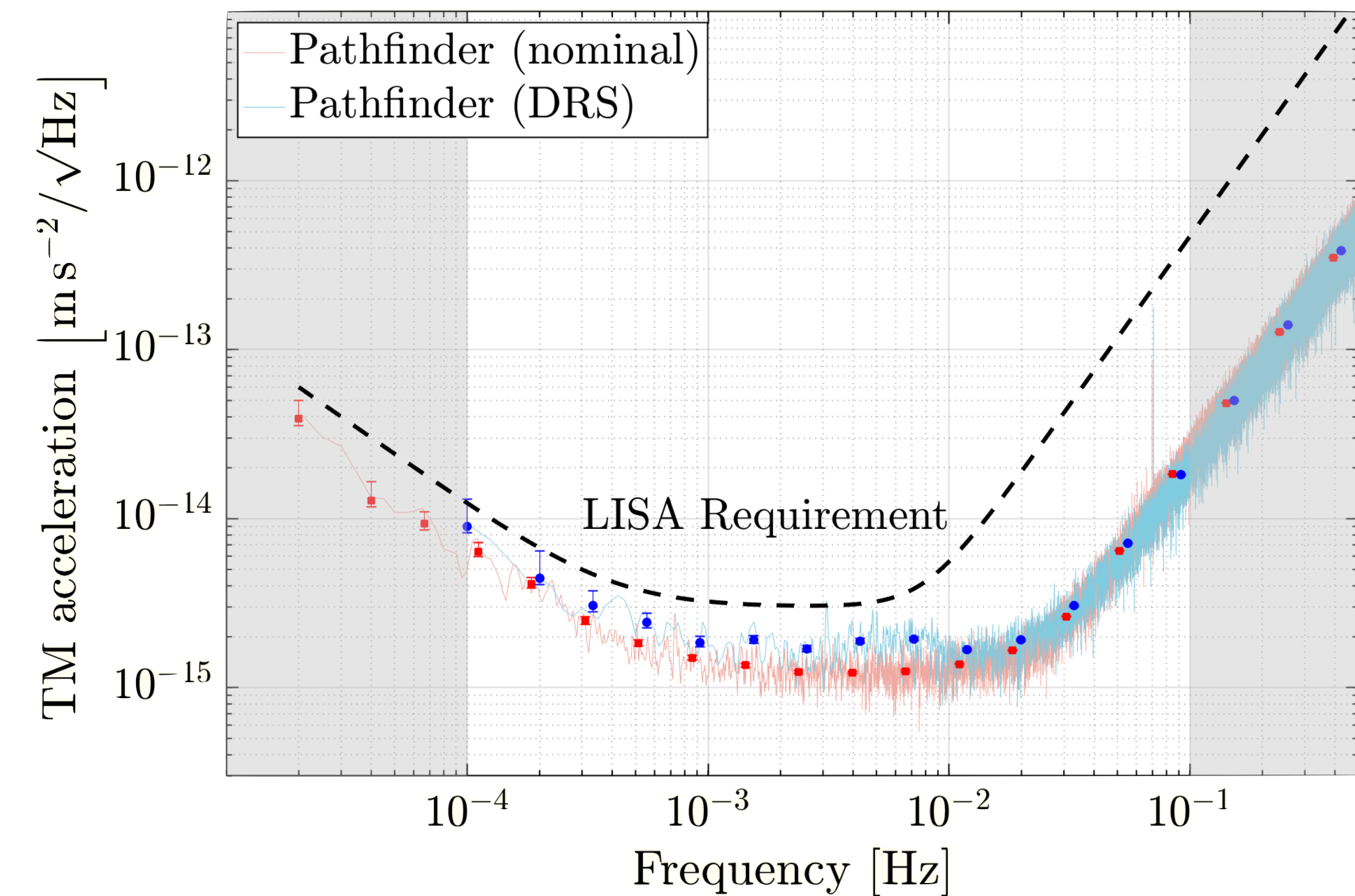




# Two LISA flight demos

**Acceleration noise:** how stable are your fiducial test particles?

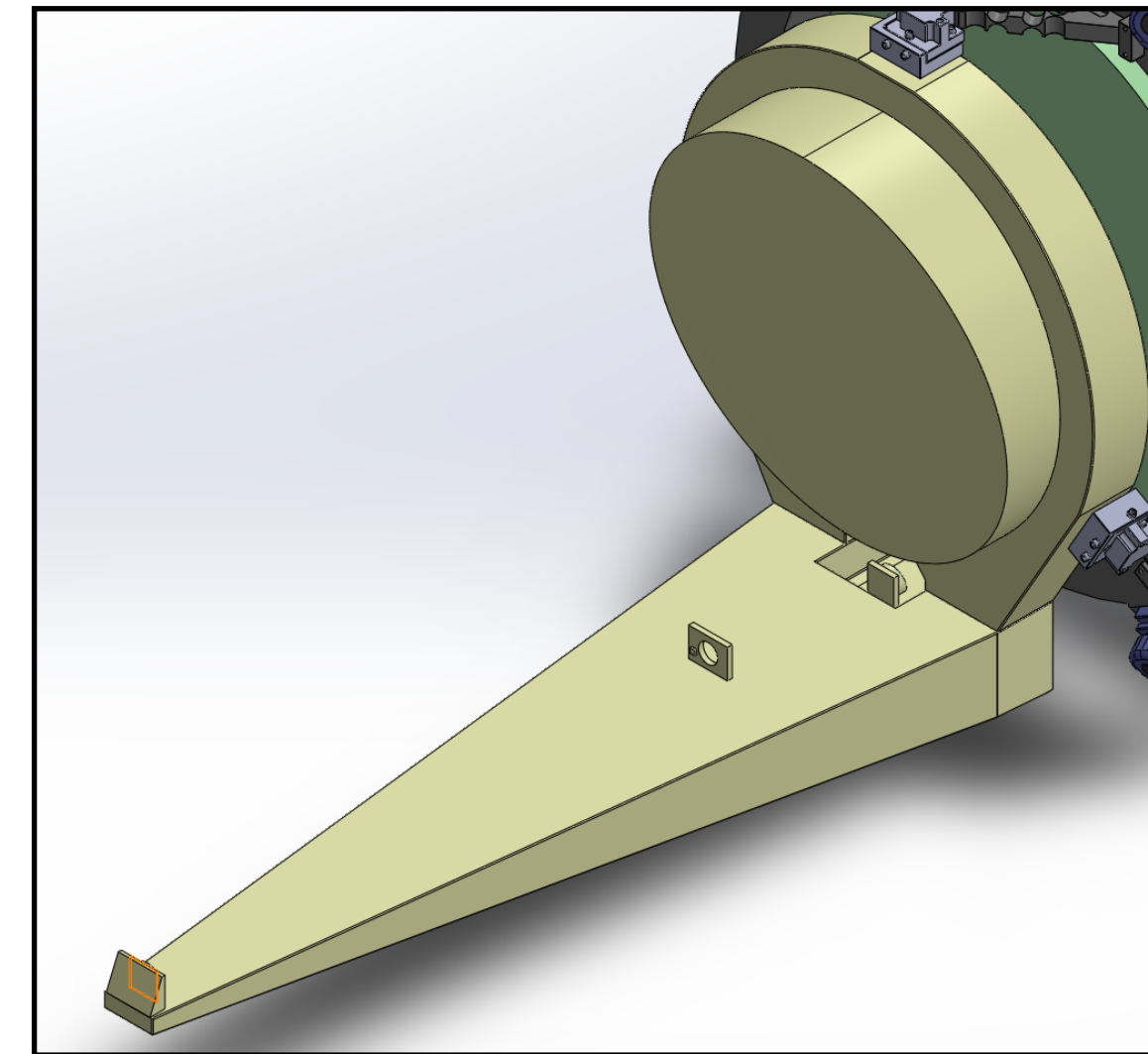
**Displacement noise:** how well can you measure (proper) distance between pairs of test particles?



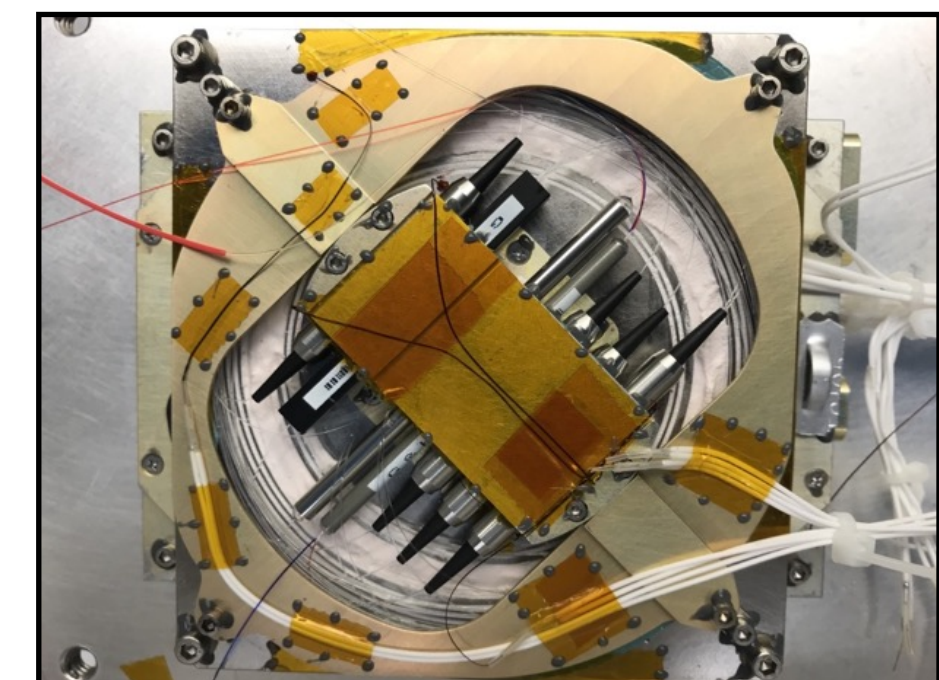
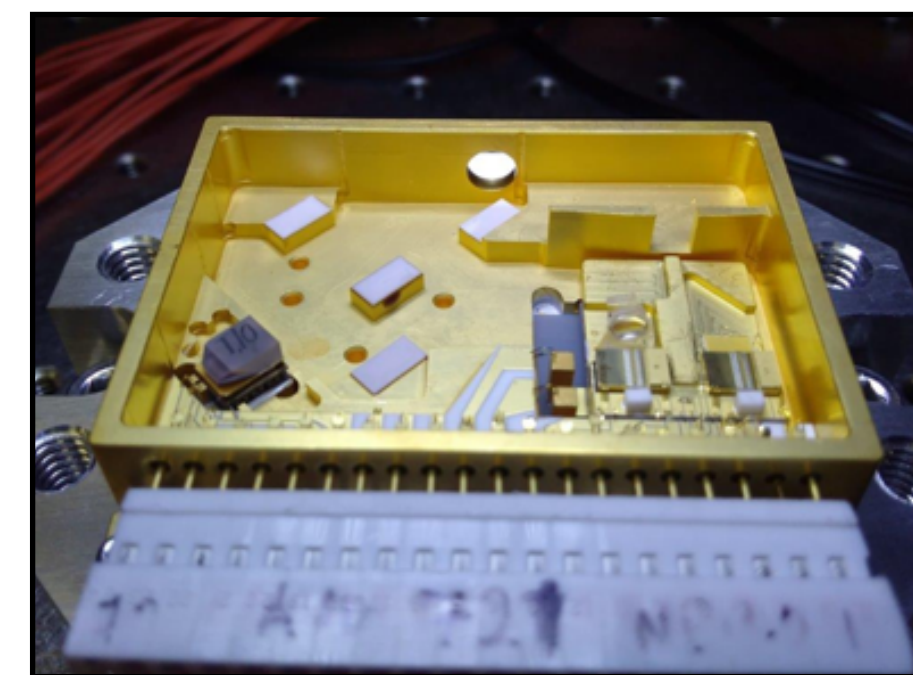


# What's left?

- Interferometry over \*really\* long distances ( $10^6$  km vs  $10^2$  km)
  - stable telescopes
  - more powerful lasers (but still stable)
  - time-delay interferometry (deal with unequal arms)
- Moving from *demonstrators* to *observatories*
  - complex operation of three satellites and six payloads
  - Long duration (4 years baseline + 6 years extension)
  - Minimal downtime and consistent science products



**top:** CAD model of potential LISA telescope **bottom left:** mNPRO seed laser  
**bottom right:** laser amplifier prototype



# Programmatics & Status



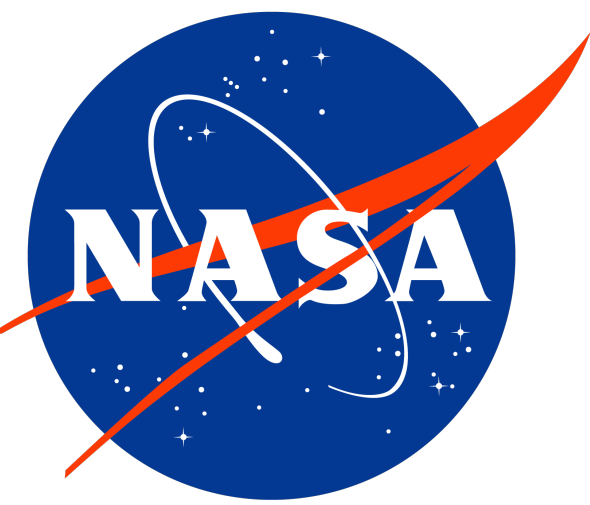
# Who's involved



## European Space Agency

- Lead agency
- Spacecraft, LV, operations, payload elements
- Science Operations Center

[lisa.esa.int](http://lisa.esa.int)



- Hardware contribution: payload-focused, ~\$400M
- Science contribution TBD: participation in science ground segment, guest investigator program, archive functions, etc.

[lisa.nasa.gov](http://lisa.nasa.gov)



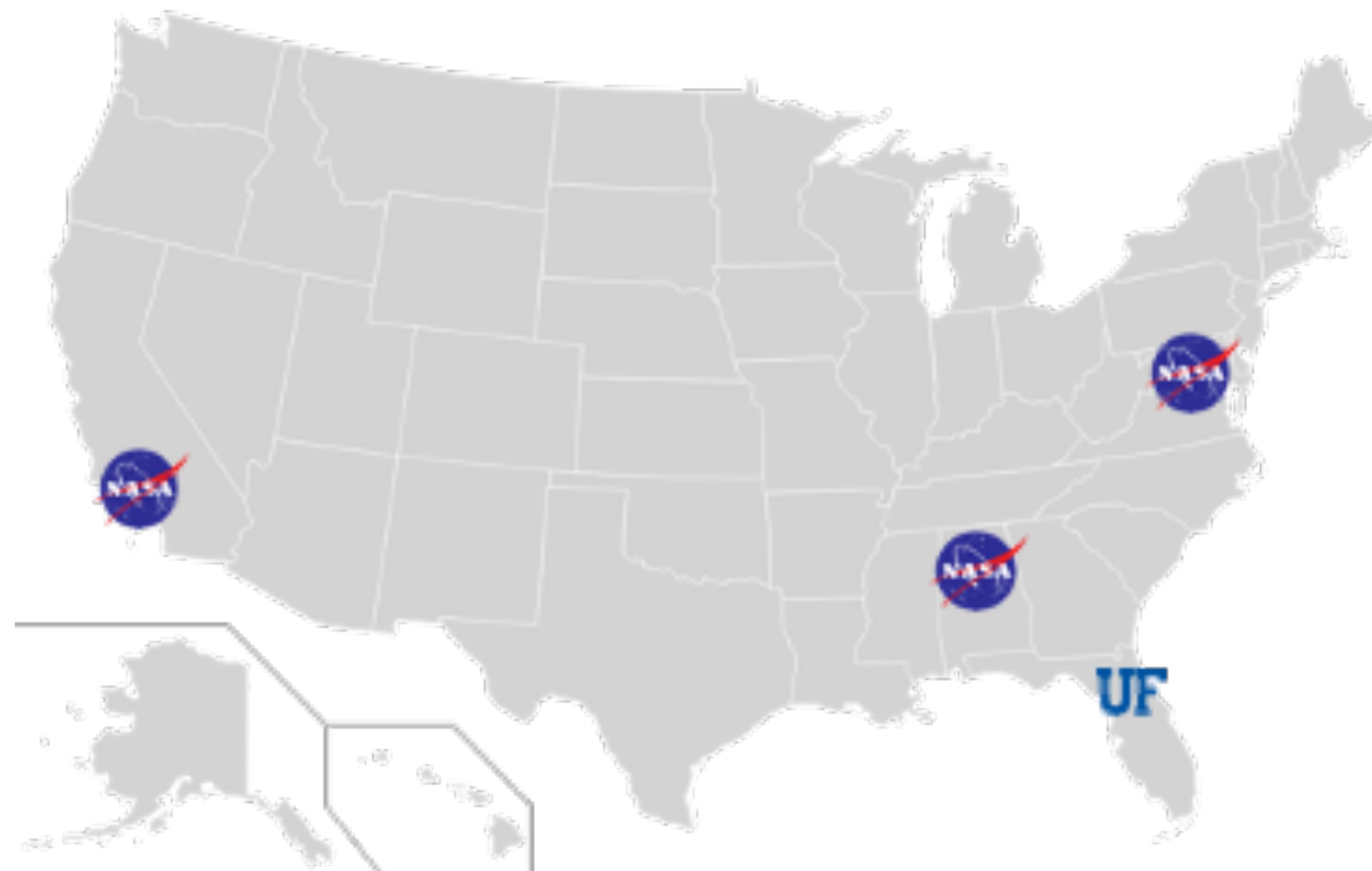
- Organize ESA Member-state contributions
  - Major payload contributions
  - science ground segment lead
- Organize (world-wide) science activities

[lisascience.org](http://lisascience.org)



# NASA LISA Study Office

- **“proto-project”**
  - Conducts pre-formulation activities (NASA is pre-phase A)
  - Will evolve into formal NASA Project Office
- **Hosted by Physics of the Cosmos Program at NASA/HQ**
  - Program responsible for managing science themes including gravitational waves
- **Executed by NASA field centers & partners**
  - GSFC: project management, science, and system engineering lead; telescope and laser development
  - JPL: science and systems engineering support; interferometry expertise and supporting technologies in micropropulsion and phase measurement
  - MSFC: science and science ground segment support
  - UF: charge management, telescope testing support





# NASA LISA *Study Team*

- **Independent group of scientists representing the future US LISA user community**
  - Provide input to NASA HQ and NASA Study Office on LISA science questions
  - Represent LISA science to Astro2020
  - Interface with broader US research community
  - Interface with LISA Consortium
- **Membership**
  - Members appointed for 3-year terms
  - Second cohort appointed in October 2019
  - Kelly Holley-Bockelman serves as Chair





# LISA Preparatory Science

- **NASA/HQ funded grants to support LISA-related science**
  - Refine the LISA science case
  - Develop the future LISA user community
- **Process**
  - ROSES element, selected through standard NASA peer-review process
  - Independent of NASA Study Office and NASA LISA Study Team
  - No obligation (or prohibition) to work with NASA Study Office or Consortium
- **First cohort awarded in 2018**
  - Progress presented at special session of January 2020 AAS meeting in Honolulu
- **Second cohort proposed December 2020**
  - Award announcement imminent
- **Goal is to hold additional calls in the future**

COMMUNITY: **The LISA Preparatory Science Program**

LISA will be the first mission of its kind, producing a unique data set with the potential to provide insight into many areas of astrophysics, fundamental physics, and cosmology. Realizing LISA's science potential will require advance work to better understand LISA's science targets and the specific ways in which LISA data can be used to understand them. To this end, NASA has offered the LISA Preparatory Science (LPS) Program to support US-based researchers to conduct research activities related to LISA. Details of the first call for proposals, can be found on [NASA NSPIRES](#). Summaries of the first cohort of LPS awardees (selected Nov. 19, 2018) are provided below.

On 7 April 2020, NASA posted a new opportunity to ROSES-2020 calling for additional proposals to the LISA Preparatory Science Program. Mandatory NOIs are due by 15 September 2020, and the proposal due date is 15 December 2020. [Read the announcement.](#)

**SEARCHING FOR THE STOCHASTIC GRAVITATIONAL-WAVE BACKGROUND WITH LISA**

Principal Investigator: Vuk Mandic, University Of Minnesota

Searching for the Stochastic Gravitational-Wave Background with LISA

In 2015, the terrestrial LIGO gravitational-wave detectors observed the first gravitational-wave signal generated in a merger of two black holes about 1.3 billion light-years away. This event has marked the beginning of the new field of gravitational-wave astronomy. Gravitational-wave detectors have since started to routinely observe objects and events in the universe that are not accessible to the traditional electromagnetic observations. Furthermore, in 2016-2017 the successful LISA Pathfinder mission demonstrated some of the key technologies needed for developing a space-borne gravitational-wave detector. Coming on the heels of these remarkable breakthroughs, the European Space Agency (ESA) recently selected the Laser Interferometer Space Antenna (LISA) as the third large-class mission in ESA's Science Programme. LISA is expected to be launched in 2034, and with a significant contribution from NASA, it will be the first space-borne gravitational-wave observatory.

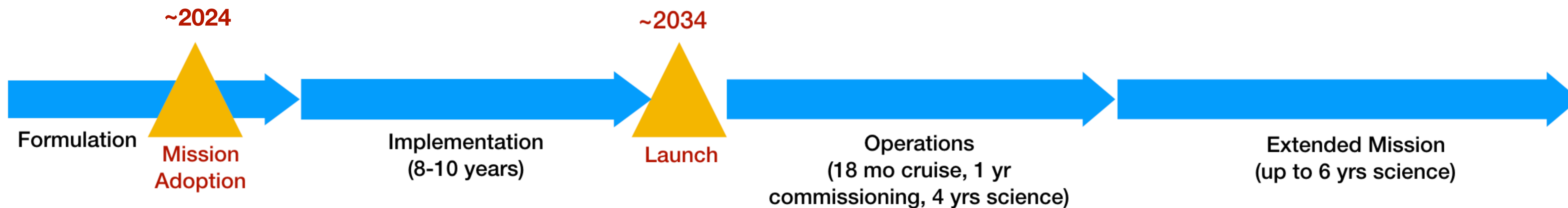
This proposal focuses on the stochastic gravitational-wave background (SGWB), which is one of the science targets of the LISA mission. The SGWB is expected to arise as a superposition (sum) of many incoherent sources of gravitational waves. It could be of astrophysical origin, for example due to contributions of numerous binary systems in the Milky Way or throughout the universe. It could also be of cosmological origin, generated by very energetic processes in the early universe. Detection of a cosmological SGWB would provide unique information about the fundamental physical laws that apply at very high energy scales, inaccessible to standard laboratory experiments. Detection of an astrophysical SGWB would provide unique information about properties and evolution of structure we observe today in the universe, including objects such as

<https://lisa.nasa.gov/LPSprogram.html>



# Status and Outlook

- “formulation” phase
- Comprehensive design study of spacecraft, payload
- Early investigations of science ground segment
- Development of remaining key technologies
- Negotiations of roles & responsibilities





# Thanks & Questions