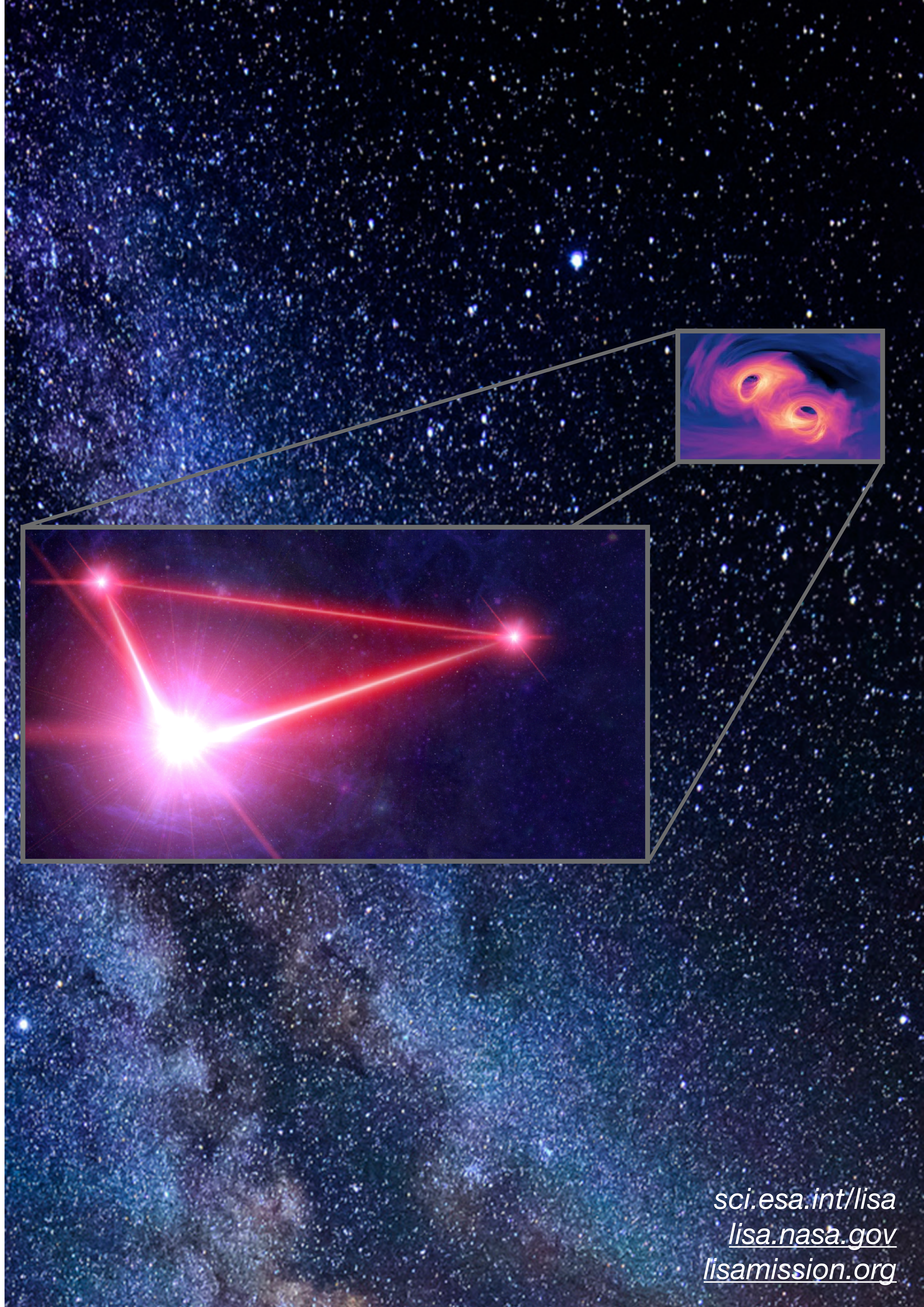
The Laser Interferometer Space Antenna: Bringing the Gravitational-wave Revolution to Space

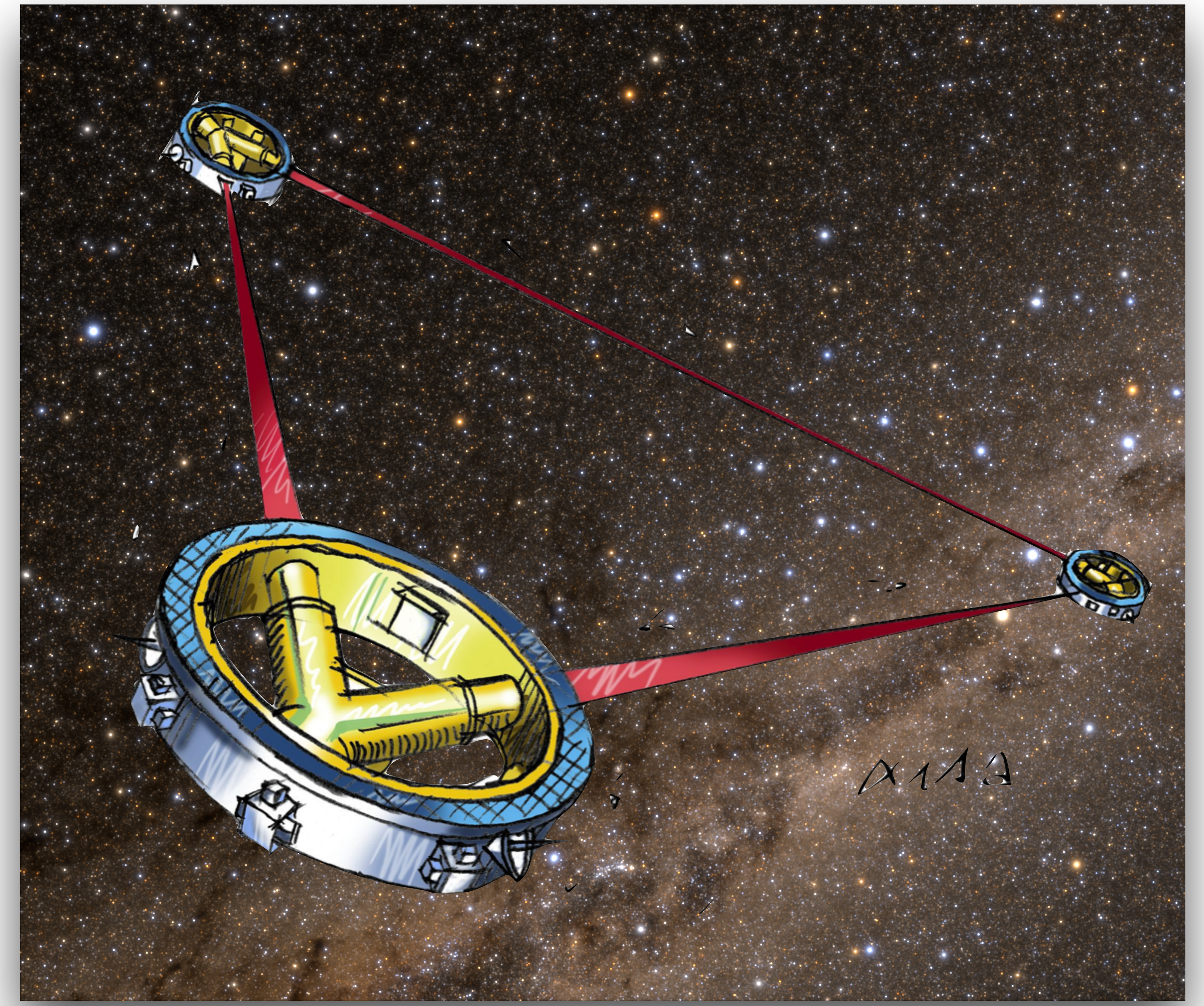
Ira Thorpe, NASA LISA Study Scientist
On behalf of the worldwide LISA Team

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



NASA/STScI

- Avoid terrestrial disturbances
- Access new spectral bands



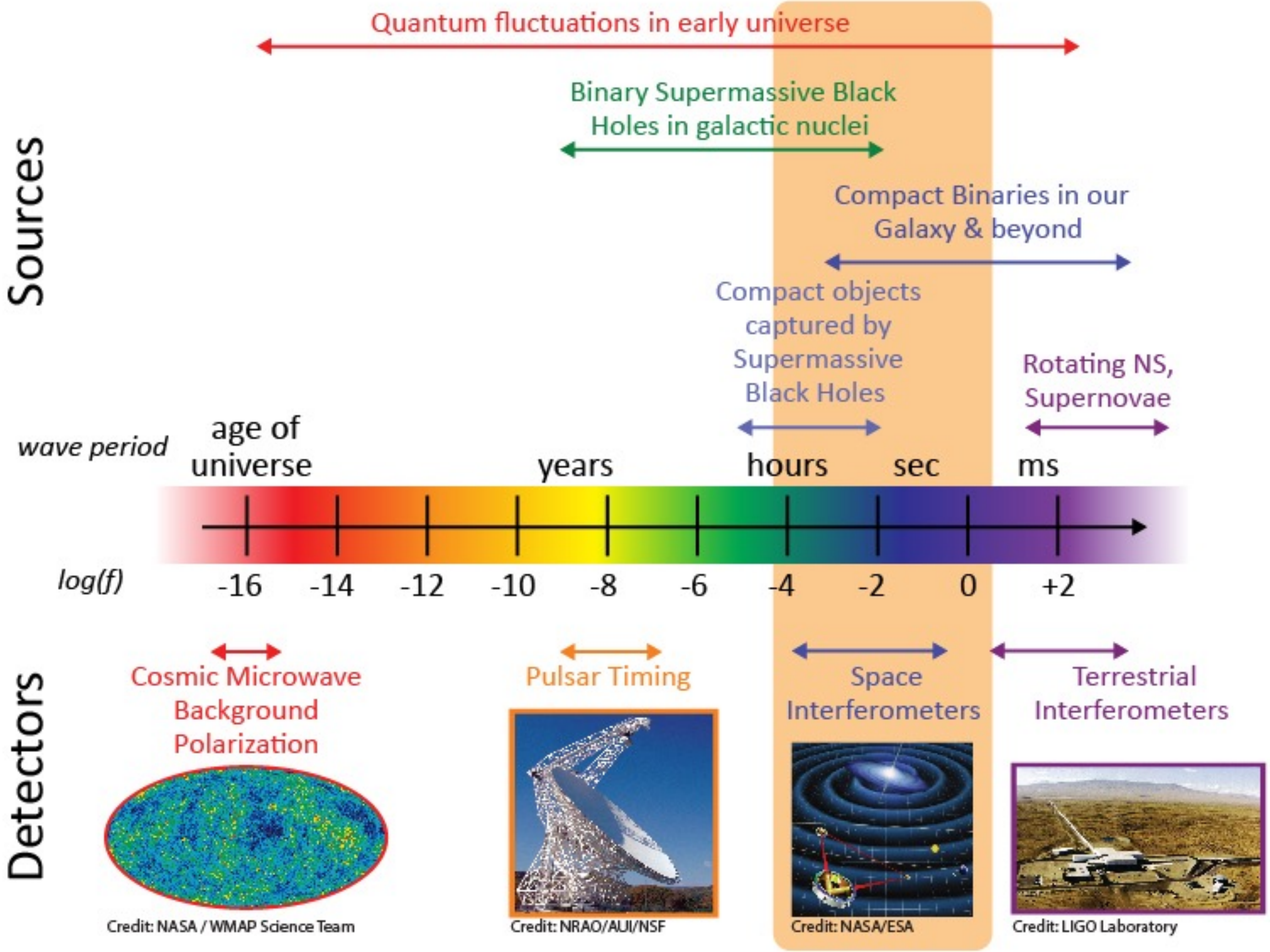
Credit: ESA-C. Vijoux

- Avoid terrestrial disturbances
- Access new spectral bands

Why go to space?

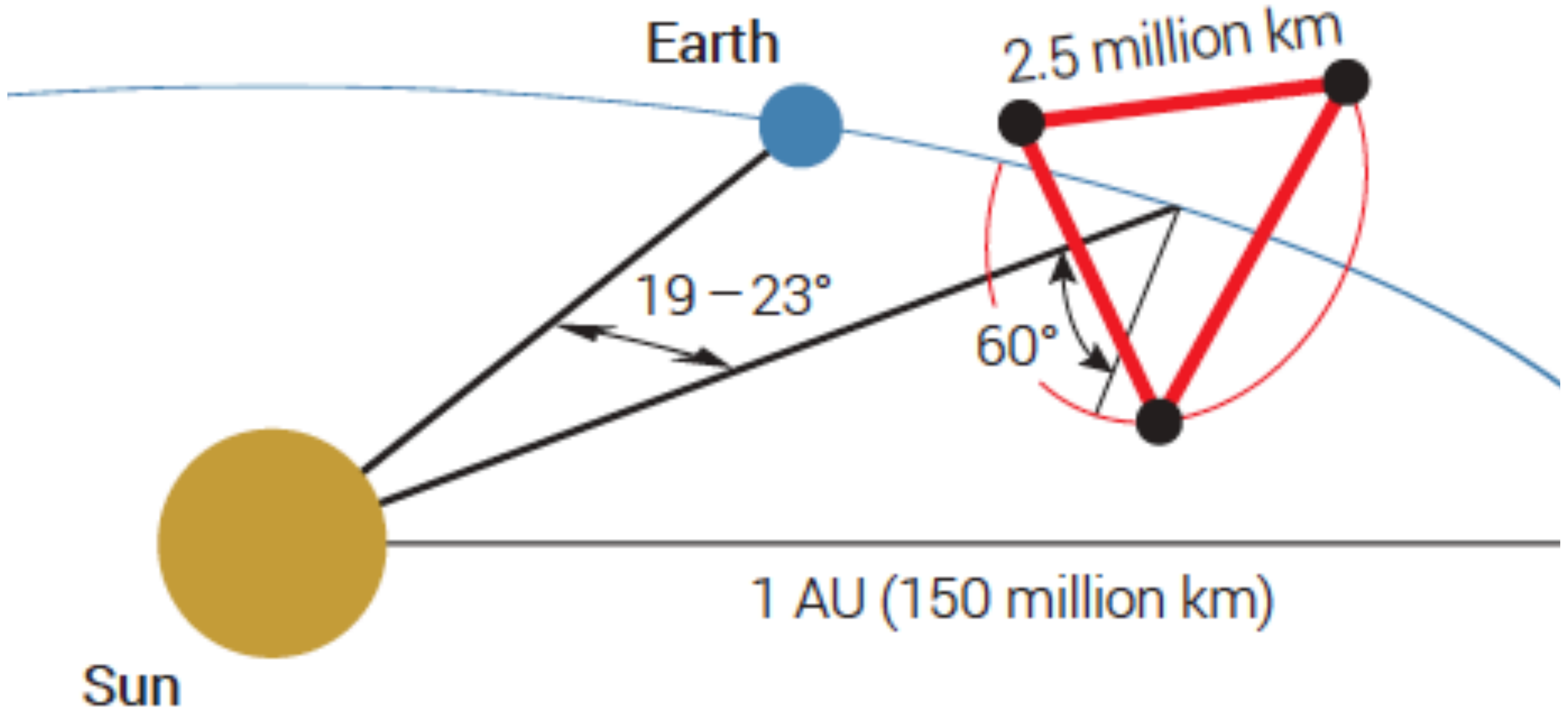
Same reasons as for EM telescopes

The Gravitational Wave Spectrum

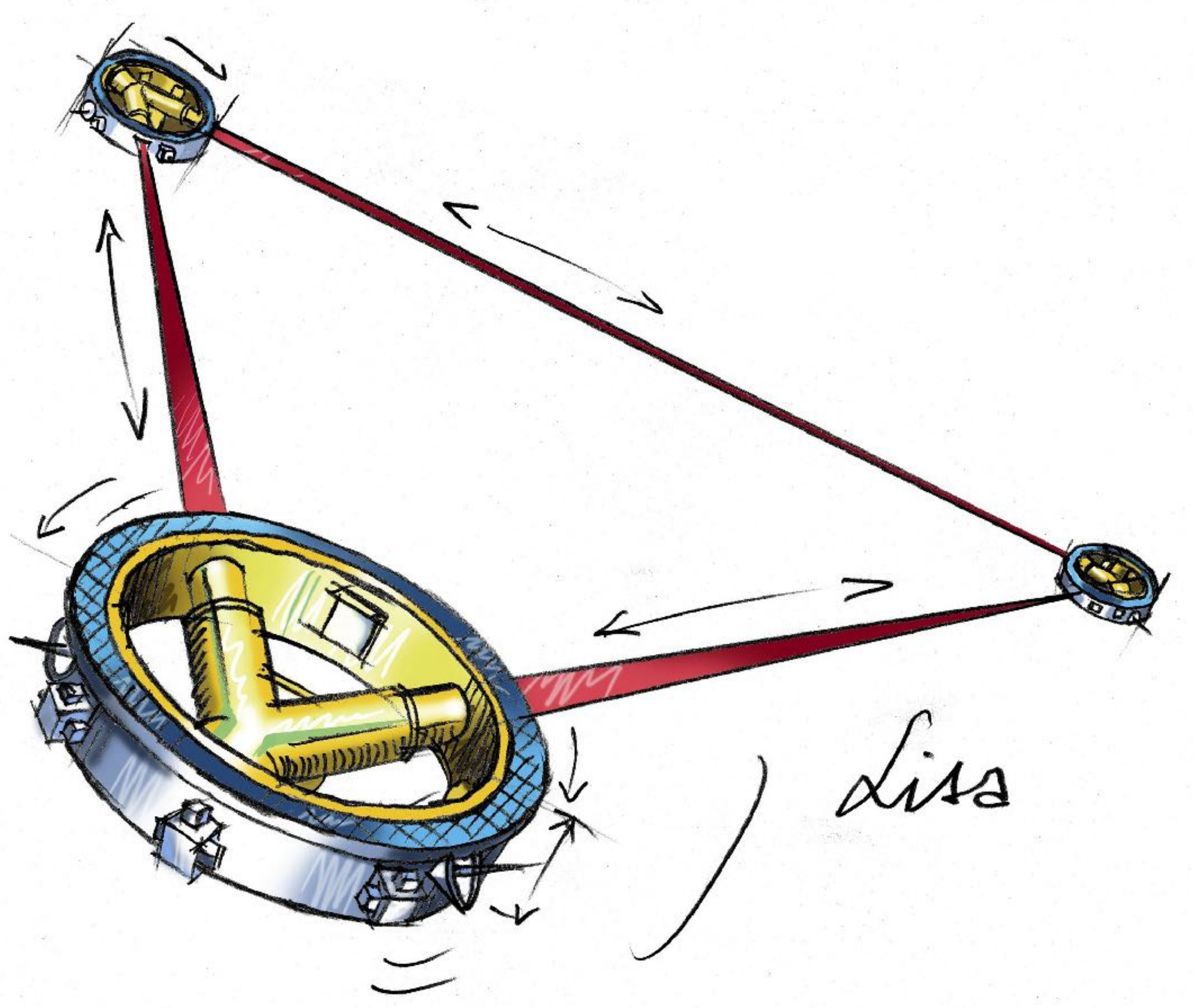


The LISA concept

- **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



Credit: M. Hewitson



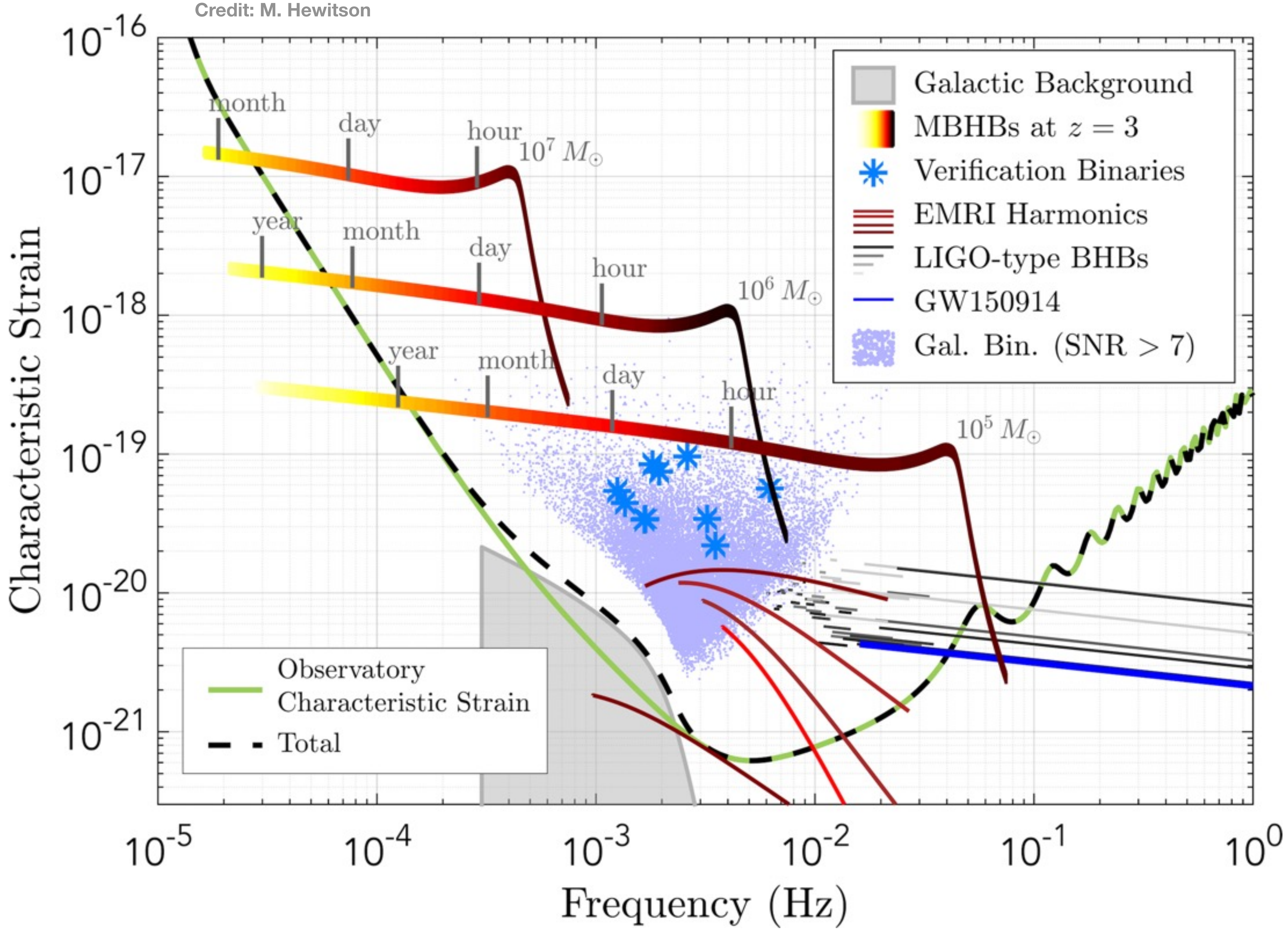
Credit: ESA-C. Vijoux

Science

Rich and complex data set

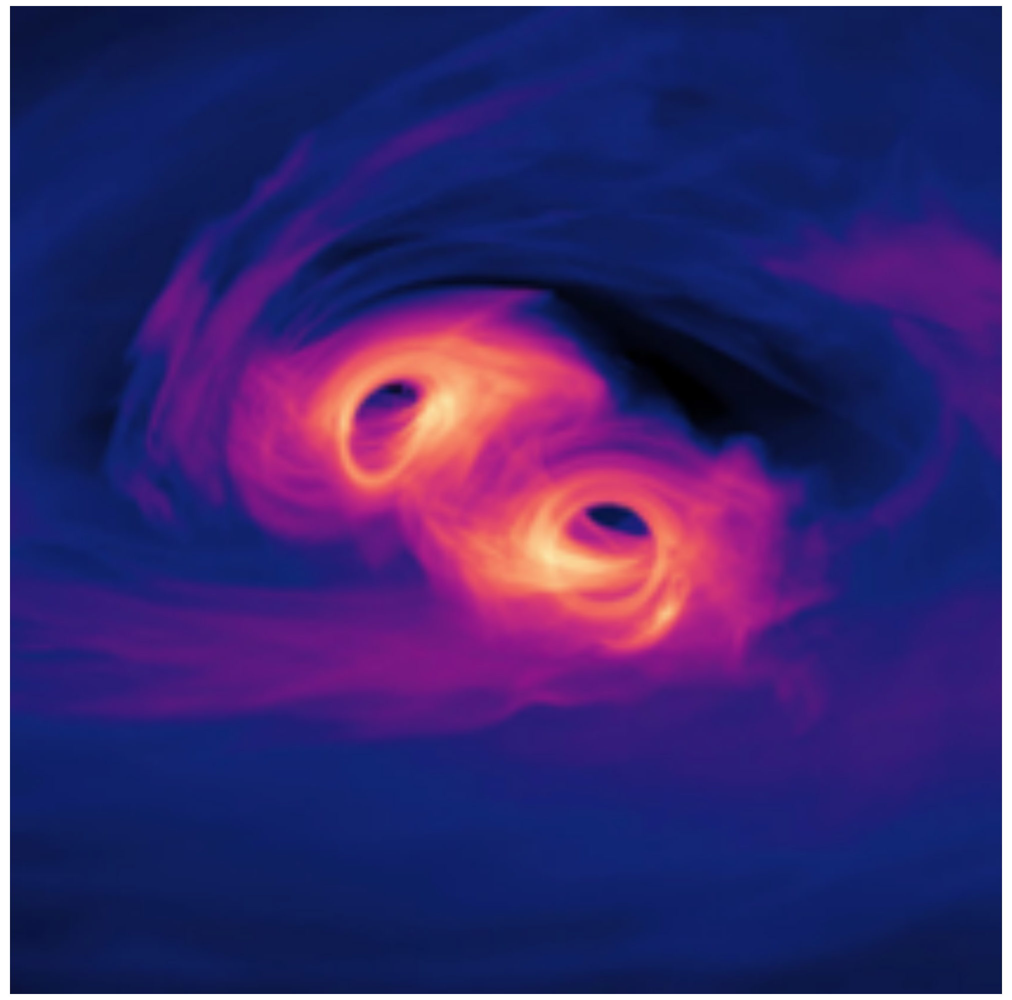
- Several different source types
- persistent and transient sources
- unresolved galactic "foreground"
- $>10^4$ sources simultaneously in band
- Global fit!

Credit: M. Hewitson



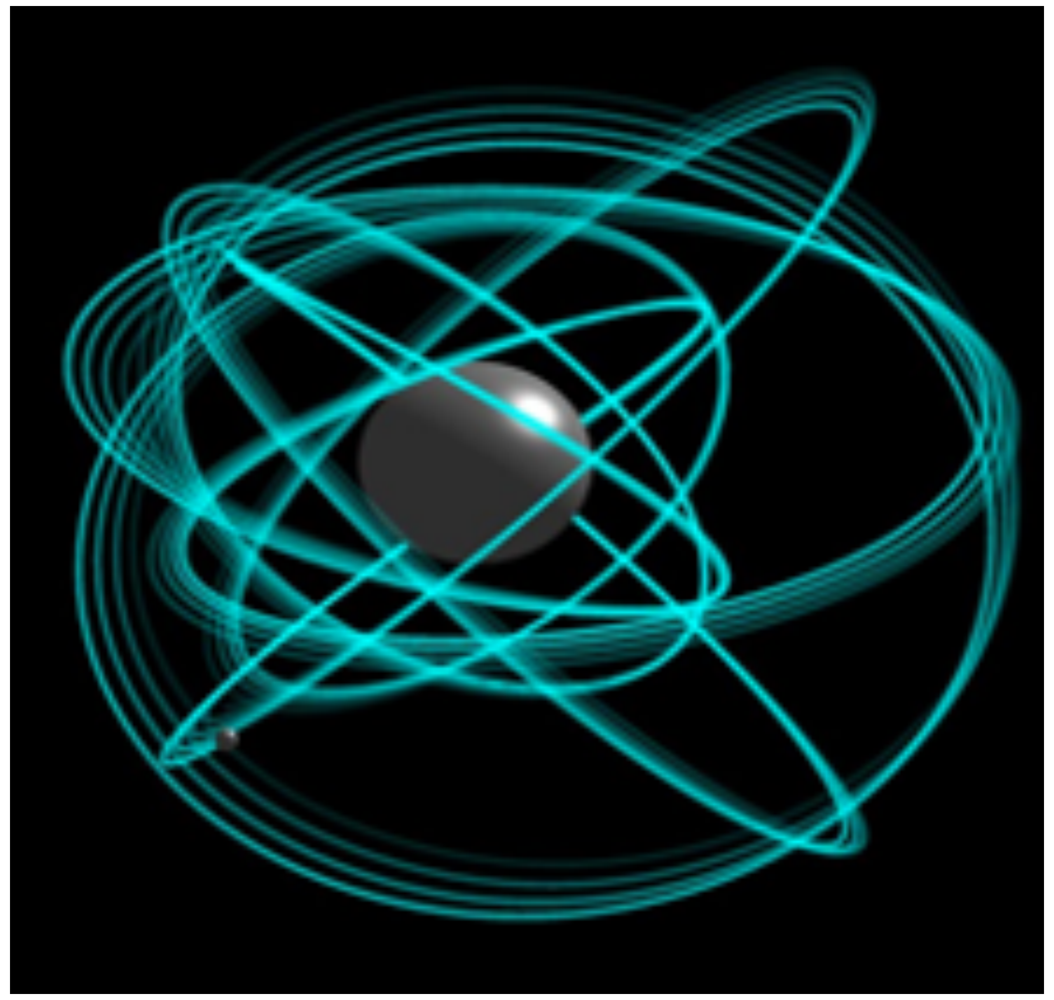
Science Highlights

Mergers of Massive BHs



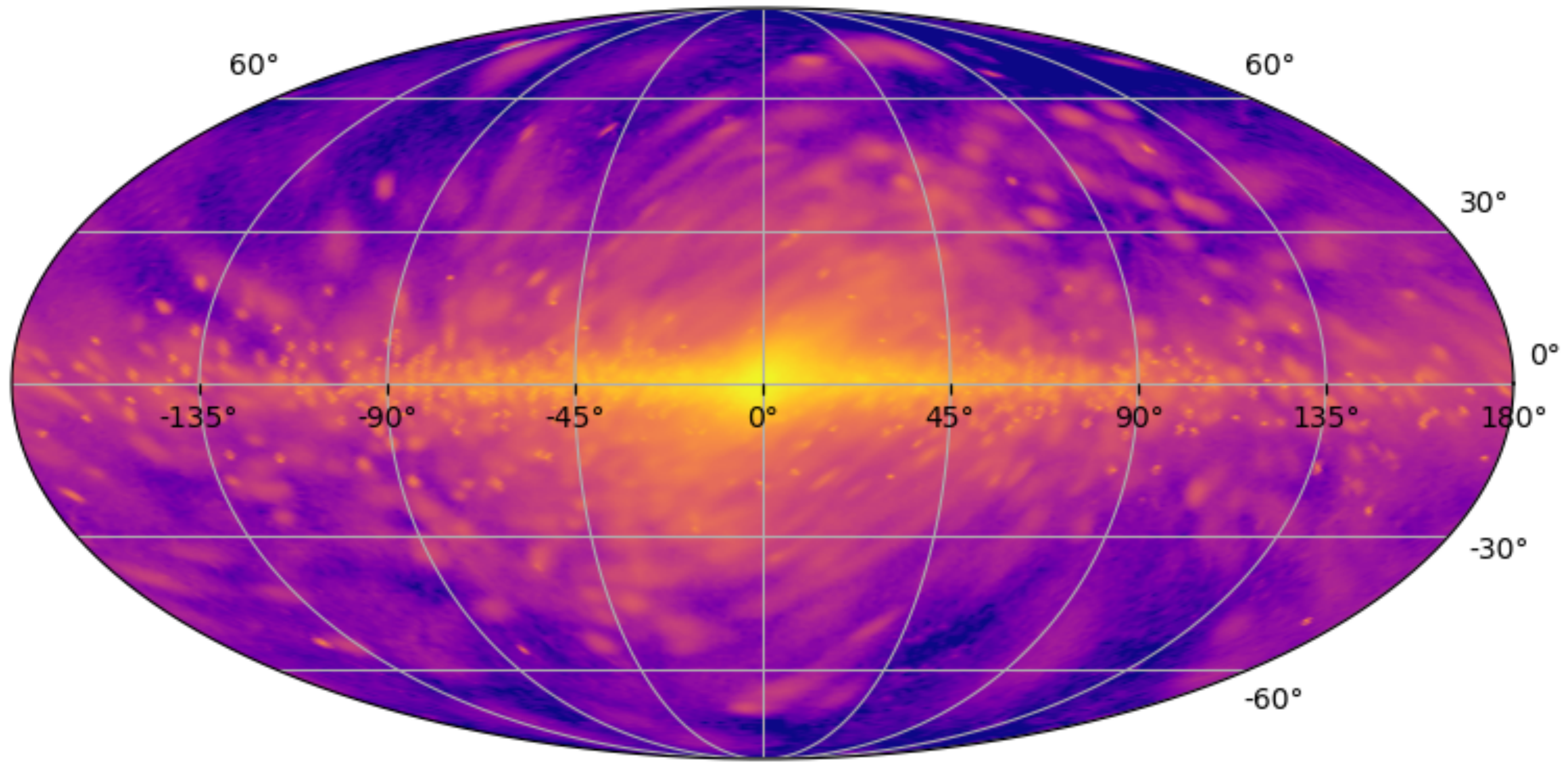
- $10^3 M_\odot$ ~ $10^8 M_\odot$
- $1 \lesssim z \lesssim 20+$
- D, M, m, χ, etc. at % level
- MBH formation and co-evolution with galaxies
- Potential EM counterparts?

Extreme Mass-ratio Inspirals



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

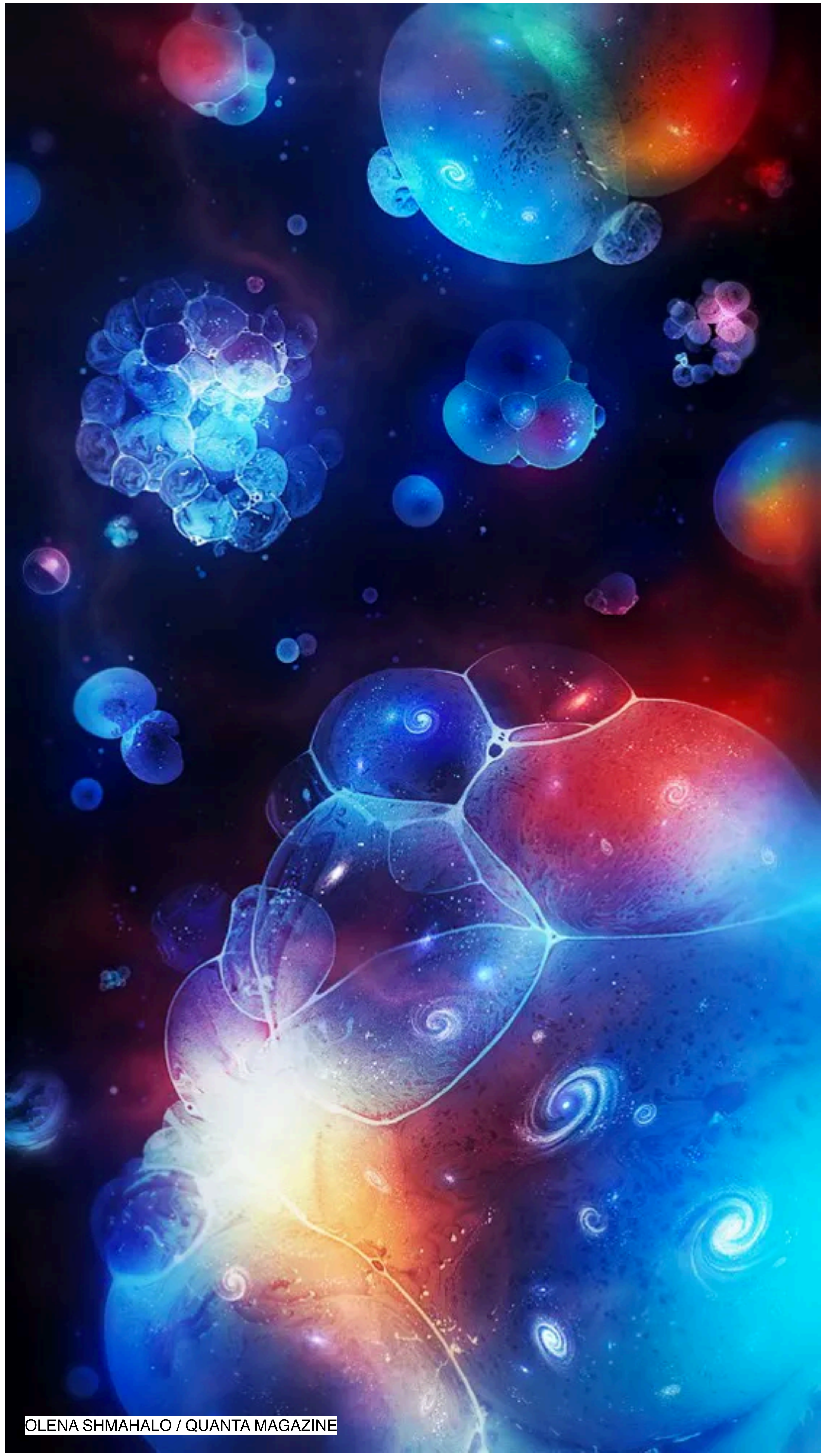
Ultra-compact binaries



- ~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.

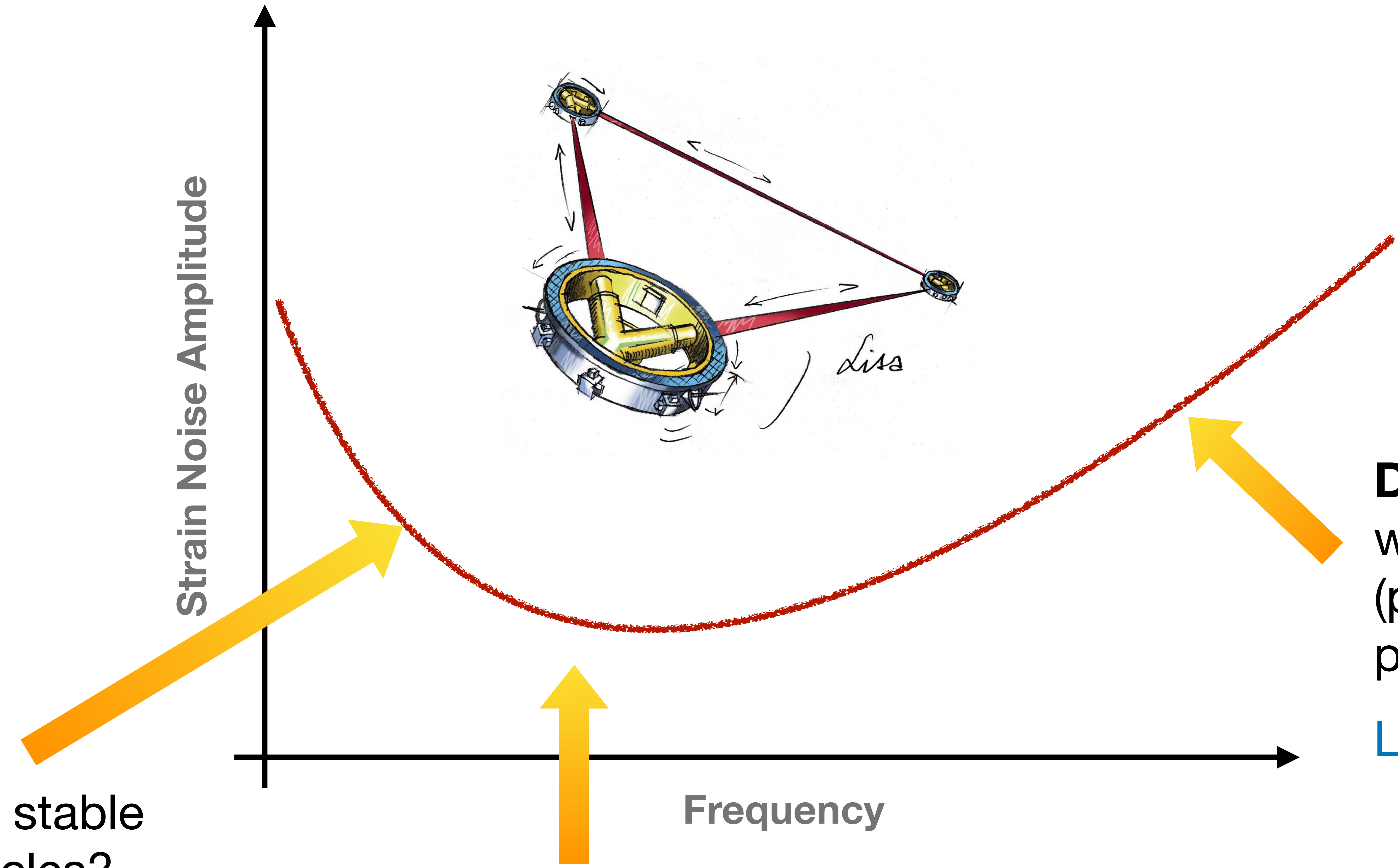
Backgrounds / Discovery Space

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



Technology

Fundamentals of GW Interferometers



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

LISA ~ picometer/Hz$^{1/2}$

Acceleration noise: how stable are your fiducial test particles?

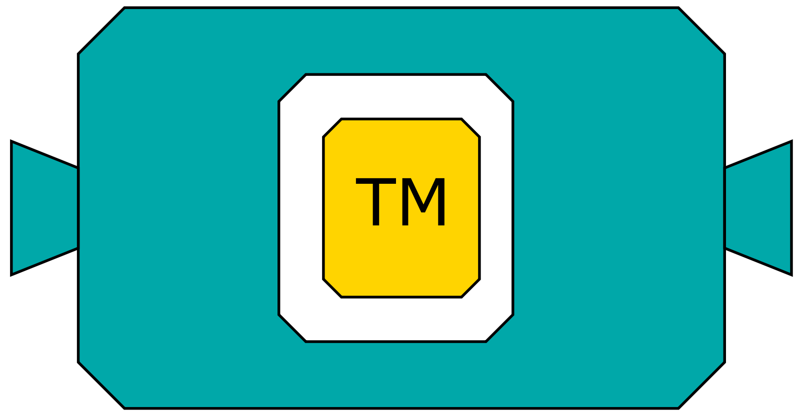
LISA ~ femto-g/Hz$^{1/2}$

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

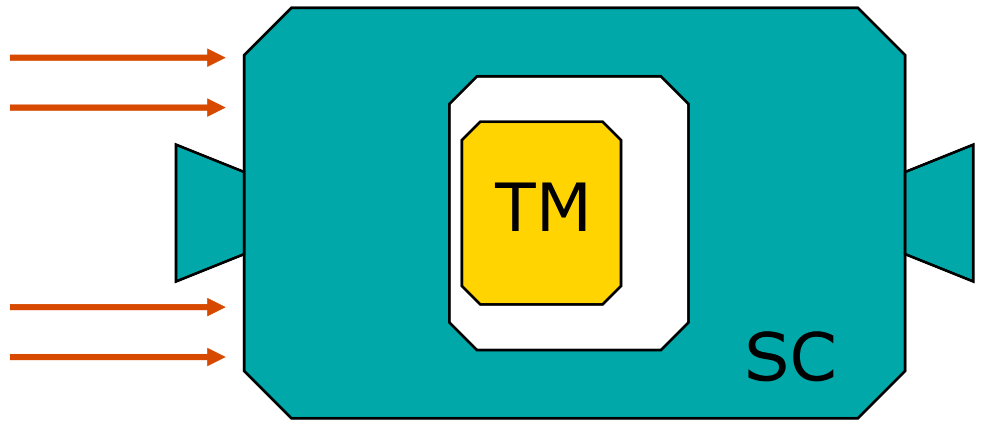
LISA ~2.5 Mkm

Acceleration Noise

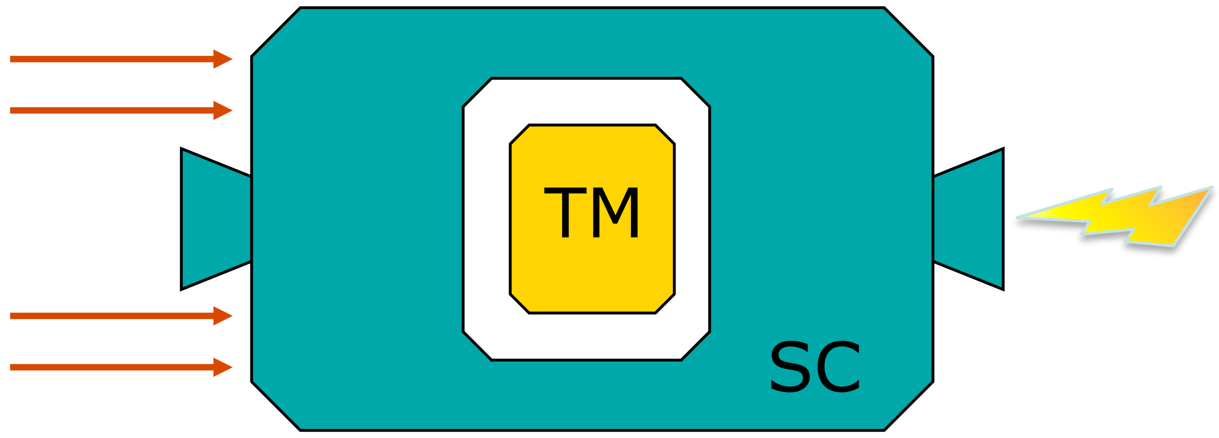
- Goal: test masses in “perfect” free-fall
  - ~ femto-g/Hz$^{1/2}$
- Drag-free control to suppress external disturbances
  - solar radiation pressure
  - micrometeoroids
- Careful engineering to suppress local disturbances
  - electric charge control
  - good vacuum
  - careful thermal design



TM and SC in free-fall



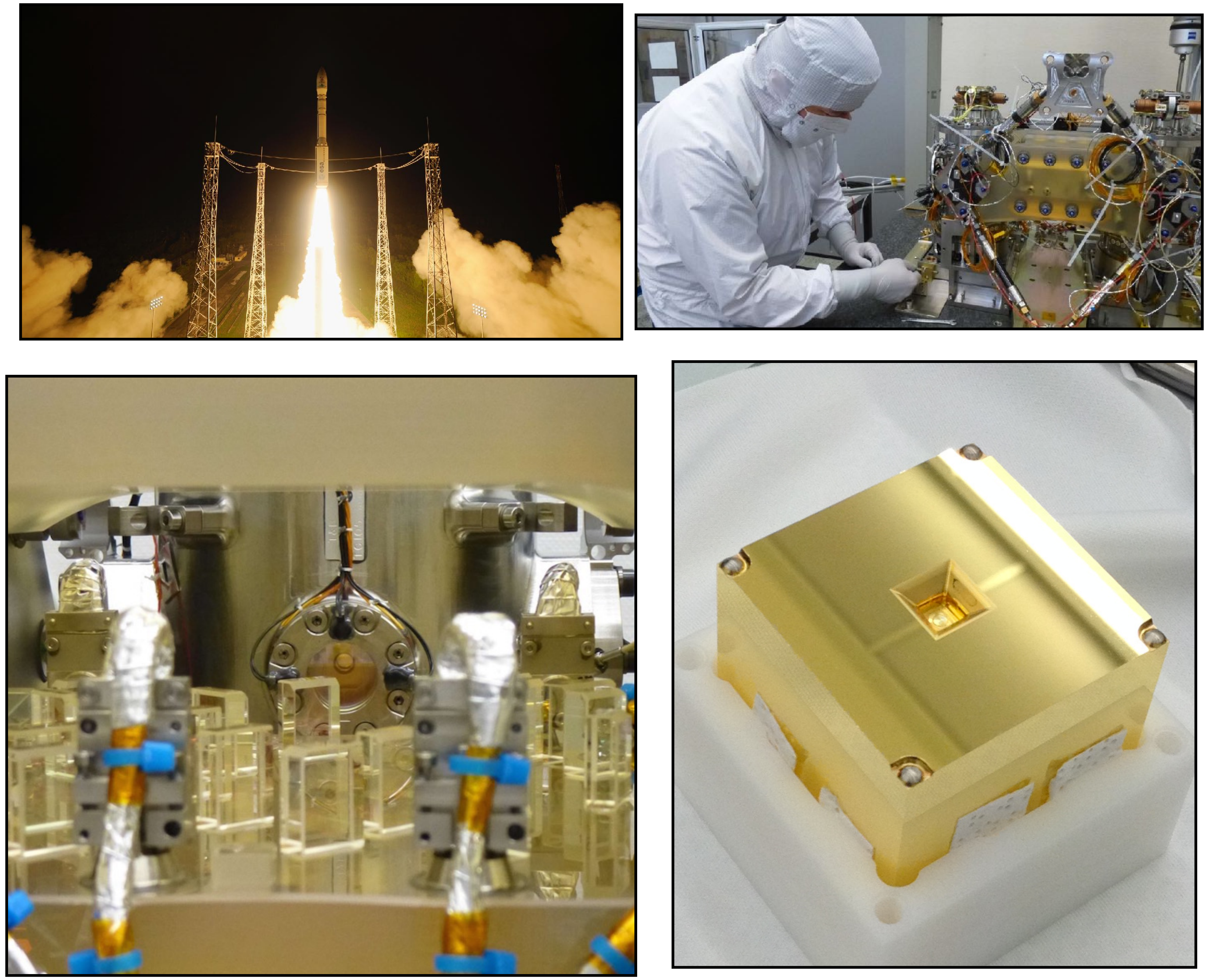
External disturbance



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

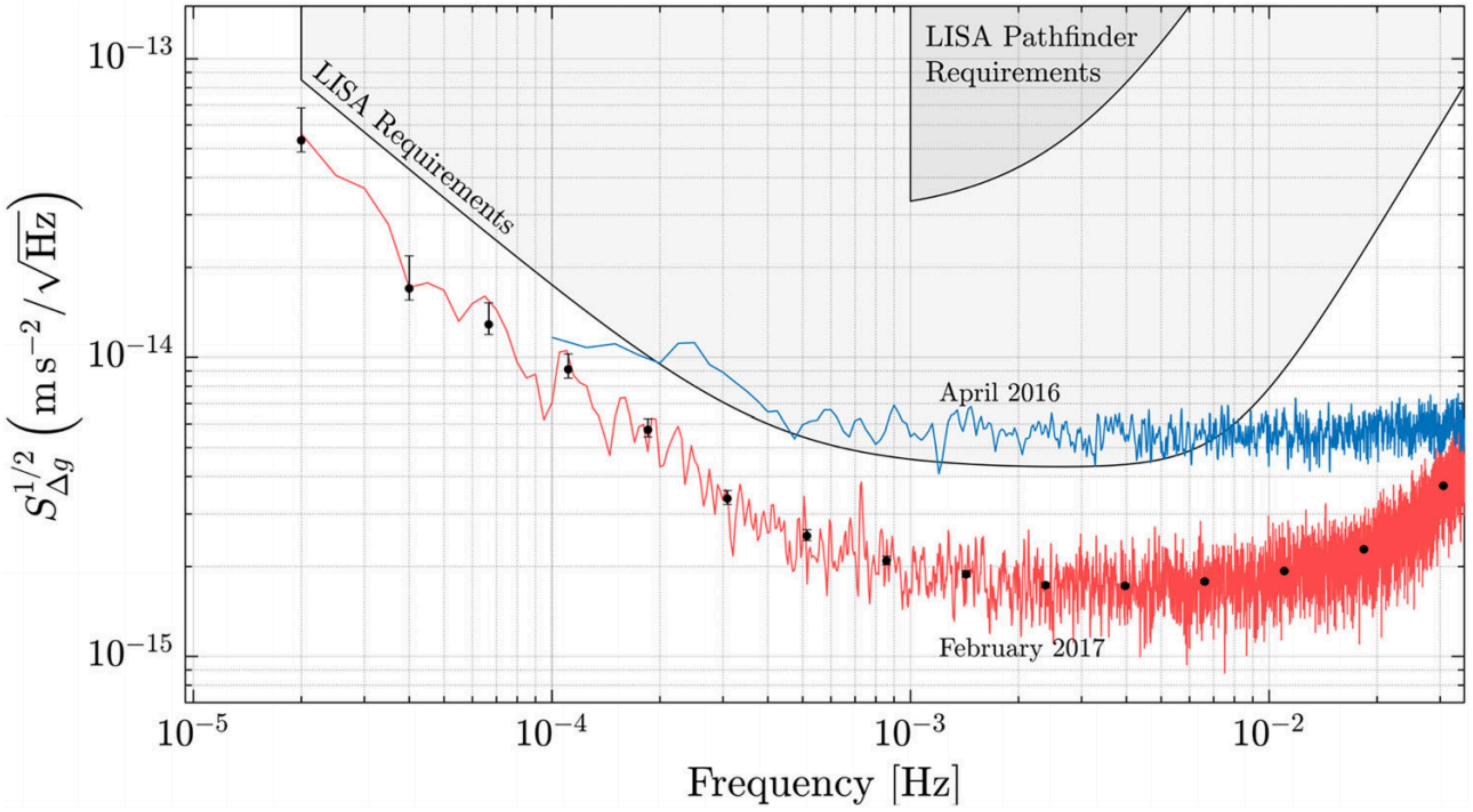


top left: *LISA Pathfinder launches from Kourou, French Guiana on Dec 3rd, 2015.* ***top right***: *technical assembling the LISA technology package (LTP) payload.* ***bottom left:*** *a view of the LTP optical bench during integration.* ***bottom right:*** *the gold-platinum LTP test mass*

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

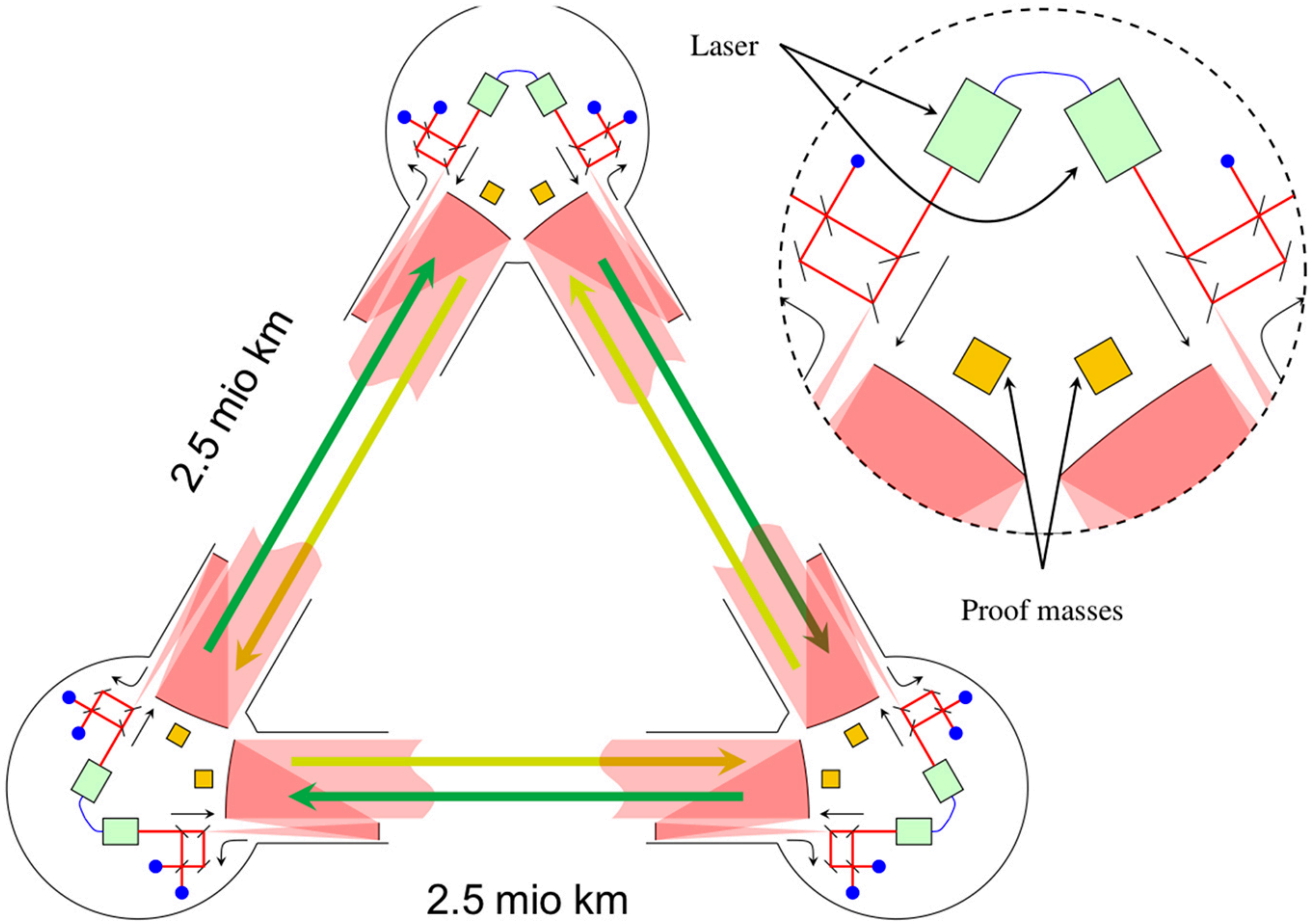


Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20μHz

Phys. Rev. Lett. **120**, 061101

Displacement Noise

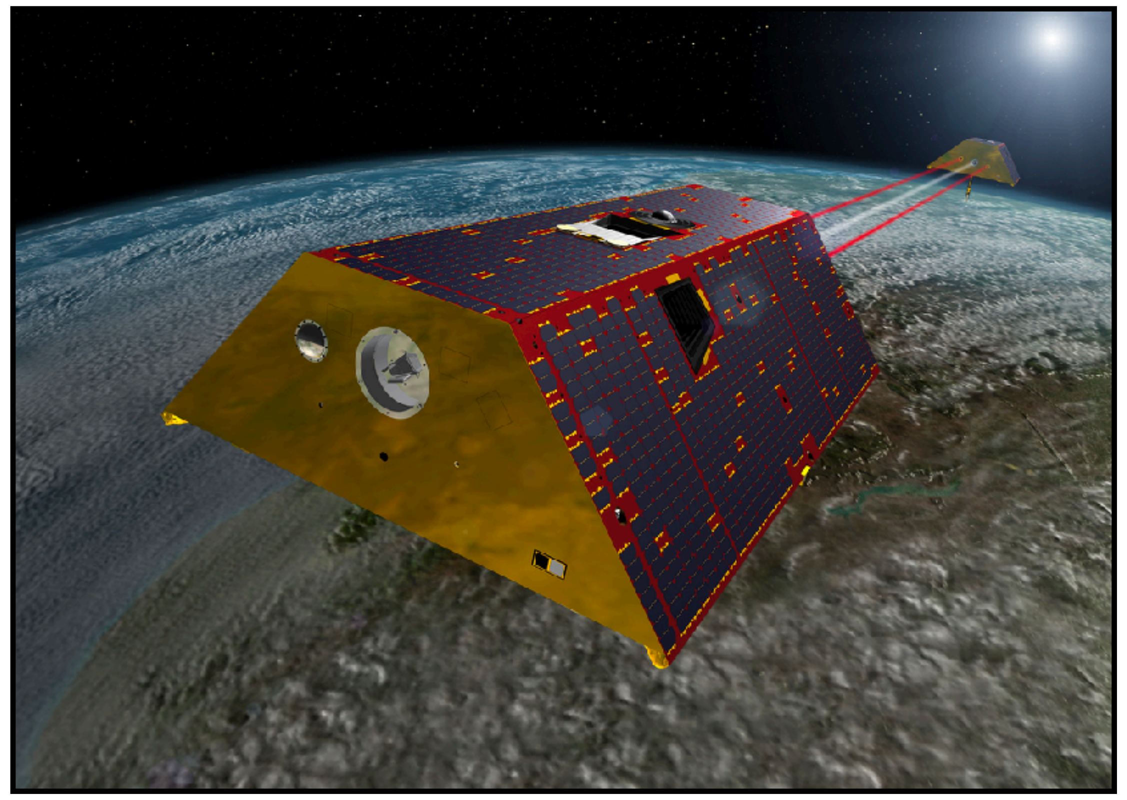
- heterodyne interferometry with ~1µm light
- Six “one-way” measurements between pairs of spacecraft
- Telescopes reduce diffraction loss, still only receive about 10^{-10} of the transmitted power.
- Passively stable orbits maintain arm lengths to ~0.5% (10^5 km)
- On ground “Time Delay Interferometry”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

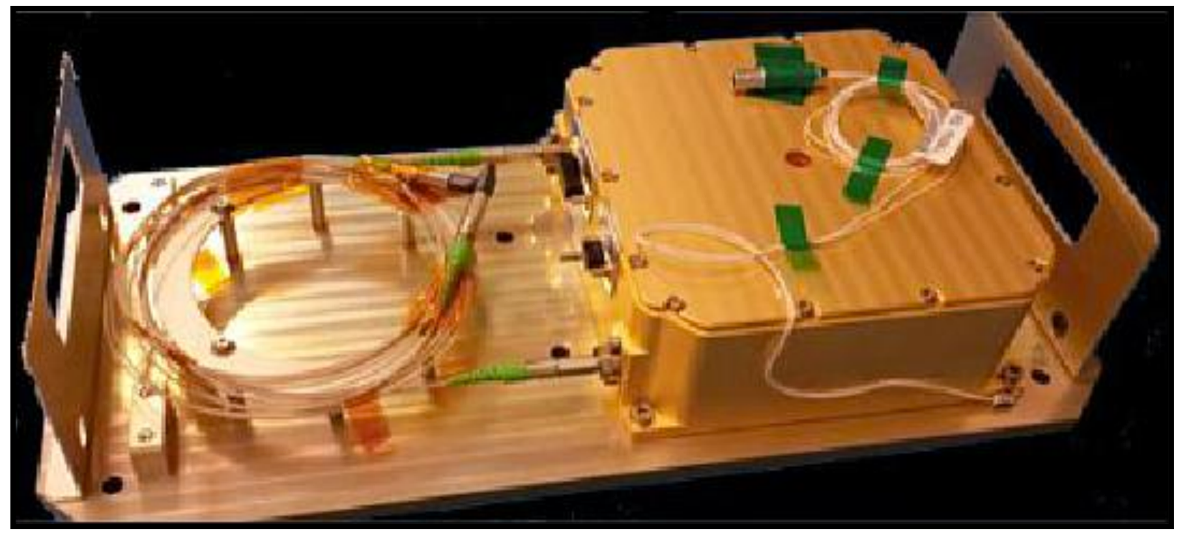
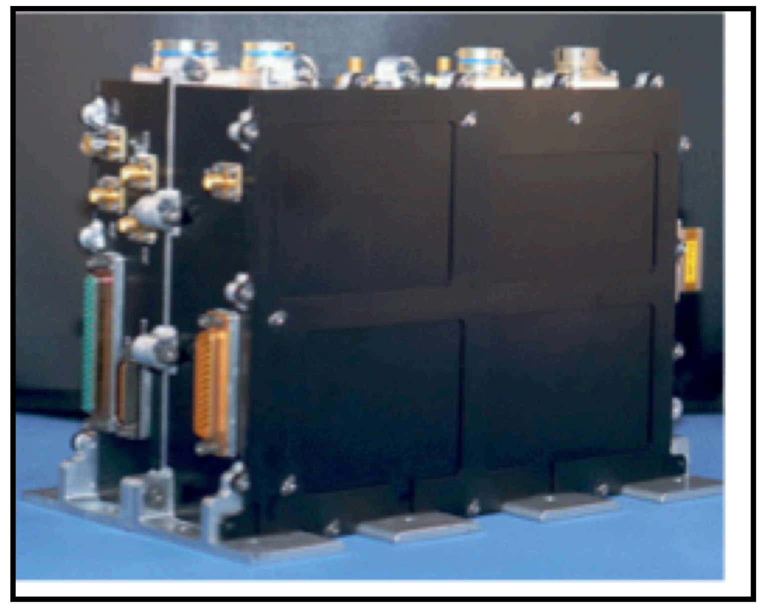


Schematic of the LISA interferometric measurement (T. Schuldt)

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.



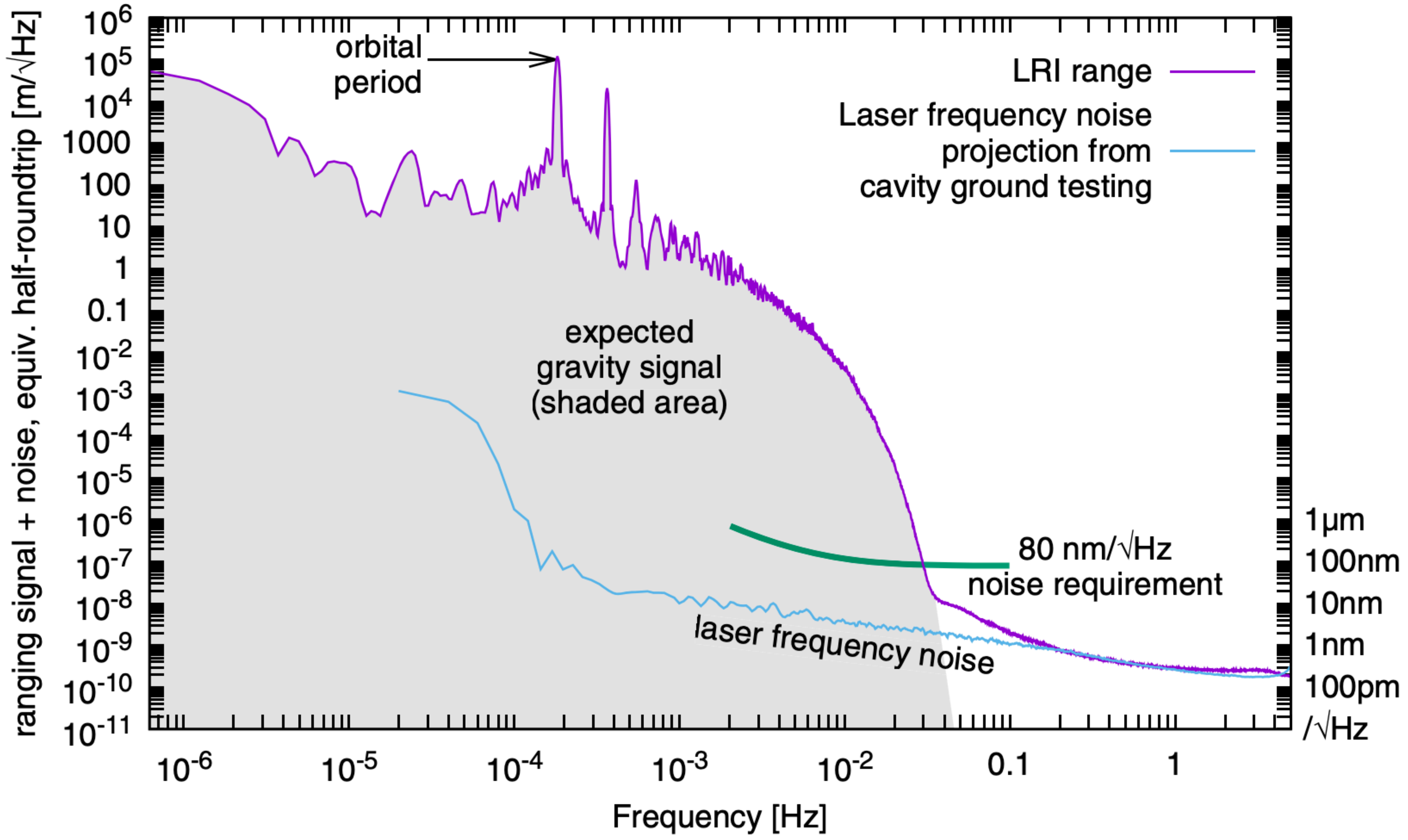



***top left**: Artist rendering of GRACE-FO spacecraft. **top right**: optical frequency reference for LRI. **bottom left:** LRI laser assembly **bottom right:** laser ranging processor (measurement and control)*

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

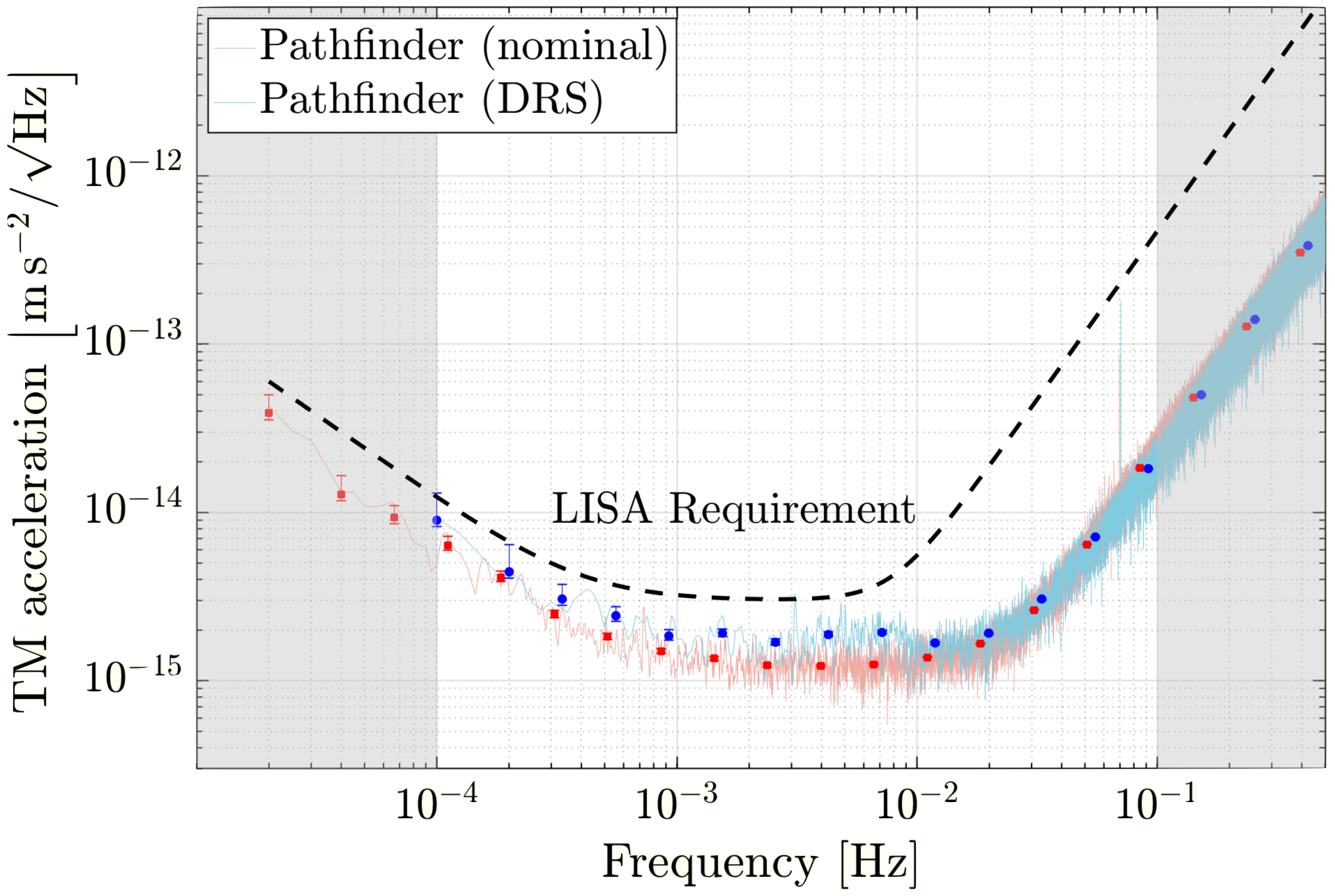


In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer

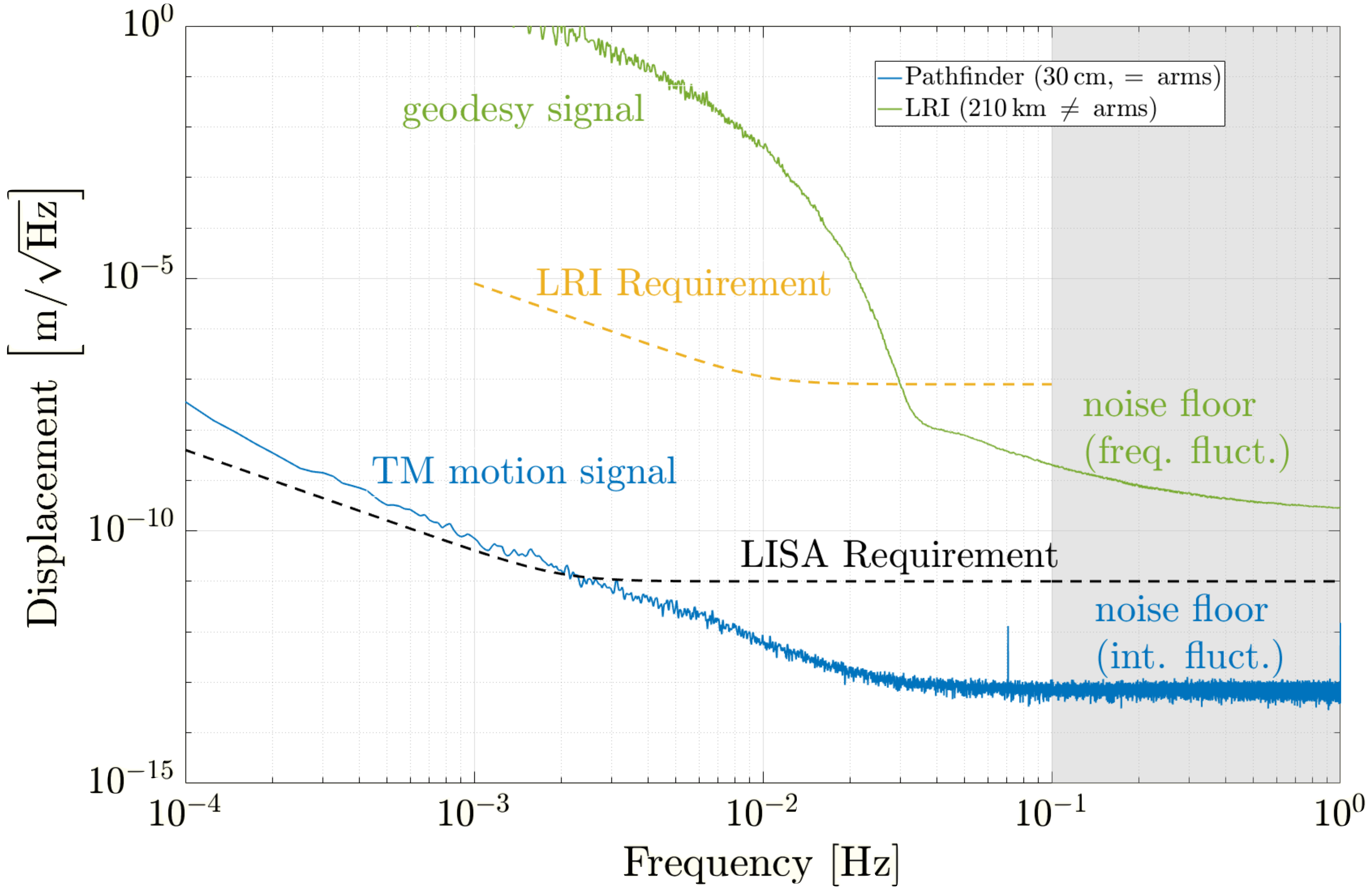
Phys. Rev. Lett. **123**, 031101

Two LISA flight demos

Acceleration noise: how stable are your fiducial test particles?

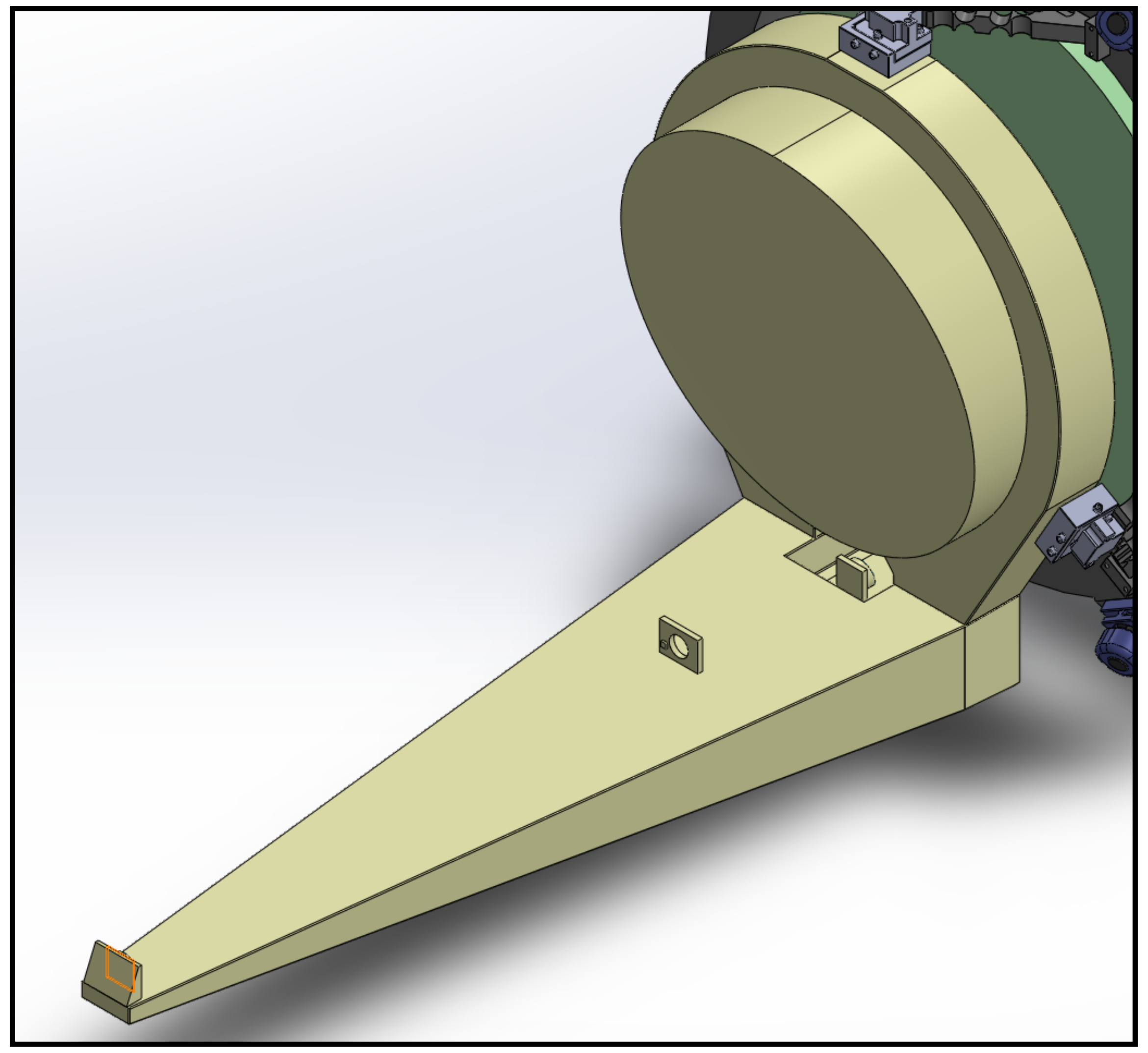


Displacement noise: how well can you measure (proper) distance between pairs of test particles?



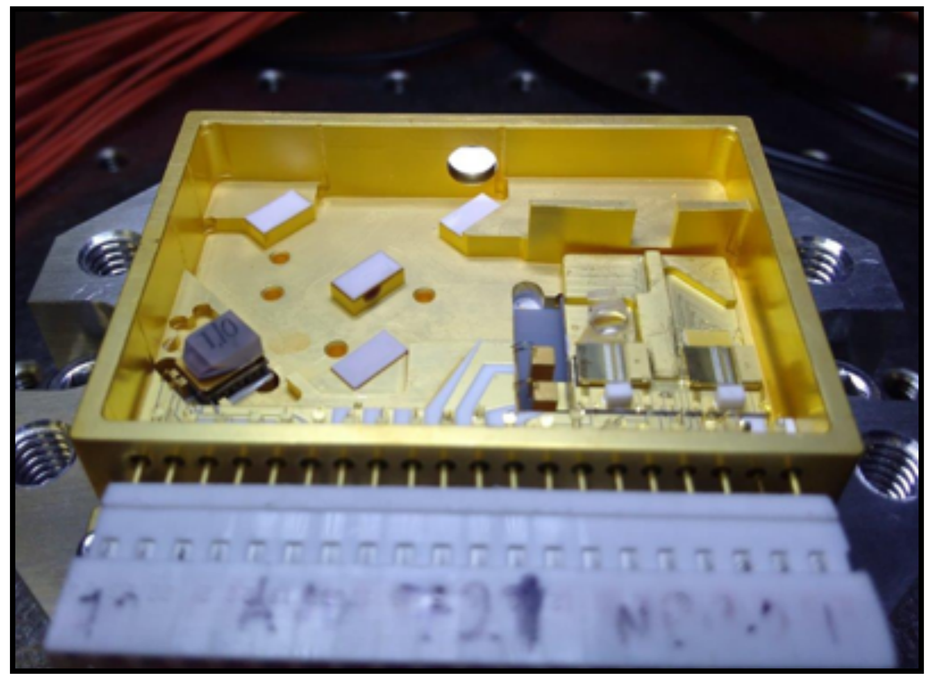
What’s left?

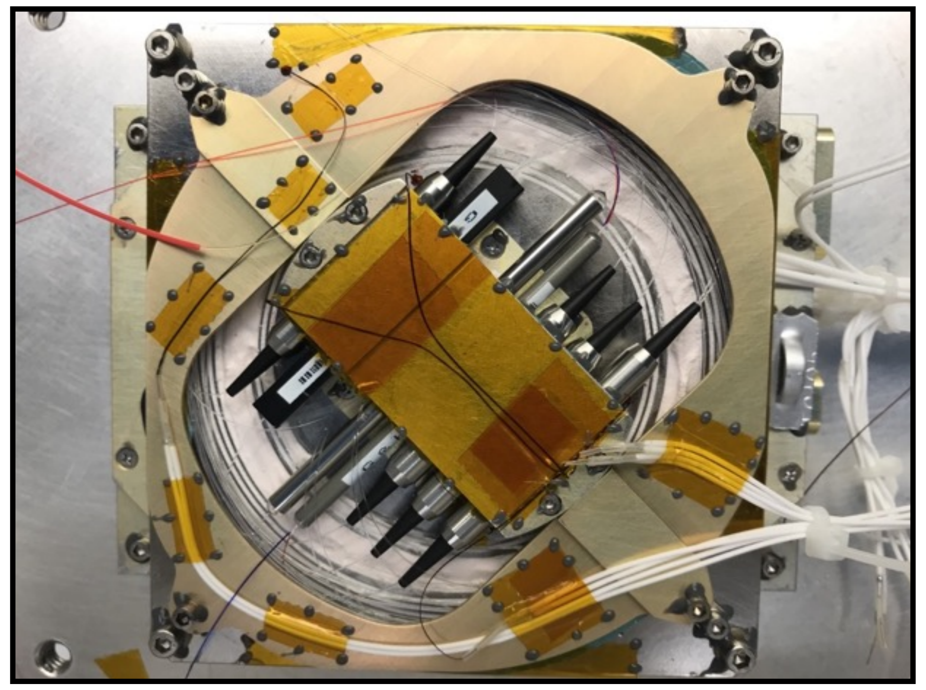
- Interferometry over *really* long distances (10^6 km vs 10^2 km)
  - stable telescopes
  - more powerful lasers (but still stable)
  - time-delay interferometry (deal with unequal arms)
- Moving from *demonstrators* to *observatories*
  - complex operation of three satellites and six payloads
  - Long 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*

Credit: NASA





Programmatics & Status

Who's involved

European Space Agency

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

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

LISA CONSORTIUM

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

lisascience.org

NASA LISA Study Office

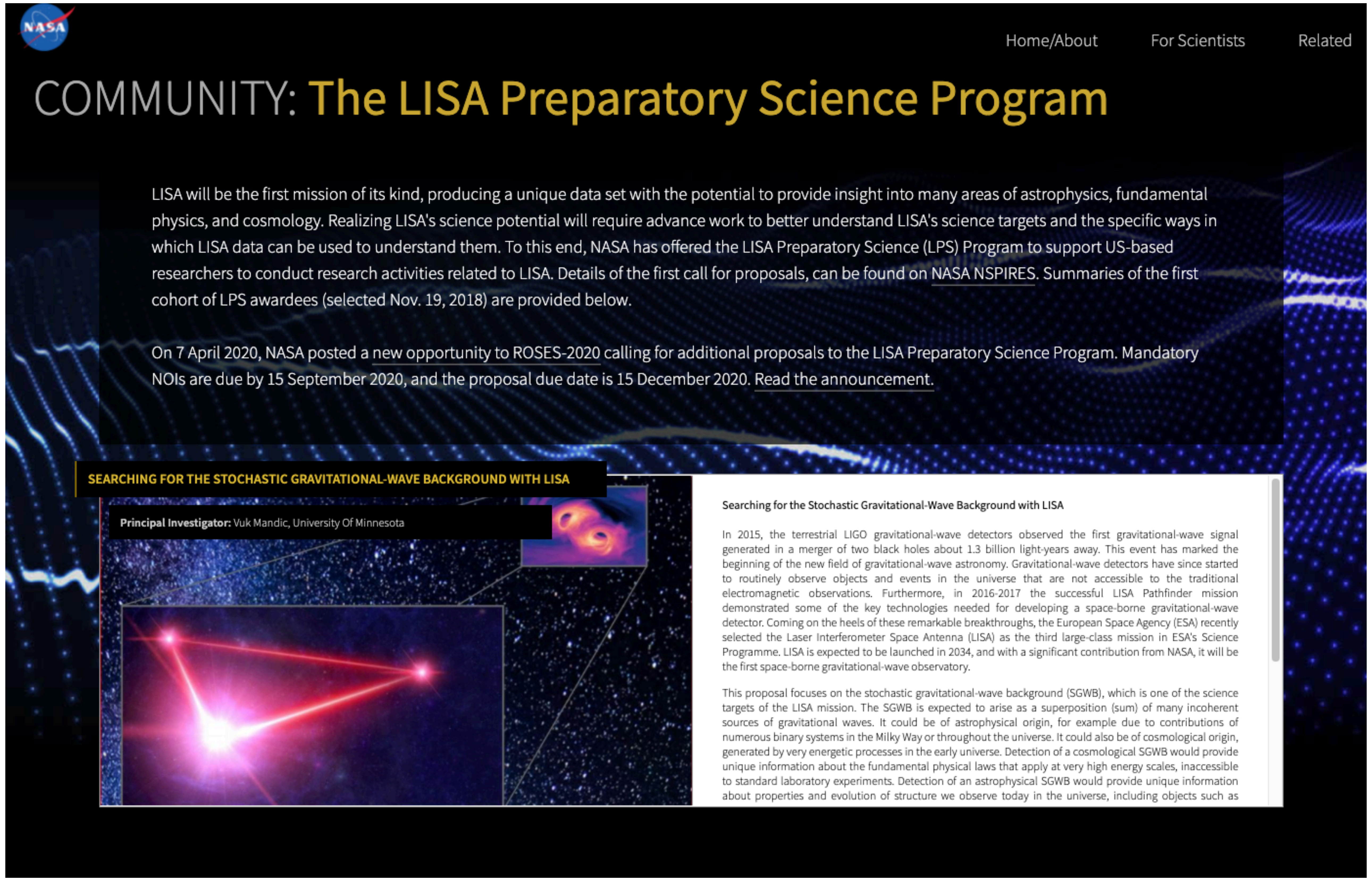
- **"proto-project"**
  - Conducts pre-formulation activities (NASA is pre-phase A)
  - Will evolve into formal NASA Project Office
- **Hosted by Physics of the Cosmos Program at NASA/HQ**
  - Program responsible for managing science themes including gravitational waves
- **Executed by NASA field centers & 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

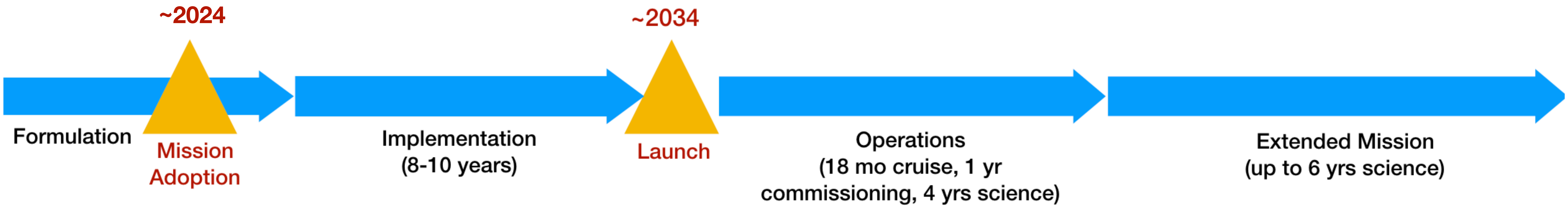
- **NASA/HQ funded grants to support LISA-related science**
  - Refine the LISA science case
  - Develop the future LISA user community
- **Process**
  - ROSES element, selected through standard NASA peer-review process
  - Independent of NASA Study Office and NASA LISA Study Team
  - No obligation (or 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**



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