

The Gravitational Universe and LISA

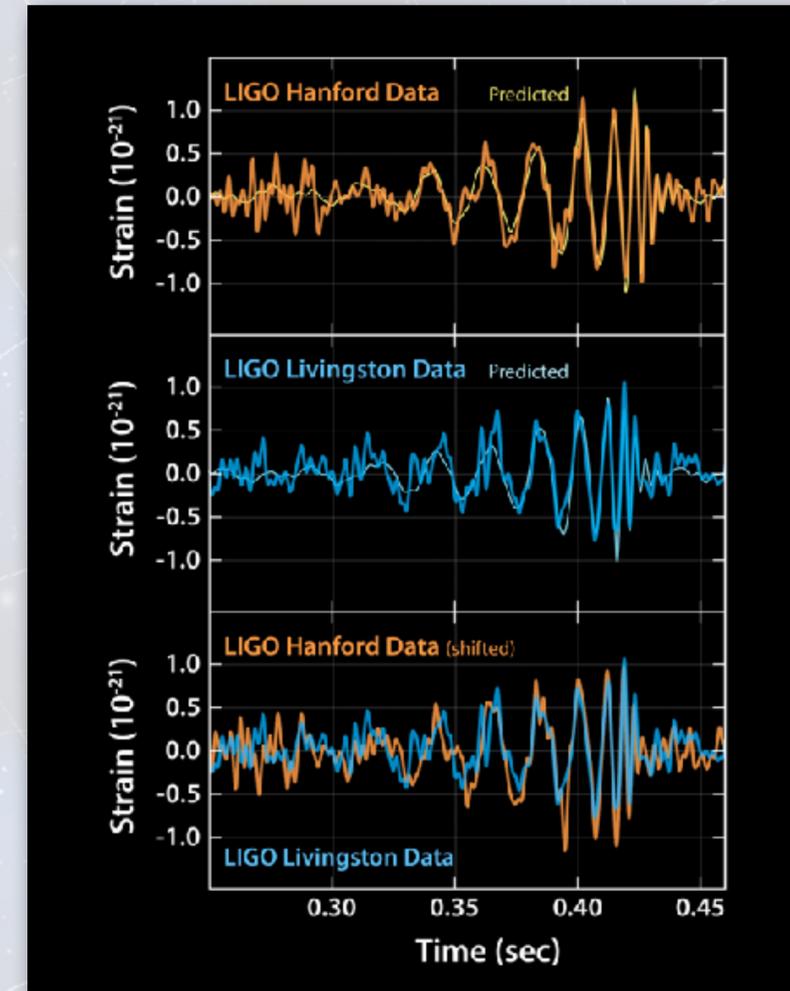
Paul McNamara
LISA Study Scientist
European Space Agency

10 years of the Czech Republic in ESA
Prague
15 November 2018

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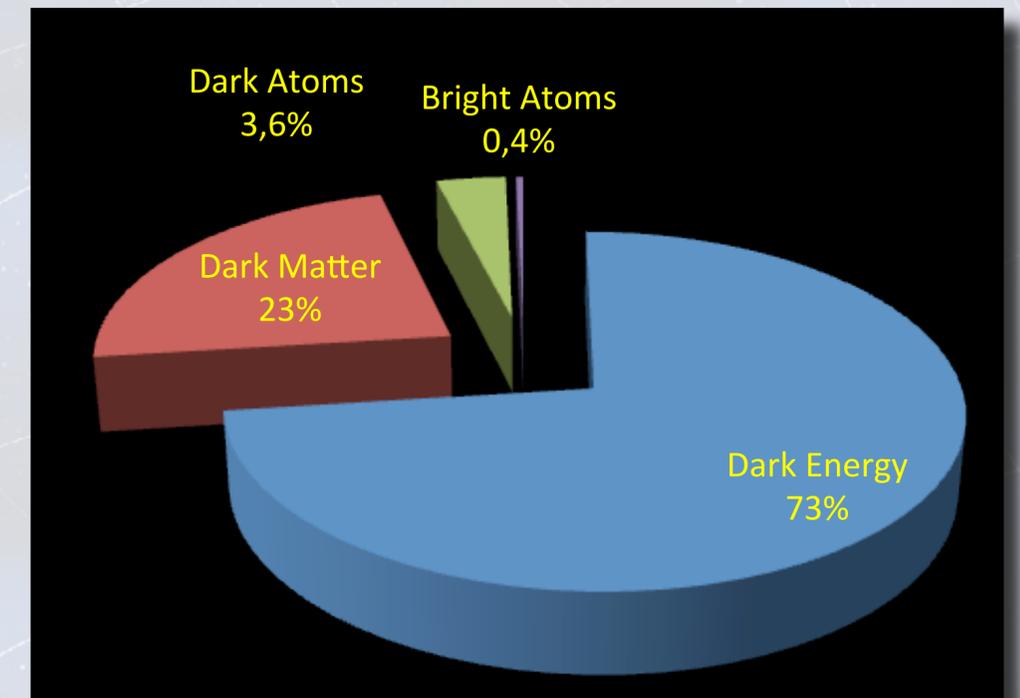
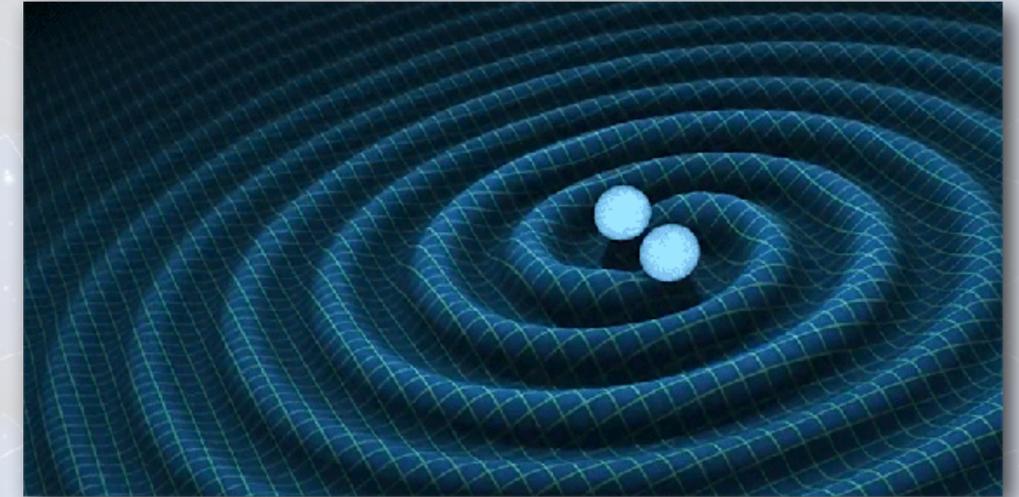


- LISA - the Laser Interferometer Space Antenna - is a European Space Agency mission to observe low frequency gravitational waves from space
- LISA has been around for over 20 years, with a science case which has remained stable over the years. However, there was always doubts that:
 1. Gravitational waves do not exist!
 2. Even if they did, we are not capable of building an instrument sensitive enough, let alone in space, which can measure the miniscule effect of a passing GW
- Then came the second half of 2015....
 - LIGO makes first direct detection of gravitational waves, GW150914 → 14 September 2015
 - LISA Pathfinder launched → 3 December 2015
 - LISA Pathfinder performance surpasses all expectations
- Both momentous events opened the door to the *Gravitational Universe*



Gravitational waves...what are they?

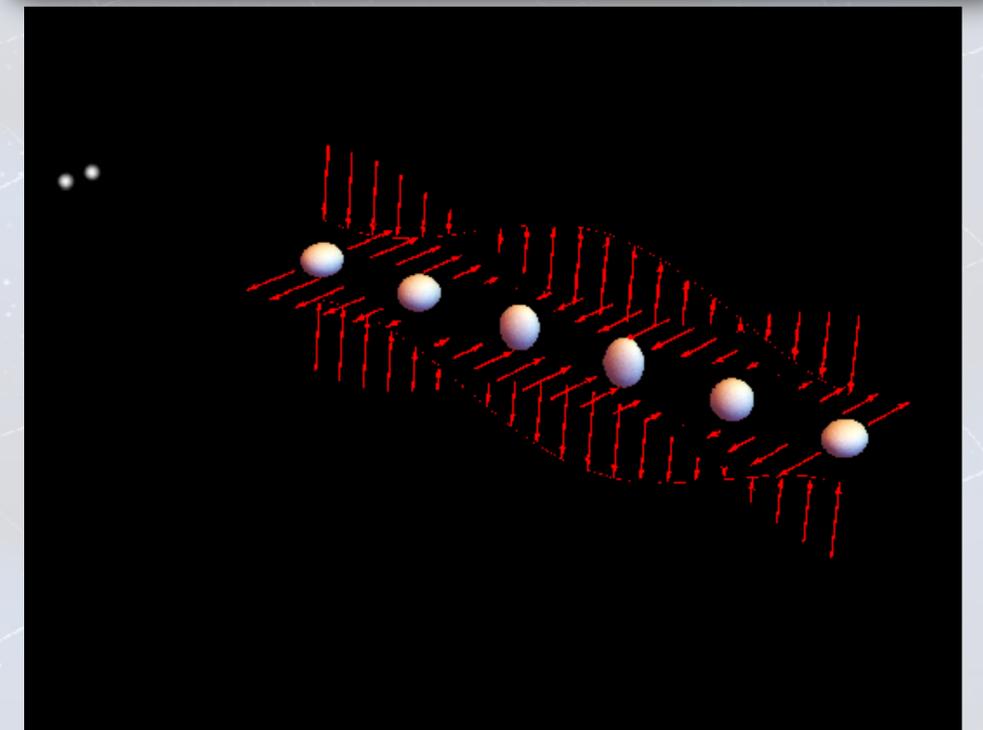
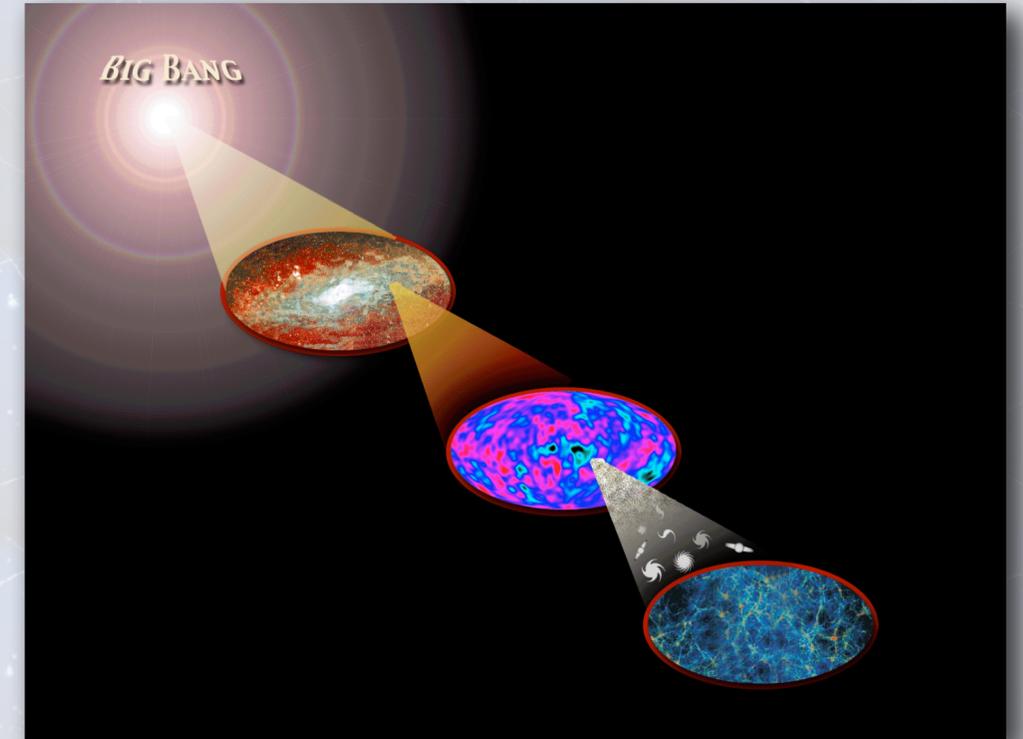
- Newton's theory of gravity:
 - "instantaneous action at a distance"
- Einstein's Special Theory of Relativity:
 - "information cannot be carried faster than the speed of light"
 - **There must be something to carry the gravitational information**
- Gravitational waves:
 - Ripples in the curvature of spacetime
 - Produced by the motion of mass and energy



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 - **There must be something to carry the gravitational information**
- Gravitational waves:
 - Ripples in the curvature of spacetime
 - Produced by the motion of mass and energy
 - Travel through the Universe (almost) unimpeded
 - Allows us to observe the very distant universe
 - Difficult to detect!

Gravitational Waves carry entirely new information about the Universe



What happens when a GW passes Earth?



Earth Diameter:
~12,800km



**Passage of gravitational wave:
Earth's diameter changes by ~1/10,000 the diameter of an atom!**



Ground based GW detectors



LIGO: Hanford, WA



VIRGO: Cascina, Italy



LIGO: Livingston, LA



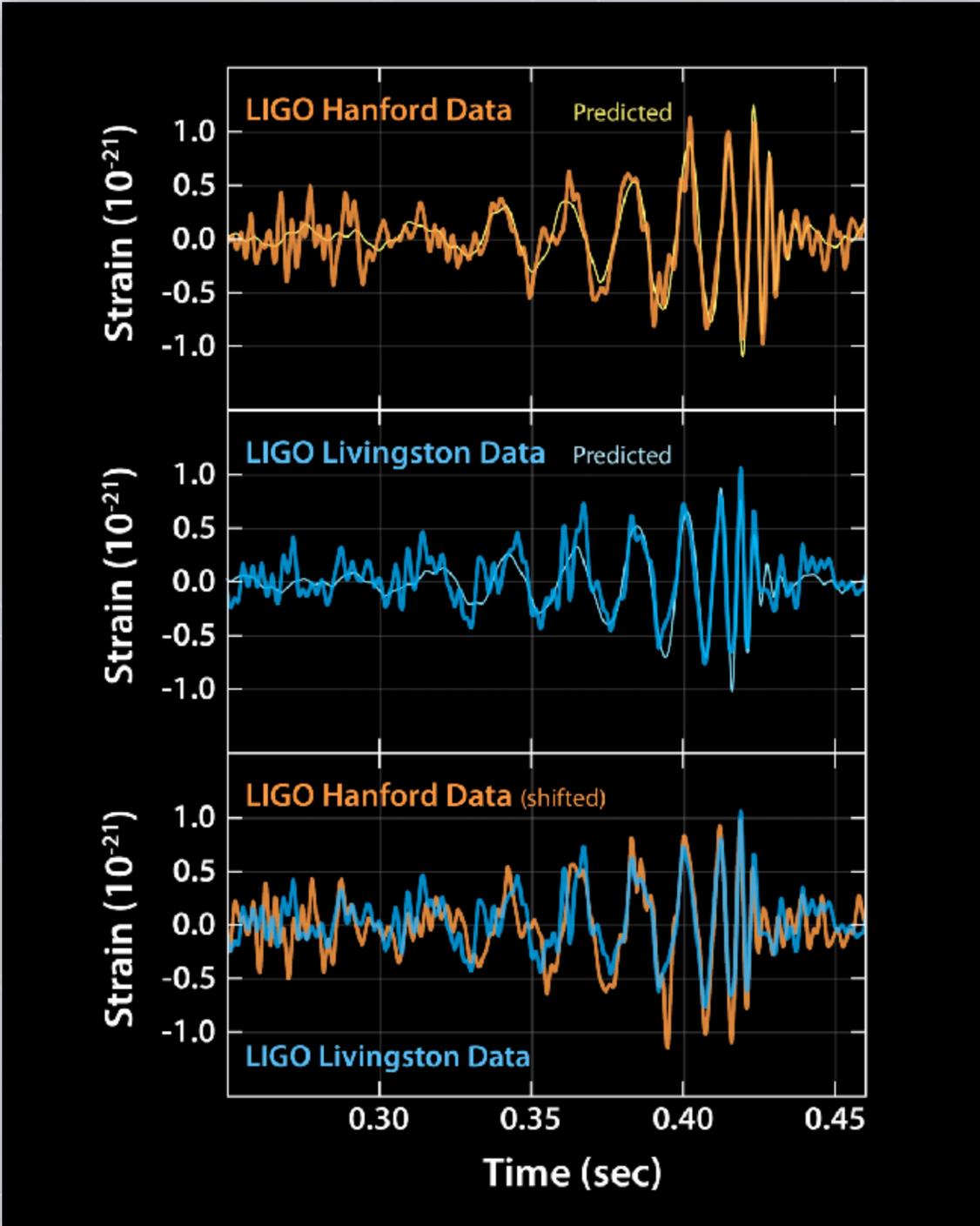
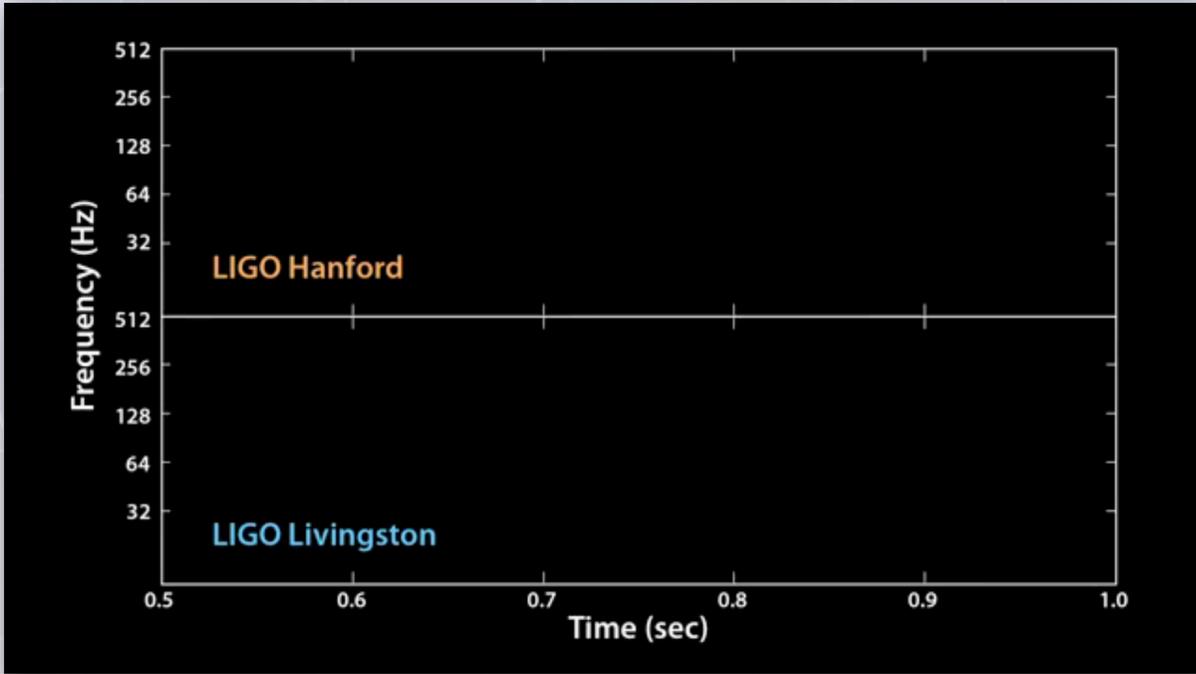
GEO600: Ruthe, Germany



KAGRA: Kamioka Japan



The first direct detection...GW150914



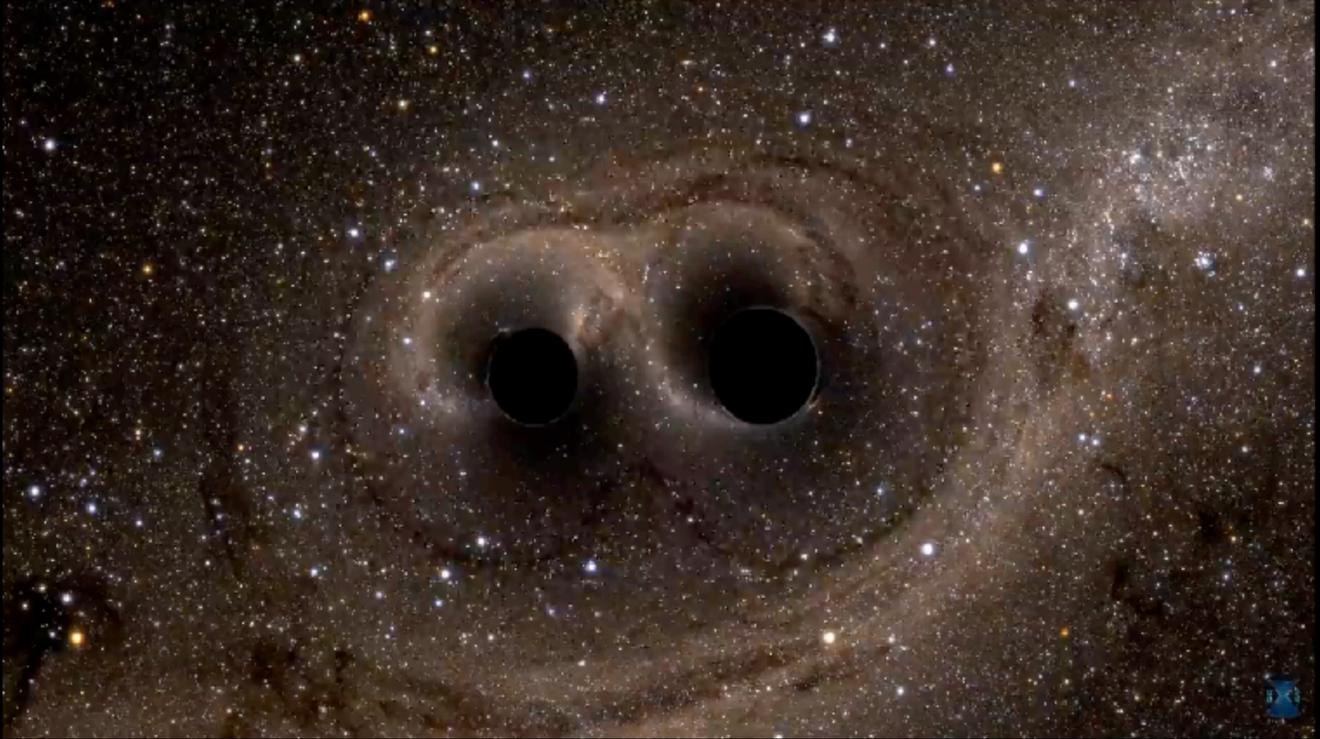
[Abbott et al, PRL 2016]



What did LIGO observe?



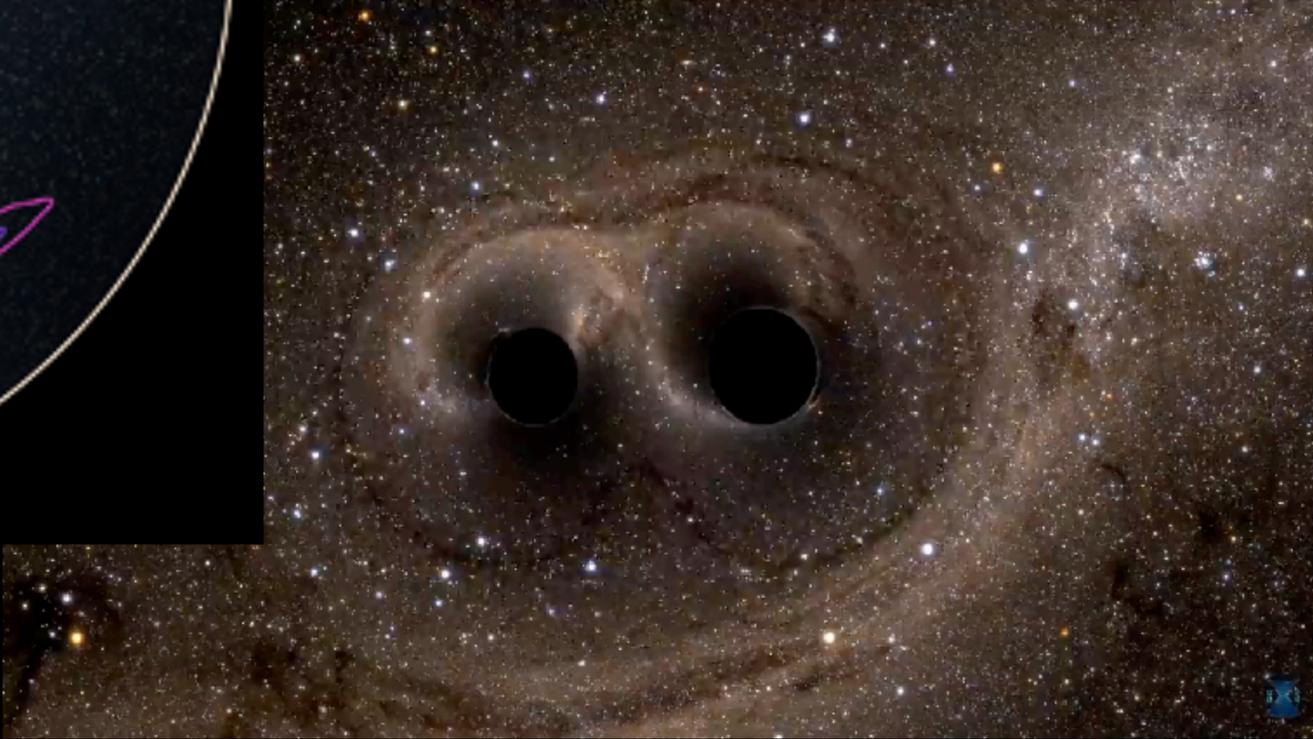
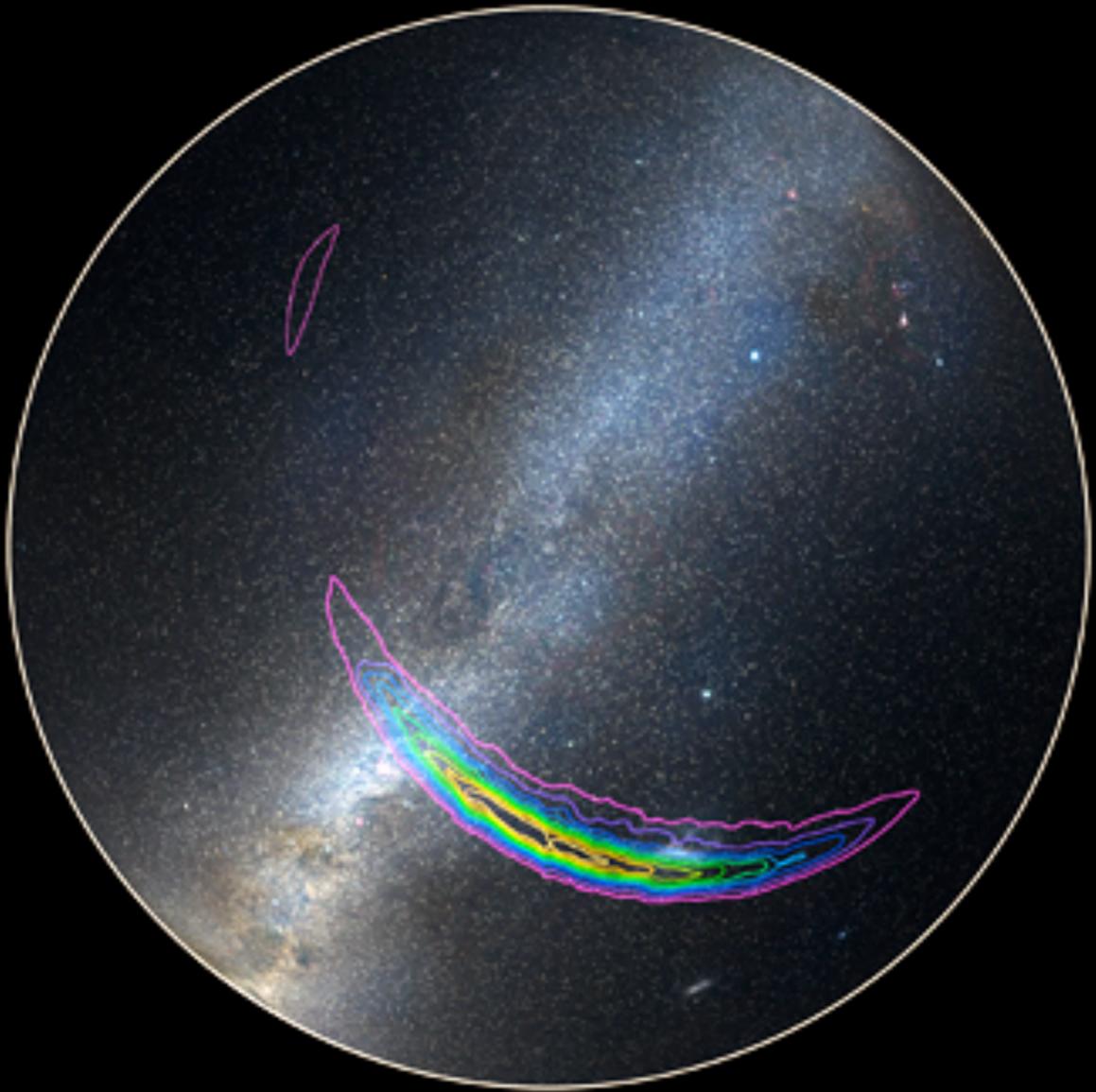
Scale of Effect Vastly Exaggerated



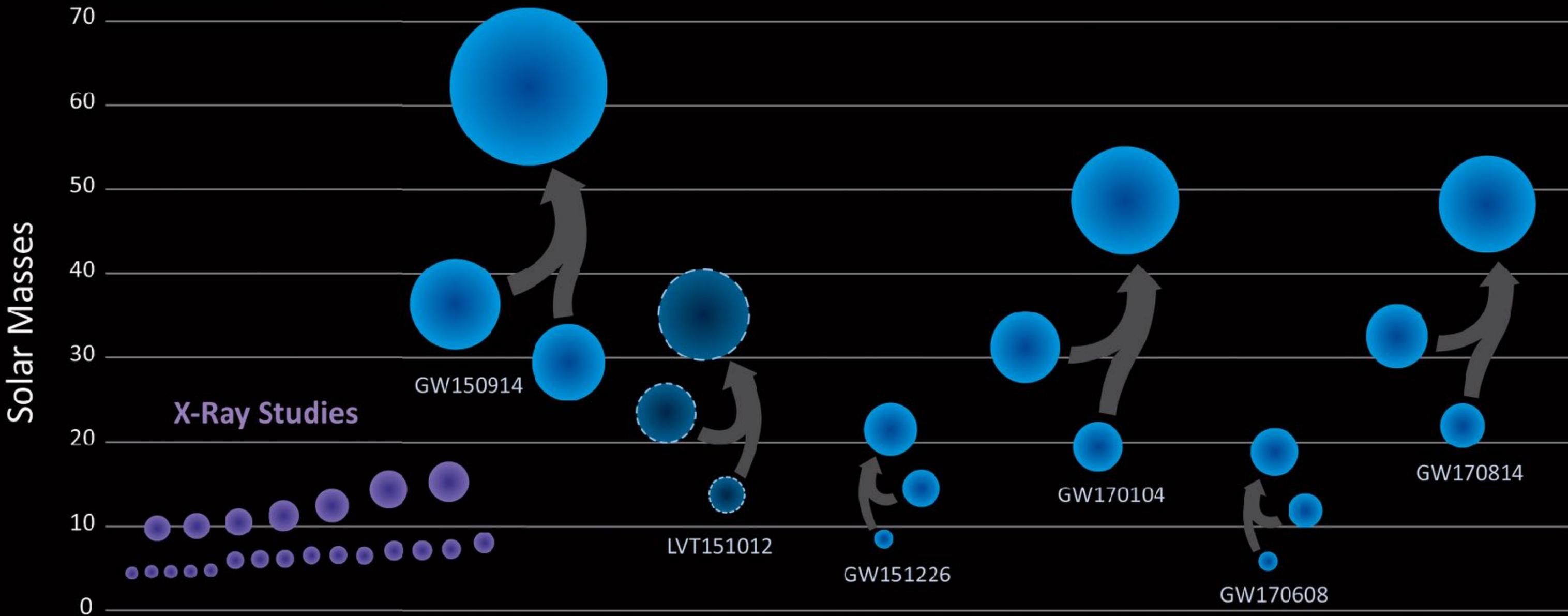
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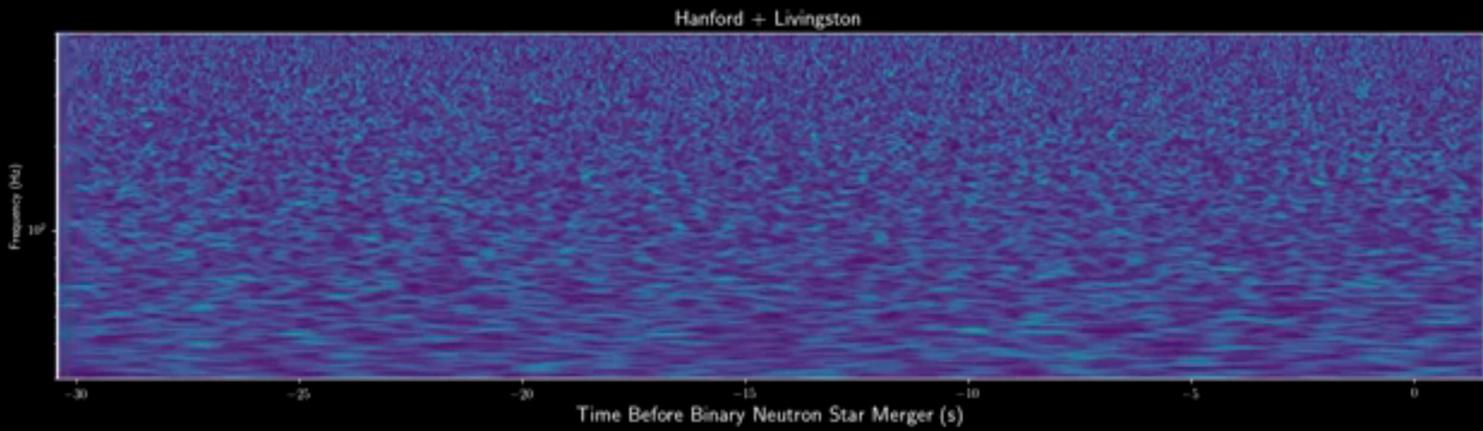
GW150914 was not alone...



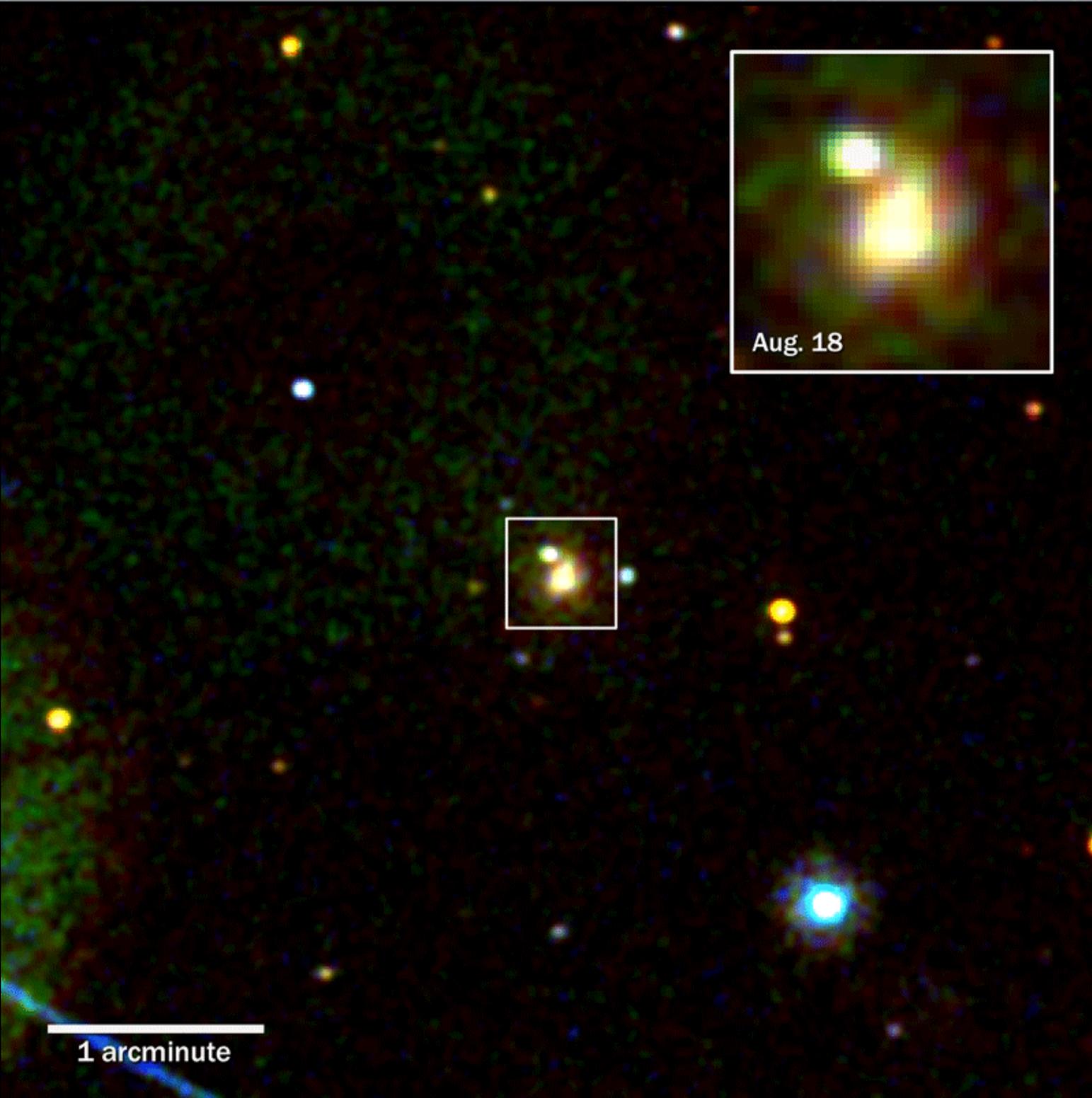
LIGO/VIRGO



Multi-messenger astronomy - GW170817



Multi-messenger astronomy - GW170817



Multi-messenger astronomy - GW170817



Fermi

Reported 16 seconds after detection



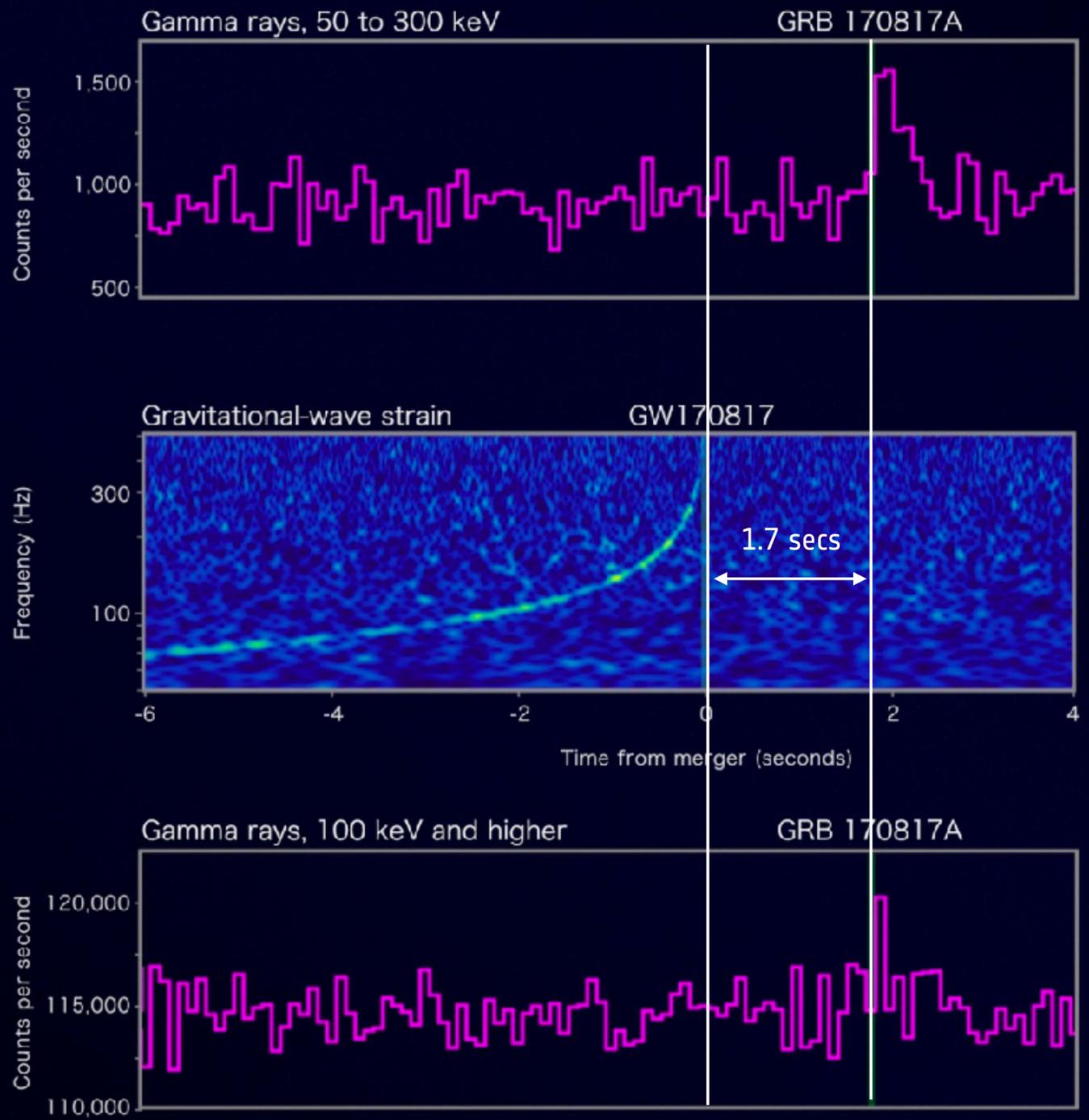
LIGO-Virgo

Reported 27 minutes after detection

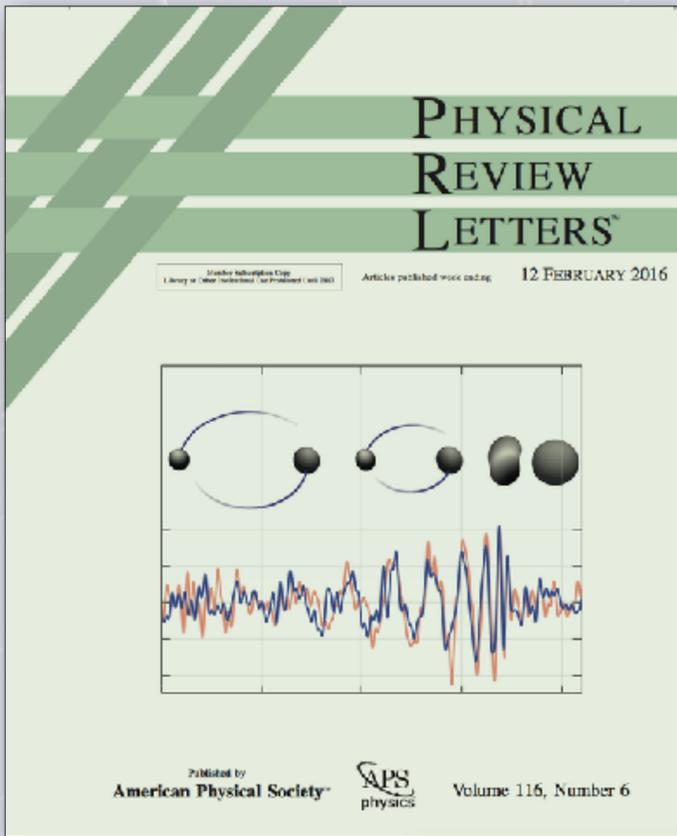


INTEGRAL

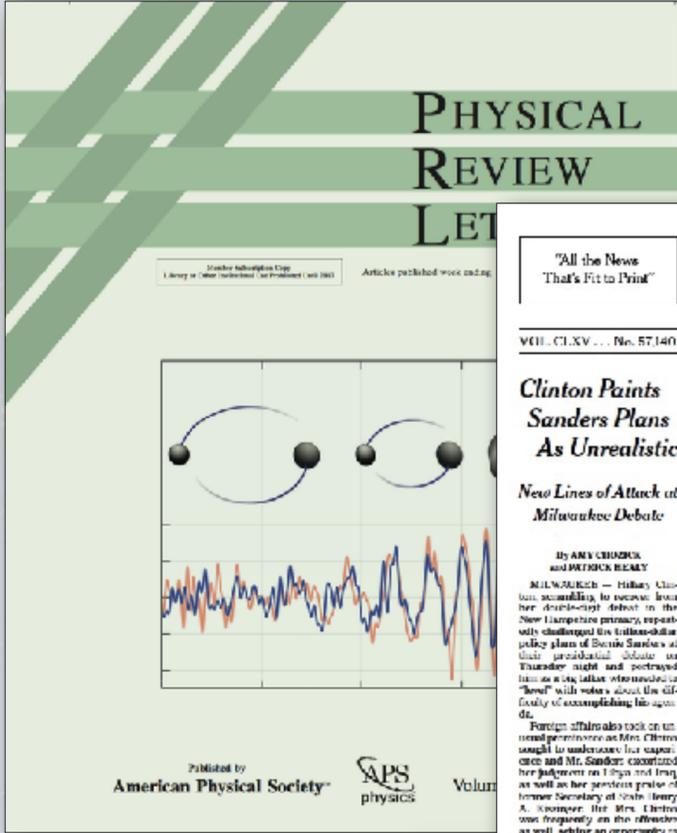
Reported 66 minutes after detection



How important are these discoveries?



How important are these discoveries?



The New York Times
 Lab Edition
 Today, some sunshine giving way to drizzle of clouds, cold, high 24. Tonight, a flurry of heavier snow late, low 20. Tomorrow, windy, blizzard, high 21. Weekend wrap, Page A3B.

Vol. CLXV No. 57,140 NEW YORK, FRIDAY, FEBRUARY 12, 2016 \$2.50

Clinton Paints Sanders Plans As Unrealistic
 New Lines of Attack at Milwaukee Debate

By AMY CHAZKIN and PATRICK BEALY

MILWAUKEE — Hillary Clinton, according to some, lost her decisive debate in the New Hampshire primary, repeatedly challenged the million-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a naïf, naïve who made a "howl" with notes about the difficulty of accomplishing his agenda.

Foreign affairs also took on its usual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders' courtized her just over an hour and long, as well as her previous praise of former Secretary of State Henry A. Kissinger. The Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by hearing his past criticisms of President Obama — a remark that Mr. Sanders called a "low blow."

With tensions between the two Democrats becoming increasingly obvious, the debate was full of new lines of attack from Mrs. Clinton, who later gestured to Mr. Sanders's growing

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT
 A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the faint chirp of two black holes colliding a billion light years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That last ringing tone, physicists say, is the last direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It comes when two stars of a universe in which space and time are intertwined and dynamic, able to stretch, shrink and pulse.

And it is intriguing confirmation of the nature of black holes, the bottomless gravitational wells which not even light can escape, which were the most fore

Long in Clinton's Corner, Blacks Notice Sanders
 Courted Hard in South Carolina, Loyalists

By RICHARD PUSSETT

CHARLESTON, S.C. — When Mrs. Clinton was asked whom she would vote for in the South Carolina primary, she said she would vote for Hillary Clinton. But when she was asked whom she would vote for in the South Carolina primary, she said she would vote for Hillary Clinton.

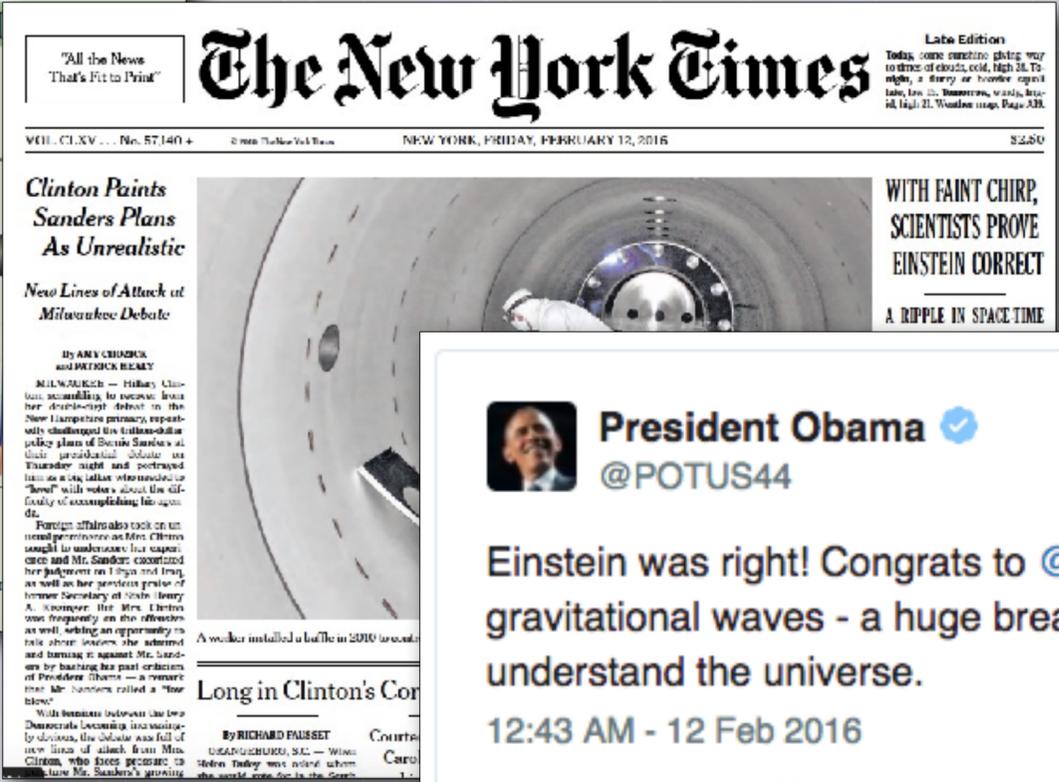
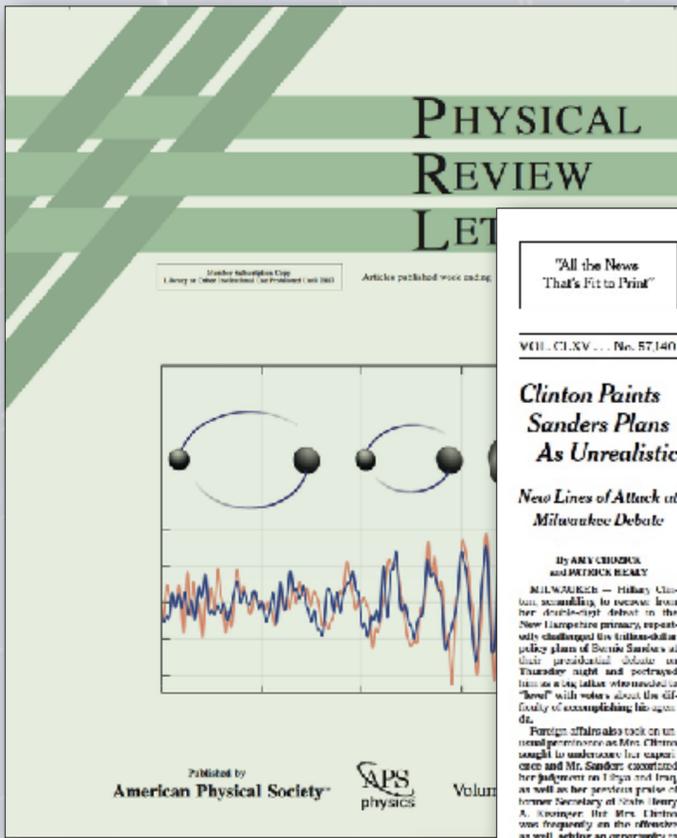
Last Occupier In Rural Oregon Is Coaxed Out

By [Name obscured]

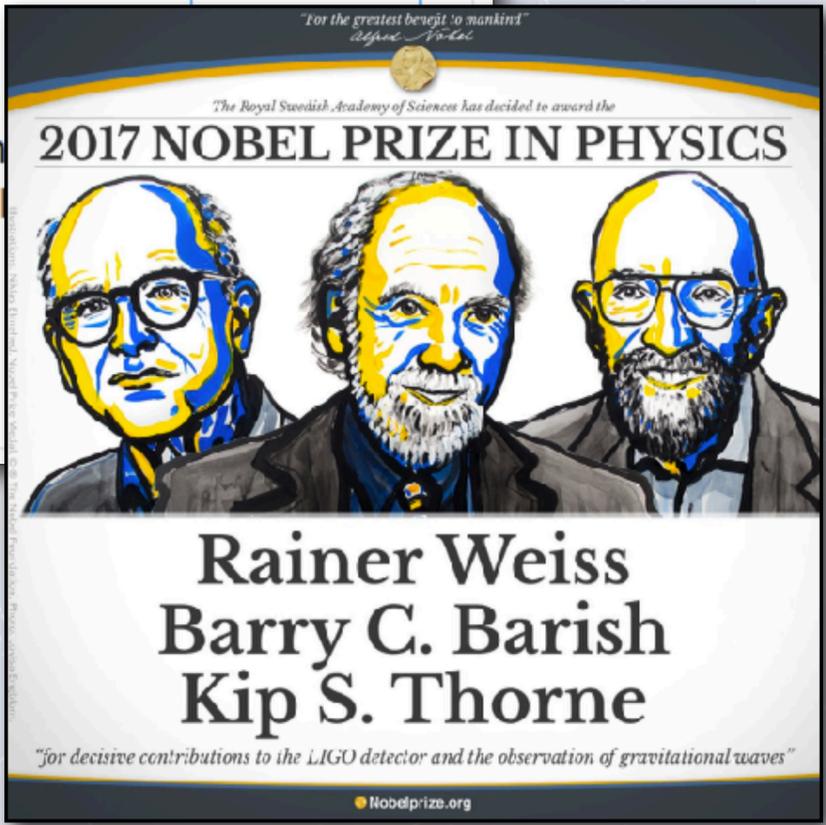
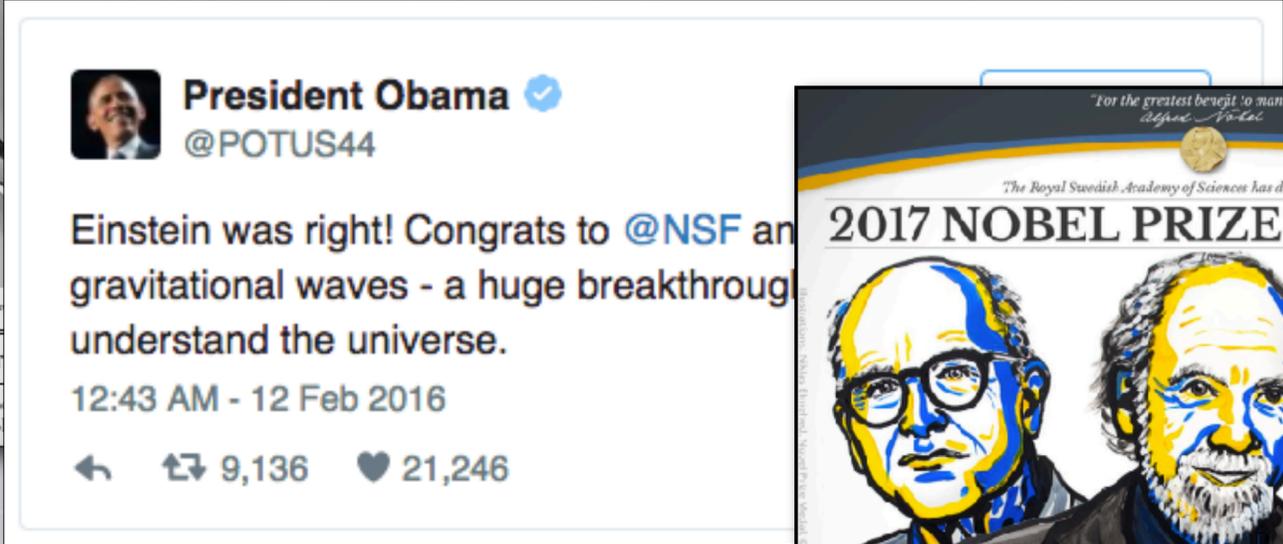
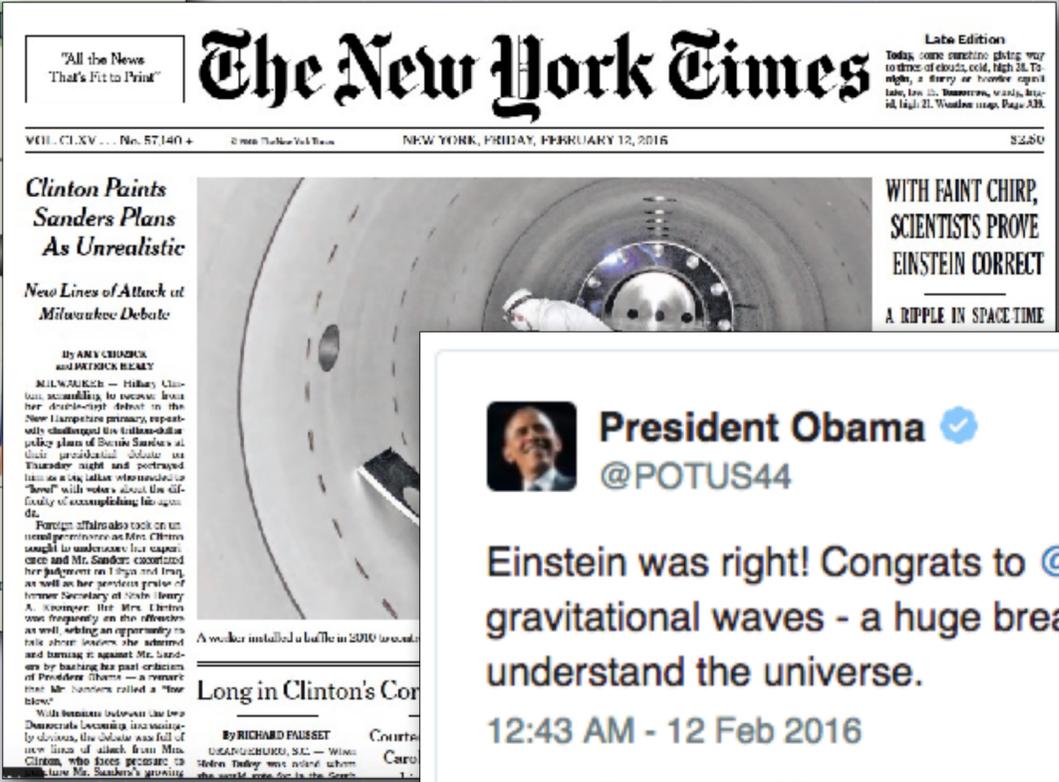
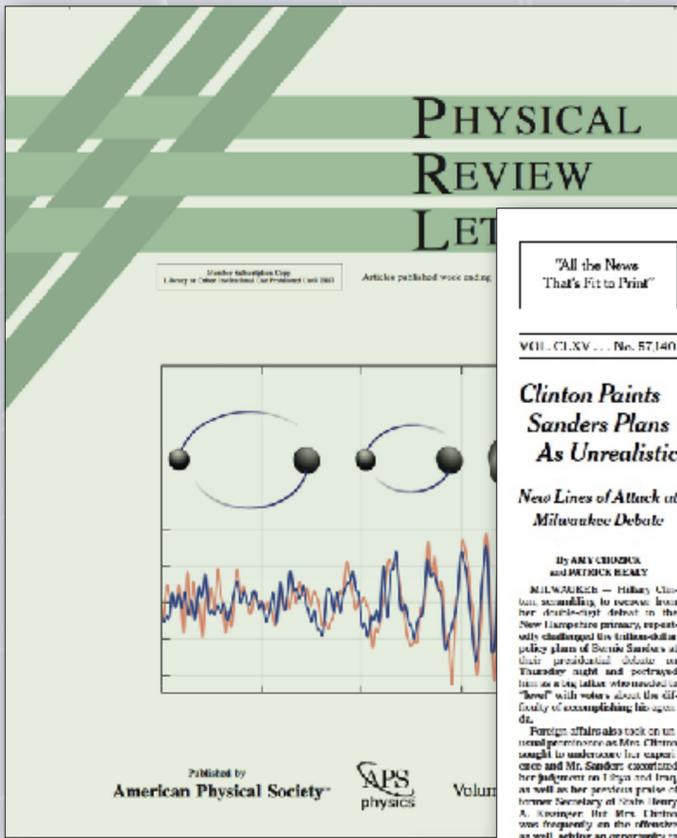
OREGON — A man who has lived in a rural Oregon town for decades was finally persuaded to leave his home after a long and difficult process.



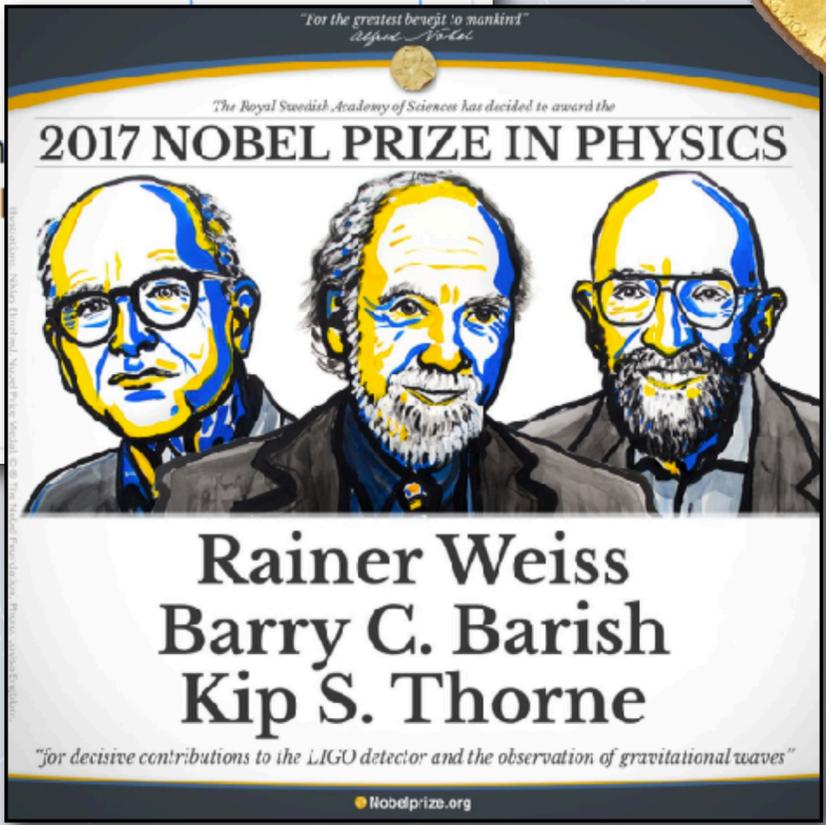
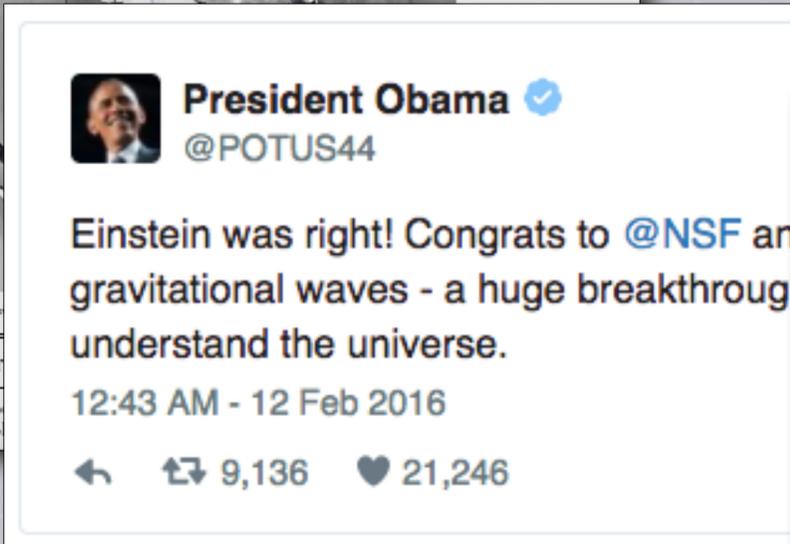
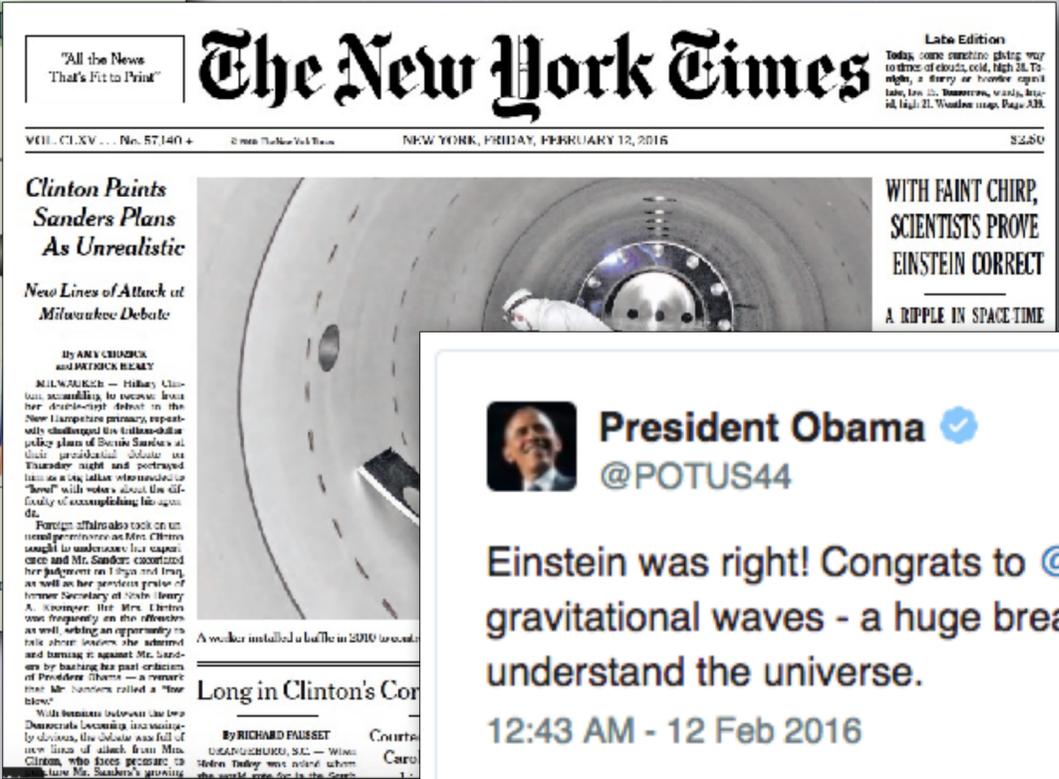
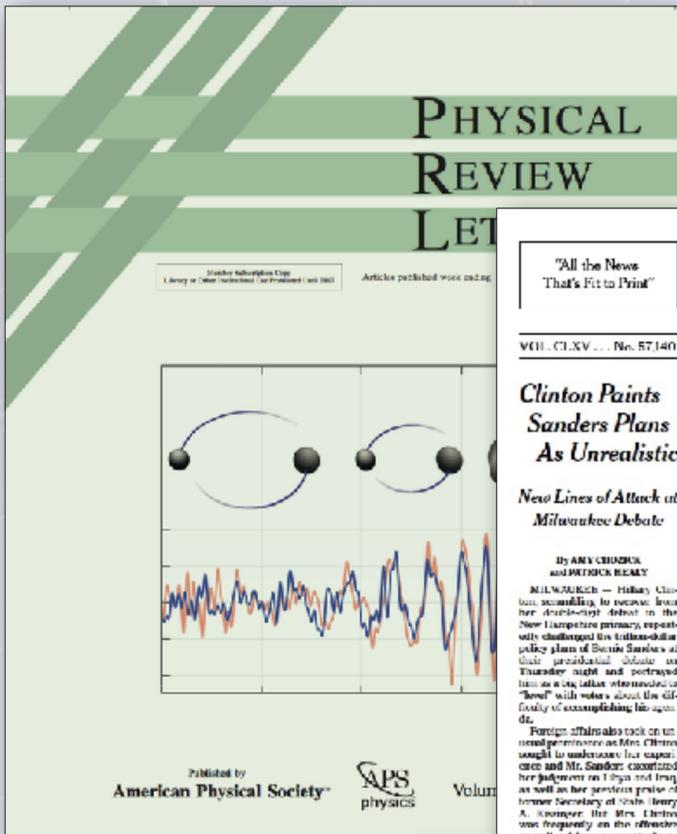
How important are these discoveries?



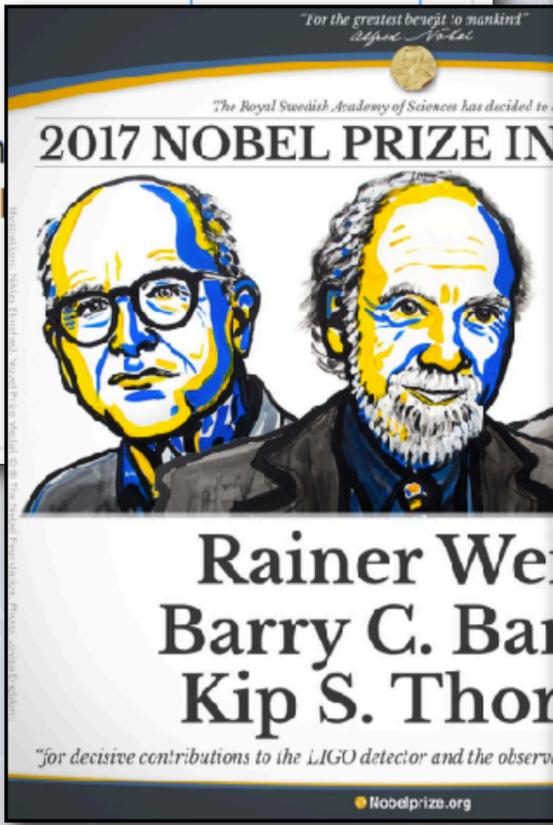
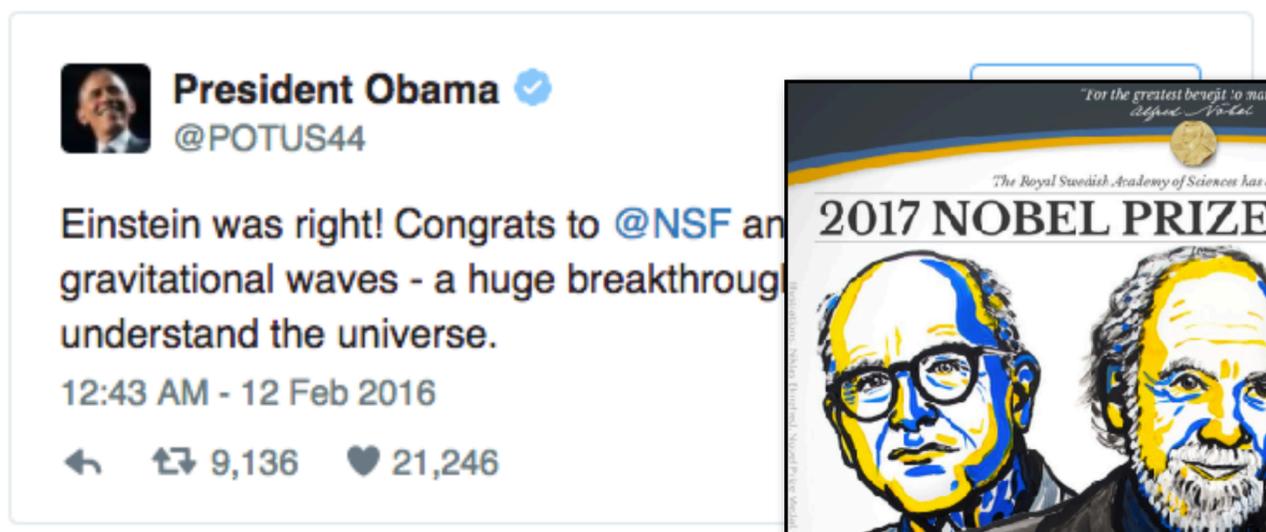
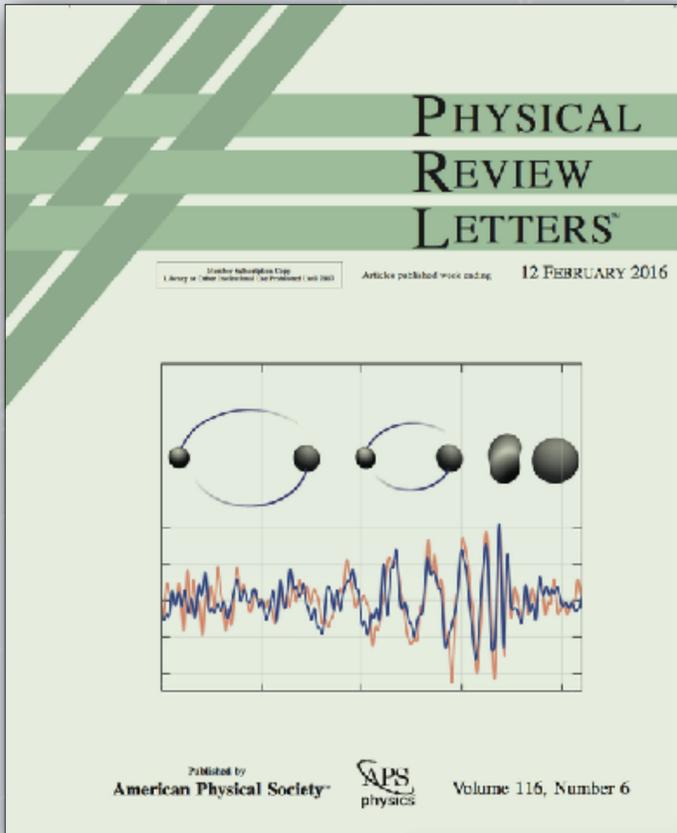
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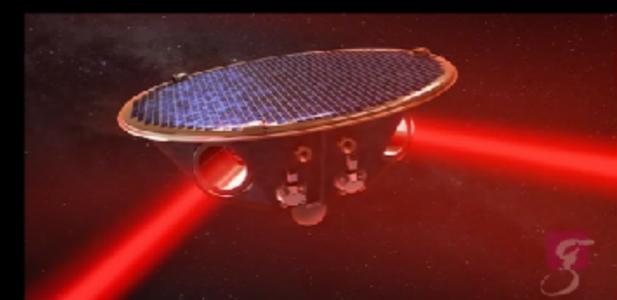
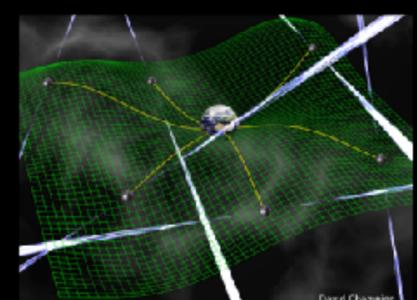
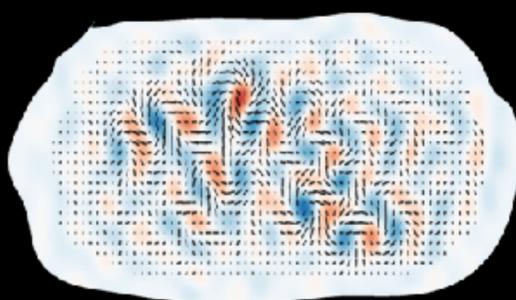
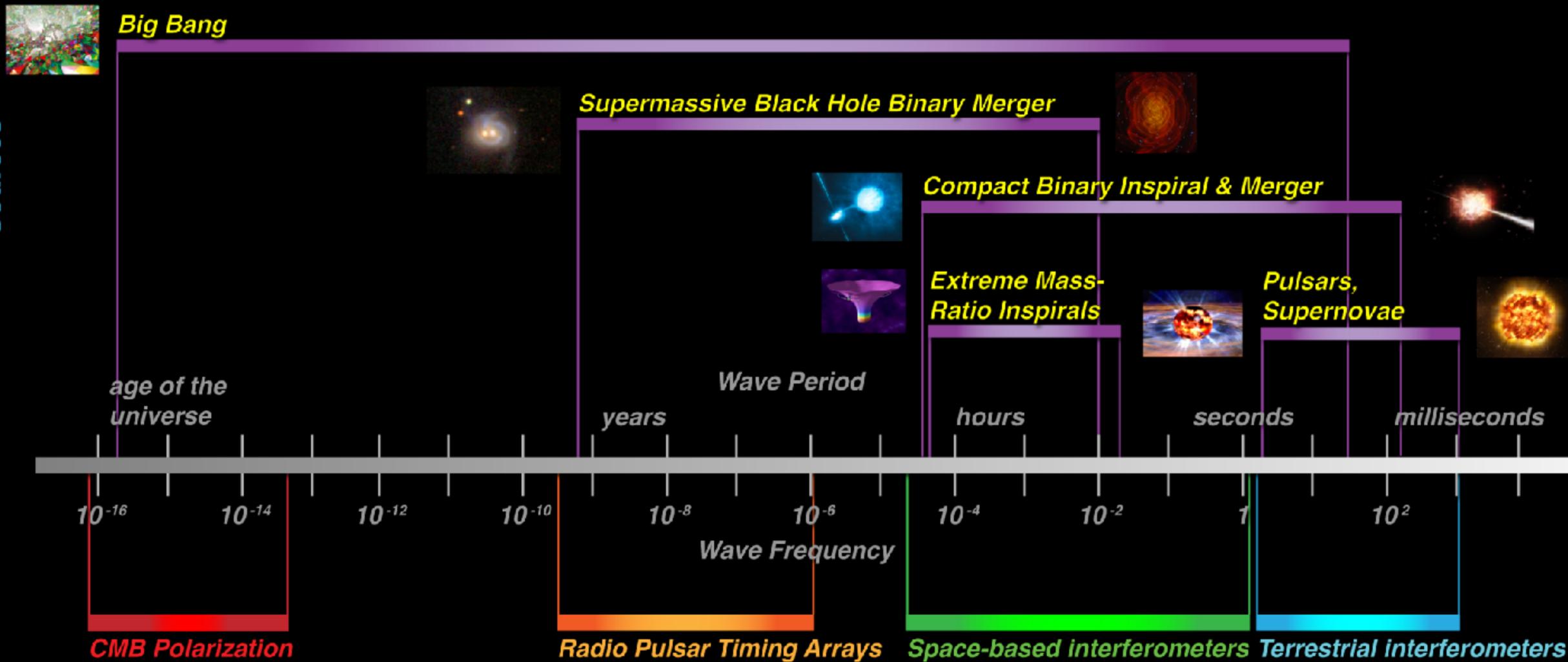


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The Gravitational Wave Spectrum

Sources



$$v_{gw} \downarrow \quad (\lambda_{gw} \uparrow) \quad \Rightarrow \quad L_{armlength} \uparrow$$

What will we learn with LISA?

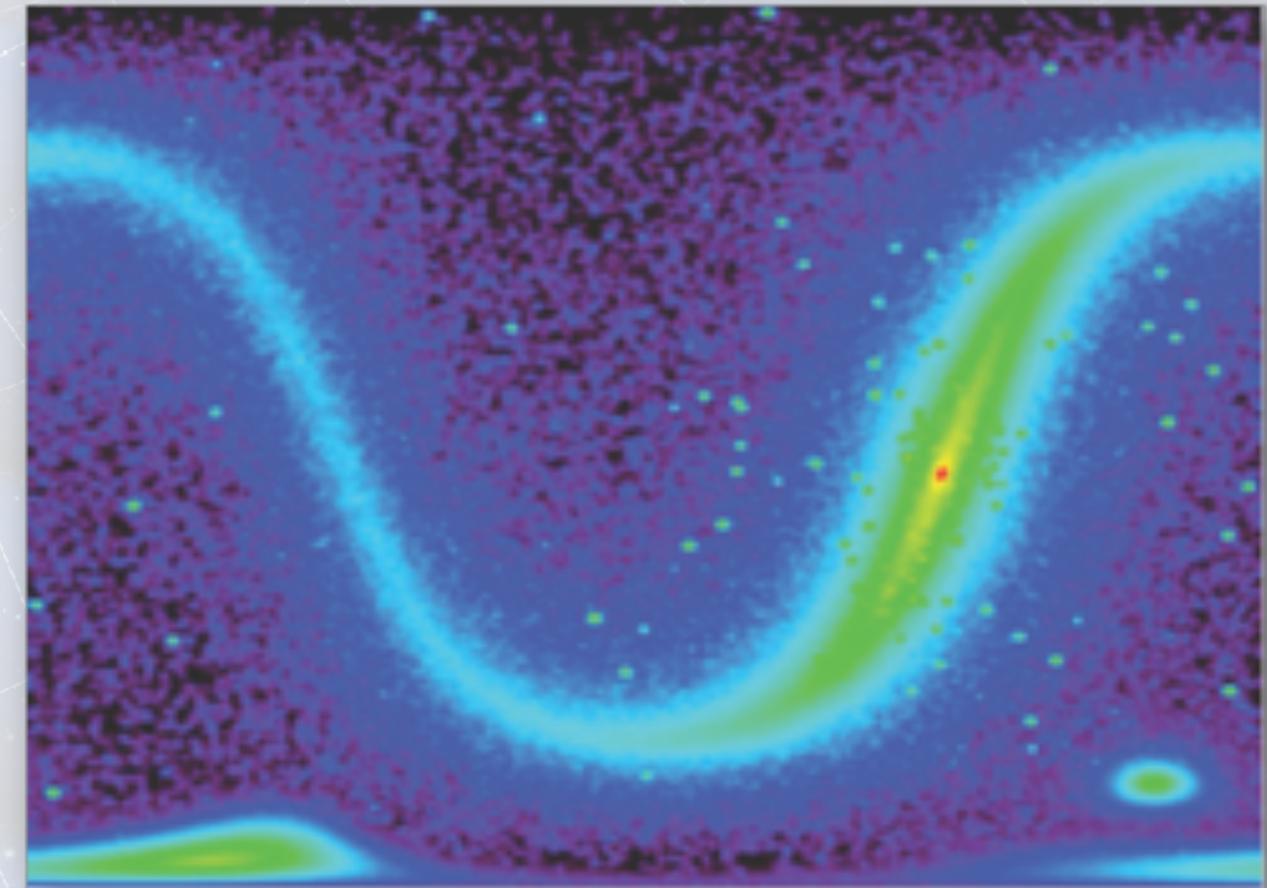
The science objectives of LISA include:

- **Study the formation and evolution of compact binary stars in the Milky Way**

- Compact binaries emit continuous and nearly monochromatic GW signals in the source frame
- Several galactic binaries have already been observed electromagnetically, and will be used as verification sources for the LISA instrument performance
- Galactic binaries will form a confusion noise *foreground* limiting LISA performance at frequencies around 1mHz

- **Objectives:**

- Period precision: $\delta P/P < 10^{-6}$
- Mass, distance and sky location for fraction of GBs, with $d < 15\text{kpc}$
- For $\sim 10,000$ systems, locate to $< 1\text{deg}^2$ to allow EM follow-up



| | Individually Resolved | $\delta P/P < 10^{-6}$ | Sky location for EM counterpart | Sky location for EM c-part + δf |
|-------|-----------------------|------------------------|---------------------------------|-----------------------------------------|
| SciRD | 24,500 | 21,000 | 10,000 | 5,200 |

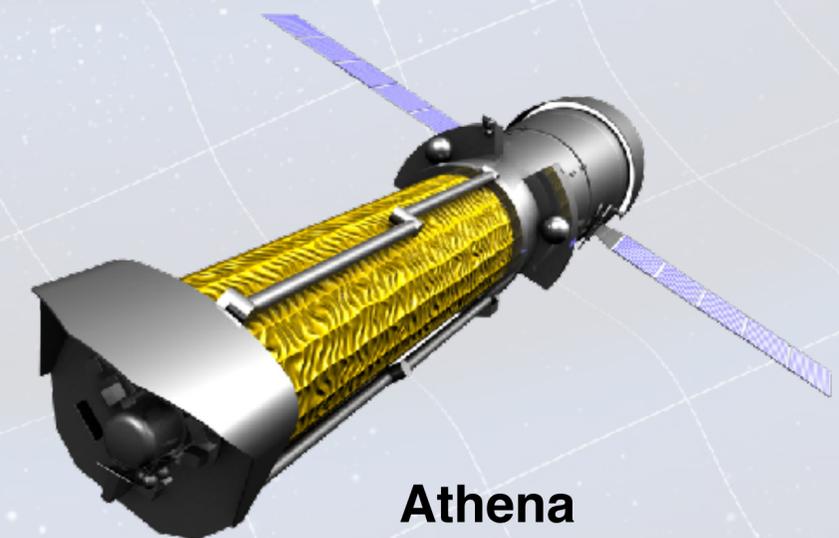
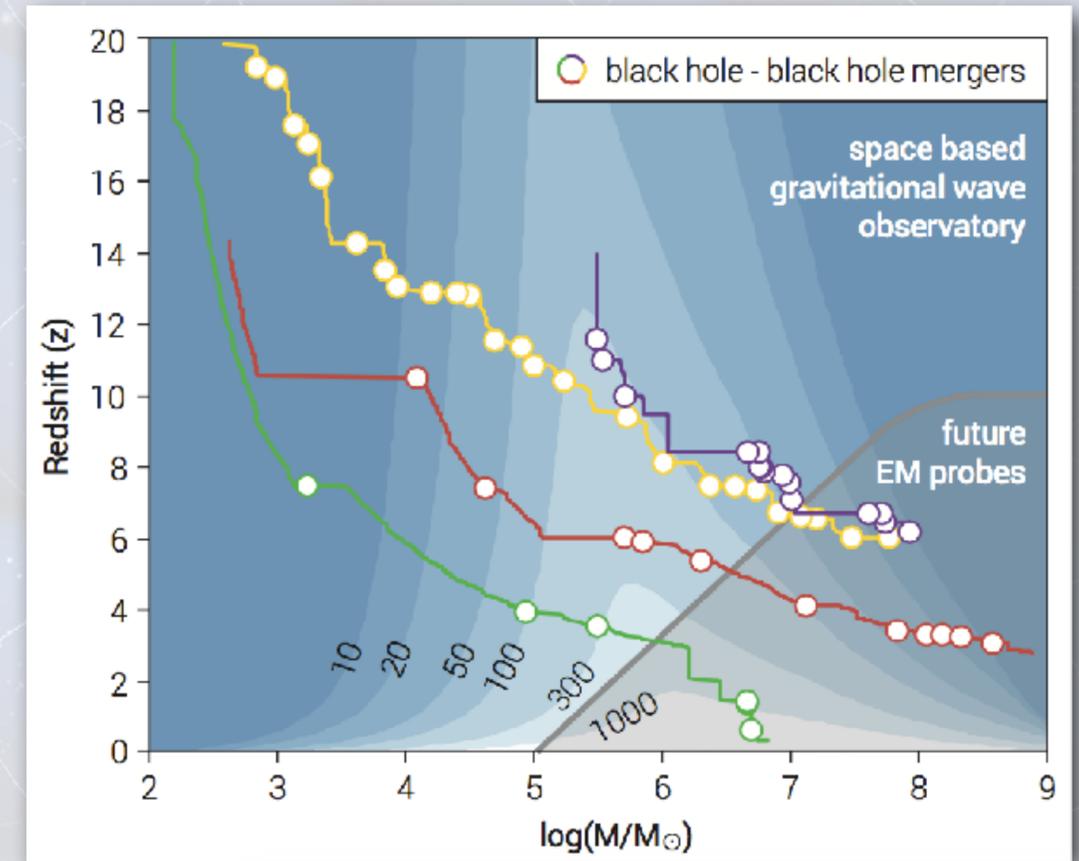
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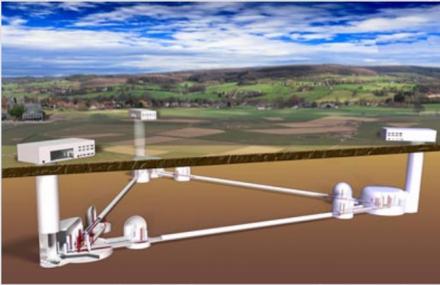
- Study the formation and evolution of compact binary stars in the Milky Way
- **Trace the origin, growth and merger history of massive black holes across cosmic ages**
 - The origin of the massive/supermassive black holes powering AGN and sitting at the centres of today's galaxies is unknown
 - LISA will be able to observe seed black holes back to Cosmic Dawn

Objectives:

- Observe the first compact objects in the Universe (seed black holes) out to $z \sim 15$
- Masses, and distance to Supermassive Black Hole mergers ($10^6 M_{\odot}$) mergers at $z < 9$
 - Masses to 1%, Distance to 10%, Spin to 1-10% precision
- Sky location to $< 10 \text{ deg}^2$ for SMBH mergers at $z \sim 2$ for EM follow-up

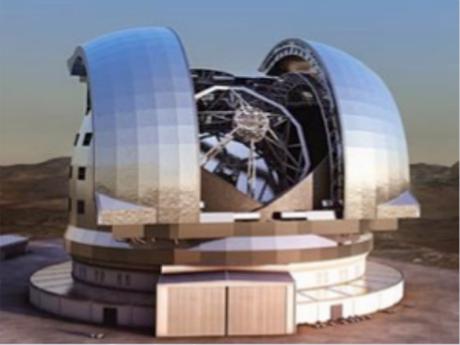
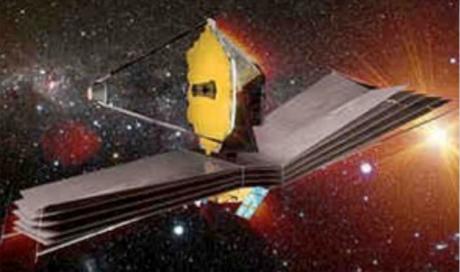
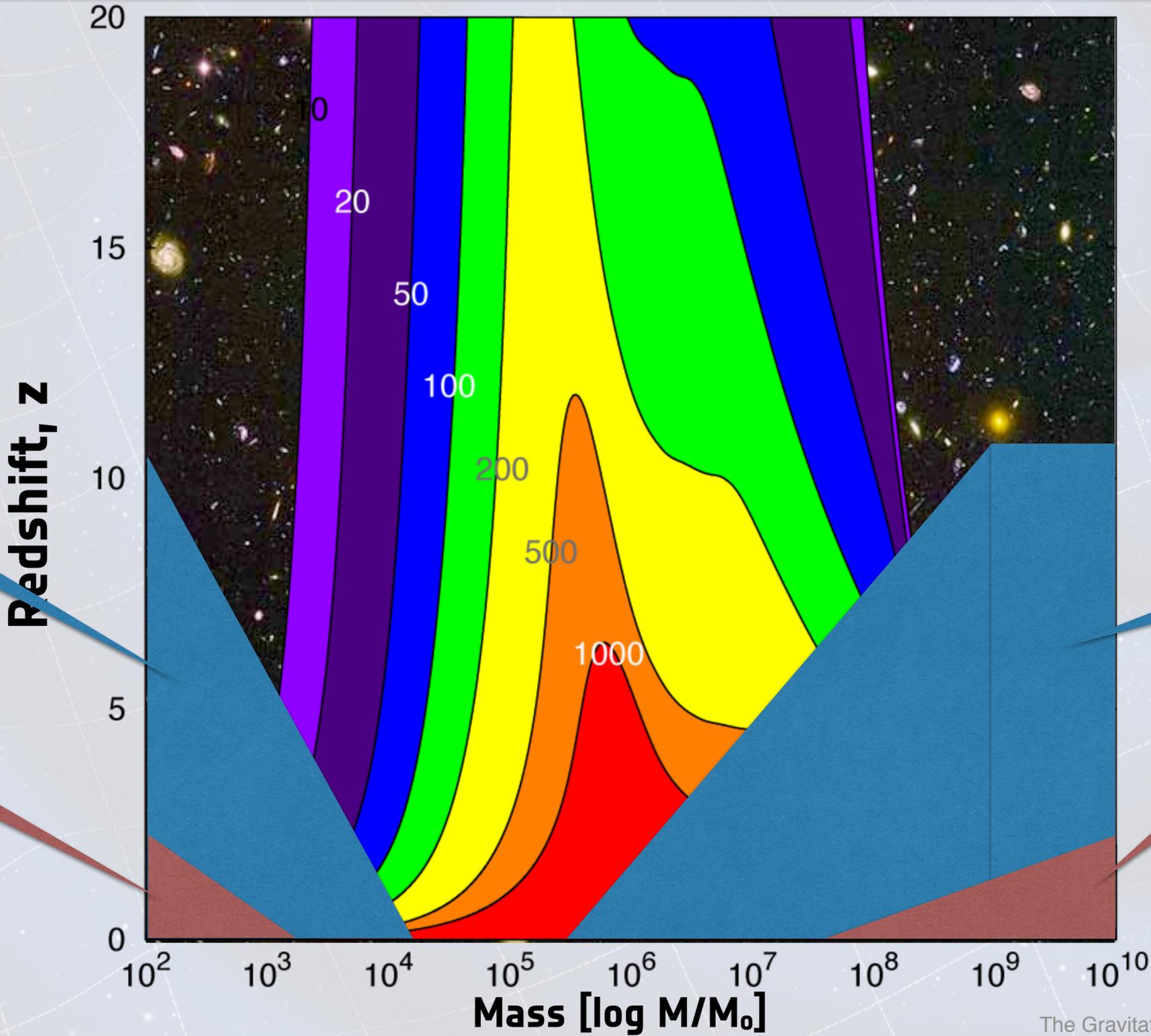


Black Hole Astronomy in the 2030s



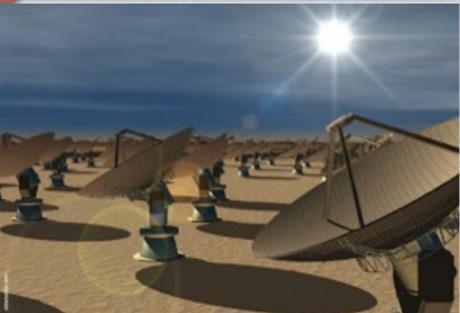
Future ground based detectors e.g. Einstein Telescope

Current ground based GW detectors



Future EM obs. e.g. LSST, JWST, EELT

SKA, Pulsar Timing



What will we learn with LISA?

The science objectives of LISA include:

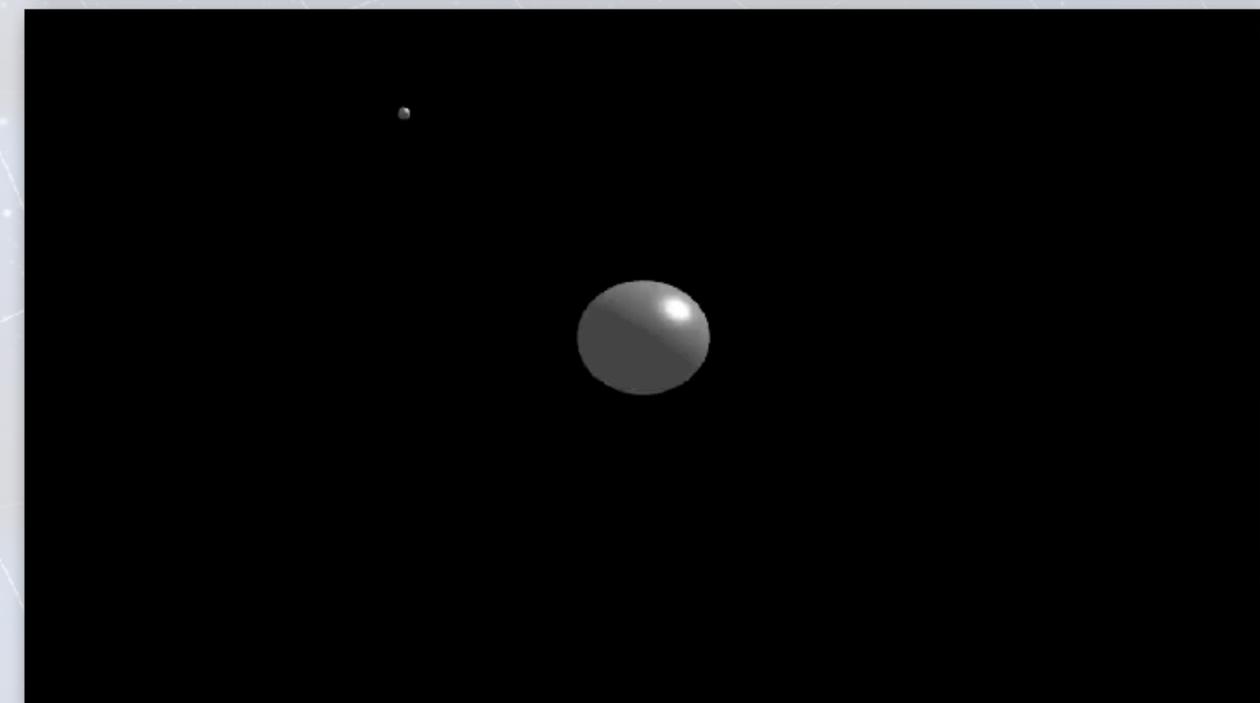
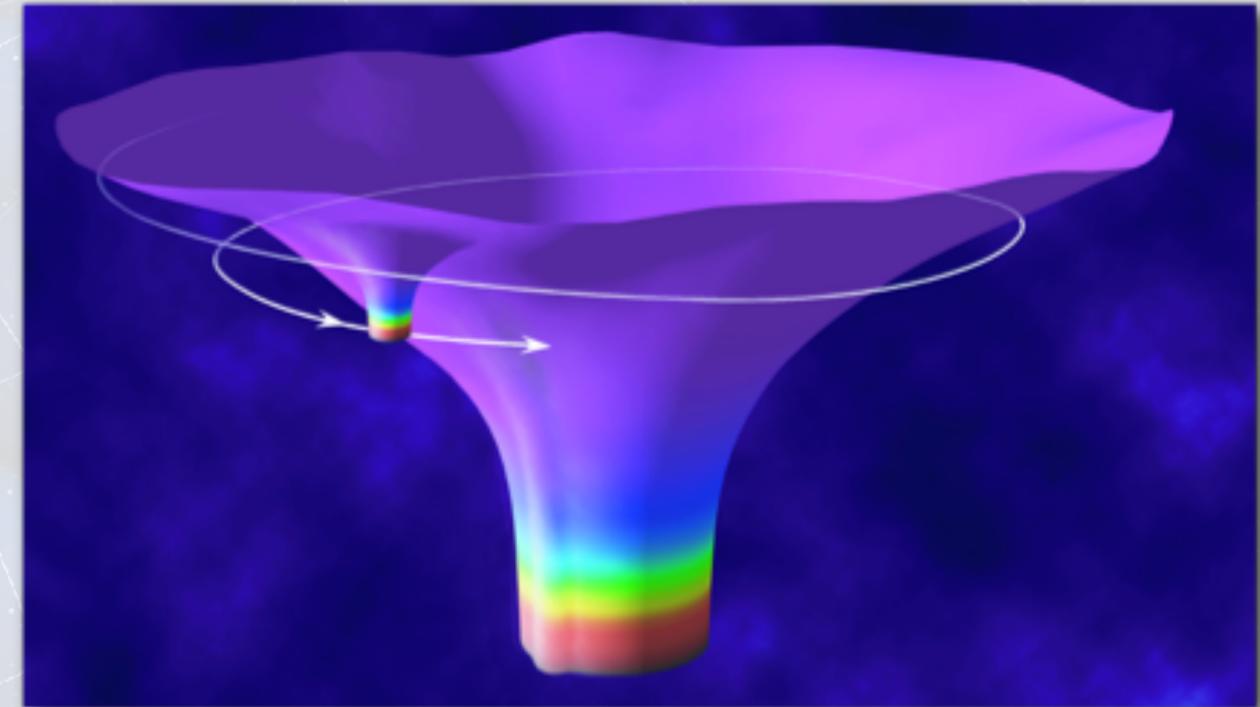
- Study the formation and evolution of compact binary stars in the Milky Way
- Trace the origin, growth and merger history of massive black holes across cosmic ages

- Probe the dynamics of dense nuclear clusters using EMRIs

- EMRIs describe the inspiral and final plunge of Stellar-Origin BH in the range of $10-60M_{\odot}$ into MBH of $10^5-10^6M_{\odot}$
- EMRIs are essentially the perfect laboratory to test GR in the strong field regime
 - The SOBH spends $\sim 10^3-10^5$ orbits in close proximity to the MBH, displaying extreme forms of periastron and orbit plane precession

- Objectives:

- Observation of EMRIs out to $z=4$ with SNR >20
- $\delta M/M < 10^{-4}$, $\delta m/m < 10^{-3}$

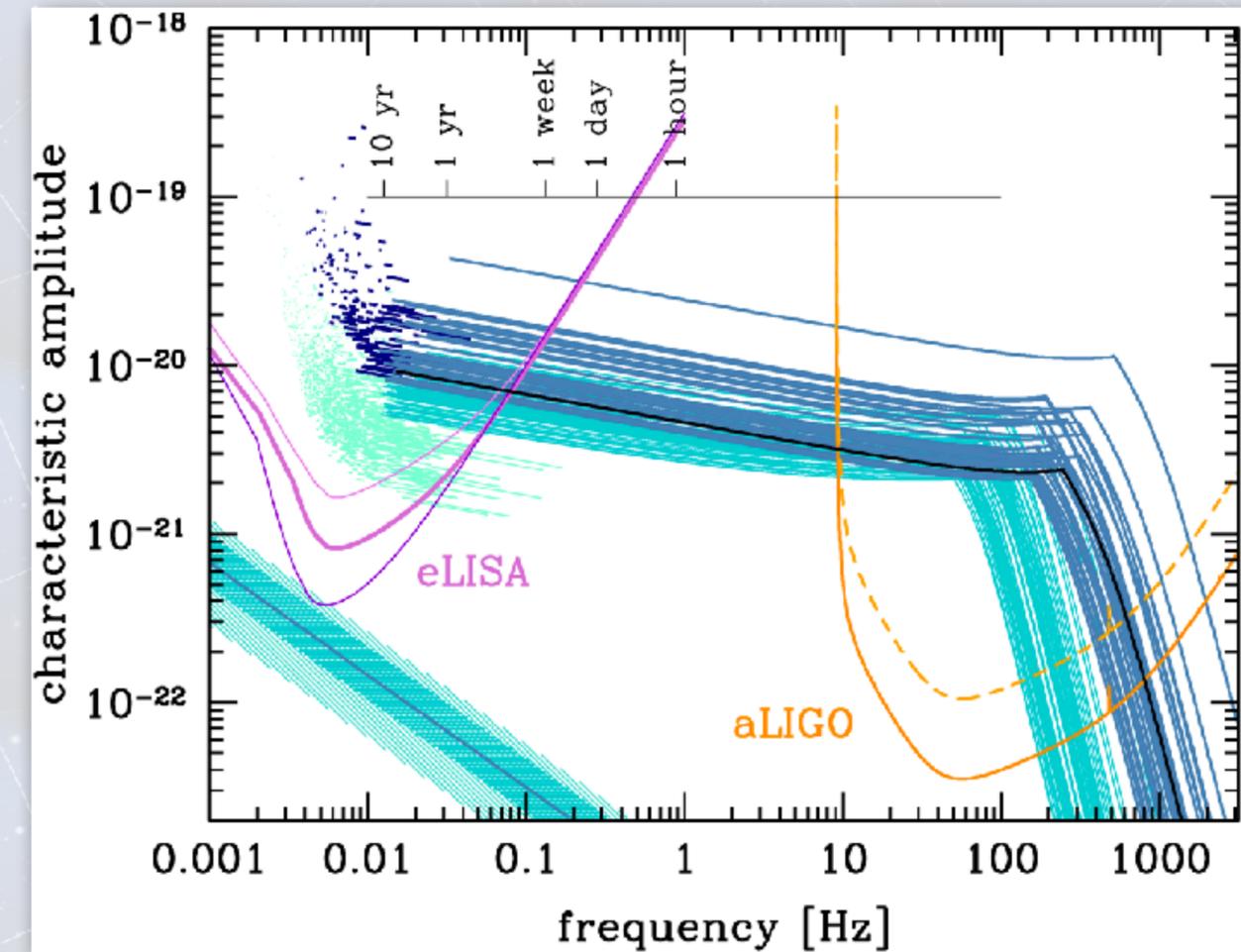


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- Probe the dynamics of dense nuclear clusters using EMRIs
- **Understand the astrophysics of stellar origin black holes**
 - As the SOBH inspiral towards final merger, the gravitational wave signal will *sweep* through the LISA band
 - LISA will observe the inspiral or months to years prior to merger
 - The signal will leave the LISA band weeks before final merger
- **Objectives:**
 - Sky location of $<1\text{deg}^2$ of GW150914-like events (SNR >7 after 3 years integration)
 - Orbit eccentricity to better than 1 part in 10^3

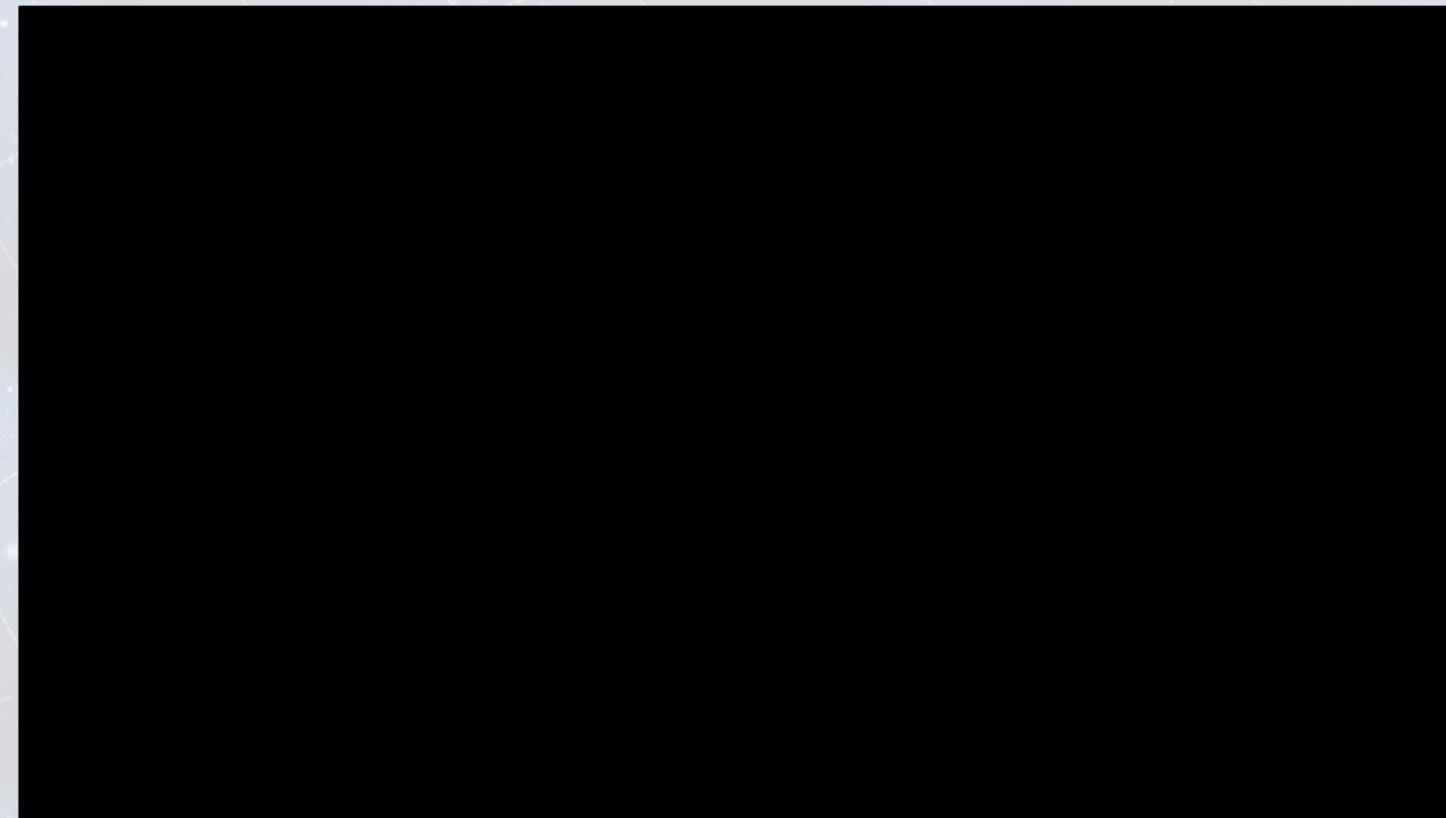


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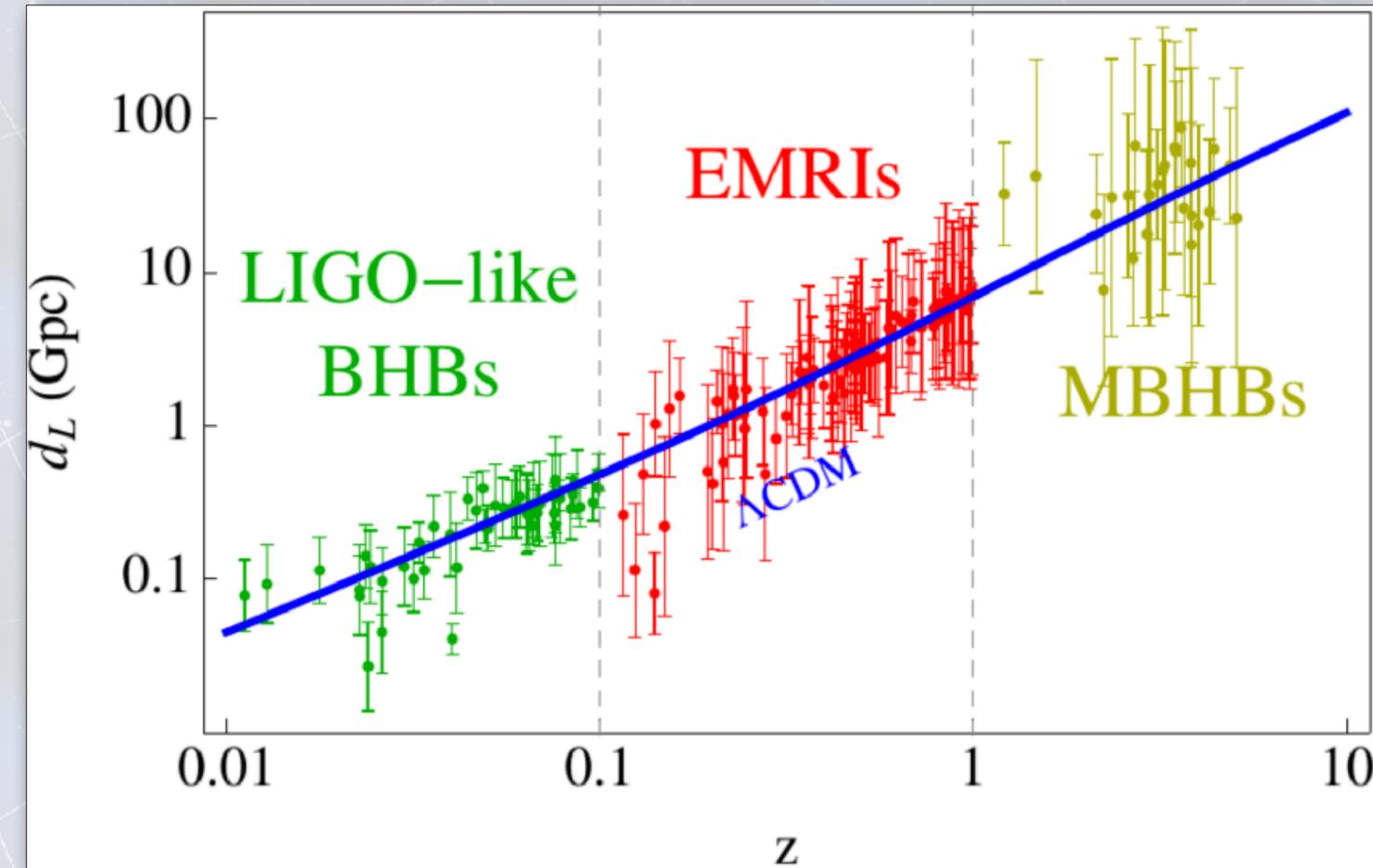
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- Probe the dynamics of dense nuclear clusters using EMRIs
- Understand the astrophysics of stellar origin black holes
- **Explore the fundamental nature of gravity and black holes**
 - SMBH binaries and EMRIs enable tests of GR in the strong field regime
 - Precision tests require *Golden binaries* with SNR >100 (SMBHB) or >50 (EMRIs)
- **Objectives:**
 - Test “no-hair” theorem of GR
 - Explore multipolar structure of MBH



Earth's geoid as measured by GOCE

• The science objectives of LISA include::

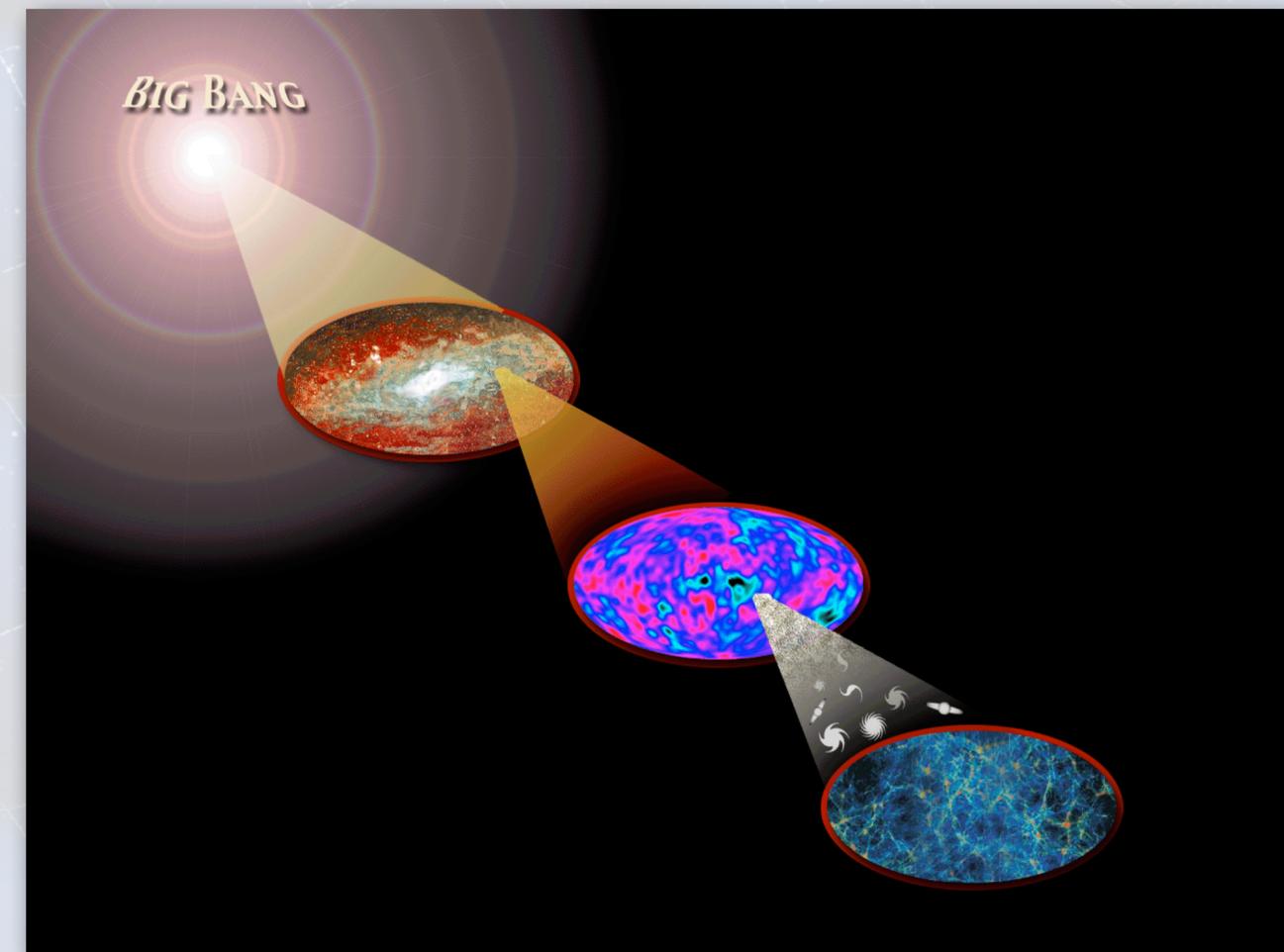
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- Explore the fundamental nature of gravity and black holes
- **Probe the rate of expansion of the Universe**
 - Source distance is proportional to GW amplitude, chirp rate, and GW polarisation
 - GW sirens: EMRIs ($z < 1.5$), SMBHB ($z < 6$)
- **Objectives:**
 - H_0 with accuracy of $< 1\%$ with only GW observations
 - Improved if we also observe the source e.g. with Athena



What will we learn with LISA?

The science objectives of LISA include::

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- Probe the rate of expansion of the Universe
- **Understand stochastic GW backgrounds and their implications for the early Universe**
 - LISA goal is to directly detect a stochastic GW background of cosmological origin
 - The shape of the signal gives an indication of its origin, while an upper limit constrains models of the early universe



What will we learn with LISA?

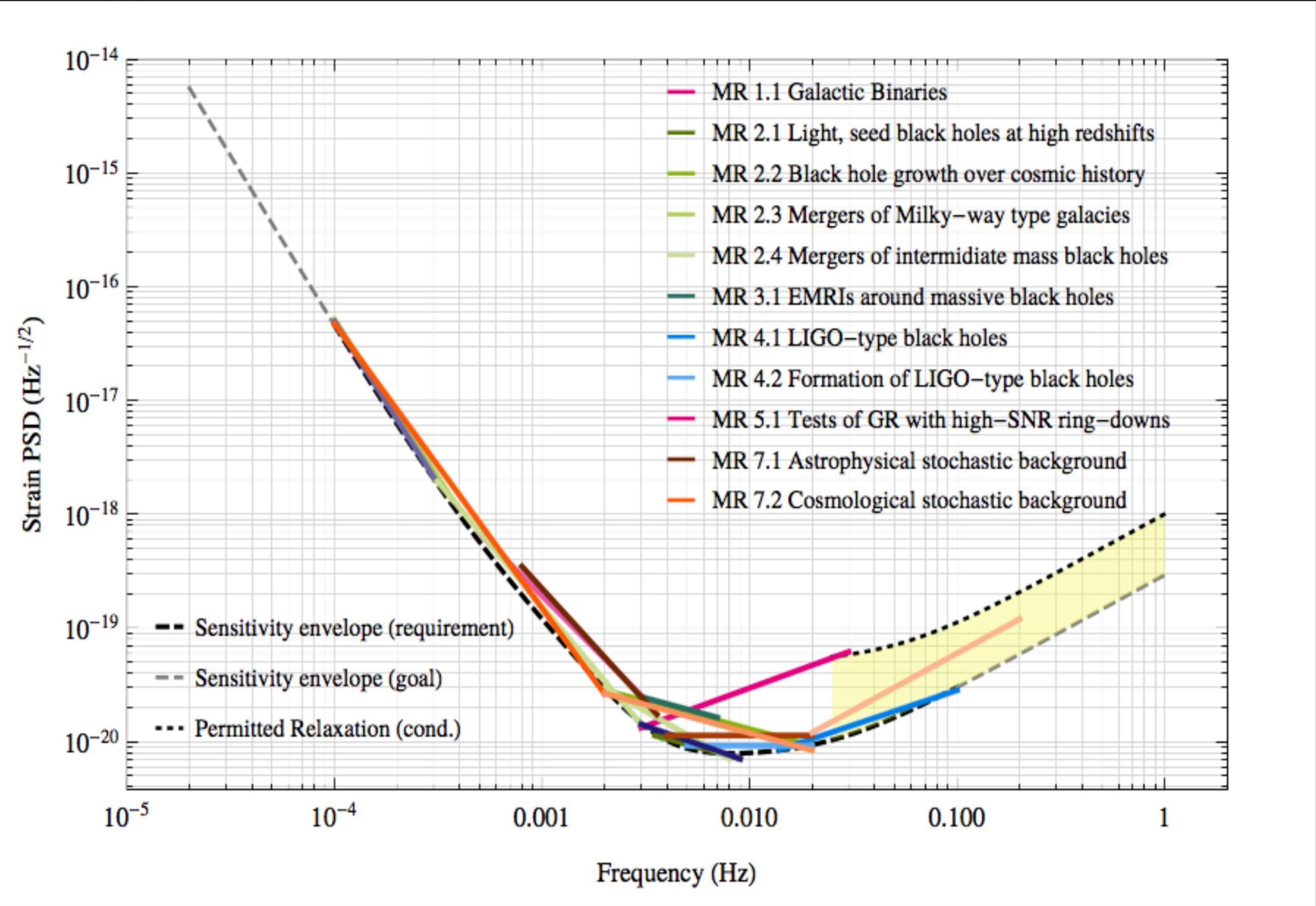


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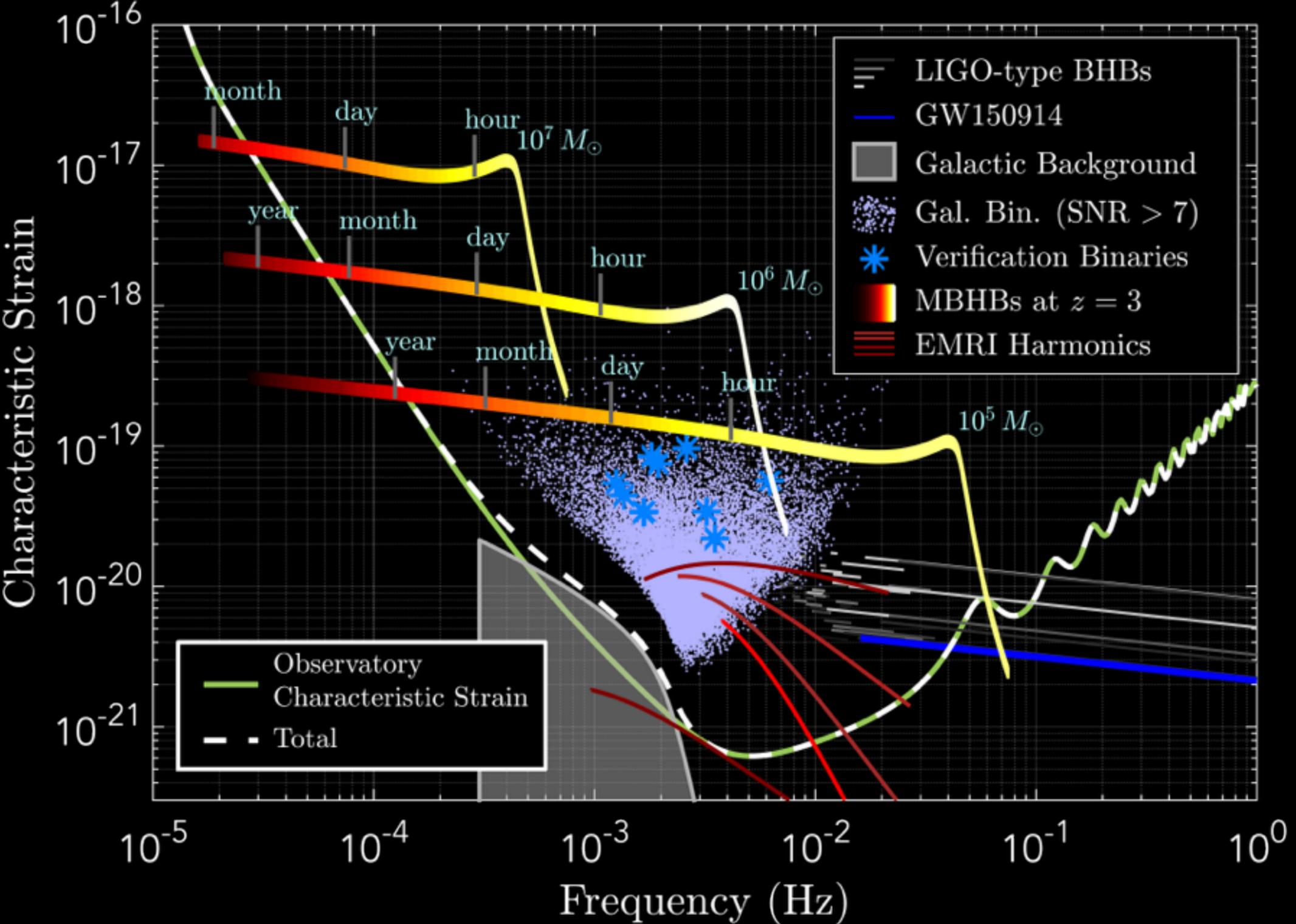
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- Probe the rate of expansion of the Universe
- Understand stochastic GW backgrounds and their implications for the early Universe
- **Search for GW bursts and unforeseen sources**
 - First LIGO observations came from unexpected sources...
...what will LISA see?



LISA discovery space



LISA discovery space





1st International LISA Symposium
Rutherford Appleton Laboratory
1996

THE GRAVITATIONAL UNIVERSE

A science theme addressed by the eLISA mission observing the entire Universe

The first century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the mammals of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetism: radiation at our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any other means. Gravity has its own messengers: Gravitational waves, ripples in the fabric of spacetime. They travel essentially unimpeded and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as $z = 20$, prior to the epoch of cosmic re-ionization. Squelch and unprecedented measurements of black hole masses and spins will make it possible to trace the history of black holes across all stages of galaxy evolution, and at the same time constrain any deviation from the core tenets of General Relativity. eLISA will be the first ever mission to study the entire Universe with gravitational waves. eLISA is an all-sky monitor and will offer a unique view of a dynamic cosmos using gravitational waves as new and unique messengers to unveil The Gravitational Universe. It provides the deepest ever view of the early processes at TeV energies, the gamma-ray sources in the form of vermillion binaries in the Milky Way, and can probe the entire Universe, from its smallest scales around singularities and black holes, all the way to cosmological dimensions.

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Fax: +49 511 762 2784

Detailed information at
<http://elisa.science.org/whitepaper>

L3 - Gravitational Universe Science Theme (May 2013)

SPC, SSAC, Working Groups and Scientific Community

Our ref.: D/SCC/LC/agr/090

Paris, 25 October 2016

Dear Colleague,

I would like to announce the release of the "Call for mission concepts for the Large-size "L3" mission in ESA's Science Programme", which follows on the selection by the Science Programme Committee in November 2013 of the "The Gravitational Universe" science theme for the L3 launch opportunity, to be pursued by implementing a Gravitational Wave Observatory with a planned launch date of 2034.

Responses to this Call are due by 16 January 2017, at 12:00 (noon) Central European Time. All information about the Call's scope, the proposal format, points of contact, etc. can be found in the Call itself, available at <http://www.cosmos.esa.int/web/2016-l3-mission-call>

Please note that submission of a Letter of Intent is mandatory, with a deadline of 15 November 2016 (12:00 noon CET).

Your sincerely,

Prof. Alvaro Giménez
Director of Science

European Space Agency
Agence spatiale européenne

Call for mission to meet L3 Science Theme (October 2016)

LISA

Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Lead Proposer
Prof. Dr. Karsten Danzmann

LISA Proposal (January 2017)

cosmic vision

ESA SCIENCE & TECHNOLOGY COSMIC VISION

Missions

- Show All Missions
- Cosmic Vision 2015-2025
- Cosmic Vision
- Candidate Missions
- Mission Timeline
- Leaders Timeline
- Missions of Opportunity

Cosmic Vision theme

- The Hot and Warm Universe
- The Gravitational Universe
- Planets and Life
- The Solar System
- Human and Earth
- The Universe

Small mission

- CHEOPS (S1)
- SMILE (S2)

Medium mission

- Solar Orbiter (M1)
- Euclid (M2)
- PLATO (M3)

Large mission

- JUICE (L1)
- Athena (L2)
- LISA (L3)

Previous candidate missions

- Cross-Goal

GRAVITATIONAL WAVE MISSION SELECTED, PLANET-HUNTING MISSION MOVES FORWARD

20 June 2017

The LISA trio of satellites to detect gravitational waves from space has been selected as the third large-class mission in ESA's Science programme, while the PLATO exoplanet hunter moves into development.

These important milestones were decided upon during a meeting of ESA's Science Programme Committee today, and ensure the continuation of ESA's Cosmic Vision plan through the next two decades.

The "gravitational universe" was identified in 2013 as the theme for the third large-class mission, L3, searching for ripples in the fabric of spacetime created by celestial objects with very strong gravity, such as pairs of merging black holes.

Predicted a century ago by Albert Einstein's general theory of relativity, gravitational waves remained elusive until their first direct detection by the ground-based Laser Interferometer Gravitational Wave Observatory in September 2015. That signal was triggered by the merging of two black holes some 1.3 billion light-years away. Since then, two more events have been detected.

Furthermore, ESA's LISA Pathfinder mission has also now demonstrated key technologies needed to detect gravitational waves from space. This includes free-falling test masses linked by laser and isolated from all external and internal forces except gravity, a requirement to measure any possible distortion caused by a passing gravitational wave.

The distortion affects the fabric of spacetime on the minuscule scale of a few millionths of a millionth of a metre over a distance of a million kilometres and so must be measured extremely precisely.

LISA Pathfinder will conclude its pioneering mission at the end of this month, and LISA, the Laser Interferometer Space Antenna, also an international collaboration, will now enter a more detailed phase of study. Three craft, separated by 2.5 million km in a triangular formation, will follow Earth in its orbit around the Sun.

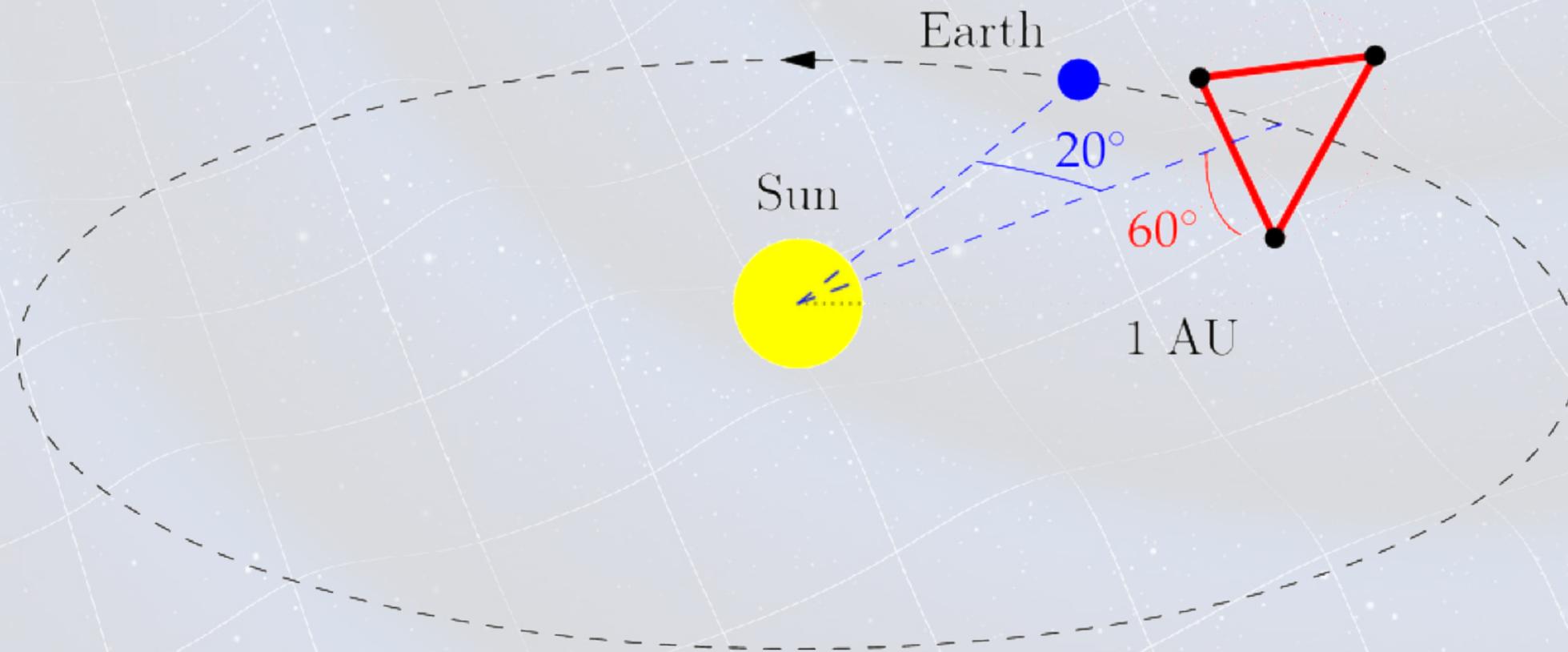
Following selection, the mission design and costing can be completed. Then it will be proposed for adoption before construction begins. Launch is expected in 2034.

Merging black holes. Credit: ESA/CC. Carreau

LISA concept. Credit: ARM/Eds. Moring/Exozet

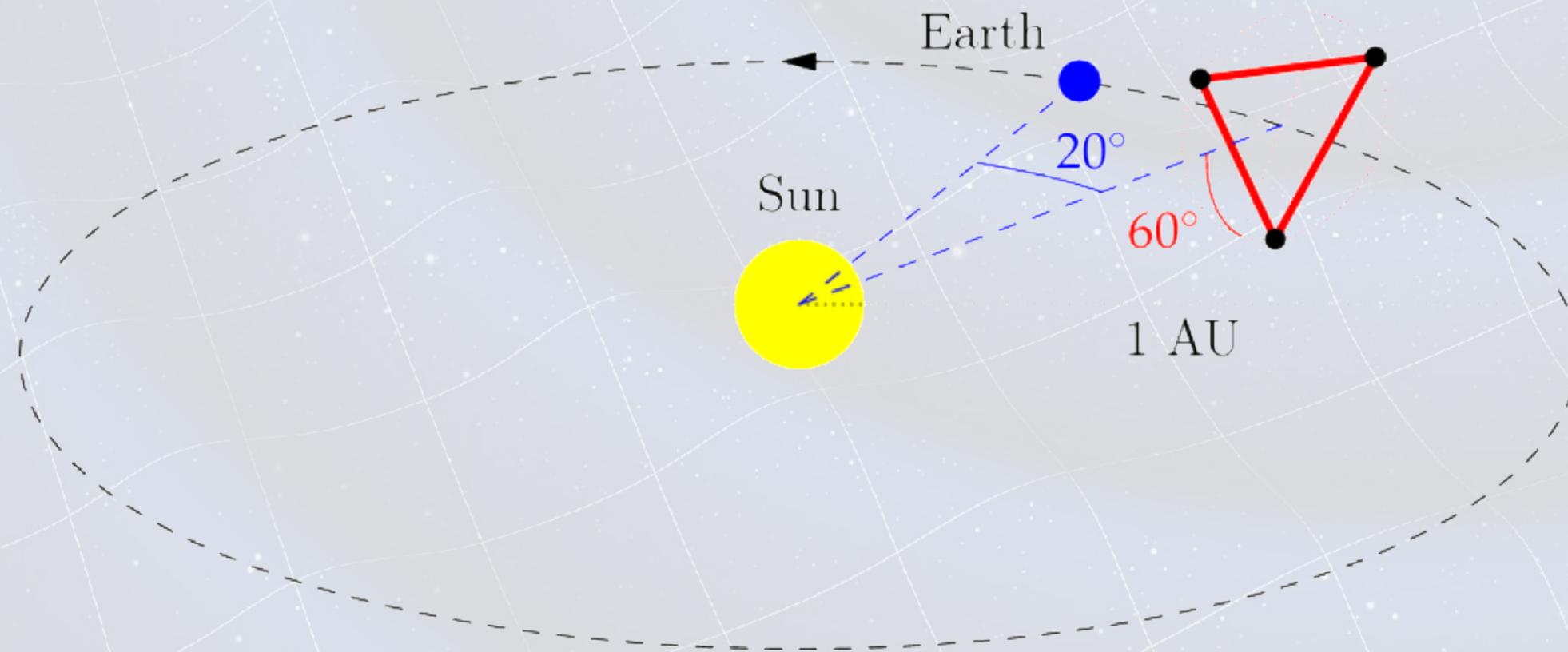
LISA Selected as L3 mission (June 2017)

- Cluster of 3 spacecraft in a heliocentric orbit
 - 3 coupled “Michelson-like” interferometers in space
 - Allows measurement of amplitude and polarisation of GW
 - Spacecraft shield the test masses from external forces (solar wind, radiation pressure)



LISA Mission Concept

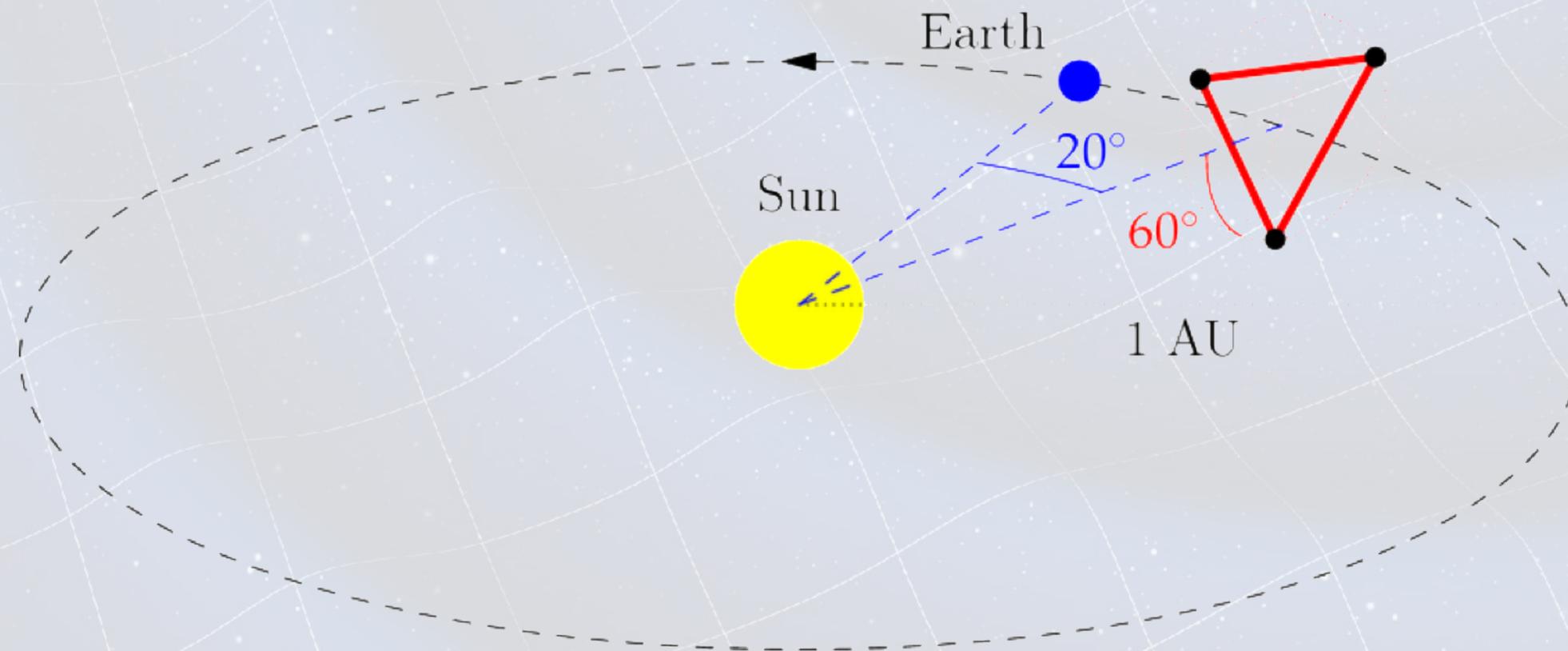
- Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by $\sim 20^\circ$ (50 million km)
 - Reducing the influence of the Earth-Moon system on the orbits
 - Keeping the communication requirements (relatively) standard



LISA Mission Concept

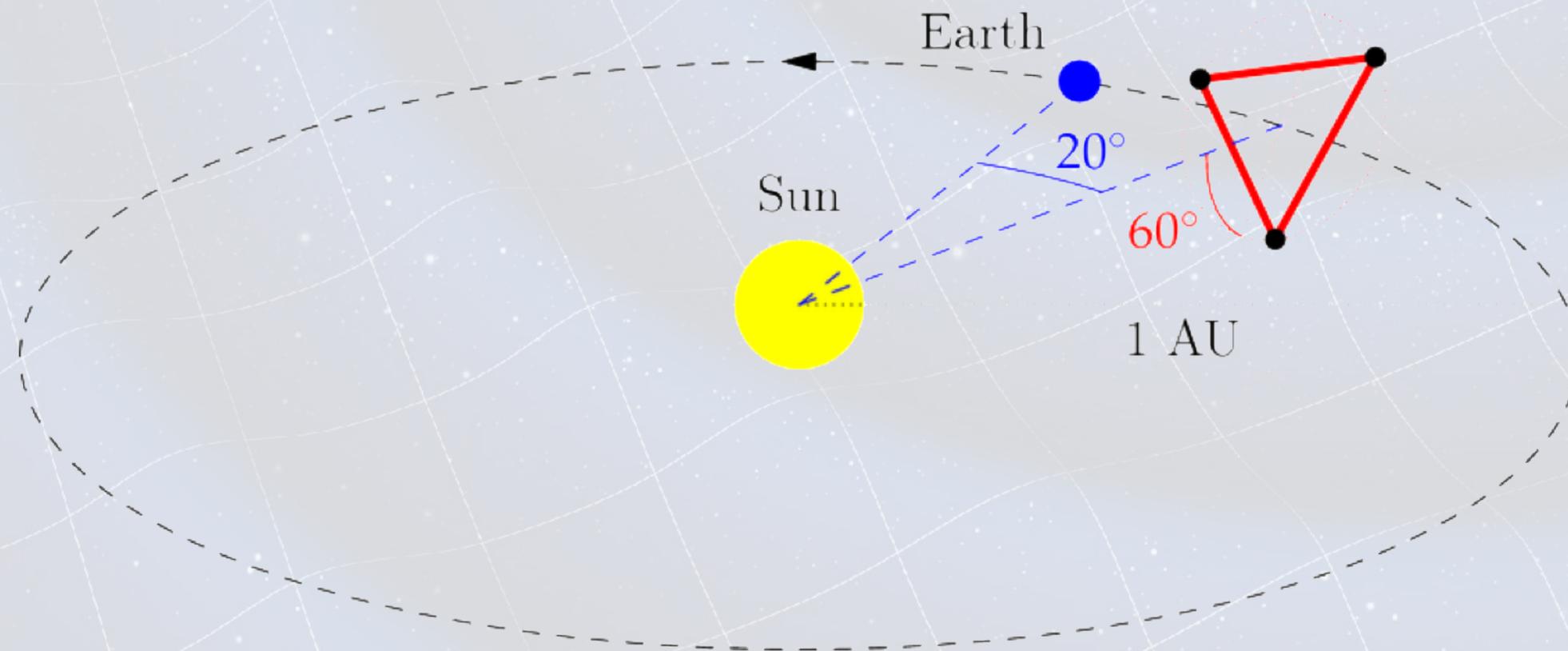


- Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by $\sim 20^\circ$ (50 million km)
- Equilateral triangle with 2.5 million km arm length
 - Results in measurable pathlength variations due to passage of GW
 - Orbit is stable enough to allow for mission duration of 10 years without active orbit maintenance



LISA Mission Concept

- Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by $\sim 20^\circ$ (50 million km)
- Equilateral triangle with 2.5 million km arm length
- Inclined with respect to ecliptic plane by 60°
 - Required by orbital mechanics



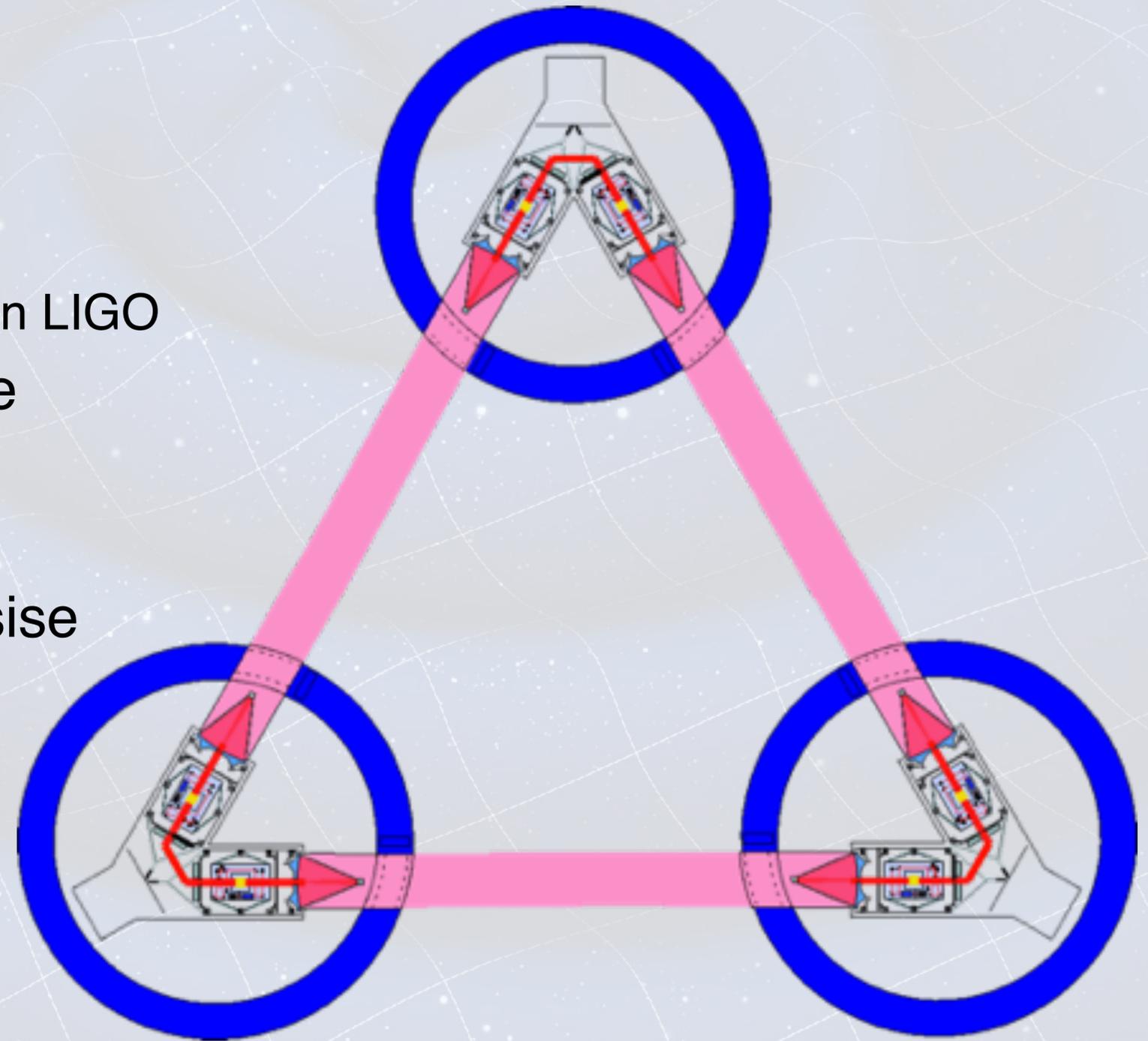
The LISA Orbit



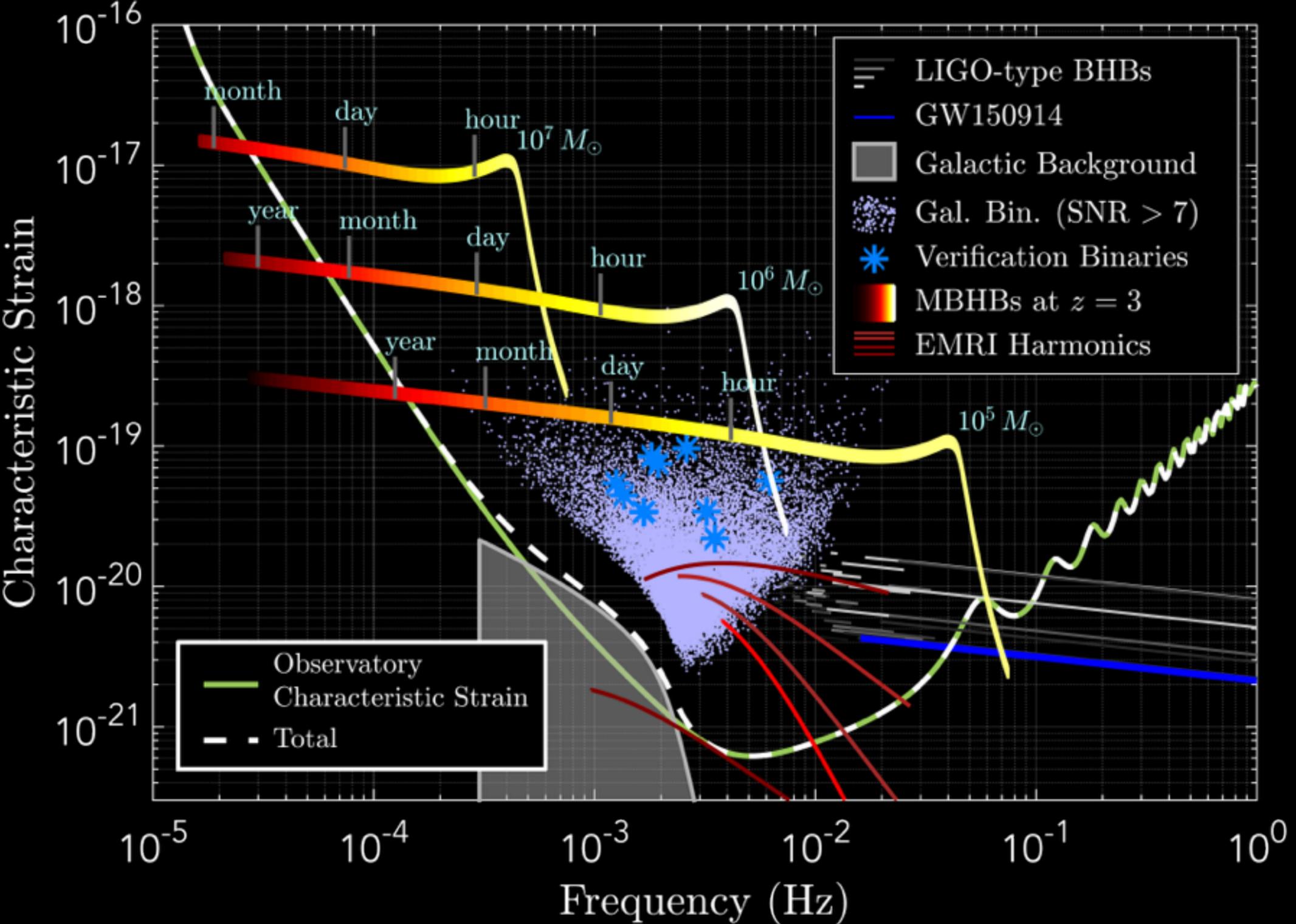
- Constellation counter-rotates during the course of the year
- No additional orbit control necessary
- Constellation forms an “almost rigid” triangle



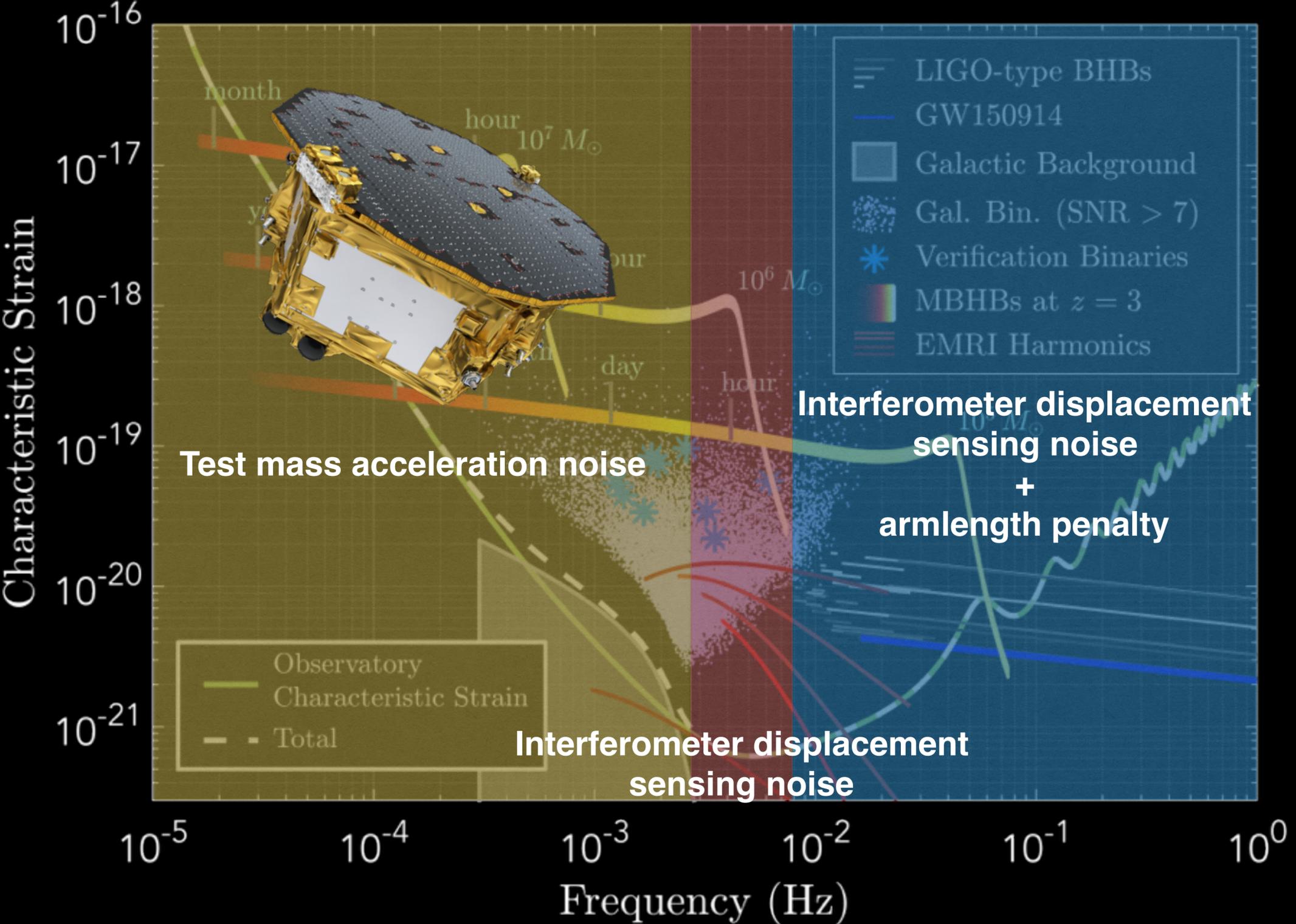
- Laser beams transmitted through 30cm off-axis telescopes
- Diffraction widens beam to several kilometres
 - ~1.5W transmitted, ~500pW received
 - LISA cannot form Fabry-Perot cavities in the arms as in LIGO
- 12 separate interferometric measurements made
 - 6 armlengths
 - 6 test mass -> spacecraft
- Time-Delay Interferometry (TDI) used to synthesise equal arm interferometer (ala LIGO)
- 3 semi-independent Michelson interferometers
 - Constellation also provides Sagnac interferometer
- Orbital motion provides direction information



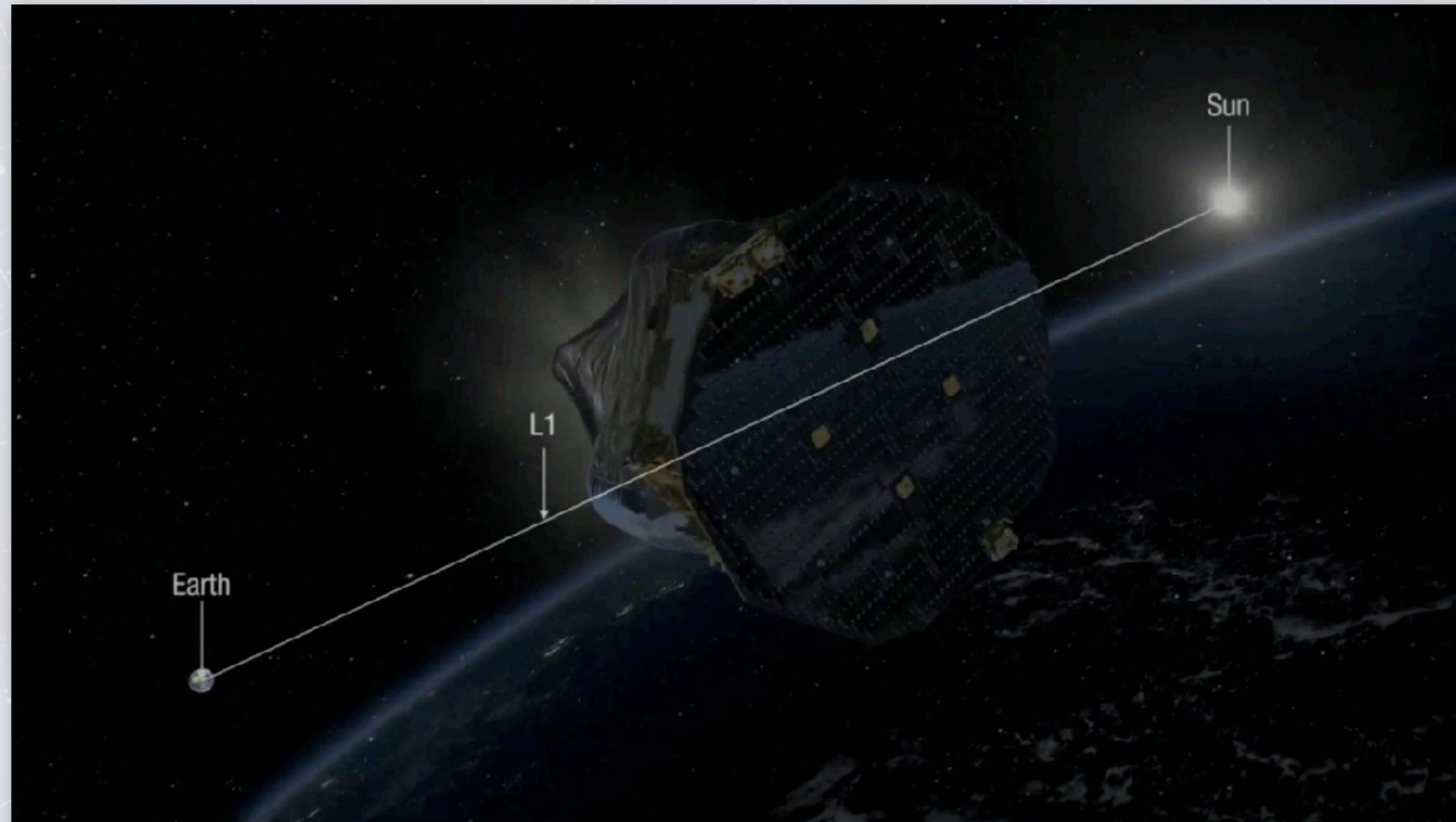
LISA Sensitivity Curve



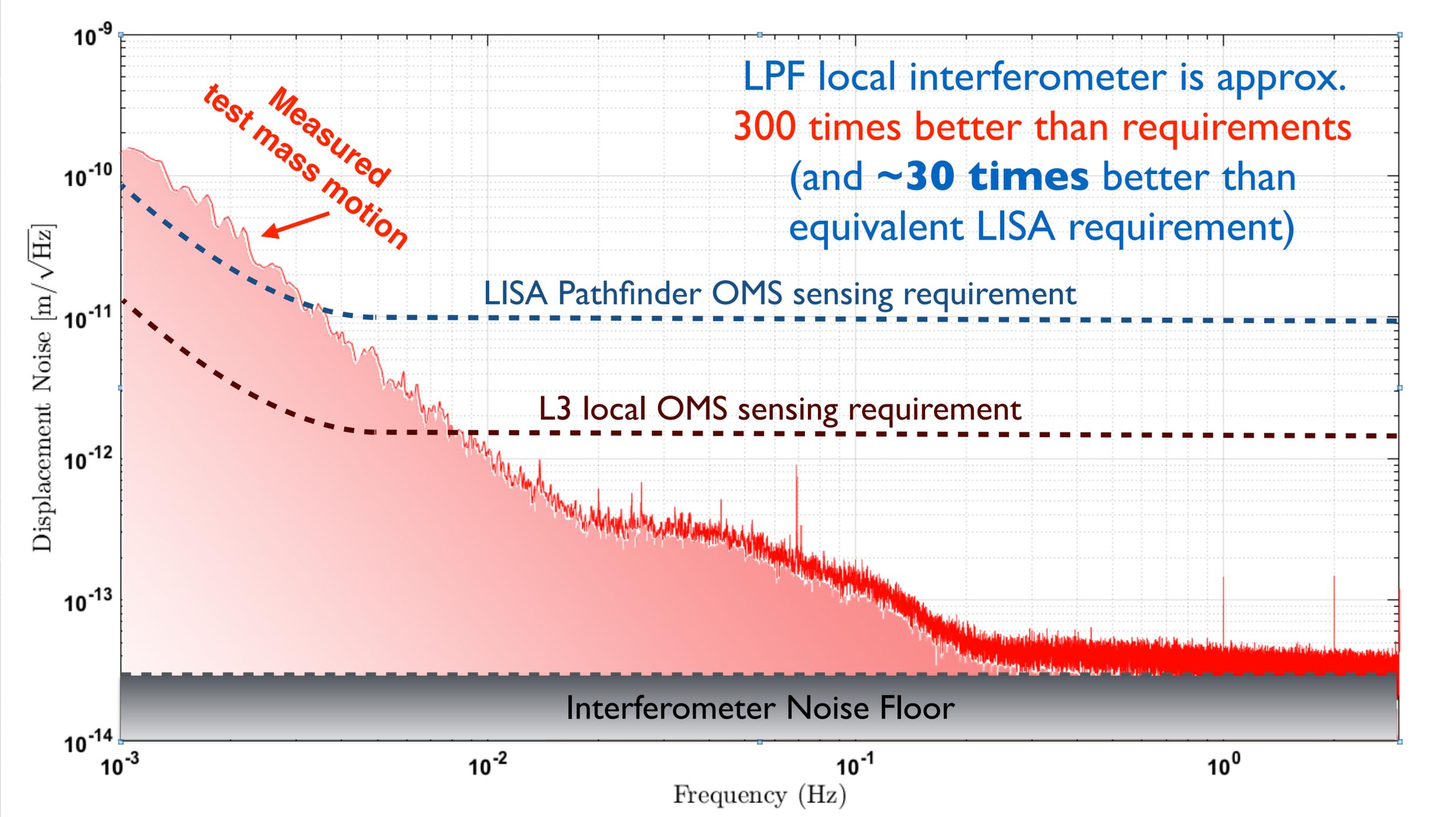
LISA Sensitivity Curve



- LISA Pathfinder was designed to test the critical technologies for LISA, namely:
 - Free-falling test mass
 - Pico-metre resolution displacement sensing
 - Drag free satellite control
 - Micro-Newton proportional thruster systems



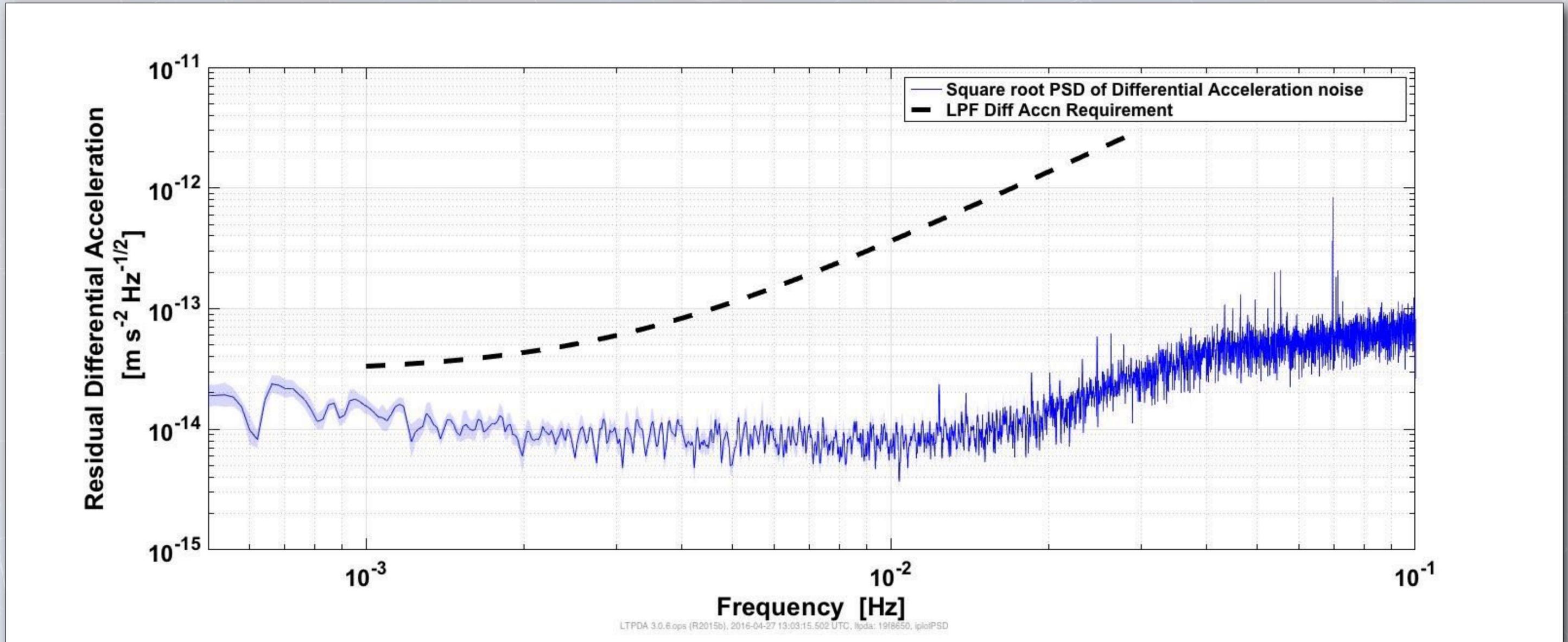
LPF On-orbit results: Displacement noise



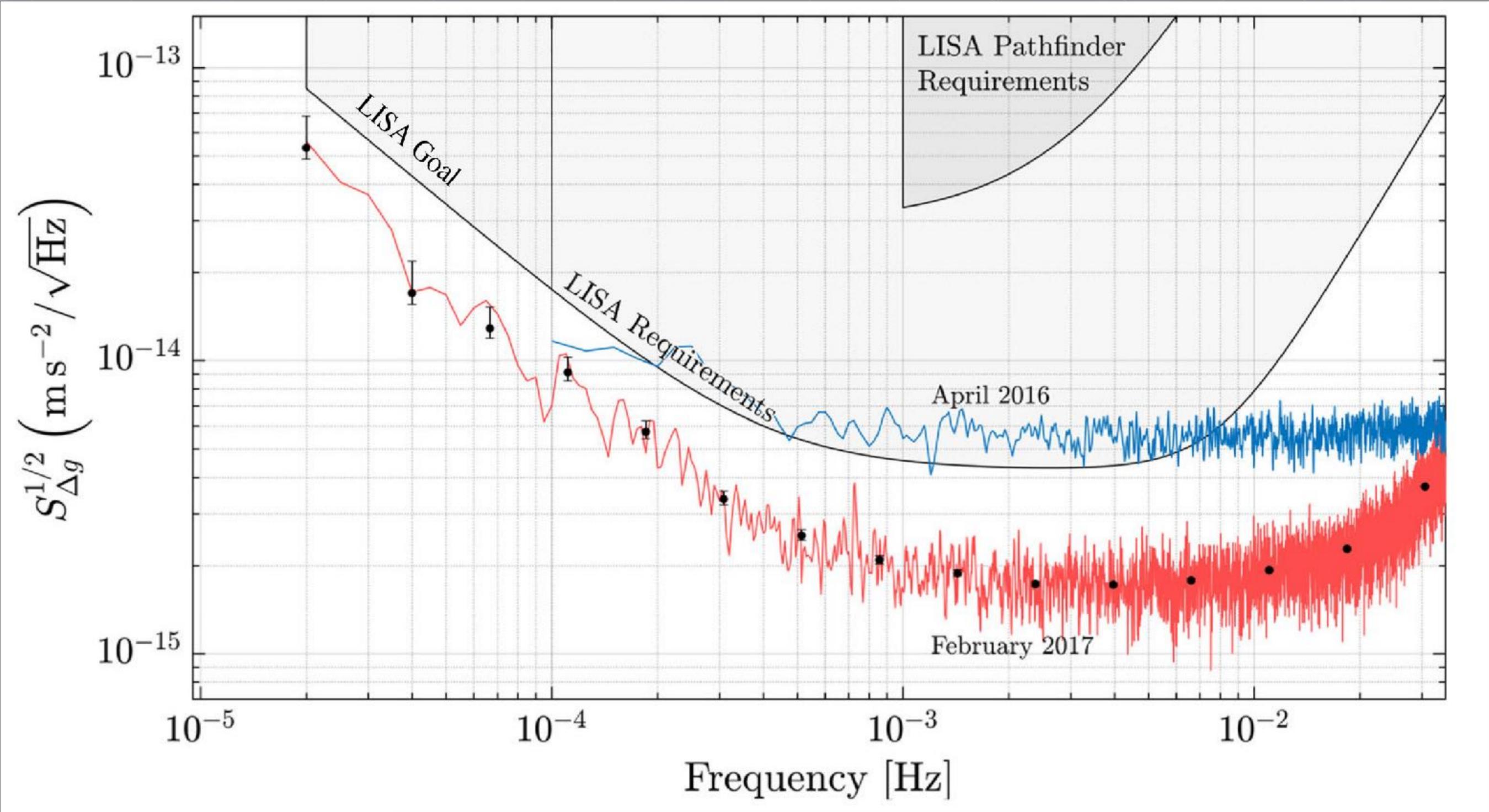
LPF on-orbit results: Differential Acceleration



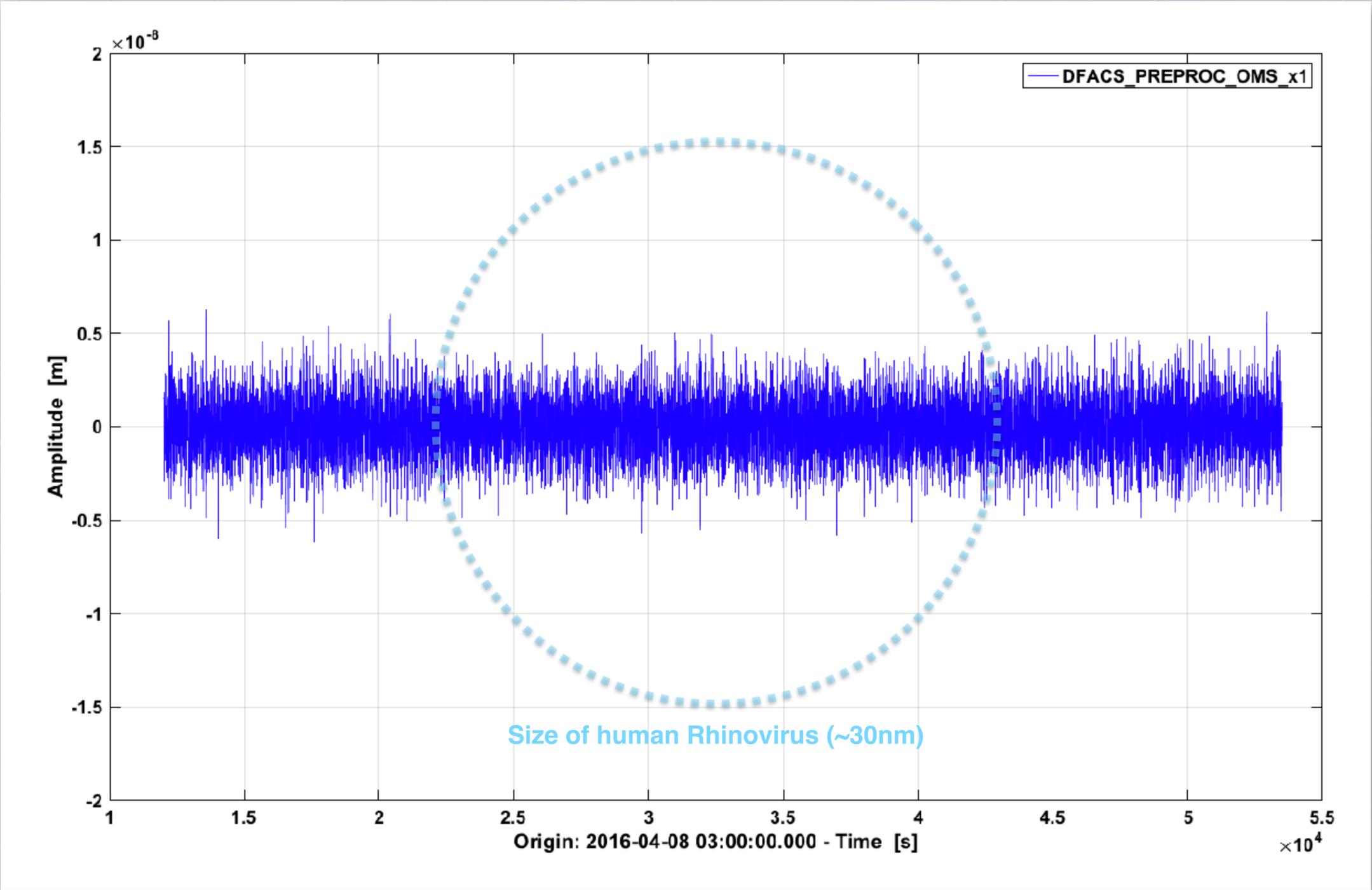
- The differential acceleration between the test masses (known as “delta-g”) is the primary performance requirement of the mission...
...and was met during commissioning!



LPF on-orbit results: Differential Acceleration



Platform stability



LPF to LISA

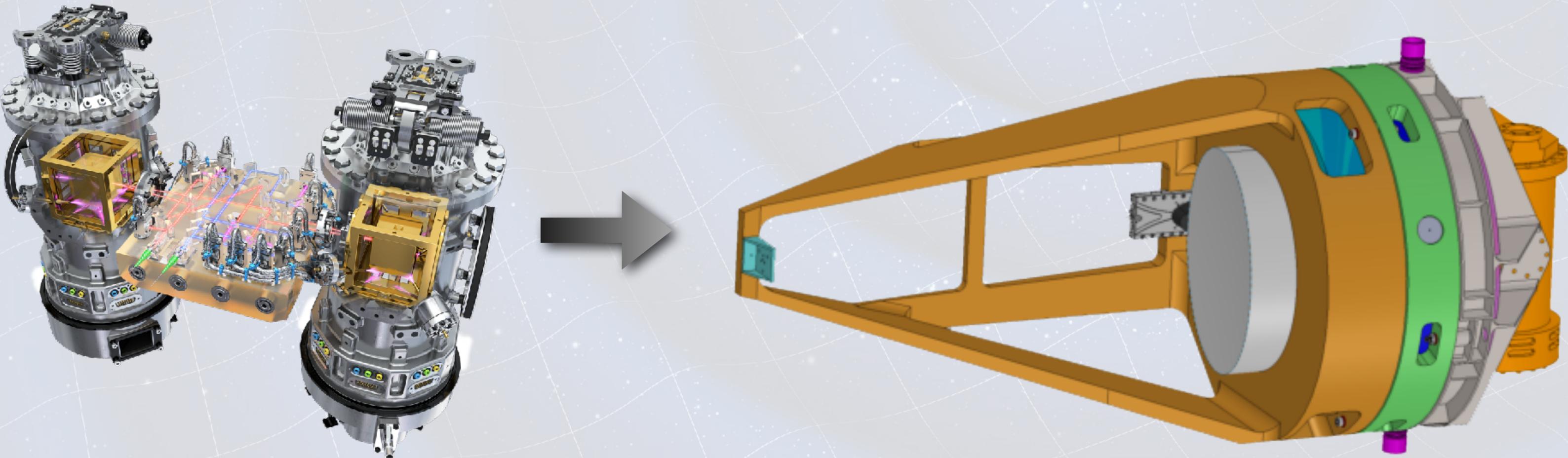
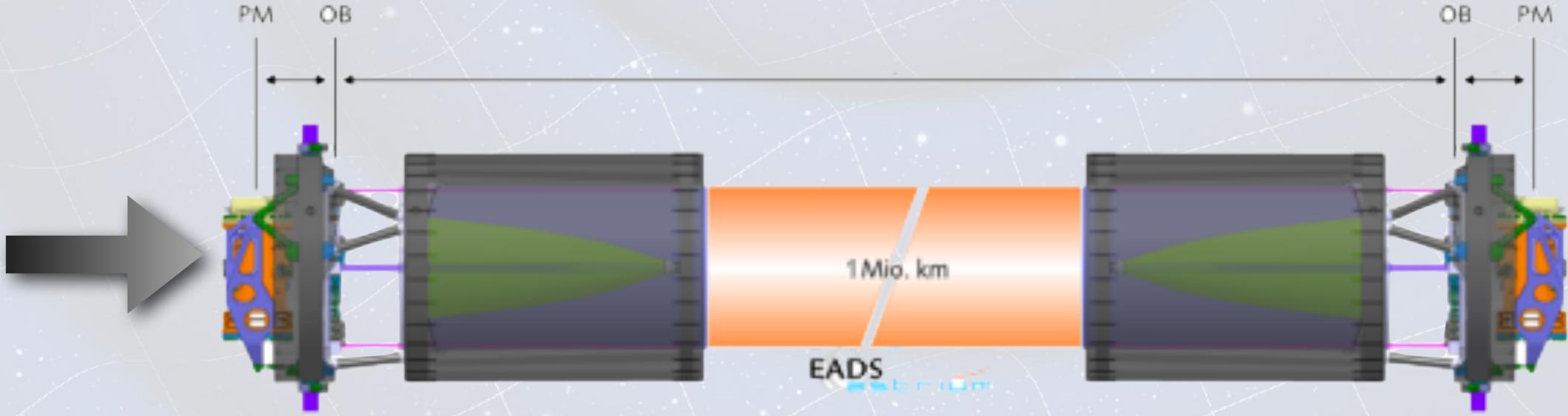
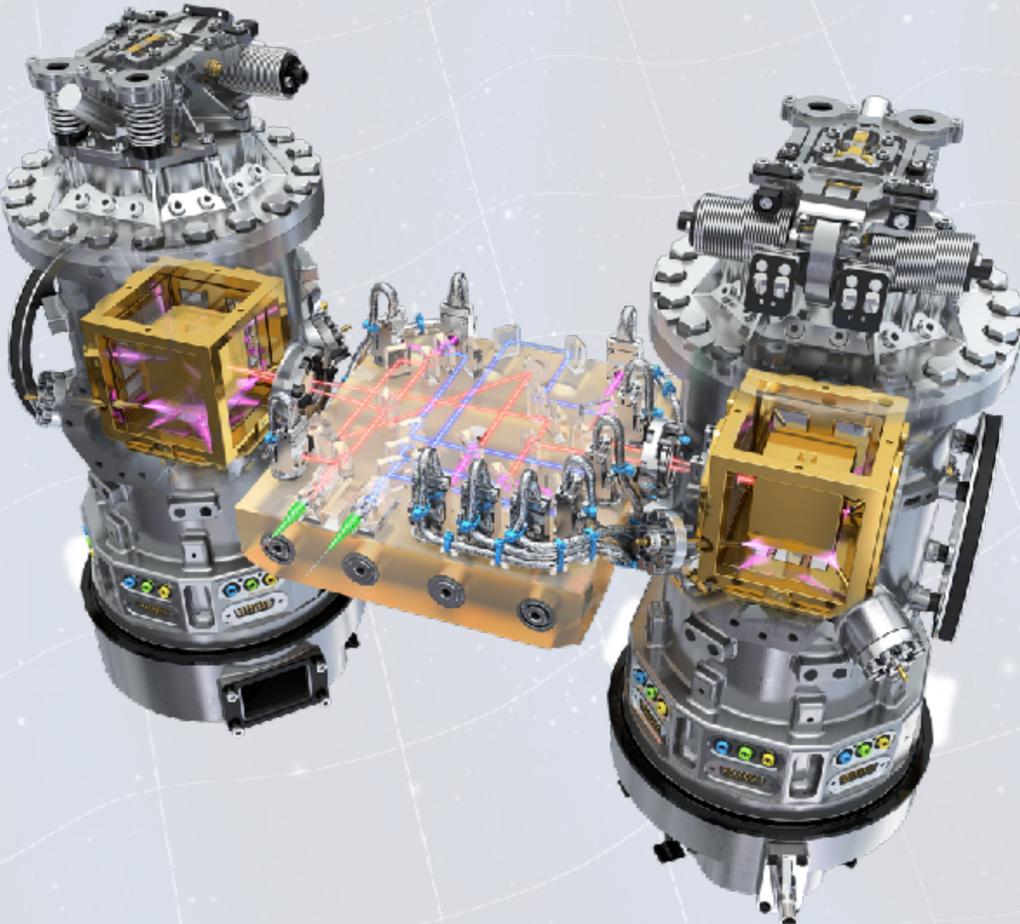
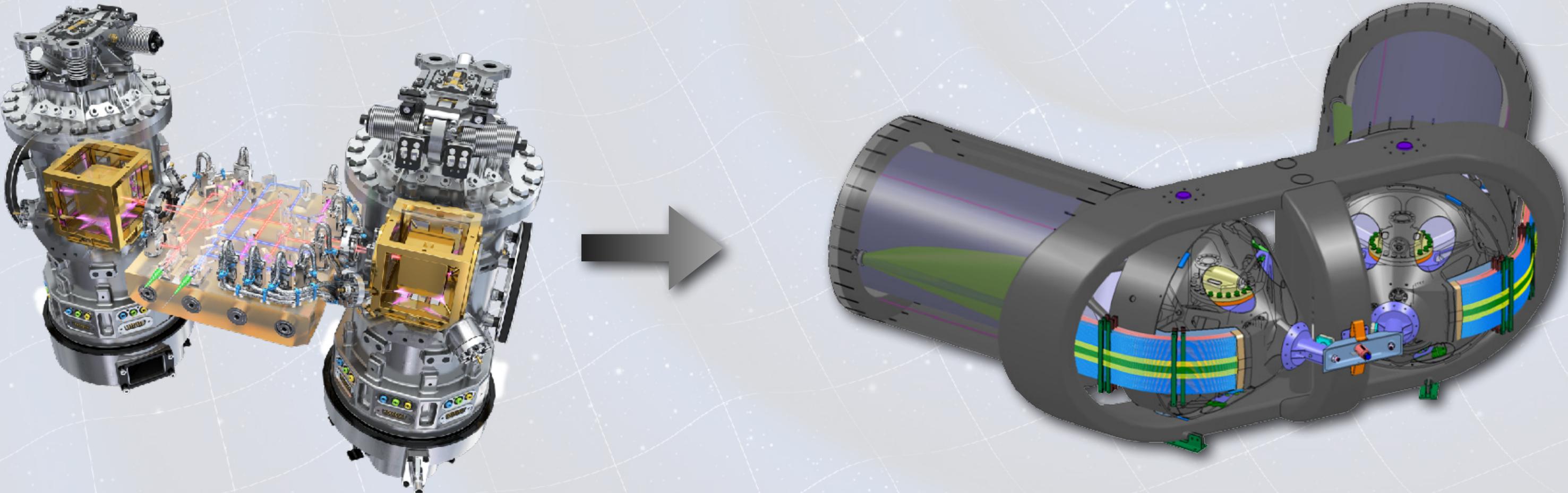


Image courtesy of NASA - GSFC

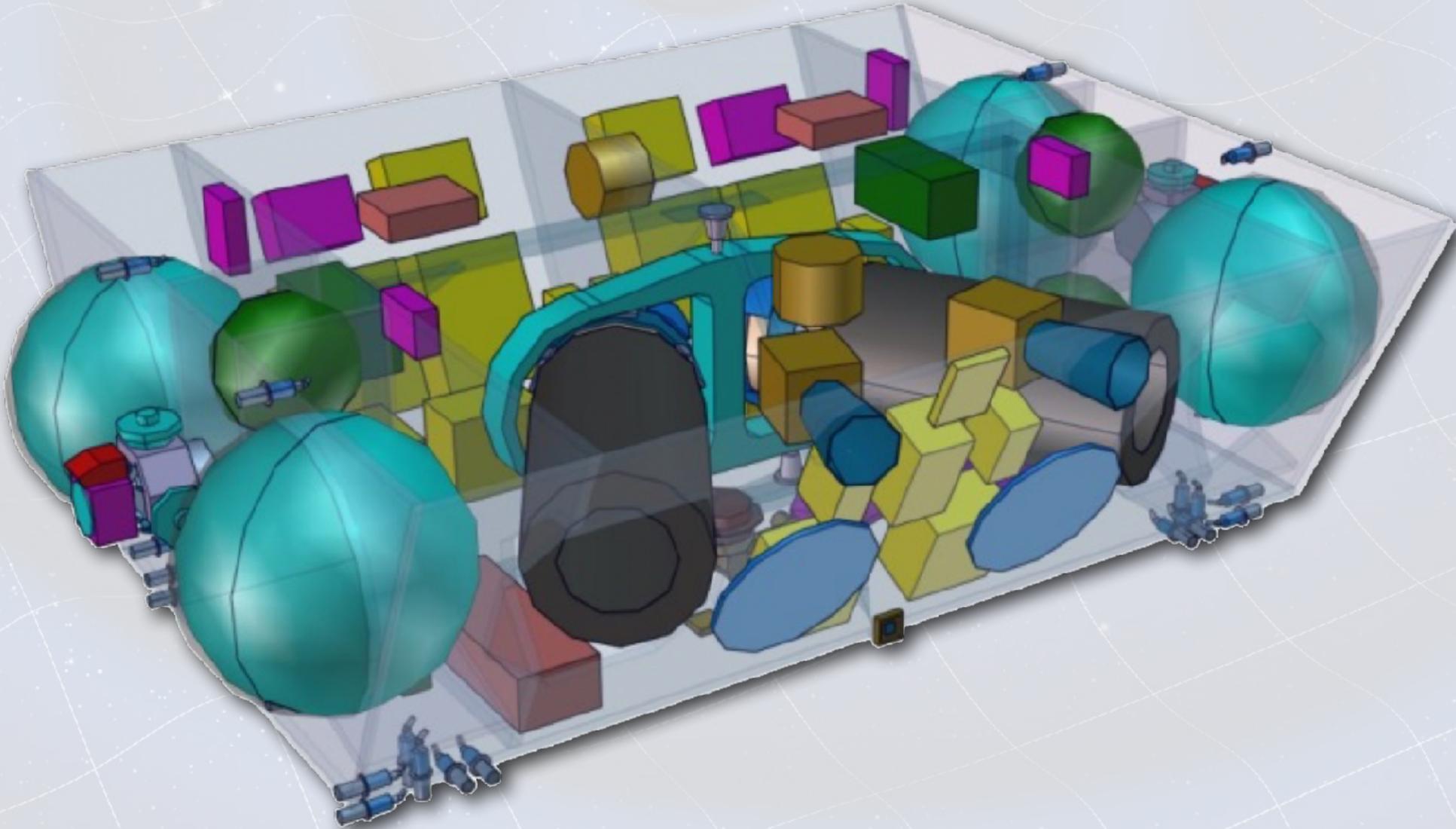
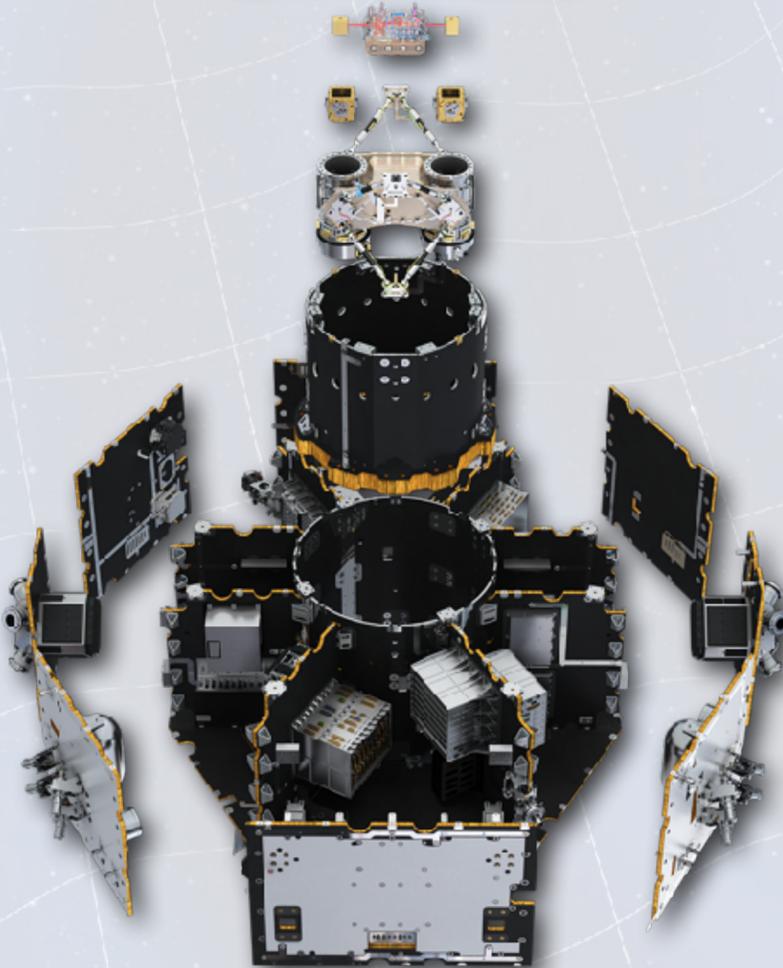
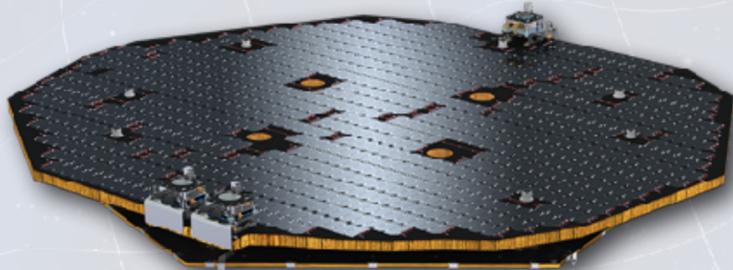
LPF to LISA



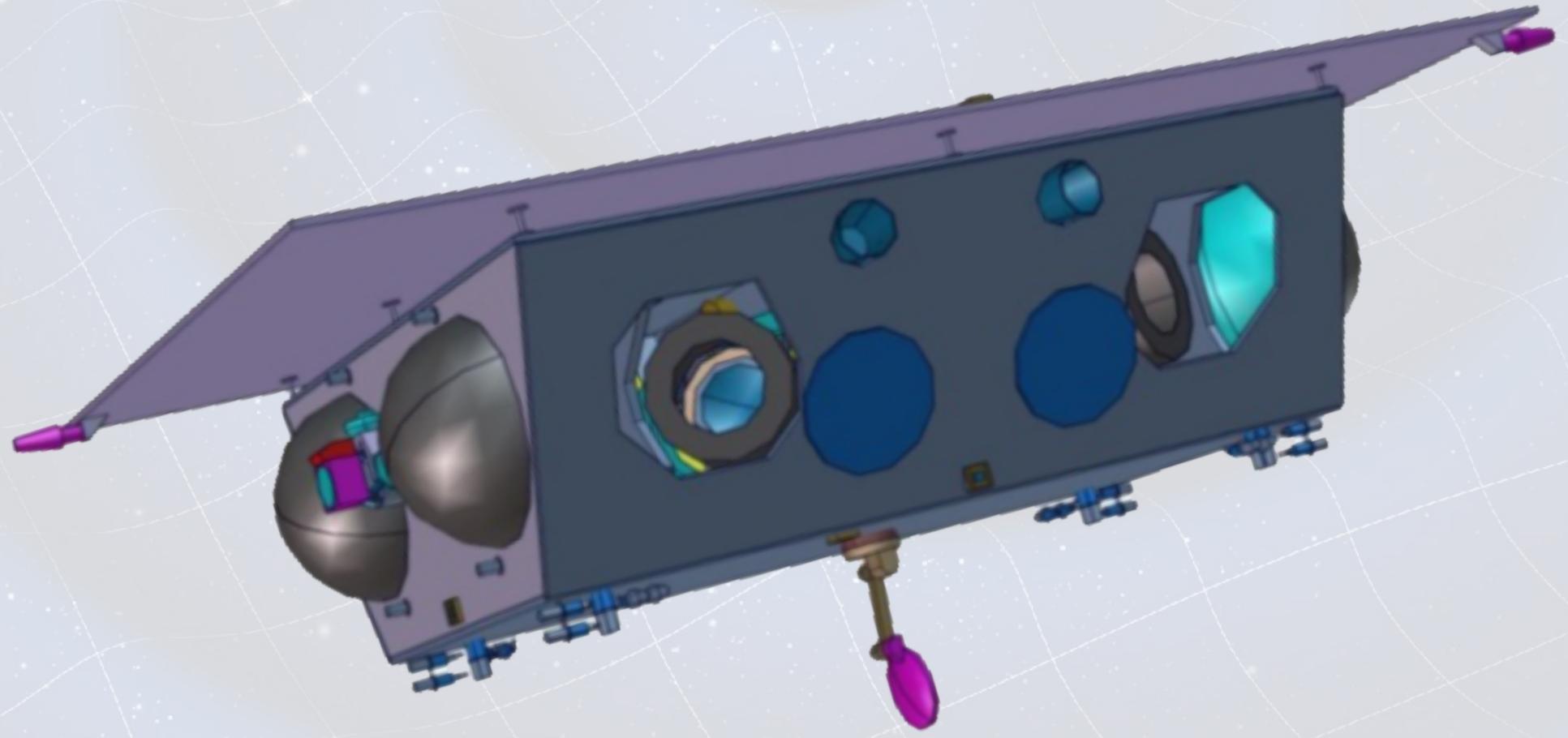
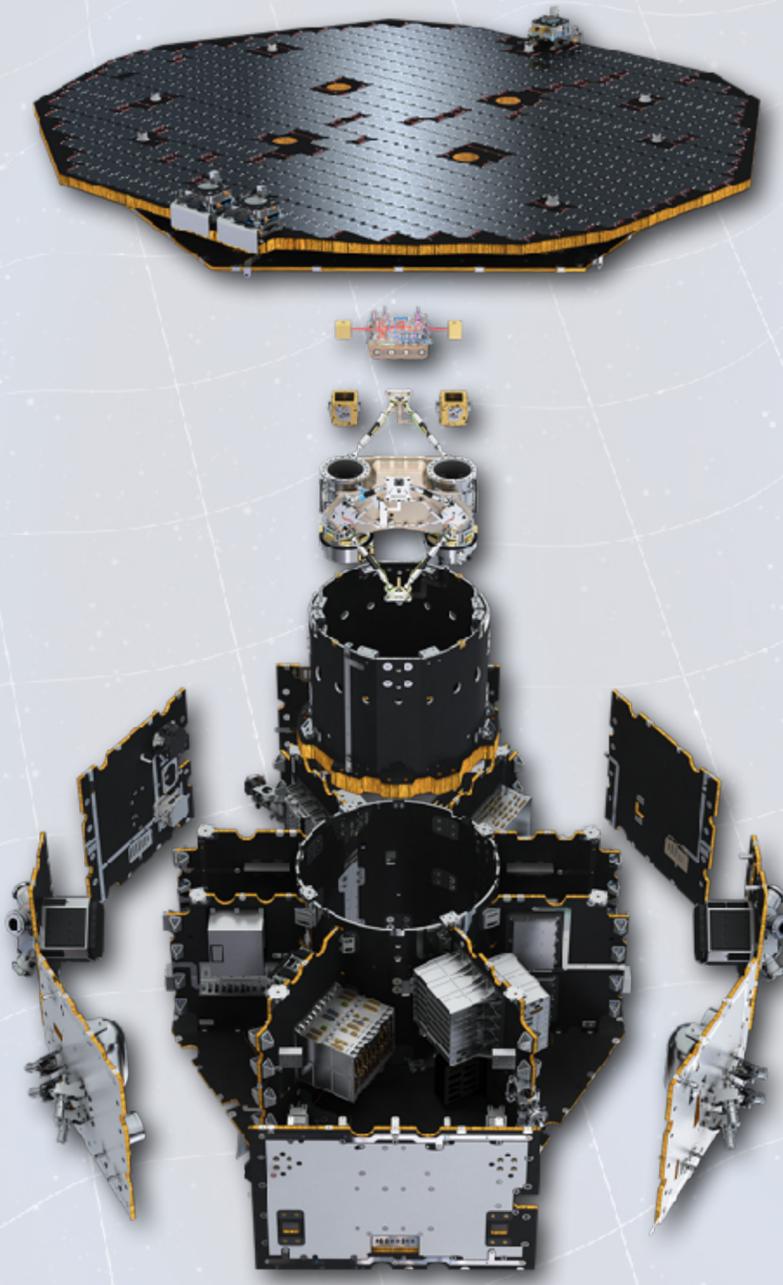
LPF to LISA



LPF to LISA



LPF to LISA



LPF to LISA



| Event | From | To | Status |
|--------------------------------------|-------------|----------|---------------------------|
| Mission Phase 0 (CDF) | 2017-Mar | 2017-May | Done |
| Phase 0 for instrument contributions | 2017-JUL | 2017-NOV | Done |
| Mission Definition Review (MDR) | 2017-NOV-27 | | Done |
| Phase A (mission & payload) | 2018-APR | 2020-Jan | Ongoing |
| Mission Formulation Review (MFR) | 2019-NOV | 2019-DEC | |
| Adoption | <=2024 | | |
| Implementation (Phase B2/C/D) | 8.5 years | | |
| Launch | 2034 | | |
| Transfer & Commissioning | 2.5 years | | |
| Operations | 4 years | | |
| Extension (TBD) | 6 years | | 10 years total of science |

Conclusions



- LISA Pathfinder on-orbit performance has far exceeded the pre-launch requirements
 - (Local) interferometer displacement noise floor: $\sim 35\text{fm}/\sqrt{\text{Hz}}$ at high frequencies
 - Differential acceleration noise: $< 2\text{fms}^{-2}/\sqrt{\text{Hz}}$ at $\sim\text{mHz}$ frequencies
 - ...LISA performance met across full LISA measurement *goal!*
 - LPF performance, along with LIGO observations, have pushed forward the LISA development programme
 - Gravitational wave astronomy is a reality
 - LISA opens the window to the low frequency GW spectrum
 - For more information on LISA, please visit:
 - sci.esa.int/LISA
 - www.lisamission.org
- LISA Consortium:
- signup.lisamission.org

The screenshot shows the LISA Consortium application form. It includes a header with the LISA logo and the word 'lisa'. The form is titled 'Consortium application form' and contains several sections: 'Name' (text input), 'E-Mail' (text input), 'Affiliation' (text input), 'Application type' (radio buttons for 'Group' and 'Associate'), 'Application document' (file upload), and 'Comments' (text area). A 'Send application' button is at the bottom. On the right side, there are three informational boxes: 'Step by step' (a 6-step process), a box about contacting support, and a box about reference documents.

Thank you

