The Gravitational Universe and LISA

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LISA Study Scientist
European Space Agency

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

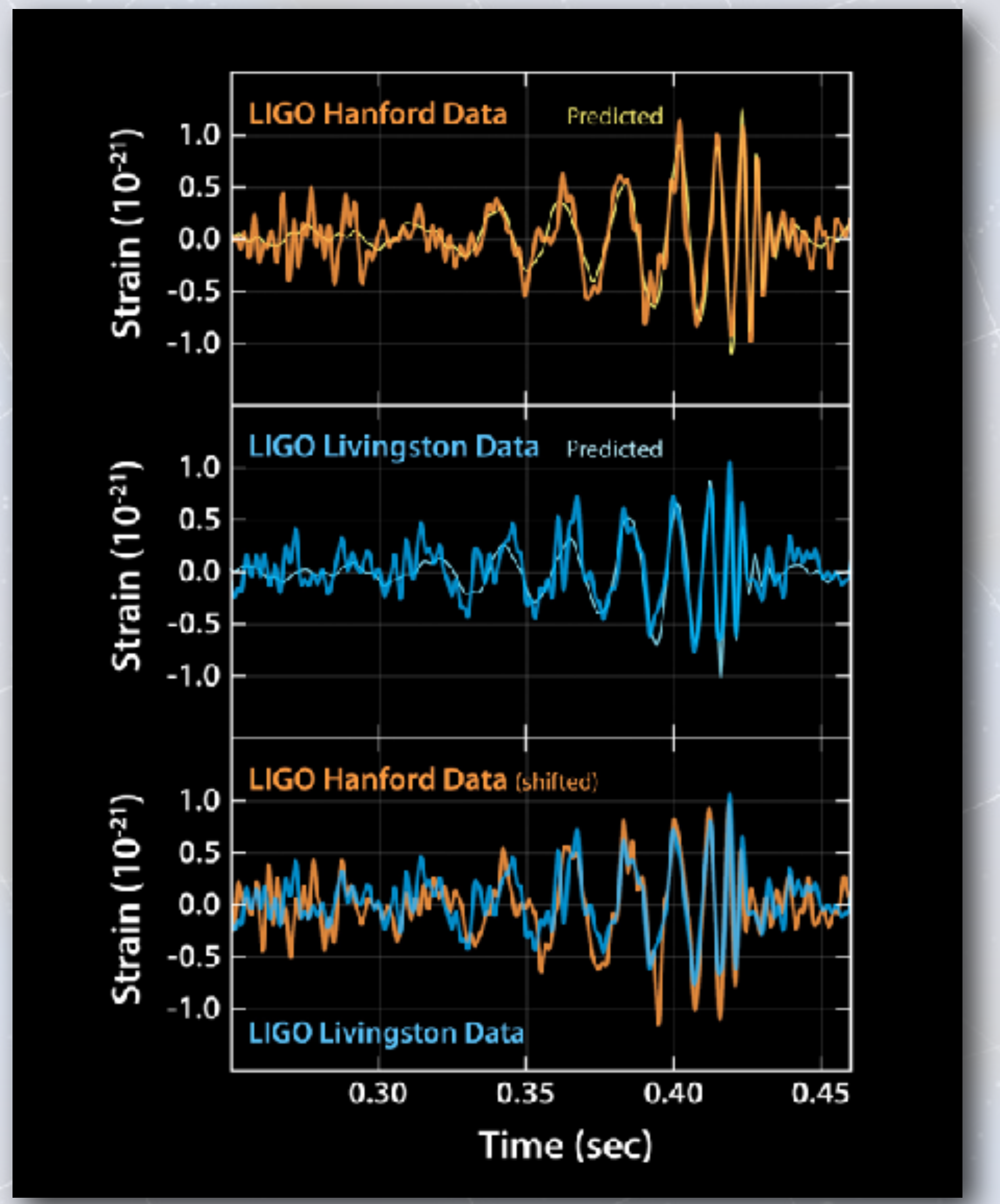
Introduction

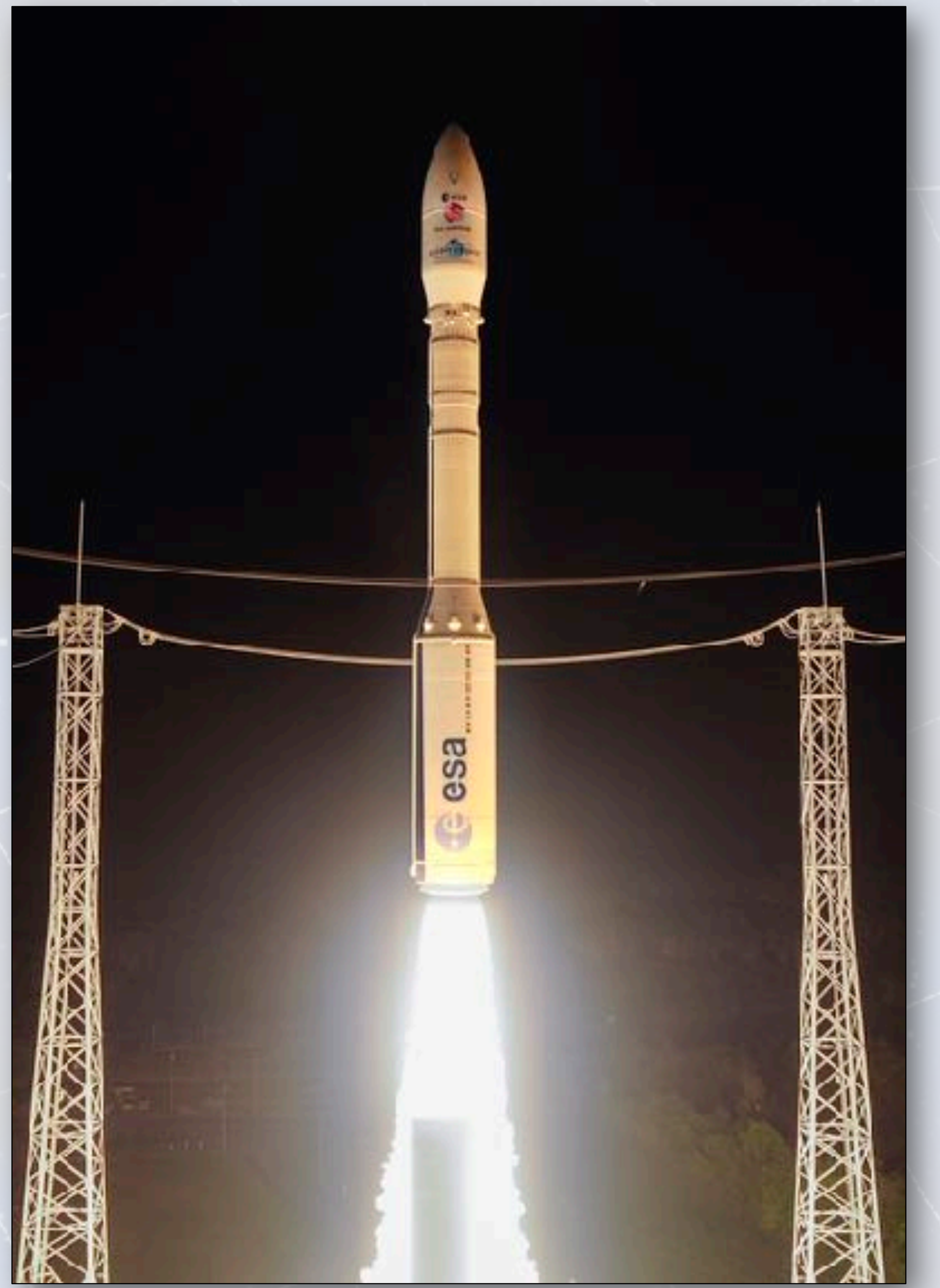
- LISA - the Laser Interferometer Space Antenna - is a European Space Agency mission to observe low frequency gravitational waves from space

- 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

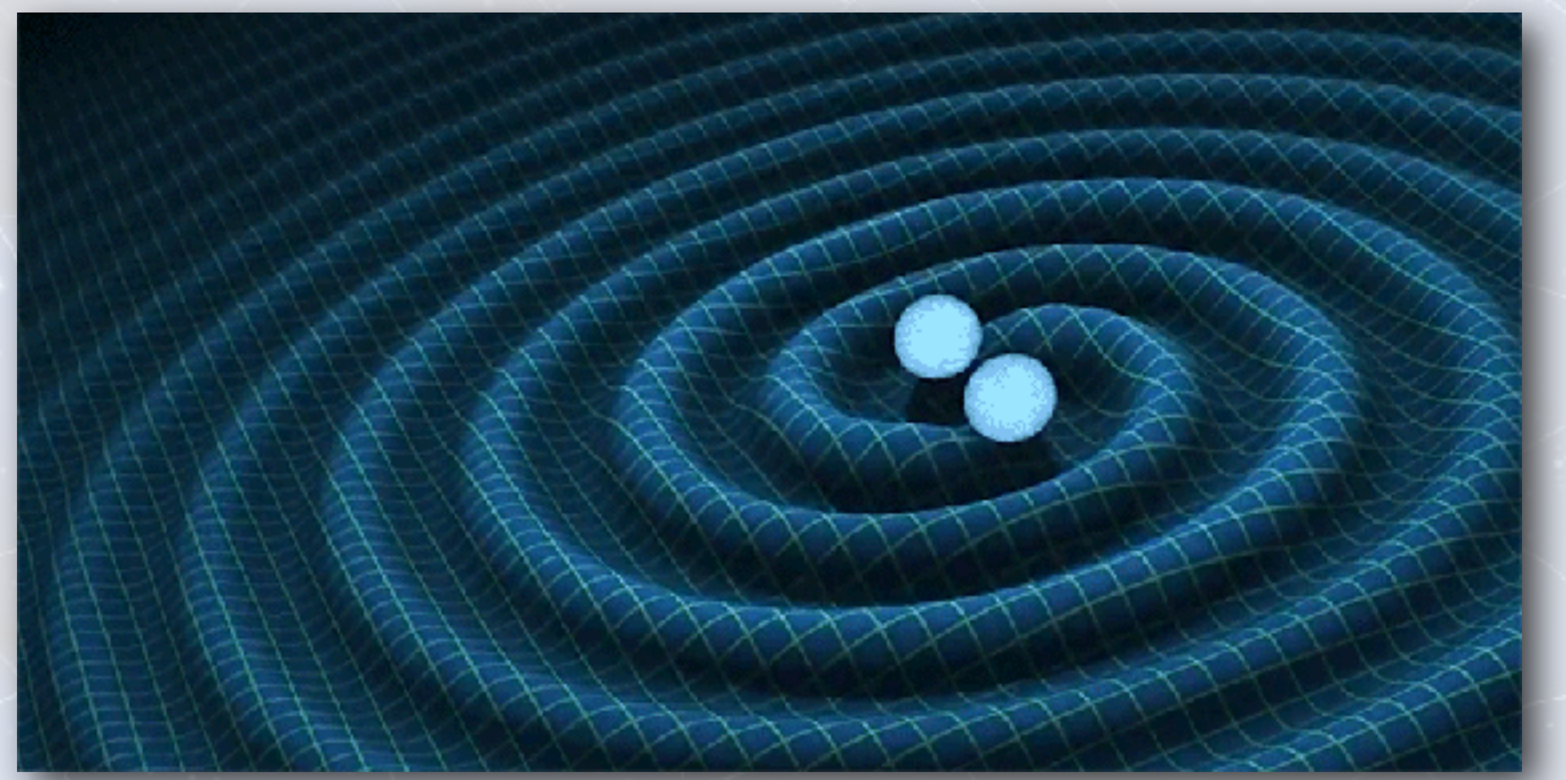
- Both momentous events opened the door to the *Gravitational Universe*

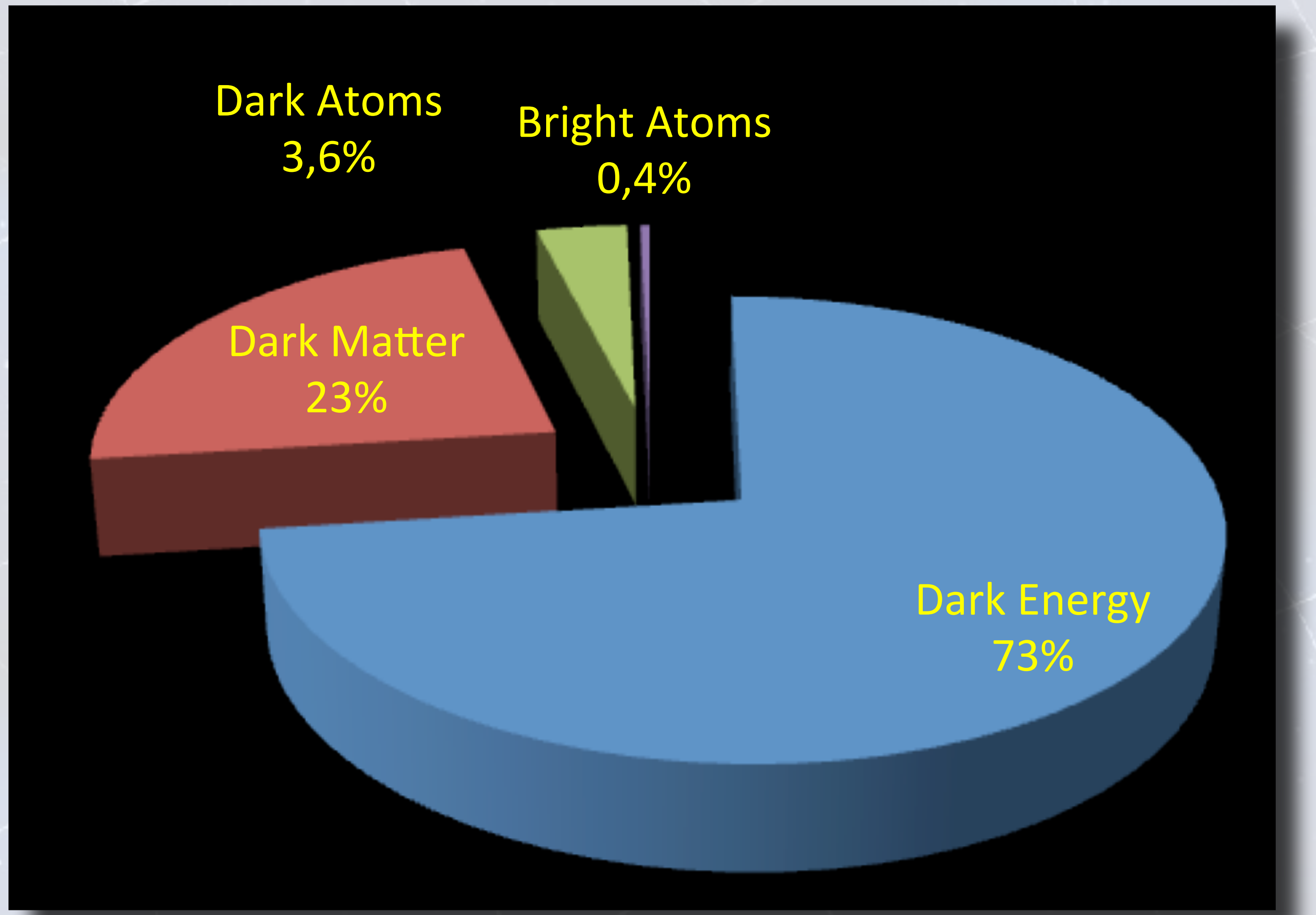




Gravitational waves…what are they?

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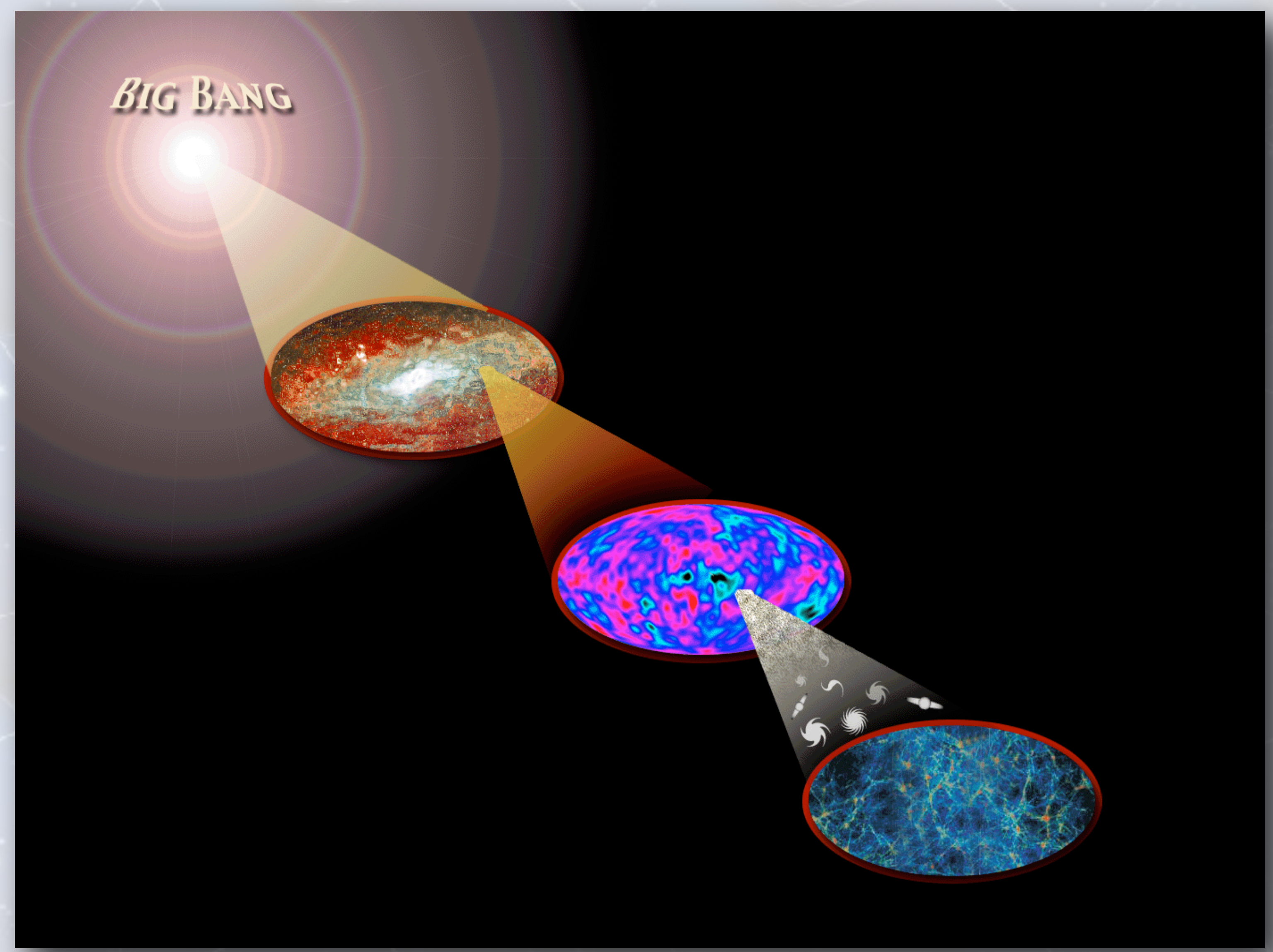
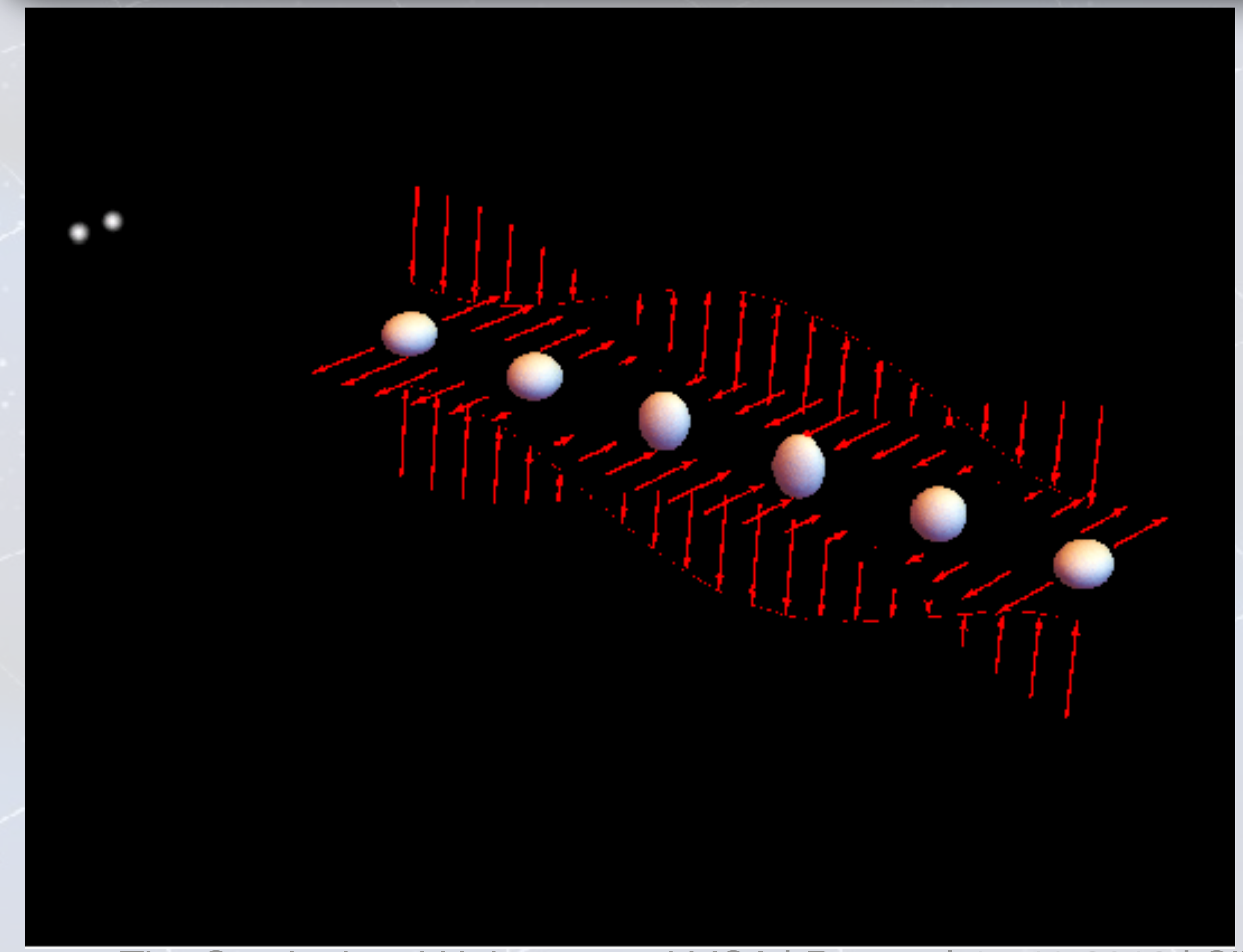
- Gravitational waves:
  - Ripples in the curvature of spacetime
  - Produced by the motion of mass and energy
  - Travel through the Universe (almost) unimpeded
    - Allows us to observe the very distant universe
    - Difficult to detect!

Gravitational Waves carry entirely new information about the Universe





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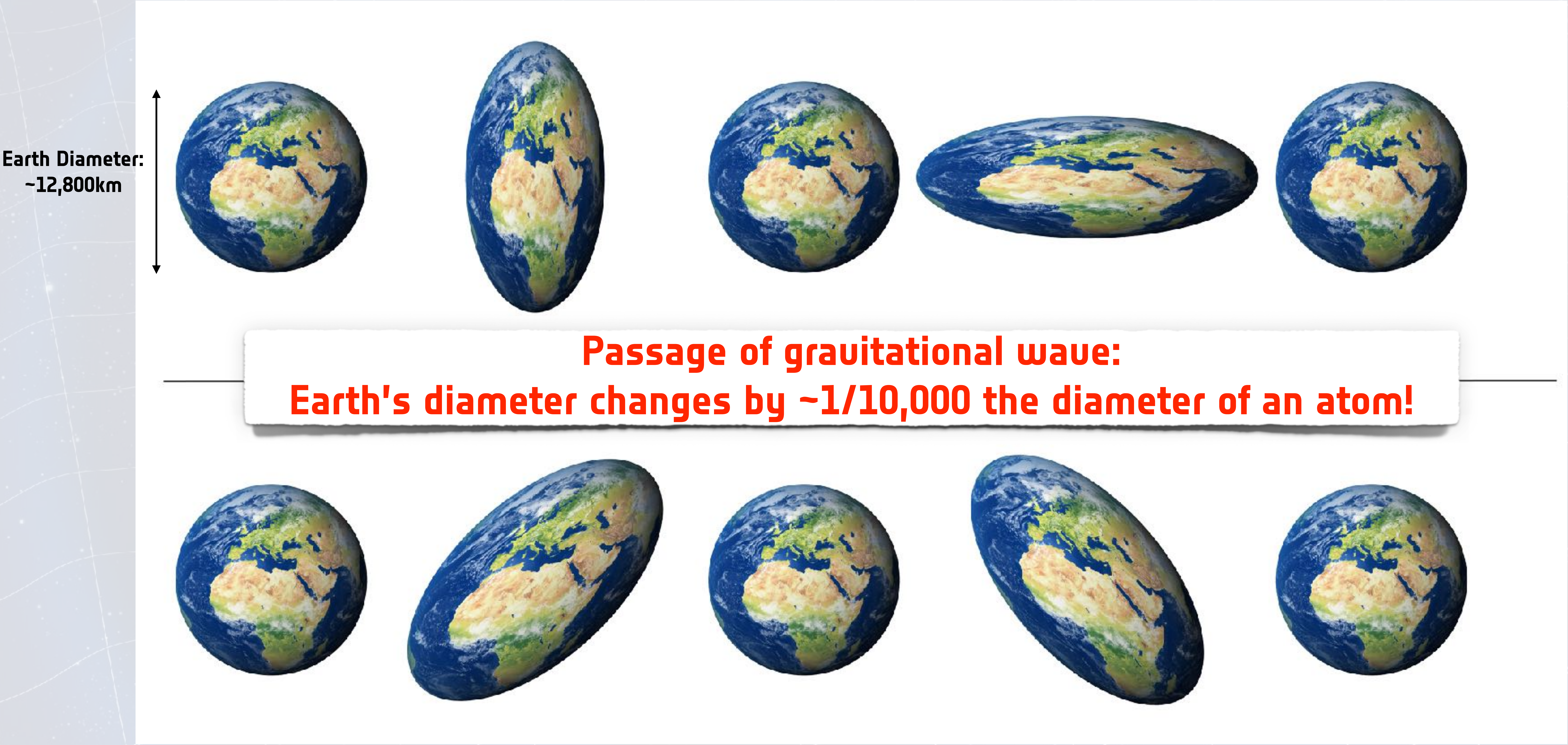
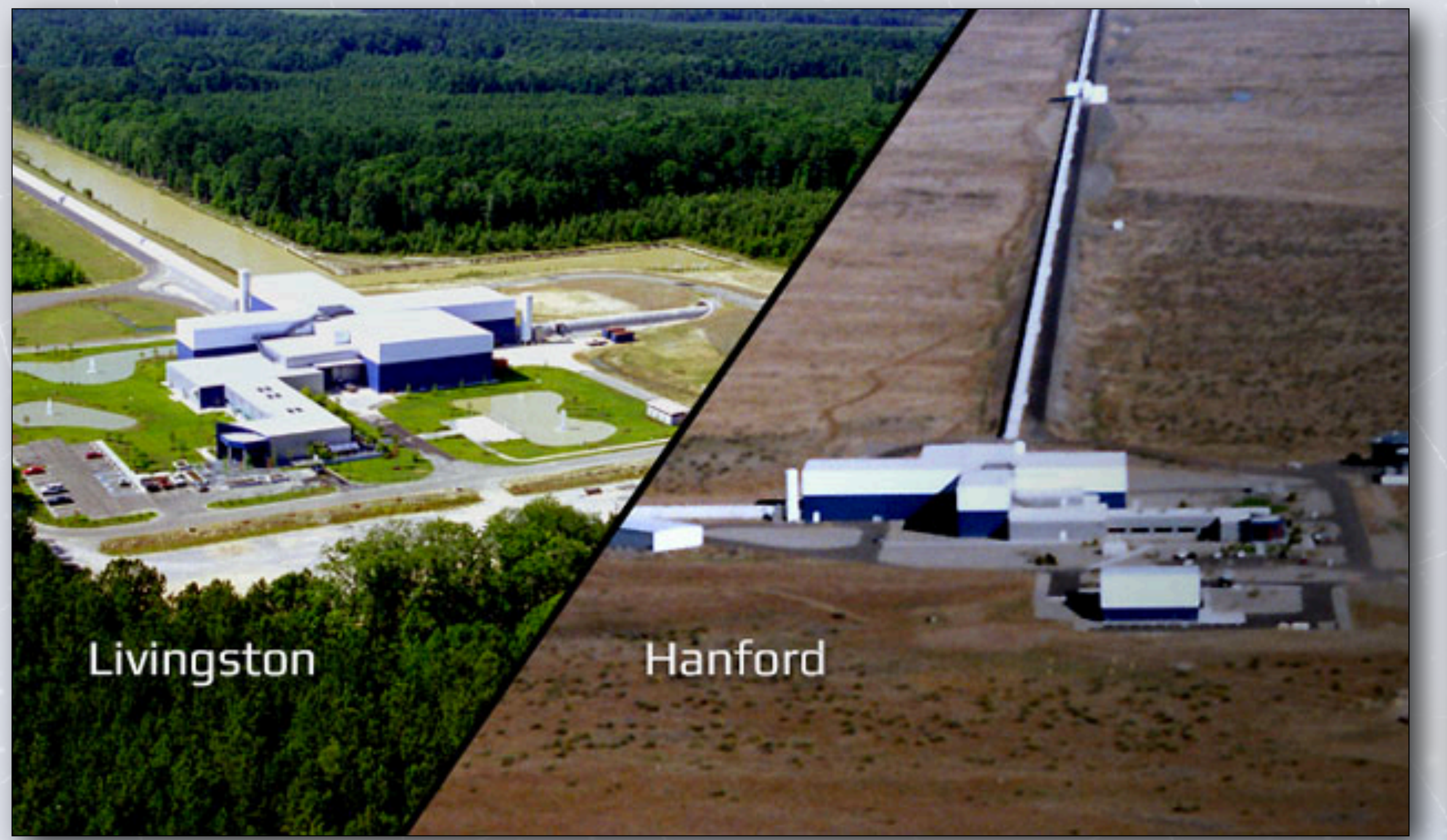
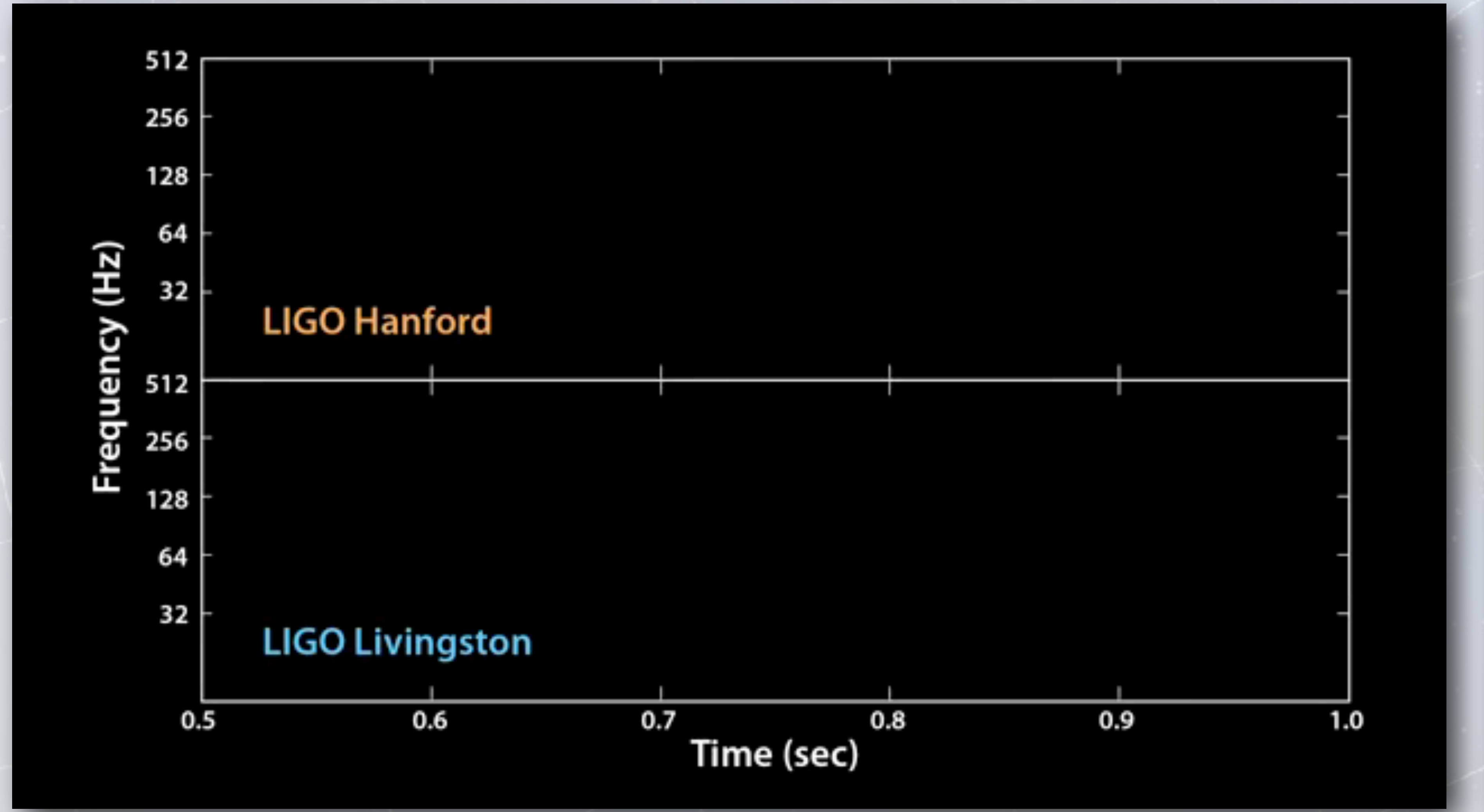
What happens when a GW passes Earth?

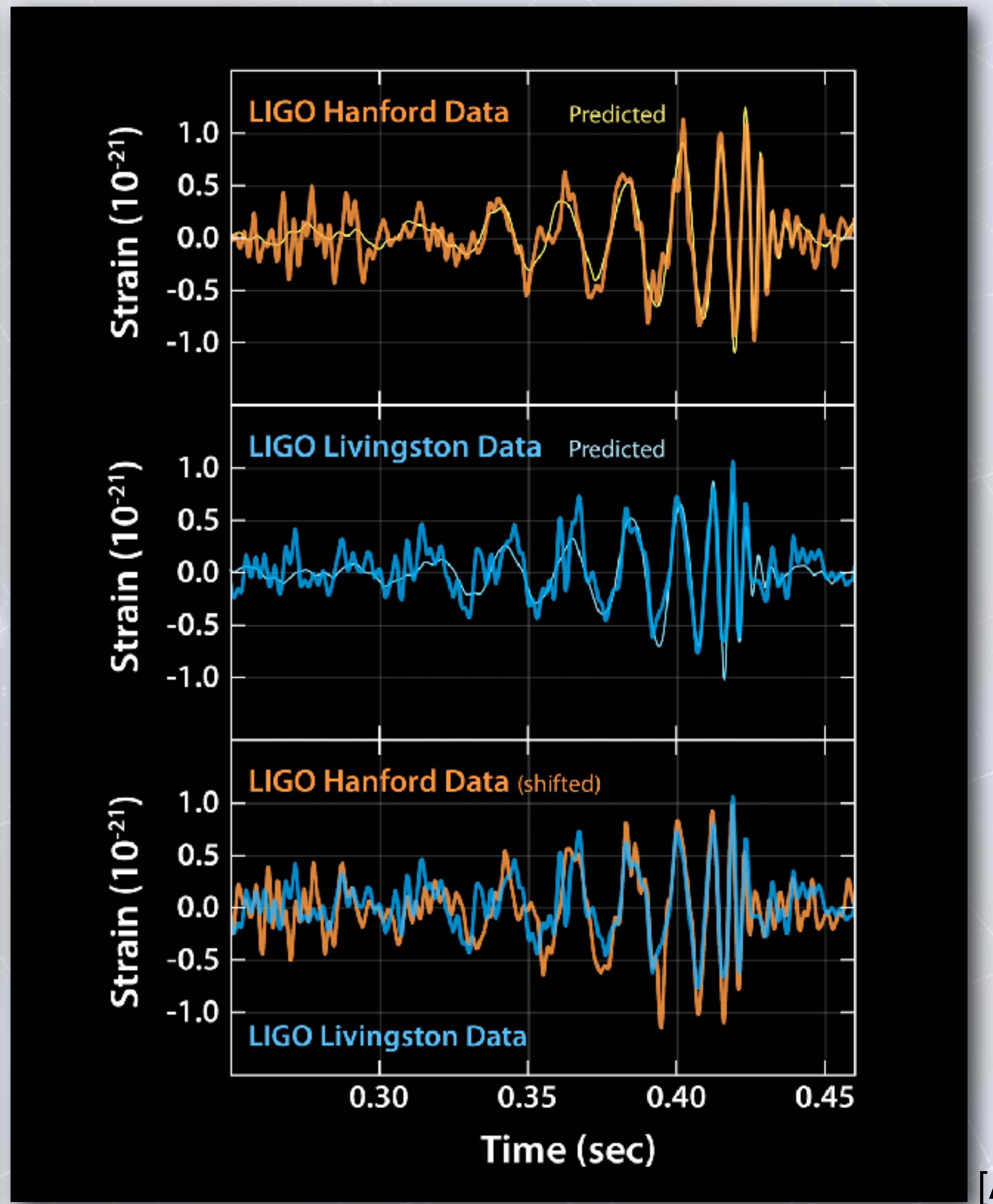


Ground based GW detectors

The first direct detection…GW150914

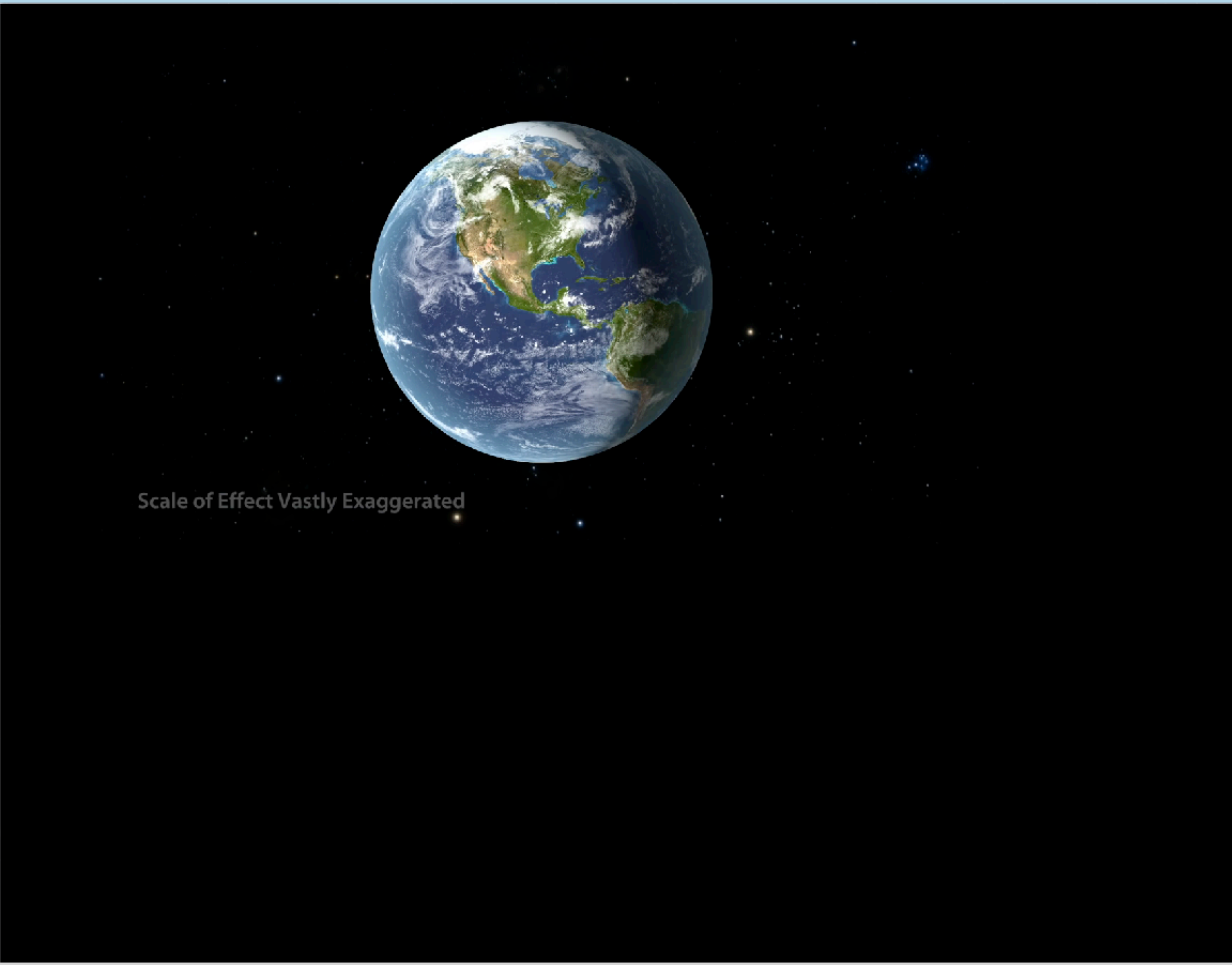


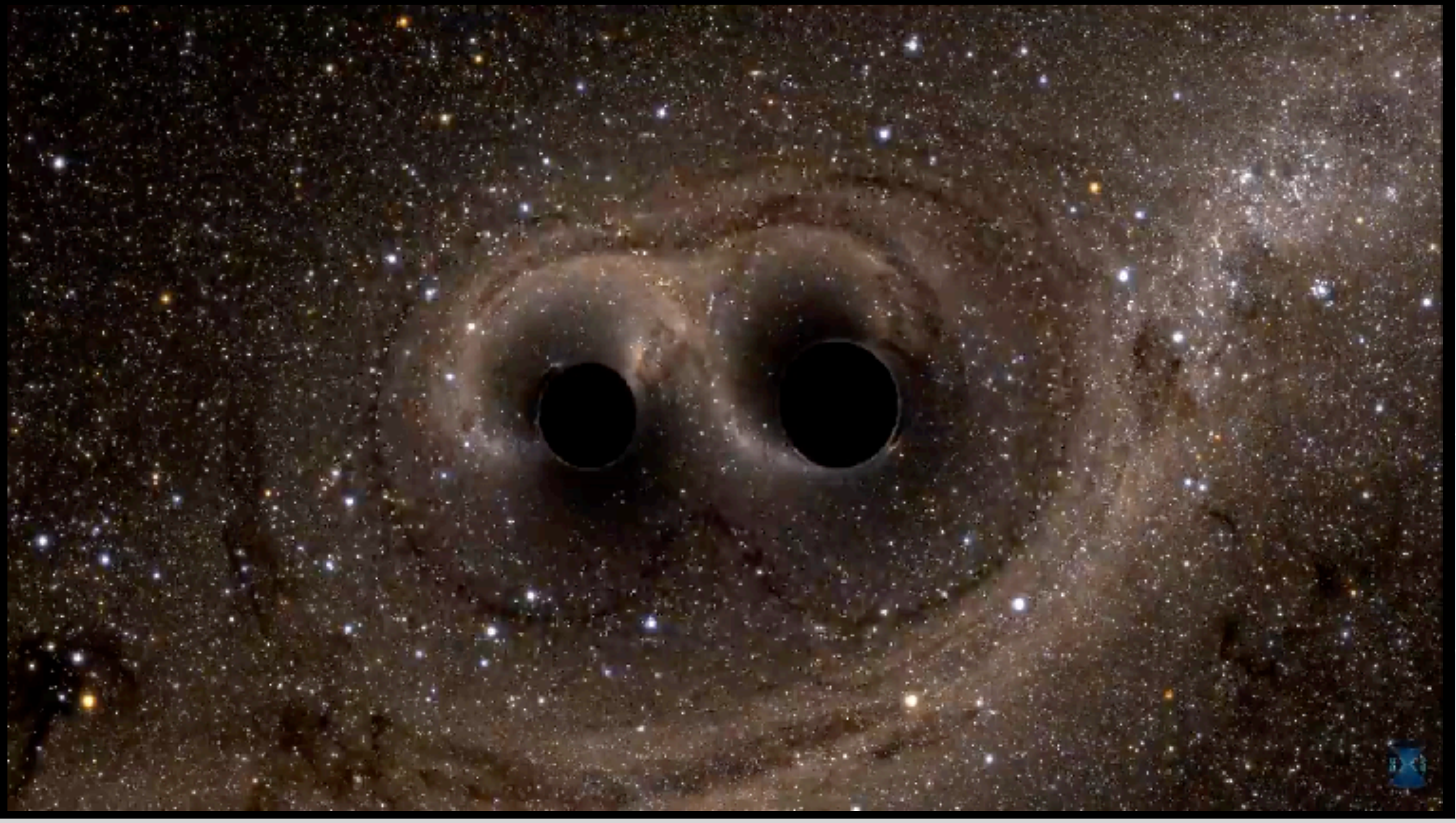




[Abbott et al, PRL 2016]

What did LIGO observe?





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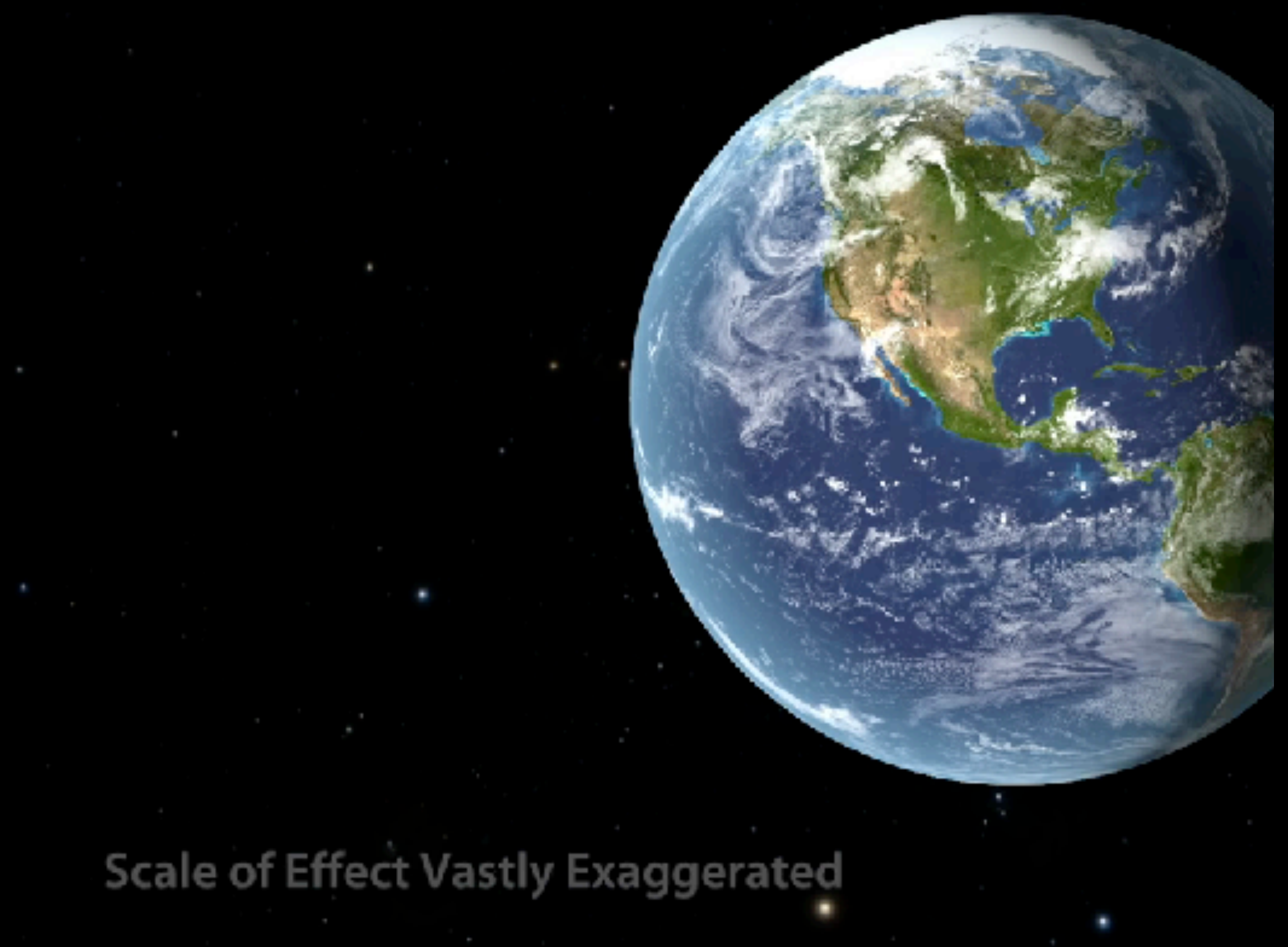
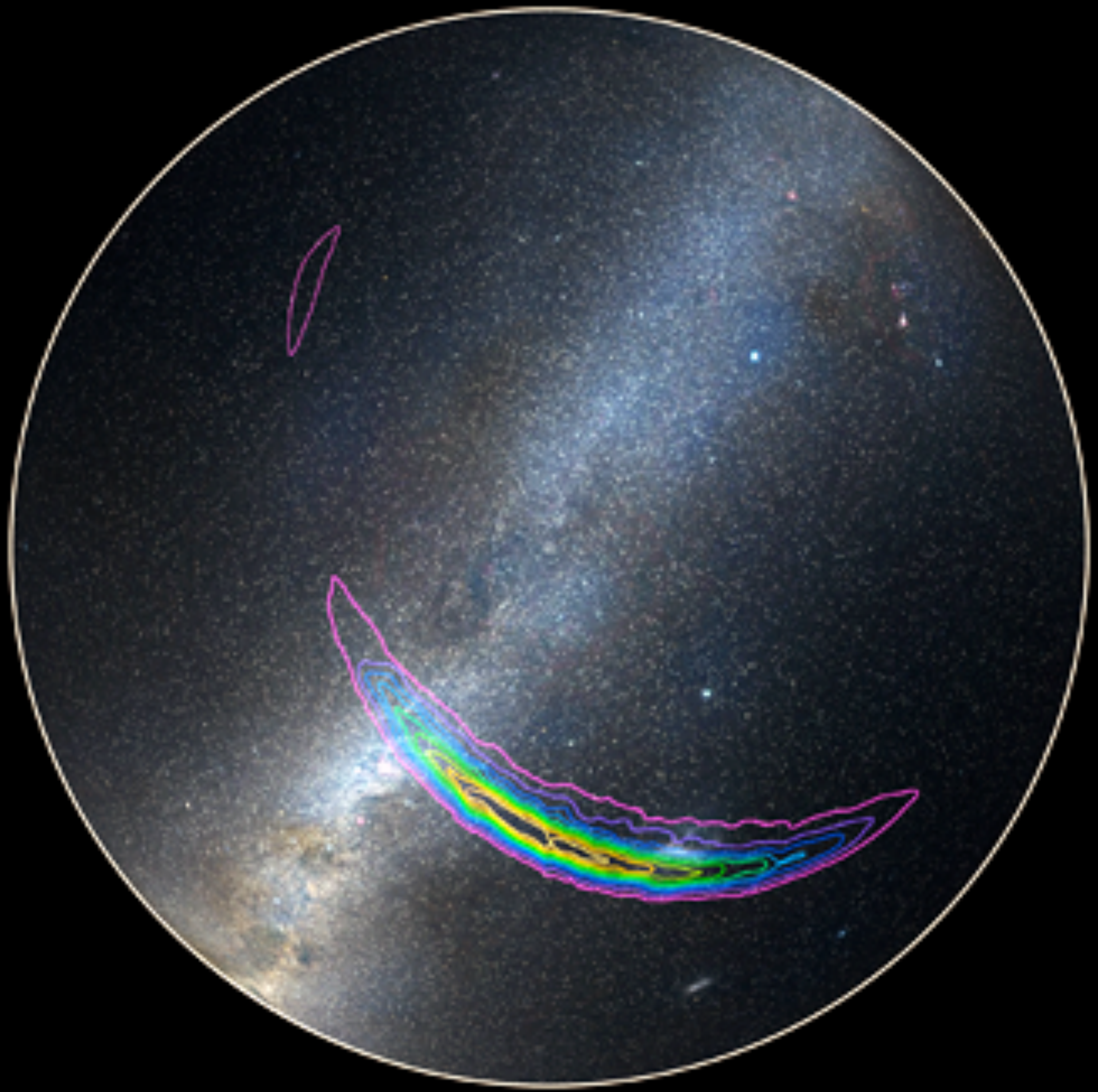
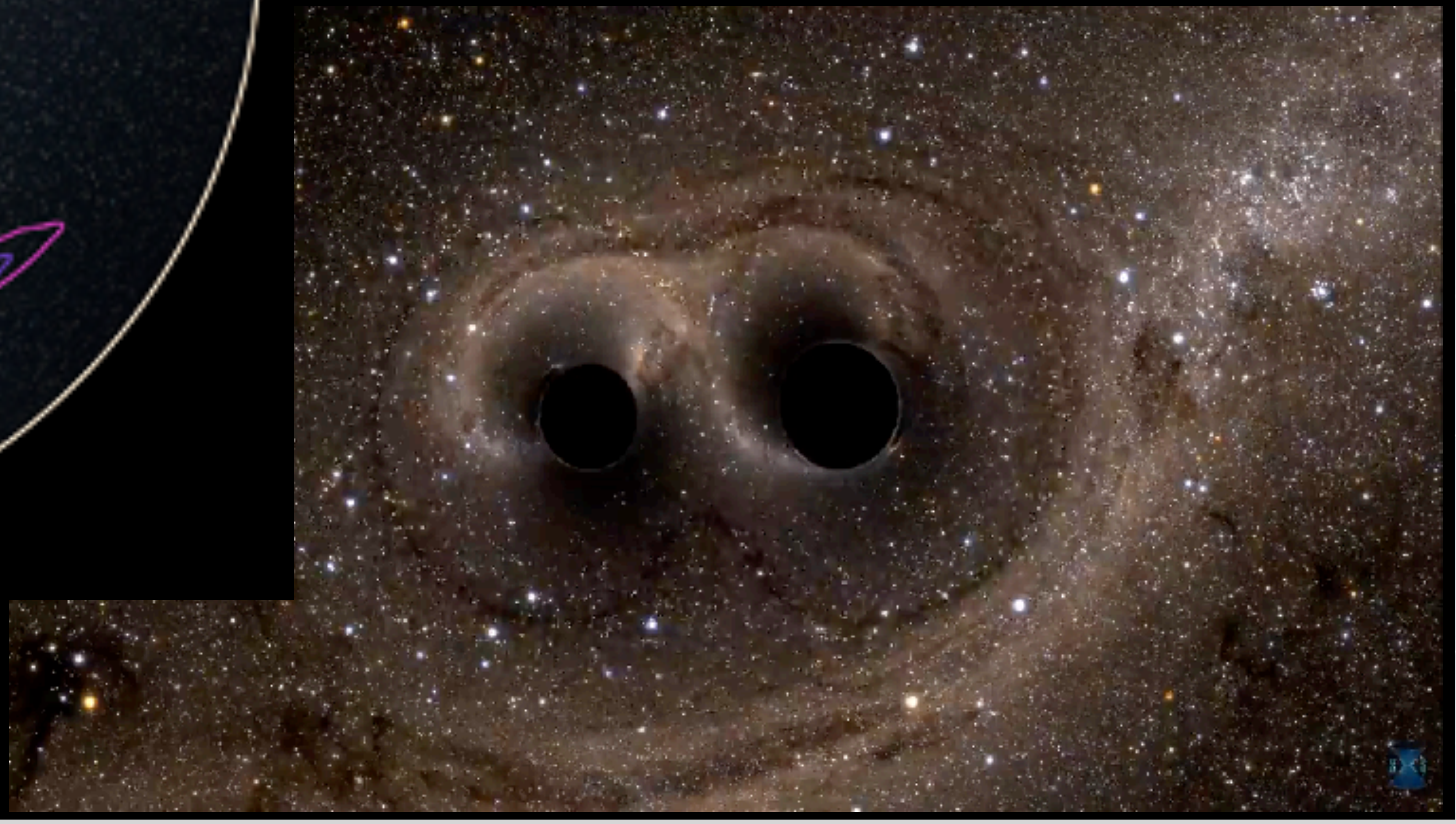
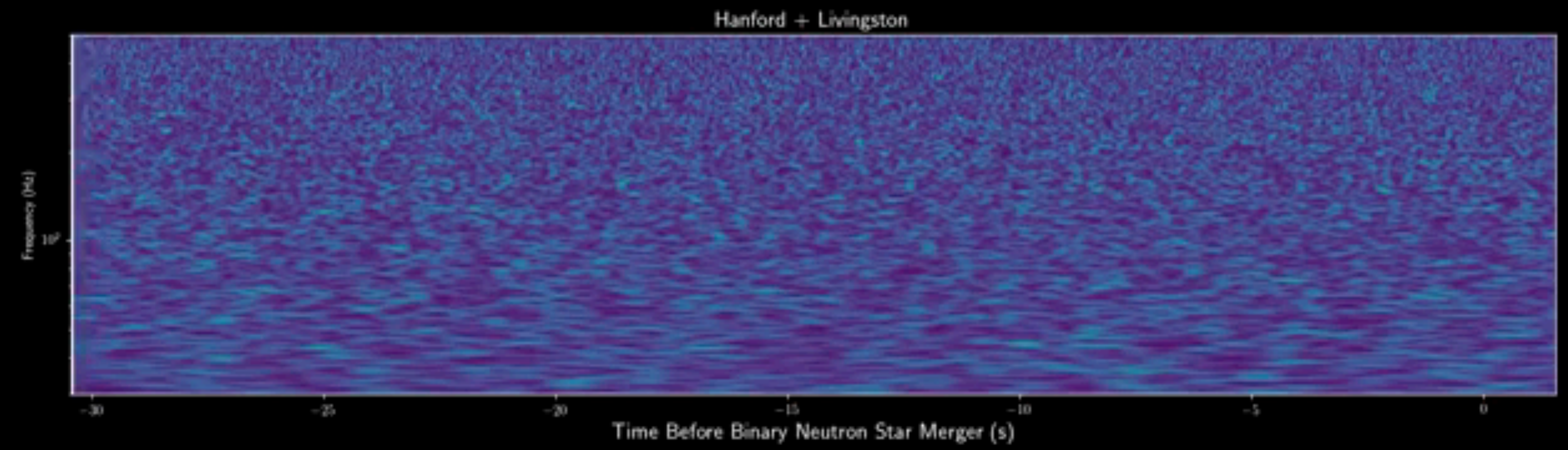






GW150914 was not alone…

Multi-messenger astronomy - GW170817



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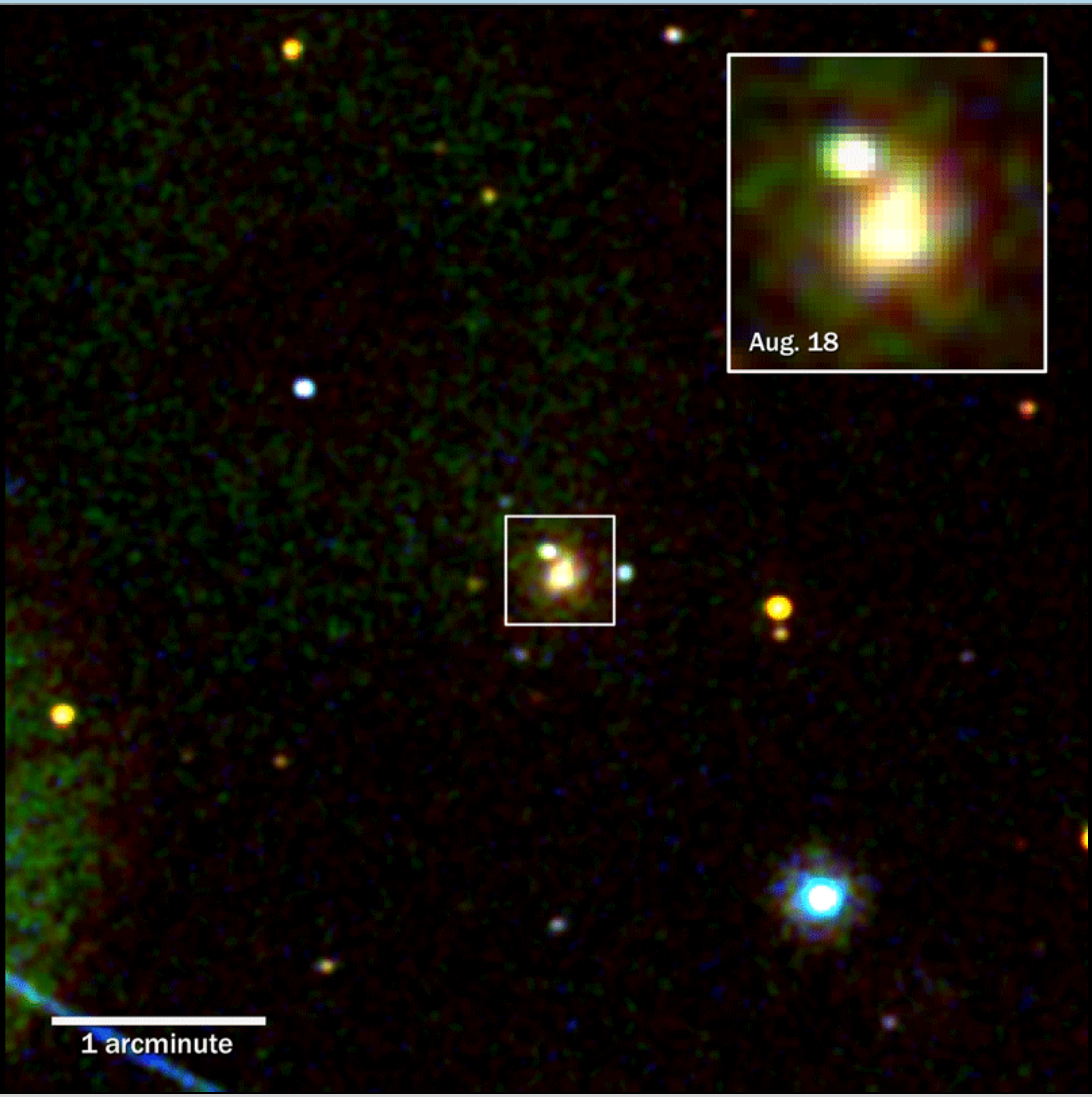

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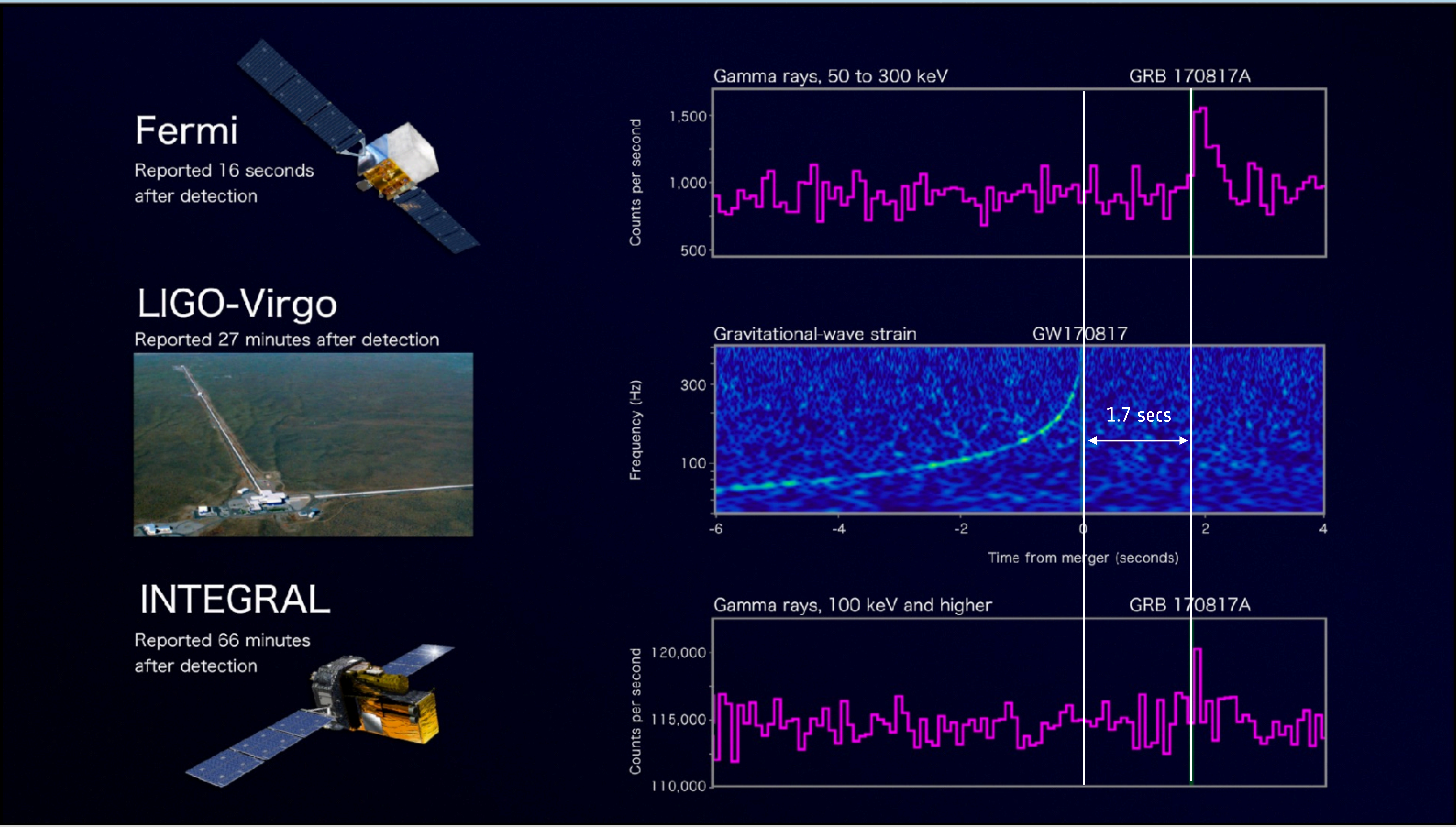
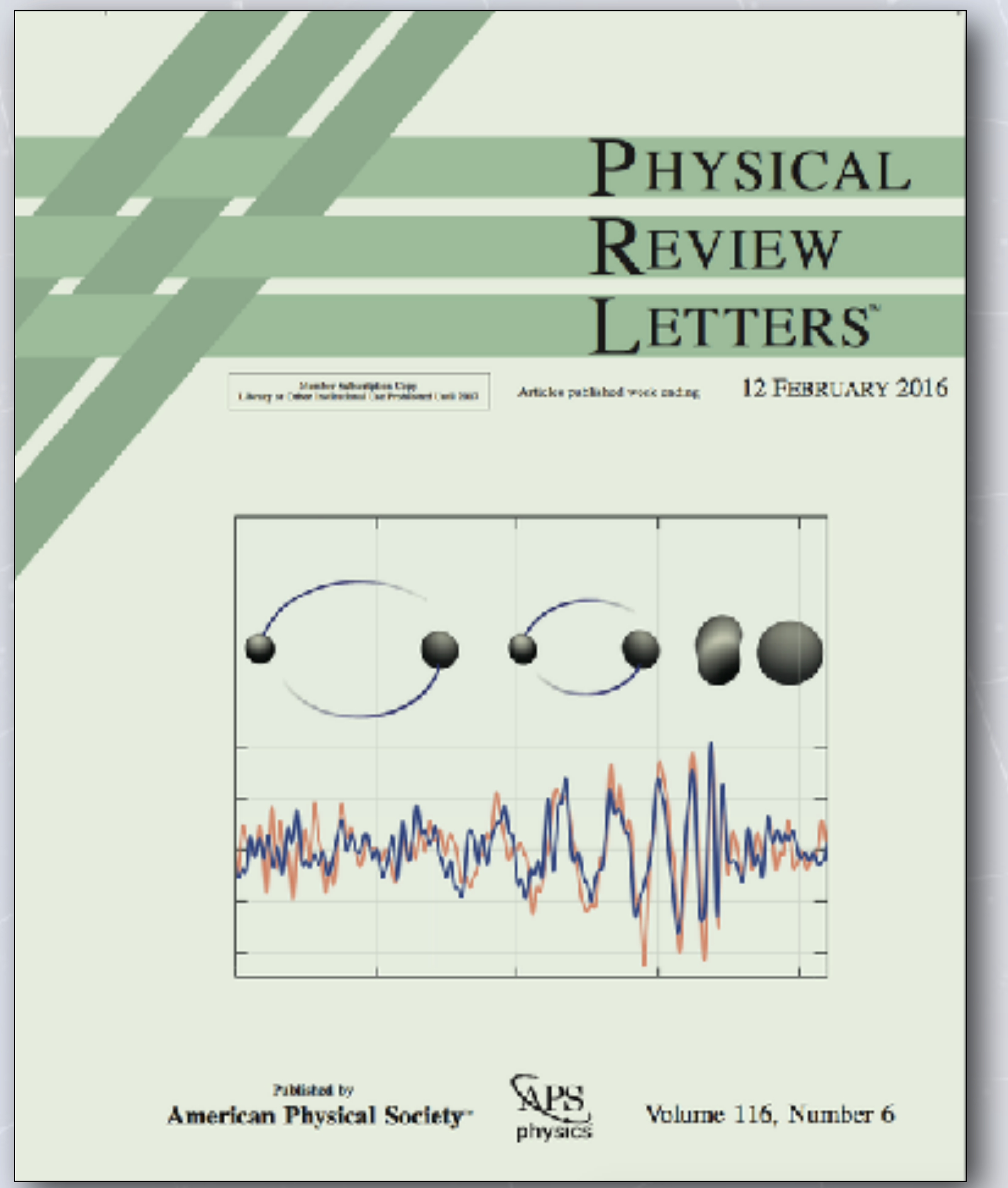


How important are these discoveries?



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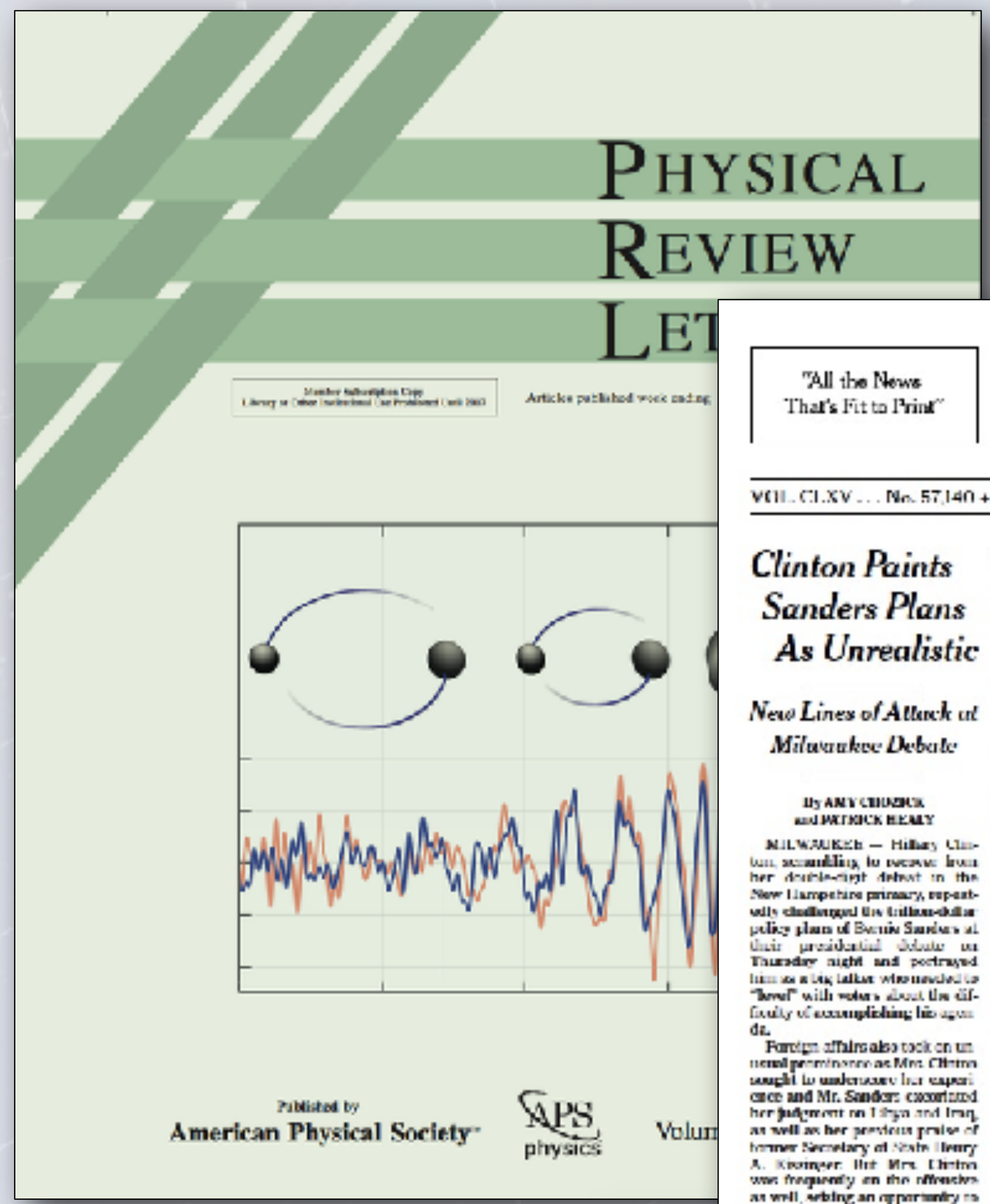

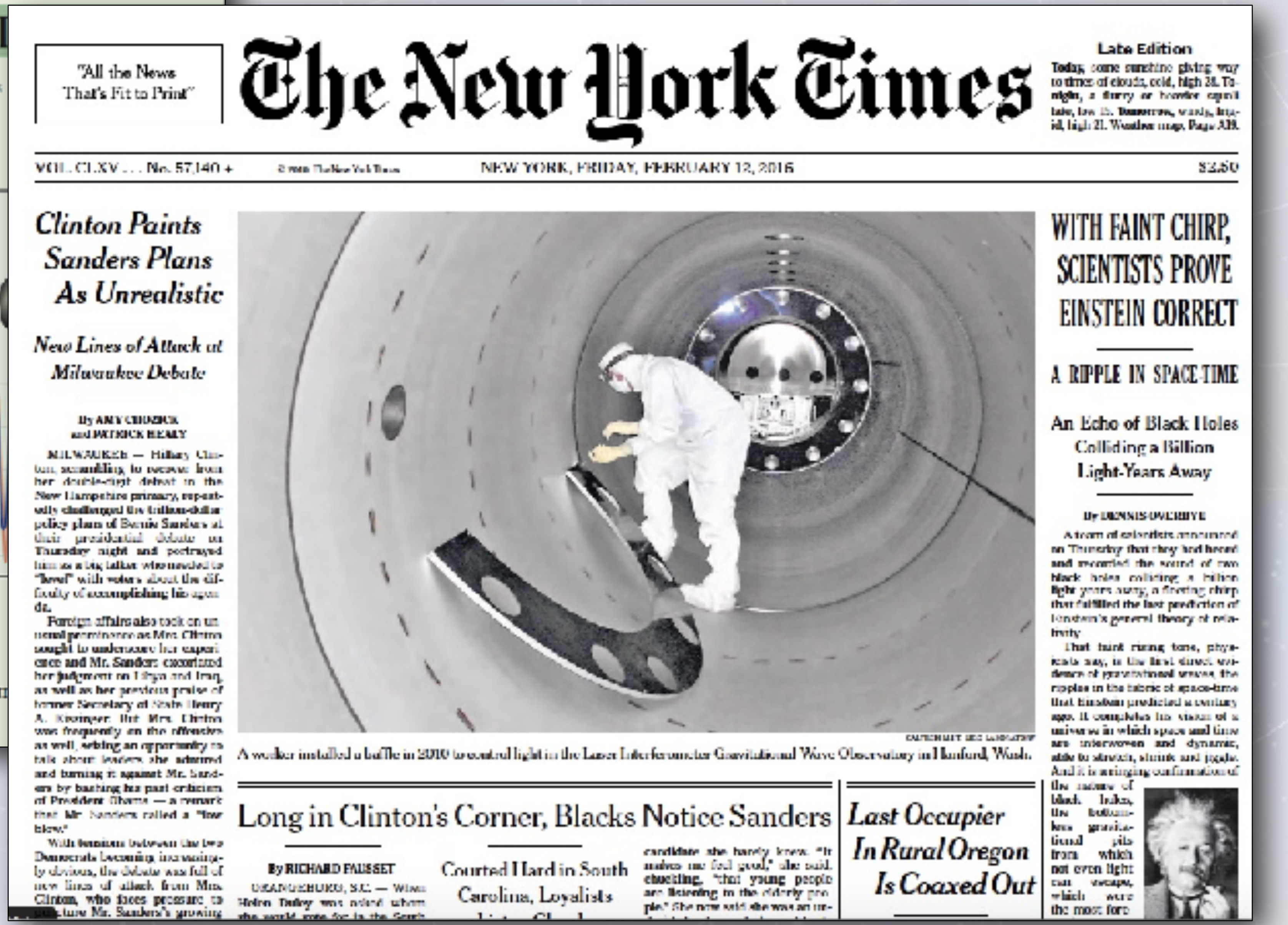

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The New York Times

Late Edition

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Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

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 worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational Wave Observatory in Hanford, Wash.

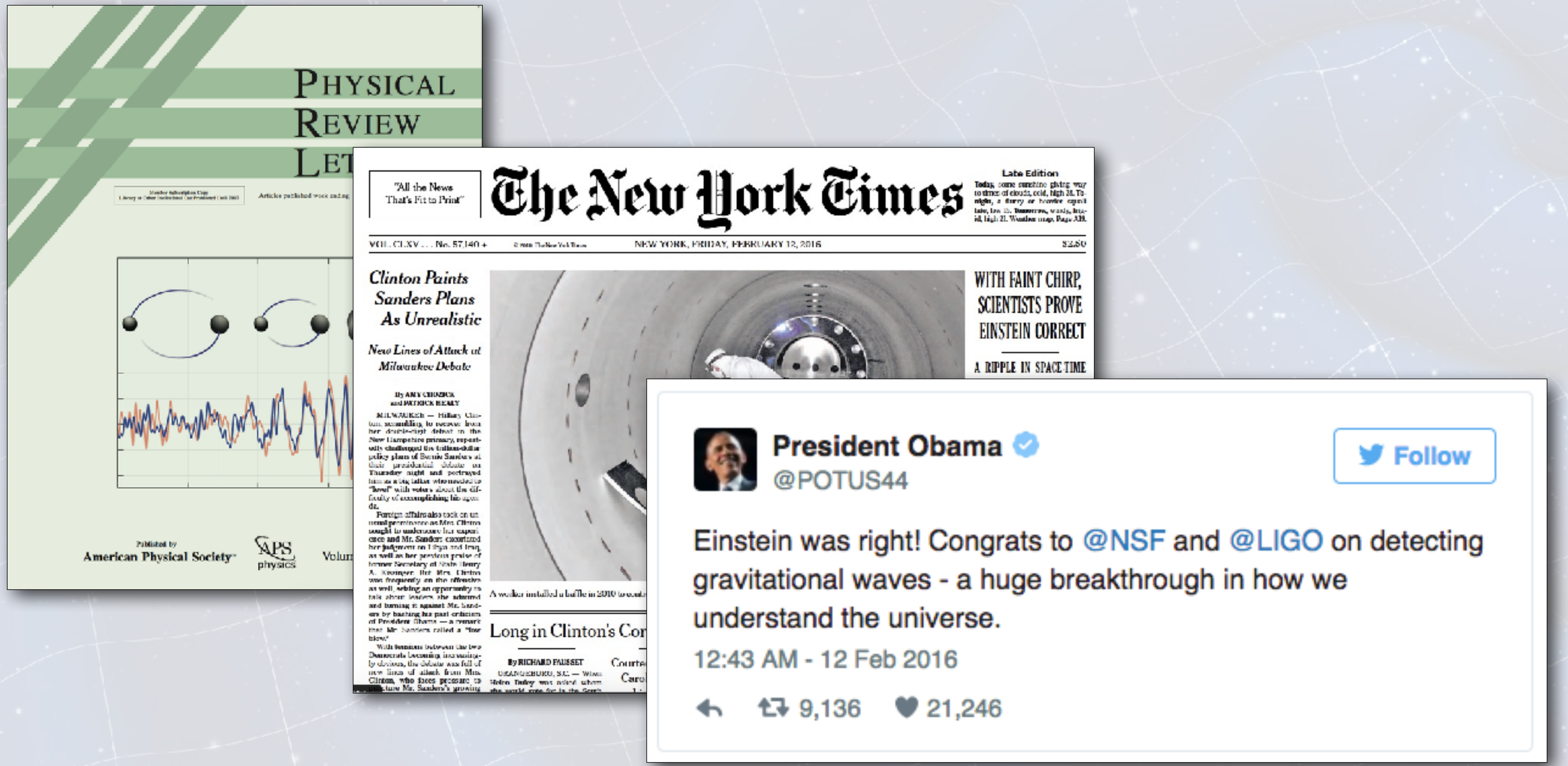
Long in Clinton's Corner, Blacks Notice Sanders

By RICHARD FAUSSET

Courted Hard in South Carolina, Loyalists

Last Occupier In Rural Oregon Is Coaxed Out

How important are these discoveries?



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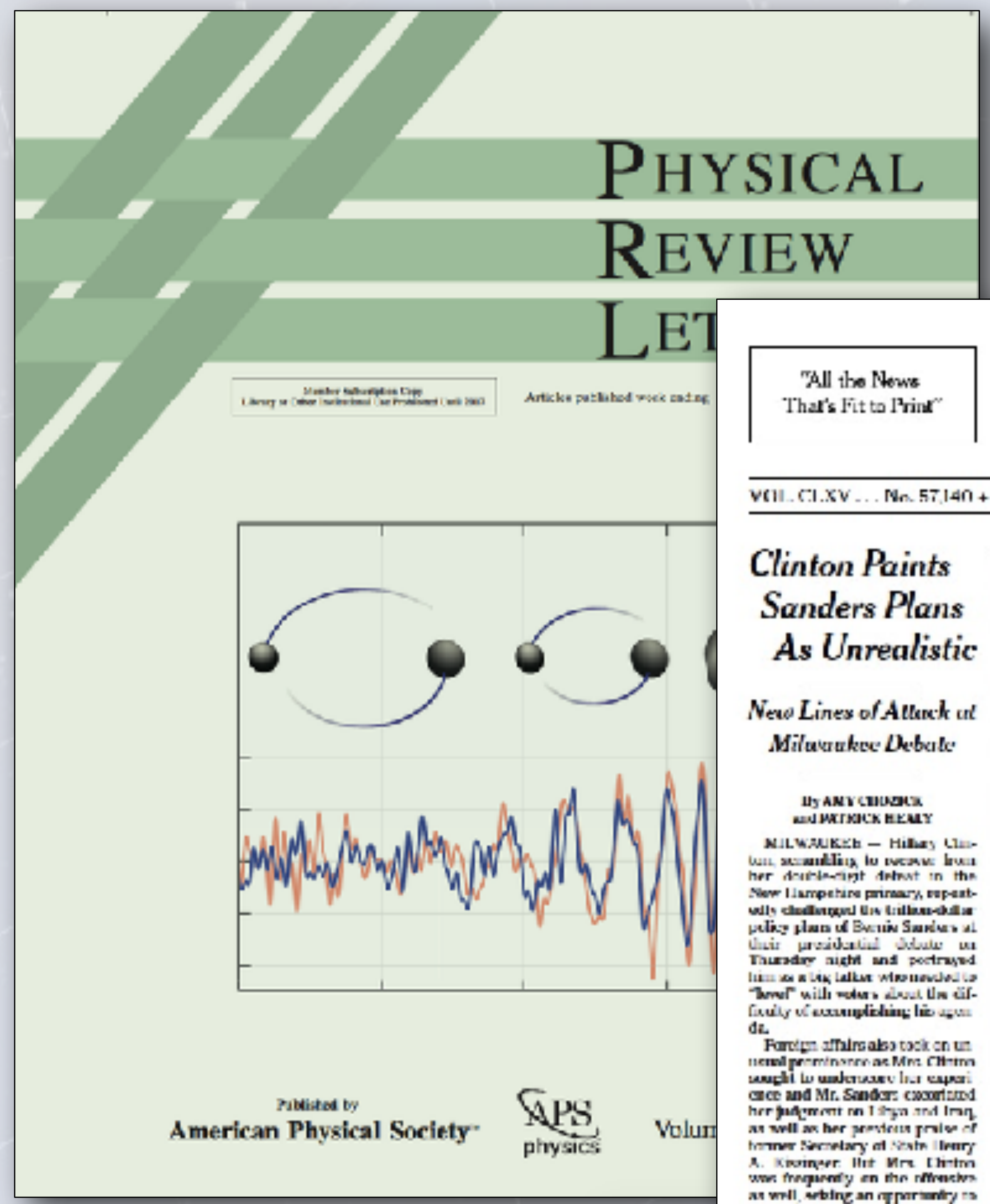
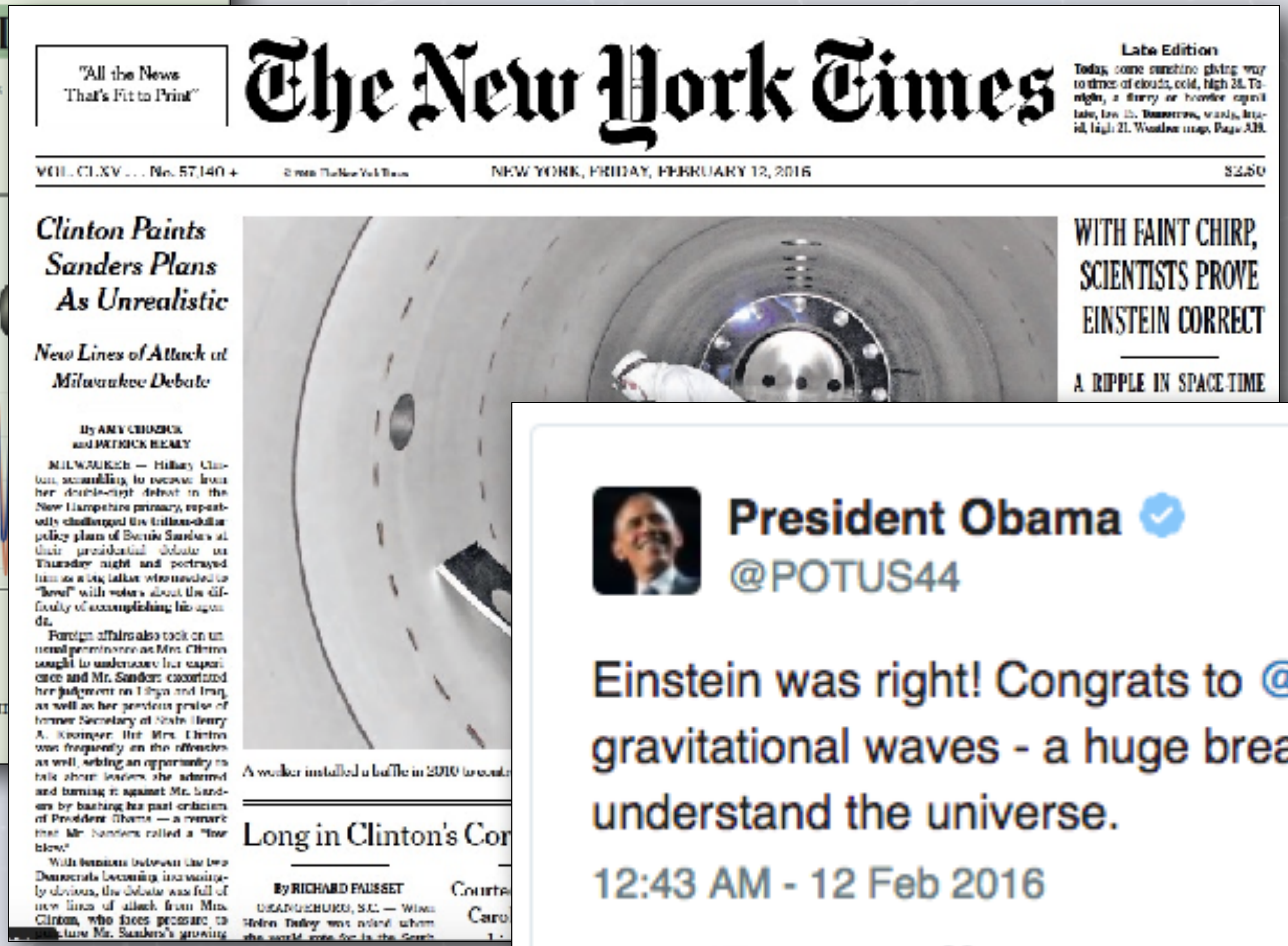
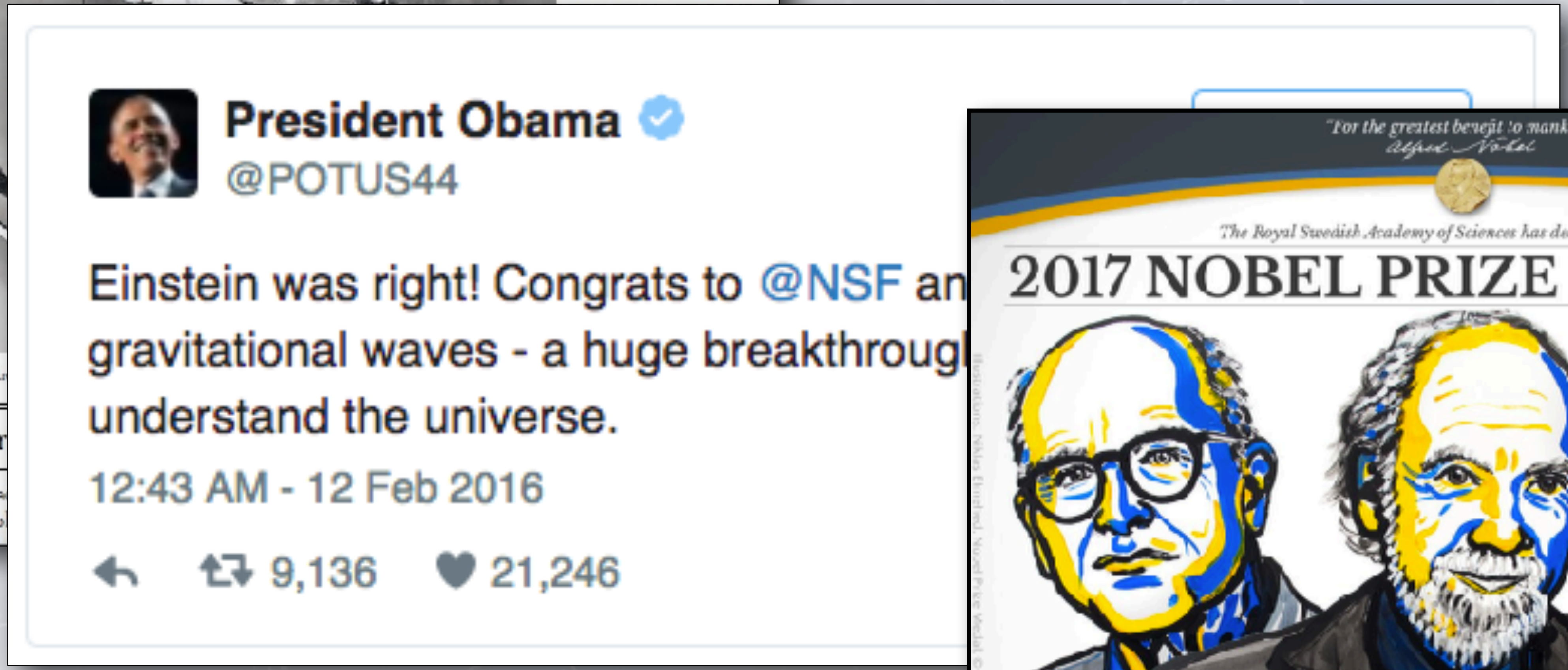
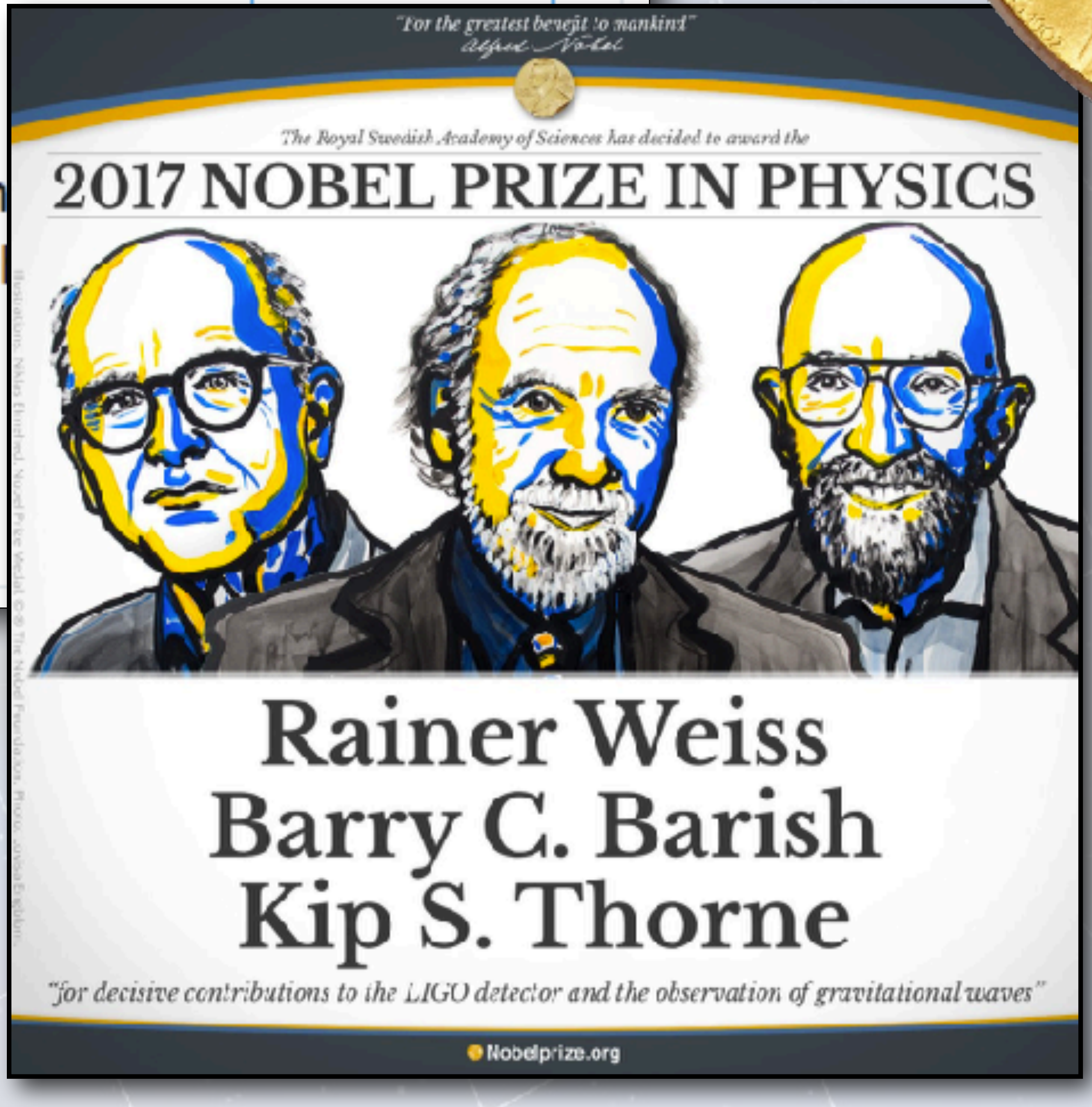


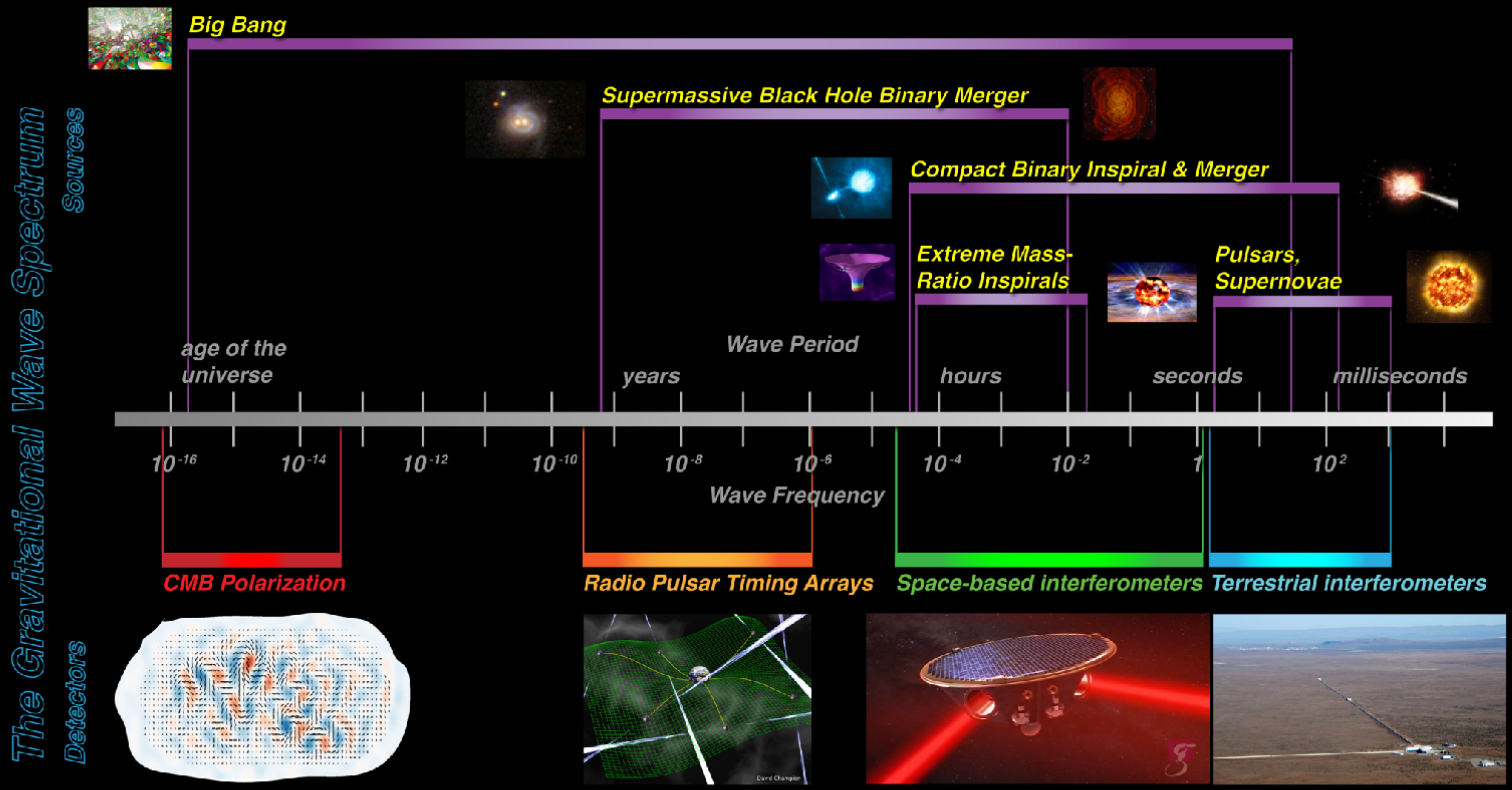






How important are these discoveries?

GW Spectrum

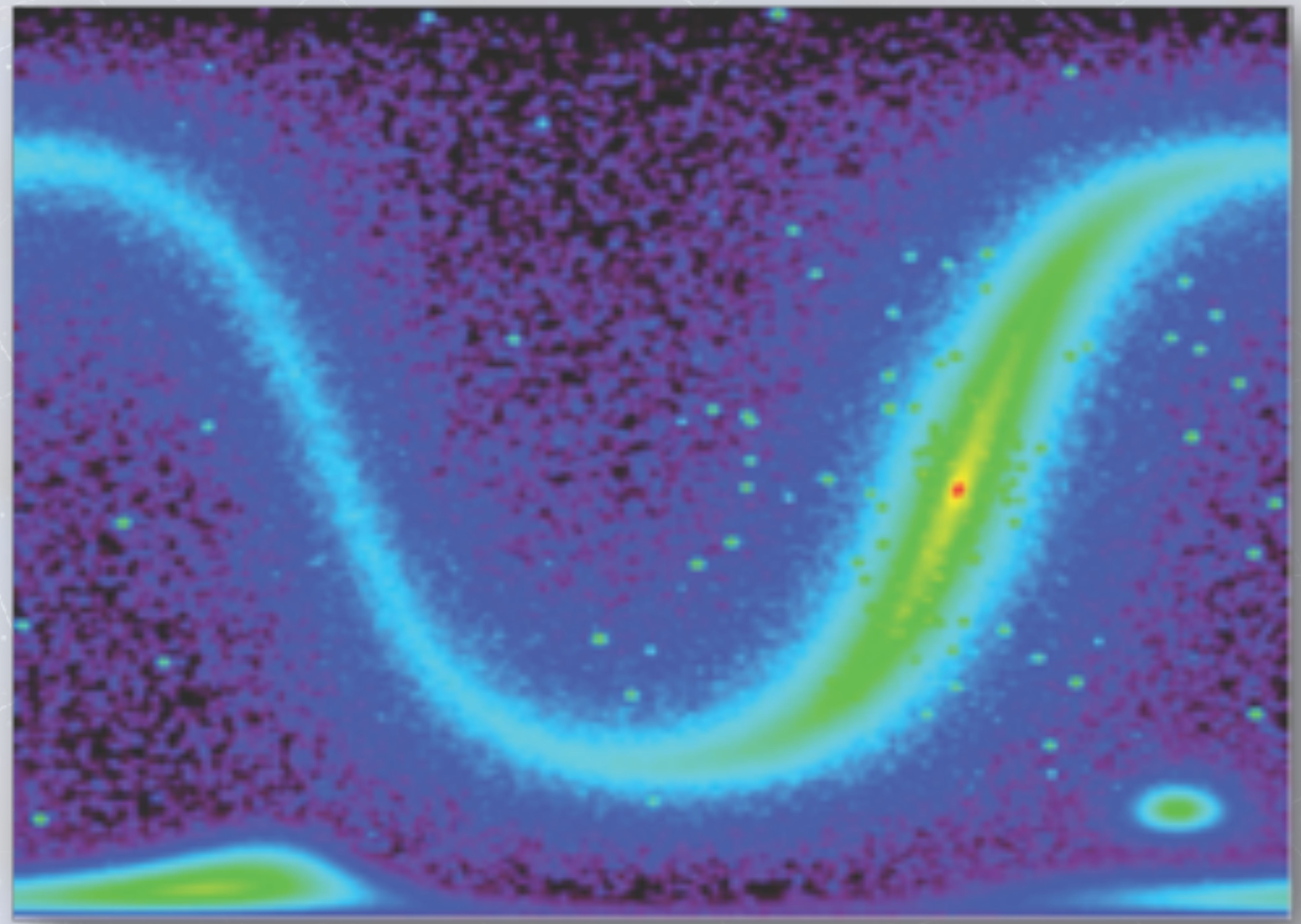


$\nu_{gw} \downarrow \quad (\lambda_{gw} \uparrow) \quad \Rightarrow \quad L_{armlength} \uparrow$

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 $d < 15$kpc
    - For ~10,000 systems, locate to <1deg² 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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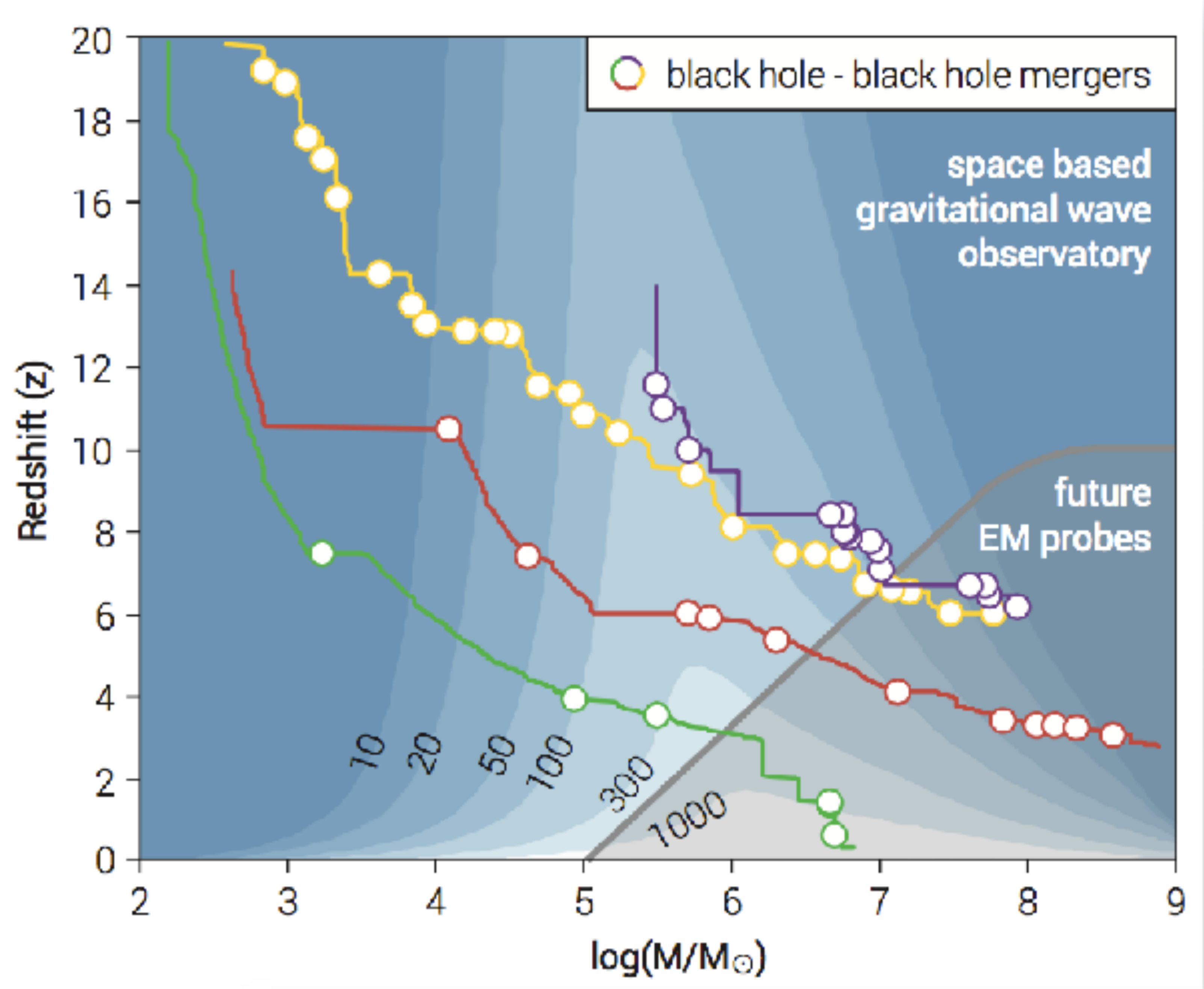
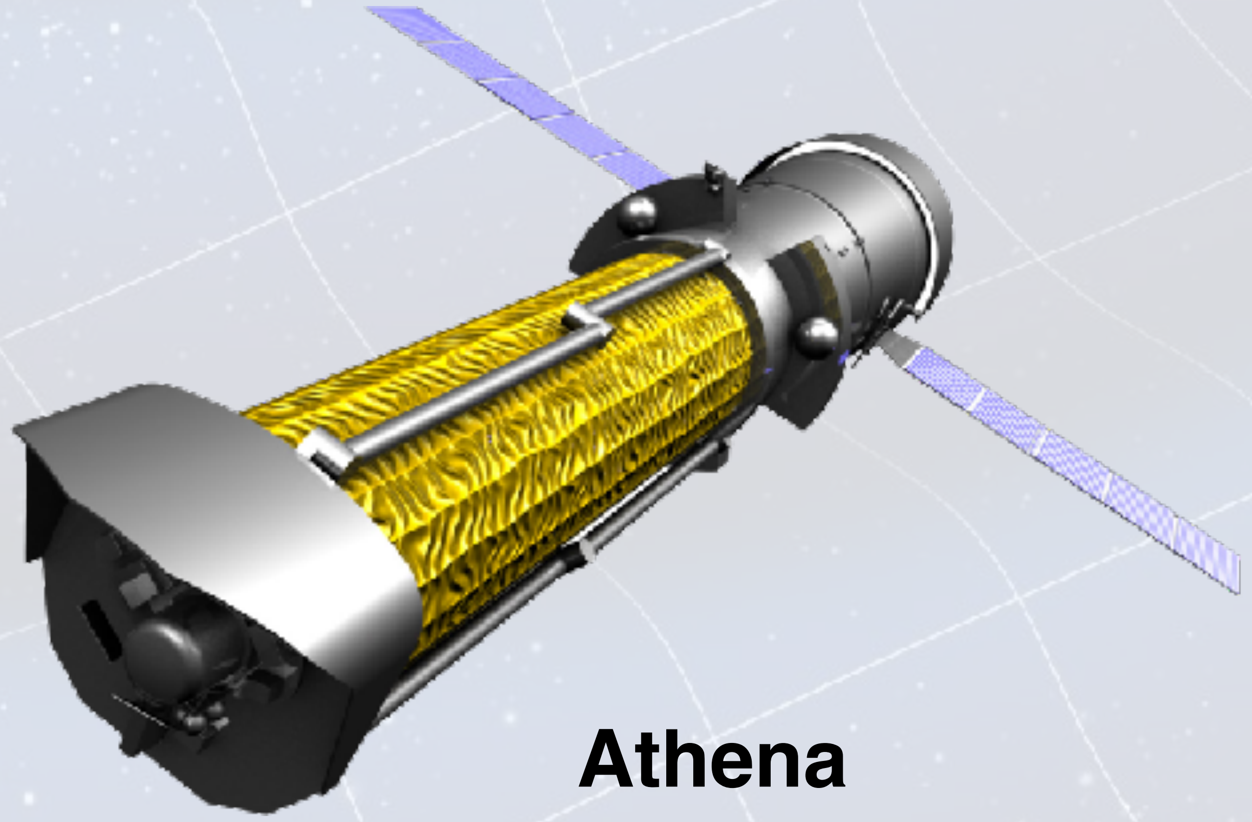
- The science objectives of LISA include:
  - Study the formation and evolution of compact binary stars in the Milky Way
  - **Trace the origin, growth and merger history of massive black holes across cosmic ages**
    - The origin of the massive/supermassive black holes powering AGN and sitting at the centres of today's galaxies is unknown
    - LISA will be able to observe seed black holes back to Cosmic Dawn

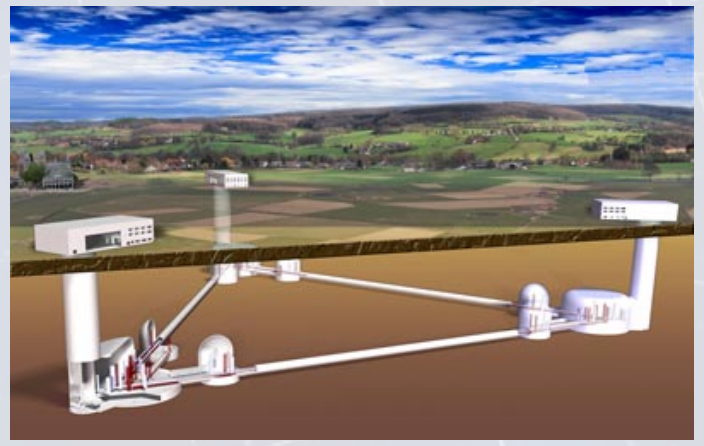


- ***Objectives:***
  - Observe the first compact objects in the Universe (seed black holes) out to z~15
  - Masses, and distance to Supermassive Black Hole mergers ($10^6 M_\odot$) mergers at z<9
    - Masses to 1%, Distance to 10%, Spin to 1-10% precision
  - Sky location to <10deg² for SMBH mergers at z ~2 for EM follow-up



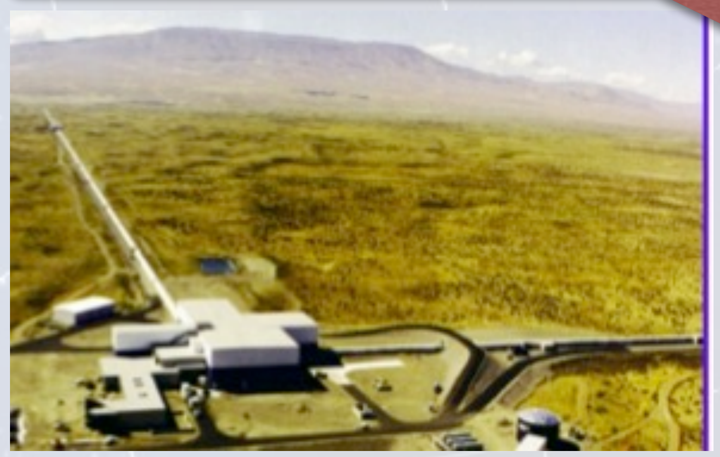
Athena

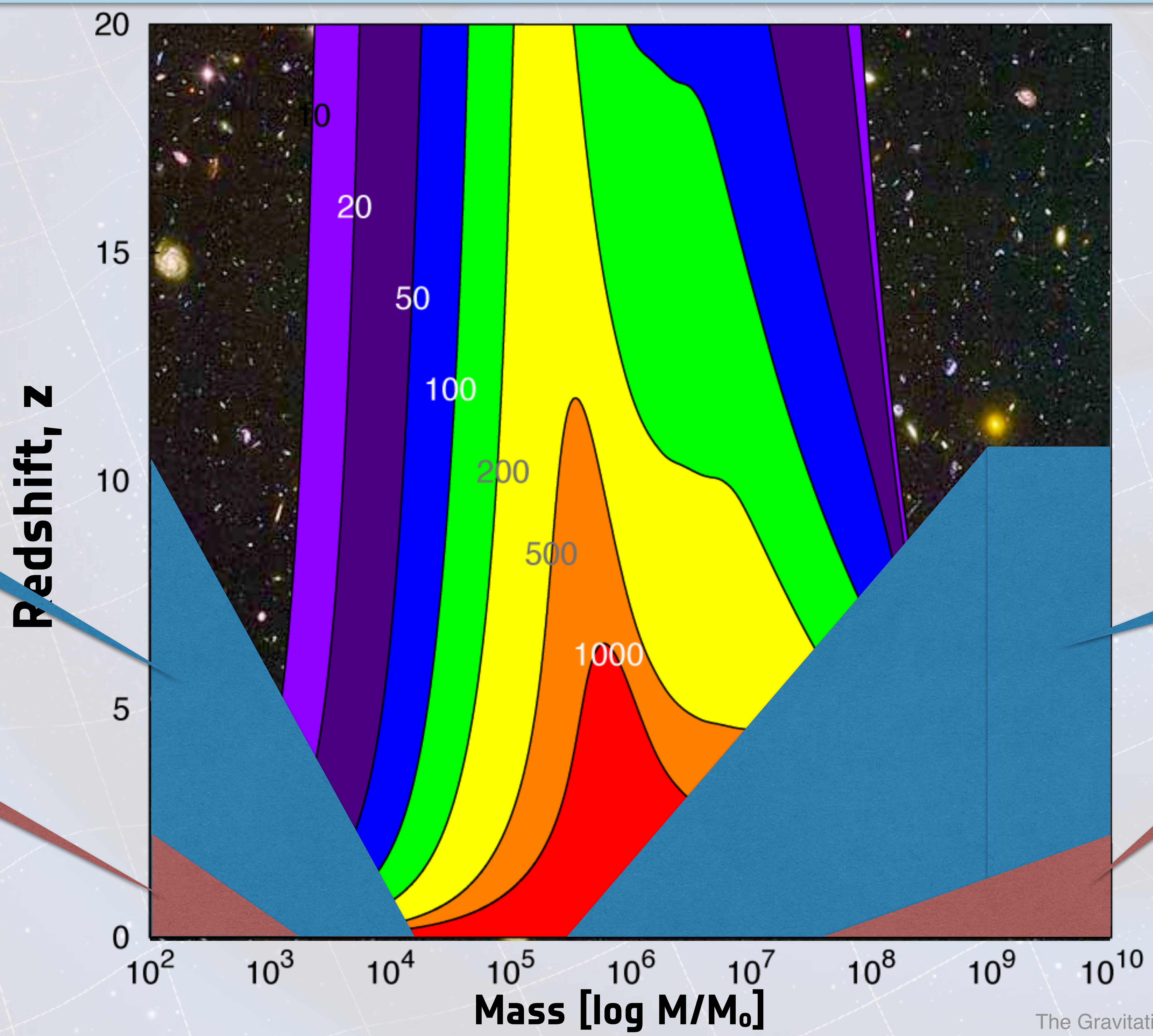
Black Hole Astronomy in the 2030s

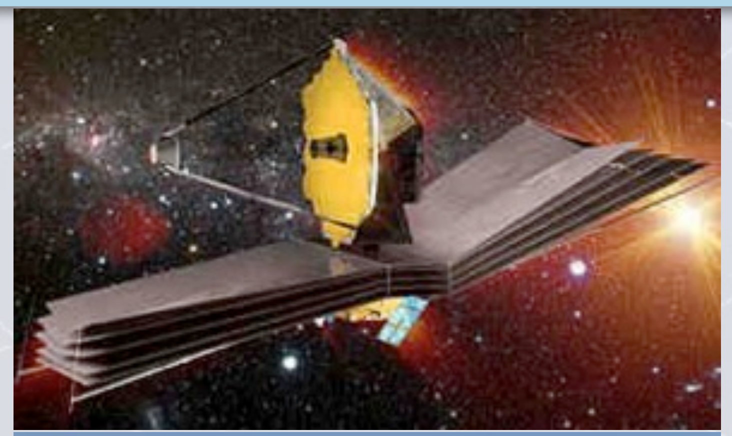


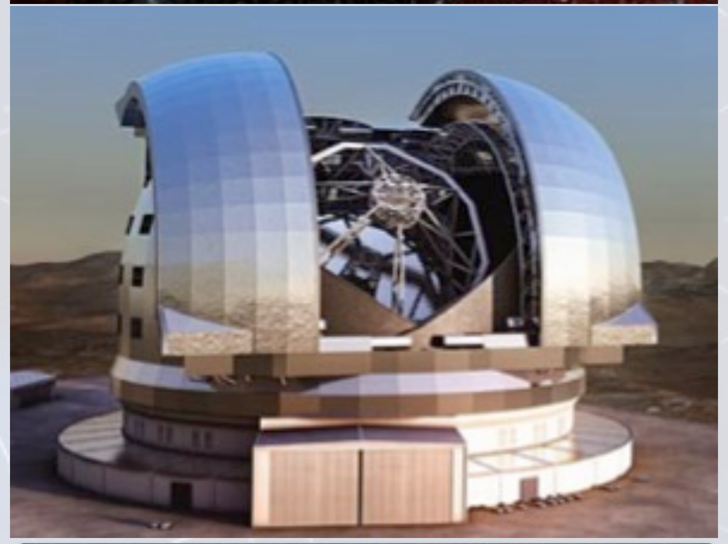
Future ground based detectors e.g. Einstein Telescope

Current ground based GW detectors



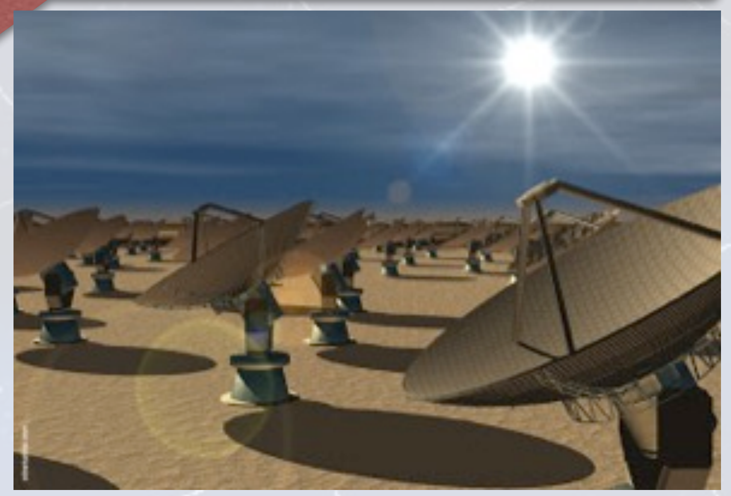






Future EM obs. e.g. LSST, JWST, EELT

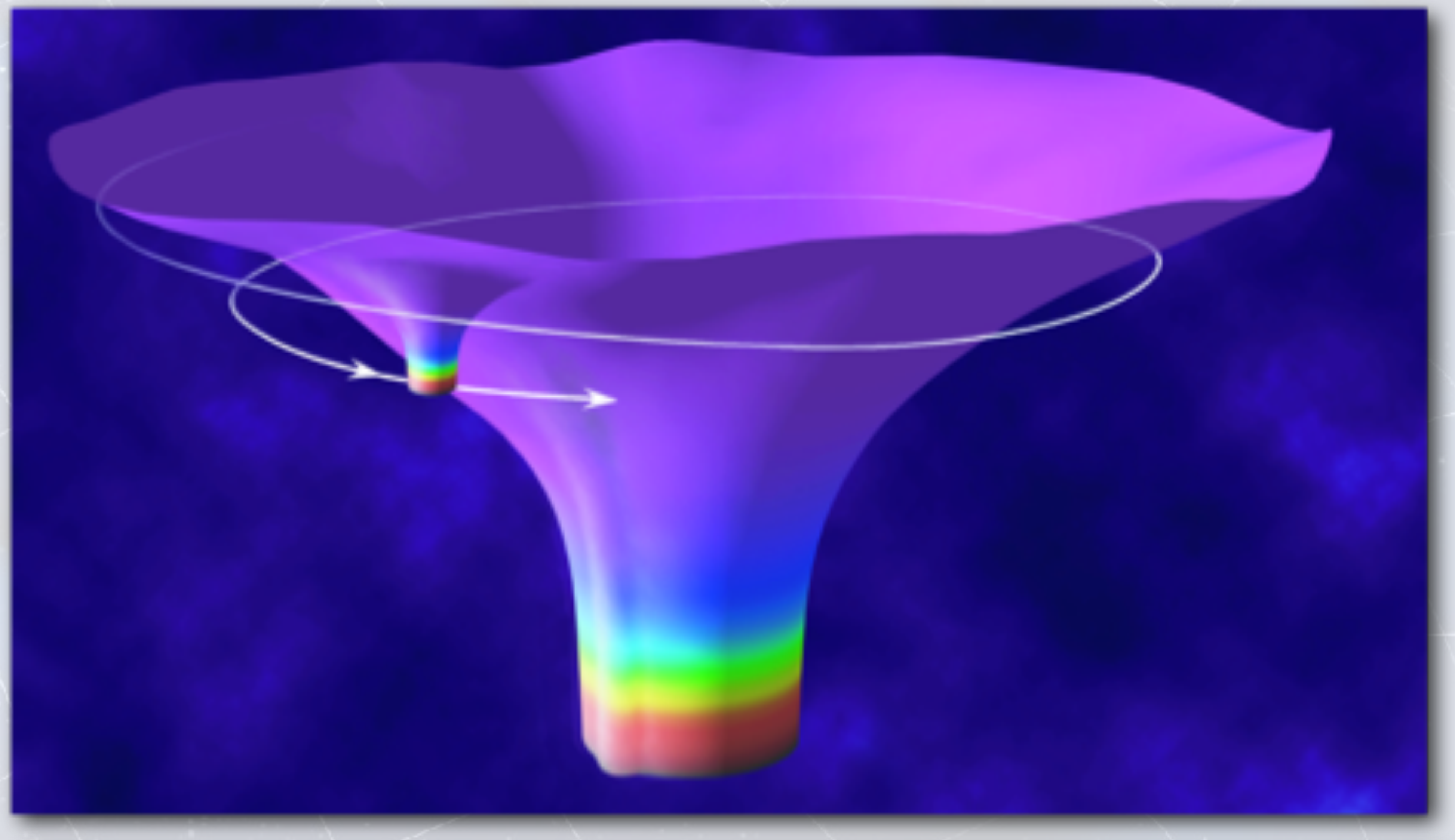
SKA, Pulsar Timing

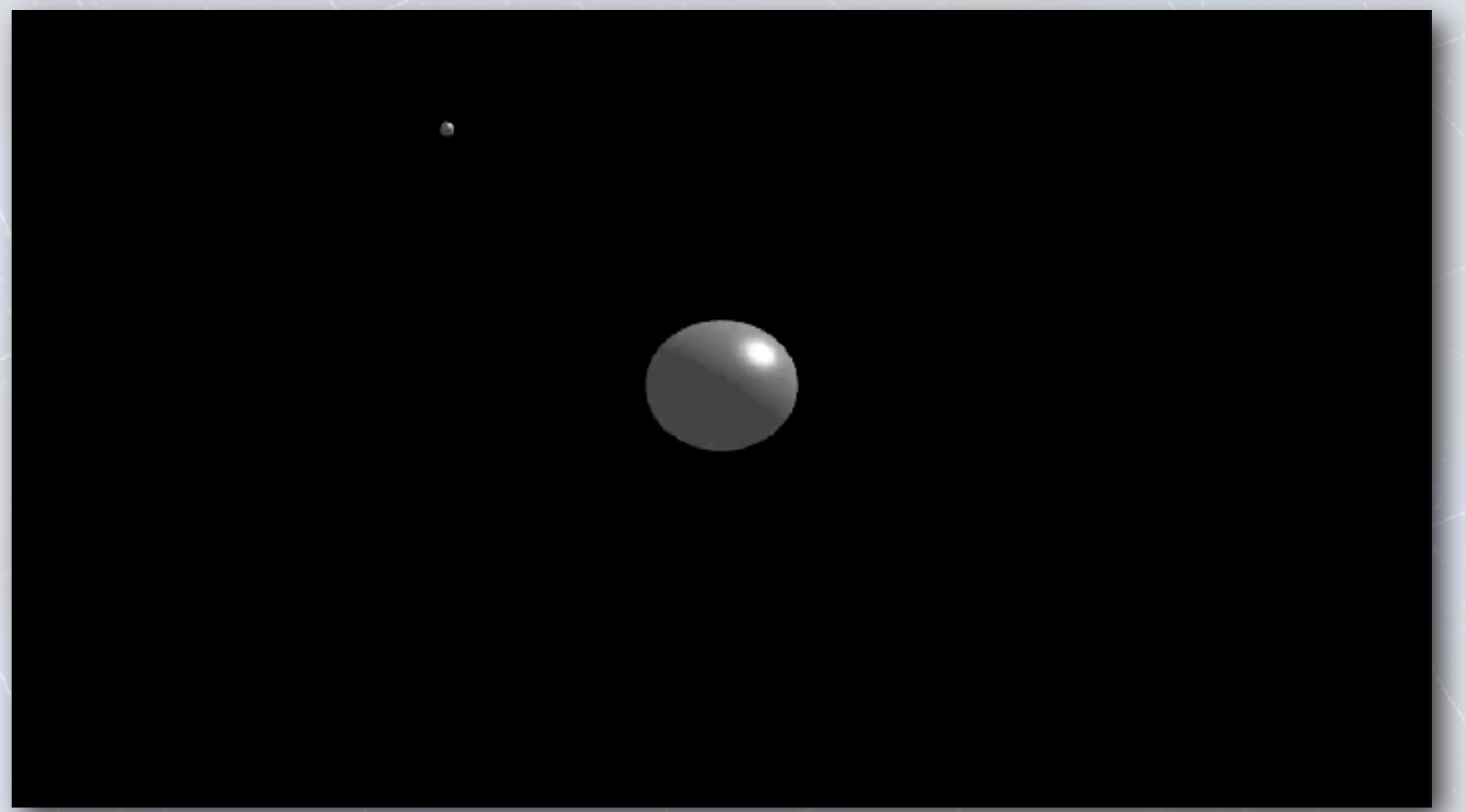


What will we learn with LISA?

- 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 10-60$M_\odot$ into MBH of 10^5-$10^6 M_\odot$
    - EMRIs are essentially the perfect laboratory to test GR in the strong field regime
      - The SOBH spends ~10^3-10^5 orbits in close proximity to the MBH, displaying extreme forms of perisastron 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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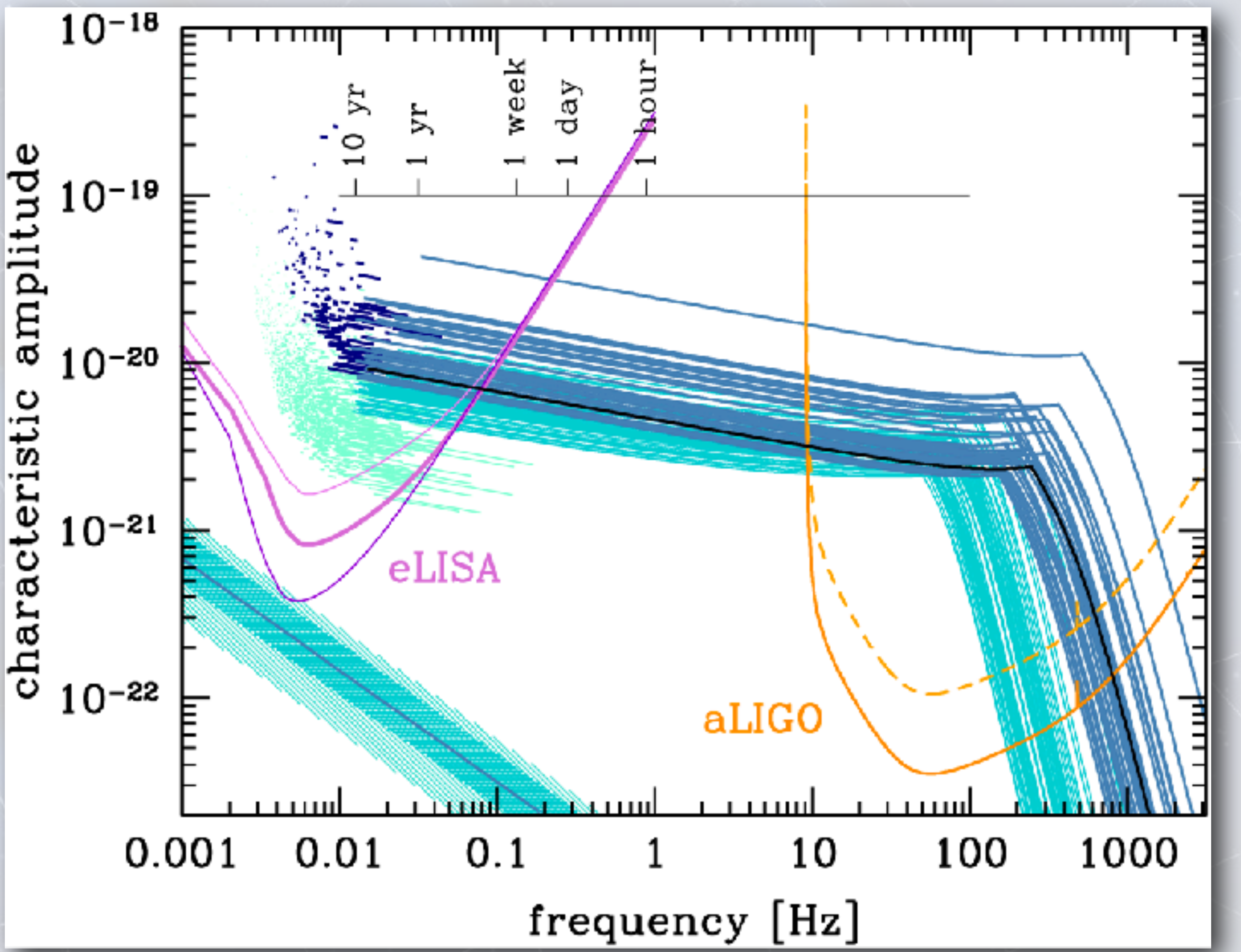
  - Probe the dynamics of dense nuclear clusters using EMRIs
  - **Understand the astrophysics of stellar origin black holes**
    - As the SOBH inspiral towards final merger, the gravitational wave signal will *sweep* through the LISA band
    - LISA will observe the inspiral or months to years prior to merger
      - The signal will leave the LISA band weeks before final merger



- ***Objectives:***
  - Sky location of <1deg² of GW150914-like events (SNR>7 after 3 years integration)
  - Orbit eccentricity to better than 1 part in 10^3

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  - 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

LISA Science

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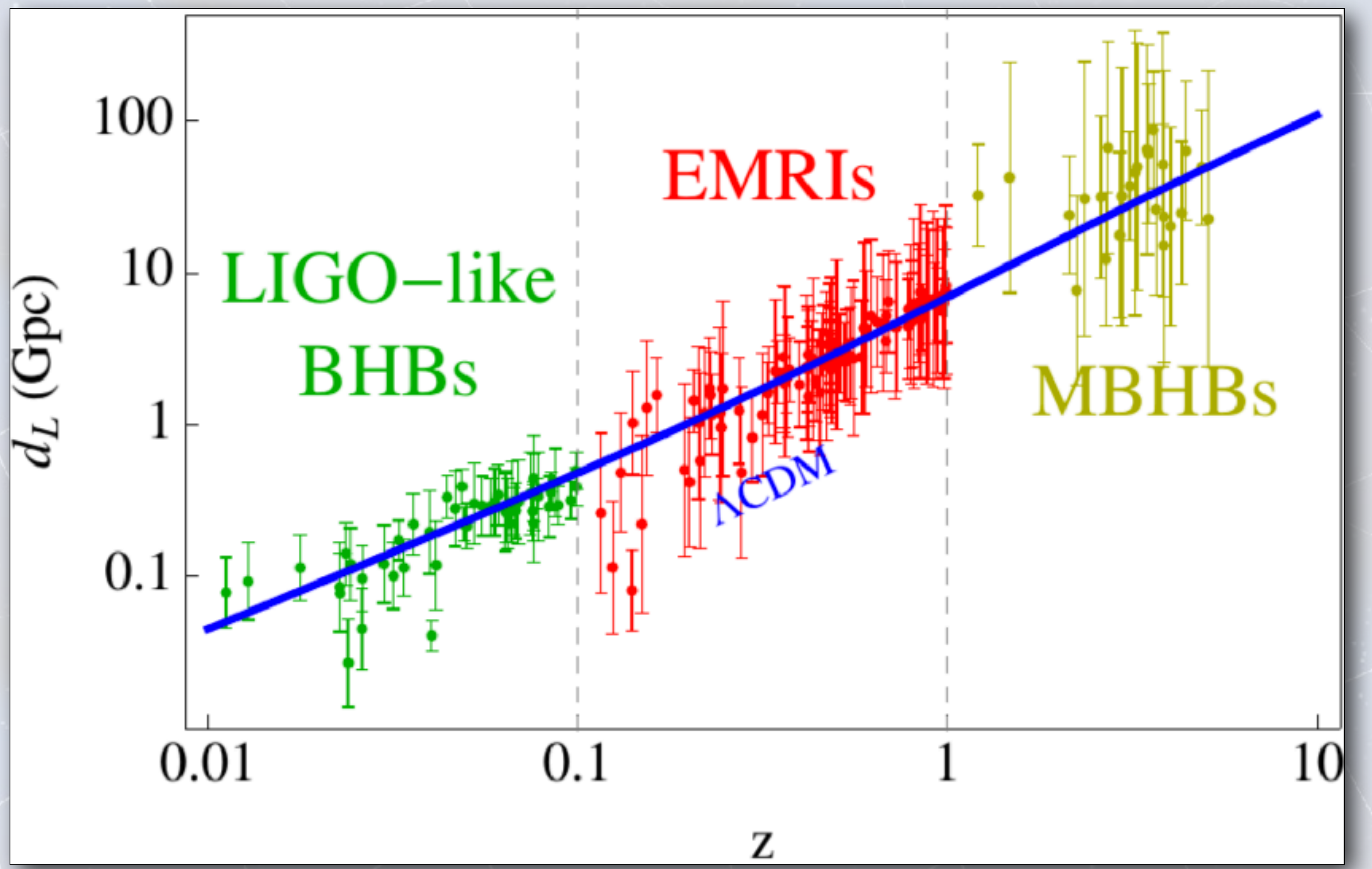
  - Explore the fundamental nature of gravity and black holes
  - **Probe the rate of expansion of the Universe**
    - Source distance is proportional to GW amplitude, chirp rate, and GW polarisation
    - GW sirens: EMRIs (z<1.5), SMBHB (z<6)

- **Objectives:**
  - H_o with accuracy of <1% with only GW observations
    - Improved if we also observe the source e.g. with Athena



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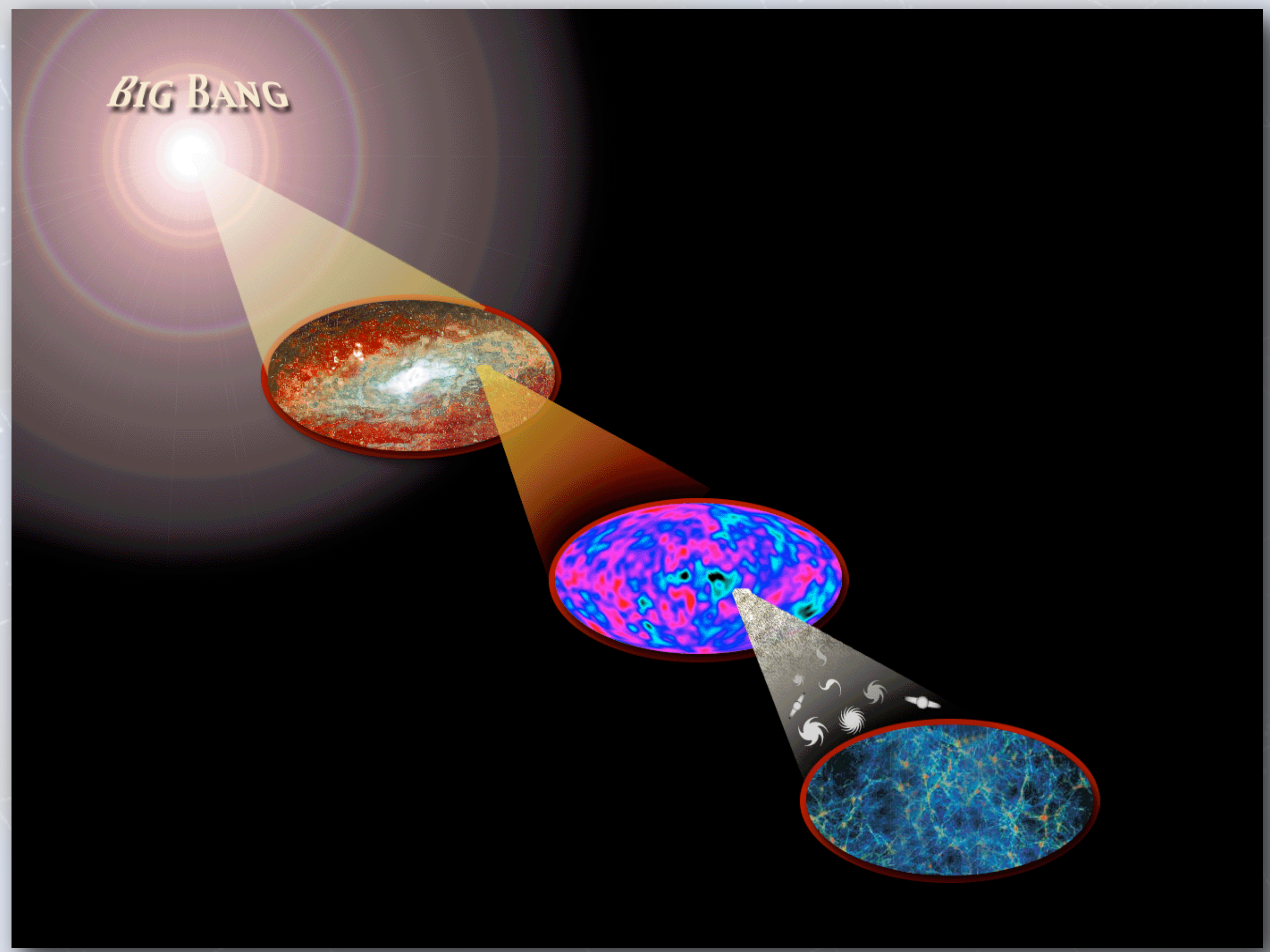
  - Probe the rate of expansion of the Universe
  - **Understand stochastic GW backgrounds and their implications for the early Universe**
    - LISA goal is to directly detect a stochastic GW background of cosmological origin
    - The shape of the signal gives an indication of its origin, while an upper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



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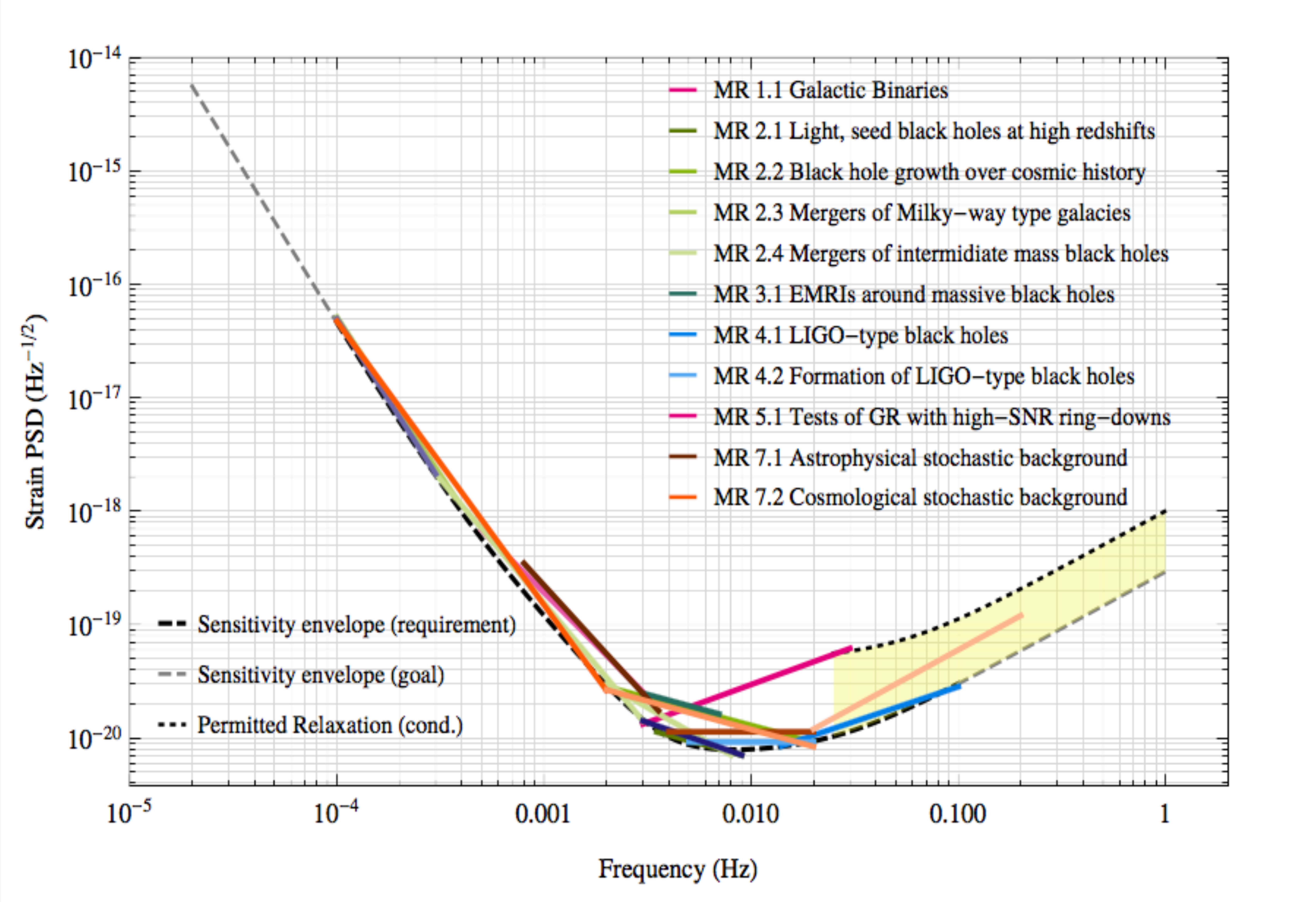
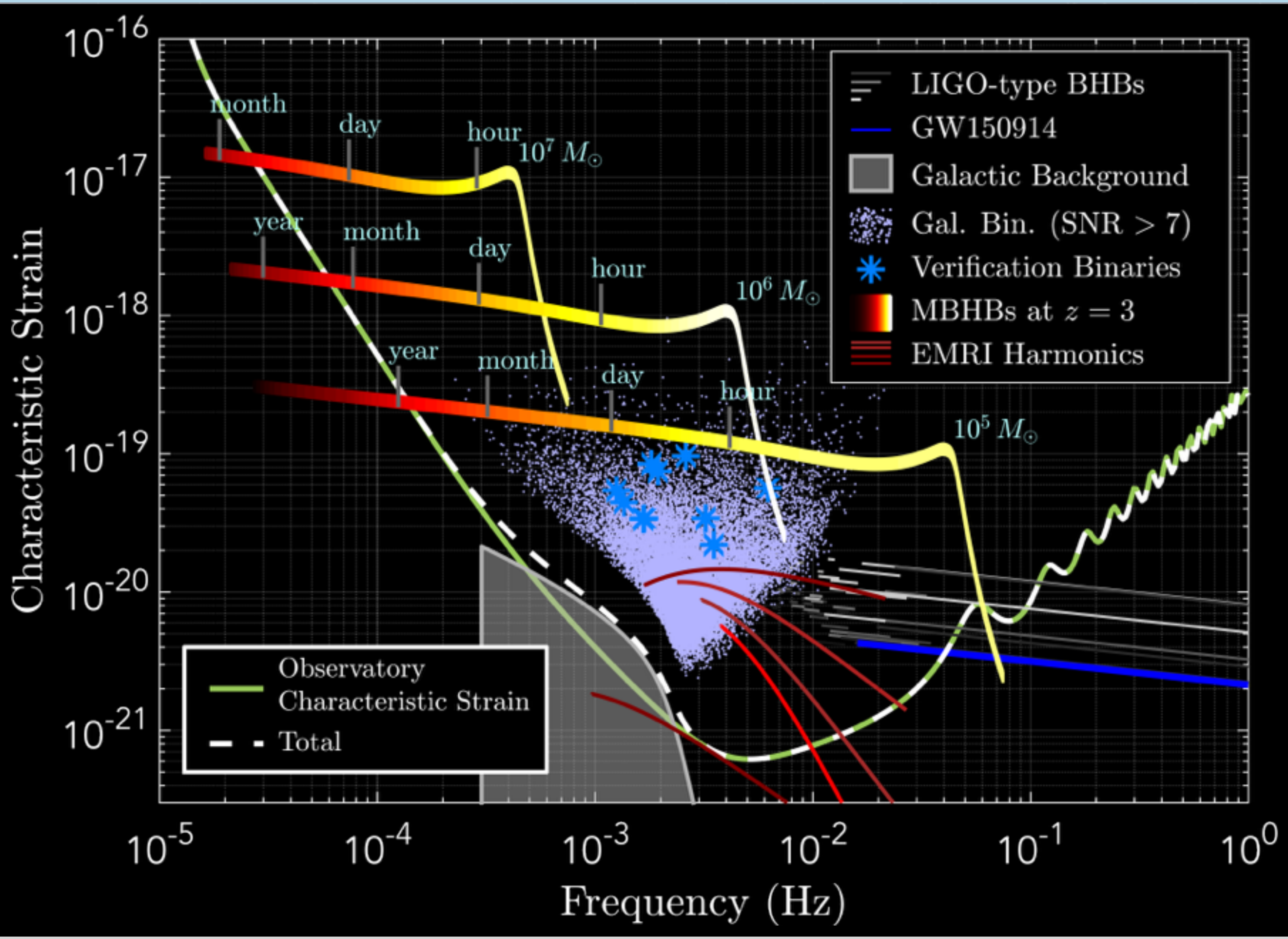
  - Probe the rate of expansion of the Universe
  - Understand stochastic GW backgrounds and their implications for the early Universe
  - **Search for GW bursts and unforeseen sources**
    - First LIGO observations came from unexpected sources…

      …what will LISA see?

LISA discovery space



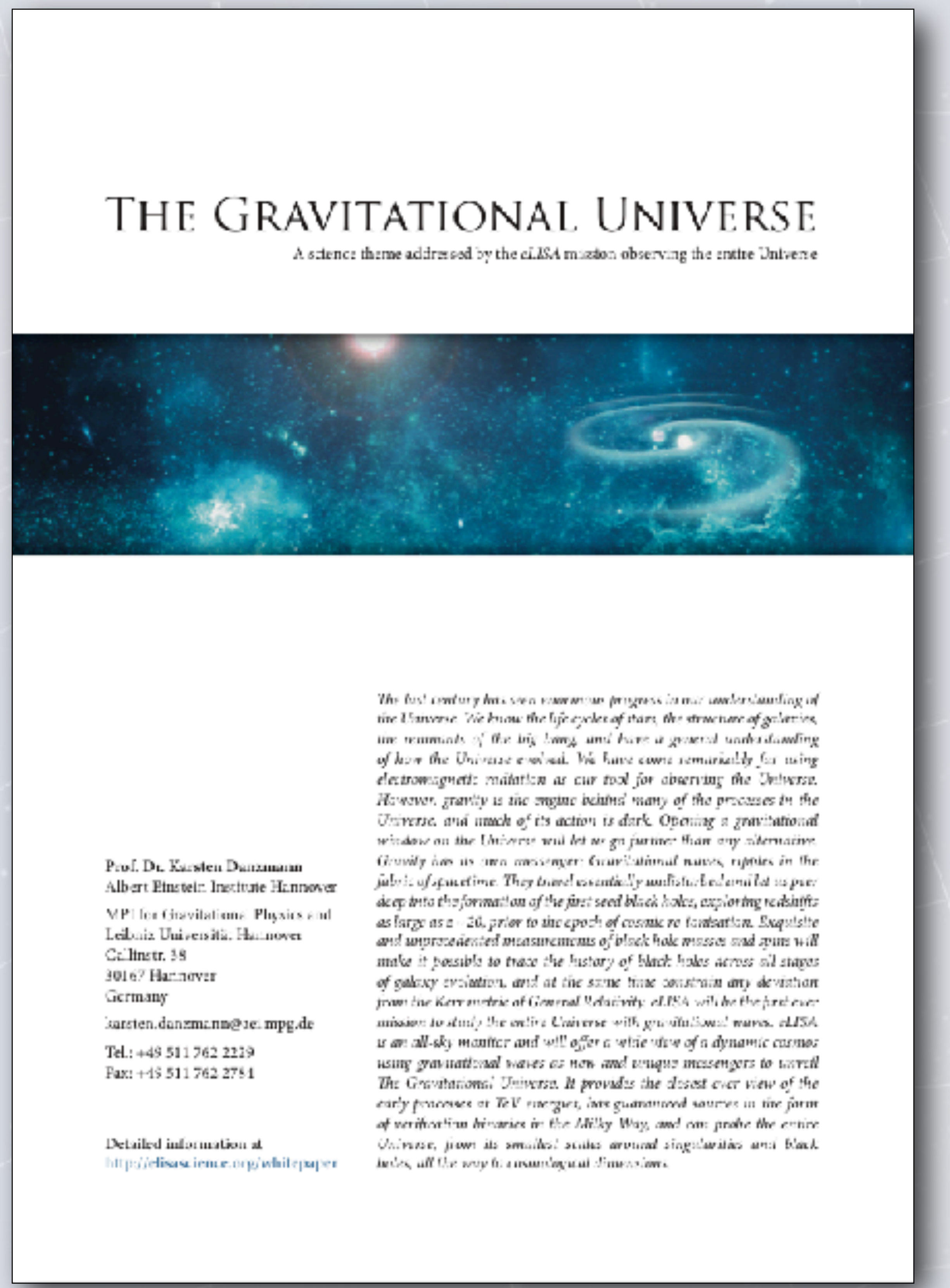
LISA discovery space



L3 - LISA


1st International LISA Symposium
Rutherford Appleton Laboratory
1996

L3 - LISA



THE GRAVITATIONAL UNIVERSE

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

Prof. Dr. Karsten Danzmann
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Fax: +49 511 762 2784

Detailed information at
http://elisascience.org/whitepaper

L3 - Gravitational Universe Science Theme (May 2013)

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SPC, SSAC, Working Groups and Scientific Community

Our ref. D/SCI/LC/ug-2966

Paris, 25October 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

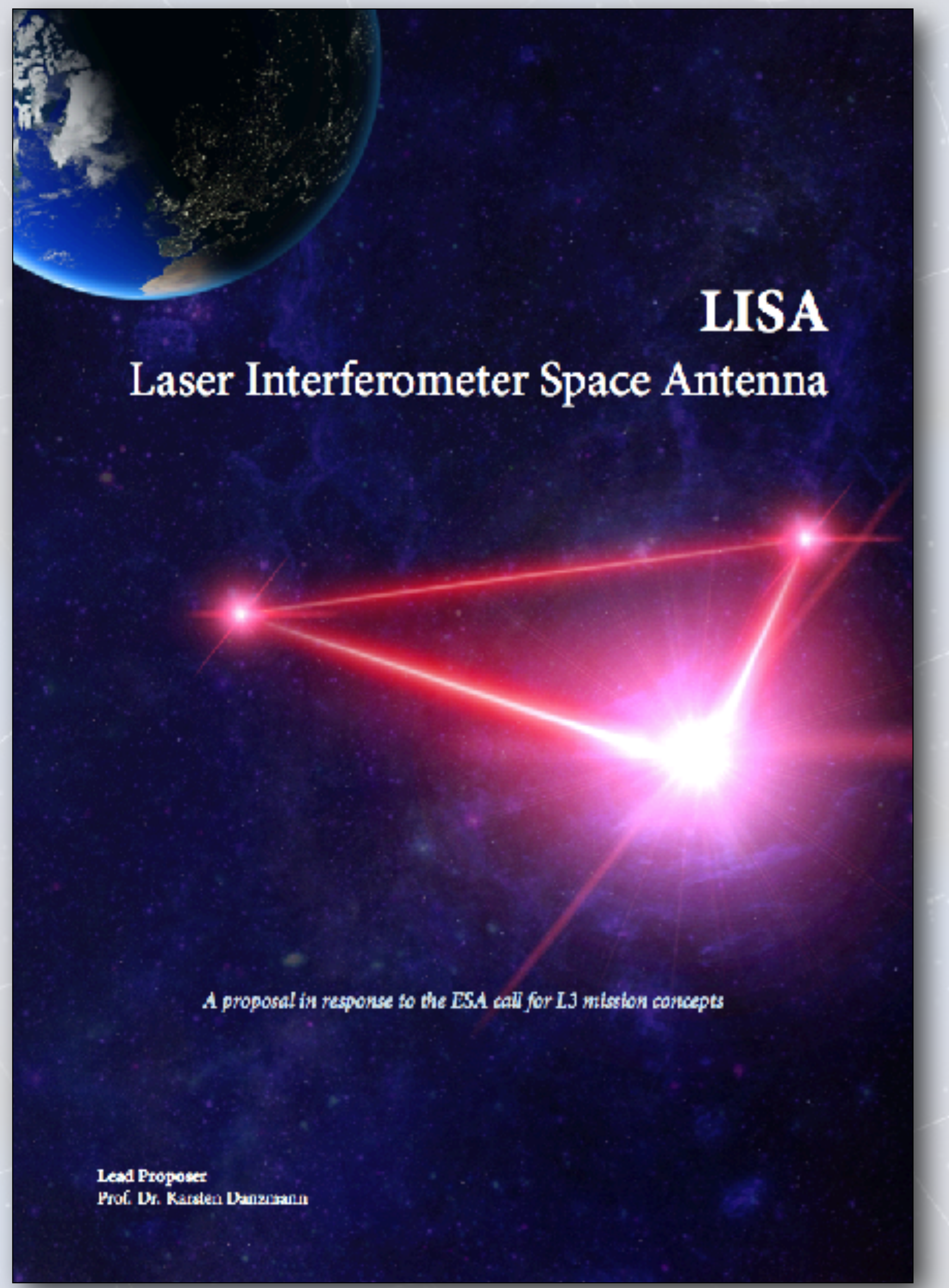
Please note that submission of a Letter of Intent is mandatory, with a deadline of 15 November 2016 (12:00 noon CET).

Your sincerely,

Prof. Alvaro Giménez
Director of Science

European Space Agency
Agence spatiale européenne

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

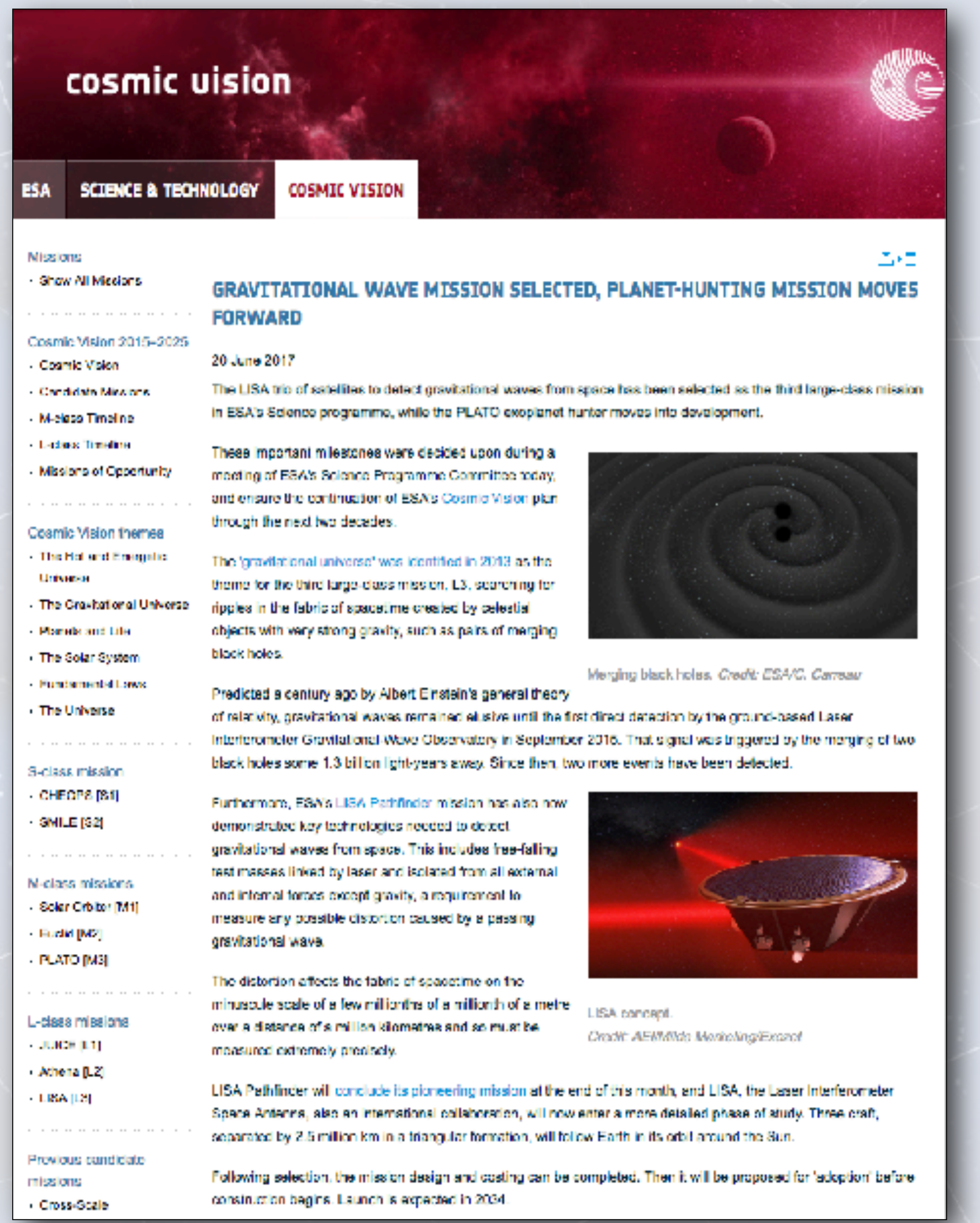


LISA
Laser Interferometer Space Antenna

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

Lead Proposer
Prof. Dr. Karsten Danzmann

LISA Proposal (January 2017)



cosmic vision

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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.

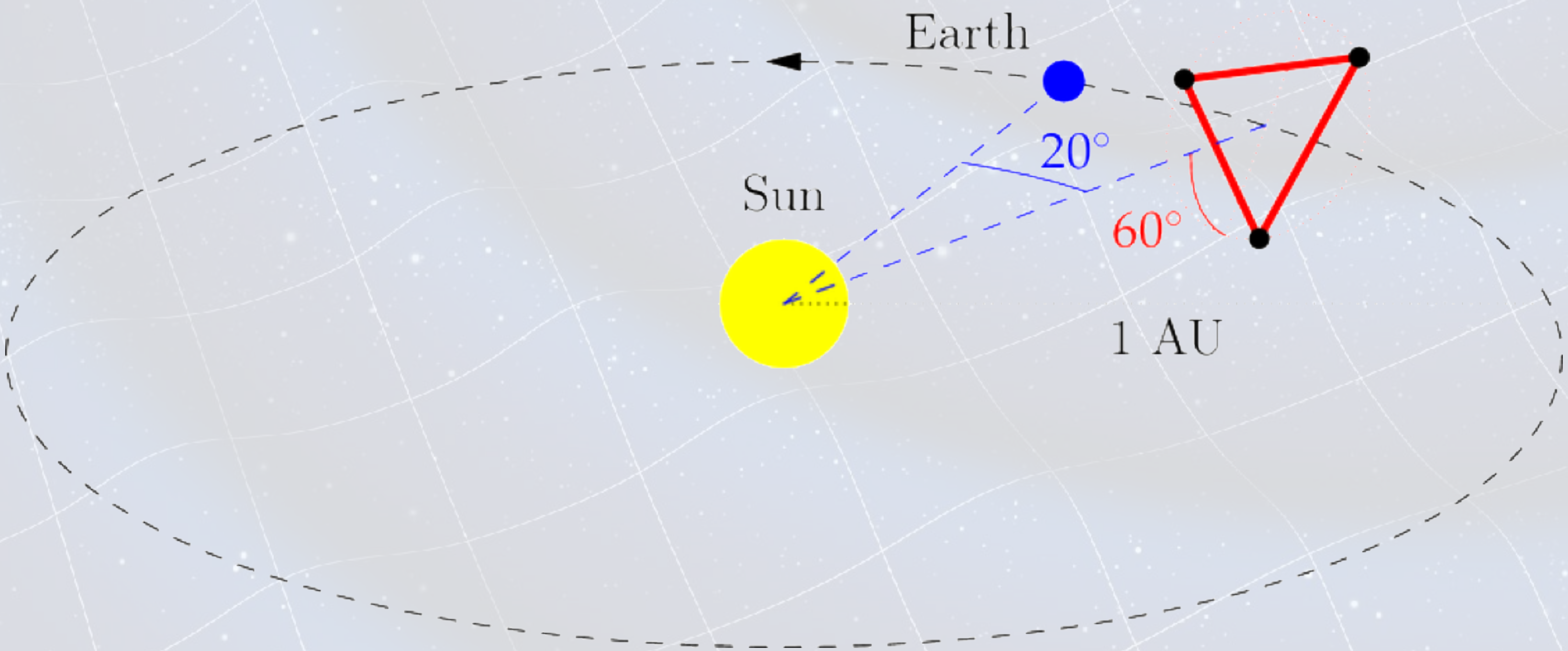
Merging black holes. Credit: ESA/C. Carreau

LISA concept

LISA Selected as L3 mission (June 2017)

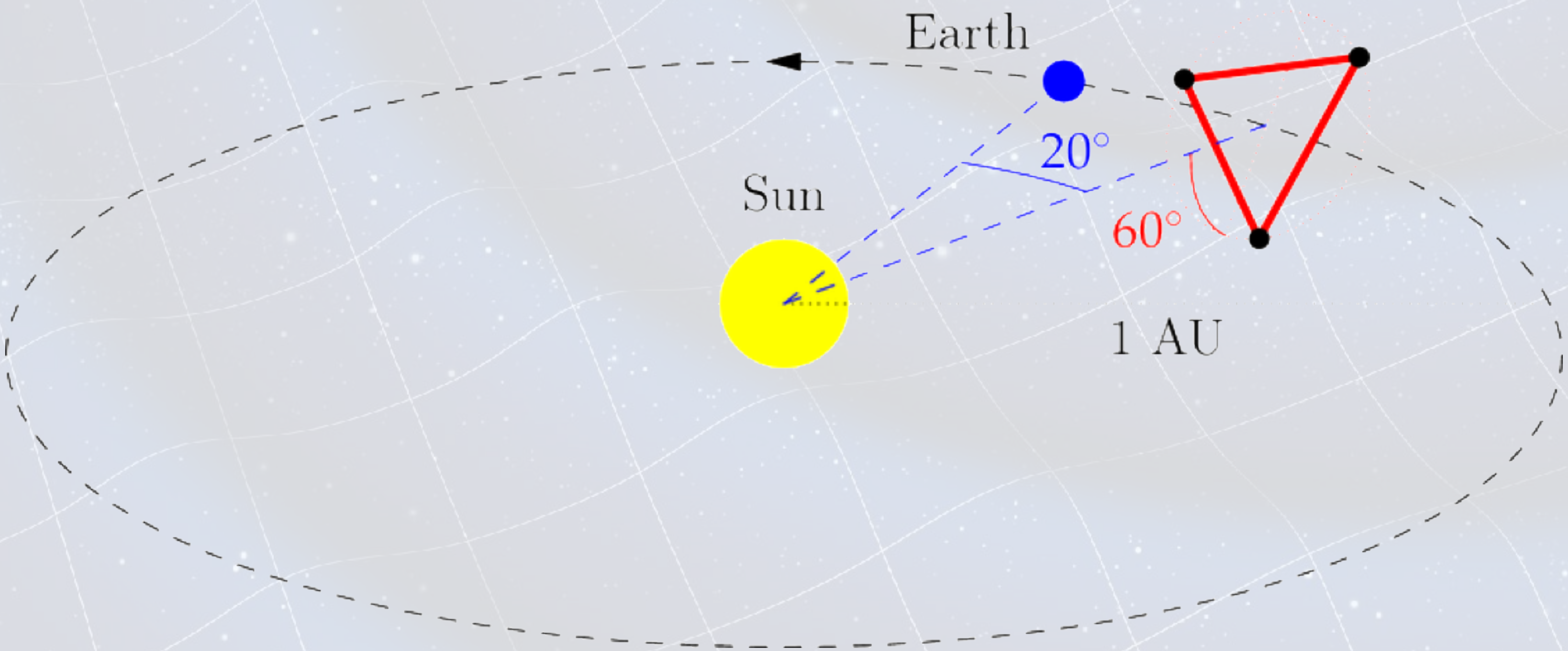
LISA Mission Concept

- 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)



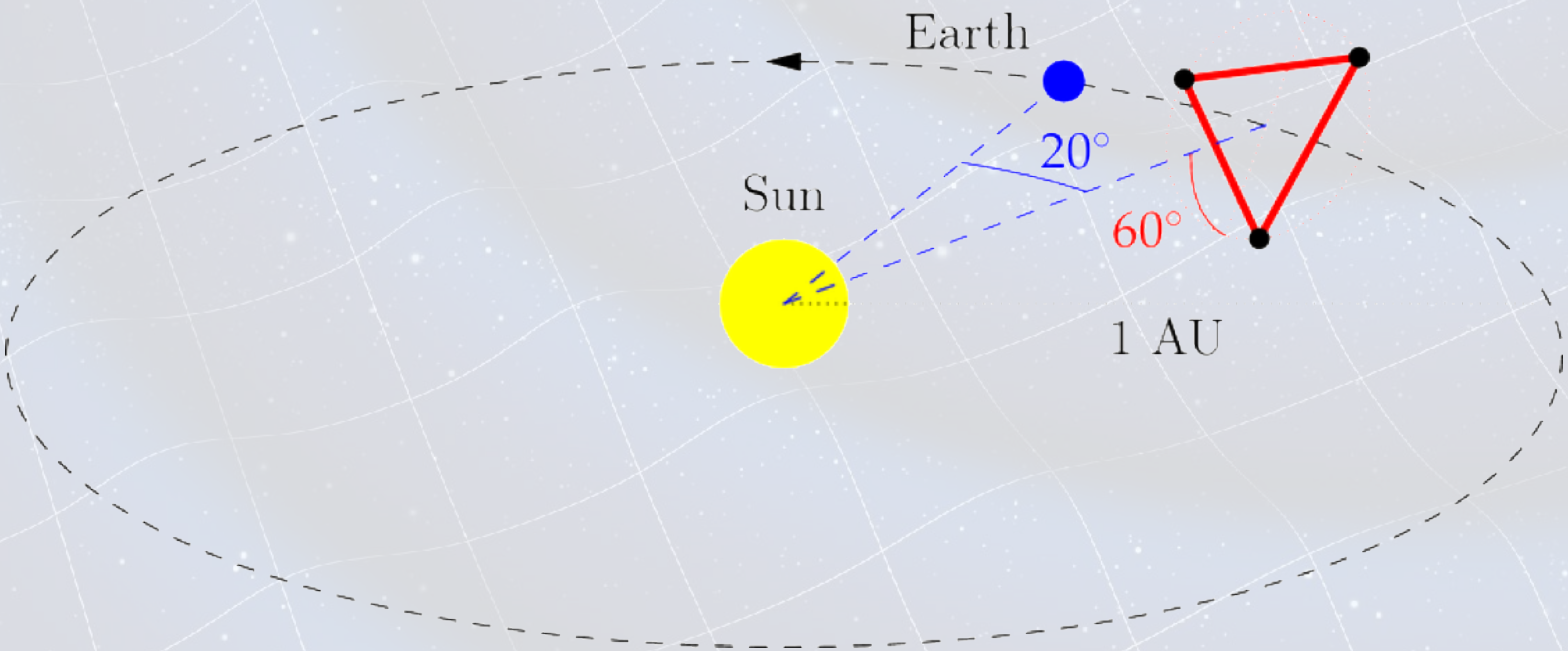
LISA Mission Concept

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



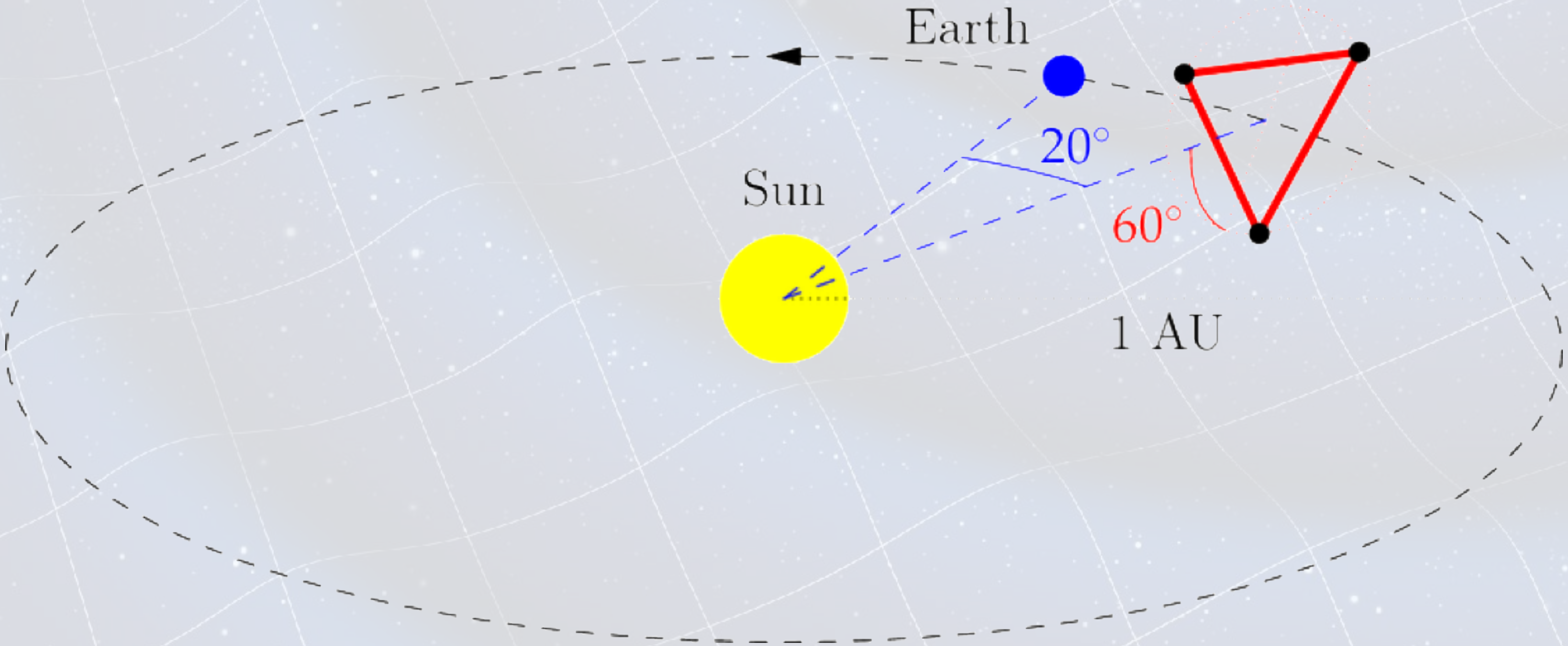
LISA Mission Concept

- Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by ~20^{o} (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 10years without active orbit maintenance



LISA Mission Concept

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

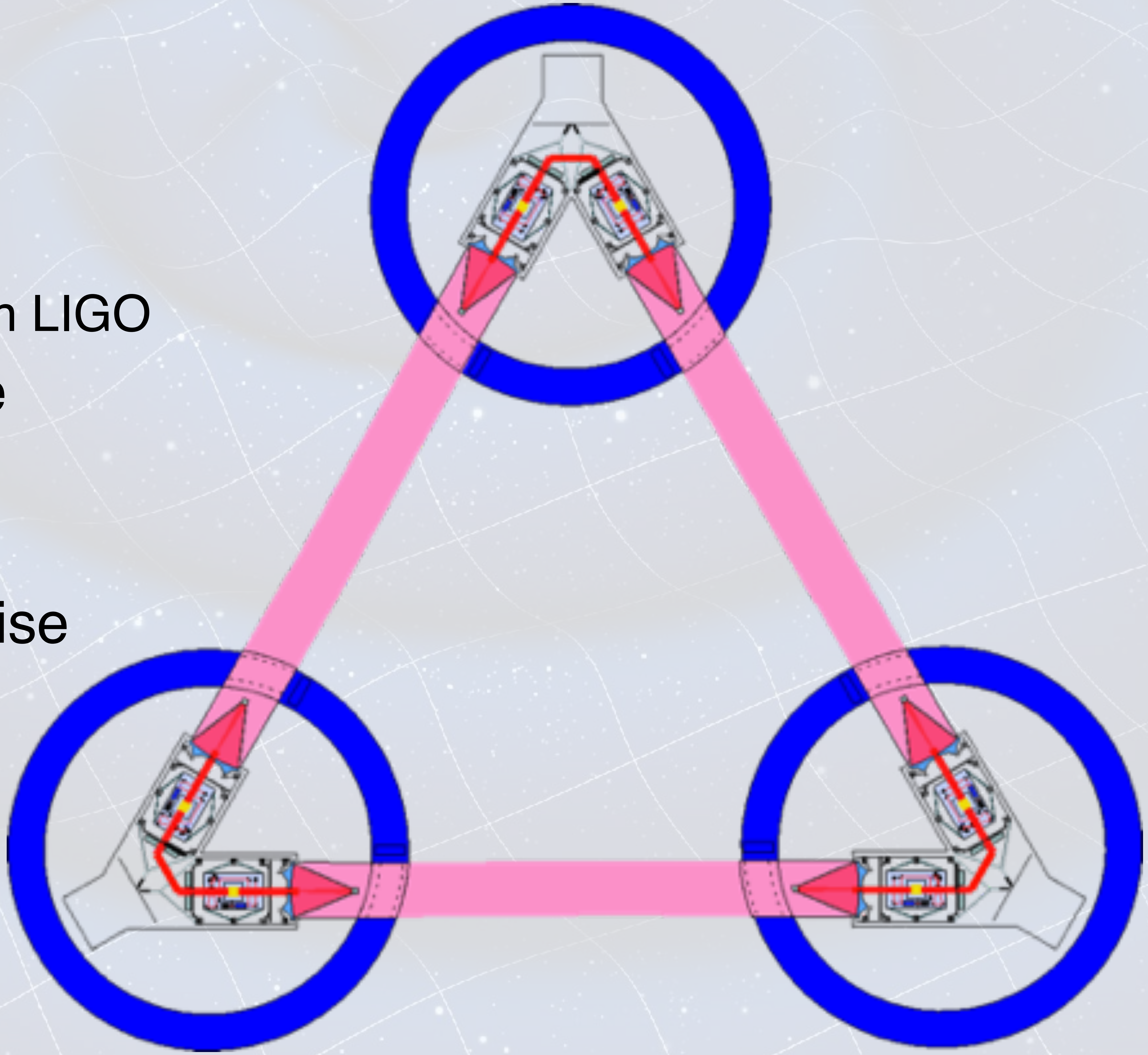


The LISA Orbit

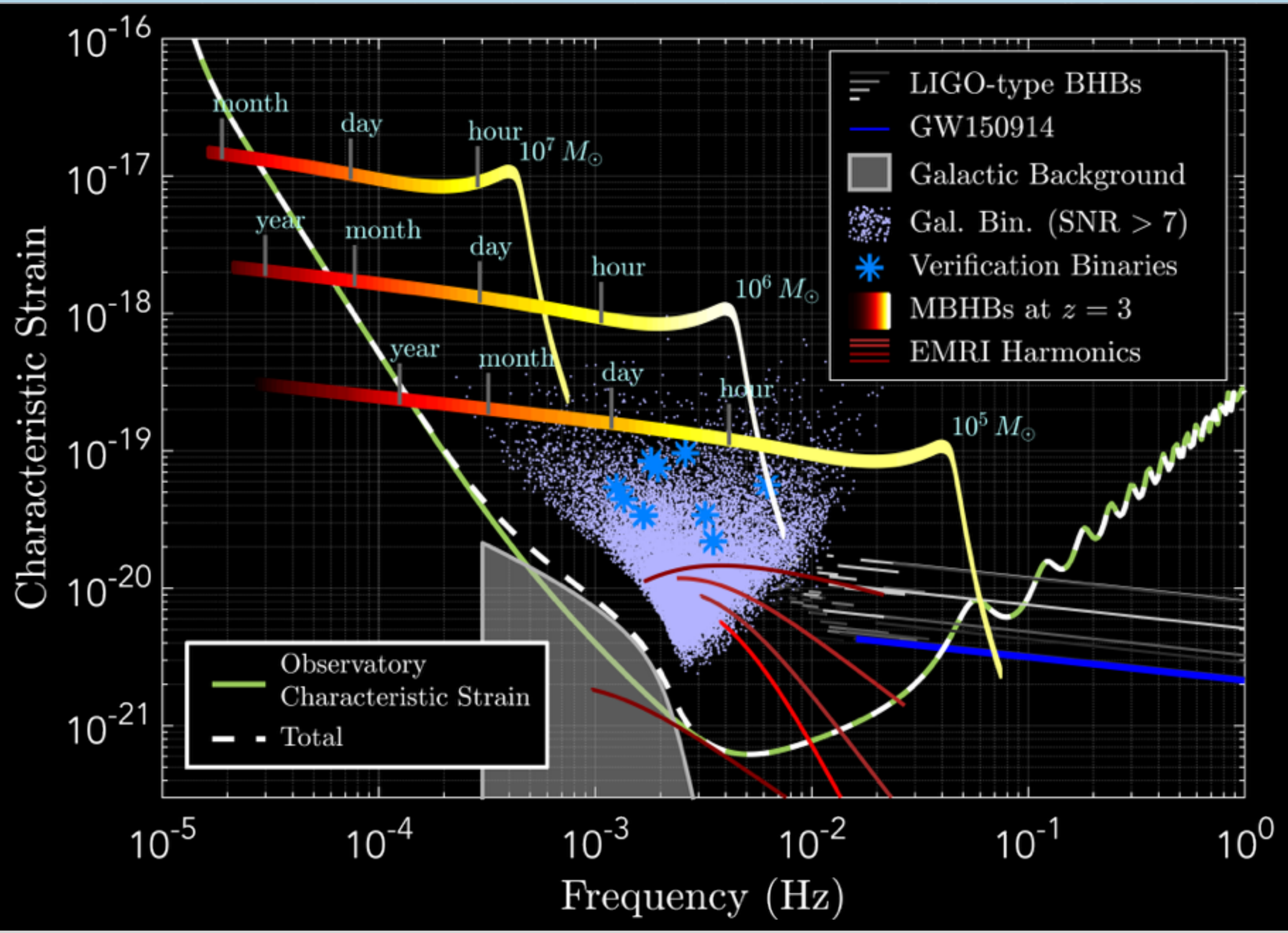
- Constellation counter-rotates during the course of the year
- No additional orbit control necessary
- Constellation forms an “almost rigid” triangle

LISA

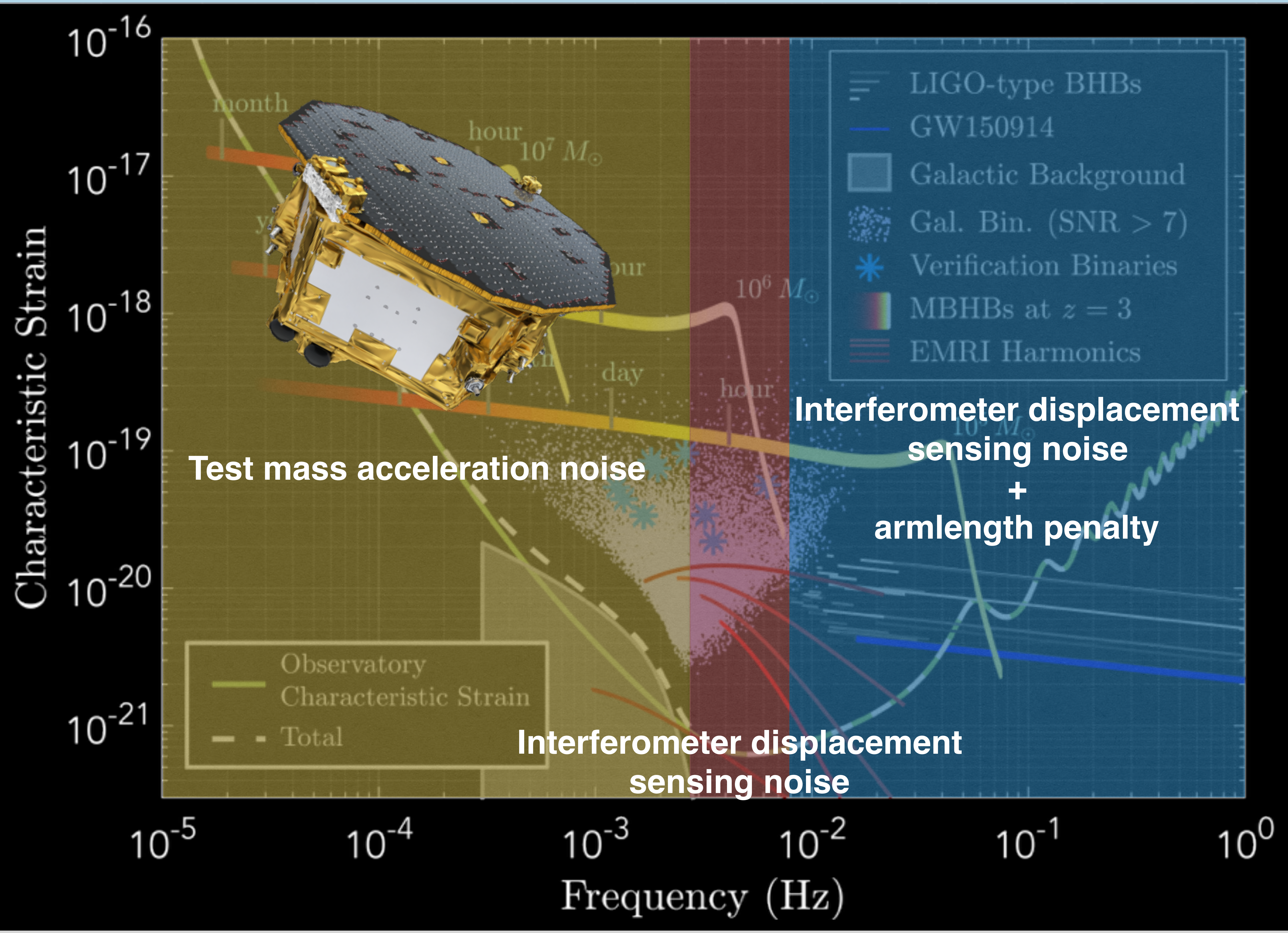
- Laser beams transmitted through 30cm off-axis telescopes
- Diffraction widens beam to several kilometres
  - ~1.5W transmitted, ~500pW received
  - LISA cannot form Fabry-Perot cavities in the arms as in LIGO
- 12 separate interferometric measurements made
  - 6 armlengths
  - 6 test mass -> spacecraft
- 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

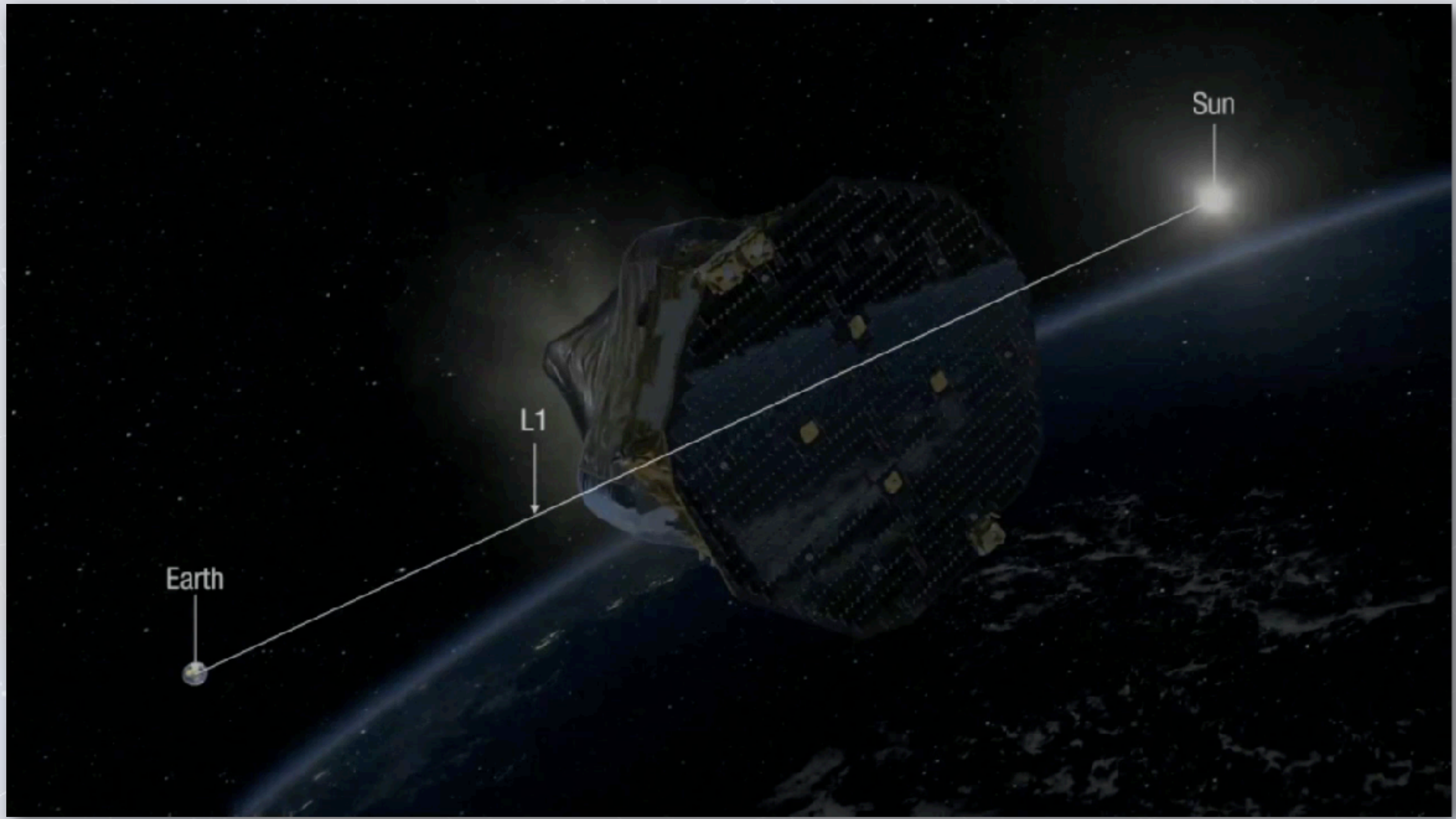


LISA Sensitivity Curve

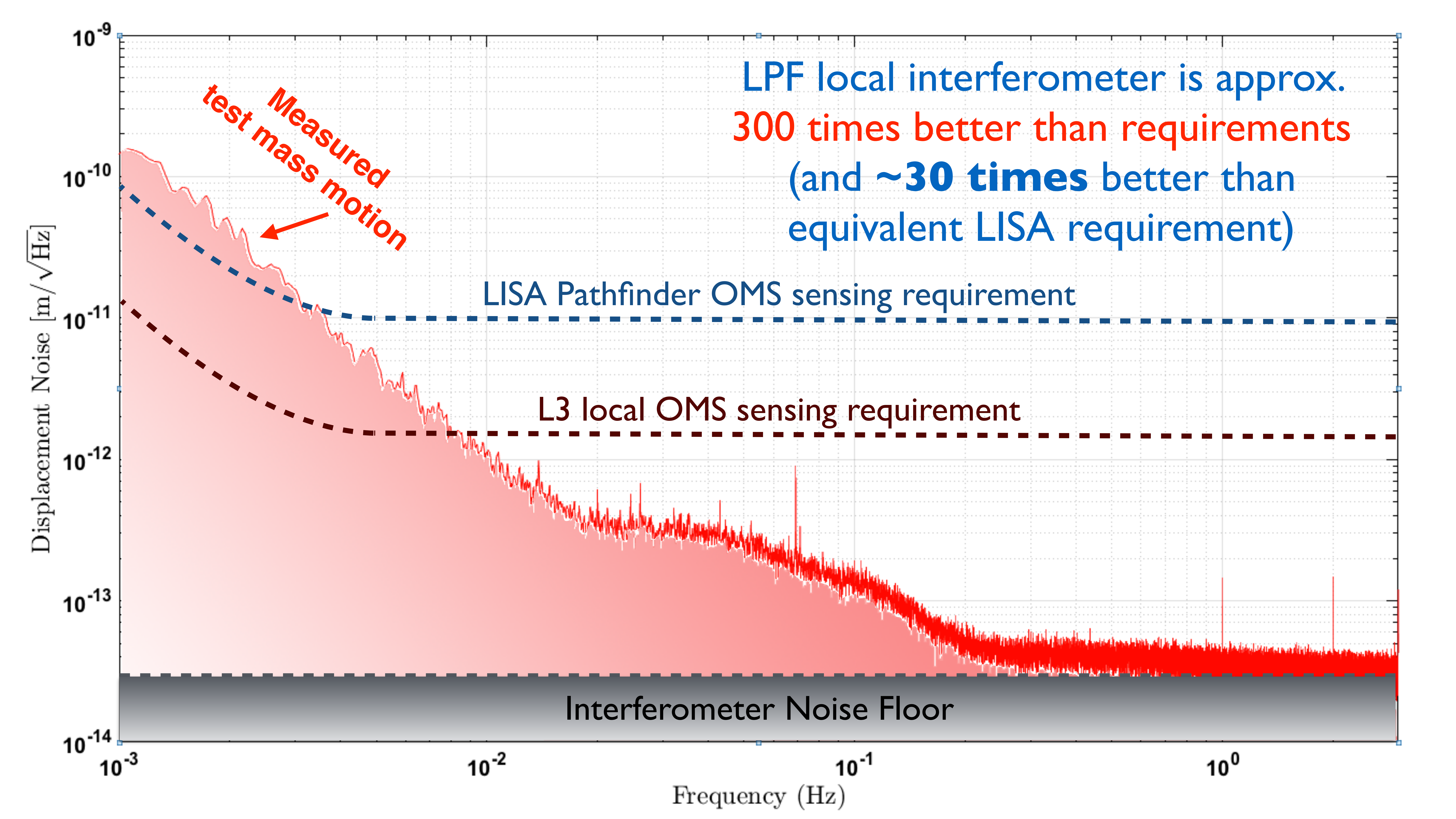


LISA Pathfinder

- 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



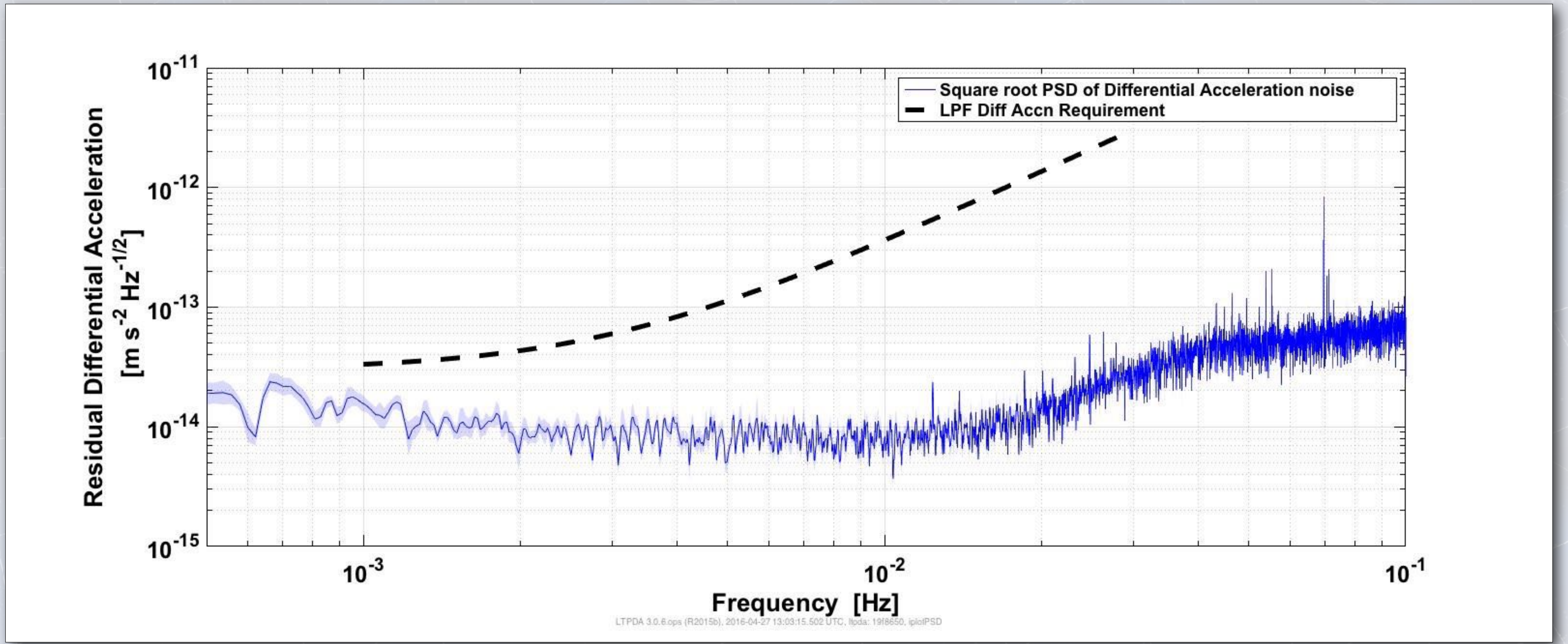
LPF On-orbit results: Displacement noise



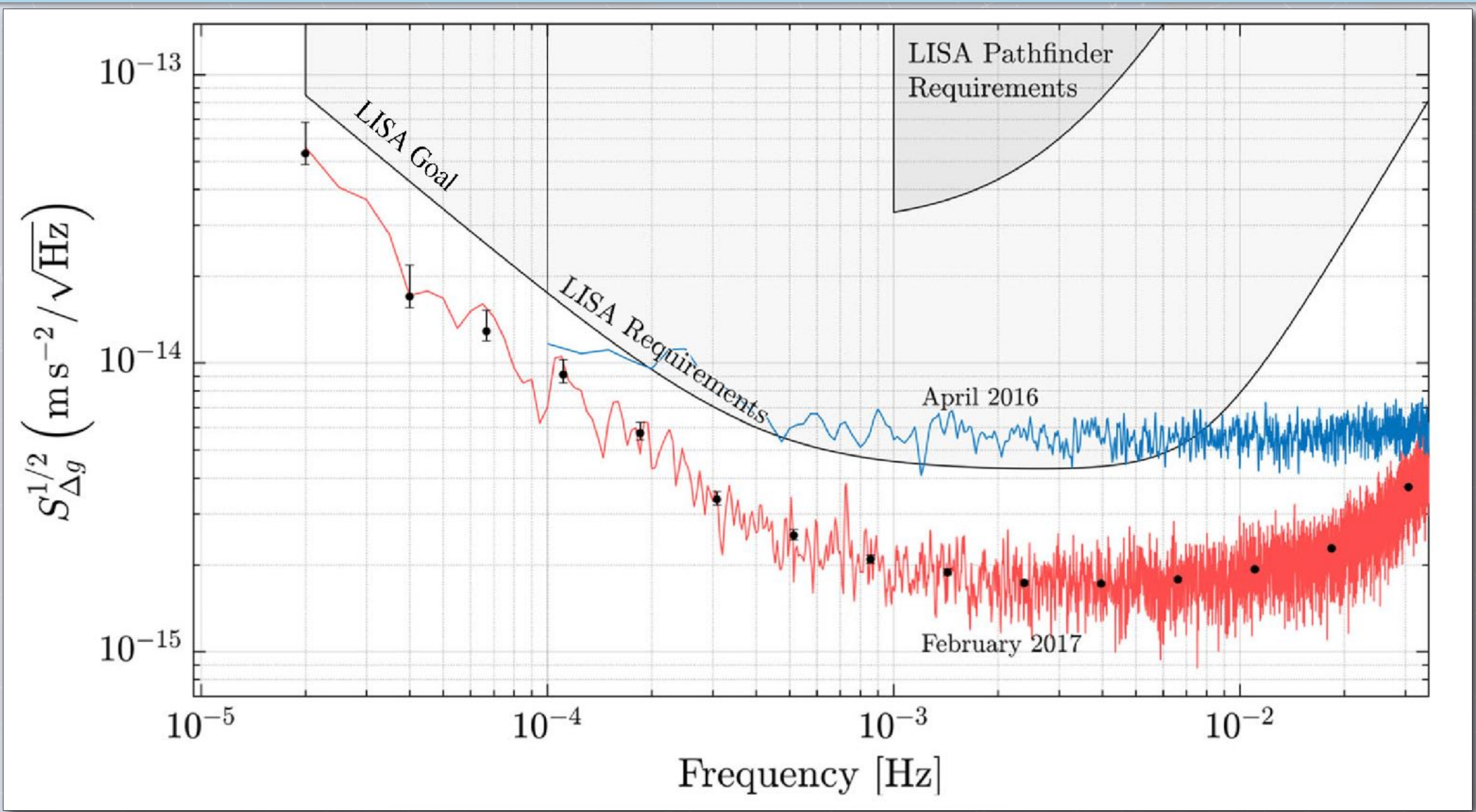
LPF on-orbit results: Differential Acceleration

- The differential acceleration between the test masses (known as “delta-g”) is the primary performance requirement of the mission…

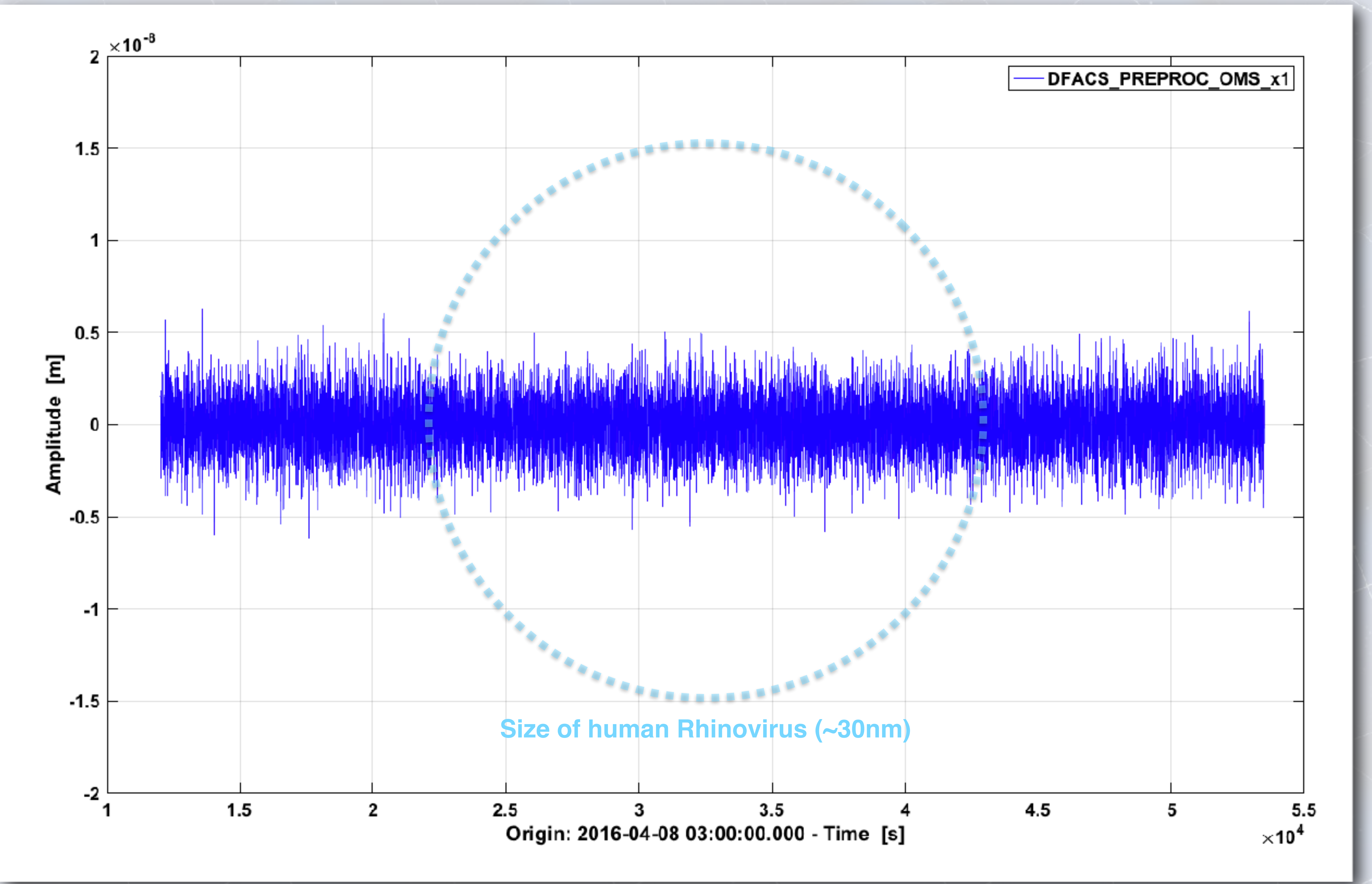
  …and was met during commissioning!



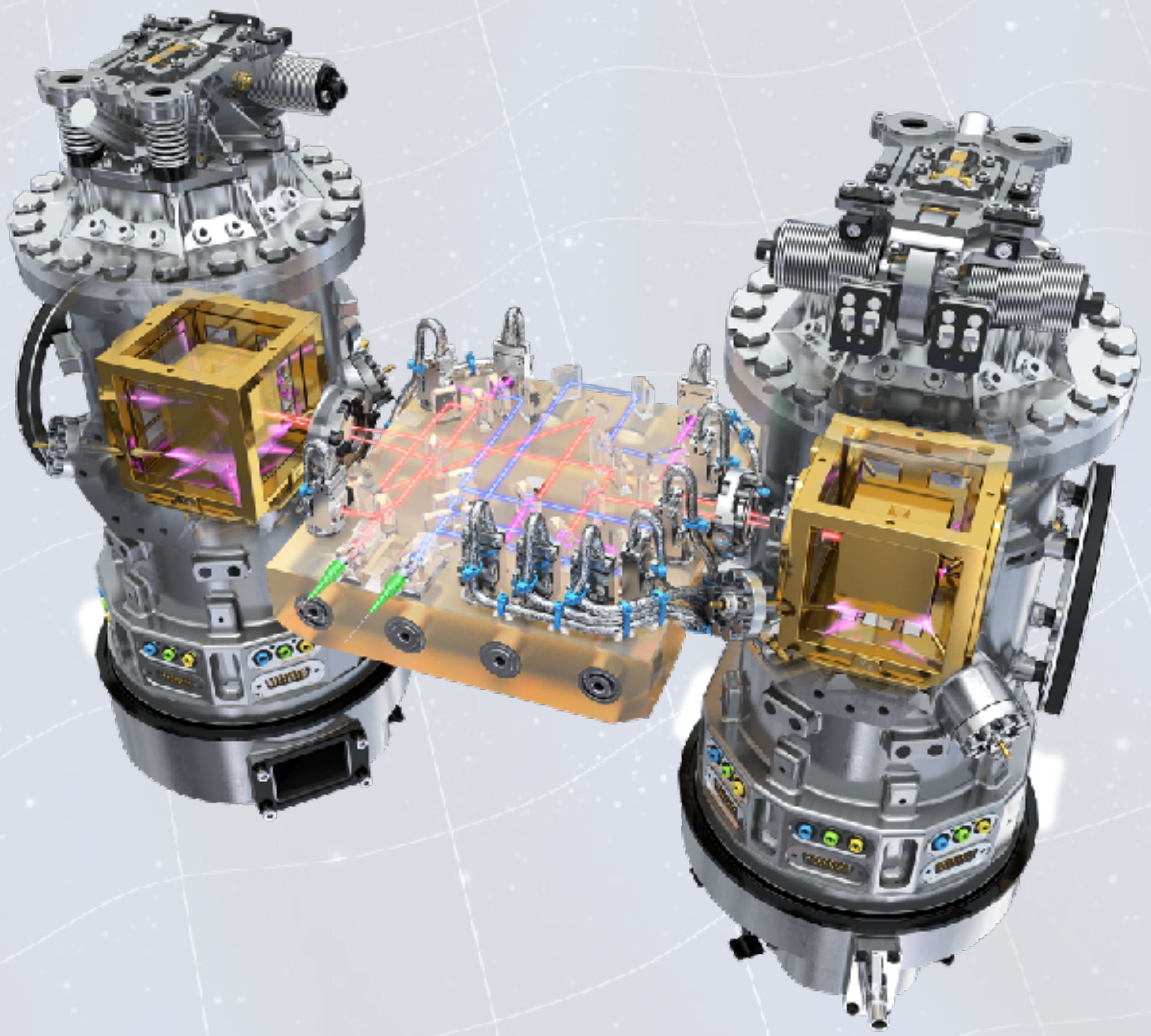
LPF on-orbit results: Differential Acceleration



Platform stability



LPF to LISA



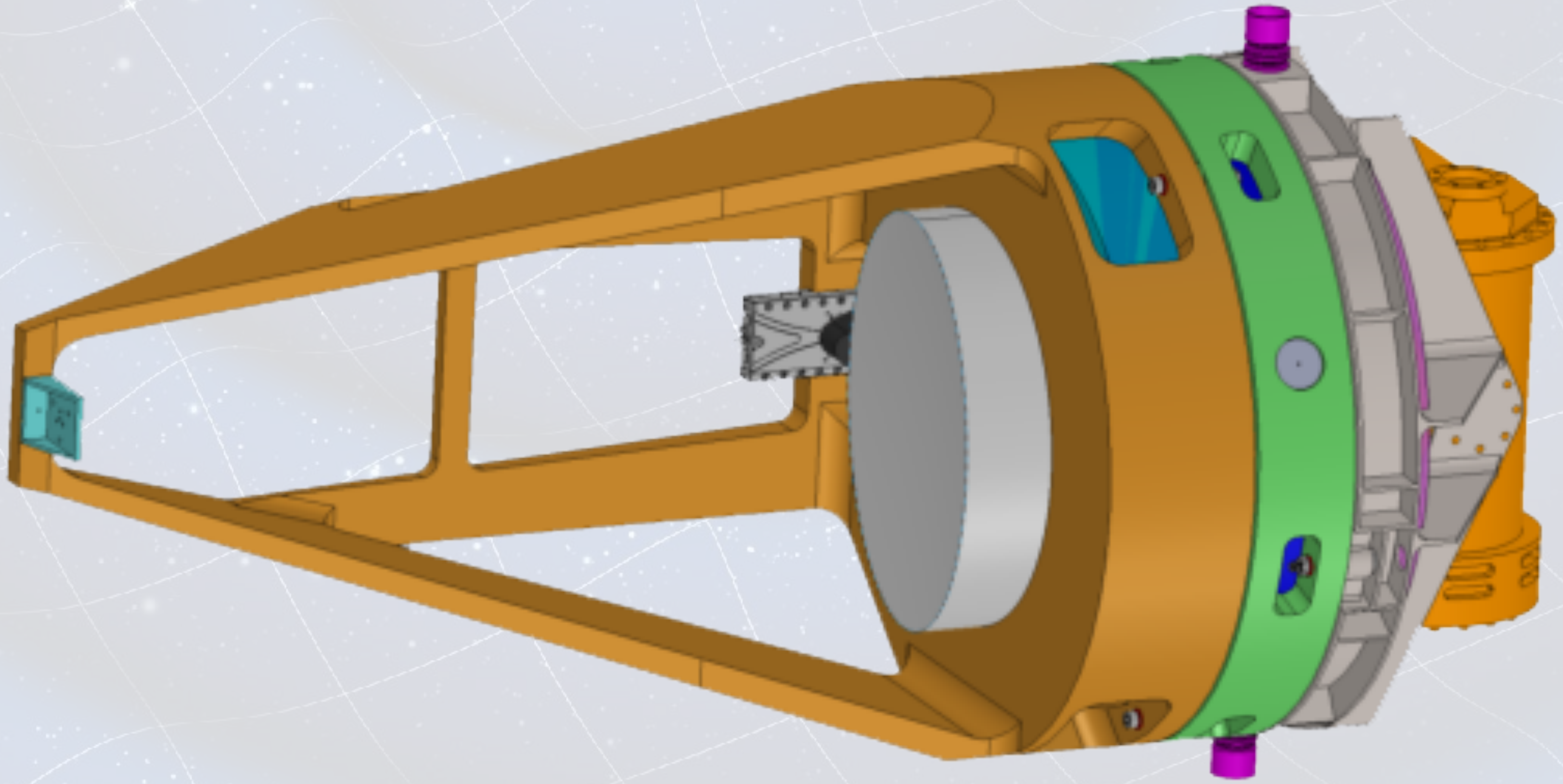
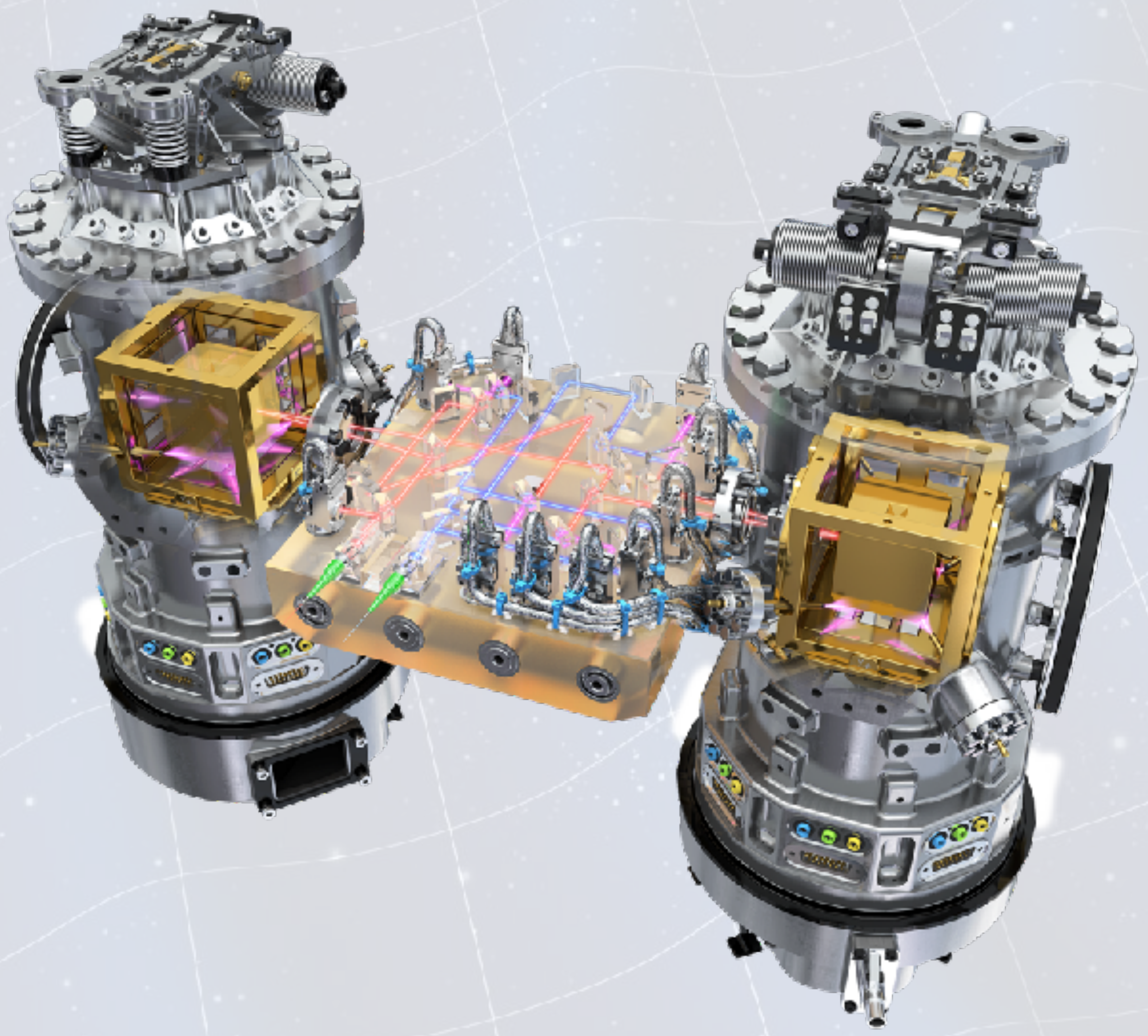
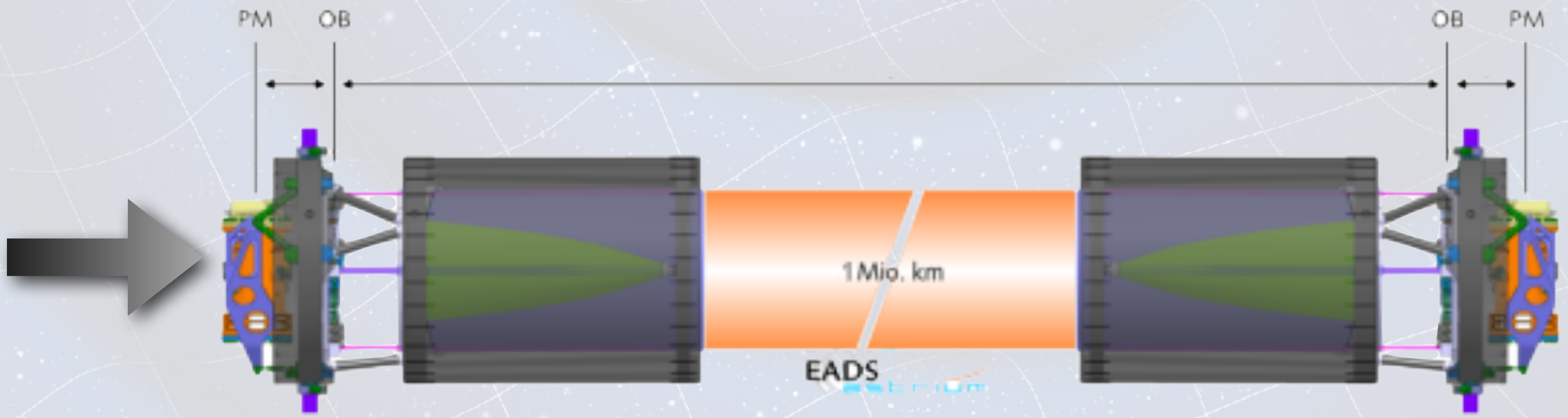


Image courtesy of NASA - GSFC

LPF to LISA





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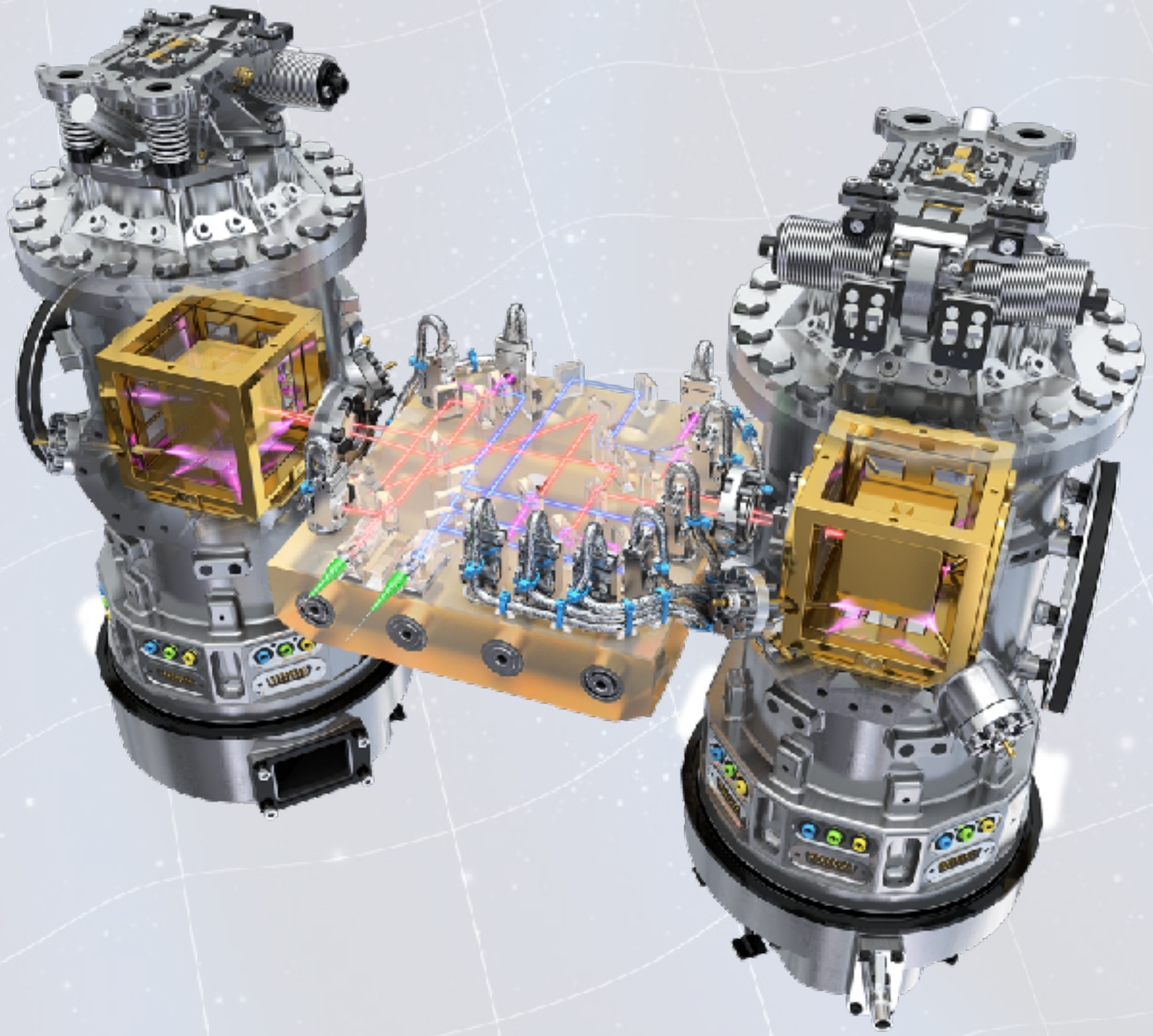
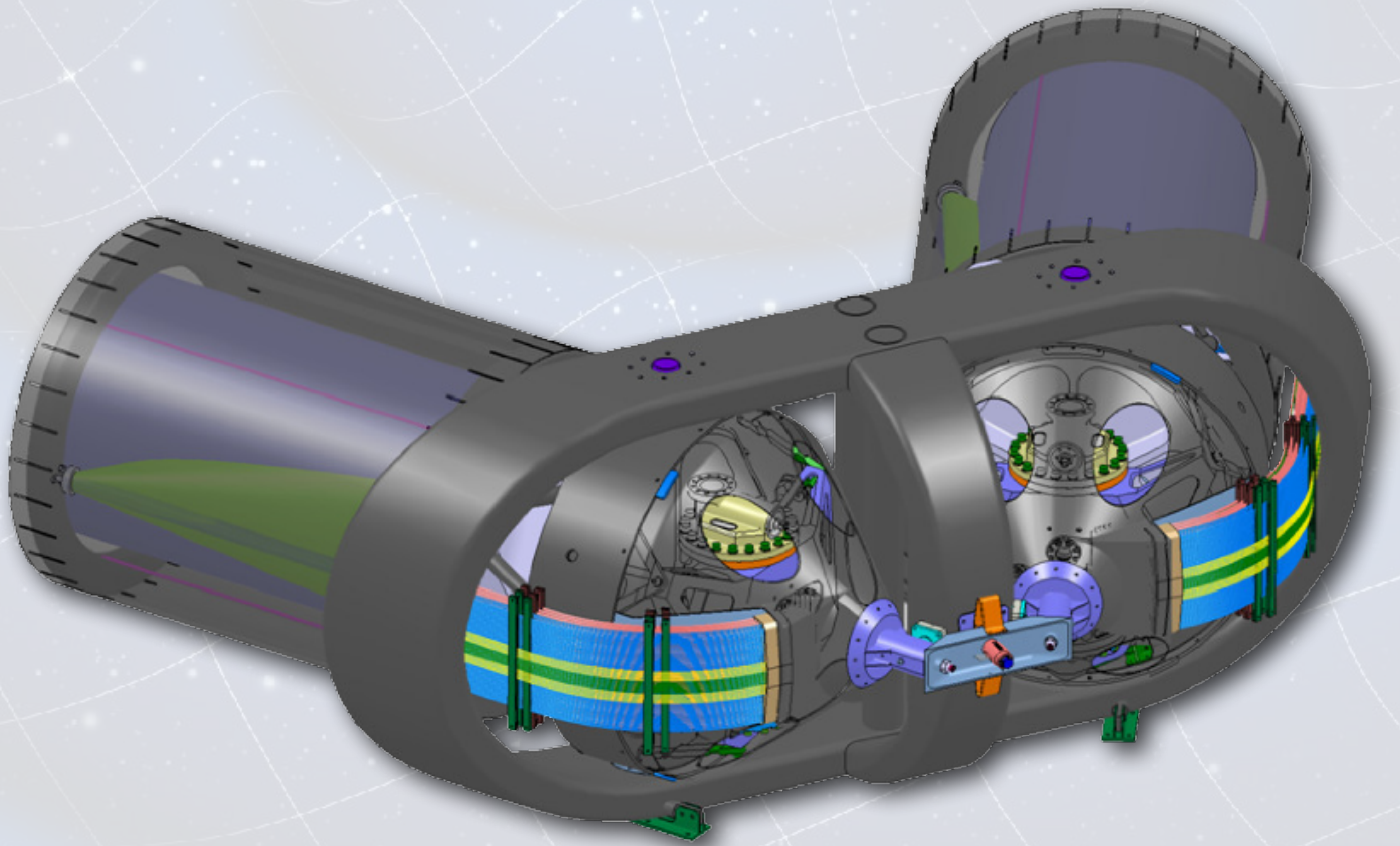
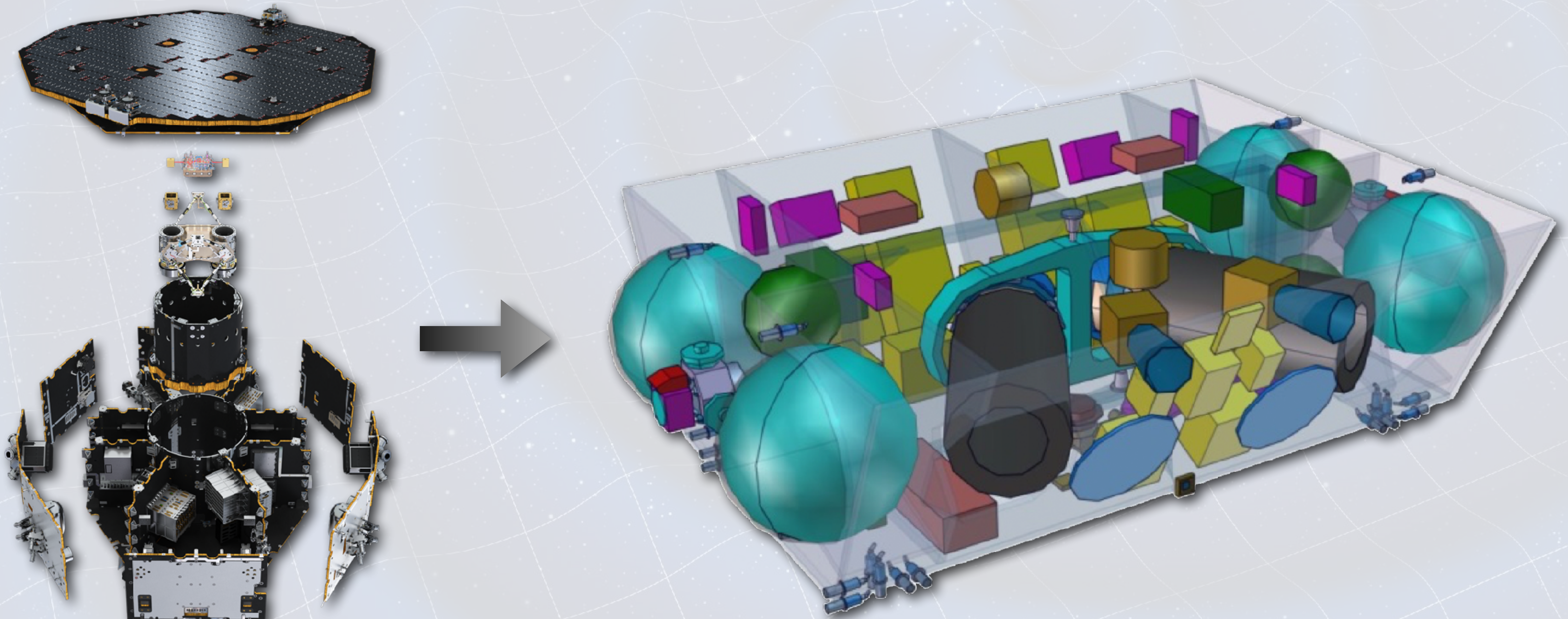
LPF to LISA





LPF to LISA



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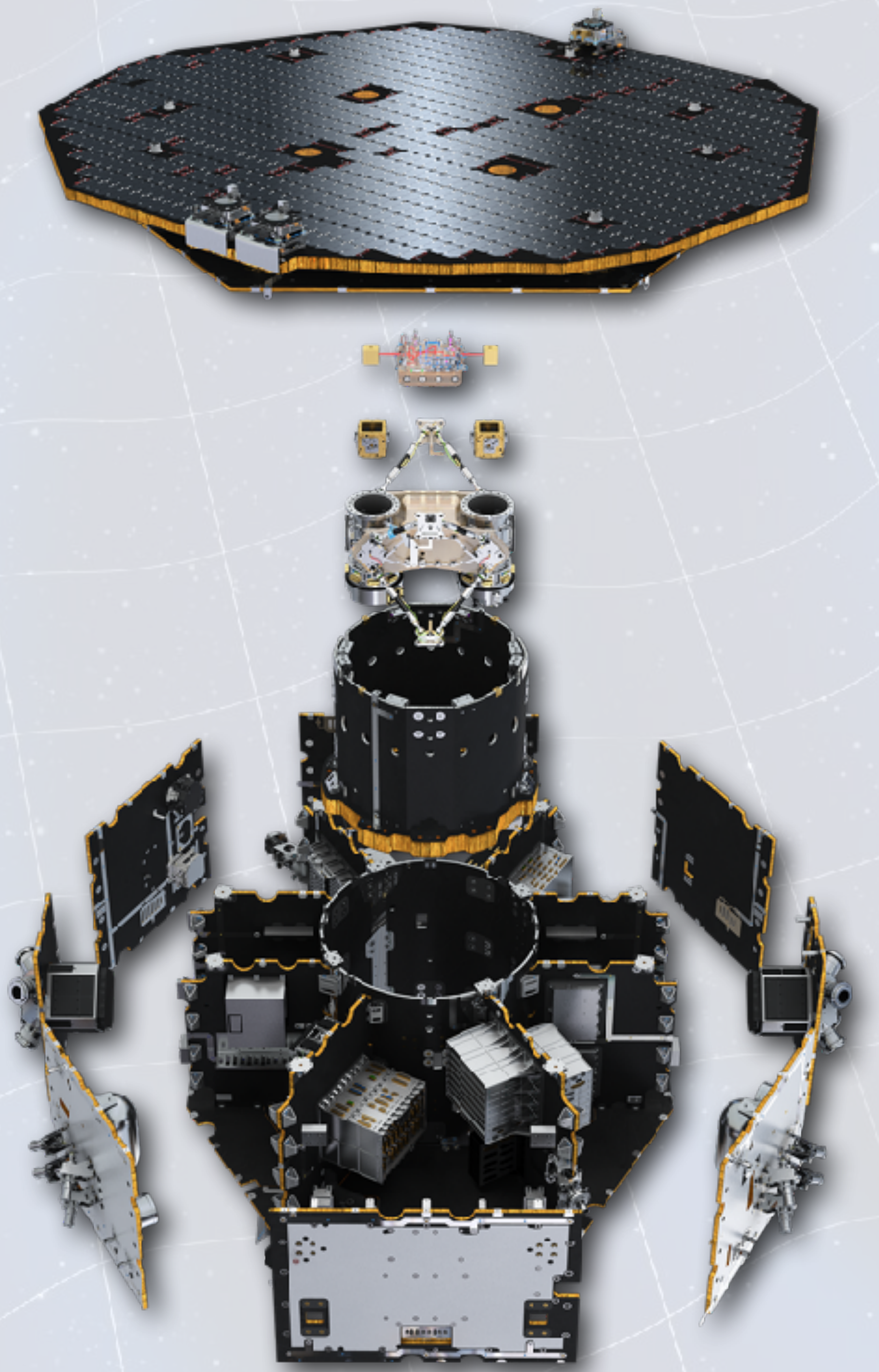
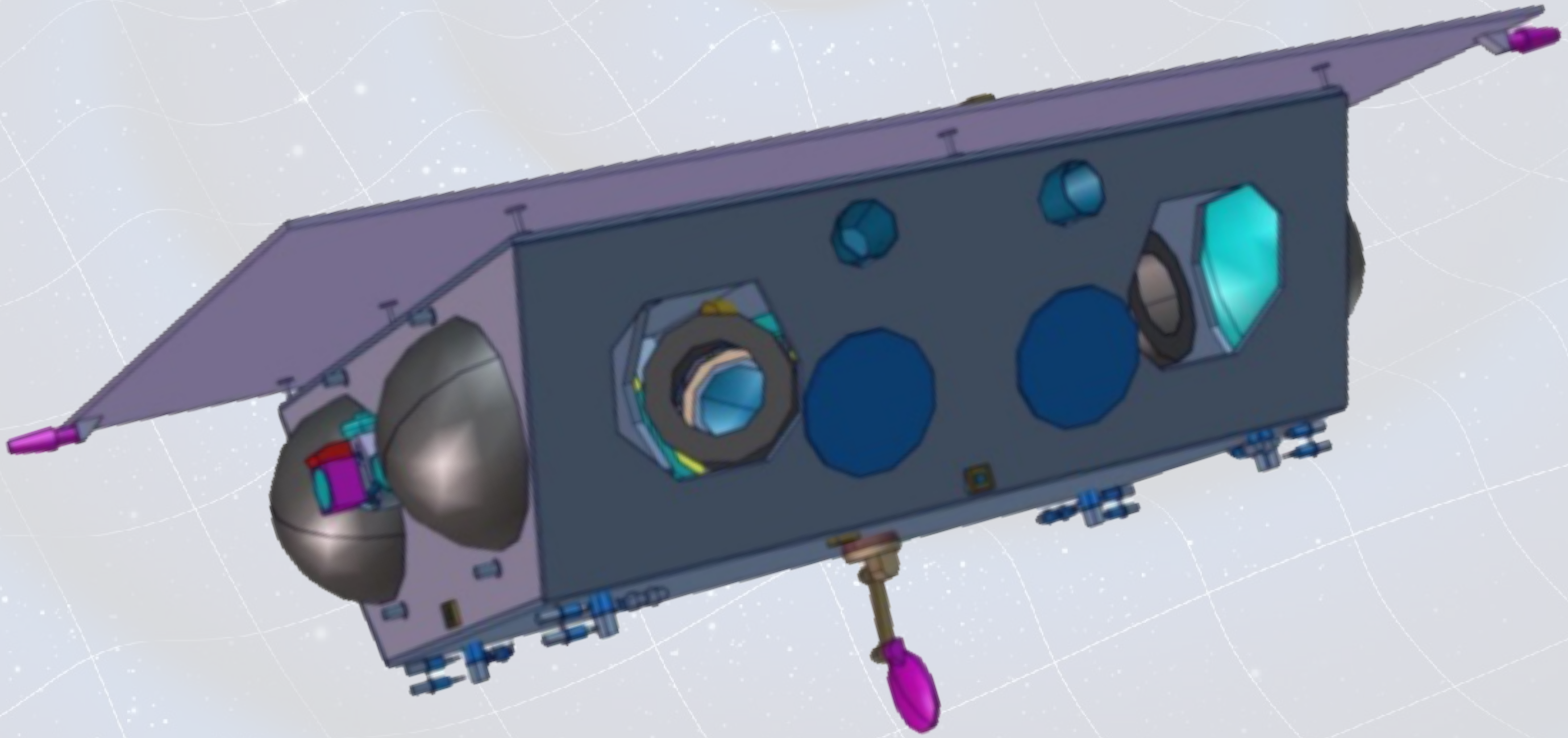
LPF to LISA





LPF to LISA

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Current status and schedule

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 & paylaod)	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

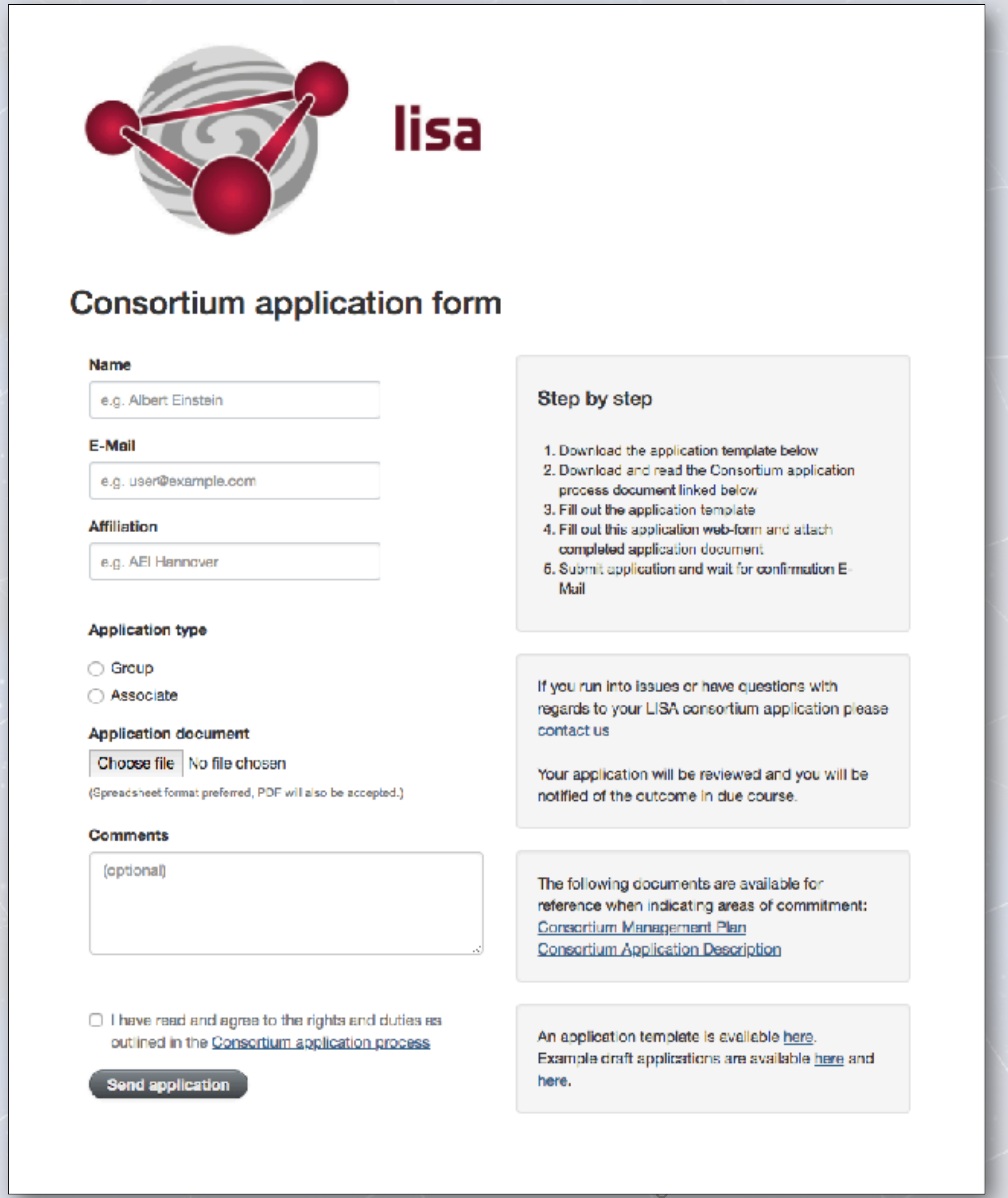
Conclusions

- LISA Pathfinder on-orbit performance has far exceeded the pre-launch requirements
  - (Local) interferometer displacement noise floor: ~35fm/√Hz at high frequencies
  - Differential acceleration noise: < 2fms^{-2}/√Hz at ~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


lisa

Consortium application form

Name

e.g. Albert Einstein

E-Mail

e.g. user@example.com

Affiliation

e.g. AEI Hannover

Application type

Group

Associate

Application document

Choose file No file chosen

(Spreadsheet format preferred, PDF will also be accepted.)

Comments

(optional)

I have read and agree to the rights and duties as outlined in the Consortium application process

Send application

Step by step

1. Download the application template below
2. Download and read the Consortium application process document linked below
3. Fill out the application template
4. Fill out this application web-form and attach completed application document
5. Submit application and wait for confirmation E-Mail

If you run into issues or have questions with regards to your LISA consortium application please contact us

Your application will be reviewed and you will be notified of the outcome in due course.

The following documents are available for reference when indicating areas of commitment:
Consortium Management Plan
Consortium Application Description

An application template is available here.
Example draft applications are available here and here.

Thank you