Listening to the Millihertz Universe with the Laser Interferometer Space Antenna (LISA)

John Baker
Laboratoire des 2 Infinis — Toulouse. (Univerisité de Toulouse/CNRS/IN2P3)

Séminaire SFP 27 Feb 2026

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- :01 What are Gravitational Waves (GWs)?
- :10 Opening a new GW band
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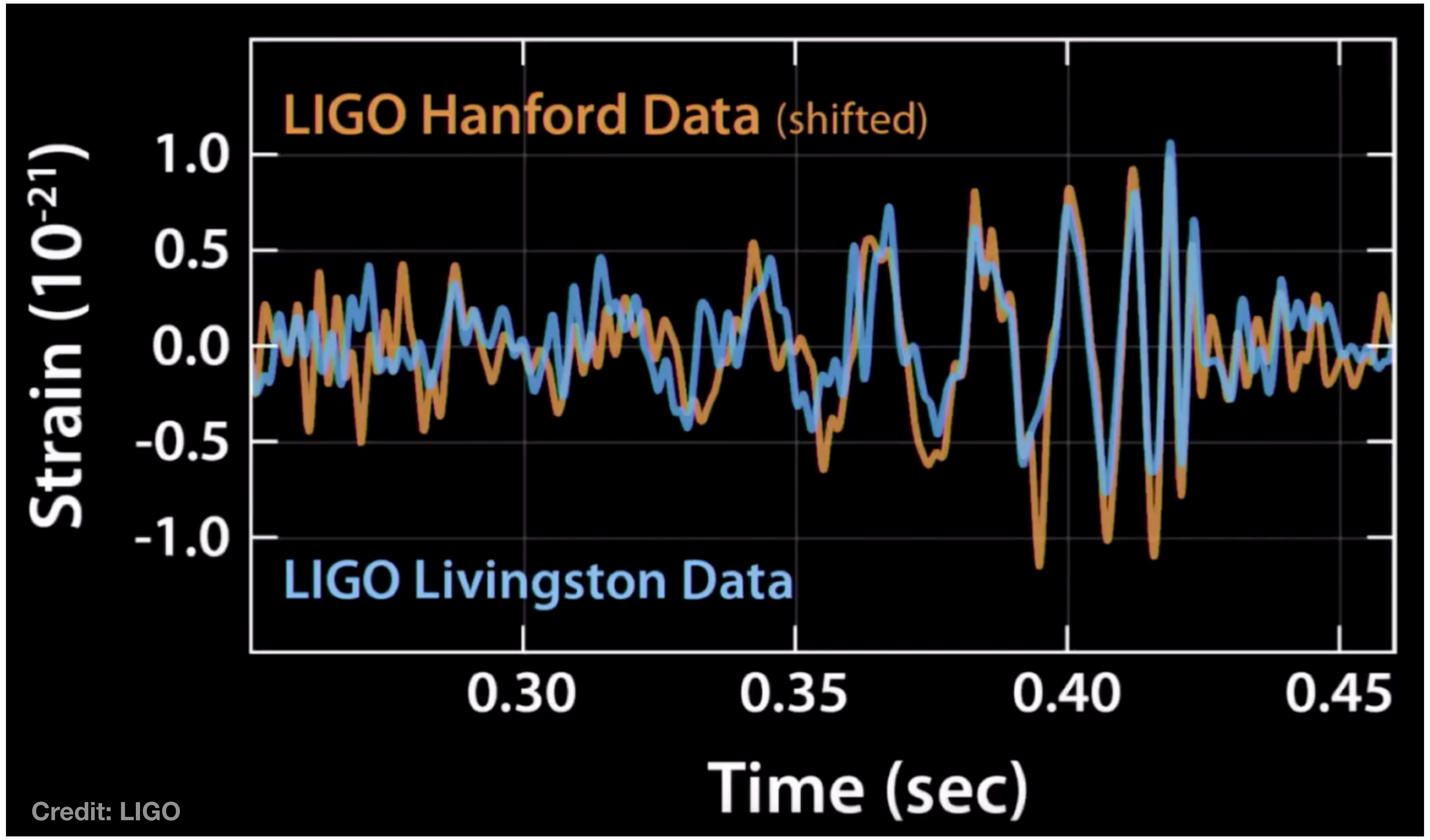
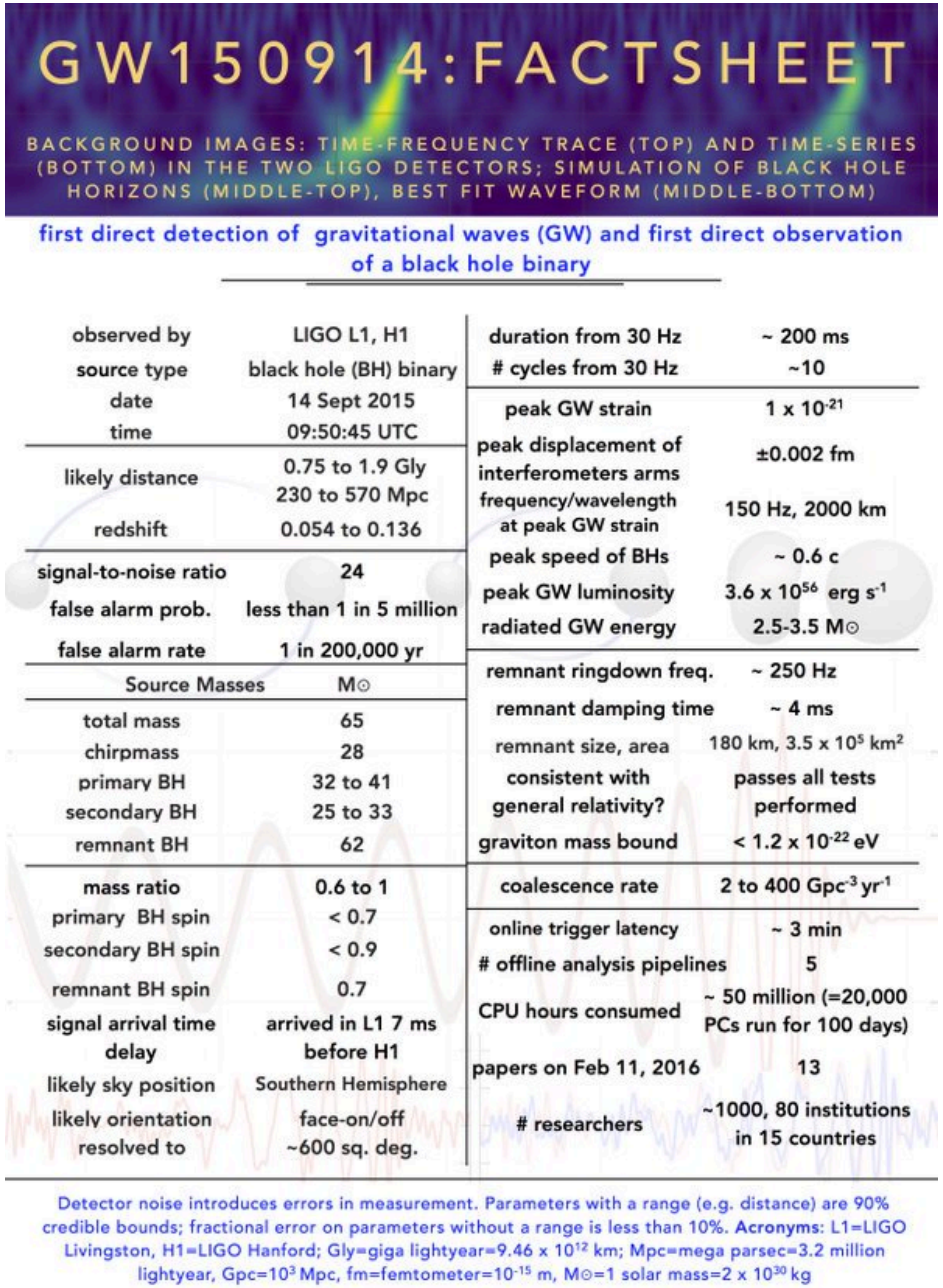
What are Gravitational Waves?

:01

The Gravitational Wave Astronomy Era has begun!



Measured waveforms from GW150914, the first directly-detected GW signal.



GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

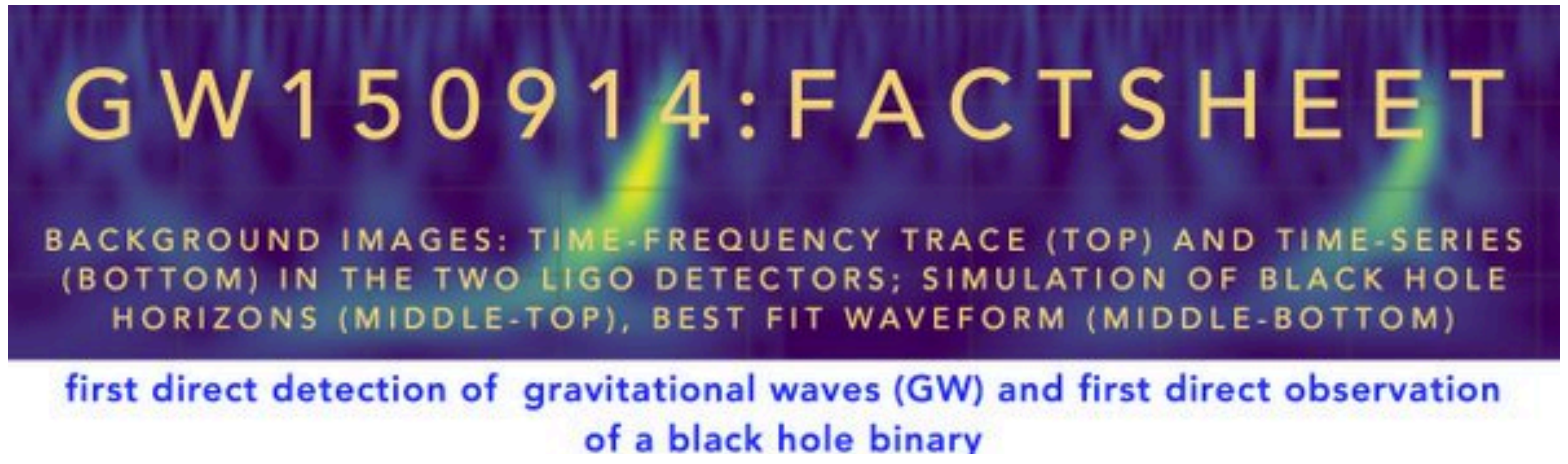
first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

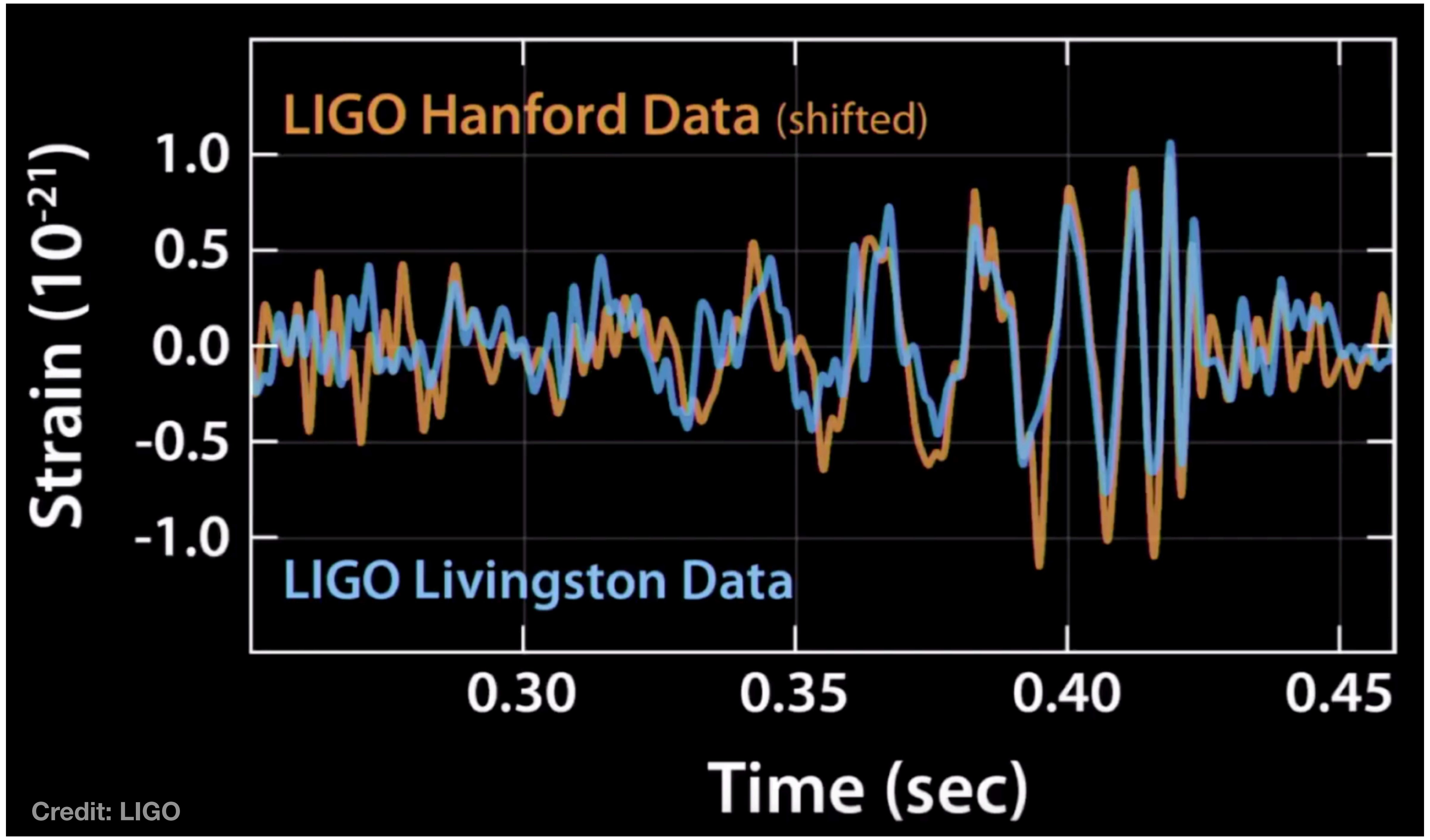
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	M⊙
total mass	65
chirpmass	28
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	62
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	< 1.2×10^{-22} eV
coalescence rate	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameters with a range (e.g. distance) are 90% credible bounds; fractional error on parameters without a range is less than 10%. Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

The Gravitational Wave Astronomy Era has begun!





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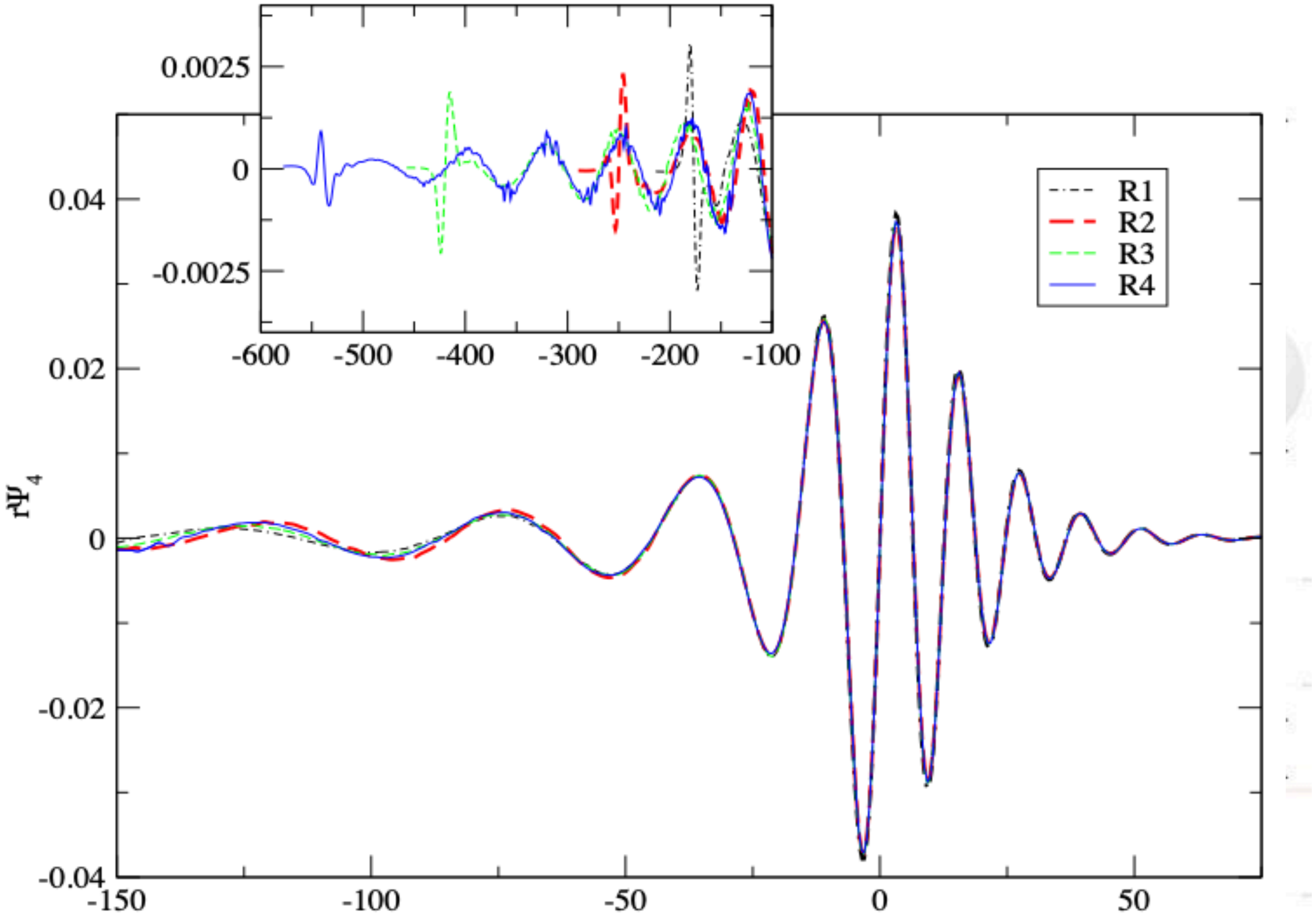
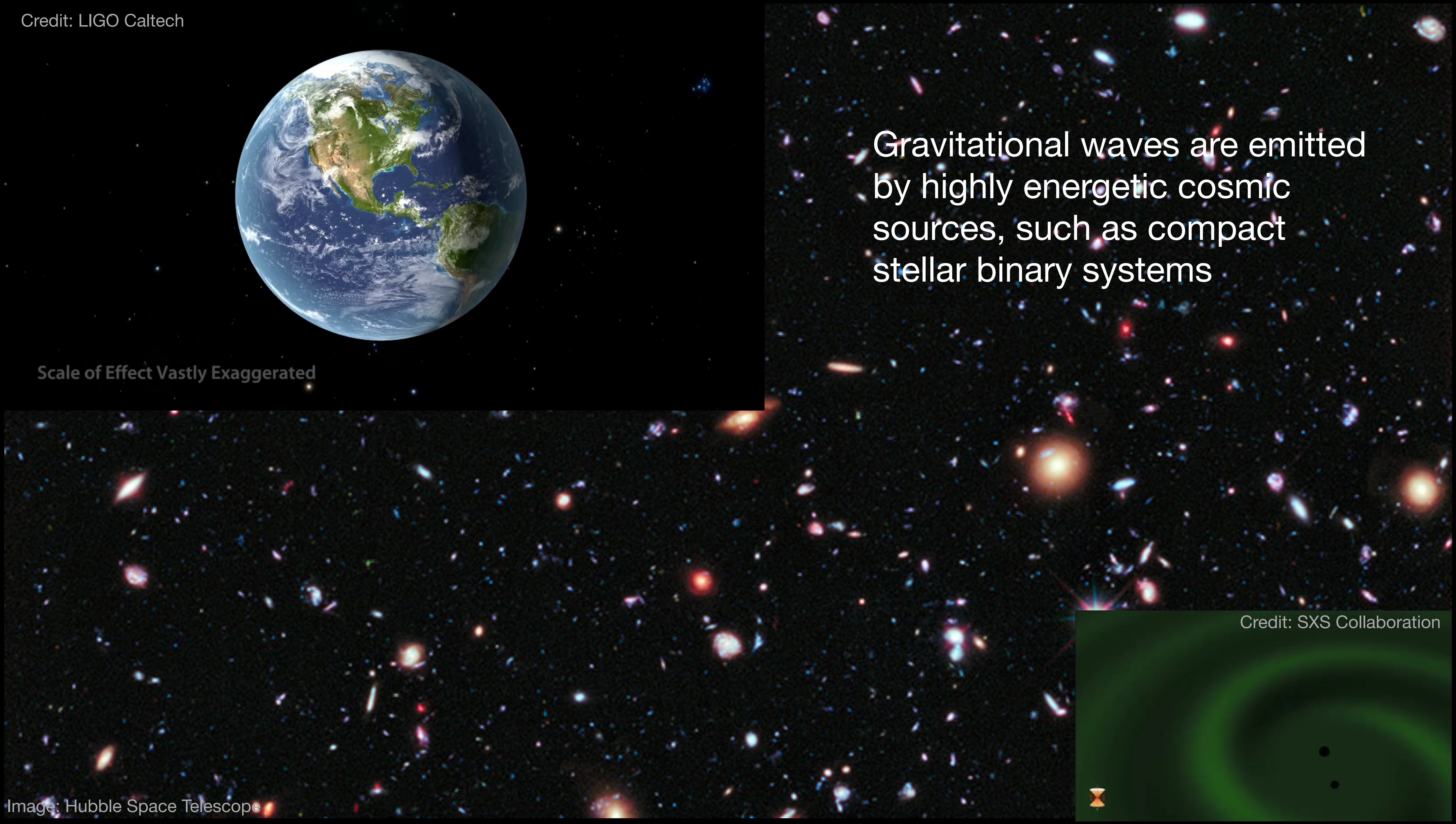


Matches first theoretical/numerical merger waveform calculations from 2006

(Appears a bit different here because prediction above corresponds to second time-derivative of strain)

Gravitational waves from a merging binary system



Gravitational waves are emitted by highly energetic cosmic sources, such as compact stellar binary systems

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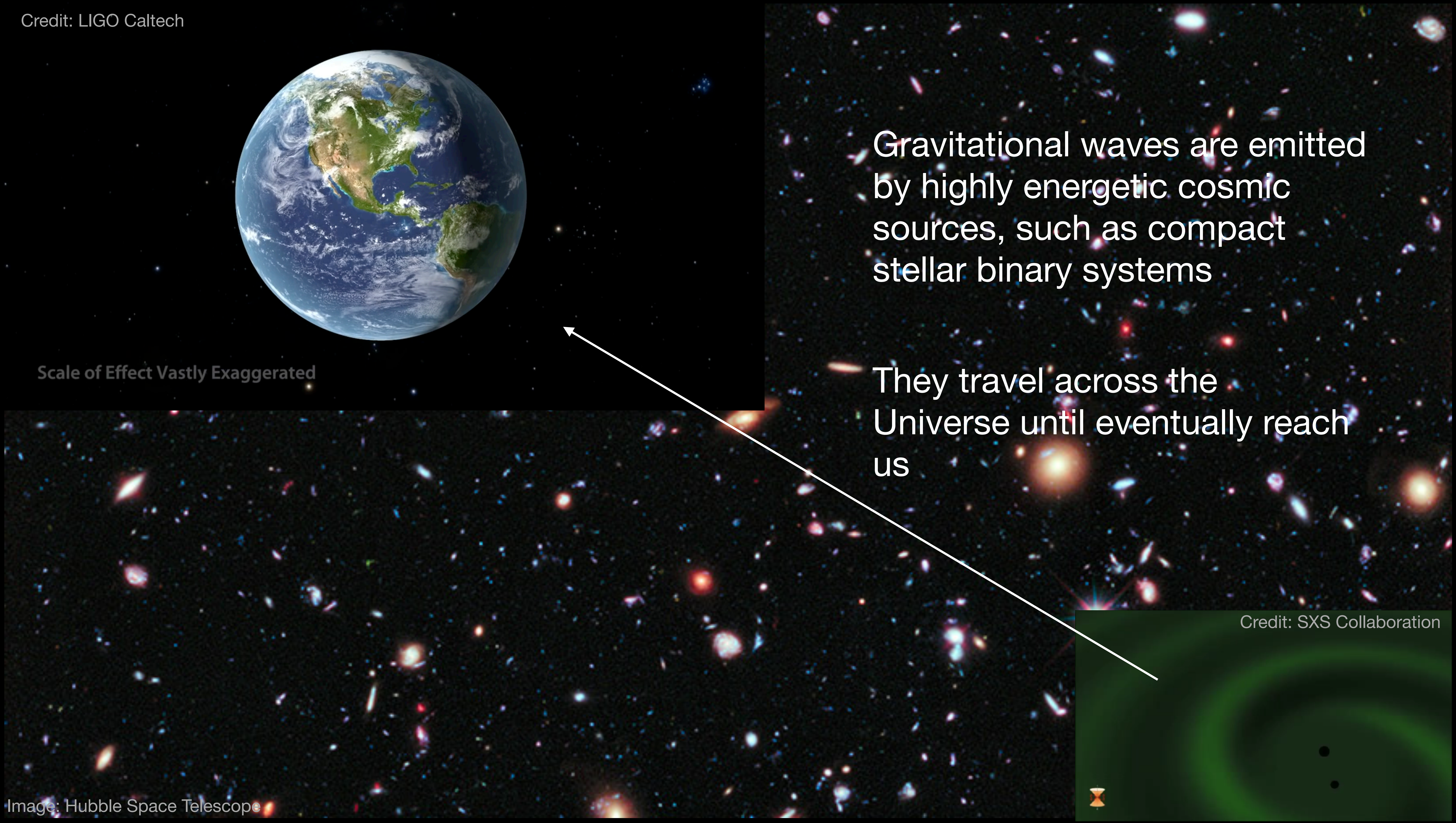


Gravitational waves are emitted by highly energetic cosmic sources, such as compact stellar binary systems

They travel across the Universe until eventually reach us

Gravitational waves from a merging binary system

Credit: LIGO Caltech

Gravitational waves are emitted by highly energetic cosmic sources, such as compact stellar binary systems

They travel across the Universe until eventually reach us

But what are gravitational waves?
In which medium do they propagate?

Credit: SXS Collaboration

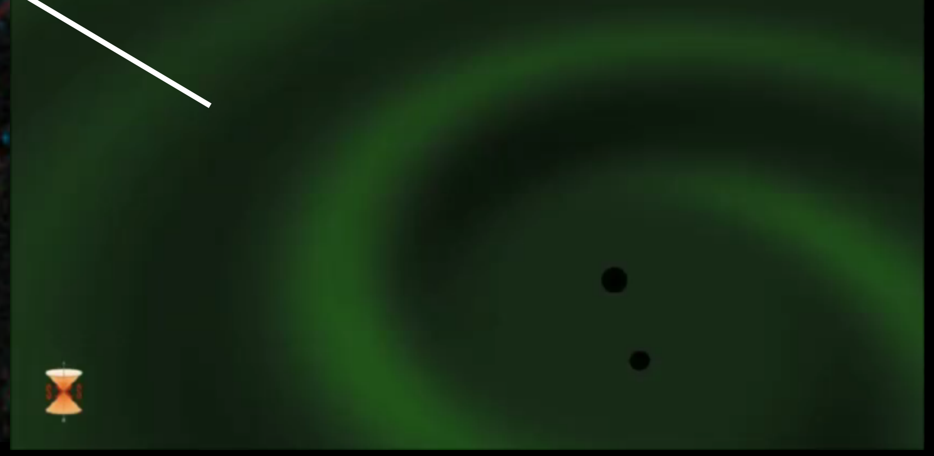
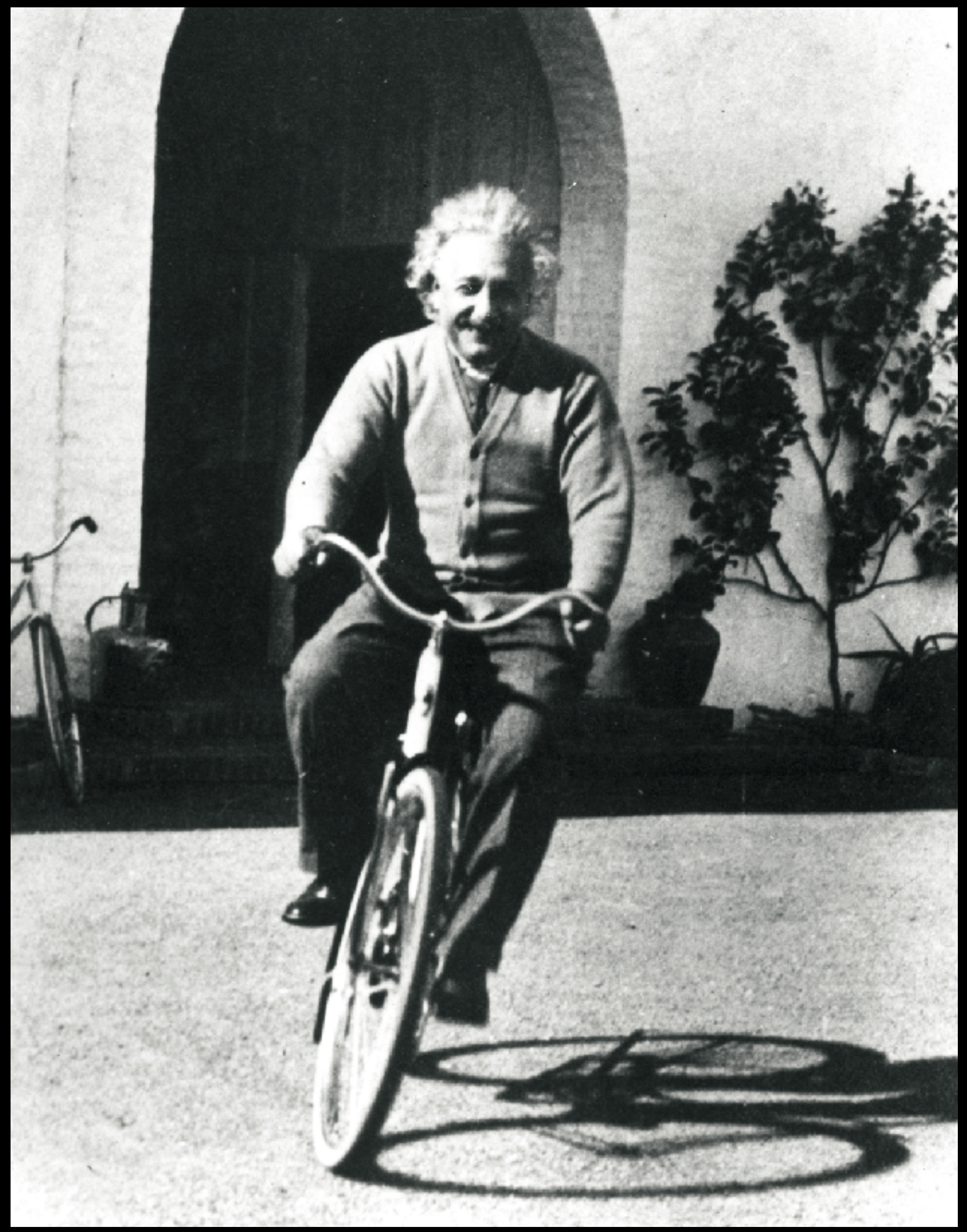


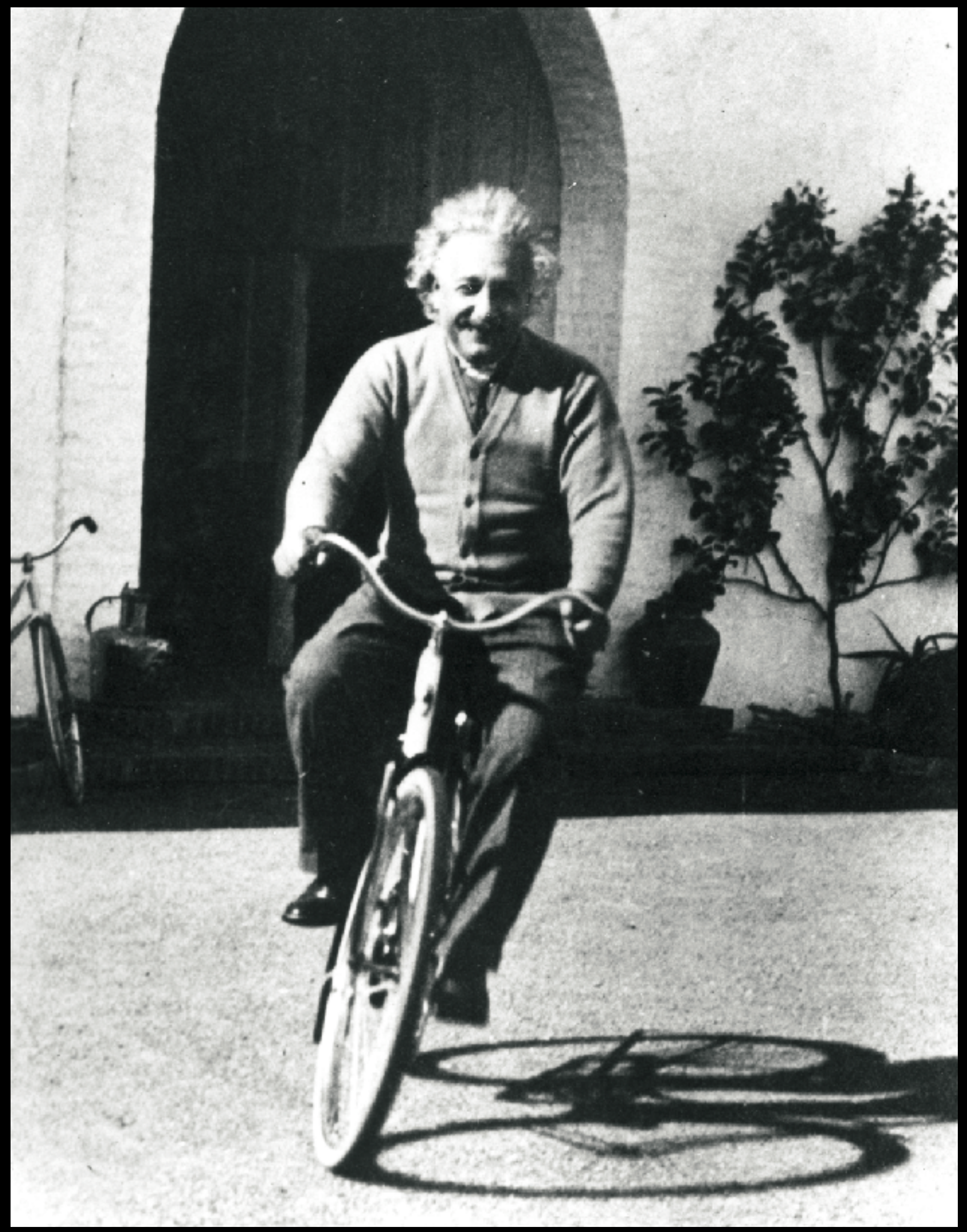
Image: Hubble Space Telescope

Einstein's general relativity theory of gravity



Gravity
=
Spacetime curvature

Einstein's general relativity theory of gravity



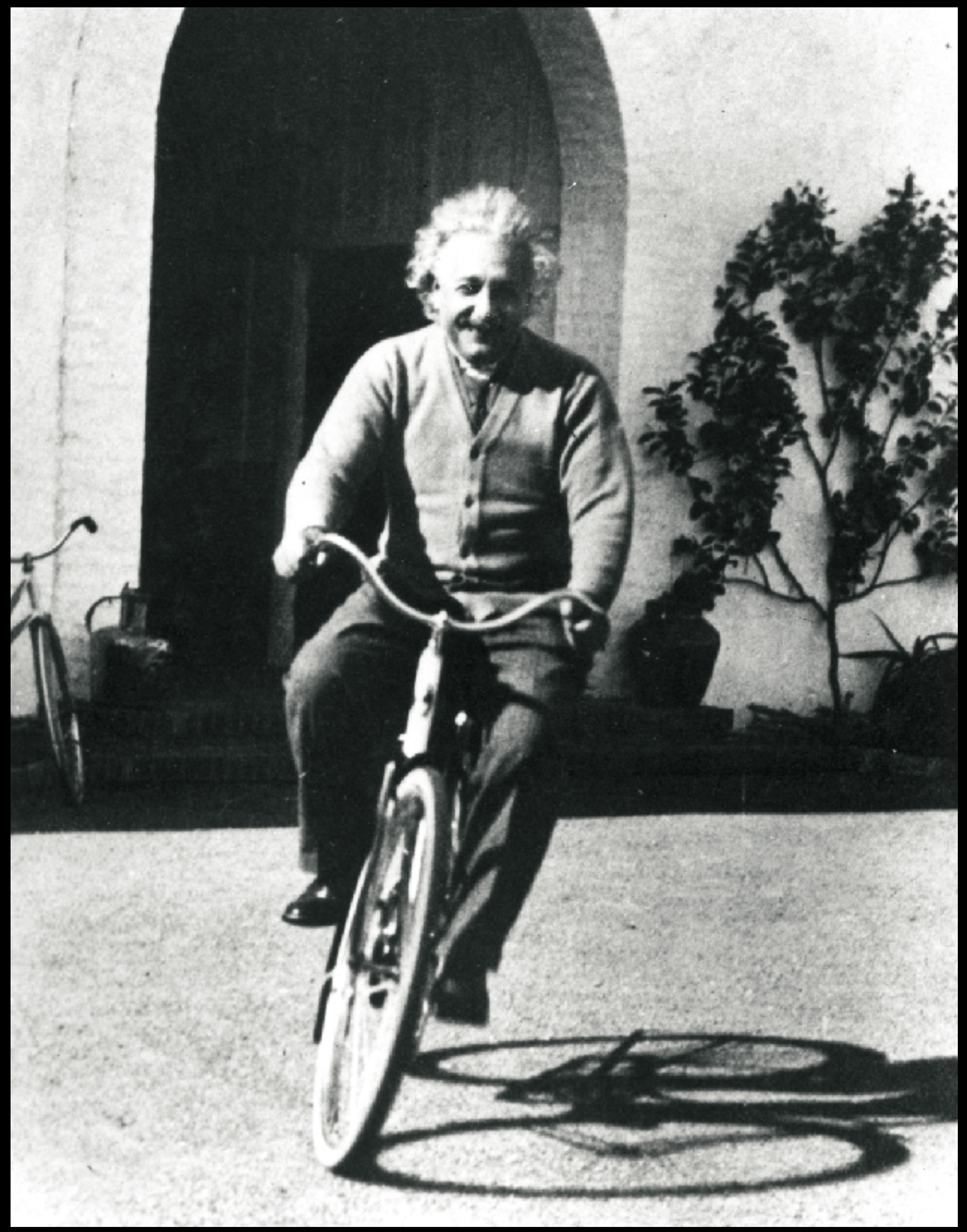
"Spacetime tells matter how to move, and matter tells spacetime how to curve"

All about GR in 1 min

- Metric g_{ab} –info about distances
- $\partial g_{ab} \rightarrow R_{abcd}$ –curvature tensor
- Part of $R_{abcd} \rightarrow G_{ab}$ – Einstein tensor
- T_{ab} – info about matter
- $G_{ab}=T_{ab}$ – 'Einstein's Equations'
- $G_{ab}= 0$ – for gravitational waves and black holes

Gravity
=
Spacetime curvature

Einstein's general relativity theory of gravity



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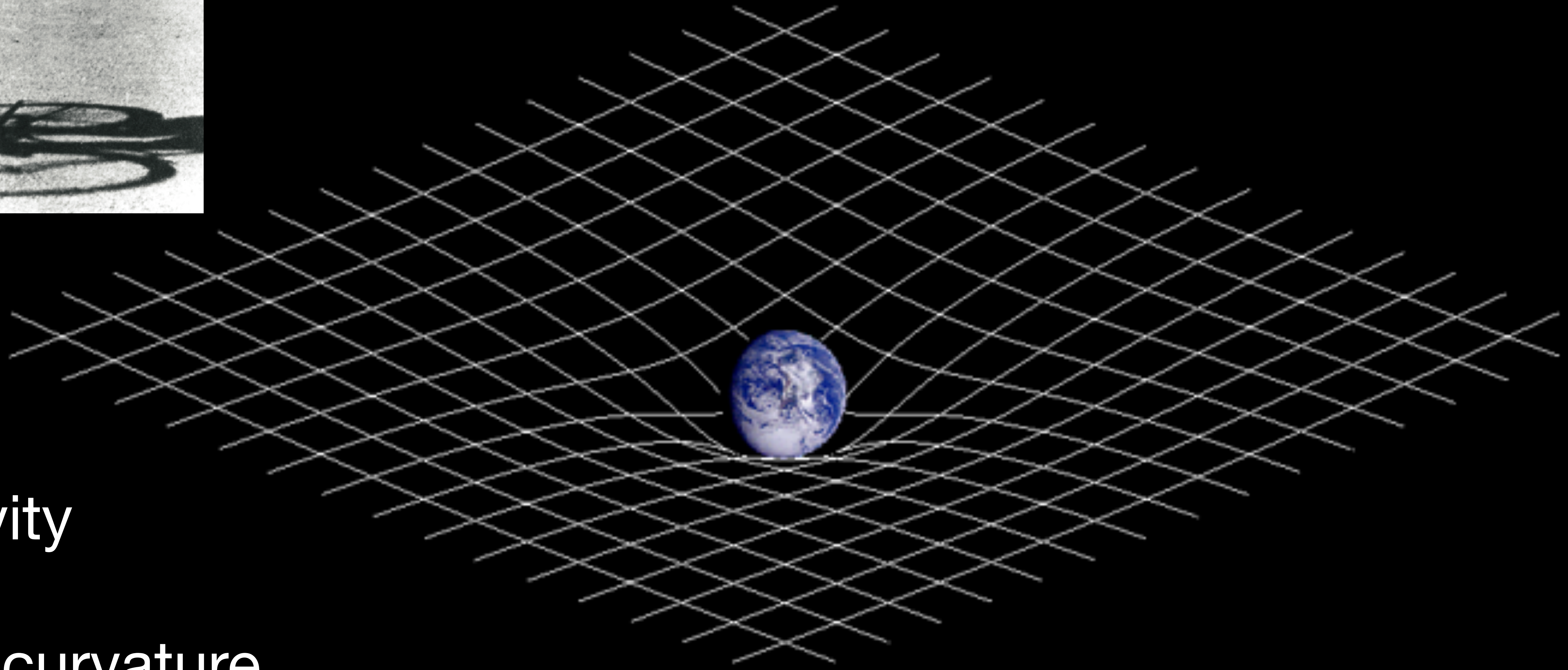

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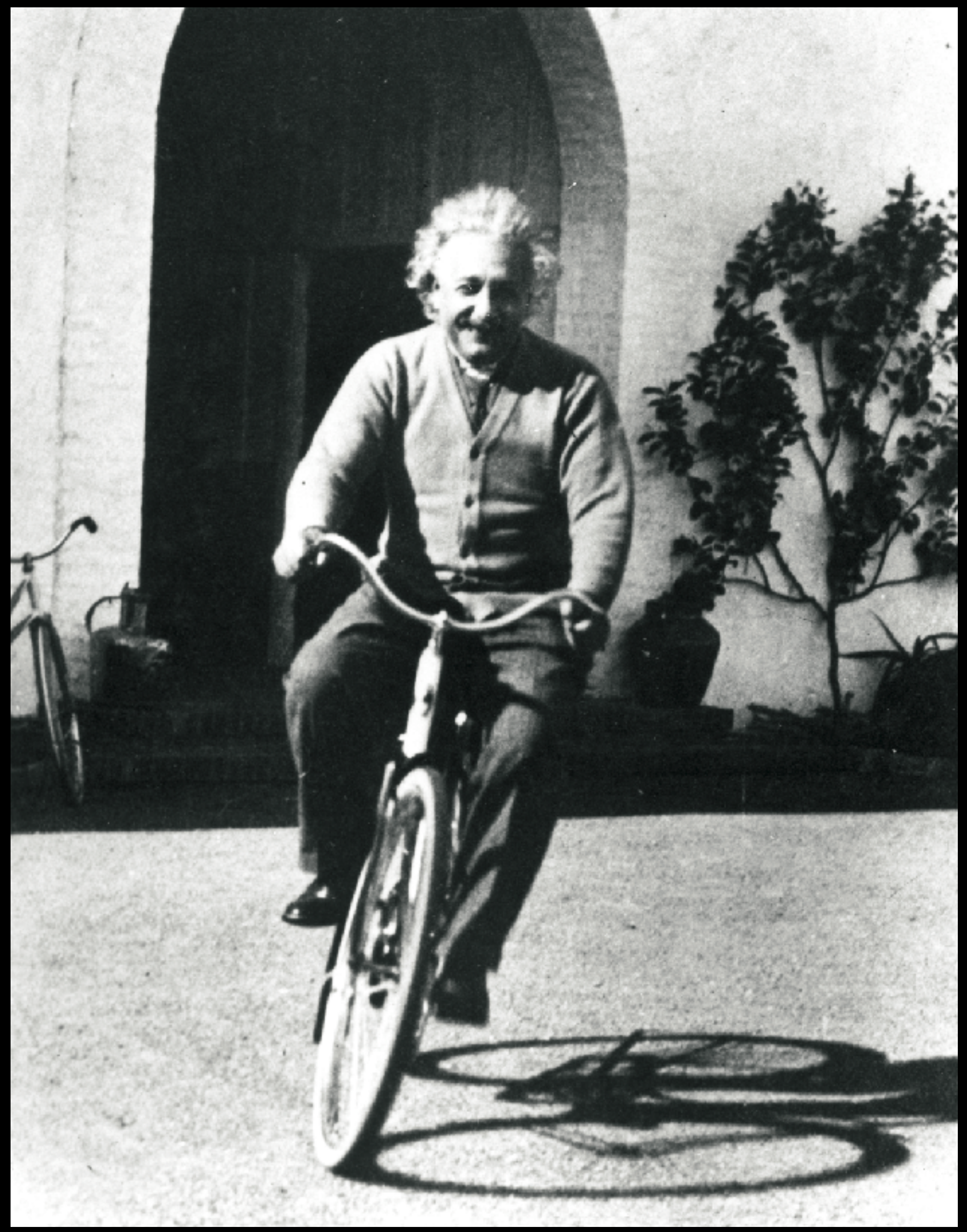

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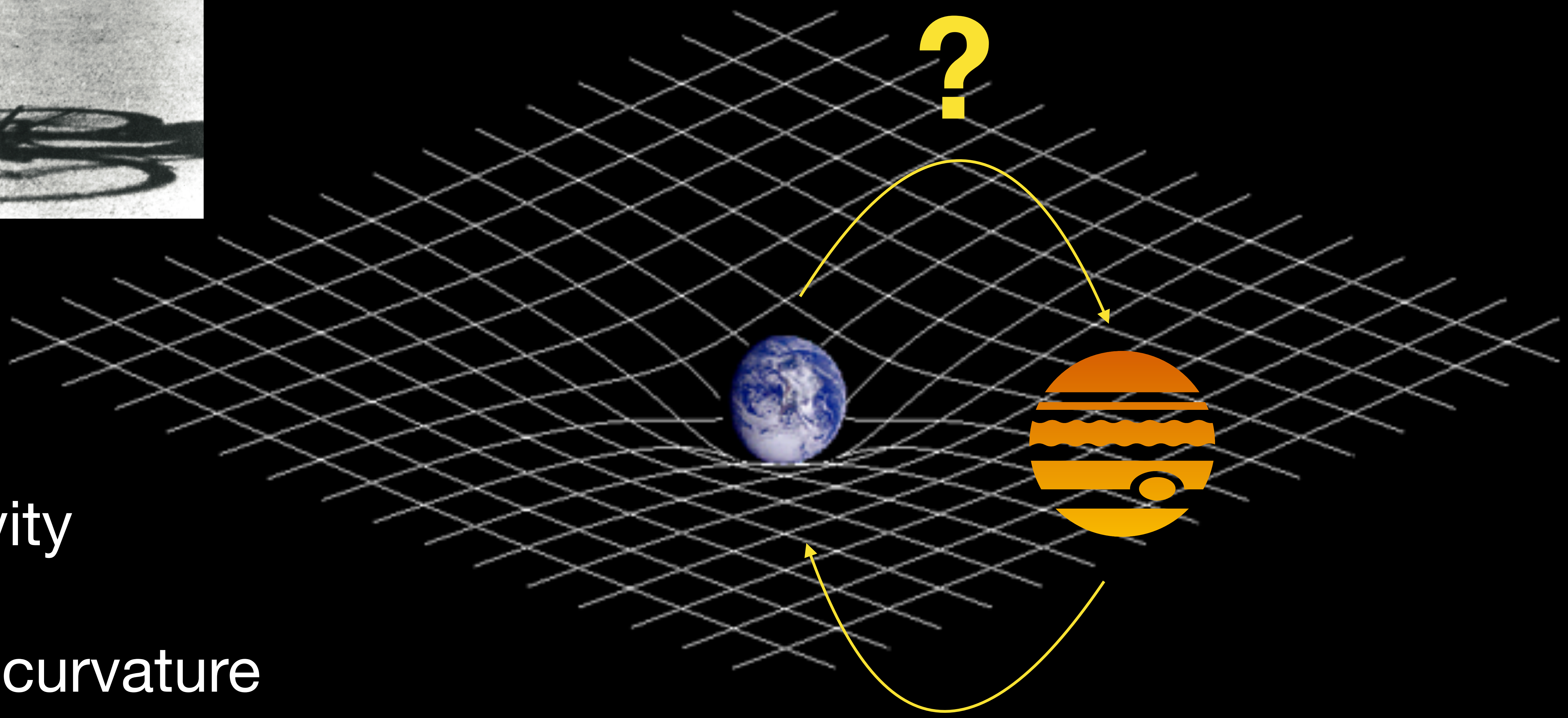
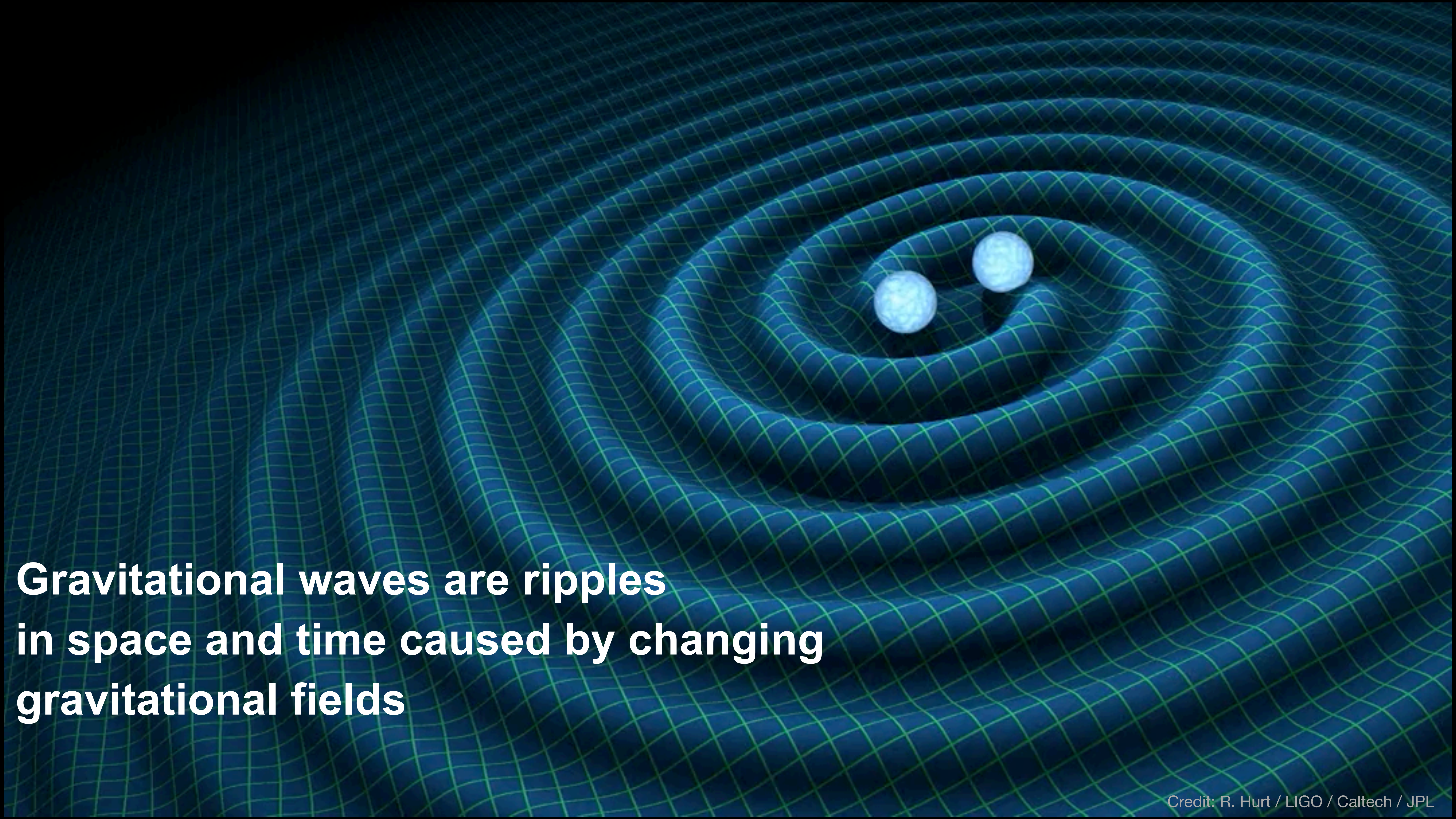
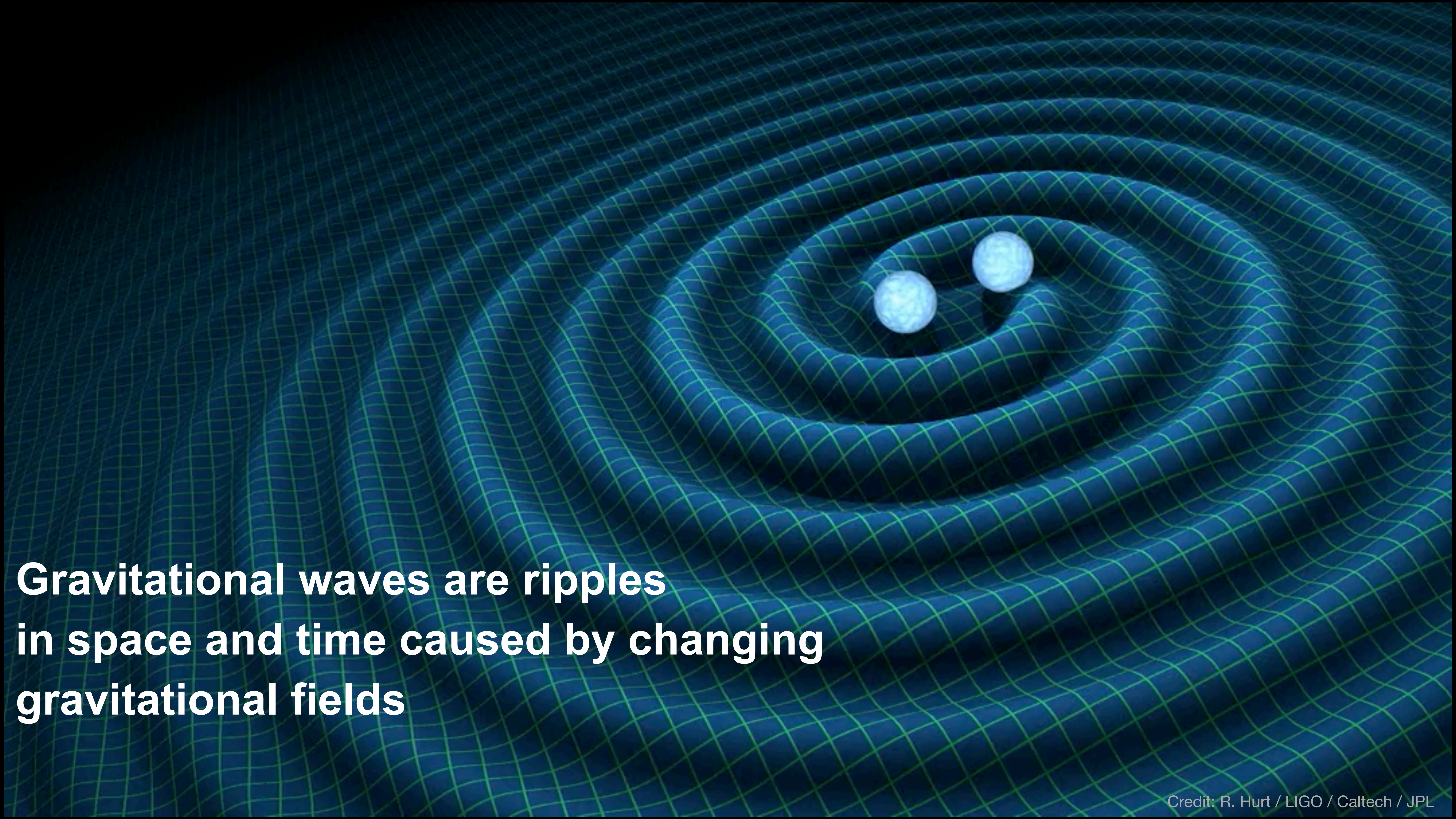


Gravity
=
Spacetime curvature

Gravitational waves = dynamical spacetime

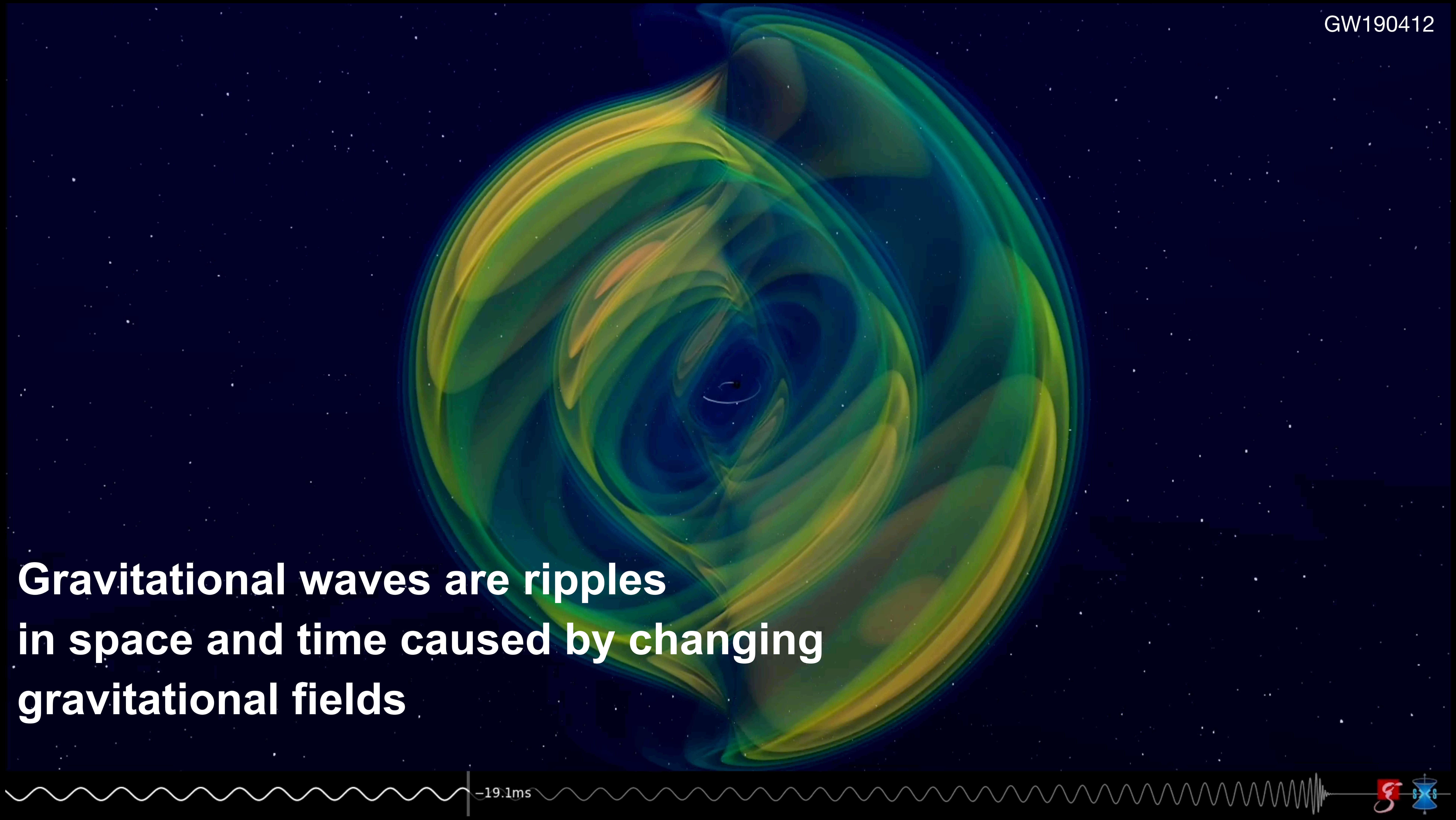


Gravitational waves = dynamical spacetime



Gravitational waves are ripples in space and time caused by changing gravitational fields

Gravitational waves = dynamical spacetime



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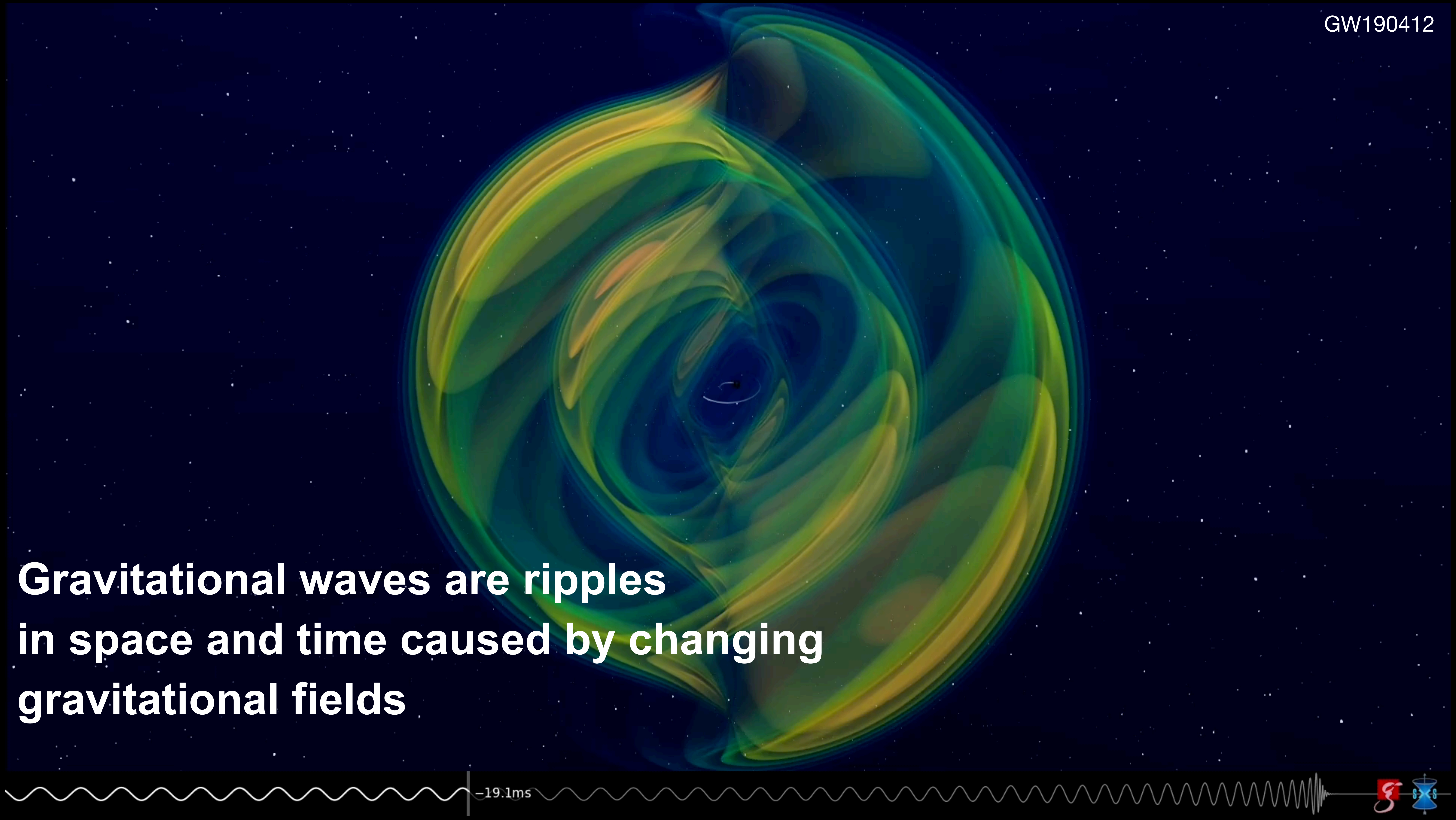
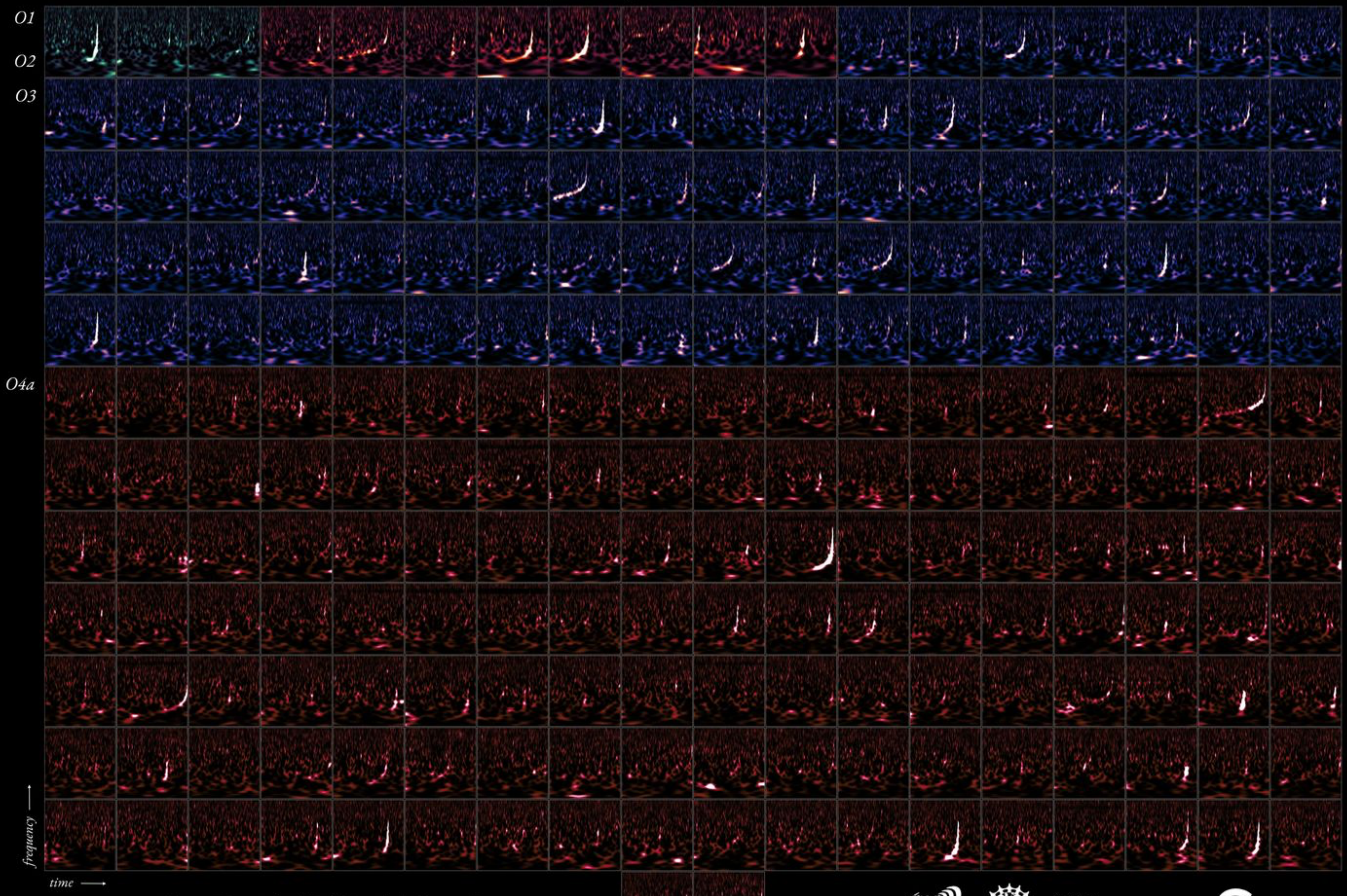


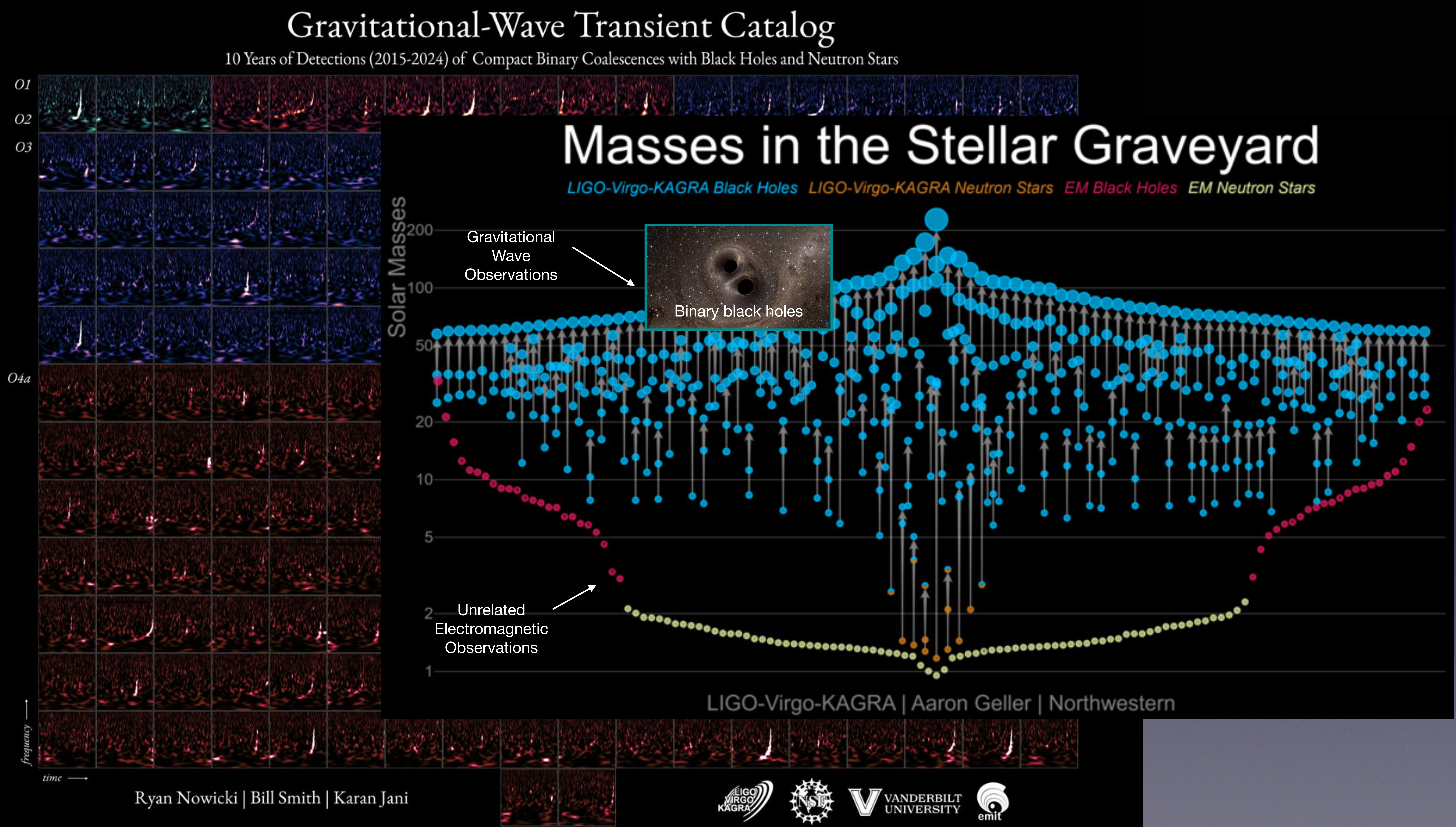
Gravitational-Wave Transient Catalog

10 Years of Detections (2015-2024) of Compact Binary Coalescences with Black Holes and Neutron Stars



Ryan Nowicki | Bill Smith | Karan Jani


Gravitational-Wave Transient Catalog
10 Years of Detections (2015-2024) of Compact Binary Coalescences with Black Holes and Neutron Stars
O1
O2
O3
O4a
frequency
time
Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
Gravitational Wave Observations
Unrelated Electromagnetic Observations
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern
Ryan Nowicki | Bill Smith | Karan Jani
VANDERBILT UNIVERSITY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LIGO VIRGO KAGRA
NSF
VANDERBILT UNIVERSITY
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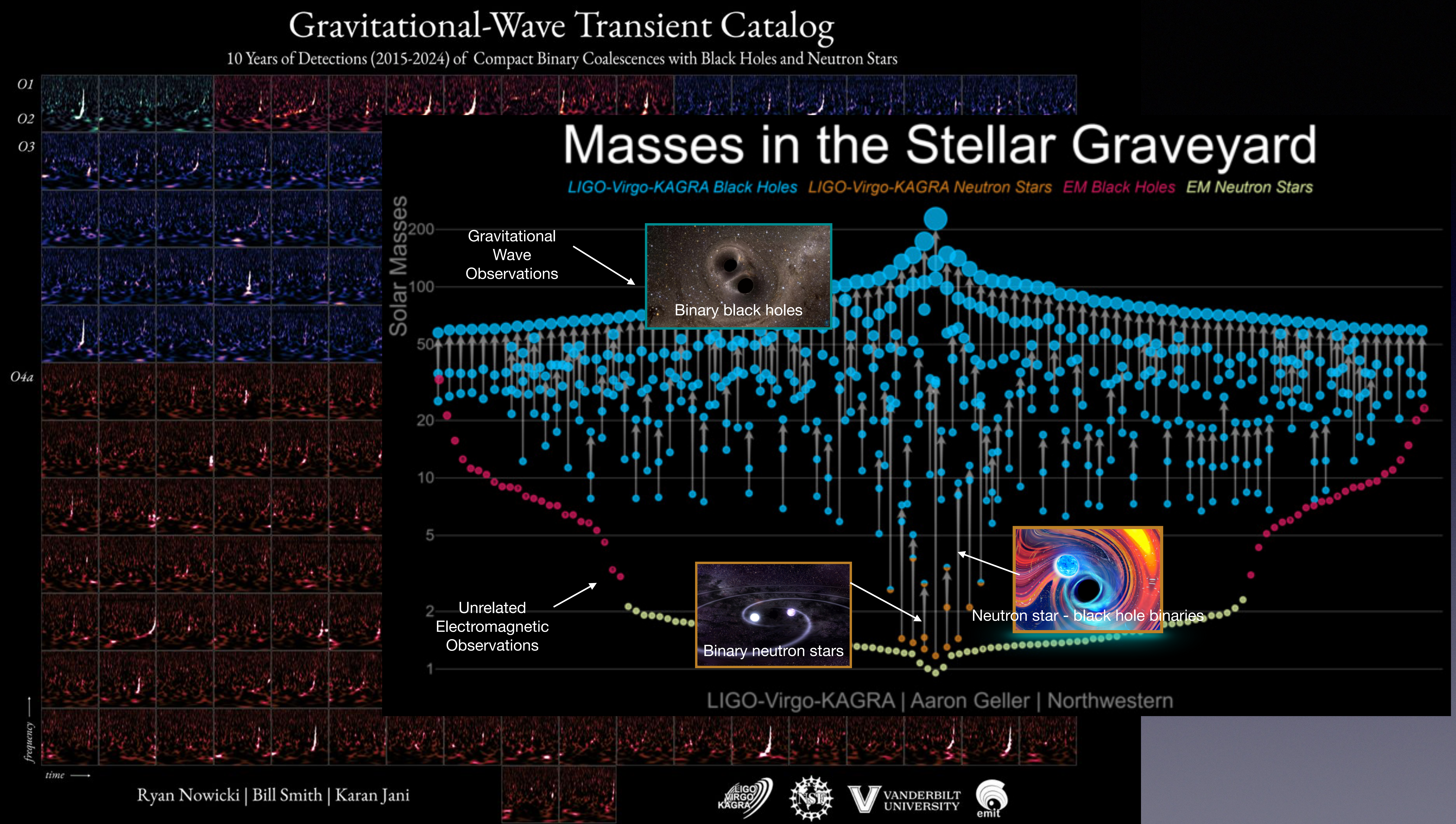
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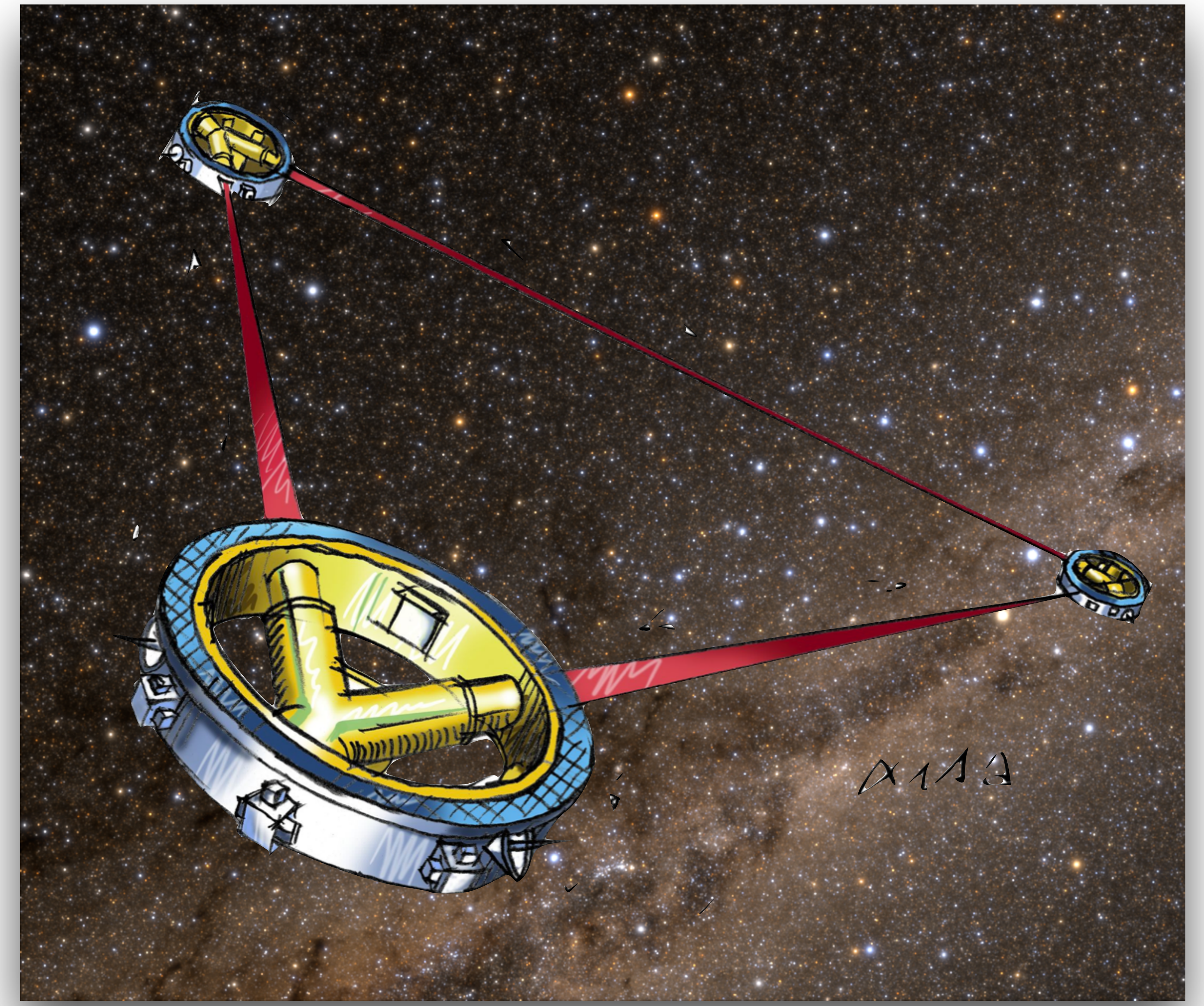
Binary neutron stars
Neutron star - black hole binaries
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Opening a new GW band

NASA/STScI



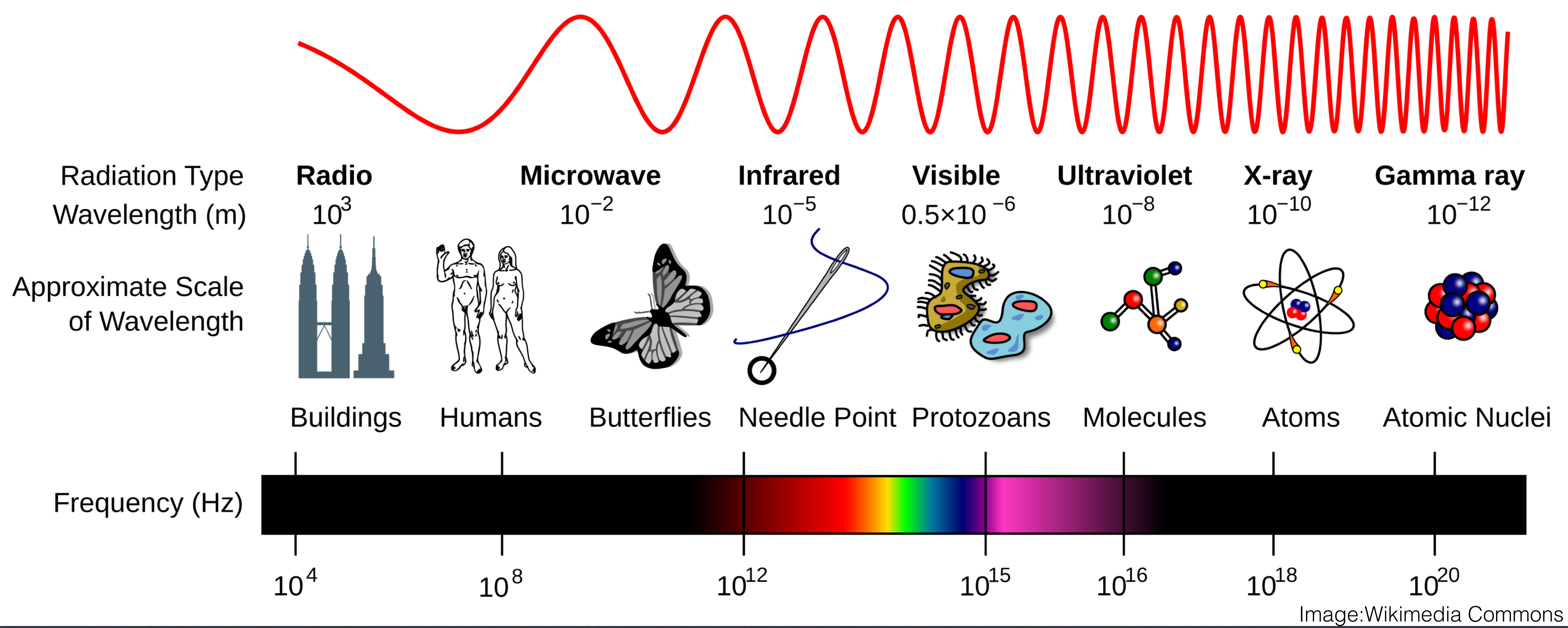
Credit: ESA-C. Vijoux

- Avoid terrestrial disturbances
- Access new spectral bands

- Avoid terrestrial disturbances
- Access new spectral bands

Why go to space?

Same reasons as for EM telescopes



Radiation Type
Wavelength (m)
Approximate Scale of Wavelength
Radio
10^3
Microwave
10^-2
Infrared
10^-5
Visible
0.5×10^-6
Ultraviolet
10^-8
X-ray
10^-10
Gamma ray
10^-12
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Image:Wikimedia Commons

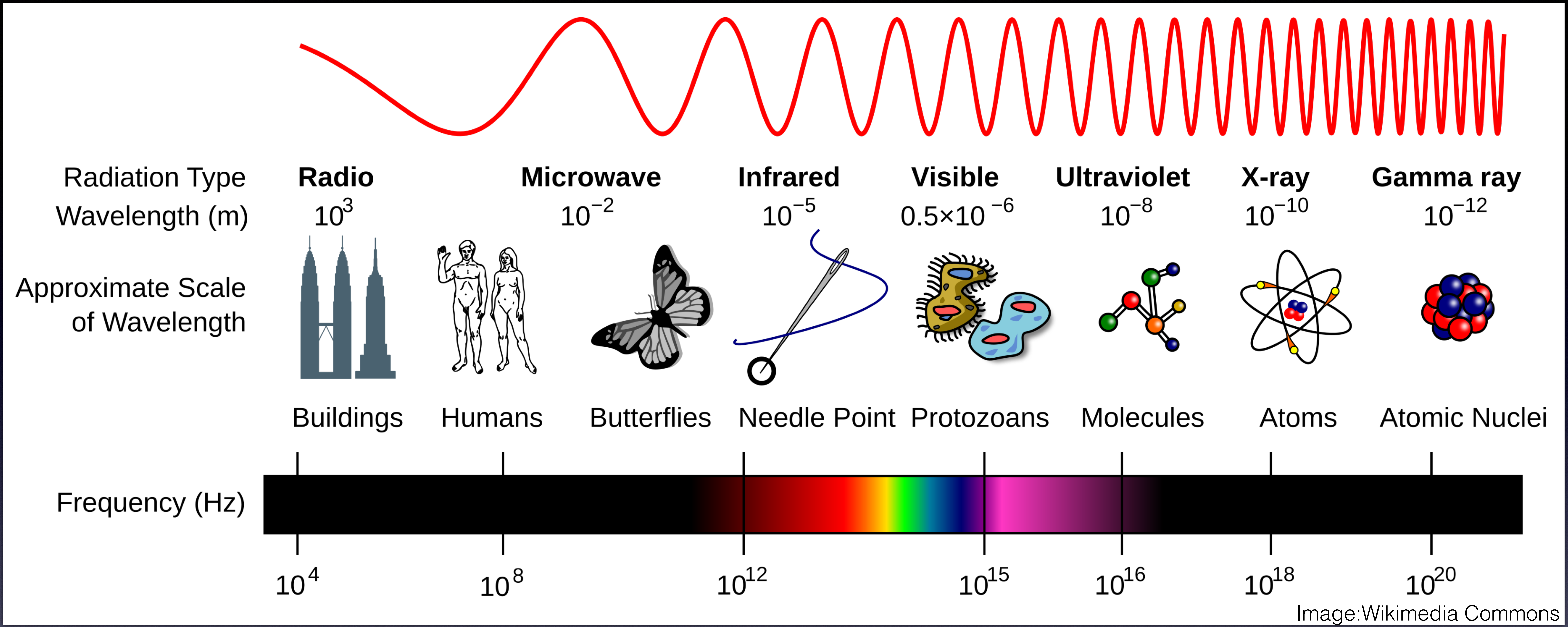


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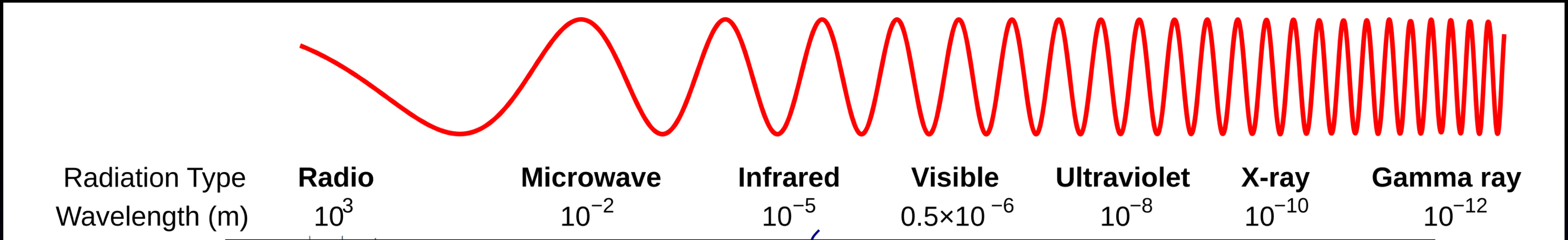
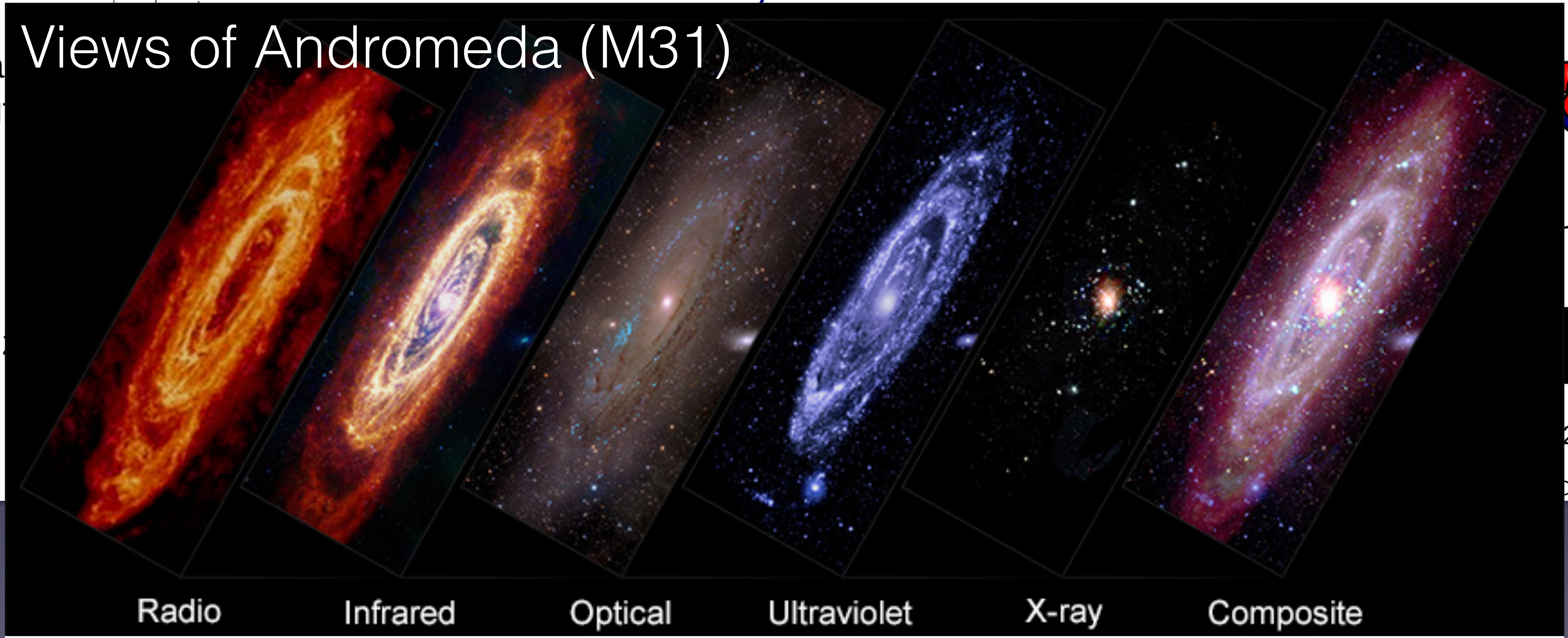
Image:Wikimedia Commons



Views of Andromeda (M31)



Credit: **X-ray:** NASA/CXO/UMass/Z. Li & Q.D. Wang, ESA/XMM-Newton; **Infrared:** NASA/JPL-Caltech/WISE, Spitzer, NASA/JPL-Caltech/K. Gordon (U. Az), ESA/Herschel, ESA/Planck, NASA/IRAS, NASA/COBE; **Radio:** NSF/GBT/WSRT/IRAM/C. Clark (STScI); **Ultraviolet:** NASA/JPL-Caltech/GALEX; **Optical:** Andromeda, Unexpected © Marcel Drechsler, Xavier Strottner, Yann Sainty & J. Sahner, T. Kottary. **Composite image processing:** L. Frattare, K. Arcand, J.Major

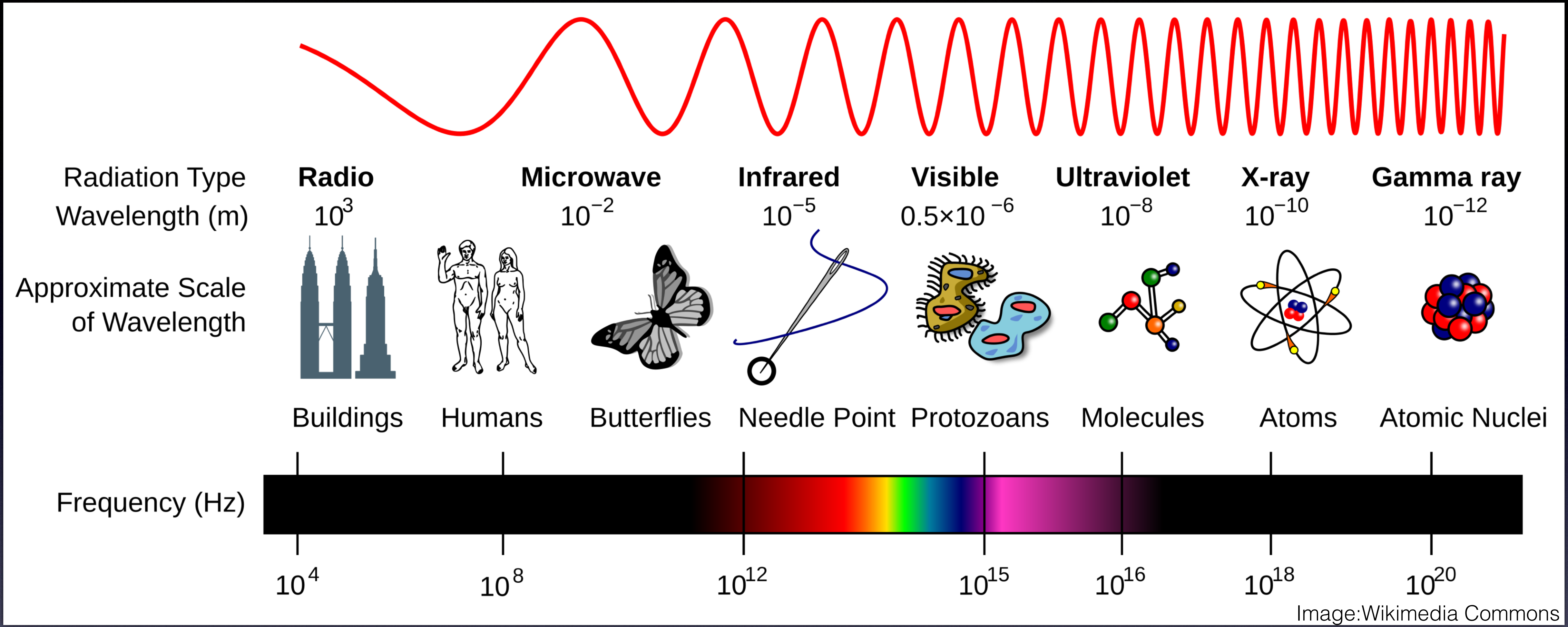

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Image:Wikimedia Commons

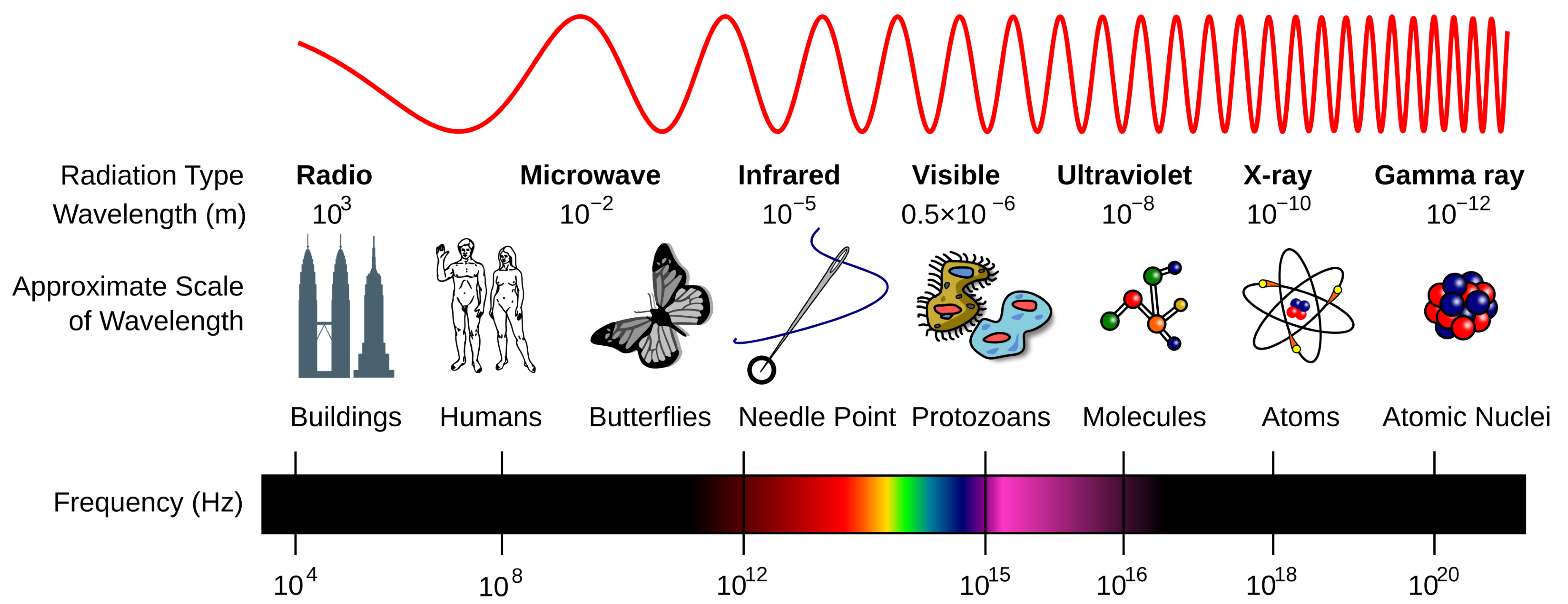
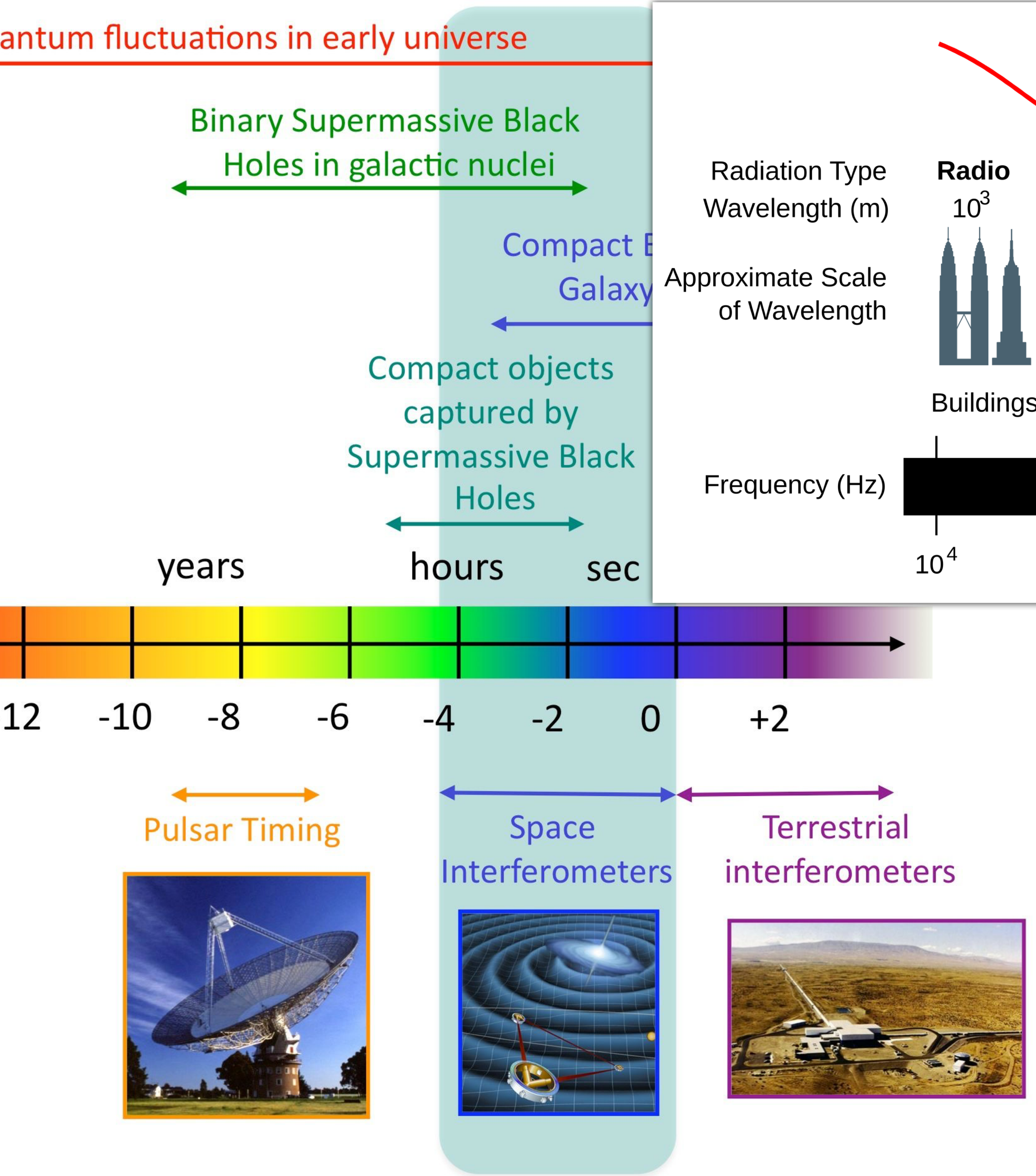
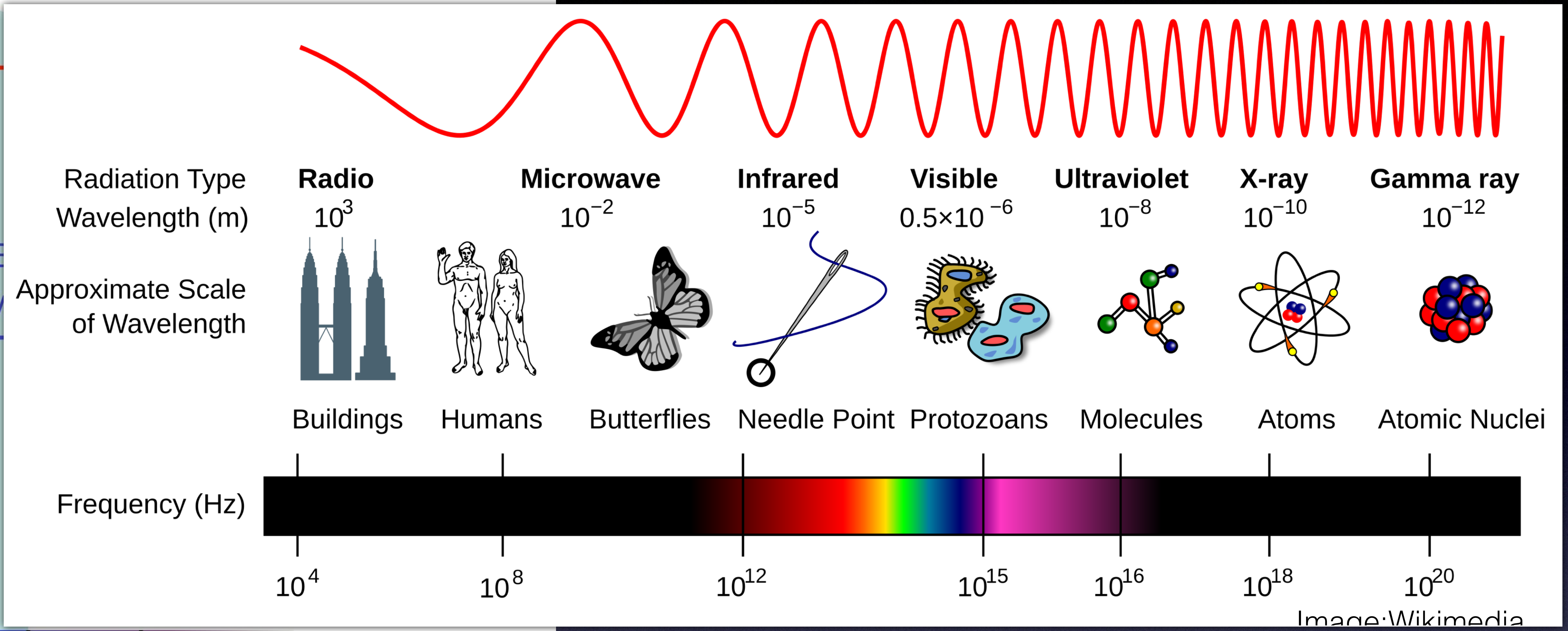


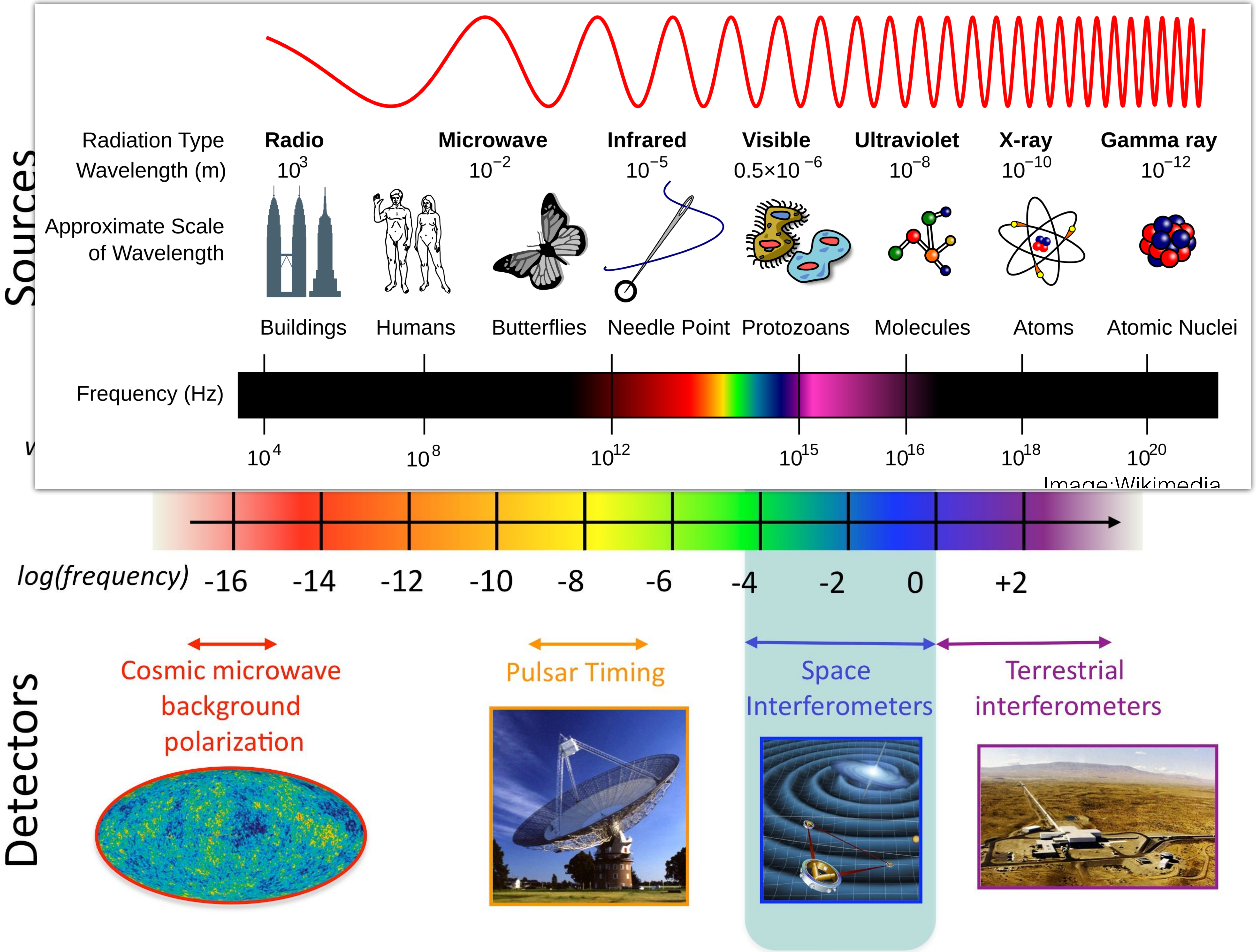
Image:Wikimedia

avitational Wave Spectrum





The Gravitational Wave Spectrum



What can we achieve in the MHz band?

The science of LISA

- SO1: Etude de la formation et de l’évolution des binaires d’étoiles compactes dans la Voie Lactée.
- SO2: Retracer l'origine, la croissance et l'histoire de la fusion des trous noirs supermassifs à travers les âges cosmiques
- SO3: Sonder les propriétés et l’environnement immédiat des trous noirs dans l’Univers local avec les Extreme Mass Ratio Inspirals et les Intermediate Mass Ratio Inspirals.
- SO4: Comprendre l’astrophysique des trous noirs d’origin stellaire.
- SO5: Explorer la nature fondamentale de la gravité et des trous noirs.
- SO6: Mesurer le taux d'expansion de l’Univers.
- SO7: Comprendre les fonds stochastiques et leurs implications pour l'Univers très jeune et la physique des particules à l'échelle du TeV.
- SO8: Rechercher des sursauts d’OGs et des sources inattendues.

Astrophysique

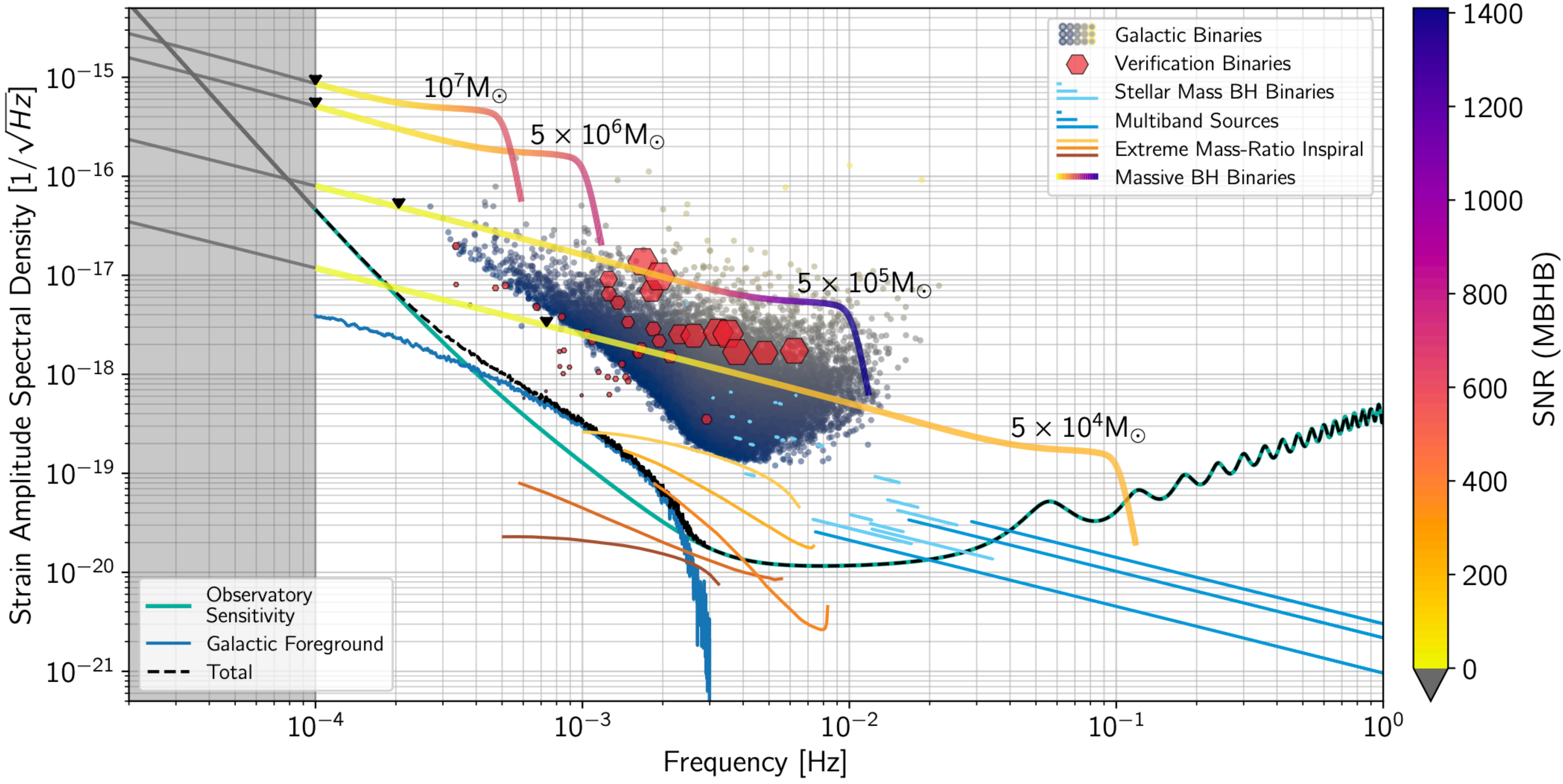
Physique fondamentale

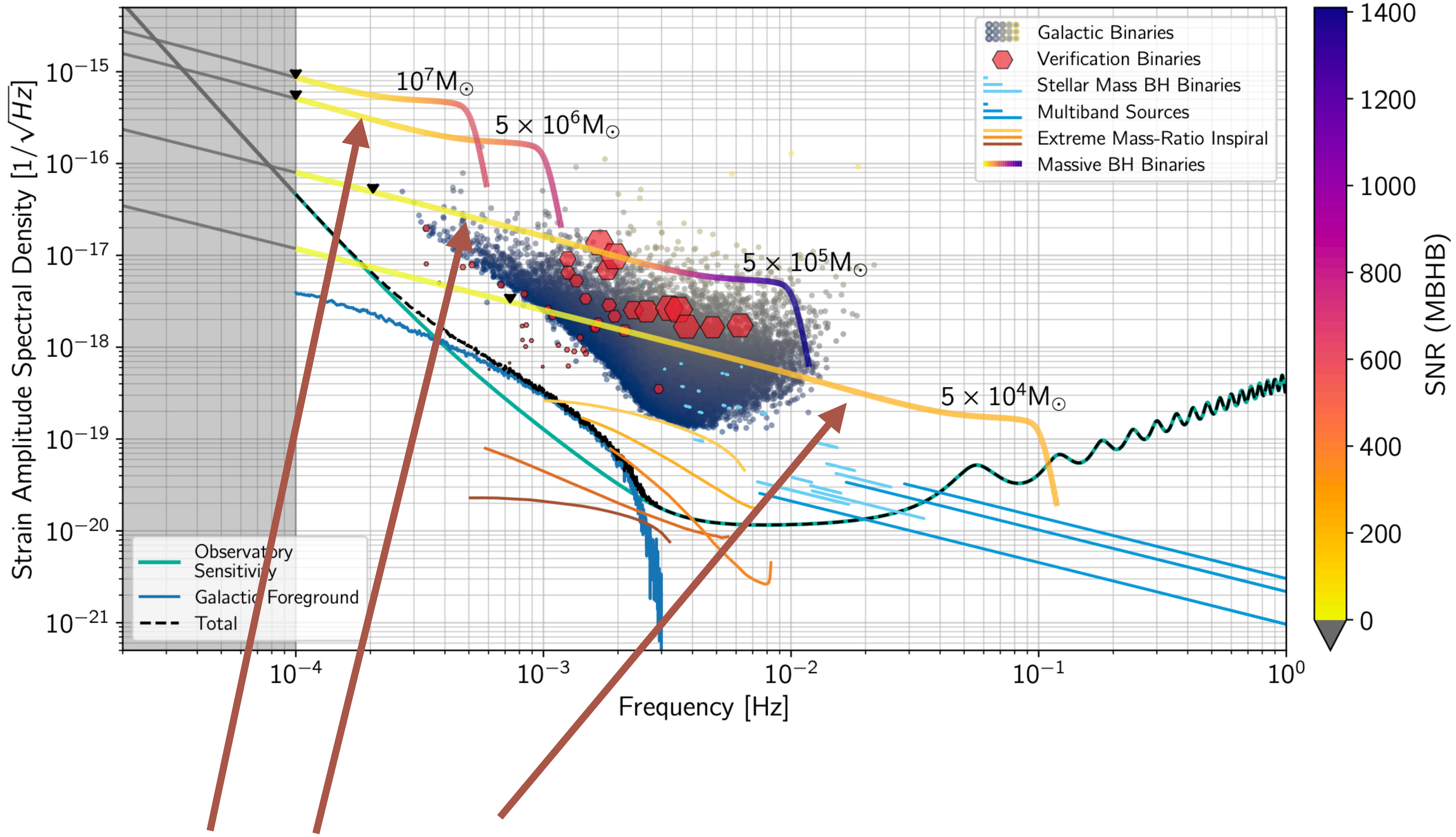
Cosmologie

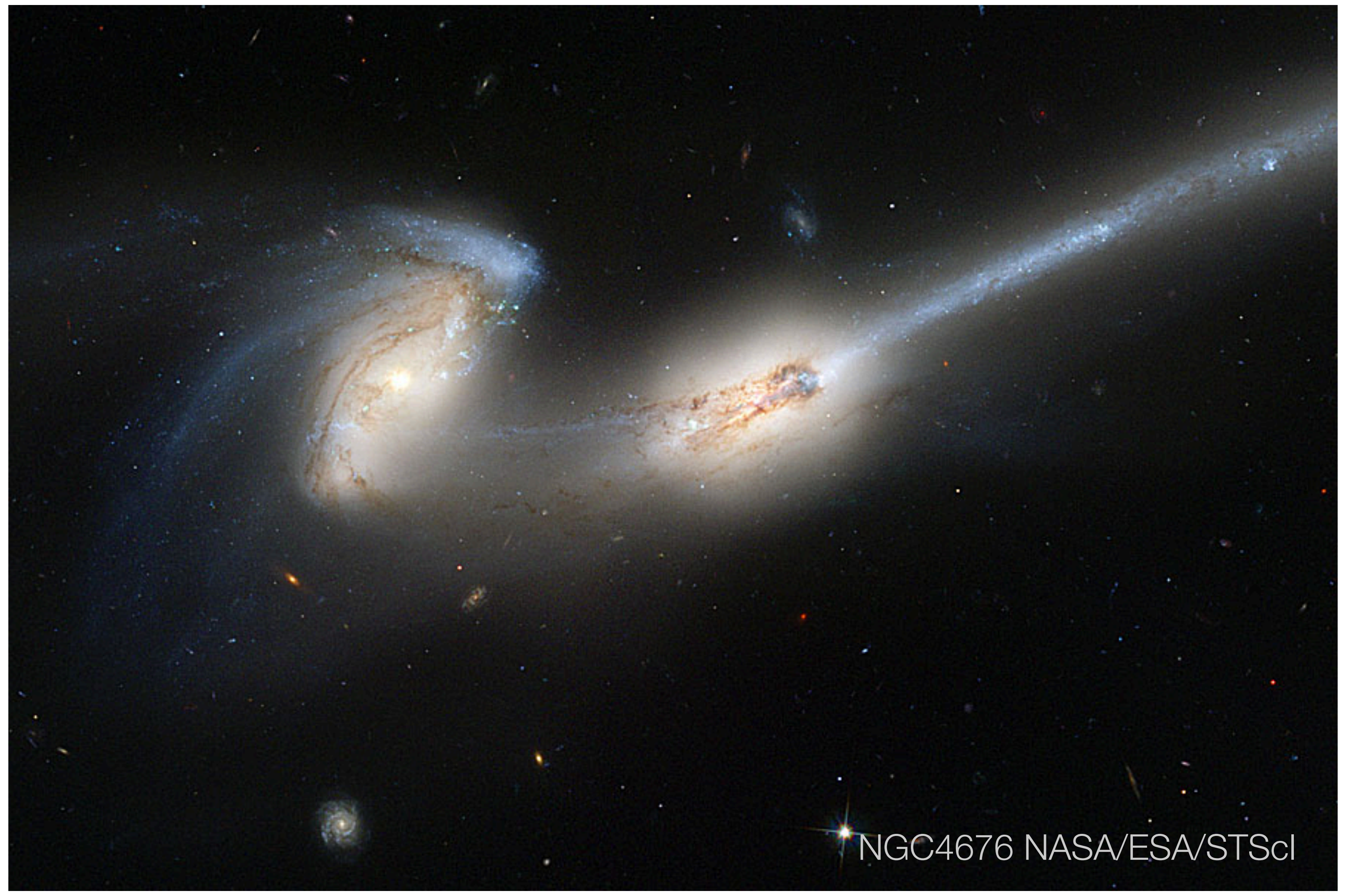
LISA Sources & Noise

Everything in one plot

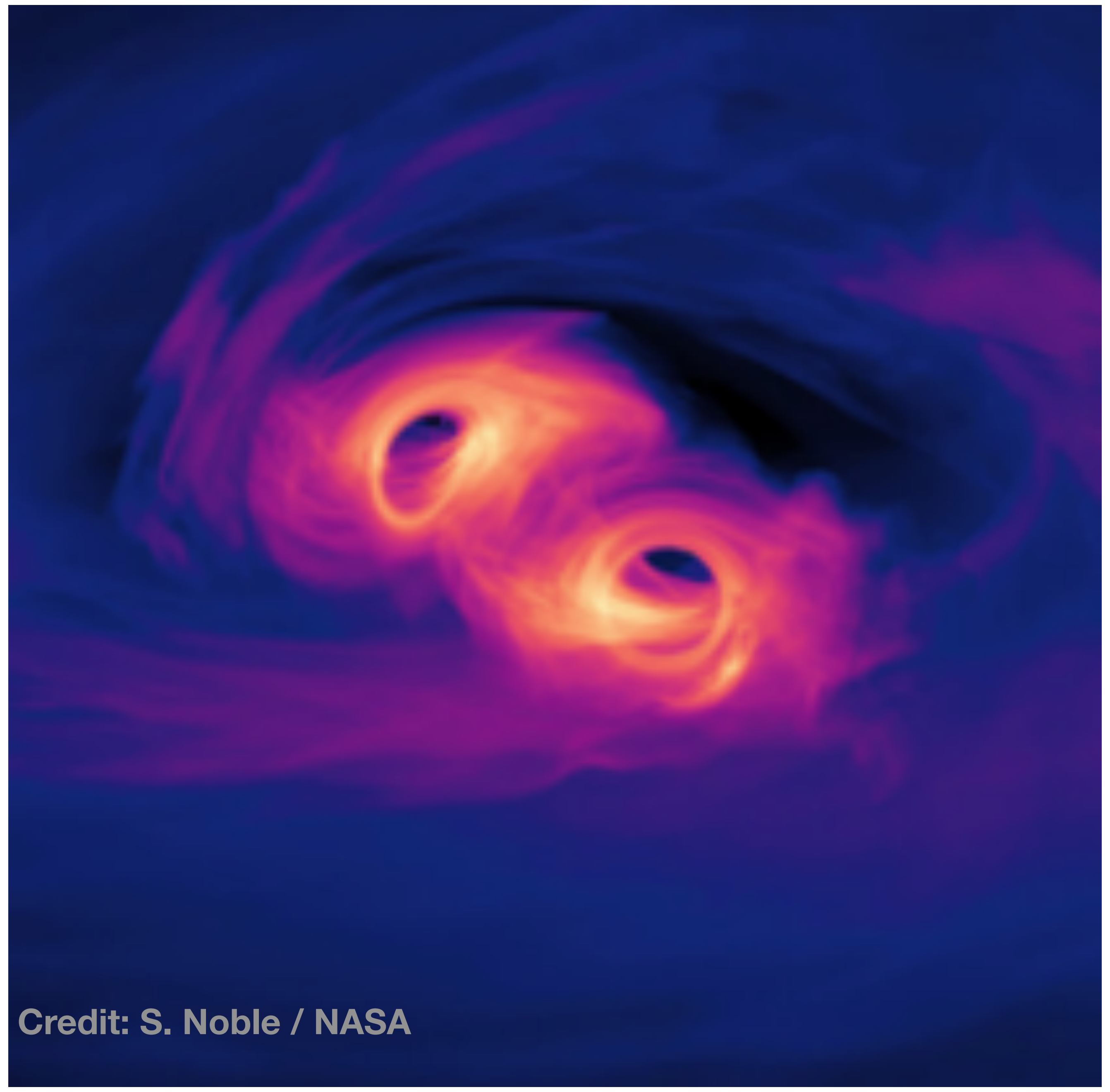
- Horizontal axis: GW frequency
- Vertical axis: GW amplitude
- Solid Green line: Instrument limit
- Blue arc: GW *foreground*
- colored dots: persistent sources
- colored tracks: transient sources





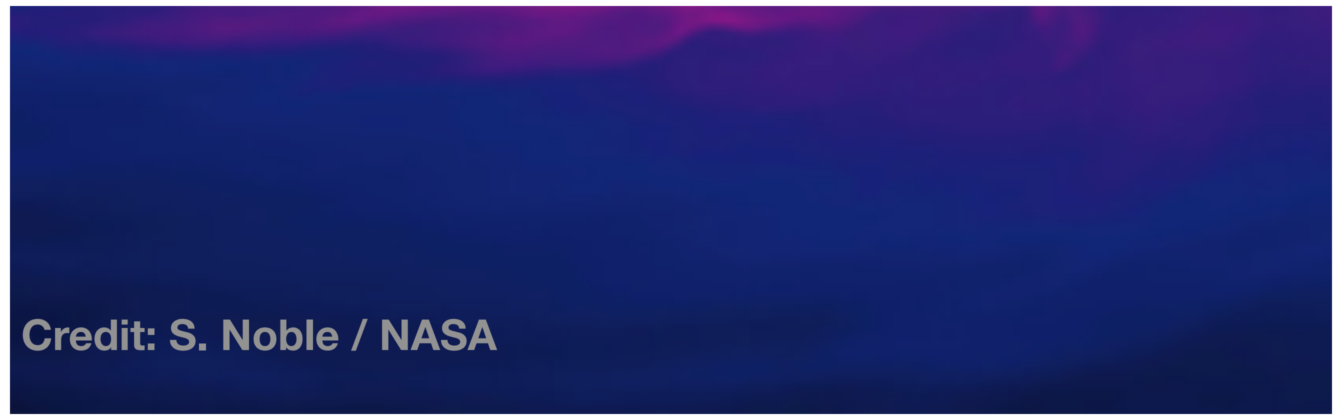


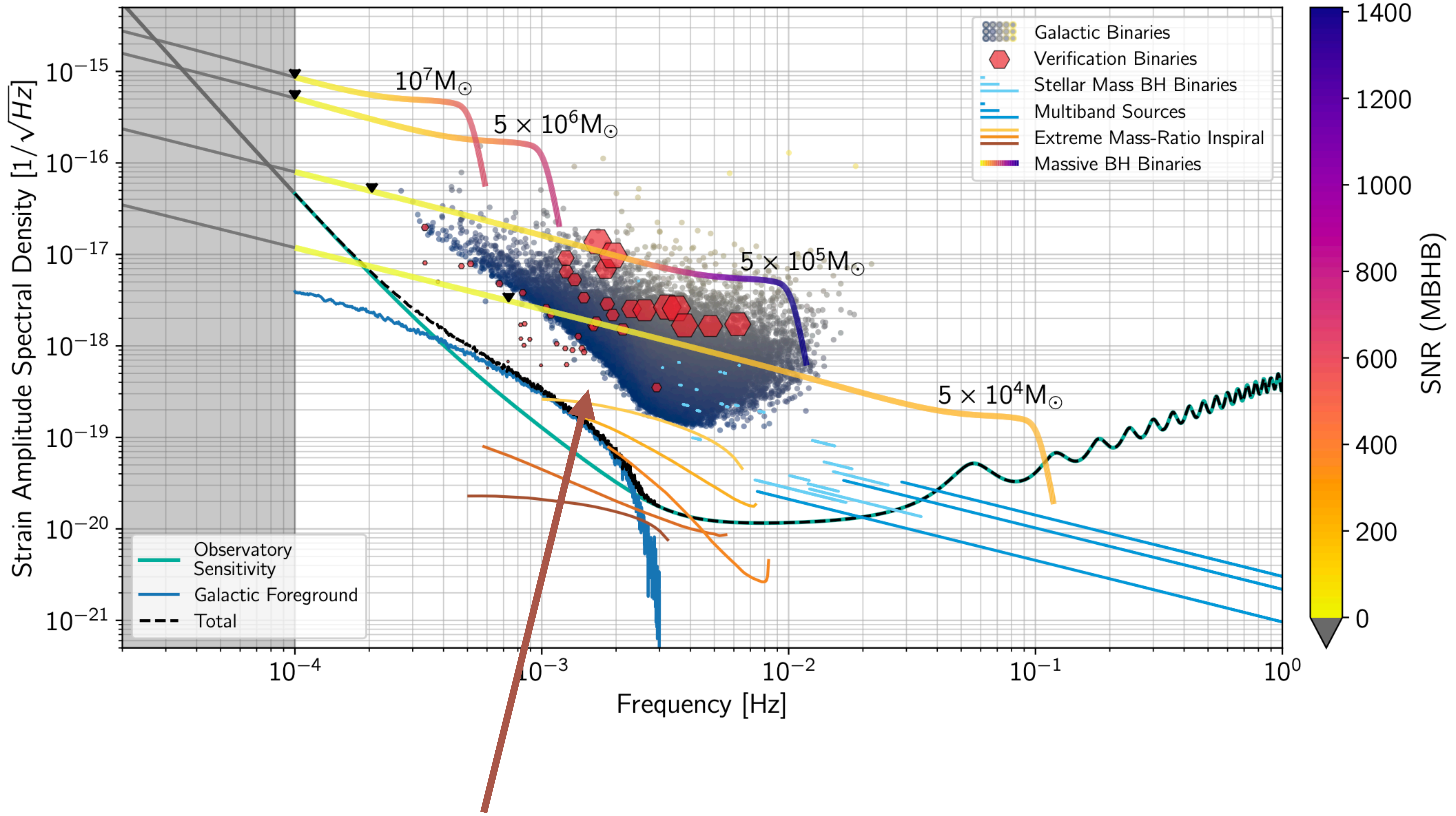
top: *Optical image of NGC4676, the merging "mice" galaxies.* ***bottom:*** *simulation of accretion flow around binary supermassive black hole*



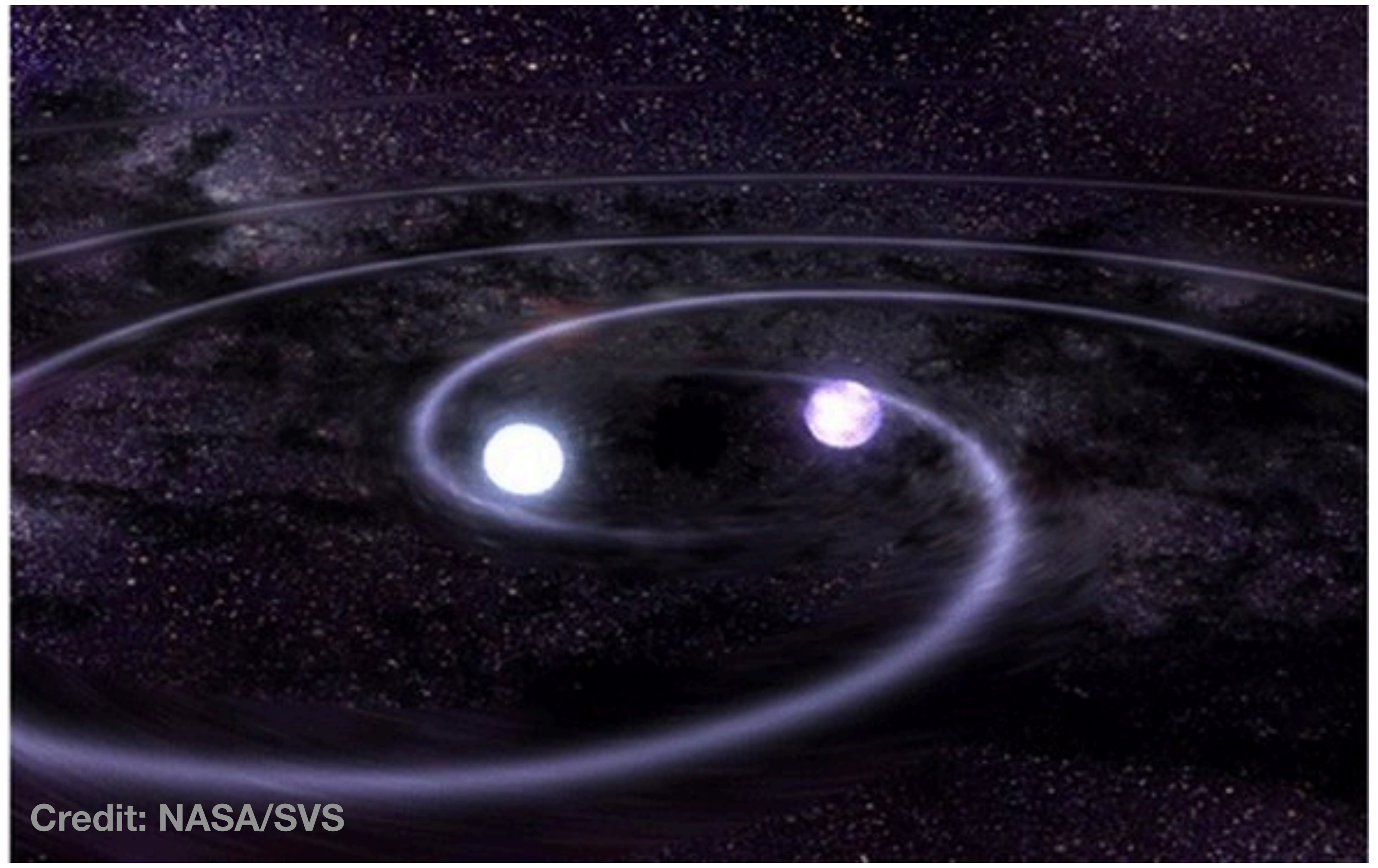
Massive Black Hole Binaries

Massive Black Hole Binaries

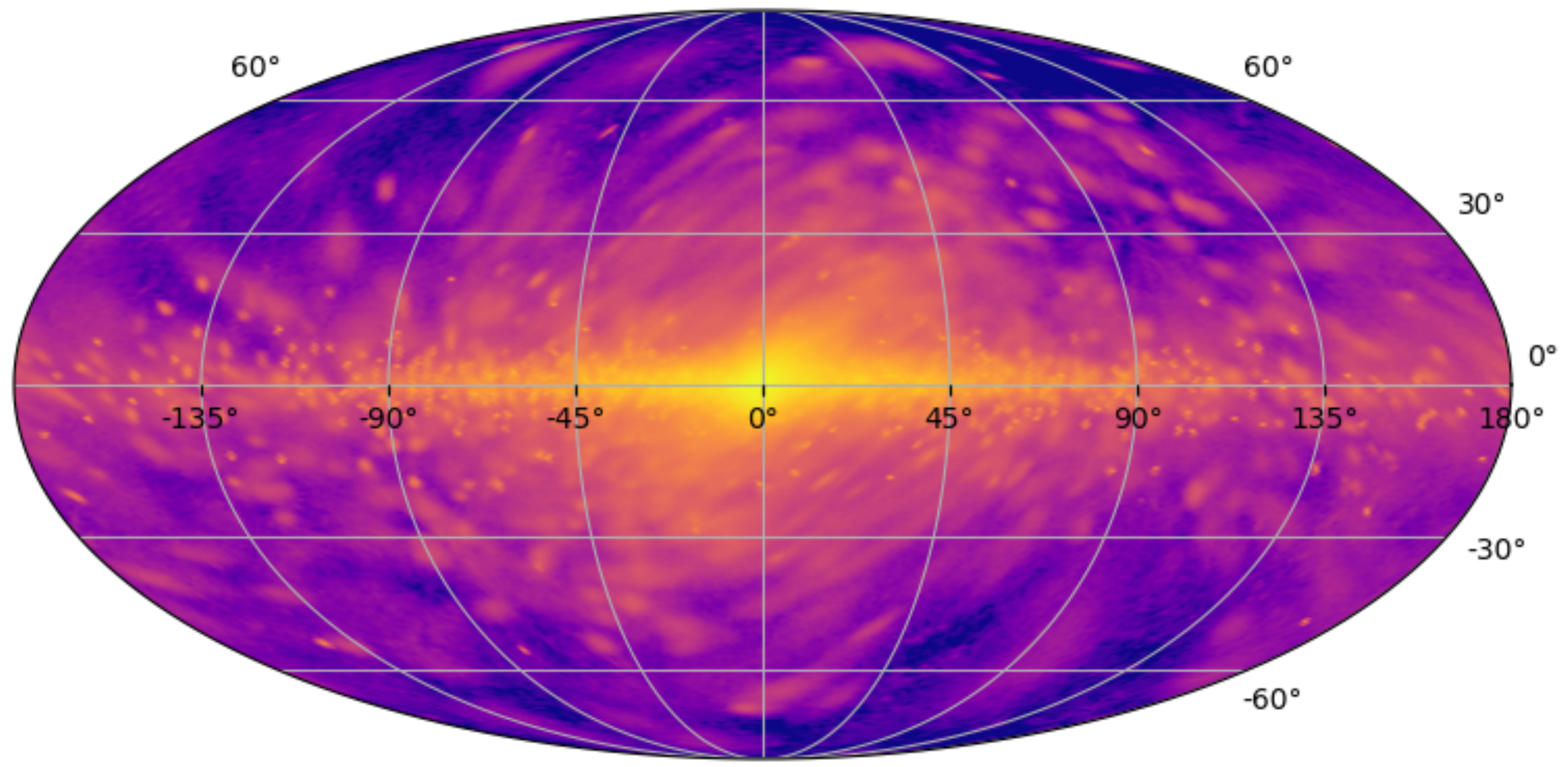


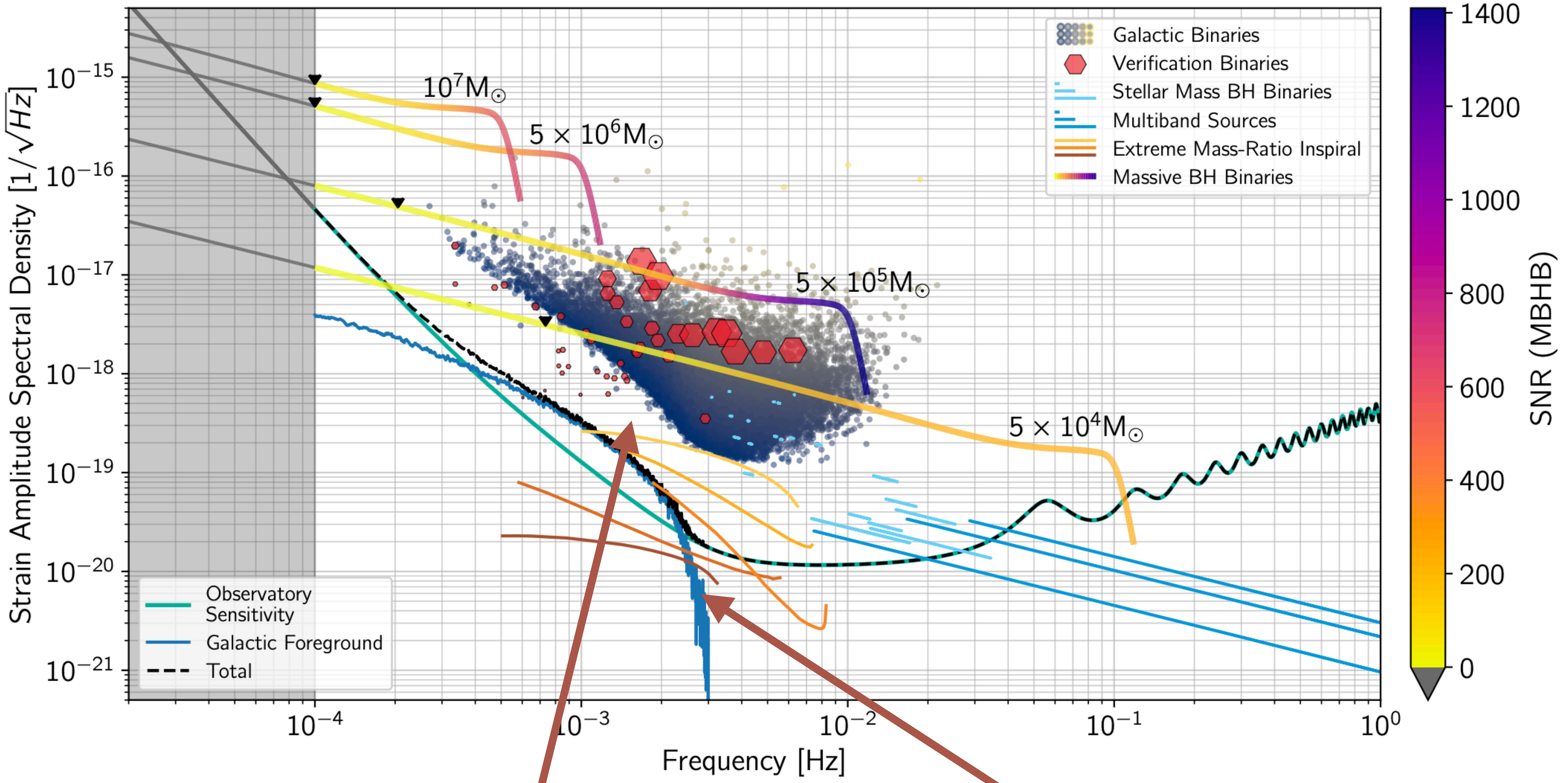


Galactic Binaries



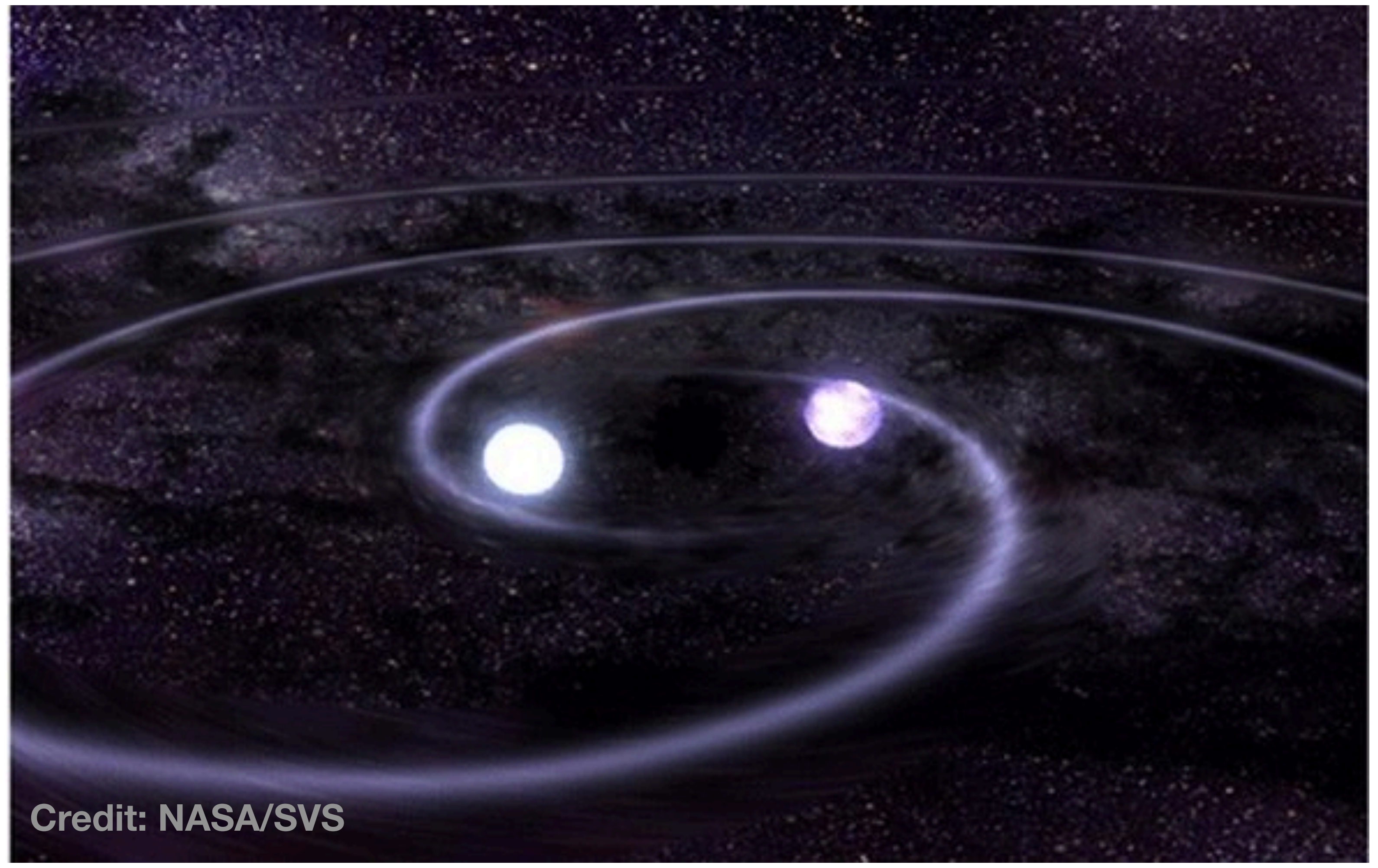
top: *artist's rendition of merging white dwarf binary.* ***bottom****: recovered localization probability from a search of simulated LISA galactic binary data (Thorpe/Littenberg/Lackeos)*



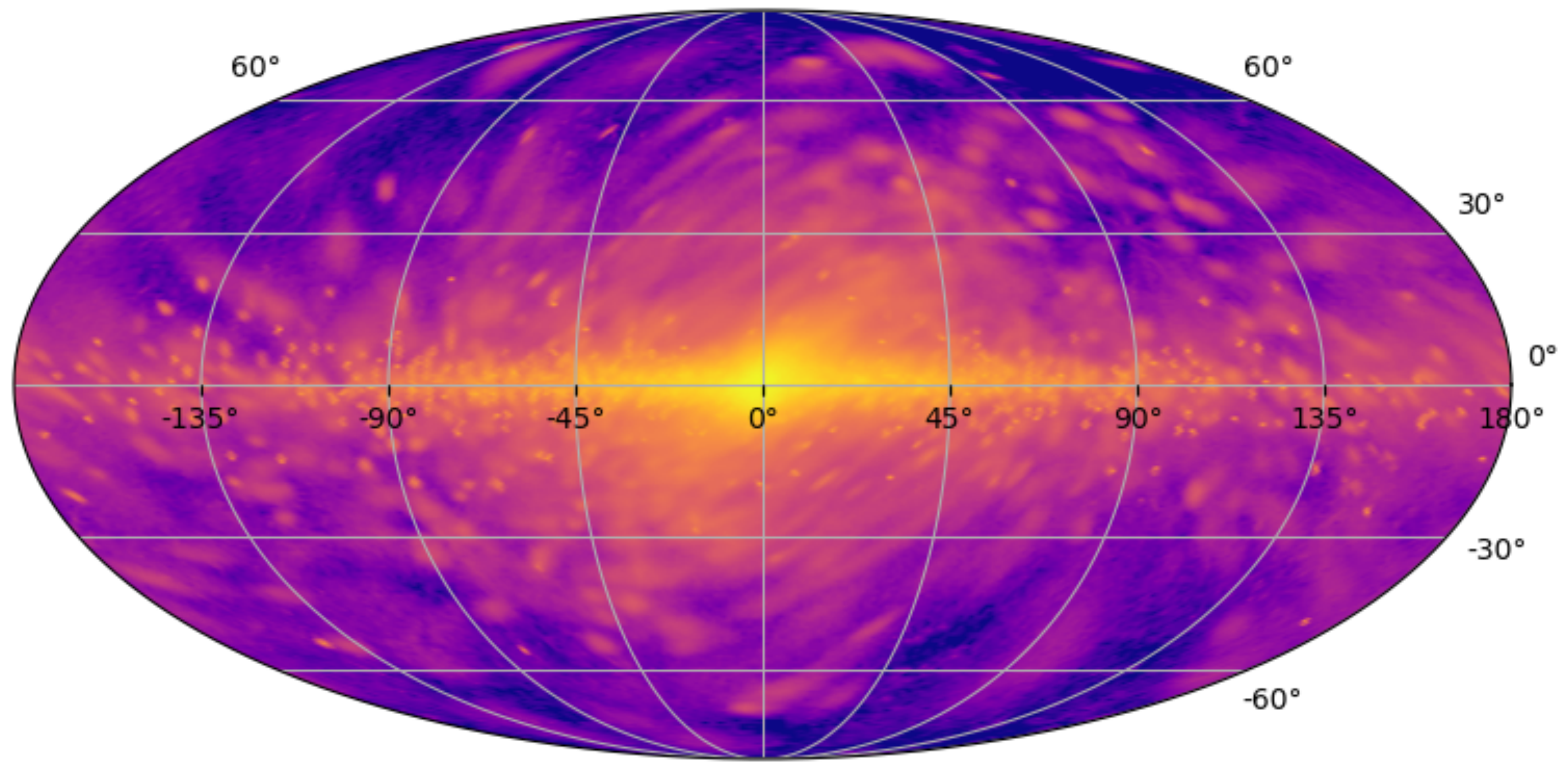


Galactic Binaries

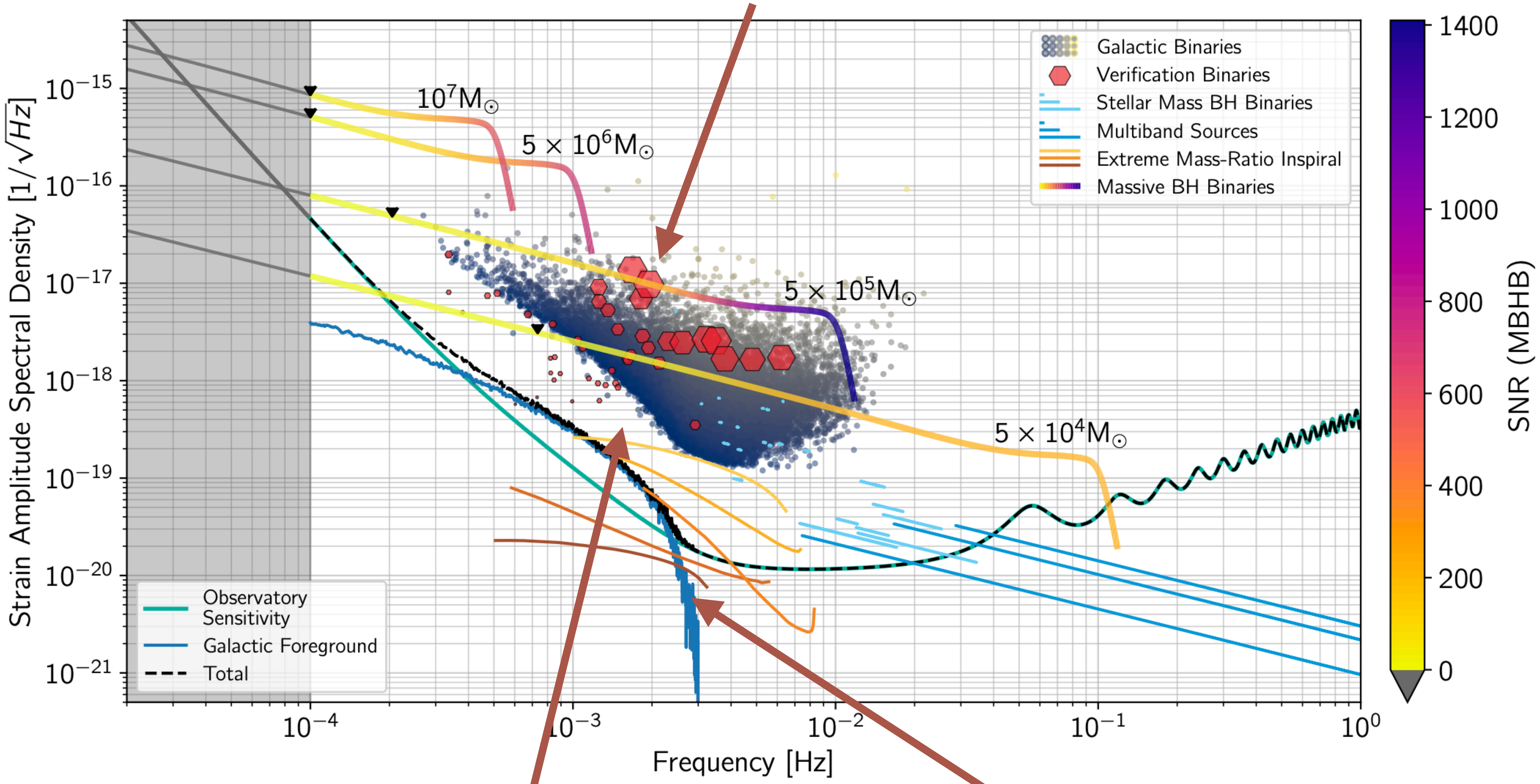
Galactic binary stochastic confusion



***top:** artist's rendition of merging white dwarf binary. **bottom**: recovered localization probability from a search of simulated LISA galactic binary data (Thorpe/Littenberg/Lackeos)*

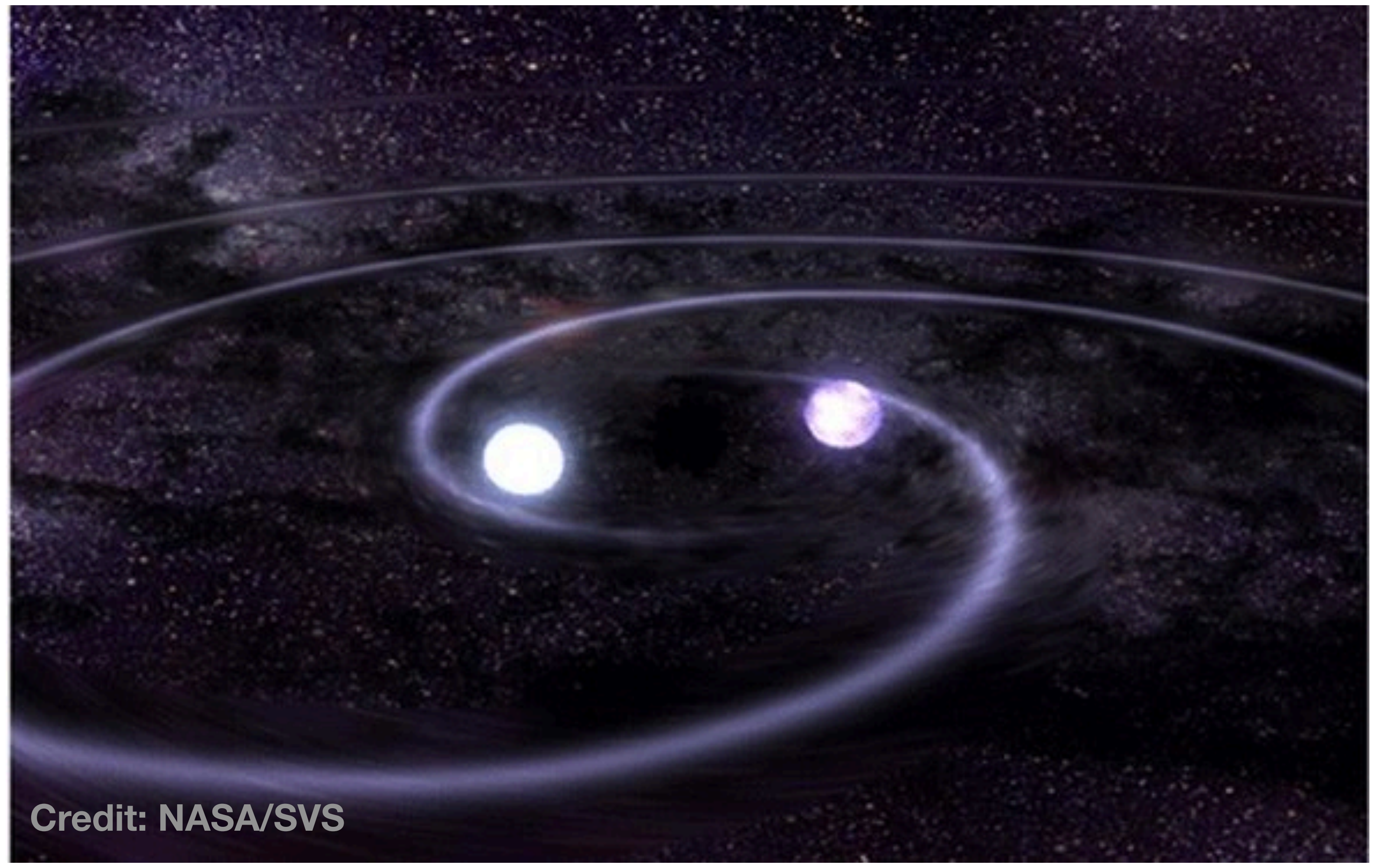


Galactic Binaries that we have already found
By EM observations!



Galactic Binaries

Galactic binary stochastic confusion



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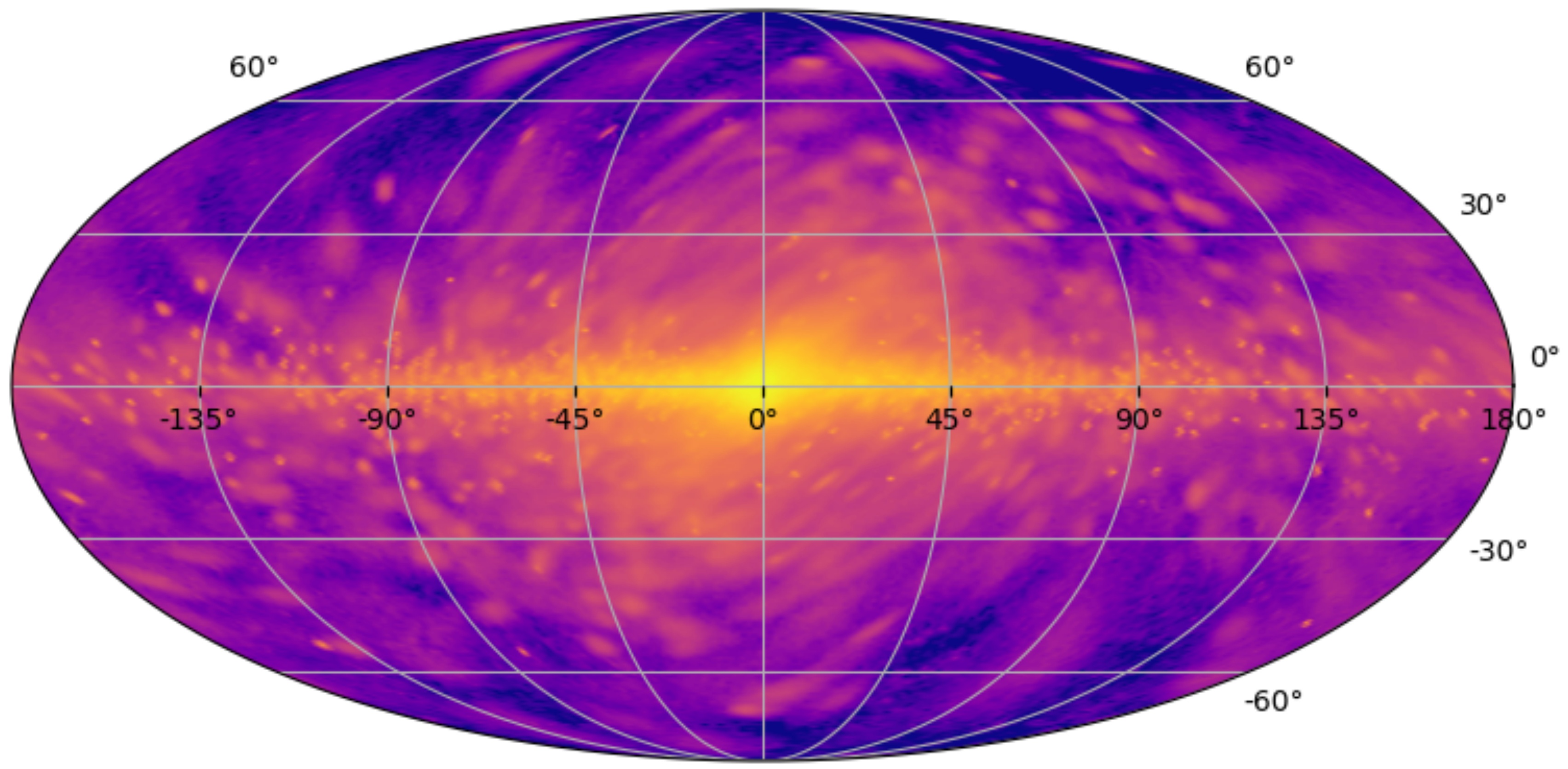
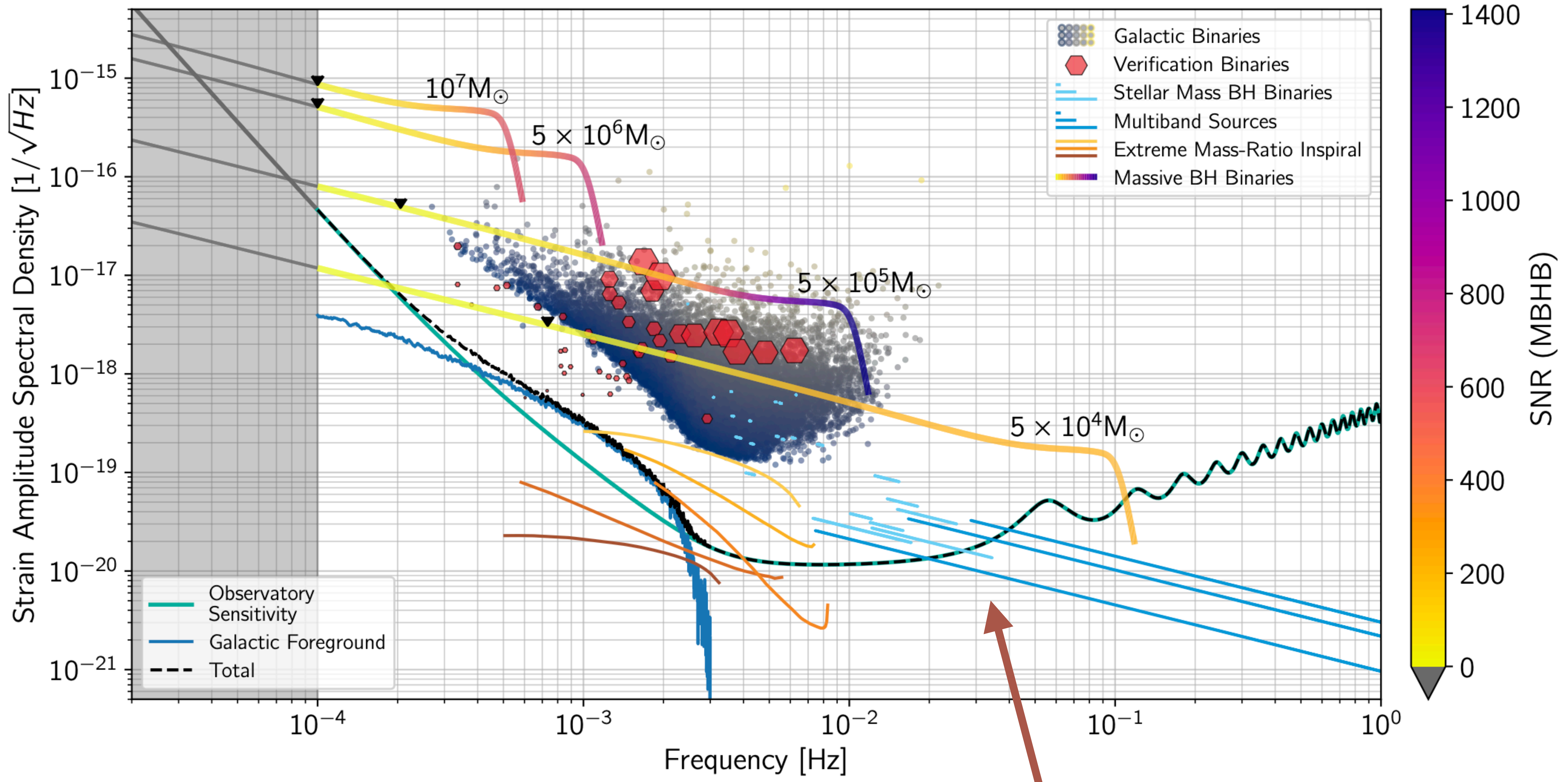
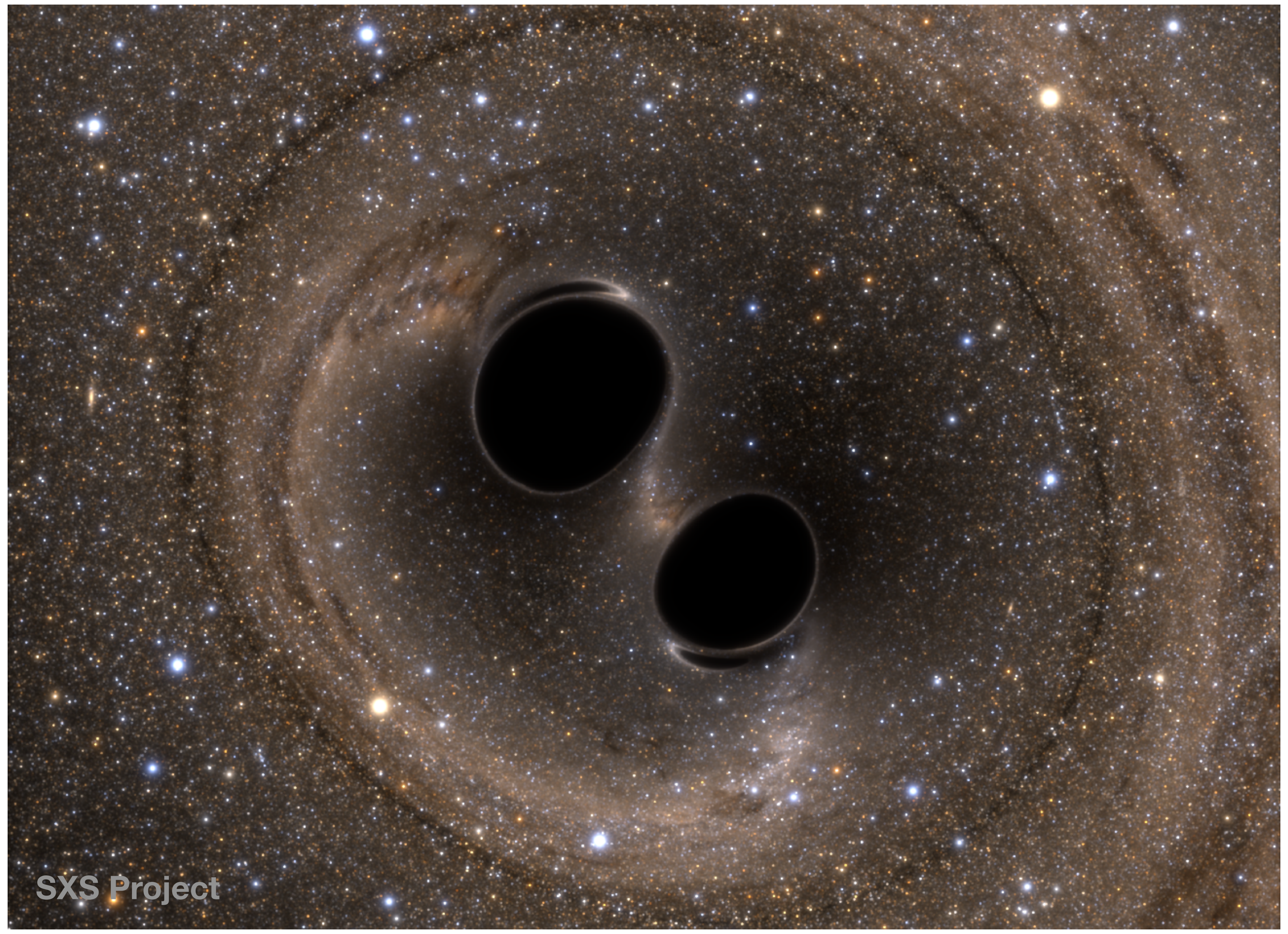
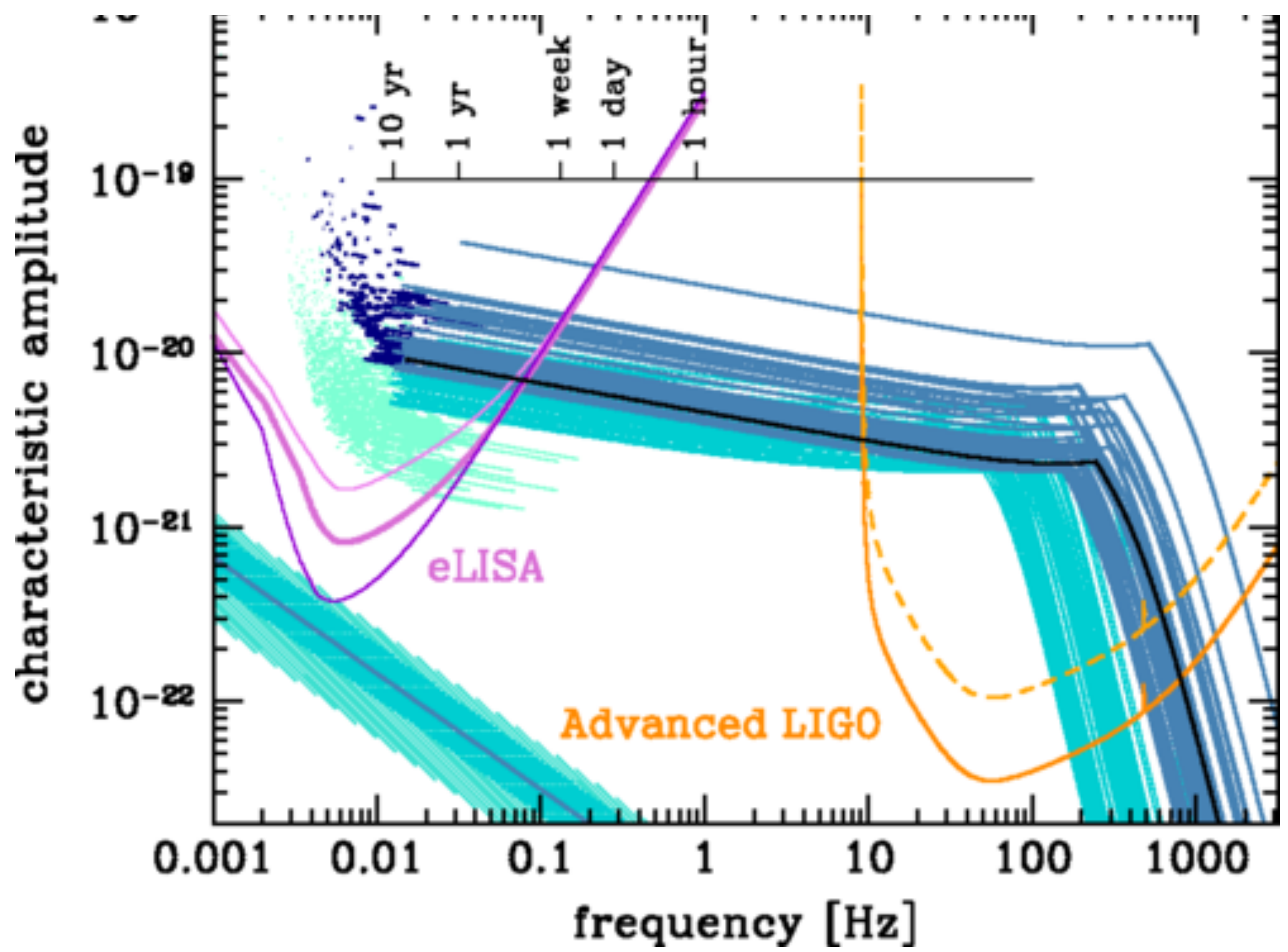




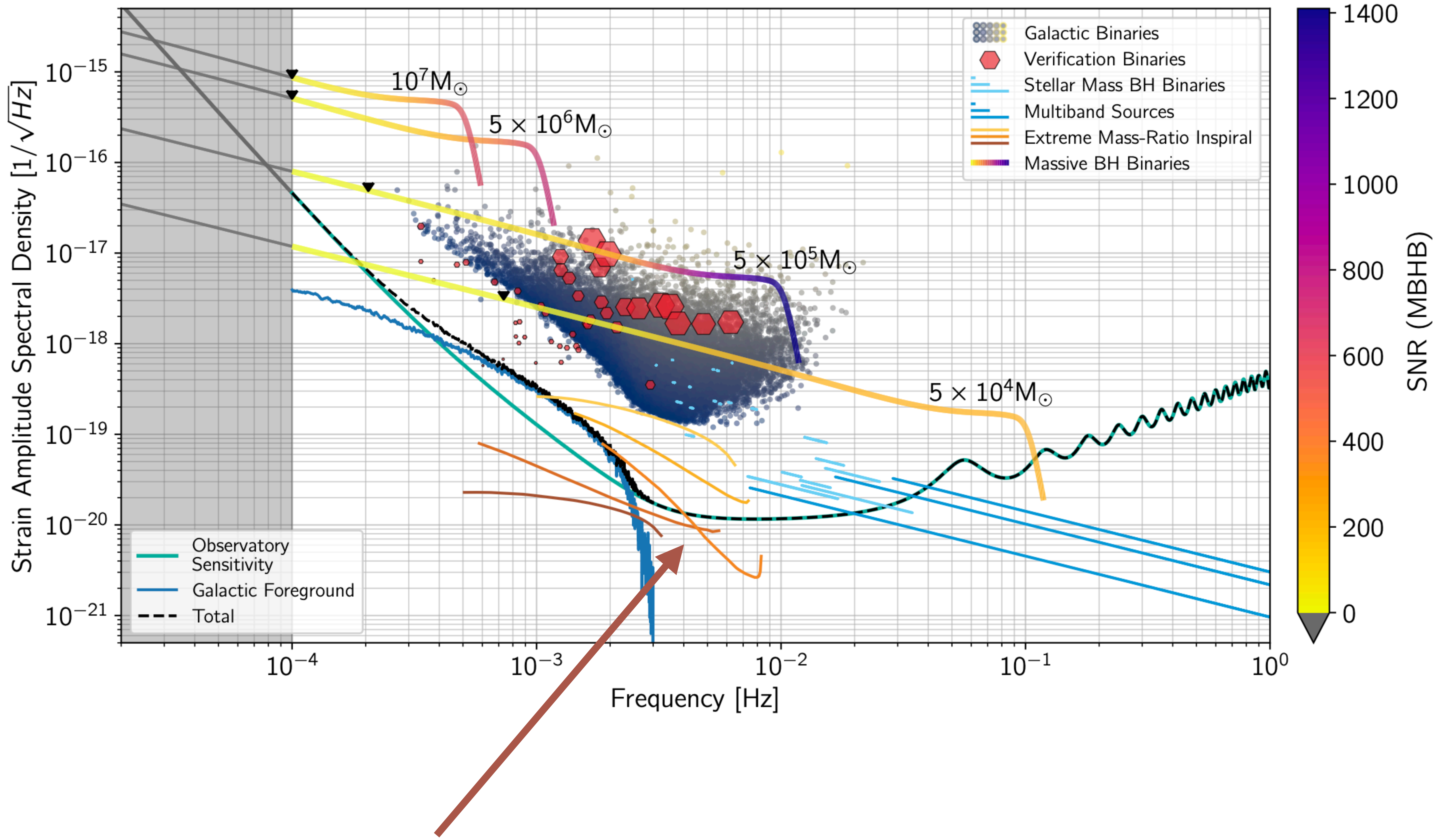
Stellar-scale BH binaries
——> multiband GW astronomy



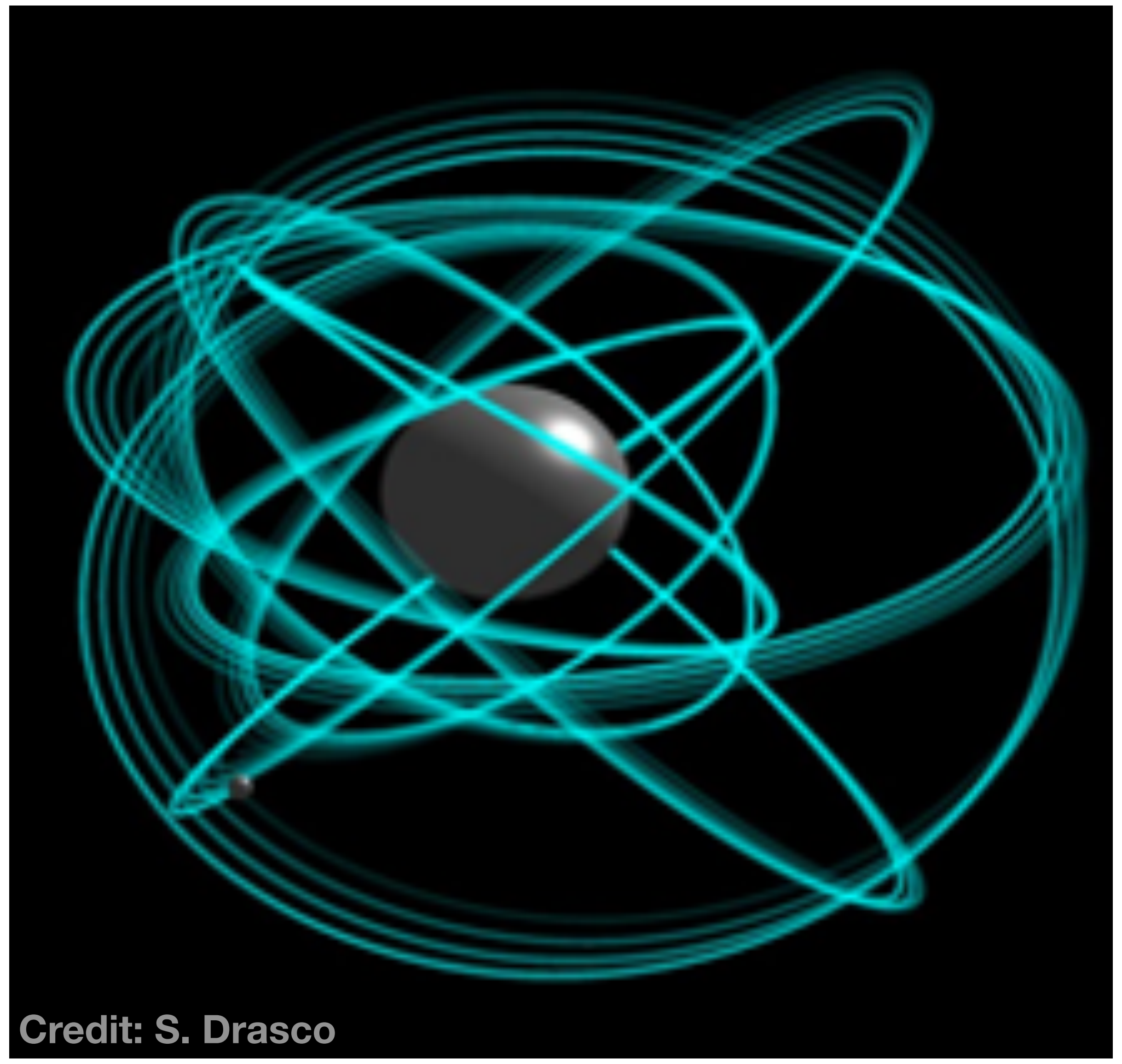
top: *visualization of merging black holes.* ***bottom:*** *comparison of BH tracks for space-based and terrestrial interferometers.*



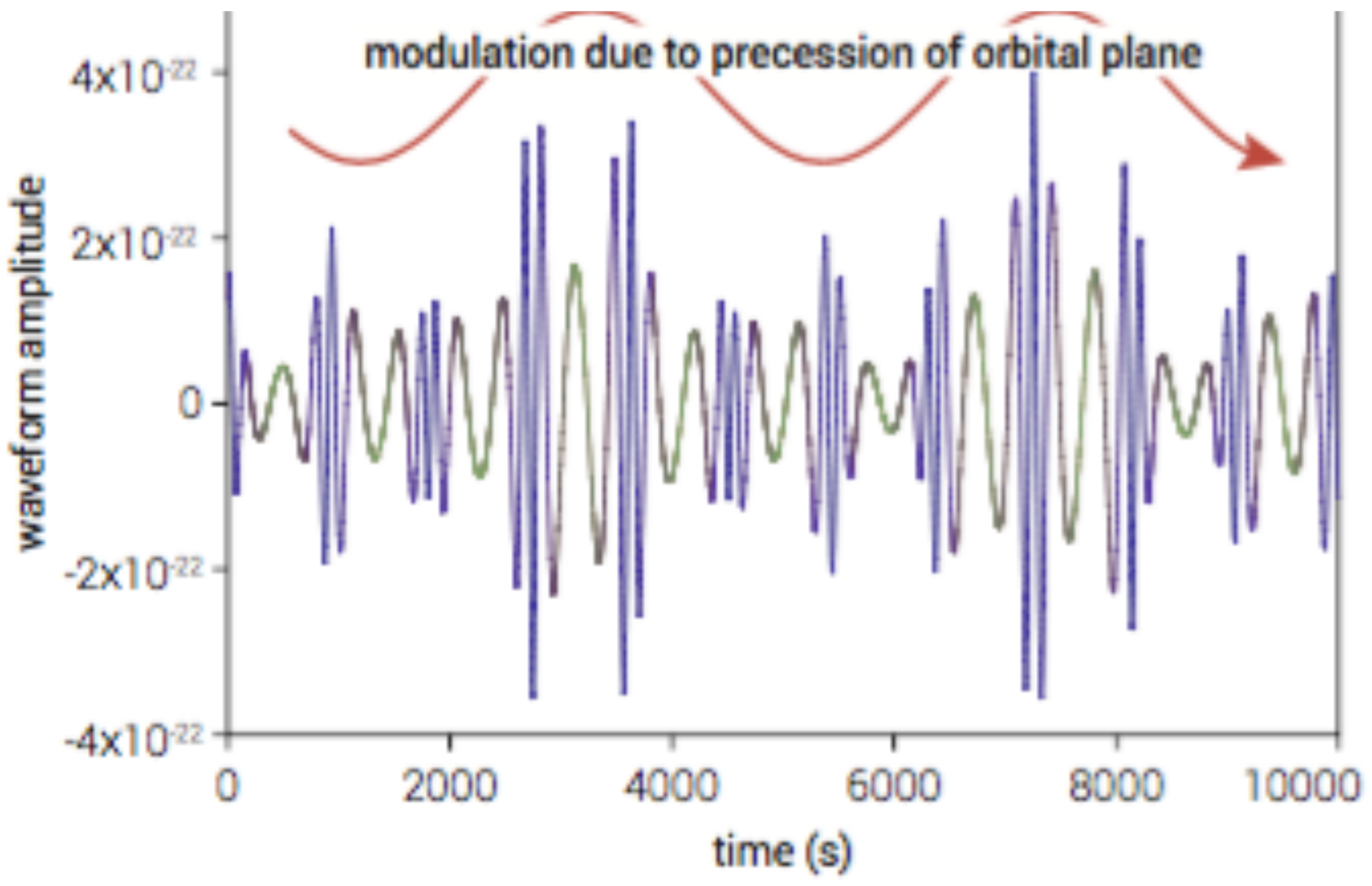
A. Sesana, Phys. Rev. Lett. 116, 231102



Extreme mass ratio inspirals

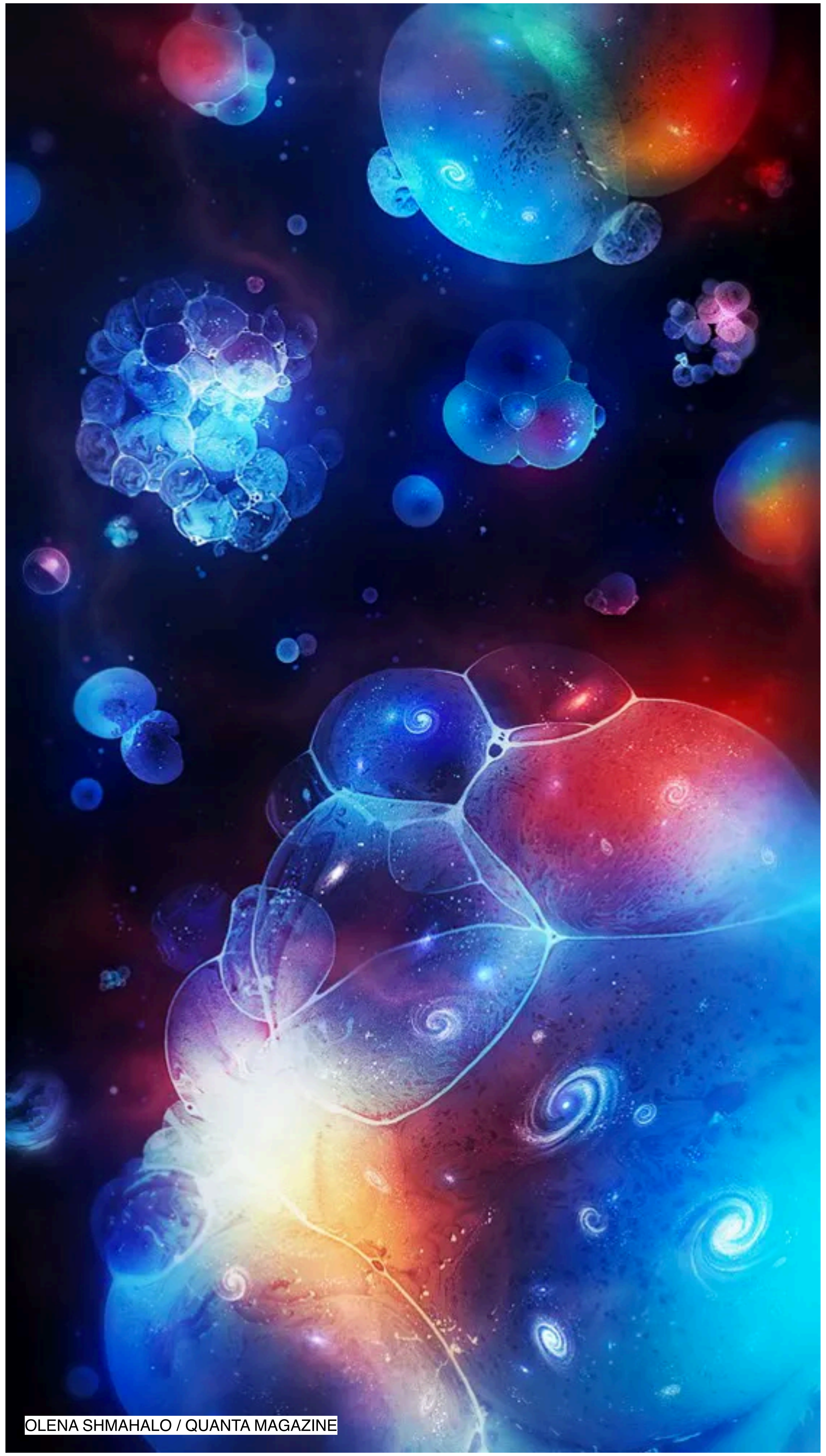


top: *visualization of EMRI orbit.* ***bottom:*** *representative EMRI waveform showing modulation from extreme precession effects*



Backgrounds / Discovery Space

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


OLENA SHMAHALO / QUANTA MAGAZINE

How to detect GW in MHz band?: LISA

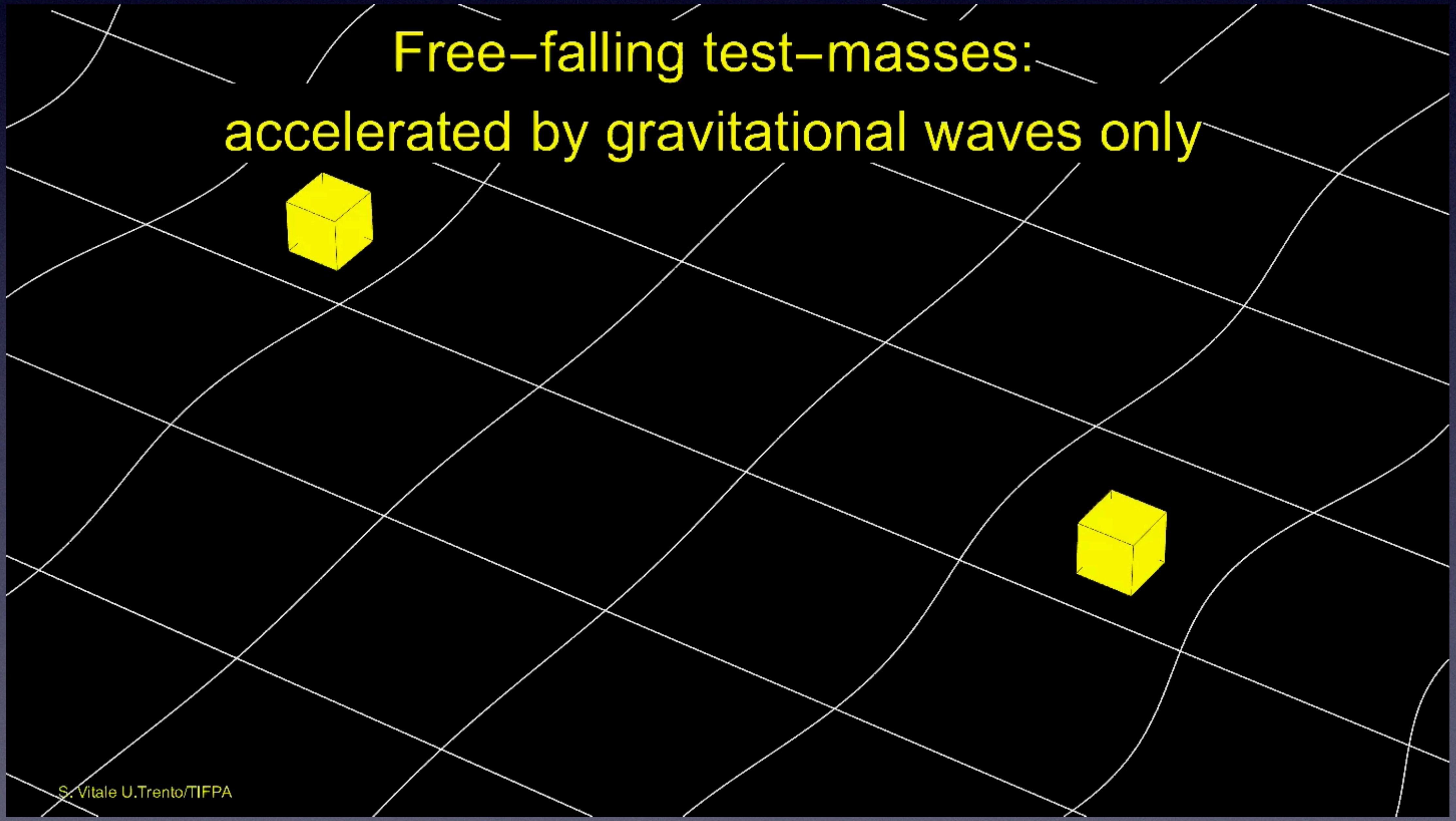
Basic challenges of GW measurement

- **Basic objective**:
  Precisely measure the relative motion of free-falling masses

- **Precisely measure:** $\Delta L/L \lesssim 10^{-20}$

- **Free-falling:** minimize non-gravitational forces

- **LISA:**
  - $L \sim 2.5e9$ m
  - $\Delta L \sim 1e-11$ m
  - $a \sim 3e-15$ m/s^2



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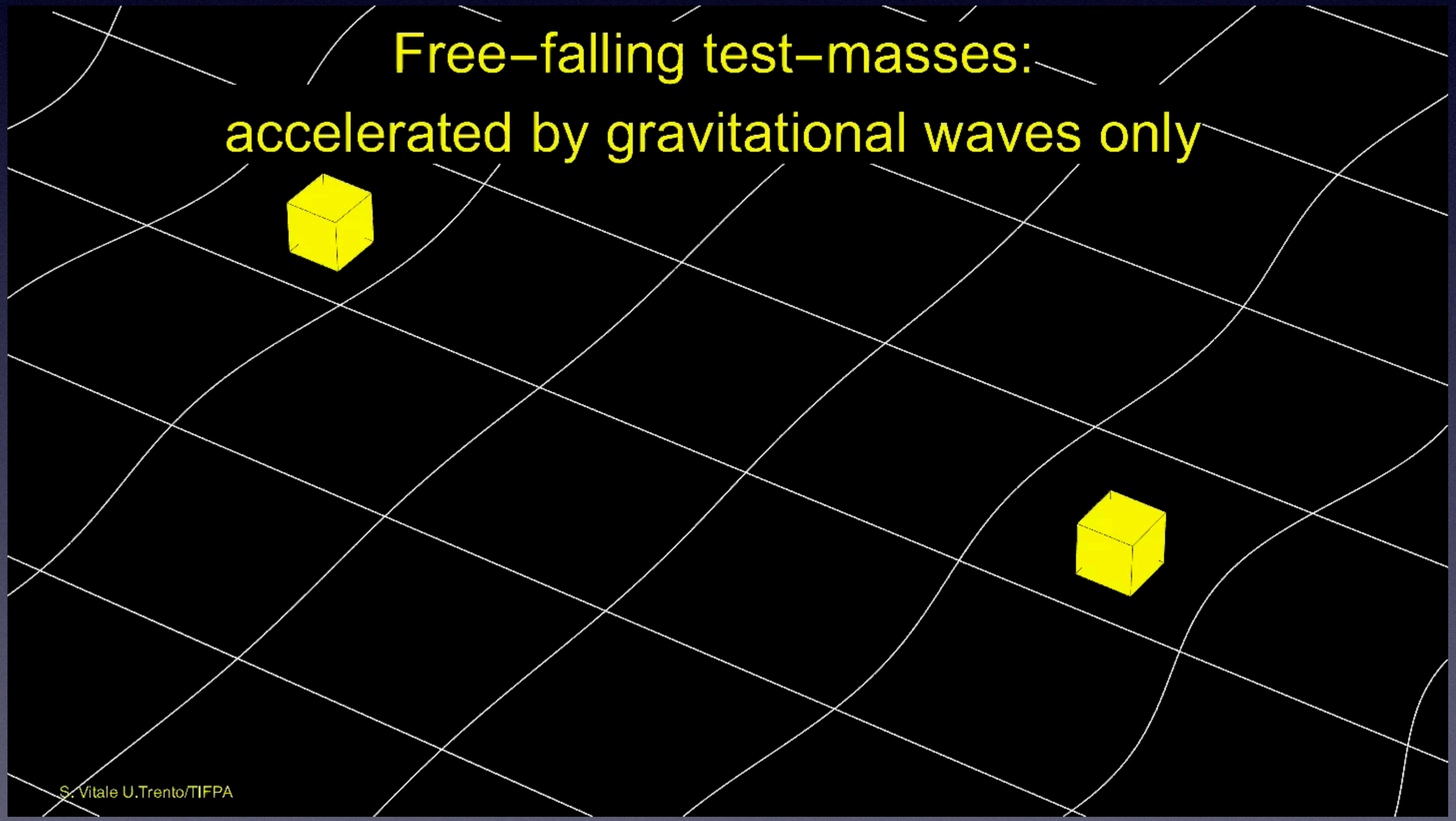

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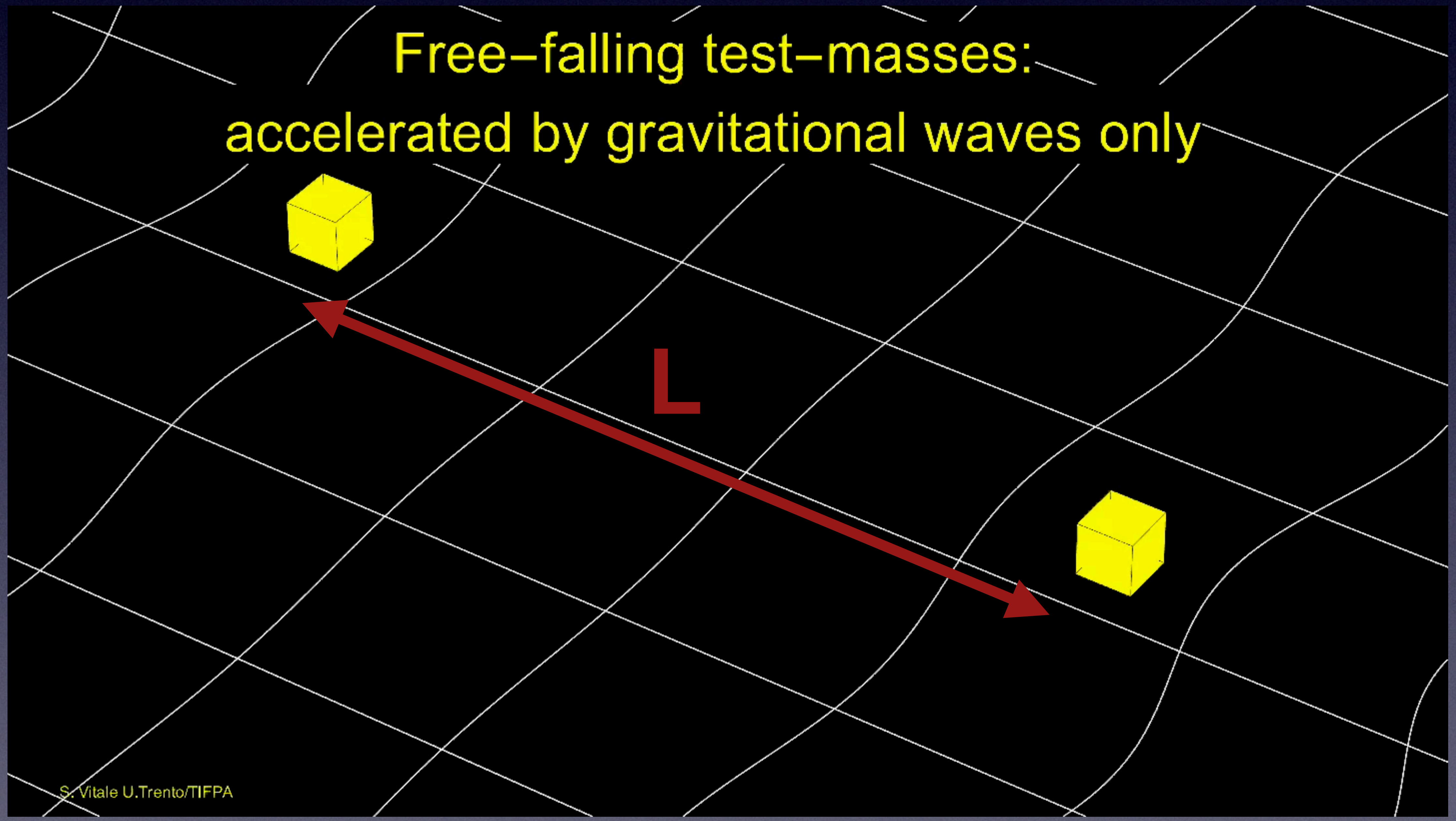
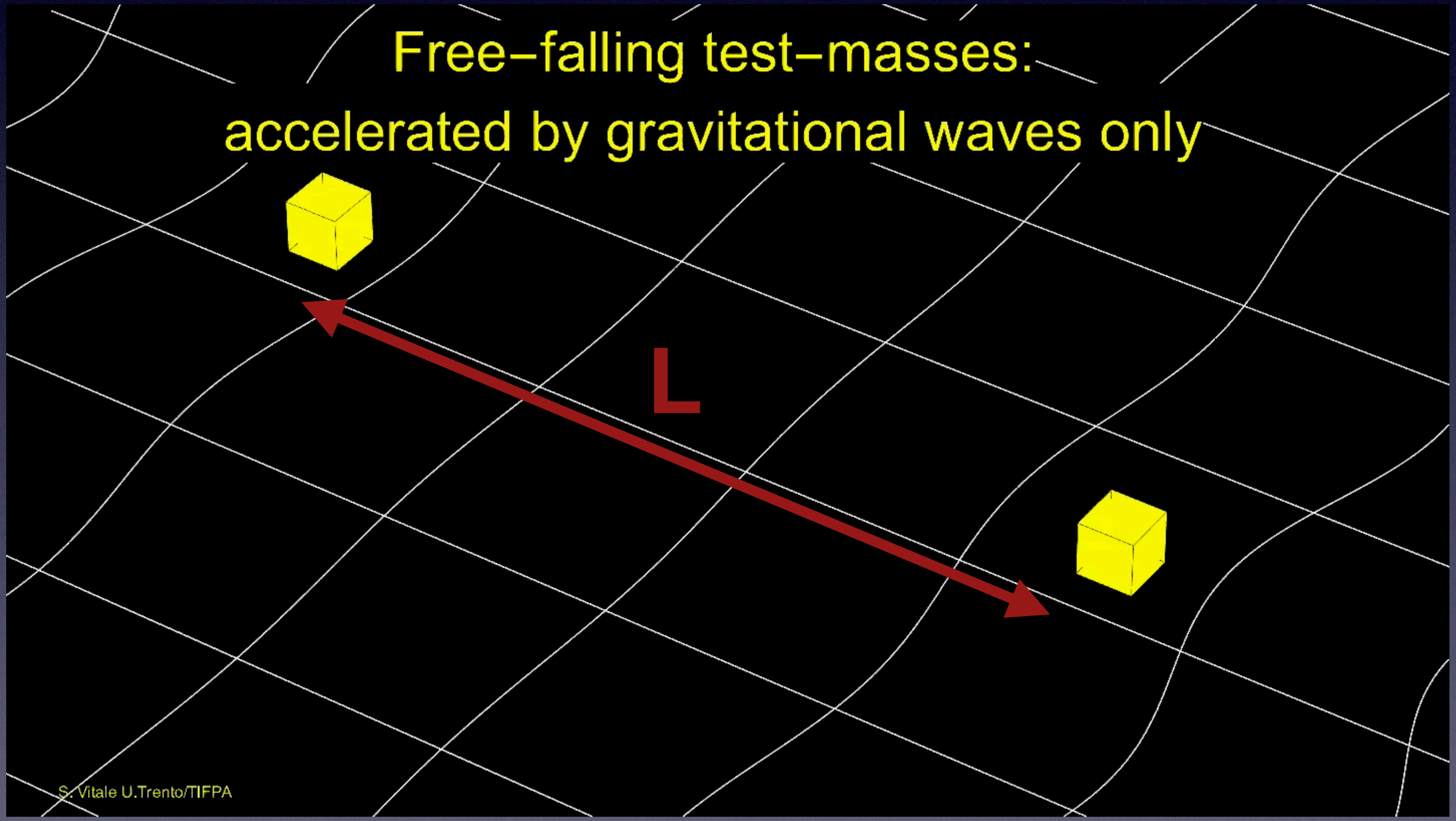


Basic challenges of GW measurement

- **Basic objective**:
  Precisely measure the relative motion of free-falling masses
- **Precisely measure:** $\Delta L/L \lesssim 10^{-20}$
- **Free-falling:** minimize non-gravitational forces
- **LISA:**
  - L ~ 2.5e9 m
  - ΔL ~1e-11 m
  - a ~ 3e-15 m/s²

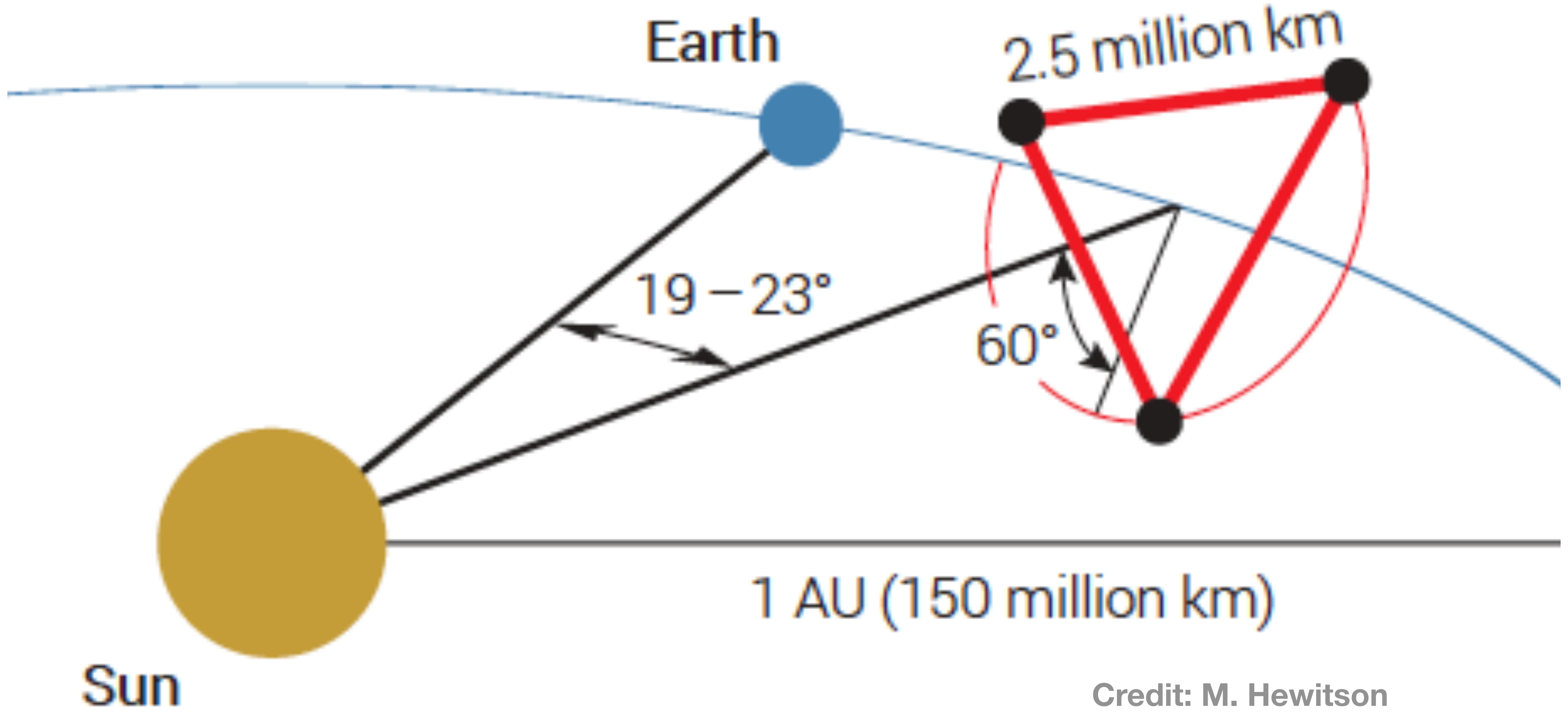
Yay space!



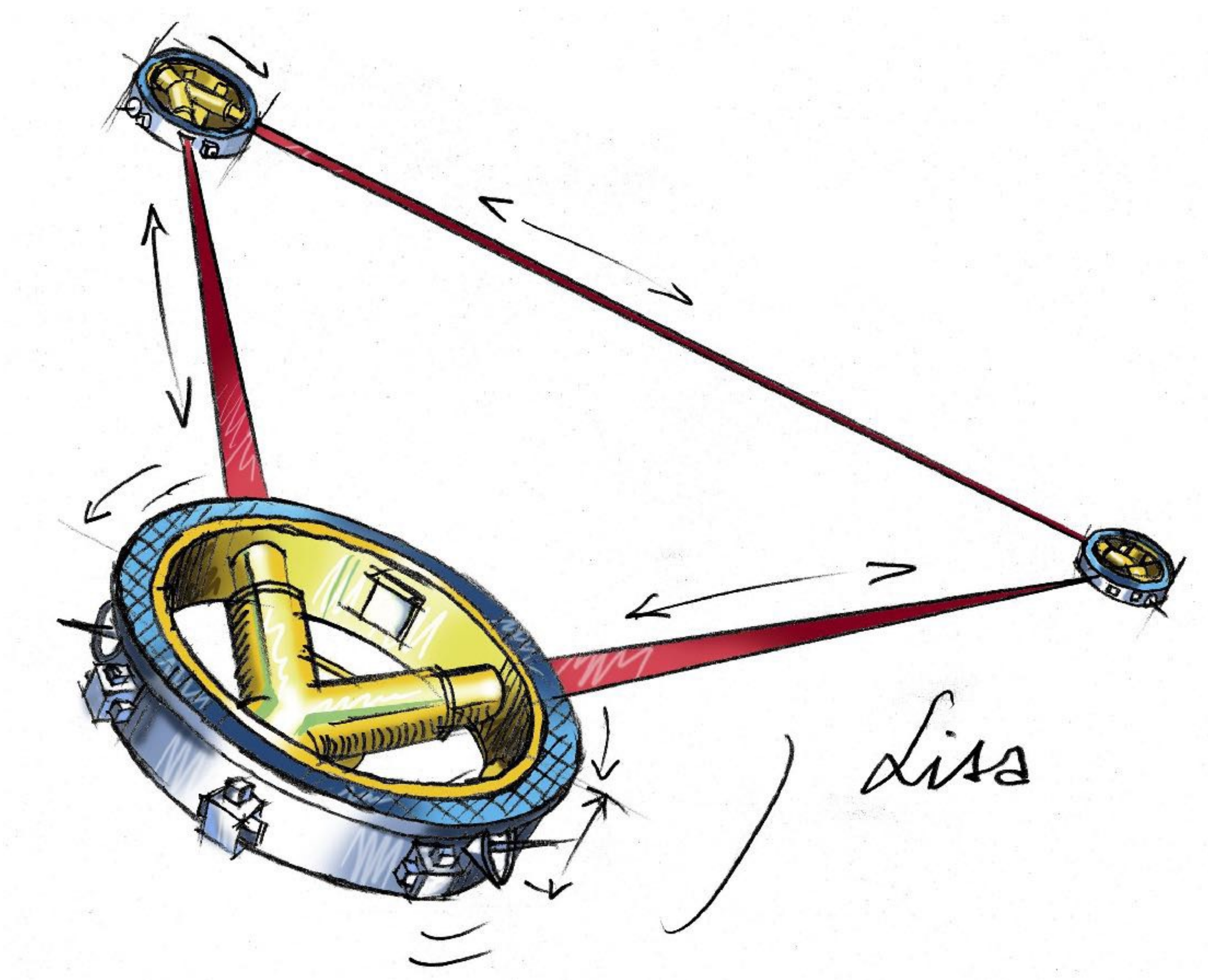
The LISA concept

Decades of Development

- 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



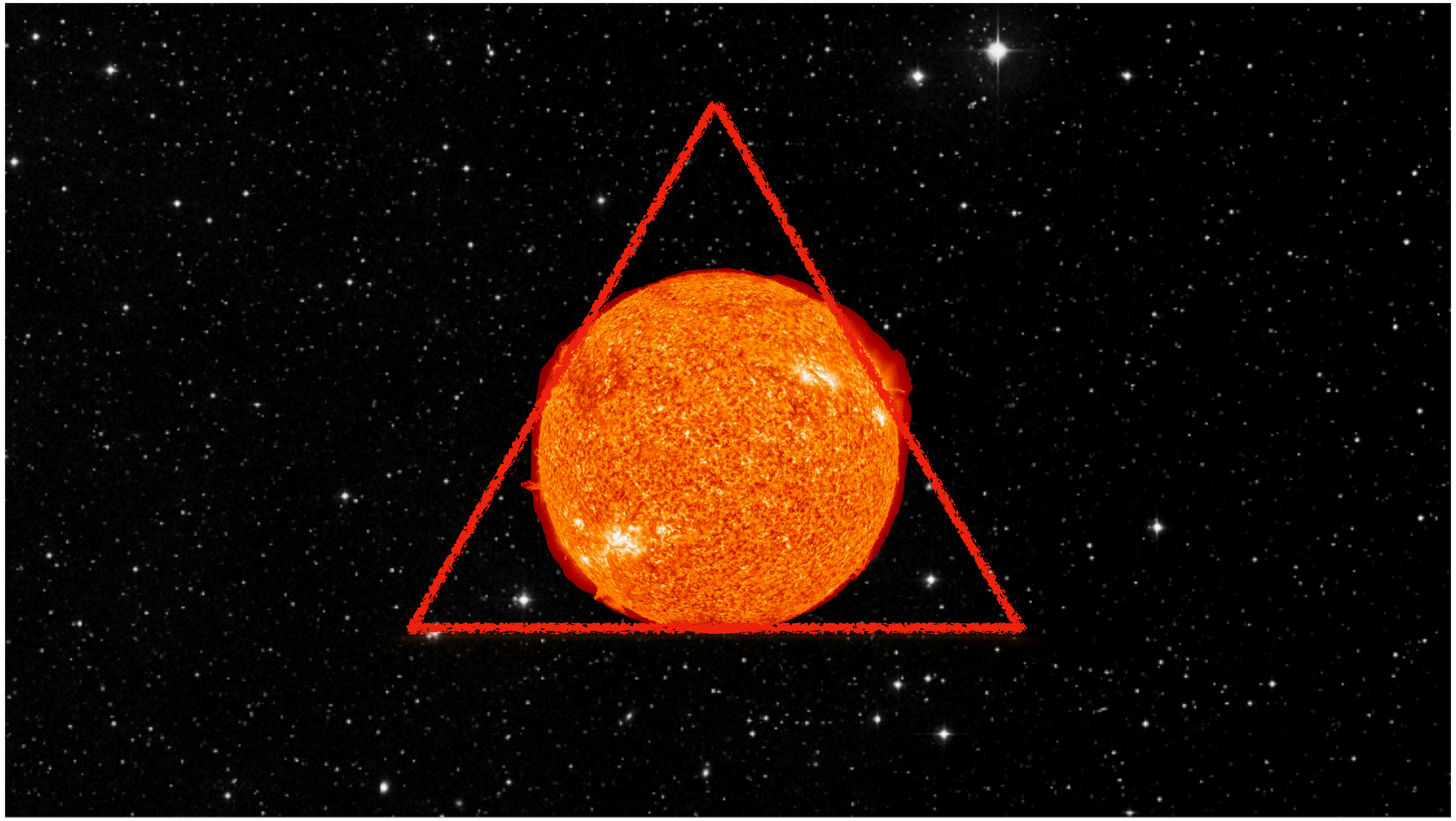
Credit: M. Hewitson



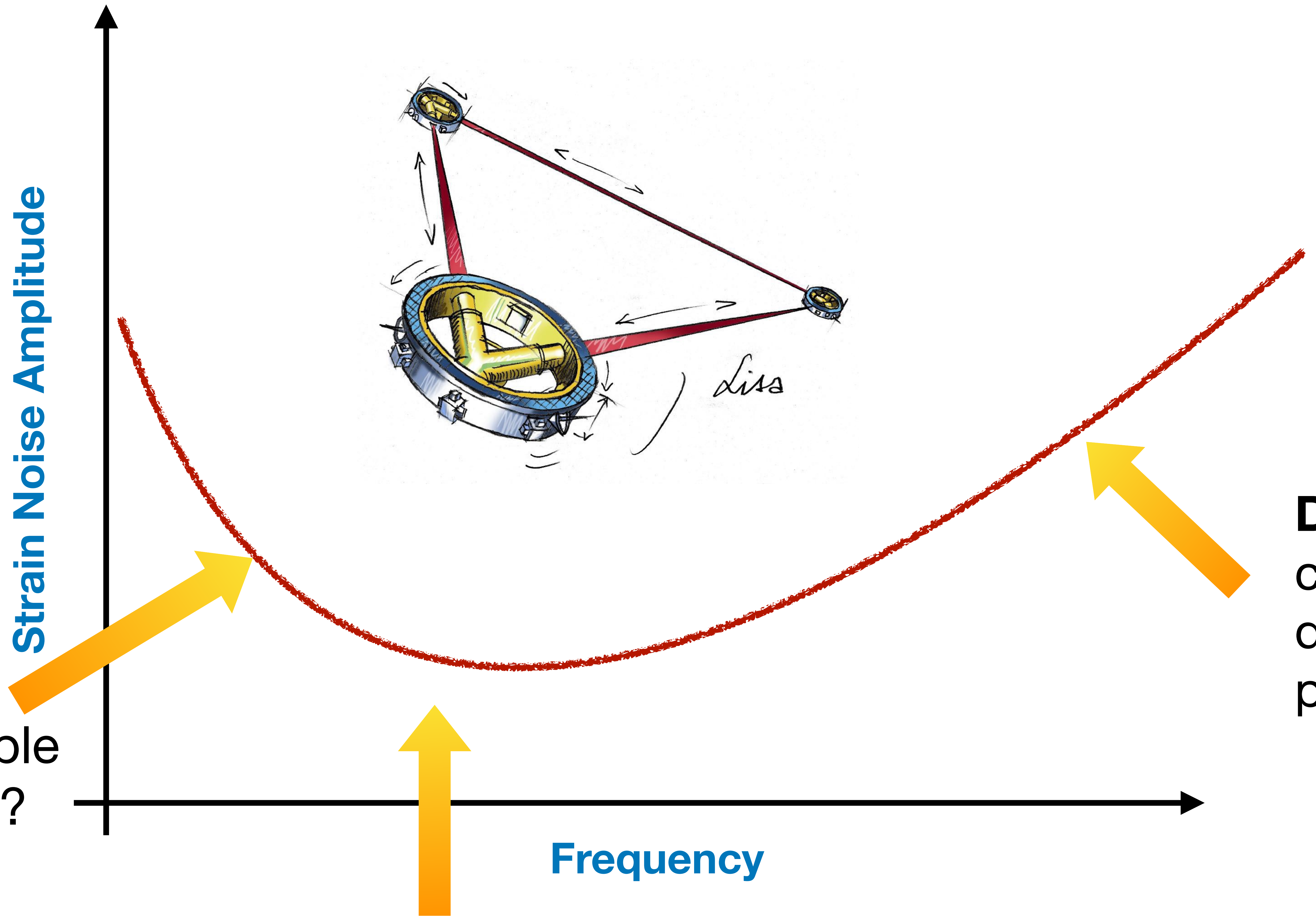
Credit: ESA-C. Vijoux

LISA is huge!

Arguably largest instrument ever conceived



Fundamentals of GW Interferometers



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

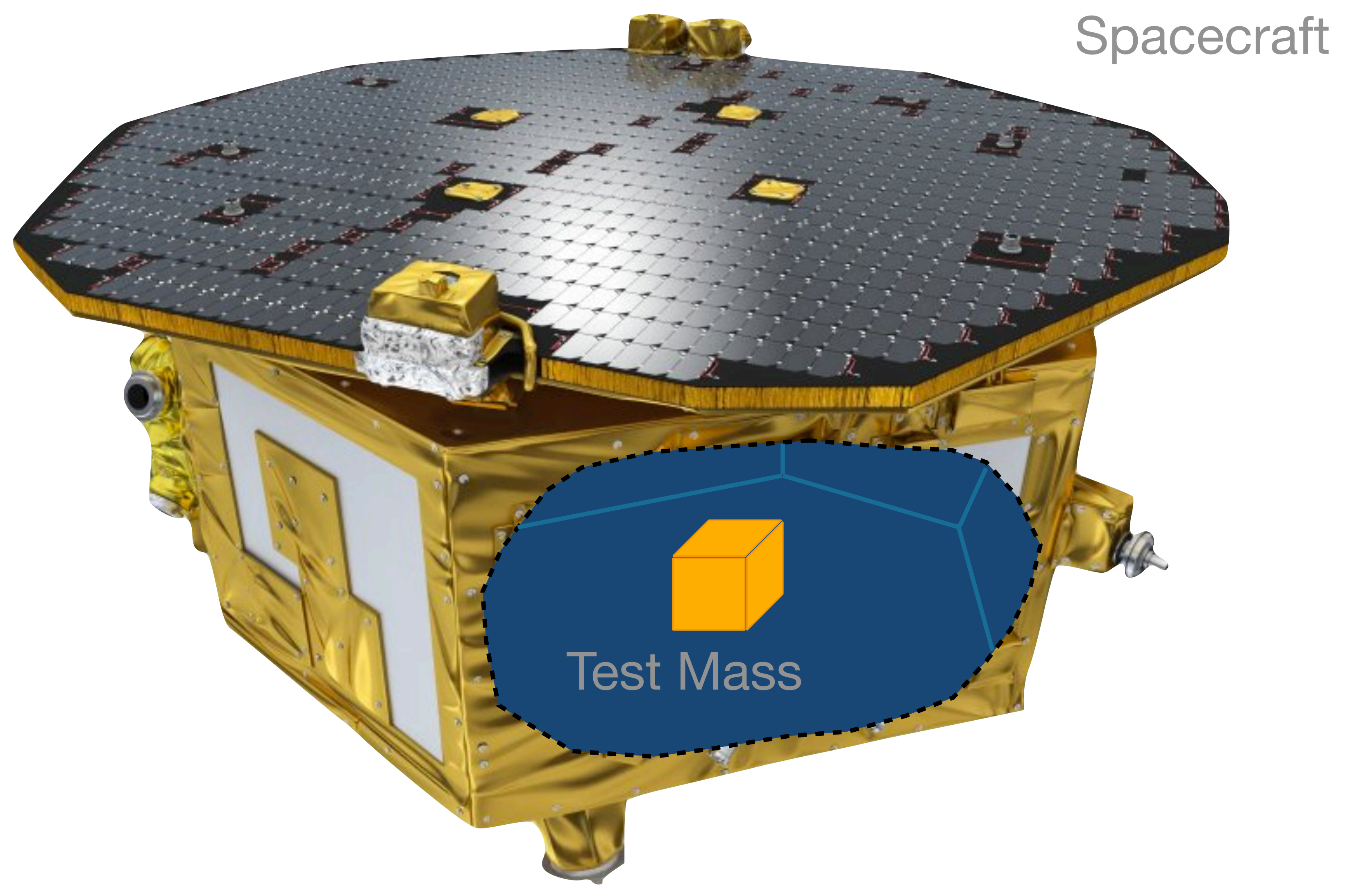
Displacement noise: how well can you measure (proper) distance between pairs of test particles?

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

Acceleration noise

‘drag-free’ flight

- Test mass placed inside hollow cavity* within spacecraft
- sensors monitor relative position of test mass and spacecraft



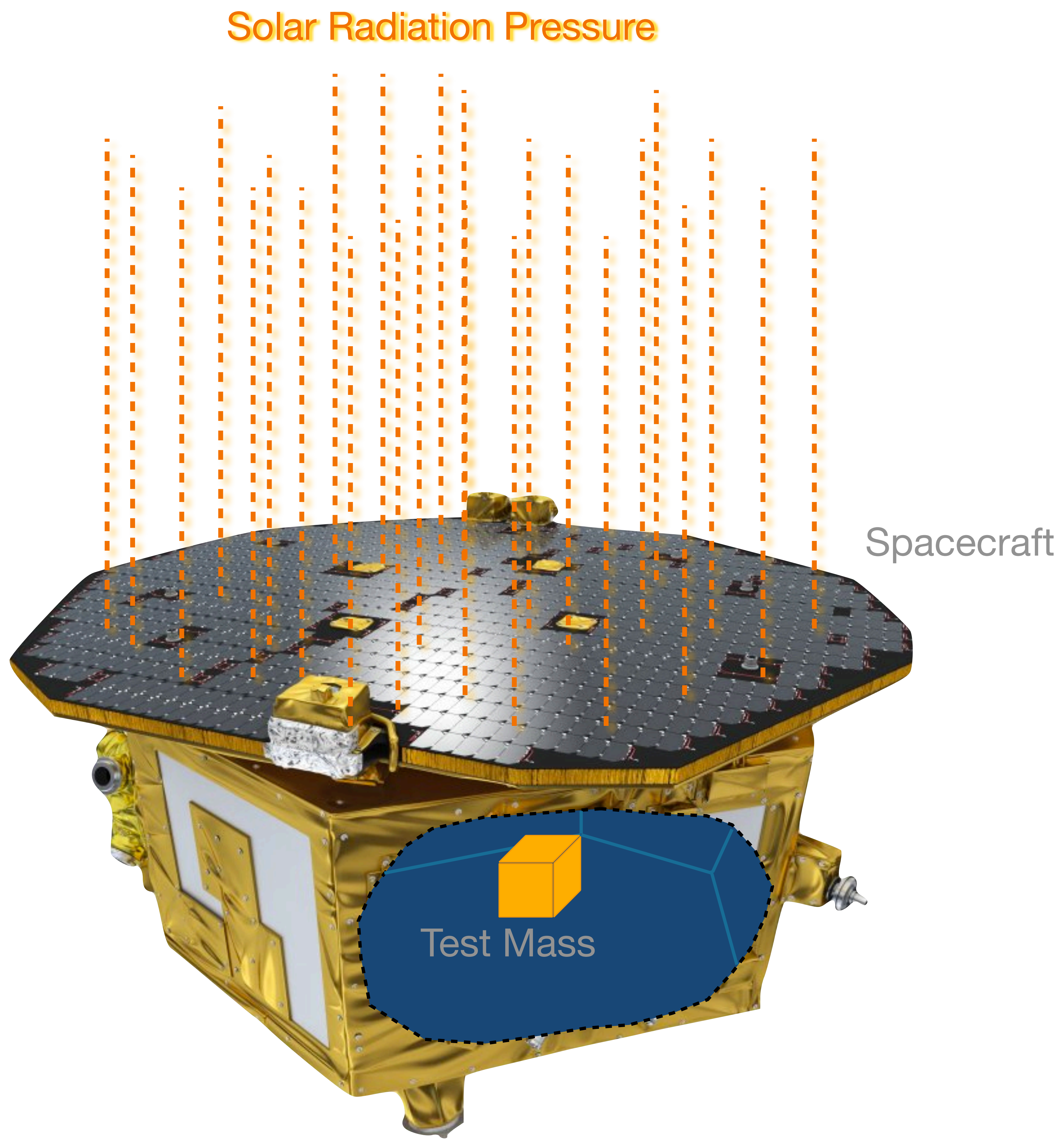
LPF Rendering: ESA Medialab

* cavity consists of a few mm gaps on all sides of the test mass

Acceleration noise

‘drag-free’ flight

- External disturbance (e.g. solar radiation pressure) causes spacecraft to drift towards test mass

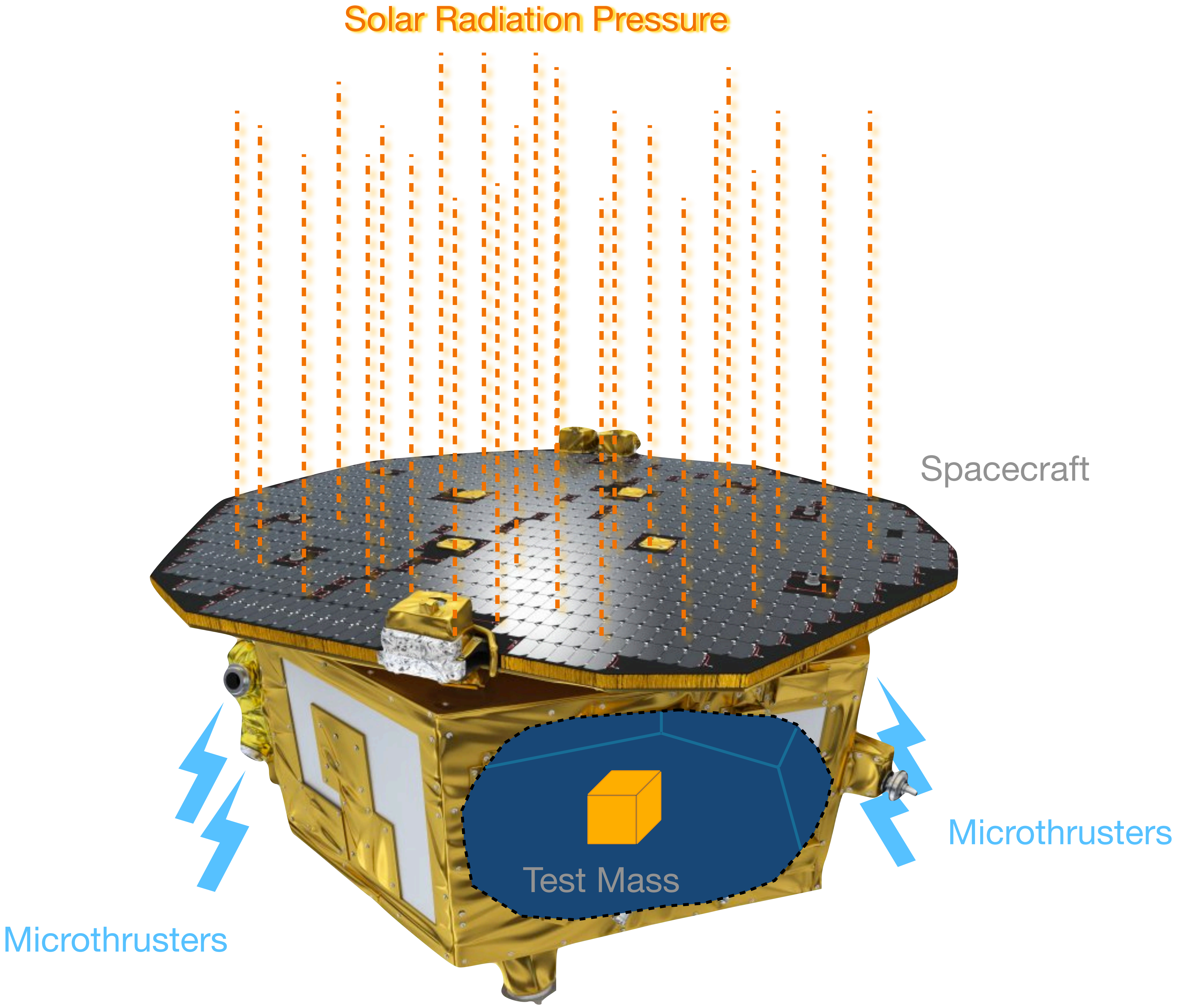


LPF Rendering: ESA Medialab

Acceleration noise

‘drag-free’ flight

- Control system fires micro thrusters to counteract disturbance.
- Test mass remains centered within cavity

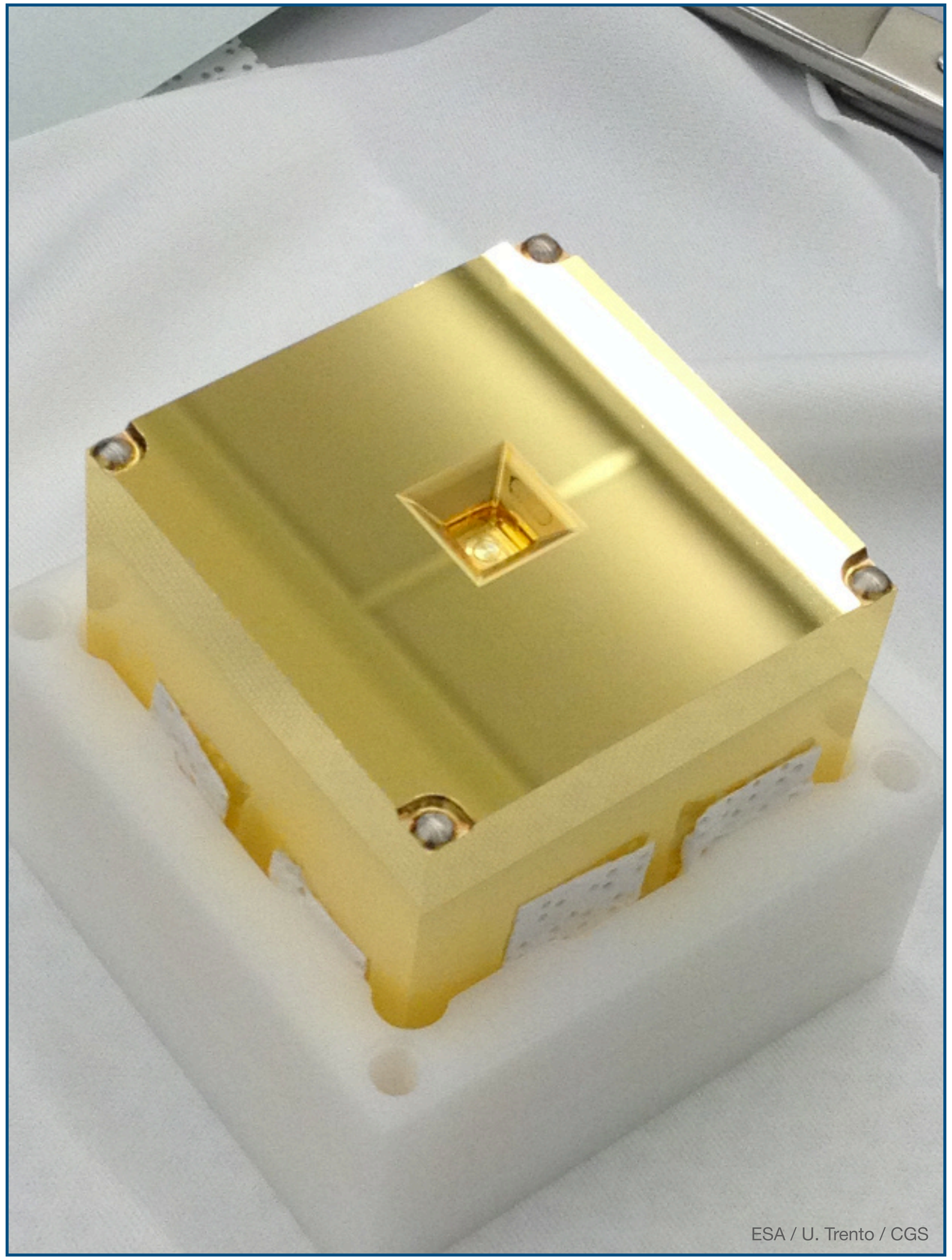


LPF Rendering: ESA Medialab

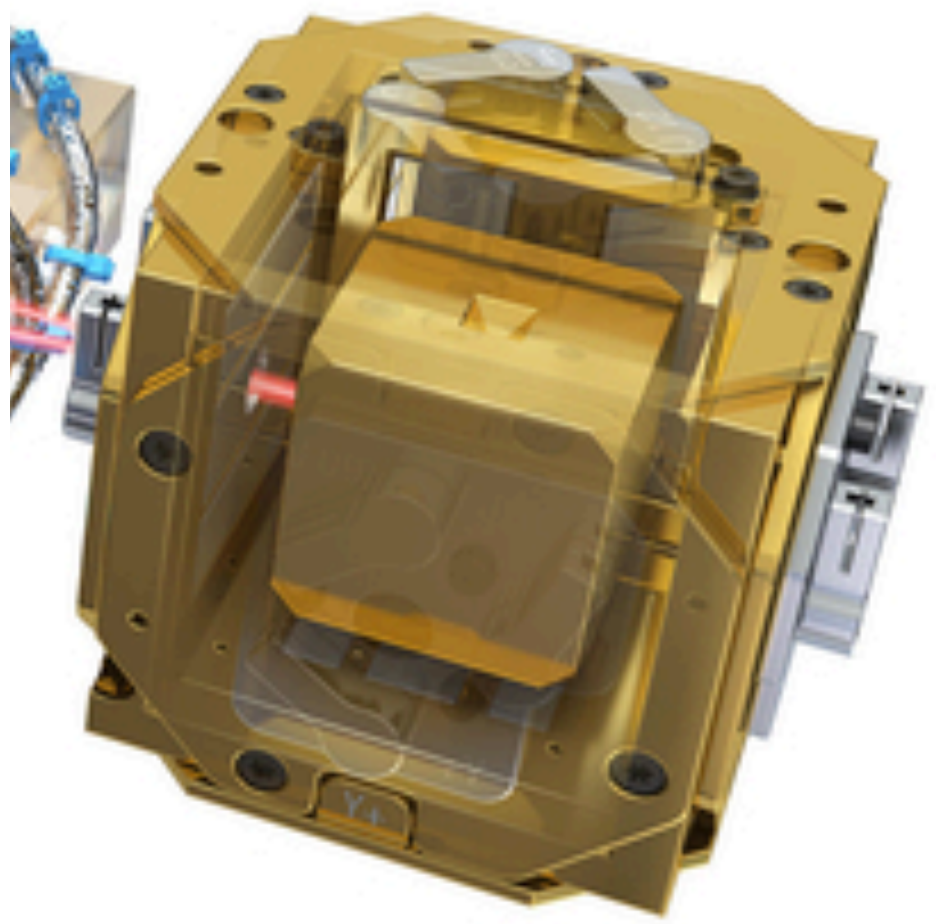
LISA Pathfinder

Demonstration of drag-free flight

- ESA-led technology demonstrator
- Single LISA arm in one spacecraft
- (Most of) the noise, none of the GW signal!

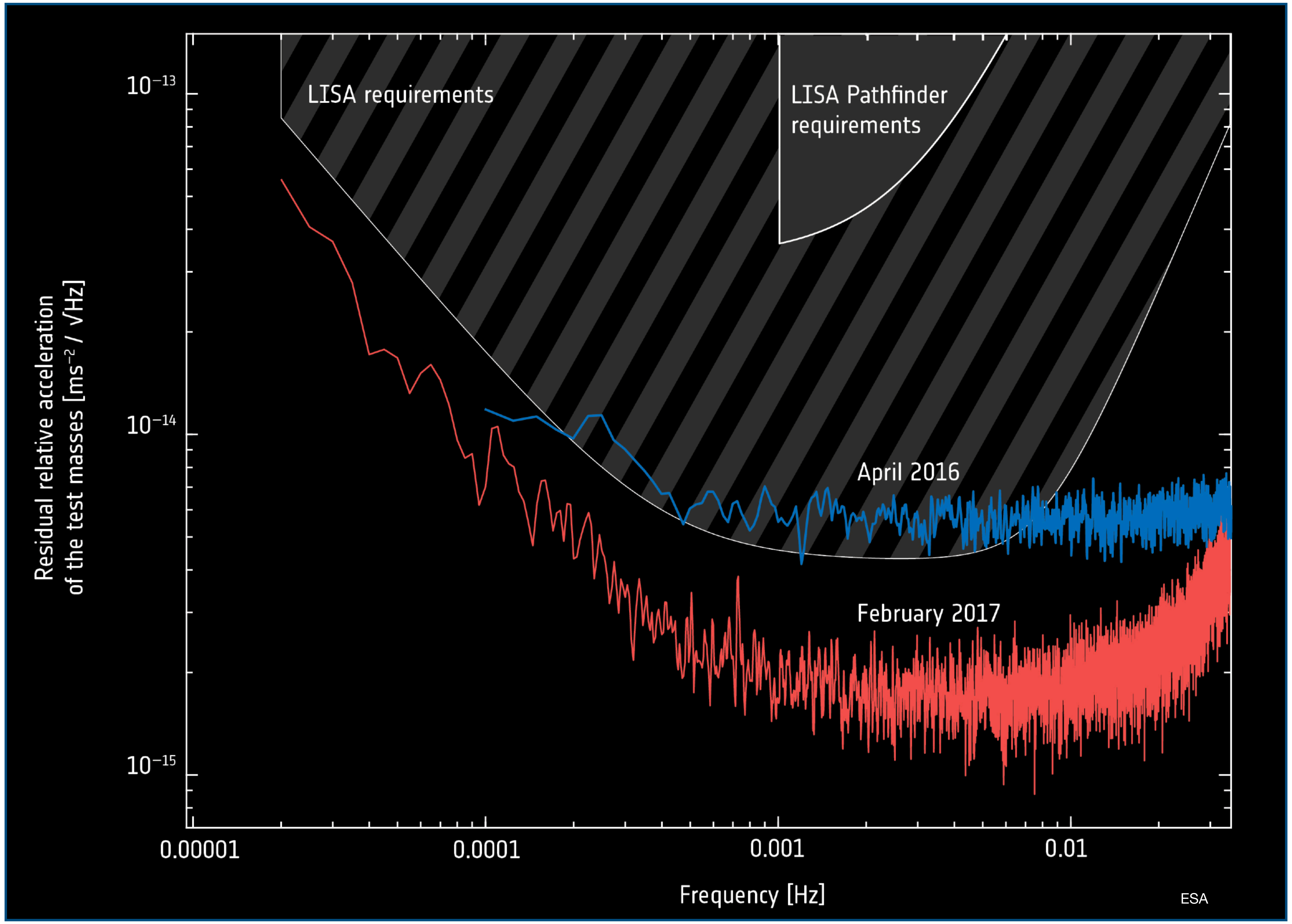

ESA / U. Trento / CGS

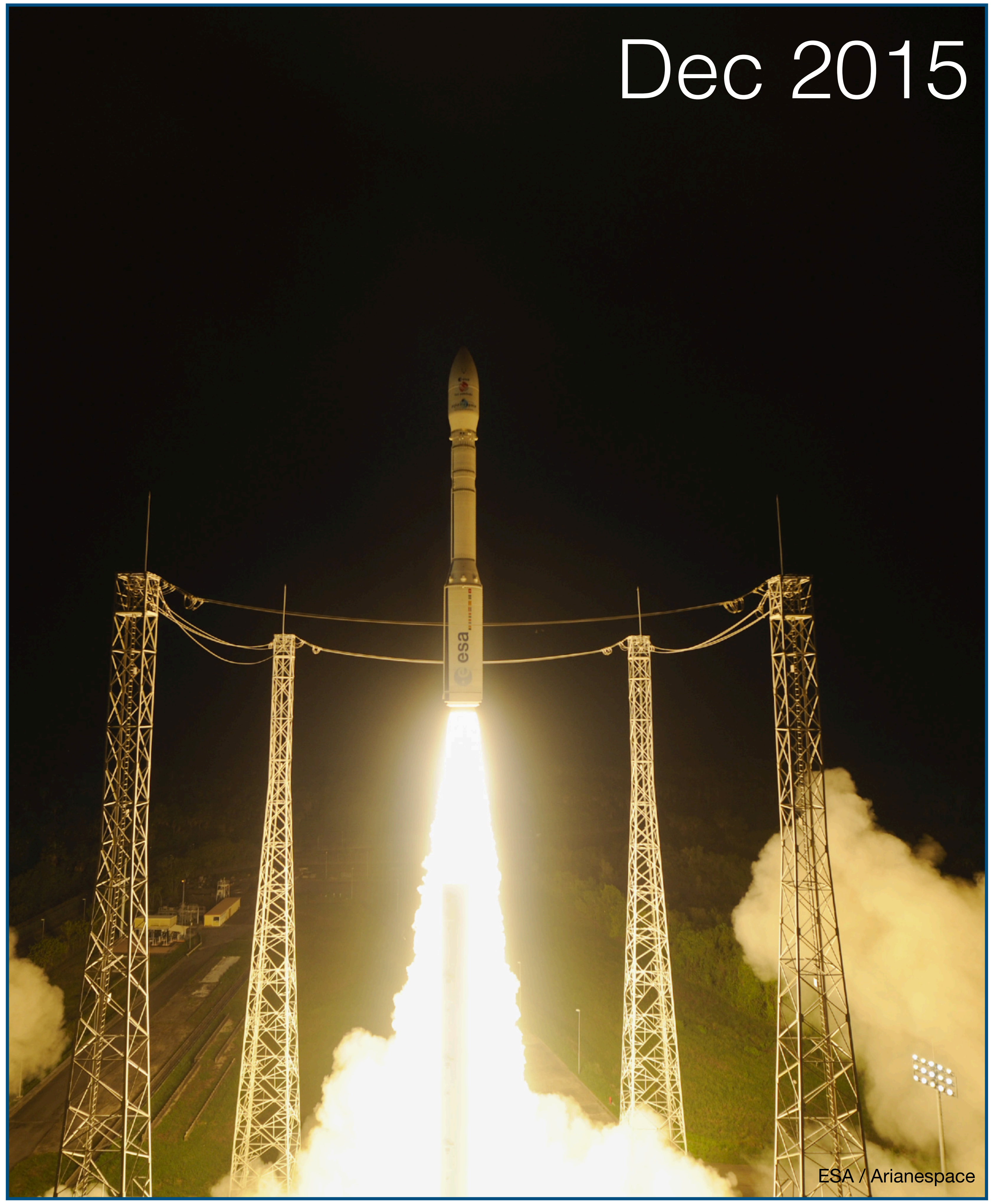

NASA / JPL / Busek


ESA Medialab

LISA Pathfinder Results

Far exceed Pathfinder goals, validate performance at LISA levels

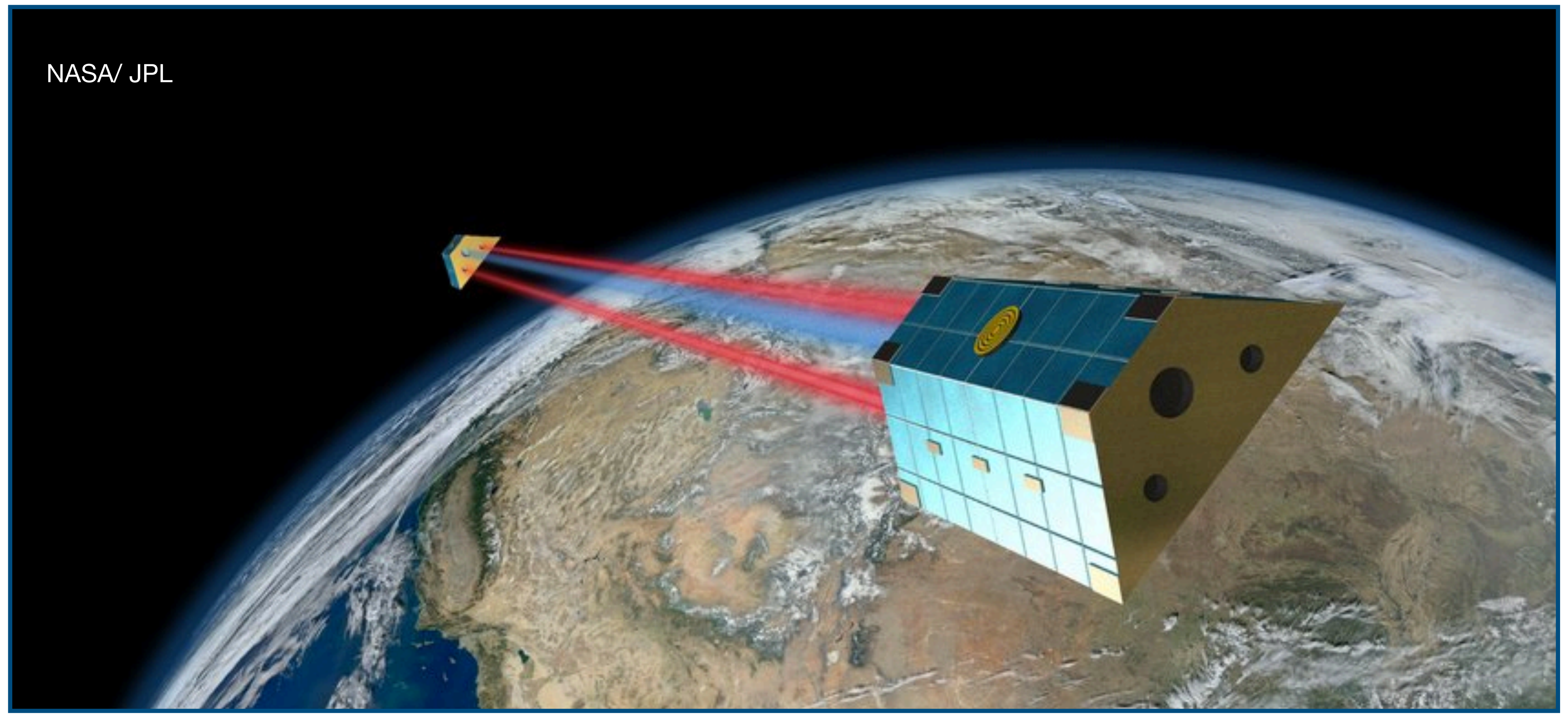


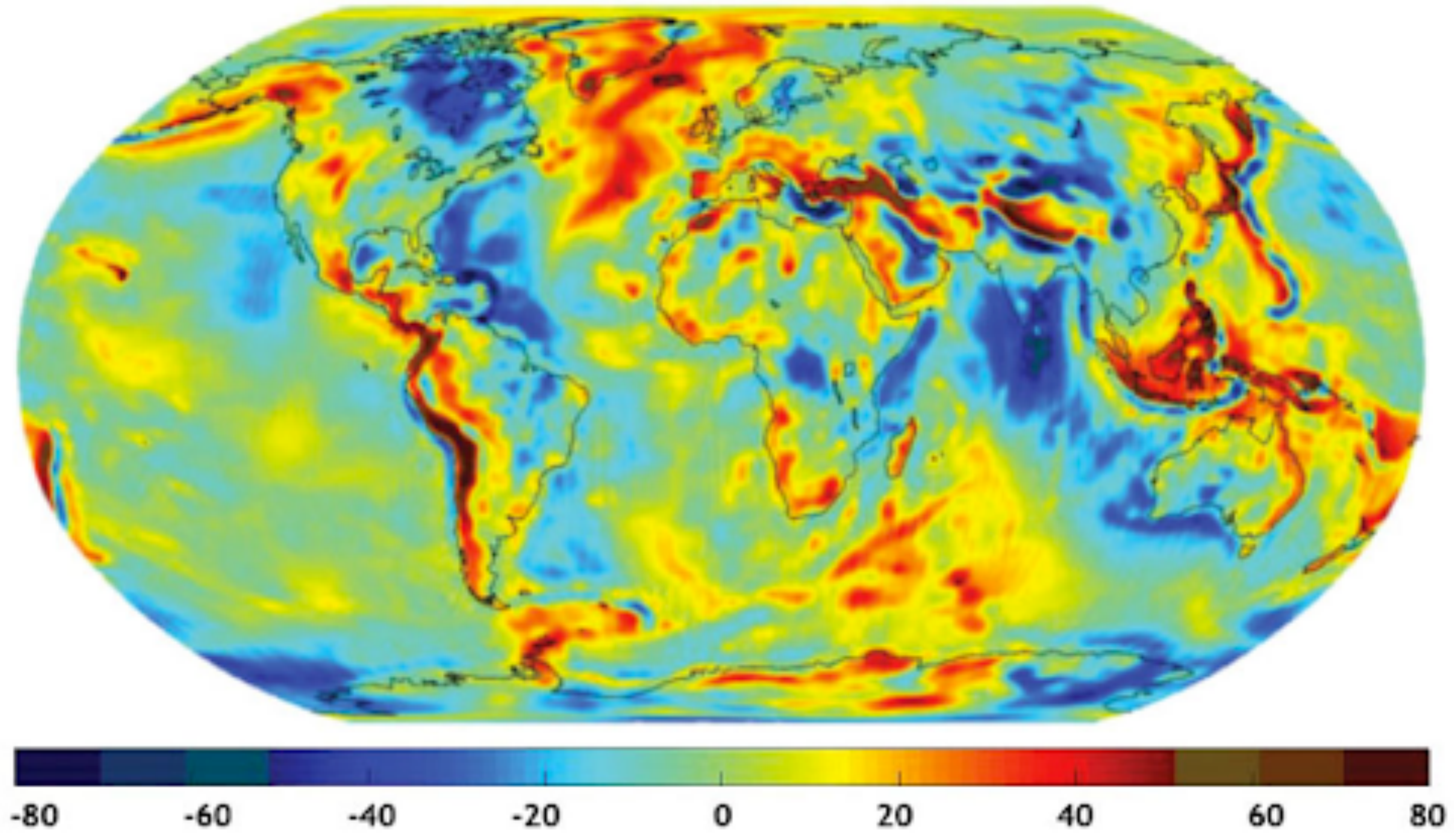


GRACE-FO LRI

Interferometry Demonstrator

- Replacement for GRACE geodesy mission
- 2 spacecraft in low-Earth (~500km) orbit, separated by 220km
- Displacements measure Earth’s gravitational field
- Laser link, based on LISA technology, supplements primary microwave link

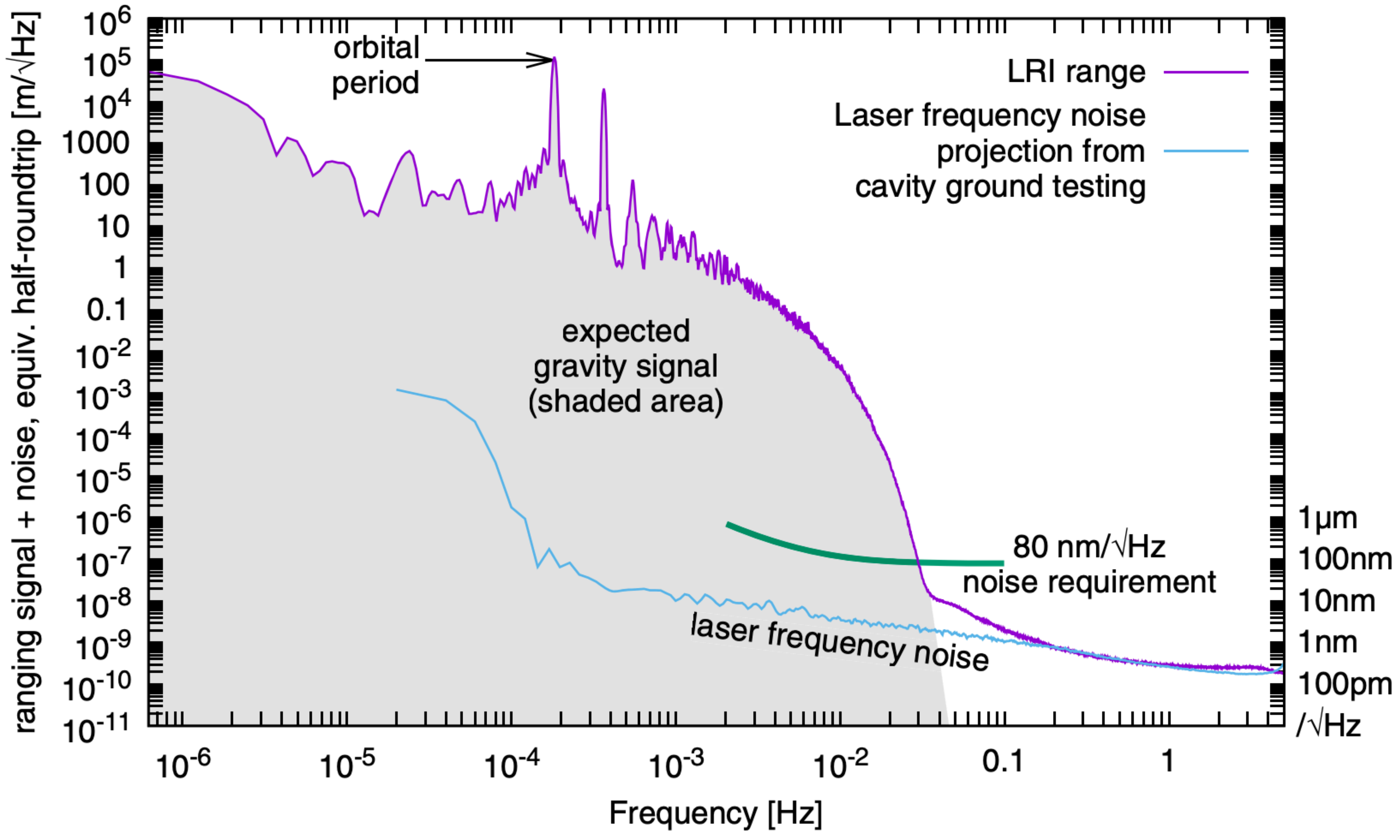




GRACE-FO LRI Results

A LISA interferometry demo

- Earth signal is *much* larger than LISA's gravitational wave signal - and always on
- Only one arm - precision limited by laser stability
- Relevant components & experience
  - similar laser
  - similar receiver
  - operations experience

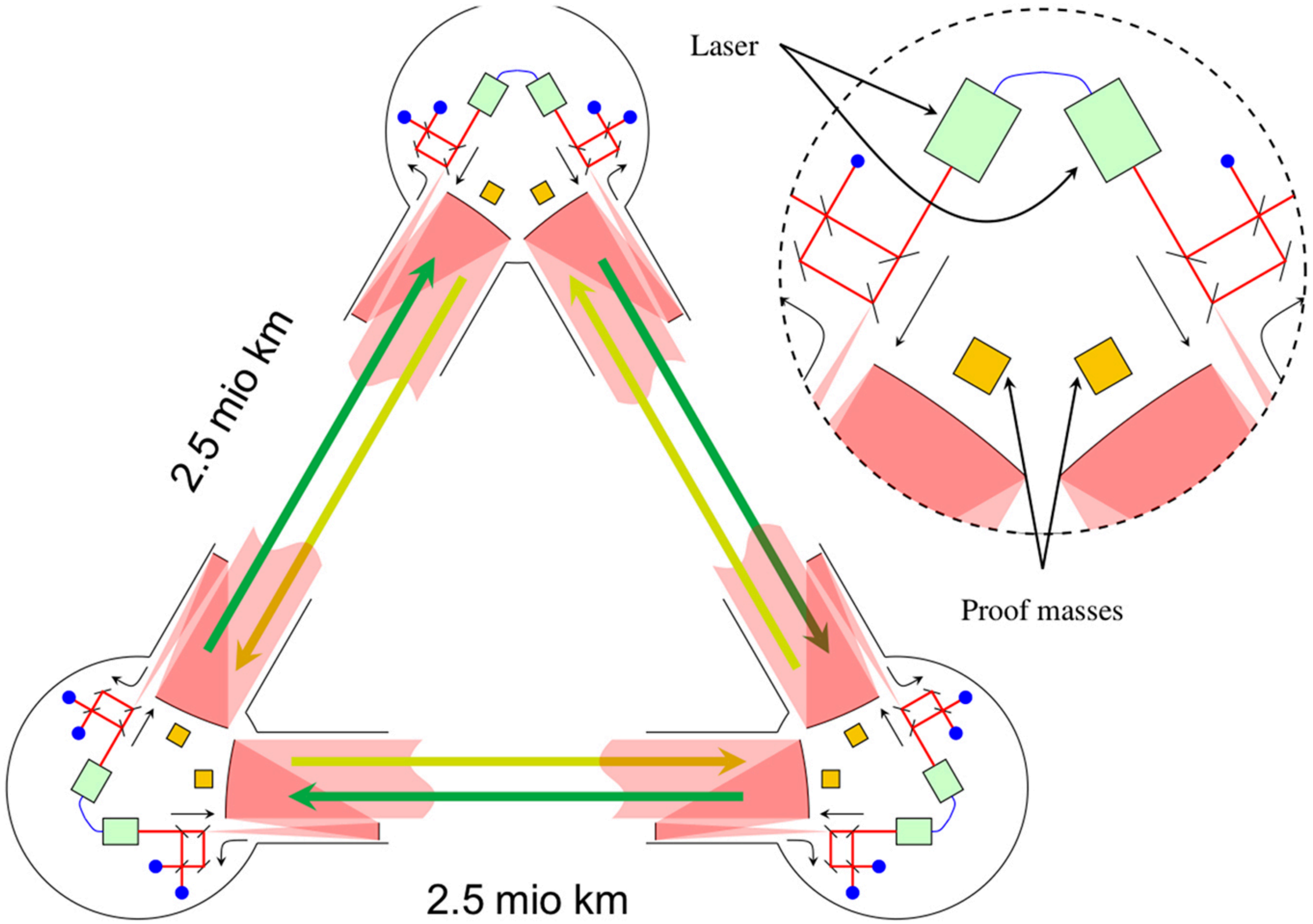


In-Orbit Performance of the GRACE Follow-on Laser Ranging Interferometer

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

LISA Displacement Noise

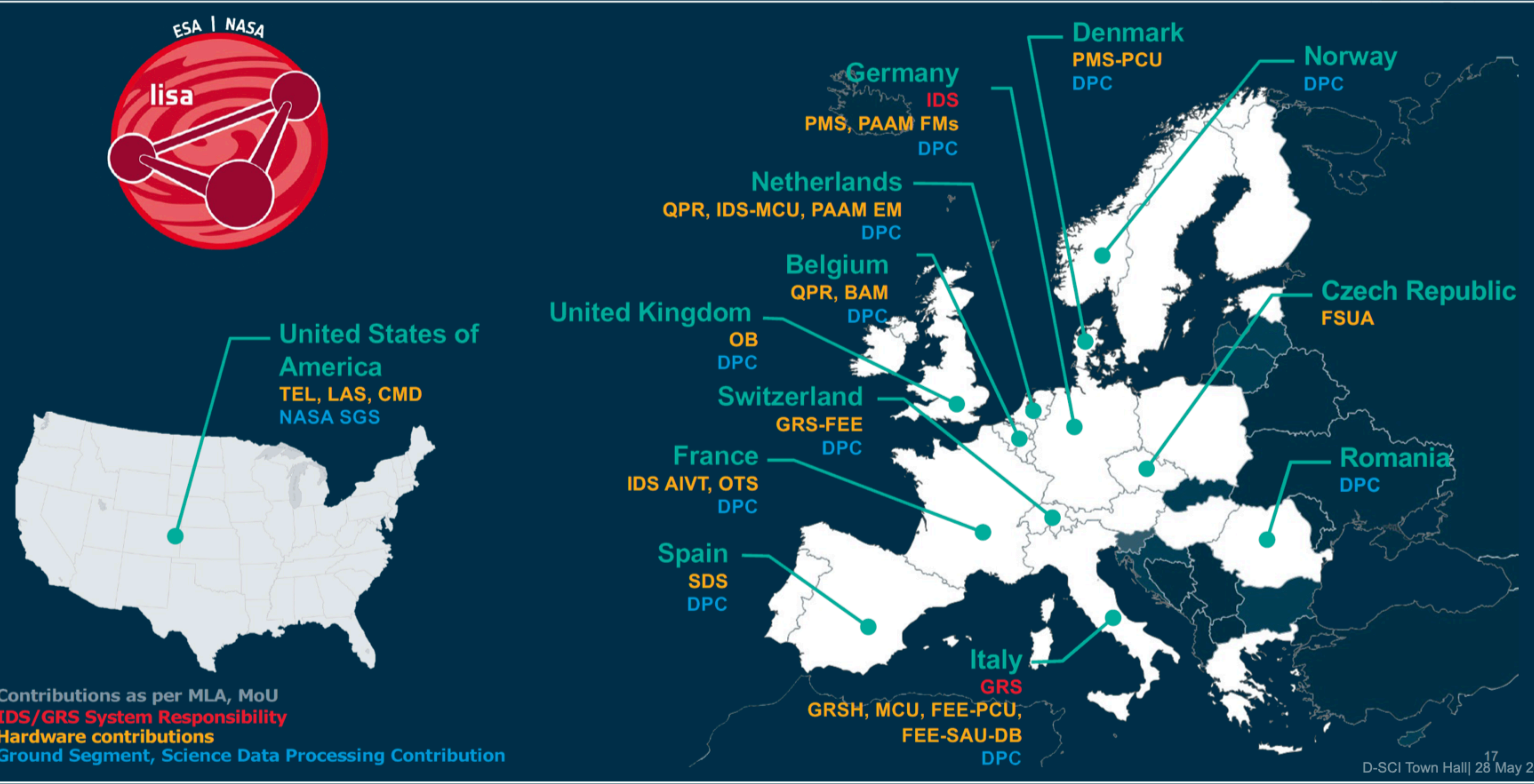
- Heterodyne interferometry with ~1μm light
- Six “one-way” measurements between pairs of spacecraft
- Telescopes reduce diffraction loss, still only receive about 10^{-10} of the transmitted power.
- Passively stable orbits maintain arm lengths to ~0.5% (10^5 km)
- On ground “Time Delay Interferometry”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



Schematic of the LISA interferometric measurement (T. Schuldt)

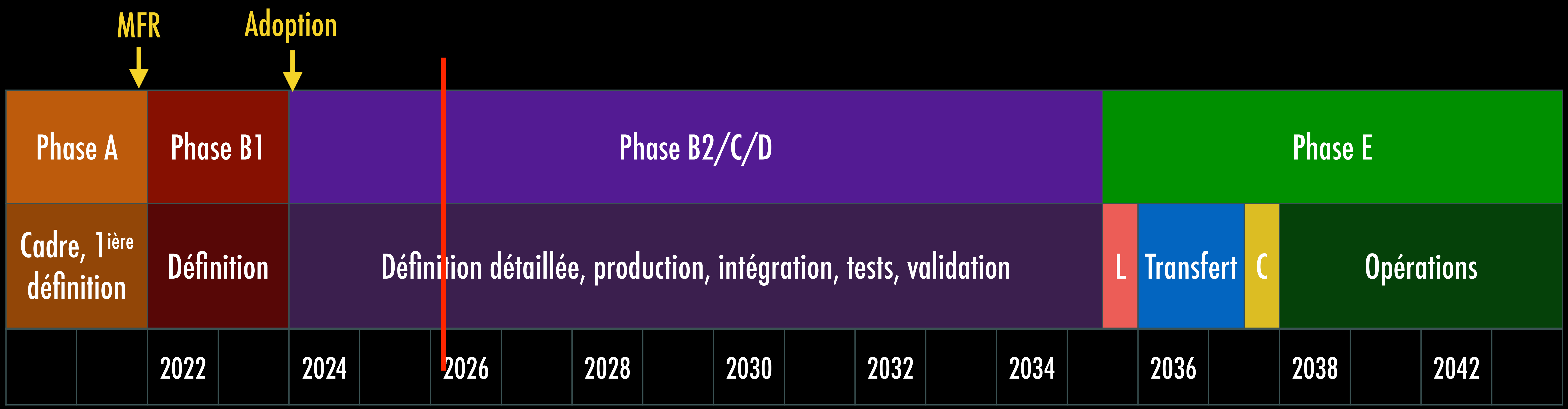
LISA Mission Status

LISA - An international mission led by ESA



Contributions as per MLA, MoU
IDS/GRS System Responsibility
Hardware contributions
Ground Segment, Science Data Processing Contribution

The roadmap to LISA



- 1993: First proposal to ESA/NASA
- 20/06/2017: mission approved by ESA after the success of LISA Pathfinder and the first detection of GWs.
- End 2021: success of the ESA Mission Formulation Review
- 25/01/2024: success of the Mission Adoption Review and adoption by ESA: design validated and we have the resources to build the instrument
- (New) LISA Science Team in place
- Long building phase ofmultiple MOSAs (6 flight models) + spacecrafts + data processing sys
- Launch 2035
- 1.5 years of orbital transfer
- 4.5 years of nominal mission + 6.5 years of possible extension

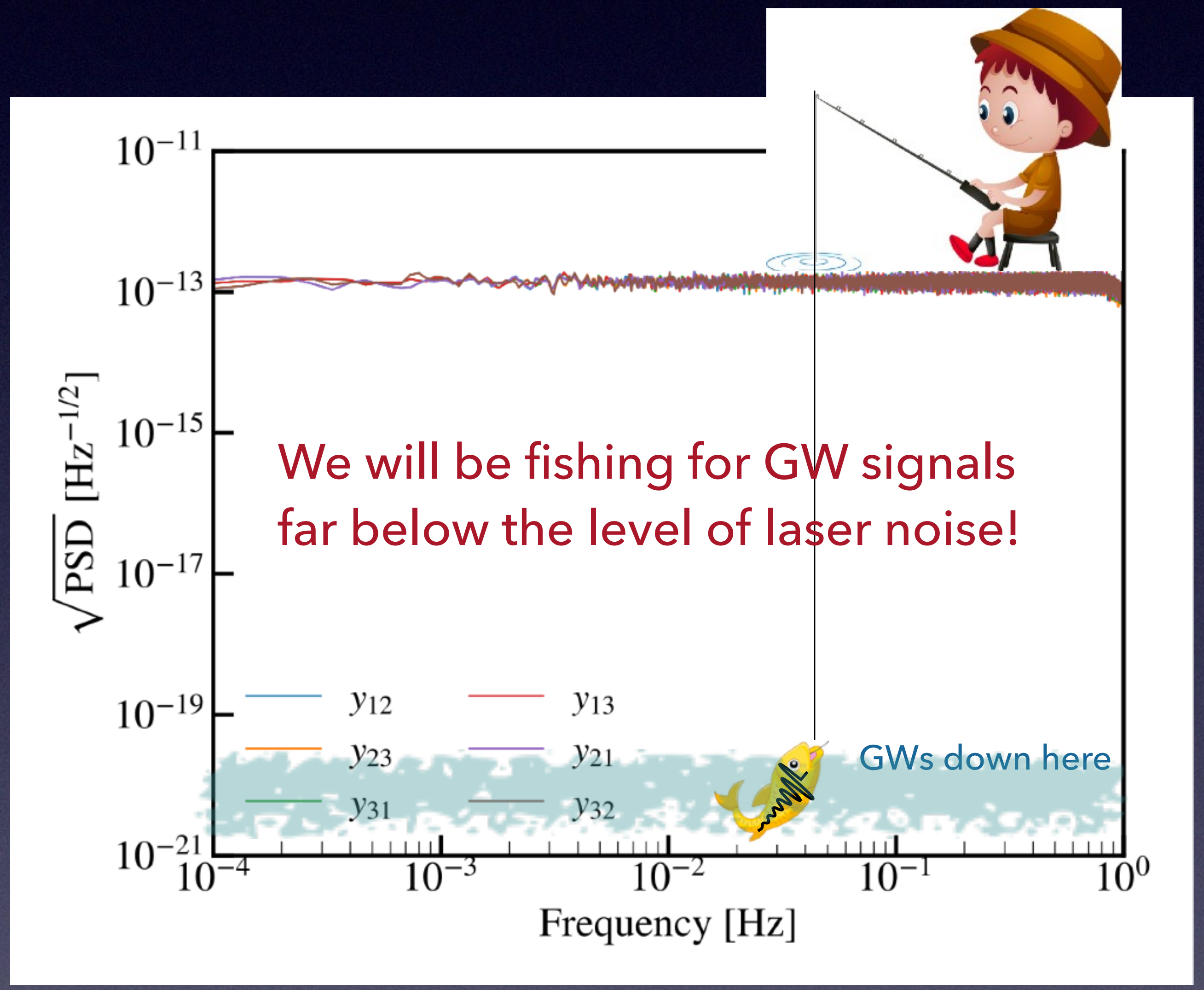
Realizing LISA Data Processing

Challenges of LISA data processing

- Must reduce dominant (laser) noise before data is useful –>(Time Delay Interferometry)
- All signals and noises overlapping in data. –> global analysis
- No repointing or second instrument for noise comparison:
  –> reliant on well-modeled Bayesian inference

- Some science depends on rapid response: Low-latency alerts
- Various science objectives require different views on the data:
  –>range of data products from low-level data streams to simplified catalogs

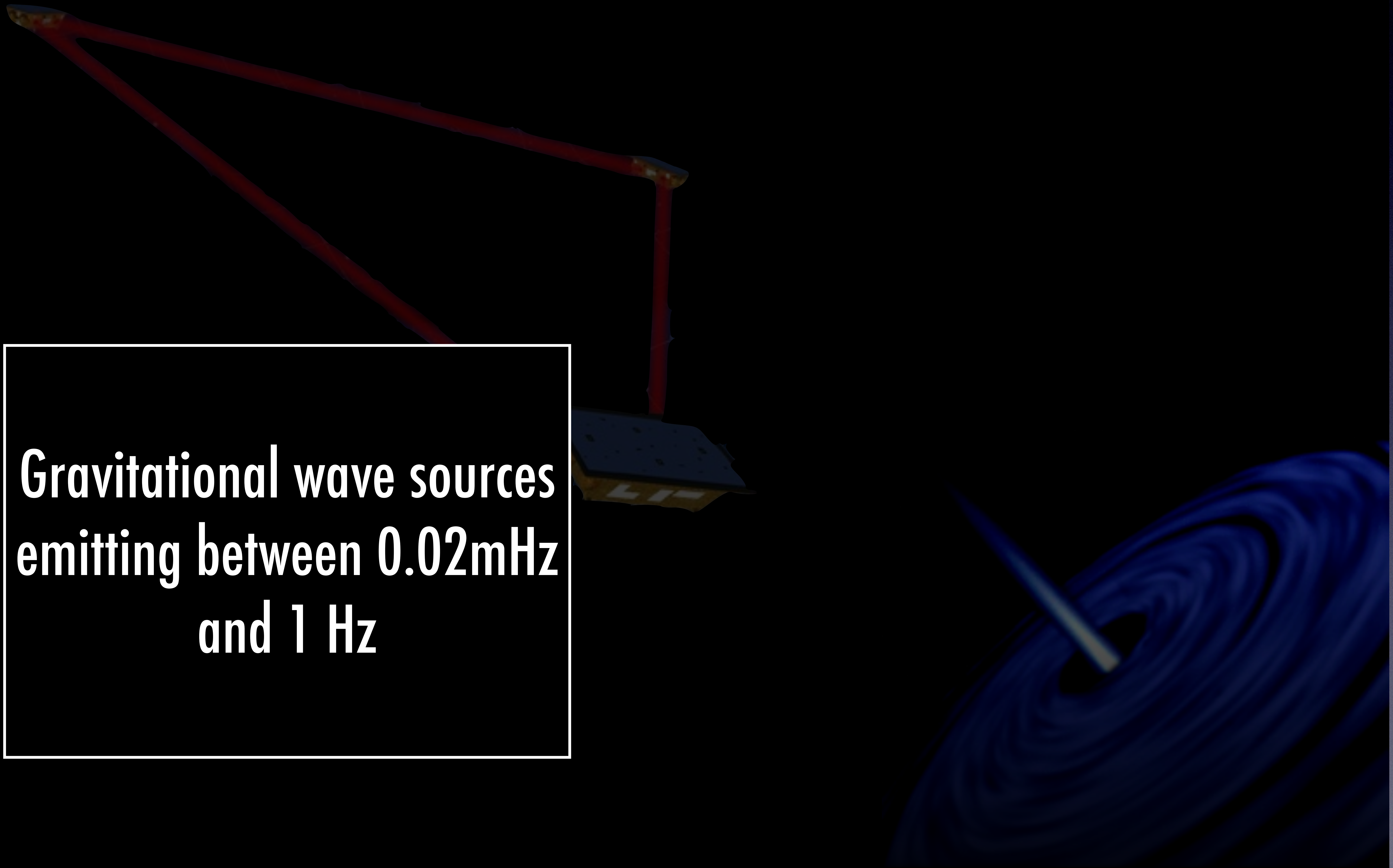
- Flexibility: first data of this kind challenge:
  - Multiple approaches, multiple pipelines
  - Quick development from prototyping to production



ESA-coordinated EU and NASA efforts: EU part –> Distributed Data Computing Center (DDPC)

Processing LISA's Data

Data

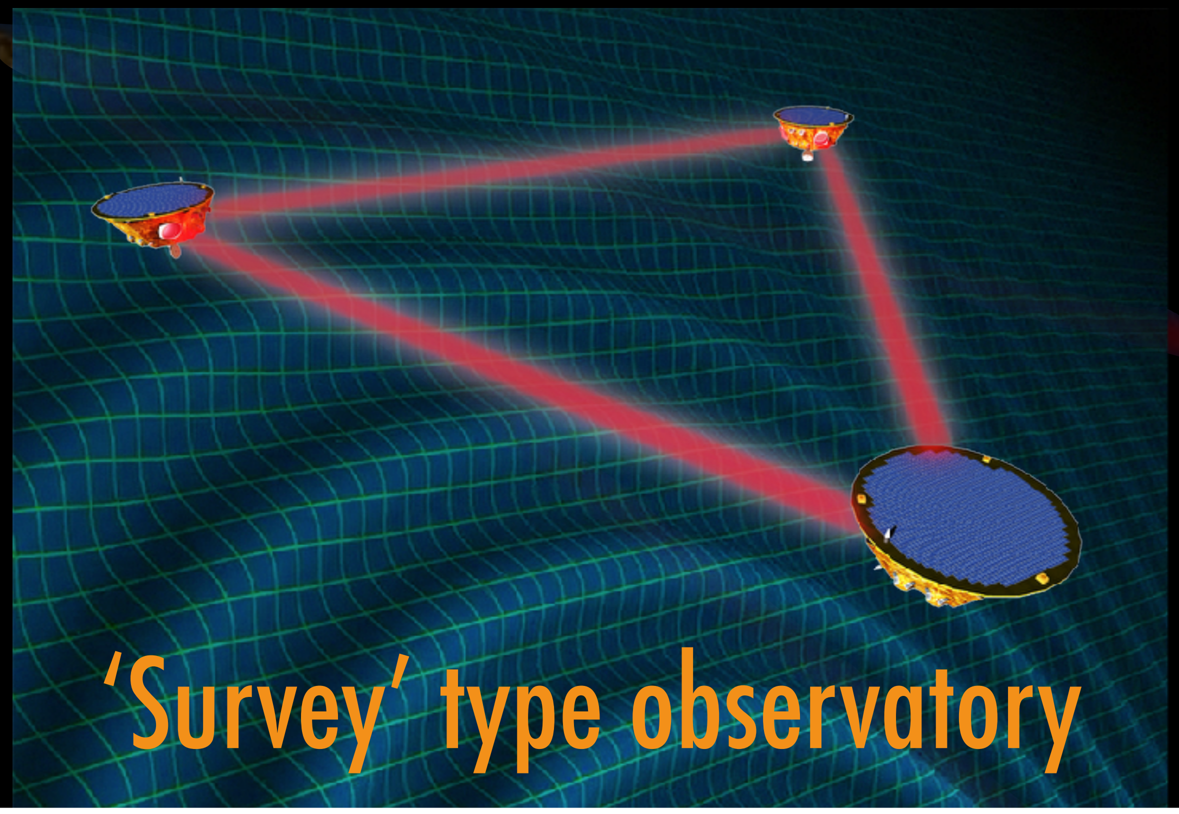


Gravitational wave sources emitting between 0.02mHz and 1 Hz

Slide courtesy of Antoine Petiteau

Processing LISA's Data

Data



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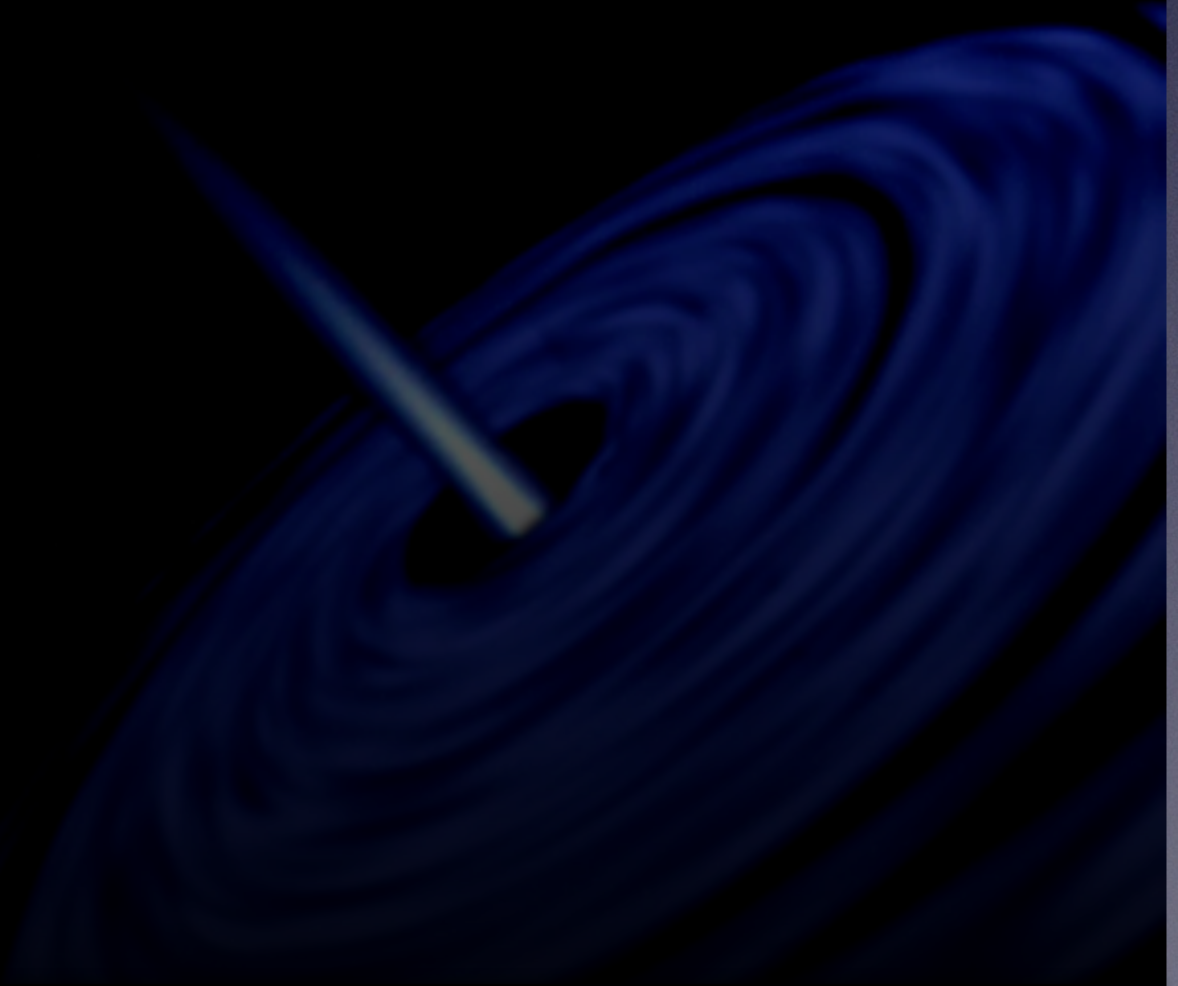


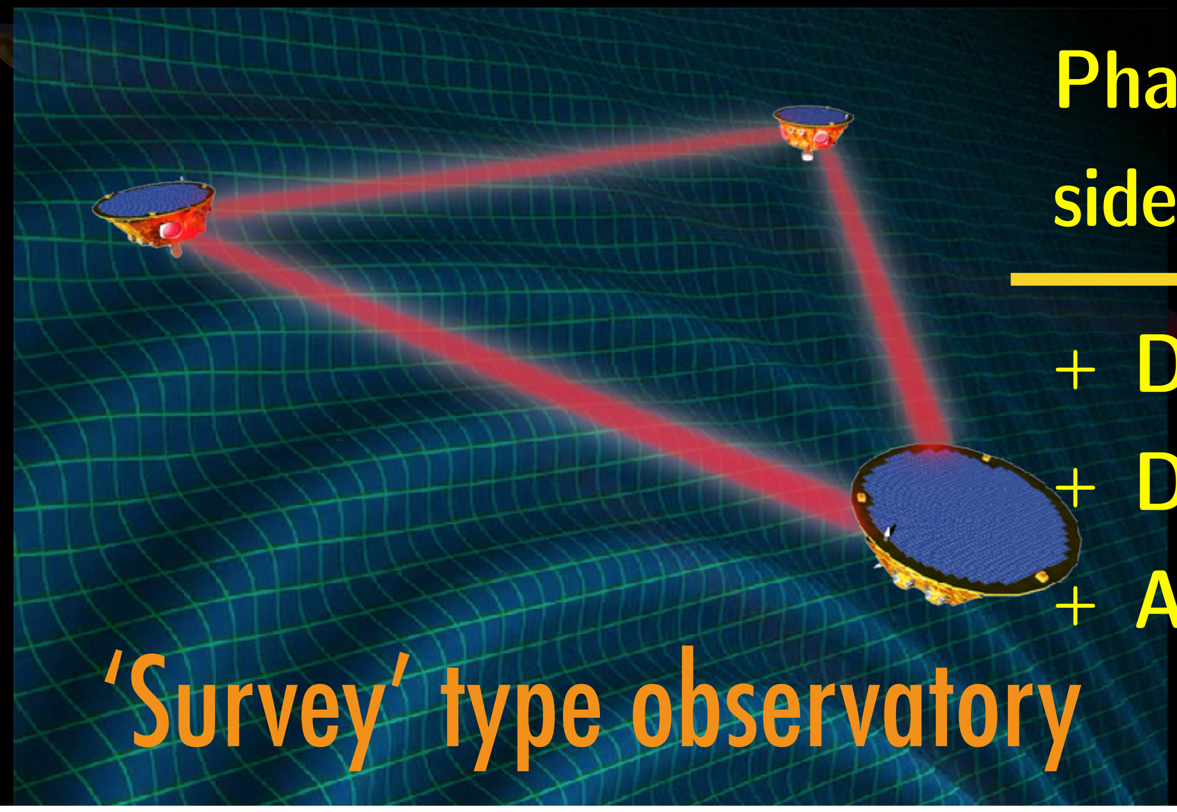
Slide courtesy of Antoine Petiteau

Processing LISA's Data

Data

Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels



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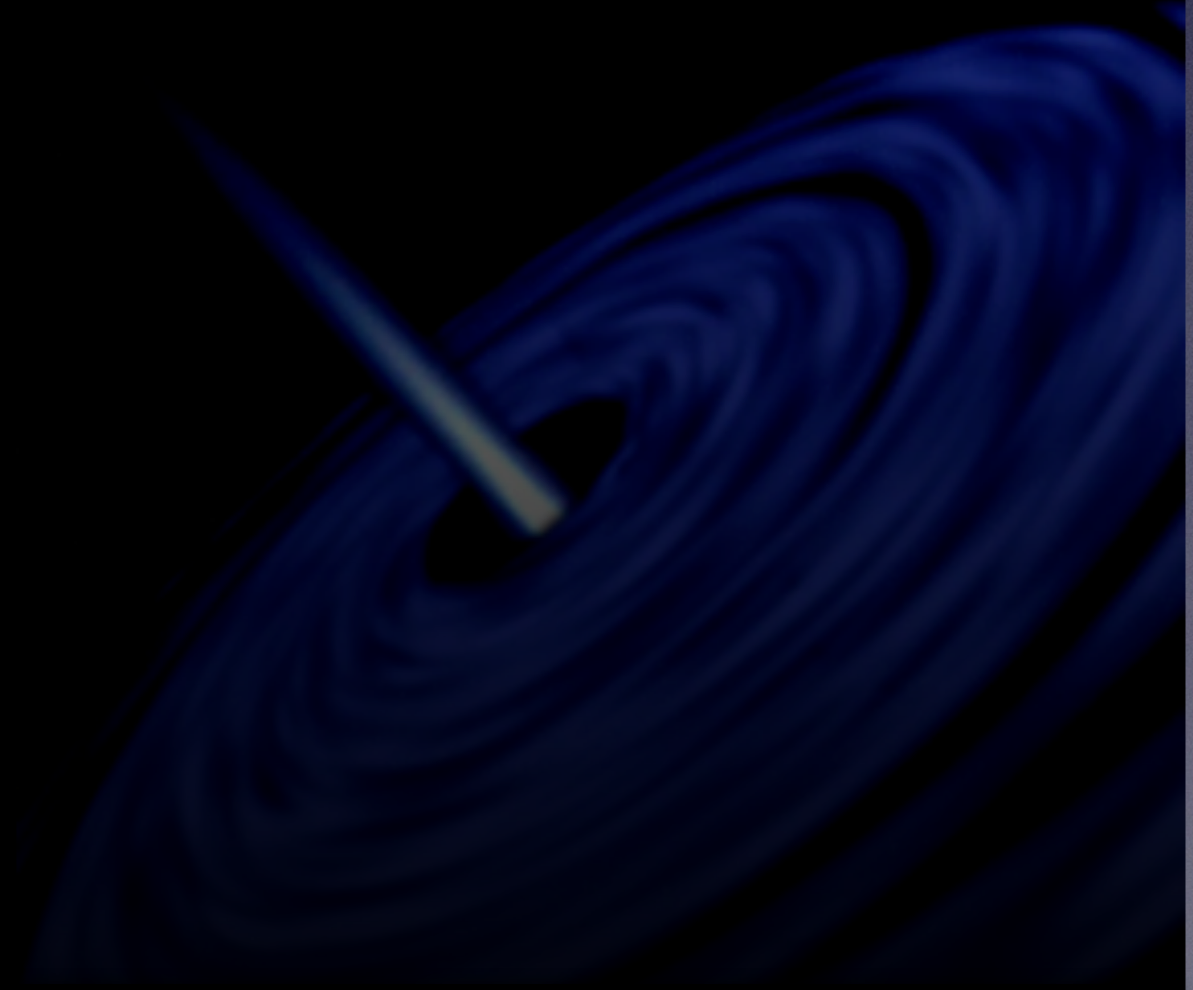


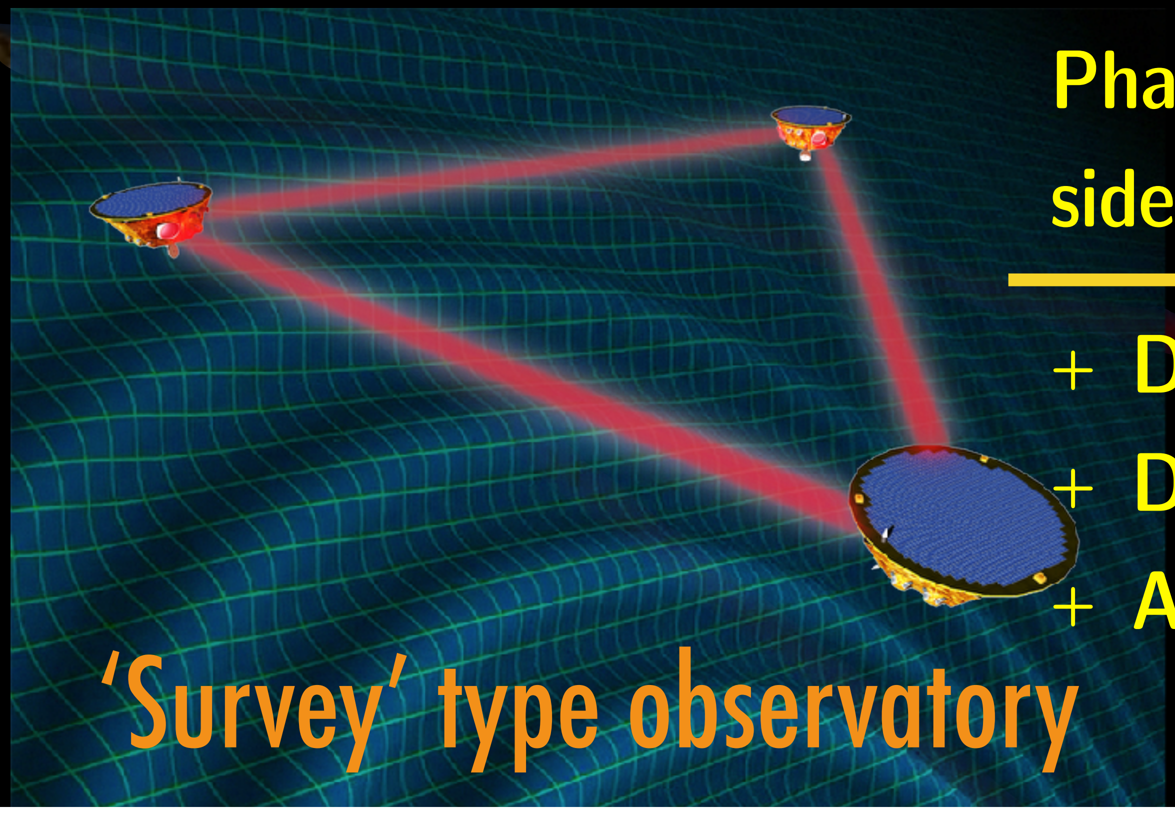
* Drag-Free Attitude Control System

** Charge Management Device

Slide courtesy of Antoine Petiteau

Processing LISA's Data

Data



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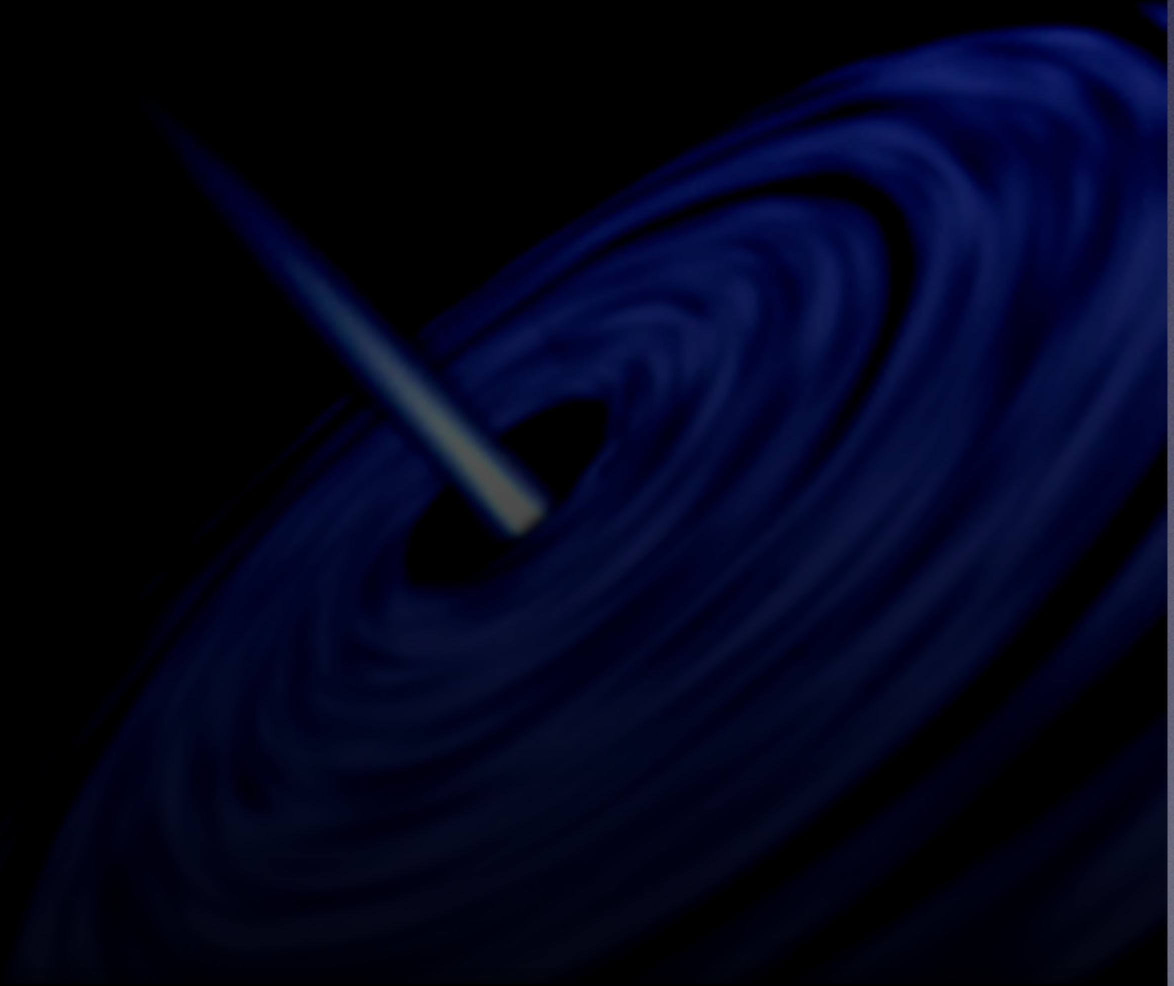

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Processing LISA's Data

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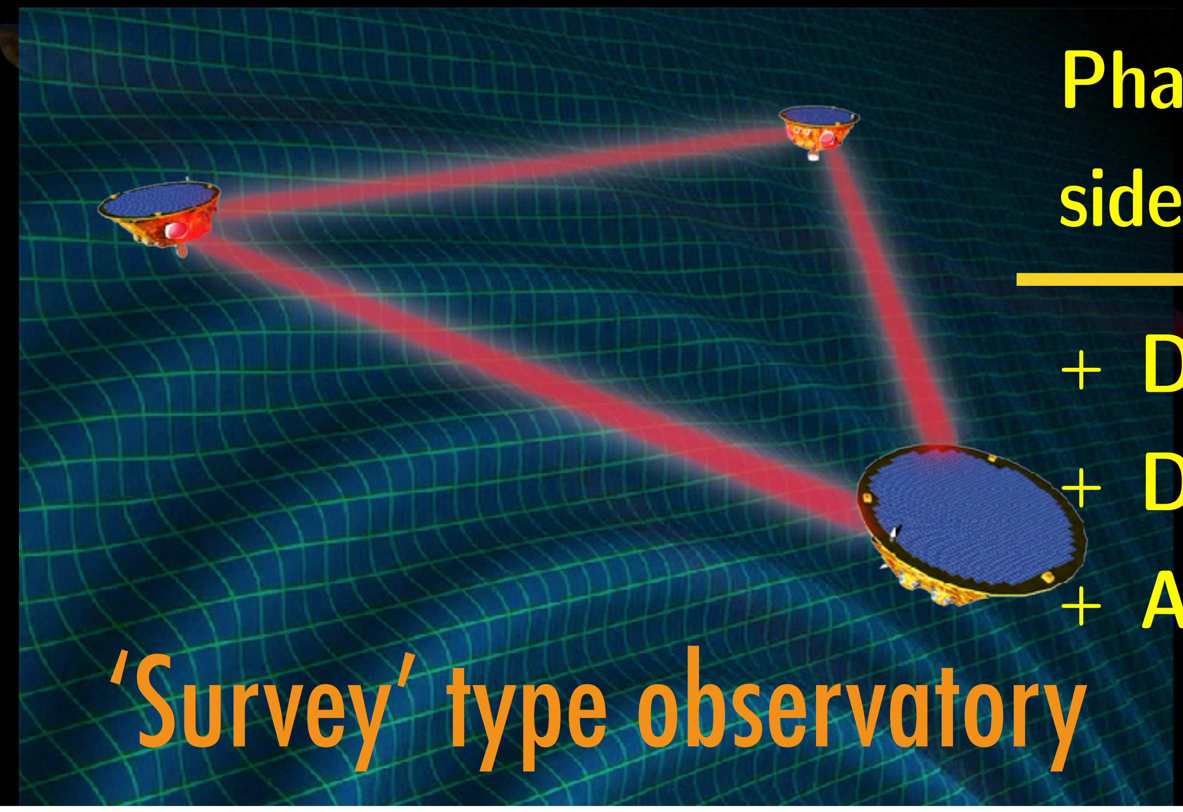


Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

'Survey' type observatory

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry reduction of laser noise

3 TDI channels with 2 "~independents"

Gravitational wave sources emitting between 0.02mHz and 1 Hz

* Drag-Free Attitude Control System

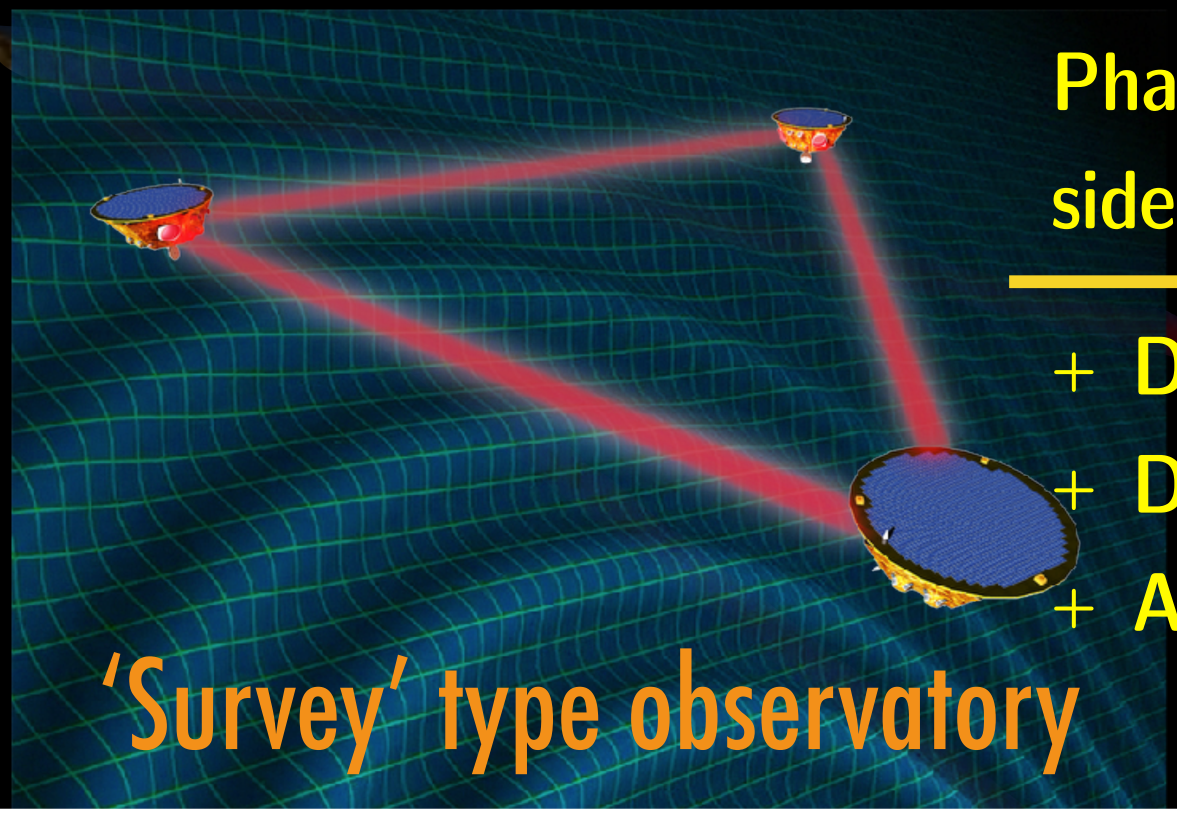
** Charge Management Device

Slide courtesy of Antoine Petiteau

Processing LISA's Data

LISA CONSORTIUM

Data



Phasemeters (carrier, sidebands, distance)

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry reduction of laser noise

Gravitational wave sources emitting between 0.02mHz and 1 Hz

3 TDI channels with 2 "~independents"

Data Analysis of GWs

Catalogs of GWs sources with their waveform

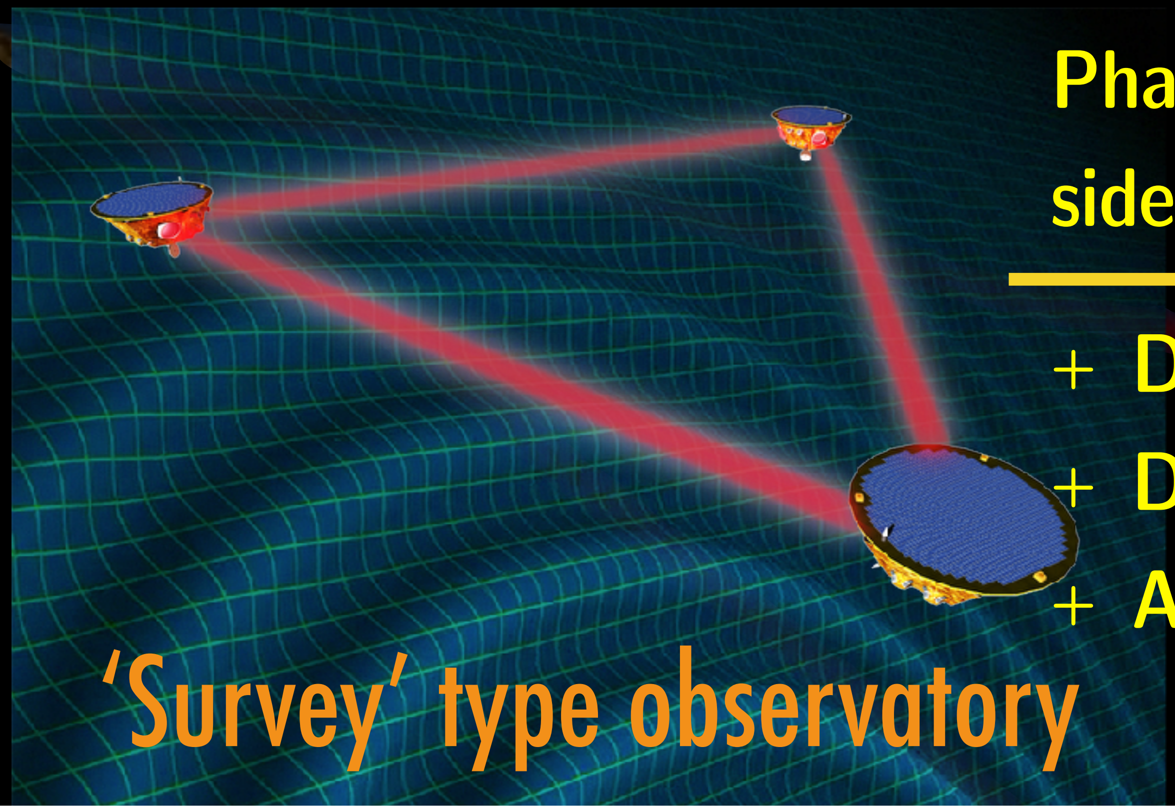
* Drag-Free Attitude Control System

** Charge Management Device

Slide courtesy of Antoine Petiteau

Processing LISA's Data

Data



Phasemeters (carrier, sidebands, distance)

L0

+ DFACS* & CMD**
+ Diagnostics
+ Auxiliary channels

L0.5

Calibrations corrections
+ Resynchronisation (clock)
+ Time-Delay Interferometry reduction of laser noise

Gravitational wave sources emitting between 0.02mHz and 1 Hz

L1 — 3 TDI channels with 2 "~independents"

Data Analysis of GWs

L2

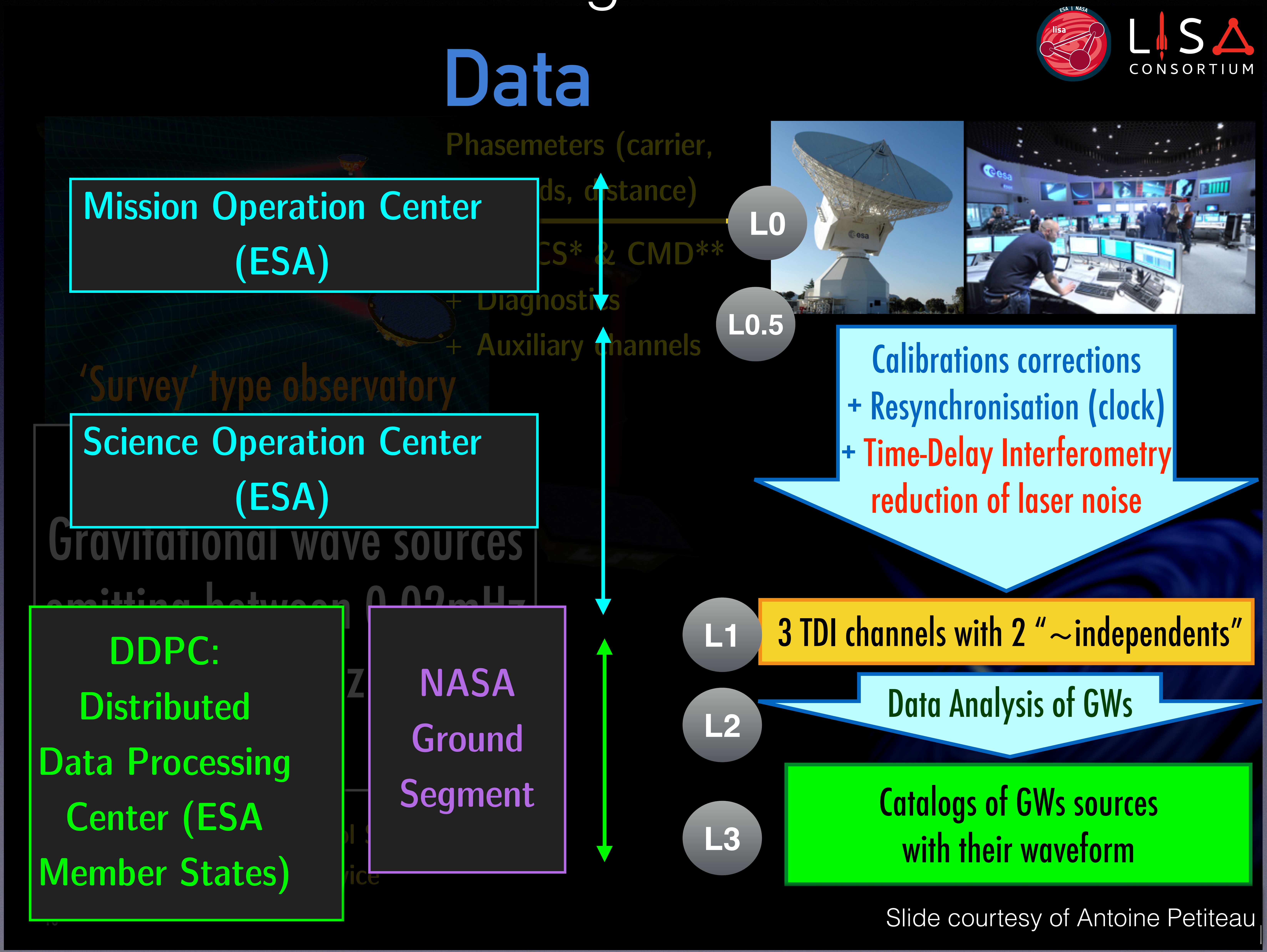
L3 — Catalogs of GWs sources with their waveform

* Drag-Free Attitude Control System

** Charge Management Device

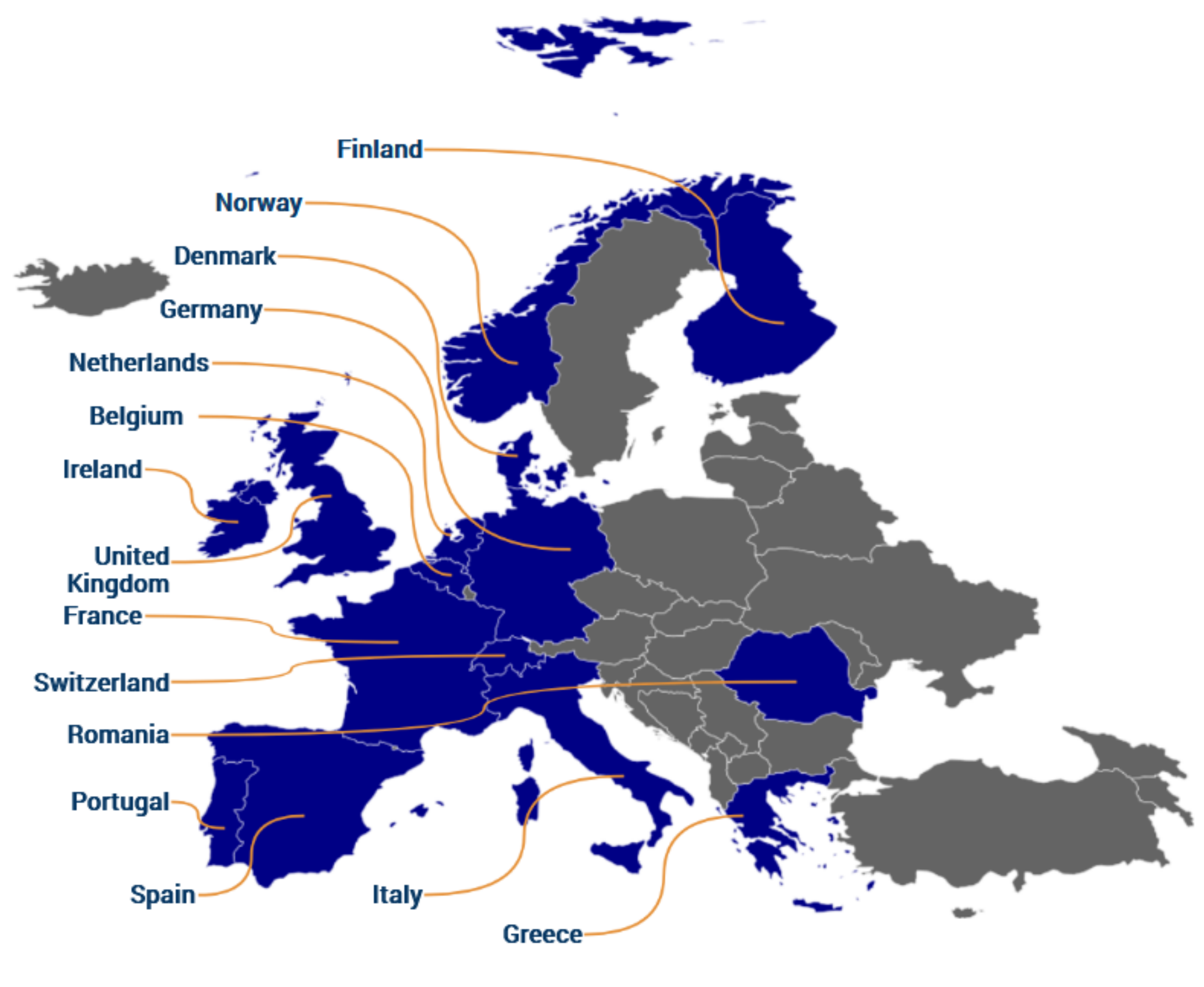
Slide courtesy of Antoine Petiteau

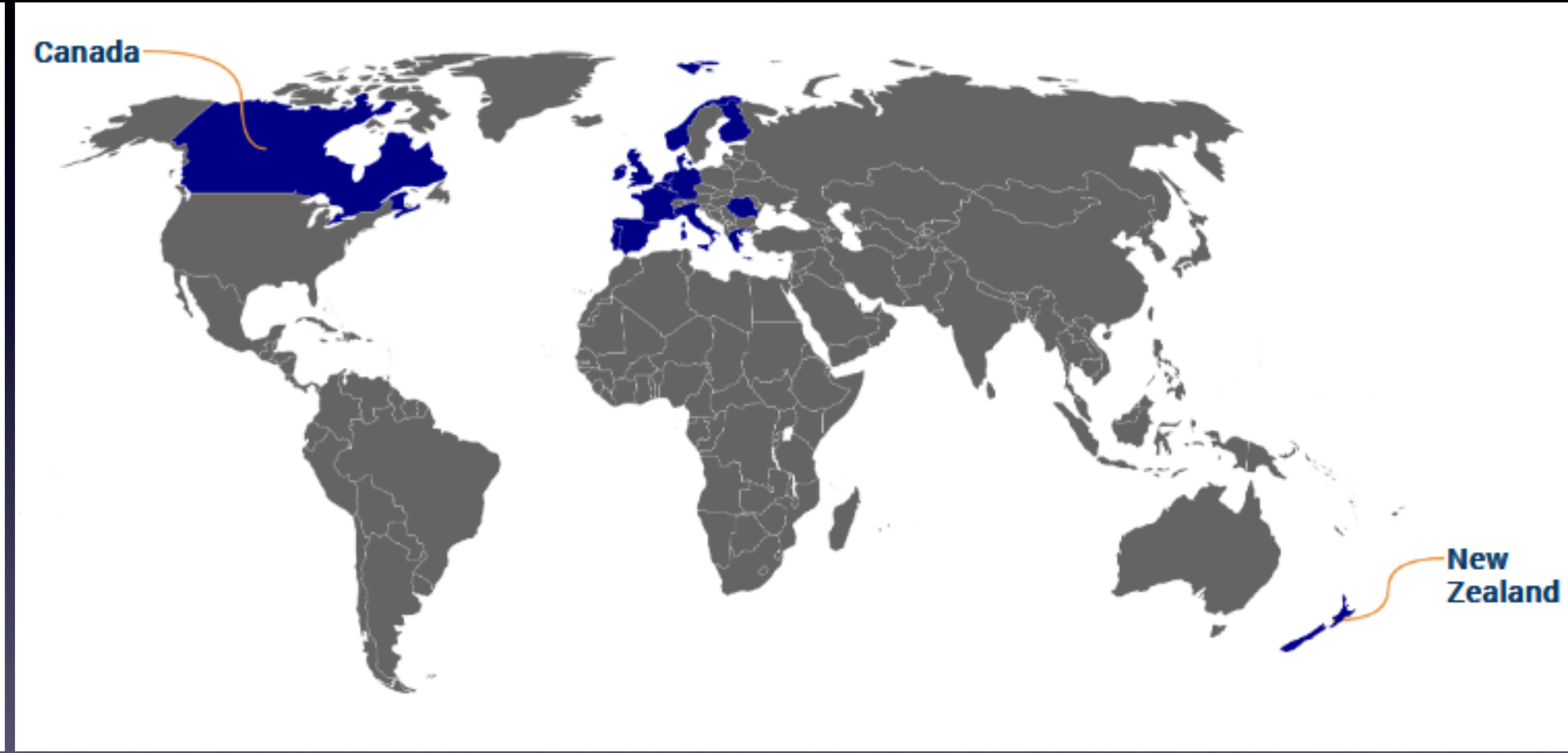
Processing LISA’s Data



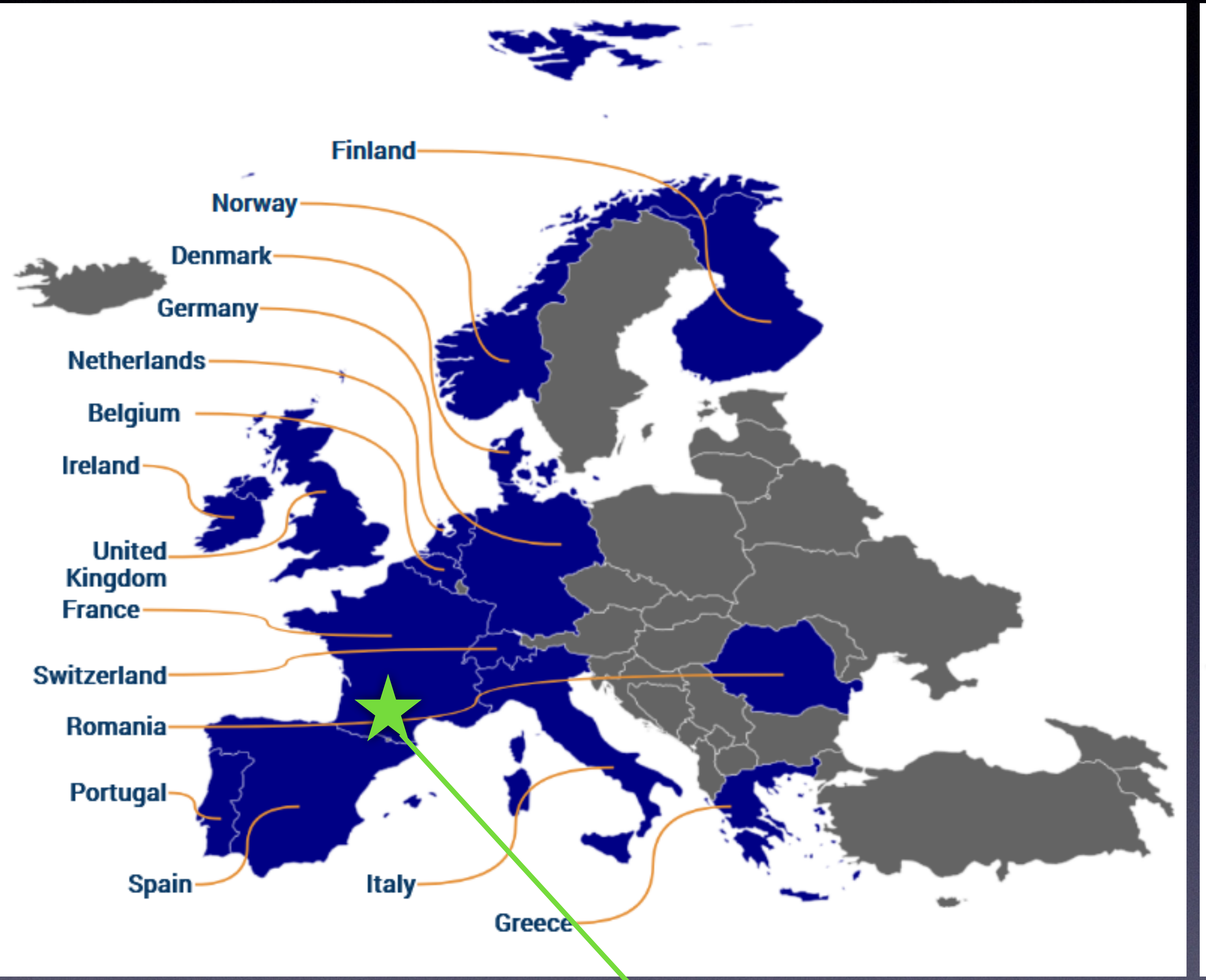
Slide courtesy of Antoine Petiteau

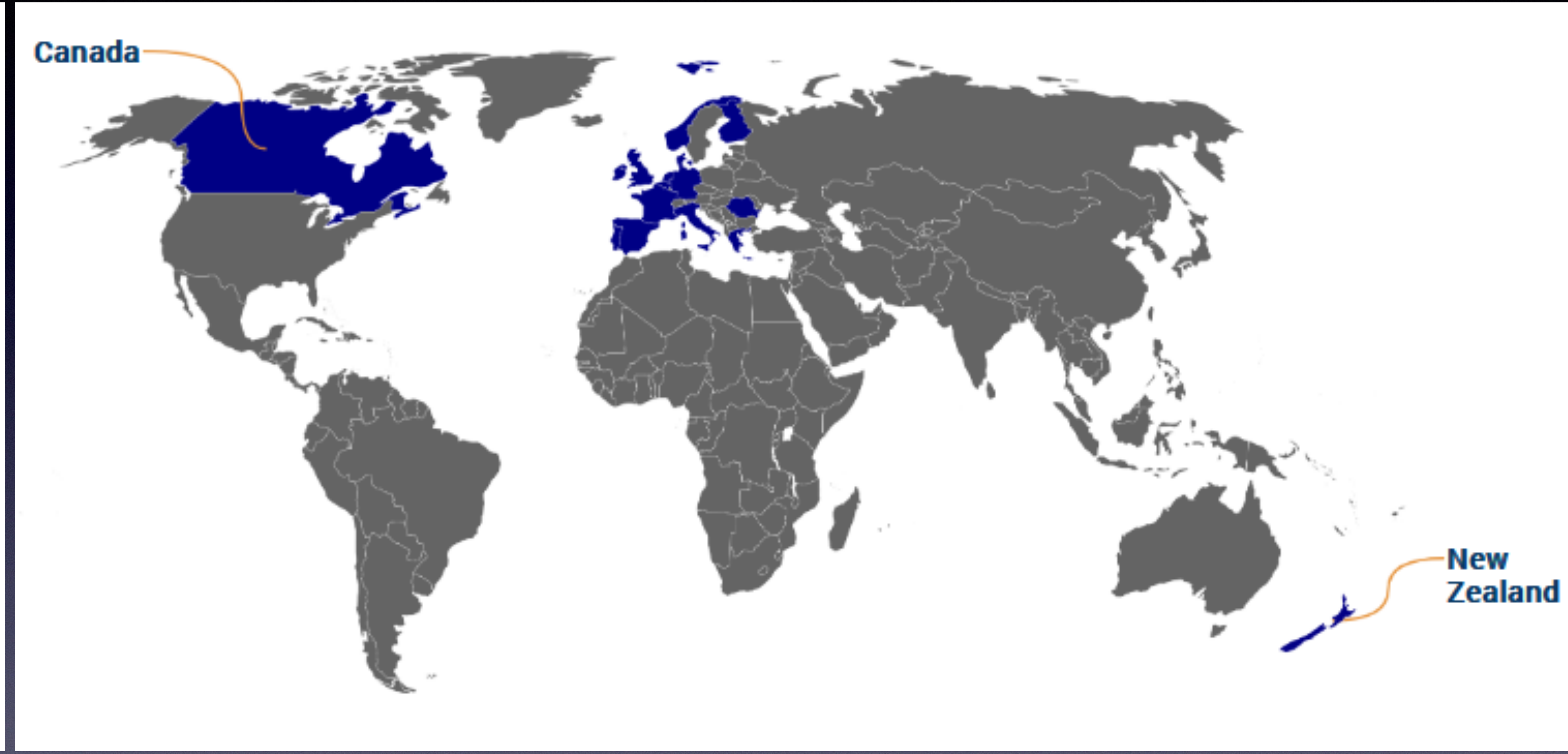
LISA Distributed Data Processing Center (DDPC) Partners





LISA Distributed Data Processing Center (DDPC) Partners





Effort led by CNES

The LISA Science Community

The LISA Consortium

- A scientific collaboration
  - Maximize LISA science return
    -support the mission in all aspects
    -particular focus on scientific application of LISA data
  - Develop the LISA science community
    -provide supporting/inclusive environment
    -training/mentoring for all esp early career
    -engage the broader science community
- Membership:
  -Core members: Commit annually to roles in consortium projects
  -Community: Access to community and resources

The LISA Consortium
(see: lisamission.org)

Governance

- Consortium Council
- Management Team

Committees

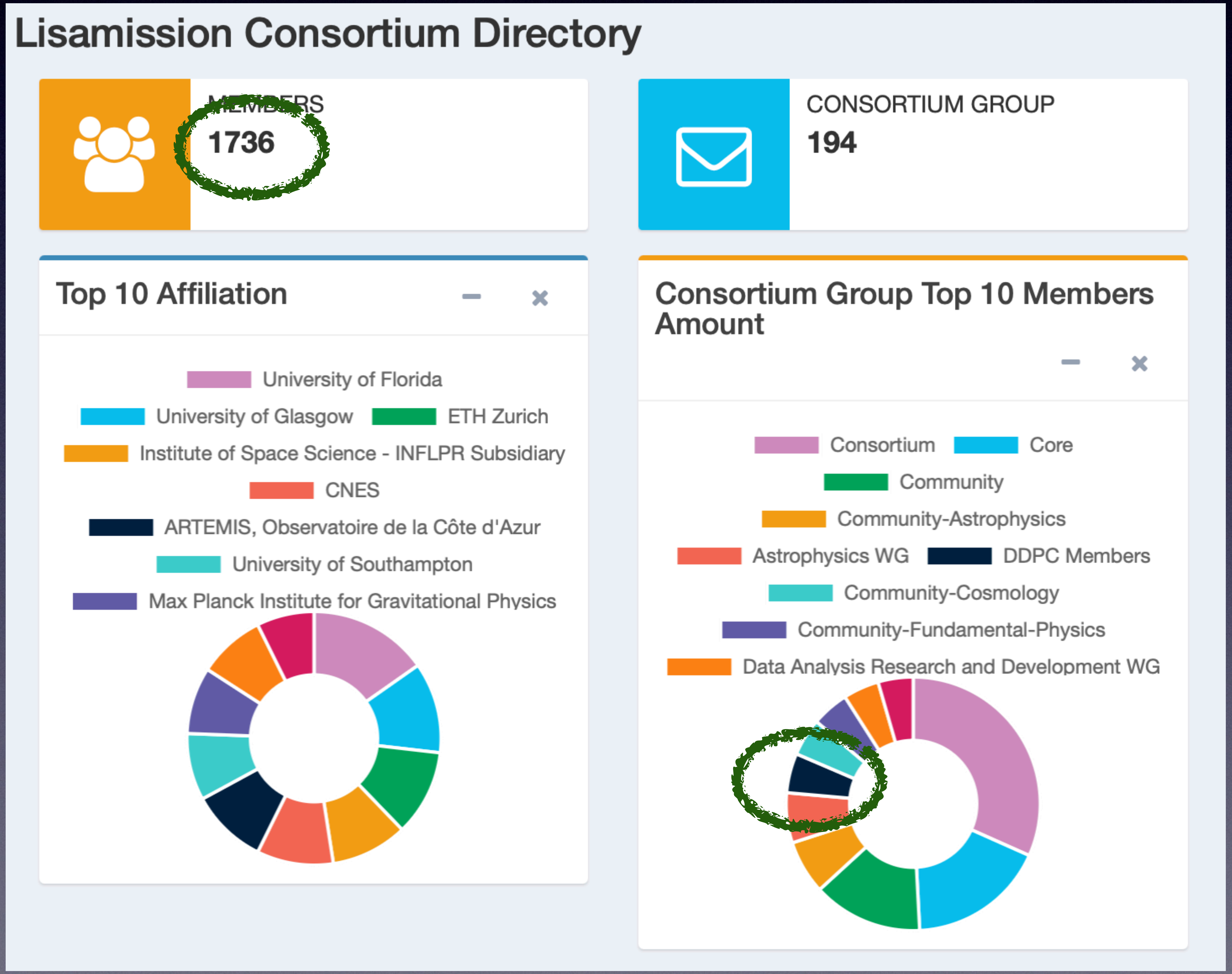
- Appointments and Elections (A&E) Committee
- Bylaws Committee
- Publication and Presentation Committee
- Diversity, Equity and Inclusion Committee
- Membership committee
- Communications Committee

Science working groups

- Astrophysics Working Group
- Cosmology Working Group
- Fundamental Physics Working Group
- Instrumentation Working Group
- Waveform Working Group
- Data Analysis and Research Development Working Group
- Instrument Simulation and Processing Working Group

Other working groups

- Communications Implementation Working Group
- Early Career Scientist Working Group



Summary

- The immense, quiet environment of space allows LISA to open a rich new band of GW astronomy in mHz
- After decades of science and technology development the mission is ready to push forward toward launch in 2035
- Much work remains to prepare to exploit LISA data
- A robust LISA science community is working on it
- You can too (see, e.g. lisamission.org)