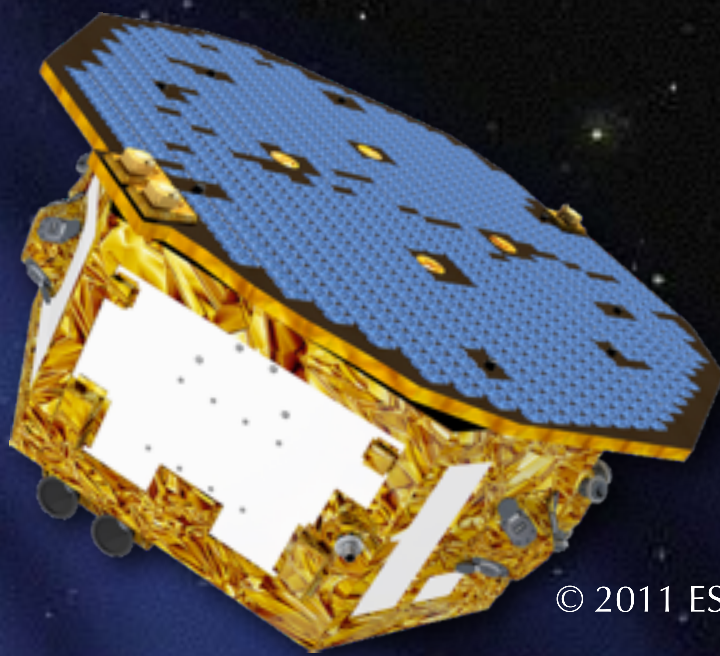
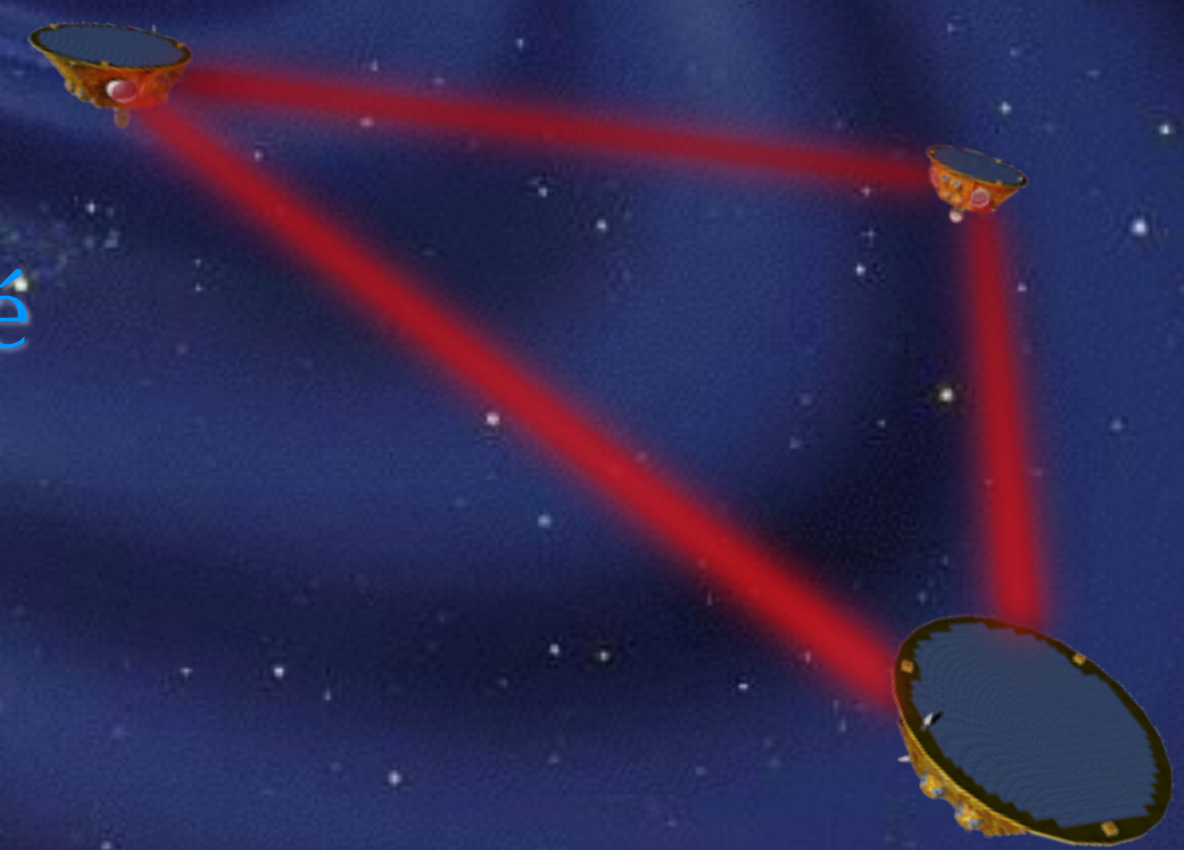
# LISA : Towards a space-borne gravitational waves detector





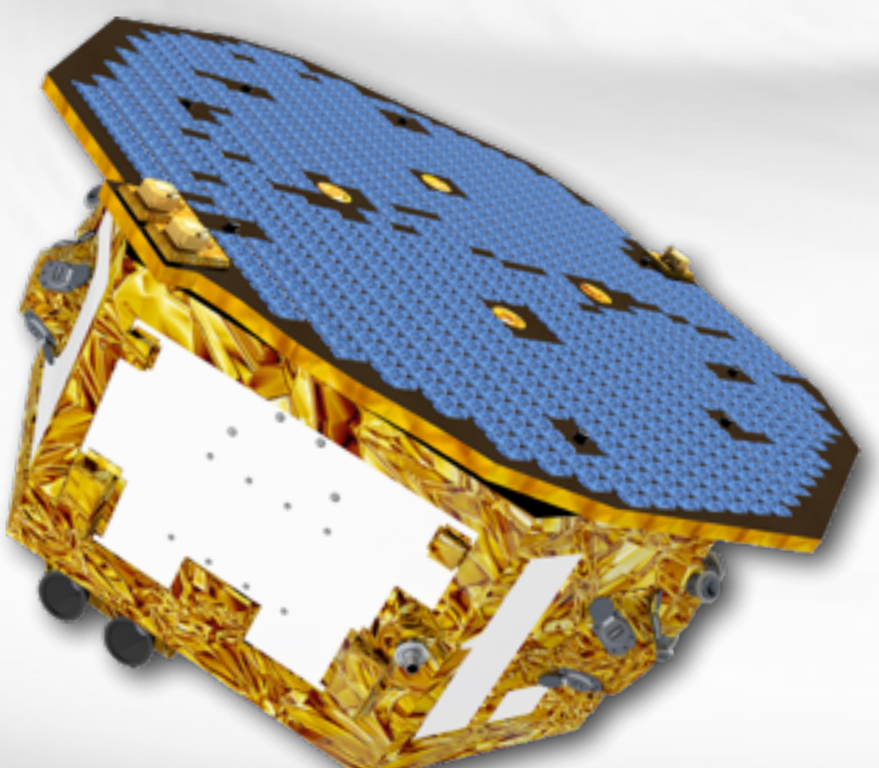


H. Halloin et al.
APC - CNRS/Université Paris Diderot

# Outline

- Gravitational waves in a nutshell
- Some sources of GW
- Ground based detectors (in brief)
- LISA Pathfinder & LISA
- The French contribution to LISA

# Gravitational waves in a nutshell

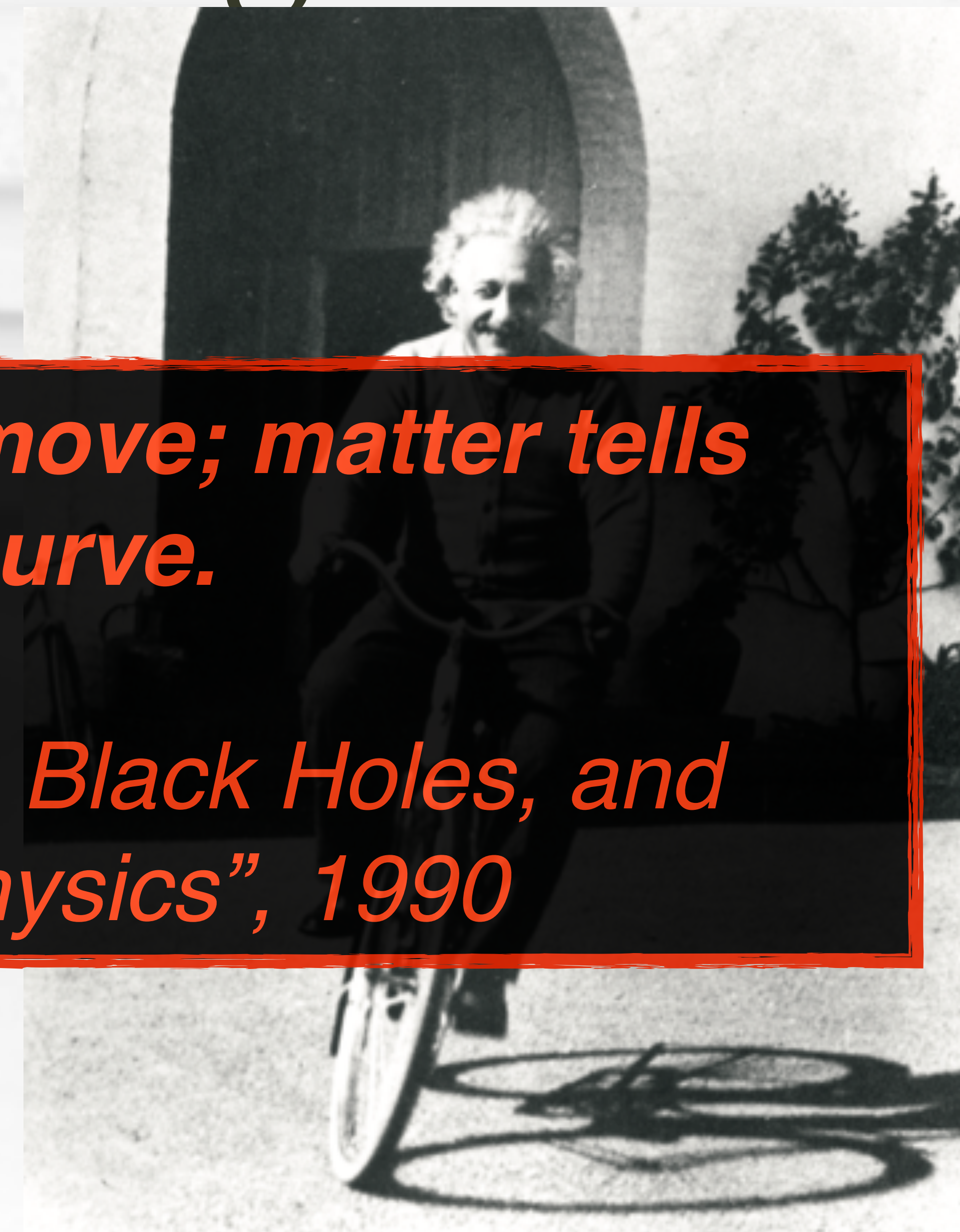


# 100 years ago …

- Albert Einstein (1915) : Gravity is not a force …
  - Mass deforms geometry of space-time.
  - Gravitational information propagates at the speed of light.
  - Dissipation of energy through deformation of space-time ==> gravitational waves

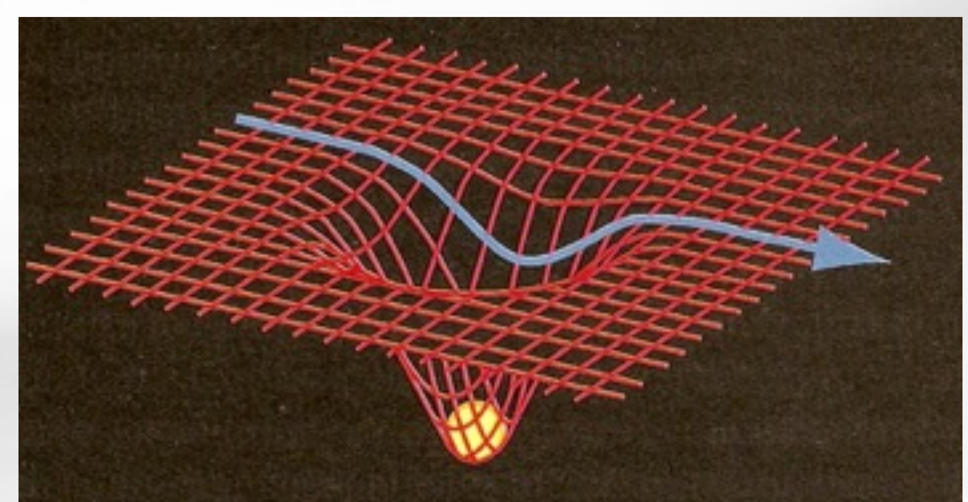
***Spacetime tells matter how to move; matter tells spacetime how to curve.***

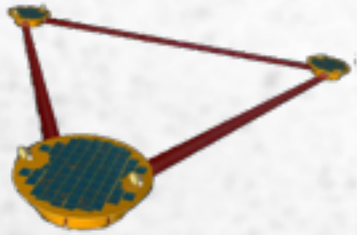
*John Archibald Wheeler, "Geons, Black Holes, and Quantum Foam: A Life in Physics", 1990*



$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

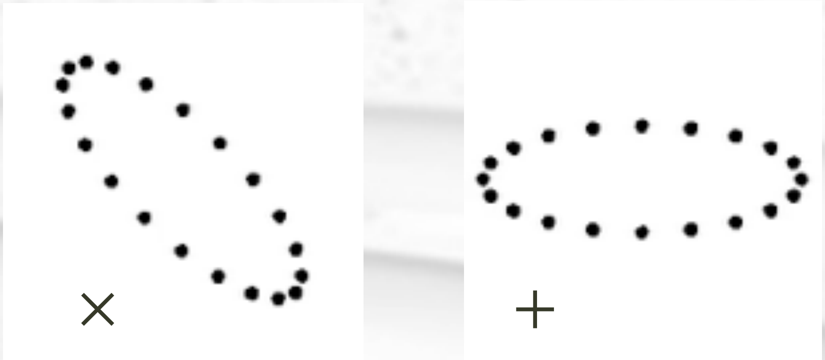
Geometry of space-time — Energy distribution



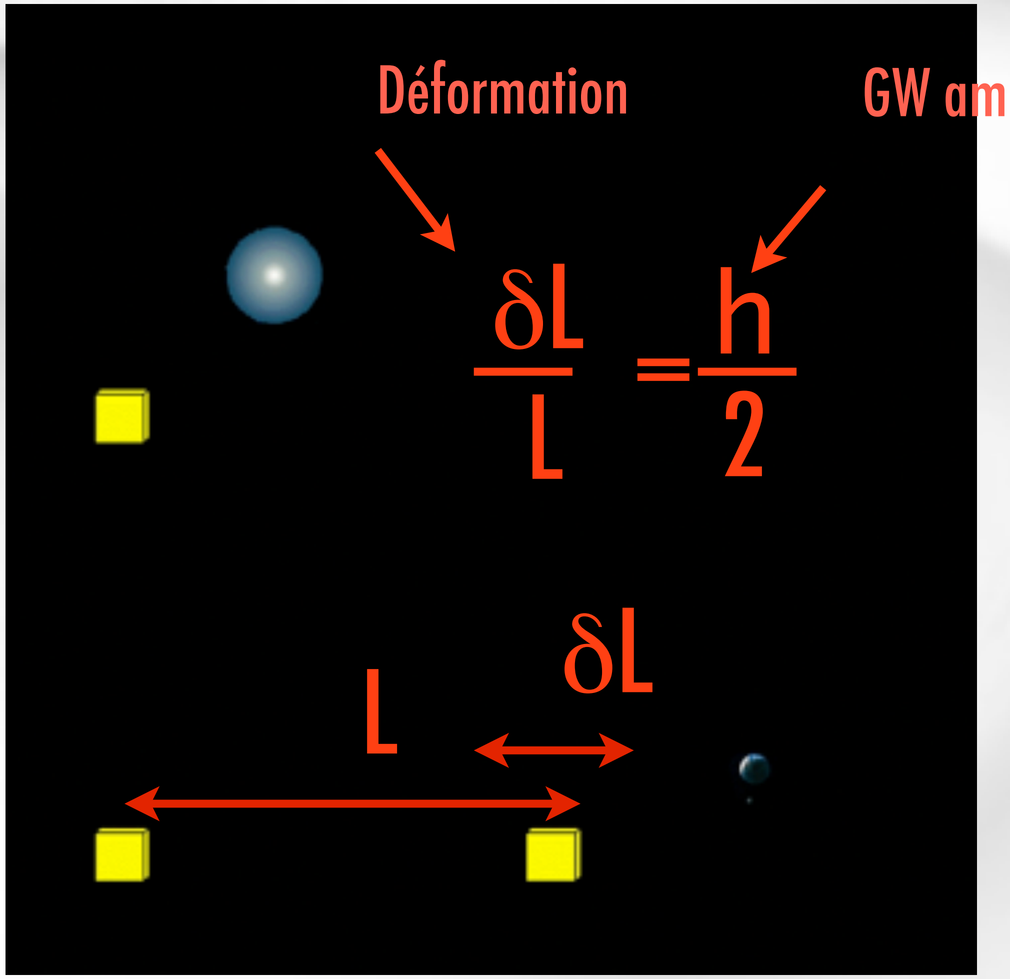


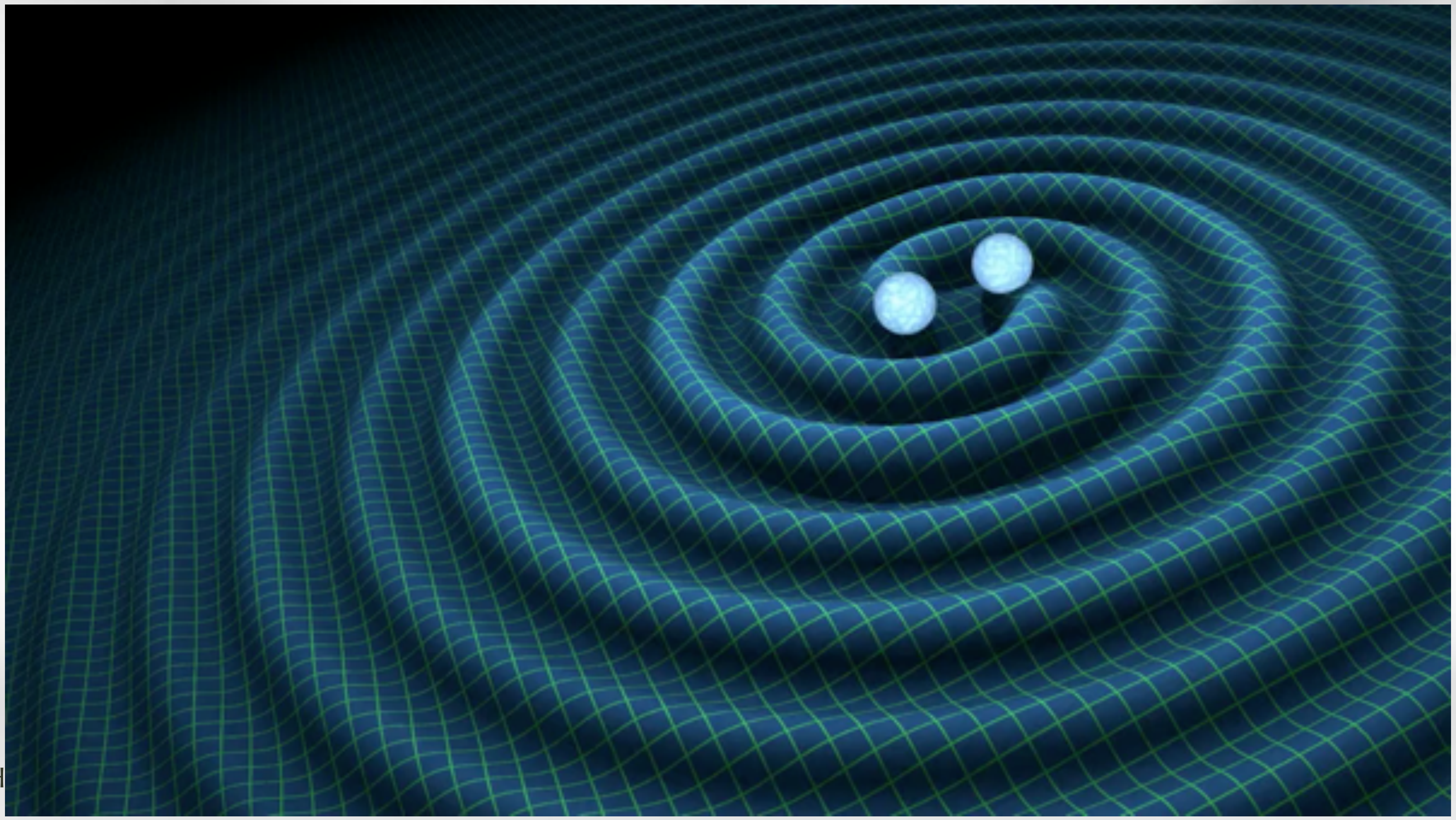
# Gravitational waves ?

- What are GW ?
  - The GW are elastic deformations of the space-time metric
  - Transverse, quadrupole waves
  - Observational effect : Variation of the light-distance between 2 masses at rest.

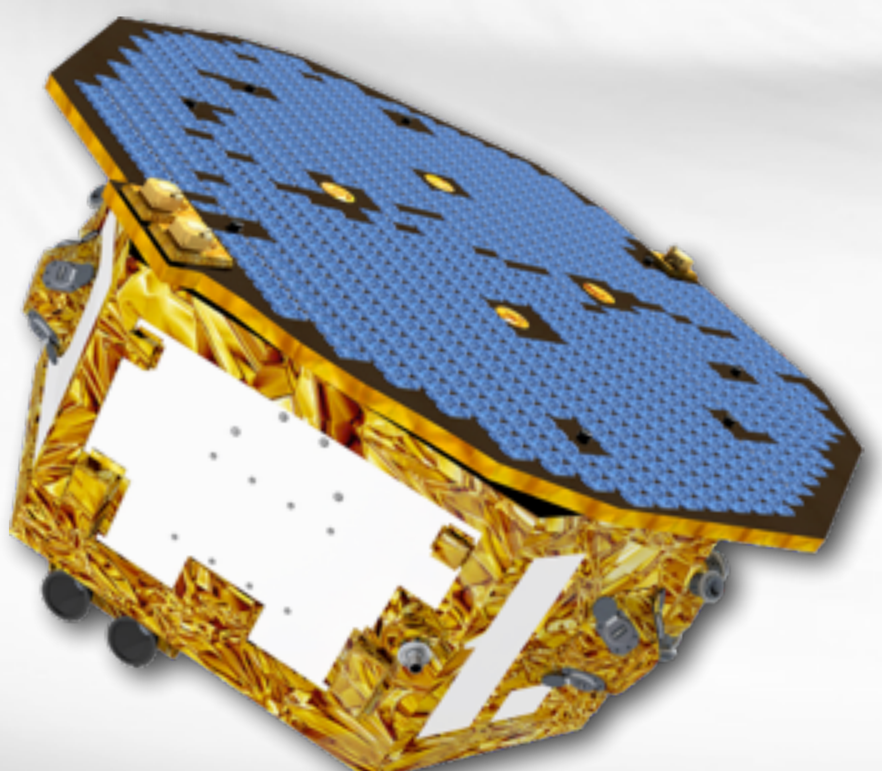



- Requires  non spherical acceleration of massive objects
  - No GW emission : isolated bodies, even rotating
  - GW emission : binary systems, asymmetric star explosion / core collapse, etc.



# Some sources of Gravitational Waves



# Orders of magnitude

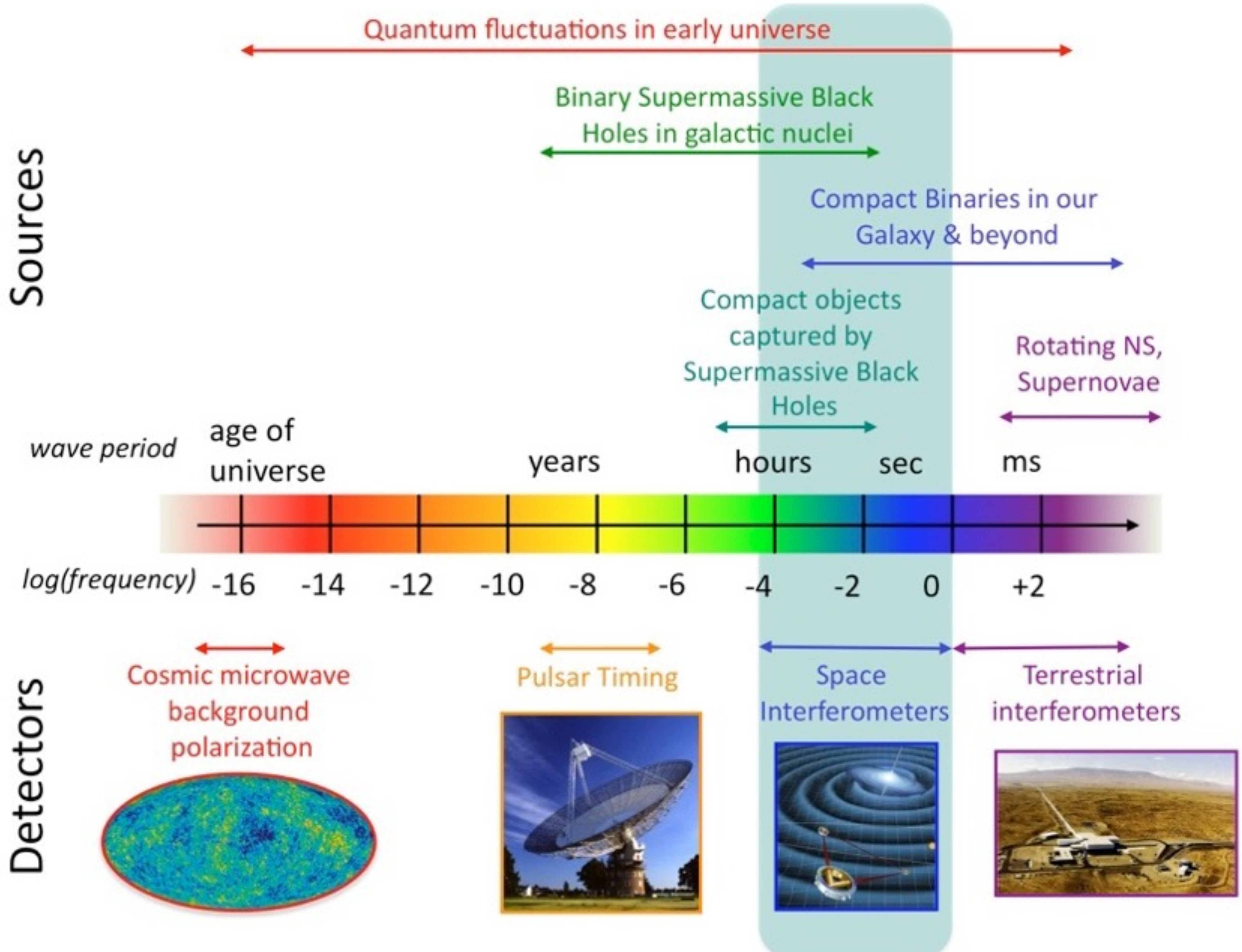
- Estimation of GW amplitude for a source of mass M, compacity $\kappa$, at a distance r :

$$h \approx 2\kappa \frac{GM}{rc^2} \approx \ 10 \text{ pm/Mkm} \ \frac{M}{M_{Soleil}} \frac{30 \text{ kal}}{r} \frac{\kappa}{0{,}001}$$

$$f \approx \sqrt{\frac{G\rho}{\pi}} \approx 2 \text{ Hz} \ \frac{M_{Soleil}}{M} \left(\frac{\kappa}{0{,}001}\right)^{3/2}$$

  - Very massive and compact objects (massive BH binaries, SN, white dwarfs binaries, etc.) can produce significant signals
  - Can be detected at very large distance (h scales as 1/r …)
  - The mass of the object drives the GW frequency

# The Gravitational Wave Spectrum

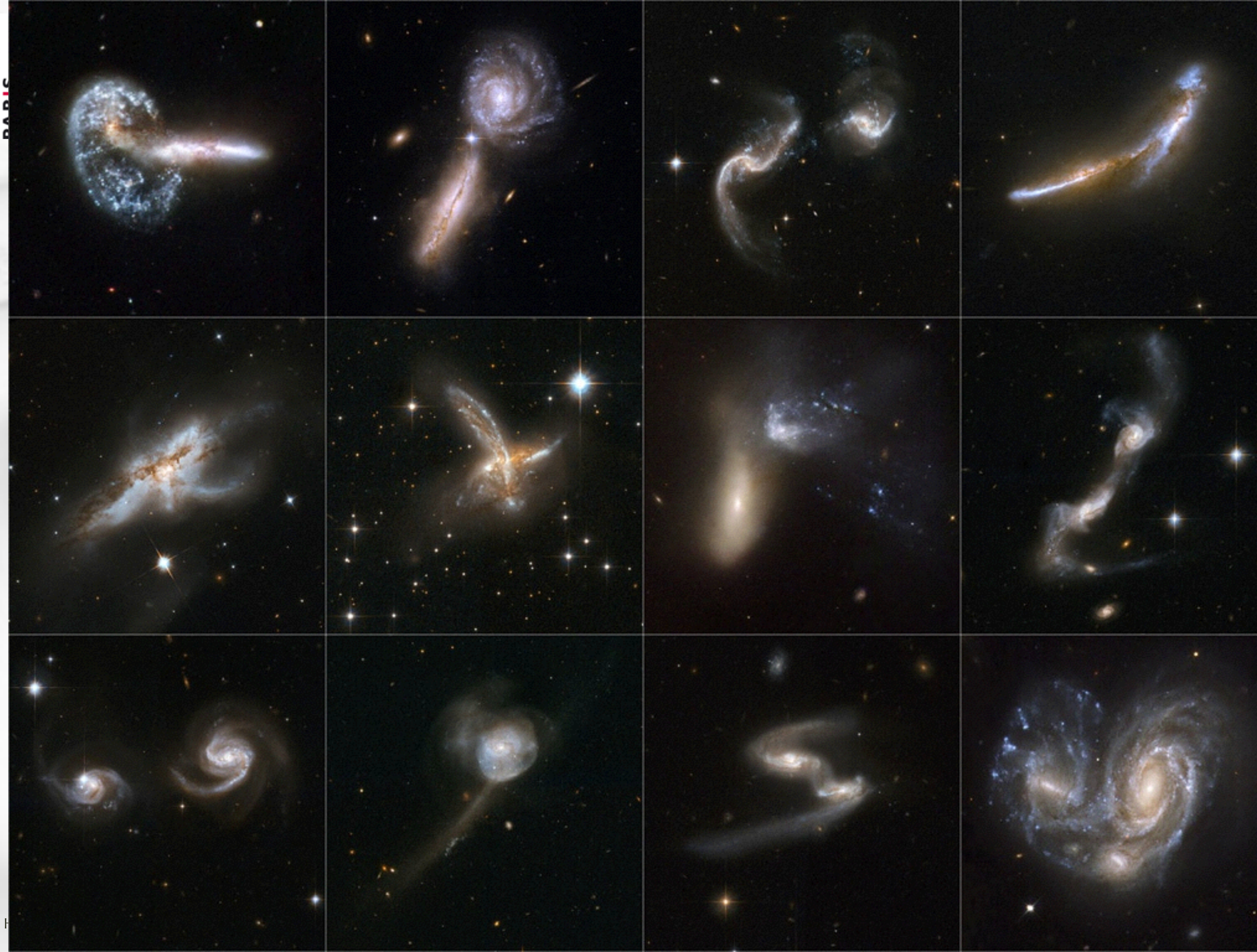


# Massive Black Holes

- Sgr A* :  a dark massive object of $4.5 \times 10^6$ $M_{Sun}$ at the centre of the Milky Way.

- Evidence of SMBH at the center of galaxies and observations of merging galaxies
—> SMBH binaries must exist …

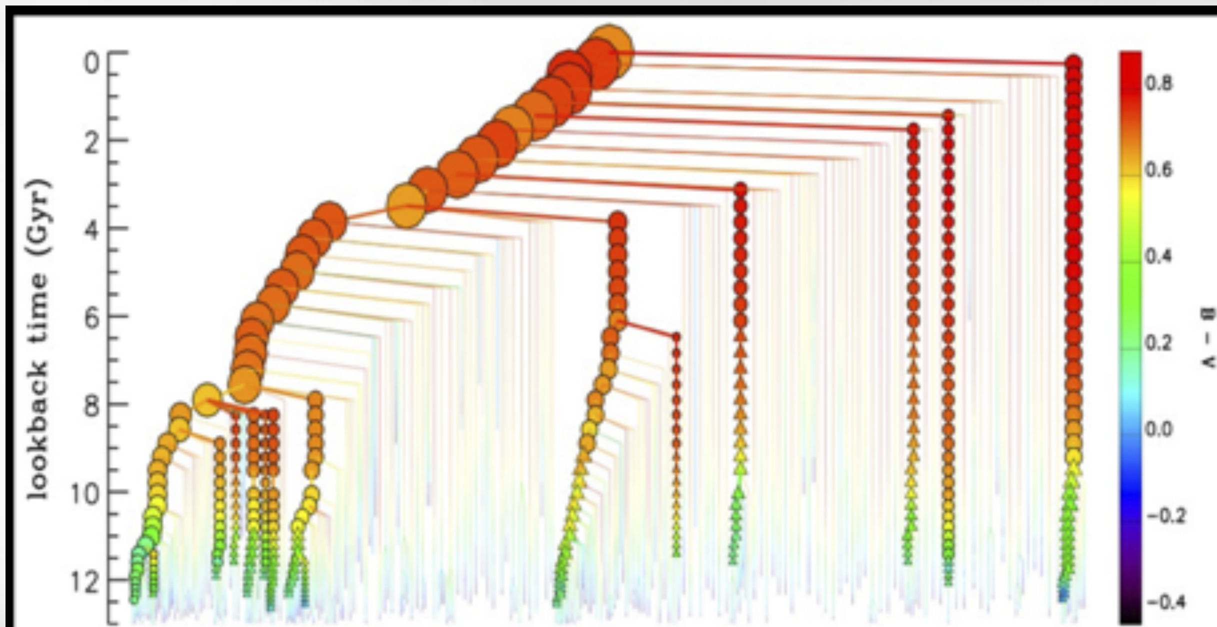
http://www.eso.org/public/f



# Massive Black Holes

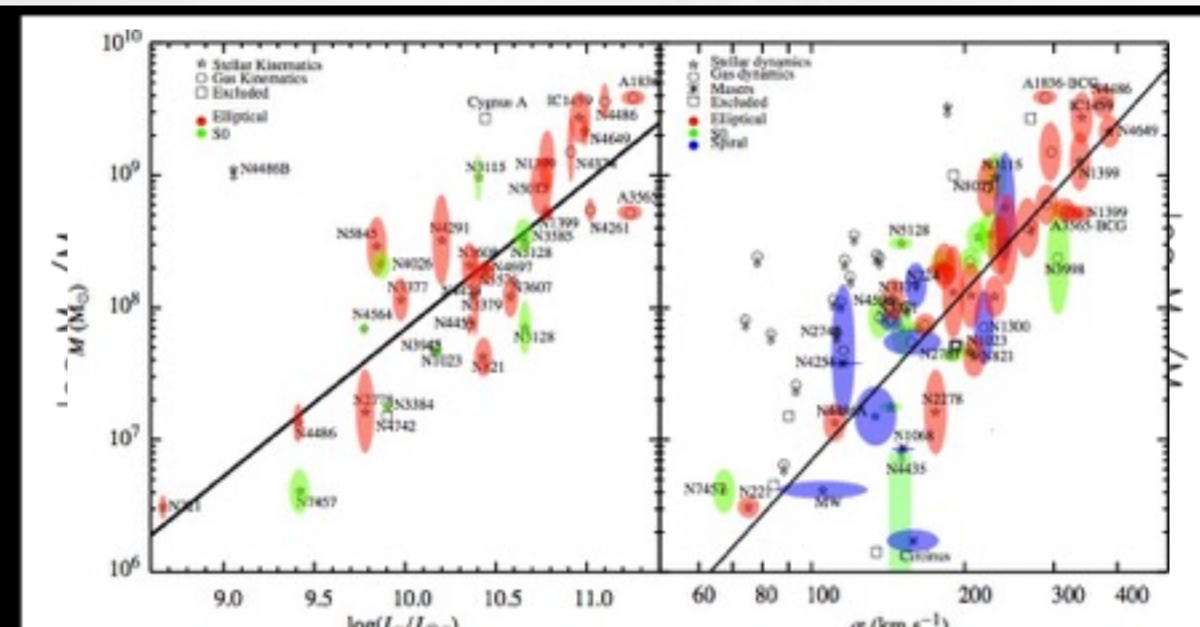
- Several scenarios for the formation of super-massive black holes
- Progenitors ?
  - From light seeds (10-100 $M_{sun}$ Pop III stars) ?
  - From run-away collapse of nuclear star clusters (~1000 $M_{sun}$)?
  - From heavy seeds (~$10^5$ $M_{sun}$ direct collapse) ?
- Growth process ?
  - Accretion : coherent (disc) or chaotic ?
  - Merging with other BH ?

—> Direct GW detection of SMBH will allow to test models against observations




From De Lucia et al 2006

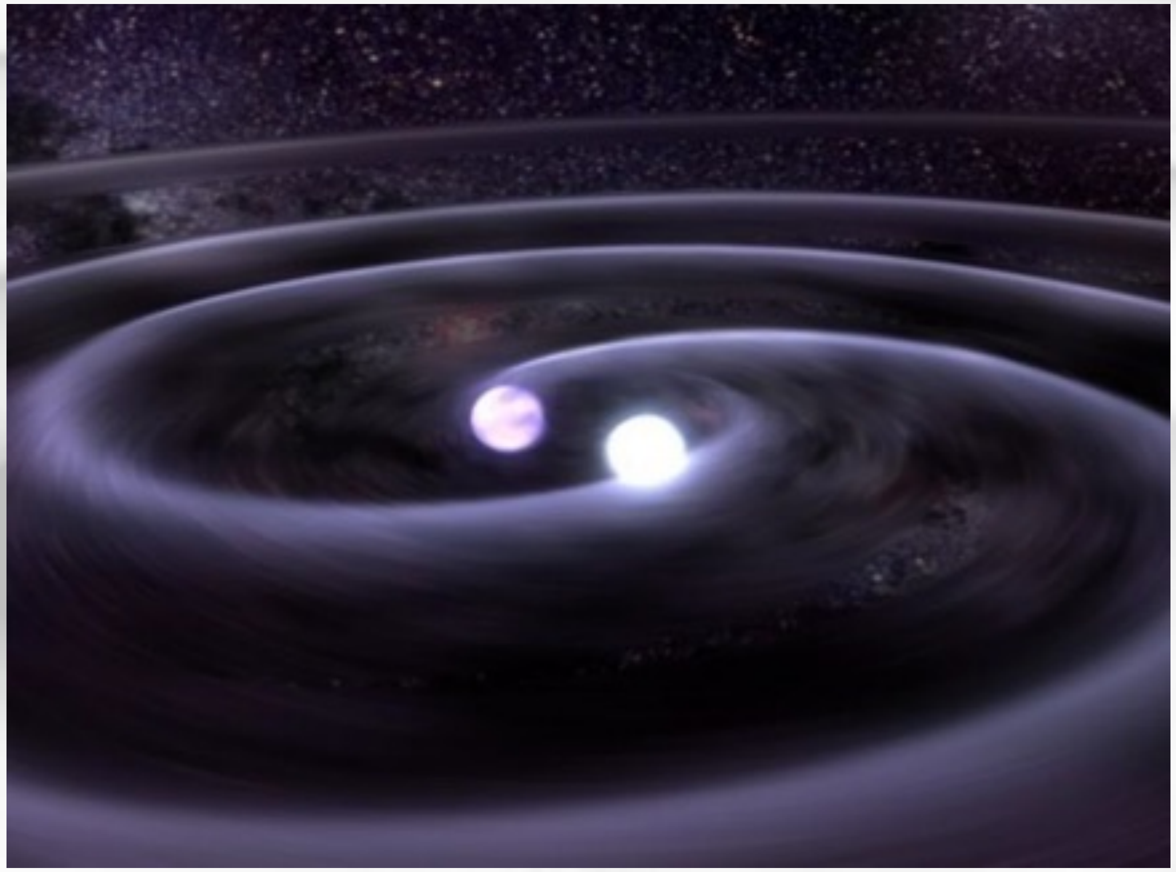
+




Ferrarese & Merritt 2000, Gebhardt et al. 2000

# Compact binaries

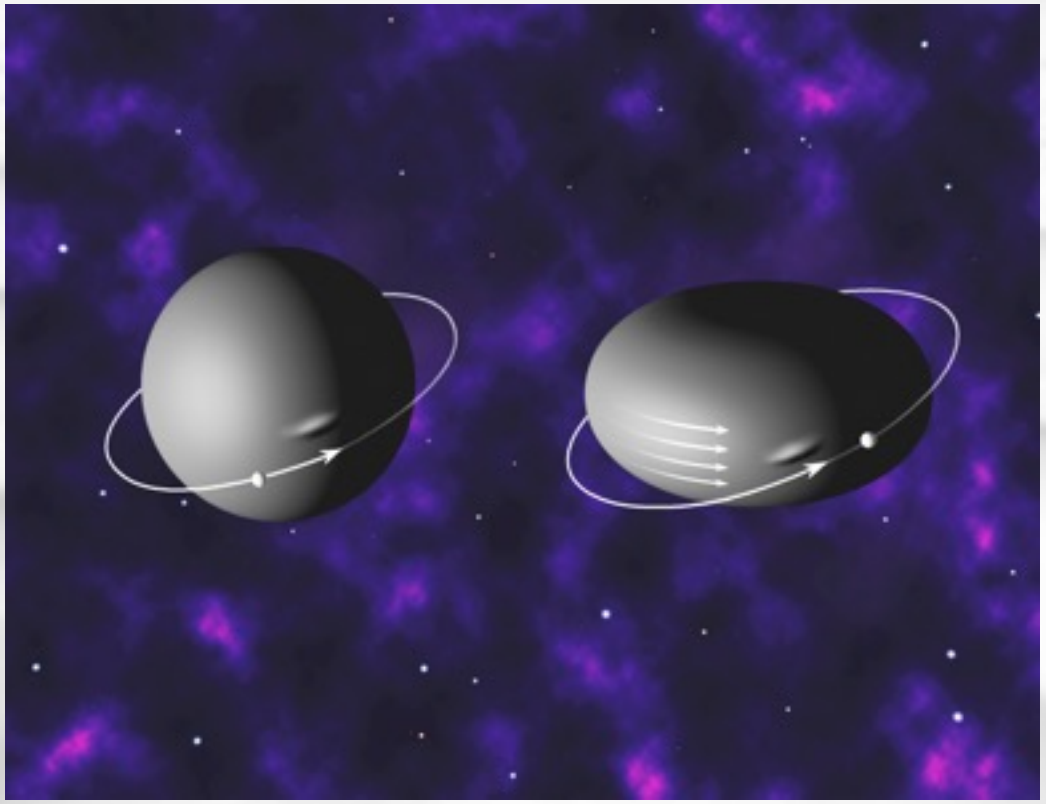
- Large number of stars are in binary systems
- Evolution in white dwarf (WD) and neutron stars (NS).
  - Existence of WD-WD NS-WD and NS-NS binaries
  - Estimated population for the Galaxy : 60 millions.

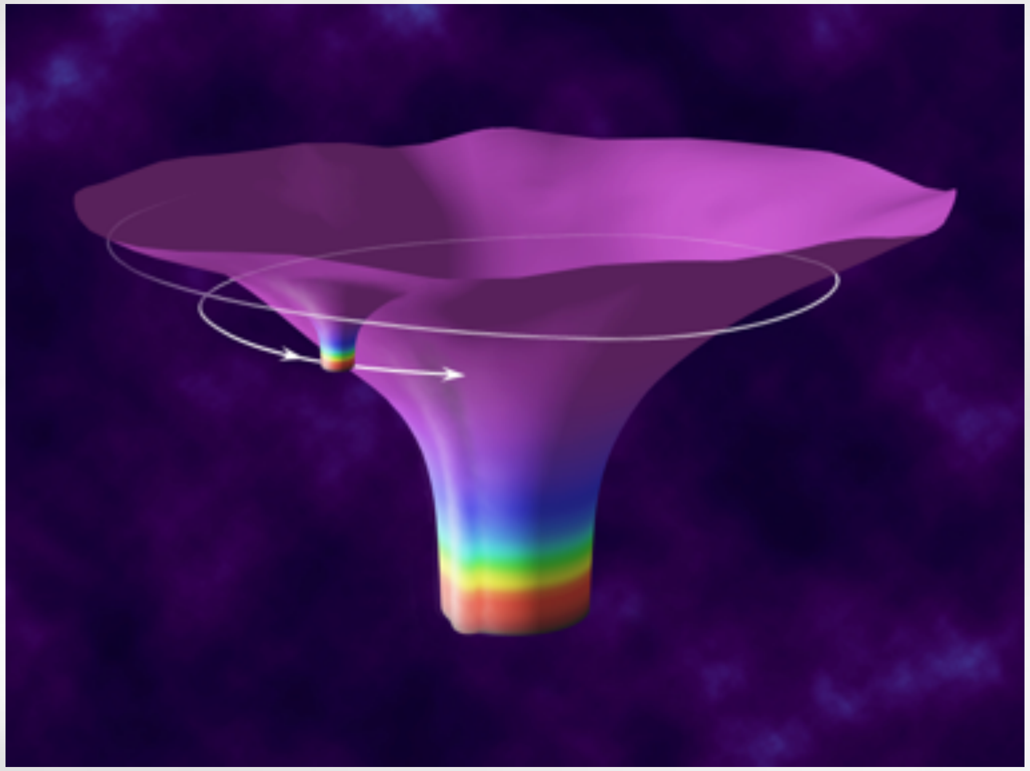


- Gravitational waves :
  - mostly in the slow inspiral regime (quasi monochromatic) : GW at mHz
  - few are coalescing : GW event of few seconds at frequencies > 10 Hz

# EMRIs

- Extreme mass-ratio inspirals
- Capture of a "small" object by a massive black hole (100 – $10^6$ $M_{sun}$)
  - Mass ratio > 200
  - Gravitational waves give information on the geometry around the black hole.
  - Test of General Relativity in strong field
  - Frequency : 0.1 mHz to 1 Hz
  - Large number of sources could be observed by space-based interferometer

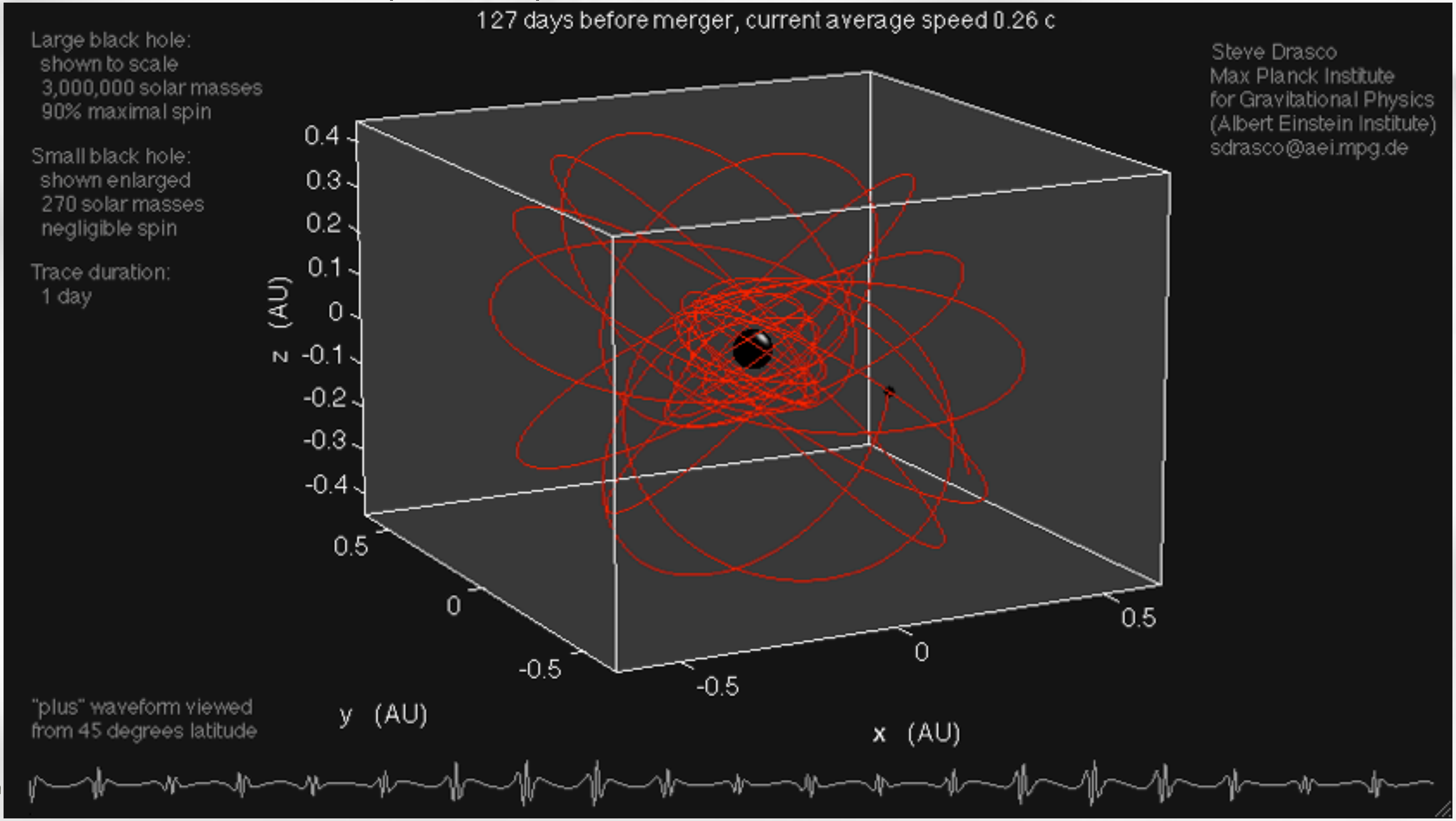




# EMRIs

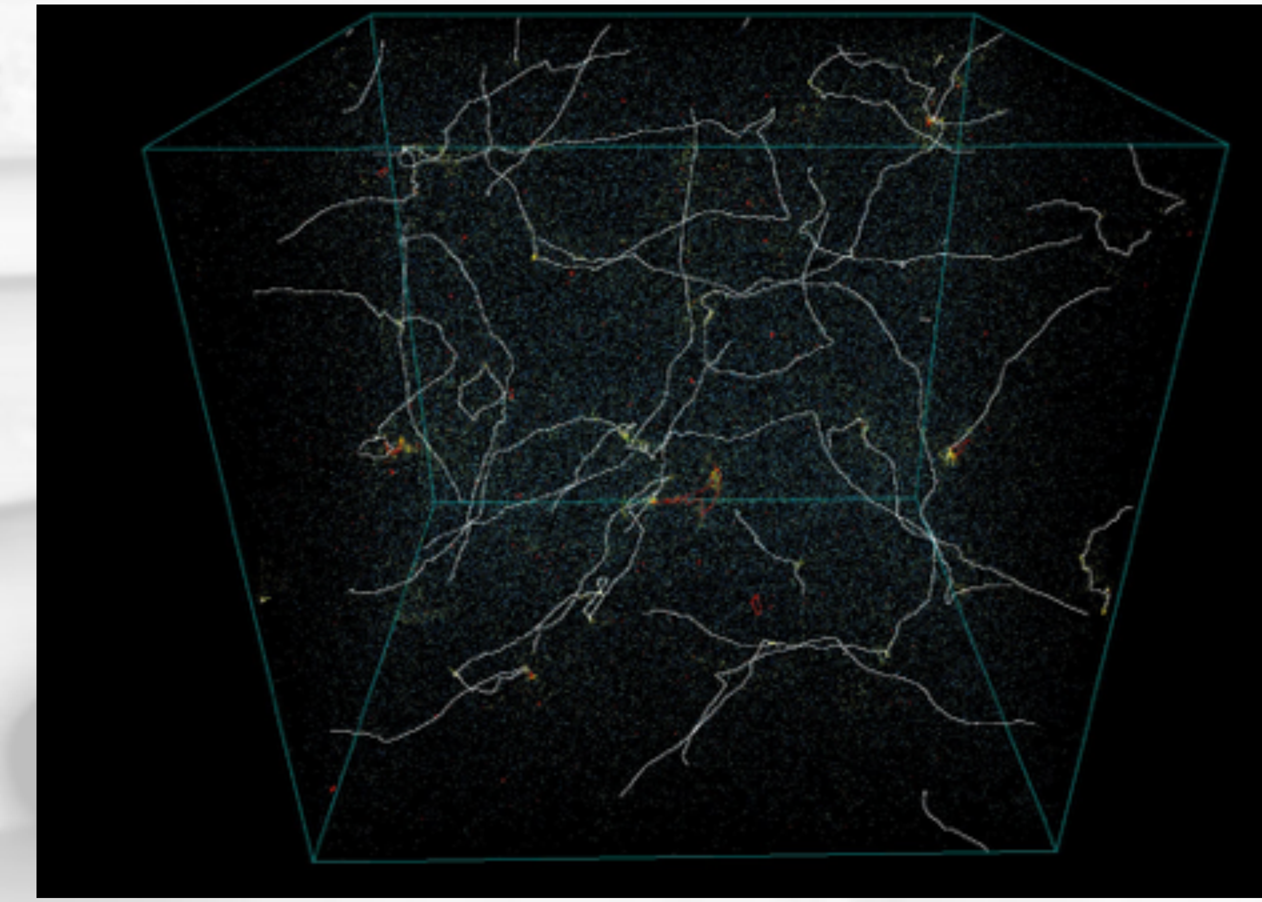
- Strong (!) relativistic effects !
  - Complex trajectory of the companion and gravitational waves signal.
  - Models are still inaccurate : requires more simulations efforts

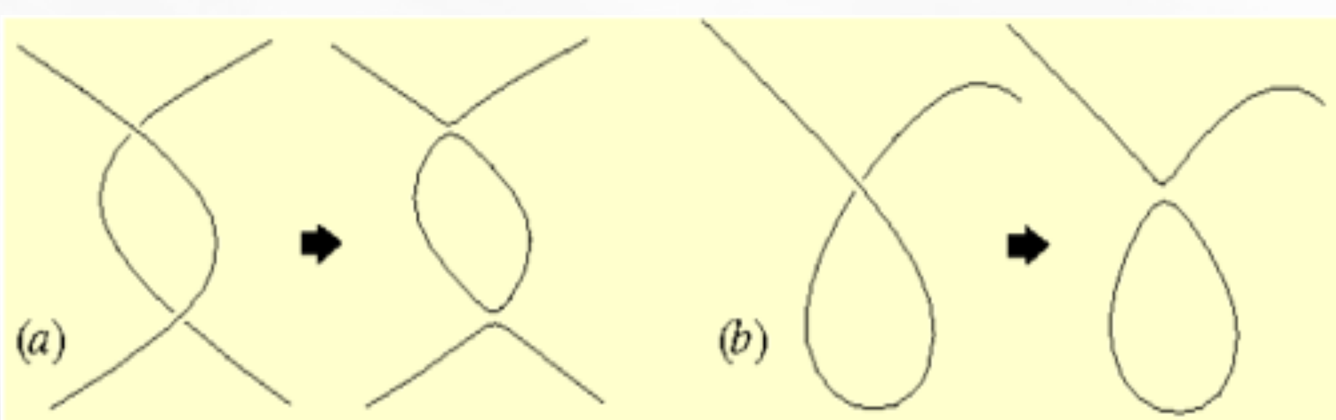
http://www.tapir.caltech.edu/~sdrasco/animations/

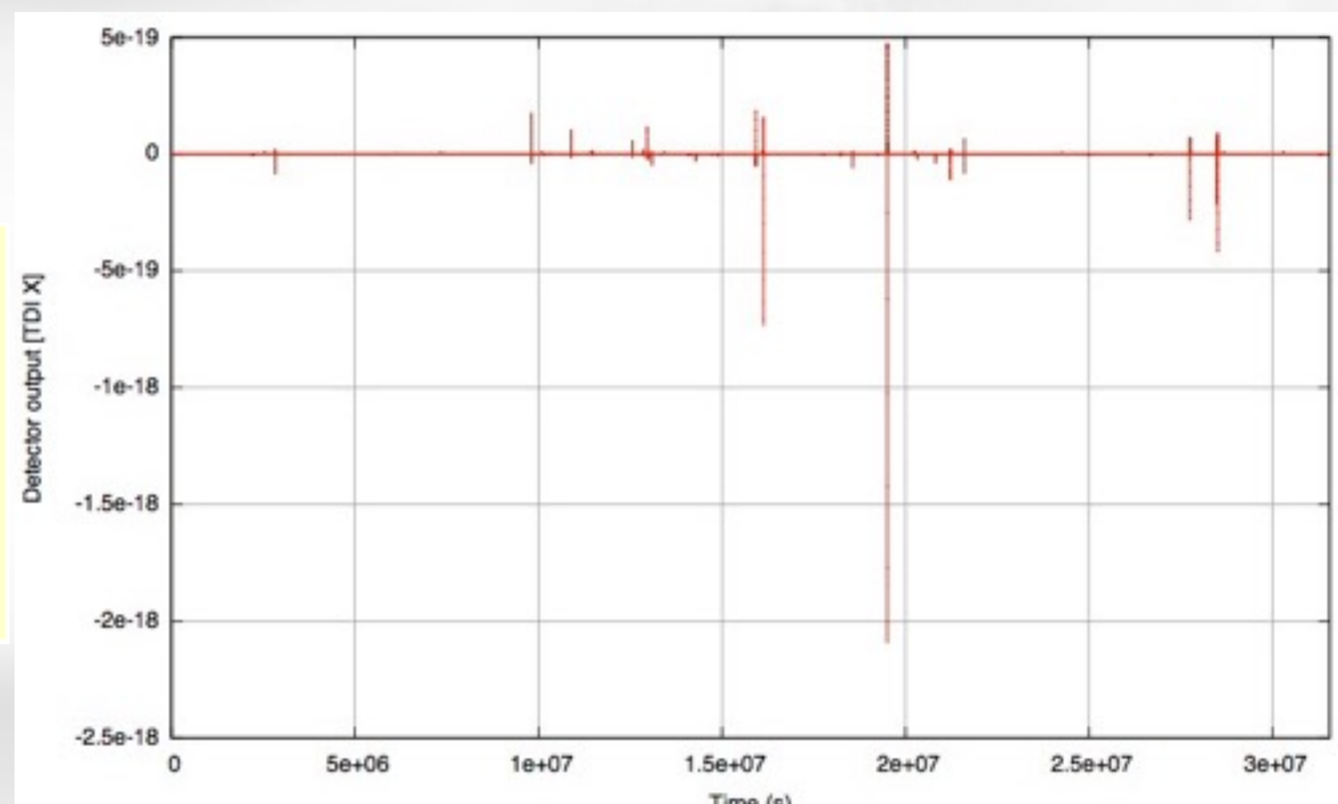


# Cosmic strings

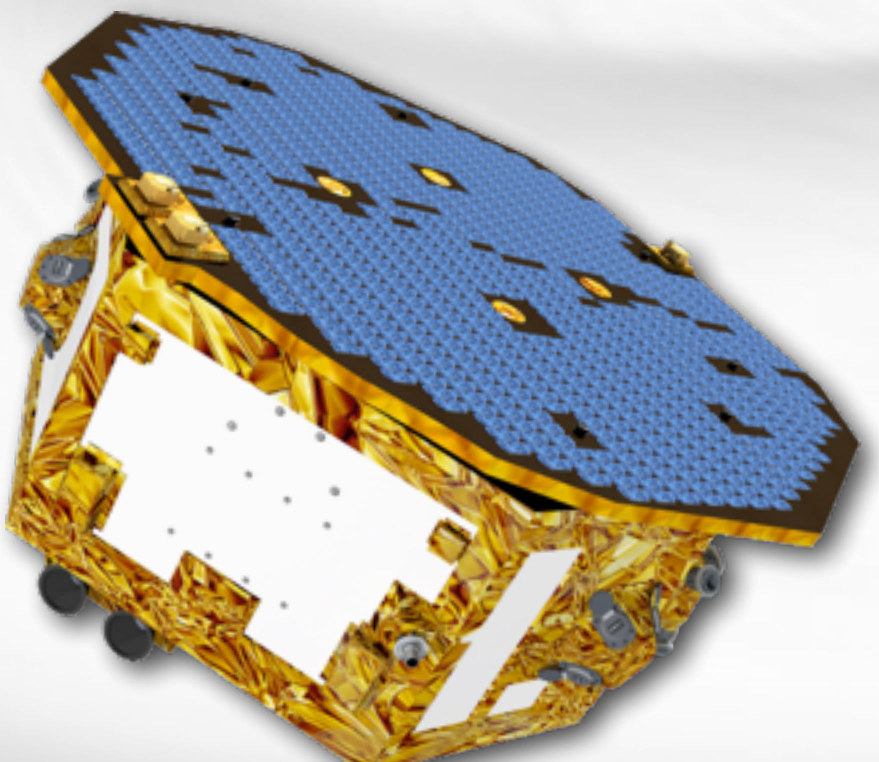
- String : topological defect that appears during phase transition in the Early Universe.
  - 1D : diameter of a proton x size of observable Universe
- Reconnection of string ==> loops
  - Loops loose energy by GW emission : mainly with 2 types of bursts events : cusps (one point of the loop reaches the speed of light) and kinks





# Ground based detectors
# (in brief …)



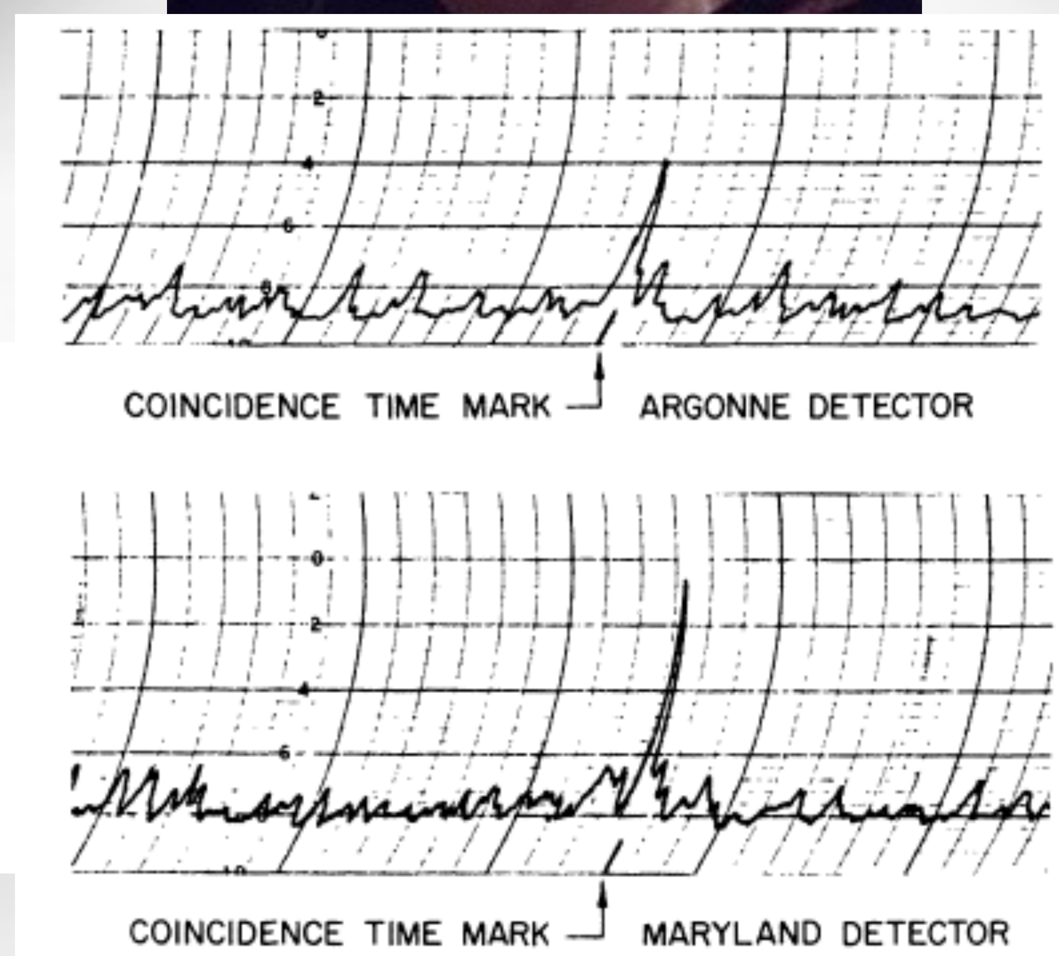
# First attempts

- Weber experiments
  - First attempts in the 1960's
  - Based on the resonance of a bar.
  - First detection published in 1969 at 1660 Hz
  - Followed by many other attempts... but no other detection ...
  - The sensitivity of Weber bar is estimated to ~$10^{-16}$ (0.1 µm/Mkm) :
    - such strong event would have led to the 'evaporation' of the Universe through GW in ~1 million years ...

**EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION***

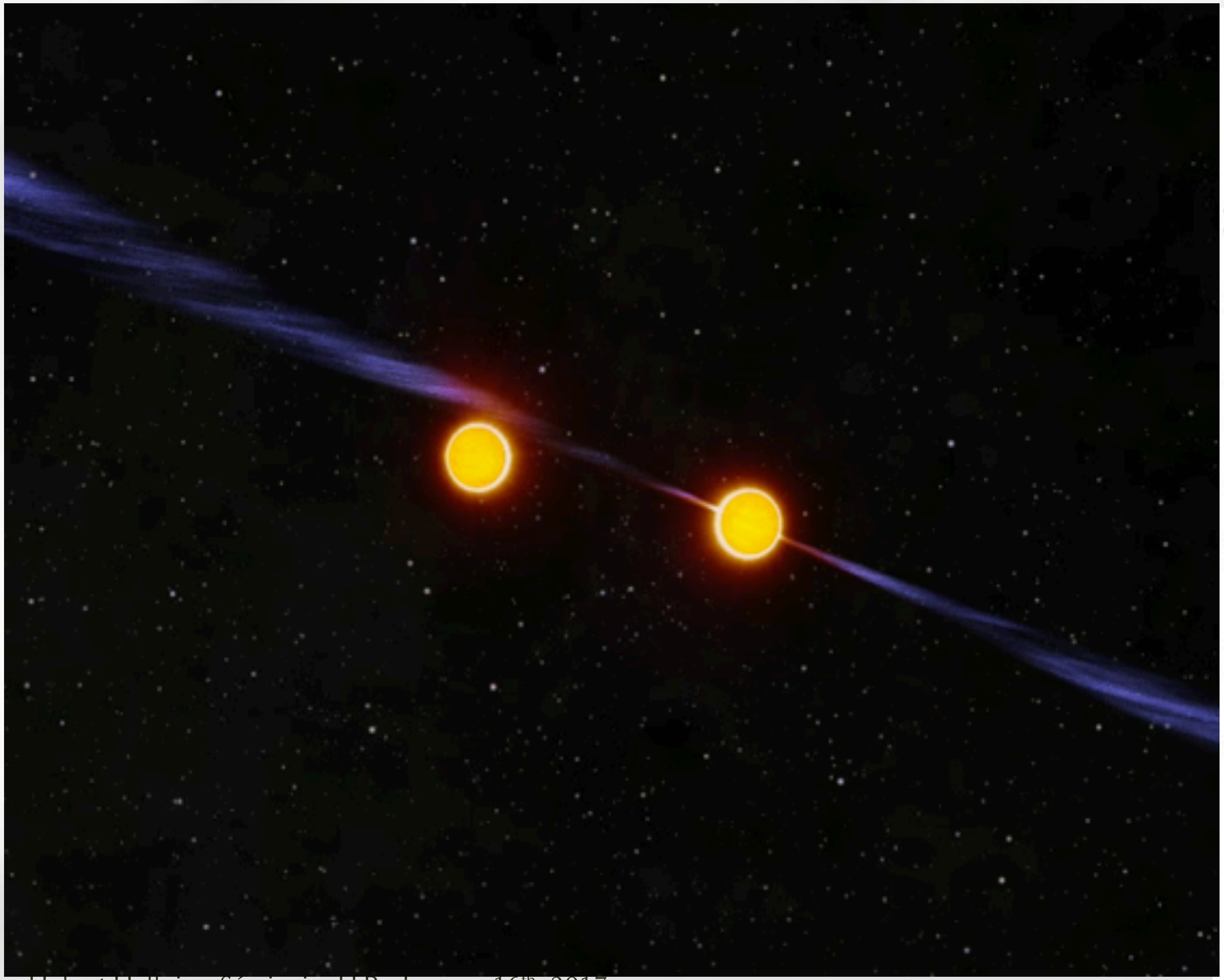
J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

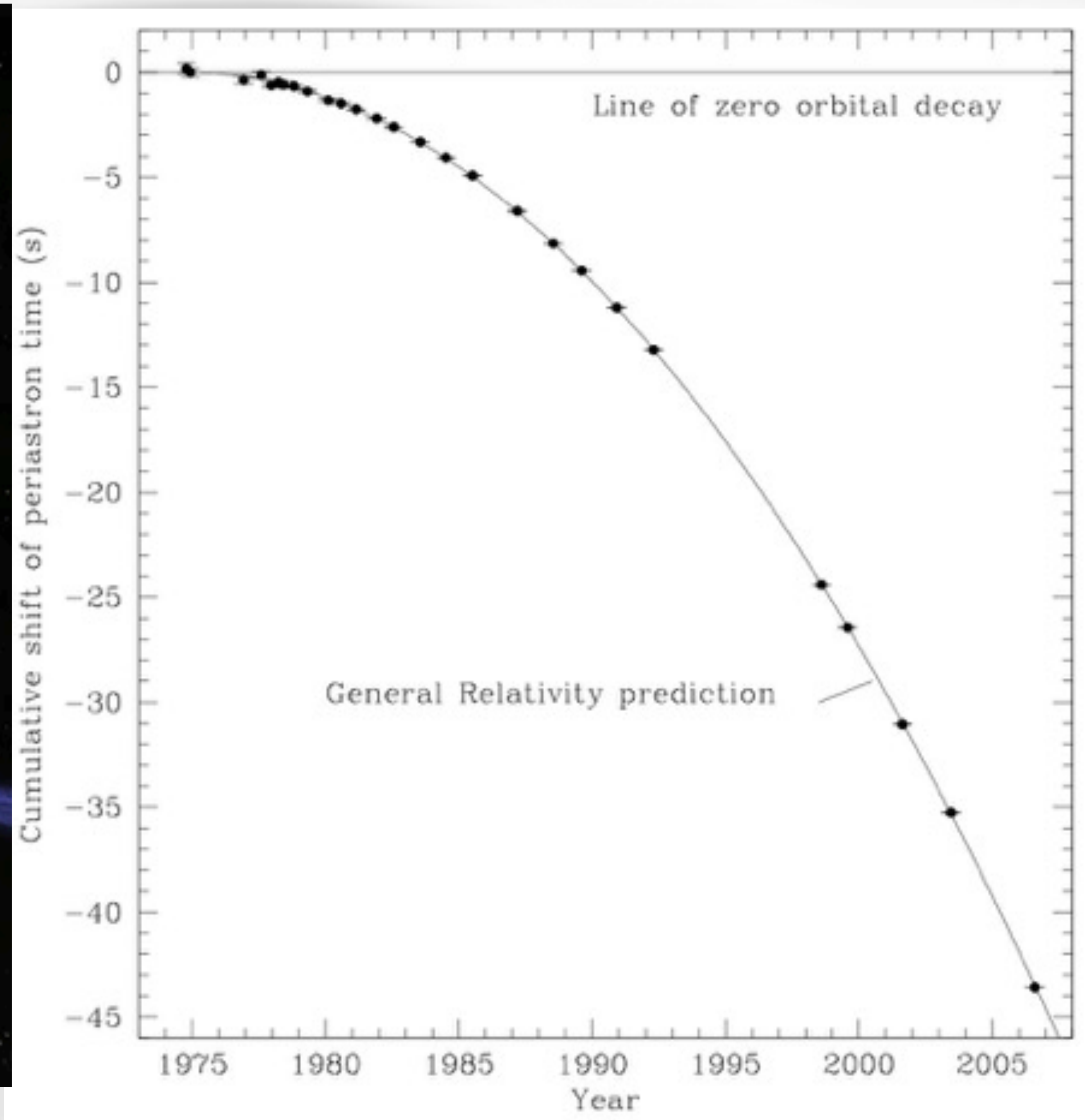
Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.



# The smoking gun …

- (indirect) detection of GW by Hulse & Taylor
- The orbital precession of the binary pulsar PSR1913+16 is perfectly predicted by the energy loss through emission of GW





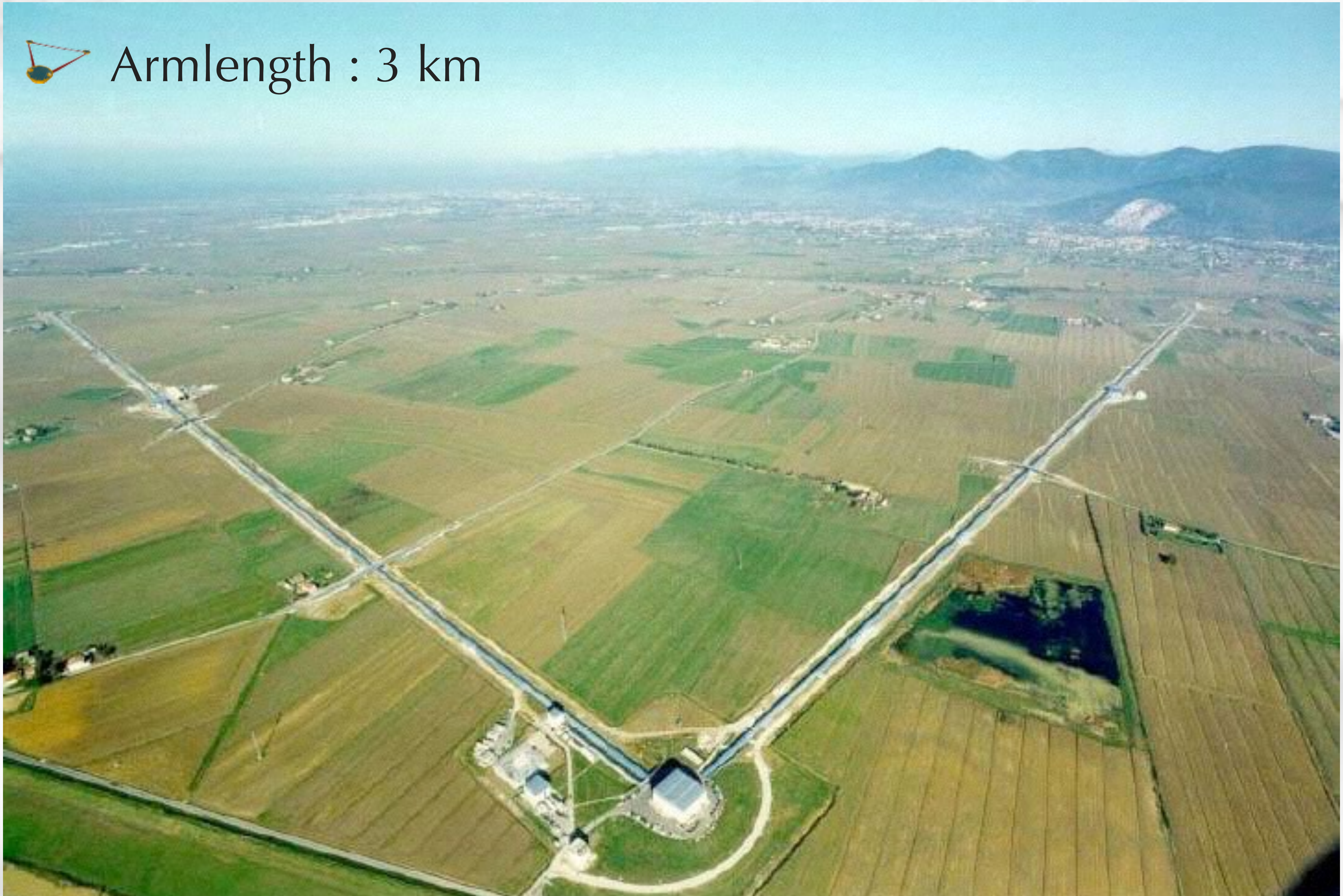
# Giant interferometers

- LIGO : 2 sites in the US
- Armlength : 4 km

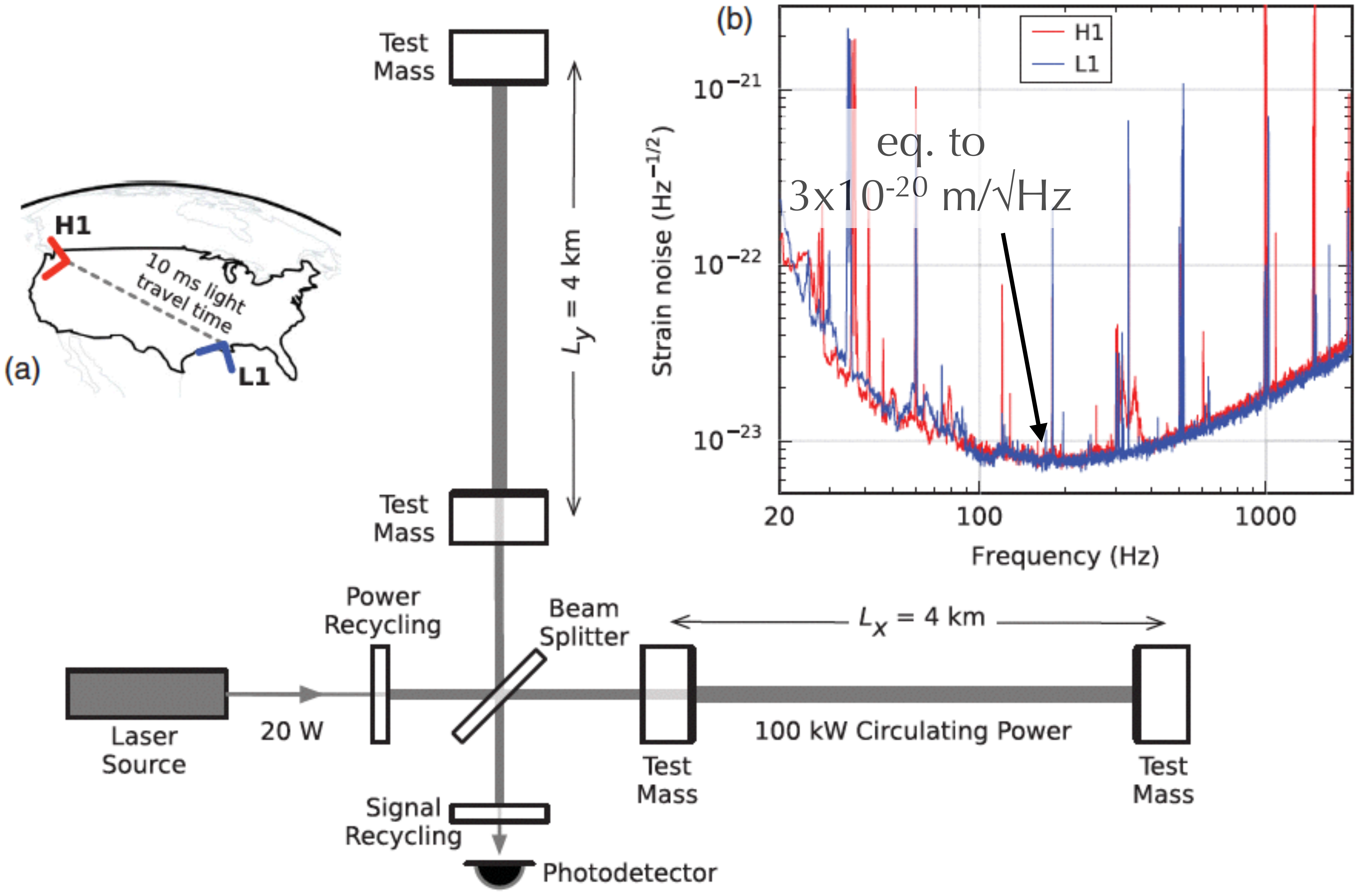
Livingston, Louisiana

Hanford, Washington

# VIRGO

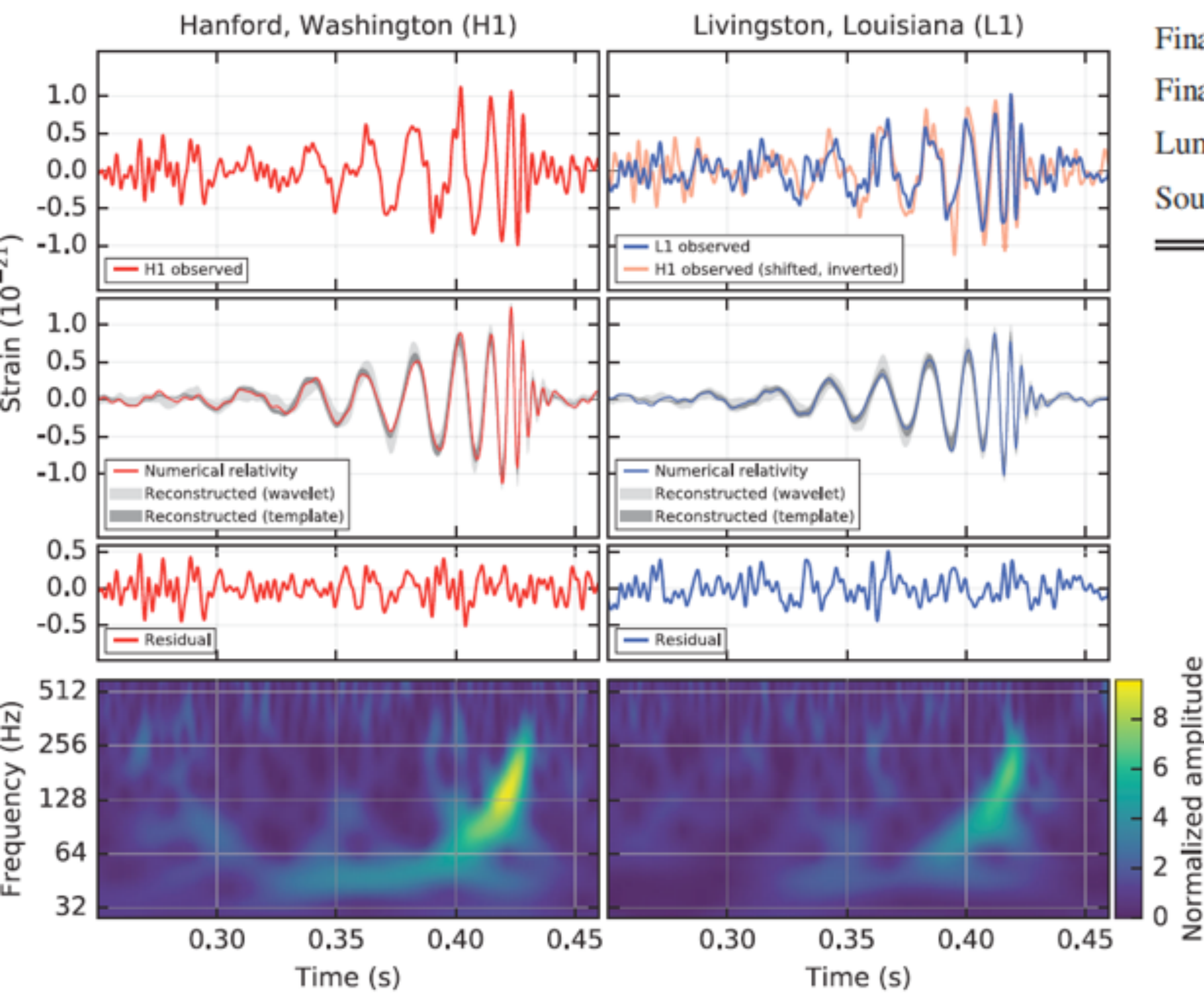


# Adv. LIGO sensitivity

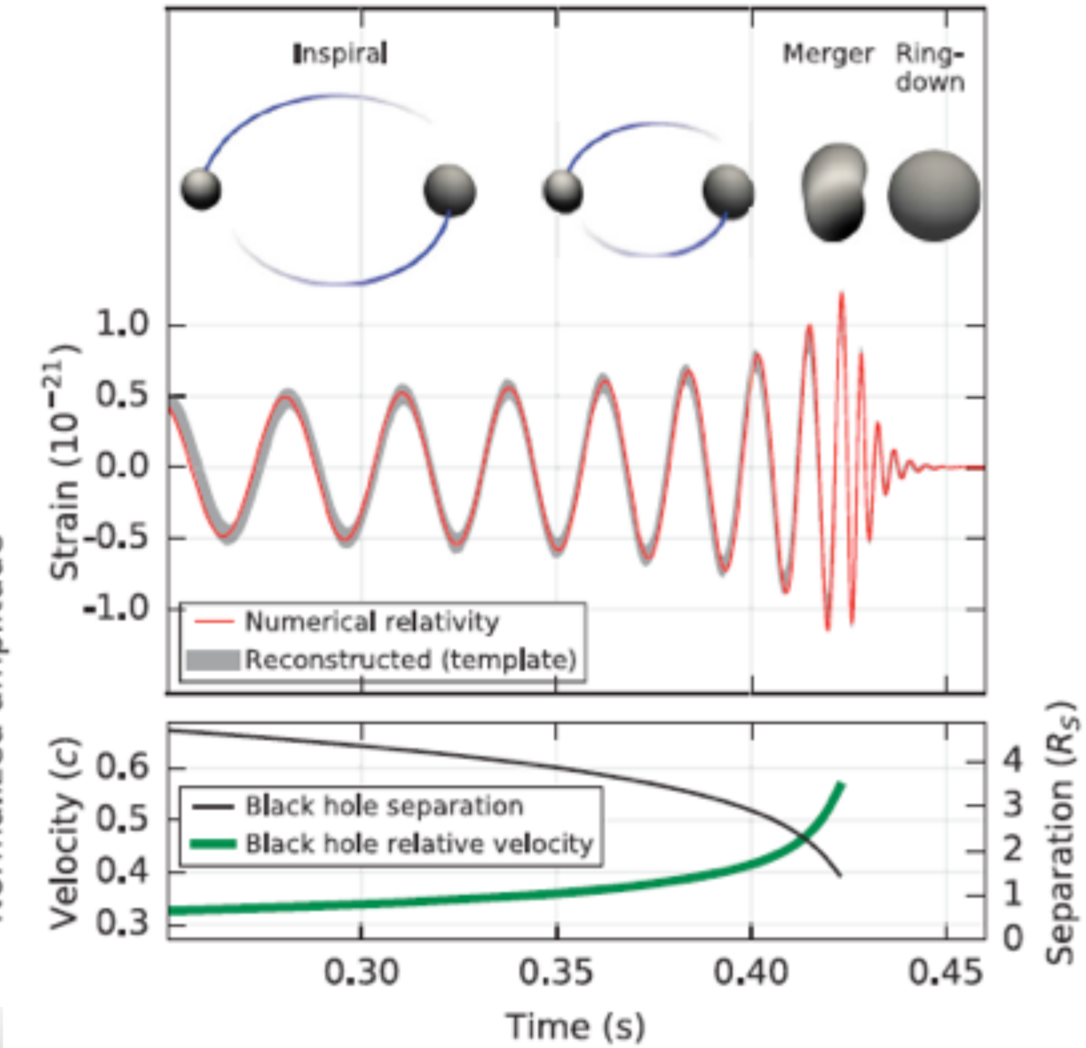


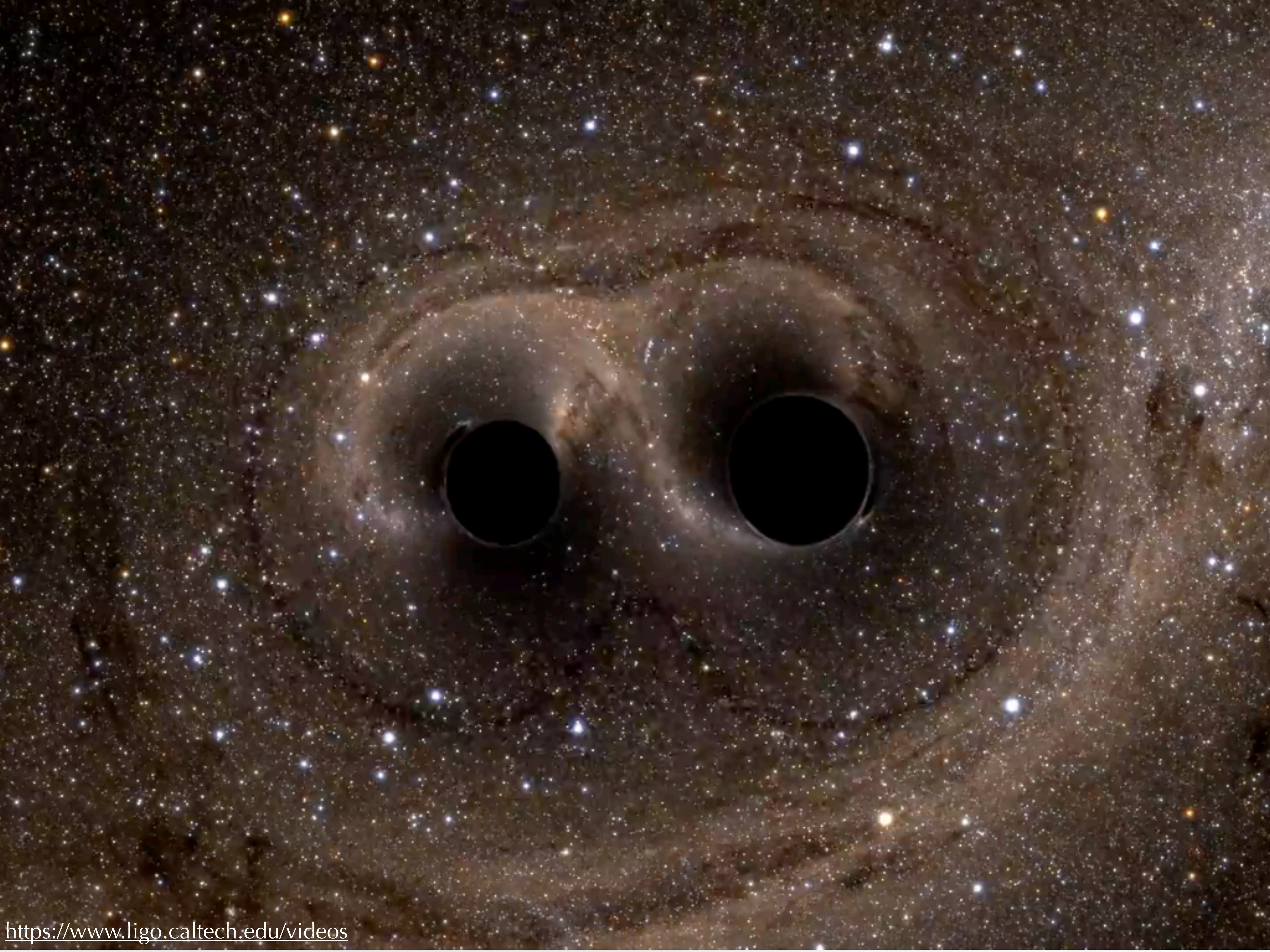
# … and on September 14th, 2015 …

## GW150914




| | |
|---|---|
| Primary black hole mass | $36^{+5}_{-4} M_\odot$ |
| Secondary black hole mass | $29^{+4}_{-4} M_\odot$ |
| Final black hole mass | $62^{+4}_{-4} M_\odot$ |
| Final black hole spin | $0.67^{+0.05}_{-0.07}$ |
| Luminosity distance | $410^{+160}_{-180}$ Mpc |
| Source redshift $z$ | $0.09^{+0.03}_{-0.04}$ |

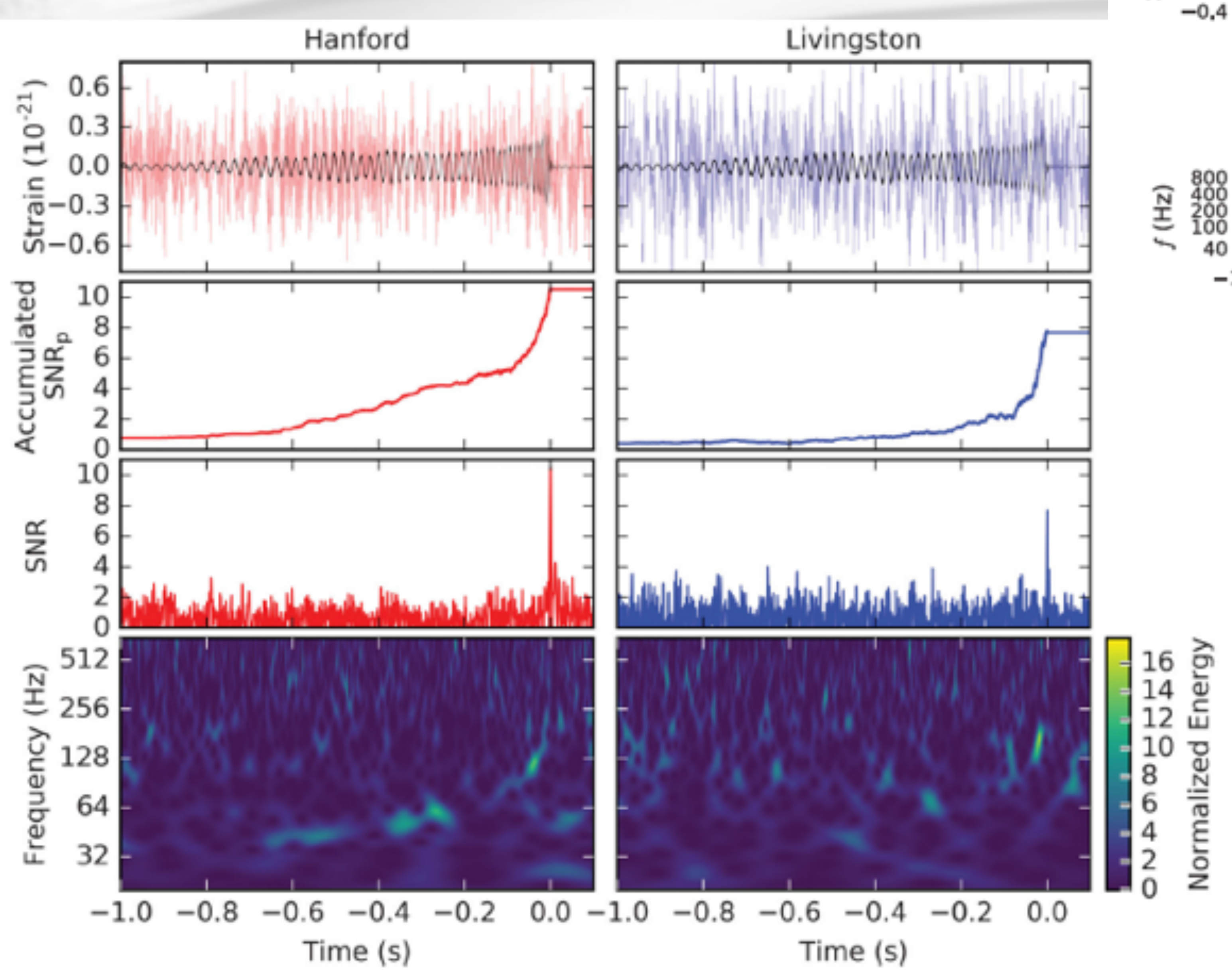


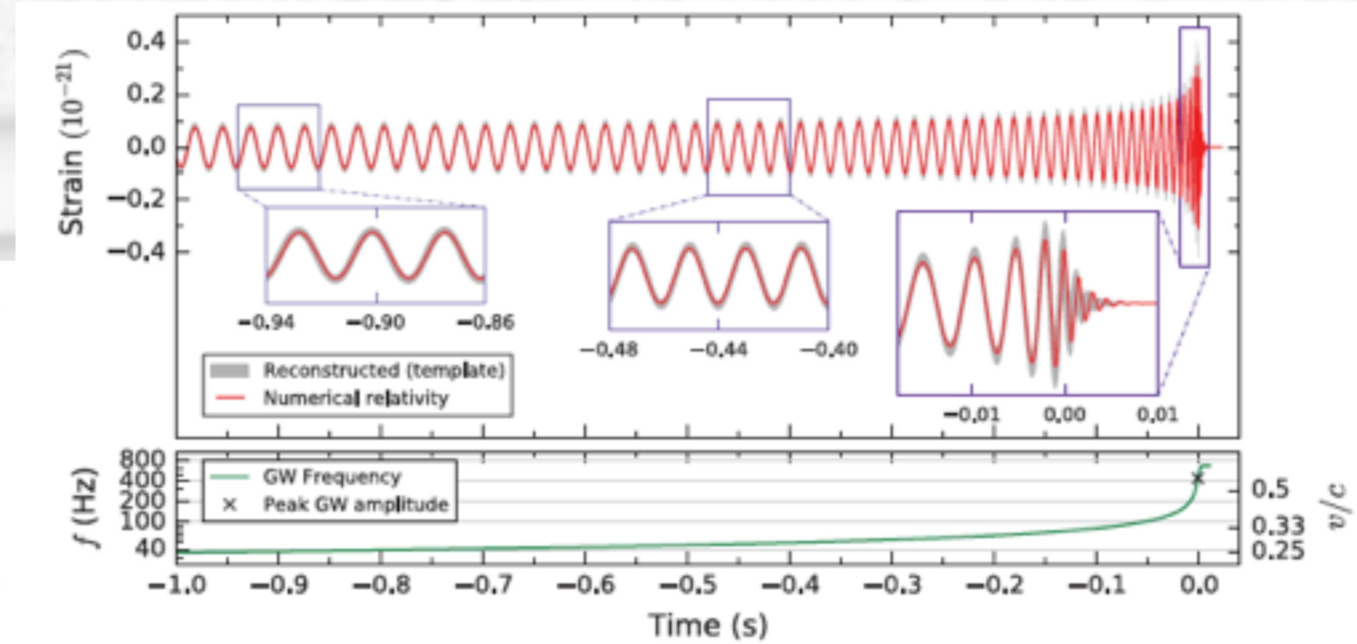


https://www.ligo.caltech.edu/videos

# … and on December 26th, 2015 …

## GW151226

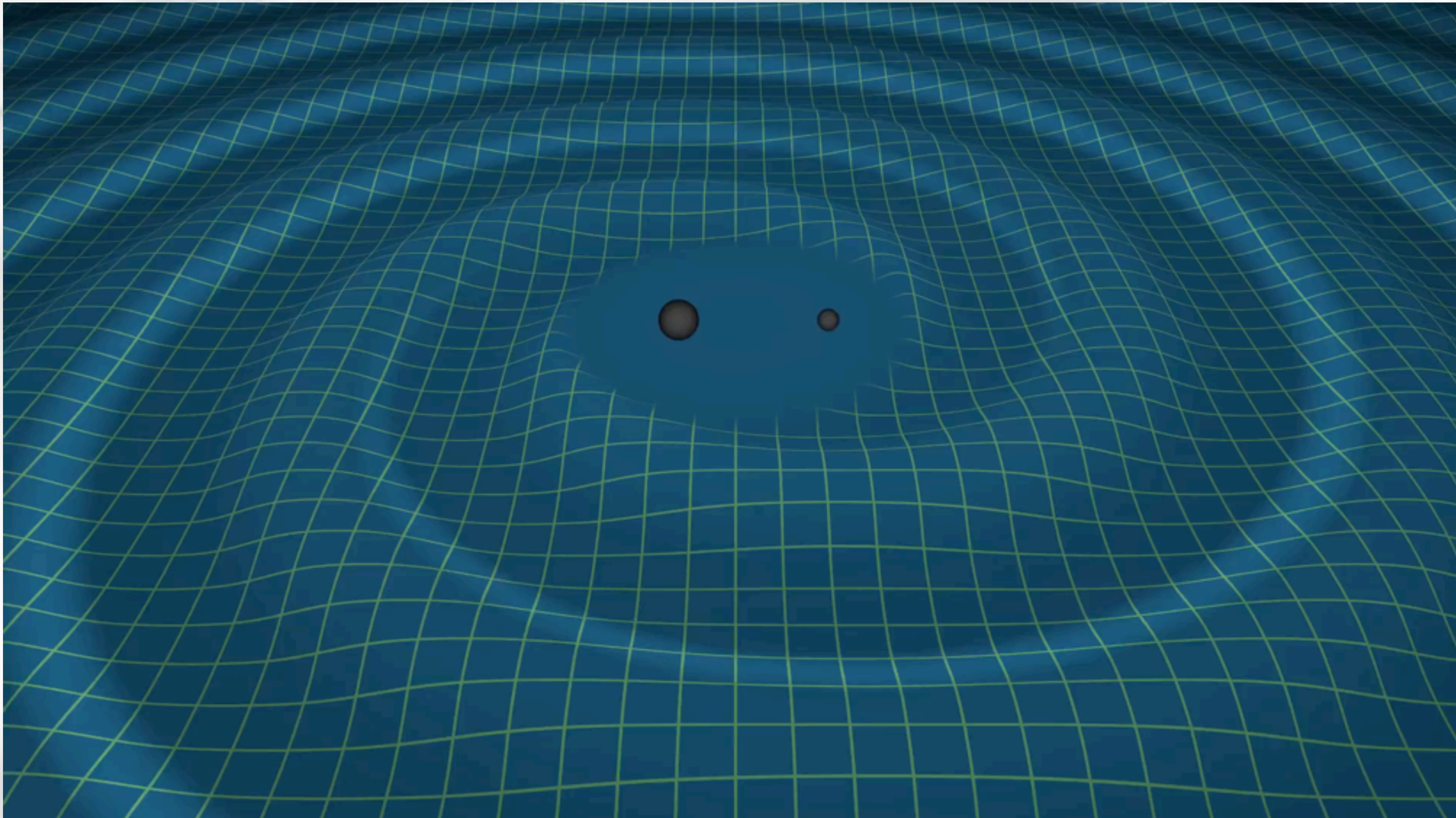


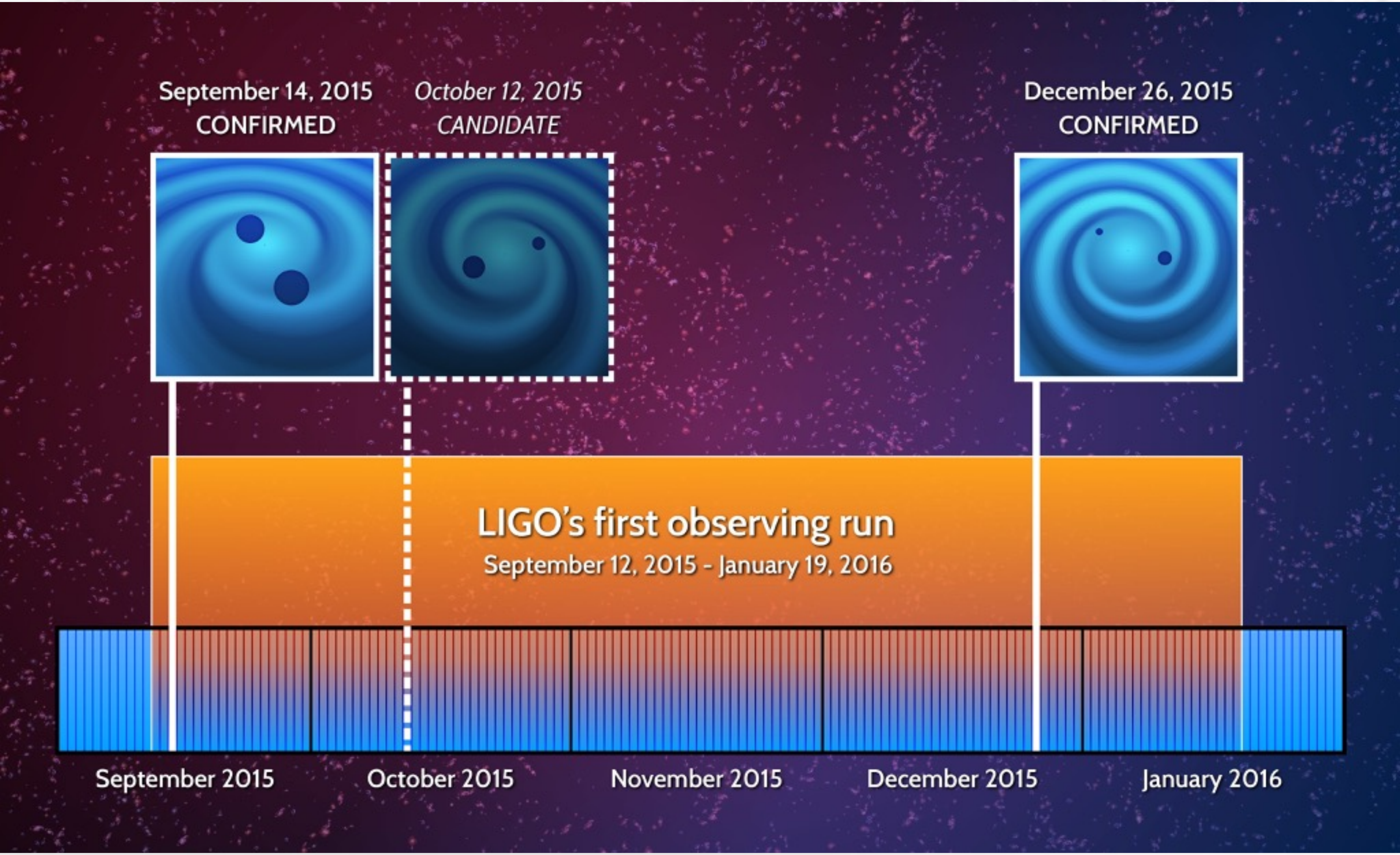

| | |
|---|---|
| Primary black hole mass | $14.2^{+8.3}_{-3.7} M_\odot$ |
| Secondary black hole mass | $7.5^{+2.3}_{-2.3} M_\odot$ |
| Chirp mass | $8.9^{+0.3}_{-0.3} M_\odot$ |
| Total black hole mass | $21.8^{+5.9}_{-1.7} M_\odot$ |
| Final black hole mass | $20.8^{+6.1}_{-1.7} M_\odot$ |
| Radiated gravitational-wave energy | $1.0^{+0.1}_{-0.2} M_\odot c^2$ |
| Peak luminosity | $3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s |
| Final black hole spin | $0.74^{+0.06}_{-0.06}$ |
| Luminosity distance | $440^{+180}_{-190}$ Mpc |
| Source redshift $z$ | $0.09^{+0.03}_{-0.04}$ |

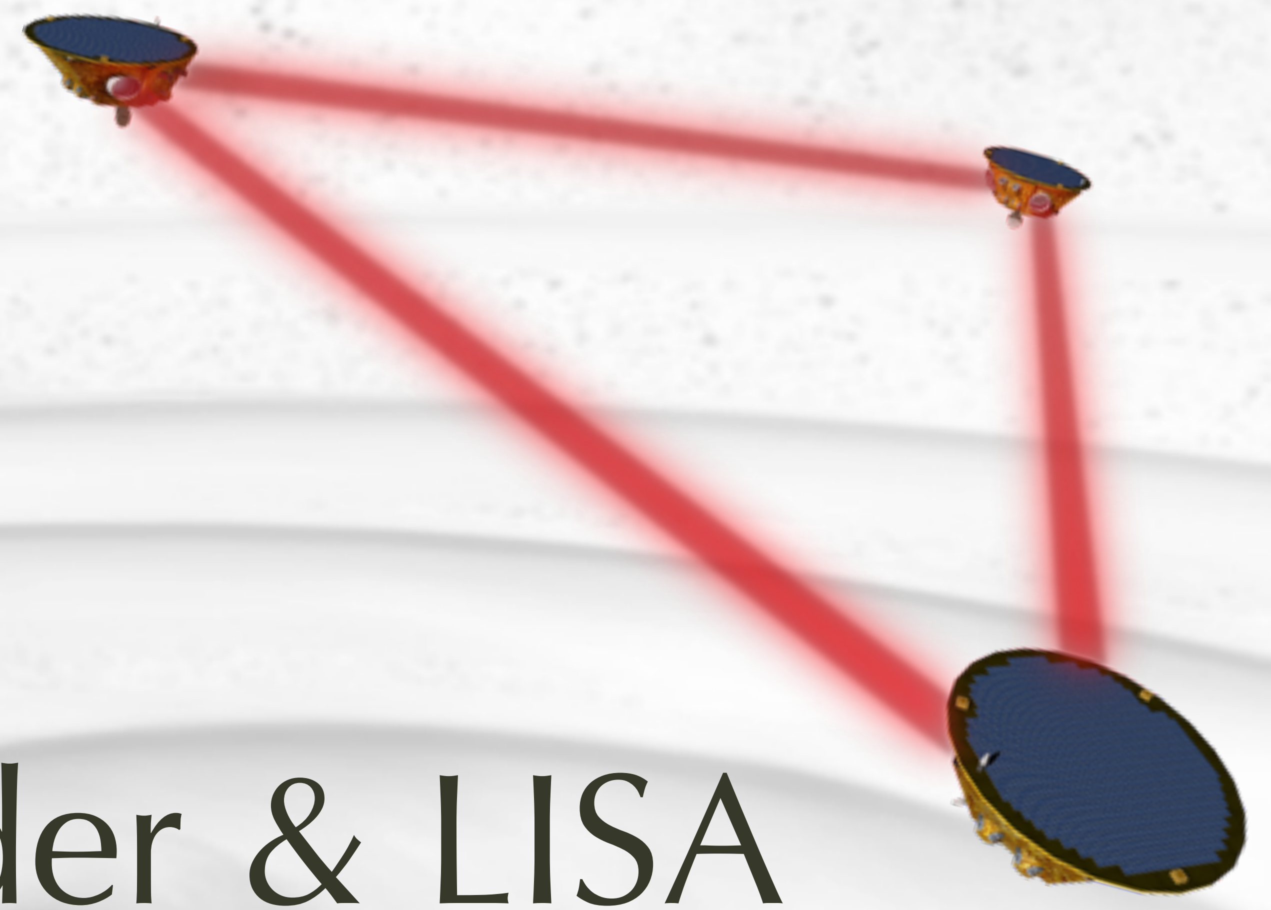
# … and on December 26th, 2015 …

## GW151226

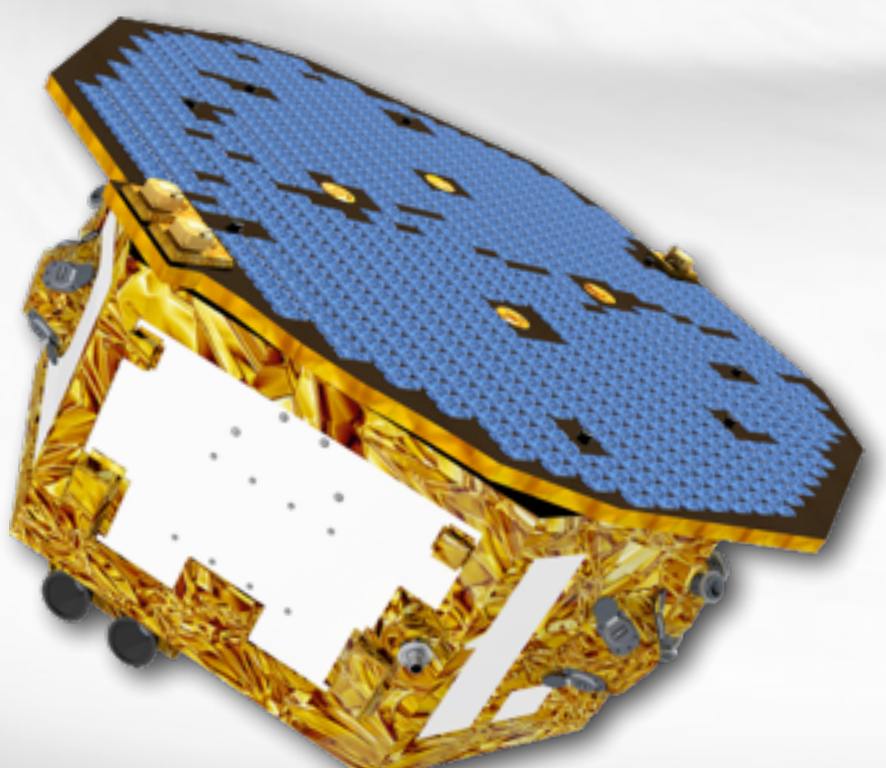


# The start of GW astronomy…



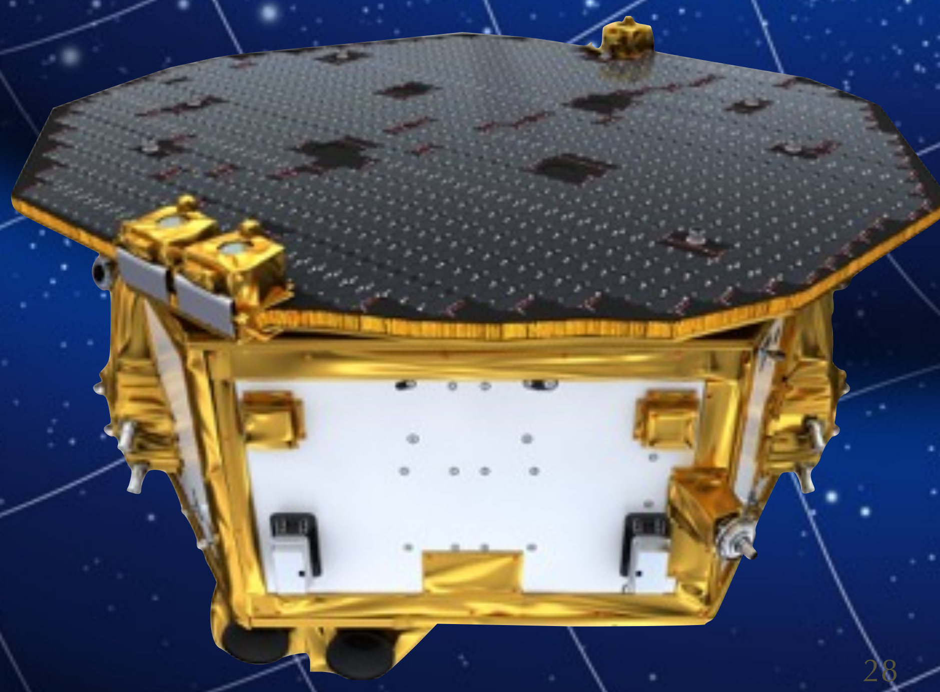


# LISA Pathfinder & LISA



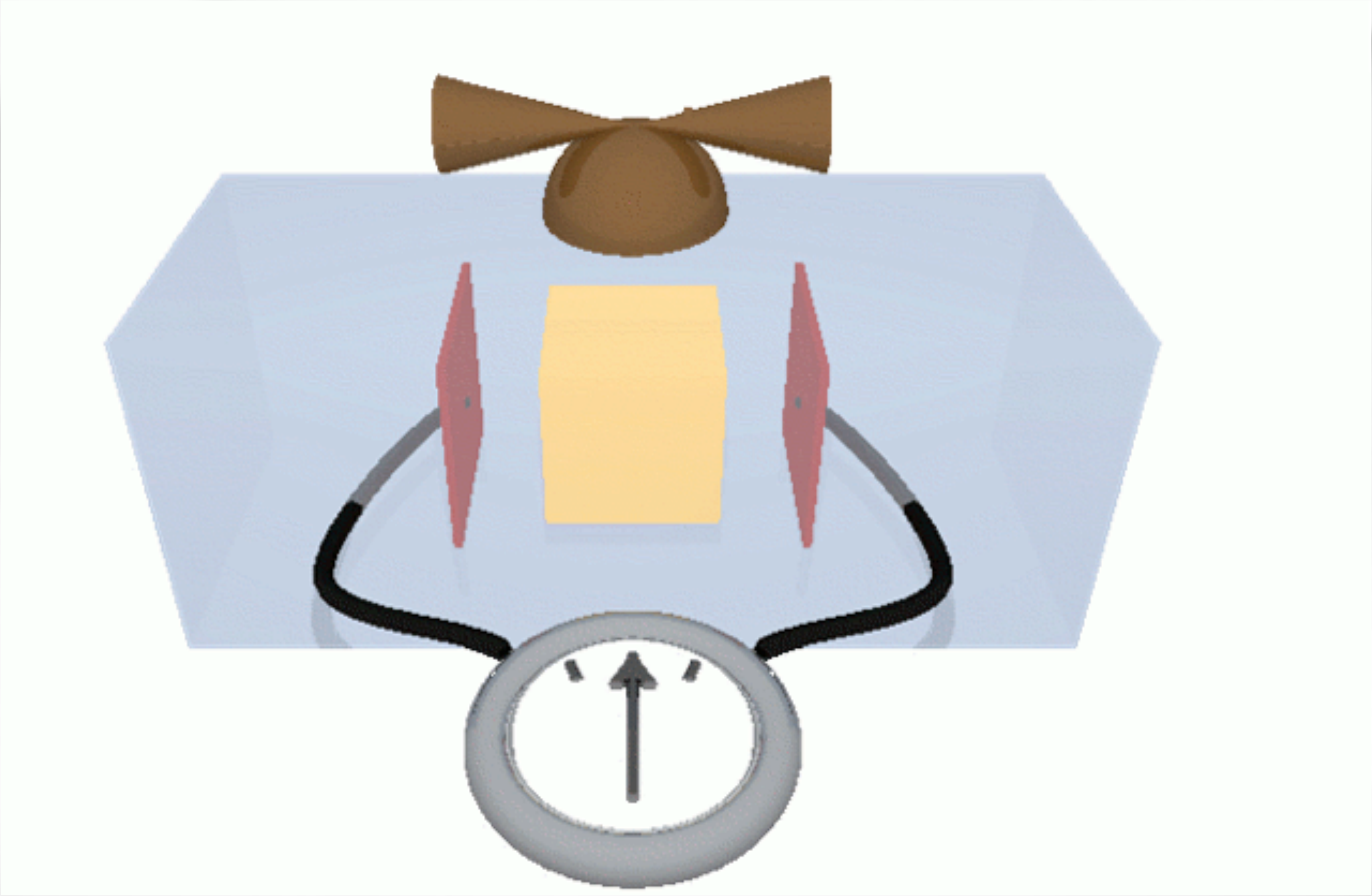
- LISA = Laser Interferometer Space Antenna
  - Space-borne, million-km arms, interferometer between free-floating test masses
  - No seismic disturbances
  - Long armlength : low GW frequencies (≈1mHz - 1 Hz), "high" antenna response

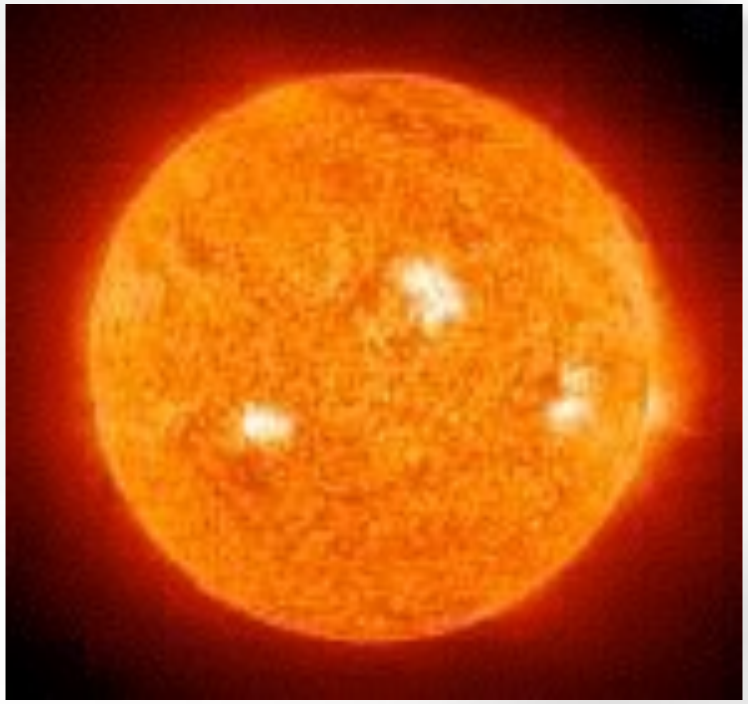
- LISA Pathfinder = technology demonstrator for LISA
  - Launched in December 2015



# Drag-free flying ?

- Test masses must be protected from external perturbations (mainly solar wind)
- Technology demonstrator : LISA Pathfinder



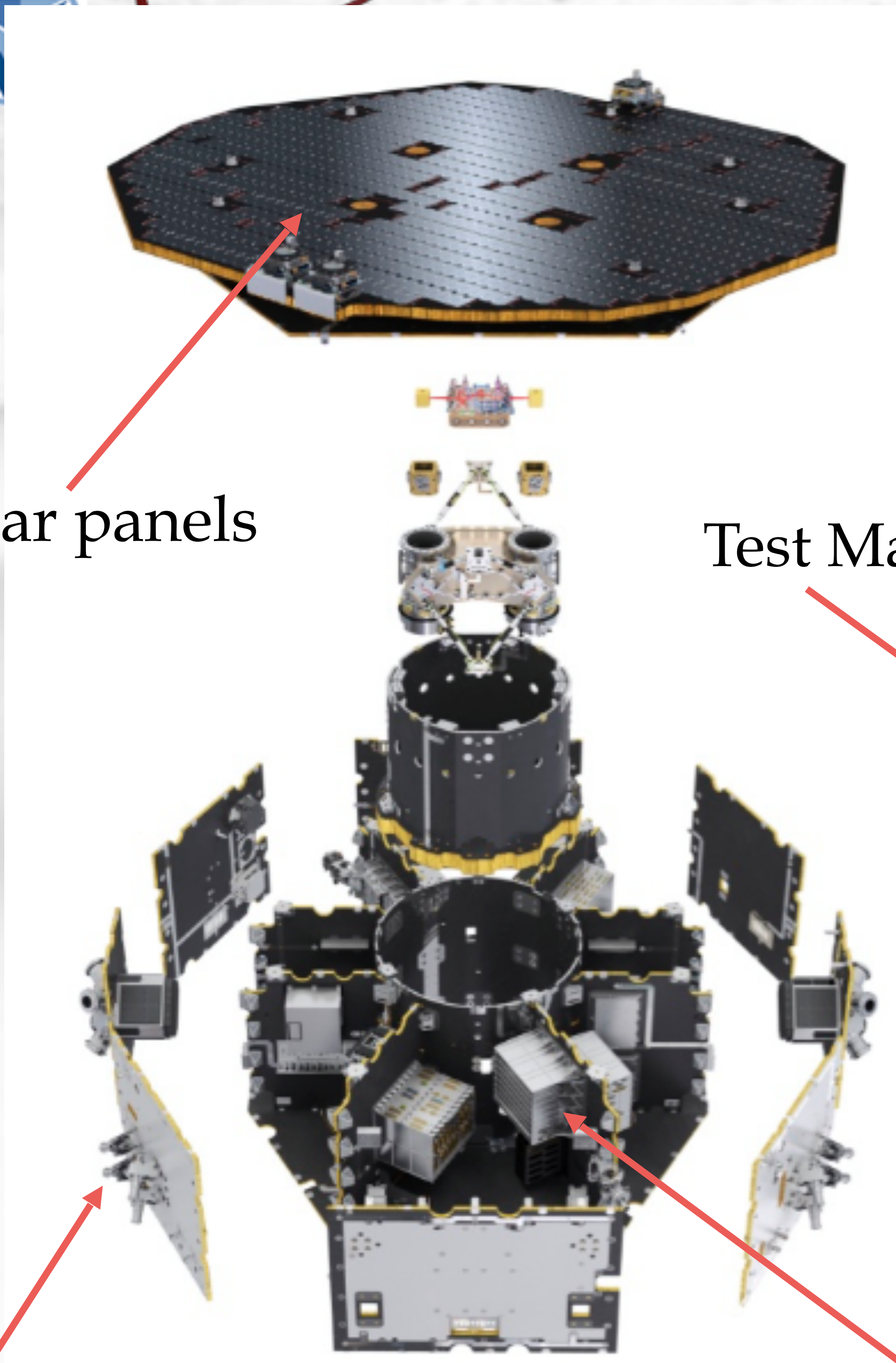


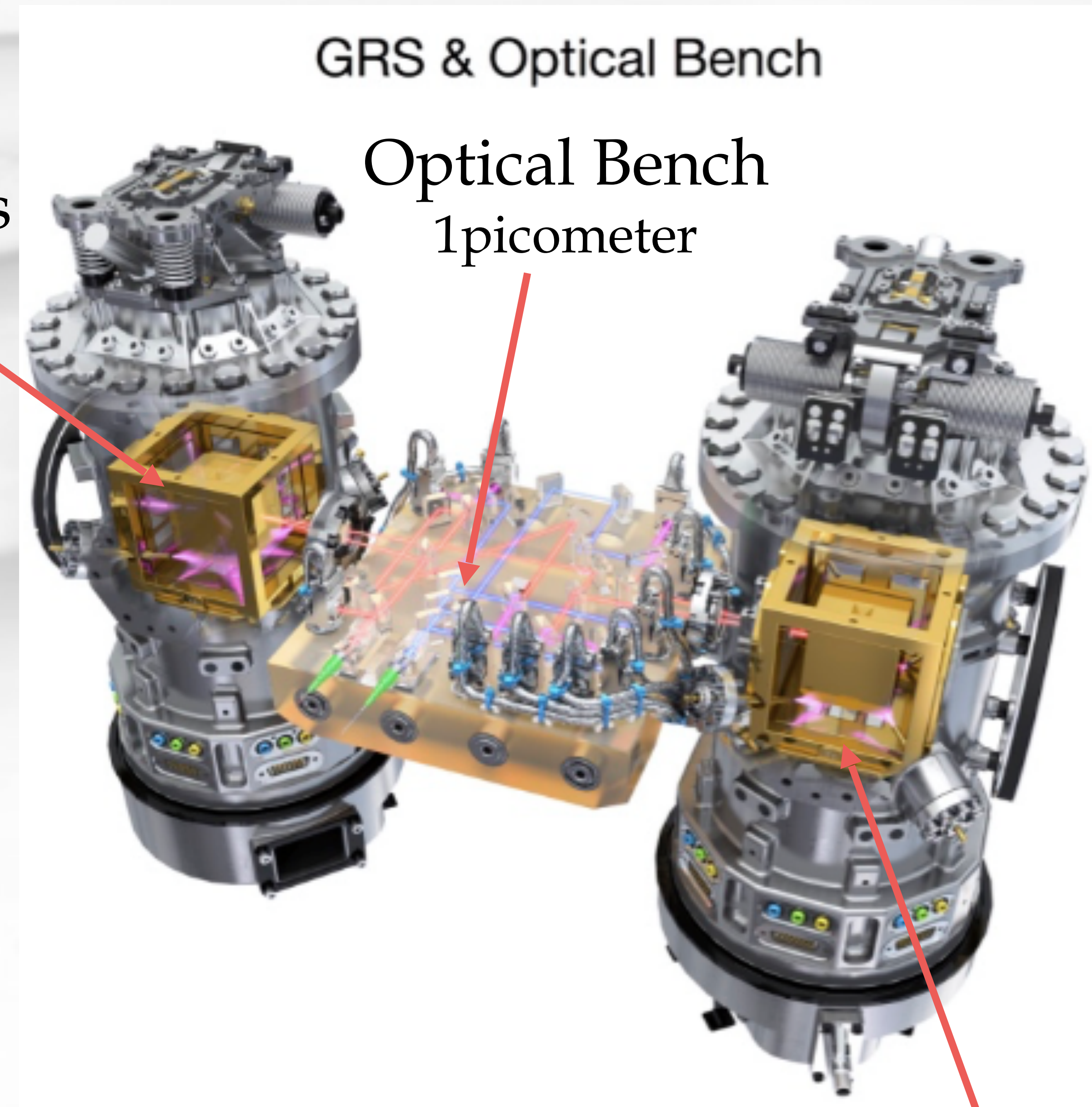
# LISA Pathfinder

- **Main goal**: demonstrate the possibility of "Free Fall" in space at the level of ≈ $10^{-14}$ $m.s^{-2}/\sqrt{Hz}$, around 1 mHz

- A number of effects have to be minimized:
  - The static gravitational potential between the TMs and the SC,
  - Residual links of the TMs w.r.t the SC via the residual vacuum,
  - Cross talk between various electrostatic actuators,
  - TM charging by cosmic rays that is eliminated by UV illumination,
  - Temperature fluctuations ,
  - Magnetic field fluctuations,
  - …

# LisaPathfinder : A technology demonstrator






Solar panels

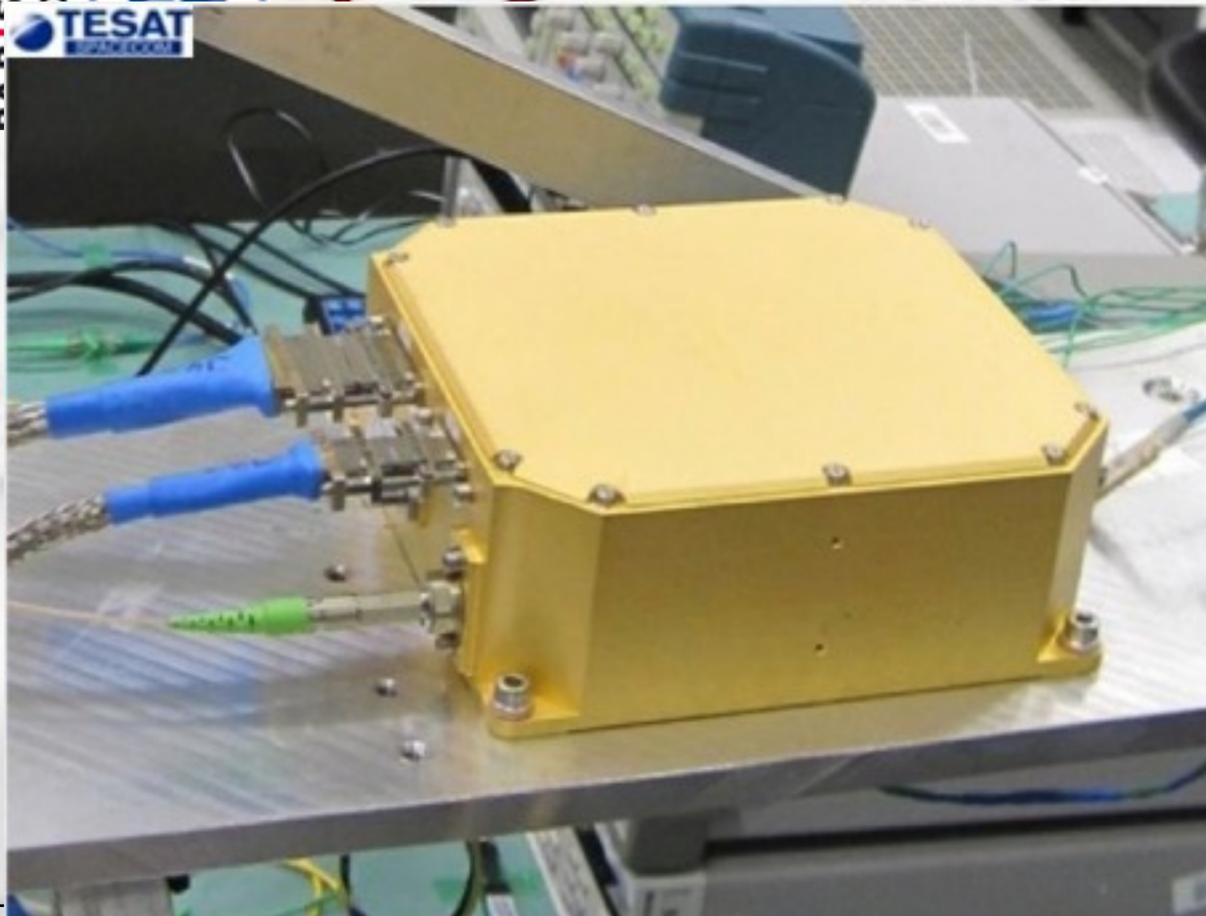
Test Mass

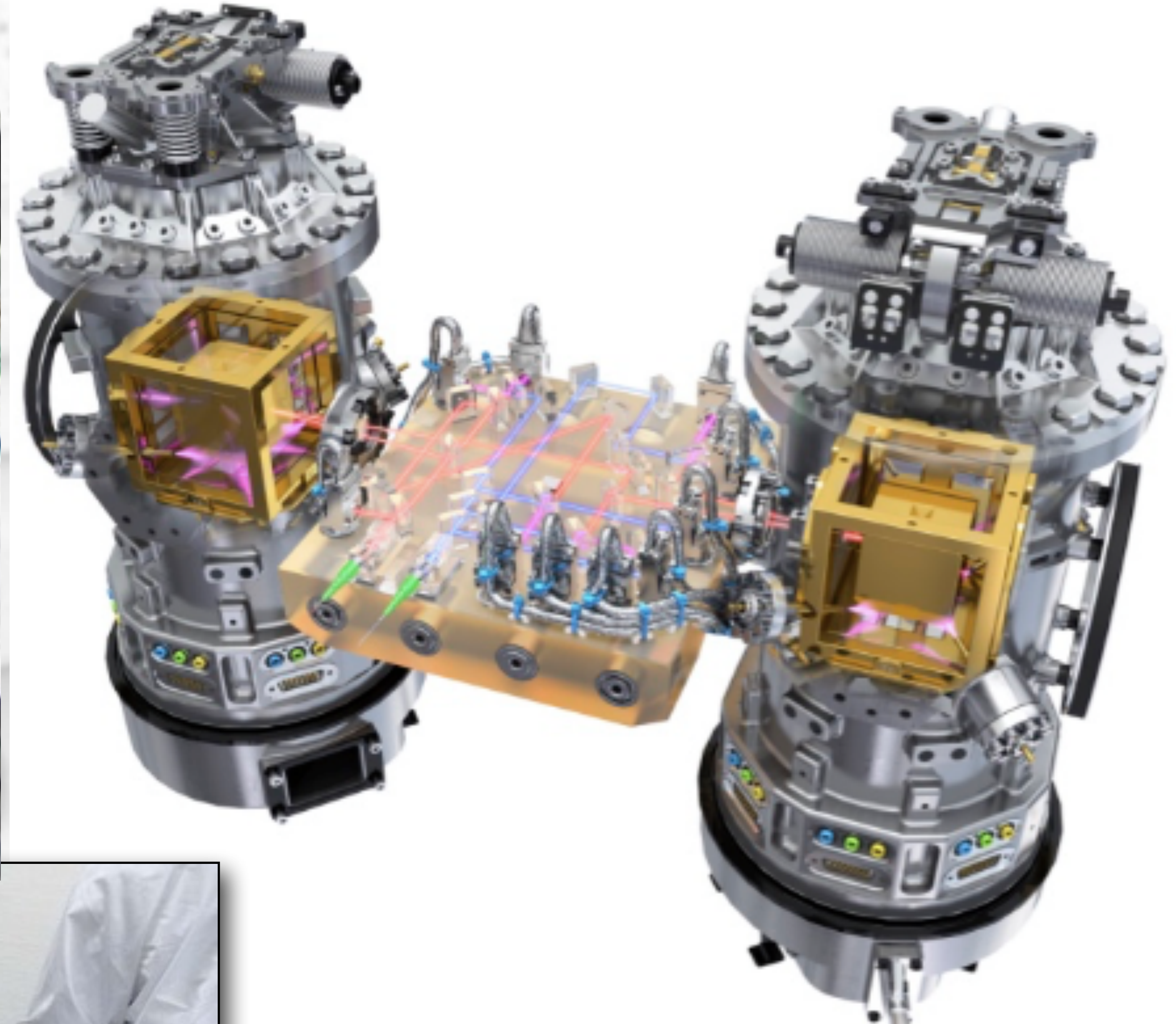
Optical Bench
1picometer

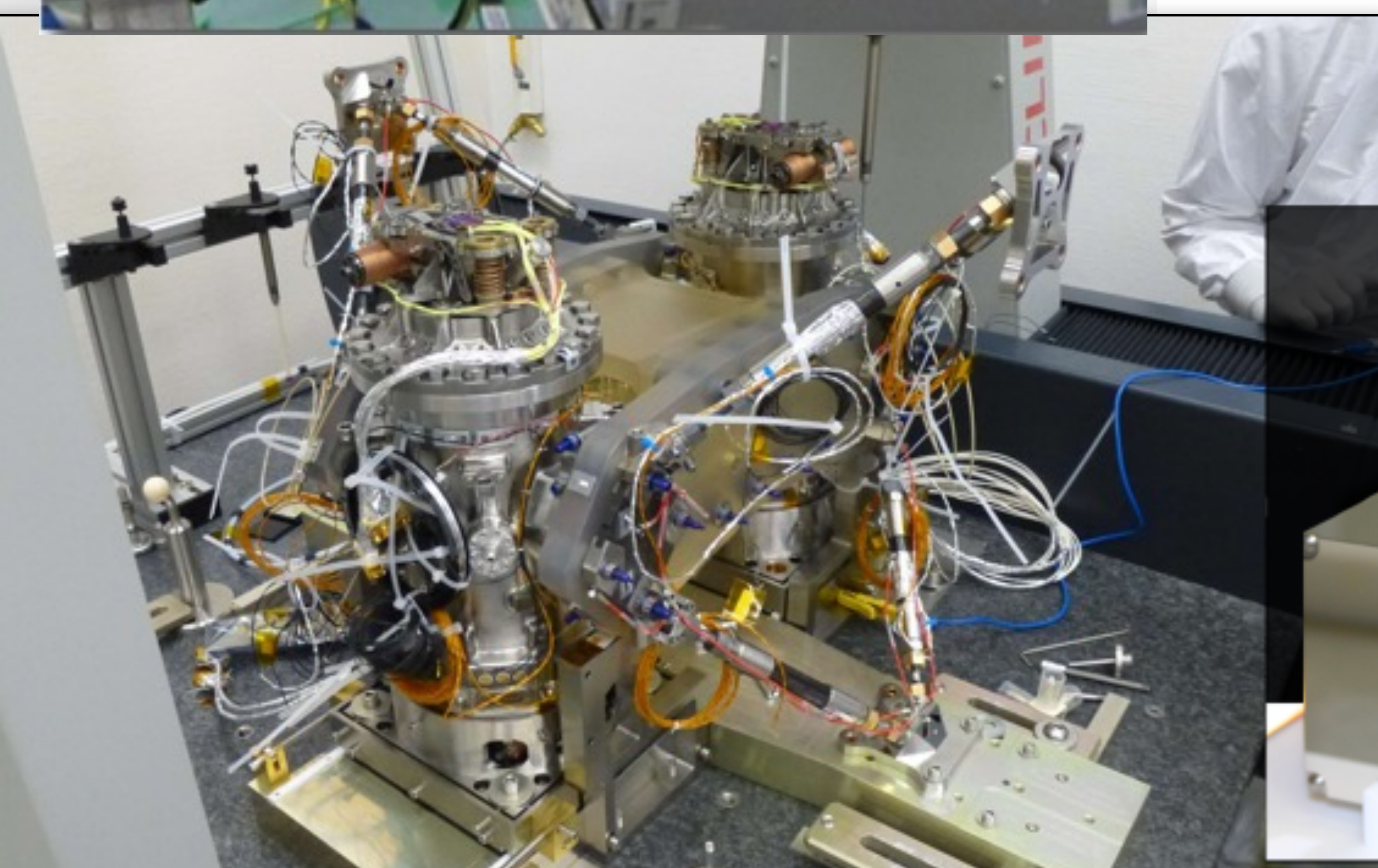
The micro-thrusters
Cold Gas (µ-Newton)

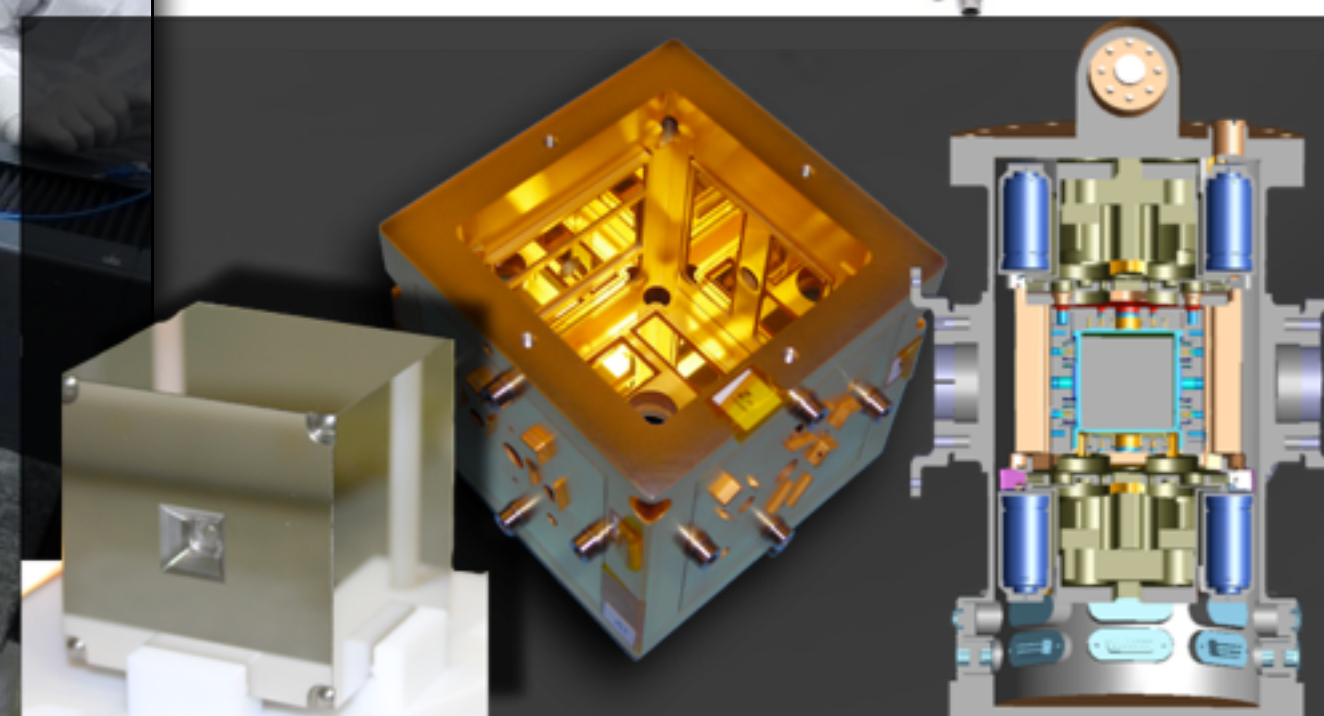
Electronics + computers

UV illumination

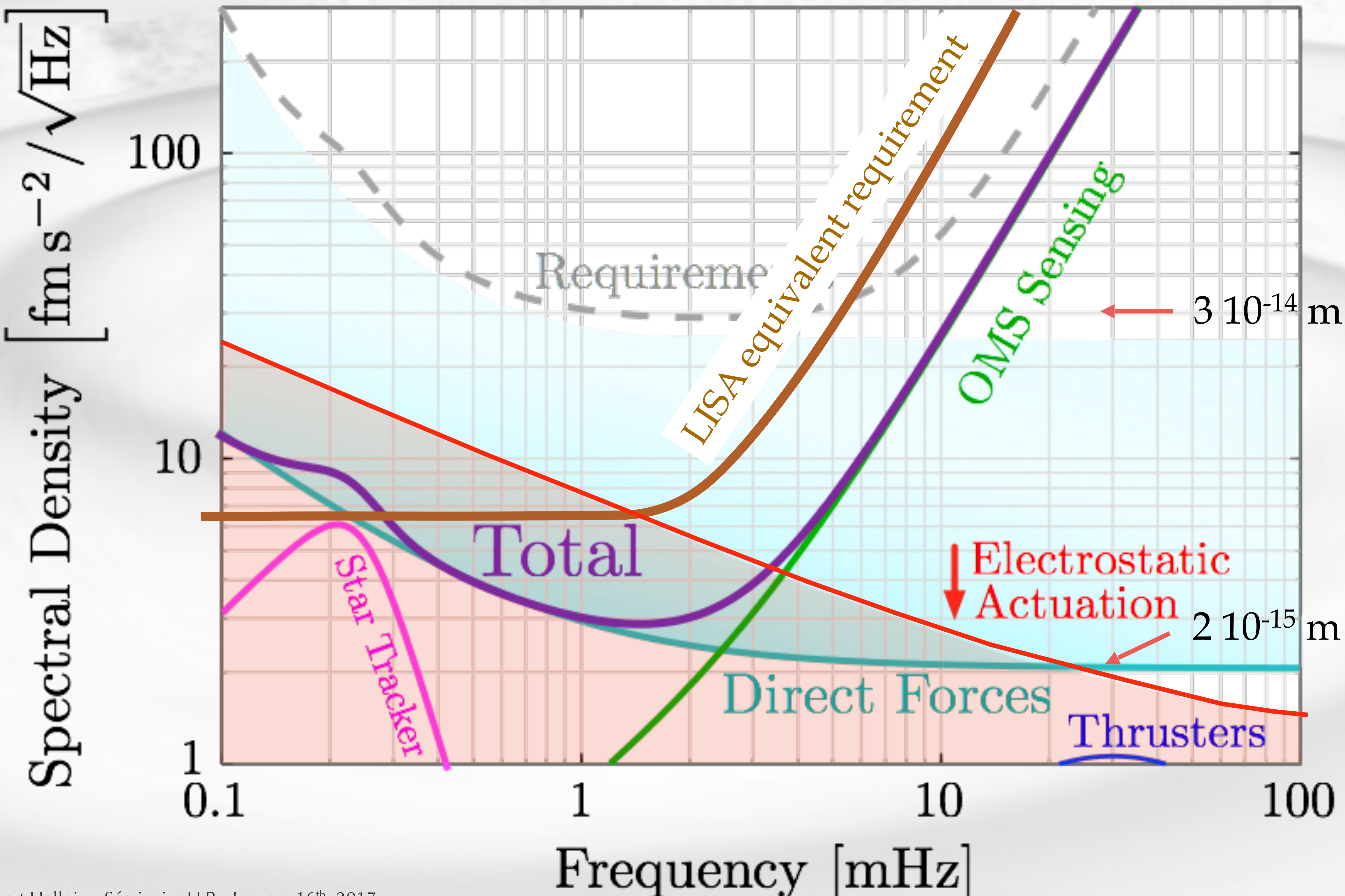








# Predictions for LISA Pathfinder

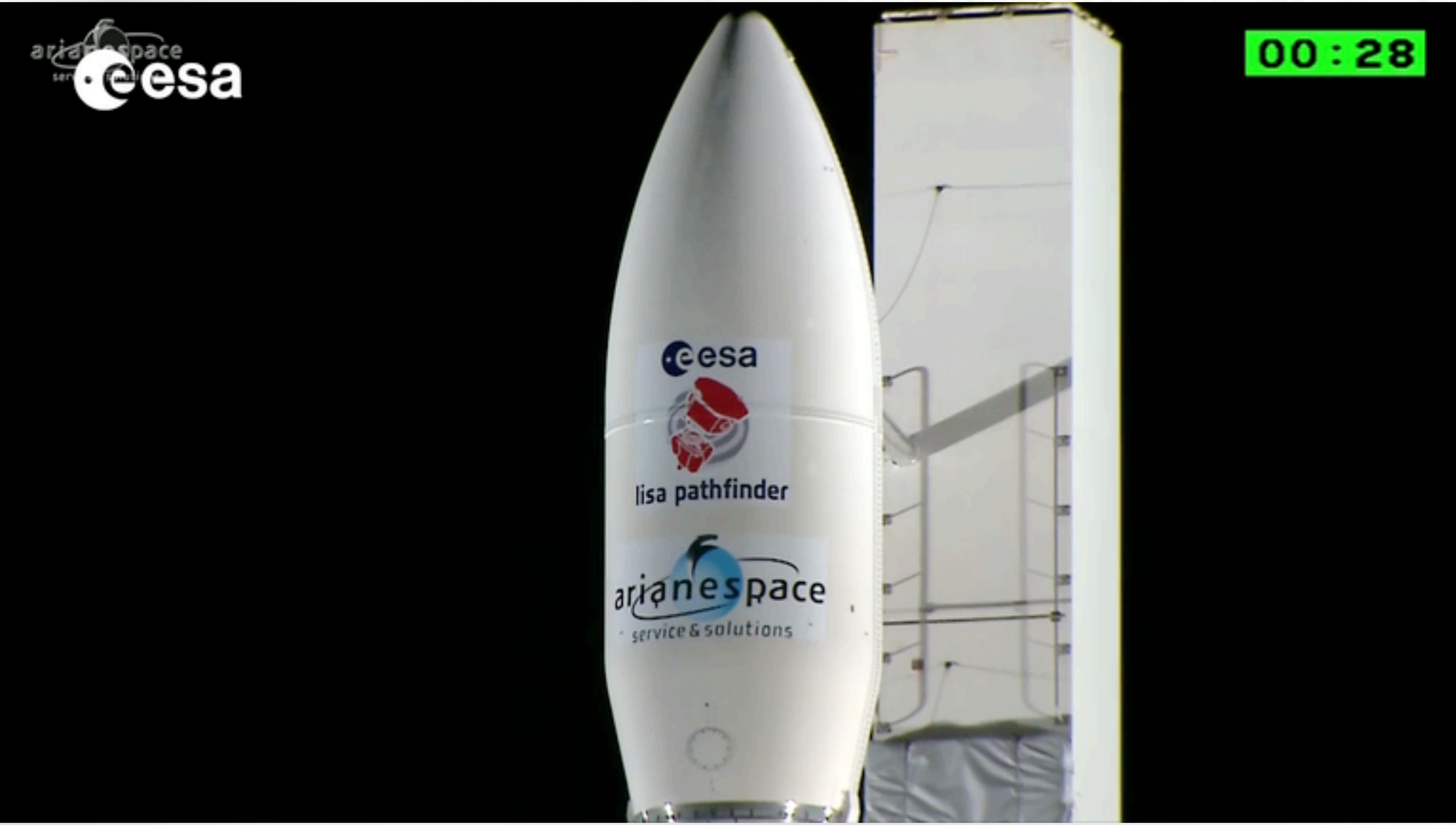



$3\ 10^{-14}$ m s$^{-2}$/ √Hz

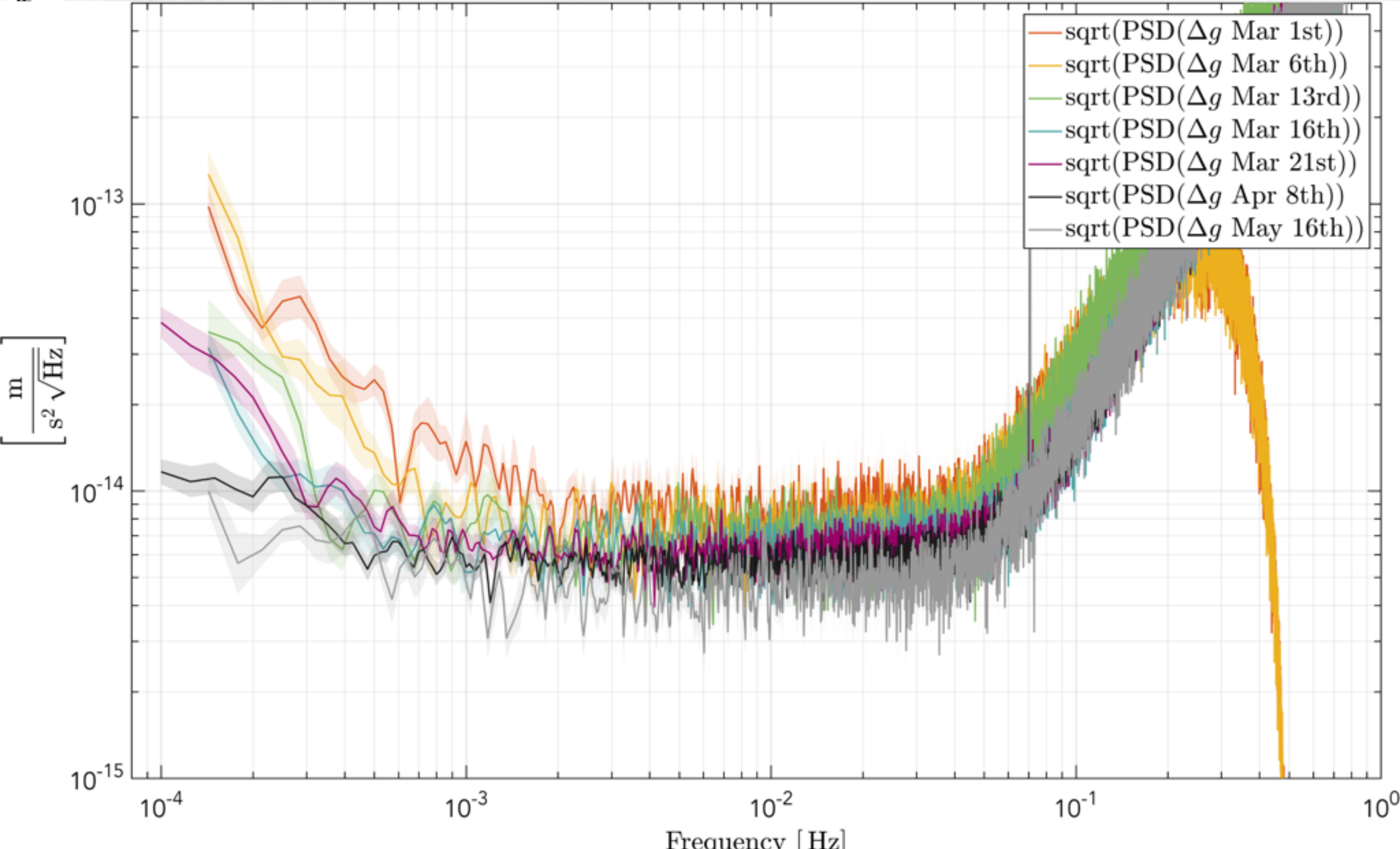
$2\ 10^{-15}$ m s$^{-2}$/ √Hz

# LISA Pathfinder - 03/12/15

http://www.esa.int/spaceinvideos/Videos/2015/12/LISA_Pathfinder_liftoff

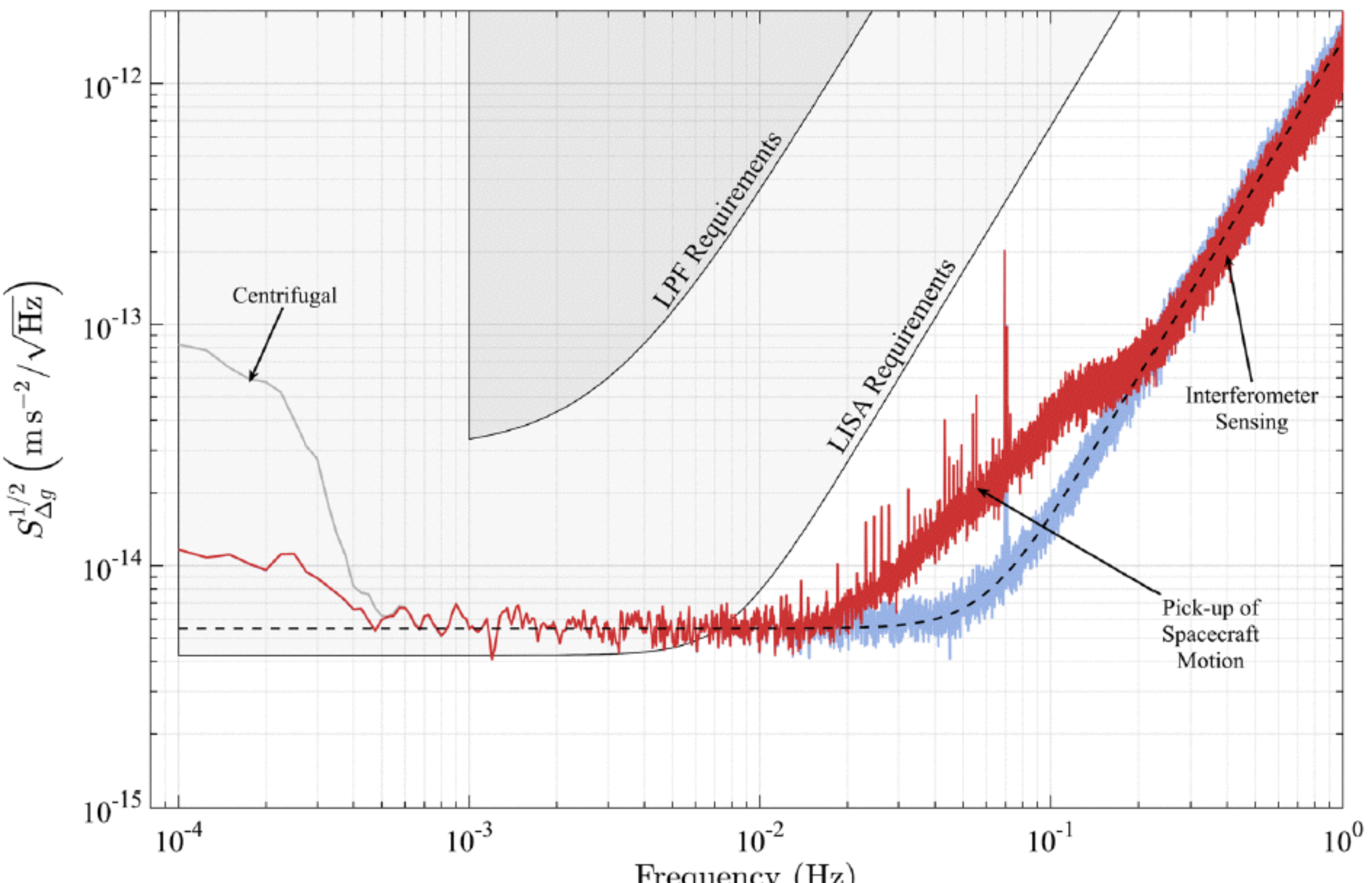


# Performance evolution



Selected for a Viewpoint in *Physics*
PRL **116,** 231101 (2016) PHYSICAL REVIEW LETTERS week ending 10 JUNE 2016

# Sub-Femto-*g* Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results

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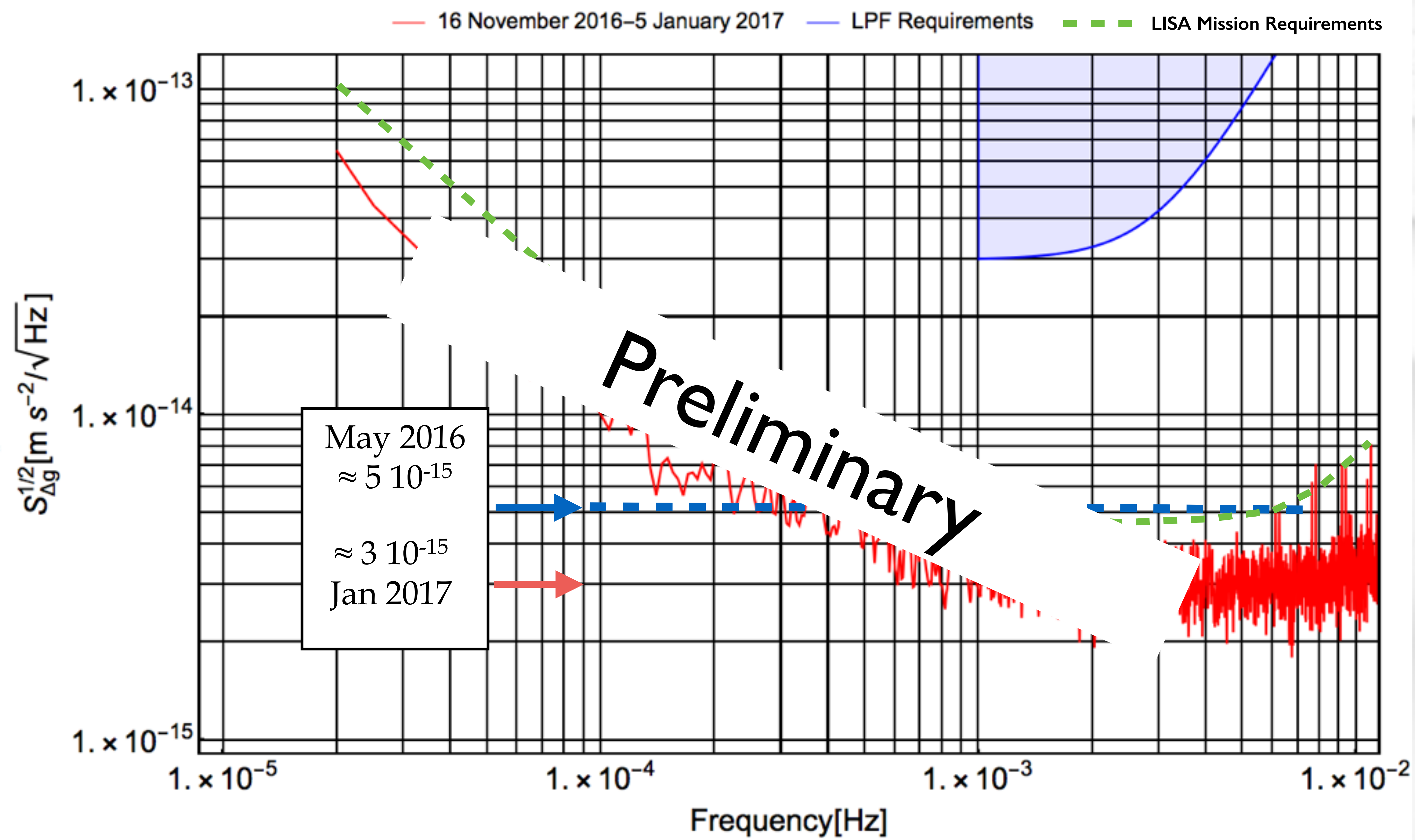
# The Present Results : January 2017

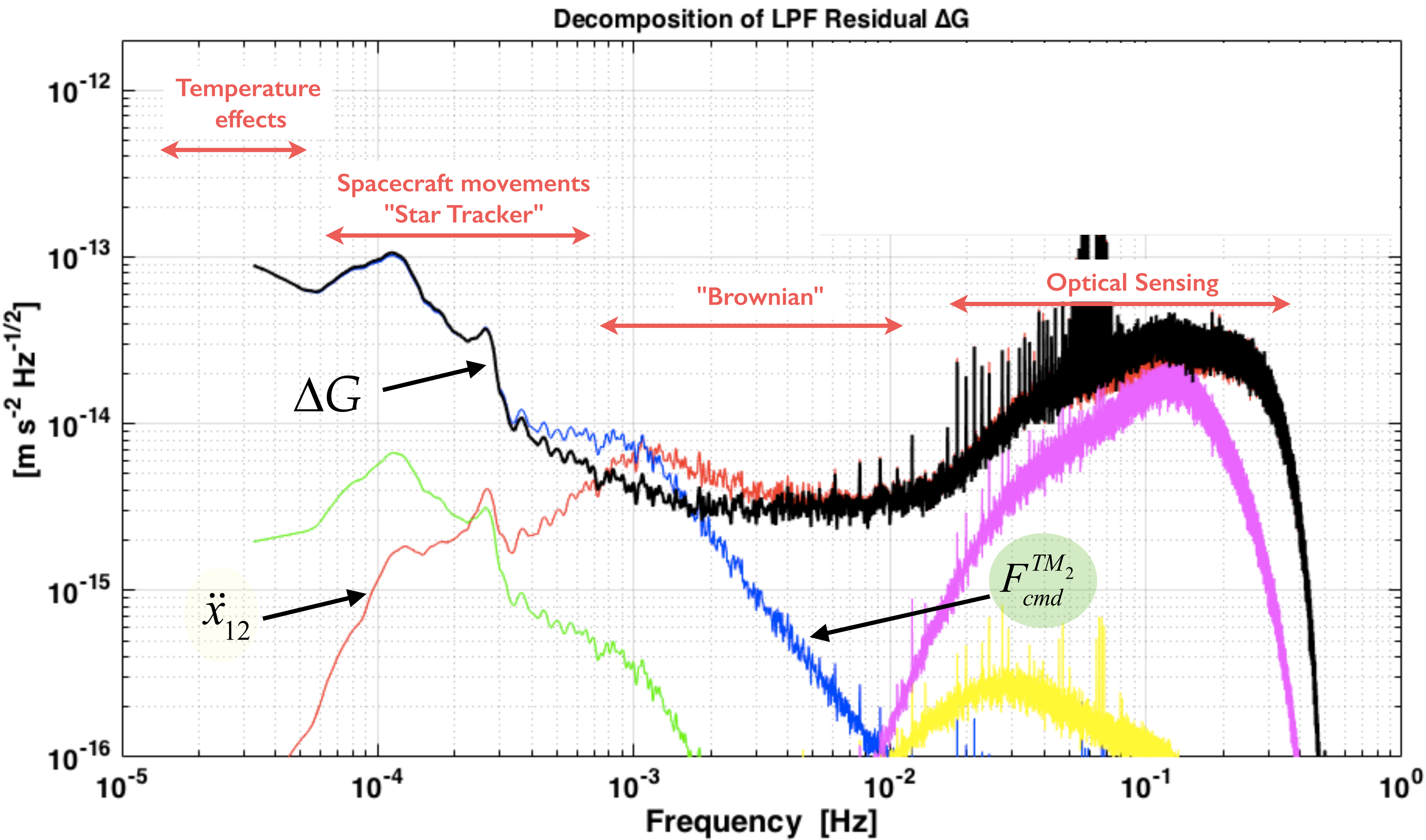


# The Different Frequency Ranges

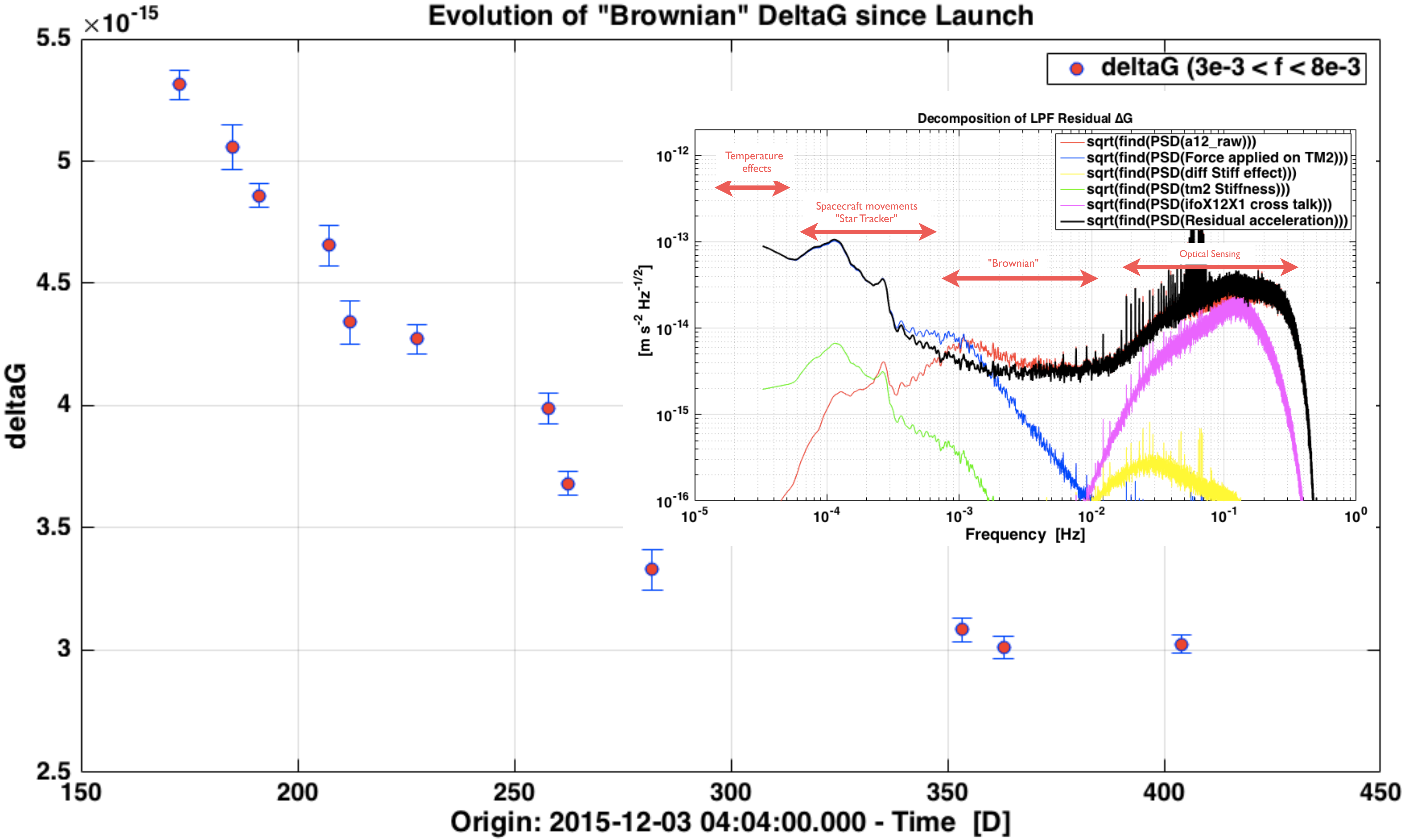
$$\Delta G = \ddot{x}_{12} + F_{cmd}^{TM_2} + \ldots$$

$x_{12}$ is measured by the optical bench

Obtained by "on board" telemetry and precisely calibrated.



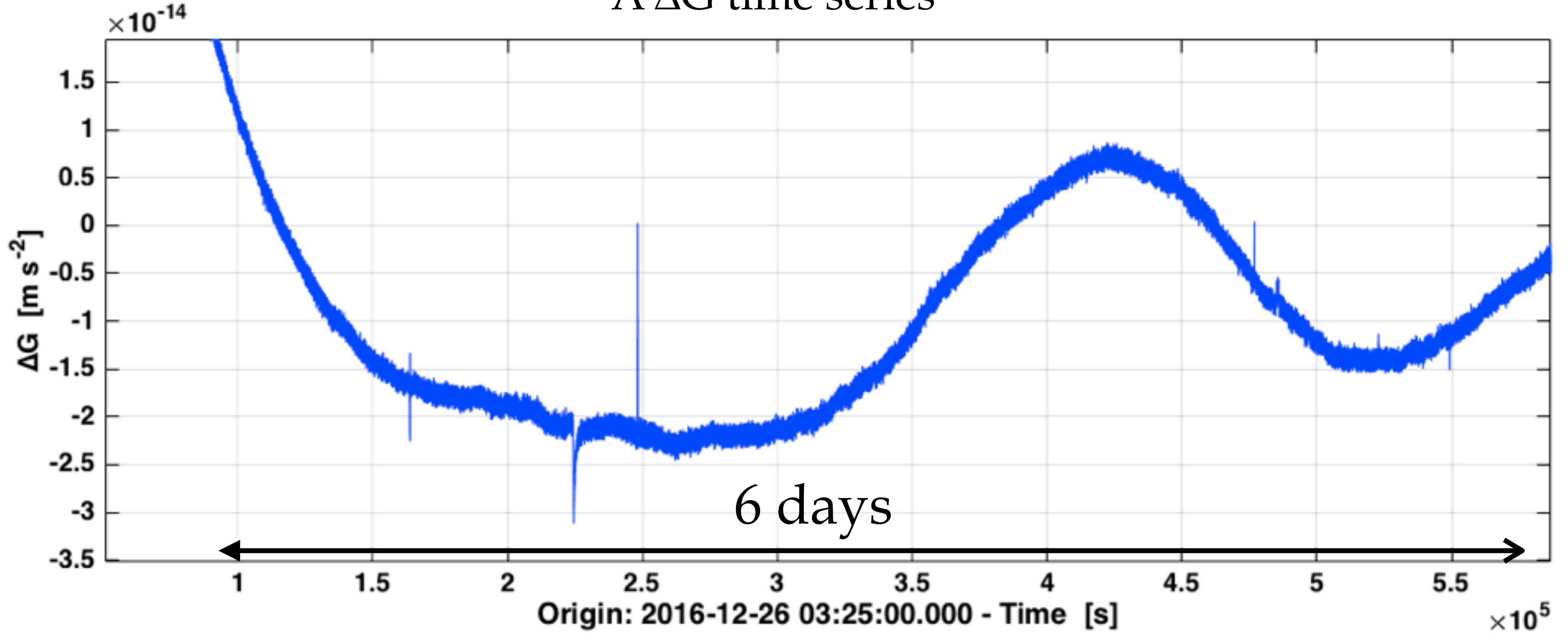
# The Evolution of the "Brownian" Contribution



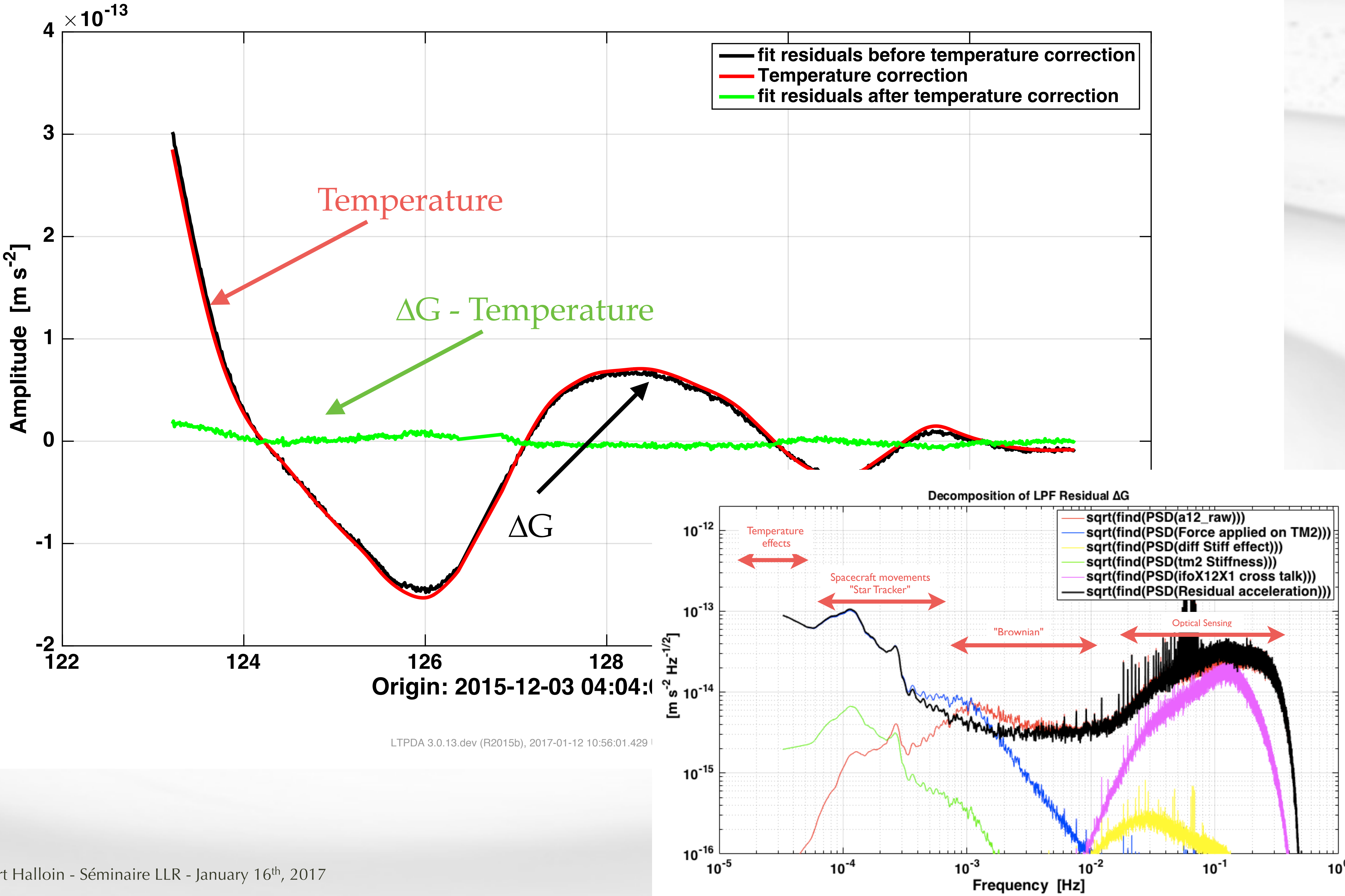
# Looking in depth: Glitches in the data

- 1 glitch every 1.5 days, on average,
- Data analysis allows to remove those glitches.
- Their cause is still under investigation…
- Their impact on LISA detection: maybe inexistant.

A ΔG time series

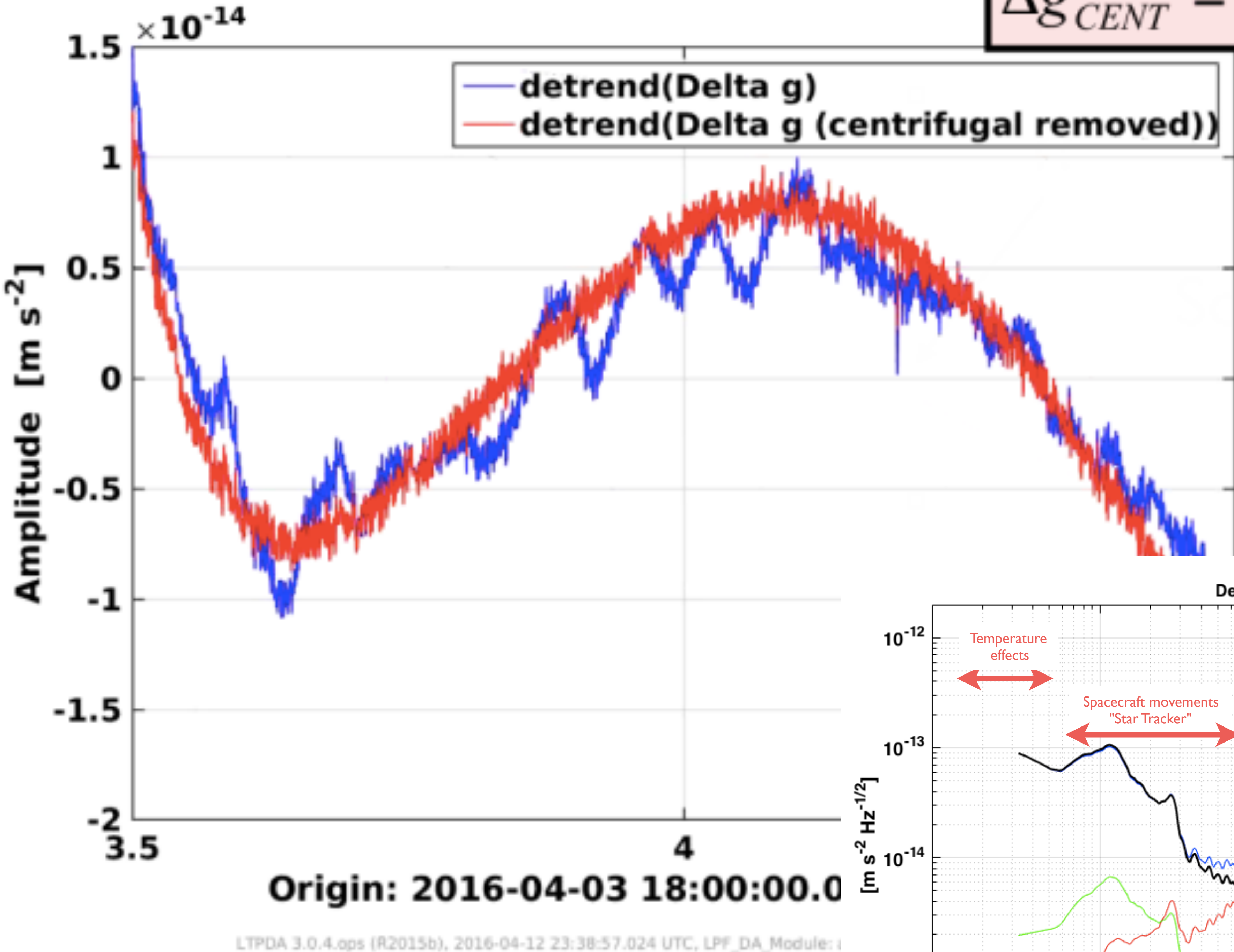


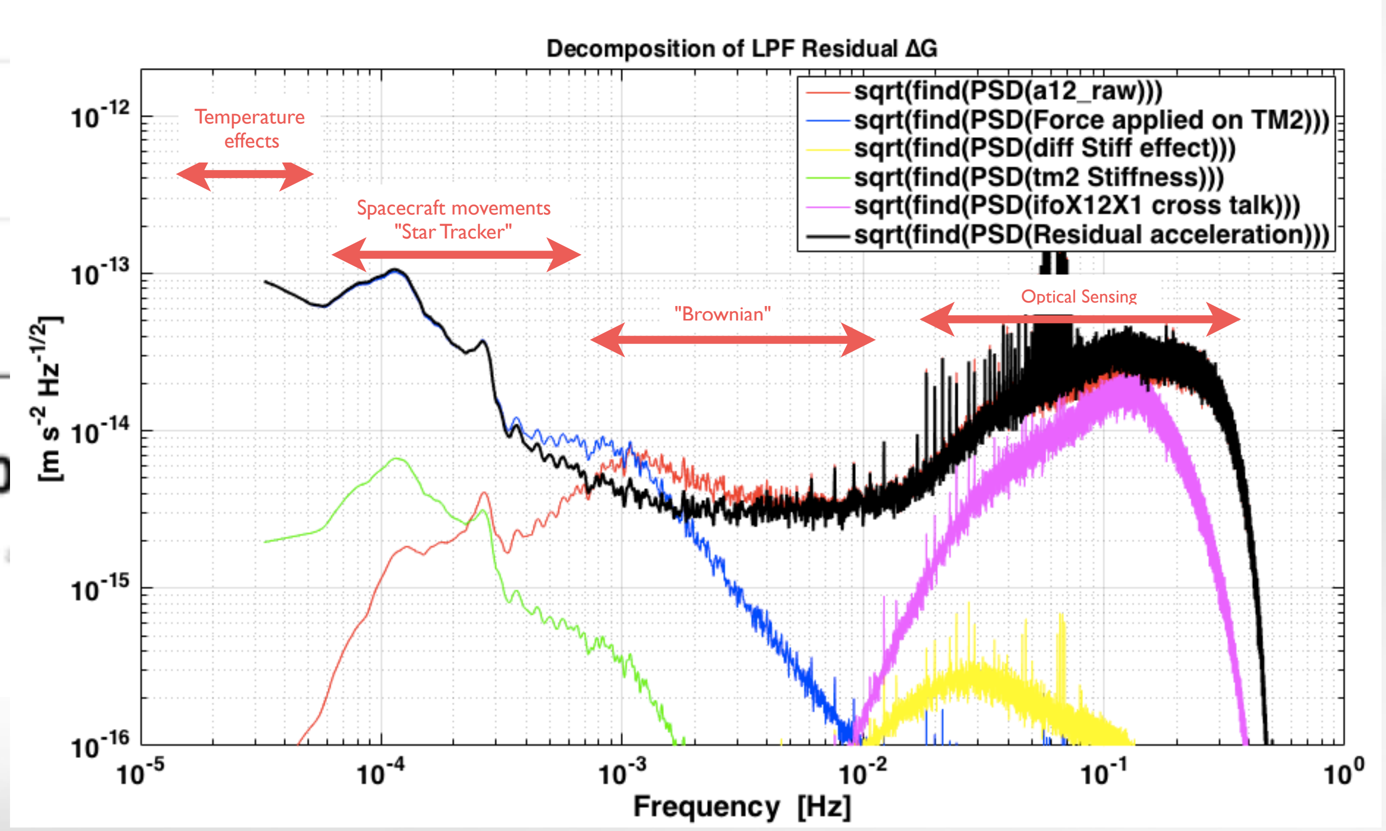
# Looking in depth: Temperature Effects on ΔG



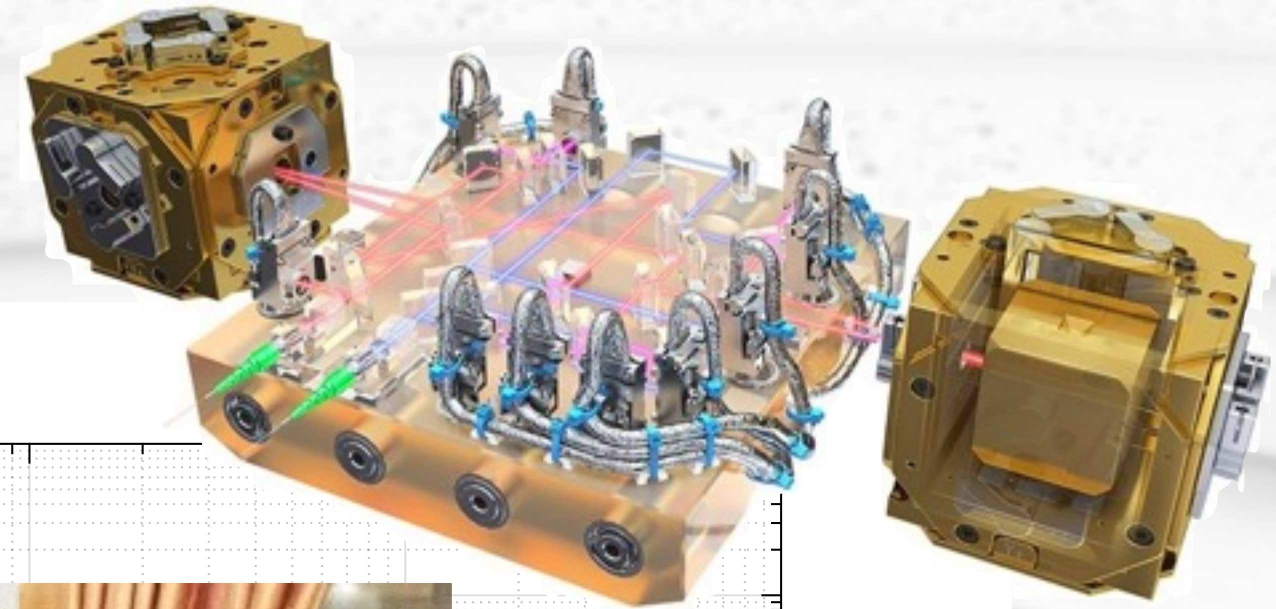
# Looking in depth: Spacecraft movements

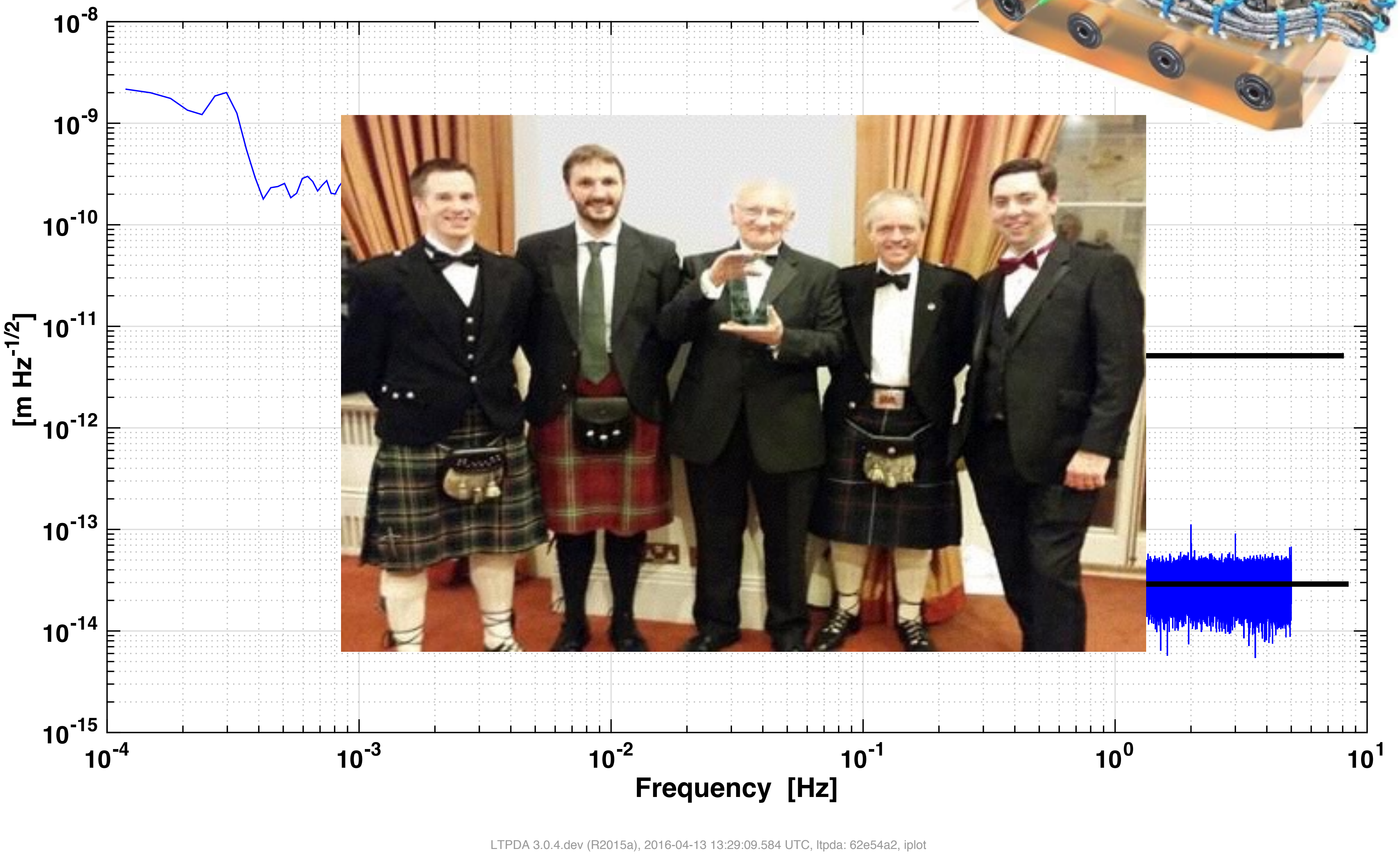
$$\Delta\hat{g}_{CENT} = -L\left(\dot{\phi}_{SC}^2 + \dot{\eta}_{SC}^2\right)$$



# Looking in depth: Optical Sensing Noise






in the lab
6 pico metre

in space
0.03 pico metre

# What does this mean for LISA?

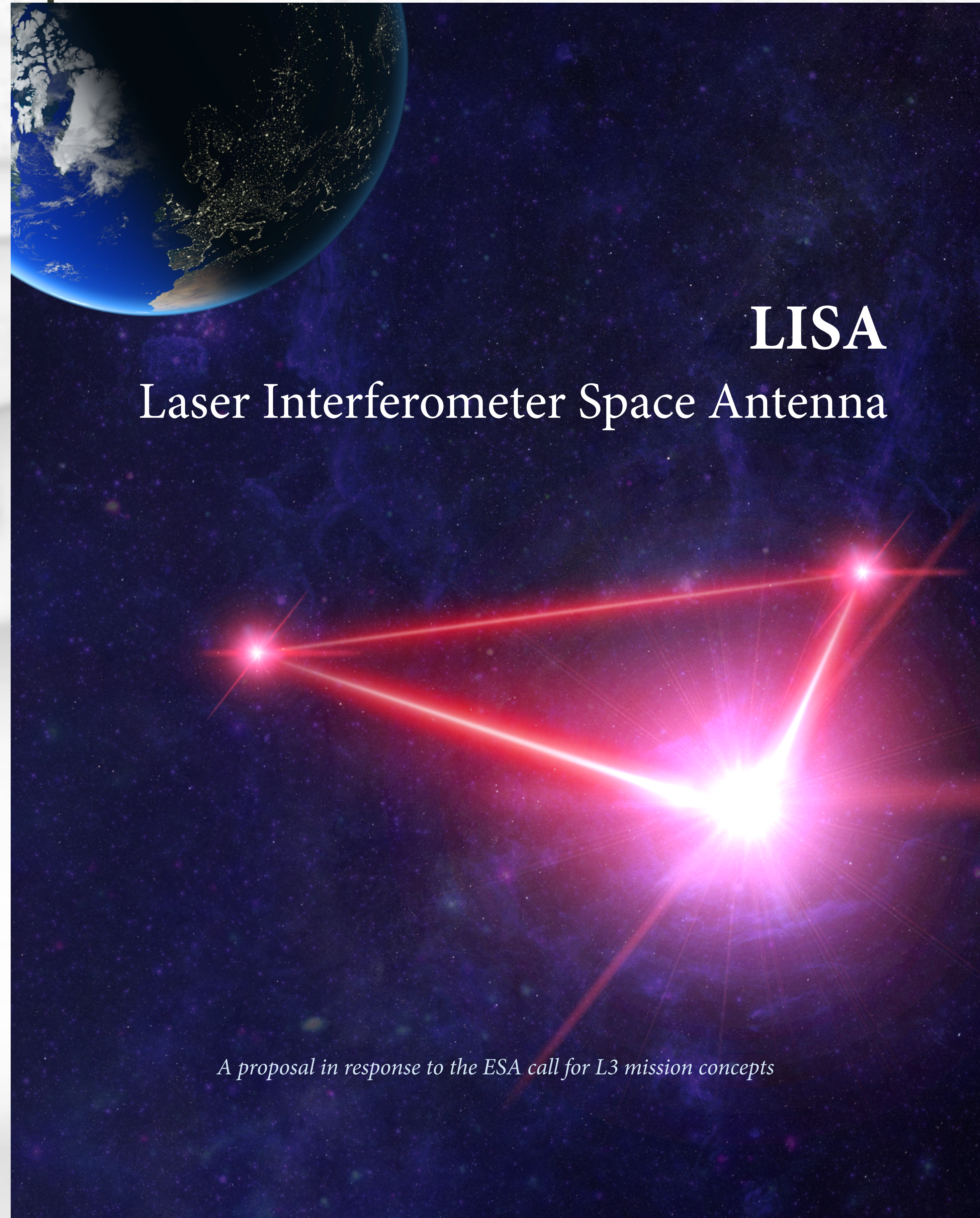
- We can put test masses in free-fall at the required level
  - stable on long durations
  - stationary noise, few glitches
    - ⇒ suitable for an observatory

- Physics of the system are well understood
  - we can explain most of the noise we see
  - design and implementation can be controlled against the physical model

- Observations of test mass motion with an optical metrology system made with very high performance
  - concepts and technology same as that needed for the local interferometry in LISA

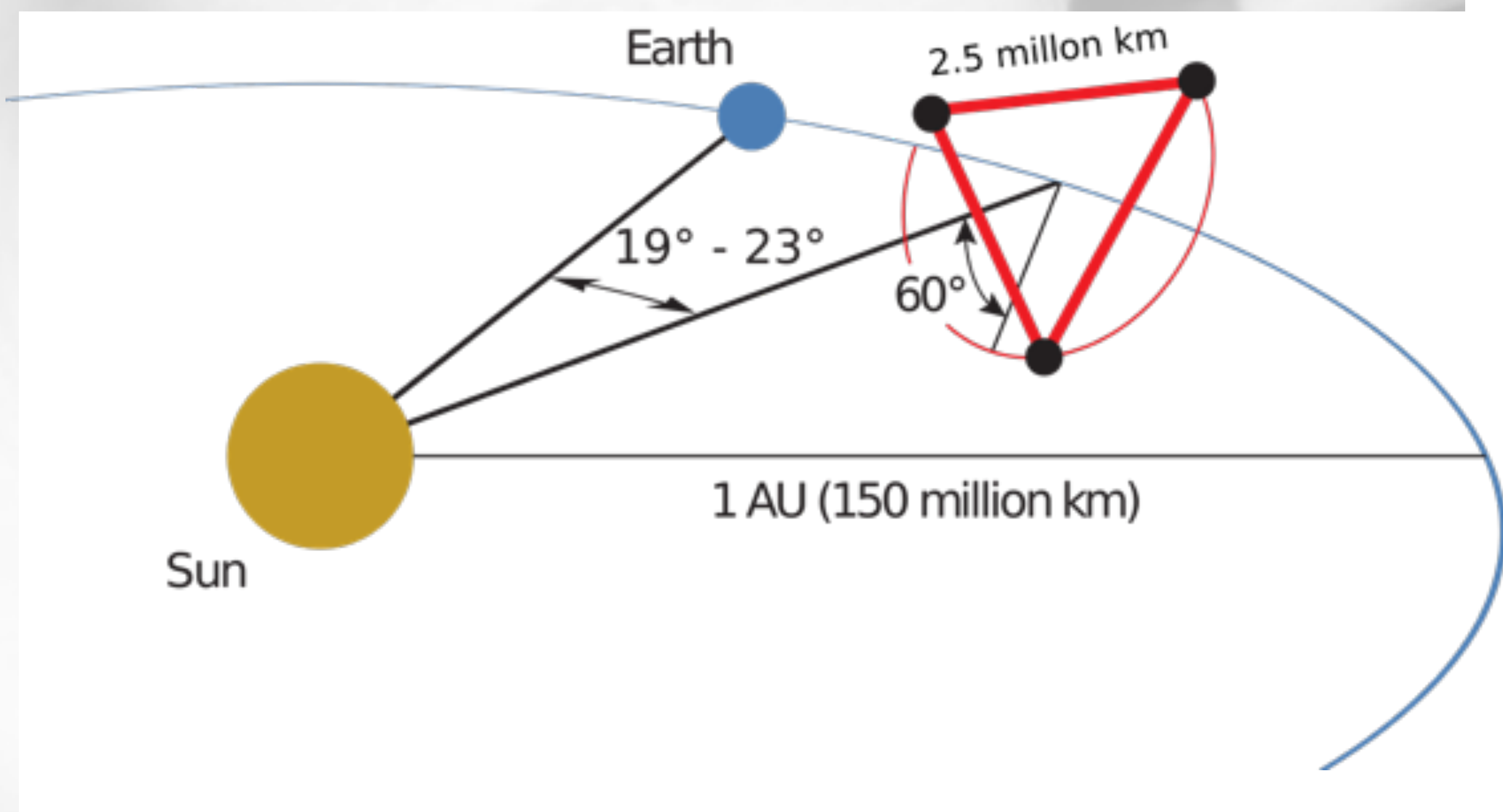
# Towards a space-borne GW detector !

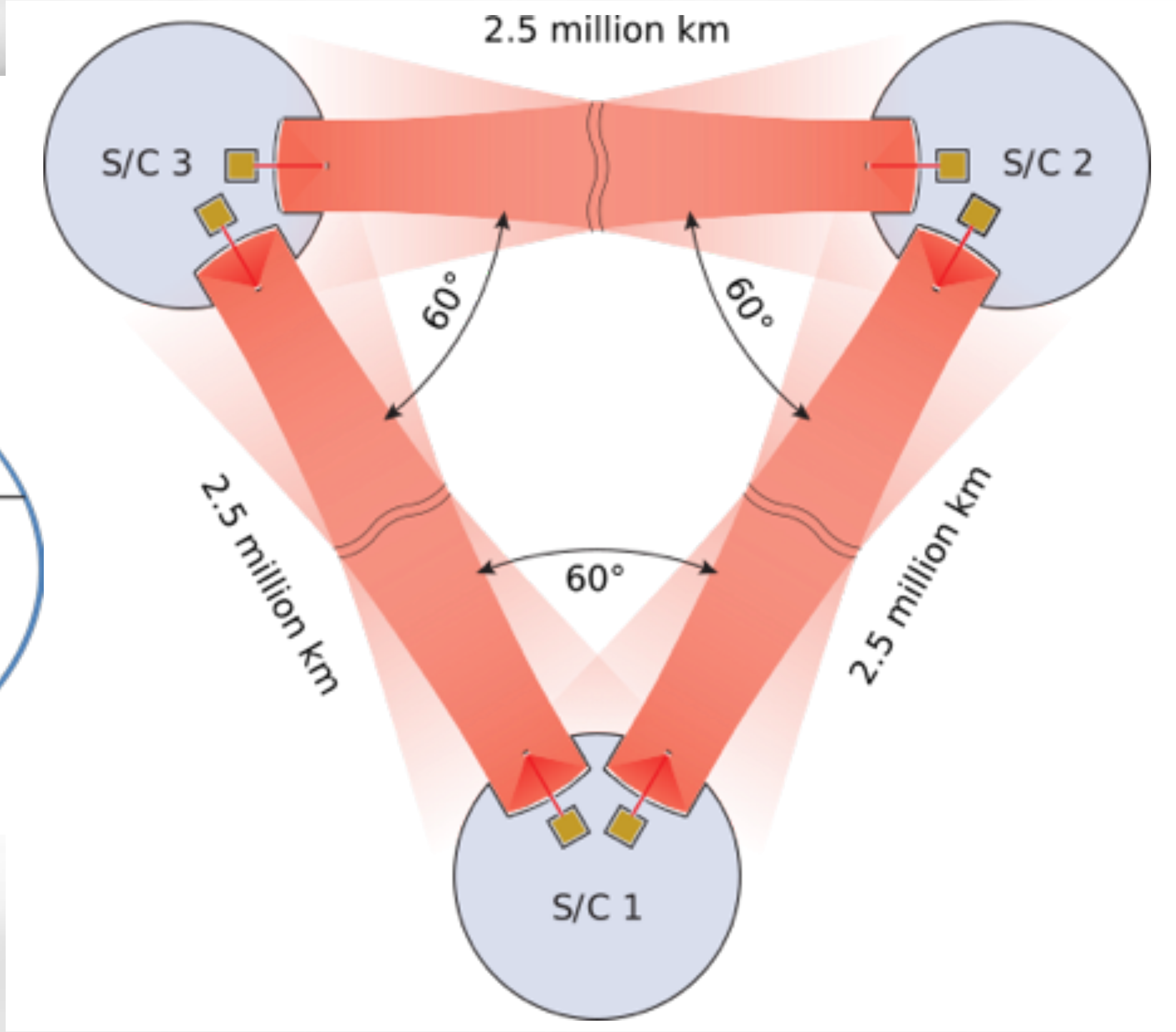
- LISA submitted to the ESA call for L3 missions concept on January 13th 2017!
  - Launch expected in 2030 - 2034
  - First studies in the early 80's …



# Proposed configuration for LISA

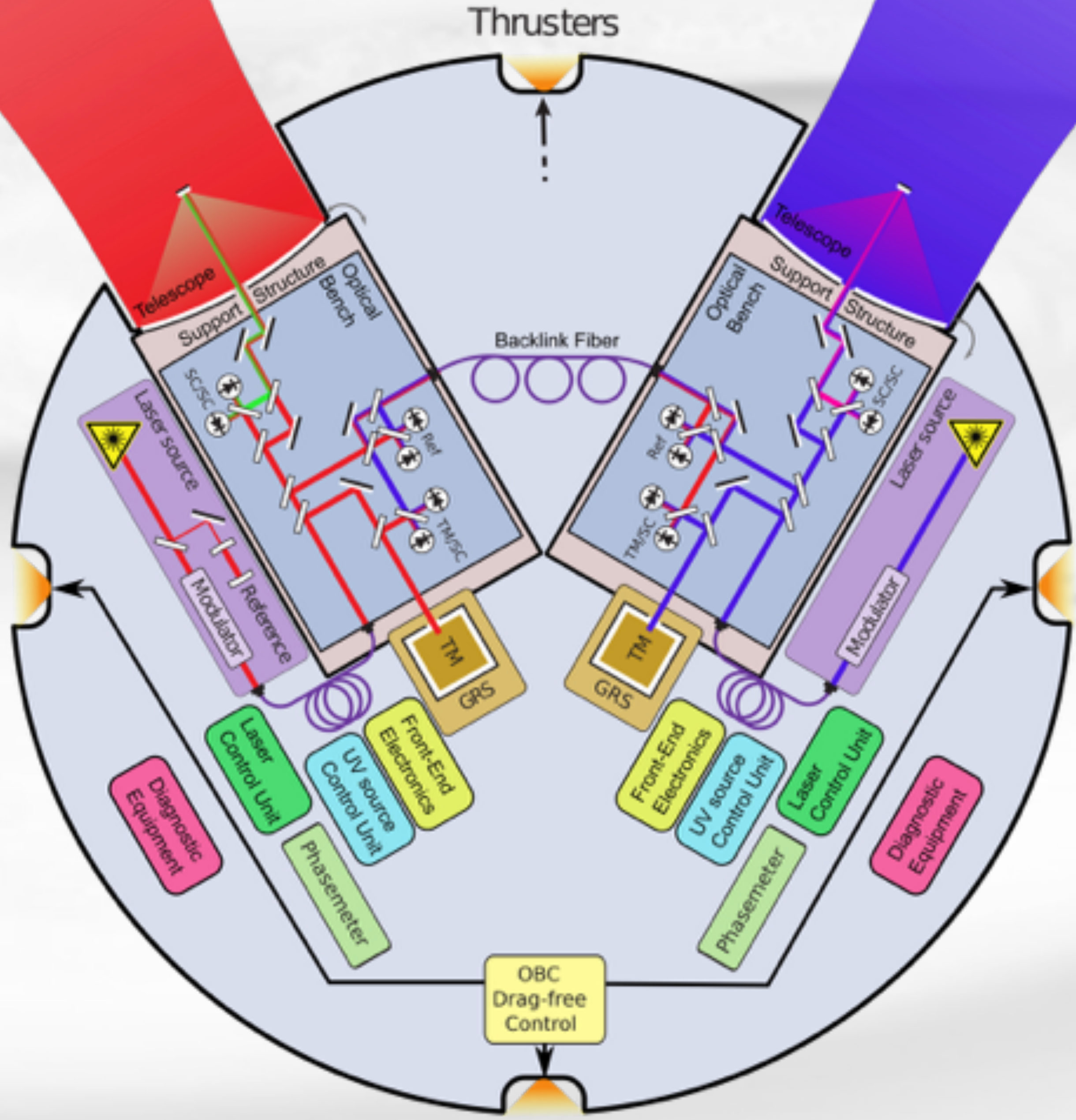
- Long arms interferometer
  - 2.5 Mkm arm length
  - 2 test masses / satellite
  - Earth-like orbit, 19° to 23° trailing
  - Mission duration : minimum 5 years (consumables for 10 years)



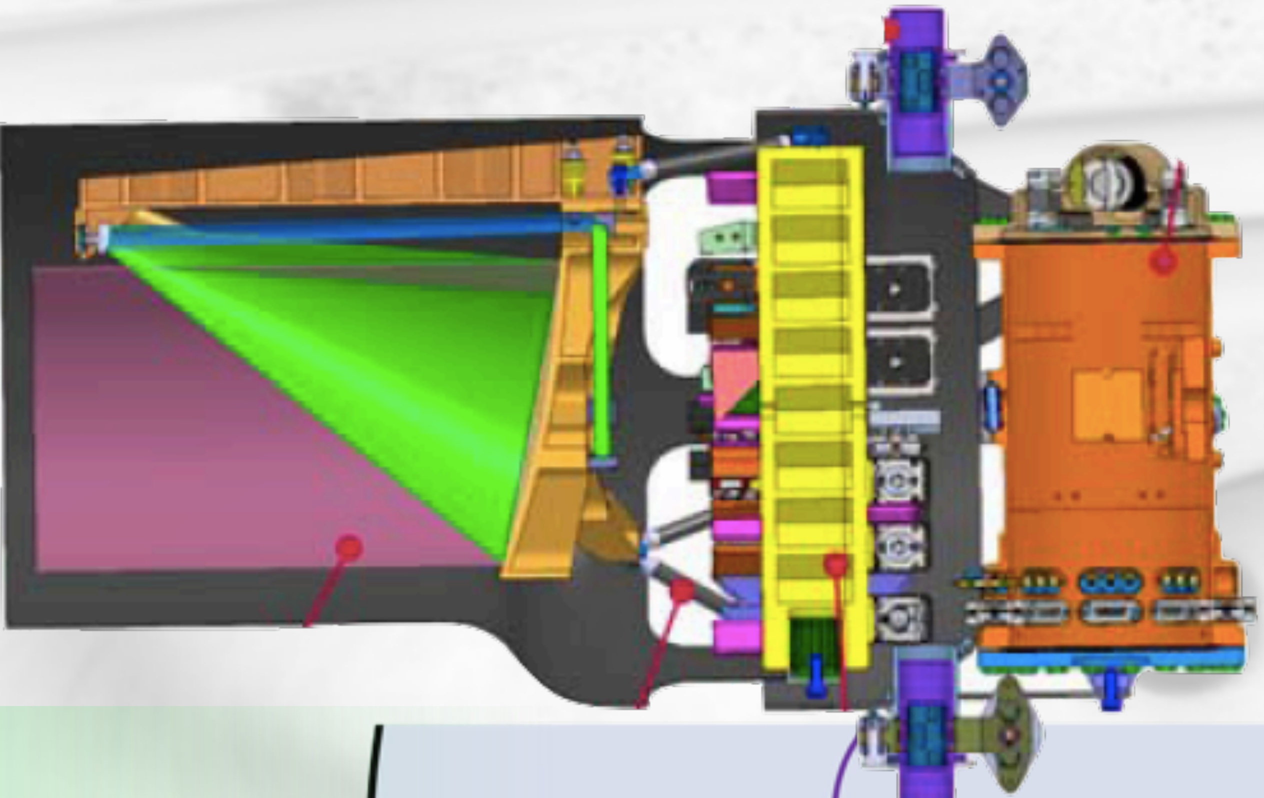



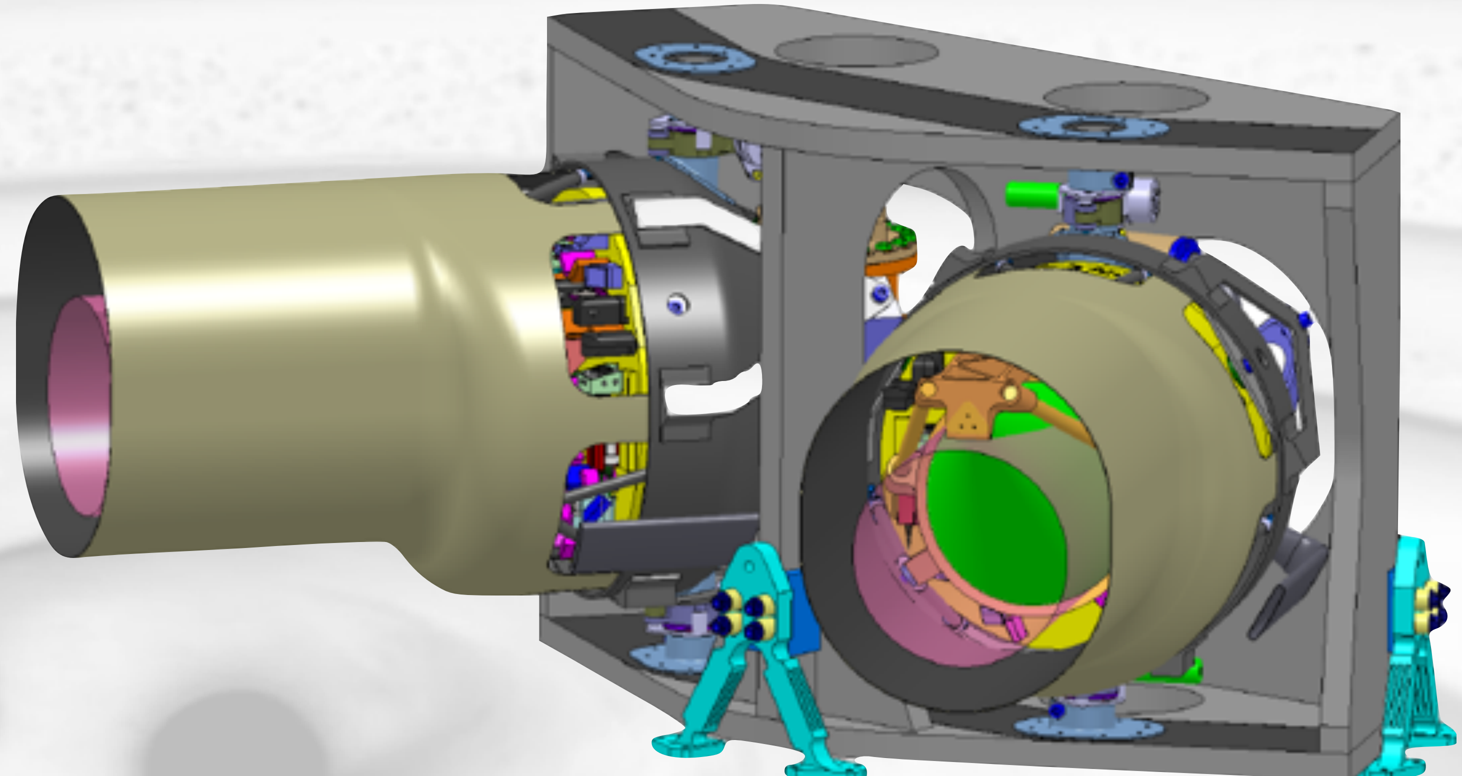
# SC configuration

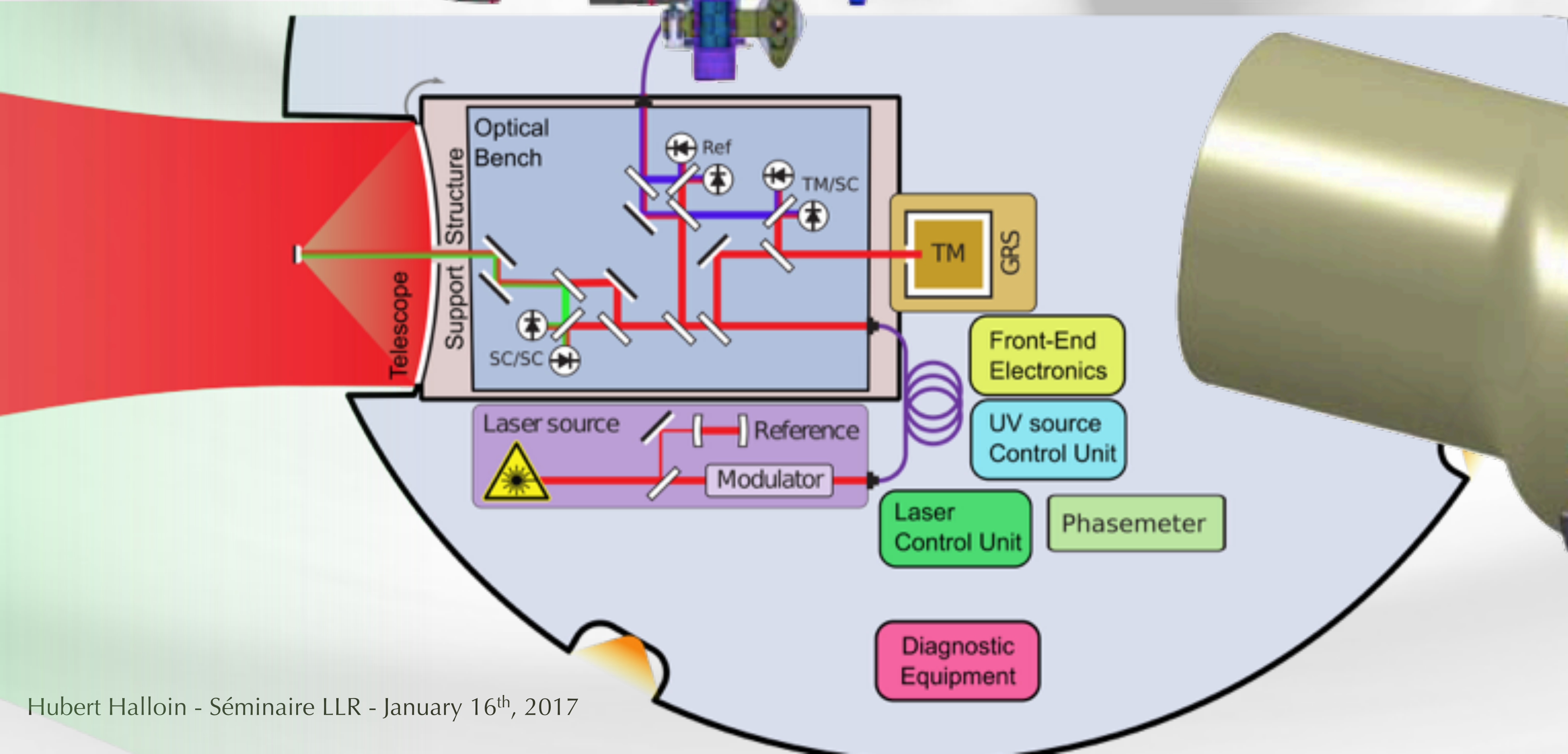
- 3 identical SC
- 3 arms / 6 laser links
- 6 instruments

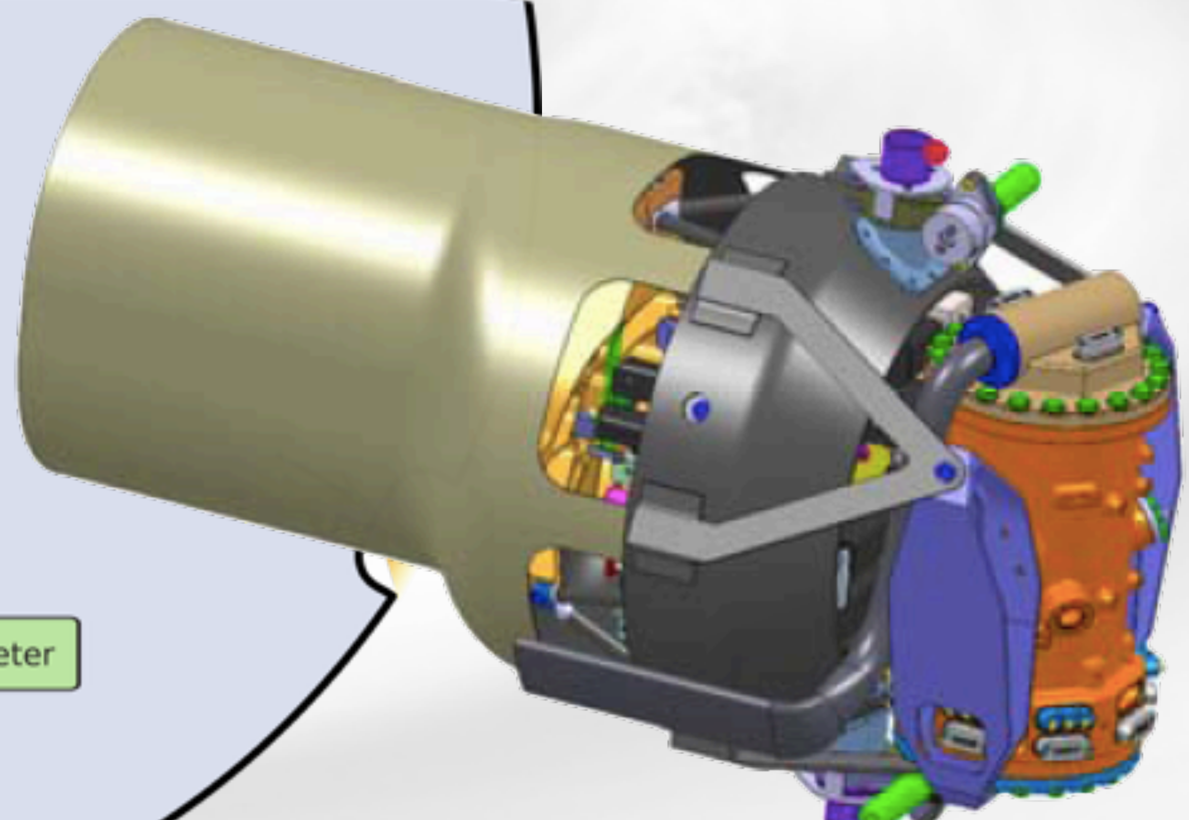


# Scheme of a payload







# Technology challenges for LISA

- Free flying test mass subject to very low parasitic forces:
  - Drag free control of spacecraft (non-contacting spacecraft)
  - Low noise microthruster to implement drag-free
  - Large gaps, heavy masses with caging mechanism
  - High stability electrical actuation on cross degrees of freedom
  - Non contacting discharging of test-masses
  - High thermo-mechanical stability of S/C
  - Gravitational field cancellation

- Precision interferometric, local ranging of test-mass and spacecraft:
  - pm resolution ranging, sub-mrad alignments
  - High stability monolithic optical assemblies

- Precision million km spacecraft to spacecraft precision ranging:
  - High stability telescopes
  - High accuracy phase-meter
  - High accuracy frequency stabilization
  - Constellation acquisition
  - Precision attitude control of S/C

# Technology challenges for LISA

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**Validated with LISA Pathfinder**

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- Precision million km spacecraft to spacecraft precision ranging:
  - High stability telescopes
  - High accuracy phase-meter
  - High accuracy frequency stabilization
  - Constellation acquisition
  - **Precision attitude control of S/C**

# Technology challenges for eLISA

- **Free flying test mass subject to very low parasitic forces:**
  - **Drag free control of spacecraft (non-contacting spacecraft)**
  - **Low noise microthruster to implement drag-free**
  - **Large gaps, heavy masses with caging mechanism**
  - **High stability electrical actuation on cross degrees of freedom**
  - **Non contacting discharging of test-masses**
  - **High thermo-mechanical stability of S/C**
  - **Gravitational field cancellation**

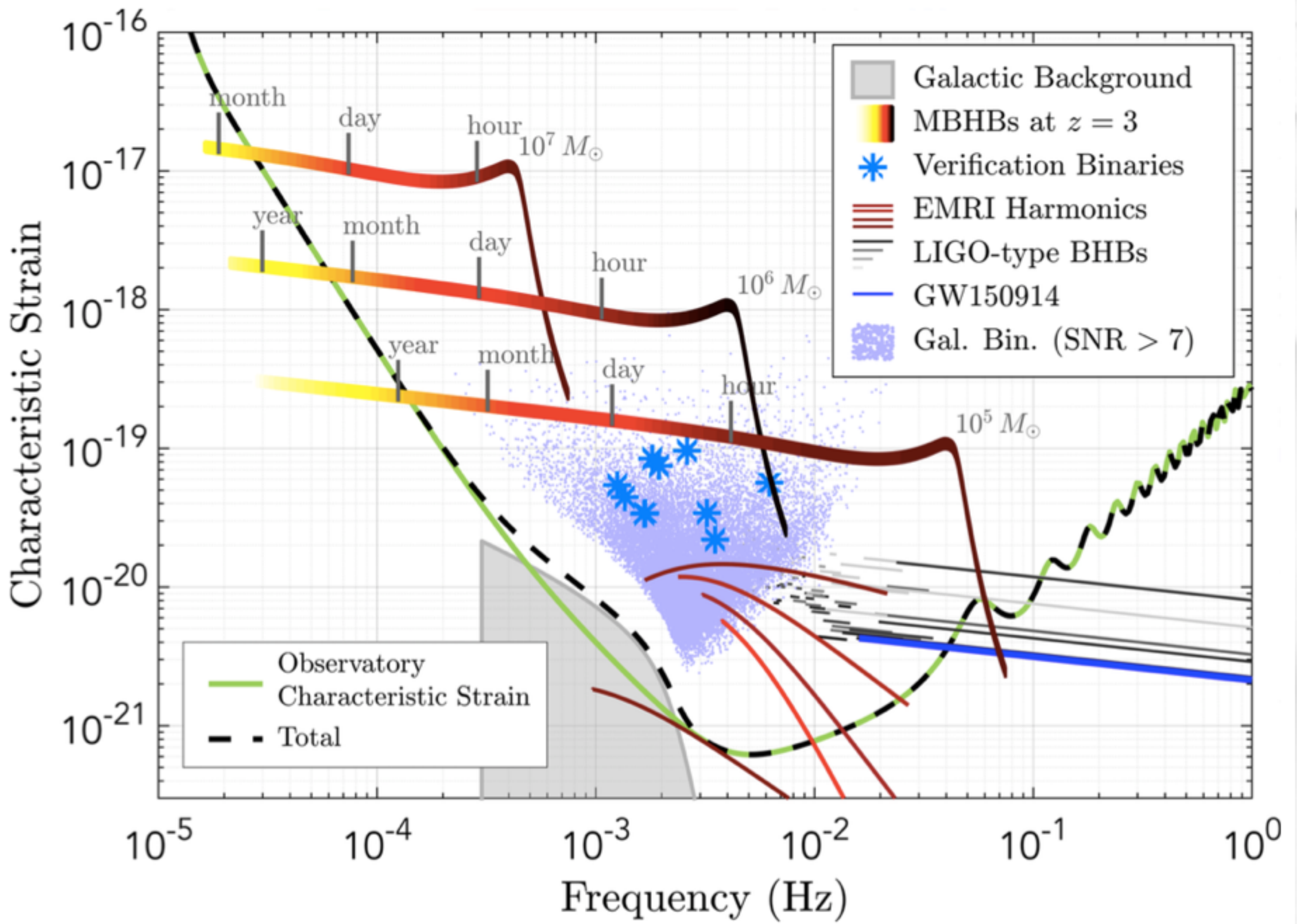
**Validated with LISA Pathfinder**

- **Precision interferometric, local ranging of test-mass and spacecraft:**
  - **pm resolution ranging, sub-mrad alignments**
  - **High stability monolithic optical assemblies**

- Precision million km spacecraft to spacecraft precision ranging:
  - **High stability telescopes**
  - **High accuracy phase-meter and frequency distribution**
  - **High accuracy frequency stabilization (incl. TDI)**
  - **Constellation acquisition and low jitter laser pointing**
  - **Precision attitude control of S/C**

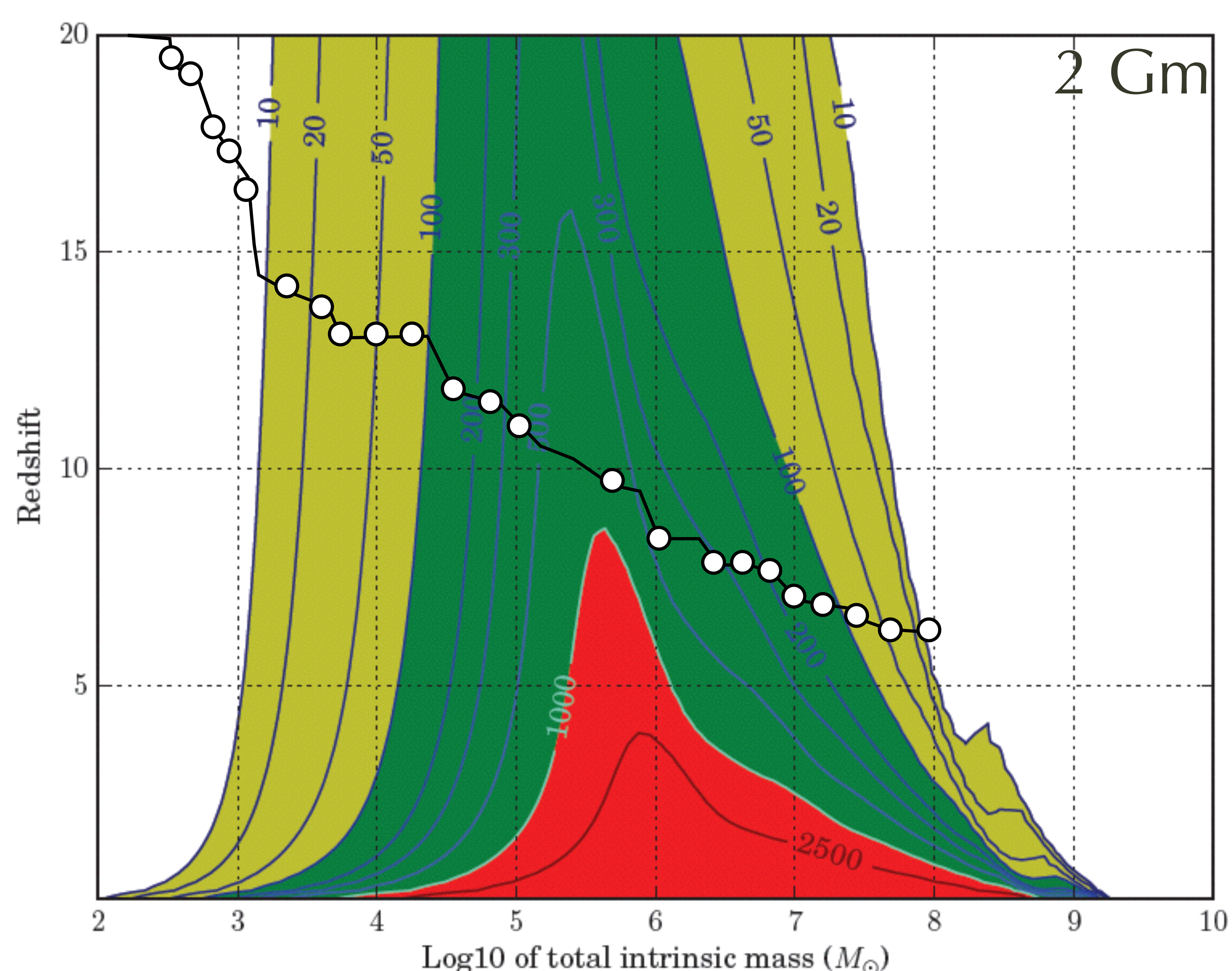
**Ground-based demonstrators**

# LISA Strain Sensitivity

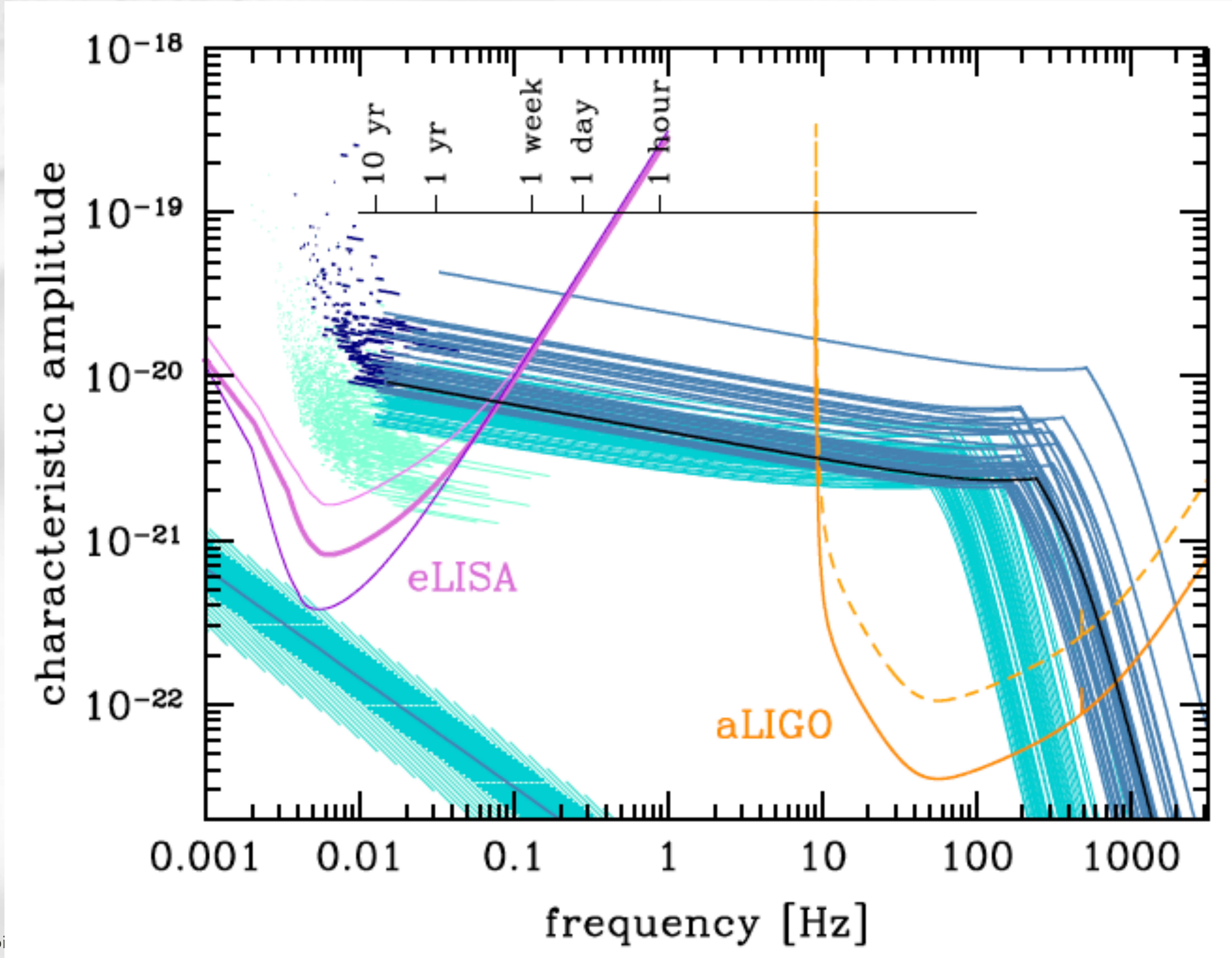


# SMBH detection

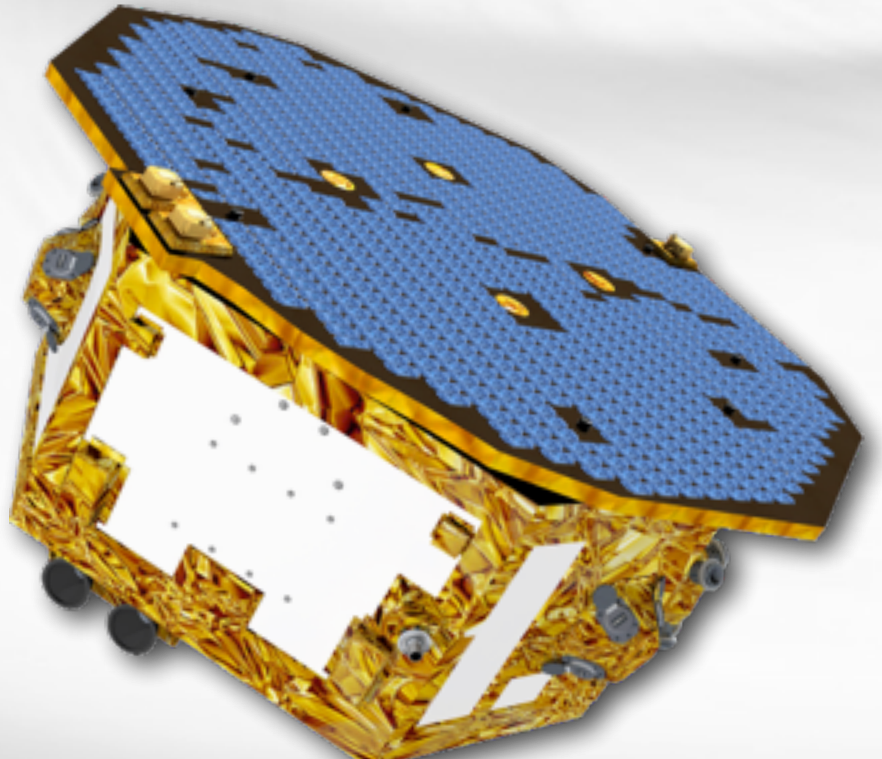
- SNR and evolution track of equal mass SMBH coalescences



# Multiband GW astronomy…

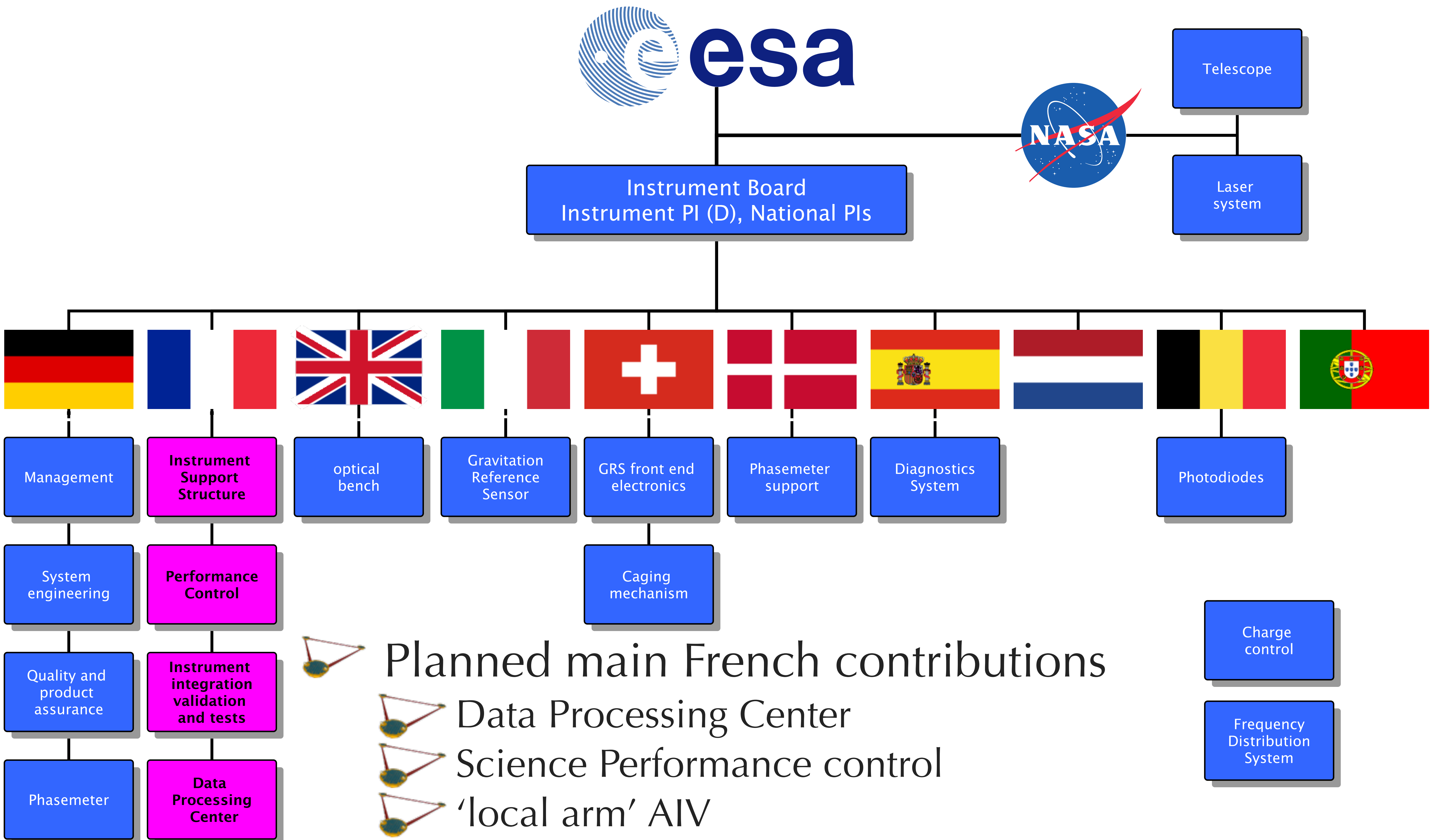


# Proposed French Contributions to eLISA



Hubert Halloin - Séminaire LLR - January 16th, 2017

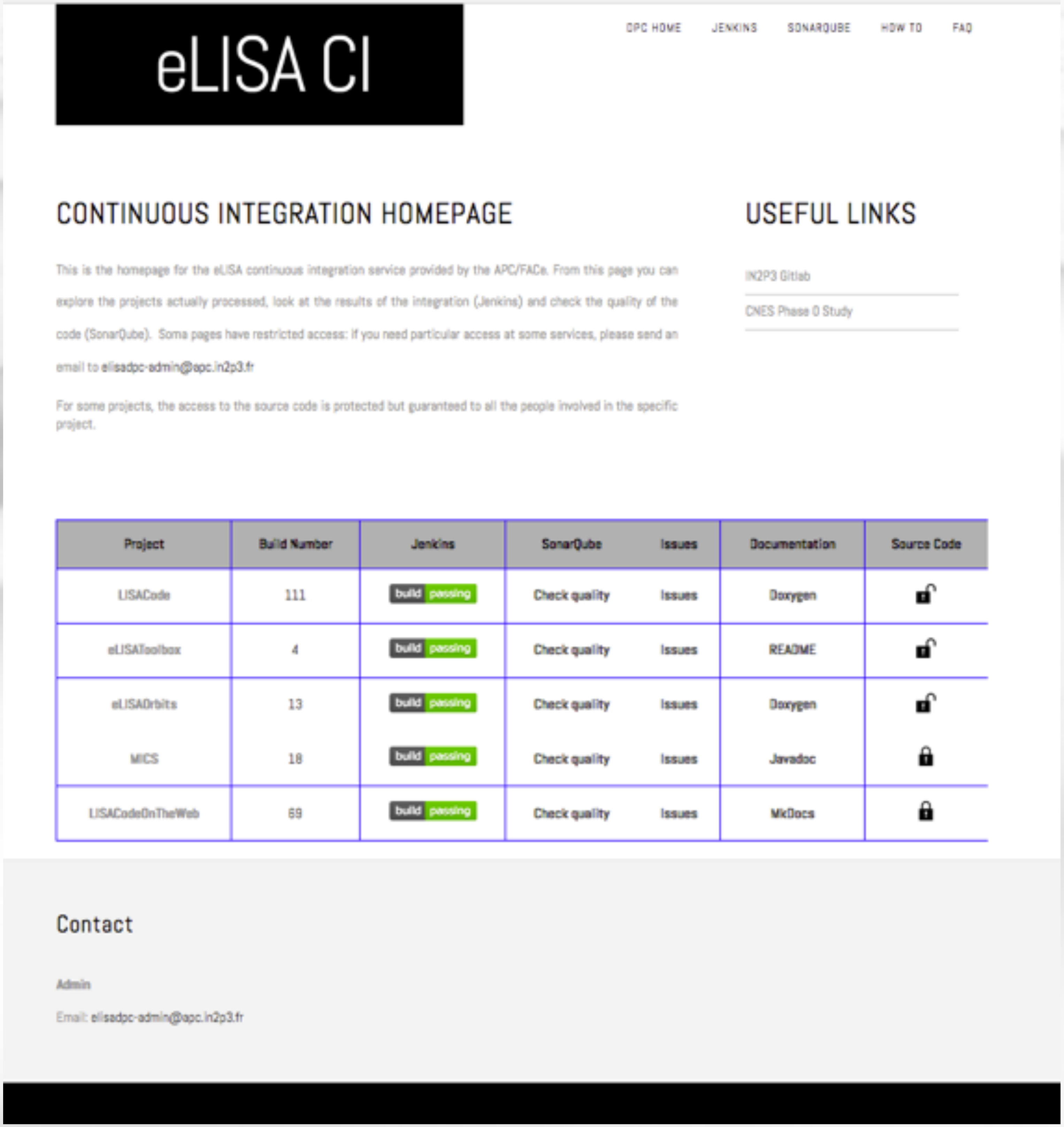
# What contribution for France ?



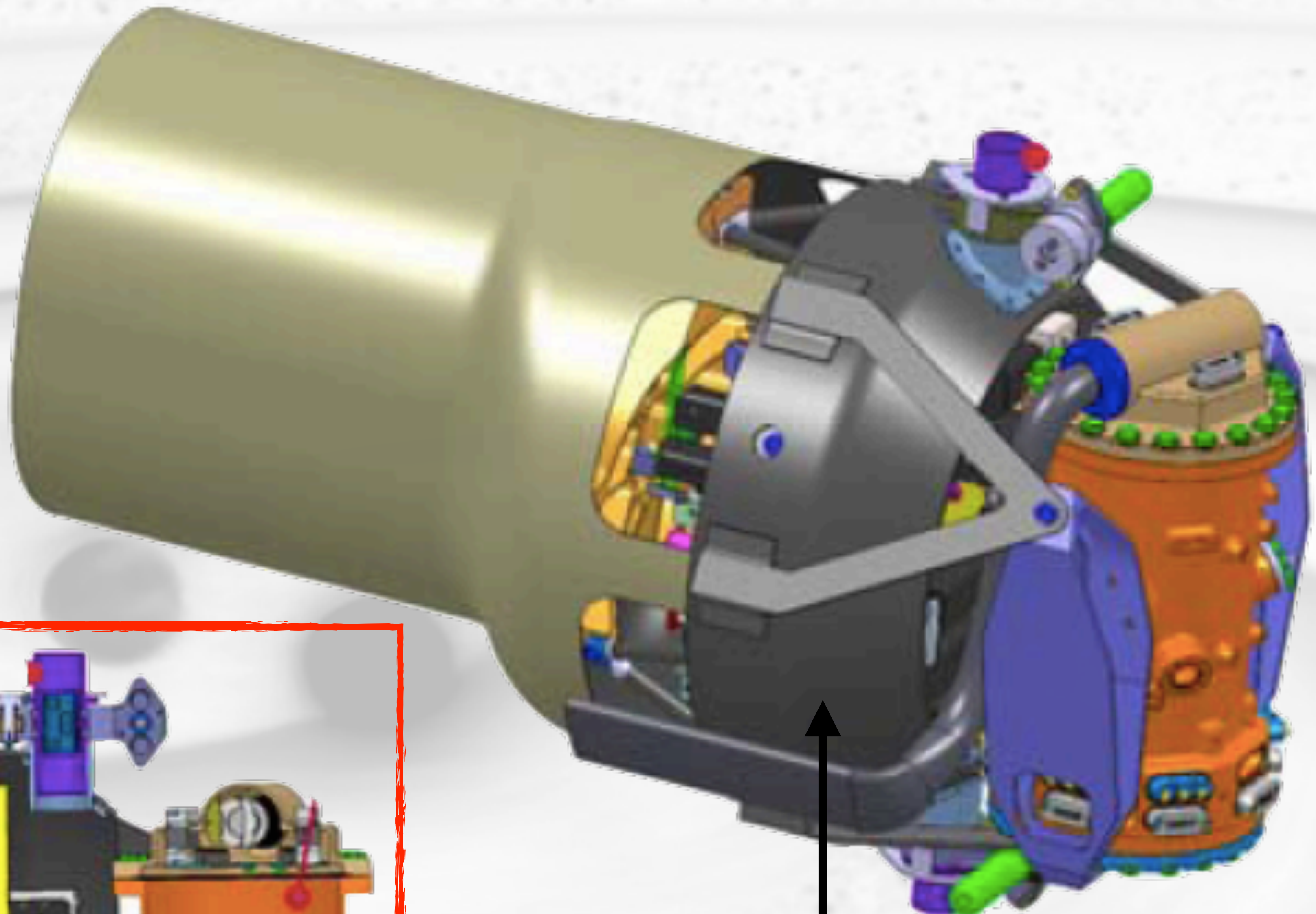

- Planned main French contributions
  - Data Processing Center
  - Science Performance control
  - ‘local arm’ AIV

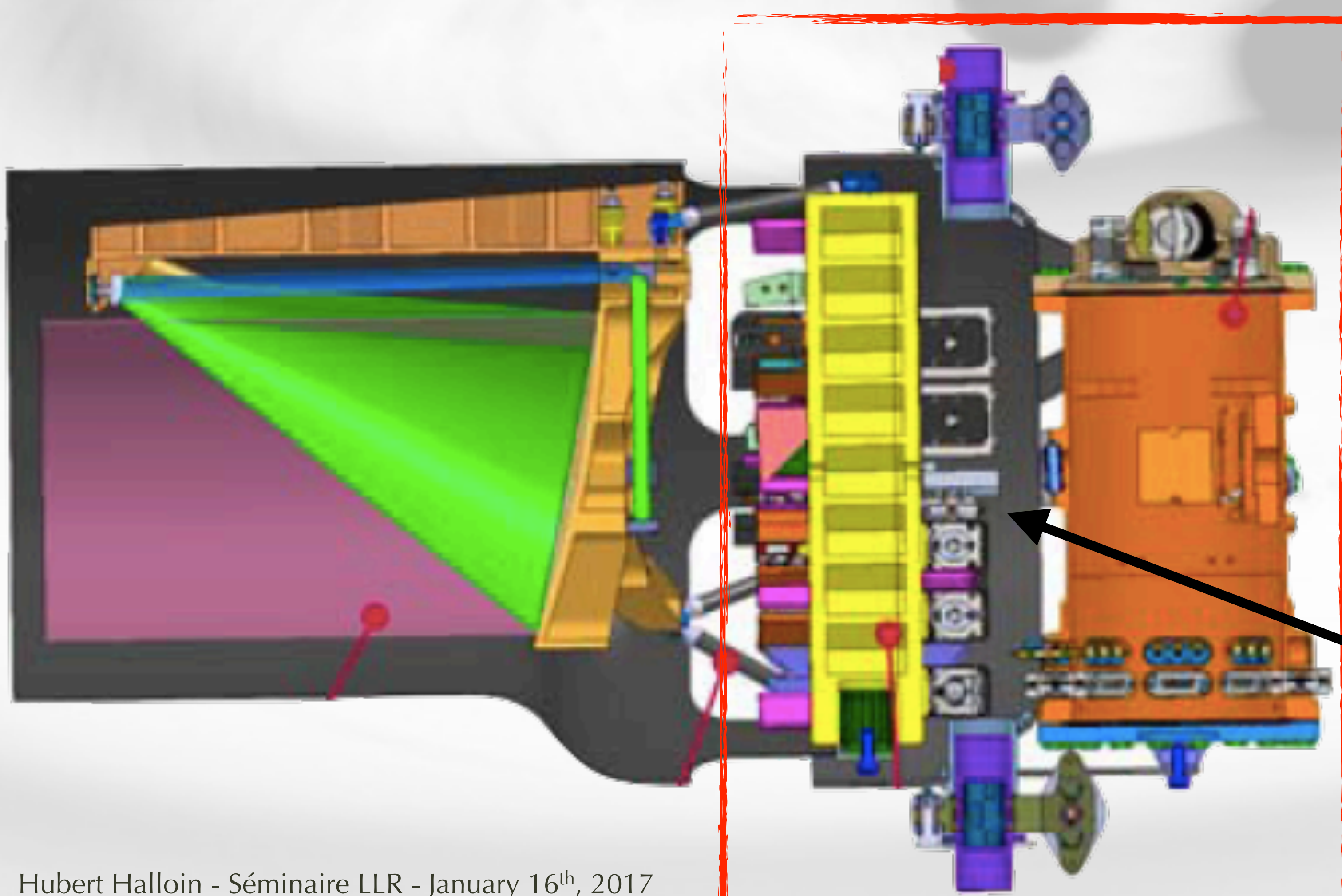
# Data processing center

- Development of a data processing center for LISA
  - Will host, validate, distribute and maintain data analysis software and documentation from and to the scientific community
  - Feasibility study conducted by the CNES in 2013-2014
    - Feasible with present technologies
    - Cloud computing seems well adapted to accommodate the required variability in computing power
- Proto-data processing center operational !
  - https://elisadpc.in2p3.fr/



# ‘Local’ arm

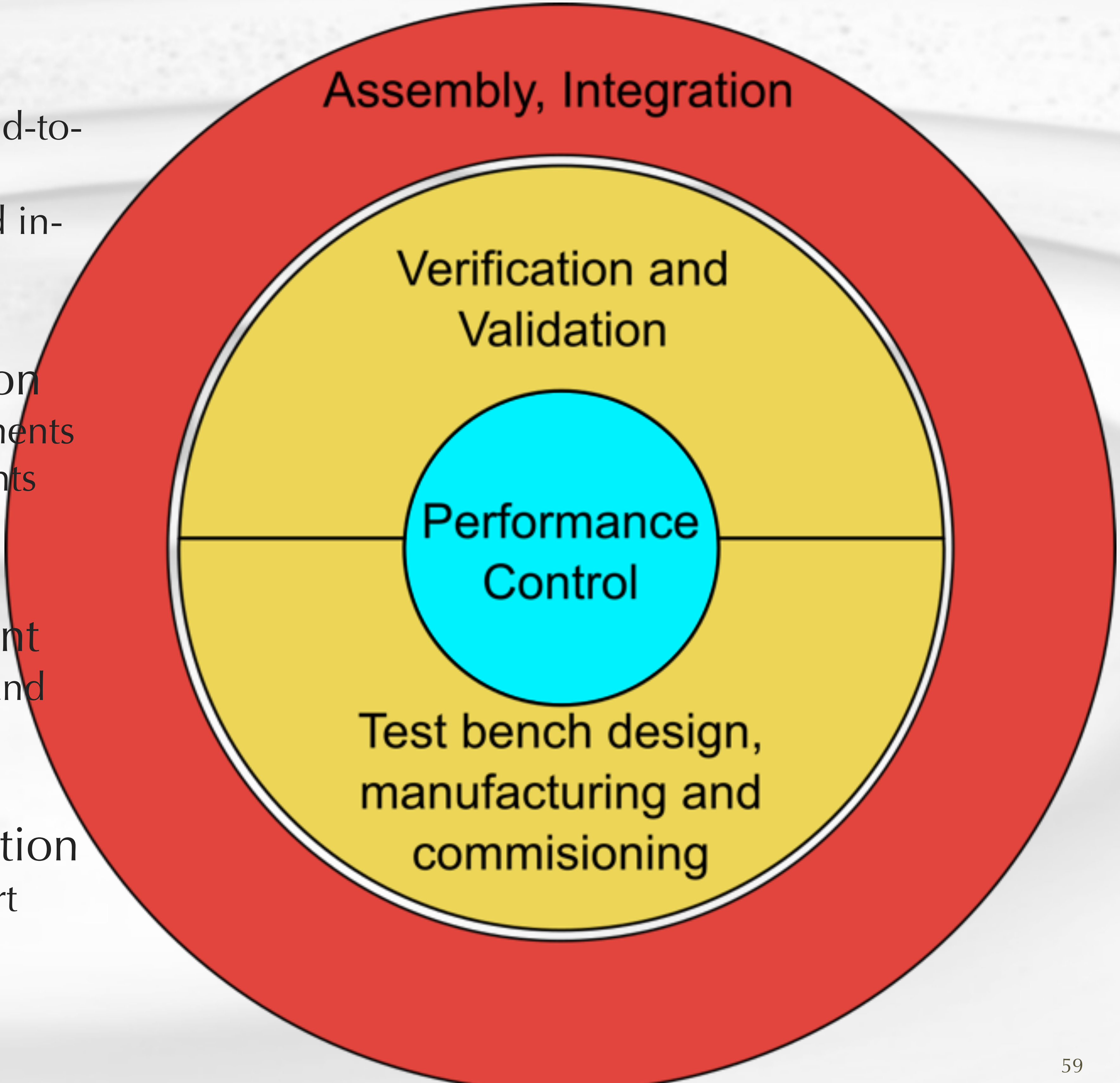




High stability CFRP mounting structure

# AIVT and performance control

- Performance control
  - System modeling and implementation in an end-to-end simulator (Started !)
  - Update from ground and in-flight measurements
- Verification and validation
  - Convert system requirements into ground measurements (as far as possible…)
- Test benches development
  - Design, manufacturing and commissioning
- Integration and qualification
  - Design of ground support equipments
  - Integration activities …



# LISA development schedule

2015 : First direct detection of GW !

- LISA Roadmap...
  - L3 Science Theme selection — 2013
  - Data Processing Center Phase 0 (CNES) — 2013 – 2014
  - Successful LISA Pathfinder flight — 2016 – 2017
  - AIVT Phase 0 (CNES) — 2016 - 2017
  - Call for mission — October 2016 —> January 2017
  - Consortium agreement — April 2017
  - Mission Phase 0 (ESA) — Mid 2017
  - Competitive industrial Phase A — Late 2017 —> Early 2020
  - Mission adoption — 2020-2022
  - Start of industrial manufacturings — 2021-2023
  - LISA launch — 2030-2034

- Critical time period : 2017-2018 ..
  - Consolidation of the mission design and roles of partners (especially NASA)
  - For France :
    - Participation to system studies (incl. performance control)
    - AIT activities (incl. participation to the provision of the support structure)
    - DPC design consolidation

# LISA needs you !

- **A new window on the Universe is opening !**

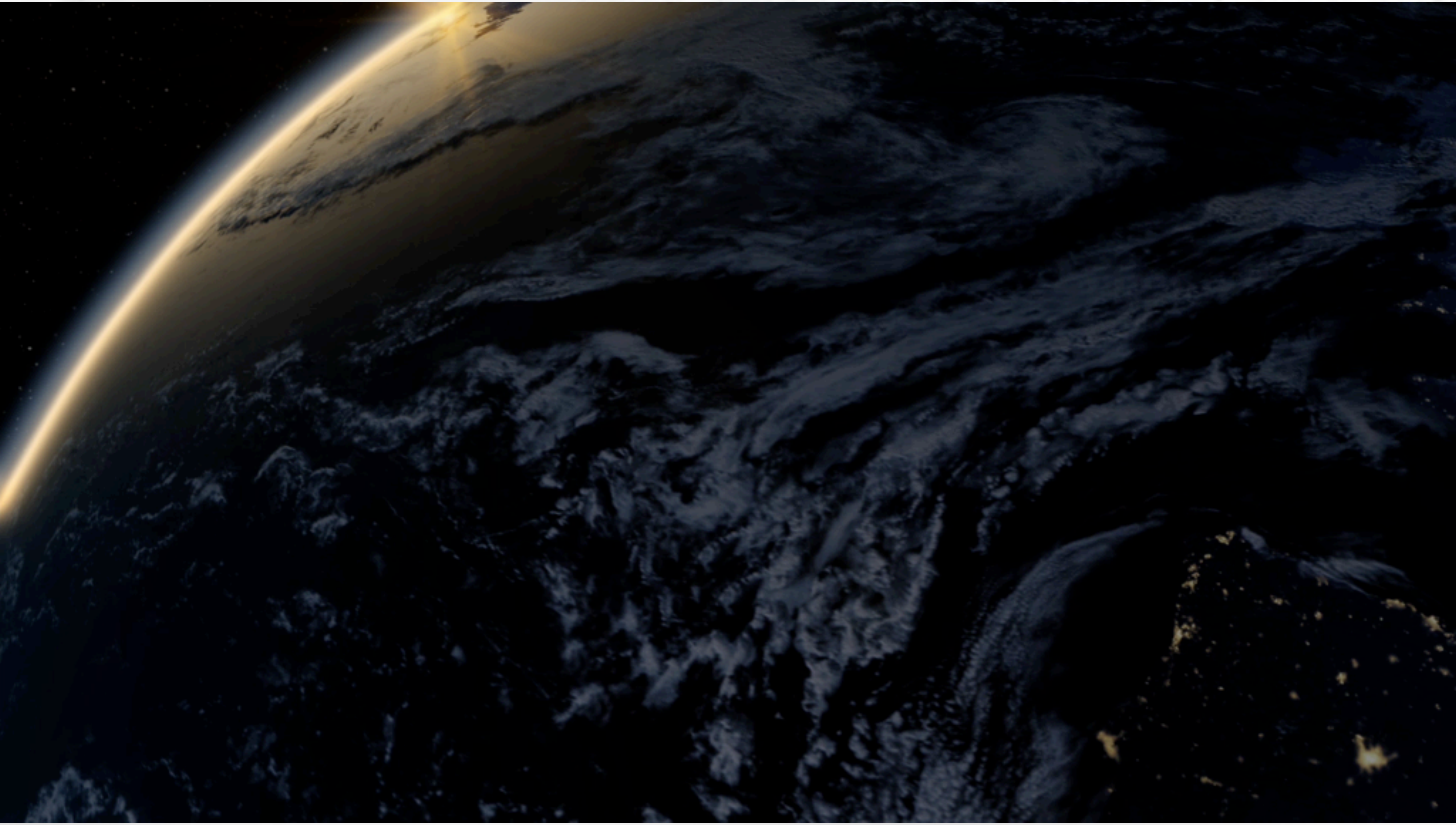
  **The contributions of French labs to LISA must increase !**

- **In astrophysics & fundamental physics:**
  - **What can we learn from GW sources ? On stellar evolution ? On large structure formations ? When and how do BH form ?**
  - **How far can we test GR and other theories (cosmic strings, inflation, etc.) ?**
  - **What counterparts can be expected in the EM spectrum ? Can we use BH as standard sirens ?**
- **Data analysis :**
  - **Source modeling**
  - **Alternative data processing algorithms**
  - **How to deal with a (probably) source dominated signal ?**
- **Instrumentation, HW and AIVT :**
  - **Instrument modeling (optics, electronics, thermo-elastic, ..**
  - **CFRP support structure design and manufacturing**
  - **Test benches design and realization**
  - **Expertise in integration and tests for space projects**
  - **…**

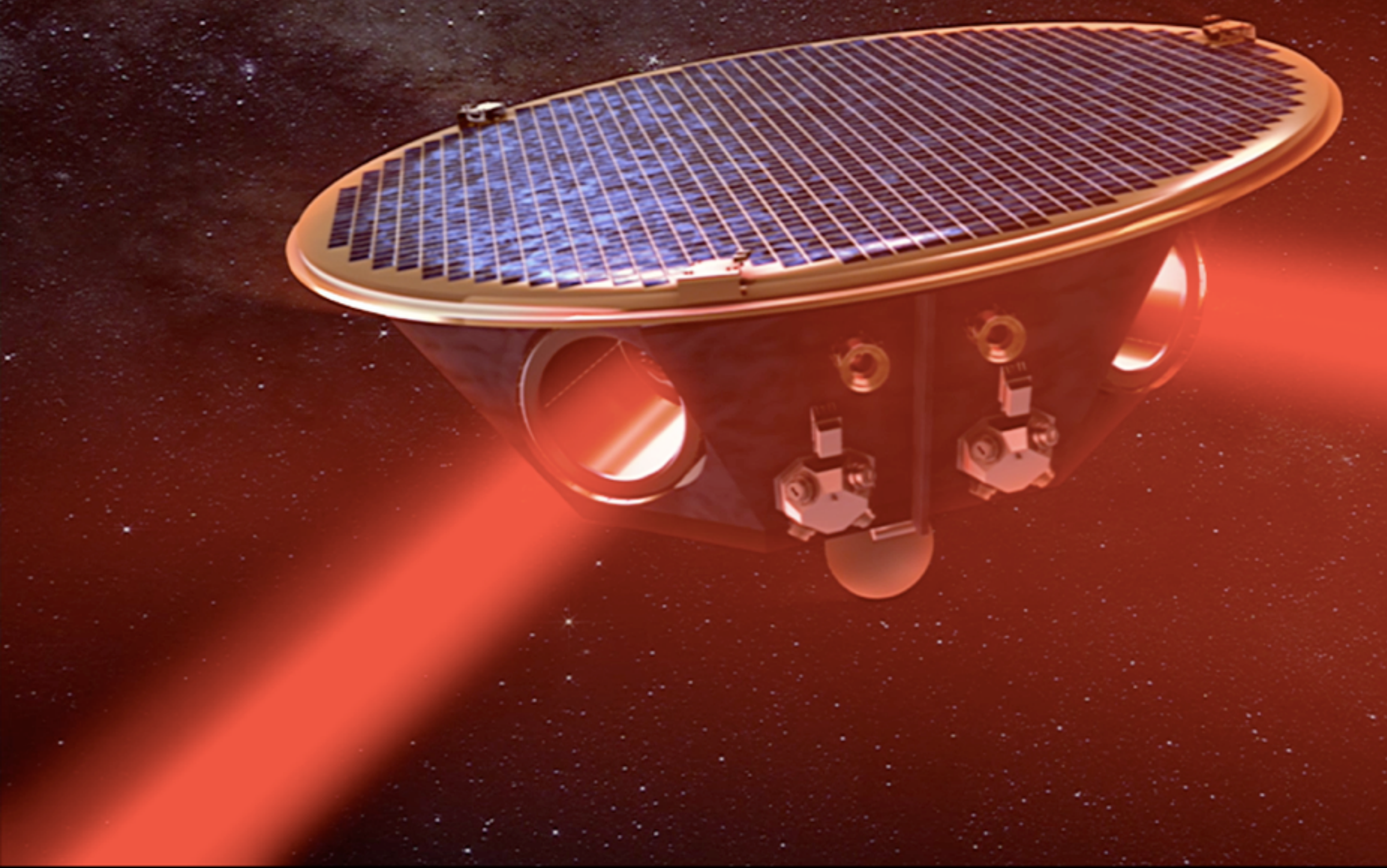
# More info on https://www.lisamission.org/

# LISA

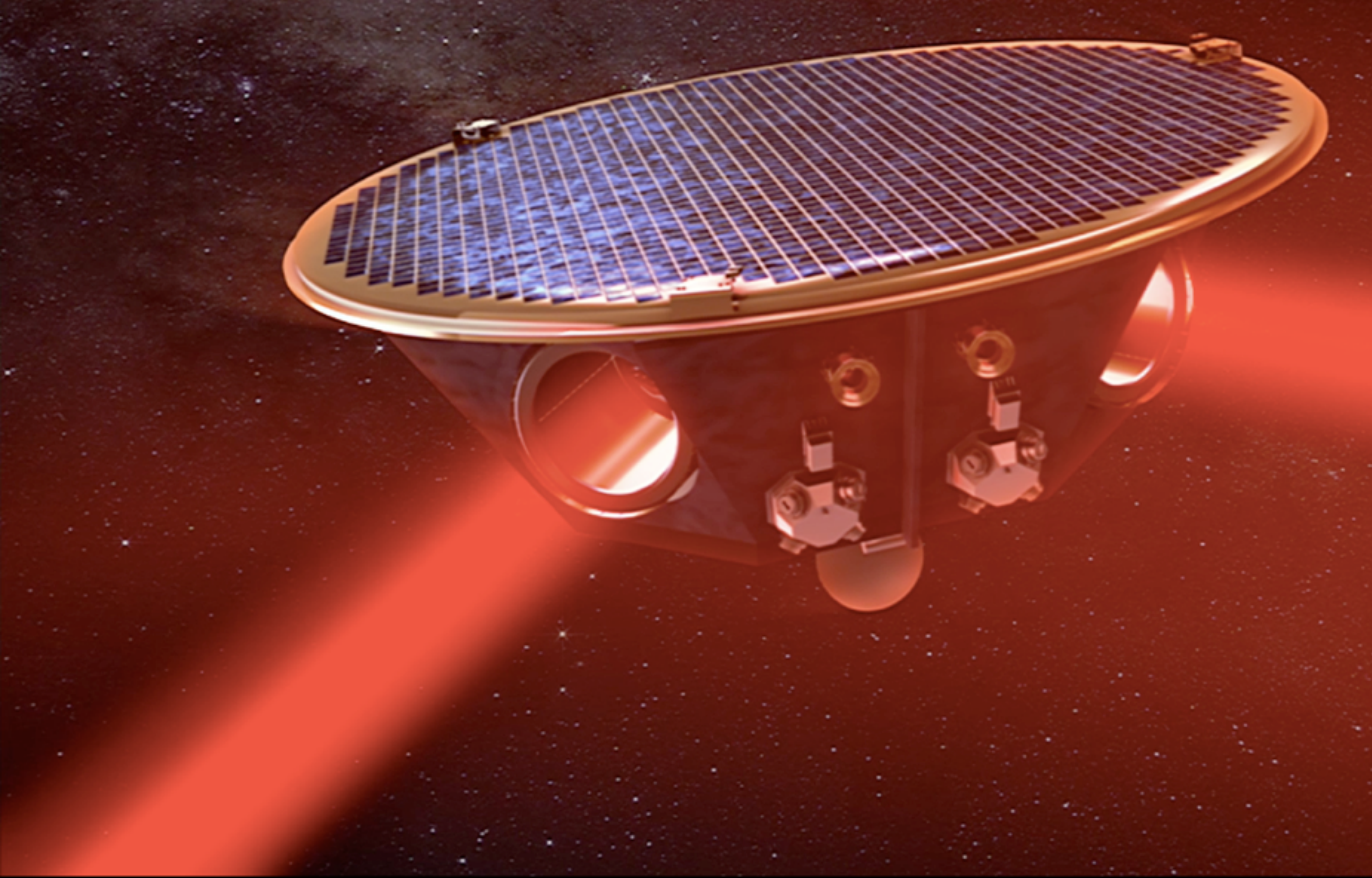
https://www.elisascience.org/multimedia/video/elisa-trailer



# Thank you

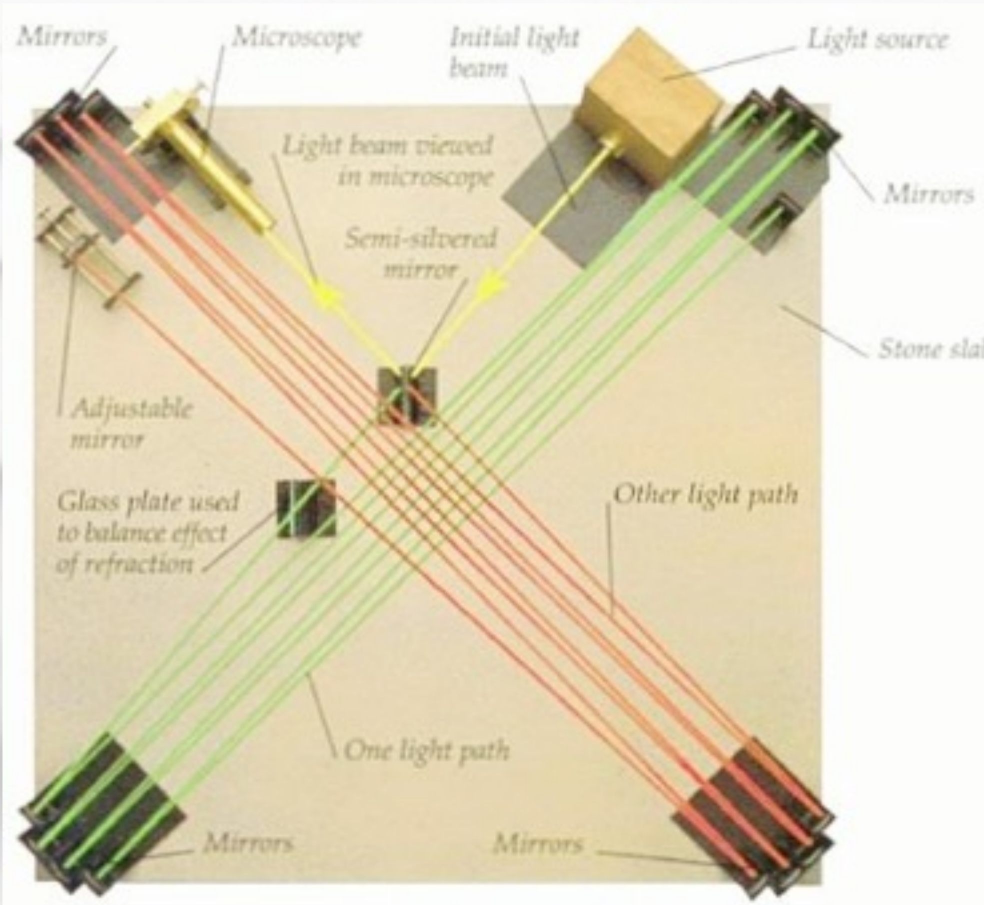


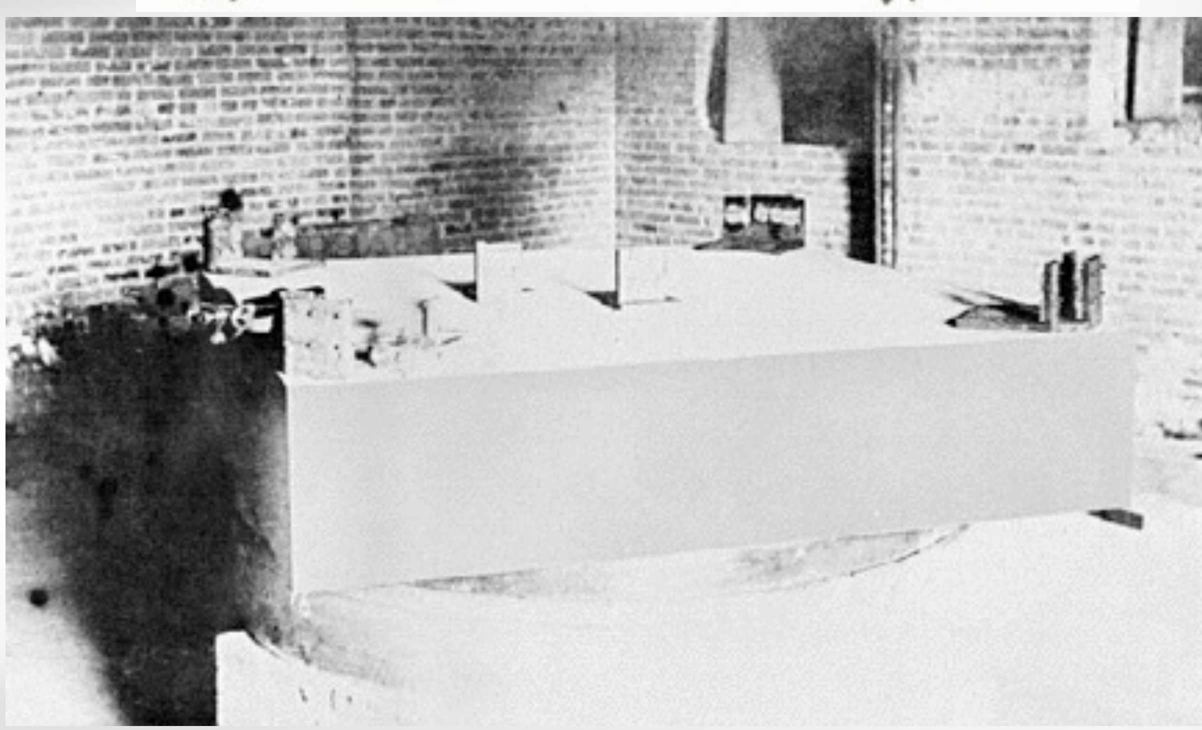
# Extras



# «They did not know it was impossible, so they did it !», Mark Twain

- Interferometry is a very precise metrology technique … from aether to gravitational waves
  - Measurement of the optical pathlength difference between 2 arms
- Michelson & Morley experiment (1887)
  - M&M experiment : the speed of light doesn't depend on the propagation direction
  - Measurement precision of the M&M experiment :
    $6\ \text{nm} / 11\ \text{m} \approx 5\ 10^{-10}$
- GW interferometers
  - Performance :
    $10^{-8}\ \text{pm} / 1\ \text{km} \approx 10^{-23}$ (VIRGO / LIGO)
    $1\ \text{pm} / 10^{6}\ \text{km} \approx 10^{-21}$ (eLISA)



Michelson & Morley interferometer (1887)

# Questions often asked about LPF

- Why the TMs are massive (2 kg):
  - The large inertia of the TM will reduce the impact on any stray forces, e.g. brownian, electrostatic forces, …
- Why the 4 mm distance between electrodes and TM:
  - This distance will average local stray potential,…
- Charging by cosmic rays of the TMs:
  - A set of UV lamps discharge, possibly continuously, the TMs (~20 $e^-$/sec).
- Internal gravitational + internal forces and stifness:
  - The gravitational force between the TMs and the SC has been minimized by positioning "correction masses" in appropriate location of the SC.
- Orders of magnitude : Acceleration and TM displacement:
  - **$3\ 10^{-15}$ m s$^{-2}$ at 1 mHz** : A simple calculation (random walk with acceleration of $3\ 10^{-15}$ m s$^{-2}$ every 1000 seconds) would give an average displacement of the TM of a few mm within a year… but the DFACS keeps it to a few picometers !
- Vacuum Quality:
  - Estimated at ≈ 5 $10^{-11}$ atmospheric pressure (in LHC, ≈ $10^{-12}$). We would like to improve this !
- What do we gain for LISA if ΔG is improved at low frequencies (~$10^{-5}$ Hz):
  - Earlier detection of MBHB,
  - Detection of more massive BHB.

# France in the Product Tree …