Groupe Gravitation

From LISAPathFinder to LISA: simulation and data analysis

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Let me walk you through...

Detecting gravitational waves

LISA and LISAPathFinder

Simulation of the mission

DETECTING GRAVITATIONAL WAVES

From General Relativity...

- Einstein's theory of **General Relativity** describes gravity as manifestation of curved spacetime
- This is described by the **metric** tensor, related to mass-energy content by **Einstein's equation**:

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{Curvature of spacetime}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{Mass-energy content}}$$

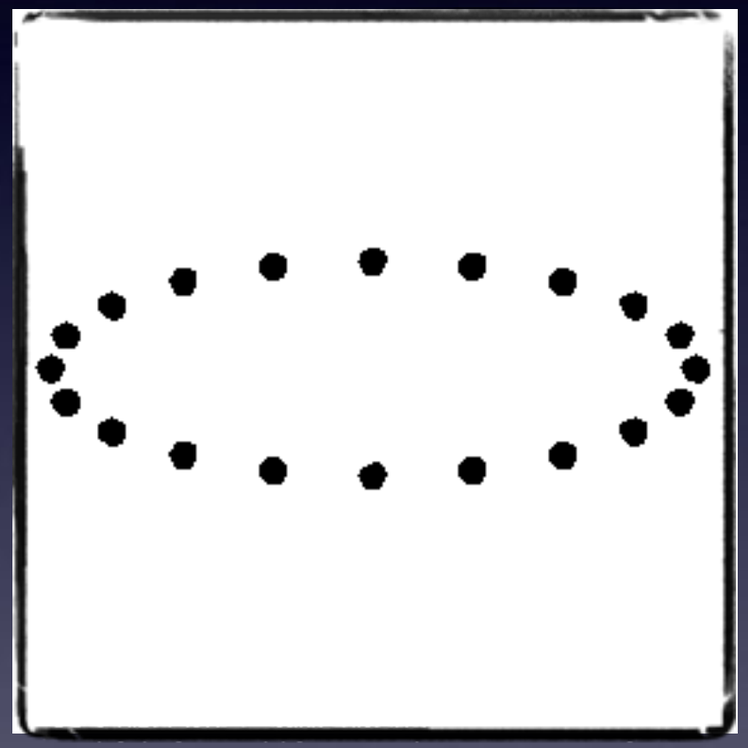
... to gravitational waves

- Analytical solutions are notoriously hard to find
- **Linearisation** of Einstein's equation for small deformations () of the metric tensor yields a **propagation equation**:

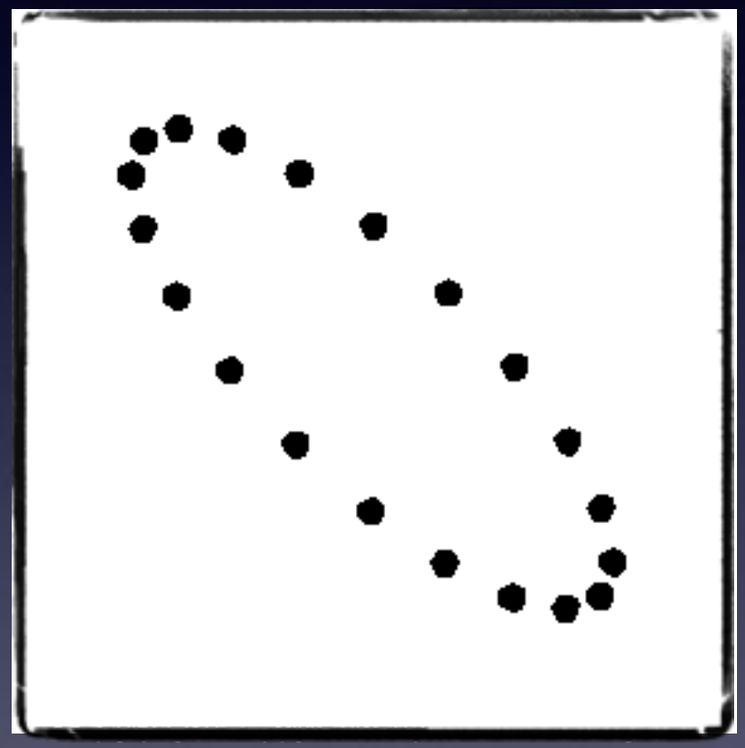
$$\eta^{\alpha\beta}\partial_\alpha\partial_\beta\bar{h}_{\mu\nu} = \frac{16\pi G}{c^4}T_{\mu\nu}$$

- Gives rise of **gravitational waves** moving through spacetime at the velocity of light

Effect of gravitational waves

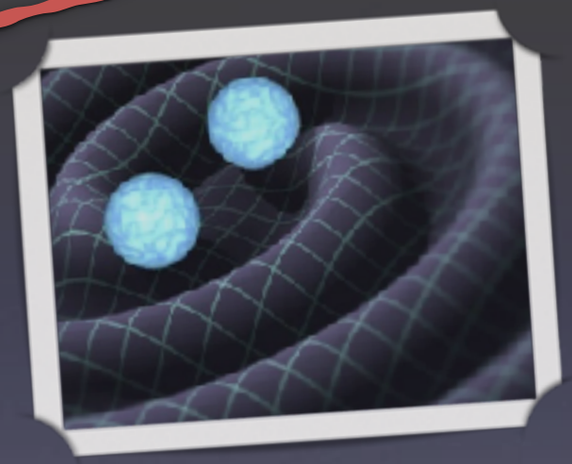


h_+



$h_\times$

HARD TO DETECT!



Gravitational Wave

GOOD MESSENGER

Velocity: c

Type: transverse

Polarisation: two modes h_+ and $h_\times$

Transport: energy

Amplitude: very small

Produced by: quadrupole moment of stress-enery tensor

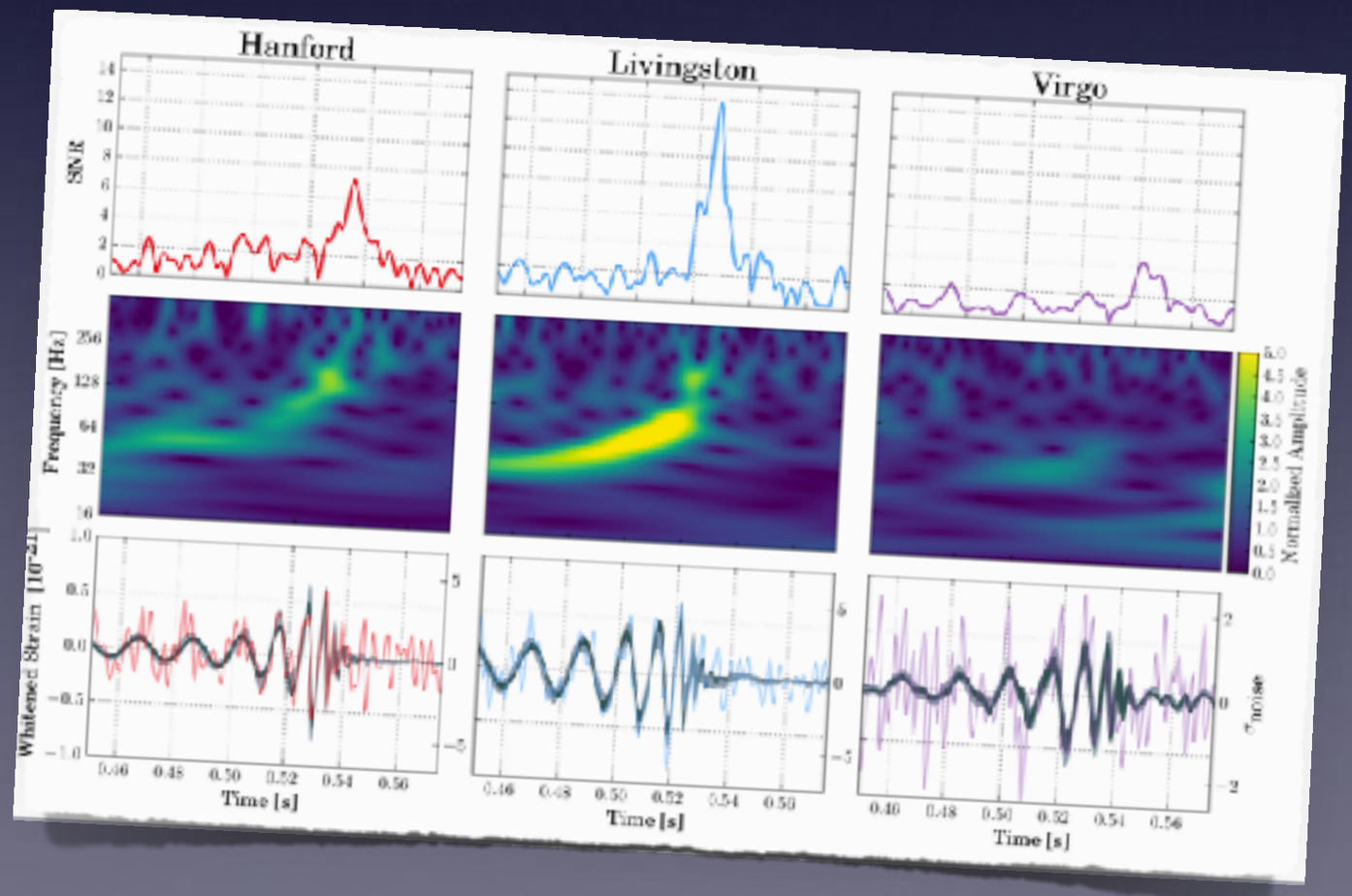
Interaction with matter: very small

Ground-based detectors

Virgo detector Cacscina, Italie

GW170814 and GW170817

- **Three-detector** observation of a binary black-hole coalescence by LIGO and Virgo on August, 14th
- **Binary neutron star** merger observed on Aug., 17th

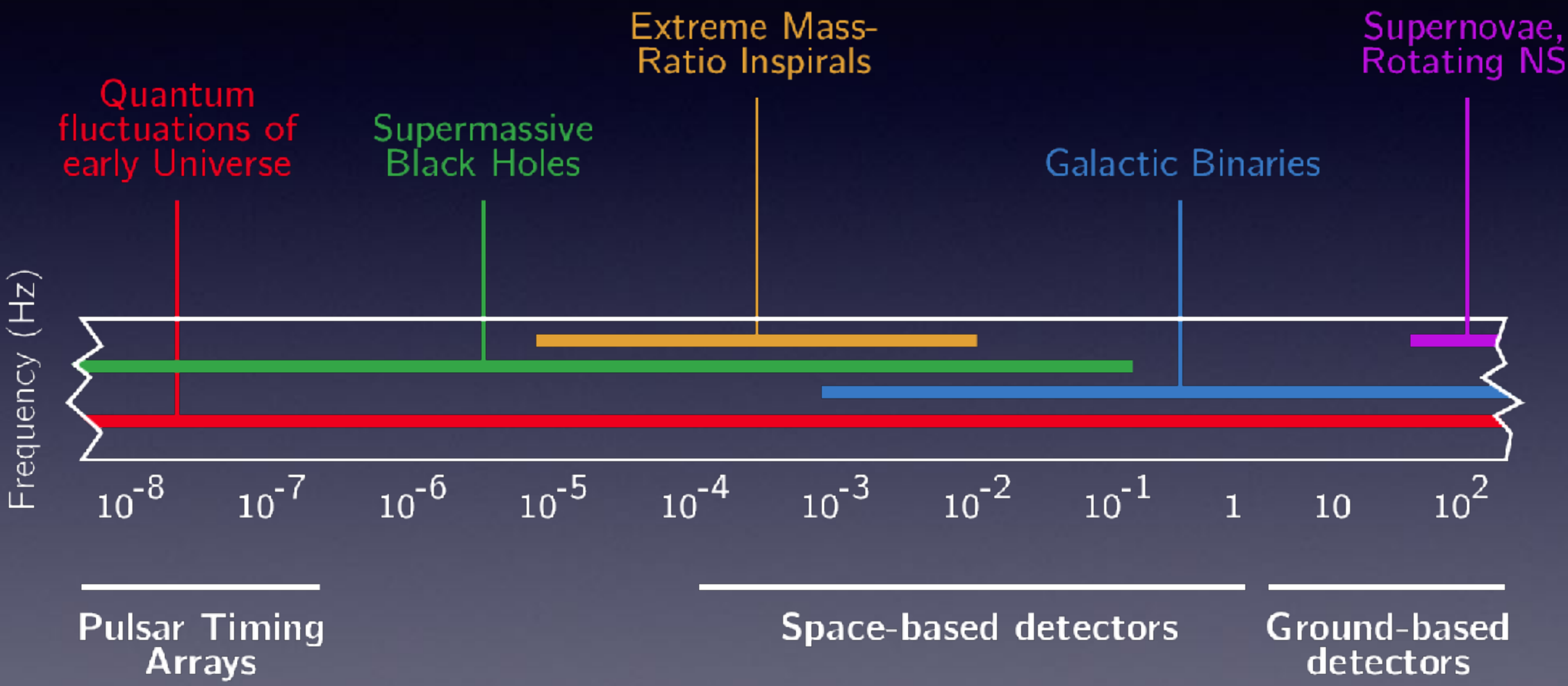


Strain from GW170814 as measured by LIGO and Virgo on August, 14 2017

Physical Review Letters

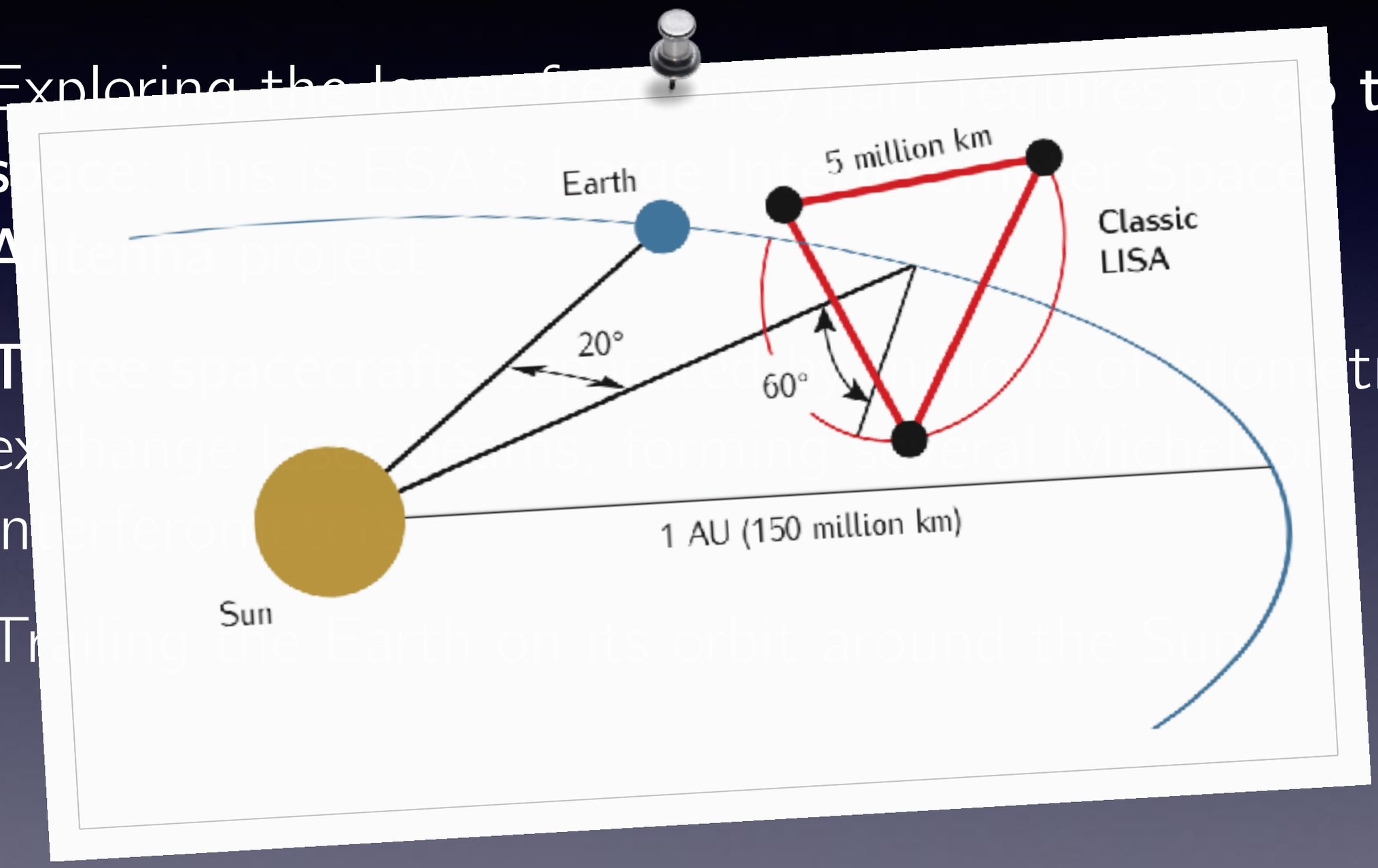
LISA AND LISAPATHFINDER

Gravitational spectrum

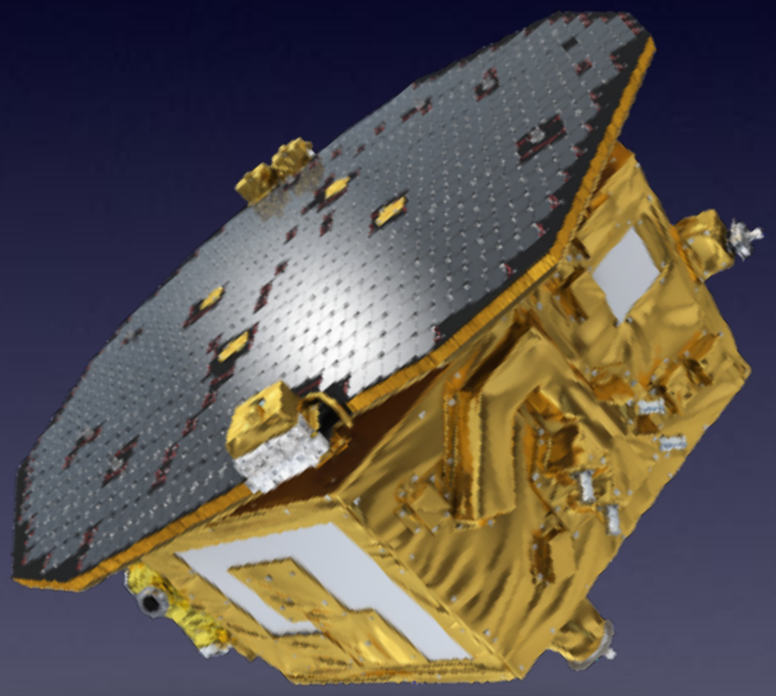


Gravitation from space

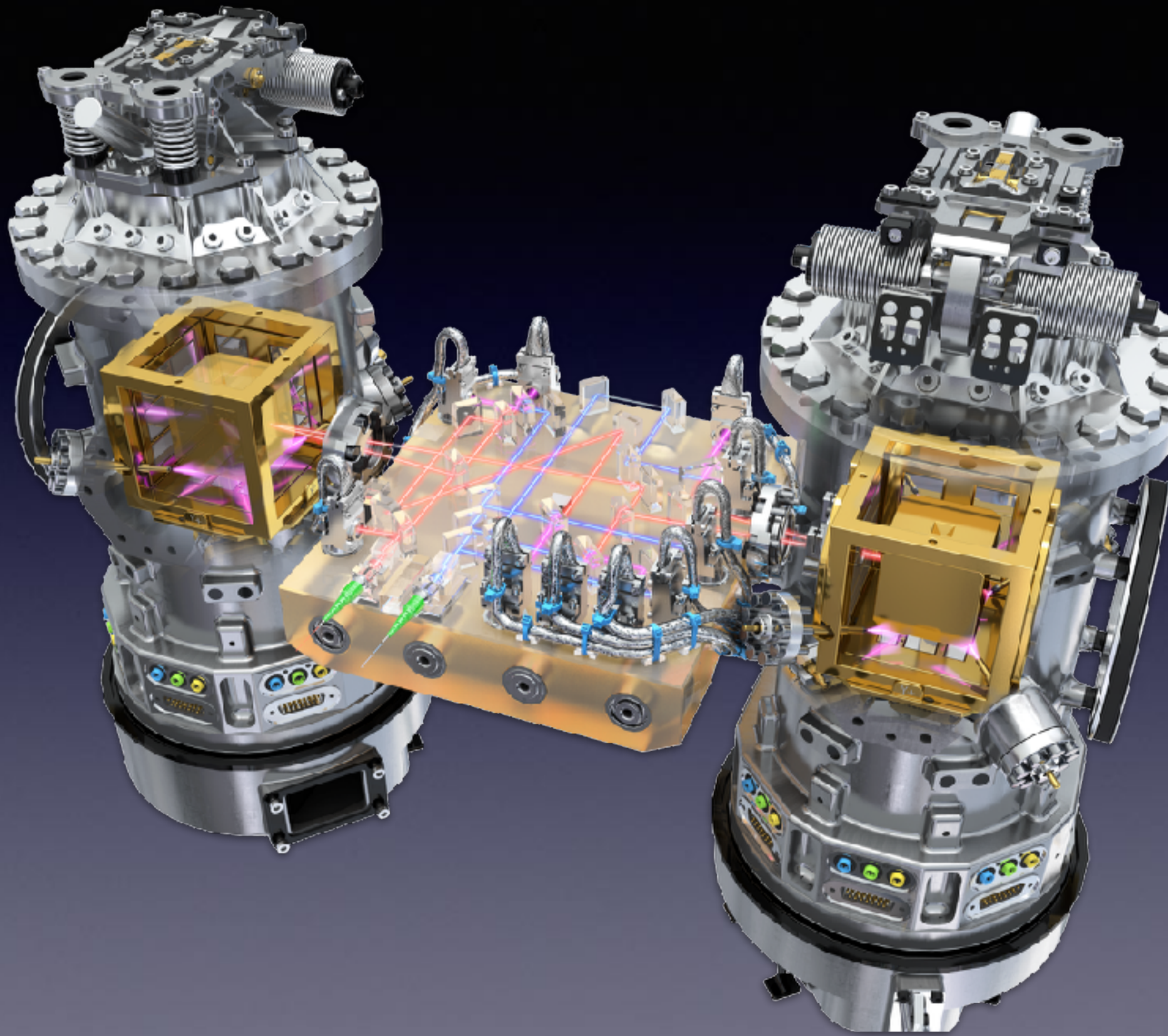
- Exploring the lowest frequency part requires to go to space: this is ESA's cornerstone mission Space Antenna project
- Three spacecraft forming an equilateral triangle centres exchange laser beams, forming several Michelson interferometers
- Trailing the Earth on its orbit around the Sun



LISAPathFinder: a proof of concept

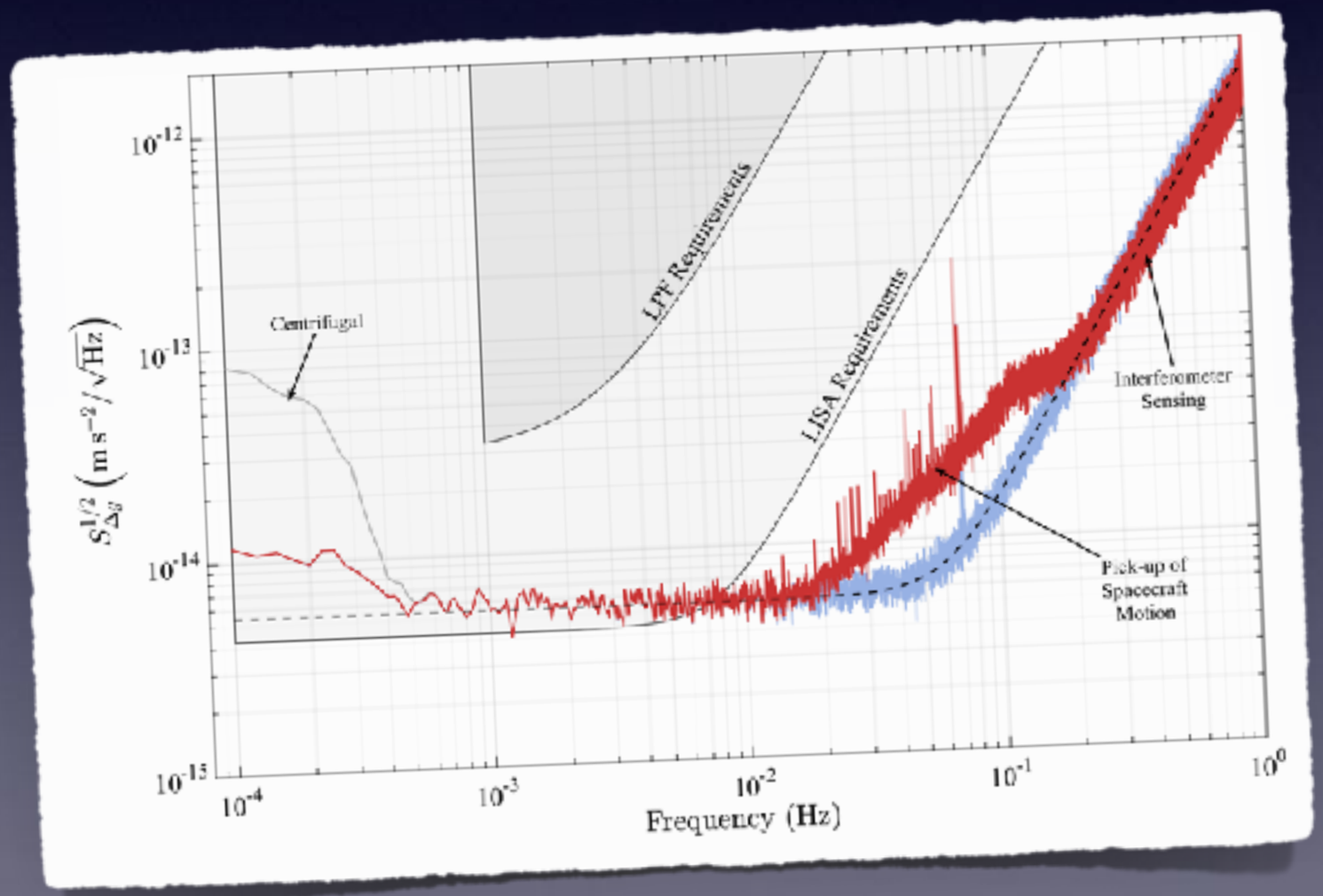


- Proof-of-concept ESA mission launched in December 2015
- An LISA arm is shrunk down to **38 cm** between two test masses that are kept drag-free
- Optical interferometry for precise measurement of the **residual acceleration** of one mass relative to the other



LISAPathFinder: a proof of concept

- The **first results** announced last June exceeded requirements in the LISAPathFinder frequency band



LPF and LISA requirements, and amplitude spectral density of residual differential acceleration (black), after centrifugal force corrections (red), after spacecraft motion corrections (blue).

Physical Review Letters, 10 June 2016

SIMULATION OF THE MISSION

French contribution

- **ESA selected LISA** as the L3 mission earlier this year, phase A starts beginning 2017
- Scientific consortium is being organized and national contributions are being decided
- Foreseen French contributions: **integration of the instrument**, **data processing center**; includes environment for analysis pipelines, collaboration tools, ...

Simulating data

- Develop the mission end-to-end simulator to produce **realistic data** from waveforms to the response of the instrument, under various configurations
    - prepare for **data analysis**, prove that scientific objectives as defined in the mission proposal can be reached in the framework of LISA Data Challenges
    - **asses scientific value** of instrumental configurations studied by industrials during phase A

Pre-processing steps

- LISA is a complex system, **pre-processing** necessary before scientific analysis (a.k.a. source extraction and parameter estimation):

The truth about LISA

'This is just another Michelson interferometer'

Offline recombinaison

TIME-DELAY INTERFEROMETRY

2W emitted

a few 100s of pW collected

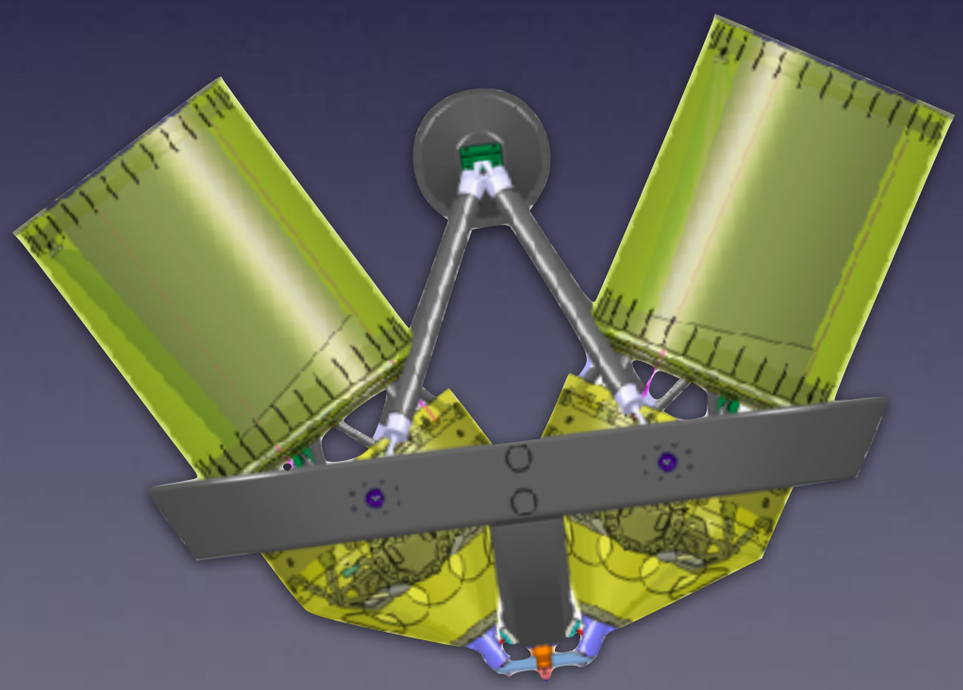
Pre-processing steps

- LISA is a complex system, **pre-processing** necessary before scientific analysis (a.k.a. source extraction and parameter estimation):
  - **Time-delay interferometry**: offline linear combinaison of several measurements to cancel out uncorrelated laser noises
  - **Clock synchronisation**: correct for ultra-stable oscillators drift onboard each spacecraft

The truth about LISA

'Spacecraft form an equilateral triangle'

- Ideals orbits do not exist!
- Distance between spacecrafts not constant, hence a **shift in phase** and **Doppler effect** that mock a passing gravitational wave
- Angle between spacecrafts is not constant, hence **moving telescopes and optical benches** to point to distance spacecraft

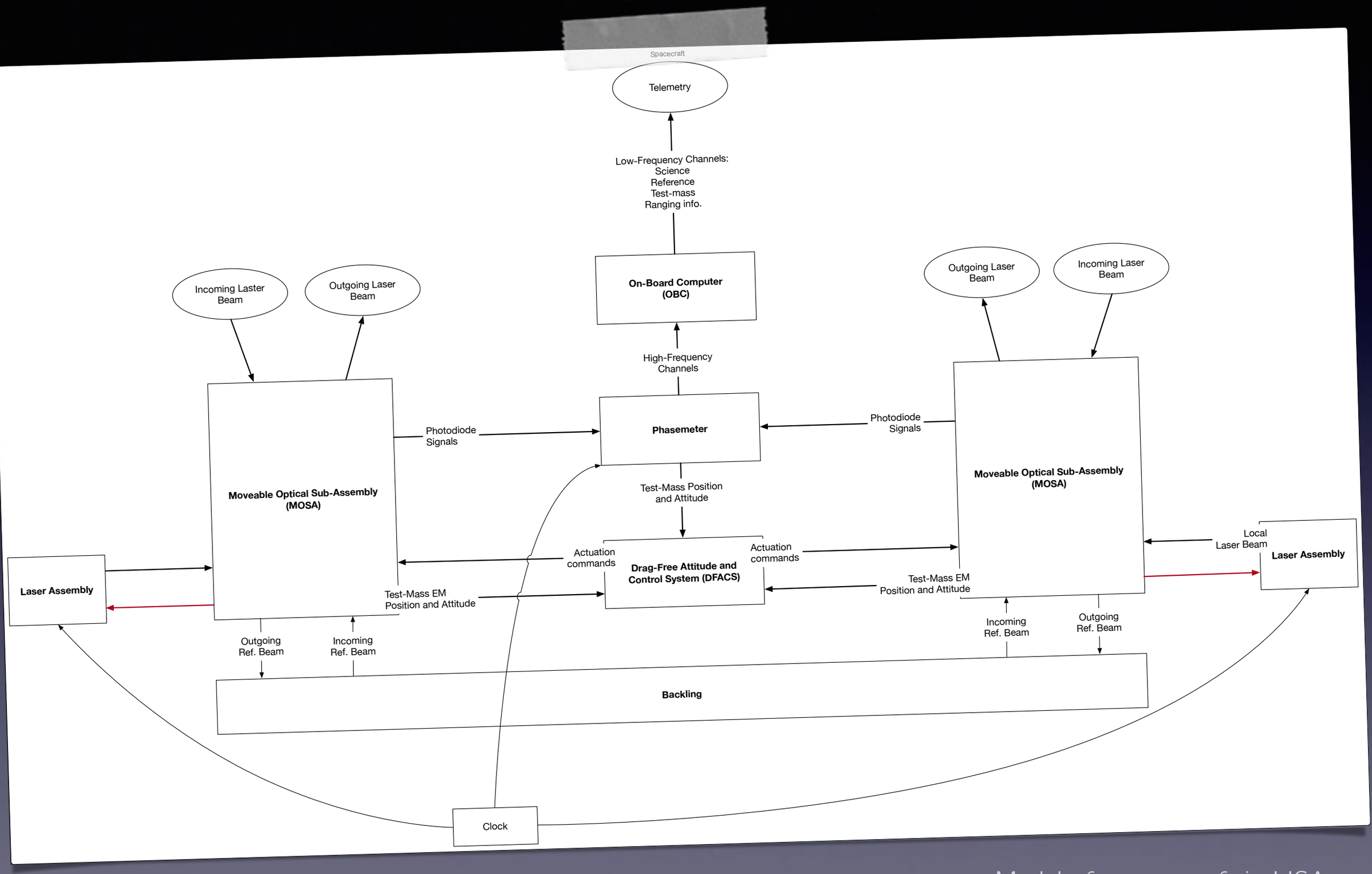


Pre-processing steps

- LISA is a complex system, **pre-processing** necessary before scientific analysis (a.k.a. source extraction and parameter estimation):
  - **Time-delay interferometry**: offline linear combinaison of several measurements to cancel out uncorrelated laser noises
  - **Clock synchronisation**: correct for ultra-stable oscillators drift onboard each spacecraft
  - **Absolute ranging**: measure the time-dependent inter-spacecraft distance for tdi

Graph-based simulator

- Offer a few **simple nodes** that can product or act on data, and be chained to form a **simulation graph**
- Nodes can be grouped inside **subgraphs** to create various levels of abstraction, and divide the instrument into subsystems
- For each “tick” of the clock, **all nodes are fired** in parallel to consume input data and computes new outputs



Model of a spacecraft in LISA

Ongoing studies

- Use **noise** sources and distributions extrapolated from LISAPathFinder investigations and findings
- Effect of ADC clock jitter on the phase measurement, antialiasing filtering before downlink
- **Laser intensity noise** coupling into phase meas.
- **Dynamics** of the constellation: equations of motion, controller strategy, effect of non-linearities
- Simple configurations for **time-delay interferometry**

Thank you.