LISA
Observing GW Universe from space

Antoine Petiteau
(UCP - Université de Paris)

Workshop GW Probes of Physics Beyond Standard Model
Remote - 16th July 2021
Overview

- Instrument
  - Space segment ("hardware")
  - Ground segment ("data processing")
- GW Science with LISA
- Organisation and status
THE GRAVITATIONAL WAVE SPECTRUM

Quantum fluctuations in the very early Universe

- Binary supermassive black holes in galactic nuclei
- Phase transitions in the early universe
- Black holes, compact stars captured by supermassive holes in galactic nuclei
- Binary stars in the galaxy and beyond
- Merging binary neutron stars and stellar black holes in distant galaxies; fast pulsars with mountains

Sources

Wave Period

Age of the Universe

Years

Hours

Seconds

Milliseconds

Frequency (Hz)

$10^{-16}$

$10^{-14}$

$10^{-12}$

$10^{-10}$

$10^{-8}$

$10^{-6}$

$10^{-4}$

$10^{-2}$

1

$10^2$

Detectors

- Inflation Probe: polarization map of cosmic microwave background
- Precision timing of millisecond pulsars
- LISA
- Big Bang Obs
- GEO, LIGO, Virgo, TAMA

GW spectrum
LISA mission

- Laser Interferometer Space Antenna
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of $10^{-21}$: few picometers
Being sensitive "only" to gravity

- Spacecraft (SC) should only be sensible to gravity:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters

- Readout:
  - interferometric (sensitive axis)
  - capacitive sensing
Being sensitive "only" to gravity

- Spacecraft (SC) should only be sensible to gravity:
  - the spacecraft protects test-masses (TMs) from external forces and always adjusts itself on it using micro-thrusters
  - Readout:
    - interferometric (sensitive axis)
    - capacitive sensing
LISAPathfinder

- Basic idea: Reduce one LISA arm in one SC.
- Operations: March 2016 to June 2017
- LISAPathfinder is testing:
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters
LISAPathfinder

- Basic idea: Reduce one LISA arm in one SC.
- Operations: March 2016 to June 2017
- LISAPathfinder is testing:
  - Inertial sensor,
  - Drag-free and attitude control system
  - Interferometric measurement between 2 free-falling test-masses,
  - Micro-thrusters
LISA Pathfinder first result

M. Armano et al. PRL 116, 231101 (2016)

Low frequency noise
Investigation still in progress

Brownian noise
Molecules within the noise hit test-masses

Interferometric noise
Not real test-mass motion
LISAPathfinder final main results

M. Armano et al. PRL 120, 061101 (2018)
Interferometric measurements

- Several steps for an extremely precise measurements
Interferometric measurements

- Several steps for an extremely precise measurements
Interferometric measurements

- Several steps for an extremely precise measurements
Interferometric measurements

- Several steps for extremely precise measurements
Interferometric measurements

- Several steps for an extremely precise measurements
Interferometric measurements

- Several steps for extremely precise measurements
  \((\text{TM}2 \rightarrow \text{SC}2) + (\text{SC}2 \rightarrow \text{SC}3) + (\text{SC}3 \rightarrow \text{TM}3)\)
Interferometric measurements

- Exchange of laser beams to form **several interferometers**
- **Phasemeter measurements** on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts
Interferometric measurements

- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts
Interferometric measurements

- Exchange of laser beams to form several interferometers
- Phasemeter measurements on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts
Interferometric measurements

- Exchange of laser beams to form several interferometers
- **Phasemeter measurements** on each of the 6 Optical Benches:
  - Distant OB vs local OB
  - Test-mass vs OB
  - Reference using adjacent OB
  - Transmission using sidebands
  - Distance between spacecrafts
Interferometric measurements

- Measurements via exchange of beams:
  - Heterodyne interferometry with carrier for inter-spacecraft measurement
    $\Rightarrow$ GWs
  - Sideband for transferring amplified clock jitter
    $\Rightarrow$ correction of additional clock jitter
  - Pseudo-Random Noise
    $\Rightarrow$ ranging (measure arm length)
  - Laser locking
Interferometric measurements

- **Quadrant Photodiodes** for measuring phase and angle (DWS)

- **Phasemeter**: the core of the measurement: complex phase-locked loop system, followed by multiple filters to provide data around 16Hz

- Several **mechanisms** are necessary:
  - PAAM: Point Ahead Angle Mechanism: emission & reception not in the same direction
  - OATM: Optical Assembly Tracking Mechanism: pointing of the MOSA
  - BAM: Beam Alignment Mechanism
  - FSU: Fiber Switching Unit

- **Science diagnostics**: temperature, magnetic field, charge, …

- For constellation acquisition, a Constellation Acquisition System (very sensitive camera) is necessary
LISA technology requirements

- Free flying test mass subject to very low parasitic forces:
  - Drag free control of spacecraft (non-contacting) with low noise microthruster
  - 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 spacecraft
  - 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 accuracy laser frequency stabilisation + noise suppression with TDI
  - “Tilt to length” coupling (control of alignment + ground correction)
  - Low level of stray-light
  - High stability telescopes
  - High accuracy phase-meter and frequency distribution
  - Constellation acquisition

Validated with LISAPathfinder

On-ground demo. + simulation
GRACE-FO
LISA noises

- In the on-board interferometric measurements the main noises sources are
  - Laser noise: $10^{-13}$ (vs $10^{-21}$)
  - Clock noise (3 clocks)
  - Longitudinal SC jitter
  - Tilt-to-Length
  - Modulation error
  - Acceleration noise
  - Read-out noises
  - Optical path noises
  - Stray Light
LISA noises

In the on-board interferometric measurements the main noises sources are:

- Laser noise: $10^{-13}$ (vs $10^{-21}$)
- Clock noise (3 clocks)
- Longitudinal SC jitter
- Tilt-to-Length
- Modulation error
- Acceleration noise
- Read-out noises
- Optical path noises
- Stray Light

To be suppressed with on-ground processing: Initial Noise REduction Pipeline (INREP)
GW sources

- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources
LISA data

GW sources
- 6 x 10^7 galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources
LISA data

‘Survey’ type observatory

GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources
**LISA data**

Phasemeters (carrier, sidebands, distance)

- Gravitational Reference Sensor
- Auxiliary channels

**‘Survey’ type observatory**

**GW sources**
- $6 \times 10^7$ galactic binaries
- Large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

LISA - A. Petiteau - GW Probes Of Physics BSM WS - Remote - 16th July 2021
GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

LISA data

Phasemeters (carrier, sidebands, distance) + Gravitational Reference Sensor + Auxiliary channels

'Survey' type observatory
LISA data

Phasemeters (carrier, sidebands, distance)
+ Gravitational Reference Sensor
+ Auxiliary channels

‘Survey’ type observatory

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry
reduction of laser noise

3 TDI channels with 2 “~independents”

GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources
LISA data

Phasemeters (carrier, sidebands, distance)
+ Gravitational Reference Sensor
+ Auxiliary channels

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

3 TDI channels with 2 “~independents”

Data Analysis of GWs

Catalogs of GWs sources with their waveform

GW sources
- 6 x10^7 galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources
LISA data

Phasemeters (carrier, sidebands, distance)

+ Gravitational Reference Sensor

+ Auxiliary channels

'Survey' type observatory

GW sources
- 6 x 10^7 galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

3 TDI channels with 2 “~independents”

Data Analysis of GWs

Catalogs of GWs sources with their waveform
LISA data flow

Phasemeters (carrier, sidebands, distance) + Gravitational Reference Sensor + Auxiliary channels

‘Survey’ type observatory

GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

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

3 TDI channels with 2 “~independents”

Data Analysis of GWs
Catalogs of GWs sources with their waveform
LISA data flow

GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

Phasemeters (carrier, sidebands, distance)
+ Gravitational Reference Sensor
+ Auxiliary channels

‘Survey’ type observatory

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

3 TDI channels with 2 “~independents”

Data Analysis of GWs
Catalogs of GWs sources with their waveform
LISA data flow

Mission Operation Centre

- 'Survey' type observatory
- Phasemeters (carrier, sidebands, distance)
  + Gravitational Reference Sensor
  + Auxiliary channels

Science Operation Centre

- 6 x 10^7 galactic binaries
- Large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

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

3 TDI channels with 2 "~independents"

Data Analysis of GWs
Catalogs of GWs sources with their waveform
LISA data flow

Mission Operation Centre

- Phasemeters (carrier, stance)
- + Gravitational Reference Sensor
- + Auxiliary channels

'Survey' type observatory

Science Operation Centre

- 6 x 10^7 galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs

Distributed Data Processing Centre

- UNKNOWN SOURCES

Calibrations corrections

Resynchronisation (clock)

Time-Delay Interferometry reduction of laser noise

3 TDI channels with 2 "~independents"

Data Analysis of GWs

Catalogs of GWs sources with their waveform
LISA data flow

Phasemeters (carrier, sidebands, distance)
+ Gravitational Reference Sensor
+ Auxiliary channels

'Survey' type observatory

GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources

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

3 TDI channels with 2 "~independents"

Data Analysis of GWs
Catalogs of GWs sources with their waveform
Segment sol LISA

Initial Noise Reduction pipeline (TDI, etc)

GW sources extraction with multiple pipelines

Generation of final products
Segment sol LISA

Telemetry:
+ Phasemeter
+ DFACS
+ GRS FEE
+ CGT
+ CMS
+ SciDiag
+ Housekeeping

Example: different schemes are possible
Noise reduction

- From L0 (raw data) to L1 (TDI: data used to extract GWs)
  - **Initial Noise Reduction Pipeline (INReP)**
    - Synchronisation of time reference
    - Estimation of armlength
    - Time Delay Interferometry
  - Monitoring of instrument
Extracting GWs

- From L1 (TDI) to L2/L3 (science products: GW catalogue, etc)
- Complex: large number of sources + artefacts (gaps, glitches, ...)

**LISA Data Challenge**

- Generate datasets provided to the community
- Organise development of data analysis
- Increase complexity of datasets
- Example: Sangria dataset
Extracting GWs

- From L1 (TDI) to L2/L3 (science products: GW catalogue, etc)
- Complex: large number of sources + artefacts (gaps, glitches, ...)

**LISA Data Challenge**

- Generate datasets provided to the community
- Organise development of data analysis
- Increase complexity of datasets
- Example: Sangria dataset
Chapter 2

Figure 2.3: Interferometric measurement on one LISA satellite, exemplarily explained for the horizontal OB. Light of a local laser (red) is used for transmission to the distant S/C and to sense the space-time variation between for GW interaction. Simultaneously, the light interferes on the local optical bench with the received weak light (wine red) to form the science interferometer beatnote. The test mass motion is read out in the TM interferometer using light (orange) from the adjacent optical bench transmitted through a back-link fibre. The reference IFO directly compares local laser and adjacent local laser. Moreover, the spacecraft is controlled by DFACS including TM position readout and thruster actuation such that the S/C follows the test masses.

Its variation due to GW is combined from three interferometric measurements: TM-to-OB on the far spacecraft, OB-to-OB between sending and receiving S/C, and OB-to-TM on the receiving spacecraft. This concept is called 'split interferometry configuration' and we will come back to it in Sec. 2.5.

Laser light from the adjacent optical bench (orange) is used for the interferometric TM readout. Since the benches are not rigidly connected to provide the angular pointing flexibility of \( \pm 1 \) \( \varpi \) (Sec. 2.1.2), the OB-to-OB connection is established by an extensible optical fibre. Laser light is transmitted through this so-called back-link...

Sensitivity

Noises

Response of the detector to GWs

![Graph showing PSD noise vs. frequency](image1)

![Graph showing response to GW vs. frequency](image2)

![Diagram of LISA satellite](image3)

![Diagram of LISA setup](image4)
Compact solar mass binaries

- Large number of stars are in binary system.
- Evolution in white dwarf (WD) and neutron stars (NS).
  - Existence of WD-WD, NS-WD and NS-NS binaries
- Estimation for the Galaxy: 60 millions.
- Gravitational waves:
  - Most part in the slow inspiral regime (quasi-monochromatic): GW at mHz
  - Few are coalescing: GW event of few seconds at $f > 10$ Hz (LIGO/Virgo)
- Several known system emitting around the mHz
  - Guaranteed sources
Galactic binaries

- Gravitational wave:
  - quasi monochromatic

- Duration: permanent

- Signal to noise ratio:
  - detected sources: 7 - 1000
  - confusion noise from non-detected sources

- Event rate:
  - 25 000 detected sources (over 30 millions sources)
  - more than 10 guaranteed sources (verification binaries)
Galactic binaries

GW sources
- $6 \times 10^7$ galactic binaries
Stellar mass BH binaries

- Binaries with 2 black holes of masses between few $M_{\text{Sun}}$ and 100 $M_{\text{Sun}}$, so called “Stellar mass BH Binaries”
- **Inspiral**: emission in the mHz band
- **Merger**: powerful emission around few tens Hz
  \[ \Rightarrow \] many sources already observed
- **Fast evolution**: few years
  from tens mHz to tens Hz
  \[ \Rightarrow \] multi-observatories observations
Stellar mass BH binaries

GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
Supermassive Black Holes

- Observations:
  - Sgr A*: $4.5 \times 10^6 \, M_{\odot}$ at the center of the Milky Way (VLT - Gravity)
  - M87: $6.5 \times 10^9 \, M_{\odot}$ (picture EHT)

- Supermassive Black Hole are indirectly observed in the centre of a large number of galaxies (Active Galactic Nuclei).

- Observations of galaxy mergers $\Rightarrow$
  $\Rightarrow$ SuperMassive BH Binaries (SMBHB) should exist.
Super Massive Black Hole Binaries

- Gravitational wave:
  - Inspiral: Post-Newtonian,
  - Merger: Numerical relativity,
  - Ringdown: Oscillation of the resulting MBH.

- Duration: between few hours and several months
- Signal to noise ratio: until few thousands
- Event rate: 10-100/year
Super Massive Black Hole Binaries

- LISA: SMBHB from $10^4$ to $10^7$ solar masses in “all” Universes
Super Massive Black Hole Binaries

GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
EMRIs

- Capture of a “small” object by massive black hole ($10 - 10^6 \text{ M}_{\odot}$): Extreme Mass Ratio Inspiral
  - Mass ratio $> 200$
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in strong field
  - Frequency: $0.1 \text{ mHz}$ to $0.1 \text{ Hz}$
  - Large number of sources could be observed by space-based interferometer
EMRIs

- Capture of a “small” object by massive black hole ($10^{-6}$ $M_{\text{Sun}}$): Extreme Mass Ratio Inspiral
  - Mass ratio $> 200$
  - GW gives information on the geometry around the black hole.
  - Test General Relativity in strong field
  - Frequency: 0.1 mHz to 0.1 Hz
  - Large number of sources could be observed by space-based interferometer
EMRIs

- Gravitational wave:
  - very complex waveform
  - No precise simulation at the moment

- Duration: about 1 year

- Signal to Noise Ratio: from tens to few hundreds

- Event rate:
  from few events per year to few hundreds
GW sources
- $6 \times 10^7$ galactic binaries
- large number of Stellar Origin BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/years EMRIs
Cosmological backgrounds

- Potential detection of cosmological background from:
  - First order phase transition in the very early Universe
  - Cosmic strings network
  - …

Caprini & Figueroa 2018, CQG 35, 163001
Detectability and characterisation: challenging!

- Separation of the SGWB and instrument noises
  - Noise knowledge? Study of possible calibrations
  - Use of TDI possibilities?
- Separation from foreground from other sources and residual after the "subtraction" of other sources
- Data analysis possibility to be deeply investigated
GW sources

- GW sources
- Characteristic strain amplitude
- Frequency [Hz]
- SNR
- Resolved galactic binaries (4 yr observation time)
- Verification binaries (4 yr observation time)
- Galactic confusion noise
- GW150914 type Black Hole Binaries
- GW150914
- 2 big black holes at z=3
- EMRI
- $M_{tot} = 10^7 M_{Sun}$
- $M_{tot} = 10^6 M_{Sun}$
- $M_{tot} = 10^5 M_{Sun}$
- $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$
- $10^{-16}$ $10^{-17}$ $10^{-18}$ $10^{-19}$ $10^{-20}$ $10^{-21}$ $10^{-22}$
- Year
- Month
- Day
- Hour
- Minute
- Day
- Month
- Year
- Day
- Month
- Year
GW sources

- $6 \times 10^7$ galactic binaries
- large number of Stellar Mass BH binaries (LIGO/Virgo)
- 10-100/year SMBHBs
- 10-1000/year EMRIs
- Cosmological backgrounds
- Unknown sources
LISA science objectives

- SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.
- SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages
- SO3: Probe the dynamics of dense nuclear clusters using EMRIs
- SO4: Understand the astrophysics of stellar origin black holes
- SO5: Explore the fundamental nature of gravity and black holes
- SO6: Probe the rate of expansion of the Universe
- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
- SO8: Search for GW bursts and unforeseen sources
LISA at ESA

- 25/10/2016: Call for mission
- 13/01/2017: submission of «LISA proposal» (LISA consortium)
- 8/3/2017: Phase 0 mission (CDF 8/3/17 → 5/5/17)
- 20/06/2017: LISA mission approved by SPC
- 8/3/2017: Phase 0 payload (CDF June → November 2017)
- 2018→2021: phase A: payload study + competitive studies for 2 primes
- 2021→2023: phase B1
- 2024: mission adoption
- During about 10 years: production: challenge (3 S/Cs with 2 MOSAs)
- 2034: launch Ariane 6.4
- 1.5 years for transfer
- 6 - 12 months for commissioning
- 4-6 years of nominal mission (75% duty cycle)
- Possible extension to 10 years
Activities during the **phase A**: 

- Scope, first definitions, organisation, performances, ... 
- For the ground segment: 
  - first mission of this kind + large number of overlapping sources: challenge for data analysis => development and prototyping started very early 
  - Support & contribution to Consortium activities: figure of merits, performance model, simulations, ...
LISA Consortium

- Currently 1439 members
  - 655 full members committing time to LISA Consortium activities
  - 774 associates
LISA Working Groups

- Large number of members:
  - Astrophysics: 502
  - Cosmology: 330
  - Fundamental Physics: 354
  - Waveforms: 212
  - LISA Data Challenge: 237

- And active:
  - Regular workshops
  - Producing white papers: state of the art of LISA Science
  - Multiple projects within groups
Conclusion

- LISA mission is in phase A and progressing well for a launch in 2034.
- No critical technology but complexity in the high level of integration.
- Instrument is the payloads + the spacecrafts + on ground processing to suppress dominant noise.
- Complex processing to suppress noises and extract GW sources.
- LISA will observe a large number and variety of GW sources in the frequency band $10^{-5}$ to 1 Hz.
- **Stochastic GW Background**: LISA has a huge potential but extracting SGWB for LISA data is challenging.
Thank you