The LISA mission at the IN2P3

Presentation to the IN2P3 Scientific Council
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LISA Science Objectives

Mission Description and Proposed French Contribution

The IN2P3 within LISA

Conclusion
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Conclusion
The GW spectrum

Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period

age of universe

years

hours

sec

ms

log(frequency)

-16

-14

-12

-10

-8

-6

-4

-2

0

+2

Cosmic microwave background polarization

Pulsar Timing

Space Interferometers

Terrestrial interferometers

Detectors
Study the formation and evolution of compact binary stars in the Milky Way Galaxy.

- 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: \( \sim 10^7 \).
  - Monochromatic sources for LISA (far from coalescence)

Three categories
- Joint EM - GW sources (Gaia, LSST)
  - Already \( \sim 10 \) known verification binaries in the LISA band
  - Individually detected: \( \sim 10^4 \)
  - Stochastic GW signal
    - foreground ‘noise’
Massive BH binaries

- Massive BHs in the nucleus of every Galaxy
  - $4 \times 10^6 \, M_{\odot}$ at the center of the Milky Way

- MBHs accumulate mass
  - gas accretion
  - merging with other BHs

- Galaxies merge
  - observed…
  - may result in a MBH binary which could merge in a reasonable time
    - Stars and/or gas required to dissipate orbital momentum and bring it in GW driven regime
Origin, growth and merger history of massive black holes across cosmic ages
Massive BHs could be embedded in stellar cusps
- high density stellar environment

Massive BH could capture a compact object
- companion: NS, stellar mass BH
- very eccentric orbit shrinking under GW radiation

EMRI: Binary system with an extreme mass ratio: $10^{-7} - 10^{-5}$
- $\sim 10^6$ orbits of the compact object close to the MBH before the plunge

Companion as ‘test particle’
- Strong relativistic effects
- Complex (and very informative…) waveforms

[credits: S. Drasco, CalTec]
Stellar BH may be detectable by LISA prior coalescing in the ground based detectors band
- Observed for ~years in LISA until ~days before merger

Possible pre-warning
- Time of coalescence at ~10s accuracy
- Sky localisation: 0.1 - 1 deg²
Possible X-ray emission during the late stages of the SMBH inspiral (days to hours before final merger) comes from:

- **Circumbinary disc:**
  - X-ray emission in soft x-rays (≤1keV)
- **Mini-discs around black holes**
  - Hard x-ray emission (≥10keV) from accretion of minidiscs individually onto each black hole
- **Interaction of circumbinary and mini discs:**
  - Accretion of circumbinary disc onto mini-discs via optically thick streams
  - Thermal radiation dominated by the inner edge of the circumbinary disc, producing soft x-rays (~2keV)
- **X-ray emission shows clear modulation on timescales as short as a few hours**
Using emitted GW to map the spacetime structure

Tests of GR
- Fundamental principles and symmetries of GR
- Testing GR with compact objects

Tests of the Nature of Black Holes

Dark matter and Primordial Black Holes

Model-independent tests
- Consistency of GR vs constraining Modified Gravity
- Parameterised tests
- Other tests including: Polarisation, GW propagation, Stochastic GW Background

Astrophysical and Waveform systematics

Deviation in quadrupole moment from Kerr value (no hair theorem):

[Babak+ PRD (2017)]
LISA may help on many cosmological problems

- Expansion rate of the Universe: late acceleration?
  - CMB: $H_0 = 66.93 \pm 0.62 \text{ km.s}^{-1}\text{.Mpc}^{-1}$
  - SN Ia: $H_0 = 73.5 \pm 1.4 \text{ km.s}^{-1}\text{.Mpc}^{-1}$

- Dark energy
  - Cosmological constant?
  - Early dark energy: DE evolves with redshift and contributes to rate of expansion at $z>1$

- Modification of GR on large scale

LISA can probe the Universe at different scales

- Use BHBs merger events as standard sirens
- Requires the knowledge of the redshift from e/m counterpart of the host galaxy or from statistical inference

Universe expansion rate from GW events:

Universe DE content:
Violent processes in the early Universe may produce stochastic GW background (SGWB).

First order phase transition
- Collision of true vacuum bubbles and conversion to the symmetry-broken phase accompanied with anisotropic stresses.
- The LISA band (10^{-4} - 0.1 Hz) corresponds to the energy scale of the EW (electroweak) phase transition (up to 10^4 TeV).
- Formation of sound wave, shocks and turbulence in the plasma

Cosmic strings:
- A network of strings formed in the early Universe generates SGWB (as superposition of many uncorrelated sources) and (possibly) individual bursts.
Potential sources for LISA: summary
Outline

- LISA Science Objectives
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Towards a space-borne GW detector!

- LISA selected as L3 mission in spring 2017
  - Launch expected in 2034/2035

- Proposal:
  - [https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf](https://www.elisascience.org/files/publications/LISA_L3_20170120.pdf)

- First concepts in the 1970s...

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Faller et al. «Kilometric Optical Arrays in Space», 1984

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A proposal in response to the ESA call for L3 mission concepts
Equilateral configuration
- 3 arms / 6 links ; 2.5 Mkm
- Earth-like orbit, 19° to 23° trailing
- Science mission duration : minimum 6 years (consumables for 10 years)

Drag free-flying
- Heritage from LISA Pathfinder

Typical metrology requirement : 
~10 pm/√Hz @ 1 mHz
LISA development schedule

persephone

- Major milestone: adoption end 2023 / early 2024
- Launch: 2034/2035
- In-flight operations: up to 12.5 years
  - 2.5 years cruise + commissioning
  - 6 years science mission, extendable to 10 years
LISA will be complementary of other operational instruments in 2035 - 2045

- 3rd generation of interferometric GW ground-based detectors (Einstein Telescope, Cosmic Explorer) and Pulsar Timing Array
  - Broad simultaneous coverage of the GW spectrum from nHz to kHz
  - LISA as early (years in advance…) detection system for some binary sources coalescing in the ET/CE band
  - Detection or constraints on the GW backgrounds from the early Universe (at $10^{10}$ GeV)

- Multimessenger astronomy
  - With ATHENA for observing the X-ray emission emitted by discs around coalescing massive black holes.
  - With wide field telescopes (e.g. LSST, SKA) for identifying e/m counterparts and host galaxies
  - With large telescopes on ground (ELT, TMT, GMT) and in space (JWST) for the measurement of redshifts at cosmological distances

- Particle physics
  - LISA may be complementary to future colliders to identify physical processes at the TeV scale: constraints on cosmic strings, inflation, ...

No equivalent mission with the same objectives in the same time frame

- Active development of the TianQin mission by the Chinese Academy of Science
  - Rapidly progressing but still a lot of technologies to master
  - Launch of TianQin in the same timeframe as LISA difficult to assess
What contribution for France?

Planned main French contributions:
- Distributed Data Processing Center
- MOSA AIVT & Perf. Control
Presently 19 laboratories / research institutes participate to the LISA France collaboration

@IN2P3 : APC, CPPM, L2IT, LPCC, LMA/IP2I, CC-IN2P3
@INSU : LAM, IAP, LPC2E
@INSIS : Institut Fresnel
@Obs de Paris / INSU : SYRTE, LUTH
@Obs. de la Côte d’Azur / INSIS : ARTEMIS
@CEA : IRFU (DEDIP, DIS, DPhN, DPhP, DAP), IPhT

CNES is managing and supporting the project activities with engineers and financial ressources (incl. short-term contracts).

Members from French institutes in the LISA Consortium

130 Full members (43 from IN2P3 labs)
63 FTEs (incl 18 at IN2P3)
1358 members in the LISA Consortium
68 Associates (7 from IN2P3 labs)
Development of a Distributed Data Processing Center for LISA

- Produces scientific L2&L3 data and supports ESA on L0 to L1 software
- Will implement, maintain and operate simulations and data analysis
- Supports the LISA community for SW and collaborative tools
- Prototype architecture based on virtualisation and continuous integration
Objective: build a ‘simplified’, system-level, performance model

- Identify critical items
- Unified view of the system performance from science requirement to sub-systems level.
- Support the allocation breakdown for each sub-system
- Sensitivity analysis to support design trade-off

Different sources of information

- Specific or ‘end-to-end’ simulations
- Mathematical & physical models
- Lab experiments

Interface with all stakeholders – Consortium, Agencies, Industry.
LISA will be the first instrument of its kind
- Not a collection of separate instruments
- Combination of finely designed equipments, forming a Mkm-scale instrument

LISA science return depends on the in-depth performance characterisation of the metrology core
- Importance of the AIVT and scientific performance modelling
- Crucial activity giving high visibility and involvement in early instrument development phases

Integration and tests in close collaboration with industries
- 10 MOSAs to integrate and validate (1 STM, 1 EQM, 1 PFM, 5 FMs, 2 spares)
- Research institutes: development of optical metrology test benches and strong involvement in the EQM characterisation
  - Experience on MOSA testing transferred to industry with PFM
- Industries: integration procedures and semi-serialisation of FMs & spares AIVT
  - The research institutes still follow the process and interpret the measurements
French LISA activities landscape

Broad and continuous coverage, from instrument to GW science
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Key roles of IN2P3 members in the LISA Consortium

- ESA committees
  - Science Study Team
  - System Engineering Office

- LISA Consortium Management
  - Executive Board
  - Coordination Team

- LISA Instrument Group
  - Core team
  - Performance Working Group

- LISA Data Processing Group
  - Lead
  - SGS Definition and organisation
  - SGS prototyping
  - SGS support
  - Simulation
  - Initial Noise Reduction Pipeline

- LISA Science Group
  - Data Analysis
  - Science Interpretation

- Working Groups
  - LISA Data Challenges
  - Cosmology
Science activities summary

- **Modelling GW sources**
  - Matched filtering requires very good knowledge of GW signals.
  - Biases and ‘false’ GR deviations to arise from mismodelled GW

- **Testing GR with coalescing binaries**
  - Very tight constraints on GR deviations from GW waveform details
  - Multiband observations of stellar mass BBHs

- **GW signals from the early Universe**
  - Modelling the signals of first-order transitions
  - Study on detection prospects with LISA
  - Cosmic strings signal modelling (burst and stochastic background)

- **Using GW sources as “standard sirens”**
  - LISA localisation compatible with e/m identification?
  - Constraints on Hubble constant, dark energy equation of state, etc.

- **Participating institutes**: APC, L2IT, IAP
Definition and organisation of the SGS

- Led by ESA and LDPG (LISA Data Processing Group)
- Definition of organisation, responsibilities, interfaces, …
- Organisation for generating and processing LISA data

Definition and preliminary design of the DDPC

- Led by CNES
- Logical design of the analysis for extracting GWs (L1 -> L2 -> L3)
- Functional tree and product tree
- Development plan

Participating institutes

**APC, LPCCaen**
Instrument Simulation

- Realistic simulation of the instrument: noises, beam propagation, dynamics, on-board processing, artefacts (glitches, gaps, ...), etc
- Current simulator: LISANode:
  - time domain, C++/python, modular
  - mainly developed at APC
- Key tool for:
  - validating instrumental concept
  - identifying correlations or particular effects
  - producing realistic data for INREP & LDC

INREP (INitial Noise REduction Processing)

- Main objective: to deliver level-1 (L1) data
  - i.e. reduced raw observations with dominant noises suppressed (mostly laser frequency noise)
- Signal calibration: from gain correction to time synchronisation of signals
- Kalman filtering for estimating absolute armlength
- Correction of laser frequency noise, clock jitter noise with application of Time-Delay-Interferometry

Participating institutes

- APC, LPCCaen, SYRTE, CEA
Objectives:

- Establish a common playground to evaluate algorithms
- Foster data-analysis research and community involvement
- Prototype and develop end-to-end data-analysis pipelines

2 released challenges

- **LDC-1**
  - Idealized noise and separated sources
  - ‘Training’ data set

- **LDC-2**
  - LDC2a: source confusion (MBHBs and Gal. binaries)
  - LDC2b: realistic instrumental noise (gaps, non-stationarity) but simple GW signals

Participating institutes

- APC, SYRTE/Obs. de Paris, ARTEMIS/OCA, CEA
LDPG WG to support Consortium activities

- Common development environment based on containers (docker, singularity)
- CCIN2P3 tools at the core of LISA Consortium tools
  - gitlab
  - Atrium
  - continuous integration
  - wiki

Computing resources

- Mainly CC-IN2P3
- Preliminary DCC (Data Computing Center)

Participating institutes

- **CCIN2P3, APC**
Performance modelling: from subsystems to LISA sensitivity

Performance Modelling activities
- Co-chair of the performance modelling working group
  - Coordination of periodical releases to ESA.
  - Information and data management with the industrial primes
- Models development on specific items
  - Data processing impact on noise (TDI)
  - Telescope stray-light noise
  - Impact of correlations on the noise budget.
- Development of the performance model software
  - incl. web interface

Figures of merit
- Assessing ability of LISA to fulfill the science objectives
- Evaluation of a given LISA configuration to deliver the expected science

Setting requirements on the performance
- Duty cycle, minimum mission duration, science frequency range
- Impact of gaps, glitches, calibration uncertainties

Participating institutes
- APC, CEA, IAP, L2IT
Instrument science: past R&D activities

- Laser frequency stabilisation [*APC*, *ARTEMIS*, *SYRTE*]
  - R&T activity funded by CNES
  - Objective of $10^{-13}/\sqrt{\text{Hz}}$ above 3 mHz
  - Based on molecular iodine spectroscopy, first ideas in *ARTEMIS/OCA*
  - Successful demonstration at *APC*, considered as alternative technique to nominal Fabry-Perot solution
  - Developments pursued at *SYRTE*, to be used in optical benches prototypes

- Telescope design studies [*APC*, *ARTEMIS*, *INRIM*, *LMA*, *TAS*]
  - Answer to an ESA ITT (Invitation To Tender) in 2016
  - Collaboration of research institutes with *TAS* for a (backup) design of a telescope for LISA
  - @*APC*: study of back-scattered light and impact on the phase measurements
  - @*LMA*: expertise in components characterisation, straylight modelling and coating design
  - Expertise and models still used and applied on the NASA telescope design for LISA performance modelling
LISA On Table [APC]

- Objectives: Generation of LISA-like beat notes for testing noise reduction algorithms with representative data
- Optical and electronically interferometers
- Demonstration of a noise reduction factor $>10^8$ with instrumental data using TDI
Purpose

Development of an ultra-stable optical bench for demonstrating the on-ground characterisation capabilities

Goals

Pathlength stability of $\sim 10 \text{ pm}/\sqrt{\text{Hz}}$ in [10 mHz:1 Hz]
Organise the French community in view of the development of the MOSA GSEs (including private companies, e.g. on optical contacting)
Identify and quantify the main noise sources in a relevant environment
Evaluate the complexity (+cost, duration, etc) of MOSA performance tests

2 steps approach

‘Metallic’ bench (MIFO) with an invar base plate
- Integrated and tested in a ‘lab’ vacuum chamber
- Validation of the mounting and tuning procedures, acquisition chain, analysis tools and performance model
- Final results expected end 2021

Zerodur bench (ZIFO) with optically contacted components
- Designed and integrated by Winlight (except photoreceivers and injectors)
- Tested and characterised in a vacuum chamber representative of AIVT environment
- Final results expected end 2022

Participating institutes:
- APC, ARTEMIS/OCA, CEA/IRFU, CNES, CPPM, L2IT, LAM, SYRTE/Obs. de Paris
MIFO/ZIFO current status

- Magt. + ing. système : APC
- Design optique : L2IT + APC
- Blindage thermique : LAM
Design of the future AIVT GSEs

Design requirements and key technologies prototyping for critical Optical Ground Support Equipments for LISA

5 main OGSEs identified:
- Beam wavefront measurement
- Beam centring measurement
- Far-Field Optical Ground Support Equipment
- Differential and global interferometric tests (2 OGSEs)

Participating institutes:
- APC, ARTEMIS/OCA, CEA/IRFU, CNES, CPPM, Institut Fresnel, L2IT, LAM, LMA, SYRTE/Obs. de Paris
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Highlights and conclusion

LISA schedule for launch in 2034 / 2035
- major milestones in end 2021 (end of Phase A) and end 2023 (adoption)
- LISA will be complementary to future ground based GW detectors and e/m observatories

Foreseen French contributions
- Science Ground Segment / Distributed Data Processing Center
- Scientific Performance Model
- Instrument core AIVT

The IN2P3 laboratories are actively involved in LISA
- IN2P3 expertise based on LIGO/VIRGO developments, computing infrastructures, previous space missions and LISA Pathfinder
- The community is presently prototyping the contributions
- Close collaborations with other institutes: CNES, CEA, INSU, INSIS, OCA, Obs. de Paris

Very strong support from CNES (financial, short term contracts and engineering)
- Deliverables and support to science exploitation

IN2P3 is the driving research institute involved on LISA in France
- Participation in GW space detectors started with LISA more than 15 years ago
- Important contributions, recognition and responsibilities in the LISA Consortium

The continuing support of IN2P3 is crucial
- permanent positions for securing the expertise brought by young engineers and researchers
- regular reviews and project status reports
Against racism and discrimination

We have been deeply touched by the brutal and senseless killing of George Floyd in Minneapolis, the recent appalling episode of violence against Black Americans, which brought into relief systemic issues of racism and discrimination that pervade our communities worldwide in subtle and blatant forms. The