LASER INTERFEROMETER SPACE ANTENNA SCIENCE

ELENA MARIA ROSSI
LEIDEN OBSERVATORY
THE NETHERLANDS

MULTIMESSANGERS WINTER WORKSHOP @PRAGUE 4-7 DECEMBER ‘19
LISA SCIENCE GROUP

Team leader : Jon Gair

Deputy team leader : Elena Maria Rossi, Michele Vallisneri
• **2013** **Gravitational Universe** selected by ESA as L3 science theme within the Cosmic Vision 2015-2025

• **2017** **LISA proposal selected** as ESA’s L3 mission

• **2034** nominal launch

https://arxiv.org/abs/1702.00786
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• 2034 **nominal launch**

News! ESA ministers commit to biggest budget ever for next decay:

Günther Hasinger, ESA Science Director “**LISA in 2032**”

https://arxiv.org/abs/1702.00786
CONSTELLATION OF 3 SATELLITES
**MEASUREMENT PRINCIPLE**

- Probe the change in proper time between pairs of **free-falling** test masses caused by GWs
- Proper time is inferred by the time of flight of photons exchanged between the satellites
- We have **multiple links** from which we can form Michelson-like signals
LISA PATHFINDER

![LISA Pathfinder Diagram](image)

The LISA Pathfinder is a space mission that tests the technology needed for the LISA mission, a space-based gravitational wave observatory. The diagram compares the residual acceleration of the test masses against frequency, showing improvements over time from April 2016 to February 2017, meeting the LISA requirements.

CREDIT: NASA
LISA LIMITING NOISE

Test-mass Force Noise
\( \sim 6 \text{ fN/}\sqrt{\text{Hz}} \)

Interferometry Sensing Noise
\( 10 \text{ pm/}\sqrt{\text{Hz}} \)

Arm-length Penalty
\( 2.5 \times 10^9 \text{ m} \)
LISA IS AN OBSERVATORY

exploring the 2 mHz ~ 15 minute time domain for Astrophysics, Cosmology and Fundamental physics

Barack et al (inc. EMR) 2018
Hierarchical growth of structure in the Universe, leads us to imply the existence of SMBH mergers.
SUPERMASSIVE BLACK HOLES

Epoch of Fist stars
Epoch of Galaxies

LISA is ideal for studying of structure formation beyond the re-ionisation epoch.
HOW DO SUPERMASSIVE BLACK HOLE FORM?

*LISA detections to discriminate between formation scenarios:*

- Dayal, EMR + 2019
- DeGraf & Sijacki 2019
- Latif et al. 2019
- Bonetti et al. 2019
- Ricarte & Natarajan 2018
- Hartwig, Agarwal & Regan, 2018
- Colpi 2018
- ....

*predictions very by an order of magnitude between papers...*

Sesana, Volonteri & Haardt 2007
HOW DO SUPERMASSIVE BLACK HOLE FORM?

PoP3 seeds can describe the average population

need massive seeds for these

Dayal, EMR + 2019; observation from Willott +2010
A FEW DETECTED PER YEAR...

Most of the information is in the background...

Dayal, EMR + 2019

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ELECTROMAGNETIC COUNTERPARTS TO MERGER

credit J. Cuadra
PRECURSORS TO MERGER

~1 week to merger  
~last 2 hr to merger

Gravitational signal

Tang et al. 2018

2 KeV

10 KeV
“AFTERGLOWS”

- Months timescale rise
- Bolometric luminosity at fraction of Eddington
HOW CAN LISA AND ATHENA WORK TOGETHER?

About 1 month before

LISA detects gravitational waves from supermassive black holes spiralling towards each other and calculates the date and time of the final merger, but the position in the sky is unknown.

2 weeks before

As the inspiral phase progresses, the gravitational wave signal gets stronger; meanwhile, LISA collects more data as it moves along its orbit, providing a better localisation of the source in the sky.

1 week to several hours before

LISA indicates a fairly large patch in the sky (around 10 square degrees) where the source is located, so that Athena can start scanning this region to look for the source with its Wide Field Imager (WFI).

A few hours before

LISA locates the source to within a smaller portion of the sky, roughly equal to the size of the Athena WFI field of view (0.4 square degrees); Athena stops scanning, and starts staring at the most likely position of the source, witnessing the final inspiral and merger of the black holes.

During and after the merger

While LISA detects the gravitational wave ‘chirp’, Athena can observe any associated X-ray emission and might witness the onset of relativistic jets: if this happens, Athena and LISA may witness the birth of a new ‘active galaxy’. 

#Space19plus  #AnsweringTheBigQuestions  Courtesy of Paul McNamara
ULTRA COMPACT STELLAR MASS BINARIES (THE MOST NUMEROUS)

<table>
<thead>
<tr>
<th>Detached double white dwarfs</th>
<th>AM CVn stars</th>
<th>Hot subdwarfs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted: $10^8$</td>
<td>$10^5$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>Observed with EM</td>
<td>~$10$</td>
<td>$10^2$</td>
</tr>
</tbody>
</table>

see e.g. Astro2020 Science White Paper
Littenberg et al. 2019

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CURRENT SAMPLE

- $\sim 10 \text{ SNR} > 20$
- $3 \text{ SNR} > 100$

Kupfer, Korol..EMR 2018

Littenberg + 2019
THE FUTURE SAMPLE!

- 25,000 resolved binaries w LISA
- 8,000 precise distance < 0.3
- 5,000 w precise localisation (~arcmin²)
- A few 100 in Gaia and/or LSST

Korol, EMR et al. 2018
Breivik + 2018
Gijs + 01, 04

Littenberg + 2019
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Massive system are required but none has been so far unambiguously identified in optical

Rebassa-Mansergas + 2018

WD-WD binary "merger"

Credit: NASA/CXC/SAO

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**LISA a unique tool to access SNIa progenitors**

Rebassa-Mansergas + 2018, Korol, Koop & EMR 2018

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NEAR FIELD COSMOLOGY WITH GRAVITATIONAL WAVES

LISA’s view of the Milky Way

Korol, EMR, Barausse 2018

Benacquista & Holley-Bockelmann 2006
Adams, Cornish & Littenberg 2012, Lambert + 2019

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MASSIVE STELLAR MASS BLACK HOLES (A LA LIGO/VIRGO)

• ~100 BHs localised weeks in advance with < 10s & < 1 deg² before merger

• Measuring binary properties (e.g. mass <1%)

• Searching counterpart when in LISA

Multi-band astrophysics!

Sesana 2016
FUNDAMENTAL PHYSICS

Probing dark matter, Mass of Graviton and Test of General Relativity

see e.g. Astro2020 Science White Paper (Berti +2019)
Gair et al. Living Review, and Barack + 2018
TESTS OF GENERAL RELATIVITY

SMBH-SMBH binary

Extreme Mass Ratio Inspiral

Image credit: The SXS Project
TESTS OF GENERAL RELATIVITY

SMBH-SMBH binary

testing deviation from GR in
• GW propagation
• BH dynamics

Image credit: The SXS Project
Tests of General Relativity

SMBH-SMBH binary

Image credit: The SXS Project

Testing deviation from GR in

- GW propagation
- BH dynamics

In modified gravity theory there is a time delay between photons and GW

Cartoon by Pilar Ruiz-Lapuente

Elena Maria Rossi
TESTS OF GENERAL RELATIVITY

SMBH-SMBH binary

testing deviation from GR in
• GW propagation
• BH dynamics

Testing no-hair theorem with BH spectroscopy in a dynamic, non-stationary spacetime (Ring-down phase)

Image credit: The SXS Project

credit: LIGO/VIRGO collaboration

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TESTS OF BH SPACETIME

Stars orbiting SrA* ~120 AU

With $10^4$-$10^5$ GW cycles in the LISA band, measurements of deviation from Kerr metric at 0.01-1% level with a few to a thousands EMRIs, with SNR up to a few 100

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COSMOLOGY
see e.g. Astro2020 Science White Paper Caldwell + 2019

Extremely rich science...
COSMOLOGY

see e.g. Astro2020 Science White Paper Caldwell + 2019

• Measurements of the cosmological parameters using LISA standard sirens (Tamanini + 2017)
• Testing modified gravity at cosmological distances with LISA standard sirens (Belgacem +2019)
• Testing cosmic strings
• Testing particle physics models’ predictions for first-order phase transitions
• Testing Inflationary models
• Cosmological stochastic background (e.g. Caprini +2019)
Primary Thematic Science Area: Multi-Messenger Astronomy and Astrophysics
Secondary Areas: Cosmology and Fundamental Physics, Galaxy Evolution,
Formation and Evolution of Compact Objects

Multimessenger science opportunities with mHz gravitational waves

John Baker, Zoltán Haiman, Elena Maria Rossi,
Edo Berger, Niel Brandt, Elmé Breedt, Katelyn Breivik, Maria Charisi, Andrea
Derdzinski, Daniel J. D’Orazio, Saavik Ford, Jenny E. Greene, J. Colin Hill,
Kelly Holley-Bockelmann, Joey Shapiro Key, Bence Kocsis, Thomas Kupfer, Shane
Larson, Piero Madau, Thomas Marsh, Barry McKernan, Sean T. McWilliams,
Priyamvada Natarajan, Samaya Nissanke, Scott Noble, E. Sterl Phinney, Gavin
Ramsay, Jeremy Schnittman, Alberto Sesana, David Shoemaker, Nicholas Stone,
Silvia Toonen, Benny Trakhtenbrot, Alexey Vikhlinin, and Marta Volonteri

1 NICER, Goddard Space Flight Center, Greenbelt, MD 20771, USA
LISA SCIENCE GROUP

LSG

WPT: waveforms
WPT: data-analysis tools
WPT: low-latency pipelines
WPT: source identification codes
WPT: catalogs
WPT: multi-messenger astro
WPT: science interpretation

simulation WG

astrophysics WG
cosmology WG
waveforms WG
fund. physics WG
LISA data challenges

CHAIRS: JON GAIR, MICHELE VALLISNERI & ELENA MARIA ROSSI
BACK UP SLIDES
PRE-MERGER LOCALISATION

Athena-LISA synergy working group document
DIFFERENT SEEDING MODELS

Dayal, EMR + 2018