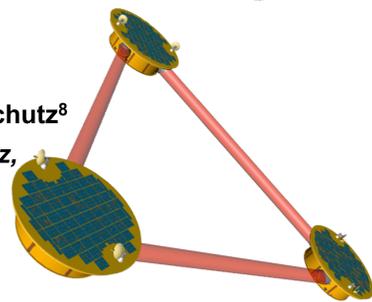


Observing the Dark Side of the Universe with LISA



Thomas Allen Prince¹, P. Binetruy², N. Cornish³, C. Cutler¹, C. Hogan⁴, J. Livas⁵, P. Madau⁶, G. Nelemans⁷, S. Phinney¹, B. Schutz⁸
¹Caltech/JPL, ²APC - College de France, France, ³Montana State Univ., ⁴Univ. of Washington, ⁵NASA GSFC, ⁶UC Santa Cruz, ⁷Radboud Univ Nijmegen, The Netherlands, ⁸AEI-MPI Potsdam
 For the LISA International Science Team



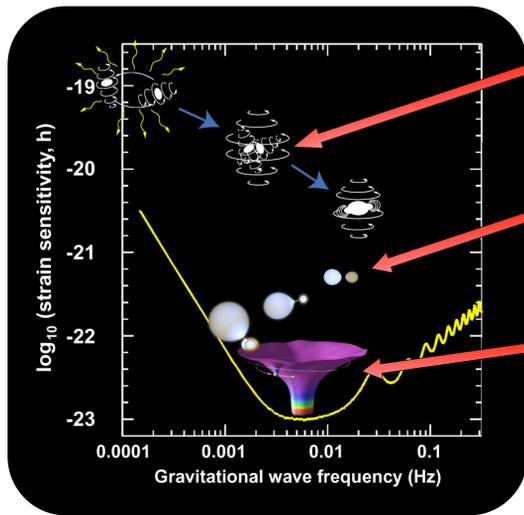
Abstract

LISA is a joint NASA/ESA space mission designed to measure gravitational waves in the band from 0.3 mHz to 0.1 Hz, a band that is richly populated by strong sources of gravitational waves. Signals will come from a wider range of sources: massive black holes merging in galaxies at all distances; stellar-mass compact objects captured by massive black holes; ultra-compact Galactic binaries; and possibly other sources including relics of the Big Bang. These sources convey detailed information addressing a wide range of physics and astrophysics: the history of galaxies and black holes in the universe; general relativity and the behavior of space-time; precision measurements of luminosity distances; the physics of dense matter and stellar remnants; and possibly new physics associated with events in the very early universe. We will survey the science goals of LISA and discuss their impact on physics and astrophysics.

The Science

LISA signals record a richly populated universe of strong sources

- Gravity Waves (GW) are not attenuated
 - Universe transparent since about 10^{-34} sec
- GW sources are “clean and simple”
 - Black Holes have mass and spin & radiate coherently
- GW sources are “standard sirens”
 - Luminosity distance measurements with 1% accuracy
- GW sources are strong
 - High signal-to-noise allows precision measurements



Supermassive Black Hole Mergers

- Study growth and evolution of massive BHs
- Test dynamical strong-field gravity
- Expect merger rates of 10s-100s yr⁻¹

Galactic close compact binaries

- Study evolution of ultra-compact binaries
- Measure orbital periods, masses, and distances
- Observe 1000s of sources continuously

Extreme Mass Ratio Inspirals (EMRIs)

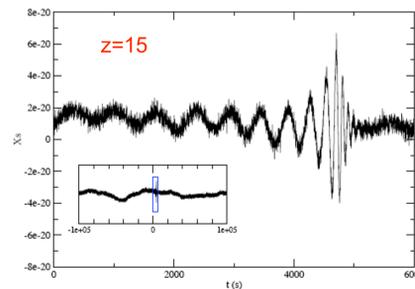
- BH, NS, or WD inspiral into massive BH
- Study compact objects in nuclei of galaxies
- Allow precision tests of GR
- Expect 10s-100s yr⁻¹

New Physics / Unexpected Sources

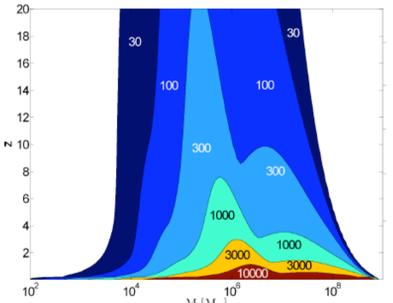
- LISA will look for:
 - Cosmological gravitational wave background
 - Superstring bursts, diffuse background

High SNR waveforms carry precision information about the emitting systems

Merger signals have high SNR even in a single wave cycle

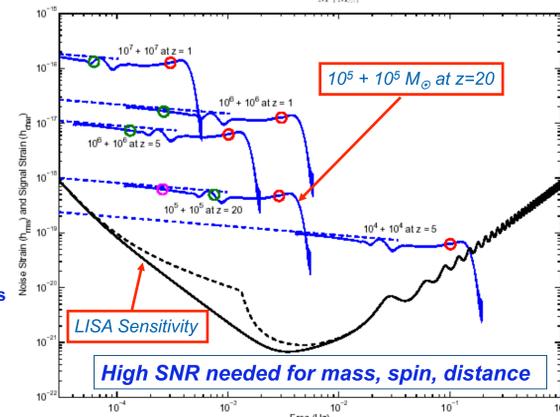


Total SNR for BH Merger

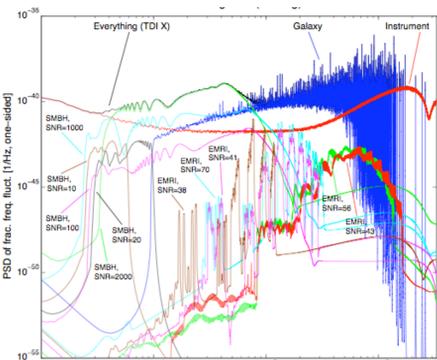


High-precision black hole properties from LISA:

- Massive black hole mergers:
 - Masses, spins to <0.1%, distances to 1% or less (z=1; an order of magnitude worse at z=20)
- Extreme mass ratio inspirals:
 - Spins to 0.01%, distances to 1% (z<1)
- Masses, spins, and numbers as a function of redshift:
 - How did black holes (BHs) initially form and what were their masses? How did accretion spin-up the BHs? How do the spins evolve over time? What happened to BHs as the initial galaxies merged to make modern galaxies.



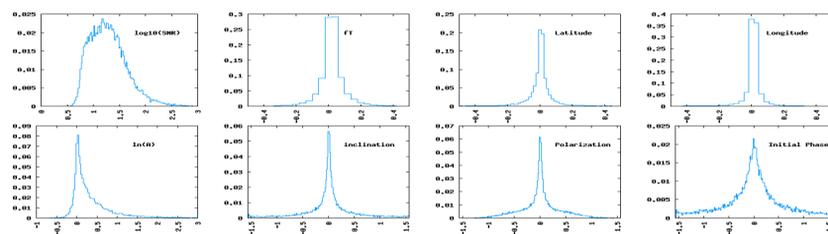
Data Analysis



Mock LISA Data Challenge

- Friendly competition to develop tools and methods for LISA data analysis and demonstrate capabilities
- Used a sophisticated simulation of LISA data stream including realistic instrument response, realistic spacecraft orbits, Time-Delay Interferometry (TDI), and signals from millions of individual gravitational wave sources
- Demonstrated conclusively that tens of thousands of sources can be individually identified and characterized in the LISA data stream
- Started in 2005. Currently in round 3
- More than 23 groups participating from 9 different countries

Histograms of WD binary SNRs + parameter estimation errors for 19,324 resolved sources



For JPL/Montana solution (Jeff Crowder)

Standard Sirens

Waveforms of black hole binaries give precise, gravitationally calibrated distances to high redshift

- Distances accurate to 0.1% to ~10% per event
- Absolute, physical calibration using only gravitational physics

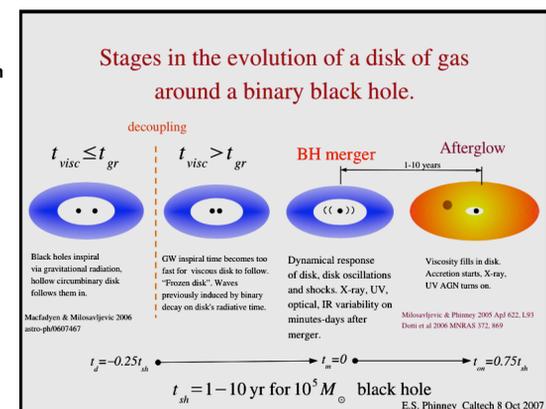
$$\text{Distance} \approx c \frac{1}{\text{frequency}^2 \times t_{\text{chirp}} \times \text{amplitude}}$$



“LISA also has the potential to measure the dark energy equation of state, along with the Hubble constant and other cosmological parameters. Through gravitational wave form measurements LISA can determine the luminosity distance of sources directly. If any of these sources can be detected and identified as infrared, optical or x-ray transients and if their redshift can be measured, this would revolutionize cosmography by determining the distance scale of the universe in a precise, calibration-free measurement.” (NRC BEPAC)

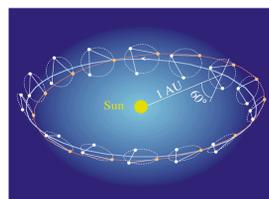
Electromagnetic Counterparts

- Not guaranteed, but if detected yields exciting scientific return
- Host galaxy identification provides unique information on galaxy-BH co-evolution
- Host galaxy identification allows precision determination of distance-redshift relation
- LISA will provide few-degree error boxes and time of merger weeks-months before event
- Error boxes shrink to degree or sub-degree size as signal-to-noise increases and merger approaches



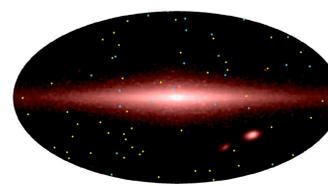
LISA Mission Quick Facts

Frequency Range	0.1 mHz - 0.1 Hz
Measurement concept	laser metrology between six fiducial masses on three spacecraft
Mission	
Orbits:	independent heliocentric orbits, trailing Earth by 20 degrees
Formation:	triangular with 5-million-km arms, passively maintained
Spacecraft:	short cylinder, 2.8 m diam x 0.76 m high, 598 kg, 810 W
Attitude/station-keeping	drag-free control of spacecraft
Thrusters:	three clusters of four, 30 N maximum thrust
Technology demonstration:	LISA Pathfinder/ST-7 (ESA/NASA launch 2011) will validate drag-free spacecraft operation
Payload (on each spacecraft)	
Lasers:	two 1-W diode-pumped 1064 nm Nd:YAG
Test masses:	two 2-kg Au-Pt cubical masses, 4.6 cm wide
Telescopes:	two 40-cm diameter, used both to transmit and receive
Science	
Data volume:	approximately 60 GB for the mission
Sources:	compact Galactic binaries, massive black hole binaries, extreme-mass-ratio inspirals, stochastic backgrounds, bursts
Source localization:	sub-degree to few degrees



Ultra-compact Galactic Binaries

- Expect thousands of individually identified compact binaries
- Also expect diffuse background at low frequency from millions of binaries
- Absolute distances will be measured to the shortest-period binaries



Simulation of GW Sky

Science Questions

- Is there a large population of ultra-compact binaries in the Galaxy?
- How did compact binaries form and what is the outcome of the common-envelope phase?
- What is the nature of the fundamental physical interactions in compact binaries?
- How are compact binaries distributed in the Galaxy and what does that tell us about the formation and evolution of the Galaxy?

For more information see: http://www.srl.caltech.edu/lisa/mission_documents.html