Listening to the Cosmic Dawn

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Summary

Structure formation has led to a great many mergers of galaxies and their massive black holes. A space-based gravitational wave observatory with sensitivity in the millihertz band will detect and measure these events over a wide range of masses and redshifts, providing information on the formation and evolution of massive black holes and the galaxies in which they reside. The observational capabilities in the gravitational-wave spectrum are complementary to those in the electromagnetic spectrum and will provide unique answers to COPAG's Big Question: "How did the universe originate and evolve to produce the galaxies, stars, and planets we see today?"

1. Key Science Questions[2]

A space-based gravitational-wave (GW) observatory such as the proposed *Laser Interferometer Space Antenna (LISA)* will **probe massive black holes over a very wide range of redshift, covering essentially all important epochs in their evolutionary history.** This will offer a unique, new way to address a number of unanswered questions:

- *Did the first black holes form in pre-galactic halos? What was their initial mass and spin?*
- *What is the mechanism of black hole formation in galactic nuclei? How do black holes evolve over cosmic time due to accretion and mergers?*
- *How did hierarchical galaxy assembly proceed in detail?*

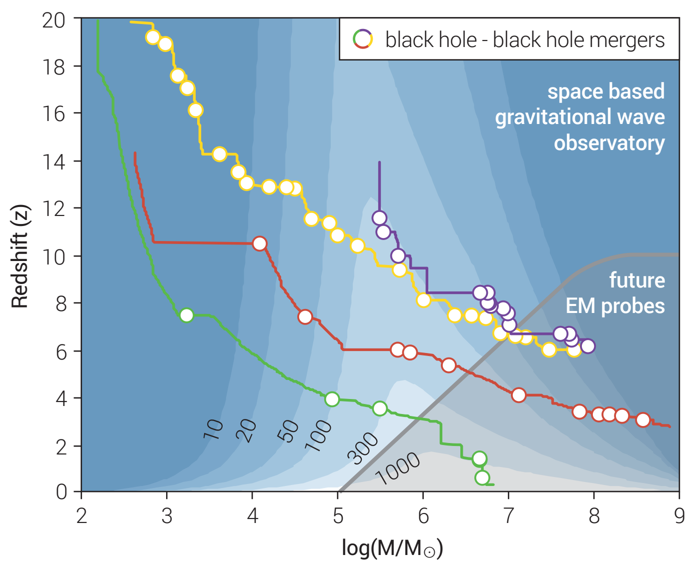

Figure 1: A space-based GW observatory will detect and characterize massive black hole mergers over a wide range of masses and redshifts, as indicated by the shaded contours showing GW SNR for the eLISA mission concept. As individual supermassive black holes evolve (colored tracks), they will undergo multiple mergers (open circles) that will be observed in GWs. A space-based GW observatory will be most sensitive to black hole mergers at higher redshift and lower mass than the black-hole-powered phenomena likely to be observed by future electromagnetic observatories (gray shaded region). (Adapted from Figure 2 of [1]).

Gravitational waves provide an exquisite probe for addressing these questions. Because each signal is emitted and detected in full coherence, sensitivity falls off only as $1/R$, not $1/R^2$. Thus, LISA will track the merger history of massive black holes from the first seeds at redshifts of $\gtrsim$20 through major mergers in the local universe using gravitational wave observations alone. As shown in Figure 1, black hole mergers with masses in the interval between 10^4 $M_\odot$ and 10^7 $M_\odot$ will be observed with significant signal-to-noise (SNR), allowing the individual masses, spins, and luminosity distances of the merging black holes to be precisely measured. **The range of black hole masses and redshifts sampled is complementary to that of black-hole-powered phenomena likely to be observed by future electromagnetic observatories.**

LISA will have all-sky sensitivity, making it a survey mission. In fact, **LISA will provide the widest and deepest survey of the universe ever produced**. LISA will detect the vast majority of all merging massive black hole binaries, even when the black holes are not electromagnetically active. This will expose an unseen population of objects which will potentially carry precious information about the black hole population as a whole. This comprehensive survey will enable investigation of the link between the black hole seed population and the rich population of active supermassive black holes observed

[2] Adapted from Chapter 1 of [1]

electromagnetically. LISA's measurements of black hole spins will provide information on whether early accretion flows were chaotic or coherent. Gravitational wave observations alone will be able to distinguish between the different massive black hole formation and evolution scenarios.

In a five year baseline mission, LISA should observe 100-250 massive black hole mergers, in addition to 800 extreme-mass-ratio inspirals and 40,000 close compact binaries in the Milky Way. For most of these sources, LISA will track the phase evolution of these millihertz signals for months to years.

2. Technical Capabilities

In *New Worlds, New Horizons*, the 2010 decadal prioritized the LISA mission and its associated science [2] after WFIRST. The capabilities of that mission or a close relative could achieve the science described here. Adjusting mission parameters such as constellation size, number of arms, telescope size, laser power, operational orbit, drag-free performance, and operational lifetime will affect the numbers of black hole mergers observed and the precision of their measured masses, spins, and sky locations.

3. Relevance of The Four Mission Concepts

A space-based gravitational wave observatory, such as the *Gravitational Wave Surveyor* found in the *Enduring Quests, Daring Visions* roadmap document, was not included in the proposed list of four mission concepts, because the NASA Astrophysics Division is pursuing a minority role in the L3 launch opportunity of ESA's Cosmic Vision Programme. ESA has already selected "The Gravitational Universe" as the science theme. The notional mission concept for L3 is significantly reduced from the LISA concept that has previously been reviewed and endorsed by NRC reviews. These changes will affect the science case, cost, and risk of the resulting mission. **A study is needed to evaluate levels of US participation in a European mission, and the associated science, cost, and technology development activities.** Because LISA has been so thoroughly studied in the past, this study can be more focused than the mission concept studies envisioned by the memo from Paul Hertz and could occur in parallel but must begin soon in order to meet the L3 timetable. **We're seeking COPAG endorsement for this study of a mission that can do unique and important Cosmic Origins science.**

4. New Technologies

More than two decades of sustained effort on the LISA project in the US and Europe has produced a mission concept and associated technologies that are highly mature. Of particular significance is the **upcoming launch of the LISA Pathfinder technology demonstrator mission in the Fall of 2015**. However, it is worth noting that European leadership in LISA Pathfinder has led to much of the expertise in key technical areas being dominated by European institutions. Should the US play a significant role in a future GW mission, it will be necessary to sustain and expand US technical and scientific capabilities.

5. Large Mission Needed?

The question of whether the NRC-endorsed science of the LISA mission could be carried out in part by a probe class mission was a key question of a 2011 NASA-sponsored study that consisted of a collection of mission concepts and technologies from the community, technical and cost assessments of each concept, and three full-scale mission concept studies. The final report [3] concluded that no viable concept capable of returning *any* of the LISA science case had a cost <$1B. However, an international partnership such as a minority role in L3 could reduce the NASA cost to well below that level.

References

[1] K. Danzmann, et al. *The Gravitational Universe,* available at https://www.elisascience.org/dl/TheGravitationalUniverse.pdf (2013)

[2] LISA Mission Science Office, *LISA: Probing the Universe with Gravitational Waves*, LISA Project internal report number LISA-LIST-RP-436 (March 2009), available at http://lisa.gsfc.nasa.gov/documentation.html.

[3] K. Anderson, R. Stebbins, R. Weiss, E. Wright, et al. *Gravitational Wave Mission Concept Study - Final Report*, available at http://pcos.gsfc.nasa.gov/physpag/GW_Study_Rev3_Aug2012-Final.pdf (2012)