Gravitational Wave Astronomy as a Probe of Galactic Nuclei

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The formation, evolution, interaction, and coalescence of supermassive black holes (SMBHs) are intimately connected to the stellar and gas dynamics at the heart of their galaxy host. Because of this strong interconnectedness, observations of SMBHs in galactic nuclei are a unique probe of their surroundings, conveying information that is highly complementary to that obtained in the electromagnetic (EM) regime. In turn, observations of the stars and gas in galactic nuclei provide detailed information about the central black hole. However, large galactic distances and optical extinction combine to make it challenging to make high precision SMBH mass measurements for most galaxies. Fortunately, since gravitational waves (GWs) do not suffer extinction, the GW signal from SMBHs are accessible even in cosmologically distant galaxies.

Science objectives attainable with GW observations:

- For merging SMBHs at the center of a galactic nucleus, we can measure the black hole masses, mass ratios, and spins to high precision (~1%);
- These parameters can serve to distinguish between competing SMBH seed models;
- Merger rates as a function of time give the evolution history and constrain models of SMBH growth and co-evolution with the galaxy (e.g, M-sigma, M-bulge, AGN-star formation correlations, feedback, metallicity);
- The sky position of the merger determined via gravitational-wave observations gives a target for coordinated EM observations;
- Details of EM counterparts, as well as residual eccentricity in the orbit, tell us about the stellar and gas content of the nucleus, and what drives the binary evolution;
- Direct observation of SMBH binaries at sufficiently low frequencies/large separations, either individually or as a stochastic ensemble, will inform the epoch of binary evolution immediately preceding the GW-driven inspiral; this can give useful insight into how nature solves the “final parsec problem”, and can further constrain hypervelocity star production;
- Extreme-mass Ratio Inspirals (EMRIs) probe the population of compact remnants in galactic nuclei. They are excellent precision probes of general relativity, they can constrain the stellar and gas content of the nucleus through modulation of the observed GWs, and they can also probe the low redshift SMBH mass function.

Figure: (left) HST image of merging galaxies NGC 2623 [credit: ESA/NASA]. (right) Artist impression of stars and gas orbiting the SMBH at the center of the Milky Way [credit: ESO].