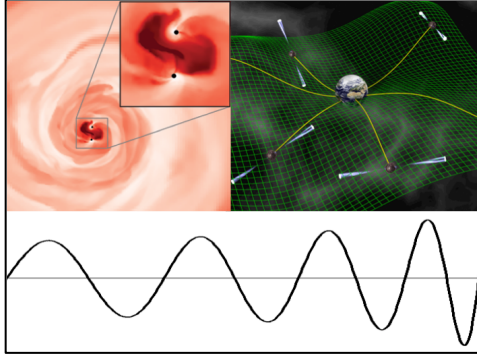


NANOHERTZ TO MICROHERTZ GRAVITATIONAL WAVE ASTRONOMY

North American Nanohertz Observatory for Gravitational Waves

The *New Worlds, New Horizons* Decadal Survey identified Gravitational Wave Astronomy as a science frontier discovery area. Supermassive black hole binaries (SMBHBs) produce gravitational waves (GWs) over a range of frequencies, from nanohertz at early times (potentially detectable for black hole masses of at least $10^8 M_\odot$ at redshifts $z < 2$) to microhertz at late times (accessible out to $z > 2$ for masses greater than $10^7 M_\odot$). Low-frequency GW studies are thus complementary to those in the mid- and high-frequency LISA and LIGO bands.



The low-frequency GW astronomy roadmap in the coming decades evolves swiftly from initial detection of GWs (within 5–10 years at nHz frequencies, subsequently extending to the μHz band) to characterization of sources, and then to addressing broader science questions inaccessible to electromagnetic studies, including:

What is the energy density contained in the stochastic background of GWs from SMBHBs?

Such a background should result from the overlapping emissions of SMBHBs at $z < 2$, and provides a direct constraint on hierarchical structure formation models. The spectrum of the stochastic background will ultimately favor a particular solution to the “last-parsec problem.”

What are the properties of individual SMBHBs? The gravitational waveforms of spectrally resolved binaries will enable parameter estimation, yielding information about the black holes and their interactions with the gaseous and stellar environment. Complementary information can be obtained via detection and followup measurements of electromagnetic counterparts.

Are there exotic contributions to the GW spectrum? Other sources, such as cosmic strings and phase transitions, could also produce nHz GWs, offering a window onto the early Universe and fundamental physics beyond electromagnetic observations and particle physics experiments.

Are there GW sources without known electromagnetic counterparts? Every time a new region of the electromagnetic spectrum has been opened (e.g., radio, X-rays, γ -rays), new and unexpected classes of objects have been discovered.

Table 1. Low-Frequency Gravitational Wave Astronomy Roadmap

Modern GW observatories operate on the principle of detecting light travel deviations between point masses caused by passing GWs. In the nHz band, the most profitable measurement approach is a *pulsar timing array* (PTA) in

which the path from each pulsar to Earth forms an arm of the GW detector. A PTA is most sensitive to GWs with periods comparable to the total observation timespan, typically 1–10 yr ($\sim 3\text{--}30$ nHz). The optimal PTA involves millisecond pulsars evenly distributed on the sky, for which a passing GW modifies the spacetime around the Earth and produces correlated shifts in the pulse times of arrival from the different pulsars. Existing and proposed NASA assets, such as the Deep Space Network and X-ray and γ -ray timing missions, can already contribute to near-term PTA implementations that will detect nHz GWs within a decade. Similar synergies between space- and ground-based capabilities—including large radio telescopes and sensitive high-energy observatories—will propel the 30-year roadmap, with a focus on sensitive GW and electromagnetic source characterization.

Timeframe	Scientific Challenge
10 yr	Measurement of the strain amplitude and spectral slope of nHz frequency GWs, providing constraints on hierarchical growth of cosmic structure.
20 yr	A census and characterization of individual sources in the nHz GW sky. Constraints on exotic contributions to the GW spectrum.
30 yr	Multi-messenger characterization of all SMBHBs in the nearby Universe, leading to a comprehensive understanding of SMBH formation and evolution. Identification of non-astronomical sources of low-frequency GW emission.