Multi-band Gravitational-Wave Cosmology Post-print

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Abstract

On February 11, 2016, the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration announced the direct detection of gravitational waves generated by the merger of two stellar-mass black holes over a billion years ago. This experimental result not only constitutes a direct verification of the gravitational waves predicted by Einstein' s general relativity a century earlier, but also opens a new window onto the universe for humanity, and provides an experimental foundation for in-depth research into quantum gravity theories beyond Einstein' s general relativity.

Full Text

Preamble

Strategic Priority Research Program (Category B) of the Chinese Academy of Sciences
Multi-band Gravitational Wave Cosmology Research

1. Project Background and Rationale

On February 11, 2016, the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration announced the direct detection of gravitational waves produced by the merger of two stellar-mass black holes more than one billion years ago. This landmark achievement not only provided the first direct verification of gravitational waves—predicted by Einstein' s general relativity a century earlier—but also opened a new window for cosmic exploration and created practical opportunities for investigating quantum gravity theories that extend beyond general relativity.

Space-based gravitational wave experimental satellite projects are planned for implementation over the next two decades. The first technology demonstration mission, LISA Pathfinder, was successfully launched by the European Space Agency at the end of 2015 and has been operating smoothly since. In China, space-based gravitational wave detection has been incorporated into the Chinese Academy of Sciences' Space 2050 Plan. In 2008, the CAS initiated a study group for space gravitational wave detection, hosted by the National Microgravity Laboratory at the Institute of Mechanics and involving multiple CAS institutes and external universities. This group began developing a roadmap for China' s space gravitational wave detection efforts over the coming decades.

Gravitational wave signals are extraordinarily weak, presenting immense experimental challenges. Detection strategies vary according to the frequency band of the source, which can be categorized as follows:

(1) High-frequency band (tens to thousands of hertz): Sources include compact binary systems composed of neutron stars and stellar-mass black holes (several to tens of solar masses). The optimal detection instruments are ground-based laser interferometers with arm lengths of several kilometers. The most prominent example is LIGO, which involves over 1,000 scientists and, after more than two decades of development, successfully detected gravitational waves using two perpendicular 4,000-meter arms.

(2) Medium-frequency band (10 to 1 Hz): Sources typically include late-stage mergers of massive black holes and white dwarf binary systems within our galaxy. These signals can be detected by deploying satellite arrays with baselines of hundreds of thousands to millions of kilometers in space. Among the more than ten proposed space-based gravitational wave detection missions, the leading concept is LISA (Laser Interferometer Space Antenna), a major project approved by the European Space Agency.

(3) Low-frequency band (10 to 10 Hz): Sources are supermassive black holes (tens of millions to billions of solar masses) that merge during the late stages of galaxy collisions. Detection requires even longer baselines, achievable only by using large ground-based radio telescopes to monitor the arrival times of millisecond pulsars, effectively extending the baseline to galactic scales. Indeed, indirect evidence for gravitational waves came from observations of binary pulsar systems, but pulsar timing arrays offer the potential for direct measurement of supermassive black hole gravitational waves with even greater significance. Beyond current large-aperture radio telescopes, the future Square Kilometer Array (SKA) will be the ideal instrument for pulsar timing. The international radio astronomy community has thoroughly evaluated the Phase 1 science goals for SKA, ranking the use of pulsar timing for precision gravitational tests and gravitational wave observations as the highest priority among 13 scientific objectives, alongside 21 cm neutral hydrogen observations of cosmic reionization. SKA' s large collecting area, wide frequency coverage, large field of view, and multiple beams make it exceptionally suitable for discovering and monitoring numerous millisecond pulsars. China' s recently completed 500-meter Aperture Spherical Telescope (FAST) also lists pulsar search and timing as primary science objectives. FAST' s unprecedented sensitivity has the potential to improve pulsar timing precision from the current hundreds of nanoseconds to tens of nanoseconds, advancing the discovery of gravitational waves from supermassive black holes via pulsar timing arrays.

(4) Very-low-frequency primordial gravitational waves: Originating from violent spacetime fluctuations during early-universe inflation, these waves carry rich cosmological information. Their detection would open a new window for exploring the early universe. Contemporary cosmology widely accepts that the early universe underwent inflation—a period of exponential spacetime expansion during which violent spacetime oscillations generated "primordial gravitational waves." Today, the longest wavelengths of these primordial waves may have stretched to scales comparable to the size of the universe. The most effective detection method involves studying the anisotropies in the cosmic microwave background (CMB) radiation left over from the Big Bang. Primordial gravitational waves produce B-mode polarization in CMB photons, making CMB polarization observations the most promising approach for their detection. Measuring CMB B-mode signals is recognized as one of the next major breakthrough directions in observational cosmology. While LIGO confirmed the existence of black hole gravitational waves—extreme astrophysical processes in the late universe—and verified general relativity' s predictions, discovering primordial gravitational waves would represent "another first," delivering the earliest and most primordial information about the universe. This would be profoundly significant for cosmology and for fundamental physics, including tests of CPT symmetry.

2. Research Plan and Expected Outcomes

This Strategic Priority Research Program will conduct forward-looking planning to establish gravitational wave astronomy through frontier research on the multi-band gravitational wave universe. The program focuses on three frequency bands—medium-low frequency, low frequency, and very low frequency—along with electromagnetic counterparts, addressing four key research areas.

In the medium-low frequency band, the program will pursue space-based laser interferometry gravitational wave detection, including overall system design and pre-research on key technologies. To avoid disturbances from Earth's gravity and solar radiation, the preliminary design adopts the natural triangular configuration for space laser interferometry, consisting of three satellites in synchronized heliocentric orbits. Using differential interferometry, six laser beams will measure real-time distance variations between freely floating test masses in adjacent spacecraft, enabling direct detection of gravitational waves in the medium-low frequency band (0.1 mHz-1 Hz).

In the low-frequency band, building upon FAST—the world' s largest single-aperture telescope—the program will construct high-precision timing systems for pulsar search and timing observations. Leveraging participation in the international SKA collaboration and domestic SKA pathfinder 21CMA, the program will master low-frequency pulsar observation and multi-beam tracking technologies, preparing for eventual pulsar timing gravitational wave detection with SKA. FAST is expected to discover hundreds of pulsars, including approximately 30 millisecond pulsars suitable for timing arrays, significantly improving timing precision and sensitivity.

In the very-low-frequency band, based at the Ali Observatory in Tibet, the program will construct the first CMB primordial gravitational wave detection telescope in the Northern Hemisphere, achieving the first high-sensitivity primordial gravitational wave survey of the northern sky. In gravitational wave source studies, the program will utilize existing and under-construction ground- and space-based facilities to observe and theoretically study electromagnetic counterparts of gravitational wave sources.

Through five years of implementation, this program will lay a solid foundation for China' s gravitational wave astronomy development. It will secure core technical solutions for space laser interferometry gravitational wave detection, identify electromagnetic counterparts, and strive to make new discoveries. The program is strategically important for understanding the nature of gravity, black hole physics, and cosmic creation and evolution, and will drive advances across astronomy, physics, and high technology. Because different frequency bands require distinct detection methods, the program encompasses not only major scientific discoveries but also numerous cutting-edge technologies, significantly enhancing China' s discovery capabilities in gravitational wave detection.

3. Scientific Team and Participating Units

According to the program implementation plan, four research projects have been established: (1) Pulsar Timing Gravitational Wave Detection Pre-research; (2) Ali Primordial Gravitational Wave Detection Plan; (3) Space Taiji Program Pre-research; and (4) Gravitational Wave Source Electromagnetic Counterpart Detection and Gravitational Wave Astrophysics Research. The program brings together approximately 200 Chinese Academy of Sciences researchers active at the forefront of gravitational wave-related research fields.

Note: Figure translations are in progress. See original paper for figures.

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