

The LISA–Taiji network

To the Editor — The Laser Interferometer Space Antenna (LISA), a space-based gravitational-wave observatory, was proposed in the 1990s to detect gravitational waves with a frequency band from 10^{-4} Hz to 10^{-1} Hz (ref. 1). LISA consists of a triangle of three identical spacecraft with a separation distance of 2.5 million kilometres in orbit around the Sun, which will bounce lasers between each other with a displacement noise of about $10 \text{ pm Hz}^{-1/2}$ in a one-way measurement. The constellation will follow the Earth by about 20° (Fig. 1). It is expected to launch between 2030 and 2035, with a mission lifetime of 4 years, extendable to 10 years. Recently, some technologies have been successfully tested in the LISA pathfinder mission².

Taiji is a gravitational-wave space facility proposed by the Chinese Academy of Sciences³. The University of the Chinese Academy of Sciences and other institutes of the Chinese Academy of Sciences are involved in building it. Like LISA, Taiji is composed of a triangle of three spacecraft with a separation distance of 3 million kilometres in a heliocentric orbit ahead of the Earth by about 20° (Fig. 1). The telescope diameter will be 40 cm, the displacement noise is expected to be $8 \text{ pm Hz}^{-1/2}$, and the acceleration noise is expected to be $3 \text{ fm s}^{-2} \text{ Hz}^{-1/2}$ at 1 mHz. Since the spacecraft are farther apart than in LISA, Taiji is slightly more sensitive to low-frequency gravitational waves⁴. The Taiji project consists of the following three steps. The first step is to launch a satellite to demonstrate the feasibility of the Taiji technology roadmap. The Taiji pathfinder, officially called Taiji-1, successfully launched on 20 September 2019 and is currently operational. Following Taiji-1, two satellites will be launched to verify the key technologies, including long-baseline interferometry in space by 2024. Finally, Taiji is planned to launch during the same period as LISA. If Taiji joins the LISA constellation, assuming a one-year overlap, the LISA–Taiji network in space (Fig. 1) is expected to significantly improve the sky localization of gravitational-wave sources (luminosity distance and solid angle) due to the large separation of the two constellations.

Localizing gravitational-wave sources quickly and accurately is one of the key tasks for ground-based and space-based gravitational-wave observations. Accurate localization is crucial for follow-up

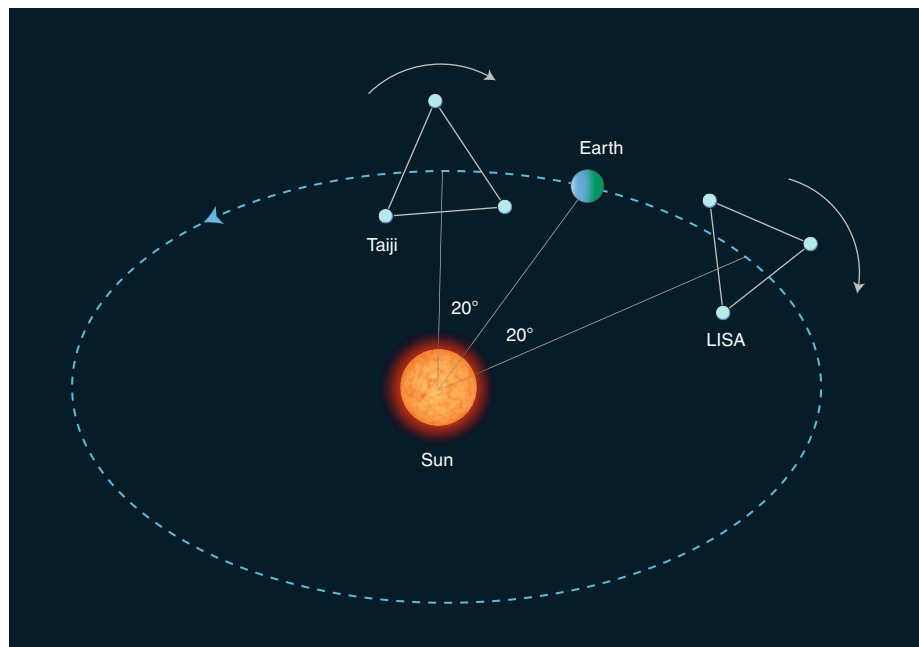


Fig. 1 | Configuration of the LISA–Taiji network. LISA consists of a triangle of three spacecraft with a separation distance of 2.5 million kilometres in a heliocentric orbit behind the Earth by about 20° , while Taiji has a separation distance of 3 million kilometres in a heliocentric orbit ahead of the Earth by about 20° . Due to a distance of about 0.7 au between the two constellations, the LISA–Taiji network is expected to significantly improve the sky localization of coalescing massive black hole binaries.

electromagnetic spectroscopic observations and the unique identification of their host galaxies. With an accurate knowledge of the redshift of the host galaxy, gravitational-wave sources can be used as standard sirens to independently explore the expansion history of the Universe⁵.

It is hard to determine the sky location of a gravitational-wave source using a single ground-based gravitational-wave detector because detectors are sensitive to gravitational waves from nearly all directions. With two detectors at different locations, the position of the source can in principle be restricted to an annulus in the sky by triangulation using the difference between the arrival time of the wave at the two detectors. A network of more than two detectors can localize the sky position of the source using the arrival time difference with the help of the phase difference and amplitude ratios of gravitational waves on arrival at the detectors. For example, the sky localization of GW170814 was significantly improved due to the addition of the Advanced Virgo detector, reducing the area of the 90% credible region from

$1,160 \text{ deg}^2$ using only the two Advanced LIGO detectors to 60 deg^2 using the LIGO–Virgo network⁶. The addition of KAGRA and LIGO–India will further improve localization for the frequency bands covered by ground-based detectors.

Unlike ground-based detectors, the main targets for LISA and Taiji will be gravitational waves from coalescing massive black hole binaries⁷ with total masses between $10^4 M_\odot$ and $10^8 M_\odot$ at the centres of galaxies. In addition, LISA and Taiji might be able to detect binary stellar black holes and black hole–neutron star mergers in their initial inspiral phase. While bound massive black hole binaries are difficult to identify through electromagnetic observations, during their inspiral phase when the orbital period of the system becomes smaller than hours, these systems should emerge as strong gravitational-wave sources. The inspiral would be followed by the coalescence of the two massive black holes, which should be detectable by space-based gravitational-wave detectors with a high signal-to-noise ratio. Joint electromagnetic and gravitational-wave detections of such

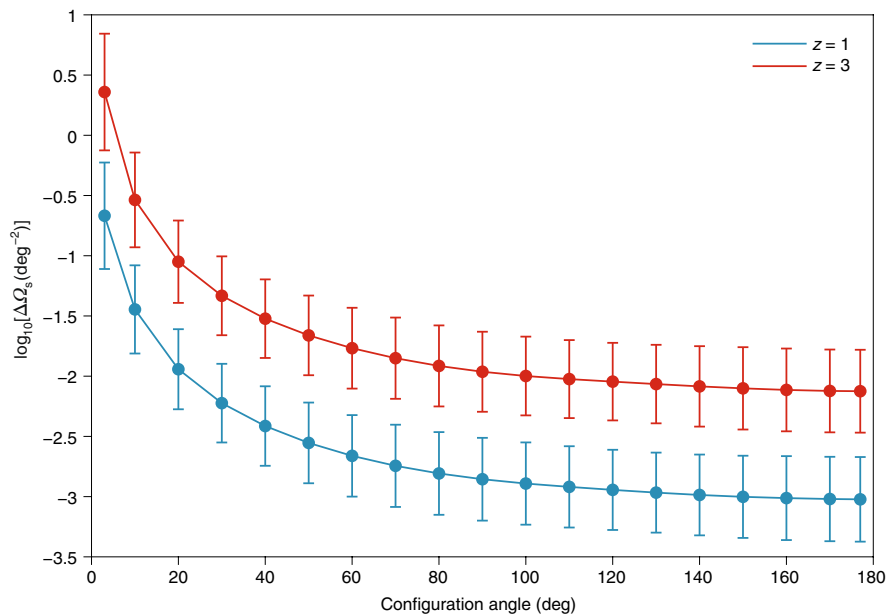


Fig. 2 | Measurements of the angular resolution. The angular resolution ($\Delta\Omega_s$) depends on the configuration angle, subtended by the heliocentric orbit between two detectors in the LISA-Taiji network. We choose an equal-mass black hole binary with a total intrinsic mass of $10^5 M_\odot$, located at redshifts of $z = 1$ (blue) and $z = 3$ (red), respectively. The 1σ uncertainties are evaluated using a catalogue of 10,000 simulated sources at different sky positions.

systems will allow the study of the accretion disk during and after the massive black hole binaries merge to a single black hole⁸.

The inspiral and coalescence of such massive black hole binaries can last between several days to years in the frequency band of LISA and Taiji. Due to the motion of the detectors in space, the time dependence of the antenna pattern function plays a crucial role in localizing the position of the gravitational-wave source⁹. Hence, a single space-based detector can be effectively treated as a network including a set of detectors at different locations along the detector's trajectory in space, which observe a given gravitational-wave event at different times. LISA is expected to localize gravitational-wave sources with

an angular resolution of 1–100 deg^2 (ref. ¹), which depends on the mass, distance and inclination angle of the sources¹⁰. However, given the expected redshift distribution of sources detectable by LISA, such an angular resolution is not good enough to identify the source galaxy. If Taiji joins LISA, the LISA-Taiji network can significantly improve the sky localization of gravitational-waves, following a similar strategy of triangulating the signal with ground-based detectors.

The angular resolution for the LISA-Taiji network depend on the configuration angle, subtended by the heliocentric orbit between LISA and Taiji (Fig. 2). For a configuration angle of 180° , the angular resolution reaches a minimum value. For an equal-mass black hole binary with a total intrinsic mass of

$10^5 M_\odot$, located at redshifts of $z = 1$ and $z = 3$, respectively, the angular resolution is improved by about 2 orders of magnitude as the configuration angle varies from 3° to 40° , while it is improved by about 0.6 orders of magnitude from 40° to 180° . Hence, the LISA-Taiji network with a configuration angle of 40° can effectively help us to quickly and accurately localize gravitational-wave sources. □

Wen-Hong Ruan^{1,2}, Chang Liu^{1,2},
Zong-Kuan Guo^{1,2*}, Yue-Liang Wu^{1,2} and
Rong-Gen Cai^{1,2}

¹CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing, China. ²School of Physical Sciences, University of Chinese Academy of Sciences, Beijing, China.

*e-mail: guozk@itp.ac.cn

Published online: 3 February 2020

<https://doi.org/10.1038/s41550-019-1008-4>

References

- Audley, H. et al. (LISA Collaboration) Preprint at <https://arxiv.org/abs/1702.00786> (2017).
- Armano, M. et al. (LISA Pathfinder Collaboration). *Phys. Rev. Lett.* **118**, 171101 (2017).
- Hu, W.-R. & Wu, Y.-L. *Natl. Sci. Rev.* **4**, 685–686 (2017).
- Ruan, W.-H., Guo, Z.-K., Cai R.-G. & Zhang, Y.-Z. Preprint at <https://arxiv.org/abs/1807.09495> (2019).
- Schutz, B. F. *Nature* **323**, 310–311 (1986).
- Abbott, B. P. et al. (LIGO Scientific Collaboration and Virgo Collaboration). *Phys. Rev. Lett.* **119**, 141101 (2017).
- Begelman, M. C., Blandford, R. D. & Rees, M. J. *Nature* **287**, 307–309 (1980).
- Milosavljevic, M. & Phinney, E. S. *Astrophys. J.* **622**, L93–L96 (2005).
- Lang, R. N. & Hughes, S. A. *Astrophys. J.* **677**, 1184–1200 (2008).
- Cutler, C. *Phys. Rev. D* **57**, 7089 (1998).

Acknowledgements

We thank W. Zhao, J.-M. Wang, and J. Zaanen for helpful comments. Z.-K.G. is supported in part by the National Natural Science Foundation of China grants no. 11690021 and no. 11575272, by the Strategic Priority Research Program of the Chinese Academy of Sciences grants no. XDB23030100 and no. XDA15020701, and by the Key Research Program of Frontier Sciences, CAS. Y.-L.W. is supported by the National Natural Science Foundation of China grants no. 11851302 and no. 11747601. R.-G.C. is supported by the National Natural Science Foundation of China grants no. 11690022, no. 11435006, and no. 11821505.