Detecting Gravitational Waves from Exoplanets Orbiting Binary Neutron Stars with B-DECIGO and DECIGO

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2025-8-26, Xichang, 19TH TAUP

arXiv:2508.17385

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1. Background
2. Method
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Conventional Exoplanet Detection

Method	Count
Transits	4422
Radial Velocity	1130
Microlensing	248
Direct Imaging	79
Others	78
Total	5957

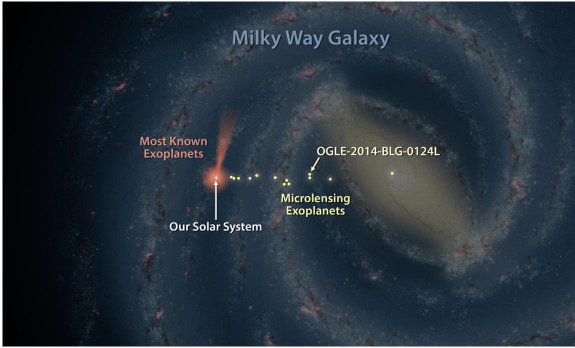

图 1: Spatial distribution of detected exoplanets

Conventional Exoplanet Detection

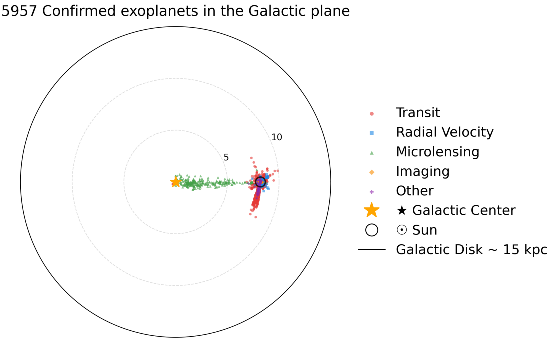

图 2: Position of detected exoplanets

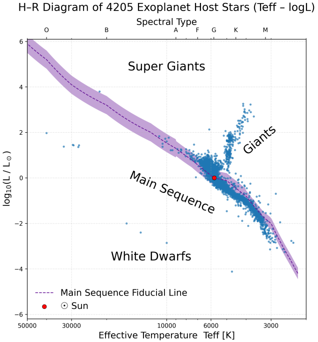

图 3: Detected exoplanets on H-R diagram

Limits of Conventional Methods

Axis	Limitation
Host-star type	Optimized for main-sequence stars (F/G/K); poor sensitivity for compact hosts (e.g., neutron stars, white dwarfs).
Stellar brightness & distance	Mostly limited to bright systems within a few hundred light-years. Pulsar timing and microlensing can reach farther, but require very specific source conditions.
Binary-system complexity	Many pipelines assume single-star models; hard to apply directly to binaries.

Why Gravitational Waves for Circumbinary Planets?

- **EM-independent –**Unaffected by stellar brightness, dust, or stellar activity; works for all host types.
- **Long-distance reach –**GWs propagate with little attenuation, so we can probe regions EM methods struggle to access.
- **Binary-friendly –**The carrier signal shows strong Doppler modulation; phase analysis lets us infer planet mass and orbit.

Why Gravitational Waves for Circumbinary Planets?

- **Planet survival conditions –**Close compact binaries are extreme; GW detections tell us when and where planets can survive.
- **Test second-generation planets –**Check whether planets can form from material ejected in the common-envelope (CE) phase.
- **Larger, less-biased samples –**Extend the search across the Milky Way and even into nearby galaxies.

Spaceborne Gravitational-Wave Observatories

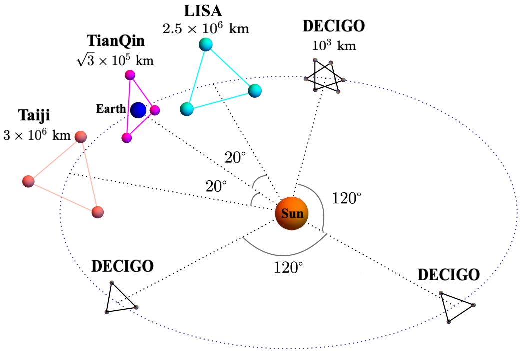

图 4: Planned space GW missions[1]

Previous work

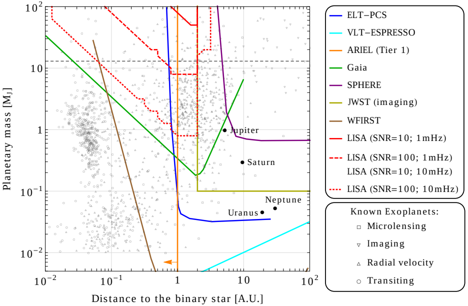

图 5: N. Tamanini & C. Danielski (2019)[2]

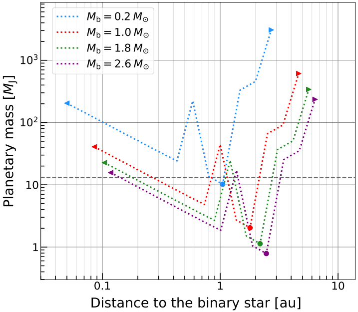

图 6: Y. Kang et al. (2021)[3]

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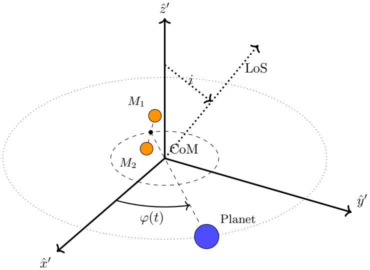
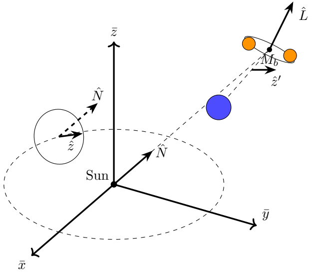
Three-body System: Planet–Binary

$$\mathbf{r}(t) = \big(R\cos\varphi(t),\ R\sin\varphi(t),\ 0\big)$$

$$\mathcal{R}(i)\,\mathbf{r}(t) = \big(R\cos\varphi(t),\ R\cos i\ \sin\varphi(t),\ -R\sin i\ \sin\varphi(t)\big)$$





The GW from the compact binary acts like a precise "clock"; a third body (the planet) makes the clock tick vary periodically via Doppler modulation.

Binary Center-of-Mass Motion and Doppler Effect

- **Binary CoM relative to system CoM:**

$$\mathbf{r}_b(t) = \frac{M_p}{M_b + M_p} \mathcal{R}(i)\, \mathbf{r}(t)$$

- **Line-of-sight (LOS) component:**

$$z_b(t) = -\frac{M_p}{M_b + M_p} R \sin i \, \sin \varphi(t)$$

- **LOS velocity of the binary CoM:**

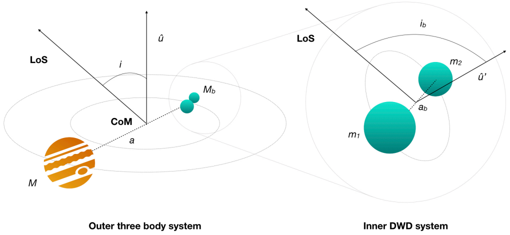
$$v_{z,b}(t) = -K \cos \varphi(t)$$

- **Source-frame GW frequency:**

$$f_{\rm GW}(t) = f_0 + f_1 t + \mathcal{O}(t^2)$$

- **Observed frequency (Doppler shifted):**

$$f_{\rm obs}(t) = \left(1 + \frac{v_{z,b}(t)}{c}\right) f_{\rm GW}(t)$$



Key semi-amplitude K

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_p}{(M_b + M_p)^{2/3}} \sin i$$

Gravitational-Wave Signal Model

The detector provides two channels ($\alpha = \mathrm{I}, \mathrm{II}$):

$$h_\alpha(t) = \frac{\sqrt{3}}{2} A_\alpha(t) \cos \chi_\alpha(t)$$

$$\chi_\alpha(t) = \int 2\pi f_{\mathrm{obs}}(t)\, dt + \Psi_0 + \Phi_\alpha^{(p)}(t) + \Phi_D(t)$$

Fisher Matrix and SNR

Parameters

$$\lambda = \{\ln \mathcal{A},\ \Psi_0,\ f_0,\ f_1,\ \bar{\theta}_S,\ \bar{\phi}_S,\ \bar{\theta}_L,\ \bar{\phi}_L,\ K,\ P,\ \varphi_0\}$$

Fisher matrix

$$\Gamma_{ij} = \frac{2}{S_n(f_0)} \sum_{\alpha=\mathrm{I,II}} \int_0^{T_{\mathrm{obs}}} \left(\frac{\partial h_\alpha(t)}{\partial \lambda_i} \frac{\partial h_\alpha(t)}{\partial \lambda_j} \right) dt$$

Signal-to-noise ratio

$$\mathrm{SNR} = \left[\frac{2}{S_n(f_0)} \sum_{\alpha=\mathrm{I,II}} \int_0^{T_{\mathrm{obs}}} h_\alpha^2(t)\, dt \right]^{1/2}$$

Parameter Uncertainties

Covariance matrix:

$$\Sigma^{ij} = \langle \Delta\lambda^i \Delta\lambda^j \rangle = (\Gamma^{-1})^{ij}$$

Uncertainty of parameter λ_i:

$$\Delta\lambda_i = \sqrt{\Sigma_{ii}}$$

Selection (detectability) criterion: $\dfrac{\Delta K}{K}, \ \dfrac{\Delta P}{P} \leq 30\%$

Detector Sensitivity Curves

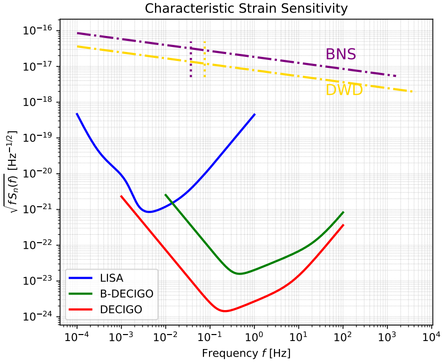
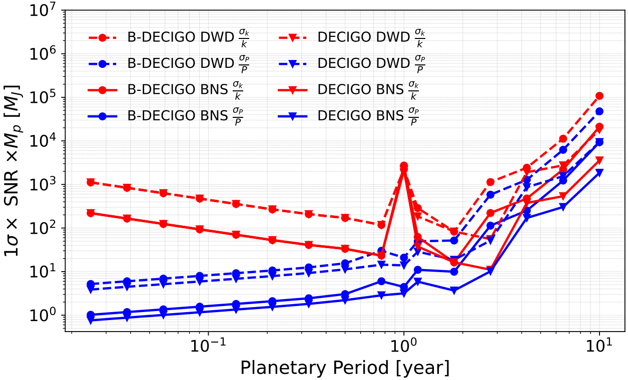
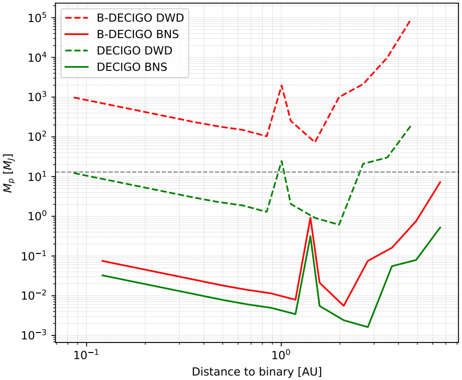


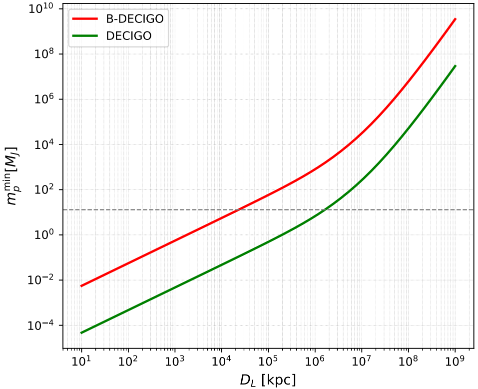
图 7: LISA and (B-)DECIGO sensitivity curves.

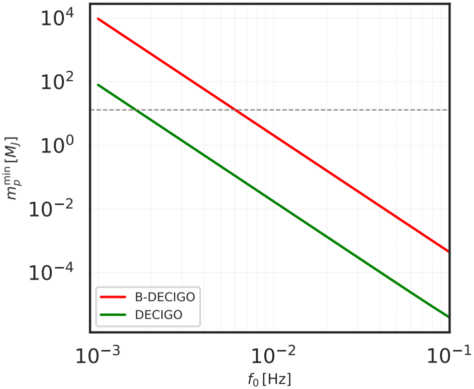
Result I: Sensitivity vs Planetary Period





Result II: Minimum Detectable Mass vs Distance & f_0

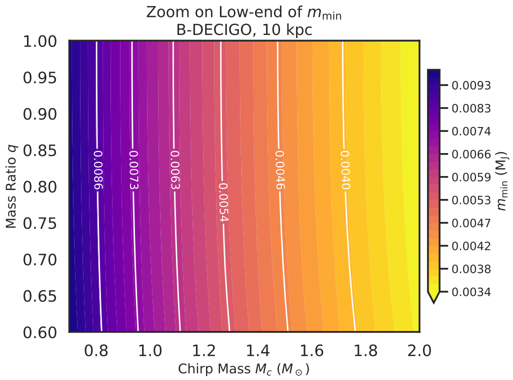




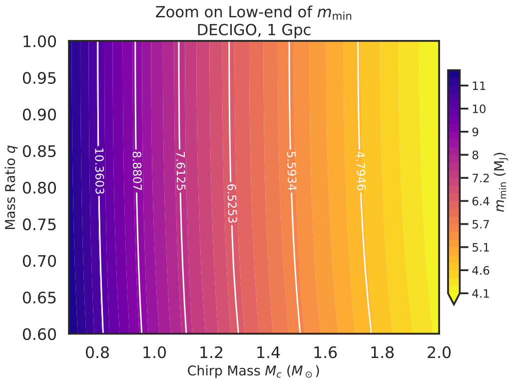
13 M_J: B-DECIGO $10^4 - 10^5$ kpc

DECIGO $10^6 - 10^7$ kpc

Results III: Low-end of $m_{\min}$ across $(\mathcal{M}_c, q)$



B-DECIGO @ 10 kpc



DECIGO @ 1 Gpc

Summary

- **Method:** planet = small periodic **Doppler** on a GW carrier; no EM light needed.
- **Detectability:** require $\Delta K/K,\ \Delta P/P \leq 30\%$.
- **Sensitivity set by:** stronger carrier (larger $\mathcal{M}_c$, higher f_0) and more sampled planet cycles.
- **Breakthrough: DECIGO reaches $\sim$1 Gpc** (giants at few–10 M_J); in the Galaxy it reaches sub-Jovian / near-Earth masses $\Rightarrow$ test survival, mass loss, second-generation formation.

References I

[1] Yungui Gong, Jun Luo, and Bin Wang. "Concepts and Status of Chinese Space Gravitational Wave Detection Projects". In: *Nature Astronomy* 5.9 (Sept. 2021), pp. 881–889. ISSN: 2397-3366. DOI: 10.1038/s41550-021-01480-3. arXiv: 2109.07442 [astro-ph]. (Visited on 05/31/2025).

[2] Nicola Tamanini and Camilla Danielski. "The Gravitational-Wave Detection of Exoplanets Orbiting White Dwarf Binaries Using LISA". In: *Nature Astronomy* 3.9 (Sept. 2019), pp. 858–866. ISSN: 2397-3366. DOI: 10.1038/s41550-019-0807-y. URL: https://www.nature.com/articles/s41550-019-0807-y (visited on 06/02/2025).

[3] Yacheng Kang, Chang Liu, and Lijing Shao. "Prospects for Detecting Exoplanets around Double White Dwarfs with LISA and Taiji". In: *Astronomical Journal* 162.6 (Dec. 1, 2021), p. 247. ISSN: 0004-6256, 1538-3881. DOI: 10.3847/1538-3881/ac23d8. arXiv: 2108.01357 [astro-ph]. URL: http://arxiv.org/abs/2108.01357 (visited on 05/07/2025).

Thanks!