Detecting warm dark matter by the stochastic gravitational waves

Shi Pi^{1,2*}

¹CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China;
²Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS, the University of Tokyo, Kashiwa Chiba 277-8583, Japan

Received May 26, 2021; accepted June 7, 2021; published online July 30, 2021

Citation: S. Pi, Detecting warm dark matter by the stochastic gravitational waves, *Sci. China-Phys. Mech. Astron.* **64**, 290431 (2021),
<https://doi.org/10.1007/s11433-021-1733-0>

NANOGrav has recently reported the detection of a common-spectrum process via the time-of-arrival data of 47 millisecond pulsars [1], which could be interpreted by a stochastic gravitational wave background (SGWB) in the nanohertz frequency band ($f \sim 10^{-9}$ Hz) with energy density parameter $\Omega_{\text{GW}} \sim 10^{-9}$. Despite the vague quadrupole correlation that obstructs the identification of gravitational waves, this report hints the possibility of some new physics at around or below 100 MeV that can generate nanohertz gravitational waves by, for instance, the first order phase transition (FOPT).

The spectral shape of SGWB detected by NANOGrav is fairly flat, i.e., $\Omega_{\text{GW}} \sim f^{-0.5 \pm 1.0}$ at $1\text{-}\sigma$ confidence level. The infrared part of SGWB from FOPT, however, is proportional to f^3 , if the universe is radiation-dominated [2]. There are some papers trying to interpret the NANOGrav signal by the near-peak part of SGWB from FOPT, indicative of some new physics around 100 MeV. However, such a FOPT is absent in the standard model, thus a dark sector has to be considered to realize it. Furthermore, the Bayesian analysis demonstrated that interpreting NANOGrav data by the near-peak part is not favorable [3].

Instead, the authors of ref. [4] consider the ultraviolet tail of SGWB from FOPT, which can be generated by a warm dark matter model. SGWB from the bubble collisions of FOPT is the dominant part in the non-runaway bubble case [5], which goes as $\Omega_{\text{GW}} \sim f^{-1}$ and fits the NANOGrav power index well. This means the peak of SGWB spectrum locates

much smaller than 10^{-9} Hz in response to a phase-transition temperature much smaller than 100 MeV, and can thus be used to probe the warm dark matter, as was first proposed in an earlier paper of some of the same authors in ref. [6]. The authors realize a phase transition by minimally extending the standard model through an extra global $U(1)_L$ symmetry, where the majoron generated is the warm dark matter. This is seen as the main alternative to the weak-interaction-massive-particle dark matter model. The parameter space of this model can be further probed by the current (NANOGrav, EPTA, PPTA) and future (IPTA, CPTA, SKA) pulsar timing array experiments. The discrimination of such a signal with the other SGWBs (cosmic strings, induced GWs, black hole binaries, etc.) can be done by the space-based interferometers like LISA/Taiji/Tianqin in the future. This paper has initiated an era for the multi-messenger detection of the warm dark matter.

- 1 Z. Arzoumanian, et al. (NANOGrav), *Astrophys. J. Lett.* **905**, L34 (2020), arXiv: 2009.04496 astro-ph.HE.
- 2 R. G. Cai, S. Pi, and M. Sasaki, *Phys. Rev. D* **102**, 083528 (2020), arXiv: 1909.13728; G. Doménech, S. Pi, and M. Sasaki, *J. Cosmol. Astropart. Phys.* **2020**, 017 (2020), arXiv: 2005.12314.
- 3 L. Bian, R. G. Cai, J. Liu, X. Y. Yang, and R. Zhou, *Phys. Rev. D* **103**, L081301 (2021), arXiv: 2009.13893.
- 4 A. Addazi, Y. F. Cai, Q. Gan, A. Marciano, and K. Zeng, arXiv: 2009.10327.
- 5 M. Hindmarsh, S. J. Huber, K. Rummukainen, and D. J. Weir, *Phys. Rev. D* **92**, 123009 (2015), arXiv: 1504.03291.
- 6 A. Addazi, Y. F. Cai, and A. Marciano, *Phys. Lett. B* **782**, 732 (2018), arXiv: 1712.03798.

*Corresponding author (email: shi.pi@itp.ac.cn)