Stochastic Gravitational Wave Background Detection through NANOGrav 15-year Data Set in the View of Massive Gravity

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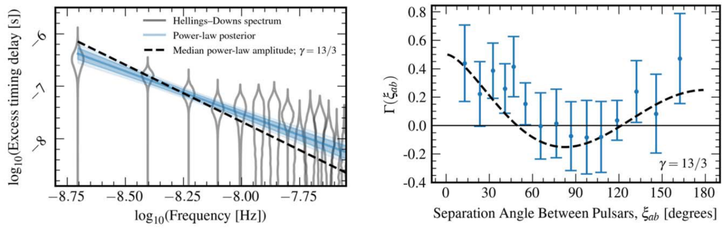
Abstract

- Convincing evidence of a stochastic gravitational wave background (SGWB) has been found by the NANOGrav 15-year data set (NG15).
- We evaluate the possibility of its source being massive tensor perturbations induced by parametric resonance during inflation, in a minimal theory of massive gravity (MTMG)
- We find values of the graviton mass, mass cutoff time, and Hubble rate of inflation that amplify the energy spectra of primordial GWs to reproduce NG15 within 1-3σ.
- However, it is difficult to obey the BBN and CMB bound without introducing a suppression mechanism or making the graviton mass cutoff time too deep into the matter dominated era.

Background

- First detection of SGWB by NANOGrav collaboration in 2023 [1]
- Most popular explanation is astrophysical: inspiraling supermassive black hole binaries (SMBHBs) emitting low-frequency GWs [2].
- More exotic explanations lie in cosmological sources: cosmic strings, domain walls, first-order phase transitions, primordial magnetic fields, primordial GWs, scalar-induced GWs, etc [3].
- Hypothesis: primordial GWs generated from quantum mechanical perturbations during inflation, amplified by parametric resonance and blue tilted by massive gravity (MG)



Massive Gravity

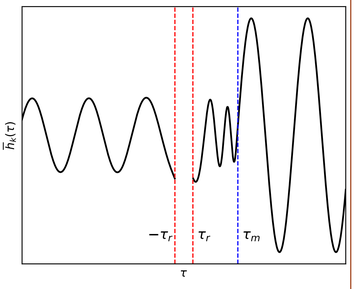
- We consider model of MTMG [4] where graviton mass M_{GW} is step-function of time [5]
- Equation of motion for the two tensor modes:

$$\bar{h}_k'' + \left(k^2 + a^2 M_{\mathrm{GW}}^2 - \frac{a''}{a}\right)\bar{h}_k = 0$$

- Scale factor a and M_{GW}:

$$a(\tau) = \begin{cases} -1/(H_{\mathrm{inf}}\tau) & \tau < \tau_r \\ a_r\tau/\tau_r & \tau > \tau_r \end{cases}$$

$$M_{\mathrm{GW}}(\tau) = \begin{cases} m & \tau < \tau_m \\ 0 & \tau > \tau_m \end{cases}$$



Energy Density of GWs

- The present-day energy densities of GWs help us look at how primordial GWs are influenced by deviations from GR
- Energy density is defined as

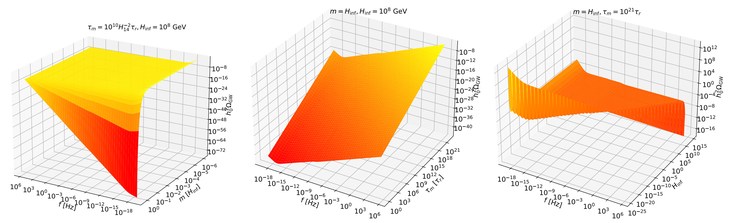
$$\Omega_{\mathrm{GW}} = \frac{1}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\log k}$$

- In massive gravity, Ω_{GW} is blue tilted / amplified:

$$\Omega_{\mathrm{GW},0}(f) = \frac{\pi^2 f^2}{3a_0^2 H_0^2}\frac{\tau_m}{\tau_r}(k\tau_r)^{3-2\nu}\mathcal{P}_{\mathrm{GR}}(k)$$

- $\mathcal{P}_{\mathrm{GR}}(k)$ is defined in our paper [6] in Eq. 14.
- ν in the exponent is defined as

$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H_{\mathrm{inf}}^2}}$$



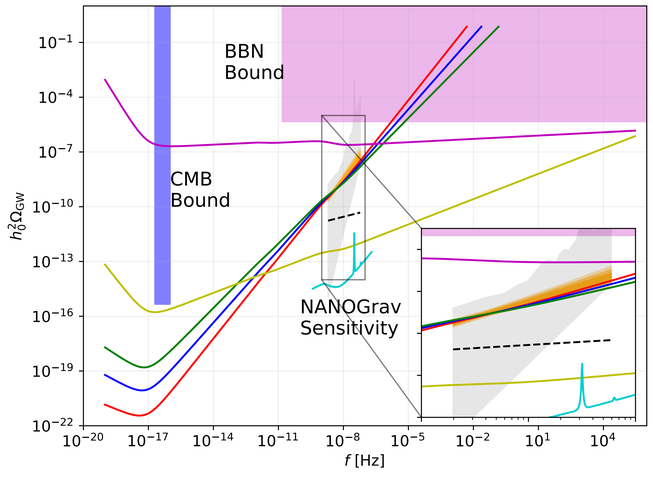
$h_0^2\Omega_{\mathrm{GW},0}$ as a function of f and M_{GW} (left), τ_m (middle), and H_{inf} (right).

Results

Our values for the parameters are

- $M_{\mathrm{GW}} = 1.298 H_{\mathrm{inf}}$, $H_{\mathrm{inf}} = 1.7\,\mathrm{GeV}$ to stay within 1σ (red curve)
- $M_{\mathrm{GW}} = 1.251 H_{\mathrm{inf}}$, $H_{\mathrm{inf}} = 8.0\,\mathrm{GeV}$ to stay within 2σ (blue curve)
- $M_{\mathrm{GW}} = 1.201 H_{\mathrm{inf}}$, $H_{\mathrm{inf}} = 50.\,\mathrm{GeV}$ to stay within 3σ (green curve)
- purple curve – partially produces the signal for large Ω_{GW} and f
- golden curve – partially produces the signal for small Ω_{GW} and f

Respecting CMB, BBN bounds and reproducing the signal are mutually exclusive. If we don't respect them, we achieve good agreement with signal with a caveat: τ_m is too deep into the matter dominated era.



Conclusions

- Time-dependent MTMG successfully reproduces NG15
- BBN bound is violated for $f \gtrsim 10^{-6}$ Hz.
- Suppression mechanism, analogous to the damping of the energy density from the free-streaming neutrinos [7], could be introduced
- More complicated functions for $M_{\mathrm{GW}}(t)$ are possible; future work can try to place constraints on the time evolution of the mass
- Further observations that place constraints on $H_{\mathrm{inf}}, a_r, \tau_r$ would be able to constrain the parameters of this theory

Source Code

The NANOGrav 15-Year data is available at nanograv.org/science/data, source code to reproduce all of the figures in our paper [6] is available at github.com/ChrisChoi314/constrain_mass_nanograv_15 and the TeX for this poster is at github.com/ChrisChoi314/mg_poster_aas243.

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Bibliography

[1] G. Agazie, A. Anumarlapudi, A. M. Archibald, *et al.*, "The nanograv 15 yr data set: Evidence for a gravitational-wave background," *The Astrophysical Journal Letters*, vol. 951, no. 1, p. L8, Jun. 2023. DOI: 10.3847/2041-8213/acdac6. [Online]. Available: https://dx.doi.org/10.3847/2041-8213/acdac6.

[2] S. Burke-Spolaor *et al.*, "The Astrophysics of Nanohertz Gravitational Waves," *Astron. Astrophys. Rev.*, vol. 27, no. 1, p. 5, 2019. DOI: 10.1007/s00159-019-0115-7. arXiv: 1811.08826 [astro-ph.HE].

[3] A. Afzal, G. Agazie, A. Anumarlapudi, *et al.*, "The nanograv 15 yr data set: Search for signals from new physics," *The Astrophysical Journal Letters*, vol. 951, no. 1, p. L11, Jun. 2023. DOI: 10.3847/2041-8213/acdc91. [Online]. Available: https://dx.doi.org/10.3847/2041-8213/acdc91.

[4] A. De Felice and S. Mukohyama, "Minimal theory of massive gravity," *Physics Letters B*, vol. 752, pp. 302–305, Jan. 2016, ISSN: 0370-2693. DOI: 10.1016/j.physletb.2015.11.050. [Online]. Available: http://dx.doi.org/10.1016/j.physletb.2015.11.050.

[5] T. Fujita, S. Kuroyanagi, S. Mizuno, and S. Mukohyama, "Blue-tilted Primordial Gravitational Waves from Massive Gravity," *Phys. Lett. B*, vol. 789, pp. 215–219, 2019. DOI: 10.1016/j.physletb.2018.12.025. arXiv: 1808.02381 [gr-qc].

[6] C. Choi, J. Magallanes, M. Gurgenidze, and T. Kahniashvili, "Stochastic Gravitational Wave Background Detection through NANOGrav 15-year Data Set in the View of Massive Gravity," *arXiv e-prints*, arXiv:2312.03932, arXiv:2312.03932, Dec. 2023. DOI: 10.48550/arXiv.2312.03932. arXiv: 2312.03932 [astro-ph.CO].

[7] R. Durrer and T. Kahniashvili, "CMB anisotropies caused by gravitational waves: A Parameter study," *Helv. Phys. Acta*, vol. 71, pp. 445–457, 1998. arXiv: astro-ph/9702226.