# Gravitational Wave Symphony from the Scalar Fields in the Early Universe

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## Abstract

*We investigate a generic source of stochastic gravitational wave background (SGWB) due to the parametric resonance of oscillating scalar fields in the early Universe. By systematically analyzing benchmark models using lattice simulation and considering a wide range of parameter space, we demonstrate that such a scenario can lead to detectable signals in GW detectors over a broad frequency range and potentially address the recent findings by NANOGrav, etc. Furthermore, these models are found to naturally yield ultra-light dark matter candidates or dark radiation detectable by CMB observatories.*

## 1. Introduction

❒ The discovery of Gravitational Waves (GWs) by LIGO in 2015 and expedited developments in the science and technology of GW detectors over a multitude of frequency ranges heralded a new era of observational Cosmology.

❒ In the absence of other direct observables, GWs are the only reliable signatures to shed light on the pre-BBN *primordial dark ages*.

❒ Null results in most dark matter searches, calling for a newer avenue for looking into their potential sources and signatures.

❒ We explore the GWs sourced by the large inhomogeneities due to excitations by a time-dependent coherently oscillating scalar.

❒ We study the consequences when such scalars can naturally yield ultra-light dark matter candidates or dark radiation detectable by CMB observatories.

## 2. Gravitational Waves from Scalar Condensate fragmentation: A recapitulation

❑ Preheating after inflation is a usual example of when GWs are generated from coherent scalar fragmentation. These GWs signals:

- ➔ Add complementary channel to inflationary GWs.
- ➔ Observed frequency depends on the typical Hubble scale (typically high frequency): $f_{\text{peak}} \propto \sqrt{H} \sim \sqrt{m} \rightarrow$ Not observable by traditional detectors.

❑ If the scalar field mass is not constrained from CMB observables (spectator fields), we can tune the frequency depending on the mass of the spectator. [2, 3]

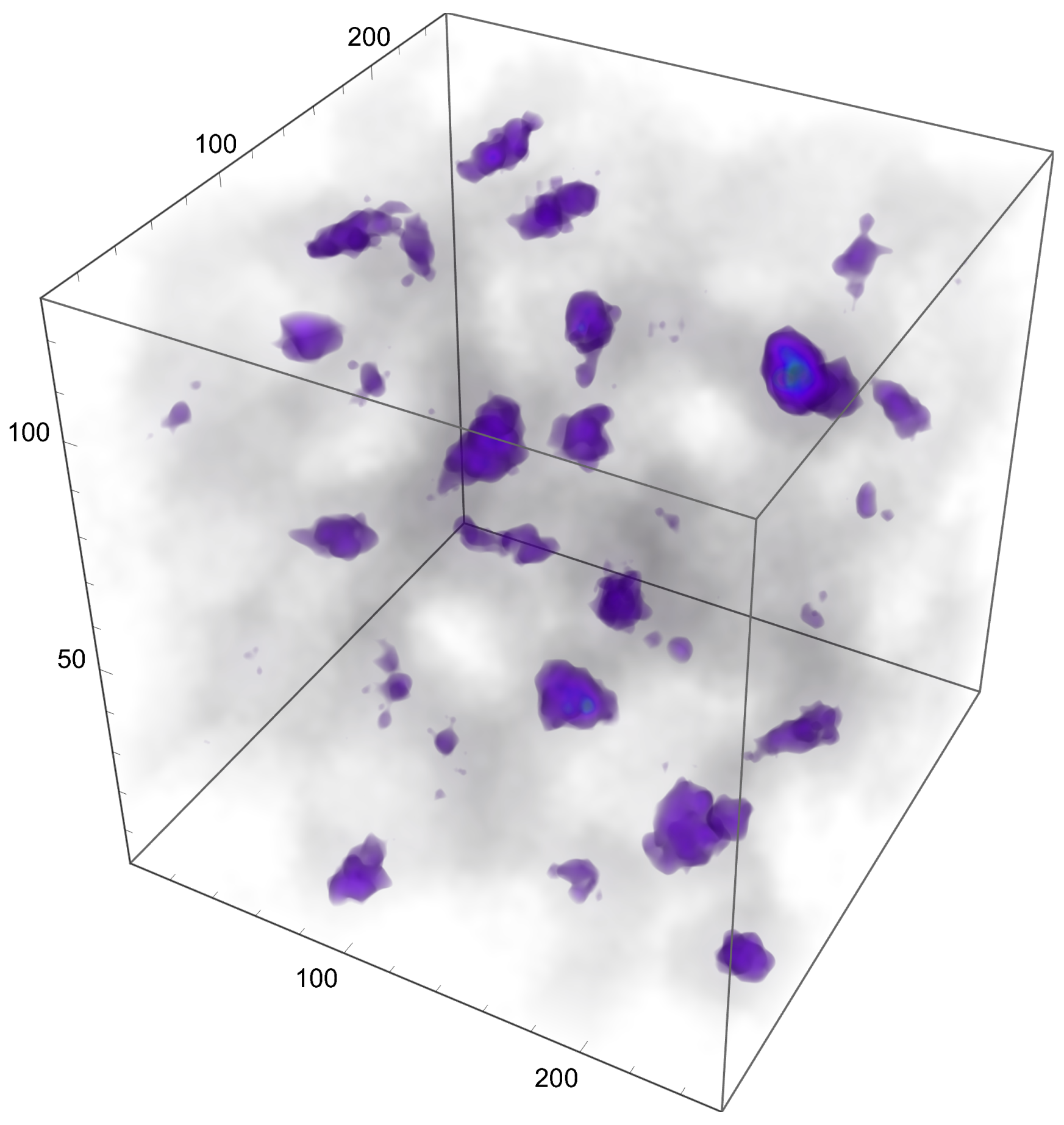

**Figure 1:** *Classical inhomogeneities due to coherent scalar fragmentation source GWs*

## 3. GWs production, quantitatively

❒ The Models:

$$\text{Model A:}\quad V = \frac{m_\phi^2}{2}\phi^2 + \frac{g}{2}\phi^2\chi^2, \tag{1}$$

$$\text{Model B:}\quad V = \frac{m_\phi^2}{2}\phi^2 + \frac{\lambda_\chi}{4}\chi^4 + \frac{\sigma}{2}\phi\chi^2, \tag{2}$$

$$\text{Model C:}\quad V = \frac{\lambda}{4}\phi^4, \tag{3}$$

$$\text{Model D:}\quad V = \frac{\lambda}{4}\phi^4 + \frac{g}{2}\phi^2\chi^2, \tag{4}$$

❒ The EoMs

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\nabla^2\phi + \frac{\partial V}{\partial\phi} = 0, \tag{5}$$

$$\ddot{\chi} + 3H\dot{\chi} - \frac{1}{a^2}\nabla^2\chi + \frac{\partial V}{\partial\chi} = 0, \tag{6}$$

$$H^2 = \frac{1}{3M_{\text{Pl}}^2}\left(V + \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\chi}^2 + \frac{1}{2a^2}|\nabla\phi|^2 + \frac{1}{2a^2}|\nabla\chi|^2\right), \tag{7}$$

❒ Gravitational waves being transverse and traceless (TT) part of the metric perturbation in the synchronous gauge sourced by TT-part of the anisotropic stress of the scalar field ($\Pi_{ij} = [\partial\phi_i\partial\phi_j]^{\text{TT}}$)

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} + \frac{\partial V}{\partial\phi} = \frac{2}{M_{\text{Pl}}^2 a^2}\Pi_{ij} \tag{8}$$

❒ The GW energy density is given by

$$\rho_{\text{GW}}(t) = \frac{M_{\text{Pl}}^2}{4}\langle \dot{h}_{ij}(\mathbf{x},t)\dot{h}_{ij}(\mathbf{x},t)\rangle_{\mathcal{V}}, \tag{9}$$

❒ The spectrum of the energy density of GWs (per logarithmic momentum interval) observable today:

$$\Omega_{\text{GW},0}h^2 = \frac{h^2}{\rho_{\text{crit}}}\frac{d\rho_{\text{GW}}}{d\ln k}\bigg|_{t=t_0} = \frac{h^2}{\rho_{\text{crit}}}\frac{d\rho_{\text{GW}}}{d\ln k}\bigg|_{t=t_e}\frac{a_e^4\rho_e}{a_0^4\rho_{\text{crit},0}}$$
$$= \Omega_{\text{rad},0}h^2\Omega_{\text{GW},e}\left(\frac{a_e}{a_*}\right)^{1-3w}\left(\frac{g_*}{g_0}\right)^{-1/3}, \tag{10}$$

❒ We take the universe to be radiation-dominated.

## 4. Results

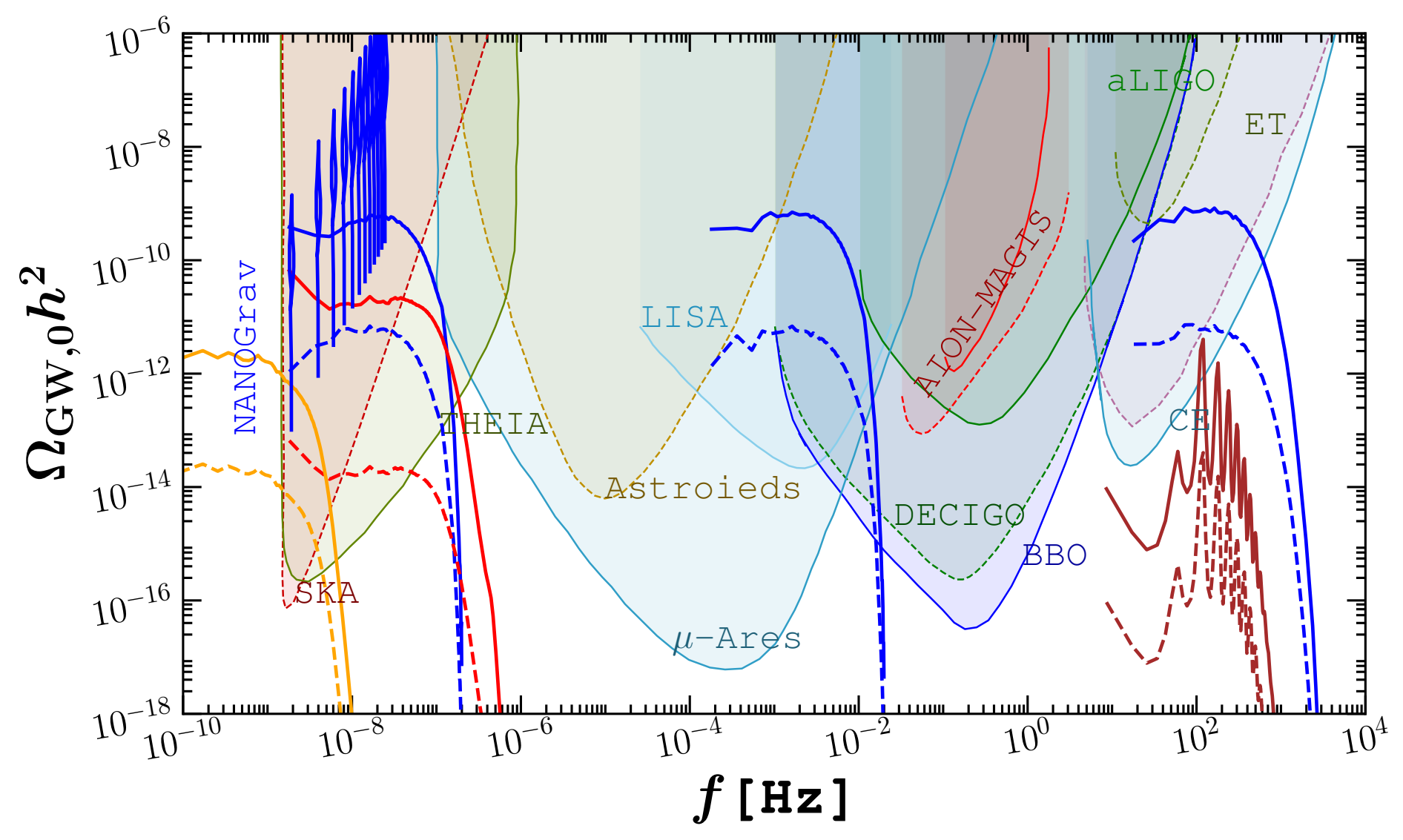

**Figure 2:** ***GWs over many decades of Frequency from coherently oscillating scalars***

| Model | $m_\phi$ (eV) | $g$ | $\sigma$ (eV) | $\lambda_\chi$ | $\nu_{\text{GW}}$(Hz) | $\Omega_{\text{GW}}$ |
|---|---|---|---|---|---|---|
| A | $10^{-13}$ | $10^{-75}$ | - | - | $10^{-9}$ | $10^{-10}$ |
| A* | $10^{8}$ | $10^{-36}$ | - | - | $100$ | $10^{-9}$ |
| B | $10^{-13}$ | - | $10^{-52}$ | $10^{-75}$ | $10^{-9}$ | $10^{-9}$ |
| B* | $10^{-2}$ | - | $10^{-30}$ | $10^{-53}$ | $10^{-3}$ | $10^{-9}$ |
| B* | $10^{8}$ | - | $10^{-10}$ | $10^{-33}$ | $10^{2}$ | $10^{-9}$ |
|  | $\lambda_\phi$ | $g$ | $\sigma$ (eV) | $\lambda_\chi$ | $\nu_{\text{GW}}$(Hz) | $\Omega_{\text{GW}}$ |
| C | $10^{-35}$ | - | - | - | $100$ | $10^{-11.5}$ |
| D | $10^{-79}$ | $10^{-79}$ | - | - | $10^{-9}$ | $10^{-12}$ |

**Table 1:** *Example model parameters leading to GW production with frequencies in observationally relevant range, from NANOGrav to LISA to LIGO.*

## 5. Dark matter and Dark Radiation

❒ The relic abundance of $\phi$ particles:

$$\Omega_{\phi,0} \equiv \frac{\rho_\phi,0}{\rho_{\text{tot},0}} = \frac{\frac{1}{2}m_\phi^2\phi_{\text{end}}^2}{3M_{\text{Pl}}^2H_0^2}\frac{g_{*,0}}{g_{*,\text{end}}}\left(\frac{T_0}{T_{\text{end}}}\right)^3 \tag{11}$$

❒ GWs contribution (amplitude $\approx 10^{-9}$) to new relativistic degrees of freedom is negligible.

$$\frac{\Omega_{\text{GW},0}h^2}{\Omega_{\gamma,0}h^2} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{\text{eff}} \tag{12}$$

❒ The 'massless' components can act as non-thermally produced dark radiation and will lead to additional contributions to $\Delta N_{\text{eff}}$

$$\Delta N_{\text{eff}} = \frac{\hat{g}_*\hat{T}^4}{\frac{7}{4}T^4} = \frac{4}{7}\alpha\xi\hat{g}_*\left(\frac{g_*}{\hat{g}_*}\right)^{4/3}\left(\frac{\hat{g}_{*,\text{osc}}}{g_{*,\text{osc}}}\right)^{1/3}. \tag{13}$$

## 6. Conclusion and outlook

❒ **Simple 'renormalizable' scalar potentials can source detectable GWs across many decades of frequencies.**

❒ **Complementary phenomenology: DM candidate with signals in the NANOGrav. [4].**

❒ **Relic scalar radiation contributes to CMB $N_{\text{eff}}$ observable.**

❒ **Possibility of early matter domination driven by the $\phi$-condensate can affect the GW signals and DM structure formation.**

## References

[1] Y. Cui, P. Saha, and E. I. Sfakianakis, "Gravitational Wave Symphony from Oscillating Spectator Scalar Fields," `arXiv:2310.13060 [hep-ph]`.

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[3] N. Kitajima, J. Soda, and Y. Urakawa, "Gravitational wave forest from string axiverse," *JCAP* **10** (2018) 008, `arXiv:1807.07037 [astro-ph.CO]`.

[4] **NANOGrav** Collaboration, A. Afzal *et al.*, "The NANOGrav 15 yr Data Set: Search for Signals from New Physics," *Astrophys. J. Lett.* **951** no. 1, (2023) L11, `arXiv:2306.16219 [astro-ph.HE]`.