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arXiv: 2510.05967

Stochastic Gravitational Waves from Modulated Reheating

ABSTRACT

We investigate scalar-induced stochastic gravitational waves from adiabatic curvature perturbations sourced by a spectator field via the modulated reheating mechanism. We consider a spectator scalar with Higgs-like couplings and inflaton decay via shift symmetric dimension-five operators. The spectator is assumed to be in the Sitter vacuum and it sources blue-tilted, strongly non-Gaussian curvature perturbations which can dominate the spectrum on small scales $k \gg \mathrm{Mpc}^{-1}$. We find that the setup could generate a gravitational wave signal testable by surveys like BBO and DECIGO but only for large coupling values not expected in low-energy particle physics setups that can be perturbatively extrapolated up to the inflationary scale.

SETUP

The inflaton ϕ reheats the Universe through higher-dimensional shift-symmetric interactions with gauge and fermion fields $X = (A_\mu, \psi)$.

$$\mathcal{L} = -\tfrac{1}{2}(\partial\phi)^2 + V(\phi) - \tfrac{1}{2}(\partial\chi)^2 + V(\chi) + \mathcal{L}_{\rm dec}(\phi,\chi,X) + \ldots$$

χ is a Higgs-like spectator field, subdominant during inflation, which affects the reheating process by modulating mass terms of the inflaton decay products.

$$m_A = \frac{g}{2}\chi, \qquad m_\psi = \frac{y_\psi}{\sqrt{2}}\chi.$$

This mass modulation leads to χ-dependent decay rates:

$$\Gamma^A = \Gamma_0^A\left(1 - \frac{g^2\chi^2}{m_\phi^2}\right)^{3/2}, \qquad \Gamma^\psi = \Gamma_0^\psi\left(1 - \frac{2y_\psi^2\chi^2}{m_\phi^2}\right)^{1/2}.$$

This gives rise to the modulated reheating scenario [1]: fluctuations of χ produced during inflation are imprinted in the decay rate and generate spatial fluctuations in the total number of e-folds.

$$\delta\chi(x) \to \delta\Gamma(x) \to \delta N(x)$$

CURVATURE PERTURBATIONS

The curvature perturbation sourced by χ is given by the δN formalism as:

$$\zeta(\mathbf{x}) = N(\chi(\mathbf{x})) - \langle N \rangle.$$

Assuming the de Sitter vacuum for the spectator field and considering that $N(\chi)$ is an even function, the leading contribution scales as χ^2, so ζ_χ is intrinsically non-Gaussian.

Expanding $\phi(\mathbf{x}) = \bar{\phi} + \delta\phi(\mathbf{x})$ to first order and using $\langle\delta\phi\rangle = 0$, the total curvature perturbation splits into:

$$\zeta(\mathbf{x}) = \zeta_\phi(\mathbf{x}) + \zeta_\chi(\mathbf{x}).$$

With uncorrelated contributions and vanishing mixed correlators, the power spectrum reduces to:

$$\mathcal{P}_\zeta(k) = \mathcal{P}_{\zeta_\phi}(k) + \mathcal{P}_{\zeta_\chi}(k).$$

We describe the super-horizon dynamics of χ using the stochastic formalism [2], where its probability distribution $P(\chi, t)$ satisfies the Fokker–Planck equation. A spectral expansion of the Fokker–Planck operator yields discrete eigenvalues Λ_n and eigenfunctions $\psi_n(\chi)$, allowing the curvature spectrum sourced by χ to be written as:

$$\mathcal{P}_{\zeta_\chi}(k) = \sum_n \left(\int d\chi\, \psi_0\, \zeta_\chi\, \psi_n\right)^2 \mathcal{N}(\Lambda_n)\left(\frac{k}{aH}\right)^{2\Lambda_n/H}.$$

where the leading contribution is controlled by the first non-vanishing eigenvalue Λ_2.
Since $\Lambda_2 > 0$ the spectrum is blue-tilted, enhancing small-scale power and providing potential sources for scalar-induced gravitational waves (GWs).

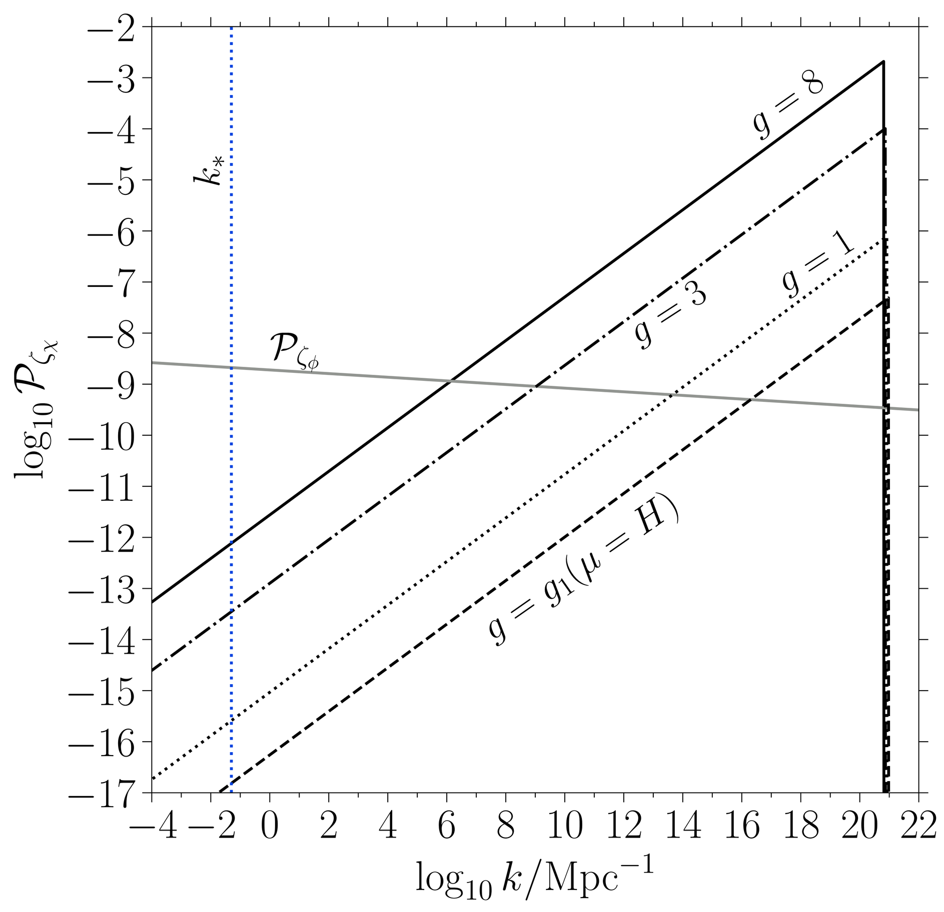

Figure 1: Power spectrum for the vector decay channel: $\mathcal{P}_{\zeta_\chi}$ is sourced by the spectator field, while $\mathcal{P}_{\zeta_\phi}$ comes from the inflaton.

CMB CONSTRAINTS

We impose the Planck limits on the amplitude, spectral tilt, and non-Gaussianity of the curvature perturbations. The most restrictive bound comes from non-Gaussianity, which we evaluate by computing the bispectrum and comparing it with the Planck limit on $f_{\rm NL}$. This leads to a small allowed spectator contribution at CMB scales, $\mathcal{P}_{\zeta_\chi}(k_*) \lesssim 10^{-12}$.

SCALAR-INDUCED GRAVITATIONAL WAVES

At second order, curvature perturbations source tensor modes via

$$h_\lambda''(\tau,k) + \frac{2}{\tau}h_\lambda'(\tau,k) + k^2 h_\lambda(\tau,k) = 4\mathcal{S}_\lambda(\tau,k),$$

where the source term $\mathcal{S}_\lambda(\tau,k)$ is quadratic in the Bardeen potential, which in a radiation-dominated Universe can be written in terms of the primordial curvature perturbation ζ. The resulting GW energy density today is

$$\Omega_{\rm GW}(\tau,k) = \frac{1}{3H(\tau)^2 M_{\rm P}^2}\frac{d\rho_{\rm GW}(\tau)}{d\log k}.$$

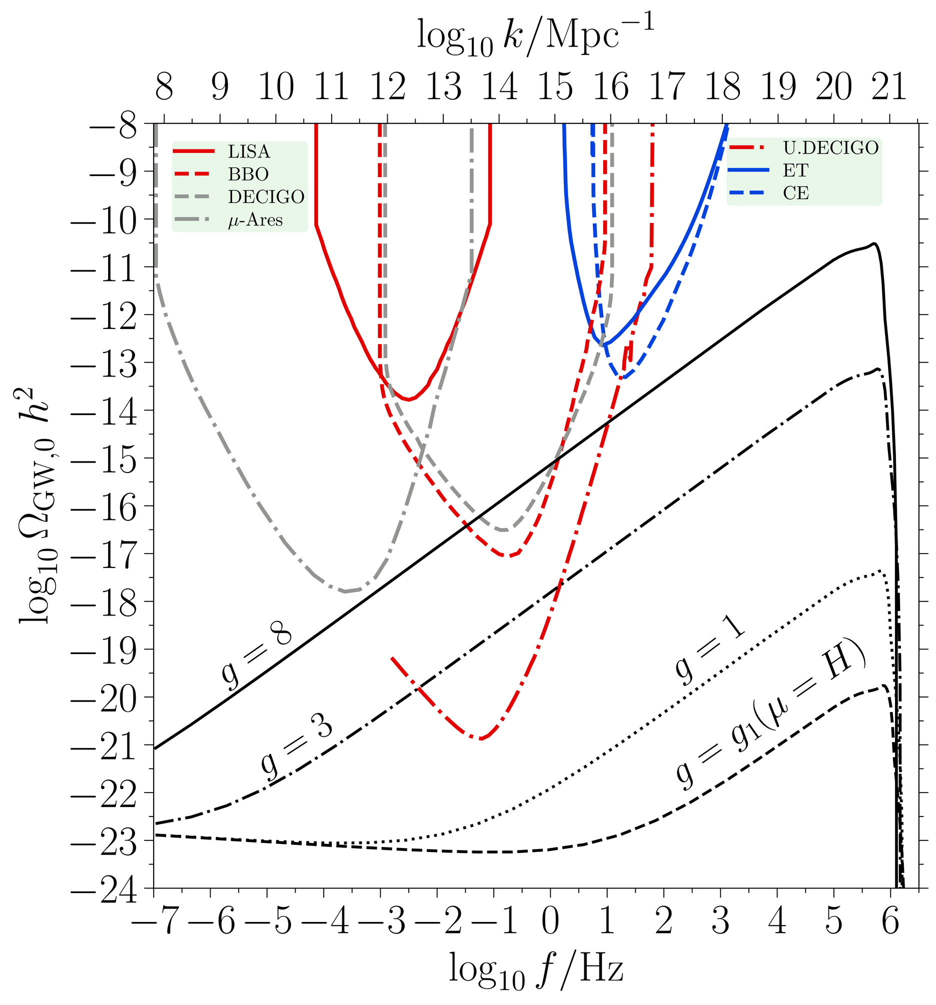

Figure 2: $\Omega_{\rm GW,0}$, for the vector decay channel, shown for different values of the gauge coupling g.

Because the χ-induced perturbations are blue-tilted, the GW spectrum peaks at high frequencies, potentially within the reach of BBO and Ultimate DECIGO.

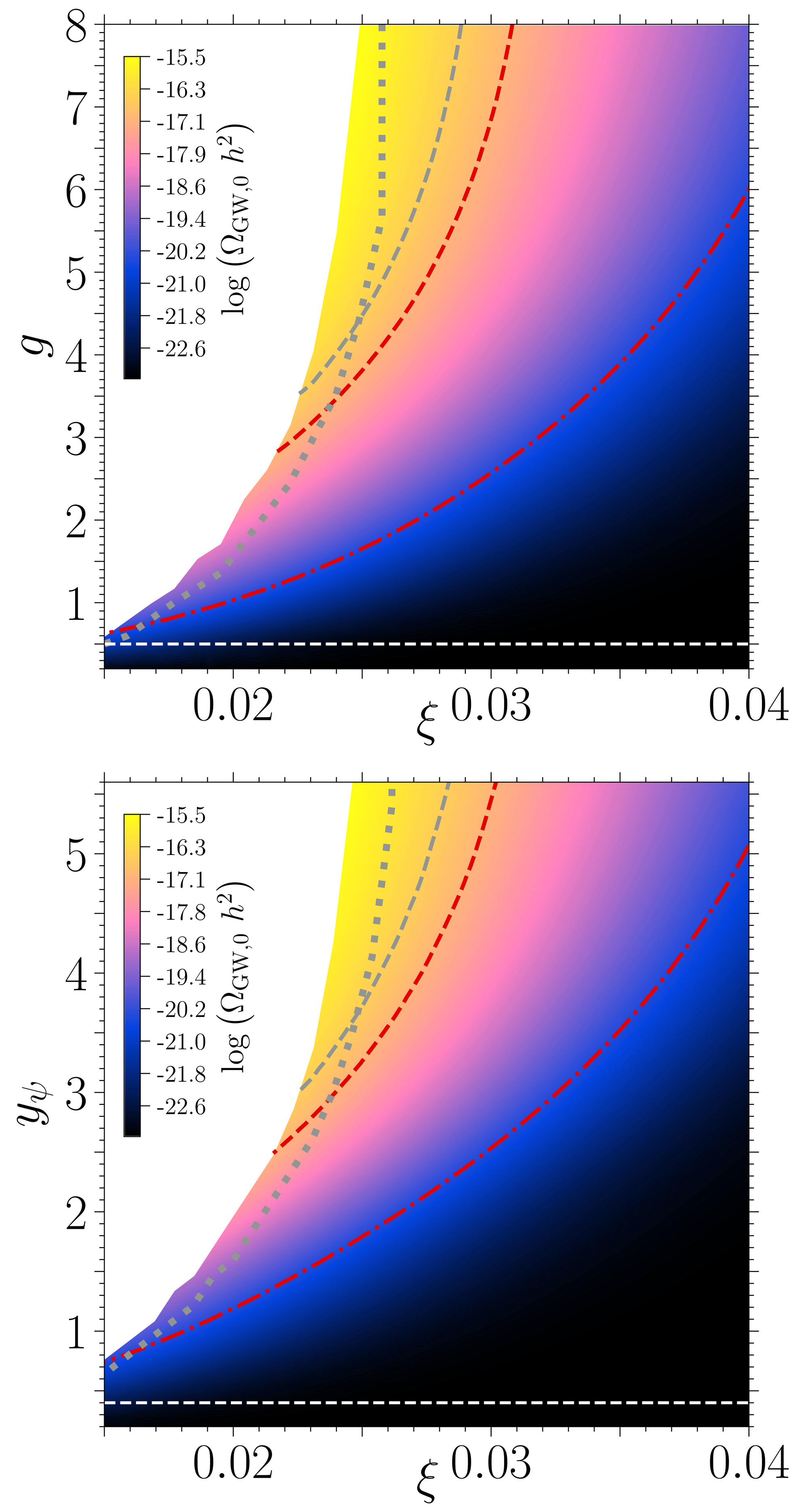

Figure 3: Top panel: $\Omega_{\rm GW,0}$ at $f = 0.15$ Hz as function of ξ and g for $\lambda = 10^{-5}$, assuming the vector decay channel. Bottom panel: Same plot, but for inflaton decay into fermions. White dotted lines correspond to Standard Model couplings. Sensitivity curves are shown for BBO (red dashed), DECIGO (grey dashed), and Ultimate DECIGO (red dash–dotted)

Figures 3 show that detecting a signal requires values of y_ψ and g exceeding those of the Standard Model (white line). This outcome emerges from a non-trivial parametric interplay where the CMB non-Gaussianity bound strongly constrains the large-scale power spectrum, while gravitational waves probe the blue-tilted spectrum on small scales. Only large couplings can satisfy CMB constraints while generating detectable signals.

CONCLUSIONS

- **The GW amplitude in this scenario depends on the spectator couplings (ξ, λ) and on the decay-channel couplings (g, y_ψ).**
- **Large couplings $g, y_\psi > 1$ could produce GWs marginally detetable by BBO and DECIGO but may be challenging to realise in nearly uv-complete SM extensions.**
- **Allowing for a non-zero background value of the spectator field relaxes non-Gaussianity bounds and can enhance the resulting GW signal.**

REFERENCES

[1] G. Dvali, A. Gruzinov and M. Zaldarriaga, Phys. Rev. D **69** (2004) .

[2] A. A. Starobinsky, Lect. Notes Phys. **246** (1986) .