GRAVITY@PRAGUE · SEPT. 14–18, 2026

Gravitational waves induced from the symmetry restoration of a Higgs phase of gravity

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Introduction

Ghost condensation is an analogue of the Higgs mechanism in general relativity [1]. A ghost condensate has equation of state $p = -\rho$, like the cosmological constant Λ, but it is a physical fluid with a physical scalar excitation. This background can arise from a real scalar field ϕ with ground state configuration $\phi = Ct$, where C is a dimensionless constant. The Lagrangian is given by

$$\mathcal{L} = \sqrt{-g}M^4 P(X, v) \tag{1}$$

where $X \equiv -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$,

$$P(X, v) = (X - v(\phi))^2 - \frac{1}{4}(C^2 - v(\phi))^2 \tag{2}$$

and

$$v(\phi) = -C^2 \tanh(\alpha(\phi - \phi_t)) \tag{3}$$

This change in the sign of $v(\phi)$ at some time η_t causes the scalar sound speed to jump from $c_s^2 \approx 0$ to 1 and **ϕ to go from a ghost condensate to a canonical scalar field**, where it then oscillates and decays, which sources gravitational waves.

Background

We consider the universe to be filled with **radiation and ghost condensate**. The ghost condensate behaves like cold dark matter when $\dot\phi$ is close but not equal to its attractor solution $\dot\phi = C$.

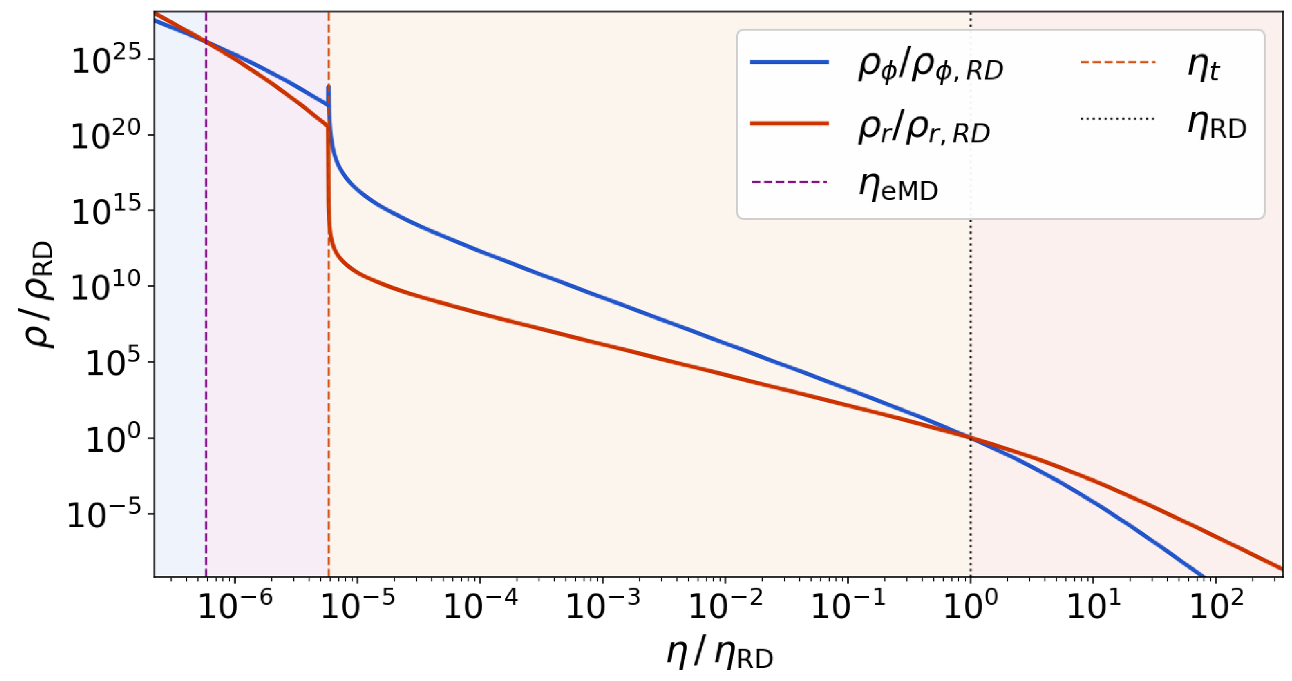


Fig. 1 — Evolution of the energy densities ρ_r and ρ_ϕ through the eras: **eRD**, **eMD**, **kination**, and **RD**.

Perturbations

We assume a scalar excitation π on this background: $\phi = Ct + \pi$. We solve the perturbed Einstein equations for the coupled radiation-ghost condensate system to get the evolution of the potential Φ.

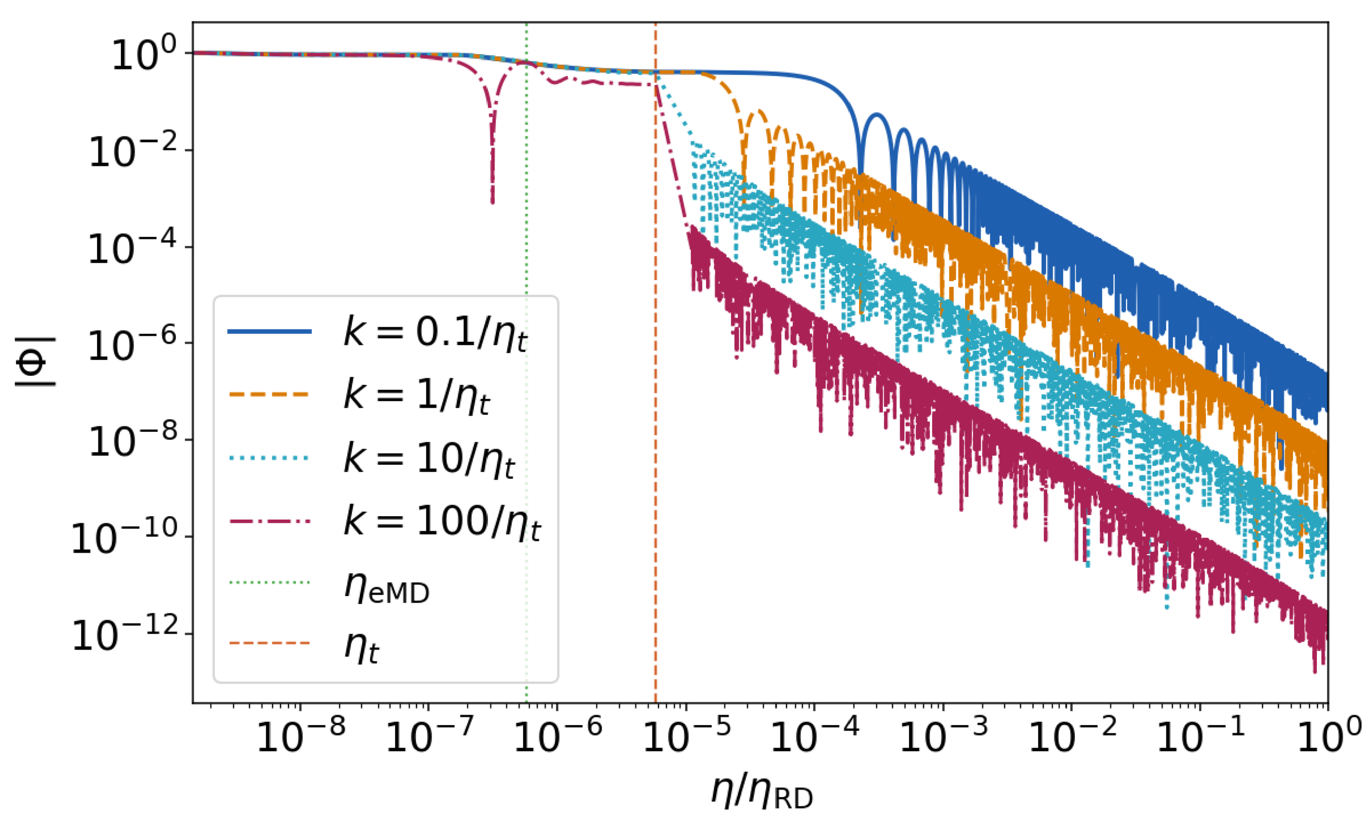


Fig. 2 — Evolution of the gravitational scalar potential Φ through the same era progression as before.

Two enhancement mechanisms are at work in this model:

1. Modes inside the horizon during eMD don't decay, so for a sufficiently fast transition, these modes start to oscillate rapidly with an unsuppressed amplitude.
2. During kination $\Omega_{GW} \sim a^2$ since $\rho_{GW} \sim a^{-4}$ while $\rho_{kin} \sim a^{-6}$.

The longer the eMD era, the more modes that enter during this time so we have a free parameter, the ratio η_t/η_{MD}, which controls the amplitude of the GW spectrum.

Induced gravitational waves

At second order, the equation of motion for the tensor perturbations is

$$h_k''(\eta) + 2\mathcal{H}h_k'(\eta) + k^2 h_k(\eta) = 4S_k(\eta) \tag{4}$$

where S_k is the source term, which depends on Φ and Φ'.

The fractional energy density for GWs induced from scalar perturbations is

$$\Omega_{GW}(\eta, k) = \frac{1}{6}\left(\frac{3+3w_k}{5+3w_k}\right)^4\left(\frac{k}{\mathcal{H}}\right)^2\int_0^\infty dv\int_{|1-v|}^{1+v} du \left(\frac{4v^2-(1+v^2-u^2)^2}{4uv}\right)^2 \overline{I^2(u,v,k,\eta)}\mathcal{P}_\mathcal{R}(kv)\mathcal{P}_\mathcal{R}(ku) \tag{5}$$

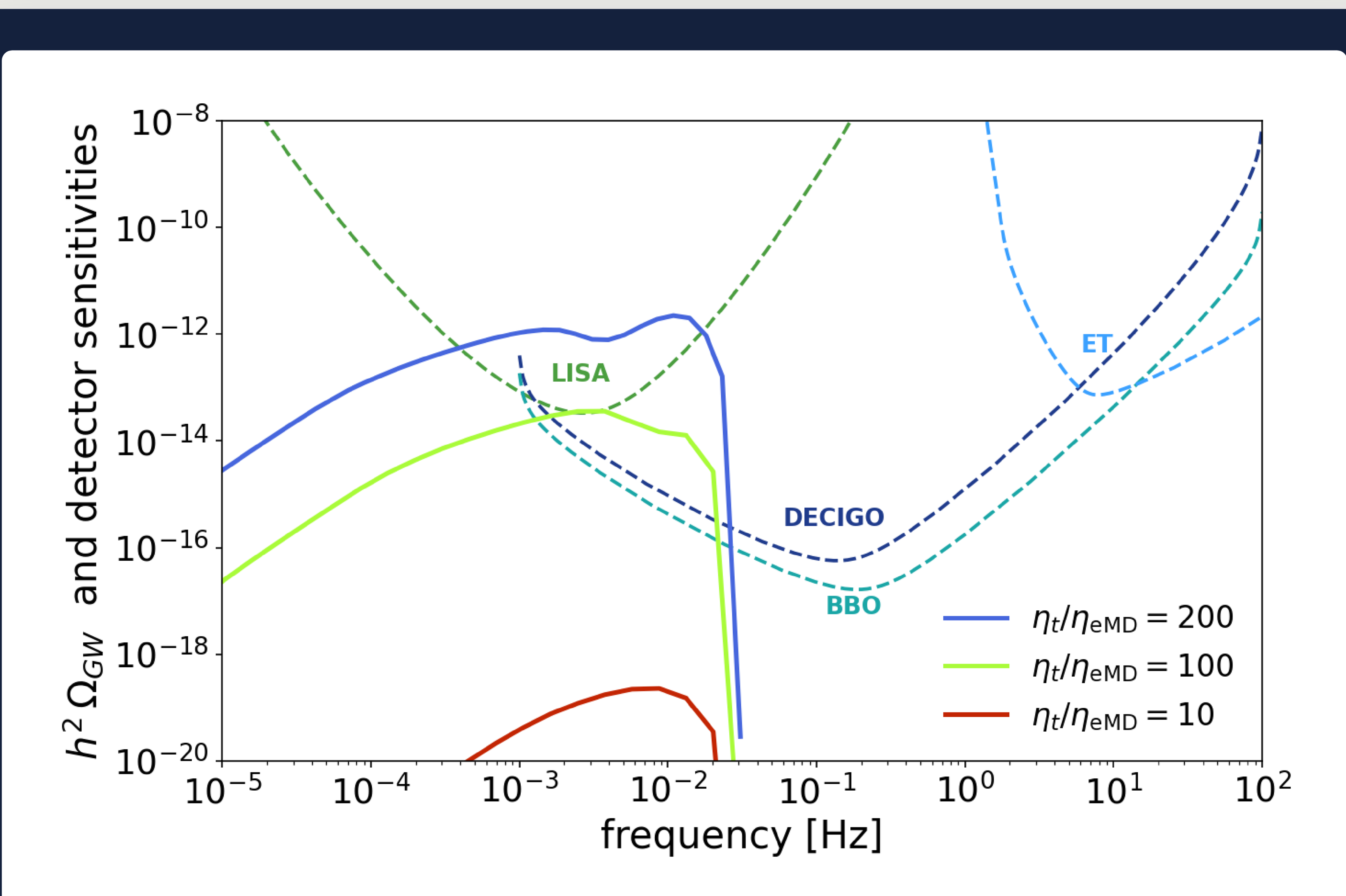
where $I^2(u, v, k, \eta)$ contains the source and tensor perturbation dependence and the overbar denotes an oscillation average. For the curvature power spectrum, we take

$$\mathcal{P}_\mathcal{R}(k) = A_\mathcal{R}\left(\frac{k}{k_*}\right)^{n_s-1}\Theta(k_{max}-k)\Theta(k-1/\eta_t) \tag{6}$$

with $A_\mathcal{R} = 2.1 \times 10^{-9},\ n_s = 0.97,\ k_* = 0.05\,\mathrm{Mpc}^{-1}$, and the Heaviside functions enforce a UV-cutoff in the power spectrum at $k_{\rm max} = \min(k_{\rm eMD}, k_{\rm NL})$ and an IR-cutoff at $1/\eta_t$ to focus on the modes that enter during the eMD era. We then evolve this to the present day as

$$h^2\Omega_{GW}(\eta_0, k) = 0.39\left(\frac{g_{*,c}}{106.75}\right)^{-1/3}\Omega_{r,0}h^2\Omega_{GW}(\eta_c, k) \tag{7}$$

where $g_{*,c} = 106.75$ and $\Omega_{r,0}h^2 = 4.2 \times 10^{-5}$.



RESULT (PRELIMINARY)

Within reach of planned detectors

Fig. 3 — Plot of the induced GW spectrum for $k_{\rm max} = 10^{13}\mathrm{Mpc}^{-1}$ and different ratios η_t/η_{eMD} overlaid with the PLI sensitivity curves for planned detectors.

Acknowledgements

C.L. and R.T. are supported by the grant No. 2023/50/E/ST2/00231 from the National Science Centre, Poland.

References

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[2] Chunshan Lin, Roxane Theriault, and Vincent Vennin. Gravitational waves induced from the symmetry restoration of a Higgs phase of gravity, *In preparation.*