Gravitational waves from a curvature-induced phase transition of a Higgs-portal dark matter sector

Andreas Mantziris

Faculdade de Ciências e Tecnologia da Universidade de Coimbra,
Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto &
Centro de Física das Universidades do Minho e do Porto

with O. Bertolami (2407.18845)

21^{st} *Recent Developments in Gravity conference, Hellenic Society for Relativity, Gravitation and Cosmology, Corfu, Greece*

4 September 2025

Motivation and overview

- Scalars and phase transitions probably common in the early universe.

- Minimal Beyond the Standard Model extension for Dark Matter (Higgs-portal scalar field with renormalizable potential).

- Curvature-induced (non-thermal) phase transition of dark sector after inflation $\rightarrow$ observable GWs $\rightarrow$ constrain parameter space.

- Curvature-induced electroweak symmetry breaking for low reheating temperatures $\rightarrow$ additional (optional) implication.

Spectator Higgs-portal ϕ non-minimally coupled to gravity

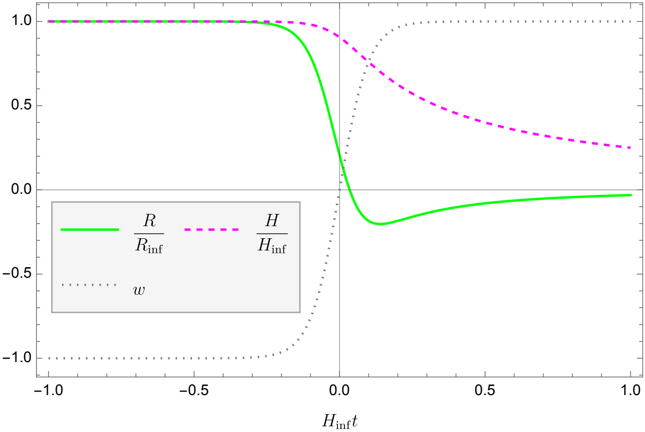
$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2 - \xi_h h^2}{2}R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V_\phi - \mathcal{L}_H - \mathcal{L}_{\text{Inf}}\right]$$

- Non-minimal coupling ξ to spacetime curvature is unavoidable and necessary for the renormalizability of the theory.
- Minimal BSM scalar singlet with Higgs-portal g for DM and EWSB (Cosme *et al*, PRD.102.063507) for low reheating temperature $T_{\text{reh}} \leq 80$ GeV.
- First-Order Phase Transition from evolving potential barrier and vacua due to dynamic curvature $R(t)$ (Mantziris *et al*, JHEP11(2023)077).

$$V_\phi(\phi, h, R) = \frac{1}{2}\left(\xi_\phi R + \frac{g^2}{2}h^2\right)\phi^2 - \frac{\sigma}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4$$

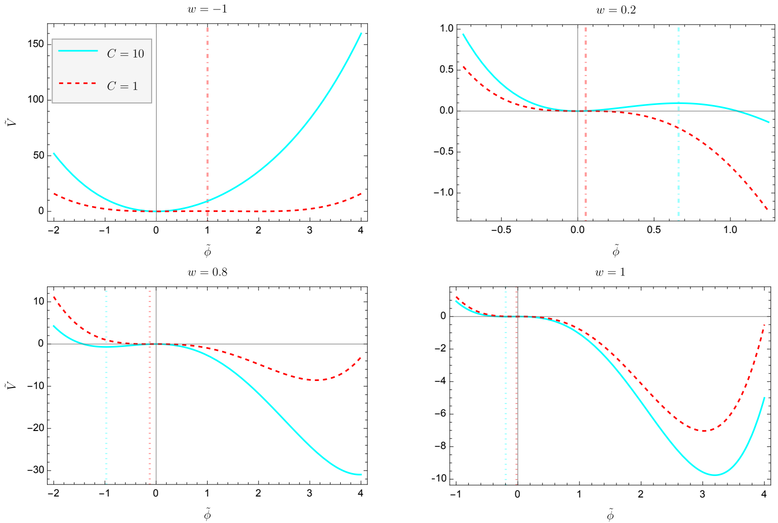
Transition from inflation ($w_{\rm inf} = -1$) to kination ($w_{\rm kin} = 1$)

EoS parameter $w = p/\rho$ and Ricci scalar $R(t) = 3\,[1 - 3w(t)]\,H^2(t)$ switch sign after inflation. Generic parametrisation: $w(t) = \tanh\left[\beta_w(t - t_0)\right]$.



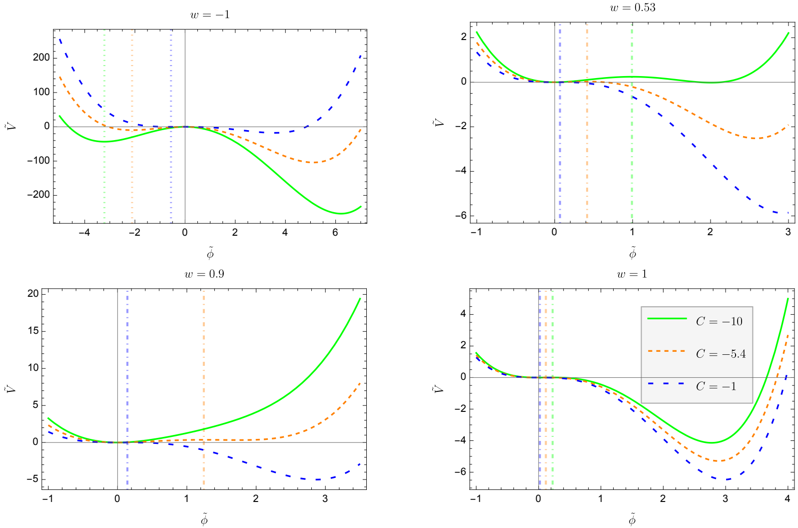
Reasons for quintessential-like inflation: (1) no oscillations of R so only one PT and (2) long kination amplifies the GW signal.

$\xi_\phi > 0$ (dash-dotted= barrier, dotted= false vacuum)



$$C = 54\lambda_\phi \xi_\phi \left(\frac{H_{\rm inf}}{\sigma}\right)^2$$

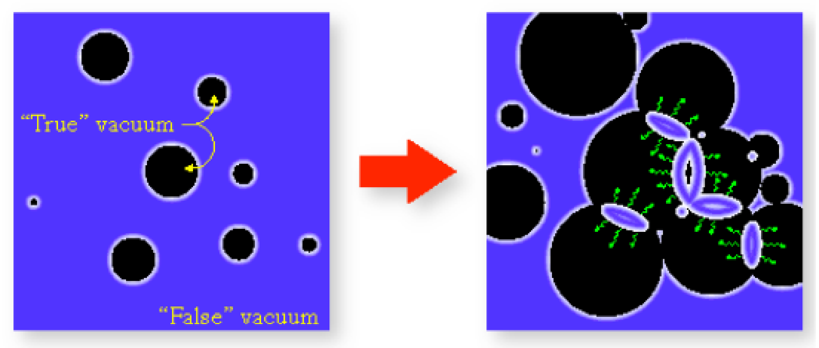
$\xi_\phi < 0$ (dash-dotted= barrier, dotted= false vacuum)



$$C = 54\lambda_\phi \xi_\phi \left(\frac{H_{\rm inf}}{\sigma}\right)^2$$

Gravitational Waves from bubble collisions in vacuum

Nucleation condition $\Gamma_{\rm nuc}(V) = H^4_{\rm nuc}$: 1 bubble/horizon for constant $H_{\rm nuc}$.

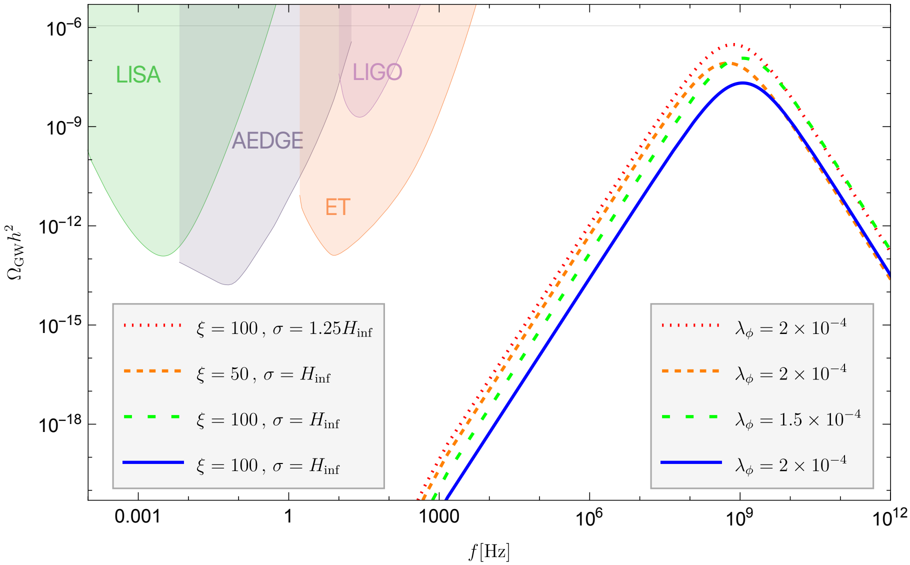


PT parameters: Strength $\alpha \equiv \frac{\rho_{\rm PT}}{\rho_{\rm kin}} = \frac{|\Delta V|}{3M_P^2 H_{\rm inf}^2}$, $10^{-4} \lesssim \alpha \lesssim 10^{-1}$.

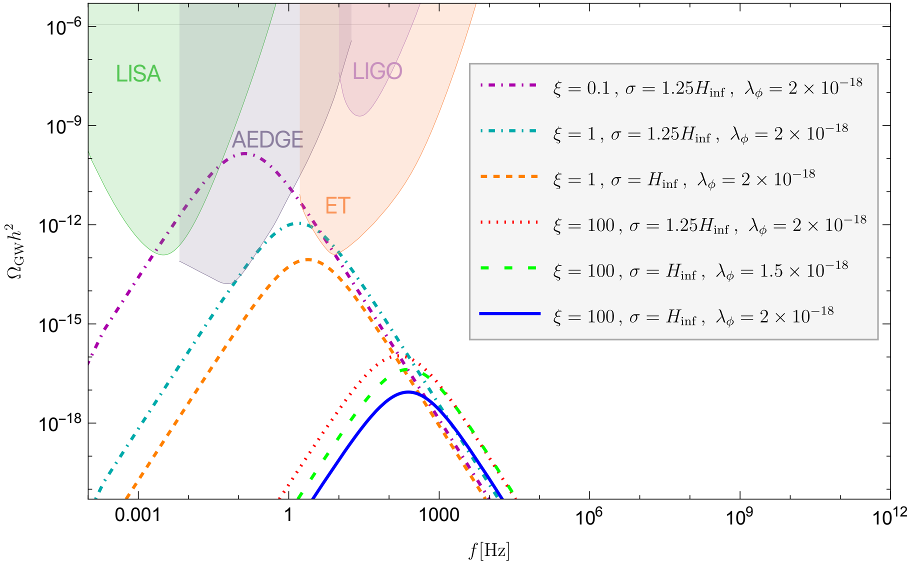
“Velocity” $\beta_{\rm col}^{\xi_\phi<0} = \sqrt{\frac{d^2 S_4^E}{dt^2}}\Big|_{t=t_{\rm col}}$, $\beta_{\rm col}^{\xi_\phi>0} = -\frac{{\rm d}t}{{\rm d}S_4^E}\Big|_{t=t_{\rm col}}$, $\beta_{\rm col} > \beta_w = 10 H_{\rm inf}$

C. Caprini, Cosmological stochastic gravitational wave backgrounds in LISA, 2022.

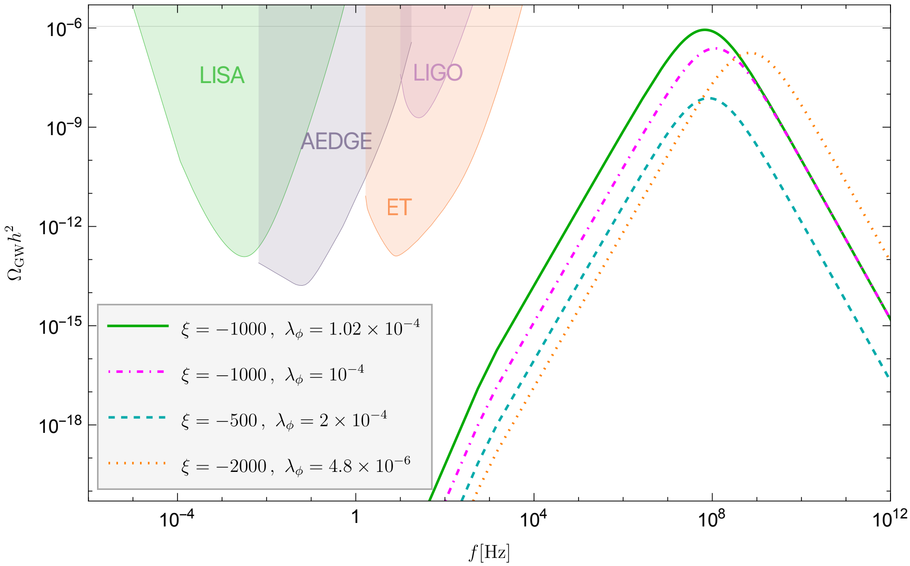
GWs: $\xi_\phi > 0$, $H_{\rm inf} = 10^{12}$ GeV, $H_{\rm reh} \approx 10^{-14}$ GeV



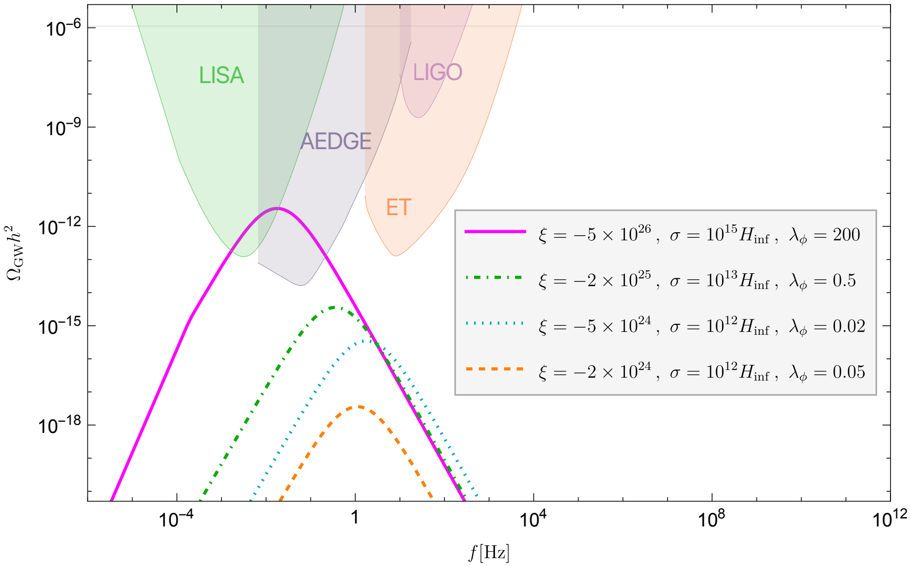
GWs: $\xi_\phi > 0$, $H_{\rm inf} = 10^{-8}$ GeV, $H_{\rm reh} \approx 10^{-14}$ GeV



GWs: $\xi_\phi < 0$, $\sigma = H_{\rm inf} = 10^{12}$ GeV, $H_{\rm reh} \approx 10^{-14}$ GeV



GWs: $\xi_\phi < 0$, $H_{\rm inf} = 10^{-8}$ GeV, $H_{\rm reh} \approx 10^{-14}$ GeV



Summary and conclusions

- GWs from curvature-induced PTs of a Higgs-portal scalar in kination: $V_\phi(\phi, h, R) = \frac{1}{2}\left(\xi_\phi R + \frac{g^2}{2}h^2\right)\phi^2 - \frac{\sigma}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4$.
- Parameter space of BSM couplings for FOPT, DM and EWSB:

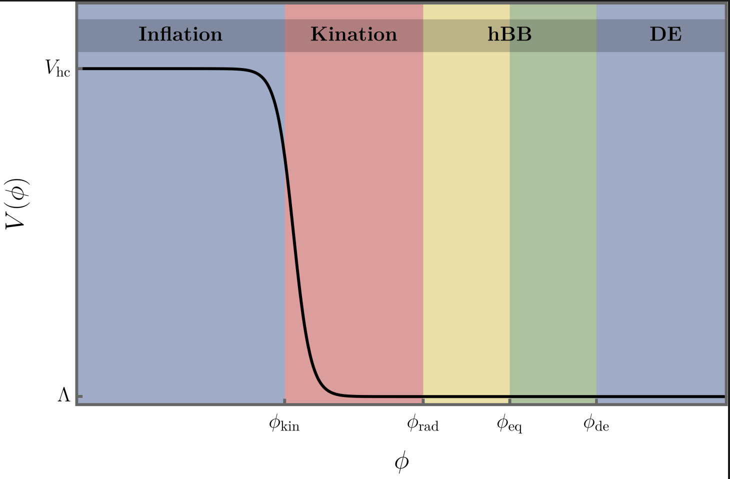
$$-10^3 \lesssim \xi_\phi \lesssim 10^2\,, \quad \sigma \gtrsim H_{\rm inf}\,, \quad \lambda_\phi \lesssim 10^{-4}\,,$$
$$10^{-32} \lesssim g \lesssim 10^{-21}\,, \qquad 10^{-30}\ \text{GeV} \lesssim m_\phi \lesssim 10^{-19}\ \text{GeV}\,.$$

- DM abundance $\Omega_{\phi,0} \simeq 0.26$ and curvature-induced EWSB:
$$g = \frac{\sqrt{12\Omega_{\phi,0}}H_0 M_P}{v}\left(\frac{g_{*\rm reh}}{g_{*0}}\right)^{\frac{1}{2}}\left(\frac{T_{\rm reh}}{T_0}\right)^{\frac{3}{2}}\phi_{\rm reh}^{-1} \simeq 3\times 10^{-17}\left(\frac{T_{\rm reh}}{80\,\text{GeV}}\right)^{\frac{3}{2}}\frac{\lambda_\phi}{\sigma}\,,$$
$g < \sqrt{\frac{2|\lambda_h|\lambda_\phi}{\sigma}}v < 125\sqrt{\frac{\lambda_\phi}{\sigma}}$ for $T_{\rm reh} \leq 80$ GeV.
- GWs at $f \gg f_{\rm LISA}$ unless $H_{\rm inf} \sim \mu_{\rm EW}$, but clearly from early universe.
- "Smoking-gun" tilt for kination, spectra different from thermal PTs.

Additional slides

Slowly rolling in (quintessential) inflationary potentials

The field ϕ drives the accelerated expansion in the early (and late) universe: primordial inflation (+ quintessence).

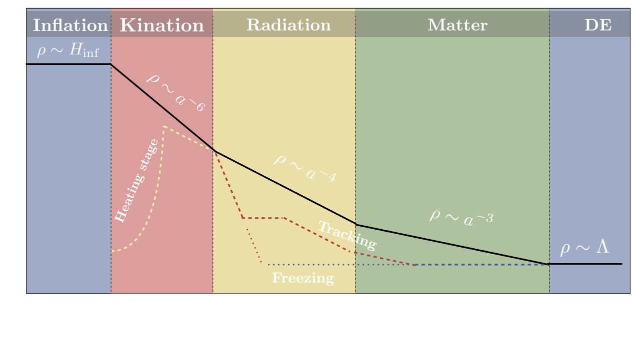


D. Bettoni & J. Rubio , "Quintessential Inflation: A Tale of Emergent and Broken Symmetries", 2021.

Quintessential inflation: evolution of energy densities

ϕ-SM interactions $\rightarrow$ decay and destabilize the $V(\phi)$ tail.

Hence, (p)reheating via indirect particle production/efficient couplings to aux. matter sector, quickly shutting down the interaction and preventing the complete decay of the inflaton condensate.



D. Bettoni & J. Rubio, "Quintessential Inflation: A Tale of Emergent and Broken Symmetries", 2021

Potential redefinition for a PT from a positive tv ($\xi_\phi < 0$)

$$W(\phi, h=0, R) = V(\phi + \phi_{\text{tv}}, h, R) - V(\phi_{\text{tv}}, h, R) =$$
$$= \left[\frac{\sigma^2}{4\lambda_\phi}\left(1 + \sqrt{1 + \frac{4\lambda_\phi|\xi_\phi|R}{\sigma^2}}\right) + |\xi_\phi|R\right]\phi^2$$
$$- \frac{|\sigma|}{2}\left(\frac{1}{3} + \sqrt{1 + \frac{4\lambda_\phi|\xi_\phi|R}{\sigma^2}}\right)\phi^3 + \frac{\lambda_\phi}{4}\phi^4 .$$

$$\tilde{\delta}(h=0, R) = \left(\frac{8\lambda_\phi}{\sigma^2}\right)\frac{\frac{\sigma^2}{4\lambda_\phi}\left(1+\sqrt{1+\frac{4\lambda_\phi|\xi_\phi|R}{\sigma^2}}\right)+|\xi_\phi|R}{\left(\frac{1}{3}+\sqrt{1+\frac{4\lambda_\phi|\xi_\phi|R}{\sigma^2}}\right)^2} = \frac{2\left(1-\frac{4\delta}{9}+\sqrt{1-\frac{4\delta}{9}}\right)}{\left(\frac{1}{3}+\sqrt{1-\frac{4\delta}{9}}\right)^2}$$

- Here $\delta(t) = \frac{9\lambda\left[\xi R(t)+\frac{g^2}{2}h^2\right]}{\sigma^2}$ follows $R(t)$, when writing the potential in the reduced dimensionless form as

$$\widetilde{V}(\tilde{\varphi},t) = \frac{1}{4}\tilde{\varphi}^4 - \tilde{\varphi}^3 + \frac{\delta(t)}{2}\tilde{\varphi}^2 \qquad \text{where} \qquad \tilde{\varphi} = \frac{3\lambda}{\sigma}\phi\,.$$

- $0 \leq \delta \leq 2$: from vanishing barrier to degenerate vacua for $\tilde{\phi}_{\mathrm{fv}} = 0$.

- Nucleation rate:

$$\Gamma = m^4 \left(\frac{S_4^E}{2\pi}\right)^2 e^{-S_4^E - \frac{1}{2}\Sigma_4}\,,$$

where $m^2_{\xi_\phi>0} = \xi_\phi R + \frac{g^2}{2}h^2$ and the regularised sum over multipoles $\Sigma_4(\delta)$ is the 1-loop contribution to the $O(4)$ Euclidean action $S_4^E(\delta) = \frac{4\pi^2}{3\lambda}(2-\delta)^{-3}\left[\alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3\right]$.

M. Matteini *et al* (2024), F. C. Adams (1993)

Consistency analysis and phenomenological considerations

- Scalar ϕ is spectator during inflation: if $\xi_\phi < 0$ then
$$\frac{\sigma^2}{\lambda_\phi^3}\left(1-\frac{4C}{3}+\sqrt{1-\frac{8C}{9}}\right)\left(1+\sqrt{1-\frac{8C}{9}}\right)^2 < 288 M_P^2\left(\frac{H_{\text{inf}}}{\sigma}\right)^2.$$

- Higgs branching ratio into invisible particles: $g < 0.13$.

- Radiative corrections to avoid fine-tuning: $\Delta\lambda_\phi \sim \frac{g^4}{16\pi^2} < \lambda_\phi$.

- Dark matter abundance $\Omega_{\phi,0} \simeq 0.26$:
$$g = \frac{\sqrt{12\Omega_{\phi,0}}H_0 M_P}{v}\left(\frac{g_{*\text{reh}}}{g_{*0}}\right)^{\frac{1}{2}}\left(\frac{T_{\text{reh}}}{T_0}\right)^{\frac{3}{2}}\phi_{\text{reh}}^{-1} \simeq 3\times 10^{-17}\left(\frac{T_{\text{reh}}}{80\,\text{GeV}}\right)^{\frac{3}{2}}\frac{\lambda_\phi}{\sigma}.$$

- Curvature-induced breaking of EW symmetry if $T_{\text{reh}} \leq 80$ GeV:
$$g < \sqrt{\frac{2|\lambda_h|\lambda_\phi}{\sigma}}v < 125\sqrt{\frac{\lambda_\phi}{\sigma}}.$$

GWs: amplitude and peak frequency redshifted to today

$t_{\rm nuc} \approx t_{\rm col}$

$$\Omega_{\rm GW,0}(f) = \frac{1.67\times 10^{-5}}{h^2}\left(\frac{H_{\rm col}}{H_{\rm reh}}\right)^{\frac{2(3w_{\rm int}-1)}{3w_{\rm int}+3}}\left(\frac{H_{\rm col}}{\beta_{\rm col}}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2 S(f)\,,$$

with $w_{\rm int}\approx 1$, $S(f) = 25.09\left[2.41\left(\frac{f}{f_{\rm peak,0}}\right)^{-0.56} + 2.34\left(\frac{f}{f_{\rm peak,0}}\right)^{0.57}\right]^{-4.2}$,

and $f_{\rm peak,0} = 1.65\times 10^{-5}\left(\frac{H_{\rm col}}{H_{\rm reh}}\right)^{\frac{3w_{\rm int}-1}{3w_{\rm int}+3}}\left(\frac{0.13\beta_{\rm col}}{H_{\rm col}}\right)\left(\frac{T_{\rm reh}}{100\ \text{GeV}}\right)$.

Assuming instantaneous thermalisation $H_{\rm reh} = \frac{\pi}{3}\sqrt{\frac{g_{*\rm reh}}{10}}\frac{T_{\rm reh}^2}{M_P}$, $T_{\rm reh}\leq 80$ GeV, $g_{*\rm reh} = 106.75$, and ϕ has decayed to SM before rad. domination.