Primordial gravitational waves from phase transitions during (quintessential) inflation

Andreas Mantziris

in collaboration with M. Kierkla, G. Laverda, M. Lewicki, M. Piani, J. Rubio, and M. Zych

Institute of Theoretical Physics, University of Warsaw

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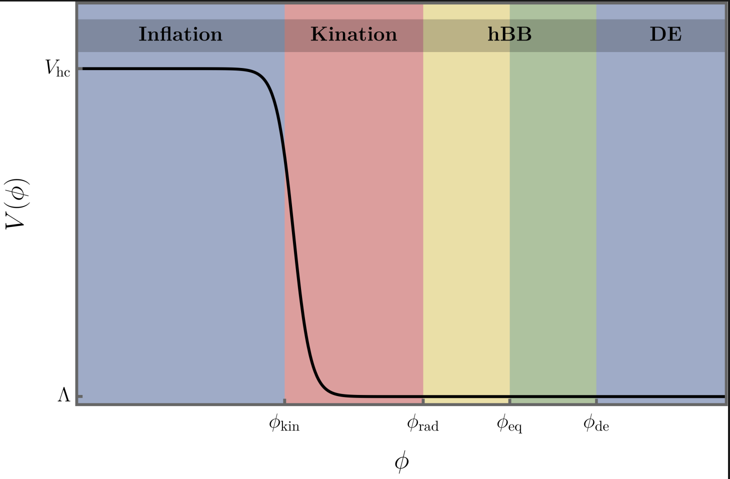
Quintessential inflation: runaway potential

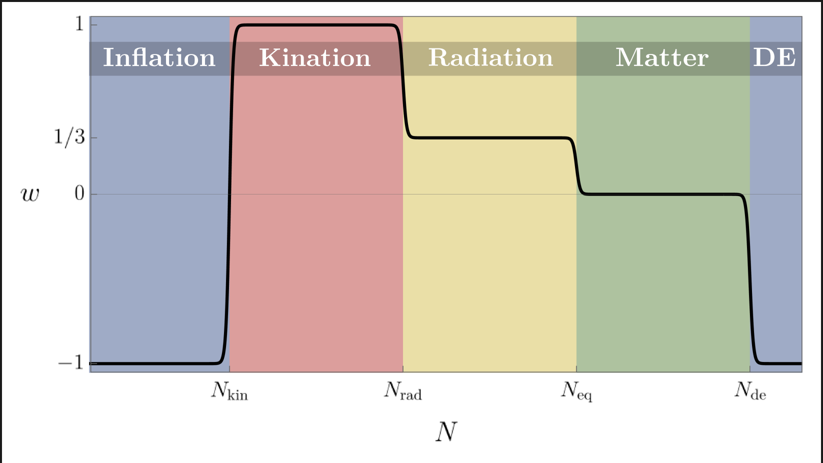
The *cosmon* field ϕ drives the accelerated expansion in the early and late universe: primordial inflation + quintessence (Dark Energy).



Bettoni et al, "Quintessential Inflation: A Tale of Emergent and Broken Symmetries", 2021.

Quintessential inflation: EoS

The energy density $\rho = \frac{1}{2}\dot{\phi}^2 + V$ and pressure $p = \frac{1}{2}\dot{\phi}^2 - V$ of the scalar field are related via the equation-of-state parameter $w \equiv \frac{p}{\rho}$.

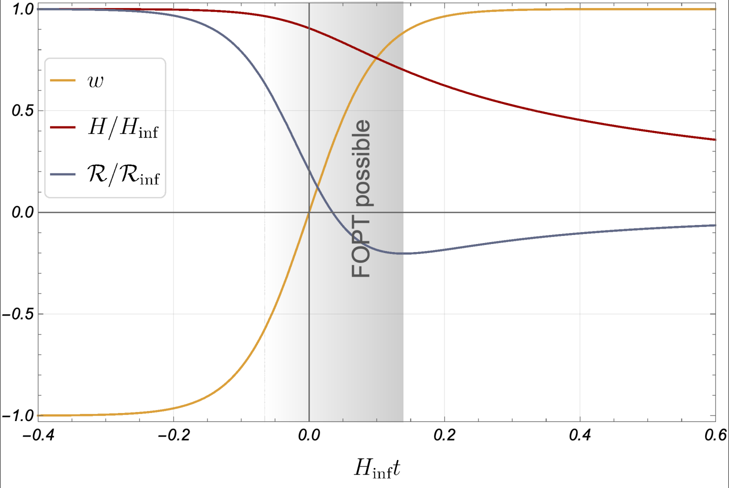


Bettoni et al, "Quintessential Inflation: A Tale of Emergent and Broken Symmetries", 2021.

Evolution from inflation to kination

The Ricci scalar generically switches sign at the end of inflation

$$\mathcal{R} = 3(1 - 3w)H^2$$



Spectator scalar χ non-minimally coupled to gravity

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2 - \xi\chi^2}{2}\mathcal{R} - \frac{1}{2}(\partial\chi)^2 - V(\chi) + \mathcal{L}(\phi)\right]$$

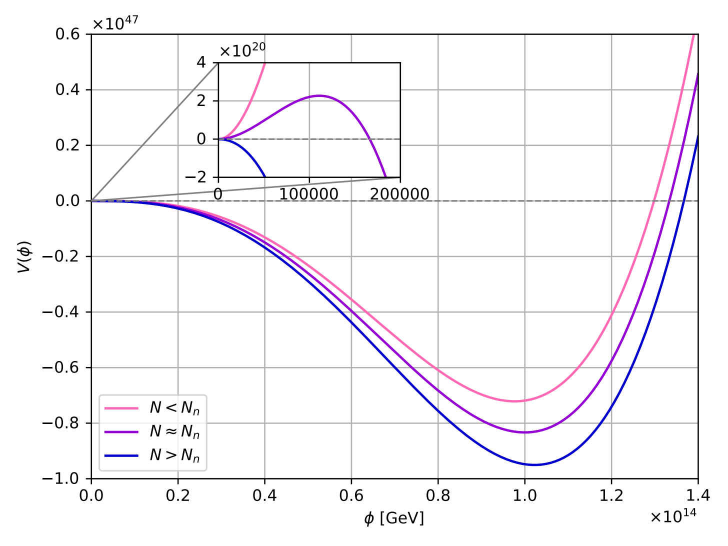
- If $\chi =$ higgs, all couplings are fixed, but complicated to solve and possibly weak PT.
- Instead, let $\chi =$ BSM scalar singlet extension and choose couplings in parameter space for a strong phase transition (PT).

PT after inflation, because the barrier of the renormalizable potential

$$V = \frac{m^2}{2}\chi^2 + \frac{\sigma}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$

is suppressed as $(m^2 + \xi\mathcal{R})\chi^2$ decreases due to $\mathcal{R}(t)$.

Evolution of barrier for sample values of the couplings



Barrier decreases → PT → bubble collisions → GWs

- Bubble nucleation rate $\Gamma = R_0^{-4}\left(\frac{S_E}{2\pi}\right)^2 e^{-S_E}$, where

$$S_E(\delta) = \frac{4\pi^2}{3\lambda}(2-\delta)^{-3}\left[\alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3\right]$$

is the Euclidean action for $O(4)$-symmetric bounce solution, with $\alpha_1 = 13.832$, $\alpha_2 = -10.819$, $\alpha_3 = 2.0765$.

- The parameter $\delta(t) = \frac{9\lambda\left(m^2+\xi\mathcal{R}(t)\right)}{\sigma^2}$ varies between 2 (degenerate minima) and 0 (vanishing barrier) and the critical thin-wall bubble radius is $R_0 = \left(\frac{2S_E}{\pi^2\Delta V}\right)^{\frac{1}{4}}$, where $\Delta V = V(\chi_{\rm fv}) - V(\chi_{\rm tv}) \propto \sigma^4/\lambda^3$.

- Nucleation condition $\Gamma(t_n) = H^4(t_n) \xRightarrow{t_n \approx t_*} R_* = -5/\dot{S}_E(t_*)$.

GW spectra: peak frequency and GW signal today

For $\tilde{w}=\frac{\int_{t_*}^{t_{\rm rad}} w(t)dt}{t_{\rm rad}-t_*}$, $S(f)=25.09\left[2.41\left(\frac{f}{f_{\rm peak,0}}\right)^{-0.56}+2.34\left(\frac{f}{f_{\rm peak,0}}\right)^{0.57}\right]^{-4.2}$,

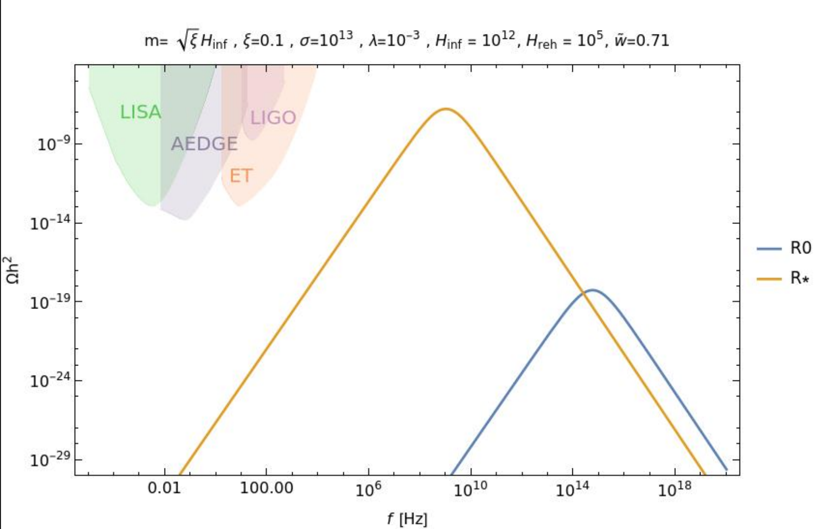
$$f_{\rm peak,0} = 1.65\times 10^{-5}\ \text{Hz}\ \left(\frac{T_{\rm reh}}{100\ \text{GeV}}\right)\left(\frac{0.65}{R_* H_*}\right)\left(\frac{H_*}{H_{\rm reh}}\right)^{\frac{3\tilde{w}+1}{3\tilde{w}+3}},$$

$$\Omega_{\rm GW,0}(f) = \frac{1.67\times 10^{-5}}{h^2}\left(\frac{H_{\rm reh}}{H_*}\right)^{2\frac{3\tilde{w}-1}{3\tilde{w}+3}}(5R_* H_*)^2\, S(f)\,.$$

The signal is boosted to the observable region as R_* increases, but successful bubble nucleation demands

$$\sigma \lesssim 10\pi H_{\rm inf}\sqrt{\xi} \qquad \text{and} \qquad \lambda^3(\sigma) \lesssim \frac{\xi^2\sigma^2}{8\times 10^{-35}} e^{-8\times 10^2\left(\frac{H_{\rm inf}}{\sigma}\right)^2}\,.$$

Preliminary results of $\Omega_{\mathrm{GW},0}$ vs f with $H_* = 10^{12}$ GeV



Overview and objectives

- Proof-of-concept study of generating GW signals from Ricci induced PT due to decreasing $(m^2 + \xi\mathcal{R})$-term after inflation.
- Identified parameter space of BSM scalar couplings for strong FOPT.
- Preliminary GW spectra beyond detector sensitivities and seemingly $H_{\rm inf}$-independent, but we need to incorporate reheating more carefully.
- Investigate Gauss-Bonnet coupling to curvature $\frac{\xi G\chi^2}{2}$, where $G^2 = R^2 - 4R^{\mu\nu}R_{\mu\nu} + R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} = -12(1+3w)H^4$, to reach more favourable values of $H_*\,, H_{\rm reh}$.