From Hubble to Bubble: curvature induced phase transitions after inflation

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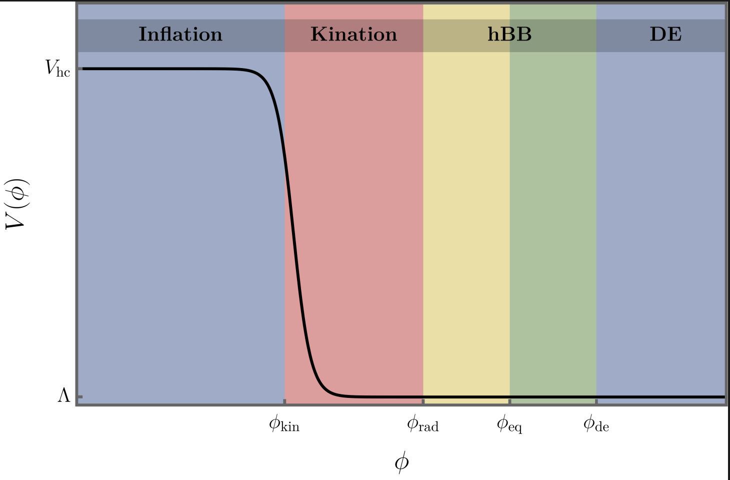
Cosmological evolution in quintessential inflation

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

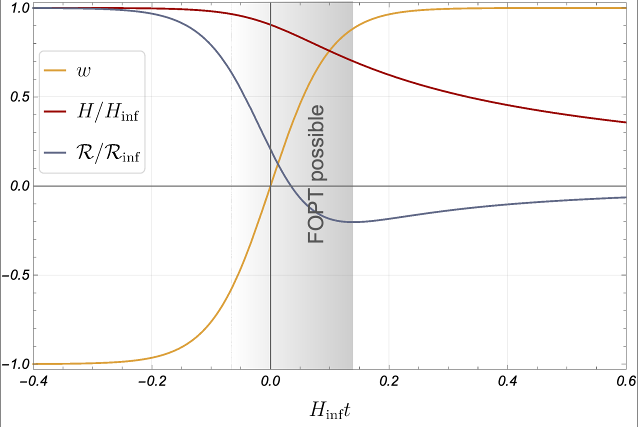


Bettoni et al, "Quintessential Inflation: A Tale of Emergent and Broken Symmetries", 2021.

Transition from inflation to kination

The Ricci scalar generically switches sign at the end of inflation

$$\mathcal{R}(t) = 3\left[1 - 3w(t)\right] H^2(t)\,, \quad w(t) = \tanh\left(\beta_w (t - t_0)\right).$$



Quintessential inflation: (1) no oscillations so only one PT and (2) long kination amplifies the GW signal.

Spectator scalar χ non-minimally coupled to gravity

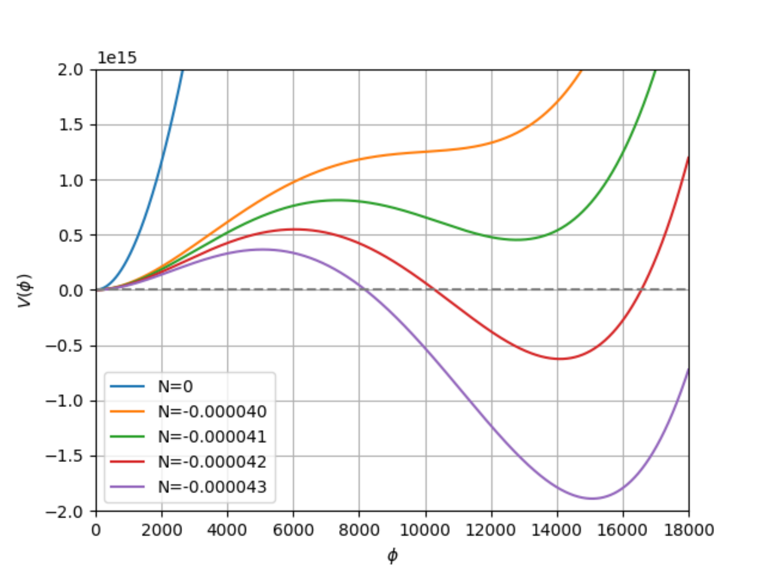
$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2 - \xi\chi^2}{2}\mathcal{R} - \frac{1}{2}(\partial\chi)^2 - V(\chi) + \mathcal{L}(\phi)\right]$$

- Minimal model of BSM scalar singlet extension with couplings that give a strong phase transition (PT).
- Non-minimal coupling to spacetime curvature is unavoidable and necessary for the renormalizability of the theory.
- PT after inflation, because the barrier of the renormalizable potential

$$V(\chi) = \frac{m^2 + \xi\mathcal{R}}{2}\chi^2 - \frac{\sigma}{3}\chi^3 + \frac{\lambda}{4}\chi^4$$

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

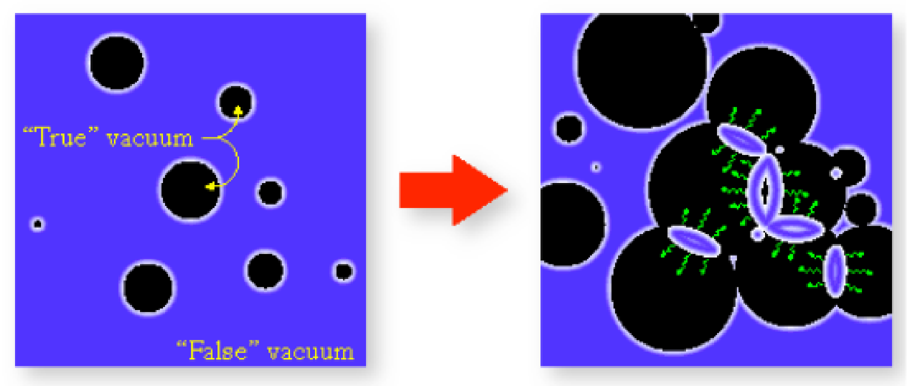
Barrier decreases → PT via tunnelling → bubble nucleation



Gravitational Waves from bubble collisions in vacuum

Nucleation condition $\Gamma(t_n) = H^4(t_n)$: one bubble/horizon for cosntant H_*.

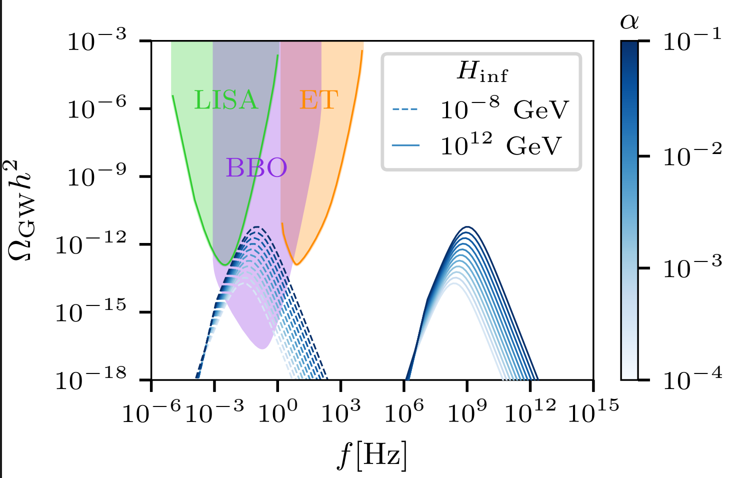
(J. Ellis, M. Lewicki and J. M. No, 2019)



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

GWs from bubble collisions with $w = 1$ and $\beta_*/H_* = 100$

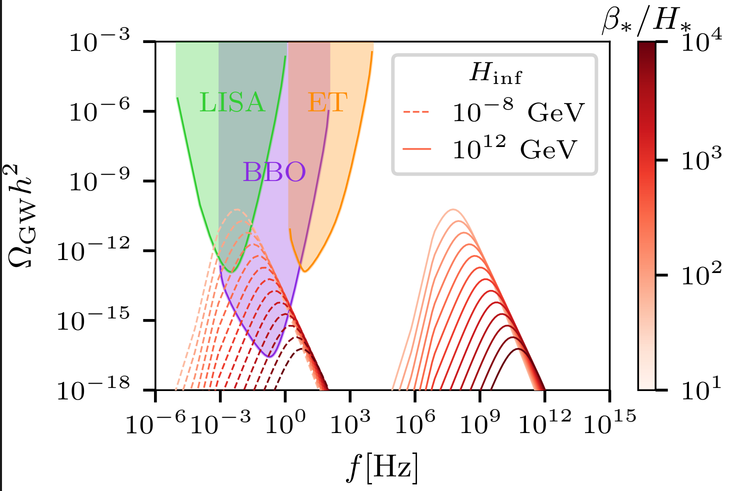
$$\Omega_{\rm GW,0} = \frac{1.67}{10^5 h^2}\alpha\left(\frac{H_*}{\beta_*}\right)^2 S(f)\,,\quad f_{\rm peak,0} = \frac{1.65}{10^5}\frac{\sqrt[4]{3M_p^2\xi_g^2 H_{\rm RD}^2}}{100\ \text{GeV}}\left(\frac{0.13\beta_*}{H_*\sqrt{\alpha}}\right)\ \text{Hz.}$$



Peak frequency determined by H_*, tilt from kination.

GWs from bubble collisions with $w = 1$ and $\alpha = 0.01$

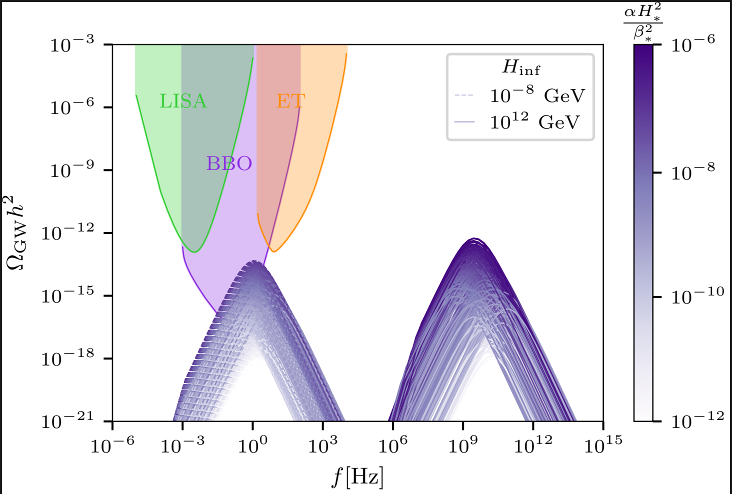
$$\Omega_{\mathrm{GW},0} = \frac{1.67}{10^5 h^2}\alpha\left(\frac{H_*}{\beta_*}\right)^2 S(f)\,,\quad f_{\mathrm{peak},0} = \frac{1.65}{10^5}\frac{\sqrt[4]{3M_p^2\xi_g^2H_{\mathrm{RD}}^2}}{100\ \mathrm{GeV}}\left(\frac{0.13\beta_*}{H_*\sqrt{\alpha}}\right)\ \mathrm{Hz}.$$



Peak frequency determined by H_*, tilt from kination.

GWs from numerical scans of couplings for bubble profiles

$$\Omega_{\mathrm{GW},0} = \frac{1.67}{10^5 h^2}\alpha\left(\frac{H_*}{\beta_*}\right)^2 S(f)\,,\ f_{\mathrm{peak},0} = \frac{1.65}{10^5}\frac{\sqrt[4]{3M_p^2\xi_g^2H_{\mathrm{RD}}^2}}{100\ \mathrm{GeV}}\left(\frac{0.13\beta_*}{H_*\sqrt{\alpha}}\right)\ \mathrm{Hz}.$$



Overview and objectives

- Proof-of-concept study of generating GWs from curvature induced PTs due to decreasing $(m^2 + \xi\mathcal{R})$-term after inflation.

$$V = \frac{m^2 + \xi\mathcal{R}(t)}{2}\chi^2 - \frac{\sigma}{3}\chi^3 + \frac{\lambda}{4}\chi^4 \, .$$

- Identified parameter space of BSM scalar couplings for strong FOPT: $m^2 \ll \xi\mathcal{R}, \quad \xi \geq \frac{\sigma^2}{54\lambda H_{\text{inf}}^2} \, , \quad \sigma \lesssim 10 H_{\text{inf}} \, , \quad \lambda \lesssim 10^{-3} \, .$

- GW spectra beyond detector sensitivities unless $H_* \sim \mu_{\text{EW}}$.

- Study "suitable" BSM potentials: currently working on Higgs-portal DM as the BSM spectator @ FCUP with O. Bertolami (2407.xxxxx).
- Investigate multiple PTs from oscillatory inflationary models.
- Necessary to incorporate reheating carefully.

Higgs-portal DM breaking EW sym. and producing GWs

$$V(\phi, h, t) = \frac{\frac{g^2}{2}h^2 + \xi_\phi \mathcal{R}(t)}{2}\phi^2 - \frac{\sigma}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4 \text{ , for } \xi_\phi \lessgtr 0$$

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