

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

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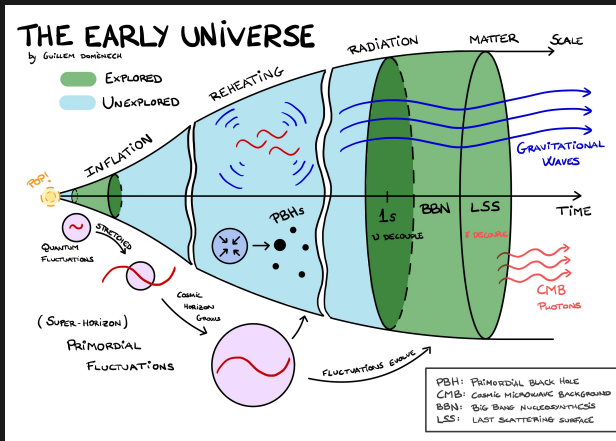
with M. Barroso Varela and O. Bertolami (2509.01532)

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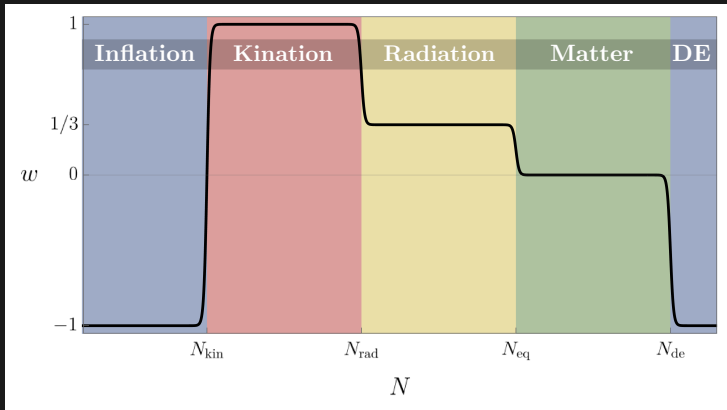
Motivation and general context

- Growing demand for cosmological implications of (B)SM physics.
- Early universe: ideal setting for HEP and its interplay with gravity.
- GWs offer a new window into particle physics and cosmology.



Cosmological evolution of the Equation of State

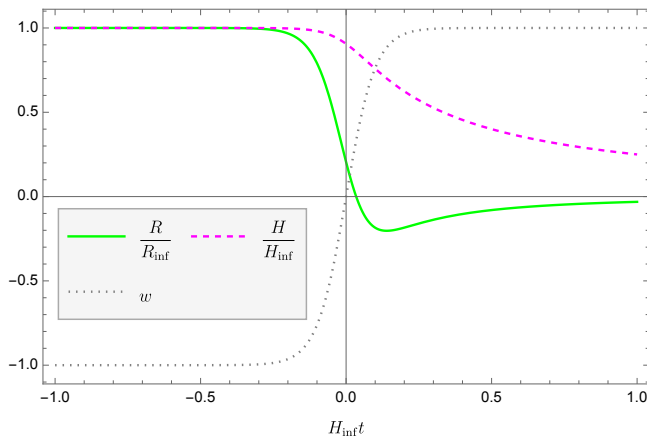
The energy density $\rho = \frac{1}{2}\dot{\phi}^2 + V$ and pressure $p = \frac{1}{2}\dot{\phi}^2 - V$ of the inflaton field are related via the EoS parameter $w \equiv \frac{p}{\rho}$.



$$e\text{-foldings: } N(t) = \ln \left(\frac{a_{\text{inf}}}{a(t)} \right)$$

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

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



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

Motivation and overview

- 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

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

- 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).

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

Cosmological phase transitions in vacuum

- When writing the potential in the reduced dimensionless form as

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

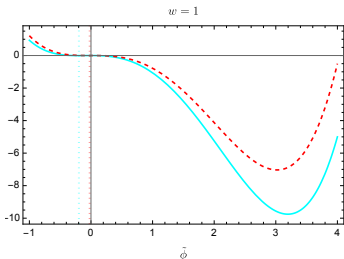
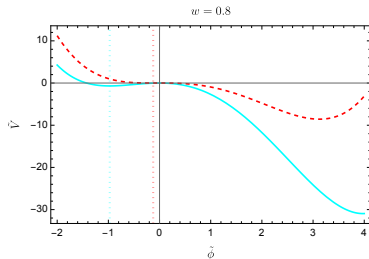
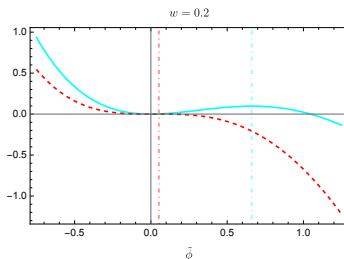
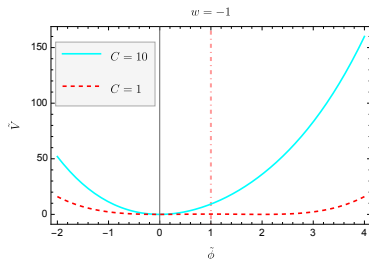
the coupling $\delta(t) = \frac{9\lambda \left[\xi R(t) + \frac{g^2}{2} h^2 \right]}{\sigma^2}$ follows the evolution of $R(t)$.

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

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

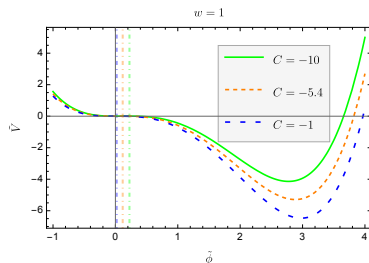
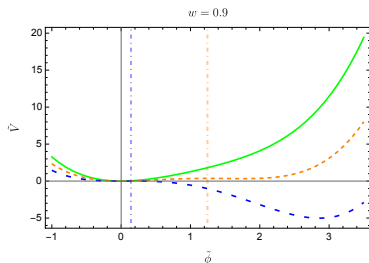
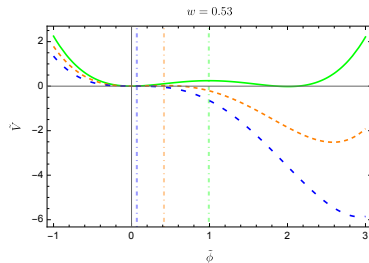
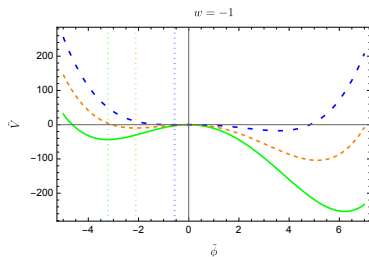
where $m_{\xi\phi>0}^2 = \xi\phi R + \frac{g^2}{2}h^2$ and the regularised sum over multipoles $\Sigma_4(\delta)$ is the 1-loop contribution to the $O(4)$ Euclidean action $S_4^E(\delta) = \frac{4\pi^2}{3\lambda}(2-\delta)^{-3} [\alpha_1\delta + \alpha_2\delta^2 + \alpha_3\delta^3]$. (α_i 's: numerical factors)

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



$$\delta = C \left[\frac{1-3w(t)}{2} \right] \left(\frac{H(t)}{H_{\text{inf}}} \right)^2, \quad C = 54\lambda_\phi \xi_\phi \left(\frac{H_{\text{inf}}}{\sigma} \right)^2$$

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



$$\delta = C \left[\frac{1-3w(t)}{2} \right] \left(\frac{H(t)}{H_{\text{inf}}} \right)^2, \quad C = 54\lambda_\phi \xi_\phi \left(\frac{H_{\text{inf}}}{\sigma} \right)^2$$

Consistency analysis and phenomenological considerations

- Scalar ϕ is a spectator field during inflation: **only for $\xi_\phi < 0$,**

$$\frac{\sigma^2}{\lambda_\phi^3} \left(1 - \frac{4C}{3} + \sqrt{1 - \frac{8C}{9}} \right) \left(1 + \sqrt{1 - \frac{8C}{9}} \right)^2 < 288 M_P^2 \left(\frac{H_{\text{inf}}}{\sigma} \right)^2.$$

- 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 $\Omega_{\phi,0} \simeq 0.26$:

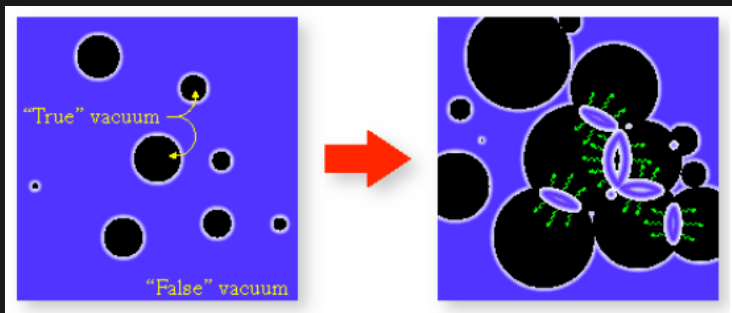
$$g = \frac{\sqrt{12\Omega_{\phi,0}} H_0 M_P}{v} \left(\frac{g_{*\text{reh}}}{g_{*0}} \right)^{\frac{1}{2}} \left(\frac{T_{\text{reh}}}{T_0} \right)^{\frac{3}{2}} \phi_{\text{reh}}^{-1} \simeq 3 \times 10^{-17} \left(\frac{T_{\text{reh}}}{80 \text{ GeV}} \right)^{\frac{3}{2}} \frac{\lambda_\phi}{\sigma}.$$

- **Curvature-induced breaking of EW symmetry only if $T_{\text{reh}} \leq 80 \text{ GeV}$:**

$$g < \sqrt{\frac{2|\lambda_h|\lambda_\phi}{\sigma}} v < 125 \sqrt{\frac{\lambda_\phi}{\sigma}}.$$

Gravitational waves from bubble collisions in vacuum

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



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

“Velocity” $\beta_{\text{col}}^{\xi_\phi < 0} = \sqrt{\frac{d^2 \mathbf{S}_4^E}{dt^2}} \Big|_{t=t_{\text{col}}}$, $\beta_{\text{col}}^{\xi_\phi > 0} = - \frac{dt}{d\mathbf{S}_4^E} \Big|_{t=t_{\text{col}}}$, $\beta_{\text{col}} > \beta_w = 10H_{\text{inf}}$.

GWs: amplitude and peak frequency redshifted to today

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

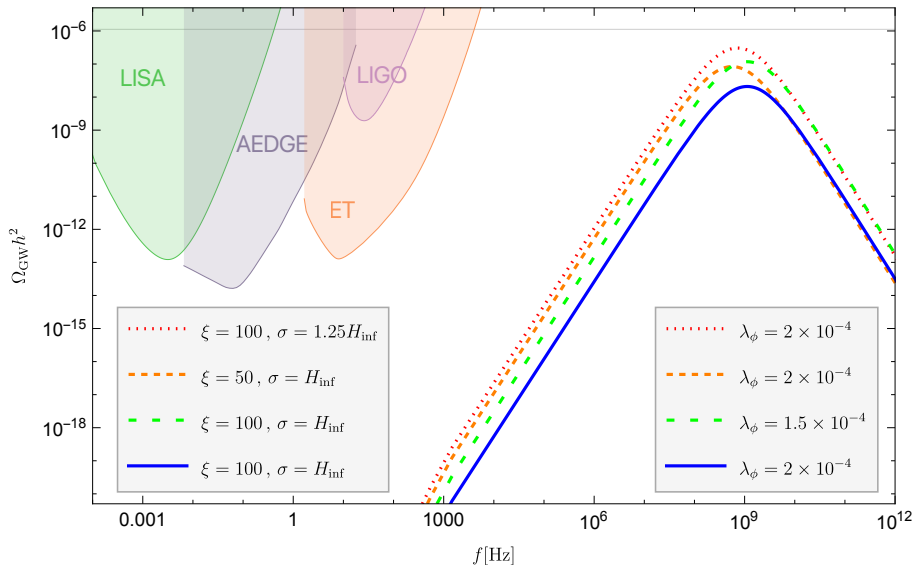
$$\Omega_{\text{GW},0}(f) = \frac{1.67 \times 10^{-5}}{h^2} \left(\frac{H_{\text{col}}}{H_{\text{reh}}} \right)^{\frac{2(3w_{\text{int}}-1)}{3w_{\text{int}}+3}} \left(\frac{H_{\text{col}}}{\beta_{\text{col}}} \right)^2 \left(\frac{\alpha}{\alpha+1} \right)^2 S(f),$$

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

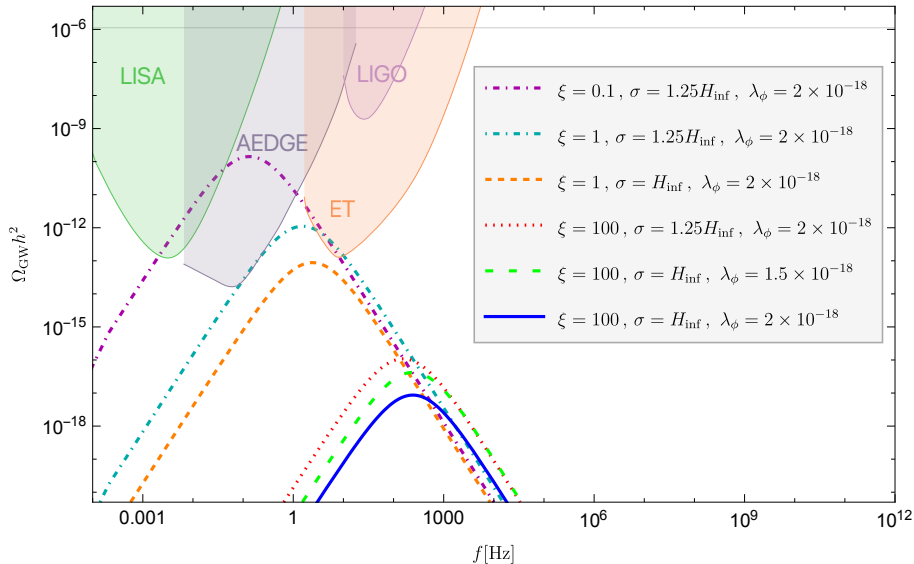
and $f_{\text{peak},0} = 1.65 \times 10^{-5} \left(\frac{H_{\text{col}}}{H_{\text{reh}}} \right)^{\frac{3w_{\text{int}}-1}{3w_{\text{int}}+3}} \underbrace{\left(\frac{f_{\text{peak,col}}}{H_{\text{col}}} \right)}_{f_{\text{peak,col}} = 0.13\beta_{\text{col}}} \left(\frac{T_{\text{reh}}}{100 \text{ GeV}}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

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

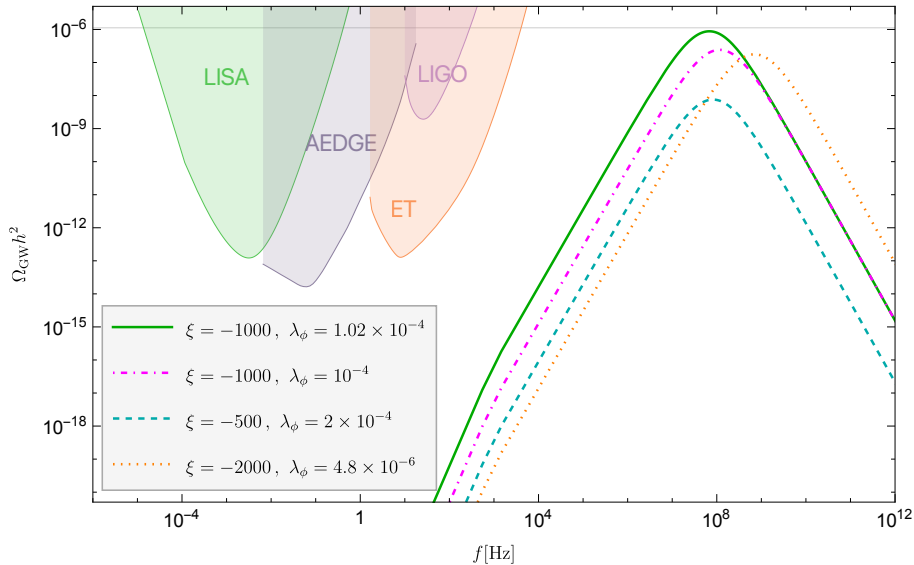
GWs: $\xi_\phi > 0$, $H_{\text{inf}} = 10^{12}$ GeV, $H_{\text{reh}} \approx 10^{-14}$ GeV



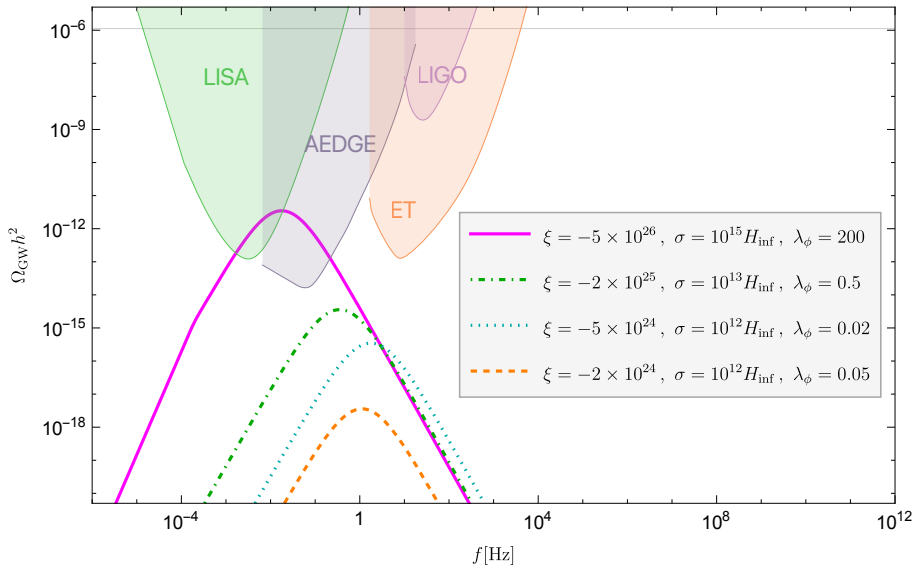
GWs: $\xi_\phi > 0$, $H_{\text{inf}} = 10^{-8}$ GeV, $H_{\text{reh}} \approx 10^{-14}$ GeV



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



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



Overview and objectives

- 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 couplings for FOPT, DM, and EWSB ($T_{\text{reh}} = 80 \text{ GeV}$):

$$\begin{aligned} -10^3 \lesssim \xi_\phi \lesssim 10^2, \quad \sigma \gtrsim H_{\text{inf}}, \quad \lambda_\phi \lesssim 10^{-4}, \\ 10^{-32} \lesssim g(T_{\text{reh}}) \lesssim 10^{-21}, \quad 10^{-30} \text{ GeV} \lesssim m_\phi(T_{\text{reh}}) \lesssim 10^{-19} \text{ GeV}. \end{aligned}$$

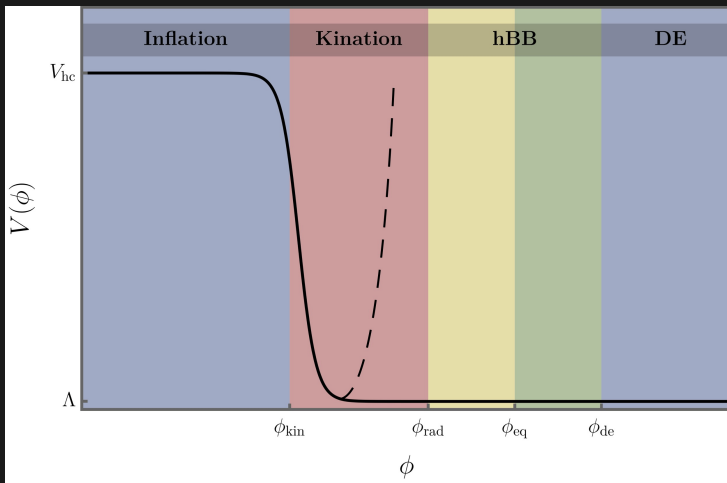
- GWs at $f \gg f_{\text{LISA}}$ unless $H_{\text{inf}} \sim \mu_{\text{EW}}$, but clearly from early universe.
- High freq. “smoking-gun”, kination tilt, spectra $\neq$ thermal PTs.

- Generic PT mechanism: applicable to “suitable” BSM potentials.
- Multiple PTs from oscillatory R in inflationary minima.
- Necessary to incorporate reheating carefully for precision studies.

Additional slides

Slowly rolling in (quintessential) inflationary potentials

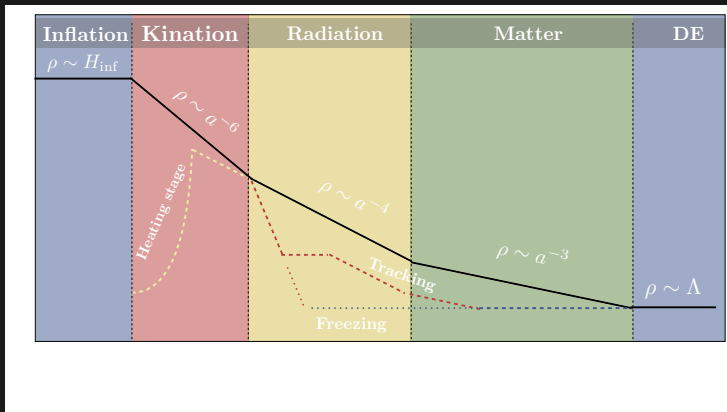
The inflaton field (here ϕ instead of φ) drives the accelerated expansion in the early (and late) universe: primordial inflation (+ quintessence).



Quintessential inflation: evolution of energy densities

Cannot have ϕ -SM interactions: decay and destabilize the $V_{\text{Inf}}(\phi)$ 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.



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

$$W(\phi, h = 0, R) = V(\phi + \phi_{\text{tv}}, h, R) - V(\phi_{\text{tv}}, h, R) =$$

$$= \left[\frac{\sigma^2}{4\lambda_\phi} \left(1 + \sqrt{1 + \frac{4\lambda_\phi |\xi_\phi| R}{\sigma^2}} \right) + |\xi_\phi| R \right] \phi^2$$

$$- \frac{|\sigma|}{2} \left(\frac{1}{3} + \sqrt{1 + \frac{4\lambda_\phi |\xi_\phi| R}{\sigma^2}} \right) \phi^3 + \frac{\lambda_\phi}{4} \phi^4,$$

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

$$m_{\xi_\phi < 0}^2(R, h = 0) = \frac{\sigma^2}{4\lambda_\phi} \left(1 + \sqrt{1 + \frac{4\lambda_\phi |\xi_\phi| R}{\sigma^2}} \right) + |\xi_\phi| R.$$