

Hubble-induced phase transitions in the Standard Model and Beyond

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BUILDINGUNIVERSE

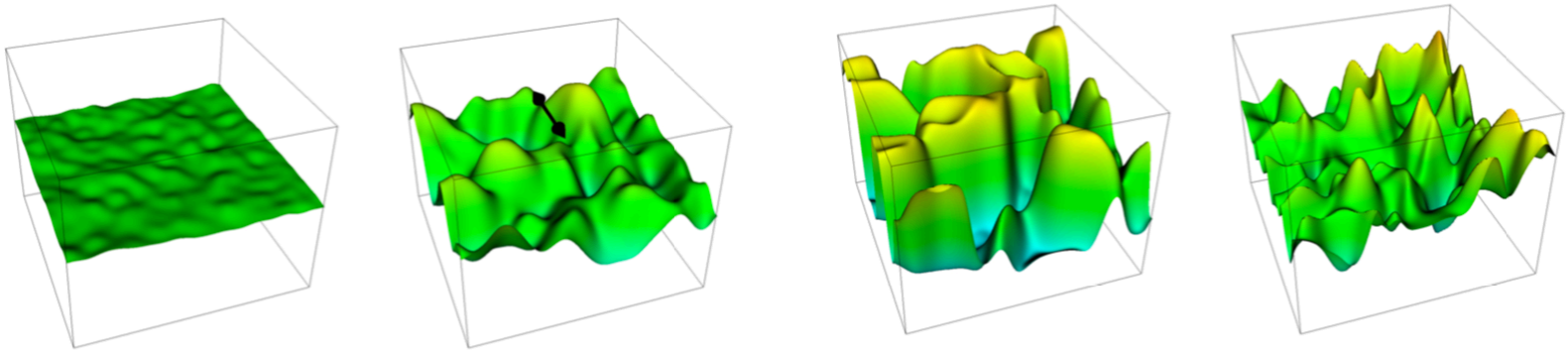


MINISTERIO
DE CIENCIA
E INNOVACIÓN

Fundación
BBVA

The general paradigm

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2}{2} R - \frac{1}{2} (\partial\chi)^2 - f(R, R_{\mu\nu}) \chi^2 - V(\chi)$$



- Natural triggering mechanism for phase transitions
- Non-thermal & non-perturbative
- Short-lived topological defects
- Specific gravitational waves signatures

A dedicated program

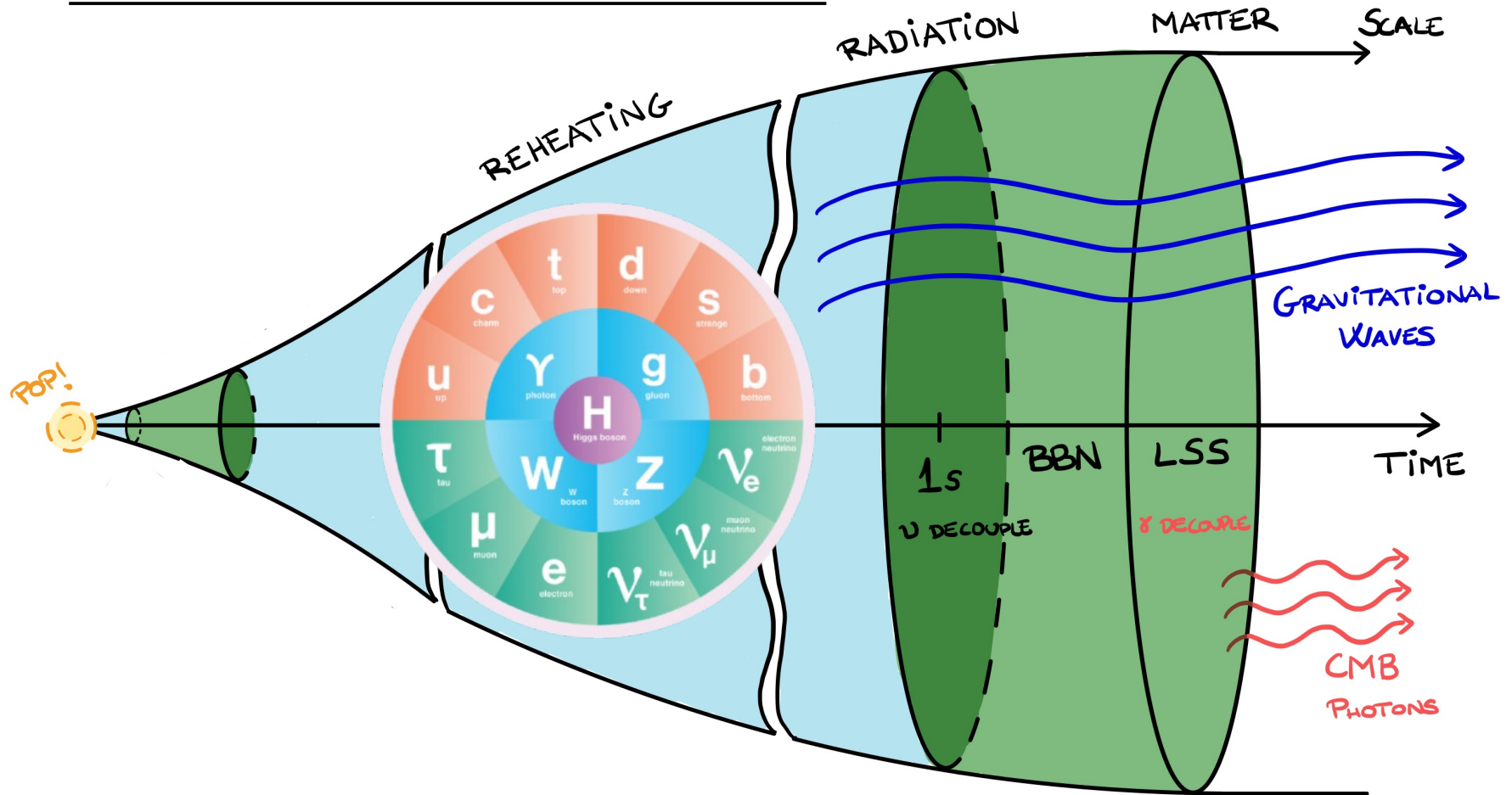
1. Quintessential Affleck–Dine baryogenesis with non-minimal couplings, D. Bettoni, J. Rubio, Phys. Lett. B 784 (2018) 122–129.
2. Gravitational waves from global cosmic strings in quintessential inflation, D. Bettoni, G. Domènech, J. Rubio, JCAP 02 (2019) 034.
3. Hubble-induced phase transitions: Walls are not forever, D. Bettoni, J. Rubio, JCAP 01 (2020) 002.
4. Hubble-induced phase transitions on the lattice with applications to Ricci reheating, D. Bettoni, J. Rubio, JCAP 01 (2022) 002.
5. Ricci reheating reloaded, G. Laverda, JCAP 03 (2024) 033.
6. From Hubble to Bubble, M. Kierkla, G. Laverda, M. Lewicki, A. Mantziris, M. Piani, JHEP 11 (2023) 077.
7. The rise and fall of the Standard-Model Higgs: electroweak vacuum stability during kination, G. Laverda, J. Rubio, JHEP 05 (2024) 339.
8. Tachyonic gravitational dark matter production after inflation, G. Laverda, T. Mendes, J. Rubio, arxiv: 2601.07670



See Tomás Mendes' talk

Spectator Higgs Reheating

The SM Higgs tracker



$$\Delta \mathcal{L}_{\text{SM}+\text{G}} = \sqrt{-g} \xi H^\dagger H g^{\mu\nu} R_{\mu\nu}(\Gamma)$$

Sensitive to cosmological history

A simple scenario

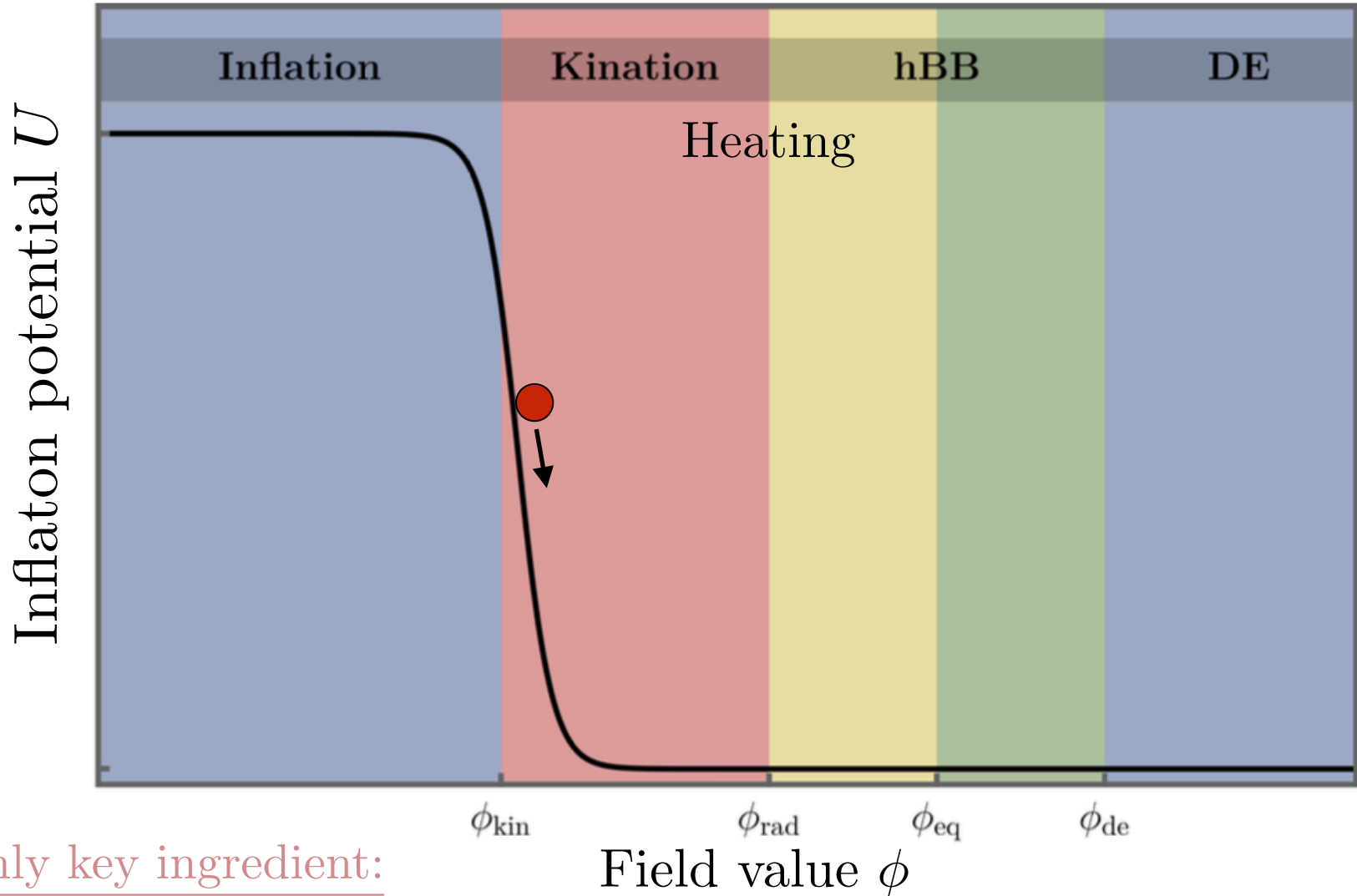
- A single field ϕ for both inflation and dark energy (quintessential inflation)
- An unavoidable non-minimal coupling of the Higgs field H to gravity
- No additional degrees of freedom beyond the electroweak scale

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\text{P}}^2}{2} R - g^{\mu\nu} (D_\mu H)^\dagger (D_\nu H) - \lambda \left(H^\dagger H - \frac{v_{\text{EW}}^2}{2} \right)^2 - \xi H^\dagger H R + \mathcal{L}_{\text{SM}} + \mathcal{L}_\phi$$

Interesting outputs

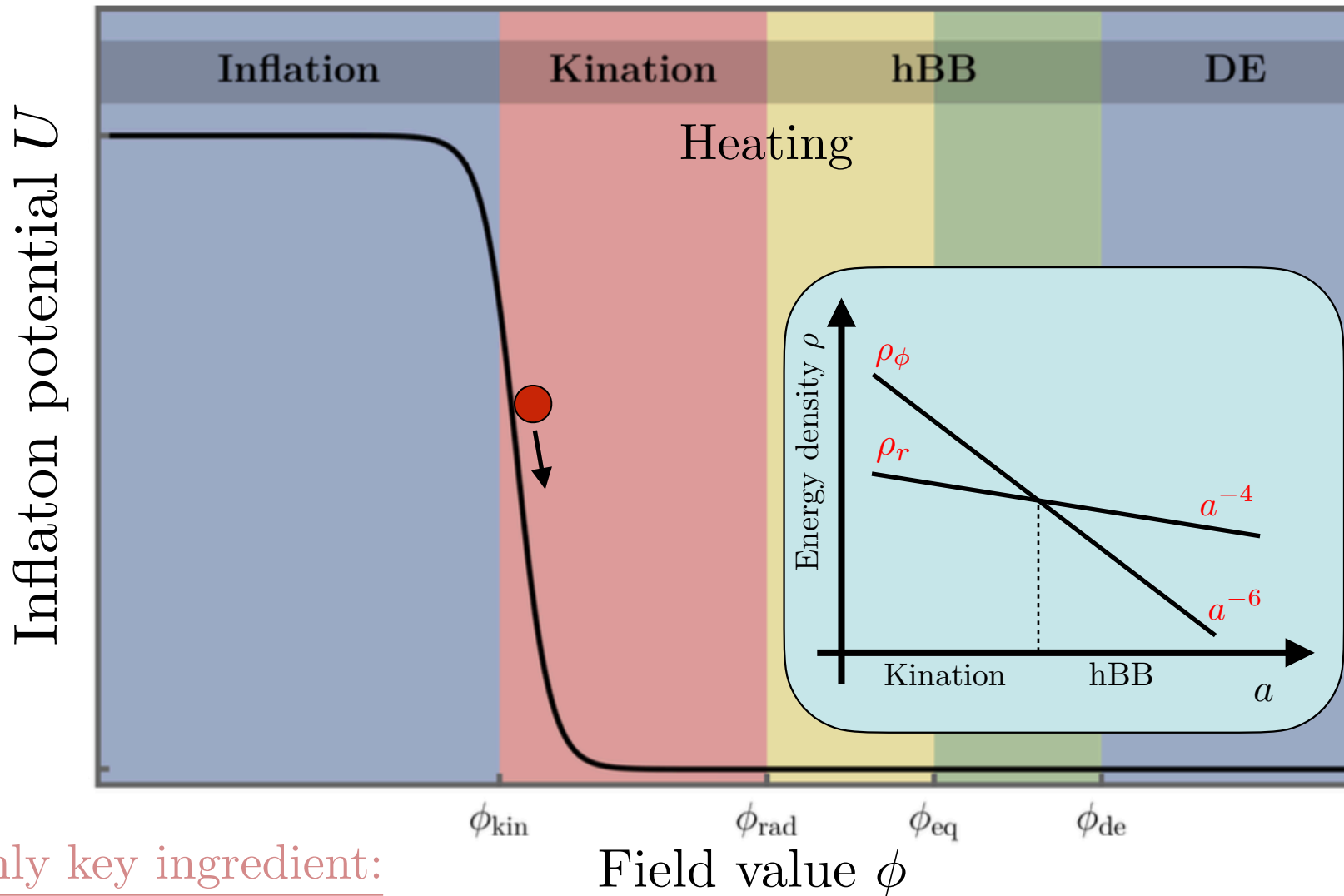
- The Higgs field is safely stabilized during inflation (no isocurvature pert.)
- Appealing connection between SM parameters and (post-)inflationary era
- The Higgs field itself can be responsible for heating the Universe

Quintessential inflation



Only key ingredient:
Period of kination

Quintessential inflation



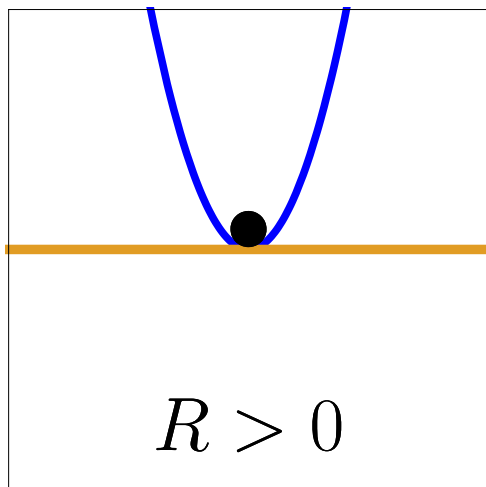
Only key ingredient:
Period of kination

Hubble-induced transition

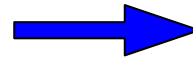
$$V_{\text{eff}}(H) = (\xi R + m_h^2)H^\dagger H + \lambda(H^\dagger H)^2$$

Energetically subdominant / Spectator field $R = 3(1 - 3w_\phi)\mathcal{H}^2$
Negligible contribution to the effective Planck mass, $\xi h^2 \ll M_P^2$

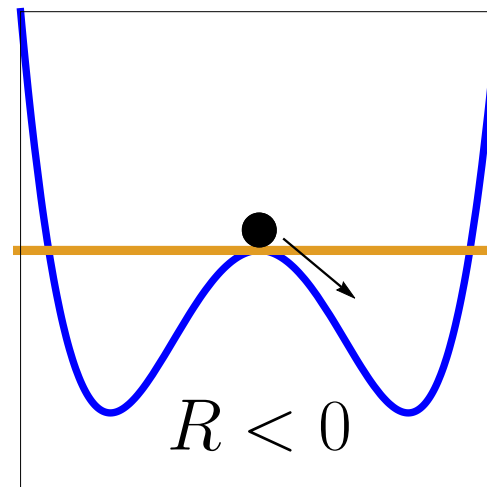
Inflation $w_\phi = -1$



No isocurvature
perturbations



Kination $w_\phi = 1$



Tachyonic
production

Tachyonic particle production

$$Y \equiv \frac{a}{a_{\text{kin}}} \frac{h}{h_*} \quad \vec{y} \equiv a_{\text{kin}} h_* \vec{x} \quad h_* \equiv \sqrt{6\xi} H_{\text{kin}}$$
$$z \equiv a_{\text{kin}} h_* \tau$$

$$S_\chi = \int d^3\vec{y} dz \left[\frac{1}{2} (Y')^2 - \frac{1}{2} |\nabla Y|^2 + \frac{1}{2} M_{\text{eff}}^2(z) Y^2 - V(Y) \right]$$

Spinodal/Tachyonic instability

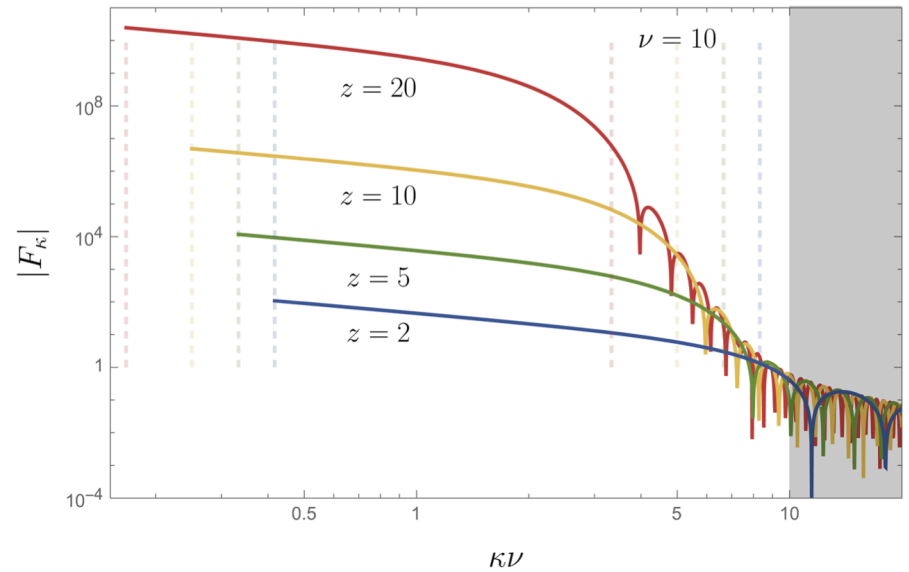
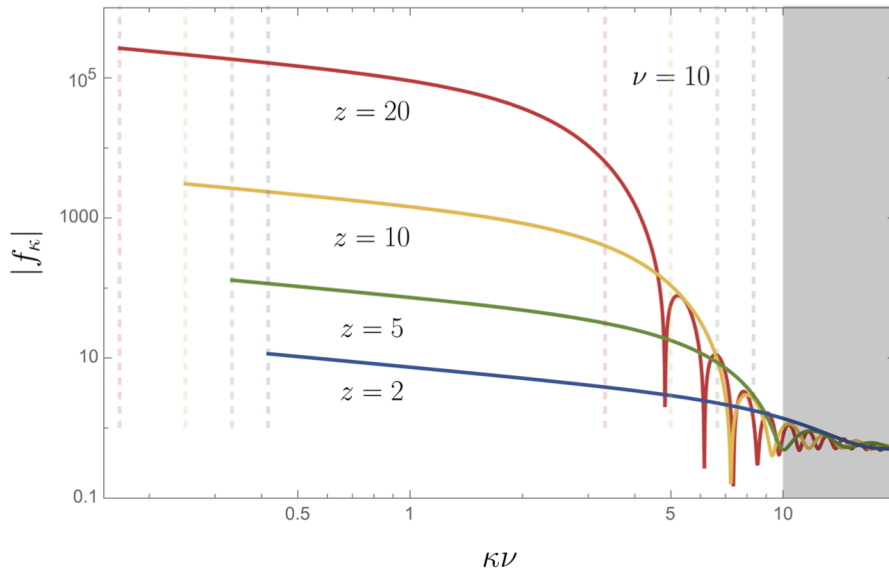
$$M_{\text{eff}}^2(z) \equiv (4\nu^2 - 1) \mathcal{H}^2 \quad \nu \equiv \sqrt{\frac{3\xi}{2}}$$

- The field is *not* classical but rather quantum.
- A homogeneous component description is *completely inaccurate*.

Classicalization

$$f''_{\kappa} + (\kappa^2 - M_{\text{eff}}^2(z))f_{\kappa} = 0$$

$$F_{\kappa}(z) = \text{Re}(f_{\kappa}^* f'_{\kappa})$$

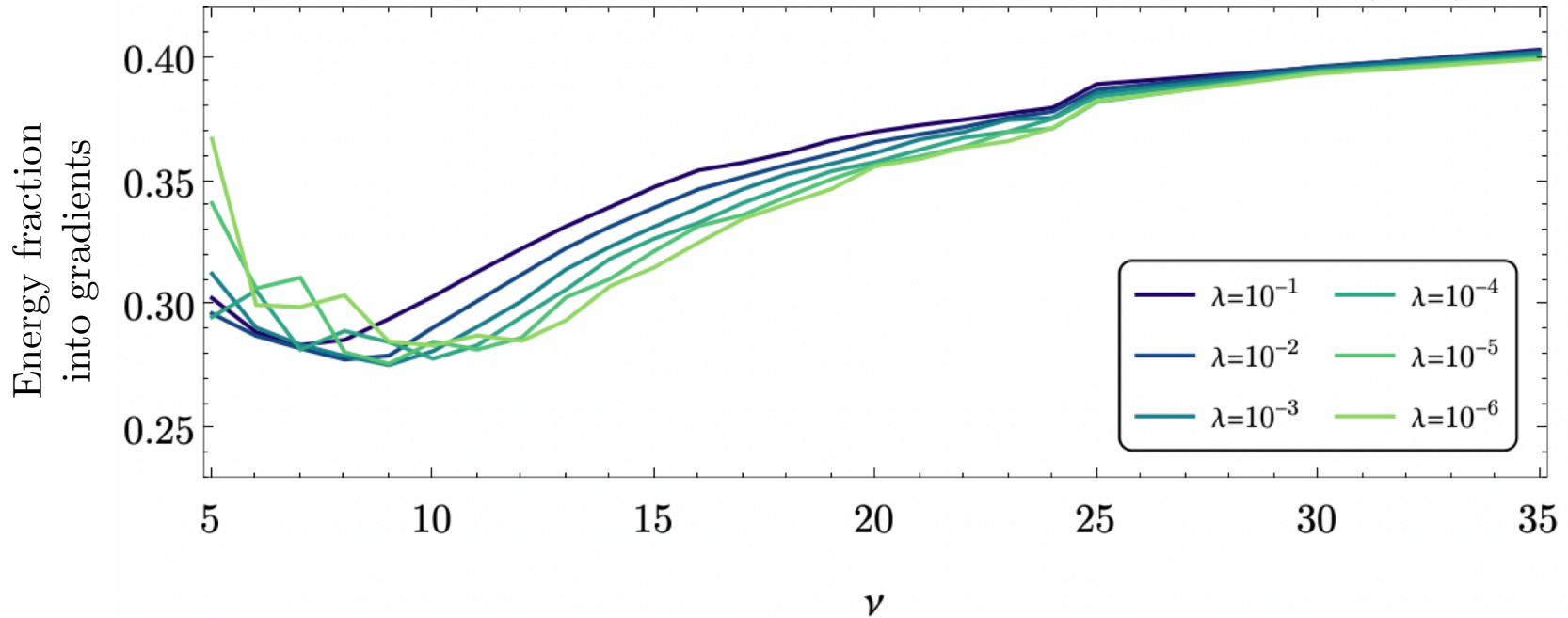


$$\Delta Y_{\kappa}^2 \Delta \Pi_{\kappa}^2 = |F_{\kappa}(z)|^2 + \frac{1}{4} \geq \frac{1}{4} \left| \langle [Y_{\kappa}(z), \Pi_{\kappa}^{\dagger}(z)] \rangle \right|^2$$

- Following dynamics needs non-analytical techniques.
- High occupation numbers \rightarrow Classical Lattice Simulations

Gradients are crucial

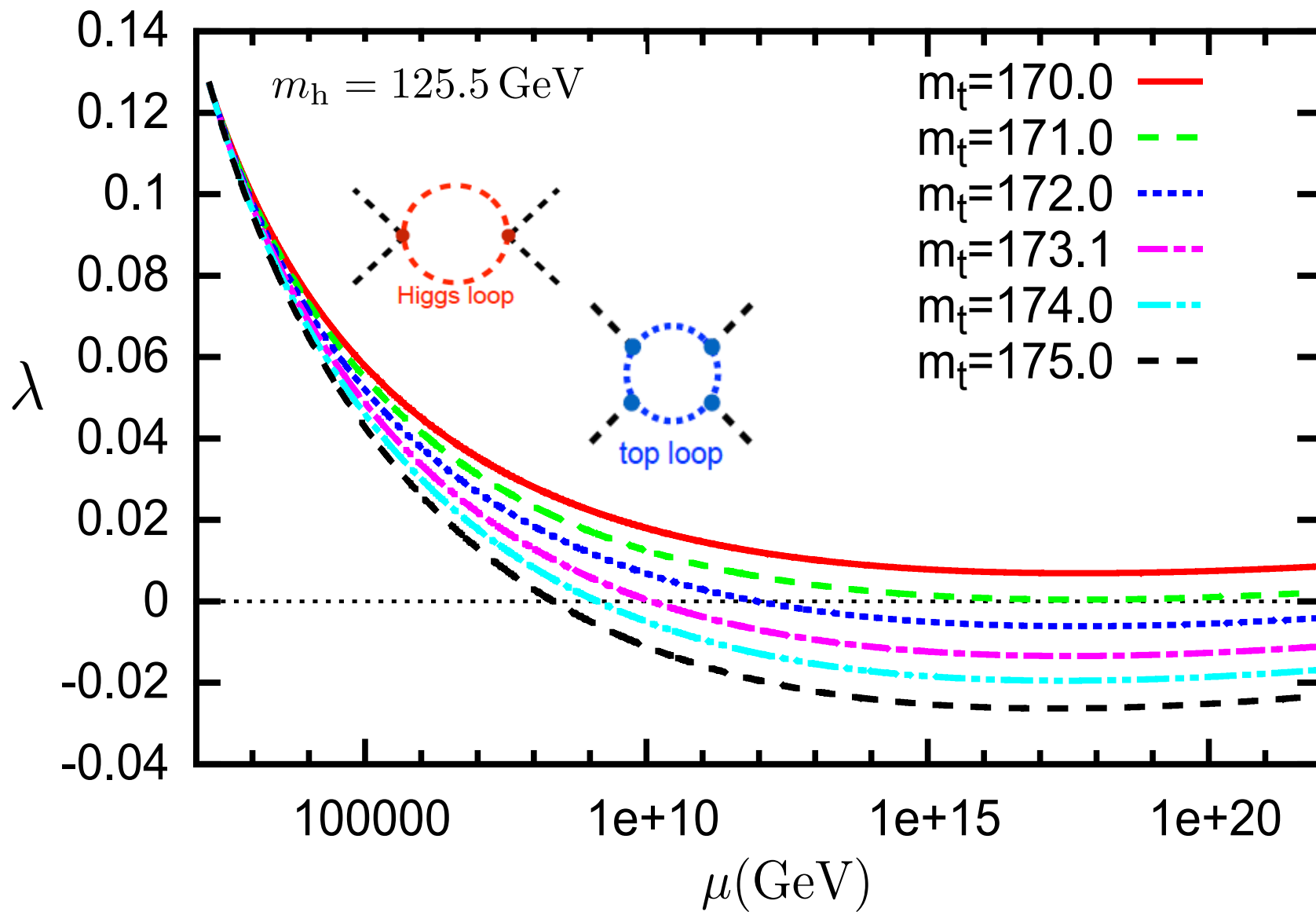
G. Laverda, JR, JCAP 03 (2024) 033



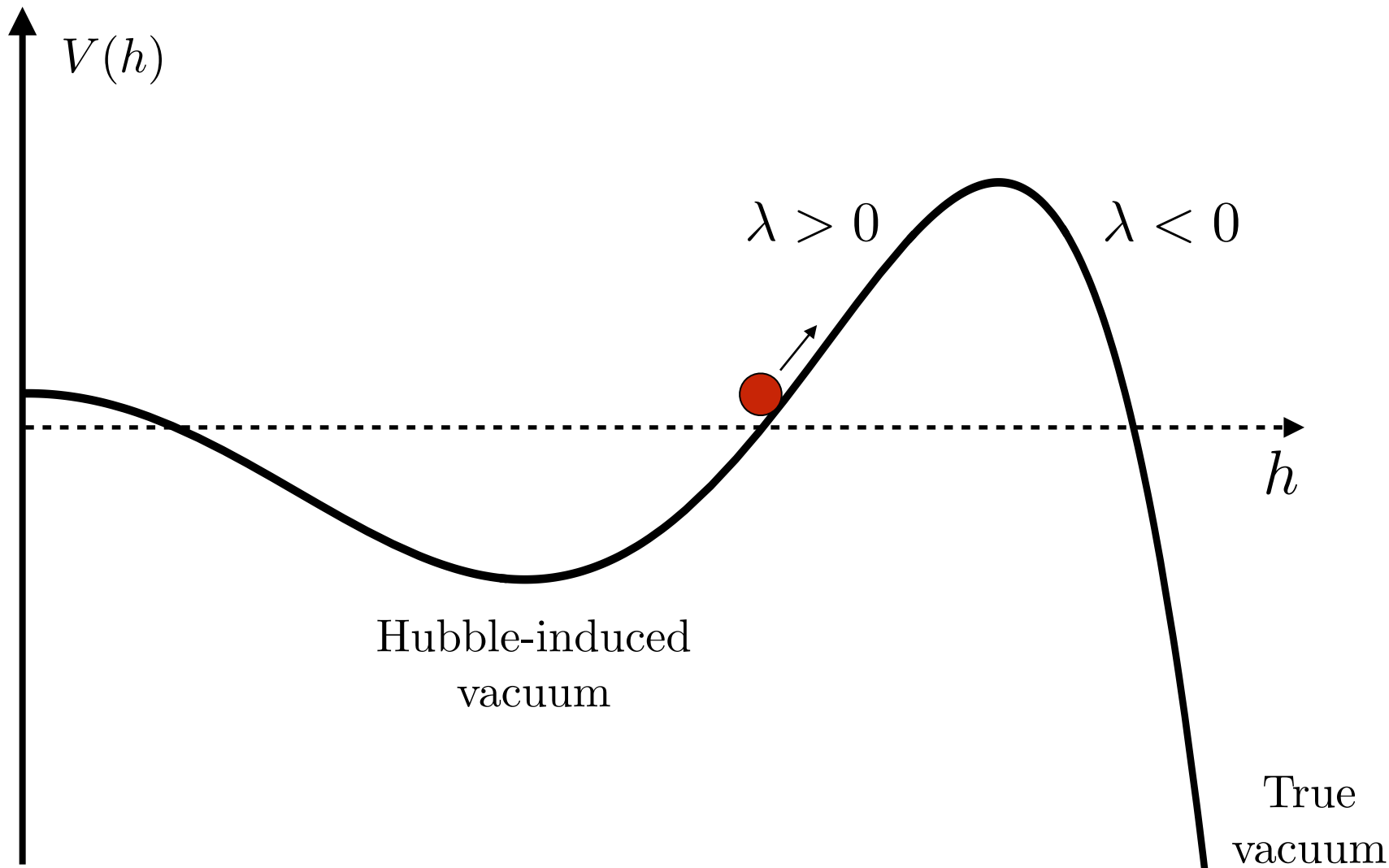
Radiation-like products for arbitrary potential

$$w_\chi = \frac{1}{3} + \frac{2}{3} \frac{(n-2)}{(n+1) + \langle (\nabla\chi/a)^2 \rangle / \langle V \rangle} \quad V \propto \chi^{2n}$$

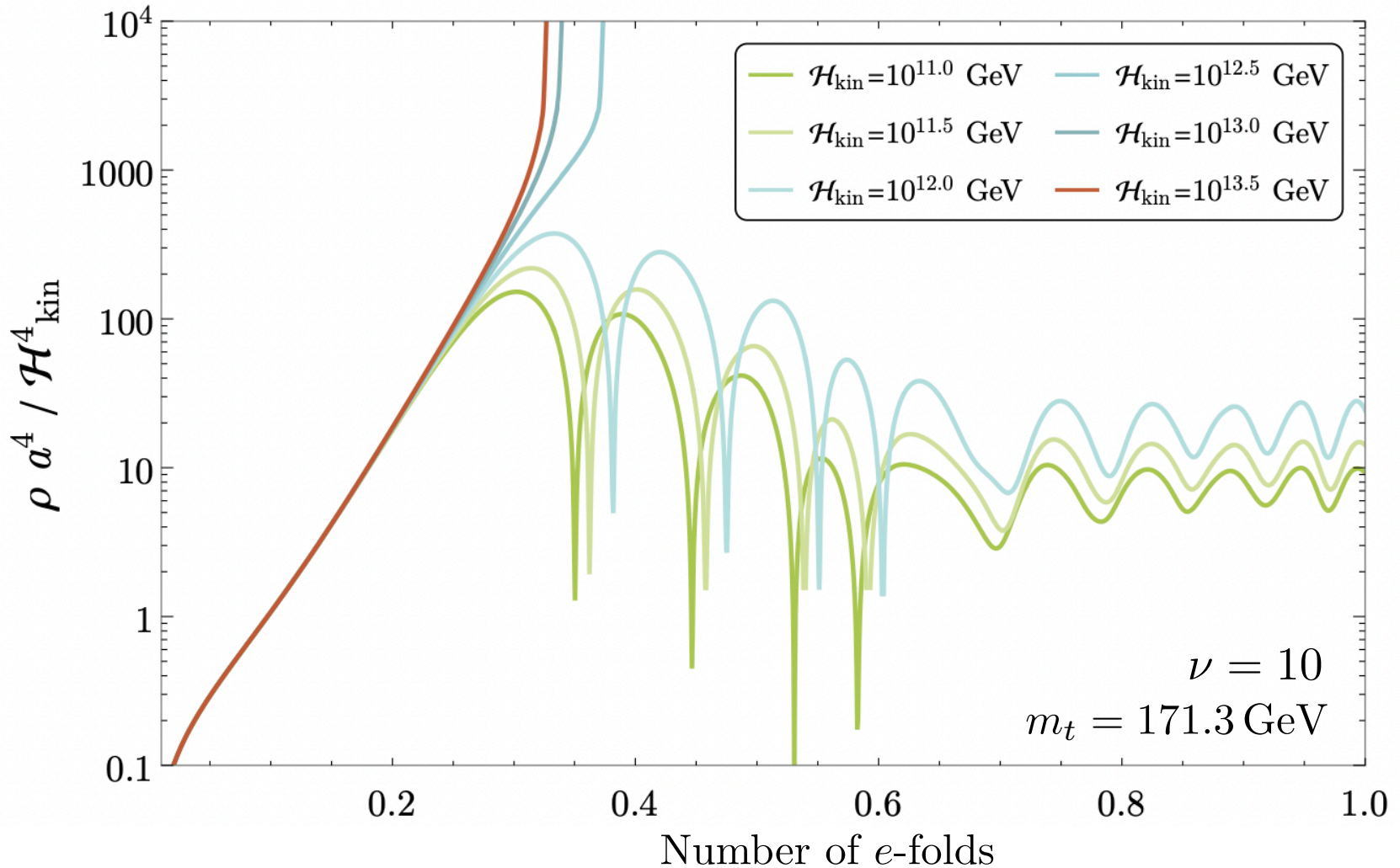
Standard Model running



Higgs effective potential



Vacuum stability during kination



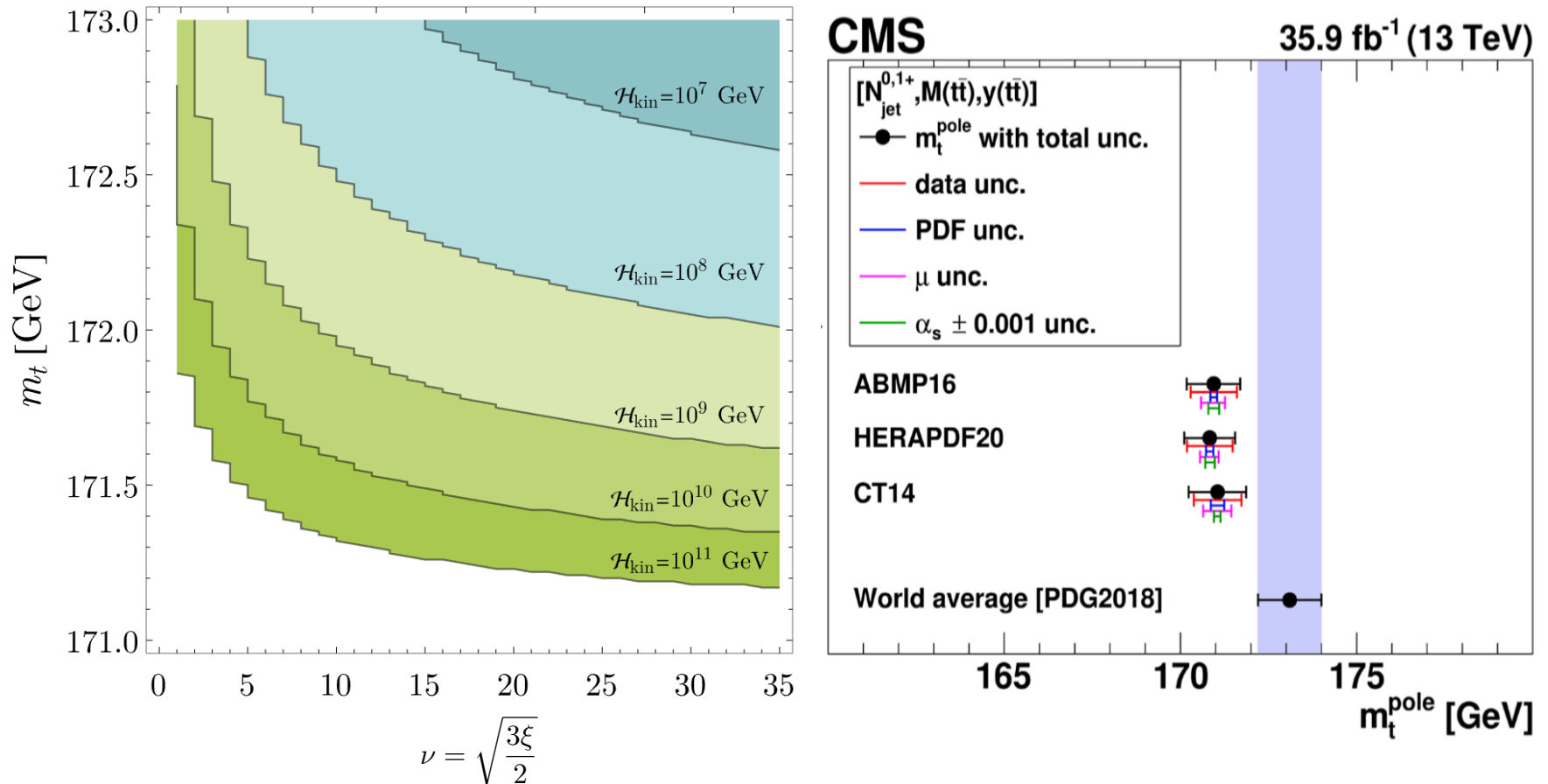
Scanning of parameter space

- Three-loop renormalisation-group running of the Higgs self-coupling
- Agnostic approach to top quark mass values, $m_t = 170 - 173$ GeV
- Wide range for non-minimal coupling parameter $\xi \sim 1 - 700$
- Wide range for the onset scale of kination $\mathcal{H}_{\text{kin}} \sim 10^6 - 10^{15}$ GeV
- O(1000) 3+1-dimensional classical lattice simulations.
- Checking for existence and crossing of the barrier

$$\xi < \frac{y_\Lambda^4 \mu_\Lambda^2}{32 e^{3/2} \pi^2 \mathcal{H}^2}$$

$$\rho_{\text{tac}}(\lambda(\mu), \xi) < V(h_{\text{max}}(\xi, y_\Lambda, \mathcal{H}, \mu_\Lambda))$$

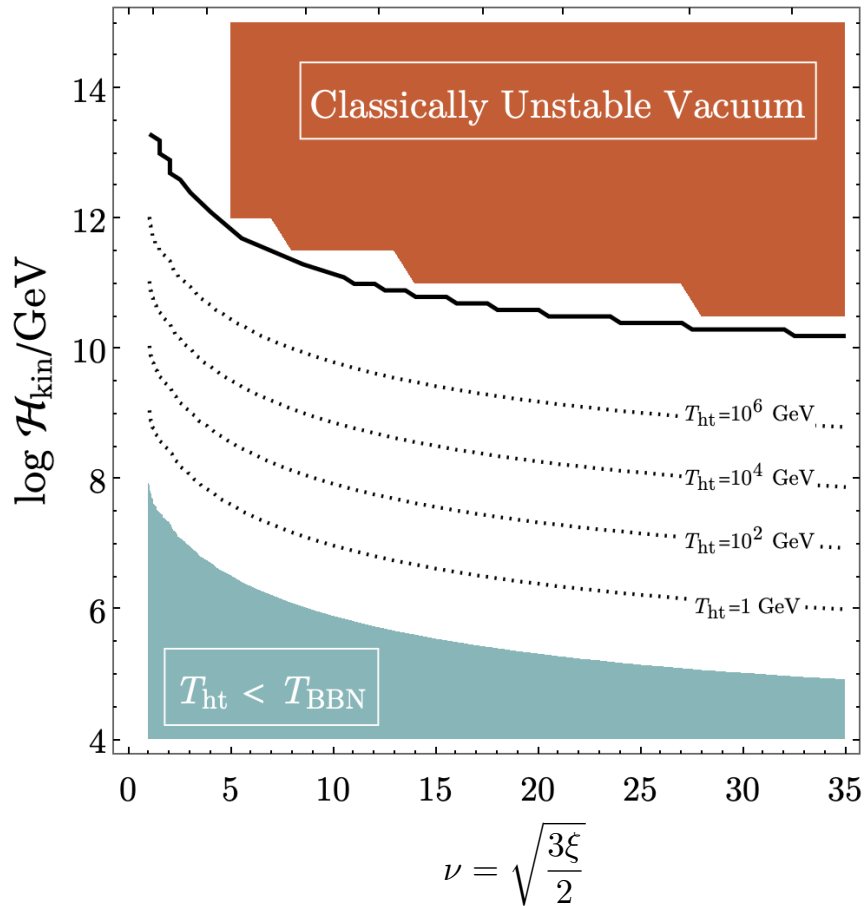
Stability constraints on the top mass



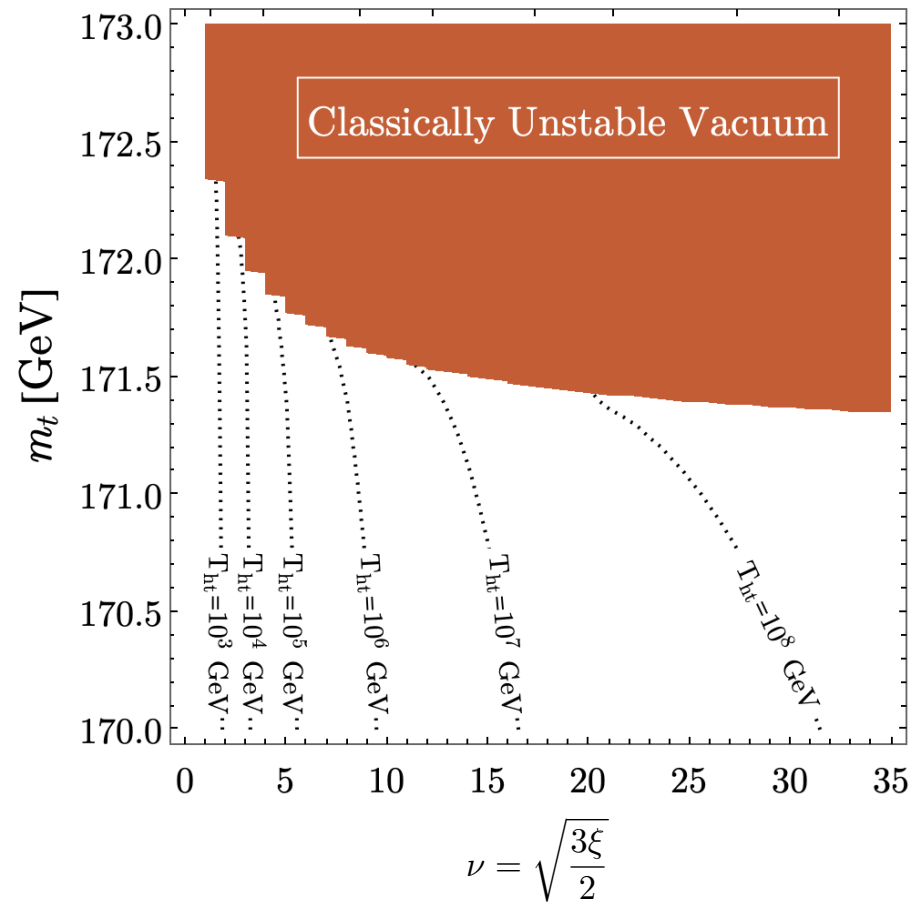
Favours lower masses for the top quark

Heating the Universe before BBN

Explosive tachyonic Higgs production allows to heat the Universe.



Lower bound on the inflationary scale

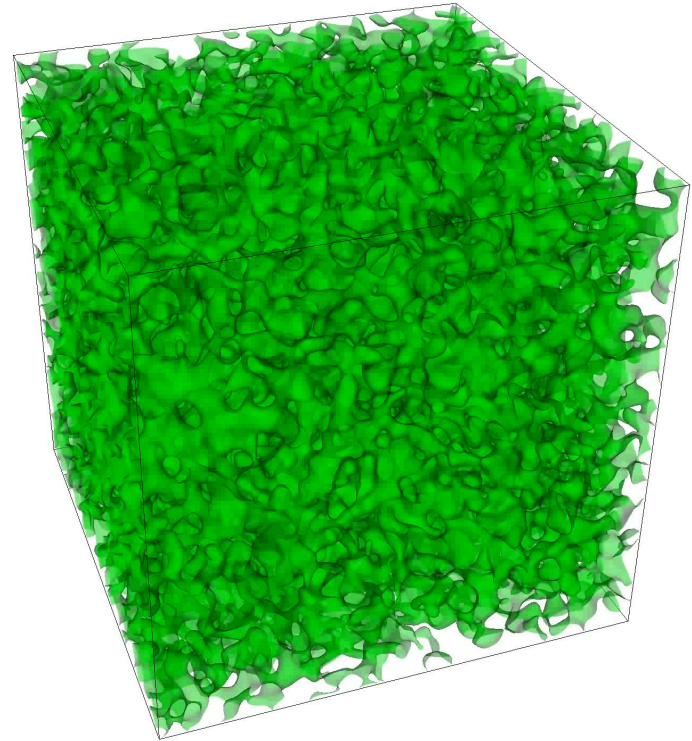
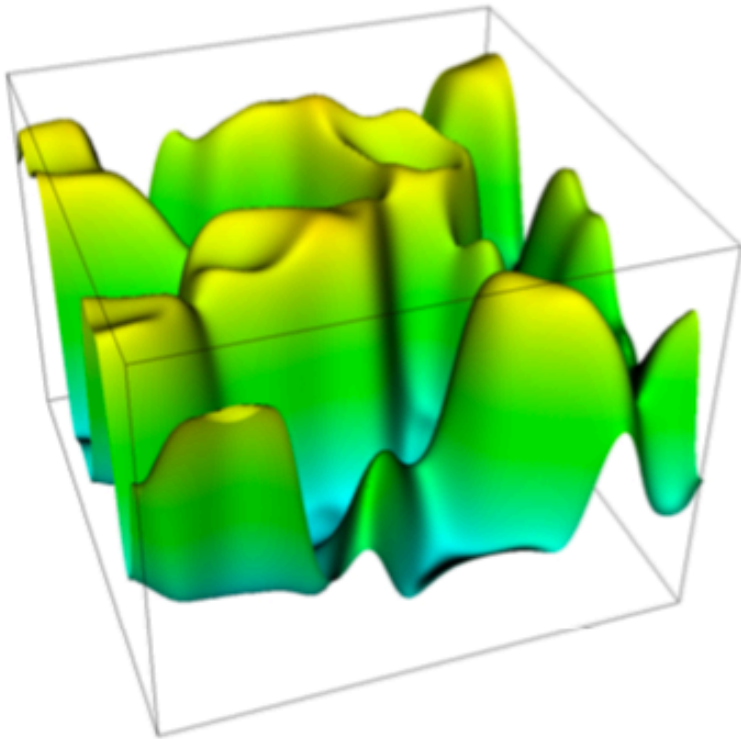


$\mathcal{H}_{\text{kin}} = 10^{10}$ GeV

Gradients are large!

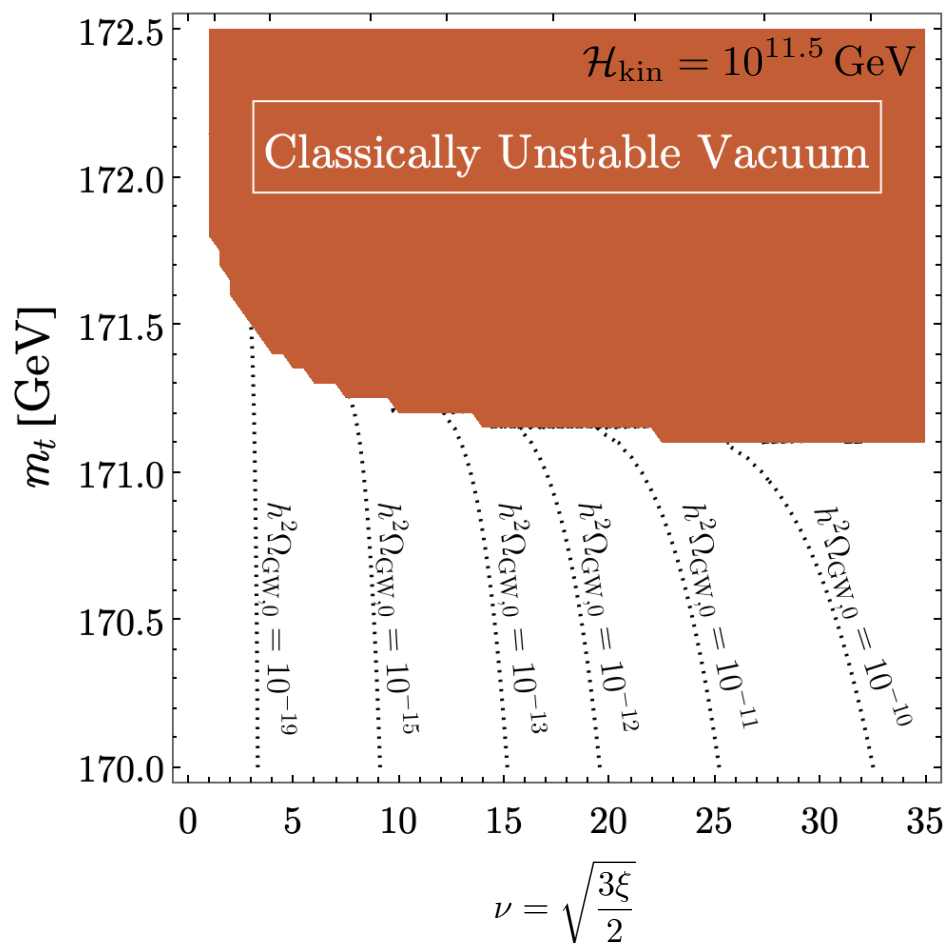
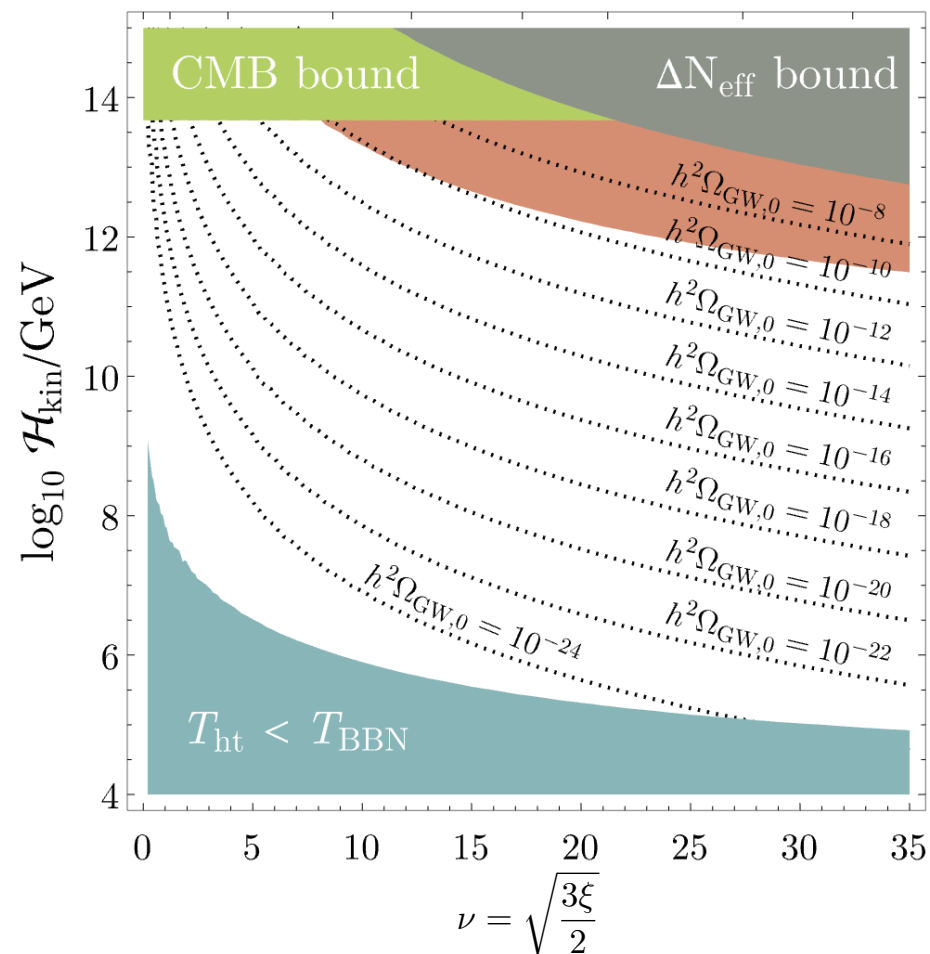
$$(h_{ij}^{TT})'' + 2H(h_{ij}^{TT})' - \frac{\nabla^2 h_{ij}^{TT}}{a^2} \simeq \frac{2a^2}{M_P^2} \Pi_{ij}^{TT}$$

$$\Pi_{ij} = \partial_i \chi \partial_j \chi - \xi \partial_i \partial_j \chi^2$$



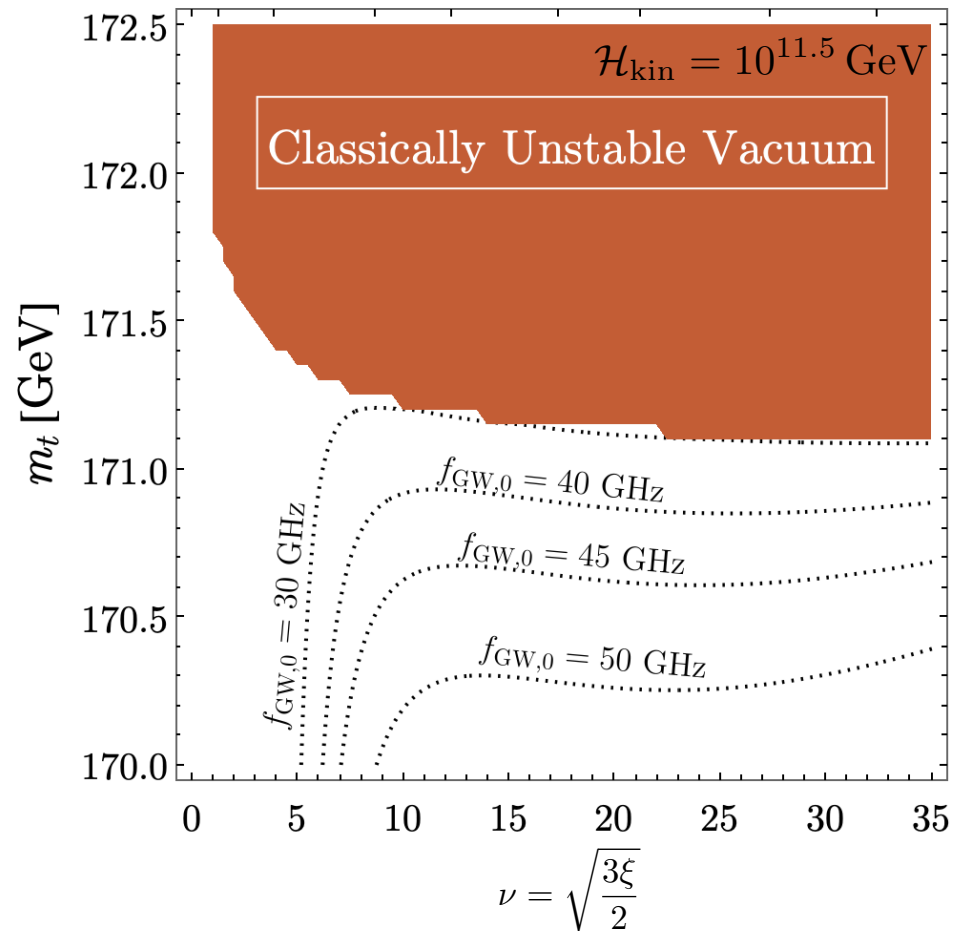
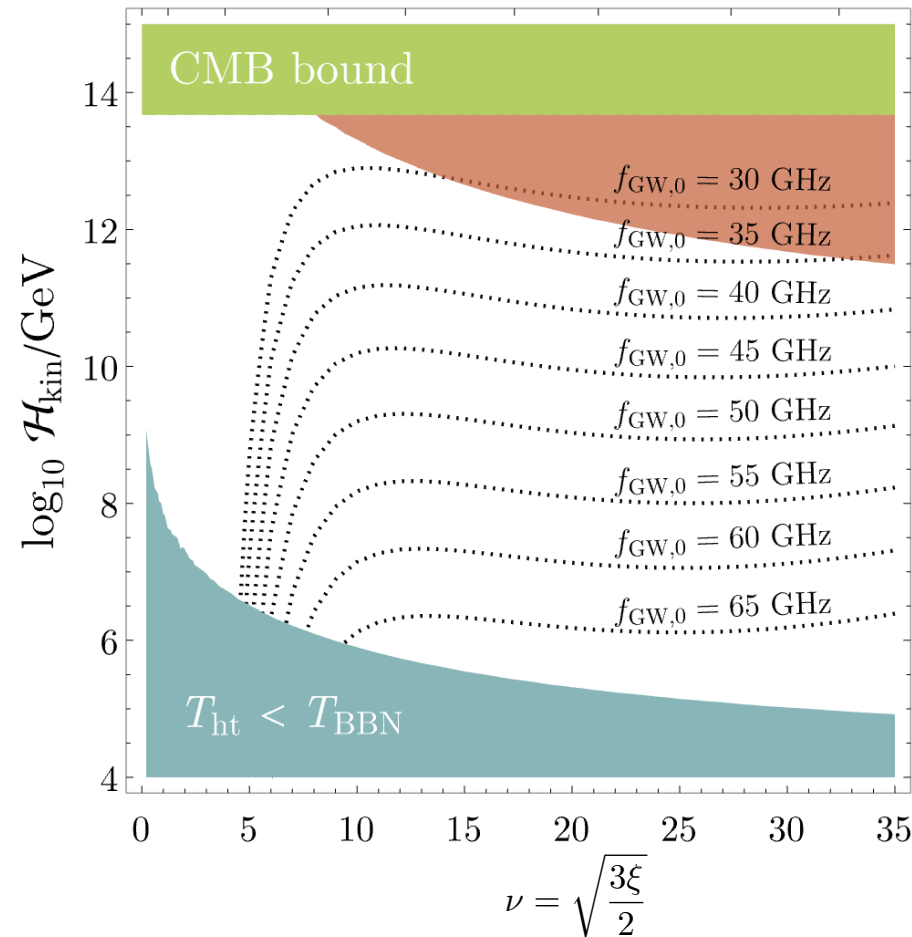
GW energy density

$$\Omega_{\text{GW},0}(\mathcal{H}_{\text{kin}}, \nu, m_t) = 1.67 \times 10^{-5} h^{-2} \left(\frac{100}{g_*^{\text{ht}}} \right)^{1/3} \times \bar{\Omega}_{\text{GW}}$$

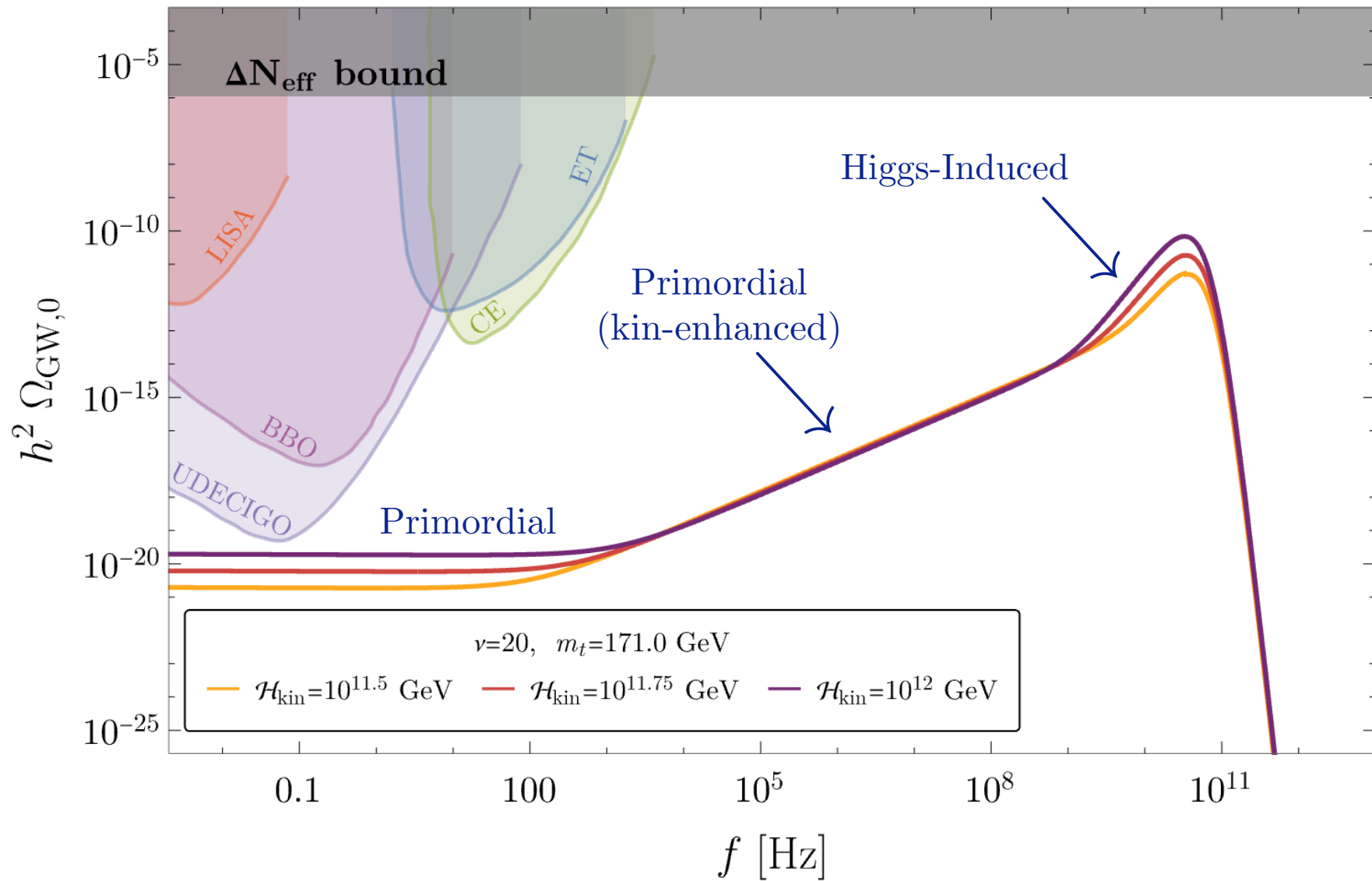


GW frequency

$$f_{\text{GW},0}(\nu, m_t) \simeq 1.3 \times 10^9 \text{ Hz} \frac{\kappa}{2\pi} \left(\frac{\mathcal{H}_{\text{kin}} a_{\text{rad}}}{10^{10} \text{ GeV}} \right)^{1/2} \left(\frac{\Theta_{\text{ht}}^h}{10^{-8}} \right)^{-1/4}$$

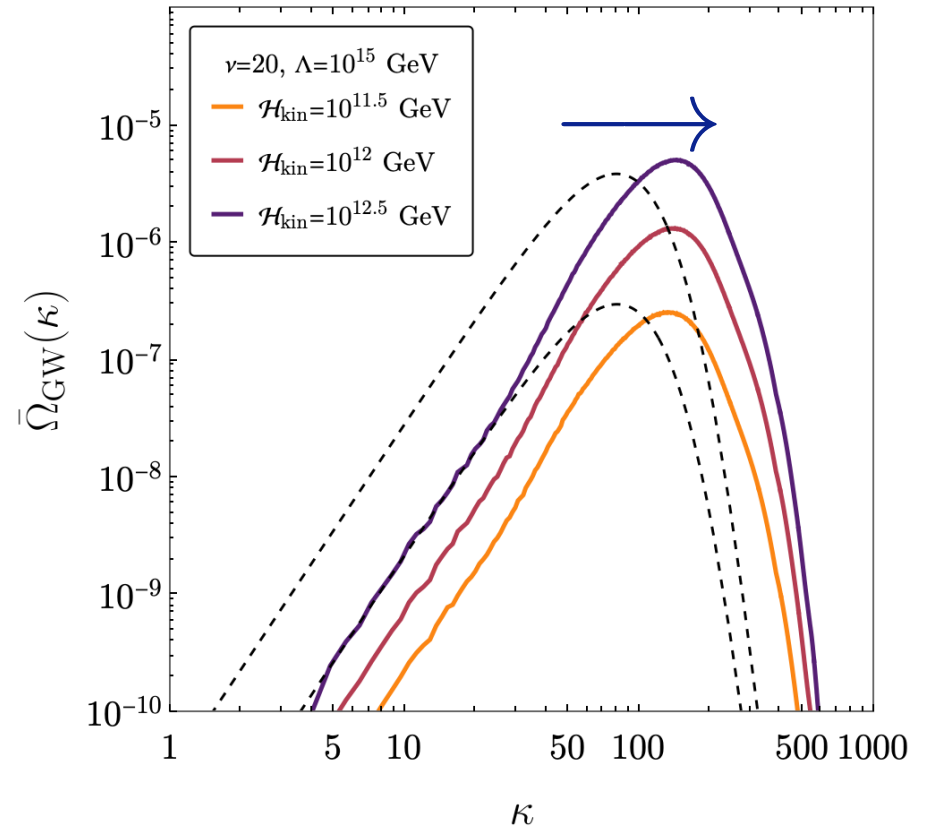
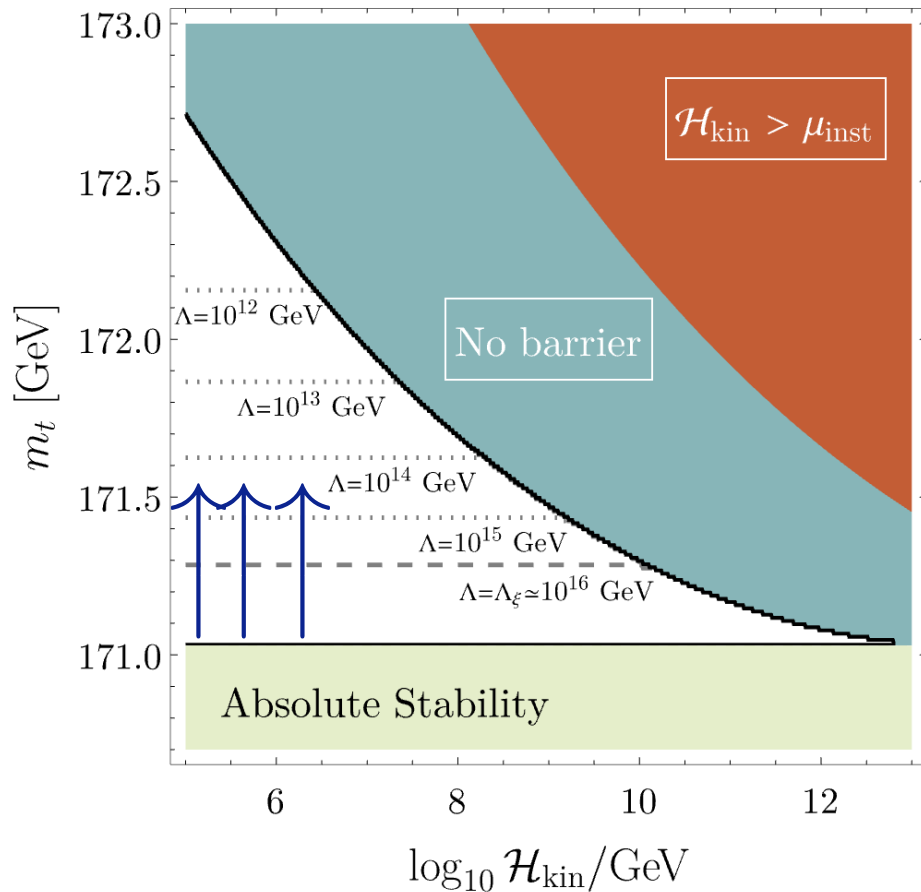


GW spectra



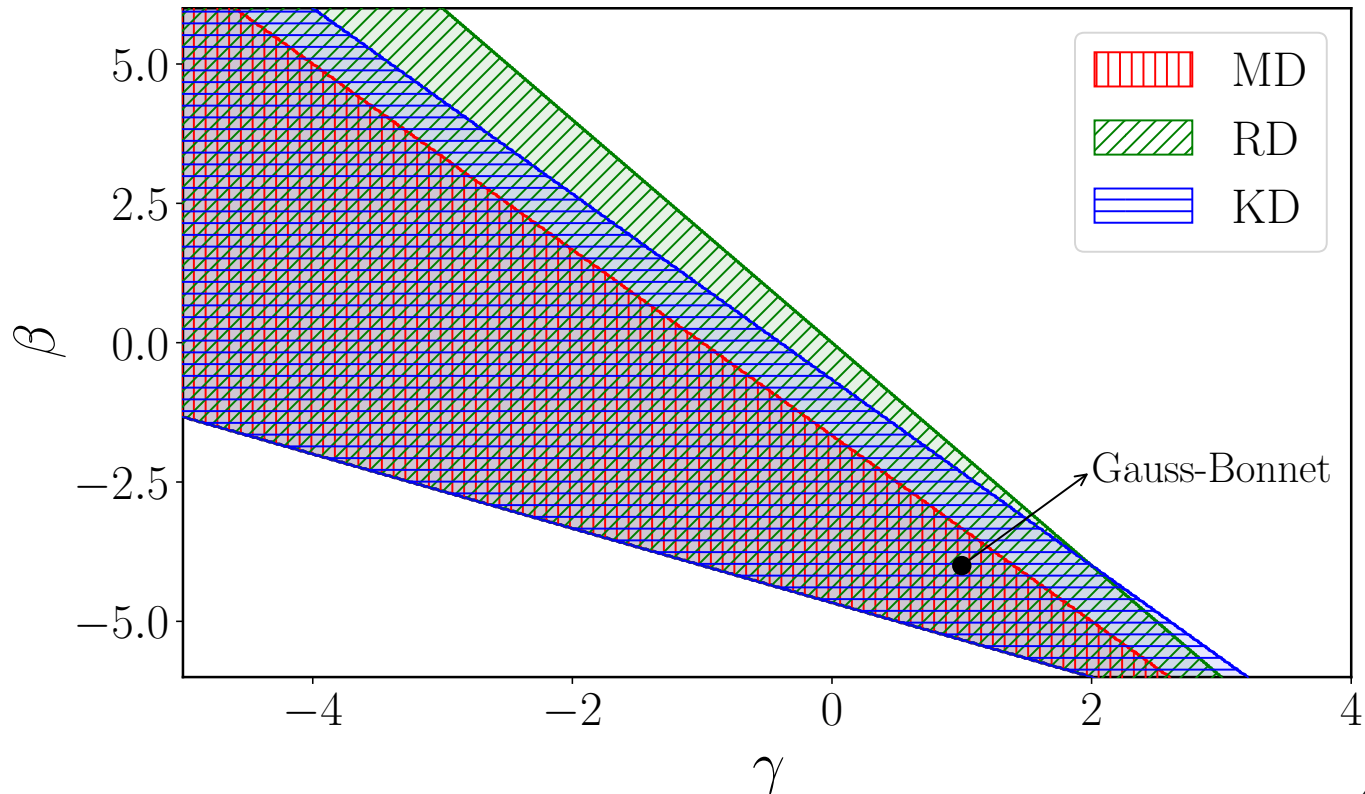
Beyond the Standard Model

$$V_{\text{eff}}(H) = (\xi R + m_h^2)H^\dagger H + \lambda(H^\dagger H)^2 + \frac{1}{\Lambda^2}(H^\dagger H)^3$$



Beyond kination: Gravitational EFT

$$\frac{\Delta\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}\xi R\chi^2 - (\alpha R^2 + \beta R_{\mu\nu}R^{\mu\nu} + \gamma R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}) \frac{\chi^2}{\Lambda^2} + \dots$$



$$M_{\text{eff}}^2 = M^2 + 3\xi(1 - 3w)H^2 + C(\alpha, \beta, \gamma, \omega) \frac{H^4}{\Lambda^2}$$

Higher-order operators may become relevant during radiation domination

Conclusions

- Time-dependent spacetime curvature can trigger phase transitions via Hubble-induced instabilities.
- Specific cosmological transitions (e.g. inflation \rightarrow kination) naturally destabilize the Higgs and other spectator fields.
- This mechanism enables efficient reheating before BBN without requiring direct couplings to new sectors.
- It predicts distinctive high-frequency gravitational-wave signatures.
- The same framework allows highly efficient, purely gravitational production of dark matter. [See Tomás Mendes' talk](#)

