Reheating after Higgs inflation

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Inflationary Reheating Meets Particle Physics Frontier,
KITP Conference, February 4, 2020

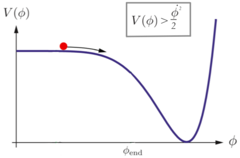
Phys.Rev. D99 (2019) no.8, 083519, arXiv:1810.01304 E. Sfakianakis, JvdV

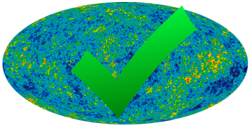
Higgs inflation Bezrukov, Shaposhnikov, 2008

- Could the Higgs be the inflaton?
- Need nonminimal coupling to gravity

$$\mathcal{L} \supset \xi R \Phi^\dagger \Phi$$
$$\frac{\lambda}{\xi^2} \approx 5 \times 10^{-10}$$

$\rightarrow$





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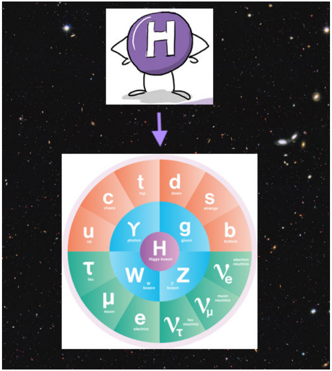
Preheating after Higgs inflation

Garcia-Bellido, Figueroa, Rubio, 2009, Bezrukov, Gorbunov, Shaposhnikov, 2009, DeCross, Kaiser, Prabhu, Prescod-Weinstein, Sfakianakis 2016, Ema, Jinno, Mukaida, Nakayama, 2017

- Couplings of Higgs to SM are known
- Determine for $10 < \xi < 10^4$
  - Dominant decay channels
  - Reheating temperature
- Reheating after Higgs inflation is a multifield phenomenom



Linearized analysis

Split into background + perturbation

$$\boxed{\phi^i = \varphi^i + \delta\phi^i}$$

Need lattice for backreaction and rescattering

Nguyen, JvdV, Sfakianakis, Giblin, Kaiser, 2019

Nguyen, JvdV, Sfakianakis, Giblin, Kaiser, in preparation

Approach

- Couple Higgs $\Phi = \frac{1}{\sqrt{2}}(\varphi + h + i\theta)$ to $U(1)$-gauge field
  - Full $SU(2) \times U(1)$-case is just 3 copies of $U(1)$-case to first order in perturbations
- $$S_J = \int d^4x \sqrt{-\tilde{g}} \Big[f(\Phi, \Phi^\dagger)\tilde{R} - \tilde{g}^{\mu\nu}(\tilde{\nabla}_\mu \Phi)^\dagger \tilde{\nabla}_\nu \Phi - \frac{1}{4}\tilde{g}^{\mu\rho}\tilde{g}^{\nu\sigma}F_{\mu\nu}F_{\rho\sigma} - \tilde{V}(\Phi, \Phi^\dagger) \Big]$$

Multiple scalar fields with nonminimal coupling to gravity

See also talk by Evangelos Sfakianakis

$$S_{\mathrm{Jordan}} = \int d^4x \sqrt{-\tilde{g}} \left[f(\phi^I)\tilde{R} - \frac{1}{2}\delta_{IJ}\tilde{g}^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J - \tilde{V}(\phi^I) \right]$$

Here:

$$f = \frac{M_p^2}{2} + \xi|\Phi|^2$$

Conformal transformation

$$S_{\text{Jordan}} = \int d^4x \sqrt{-\tilde{g}} \left[f(\phi^I)\tilde{R} - \frac{1}{2}\delta_{IJ}\tilde{g}^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J - \tilde{V}(\phi^I) \right]$$

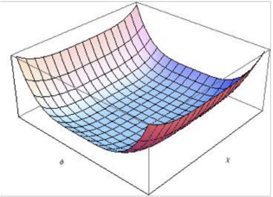
$$g_{\mu\nu}(x) = \frac{2}{M_p^2} f(\phi^I(x))\, \tilde{g}_{\mu\nu}(x)$$

$$\downarrow$$

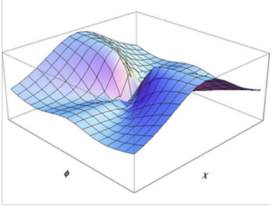
$$S_{\text{Einstein}} = \int d^4x \sqrt{-g} \left[\frac{M_p^2}{2} R - \frac{1}{2}\mathcal{G}_{IJ} g^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J - V(\phi^I) \right]$$

Potential in Einstein and Jordan frame

Jordan frame: $V = \lambda|\Phi|^4$



Jordan



Einstein

During inflation: single-field attractor Kaiser, Sfakianakis, 2014

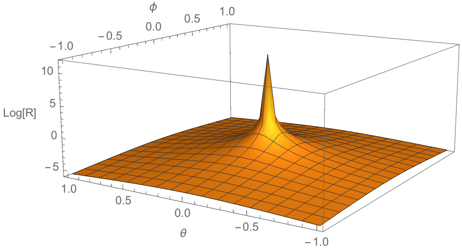
Curved field-space manifold Gong, Tanaka 2012

$$\boxed{\mathcal{G}_{IJ} = \frac{M_p^2}{2f}\left[\delta_{IJ} + \frac{3}{f} f_{,I} f_{,J}\right]}$$

Analogy with GR:

Curved field-space	GR
ϕ^I	x^μ
$\mathcal{G}_{IJ}$	$g_{\mu\nu}$

$\mathcal{G}_{IJ} \propto \frac{1}{f}$



Very efficient production of isocurvature modes!

Equations of motion

Expand fields and metric around background value:

$$\boxed{\phi^I = \varphi^I + \delta\phi^I}$$

$$\boxed{ds^2 = -(1+2\psi)dt^2 + a^2(1-2\psi)\delta_{ij}dx^i dx^j}$$

Generalization of the Mukhanov-Sasaki variable:

$$\boxed{Q^I = \delta\phi^I + \frac{\dot{\varphi}^I}{H}\psi}$$

Equations of motion

Background

$$\boxed{\mathcal{D}_t \dot{\varphi}^I + 3H\dot{\varphi}^I + \mathcal{G}^{IJ} V_{,J} = 0}$$

with

$$\boxed{\mathcal{D}_J A^I = \partial_J A^I + \Gamma^I{}_{JK} A^K}$$

(Linearized) equations of motion

$$\boxed{\mathcal{D}_t^2 Q^h + 3H\mathcal{D}_t Q^h + \left[\frac{k^2}{a^2} + \mathcal{M}^h{}_h\right] Q^h = 0}$$

(Linearized) equations of motion

$$\mathcal{D}_t^2 Q^h + 3H\mathcal{D}_t Q^h + \left[\frac{k^2}{a^2} + \mathcal{M}^h{}_h\right] Q^h = 0$$

$$\mathcal{D}_t^2 Q^\theta + 3H\mathcal{D}_t Q^\theta + \left[\frac{k^2}{a^2} + \mathcal{M}^\theta{}_\theta\right] Q^\theta - e\frac{M_p^2}{2f}\mathcal{G}^{\theta\theta}\left(2B^\mu\partial_\mu\varphi + (D_\mu B^\mu)\varphi + 2fB^\mu\varphi D_\mu\left(\frac{1}{2f}\right)\right) = 0$$

(Linearized) equations of motion

$$\mathcal{D}_t^2 Q^h + 3H\mathcal{D}_t Q^h + \left[\frac{k^2}{a^2} + \mathcal{M}^h{}_h\right] Q^h = 0$$

$$\mathcal{D}_t^2 Q^\theta + 3H\mathcal{D}_t Q^\theta + \left[\frac{k^2}{a^2} + \mathcal{M}^\theta{}_\theta\right] Q^\theta - e\frac{M_p^2}{2f}\mathcal{G}^{\theta\theta}\left(2B^\mu\partial_\mu\varphi + (D_\mu B^\mu)\varphi + 2fB^\mu\varphi D_\mu\left(\frac{1}{2f}\right)\right) = 0$$

$$\mathcal{M}^I{}_J = \mathcal{G}^{IK}(\mathcal{D}_J\mathcal{D}_K V) - \mathcal{R}^I{}_{LMJ}\dot{\varphi}^L\dot{\varphi}^M - \frac{1}{M_p^2 a^3}\mathcal{D}_t\left(\frac{a^3}{H}\dot{\varphi}^I\dot{\varphi}_J\right)$$

(Linearized) equations of motion

$$\mathcal{D}_t^2 Q^h + 3H\mathcal{D}_t Q^h + \left[\frac{k^2}{a^2} + \mathcal{M}^h{}_h\right] Q^h = 0$$

$$\mathcal{D}_t^2 Q^\theta + 3H\mathcal{D}_t Q^\theta + \left[\frac{k^2}{a^2} + \mathcal{M}^\theta{}_\theta\right] Q^\theta - e\frac{M_p^2}{2f}\mathcal{G}^{\theta\theta}\left(2B^\mu\partial_\mu\varphi + (D_\mu B^\mu)\varphi + 2fB^\mu\varphi D_\mu\left(\frac{1}{2f}\right)\right) = 0$$

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$$D_\nu F^{\nu\mu} - \frac{M_p^2 e^2}{2f}\varphi^2 B^\mu + e\frac{M_p^2}{2f}g^{\mu\nu}(\theta\partial_\nu - \varphi\partial_\nu\theta) = 0$$

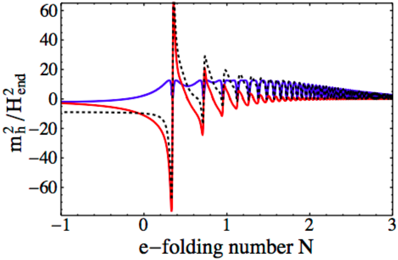
Higgs mode equation

$$\boxed{\partial_\tau^2 v_k + \omega^2(k,\tau) v_k = 0}$$

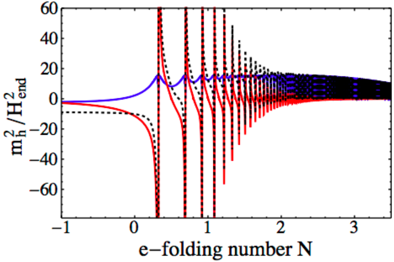
$$
\begin{aligned}
\omega^2 &= k^2 + a^2 m_{\text{eff},h}^2 \\
m_{\text{eff},h}^2 &= \mathcal{G}^{hh}(\mathcal{D}_\varphi \mathcal{D}_\varphi V) - \mathcal{R}^h{}_{hhh}\dot{\varphi}^2 - \frac{1}{M_p^2 a^3}\mathcal{D}_t\left(\frac{a^3}{H}\dot{\varphi}\mathcal{G}_{hh}\right) - \frac{1}{6}R \\
&= m_{1,h}^2 + m_{3,h}^2 + m_{4,h}^2
\end{aligned}
$$

Effective mass *h*-modes

$\xi = 10$

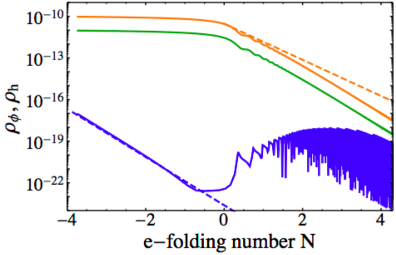


$\xi = 100$

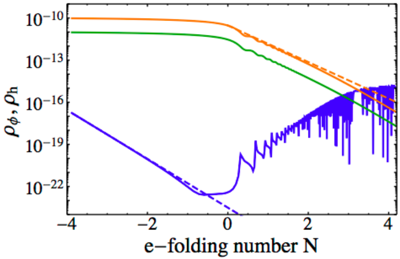


Energy density in Higgs modes

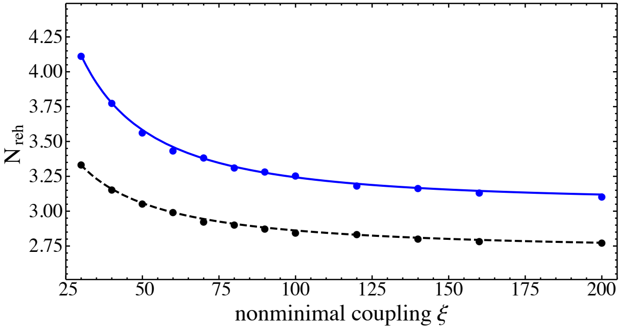
$\xi = 10$



$\xi = 100$



ξ-dependence of $N_{\rm reh}$



Perturbative decay Garcia-Bellido, Figueroa, Rubio, 2009, Bezrukov, Gorbunov, Shaposhnikov, 2009

- Does perturbative decay shut off the resonance?
- $$\boxed{m_f^2 = \frac{y_f^2}{2}\frac{\varphi^2}{2f}}$$
  Only decay into light fermions is kinematically allowed
- $$\boxed{\Gamma = \frac{y_f^2}{8\pi} m_h}$$
  Decay rate is too slow to shut off resonance

Gauge choice

- Coulomb gauge $Q_k^h, Q_k^\theta, B_k^\pm$

$$\boxed{\partial_i B^i = 0}$$

- Unitary gauge $Q_k^h, B_k^L, B_k^\pm$

$$\boxed{Q_k^\theta = 0}$$

- Q_k^θ, B_k^L feel non-trivial field-space metric

Goldstone/gauge mode equation

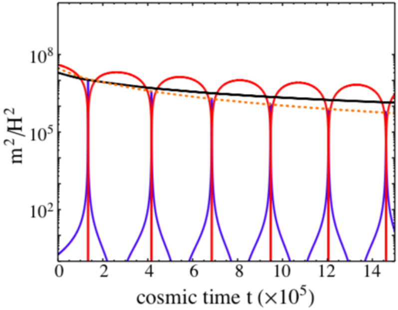
$$\mathcal{M}^I{}_J = \mathcal{G}^{IK}(\mathcal{D}_J\mathcal{D}_K V) - \mathcal{R}^I{}_{LMJ}\dot{\varphi}^L\dot{\varphi}^M - \frac{1}{M_p^2 a^3}\mathcal{D}_t\left(\frac{a^3}{H}\dot{\varphi}^I\dot{\varphi}_J\right)$$

$$\partial_\tau^2 z_k + \omega^2(k,\tau) z_k = 0$$

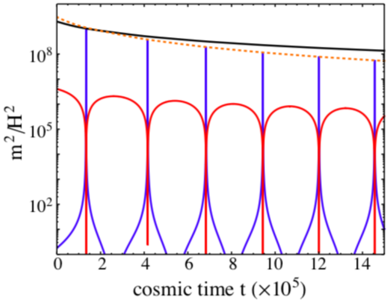
$$\begin{aligned} \omega^2 &= k^2 + a^2 m_{\text{eff},\theta}^2 \\ m_{\text{eff},\theta}^2 &\approx -\mathcal{R}^\theta{}_{hh\theta}\dot{\varphi}^2 + e^2\varphi^2\frac{M_p^2}{2f} \\ &= \quad m_{2,\theta}^2 \quad + m_B^2 \end{aligned}$$

Effective mass θ-modes

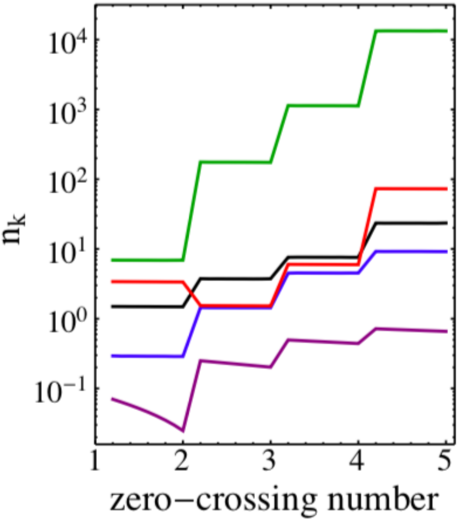
$\xi = 10^3$



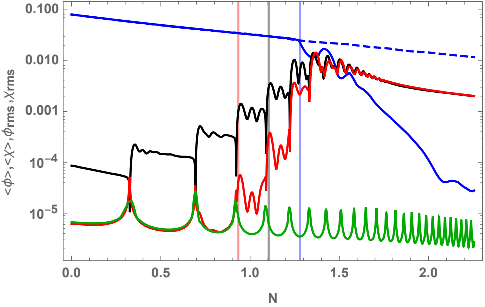
$\xi = 10^4$



Growth of particle number density ($\xi = 10^4$)



Efficient growth of isocurvature mode also observed on the lattice



Nguyen, JvdV, Sfakianakis, Giblin, Kaiser, 2019

Nguyen, JvdV, Sfakianakis, Giblin, Kaiser, in preparation

Perturbative decay

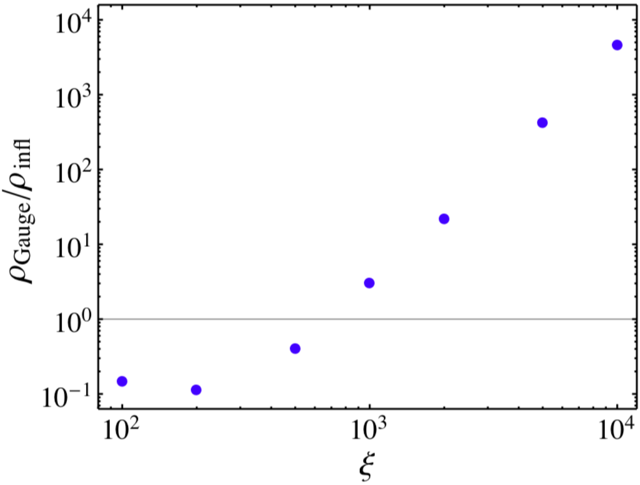
- Does perturbative decay shut off the resonance?
- Gauge bosons are very heavy

$$\Gamma_W = \frac{3g^2}{16\pi} m_W$$
$$\Gamma_Z = \frac{g_2^2}{8\pi^2 \cos^2\theta_W} m_Z \left(\frac{7}{2} - \frac{11}{3}\sin^2\theta_W + \frac{49}{9}\sin^4\theta_W \right)$$

- All particles decay between subsequent inflaton zero-crossings
- Only complete preheating within one oscillation is efficient

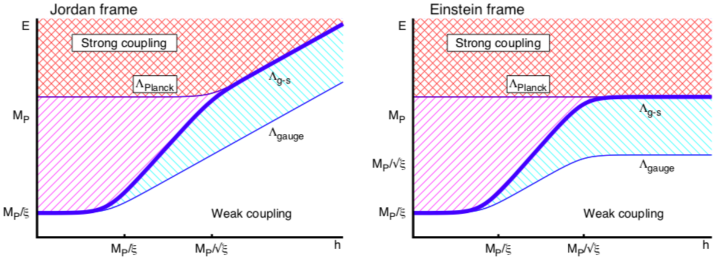
Energy density after first zero-crossing

Apologies to lattice people for this graph



Unitarity cut-off

- Higgs inflation is an effective theory
  - $\Lambda_{\rm UV} = \frac{M_{\rm pl}}{\sqrt{\xi}}$ for large field values
  - $\Lambda_{\rm UV} = \frac{M_{\rm pl}}{\xi}$ for small field values



Bezrukov, 2013

- No unitarity problem *during* inflation Bezrukov, Magnin, Shaposhnikov, Sibiryakov, 2010, Ren, Xianyu, He, 2014, Escriva, Germani, 2016

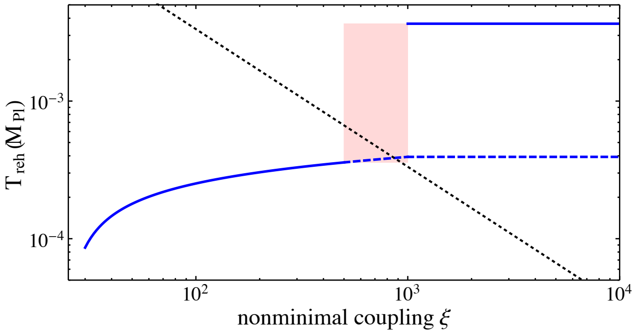
Unitarity during reheating

- Reheating into Higgs modes does not violate unitarity
- k_{max} of the gauge modes is above the unitarity scale

- The peak of the thermal spectrum could lie above the unitarity scale (if thermalization is fast)

Reheating temperature

- Assume fast thermalization
- $\rho_{\text{inf}} = \rho_{\text{pert}} = 3M_p^2 H^2 = \sigma_{\text{SB}}\, T_{\text{reh}}^4$



Summary

- Preheating into Higgs modes due to coupled metric perturbation
- Preheating into Goldstone/gauge-modes efficient for $\xi \gtrsim 10^3$
- Modes above unitarity scale get excited
- Do these results hold in lattice simulations?

Particle decay between oscillations ($\xi = 10^3$ & 10^4)