Some like it hot: Reheating in R^2-healed Higgs inflation

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arXiv 1904.04737: Fedor Bezrukov[a], C.S, Dmitry Gorbunov[b,c] , Anna Tokareva[b]

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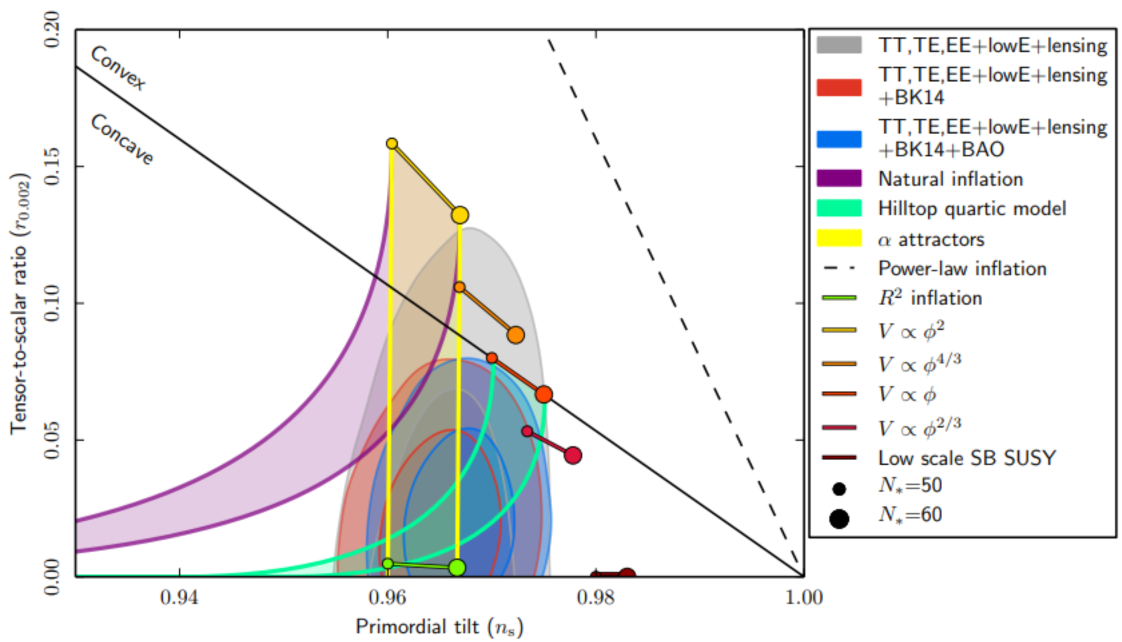
Higgs inflation: why do we want it?

- Scalar field inflation: pick your favourite model
- Model predictions for n_s, r, c.f. observational constraints



PLANCK collaboration, 2018

- Power laws look a bit dubious.
- Bigger problem: **what is this scalar field?!**
- Standard model only has one spin-0 field…

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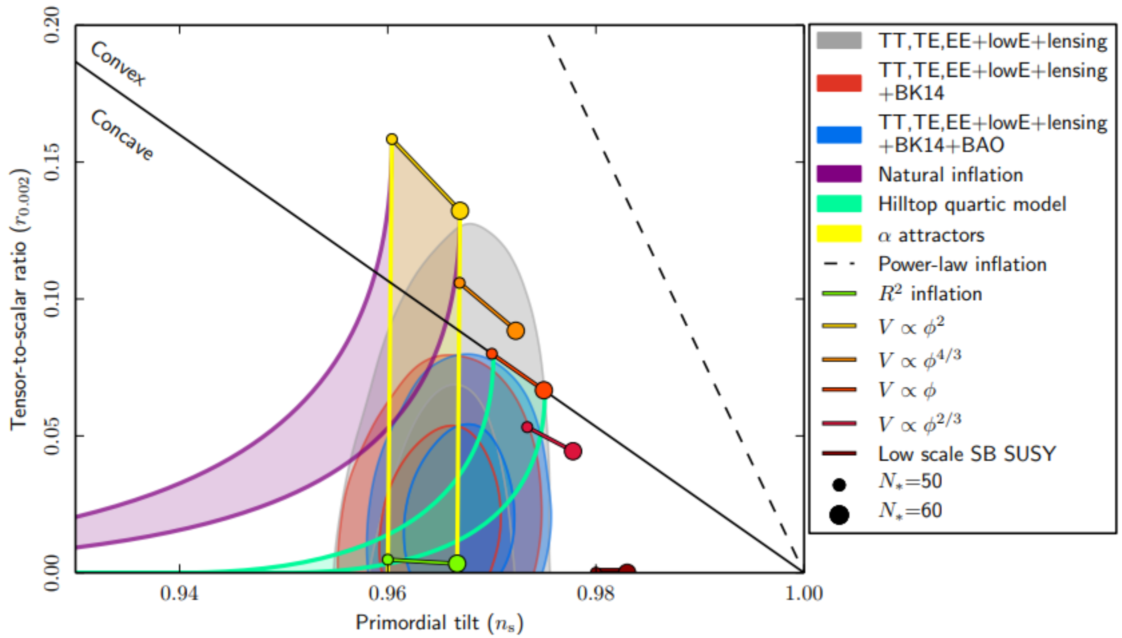

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Higgs inflation: the basic idea

- Dimensionless Higgs-curvature coupling:

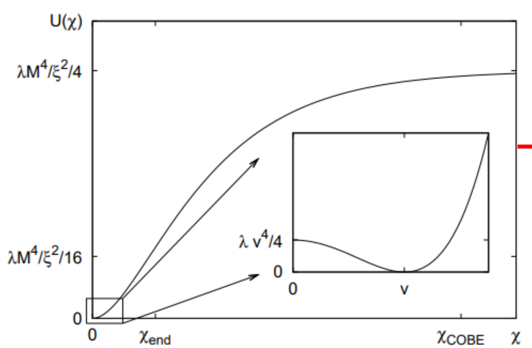
$$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M^2+\xi h^2}{2}R + \frac{\partial_\mu h \partial^\mu h}{2} - \frac{\lambda}{4}\left(h^2-v^2\right)^2\right\}$$

- Weyl transformation into Einstein frame:

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}\ , \quad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

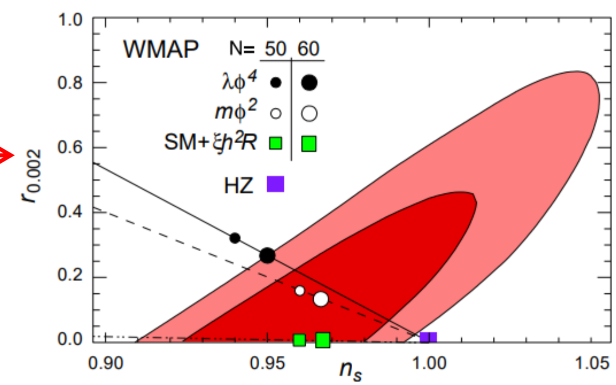
- Nice inflationary Action:

$$S_E = \int d^4x\sqrt{-\hat{g}}\left\{-\frac{M_P^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - U(\chi)\right\}\ , \quad U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$$



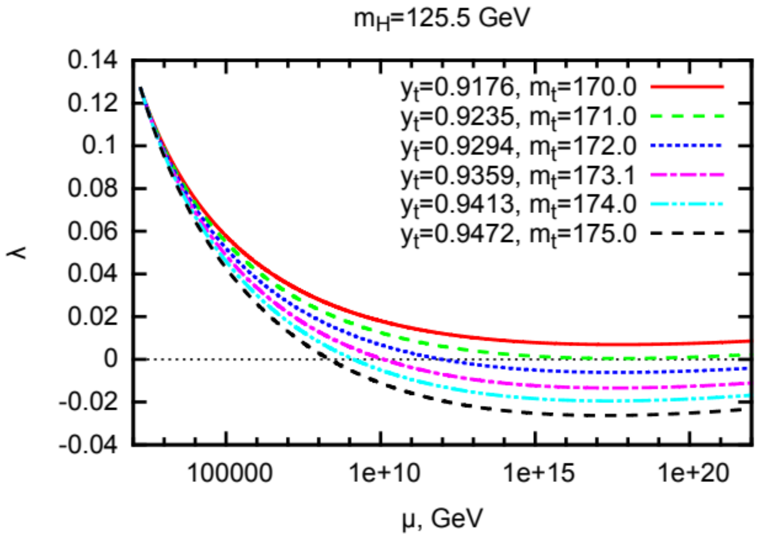
$$n_s = 1 - 6\epsilon + 2\eta \approx 0.97$$

$$r = 16\epsilon \approx 0.0033$$



Higgs inflation: what's the catch?

- Central LHCb measurements of $m_H, m_T, g_{EW}, y_T \rightarrow \lambda_H$ is negative at inflationary scales!



Bezrukov et al: arXiv:1412.3811

- Large dimensionless coupling $\xi \sim 10^4 \rightarrow$ lose perturbativity around scale $\sim M_P/\xi$
- (so no connection between standard model couplings and UV ones)

So fix it already!

- If we're adding dimension-4 operators, why not add R^2 ?

$$S_0 = \int d^4x\sqrt{-g}\left(-\frac{M_P^2+\xi h^2}{2}R + \frac{\beta}{4}R^2 + \frac{1}{2}g^{\mu\nu}\partial_\mu h\partial_\nu h - \frac{\lambda}{4}h^4\right)$$

- Lagrange multiplier and auxiliary scalar, Weyl transformation
- → Einstein frame Action:

$$S = \int d^4x\sqrt{-g}\left[-\frac{M_P^2}{2}R + \frac{1}{2}e^{-\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}g^{\mu\nu}\partial_\mu h\partial_\nu h + \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{4}e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_P}}\left(\lambda h^4 + \boxed{\frac{M_P^4}{\beta}}\left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} - 1 - \boxed{\xi\frac{h^2}{M_P^2}}\right)^2\right)\right].$$

- ϕ: new "scalaron" degree of freedom.

- Extra quartic coupling: perturbative if $\boxed{\beta \geq \frac{\xi^2}{4\pi}}$

- Extra contribution to RG beta-function → λ positive at inflationary scales

Higgs + R^2: inflationary dynamics

- Potential:

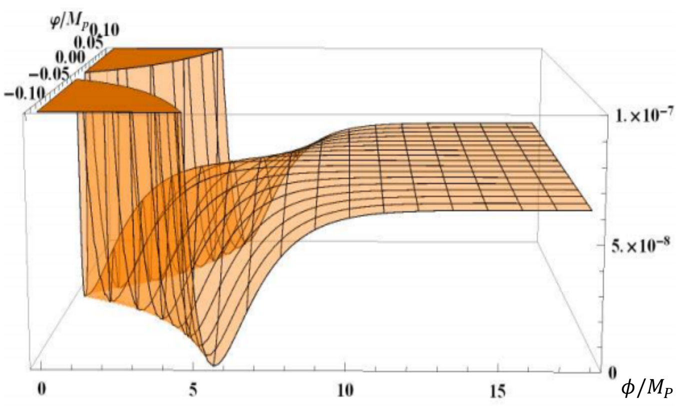
$$V(h,\phi) = -\frac{1}{4} e^{-2\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} \left(\lambda h^4 + \frac{M_P^4}{\beta} \left(e^{\sqrt{\frac{2}{3}}\frac{\Phi}{M_P}} - 1 - \xi \frac{h^2}{M_P^2} \right)^2 \right)$$

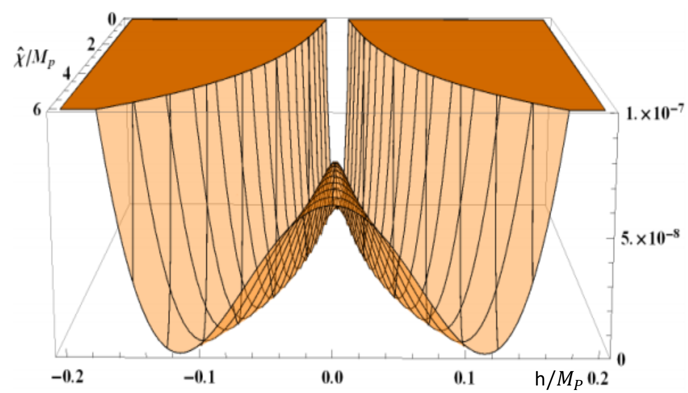
$\lambda \sim 10^{-2} \rightarrow 10^{-3}$

- Along $h = h_{min}(\phi)$,

$$V_{inf}(\phi) = \frac{M_P^4}{4\left(\xi^2 + \lambda\beta\right)} \left(e^{\sqrt{\frac{2}{3}}\frac{\phi}{M_P}} - 1 \right)^2$$

- Exactly the same form as Higgs inflation! → $\beta + \frac{\xi^2}{\lambda} \approx 2 \times 10^9$





Gundhi, Steinwachs: arXiv:1810.10546

Inflationary dynamics: end of story?

- Homogeneous fields decay nonperturbatively: “preheating”
- Pure Higgs and pure R^2 preheat very differently!
- Mixed case: interpolation between limits, or something different?

The setup: classical dynamics

- Change of variables, $(\phi, h) \to (\Phi, H)$: $h \equiv \sqrt{6} M_P \, \mathrm{e}^{\frac{\Phi}{\sqrt{6} M_P}} \tanh \frac{H}{\sqrt{6} M_P}$, $\quad \mathrm{e}^{\frac{\phi}{\sqrt{6} M_P}} \equiv \frac{\mathrm{e}^{\frac{\Phi}{\sqrt{6} M_P}}}{\cosh \frac{H}{\sqrt{6} M_P}}$,
- "Small" fields: $|\Phi_0| \lesssim 0.3 M_P, \qquad |H_0| \lesssim 0.03 M_P$
- Potential in this limit:

$$V(H, \Phi) = \boxed{\frac{1}{4}\left(\lambda + \frac{\xi^2}{\beta}\right) H^4 + \frac{M_P^2}{6\beta}\Phi^2 - \frac{\xi M_P}{\sqrt{6}\beta}\Phi H^2} + \frac{7}{108\beta}\Phi^4 + \frac{\xi}{6\beta}\Phi^2 H^2 - \frac{M_P}{3\sqrt{6}\beta}\Phi^3.$$

Leading

- : Hubble $\ll \omega_{\Phi_0}^{-1}$

$$H_{min} = 0$$

$$\omega_{H_0}^2\big|_{\Phi_0<0} = -\frac{\sqrt{2}\xi}{\sqrt{3}\beta} M_P \Phi_0.$$

$$\omega_{\Phi_0}^2\big|_{\Phi_0<0} > M_P^2/3\beta.$$

$$H_{\rm min}^2 \equiv \frac{2\xi}{\sqrt{6}(\xi^2 + \lambda\beta)} M_P \Phi_0 \simeq \sqrt{\frac{2}{3}} \frac{M_P \Phi_0}{\xi}.$$

$$\omega_{\Phi_0}^2\big|_{\Phi_0>0} = \frac{M_P^2}{3} \frac{\lambda}{\xi^2 + \lambda\beta} \simeq \frac{\lambda M_P^2}{3\xi^2}.$$

$$\omega_{H_0}^2\big|_{\Phi_0>0} = 2\sqrt{\frac{2}{3}} \frac{\xi M_P}{\beta} \Phi_0.$$

Classical dynamics: a special situation

$$V(H,\Phi) = \frac{1}{4}\left(\lambda + \frac{\xi^2}{\beta}\right)H^4 + \frac{M_P^2}{6\beta}\Phi^2 - \frac{\xi M_P}{\sqrt{6}\beta}\Phi H^2 + \frac{7}{108\beta}\Phi^4 + \frac{\xi}{6\beta}\Phi^2 H^2 - \frac{M_P}{3\sqrt{6}\beta}\Phi^3.$$

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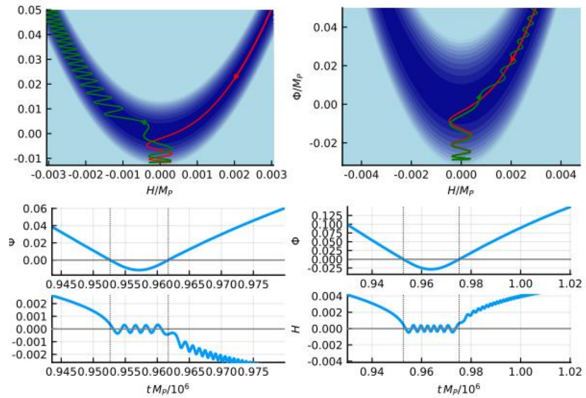
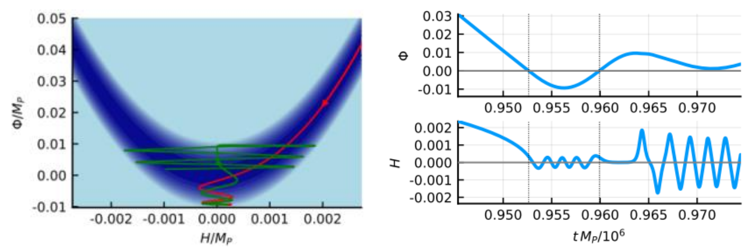


$$H^2_{\rm min} \equiv \frac{2\xi}{\sqrt{6}(\xi^2+\lambda\beta)}M_P\Phi_0 \simeq \sqrt{\frac{2}{3}}\frac{M_P\Phi_0}{\xi}$$

$$\omega^2_{\Phi_0}\big|_{\Phi_0>0} = \frac{M_P^2}{3}\frac{\lambda}{\xi^2+\lambda\beta} \simeq \frac{\lambda M_P^2}{3\xi^2}$$

$$\omega^2_{H_0}\big|_{\Phi_0>0} = 2\sqrt{\frac{2}{3}}\frac{\xi M_P}{\beta}\Phi_0.$$

- Bifurcation point: H_0 gets stuck on hilltop at $H_0 = 0$
- Once H_0 "tips", very energetic!



Inhomogeneous equations of motion: longitudinal W bosons

- Toy $U(1)$ model: $H(x) \equiv \frac{1}{\sqrt{2}} h(x) e^{i\theta(x)}$

- After conformal transformation:

$\alpha \equiv \sqrt{2/3}$

$$\sqrt{-g_{\mathrm{E}}}\mathcal{L}_{\mathrm{E}} \supset -\frac{1}{2}\sqrt{-g_{\mathrm{E}}}e^{-\alpha\varphi}h^2 g_{\mathrm{E}}^{\mu\nu}\partial_\mu\theta\partial_\nu\theta = \frac{1}{2}\dot{\theta}_c^2 - \frac{1}{2a^2}(\nabla\theta_c)^2 + \frac{1}{2}\frac{\ddot{F}}{F}\theta_c^2 + \cdots$$

- → Mass of phase direction

$$m_{\theta_c}^2 = -\frac{\ddot{F}(t)}{F(t)} = -\frac{\alpha}{2}\frac{\partial U}{\partial\varphi} + \frac{e^{\alpha\varphi}}{h}\frac{\partial U}{\partial h} - \frac{3}{4}\frac{U}{M_{\mathrm{pl}}^2} + \frac{5}{24}\frac{1}{M_{\mathrm{pl}}^2}\left(\dot{\varphi}^2 + e^{-\alpha\varphi}\dot{h}^2\right)$$

- Full $SU(2)_L \times U(1)_Y$, frequency squared of angular Higgs modes (conformal mode k):

$$\omega_W^2 = \frac{k^2}{a^2} + \frac{g^2}{4}H_0^2 + \frac{\xi}{3\beta}\Phi_0^2 + \left(\lambda + \frac{\xi^2}{\beta}\right)H_0^2 - \frac{\xi\sqrt{2}}{\beta\sqrt{3}}M_P\Phi_0$$

Inhomogeneous equations of motion: perturbations of Φ, H

- Perturbations on homogeneous background:

$$\Phi(t,\mathbf{x}) = \Phi_0(t) + \tilde{\Phi}(t,\mathbf{x})$$

$$H(t,\mathbf{x}) = H_0(t) + \tilde{H}(t,\mathbf{x})$$

- $\widetilde{\Phi} \ll \Phi_0$, $\widetilde{H} \ll H_0$, Euler-Lagrange equations can be linearized.
- …Mode k:

$$\ddot{H}_k + 3\mathcal{H}\dot{H}_k + \frac{k^2}{a^2}H_k + V_{H_0H_0}H_k + V_{\Phi_0H_0}\Phi_k = 0$$

$$\ddot{\Phi}_k + 3\mathcal{H}\dot{\Phi}_k + \frac{k^2}{a^2}\Phi_k + V_{\Phi_0\Phi_0}\Phi_k + V_{\Phi_0H_0}H_k = 0.$$

- Mass eigenstates → heavy (Higgs) mass

$$m^2_{H,L} \approx V_{H_0H_0} \approx 3\left(\lambda + \frac{\xi^2}{\beta}\right)H_0^2 - \frac{\sqrt{2}\xi}{\sqrt{3}\beta}M_P\Phi_0$$

- (Light mass turns out to be unimportant).

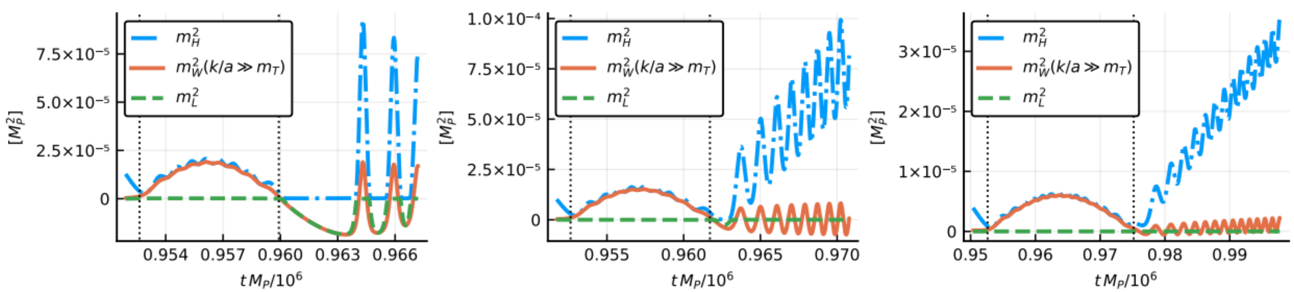
Enhancement of inhomogeneous modes

$$\omega_W^2 = \frac{k^2}{a^2} + \frac{g^2}{4}H_0^2 + \frac{\xi}{3\beta}\Phi_0^2 + \left(\lambda + \frac{\xi^2}{\beta}\right)H_0^2 - \frac{\xi\sqrt{2}}{\beta\sqrt{3}}M_P\Phi_0$$

$$m_{H,L}^2 \approx V_{H_0H_0} \approx 3\left(\lambda + \frac{\xi^2}{\beta}\right)H_0^2 - \frac{\sqrt{2}\xi}{\sqrt{3}\beta}M_P\Phi_0$$

- Always positive: adiabatic frequencies for most of Φ_0 oscillation.
- $\Phi_0 < 0$: always +ve
- $\Phi_0 > 0$: oscillatory about zero!

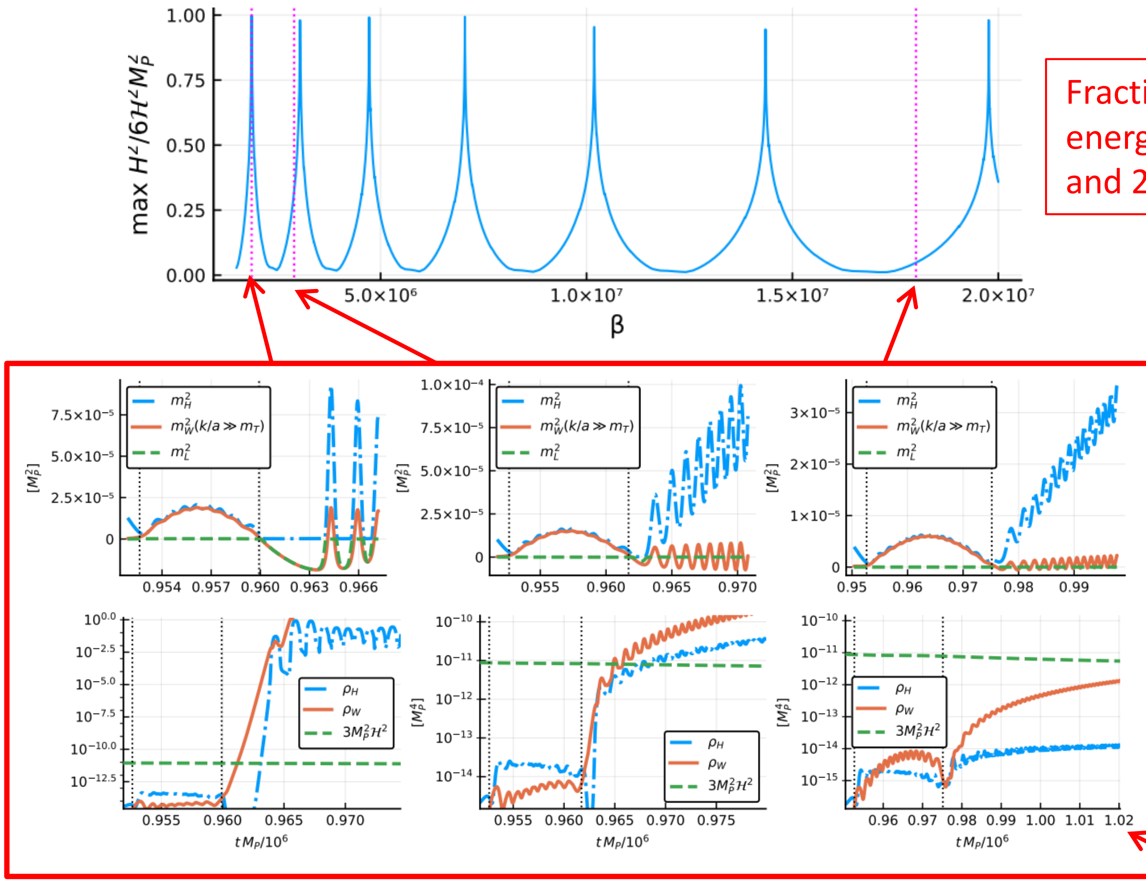
- For small scalaron (near zero-crossing), red stuff wins!
- Tachyonic masses → exponential enhancement of modes
- More energy in H_0 → deeper dip, stronger enhancement.



Further away from bifurcation →

Inhomogeneous modes: particle production

- Quantify growth of inhomogeneities: method of Bogliubov coefficients.
- **Results**



Fraction of background energy in H_0 , between 1st and 2nd scalaron crossings

Incomplete draining of background: "roll again"!

SUMMARY

- In R^2-healed Higgs inflation, special dynamics trigger instant preheating.
- In the Higgs-like limit, this situation is *general* after a few scalaron oscillations
- $\rightarrow T_{reh} \sim 10^{15}$ GeV
- In R^2-like limit, preheating can be slower.
- Solve full self-consistent Euler-Lagrange equations (Hartree, rescattering)

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