Fate of the spectator Higgs during and after inflation

Kari Enqvist

Helsinki University

and

Helsinki Institute of Physics

inflation

$$H_* \approx const.$$

dynamics unknown (slow rolling scalar(s)?)

light scalar spectators (might) exist

$$m << H_*$$

$$\rho_\sigma << \rho_{\inf}$$

example: the higgs

contents:

spectator Higgs dynamics

1. during

2. after inflation

3. when coupled
to inflaton

DURING INFLATION

(near) massless scalars in an expanding background

⇨ stochastic treatment (cf. Starobinsky)

Langevin (simplified):

decompose field into UV and IR parts:

$$\Phi_{IR} \propto \int dk W(k,t) \phi_k(t)$$

$$W(k,t) = \theta(k - xaH)$$

$$\dot{\Phi}_{IR} = -\frac{\partial}{3H\partial\Phi} V(\Phi_{IR}) + s(x,\eta)$$

k<<aH

stochastic term, white noise correlators

$$\langle SS \rangle (dN) = (1 + x^3) \frac{H^2 dN}{4\pi^2}, \quad k = xa(N)H$$

N = # efoldings

inflationary fluctuations

variance of massless field spreads out

$$\langle \phi^2 \rangle = \frac{1}{4\pi^2} H^2 N$$

N = # of efolds

evolution of pdf: Langevin → Fokker-Planck

$$\frac{\partial P}{\partial t} = \frac{1}{3H} \frac{\partial}{\partial \phi} \left[V'(\phi) P \right] + \frac{H^3}{8\pi^2} \frac{\partial^2}{\partial \phi^2} P$$

equilibrium pdf:

$$\boxed{P \propto \exp(-8\pi^2 V / 3H^4)}$$

not in slow roll?

Moss, Rigopoulos

equilibrium pdf:

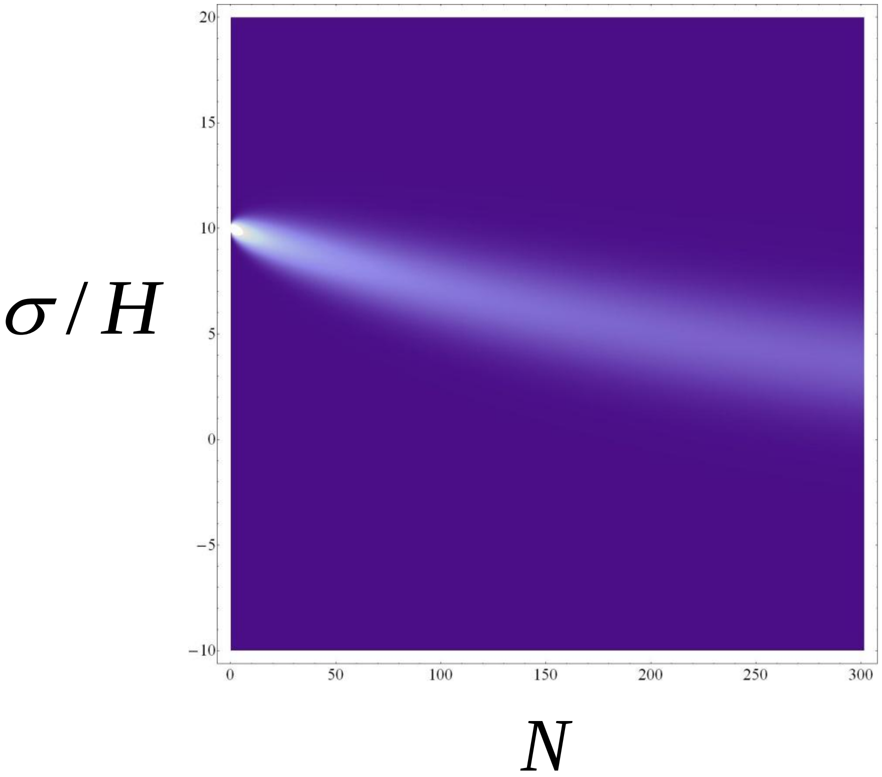
$$P \propto \exp\left[-8\pi^2\left(\tfrac{1}{2}v^2+V\right)/3H^4\right]$$

(Gaussian window)

$$v=\dot{\phi}$$

v equilibrates at the time scale $\Delta t = H^{-1}$

EQUILIBRATION TIME



example

$$V = \tfrac{1}{2} m^2 \sigma^2$$

$$m = 0.01H$$

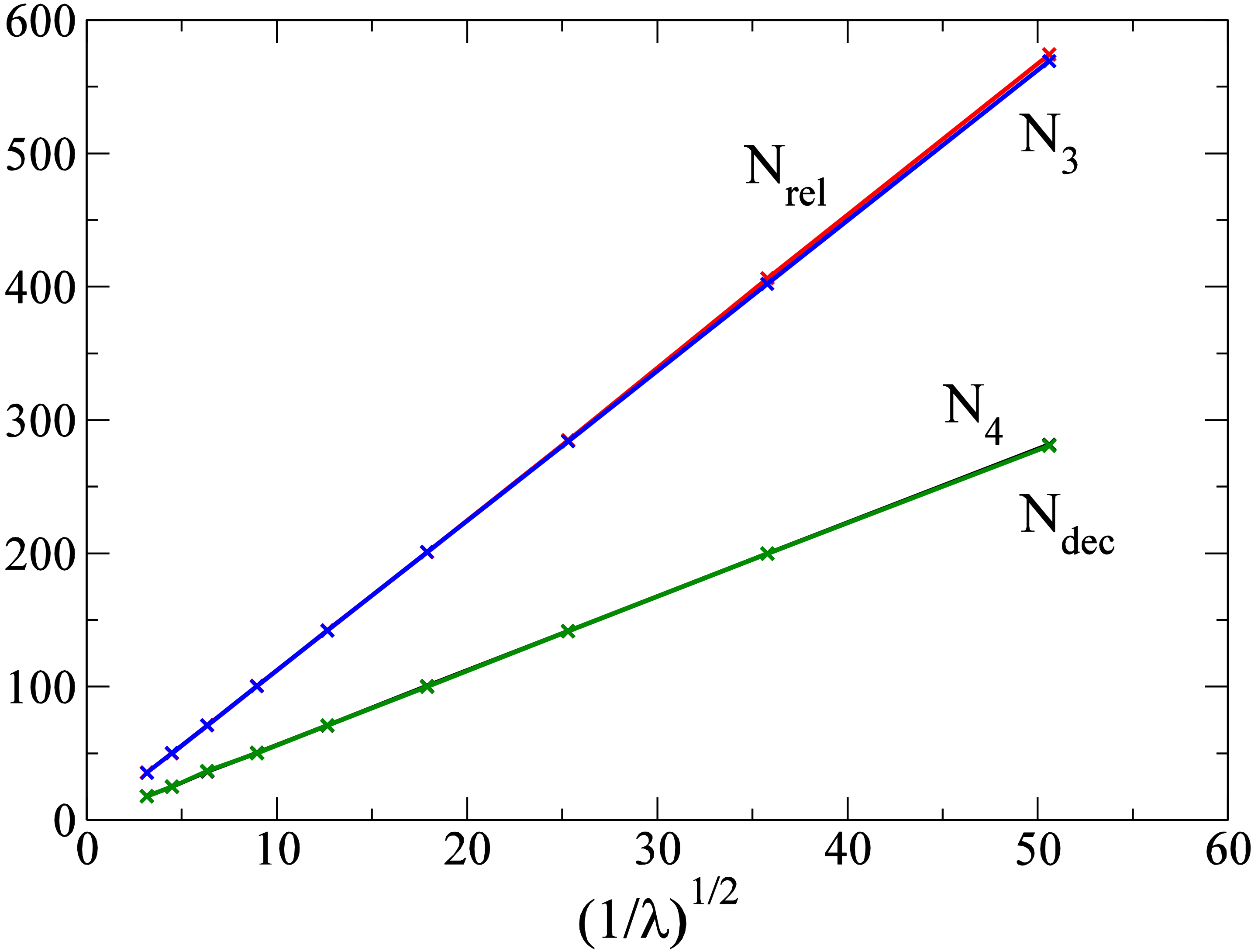
KE, Lerner, Taanila, Tranberg

relaxation time $$N_{rel} = \frac{3H_*^2}{m^2}$$

decoherence time $$N_{dec} = \frac{3H_*^2}{2m^2}$$

moving

spreading



quartic potential $V = \frac{1}{4}\lambda\phi^4$

relaxation time $$N_{rel} \approx \frac{11.3}{\sqrt{\lambda}}$$

decoherence time $$N_{dec} \approx \frac{5.65}{\sqrt{\lambda}}$$

Example: the higgs $V \approx \frac{1}{4}\lambda h^4$

RGE → $\lambda \approx 0.01$ at inflationary scales (?)

⇨ decoherence at ~ 60 efolds ⇨ mean field from equilibrium dist

⇨ $$h_* \approx 0.36\lambda^{-1/4} H_* \approx 1.1 H_*$$

⇨ effective higgs mass $$m_{h_*}^2 \approx V''(h_*) = 0.40\lambda^{1/2} H_*^2 = 0.04 H_*^2$$

the Higgs

at equilibrium after inflation:

$$h_* \approx 0.36\lambda^{-1/4} H_* \approx 1.1 H_*$$

”typical value”

how does the condensate decay?

1. **inflaton decays first → thermal background**
   (assuming thermalization)

more complicated

2. **Higgs decays first (in matter dominated universe)**

KE, Meriniemi, Nurmi

after inflation

MATTER DOMINATION

Higgs starts to move ... and becomes effectively massive at

$$\frac{H_{\rm osc}}{H_*} \sim \frac{1}{4}\lambda_*^{3/4}$$

⇒ oscillations $t_{\rm osc} \lesssim \mathcal{O}(10^2)H_*^{-1}$

decay rates depend on the value of the Higgs background field

perturbative decays

to gauge bosons: kinematically blocked until

$$t \sim \lambda(H_*)^{-3/8} \left(\frac{H_*}{10^2 \mathrm{GeV}} \right)^{3/2} H_*^{-1}$$

not efficient unless $H_* \ll 10^5$ GeV.

to fermions: top channel kinematically blocked, others ok

$$\Gamma(h \to bb) = \frac{3\sqrt{3\lambda} y_b^2 h_{\rm osc}}{16\pi} \left(1 - \frac{2y_b^2}{3\lambda} \right)^{3/2} \sim 10^{-6} \lambda_*^{3/4} H_*$$

takes >> 10^6 Hubble times

not efficient

non-perturbative decays

KE, Nurmi, Rusak

resonant production of gauge bosons

W’s in the unitary gauge: (abelian approx.)

$$\ddot{\mathcal{W}}^{\pm}_{\mu}(z,k) + \omega_k^2 \mathcal{W}^{\pm}_{\mu}(z,k) = 0\,, \qquad \omega_k^2 = \frac{k^2}{a^2 \lambda h_{\rm osc}^2} + q_W \frac{h(z)^2}{h_{\rm osc}^2} + \Delta\,. \qquad q_W = \frac{m_W^2(t)}{\lambda h^2(t)} = \frac{g^2}{4\lambda}$$

= 0 for matter domination

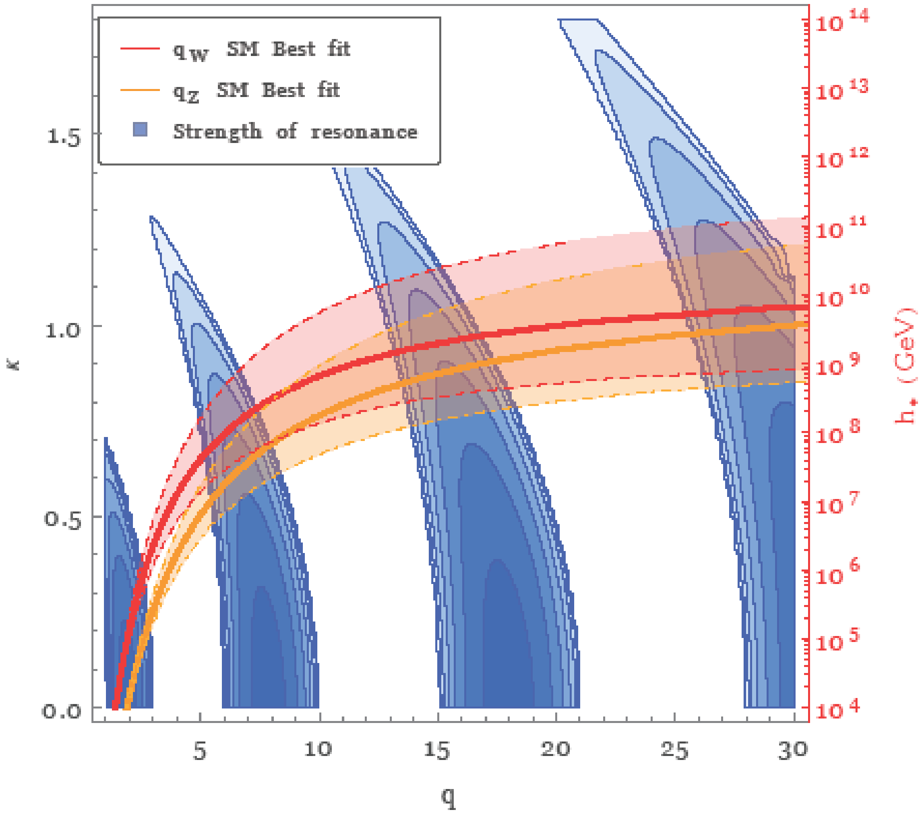
Higgs eq of motion

$$\frac{\ddot{h}}{h_{\rm osc}} + 3\frac{H}{\sqrt{\lambda} h_{\rm osc}}\frac{\dot{h}}{h_{\rm osc}} + \left(\frac{h}{h_{\rm osc}}\right)^3 = 0$$

abelian estimate:

H_*/GeV	λ	$H_{\rm osc}/H_{\rm dec}$	$n_\phi^{\rm dec}$
10^4	0.09	370	1 000
10^6	0.04	360	1 700
10^8	0.02	630	5 100
10^{10}	0.005	340	7 700

resonance structure



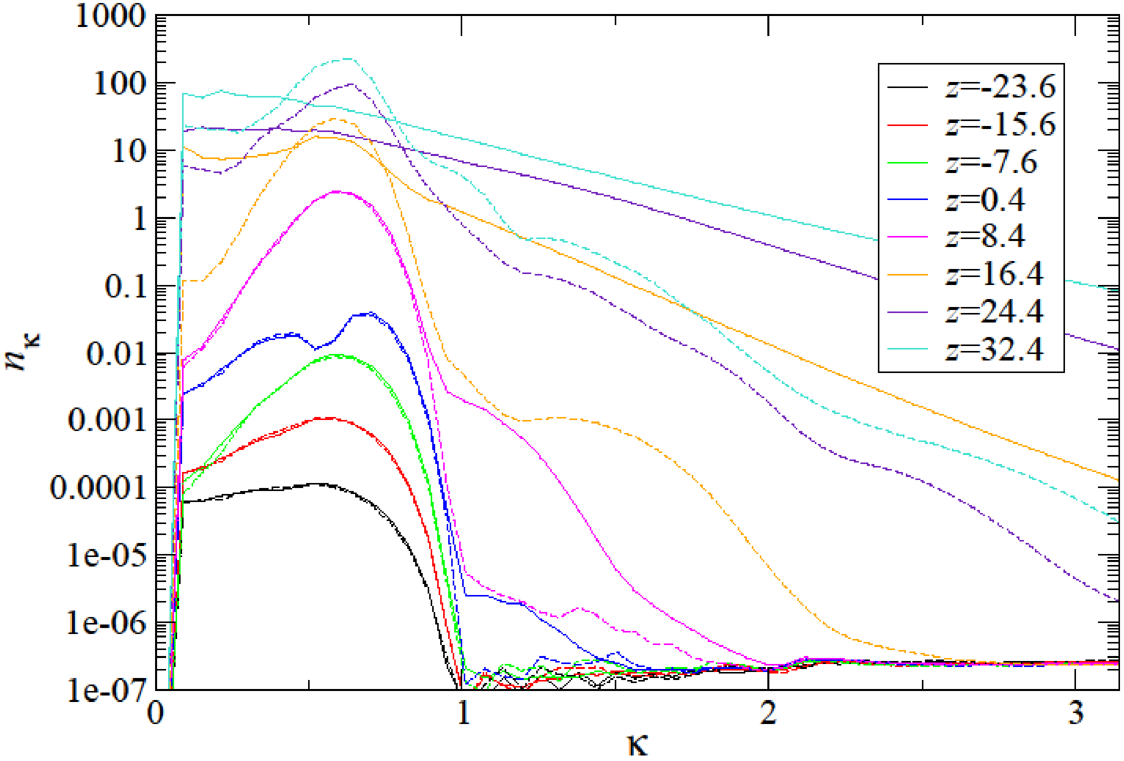
for SM, the resonance is broadish

best fit SM: $q_W = 18$, $q_Z = 29$

non-abelian terms matter

KE, Nurmi, Rusak, Weir

SU(2) on lattice



$$z = \left(\lambda_h (ah)_{osc}^2\right)^{1/2} (\tau - \tau_{osc})$$

$$\kappa^2 = \frac{k^2}{\lambda_h (ah)_{osc}^2}$$

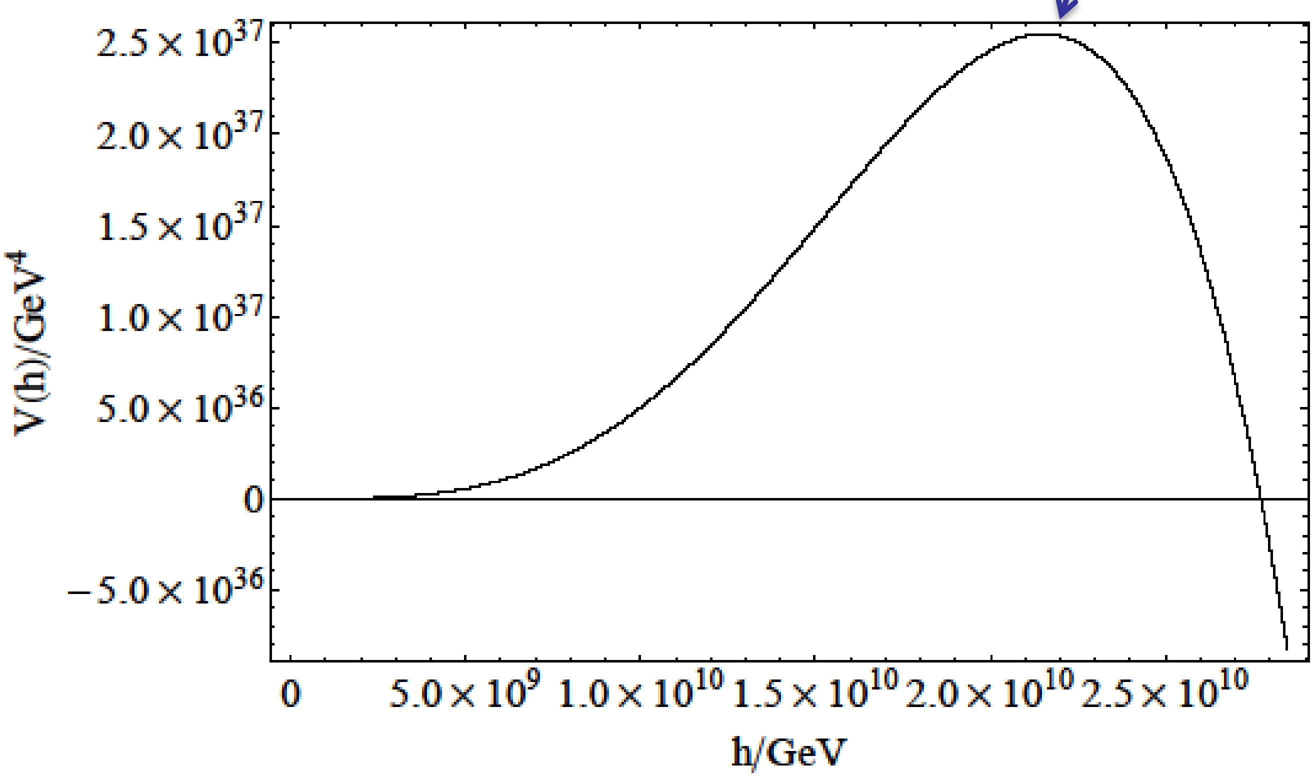
abelian: dashed non-abelian: solid

non-abelian interactions destroy effectively the Higgs condensate

Higgs vacuum instability

fluctuate over the top? – very bad

very sensitive to RGE



$$\lambda(h_{\rm max}) + \frac{\beta(h_{\rm max})}{4} = 0$$

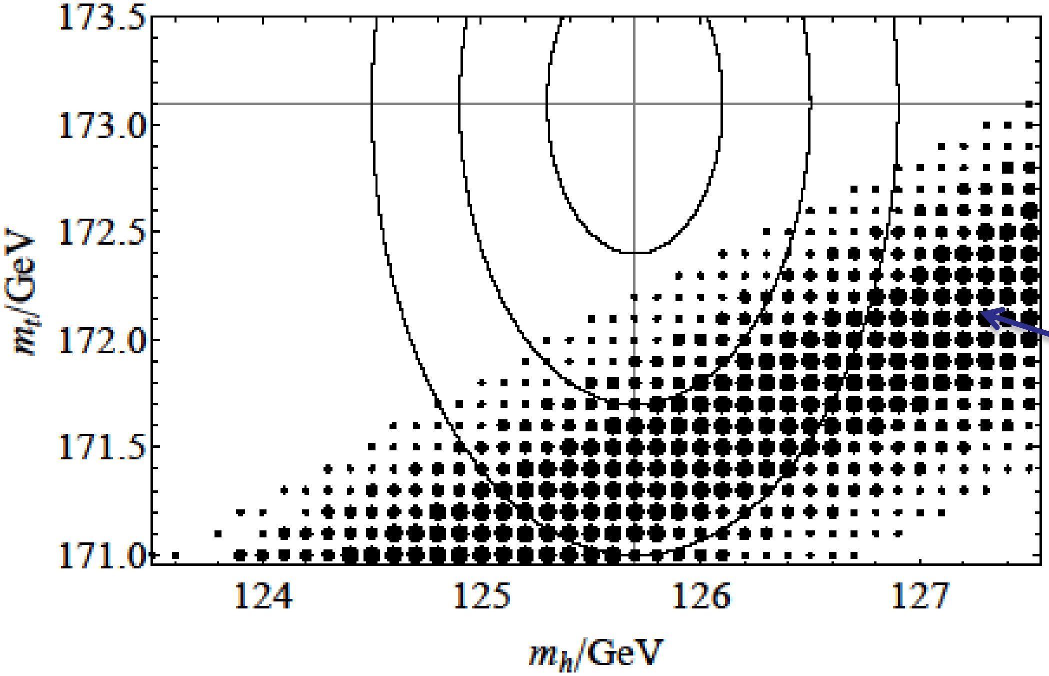
Espinosa, Giudice,Riotto
Kobakhidze, Spencer-Smith
KE, Meriniemi, Nurmi

fluctuations in kinetic energy ~ H^4

⇨ wrong vacuum unless $V > H^4$

→ possible problems for high inflationary scale

$H = 10^{14}$ GeV



marginalized over α_s

1 σ

KE, Meriniemi, Nurmi

Coupling the Higgs and the inflaton

Reheating → ... → Standard Model $\supset$ Higgs

⇒ loop induced Higgs-inflaton couplings

even tiny ones matter!

Coupling the Higgs and the inflaton

KE, Lebedev, Karciauskas, Rusak, Zatta

$$L = L_{chaotic}(\phi) + L_{higgs}(h) - \tfrac{1}{4}\lambda_{h\phi} h^2 \phi^2 - \tfrac{1}{2}\sigma_{h\phi}\phi h^2$$

$$m = 1.3 \times 10^{-6} M_{Pl}$$

$$V = \tfrac{1}{4}\lambda_h(h) h^4$$

inflaton oscillates $\phi = \Phi(t)\cos(mt)$

$$\Phi(t) \approx (3\pi)^{-1/2}\frac{M_{Pl}}{mt}, \quad \Phi(t) < \Phi_0 = 0.2 M_{Pl}$$

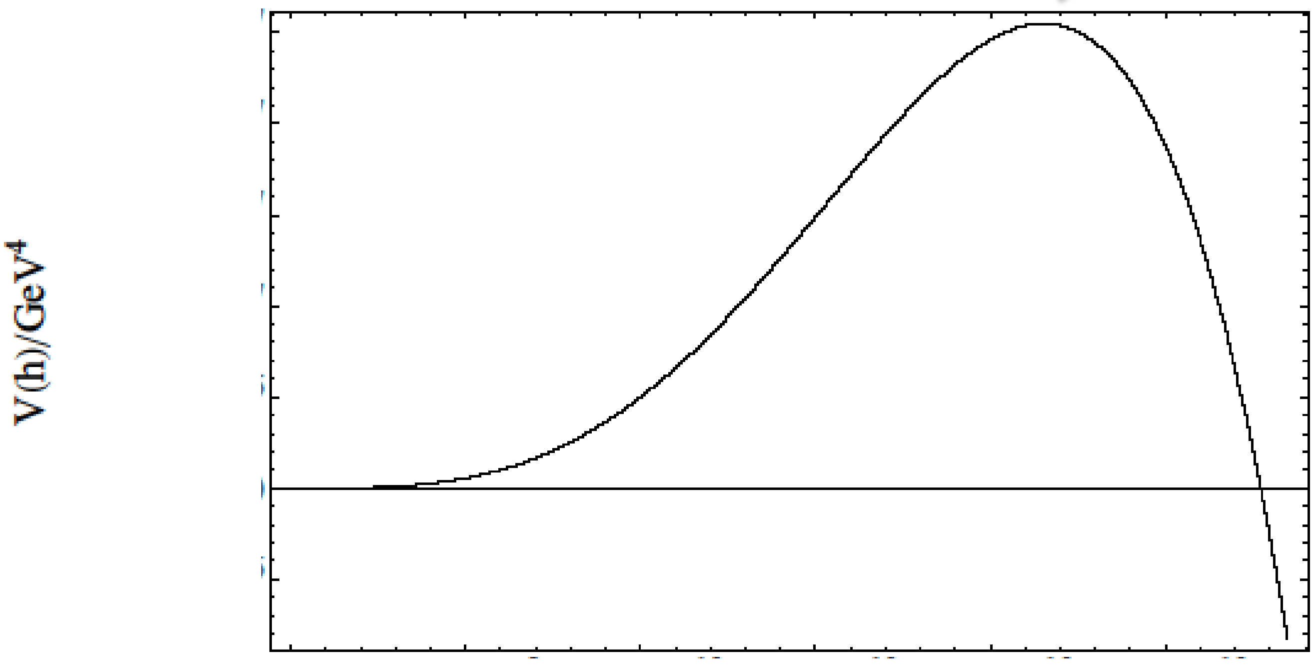
⇒ oscillating Higgs mass

Ema, Mukaida, Nakayama
KE, Lebedev, Karciauskas, Rusak, Zatta

resonant excitation of Higgs modes h_k

$$h_c \approx 10^{10}\,\text{GeV}$$

⇨ $\langle h^2 \rangle$ over the top?



some constraints

$$10^{-10} < \lambda_{h\phi} < 10^{-6}$$

eff mass > H, flatness of potential

$$\lambda_{h\phi}\phi^{2} >> \sigma_{h\phi}\phi$$

effective mass not dependent
on the sign of inflaton field

(A) neglect trilinear coupling

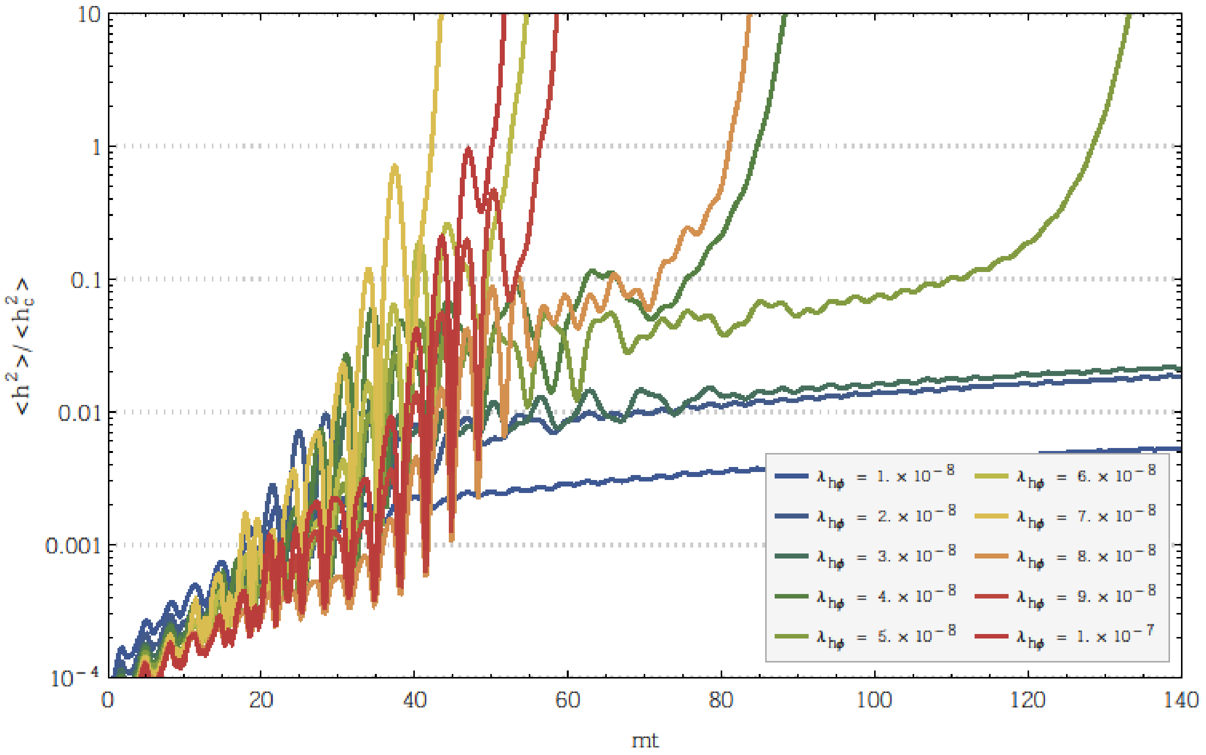
⇨ broad parametric resonance

Hartree approximation $h^4 \to 6h^2 \langle h^2 \rangle$

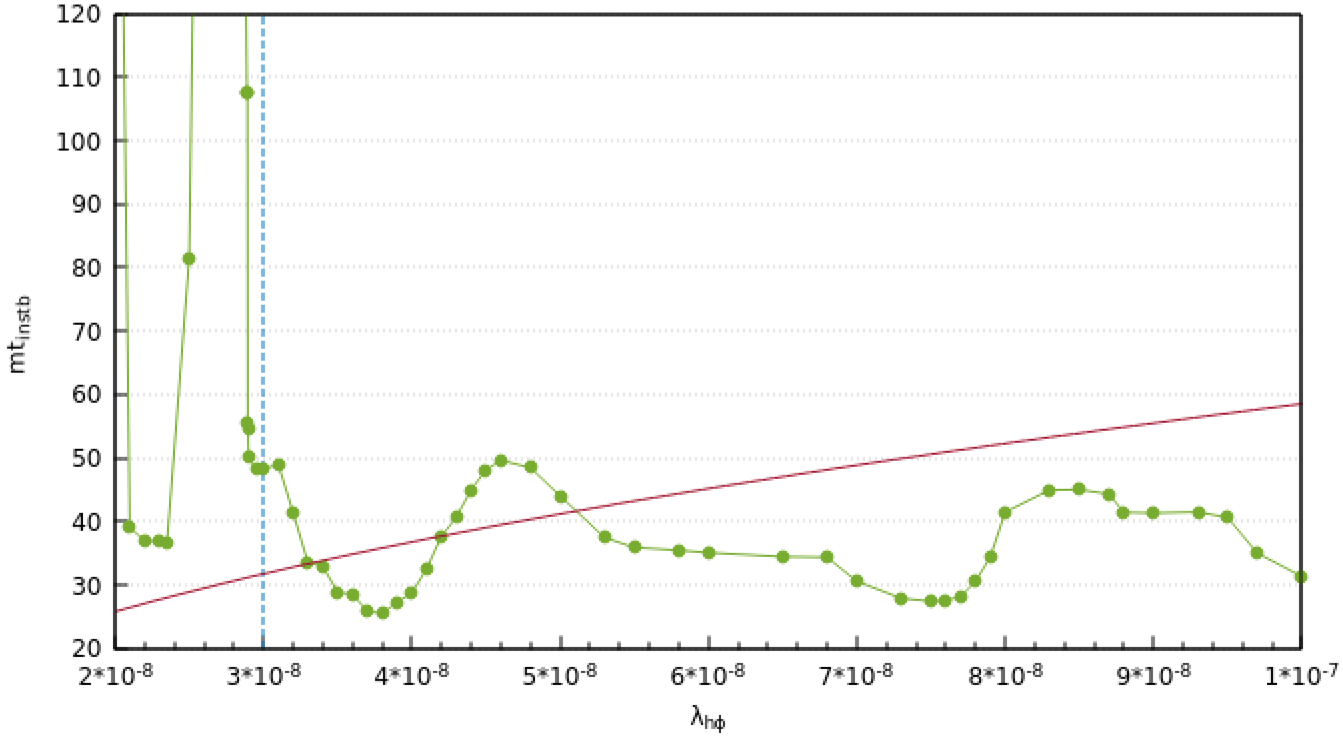
⇨

$$\omega_k^2 = \frac{k^2}{a^2} + \tfrac{1}{2}\lambda_{h\phi}\Phi^2\cos^2(mt) + 3\lambda_h a^{-3}\langle X^2 \rangle$$

$$X_k = a^{3/2} h_k$$

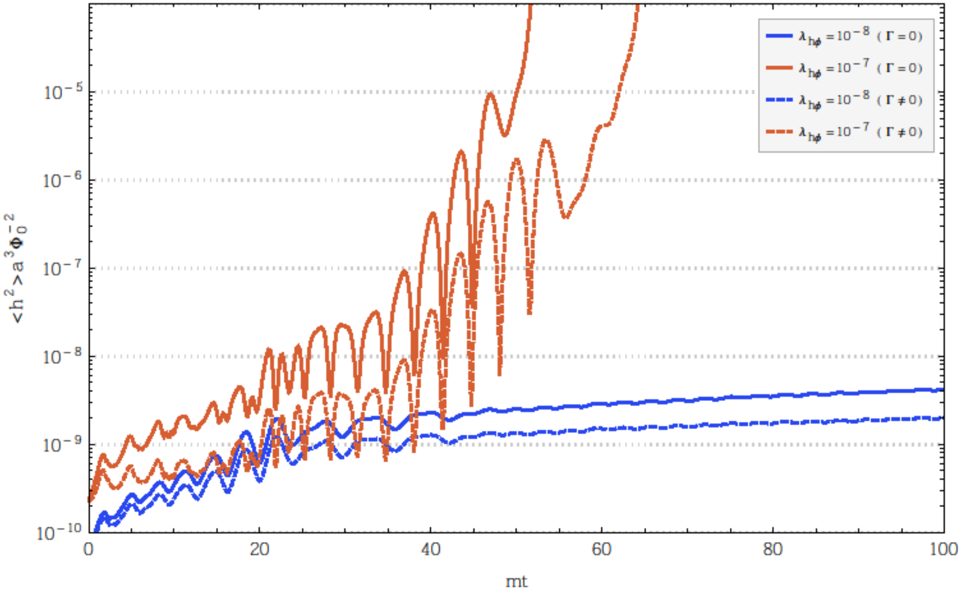

10
1
0.1
0.01
0.001
10^{-4}
$\langle h^2\rangle/\langle h_c^2\rangle$
0
20
40
60
80
100
120
140
mt
$\lambda_{h\phi}$ = 1. × 10^{-8}
$\lambda_{h\phi}$ = 2. × 10^{-8}
$\lambda_{h\phi}$ = 3. × 10^{-8}
$\lambda_{h\phi}$ = 4. × 10^{-8}
$\lambda_{h\phi}$ = 5. × 10^{-8}
$\lambda_{h\phi}$ = 6. × 10^{-8}
$\lambda_{h\phi}$ = 7. × 10^{-8}
$\lambda_{h\phi}$ = 8. × 10^{-8}
$\lambda_{h\phi}$ = 9. × 10^{-8}
$\lambda_{h\phi}$ = 1. × 10^{-7}

beyond Hartree approximatrion: LATTICEEASY



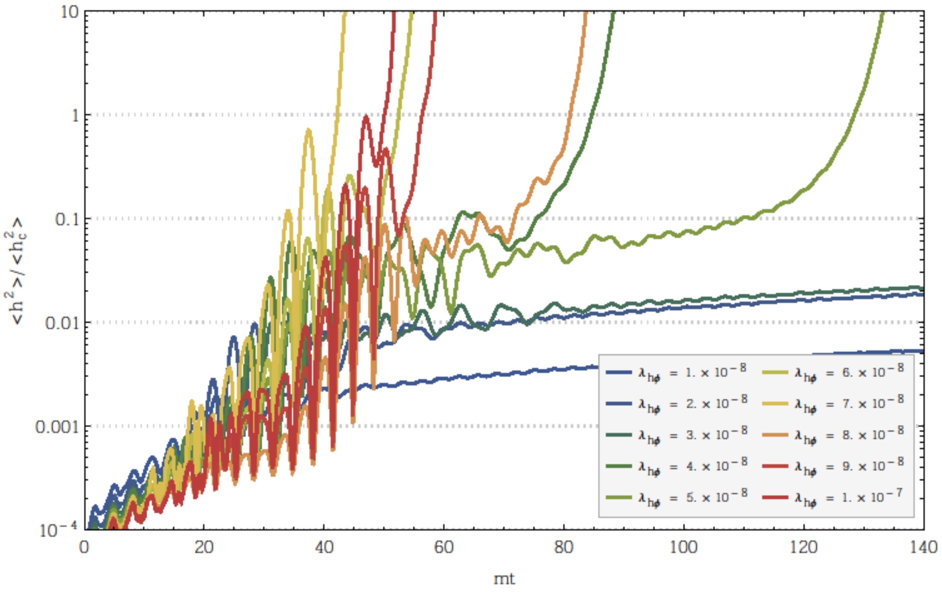
← vacuum instability

with h → top



reduces Higgs quanta by ~ 2

without



(B) switch on trilinear coupling

tachyonic instability

$$\omega_k^2 = \frac{k^2}{a^2} + \sigma_{h\phi}\Phi\cos(mt) + \tfrac{1}{2}\lambda_{h\phi}\Phi^2\cos^2(mt) + 3\lambda_h a^{-3}\left\langle X^2 \right\rangle$$

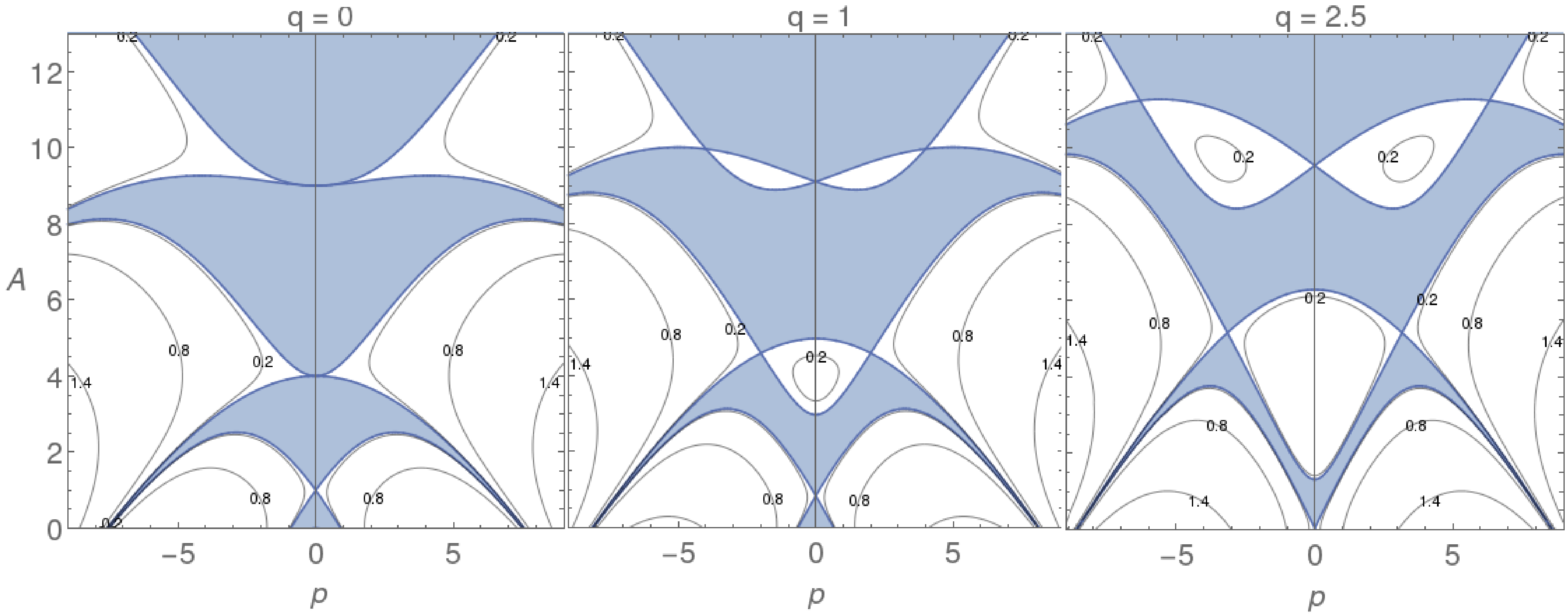
p

q

$$X_k = a^{3/2}h_k$$

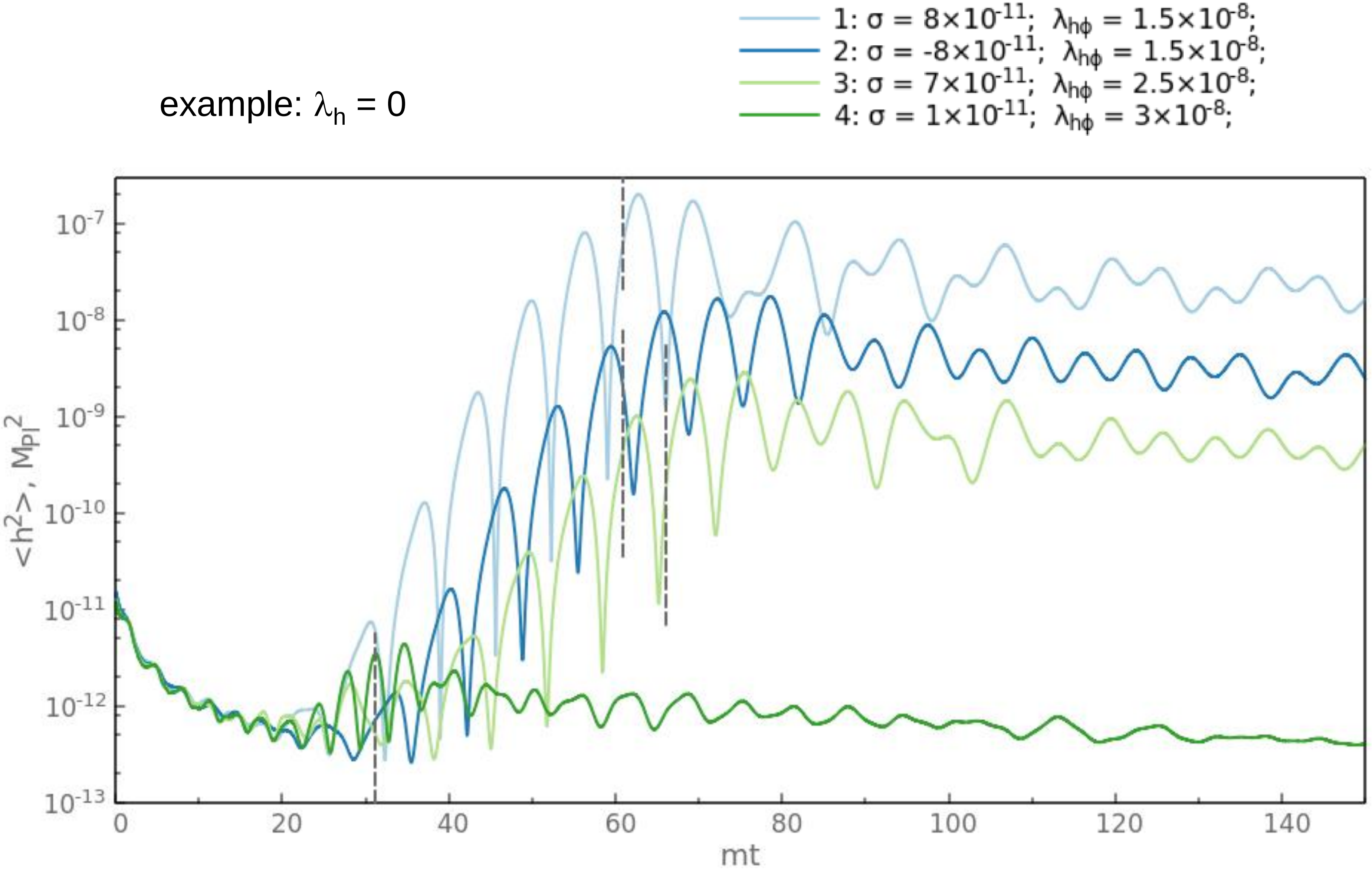
Whittaker-Hill (= complicated Matthieu)

recipe: choose stable vacuum, switch on σ (sign also matters)

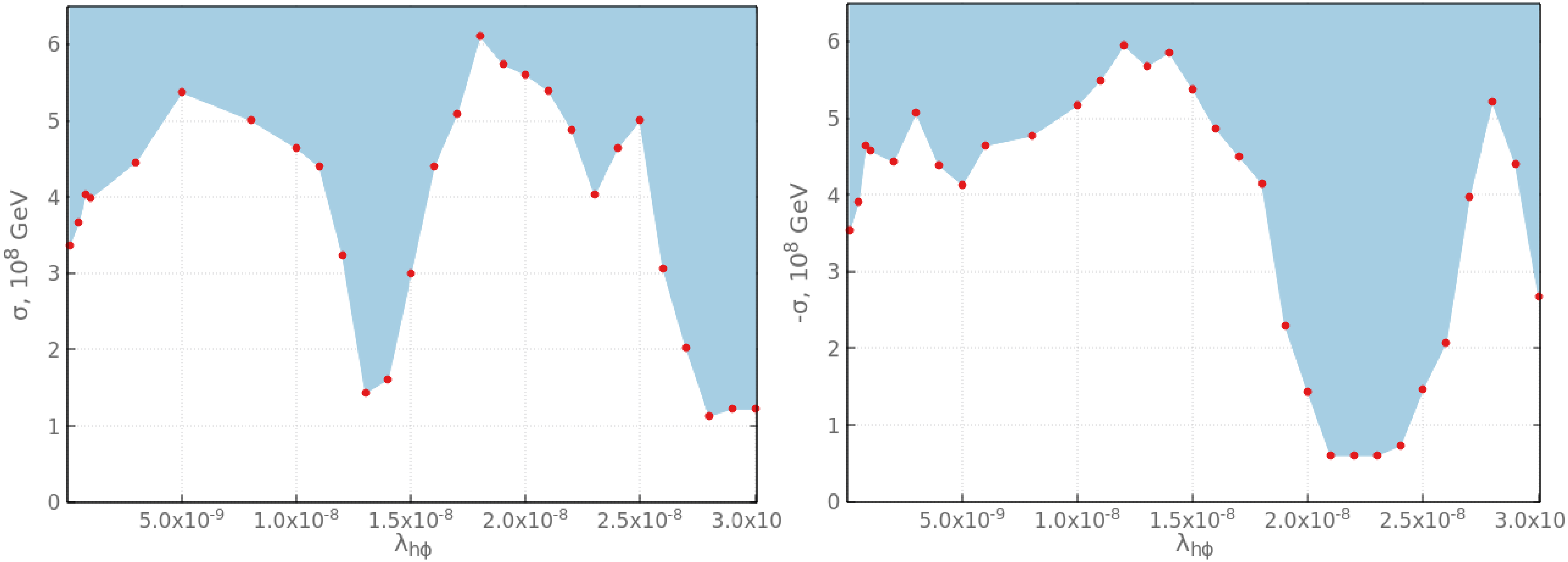


Whittaker-Hill stability bands

expansion of the universe → in and out of the stability bands example: $\lambda_h = 0$



instability regions, LATTICEEASY



shaded = excluded

CONCLUSION:

Inflationary Higgs fluctuations: tool to tackle

-Higgs vacuum instability

-Higgs-inflaton coupling