Fate of Electroweak Vacuum during Preheating

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Based on **arXiv:1602.00483**

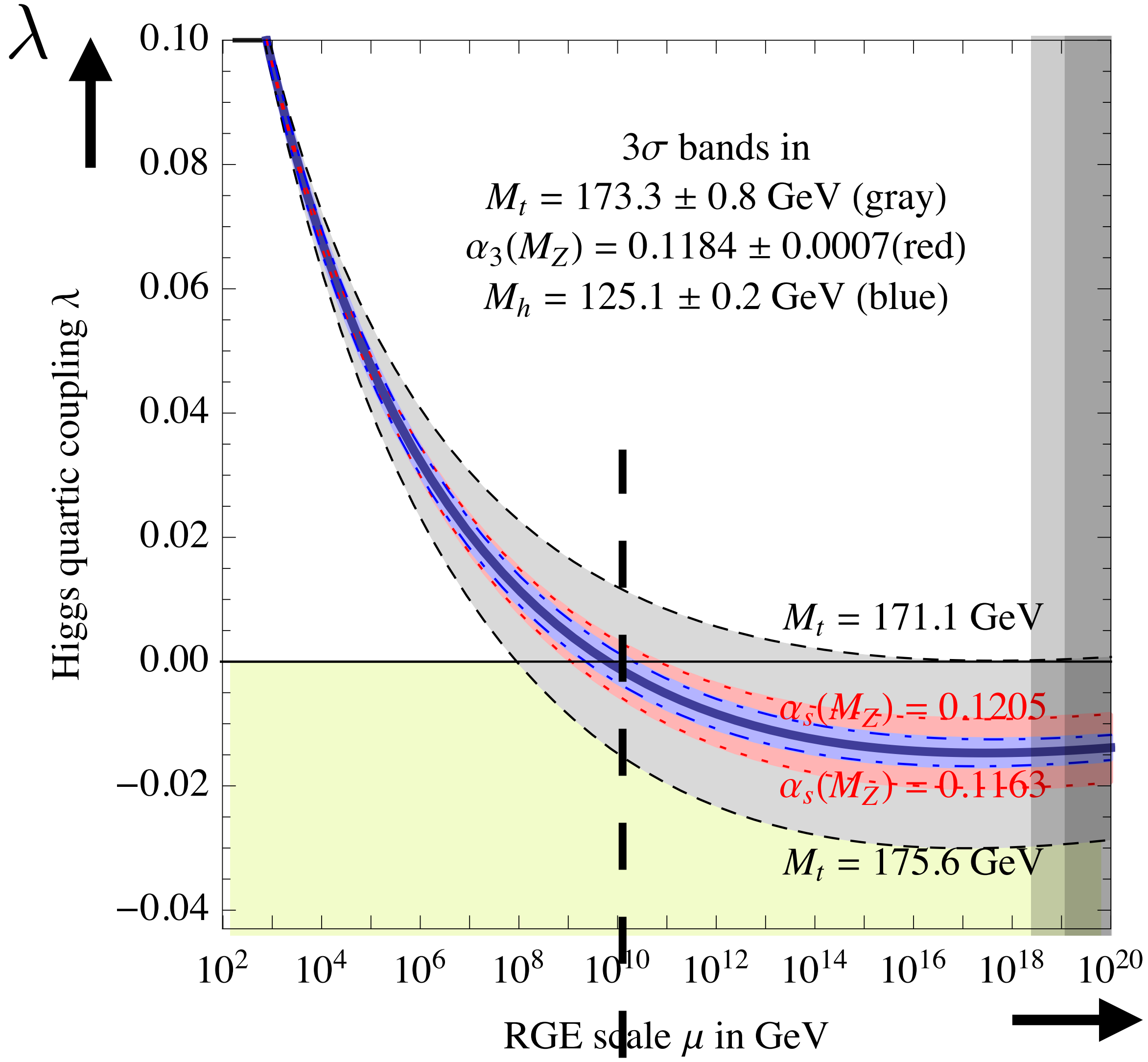
In collaboration with K. Mukaida and K. Nakayama

Introduction

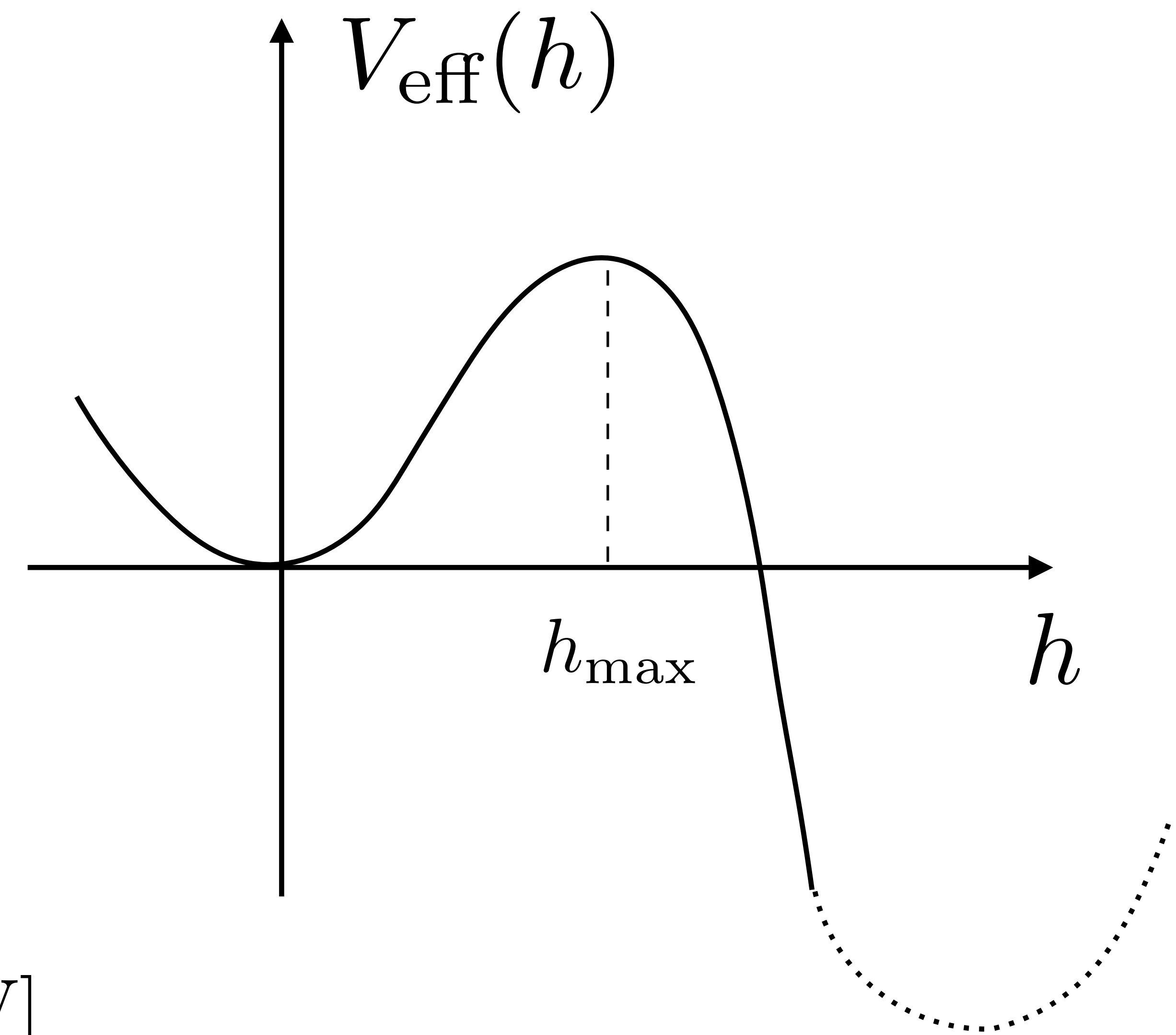
Metastability

[Buttazzo+ 13]

Electroweak (EW) vacuum may be metastable??



$h_{\rm max} \sim 10^{10}\,{\rm GeV}$ $\mu\,[{\rm GeV}]$



λ becomes negative $\sim 10^{10}\,{\rm GeV}$ for the center value of $M_{\rm top}$.

➡ **Cosmology must be compatible with it.**

Metastability

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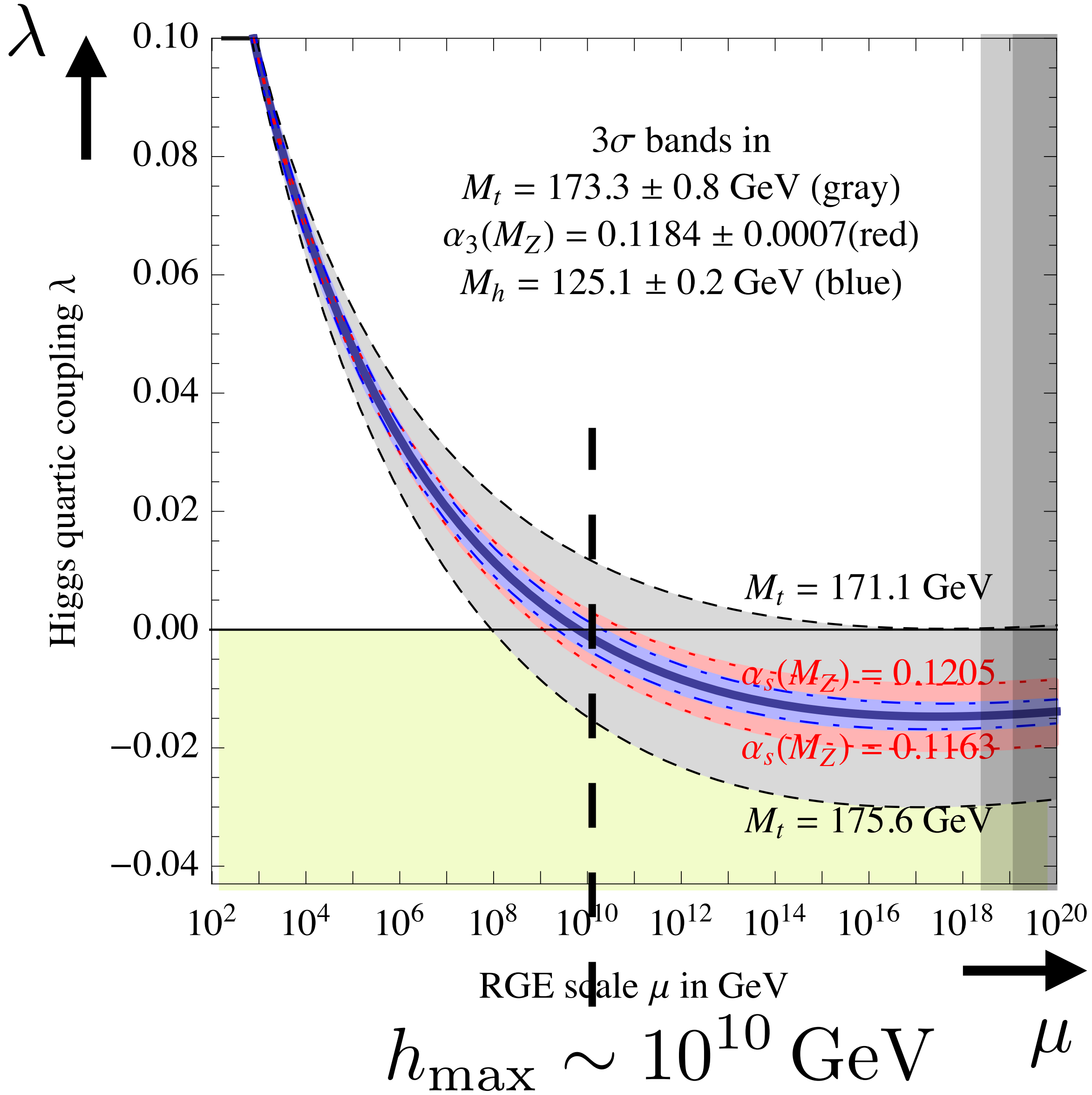

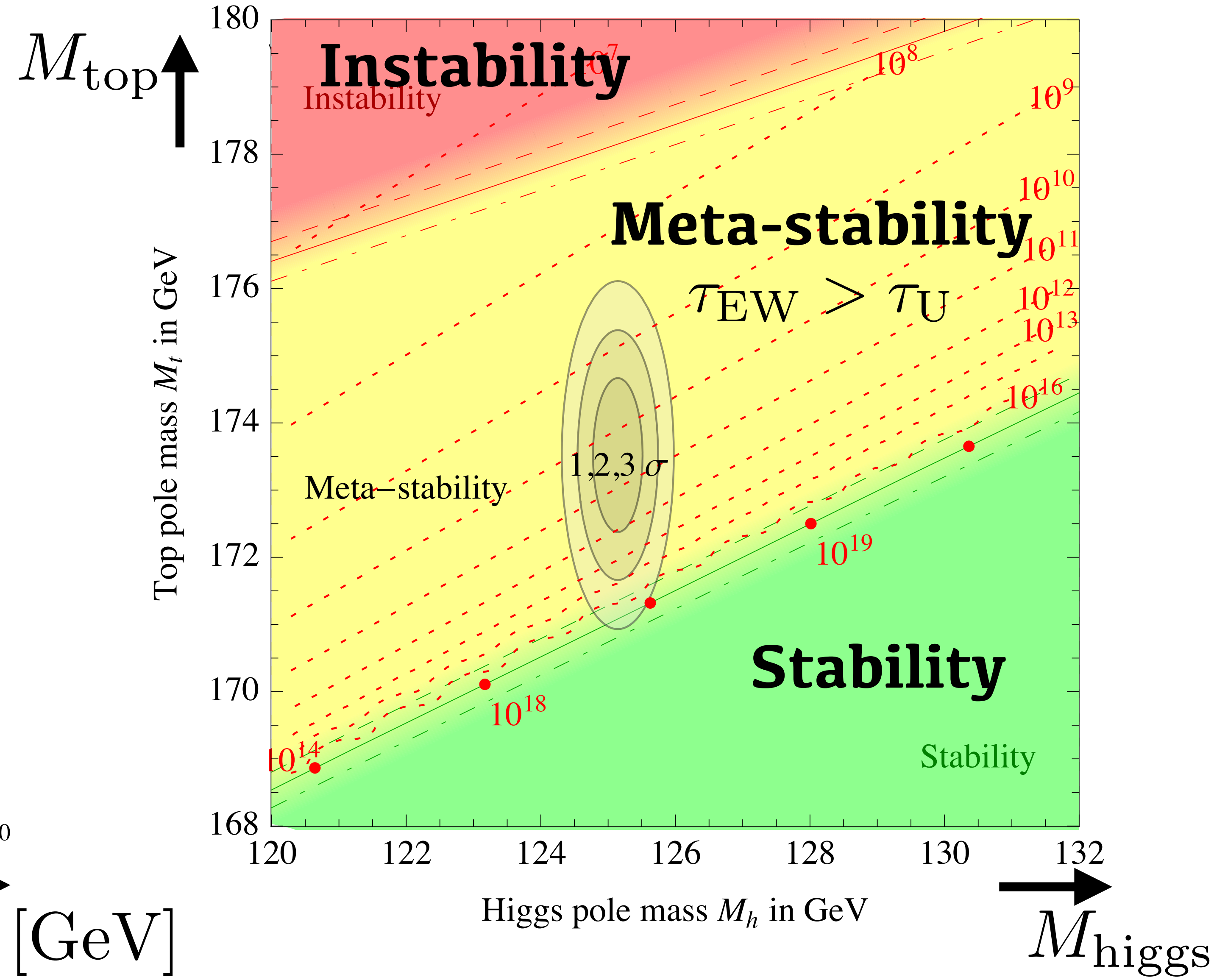

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➡ **Cosmology must be compatible with it.**

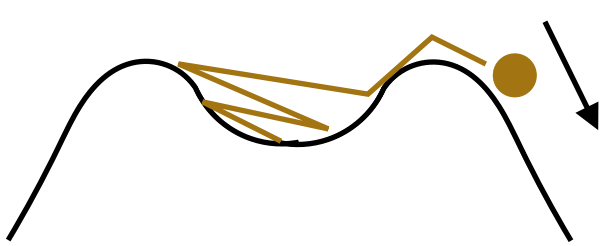
Metastability vs. inflation

- Light fields acquire fluctuations during inflation.

$$\sqrt{\langle \delta h^2 \rangle} \simeq \frac{H_{\rm inf}}{2\pi}\sqrt{\mathcal{N}}$$ (random walk with $H_{\rm inf}/2\pi$ for each one e-folding)

[Starobinsky, Yokoyama 94]

- **Inflation scale must be low** for EW vacuum to be stable.



(if BSM does not affect much on the higgs potential)

[e.g. Hook+ 14; Espinosa+ 15]

Roughly, $P(|h| > h_{\rm max}) \simeq e^{-x^2}/\sqrt{\pi}x < e^{-3\mathcal{N}},\ x = \sqrt{2}\pi h_{\rm max}/\sqrt{\mathcal{N}}H_{\rm inf}$ **or,**

$$H_{\rm inf} \lesssim 4 \times 10^8\,{\rm GeV}\left(\frac{60}{\mathcal{N}}\right)\left(\frac{h_{\rm max}}{10^{10}\,{\rm GeV}}\right)$$

(Potential and reheating dynamics are neglected.)

Stabilization during inflation

- One way to avoid this constraint:

Induce **effective mass** for higgs during inflation.

(BSM or low-scale inflation are of course other choices…)

- The following couplings are often considered:

$$-\mathcal{L}_{\rm int} = \begin{cases} \frac{1}{2}c^2\phi^2h^2 & \cdots \text{quartic} \\ \frac{1}{2}\xi R h^2 & \cdots \text{curvature} \end{cases}$$

[e.g. Espinosa+ 08; Lebedev+ 13]

➡ $m^2_{\rm eff;h} = c^2\Phi^2,\ 12\xi H^2_{\rm inf}$ during inflation

Suppress fluctuations if $c \gtrsim \mathcal{O}(H_{\rm inf}/\Phi_{\rm inf}),\ \xi \gtrsim \mathcal{O}(0.1)$

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How about after inflation??

Motivation

1. EW vacuum metastability (BSM negligible)

vs.

high scale inflation

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3. How about after inflation?? [our work]

- Mass term oscillates → resonance.
- Even tachyonic during some period (curvature).

Outline

1. Introduction

2. Resonant particle production

3. Preheating dynamics of Higgs

4. Summary

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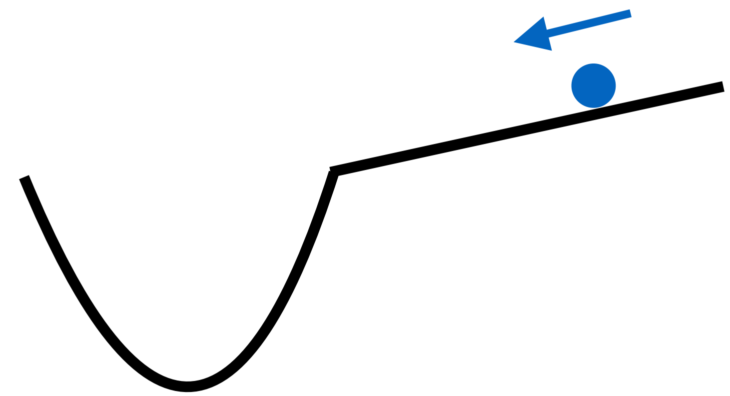
Dynamics of inflaton

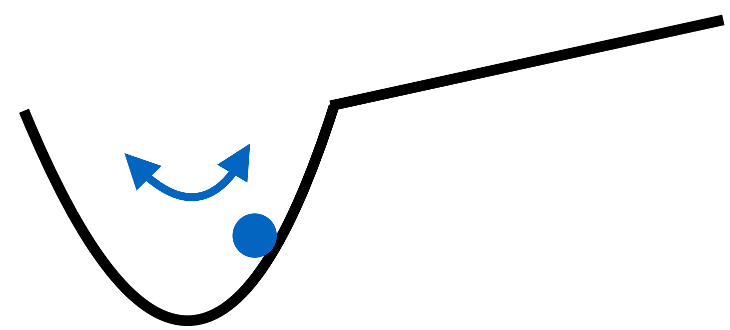
1. Slow-roll during inflation.



= accelerated expansion

2. Oscillate after inflation.

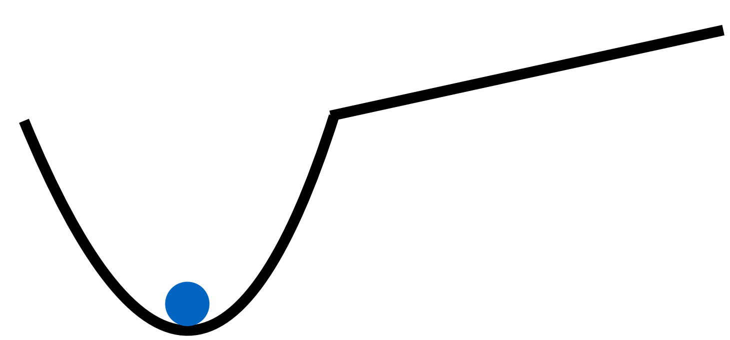
if exponential particle production



preheating epoch

3. Finally decay, and reheating completes.

= beginning of hot big bang



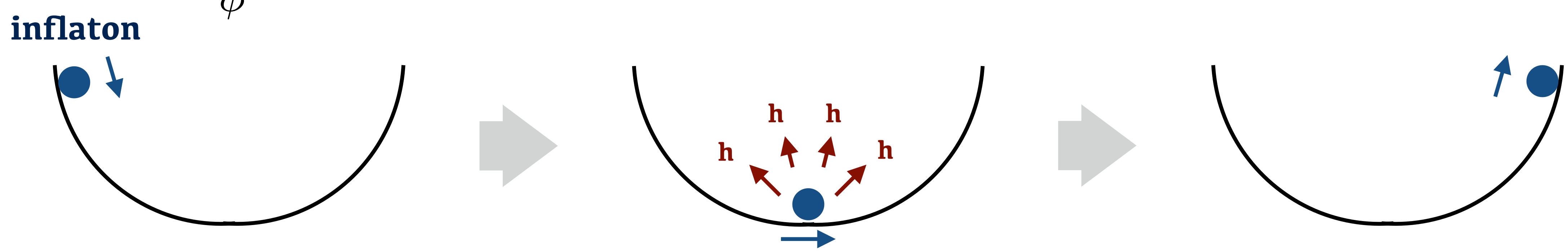
Parametric resonance

Quartic coupling: $-\mathcal{L}_{\text{int}} = \frac{1}{2} c^2 \phi^2 h^2$

[Kofman+ 94; 97]

$\sim \frac{\tilde{m}^2_{\text{eff};h}}{m^2_\phi}$

If $q \equiv \frac{c^2 \Phi^2}{4 m_\phi^2} \gg 1$, ~~adiabaticity~~ only at around the origin.



+ Bose enhancement [many times of oscillation].

Parametric resonance occurs.

$$n_h \sim p_*^3 \, e^{2\mu_{\text{qtc}} m_\phi t}, \qquad \mu_{\text{qtc}} \simeq \mathcal{O}(0.1)$$

where the typical momentum is $p_* \equiv \sqrt{c m_\phi \Phi} \sim m_\phi q^{1/4}$.

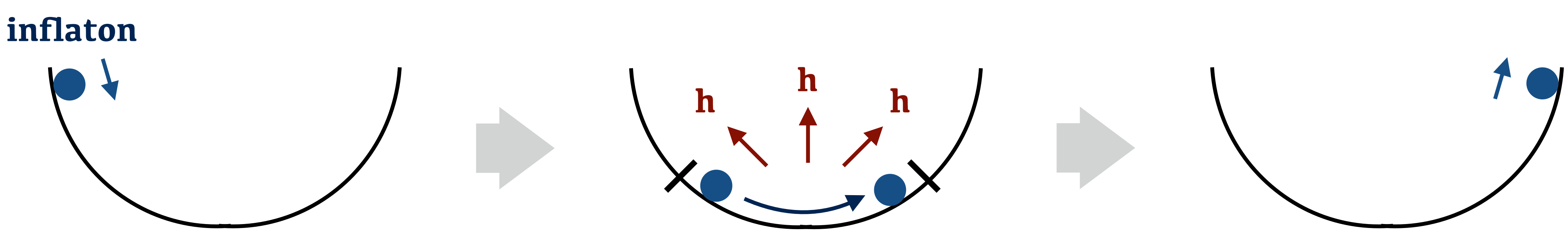
Tachyonic resonance

Curvature coupling: $-\mathcal{L}_{\rm int} = \frac{1}{2}\xi R h^2$

[Bassett+ 97; Tujikawa+ 99; Dufaux+ 06]

$R = \frac{1}{M_P^2}\left[4V(\phi) - \dot{\phi}^2\right]$ from Friedmann equations.

Higgs is tachyonic for some region at around the origin.



Tachyonic resonance occurs for $q \gg 1$:

$$n_h \sim p_*^{(\rm tac)^3} e^{\mu_{\rm crv}\sqrt{\xi}\frac{\Phi_{\rm ini}}{M_P}}, \quad \mu_{\rm crv} \simeq 2$$

where the typical momentum is $p_*^{(\rm tac)} \simeq m_\phi q^{1/4}, \; q \equiv \frac{3}{4}\left(\xi - \frac{1}{4}\right)\frac{\Phi^2}{M_P^2}.$

* particle production is dominated by the first a few oscillations.

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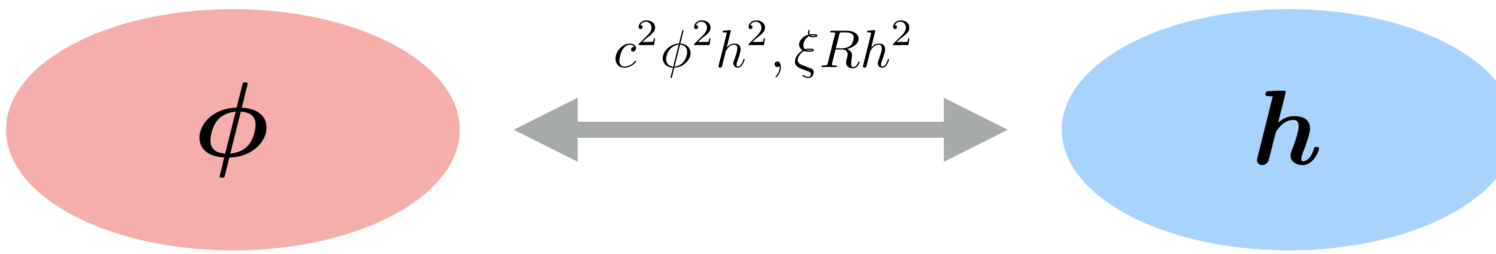
Set up

- Consider inflaton oscillation epoch
- Inflaton potential: $V(\phi) = \frac{1}{2} m_\phi^2 \phi^2$



Main idea: resonant Higgs production induces tachyonic mass.

$$\delta m^2_{\mathrm{self};h} \simeq -3|\lambda|\langle h^2 \rangle$$

It may force Higgs to roll down to the true vacuum.

From now,

- Analytically derive the condition for EW vacuum decay.
- Verify it by numerical simulations.

Higgs-inflaton coupling

$$\mathcal{L}_{\rm int} = -\frac{1}{2}c^2\phi^2h^2 \quad : \quad n_h \sim \frac{1}{32\pi^2}\sqrt{\frac{\pi}{2\mu_{\rm qtc}m_\phi t}}e^{2\mu_{\rm qtc}m_\phi t}p_*^3$$ with $\mu_{\rm qtc} \simeq \mathcal{O}(0.1)$

- Higgs tachyonic mass grows:

$$\delta m^2_{{\rm self};h}(t) \simeq 3\lambda\langle h^2(t)\rangle \sim -3|\lambda|\frac{n_h(t)}{\omega_{k_*;h}(t)}$$

- $\delta m^2_{{\rm self};h}$ dominates $c^2\phi^2$ at around the origin.

That time interval $\Delta t : c^2\Phi^2(m_\phi\Delta t)^2 \sim \left|\delta m^2_{{\rm self};h}\right|_{\phi\sim 0}$

- If the growth rate exceeds unity, $|\delta m_{{\rm eff};h}|\Delta t \sim |\delta m^2_{{\rm self};h}|/p_*^2 > 1$, **EW vacuum decays.**

- Cosmic expansion should kill resonance before that time.

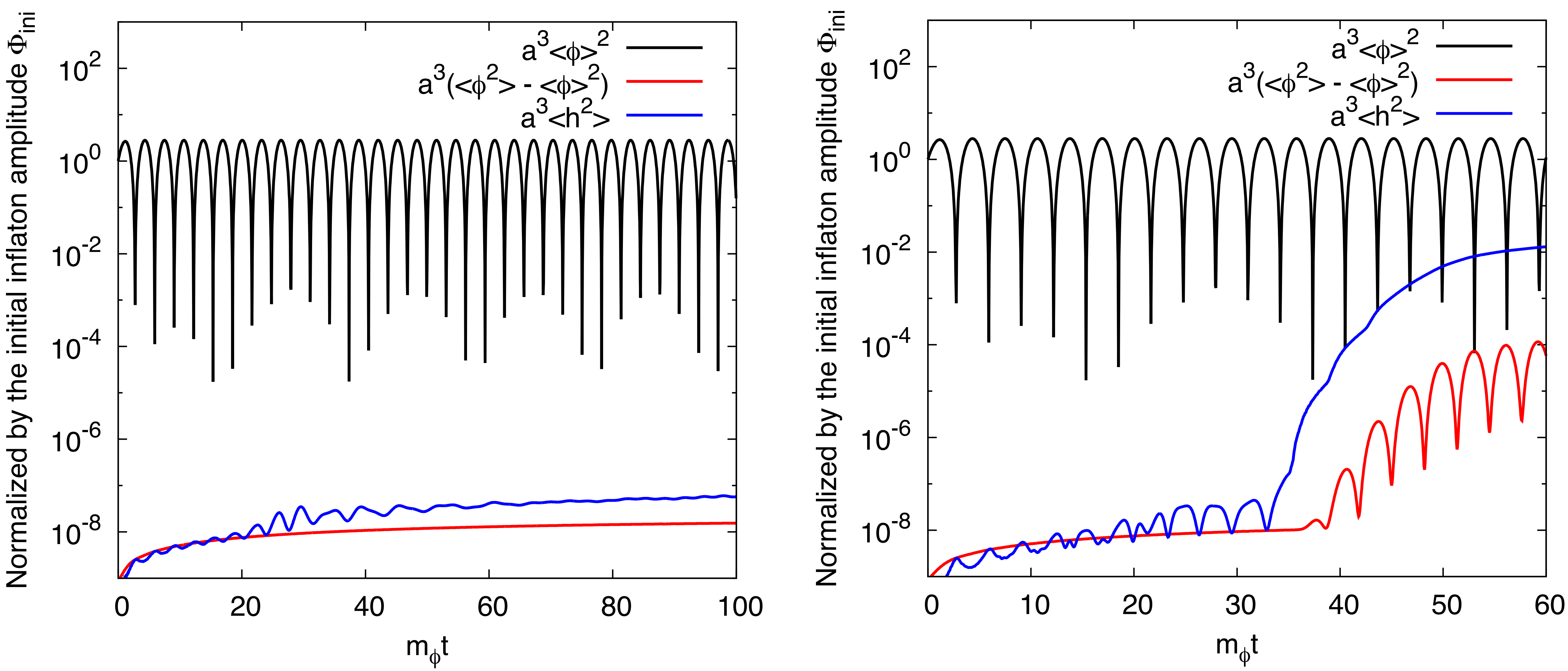
$\left|\delta m^2_{\rm self;h}(t)\right|_{\phi\sim 0} \lesssim p_*^2$ at the end of the resonance, or

$$c \lesssim 10^{-4}\left[\frac{0.1}{\mu_{\rm qtc}}\right]\left[\frac{m_\phi}{10^{13}\ {\rm GeV}}\right]$$

Quartic: lattice simulation

We have verified our condition by **classical lattice simulations**.

$c = 1 \times 10^{-4}$ $\qquad$ $c = 2 \times 10^{-4}$



$$\Phi_{\rm ini} = \sqrt{2}\, M_{\rm pl}, m_\phi = 1.5 \times 10^{13}\,{\rm GeV}, N = 128^3, L = 10/m_\phi, dt = 10^{-3}/m_\phi$$

(added 6th term for large field for convergence)

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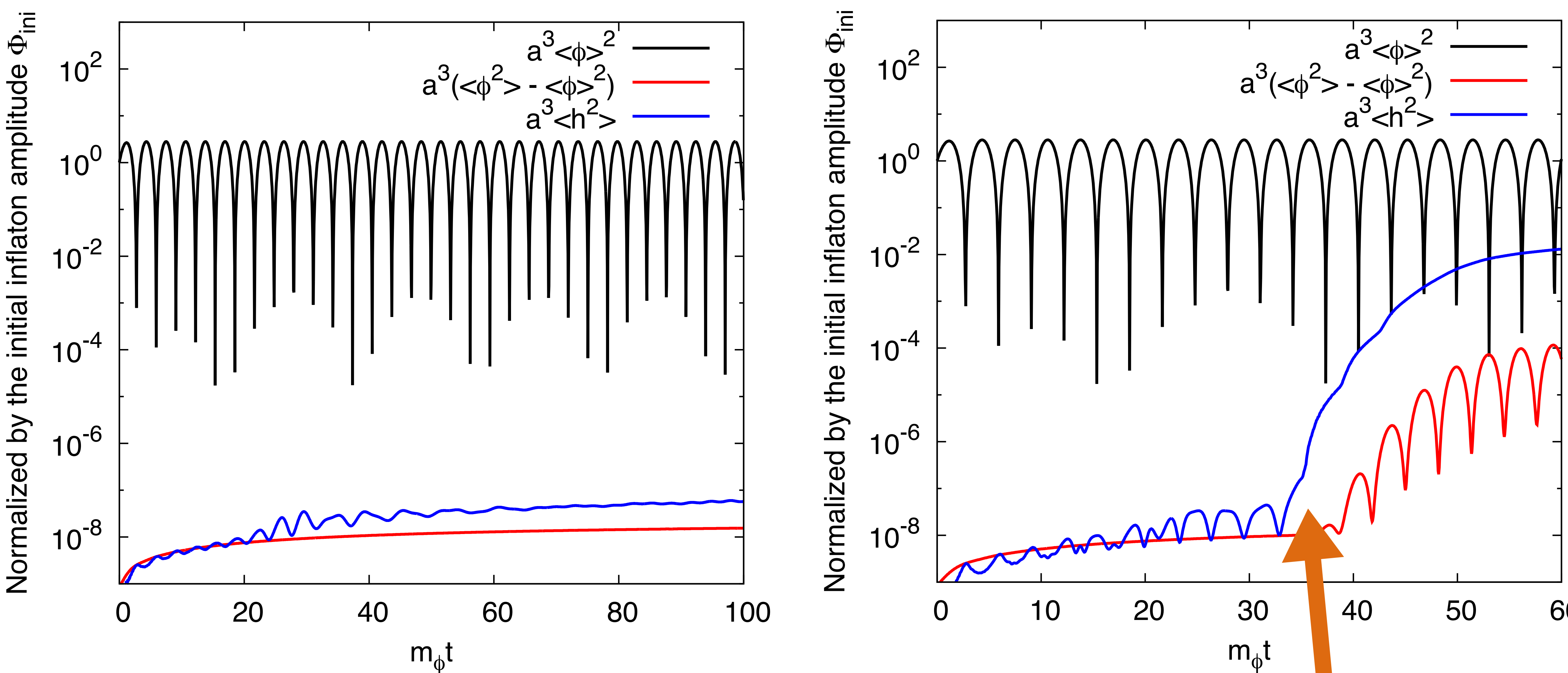

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EW vacuum decays!!

Higgs-curvature coupling

$$\boxed{\mathcal{L}_{\rm int} = -\frac{1}{2}\xi R h^2}$$: $n_h \sim \frac{1}{16\pi^2}\sqrt{\frac{\pi}{2}} e^{n_{\rm eff}\mu_{\rm crv}\sqrt{\xi}\Phi_{\rm ini}/M_{\rm pl}} p_*^{({\rm tac})^3}$ with $\mu_{\rm crv} \simeq 2,\ n_{\rm eff} \gtrsim 1$

We require $|\delta m^2_{{\rm self};h}|_{\xi R\sim 0} \lesssim \xi \tilde{R}$ at the end of the resonance, or

$$\boxed{\xi \lesssim 10 \times \left[\frac{2}{n_{\rm eff}\mu_{\rm crv}}\right]^2 \left[\frac{\sqrt{2}\,M_{\rm pl}}{\Phi_{\rm ini}}\right]^2}$$

- Bound depends on the initial inflaton amplitude.

cf. $c \lesssim 10^{-4}\left[\frac{0.1}{\mu_{\rm qtc}}\right]\left[\frac{m_\phi}{10^{13}\,{\rm GeV}}\right]$: independent of the initial inflaton amplitude

- $n_{\rm eff}$: effective number of times of oscillation

$$n_{\rm eff} \simeq 1 \text{ for } \Phi_{\rm ini} = \sqrt{2}M_P, \quad n_{\rm eff} \simeq 1.5\text{-}2 \text{ for } \Phi_{\rm ini} = \sqrt{0.2}M_P$$

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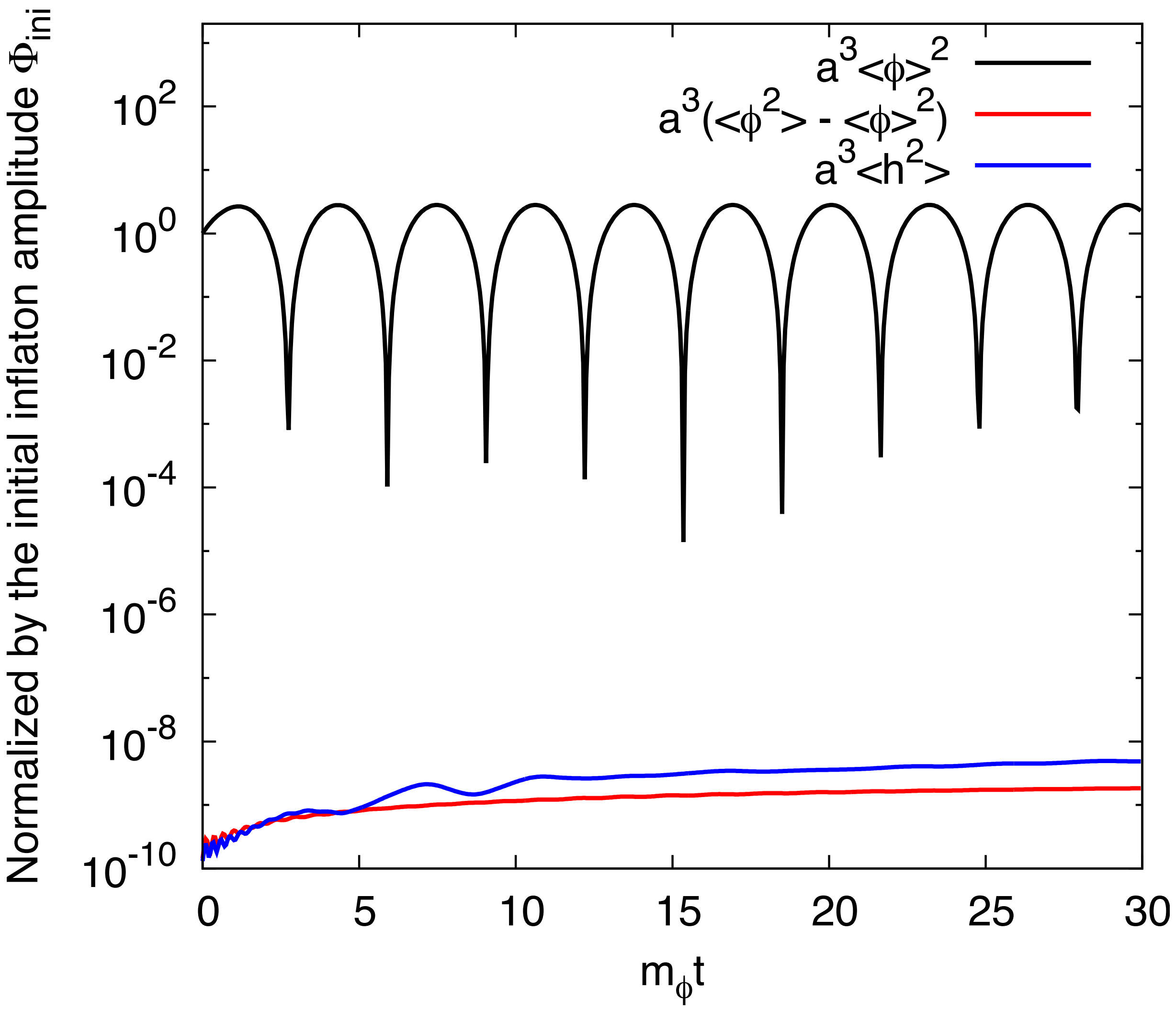
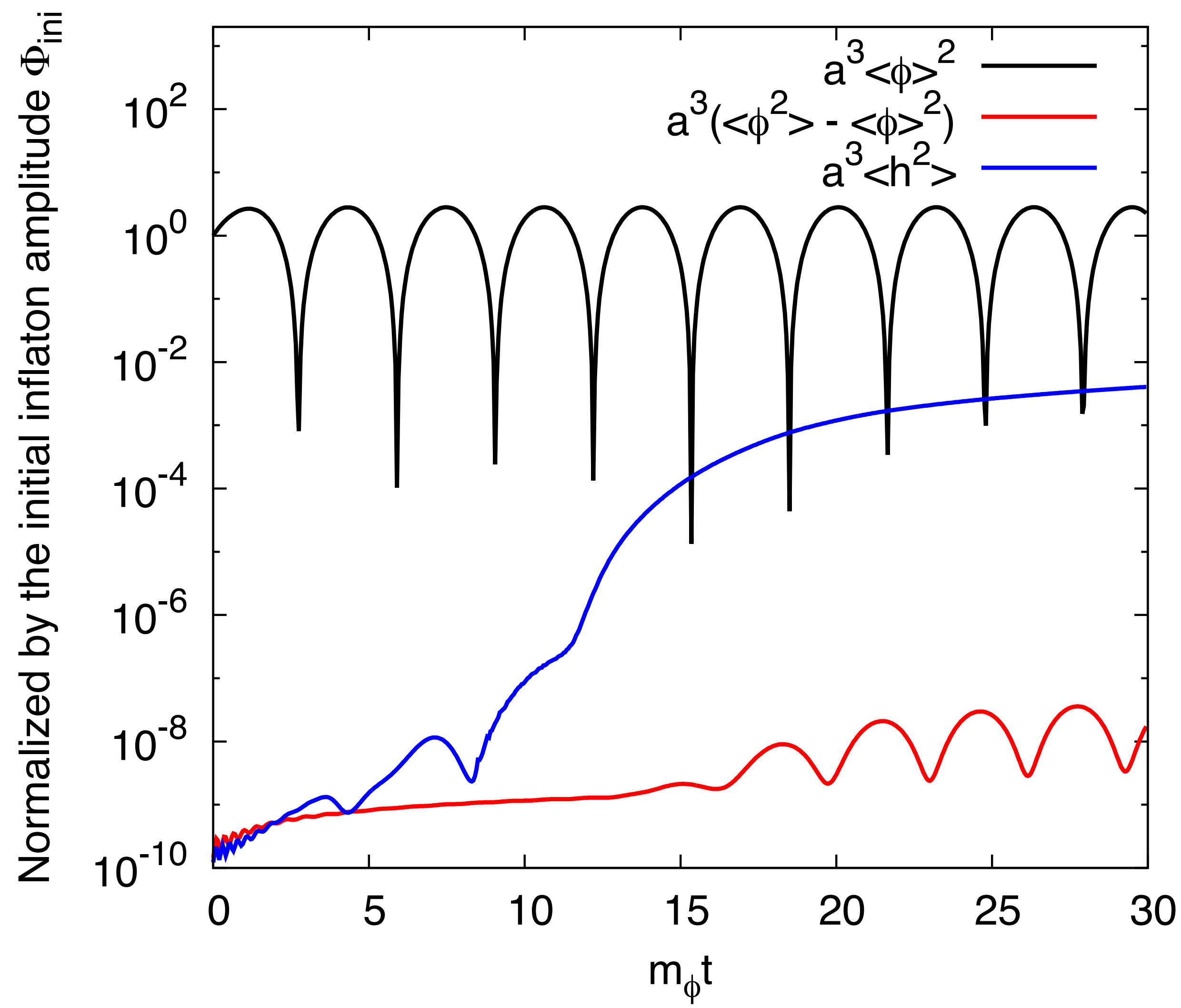
$\xi = 10$



$\xi = 20$



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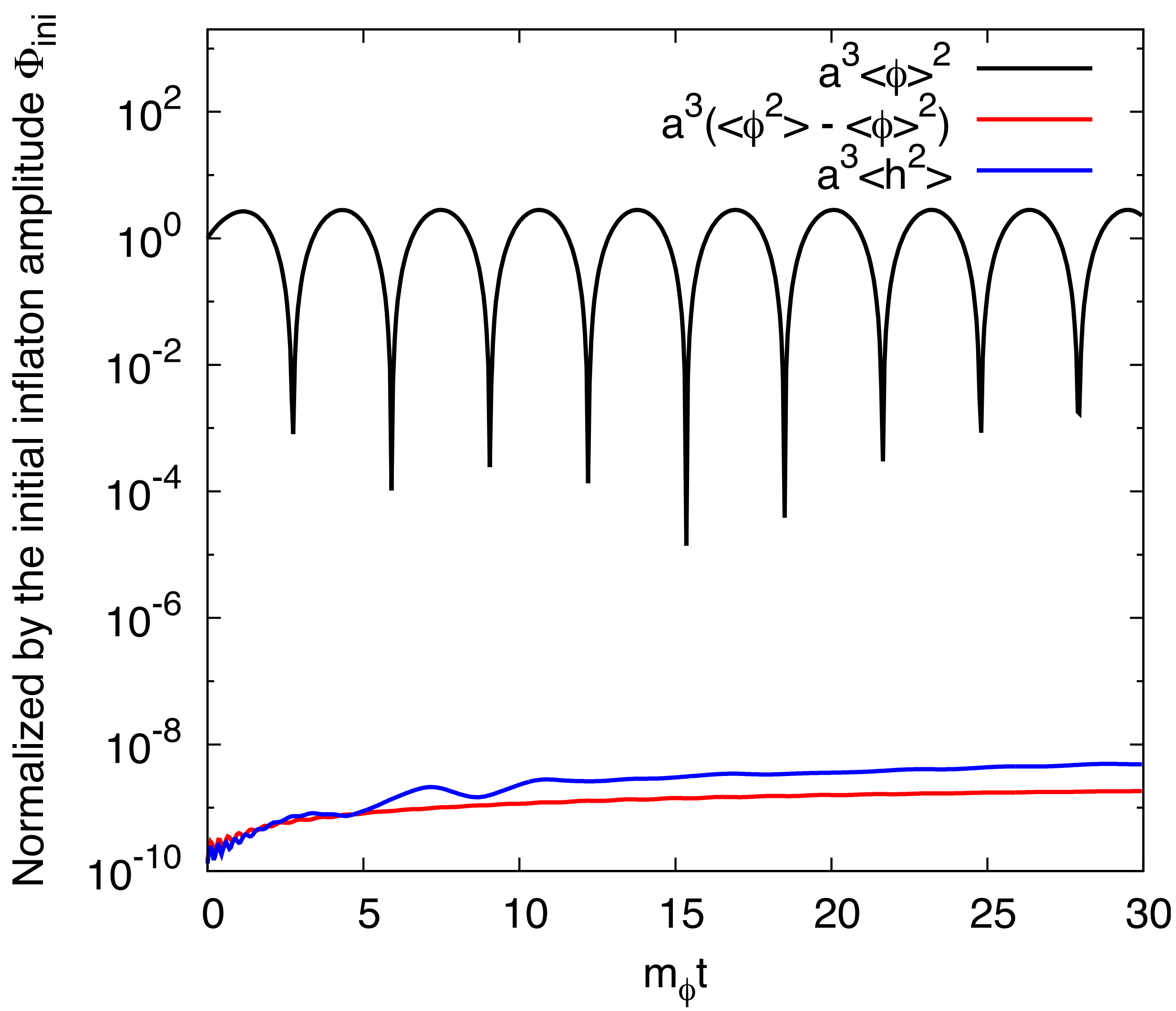

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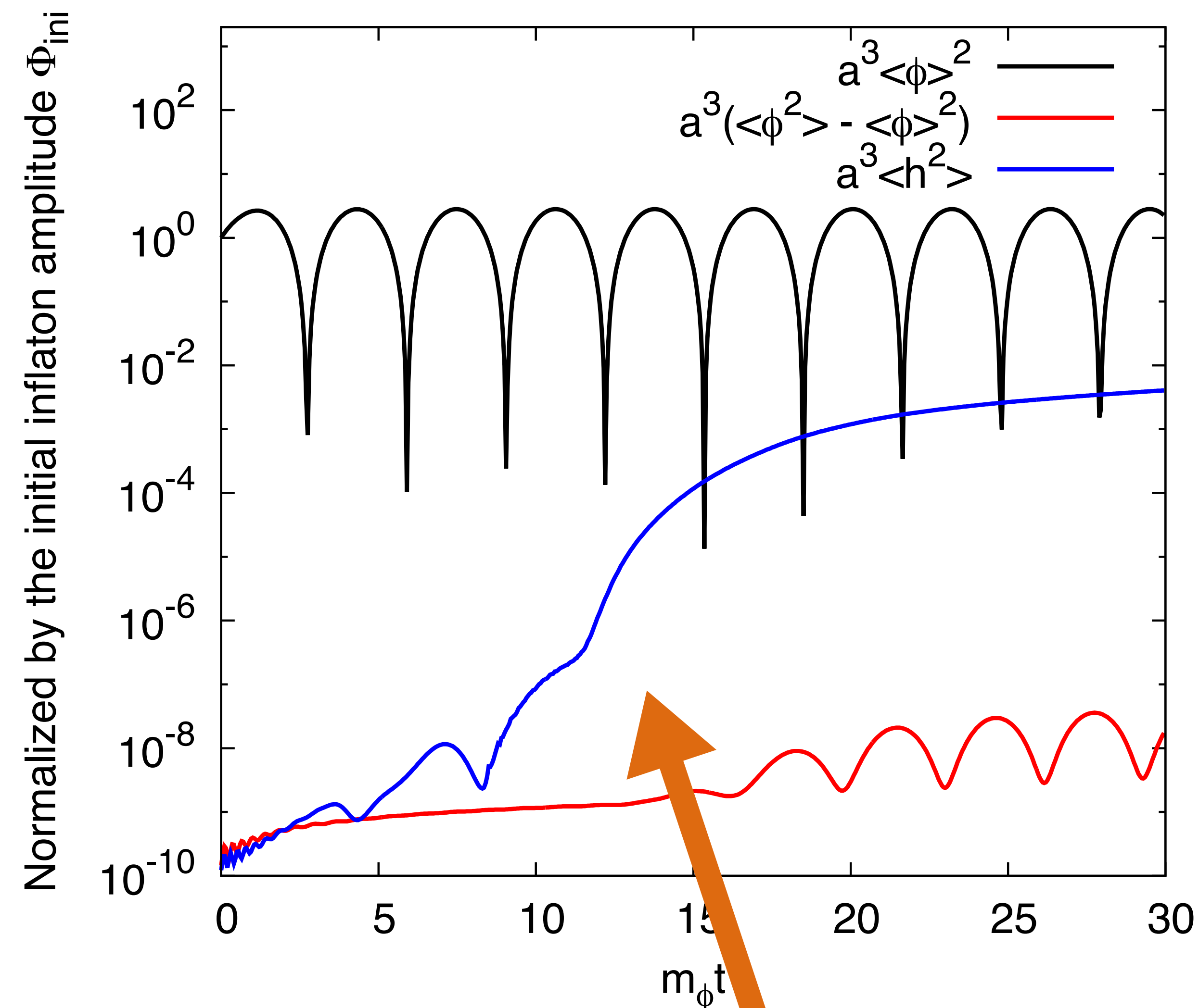

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EW vacuum decays!!

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$$-\mathcal{L}_{\rm int} = \frac{1}{2}c^2\phi^2h^2, \;\; \frac{1}{2}\xi R h^2.$$

3. How about during preheating?? [our work]

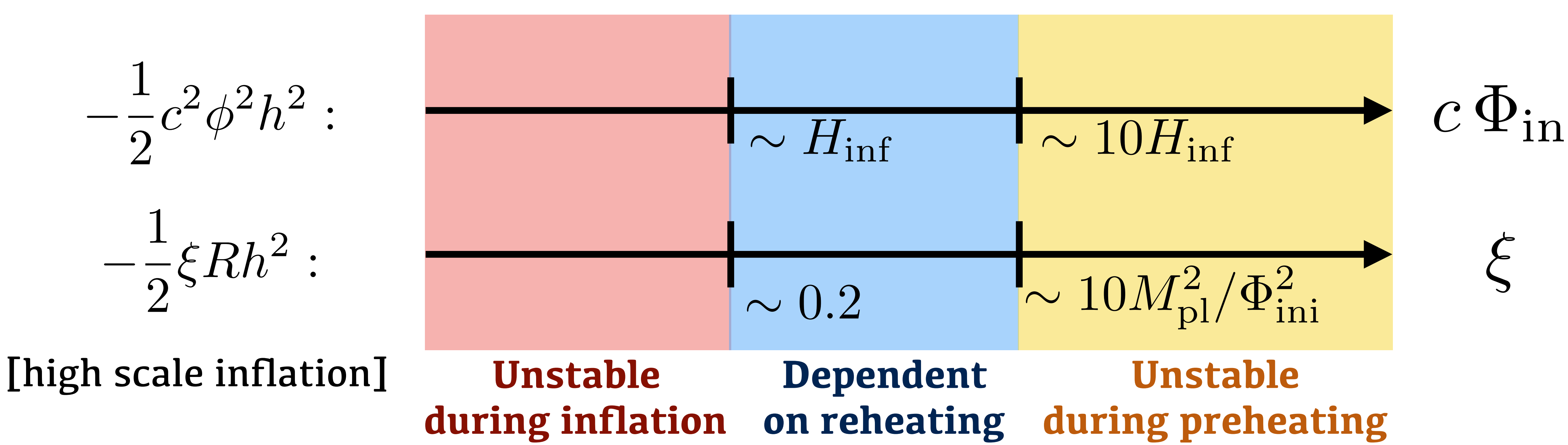
- Mass term oscillates → resonance.
- Even tachyonic during some period (curvature).

Summary

- Studied EW vacuum stability during the preheating epoch with:

$$\mathcal{L}_{\text{int}} = -\frac{1}{2}c^2\phi^2h^2, \quad -\frac{1}{2}\xi R h^2$$

- Obtained upper bounds on the couplings:



Back up

Adiabaticity

- Mode equation of Higgs:

$$\ddot{h}_{\mathbf{k}} + \left[\omega_{k;h}^2(t) + \Delta^2(t)\right] h_{\mathbf{k}} = 0,$$

where $\Delta^2 = -9H^2/4 - 3\dot{H}/2,\ \omega_{k;h}^2(t) = m_{\text{eff};h}^2(t) + k^2/a^2 + \delta m_{\text{self};h}^2.$

$$m_{\text{eff};h}^2(t) = c^2\phi^2,\ \text{ or } \frac{\xi}{M_P^2}\left[4V - \dot{\phi}^2\right],\quad \phi = \Phi(t)\sin m_\phi t,\quad \Phi(t) \simeq \frac{\Phi_i}{a(t)^{3/2}}$$

$$R = \frac{1}{M_P^2}\left[4V - \dot{\phi}^2\right]$$

- Number density of Higgs:

$$n_{k;h}(t) = \frac{1}{2\omega_{k;h}(t)}\left[\left|\dot{h}_{k;h}\right|^2 + \omega_{k;h}^2\left|h_{k;h}\right|^2\right] - \frac{1}{2}$$

Its time evolution is $\dot{n}_{k;h} = \mathcal{O}(|\dot{\omega}_{k;h}/\omega_{k;h}^2|)\omega_{k;h}n_{k;h}$

⇒ $\begin{cases} |\dot{\omega}_{k;h}/\omega_{k;h}^2| \gtrsim 1 \\ \omega_{k;h}^2 < 0 \end{cases}$: [violation of adiabaticity] or,
: [tachyonic] is important for particle production.

Mathieu equation

$$\frac{d^2 h_k}{dz^2} + (A_k - 2q\cos z)\, h_k = 0$$

$z = m_\phi t + \text{const.}$

- Quartic coupling

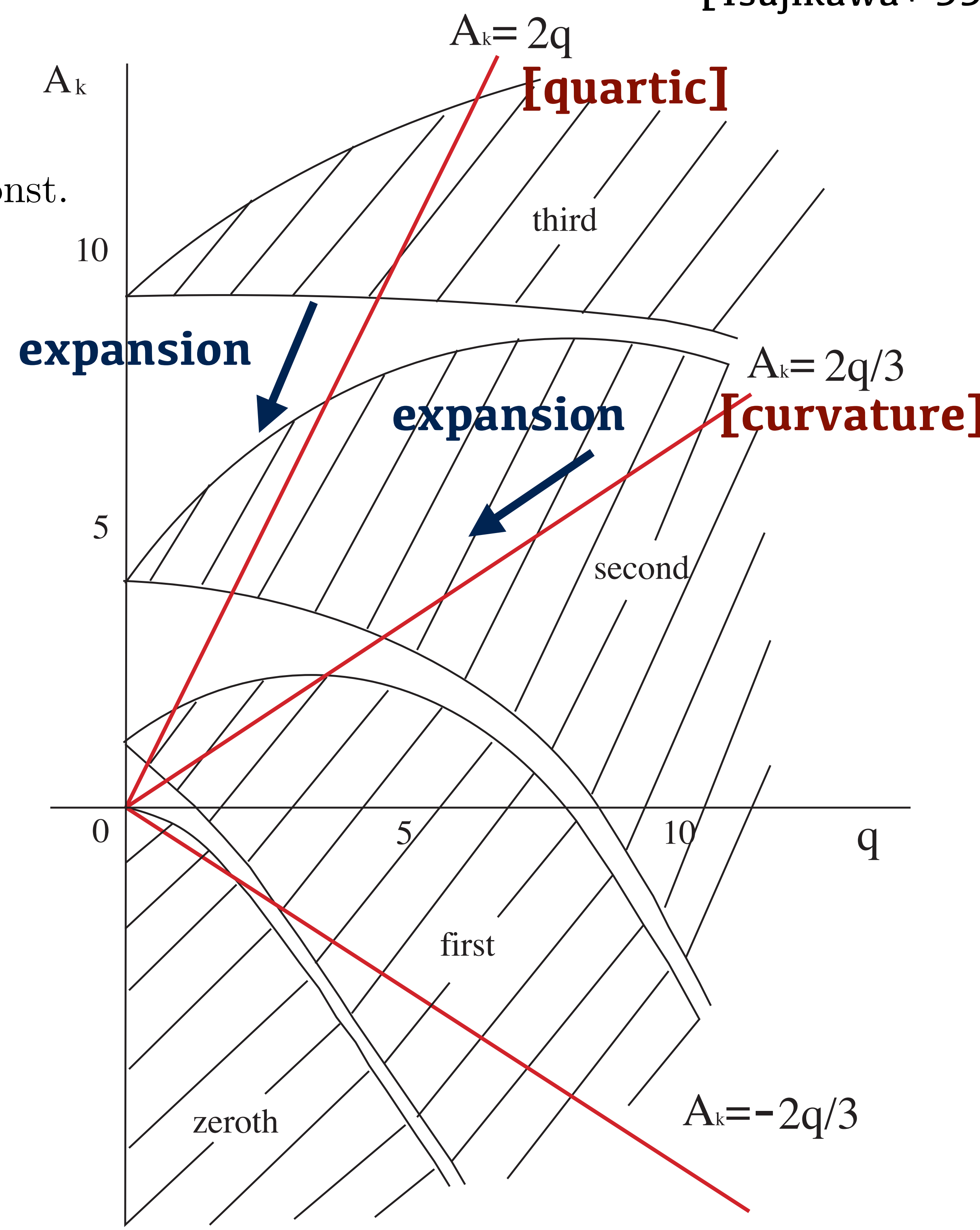
$$A_k = \frac{k^2}{a^2 m_\phi^2} + 2q,\ \ q = \frac{c^2\Phi^2}{4m_\phi^2}$$

- Curvature coupling

$$A_k = \frac{k^2}{a^2 m_\phi^2} + \frac{\xi\Phi^2}{2M_{\rm pl}^2},$$

$$q = \frac{3}{4}\left(\xi - \frac{1}{4}\right)\frac{\Phi^2}{M_{\rm pl}^2}$$

[Tsujikawa+ 99]



Quartic: lattice simulation

We have verified our condition by **classical lattice simulations**.

Classical lattice simulation: [Khlebnikov, Tkachev 96]

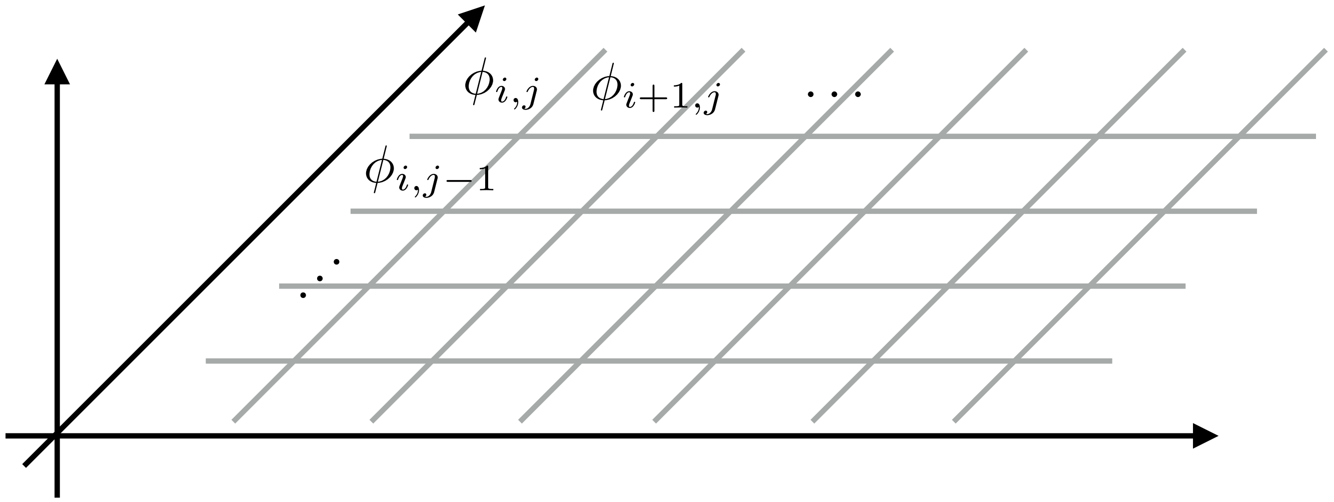
(1) Divide space coordinates into meshes.

(2) Introduce gaussian fluctuations (quantum fluctuation).

(3) Solve the discretized classical equations of motion.

* Classical approximation is valid in the large occupation number limit.

[Polarski, Starobinsky 96]



Quartic: spectrum

The number density of higgs for each momentum:

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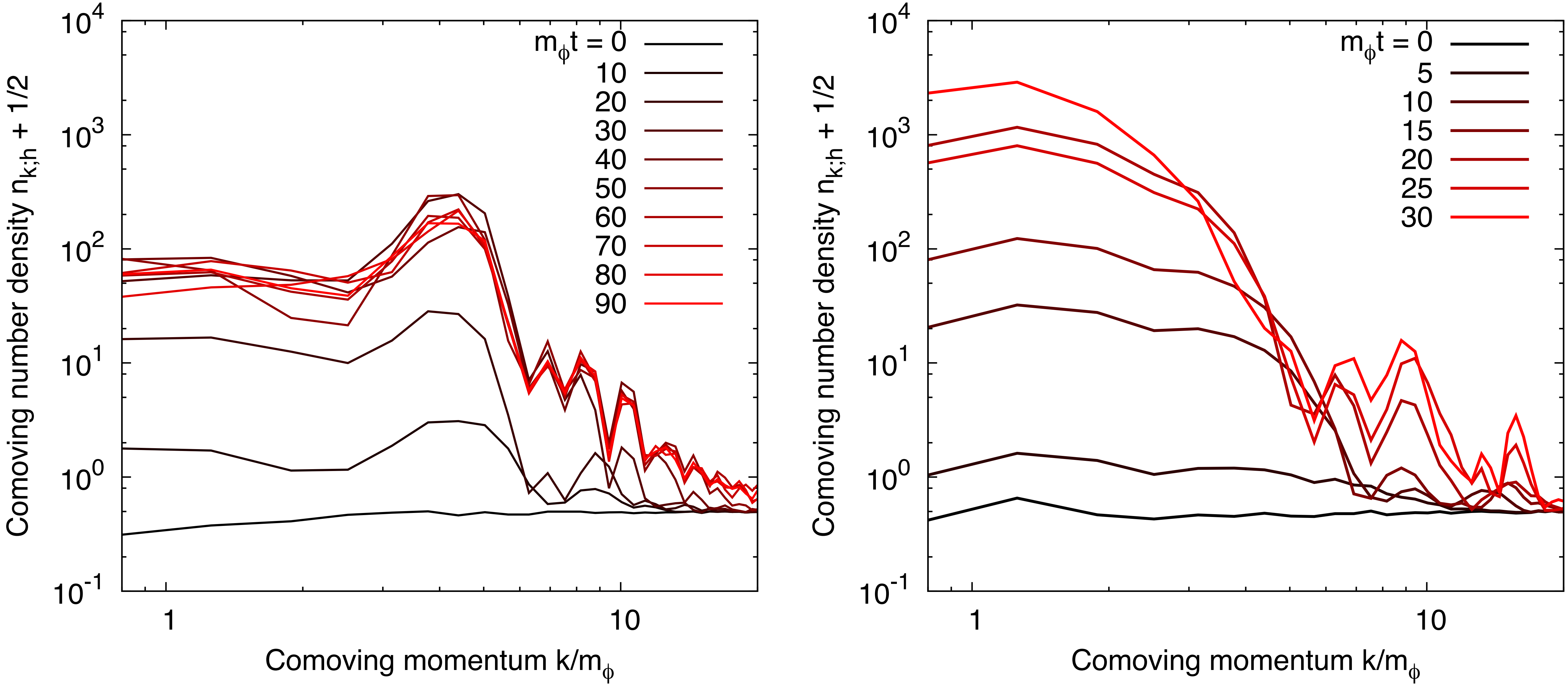

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Curvature: spectrum

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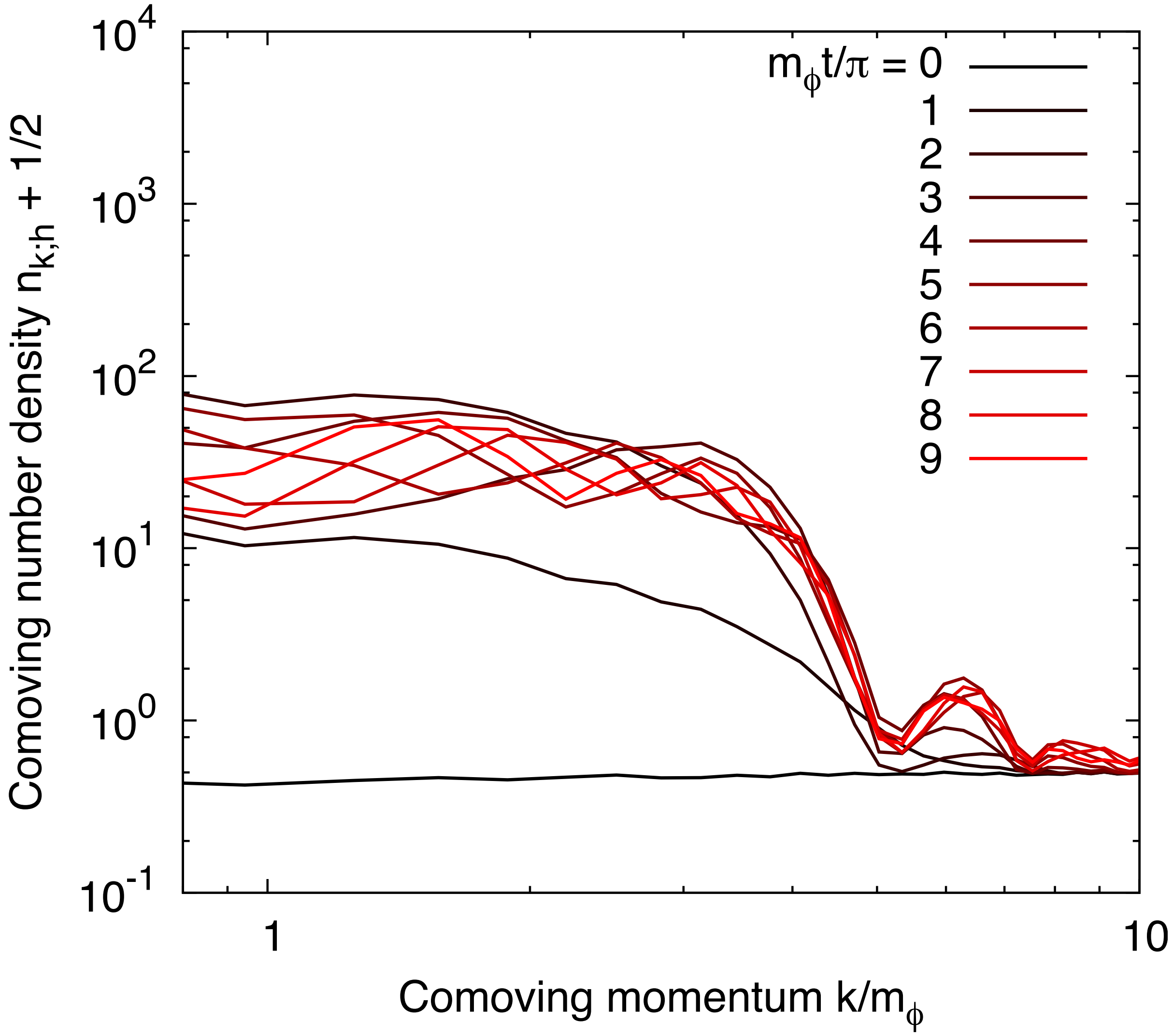

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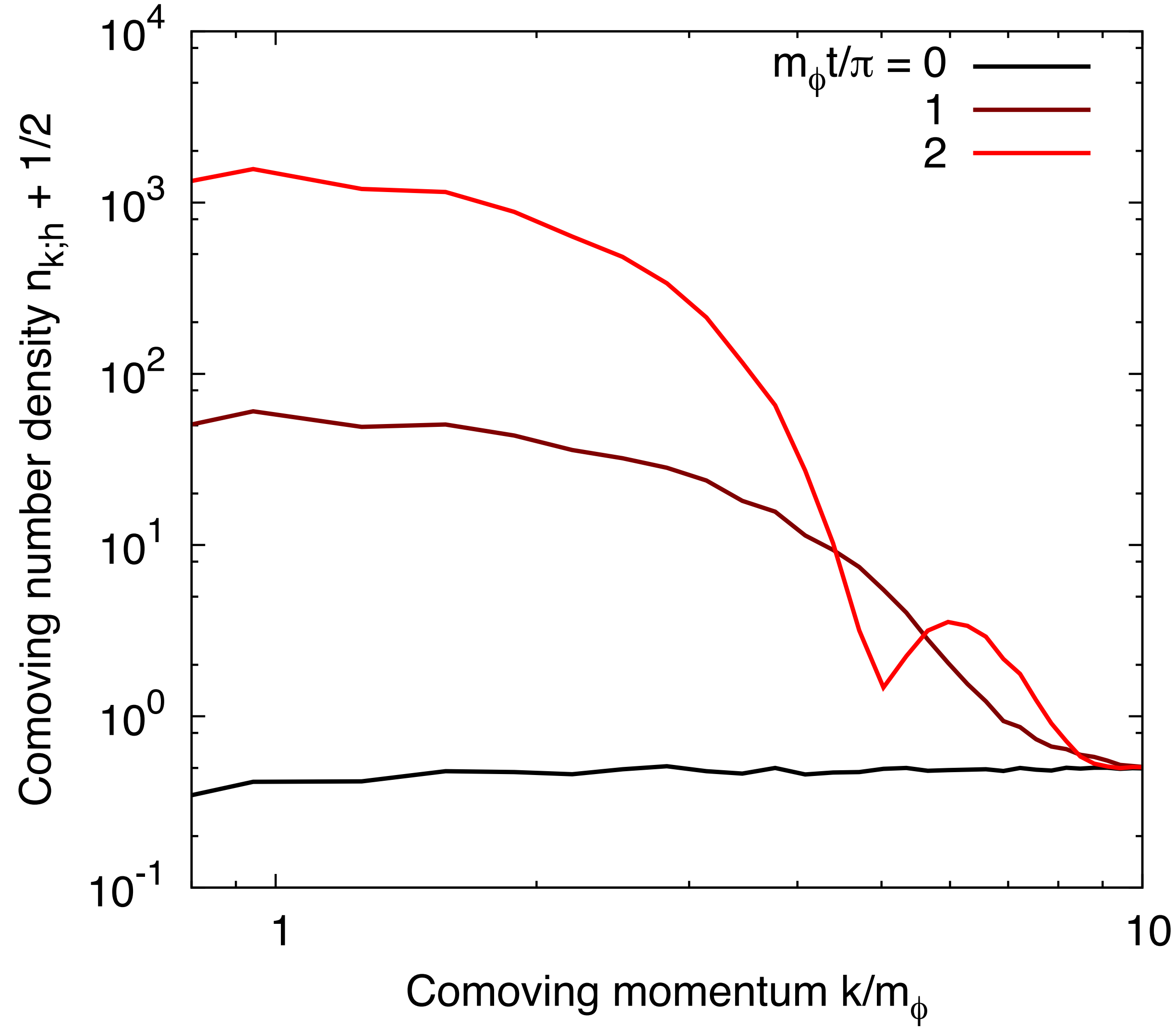

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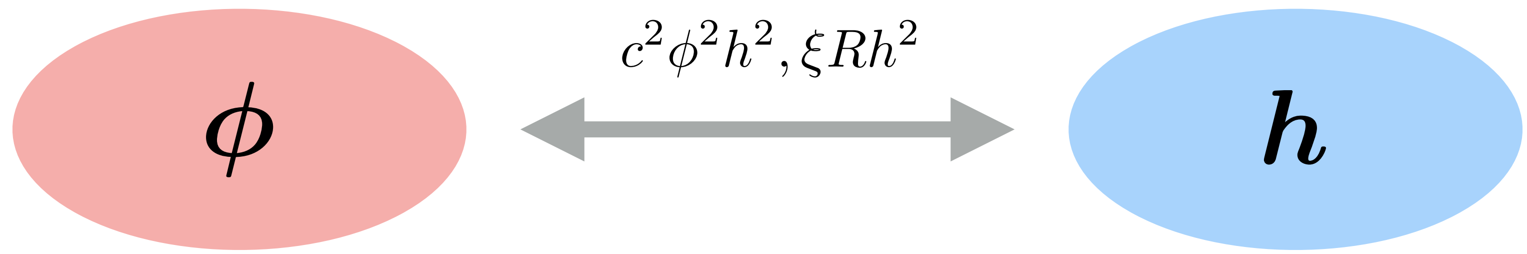
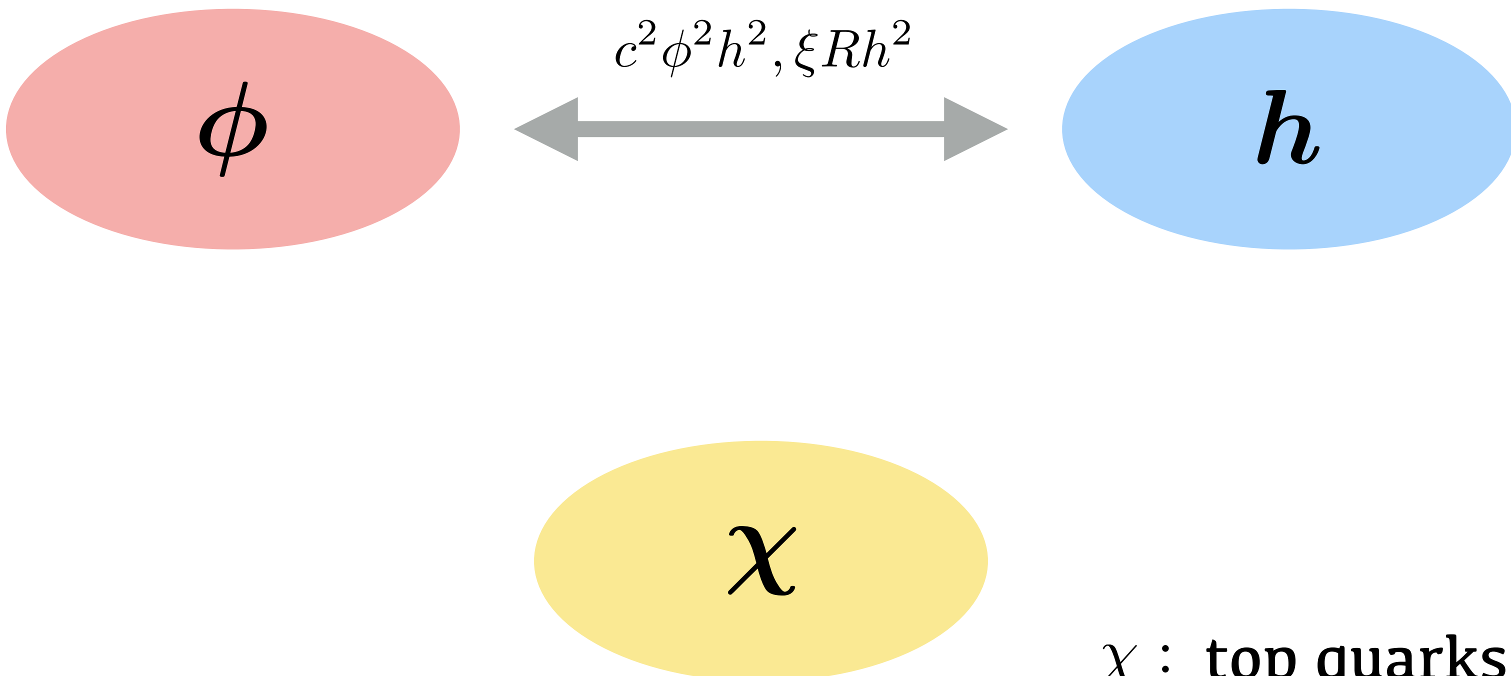
Coupling with SM particles

So far…



Coupling with SM particles

In reality…



χ : top quarks, EW gauge bosons

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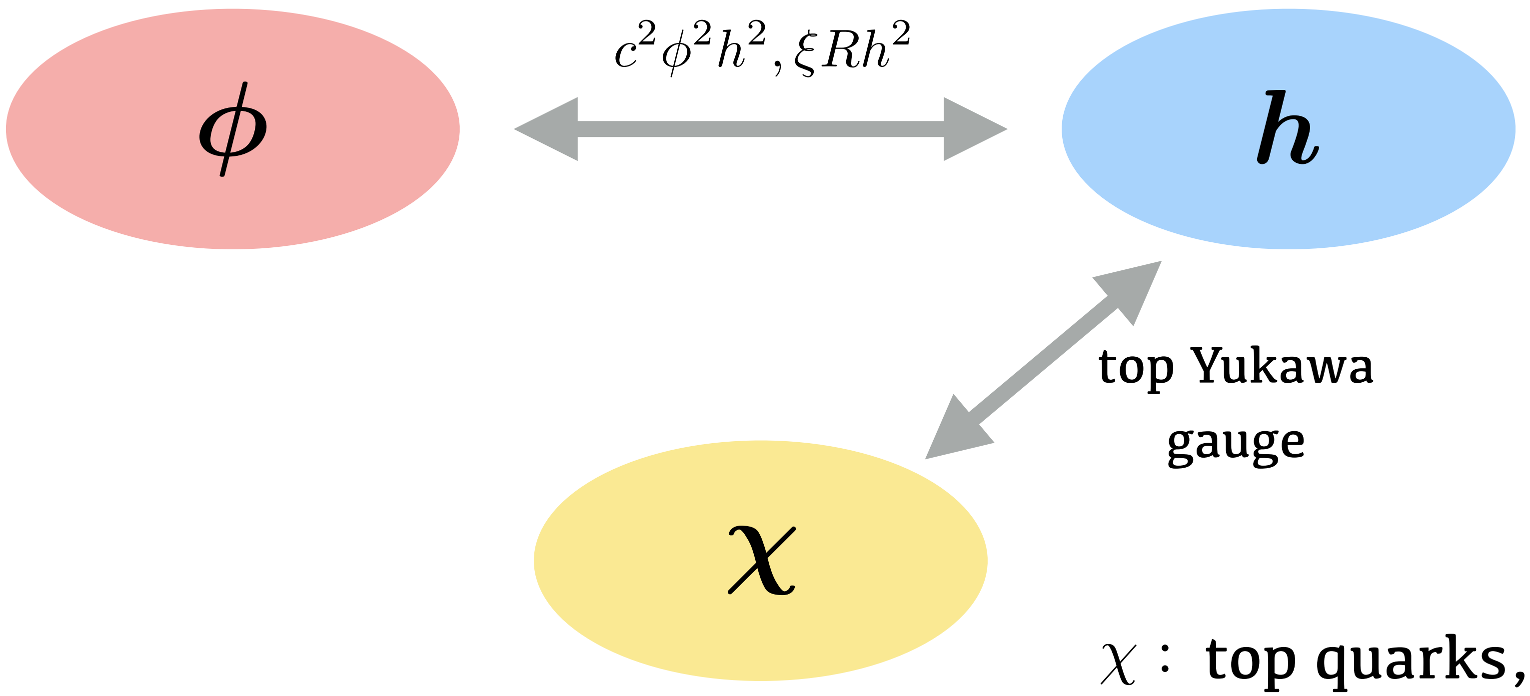

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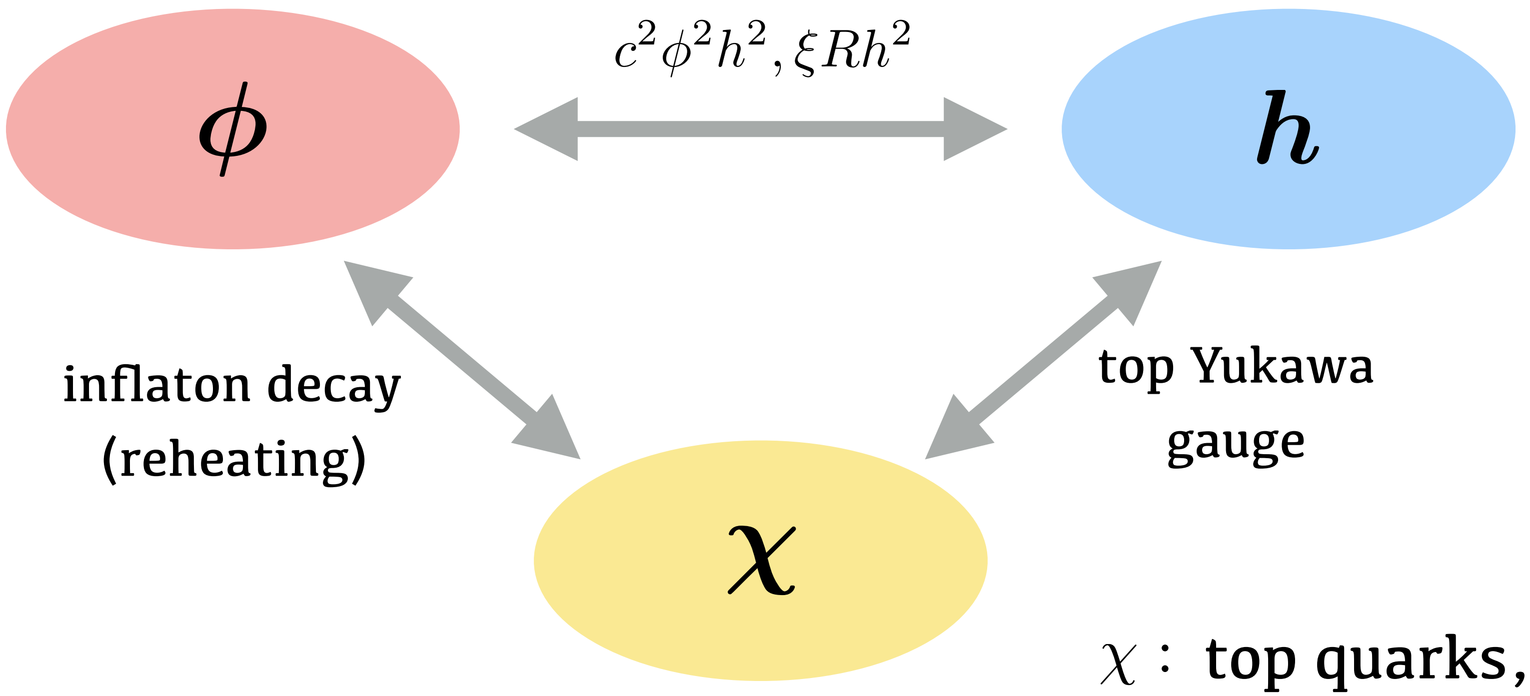

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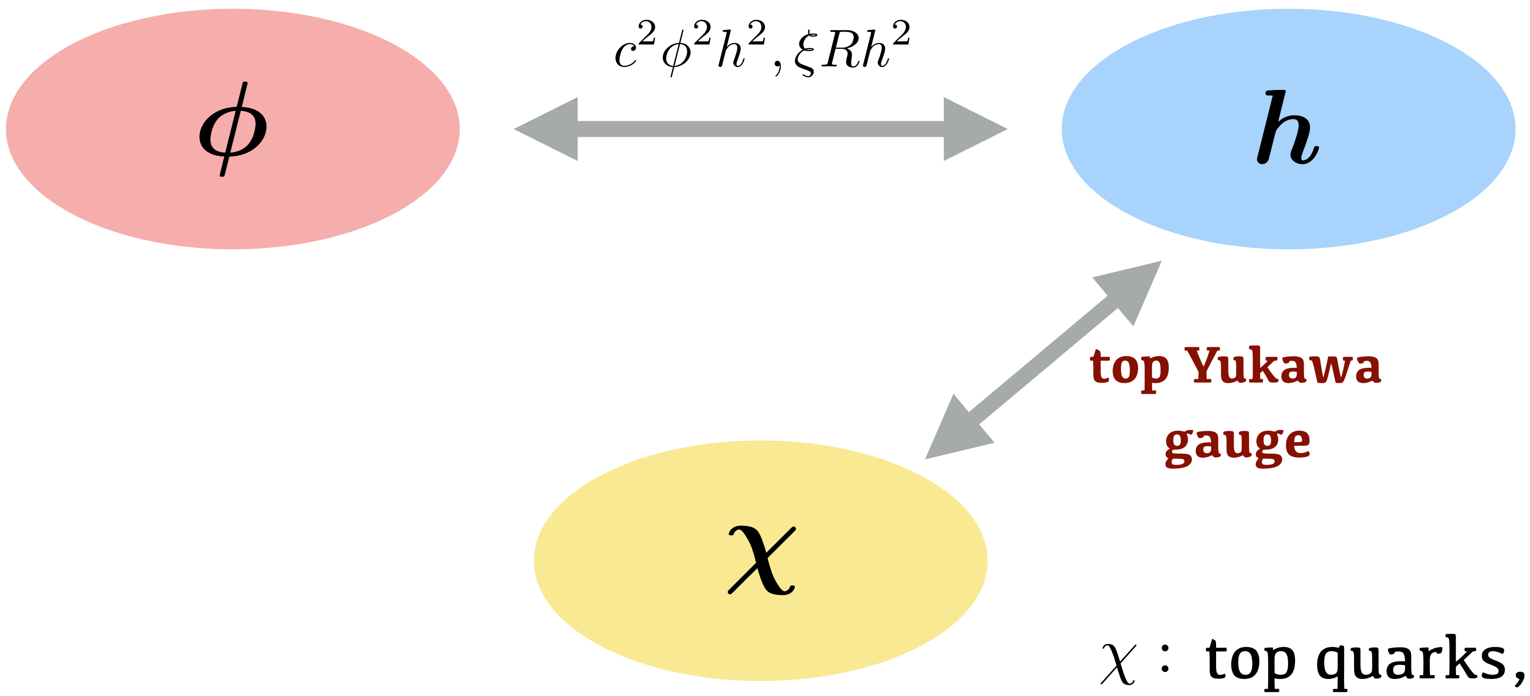

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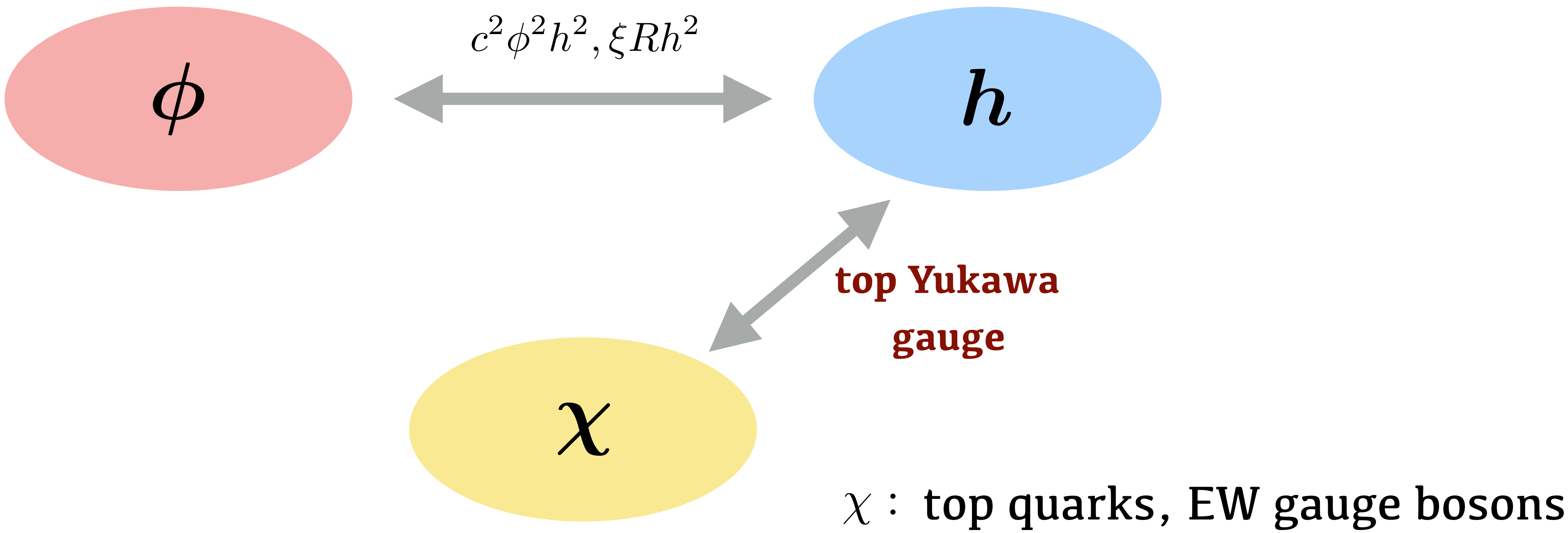


- Higgs decays into top quarks via top Yukawa coupling.

  Reduce Higgs resonance efficiency (instant preheating)

- Higgs annihilates into gauge boson pairs.

  Induce effective potential for Higgs

We will see they are **less significant** during preheating.

Instant preheating

Higgs is massive for the large field value region of inflaton.

$$m_{H;h}^2 = c^2\phi^2, \xi R$$

Higgs can decay via Yukawa at that region. [Felder+ 98]

There are two cases:

(1) [Resonant production rate] $\ll$ [Decay rate]

- Early stage of quartic coupling

(2) [Resonant production rate] $\gg$ [Decay rate]

- Late stage of quartic coupling
- Curvature coupling

* For curvature coupling, growth/decay rate $\propto \sqrt{\xi}$, and hence (2) always holds.

Instant preheating

(1) [Resonant production rate] $\ll$ [Decay rate]

- Higgs decay rate: $\Gamma_{h\to tt} \sim \alpha_t c\Phi$ $\alpha_t = y_t^2/4\pi$

  ➡ Higgs completely decays for $\alpha_t c\Phi \gg m_\phi/\pi$.

- Inflaton decay rate at that epoch: $\Gamma_{\rm inst} \sim \dfrac{c^2}{4\pi^4\sqrt{3\alpha_t/2}} m_\phi$

For $c \gtrsim \mathcal{O}(0.1)$, inflaton completely decays via this process.

Otherwise, (1) is eventually violated and the situation reduces to (2).

(2) [Resonant production rate] $\gg$ [Decay rate]

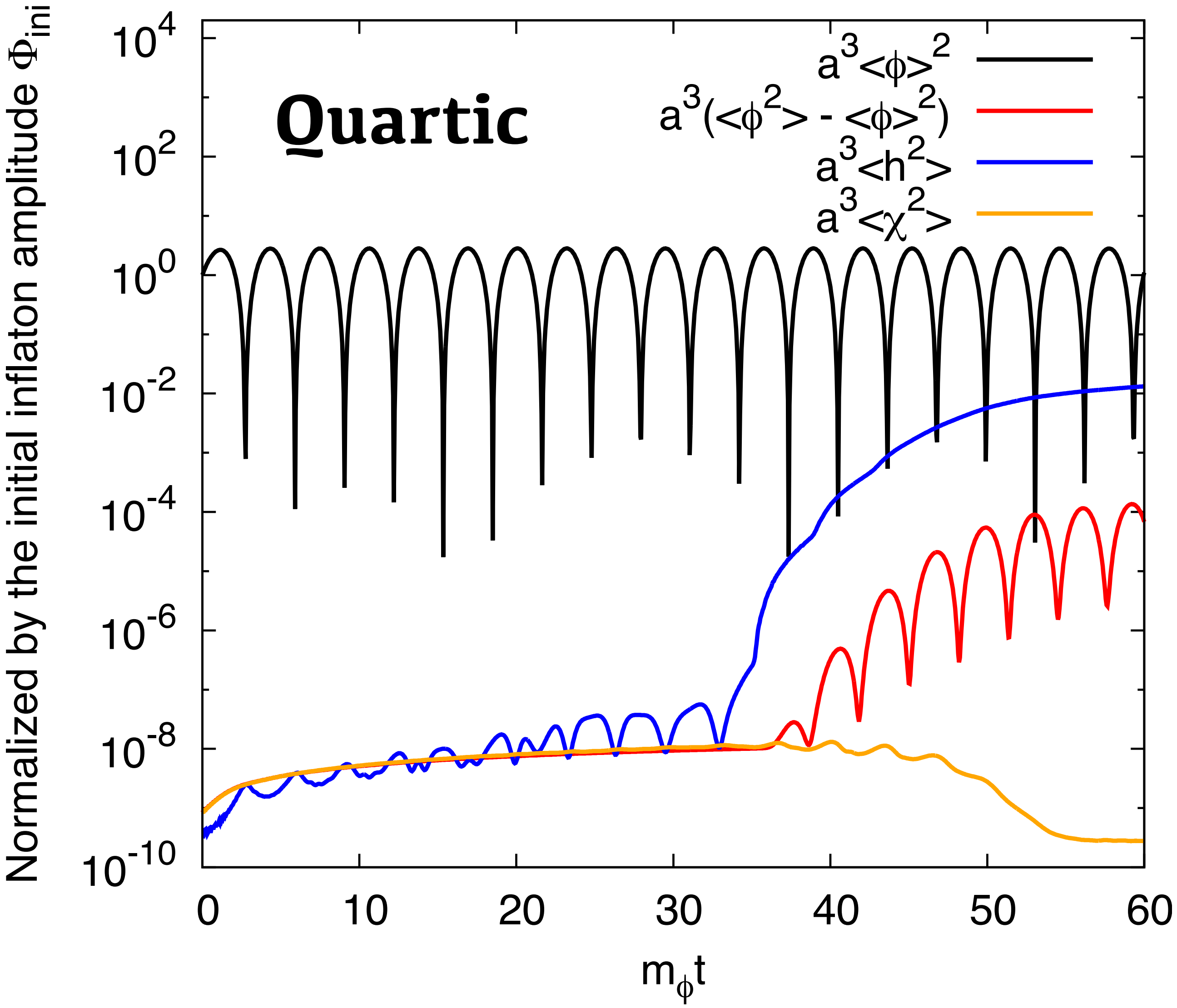
In this case, the decay just slightly reduces the production rate.

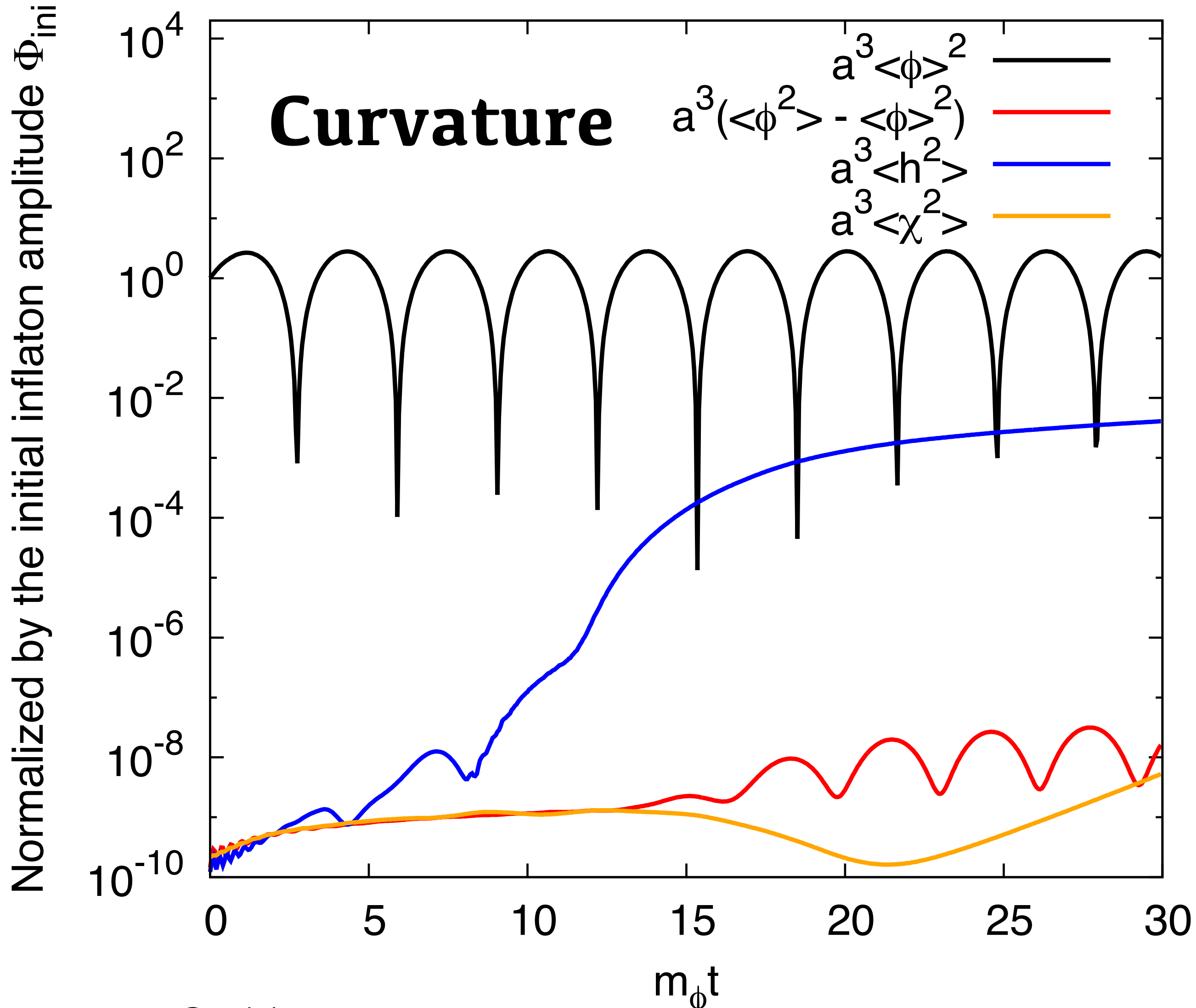
Annihilation

Consider the following simplified Lagrangian:

$$-\mathcal{L}_{\rm int} = \frac{1}{2} g_{h\chi}^2 h^2 \chi^2 + \frac{1}{4} g_{\chi\chi}^2 \chi^4,$$

with χ : light scalar field (mimicking gauge bosons).





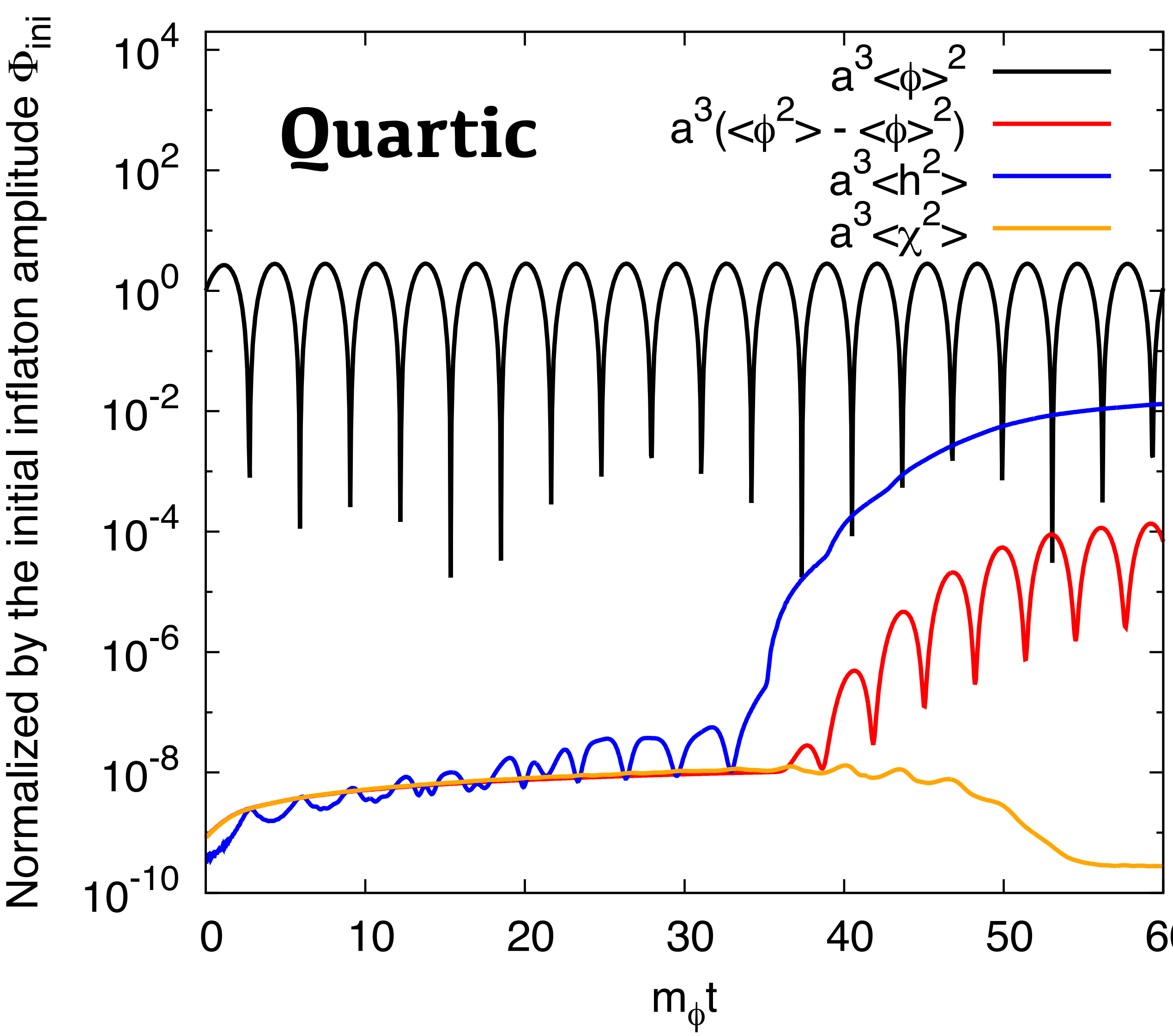
$$g_{h\chi} = g_{\chi\chi} = 0.5$$

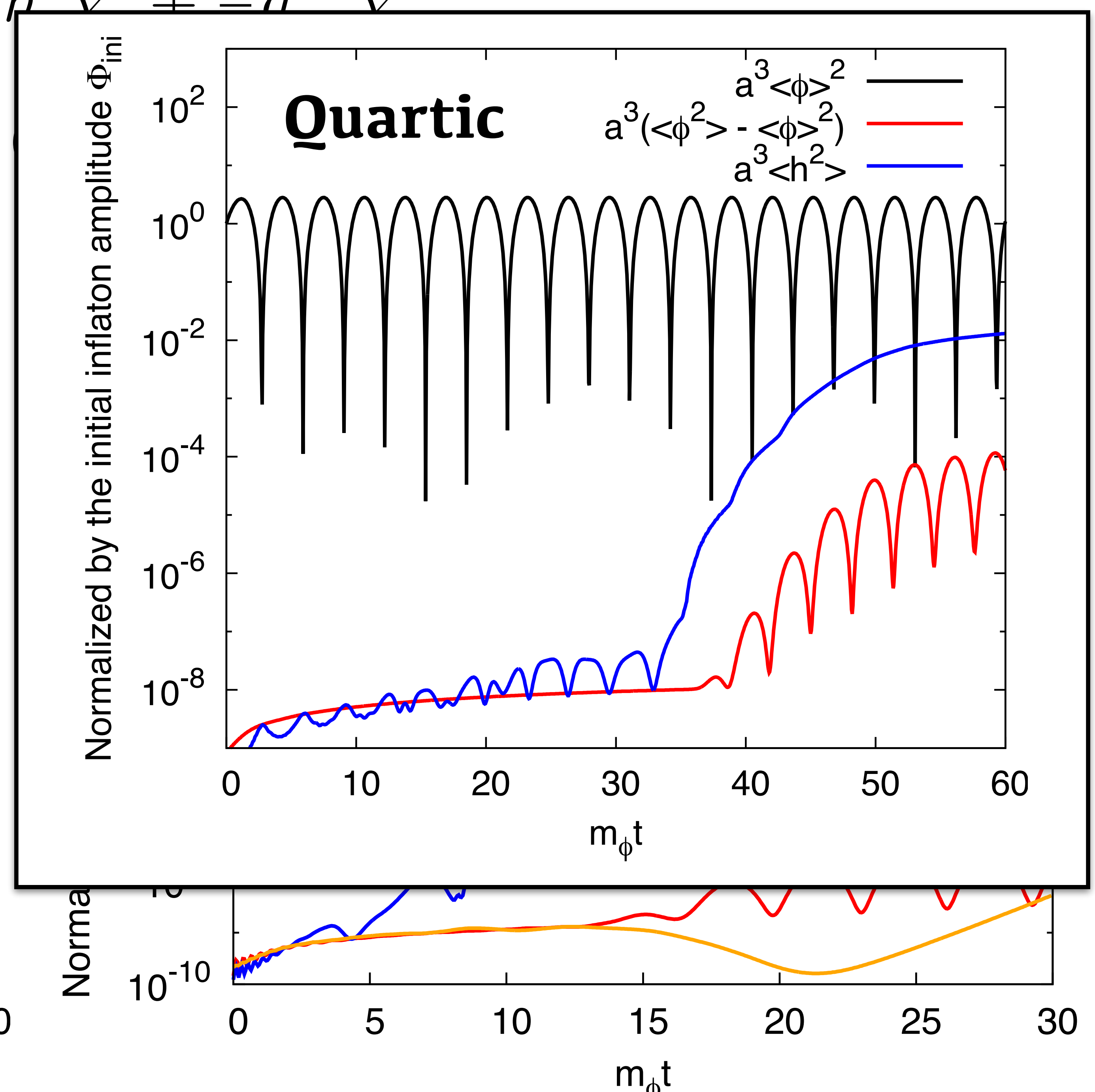
Annihilation

Consider the following simplified Lagrangian:

$$-\mathcal{L}_{\rm int} = \frac{1}{2}g_{h\chi}^2 h^2\chi^2 + \frac{1}{2}g^2\ \chi^4$$

with χ : light scalar field (





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Annihilation

Consider the following simplified Lagrangian:

$$-\mathcal{L}_{int} = \frac{1}{2} g_{h\chi}^2 h^2 \chi^2 + \frac{1}{4} g_{\chi\chi}^2 \chi^4,$$

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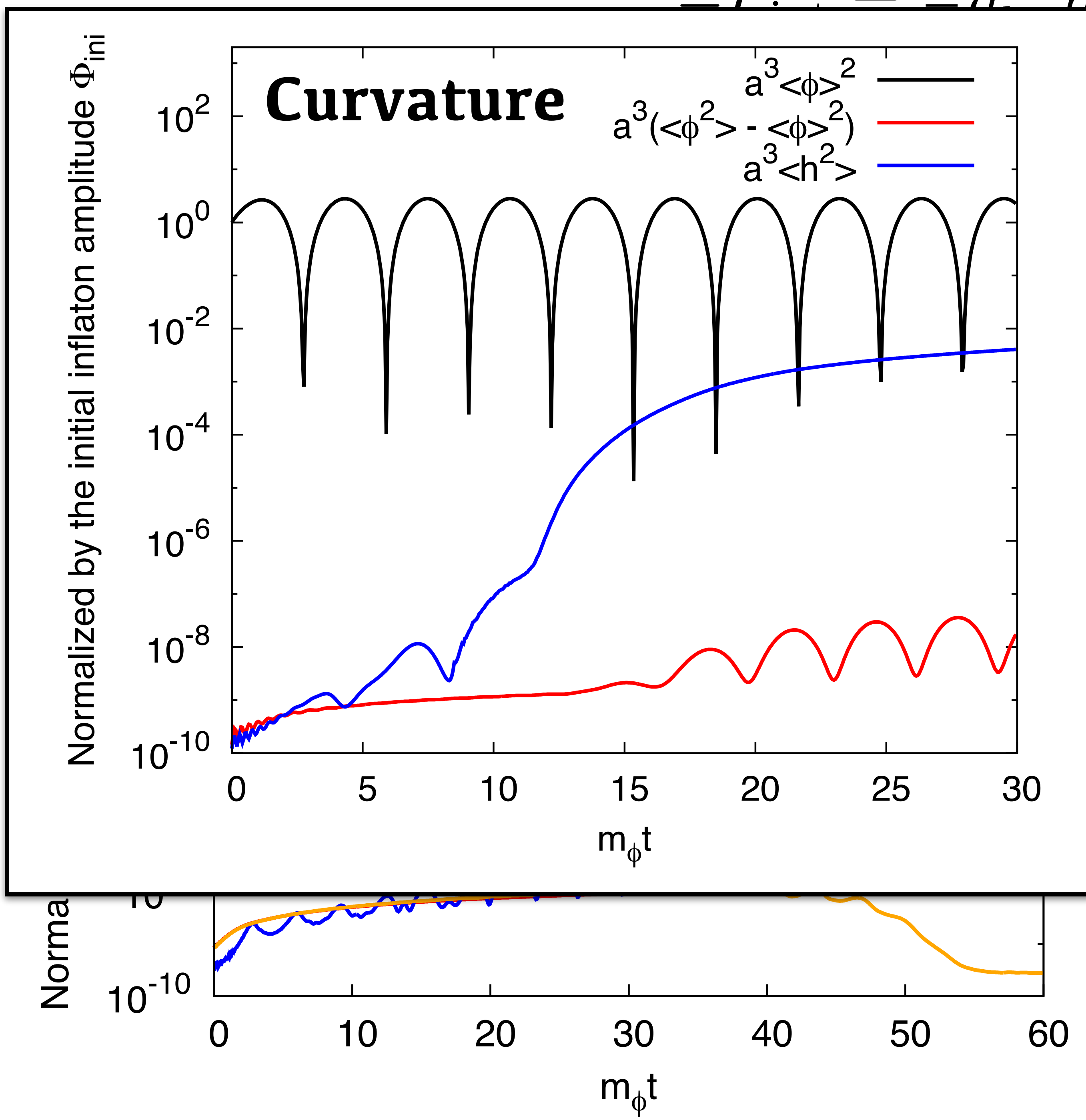
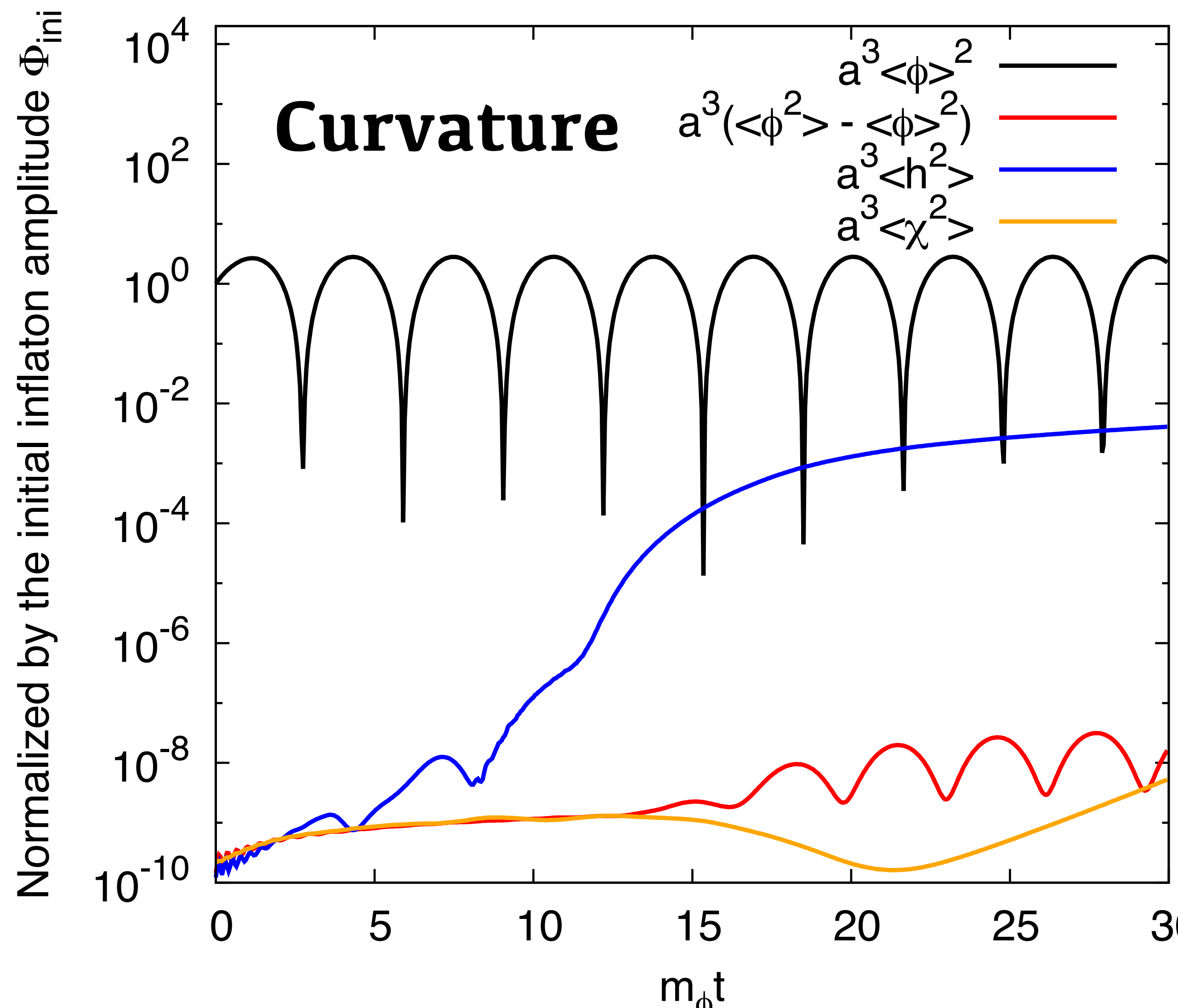




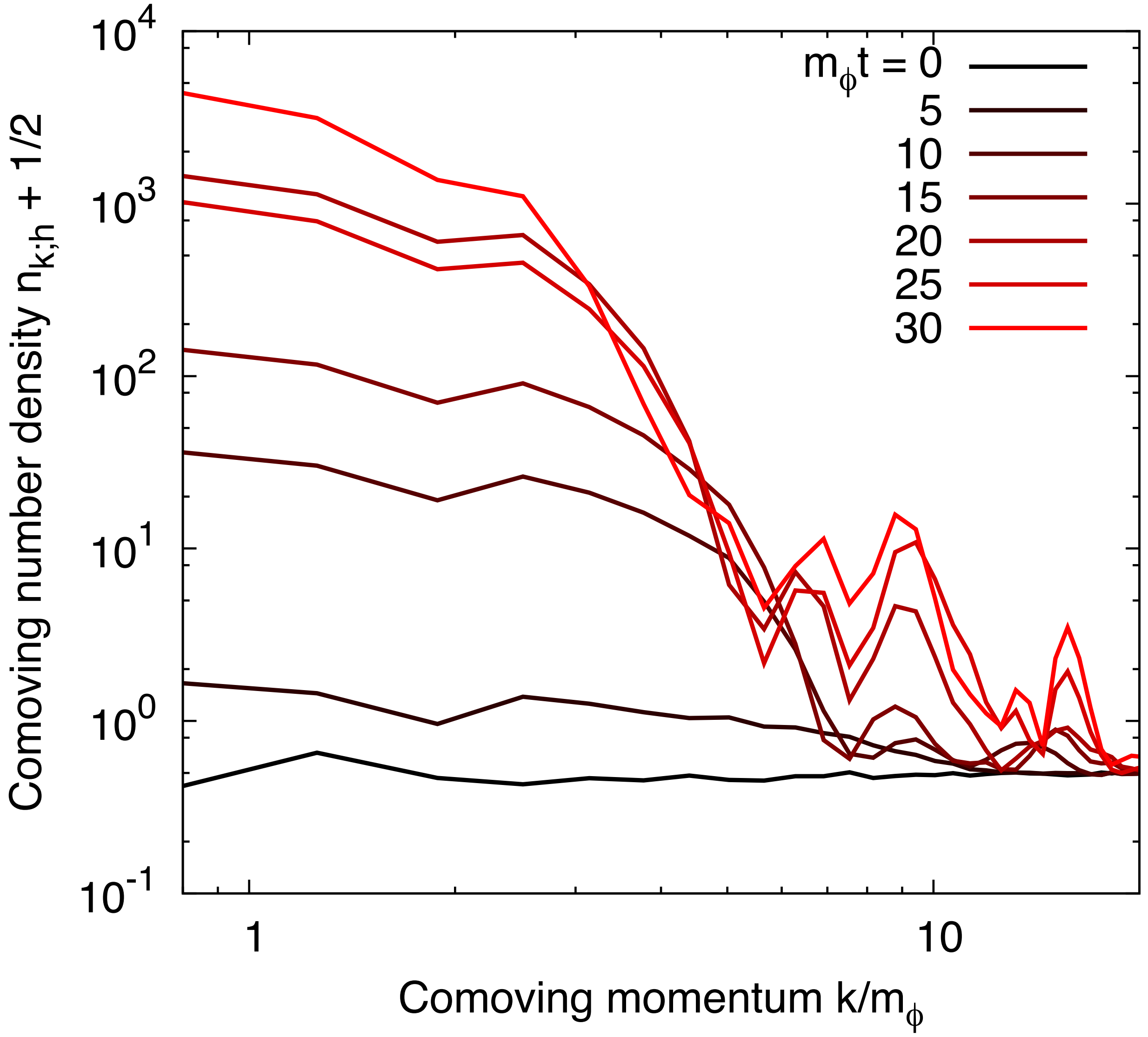
$$g_{h\chi} = g_{\chi\chi} = 0.5$$

Annihilation

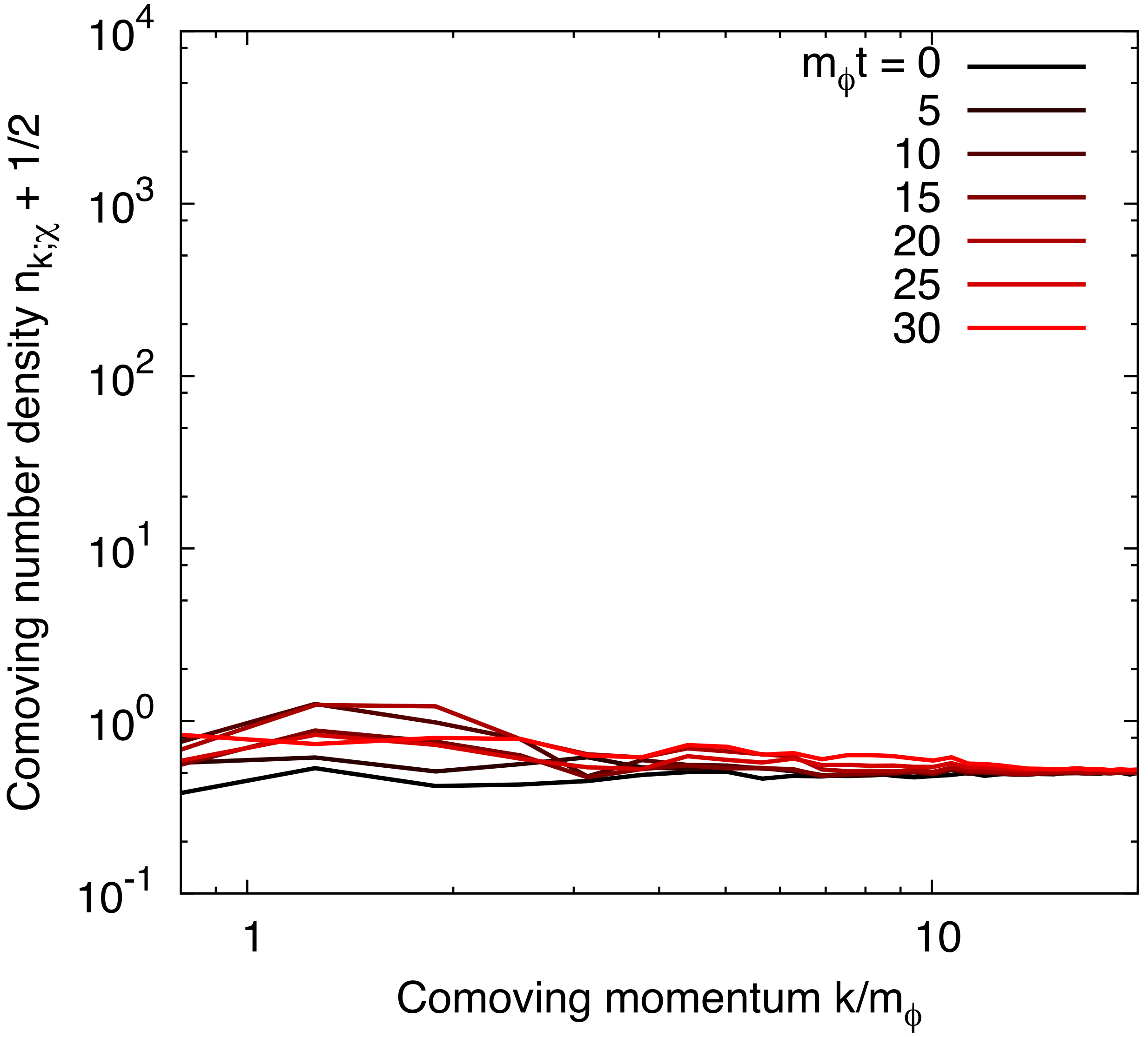
Higgs is resonantly produced, while χ is not efficiently produced.

(Effective mass $m^2_{\mathrm{eff};\chi} \simeq g^2_{h\chi}\langle h^2 \rangle$ might suppress the production.)

Spectrum of Higgs



Spectrum of χ



Cosmic expansion

- Assume EW vacuum survives the preheating epoch.
- For illustration, neglect top Yukawa and gauge couplings.

Just after preheating, Higgs is stabilized by $m^2_{H;h} = c^2\phi^2, \xi R.$

However, $m^2_{H;h} \propto a^{-3}$, while $\delta m^2_{\mathrm{self};h} \propto \langle h^2 \rangle \propto a^{-2}.$

➡ $\delta m^2_{\mathrm{self};h}$ eventually dominates over $m^2_{H;h}.$

For $\langle h^2 \rangle < h^2_{\mathrm{max}}$ before $m^2_{H;h} < |\delta m^2_{\mathrm{self};h}|$,

$$c \lesssim 3 \times 10^{-5} \left[\frac{0.1}{\mu_{\mathrm{qtc}}}\right], \quad \xi \lesssim 0.5 \left[\frac{2}{n_{\mathrm{eff}}\mu_{\mathrm{crv}}}\right]^2 \left[\frac{\sqrt{2}M_P}{\Phi_{\mathrm{ini}}}\right]^2 .$$

$m_\phi = 1.5 \times 10^{13}\,\mathrm{GeV}, \quad h_{\mathrm{max}} = 10^{10}\,\mathrm{GeV}$

* It means most parameters for stabilization during inflation cause catastrophe.

Cosmic expansion

- Assume EW vacuum survives the preheating epoc...
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Just after preheating, Higgs is ...

However, m_H^2 ... .

... er $m_{H;h}^2$.

F... $m_{\mathrm{self};h}^2|$,

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Dynamics after preheating is also non-trivial.

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Cosmic expansion

- ...e EW vacuum survives the preheating epo...
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Thermalization ... preheating
for EW vacuum ... is crucial
Dynamic... vacuum stability.
is also ... vial.

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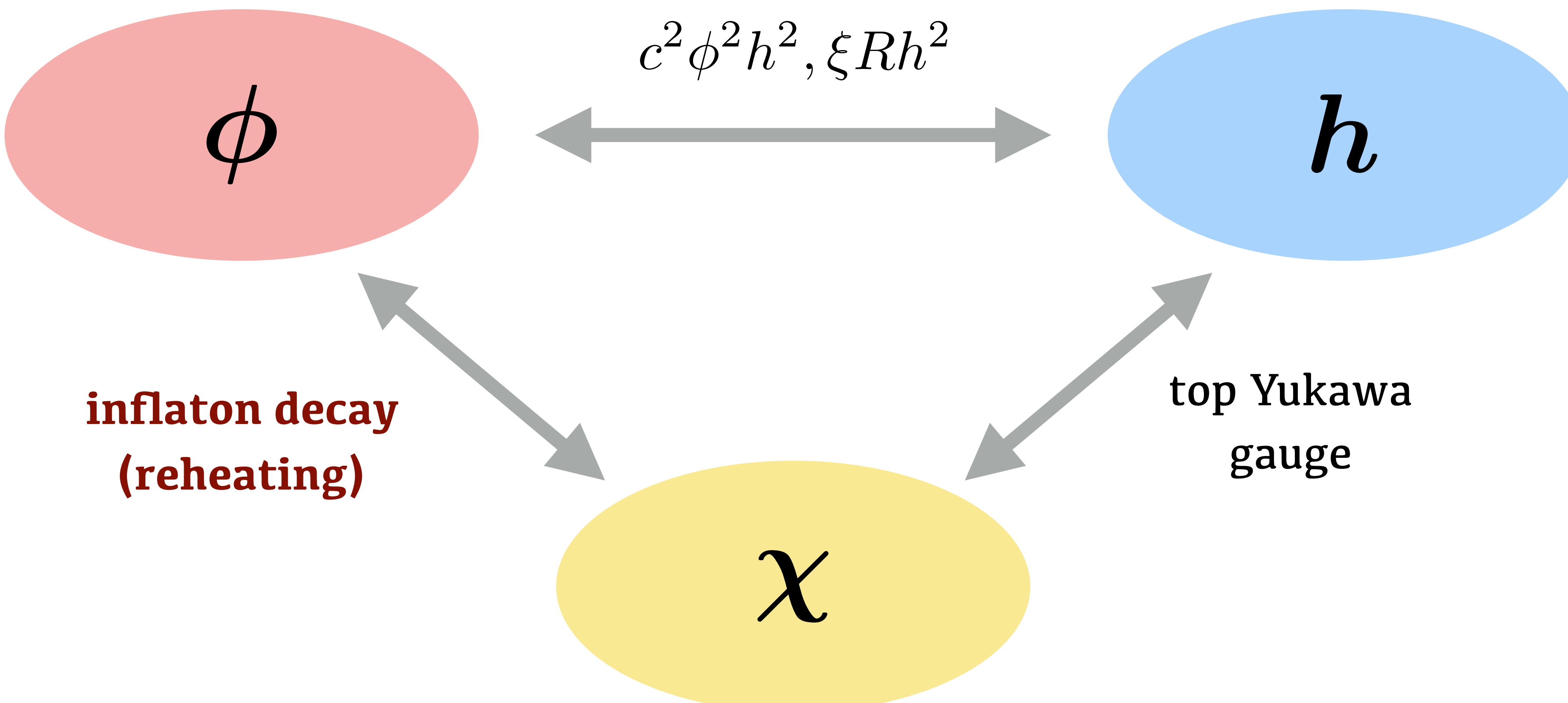
Complete reheating

Inflaton must decay
to complete the reheating process.



χ : top quarks, EW gauge bosons

Characterized by the reheating temperature $T_{\rm RH}$.

Complete reheating

- For $10^5\,\mathrm{GeV} \lesssim T_{\mathrm{RH}} \lesssim 10^{10}\,\mathrm{GeV}$,

  radiation from inflaton decay may stabilize Higgs after preheating.

  ➡ Thermal bounce is valid after that.

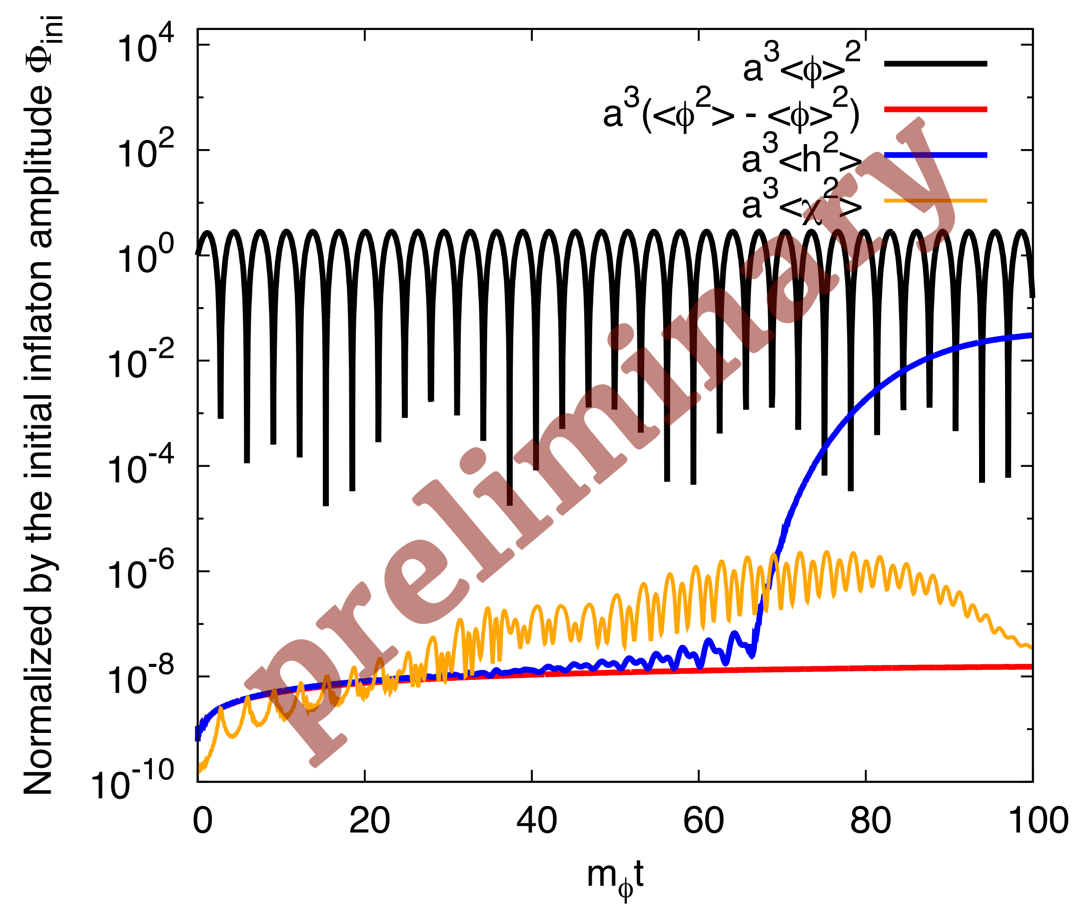
- For $T_{\mathrm{RH}} \gg 10^{10}\,\mathrm{GeV}$,

  parametric resonance might occur

  in other sectors during preheating.

  It might also induce EW vacuum decay??

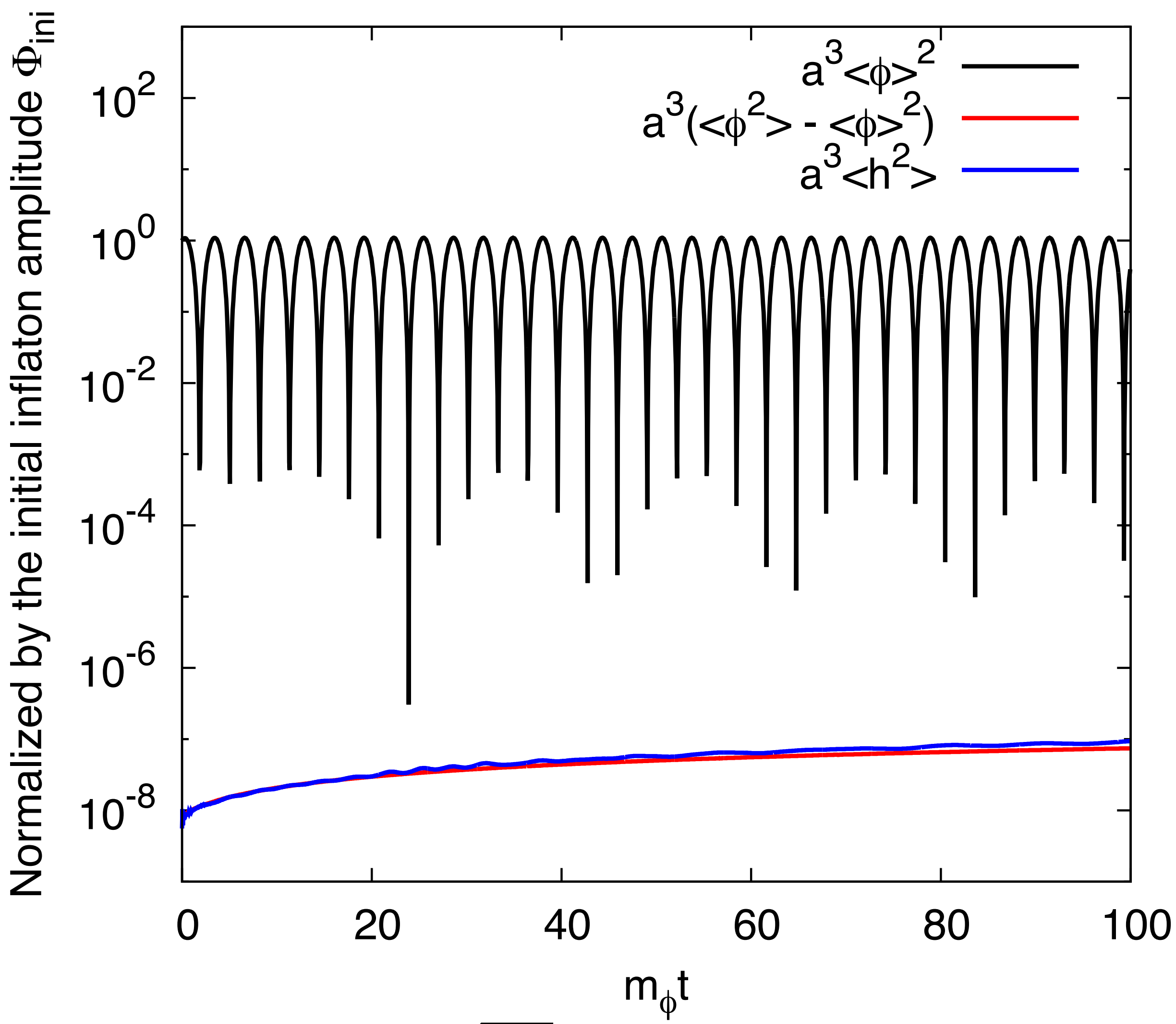
$$\Phi_{\mathrm{ini}} = \sqrt{2}\,M_{\mathrm{pl}}, m_\phi = 1.5\times 10^{13}\,\mathrm{GeV}, N = 128^3,$$
$$L = 10/m_\phi, dt = 10^{-3}/m_\phi, g_{\phi\chi} = 5\times 10^{-4}$$



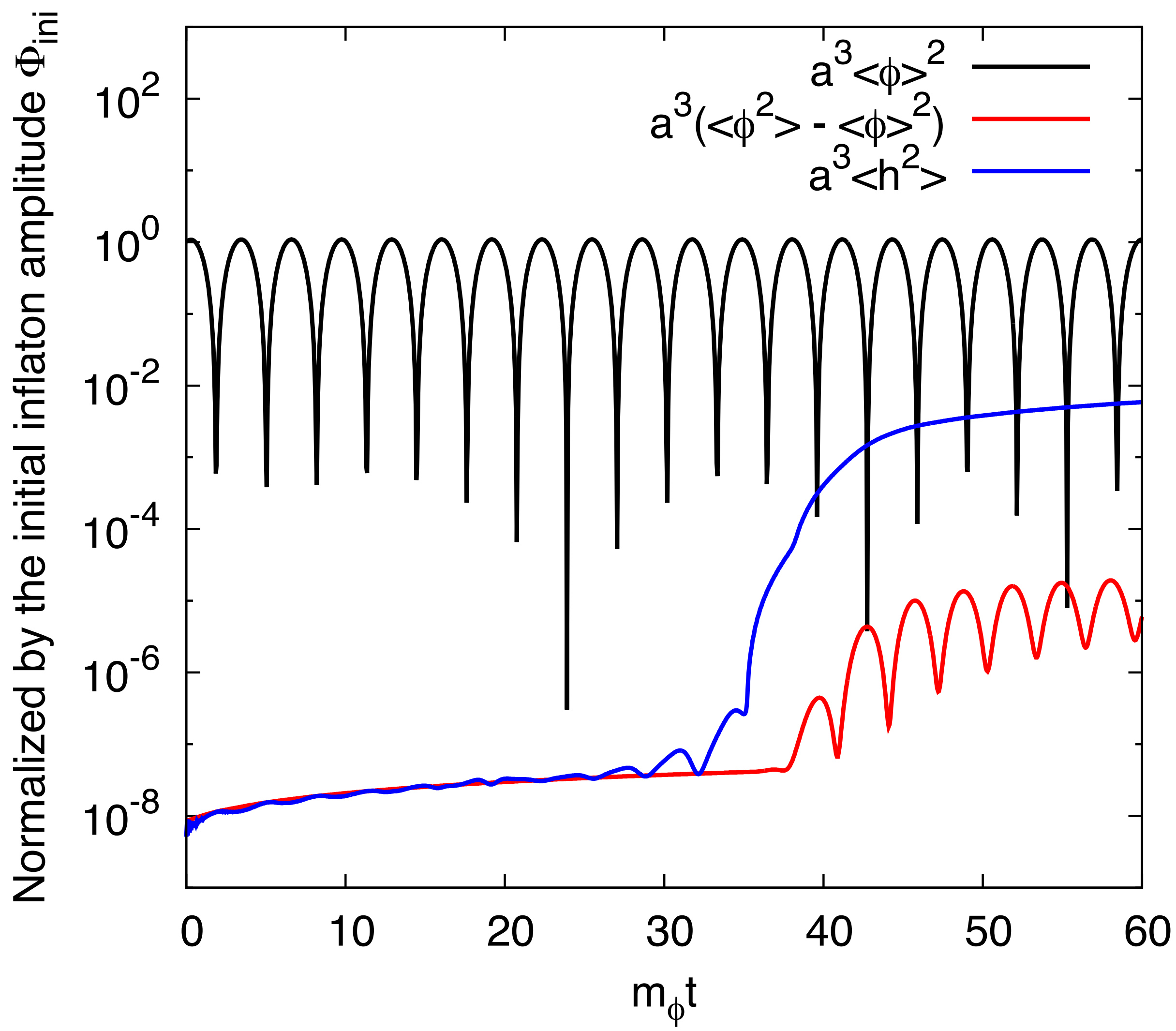
Quartic: lattice simulation

We have changed the initial inflaton amplitude as $\Phi_{\rm ini} = \sqrt{0.2}\, M_{\rm pl}$.

$c = 1 \times 10^{-4}$



$c = 2 \times 10^{-4}$



$\Phi_{\rm ini} = \sqrt{0.2}\, M_{\rm pl}, m_\phi = 1.5 \times 10^{13}\, {\rm GeV}, N = 128^3, L = 40/m_\phi, dt = 10^{-3}/m_\phi$

(added 6th term for large field for convergence)

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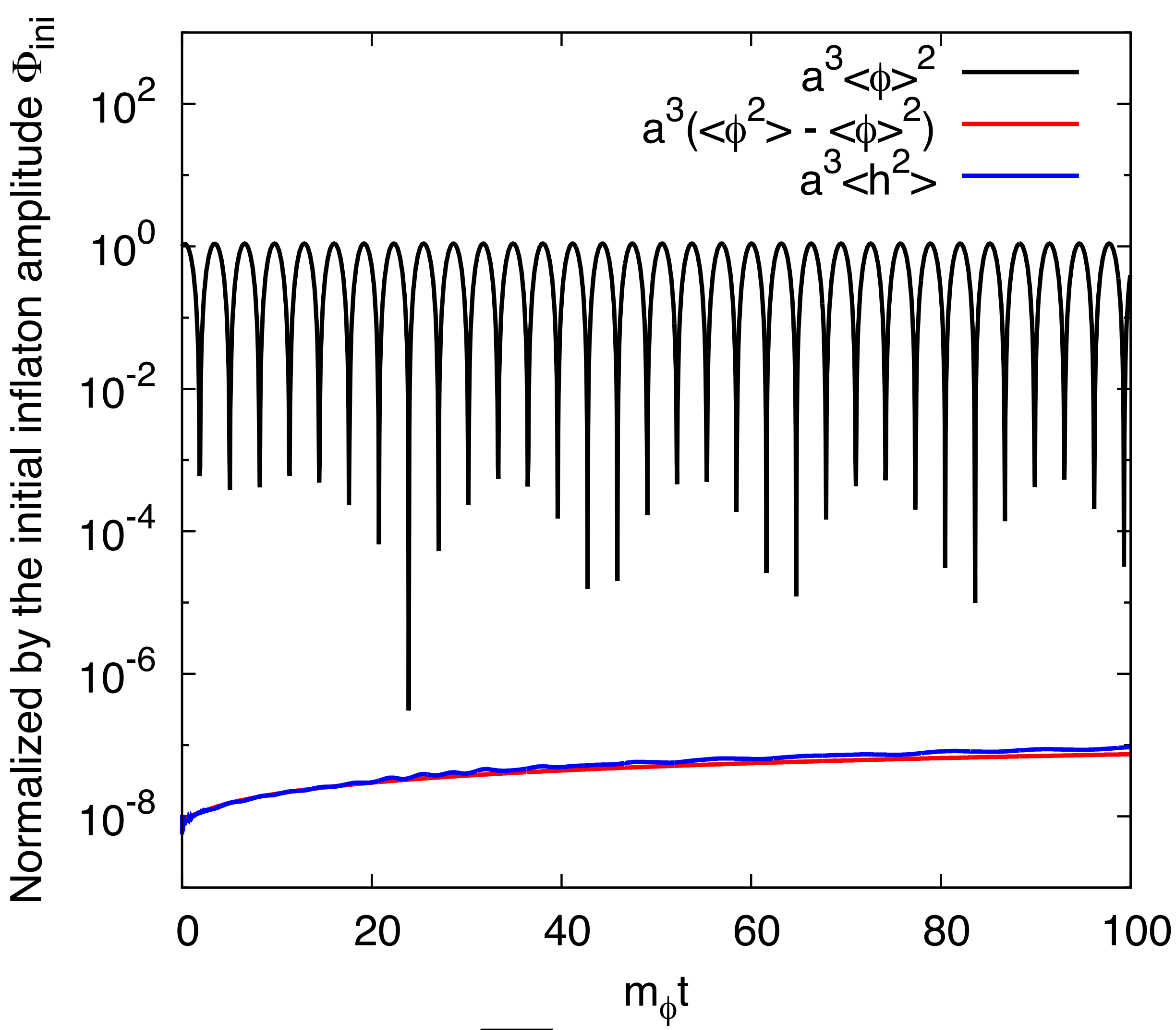

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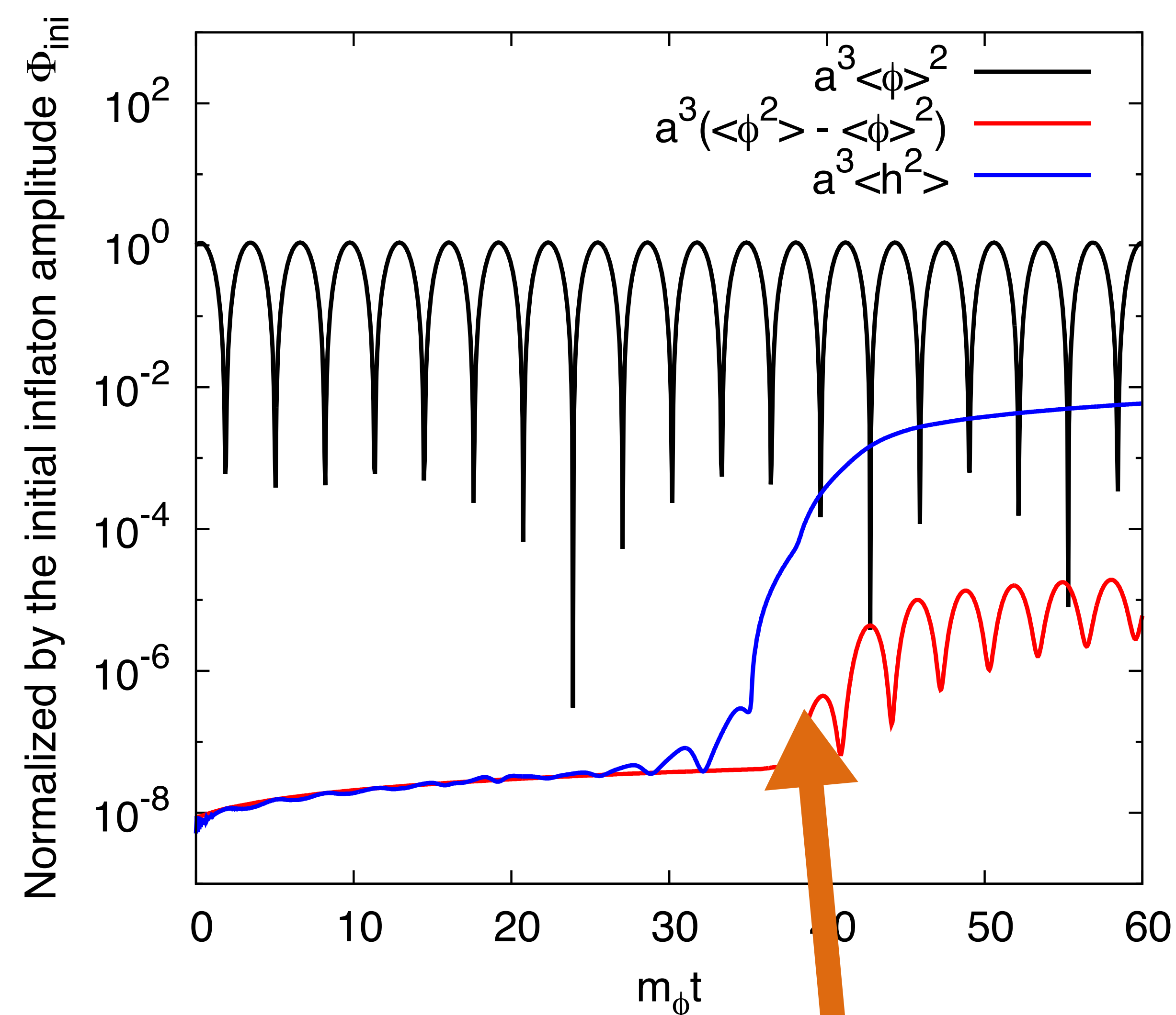

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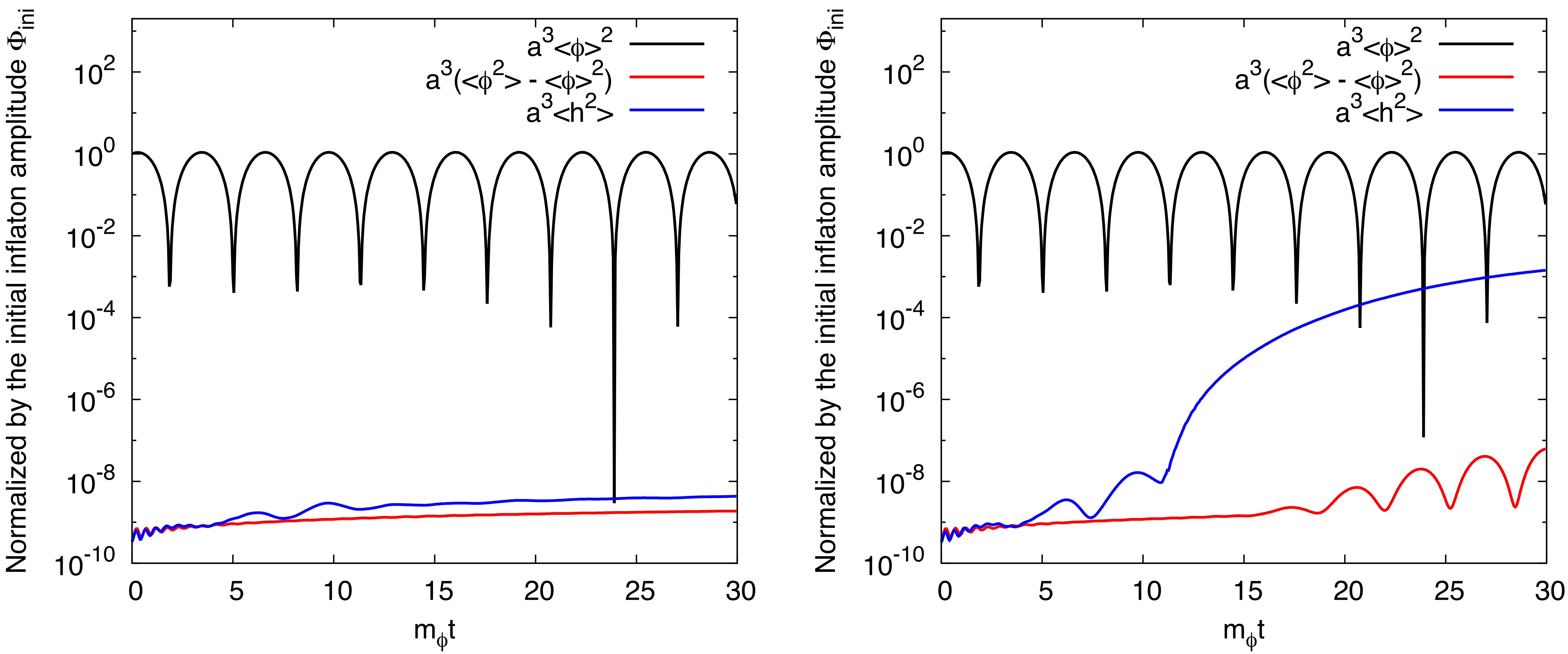
EW vacuum decays!!

Curvature: lattice simulation

We have changed the initial inflaton amplitude as $\Phi_{\rm ini} = \sqrt{0.2}\, M_{\rm pl}$.

$\xi = 20$ $\xi = 30$



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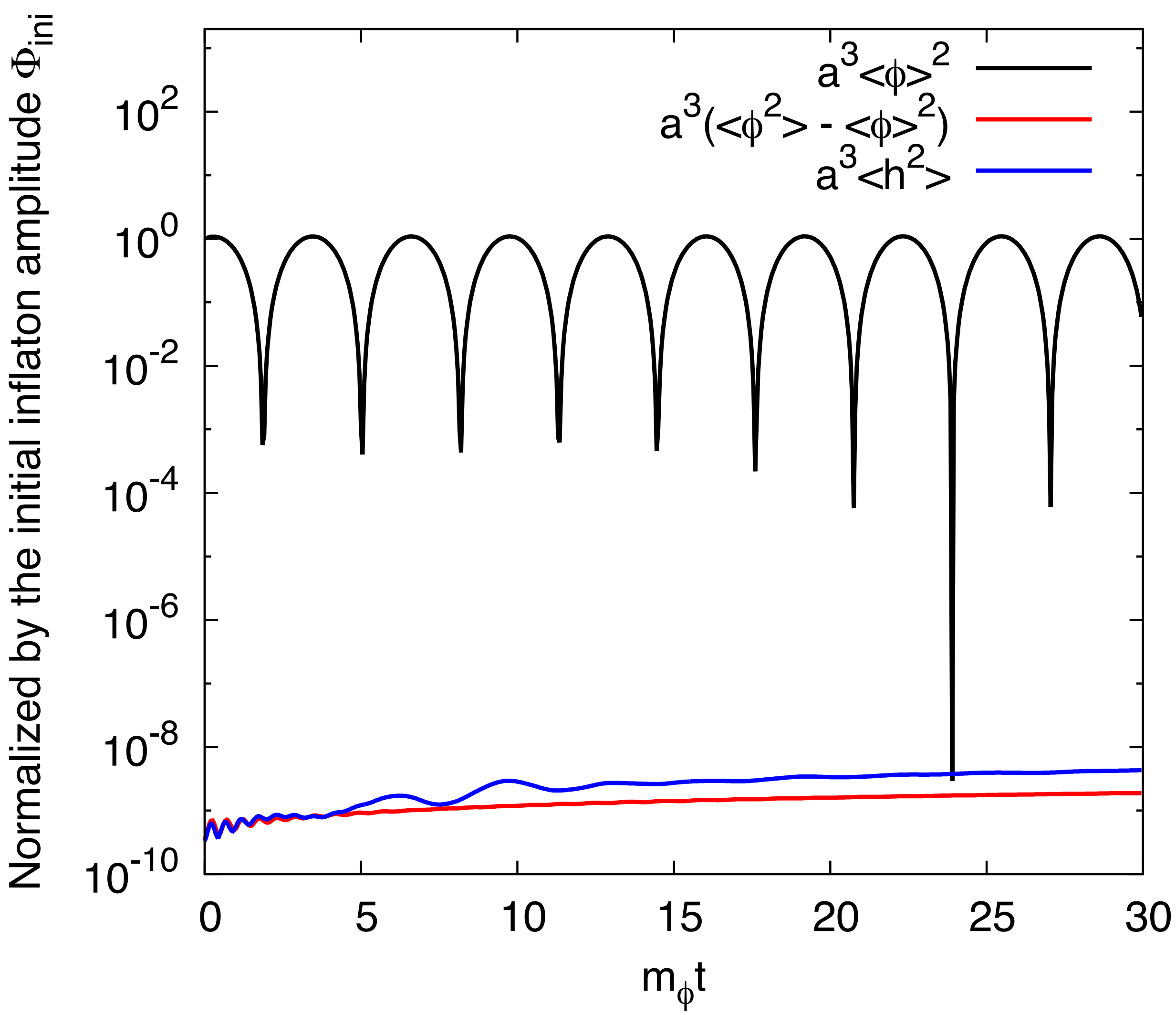

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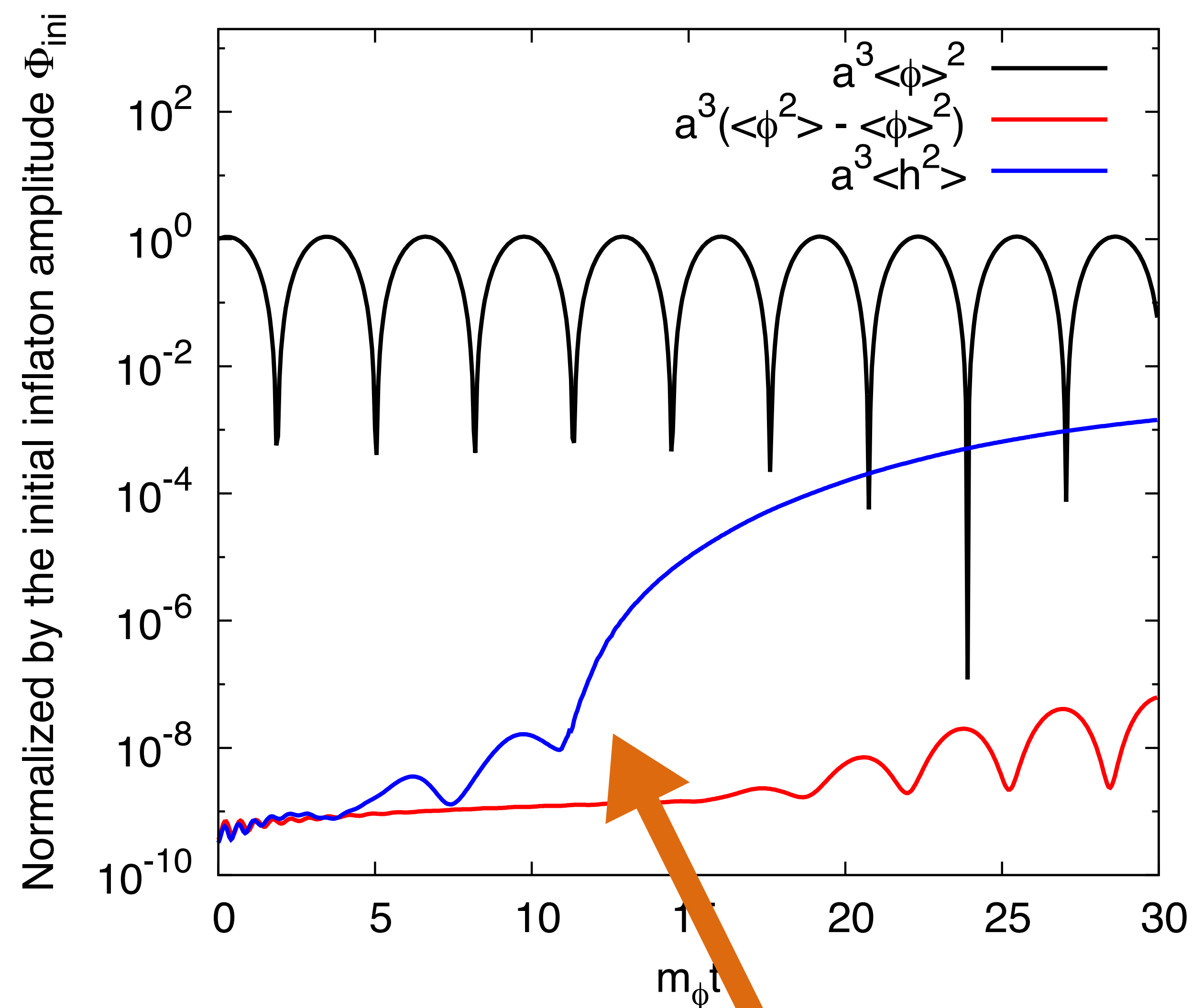

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