Metastable Electroweak Vacuum and Chaotic Inflation

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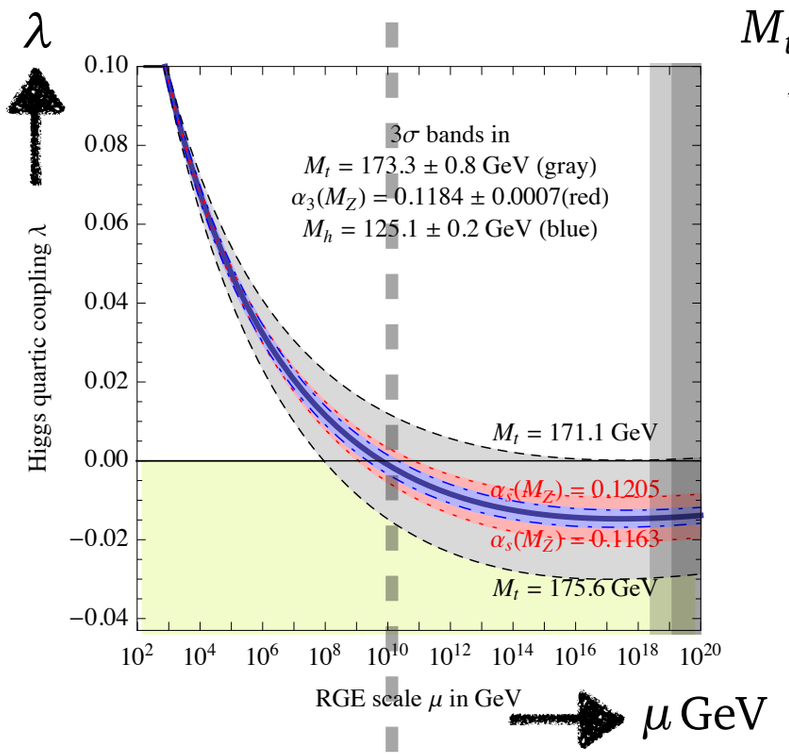
Based on 1602.00483; and 1605.04974
In collaboration with Ema, Nakayama; and Kawasaki, Yanagida

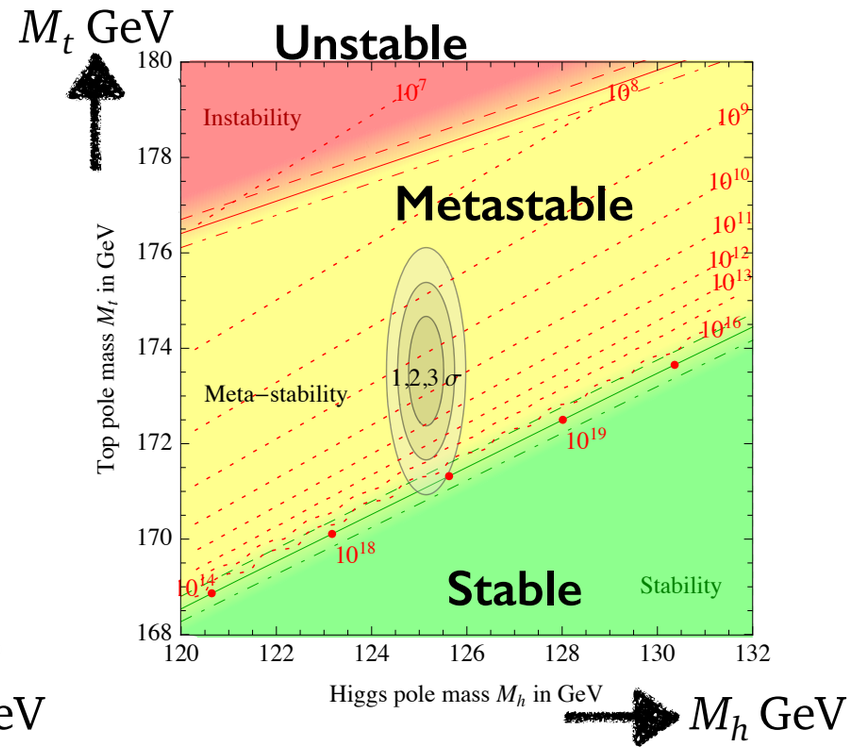
Introduction

Metastable EW Vacuum

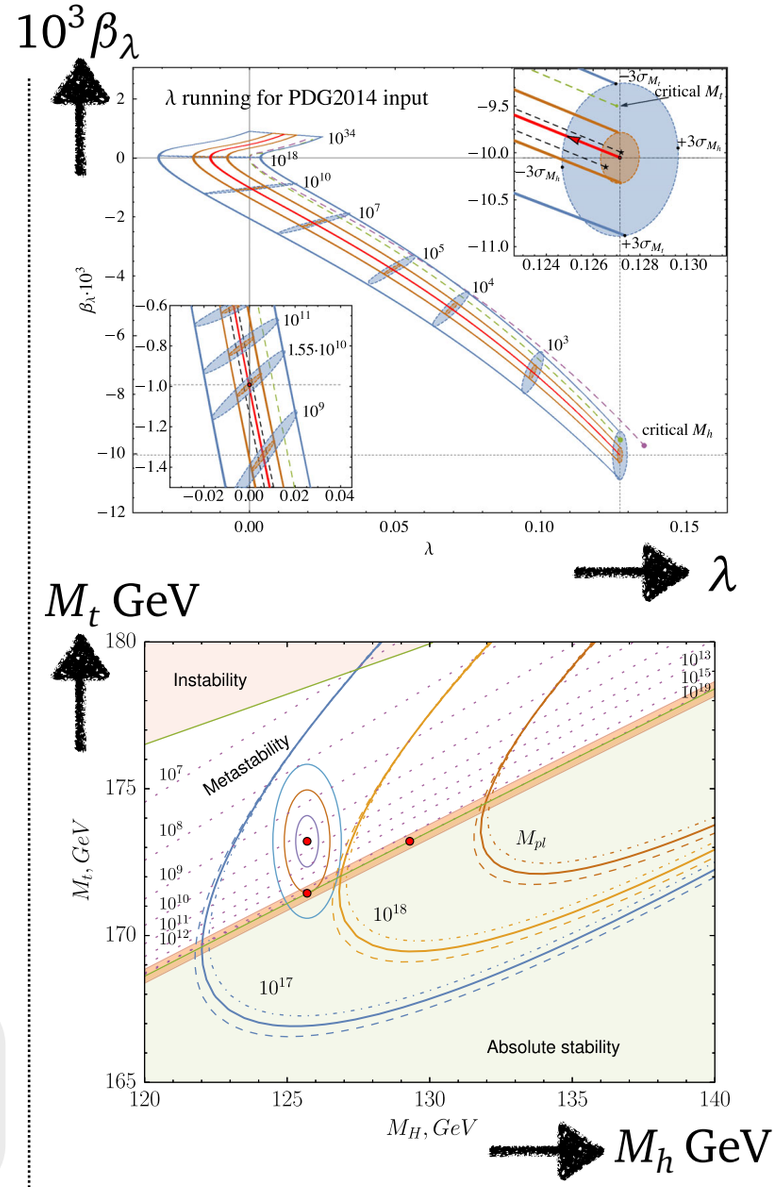
■ **Near-criticality** of the Standard Model?



10^{10}GeV



[Buttazzo+, JHEP12(2013)089]



[Bednyakov+, PRL115(2015)201802]

- λ < 0 at ~ **10^{10} GeV** for the center value of M_t.

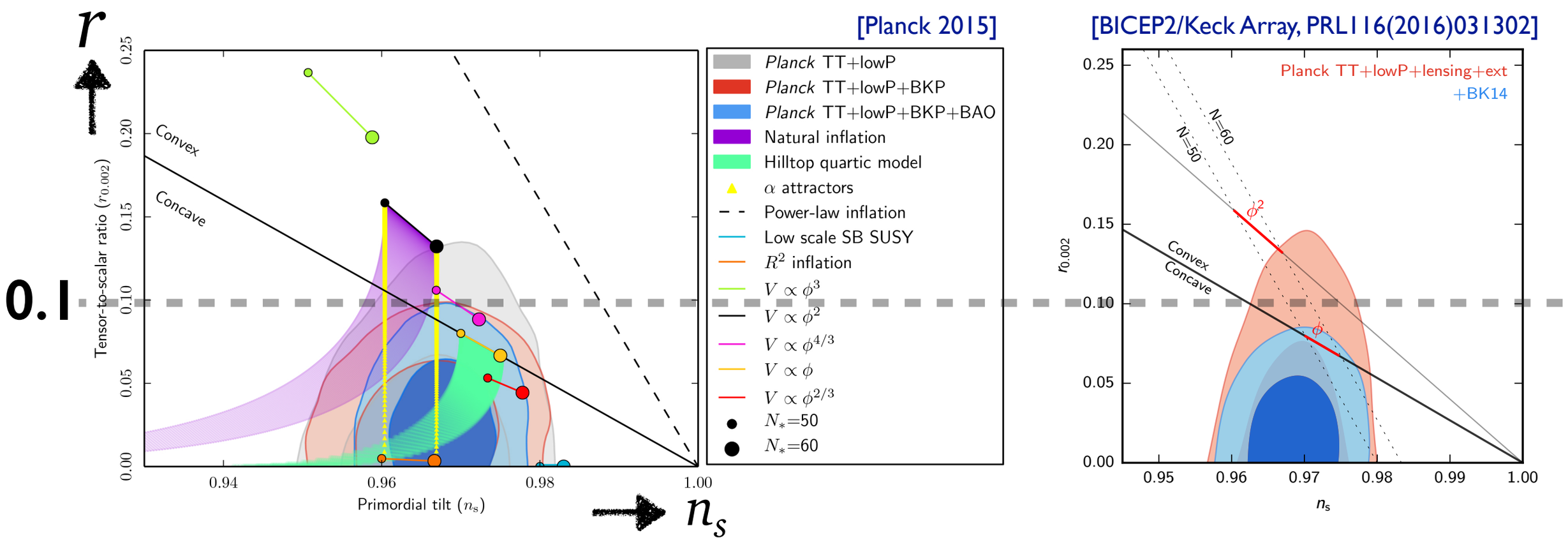
◉ **v.s. Cosmology**; Stability against cosmological evolution

- High scale inflation v.s. Metastable electroweak vacuum

- v.s. New Physics; modify the effective potential. [Many works…]

Chaotic Inflation

- Large Hubble parameter during inflation: $\mathbf{H_{inf} \sim 10^{13\text{-}14}\ GeV}$.
  - Smoking gun signature: large tensor to scalar ratio: $r \sim 0.1 \left(\frac{H_{\rm inf}}{10^{14}\,{\rm GeV}} \right)^2$
  - Simple, solve initial condition problem; but require a Planckian field excursion.



- **r > 0.1** : disfavored; **r ~ O(0.01)** : now being constrained.
- **r ~ 10^{-3}** : may be probed in the future (e.g. LiteBIRD, PIXIE).

Metastability v.s. Cosmology

■ Thermal History of Universe

- Vacuum decay during inflation

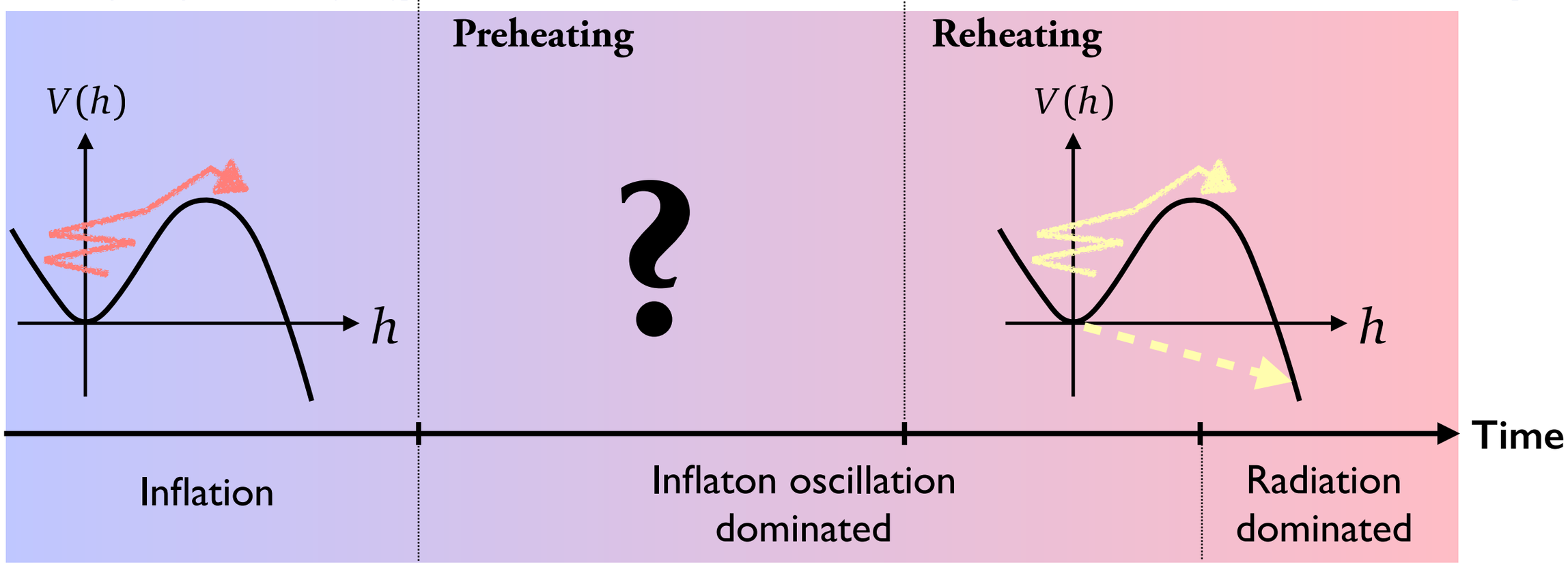
[Hawking, Moss, PLB110(1982); Starobinsky, Yokoyama, PRD50(1994)]

- **Vacuum decay during preheating?**

Our Work!

- Vacuum decay (in finite temp.)
  - Long enough life time even at T ~ 10^{18}GeV for the center value of the top quark mass.

[e.g. Espinosa, Giudice, Riotto, JCAP05(2008)002; Rose, Marzo, Urbano, 1507.06912]



Non-thermal equil.

Thermal equil.

During Inflation

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Higgs-Inflaton Coupling

- **Light** fields, m ≪ H_{inf}, acquire fluctuations during inflation.

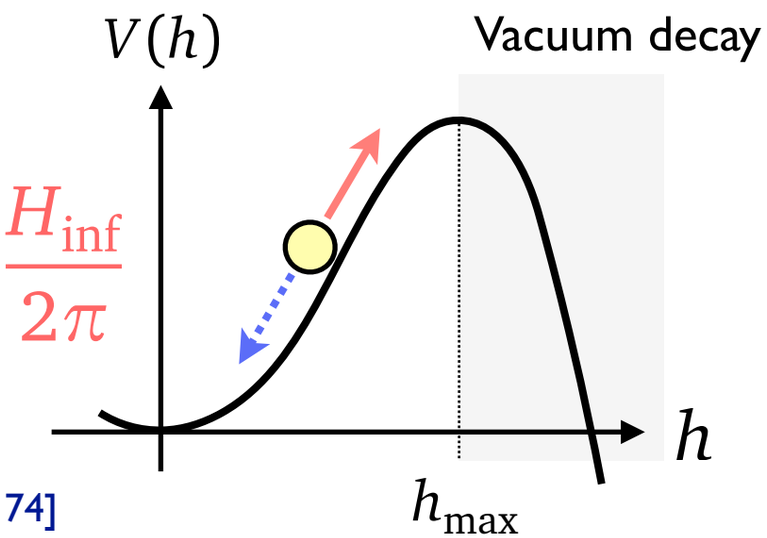
[Hawking, Moss, PLB110(1982); Starobinsky, Yokoyama, PRD50(1994)]

- Stochastic fluctuation v.s. Potential force
  - To avoid the vacuum decay

Tension w/ High scale inflation

$$H_{\rm inf} \lesssim 10^9\,{\rm GeV}\left(\frac{h_{\rm max}}{10^{10}\,{\rm GeV}}\right)$$

$$T \simeq \frac{H_{\rm inf}}{2\pi}$$



✦Observed patches ~exp(3N) should not exhibit the vacuum decay.

➡ One order of magnitude severer bound is obtained. [e.g. Espinosa+, JHEP09(2015)174]

- **Heavy** fields fluctuations, m ≫ H_{inf}, are **suppressed**.

◉ **Higgs-inflaton coupling can save the EW vacuum!**

- Quartic coupling

$$-\mathscr{L}_{\rm int}(\phi,h) = \frac{1}{2}c^2\phi^2h^2$$

- Curvature coupling

$$-\mathscr{L}_{\rm int}(\phi,h) = \frac{1}{2}\xi R h^2$$

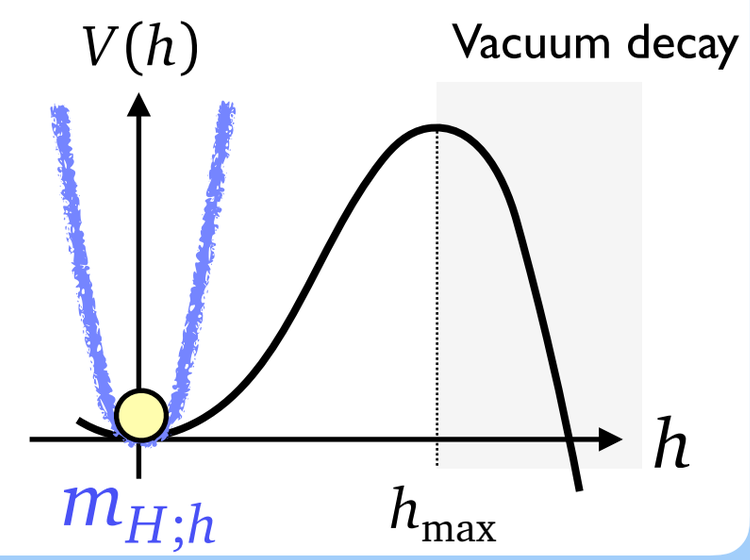
during inflation

$$m_{H;h}^2 = c^2\phi_{\rm inf}^2$$

$$m_{H;h}^2 = 12\xi H_{\rm inf}^2$$

Stabilized if

$$\gtrsim H_{\rm inf}^2$$



Outlook during Inflation

■ High scale inflation v.s. Metastable EW vacuum

◉ **Lower bound on the couplings from $m_{H;h} > 3H_{inf}/2$**

- Quartic coupling

$$c \gtrsim \frac{3H_{\rm inf}}{2\phi_{\rm inf}} \sim 3\times 10^{-6}\left(\frac{m_\phi}{10^{13}\,{\rm GeV}}\right)$$

- Curvature coupling

$$\xi \gtrsim \frac{3}{16} \sim 0.2$$

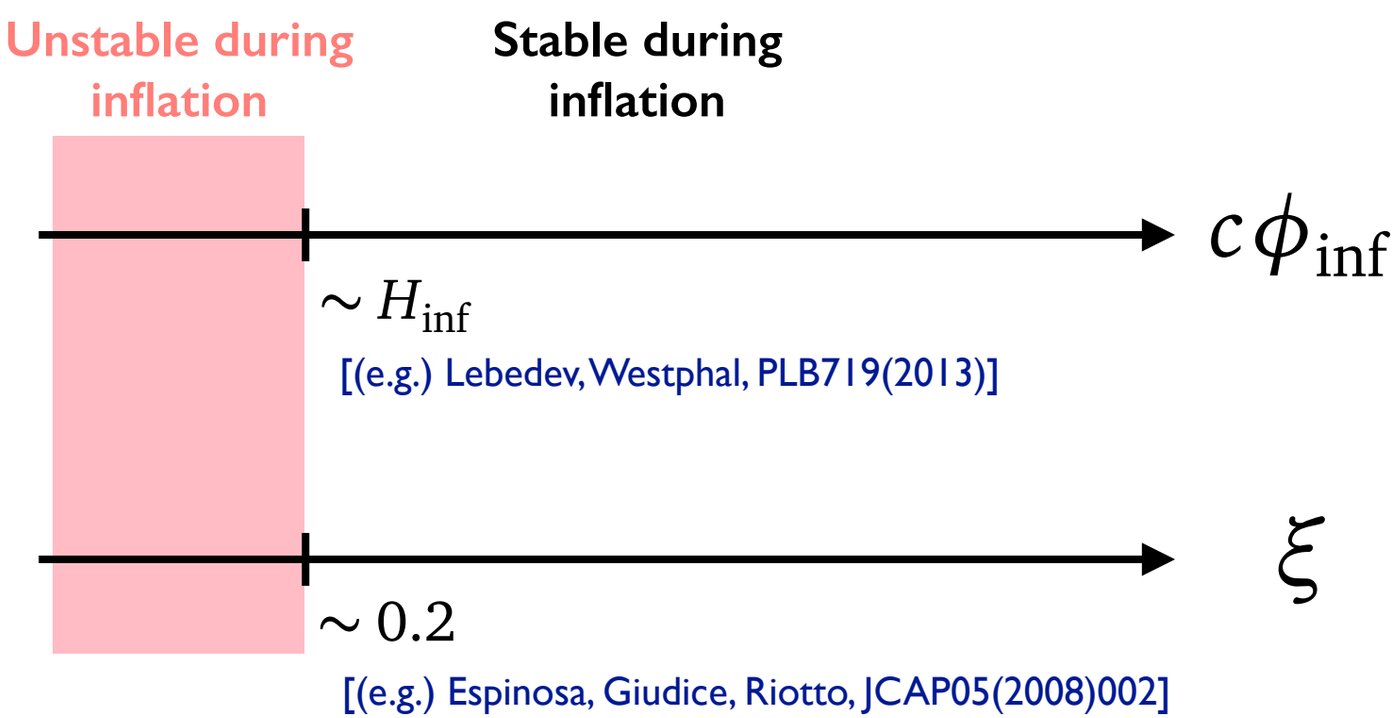
- **Small Higgs-inflaton coupling can save the EW vacuum**

- Quartic coupling

$$-\mathscr{L}_{\rm int}(\phi,h) = \frac{1}{2}c^2\phi^2h^2$$

- Curvature coupling

$$-\mathscr{L}_{\rm int}(\phi,h) = \frac{1}{2}\xi R h^2$$



During Preheating

Based on 1602.00483.
In collaboration with Y.Ema and K.Nakayama.

Related works:
[Herranen et al., PRL115(2015)241301; Kohri, Mastui]

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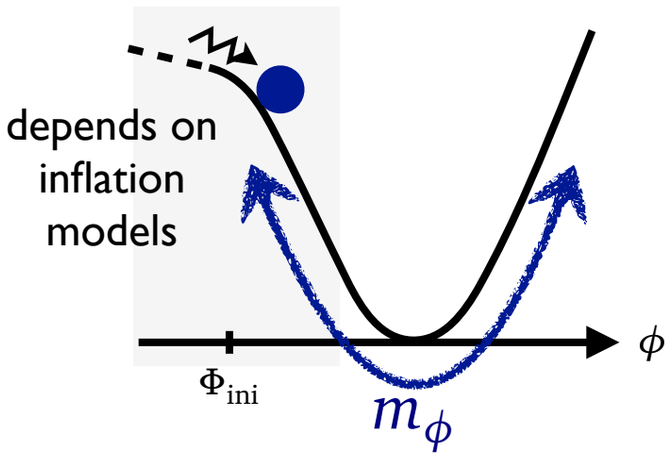
Parametric Resonance

■ Non perturbative Higgs production

- Inflaton oscillation → Higgs mass oscillation → Higgs production



$$\phi(t) \simeq \Phi(t)\cos(m_\phi t)$$

where $\Phi(t) = \dfrac{\Phi_{\rm ini}}{a^{3/2}(t)}$

- Quartic coupling : $c^2\phi^2h^2/2$

$$m^2_{H;h}(t) \simeq \frac{c^2\Phi^2(t)}{2}\left[\cos(2m_\phi t)+1\right]$$

▸ "**Ordinary**" resonance: $q(t) \sim c^2\Phi^2(t)/m_\phi^2$

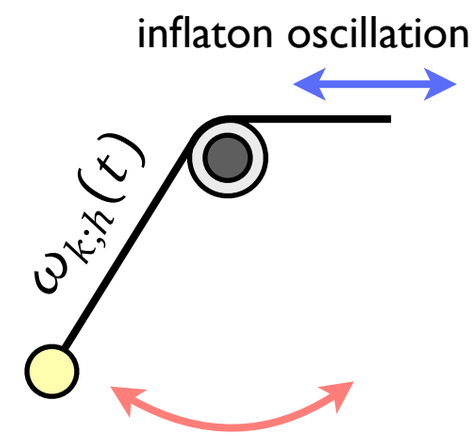
[Kofman, Linde, Starobinsky]

- Curvature coupling : $\xi Rh^2/2$

$$m^2_{H;h}(t) \simeq \frac{\xi m_\phi^2\Phi^2(t)}{2M_{\rm pl}^2}\left[3\cos(2m_\phi t)+1\right]$$

▸ "**Tachyonic**" resonance: $q(t) \sim \xi\Phi^2(t)/M_{\rm pl}^2$

[Bassett, Liberati]



$$\omega^2_{k;h}(t) = m^2_{H;h}(t) + k^2$$

◉ Non-adiabatic change of the effective mass → Large Higgs fluctuations

$$\left|\frac{\dot\omega_{k;h}}{\omega^2_{k;h}}\right| > 1 \longrightarrow$$

Condition for explosive Higgs Production

$$q(t) > 1$$

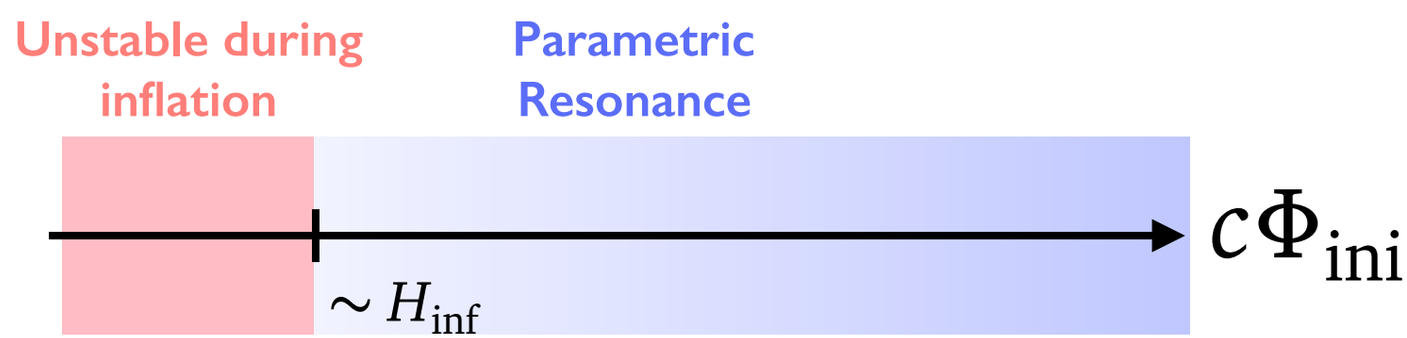
Resonance is Inevitable

- Higgs production via **Parametric Resonance:** $-\mathscr{L}_{\rm int}(\phi, h) = \frac{1}{2}c^2\phi^2h^2$

  - Parametric resonance is almost **inevitable**!
    - Required coupling

      $c\Phi_{\rm ini} \gtrsim H_{\rm inf}$
    - Condition for resonance

      $q(t_{\rm ini}) > 1 \to c\Phi_{\rm ini} \gtrsim m_\phi$

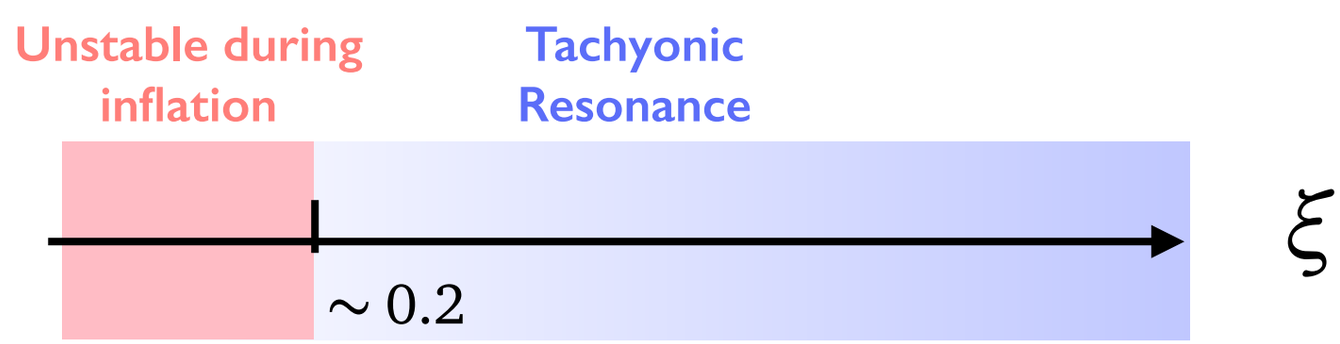


- Higgs production via **Tachyonic Resonance:** $-\mathscr{L}_{\rm int}(\phi, h) = \frac{1}{2}\xi R h^2$

  - Tachyonic resonance is almost **inevitable**!
    - Required coupling

      $\xi \gtrsim 0.2$
    - Condition for resonance

      $q(t_{\rm ini}) > 1 \to \xi \gtrsim M_{\rm pl}^2/\Phi_{\rm ini}^2$



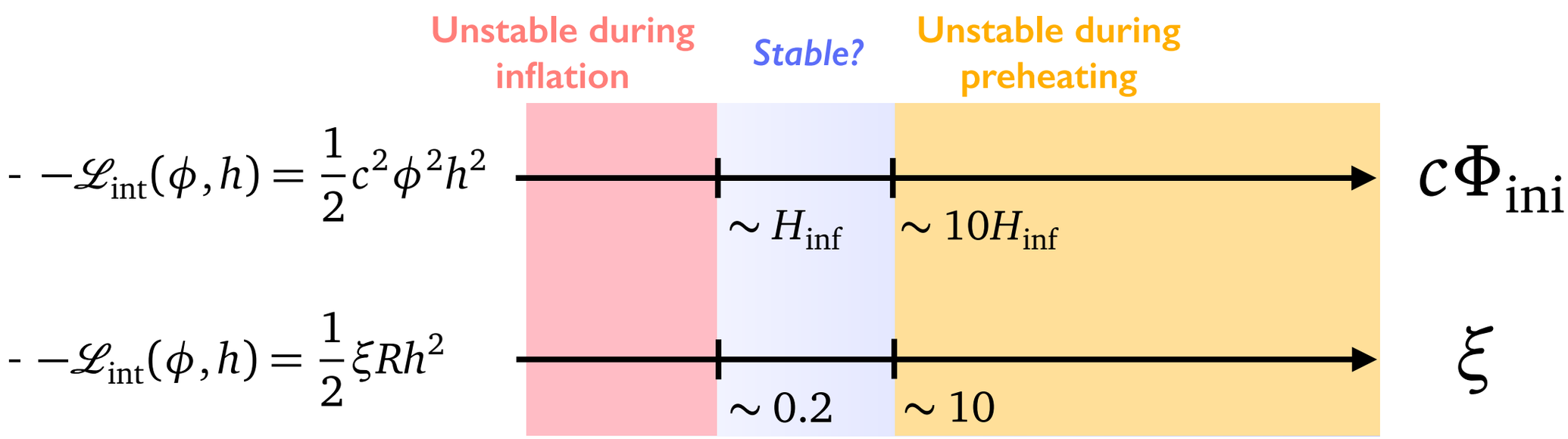
Vacuum decay via Resonance

- Vacuum decay **during** resonance: $1 < q(t) \propto \Phi^2(t)$

  - **Tachyonic effective mass < Inflaton induced mass.**

$$|\delta m^2_{\rm self;h}| \equiv 3|\lambda|\left\langle h^2\right\rangle \propto |\lambda| p_*^2 \begin{cases} e^{2\mu_{\rm qtc} m_\phi t} \\ e^{\mu_{\rm crv}\sqrt{\xi}\frac{\Phi_{\rm ini}}{M_{\rm pl}}} \end{cases} \quad \textbf{V.S.} \quad m^2_{H;h} = \begin{cases} \frac{c^2\Phi^2(t)}{2}\left[\cos(2m_\phi t)+1\right] \\ \frac{\xi m_\phi^2 \Phi^2(t)}{2M_{\rm pl}^2}\left[3\cos(2m_\phi t)+1\right] \end{cases}$$

  - **Upper bounds** on Higgs-inflaton coupling.



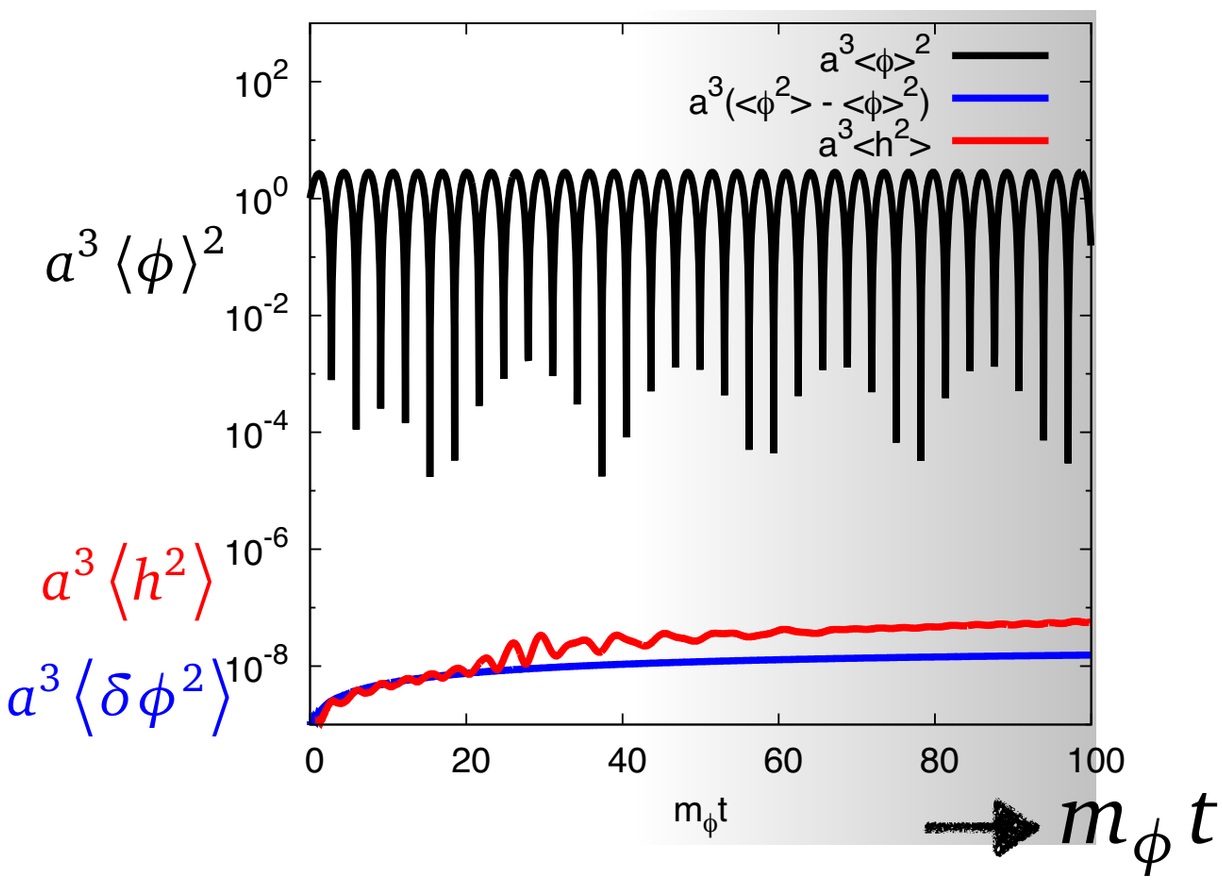
$$c \lesssim 10^{-4} \times \left[\frac{0.1}{\mu_{\rm qtc}}\right]\left[\frac{m_\phi}{10^{13}\,{\rm GeV}}\right]; \qquad \xi \lesssim 10 \times \left[\frac{1}{\mu_{\rm crv}}\right]^2\left[\frac{\sqrt{2}M_{\rm pl}}{\Phi_{\rm ini}}\right]^2$$

Numerical Simulation

- Vacuum decay via Parametric Resonance: $-\mathscr{L}_{\rm int}(\phi,h)=\frac{1}{2}c^2\phi^2h^2$

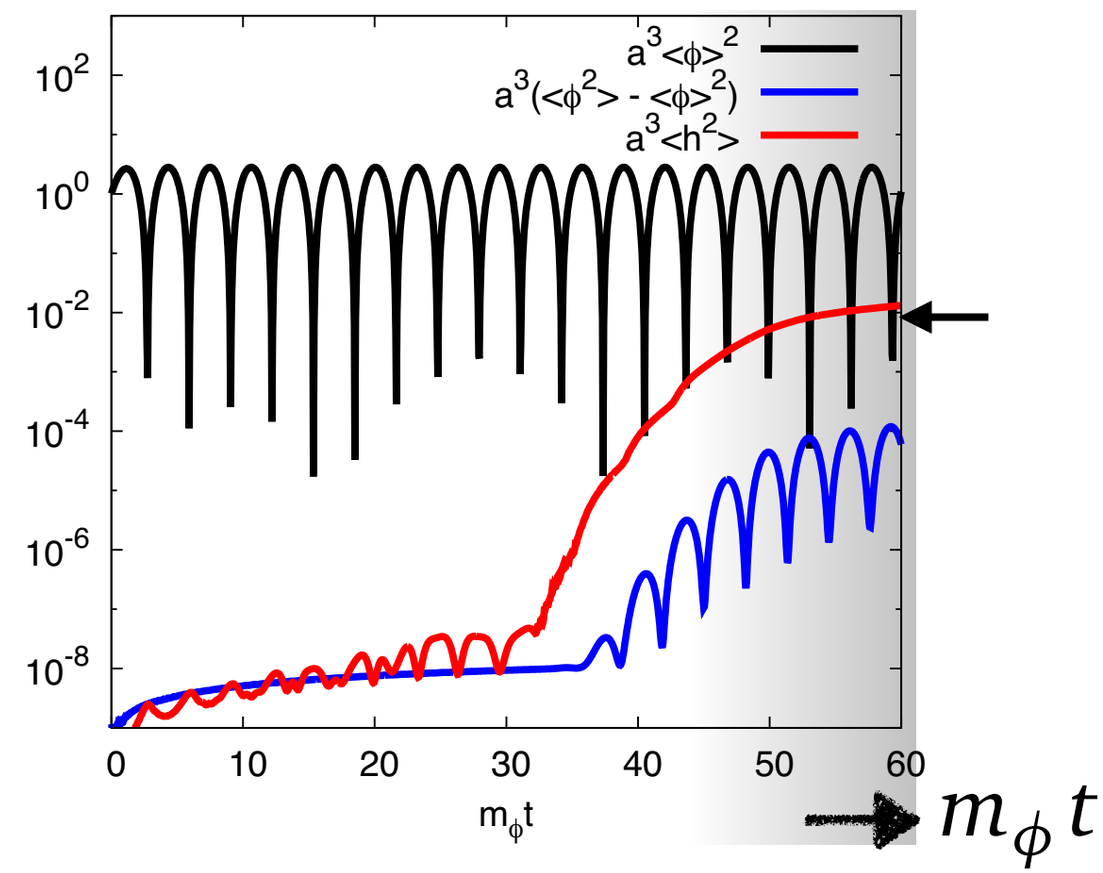
  - To check $c \lesssim 10^{-4}\times\left[\frac{0.1}{\mu_{\rm qtc}}\right]\left[\frac{m_\phi}{10^{13}\,{\rm GeV}}\right]$, we performed a classical lattice simulation.

- Stable: c = 1 × 10^{-4}



Resonance is over:
$p_* < m_\Phi$

- Unstable: c = 2 × 10^{-4}



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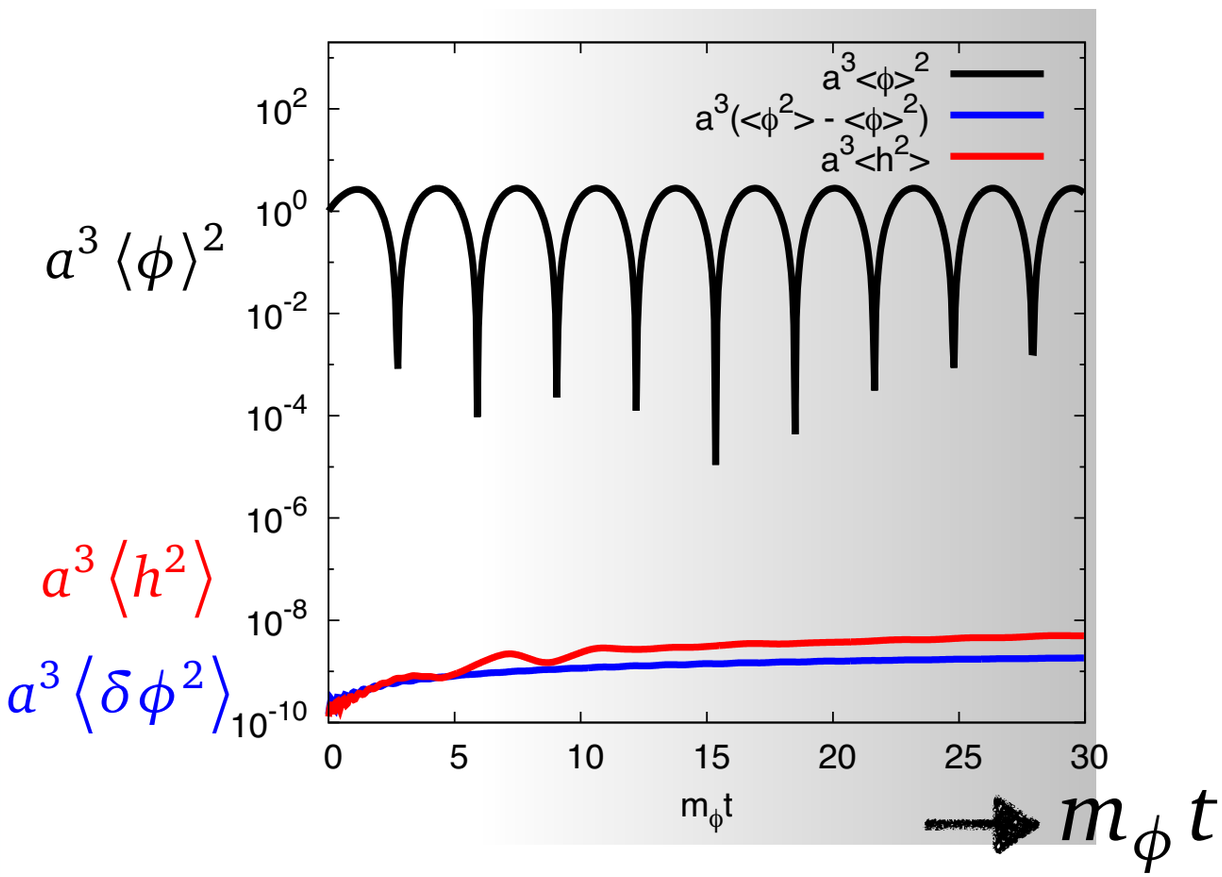
  - To check $\xi \lesssim 10 \times \left[\frac{1}{\mu_{\rm crv}}\right]^2 \left[\frac{\sqrt{2}M_{\rm pl}}{\Phi_{\rm ini}}\right]^2$, we performed a classical lattice simulation.

- Stable: ξ = 10



Resonance is over:

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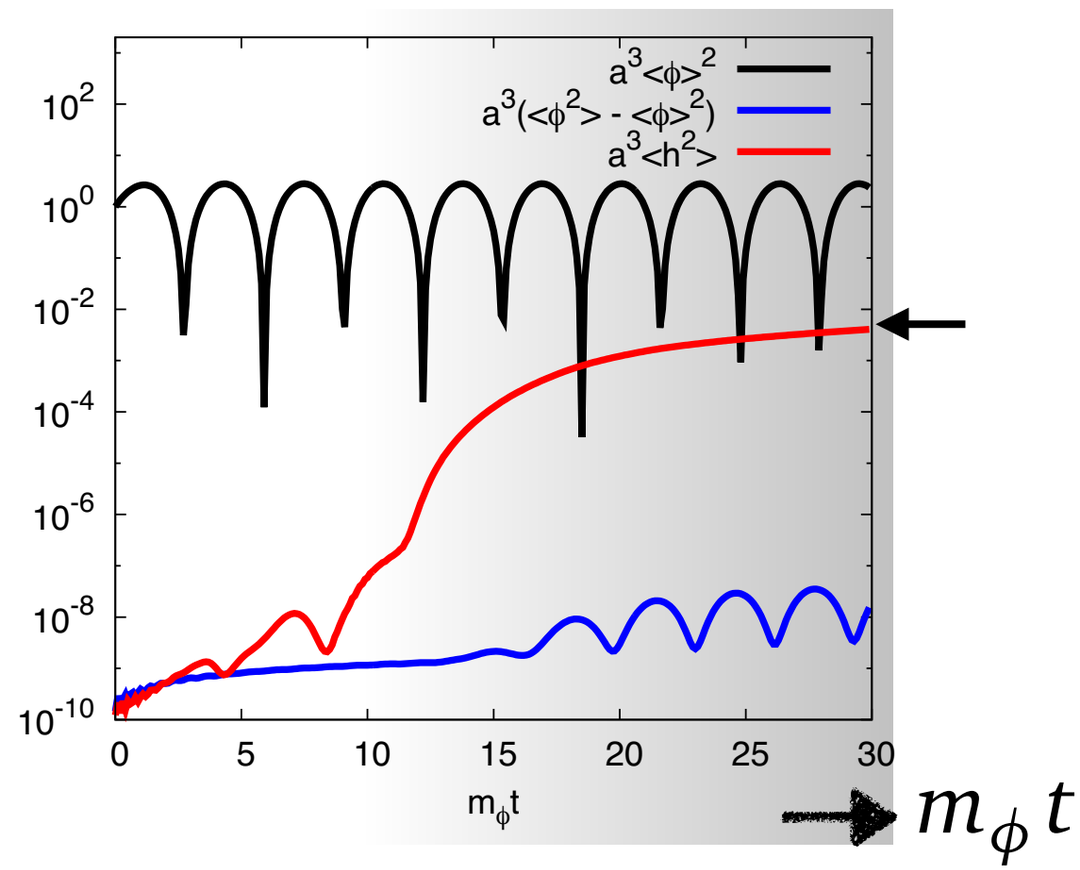
- Unstable: ξ = 20



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Summary

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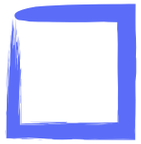
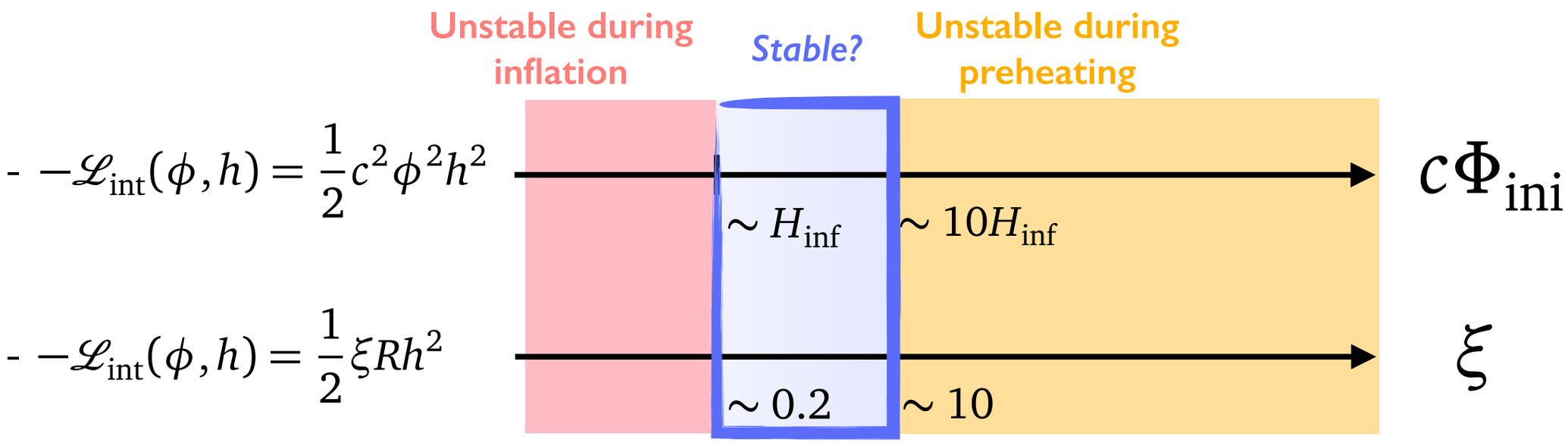
- Higgs-inflaton coupling may **destabilize it at the preheating**.
- We have obtained **upper bounds** on Higgs-inflaton couplings.
  - **Bounds could be severer if you look at all the observable patches ~ e^{3N}.**
  - **Towards precise bounds → Full inclusion of EW gauges on the lattice.**
- Depend on reheating/thermalization in  .

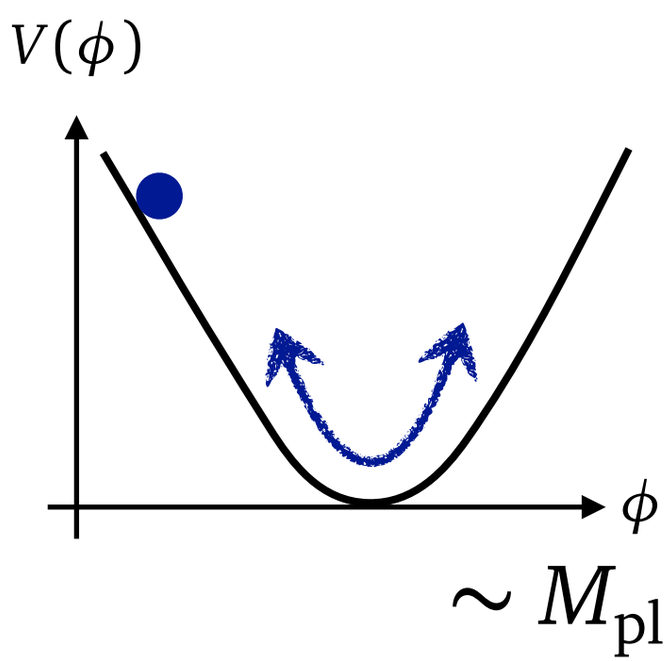


It is not easy to reheat the universe "adiabatically".

Simple Scenario

■ What we have discussed

- **Curvature coupling + Chaotic inflation**
  - **Curvature coupling**: stabilize the EW vacuum during inflation
  - Chaotic inflation: solve initial condition + provide the density fluctuations observed by Planck



- **Resonance is almost inevitable.**

$$q \sim \frac{\xi \phi_{\rm ini}^2}{M_{\rm pl}^2} \gtrsim 1$$

Simple Scenario

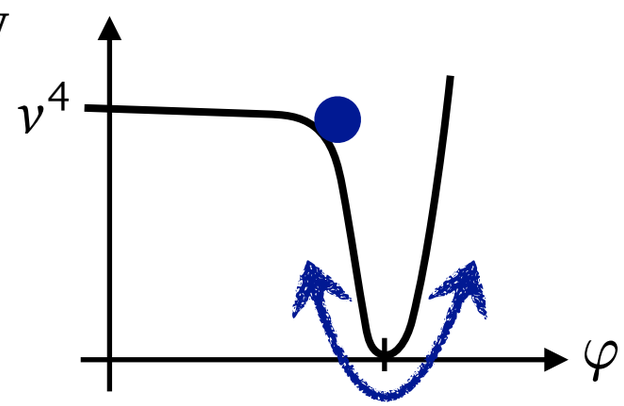
[Kawasaki, **KM**, Yanagida; 1605.04974]

■ Simple scenario consistent with the metastability

- **Curvature coupling + Chaotic inflation + New inflation**
  - **Curvature coupling**: stabilize the EW vacuum during inflation
  - Chaotic inflation: solve initial condition + provide the density fluctuations observed by Planck
  - New inflation: **avoid the resonance** + **provide the dominant component of DM as PBHs**

$$V(\varphi) = \left(v^2 - g\frac{\varphi^4}{M_{\rm pl}^2}\right)^2 - \kappa v^4 \frac{\varphi^2}{2M_{\rm pl}^2} - \varepsilon v^4 \frac{\varphi}{M_{\rm pl}}$$

$v \sim 10^{16}\,\mathrm{GeV}$



$$\langle\varphi\rangle \ll M_{\rm pl}$$

- **Resonance does not take place.**

$$q \sim \frac{\xi\,\langle\varphi\rangle^2}{M_{\rm pl}^2} \lll 1$$

- **Higgs is stabilized at its origin during the new inflation.**

$$N \sim \left(\frac{v^2}{8g\epsilon^2 M_{\rm pl}^2}\right)^{1/3} \sim \mathcal{O}(10) \quad \text{for} \quad \epsilon \sim \frac{v^2}{M_{\rm pl}^2}$$

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[Kawasaki, **KM**, Yanagida; 1605.04974]

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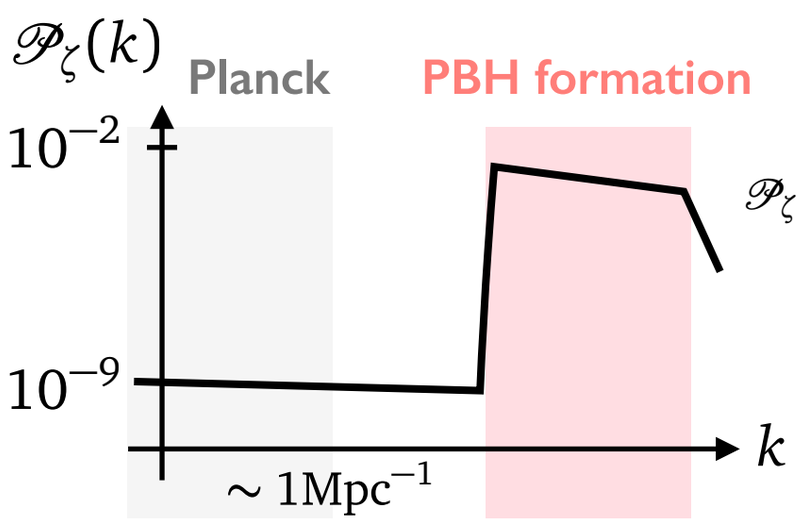
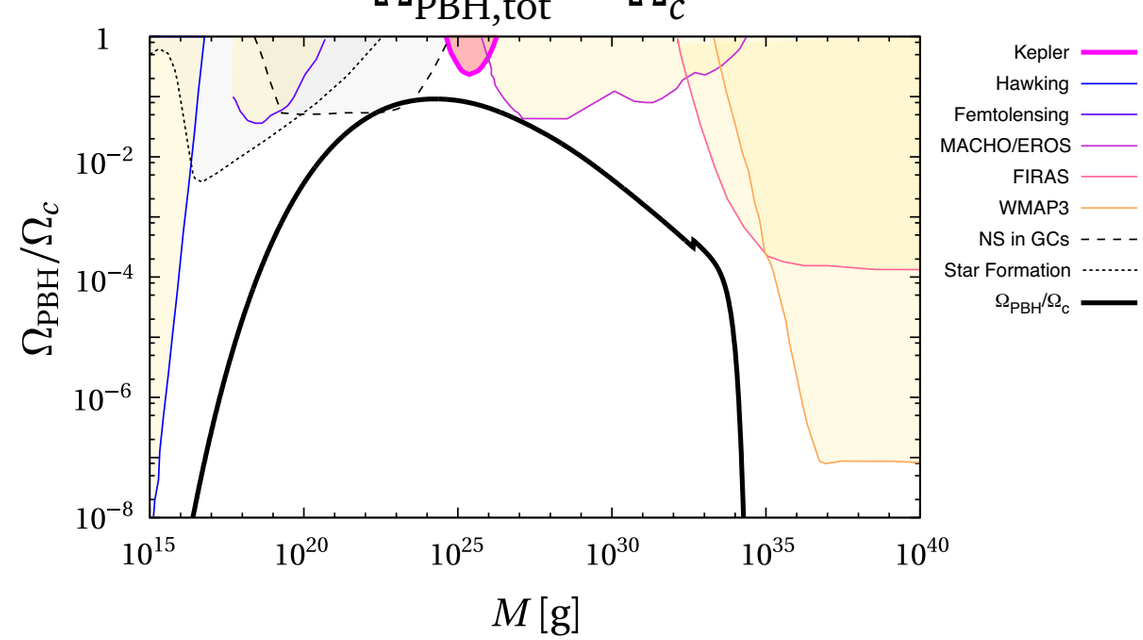


$$\mathscr{P}_\zeta \sim \left(\frac{1}{2\sqrt{3}\pi}\frac{v^2}{\epsilon M_{\rm pl}^2}\right)^2$$

$$k \sim 10^{11}\mathrm{Mpc}^{-1}\left(\frac{M_{\rm PBH}}{10^{24}\,\mathrm{g}}\right)^{-1/2}$$

$\Omega_{\rm PBH,tot} = \Omega_c$



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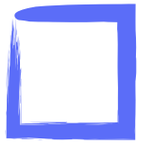
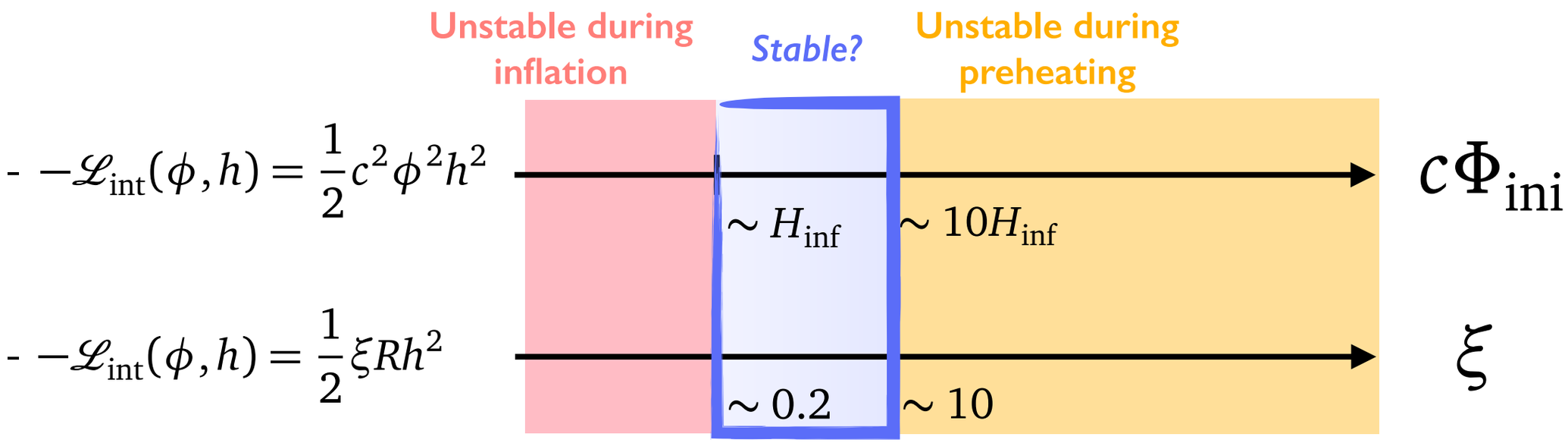
- Depend on reheating/thermalization in  .



It is not easy to reheat the universe "adiabatically".

- See however 1605.04974 (and also 1605.07342.)

Back up

Simple Scenario

[Kawasaki, **KM**, Yanagida; 1605.04974]

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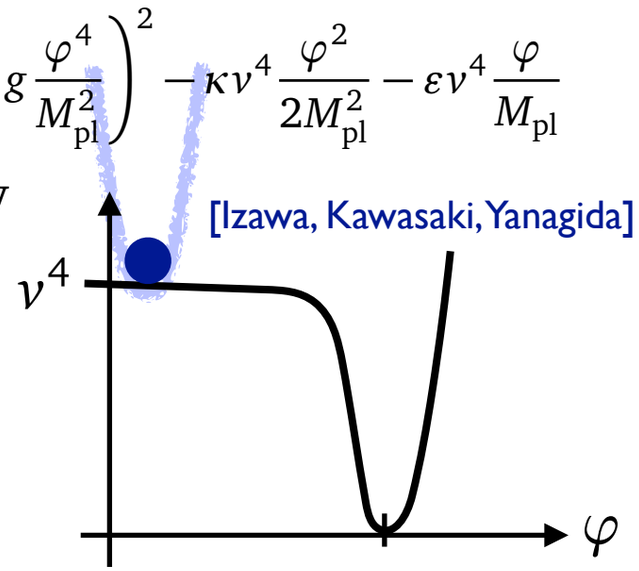

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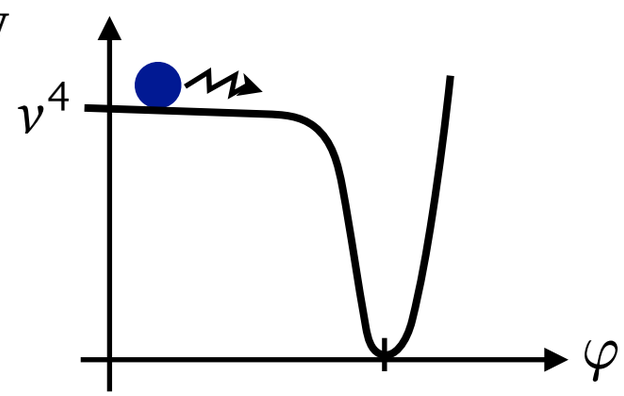

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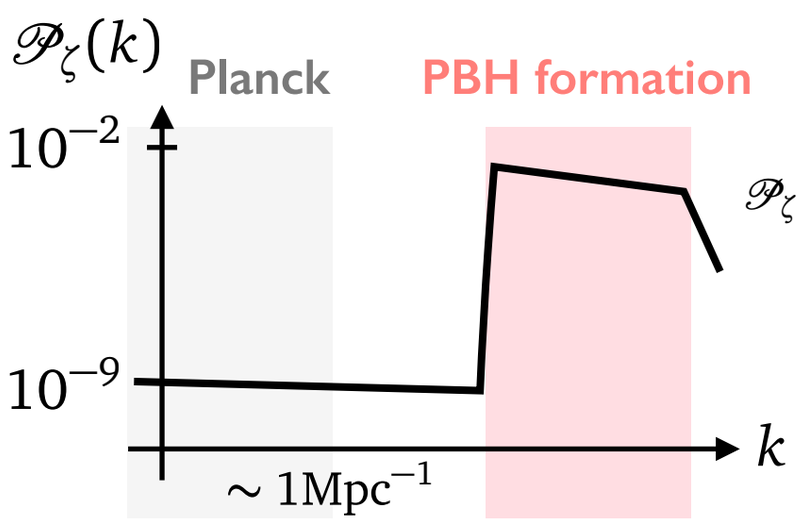

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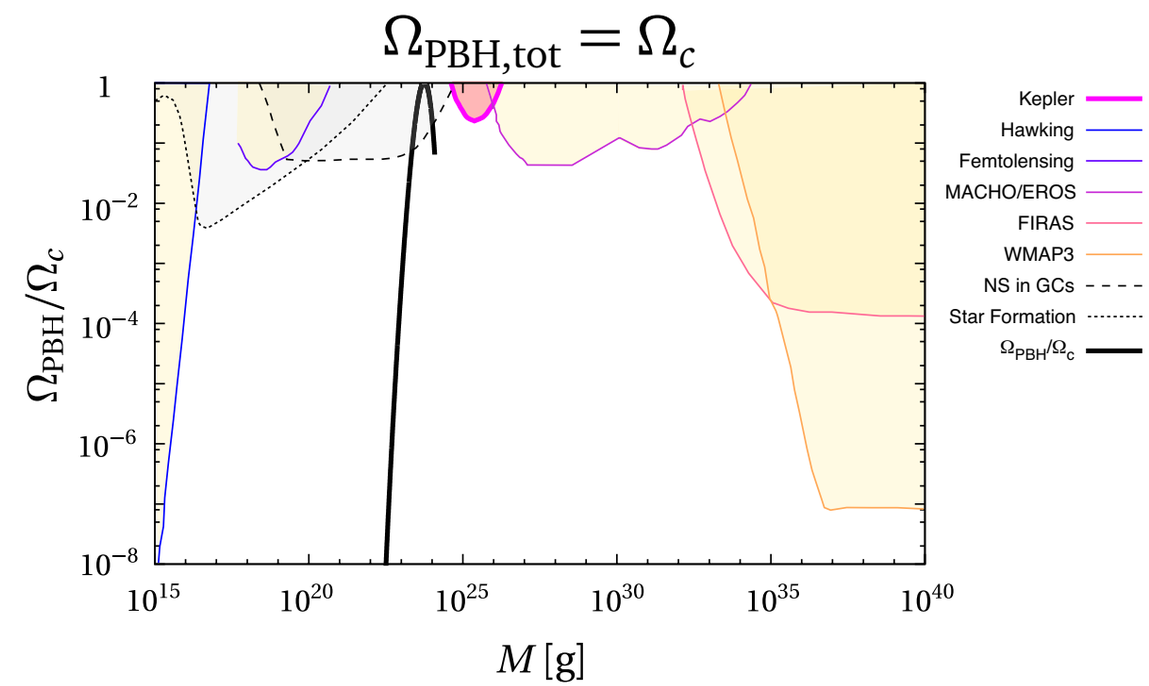
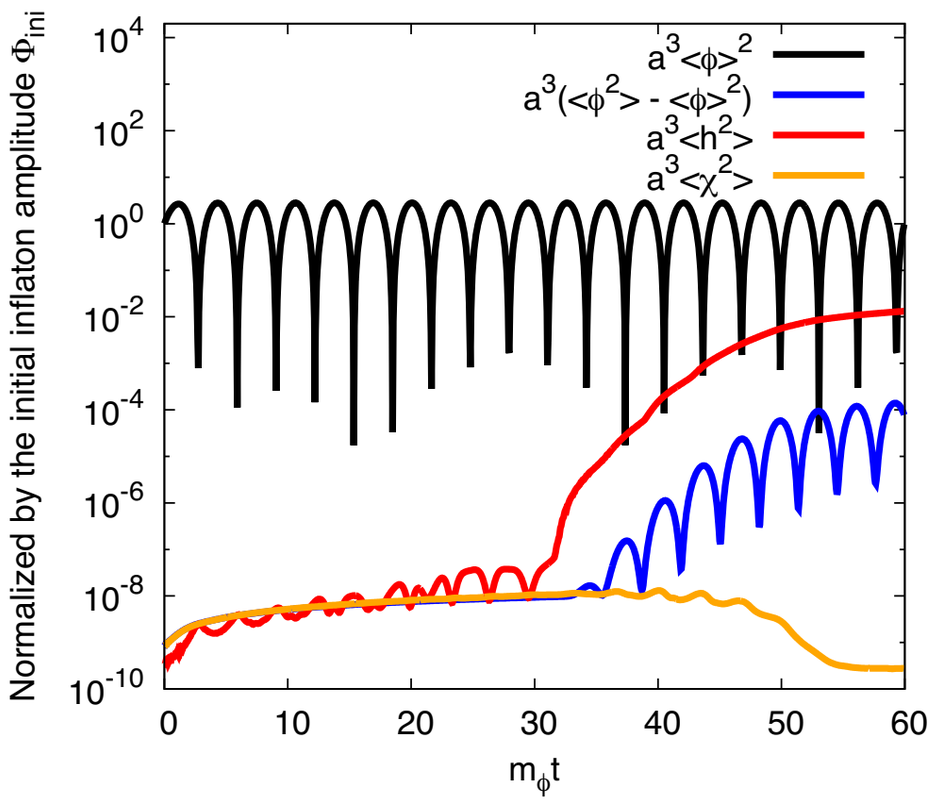
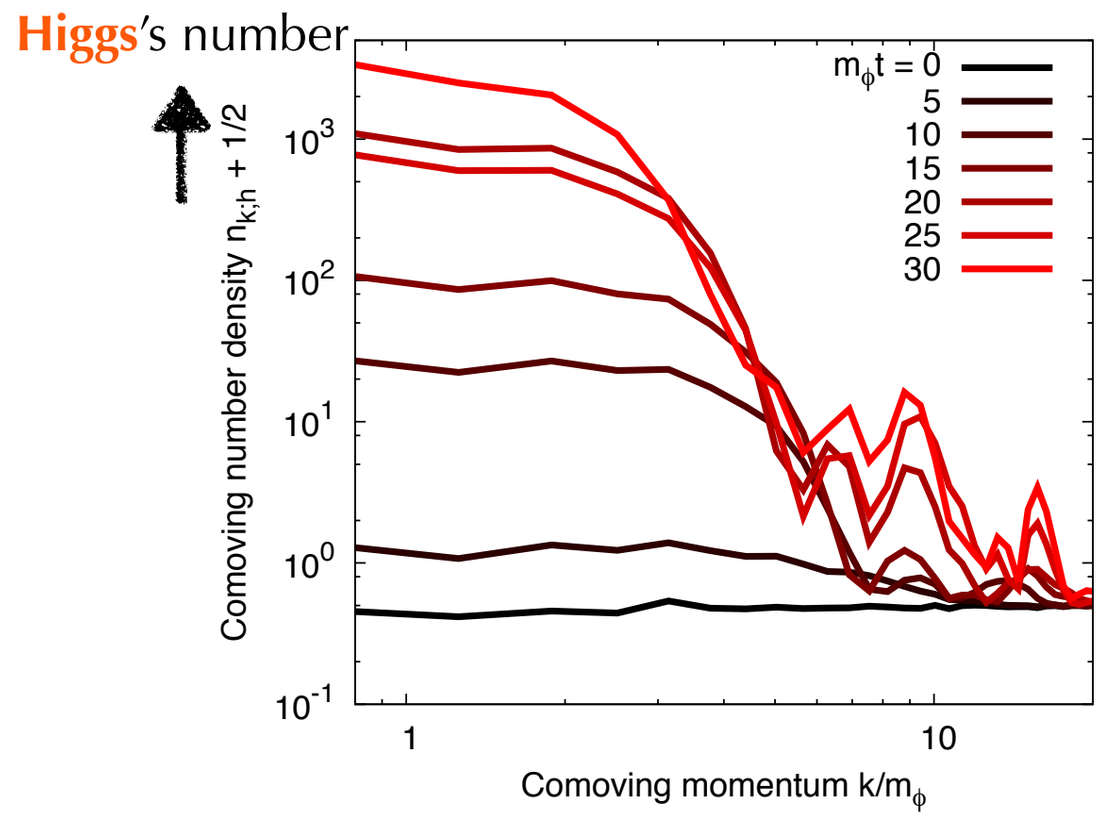


Electroweak gauges

■ EW gauge production from Higgs

- $g^2A^2h^2$ might stabilize the Higgs.
- To mimic it, we have introduced another scalar χ via $g^2\chi^2h^2$.



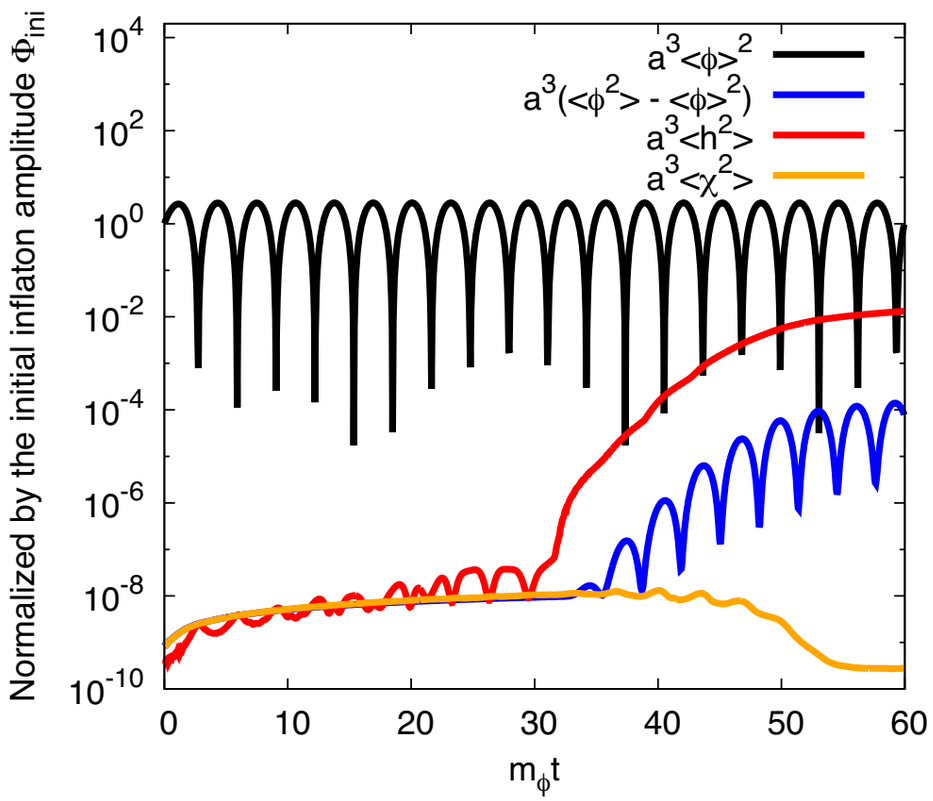


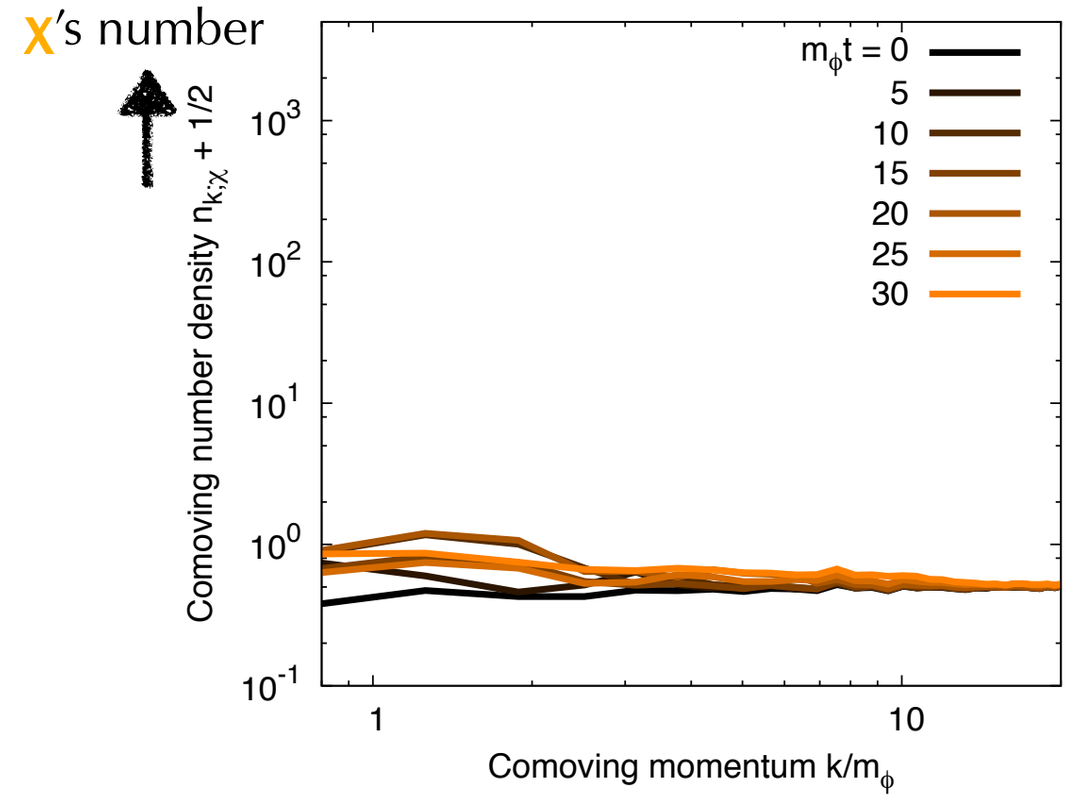
- χ-production is suppressed due to $g(\langle h^2\rangle)^{1/2}$ → **Higgs dynamics is not altered.**
- Same for the curvature coupling.

Electroweak gauges

■ EW gauge production from Higgs

- $g^2A^2h^2$ might stabilize the Higgs.
- To mimic it, we have introduced another scalar χ via $g^2\chi^2h^2$.





- χ-production is suppressed due to $g(\langle h^2\rangle)^{1/2}$ → **Higgs dynamics is not altered.**
- Same for the curvature coupling.

Inflaton decays into other SMs

- ***Caution***: relevant time scales are quite short, and thus **instantaneous thermalization assumption** is questionable…

- Quartic coupling

$$m_\phi t \lesssim \mathcal{O}(10) \times \left(\frac{c}{10^{-4}}\right)\left(\frac{10^{13}\,\mathrm{GeV}}{m_\phi}\right)$$

- Curvature coupling

$$m_\phi t \lesssim 10 \times \left(\frac{\xi}{10}\right)^{\frac{1}{2}}$$

1. Perturbative inflaton decay: **$T_R < 10^{10}$ GeV**.

- Thermal mass is always **smaller**: $p_*(t) > m_\phi \gtrsim g T_{\max} \simeq 10^{13}\,\mathrm{GeV} \times g \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)^{\frac{1}{2}} \left(\frac{H_{\mathrm{inf}}}{10^{14}\,\mathrm{GeV}}\right)^{\frac{1}{4}}$

  ✳ Here we naively assume instantaneous thermalization, but **T_{max} may be much lower**.

[Harigaya, **KM**, JHEP05(2014)006 ;**KM**, Yamada, JCAP02(2016)003; (cf.) Ellis+, JCAP03(2016)008]

2. Non-perturbative inflaton decay: **$T_R > 10^{10}$ GeV**.

- Parametric resonance of other SM particles (χ) becomes relevant.
- Large χ fluctuations with long wave length modes are produced.
- They might "kick" the Higgs towards True Vacuum(?).