Reheating Process after Inflation

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Based on 1312.3097, 1402.2846, 1506.07661, 1602.00483, 1605.04974
Collaborators: Ema, Harigaya, Kawasaki, Nakayama, Yamada, Yanagida

Introduction

Inflationary Cosmology

■ Cosmic Inflation: accelerated expansion of Universe

- Solve Horizon/Flatness problem
- Generate primordial density perturbations
- Dilute unwanted relics

◉ Suggested by the slightly red-tilted spectrum of CMB:

Two implications of inflation

$$\zeta : \mathcal{P}_\zeta(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

scalar

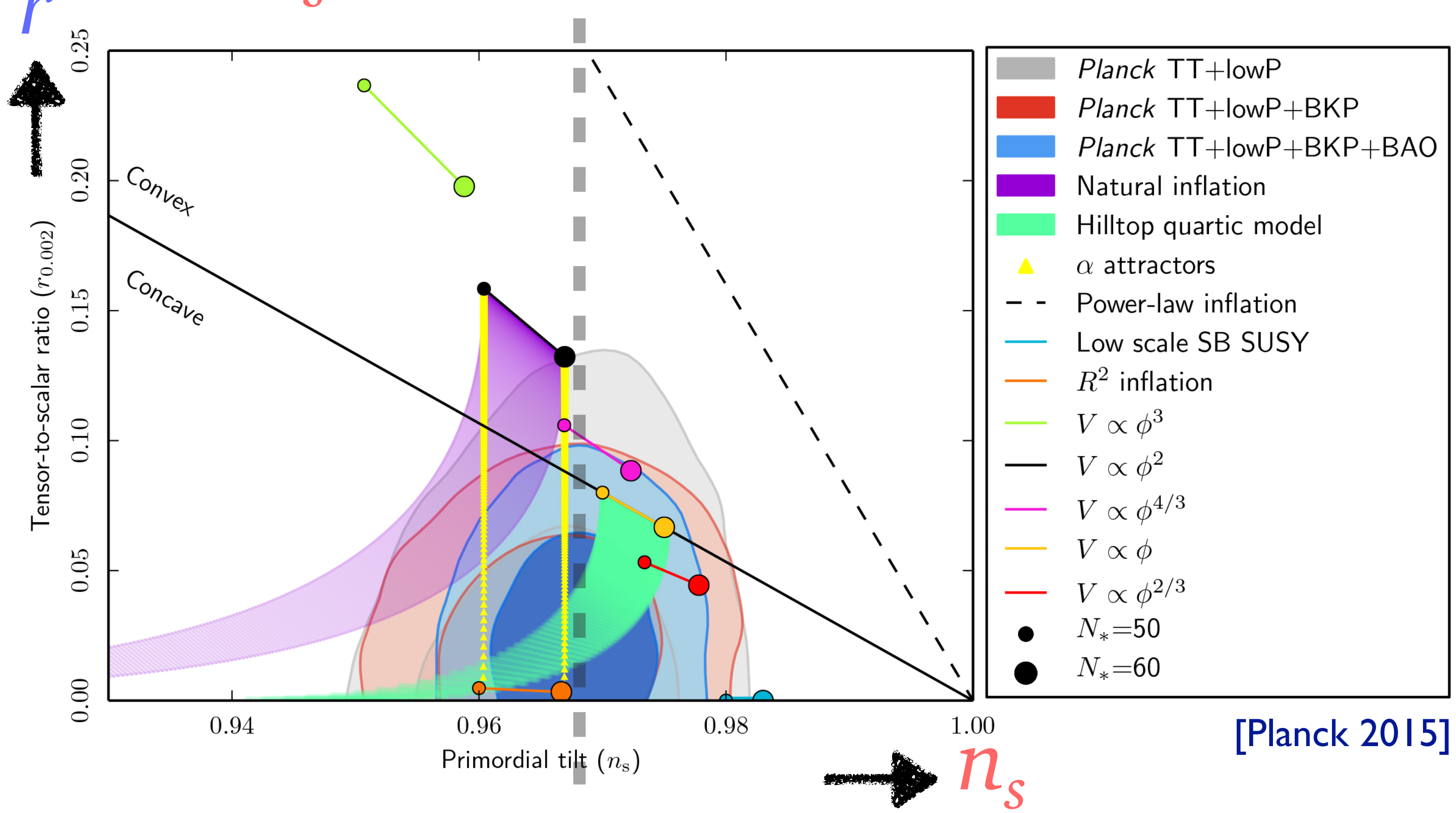
- Typically, $n_s \lesssim 1$ is expected.

$$h_{ij} : r = \frac{\mathcal{P}_h}{\mathcal{P}_\zeta}$$

Tensor

- Depends on energy scale of inflation.

$$n_s = 0.968 \pm 0.006$$

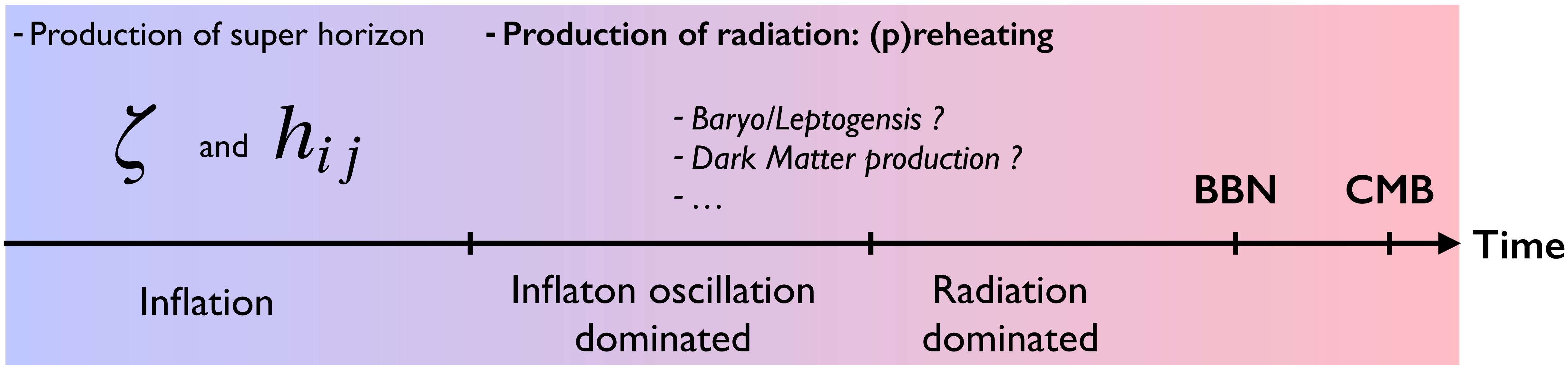


[Planck 2015]

Inflationary Cosmology

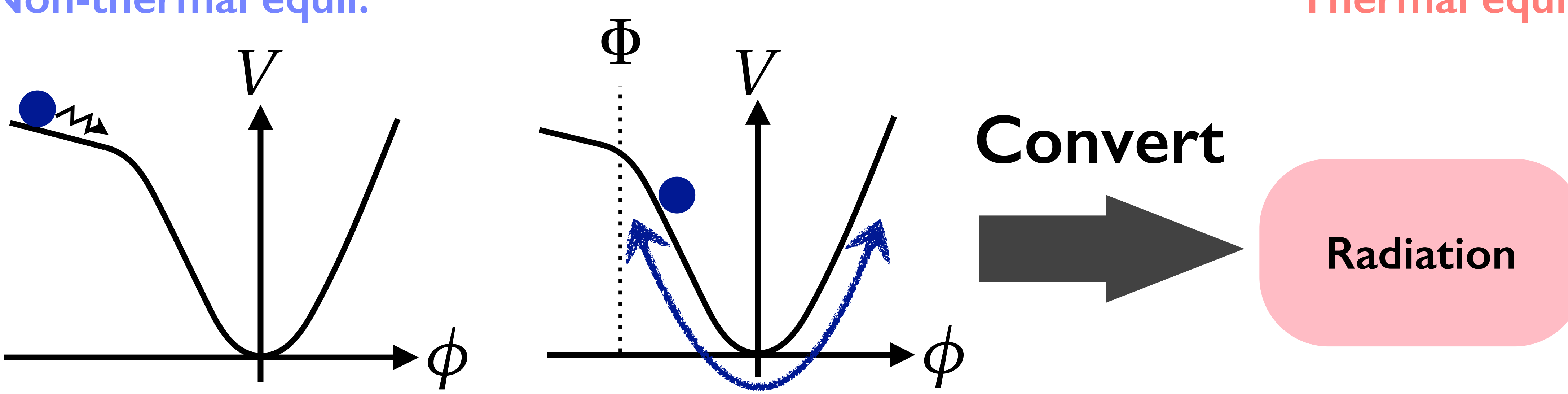
■ Thermal History of Universe

- Creation of hot Universe after inflation: **(p)reheating**
- **Inflaton, Φ, must convert its energy into radiation.**



Non-thermal equil.

Thermal equil.



Inflationary Cosmology

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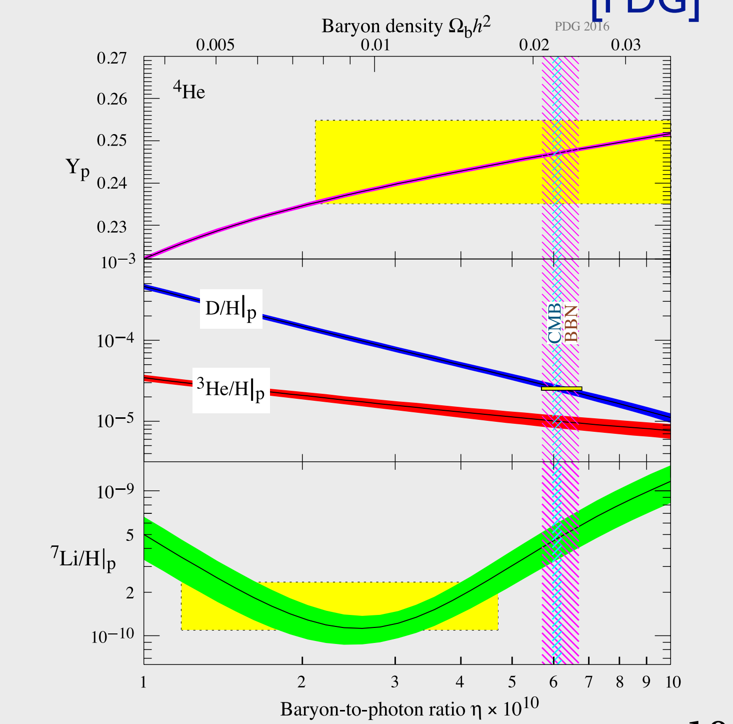
[PDG]



$$\eta_b \equiv n_b/n_\gamma; \quad \eta_b \sim 6 \times 10^{-10}$$

- Production of super horizon

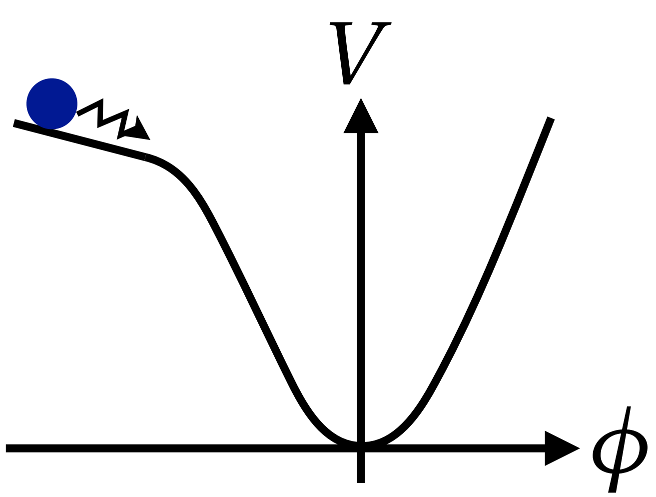
ζ and h_{ij}

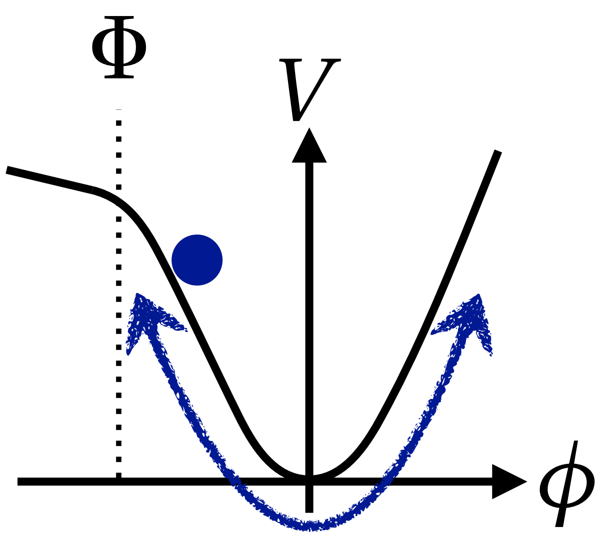
- **Production of radiation: (p)reheating**

- *Baryo/Leptogensis ?*
- *Dark Matter production ?*
- …

Inflation | Inflaton oscillation dominated | Radiation dominated

Non-thermal equil. → Thermal equil.





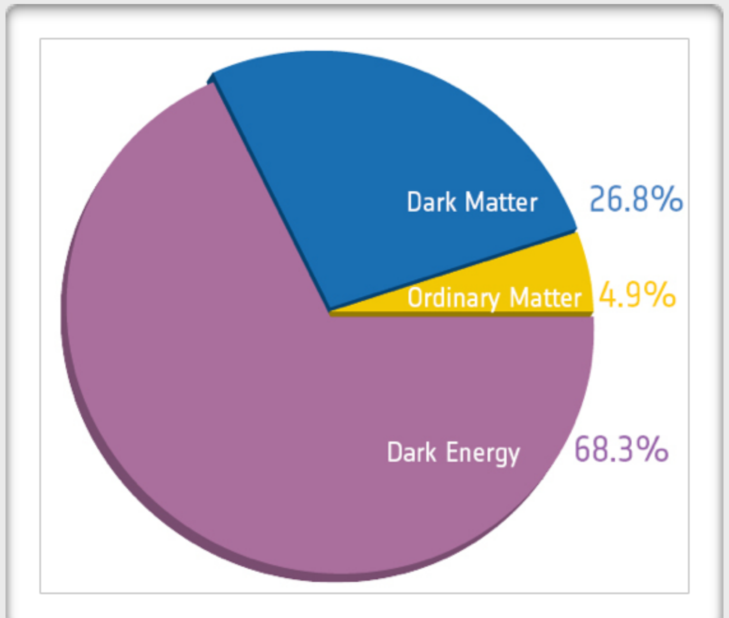
Convert → **Radiation**

Inflationary Cosmology

■ Thermal History of Universe

- Creation of hot Universe after inflation: **(p)reheating**
- **Inflaton, Φ, must convert its energy into radiation.**

Energy contents
[Planck]



- Production of super horizon

ζ and h_{ij}

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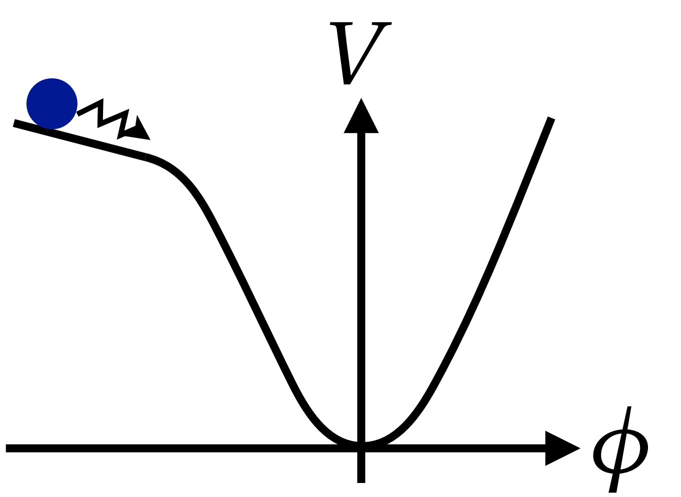

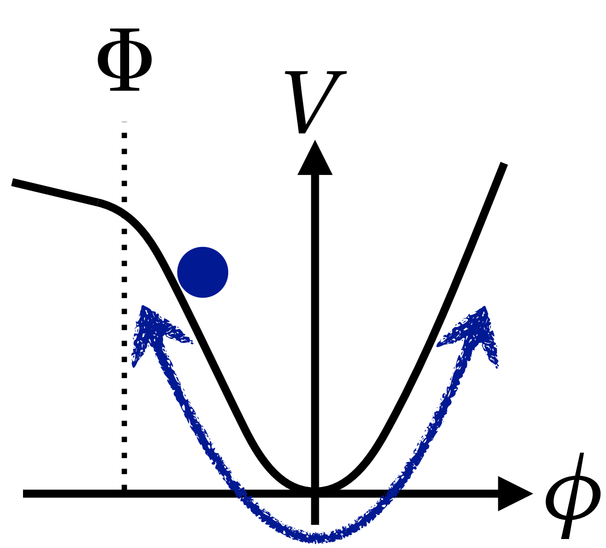

Convert → **Radiation**

Inflationary Cosmology

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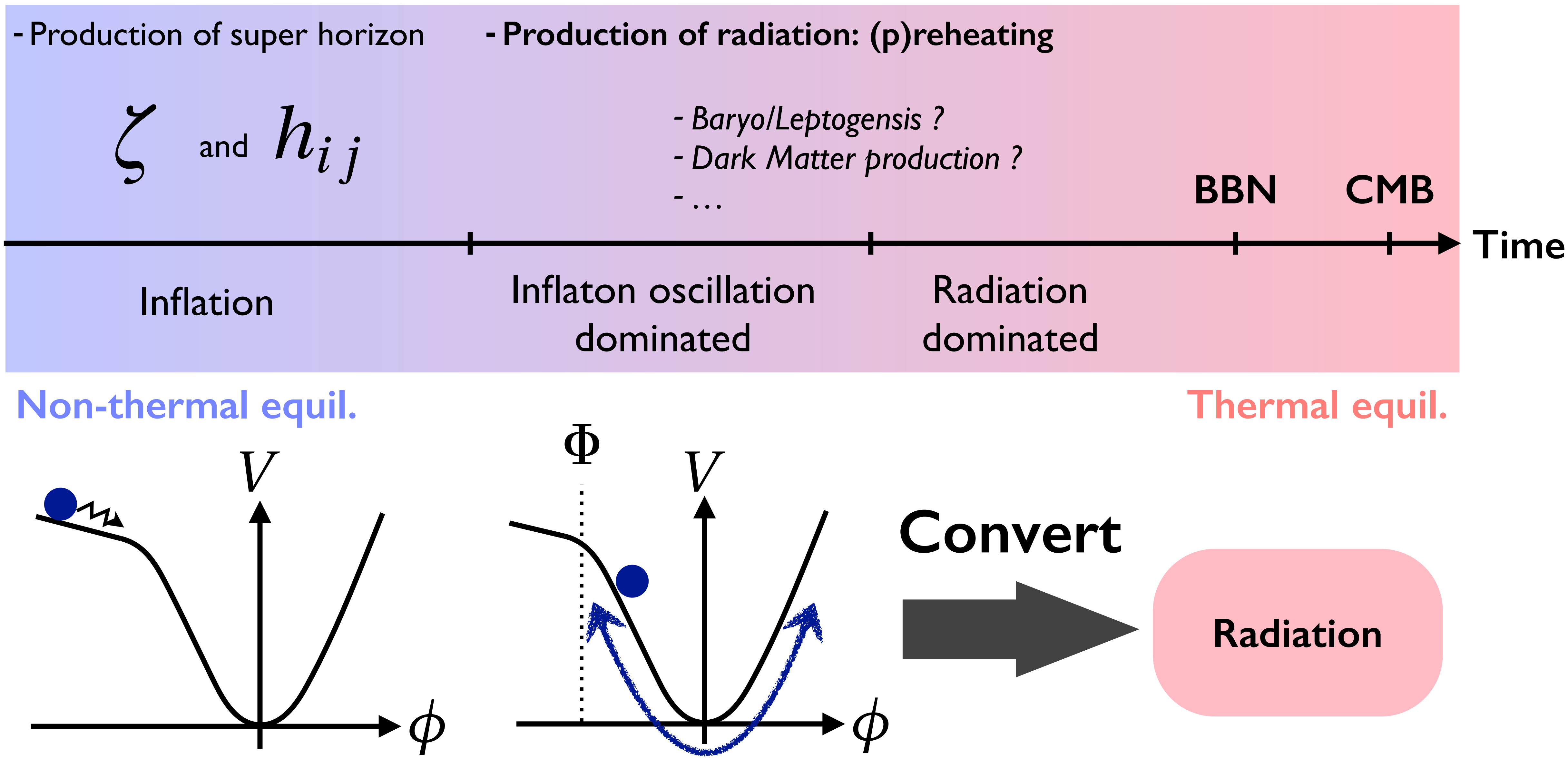


Inflationary Cosmology

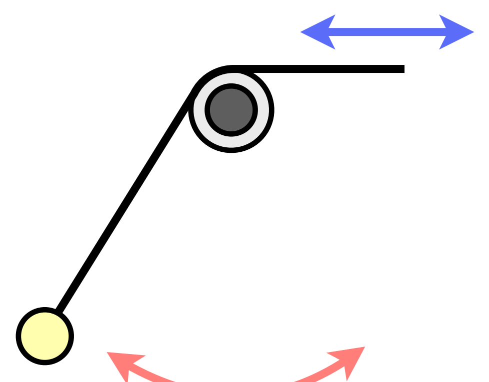
■ Reheating processes after inflation

- Interaction between inflaton and radiation is required.

χ and ψ should have interactions with SM particles or be SM particles.

inflaton ϕ ⟷ $c^2\phi^2\chi^2, \;\; c\phi\bar{\psi}\psi$ ⟷ radiation $\chi, \psi, \ldots$

◉ Characterized by… $$q \sim \frac{\Delta m^2_{\chi,\psi}(\Phi)}{m_\phi^2} \sim \frac{c^2\Phi^2}{m_\phi^2}$$ (decreases with time)



$$\omega_k^2(t) = k^2 + m^2_{\chi,\psi}(t)$$

Adiabaticity

$$\left|\frac{\dot{\omega}_k}{\omega_k^2}\right| \lessgtr 1 \longleftrightarrow q \lessgtr 1$$

- **Large:** $q \gtrsim 1$

  Non-perturbative particle production

- **Small:** $q \lesssim 1$

  Perturbative particle production

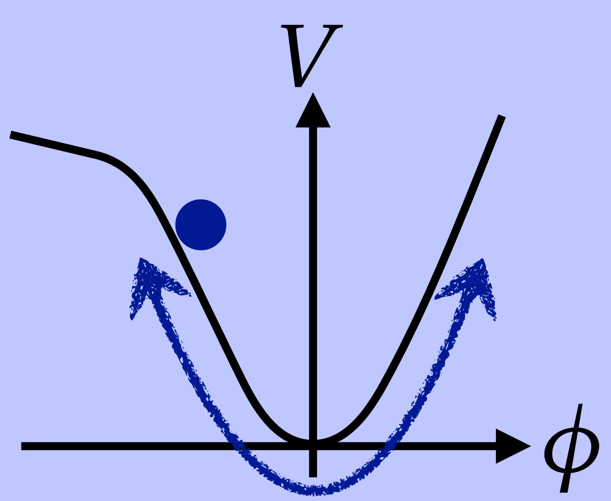
Inflationary Cosmology

■ Typical processes of reheating

Large: $q \gtrsim 1$

Small: $q \lesssim 1$

Far from thermal equil.



Non-perturbative Production

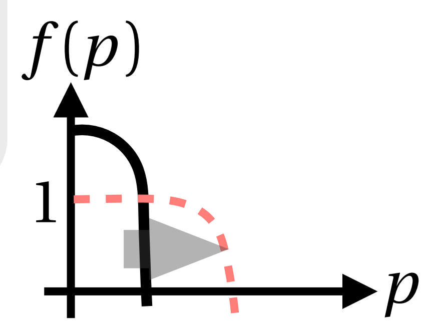
- **Over-occupied/soft** (bosons).
- Killed by back-reaction or cosmic expansion.

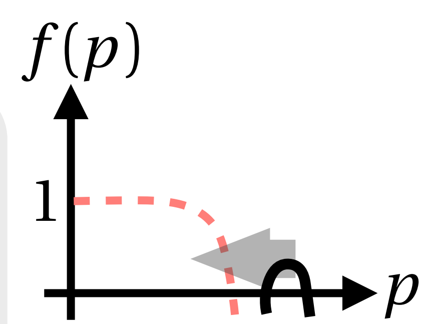
Perturbative Production

- Can be **under-occupied/ hard.**
- Planck-suppressed decay is an extreme example.

Depend on properties of radiation…

Turbulent thermalization ?
Instant/mixed preheating ?
…





Bottom-up thermalization ?
…

Thermalized Plasma

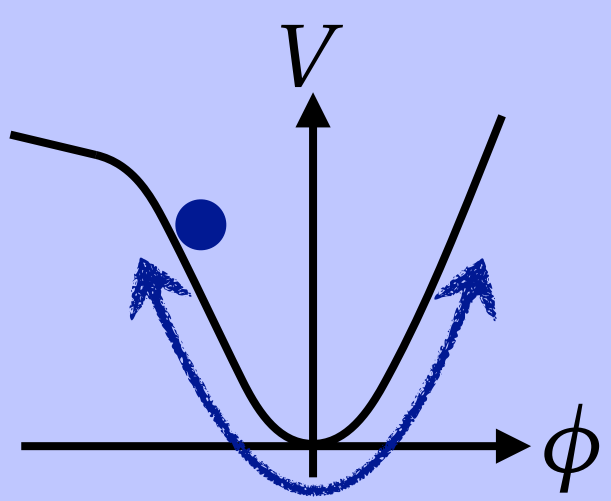
Inflationary Cosmology

■ Two topics of my talk

1. Metastable EW vacuum v.s. Chaotic Inflation

Large: $q \gtrsim 1$

Far from thermal equil.



Small: $q \lesssim 1$

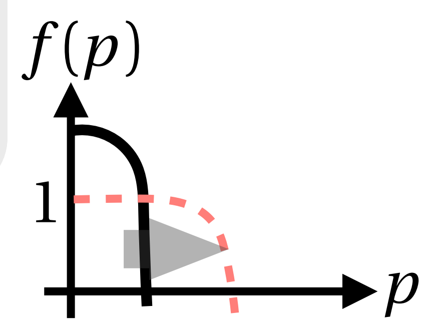
2. Dark Matter Production in Late Time Reheating

Non-perturbative Production

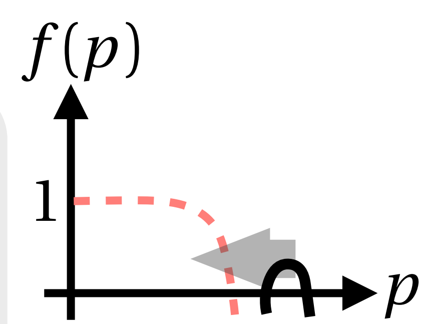
- **Over-occupied/soft** (bosons).
- Killed by back-reaction or cosmic expansion.

Depend on properties of radiation…

Turbulent thermalization ?
Instant/mixed preheating ?
…



Thermalized Plasma



Perturbative Production

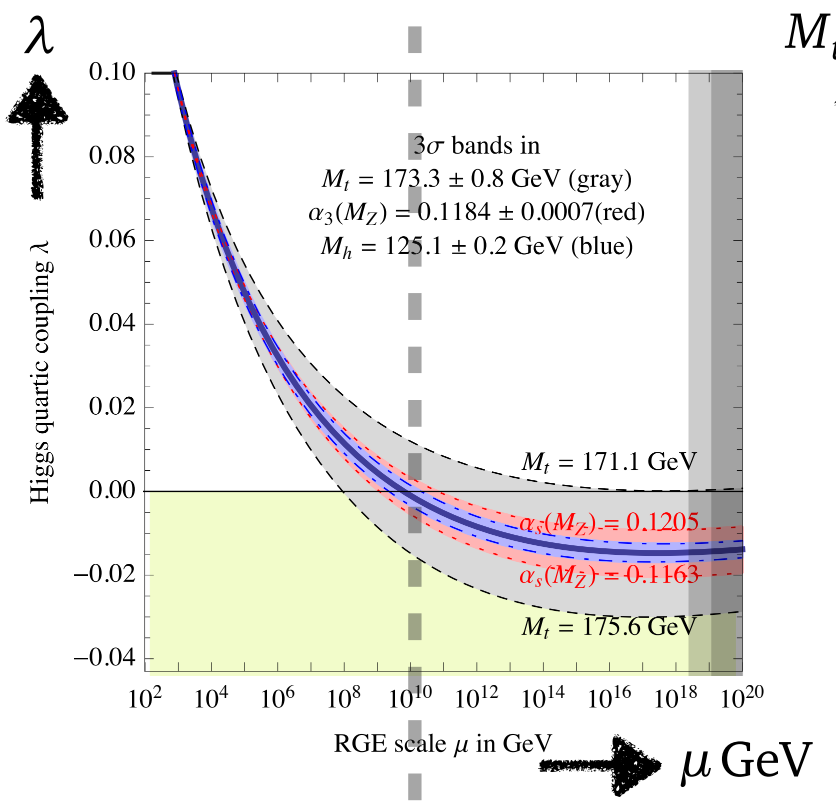
- Can be **under-occupied/hard.**
- Planck-suppressed decay is an extreme example.

Bottom-up thermalization ?
…

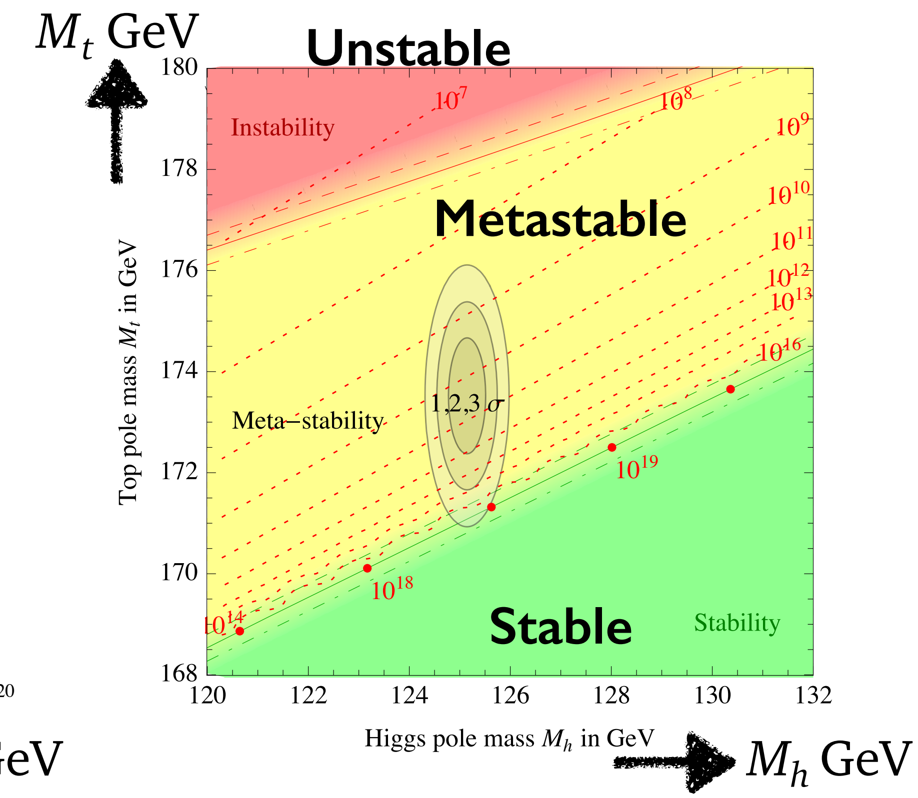
Metastable EW vacuum and Chaotic Inflation

Metastable EW Vacuum

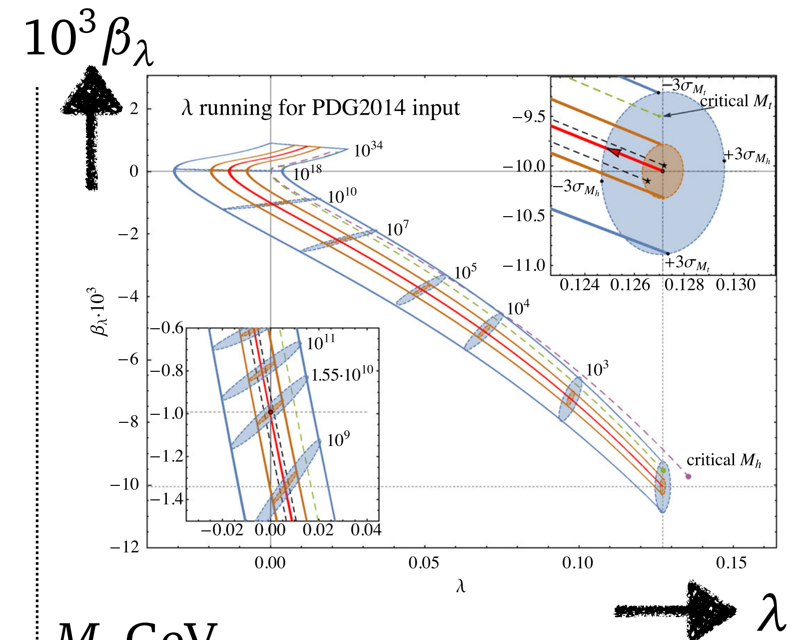
■ **Near-criticality** of the Standard Model?

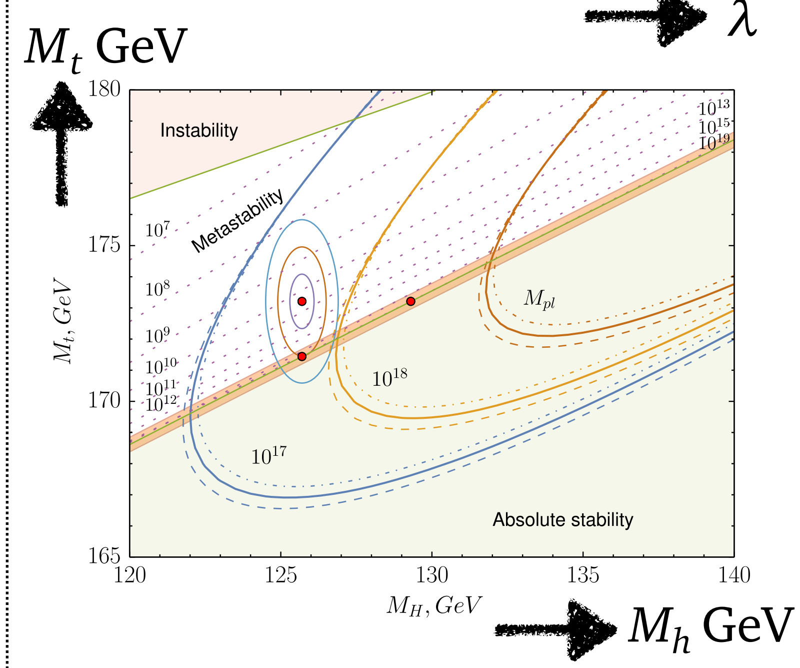


10^{10}GeV



[Buttazzo+, JHEP12(2013)089]





[Bednyakov+, PRL115(2015)201802]

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

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

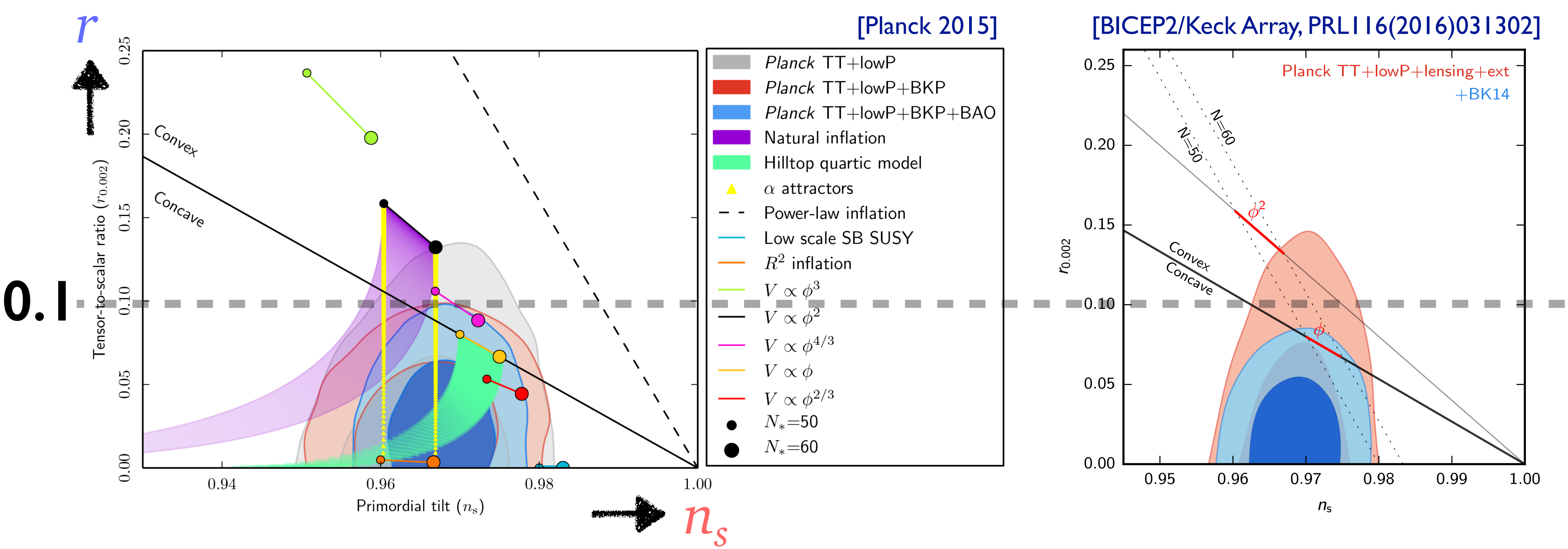
- Chaotic inflation v.s. Metastable electroweak vacuum

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

Chaotic Inflation

■ Large Hubble parameter during inflation: **H_{inf} ~ $10^{13\text{-}14}$ 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

- Metastable EW vacuum in inflationary cosmology

  - Vacuum decay during inflation

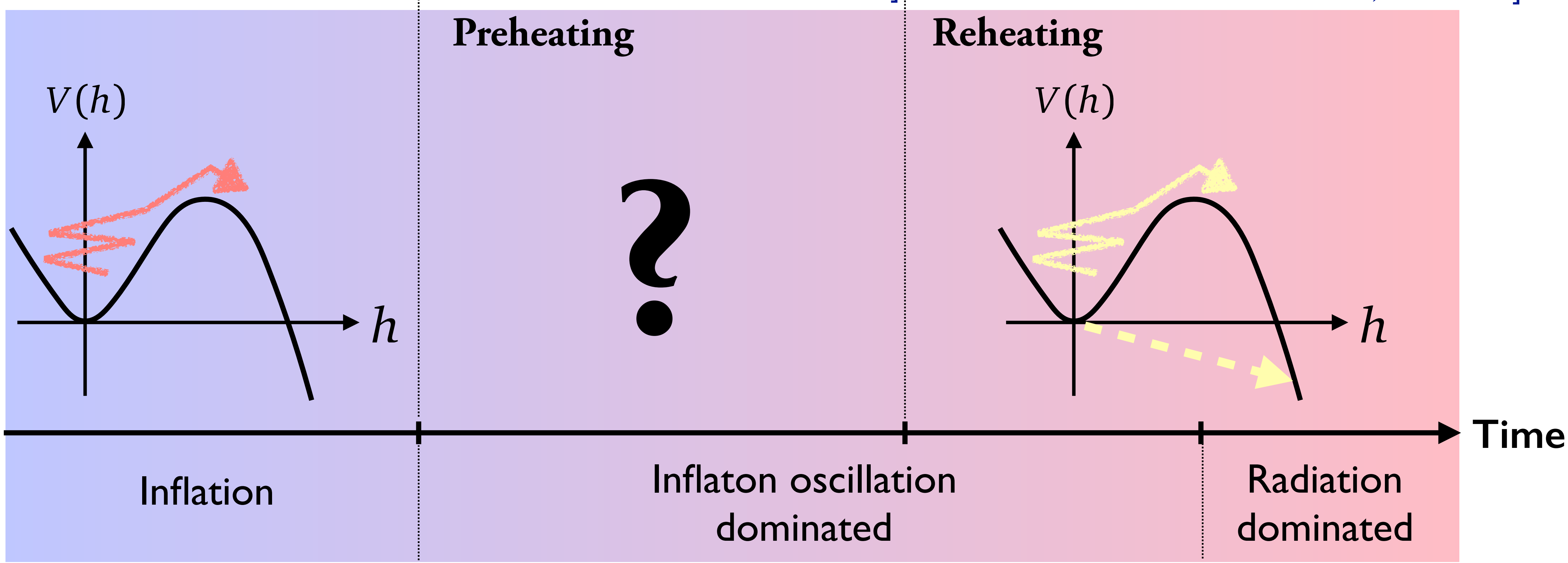
    [Hawking, Moss, PLB110(1982); Starobinsky, Yokoyama, PRD50(1994)]

  - **Vacuum decay during preheating?**

    [Ema, KM, Nakayama 1602.00483; Herranen et al., PRL115(2015)241301; Kohri, Mastui]

  - Vacuum decay (in finite temp.)
    - Long enough life time even for the center value of the top quark mass.

    [e.g. Espinosa, Giudice, Riotto, JCAP05(2008)002; Rose, Marzo, Urbano, 1507.06912; Salvio et al., 1608.02555]



Non-thermal equil.

Thermal equil.

Higgs-Inflaton Coupling

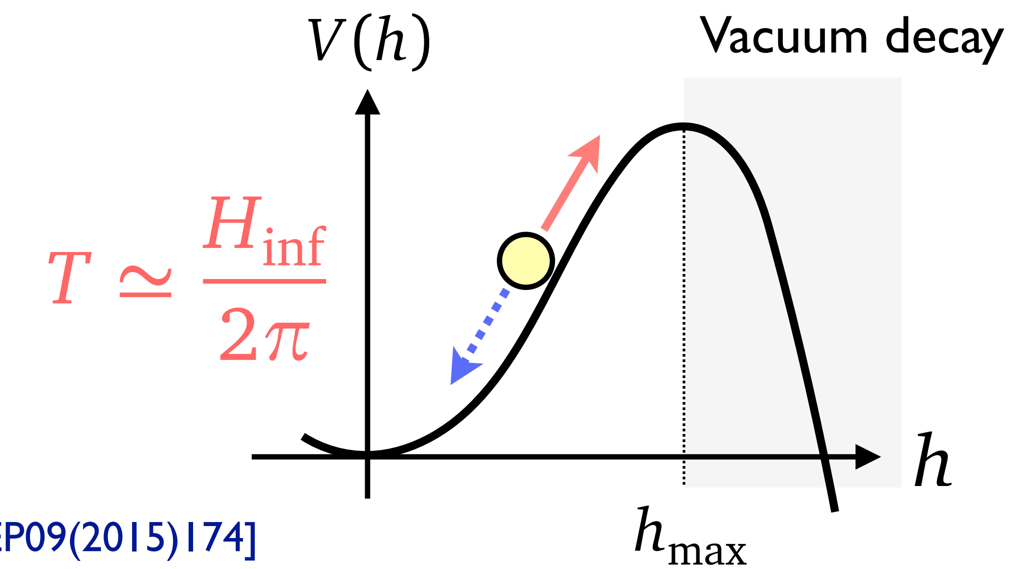
- **Light** fields, m ≪ H_{inf}, acquire fluctuations during inflation.

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

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

Tension w/ High scale inflation

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



✦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

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

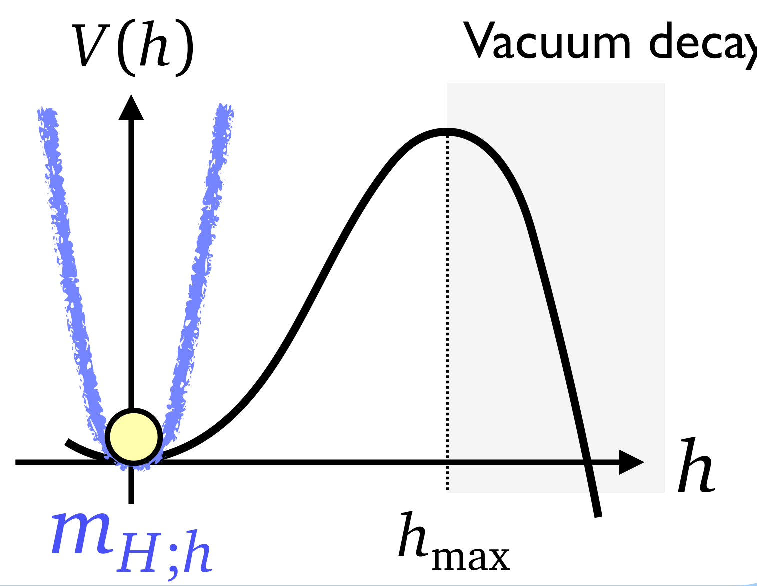
during inflation

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

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

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

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

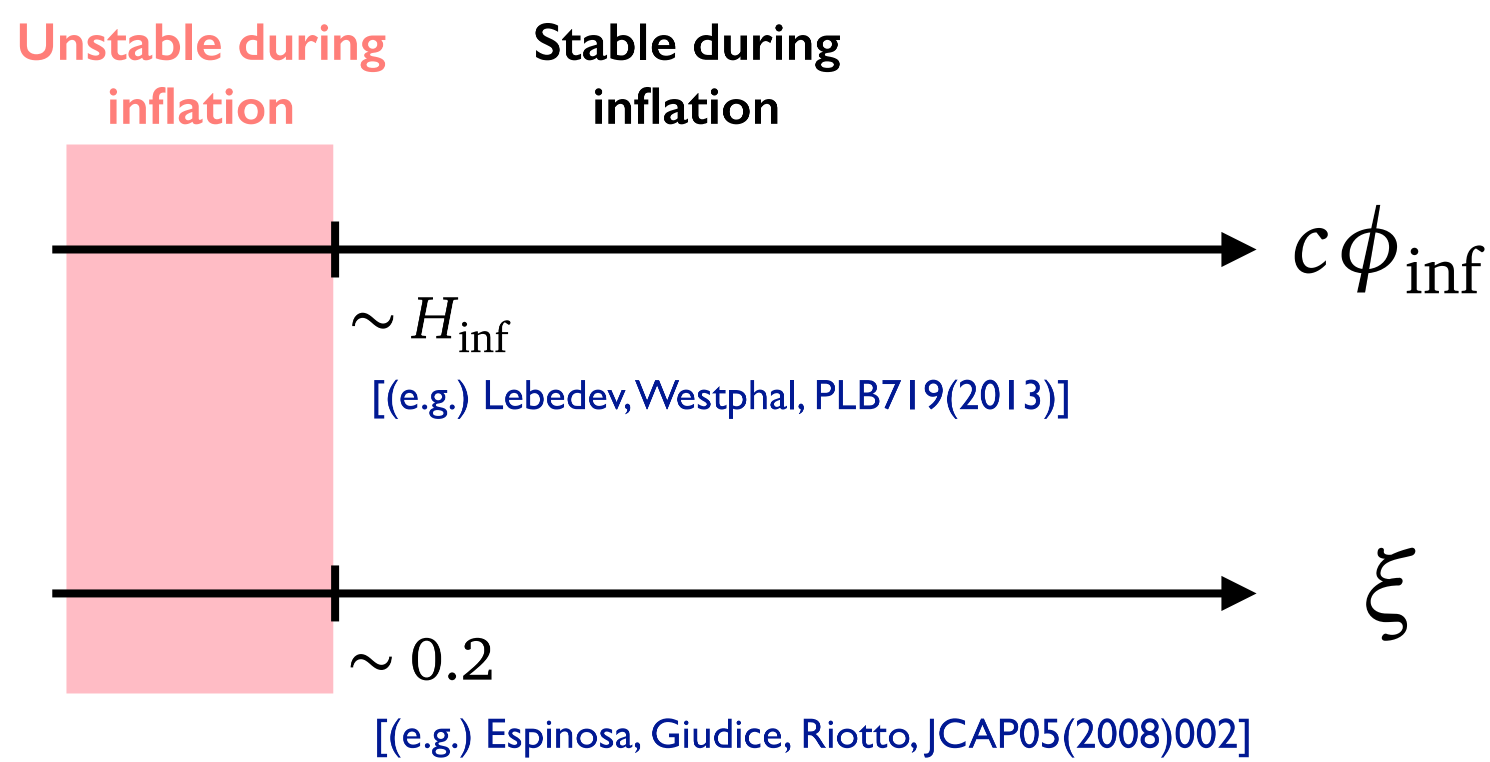
- **Small Higgs-inflaton coupling can save the EW vacuum**

- Quartic coupling

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

- Curvature coupling

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



Parametric Resonance

■ Non perturbative Higgs production

- However, inflaton oscillates after inflation…

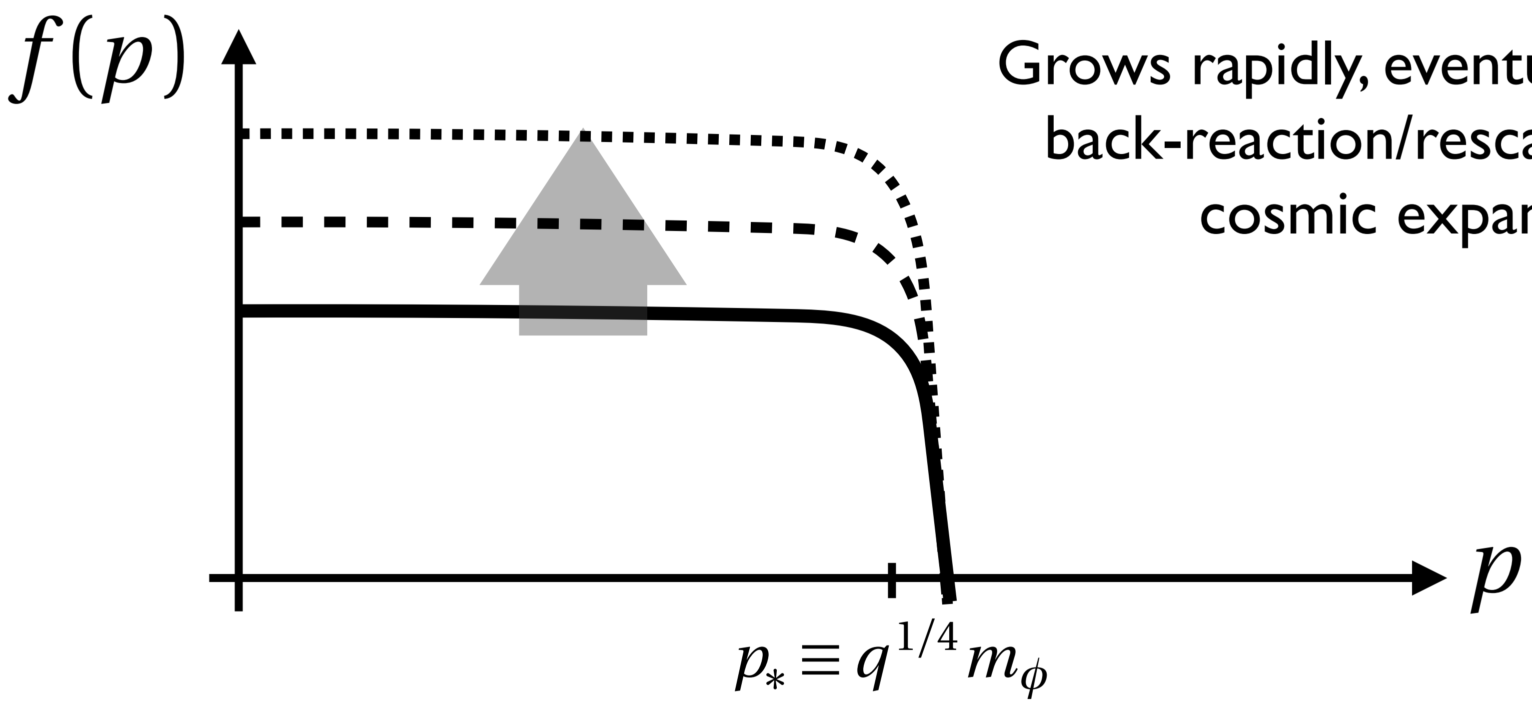
◉ Non-adiabatic change of the effective mass → Large Higgs fluctuations

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

Condition for explosive Higgs Production

$$q(t) > 1$$

- Typical distribution function for q(t) > 1:



Grows rapidly, eventually killed by back-reaction/rescatterings or cosmic expansion.

Parametric Resonance

Non perturbative Higgs production

- However, inflaton oscillates after inflation…

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

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

Condition for explosive Higgs Production

$$q(t) > 1$$

- Quartic coupling

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

$$q(t) \sim \frac{c^2 \Phi^2(t)}{m_\phi^2}$$

Ordinary Resonance

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

- Curvature coupling

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

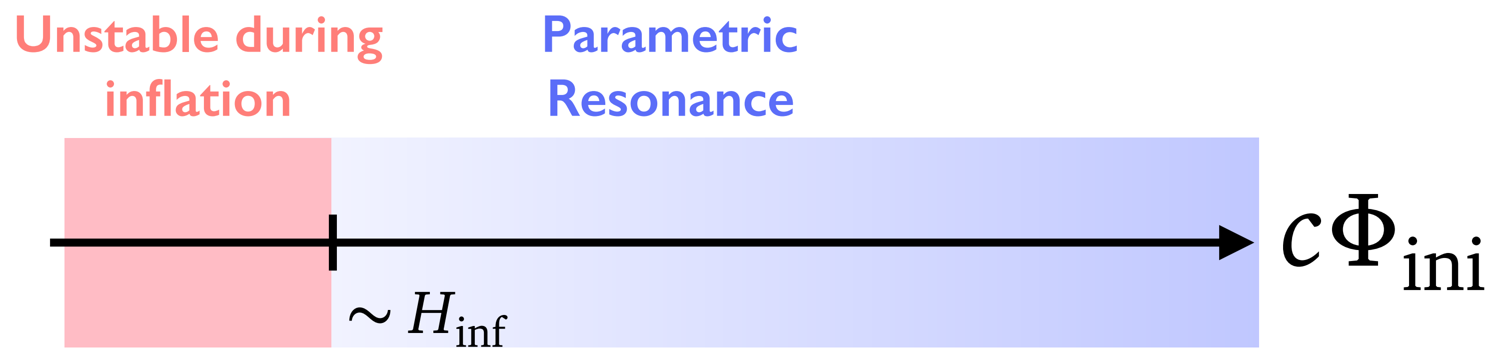
$$q(t) \sim \frac{\xi \Phi^2(t)}{M_{\rm pl}^2}$$

Tachyonic Resonance

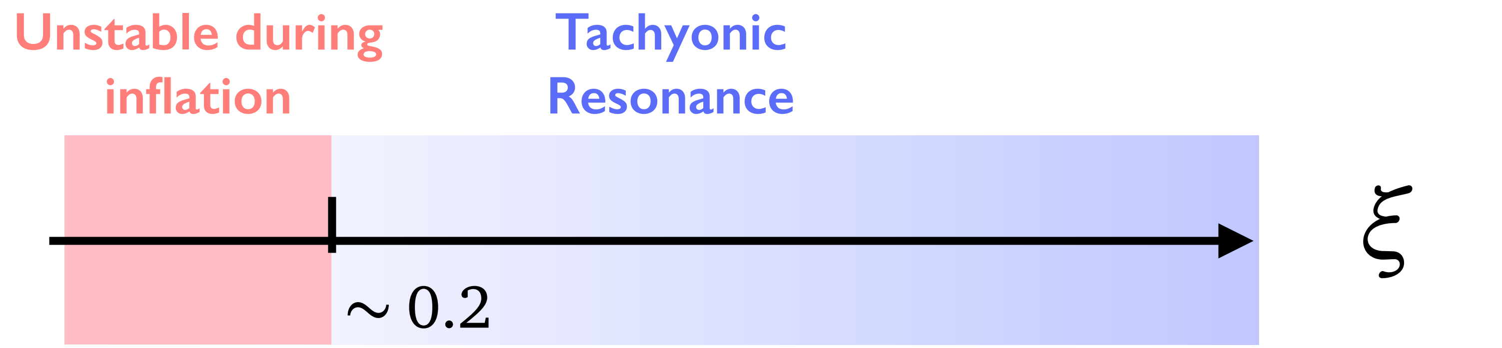
$$m_{H;h}^2(t) \simeq \frac{\xi m_\phi^2 \Phi^2(t)}{2 M_{\rm pl}^2} \left[3 \cos\left(2 m_\phi t\right) + 1\right]$$

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

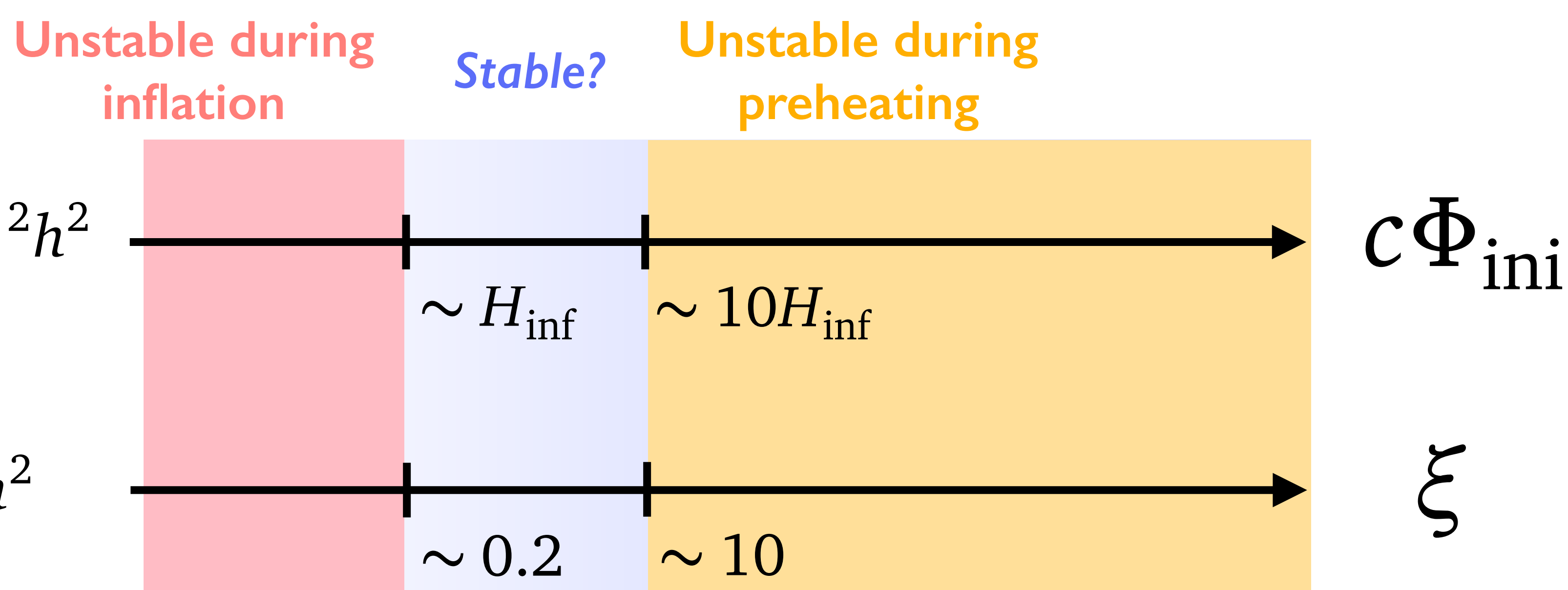
[Ema, KM, Nakayama 1602.00483]

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

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

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

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



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

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

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

Vacuum decay via Resonance

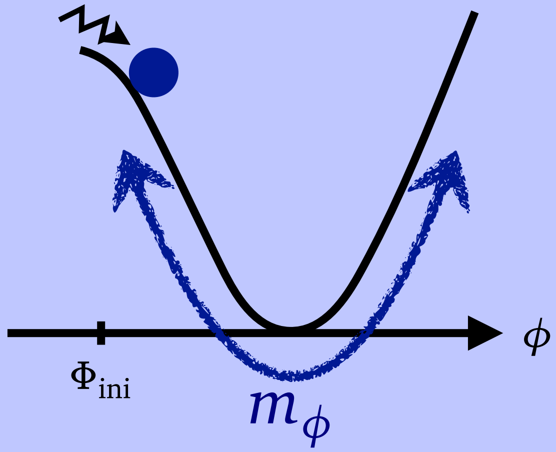
■ Setup of classical lattice simulation

- To confirm our estimation, we performed a classical lattice simulation.
  - The Lagrangian: $\mathscr{L} = \mathscr{L}_{\rm inf}(\phi) + \mathscr{L}_{\rm Higgs}(h) + \mathscr{L}_{\rm int}(\phi, h),$

[Polarsky, Starobinsky, CQG13 (1996); Khlebnikov, Tkachev, PRL77(1996)]

Inflaton Sector

$$\mathscr{L}_{\rm inf}(\phi) = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2$$



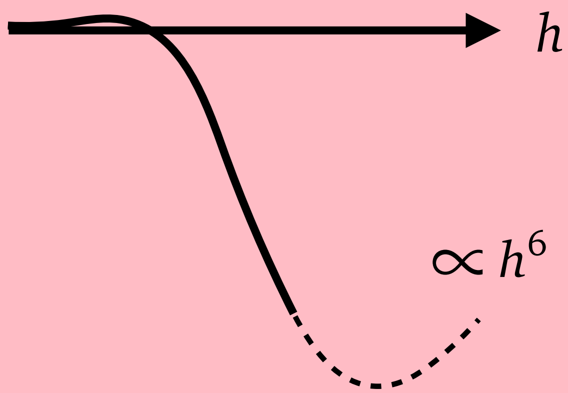
$m_\Phi \sim 10^{13}$ GeV

$$\mathscr{L}_{\rm int}(\phi, h) = \begin{cases} -\dfrac{1}{2} c^2 \phi^2 h^2 & \cdots \text{quartic,} \\ -\dfrac{1}{2} \xi R h^2 & \cdots \text{curvature} \end{cases}$$

Interaction

Higgs Sector

$$\mathscr{L}_{\rm Higgs}(h) = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h)$$



Add h^6 to avoid numerical div.

  - Properties of our discretized world

    Grid Number = 128^3, Time step = $10^{-3}/m_\Phi$, Length of box = **10**$/m_\Phi$ ($20/m_\Phi$), periodic bdry.

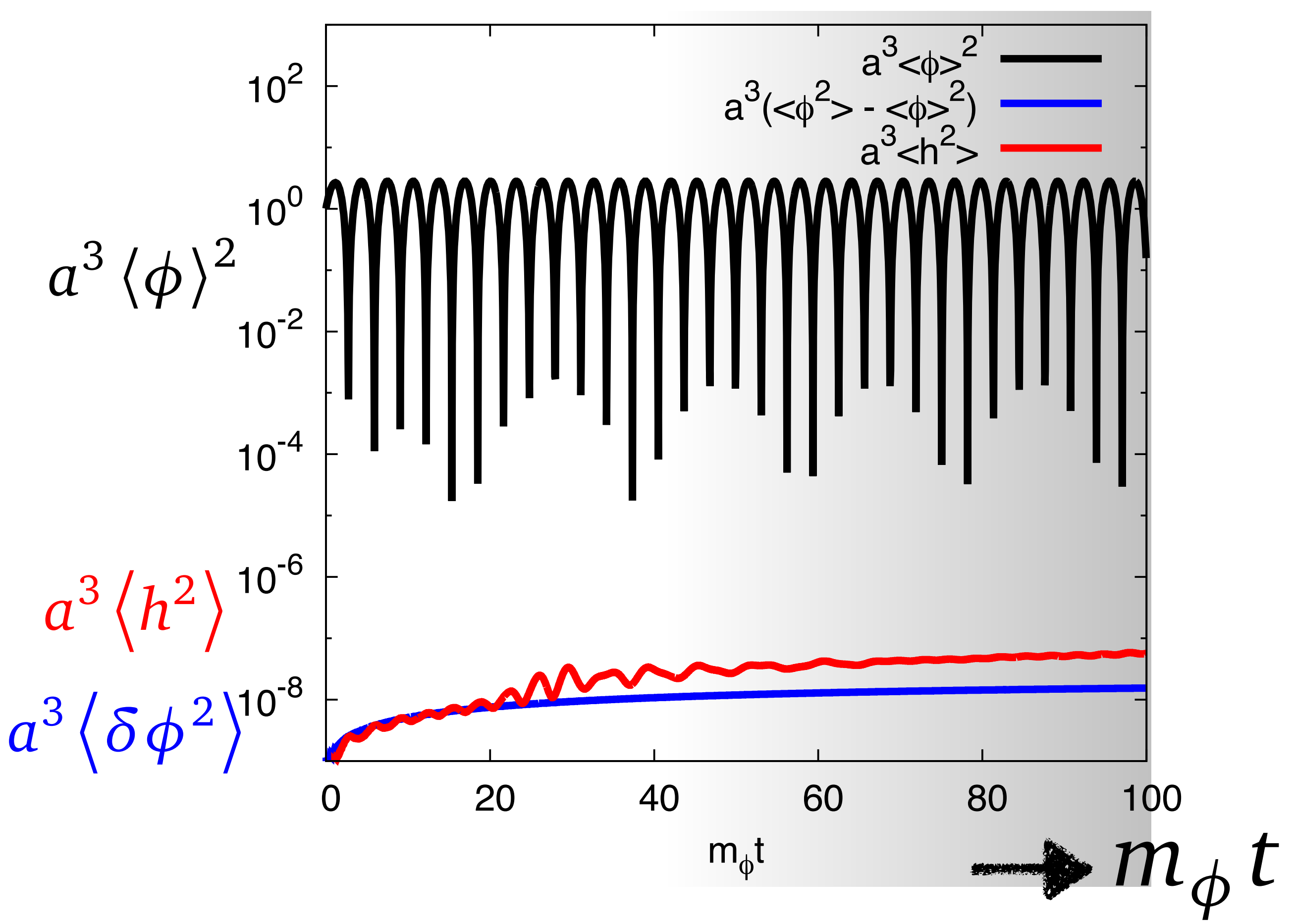
  - Numerically solve the Einstein equation w/ Gaussian initial conditions mimicking vacuum fluctuations.

Numerical Simulation

[Ema, KM, Nakayama 1602.00483]

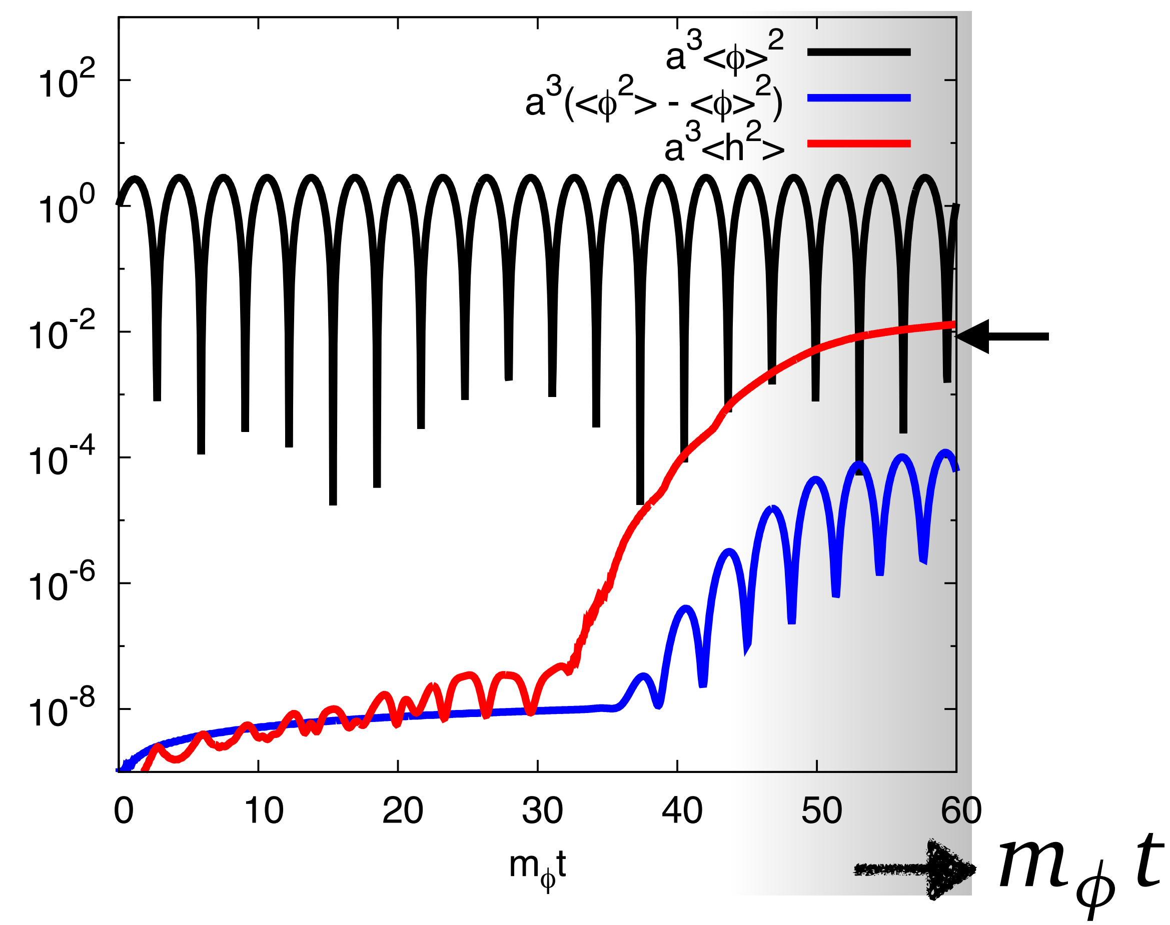
- Vacuum decay via Parametric Resonance: $-\mathcal{L}_{\rm int}(\phi,h) = \frac{1}{2}c^2\phi^2h^2$
  - To check $c \lesssim 10^{-4} \times \left[\frac{0.1}{\mu_{\rm qtc}}\right]\left[\frac{m_\phi}{10^{13}\,{\rm GeV}}\right]$, we performed a classical lattice simulation.

- Stable: c = 1 × 10^{-4}



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

- Unstable: c = 2 × 10^{-4}



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

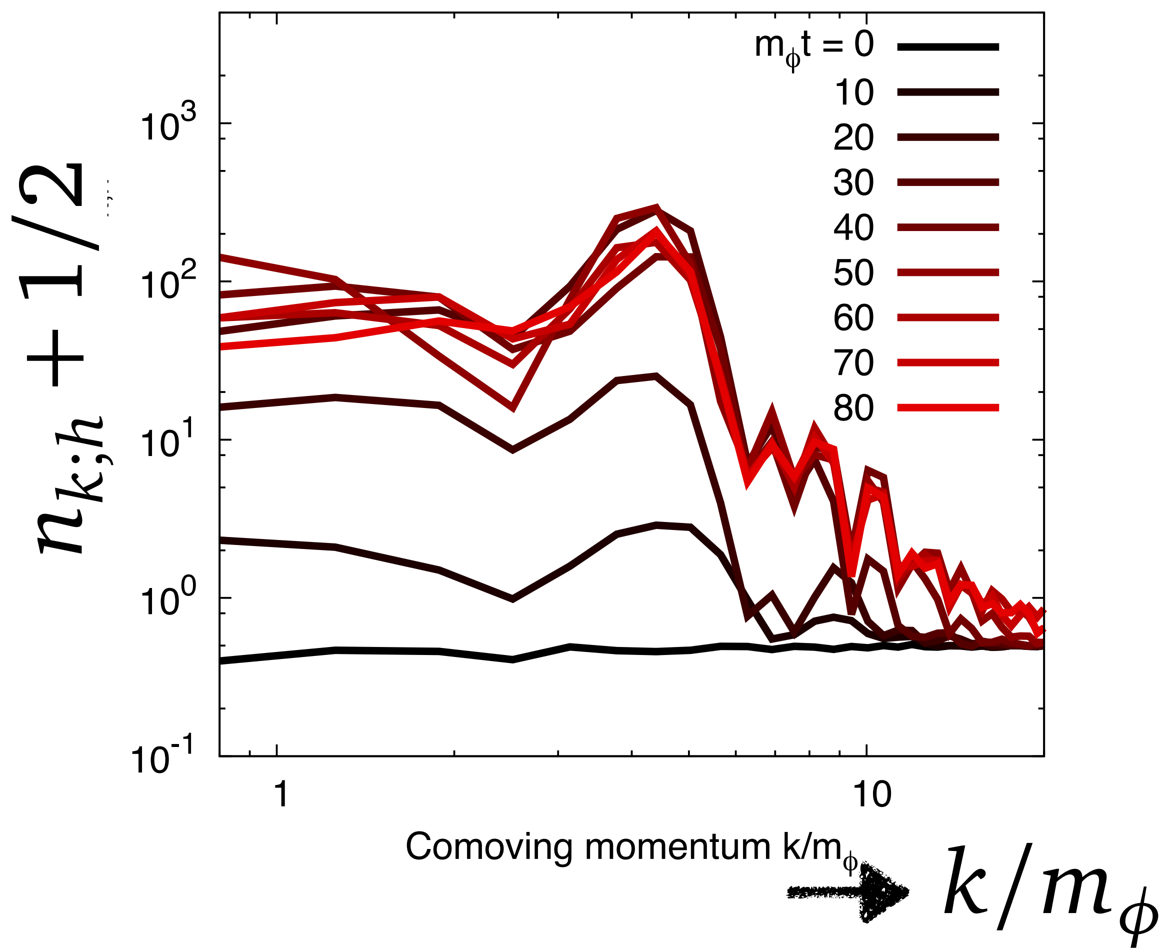
Numerical Simulation

[Ema, KM, Nakayama 1602.00483]

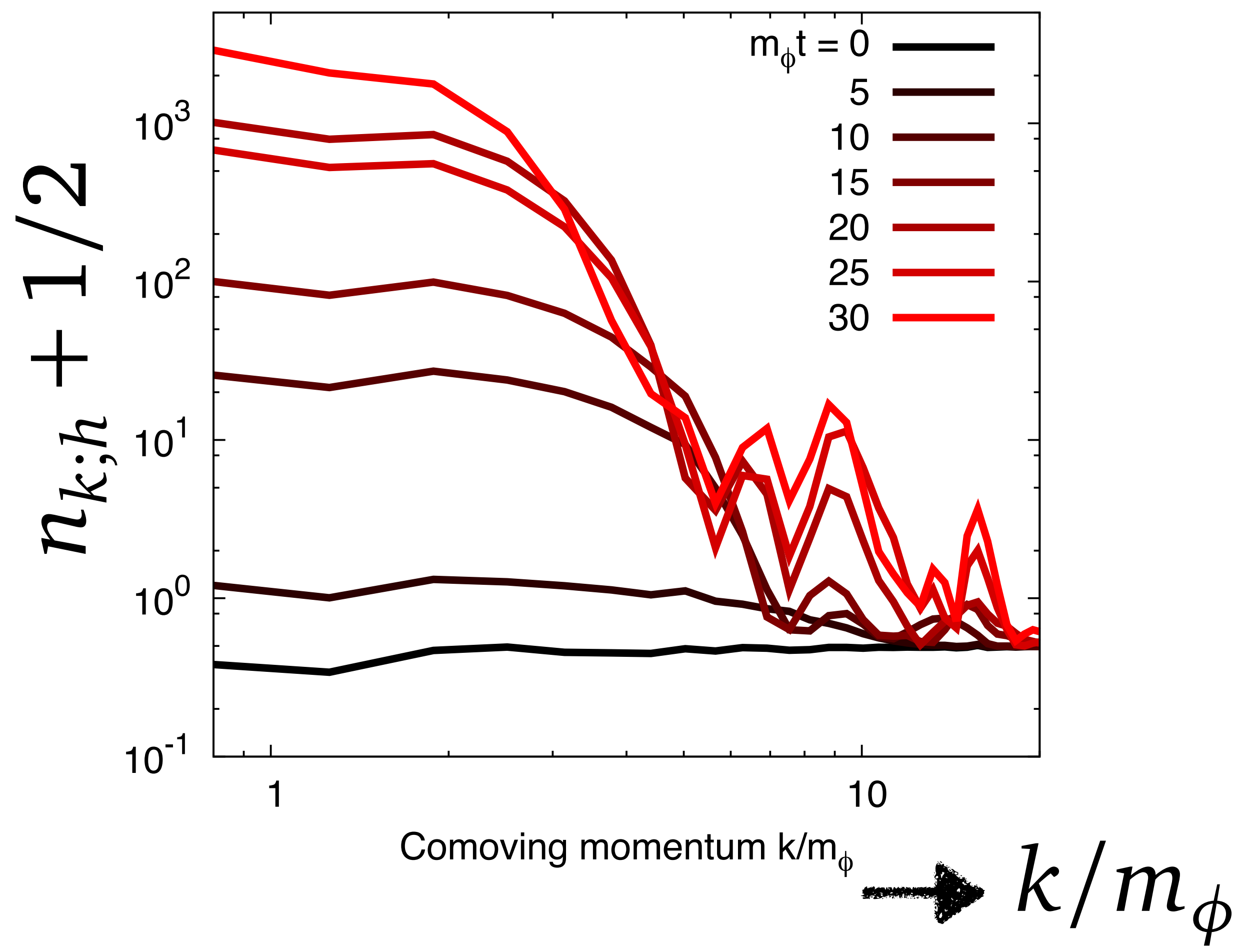
- Vacuum decay via Parametric Resonance: $-\mathcal{L}_{\rm int}(\phi, h) = \frac{1}{2}c^2\phi^2h^2$

  - Evolution of comoving phase space number density of Higgs, $n_{k;h}(t)$.

- c = 1 × 10^{-4}



- c = 2 × 10^{-4}



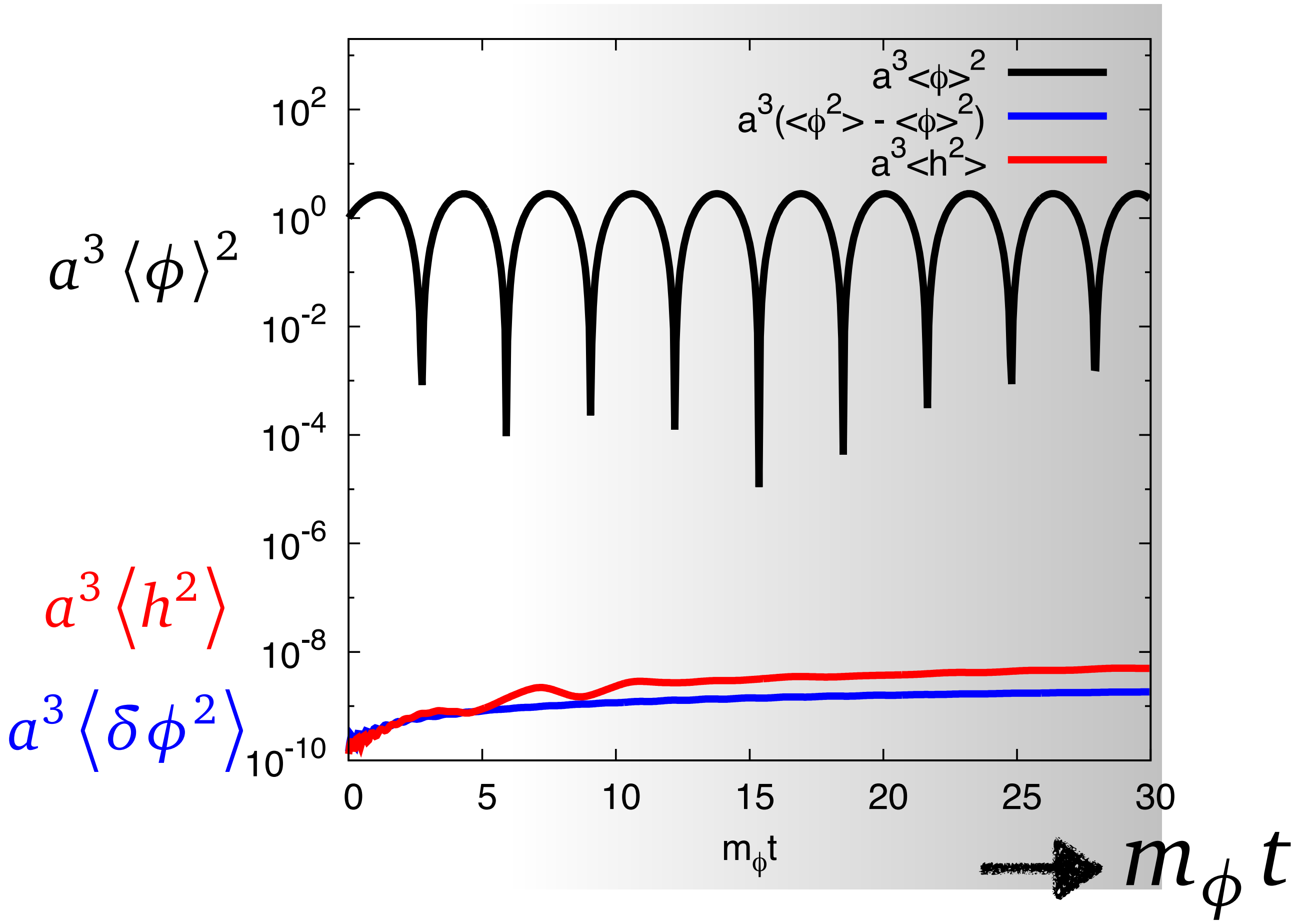
Numerical Simulation

[Ema, KM, Nakayama 1602.00483]

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

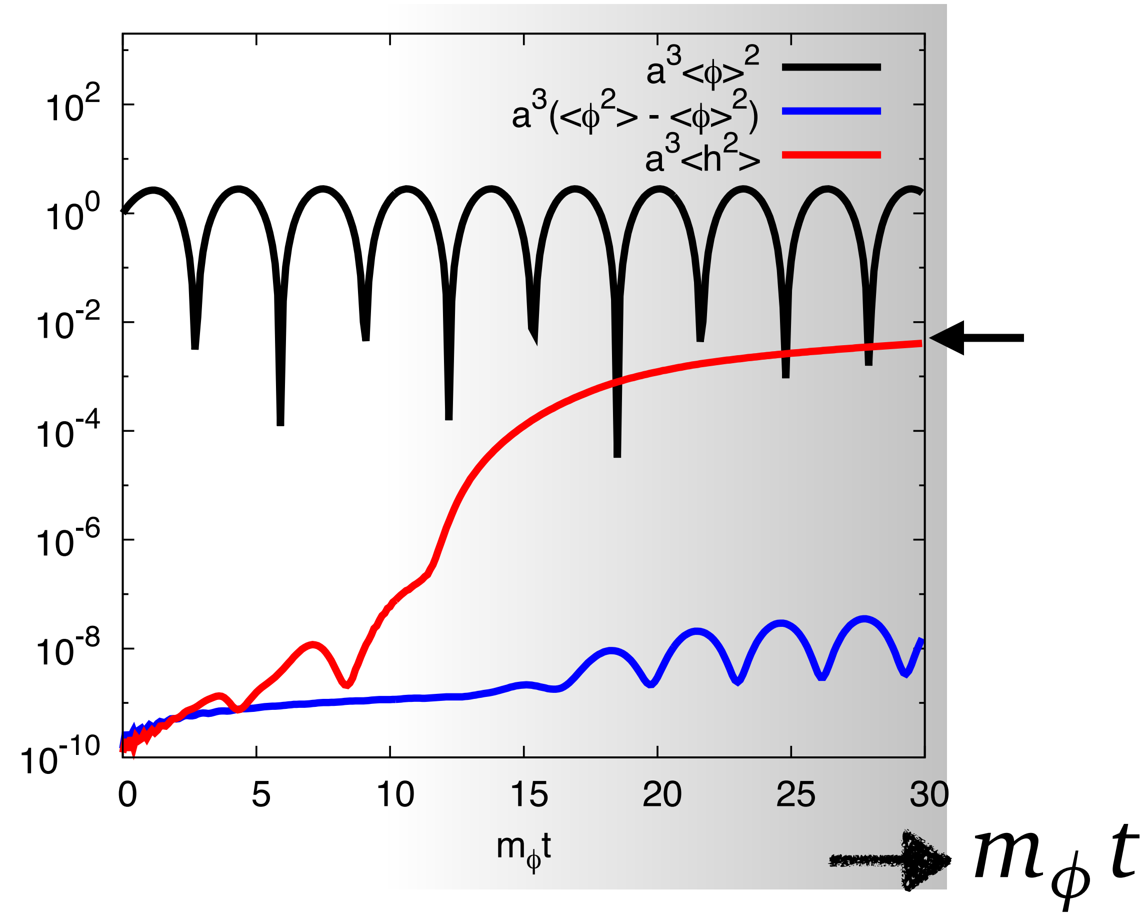
- To check $\xi \lesssim 10 \times \left[\frac{1}{\mu_{\rm crv}}\right]^2 \left[\frac{\sqrt{2} M_{\rm pl}}{\Phi_{\rm ini}}\right]^2$, we performed a classical lattice simulation.

- Stable: ξ = 10



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

- Unstable: ξ = 20



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

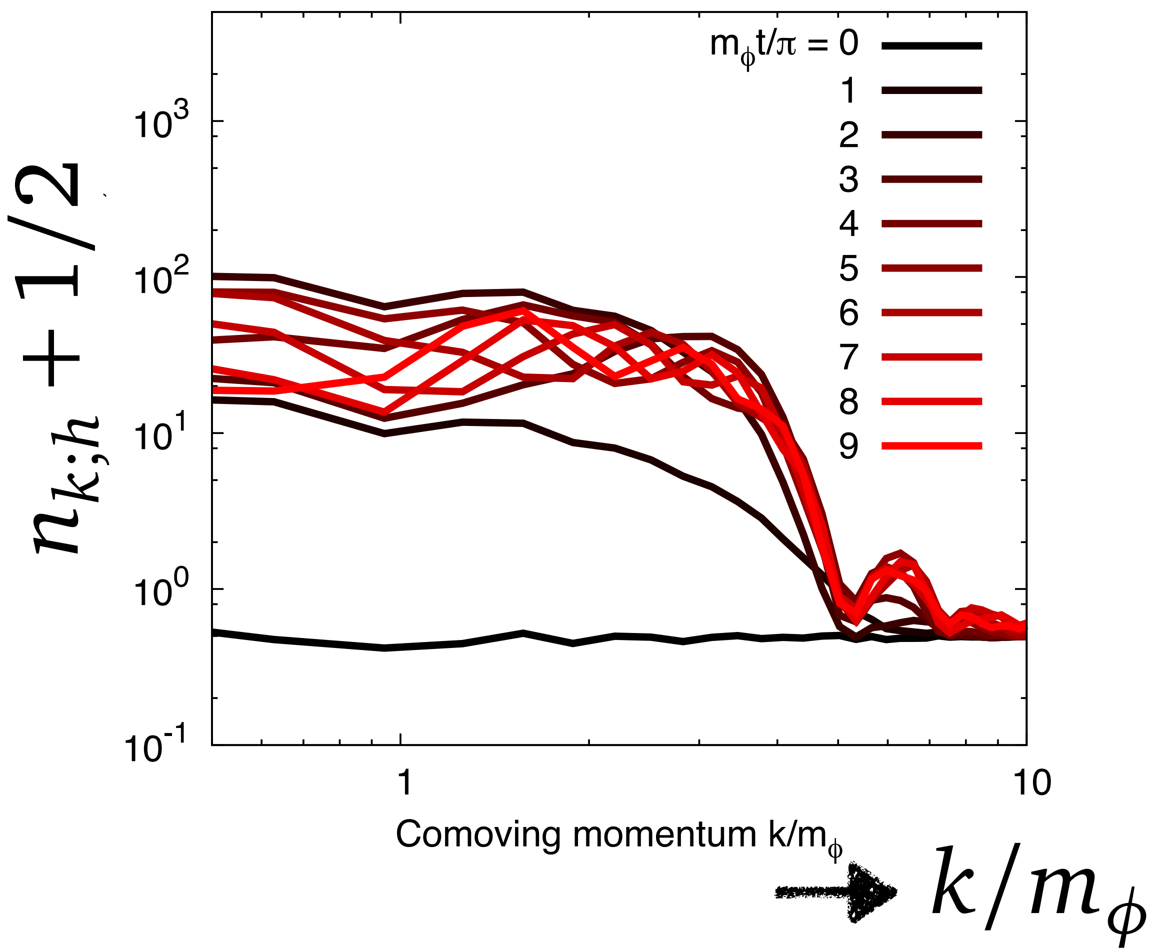
Numerical Simulation

[Ema, KM, Nakayama 1602.00483]

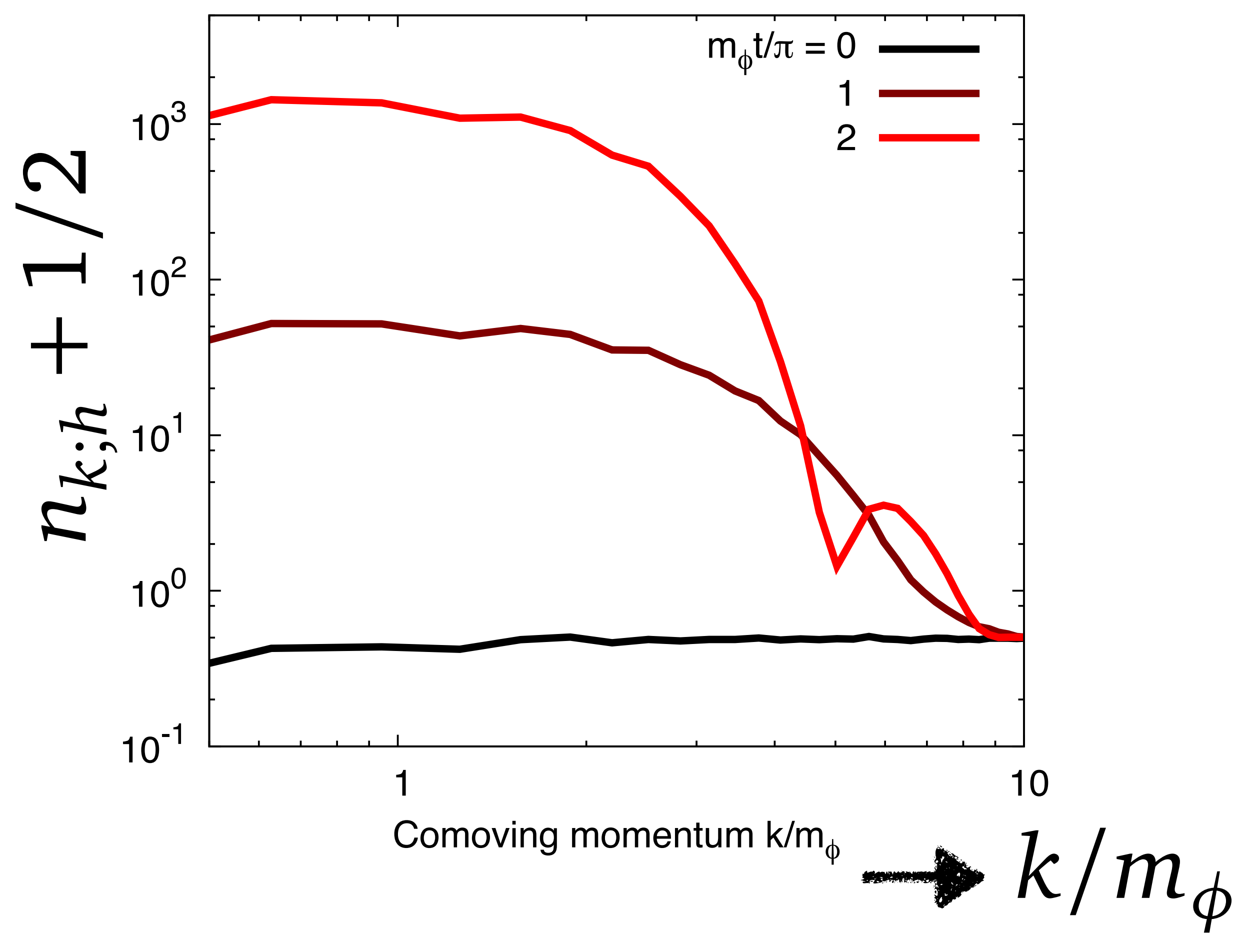
■ Vacuum decay via Tachyonic Resonance: $-\mathscr{L}_{\rm int}(\phi, h) = \frac{1}{2}\xi R h^2$

- Evolution of comoving phase space number density of Higgs, $n_{k;h}(t)$.

- ξ = 10



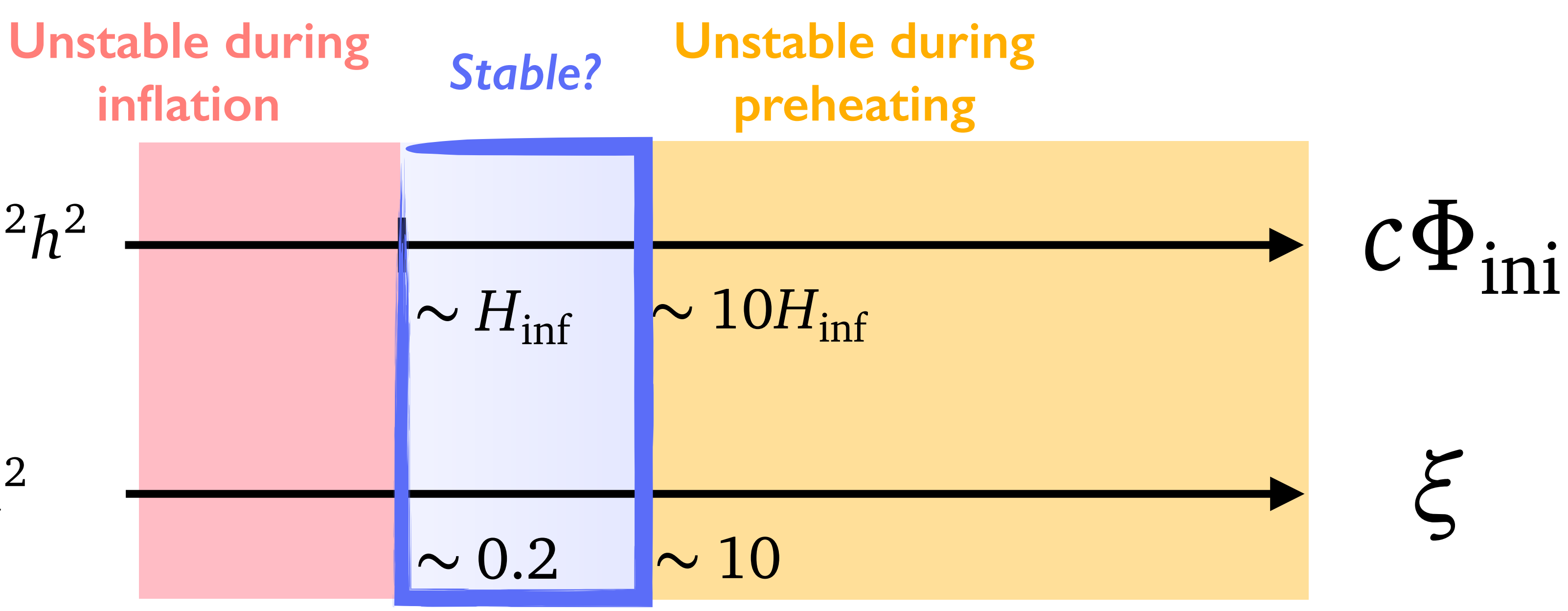
- ξ = 20



Summary of the 1st part

- Preheating may **destabilize the EW vacuum**.
- 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 □.

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



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

[Ema, KM, Nakayama 1602.00483]

DM Production
in
Late Time Reheating

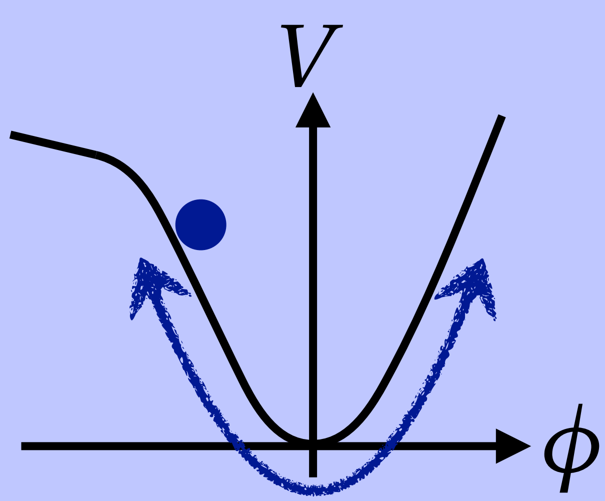
Inflationary Cosmology

■ **Two topics of my talk**

1. Metastable EW vacuum v.s. Chaotic Inflation

Large: $q \gtrsim 1$

Far from thermal equil.



Small: $q \lesssim 1$

2. Dark Matter Production in Late Time Reheating

Non-perturbative Production

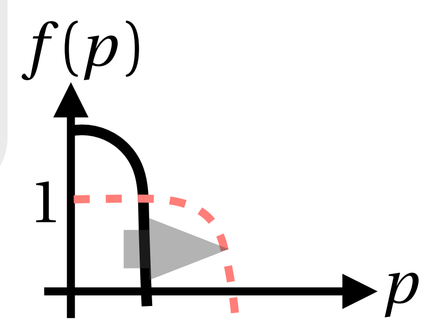
- **Over-occupied/soft** (bosons).
- Killed by back-reaction or cosmic expansion.

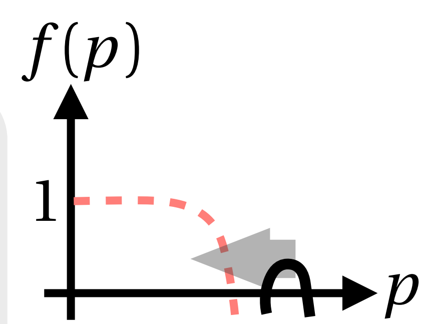
Perturbative Production

- Can be **under-occupied/hard**.
- Planck-suppressed decay is an extreme example.

Depend on properties of radiation…

Turbulent thermalization ?
Instant/mixed preheating ?
…





Bottom-up thermalization ?
…

Thermalized Plasma

Perturbative Reheating

■ Reheating temperature T_R

- Temperature when inflaton decays completely.

$$\Gamma_\phi \sim H \longleftrightarrow T_R \sim \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma_\phi M_{pl}}$$

✦Assumption1. Resonance does not take place;
✦Assumption2. Radiation is thermalized.

- Relation between T_R and q for $q < 1$.

  - Boson:

$$\Delta m_\chi^2(\phi)\chi\chi \sim \frac{q(\Phi)m_\phi^2}{\Phi}\phi\chi\chi \quad \Rightarrow \quad \Gamma_\phi \sim \left(\frac{q^2(\Phi)m_\phi^2}{\Phi^2}\right)m_\phi \quad \Rightarrow \quad \left(\frac{q^2(\Phi_{ini})m_\phi^2}{\Phi_{ini}^2}\right)m_\phi$$

  - Fermion:

$$\Delta m_\psi(\phi)\bar{\psi}\psi \sim \frac{\sqrt{q(\Phi)}m_\phi}{\Phi}\phi\bar{\psi}\psi \quad \Rightarrow \quad \Gamma_\phi \sim \left(\frac{q(\Phi)m_\phi^2}{\Phi^2}\right)m_\phi \quad \Rightarrow \quad \left(\frac{q(\Phi_{ini})m_\phi^2}{\Phi_{ini}^2}\right)m_\phi$$

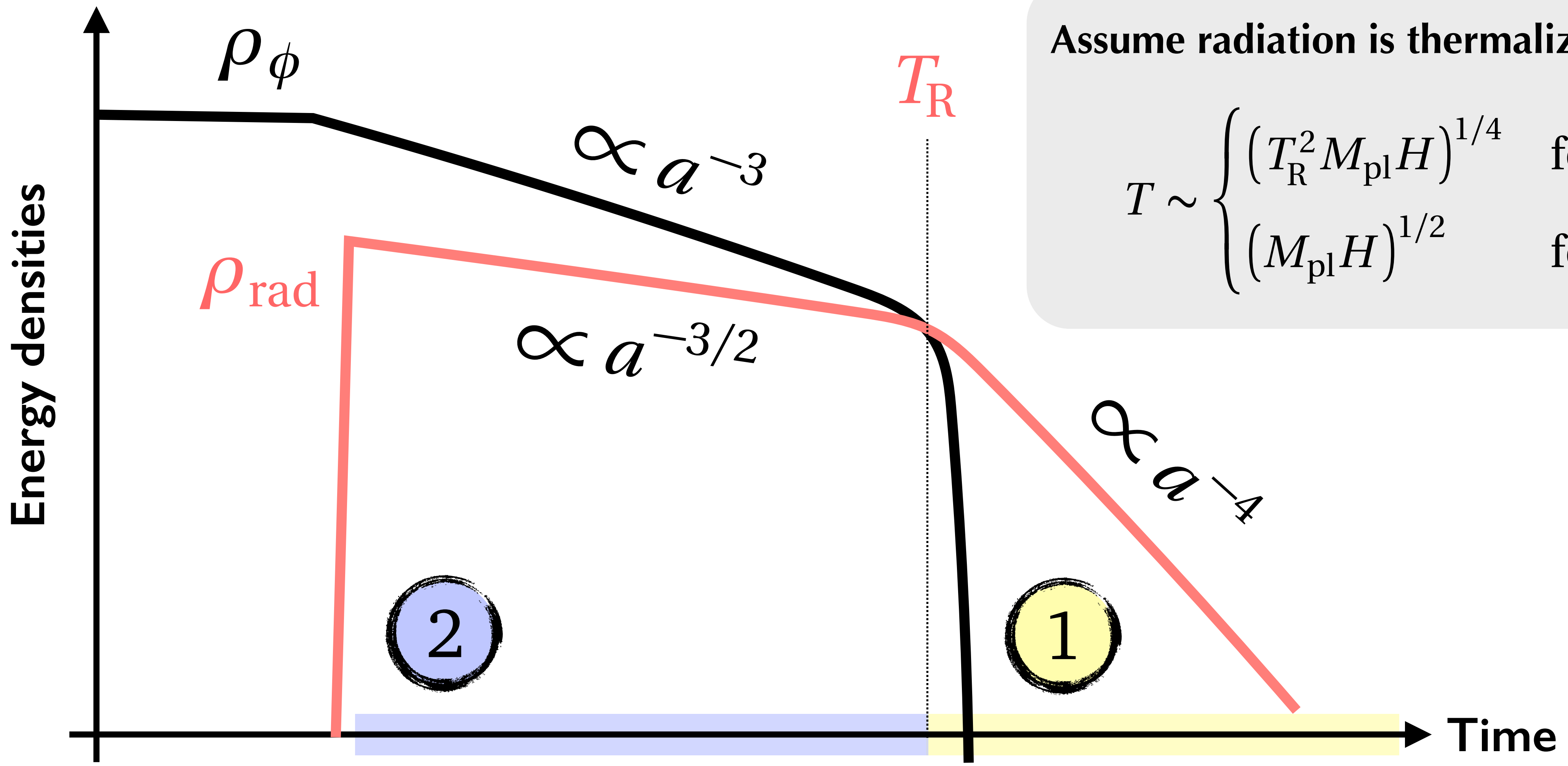
◉T_R could be low for $q_{ini} \lll 1$ and/or $m_\phi \ll \Phi_{ini} \sim M_{pl}$.

$$T_R \sim 100\mathrm{GeV}\left(\frac{\tilde{q}}{10^{-17}}\right)^{1/2}\left(\frac{m_\phi}{10^{13}\,\mathrm{GeV}}\right)^{3/2}\left(\frac{M_{pl}}{\Phi_{ini}}\right), \qquad \tilde{q} \equiv q^2(\Phi_{ini}) \text{ or } q(\Phi_{ini})$$

Perturbative Reheating

■ Schematic picture

- Evolution of energy densities (obtained from Boltzmann eqs.)



Assume radiation is thermalized: $T \sim \rho_{\rm rad}^{1/4}$

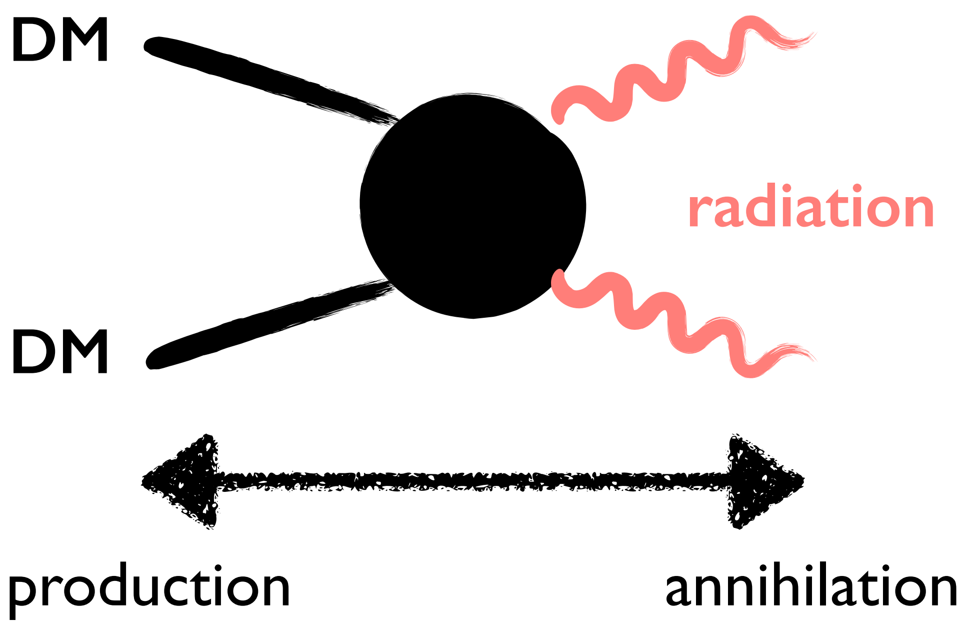
$$T \sim \begin{cases} \left(T_{\rm R}^2 M_{\rm pl} H\right)^{1/4} & \text{for } \Gamma_\phi < H \\ \left(M_{\rm pl} H\right)^{1/2} & \text{for } H < \Gamma_\phi \end{cases}$$

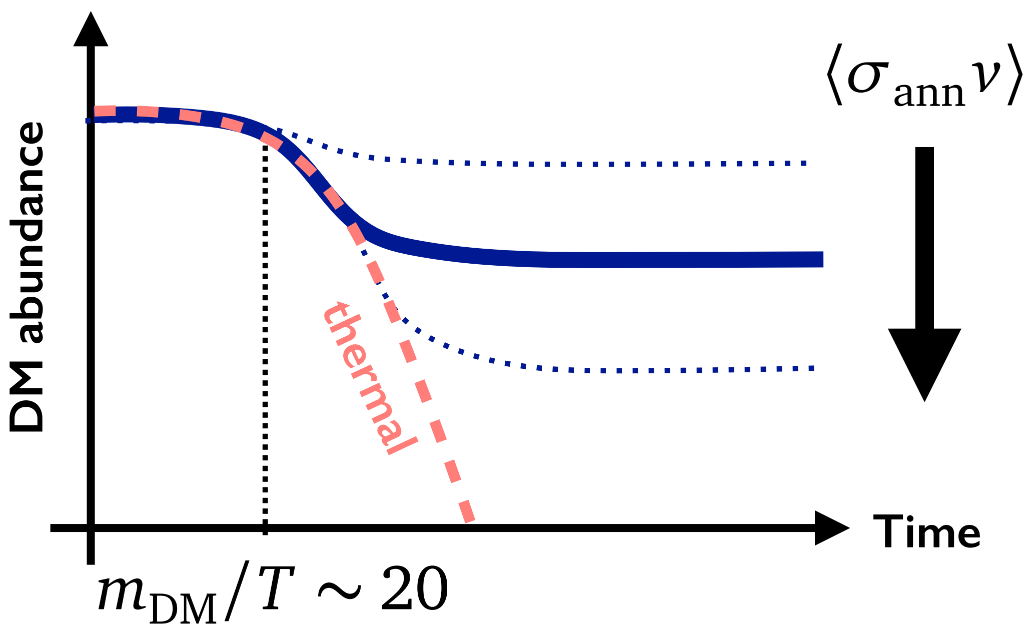
DMs are produced at some period

Dark Matter Production

1 Thermal freeze-out

- DM was **in thermal equilibrium** → decoupled later by the cosmic expansion.





$$n_{\rm DM}^{\rm eq}(T_{\rm F}) \langle \sigma_{\rm ann} v \rangle \simeq H(T_{\rm F}), \quad T_{\rm F} \sim \frac{m_\phi}{20}$$

◉Question: production of DM with $m_{\rm DM} \gg T_{\rm R}$

Dark Matter Production

② "Heavy" DM production with $m_{\rm DM} \gg T_{\rm R}$

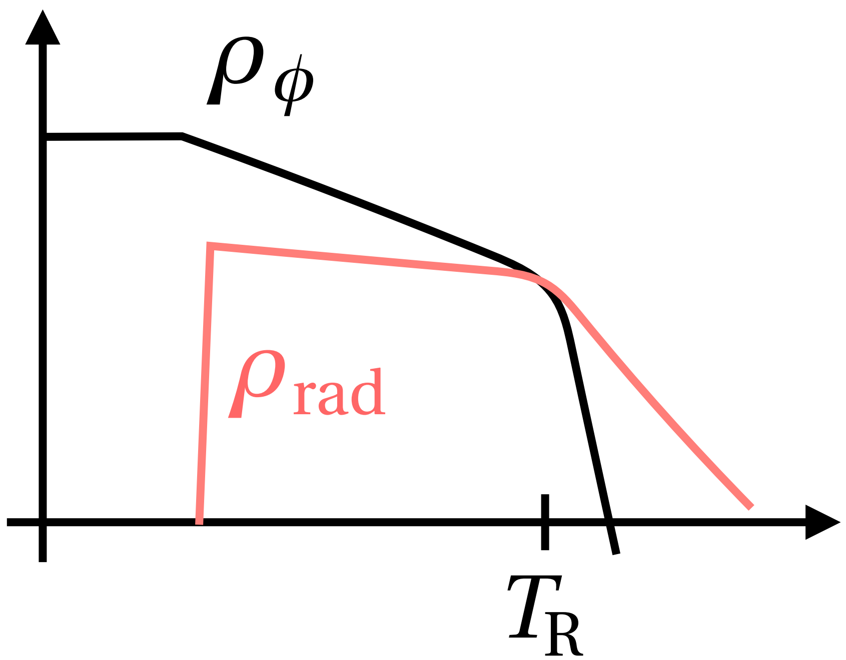
- Production from direct inflaton decay

$$\left.\frac{n_{\rm DM}^{\rm dir}}{s}\right|_{\rm now} \simeq T_{\rm R} \left.\frac{3n_{\rm DM}^{\rm dir}}{4\rho_\phi}\right|_{T \simeq T_{\rm R}} \simeq \frac{3T_{\rm R}}{4m_\phi} {\rm Br}(\phi \to {\rm DM})$$

- Production from thermal plasma with **T > m**

Production from thermal plasma with $\mathbf{T > m_{DM}} \gg T_{\rm R}$

  - Radiation with $T \gg T_{\rm R}$; (assume radiation is thermalized)



$$T \sim \rho_{\rm rad} \sim \left(T_{\rm R}^2 M_{\rm pl} H\right)^{1/4} \quad \text{for} \quad H > \Gamma_\phi$$

$$\left.\frac{n_{\rm DM}^{\rm th}}{s}\right|_{\rm now} \simeq T_{\rm R} \left.\frac{3n_{\rm DM}^{\rm th}}{4\rho_\phi}\right|_{F} \simeq \left.\frac{n_{\rm DM}^{\rm th}}{s}\right|_{\rm F} \left(\frac{T_{\rm R}}{T_{\rm F}}\right)^5$$

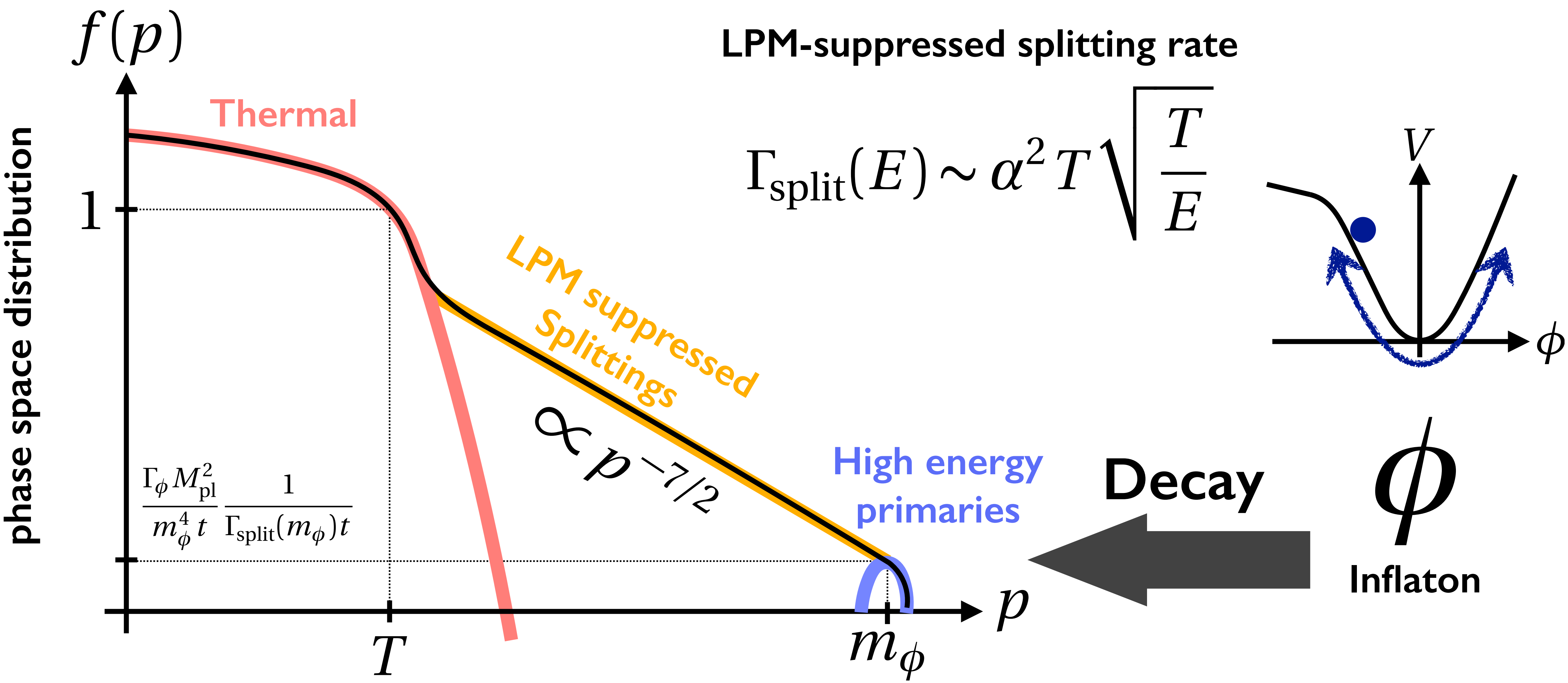
Dilution factor

Dark Matter Production

② "Heavy" DM production with $m_{\mathrm{DM}} \gg T_{\mathrm{R}}$

◉Production via interaction between thermal population and high energy tail.

- Typical phase space distribution of radiation f(p) for $\Gamma_\phi < H$. [Baier et al., '00; Kurkela, Moore, '11]



✦ Thermal population dominates both energy and number of radiation for $\Gamma_{\mathrm{split}}(m_\phi) > H$.

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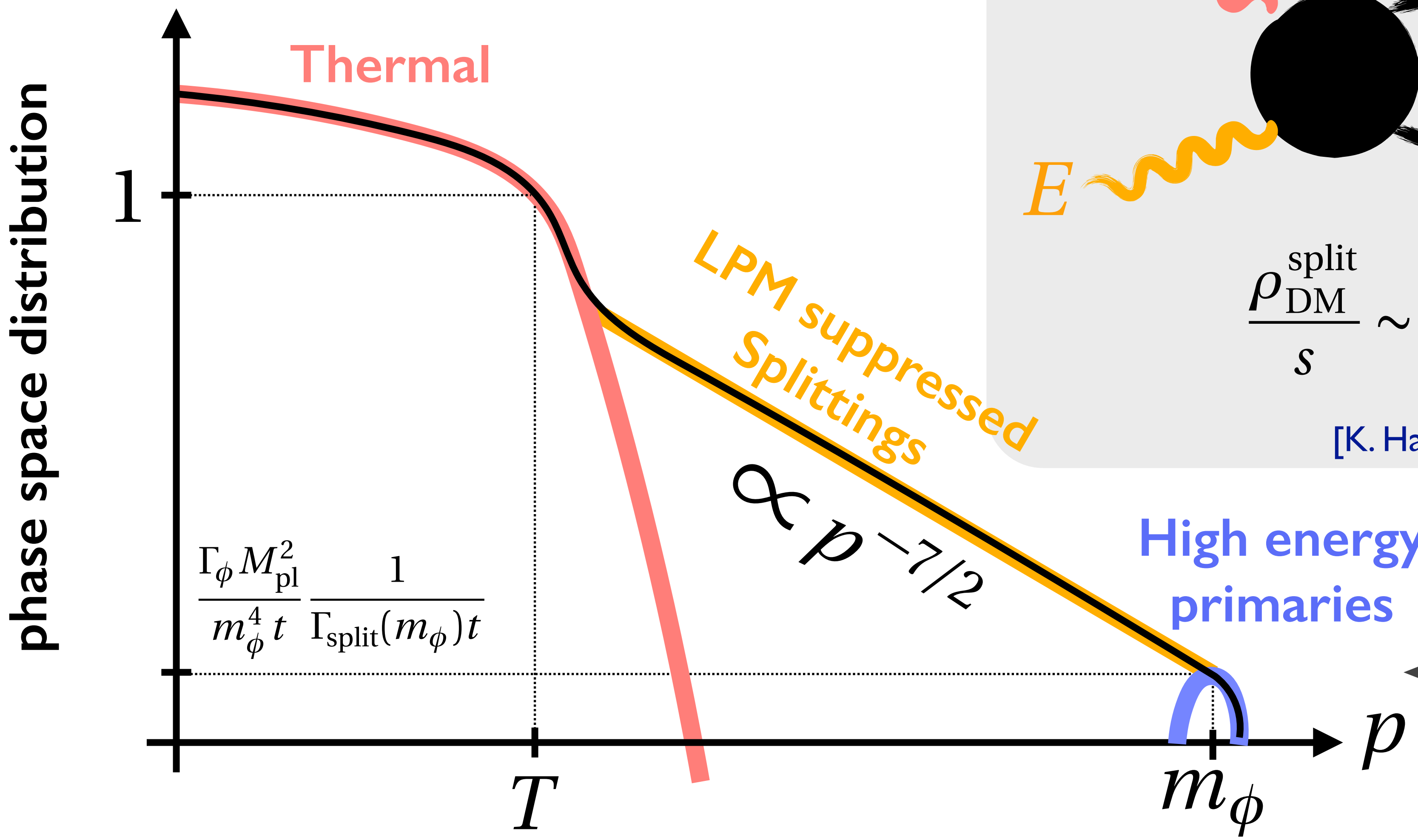
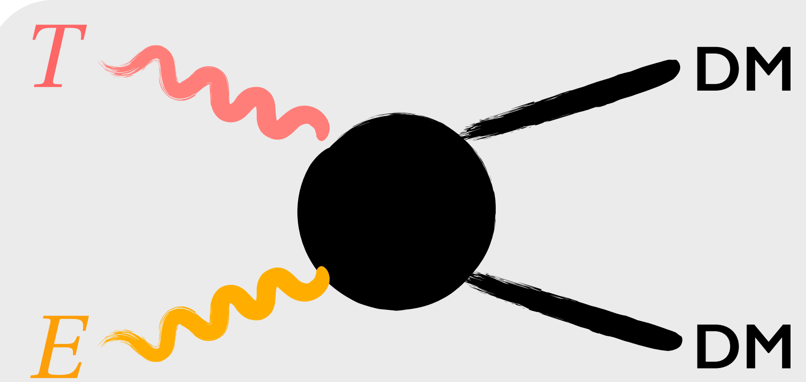
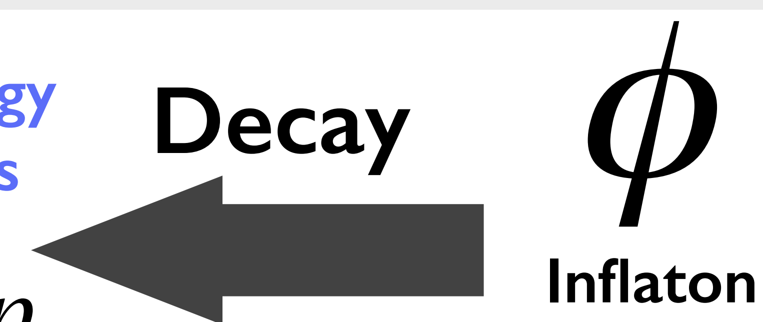




$$E \gtrsim \frac{m_{\mathrm{DM}}^2}{T}$$

$$\frac{\rho_{\mathrm{DM}}^{\mathrm{split}}}{s} \sim \frac{T_{\mathrm{R}}^3}{m_{\mathrm{DM}}^2} \quad \text{for } m_\phi \gg \frac{m_{\mathrm{DM}}^2}{T_{\mathrm{R}}}$$

[K. Harigaya, M. Kawasaki, KM and M. Yamada, 1312.3097]

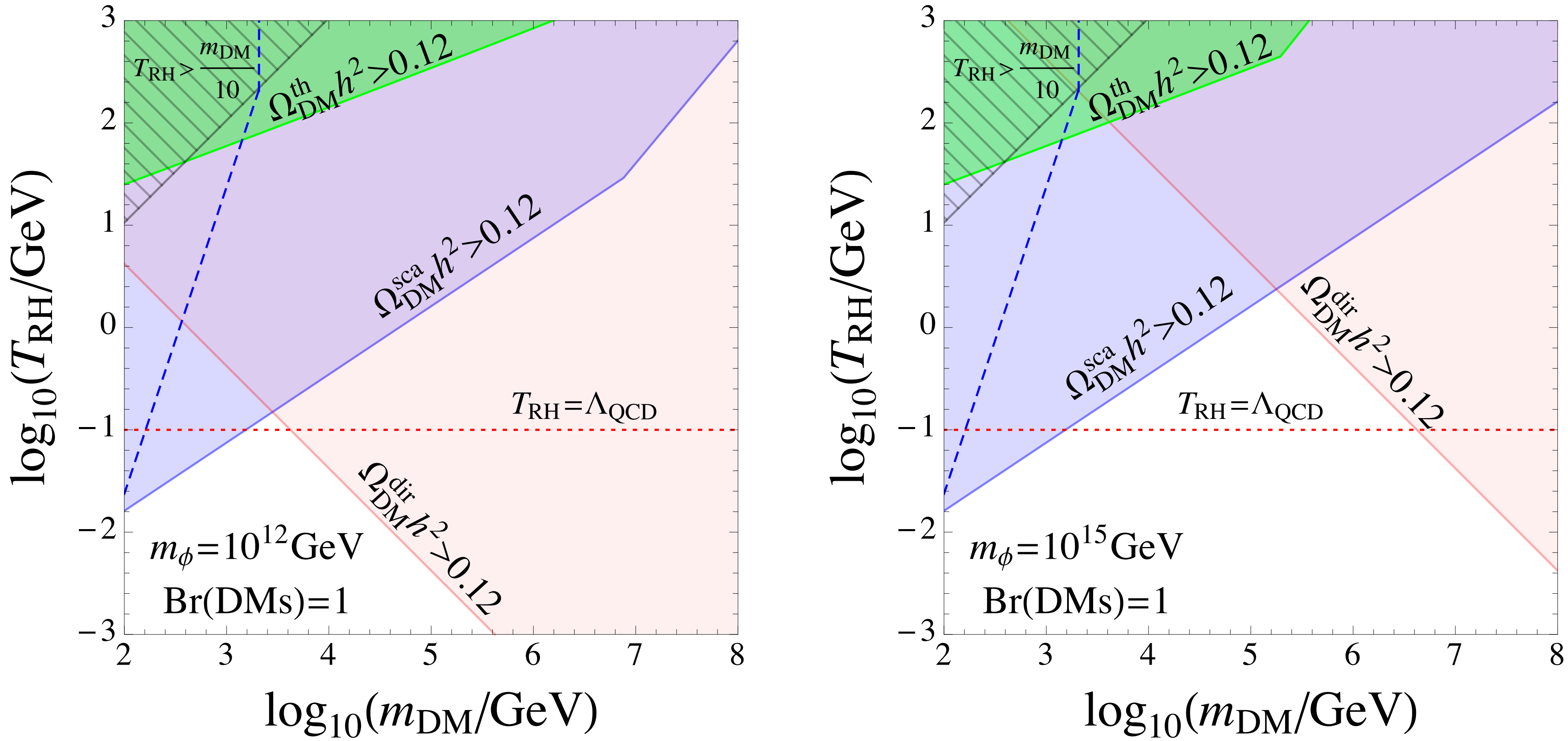


✦ Thermal population dominates both energy and number of radiation for $\Gamma_{\mathrm{split}}(m_\phi) > H$.

Dark Matter Production

- **"Heavy" DM production with** $m_{\rm DM} \gg T_{\rm R}$
  - Contour plot of DM density as a function of T_R and m_Φ.
  - Processes: (i) Production from inflaton decay, (ii) Thermal production, (iii) Production via splittings

[K. Harigaya, M. Kawasaki, KM and M. Yamada, 1312.3097]



Br(inflaton → DMs) = 1

Dark Matter Production

- **"Heavy" DM production with $m_{\rm DM} \gg T_{\rm R}$**
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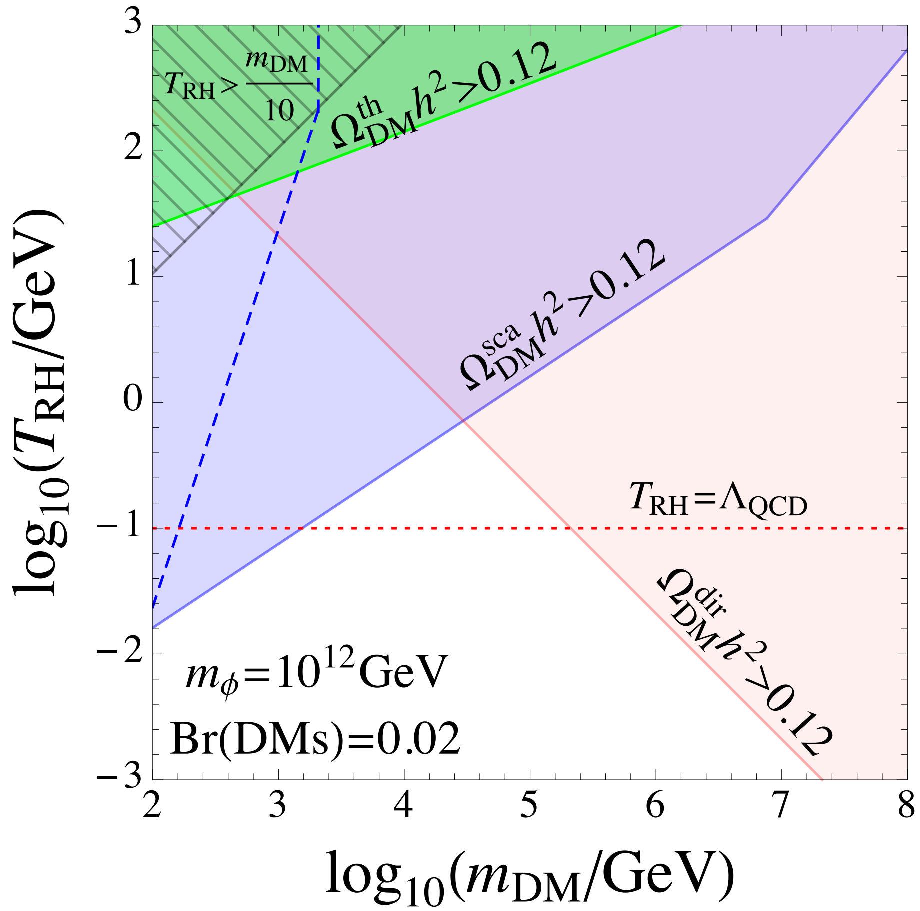
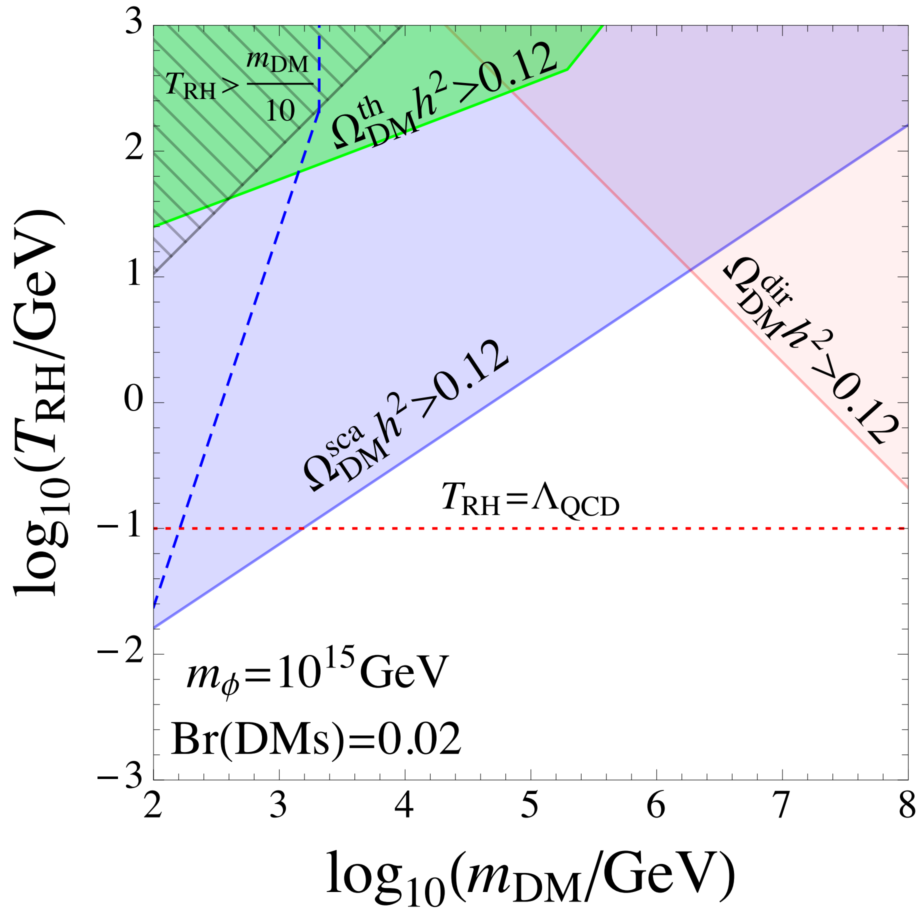
[K. Harigaya, M. Kawasaki, KM and M. Yamada, 1312.3097]





Br(inflaton → DMs) = 0.02

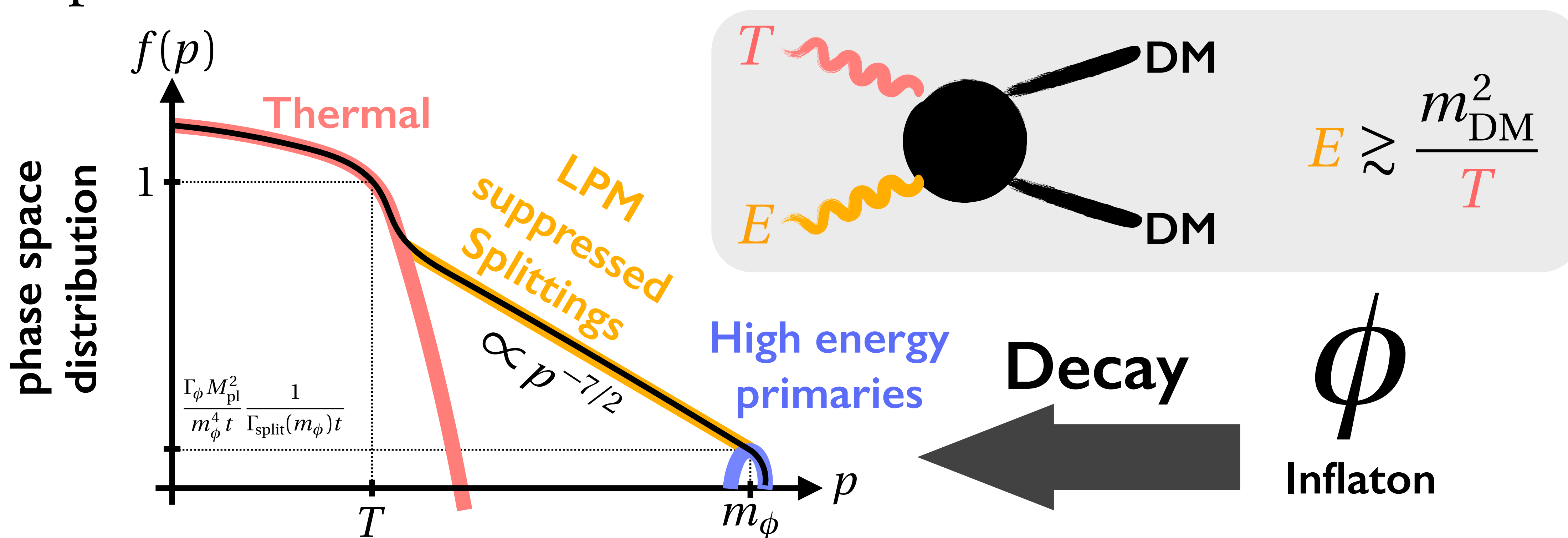
Summary of the 2nd part

- For an extremely small decay rate of inflaton (e.g. Planck-suppressed), primary particles are under occupied.
- Splittings of hard primaries play important roles in particle production (also in thermalization).

[K. Harigaya and KM, 1312.3097]

- "Heavy" DM with $m_{DM} > T$ can be produced via splittings of hard primaries.

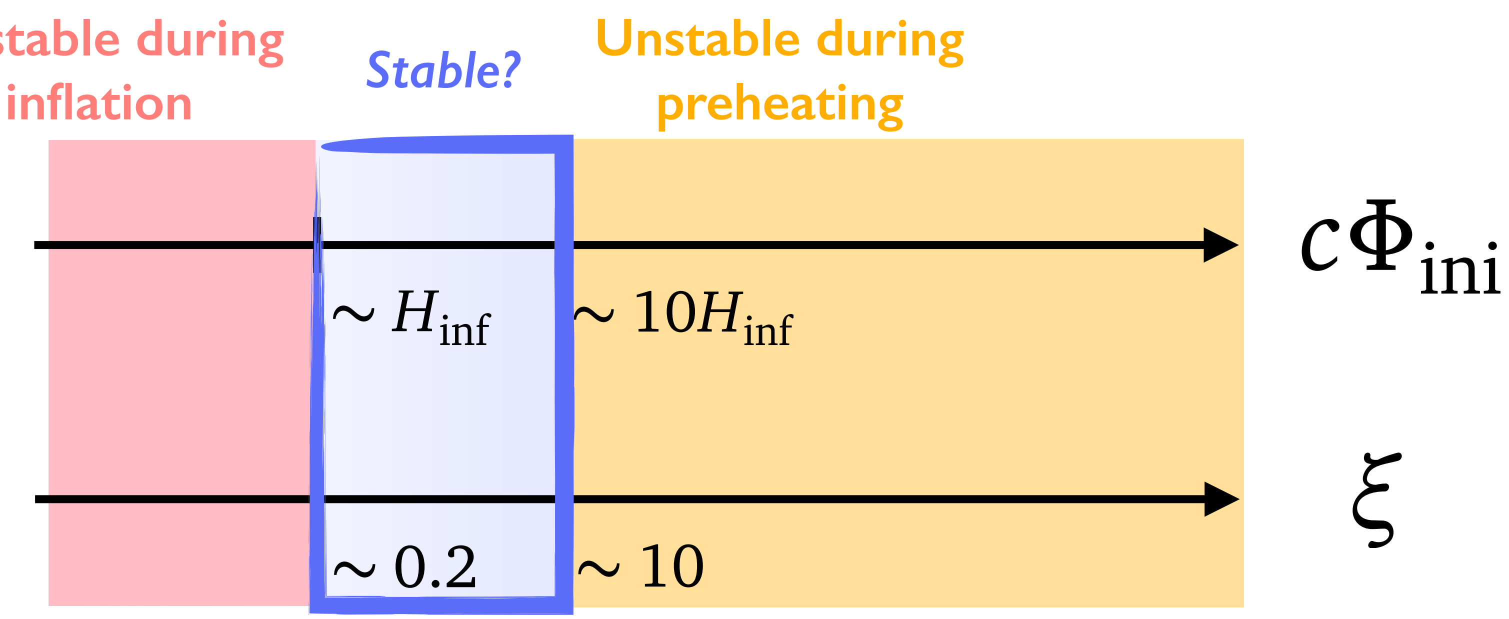
[K. Harigaya, M. Kawasaki, KM and M.Yamada, 1312.3097]



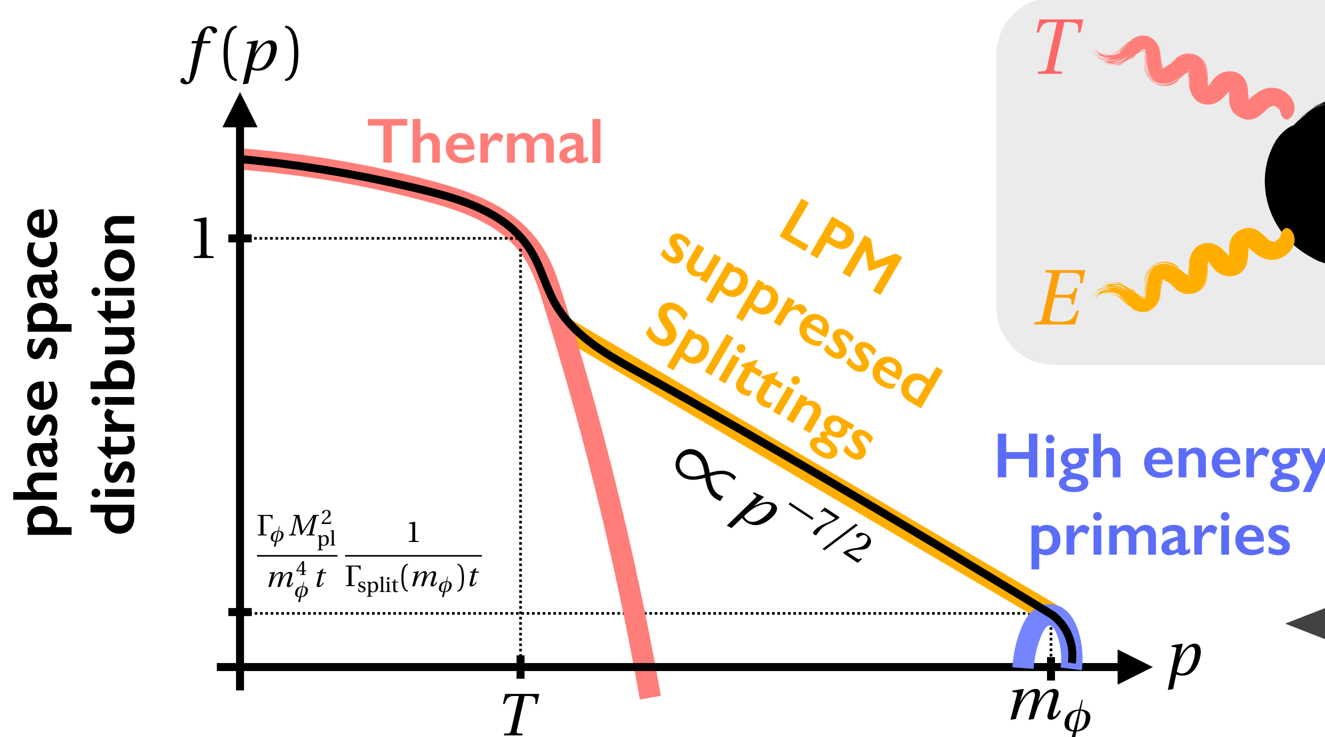
Summary

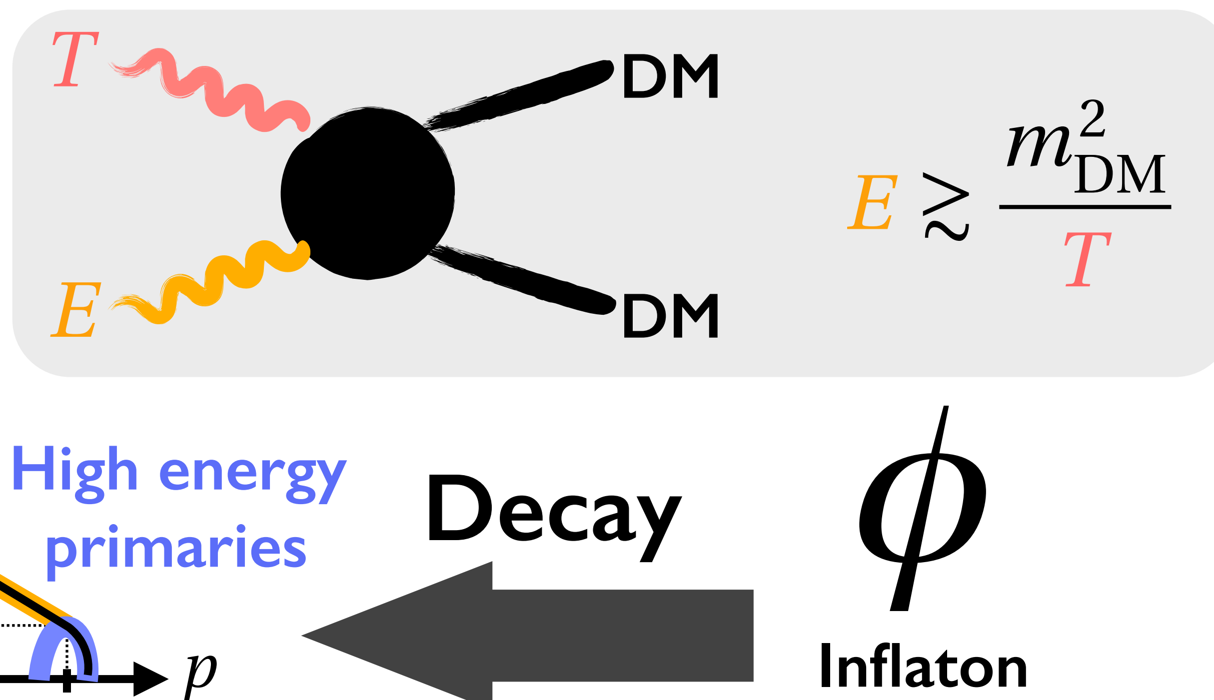
[Ema, KM, Nakayama 1602.00483]

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



[K. Harigaya, M. Kawasaki, KM and M. Yamada, 1312.3097]



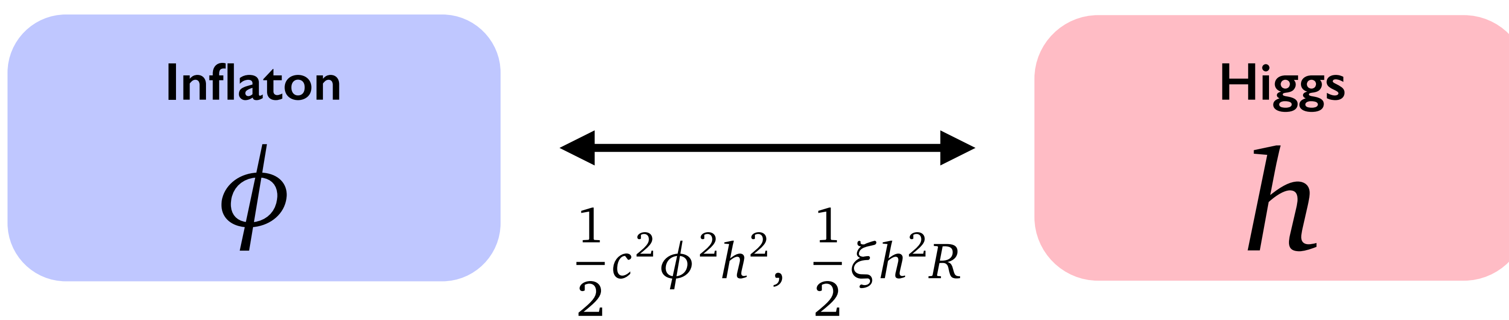


Back up

EW gauges and Top quarks

- Production of EW gauge bosons/top quark might affect the dynamics of Higgs via gauge and Yukawa couplings.

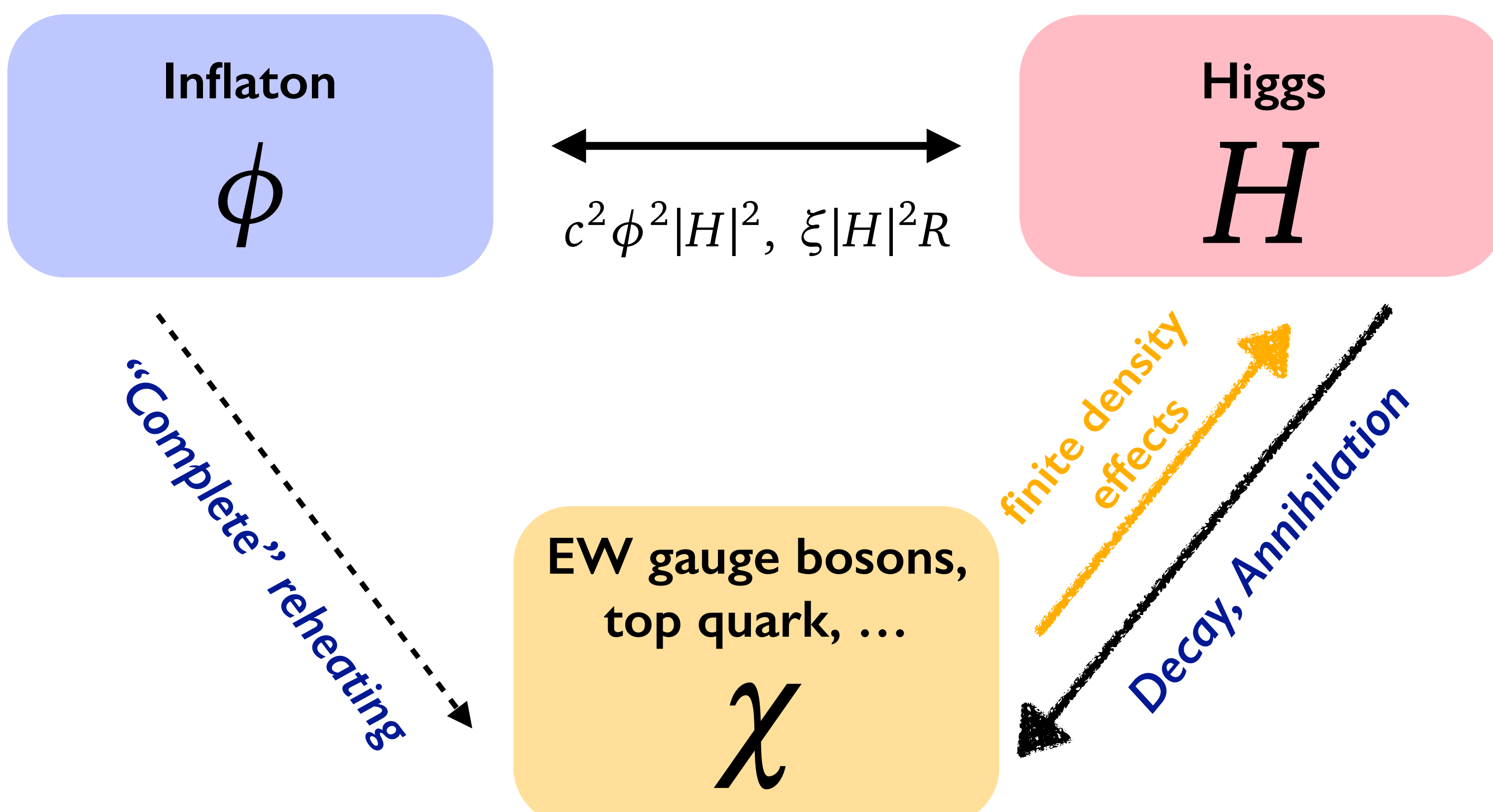
- **Two ways** to produce them.
  - Schematic figure of the setup we have discussed.



EW gauges and Top quarks

- Production of EW gauge bosons/top quark might affect the dynamics of Higgs via gauge and Yukawa couplings.

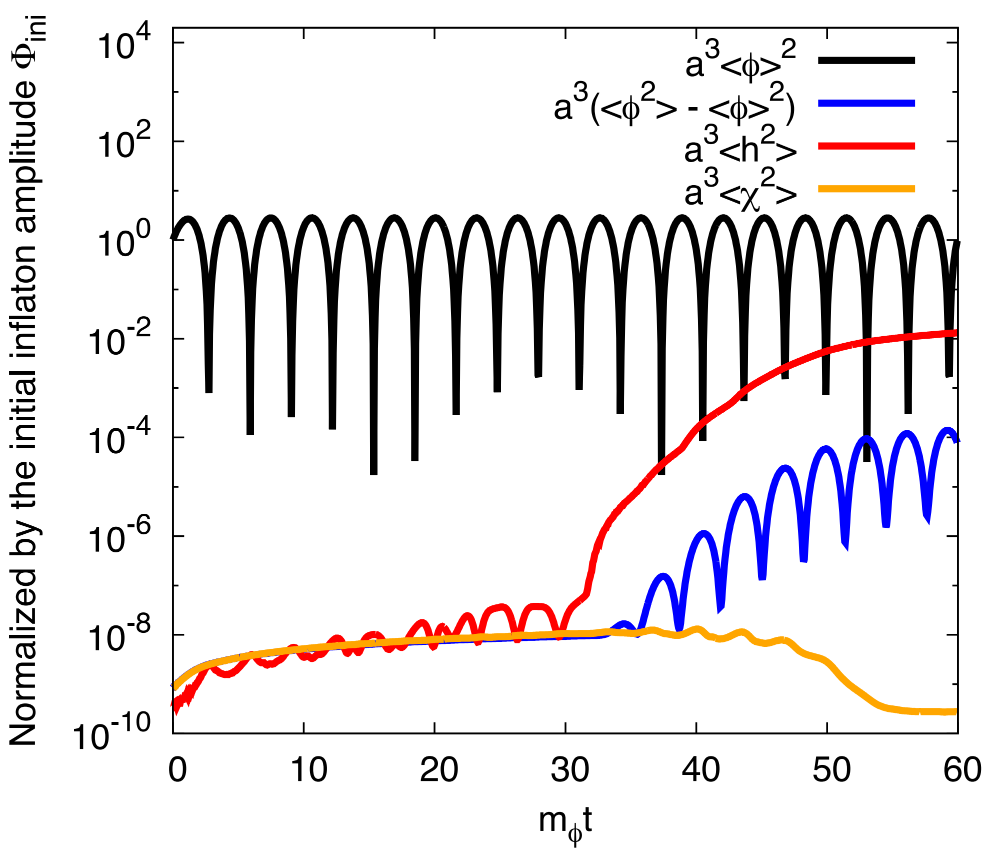
- **Two ways** to produce them.
  - Schematic figure of the setup we **would like to** discuss.

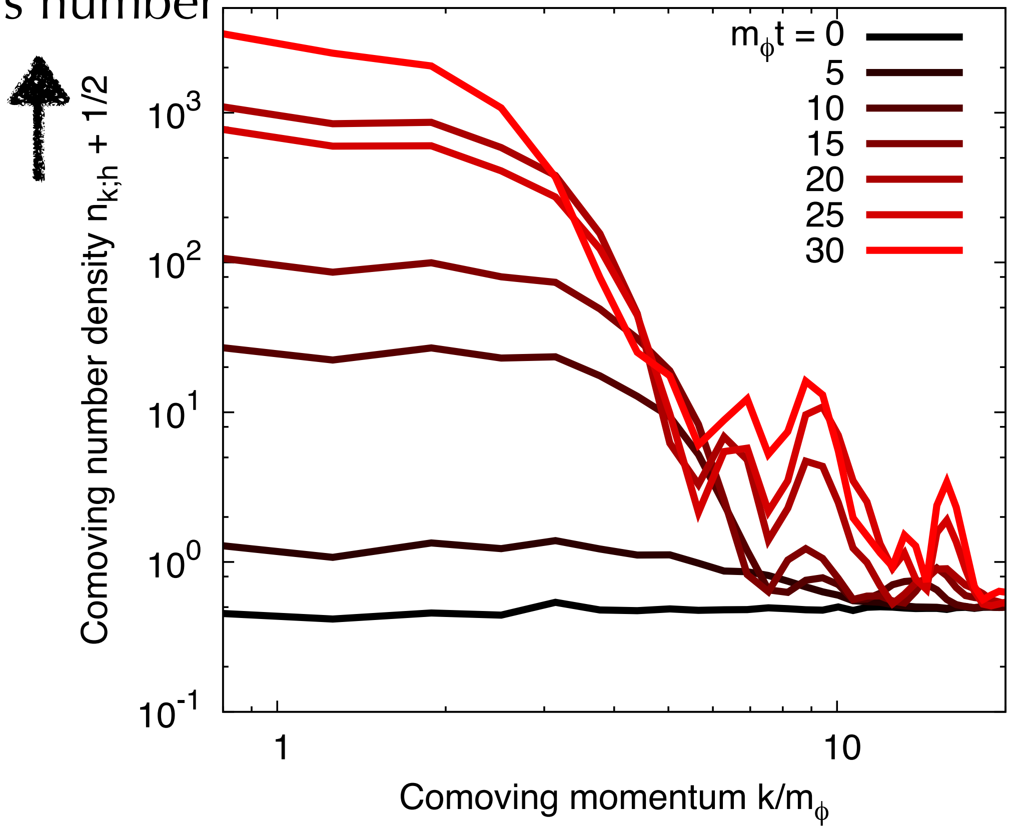


Electroweak gauges

■ 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.

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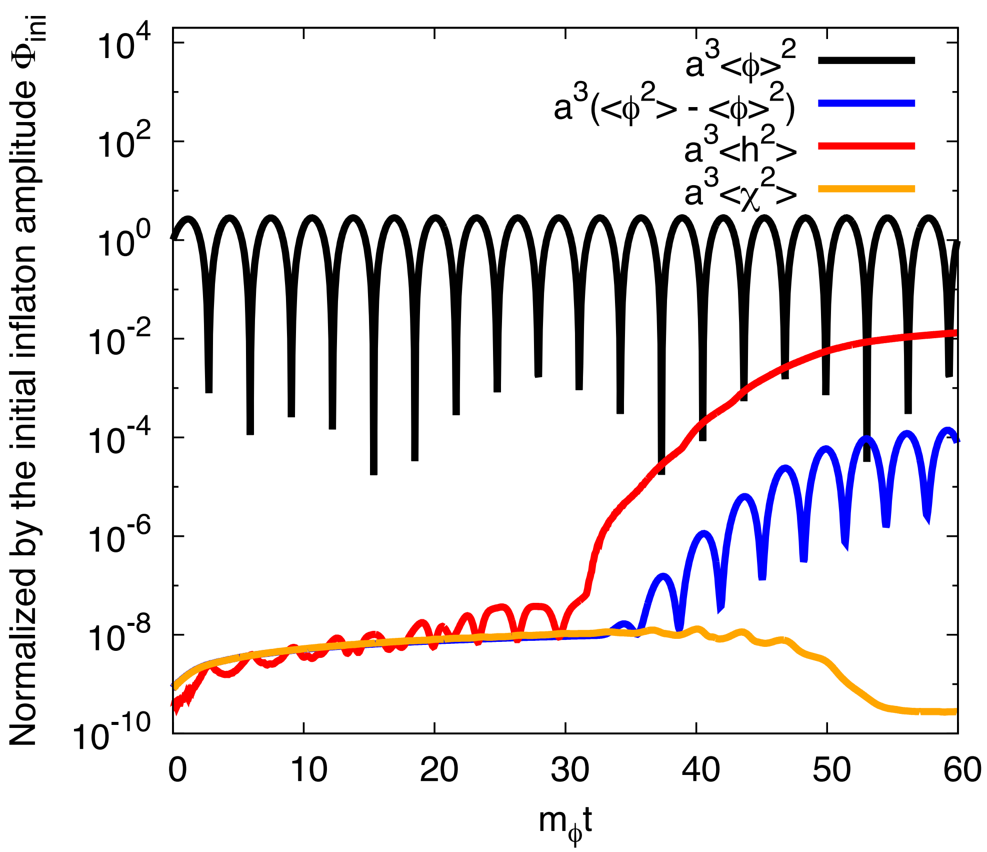
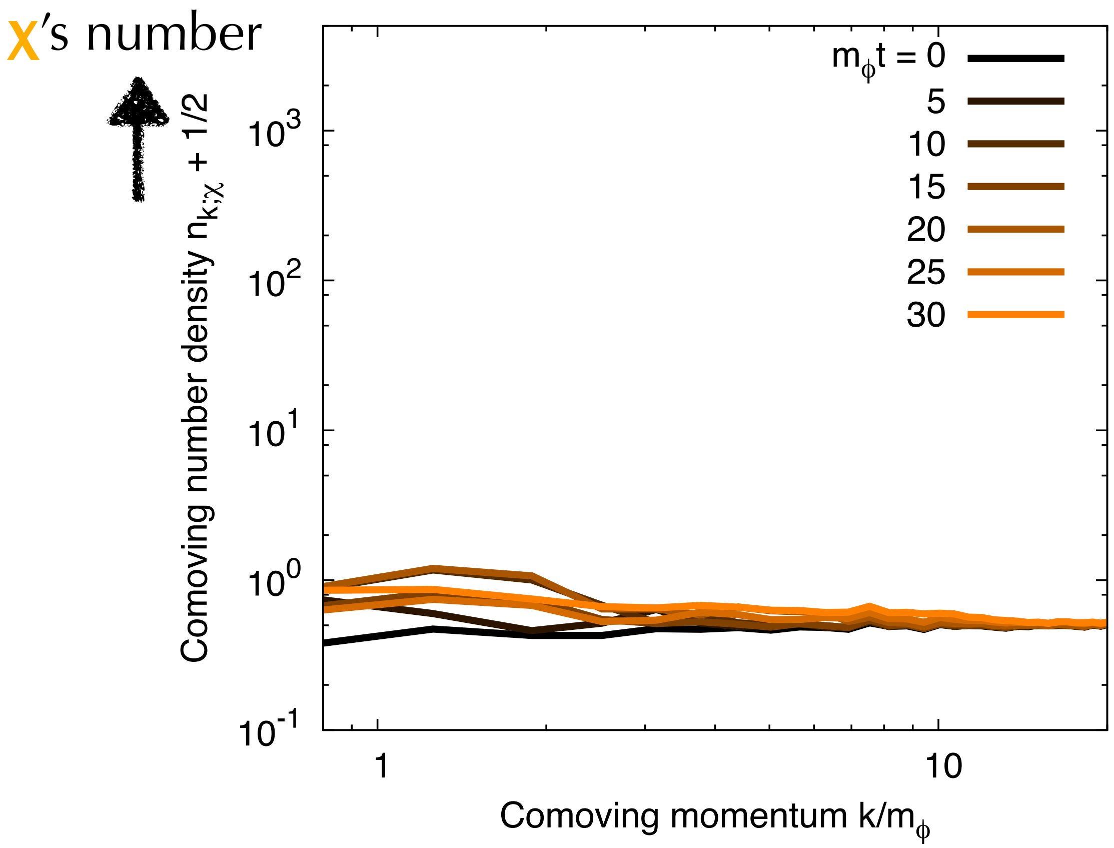




- χ-production is suppressed due to $g(\langle h^2\rangle)^{1/2}$ → **Higgs dynamics is not altered.**
- Same for the curvature coupling.

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: $\mathbf{T_R < 10^{10}}$ **GeV**.

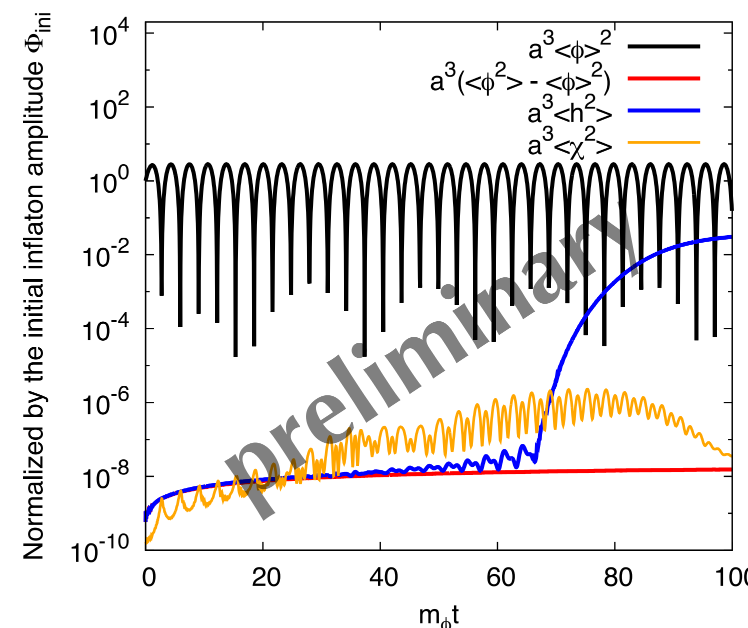
- Thermal mass is always **smaller**: $p_*(t) > m_\phi \gtrsim g T_{\mathrm{max}} \simeq 10^{13}\,\mathrm{GeV} \times g \left(\frac{T_\mathrm{R}}{10^{10}\,\mathrm{GeV}}\right)^{\frac{1}{2}} \left(\frac{H_{\mathrm{inf}}}{10^{14}\,\mathrm{GeV}}\right)^{\frac{1}{4}}$

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

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

2. Non-perturbative inflaton decay: $\mathbf{T_R > 10^{10}}$ **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(?).



Vacuum decay via Resonance

- Vacuum decay **after** resonance in the case ☐.
  - **Initially**, tachyonic effective mass < inflaton induced mass

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

$$m^2_{\mathrm{H;h}} \propto \Phi^2 \propto a^{-3}$$

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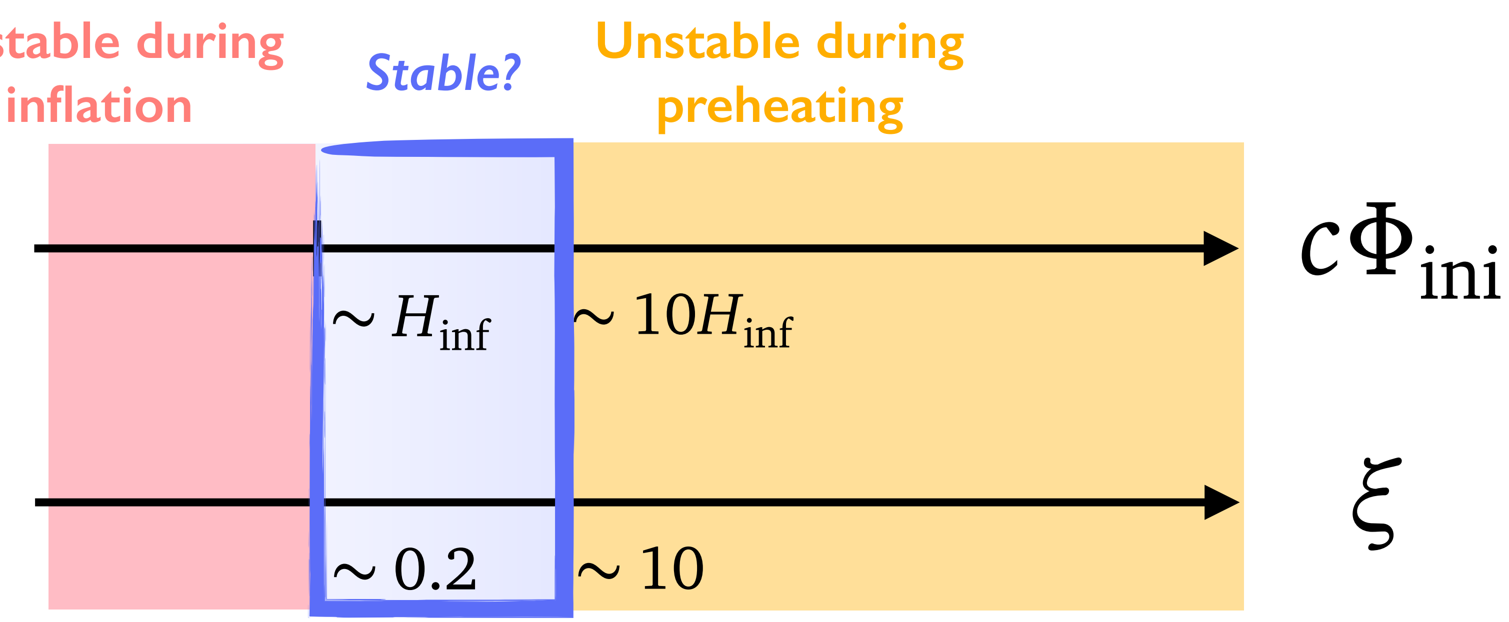

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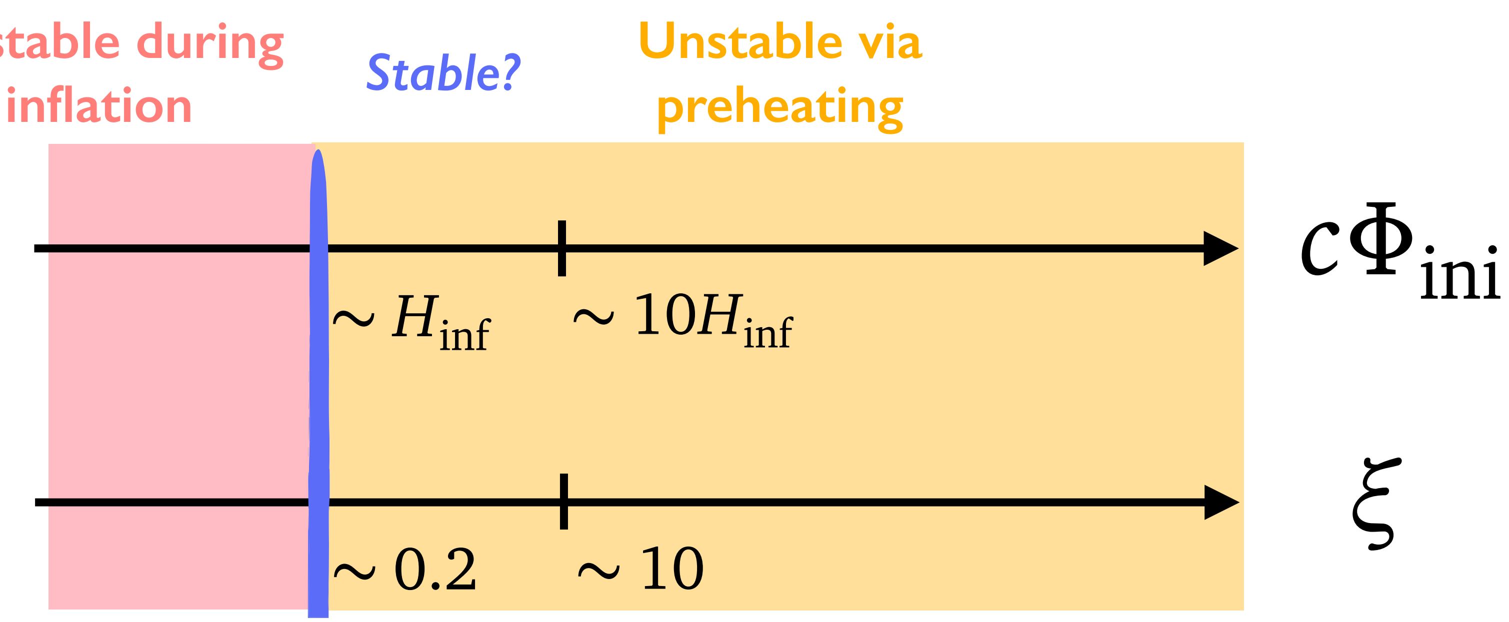

Vacuum decay via Resonance

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- Production of EW gauge bosons and top quarks might save the vacuum:
  - Direct decay of inflaton into these particles (required for complete reheating) → **depend on T_R**
  - **Thermalization** v.s. **Vacuum decay**…Further studies are required.

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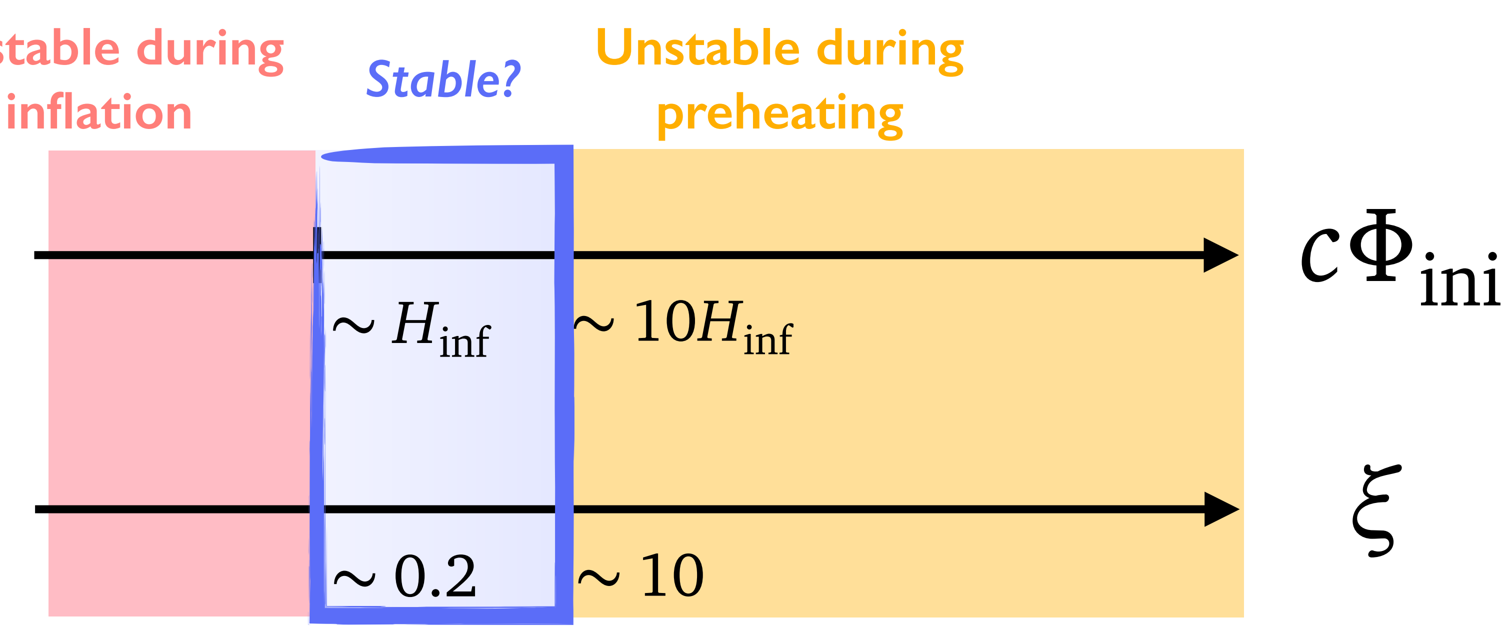

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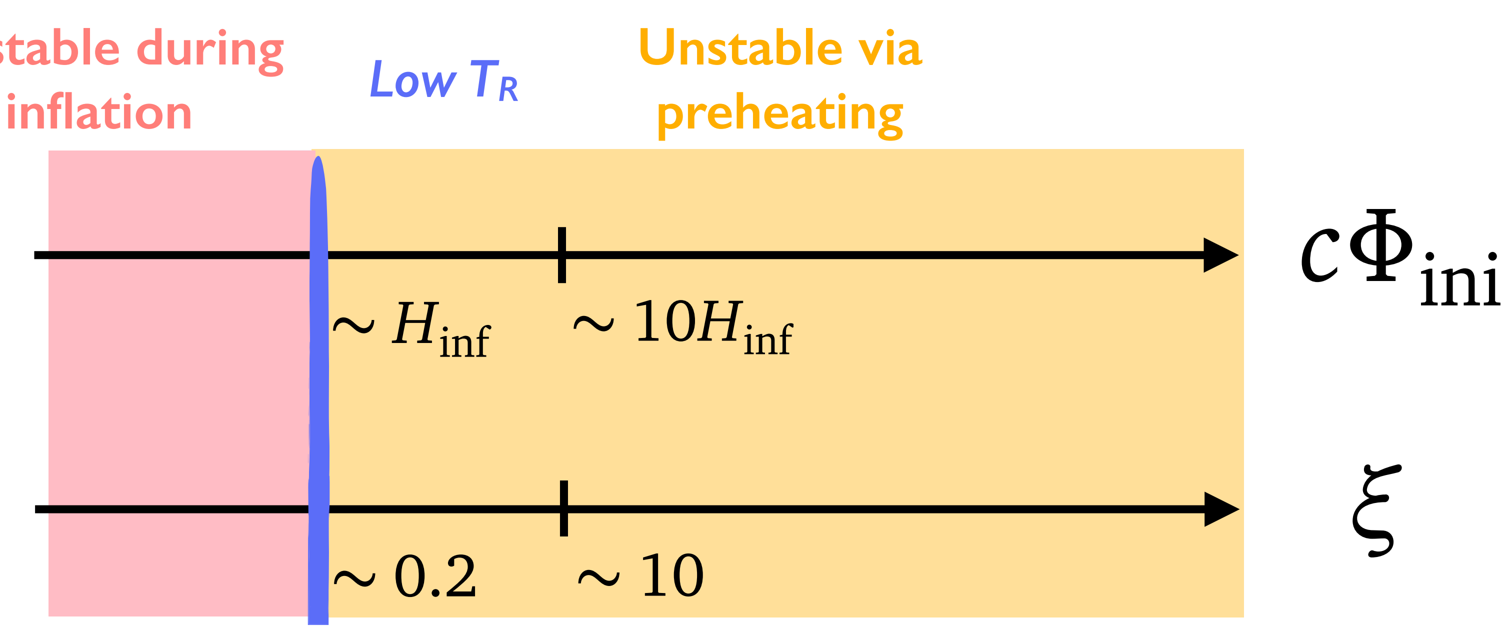

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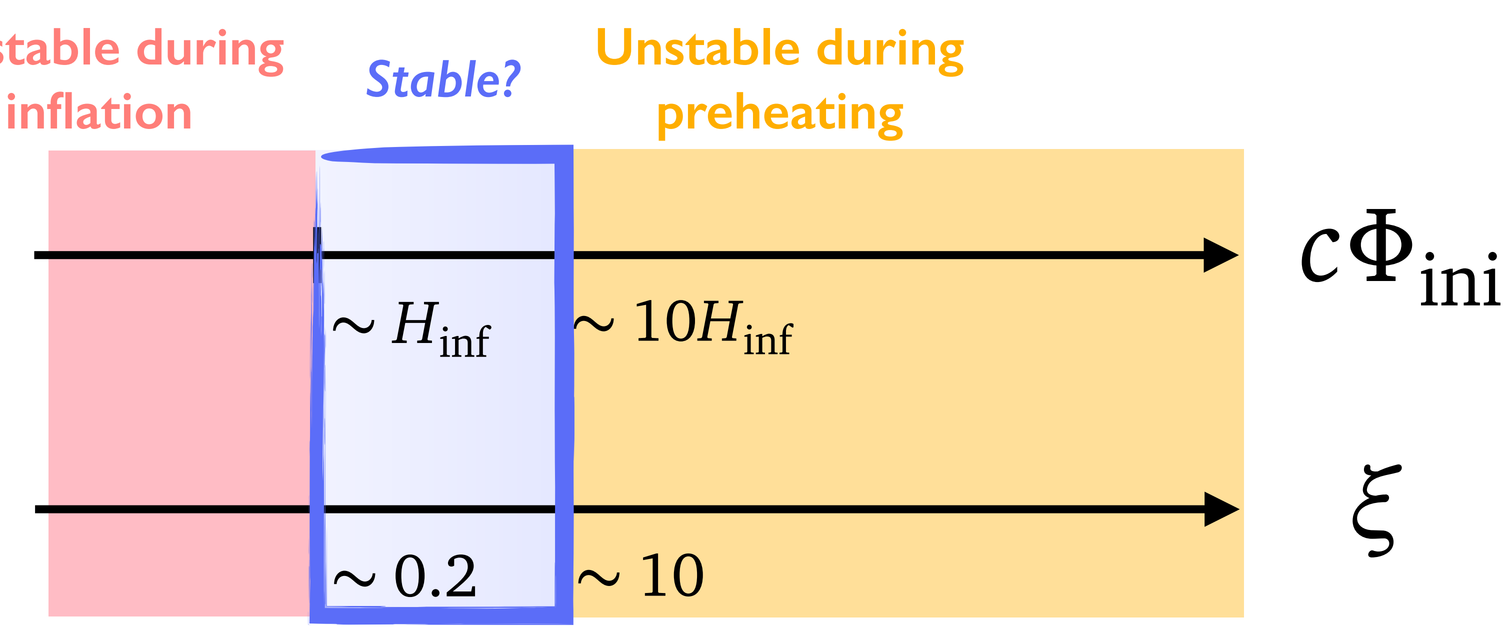
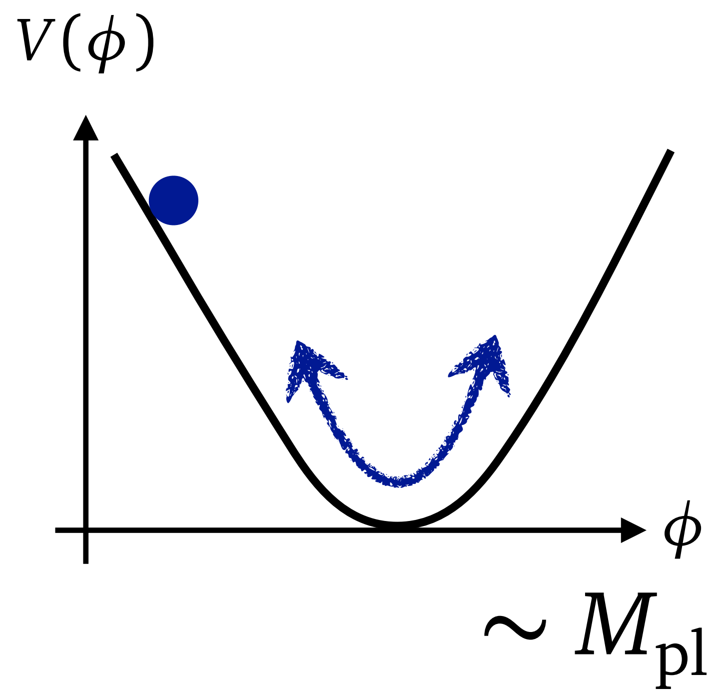


Simple Scenario

- 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.**

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

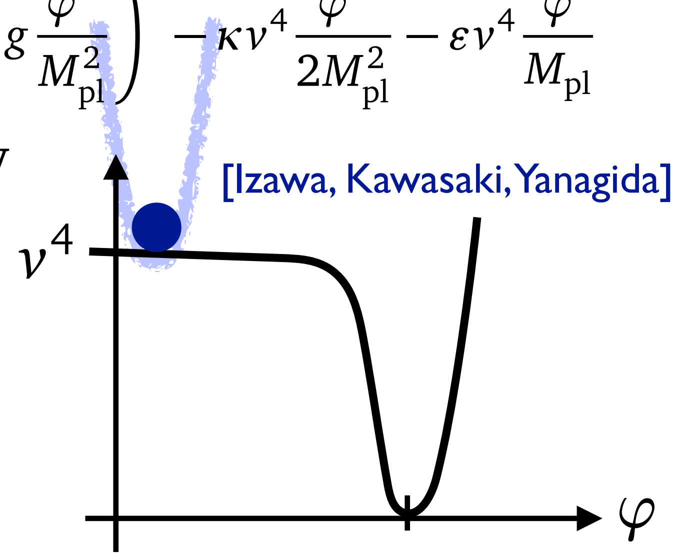
Simple Scenario

[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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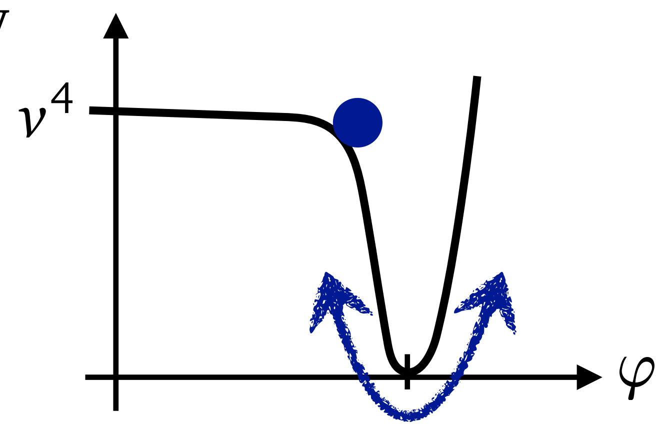

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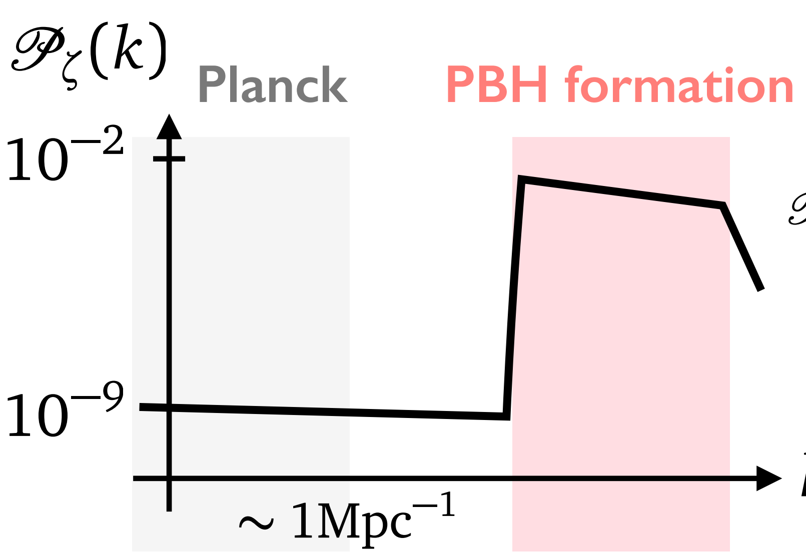

$$\mathcal{P}_\zeta \sim \left(\frac{1}{2\sqrt{3}\pi} \frac{v^2}{\epsilon M_{\rm pl}^2} \right)^2$$

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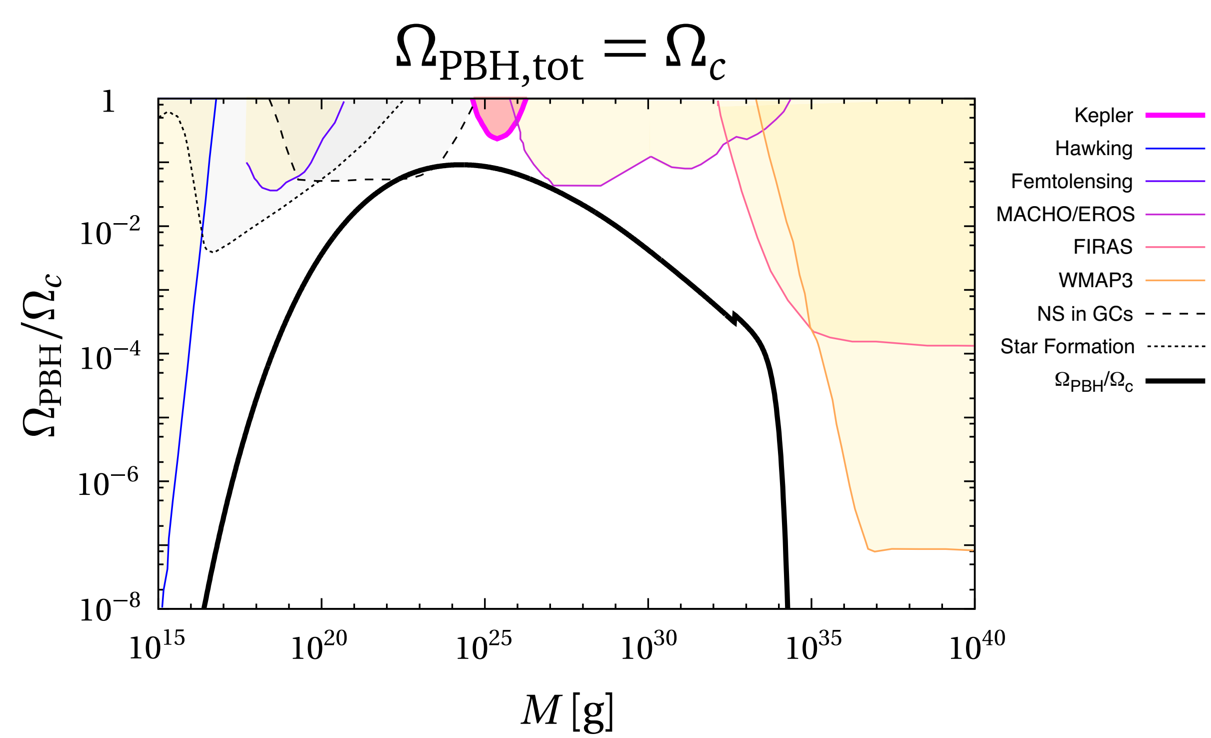

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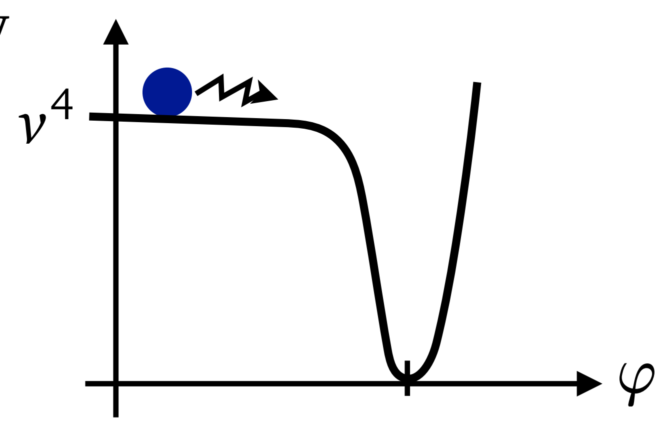

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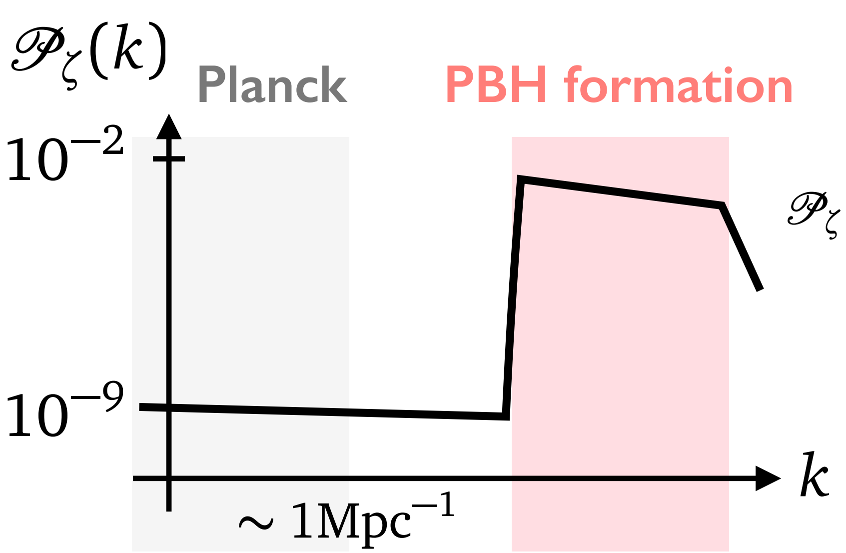

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