# Metastability, Chaotic Inflation, and Primordial Black Holes

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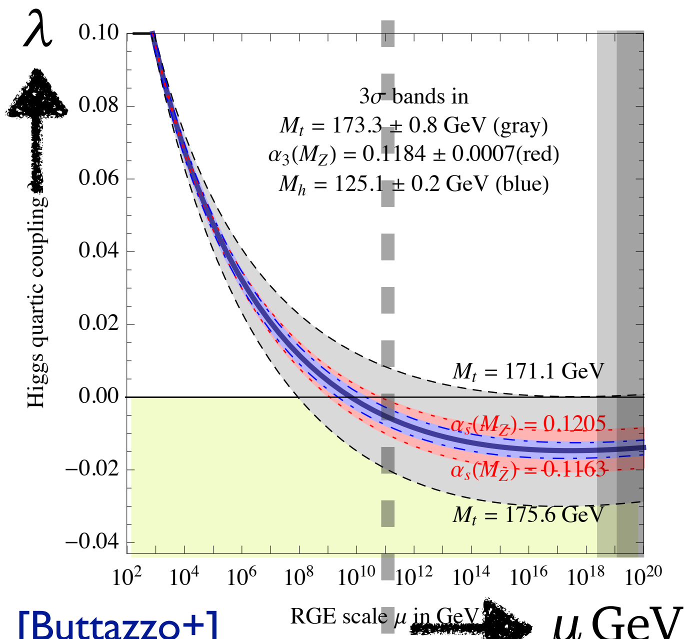
Based on 1605.04974 (PhysRevD.94.063509)
In collaboration with M.Kawasaki, T.T.Yanagida

# Introduction

# Metastability v.s. Inflation

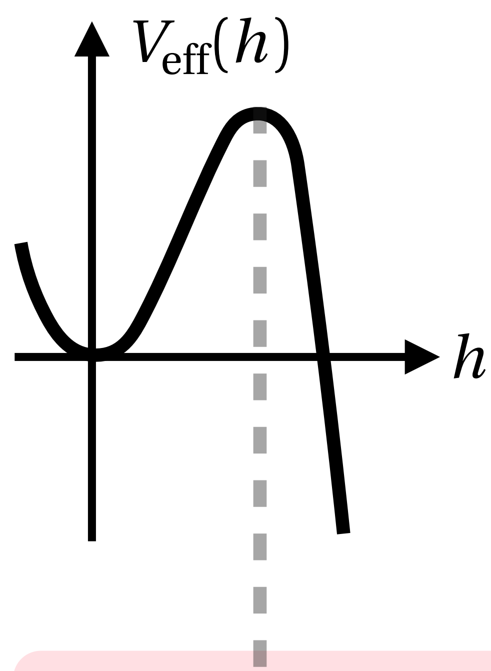
## ■ Metastable Electroweak Vacuum v.s. Chaotic Inflation

- **SM valid up to high energy scales**
  - Our vacuum: likely to be metastable?
  - $\lambda<0$ for $\mu>10^{10}$ GeV @ best-fit of top Yukawa.

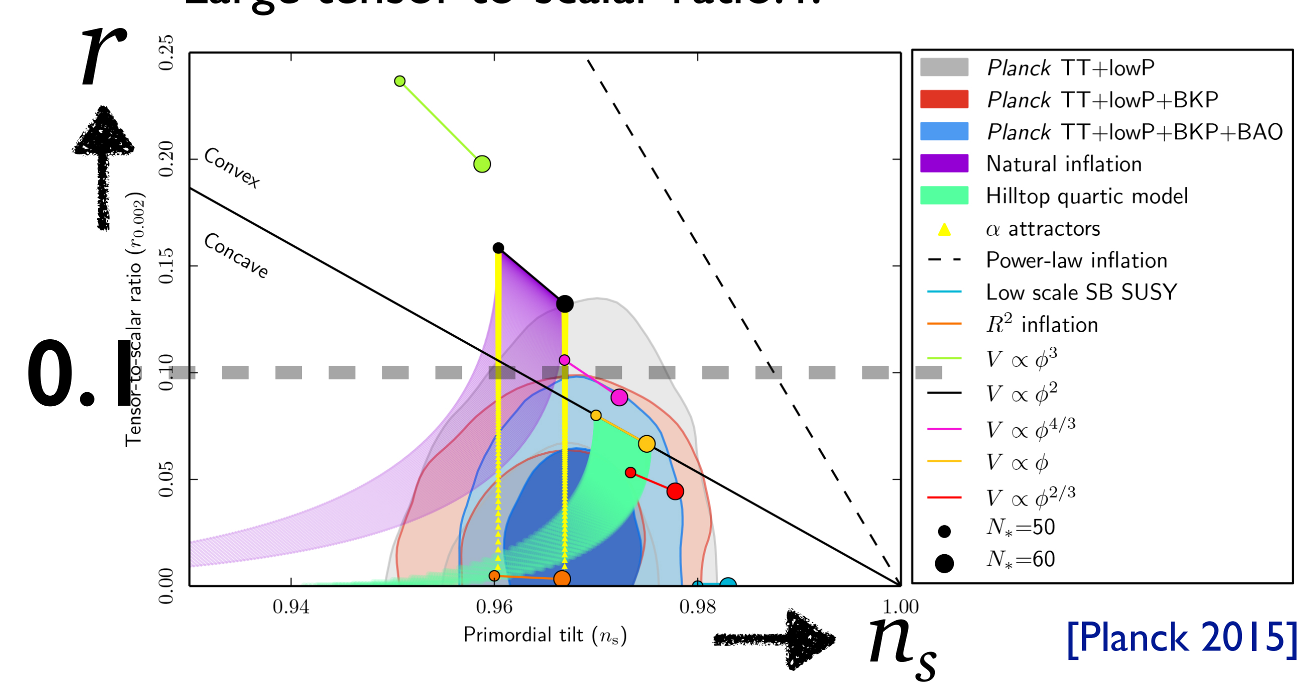



[Buttazzo+]

**$10^{10}$GeV**




- **Chaotic Inflation**
  - Solve the *initial condition problem*. [See e.g. 1601.01918]
  - Large tensor-to-scalar ratio: r.




[Planck 2015]

$$h_{\rm max} \sim 10^{10}\,{\rm GeV} \quad \text{v.s.} \quad H_{\rm inf} \sim 10^{14}\,{\rm GeV}\sqrt{\frac{r}{0.1}}$$

◉ **Hawking-Moss transition**

- Higgs acquires large fluctuations of

$$T_{\rm GH} = \frac{H_{\rm inf}}{2\pi}$$

## Severe Tension

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

One order of magnitude severer bound is obtained if you look at $e^{3N}$ patches.

# Metastability v.s. Inflation

## ■ Curvature coupling of Higgs: $\xi R h^2$

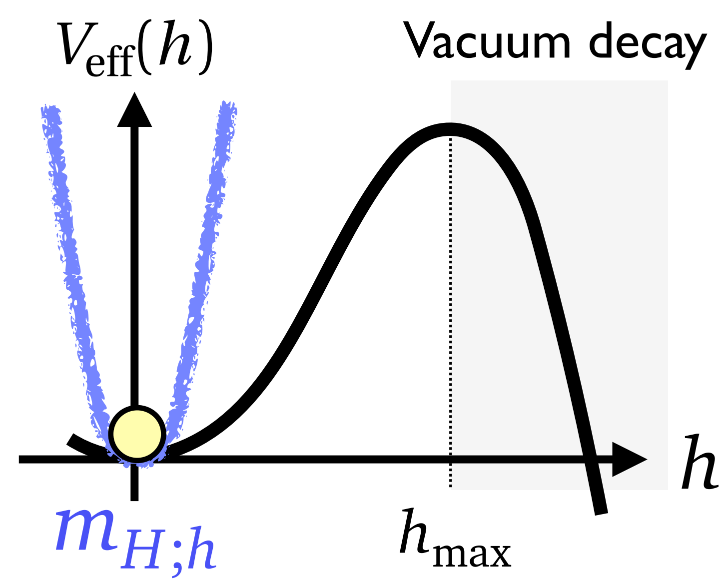
- Stabilize the EW vacuum **during inflation** @ ξ > O(0.1)

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

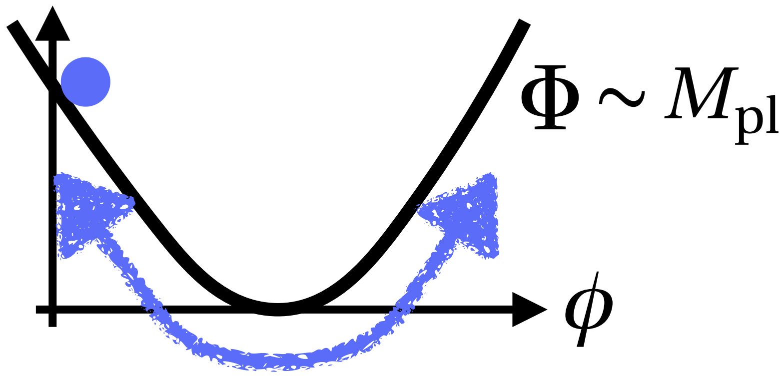
**during inflation**

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

**stabilized for** $\gtrsim H_{\rm inf}^2$




- **However,** the "**tachyonic resonance**" can destabilize it **afterwards!**

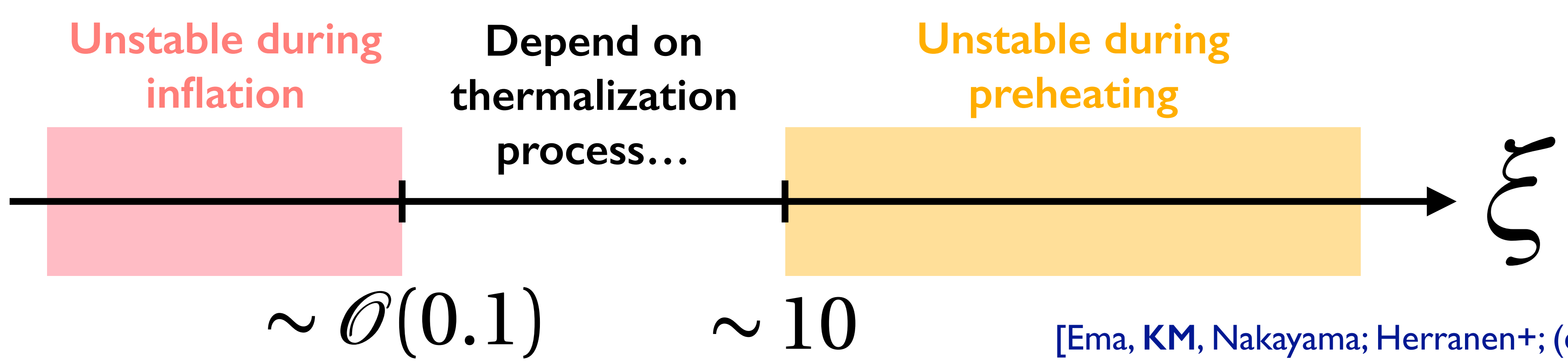



- Oscillating mass term

$$R = \frac{1}{M_{\rm pl}^2}\left[4V(\phi) - \dot{\phi}^2\right]$$

**Tachyonic Resonance**

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




[Ema, **KM**, Nakayama; Herranen+; (cf.) Zatta's talk]

# Motivation

- Is there any interesting scenario that is consistent with the **metastable electroweak vacuum** and **chaotic inflation**?

**Requirements:**

- EW vacuum should be stabilized during the course of cosmological evolution.
- A candidate of **DM** is provided.
- **BAU** can be explained.

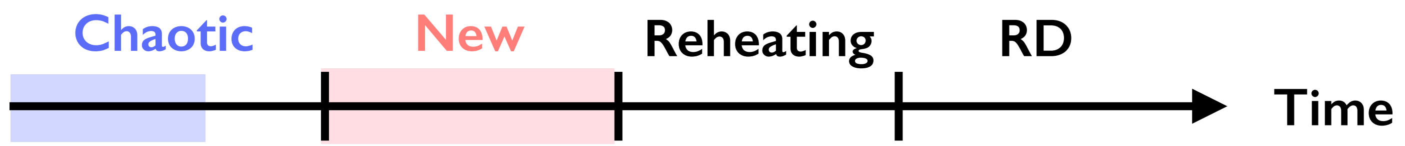
- We have proposed **a simple scenario** in which

  - **Initial condition problem** is solved.
  - EW vacuum is **always** stabilized during inflation, preheating, and afterwards.
  - Our solution naturally yields **PBHs** that can be a dominant component of **DM.**
  - Leptogenesis can be accommodated (**BAU**).

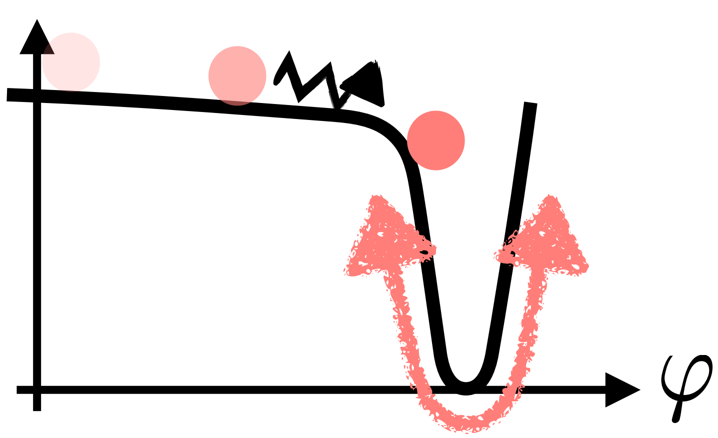
# Our Scenario

# Our Scenario

- **Ingredients:**




- Chaotic inflation
  - (0) Solve the initial condition problem + (ii) provide primordial density perturbations.
- **Curvature coupling**
  - Stabilize the EW vacuum during inflation(s).
- New inflation
  - (i) Avoid the resonance after inflation + (ii) produce **PBHs** as a candidate of DM!



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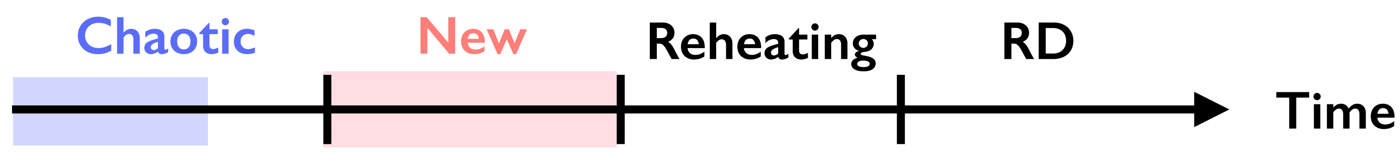


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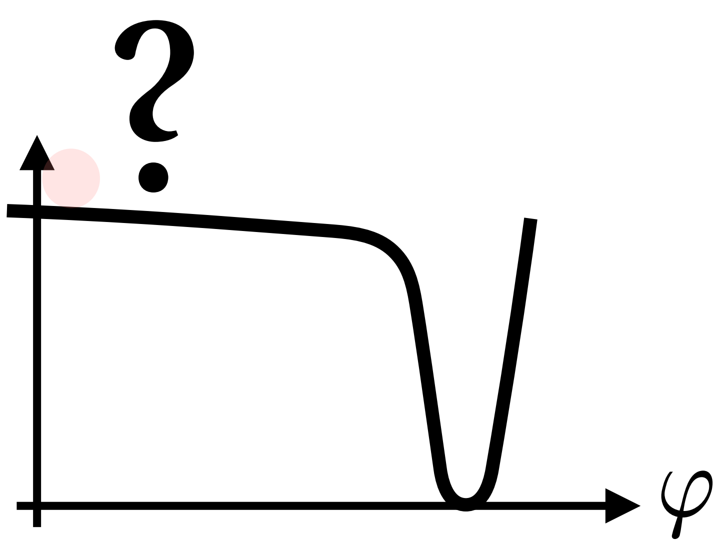
◉ **(0) Solve the initial condition problem**

- **Drawback of new inflation:** Universe has to start with a large region in which new inflaton is homogeneous and close to the local minimum of its potential…extreme fine tuning is required.



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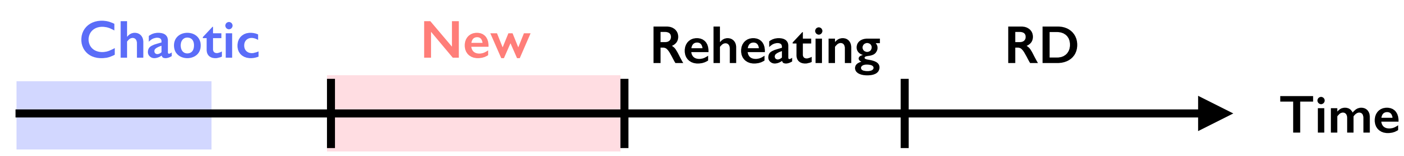


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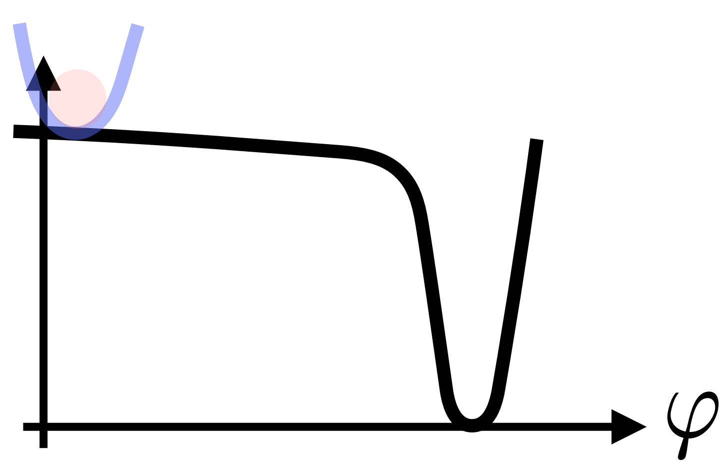
### ◉ (0) Solve the initial condition problem

- **Drawback of new inflation:** Universe has to start with a large region in which new inflaton is homogeneous and close to the local minimum of its potential…extreme fine tuning is required.

➡ Chaotic inflaton can provide a dynamical reason why new inflaton had such a specific value initially.

[Izawa, Kawasaki, Yanagida]



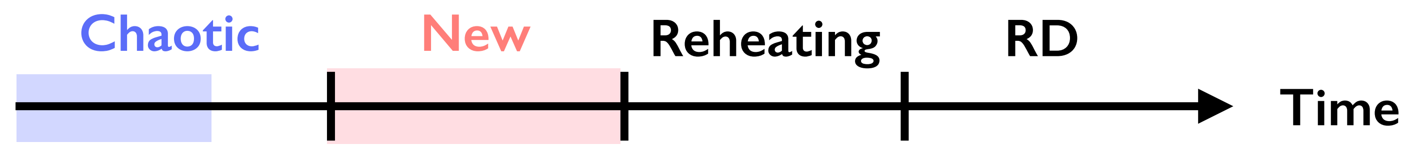

e.g. $-\mathscr{L}_{\rm int} = c^2\phi^2\varphi^2$ ▶ $m_\varphi^2 \sim c^2\Phi^2$

New inflation starts @ $m_\varphi \sim H_{\rm new}$

(c.f.) another solution: tunneling via CDL instanton → open Universe

# Our Scenario

■ **Ingredients:**

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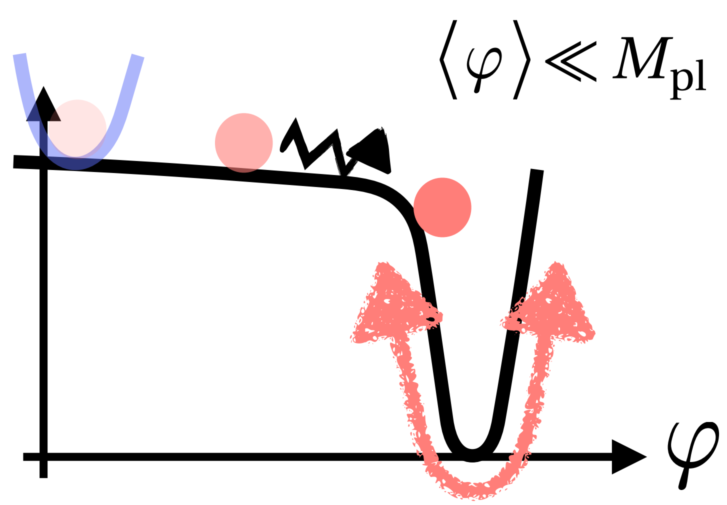
◉ **(i) Free from the resonance**

- Flat potential → **small amplitude**




**No Resonance!**

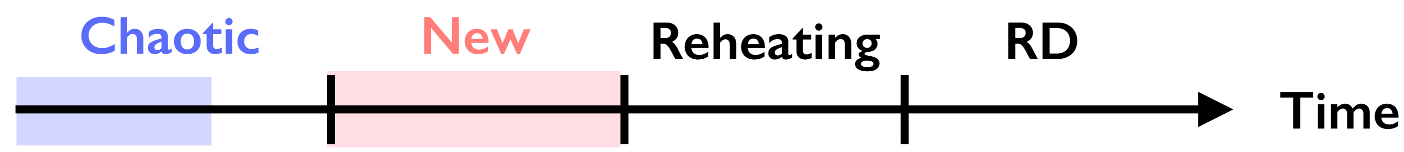
$$q \sim \frac{\xi \langle\varphi\rangle^2}{M_{\rm pl}^2} \lll 1$$

One requirement: $H_{\rm new} \sim H_{\rm ch}$

➡ High $T_R$ (good for leptogenesis)

# Our Scenario

## ■ Ingredients:

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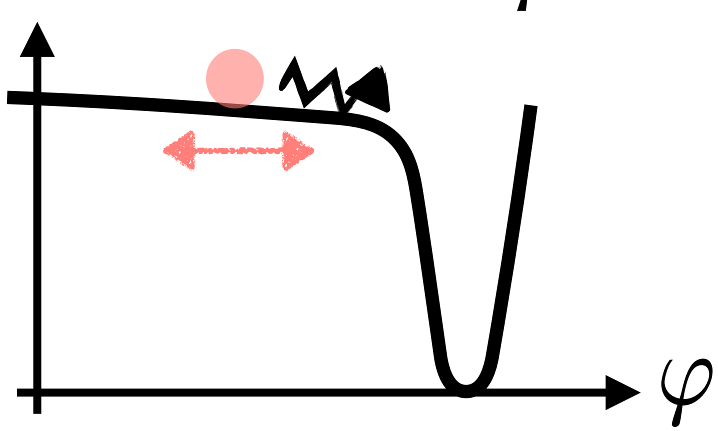
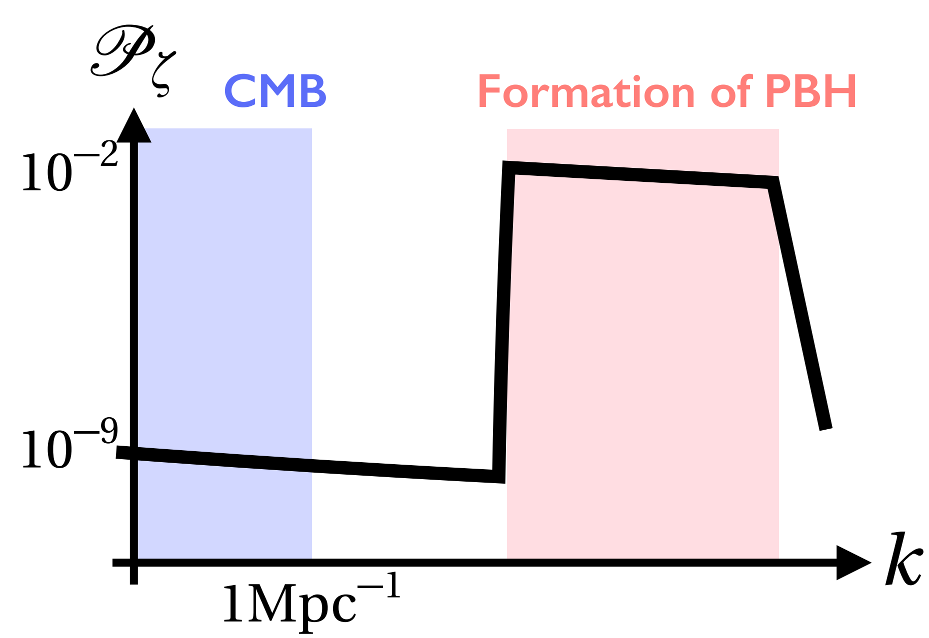
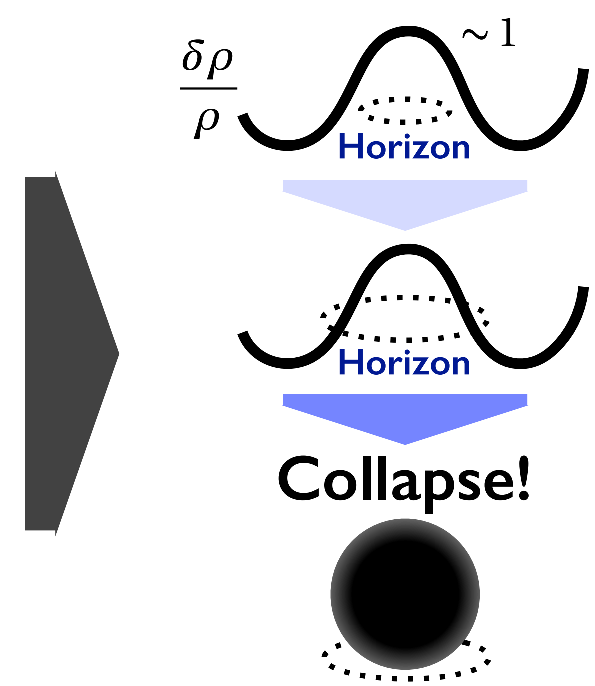
◉ **(ii) Formation of PBHs by large scalar perturbations $\zeta$ of new inflation**

- Flat potential → **large $\zeta$**

$$\mathcal{P}_\zeta \sim \langle \zeta\zeta \rangle; \quad \zeta \sim \frac{\delta\rho}{\rho}$$



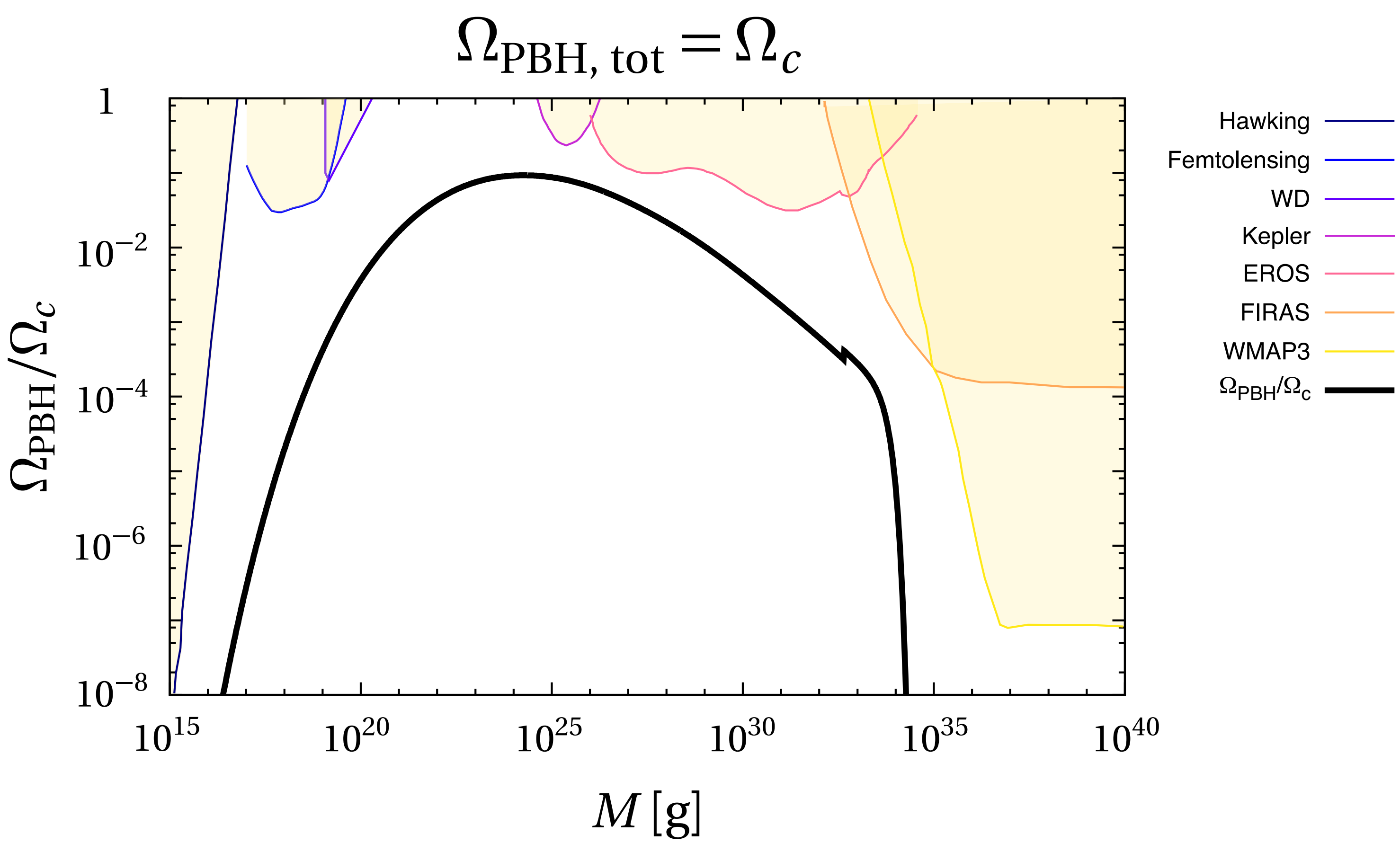
# Our Scenario

## ■ Primordial Black Holes as whole DM

- New inflation potential:

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

- Abundance of PBHs for one particular parameter of the new inflation potential




✳ Constraints from Neutron Star capture are evaded for a conservative value of DM inside the globular clusters. [See e.g. Kusenko+, 1310.8642; Carr+,1607.06077]

$$\frac{M}{M_\odot} \simeq \left(\frac{\gamma}{0.2}\right)\left(\frac{g_*}{g_{*,\rm eq}}\right)^{-1/6}\left(\frac{k}{2\times 10^6\,{\rm Mpc}^{-1}}\right)^{-2}$$

where $M \simeq \gamma \rho_{\rm rad} \times \frac{4\pi}{3} H^{-3}$

$$\frac{\Omega_{\rm PBH}}{\Omega_c} \simeq \left(\frac{\beta(M)}{7\times 10^{-9}}\right)\left(\frac{\gamma}{0.2}\right)^{1/2}\left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{M}{M_\odot}\right)^{-1/2}$$

where

$$\beta(M) = \int_{\delta_c} {\rm d}\delta \, \frac{1}{\sqrt{2\pi\sigma^2(M)}} e^{-\delta^2/2\sigma^2(M)}$$

$$\sigma^2(M) = \frac{16}{81}\int {\rm d}\log q \; W^2(qk^{-1})(qk^{-1})^4 \mathcal{P}_\zeta(q)$$

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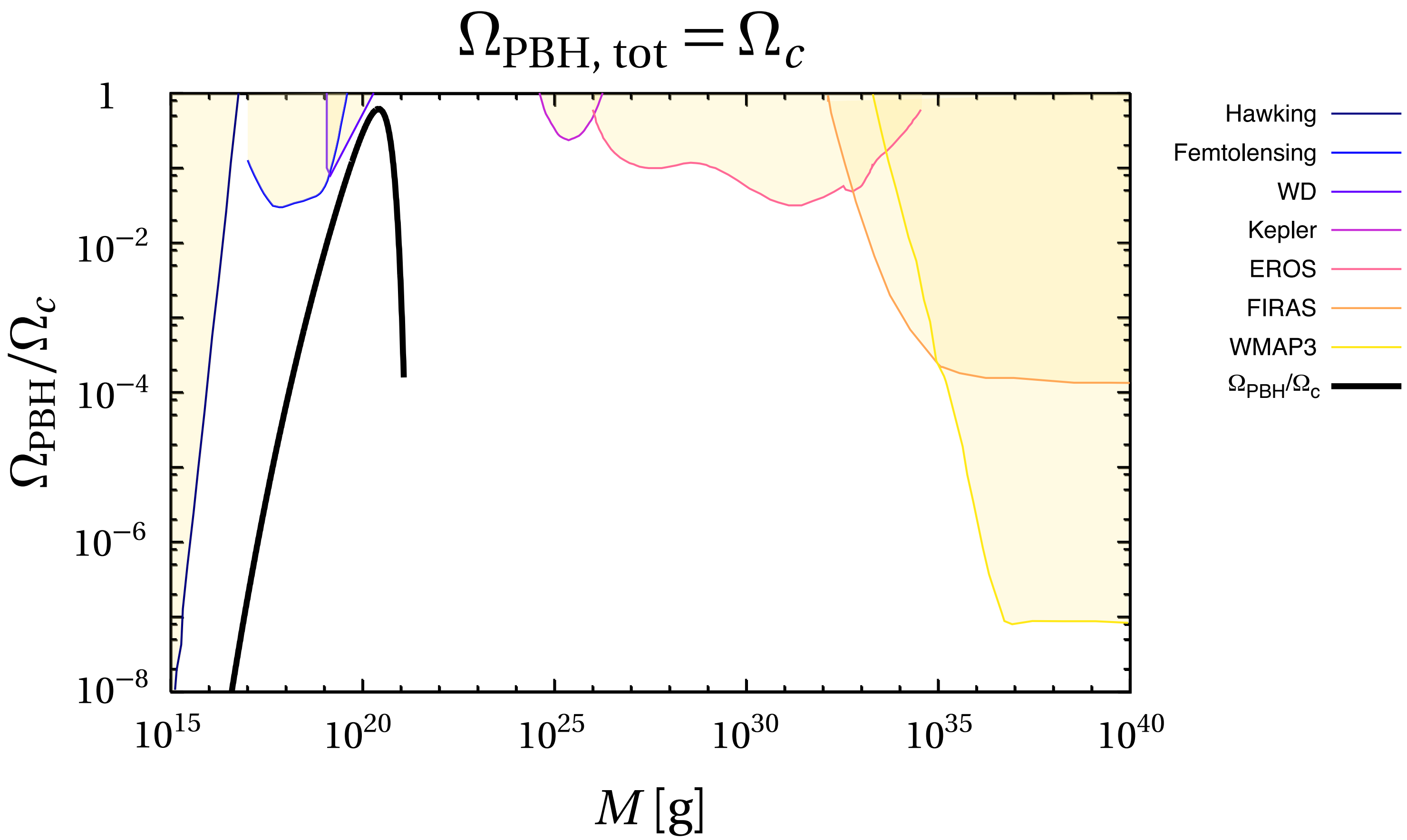


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# Conclusions

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- Chaotic inflation poses a threat to the stability of EW vacuum because it easily generates large fluctuations of Higgs during **inflation** or **preheating**.

- We have proposed a simple scenario (curvature coupling + chaotic inflation + new inflation) in which
  - Initial condition problem is solved.
  - EW vacuum is **always** stabilized during inflation, preheating, and afterwards.
  - Our solution naturally yields **PBHs** that can be a dominant component of **DM.**
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  [M.Kawasaki. **KM**, T.T, Yanagida, 1605.04974, PhysRevD.94.063509]

- **Gravitational waves** via second order effects of large scalar perturbations can be an interesting probe. [Saito, Yokoyama; Bugaev, Klimai]

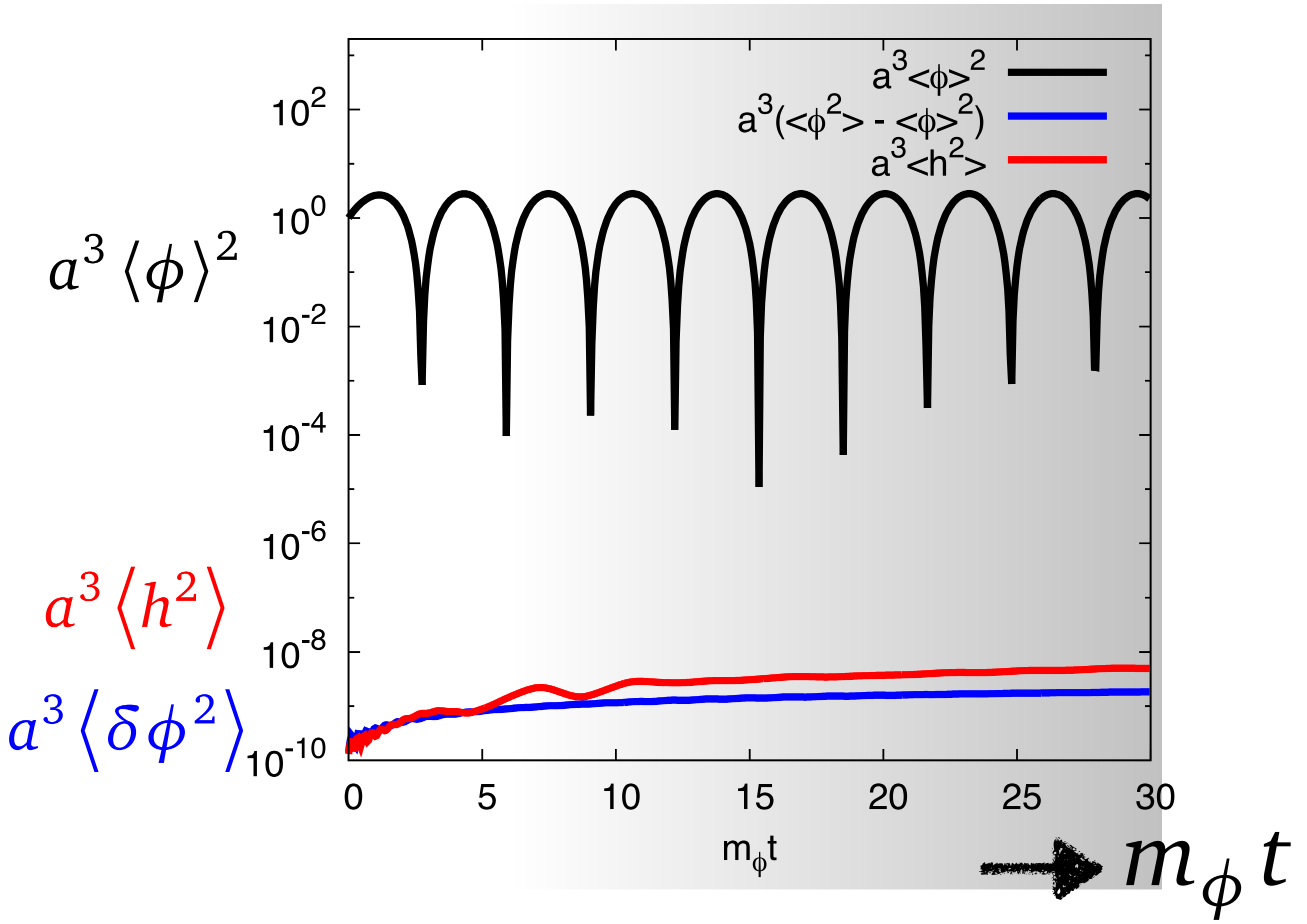
# Back up

# Numerical Simulation

[Ema, **KM**, Nakayama, 1602.00483]

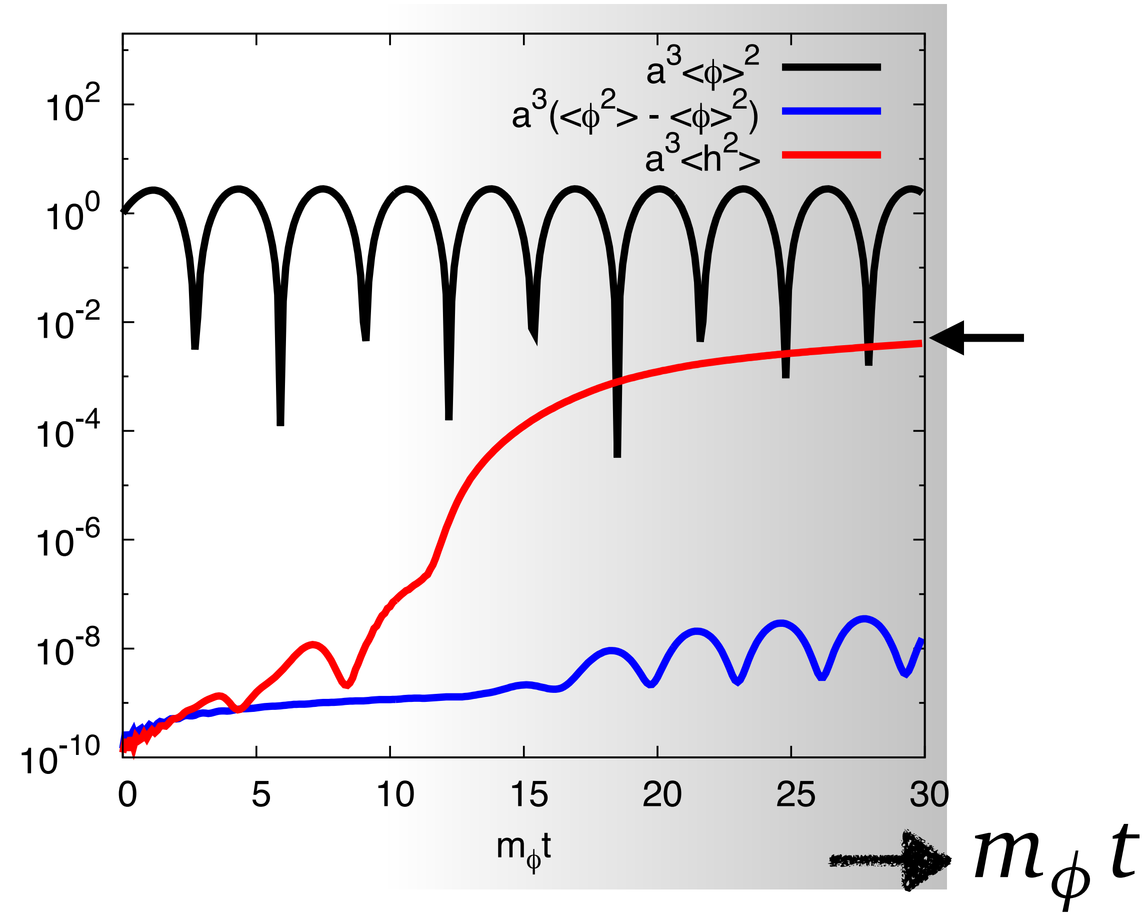
- Vacuum decay via Tachyonic Resonance: $-\mathscr{L}_{\rm int}(\phi, h) = \frac{1}{2}\xi R h^2$
  - To check $\xi \lesssim 10 \times \left[\frac{1}{\mu_{\rm crv}}\right]^2 \left[\frac{\sqrt{2}M_{\rm pl}}{\Phi_{\rm ini}}\right]^2$, we performed a classical lattice simulation.

**- Stable: ξ = 10**




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

**- Unstable: ξ = 20**

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# Gravitational Wave

## ■ GWs are produced via second order effects [Saito, Yokoyama; Bugaev, Klimai]

- Perturbed metric:

$$ds^2 = -a^2(\eta)\left[e^{2\Phi}d\eta^2 - e^{-2\Psi}\left(\delta_{ij} + \frac{1}{2}h_{ij}\right)dx^i dx^j\right]$$

Scalar perturbs: $\Psi = \Phi$ (neglect anisotropic stress) Tensor perturb

- Large scalar perturbations act as a source term in equation of motion for GWs.

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\hat{\mathcal{T}}_{ij;kl}S_{kl}$$

projection to transverse-traceless part

**Source term:** $S_{ij} \equiv 4\Psi\partial_i\partial_j\Psi + 2\partial_i\Psi\partial_j\Psi - \dfrac{4}{3(1+w)}\partial_i\left(\dfrac{\Psi'}{\mathcal{H}} + \Psi\right)\partial_j\left(\dfrac{\Psi'}{\mathcal{H}} + \Psi\right)$

- Abundance of GWs is roughly given by…

$$\Omega_{\rm GW}(k) \sim 3\times 10^{-8}\left(\frac{\mathcal{P}_\zeta(k)}{0.01}\right)^2$$