Metastability, Chaotic Inflation, and Primordial Black Holes

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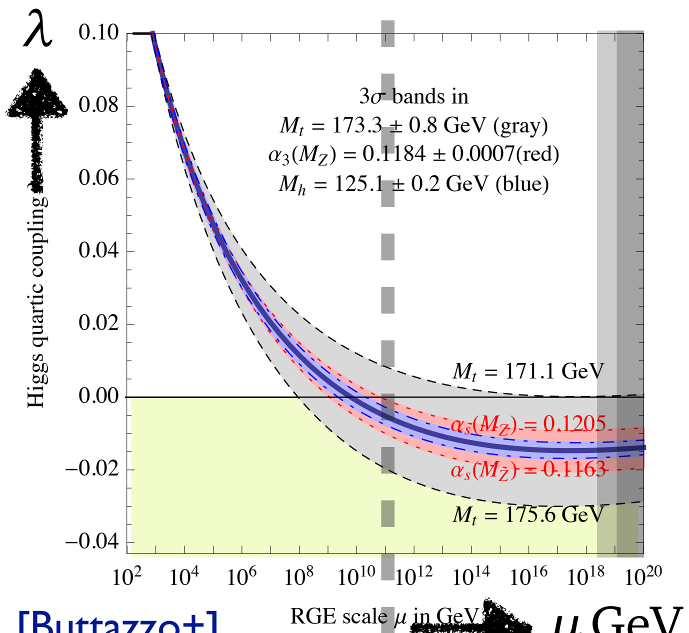
Based on 1605.04974 (PhysRevD.94.063509)
In collaboration with M.Kawasaki, T.T.Yanagida

Introduction

Metastability v.s. Inflation

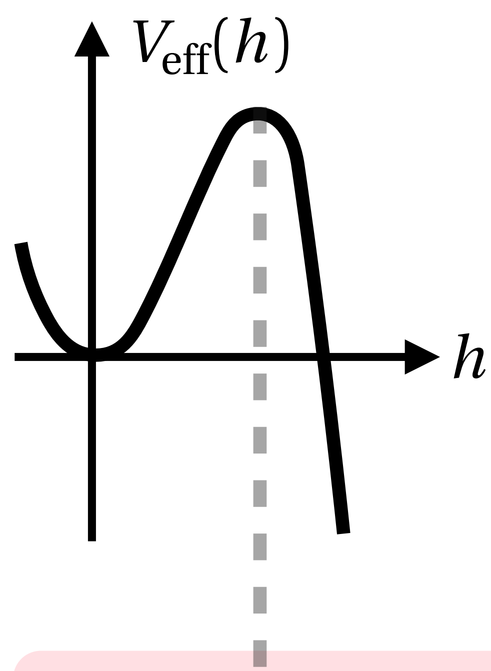
■ Metastable Electroweak Vacuum v.s. Chaotic Inflation

- **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.

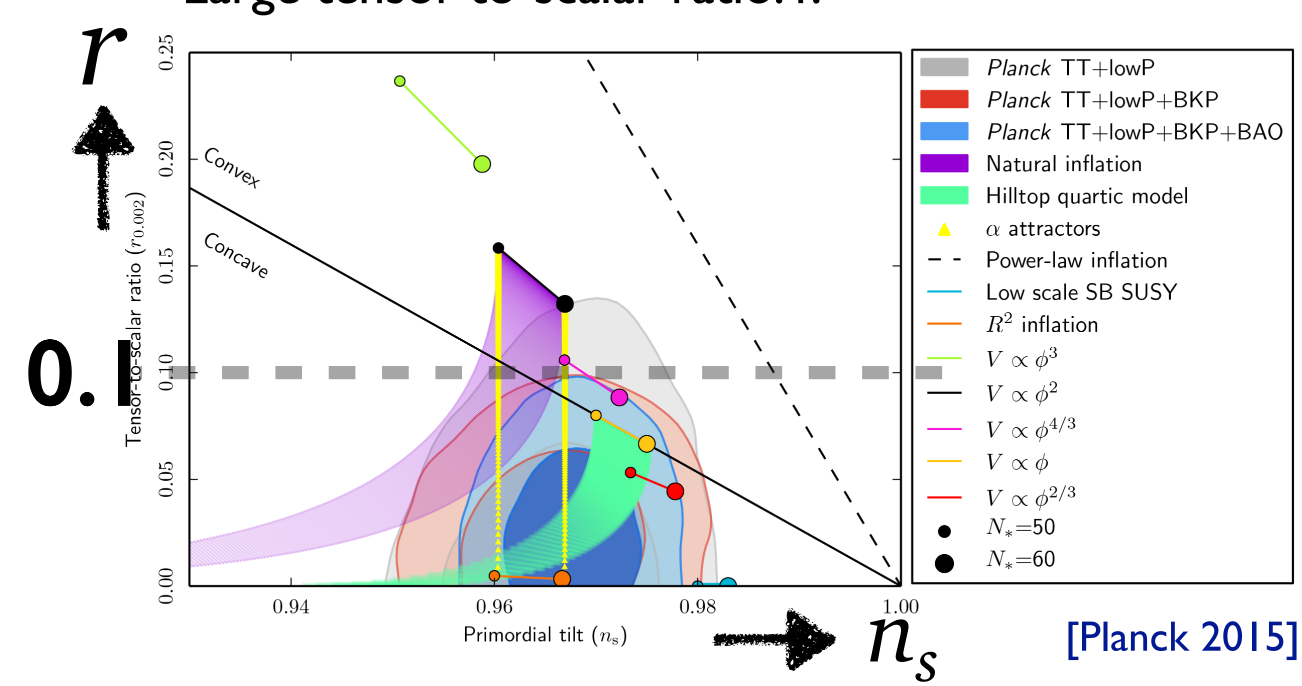


[Buttazzo+]

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: $\xi R h^2$

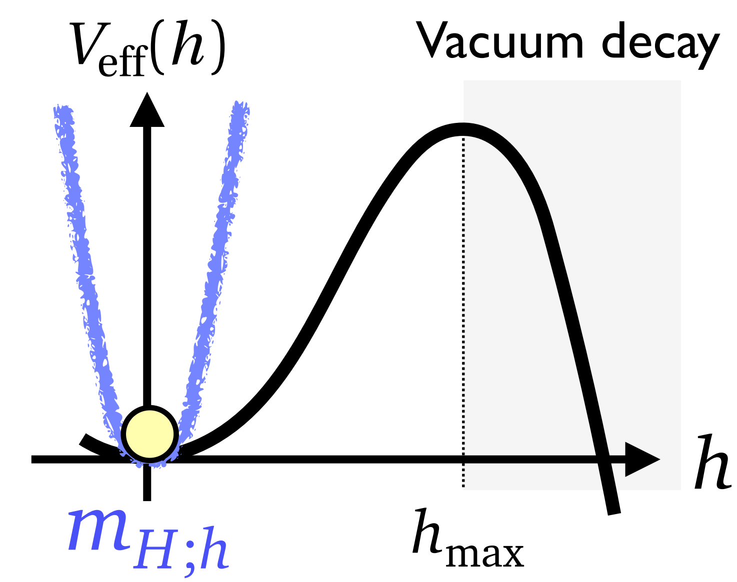
- Stabilize the EW vacuum **during inflation** @ ξ > O(0.1)

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

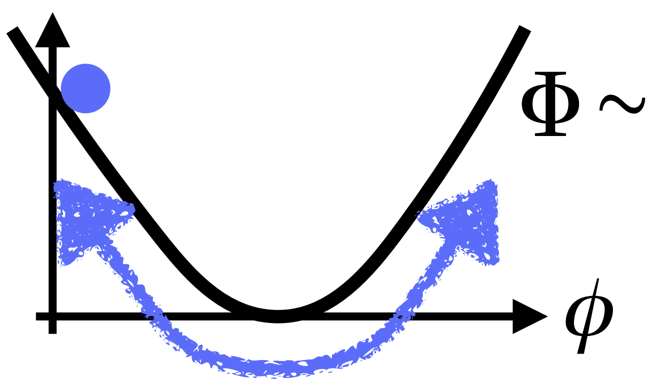
during inflation

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

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



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

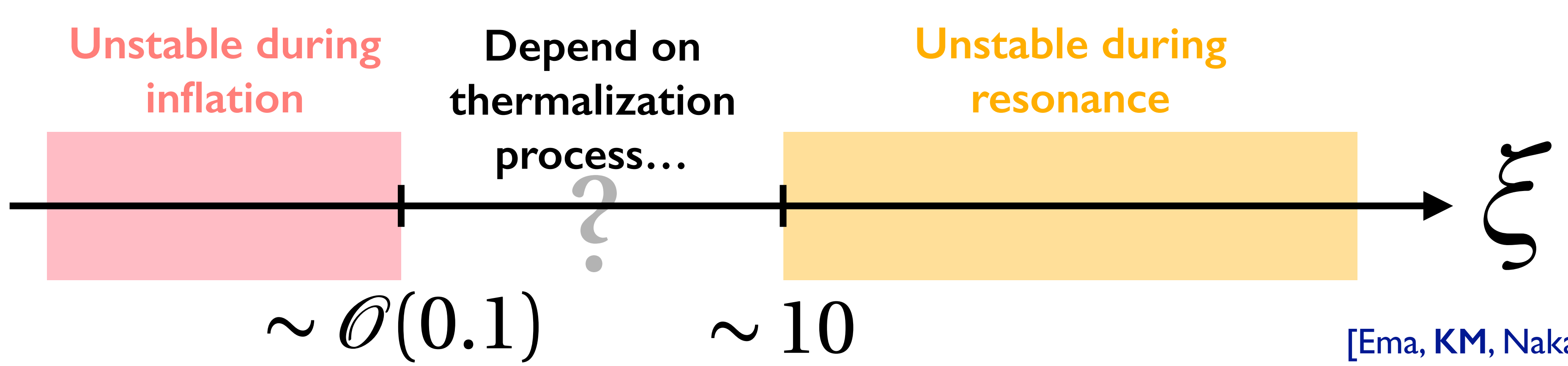


- Oscillating mass term

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

Tachyonic Resonance

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

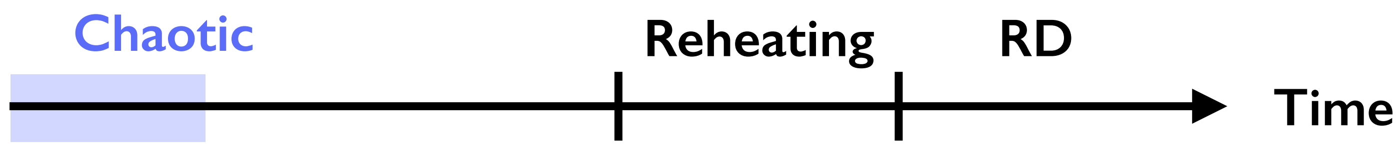


[Ema, **KM**, Nakayama; Herranen+]

Our Scenario

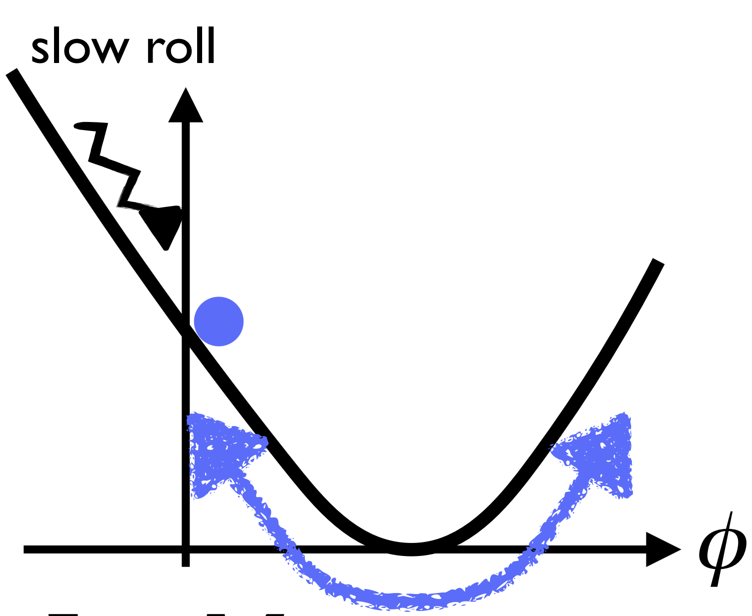
What we have discussed

■ **Ingredients:**



- **Chaotic inflation**
  - Solve the initial condition problem + provide primordial density perturbations
- **Curvature coupling**
  - Stabilize the EW vacuum during inflation(s) + universally couples to the trace of energy-momentum

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



$\Phi \sim M_{\rm pl}$

- End of slow roll

$$\epsilon_V = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2, \quad \eta_V = M_{\rm pl}^2 \frac{V''}{V}$$

$$\max[\epsilon_V, |\eta_V|] = 1$$

For chaotic inflation

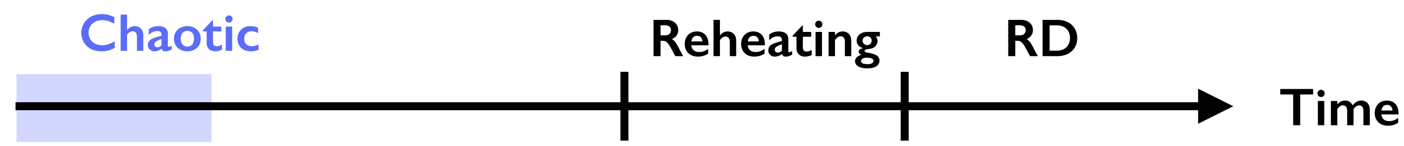
$$\Phi \sim M_{\rm pl}$$

Resonance is inevitable

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

Our Scenario

■ Ingredients:



- Chaotic inflation
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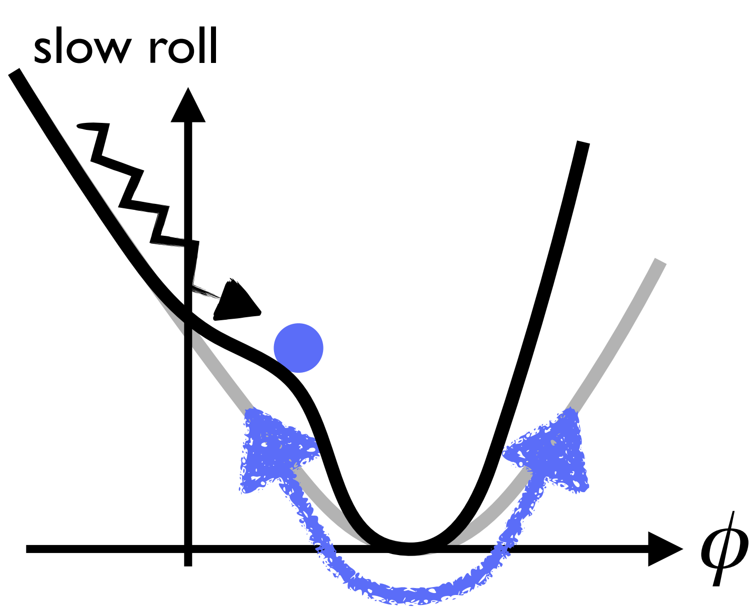
- If the potential is **flat** near the origin,…



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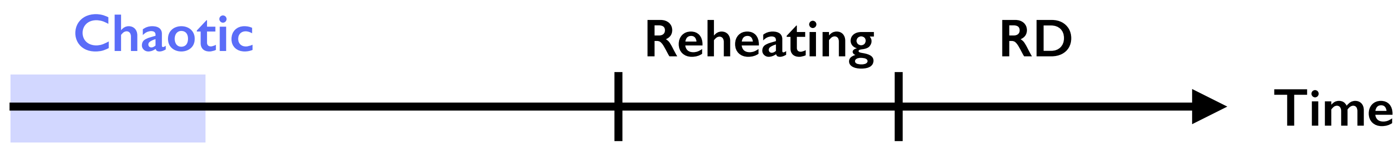

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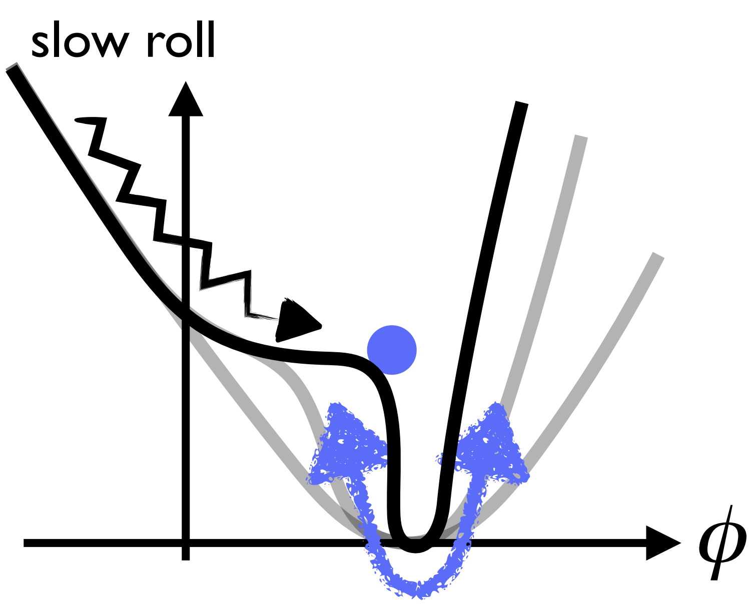

$$\Phi \lll M_{\rm pl}$$

No Resonance

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

Our Scenario

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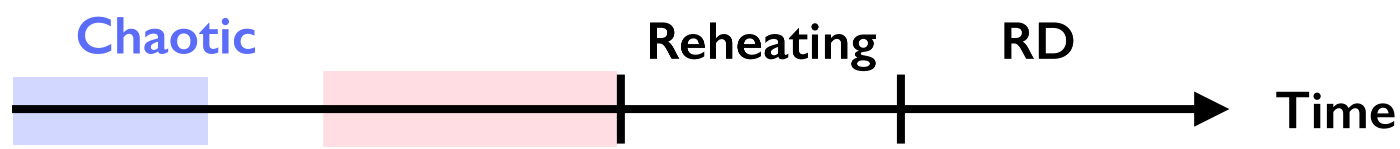

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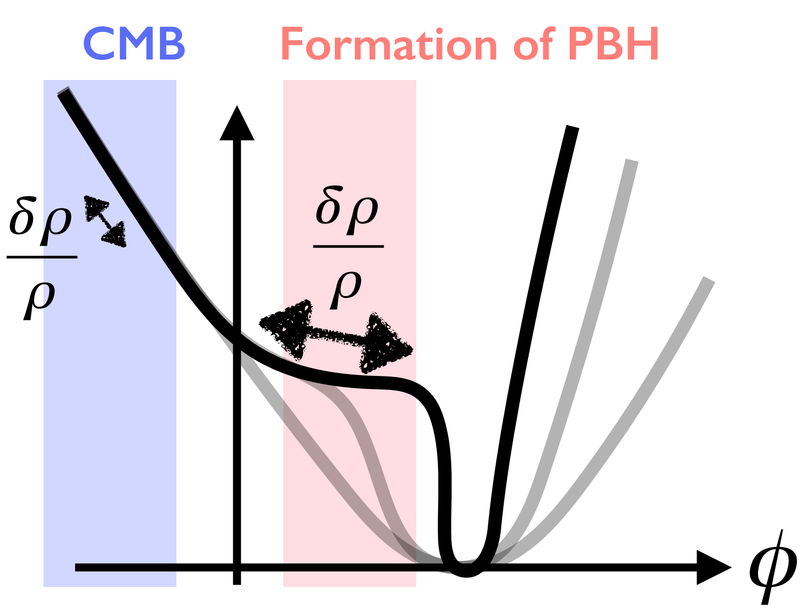
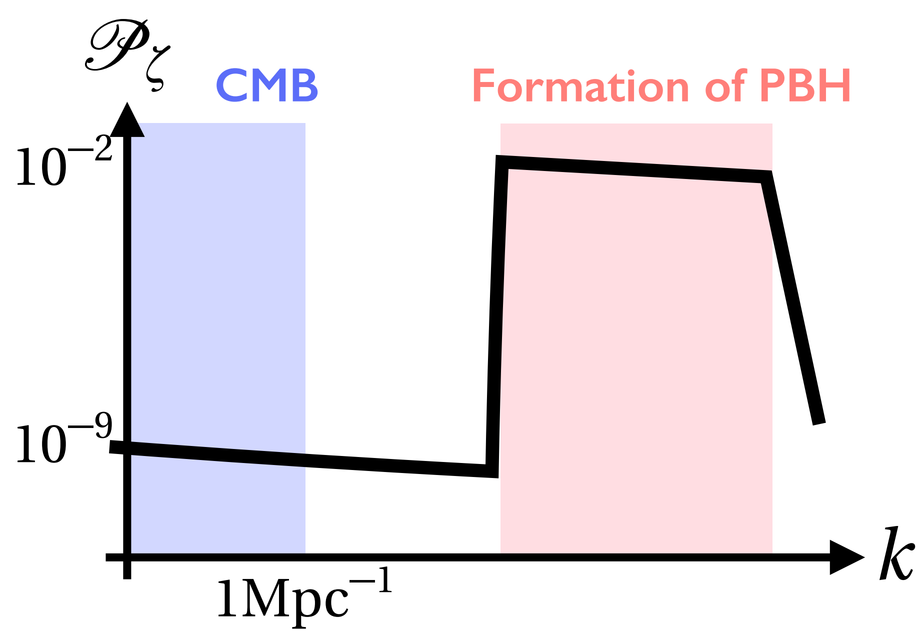
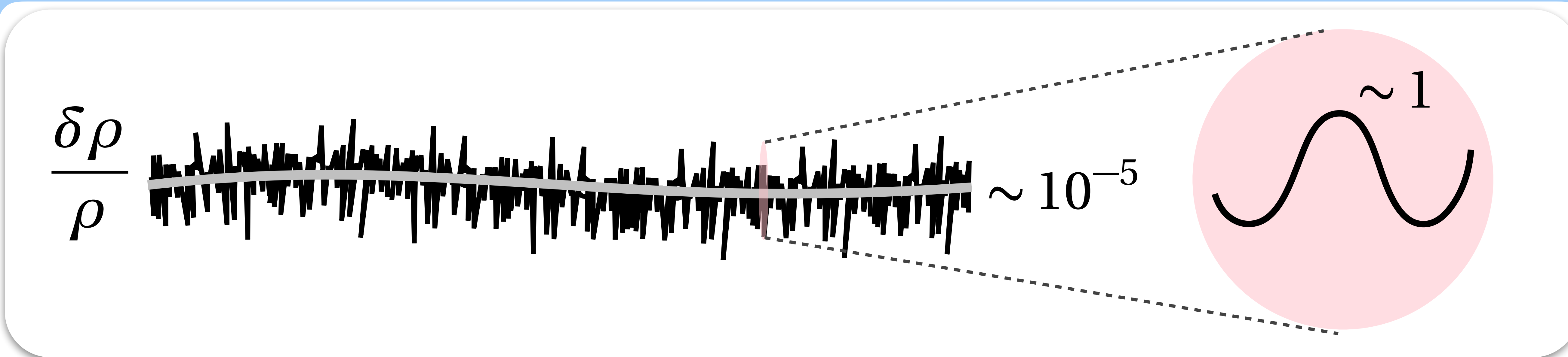




$$\Phi \lll M_{\rm pl}$$

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

Our Scenario



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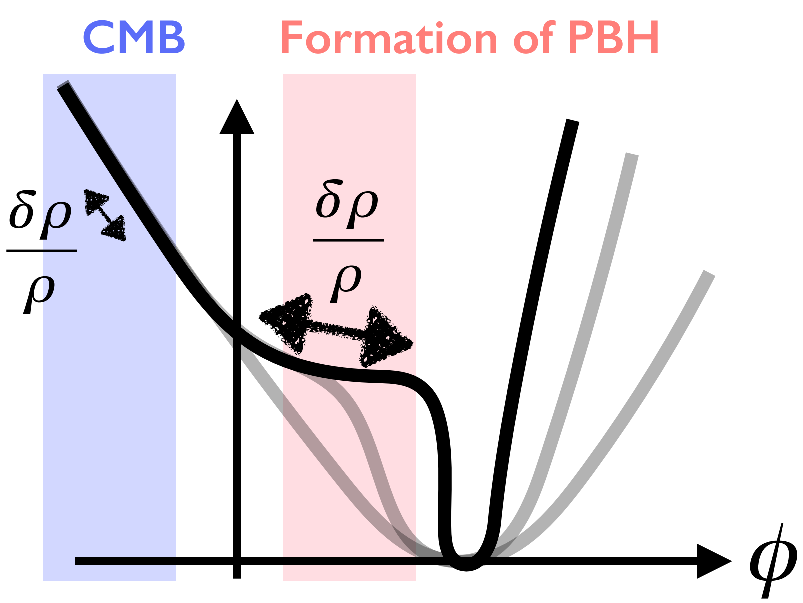

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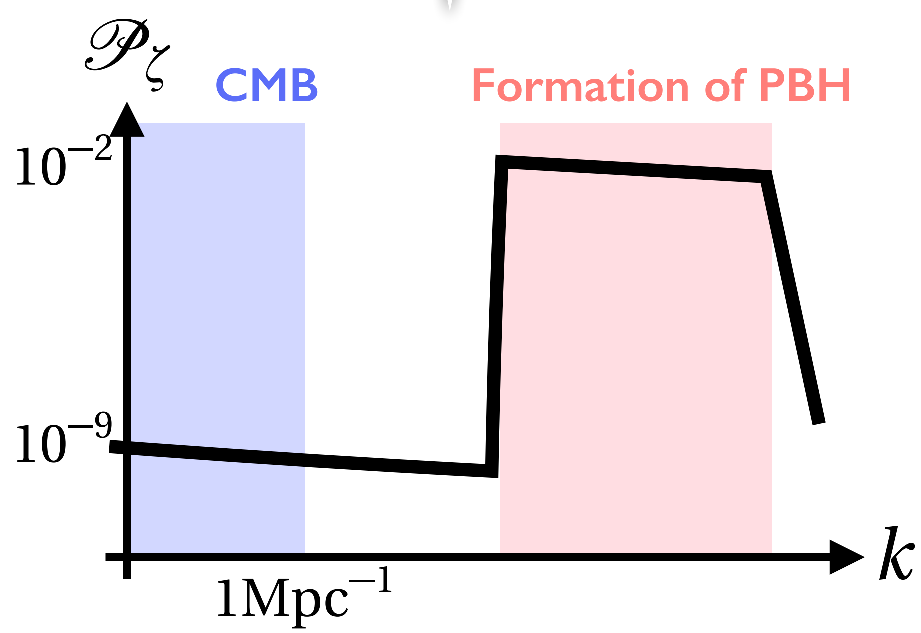

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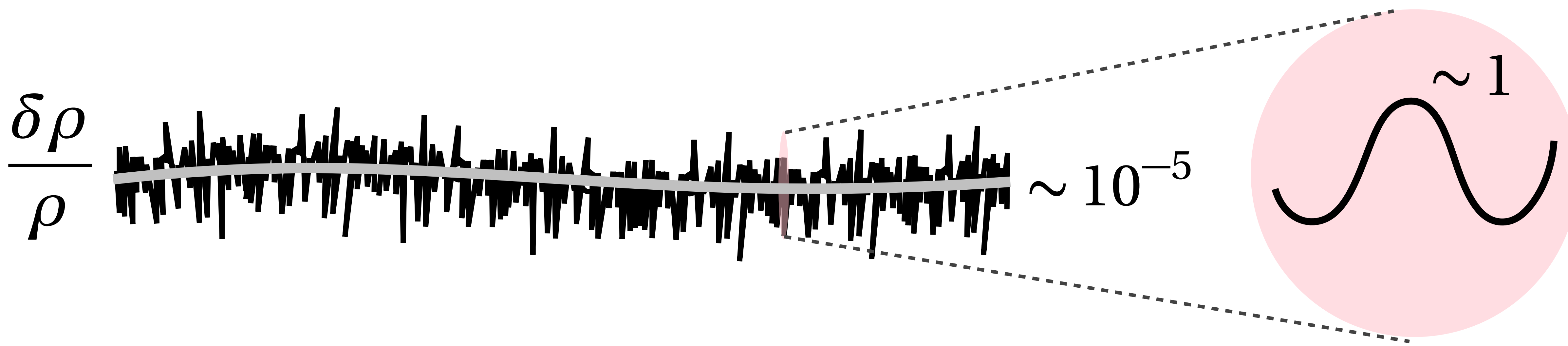

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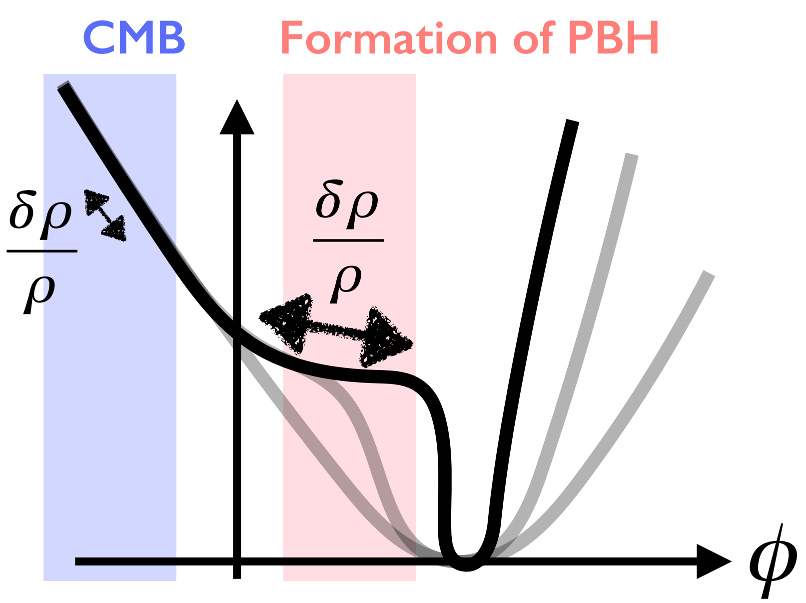

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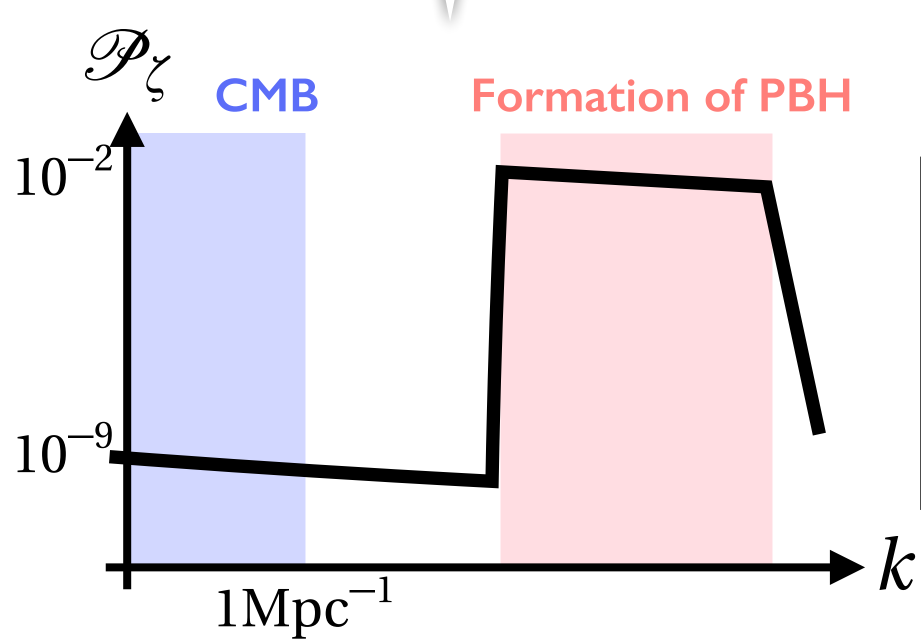

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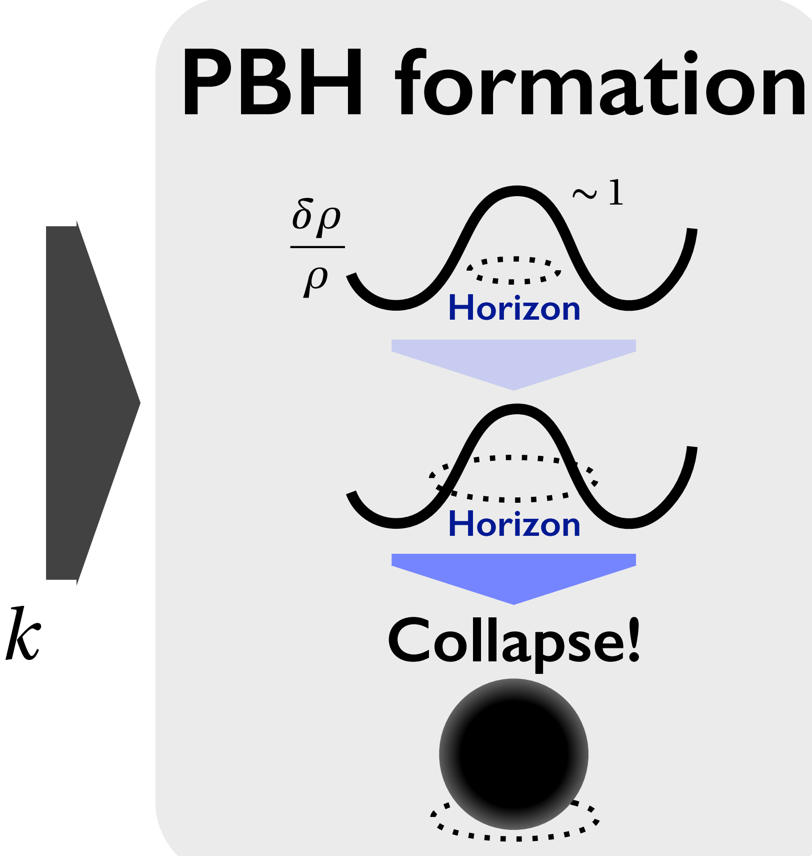
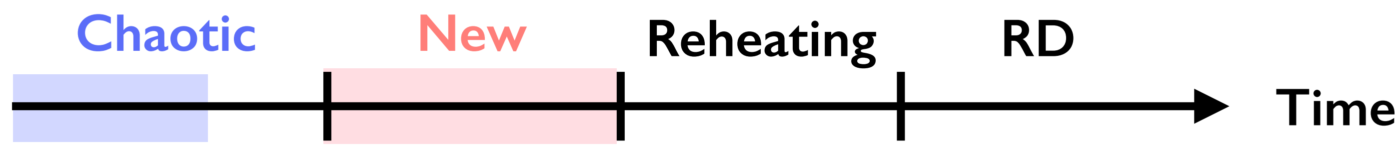
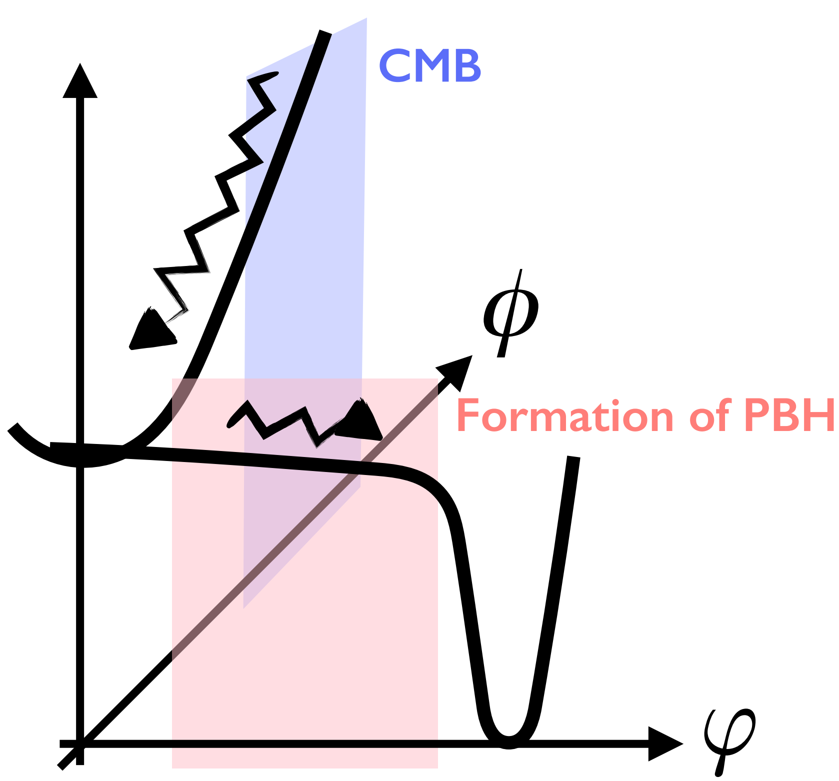


Example: Double Inflation

- **Ingredients:**



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



- Stabilize φ during chaotic inflation

$$-\mathscr{L}_{\rm int} \propto \frac{V_{\rm ch}(\phi)}{M_{\rm pl}^2}\varphi^2$$

- Potential in the flat regime (new inflation)

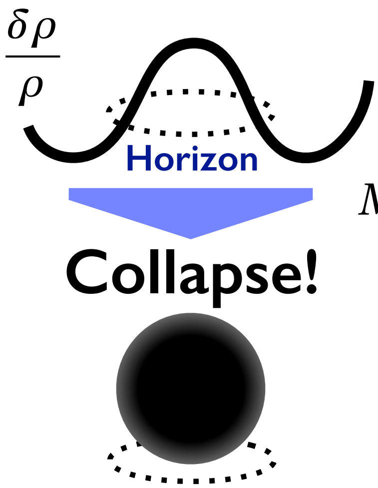
$$V_{\rm new}(\varphi) = \left(v^2 - g\frac{\varphi^4}{M_{\rm pl}^2}\right)^2 - \kappa v^4 \frac{\varphi^2}{2M_{\rm pl}^2} - \epsilon v^4 \frac{\varphi}{M_{\rm pl}}$$

Example: Double Inflation

■ PBHs as whole Dark Matter

- PBH is formed when the over-dense region enters the horizon.

- **PBH mass** ∝ Horizon mass @ horizon reenter



$$M = \gamma \rho \left. \frac{4\pi H^{-3}}{3} \right|_{k=aH}$$
$$\simeq M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{g_*}{3.36}\right)^{-\frac{1}{6}}\left(\frac{k}{2\times 10^6\,\mathrm{Mpc}^{-1}}\right)^{-2}$$

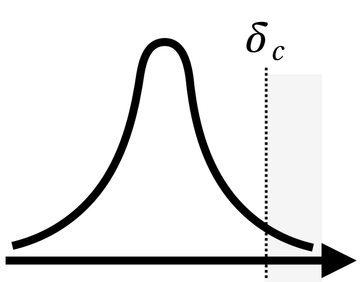
[Carr, Astrophys. J. 201, 1(1975)]

- PBH is formed if **δρ/ρ > δc** (=1/3).

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

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

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

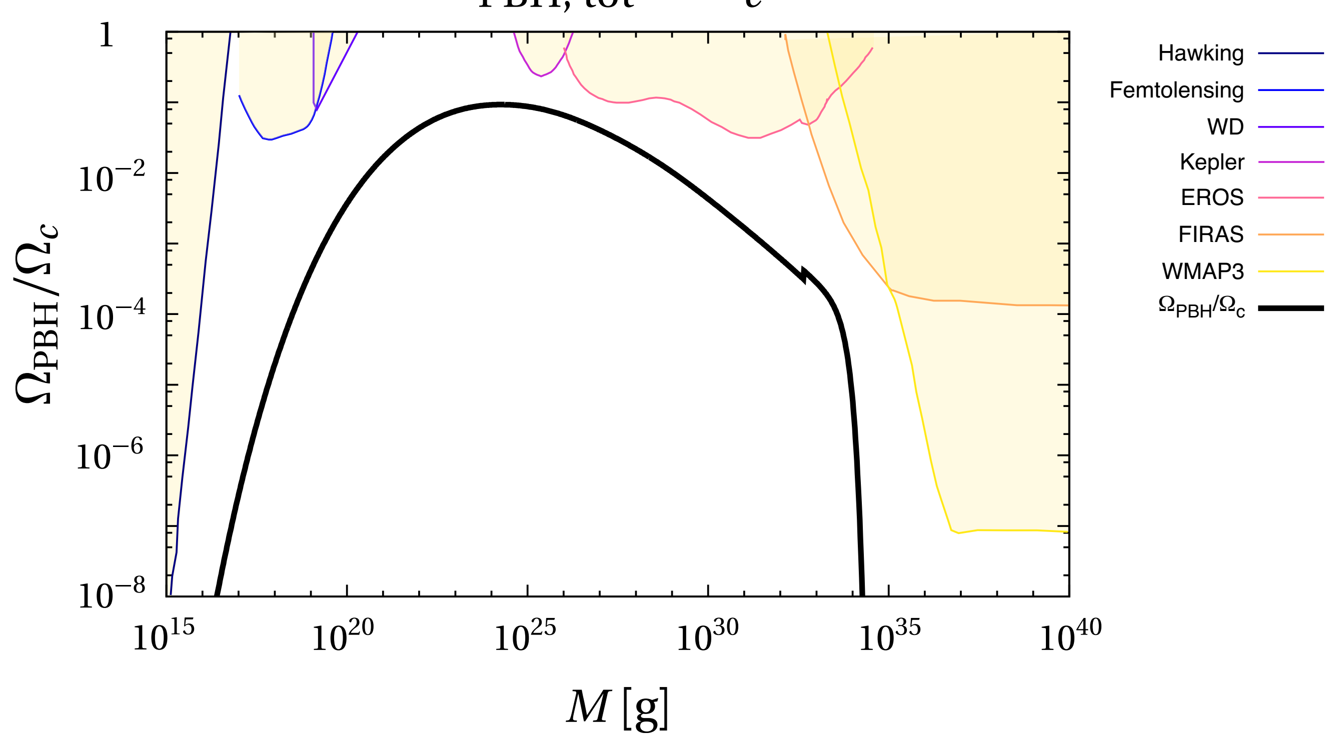


$\delta \equiv \frac{\delta\rho}{\rho}$

[Carr, Astrophys. J. 201, 1(1975);
Young et al., JCAP 1407 (2014) 045]

- Abundance of PBHs as a function of mass

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



✳ 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]

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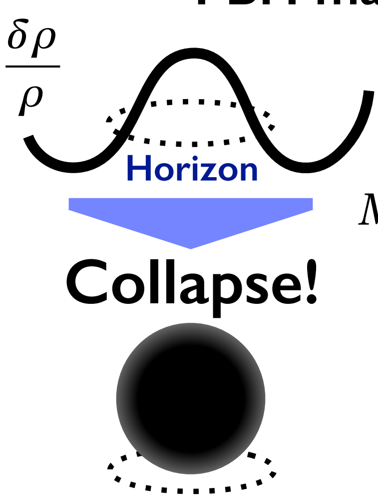

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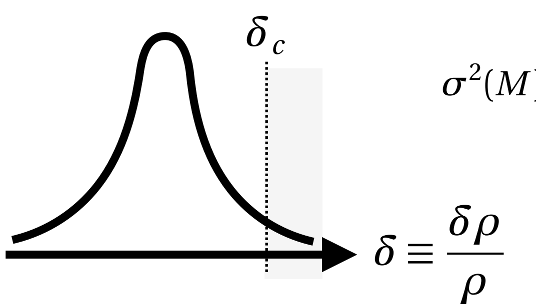
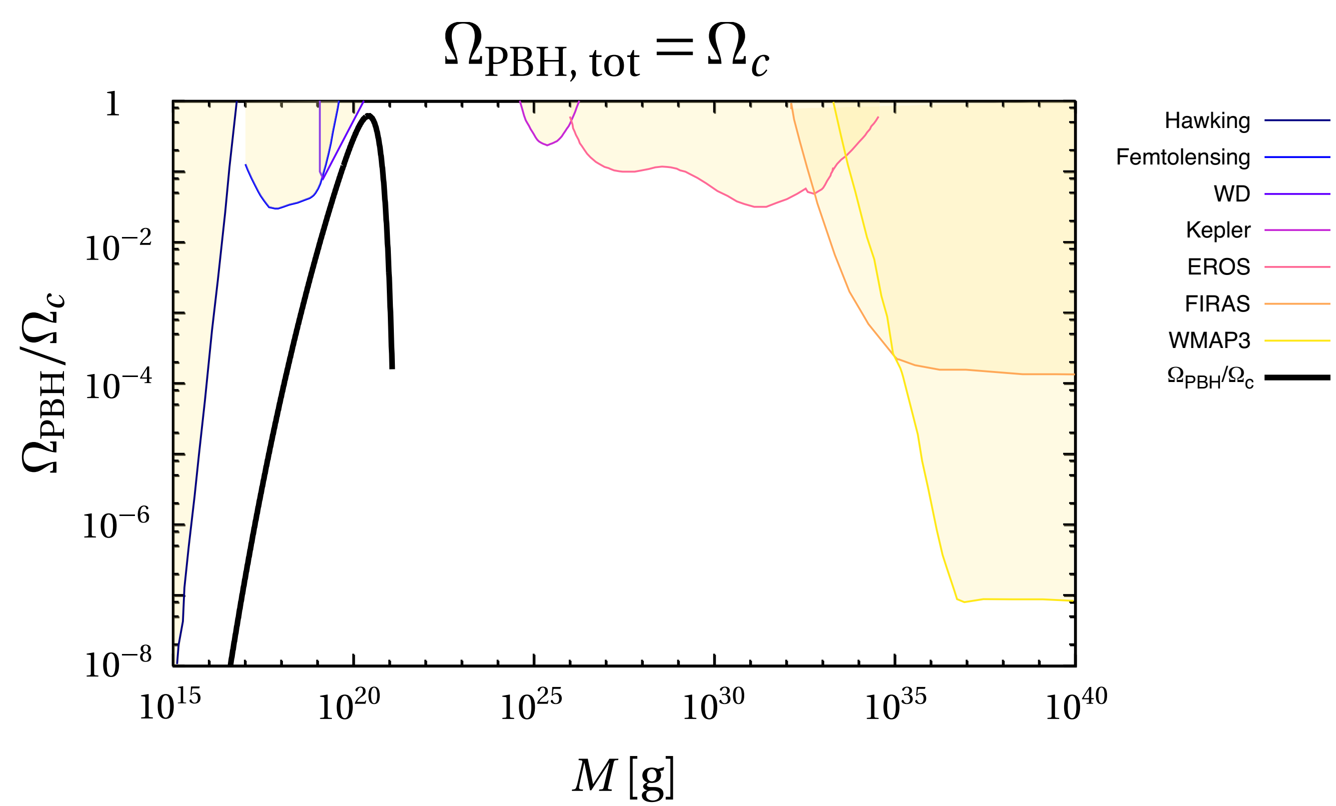


- Abundance of PBHs as a function of mass



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Summary

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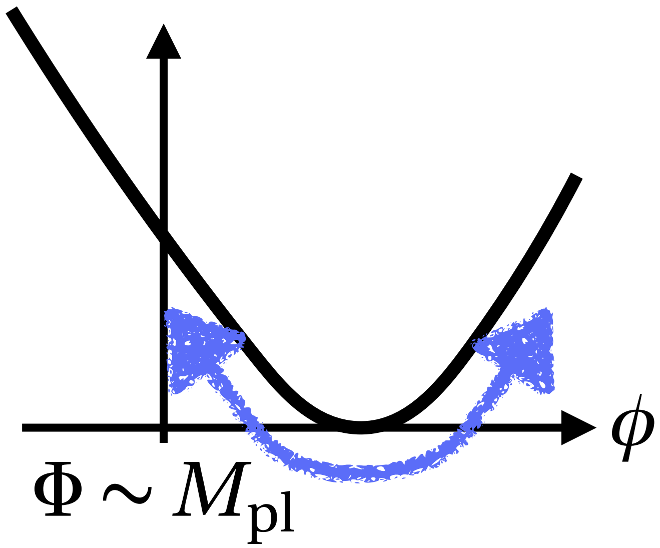
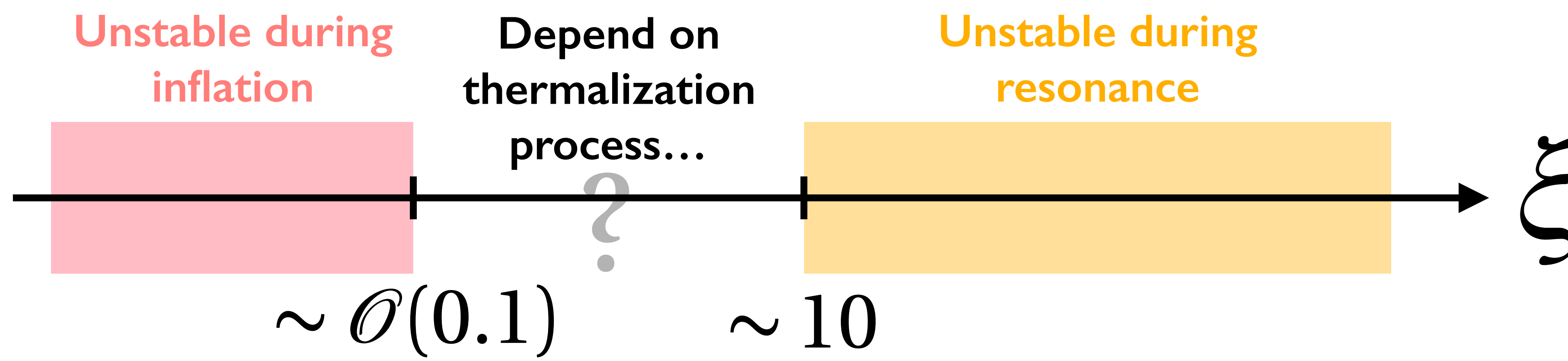
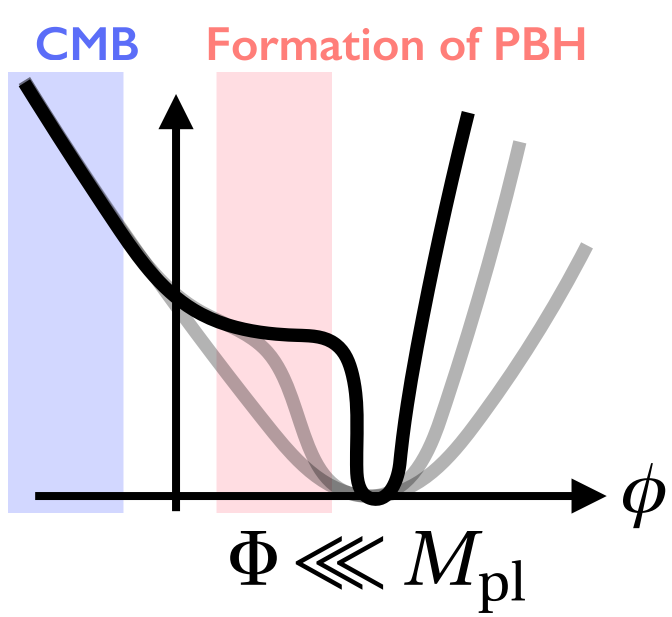
- **Chaotic inflation** v.s. **Metastable EW Vacuum**:





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

- Slight modification of inflaton potential can dramatically **relax the tension**. Moreover, it can generate **PBHs as all DM**!

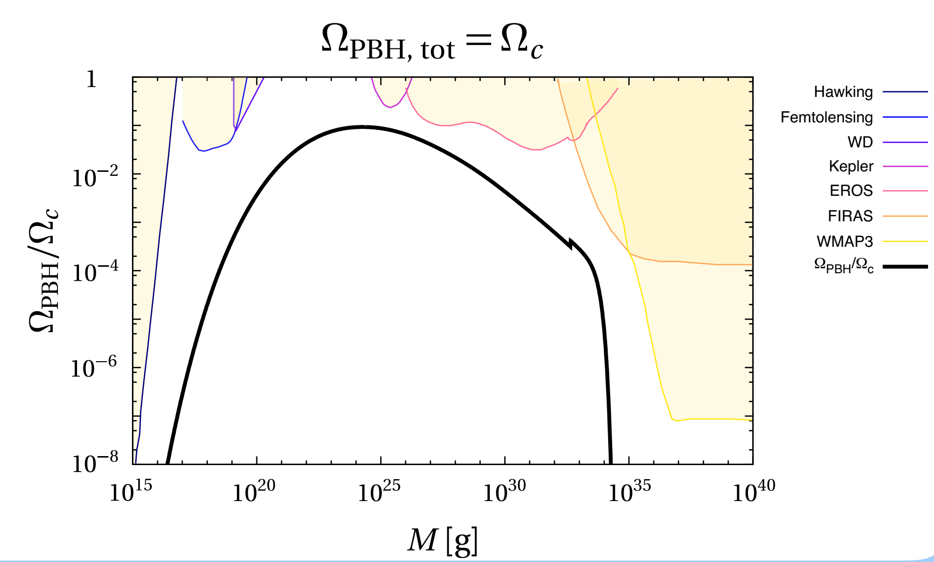


No Resonance

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

&

[Kawasaki, KM, Yanagida, 1605.04974]



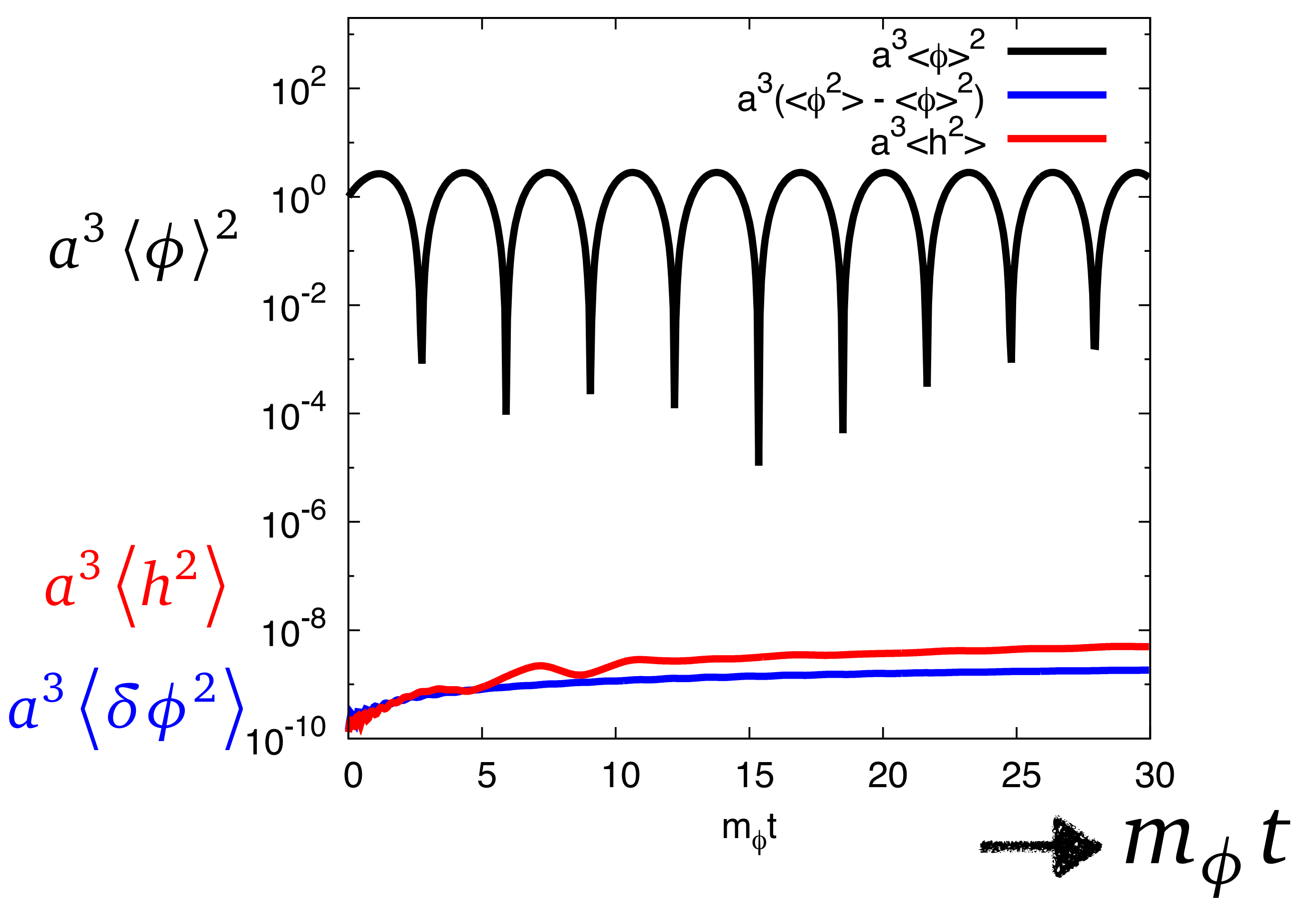
Back up

Numerical Simulation

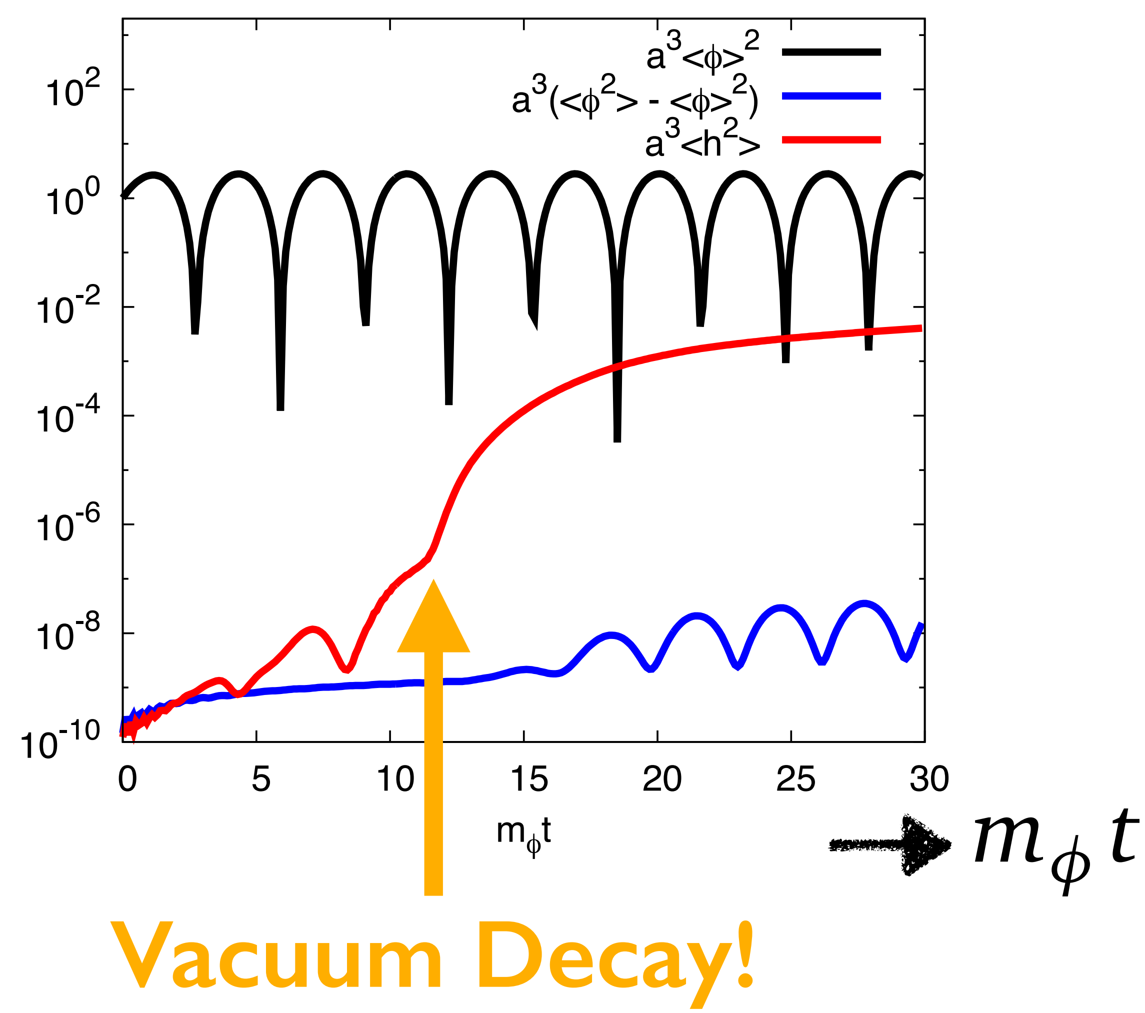
[Ema, **KM**, Nakayama, 1602.00483]

- **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



- Unstable: ξ = 20



Gravitational Wave

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

- Perturbed metric:

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

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

Tensor perturb

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

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

projection to transverse-traceless part

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

- Abundance of GWs is roughly given by…

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