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Formation of primordial black holes from Affleck-Dine mechanism

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Refs. Kasai, MK, Murai arXiv:2205.10148
Kasai, MK, Murai, Neda arXiv:2405.09790

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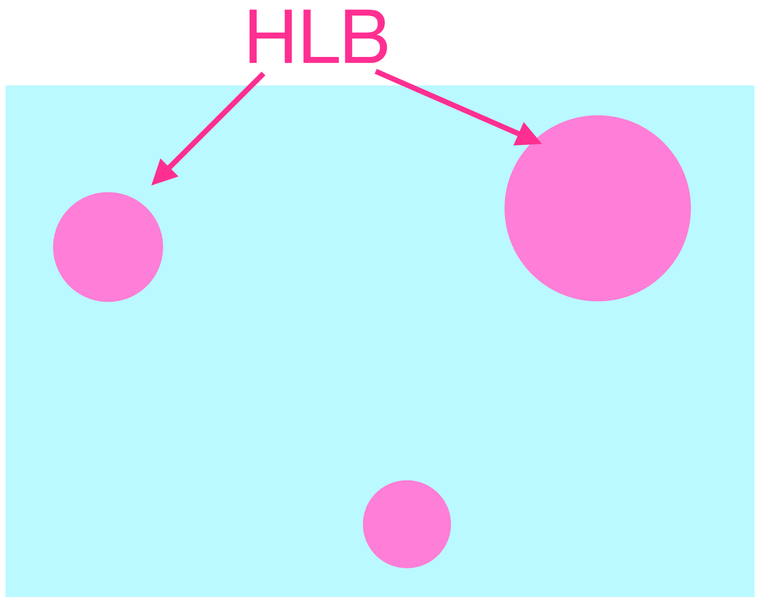
1. Introduction

- Supermassive Black Holes (SMBHs) ($> 10^6 M_\odot$) exist in the centers of almost all massive galaxies
- PTA experiments reported the detection of GWs that may be produced by binaries of SMBHs
- Recent GWST observation suggests SMBHs with $10^{6-10} M_\odot$ at $z \sim 10$
- Primordial black holes (PBHs) ($\sim 10^4 M_\odot$) are seeds for SMBHs?

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}} \simeq 3 \times 10^{-9}$$

- However, PBHs with $> 10^4 M_\odot$ are excluded by CMB spectral distortion if PBHs are produced from Gaussian density fluctuations
- Need highly non-gaussian fluctuations
- We consider PBH formation from high lepton bubble (HLBs) produced by Affleck-Dine mechanism

Dolgov, Silk (1993)
Dogov MK Kevlishvili (2009)
Hsegawa, MK (2018)



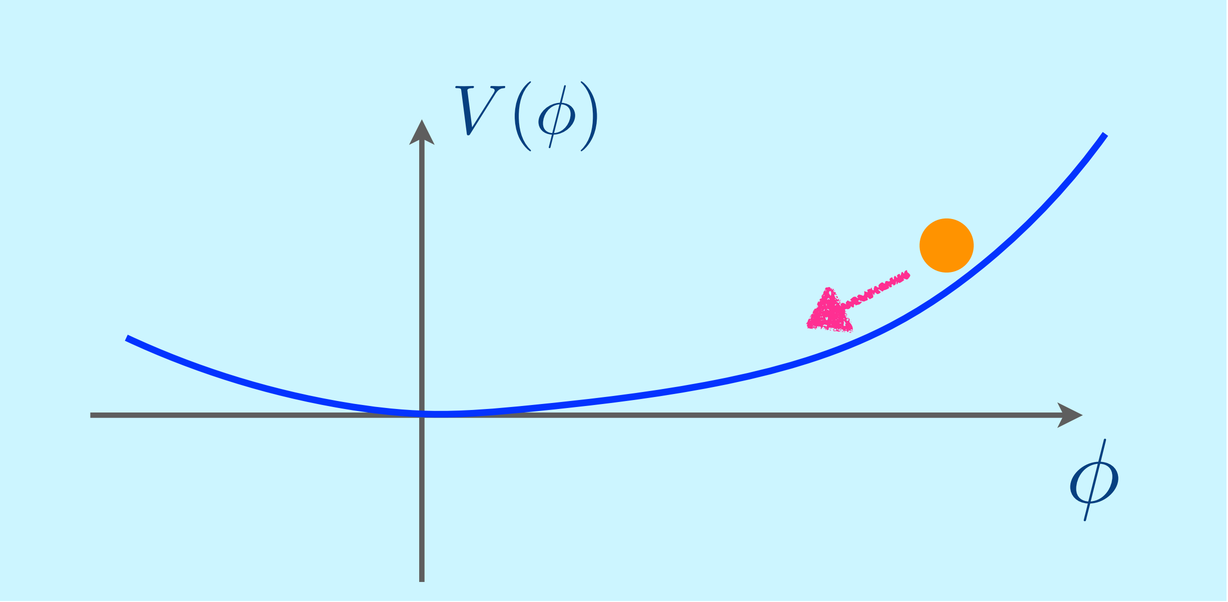
2. Affleck-Dine mechanism and Q-ball

2.1 Affleck-Dine mechanism

- Flat directions in the scalar potential of minimal SUSY standard model (MSSM) $\ni$ (squark, slepton, Higgs)
- One of flat directions = AD field Φ
- AD field has a baryon number or/and a lepton number

We assume here (→ lepton number)

- The flat direction is lifted by the effects of SUSY breaking and the existence of the cutoff scale



- Potential

$$V(\phi) = (m_\phi^2 + c_H H^2)|\phi|^2 + \lambda^2 \frac{|\phi|^{2(n-1)}}{M_p^{2(n-3)}} + A\frac{\phi^n}{M_p^{(n-3)}} + h.c.$$

V_{susy} : SUSY breaking mass term

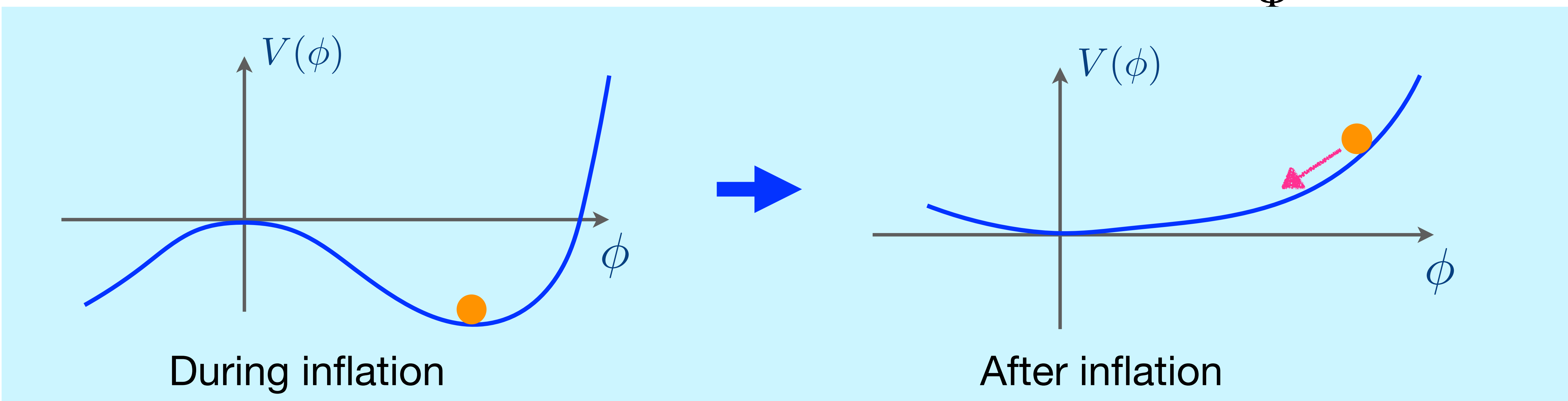
Hubble induced mass term

V_{NR} : Non-renormalizable term (n≥4)

V_A : A-term $(A \sim m_{3/2})$

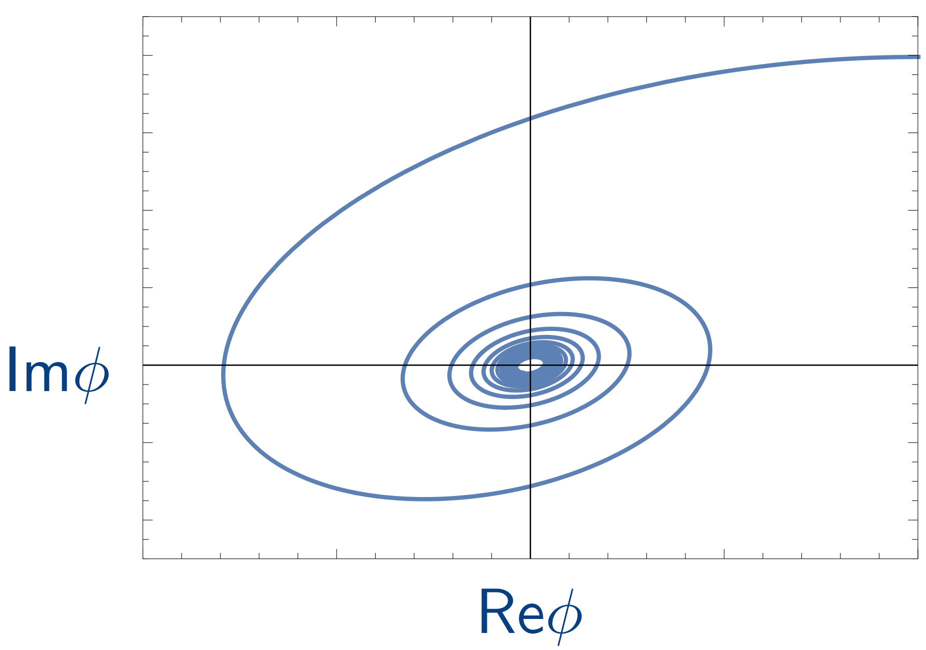
2.1 Affleck-Dine mechanism

- During inflation AD field has a large field value (if $c_H < 0$)
- After inflation AD field starts to oscillate when $H \sim m_\Phi$



- AD field is kicked into phase direction due to θ-dependent potential

V_A : A-term



$n_L \sim \dot{\theta}|\phi|^2$

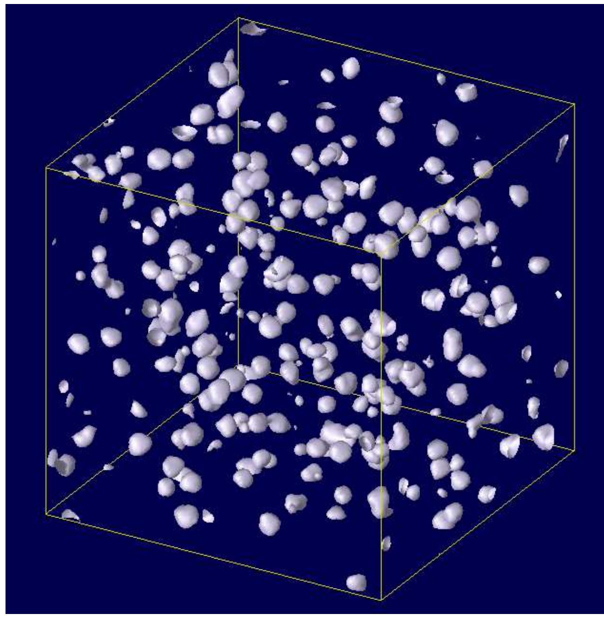
Lepton number generation

$$\eta_L = \frac{n_L}{s} \sim \frac{T_R}{m_{3/2}} \left(\frac{\phi_{\text{ocs}}}{M_p} \right)^2$$

2.2 Q-balls from AD mechanism

Kusenko Shaposhnikov (1998)
Kasuya MK (1999)

- AD field oscillation has spatial instabilities if the potential is flatter than ϕ^2
- AD field fragments into spherical lumps called Q-balls
  - Q-balls with lepton number are called L-balls



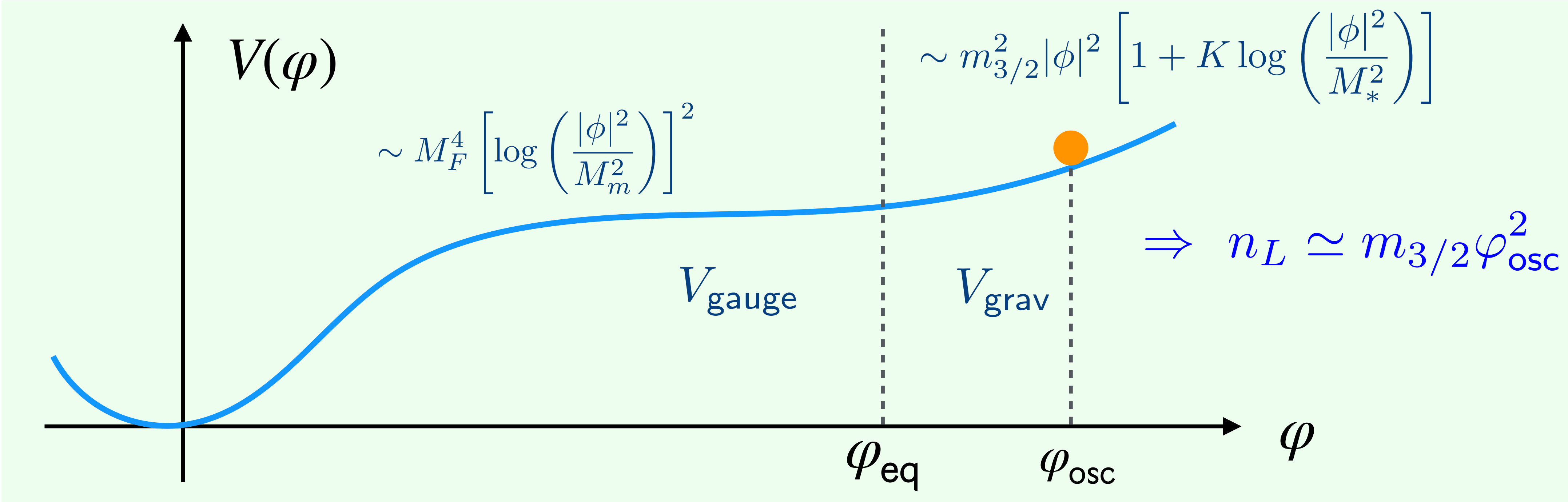
Hiramatsu MK Takahashi (2010)

- Q-ball properties depend on SUSY-breaking models
- We consider gauge-mediated SUSY breaking models

$$V(\Phi) = \underbrace{M_F^4 \left[\log\left(1+\frac{|\Phi|^2}{M_{\text{mess}}^2}\right)\right]^2}_{V_{\text{gauge}}} + \underbrace{m_{3/2}^2|\Phi|^2\left[1+K\log\left(\frac{|\Phi|^2}{M_*^2}\right)\right]}_{V_{\text{grav}}}$$

  - Q-balls are always formed when V_{gauge} dominates the potential
  - Q-balls are formed if $K<0$ when V_{grav} dominates the potential

2.3 L-ball formation



- AD field starts oscillation with amplitude $\varphi_{\rm osc} > \varphi_{\rm eq}$ at $H \sim m_{3/2}$
- If $K > 0 \;\; \Rightarrow$ L-balls do not form until $\varphi < \varphi_{\rm eq}$
  - L-ball formation is delayed [delayed-type L-ball]
- L-ball mass, radius and energy per lepton number

$$M_Q = \frac{2\sqrt{2}\pi}{3}\zeta M_F Q^{3/4} \qquad R_Q = \frac{1}{\sqrt{2}}\zeta^{-1} M_F Q^{-1/4}$$

$$\omega = dM_Q/dQ = \sqrt{2}\zeta M_F Q^{-1/4} \qquad \zeta \sim 3.6$$

Hisano Nojiri Okada (2001)

- L-balls decay into neutrinos with decay rate $\Gamma_Q \simeq \frac{1}{Q}\frac{\omega_Q^3}{4\pi^2}4\pi R_Q^2$

3. Inhomogeneous AD and PBHs

3.1 Inhomogeneous AD mechanism

Dolgov, Silk (1993)
Dogov MK Kevlishvili (2009)
Hsegawa, MK (2018)

- Modified AD mechanism can produce lepton (baryon) number inhomogeneously
- Two unconventional assumptions:
  - Hubble mass is positive during inflation and becomes negative after inflation
  - Thermal mass overcomes Hubble mass after inflation
- Potential for AD field

$$V = \begin{cases} (m_\phi^2 + c_I H^2)|\phi|^2 + V_{\mathrm{NR}} + V_{\mathrm{A}} & \text{(during inflation)} \\ (m_\phi^2 - c_M H^2)|\phi|^2 + V_{\mathrm{NR}} + V_{\mathrm{A}} + V_{\mathrm{T}} & \text{(after inflation)} \end{cases}$$

$$V_T = \begin{cases} c_1 T^2 |\phi|^2 & |\phi| \lesssim T \\ c_2 T^4 \ln(|\phi|^2/T^2) & |\phi| \gtrsim T \end{cases}$$

3.1 Inhomogeneous AD mechanism

- During inflation
  - $c_H > 0$ (positive Hubble mass)
  - Flat potential $c_H << 1$
- Quantum fluctuations of AD field
  - Gaussian distribution

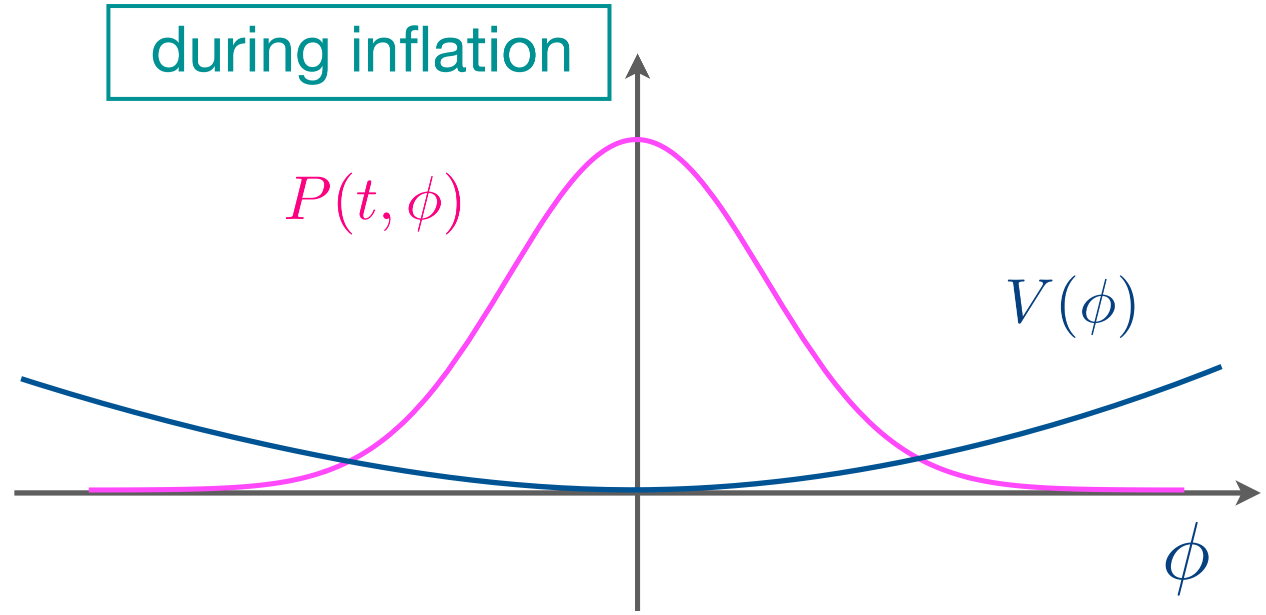
$$P(t,\phi) = \frac{1}{2\pi\sigma(t)^2}\exp\left[-\frac{|\phi|^2}{2\sigma(t)^2}\right]$$

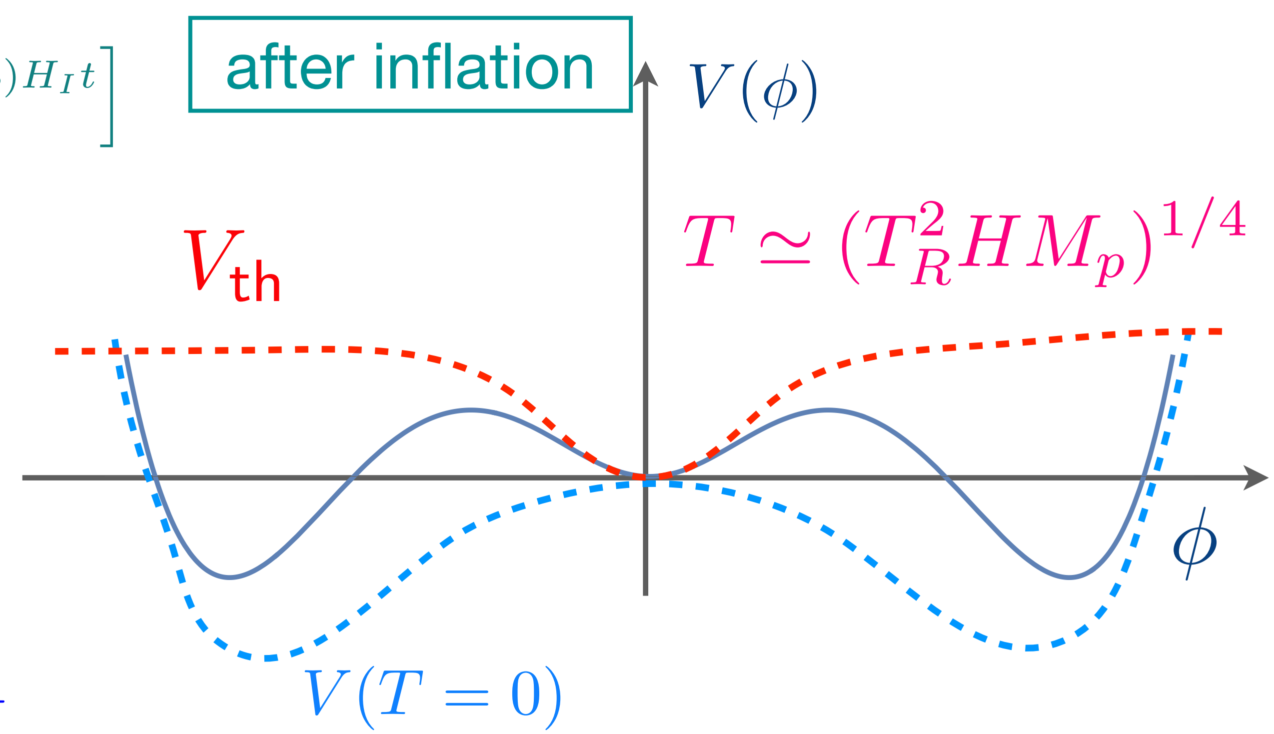
$$\sigma^2 = \left(\frac{H_I}{2\pi}\right)^2\left(\frac{2}{3c_H}\right)\left[1-e^{-(2c_H/3)H_I t}\right]$$

- After inflation
  - $c_H < 0$ (negative Hubble mass)
  - Thermal effect due to inflaton decay

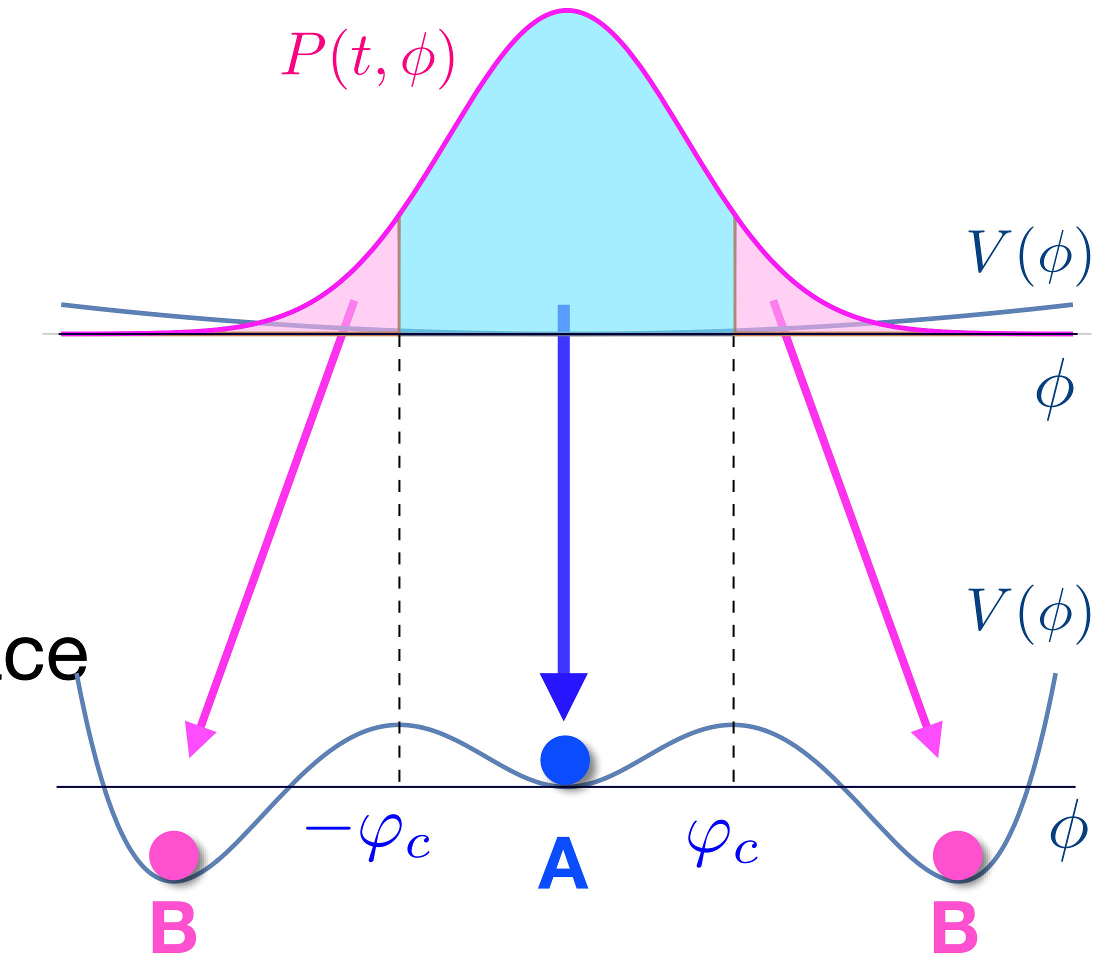
→ multi-vacua

$$\Delta \equiv \frac{T_R^2 M_p}{H_I^3} \gtrsim 1$$



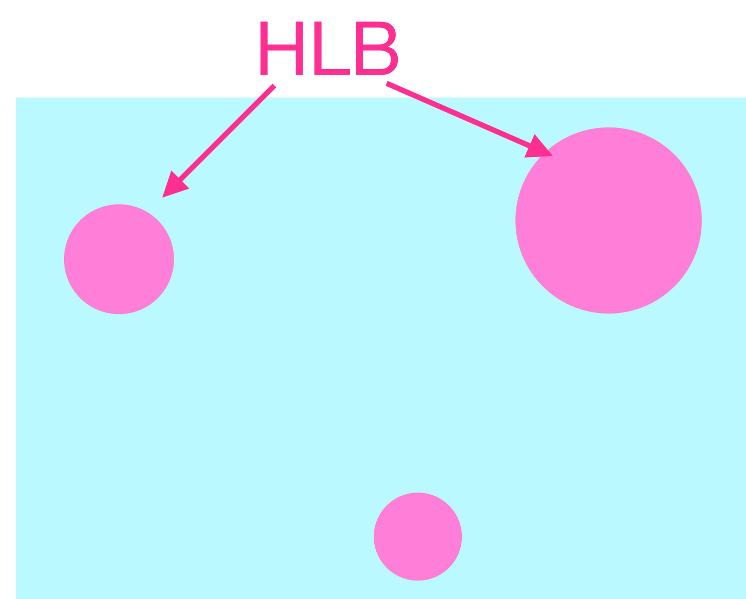


3.1 Inhomogeneous AD mechanism



- Regions with $|\phi| < \varphi_c$ go to A-vacuum
  - no lepton number generation
- Regions with $|\phi| > \varphi_c$ go to B-vacuum
  - lepton number generation takes place (same way as the standard AD)
  - Efficient AD leotogenesis

➡ Formation of high-lepton bubbles (HLBs)



- Oscillation of AD field forms L-balls
  - L-balls decay into neutrinos at $T \sim \mathcal{O}(\text{MeV})$
- Volume fraction of HLBs with size k^{-1}

$$\beta(k) = \frac{d}{dN}\int_{\varphi>\varphi_c} d\varphi\, P(N,\varphi)$$

N : e-fold $\propto \ln k$

3.2 PBH formation in inhomogeneous AD mechanism

- L-balls behaves like matter
  - Density contrast between inside and outside of HLBs

$$\delta \equiv \frac{\rho_{\rm HLB} - \bar{\rho}}{\bar{\rho}} \sim \frac{1}{T}\left(\frac{\rho_Q}{s}\right)_{\rm HLB} \simeq \frac{\omega_Q}{T}\eta_L^{\rm in} \simeq \frac{m_{3/2}}{T}\eta_L^{\rm in}$$

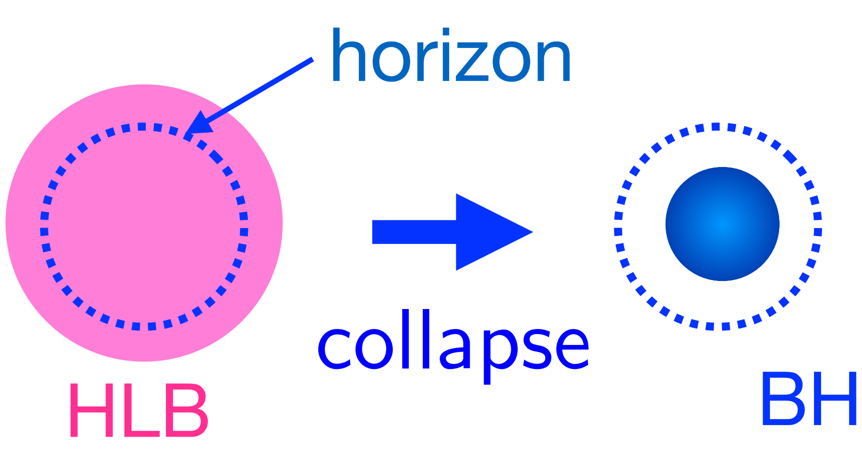
- Density contrast increases as the cosmic temperature decreases

$$\delta \gtrsim \delta_c \simeq 0.4 \quad \text{for} \quad T \lesssim 3\,\text{MeV}\left(\frac{m_{3/2}\eta_L^{\rm in}}{\text{MeV}}\right)$$

→ PBH formation when HLBs reenter the horizon

- PBH mass has a lower cutoff

$$M_c \sim 10^4 M_\odot \left(\frac{m_{3/2}\eta_L^{\rm in}}{\text{MeV}}\right)^{-2}$$



- PBH mass fraction at formation time

$$\beta_{\rm PBH}(M_{\rm PBH}) = \beta(M_{\rm PBH})\theta(M_{\rm PBH} - M_c) \rightarrow f_{\rm PBH} \sim \int d(\ln M)\,\beta_{\rm PBH}(M)\frac{T(M)}{T_{\rm eq}}$$

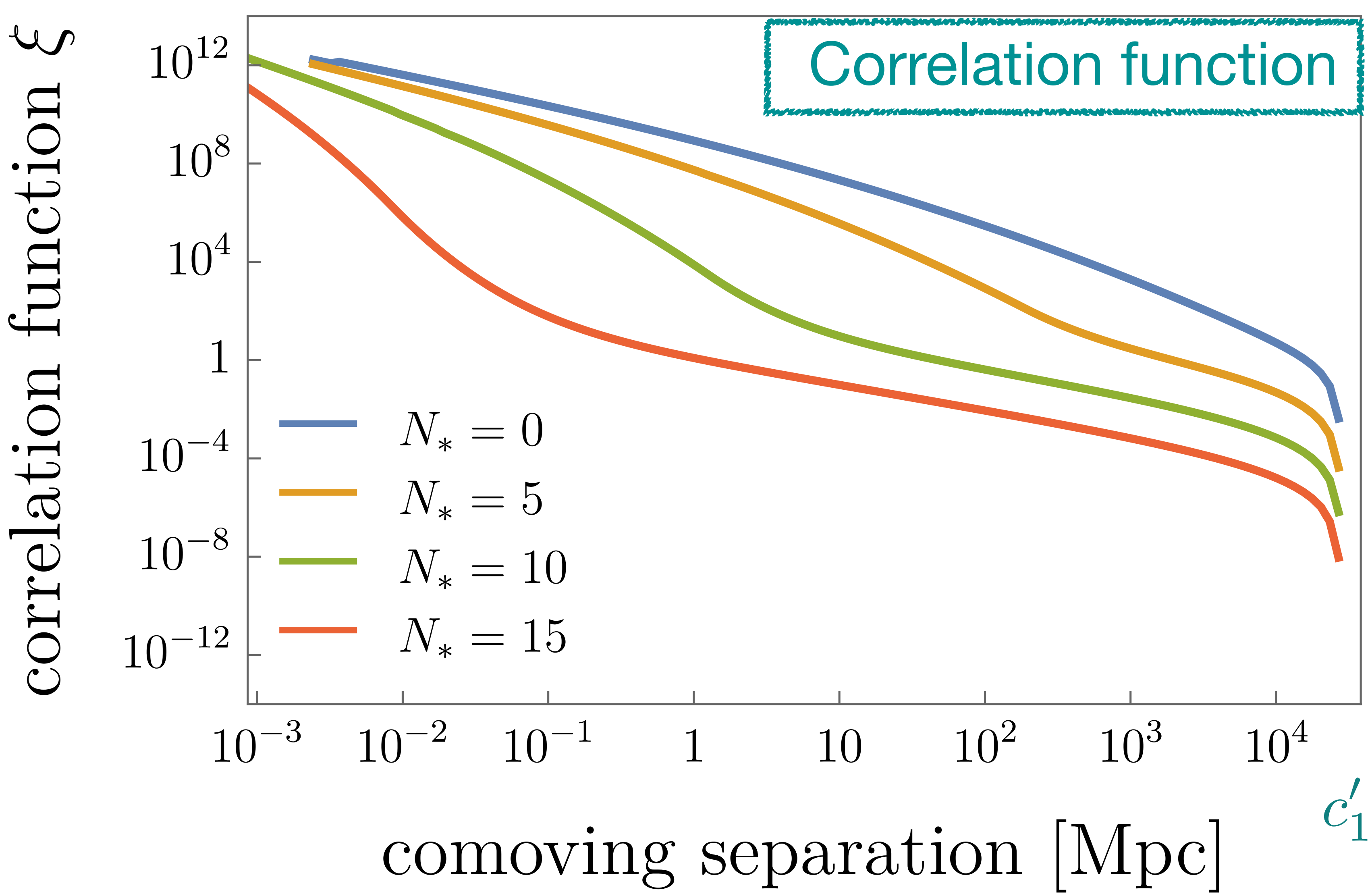
3.3 PBH strong clustering problem

- PBHs from HLBs can account for seeds of Supermassive BHs (SMBHs) avoiding stringent constraints from CMB
- However, Inhomogeneous AD mechanism predicts strong clustering of PBHs MK Murai Nakatsuka arXiv: 2107.03580
- Two observational effects
  - Large isocurvature density fluctuations on CMB scales
  - Large angular correlations of quasars
- In particular, observational data of angular correlation of quasars excludes this scenario Shinohara, Suyama and Takahashi (2021)
- Both effects come from AD field fluctuations at large scales
  - Need to suppress the large-scale fluctuations

3.4 Modified model

MK Murai Neda arXiv:2405.09790

- Hubble induced mass changes during inflation (e.g. double inflation)
  - First stage of inflation ($0 < N < N_*$) c_I : large $= c_1$
  - Second stage ($N_* < N \lesssim 60$) c_I : small $= c_2$ $(c_2' = 2c_1/3 = 0.005)$
- This suppresses PBH clustering at large scales and explain SMBH abundance $f_{\rm PBH} = 3 \times 10^{-9}$

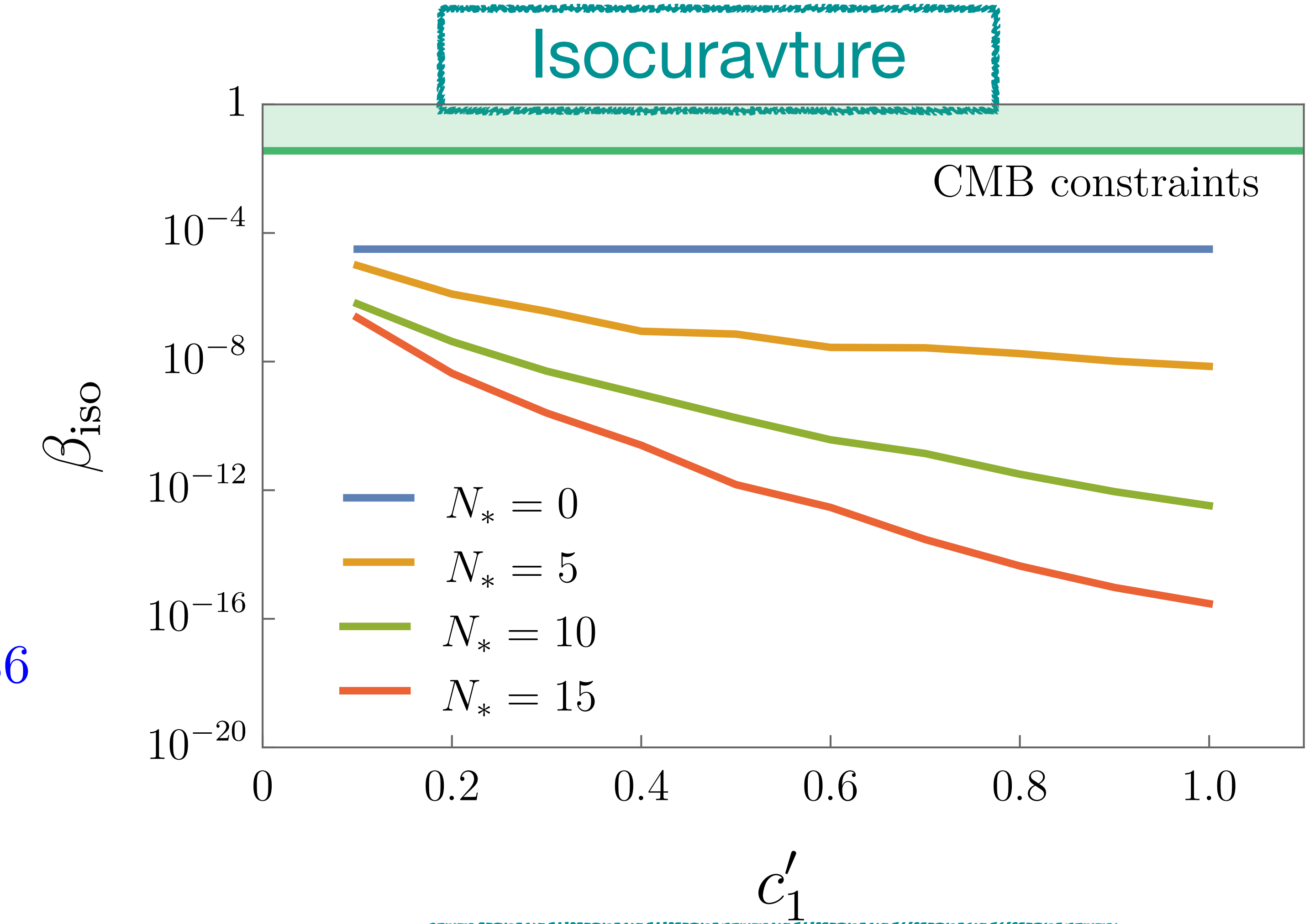


$c_1' = 2c_1/3 = 0.5$

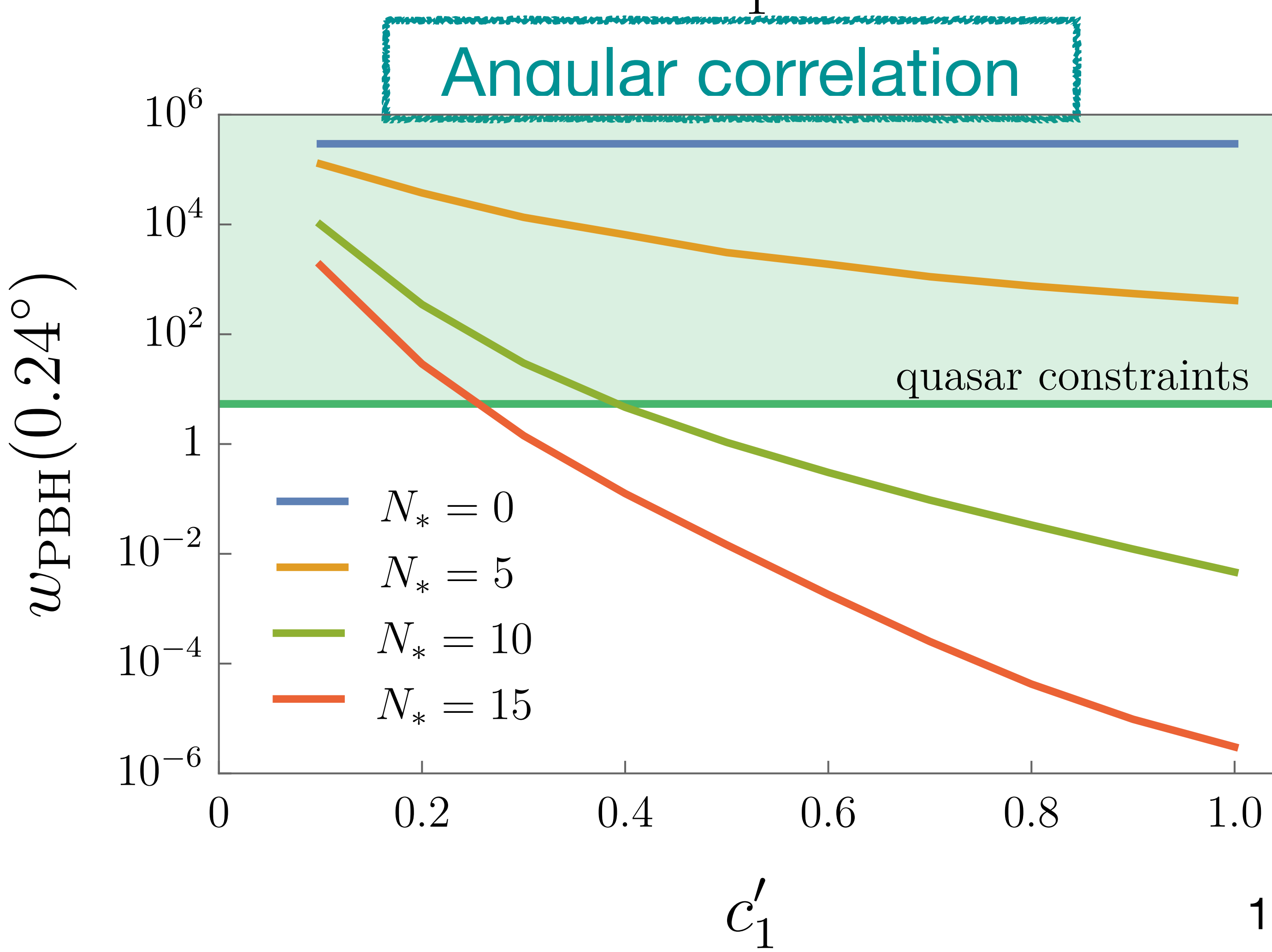
3.4 Modified model

- Isocurvature perturbations are small (even original model satisfies CMB constraint)

$$\beta_{\rm iso} \equiv \frac{\mathcal{P}_{\rm iso}(k_{\rm CMB})}{\mathcal{P}_{\rm iso}(k_{\rm CMB}) + \mathcal{P}_{\mathcal{R}}(k_{\rm CMB})} < 0.036$$



- Angular correlation is small enough for $N_* \gtrsim 10$ and $c_1' \gtrsim 0.4$

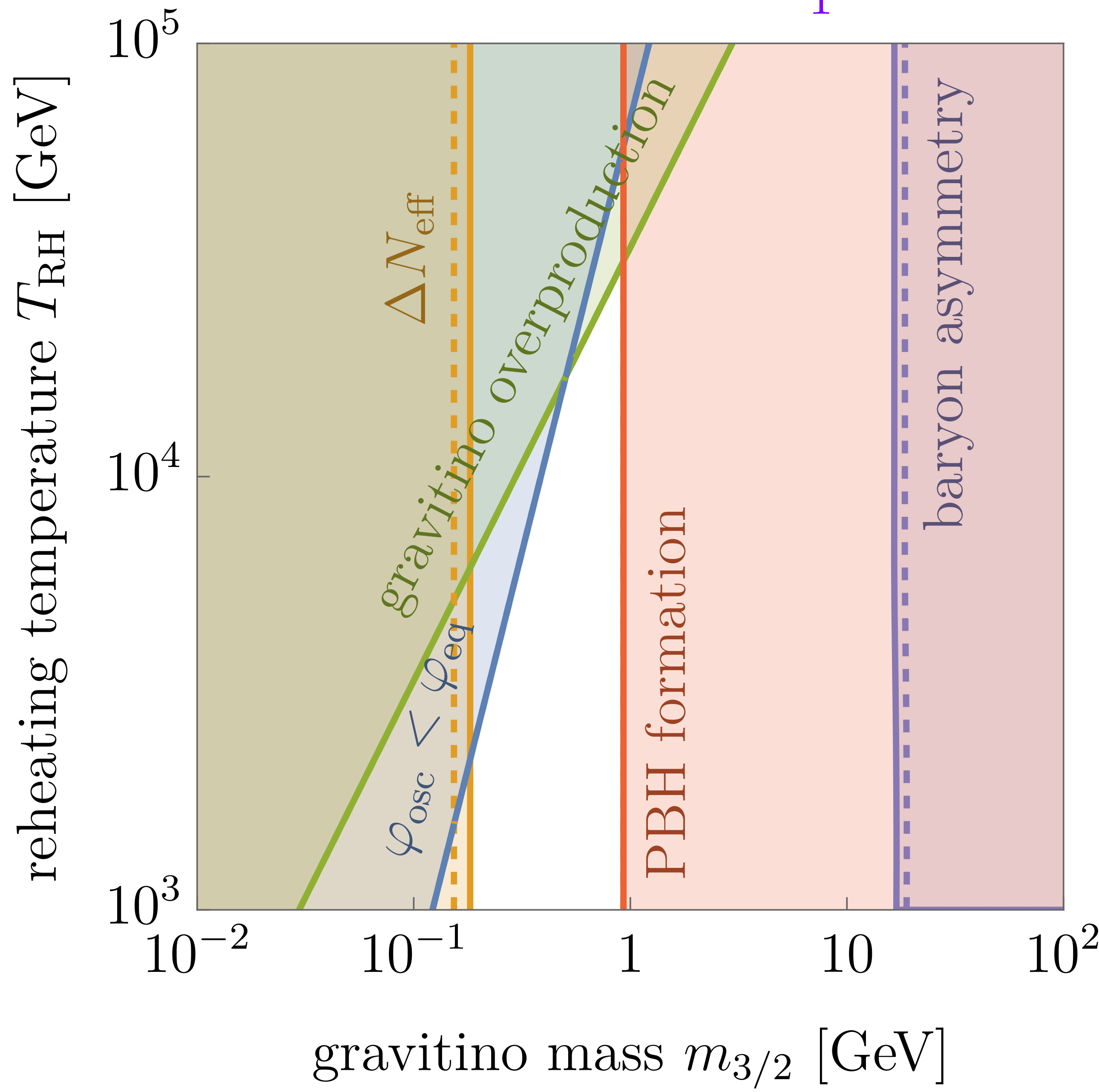


3.4 Modified model

- The model satisfies other constraints for successful PBH formation
  - Decay after PBH formation
  - $\Delta N_{\text{eff}} < 0.24$ $\Leftarrow$ ν from L-balls
  - $\Omega_{3/2} \leq \Omega_{\text{DM}}$ $\Rightarrow$ gravitino DM
  - Oscillation start with $\varphi_{\text{osc}} > \varphi_{\text{eq}}$

$\Rightarrow$ $m_{3/2} \simeq 0.2 - 1$ GeV

$T_R \lesssim 3 \times 10^4$ GeV



- PBHs from HLBs can account for seeds of Supermassive BHs (SMBHs)