PBH Formation from QCD Axion Bubbles as SMBH Seeds

Based on JCAP10(2023)049, arXiv:2310.13333.

Collaboration with K. Kasai, M. Kawasaki, N. Kitajima, K. Murai, and F. Takahashi.

Shunsuke Neda(ICRR, University of Tokyo), Berkeley Week 2024 (Mar. 15, 2024)

To build the model of primordial origin of SMBH which is consistent with observations

Backgrounds

Supermassive Black Hole (SMBH)

- SMBH=$\mathcal{O}(10^6)\ M_\odot$ black holes, which are frequently observed at the center of galaxy.

- Quite large SMBH (e.g. $10^{7-9}\ M_\odot$) is observed at high red shift (e.g. $z \sim 7-10$)

$\longrightarrow$ non-standard BH growth: super-Eddington accretion

or

non-standard BH origin: PBH

Primordial Black Hole (PBH)

- Hypothetical black hole which formed from overdense region in the early universe.

- Lots of motivations: DM, GW source, SMBH seed, etc.

- Formation condition: Their density contrast exceeds some threshold. [B. J. Carr(1975), Harada et. al.(2022)]

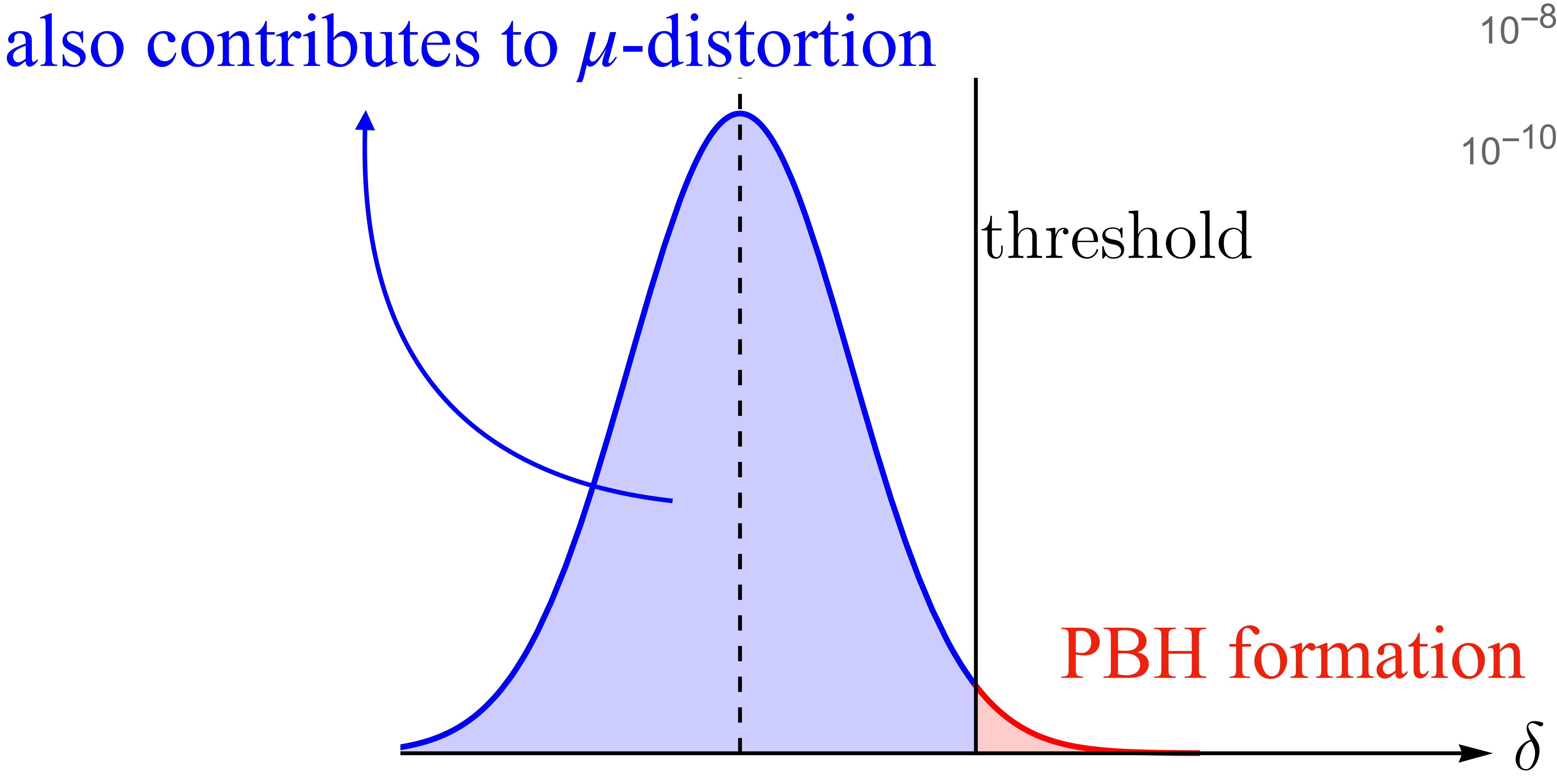
$$\delta = \frac{\rho - \rho_{BG}}{\rho_{BG}} > \mathcal{O}(1)$$

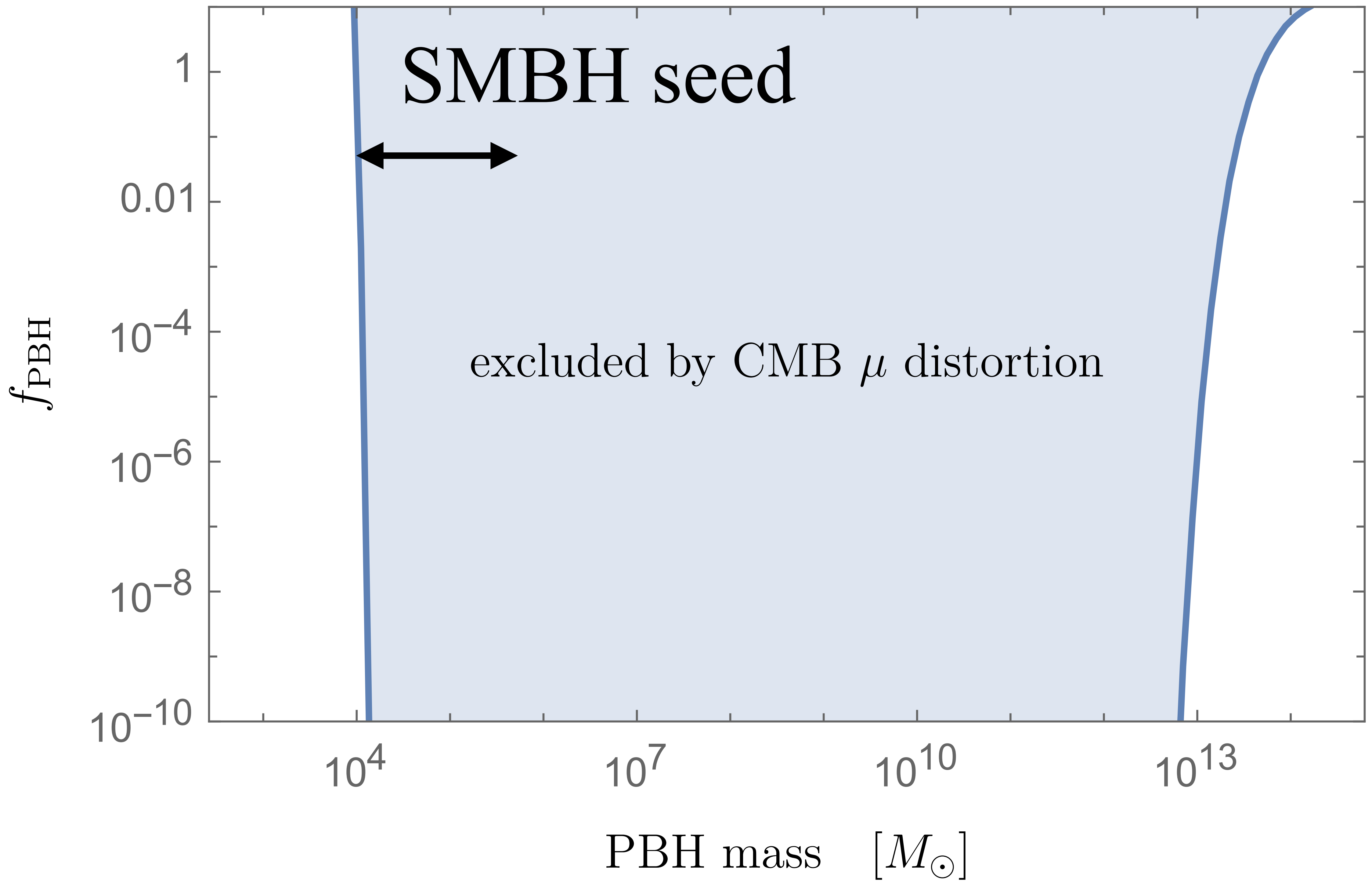
energy density : ρ
BG energy density : ρ_{BG}

Constraints on PBH

- Simplest model: PBH formation from inflationary density fluctuations

→ Gaussian density perturbation





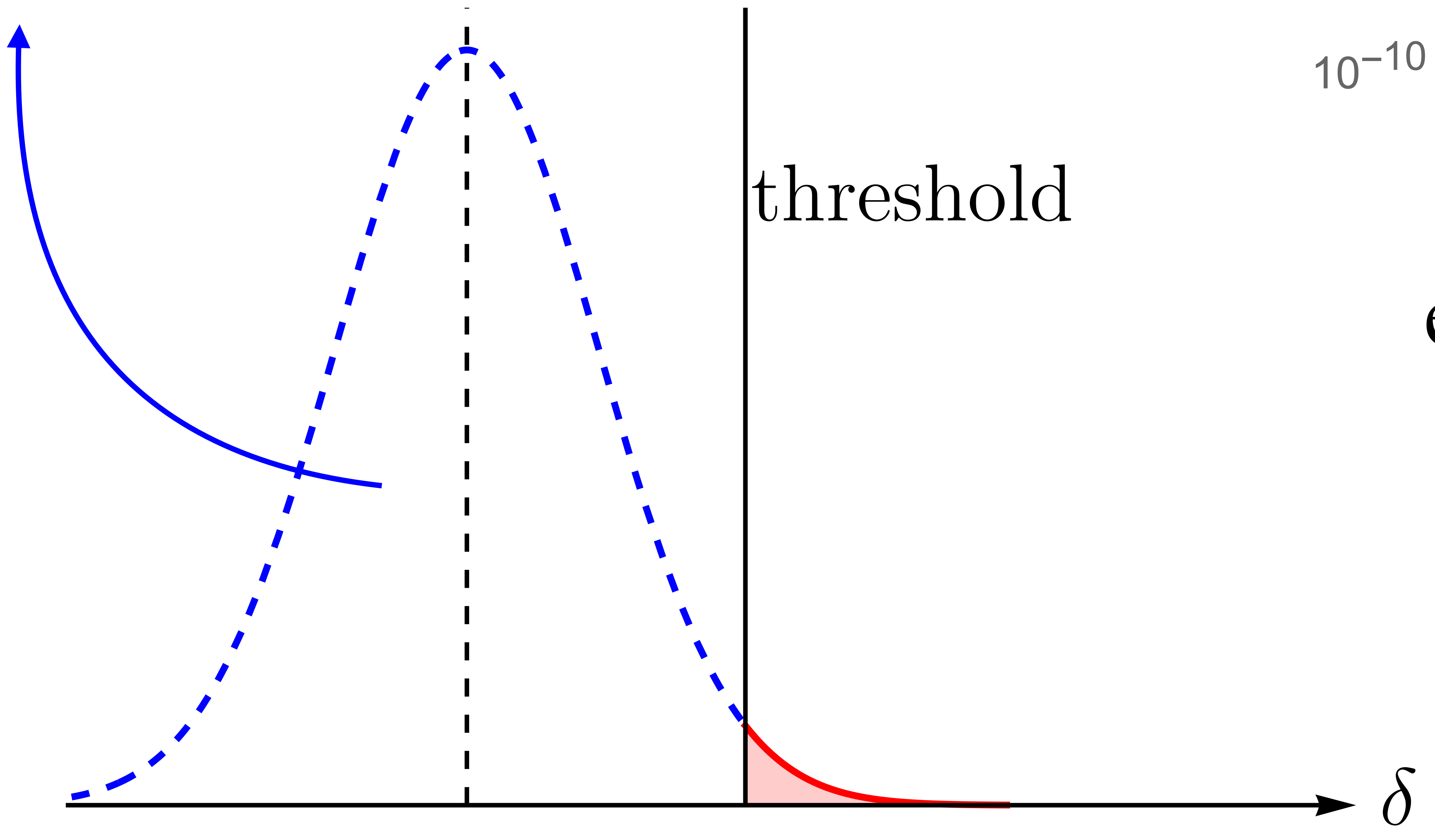
extracted from Carr et. al.(2020)

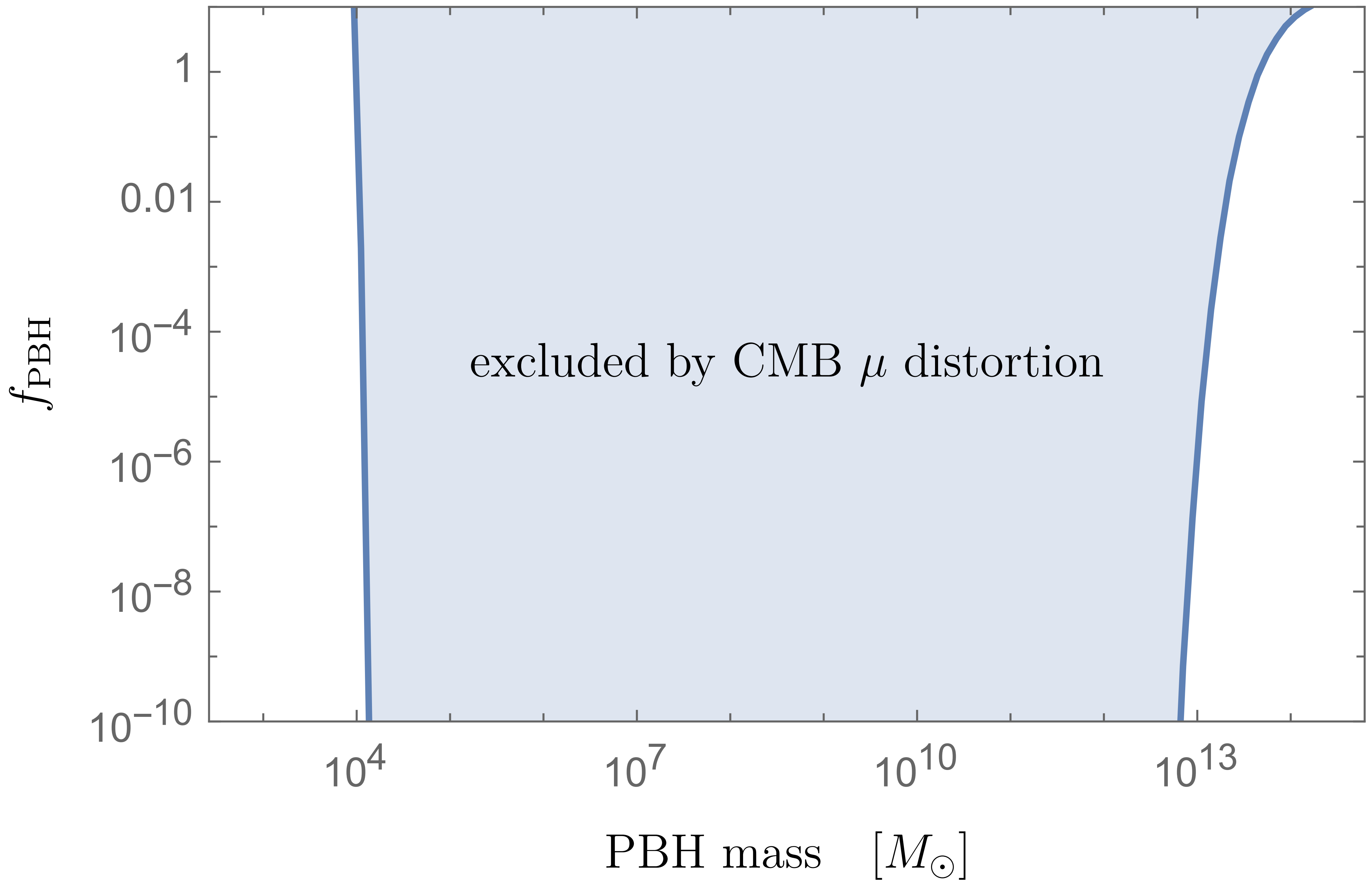
Constraints on PBH

- PBH formation to explain SMBH seeds

  $\longrightarrow$ non-Gaussian density perturbation

no contribution to μ-distortion



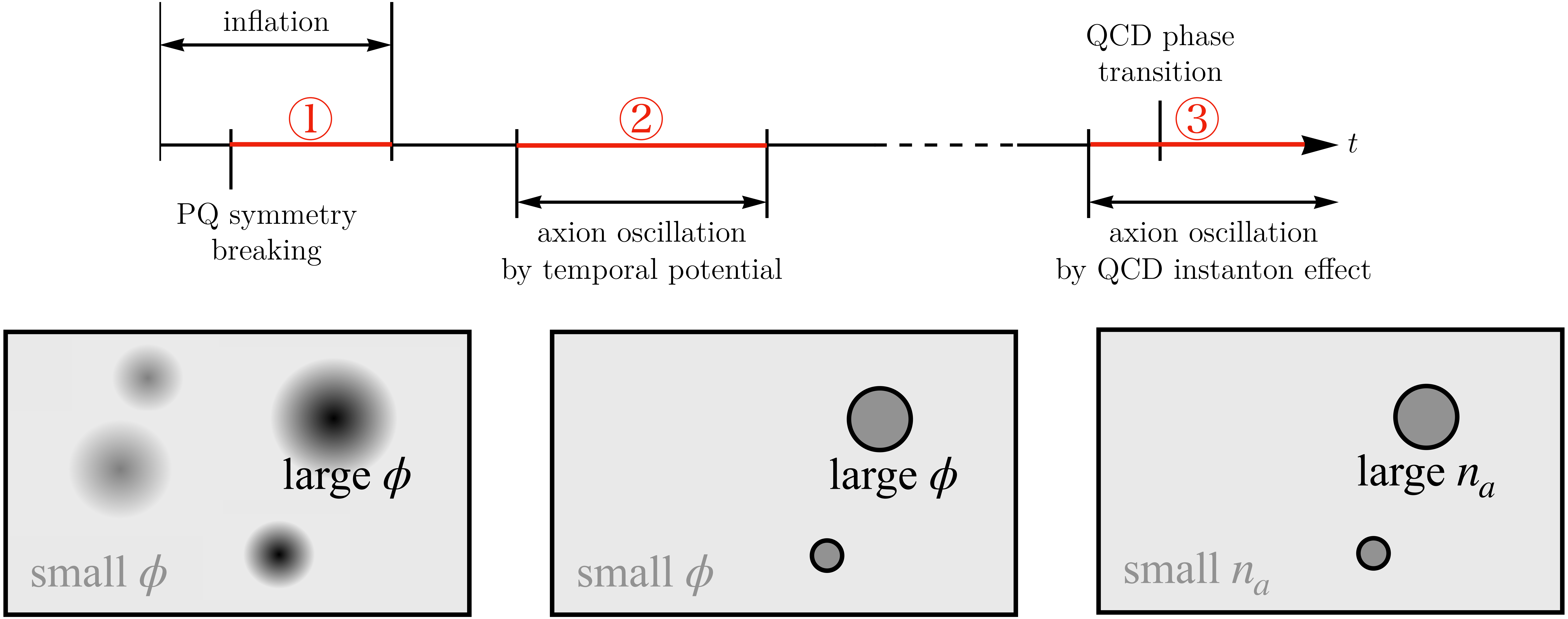


extracted from Carr et. Al.(2020)

Overview of the Model

PBH Formation from QCD Axion Bubbles

Previous study[N. Kitajima & F. Takahashi(2020)]



inflation

①

PQ symmetry breaking

②

axion oscillation by temporal potential

QCD phase transition

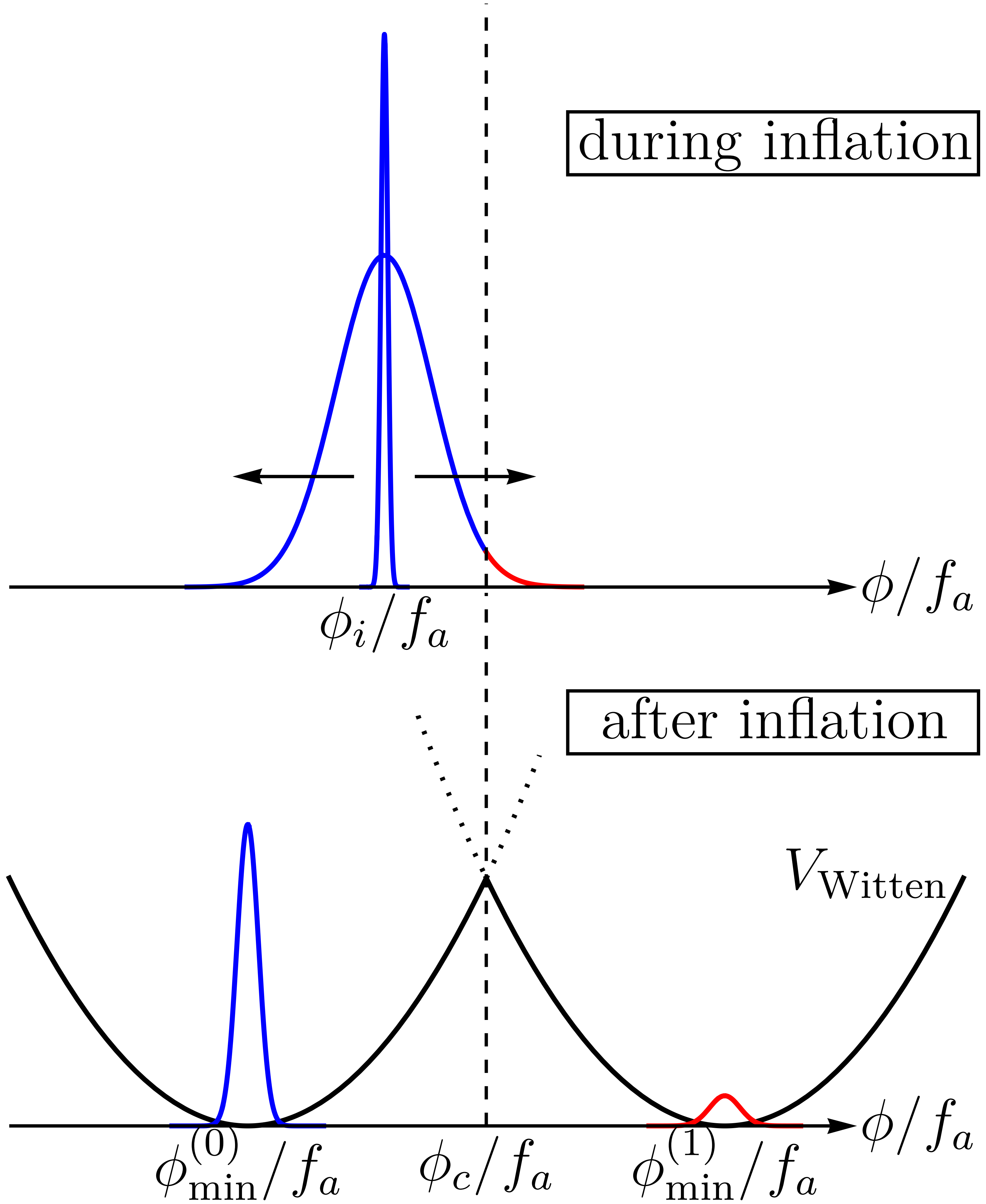
③

t

axion oscillation by QCD instanton effect

PBH Formation from QCD Axion Bubbles

Previous study[N. Kitajima & F. Takahashi(2020)]



homogeneous   Rare

① During inflation, axion field acquires quantum fluctuations as a spectator field.

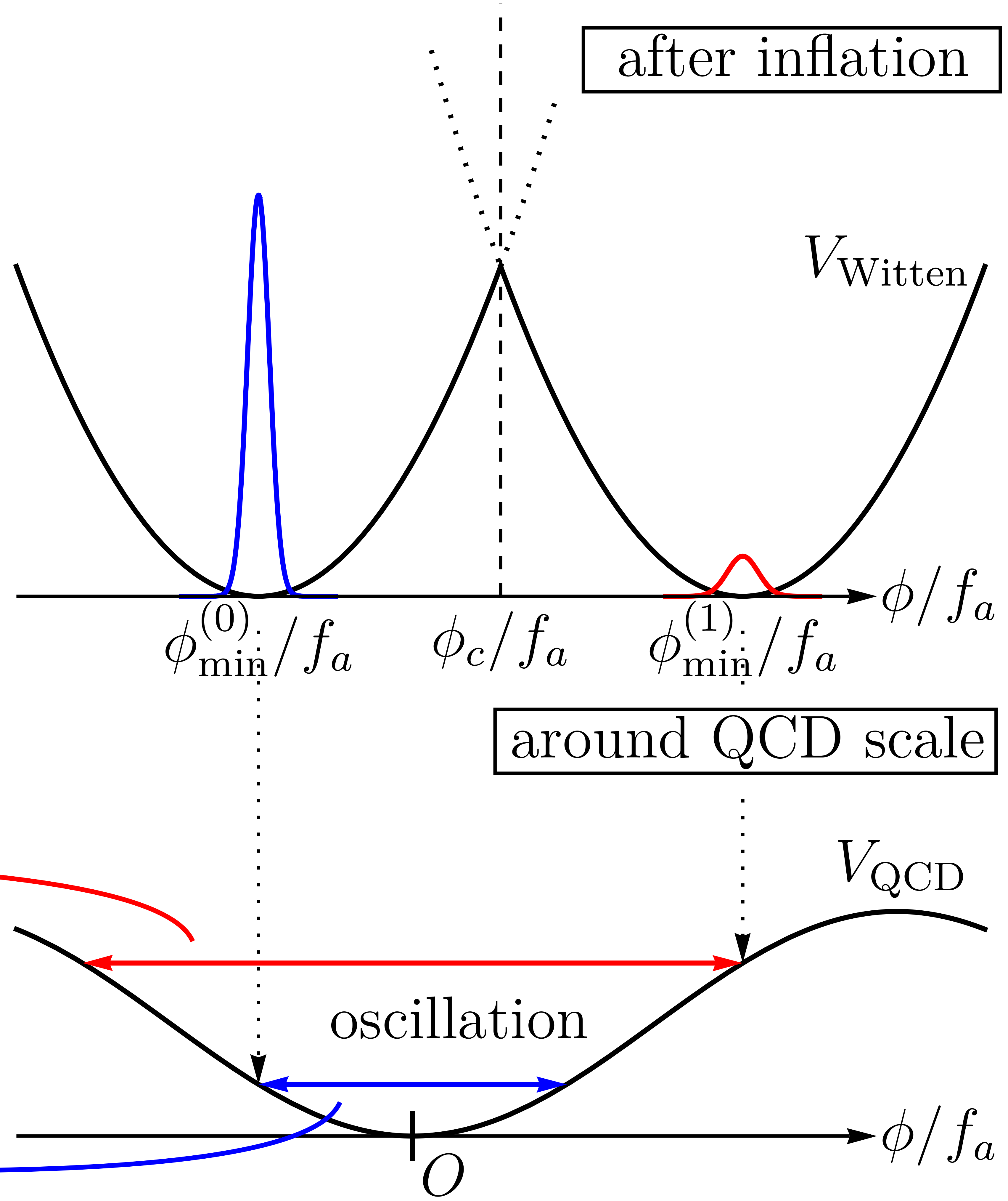
② Axion acquires a temporal potential and starts oscillation.

⟶ field value settles down to minima

PBH Formation from QCD Axion Bubbles

③ Around the QCD phase transition, axion acquires its mass thanks to the non-perturbative QCD effect.

$$V_{\rm QCD}(\phi) = m_a^2(T)\, f_a^2 \left(1 - \cos\frac{\phi}{f_a}\right)$$



overdense & rare

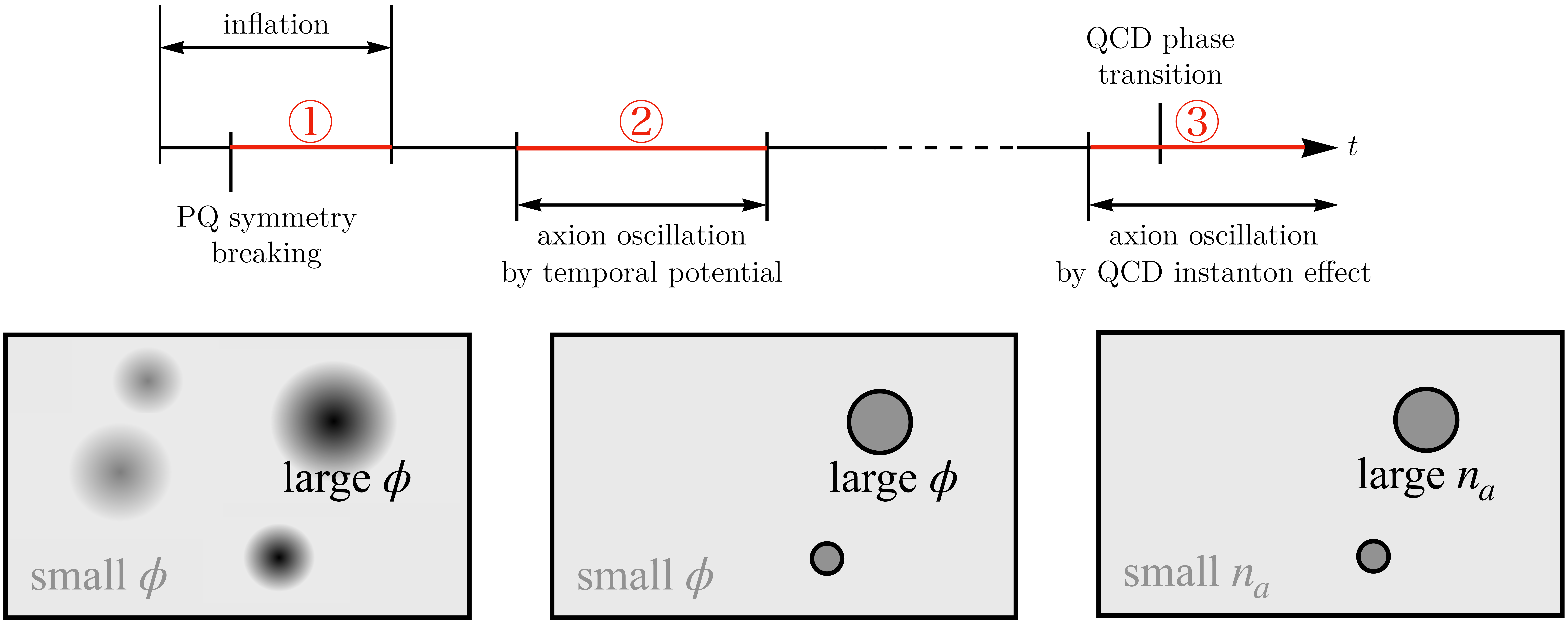
→ axion bubble

background & homogeneous

→ dark matter

PBH Formation from QCD Axion Bubbles

Previous study[N. Kitajima & F. Takahashi(2020)]



inflation

①

②

QCD phase transition

③

t

PQ symmetry breaking

axion oscillation by temporal potential

axion oscillation by QCD instanton effect

Details of the model

Dark Matter(DM) Abundance

Previous study[N. Kitajima & F. Takahashi(2020)]

- Axion oscillation starts

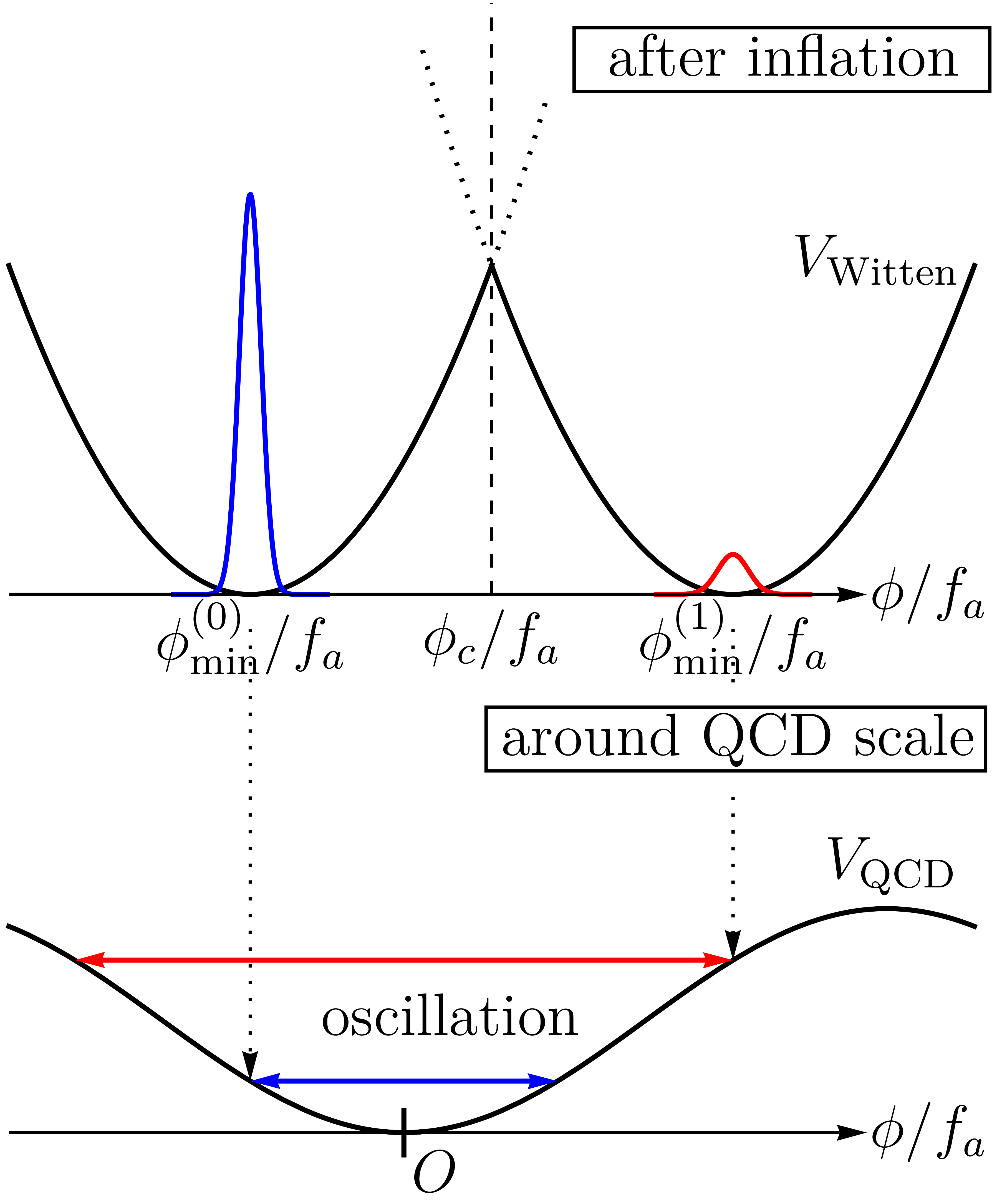
$$m_a(T_{\rm osc}) = 3H(T_{\rm osc})$$

- Axion number density.

$$n_a(T_{\rm osc}) \simeq \frac{1}{2} m_a(T_{\rm osc})\ \phi_{\rm osc}^2$$

- To account for the DM abundance, we set,

$$\frac{\phi_{\rm min}^{(0)}}{f_a} = 4.25 \times 10^{-3} \left(\frac{g_{\rm osc}}{60}\right)^{0.21} \left(\frac{f_a}{10^{16}{\rm GeV}}\right)^{-0.58}$$



Threshold for PBH Formation

Previous study[N. Kitajima & F. Takahashi(2020)]

- PBH formation condition

$$\mathcal{O}(1) < \delta \simeq \frac{\rho_a}{\rho_{BG}} \propto a$$

axion density: $\rho_a \propto a^{-3}$
BG radiation density: $\rho_{BG} \propto a^{-4}$

- $\rho_a > \rho_{BG}$ inside axion bubble at

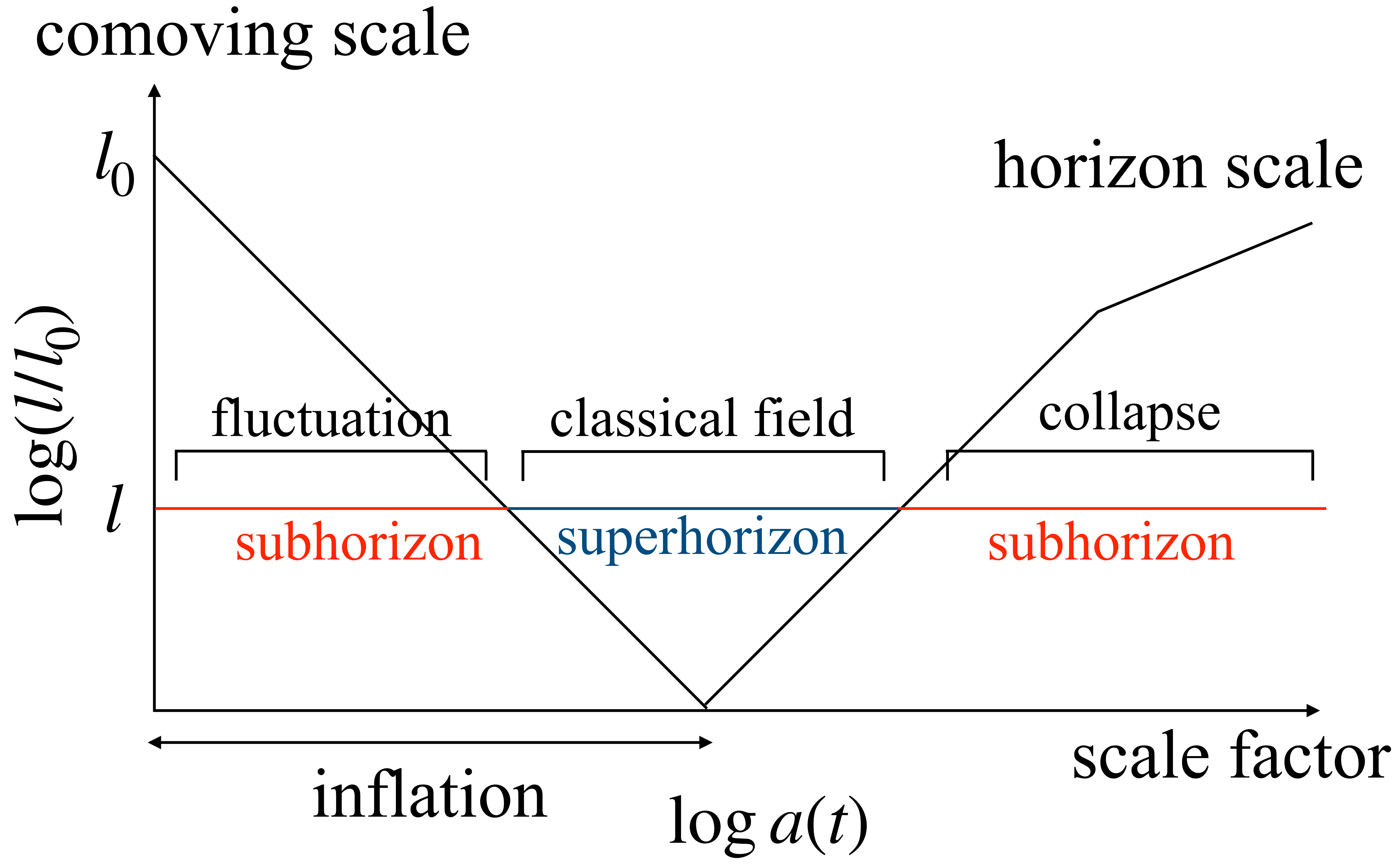
$$T_{\mathrm{B}} = \frac{4}{3} m_a \frac{n_a}{s}\bigg|_{\text{bubble}}$$

- The lower bound on the PBH mass

$$M_c \simeq 1.68 \times 10^4 M_\odot \left(\frac{f_a}{10^{16}\ \text{GeV}}\right)^{-2.33}$$

PBH Formation

- Gravitational interactions start after the horizon re-entering.



⟶ PBH formation

⇒ at horizon re-entering

⟶ Fluctuations at the horizon exit

⇒ density fluctuations

time of horizon exit ⟷ scale of perturbation

Volume Fraction of Axion Bubbles

Previous study[N. Kitajima & F. Takahashi(2020)]

- Axion field value at the horizon exit

  ⟶ Axion bubble formation

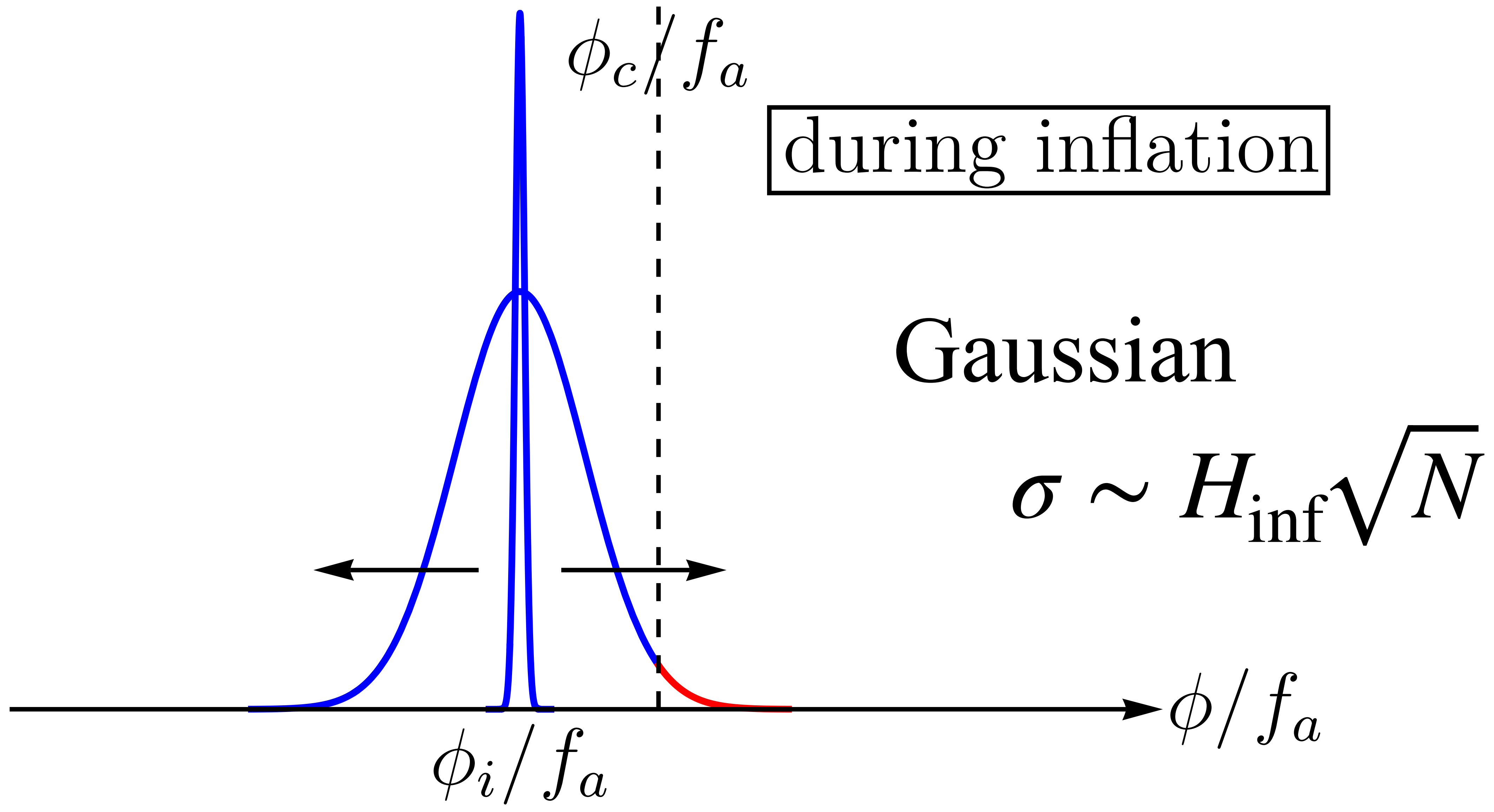
- Probability distribution for the coarse-grained axion field, $P(N, \phi)$.

$$\frac{\partial P(N,\phi)}{\partial N} = \frac{H_{\mathrm{inf}}^2}{8\pi^2}\frac{\partial^2 P(N,\phi)}{\partial \phi^2}$$

$$P(N=0,\phi;\phi_i) = \delta(\phi - \phi_i)$$

- Volume fraction of axion bubbles

$$\beta(\phi_i) = \int_{\phi_c}^{\infty} P(N_{\mathrm{end}}, \phi; \phi_i)\mathrm{d}\phi$$



Gaussian

$$\sigma \sim H_{\mathrm{inf}}\sqrt{N}$$

Abundance of PBHs

Previous study[N. Kitajima & F. Takahashi(2020)]

- Axion decay constant f_a

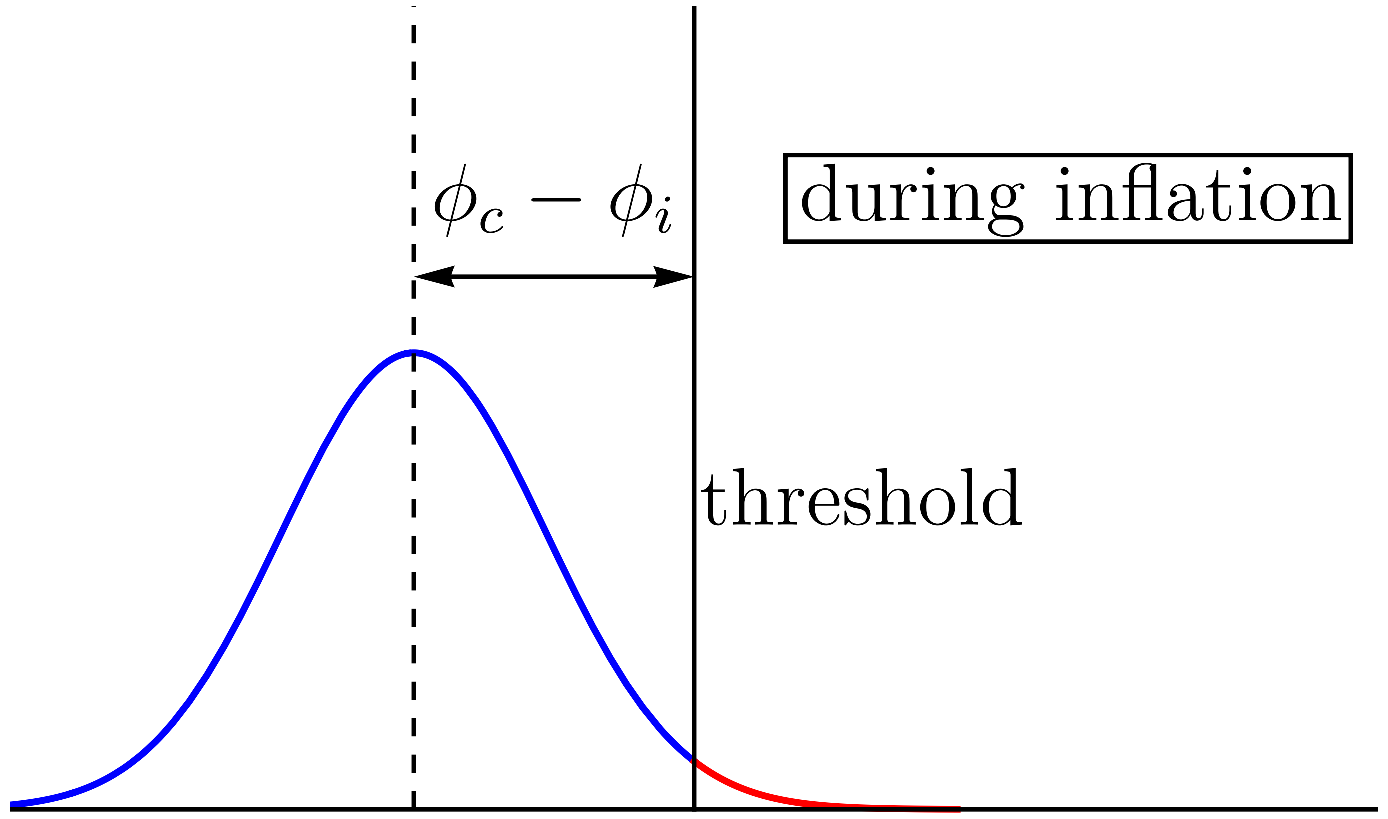
  → PBH mass range

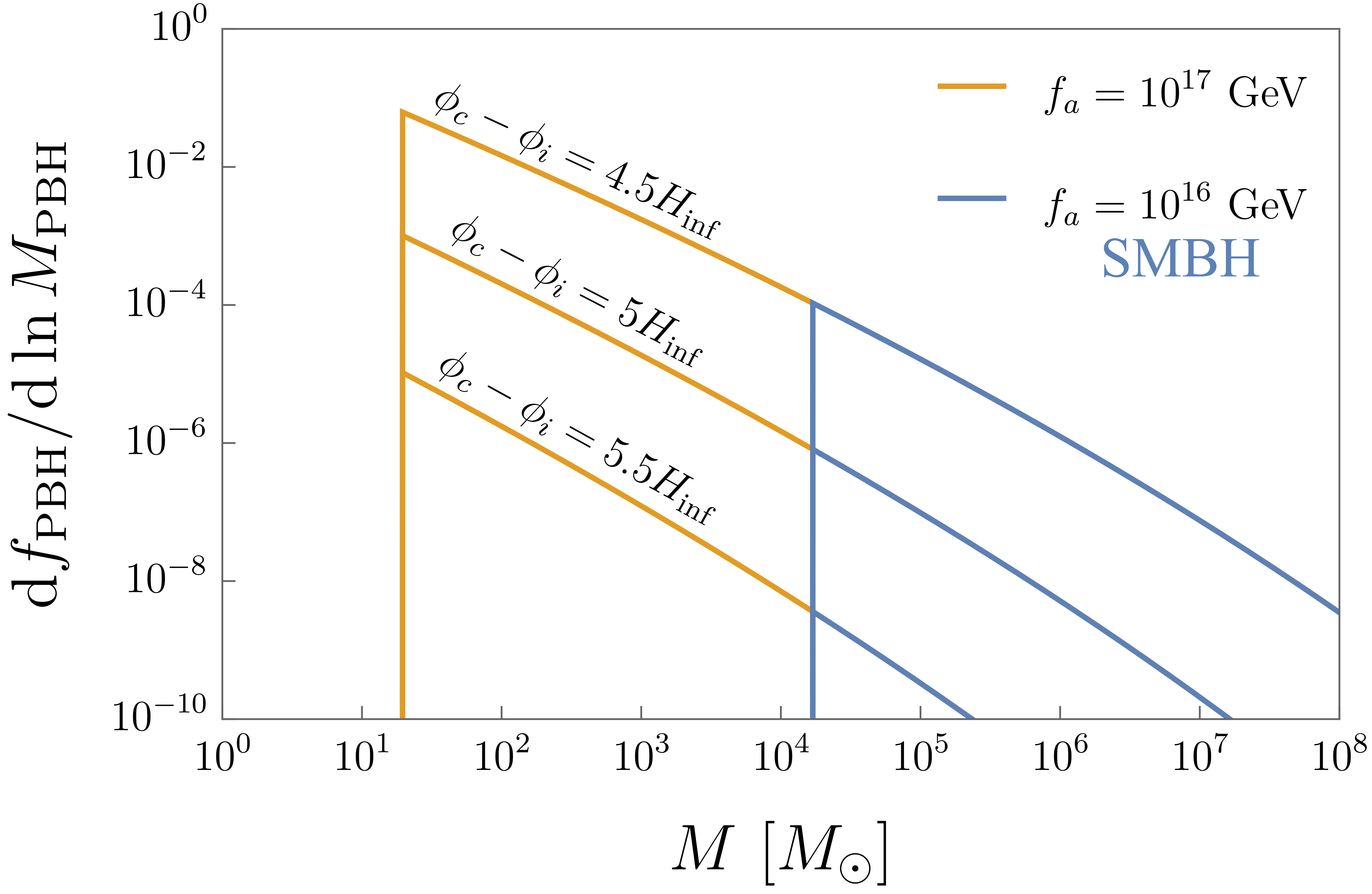
- PBH model for SMBH seed

  ↔ $f_a = 10^{16}$ GeV

- Mass spectrum with a peak

  → monochromatic mass approximation





Abundance of AMCs

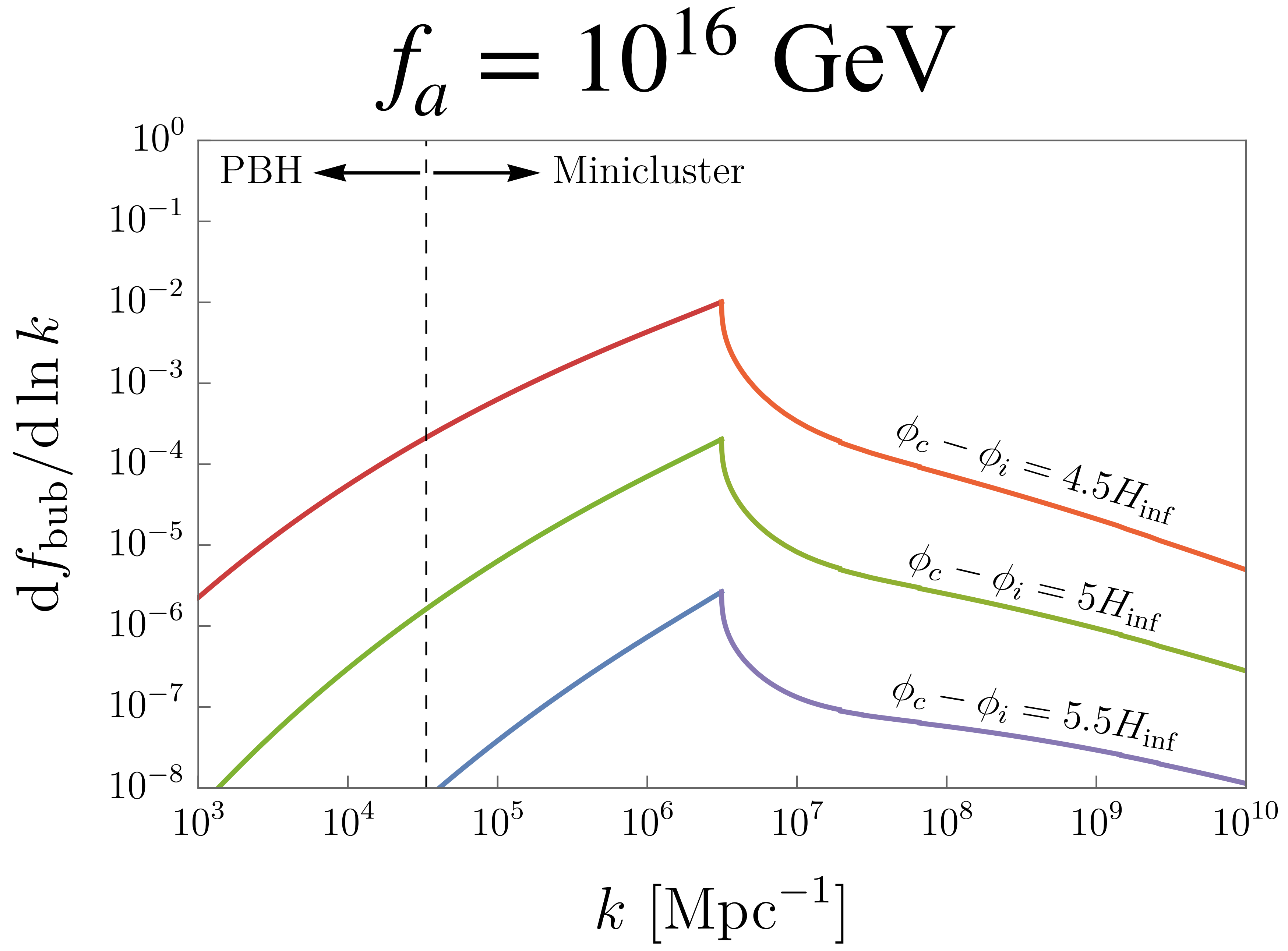
Previous study[N. Kitajima & F. Takahashi(2020)]

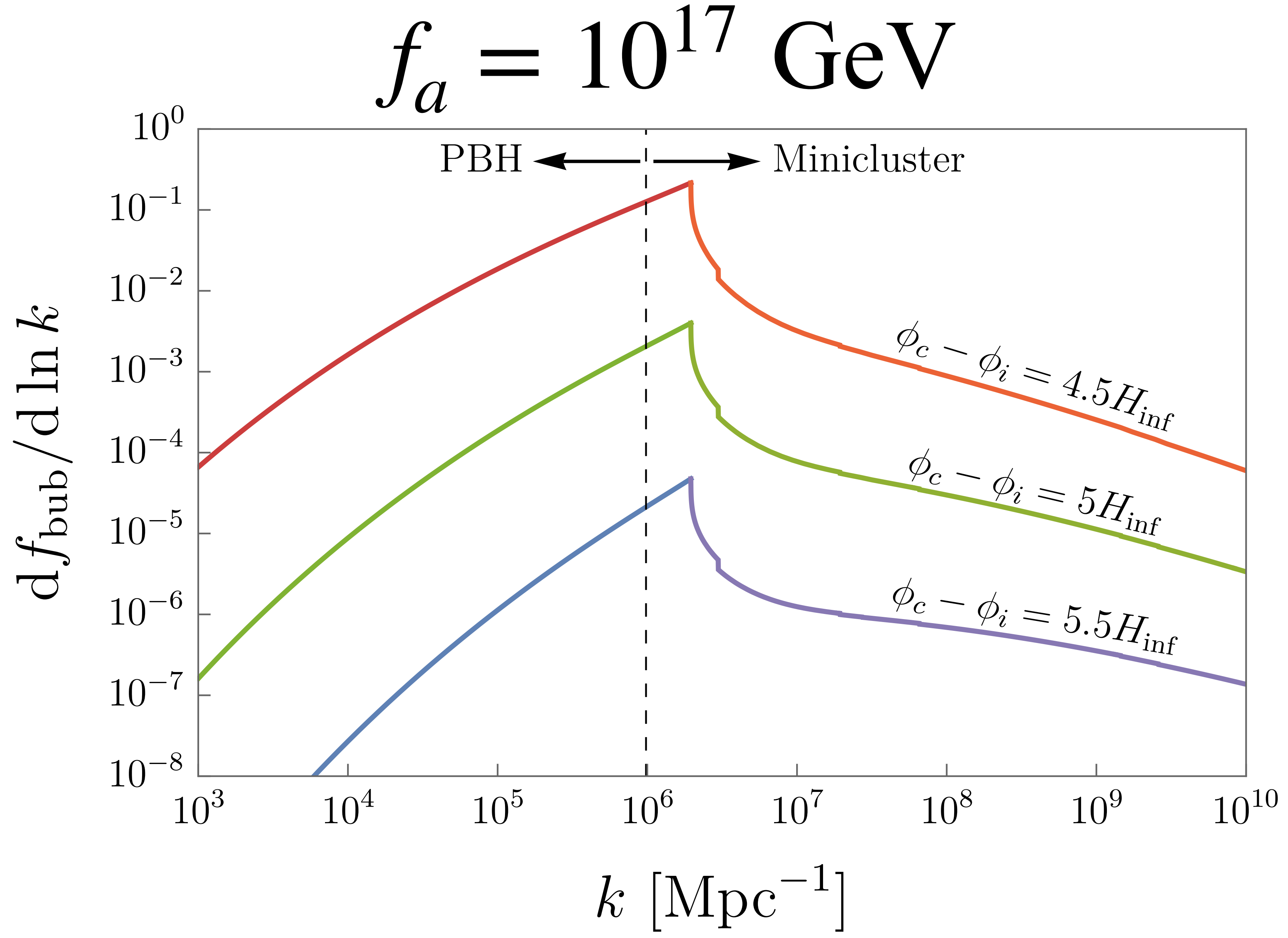
- In this model, small bubbles form axion-dense region, called axion minicluster(AMC).
- AMC fraction to dark matter is,

$$\frac{\mathrm{d}f_{\mathrm{AMC}}}{\mathrm{d}\ln k} = \frac{1}{\rho_{\mathrm{DM}}}\frac{\mathrm{d}\rho_{\mathrm{AMC}}(k)}{\mathrm{d}\ln k}$$

- Spectrum with a peak

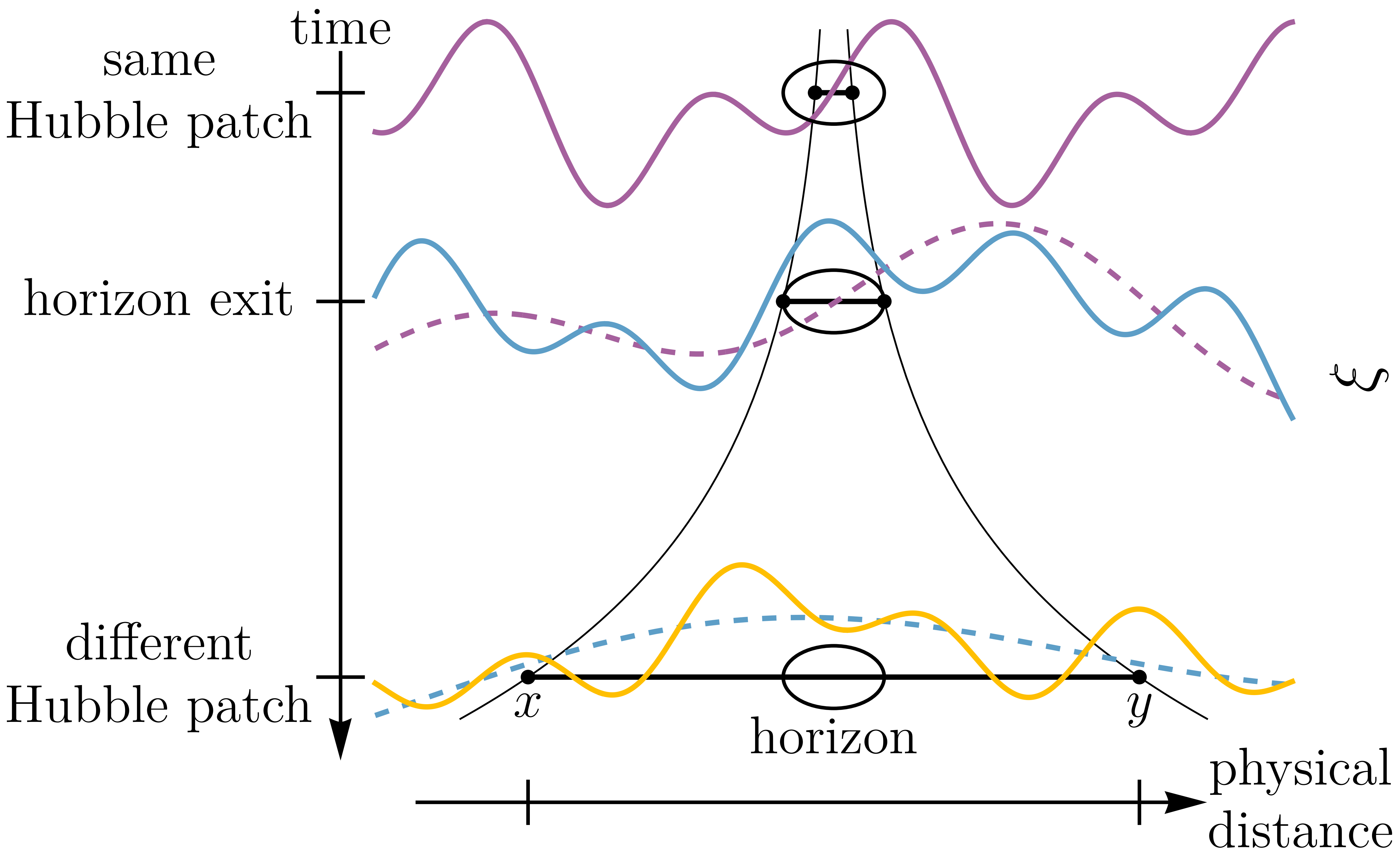
$\longrightarrow$ monochromatic mass approximation

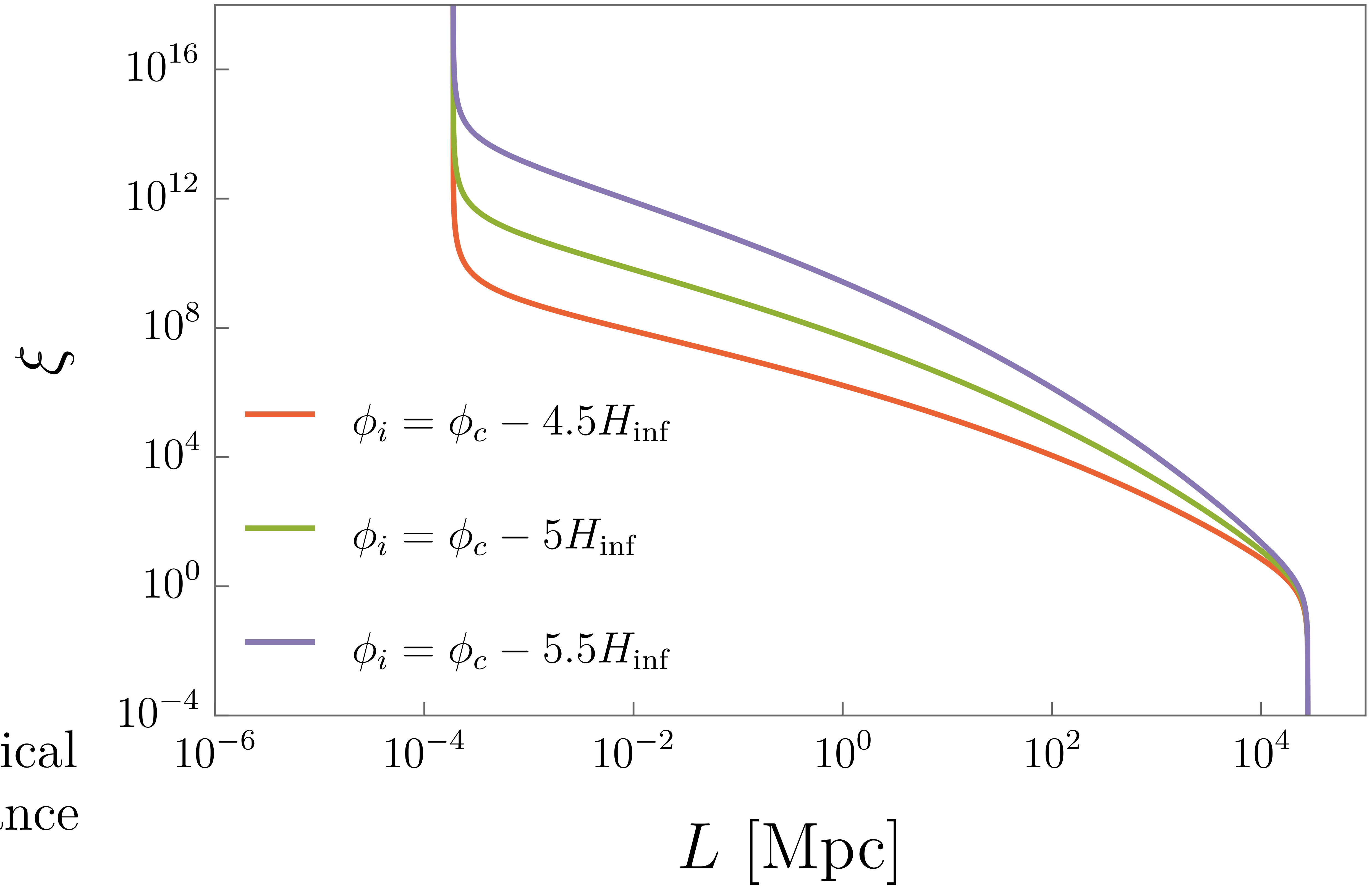




Two-point Correlations of PBHs and AMCs

Our work[JCAP10(2023)049]





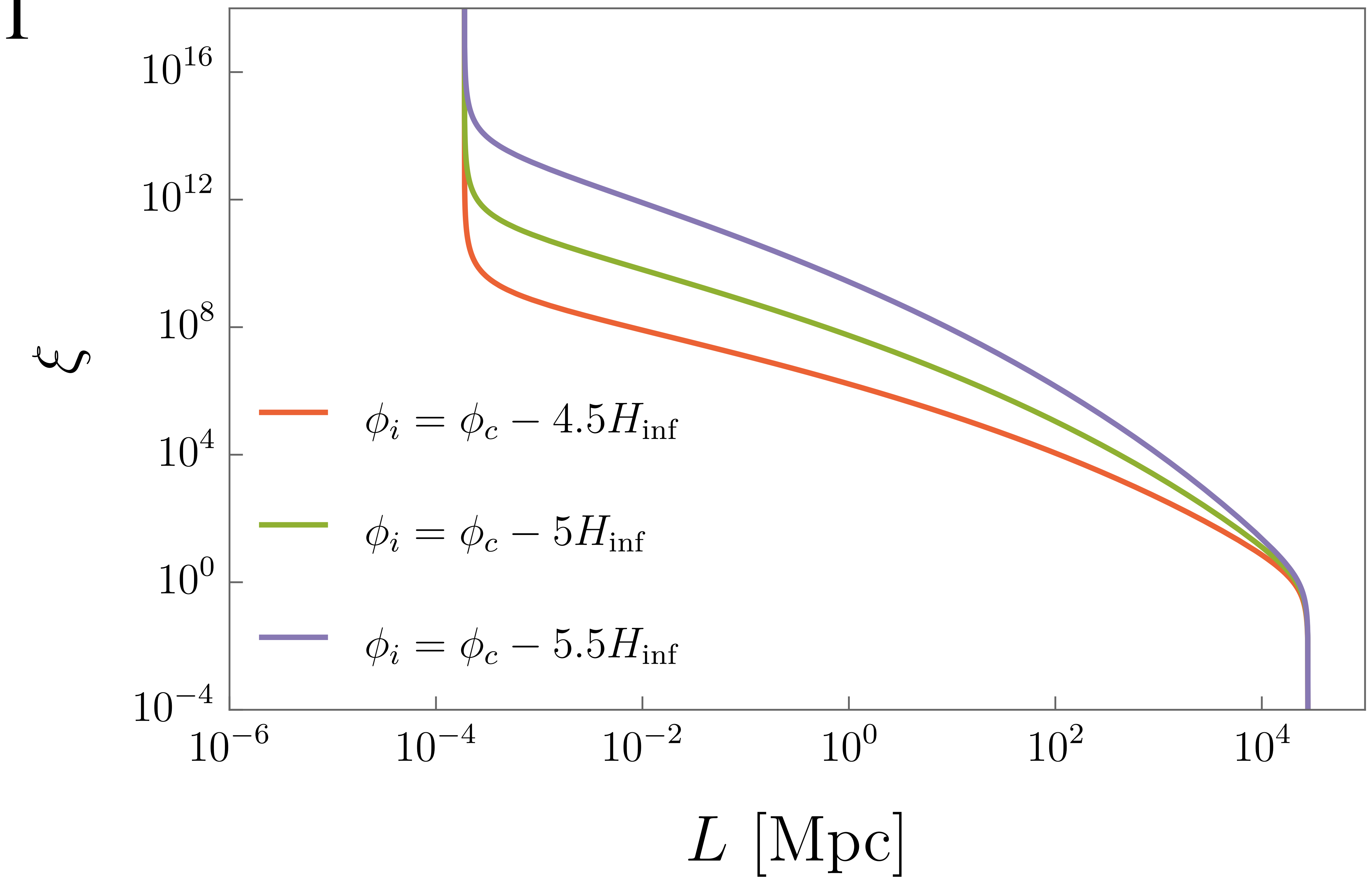
Two-point Correlations of PBHs and AMCs

Following previous study[M. Kawasaki, et.al.(2021)]

- Correlation function (i and j specify a PBH)

$$\xi(\mathbf{x}) = \sum_{i\neq j} \frac{M_i M_j}{\rho_{\rm PBH}^2} \left\langle \delta^{(3)}(\mathbf{x}-\mathbf{x}_i)\delta^{(3)}(-\mathbf{x}_j) \right\rangle - 1$$

comes from $\left\langle \delta_{\rm PBH}(0)\delta_{\rm PBH}(\mathbf{x}) \right\rangle$

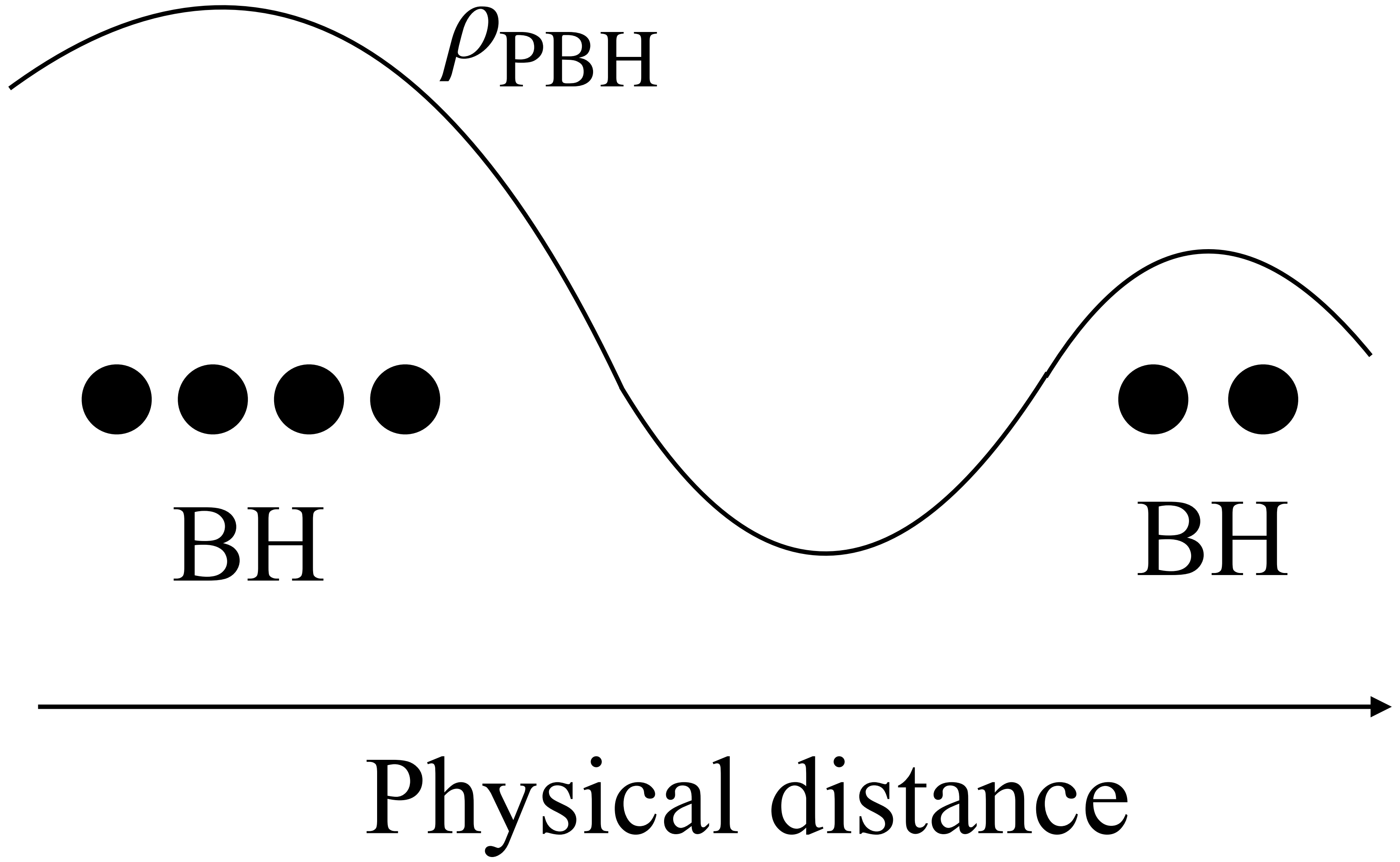


Isocurvature Perturbations

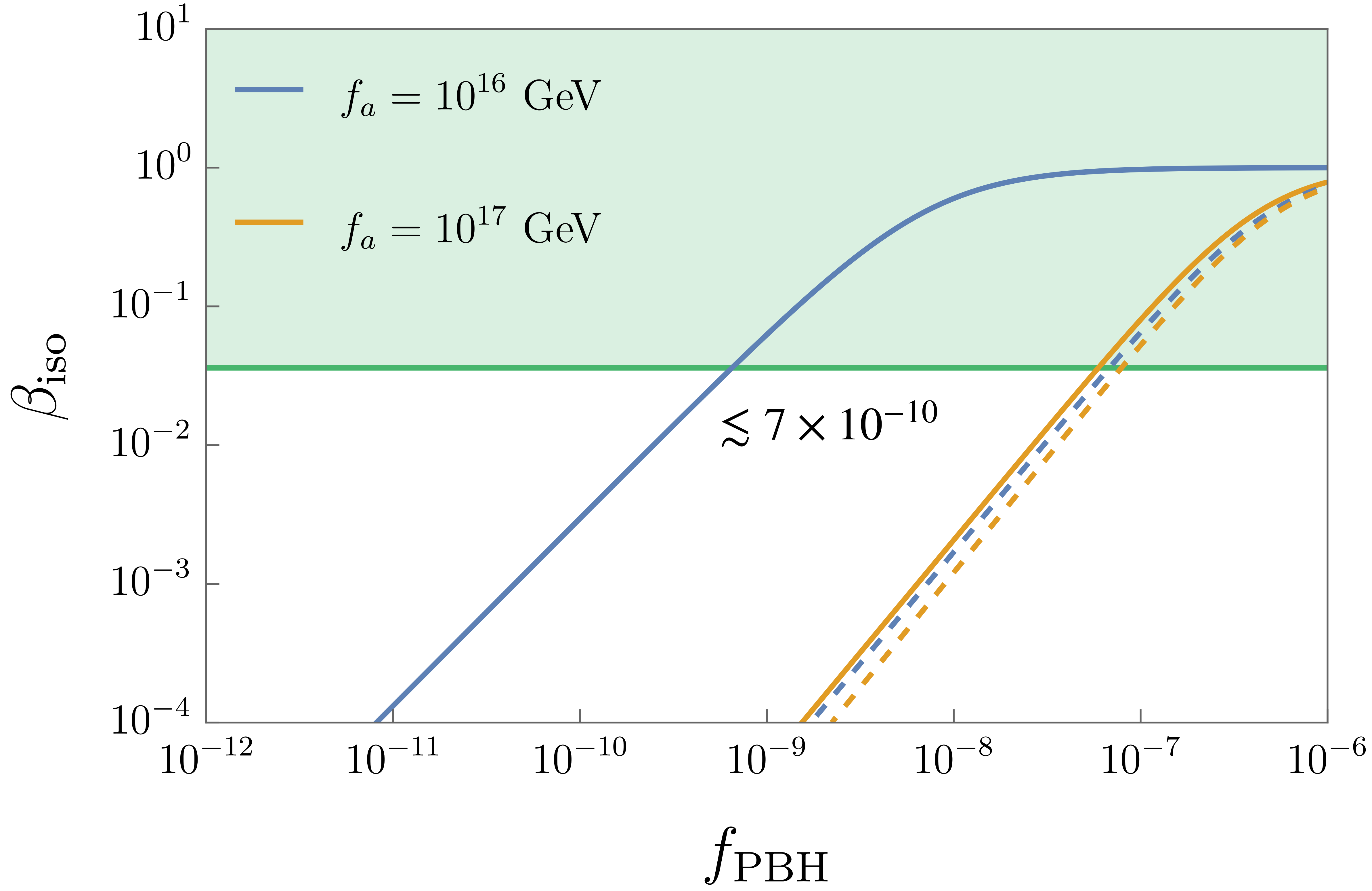
Our work[JCAP10(2023)049]

- PBH clustering

$\longrightarrow$ Isocurvature perturbation



- CMB constraint on isocurvature perturbation



$f_{\mathrm{SMBH}}^{(\mathrm{obs})} \sim 3 \times 10^{-9}$ [C. J. Willott et. al.(2010)]

Angular Correlation Functions of SMBH

Previous study[T. Shinohara et.al. (2023)]

- New observational constraint: Angular correlation function of SMBH.

- Much larger angular correlation than the observational upper limit.

$$w(0.24^\circ) \sim 10^{6-7} \gg w^{(\mathrm{obs})}_{\mathrm{upper}}(0.24) = 5.37$$

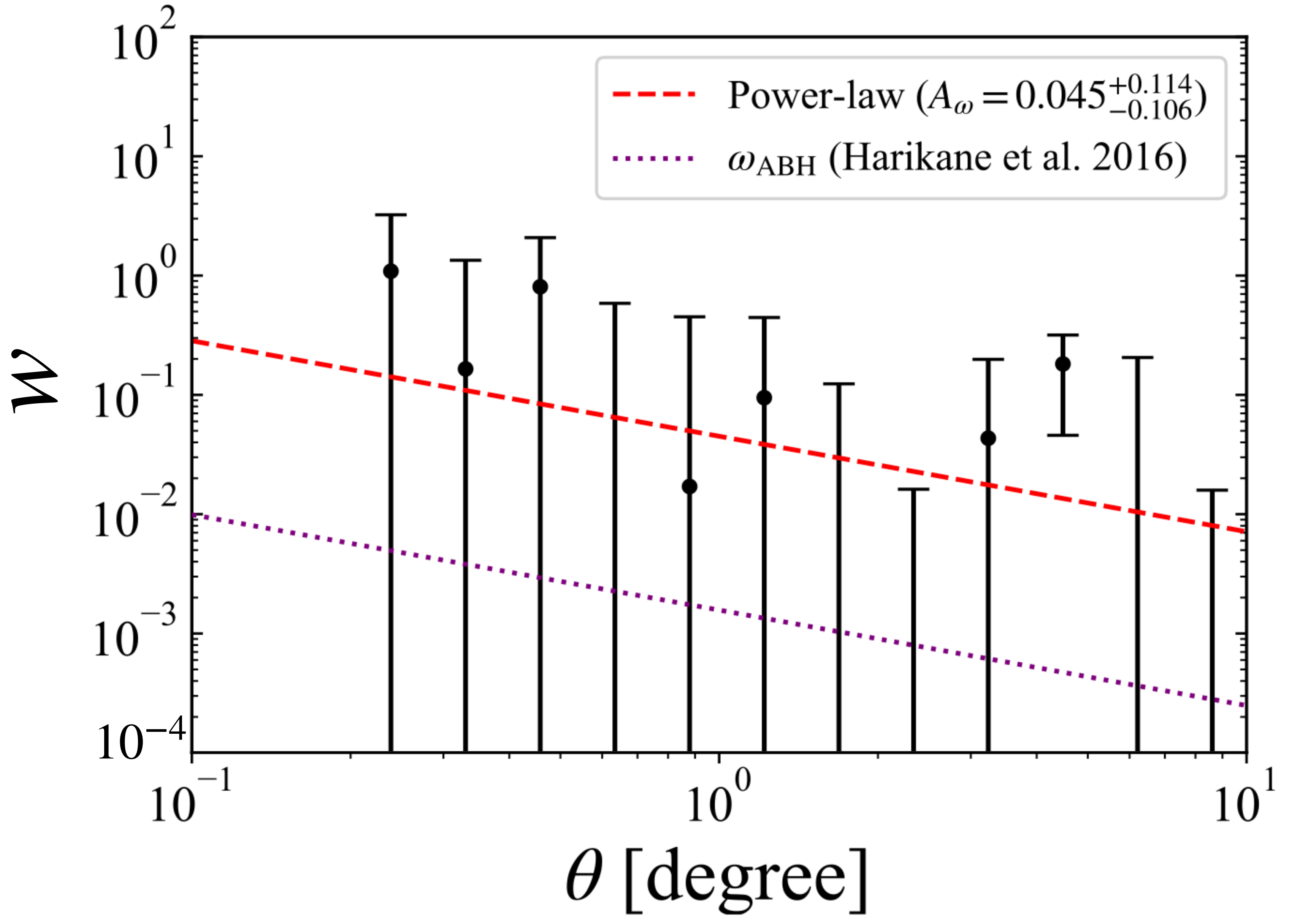
- The angular correlation function

$$w(x) = \left\langle \Delta_{\mathrm{PBH}}(0{,}0)\Delta_{\mathrm{PBH}}(\theta,\varphi) \right\rangle$$

where

$$\Delta_{\mathrm{PBH}} = \text{fluctuation of 2D number density}$$

$$\mathbf{x} = (r,\theta,\varphi)$$



Cite: Shinohara et.al. (2023)

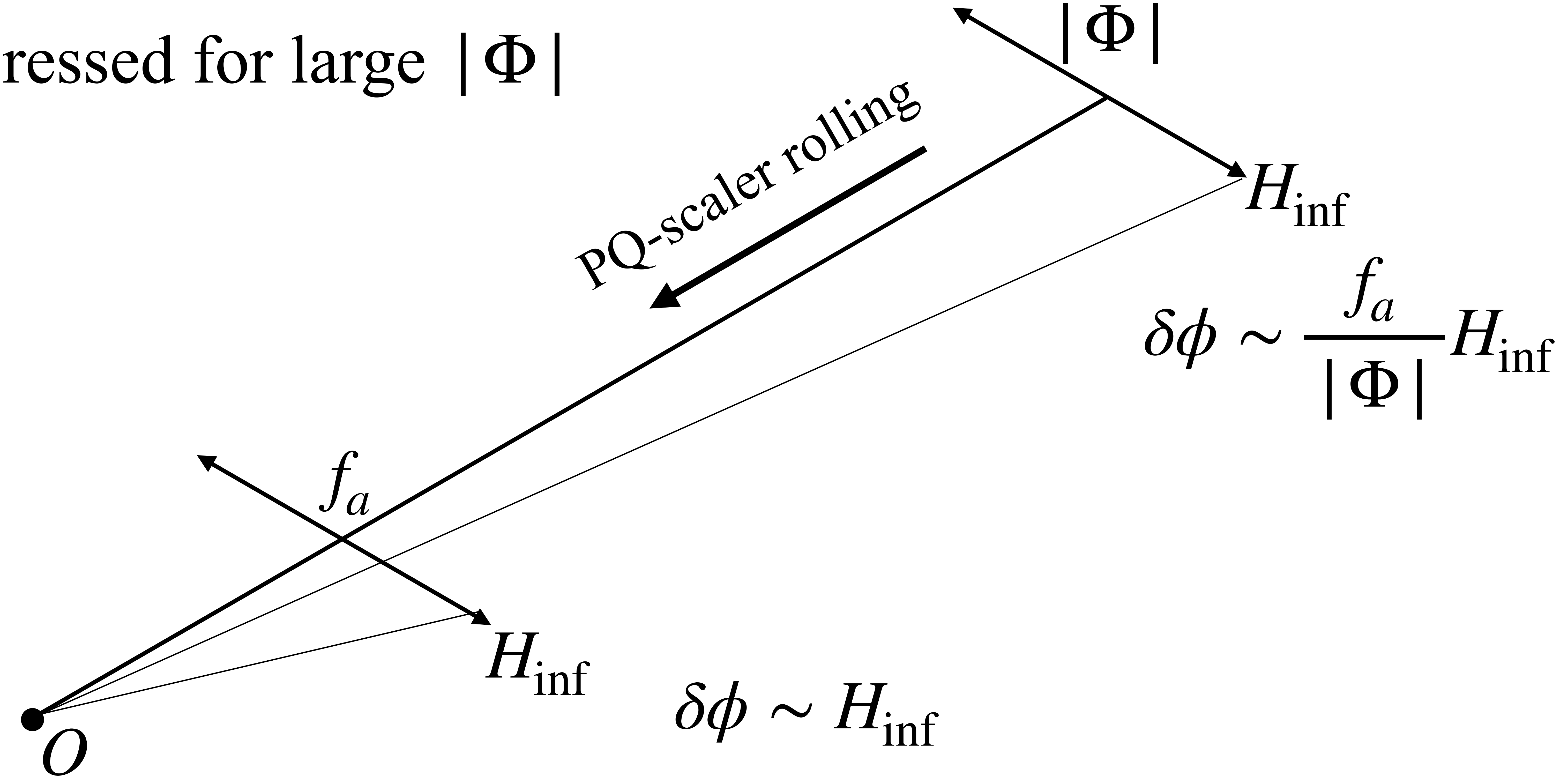
Suppression of Isocurvature Perturbation

Our work[arXiv:2310.13333]

- Idea: PQ-scalar rolling in the early stage of inflation

$$\Phi = |\Phi| e^{i\frac{\phi}{f_a}}$$

- Axion fluctuation is suppressed for large $|\Phi|$



Modified Model

Our work[arXiv:2310.13333]

- Assumption:

PQ-scalar potential at $|\Phi| \gtrsim f_a$

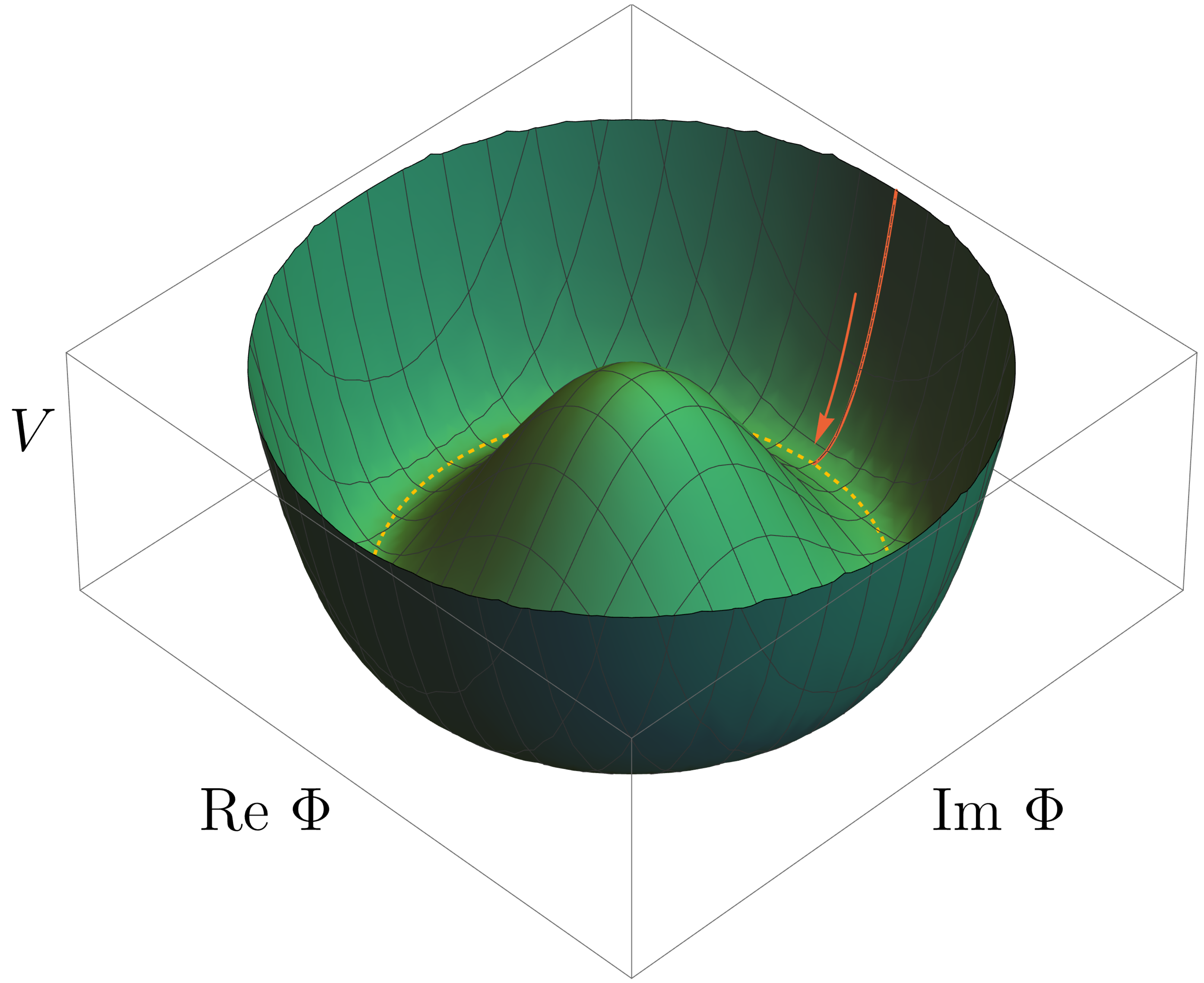
$\simeq$ the Hubble-induced mass term

$$V(|\Phi|) \simeq \frac{1}{2} c_I H_{\rm inf}^2 |\Phi|^2, \quad c_I = \mathcal{O}(1)$$

$$\xrightarrow{\text{EOM}} \quad |\Phi| = |\Phi_*| e^{-\lambda H_{\rm inf}(t - t_*)},$$

$$\lambda = \frac{3}{2}\left(1 \pm \sqrt{1 - \frac{4}{9} c_I}\right),$$

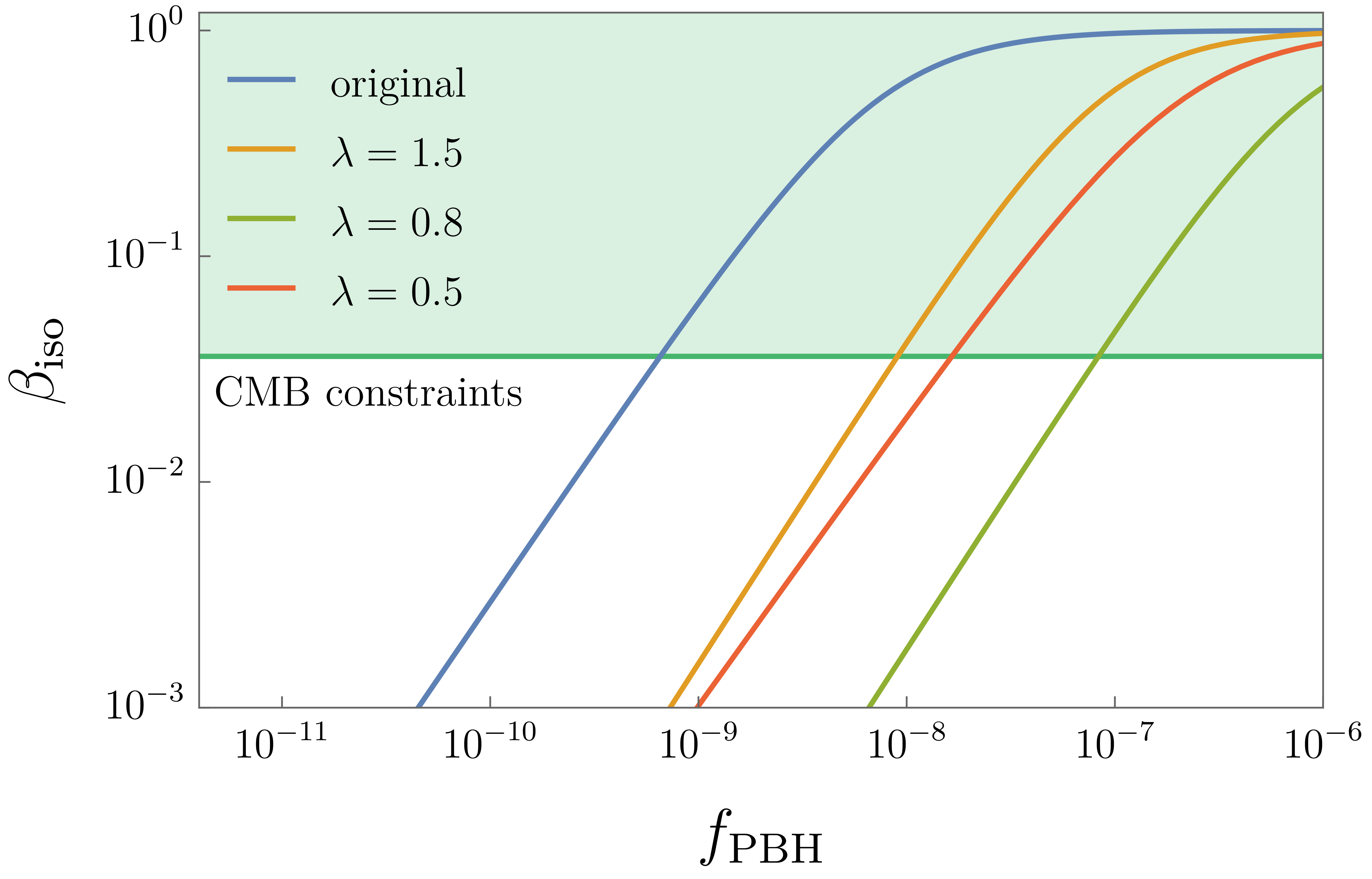
PQ scalar: Φ, axion field: $\phi = \arg\Phi$

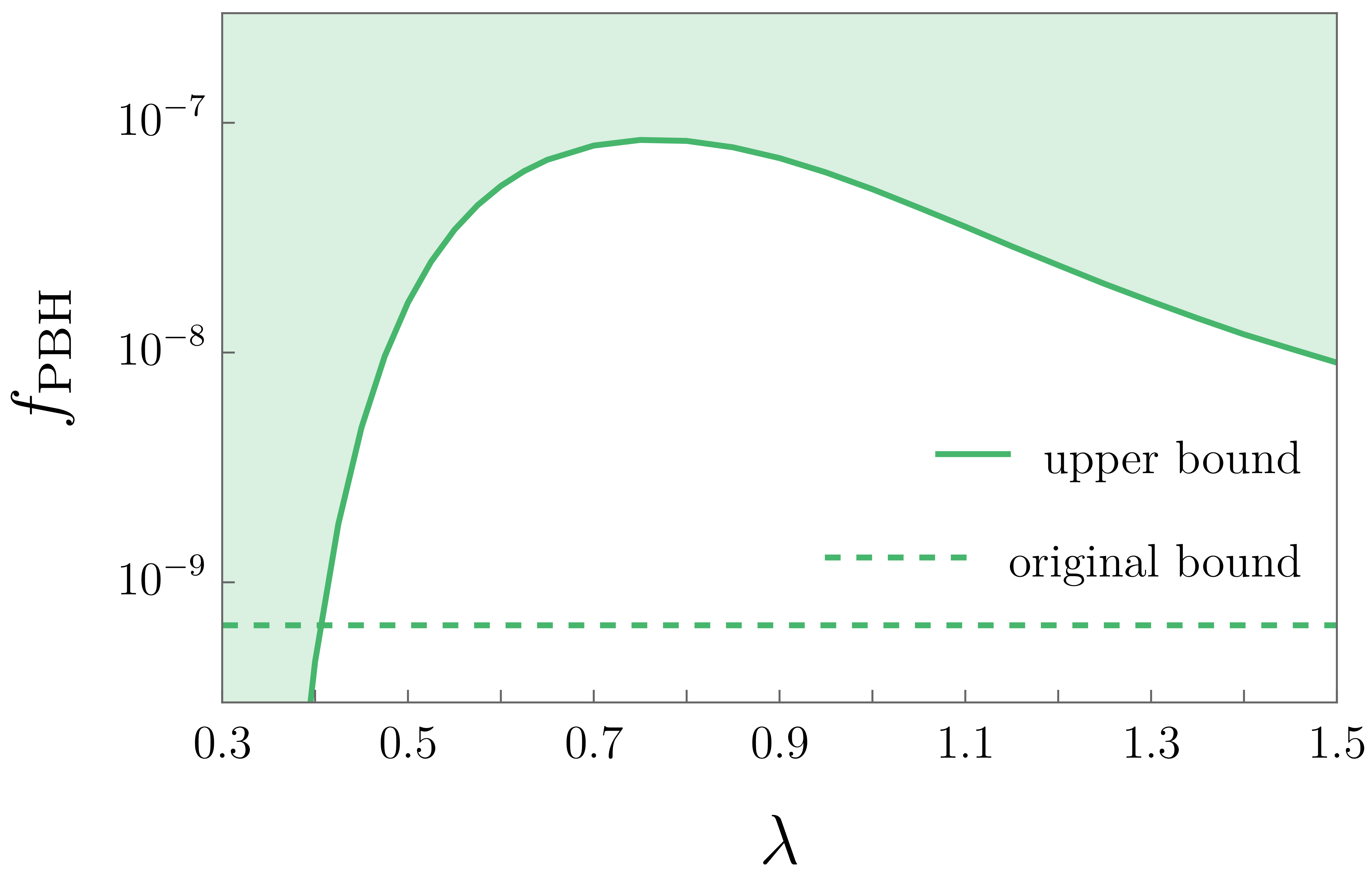


※This is just an schematic image.

Suppression of Isocurvature Perturbation

Our work[arXiv:2310.13333]

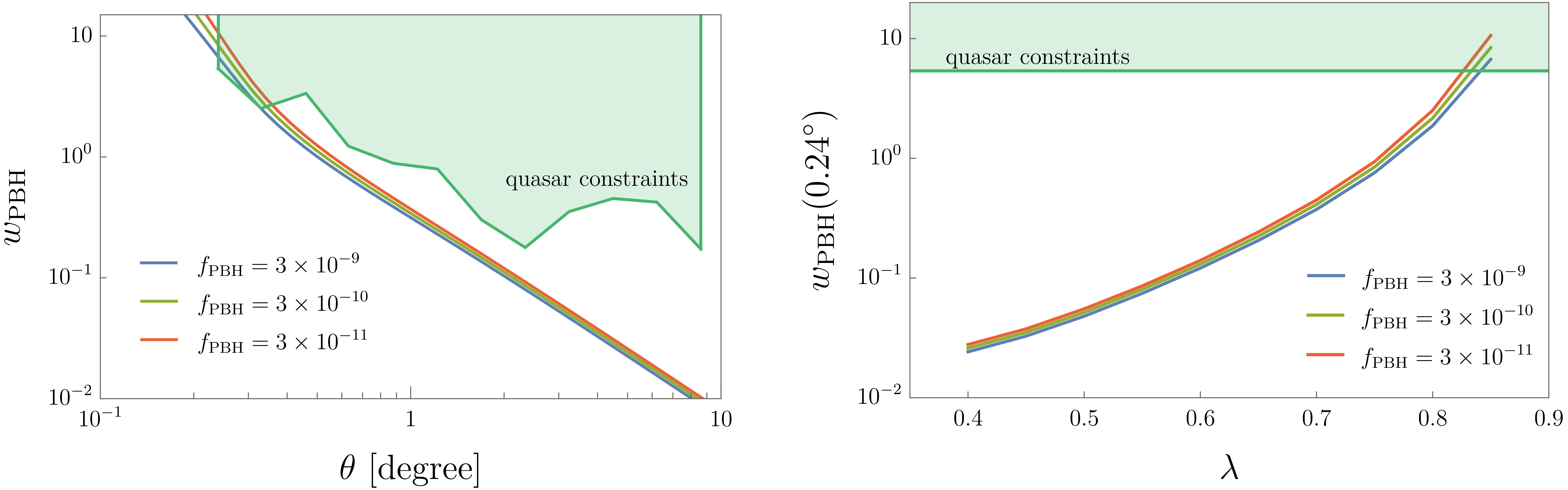




The observational constraint is $0.45 \lesssim \lambda$.

Angular Correlation Function of PBH

Our work[arXiv:2310.13333]



The observational constraint is $\lambda \lesssim 0.8$.

Summary

- PBH model with large inflationary curvature fluctuation is strongly constrained by CMB μ-distortion, in the mass region of SMBH seeds.

- To avoid the constraint, PBH formation from axion bubbles is proposed but its spatial distribution has strong observational constraints.

- Our modified model can explain primordial origin of SMBH without any violation of the observational constraints.

Thank you for your attention.