Generation of sparse and localized curvature perturbation from inflation

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What is the origin of SMBHs?

Super massive black holes (SMBHs) observed at high redshift

$M \sim 10^9 M_\odot$ $z=6\sim7$

$M = 1.2 \times 10^{10}\ M_\odot$ at $z = 6.3$ (Wu et al. 2015)

There is no convincing astrophysical explanation of this.

Time is too short to make the seed BHs grow into the SMBHs.

What is the origin of SMBHs?

It is intriguing to consider a possibility that SMBHs are primordial BHs.

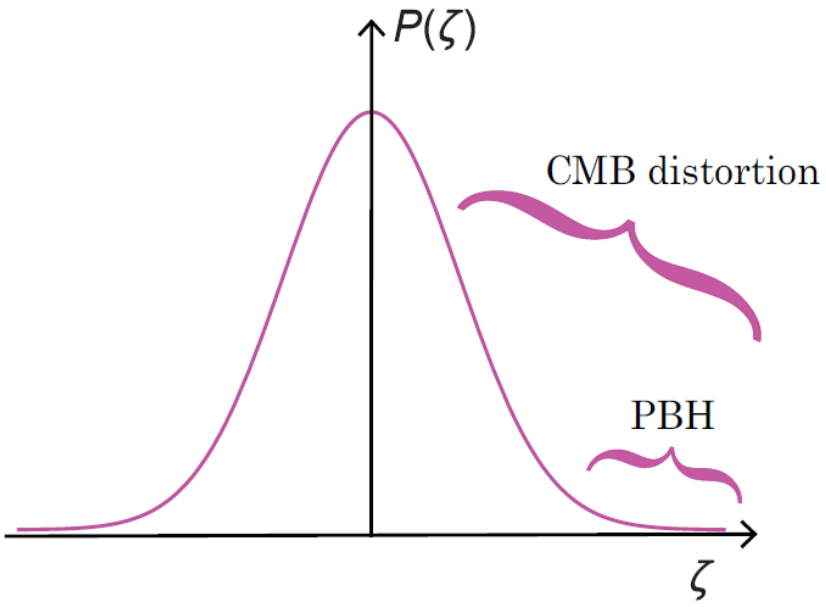
Primordial black holes (PBHs)

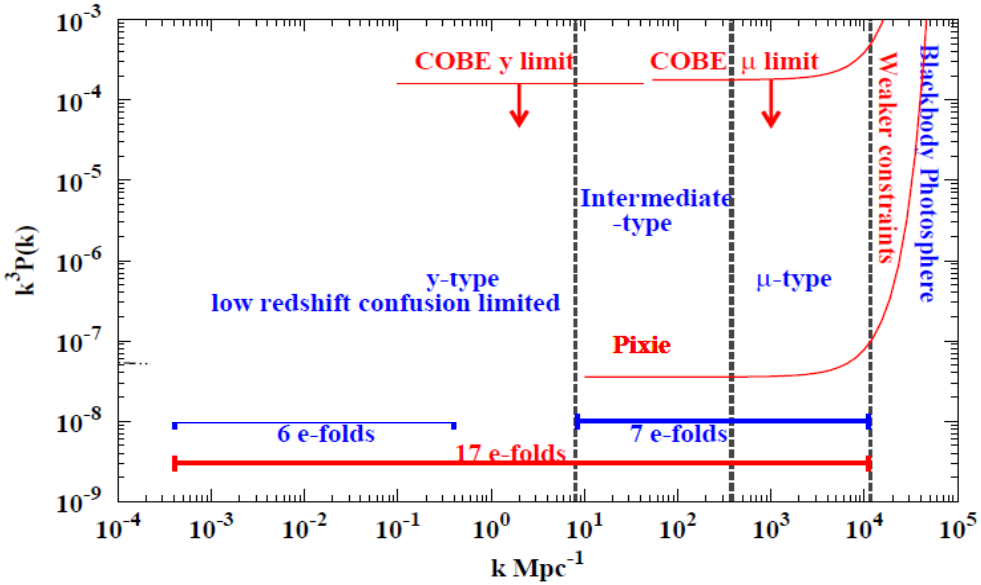
- PBH is formed when the primordial density perturbation of $O(1)$ amplitude re-enters the Hubble horizon.
- PBH mass = horizon mass at the formation time

$$k_{\rm BH} \sim 47 \left(\frac{M_{\rm BH}}{10^{10} M_\odot} \right)^{-1/2} {\rm Mpc}^{-1}$$

- Just preparing such primordial perturbation at given scale results in the formation of PBHs.

What is the origin of SMBHs?





(Khatri, 2013)

Gaussian perturbation explaining the observed SMBHs as PBHs ($M_{PBH} \gtrsim 10^4\, M_\odot$) requires relatively large variance. Such perturbation is already inconsistent with the non-observation of the CMB spectral distortion.

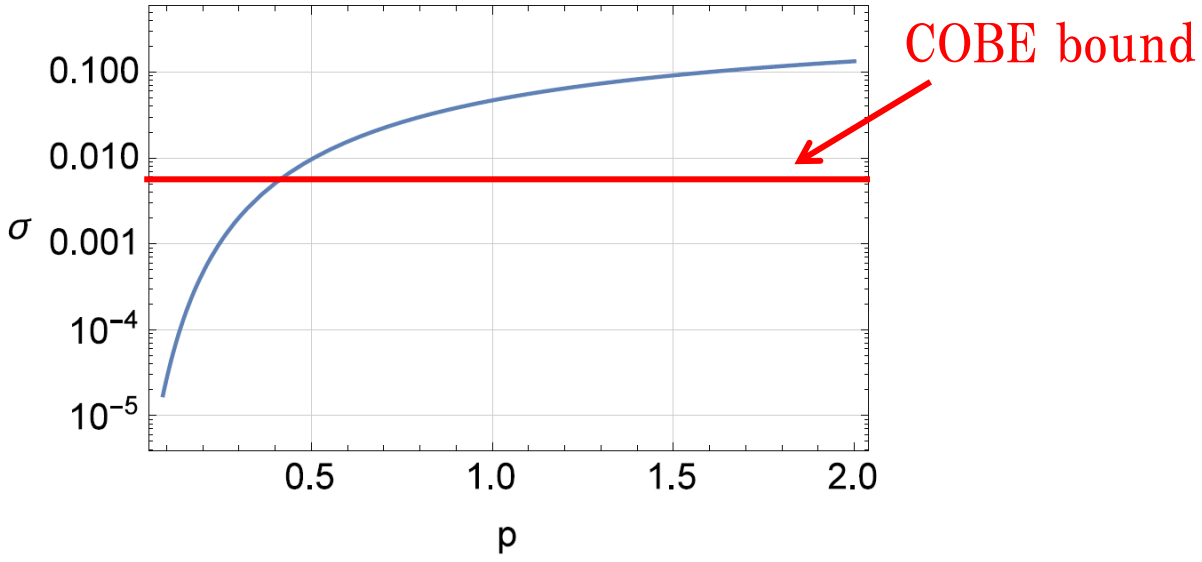
(Kohri, Nakama, TS, 2014)

Non-Gaussian pdf

$$P(\zeta) = \frac{1}{2\sqrt{2}\tilde{\sigma}\Gamma\left(1+1/p\right)} \exp\left[-\left(\frac{|\zeta|}{\sqrt{2}\tilde{\sigma}}\right)^p\right]$$

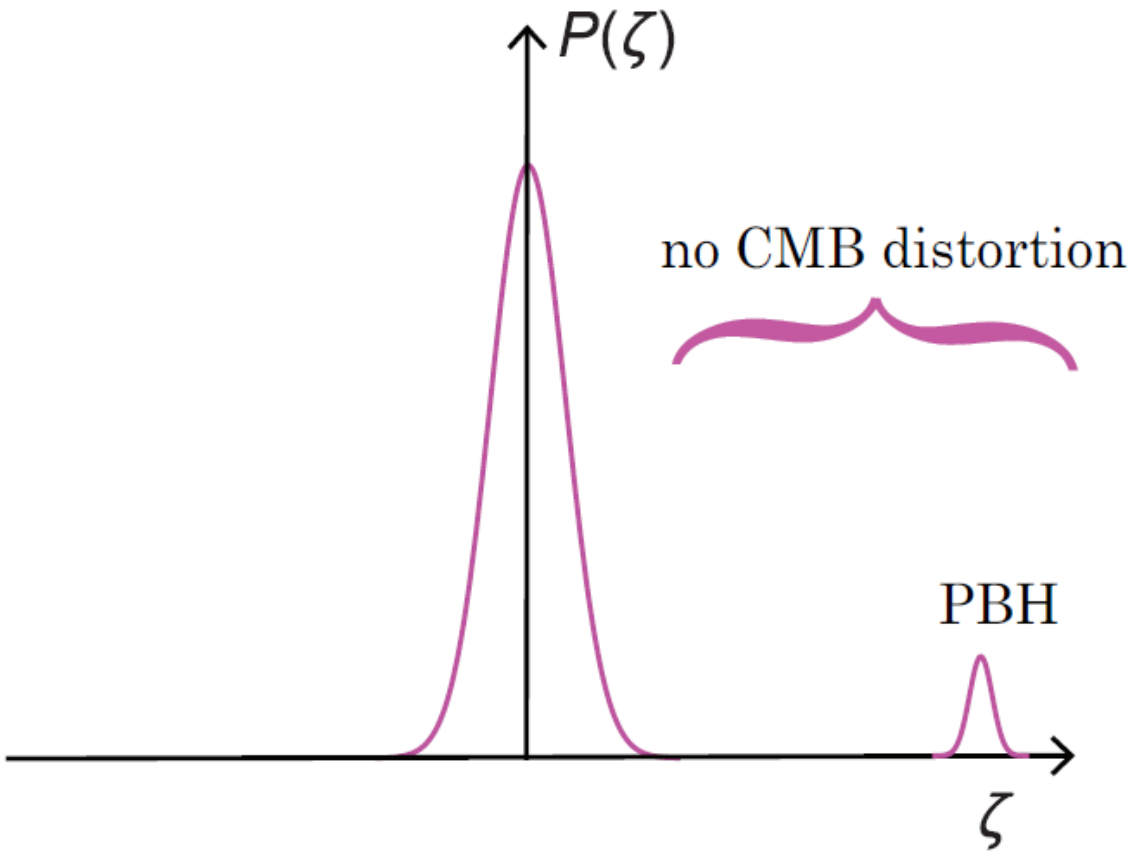
($p = 2$ is Gaussian case)

$$\beta = \int_{\zeta_c}^{\infty} P(\zeta) d\zeta = \frac{\Gamma(1/p, 2^{-p/2}(\zeta_c/\tilde{\sigma})^p)}{2p\Gamma(1+1/p)}$$ is fixed by observations.



Tremendous non-Gaussian perturbation ($p \lesssim 0.43$) is required.

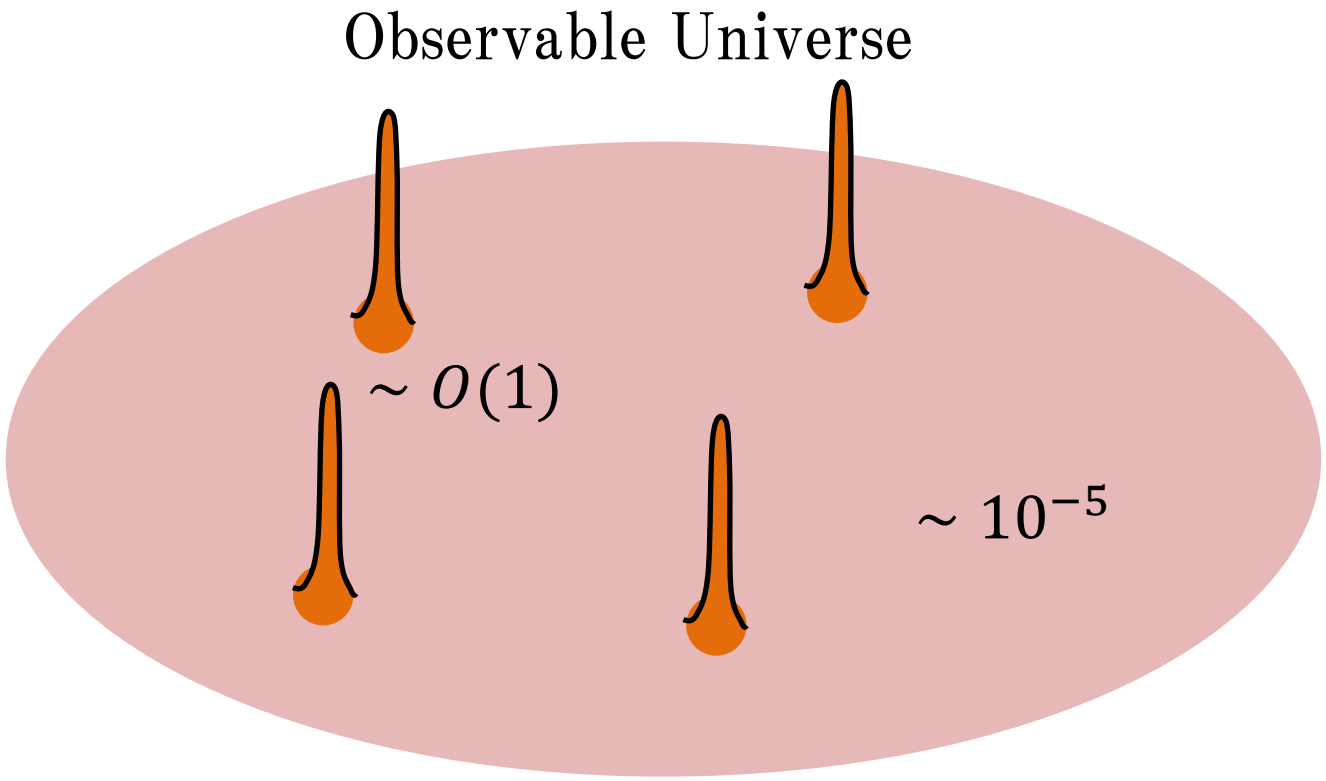
Basic idea



We propose that this type of pdf can be realized.

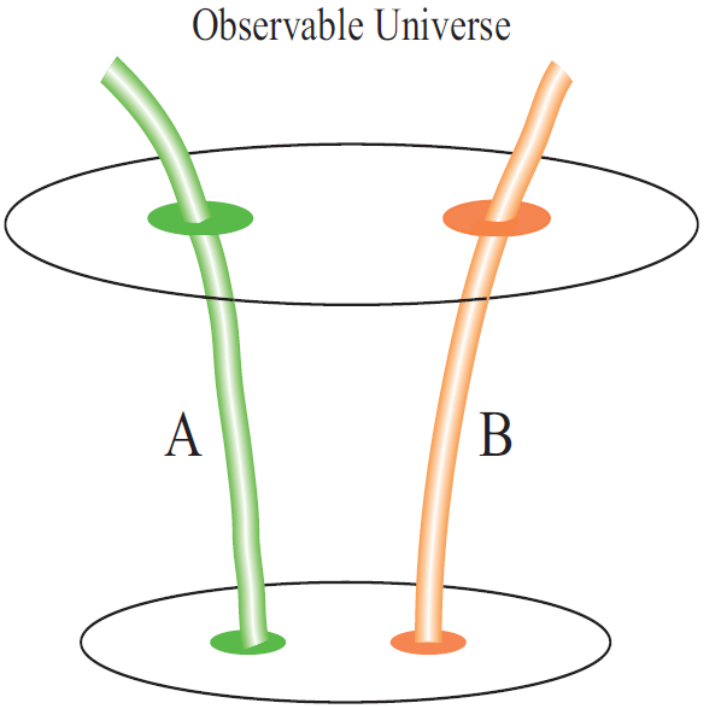
This type of pdf safely passes the CMB constraint and generate the seeds of SMBHs.

Basic idea

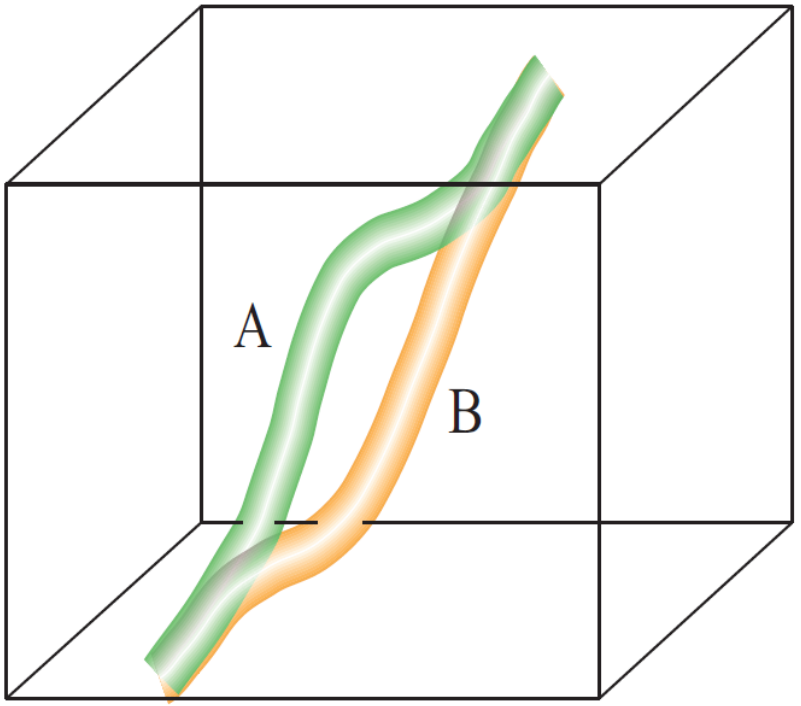


Sparse and localized primordial perturbation

Basic idea : multiple-field inflation



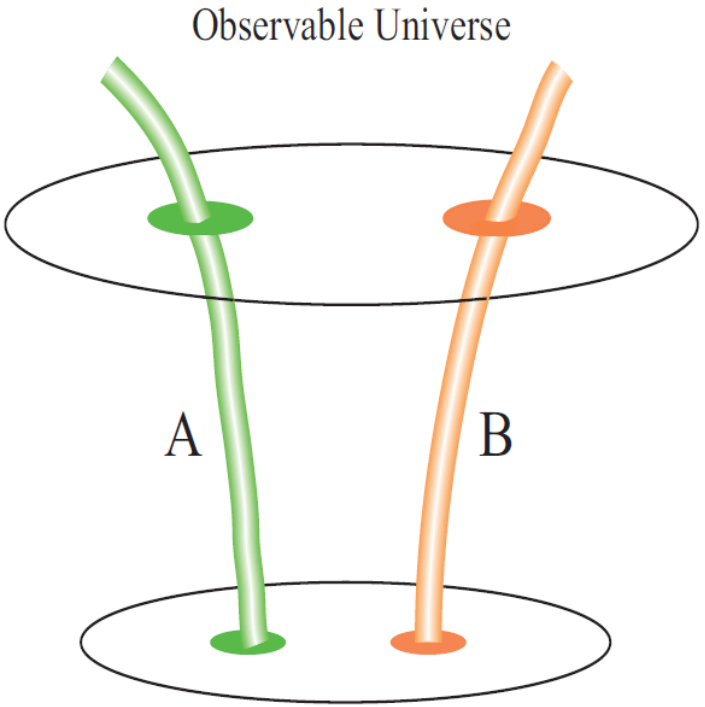
Separate Universe picture



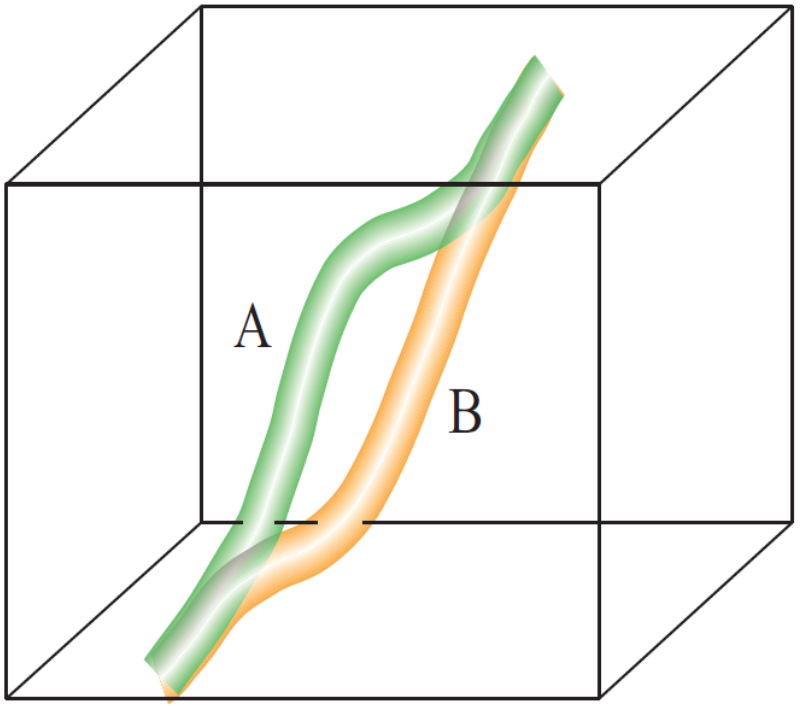
Trajectories in field space

- Each mini-Universe follows either trajectory A or B.
- Most mini-Universes follow the trajectory A and only a very small fraction follow B.

Basic idea : multiple-field inflation



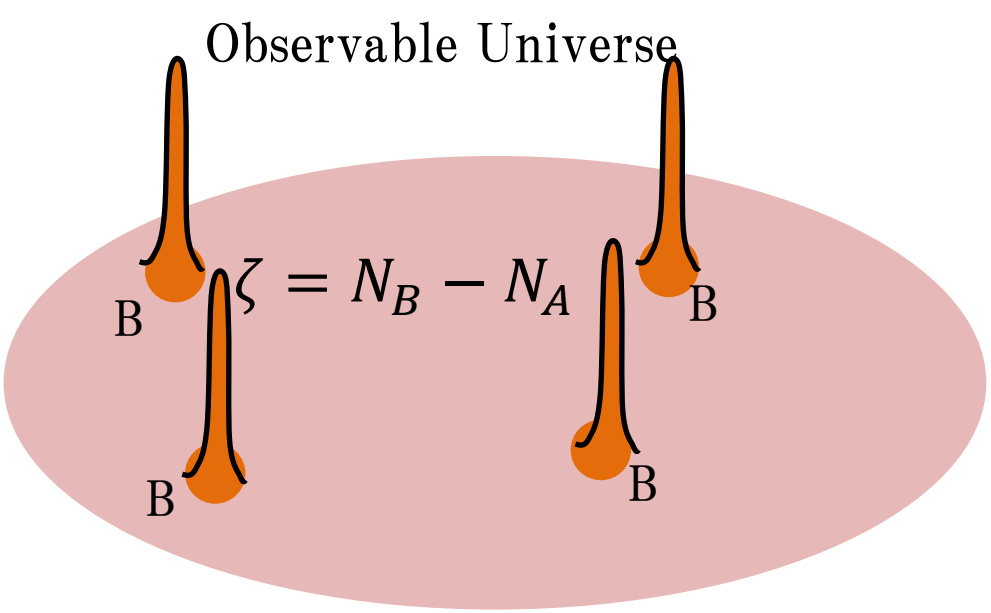
Separate Universe picture

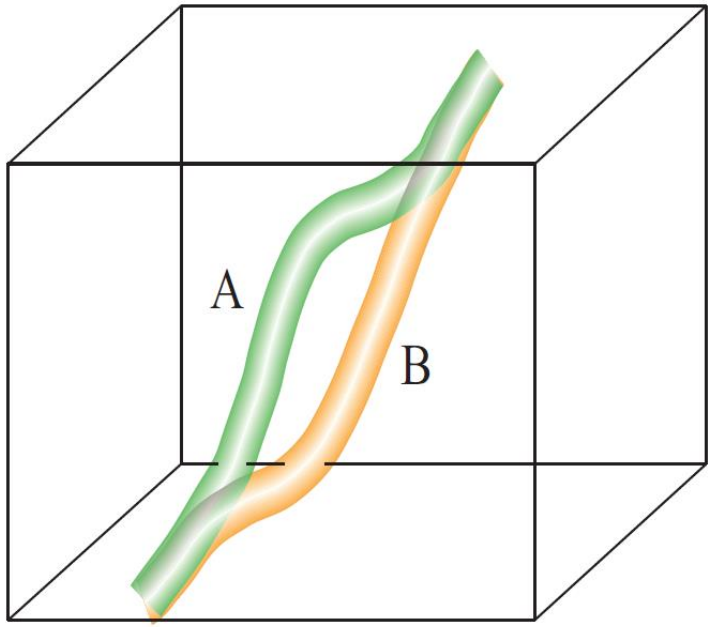


Trajectories in field space

δN formalism states that curvature perturbation between the patch A and the patch B is given by $N_A - N_B$.

Basic idea : multiple-field inflation





We require $N_B - N_A > \zeta_c = 1$ in order for the patch B to collapse into BH.

There is not unique value of ζ_c (0.7~1.2 depending on the perturbation profile, Shibata&Sasaki 1999)

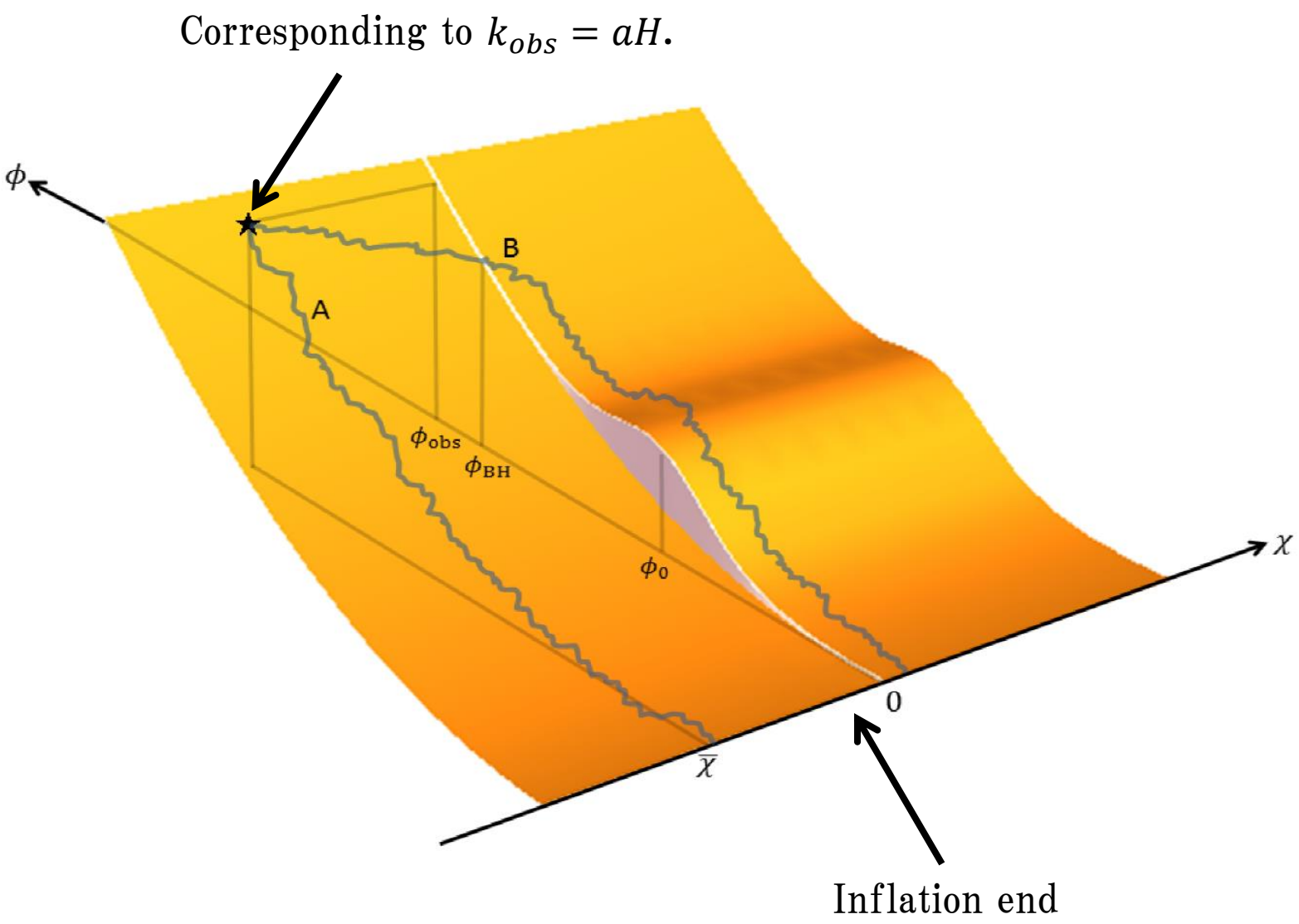
$$\beta = \frac{\text{number of patches B}}{\text{number of patches A}}.$$

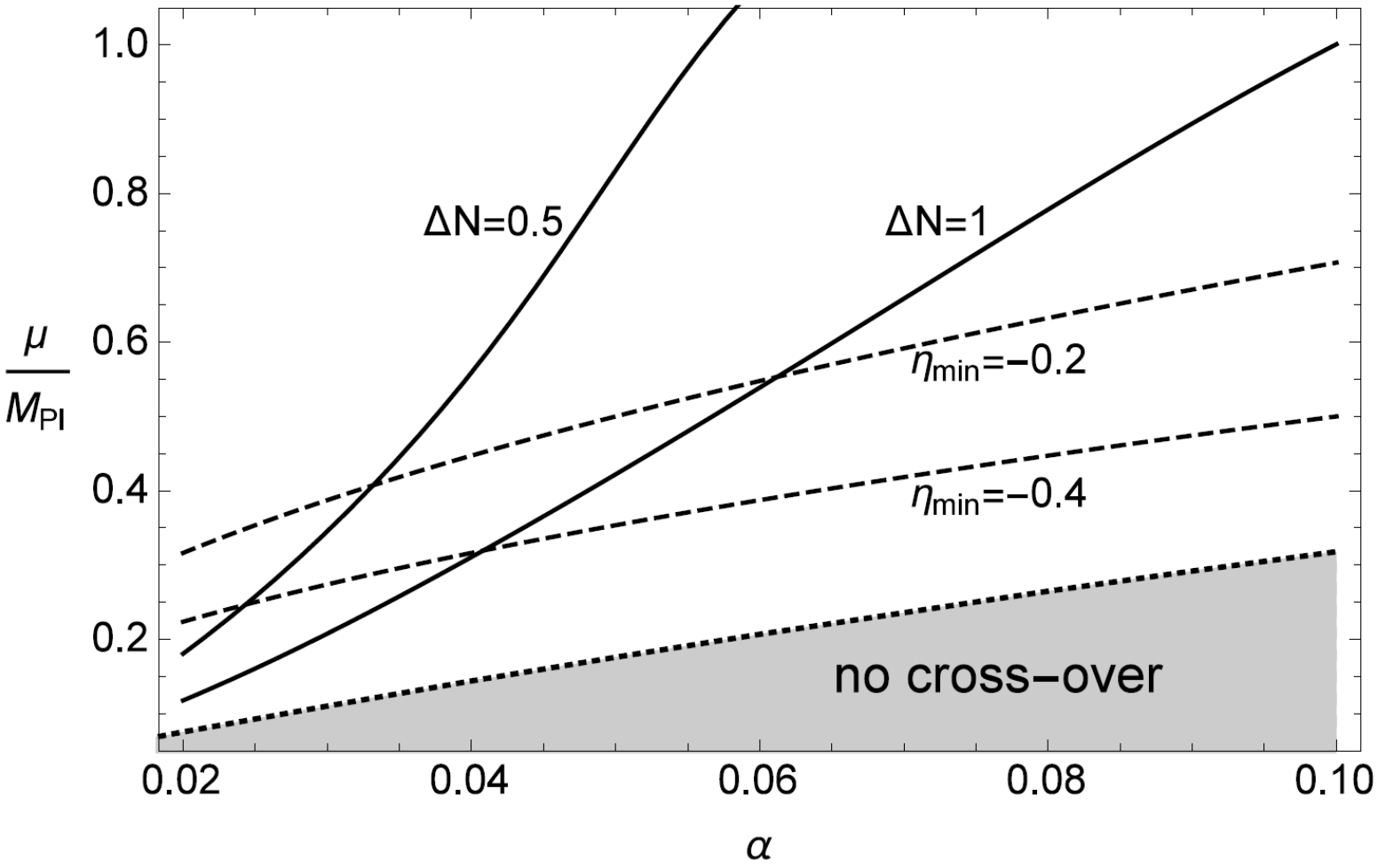
Simple toy model : two-field model

A hill is superposed on the potential $V(\phi)$ for $\chi > 0$.

$$\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}(\partial\chi)^2 - V(\phi)\left(1 + \theta(\chi)v(\phi)\right)$$

$$V(\phi) = \frac{1}{2}m^2\phi^2, \qquad v(\phi) = \alpha \exp\left(-\frac{(\phi-\phi_0)^2}{2\mu^2}\right)$$

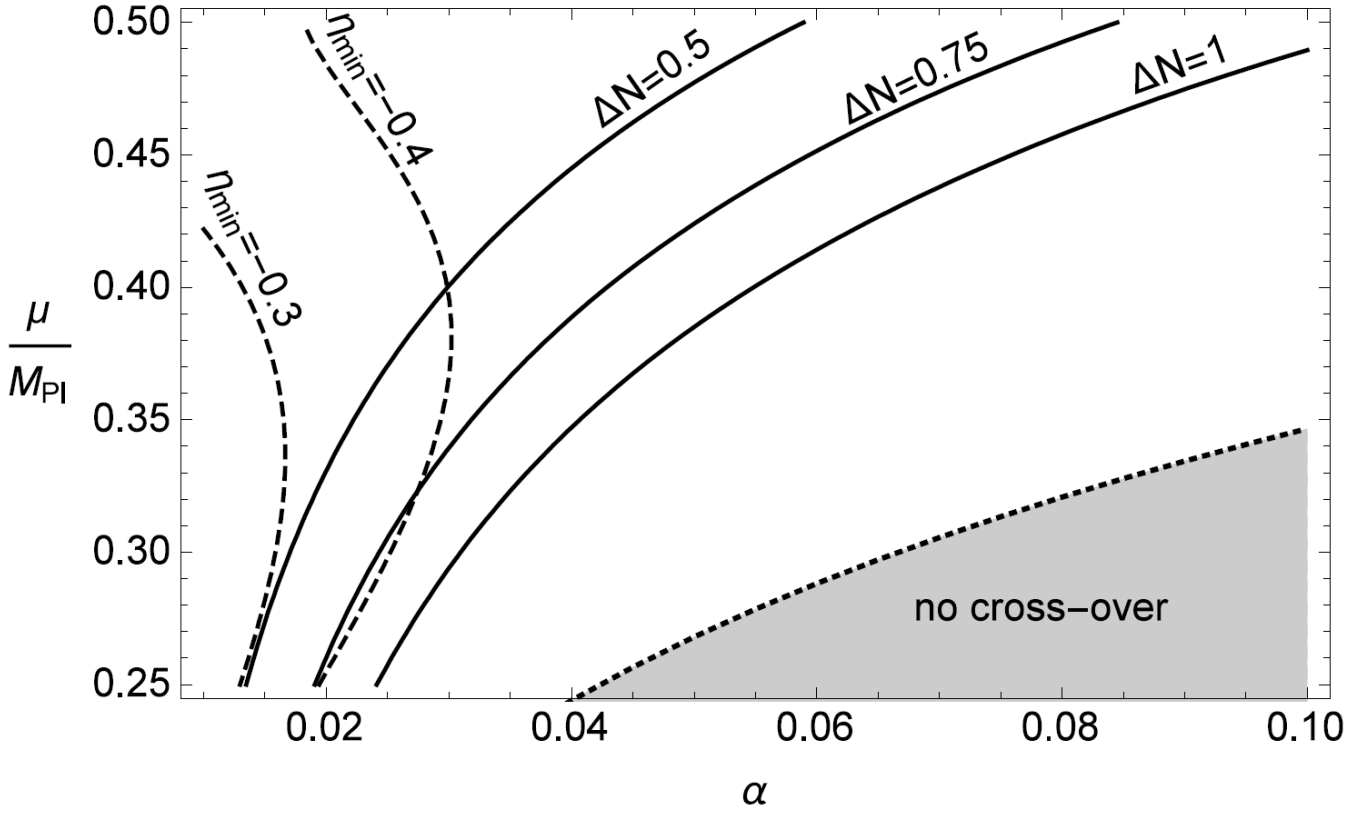

Corresponding to $k_{obs} = aH$.
ϕ
B
A
ϕ_{obs}
ϕ_{BH}
ϕ_0
χ
0
$\bar{\chi}$
Inflation end



$\Delta N = 1$ is realized without violating the slow-roll conditions.

Second model: R^2-type inflation for $V(\phi)$

$$V(\phi) = \frac{3M^2 M_{\rm Pl}^2}{4}\left\{1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}\right)\right\}^2$$



Qualitatively the same result as the previous case

Discussion

Observed SMBHs $\sim 10^{9-10}\, M_{\odot}$ at redshift $z = 6 \sim 7$ may be formed in the very early Universe from the direct collapse of the primordial density perturbation.

This is possible, without conflicting with the non-observation of the CMB spectral distortion, if only a small fraction of mini-Universes experienced different trajectory in the field space during inflation.

In this scenario, SMBHs exist at all redshifts relevant to astrophysical observations. Thus, future observations like JWST should be able to detect SMBHs with the same comoving number density even at higher redshifts.