Primordial Black Holes from String Inflation

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Related Talk's : Cicoli, Zavala

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Outline

- Motivation → why PBHs? / astrophysical constraints / why string theory?

- PBH formation

- PBHs from fibre inflation

- Summary & conclusions

Motivation

LIGO Experiment

(Obs. of gravitational wave merge of two BH's)

Why PBHs? → revived → Idea of BHs as part of/main constituent of DM

↓ suggest existence

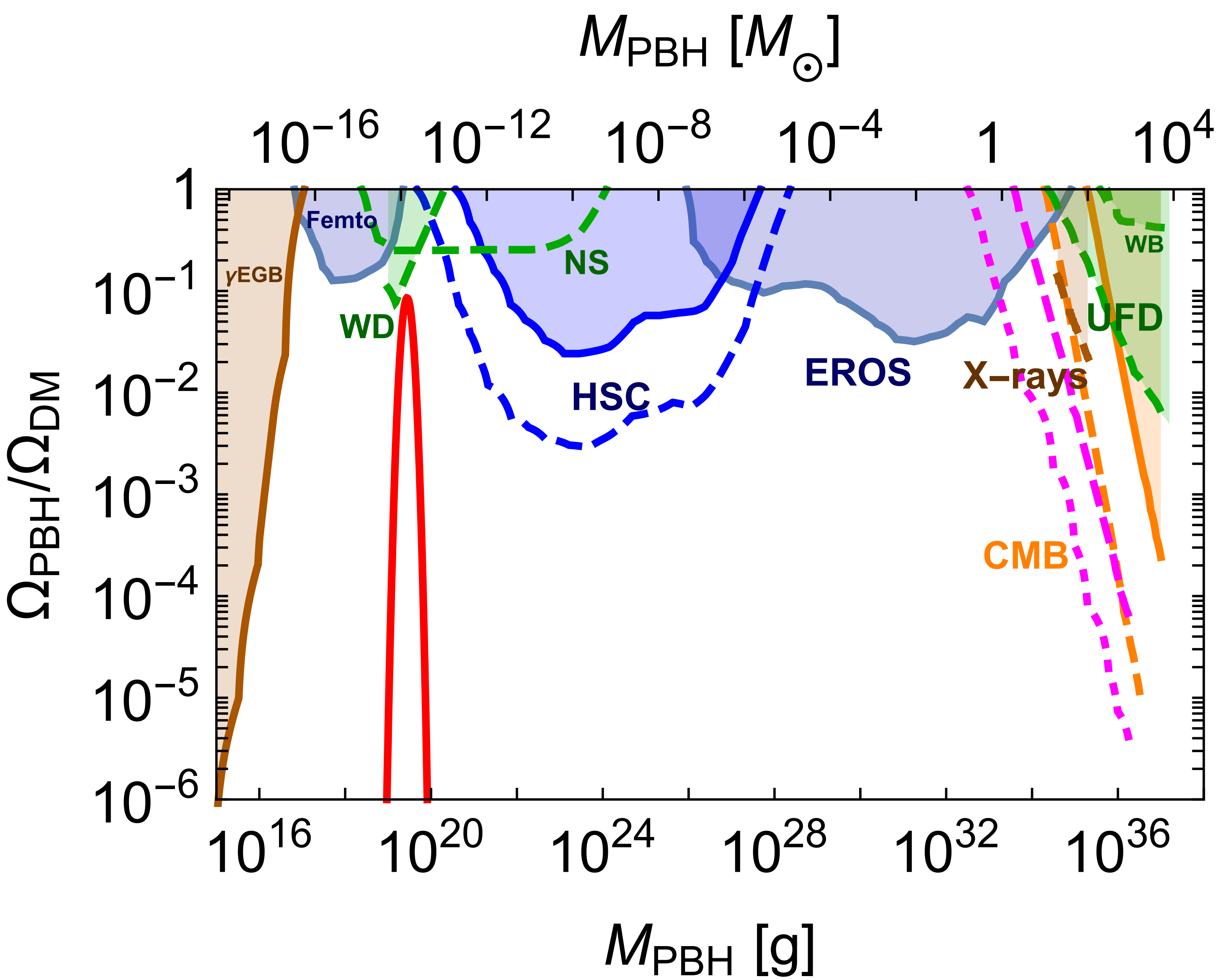
large population of BHs of 10's $M_\odot$

fulled old idea →

long-lived BHs produced during the early stage of the universe

[Hawking'71]
[Carr, Hawking'74]

What about smaller masses?



[Ballestero, Taoso'18]

$$10^{-16}\ M_\odot \le M_{PBH} \le 10^{-14} M_\odot$$

way far from the LIGO region
but still an interesting idea to study due to
the lack of astrophysical explanation

How can we form PBH? → amplification of the density perturbation during inflation is need it

that form an important contribute to DM abundance $\sim (10\%-100\%)$

Enhancement of the power spectrum → (natural questions) How to generate this enhancement? → Can it be done at the right scales?

Answer: framework of single field inflation reproducing the Planck data.

Enhancement achieved → **Inflationary potential requiring** : slow-roll → near inflection point → slow-roll

[Ballestero, Taoso'18] [Özsoy,Parameswaran,Tasinato,Zavala'18]

[Ivanov,Naselsky,Novikov'94] [Ezquiaga,Bellido,Ruiz'17]

NOTE:

- DM $\equiv$ PBHs $\Rightarrow$ Potential need to have enough tuning freedom

few examples : [Germani, Prokopec'17][Ballestero,Taoso'17] [Ivanov, Naselsky, Novikov'94] [Ezquiaga, Bellido, Ruiz'17]

These models are a bottom-up approach $\longrightarrow$ lack/ignores the fund. issues of deriving the model from a UV perspective

Possible solution:

String Theory can search for concrete examples of infl. models to allow PBH formation from a top-down perspective

PBH formation

PBH $\xrightarrow{\text{form}}$ Large & rare $\delta\rho$ re-enter the Hubble horizon and collapse

$$\beta_{\rm f}(M) = \frac{\rho_{\rm PBH}(M)}{\rho_{\rm tot}}\Big|_{\rm f}$$

$\beta_{\rm f}(M)$: fraction of the total energy density in PBH with mass M at formation

Probability of large distribution $\xrightarrow{\text{gaussian}}$ $\beta_{\rm f}(M) = \int_{\delta_c}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma_{\rm M}}\, e^{-\frac{\delta^2}{2\sigma_{\rm M}^2}}\, d\delta$

δ_c : critical value for collapse into PBH

Gaussian distributions, we know $\sigma_M^2 \sim \langle \zeta\,\zeta \rangle$ at CMB scales is $\mathcal{O}(10^{-9})$

$\zeta = u/z$; for $\sigma_M \ll \delta_c \;\Rightarrow$ $\beta_{\rm f}(M) \sim \frac{\sigma_{\rm M}}{\sqrt{2\pi}\,\delta_c}\, e^{-\frac{\delta_c^2}{2\sigma_{\rm M}^2}}$

If PBH = important fraction of DM $\Rightarrow$ few order of magnitude large than on CMB scales

Estimation of the enhancement

$$M = \gamma_{\rm G} \frac{4\pi}{3} \frac{\rho_{\rm tot}}{H^3}\Big|_{\rm f} = 4\pi\gamma_{\rm G} \frac{M_p^2}{H_{\rm f}}$$

γ_G : correction factor

M : Mass of PBH forming when large density pert. re-enter the horizon

PBH behave like matter $\Rightarrow$ $$\beta_{\rm f}(M) = \left(\frac{H_0}{H_{\rm f}}\right)^2 \frac{0.26}{a_{\rm f}^3} f_{\rm PBH}(M)$$

<u>**Assumption**</u> : PBH form before Matter-Radiation equality

$$H_{\rm f}^2 = 8\times 10^{-5} \frac{H_0^2}{a_{\rm f}^4} \left(\frac{g_{*\rm f}}{g_{*0}}\right)^{-1/3} \quad \Rightarrow \quad \beta_{\rm f}(M) \simeq \frac{4}{\sqrt{\gamma_{\rm G}}} \times 10^{-9} \left(\frac{g_{*\rm f}}{g_{*0}}\right)^{1/4} \sqrt{\frac{M}{M_\odot}}\, f_{\rm PBH}(M)$$

$$\beta_{\rm f}(M) \simeq 10^{-8} \sqrt{\frac{M}{M_\odot}} \quad \underset{M = 10^{-15} M_\odot}{\Rightarrow} \quad \delta_c \sim 1 \qquad \sigma_M \sim 0.12$$

$\Downarrow$

Power spectrum $P_k \sim \sigma^2 \sim \mathcal{O}(10^{-2})$

We need an enhancement of 7 orders of magnitude respect to CMB

Observations:

1. Estimation

Broadly distributed $\longleftarrow$ $$f_{PBH}(M) = \int df_{PBH}(M) = \int \frac{df_{PBH}(M)}{d\log(M)}\, d\log(M)$$

$df_{PBH}(M)$ is the fraction between M and $M + d\log(M)$

2. $H \sim$ is constant during inflation

$$\Delta N_{\rm CMB}^{\rm PBH} = \ln\left(\frac{a_{\rm PBH} H_{\rm inf}}{a_{\rm CMB} H_{\rm inf}}\right) = \ln\left(\frac{a_{\rm f} H_{\rm f}}{0.05\,{\rm Mpc}^{-1}}\right)$$

$$= 18.4 - \frac{1}{12}\ln\left(\frac{g_*}{g_{*0}}\right) + \frac{1}{2}\ln\gamma_{\rm G} - \frac{1}{2}\ln\left(\frac{M}{M_\odot}\right)$$

$M \in [10^{-16}, 10^{-14}]\, M_\odot$ $\longrightarrow$ $\Delta N_{\rm CMB}^{\rm PBH} \sim 34.2 - 36.5$ efoldings

PBH from fibre inflation

$$\mathcal{V} = t_{\mathbb{P}^1}\tau_{\mathrm{K3}} - \tau_{\mathrm{dP}}^{3/2}$$

[Cicoli, Burgess, Quevedo'09]

τ_{K3} : Volume of K3-surface fibre over a $\mathbb{P}^1$

τ_{dP} : Volume of a diagonal del Pezzo

$t_{\mathbb{P}^1}$: Volume of $\mathbb{P}^1$

$\mathcal{V}$, τ_{dP} $\xrightarrow{\text{LVS}}$ Lifted by non-pert. effects to W & α' correct. to K at leading order in $1/\mathcal{V}$

τ_{K3}: remain as a flat direction $\Rightarrow$ our inflaton candidate

Way of lifting :

- 1-loop string corrections: KK-corrections & Winding corrections

[Berg, Haack, Kors'05]
[Berg, Haack, Pajer'07]

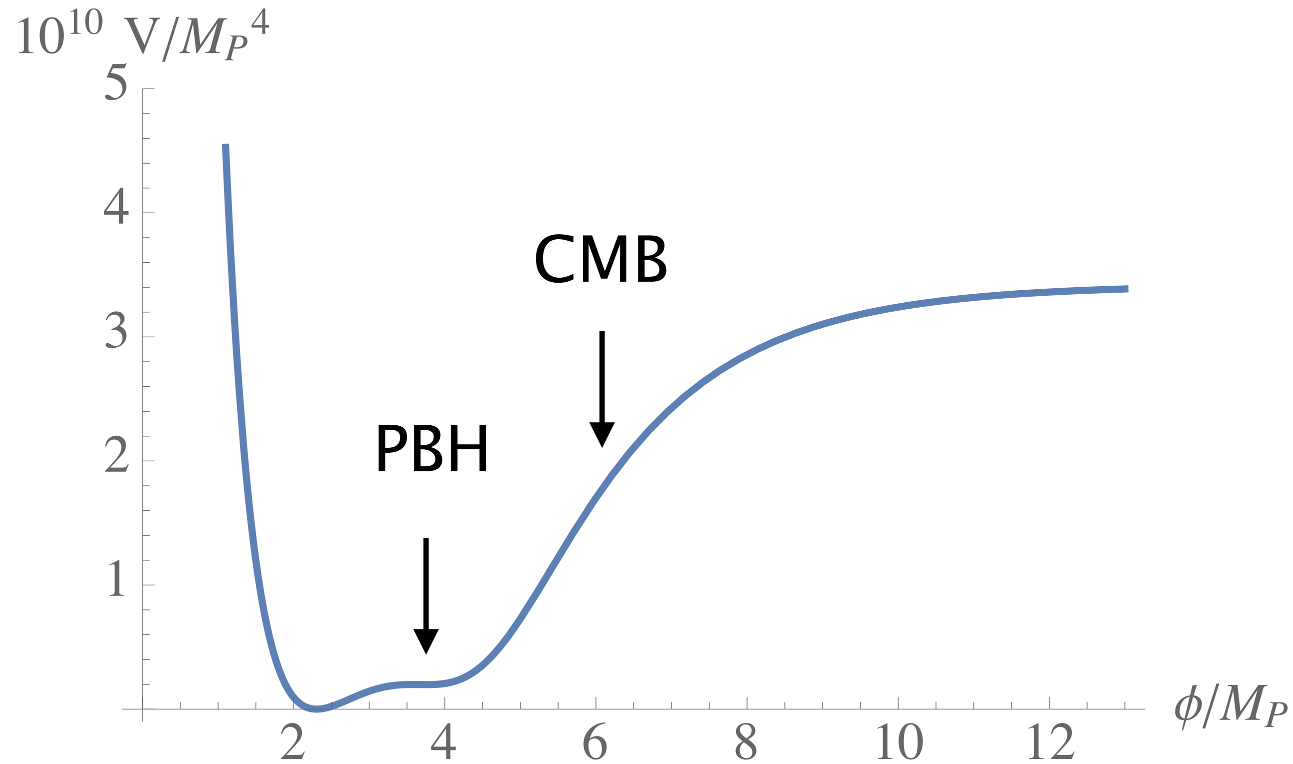
- Higher derivative α' effects

[Ciupke, Louis, Westphal'15]

Scalar potential

[Cicoli, VAD, Pedro'18]

[Cicoli, Ciupke, VAD, Guidetti, Muia, Shukla'17]



$$V_{\rm inf} = \frac{W_0^2}{\mathcal{V}^3}\left[\frac{C_{\rm up}}{\mathcal{V}^{1/3}} - \frac{C_{\rm W}}{\sqrt{\tau_{\rm K3}}} + \frac{A_{\rm W}}{\sqrt{\tau_{\rm K3}} - B_{\rm W}} + \right.$$

$$\left. + \frac{\tau_{\rm K3}}{\mathcal{V}}\left(D_{\rm W} - \frac{G_{\rm W}}{1 + R_{\rm W}\frac{\tau_{\rm K3}^{3/2}}{\mathcal{V}}}\right)\right]$$

$$\tau_{\rm K3} = \langle\tau_{\rm K3}\rangle\, e^{\frac{2}{\sqrt{3}}\hat{\phi}}$$

	$C_{\rm W}$	$A_{\rm W}$	$B_{\rm W}$	$G_{\rm W}$	$R_{\rm W}$	$\langle\tau_{\rm K3}\rangle$	$\langle\mathcal{V}\rangle$
$\mathcal{P}_2$	4/100	2/100	1	3.080548×10^{-2}	0.7071067	14.30	1000

- minimum : $\langle\tau_{\rm K3}\rangle \sim \dfrac{C_{\rm W} B_{\rm W}^2}{(\sqrt{C_{\rm W}} - \sqrt{A_{\rm W}})^2}$

- 5th term in the potential has a critical point : $\dfrac{2^{2/3}}{(R_{\rm W}/\mathcal{V})^{2/3}}$

$G_{\rm W}\,,\ R_W \longrightarrow$ crucial for the generation of the near inflection point

Power spectrum

Mukhanov–Sasaki

$$P_k = \frac{k^3}{2\pi^2}\left|\frac{u_k}{z}\right|^2$$

slow–roll

$$P_k = \frac{H^2}{8\pi^2\epsilon}\Big|_{k=aH}$$

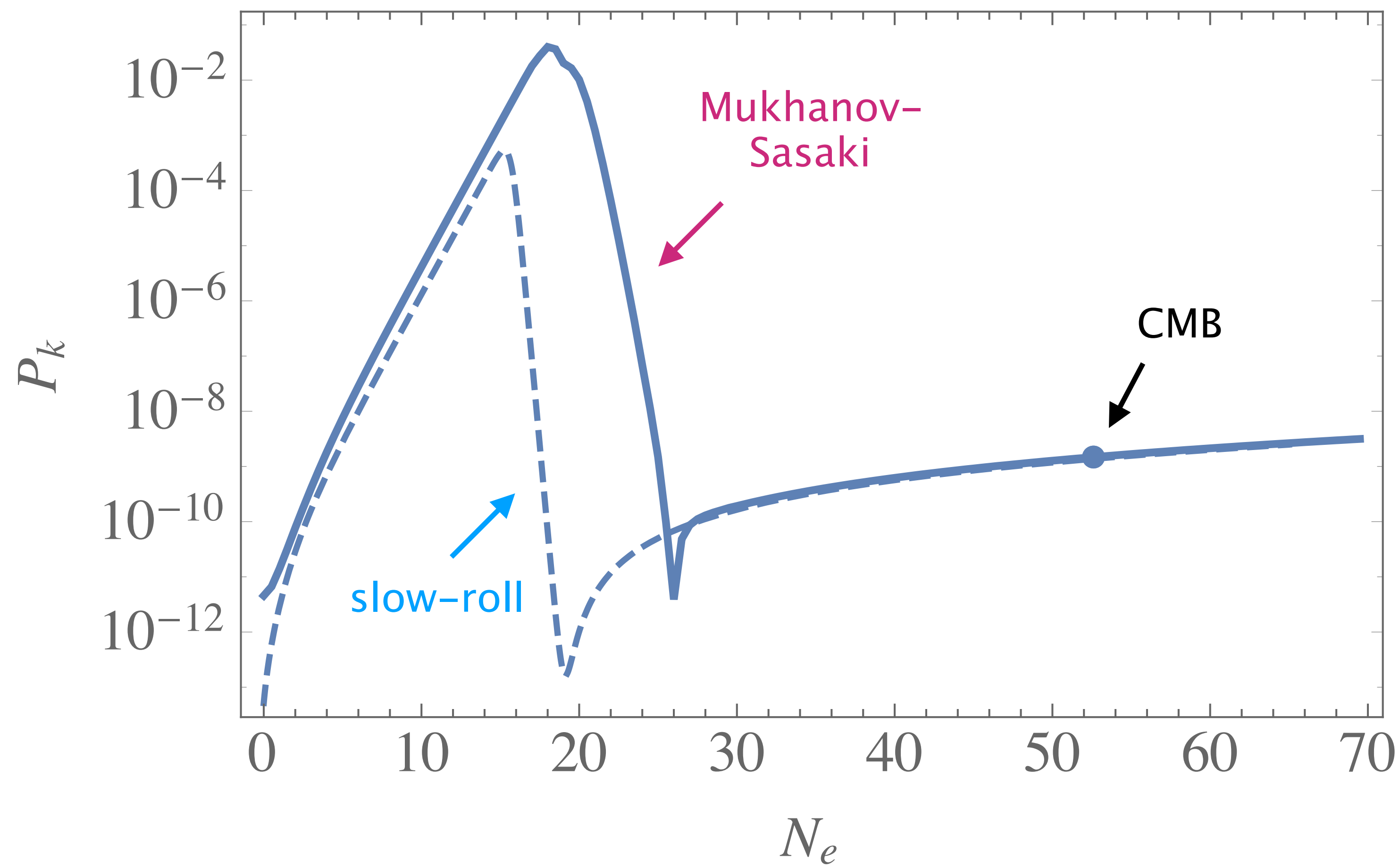
$$u_k''(\eta) + \left(k^2 - z''/z\right) u_k(\eta) = 0$$

$$\frac{z''}{z} = (aH)^2\left[2 - \epsilon + \frac{3}{2}\eta - \frac{1}{2}\epsilon\eta + \frac{1}{4}\eta^2 + \frac{1}{2}\eta\kappa\right]$$

$$\epsilon = -\frac{\dot H}{H^2} \qquad \eta = \frac{\dot\epsilon}{\epsilon H} \qquad \kappa = \frac{\dot\eta}{\eta H}$$

u_k : re–scaled curvature pert. $\zeta = u/z$

$$z \equiv \sqrt{2\epsilon}\, a$$



	C_W	A_W	B_W	G_W	R_W	$\langle\tau_{K3}\rangle$	$\langle\mathcal{V}\rangle$
$\mathcal{P}_1$	1/10	2/100	1	0.1398533	0.706811	3.89	107.3
$\mathcal{P}_2$	4/100	2/100	1	3.080548×10^{-2}	0.7071067	14.30	1000
$\mathcal{P}_3$	1.978/100	1.65/100	1.01	4.628858×10^{-3}	0.7070	168.03	5×10^4

Cosmological observables:

	n_s	r	$\frac{dn_s}{d\ln k}$	$\Delta N_{\rm CMB}^{\rm PBH}$	$P_k\vert_{\rm peak}$
$\mathcal{P}_1$	0.9457	0.015	−0.0017	34.5	0.01365
$\mathcal{P}_2$	0.9437	0.015	−0.0017	34.5	0.03998
$\mathcal{P}_3$	0.9457	0.015	−0.0019	34.5	0.013341

Universe evolve → slow-roll → constant roll → slow-roll (with big η)

constant roll → non-negligible acceleration

$$\ddot{\phi} \equiv -(3+\alpha)H\dot{\phi}$$

[Motohashi, Starobinsky,Yokoyama'15]

[Martin,Motohashi,Suyama'13]

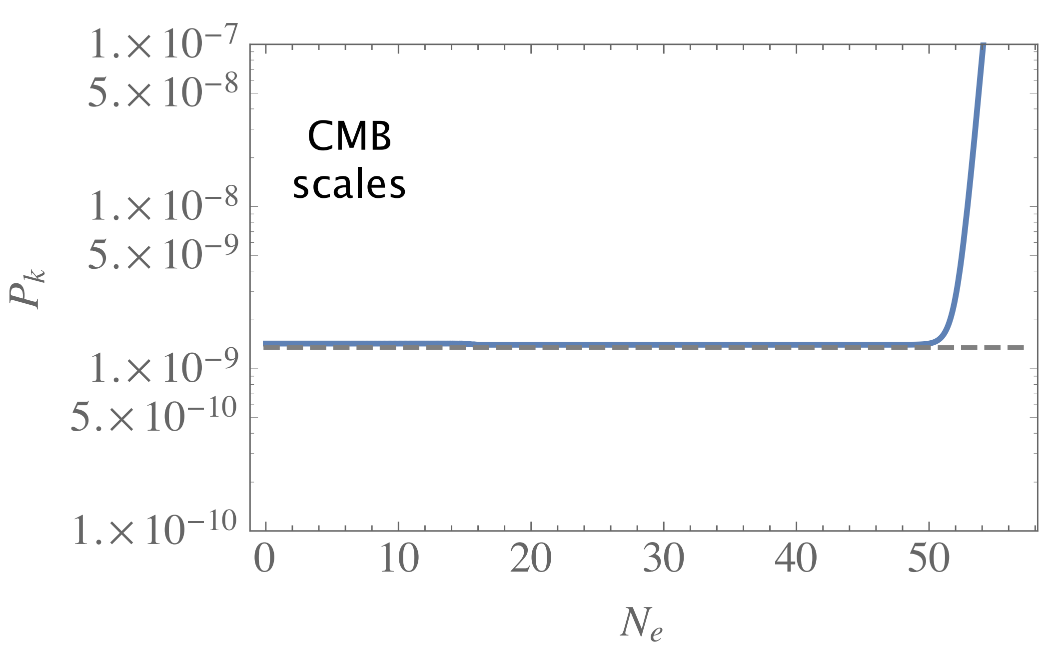
→ slow-roll $\alpha = -3 \Rightarrow \ddot{\phi} = 0$

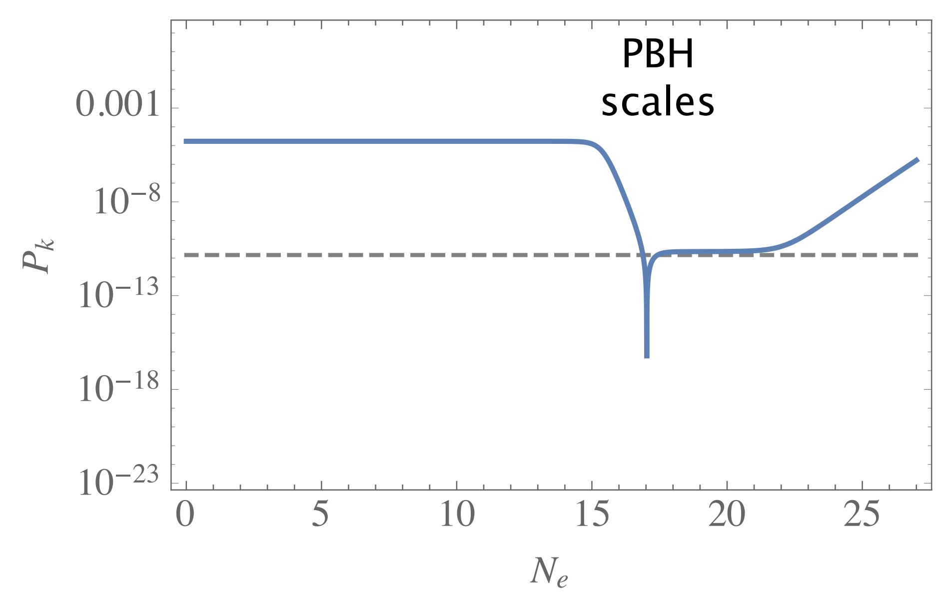
→ Ultra slow-roll $\alpha = 0 \Rightarrow \ddot{\phi} = -3H\dot{\phi}$

constant roll appear due to the presence of extreme flat region causing the inflaton to brake upon reaching it

super horizon evolution : $P_k \propto H^{|2\alpha+3|-1} a^{3+2\alpha+|3+2\alpha|}$

- $2\alpha + 3 < 0$ — constant mode
- $2\alpha + 3 > 0$ — growing mode





Summary & Outlooks

- First string theory inflationary model $\xrightarrow{\text{consistent}}$ cosmological obs. at CMB scales

  → generates PBH at small distances scales

- PBH formed in the low-mass region $\Rightarrow$ significant fraction of DM

Relevant features of fibre models:

(i) Coeff. of potential depends on background fluxes & intersection numbers

(ii) Potential enjoys approx. abelian re-scaling symmetry suppressing quantum corrections

(iii) The contribution generating the near inflection point has been generated in
[Cicoli, Ciupke, VAD, Guidetti, Muia, Shukla'17]

To do:

- Re-do analysis with $\delta_c \sim 0.5$, quantum diffusion & non-Gaussianities

- More general fibre inflation potential

- Consider formation in a matter-dominated period

- Find curvaton-like mechanism for PBH production

[Ando,Kinomata,Kawasaki,Mukaida,Yanagida]

- Study oscillon scope collapse into BHs at the end of inflation

Gracias.