Formation of Primordial Black Holes in Double Inflation

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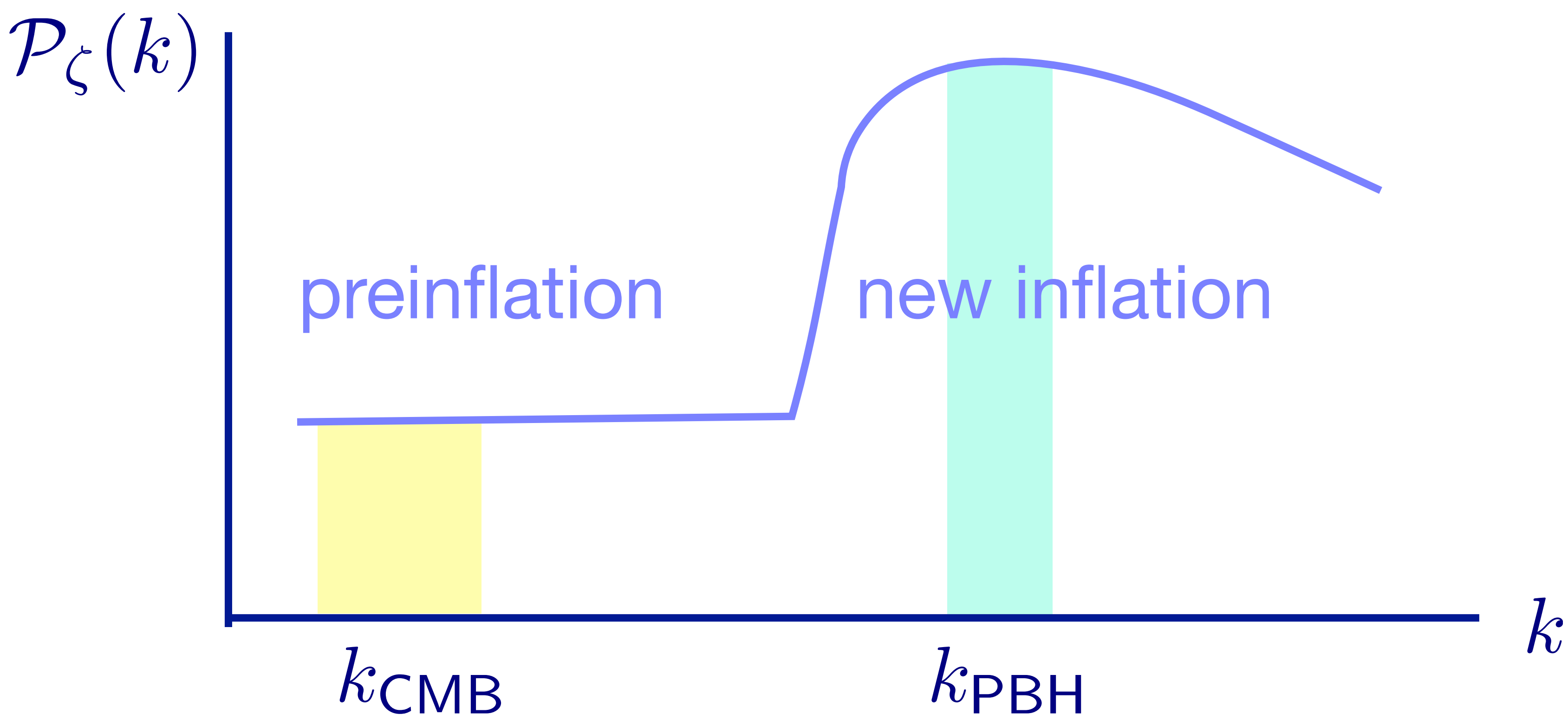
Based on MK Mukaida Yanagida, arXiv:1605.04974
MK Kusenko Tada Yanagida arXiv:1606.07631
Inomate MK Tada in preparation

1. Introduction

- Primordial Black Holes (PBHs) have attracted interest for many years Hawking (1971)
- PBHs can be formed by gravitational collapse of over-density region with Hubble radius in the early universe
- PBHs with mass < 10^{15} g would have evaporated by now through Hawking radiation Hawking (1974)
- PBHs with larger masses can exist in the present universe but various constraints on their abundance are imposed
- PBHs can give a significant contribution to dark matter if $M_{BH} = 10^{21\text{-}24}$ g
- Large density fluctuations δ with $O(0.1)$ are required for PBH formation but $\delta \sim O(10^{-5})$ on CMB scale

- We consider double inflation (preinflation+new inflation)
  - Preinflation (no specific model is required) accounts for perturbations on large scale observed by Planck
  - New inflation (after preinflation) with e-fold $N_{new} < 50$ produces large curvature perturbations on small scales



- This double inflation is realized in supergravity framework

Today’s Talk

1. Introduction

2. PBH formation in radiation dominated universe

3. New inflation model and PBH formation

4. New inflation in supergravity

5. Production of gravitational waves

6. Conclusion

2. PBH formation in radiation dominated universe

- Region with Hubble radius collapses if its over-density is higher than δ_c (≈ 0.3)
- PBH mass

$$M_{\rm PBH} \simeq 3.6 M_\odot \left(\frac{k}{10^6 {\rm Mpc}^{-1}}\right)^{-2} \simeq 4.5 M_\odot \left(\frac{T}{0.1 {\rm GeV}}\right)^{-2}$$

- PBH abundance is estimated by Press-Schechter formalism
- PBH mass fraction $\beta = \rho_{\rm PBH}(M)/\rho$

$$\beta(M) = \int_{\delta_c} d\delta \frac{1}{\sqrt{2\pi\sigma^2(k)}} \exp\left(-\frac{\delta^2}{2\sigma^2(k)}\right)$$

$\mathcal{P}_\zeta(k)$

$\mathcal{P}_\zeta(k) \sim O(10^{-2})$ for PBH formation

$\sigma^2(k)$: variance of the comoving density perturbation coarse-grained on k^{-1}

$$\sigma^2(k) = \int d\log k' \, W^2(k'/k) \frac{16}{81} (k'/k)^4 \mathcal{P}_\zeta(k')$$

- Present PBH fraction to DM

$$f_{\rm PBH}(M) = \frac{\Omega_{\rm PBH}(M)}{\Omega_{\rm DM}} \simeq 1.3 \times 10^8 \, \beta(M) \left(\frac{M_{\rm PBH}}{M_\odot}\right)^{-1/2}$$

[fraction per log M]

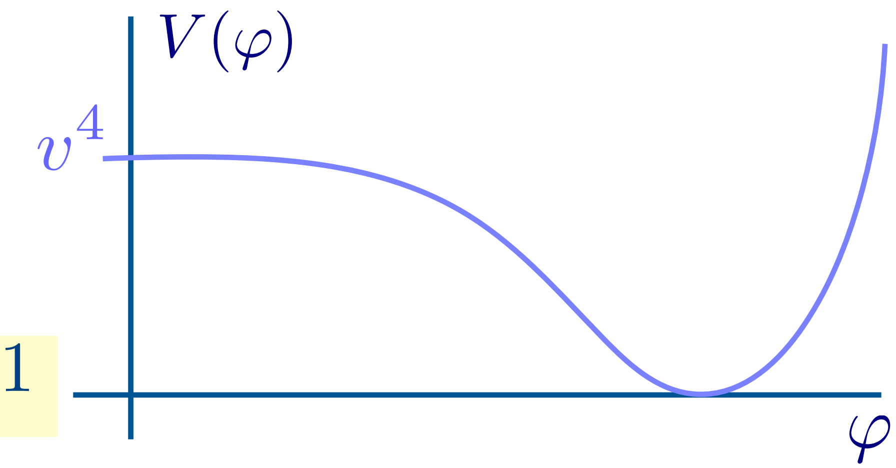
$$f_{\rm PBH,tot} = \int d\log M \, f_{\rm PBH}(M)$$

3. New Inflation after Preinflation

- Potential for new inflation

$$V(\varphi) = \left(v^2 - g\varphi^n\right)^2 - cv^2\varphi - \frac{1}{2}\kappa v^4 \varphi^2$$

$n = 3, 4, \cdots$ $M_p = 1$



Hubble $H_{\text{inf}} \simeq \dfrac{v^2}{\sqrt{3}}$

- Slow-roll parameter

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 = \frac{1}{2}\left(-\frac{c}{v^2} - \kappa\varphi - 2ng\frac{\varphi^{n-1}}{v^2} + \cdots\right)^2$$

$$\eta = \frac{V''}{V} = -\kappa - 2n(n-1)g\frac{\varphi^{n-2}}{v^2} + \cdots$$

$\epsilon \ll 1 \quad \eta \ll 1 \quad \Rightarrow$ inflation

- Curvature perturbation

$$\mathcal{P}_\zeta^{1/2} = \frac{H_{\text{inf}}}{2\pi}\frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{2\sqrt{3}\pi}\frac{v^4}{c + \kappa v^2\varphi + 2ng\varphi^{n-1}} \sim \frac{1}{2\sqrt{3}\pi}\frac{v^4}{c} \quad \left(\varphi \lesssim \frac{c}{v^2}\right)$$

$\mathcal{P}_\zeta^{1/2} \sim O(0.1)$ for $c \sim v^4$ → PBH formation

New inflation after preinflation

- Initial value for the inflaton φ ?
  - Interaction with the inflaton χ of preinflation (e.g. $\Delta V \sim \lambda m^2 \chi^2 \varphi^2$)

    → Hubble induced mass term $\Delta V \sim H^2 \varphi^2$

$$V(\phi) + \Delta V \sim H^2 \varphi^2 - c v^2 \varphi + \cdots \quad \Rightarrow \quad \varphi \sim \frac{c v^2}{H^2}$$

  - Just before new inflation $H \sim v^2$

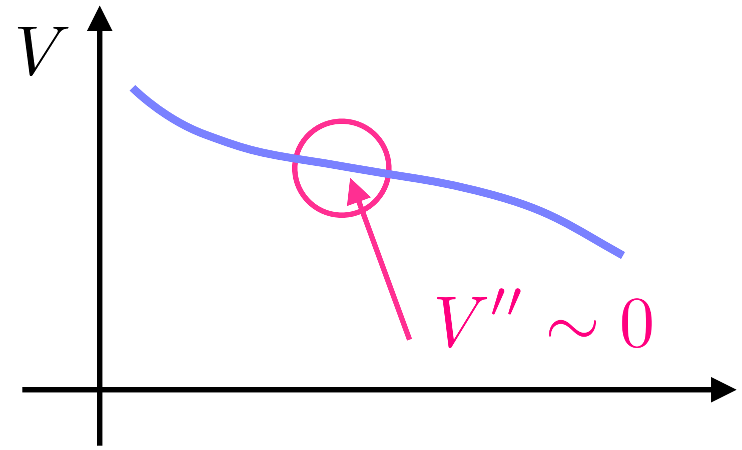
$$\boxed{\varphi_{\text{ini}} \sim \frac{c}{v^2}} \quad \rightarrow \quad \mathcal{P}_\zeta^{1/2} \sim \frac{1}{2\sqrt{3}\pi} \frac{v^4}{c} \sim O(0.1) \text{ for } c \sim v^4$$

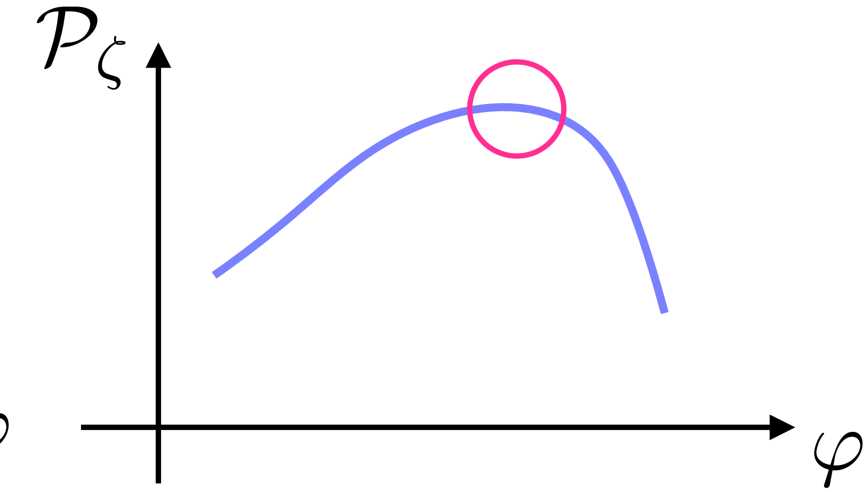
- Shape of power spectrum of curvature perturbations
  - depends on κ > 0 or κ < 0

    spectral index

$$\boxed{n_s - 1 \simeq 2\eta - 6\epsilon \simeq -3\frac{c^2}{v^4} - 2\kappa - 4n(n-1)g\frac{\varphi^{n-2}}{v^2}}$$

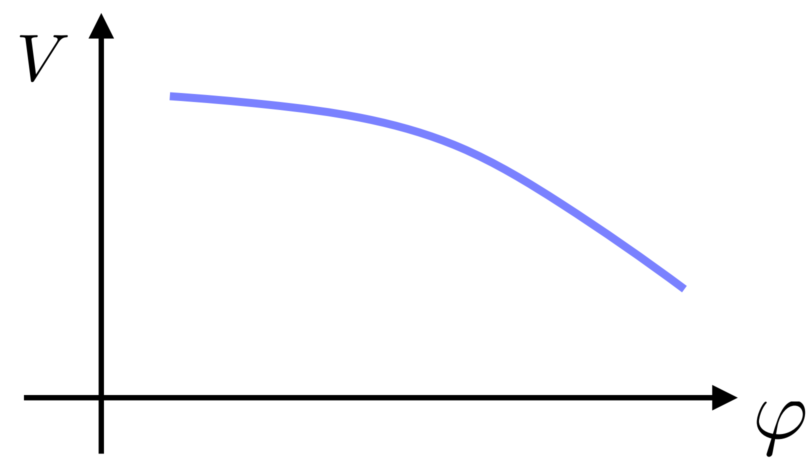
- κ < 0
  - power spectrum has a peak when $V'' \sim 0$
    $\Rightarrow \; n_s - 1 = 0$

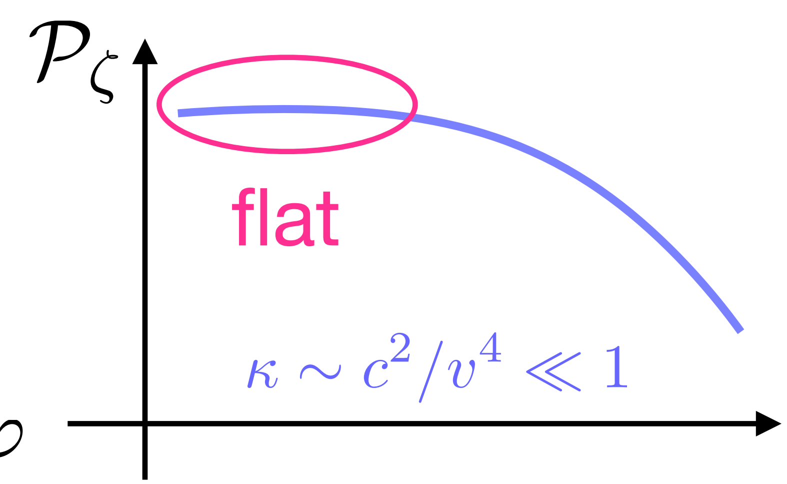




➡ PBHs with wide range of mass are produced

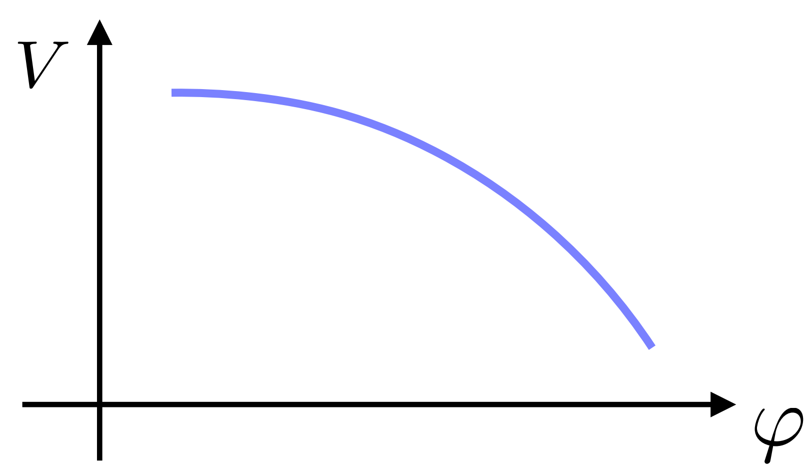
- κ ~0 $|\kappa| \lesssim c^2/v^4 \sim v^4 \ll 1$
  - power spectrum is almost flat around $\varphi \sim \varphi_{\rm ini}$

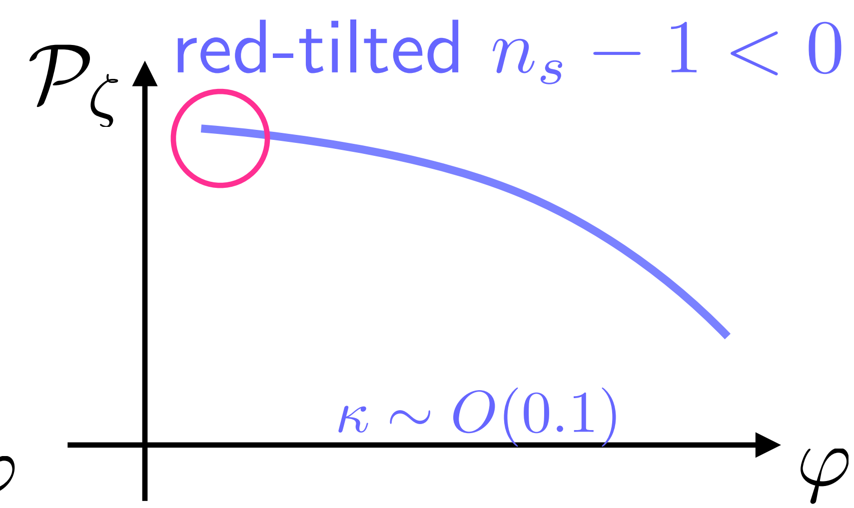




➡ PBHs with very wide range of mass are produced

- κ > 0
  - power spectrum takes the largest value at $\varphi \sim \varphi_{\rm ini}$

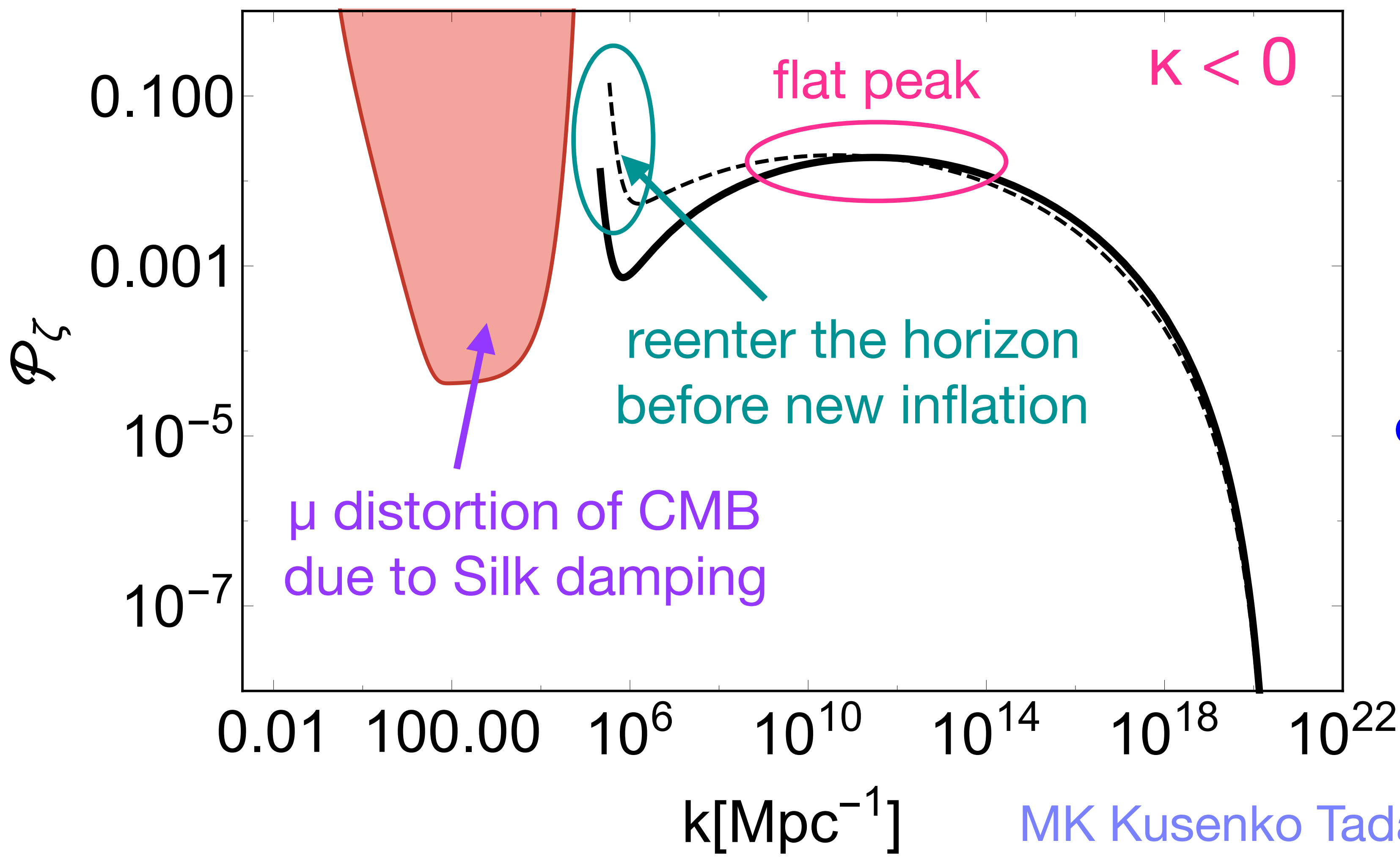




➡ PBHs with narrow range of mass are produced

Power spectrum of curvature perturbations

- Estimate power spectrum using slow-roll approximation



solid

$v = 10^{-4}$
$\kappa = -0.44$
$c = 5.20 \times 10^{-16}$
$g = 5.04 \times 10^{-3}$

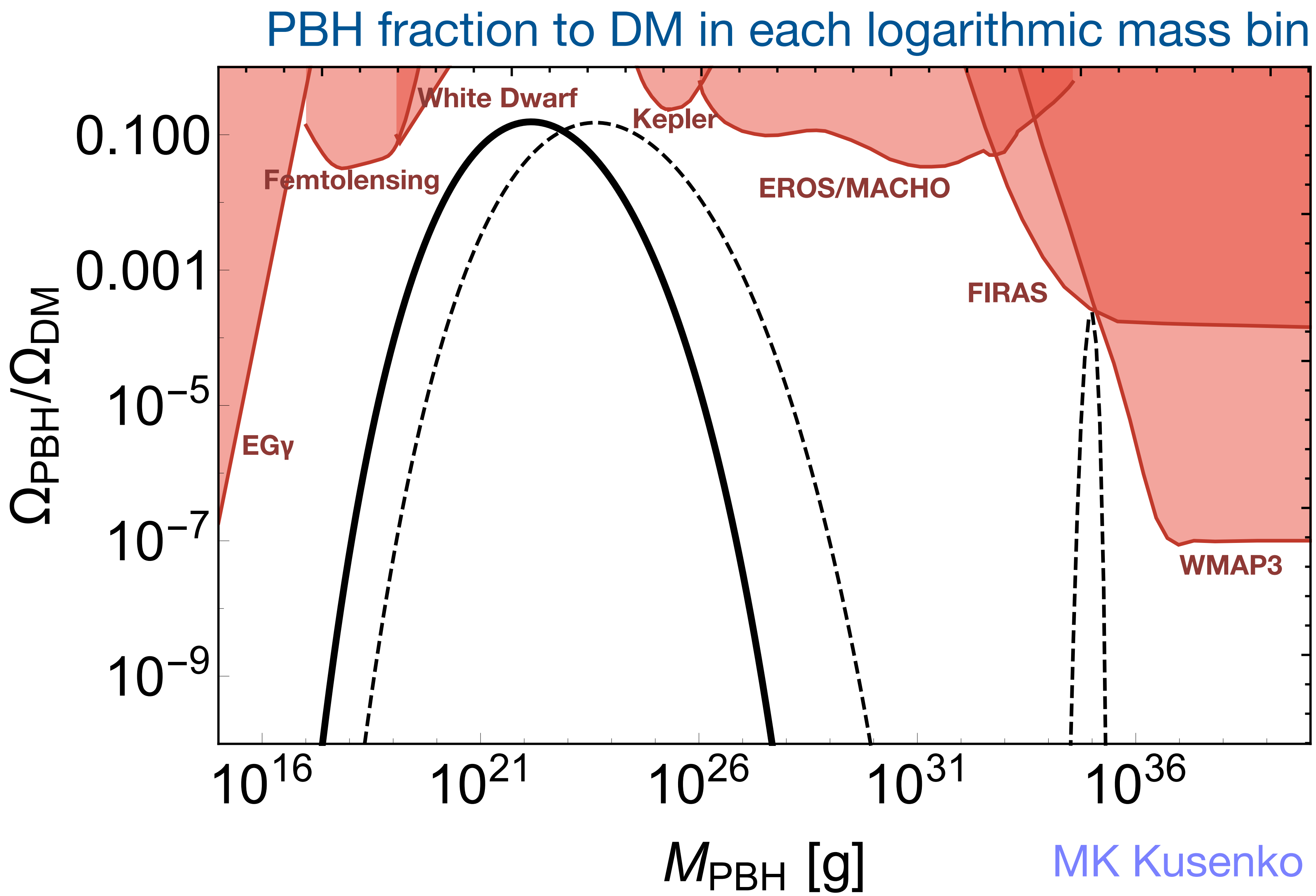
dashed

$v = 10^{-4}$
$\kappa = -0.18$
$c = 1.56 \times 10^{-16}$
$g = 4.26 \times 10^{-3}$

MK Kusenko Tada Yanagida (2016)

- Another peak at $k \sim 10^6$ Mpc^{-1}
  - Hubble induced term cannot neglected at the beginning of new inflation, which flattens the potential
  - However, it should be examined more carefully

Abundance of produced PBHs



κ < 0

MK Kusenko Tada Yanagida (2016)

- Total PBH fraction to DM can be 1

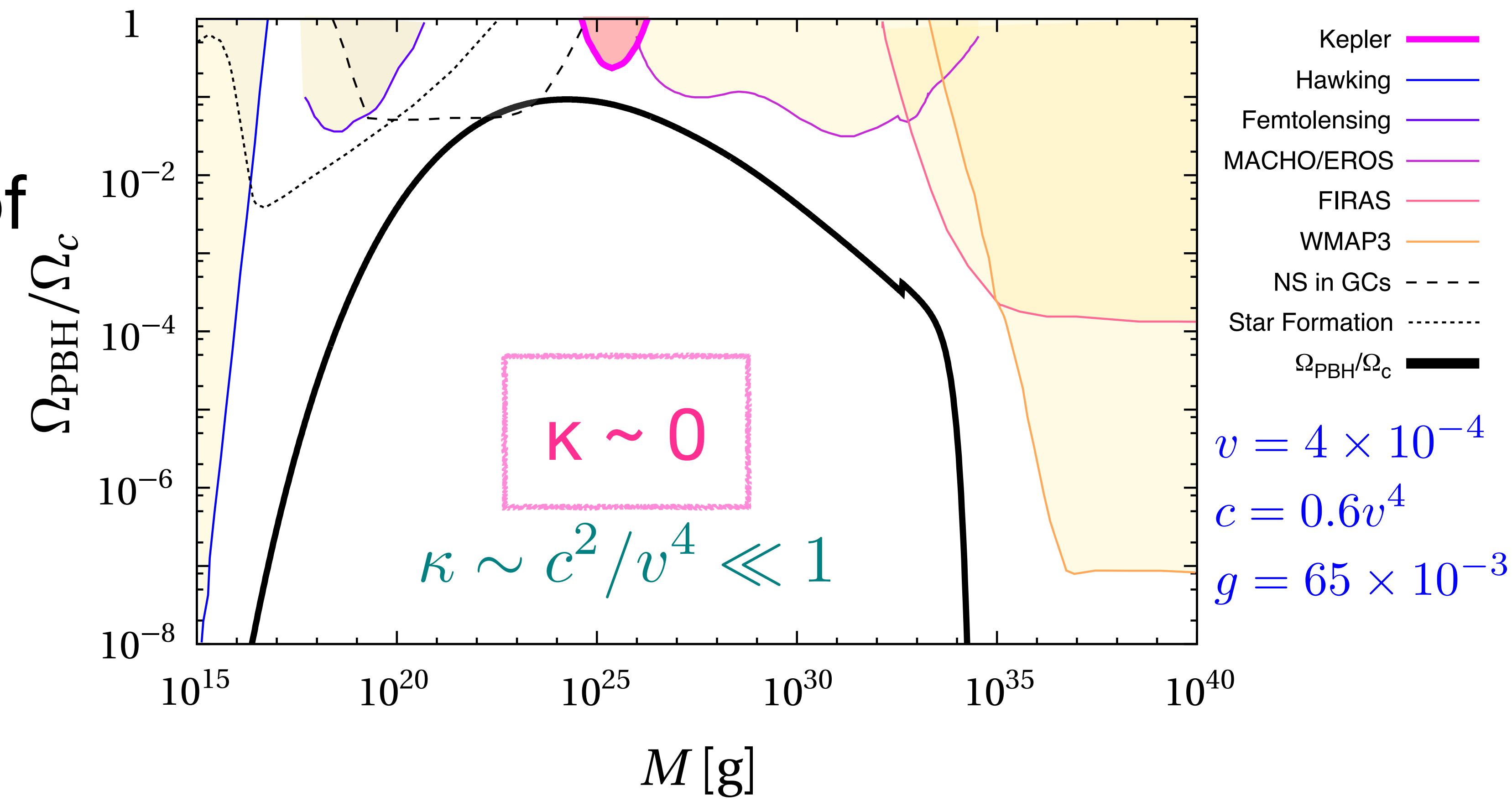
$$\Omega_{\mathrm{PBH}}/\Omega_{\mathrm{DM}} = \int d\log M\, f_{\mathrm{PBH}}(M) \simeq 1$$

- Another peak at $M_{\mathrm{PBH}} \sim 30 M_{\odot}$
  - GW150914 recently detected by LIGO/Virgo collaboration?

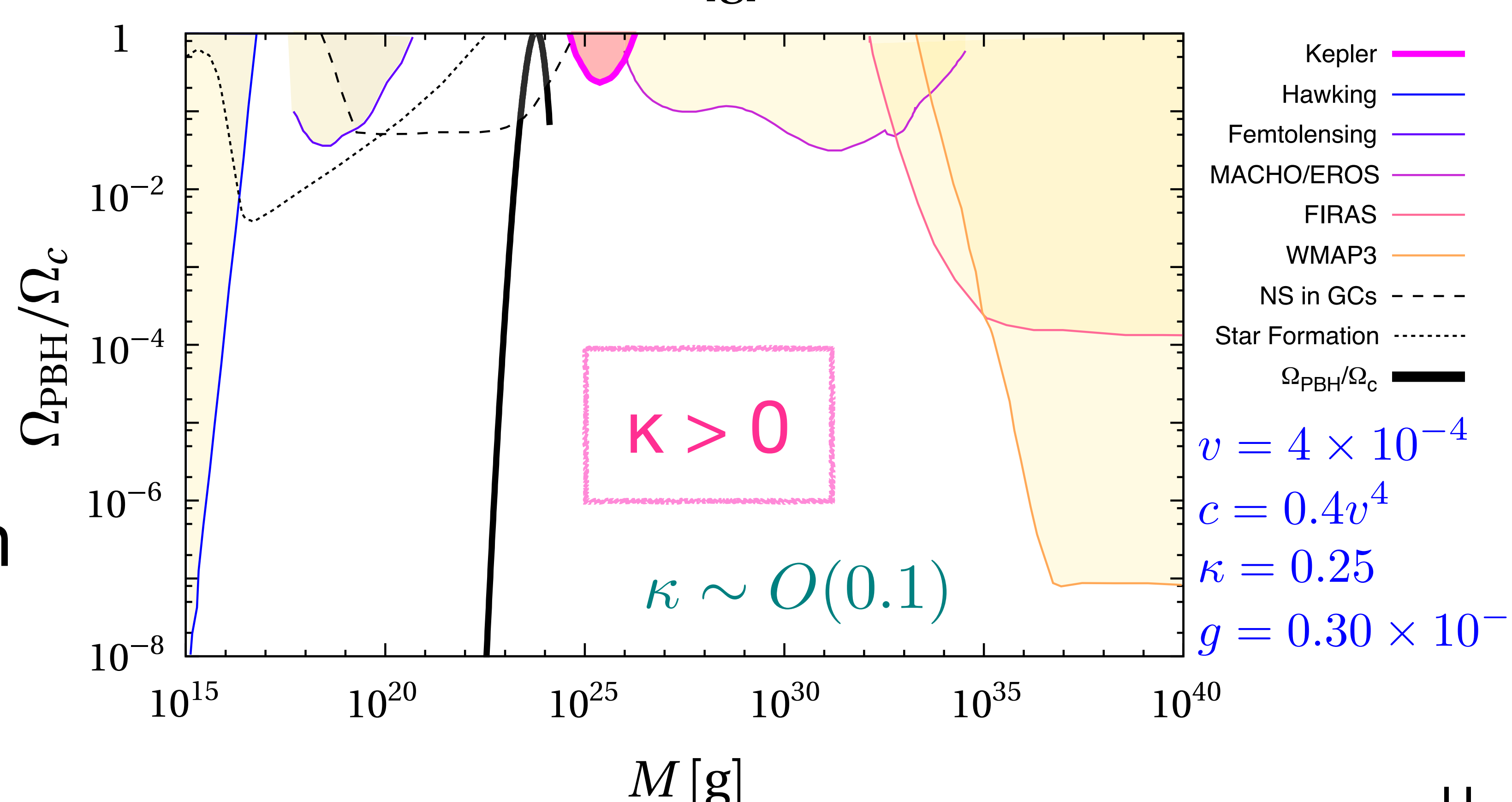
Abundance of produced PBHs

MK Mukaida Yanagida (2016)

- For $\kappa \sim c^2/v^4 \ll 1$
  PBHs with wide range of mass are produced



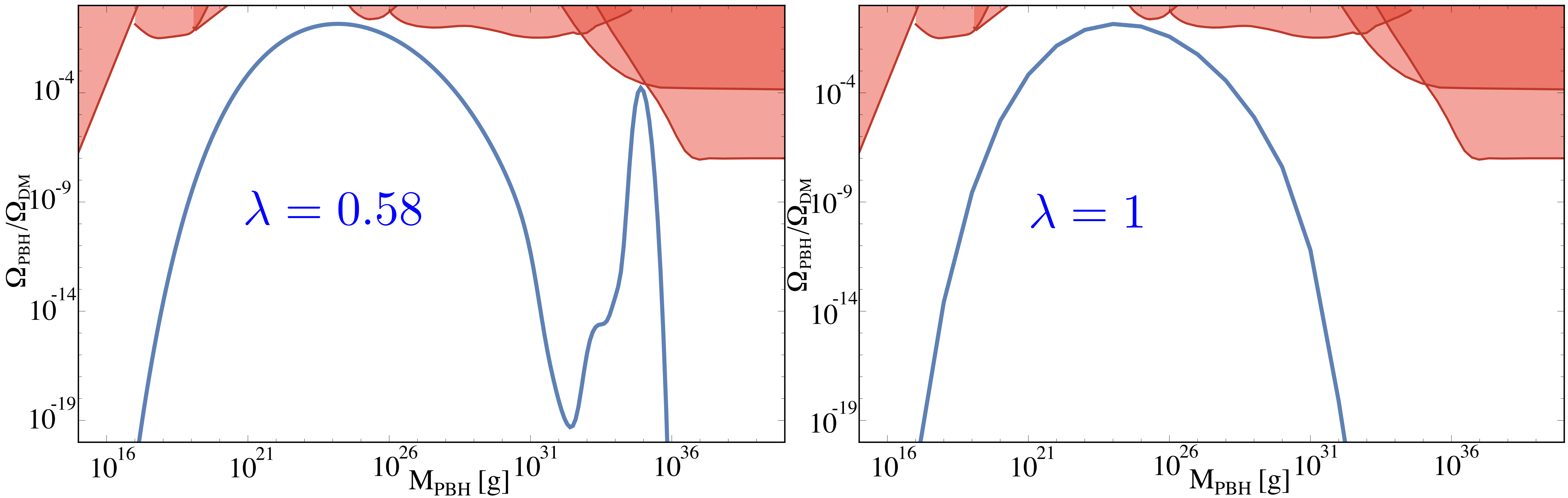
- For $\kappa \sim O(0.1)$
  PBHs with very narrow range of mass are produced



- For both cases PBH can be DM

Another peak at large PBH mass

- The corresponding perturbations reenter the horizon before new inflation
- We need careful numerical calculation including all 1st order perturbations of metrics and scalar fields Inomate MK Tada (2016)
- Chaotic inflation + New inflation with $\Delta V = -\frac{\lambda}{4} m^2 \chi^2 \varphi^2 \sim \lambda H^2 \varphi^2$
- Peak height crucially depends on the Hubble induced term



4. New Inflation in Supergravity

Izawa Yanagida (1997)

- Potential of a scalar field in supergravity

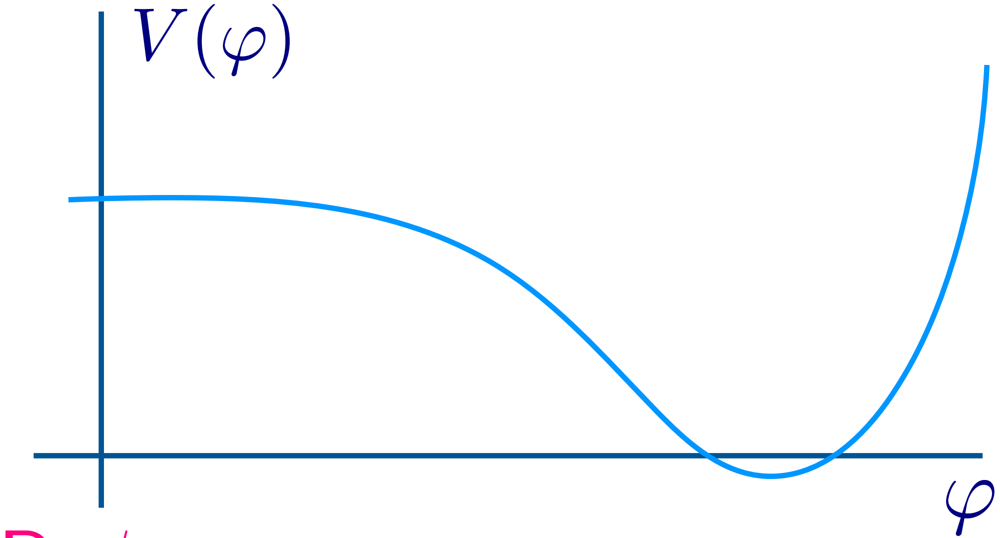
$$V(\phi) = e^K \left((D_\phi W) K^{\phi\bar\phi} (D_\phi W)^* - 3|W|^2 \right)$$

$$D_\phi W = \frac{\partial W}{\partial \phi} + \frac{\partial K}{\partial \phi} W$$

$$K^{\phi\bar\phi} = \left(\frac{\partial^2 K}{\partial \phi \partial \bar\phi} \right)^{-1}$$

- Superpotential W (assuming Z_{2nR} R-symmetry)

$$W(\phi) = v^2 - \frac{g}{n+1}\phi^{n+1}$$



- Kähler potential

$$K(\phi) = |\phi|^2 + \frac{\kappa}{4}|\phi|^4 + \cdots$$

- Inflaton potential   Inflaton $\varphi = \sqrt{2}\mathrm{Re}\phi$

$$\Rightarrow \quad V(\varphi) = v^4 - \frac{\kappa}{2} v^4 \varphi^2 - \frac{g}{2^{n/2-1}} v^2 \phi^n + \cdots$$

- Potential minimum

$$\langle V(\varphi) \rangle \simeq -3 v^4 \left(\frac{v^2}{g} \right)^{2/n}$$

⬅ canceled by ~~SUSY~~ contribution μ_{SUSY}^4

$$\Rightarrow \quad m_{3/2} \simeq \mu_{\mathrm{SUSY}}^2/\sqrt{3} \simeq v^2 \left(\frac{v^2}{g} \right)^{1/n}$$

New Inflation in Supergravity

- Constant term in superpotential $W = W(\phi) + c$
  - Linear term → $V_{\rm lin} = -2\sqrt{2}v^2\varphi$
- Hubble induced term
  - Inflaton φ obtains the Hubble induced mass during and after the first inflation(=preinflation) through the term

$$V \simeq e^K(V_{\rm pre} + \cdots) \rightarrow \lambda H^2\varphi^2 \qquad \lambda \sim O(1)$$

- Just before new inflation starts, the inflaton has the initial value

$$\varphi_i \sim \frac{c}{v^2}$$

No initial value problem

- Potential

$$V(\varphi) = v^4 - 2\sqrt{2}cv^2\varphi - \frac{\kappa}{2}v^4\varphi^2 - \frac{g}{\sqrt{2}}v^2\phi^3 + \cdots$$

- PBH formation → $c \sim v^4$

SUSY breaking sector

- Dynamical SUSY breaking models

Izawa Yanagida (1996), Intriligator Thomas(1996)

$$W_{\not{\text{SUSY}}} = \frac{\Lambda^2}{4\pi} Z \qquad (Z\text{: } \not{\text{SUSY}} \text{ breaking field})$$

$$\mu^2_{\text{SUSY}} = \frac{\Lambda^2}{4\pi}$$

- If the origin of Z is destabilized due to a large Yukawa coupling (~ 4π)

Chacko Luty Ponton (1998)

$$\langle Z \rangle \simeq \frac{\Lambda}{4\pi}$$

$$\rightarrow W_{\not{\text{SUSY}}} \sim \frac{\Lambda^3}{(4\pi)^2} \sim \boxed{c \sim \mu^3_{\text{SUSY}}}$$

- New inflation model (n=3)

$$\boxed{\begin{array}{c} \mu_{\text{SUSY}} \sim v^{4/3} \\ c \sim v^4 \end{array}} \rightarrow \boxed{c \sim \mu^3_{\text{SUSY}}}$$

consistent

5. Production of gravitational waves

- PBHs form from large curvature perturbations

- 2nd order perturbations ~ $O(\zeta_{\vec{k}}\zeta_{\vec{k}-\vec{k}'})$ induce a source term of tensor perturbations

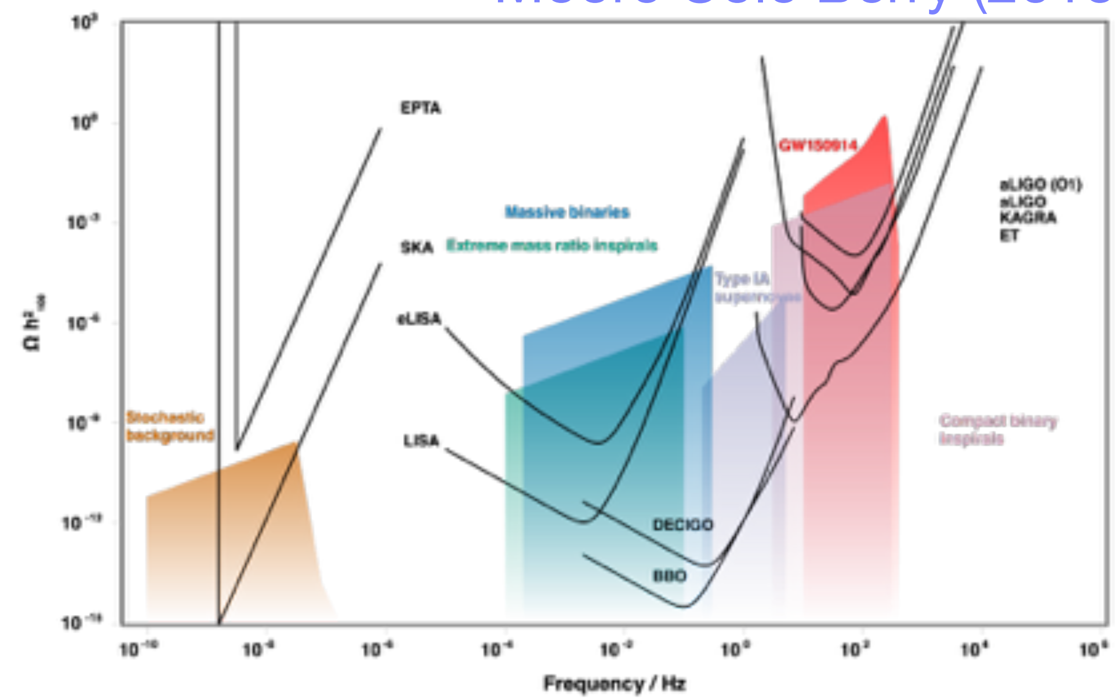
Saito Yokoyama (2009) Bugaev Kulimai (2010)

$$h''_{\vec{k}} + 2\mathcal{H}h'_{\vec{k}} + k^2 h_{\vec{k}} = \mathcal{S}(\vec{k}, t)$$

$$\rightarrow \Omega_{\rm GW}h^2 \sim 10^{-8}(\mathcal{P}_\zeta/10^{-2})^2$$

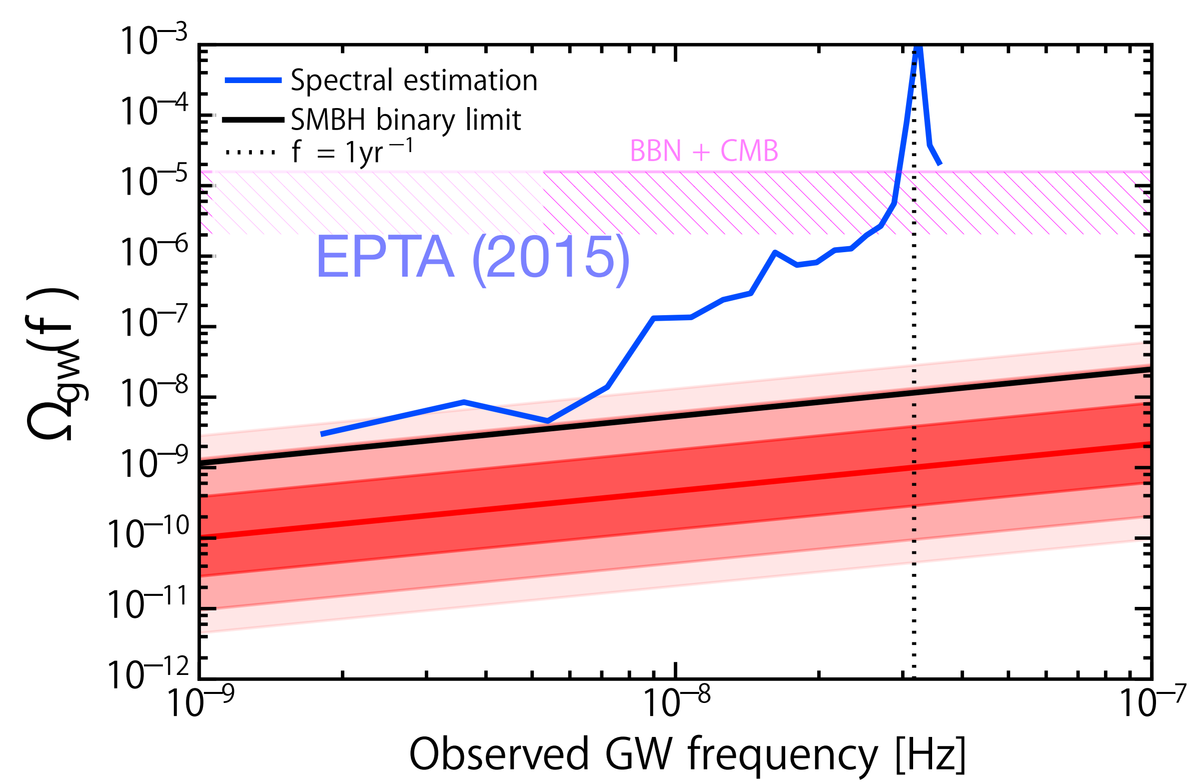
$$f_{\rm GW} \sim 2\times 10^{-9}\,{\rm Hz}(M_{\rm PBH}/M_\odot)^{-1/2}$$

Moore Cole Berry (2015)



- GWs can be probed future detectors

- Pulsar timing experiments already give a stringent constraint on PBHs with $M_{\rm PBH} \sim 0.1 - 10\ M_\odot$



6. Conclusion

- PBHs can be formed in double inflation (=preinflation + new inflation)
- The new inflation potential has linear and quadratic terms which play an important role in determining the initial value and amplitude of curvature perturbations
- In this model PBHs with wide range of mass can be produced and account for DM of the universe
- The model is realized in framework of supergravity
- Large curvature perturbations required for PBH production also produce gravitational waves which will be proved by future detectors

Backup

Power spectrum of curvature perturbations with double peaks