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Primordial Black Holes in Multi-field Inflation Models

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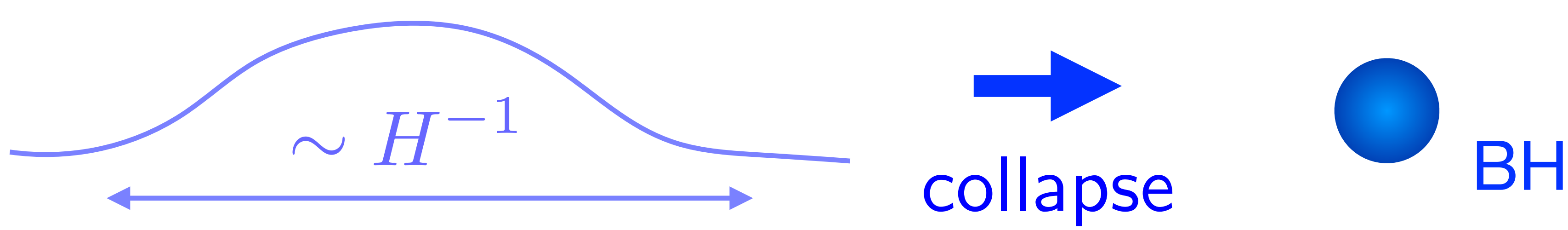
Based on MK Mukaida Yanagida, arXiv:1605.04974
MK Kusenko Tada Yanagida arXiv:1606.07631
Inomate MK Mukaida Tada Yanagida, arXiv:1611.06130, 1701.02544
Ando, Inmate, MK, in preparation

1. Introduction

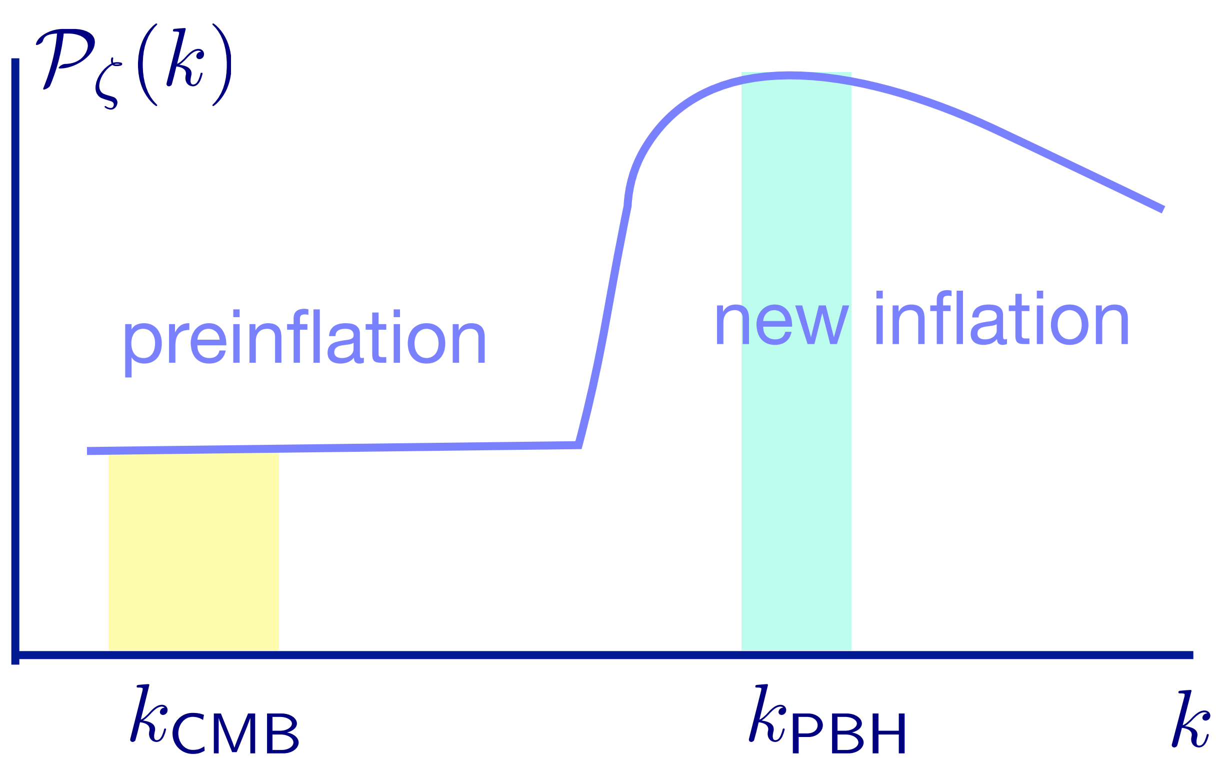
- Primordial Black Holes (PBHs) Zeldovich-Novikov (1967) Hawking (1971)
- PBHs has attracted our interest because they could
  - Give a significant contribution to dark matter
  - Account for GW events detected by LIGO recently
- PBHs can be formed by gravitational collapse of over-density region with Hubble radius in the early universe

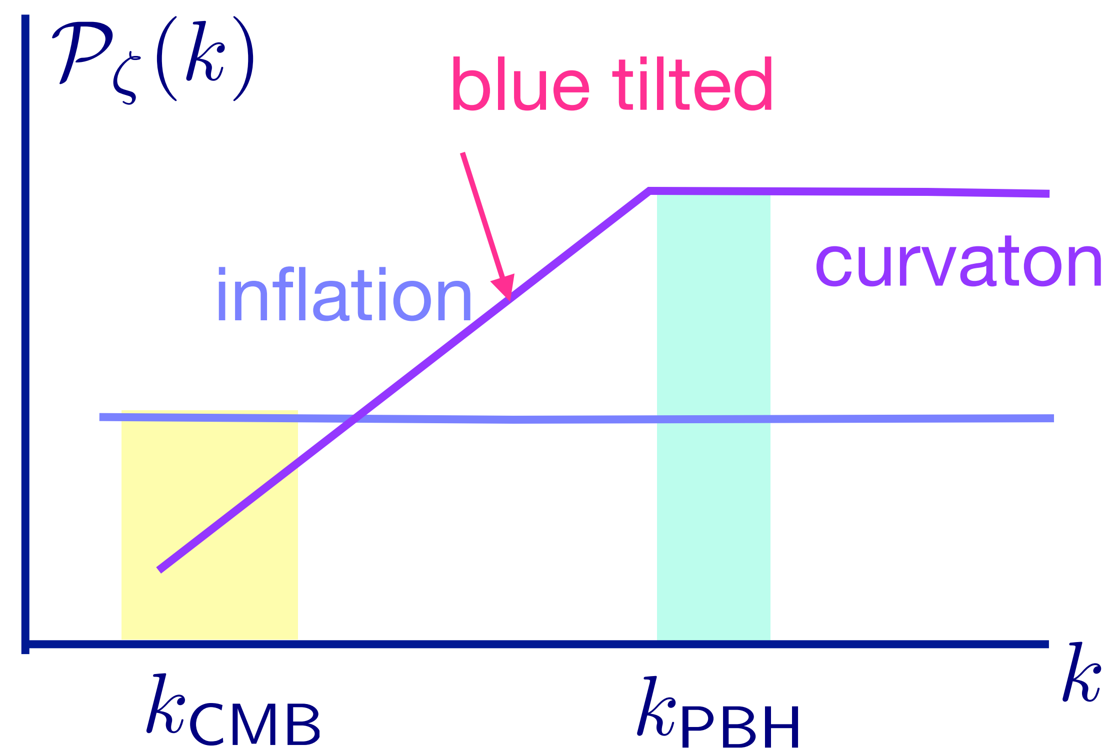


- Large density fluctuations δ with O(0.1) are required for PBH formation but $\delta \sim O(10^{-5})$ on CMB scale

→ need to break scale invariance of spectrum of density fluctuations

- We consider the following two-field models for PBH formation
  - Double inflation (preinflation+new inflation) MK, Sugiyama, Yanagida (1998)
  - Axion-like curvaton MK, Kitajima, Yanagida (2013)

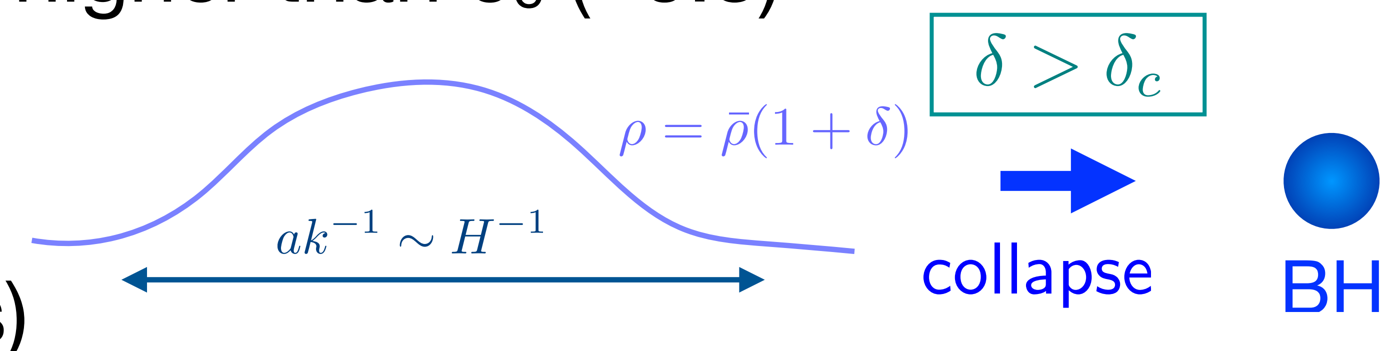




- Large curvature perturbations lead to PBH formation when they re-enter the horizon after inflation

2. PBH formation in radiation dominated universe

- When density fluctuations reenter the horizon, a PBH is formed if its over-density is higher than δ_c (≈ 0.3)



- PBH mass (~ Horizon mass)

$$M_{\text{PBH}} \simeq 3.6 M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{k}{10^6 \text{Mpc}^{-1}}\right)^{-2} \simeq 4.5 M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{T}{0.1 \text{GeV}}\right)^{-2}$$

$M_{\text{PBH}} = \gamma M_H$ (horizon mass) [$\gamma = 0.2$ Carr (1975)]

- PBH abundance is estimated by Press-Schechter formalism

$\mathcal{P}_\zeta(k)$ → PBH mass fraction $\beta = \rho_{\text{PBH}}(M)/\rho$

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

- Present PBH fraction to DM

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

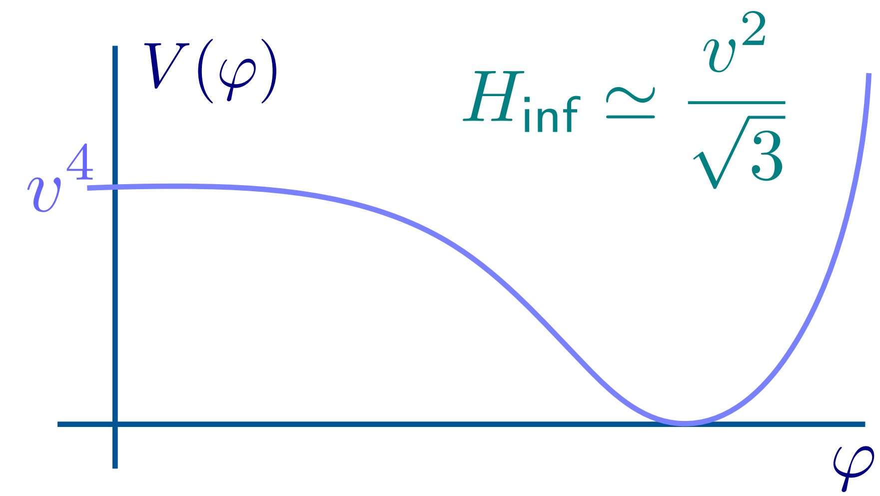
3. Double inflation model

- Potential for new inflation

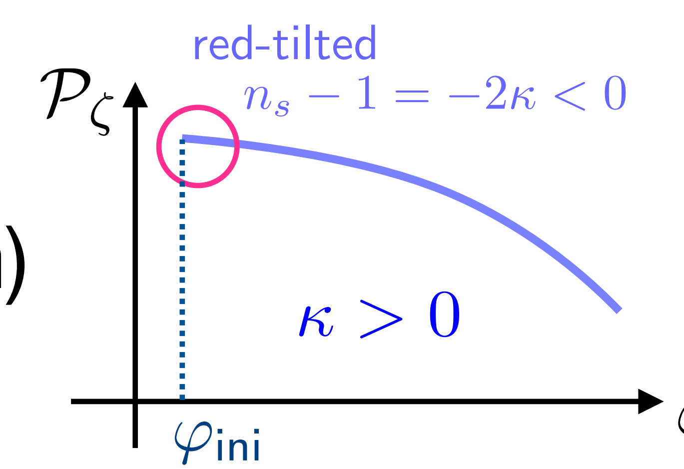
$$V(\varphi) = (v^2 - g\varphi^n)^2 - \varepsilon v^4 \varphi - \frac{1}{2}\kappa v^4 \varphi^2 \quad + cH^2\varphi^2$$

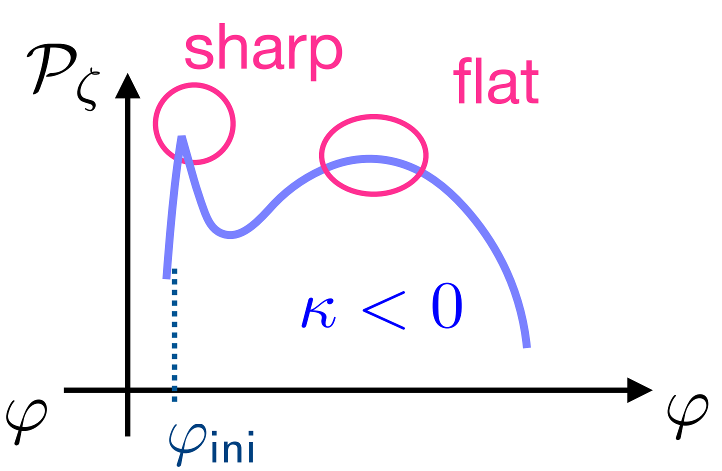
before new inf. ($+ cH^2\varphi^2$)

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



- Linear term $\varepsilon \ll 1$
  - amplitude of curvature perturbations
  - determining initial value $\varphi_{\rm ini} \sim \varepsilon$
- Quadratic term $\kappa \sim O(0.1)$
  - spectrum index
    (shape of power spectrum)





- Curvature perturbation

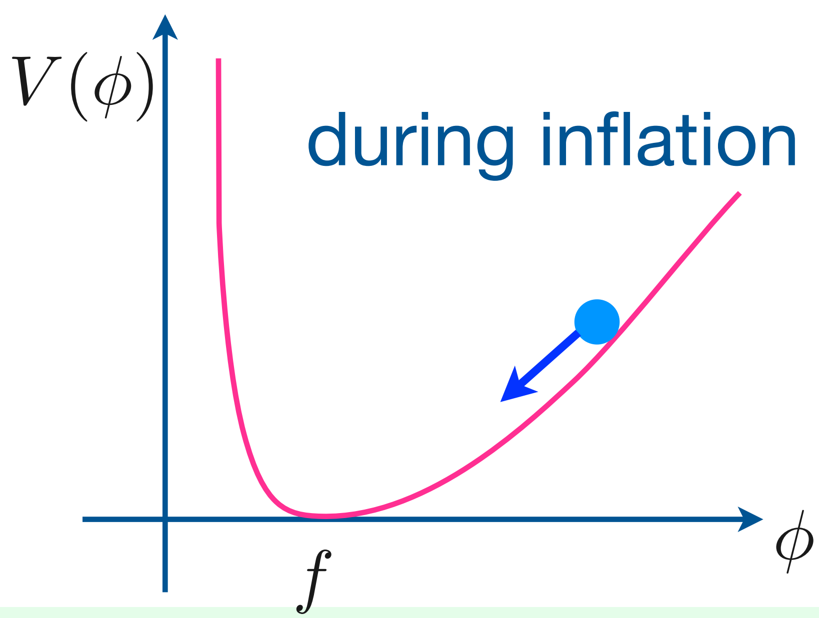
$$\mathcal{P}_\zeta^{1/2} = \frac{H_{\rm inf}}{2\pi}\frac{1}{\sqrt{2\epsilon}} \simeq \frac{1}{2\sqrt{3}\pi}\frac{v^2}{\varepsilon + \kappa\varphi} \sim \frac{1}{2\sqrt{3}\pi}\frac{v^2}{\varepsilon} \qquad (\varphi \lesssim \varepsilon)$$

$\mathcal{P}_\zeta \sim O(0.01)$ for $\varepsilon \sim v^2$ ➡ PBH formation

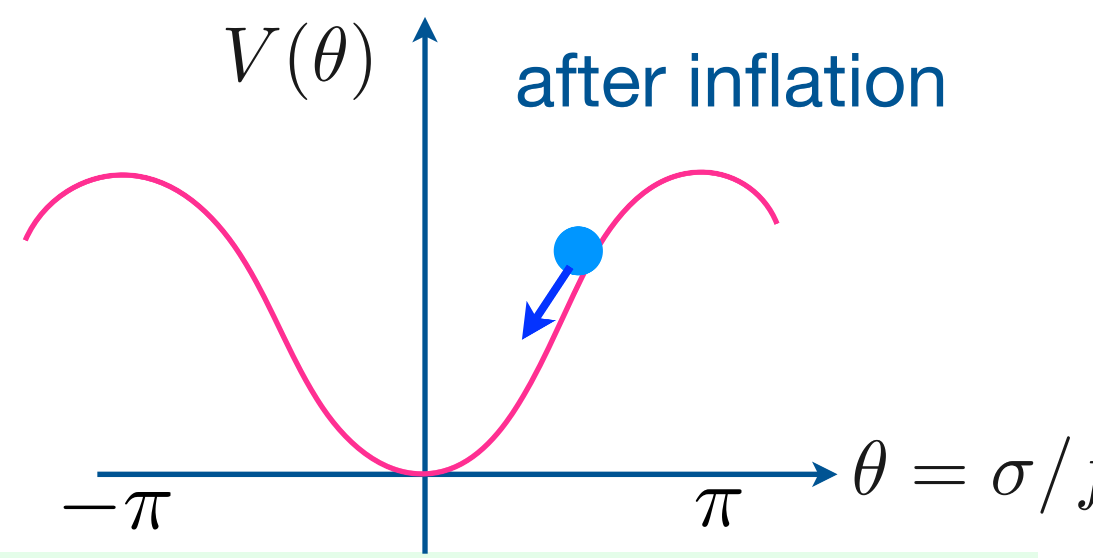
4. Axion-like curvaton model

- Curvaton scenario
  - Scalar field acquires fluctuations during inflation
  - When the curvaton decays its fluctuations produce curvature perturbations
- Axion-like curvaton (curvaton= phase of Φ)

$$\Phi = \phi e^{i\theta}$$



$$V(\phi) = cH_{\rm inf}^2(\phi - f)^2$$



$$V(\sigma) = \Lambda^4\left[1 - \cos(\sigma/f)\right] \simeq \frac{1}{2}m_\sigma^2\sigma^2$$

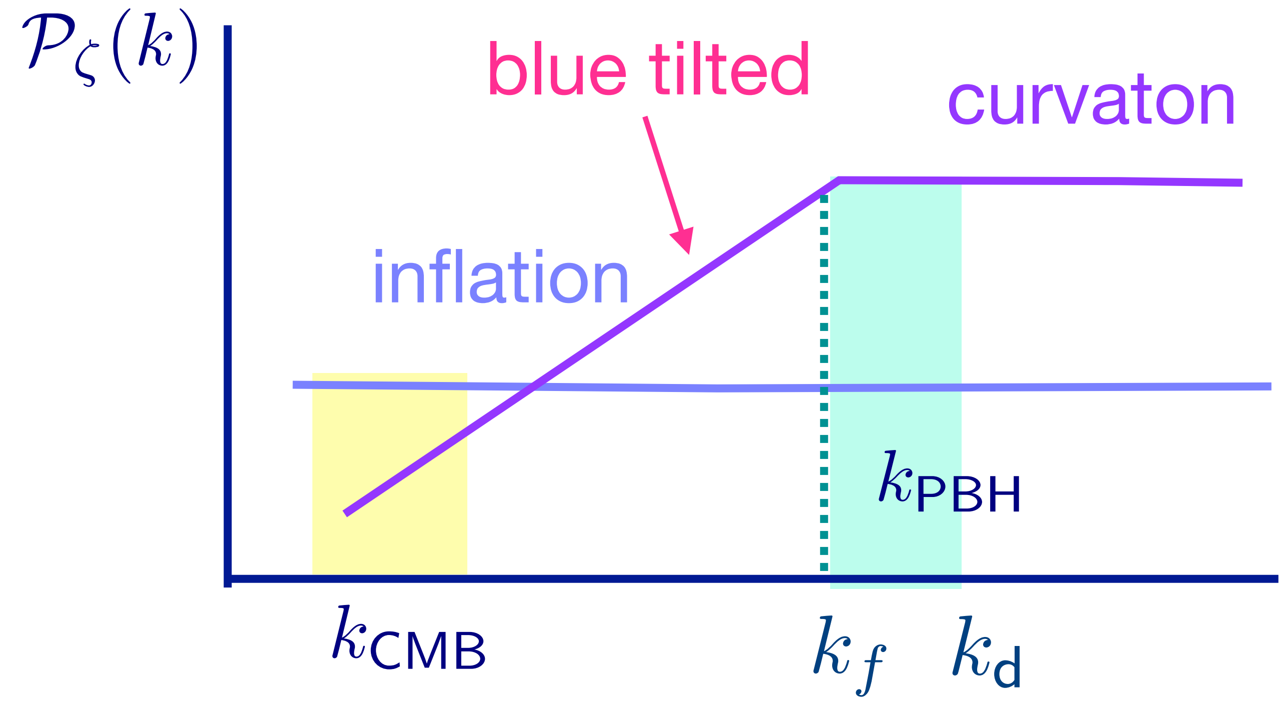
  - curvaton fluctuation

$$\frac{\delta\rho_\sigma}{\rho_\sigma} = 2\frac{\delta\theta}{\theta} = \frac{H_I}{\pi\theta\phi}$$

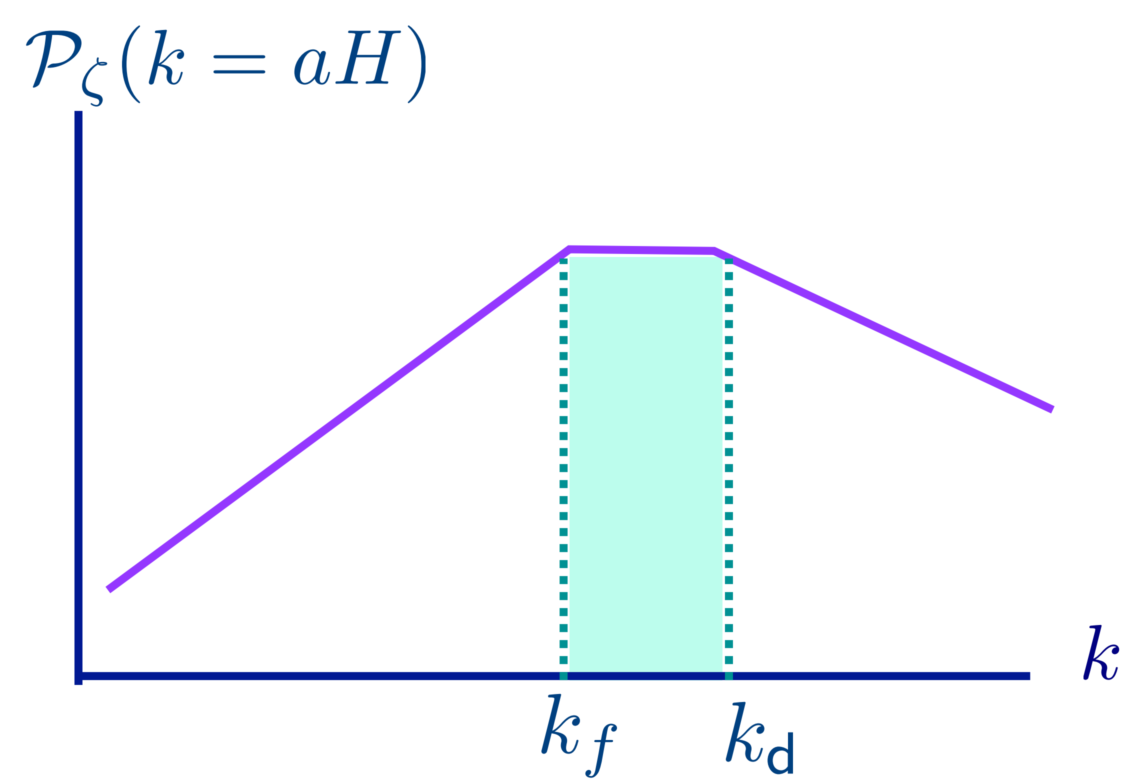
→ **Blue-tilted spectrum**

ϕ decreases during inflation

- Cuvature perturbations
  - blue-tilted at $k < k_f$
    (before ϕ reaches f)
  - scale-invariant at $k > k_f$
    (after ϕ reaches f)
- Power spectrum of curvature perturbations at horizon crossing takes maximum for $k = k_f - k_d$
- Those fluctuations produce PBHs
- If $k_f \sim k_d$ produced PBHs have a sharp mass function



k_f : scale exiting horizon when $\phi = f$

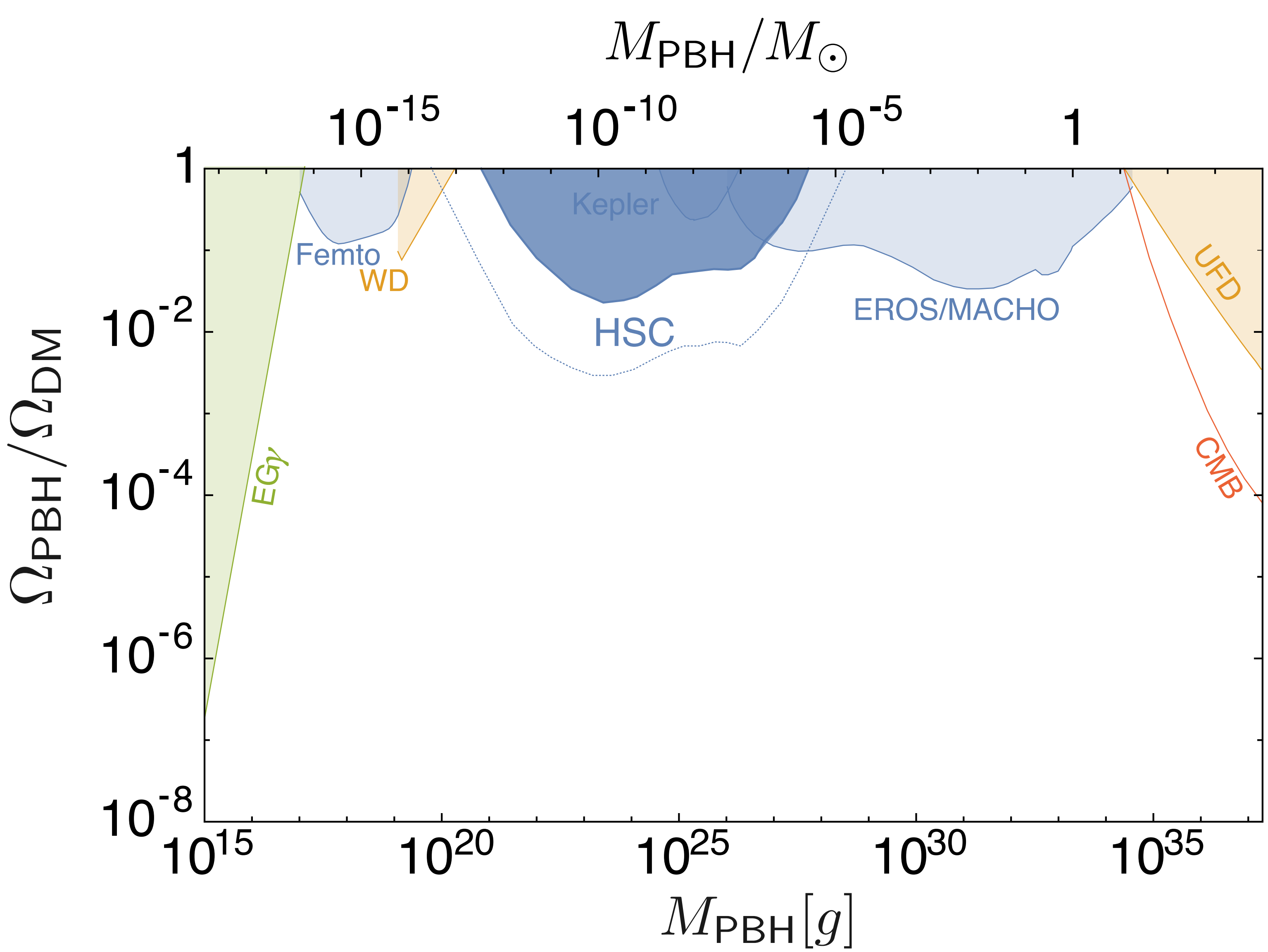


$k_{\rm d}$: scale reenter horizon at curvaton decay

5. Black Hole as Dark Matter

- PBHs can account for all dark matter of the universe?
- Observational constraints on wide range of PBH mass
- In particular the new microlensing constraint

  ➡ only mass region~ 10^{20}g remains
- Double inflation model can produce such DM PBHs



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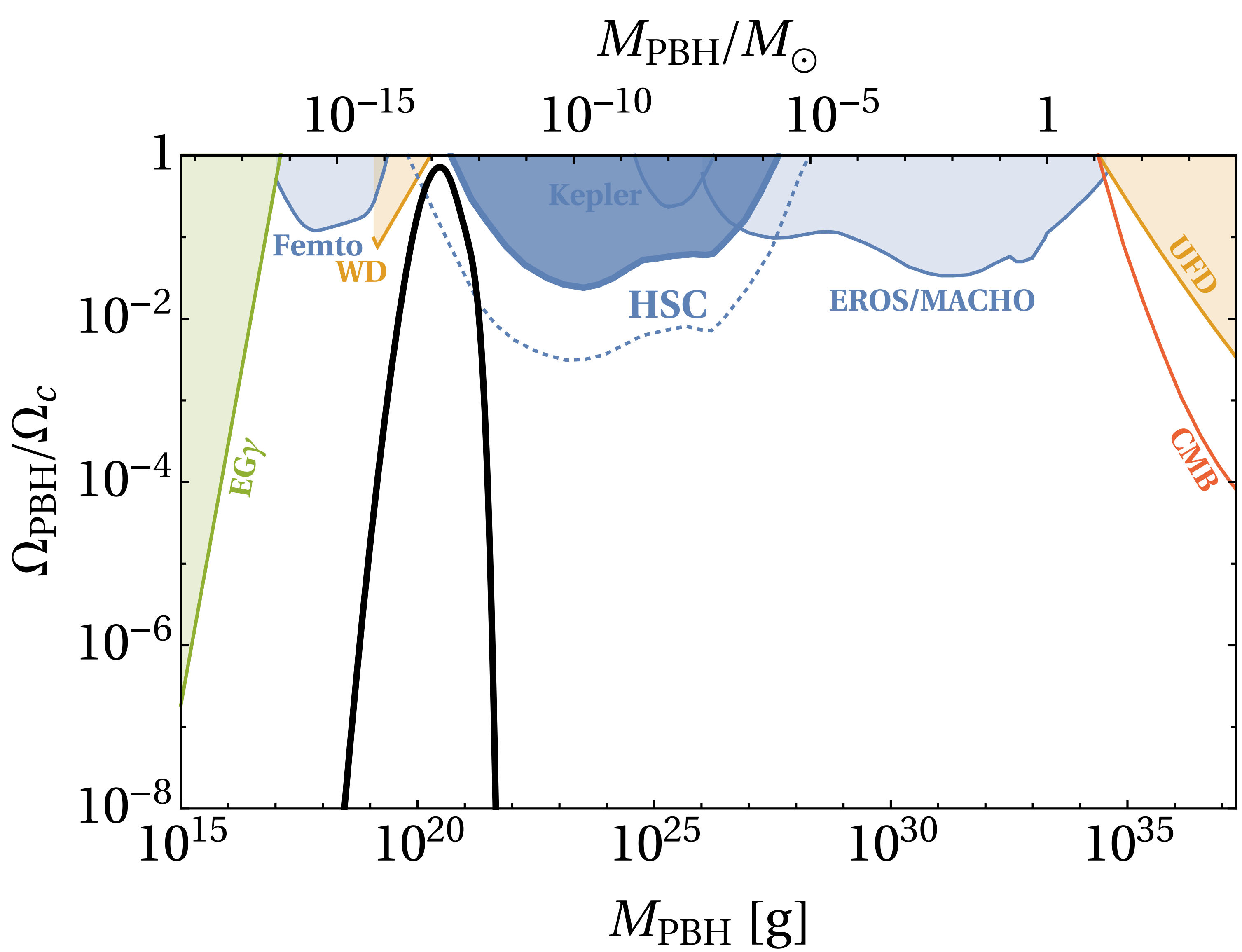


Inomata MK Mukaida Tada Yanagida (2017)

$v = 10^{-3}$ $c_{\rm pot} = 1$

$\kappa = 0.13$

6. PBHs for LIGO gravitational wave events

- GW events by LIGO ➔ BH-BH binary with ~ 30 solar masses

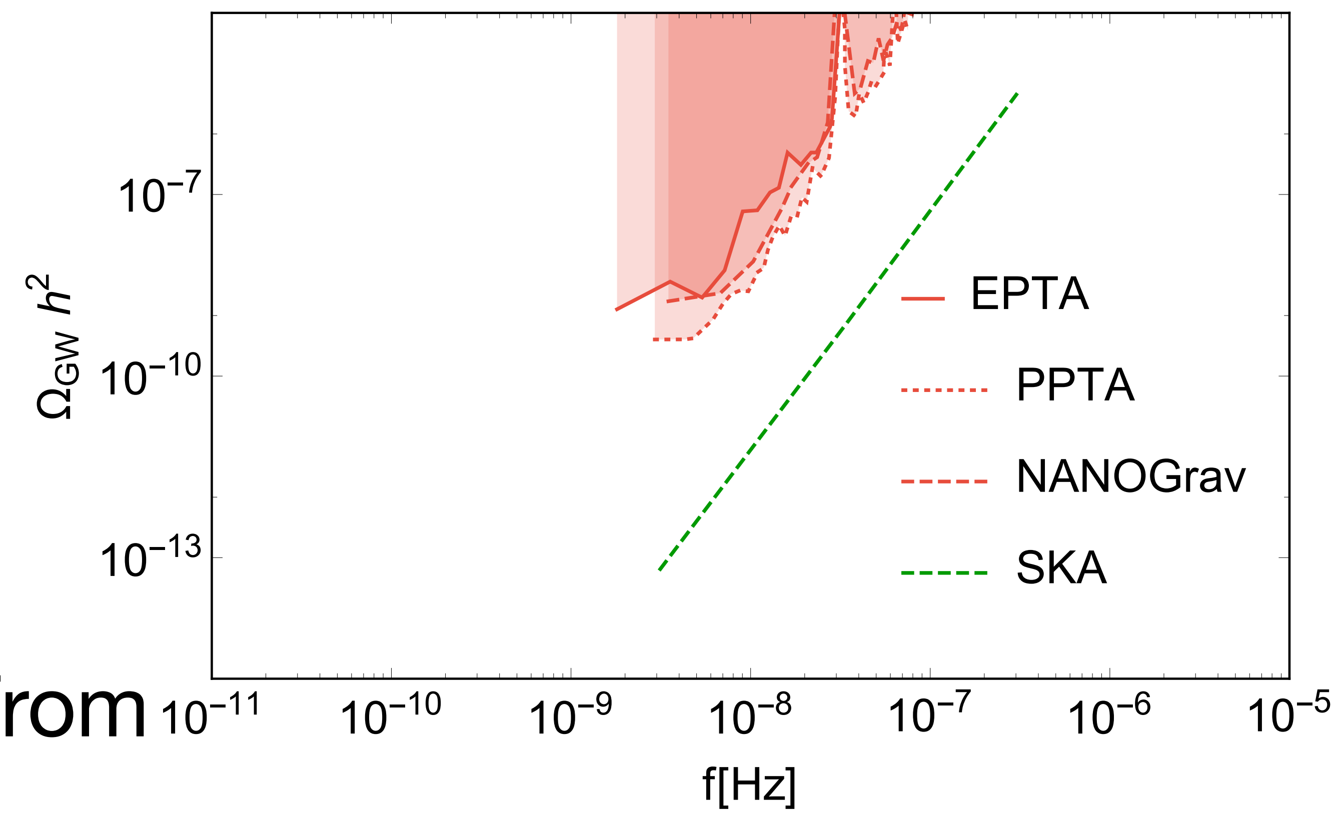
Abbott et al (2016, 2017)

- Origin of BHs ➔ PBHs are one of candidates

- Required fraction of PBHs

$$\Omega_{\mathrm{PBH}}/\Omega_c \sim 10^{-3} - 10^{-2}$$

Sasaki et al (2016)



- However, stringent constraint from pulsar timing experiment

Saito Yokoyama (2009)
Bugaev Kulimai (2010)

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

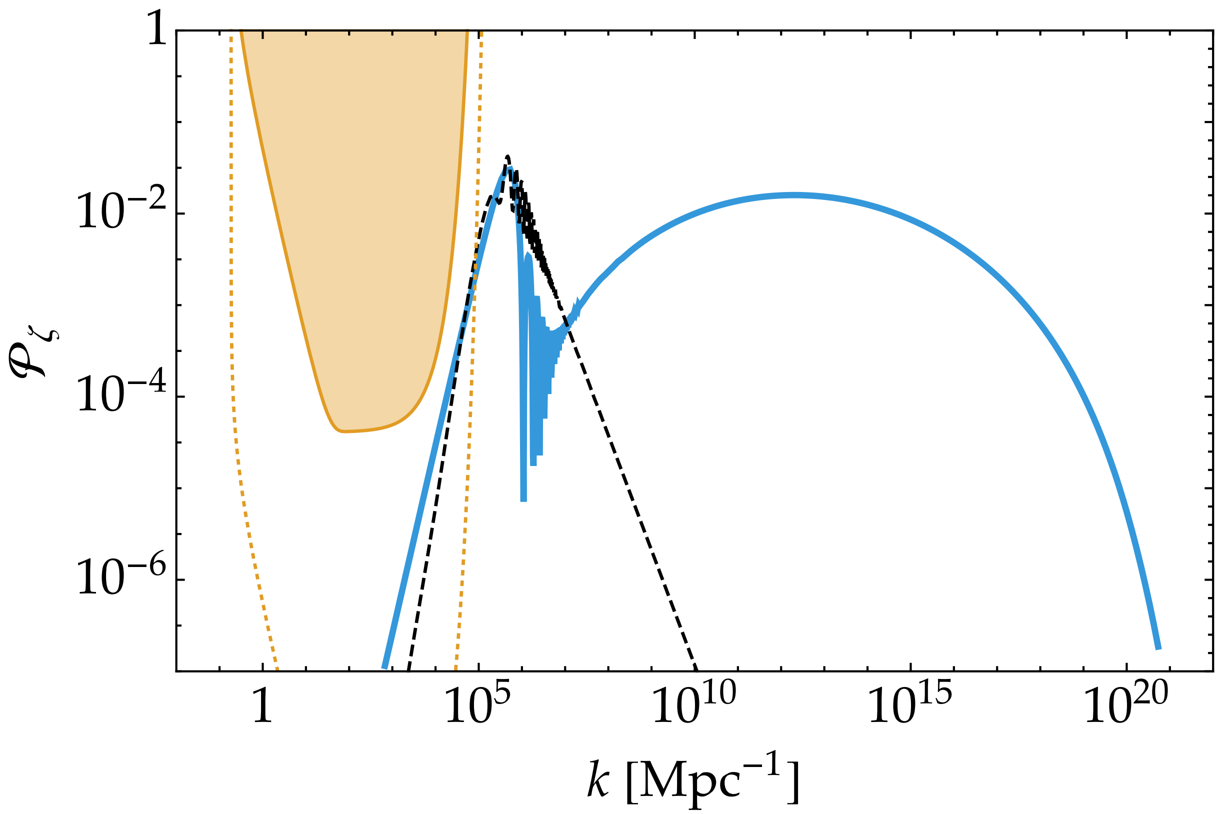
$$\Omega_{\mathrm{GW}} h^2 \sim 10^{-8} (\mathcal{P}_\zeta / 10^{-2})^2$$

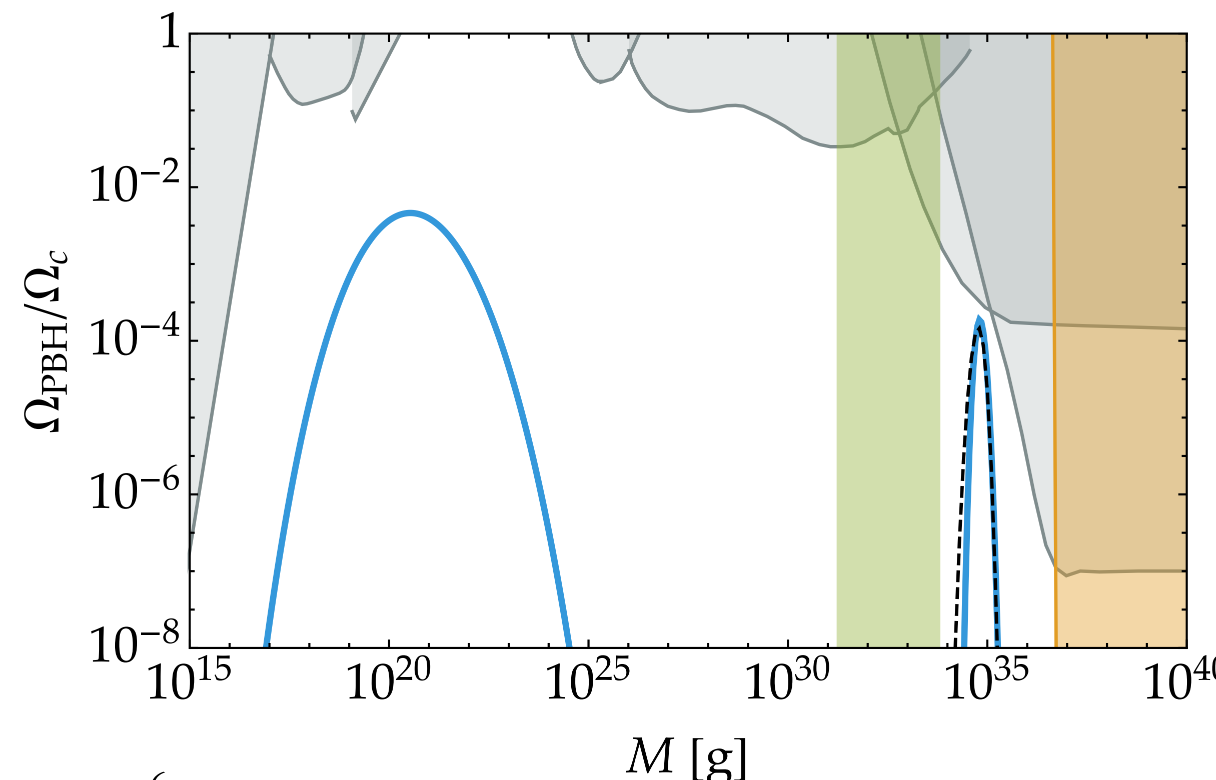
$$f_{\mathrm{GW}} \sim 2 \times 10^{-9}\mathrm{Hz} \left(\frac{\gamma}{0.2}\right)^{1/2} \left(\frac{M_{\mathrm{PBH}}}{M_\odot}\right)^{-1/2}$$

6.1 Double inflation model

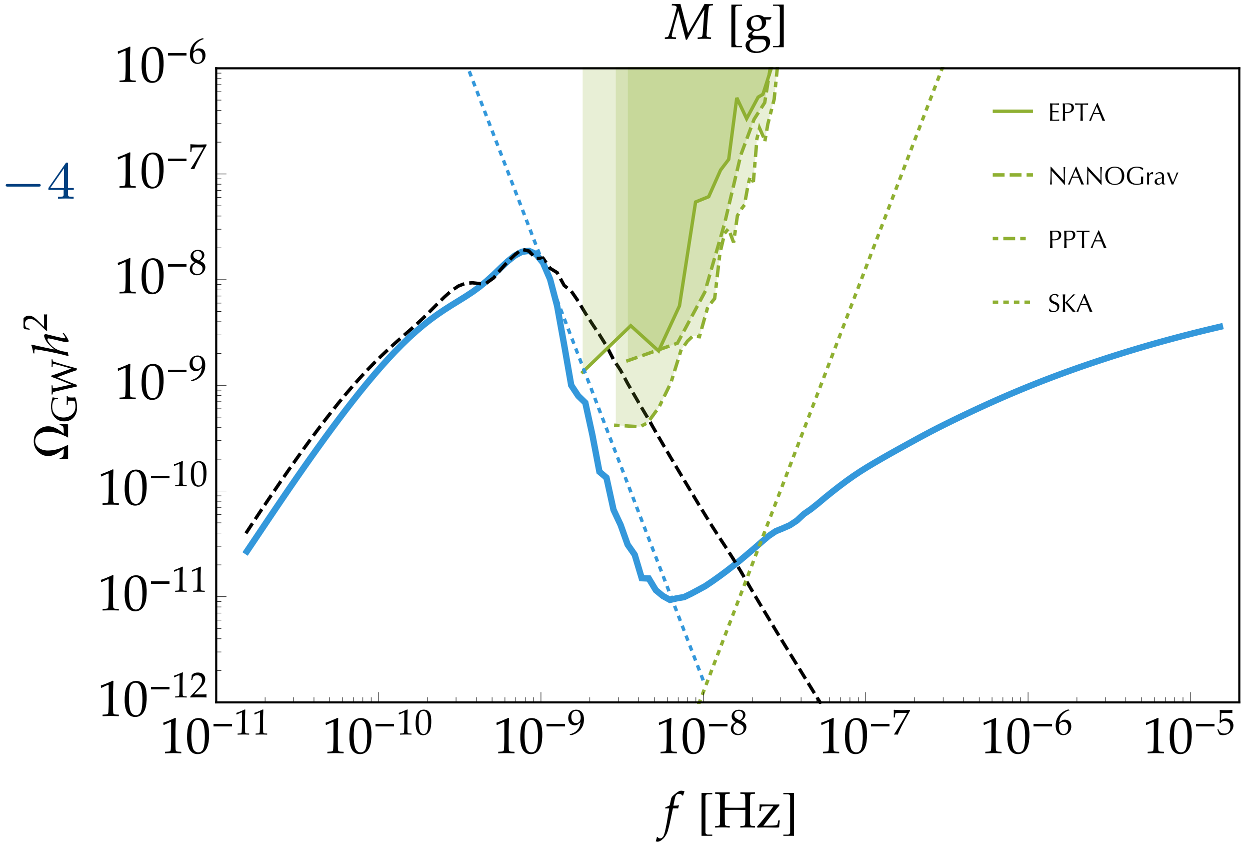
Inomata MK Mukaida Tada Yanagida (2016)

- We need a sharp peak to avoid PTA constraints
- This is possible to choose appropriate sets of parameters





$$\kappa = -0.61 \quad c = 0.005 \quad v = 10^{-4}$$



- Current PTA constraints can be (marginally) avoided

6.2 Axion-like curvaton model

Ando, Inomata MK (2017)

- Axion-like curvaton model can produce PBHs with $M_{\rm PBH} \sim 30 M_\odot$
- PTA constraint is stringent
- However, the model predicts large non-gaussianity

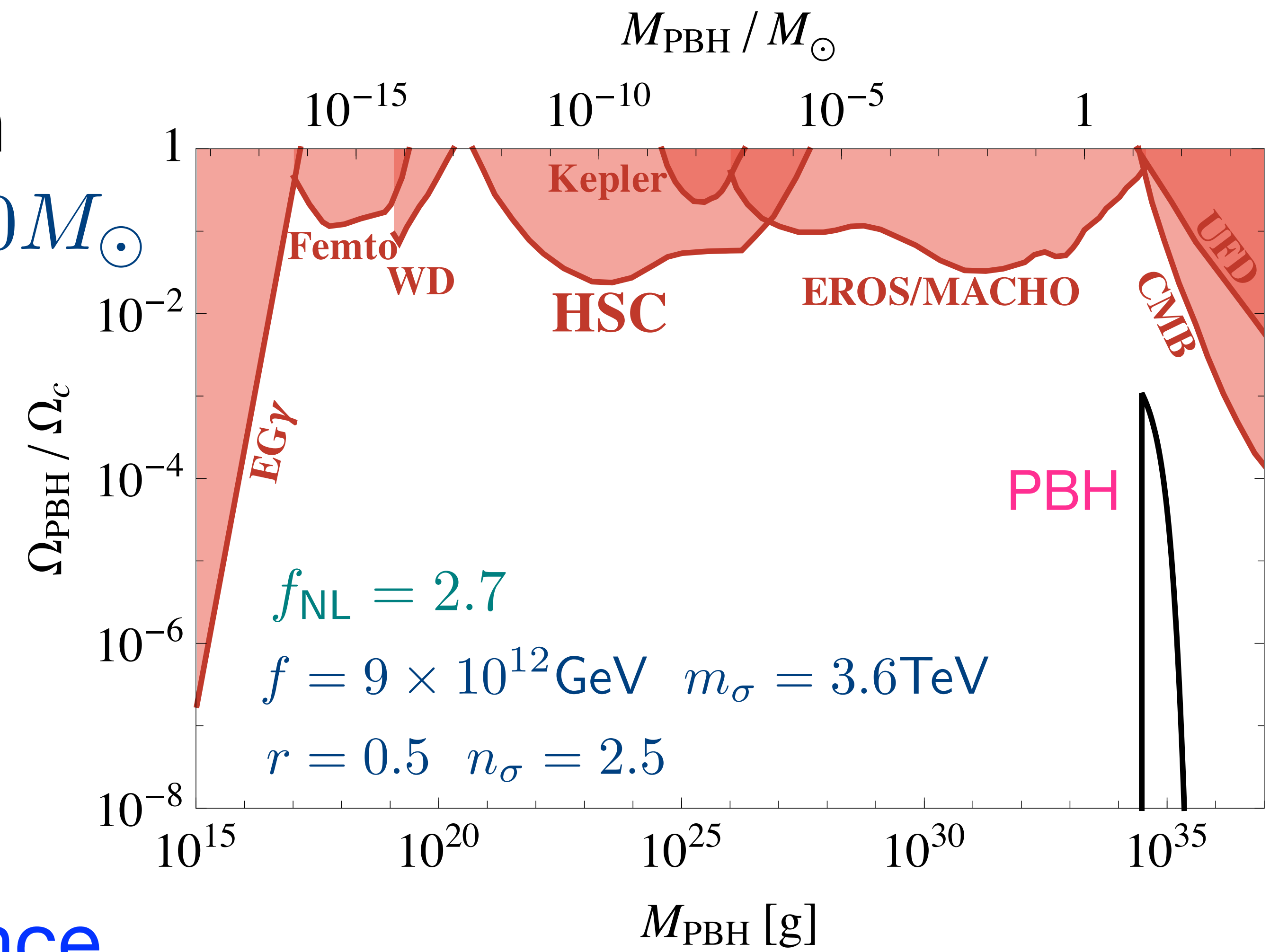
$$\zeta = \zeta_g + \frac{3}{5} f_{\rm NL} (\zeta_g^2 - \langle \zeta_g^2 \rangle)$$

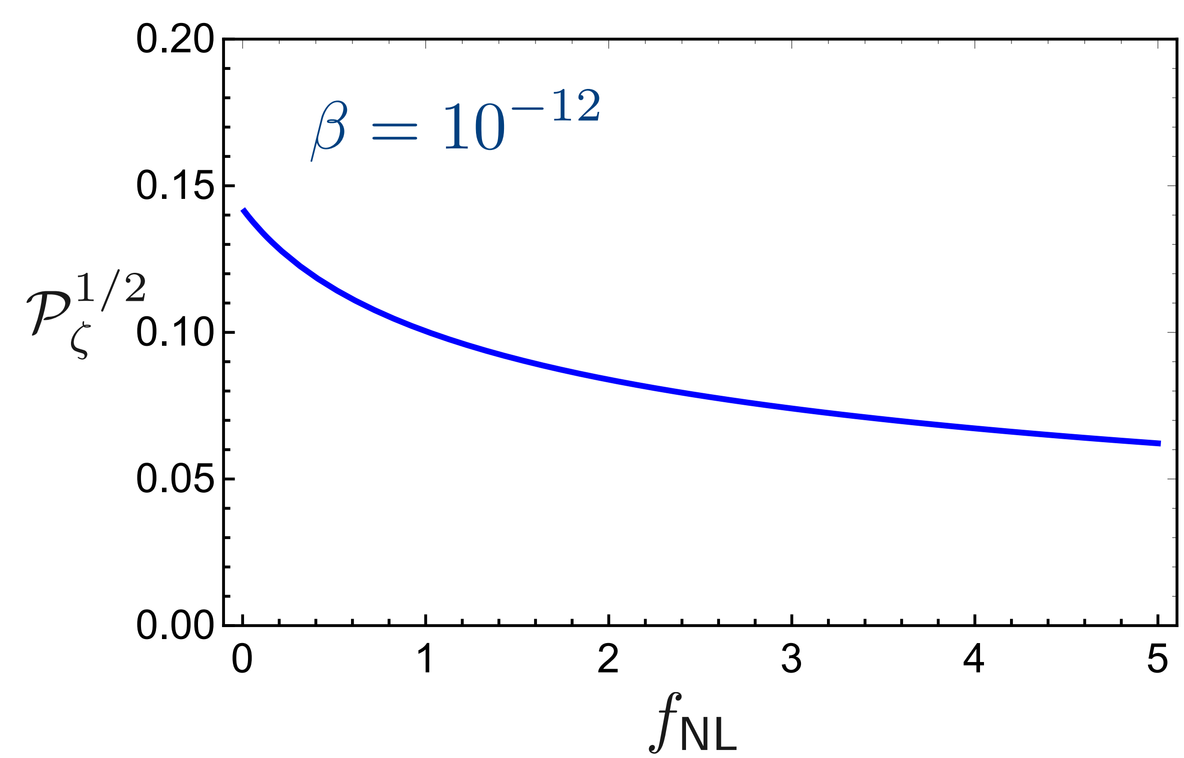
- Non-gaussianity ($f_{\rm NL}$ >0) enhance PBH formation

→ $\mathcal{P}_\zeta$ is reduced by factor 4

→ $\Omega_{\rm GW}$ decreases by factor 16

PTA constraint is expected to be less stringent





7. Conclusion

- Double inflation model (=preinflation + new inflation) and axion-like curvaton model can produce PBHs
- By appropriate choice of model parameters the models can produce PBHs with various masses and abundances
- Although observational constraints are stringent, double inflation model can produce PBHs that account for all DM of the universe
- The models also can produce PBHs for LIGO events and (marginally) evade constraints from PTA experiments on gravitational waves