Primordial Black Holes in Inflationary Cosmology

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Based on arXiv:1611.06130
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Gordon Research Conference @ HKUST 29/6/2017

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- Introduction of PBH
- PBHs for LIGO events and PTA experiments
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What is PBH ?

Primordial Black Hole(PBH)

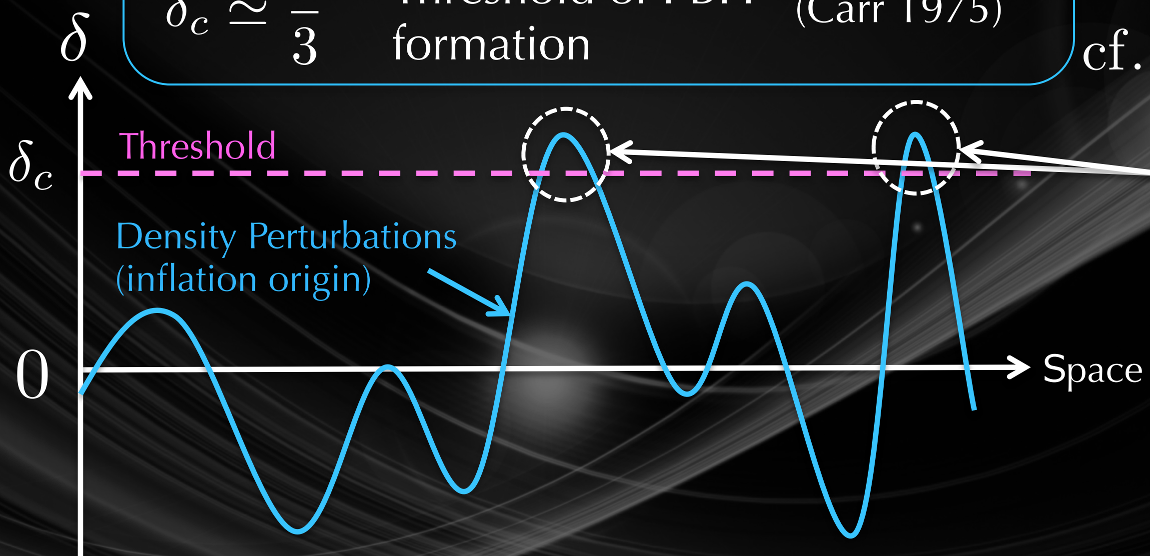
Black hole formed by gravitational collapse in very early universe

cf. Black hole formed through supernova

$\delta \equiv \dfrac{\rho - \bar{\rho}}{\bar{\rho}}$ Perturbations of energy density

$\delta_c \simeq \dfrac{1}{3}$ Threshold of PBH formation (Carr 1975)

cf. $\delta \simeq \mathcal{O}(10^{-5})\ (k < 1\mathrm{Mpc}^{-1})$



PBH is formed by self-gravitational collapse

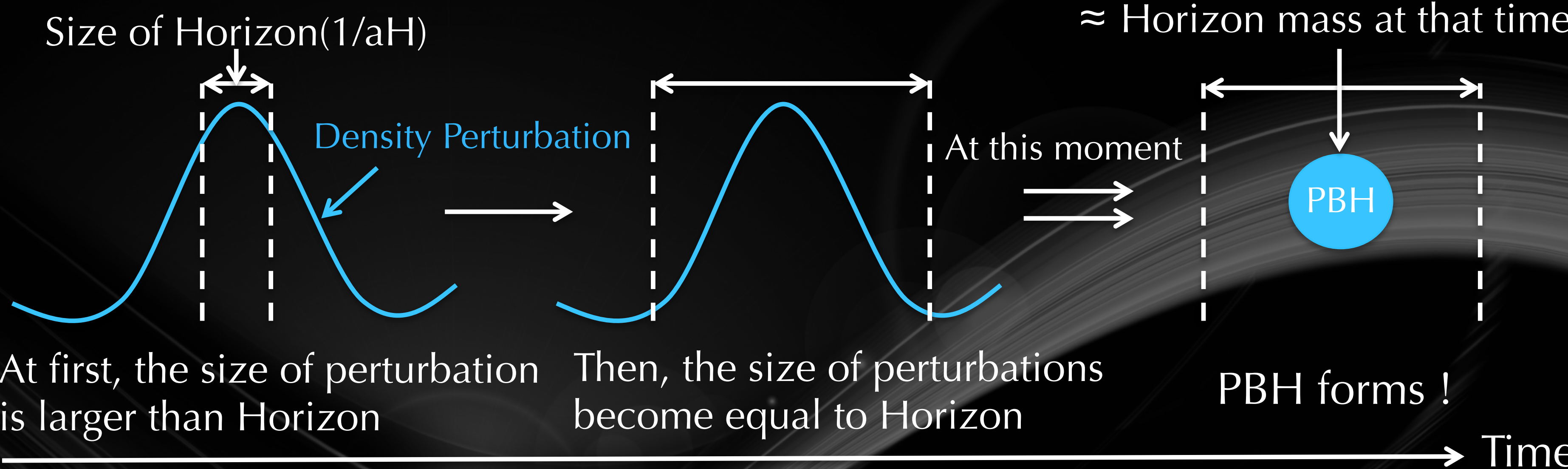
The timing of PBH formation

PBH forms when overdensed region enters the Horizon.

$$\left(M_{\rm PBH} = \gamma M_{\rm H}|_{k=aH}\right)$$

Image in comoving

PBH mass
≈ Horizon mass at that time



The size of perturbation corresponds to PBH mass one to one.
(γ≈0.2 Carr 1975)

$$M_{PBH}(k) \simeq M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{T}{176\mathrm{MeV}}\right)^{-2}\Bigg|_{k=aH}$$

$$\simeq M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{k}{3.1\times 10^5\mathrm{Mpc}^{-1}}\right)^{-2}$$

PBH-DM ratio and perturbations

Production rate of PBH with M_{PBH}=M:

$$\beta(M) \equiv \int_{>\delta_c} \frac{d\delta}{\sqrt{2\pi\sigma^2(M)}} e^{-\frac{\delta^2}{2\sigma^2(M)}}$$

$$\boxed{\sigma^2(M(k)) \sim \mathcal{O}(\mathcal{P}_{\mathcal{R}}(k)) \sim \mathcal{O}(\delta^2)}$$

PBH-DM ratio:

$$\frac{\Omega_{\rm PBH}(M)}{\Omega_{DM}} \simeq \left(\frac{\beta(M)}{1.84\times 10^{-8}}\right)\left(\frac{\gamma}{0.2}\right)^{3/2}\left(\frac{M}{M_\odot}\right)^{-1/2}$$

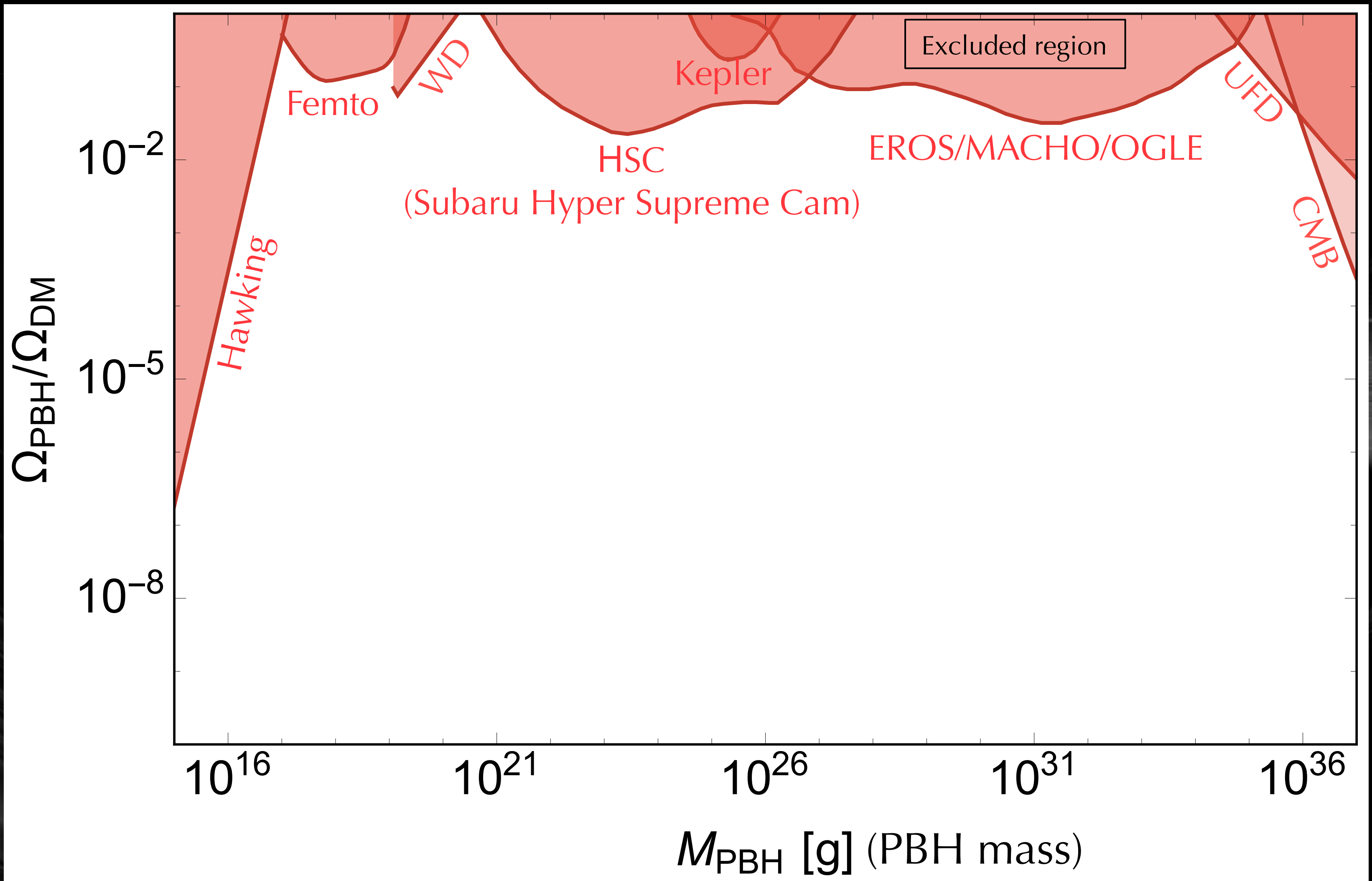
Small value of β(M) (~10^{-8}) is enough to achieve Ω_{PBH}/Ω_{DM} ~O(1).

$$\beta(M) \simeq \mathcal{O}(10^{-8}) \Rightarrow \mathcal{P}_{\mathcal{R}} \simeq \mathcal{O}(0.01)$$

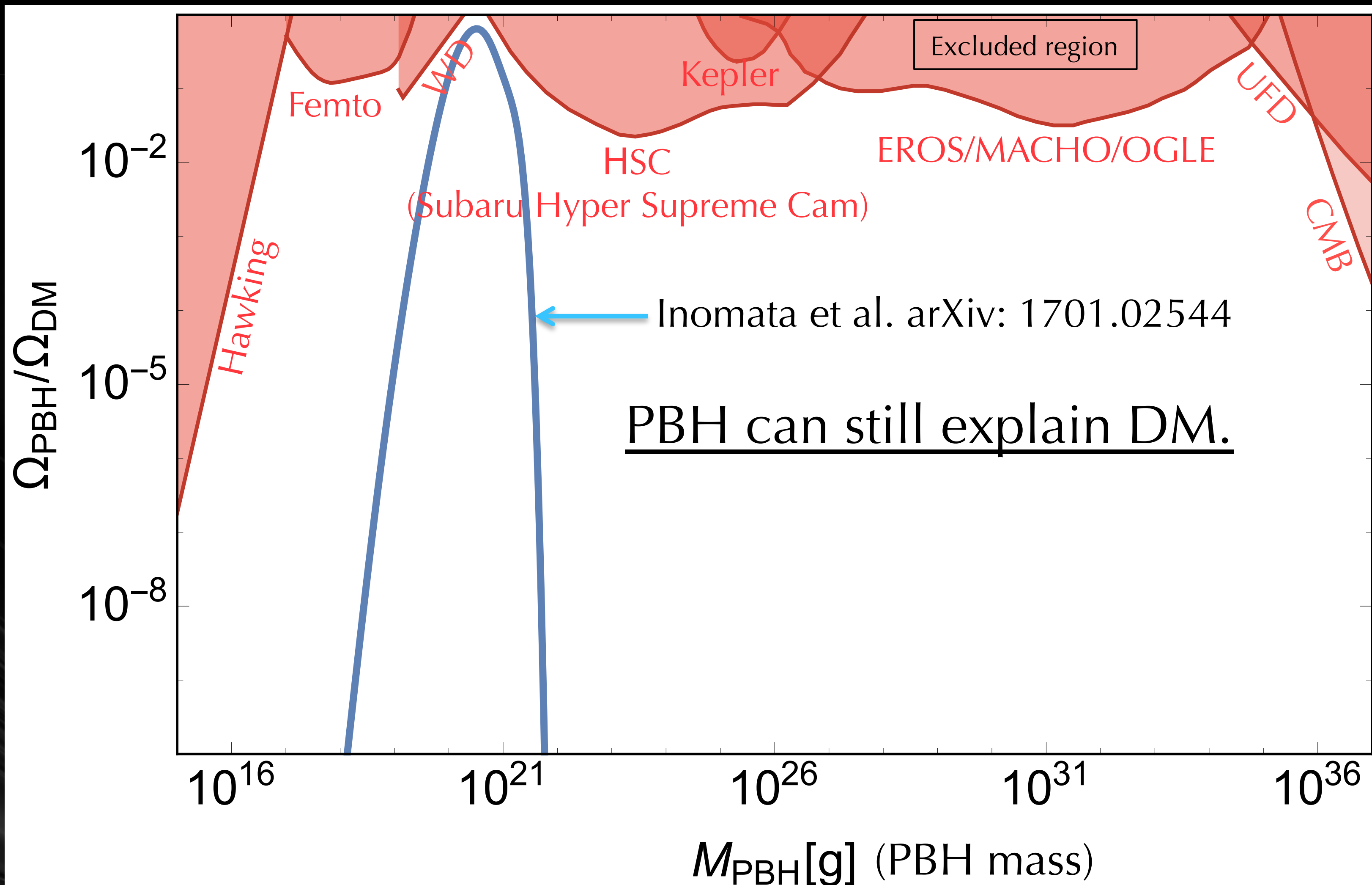
cf. $\mathcal{P}_{\mathcal{R}}(k) \simeq \mathcal{O}(10^{-9})$ $(k < 1\mathrm{Mpc}^{-1})$

PBHs need large perturbations !

Constraints on PBH-DM ratio



Constraints on PBH-DM ratio



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BHs LIGO has detected

LIGO has already detected several GWs.

	Primary BH	Secondary BH
GW150914	$36.2^{+5.2}_{-3.8} M_\odot$	$29.1^{+3.7}_{-4.4} M_\odot$
GW151226	$14.2^{+8.3}_{-3.7} M_\odot$	$7.5^{+2.3}_{-2.3} M_\odot$
GW170104	$31.2^{+8.4}_{-6.0} M_\odot$	$19.4^{+5.3}_{-5.9} M_\odot$
LVT151012	$23^{+18}_{-6} M_\odot$	$13^{+4}_{-5} M_\odot$

B. P. Abbott et al. Phys. Rev. X 6, 041015
B. P. Abbott et al. Phys. Rev. Lett. 118, 221101

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Three out of eight are $M \sim 30M_\odot$.

It seems that there are many BHs with $M \sim 30M_\odot$.

The origin of 30 Solar mass BHs

Usual stellar black holes cannot be larger than $20M_{\odot}$ because of mass loss by stellar wind.

PBH is a good candidate of 30 Solar mass BH !

Calculating the merger rate, Sasaki et al.(2016) shows that if $\Omega_{PBH}(30M_{\odot})/\Omega_{DM} \sim 10^{-4}$-$10^{-2}$, PBH can explain LIGO event.

(Talk by T.Suyama)

In our research,

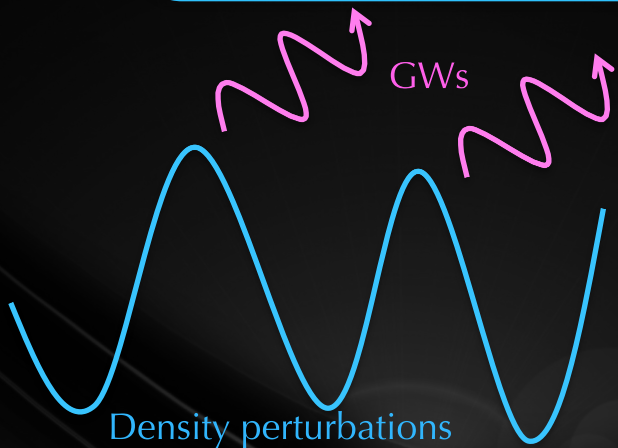
Taking account of the PTA constraints on the GWs from second order scalar perturbations, we investigate whether PBHs can explain the LIGO events.

GWs from second order perturbations

GWs from second order density perturbations

Totally different

GWs from merger of BHs (detected by LIGO)



In first order, density(scalar) perturbations are independent of GWs(tensor).

However

In second order, density perturbations can be source of GWs

To produce enough PBHs to explain LIGO events, we need large density perturbations

➡ GWs from second order is constrained by PTA observations.

(Saito, Yokoyama, Phys.Rev.Lett.102.161101)

Equation of motion for GWs (Ananda el al. 2007)

Scalar perturbations

Tensor perturbation

Metric perturbations:

$$ds^2 = a^2[-(1-2\Phi)d\eta^2 + ((1+2\Psi)\delta_{ij} + \frac{h_{ij}}{2})dx^i dx^j]$$

$$\boxed{h^i{}_i = 0, h^{ij}{}_{,j} = 0}$$

E.o.M for GWs:

$$h_k^{\lambda\,\prime\prime} + 2\mathcal{H}h_k^{\lambda\,\prime} + k^2 h_k^\lambda = 4\underline{\mathcal{S}^\lambda(k,\eta)}$$

Source term from second order scalar perturbations

$$\begin{aligned}\mathcal{S}^\lambda(k,\eta) &\equiv -e^{\lambda lm}(\hat{k})\mathcal{S}_{lm}(k) \\ &= \int \frac{d^3k'}{(2\pi)^3} e^{\lambda lm}(\hat{k}) k'_l k'_m \Bigg[2\Phi_{k'}(\eta)\Phi_{k-k'}(\eta) \\ &\quad + \frac{4}{3(1+\omega)}\left(\Phi_{k'}(\eta) + \frac{\Phi'_{k'}(\eta)}{\mathcal{H}}\right)\left(\Phi_{k-k'}(\eta) + \frac{\Phi'_{k-k'}(\eta)}{\mathcal{H}}\right)\Bigg]\end{aligned}$$

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Double Inflation Model (Kawasaki et al 1998)

Inflaton: χ, ϕ

Lagrangian:

$$\mathcal{L} = -\frac{1}{2}(1 - \frac{c_{\rm kin}}{2M_{\rm Pl}^2}\phi^2)\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\chi,\phi)$$

Potential:

$$V(\chi,\phi) = V_{\rm pre}(\chi) + V_{\rm stb}(\chi,\phi) + V_{\rm new}(\phi)$$

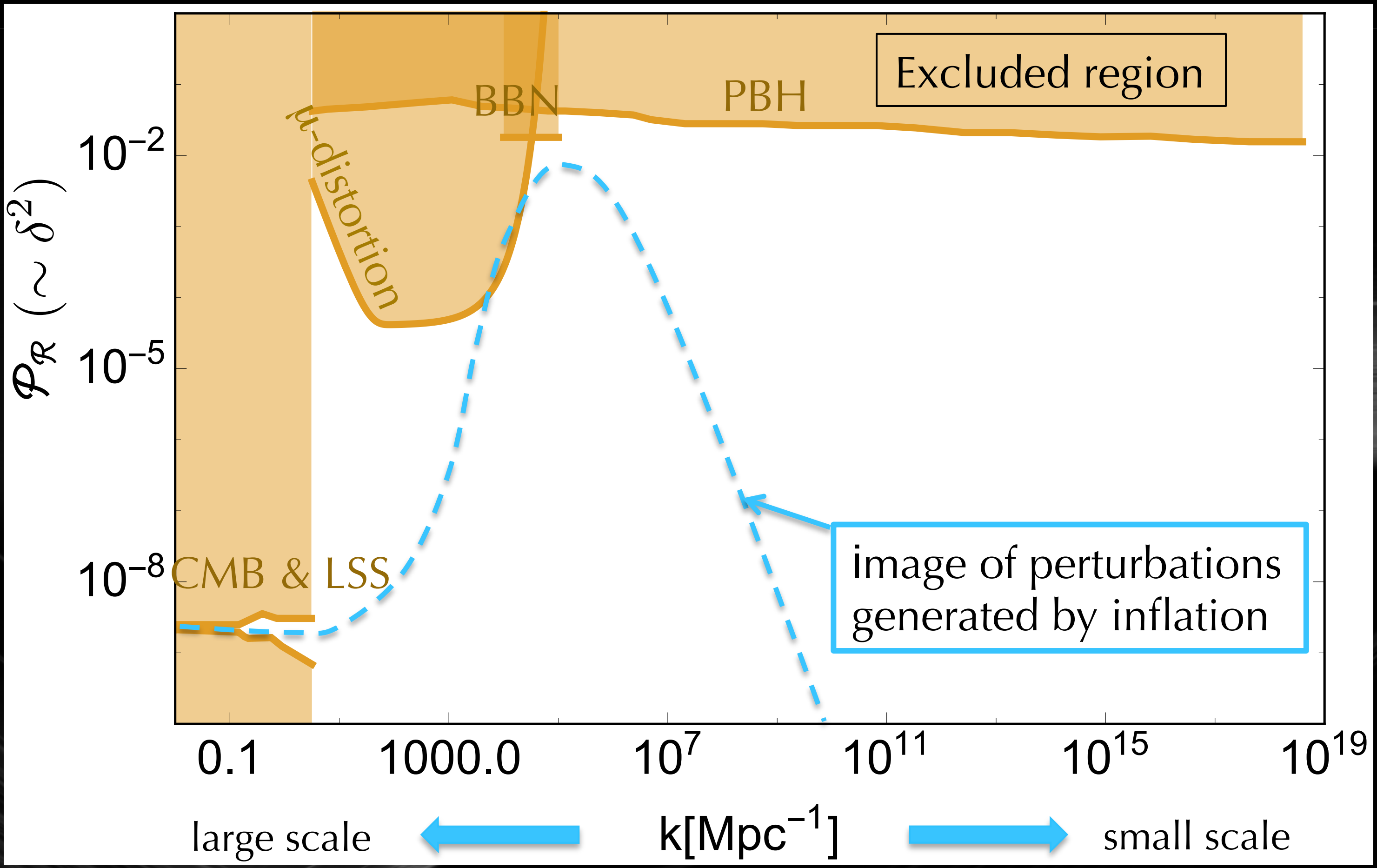
$$V_{\rm new}(\phi) = \left(v^2 - g\frac{\phi^3}{M_{\rm Pl}}\right)^2 - \frac{\kappa}{2}v^4\frac{\phi^2}{M_{\rm Pl}^2} - \epsilon v^4\frac{\phi}{M_{\rm Pl}}$$

$$V_{\rm stb}(\chi,\phi) = \underline{c_{\rm pot}\frac{V_{\rm pre}(\chi)}{2M_{\rm Pl}^2}\phi^2}$$

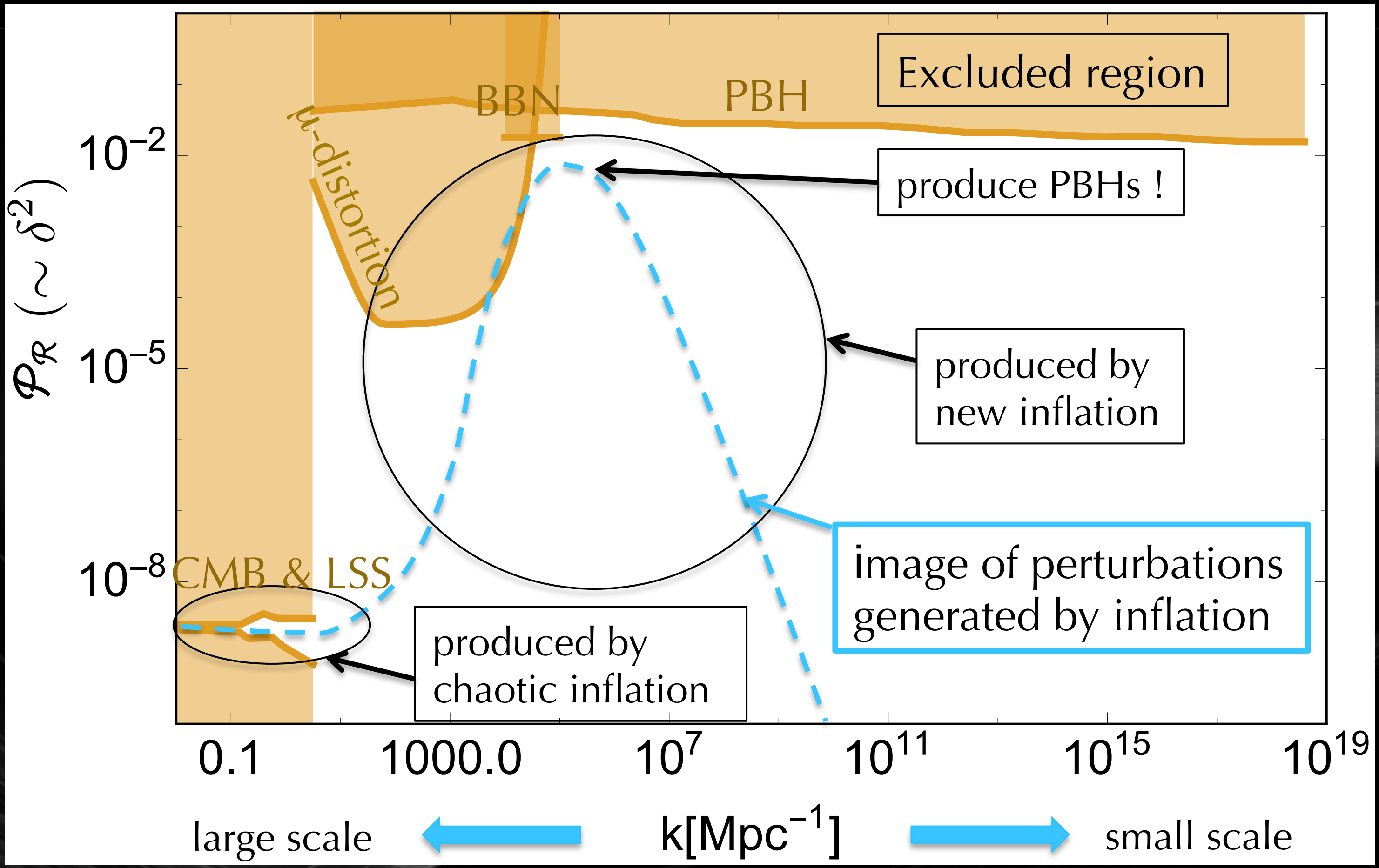
This term stabilizes ϕ at origin during chaotic inflation

Chaotic inflation χ → New inflation ϕ

Curvature perturbations

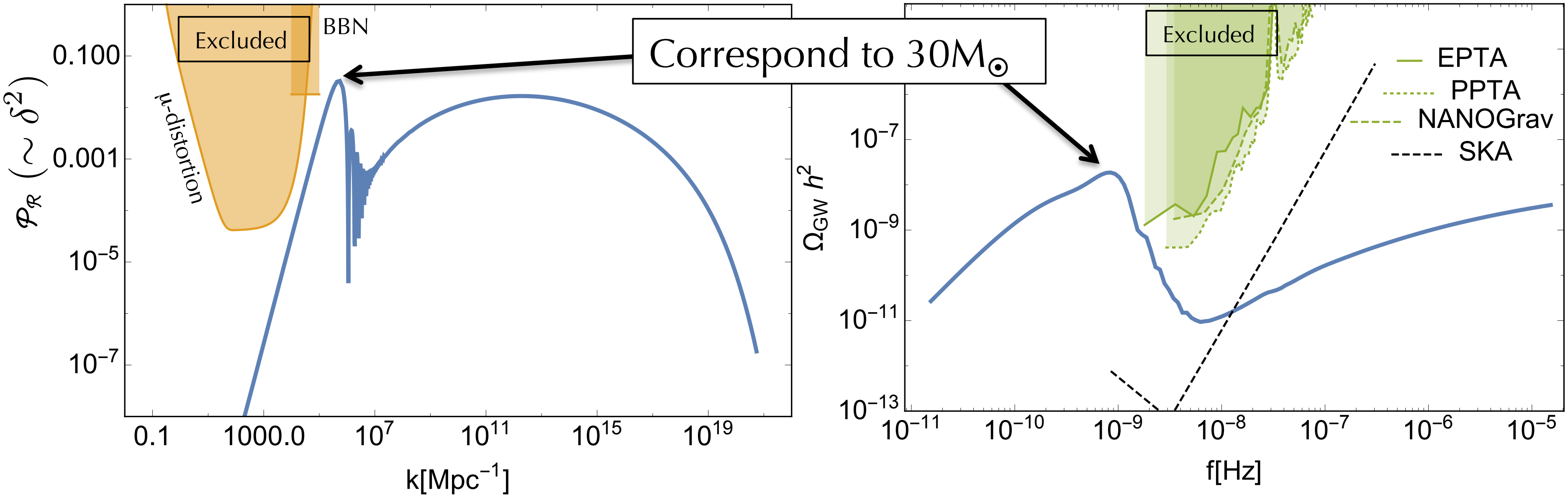


Curvature perturbations



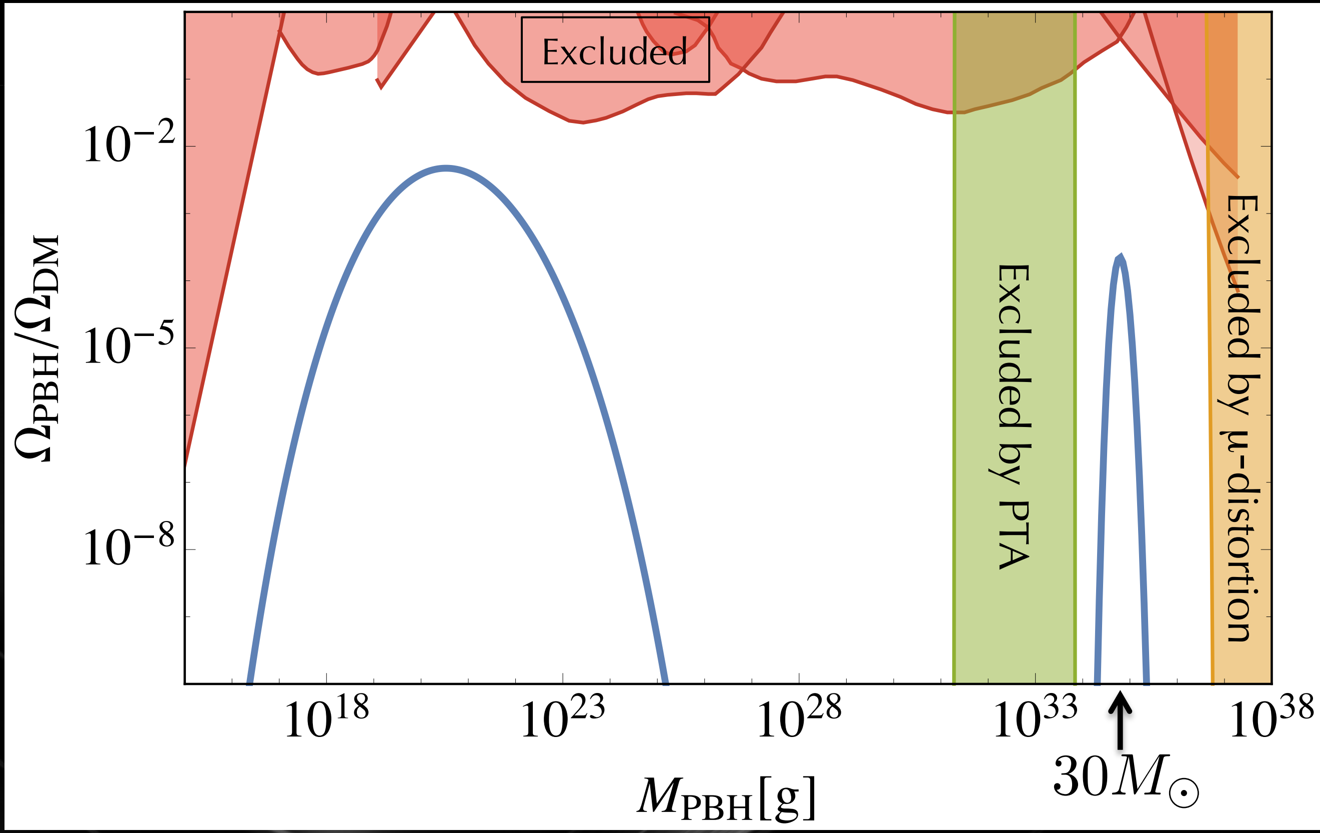
Curvature perturbations and GWs

$$\frac{v}{M_{\rm Pl}} = 10^{-4}, \kappa = -0.61, \epsilon = 9.19 \times 10^{-8}, g = 1.83 \times 10^{-3}, c_{\rm pot} = 0.681, c_{\rm kin} = -0.676$$



This curvature perturbation and GWs are sharp enough to avoid both μ-distortion and PTA constraints.

PBH-DM ratio



PBHs can explain $30M_\odot$ BHs detected by LIGO.

(If $\Omega_{\rm PBH}(30M_\odot)/\Omega_{\rm DM} \sim 10^{-4}$-$10^{-2}$, PBH can explain LIGO event. (Sasaki et al. 2016))

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Summary

What we did

We investigate whether PBHs can explain the LIGO $30M_{\odot}$ events. In particular, we focus on the PTA constraints on the GWs from second order scalar perturbations.

Result

Although the peak needs to be so sharp, PBHs can explain the LIGO events. We shows that the double inflation model can make sharp peak of curvature perturbations.

Future prospect

It is possible that future PTA experiments or μ-distortion observation detect the signals.