LTPDM2020 ICTS
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Primordial Black Holes and Gravitational Waves

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inflationary model construction

Curvature perturbation to PBH

➢ gradient expansion/separate universe approach

$$6H^2(t,x) + R^{(3)}(t,x) = 16\pi G\rho(t,x) + \cdots$$ Hamiltonian constraint (Friedmann eq.)

$$R^{(3)} \approx -\frac{4}{a^2}\nabla^2\mathscr{R}_c \approx \frac{8\pi G}{3}\delta\rho_c \quad \Rightarrow \quad \frac{\delta\rho_c}{\rho} \approx \mathscr{R}_c \ \text{ at } \ \frac{k^2}{a^2} = H^2$$

$R^{(3)} \simeq 0$ — $R^{(3)} \sim H^2$ ($H^{-1} = a/k$) — formation of a closed universe

➢If $R^{(3)} \sim H^2$ $\left(\Leftrightarrow \delta\rho_c/\rho \sim 1\right)$, it collapses to form BH

Young, Byrnes & MS '14

$$M_{\rm PBH} \sim \rho H^{-3} \sim 10^5 M_\odot \left(\frac{t}{1s}\right) \sim 20 M_\odot \left(\frac{k}{1{\rm pc}^{-1}}\right)^{-2}$$

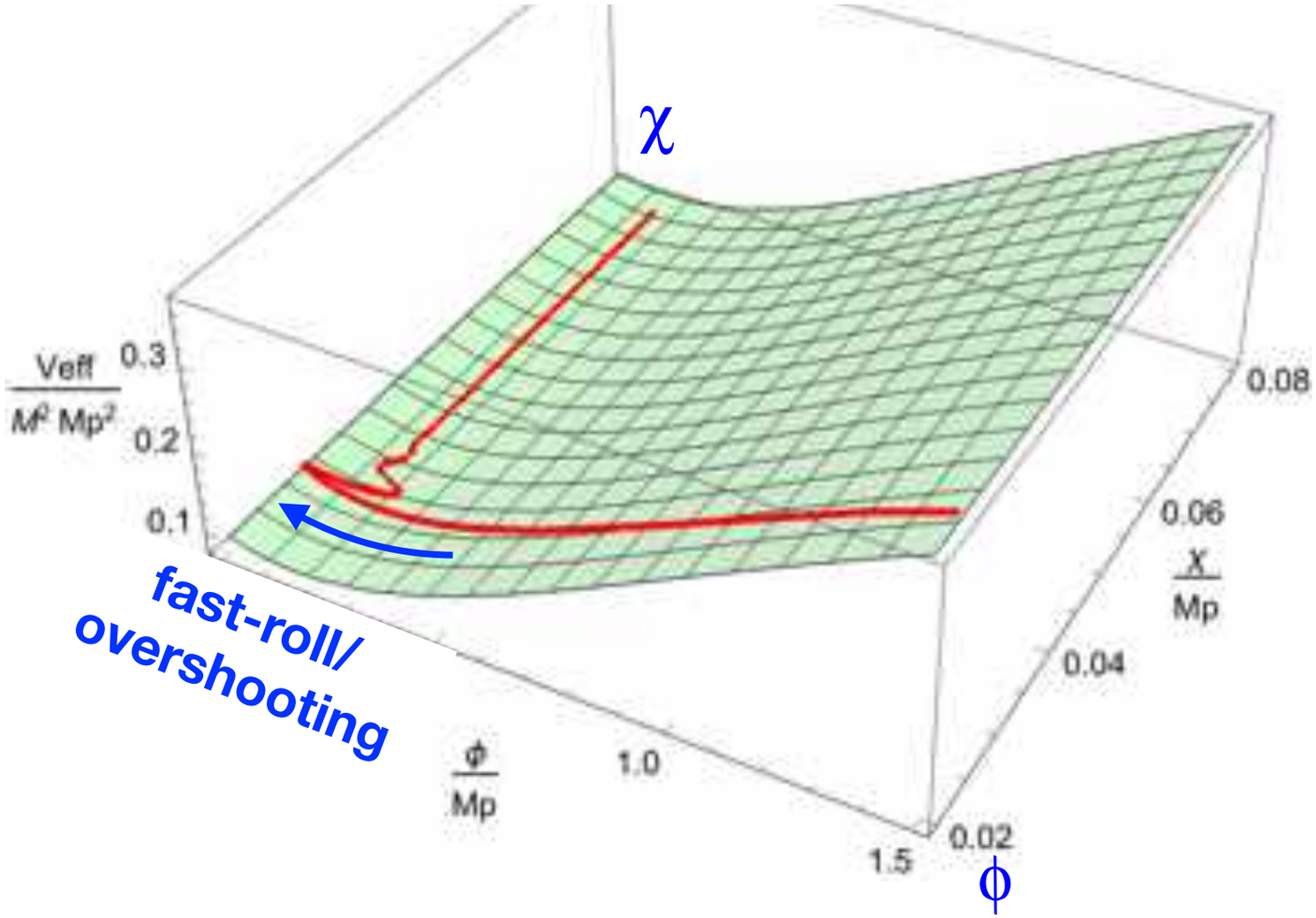
➢Spins of PBHs are expected to be very small

de Luca et al. 2019, Harada et al. 2020, …

Model 1: Scalaron+χ model

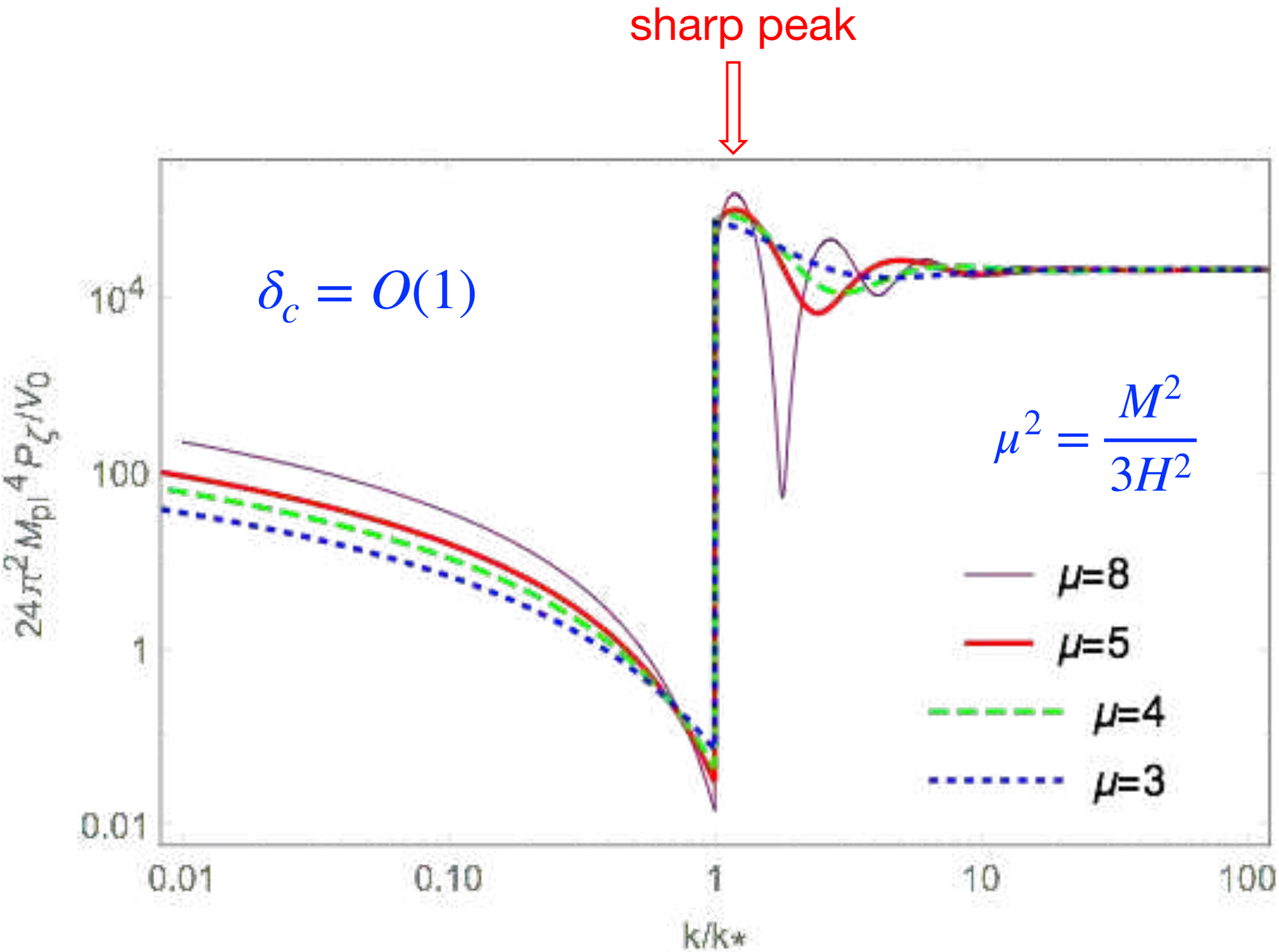
Pi, Zhang, Huang & MS '17

$$S_J = \int d^4x\sqrt{-g}\left\{\frac{M_{\rm Pl}^2}{2}\left(R+\frac{R^2}{6M^2}\right) - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi) - \frac{1}{2}\xi R\chi^2\right\}.$$



2-stage inflation

- Scalaron ϕ becomes massive at the end of the 1st stage.
- Field χ plays the role of inflaton at the 2nd stage.



scalaron + x model can produce a sharp peak in the curvature perturbation spectrum at small scale

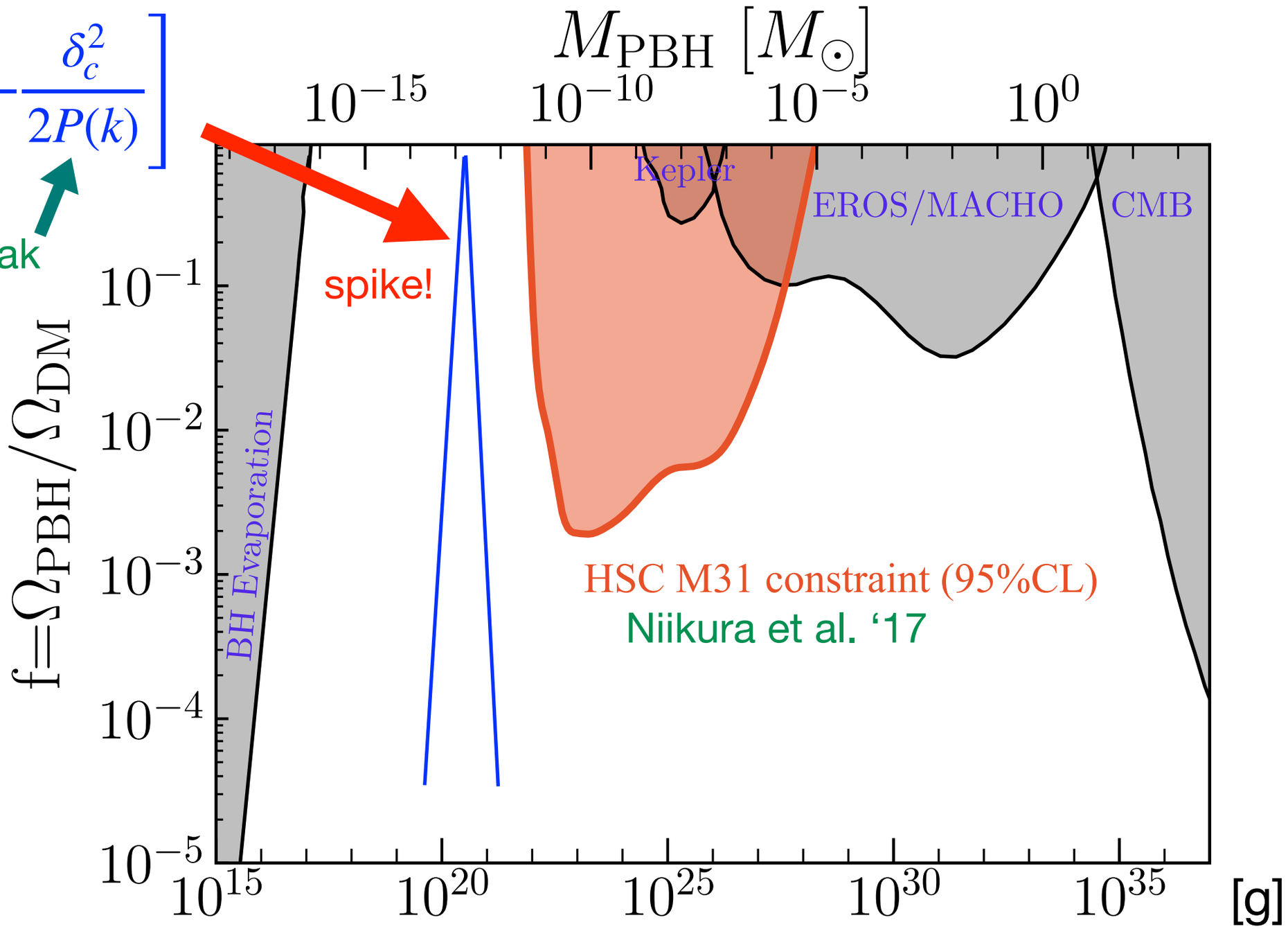
non-Gaussianity is found to be small in this model

PBH mass function

$$\delta_c = O(1)$$

$$f(M_{\rm PBH}) \propto \exp\left[-\frac{\delta_c^2}{2P(k)}\right]$$

sharp peak

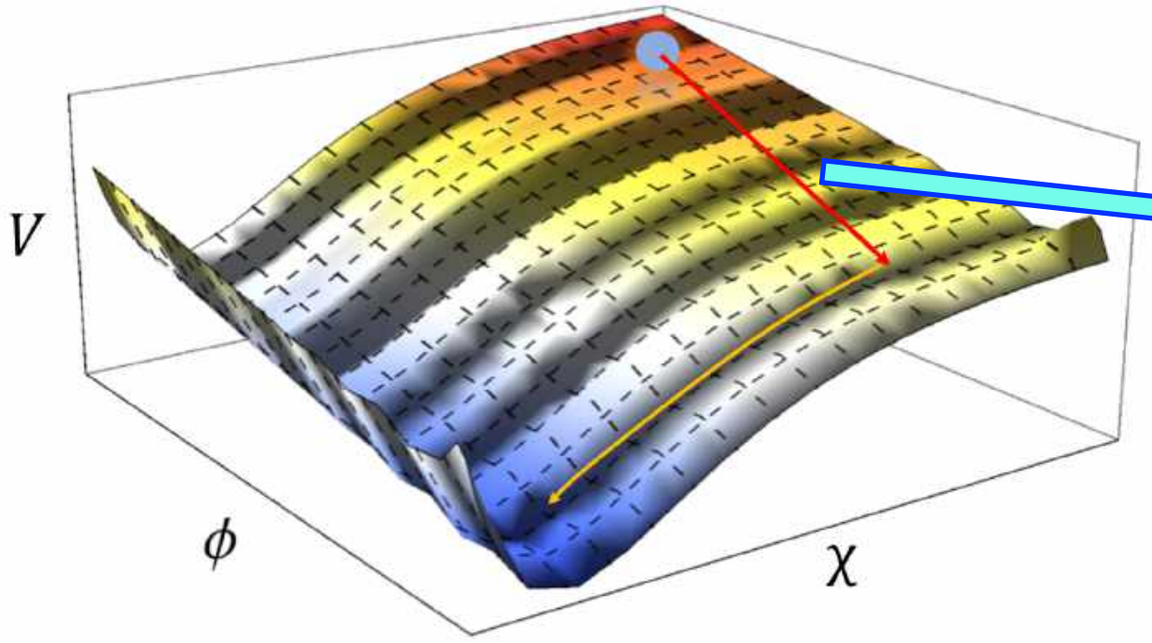


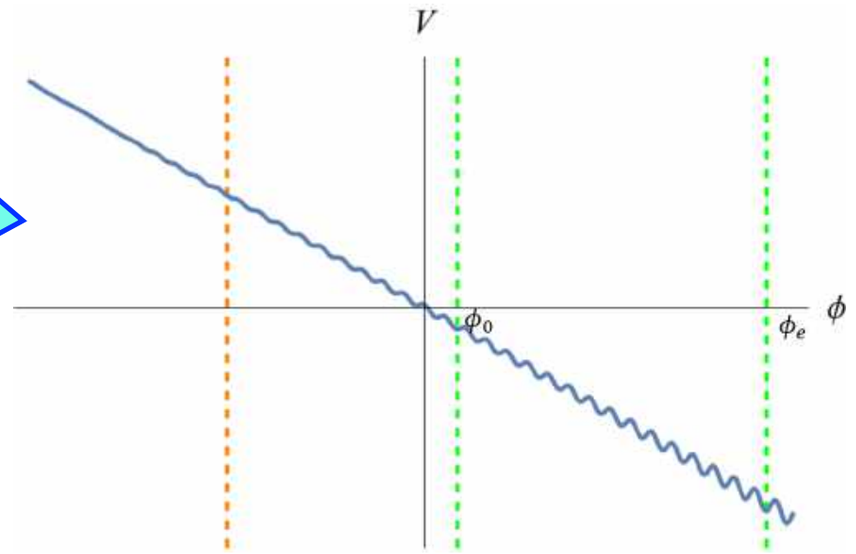
scalaron+x model can realize

PBH=CDM scenario with a monochromatic PBH mass!

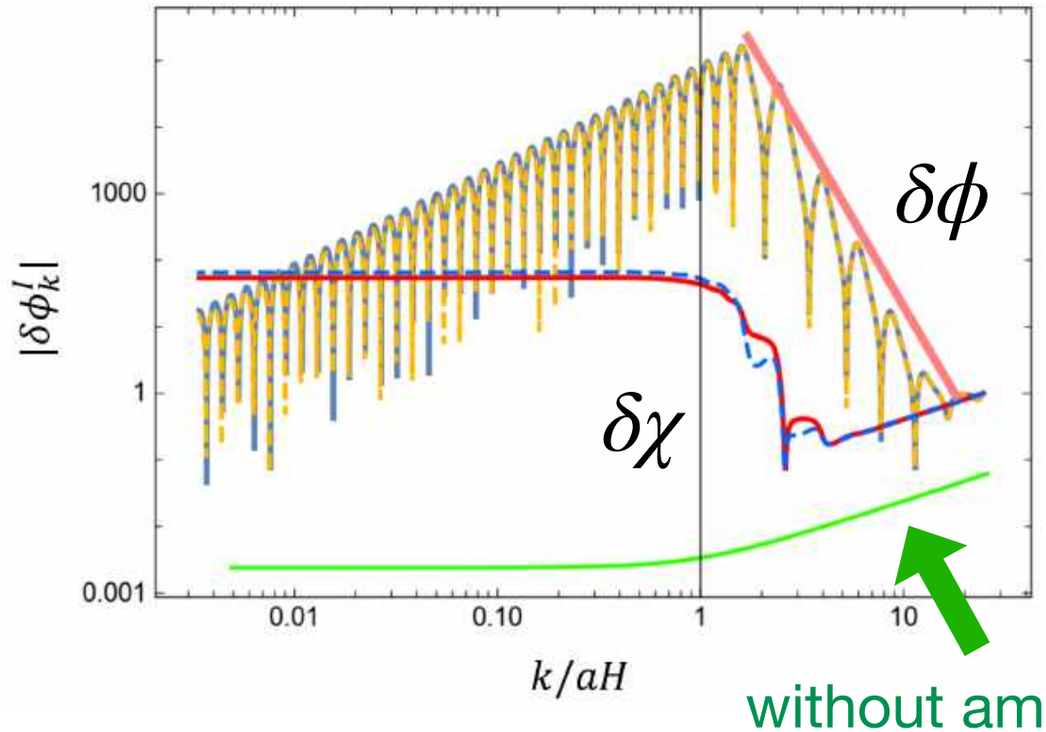
Model 2: Resonant Amplification Model

Z. Zhou, J. Jiang, Y. Cai, MS & S. Pi, 2020





$$V(\phi) \sim \Lambda(\phi)\cos\left(\frac{\phi}{f_a}\right) \text{ with growing } \Lambda(\phi)$$



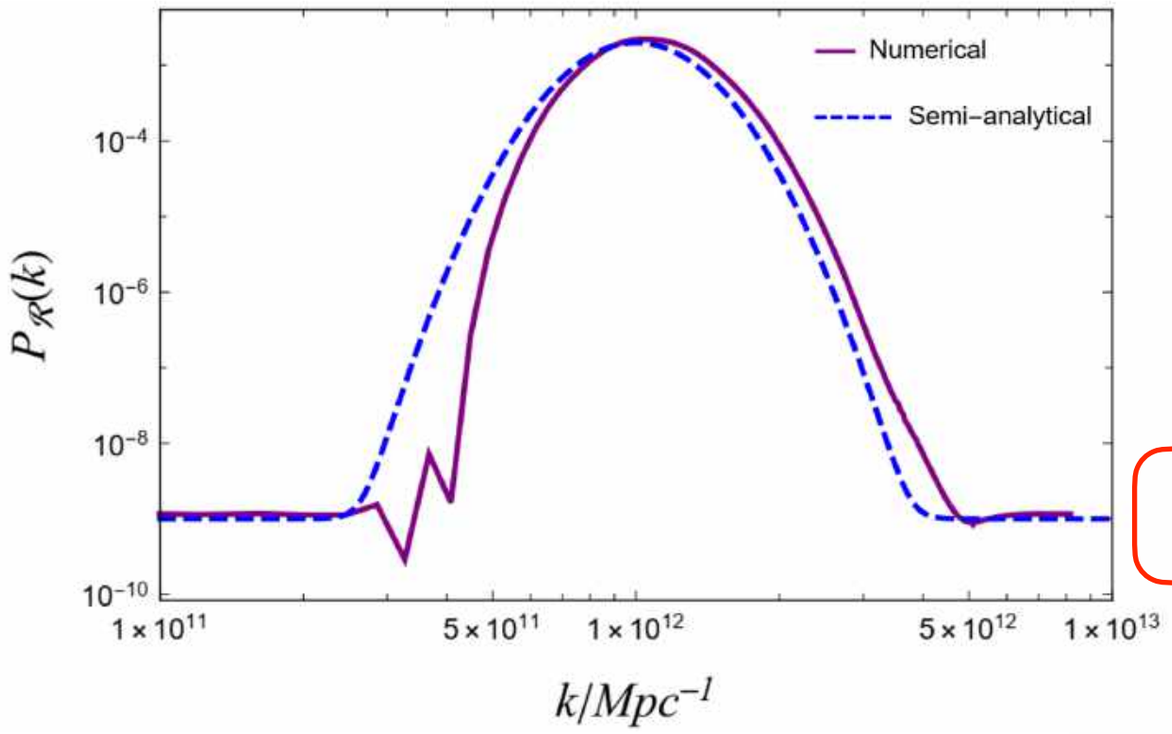
without amplification

$\delta\phi$: amplified by oscillating potential

$\delta\chi$: amplified through coupling to $\delta\phi$

This leads to enhancement of curvature perturbation

Curvature perturbation spectrum and PBH mass function: an example



$$P_{\mathcal{R}}(k) = \frac{H^2}{8\pi^2 M_p^2 \epsilon_{\chi\chi}} \mathcal{A}^2(k)$$

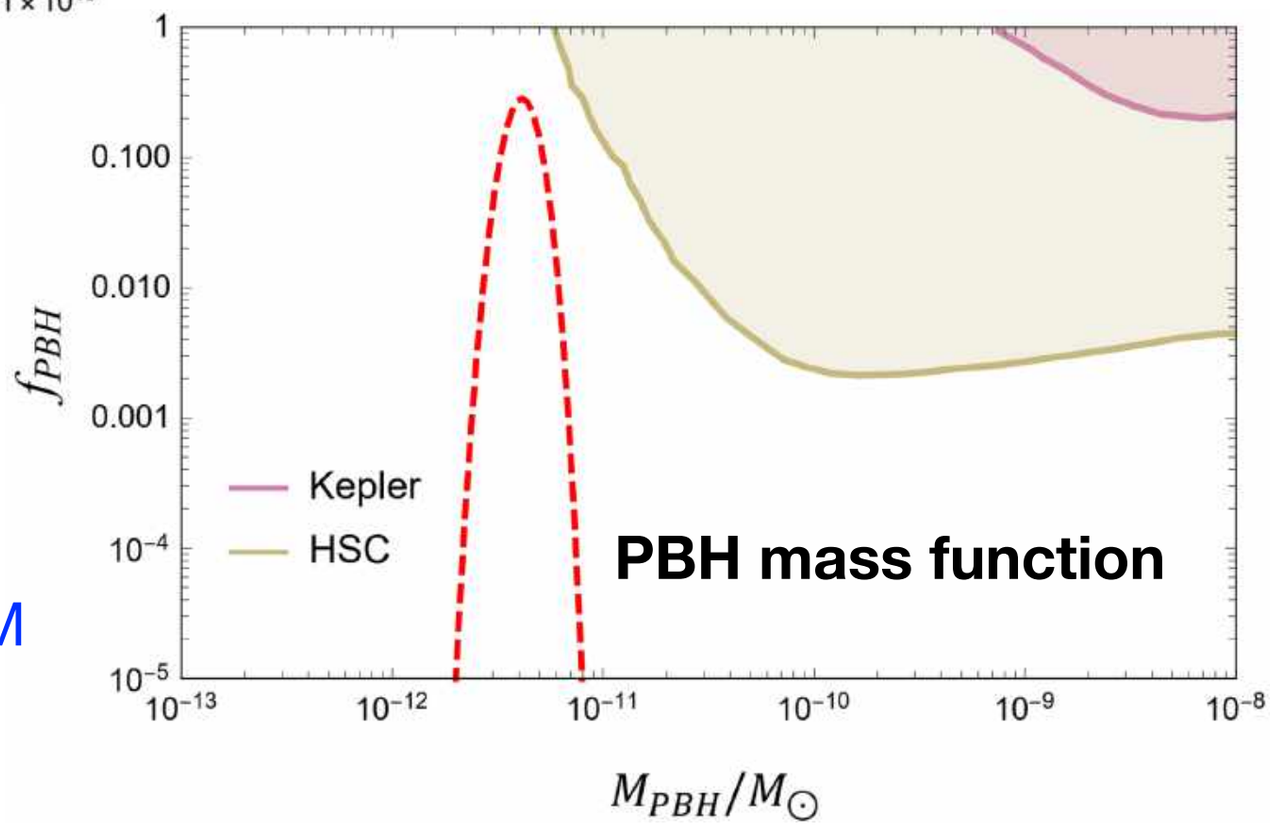
$$\mathcal{A}^2(k) = 1 + \mathcal{A}^2(k_*) \exp\left(-\frac{\ln^2(k/k_*)}{2\Delta^2}\right)$$

amplification factor $\sim 10^6$

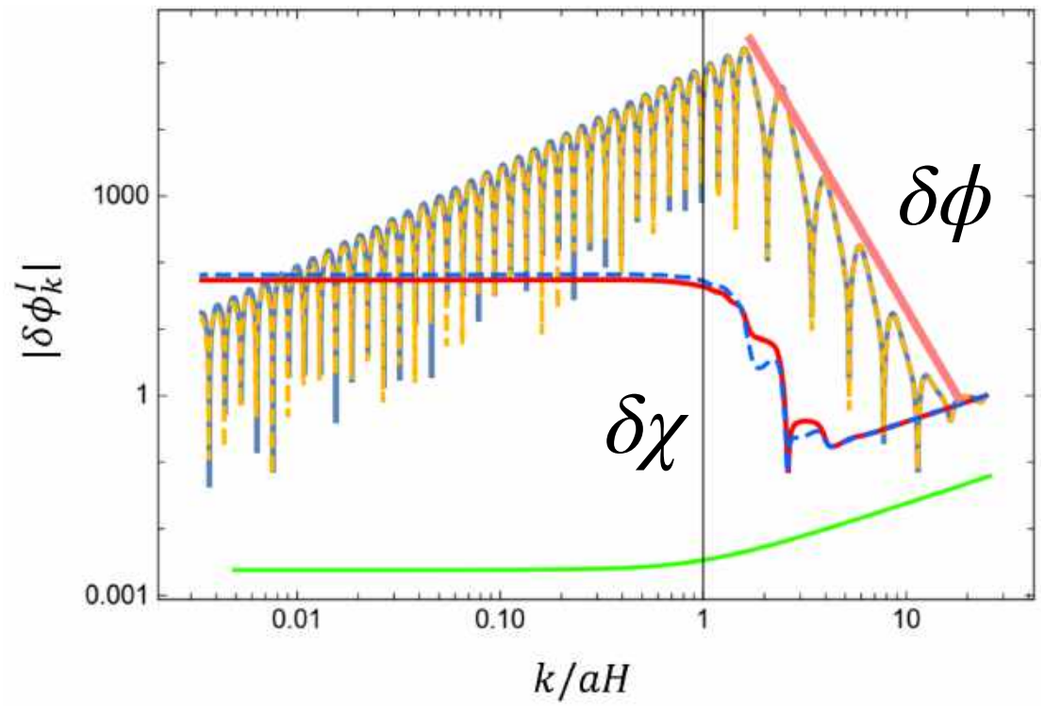
very good fit with log-normal function

$\Delta = O(1)$ for typical values of model parameters

PBHs can account for CDM



GWs Generated during Inflation



This leads to GW generation during inflation

$\delta\phi$: amplified by oscillating potential

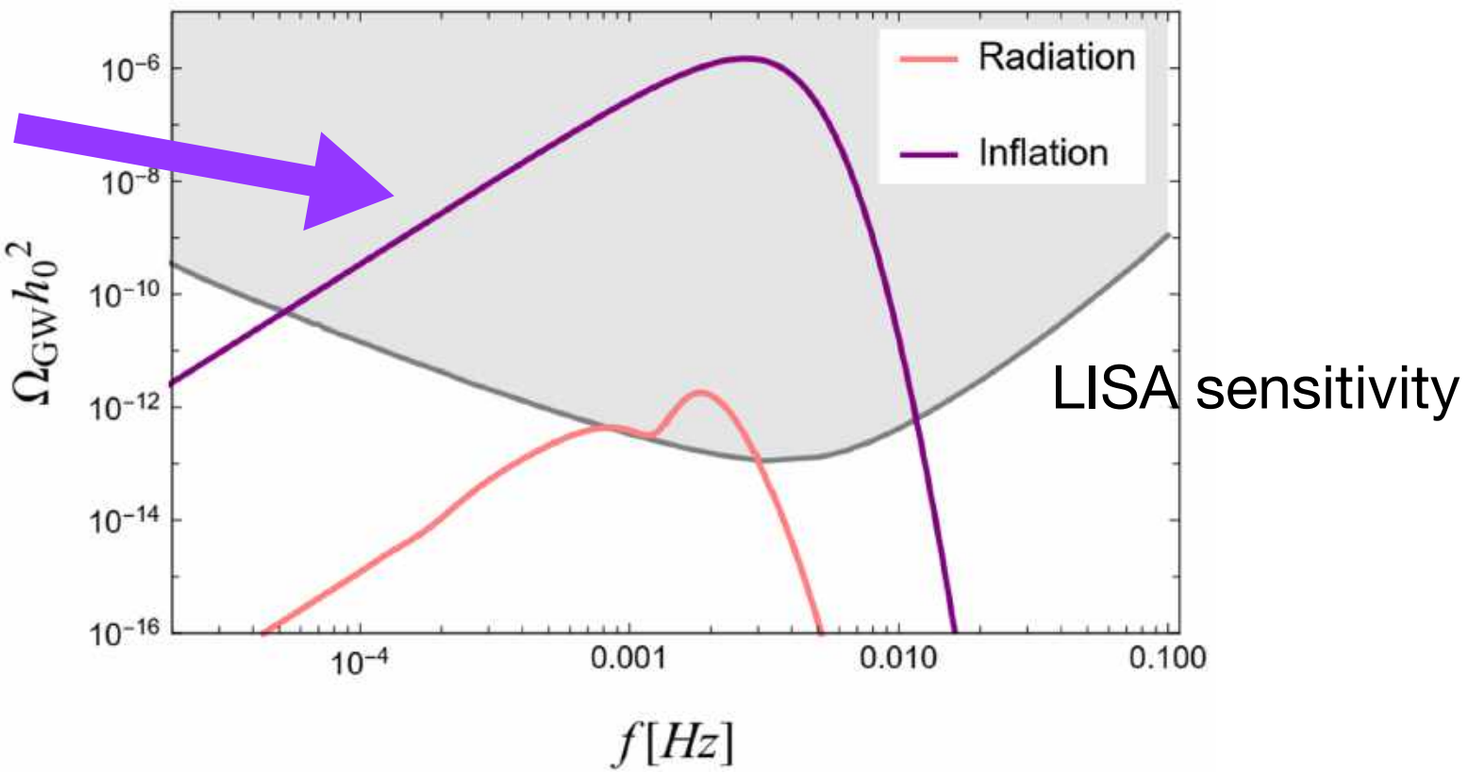
$\delta\chi$: amplified through coupling to $\delta\phi$

This leads to enhancement of curvature perturbation

$\Box h_{ij} \sim G\partial_i\delta\phi\partial_j\delta\phi$

GW probes $\delta\phi$

PBH probes $\delta\chi$



LISA sensitivity

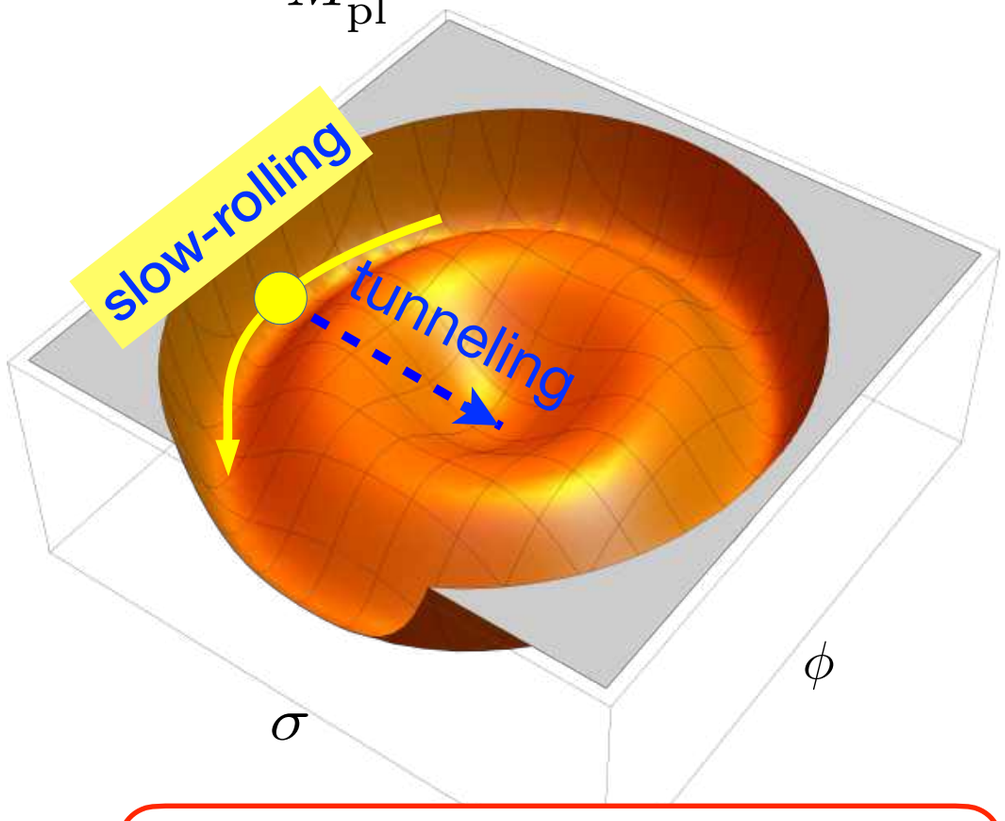
Model 3: PBH-as-MVP scenario

PBH formation during inflation due to vacuum tunneling

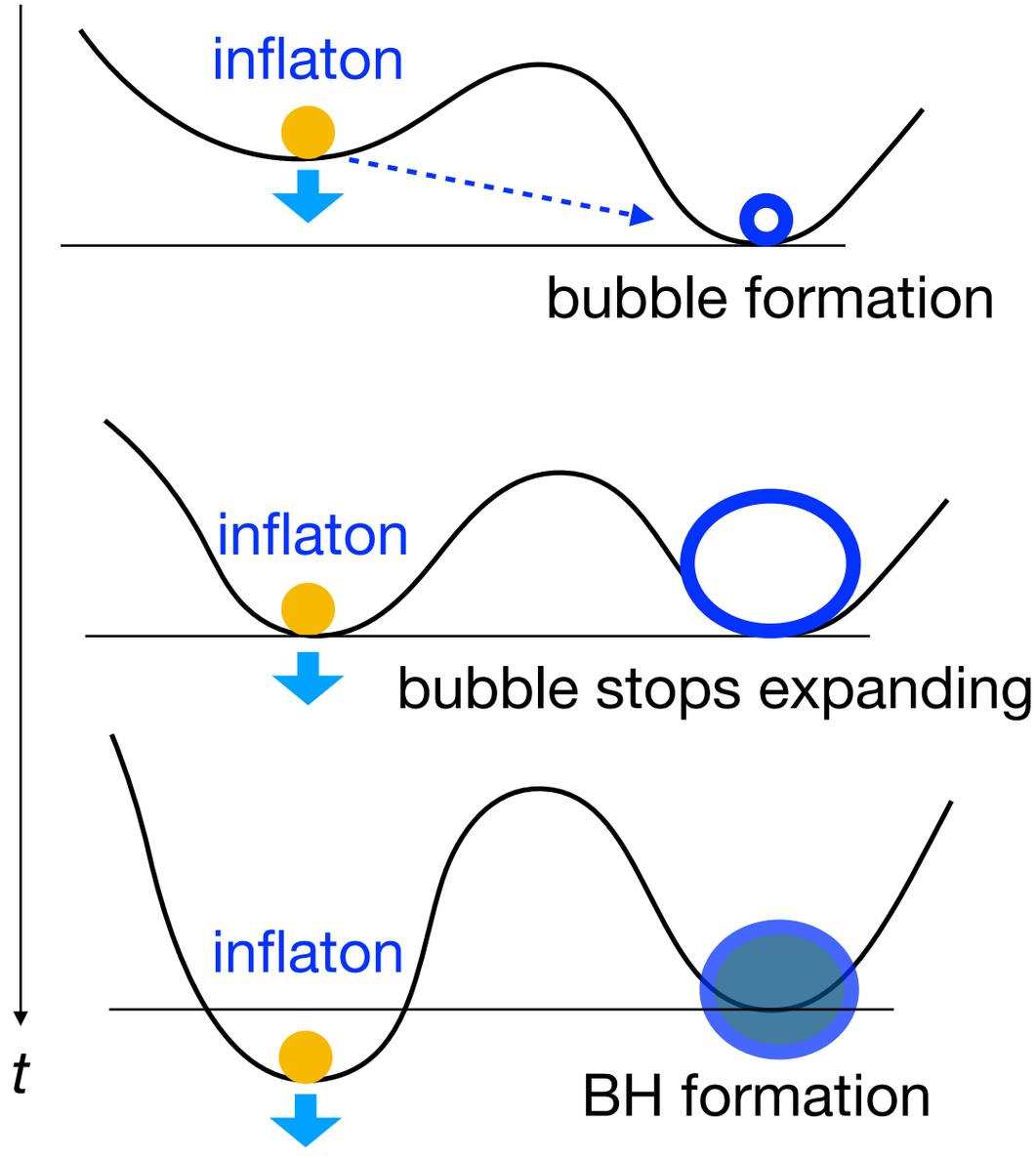
Garriga, Vilenkin & Zhang ’15, Deng & Vilenkin ’17,…

example:

$$V(\phi,\sigma) = m^2(\phi^2+\sigma^2) - a(\phi^2+\sigma^2)^2 + \frac{c}{M_{\rm pl}^2}(\phi^2+\sigma^2)^3 + gM_{\rm pl}^4 \sin\left(\frac{\phi}{fM_{\rm pl}}\right)$$

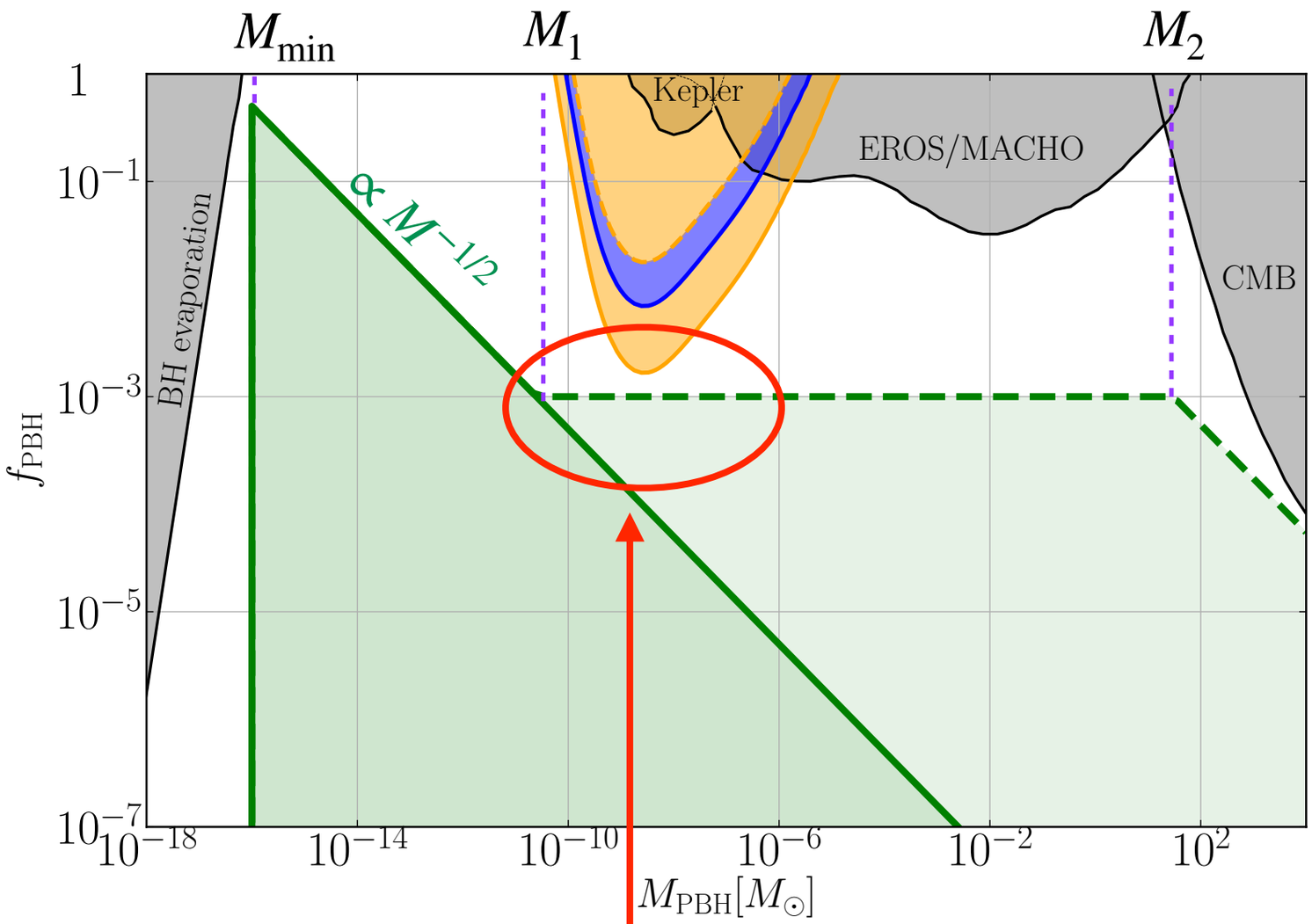


can probe multiverse!



PBH mass function

Kusenko, MS, Sugiyama, Takada, Takhistov & Vitagliano ‘20



may be tested by Subaru HSC

Subaru accepted our proposal!

obs is ongoing now!

- for scale M re-entering horizon during radiation-dom stage

$$f(M) = \lambda \left(\frac{M}{M_{\rm min}} \right)^{-1/2} : M_{\rm min} < M$$

$M \simeq M_{\rm min}$ ⋯ CDM

- if there is an intermediate matter-dom stage

$$f(M) = \lambda \left(\frac{M_1}{M_{\rm min}} \right)^{-1/2} : \ M_1 < M < M_2$$

$M \simeq M_2$ ⋯ LIGO BHs

$$f(M) = \lambda \left(\frac{M_2}{M_1} \right)^{1/2} \left(\frac{M}{M_{\rm min}} \right)^{-1/2} : \ M_2 < M$$

$M \gg M_2$ ⋯ SMBHs

GWs from Large Curvature Perturbation

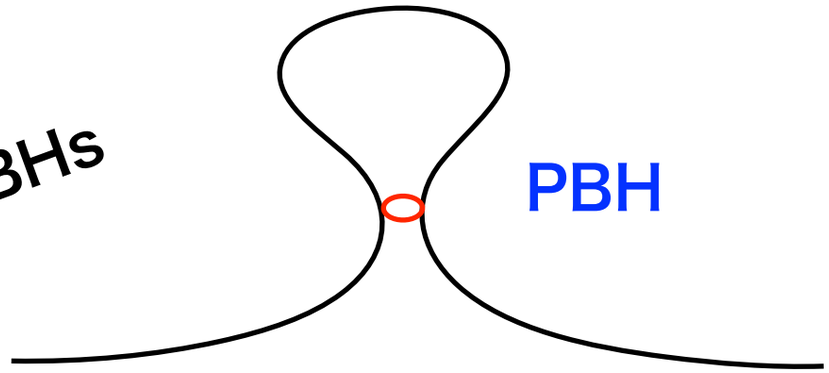
GWs can capture PBHs!

curvature perturvation

$\mathscr{R}(t,x)$

(~Newton potential)

large peaks form PBHs

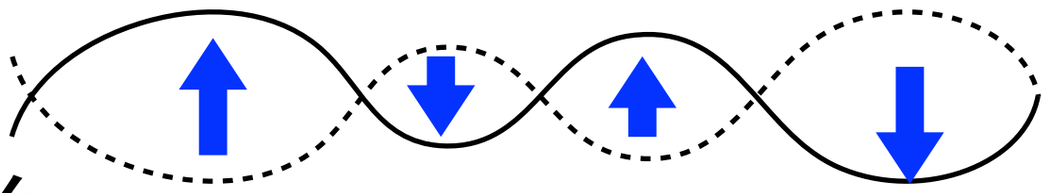


PBH

$$f \sim 3\mathrm{Hz}\left(\frac{M_{\mathrm{PBH}}}{10^{16}\mathrm{g}}\right)^{-1/2}$$

NL effect induces GWs

$$\Box h_{ij} \sim G\partial_i\mathscr{R}\partial_j\mathscr{R}$$



spacetime oscillations

PBHs = CDM with $M_{\mathrm{PBH}} \sim 10^{21}$g
generates GWs with $f \sim 10^{-3}$ Hz

⇒ Background GWs at LISA band!

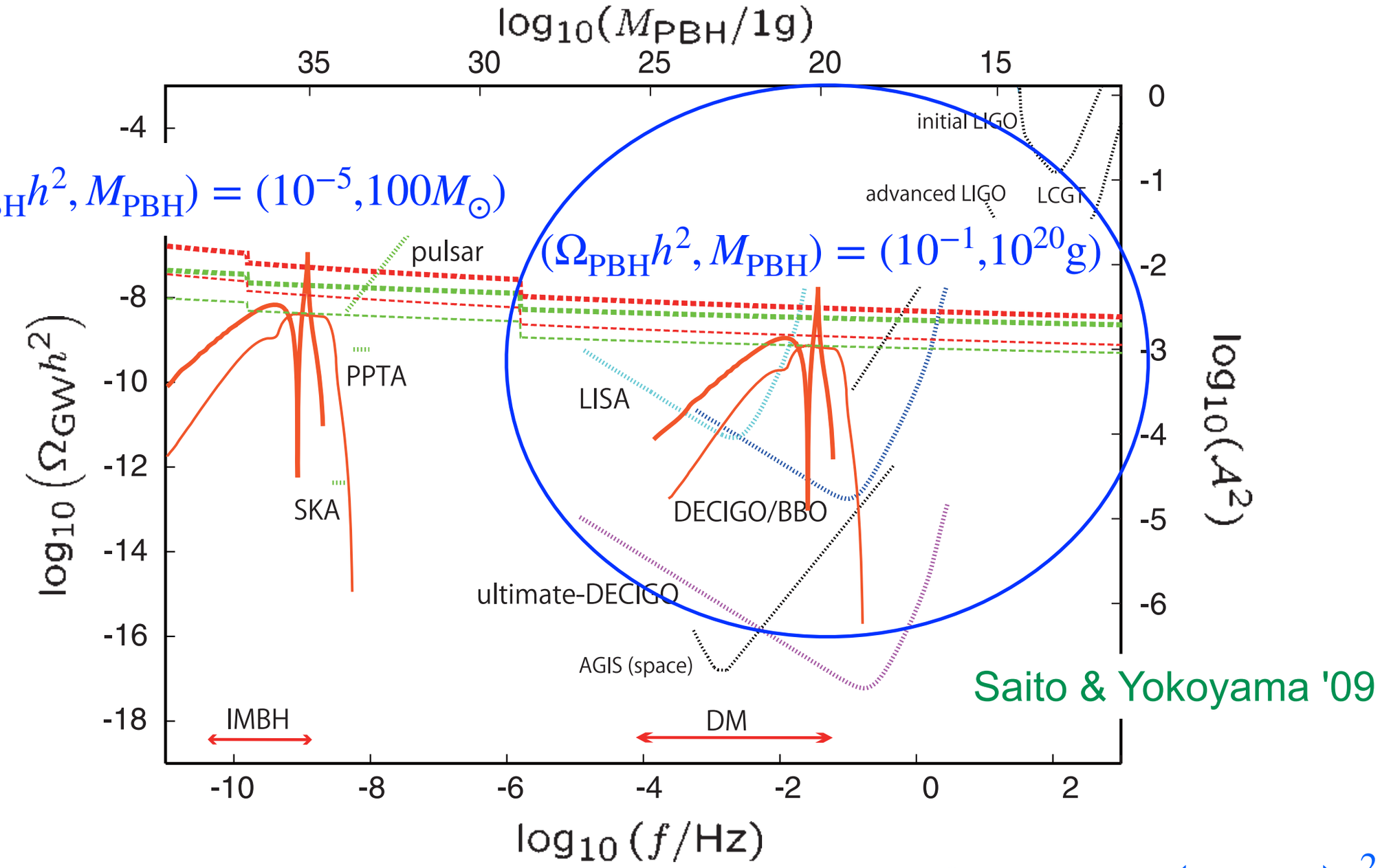
cf. $f \sim 10^{-9}$ Hz for $M_{\mathrm{PBH}} \sim 1\text{-}10\ M_\odot$

~ Pulsar Timing Array band

LIGO-Virgo(-KAGRA):10-1000 Hz

too high…

Gaussian Case



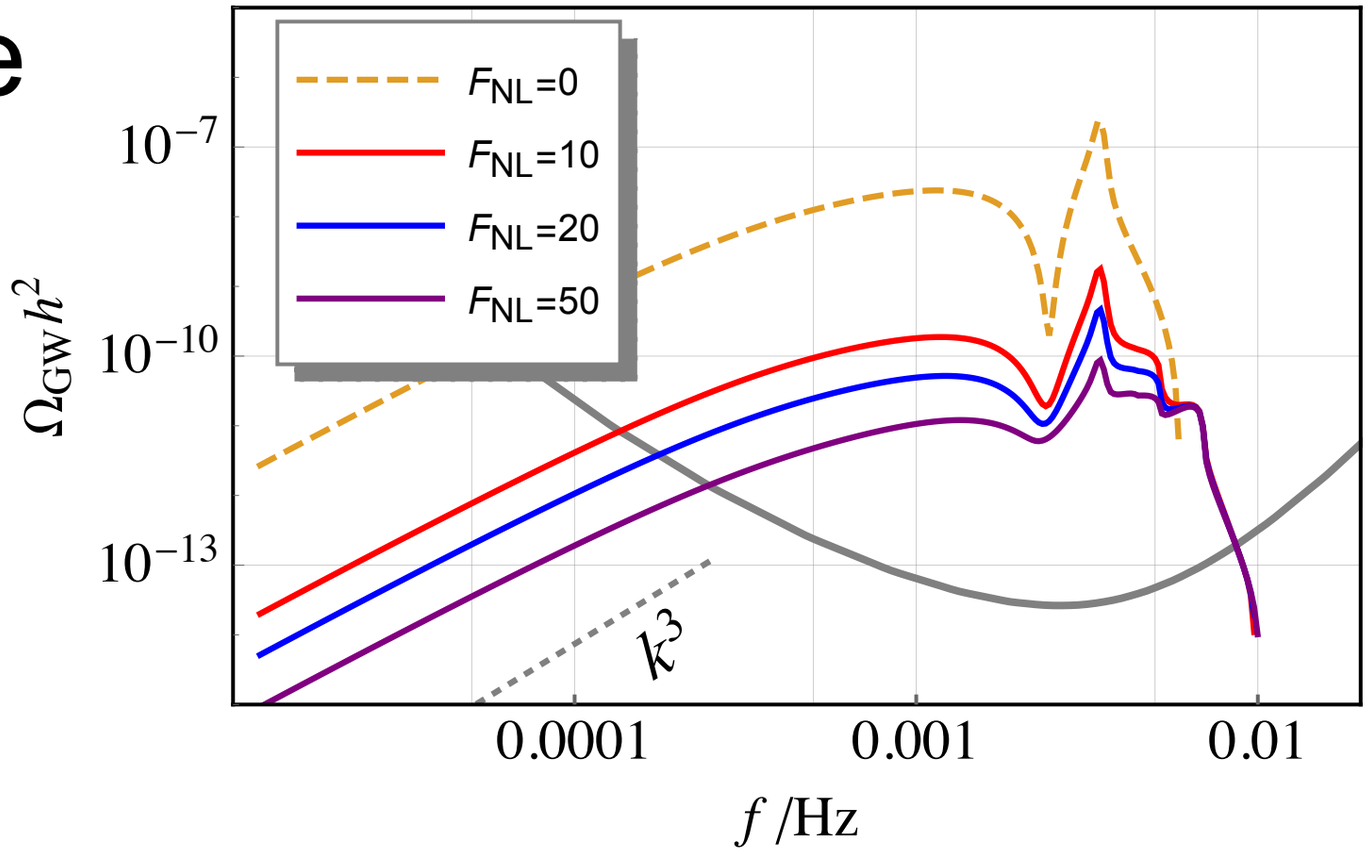
Saito & Yokoyama '09

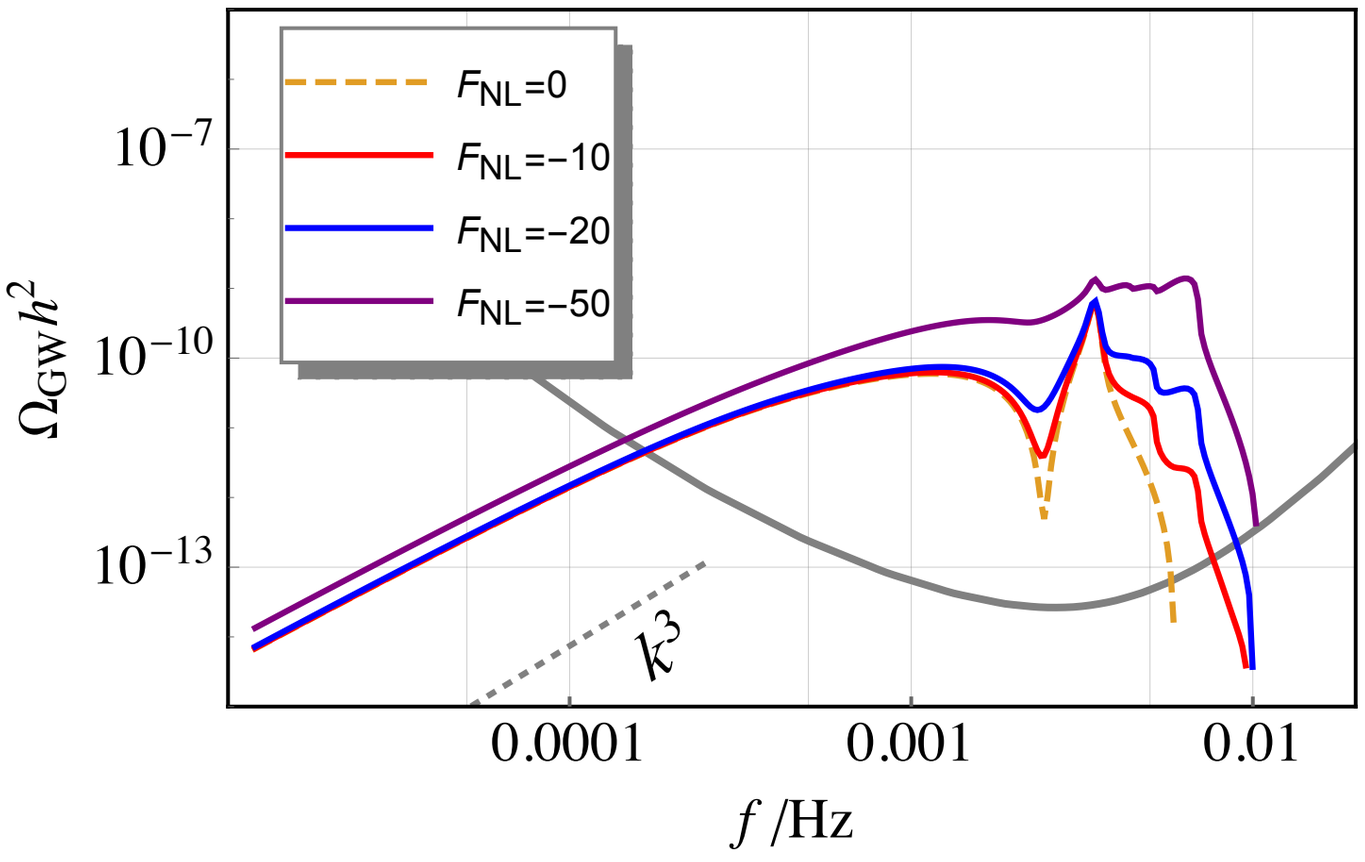
$$M_{\rm PBH} \sim 0.1 M_\odot \left(\frac{1{\rm GeV}}{T}\right)^2 \sim 10 M_\odot \left(\frac{1{\rm pc}^{-1}}{k}\right)^2$$

Non-Gaussian Case

$$\mathscr{R}(\mathbf{x}) = \mathscr{R}_g(\mathbf{x}) + F_{\rm NL}\left[\mathscr{R}_g^2(\mathbf{x}) - \langle \mathscr{R}_g^2(\mathbf{x})\rangle\right].$$

- Up: $F_{NL} > 0$, and we fix the PBH abundance to be 1.
- Down: $F_{NL} < 0$, and we fix the peak amplitude to be $\mathscr{A}_{\mathscr{R}} = 10^{-2}$
- Frequency: PBH window <—> LISA band
- GWs will be detected if BHs=CDM
- Conversely, if LISA doesn't see GWs, PBHs≠CDM





Summary

- 2-field inflation models can produce abundant PBHs as well as GWs.

- If PBHs = CDM, M_{PBH}~$10^{19\text{-}22}$g, induced GWs must be detectable by LISA, indep of non-Gaussianity.

- Conversely if LISA doesn't detect the induced GWs, it constrains the PBH abundances of M_{PBH}~$10^{19\text{-}22}$g, where no other experiment can explore.

- If resonant amplification occurs, GWs generated during inflation can dominate GW background: PBHs and GWs give complimentary info of the 2-fields.

- PBHs from vacuum tunneling during inflation may explain everything!