Gordon Godfrey
astroparticle physics
Dec 2, 2020

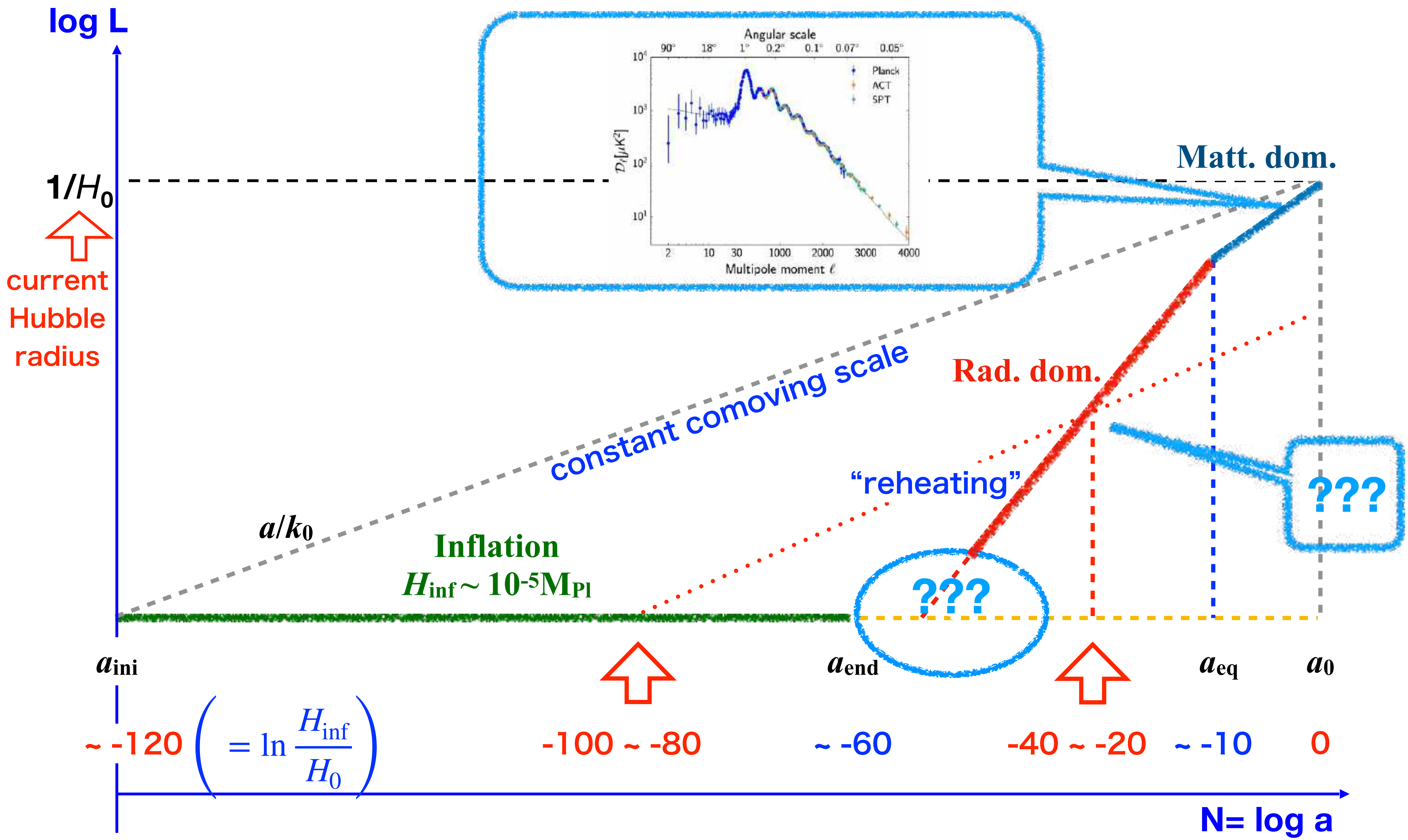
Primordial Black Holes and Gravitational Waves

Misao Sasaki

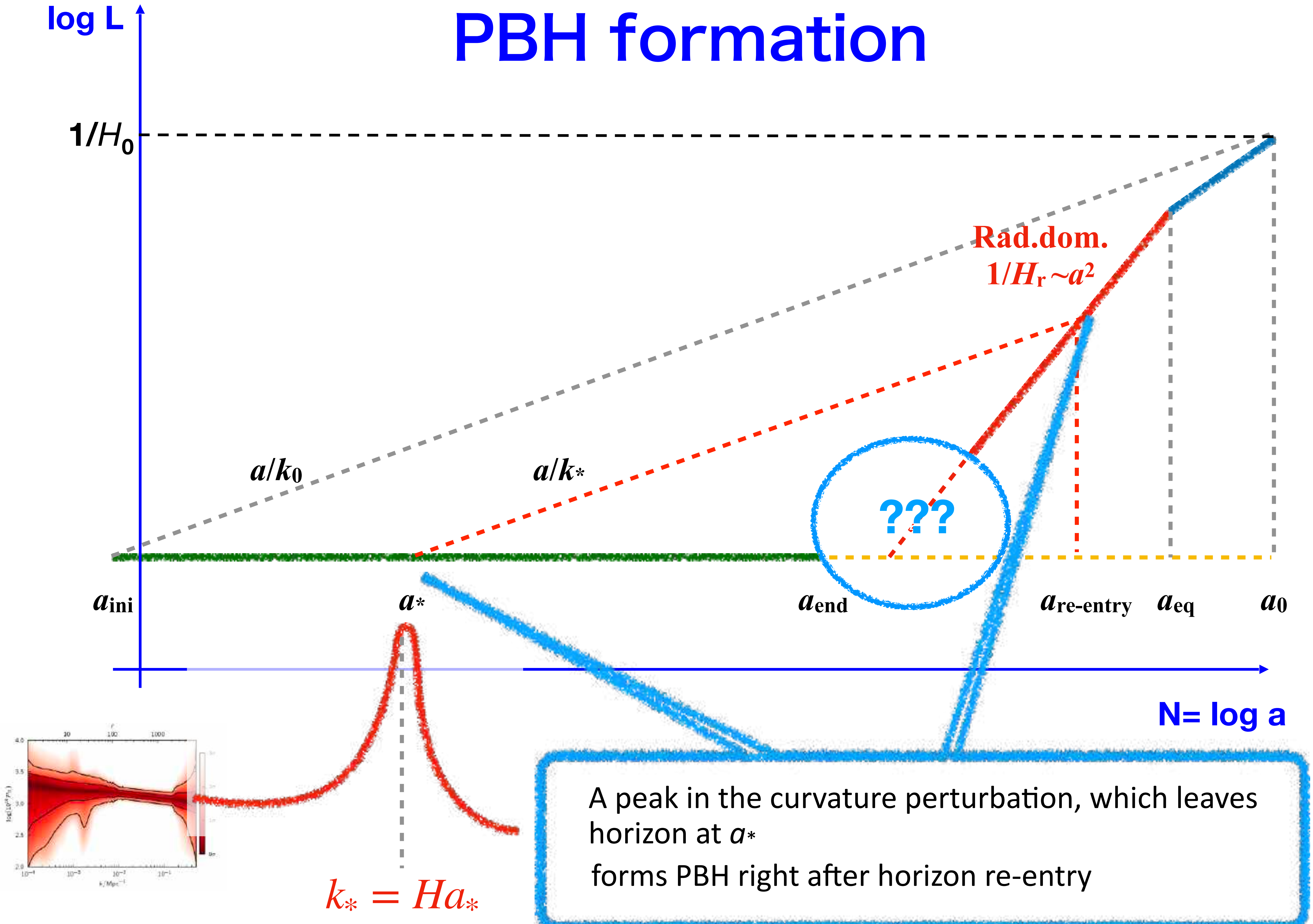
Kavli IPMU, University of Tokyo
YITP, Kyoto University
LeCosPA, National Taiwan University

inflationary model construction

cosmic spacetime diagram



PBH formation



Curvature perturbation to PBH

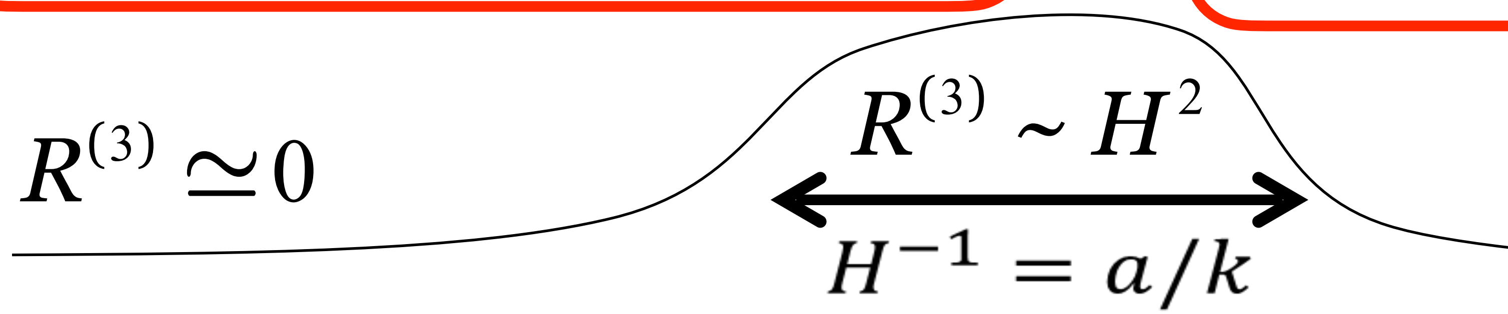
➢ gradient expansion/separate universe approach

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

Hamiltonian constraint (Friedmann eq.)

$$R^{(3)} \approx -\frac{4}{a^2}\nabla^2\mathcal{R}_c \approx \frac{8\pi G}{3}\delta\rho_c$$

$$\frac{\delta\rho_c}{\rho} \approx \mathcal{R}_c \quad \text{at} \quad \frac{k^2}{a^2} = H^2$$



formation of a closed universe

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

Young, Byrnes & MS ‘14

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

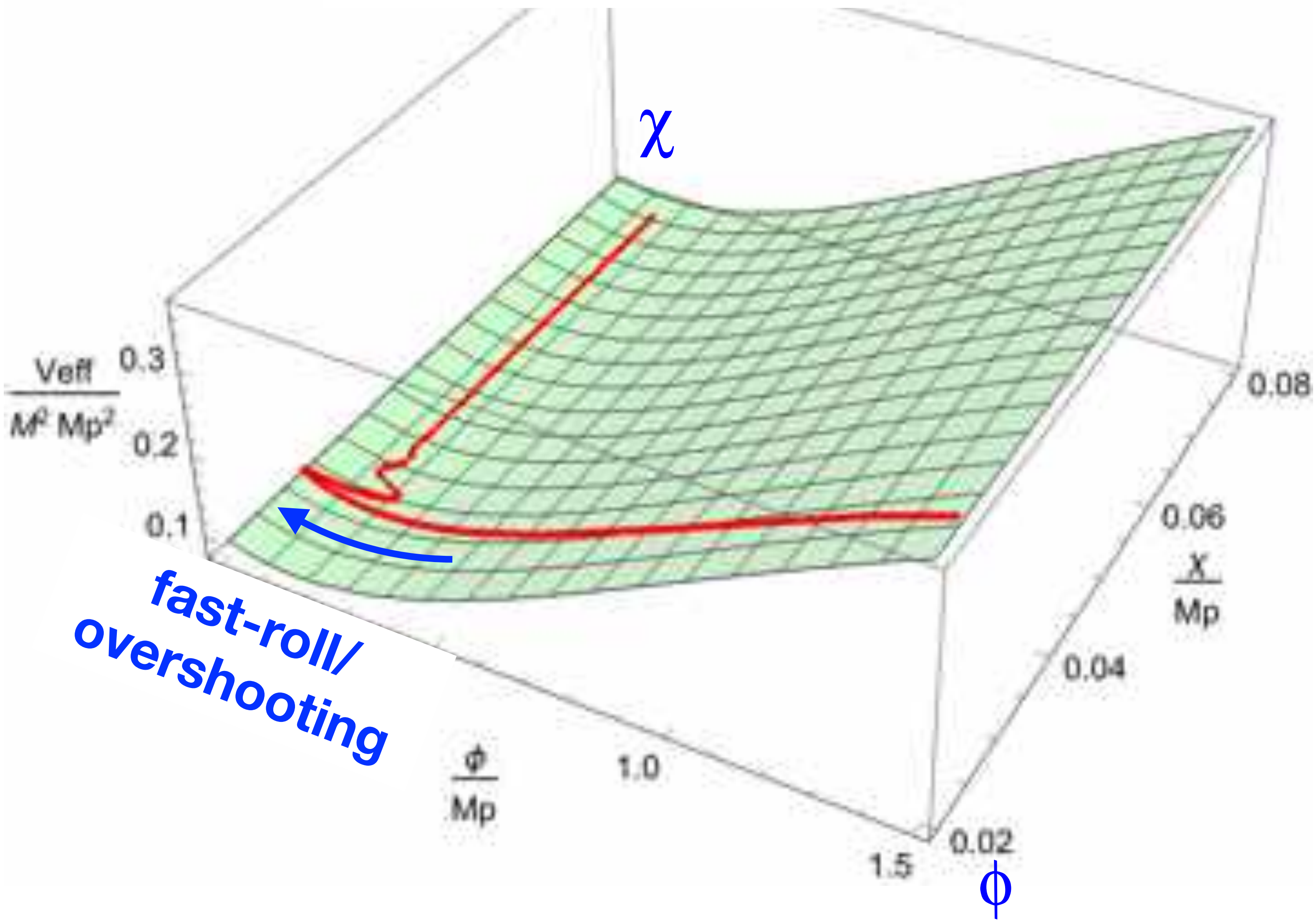
➢Spins of PBHs are expected to be very small

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

Model 1: Scalaron+χ model

Pi, Zhang, Huang & MS '17

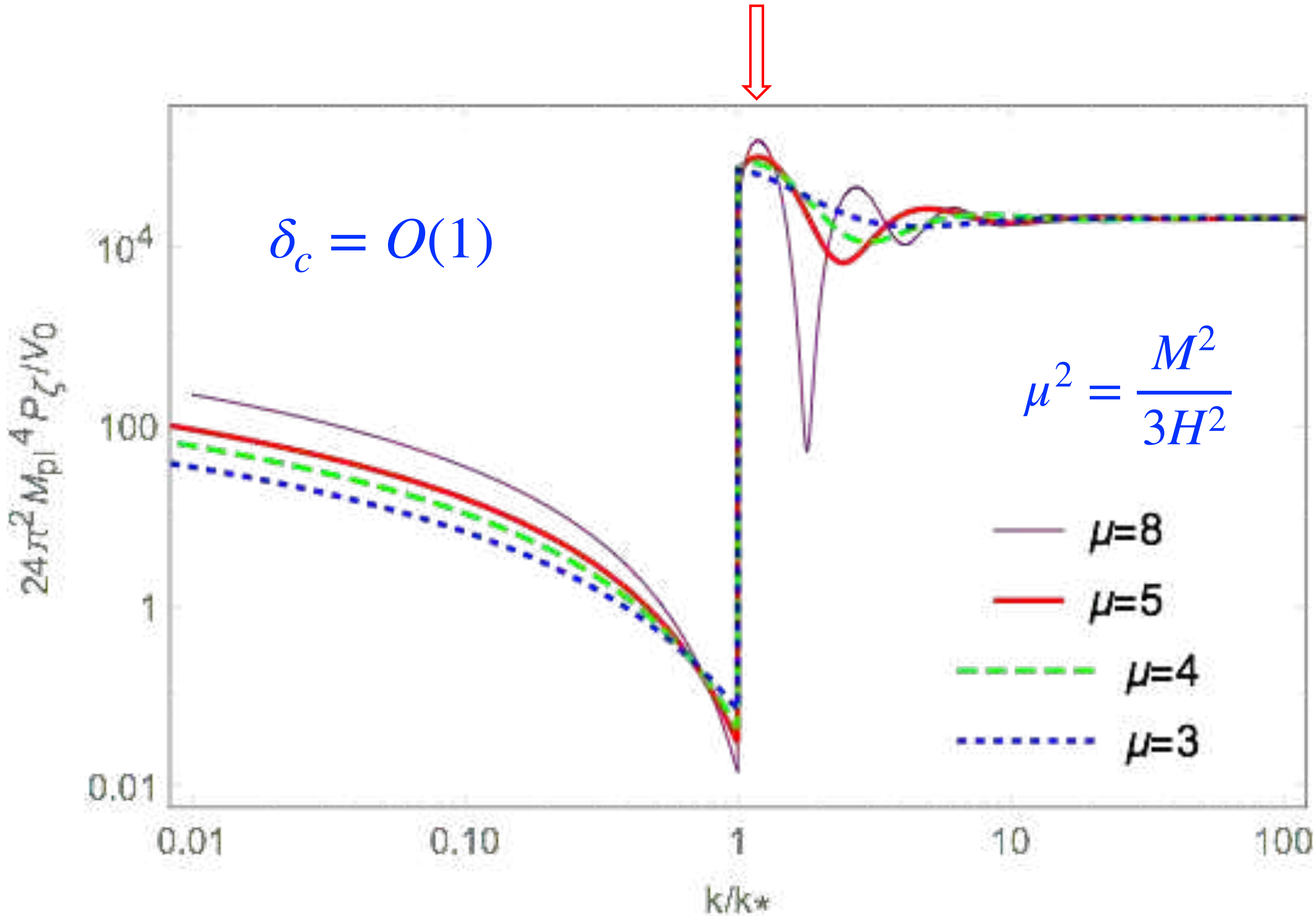
$$S_J = \int d^4x\sqrt{-g}\left\{\frac{M_{\rm Pl}^2}{2}\left(R+\frac{R^2}{6M^2}\right)-\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi) - \frac{1}{2}\xi R\chi^2\right\}.$$



2-stage inflation

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

sharp peak



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

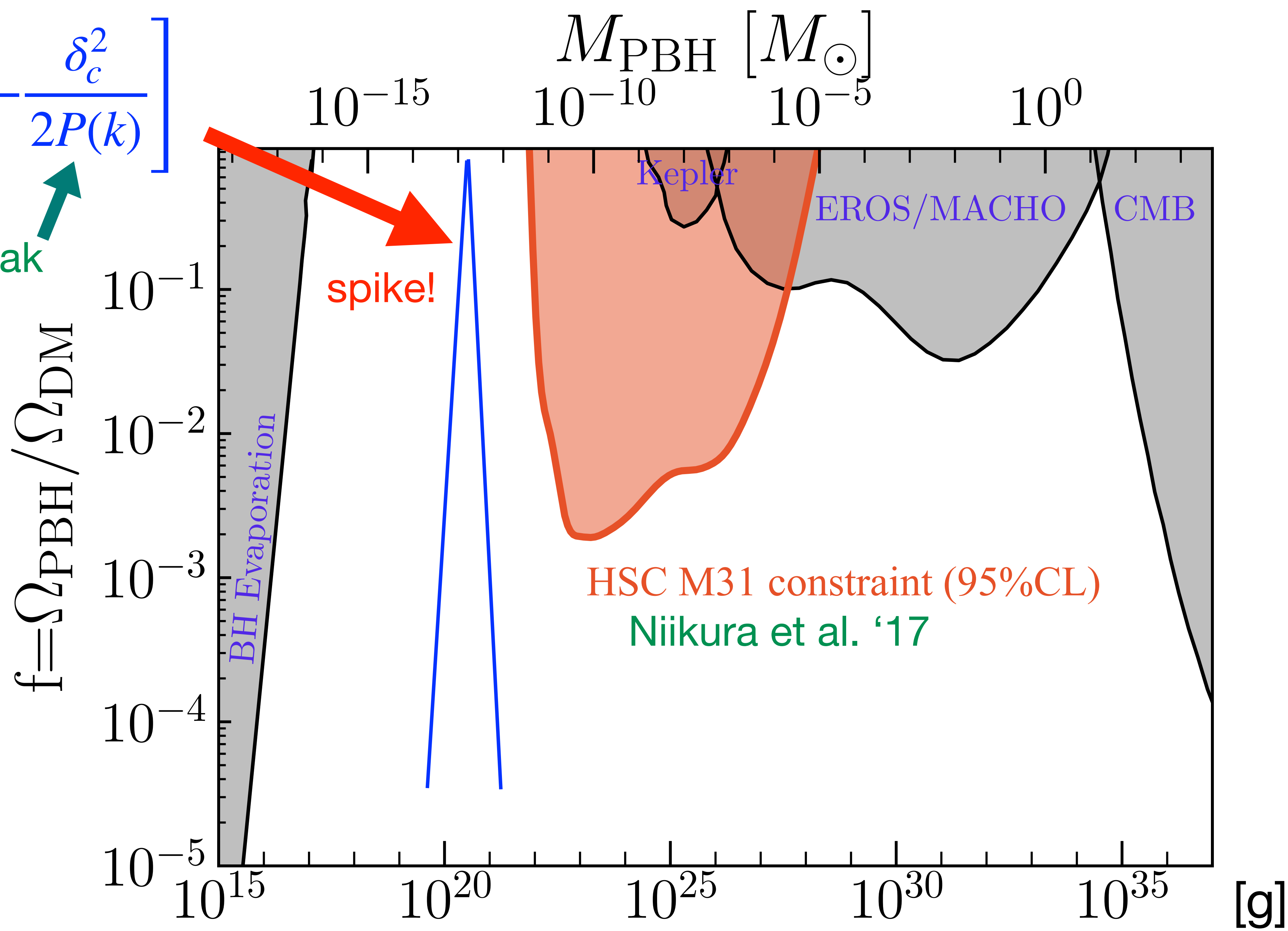
non-Gaussianity is found to be small in this model

PBH mass function

$\delta_c = O(1)$

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

sharp peak

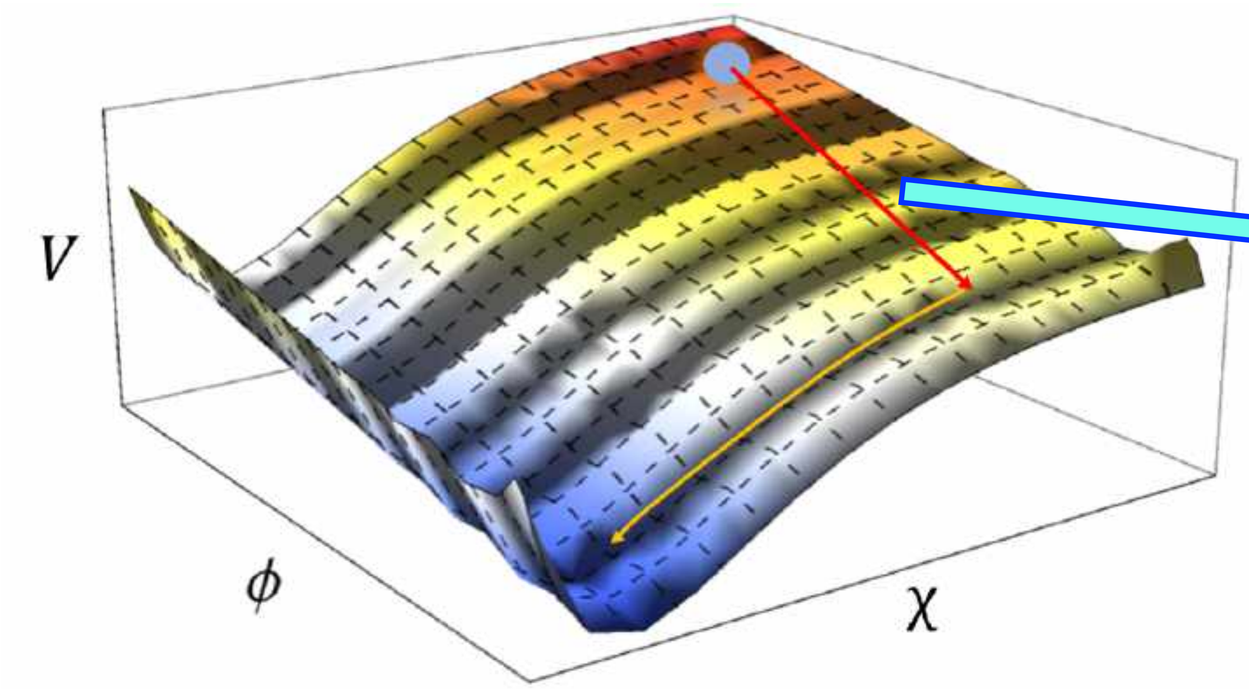


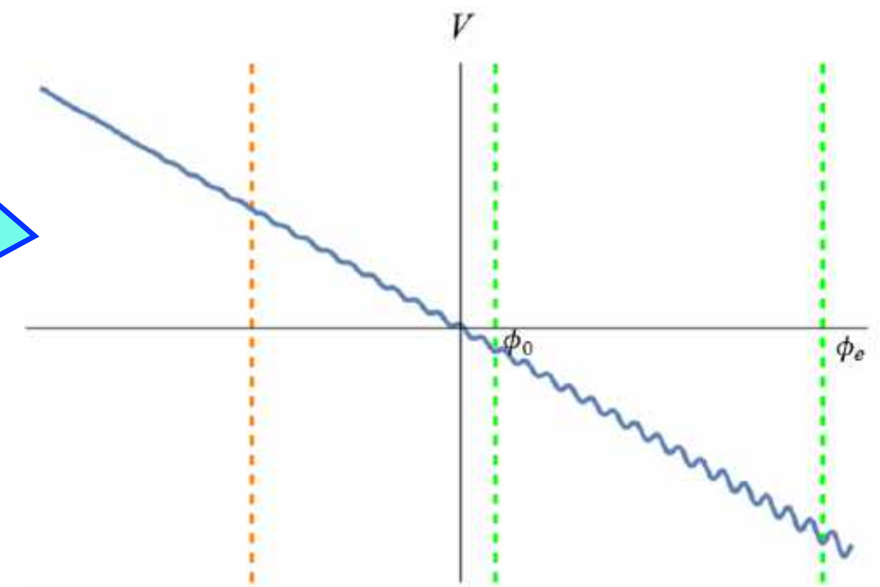
scalaron+x model can realize

PBH=CDM scenario with a monochromatic PBH mass!

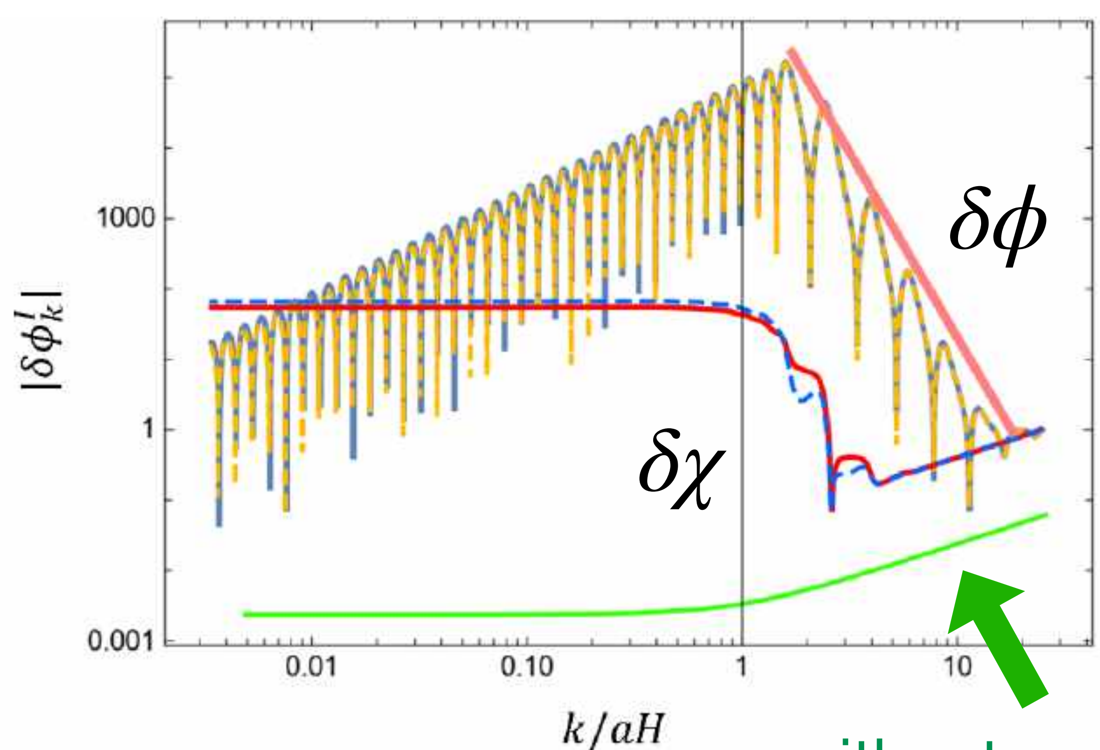
Model 2: Resonant Amplification Model

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





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



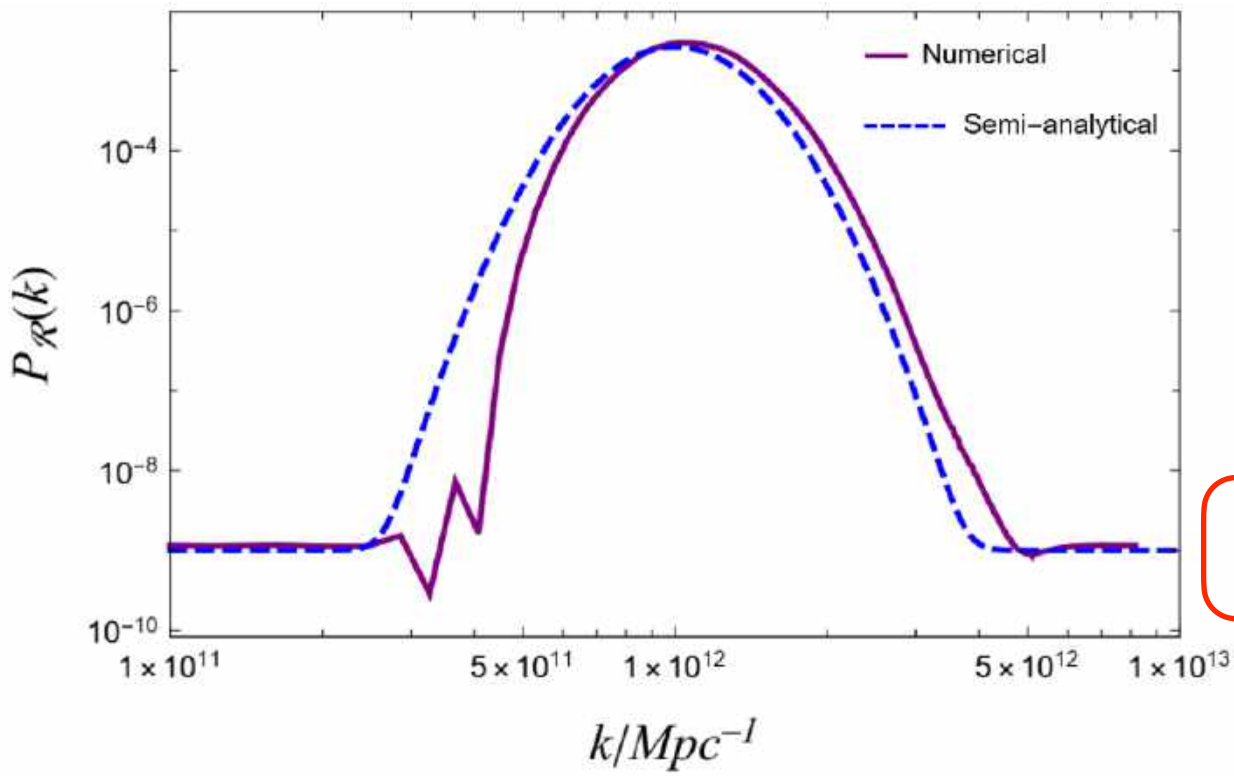
without amplification

$\delta\phi$: 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



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

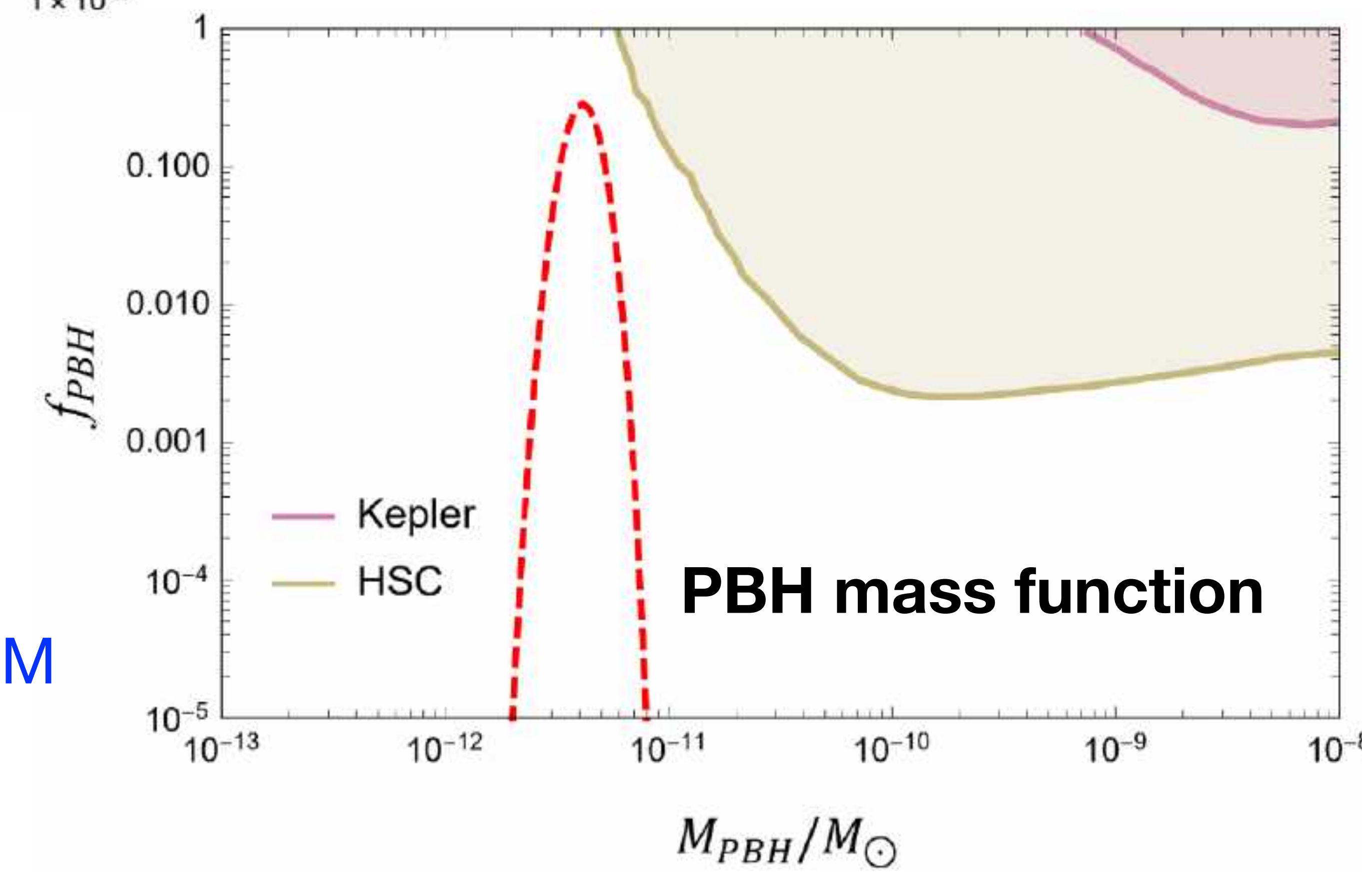
$$\mathcal{A}^2(k) = 1 + \mathcal{A}^2(k_*) \exp\left(-\frac{\ln^2(k/k_*)}{2\Delta^2}\right)$$

amplification factor $\sim 10^6$

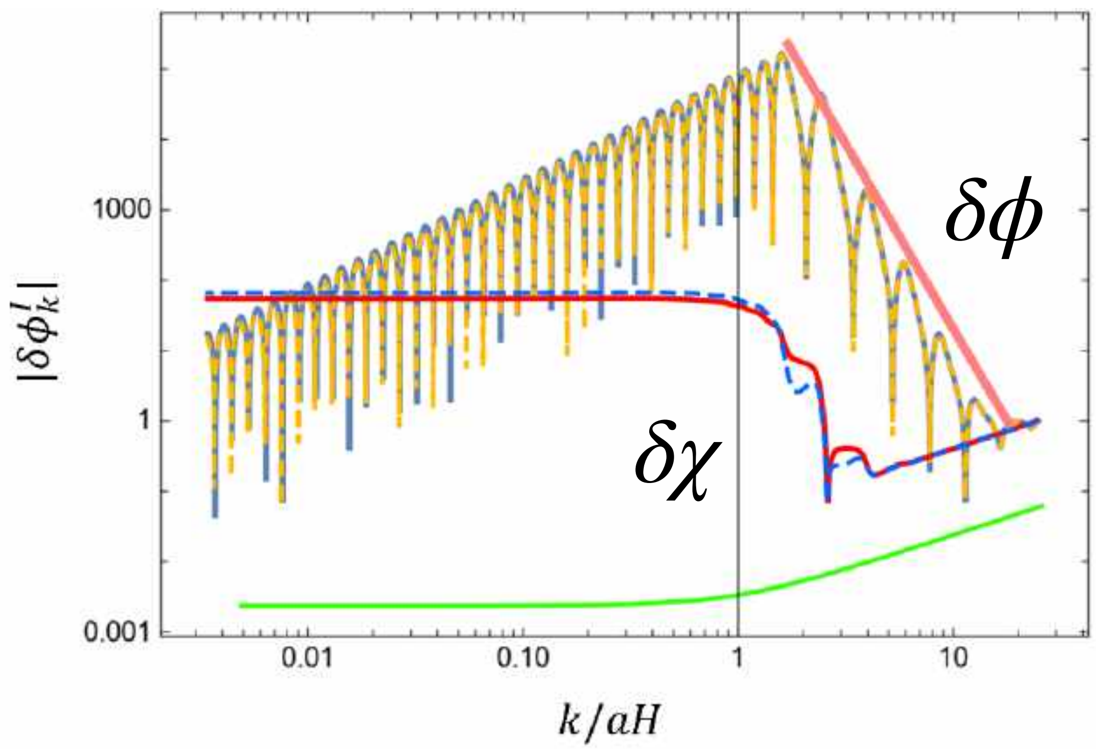
very good fit with log-normal function

$\Delta = O(1)$ 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

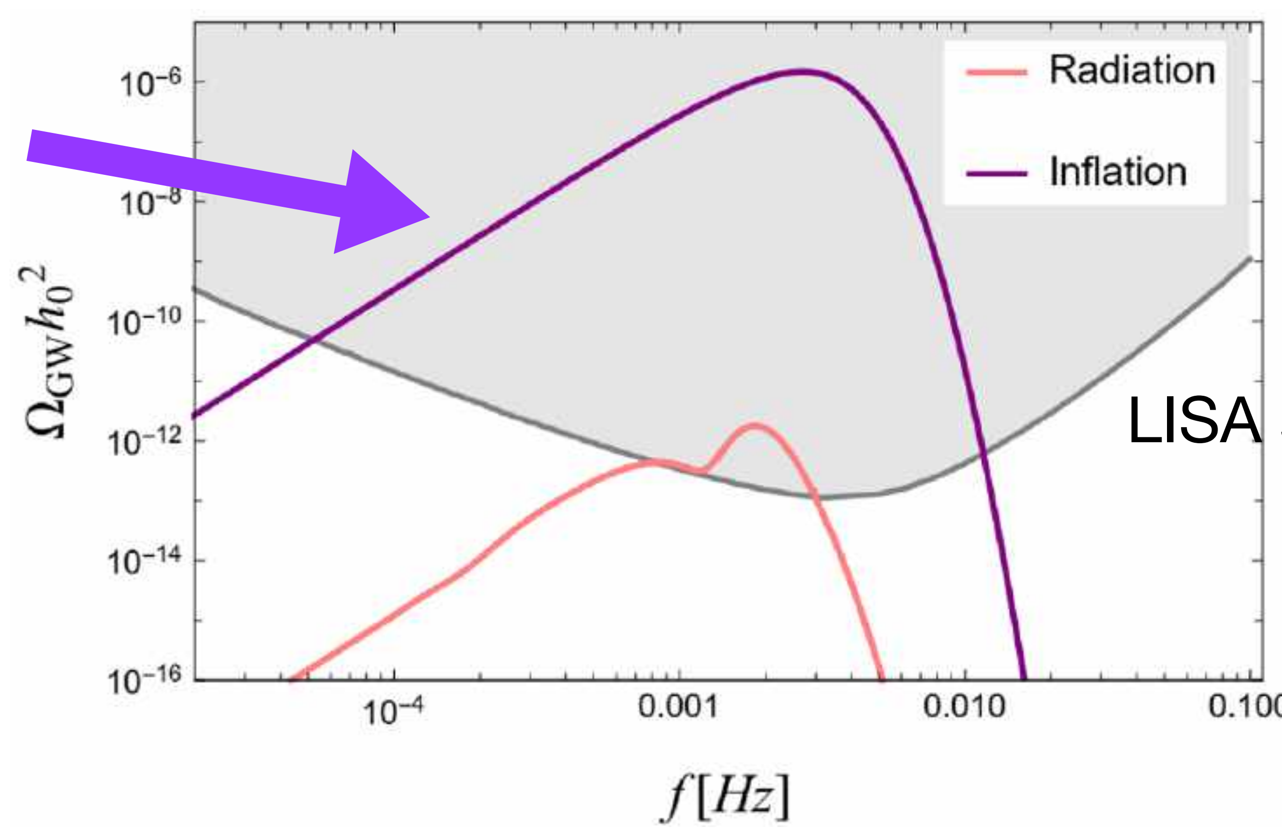
$\delta\chi$: amplified through coupling to $\delta\phi$

This leads to enhancement of curvature perturbation

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

GW probes $\delta\phi$

PBH probes $\delta\chi$



LISA sensitivity

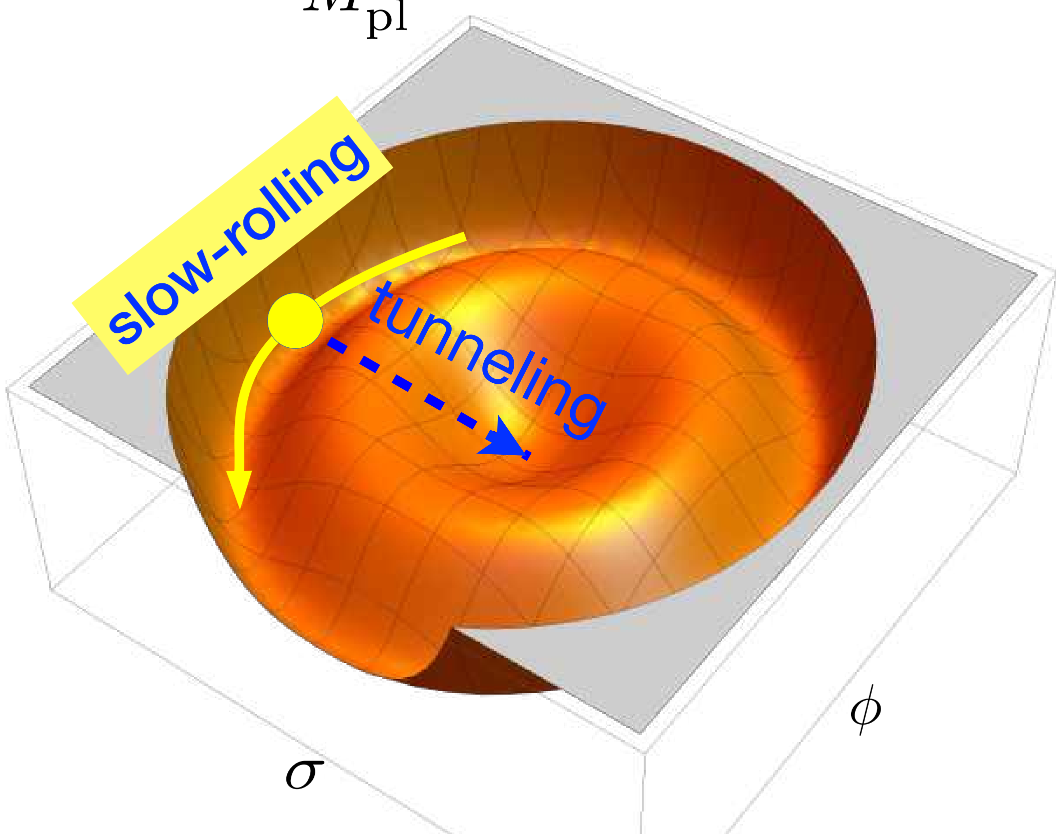
Model 3: PBH-as-MVP scenario

PBH formation during inflation due to vacuum tunneling
(not from curvature perturbation)

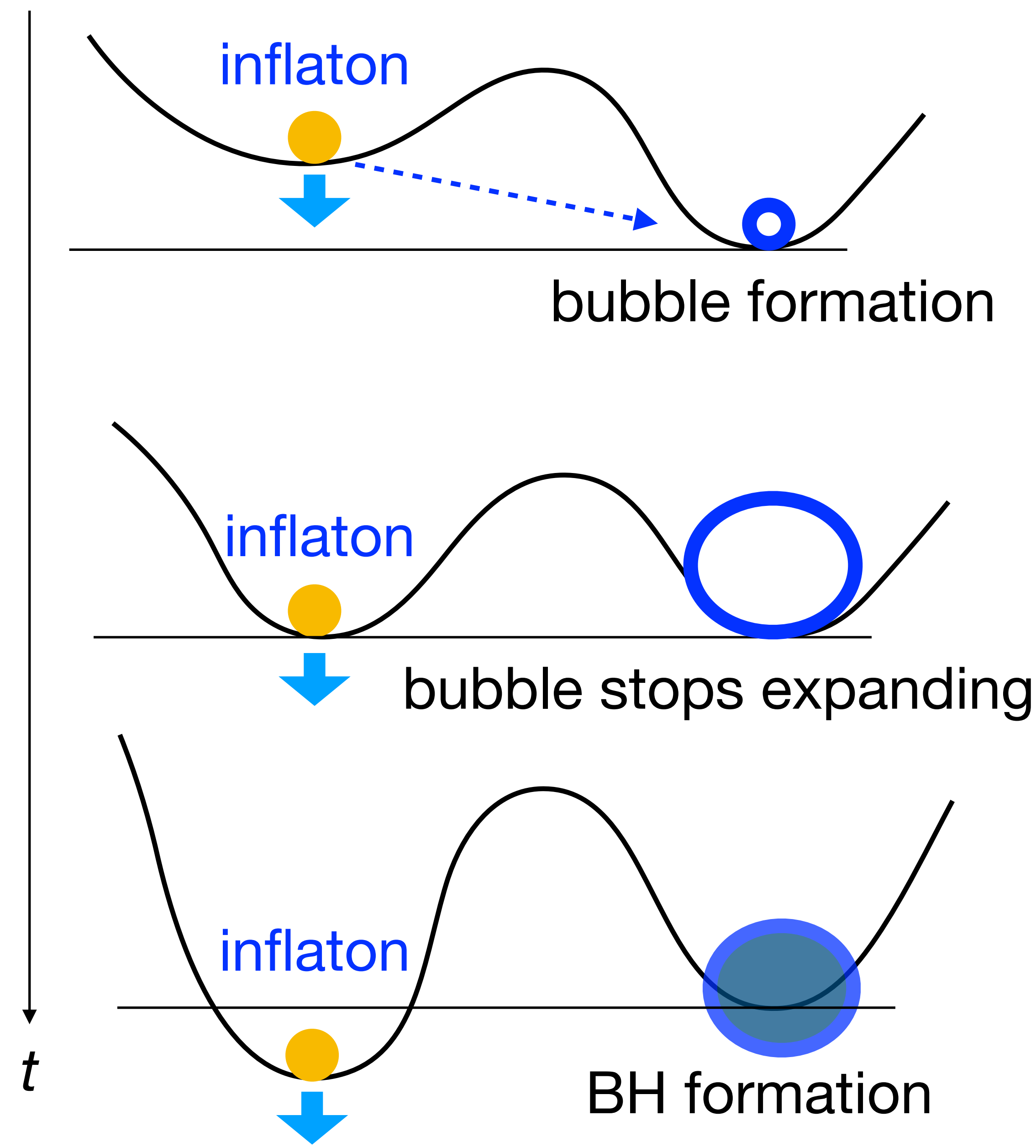
Garriga, Vilenkin & Zhang '15, Deng & Vilenkin '17,…

example:

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

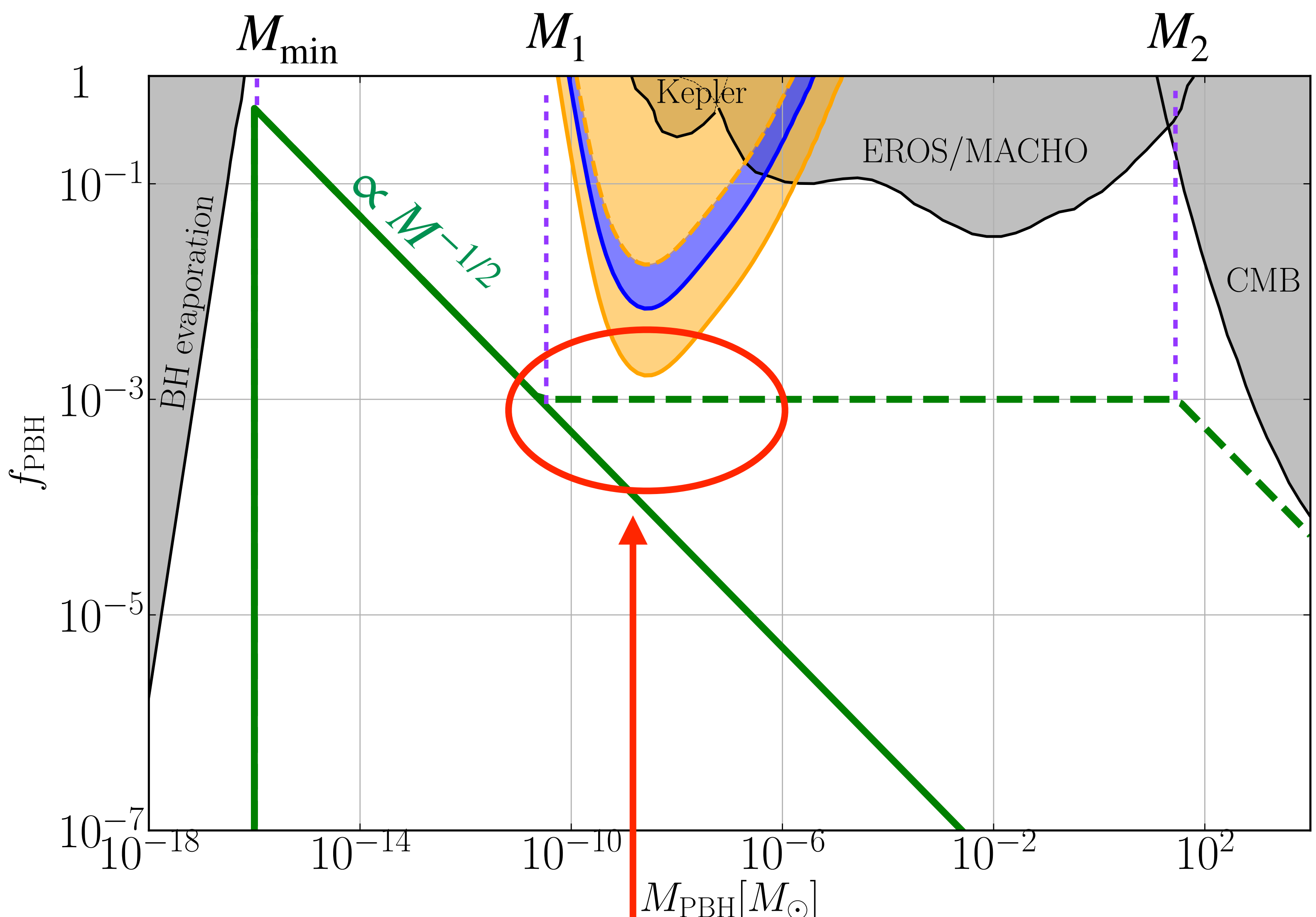


can probe multiverse!



Mass function in PBH-as-VIP scenario

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



may be tested by Subaru HSC

Subaru accepted our proposal!

4 night obs just done!

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

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

$M \simeq M_{min}$ ⋯ CDM

- if there is an intermediate matter-dom stage

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

$M \simeq M_2$ ⋯ LIGO BHs

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

$M \gg M_2$ ⋯ SMBHs

GWs from
Large Curvature Perturbation

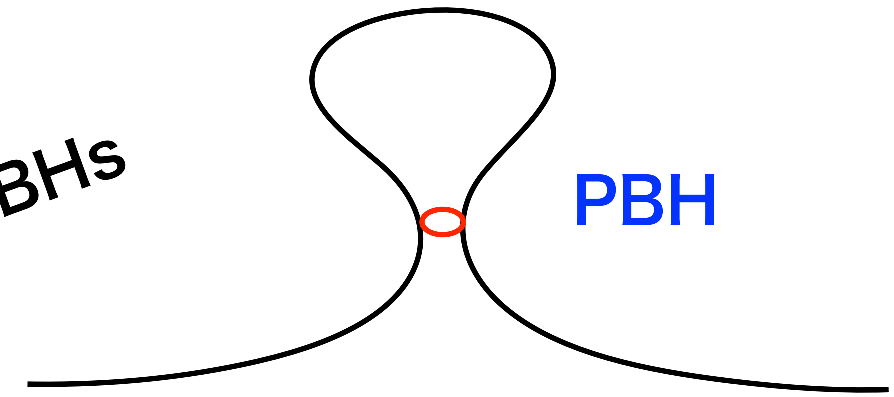
GWs can capture PBHs!

curvature perturvation

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

(~Newton potential)

large peaks form PBHs

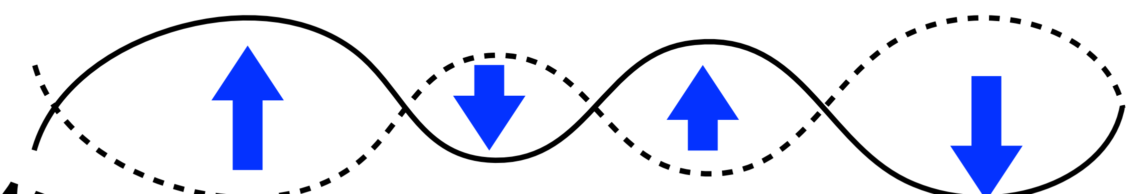


PBH

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

NL effect induces GWs

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



spacetime oscillations

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

⇒ Background GWs at LISA band!

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

~ Pulsar Timing Array band

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

too high…

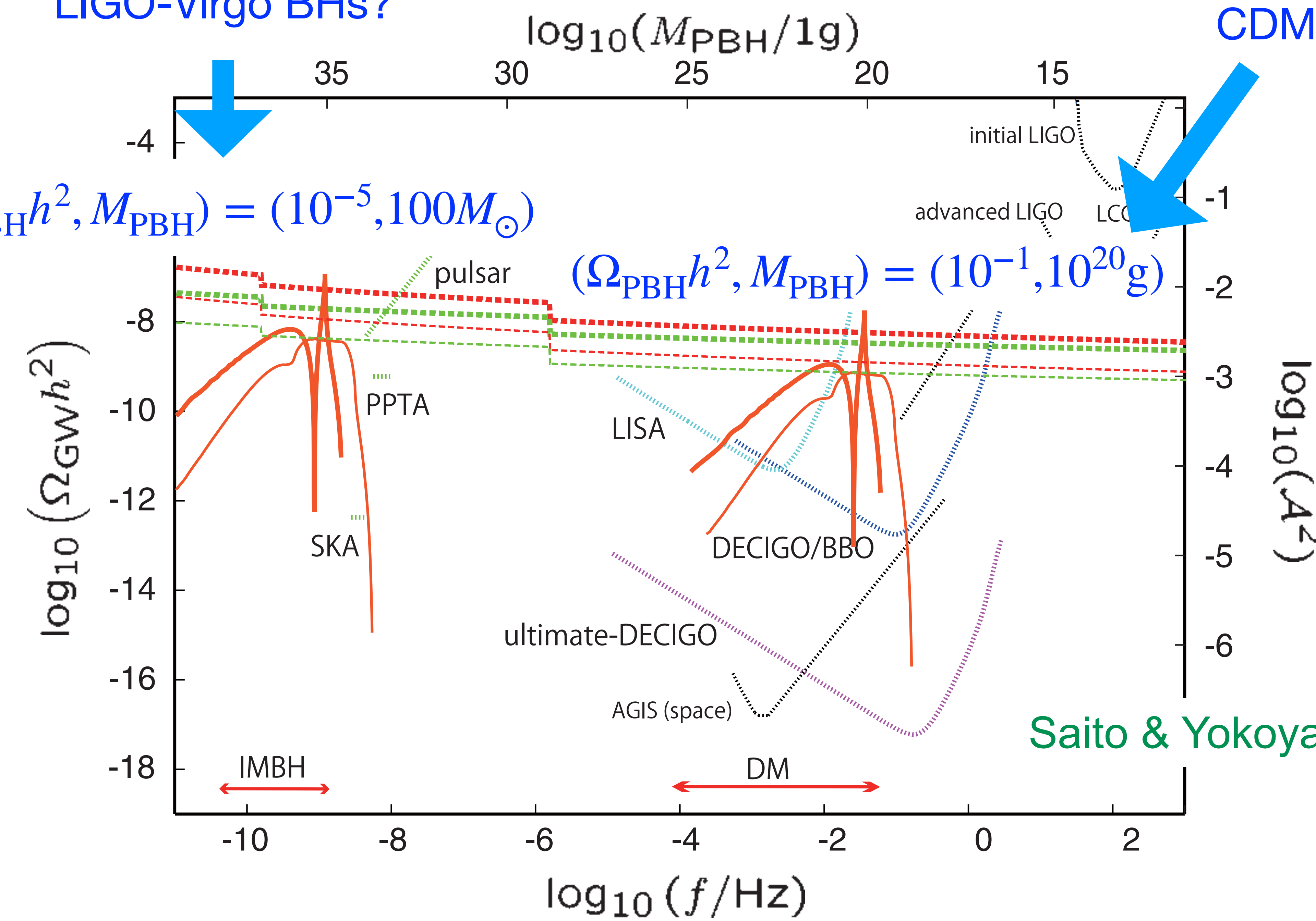
Gaussian Case

LIGO-Virgo BHs?

CDM?

$(\Omega_{\rm PBH}h^2, M_{\rm PBH}) = (10^{-5}, 100M_\odot)$

$(\Omega_{\rm PBH}h^2, M_{\rm PBH}) = (10^{-1}, 10^{20}{\rm g})$



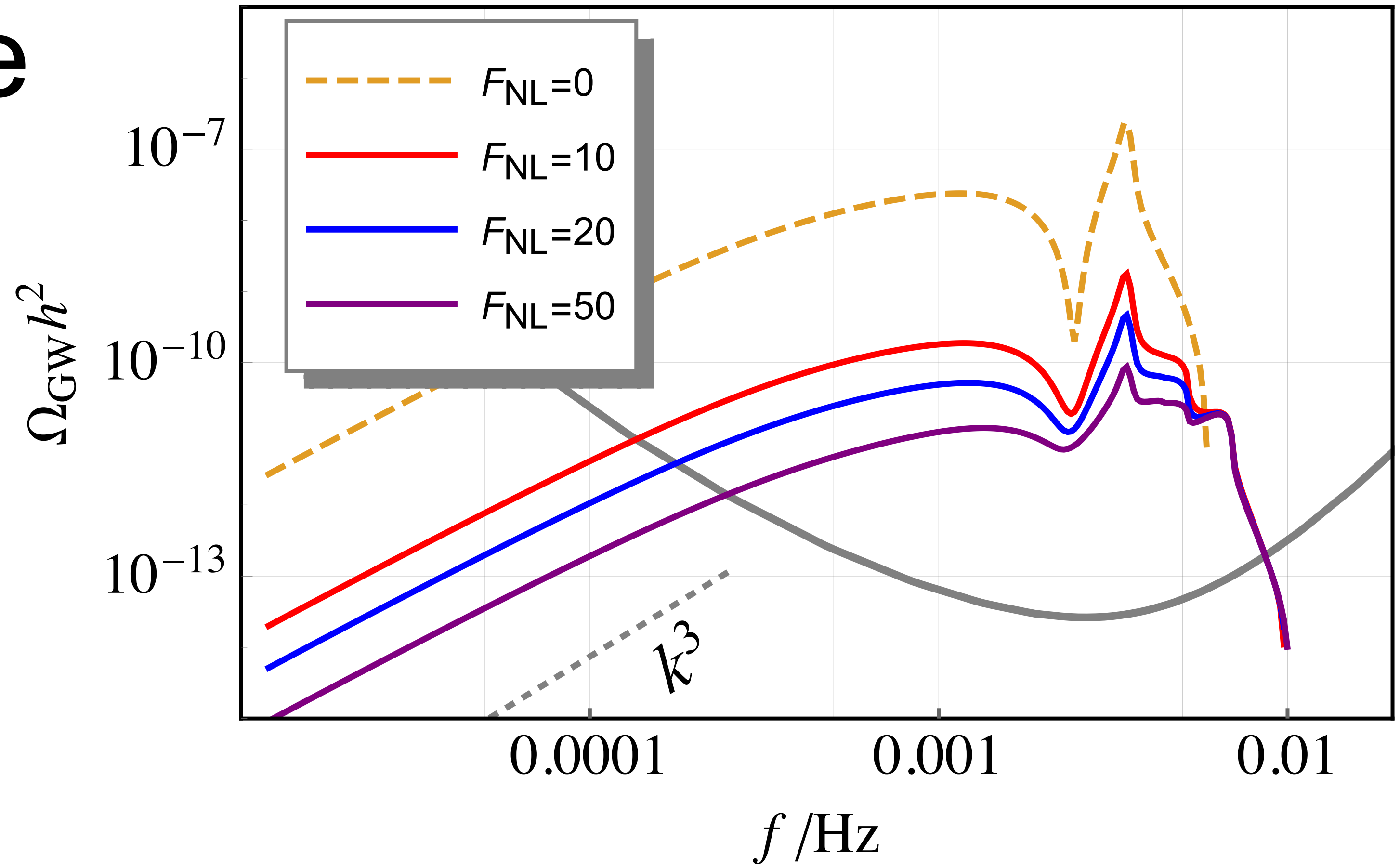
Saito & Yokoyama '09

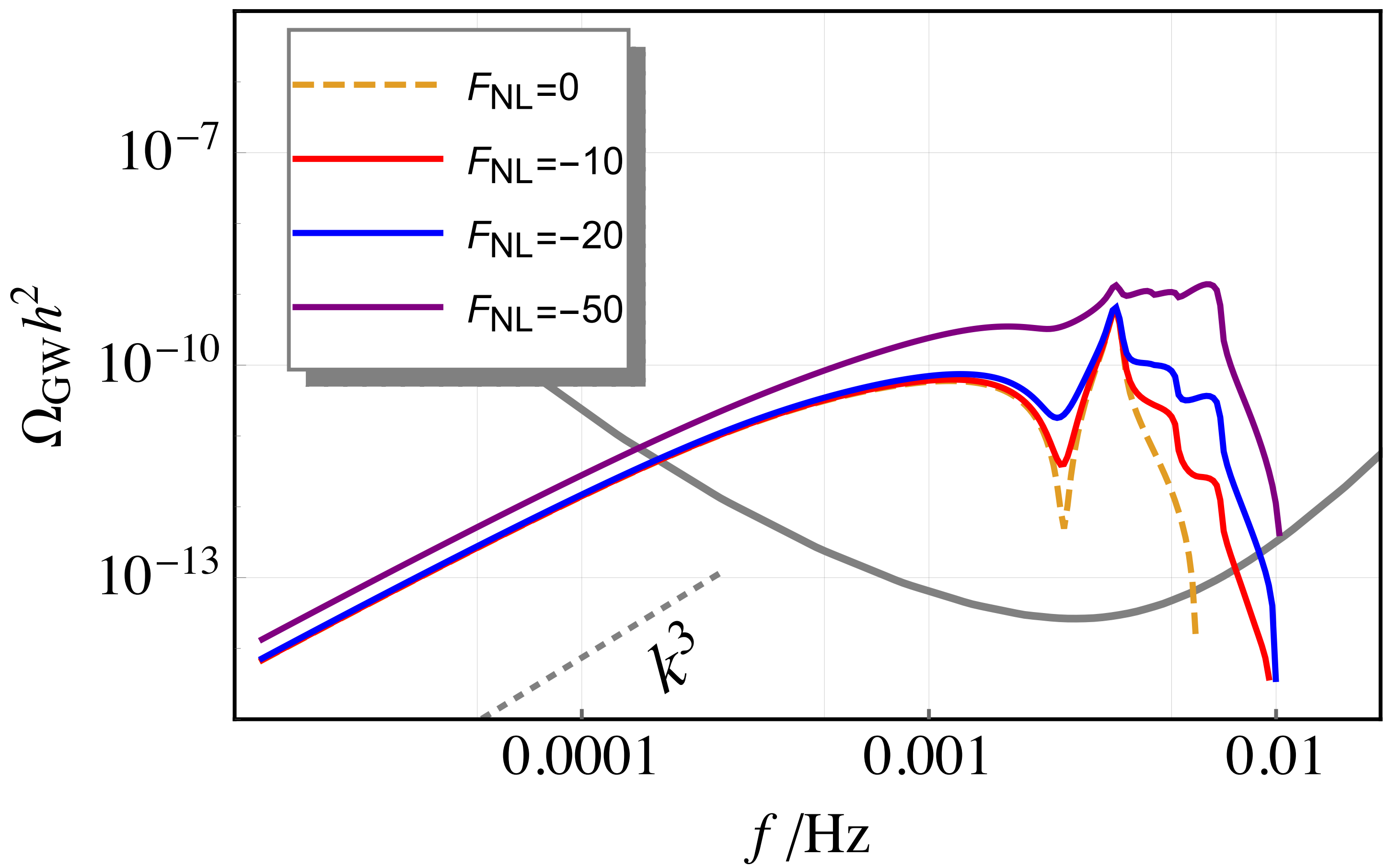
$$M_{\rm PBH} \sim 0.1 M_\odot \left(\frac{1{\rm GeV}}{T}\right)^2 \sim 10 M_\odot \left(\frac{1{\rm pc}^{-1}}{k}\right)^2$$

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



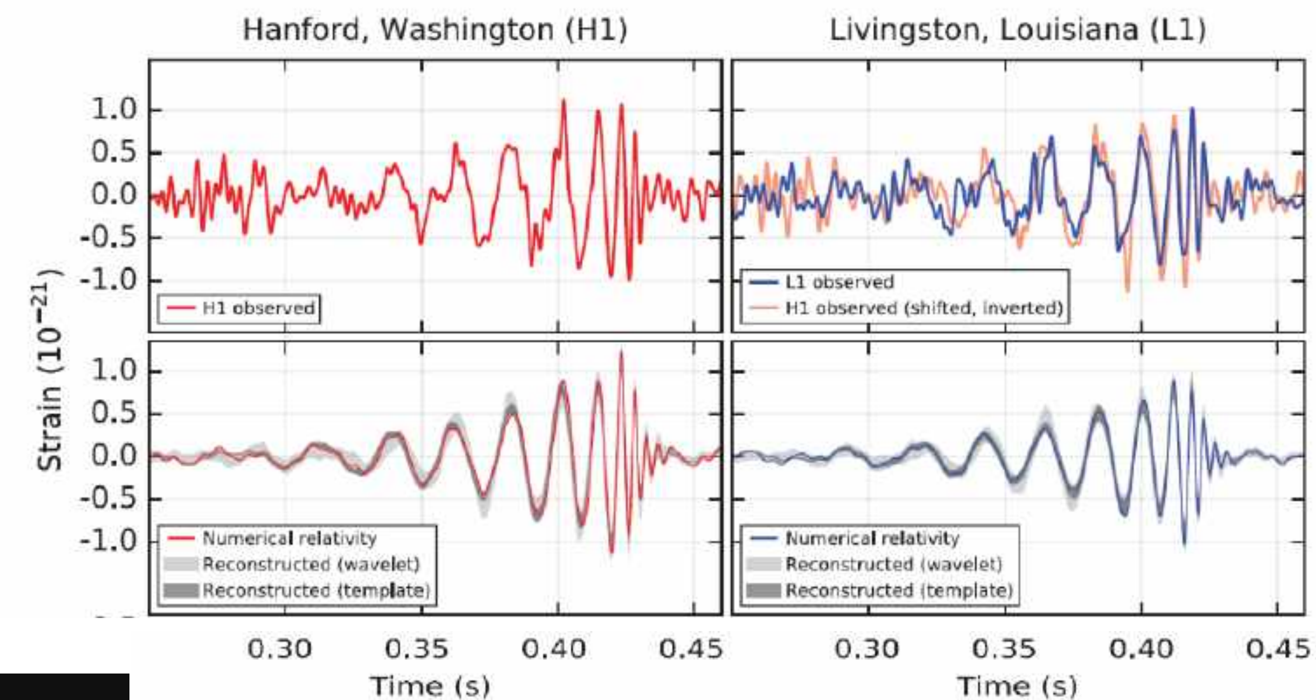


GWs from Binary PBHs

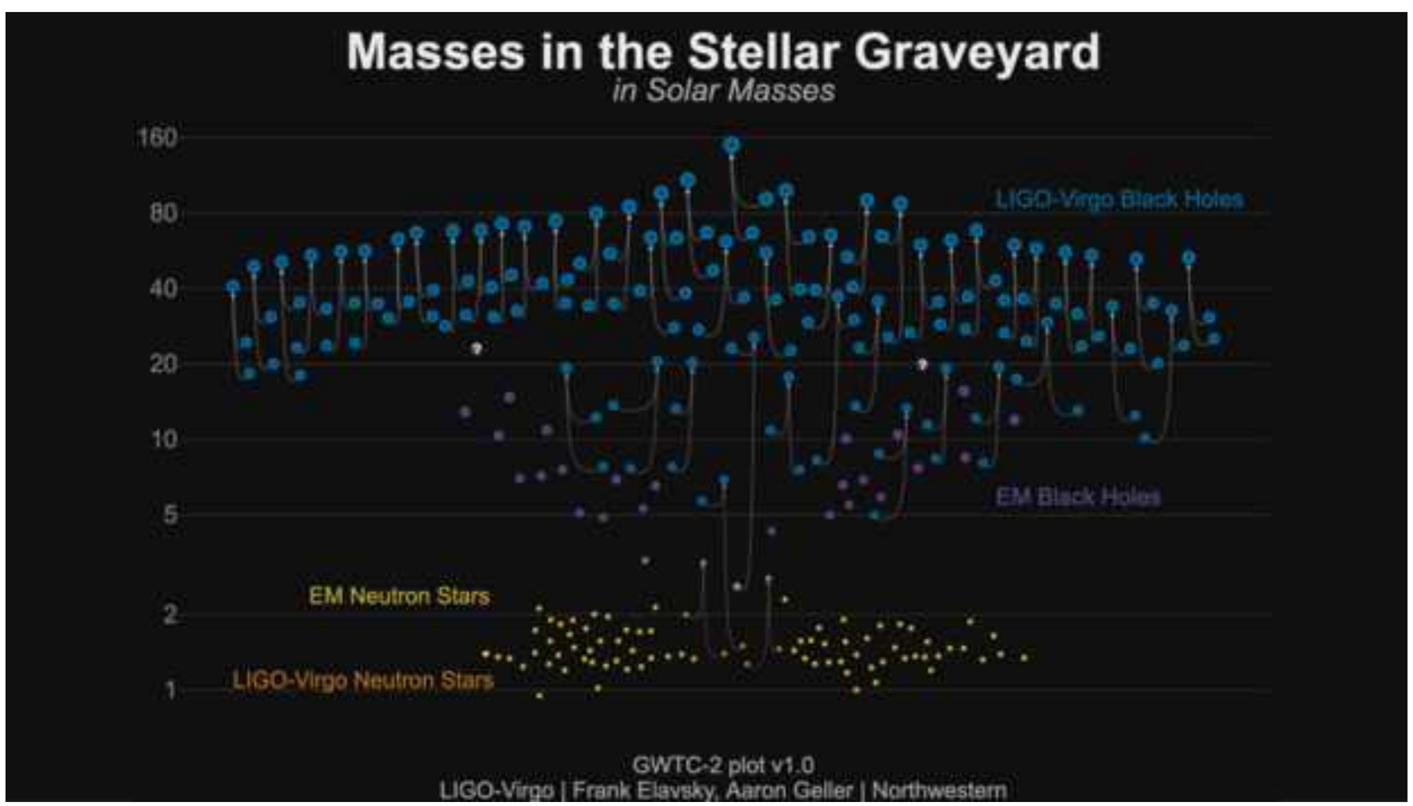
LIGO-Virgo (LV) BBHs

- LIGO discovered GWs from Binary BHs !
- Mass was large: $M_{\rm PBH} \sim 30 M_\odot$
- ~ 50 BBH mergers up to now!

  LIGO-Virgo O1+O2+O3a



GW150914

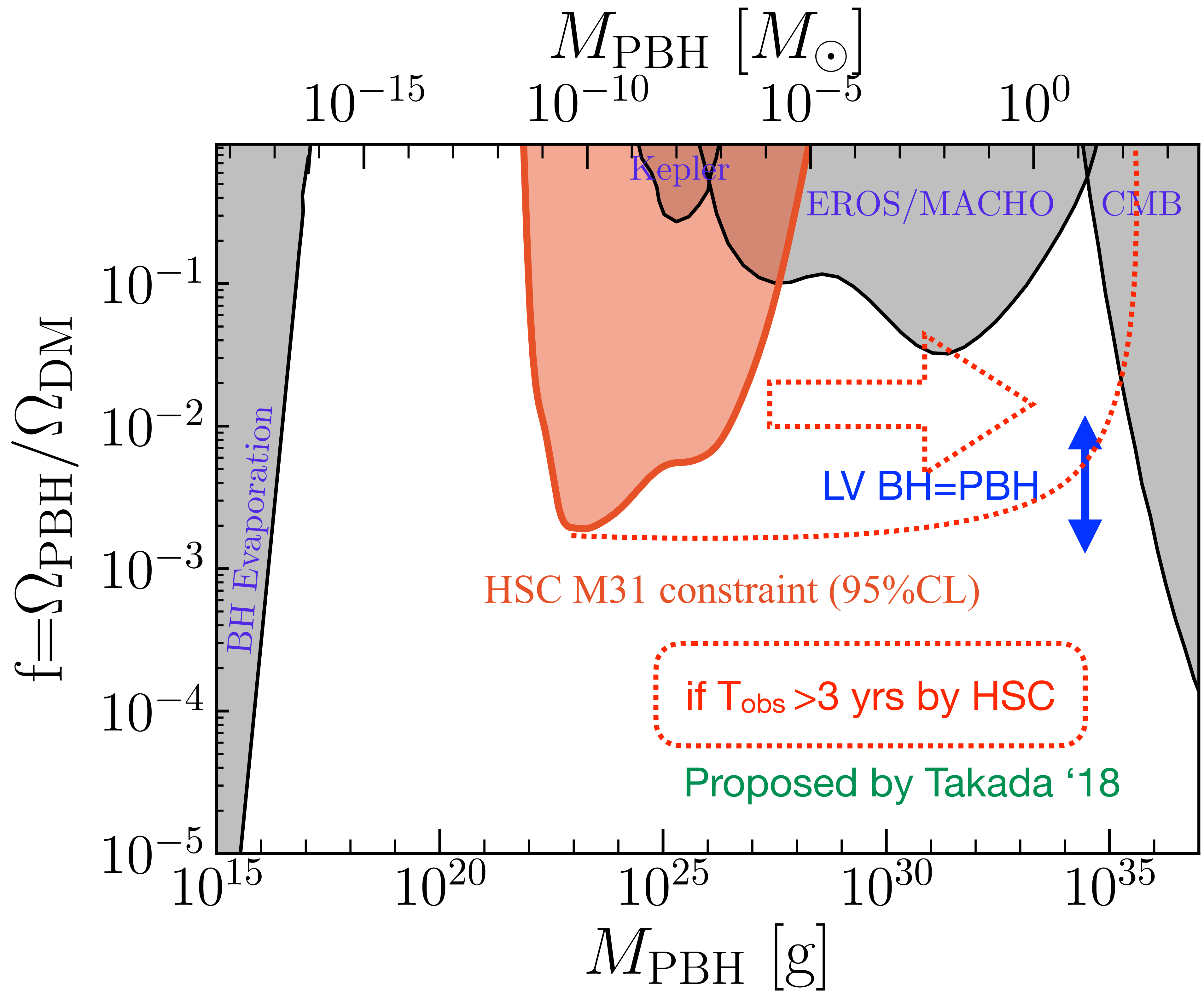


~ consistent with spin=0

→ PBHs with $f_{\rm PBH} \sim 10^{-2}$-10^{-3}

MS, Suyama, Tanaka & Yokoyama, '16

Testing LV BH=PBH scenario



Testing LV BH=PBH scenario (cont.)

"Hidden Universality in …"

Kocsis et al. '17

BBH merger rate: $\mathscr{R}$

$$\alpha \equiv -(m_1+m_2)^2 \times \frac{\partial^2}{\partial m_1 \partial m_2}\mathscr{R}(m_1,m_2,t)$$

$0.97 \lesssim \alpha \lesssim 1.05$ for PBHs

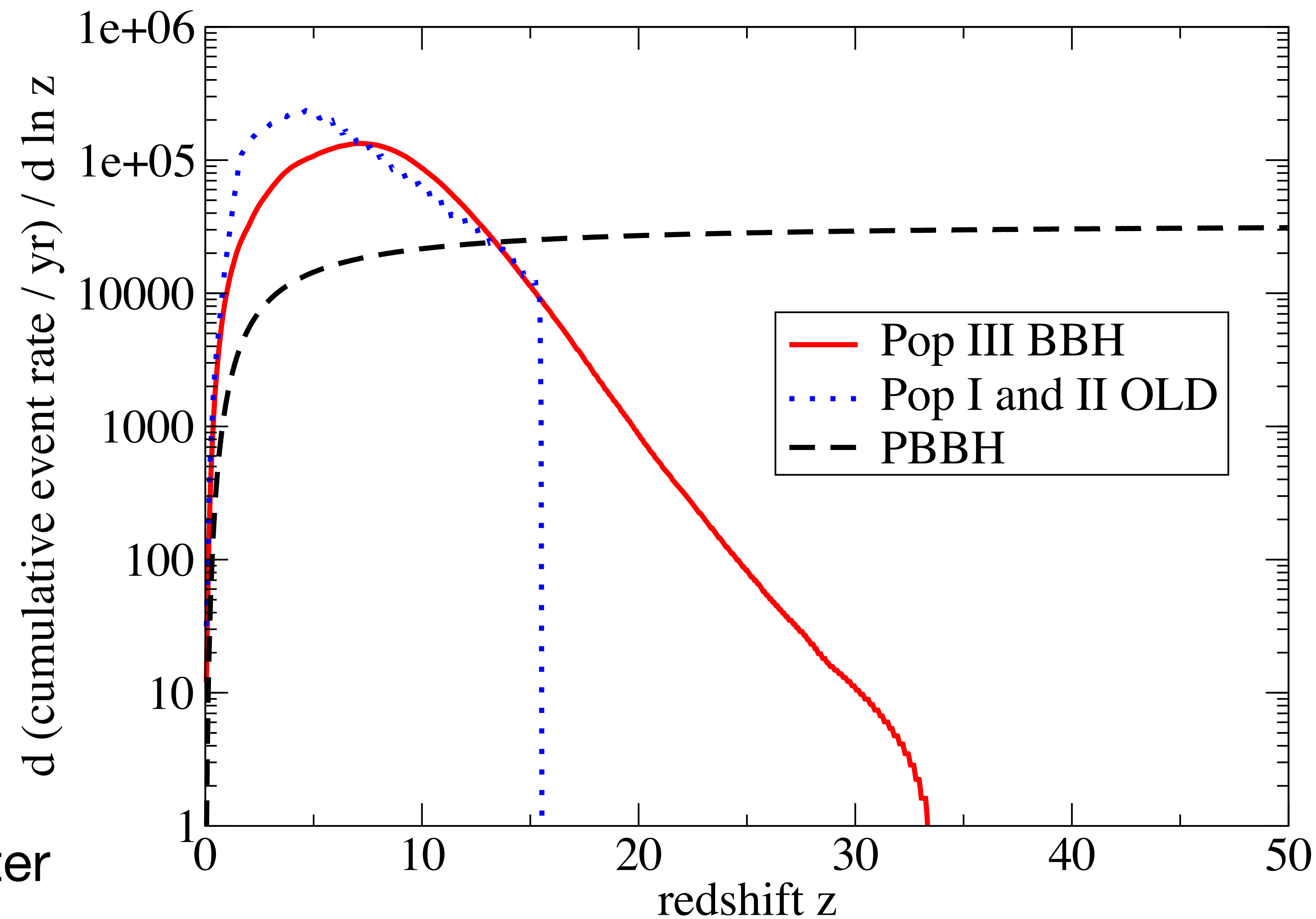
⇕

$\alpha \sim 4$ for BBH in dense stellar cluster

$\alpha \sim 1.4$ for BBH from close encounters

"Pre-DECIGO can get the smoking gun …"

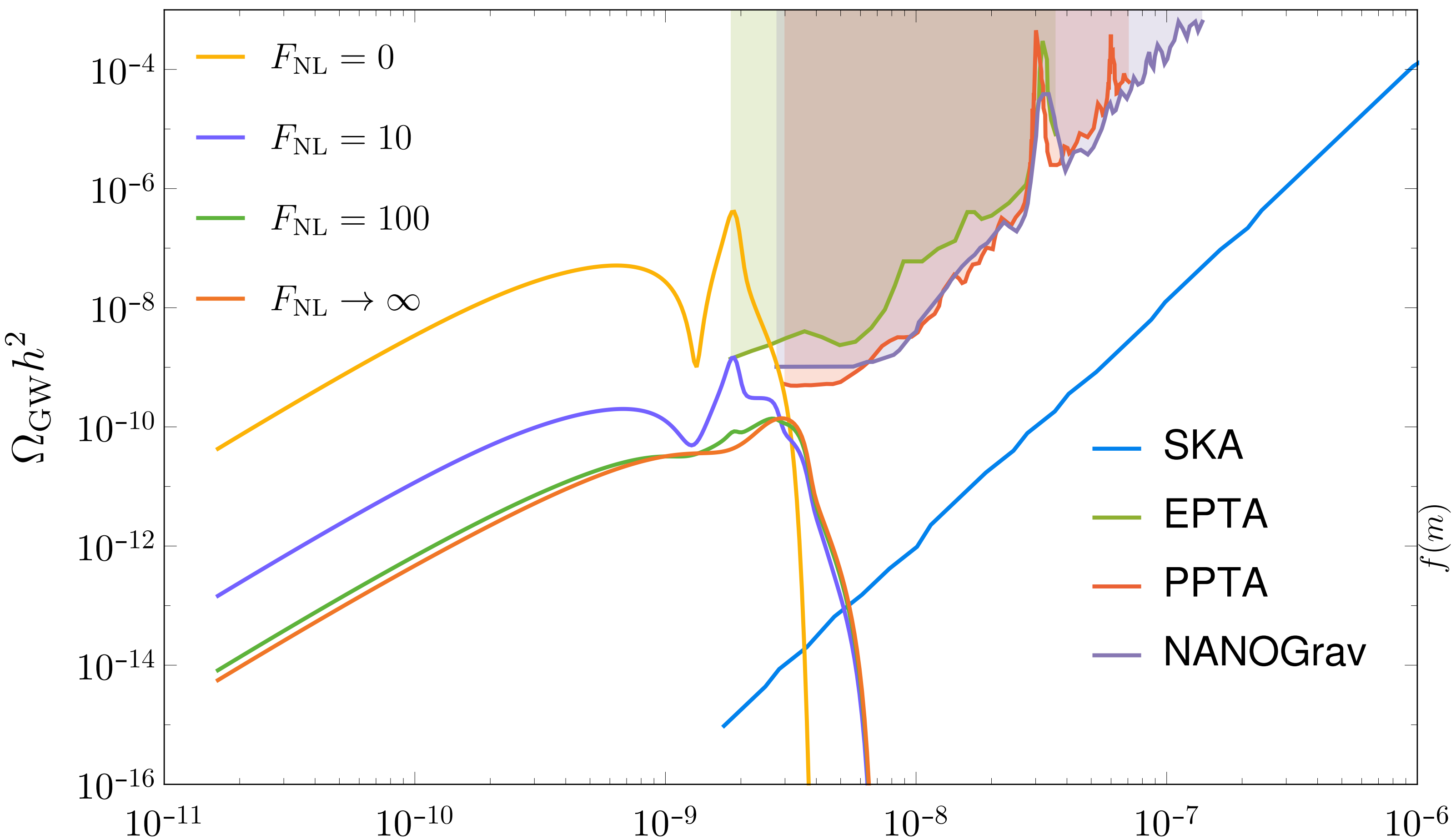
Nakamura et al. '15

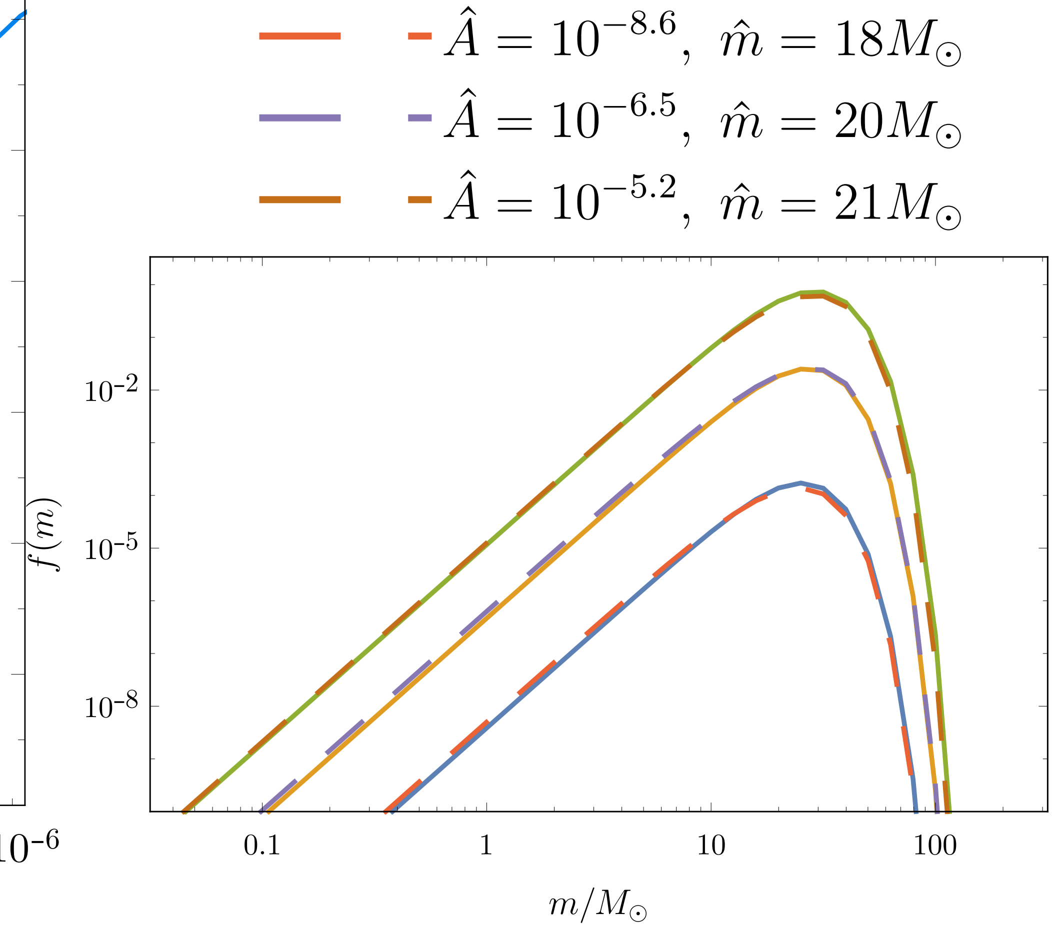


Testing LV BH=PBH scenario (cont. 2)

“Pulsar Timing Array Constraints on …” Cai, Pi, Wang & Yang ‘19

$$f_{\rm peak} \sim 6.7 \times 10^{-9} \left(\frac{M_{\rm PBH}}{M_\odot} \right)^{-1/2} \mathrm{Hz}$$





for $f(m)$ peaked at $m \sim 17 M_\odot$

Gaussian case seems on the verge of exclusion/or detection!

➡ lots of speculations after recent NANOGrav 12.5 years result…

NANOGrav collaboration ‘20

Summary

- 2-field inflation models can produce abundant PBHs as well as GWs.
- If PBHs = CDM, M_{PBH}~10^{19-22}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^{19-22}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.
- LV BHs = PBHs scenario with M_{PBH} >~20 M_solar, is on the verge of exclusion/ detection by HSC & PTA.
- PBHs from vacuum tunneling during inflation may explain everything!