AstroDark
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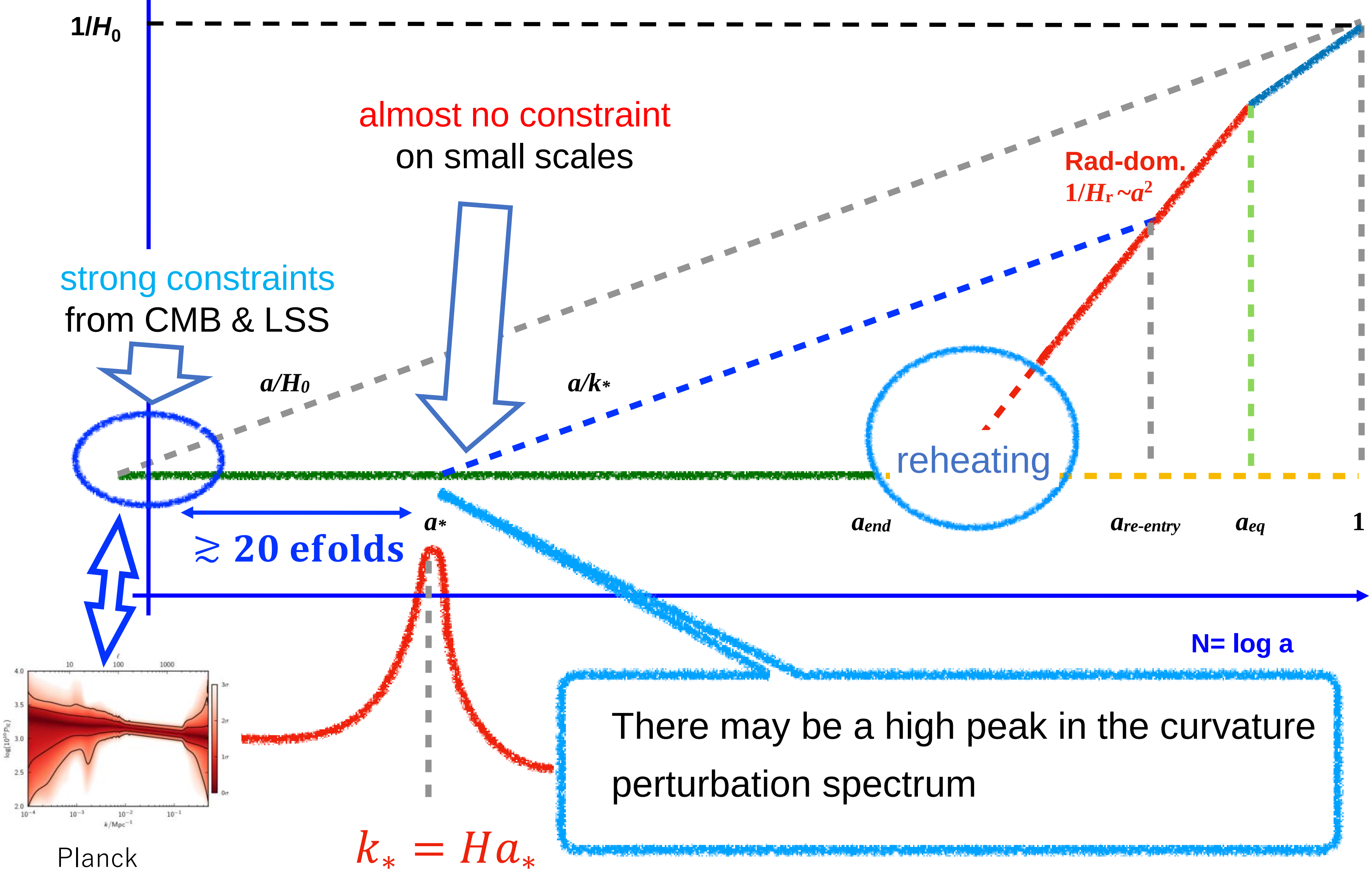
PBH-GW Cosmology

Misao Sasaki

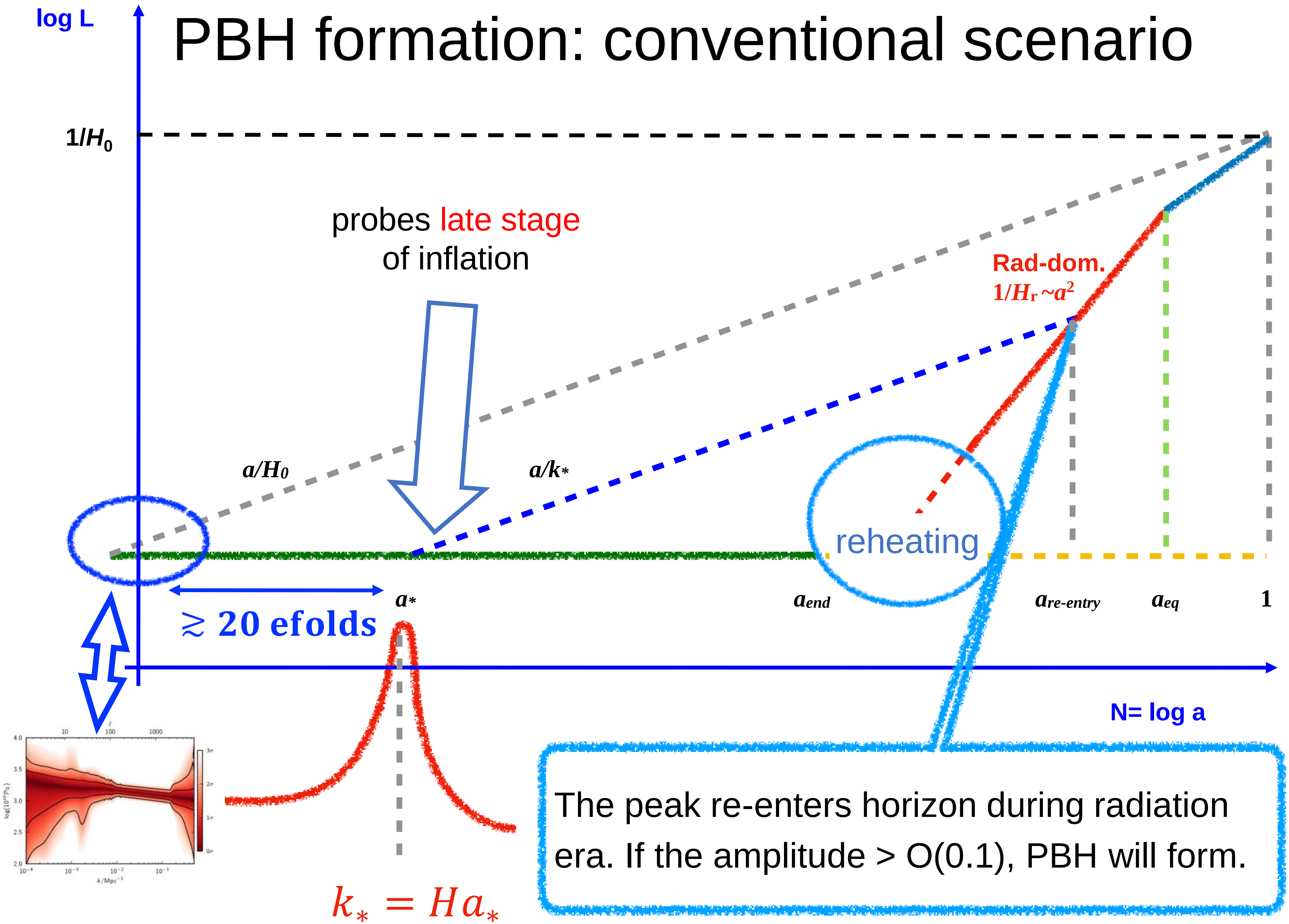
Kavli IPMU, University of Tokyo
YITP, Kyoto University
LeCosPA, Taiwan National University

Primordial Black Holes

PBH formation: conventional scenario



PBH formation: conventional scenario

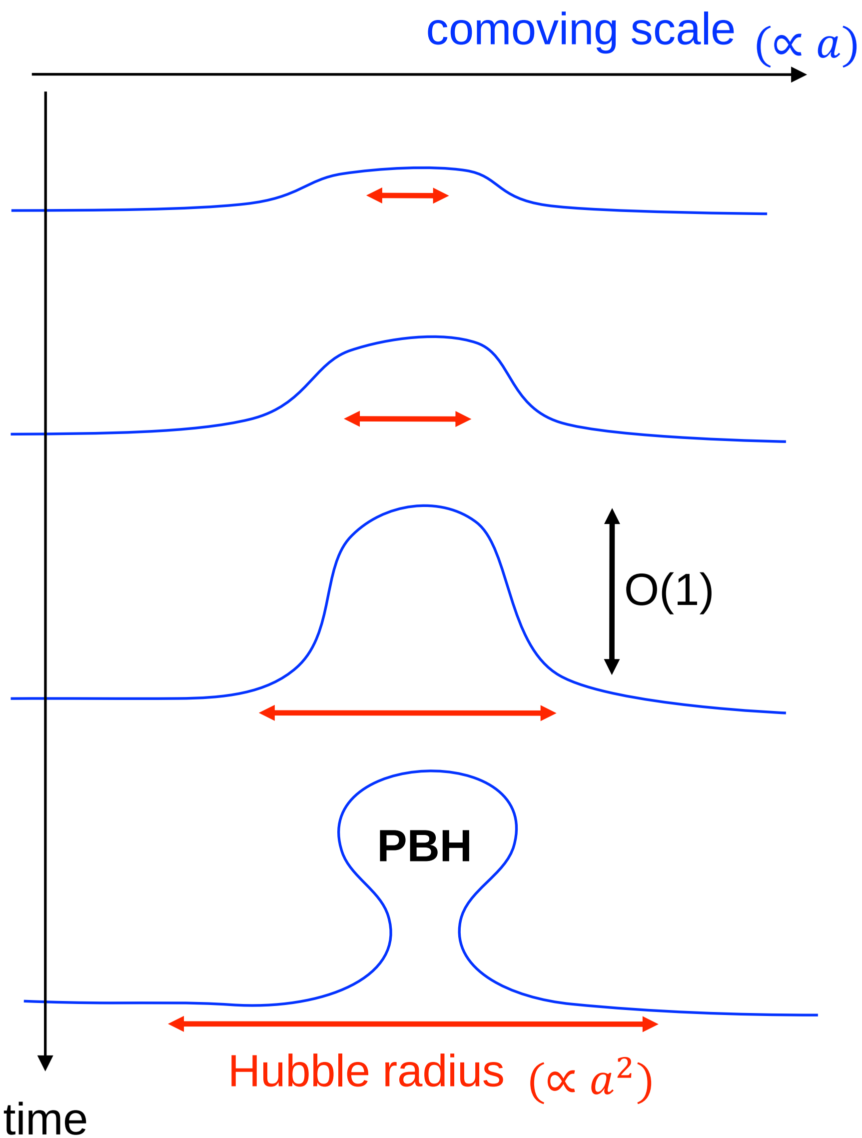


PBH in a nutshell

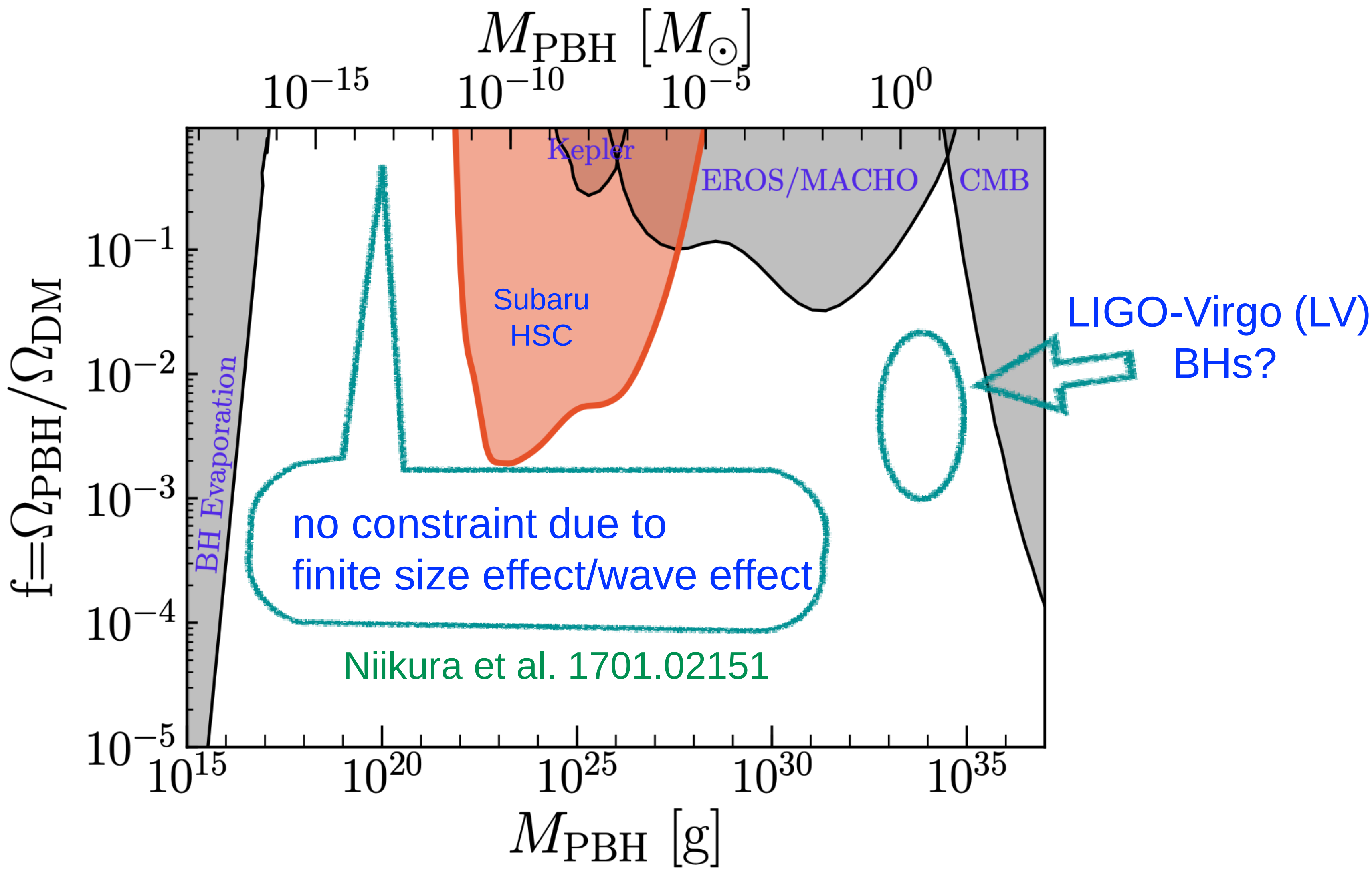
- Primordial Black Holes (PBHs) are those formed in the very early universe, conventionally when the universe was radiation-dominated.
- Presumably they originate from a large positive curvature perturbation produced during inflation (which hence should be a rare event).
- For a BH to form during radiation dominance, the perturbation must be O(1) on the Hubble horizon scale.

$$\boldsymbol{M}_{\mathbf{PBH}} \sim \boldsymbol{M}_{\mathbf{horizon}}$$

$$\sim \left(\frac{100\mathrm{MeV}}{T}\right)^2 M_\odot \sim \left(\frac{\ell}{1\mathrm{pc}}\right)^2 M_\odot$$



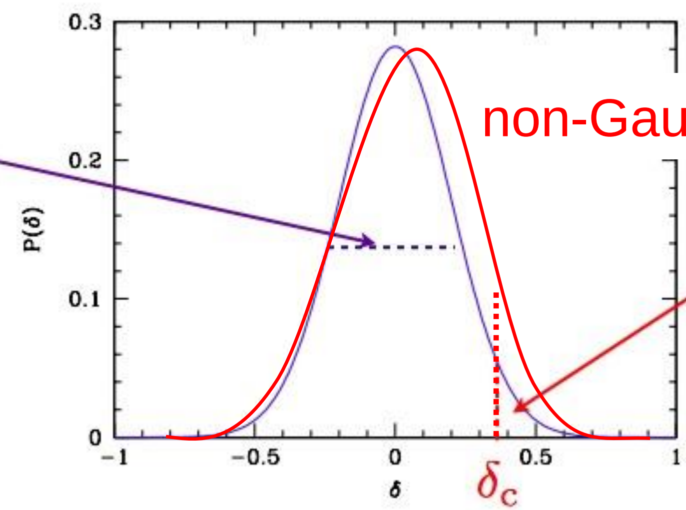
observational constraints



big window at $M_{\rm PBH} \approx 10^{17} - 10^{22}$g ⟺ $T_{\rm re\text{-}entry} \sim 10^4$ -10^8 GeV

fraction β that turns into PBHs

for Gaussian probability distribution



- When $\sigma_M << \delta_c$, β can be approximated by exponential:

$$\beta \approx \sqrt{\frac{2}{\pi}} \frac{\sigma_M}{\delta_c} \exp\left(-\frac{\delta_c^2}{2\sigma_M^2}\right) \qquad \delta_c \equiv \left(\frac{\delta\rho_c}{\rho}\right)_{\rm crit} \sim 0.4$$

Carr, ApJ 201, 1 (1975), …

- Recent studies indicates enhanced production: $\delta_c \sim 0.2$

  using peak theory

Yoo, Harada, Garriga & Kohri, 1805.03946

- Non-Gaussianity may significantly affect β

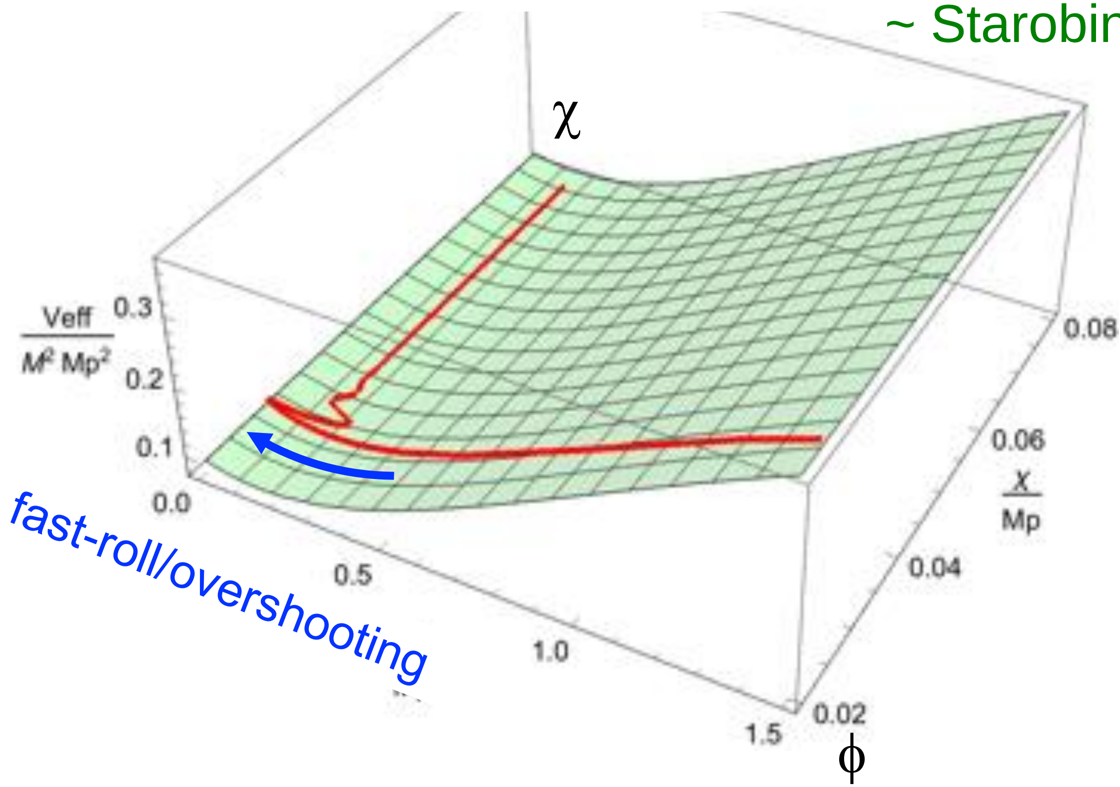
Inflation models

Model 1: two-field inflation model

Pi, Zhang, Huang & MS, 1712.09896

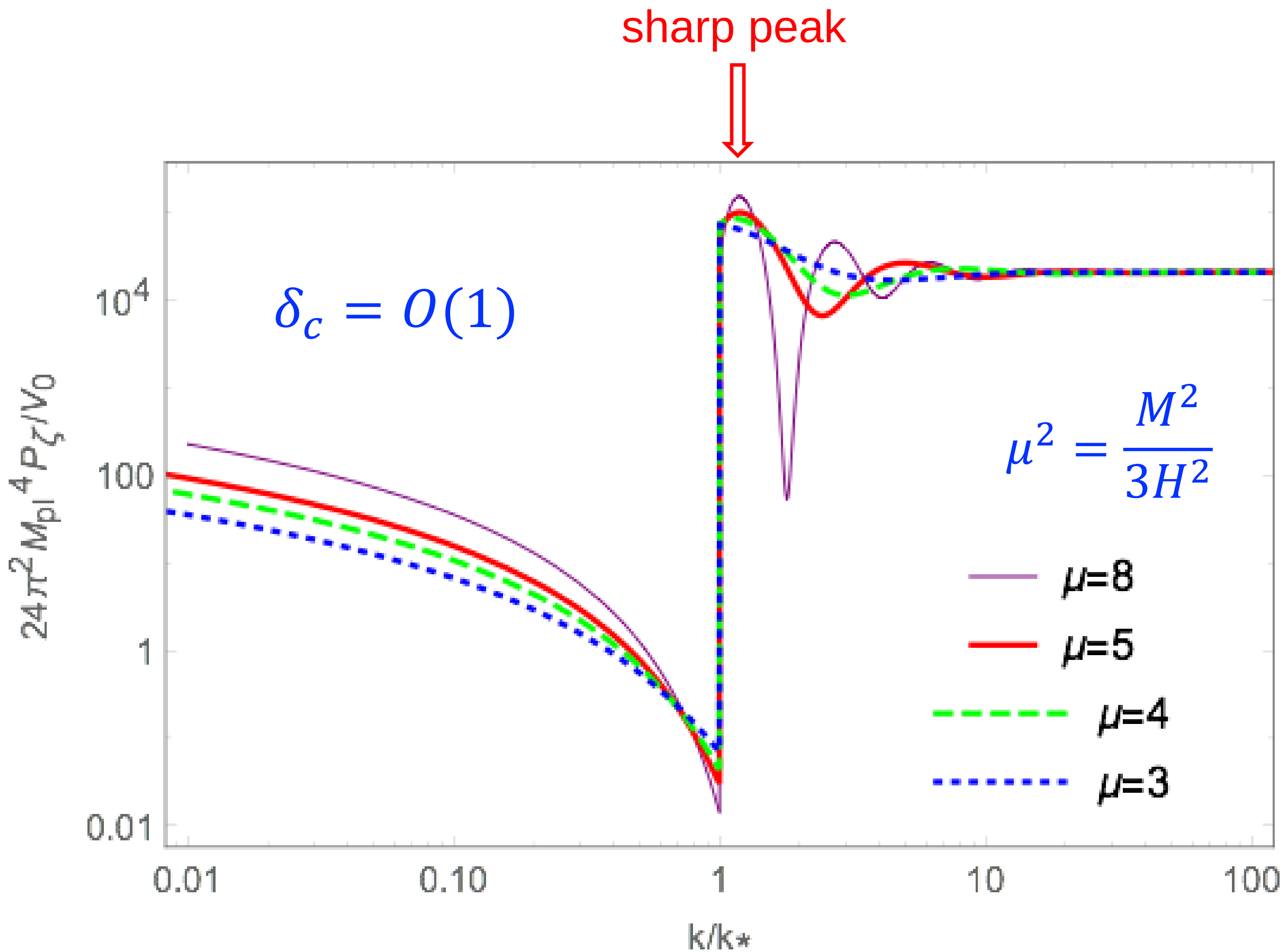
$$S_J = \int d^4x\sqrt{-g}\left\{\frac{M_{\rm Pl}^2}{2}\left(R+\frac{R^2}{6M^2}\right)-\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi)-\frac{1}{2}\xi R\chi^2\right\}.$$

~ Starobinsky (scalaron) + curvaton



many 2-stage models can account for PBH formation

- 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

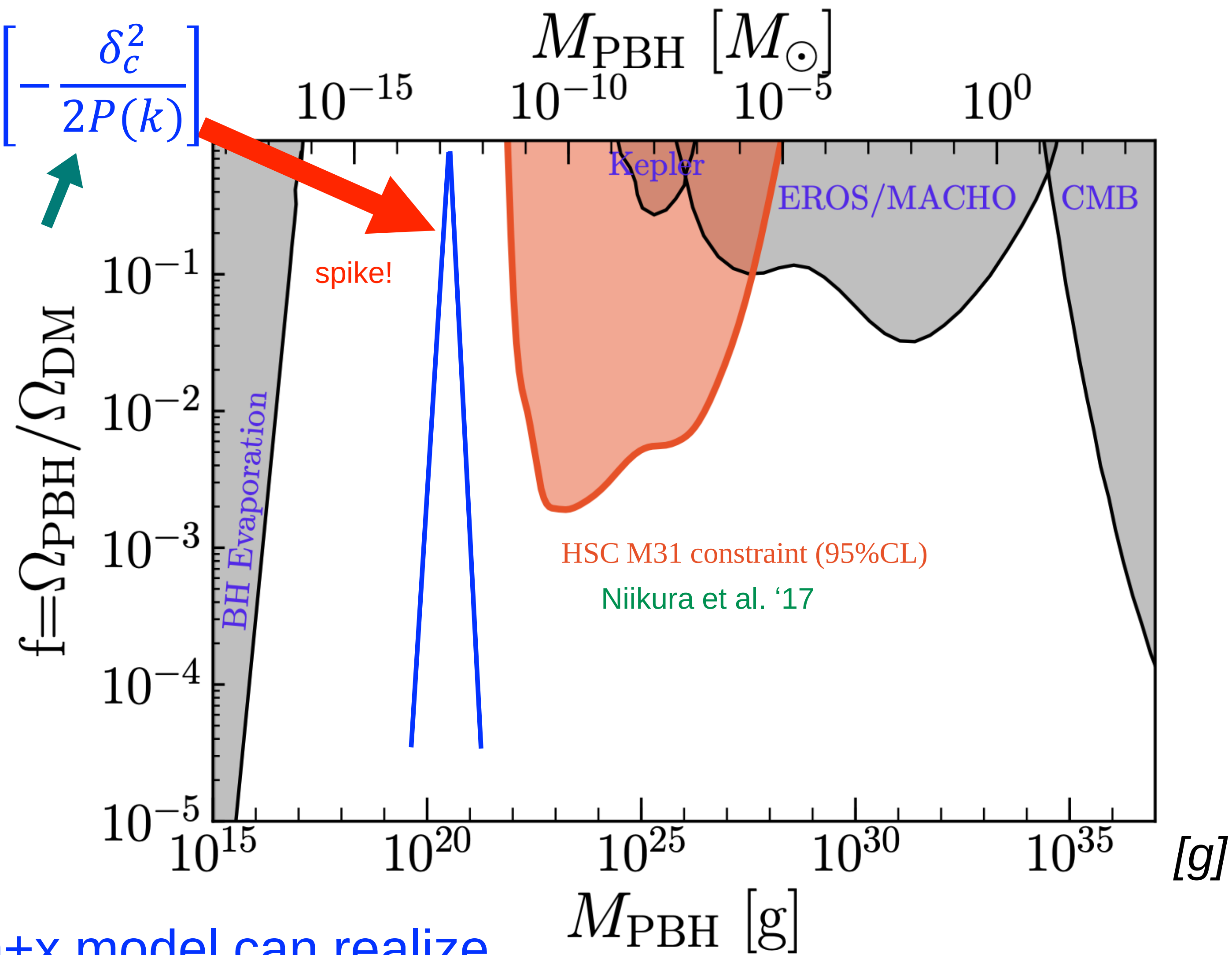
PBH mass function

$\delta_c = O(1)$

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

sharp peak

spike!

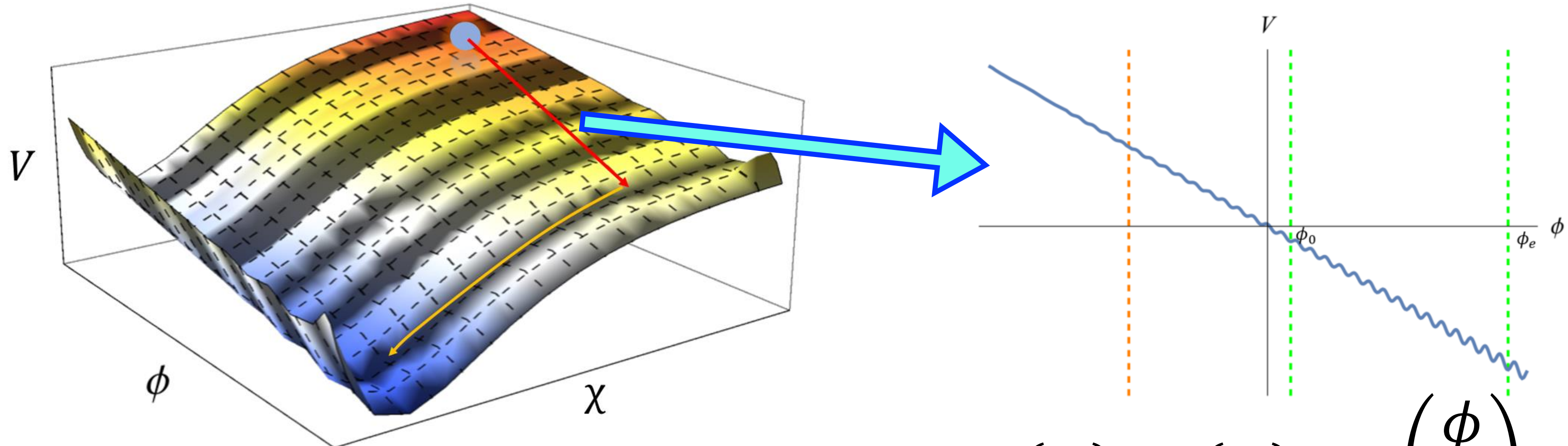


scalaron+x model can realize

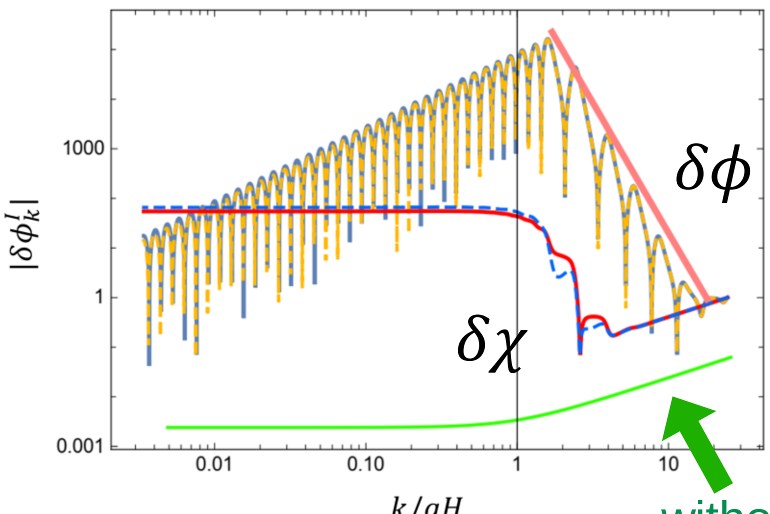
PBH=CDM scenario with a monochromatic PBH mass!

Model 2: Resonant Amplification Model

Z. Zhou, J. Jiang. Y-f. Cai, MS & S. Pi, 2010.03537



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



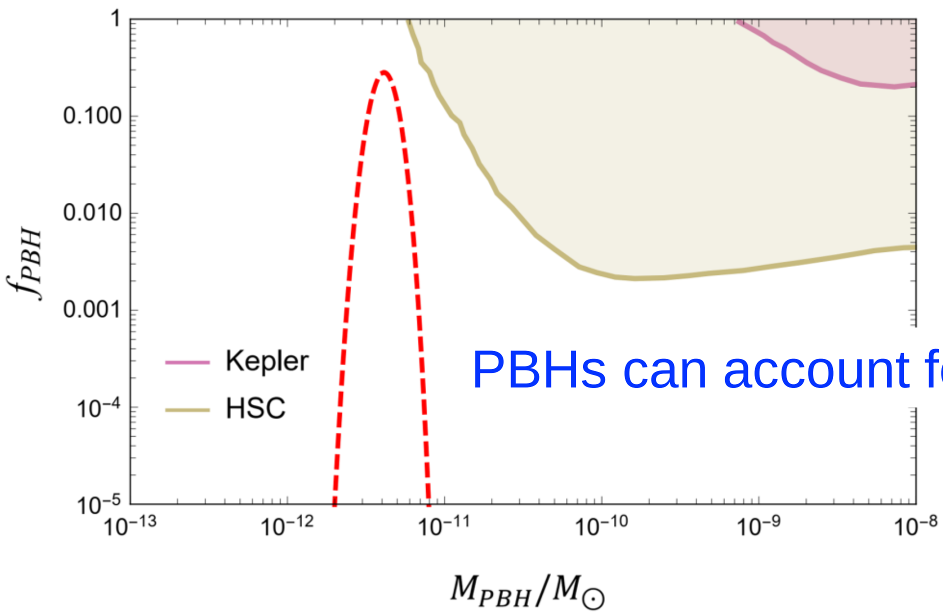
without amplification

$\delta\phi$: amplified by oscillating pot

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

This leads to enhancement of curvature perturbation

Curvature pertn, PBH mass fcn, Induced GWs



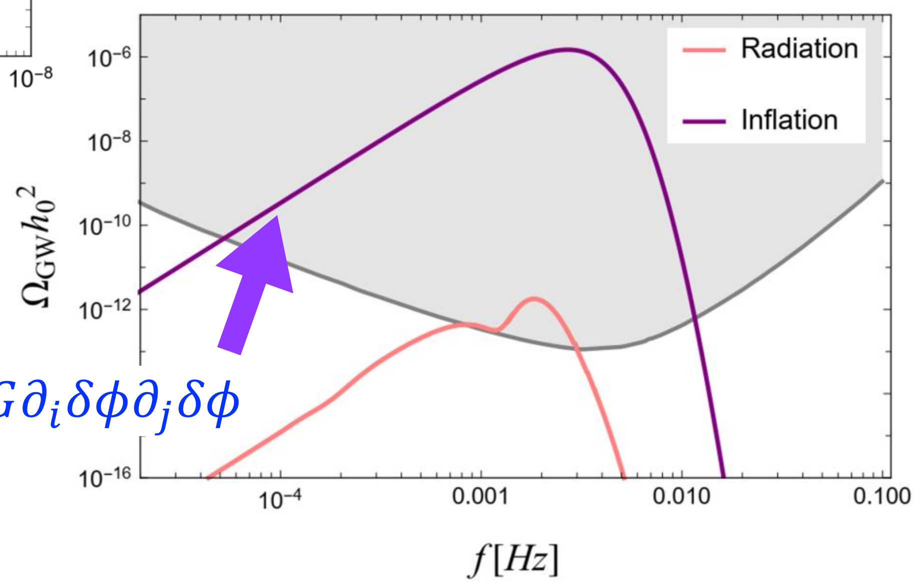
$$P_{\mathcal{R}}(k) = \frac{H^2}{8\pi^2 M_p^2 \epsilon_{\chi\chi}} \mathcal{A}^2(k)$$

$\Delta = O(1)$

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

amplification factor $\sim 10^6$

PBHs can account for CDM



GW probes $\delta\phi$

PBH probes $\delta\chi$

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

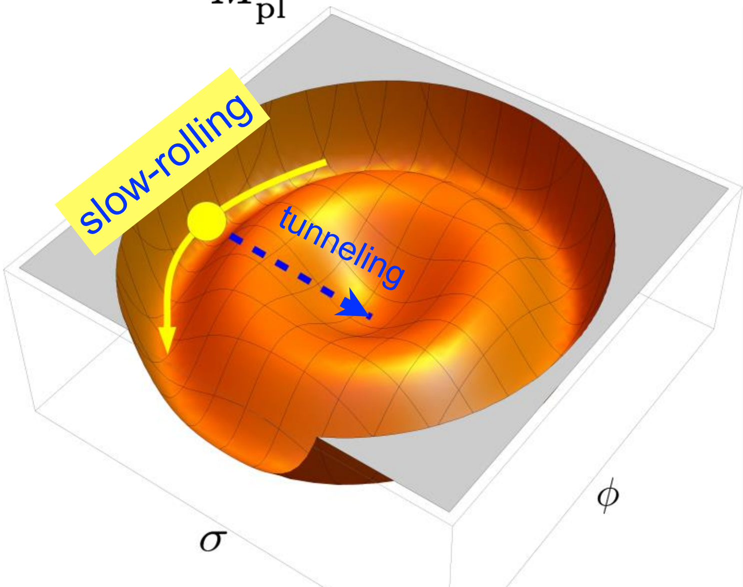
Model 3: PBH-as-MVP scenario

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

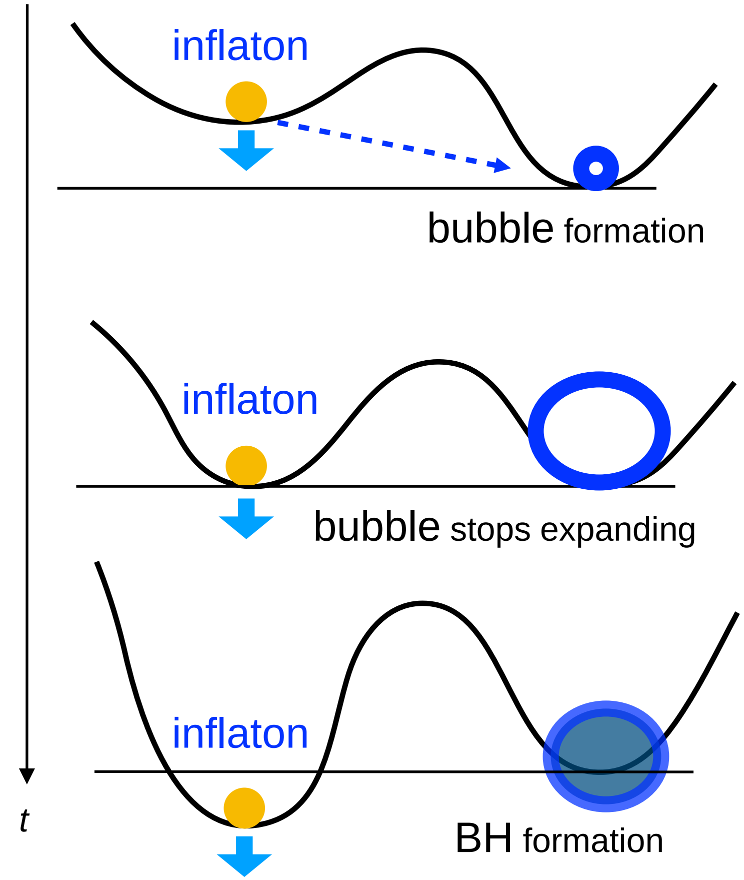
Garriga, Vilenkin & Zhang, 1512.01819, Deng & Vilenkin, 1710.02865,…

example:

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

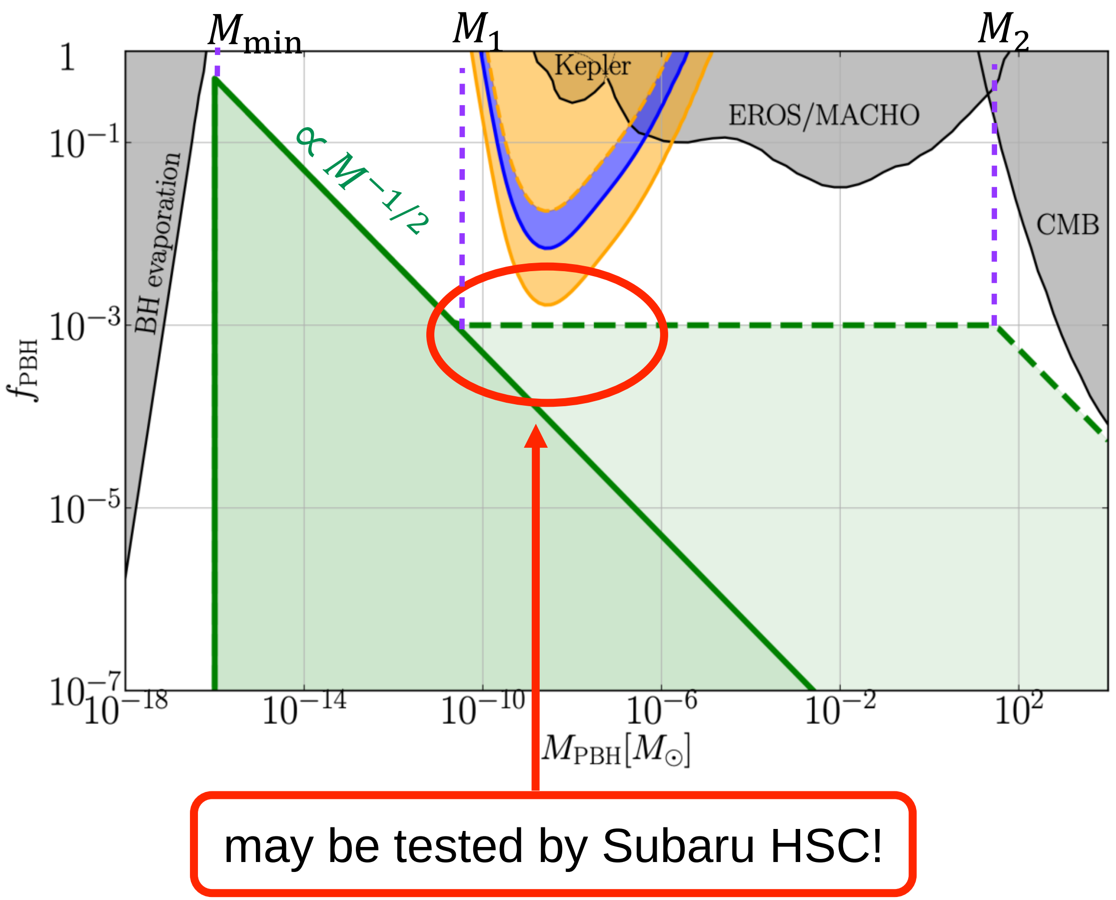


can probe multiverse!



Mass function

Kusenko, MS, Sugiyama, Takada, Takhistov & Vitagliano, 2001.09160



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

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

$M \simeq M_{\rm min} \cdots$ CDM

- if there is an intermediate matter-dom stage

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

$M \simeq M_2 \cdots$ LIGO BHs

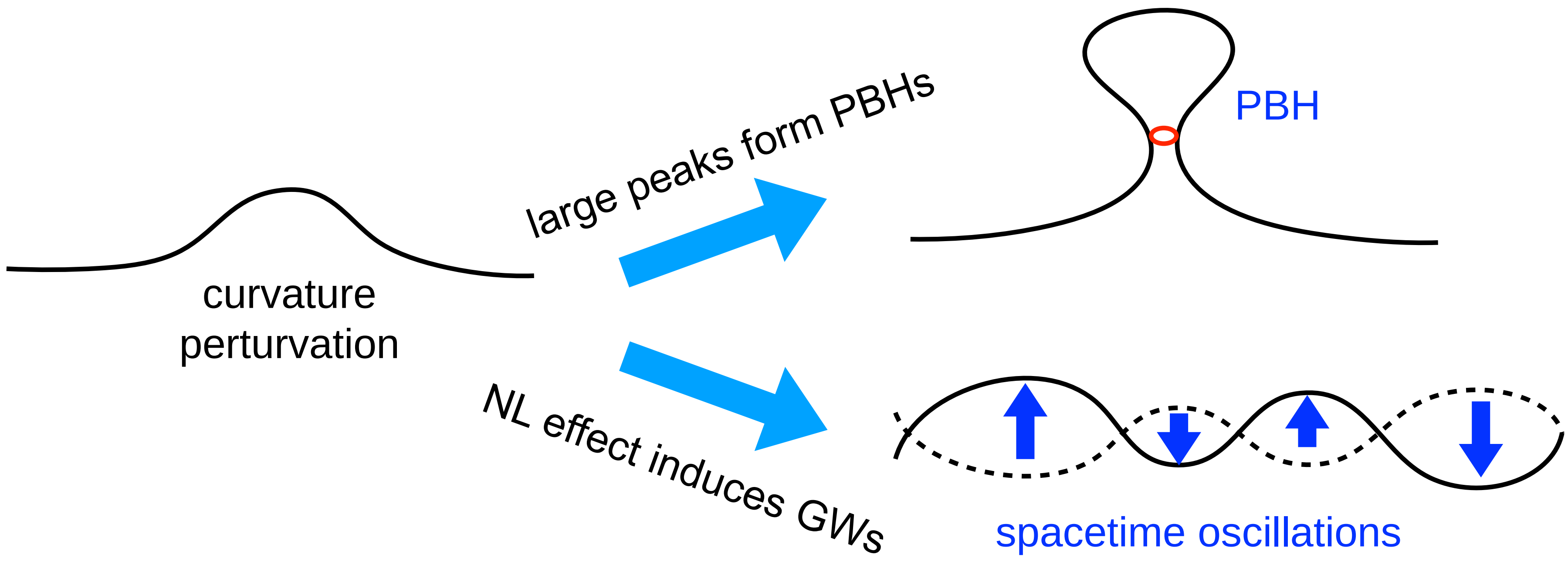
$$f(M) = \lambda \left(\frac{M_2}{M_1}\right)^{1/2} \left(\frac{M}{M_{\rm min}}\right)^{-1/2} : M_2 < M$$

$M \gg M_2 \cdots$ SMBHs

Implications to GW cosmology?

Induced GWs

GWs can capture PBHs!



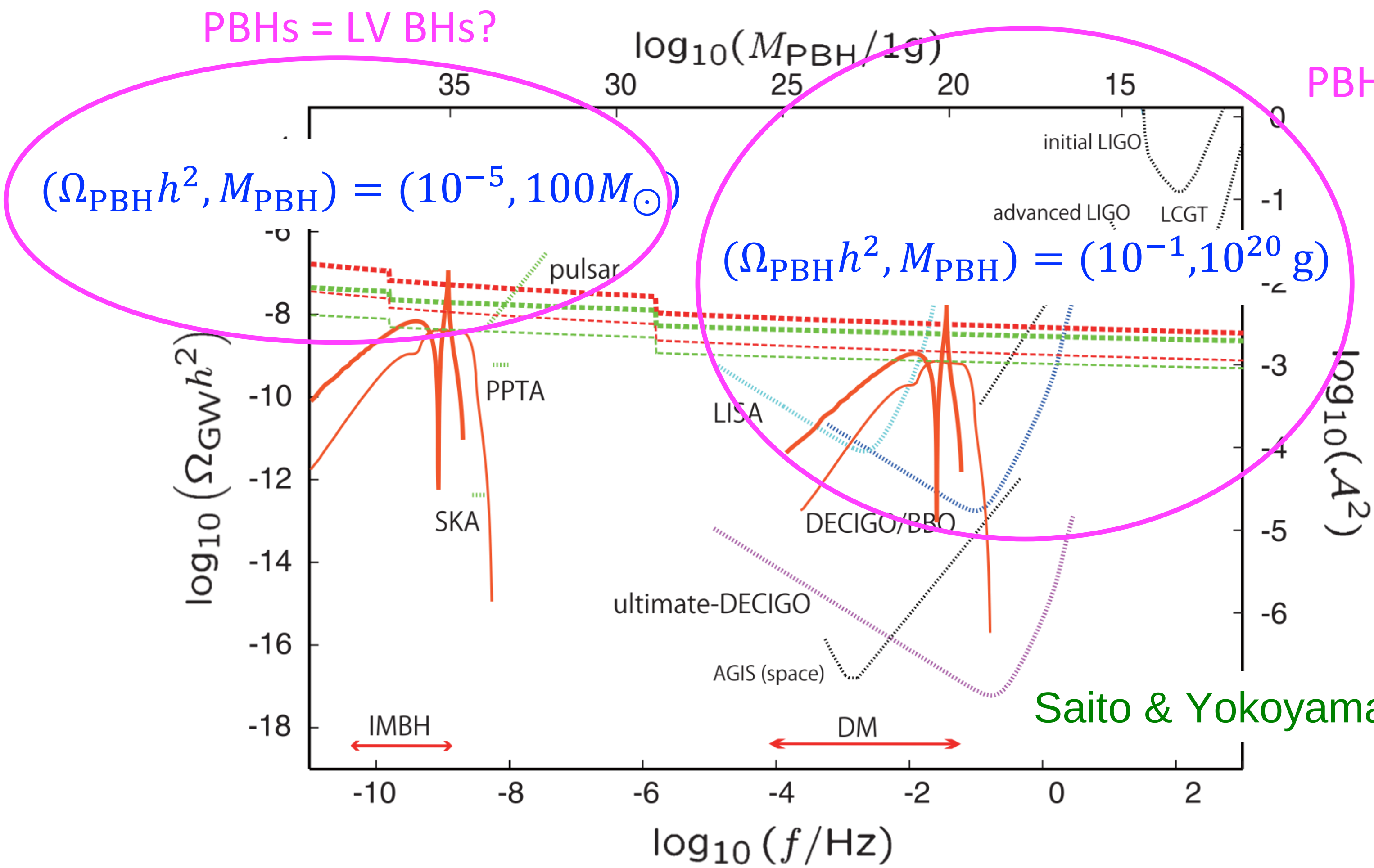
PBHs = CDM with $M_{PBH} \sim 10^{21}$g generates GWs with $f \sim 10^{-3}$ Hz

⇨ Background GWs at LISA band

PBHs =LV BHs with $M_{PBH} \sim 10 M_{\odot}$ generates GWs with $f \sim 10^{-8}$ Hz

⇨ Background GWs at PTA band

GWs can test PBH scenario!



Saito & Yokoyama 0812.4339

- PBHs =LV BHs scenario is already constrained by NANOGrav(PTA)

Cai, Pi, Wang & Yang 1907.06372

Isocurvature

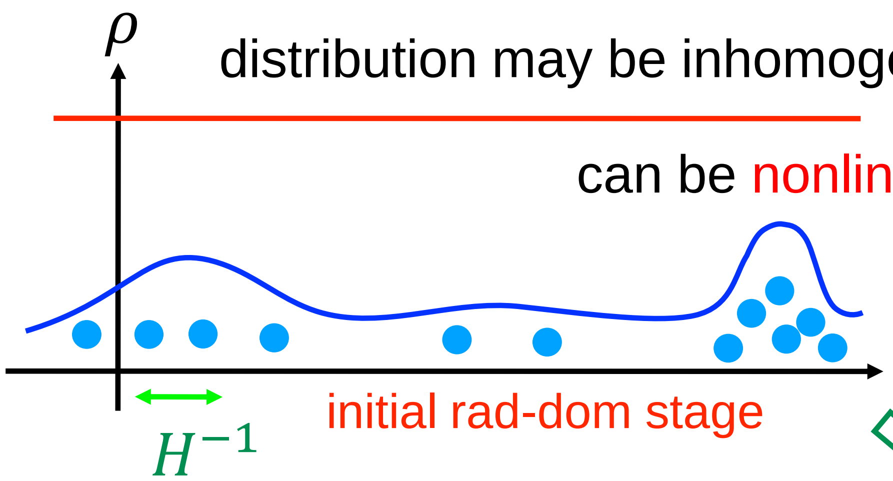
PBHs from Isocurvature Perturbation

eg, E. Cotner, A. Kusenko, MS & V. Takhistov,1907.10613

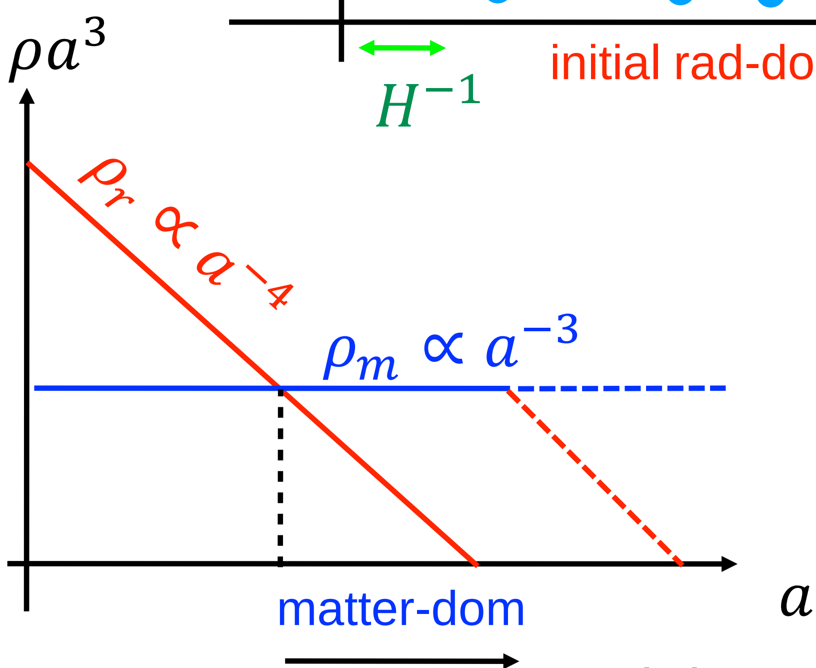
non-grav formation of compact objects/Q-balls/etc inside horizon.

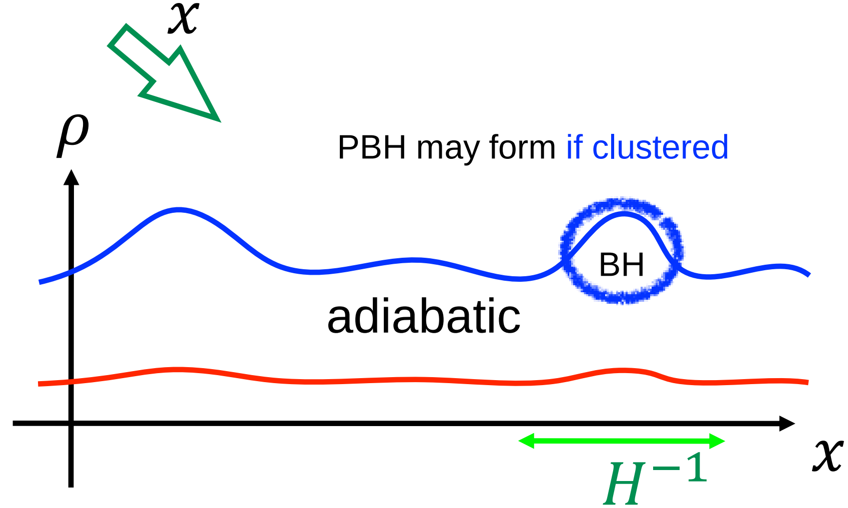
distribution may be inhomogeneous = isocurvature

can be nonlinear from the beginning



initial rad-dom stage





matter-dom stage

rad-dom again if objects are unstable

Constraints on CDM isocurvature on small scales

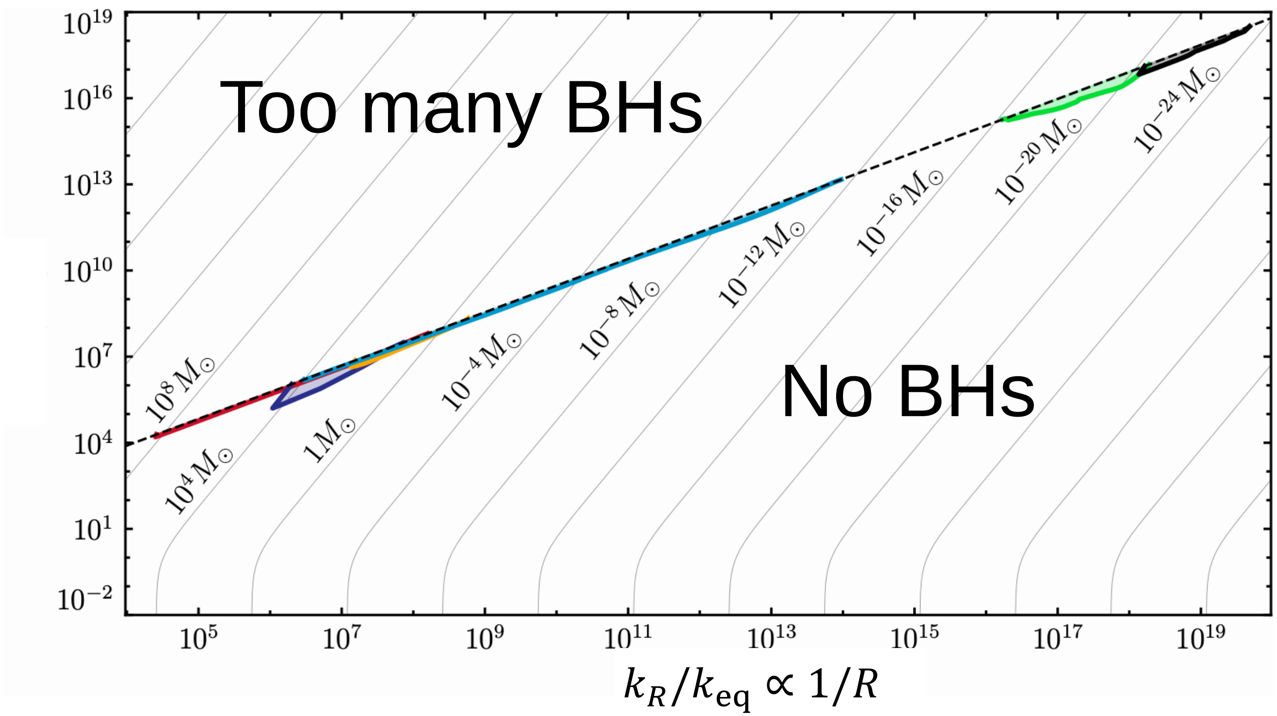
- Putting aside possible nonlinear corrections, one can derive model-independent constraints on primordial CDM isocurvature perturbation

Passaglia & MS, 2109.12824

$\sigma_c(R)$

$$\sigma_c(R) = \sqrt{\langle S^2(R) \rangle}$$

$$S \equiv \delta_{CDM} - \frac{3}{4}\delta_\gamma$$



- S>>1 perturbations would collapse during radiation-dominance might lead to interesting secondary effects? (induced GWs,…)

Domenech & Passaglia, private comm.

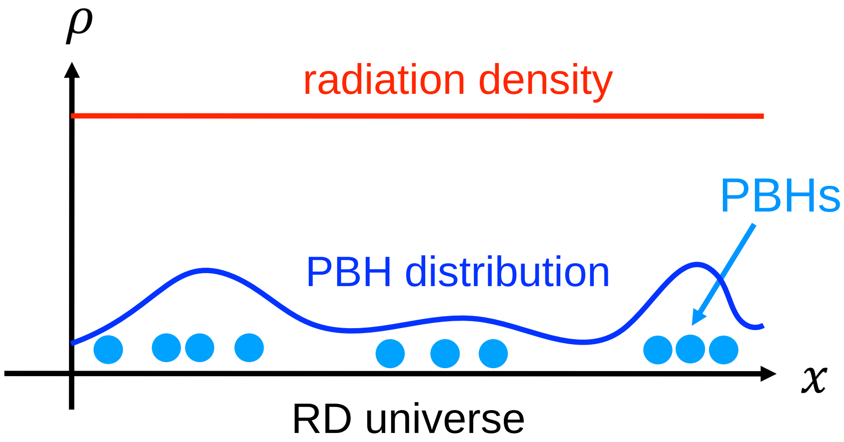
What if formed objects are PBHs?

Papanikolaou, Vennin & Langlois, 2010.11573

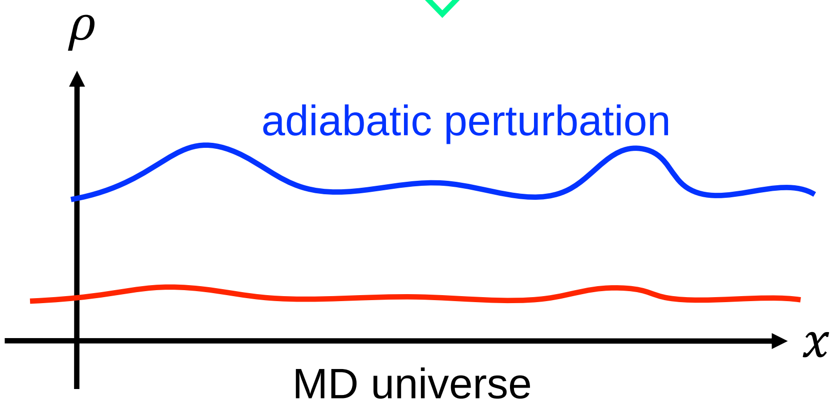
Domenech, Lin & MS, 2012.08151

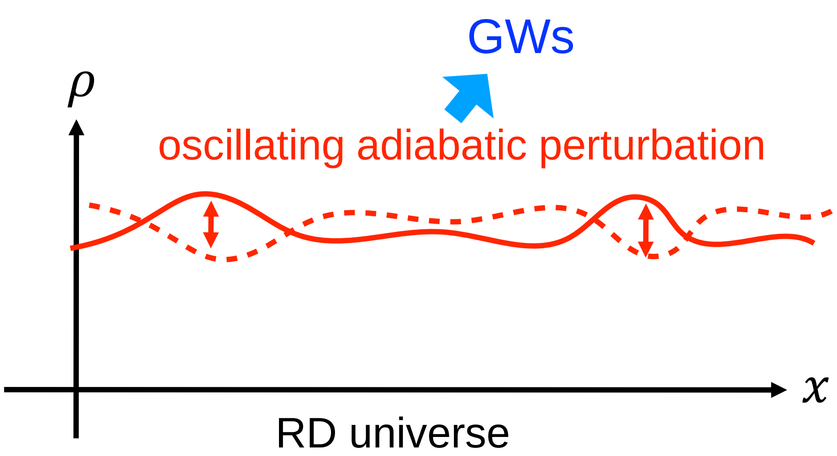
- PBHs may be formed from curvature perturbation or by alternative strong force

Flores & Kusenko, 2008.12456



inhomogeneous PBH distribution may induce GWs when the universe is reheated by PBH evaporation





Constraints on early PBH dominated universe

Domenech, Lin & MS, 2012.08151
Domenech, Takhistov & MS, 2105.06816

- Assumptions
  - Monochromatic mass function for PBHs.
  - Poisson distribution for $\delta n_{\rm PBH}/n_{\rm PBH}$:

$$\mathcal{P}_S(k) = \frac{2}{3\pi}(k/k_{\rm UV})^3; k < k_{\rm UV} = n_{\rm PBH}^{-1/3}$$

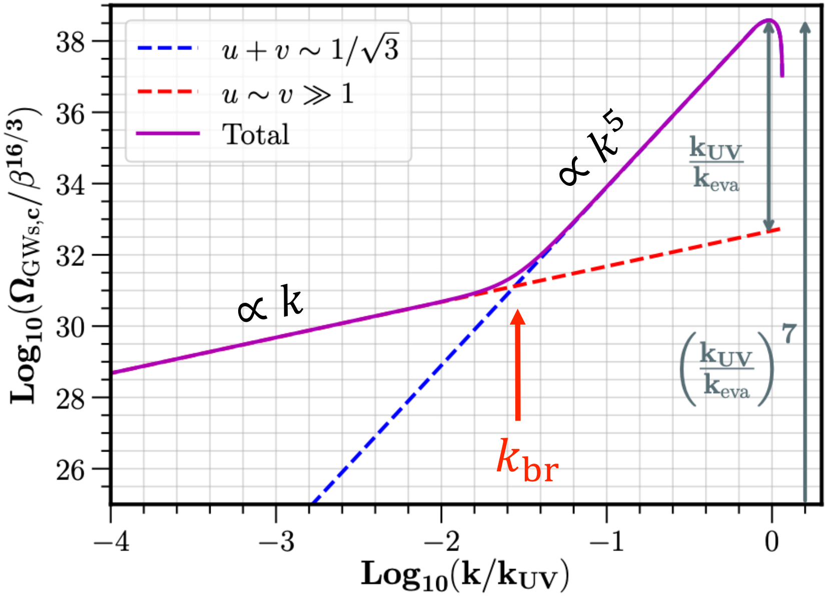
- Resulting spectrum
  - sharp rise ~ k^5 near the peak.
  - Peak value:

$$\left(\frac{\Omega_{GW,max}}{\Omega_{r,0}}\right) \approx 5 \times 10^{34} \beta^{16/3} \left(\frac{M}{10^4 {\rm g}}\right)^{14/3}$$

β: PBH fraction at formation

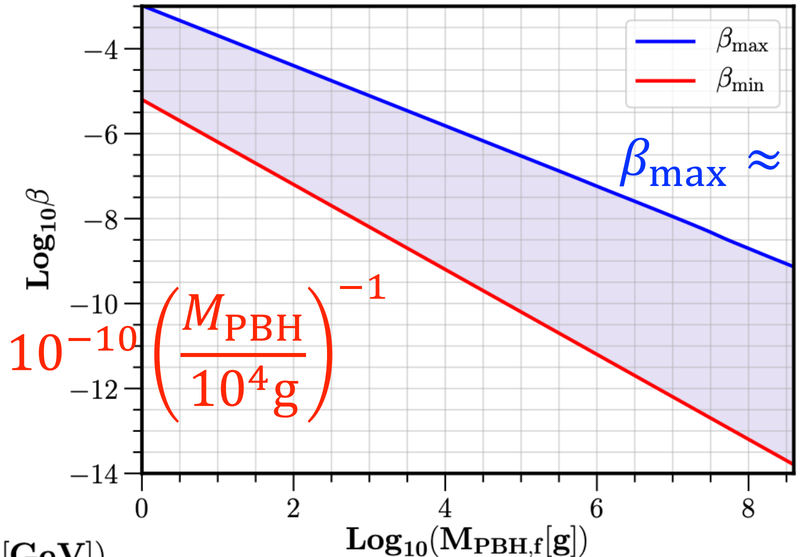
↓

constraints on β



$$k_{\rm br} \approx 0.04 k_{\rm UV} (M_{\rm PBH}/10^4 {\rm g})^{-1/6}$$

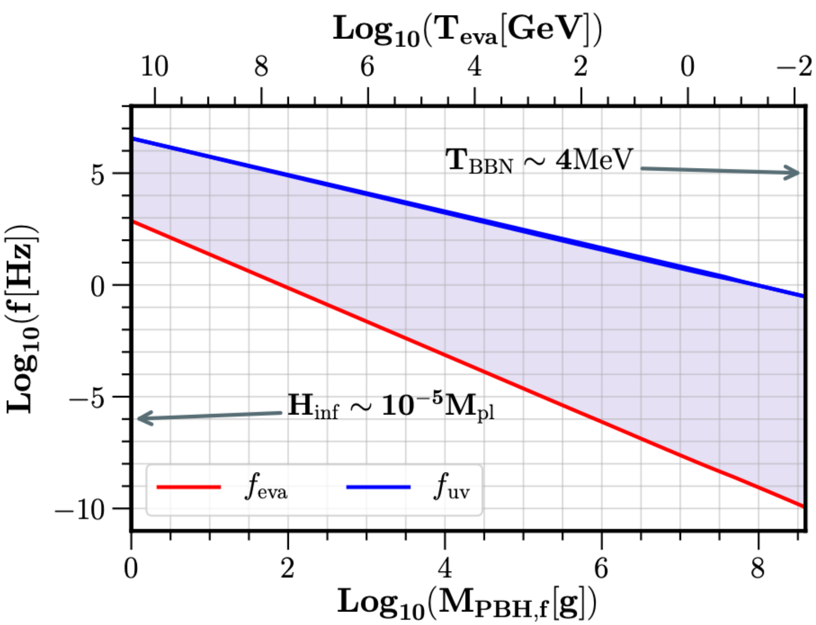
Constraints on β and frequencies



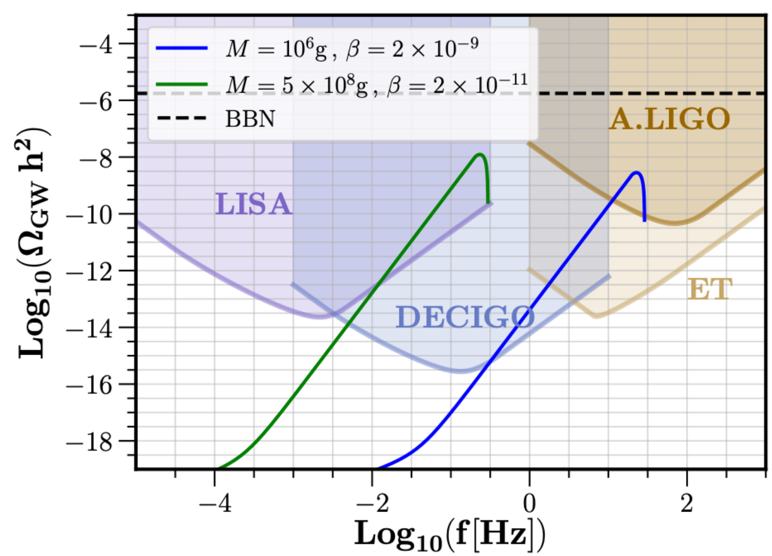
$$\beta_{\rm max} \approx 1 \times 10^{-6} \left(\frac{M_{\rm PBH}}{10^4 {\rm g}}\right)^{-17/24}$$

$$\beta_{\rm min} \approx 6 \times 10^{-10} \left(\frac{M_{\rm PBH}}{10^4 {\rm g}}\right)^{-1}$$

allowable range of β



frequency range vs $M_{\rm PBH}$



GW detectors sensitivity curves

take-home message:

- late stage of inflation can be probed by PBHs and the associated secondary/induced GWs
- (nonlinear) isocurvature perturbations may play important roles in PBH cosmology
- PBHs may play central roles in GW cosmology

PBH-GW Cosmology!