

Probing Inflationary PBHs for the LIGO GW Events

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Based on **1611.06130** (published in PRD)

In collaboration with K.Inomata, M.Kawasaki, Y.Tada, T.T.Yanagida



1.

Introduction

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What is “**Primordial**” Black Hole (PBH)?

- ▶ BH formed **before** any astrophysical objects exist (even in **RD** era).
- ▶ Need **large density perturbations** for **Gravity** > **Pressure**.
 - Collapse of localized configurations: bubble collision, cosmic string,...
 - Collapse of **primordial density perturbations**: inflation, curvaton,...

Is there any motivation to study them?

- ▶ **Non-particle** candidate of DM
- ▶ Candidates of **gravitational wave events** observed by LIGO.
- ▶ Constrain **other** DM models; WIMP by UCMH, axion by super-radiance,...

[Bringmann+, '11, ...]

[Arvanitaki+, '14, ...]

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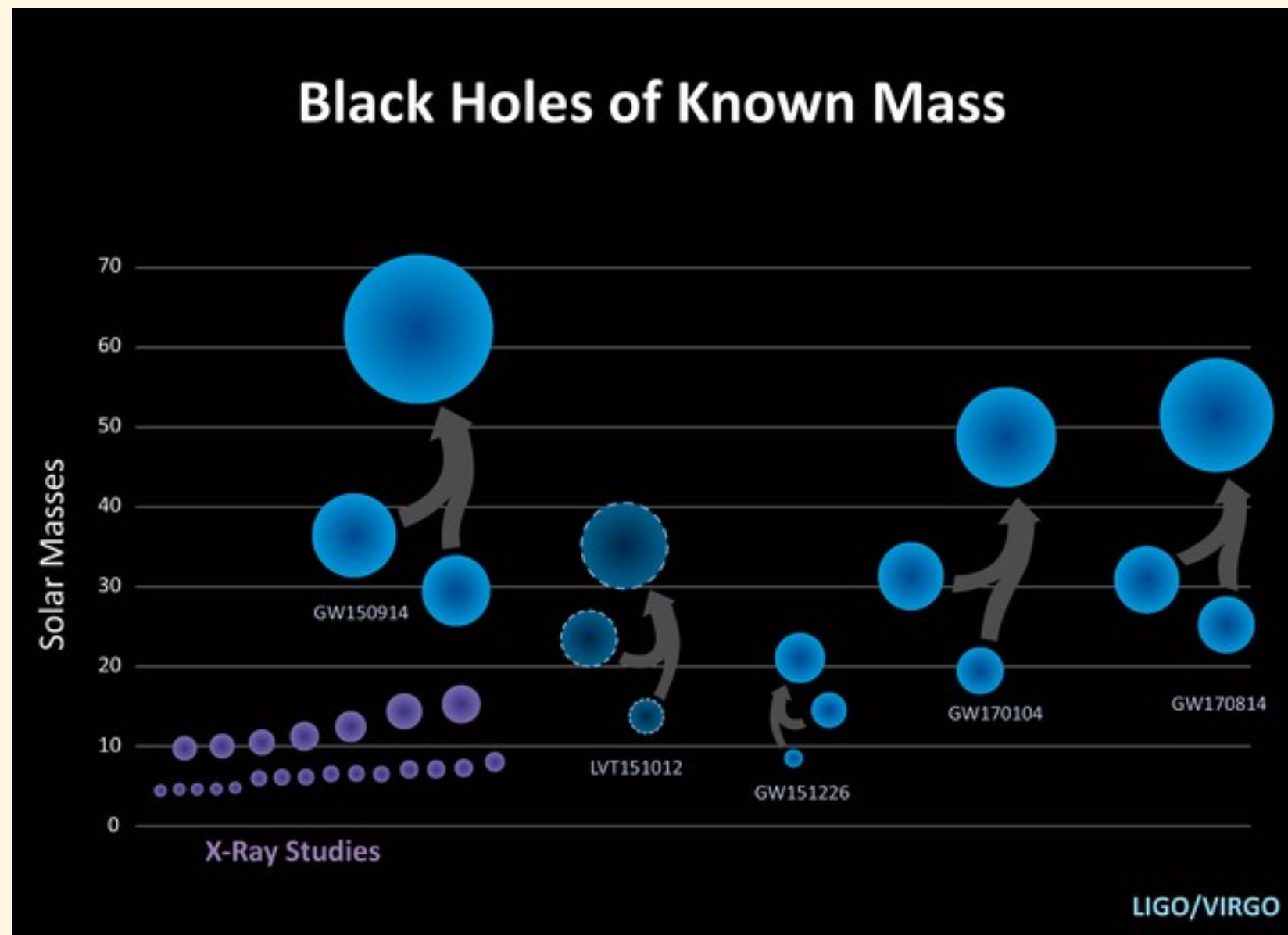
[Bringmann+, '11, ...]

[Arvanitaki+, '14, ...]

Outlook of LIGO events

Merging of **Binary BH** observed by LIGO

- ▶ Estimated event rate **OB**: $9 - 240 \text{Gpc}^{-3} \text{yr}^{-1}$, **Total**: $12 - 213 \text{Gpc}^{-3} \text{yr}^{-1}$

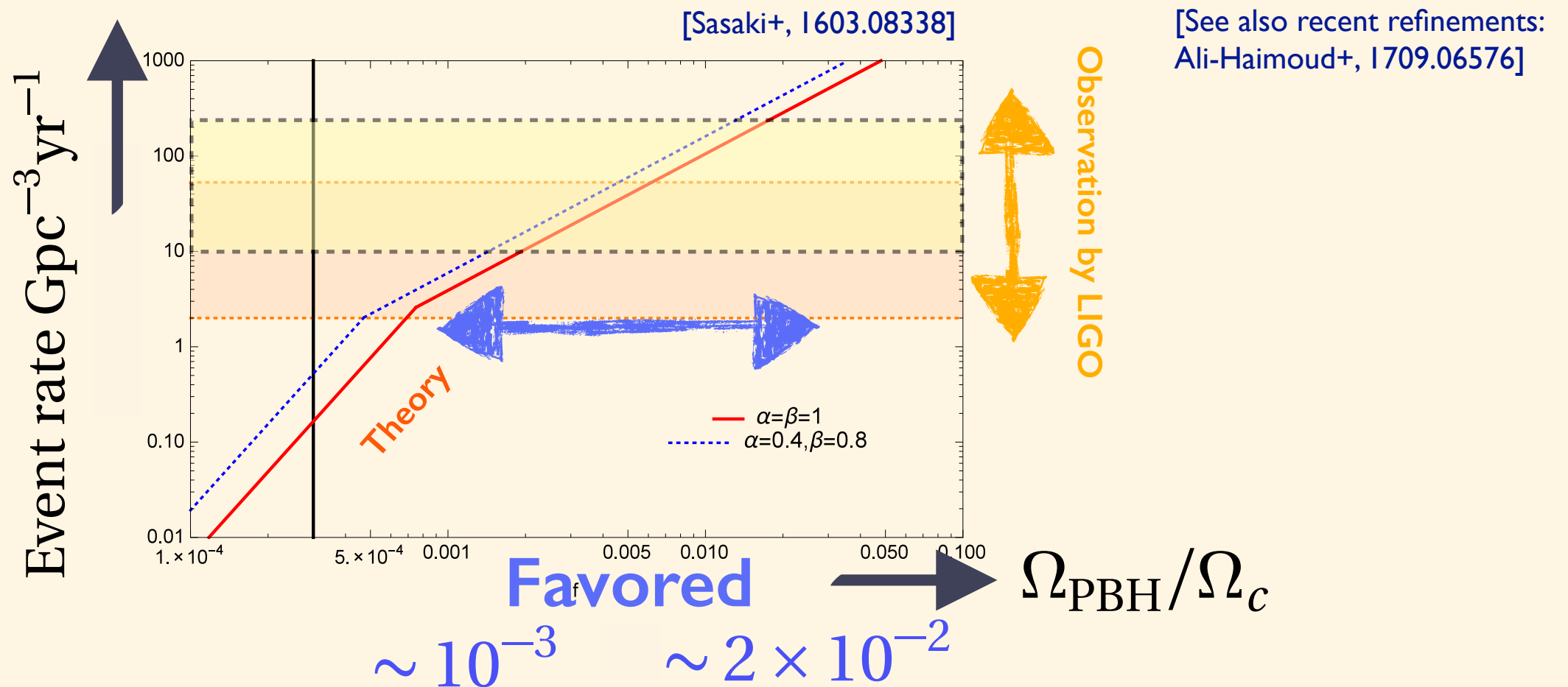


[Ref. <https://www.ligo.caltech.edu>]

PBH for LIGO

Indicated PBH-abundance: $f = \Omega_{\text{PBH}}/\Omega_c \sim 10^{-3} - 10^{-2}$

► **Merger rate** as a function of the **PBH-fraction: f**



► Possible corrections?

- Continuous mass function of PBH, Surrounding DM halo (UCMH), Angular momentum transfer via surrounding baryons.

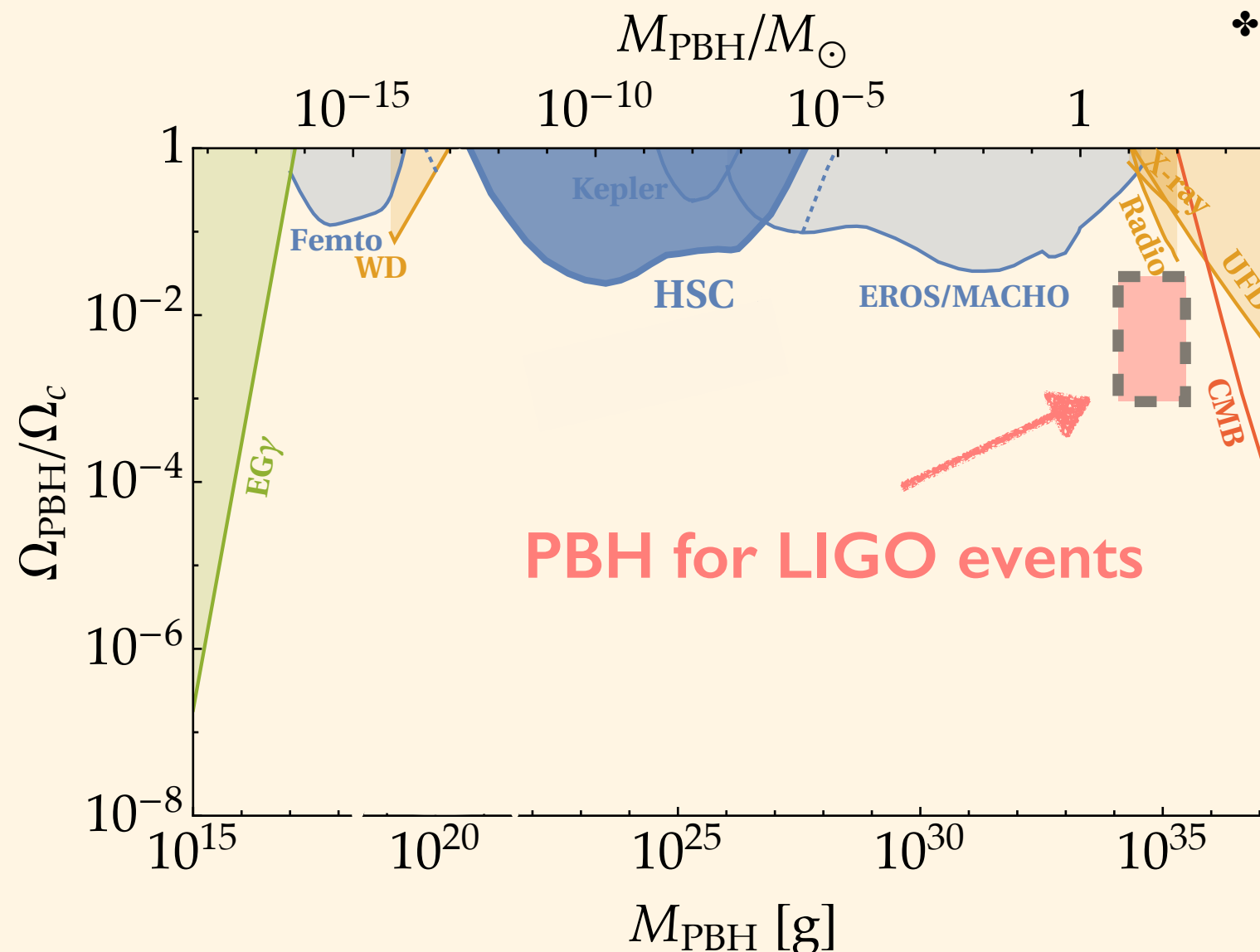
[Hayasaki+, 0909.1738; Yu.N. Eroshenko 1604.04932; Ali-Haimoud+, 1709.06576]

PBH for LIGO

Current observational constraints

- ▶ PBH as **all DM**: marginal, maybe excluded/probed soon. [KM+, 1701.02544; Kuhnel+, 1705.10361; Carr+, 1705.05567;...]
- ▶ PBH for **LIGO events**: seems to be viable.

♣ Constraints from Neutron Star capture are evaded for a conservative value of DM inside the globular clusters.
[See e.g. Kusenko+, 1310.8642; Carr+, 1607.06077]



Hawking radiation

EGY: 0912.5297

Gravitational lensing

Femto: 1204.2056

HSC: 1701.02151

Kepler: PhysRevLett.111.181302

EROS/MACHO: 0607207

Dynamical

WD: 1505.04444

UFD: 1605.03665

Accretion

CMB: 1612.05644 (1612.06811, 1612.07264)

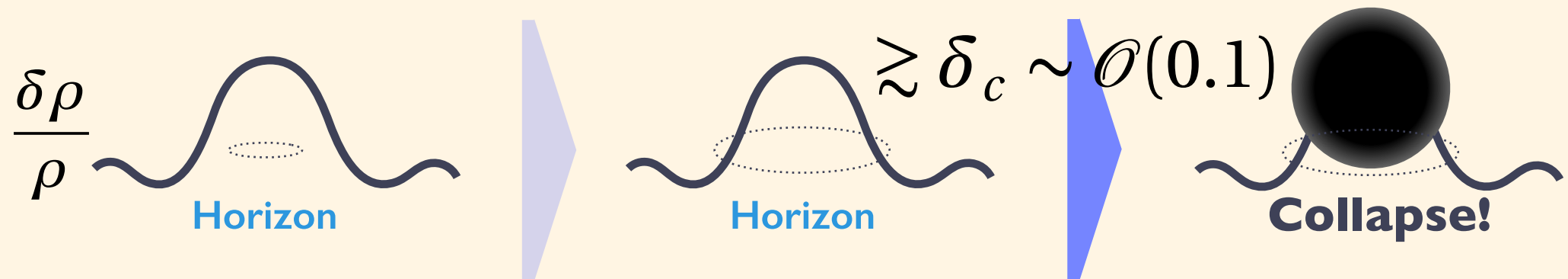
Radio/Xray: 1612.00457

2.

Formation of PBHs

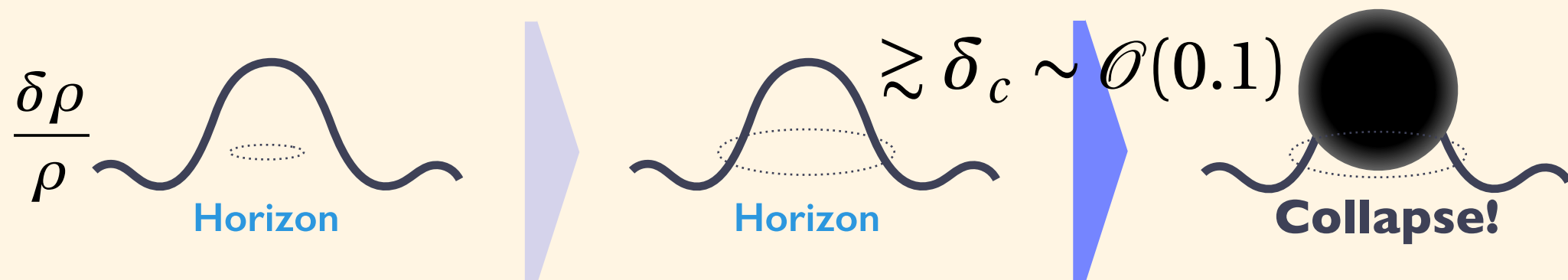
Formation of PBHs

Need **large** $\delta\rho/\rho$ for **Gravity** > **Pressure**



Formation of PBHs

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- ▶ PBH **mass** (**M**) \Leftrightarrow **scale** of perturbation (**k**)

$$M = \gamma \rho \frac{4\pi H^{-3}}{3} \simeq M_{\odot} \left(\frac{\gamma}{0.2} \right) \left(\frac{g_*}{3.36} \right)^{-\frac{1}{6}} \left(\frac{k/(2\pi)}{3 \times 10^{-9} \text{ Hz}} \right)^{-2}$$

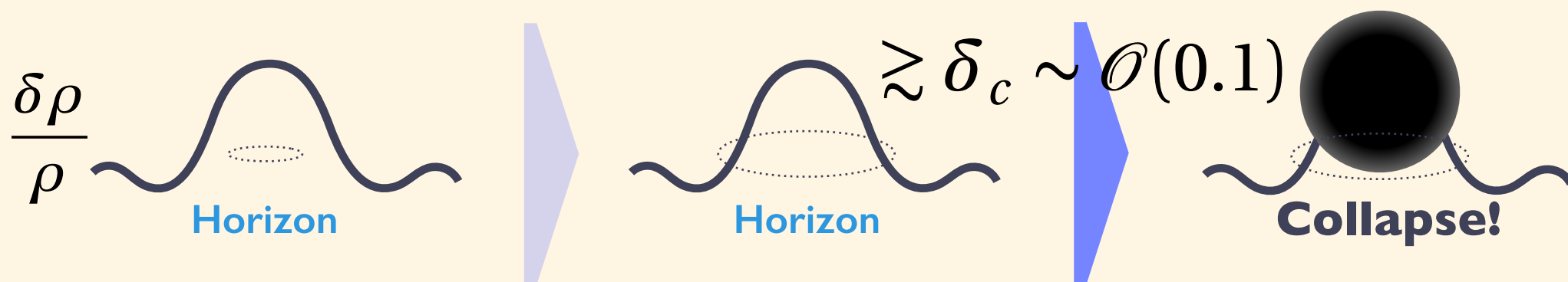
[Carr, '75]

- ▶ PBH **abundance** (**β**) \Leftrightarrow **amplitude** of perturbation (**P_ζ**)

$$\beta(M) = \int_{\delta_c} d\delta \frac{e^{-\frac{\delta^2}{2\sigma^2(M)}}}{\sqrt{2\pi\sigma^2(M)}} \sim \sigma(M) e^{-\frac{\delta_c^2}{2\sigma^2(M)}}; \quad \sigma^2(M) \sim P_{\zeta}(k)$$

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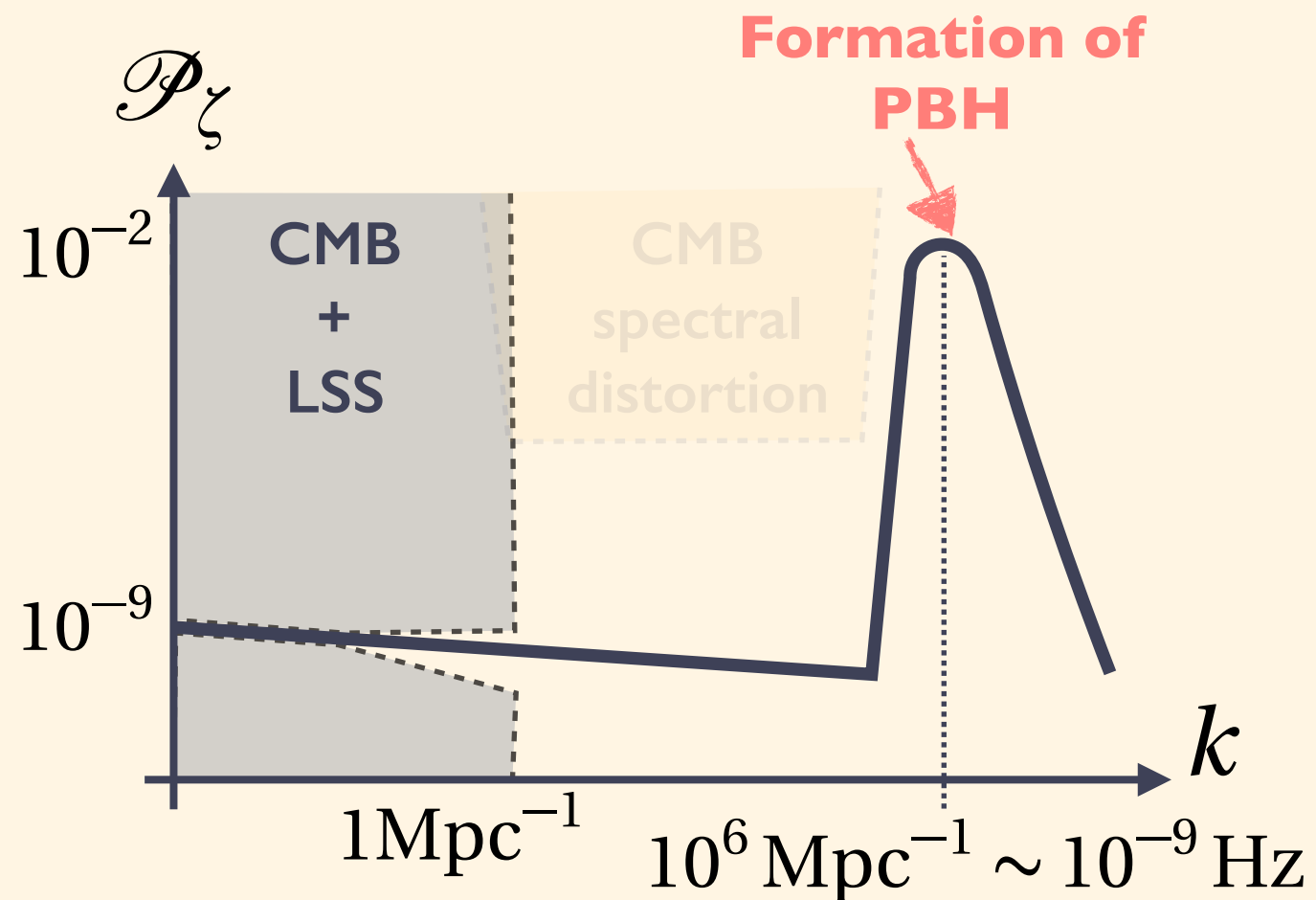
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For **LIGO**, **P_ζ(k)** ~ **10⁻²** @ **k/2π** ~ **10⁻⁹ Hz**.

Curvature Perturbation

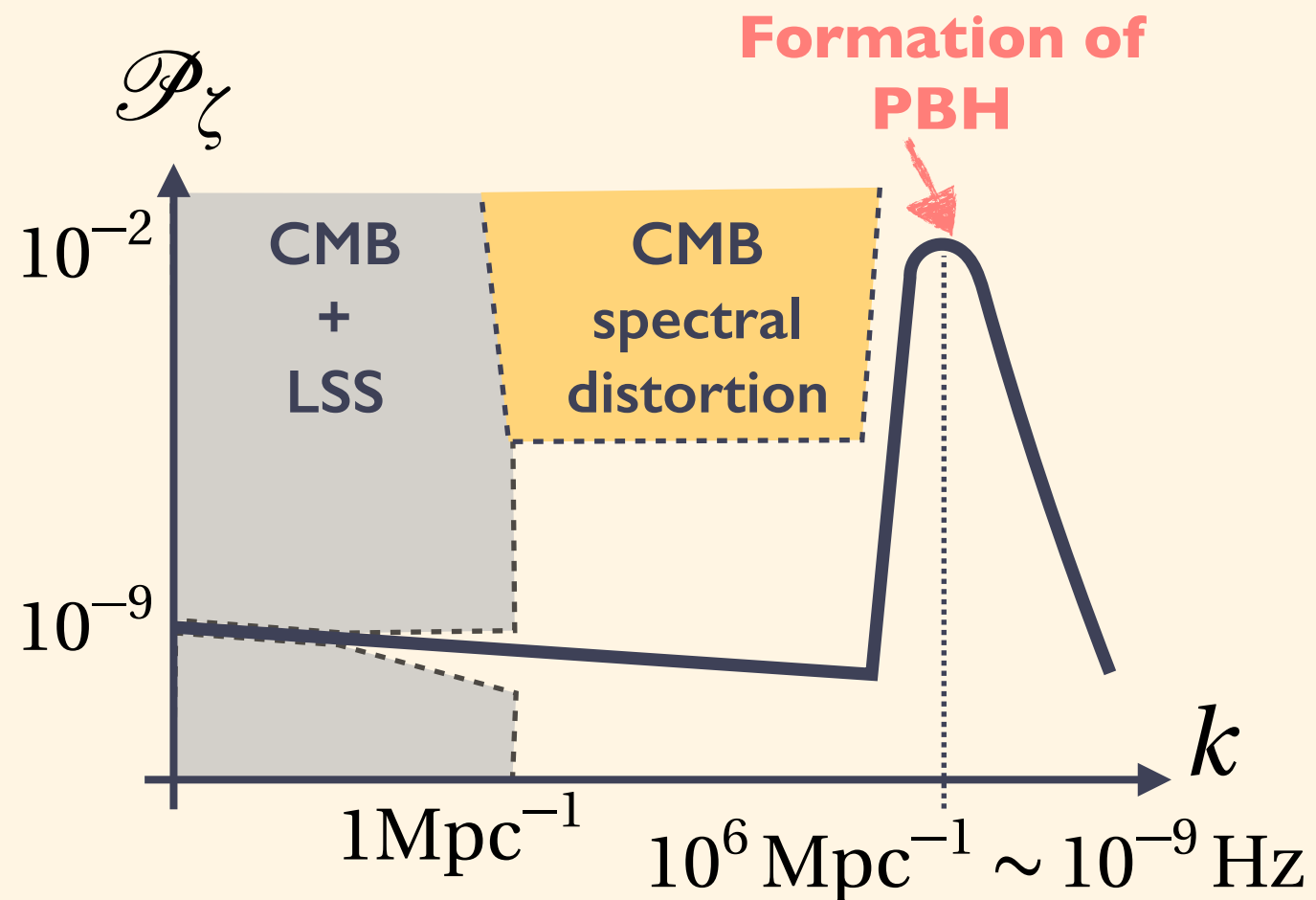
Power-spectrum (\mathbf{P}_ζ) for the **LIGO** events



For **LIGO**, $\mathbf{P}_\zeta(\mathbf{k}) \sim 10^{-2}$ @ $\mathbf{k}/2\pi \sim 10^{-9} \text{ Hz}$.

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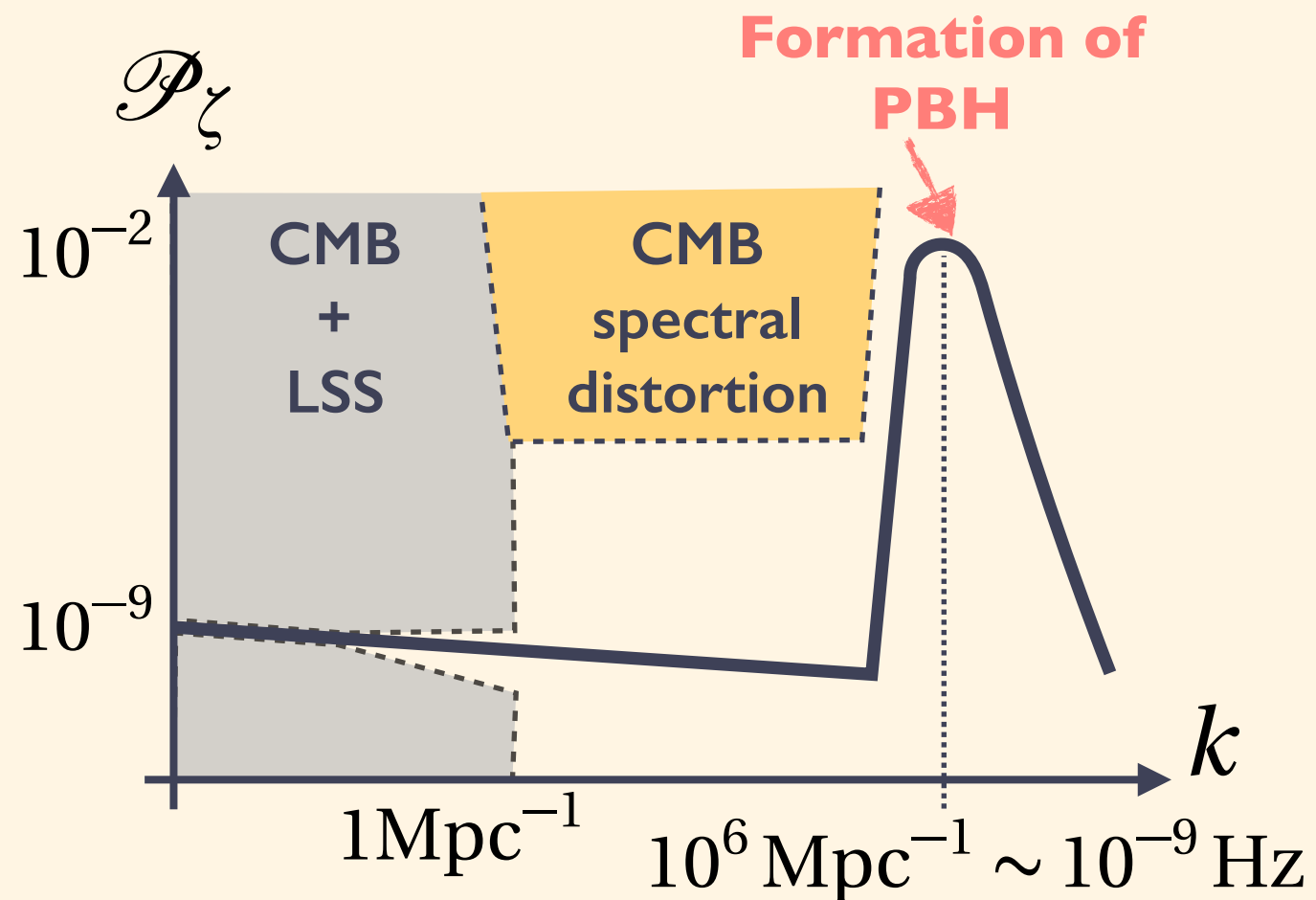
Power-spectrum (\mathcal{P}_ζ) for the **LIGO** events



- ▶ **CMB spectral distortion:** μ -distortion, ... [Kohri+, '14]
- ▶ **Induced GWs** via 2nd order effects: PTA experiments

Curvature Perturbation

Power-spectrum (\mathcal{P}_ζ) for the **LIGO** events



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3.

Induced GWs and PTA experiments

Induced GWs

Large density perturbation as a source of GWs

► Tensor perturbation obeys...

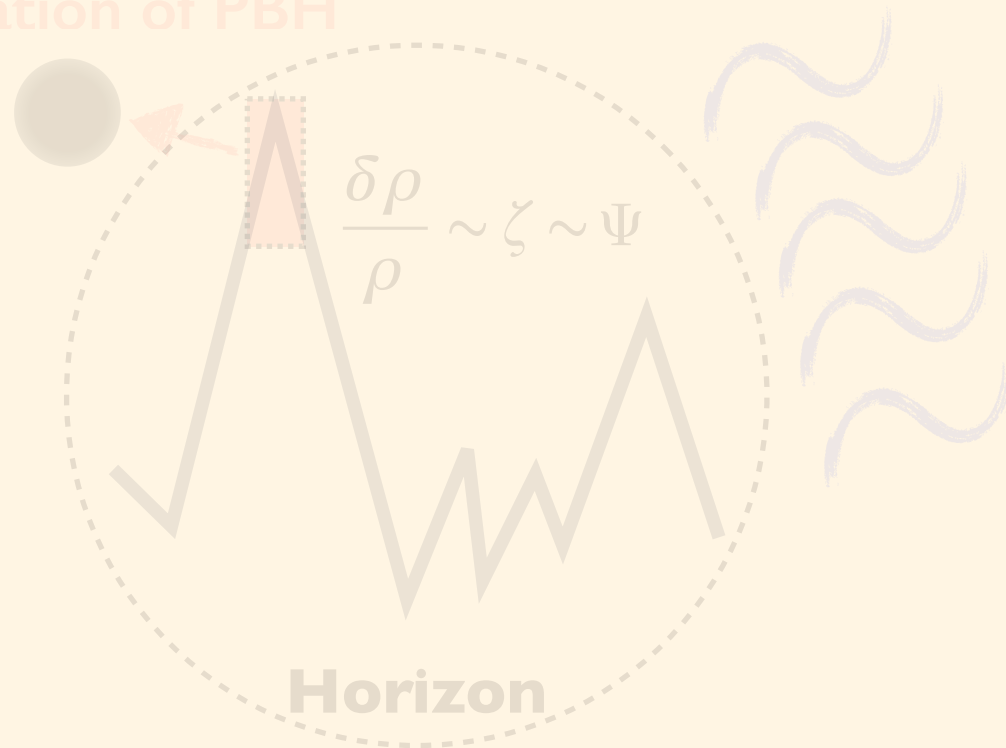
[Saito, Yokoyama, '09; Bugaev, Klimai, '10]

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = -4\hat{\mathcal{T}}_{ij;kl}S_{kl}$$

Depends on the **density perturb.**, $\Psi \sim \zeta$

$$S_{ij} \equiv 4\Psi\partial_i\partial_j\Psi + 2\partial_i\Psi\partial_j\Psi - \frac{4}{3(1+w)}\partial_i\left(\frac{\Psi'}{\mathcal{H}} + \Psi\right)\partial_j\left(\frac{\Psi'}{\mathcal{H}} + \Psi\right)$$

Formation of PBH



Production of GW by second order effects

$$h_{ij} \propto \Psi^2 \sim \zeta^2$$

$$\Omega_{\text{GW}}(k)h^2 \sim 10^{-9} \left(\frac{\mathcal{P}_\zeta(k)}{10^{-2}} \right)^2$$

$$\text{where } \Omega_{\text{GW,tot}} = \int d\log k \Omega_{\text{GW}}(k)$$

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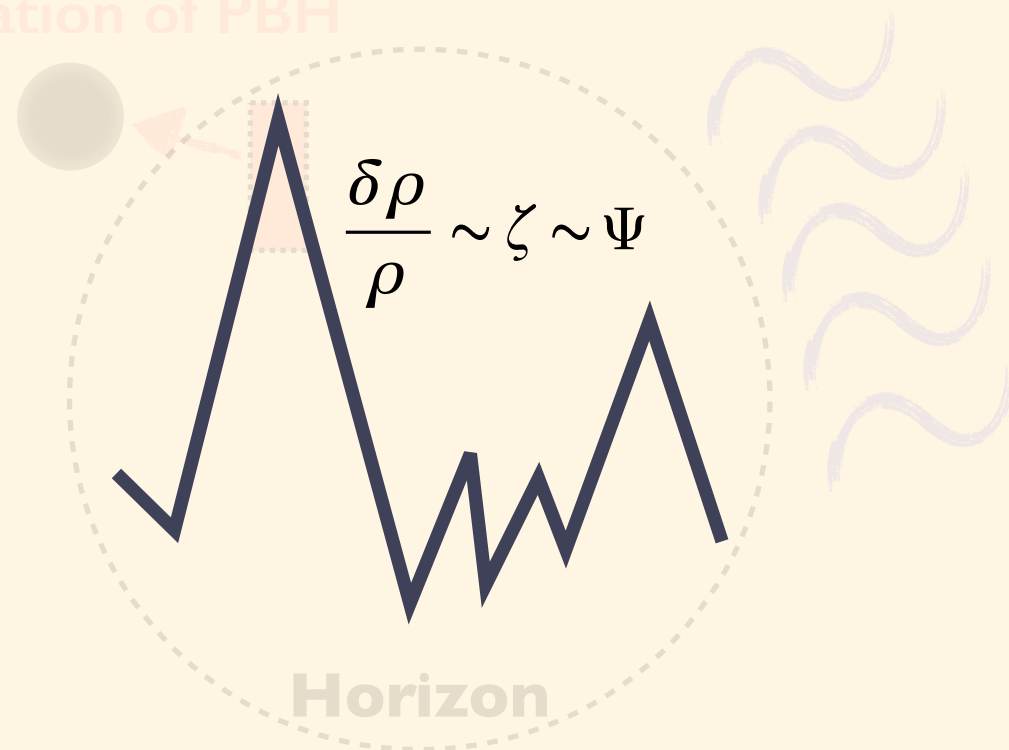
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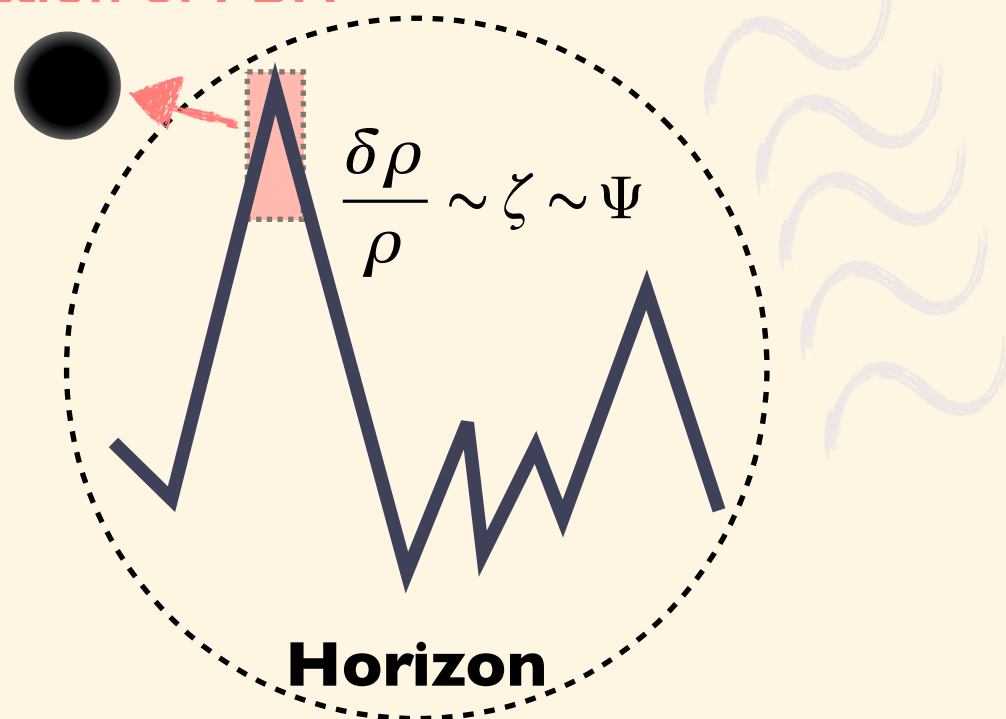
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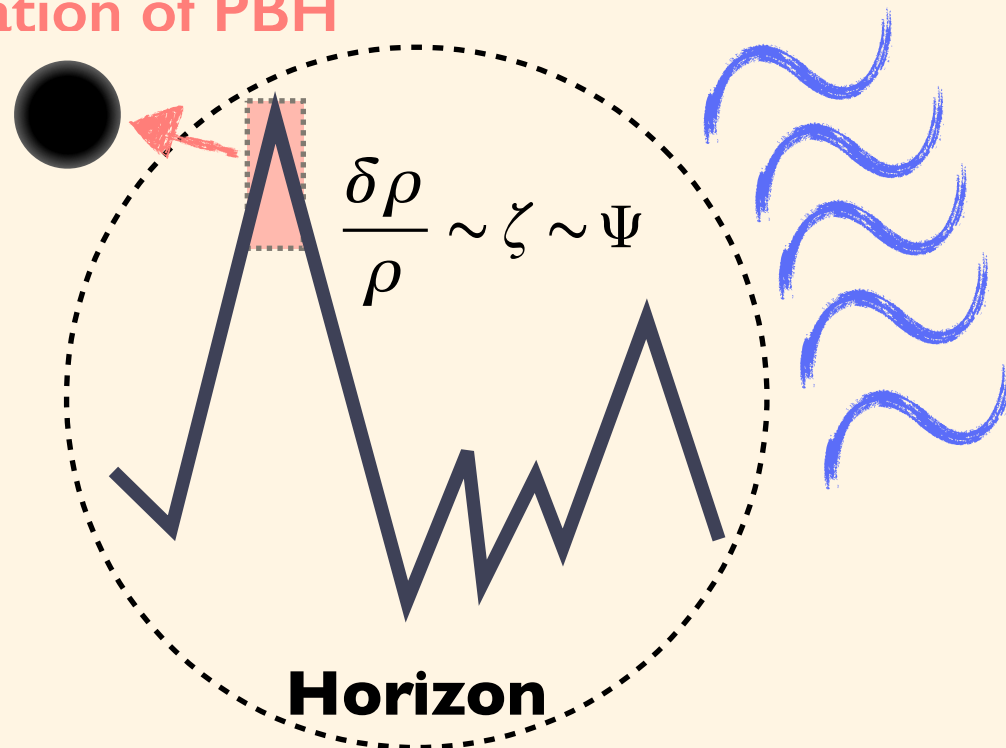
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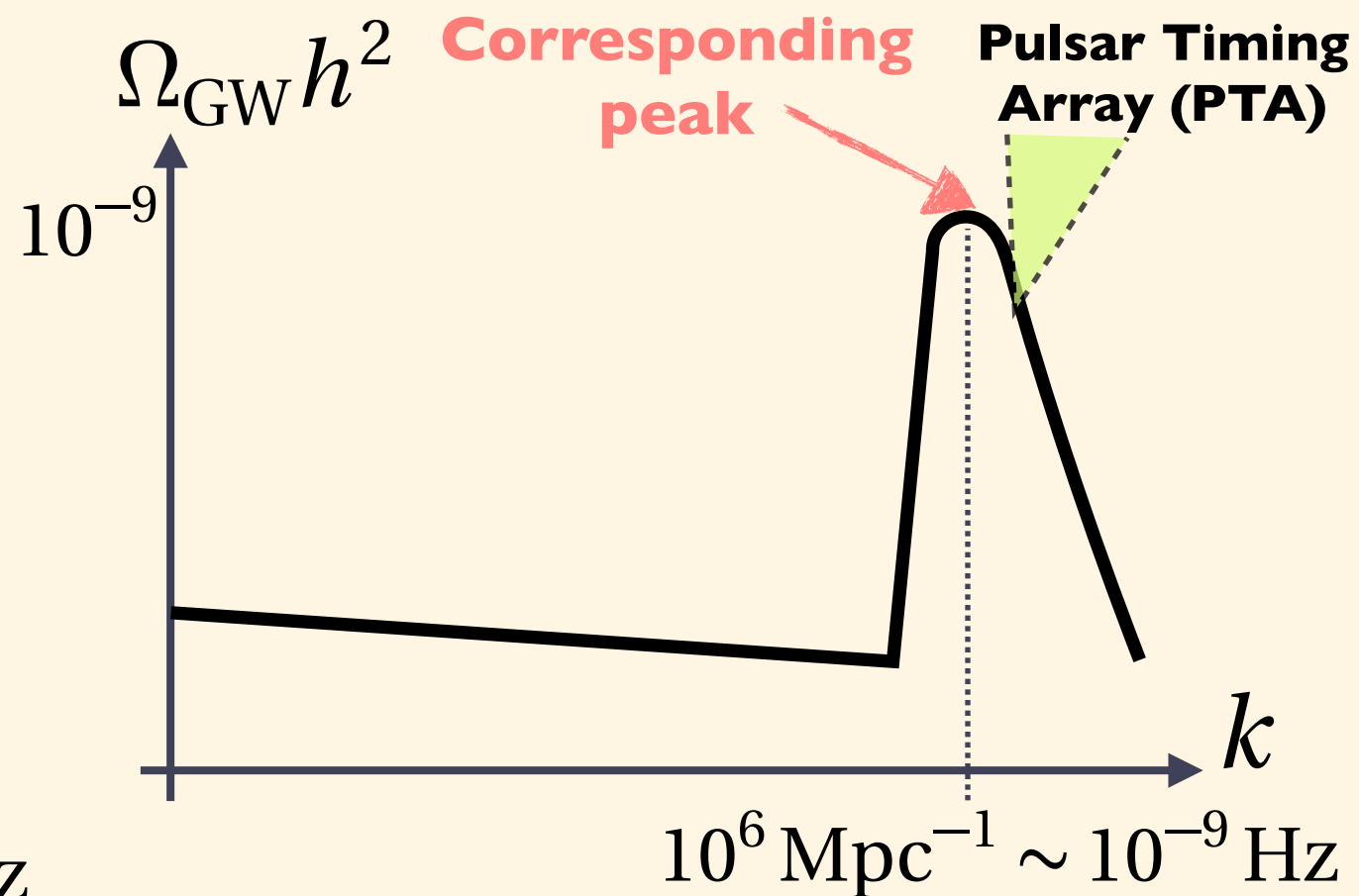
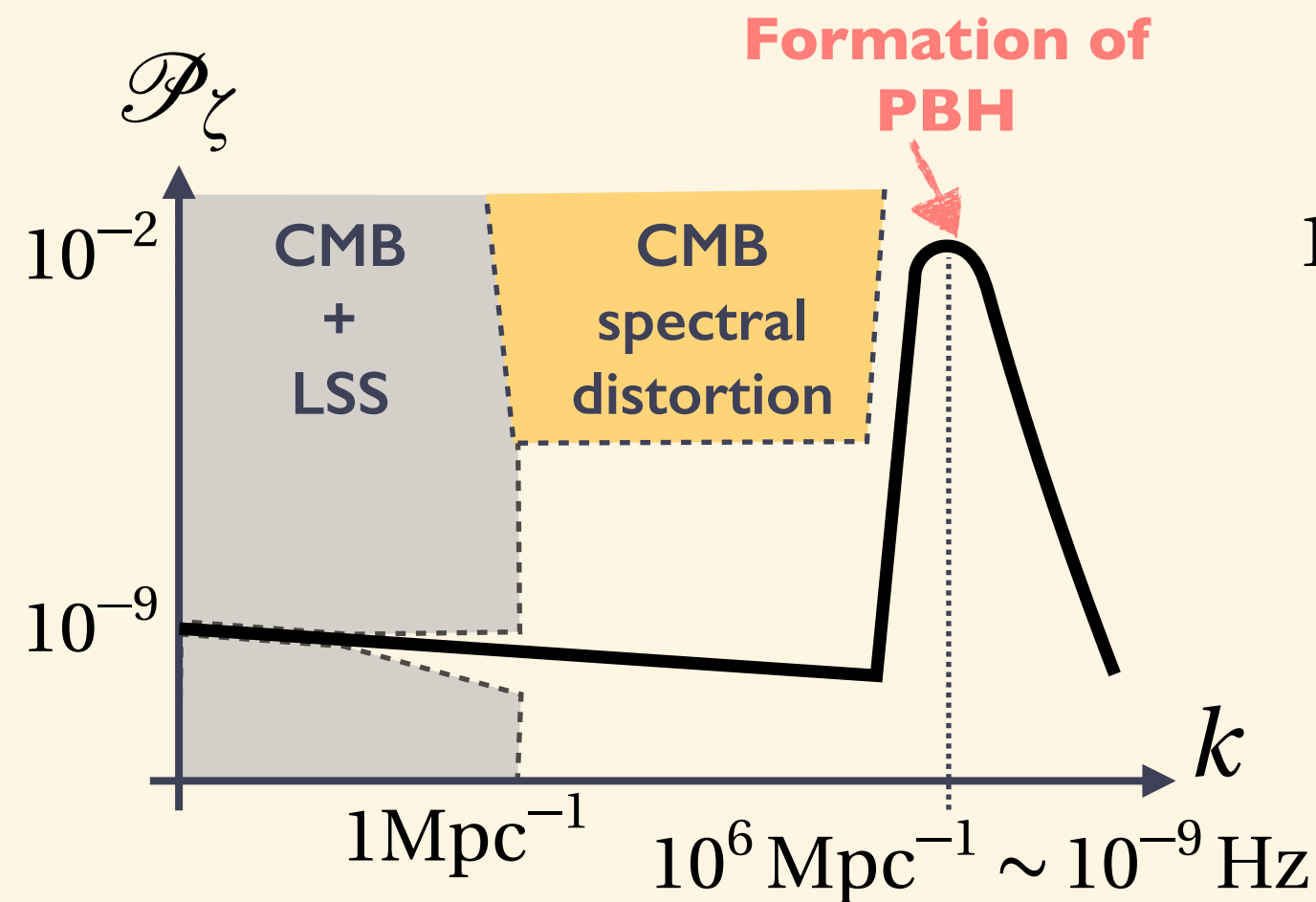
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Induced GWs

[K.Inomata, M.Kawasaki, **KM**, Y.Tada, T.T.Yanagida]

Only **steep spectrum** is allowed!

- ▶ GW has a **corresponding peak at the same k**.



- ▶ **Steepness** of the spectrum

$$\mathcal{P}_\zeta \propto \begin{cases} k^x & \dots k < k_{\text{peak}} \\ k^{-y} & \dots k > k_{\text{peak}} \end{cases}$$

Current constraints

$$x \gtrsim 1.5, y \gtrsim 2$$

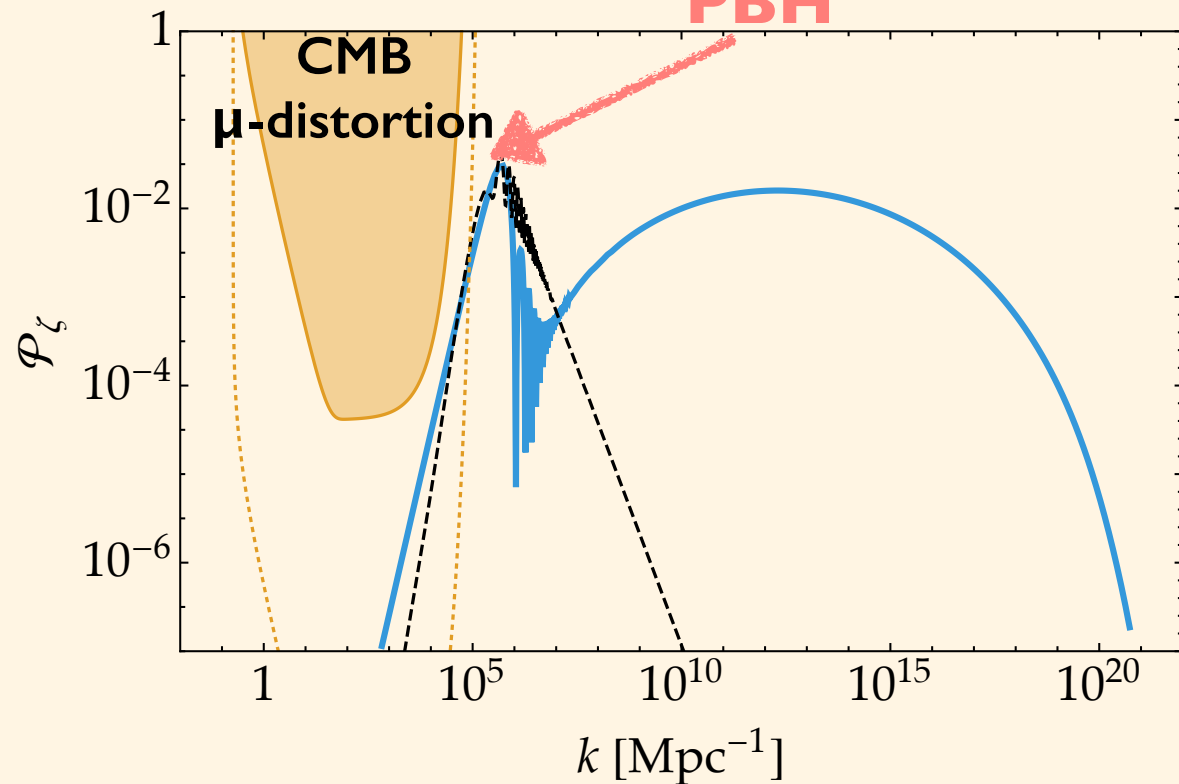
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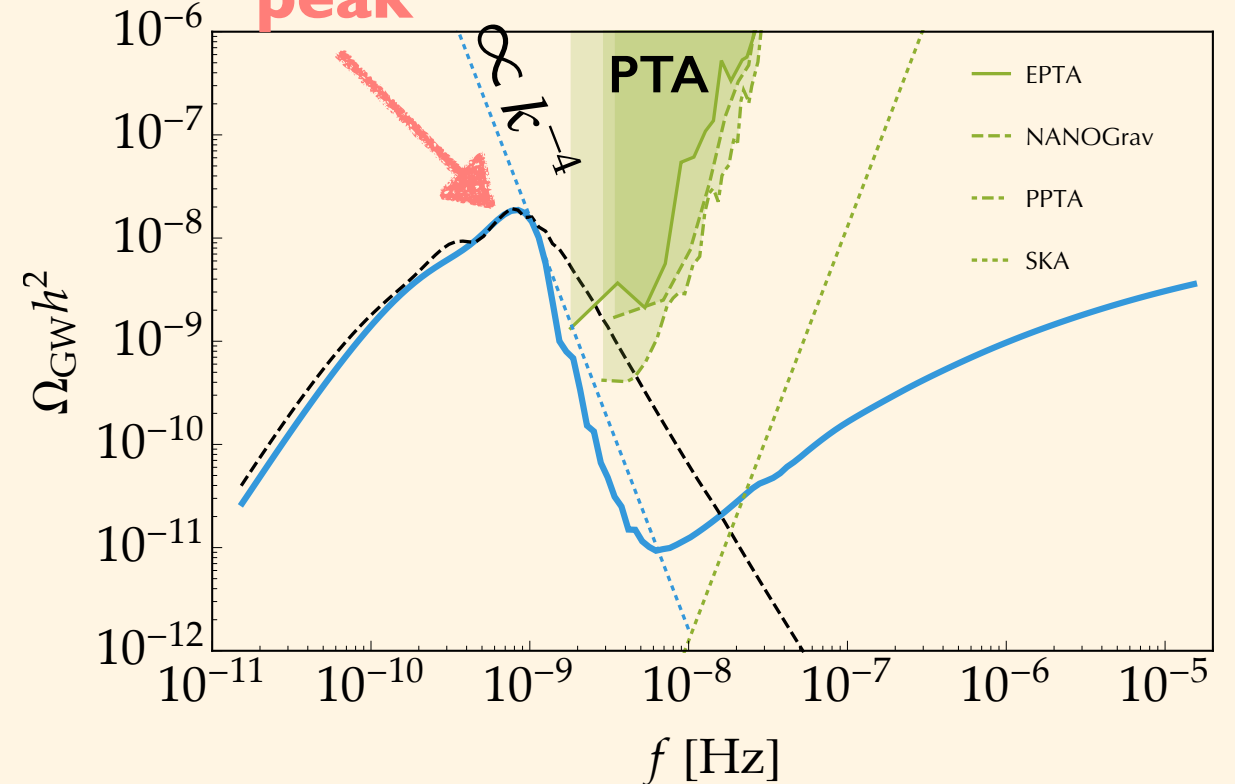
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► **Double inflation** as an example

Formation of
PBH



Corresponding
peak



► **Steepness of the spectrum**

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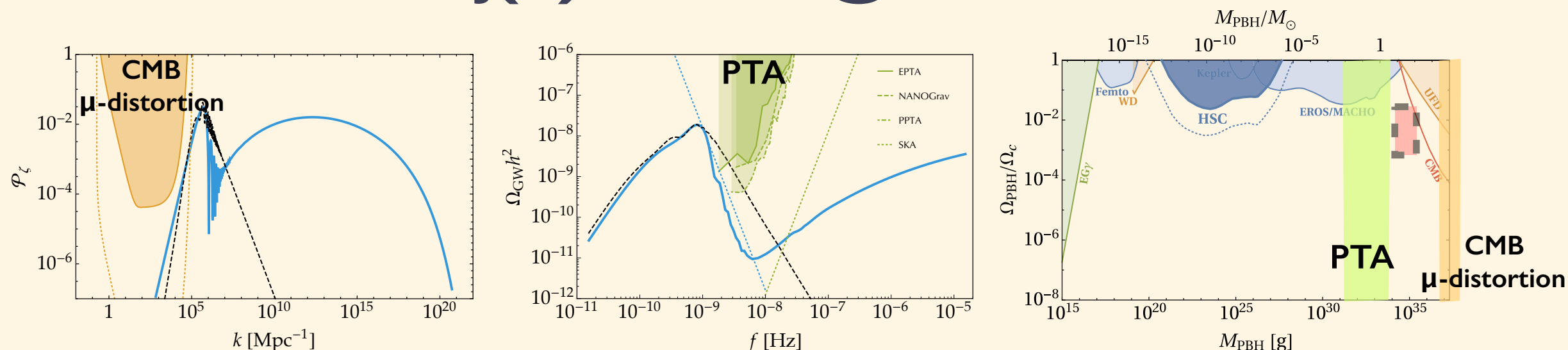
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Summary

Inflation can be an origin of **PBHs** whose mergers account for the **LIGO GW** events.

But, need **large $P_\zeta(k) \sim 10^{-2}$ @ $f \sim 10^{-9}$ Hz.**

CMB spectral distortion and **induced GWs** can constrain **$P_\zeta(k) \sim 10^{-2}$ @ $f \sim 10^{-9}$ Hz.**



[K.Inomata, M.Kawasaki, **KM**, Y.Tada, T.T.Yanagida; 1611.06130]

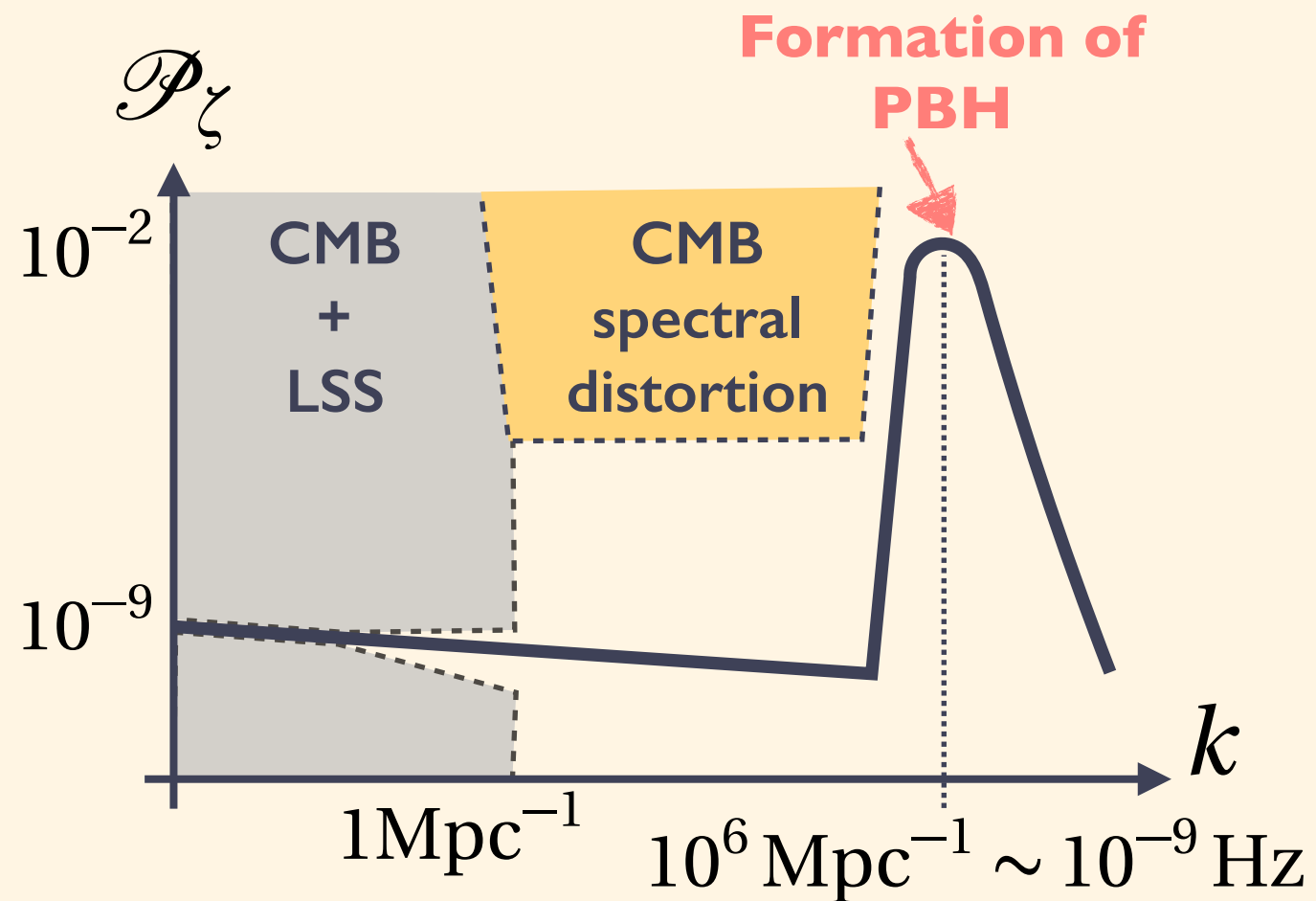
- ♣ Enhanced **non-Gaussianity** @ small-scales could generate PBHs w/ **smaller P_ζ**
 ➔ possibility to evade these constraints. [Nakama, Silk, Kamionkowski; '16; Ando, Inomata, Kawasaki: perp.]

Backup

Inflationary PBHs

Inflation models as the origin of **PBHs**

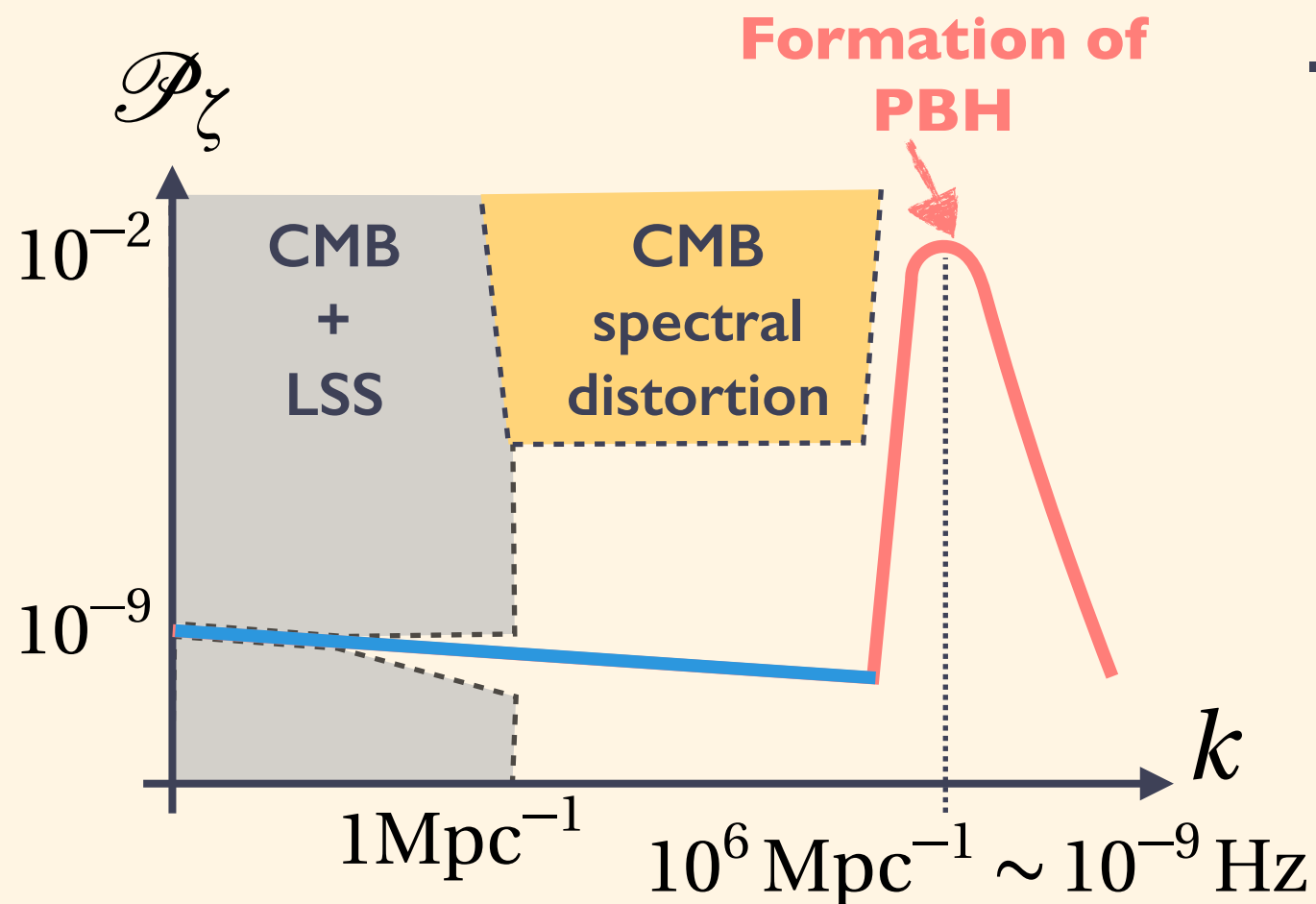
- ▶ How to **enhance** \mathcal{P}_ζ @ small-scales \Rightarrow **Flatten** your potential!



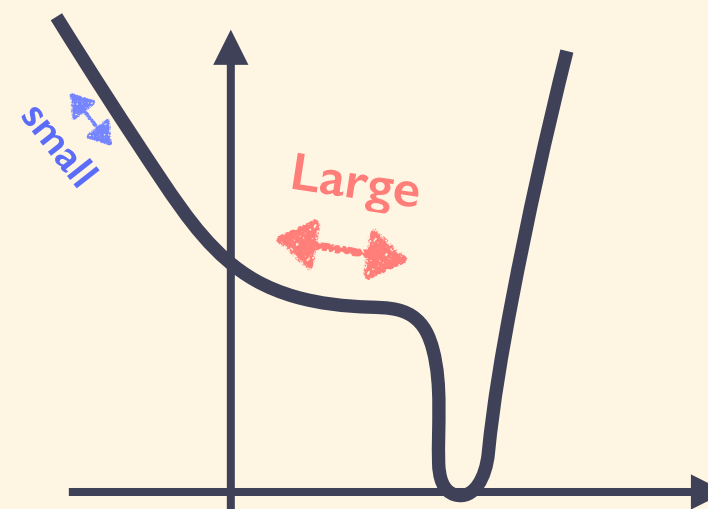
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Inflation models as the origin of **PBHs**

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- Running mass

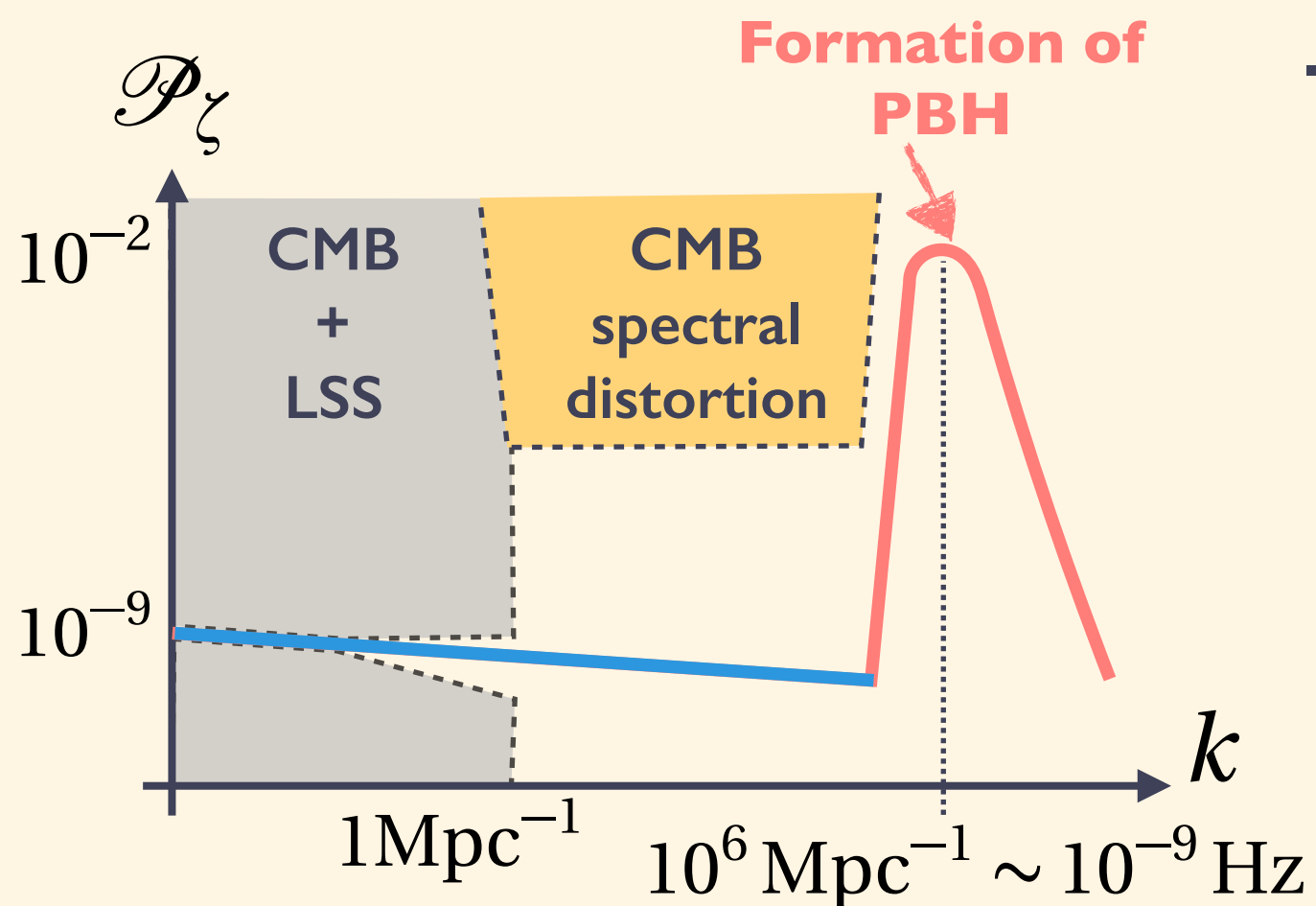


$$\zeta \sim \frac{\delta \rho}{\rho} \sim H \delta t \sim H \frac{\delta \phi}{\dot{\phi}} \sim \left| \frac{V^{3/2}}{V' M_{\text{pl}}^3} \right|$$

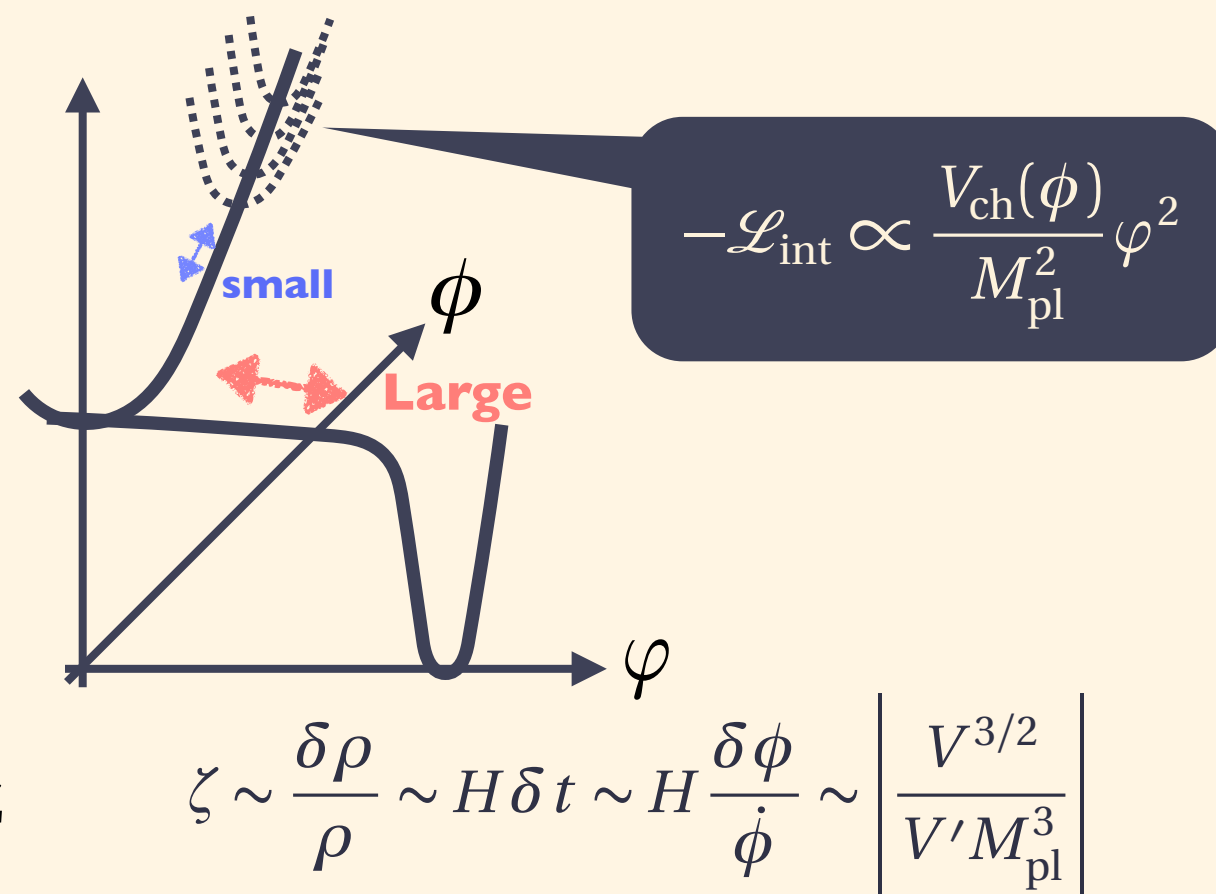
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Inflation models as the origin of **PBHs**

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- Double Inflation



PBH as all DM

Constraints on **extended mass function**

[KM+, 1701.02544]

