PBHs from Inflation and their Implications

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Kavli IPMU, Univ. of Tokyo
→ DESY, Hamburg (Oct. 2017)

Based on **1611.06130, 1701.02544, 1711.xxxxx**
In collaboration with K.Inomata, M.Kawasaki, Y.Tada, T.T.Yanagida

1.

Introduction

Introduction

Why Primordial Black Holes (PBHs)?

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

How do you produce them?

- Need **Large density perturbations** for **Gravity > Pressure**.
  - Collapse of localized configurations: bubble collision, cosmic string, Q-ball,…
  - Collapse of **primordial** density perturbations: **inflation**, curvaton,…

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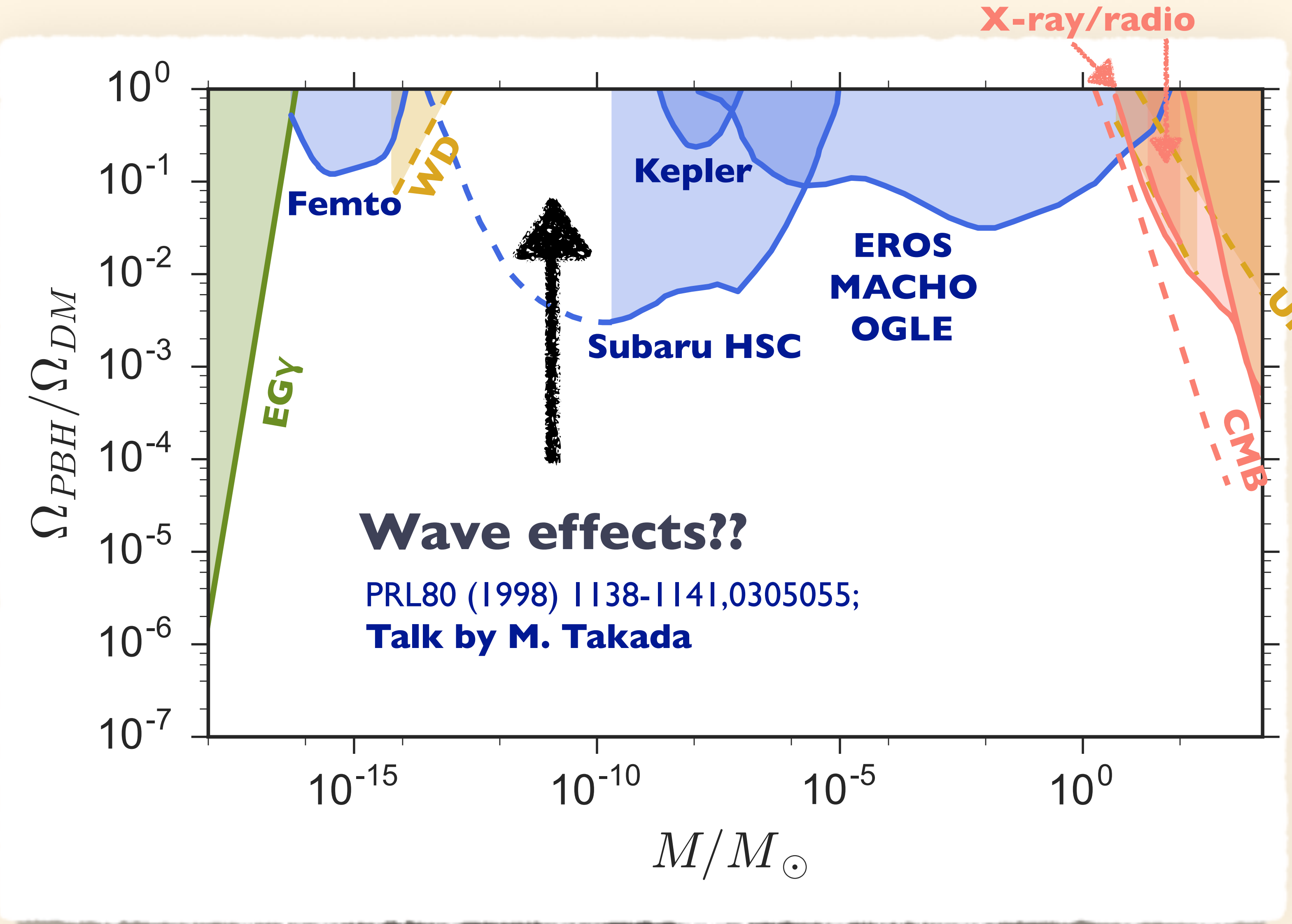
This Talk!

Current Constraints

Constraints **independent** of production mechanisms.

- Note: a **delta function** for PBH spectrum is assumed.



✤ 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

EGγ: 0912.5297

Gravitational lensing

Femto: 1204.2056

HSC: 1701.02151

Kepler: PhysRevLett.111.181302

EROS/MACHO/OGLE: 0011506, 0607207, 1106.2925

Dynamical

WD: 1505.04444

UFD: 1605.03665, 1704.01668

Accretion

CMB: 1612.05644,1707.04206,…

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Talk by Y. Inoue

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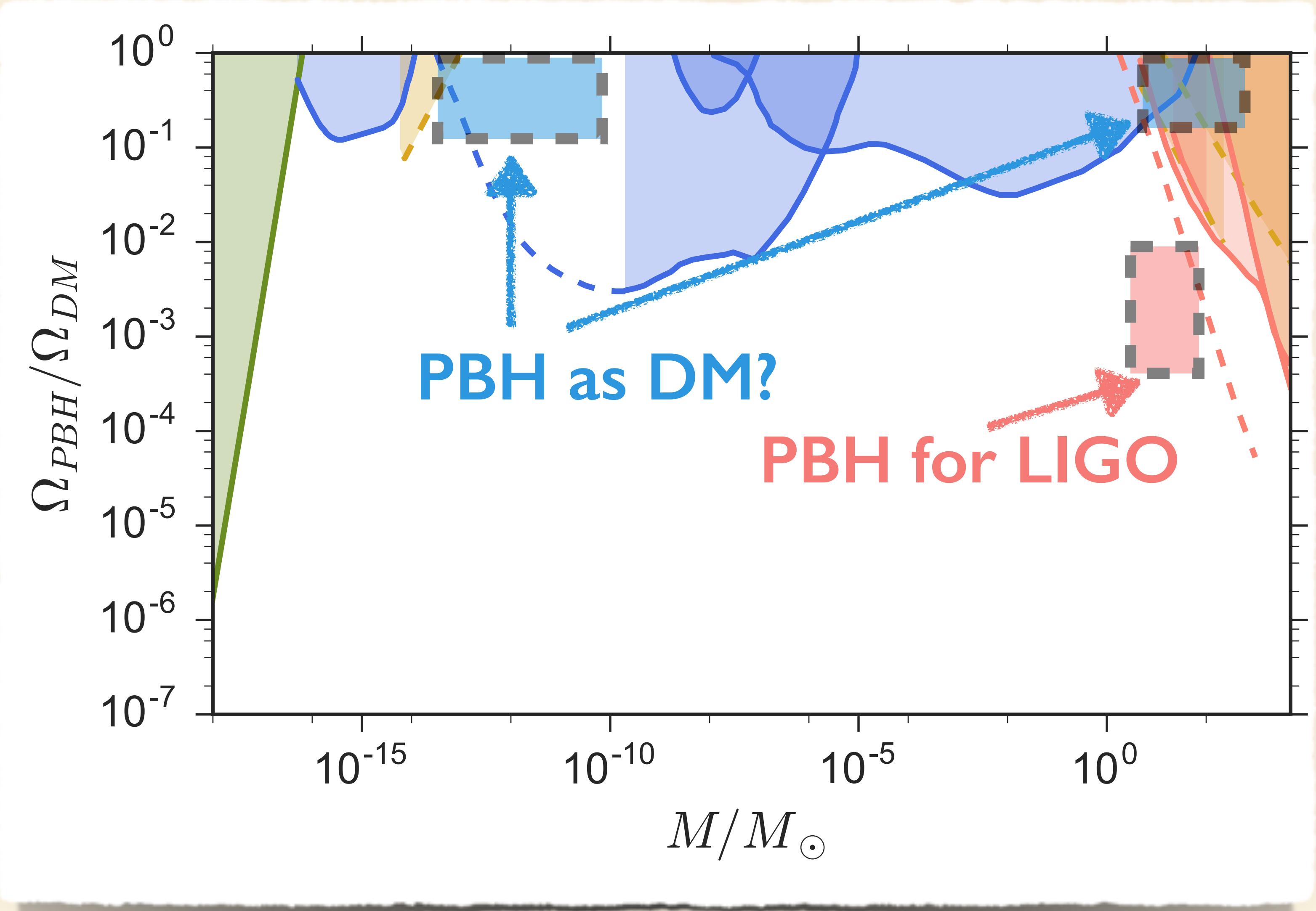

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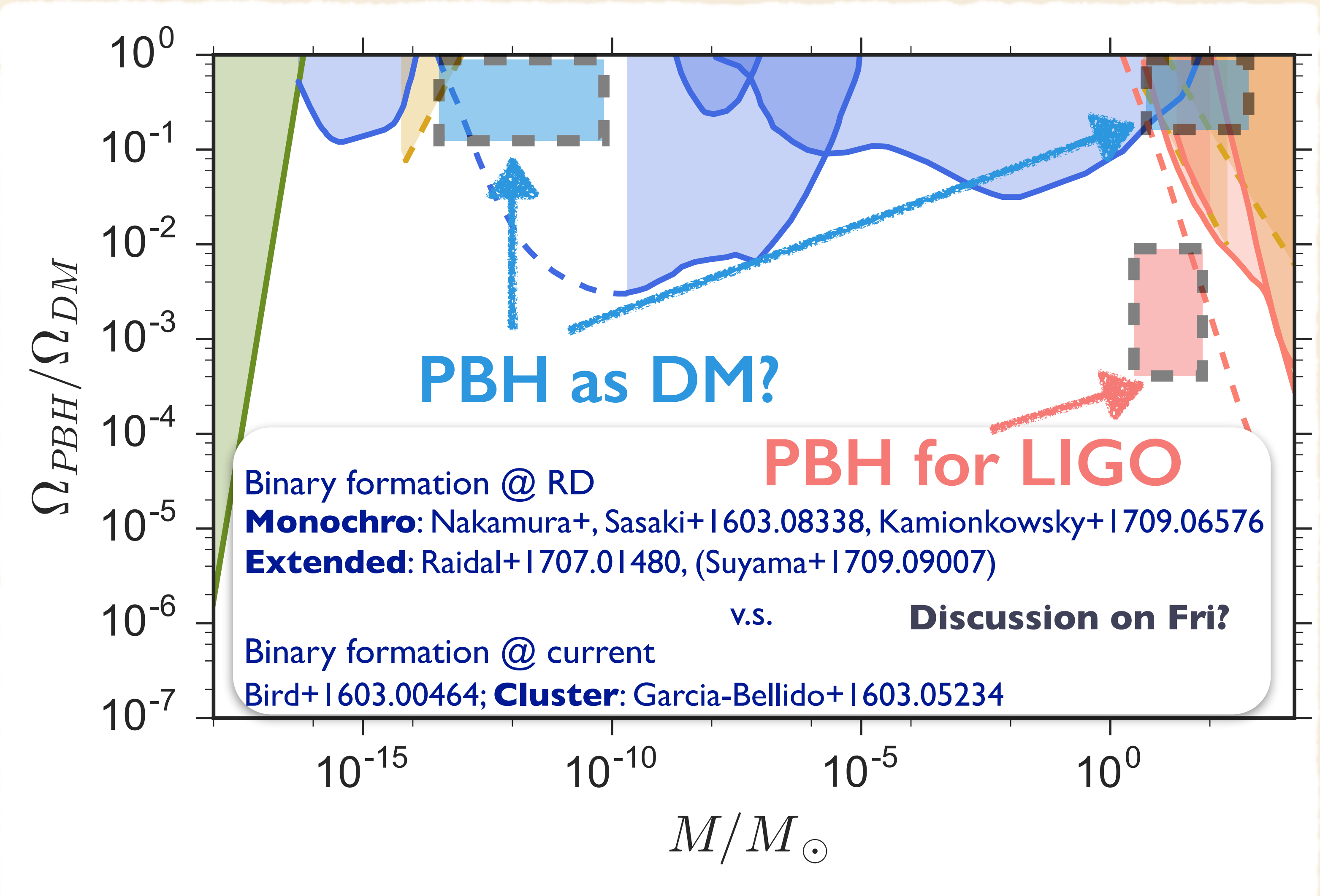

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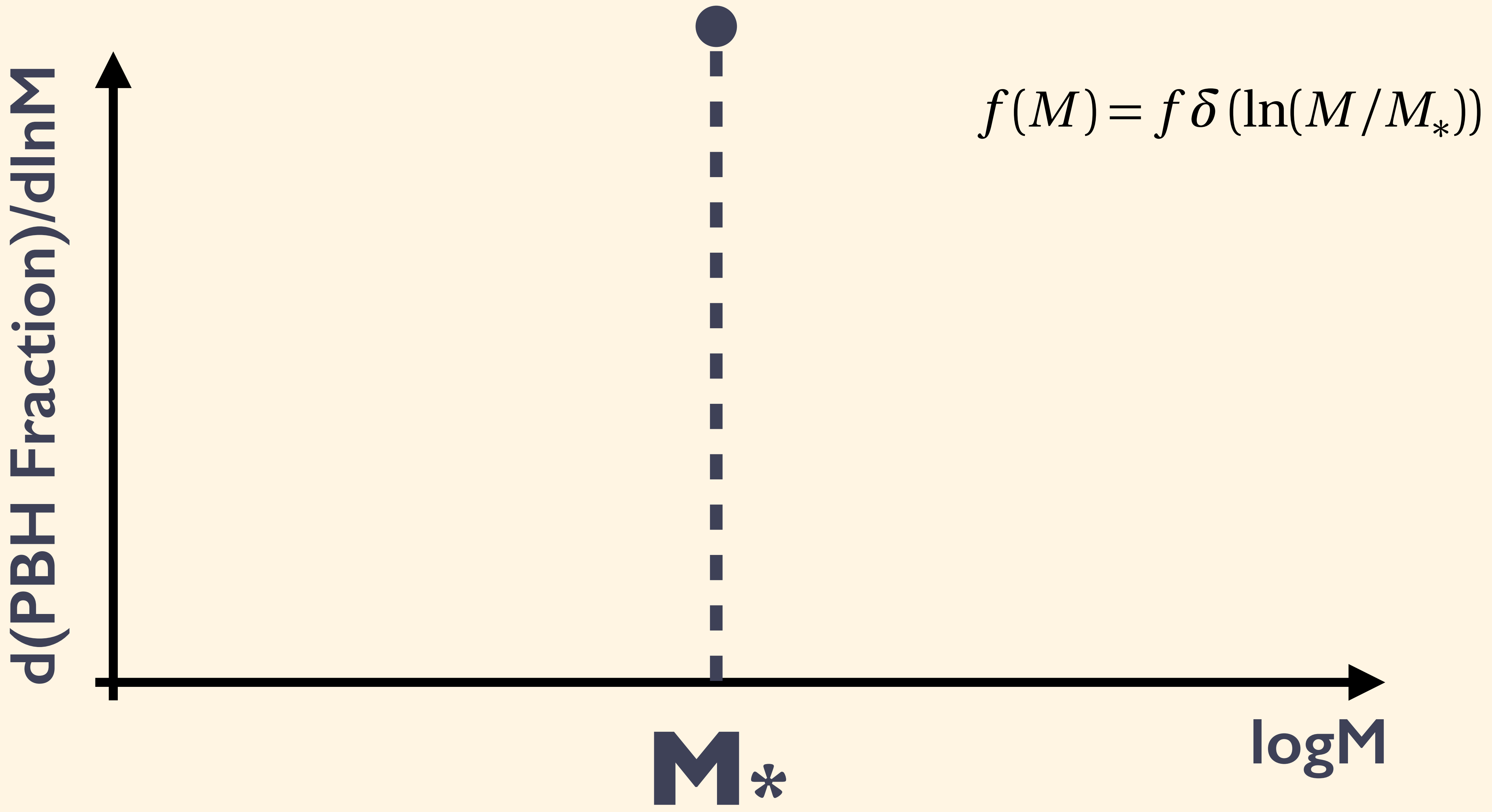

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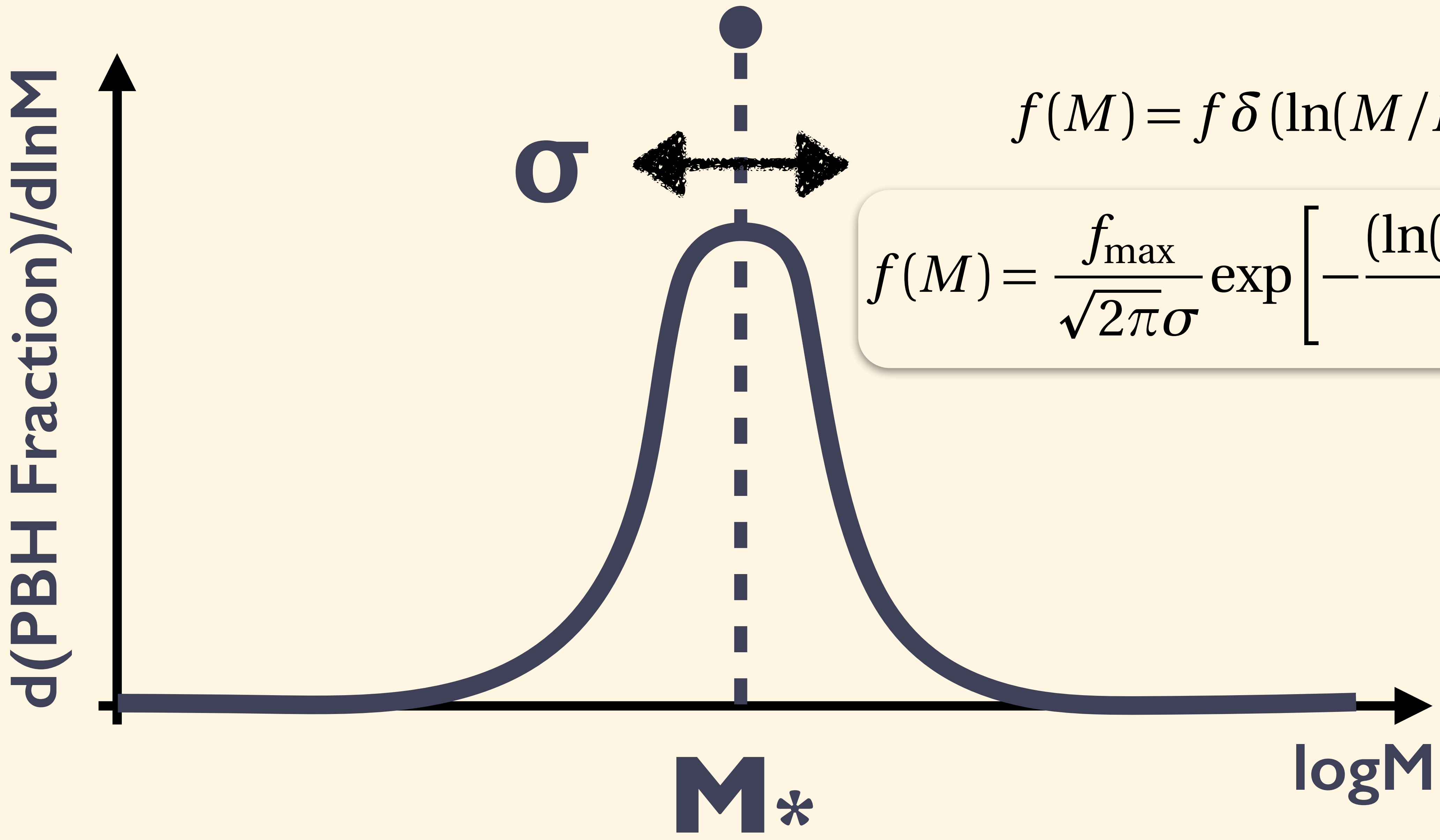


$$f(M) = f\,\delta(\ln(M/M_*))$$

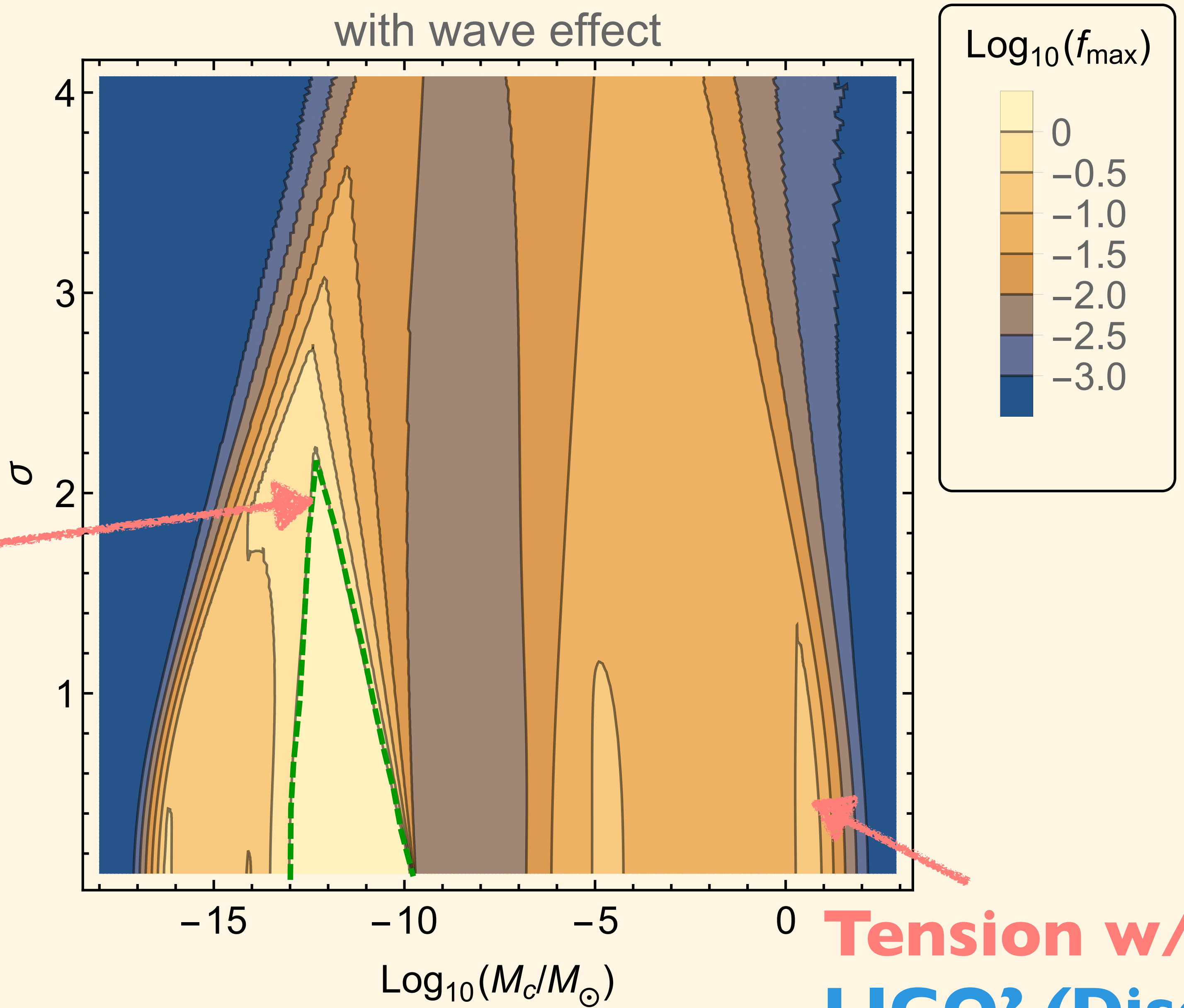
$$f(M) = \frac{f_{\max}}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(\ln(M/M_*))^2}{2\sigma^2}\right]$$

Current Constraints

Constraints **independent** of production mechanisms.

- Constraints on **extended** mass function.

[**KM+, 1701.02544**; Kuhnel+, 1701.07223; Carr+, 1705.05567;…]



Large σ is allowed

Talk by Y. Inoue

Tension w/ radio/X-ray

LIGO? (Discussion on Fri?)

Current Constraints

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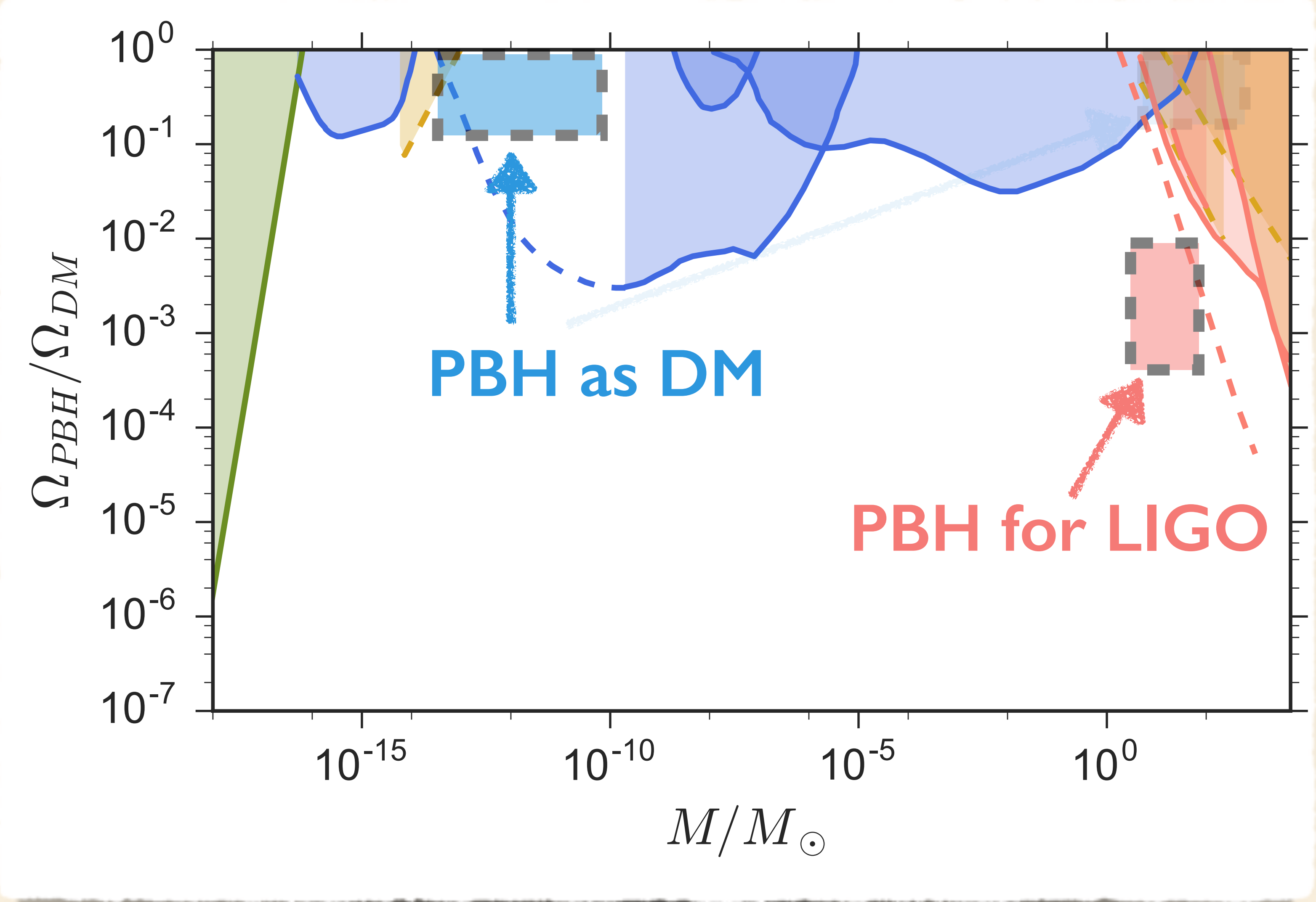
- PBH for **LIGO events**: marginal, but still viable.



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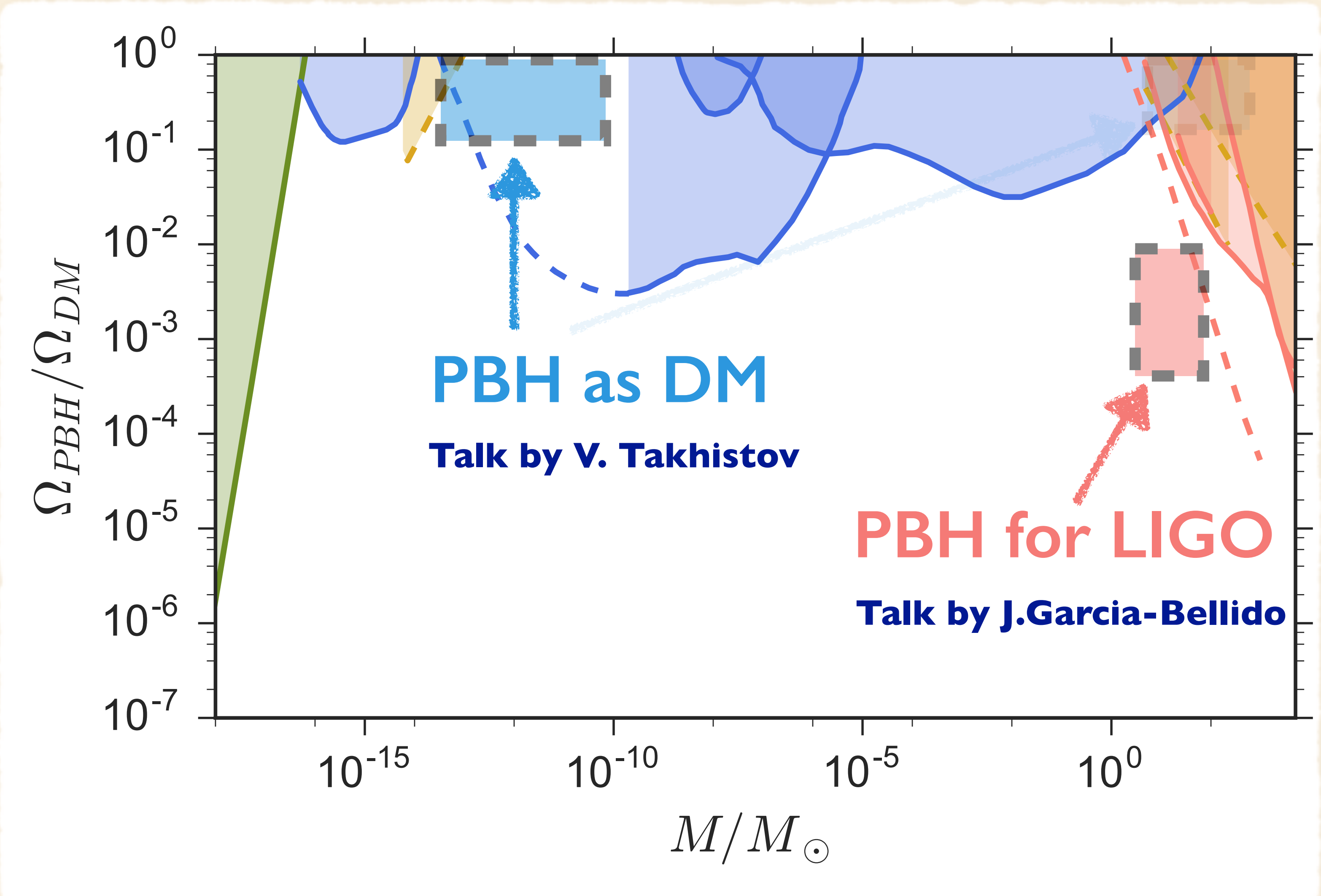

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Q.

Assume a specific production mechanism (**inflation**).

Are there any other ways to probe them?

Can we construct concrete inflation models?

Outline of Talk

- Introduction
- Constraints on PBHs from Inflation
- Double inflation: PBHs for LIGO or DM
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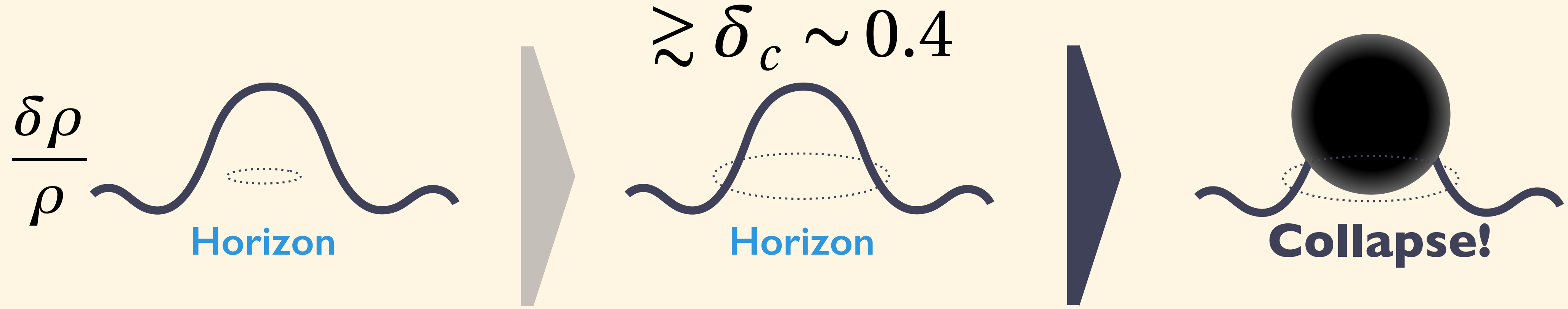
Constraints on PBHs from Inflation

Formation of PBHs

Need **large δρ/ρ** for **Gravity > Pressure**

Talk by T. Harada



- PBH **mass** (**M**) ⇆ **scale** of perturbation (**k**)

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

[Carr, '75]

- PBH **abundance** (**β**) ⇆ **amplitude** of perturbation (**P$_\zeta$**)

$$\beta(M) = \int_{\delta_c} \mathrm{d}\delta \frac{\mathrm{e}^{-\frac{\delta^2}{2\sigma^2(M)}}}{\sqrt{2\pi\sigma^2(M)}} \sim \sigma(M)\,\mathrm{e}^{-\frac{\delta_c^2}{2\sigma^2(M)}}$$

$$\sigma^2(M(k)) = \int \mathrm{d}\ln q\, W^2(qk^{-1})\frac{16}{81}\left(qk^{-1}\right)^4 \mathscr{P}_\zeta(q)$$

$$\propto \mathscr{P}_\zeta(k)$$

✤ Enhanced **non-Gaussianity** → same amount of PBHs w/ **smaller/larger** P$_\zeta$

Formation of PBHs

Typical probability we need

- 1% of DM @ O(10) solarmass: **β ~ 10^-10^.**

β ≪ **1** → PBHs

➡ independent of how they produced.

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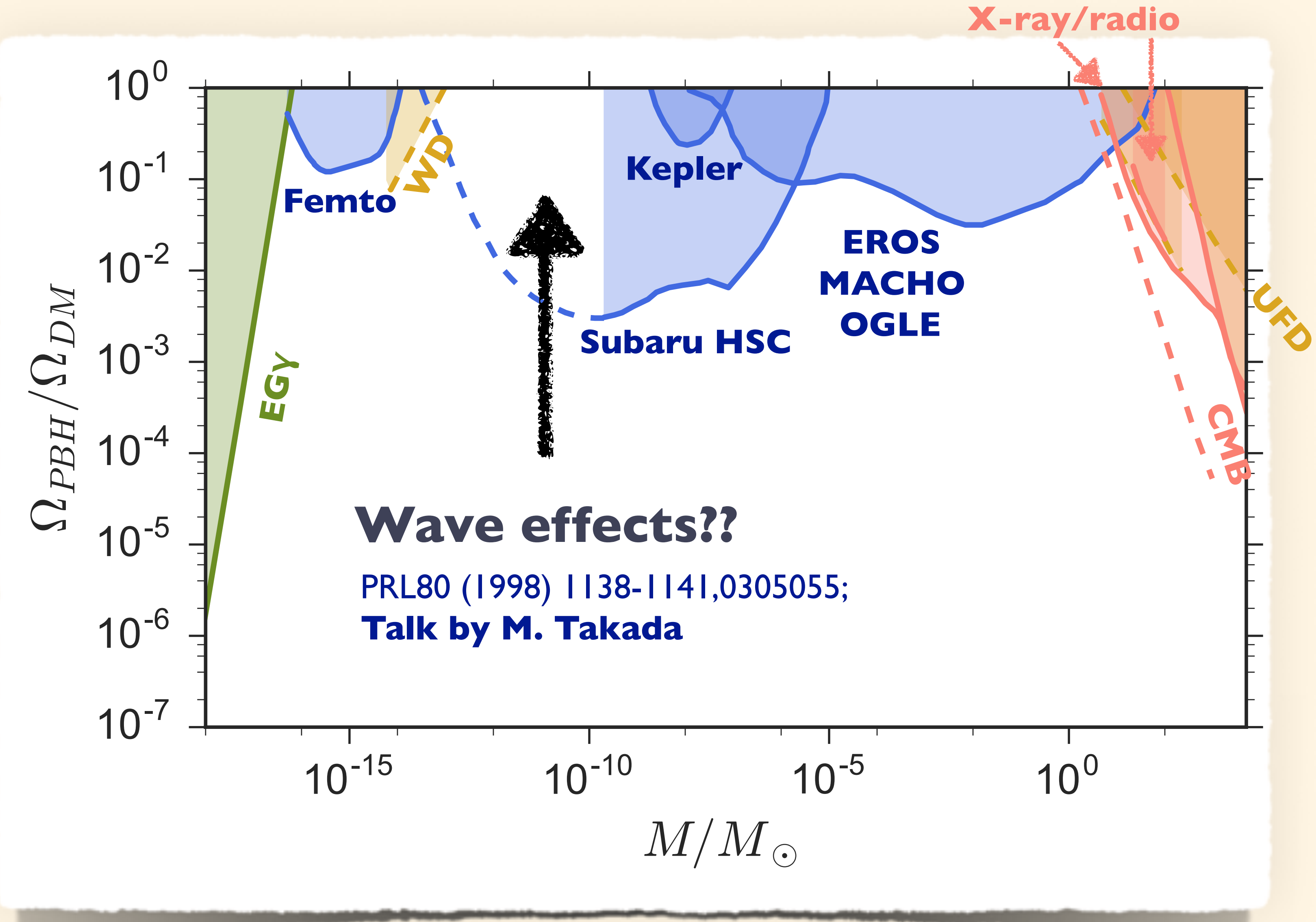

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β ≪ 1 → PBHs

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1 - β → **plenty of** over-densities

➡ **Use them!**

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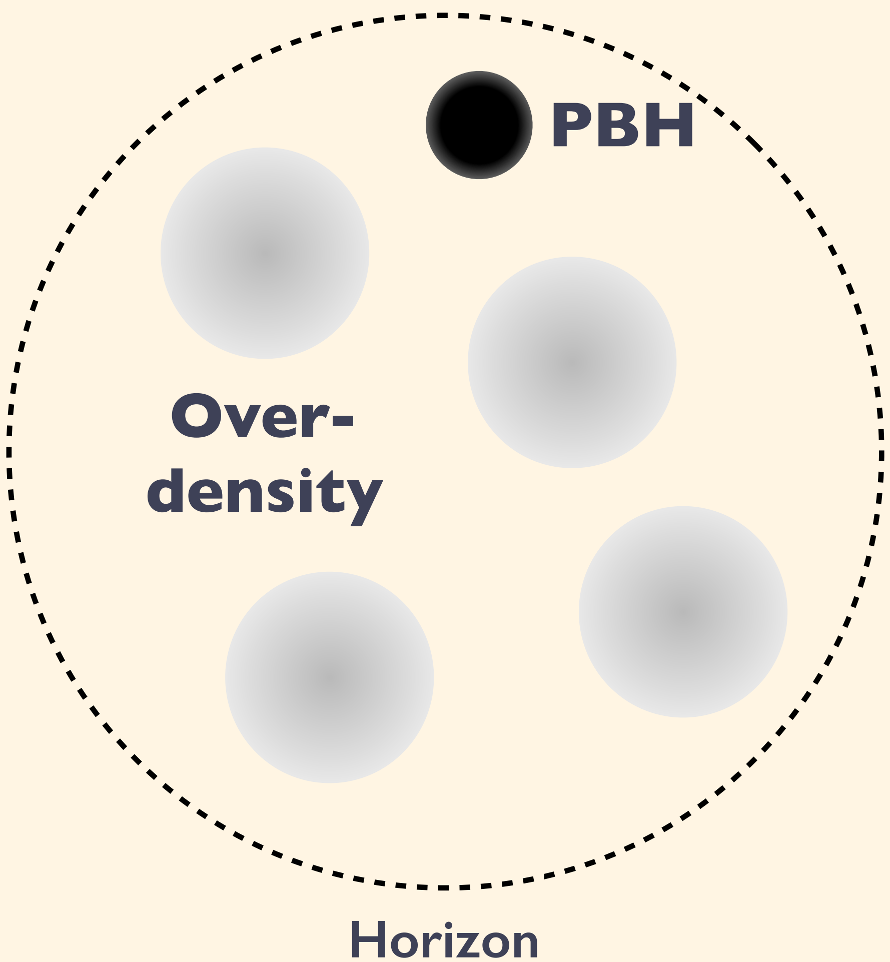
Probes of small-scale perturb.

Energy injection from large small-scale perturbs.

- How do they affect? → **Depends on components and era.**

After reentry



Now

Are their effects erased? Or not.

- via **radiation**
  - ➡ **CMB/BBN**
- via **GW**
- via **CDM**
  - ➡ **UCMH**; depends on DM models

Horizon

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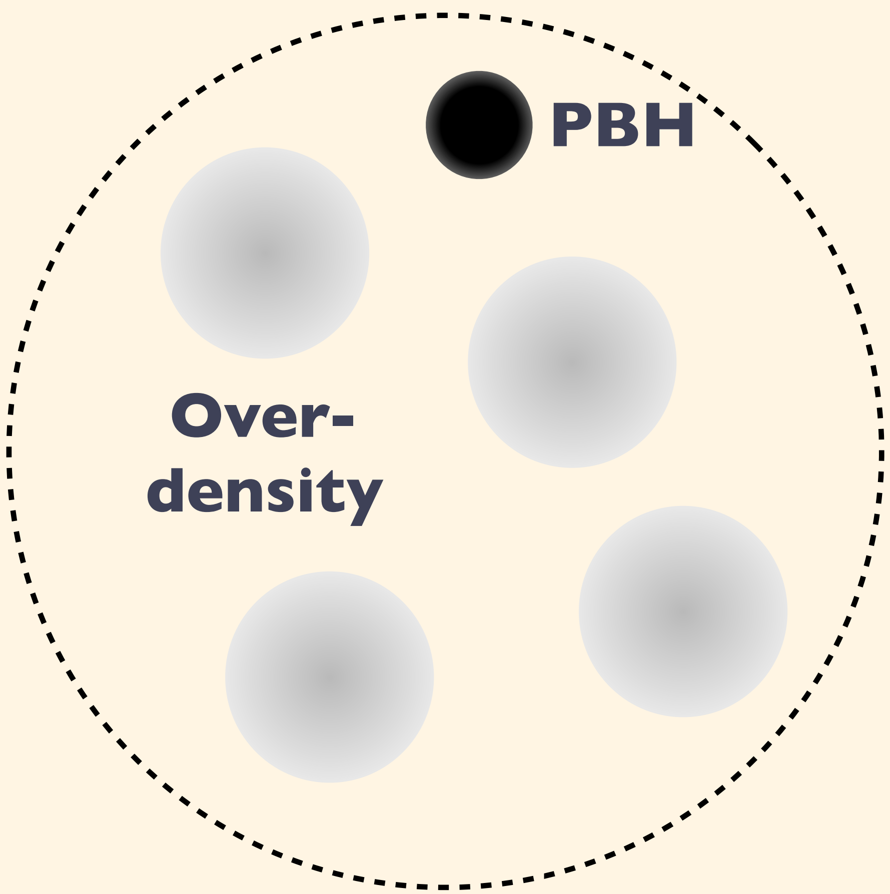

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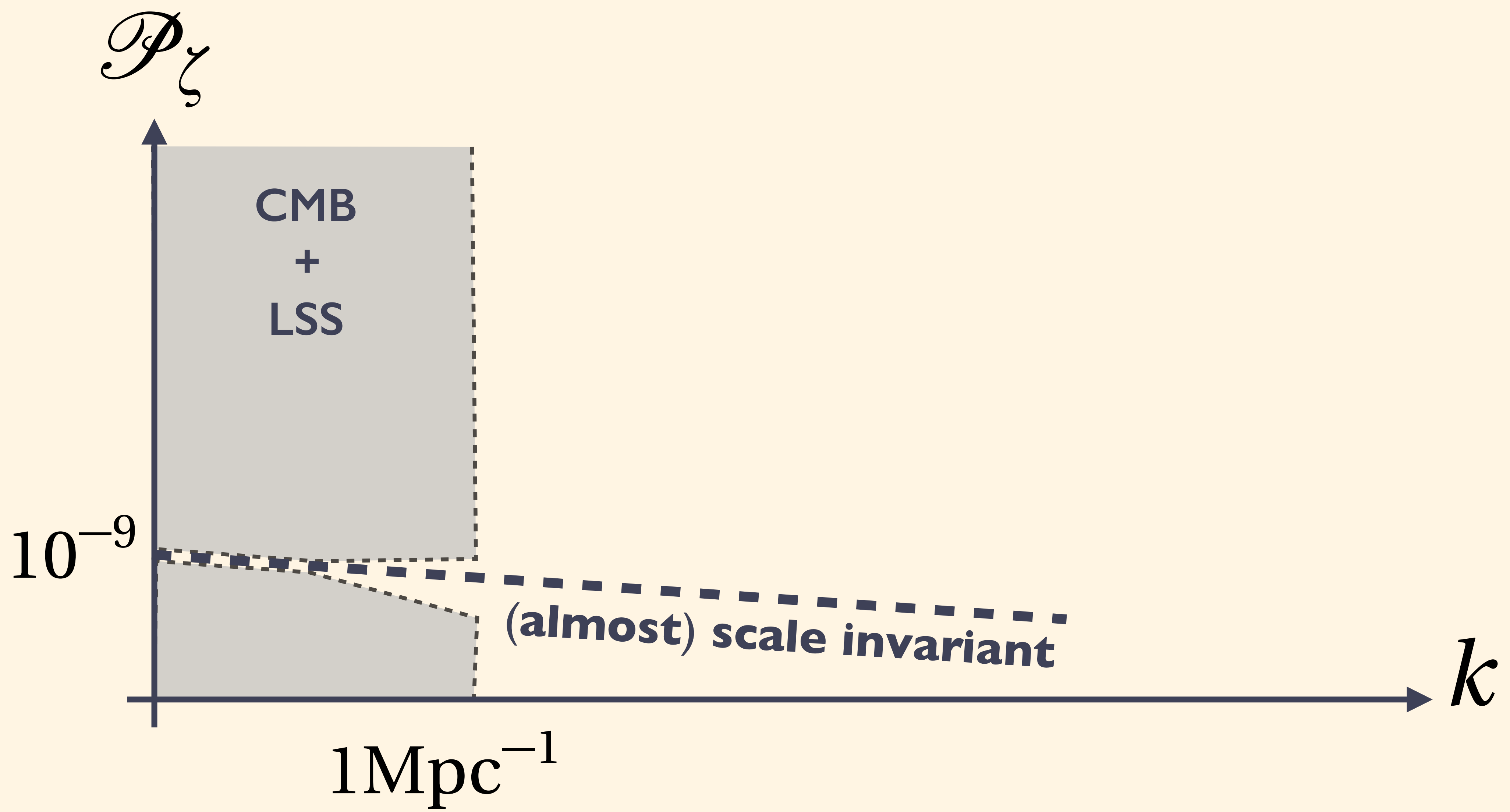
Enhanced Curvature Perturb.

Constraints on the **Power spectrum** (**P**ζ)



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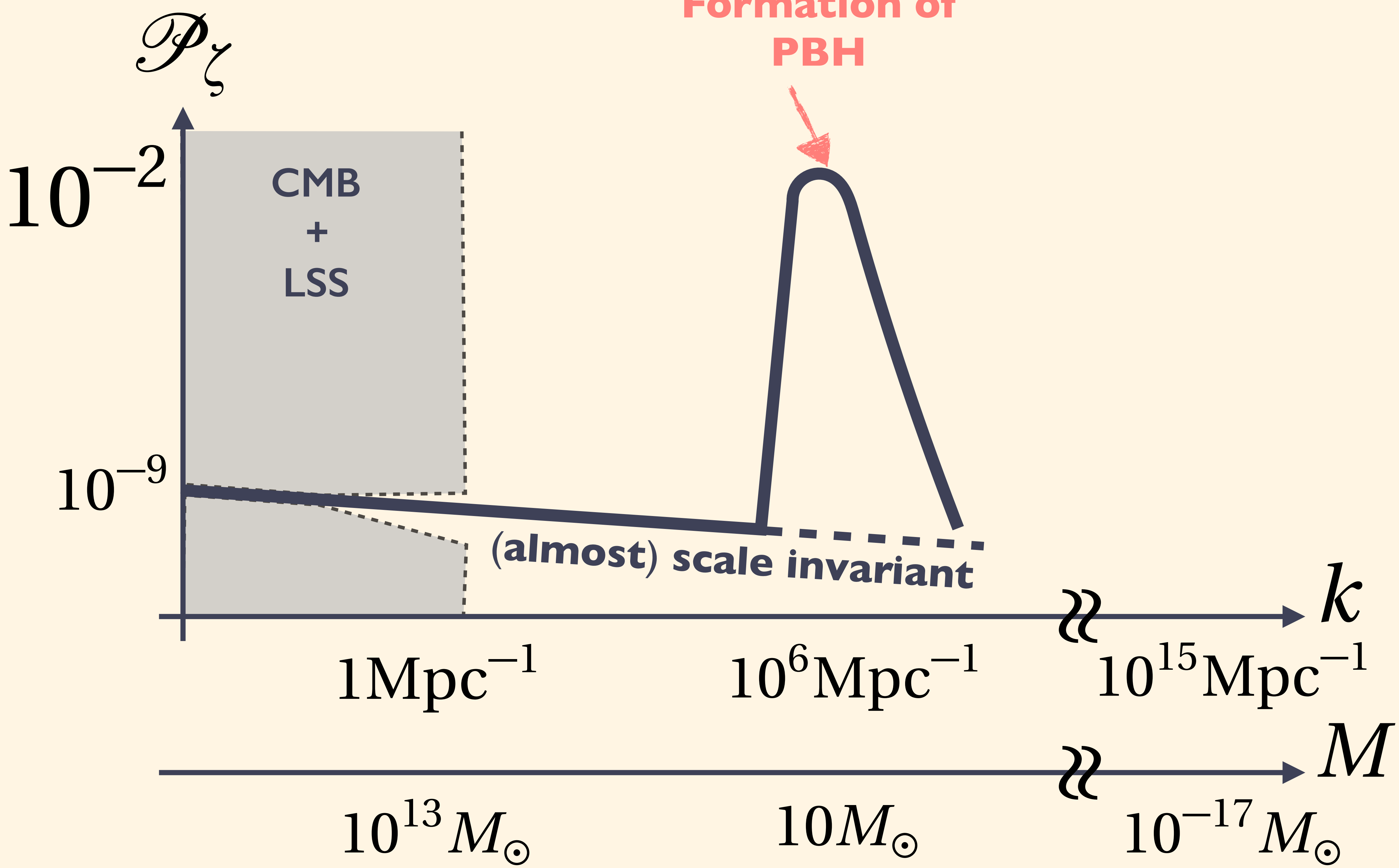

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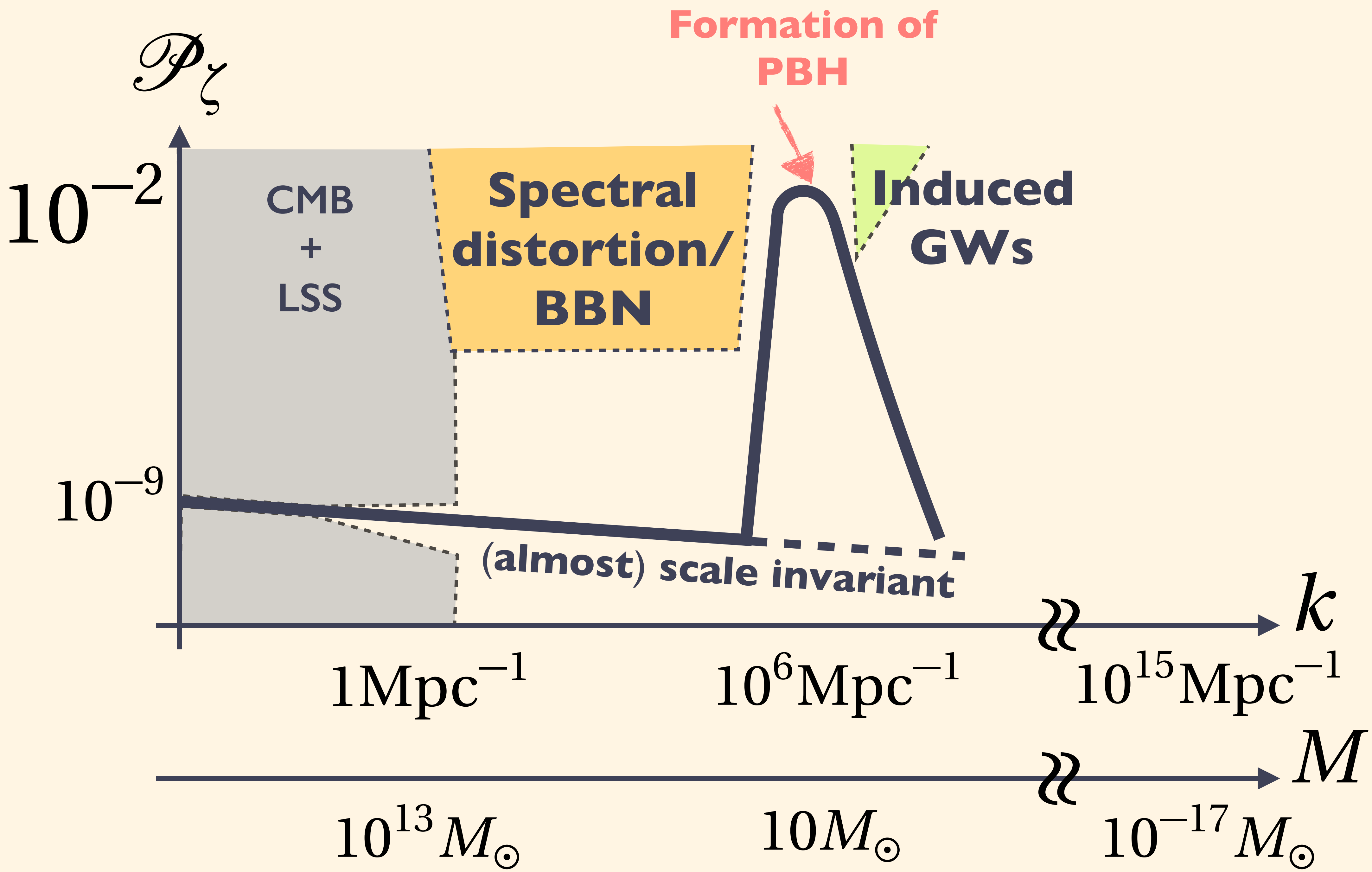

Spectral distortion/BBN

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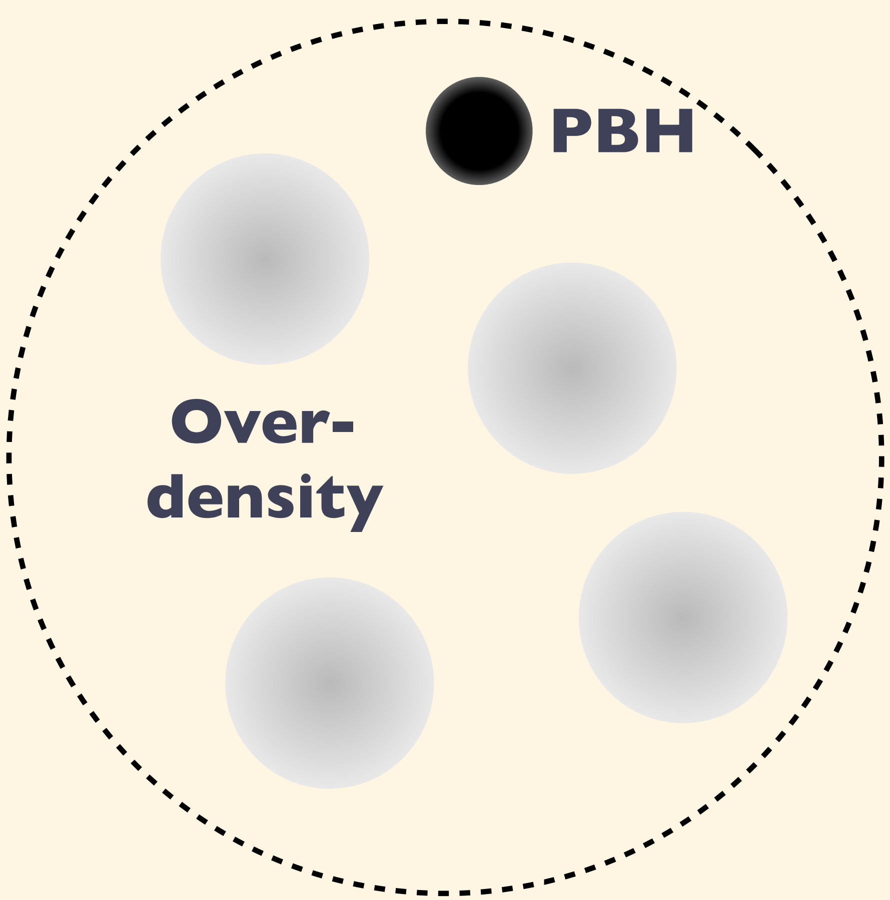

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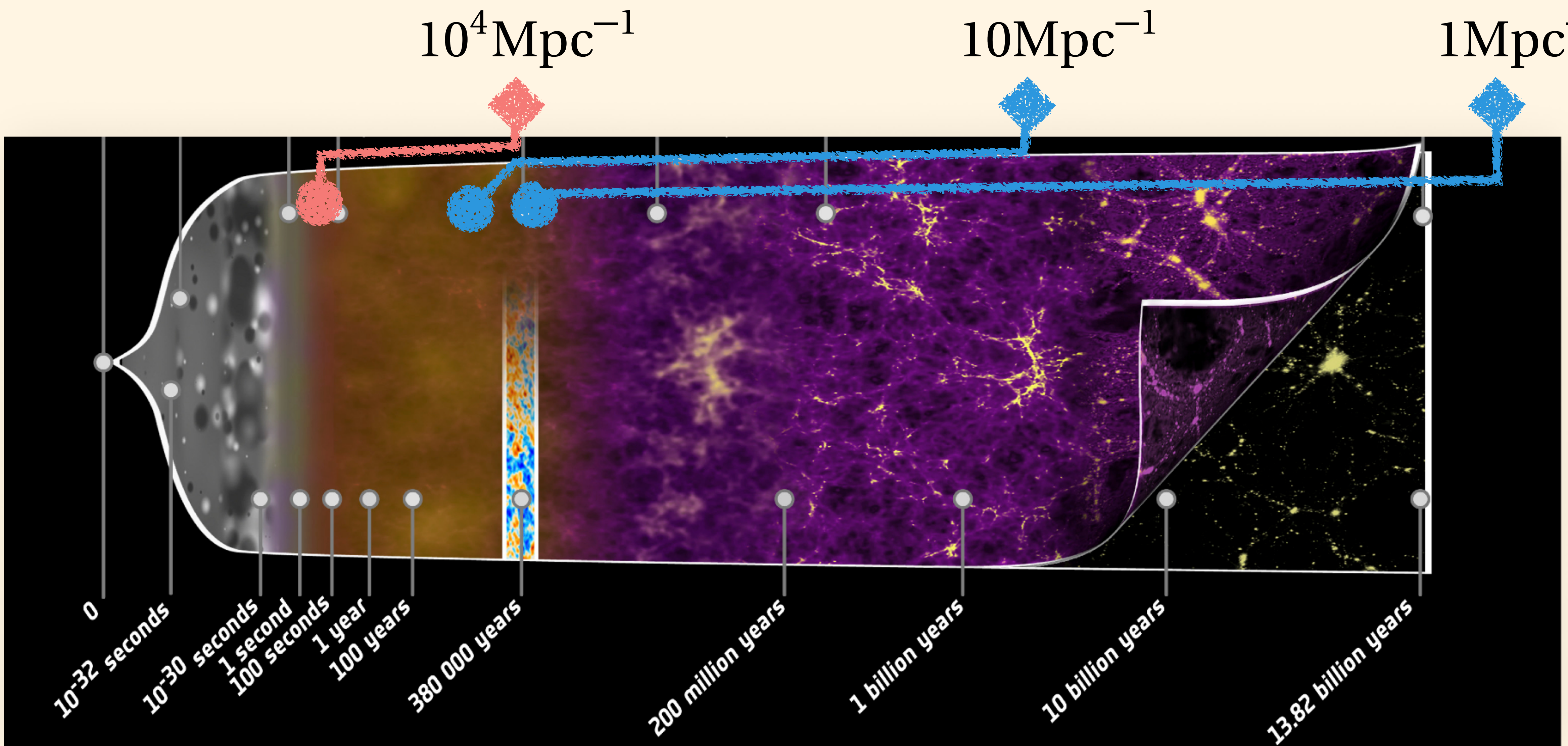
- How are they dissipated among background? → **Depends on Era.**



Spectral distortion/BBN

Black-Body

- **Energy/#**-changing

$$e+\gamma \longleftrightarrow e+2\gamma$$

$$e+X \longleftrightarrow e+X+\gamma$$

μ-distortion

- **Energy**-changing

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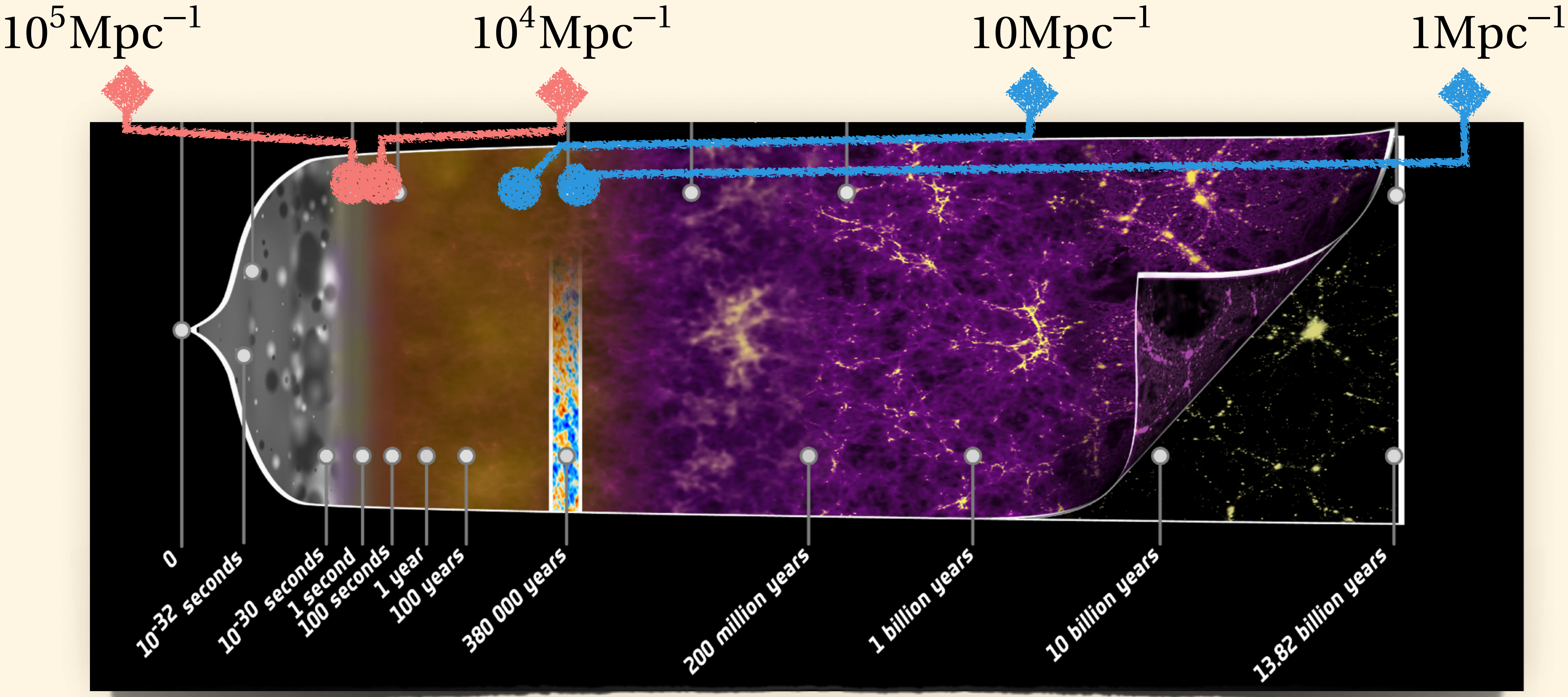
y-distortion

- **Thomson** scat.

$$e+\gamma \longleftrightarrow e+\gamma$$

(**Elastic** Compton)



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- neutron-to-proton ratio
  Jeong+1403.3697; Inomata+1605.04646

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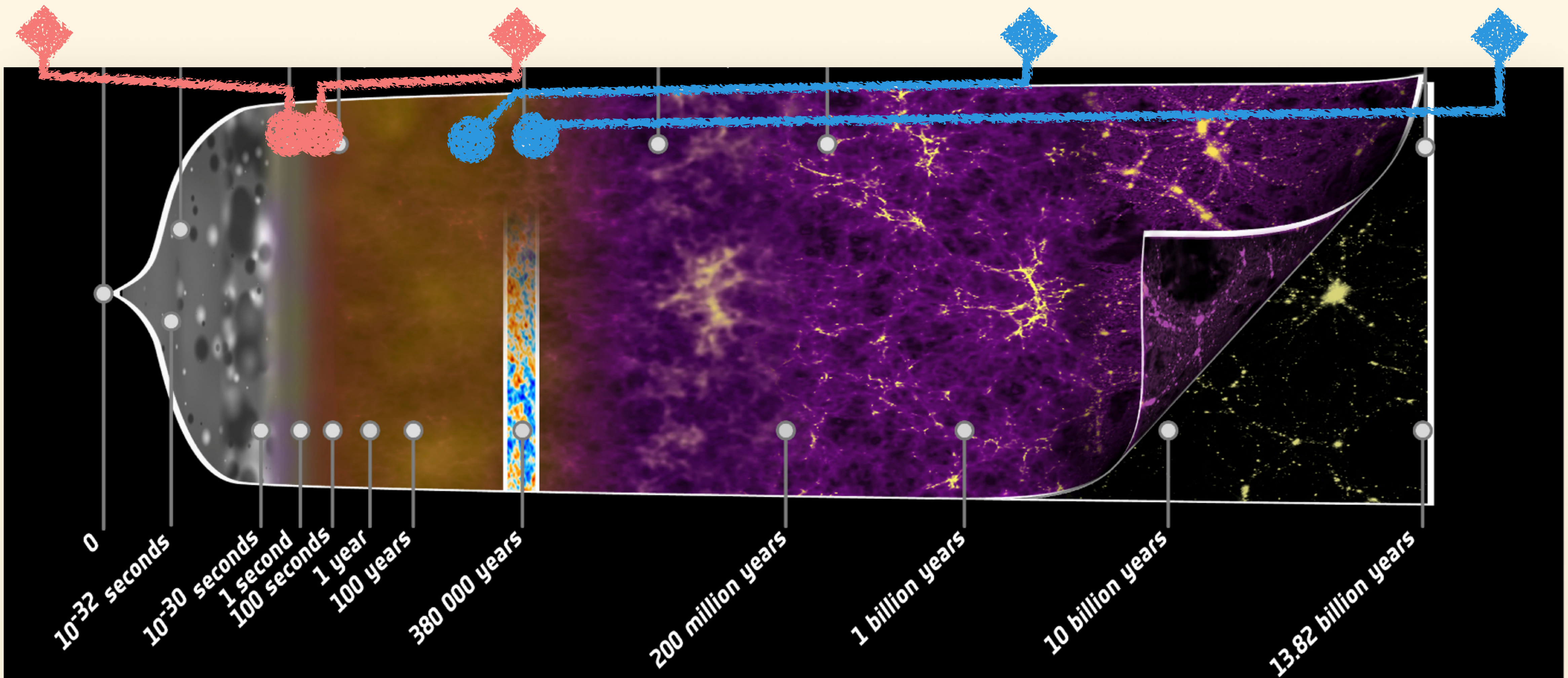

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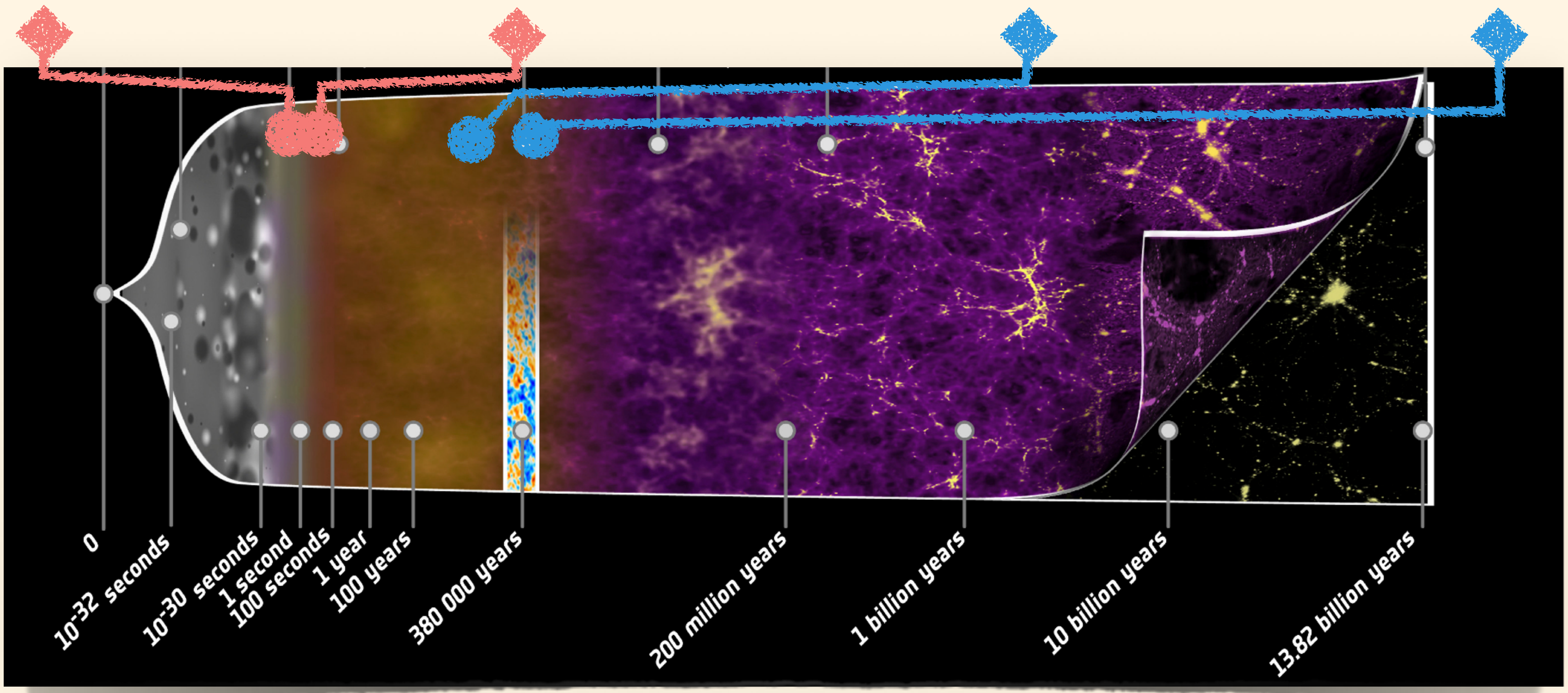

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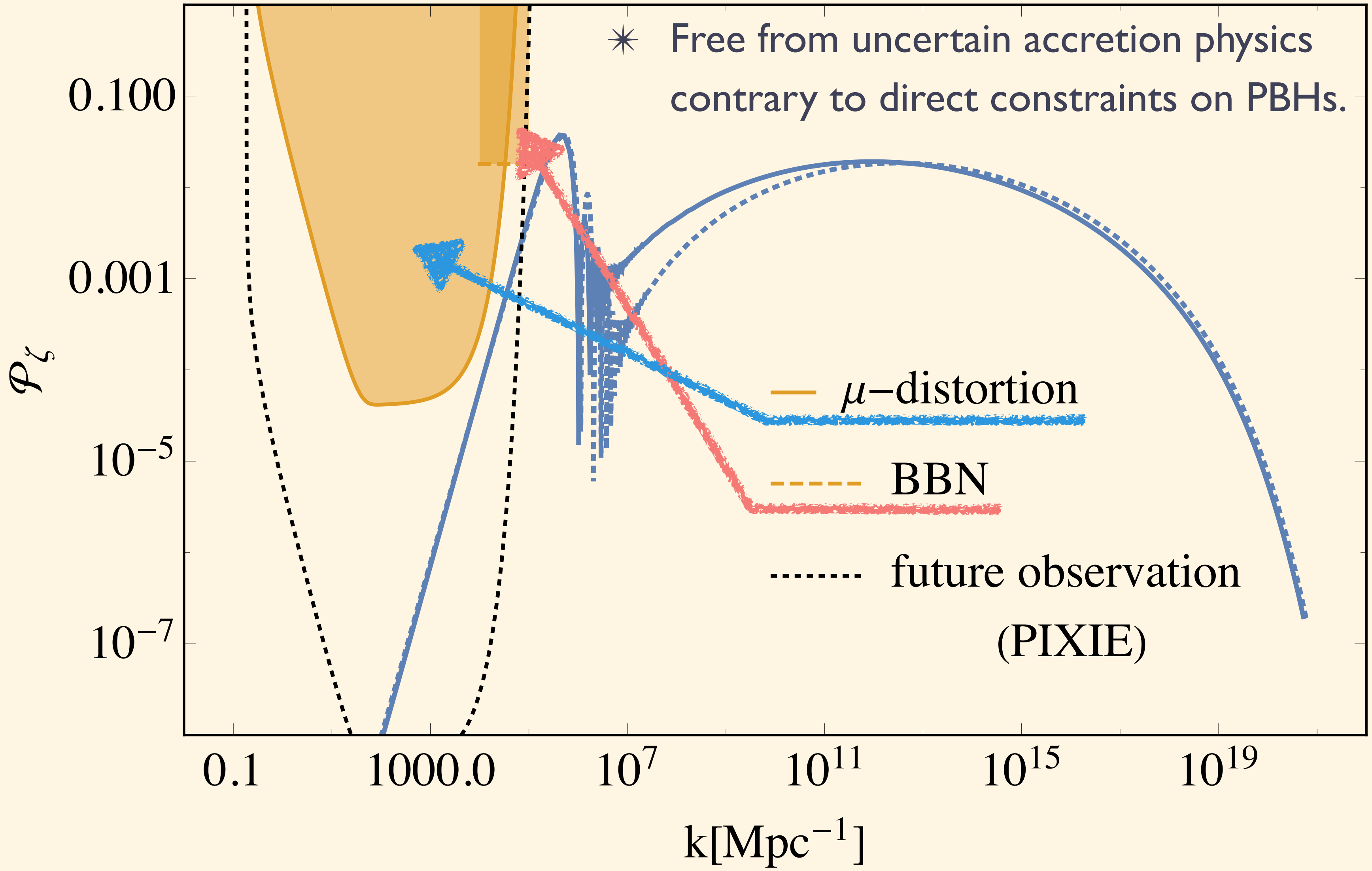

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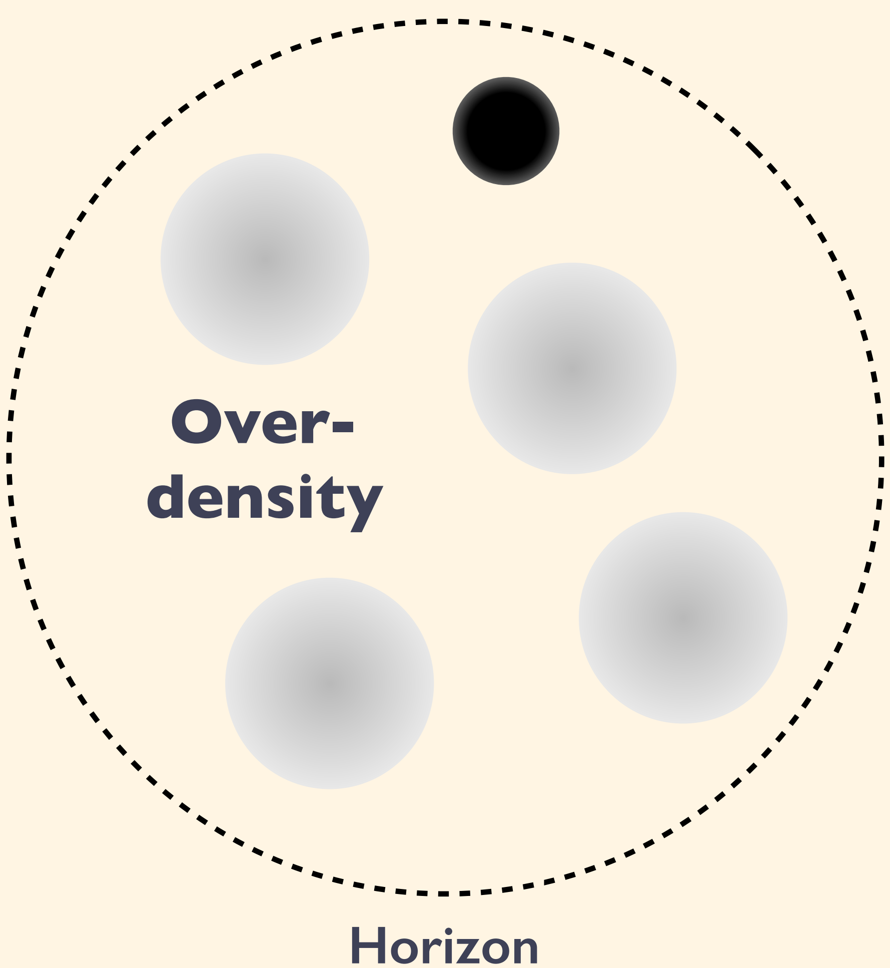

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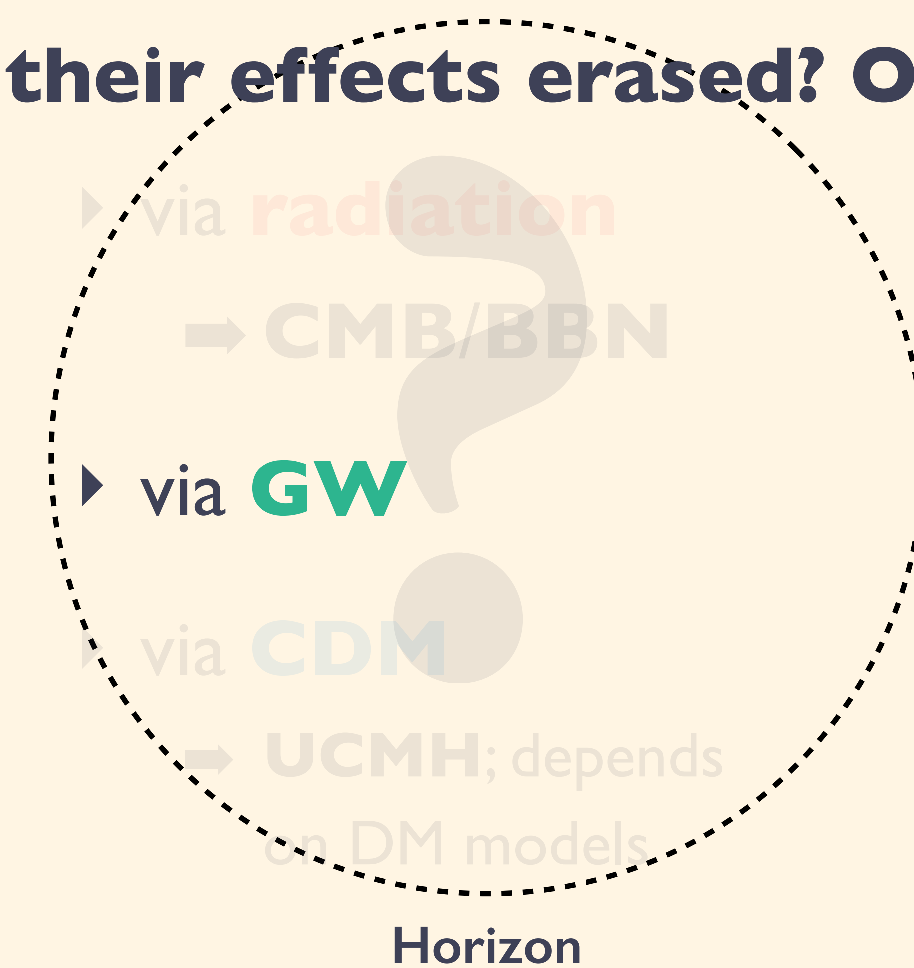

Induced GWs

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.**, **Ψ~ζ**

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

Production of GW by second order effects

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

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

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

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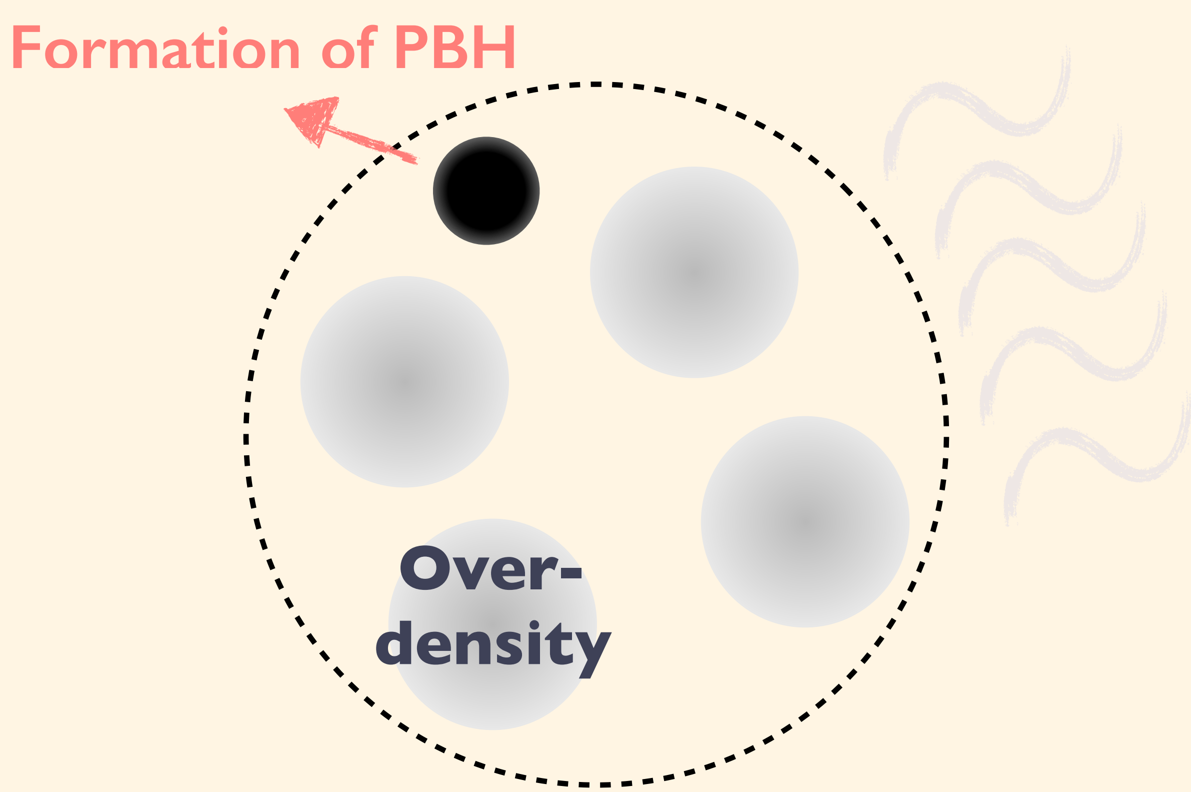

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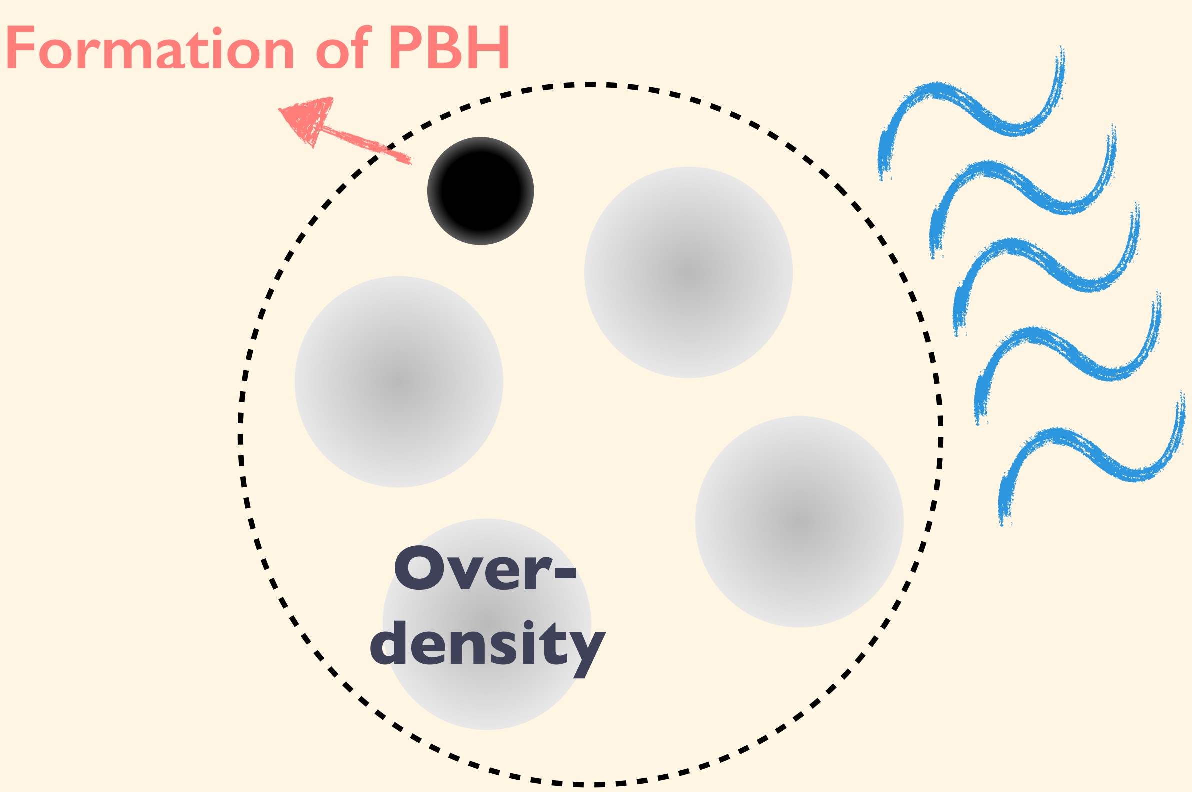
Depends on the **density perturb.**, $\Psi \sim \zeta$

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



Production of GW by second order effects

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

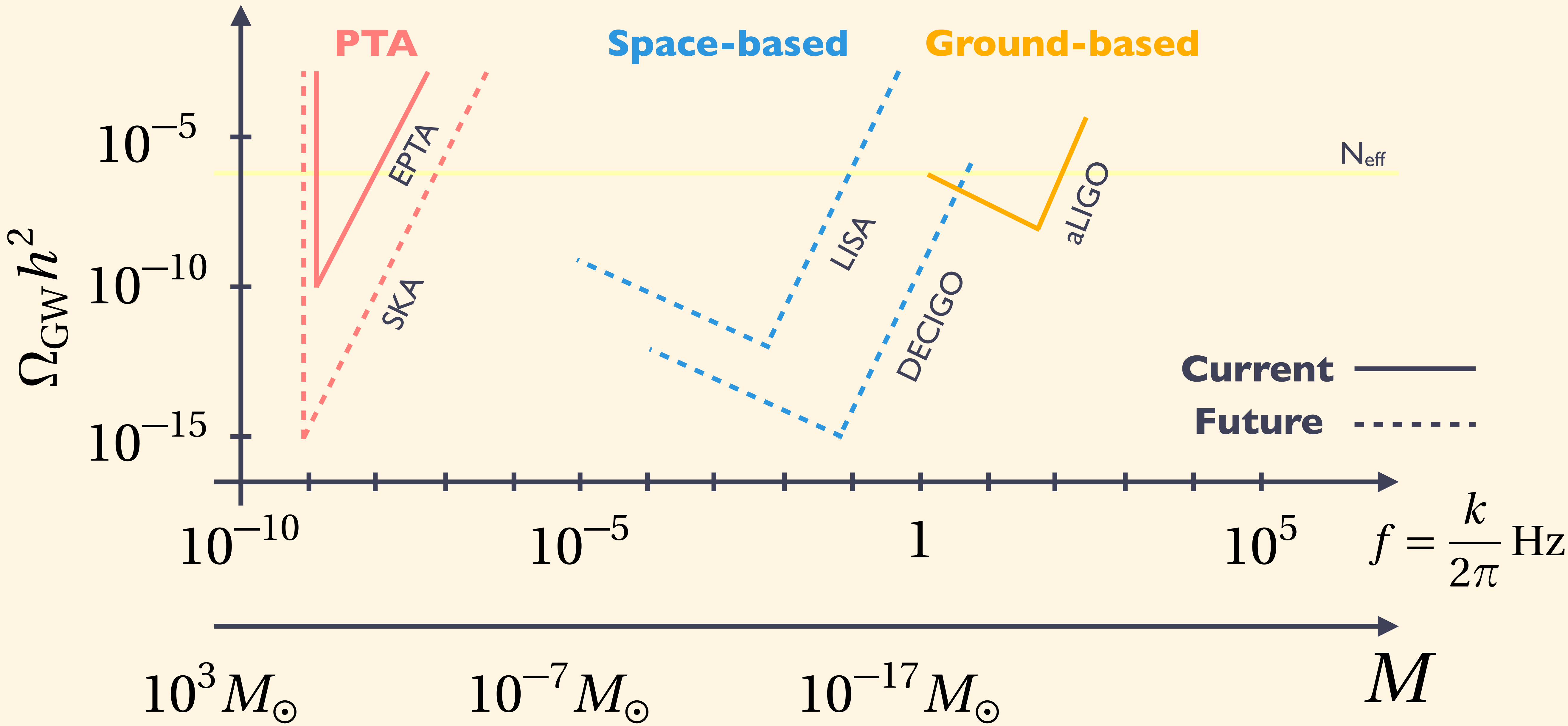
$$\Omega_{\mathrm{GW}}(k)h^2 \sim 10^{-9}\left(\frac{\mathcal{P}_\zeta(k)}{10^{-2}}\right)^2$$

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

Induced GWs

Large density perturbation as a source of **GWs**

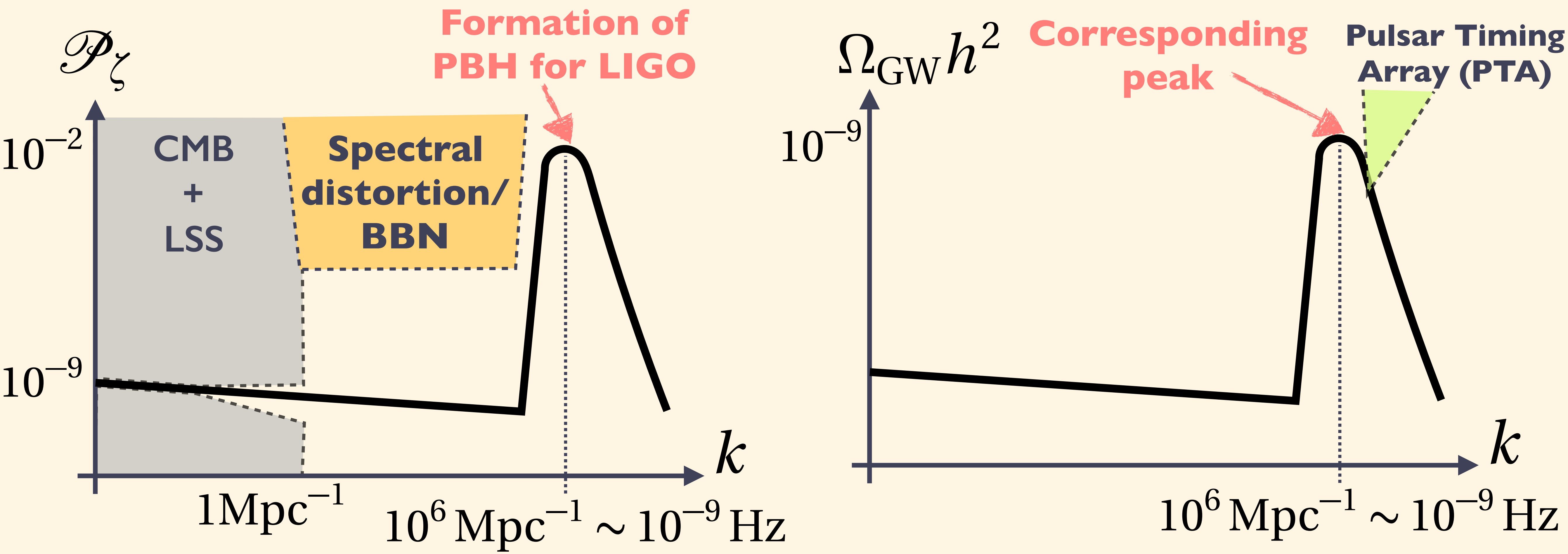
- Current and future observations of GWs



Induced GWs

Large density perturbation as a source of **GWs**

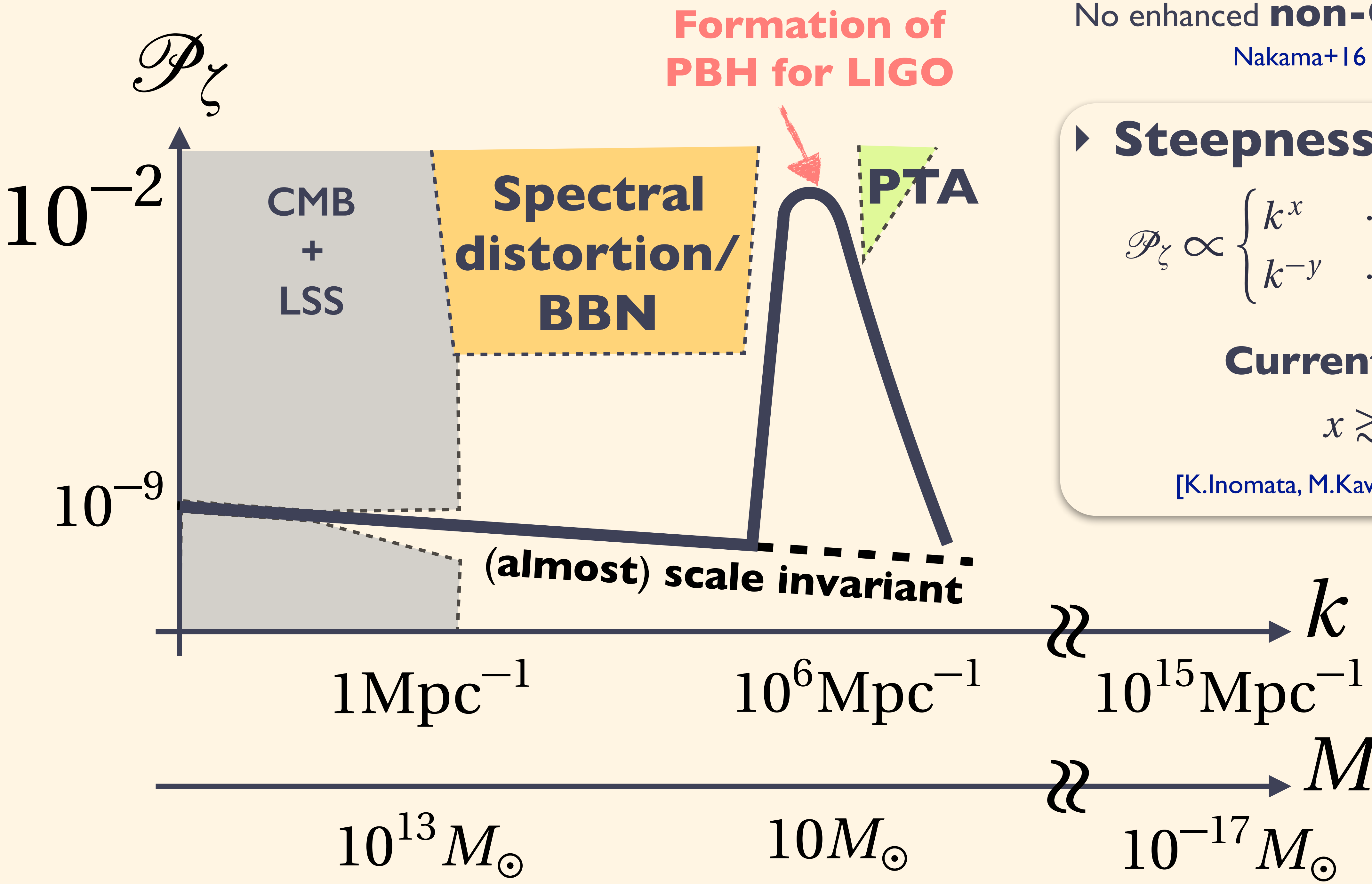
- GW has a **corresponding peak at the same k**.



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

Enhanced Curvature Perturb.

Constraints on the **Power spectrum** (P_ζ)



No enhanced **non-Gaussianity**.
Nakama+1612.06264, 1710.06945

- **Steepness** of the spectrum

$$\mathscr{P}_\zeta \propto \begin{cases} k^x & \cdots\ k < k_{\rm peak} \\ k^{-y} & \cdots\ k > k_{\rm peak} \end{cases}$$

Current constraints

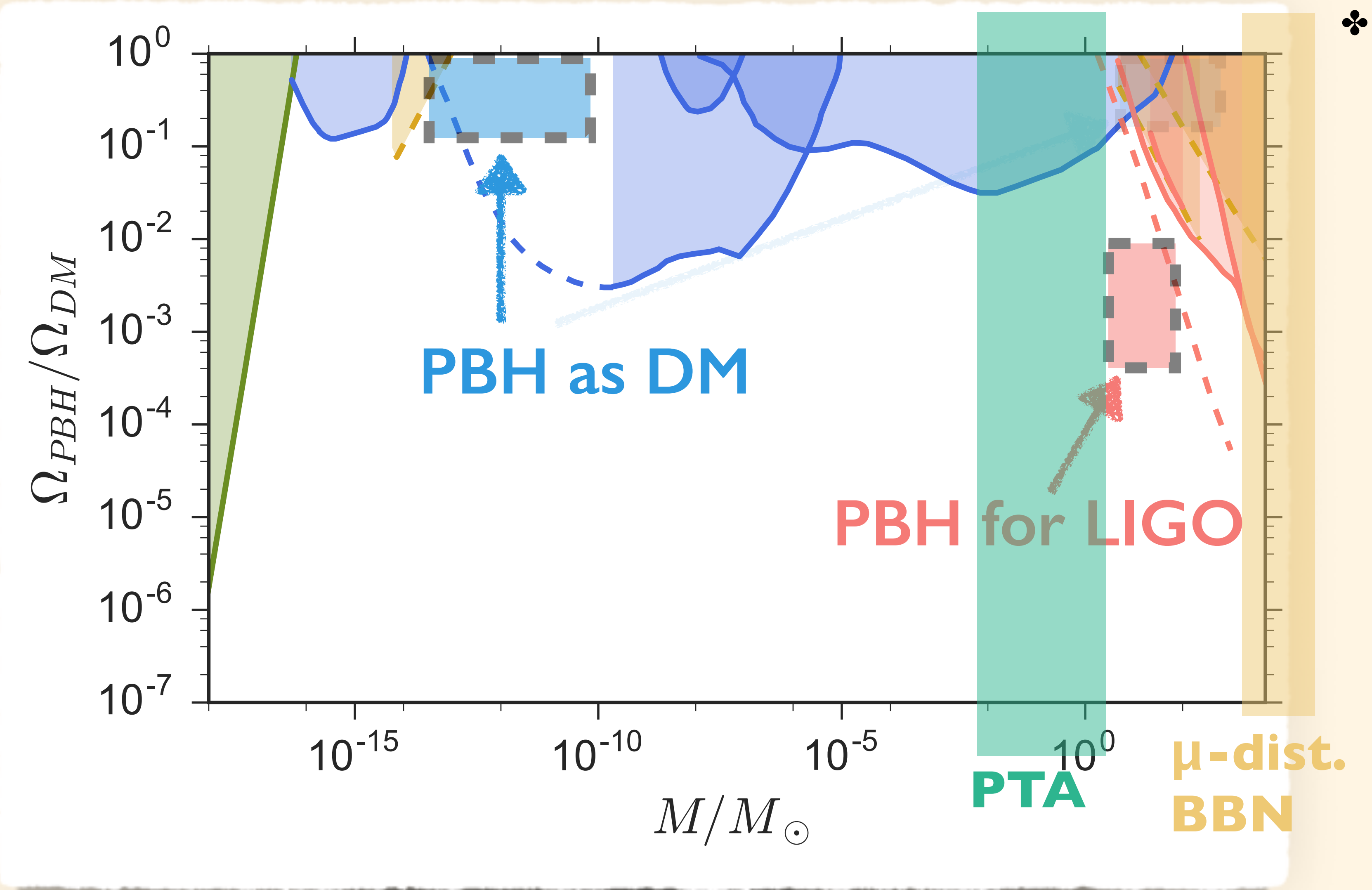
$$x \gtrsim 1.5,\ \ y \gtrsim 2$$

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

Current Constraints

Constraints on **PBHs from inflation** (*misleading)

- PBH as **all DM**: marginal, but still viable. No enhanced **non-Gaussianity**.
  Nakama+1612.06264, 1710.06945
- PBH for **LIGO events**: **marginal**, but still **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

EGγ: 0912.5297

Gravitational lensing

Femto: 1204.2056

HSC: 1701.02151

Kepler: PhysRevLett.111.181302

EROS/MACHO/OGLE: 0011506, 0607207, 1106.2925

Dynamical

WD: 1505.04444

UFD: 1605.03665, 1704.01668

Accretion

CMB: 1612.05644,1707.04206,…

Radio/Xray: 1612.00457, **1705.00791**

Talk by Y. Inoue

Outline of Talk

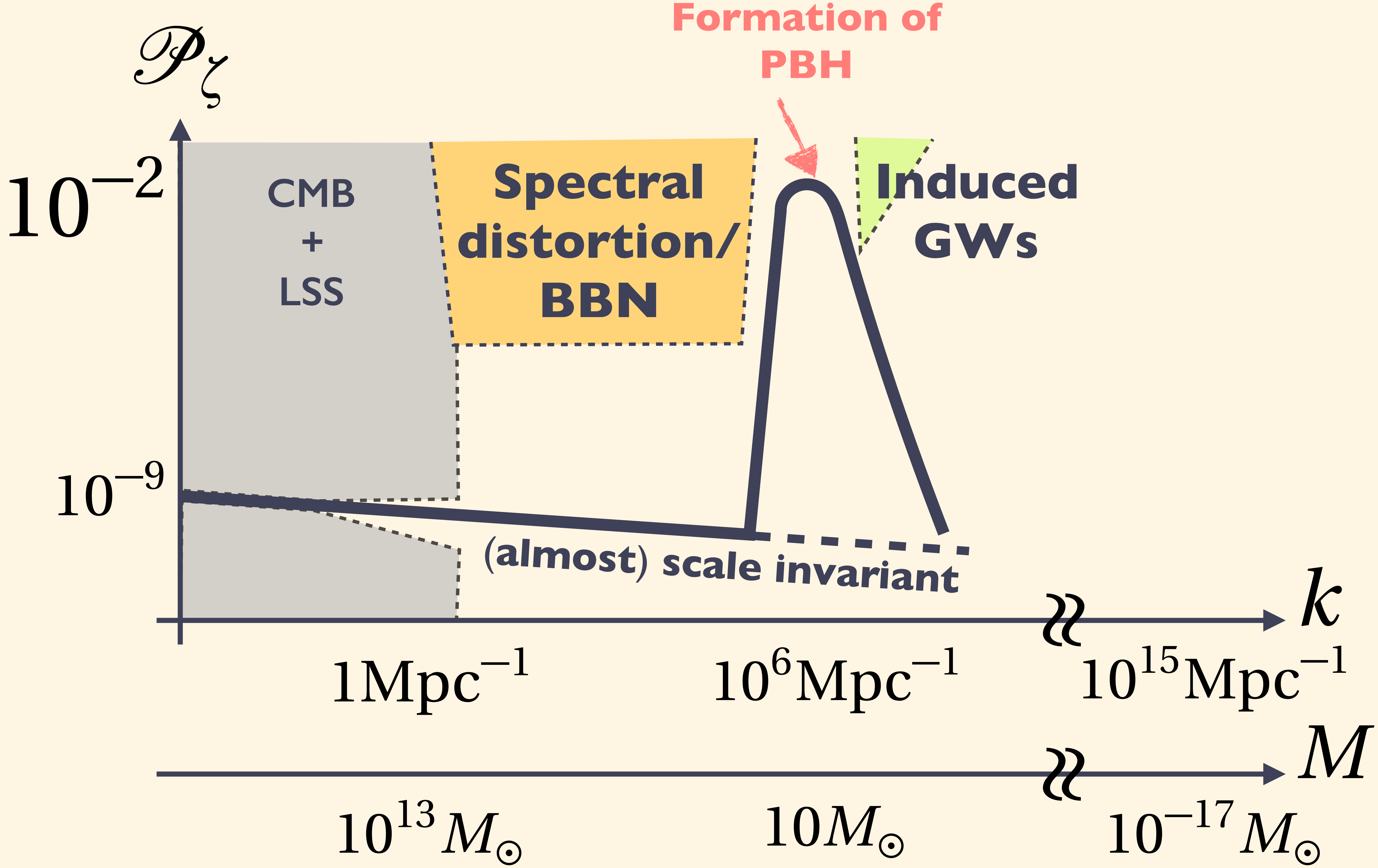
- Introduction
- Constraints on PBHs from Inflation
- Double inflation: PBHs for LIGO or DM
- Summary

3.

Double Inflation: PBHs for LIGO or DM

How to enhance P_ζ ?

Constraints on the **Power spectrum** (P_ζ)



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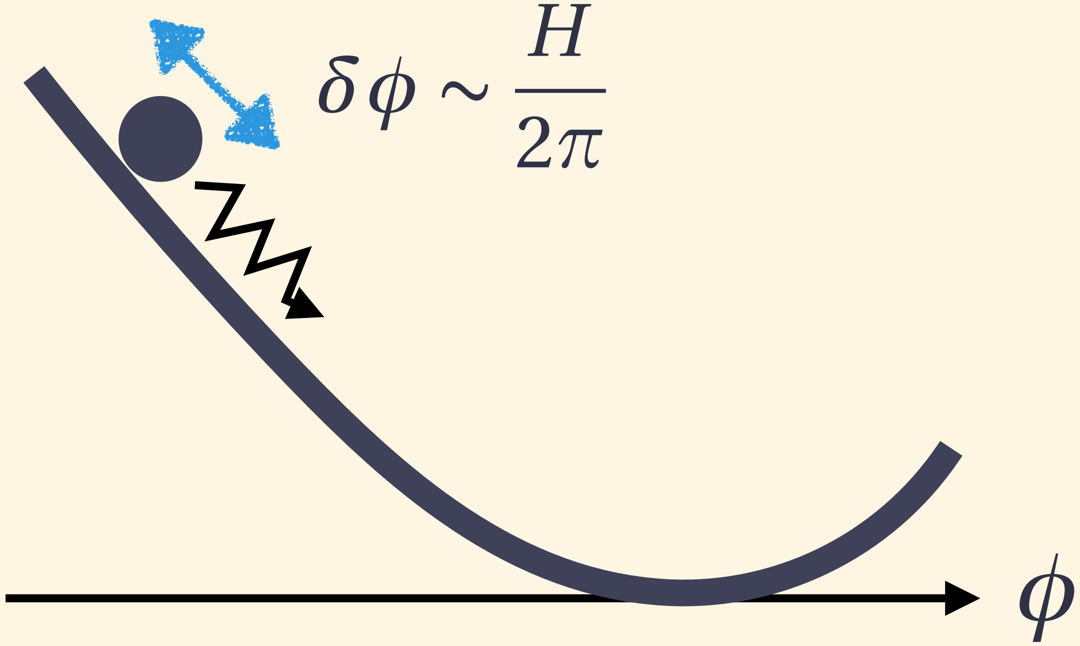
Flatten your potential

- Single-field inflation for the total e-folds of N = 50-60



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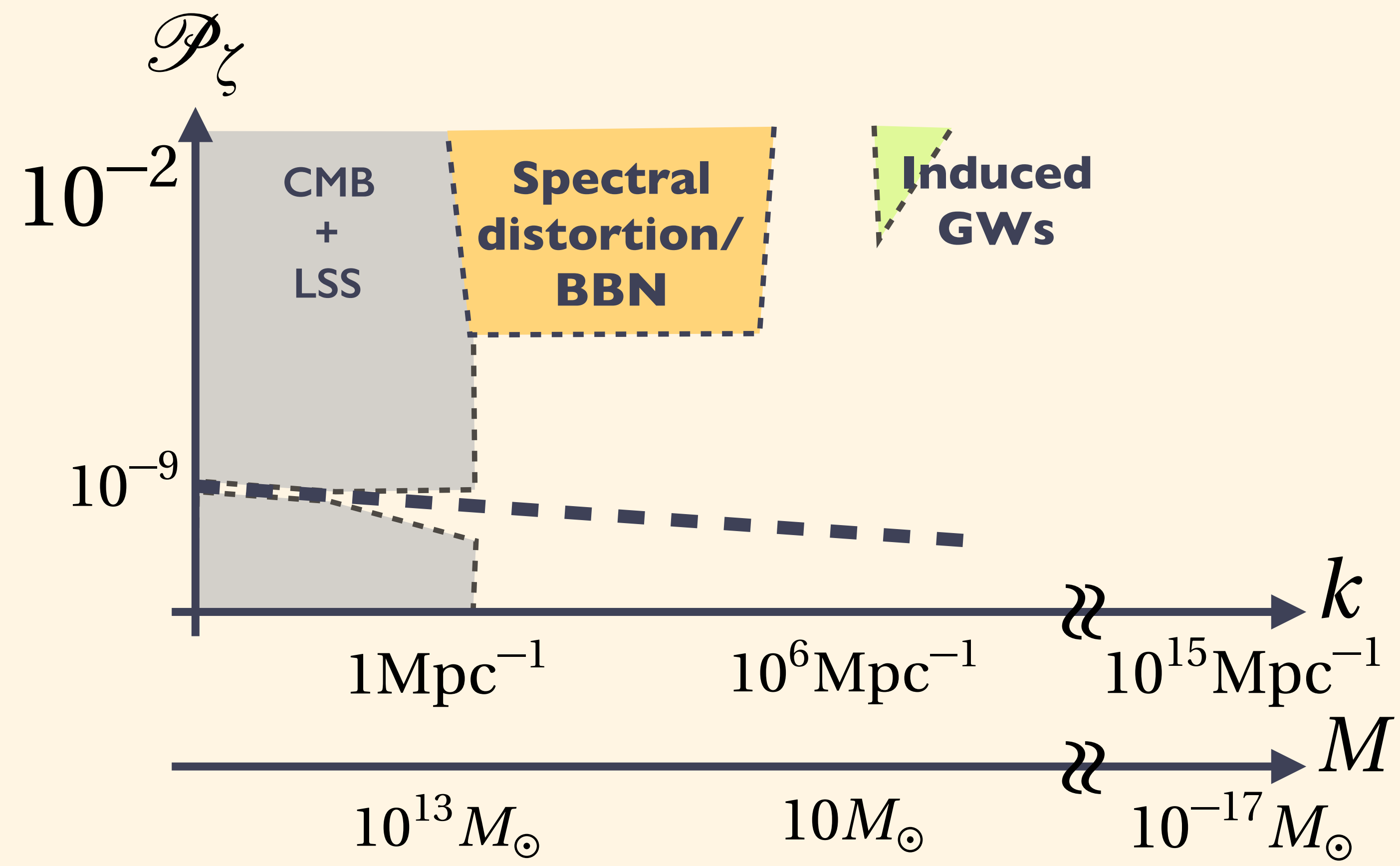

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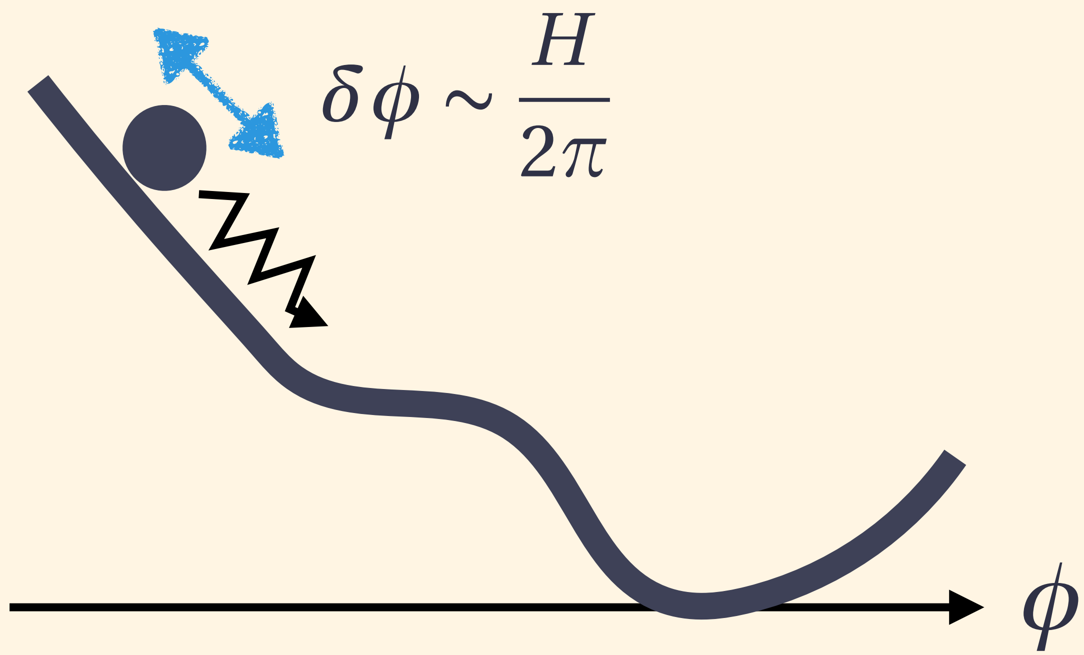

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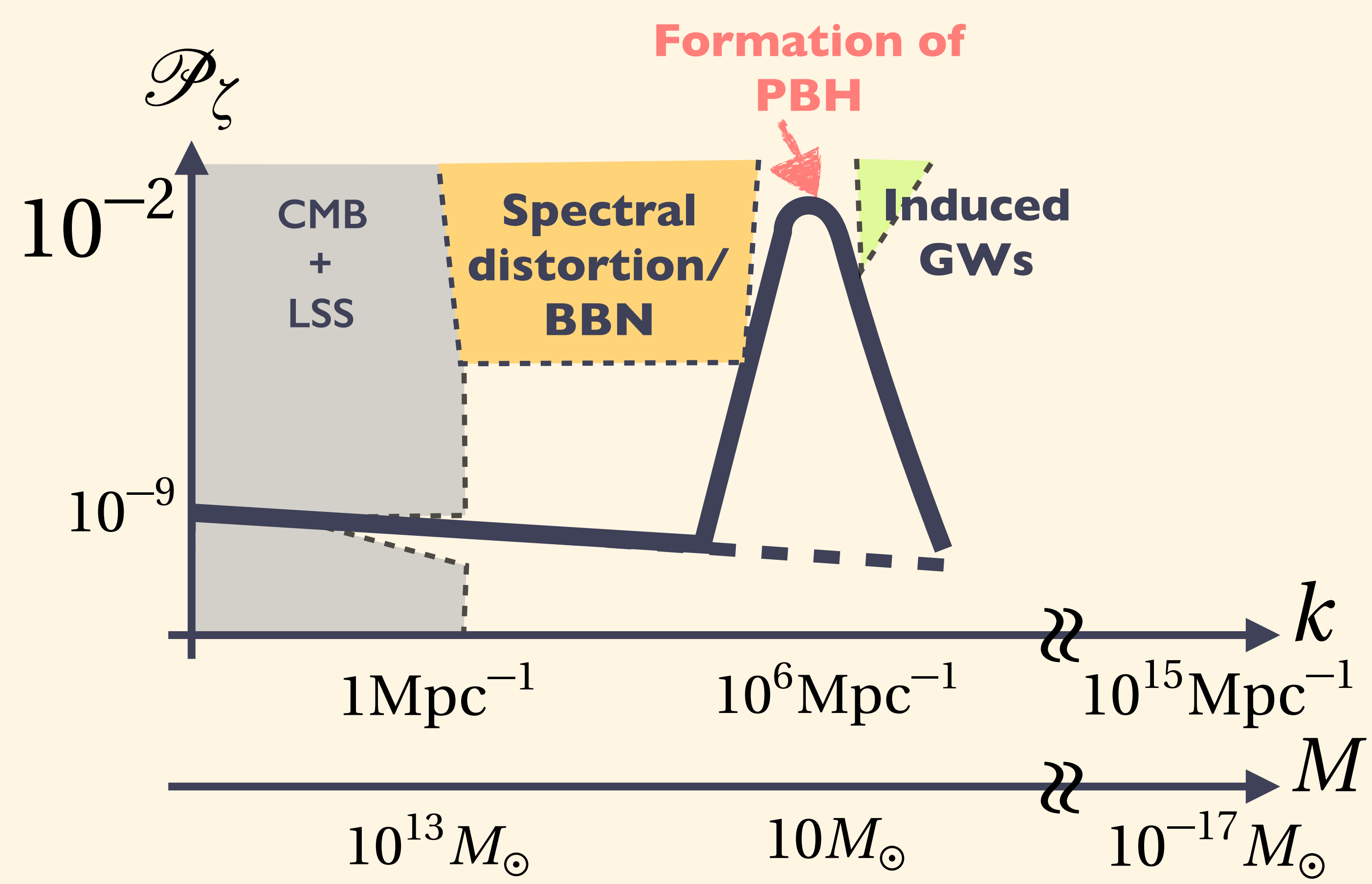

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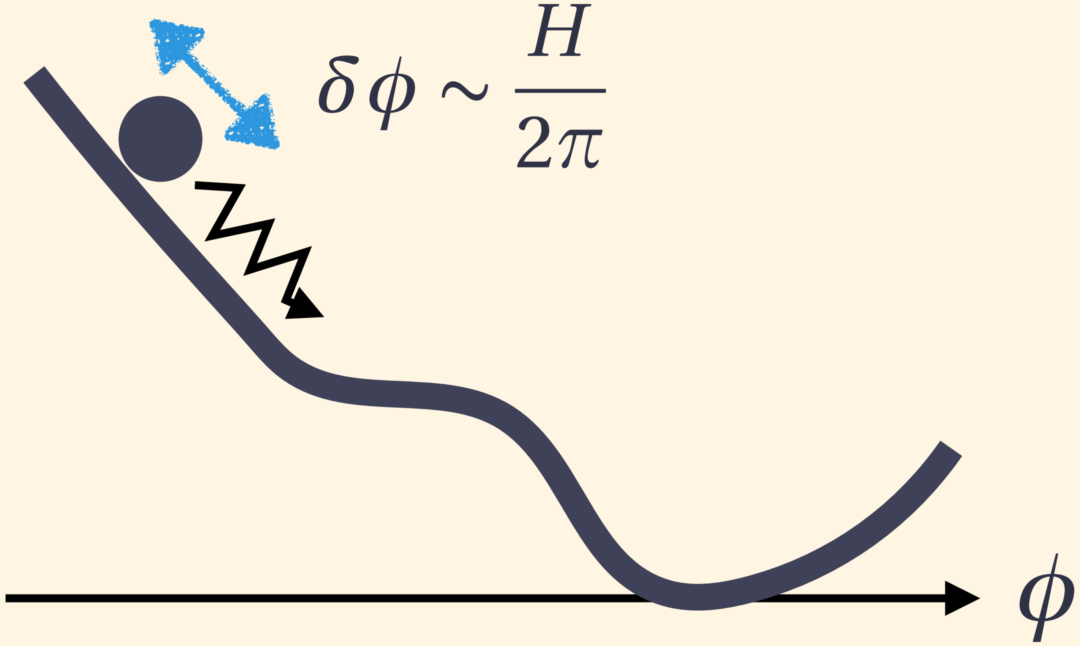
Slow-roll must be violated for PBHs with M > 10^{15} g.

Marginal slow roll violation → broad spectrum.



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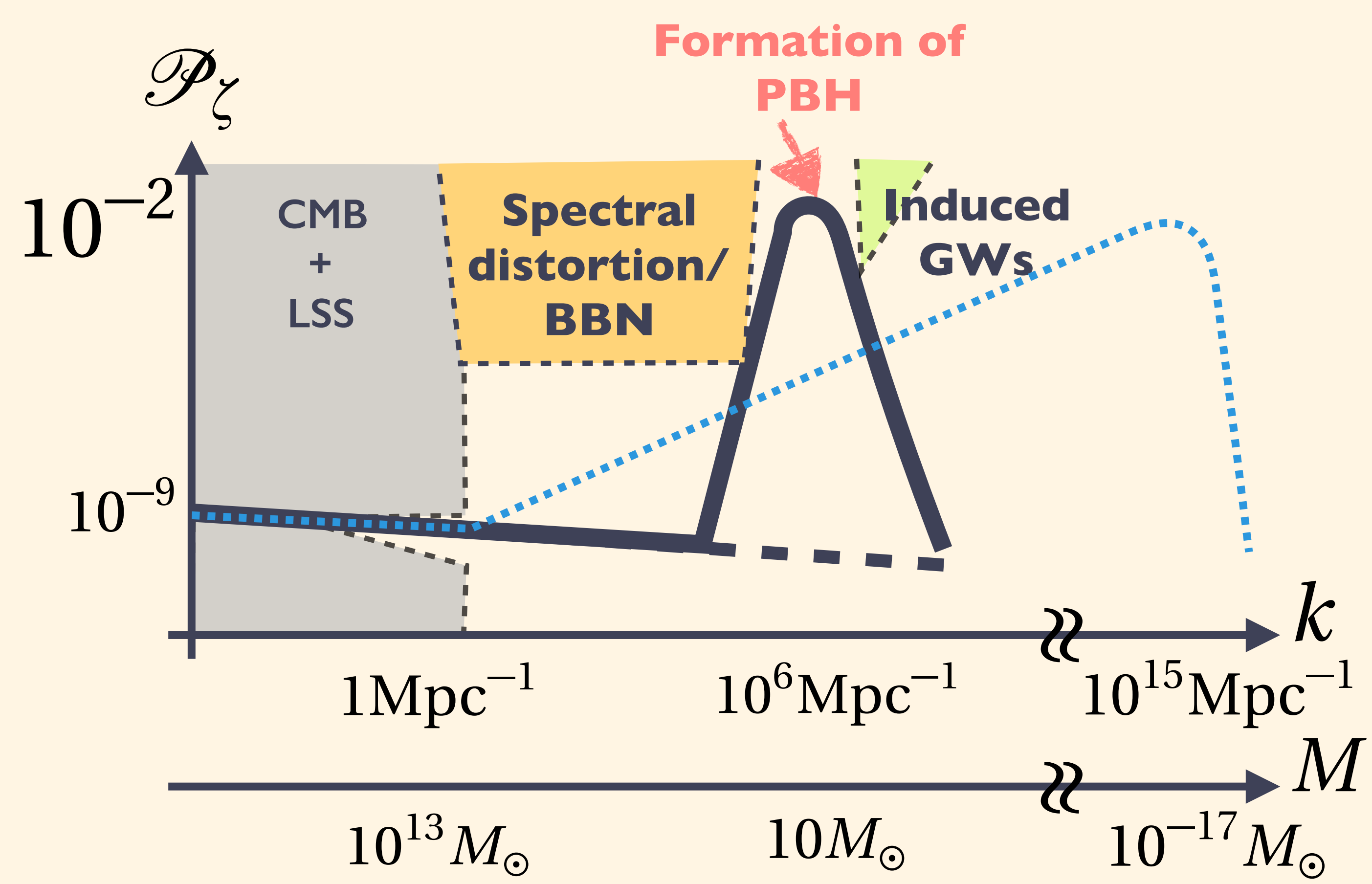

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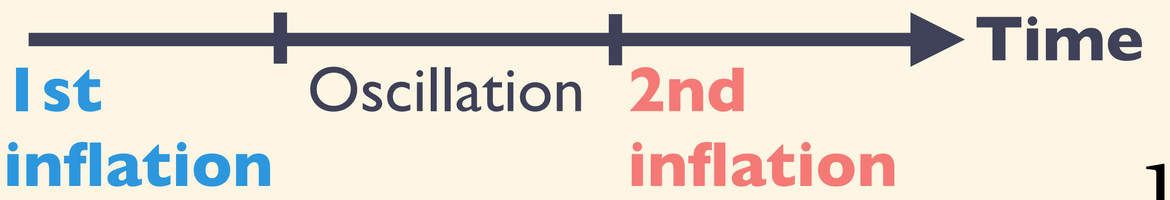

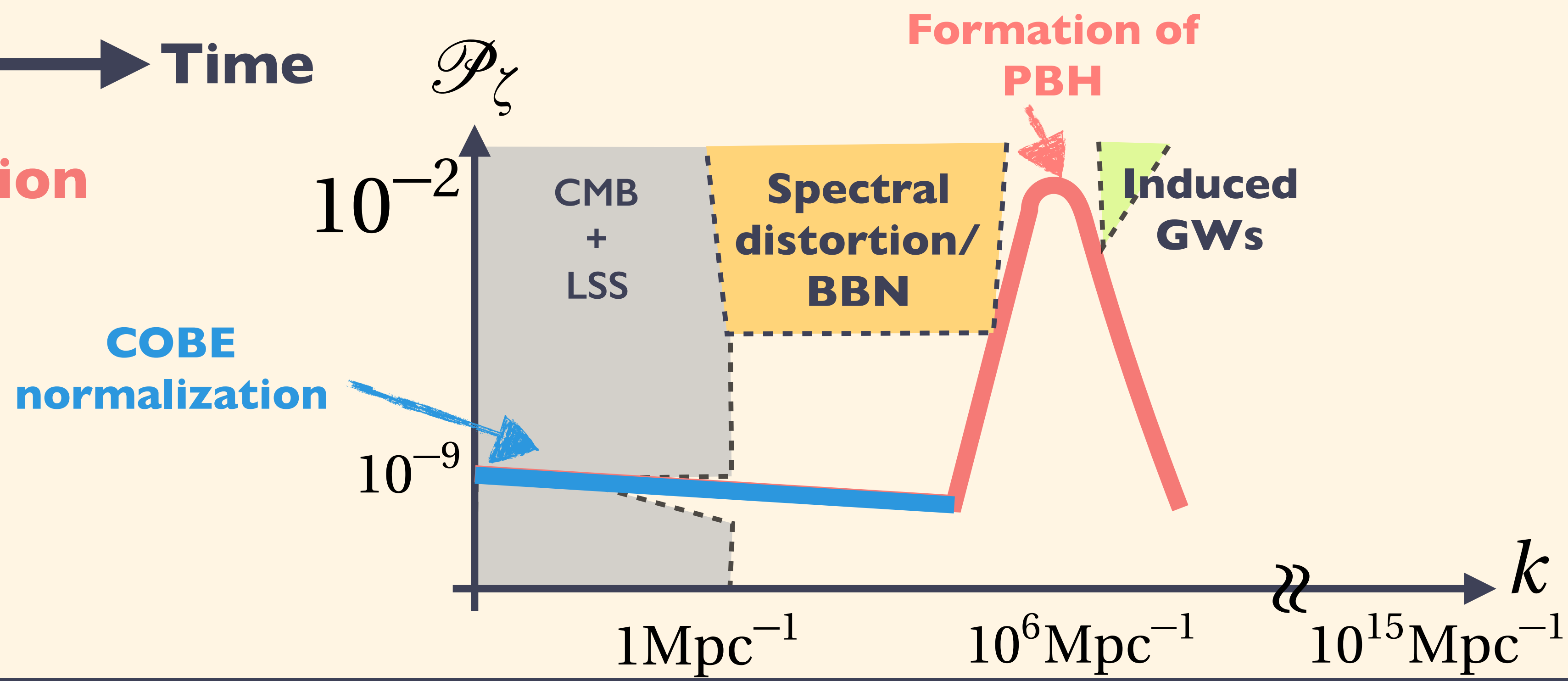

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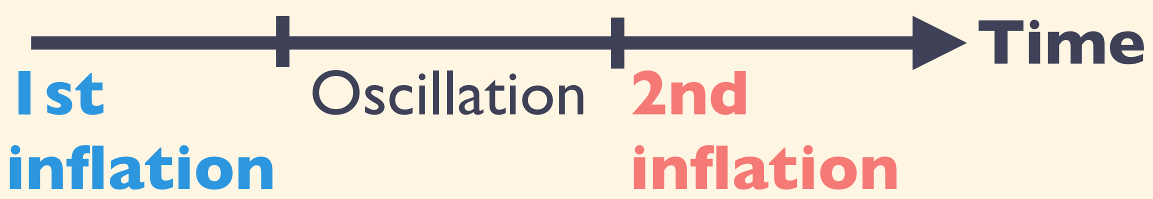

Slow-roll is strongly violated!

(cf.) Inflation landscape(?): many different vacua, inflations may take place @ each vacuum.

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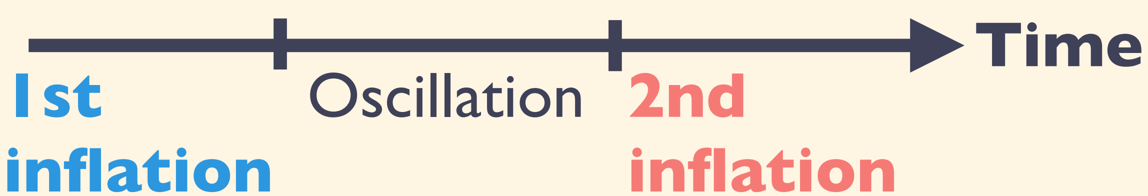

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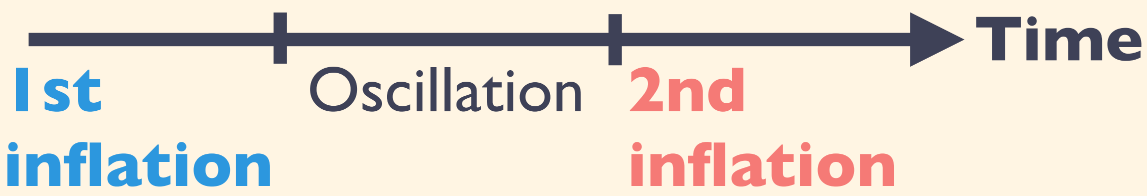

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PBHs for LIGO or DM from **Double Inflation**

- Total e-folds (N=50-60) = **1st-inflation** + **2nd inflation**

$$V(\varphi,\chi)=V_{\rm pre}(\chi)$$
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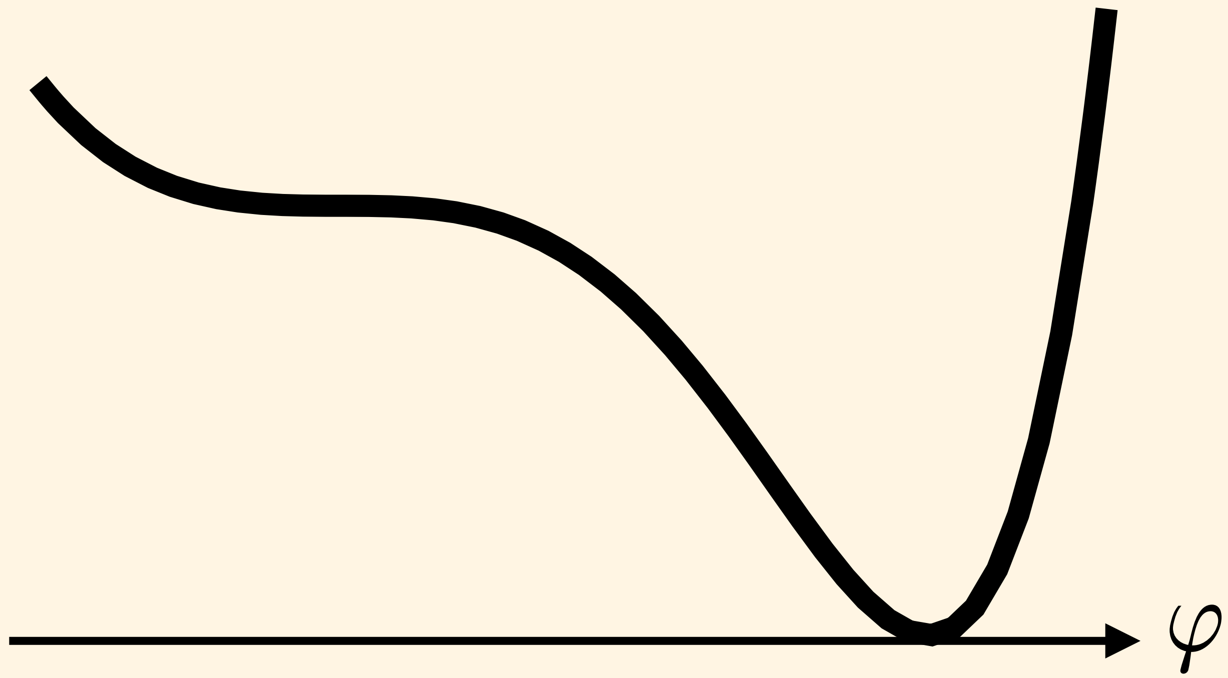

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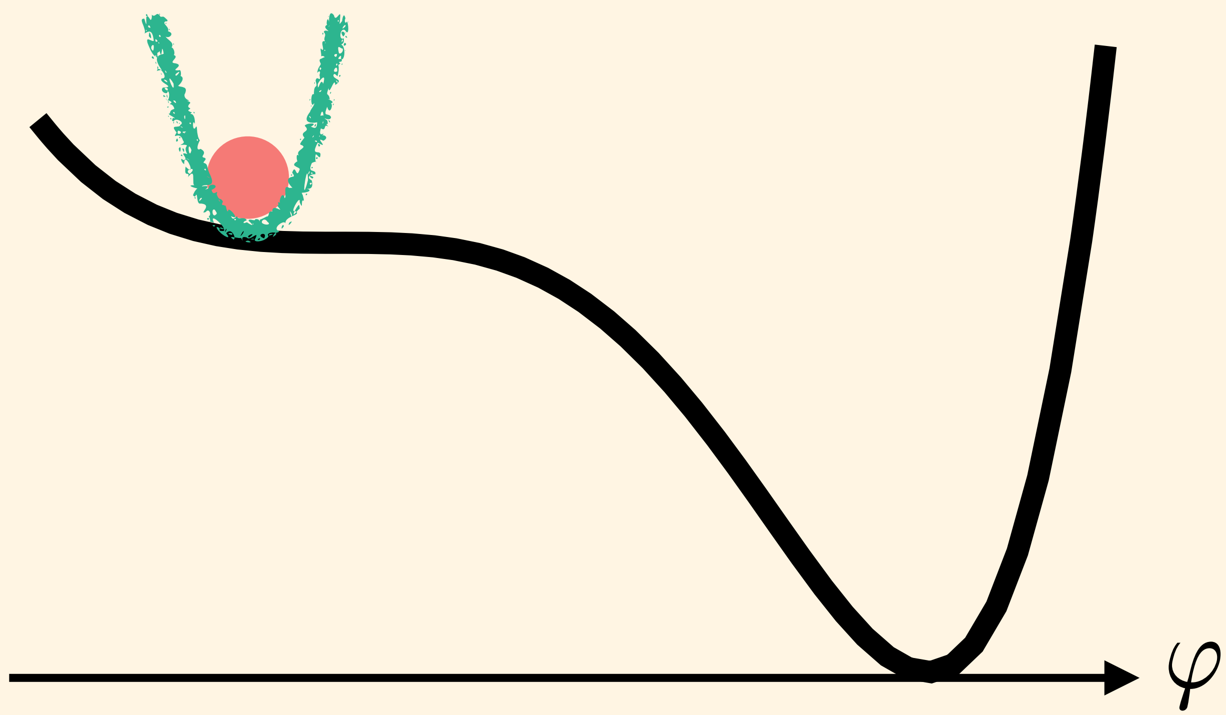
Hubble-induced mass



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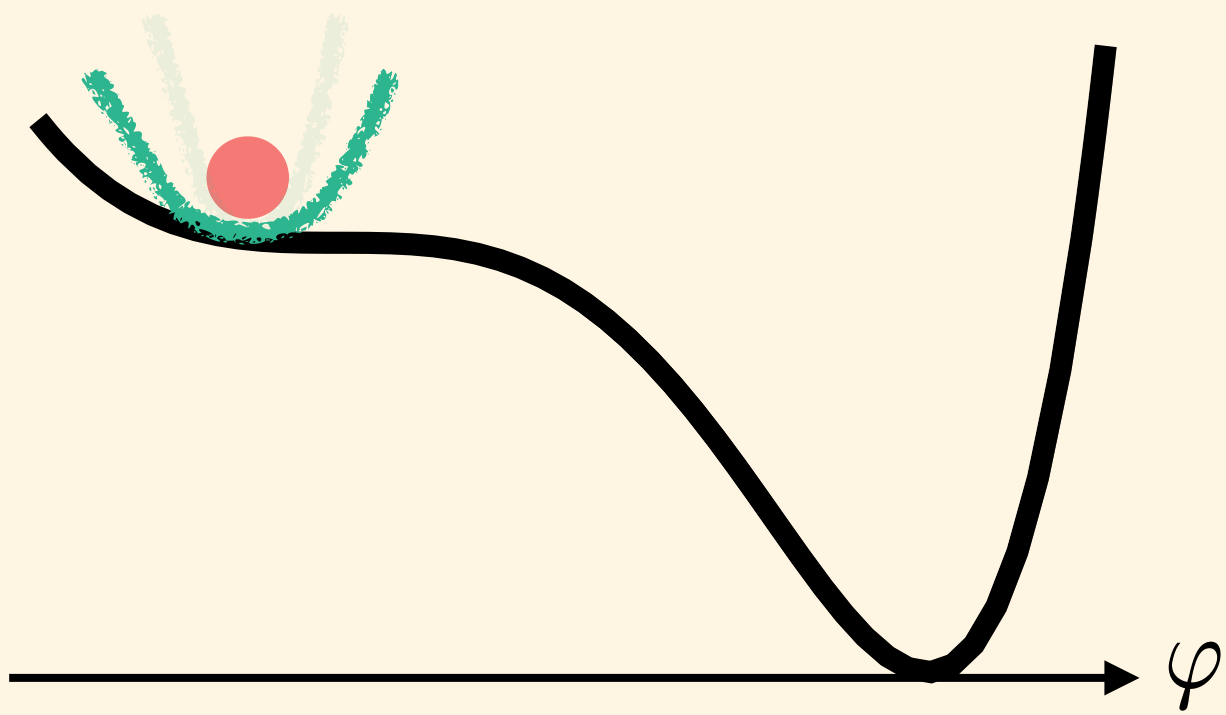

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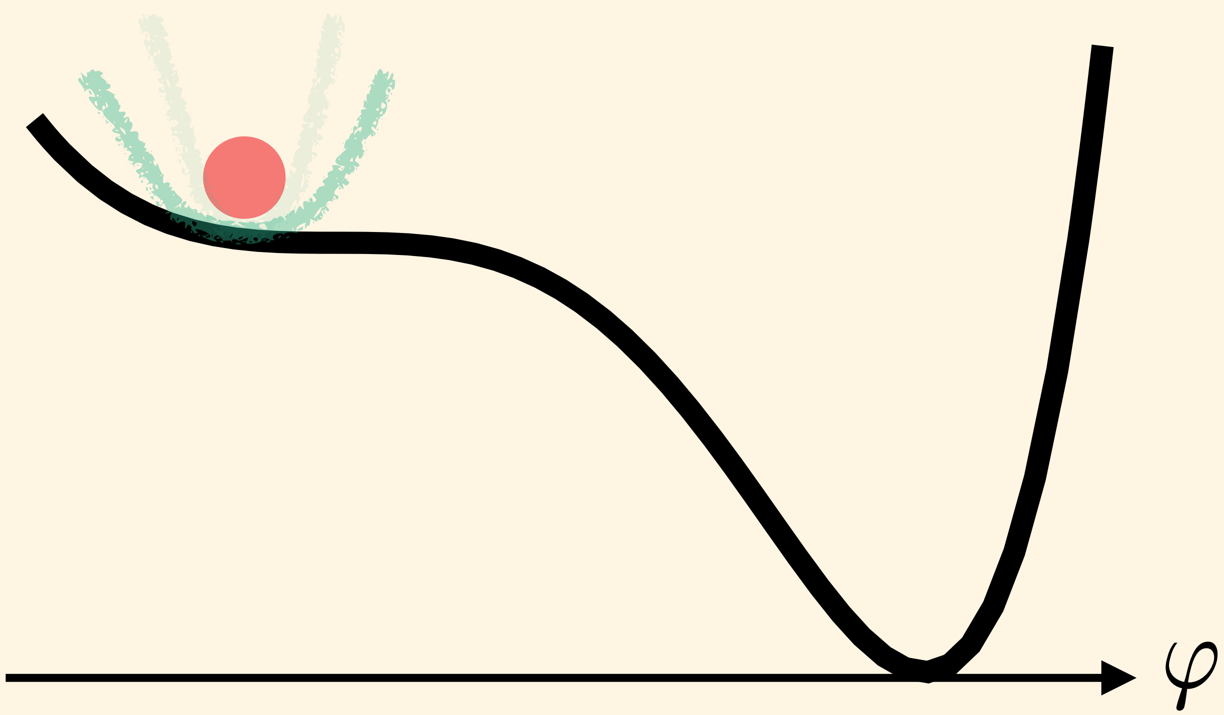

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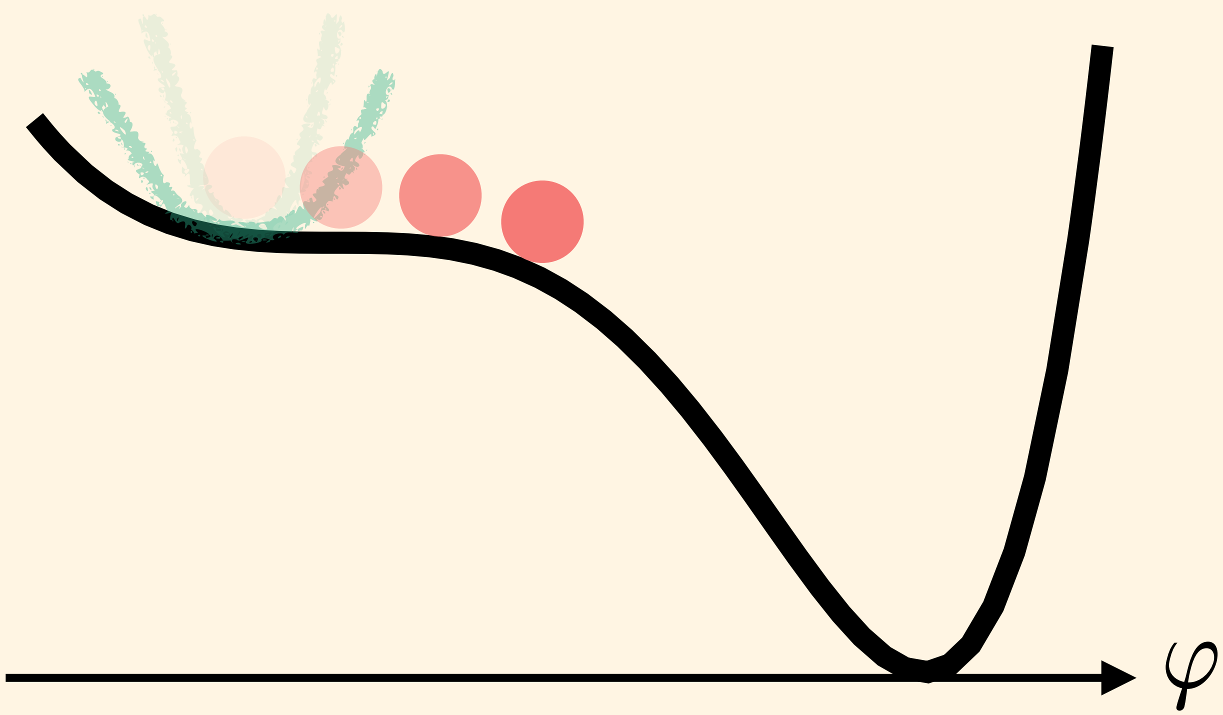

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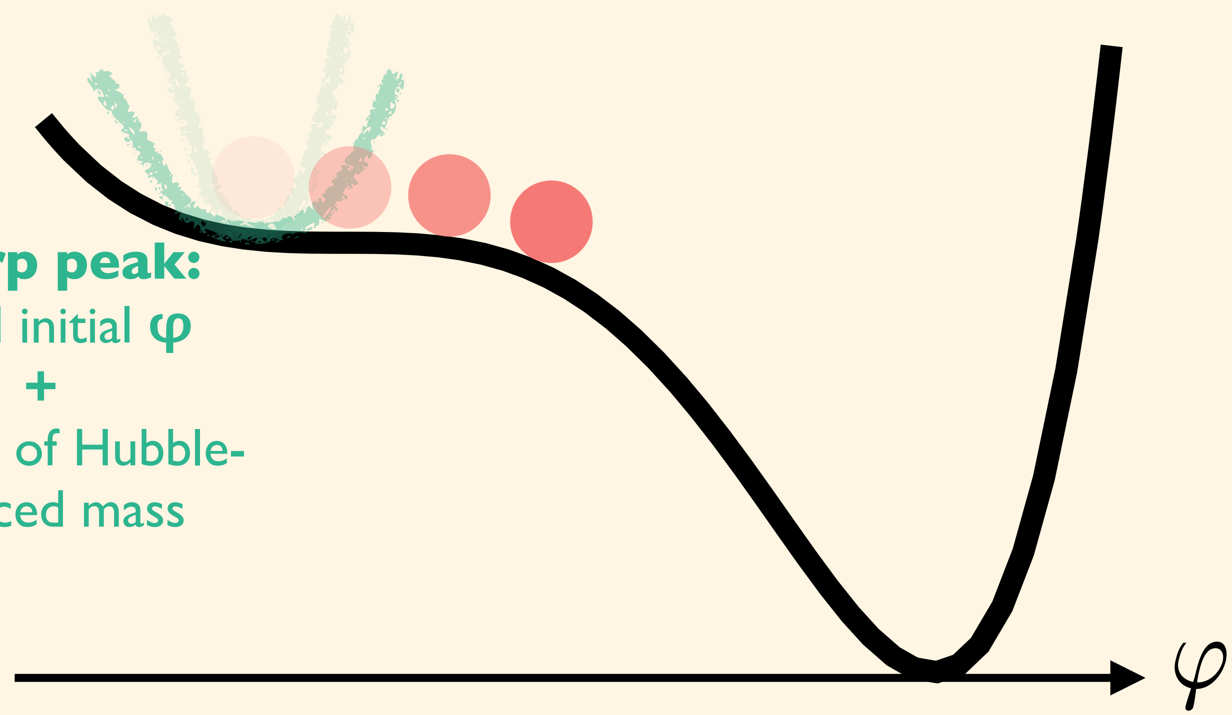
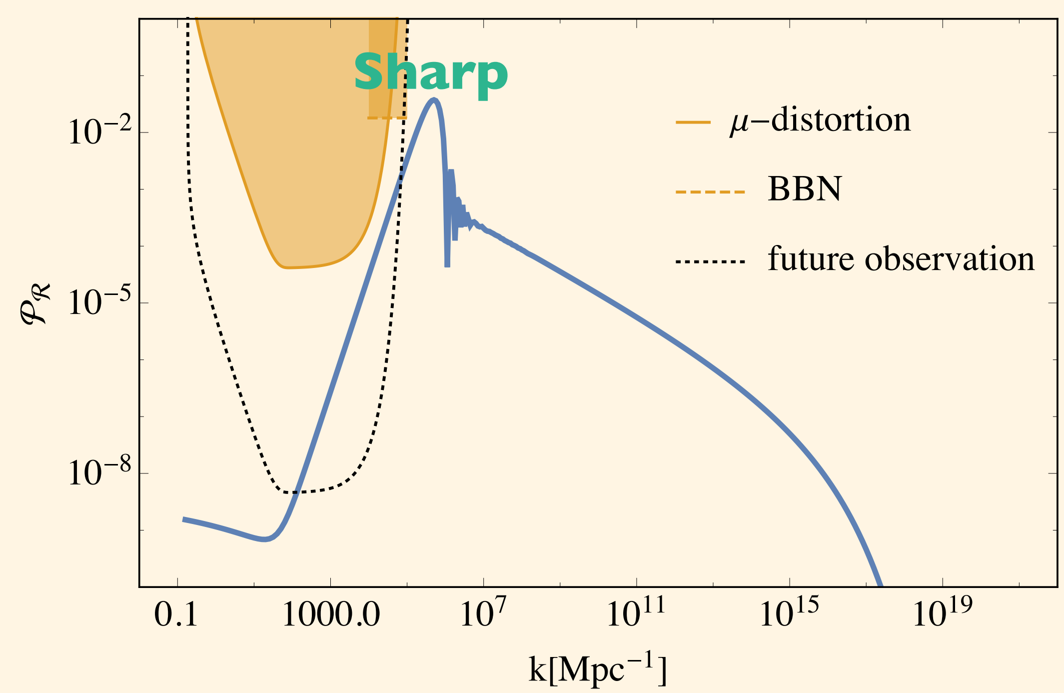
Hubble-induced mass

Sharp peak:
Small initial φ
+
Change of Hubble-induced mass





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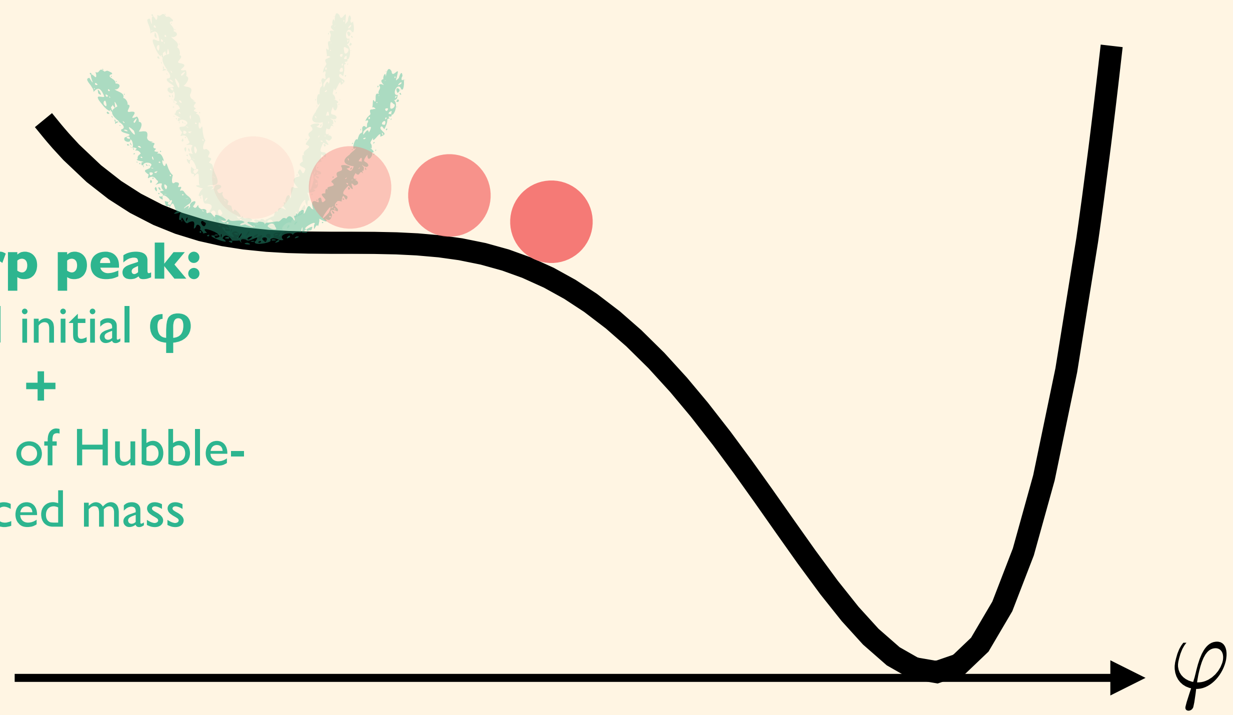

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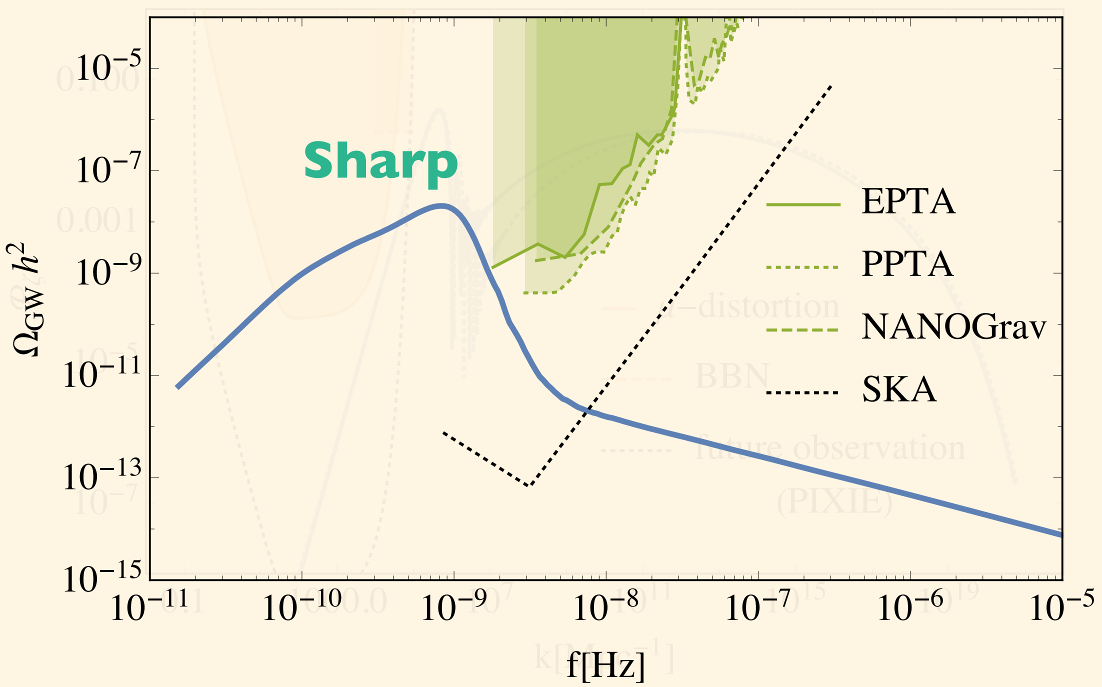

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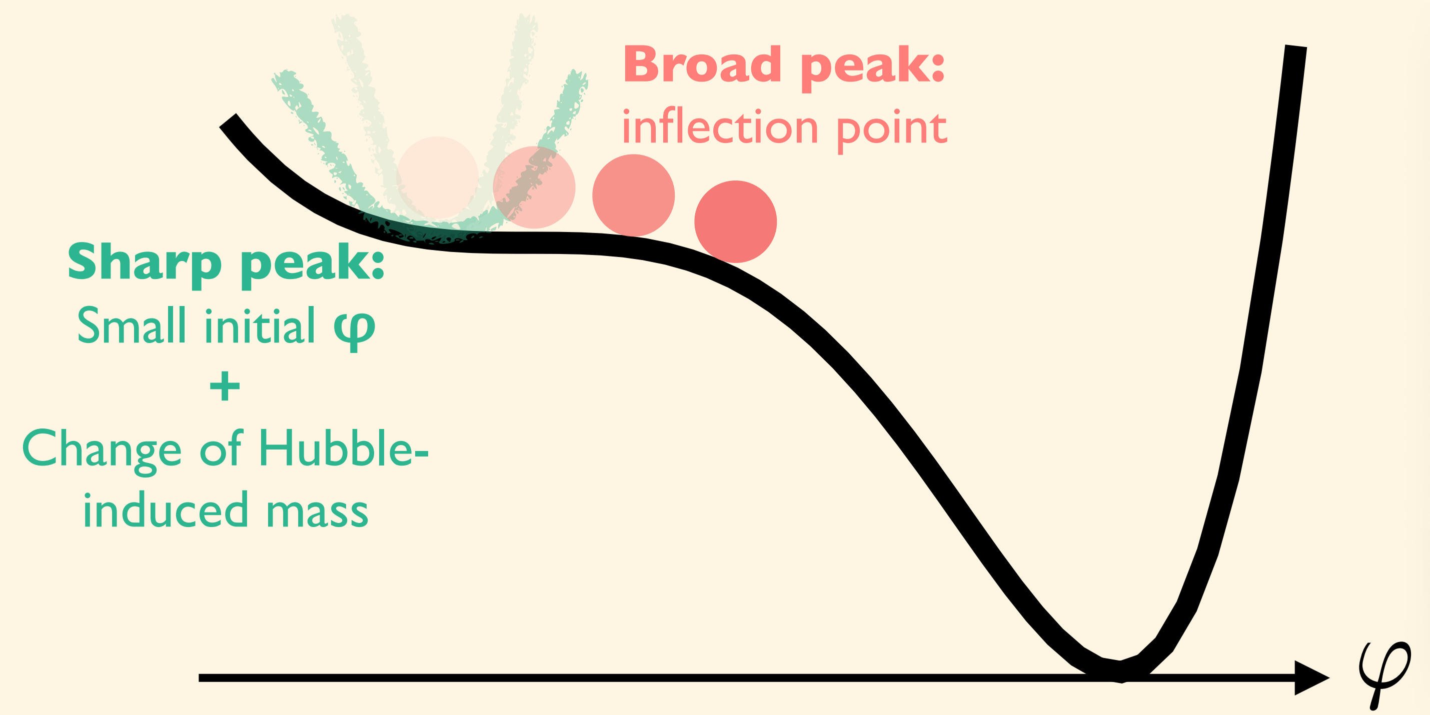
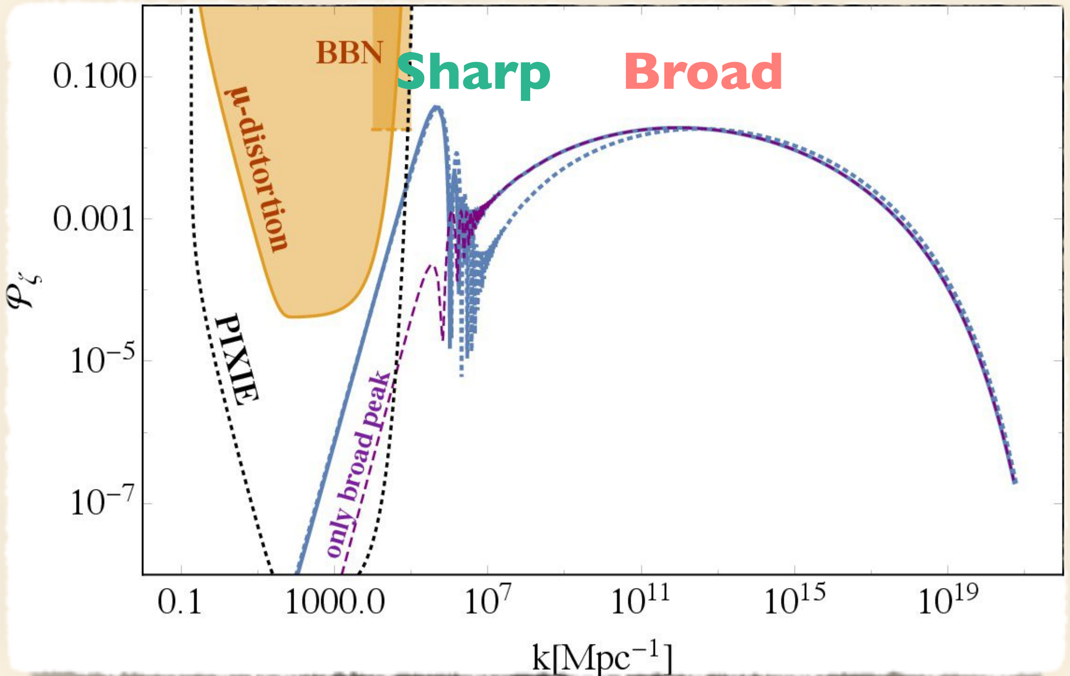




Double Inflation

PBHs for LIGO or DM from **Double Inflation**

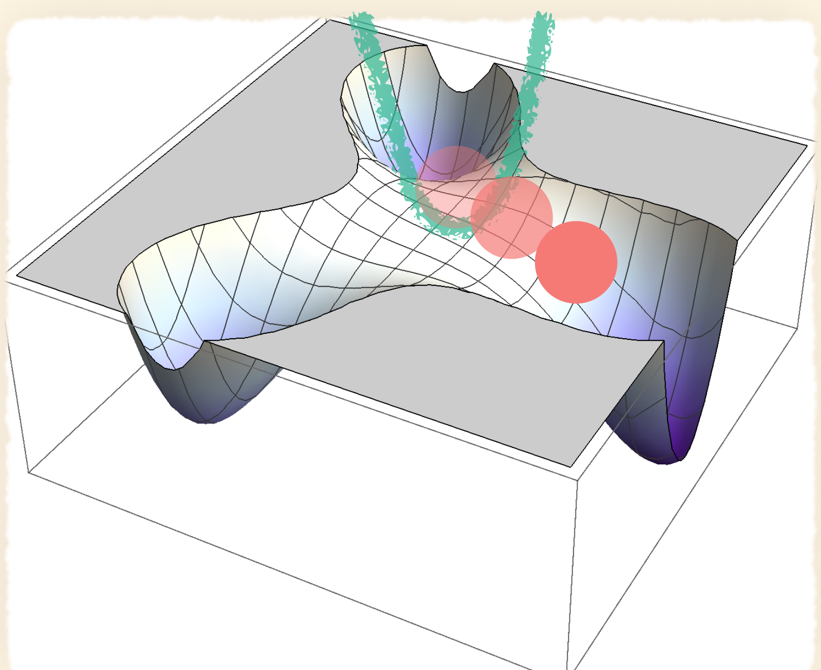
- Total e-folds (N=50-60) = **1st-inflation** + **2nd inflation**
  - **SUGRA**: discrete R symmetry breaking model. [Kawasaki+1606.07631, Inomata+1611.06130]

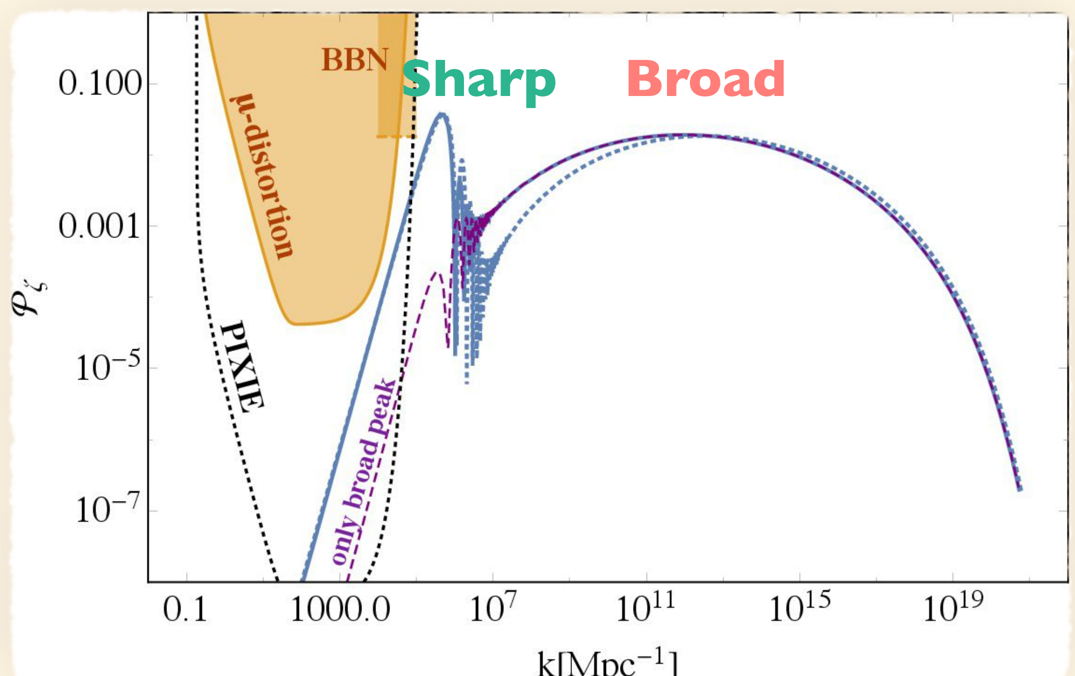
$$W = mX\Psi - \frac{g}{4}\Phi^4 + v^2\Phi + c$$

$$K = \frac{1}{2}\left(\Psi + \Psi^\dagger\right)^2 + |X|^2 + |\Phi|^2 + \frac{\kappa}{4}|\Phi|^4 + c'_{\rm pot}|X|^2|\Phi|^2 + \frac{c'_{\rm kin}}{2}|\Phi|^2\left(\Psi + \Psi^\dagger\right)^2 + \cdots$$

	Ψ	X	Φ	v^2	c
R charge	0	2	$\frac{2}{n+1}$	$2 - \frac{2}{n+1}$	2

Ψ: 1st-inflaton; **X**: stabilizer; **Φ**: R-breaking field, 2nd-inflaton





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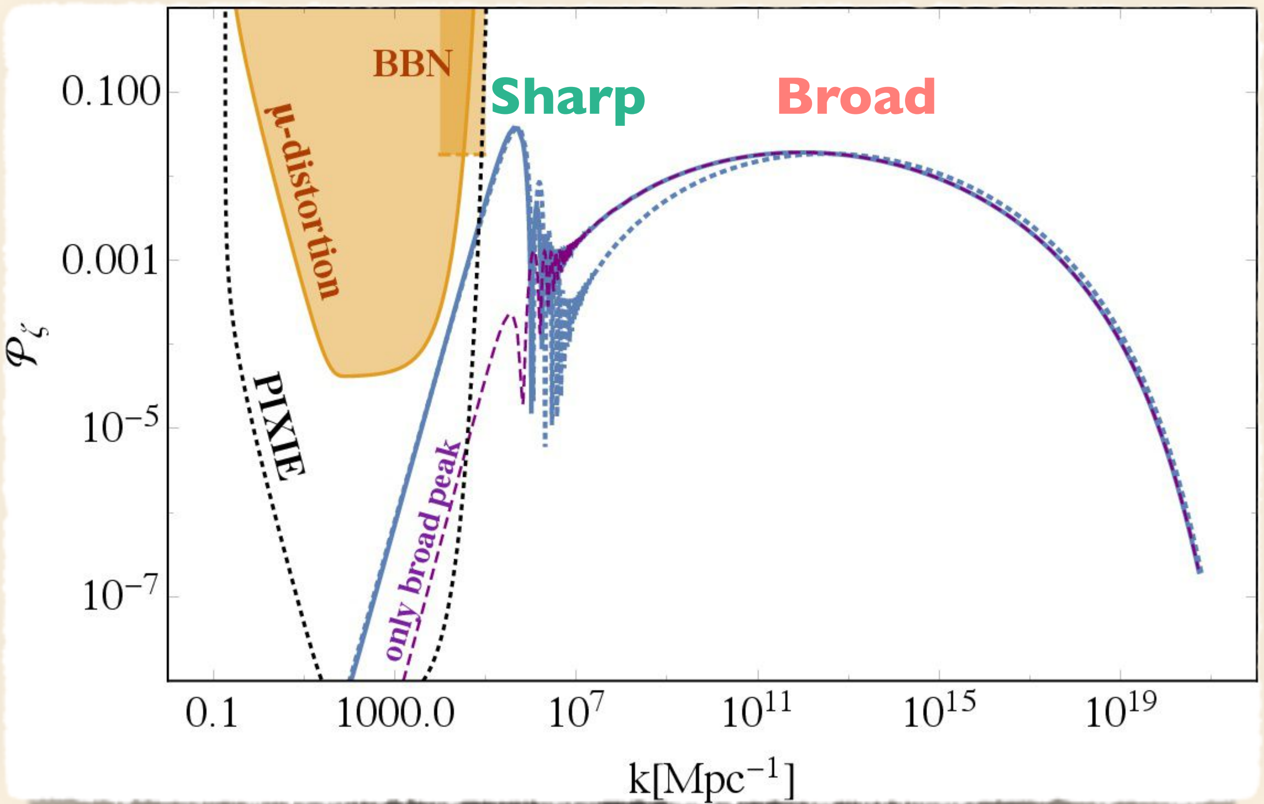

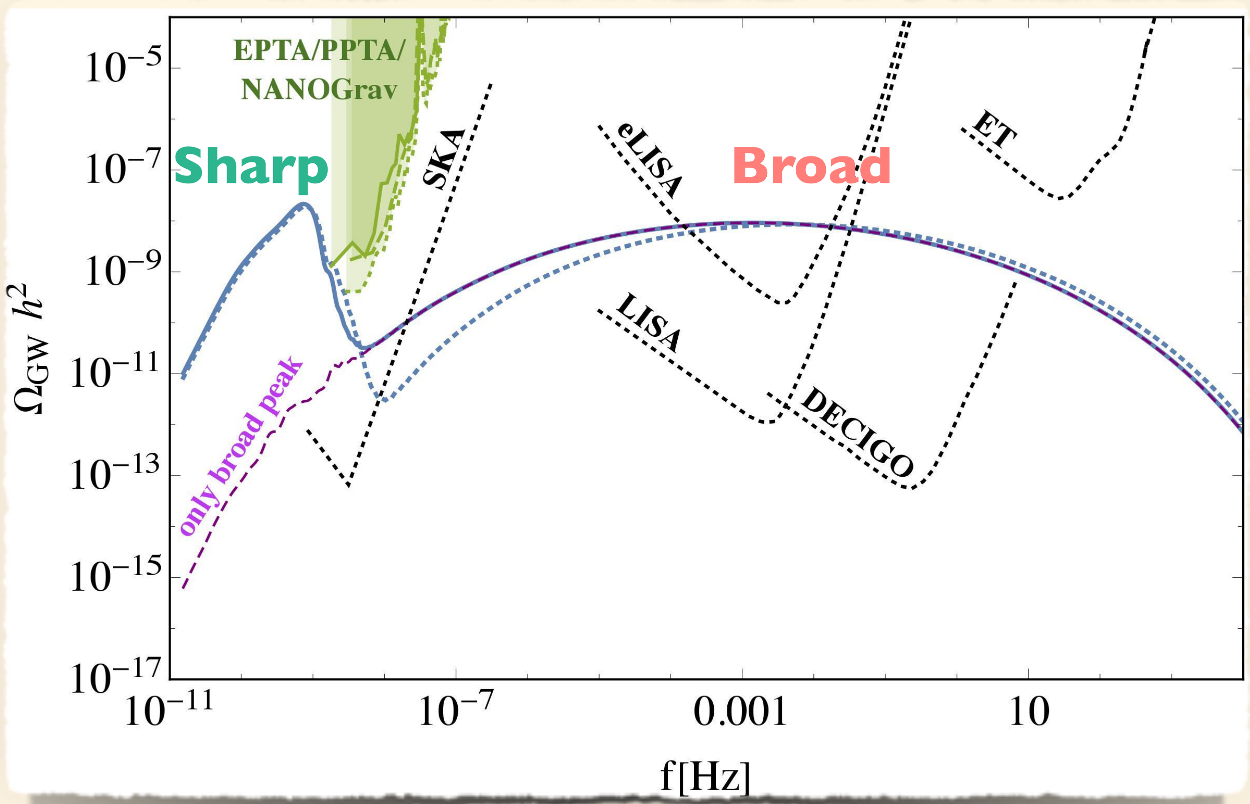

- PBHs for LIGO → **SKA** and future CMB observation.
- PBHs for DM → **eLISA** and LISA.

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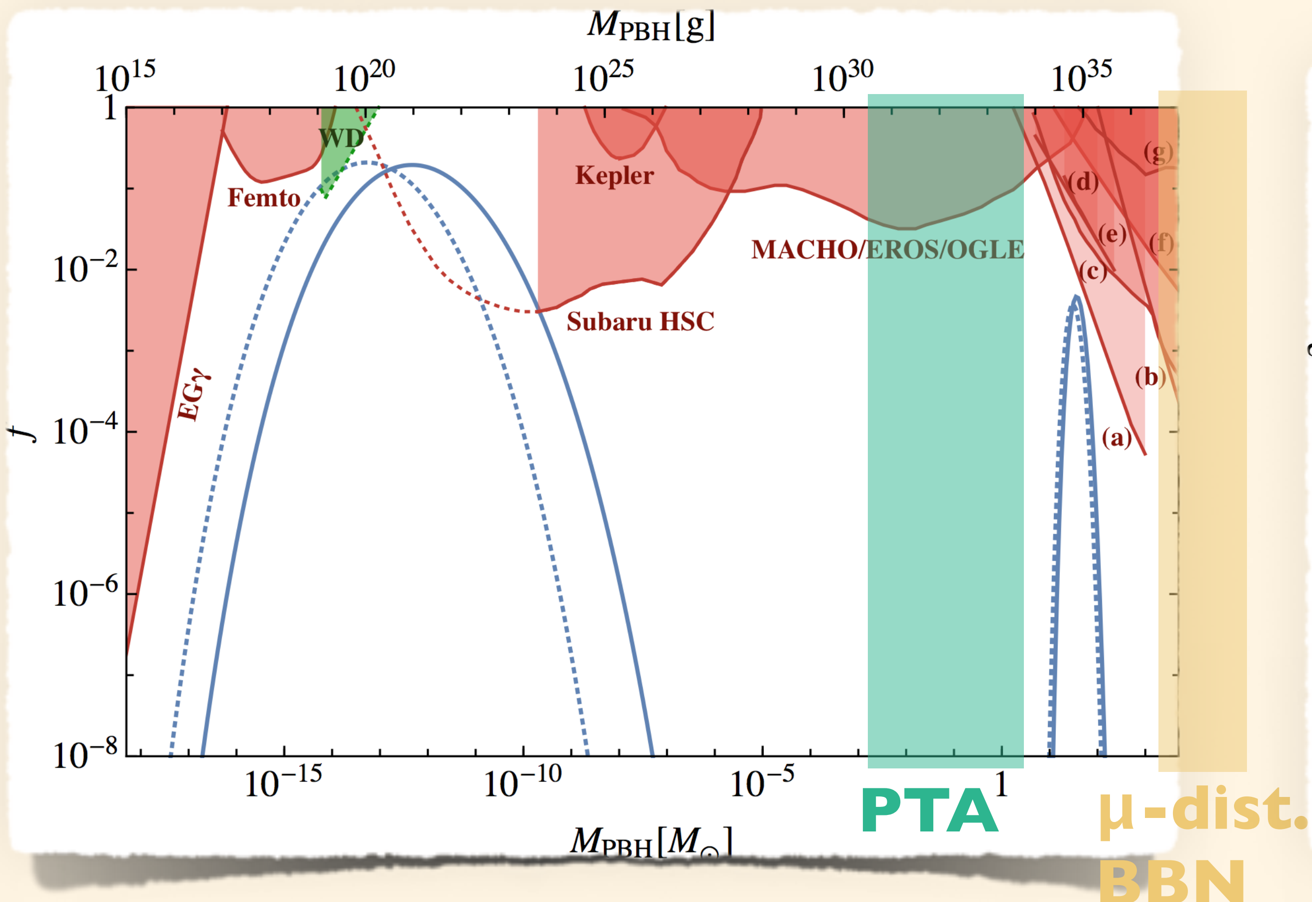

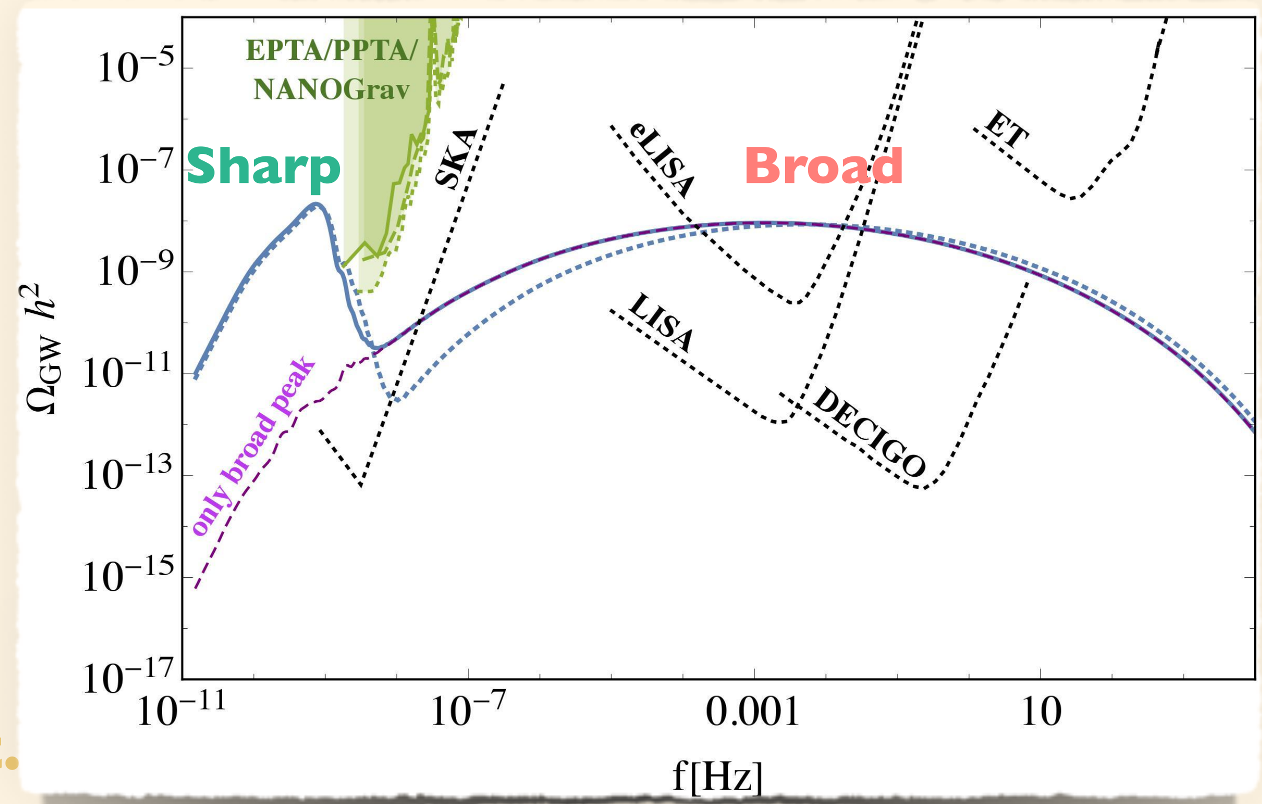

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4.

Summary

Summary

Inflation for PBHs needs **LARGE $P_\zeta(k) \sim 10^{-2}$**.

Many over-densities are generated per one PBH:

- **CMB spectral distortion** @ 10^4–1 Mpc^{-1}; **BBN** @ 10^5-10^4 Mpc^{-1}
- **Induced GWs**: PTA @ $\sim 10^6$ Mpc^{-1}; eLISA @ 10^{11}-10^{13} Mpc^{-1}
- **UCMHs**…depends on models and DM profile.

PBHs for LIGO → need a sharp peak@ **$k \sim 10^{-2}$** Mpc^{-1}

Inomata, Kawasaki, **KM**, Tada, Yanagida; 1611.06130

PBHs for DM → could be broad (wave eff. on HSC).

Double inflation (SUGRA) can explain both at once!

Inomata, Kawasaki, **KM**, Yanagida; in prep.

Enhance the **non-Gaussianity** → **multi-field?**

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