PBHs from Inflation and their Implications

Kyohei Mukaida

DESY, HAMBURG

Based on **1611.06130, 1701.02544, 1711.08956**
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
- Seeds of SMBHs
- 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, DW, cosmic string, Q-ball,…
  - Collapse of **primordial** density perturbations: **inflation**, **curvaton**,…

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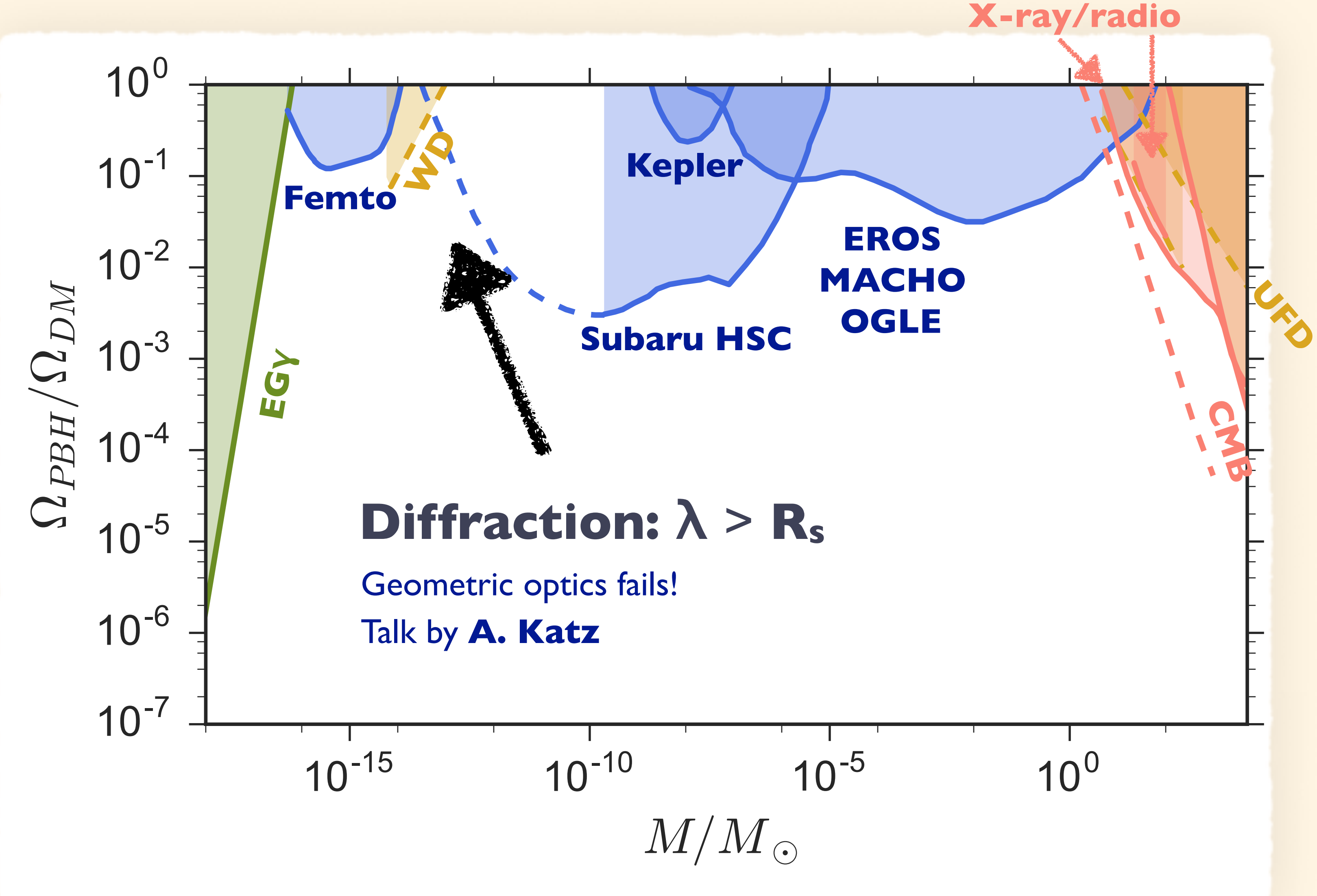
This Talk!

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,…

Radio/Xray: 1612.00457, 1705.00791

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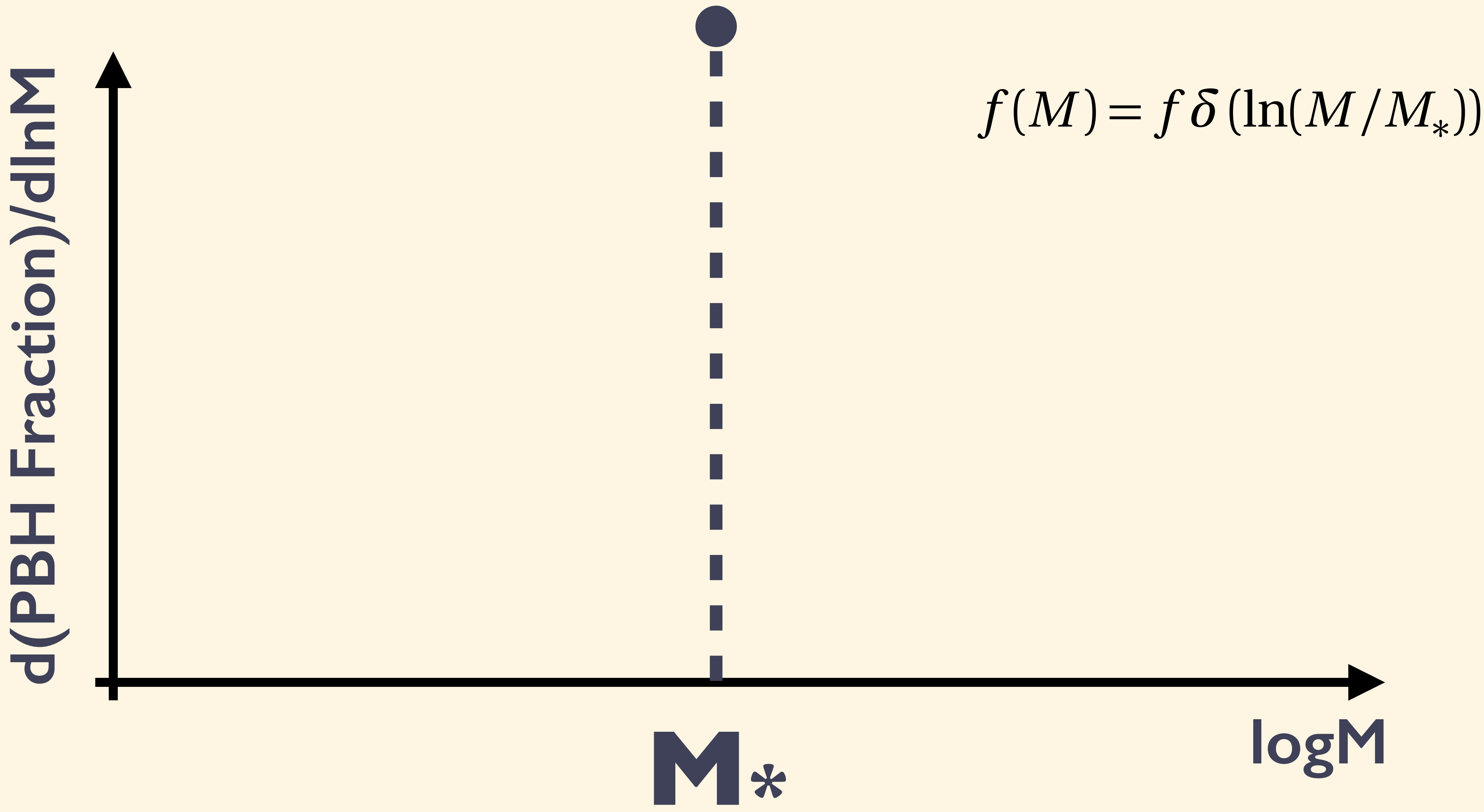

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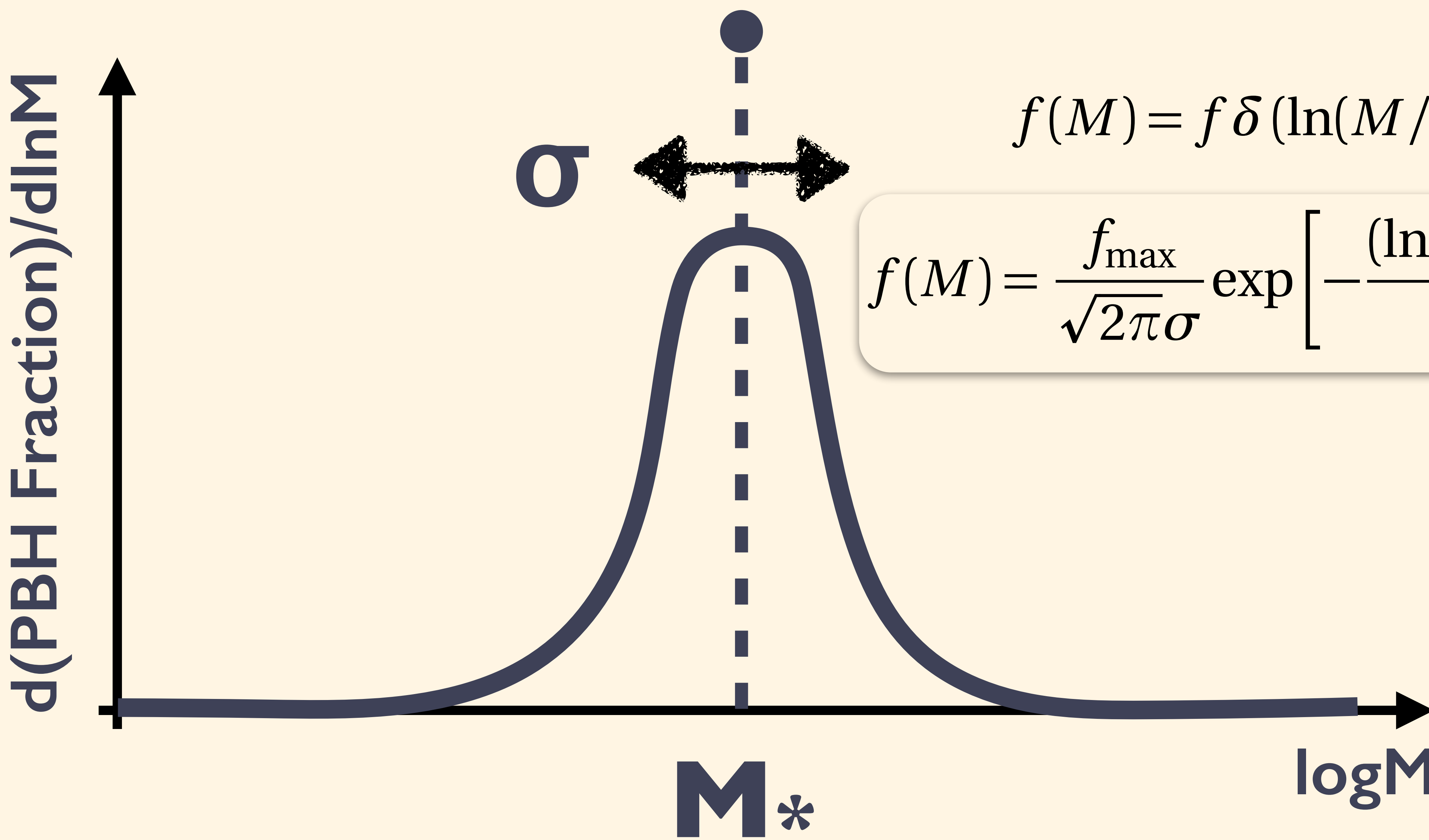


$$f(M) = f\,\delta(\ln(M/M_*))$$

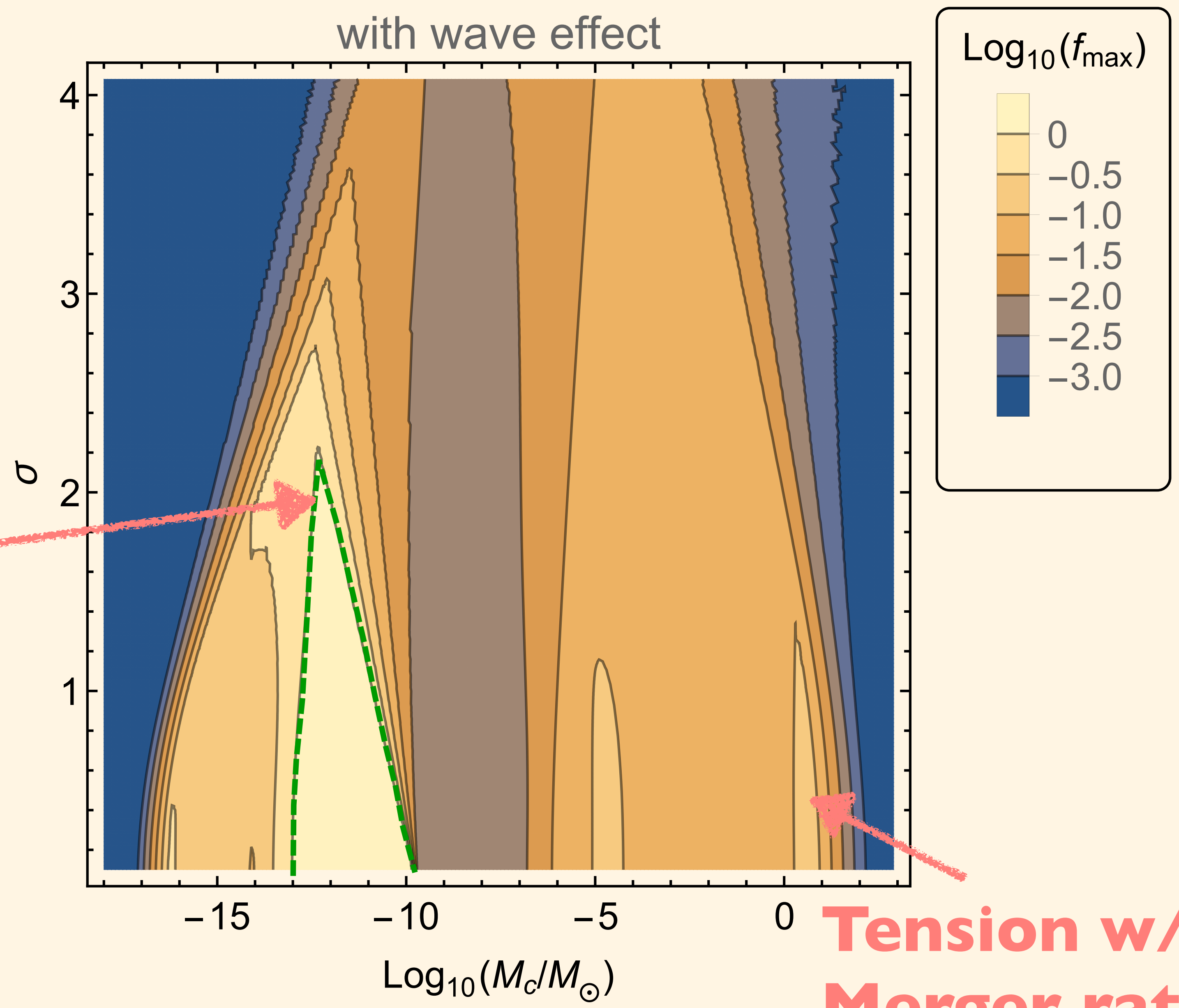
$$f(M) = \frac{f_{\max}}{\sqrt{2\pi}\sigma}\exp\left[-\frac{(\ln(M/M_*))^2}{2\sigma^2}\right]$$

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

Tension w/ radio/X-ray
Merger rate?

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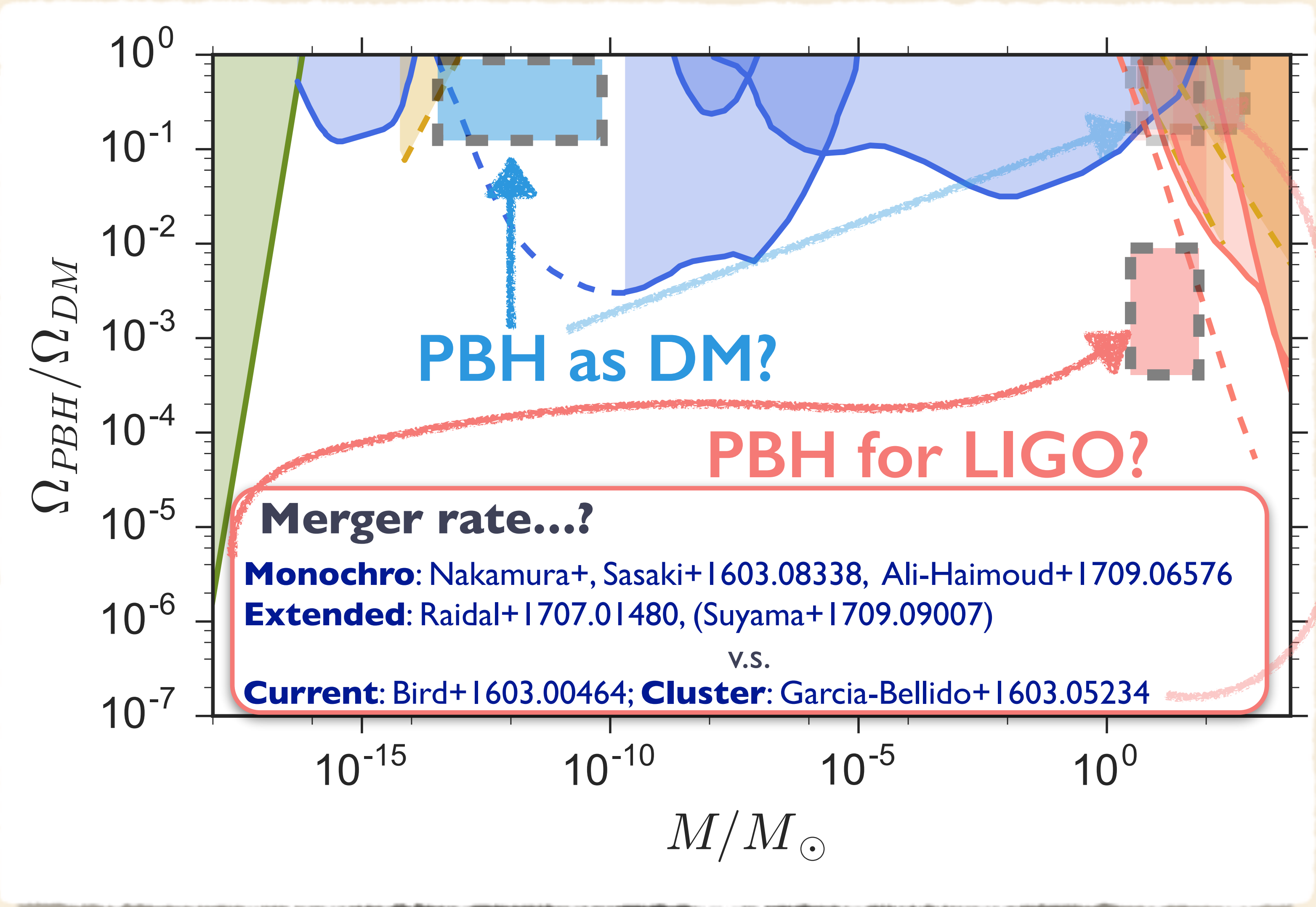
- PBH as **all DM**: marginal
- PBH for **LIGO events**: marginal



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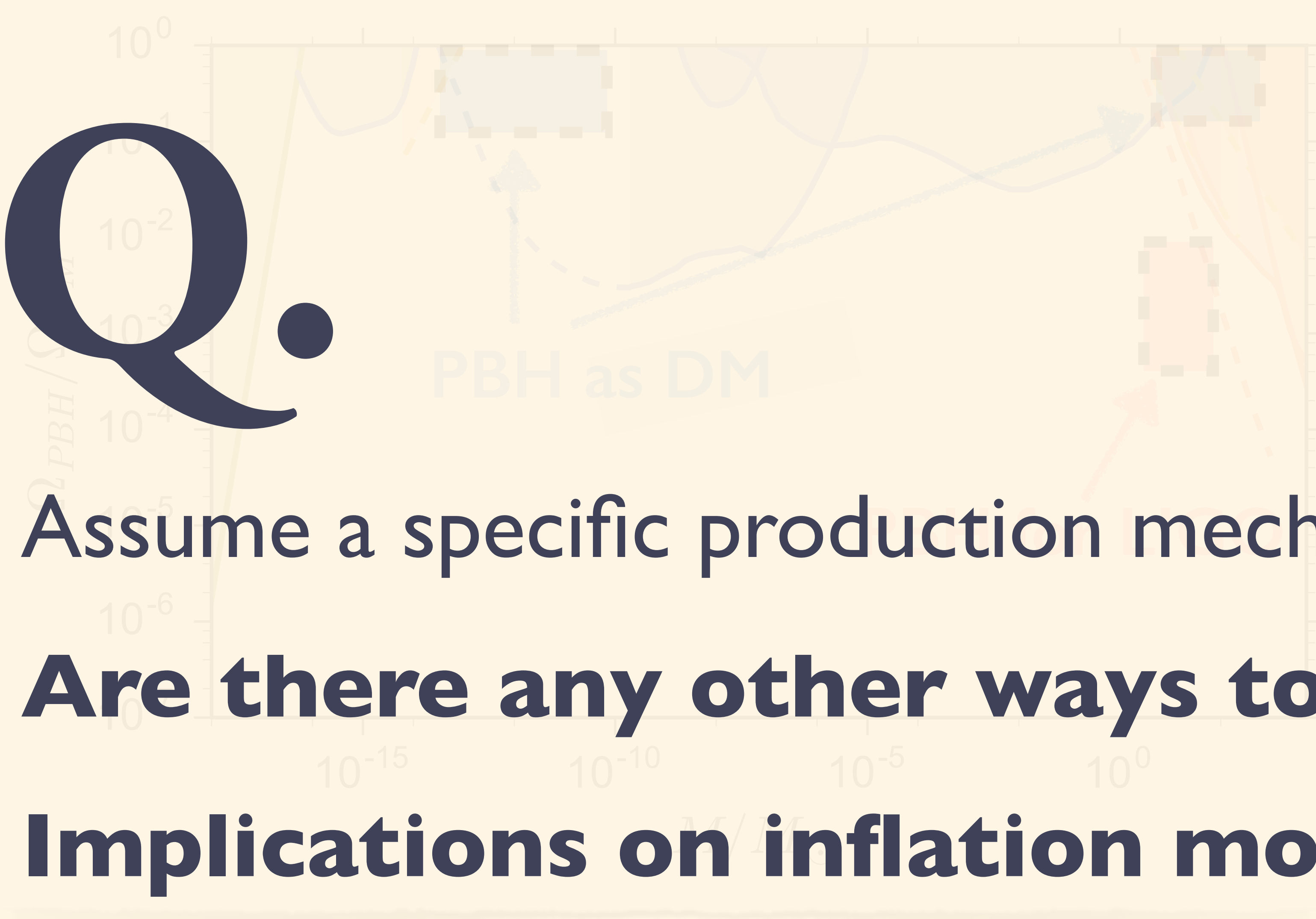

Q.

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

Are there any other ways to probe them?

Implications on inflation models?

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- Constraints on PBHs from Inflation
- Inflation Models
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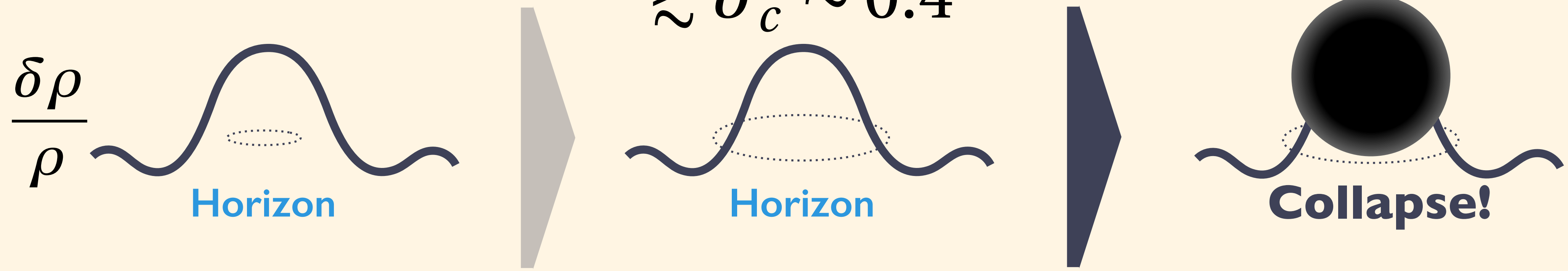
2.

Constraints on PBHs from Inflation

Formation of PBHs

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

$\gtrsim \delta_c \sim 0.4$



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

$$M = \gamma\rho\frac{4\pi H^{-3}}{3} \simeq M_\odot \left(\frac{\gamma}{0.2}\right)\left(\frac{g_*}{3.36}\right)^{-\frac{1}{6}}\left(\frac{k/(2\pi)}{3\times10^{-9}\,\mathrm{Hz}}\right)^{-2}$$

Carr, '75

- PBH **abundance (β)** ⇆ **amplitude** of perturbation **(P_ζ)**

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

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

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

✤ **Loophole** → Large **non-Gaussianity**

Formation of PBHs

PBH production by high-σ tail:

- **1%** of DM @ O(10) solarmass → **$\beta \sim 10^{-10} \ll 1$** ↔ **$P_\zeta \sim O(0.01)$**

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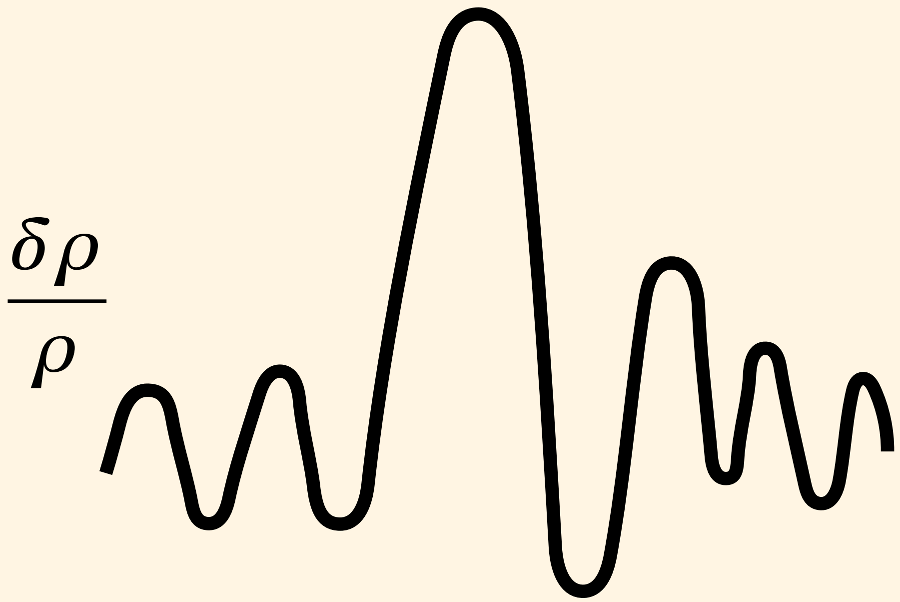

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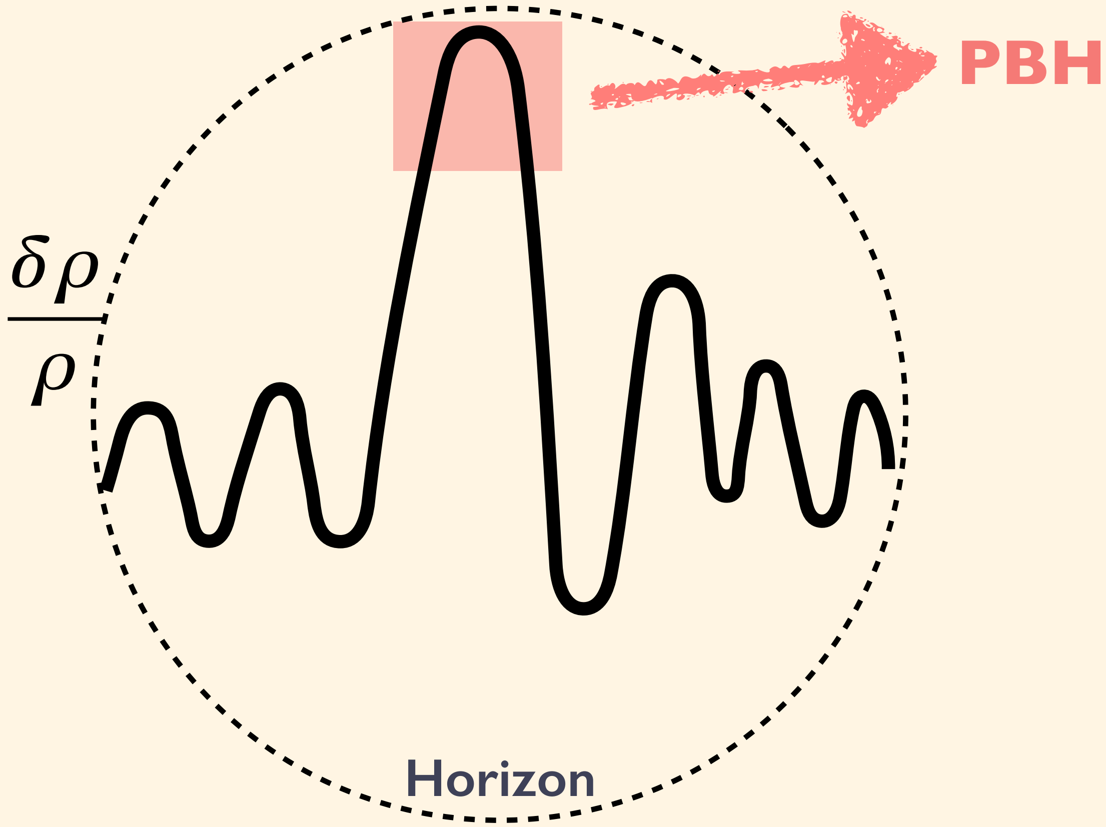
After reentry



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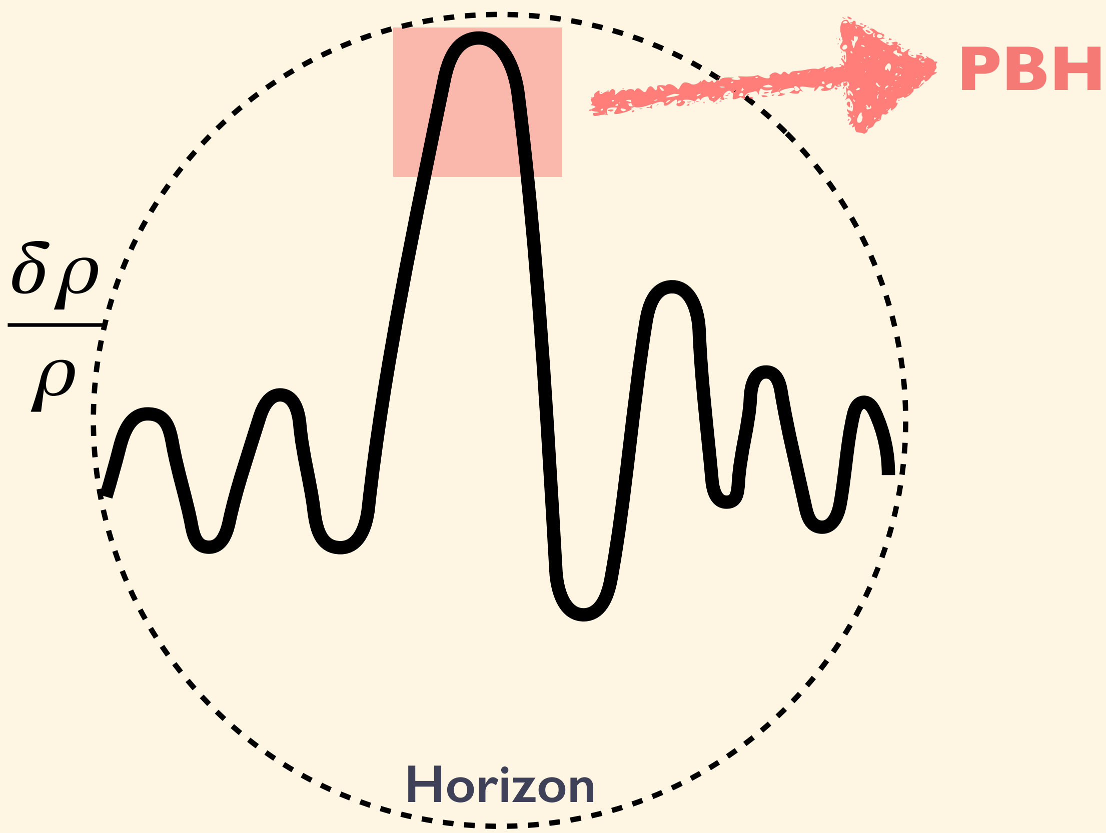

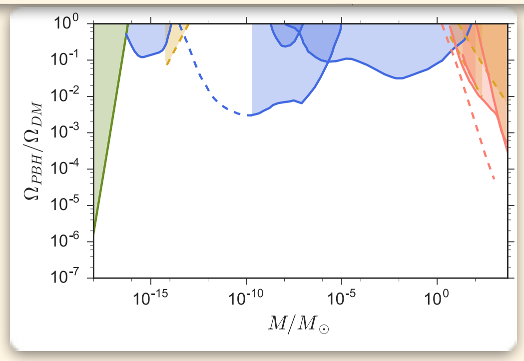

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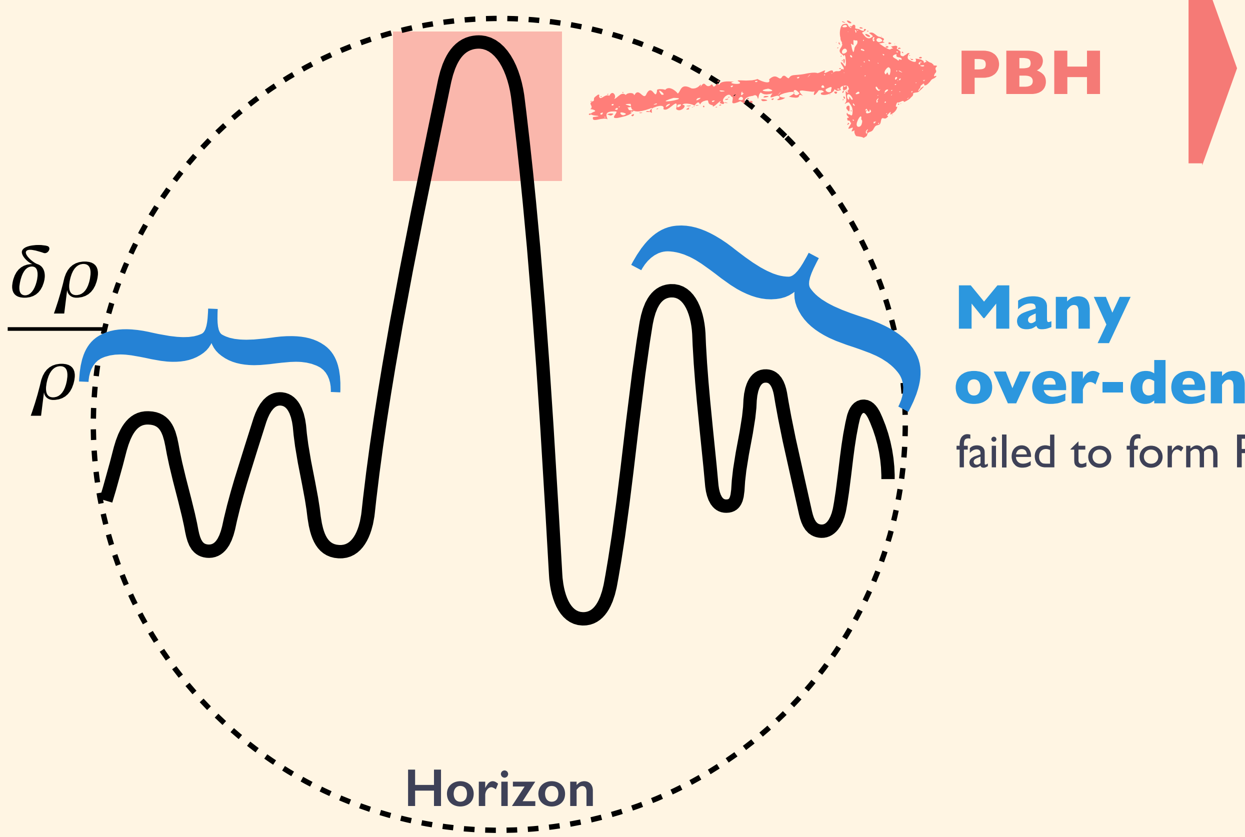

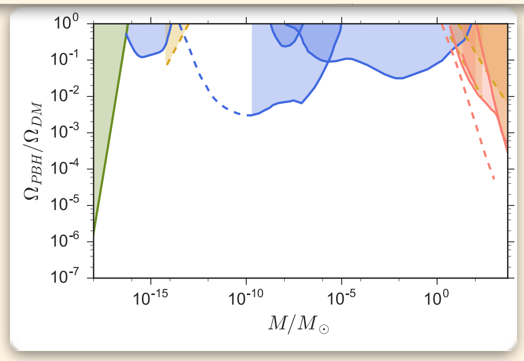

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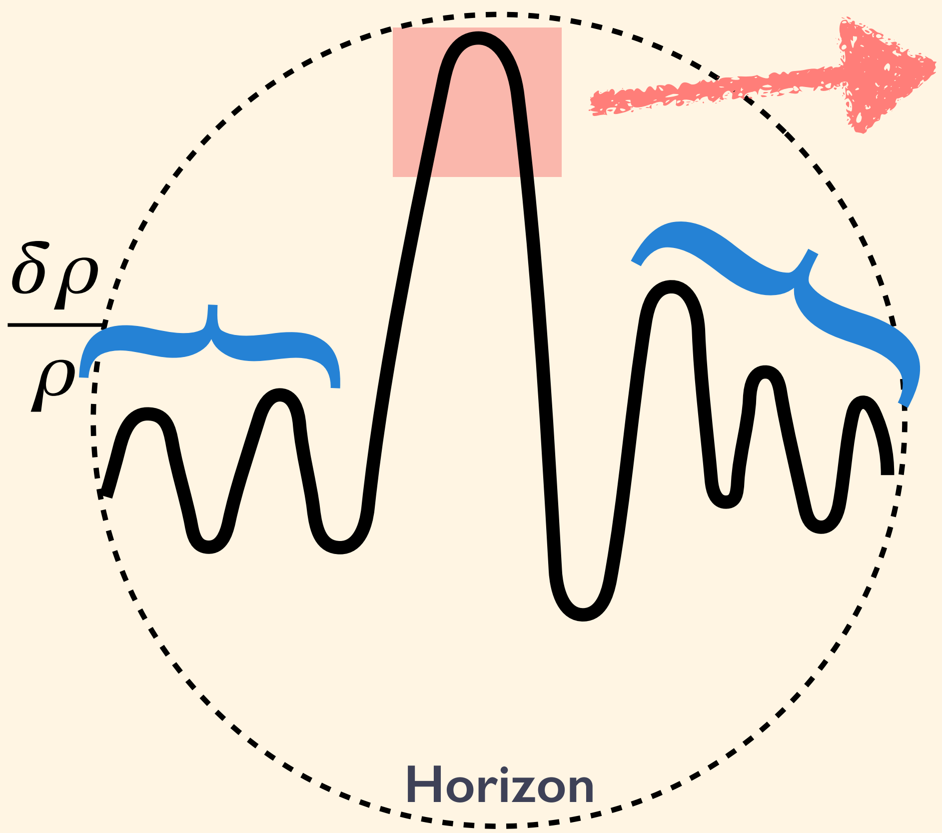

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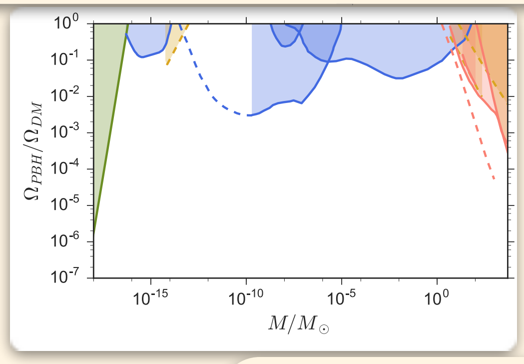

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We can probe them

- via **radiation**
  ➡ **CMB/BBN**
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- via **CDM**
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  depends on DM models/profiles

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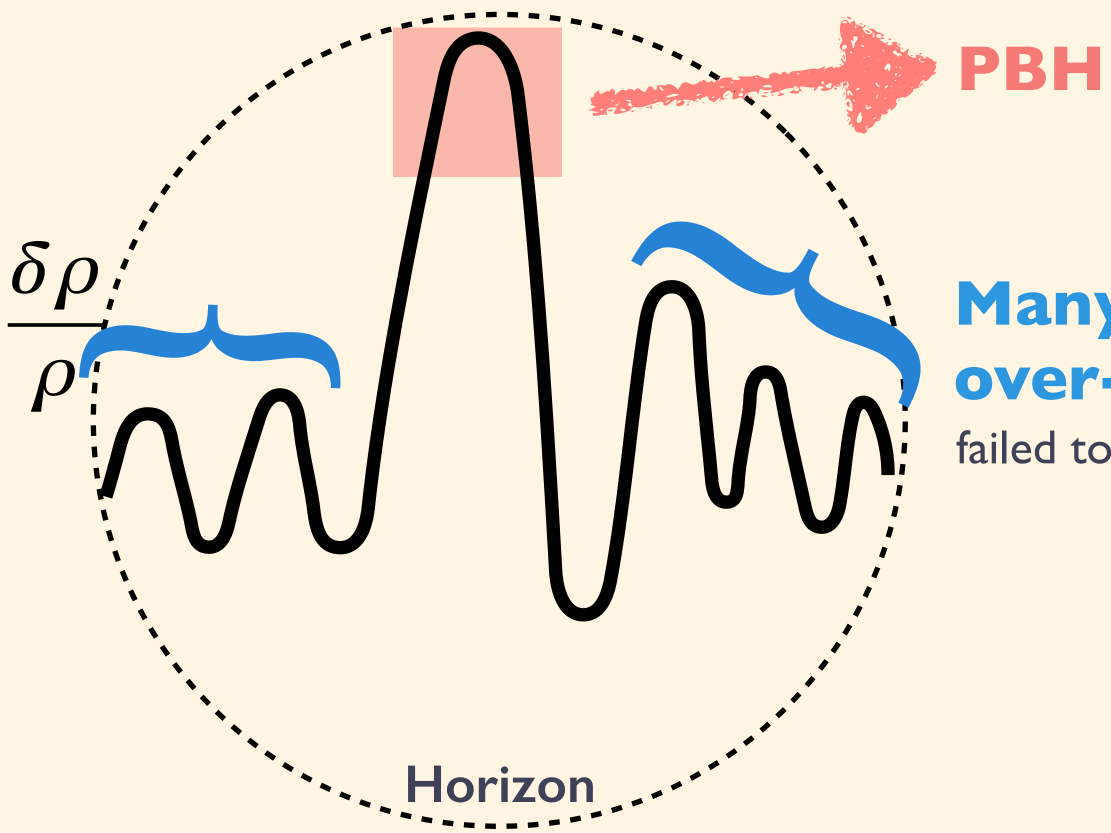

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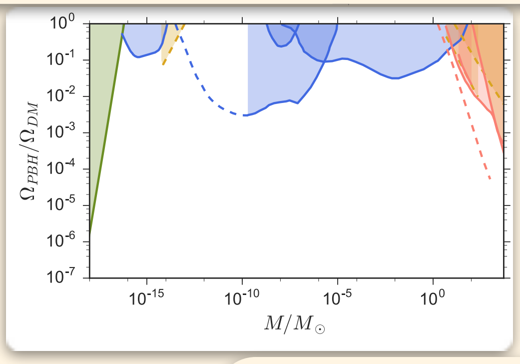

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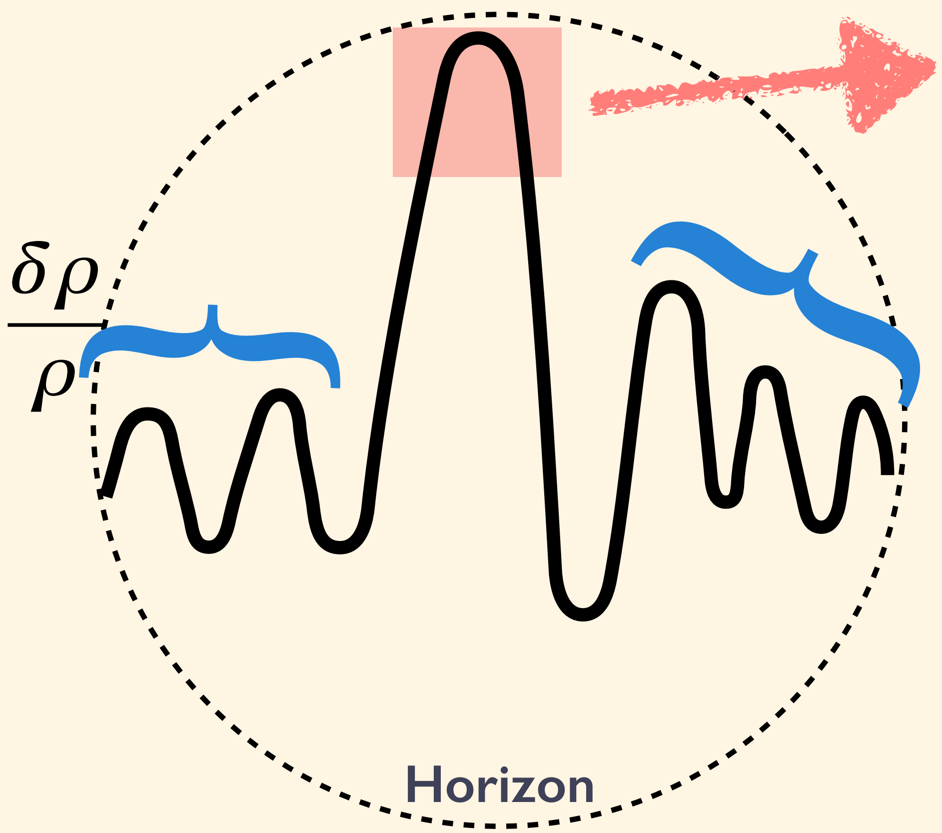

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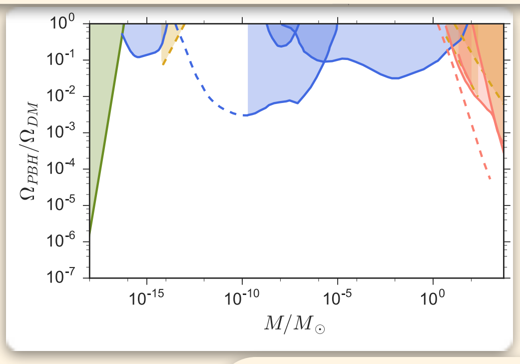

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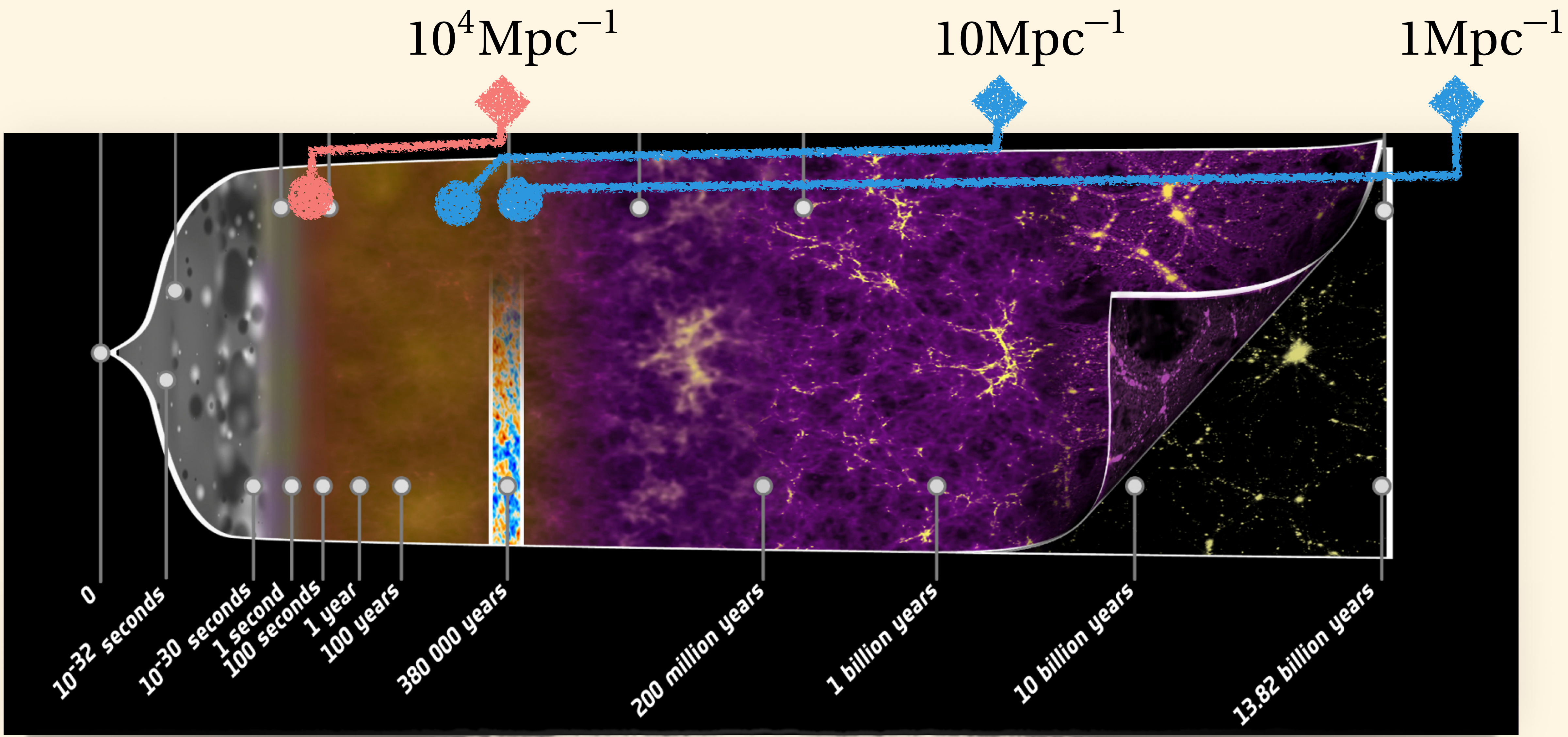
Spectral distortion/BBN

Energy injection from large small-scale perturbs.

- 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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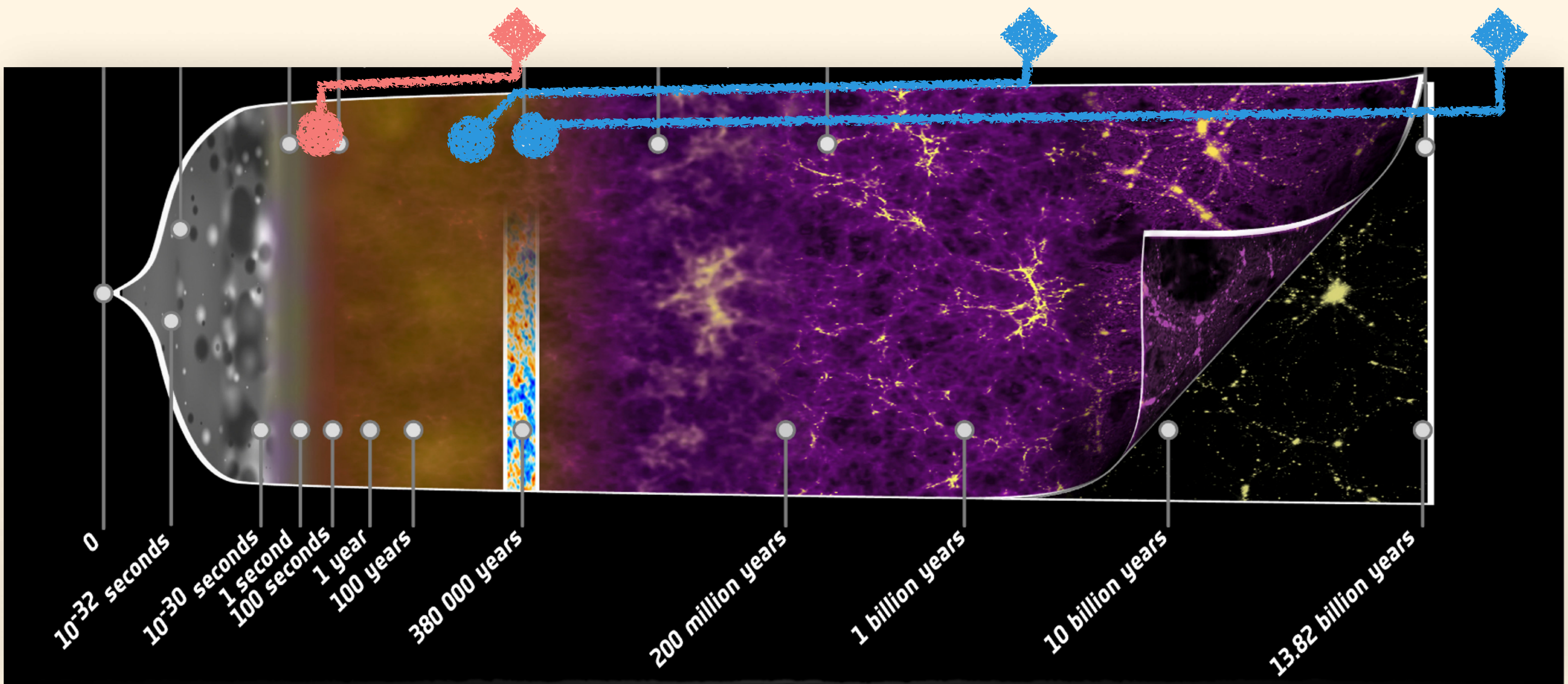
y-distortion

- **Thomson** scat.

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

(**Elastic** Compton)

$10^4\mathrm{Mpc}^{-1}$ $10\mathrm{Mpc}^{-1}$ $1\mathrm{Mpc}^{-1}$



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- **Energy/#-changing**
- Baryon-to-photon ratio
  Nakama+1403.5407
- neutron-to-proton ratio
  Jeong+1403.3697; Inomata+1605.04646

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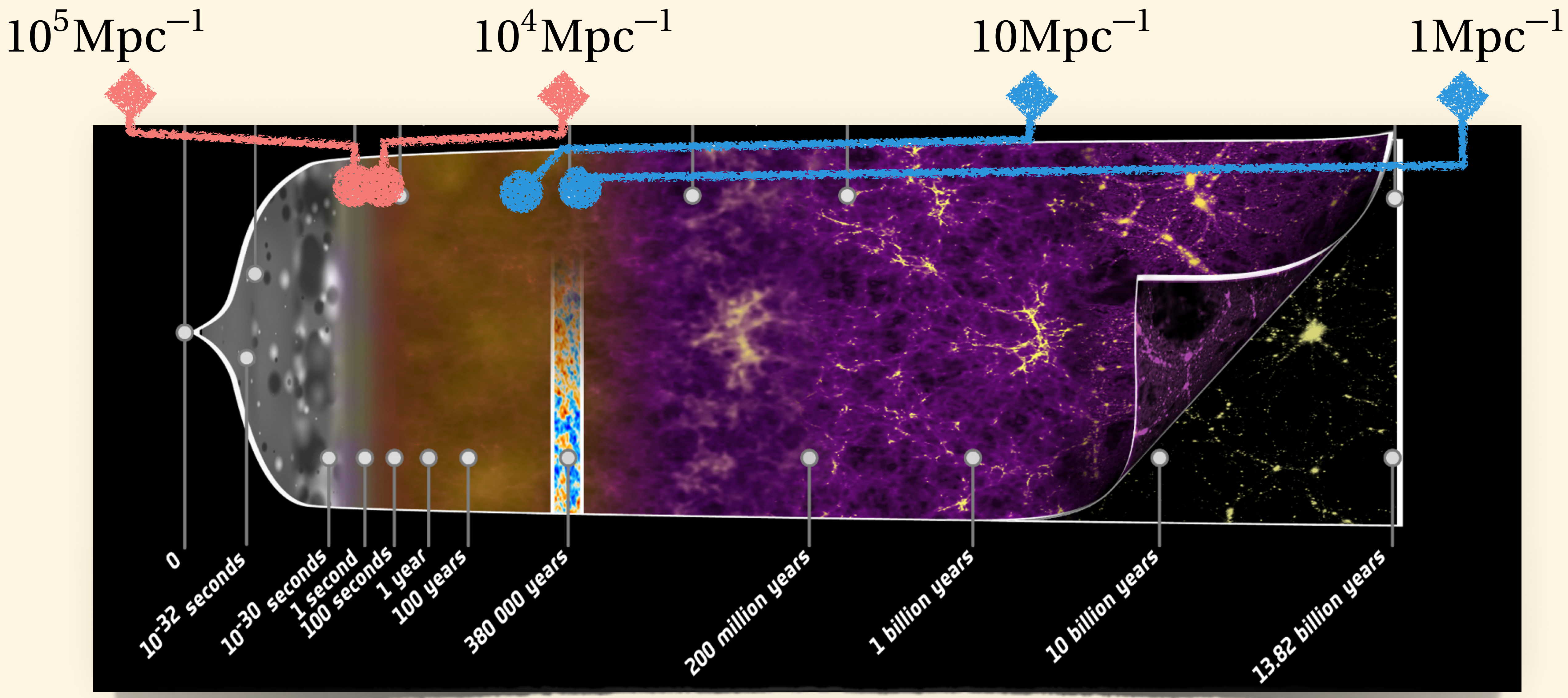

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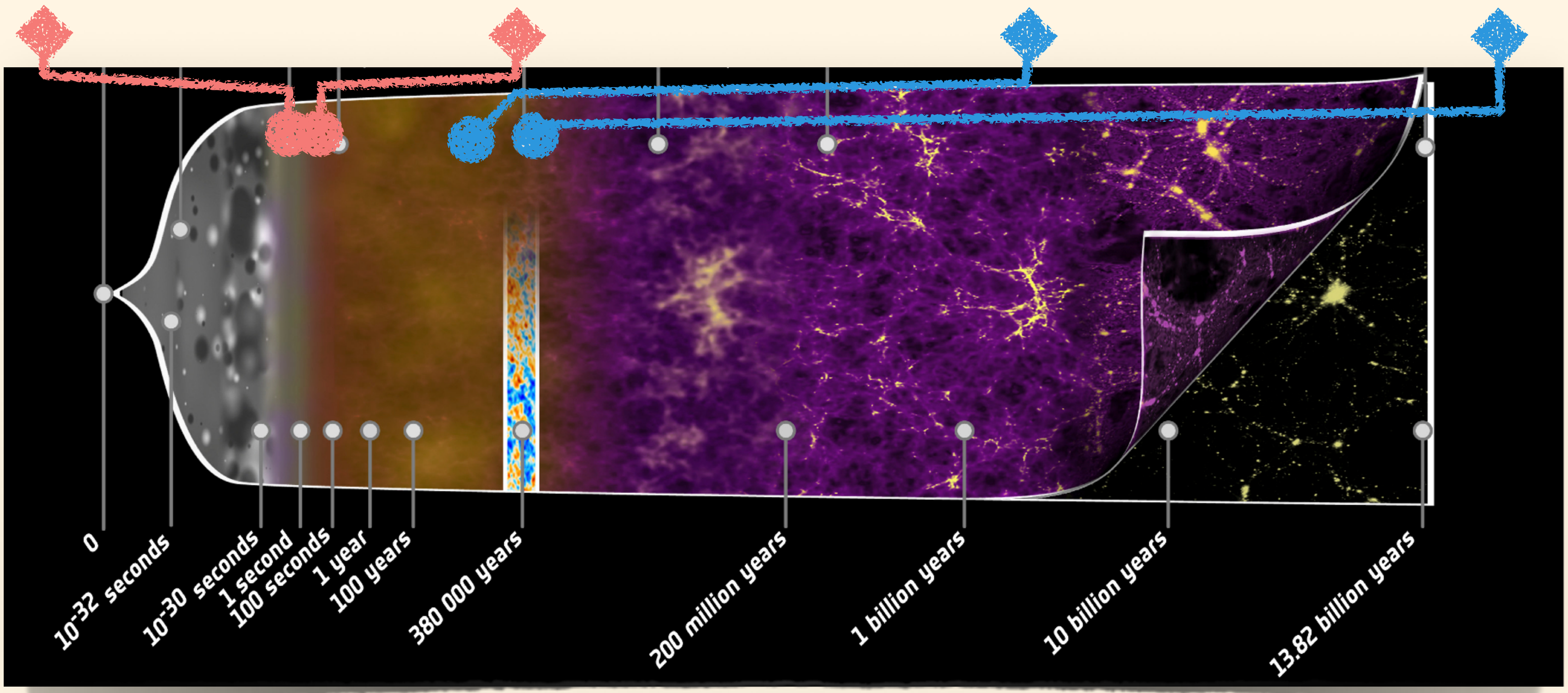

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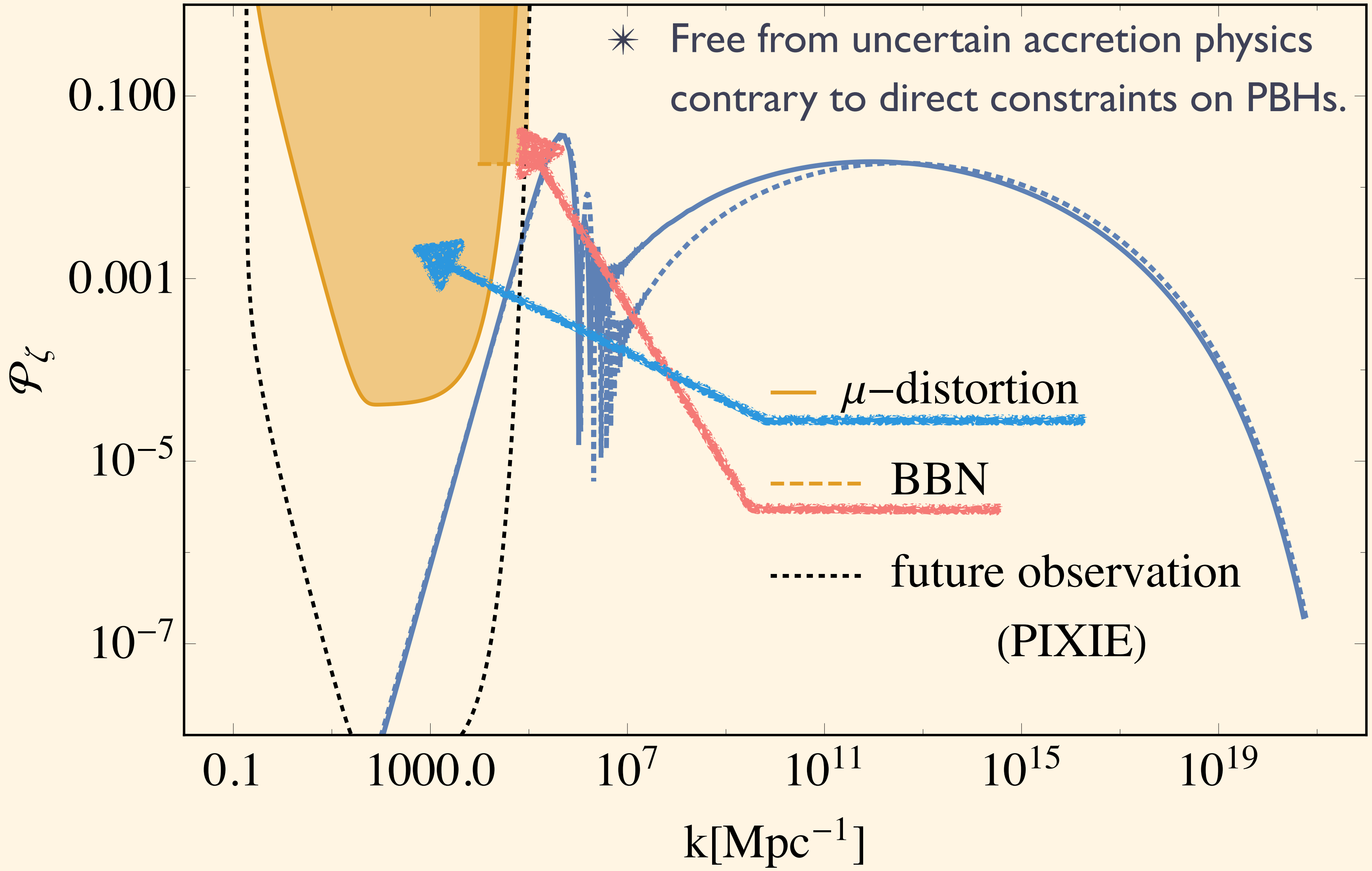

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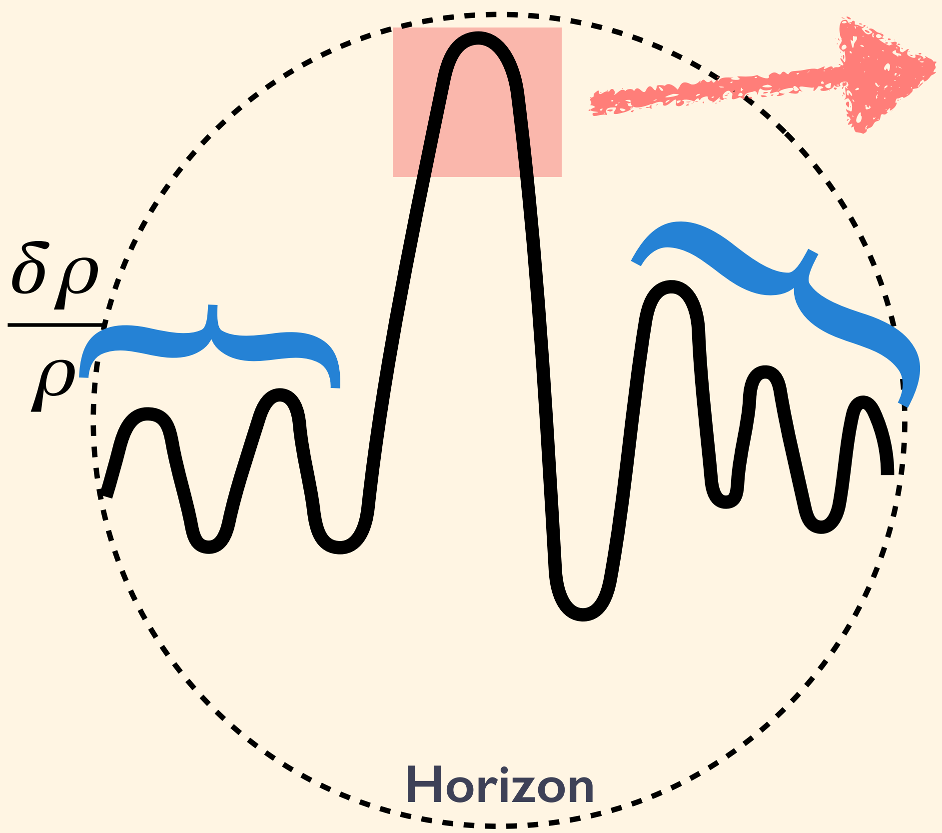

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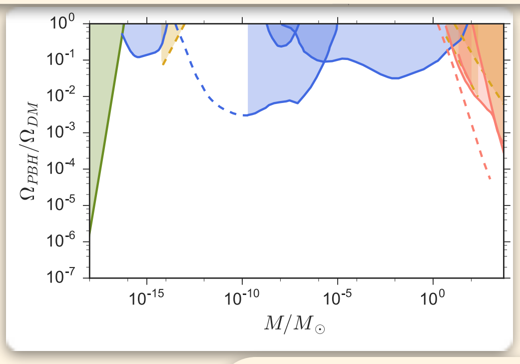

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Induced GWs

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

- **Tensor perturbation** obeys...

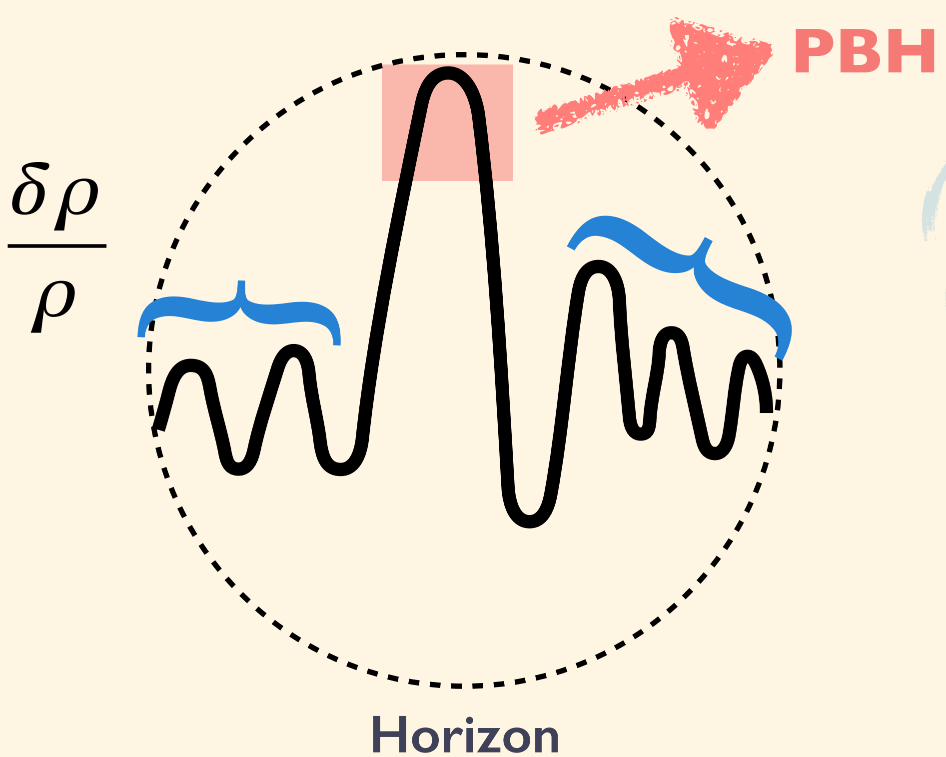
Saito, Yokoyama,'09; Bugaev, Klimai,'10

Talk by **J.R. Espinosa**

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

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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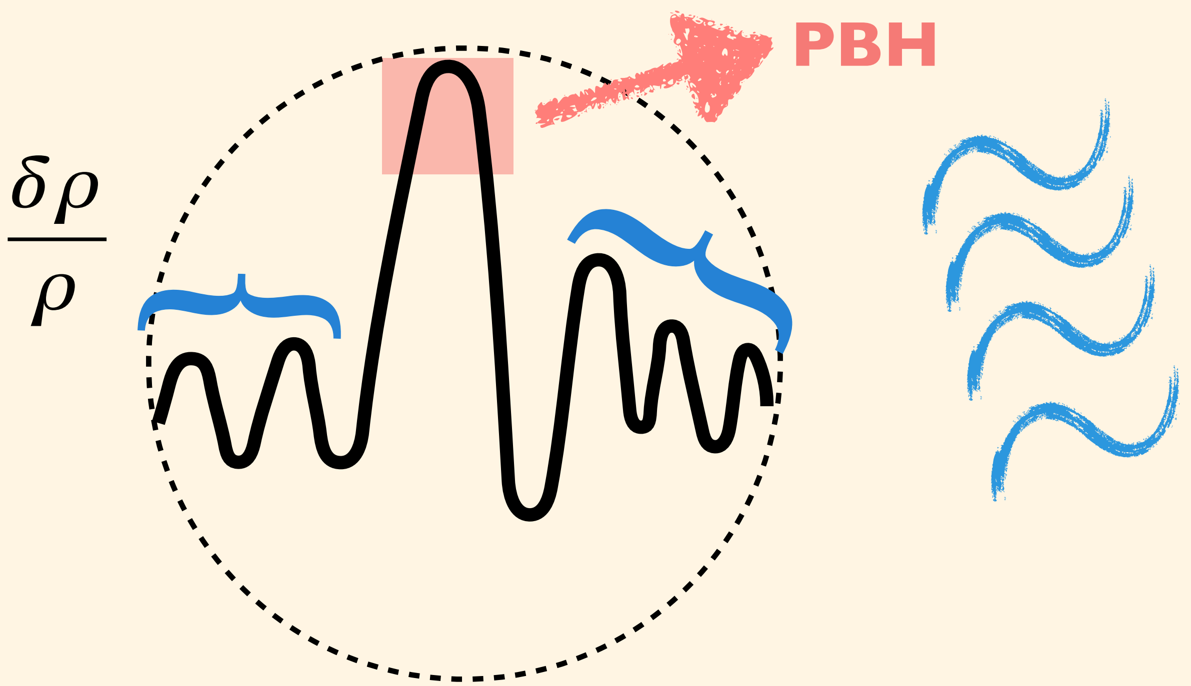

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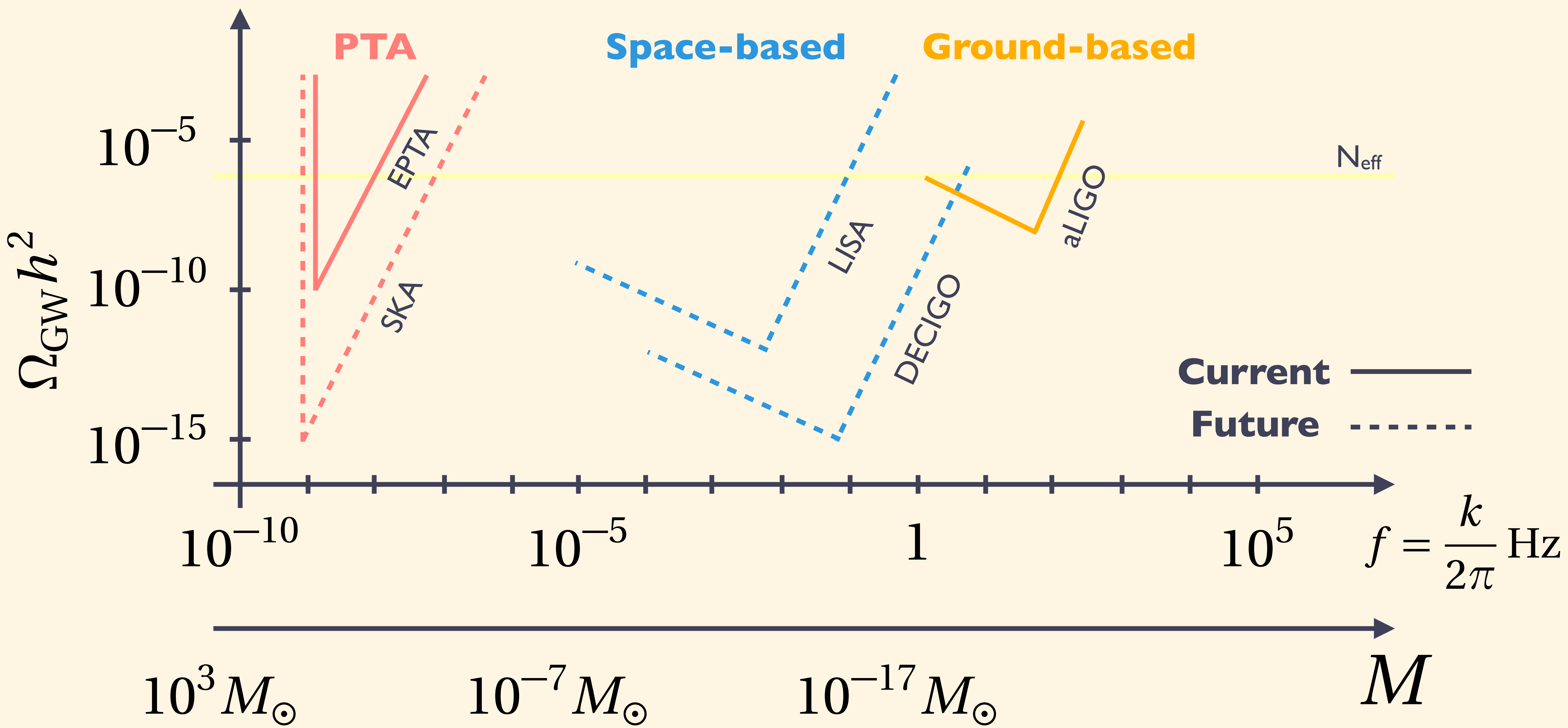
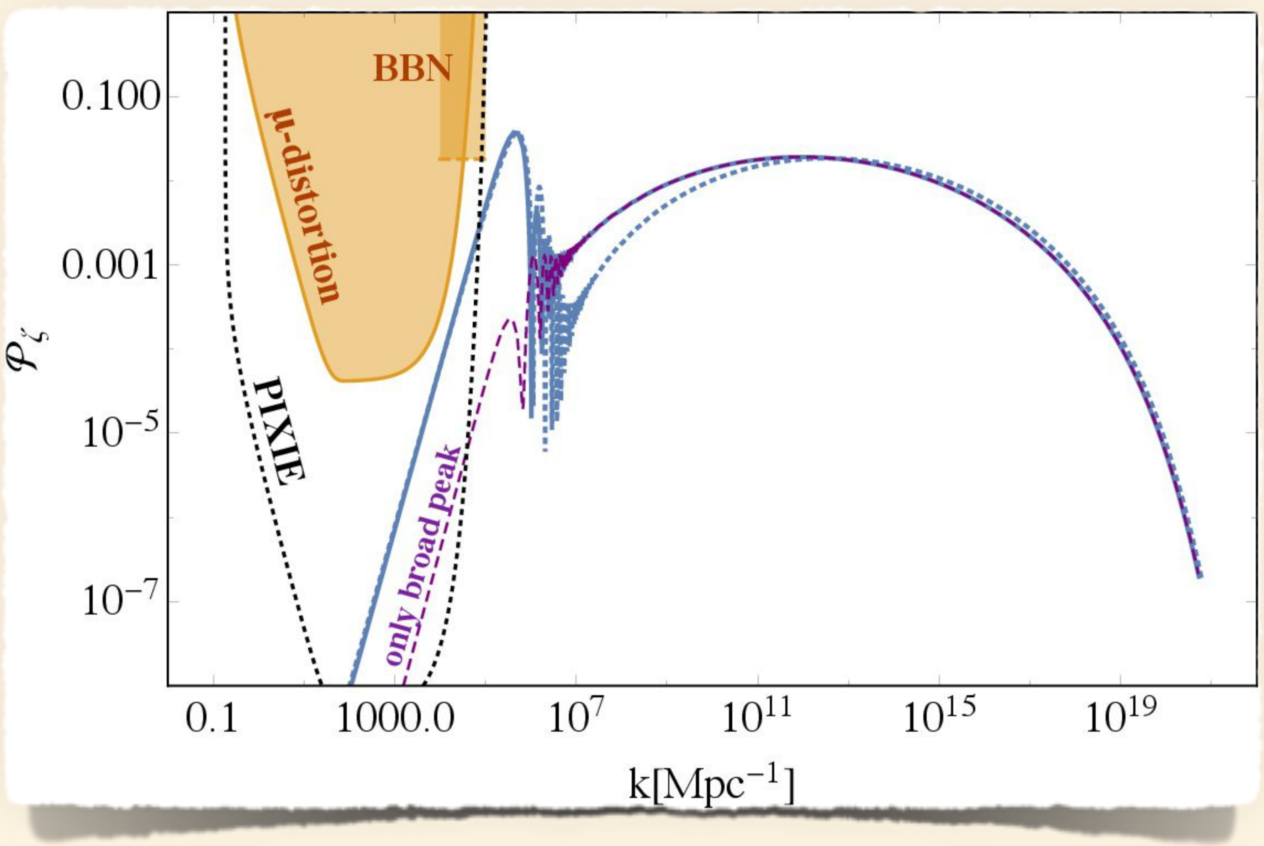
- Current and future observations of GWs

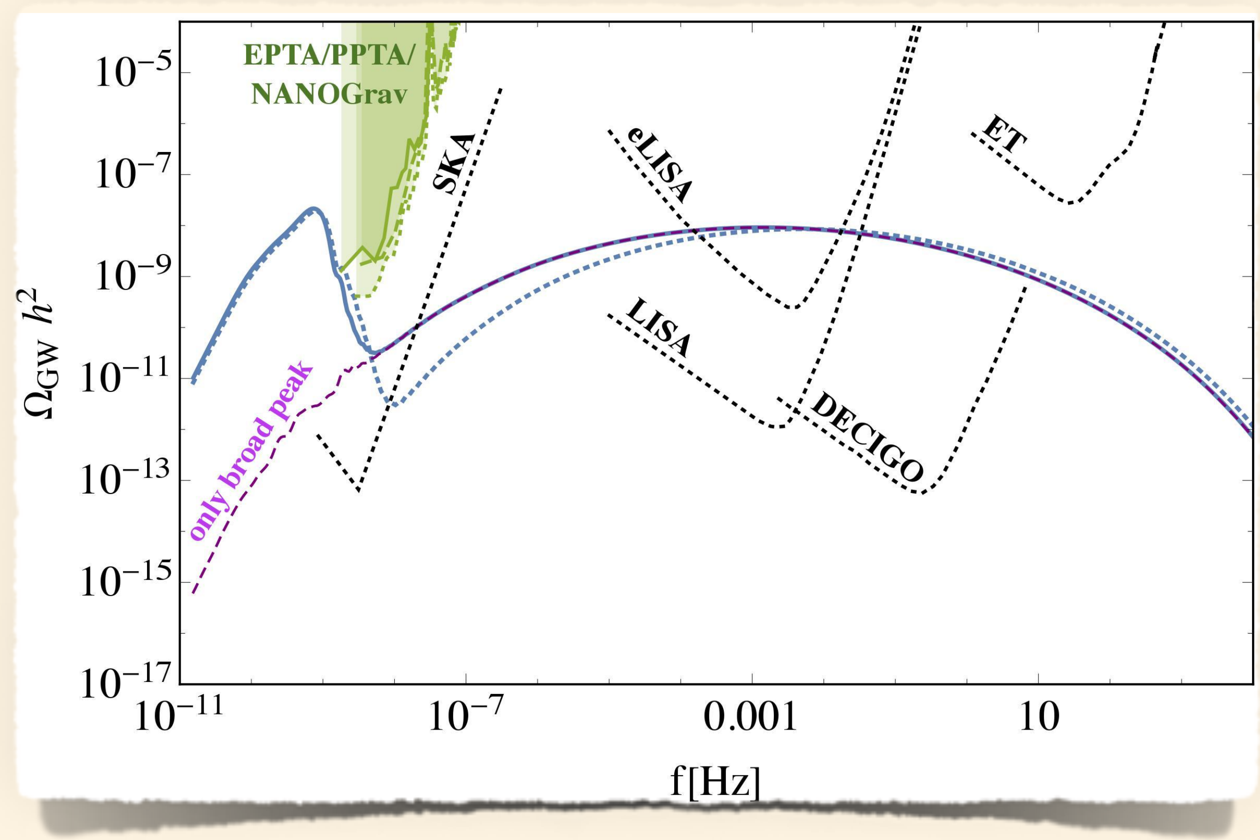


Induced GWs

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

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

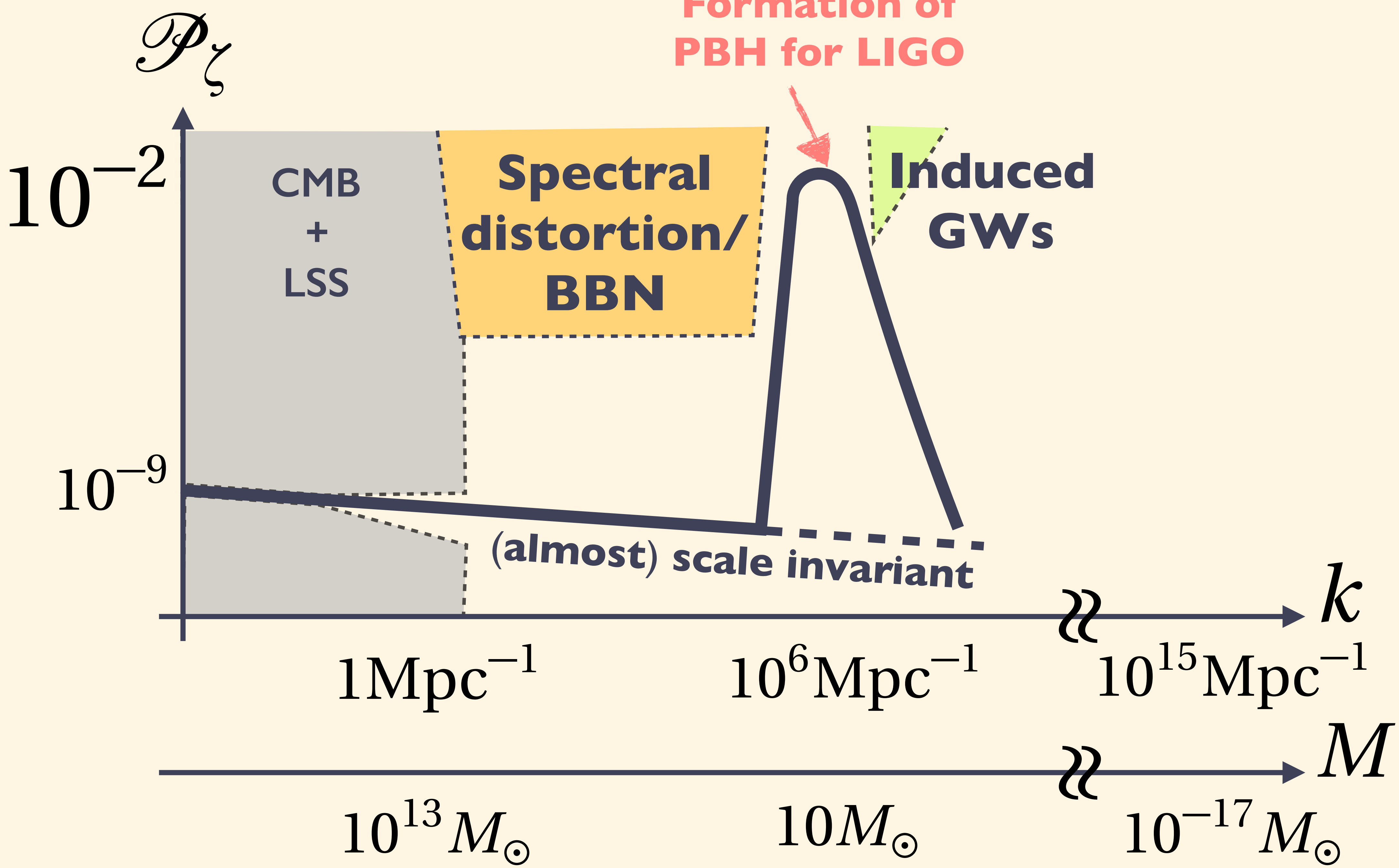




$$\Omega_{\rm GW}(k)h^2 \sim 10^{-9}\left(\frac{\mathcal{P}_\zeta(k)}{10^{-2}}\right)^2$$

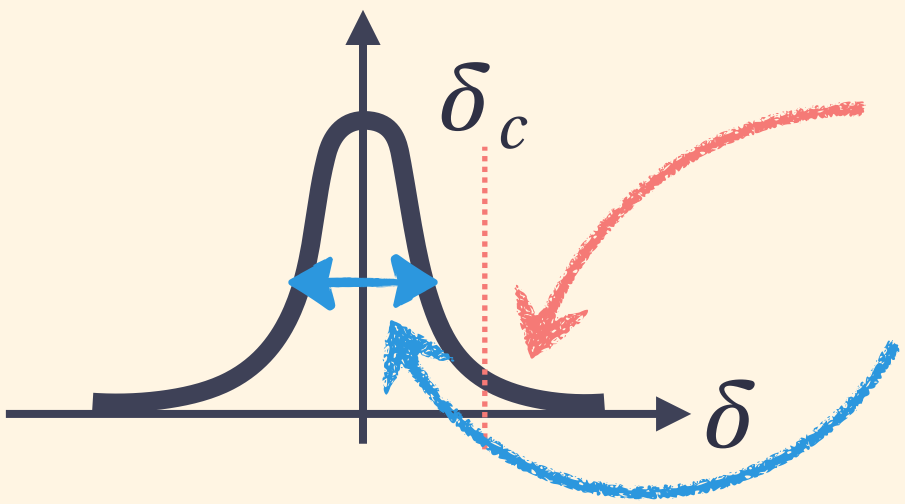
Enhanced Curvature Perturb.

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



Assume Gaussian P_ζ

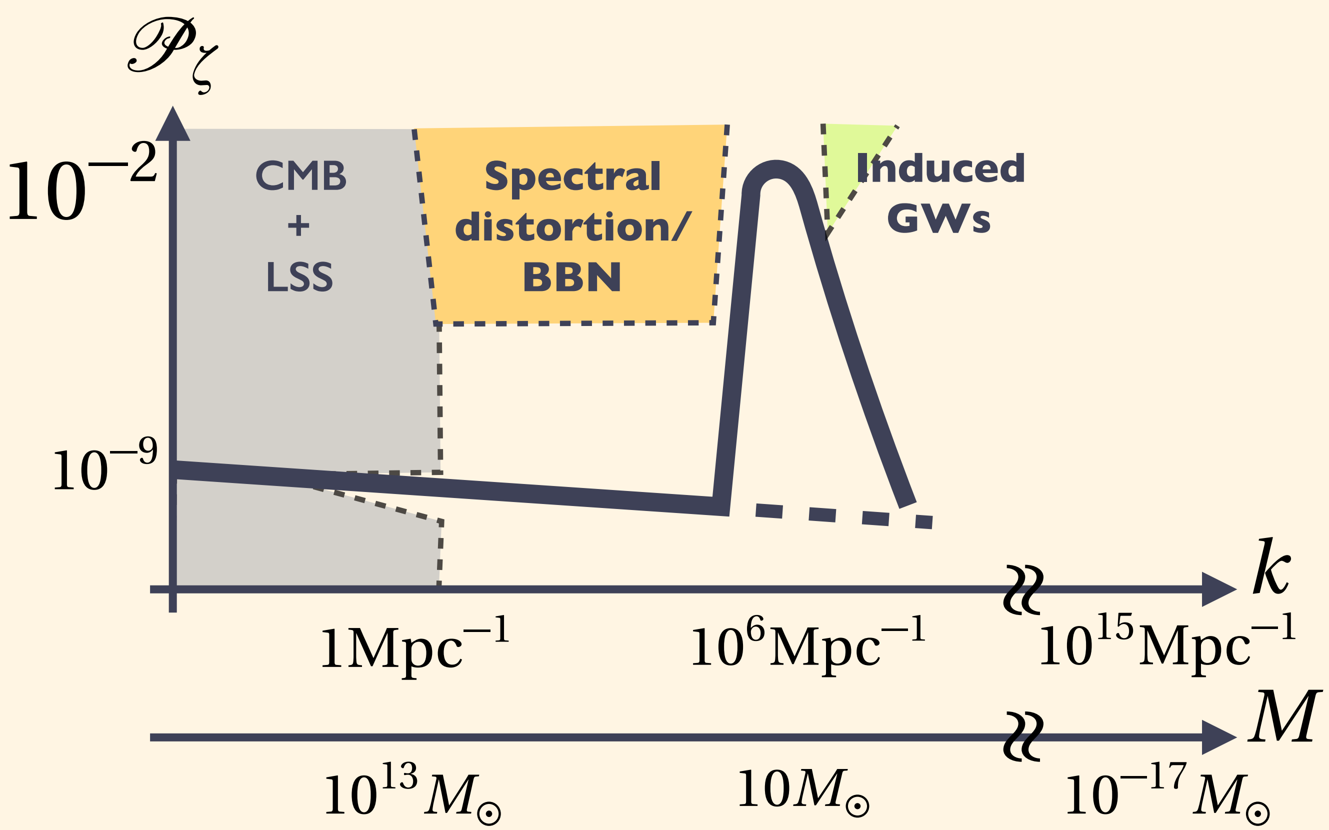
Constraints on $P_\zeta \leftrightarrow$ abundance of PBHs

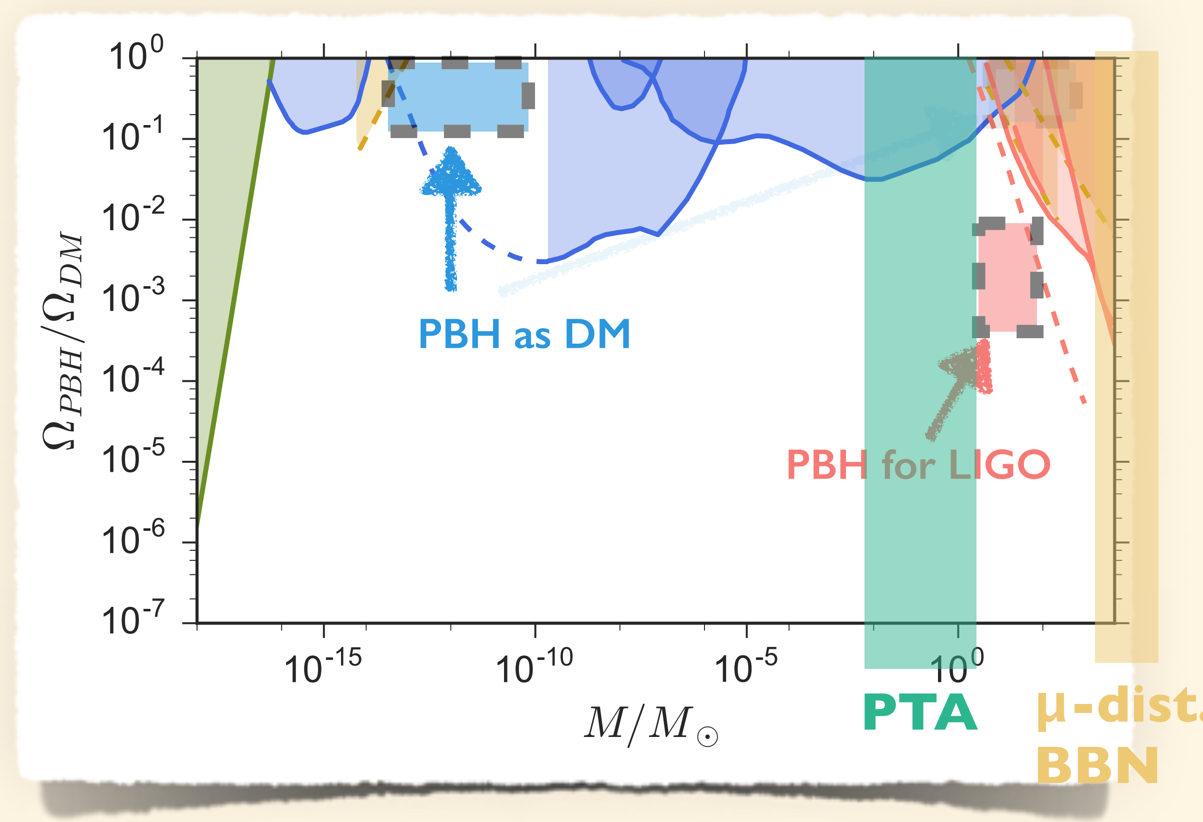


$$\beta(M) = \int_{\delta_c} \mathrm{d}\delta \frac{e^{-\frac{\delta^2}{2\sigma^2(M)}}}{\sqrt{2\pi\sigma^2(M)}} \sim \sigma(M) e^{-\frac{\delta_c^2}{2\sigma^2(M)}}$$

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

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

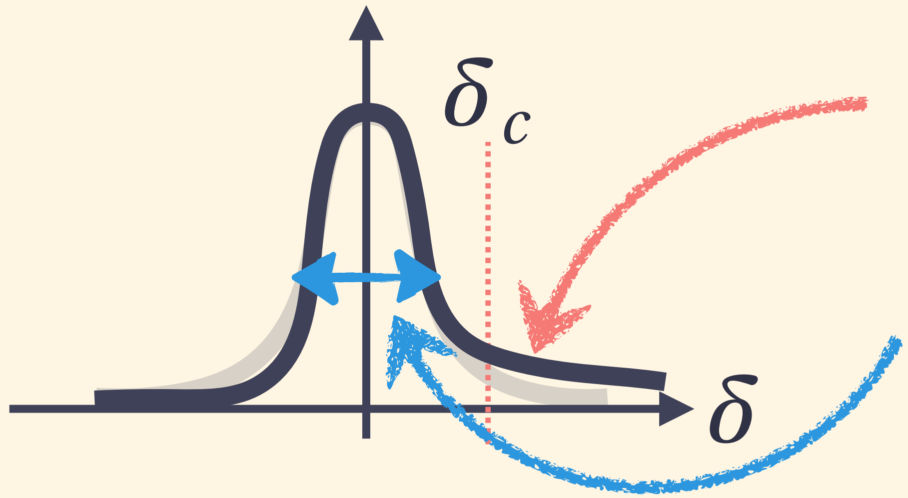




KM+1611.06130

Enhanced non-Gaussianity

We can **enhance** the tail while the width is fixed.



PBH formation

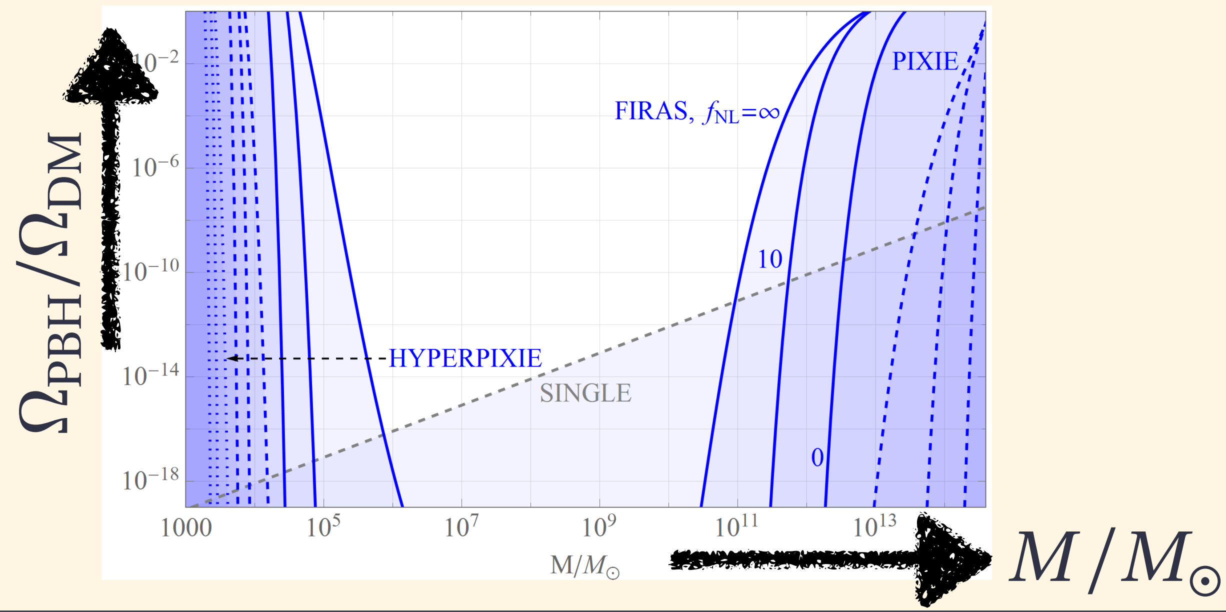
$$\beta(M) = \int_{\delta_c} \mathrm{d}\delta \frac{e^{-\frac{\delta^2}{2\sigma^2(M)}}}{\sqrt{2\pi\sigma^2(M)}} \sim \sigma(M) e^{-\frac{\delta_c^2}{2\sigma^2(M)}}$$

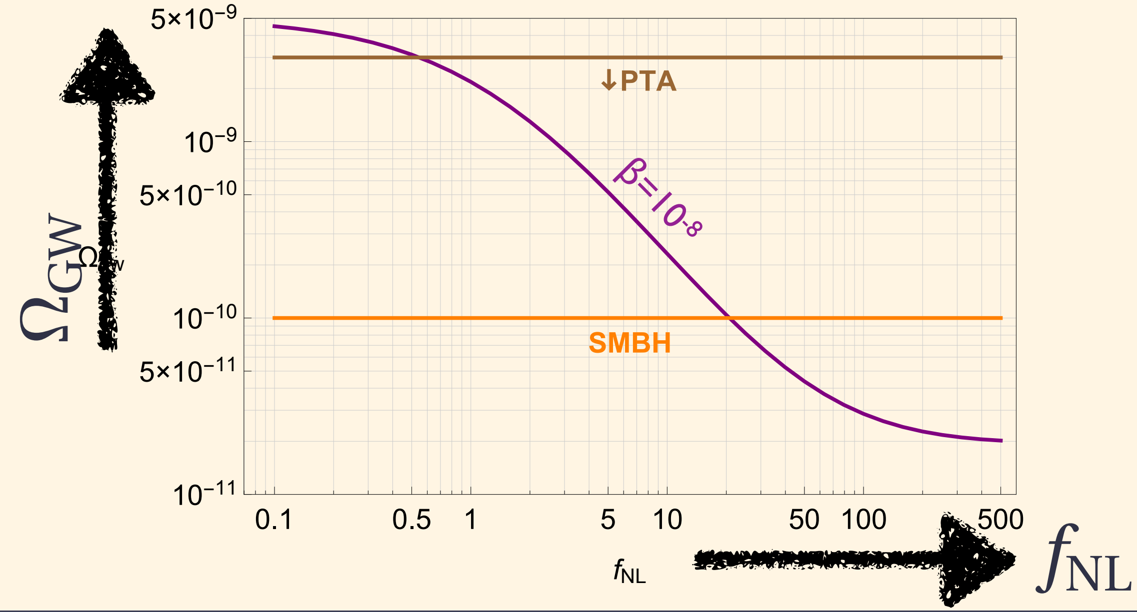
# of over-densities failed to form PBHs

- **spectral dist/BBN**
- **Gravitational Wave**
- **UCMH**

- Can enhance the PBH formation for a fixed # of over-densities.
  - ➡ Constraints from such over-densities become **weaker**.

Nakama+1612.06264, 1710.06945





Outline of Talk

- Introduction
- Constraints on PBHs from Inflation
- Inflation Models
- Summary

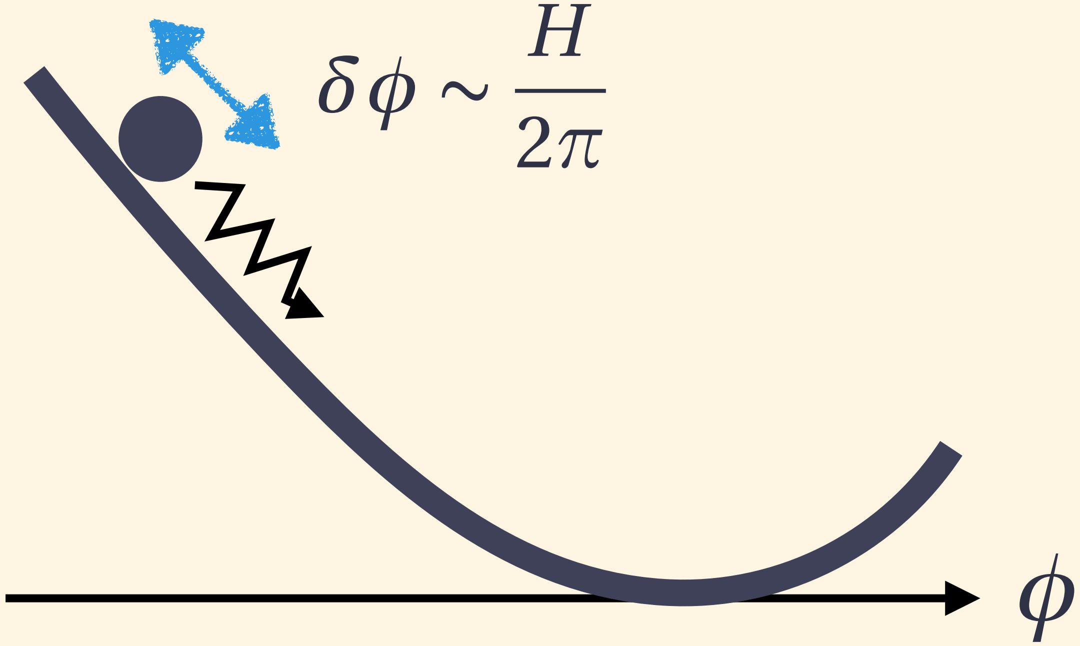
3.

Inflation Models

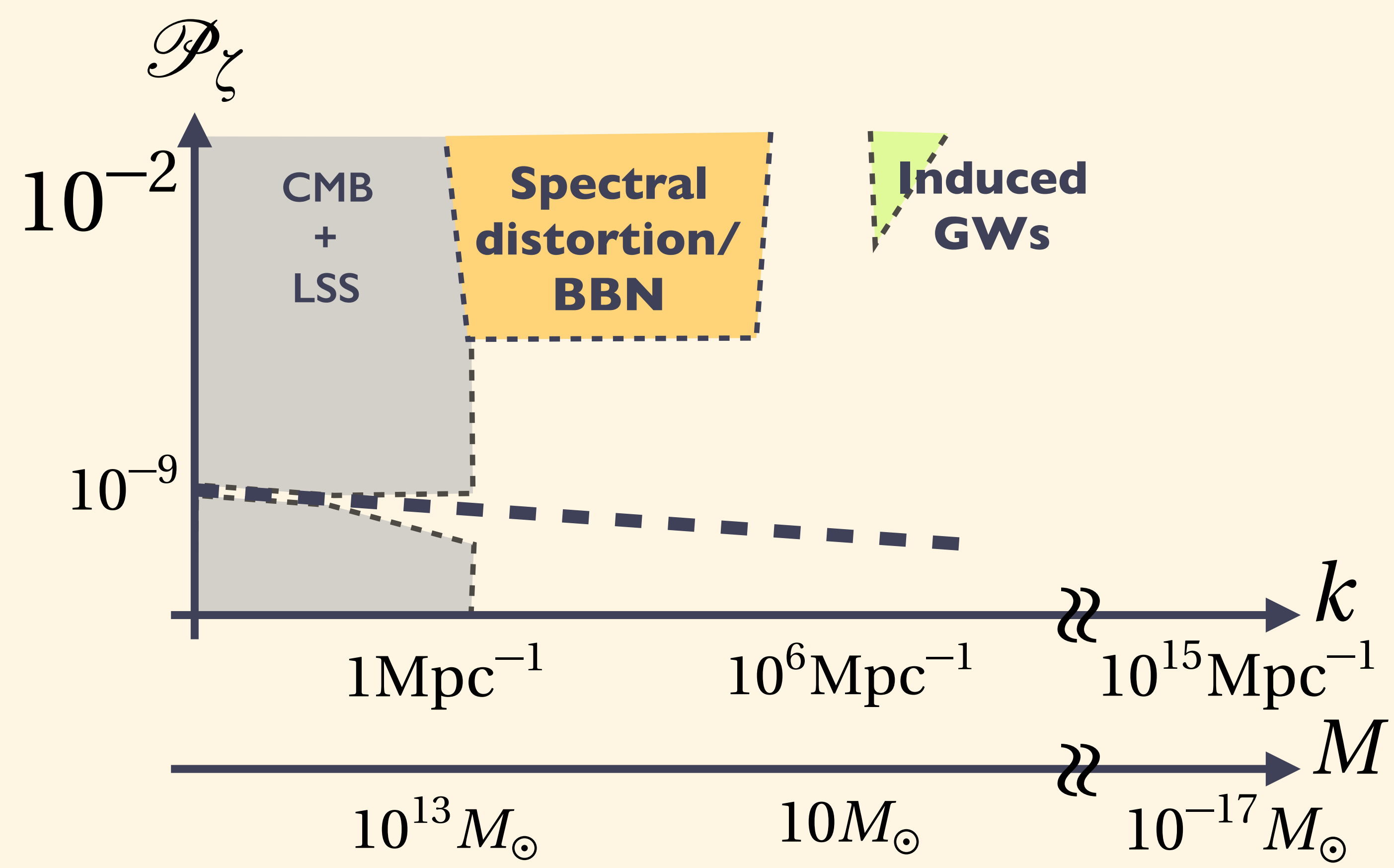
How to enhance Pζ ?

Flatten your potential

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



$$\zeta \sim \frac{\delta\rho}{\rho} \sim H\delta t \sim H\frac{\delta\phi}{\dot{\phi}} \sim \frac{V^{3/2}}{V' M_{\rm Pl}^3}$$



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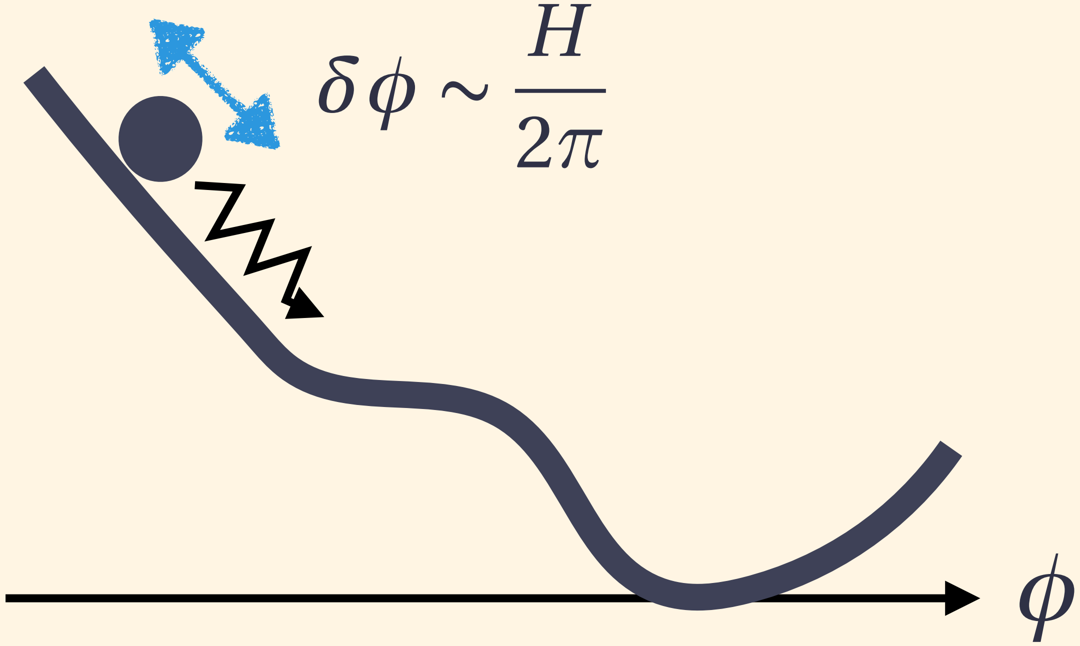

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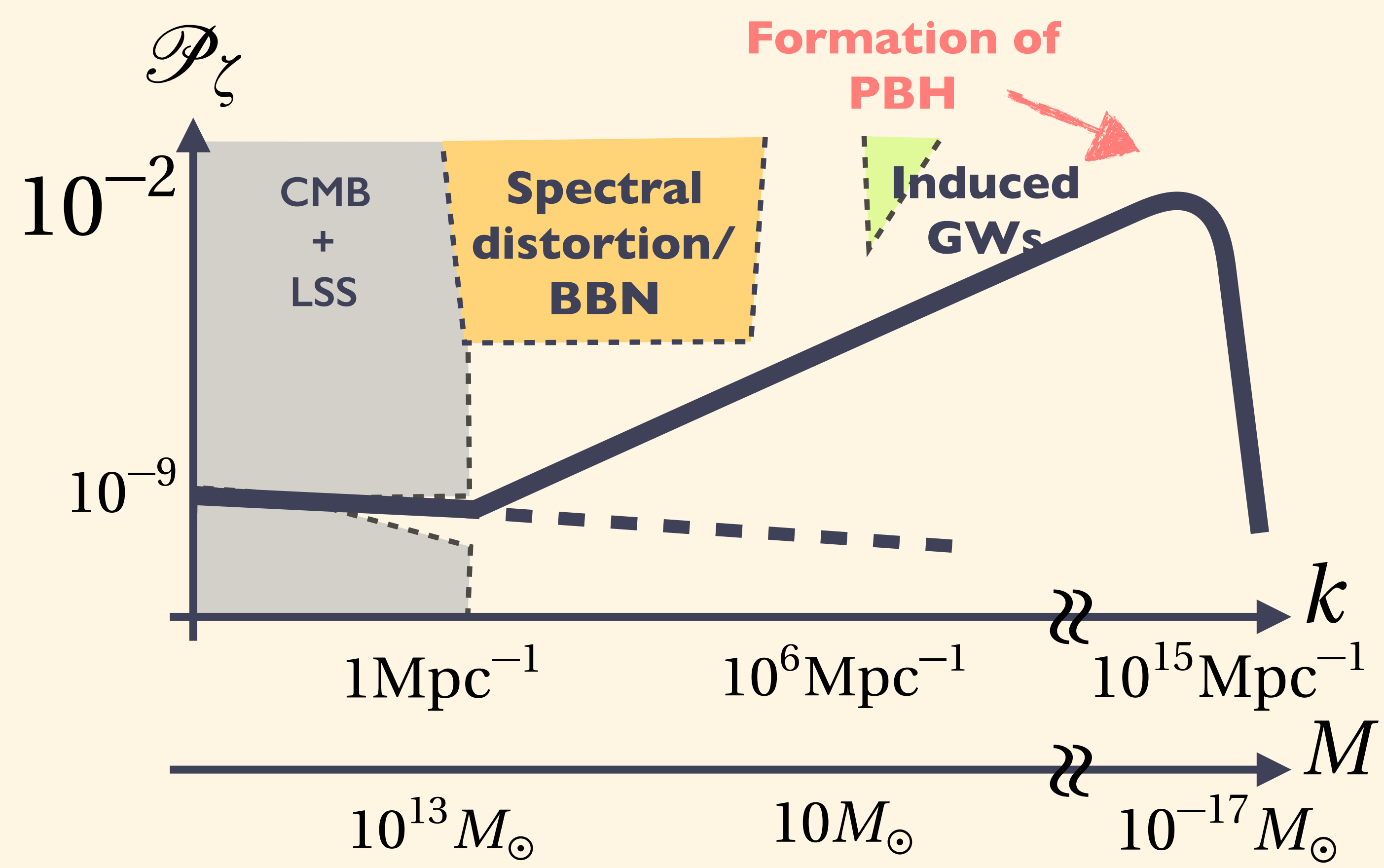

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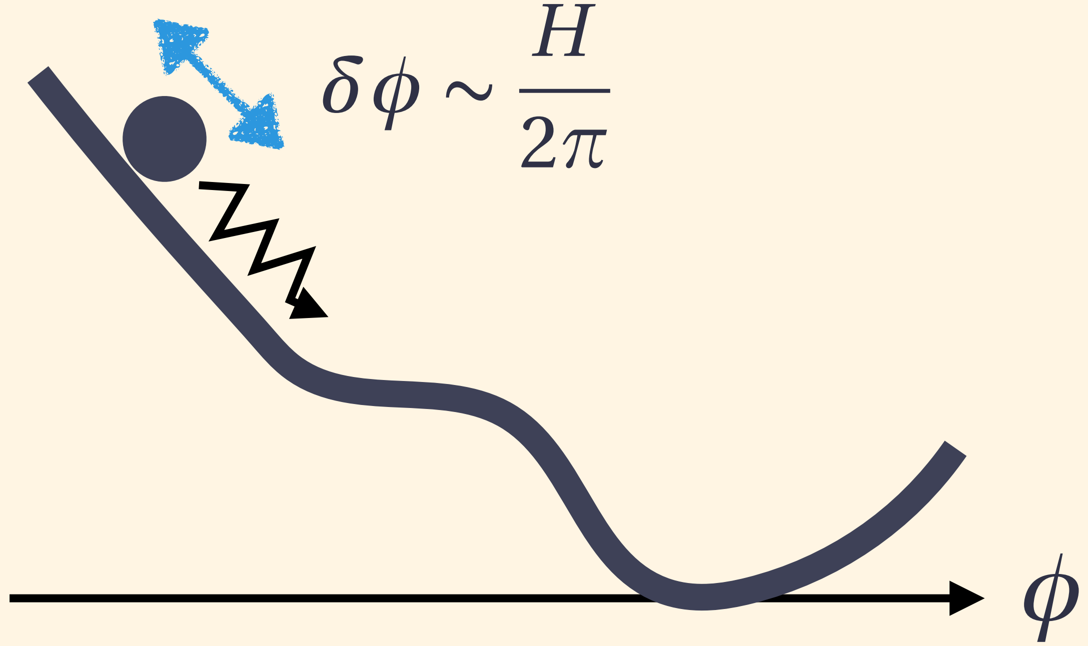
- Single-field inflation for the total e-folds of N = 50-60
  - Single-field **slow-roll** inflation for PBH DM (M > 10^{15} g) is **ruled out!** Motohashi+1706.06784

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

➡ Quantum diffusion, non-Ganssianity? Pattison+ 1707.00537, Biagetti+ 1804.07124

$$\delta\phi \sim \frac{H}{2\pi}$$



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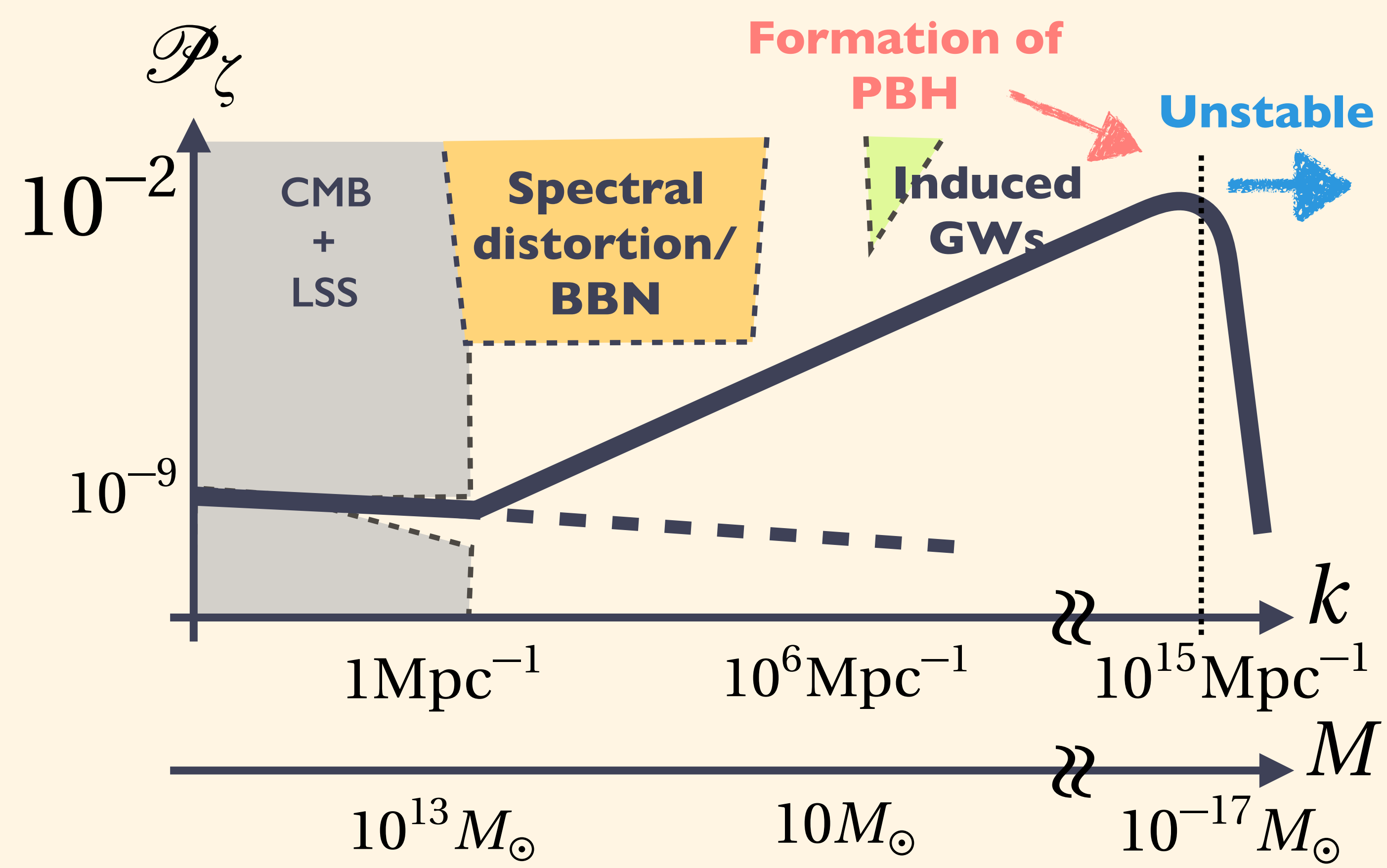

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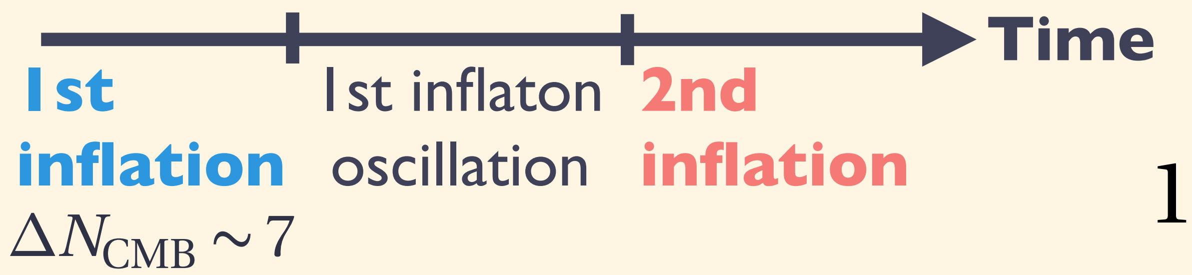

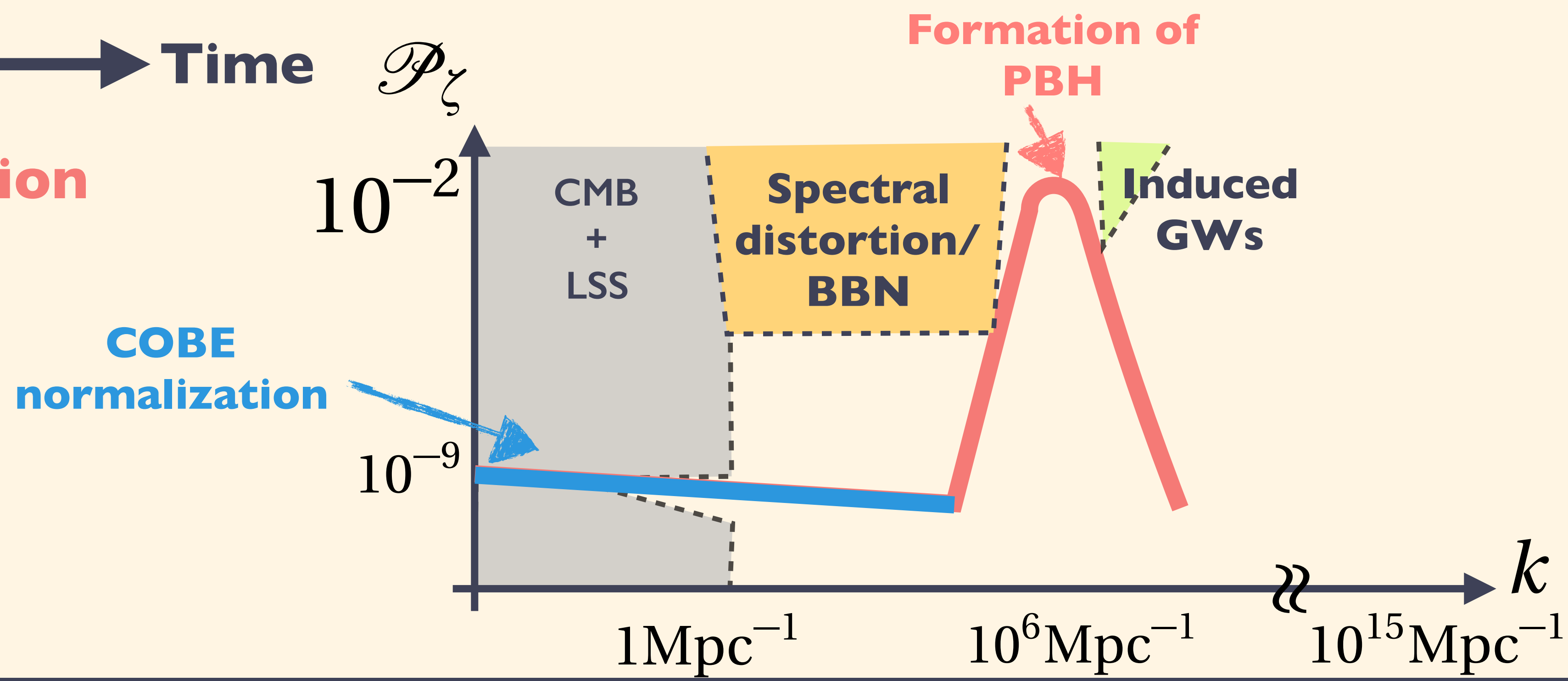

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Time

1st inflation	1st inflaton oscillation	2nd inflation
$\Delta N_{\rm CMB} \sim 7$		

Slow-roll is strongly violated

Multi-**fields** dynamics

- Gauge preheating, Curvaton,…

$\phi F \tilde{F}$

Domcke+1704.03464

Higgs: Espinosa+ 1710.11196,
Axion-like: **KM**+ 1711.08956

Enhanced **non-Gaussianity** can be obtained.

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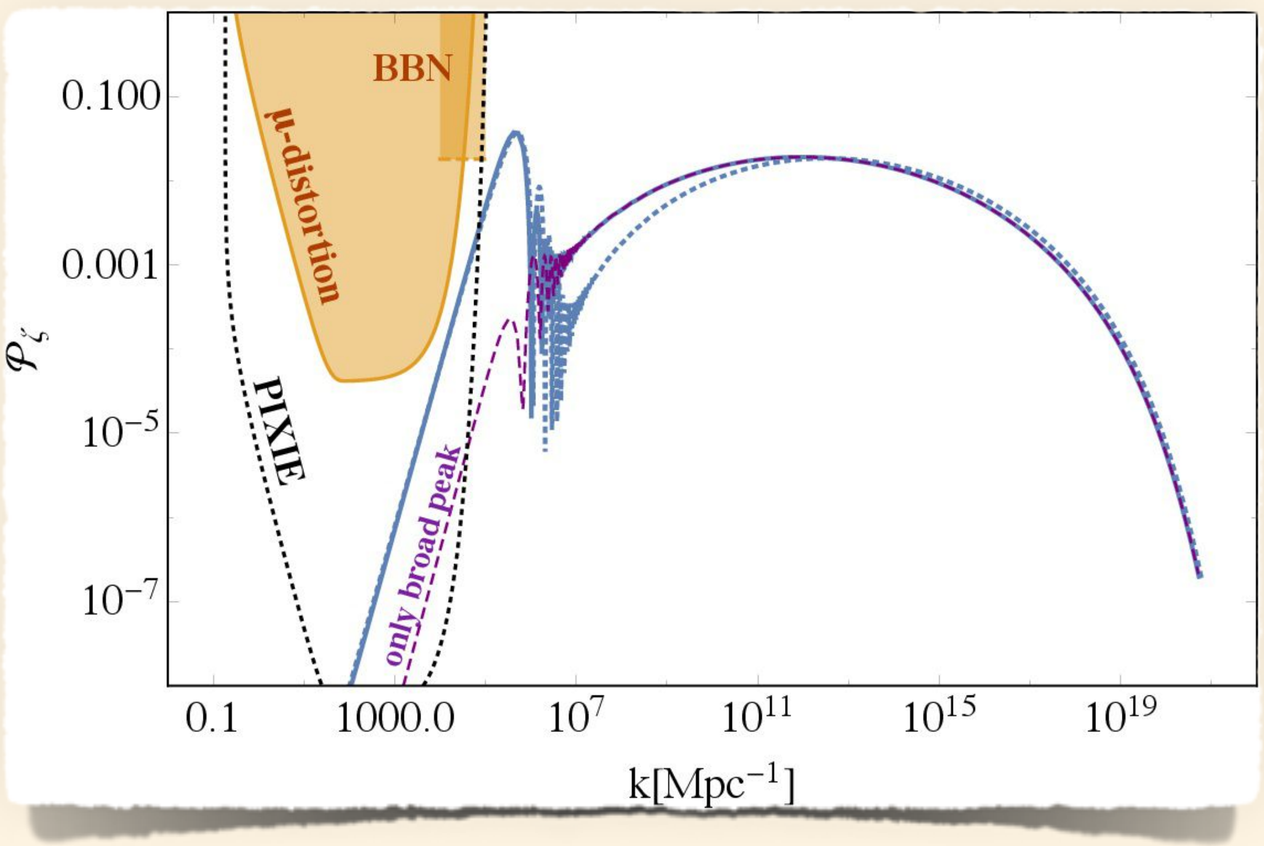
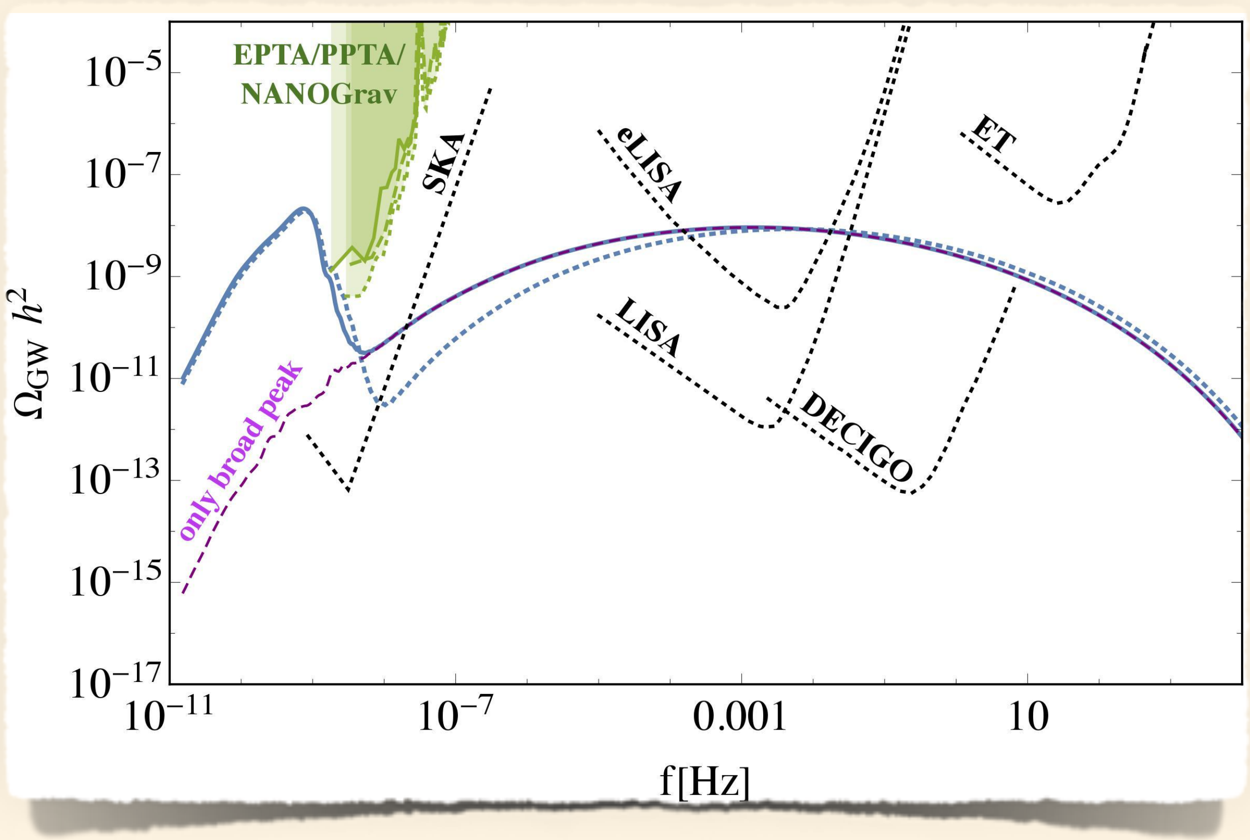
Double Inflation

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

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





KM+1611.06130, 1701.02544

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

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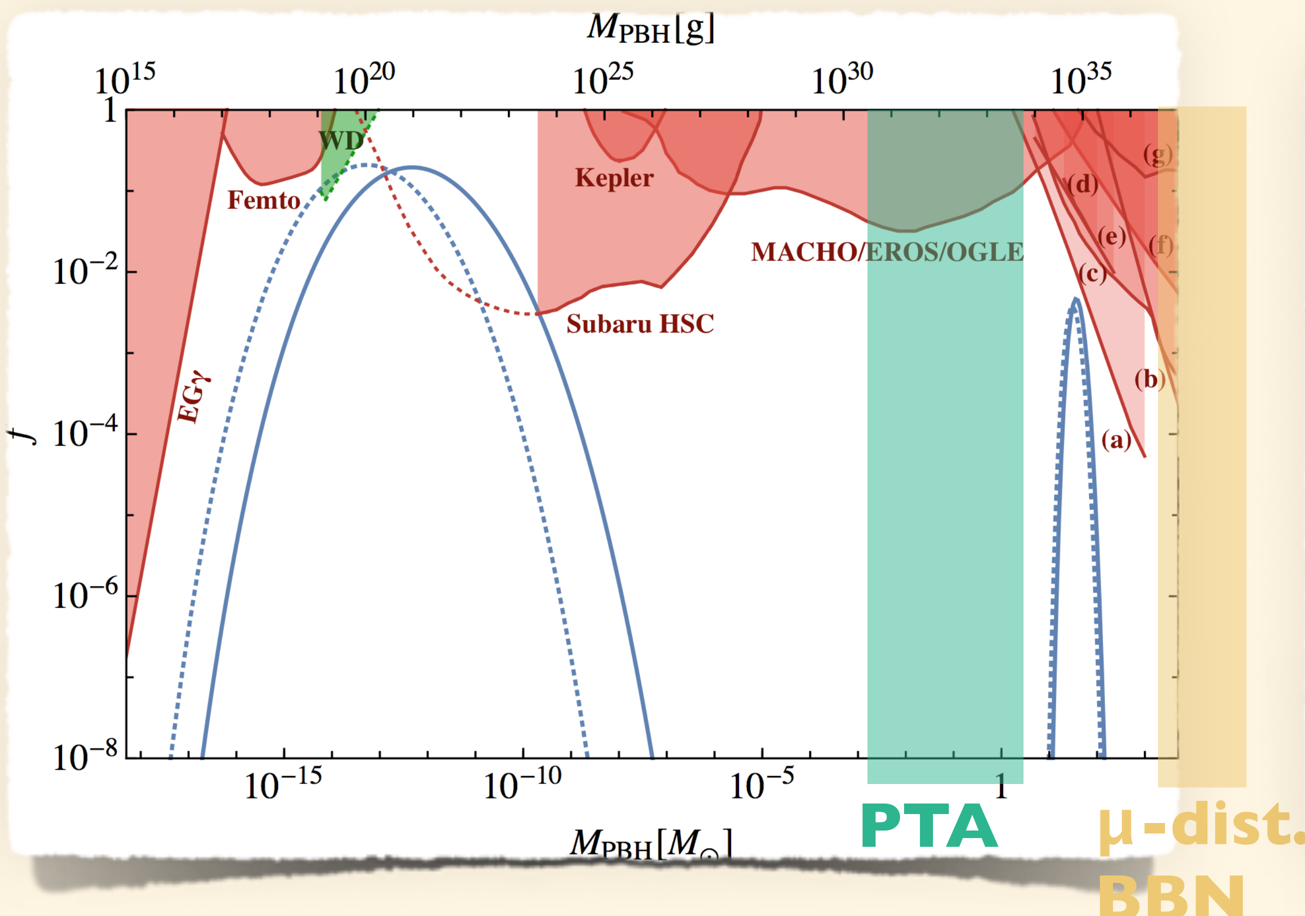

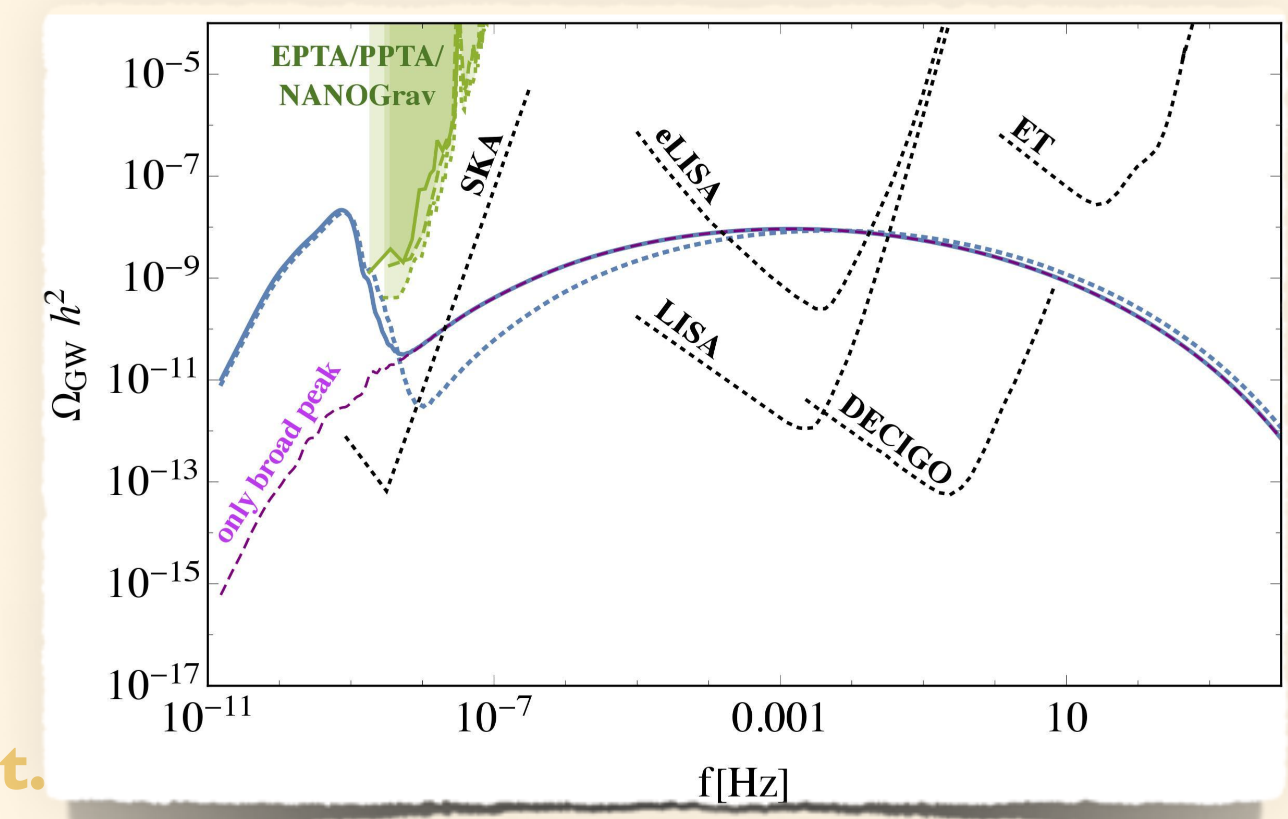

KM+1611.06130, 1701.02544

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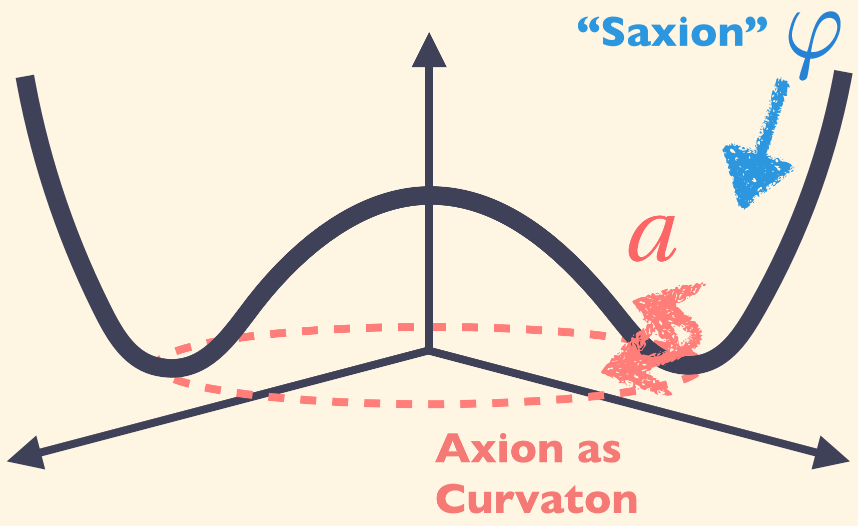
- PBHs for DM → **eLISA** and LISA.

Axion-like Curvaton

PBHs for LIGO from **Axion-like Curvaton**

- **Blue-tilted spectrum** of "axion" from "saxion" dynamics



Curvature perturb.

$$\zeta = -H\frac{\delta\rho}{\dot\rho} \simeq \frac{\delta\rho_a}{4\rho_r + 3\rho_a} = \frac{r}{4+3r}\frac{\delta\rho_a}{\rho_a} \quad \text{w/} \quad r = \frac{\rho_a}{\rho_r}$$

Blue-tilted via $\varphi : M_{\rm Pl} \to f_a$ during inflation

$$\rho_a \propto a^2,\ \delta\rho_a \propto 2a\delta a \quad \text{w/} \quad a = \varphi\theta,\ \delta a = \frac{H_{\rm inf}}{2\pi}$$

$$\mathscr{P}_\zeta = \left(\frac{2r}{4+3r}\right)^2\left(\frac{H_{\rm inf}}{2\pi\varphi\theta}\right)^2 \propto r^2\varphi^{-2}$$

- **Non-Gaussianity**

$$f_{\rm NL} = \frac{5}{12}\left(-3 + \frac{4}{r} + \frac{8}{4+3r}\right) \sim \frac{5}{3r}$$

Tension…

PBH formation → Large r

v.s.

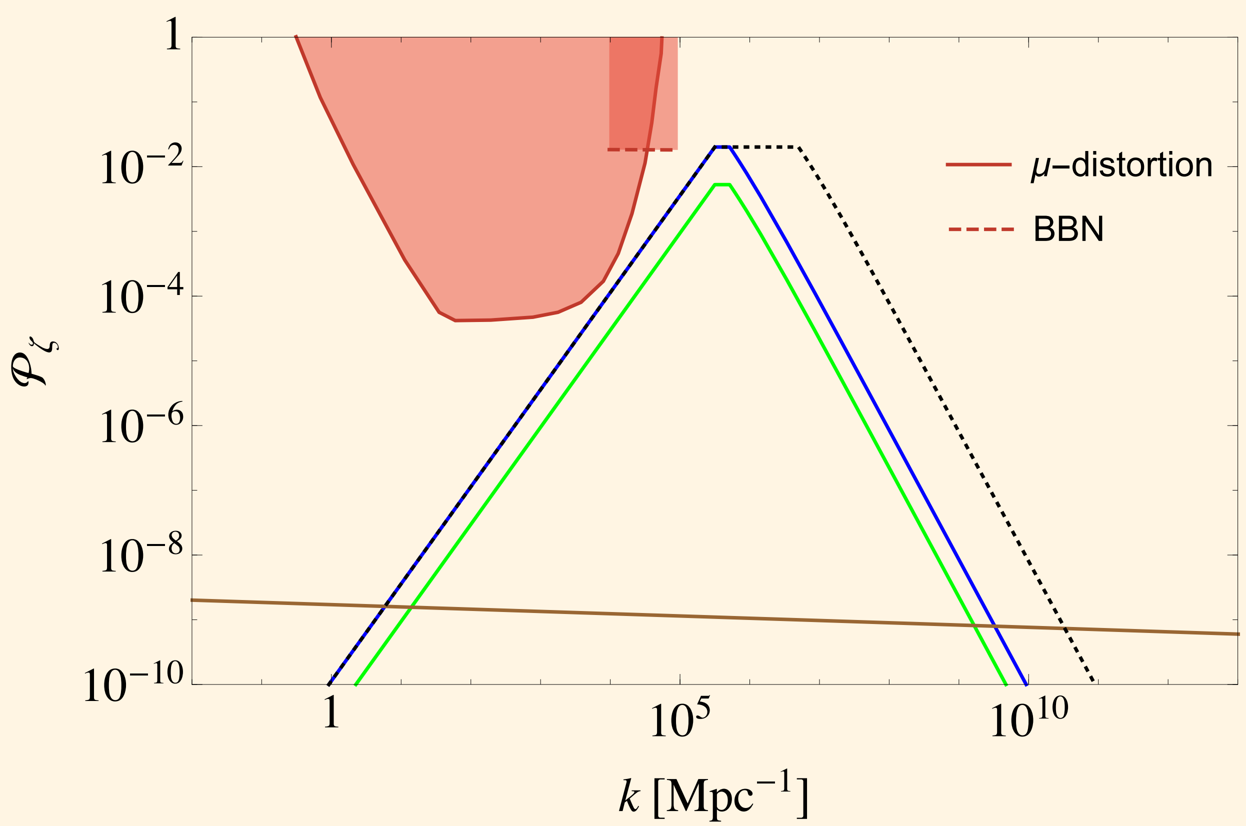
Suppress GWs/μ-dist. → non-Gaussianity → Small r

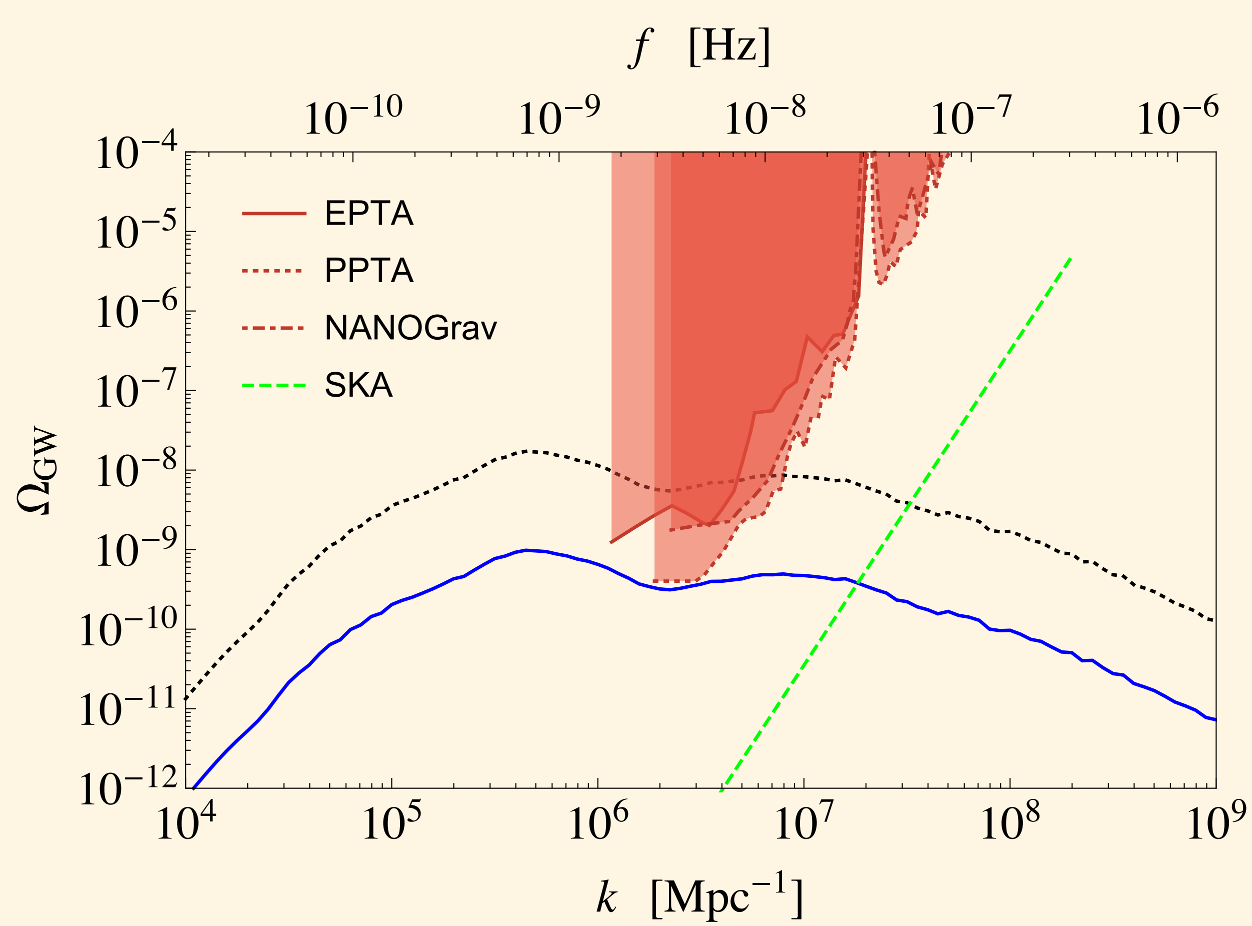
Axion-like Curvaton

PBHs for LIGO from **Axion-like Curvaton**

- **non-Gaussianity** cannot be so large… **KM**+ 1711.08956

$$f_{\rm NL} \propto 1/r \qquad \text{v.s.} \qquad \mathscr{P}_\zeta \propto r^2$$





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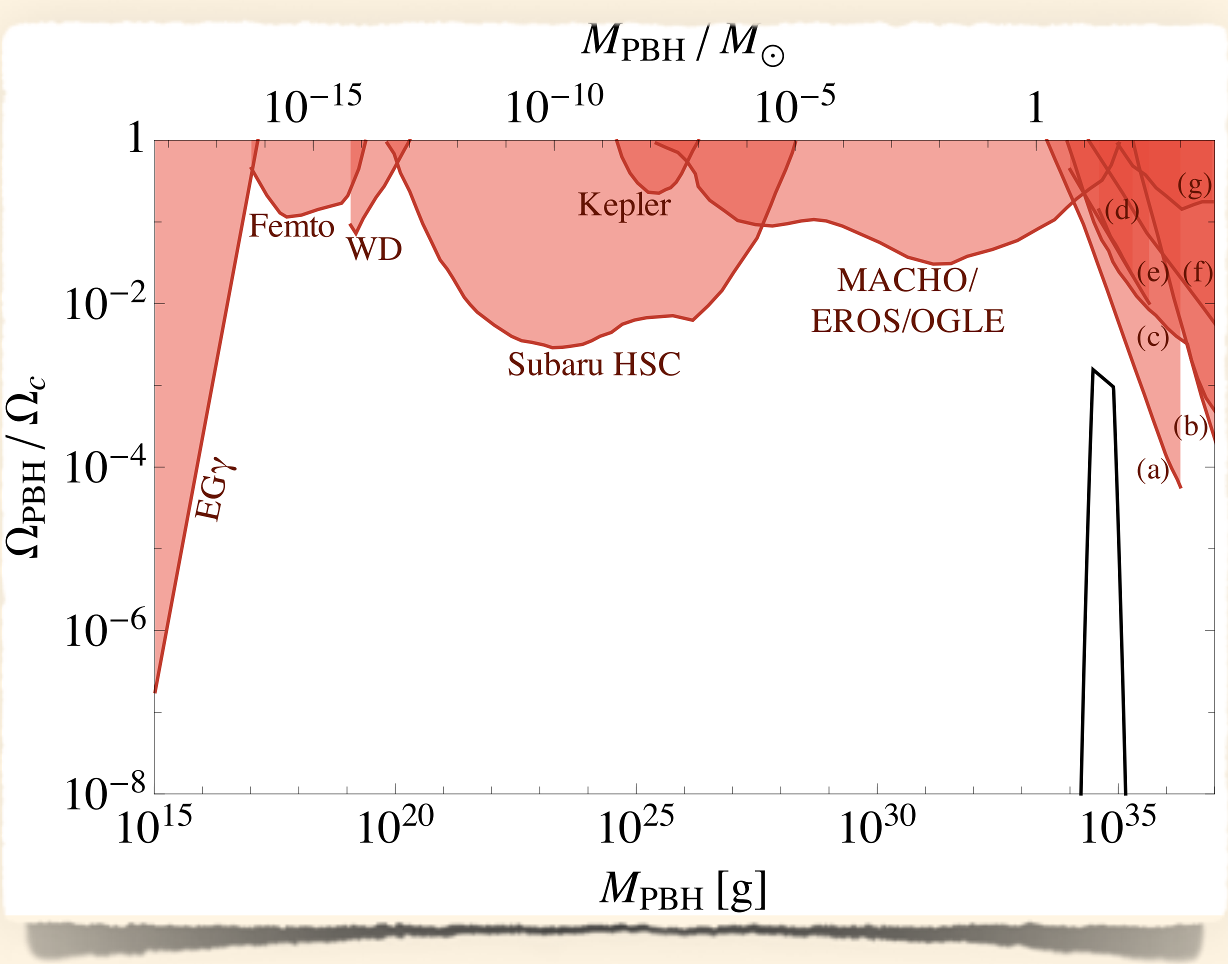
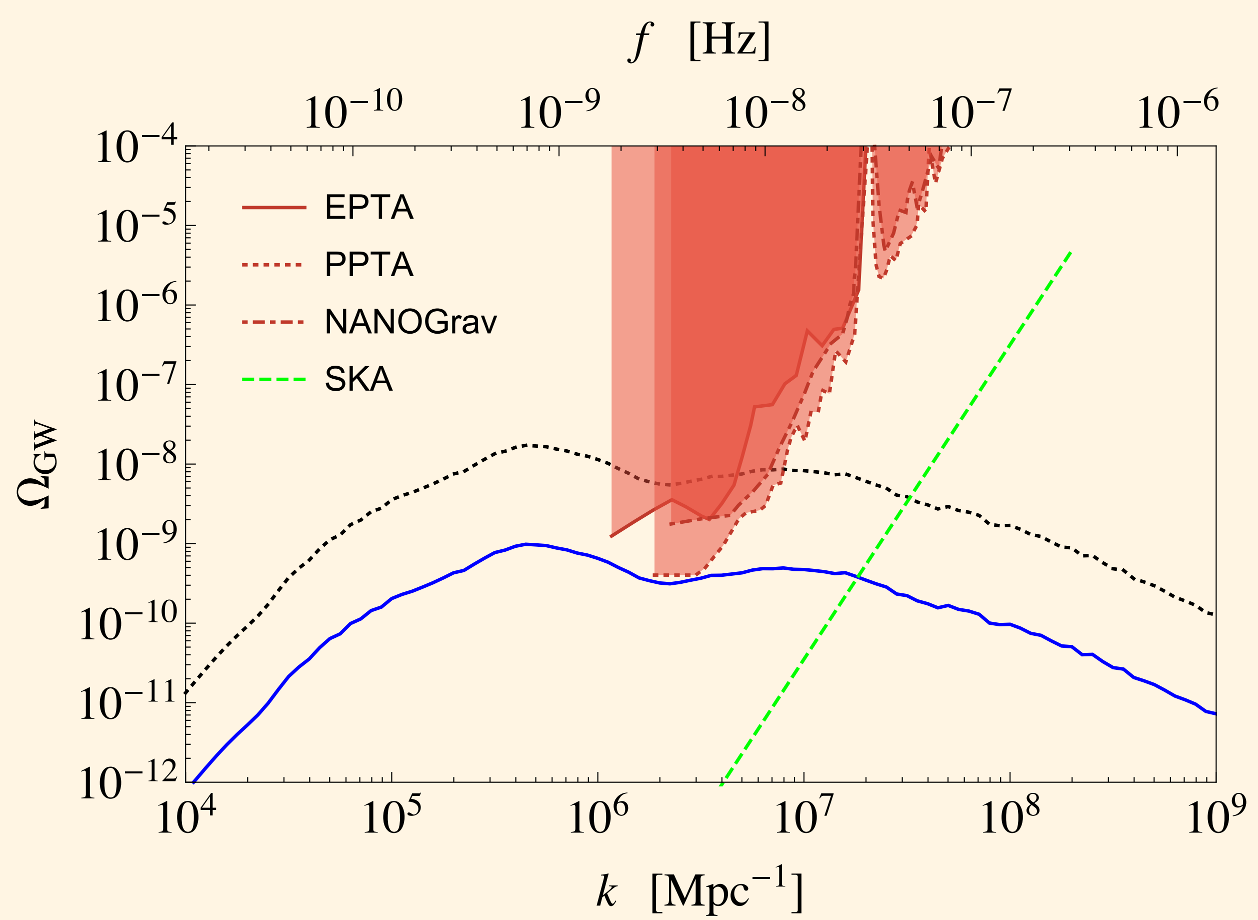




4.

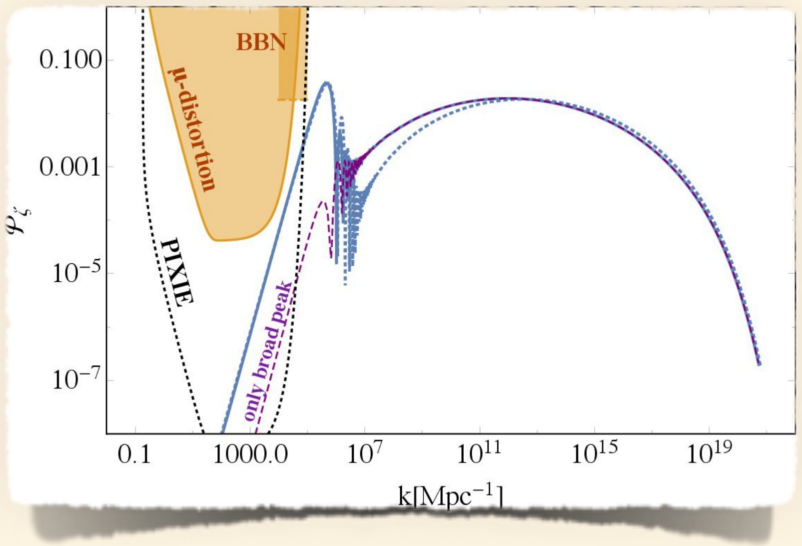
Summary

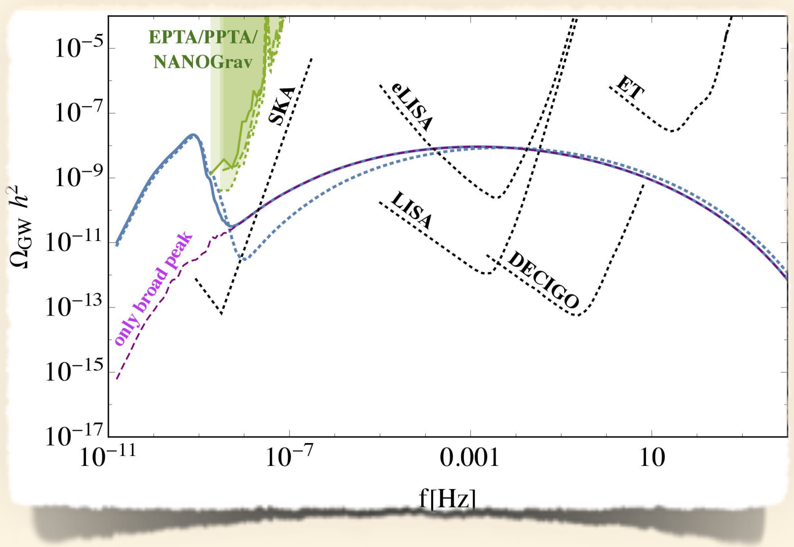
Summary

Inflation for PBHs needs **LARGE δρ/ρ** $\gg 10^{-5}$.

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 @ ~10^6 Mpc^{-1}; eLISA @ 10^{11}-10^{13} Mpc^{-1}
- **UCMHs**…depends on models and DM profile.





Almost **Gaussian**

➡ PBHs for DM @ ~10^{20} g → eLISA/LISA; @ O(10) solarmass → marginal… PTA and spectral distortion.

➡ PBHs for LIGO → same as PBHs for DM @ O(10) solarmass

KM+1611.06130, 1701.02544

Large non-Gaussianity → currently safe, model building?

e.g., Domcke+1704.03464, Espinosa+ 1710.11196, **KM**+ 1711.08956

Backup

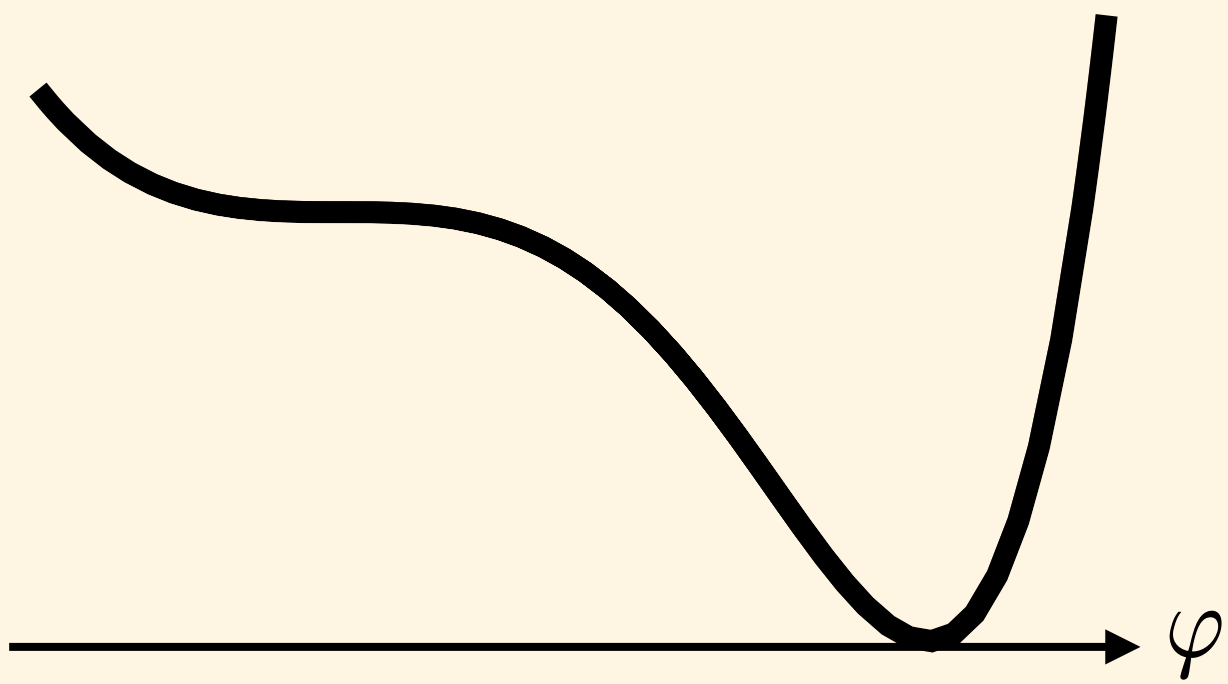
Double Inflation

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

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

$$V(\varphi,\chi) = V_{\rm pre}(\chi) - 2\sqrt{2}c\,v^2\varphi - \frac{\kappa}{2}v^4\varphi^2 + \left(v^2 - \frac{g}{2^{\frac{3}{2}}}\varphi^3\right)^2 + \frac{1}{2}c_{\rm pot}V_{\rm pre}(\chi)\varphi^2$$

$$\mathcal{L}_{\rm kin} = -\frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi + \frac{c_{\rm kin}}{4}\left(\partial_\mu\chi\partial^\mu\chi\right)\varphi^2 + \cdots.$$



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$$
\begin{aligned}
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\end{aligned}
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$$
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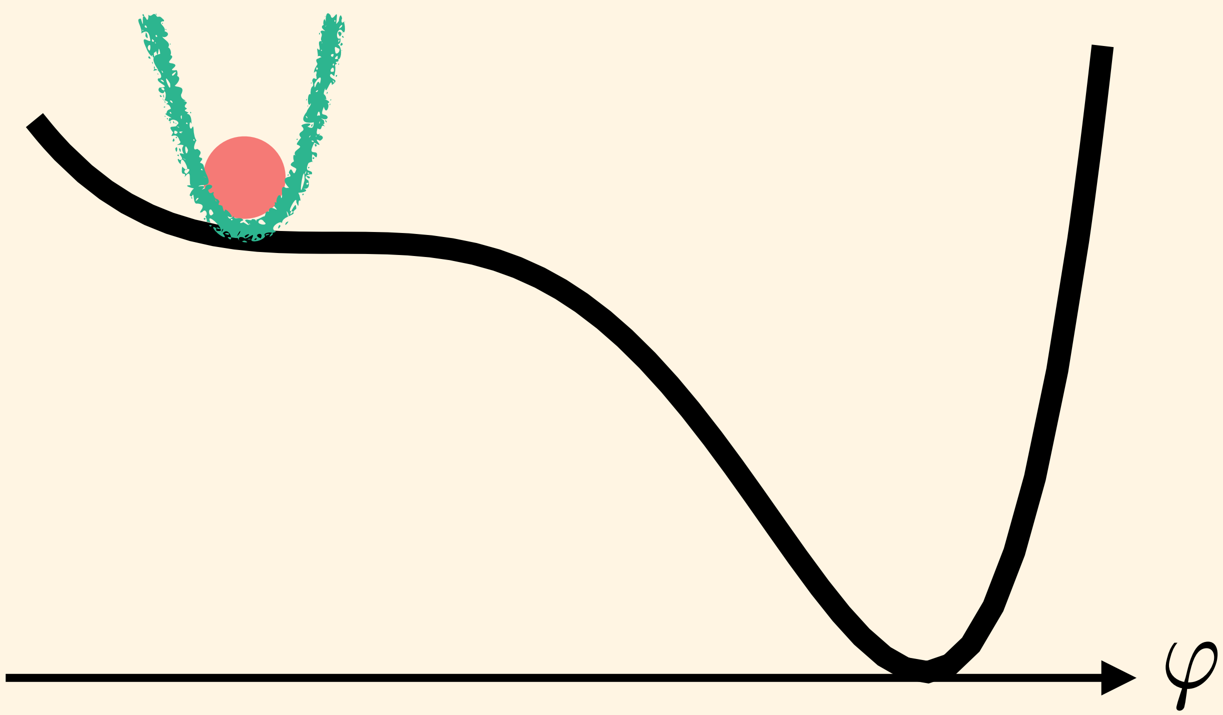
$$

Hubble-induced mass



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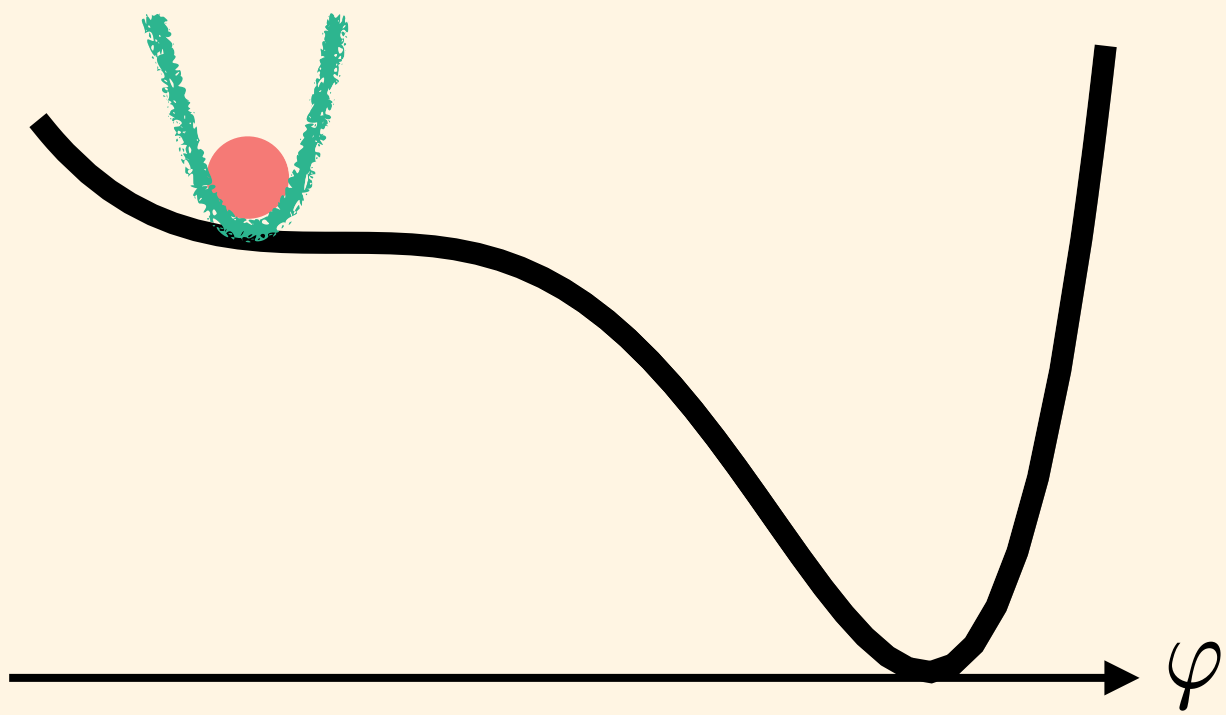

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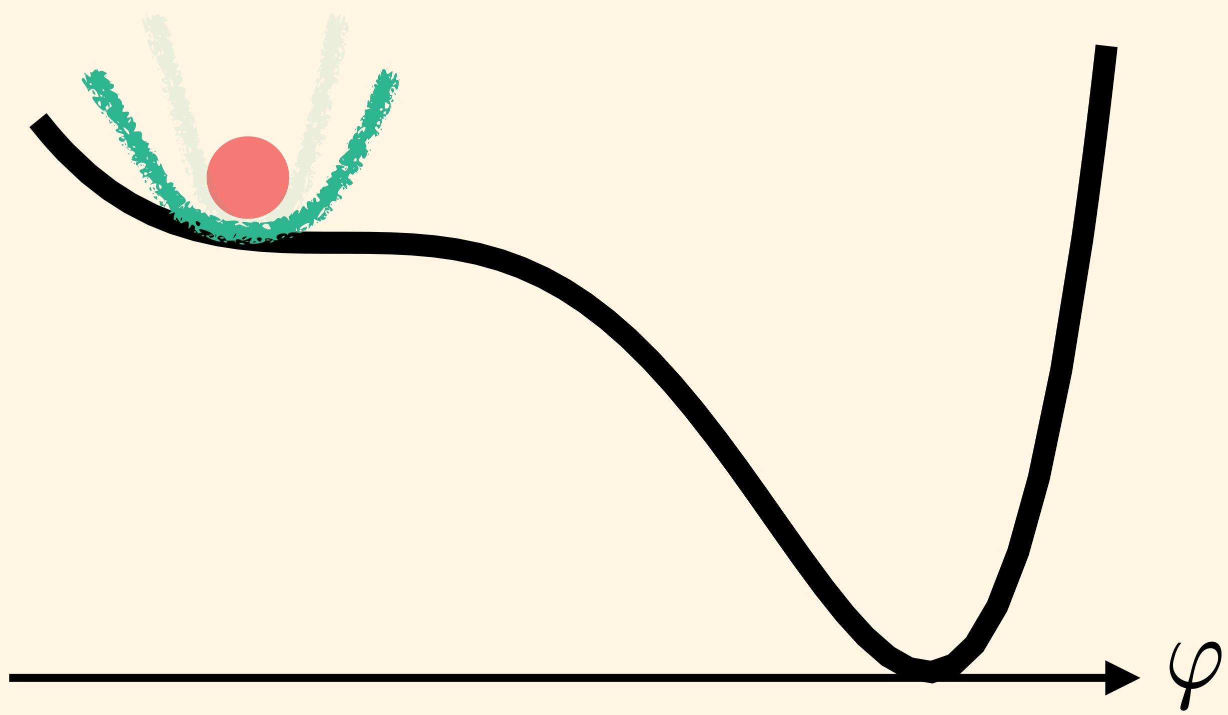

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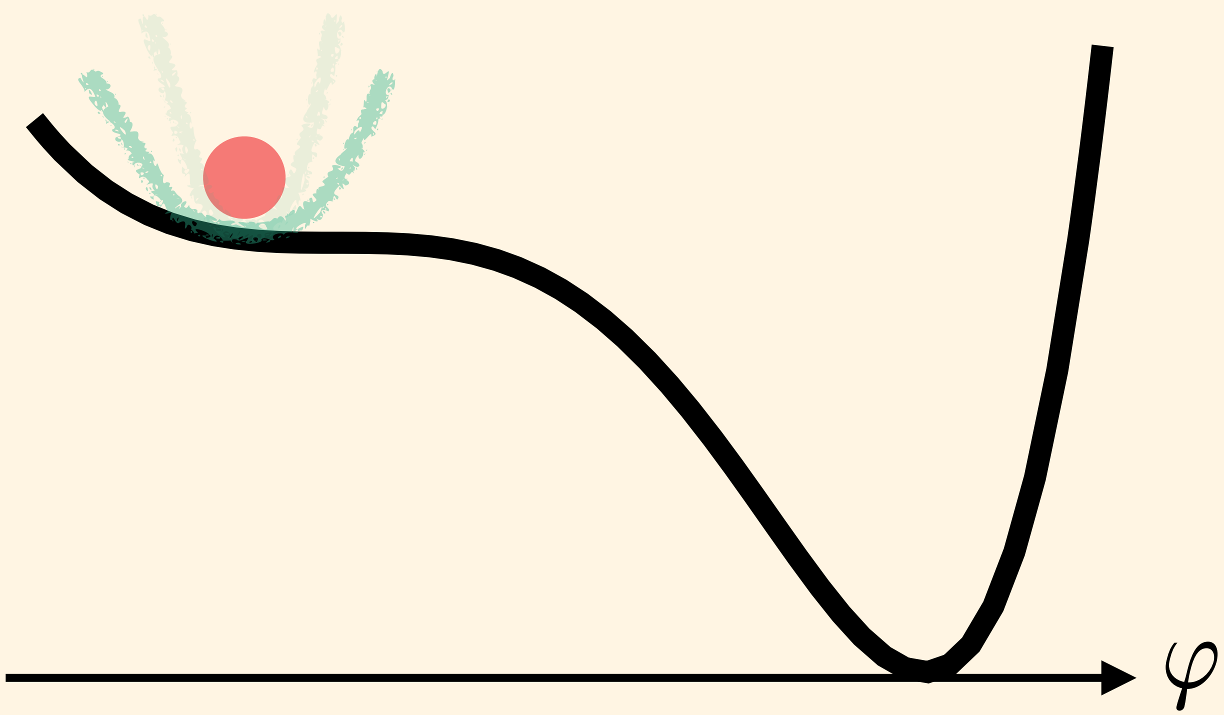

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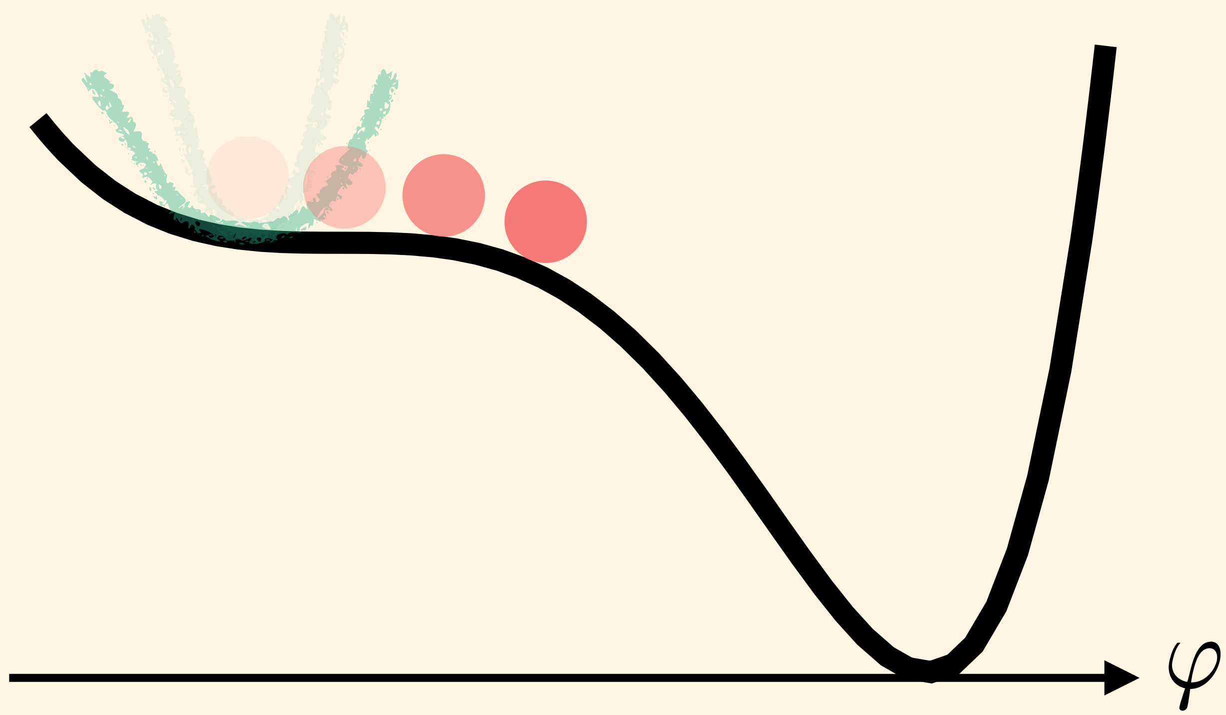

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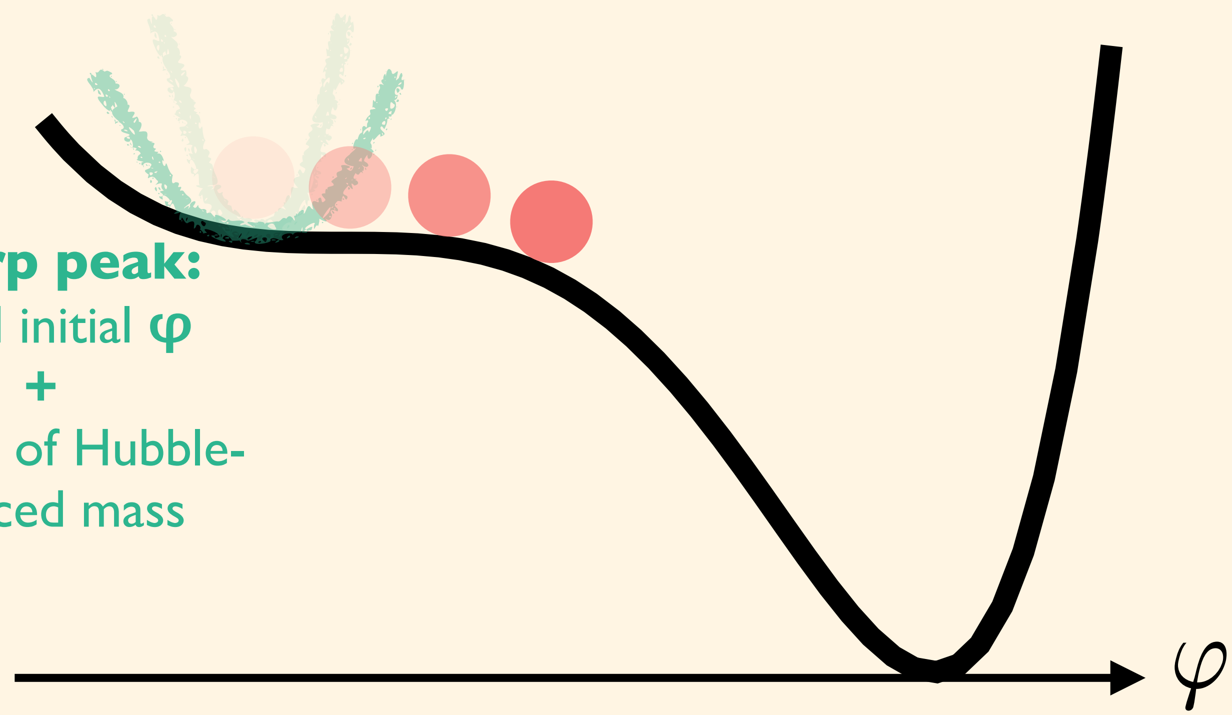
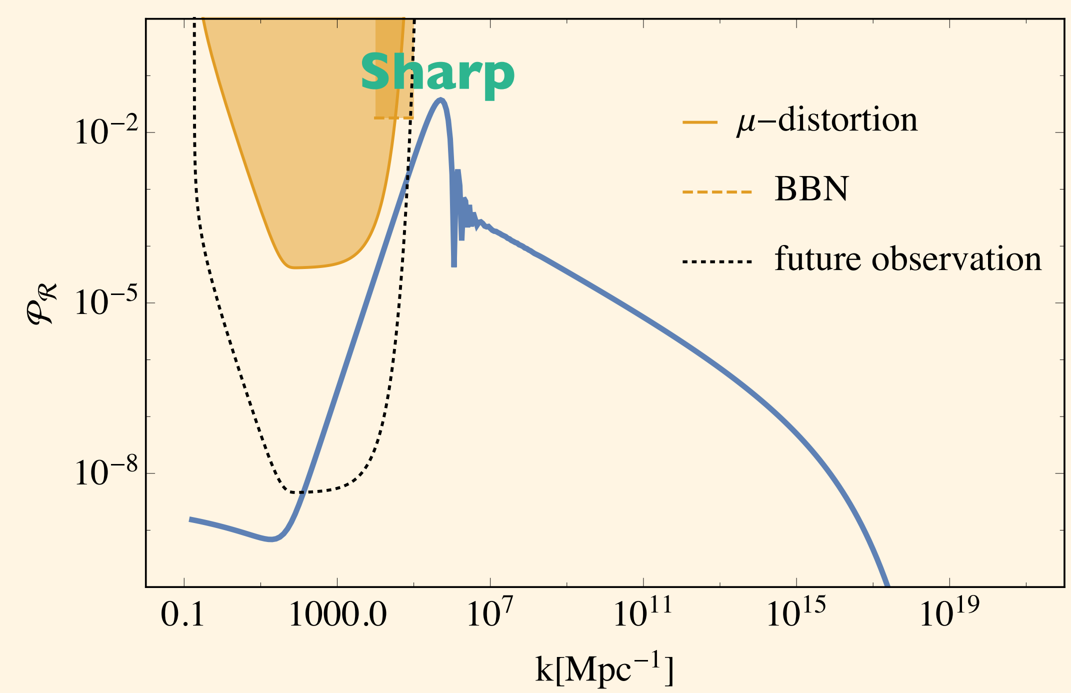
$$V(\varphi,\chi) = V_{\rm pre}(\chi) - 2\sqrt{2}c\,v^2\varphi - \frac{\kappa}{2}v^4\varphi^2 + \left(v^2 - \frac{g}{2^{\frac{3}{2}}}\varphi^3\right)^2 + \frac{1}{2}c_{\rm pot}V_{\rm pre}(\chi)\varphi^2$$

$$\mathscr{L}_{\rm kin} = -\frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi + \frac{c_{\rm kin}}{4}(\partial_\mu\chi\partial^\mu\chi)\varphi^2 + \cdots.$$

Hubble-induced mass

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





Double Inflation

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

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

$$V(\varphi,\chi) = V_{\rm pre}(\chi) - 2\sqrt{2}c\,v^2\varphi - \frac{\kappa}{2}v^4\varphi^2 + \left(v^2 - \frac{g}{2^{\frac{3}{2}}}\varphi^3\right)^2 + \frac{1}{2}c_{\rm pot}V_{\rm pre}(\chi)\varphi^2$$

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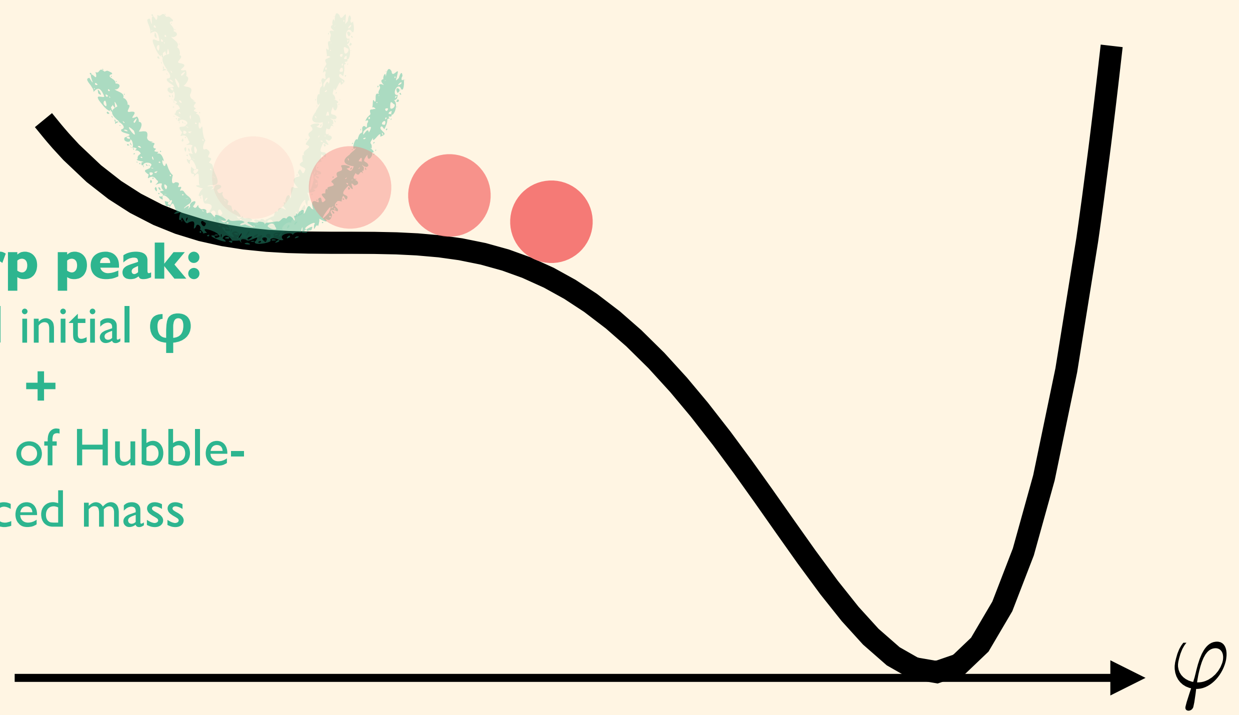
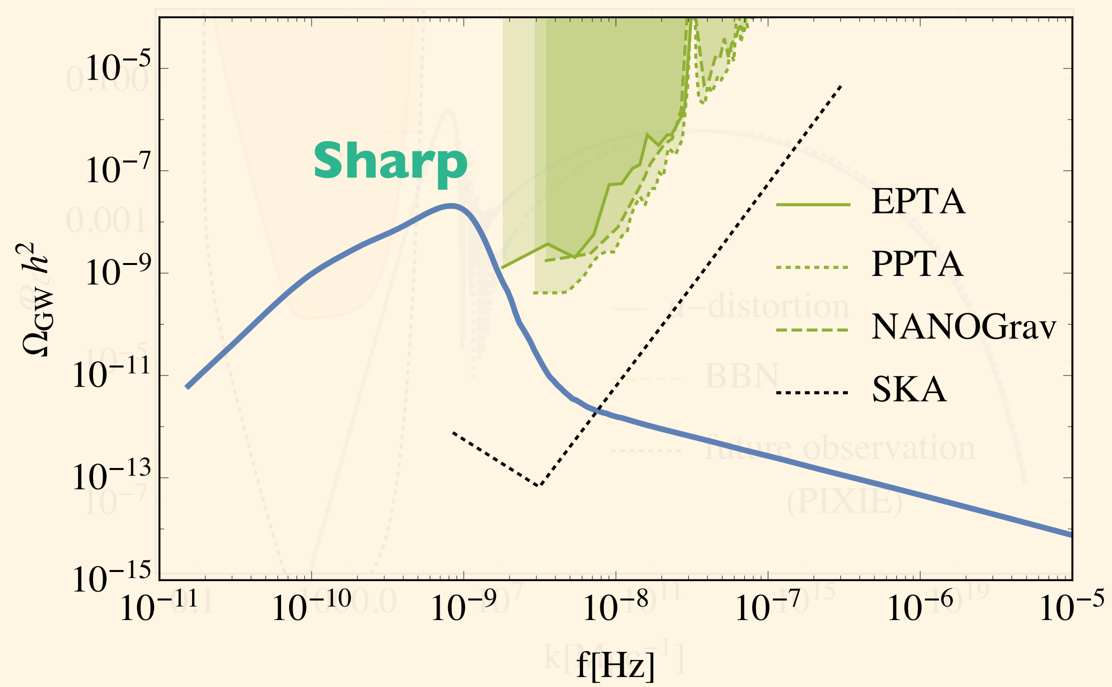




Double Inflation

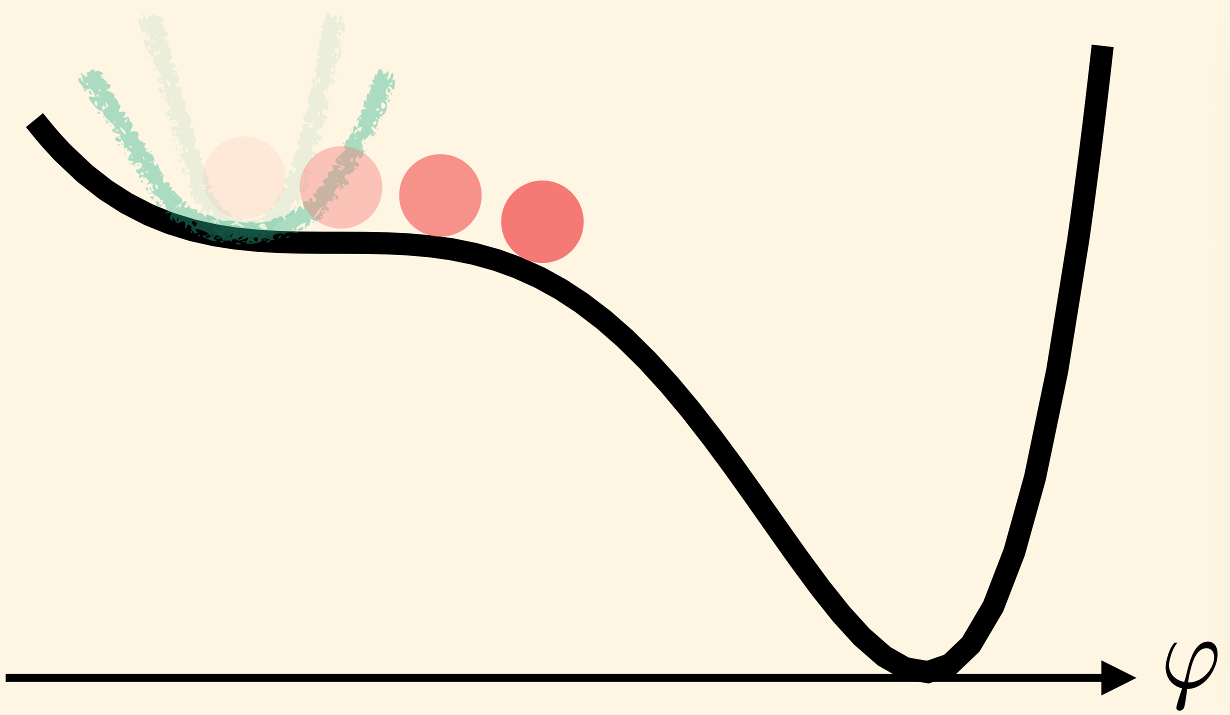
PBHs for LIGO or DM from **Double Inflation**

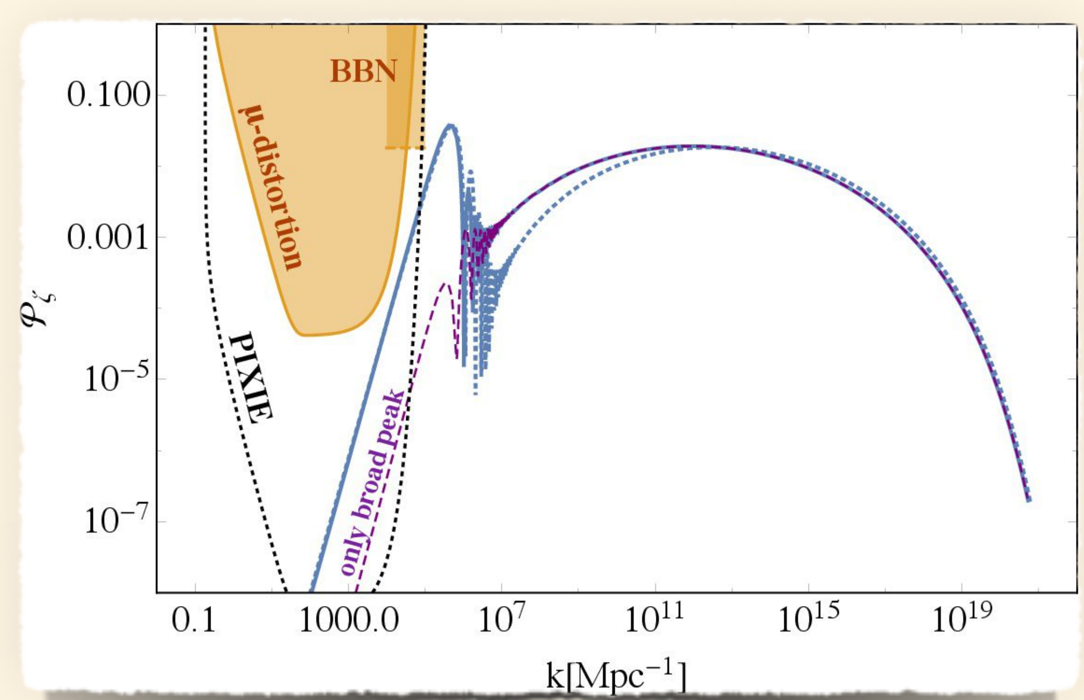
- Total e-folds (N=50-60) = **1st-inflation** + **2nd inflation**

$$V(\varphi,\chi)=V_{\rm pre}(\chi)$$
$$-2\sqrt{2}c\,v^2\varphi-\frac{\kappa}{2}v^4\varphi^2+\left(v^2-\frac{g}{2^{\frac{3}{2}}}\varphi^3\right)^2$$
$$+\frac{1}{2}c_{\rm pot}V_{\rm pre}(\chi)\varphi^2$$

$$\mathcal{L}_{\rm kin}=-\frac{1}{2}\partial_\mu\chi\partial^\mu\chi-\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi+\frac{c_{\rm kin}}{4}(\partial_\mu\chi\partial^\mu\chi)\varphi^2+\cdots.$$

Hubble-induced mass





Double Inflation

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

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

$$V(\varphi,\chi) = V_{\rm pre}(\chi) - 2\sqrt{2}c\,v^2\varphi - \frac{\kappa}{2}v^4\varphi^2 + \left(v^2 - \frac{g}{2^{\frac{3}{2}}}\varphi^3\right)^2 + \frac{1}{2}c_{\rm pot}V_{\rm pre}(\chi)\varphi^2$$

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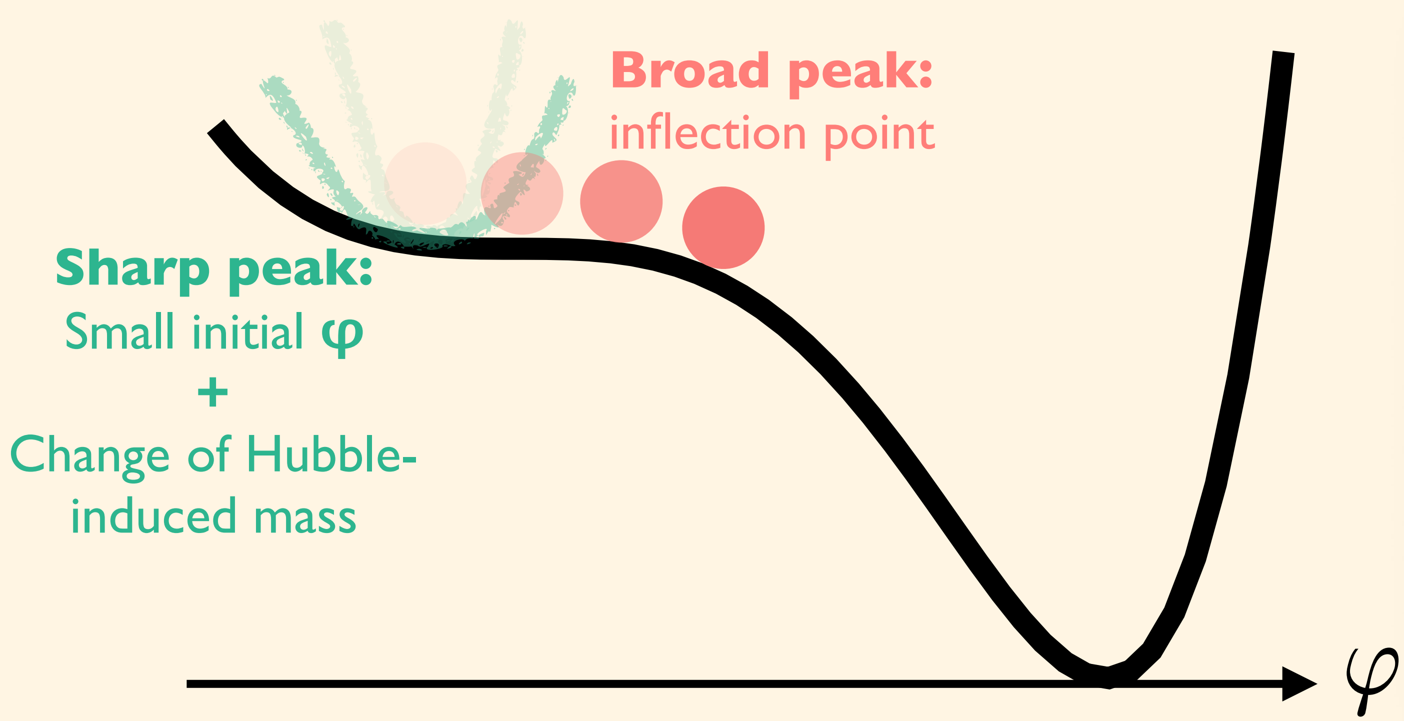
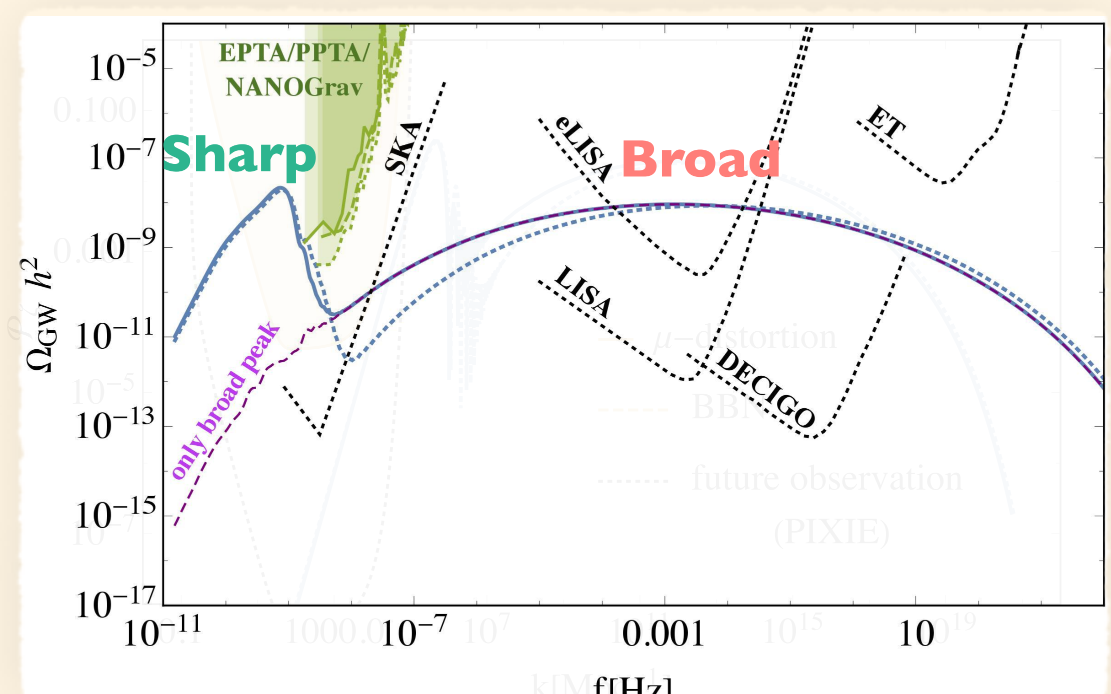
Hubble-induced mass





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