

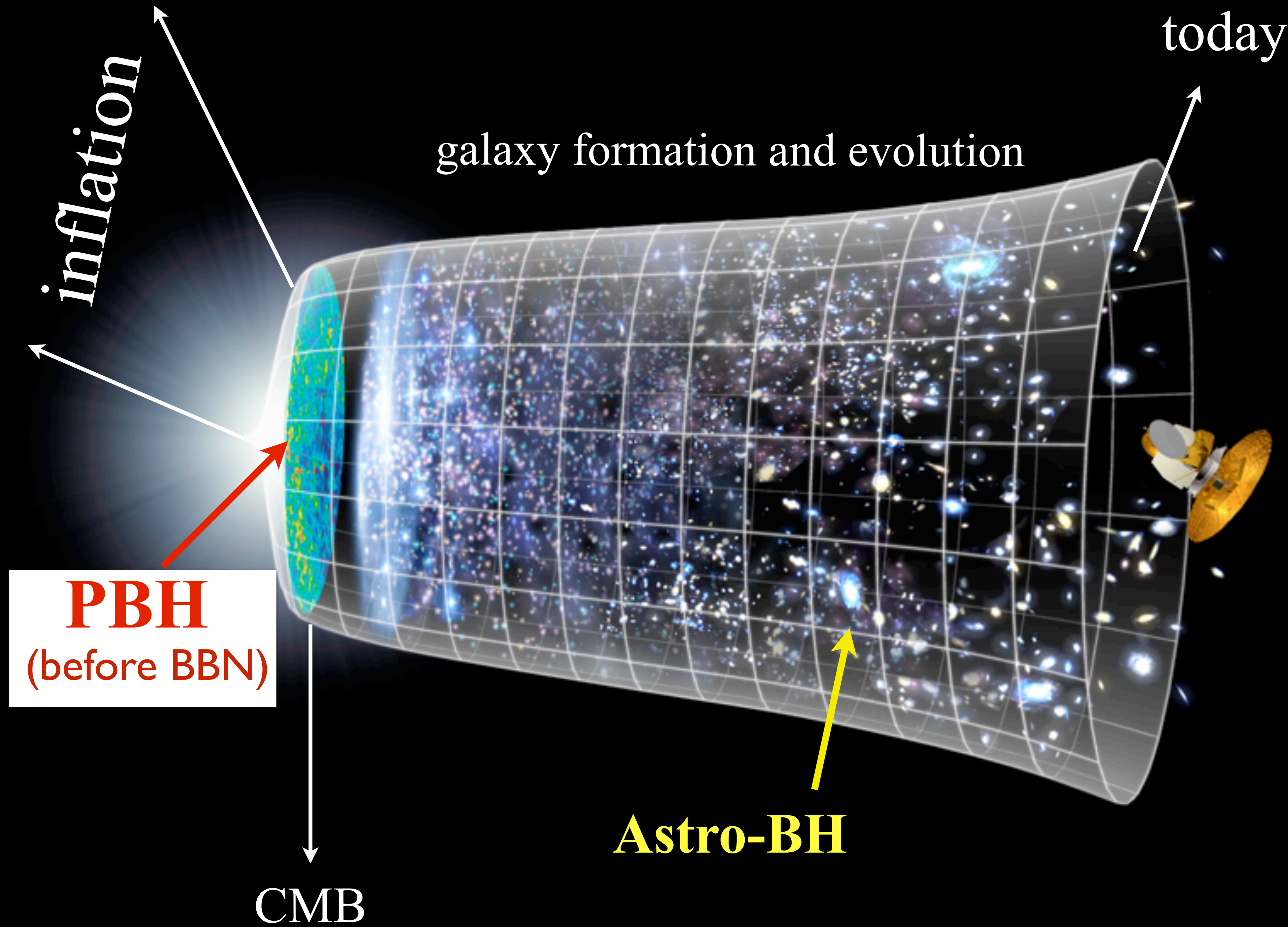
Primordial black holes as dark matter

Guillermo Ballesteros



15/05/2025

Dark matter and neutrinos. Institut Henri Poincaré.



Adapted from NASA/WMAP Science Team

Primordial black holes

Zeldovich and Novikov 1967, Hawking 1971, Hawking & Carr 1974, ...

- **Dark matter candidate**
- Reheat the universe after inflation
- Catalysers for **particle dark matter** or other BSM production
- Baryogenesis
- Seeds of supermassive black holes
- Possible BH merger outliers in LIGO/Virgo/Kagra
- Possible BH microlensing events
- PTA indications of a stochastic GW background
- Theoretical/experimental tool to learn about the early universe

dark matters

(pre-BBN) PBHs

WIMPS

WDM

Axion and Co.

Fuzzy DM

$6 \cdot 10^{38} \text{ GeV}$

1 TeV

1 GeV

1 keV

1 eV

1 meV

10^{-22} eV

$1 M_{\odot} = 2 \times 10^{30} \text{ kg}$

$5 \times 10^{-19} M_{\odot} \sim \text{evaporation limit}$

$10^{-54} M_{\odot}$

$10^{-68} M_{\odot}$

$10^{-90} M_{\odot}$

PBHs and other dark matter candidates

- * WIMPs: possibly largely incompatible (absence of annihilation signals)

(e.g. Lacki+ 2018, Adamek+2019, Gaggero+2019)

- * axions: no problem

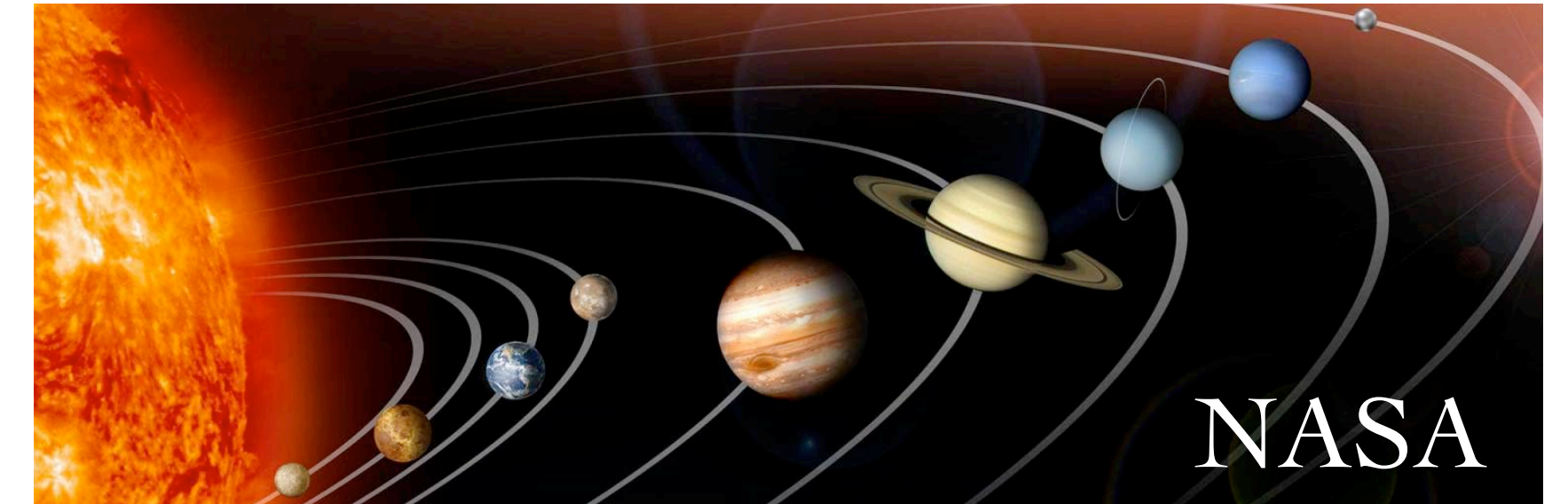
(as far as I know)

dark matter density: $10^{-24} \text{ g cm}^{-3} \sim 10^{-2} \text{ M}_{\odot} \text{ pc}^{-3}$

● PBH mass: $10^{-13} \text{ M}_{\odot} \sim 2 \times 10^{20} \text{ g}$

radius of the orbit of Neptune: $10^{-4} \text{ pc} \sim 5 \times 10^9 \text{ km}$

1 PBH in the Solar System



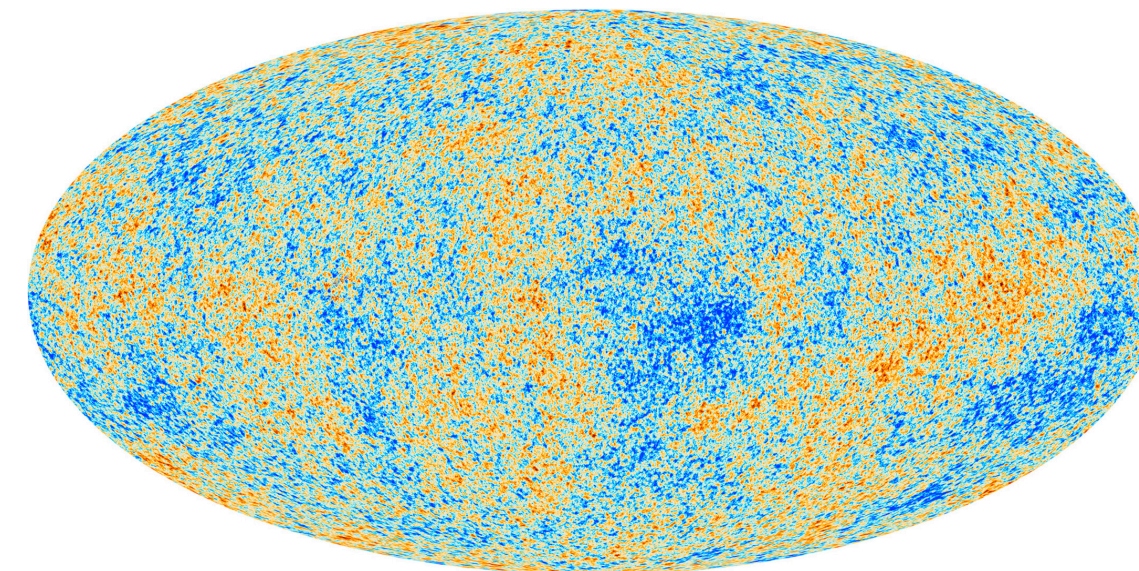
radius of a galaxy's halo: 10^5 pc

10^{26} PBH in a halo



Hubble radius: 10^4 Mpc

10^{41} PBH in a Hubble patch

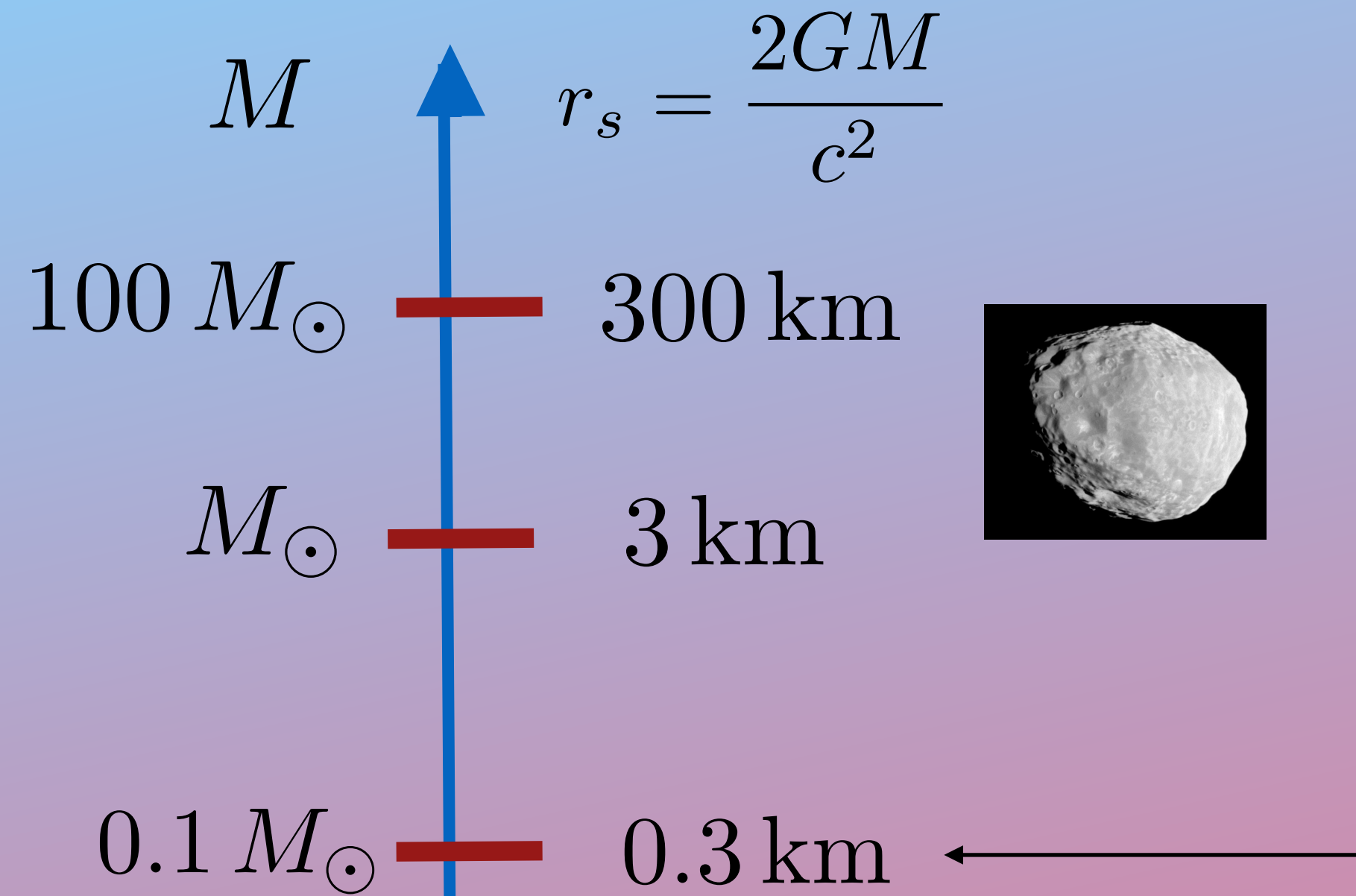


ESA - Planck CMB

binary BH mergers

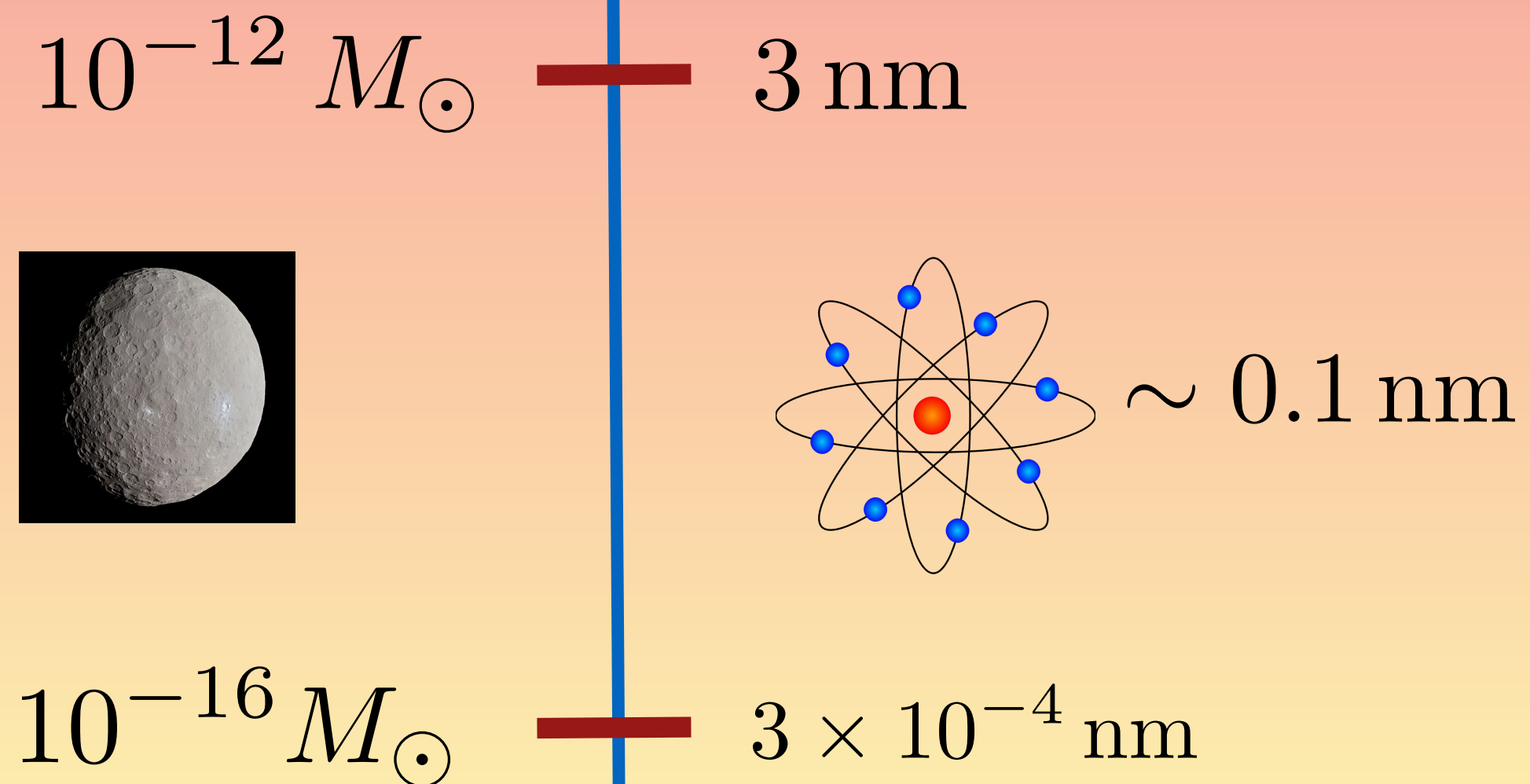
100 Hz

Courtesy
Caltech/MIT/LIGO Laboratory



100% of the
Dark Matter
possible

asteroid
mass
window

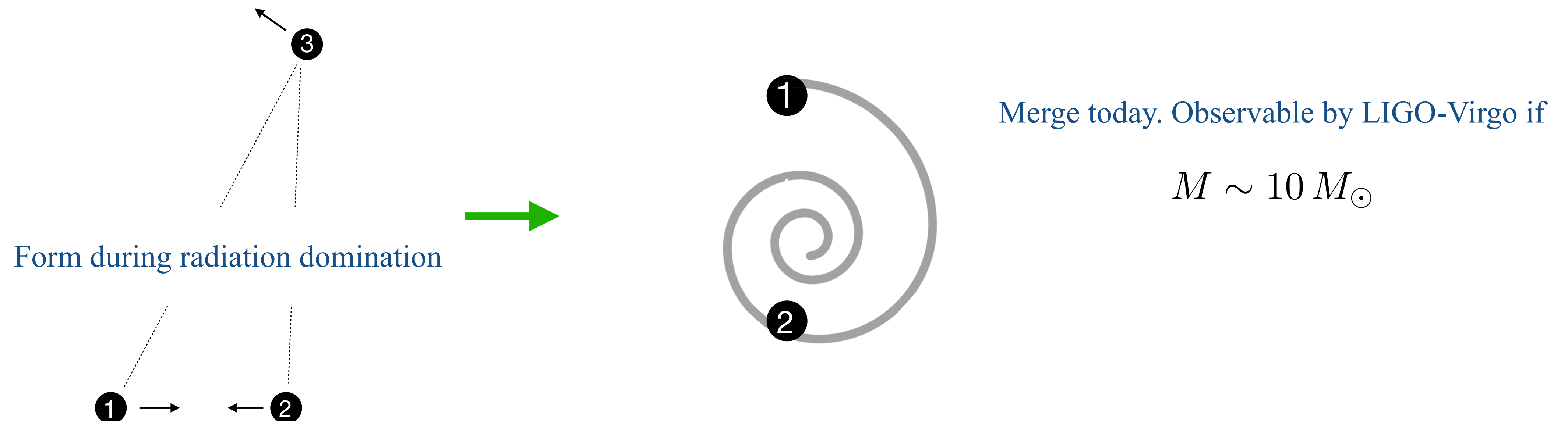


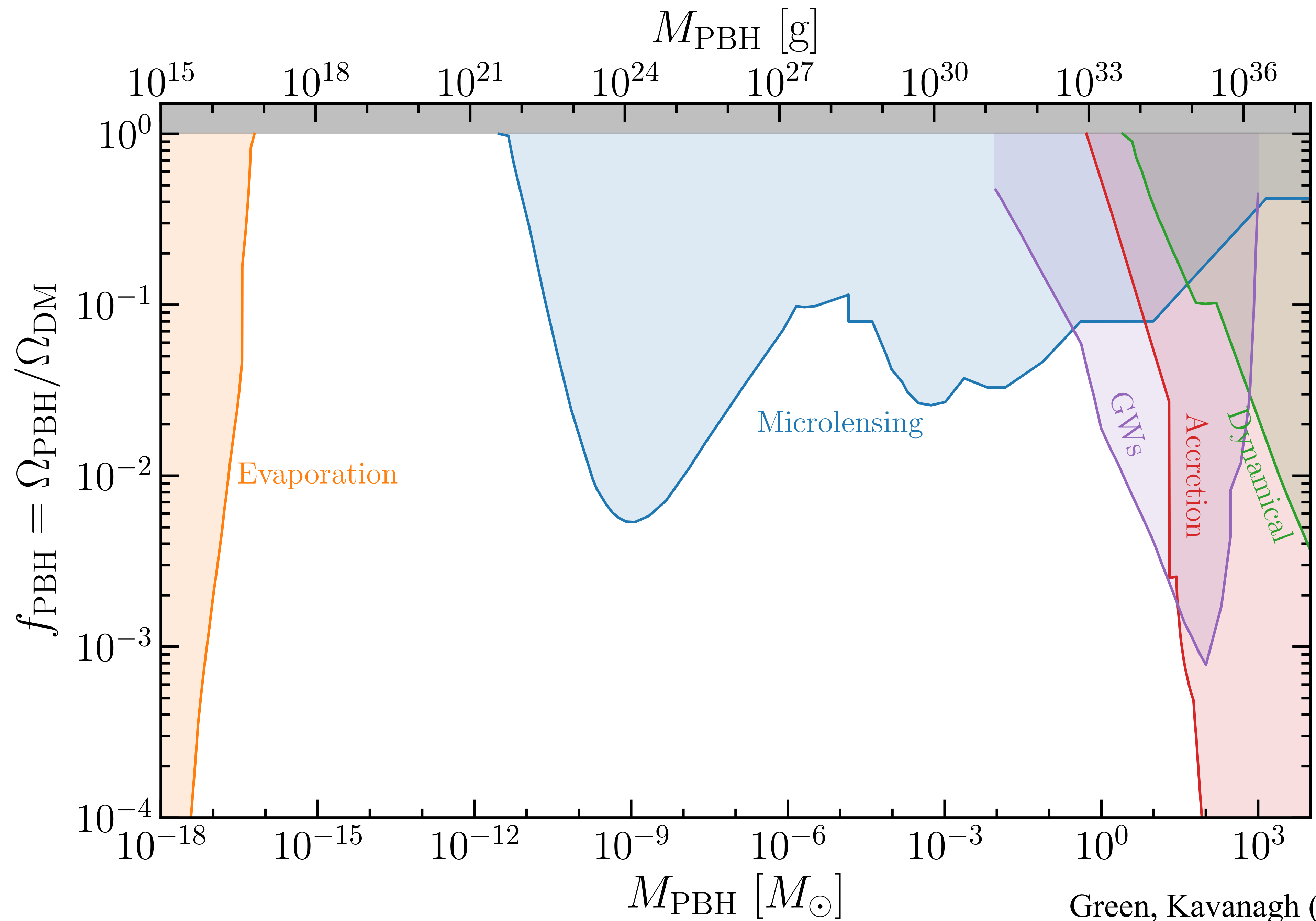
PTA $\sim$ nHz

Possible Stochastic
GW backgrounds
from inflation

0.03 Hz – 3 Hz
e.g. LISA

- 2016: LIGO: merger with **~ 30 Solar masses BH**
- Did **LIGO** detect (**THE**) dark matter? (Bird et al 2016...)
- ~~Most likely~~ **NO**. Or at least, ~~most likely~~ not the main component of it.
- Two mechanisms to form PBHs binaries:
 - Late Universe (in dark matter halos)
 - Early Universe (before matter radiation equality). **Nakamura et al 1997**
- **MAX 0.1% – 1%** of the DM in the range **1-100 Solar Masses**





Evaporation by Hawking radiation

$$T = \frac{\hbar c^2}{8\pi G k_B M} = 6 \times 10^{-8} \frac{M_\odot}{M} K$$

Bound for $M \lesssim 10^{17} g \simeq 5 \times 10^{-17} M_\odot$

Carr+ 2009

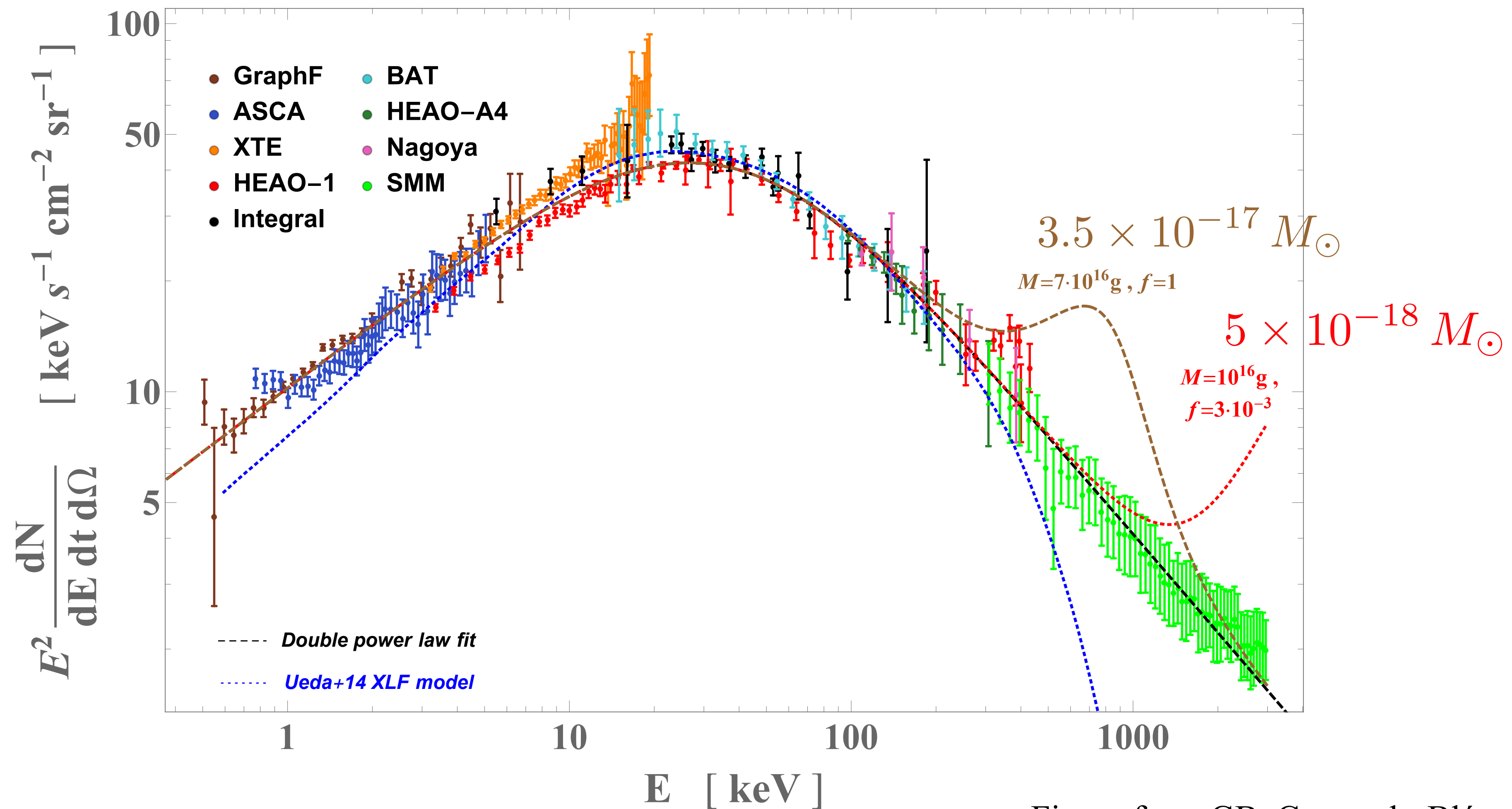


Figure from GB, Coronado-Blázquez, Gaggero, 2019

Situation before ~2019

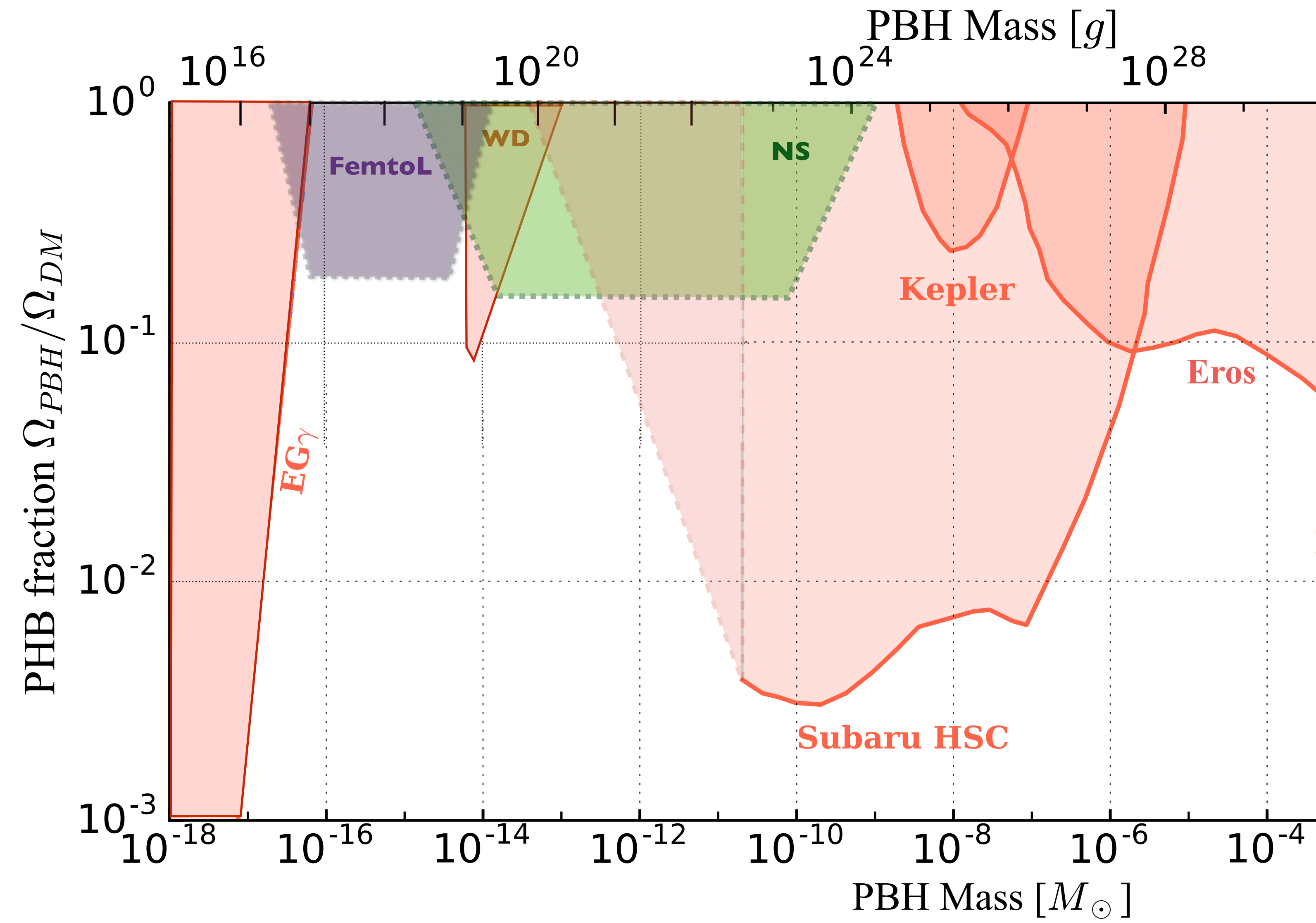


Figure from Katz et al. 2018
(modified)

See also Montero-Camacho et al. 2019
Smyth et al. 2019

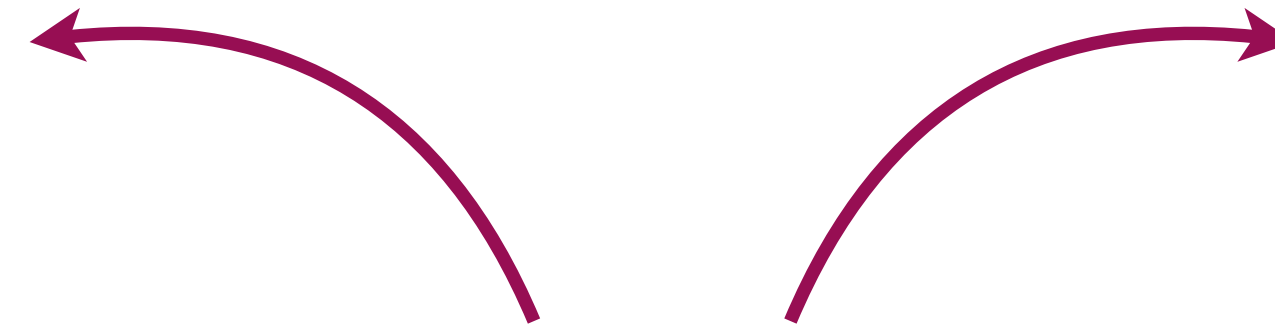
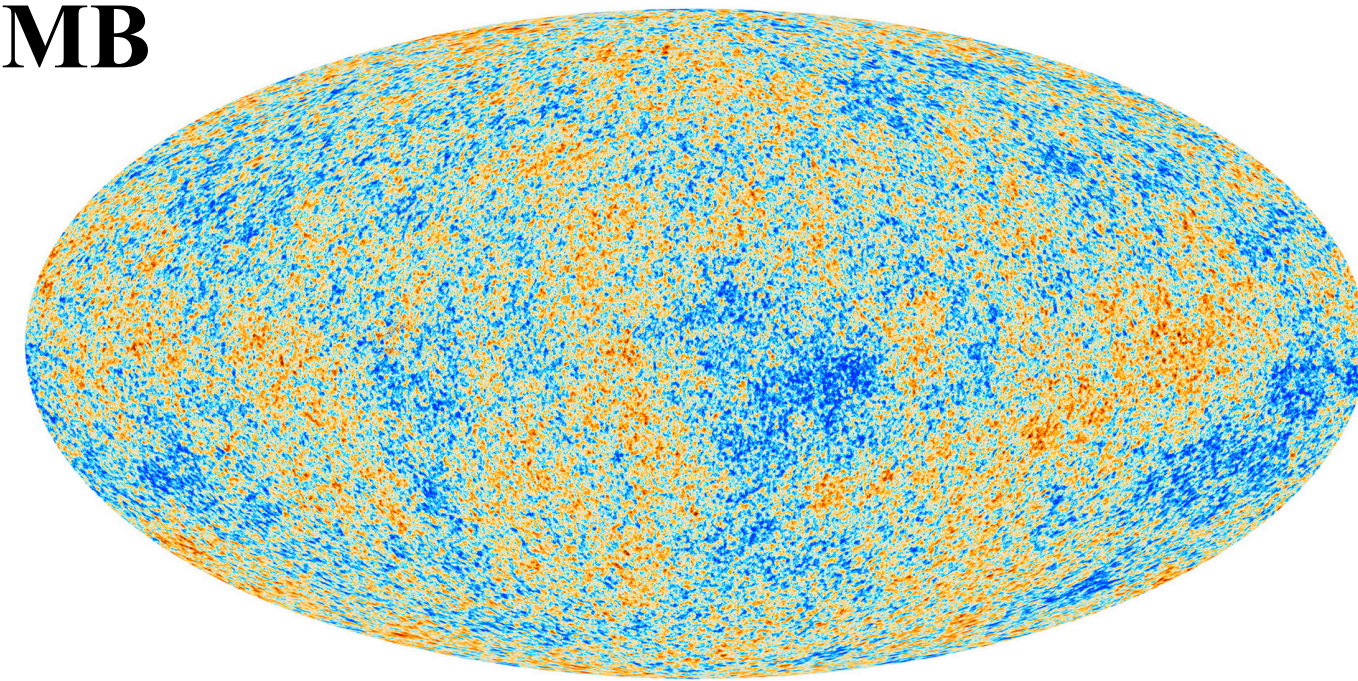
Mechanisms for PBH formation

- Large primordial fluctuations (inflation)
- Reheating after inflation
- 1st order phase transitions
- Collapse of topological defects
- False vacuum decay
- ...

PBH dark matter (from inflation)

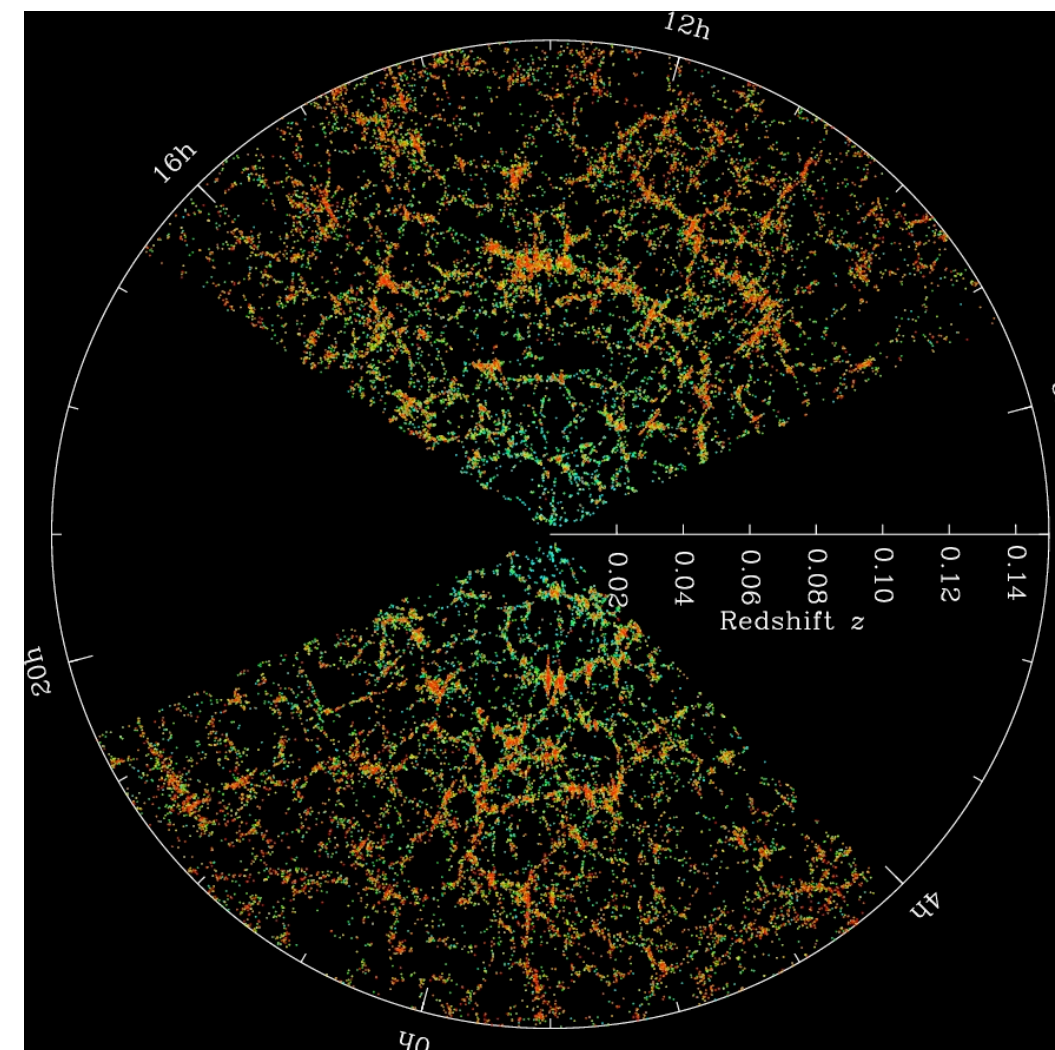
Credit: ESA/Planck

CMB



Quantum fluctuations
of space-time

LSS



Credit: M Blanton
and SDSS

Milky Way halo structure

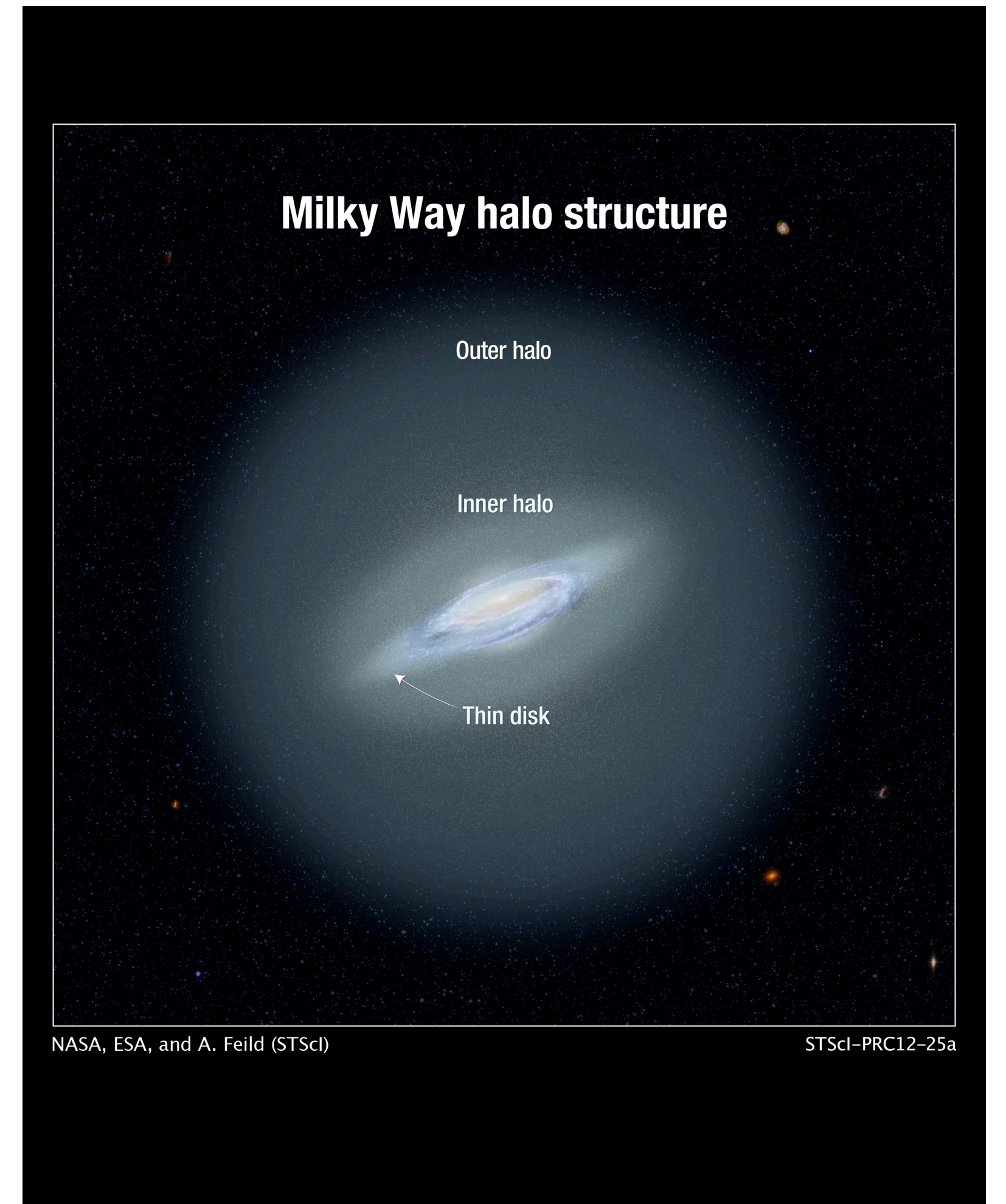
Outer halo

Inner halo

Thin disk

NASA, ESA, and A. Feild (STScI)

STScI-PRC12-25a



PBH dark matter (from inflation)

CMB

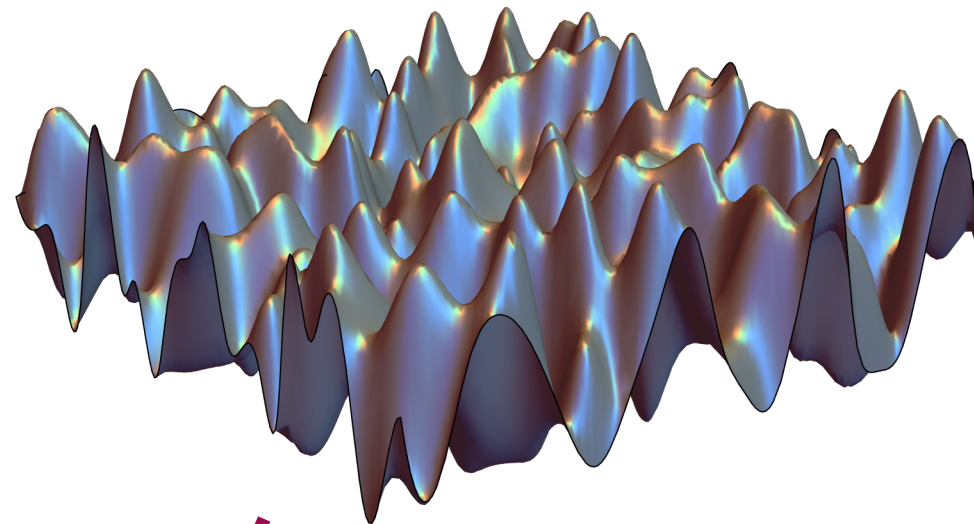
$$\frac{\Delta T}{T}$$

$$\delta \equiv \frac{\delta \rho}{\rho} \text{ of radiation}$$

Curvature fluctuations

$$\mathcal{R} \text{ (or } \zeta \text{)}$$

(for the most common
PBH formation scenarios)

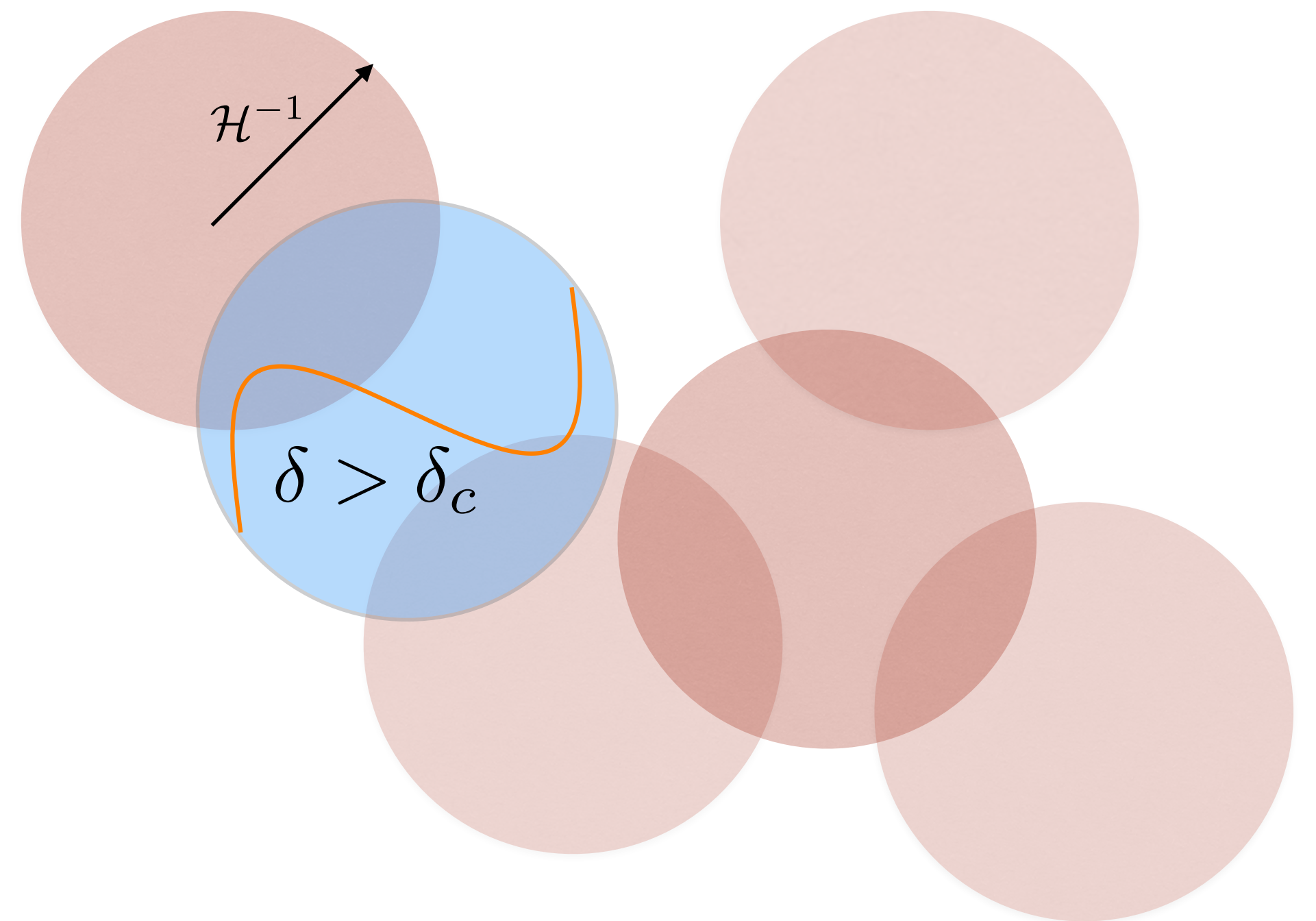
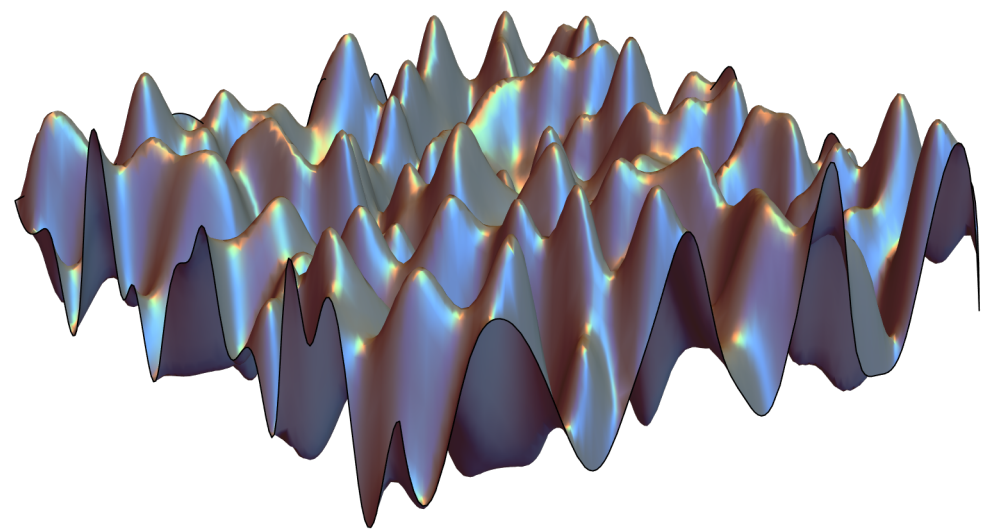
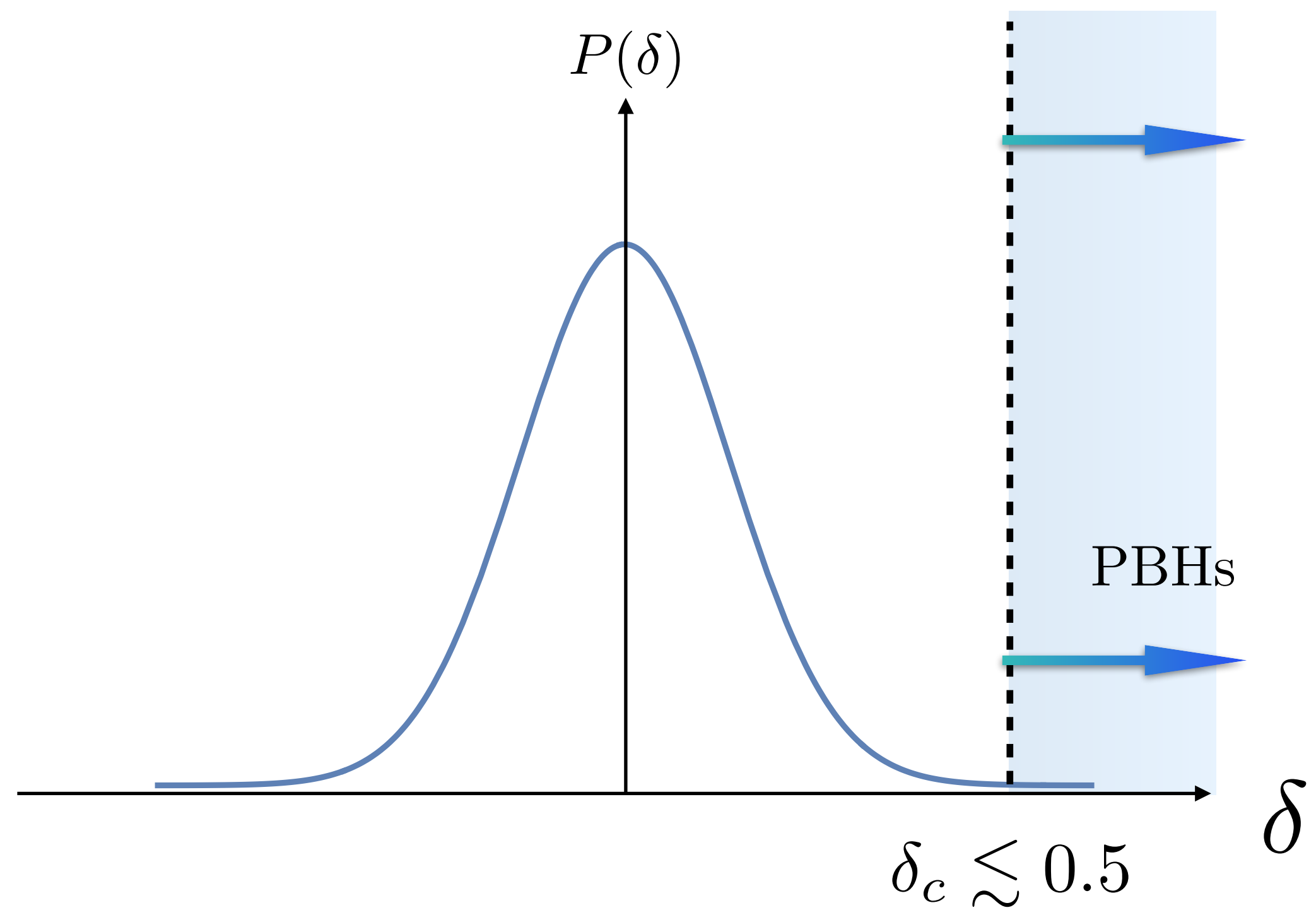


LSS

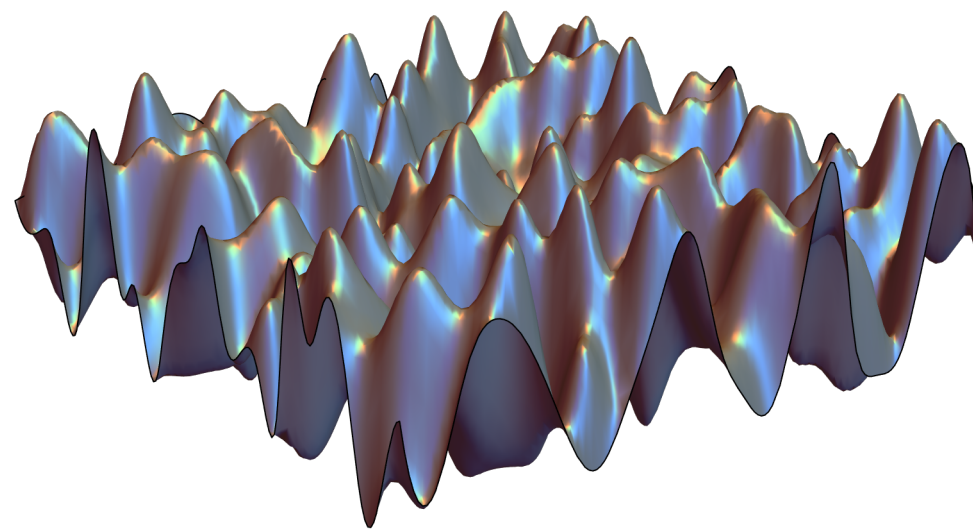
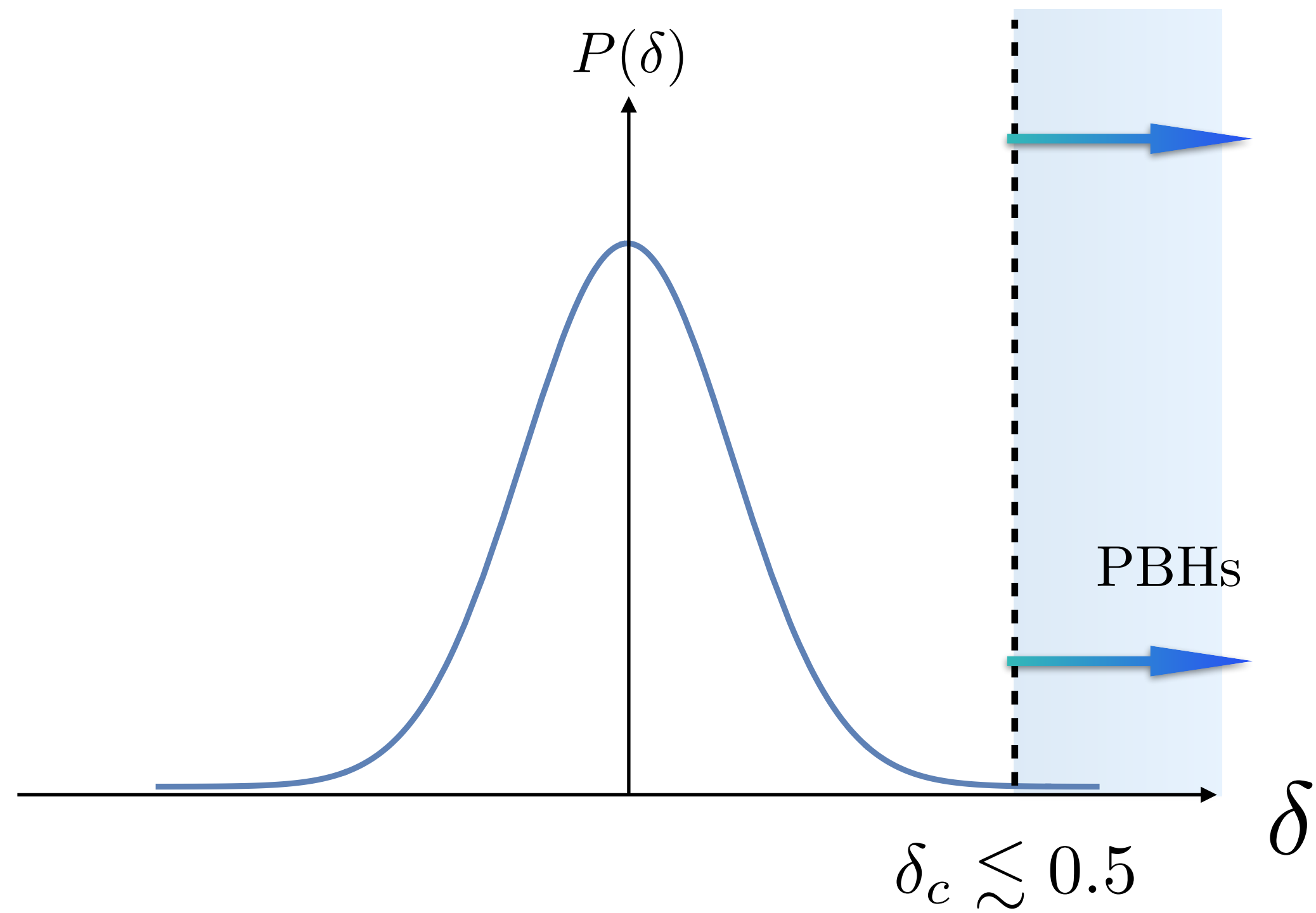
$$\frac{\delta \rho_{\text{DM}}}{\rho_{\text{DM}}}$$

$$\mathcal{P}_{\mathcal{R}}(k)$$

(primordial power spectrum)



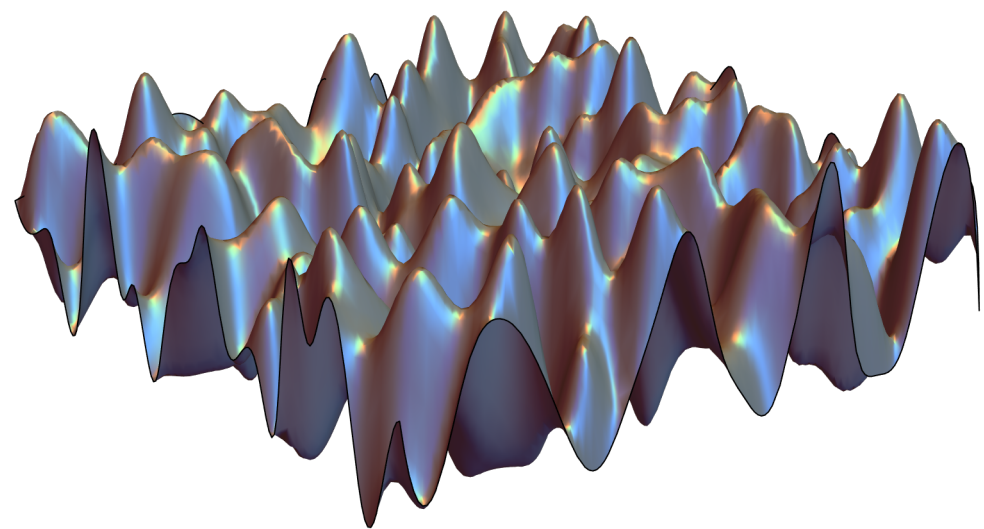
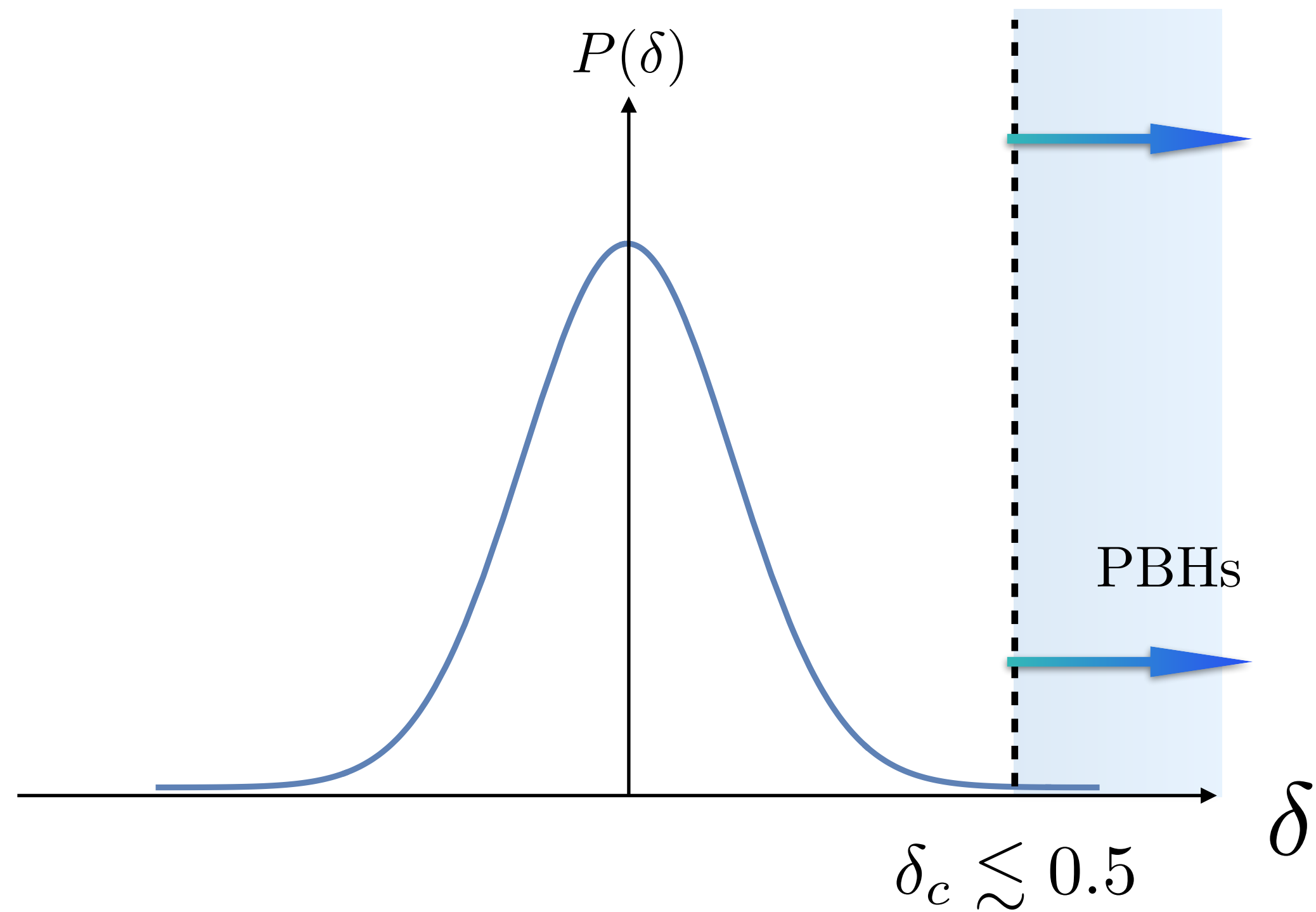
$$\rho(t, \mathbf{x}) = (1 + \delta(t, \mathbf{x})) \bar{\rho}(t)$$



Mass:

$$M \sim 10^{-14} \left(\frac{10^{13} \text{ Mpc}^{-1}}{k} \right)^2 M_{\odot}$$

(for PBHs formed during
radiation domination)



Mass:

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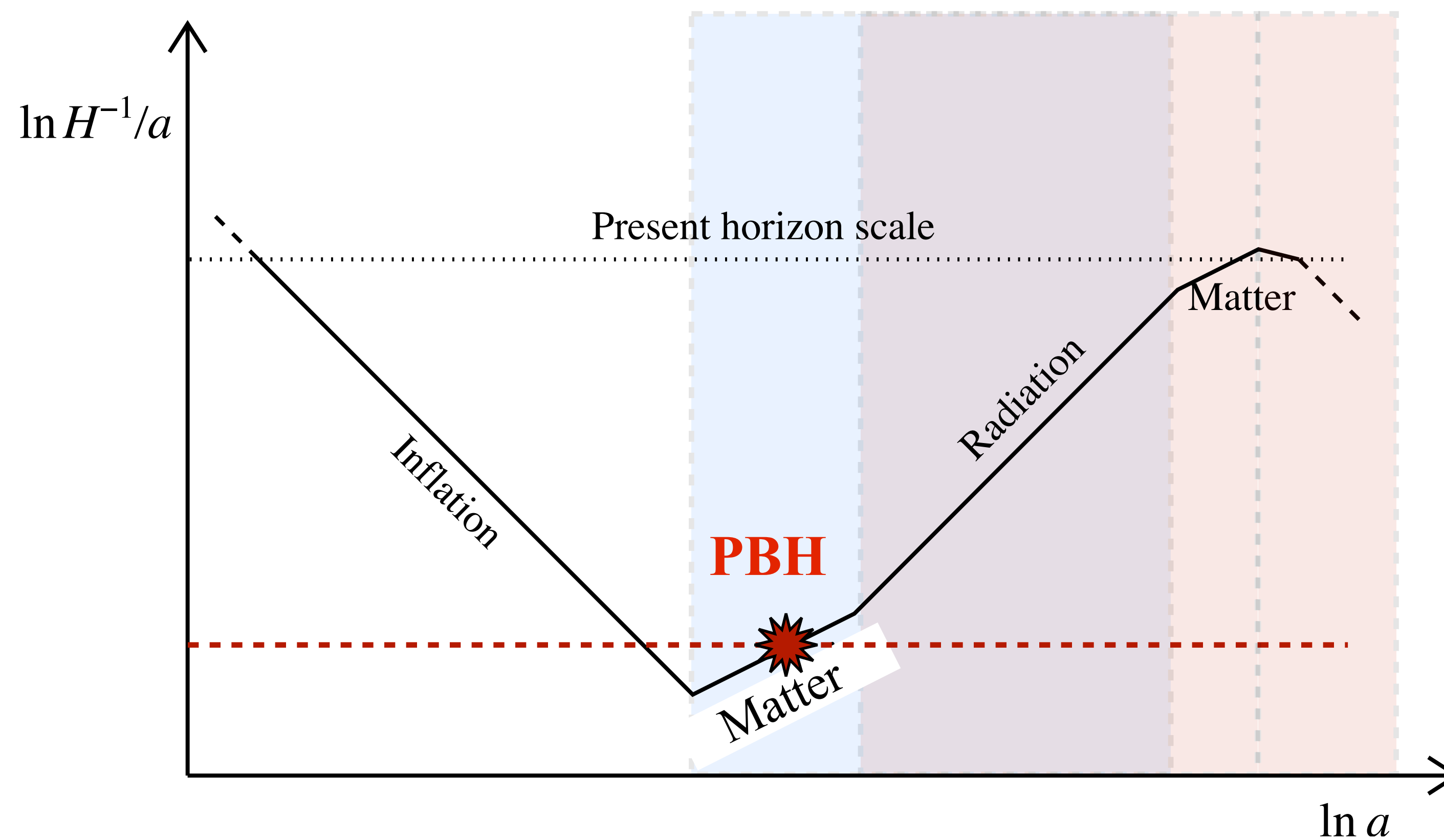
(for PBHs formed during
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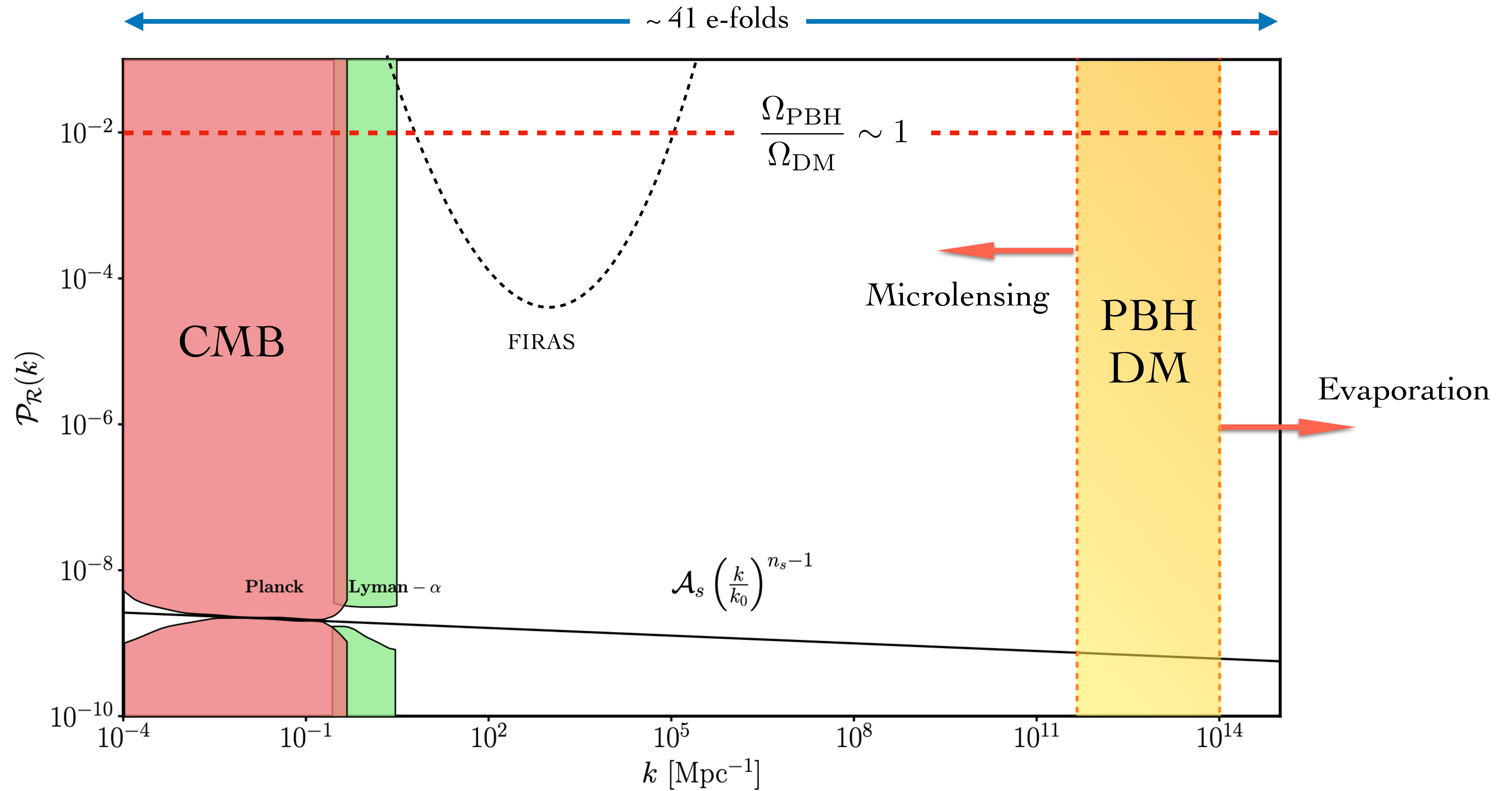
Abundance (naive Gaussian estimate):

$$f_{\text{PBH}} = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \propto \int_{\delta_c}^{\infty} \exp \left(-\frac{\delta^2}{2\sigma^2} \right) d\delta$$

$$\sigma \sim \mathcal{P}_{\mathcal{R}} \sim 10^{-2} \quad \Rightarrow \quad \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \sim 1$$

Equation of state after inflation

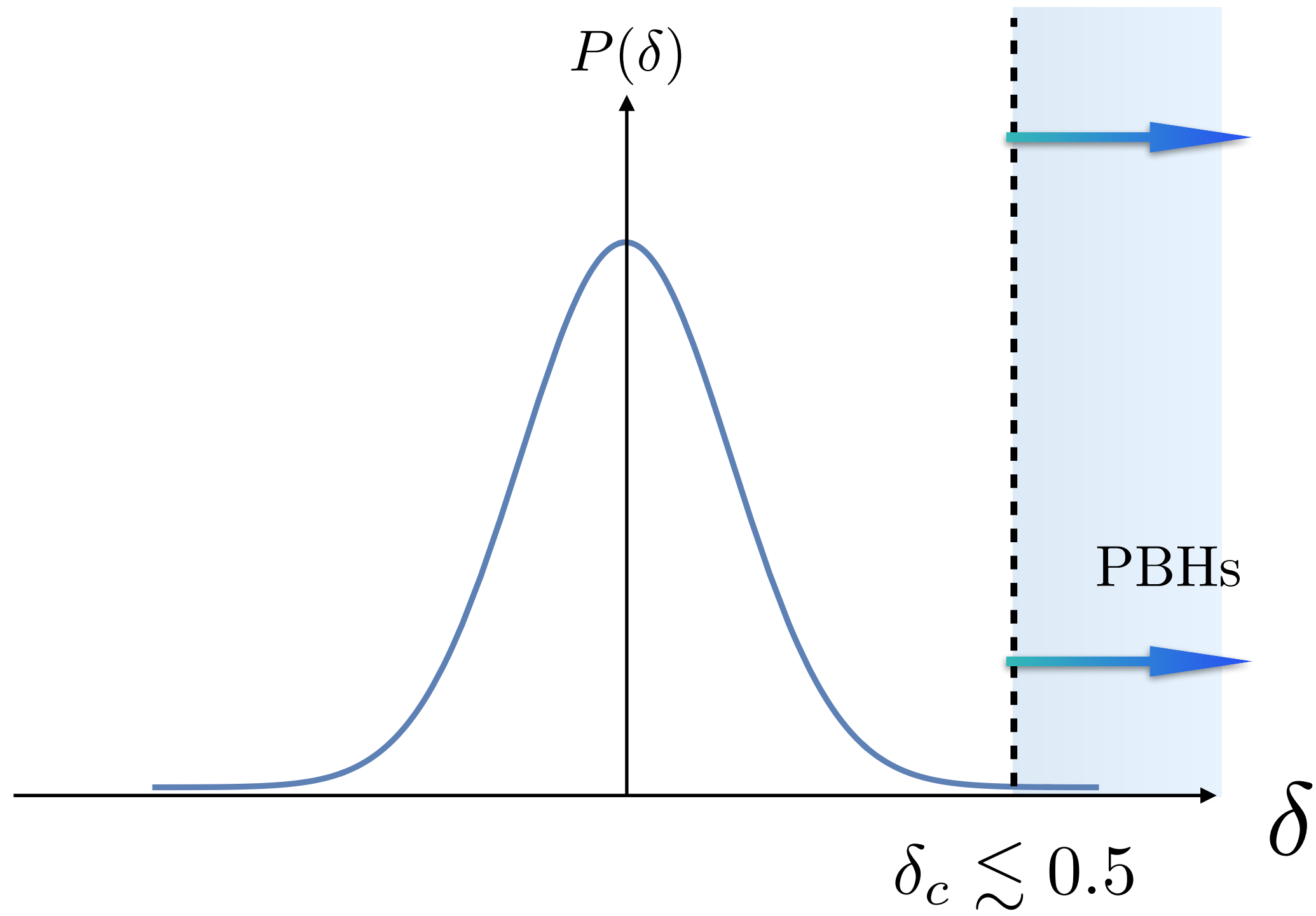




Franco-Abellán, EUCAPT symposium 2023 (modified)

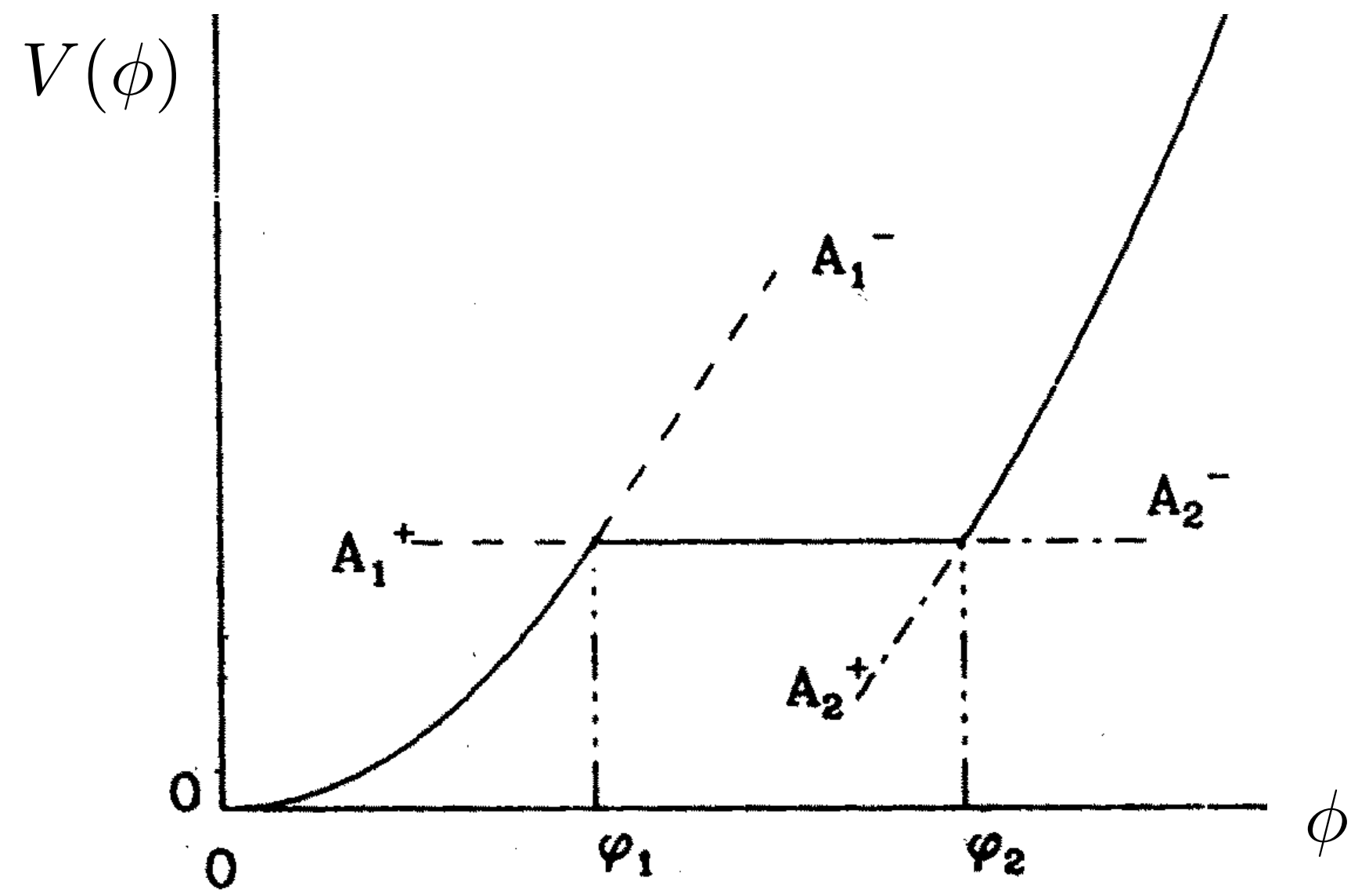
+ enough inflation & successful reheating

Inflation and primordial black holes as dark matter



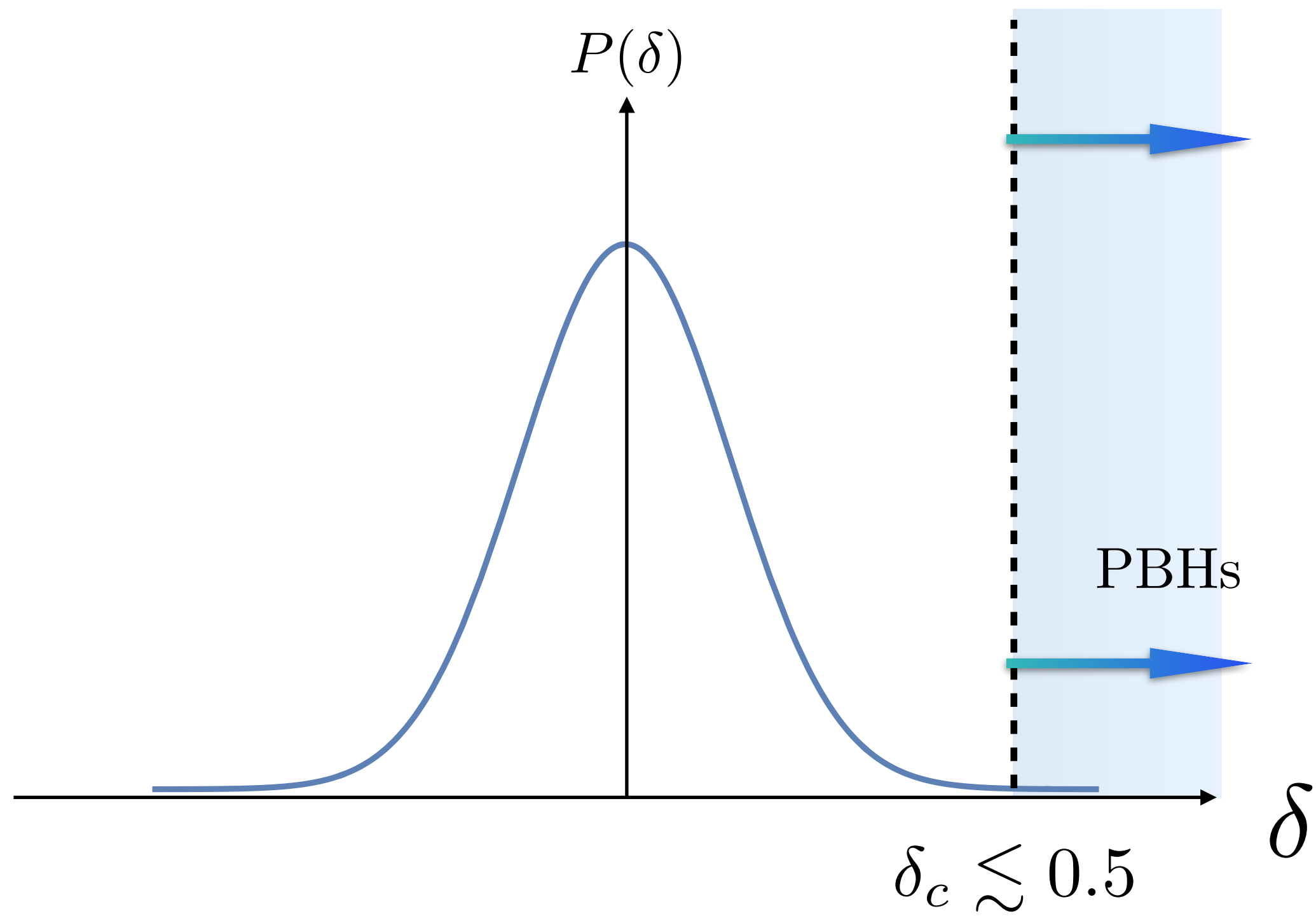
$$\mathcal{P}_{\mathcal{R}} \sim \left(\frac{H}{m_P} \right)^2 \left(\frac{H}{\dot{\phi}} \right)^2 \sim \frac{1}{m_P^2} \left(\frac{V}{V'} \right)^2 \frac{V}{m_P^4}$$

Ivanov, Naselsky, Novikov. 1994



$$V(\phi) = \begin{cases} V_0 + A_+(\phi - \phi_0) & \text{for } \phi > \phi_0 \\ V_0 + A_-(\phi - \phi_0) & \text{for } \phi < \phi_0 \end{cases}$$

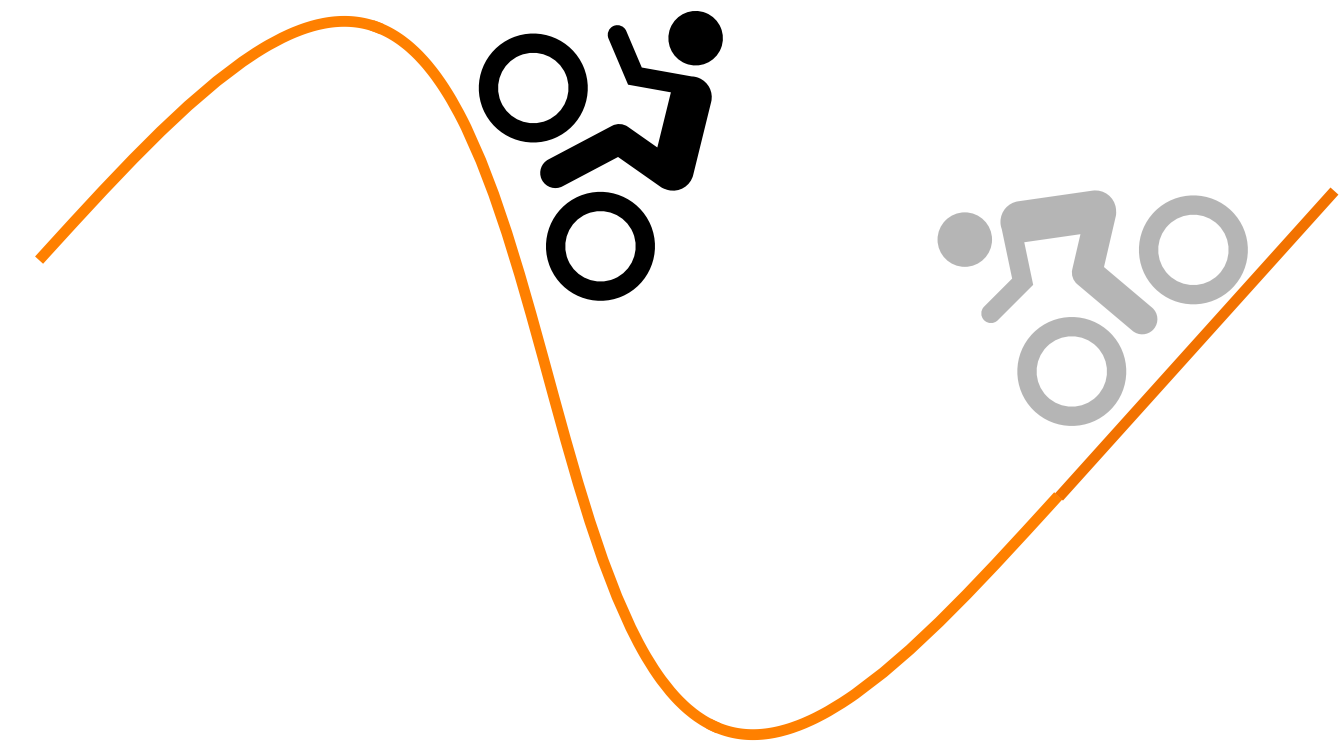
Starobinsky 1992



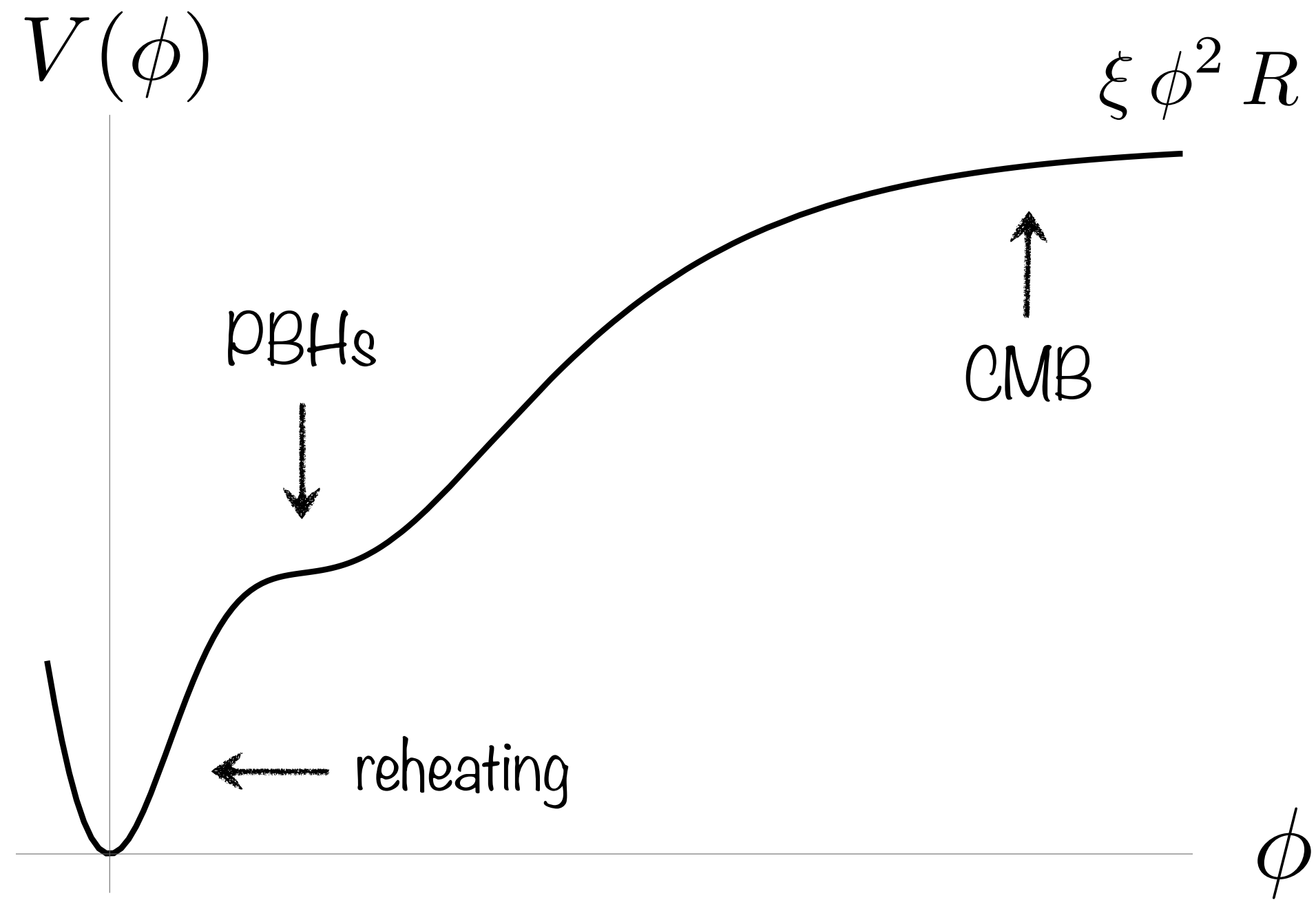
$$\mathcal{P}_{\mathcal{R}} \sim \left(\frac{H}{m_P} \right)^2 \left(\frac{H}{\dot{\phi}} \right)^2 \sim \frac{1}{m_P^2} \left(\frac{V}{V'} \right)^2 \frac{V}{m_P^4}$$

Ultra Slow-Roll (USR)

$$\ddot{\phi} + 3H\dot{\phi} \simeq 0$$



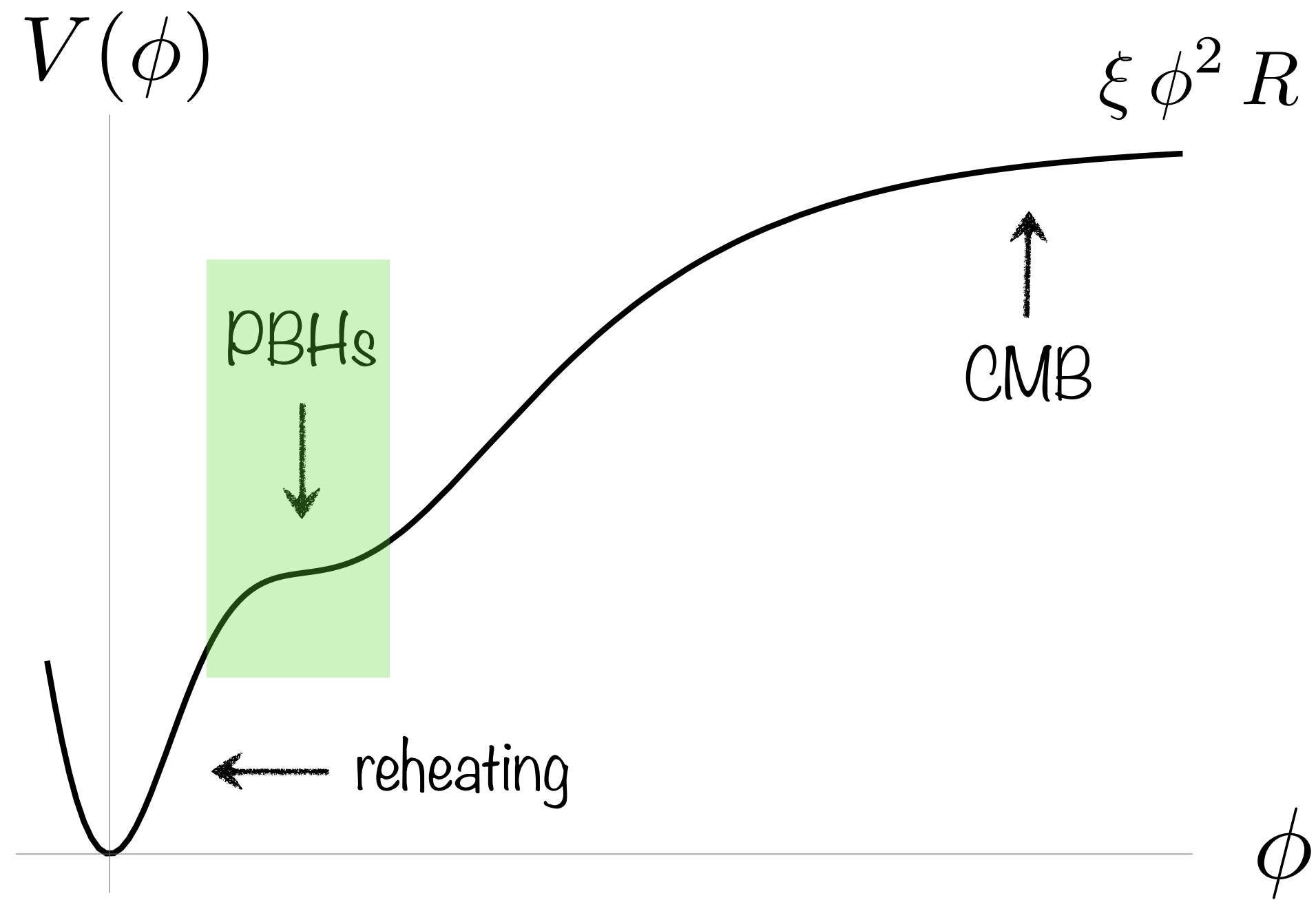
$$\eta \sim \frac{\ddot{\phi}}{\dot{\phi} H} \sim -3$$



$$V = \sum_{n=2}^{4+\epsilon \mathcal{O}(5)} a_n \phi^n$$

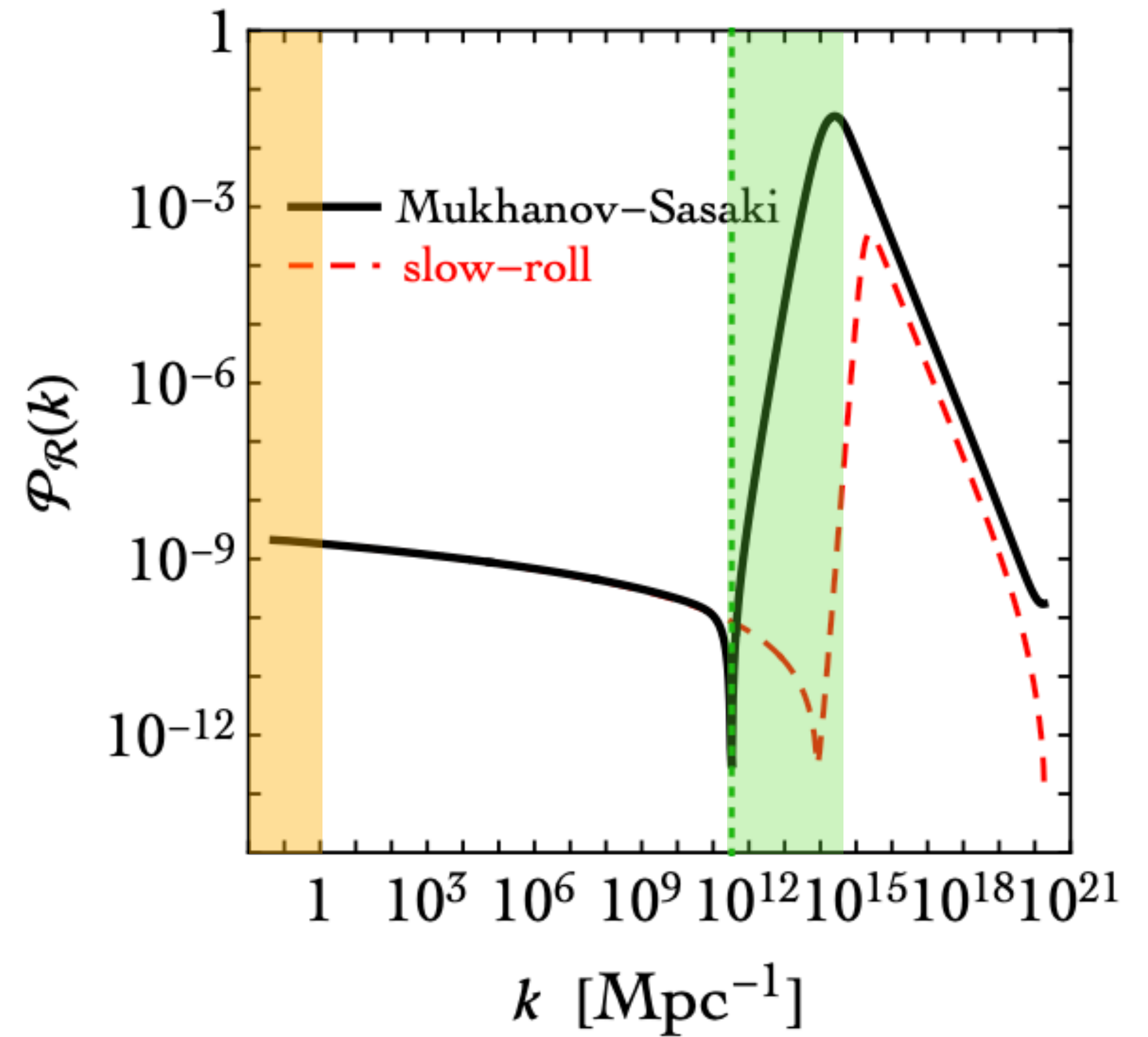
$$\frac{V(\phi)}{\phi^4} = \lambda(\phi_0) + \frac{1}{2} \beta_\lambda(\phi_0) \log \frac{\phi^2}{\phi_0^2} + \frac{1}{8} \beta'_\lambda(\phi_0) \left(\log \frac{\phi^2}{\phi_0^2} \right)^2 + \dots$$

GB, Taoso 2017
GB, Rey, Taoso, Urbano 2020



$$V = \sum_{n=2}^{4+\epsilon \mathcal{O}(5)} a_n \phi^n$$

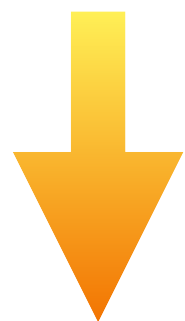
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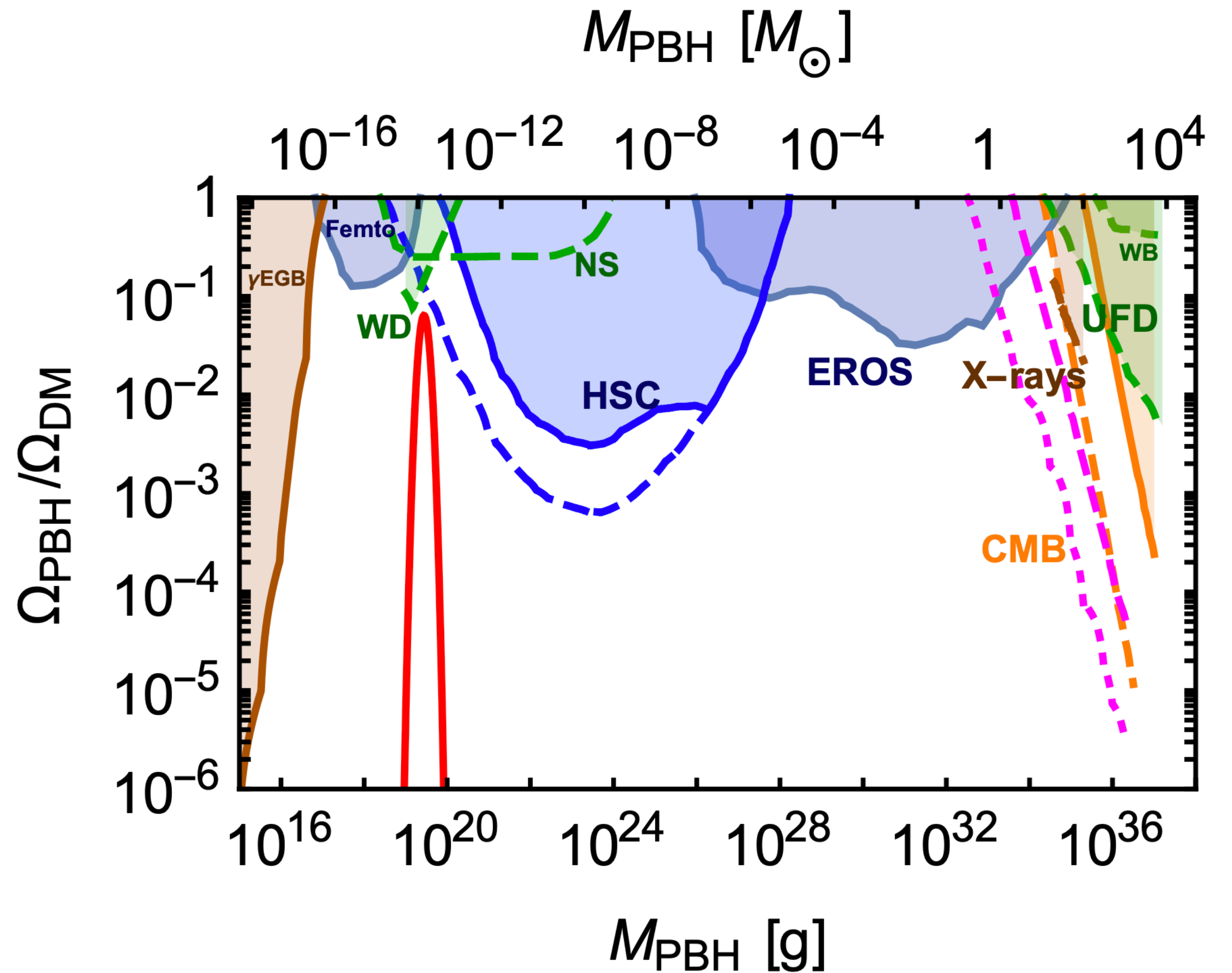
Ballesteros, Taoso 2017

Ballesteros, Rey, Taoso, Urbano 2020

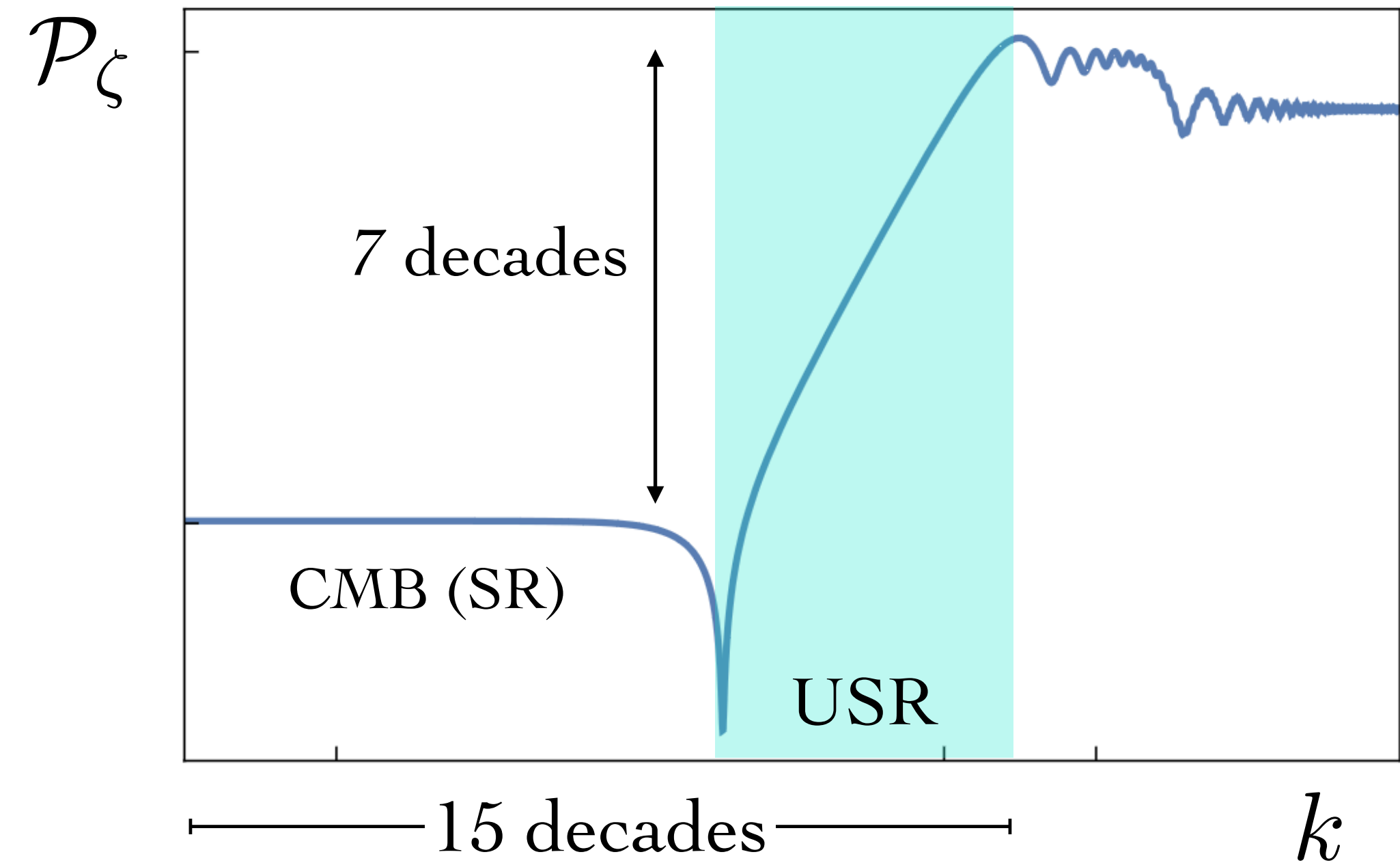
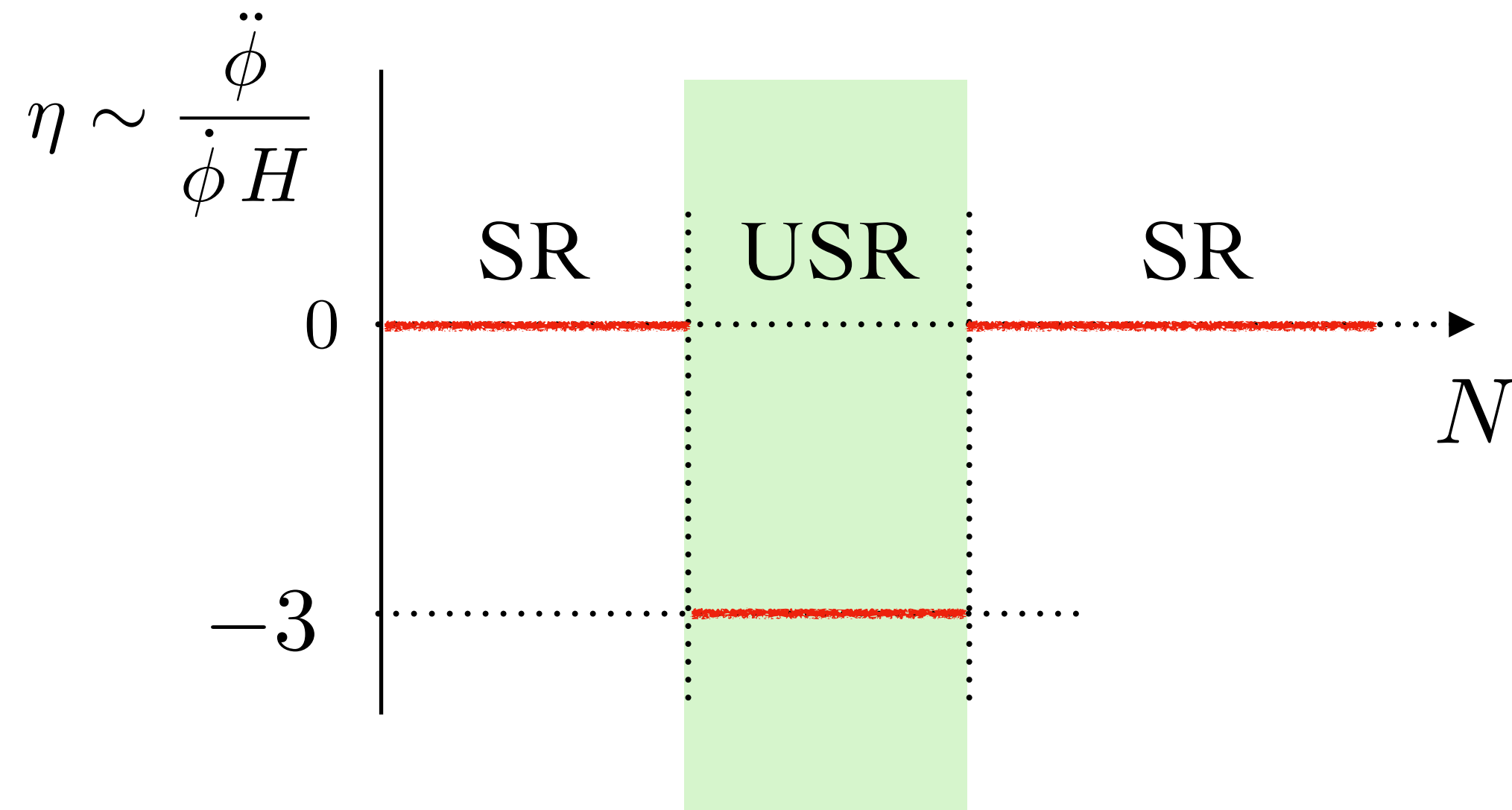
- Enough inflation
- Agreement with the CMB
(n_s within 2σ)
- $\frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \sim 1$ (Gaussian, RD)



$$10^{-16} M_{\odot} \longleftrightarrow 10^{-12} M_{\odot}$$



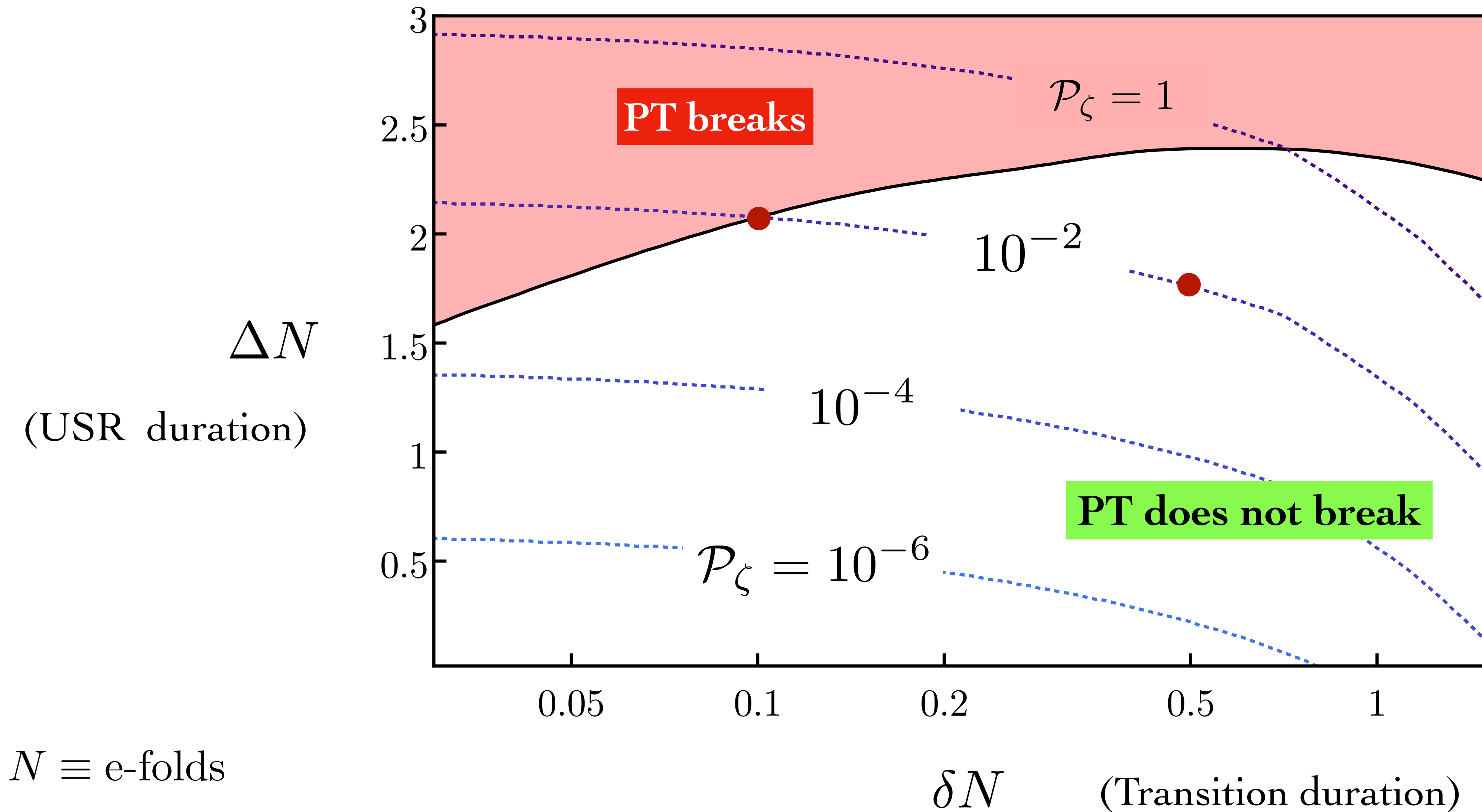
Does perturbation theory break in these models?



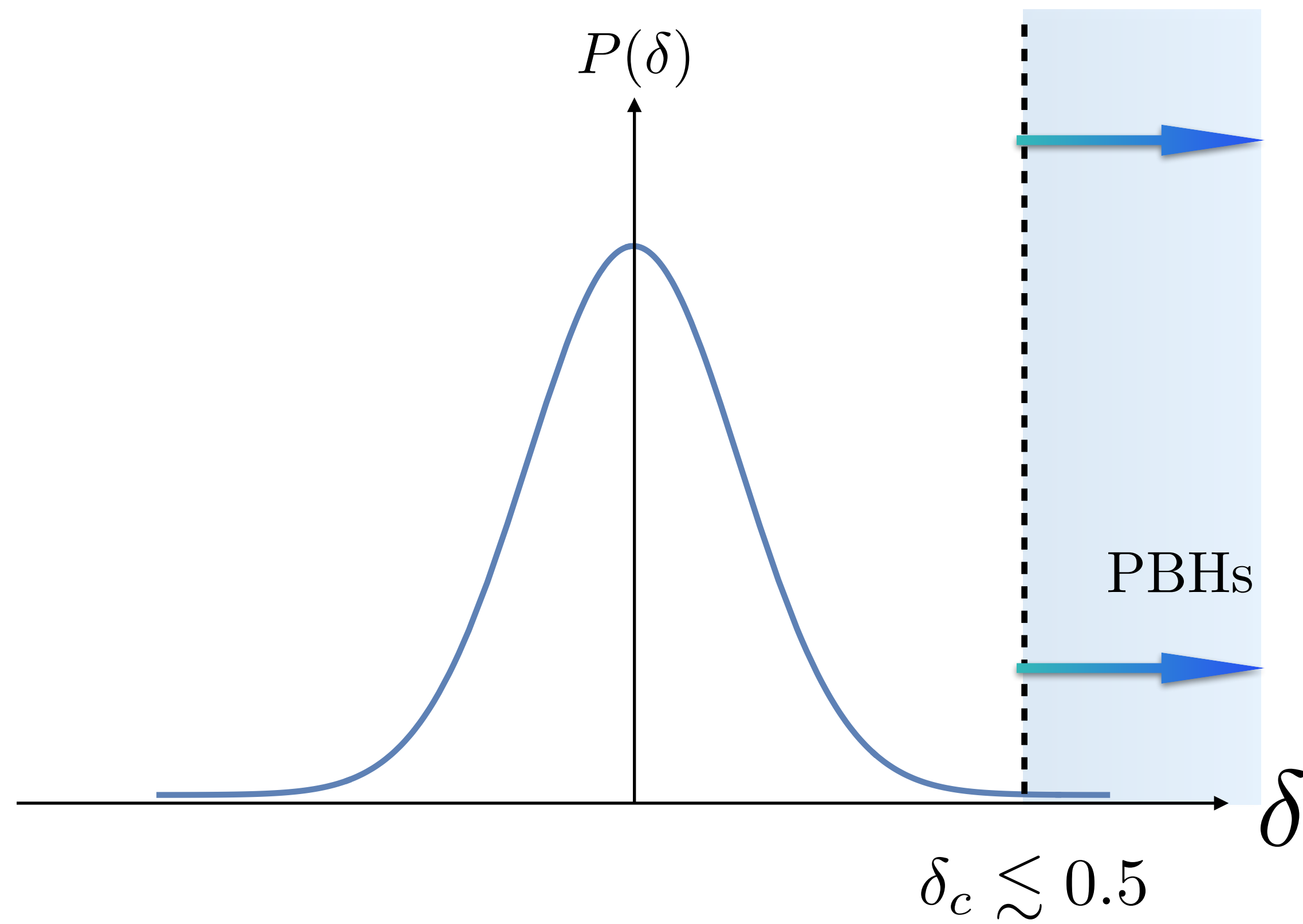
$$\mathcal{P}_\zeta \ll \frac{1}{(\Delta\eta)^2} \simeq 0.03 \quad (\text{for perturbation theory to hold})$$

Kristiano & Yokoyama, 2022 & 2023

Does perturbation theory (PT) break?

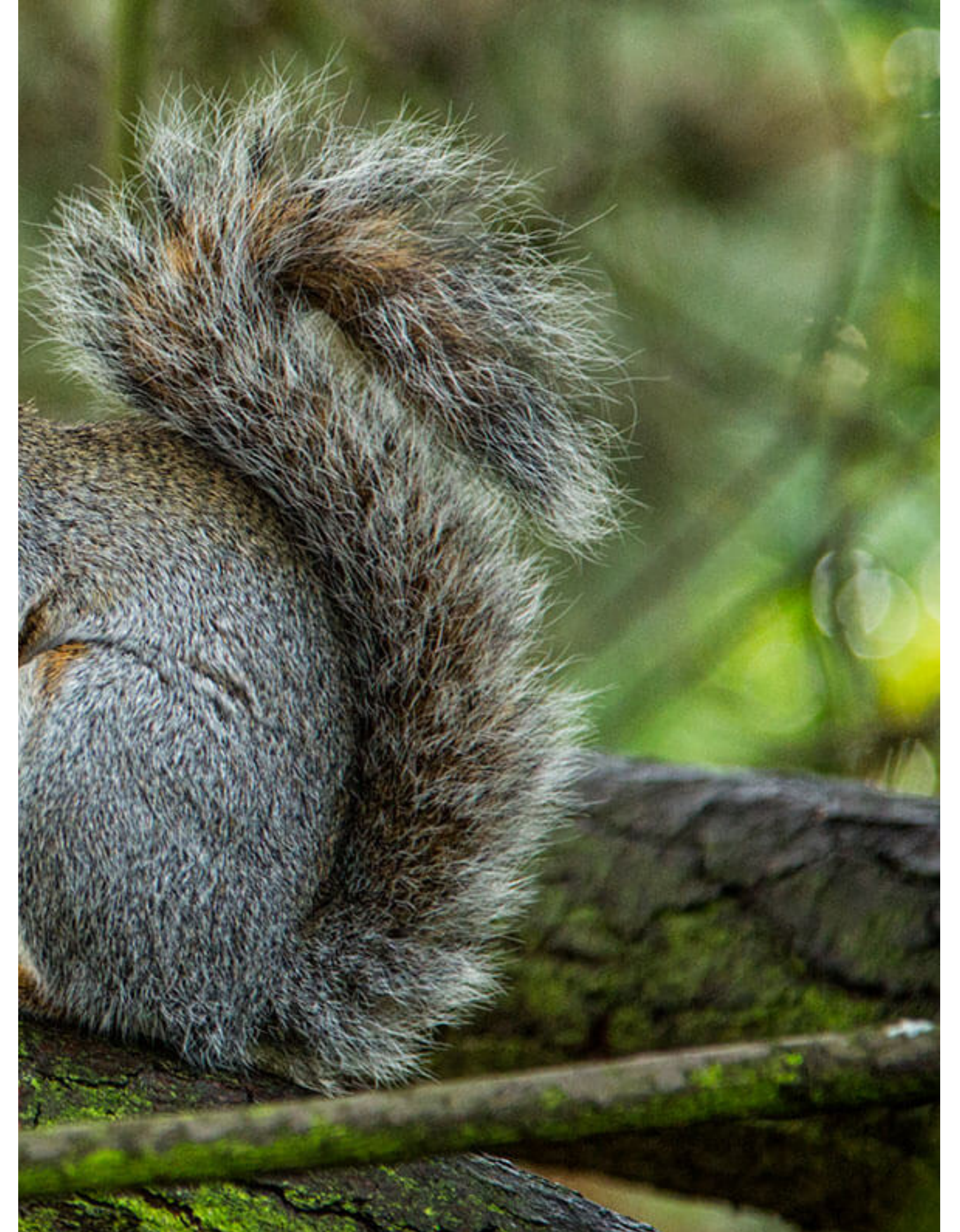
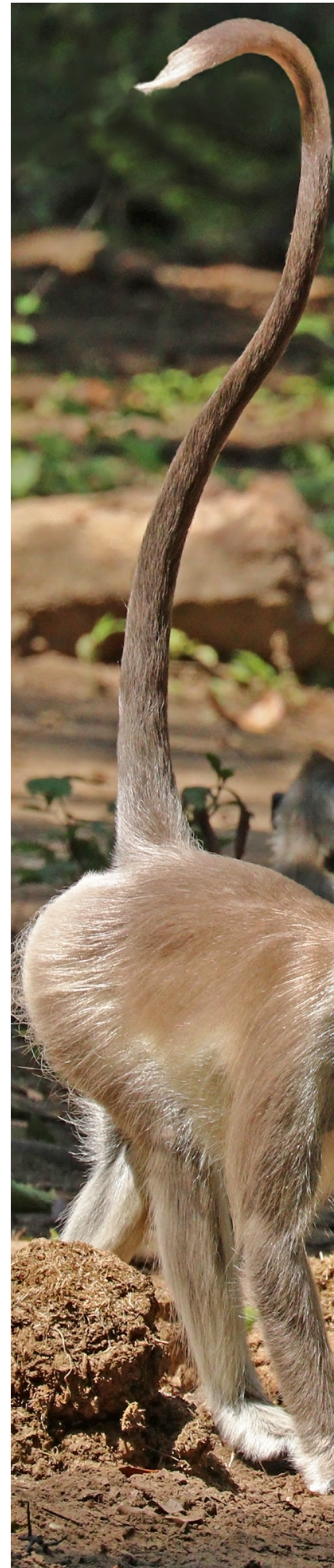
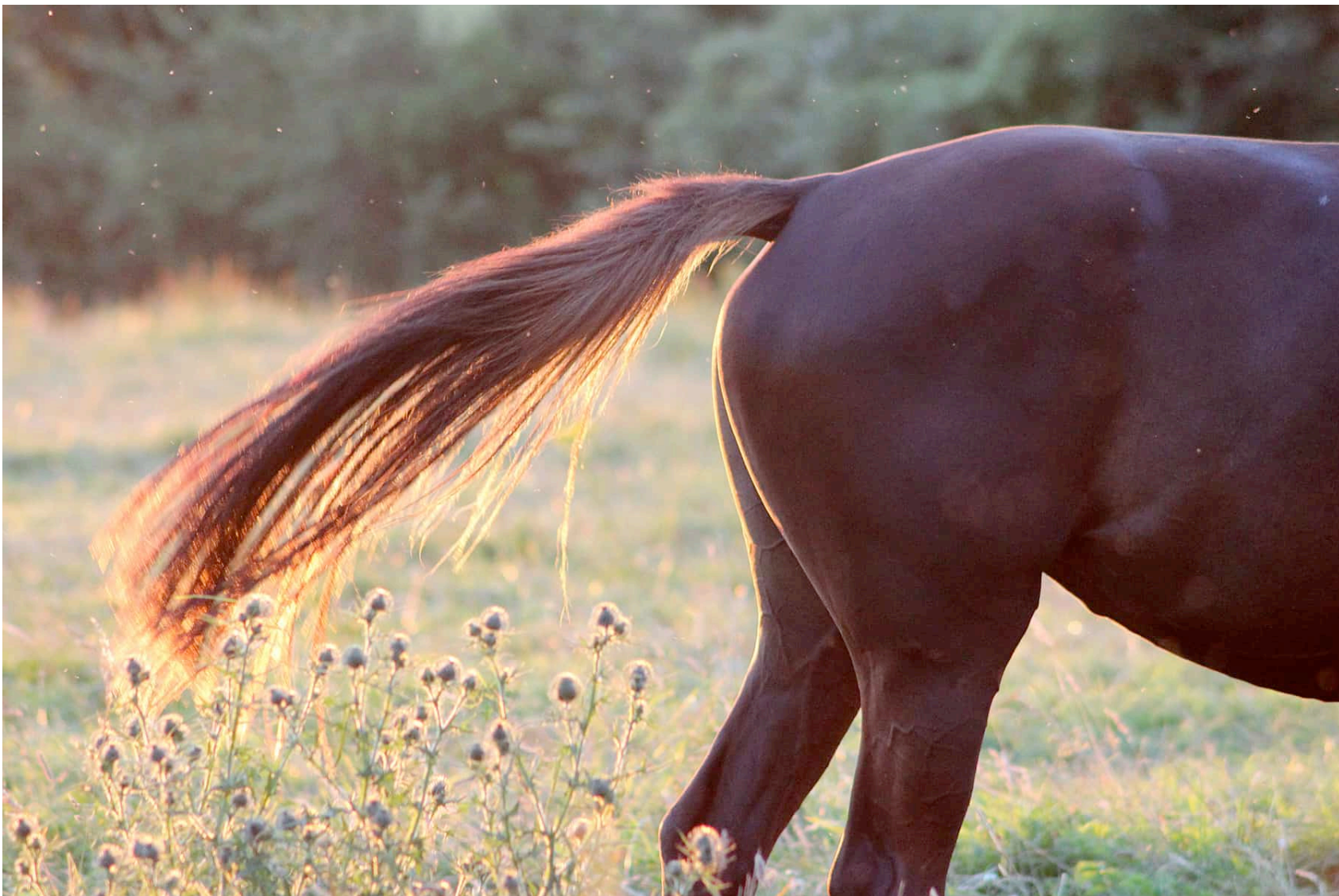


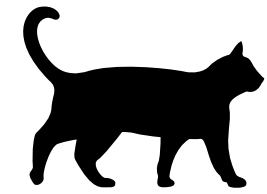
The problem of the abundance



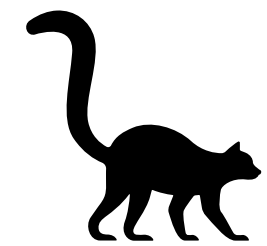
$$\frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} = \int_{\delta_c}^{\infty} f(\delta) d\delta$$

How does the tail of the PDF look like?





The relation between $\mathcal{R}$ and δ is non-linear



$\mathcal{R}$ is, in general, intrinsically non-gaussian

Several indications of non-gaussian tails, for large $\mathcal{R}$
(from non-linear perturbation methods)

Gravitational wave signatures of PBH DM

- * Second order induced gravitational waves
- * Gravitational wave emission from PBH mergers

✱ Second-order induced gravitational waves

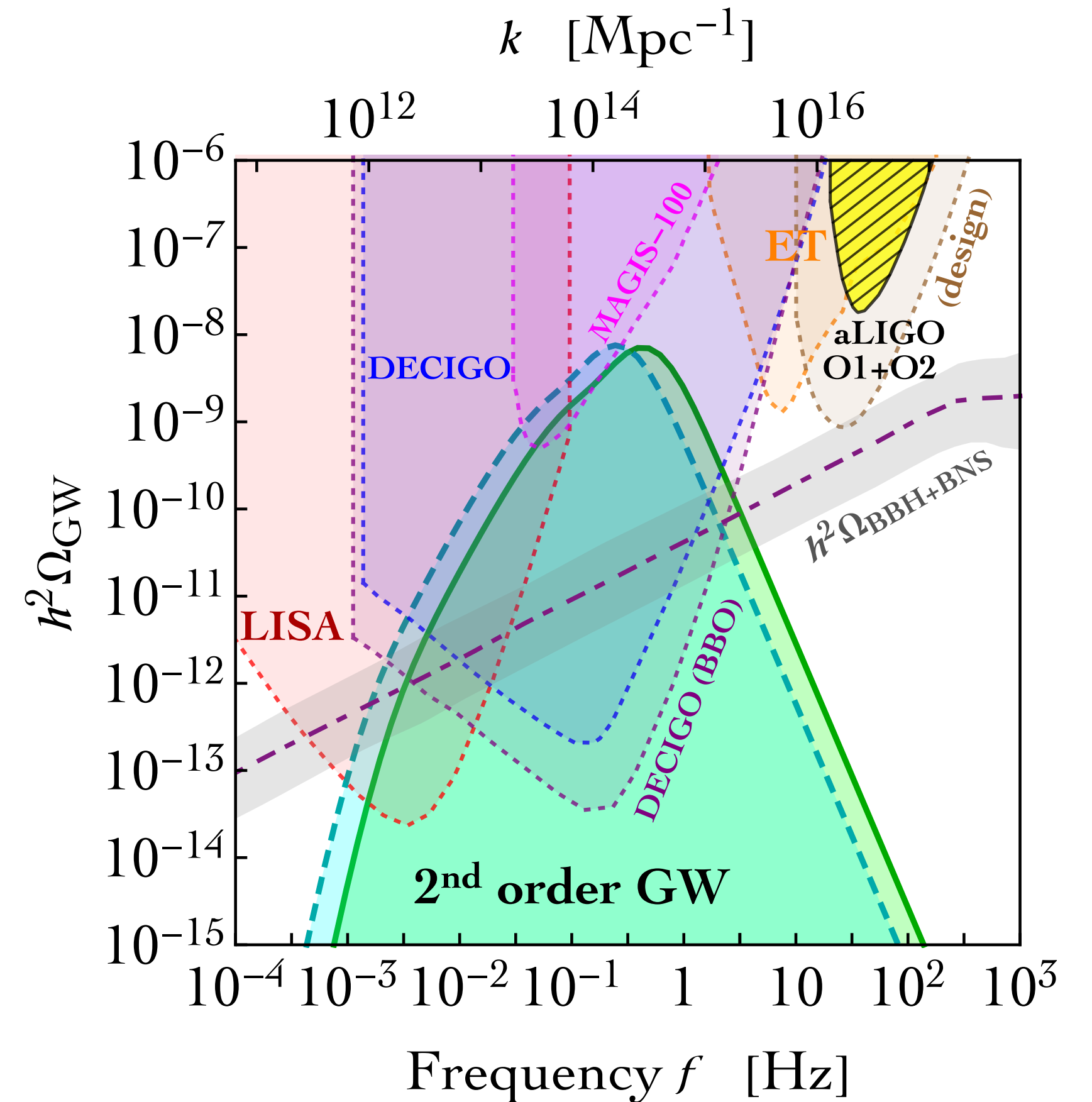
$$h''_{ij} + 2\frac{H'}{h} h_{ij} - \nabla^2 h_{ij} = S_{ij} \sim \partial_i \mathcal{R} \partial_j \mathcal{R} \quad \Rightarrow \quad \Omega_{\text{GW}} \sim \mathcal{P}_h \sim (\mathcal{P}_{\mathcal{R}})^2$$

$$\left(\frac{M_{\text{PBH}}}{10^{17} \text{ g}} \right)^{-1/2} \simeq \frac{k}{2 \cdot 10^{14} \text{ Mpc}^{-1}} \simeq \frac{f}{0.3 \text{ Hz}}$$

* LISA: for PBH DM

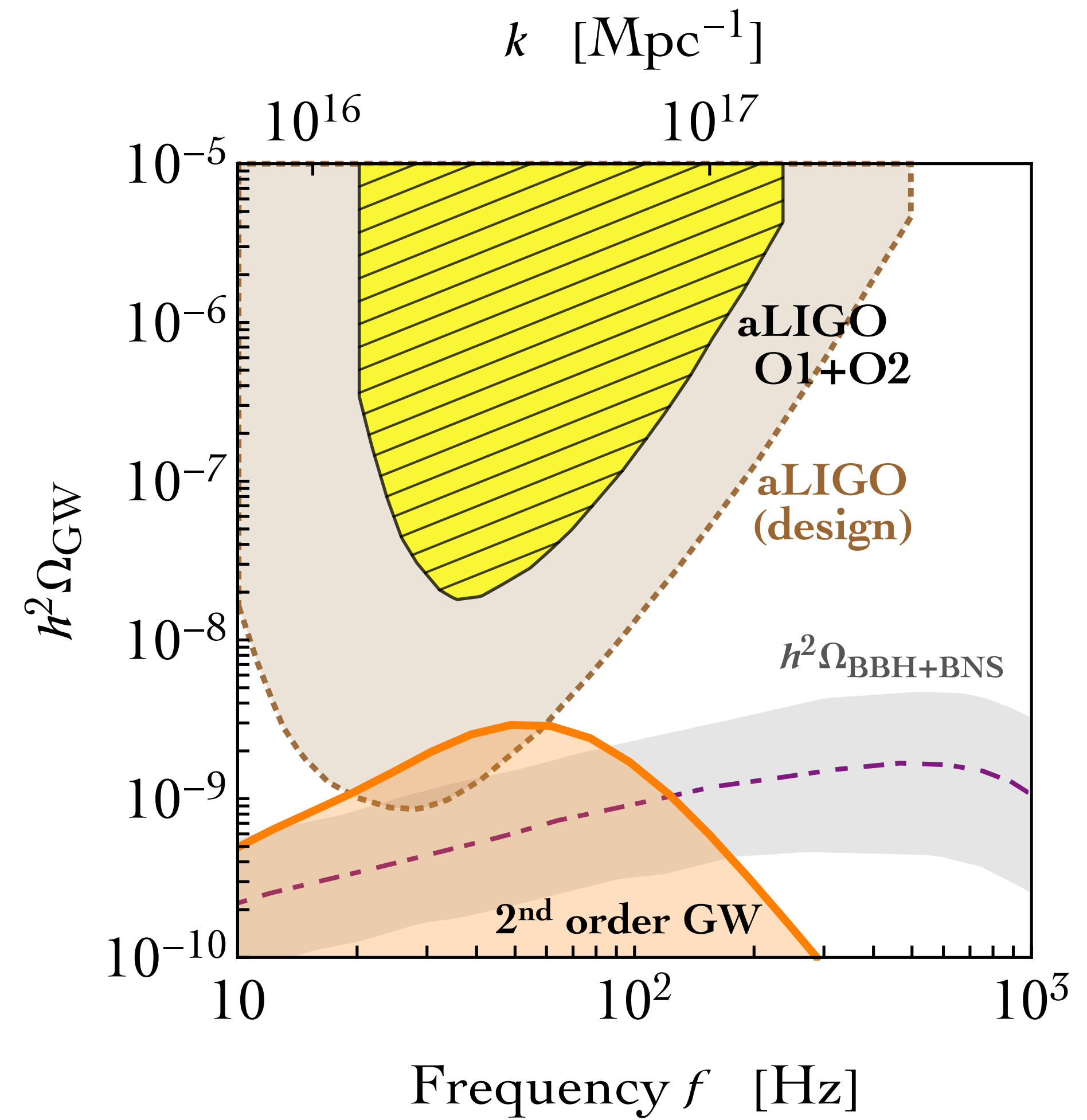
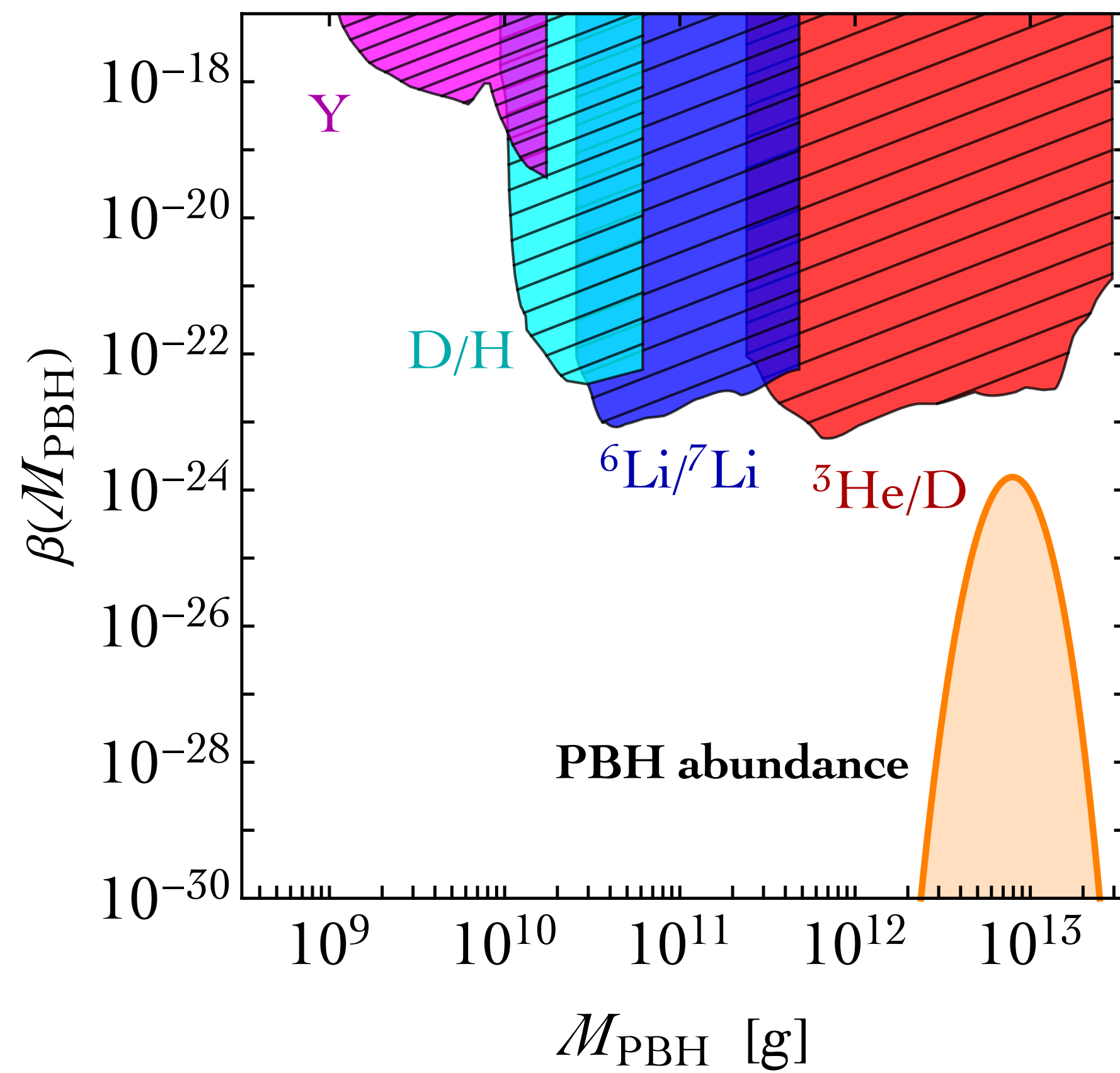
* LIGO/Virgo/KAGRA: if PBHs already evaporated

* PTA: if PBHs of ~ 0.1 Solar masses

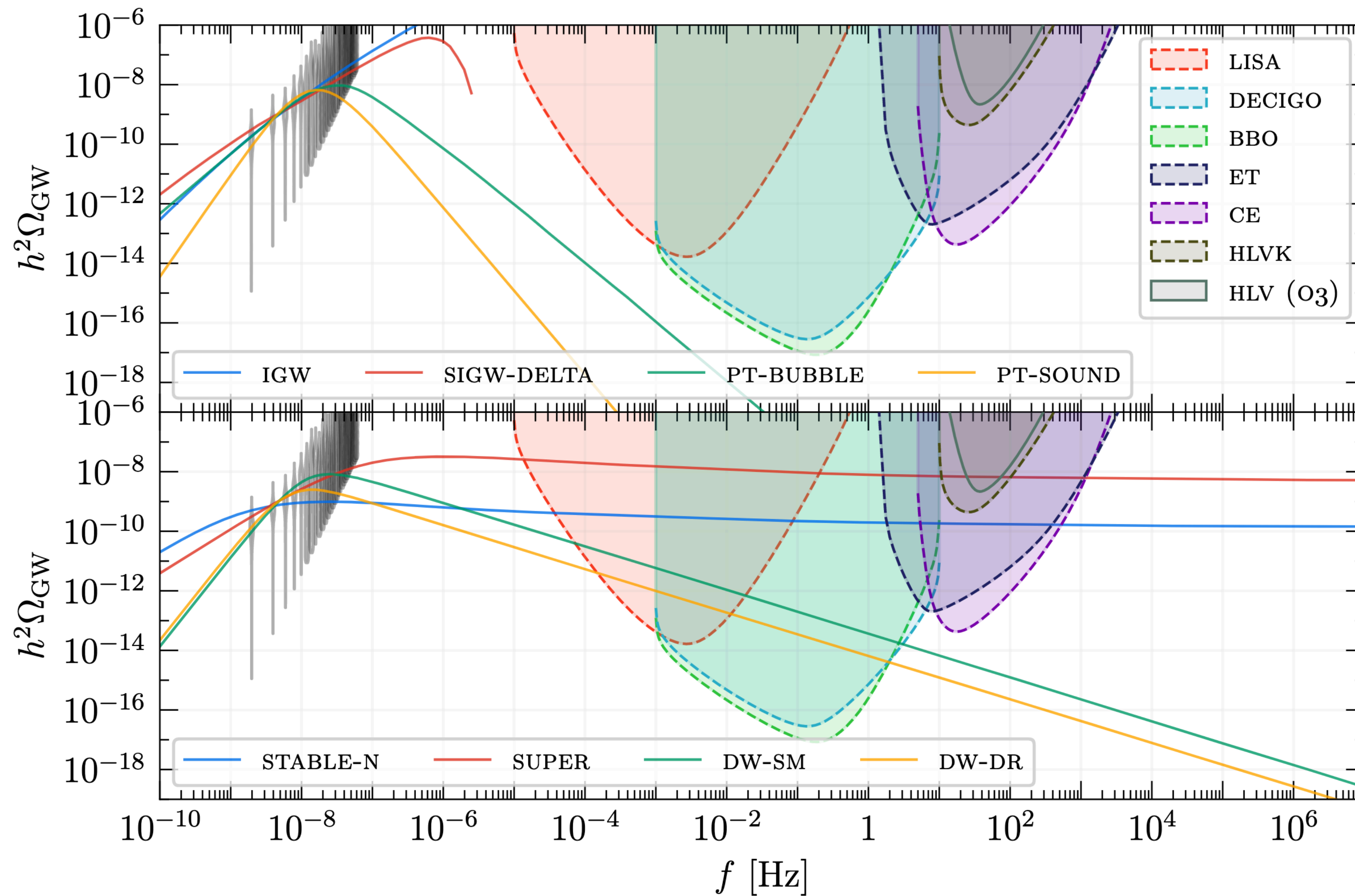


See e.g. Ballesteros, Rey, Taoso, Urbano 2020

✱ Second-order induced gravitational waves

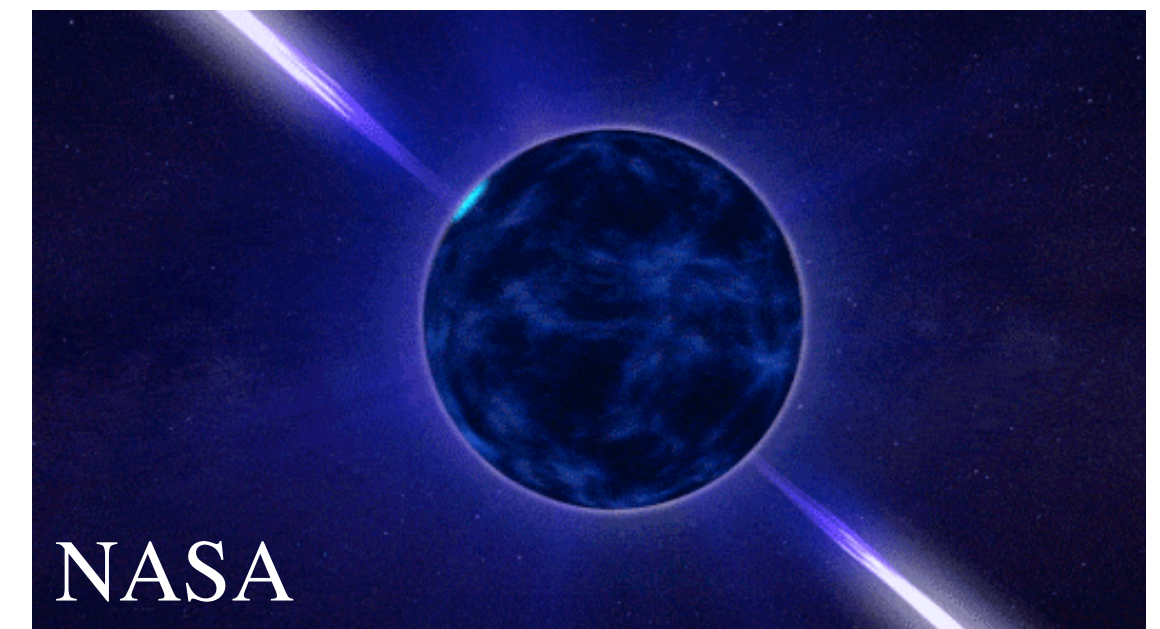


* Second-order induced gravitational waves



PTA experiments

$\sim \text{NHz} \sim 10 M_{\odot}$



✧ High frequency GW from PBH DM mergers

No known astrophysical sources of GWs at GHz

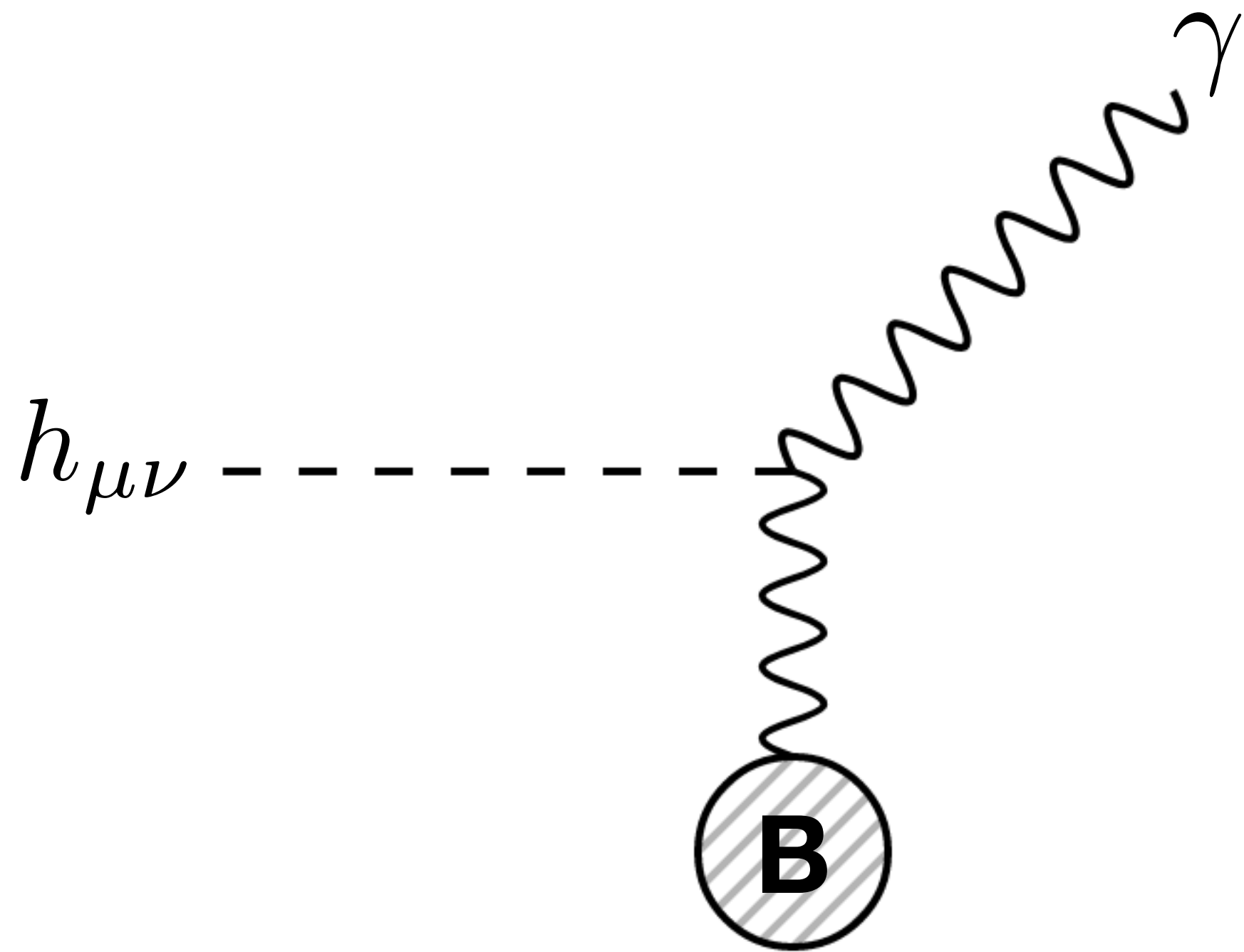
Asteroid mass PBH mergers: GW frequency $\gtrsim$ GHz

Very small characteristic strain $\sim 10^{-25}$

(BIG experimental challenge)

✧ High frequency GW from PBH DM mergers

Inverse Gertsenshtein effect. Connection with axion physics



ALPS II. DESY / Heiner Müller-Elsner

Conclusions

- Asteroid-mass PBHs are a strong contender to explain the DM.
- PBH from inflation. Interesting for phenomenology and theory playground
- GWs: indirect probe of PBH DM. Technical challenges.
- Goal 1: Narrow the asteroid-mass window. How?
- Goal 2: Detect subsolar BH with lensing, GW interferometry, etc.