

OPENING THE WINDOW FOR ULTRA-LIGHT PBH

PLANCK 25

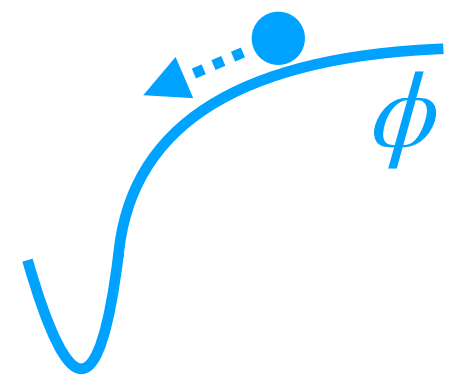
29.05.2025

Nicholas Leister

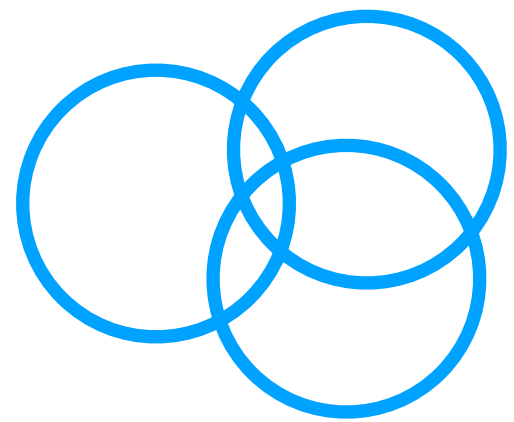
*Based on work with Yann Gouttenoire and Pedro Schwaller
in preparation*



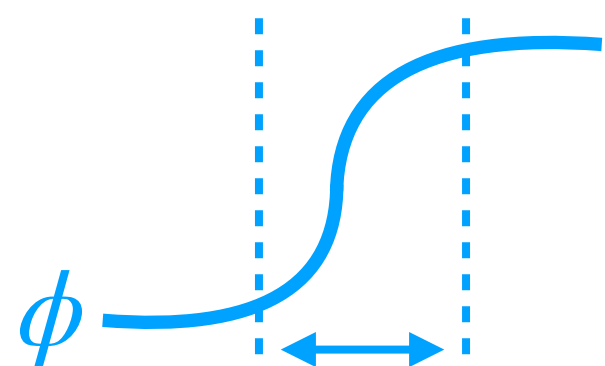
INTRODUCTION



INFLATION

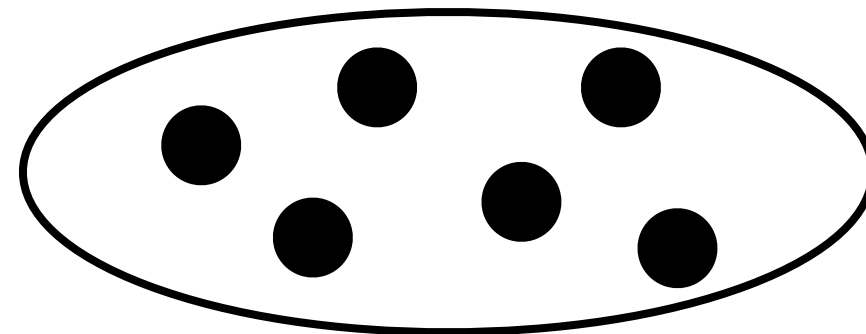


FOPT

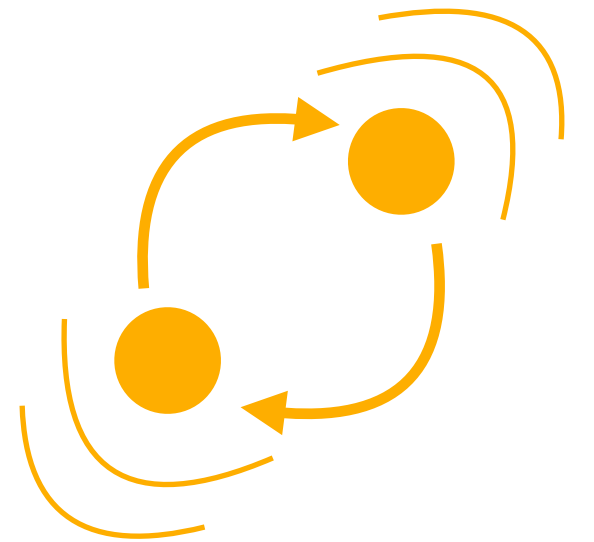


DWs

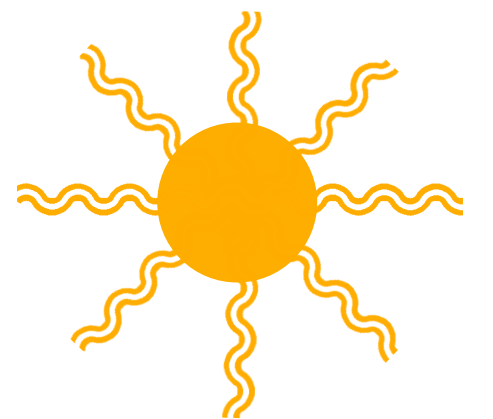
**PRIMORDIAL
BLACK HOLES**



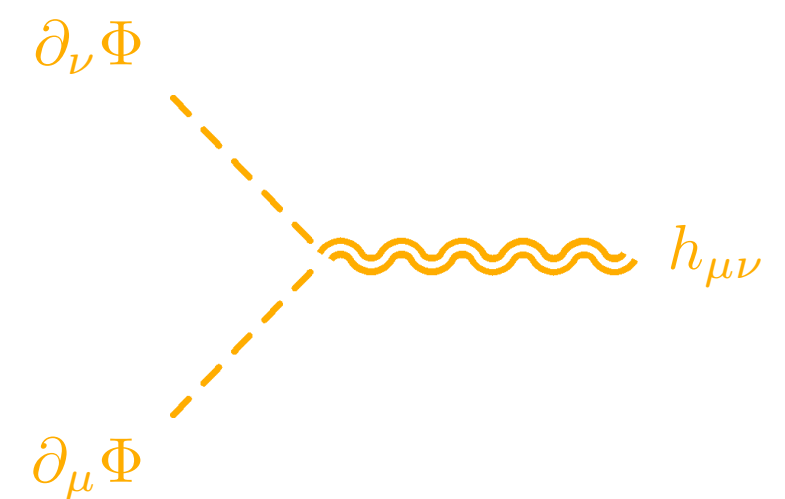
BINARIES



GRAVITONS



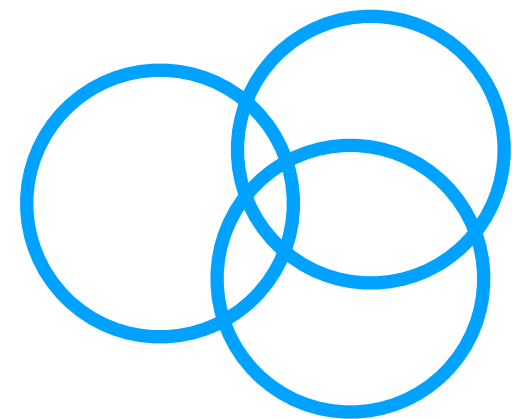
SCALAR-INDUCED



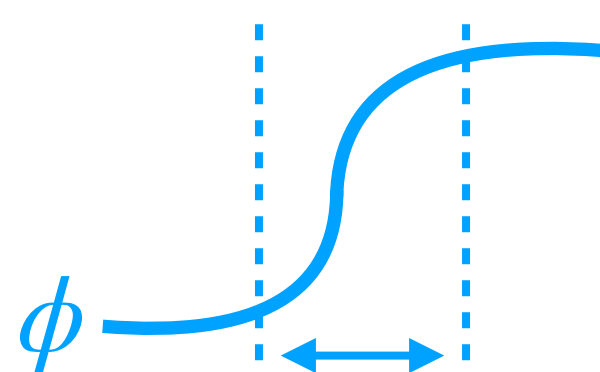
INTRODUCTION



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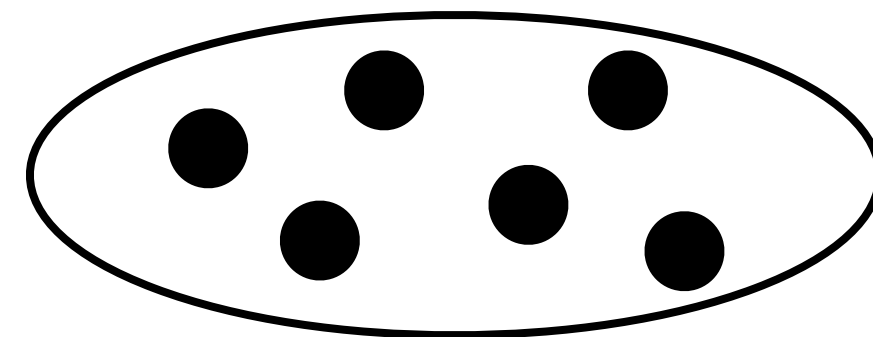


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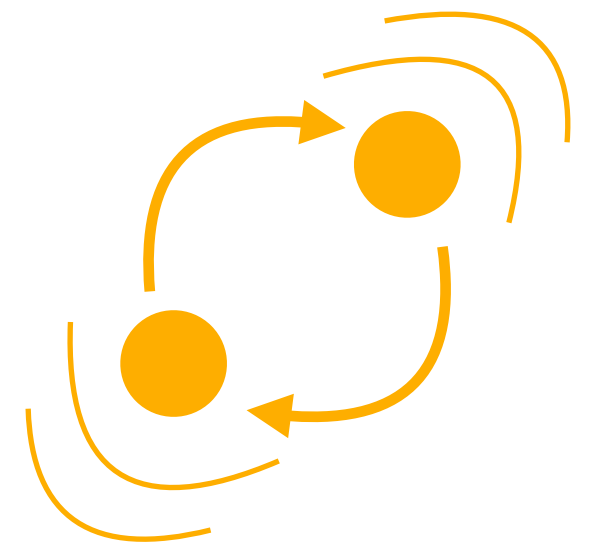


DWs

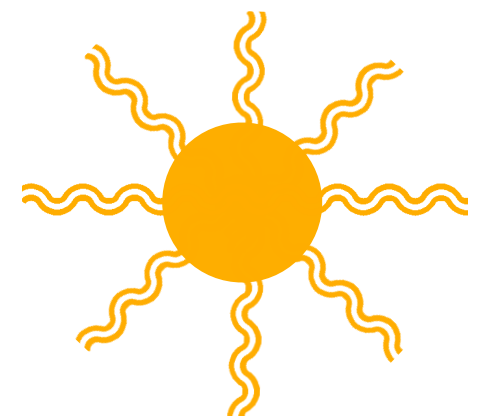
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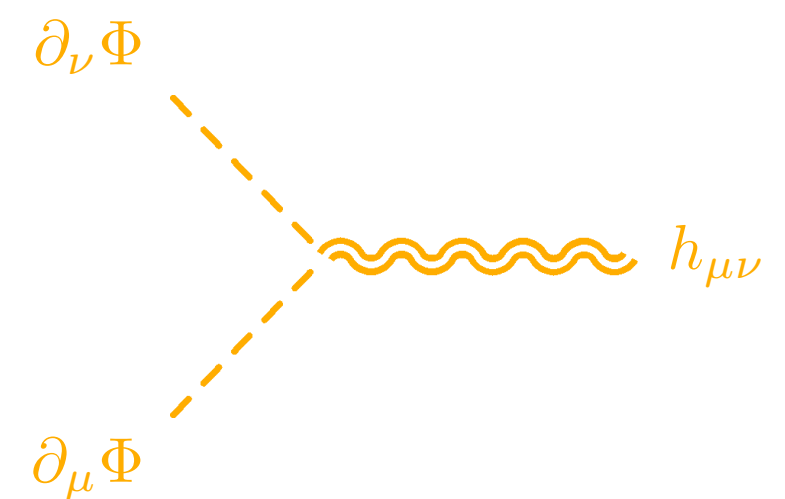
BINARIES



GRAVITONS



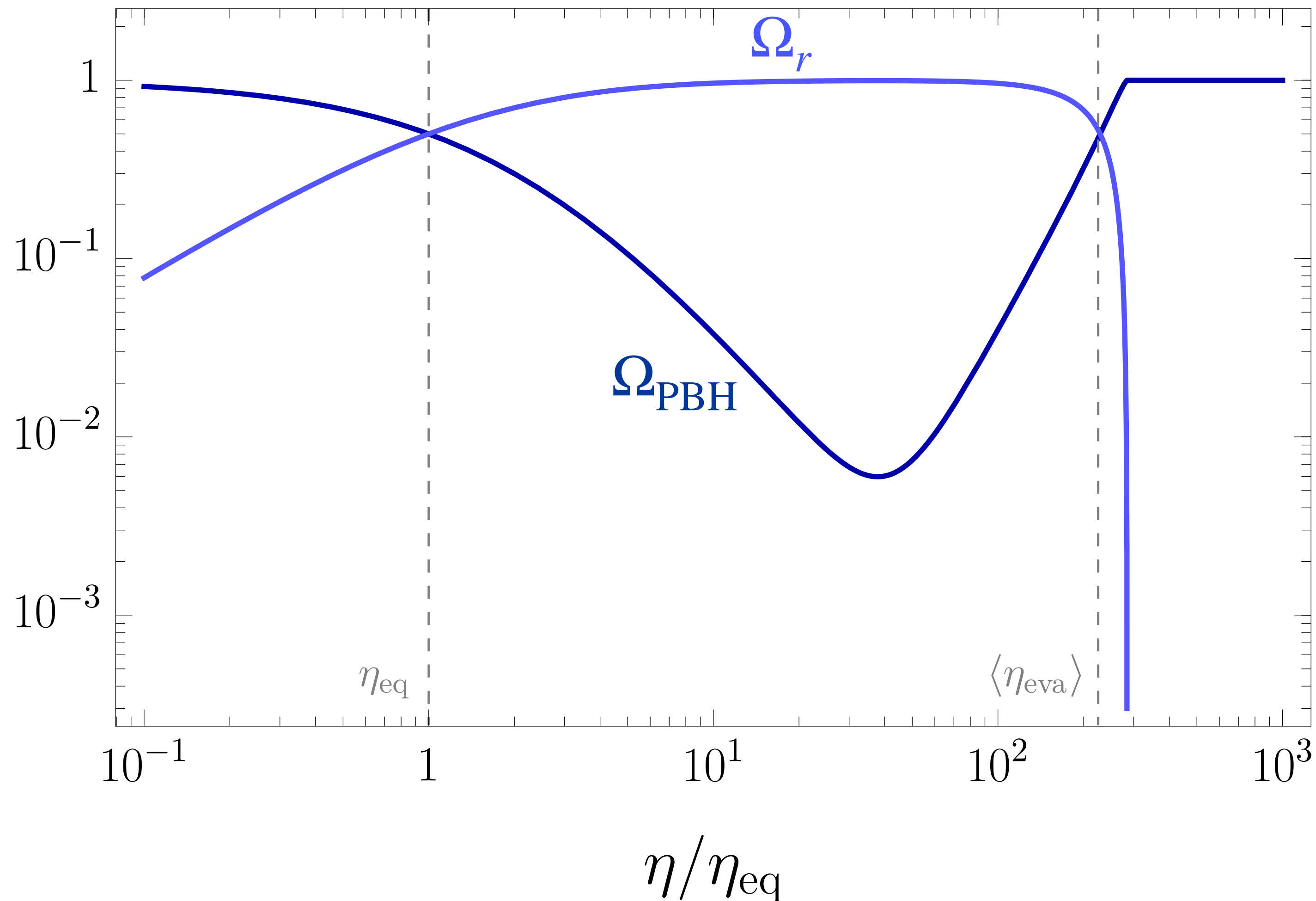
SCALAR-INDUCED



PART I:

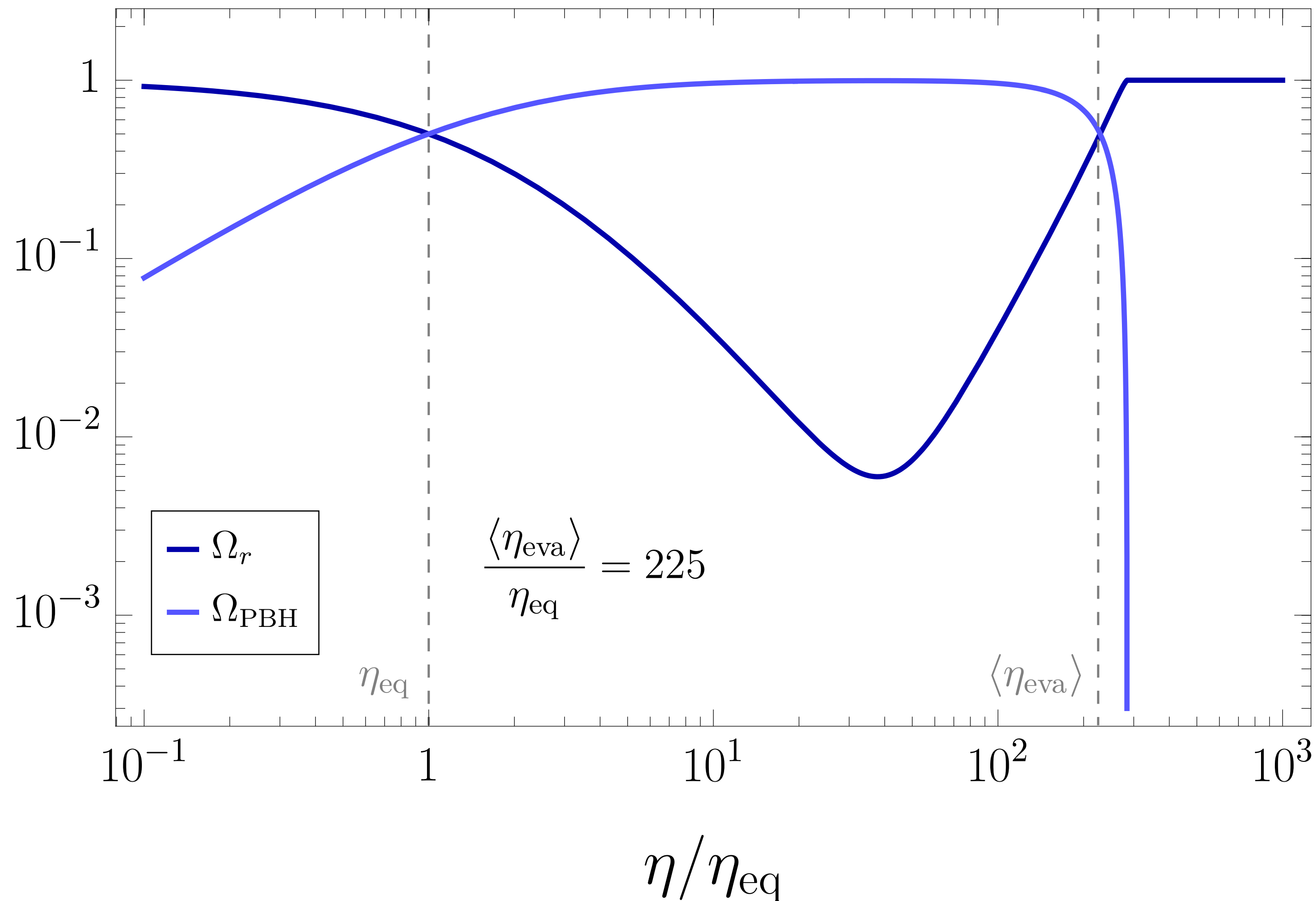
What we know ...

PRIMORDIAL BLACK HOLES



$$\begin{aligned}\rho'_m &= -(3\mathcal{H} + \Gamma)\rho_m \\ \rho'_r &= -4\mathcal{H}\rho_r + \Gamma\rho_m \\ \mathcal{H} &= \frac{a}{\sqrt{3}M_{\text{pl}}}\sqrt{\rho_{\text{tot}}}\end{aligned}$$

PRIMORDIAL BLACK HOLES

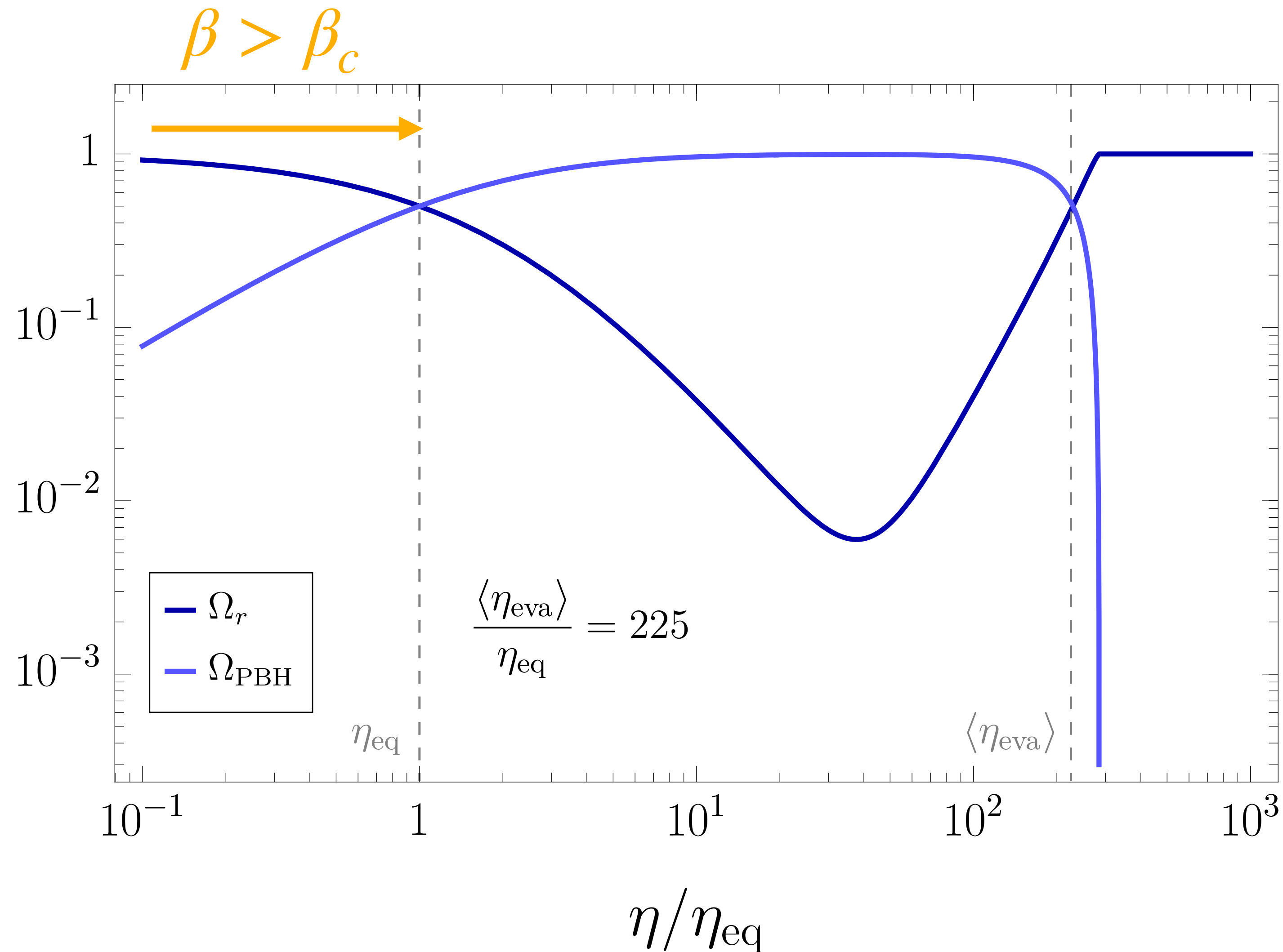


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PRIMORDIAL BLACK HOLES

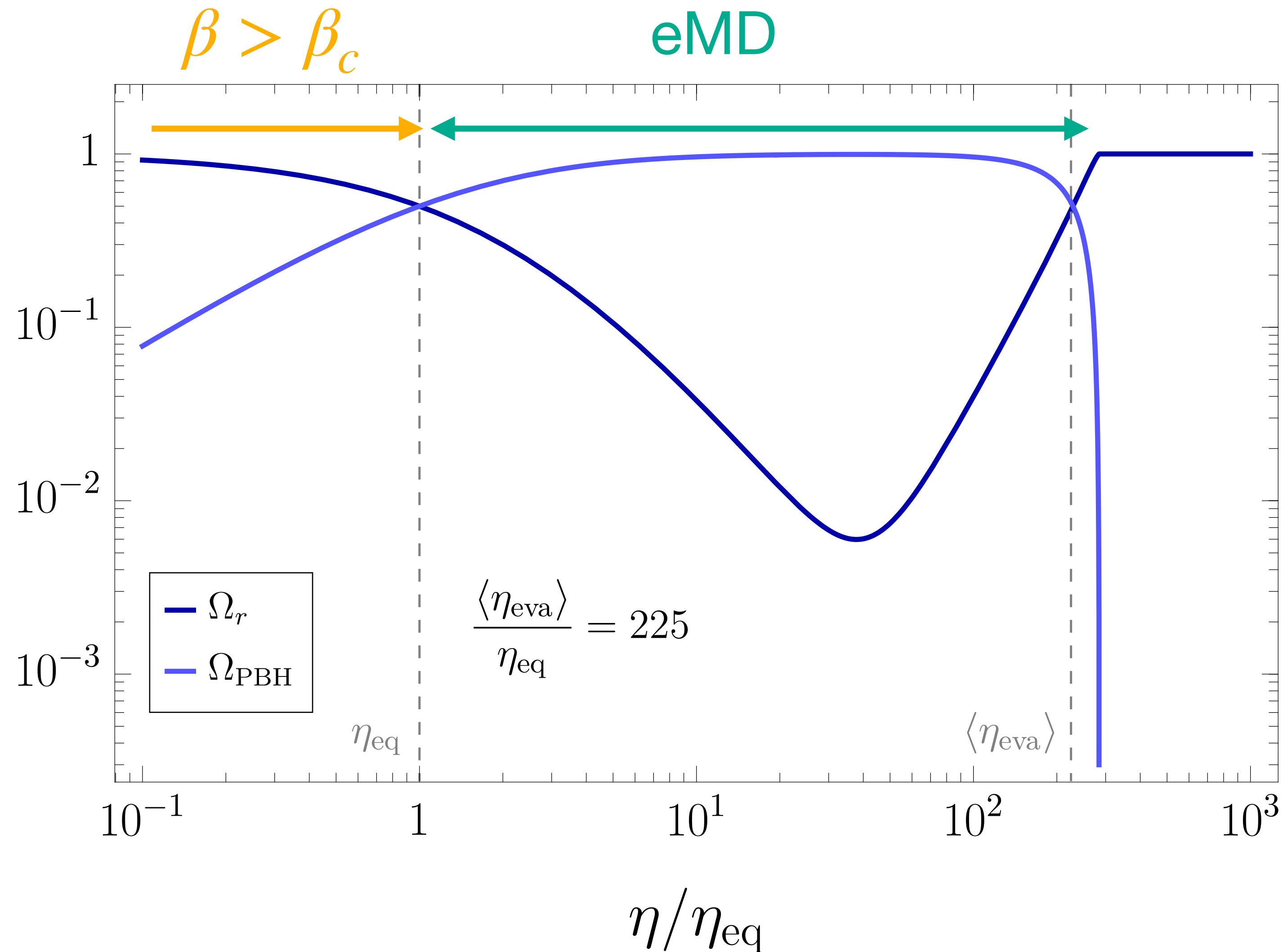


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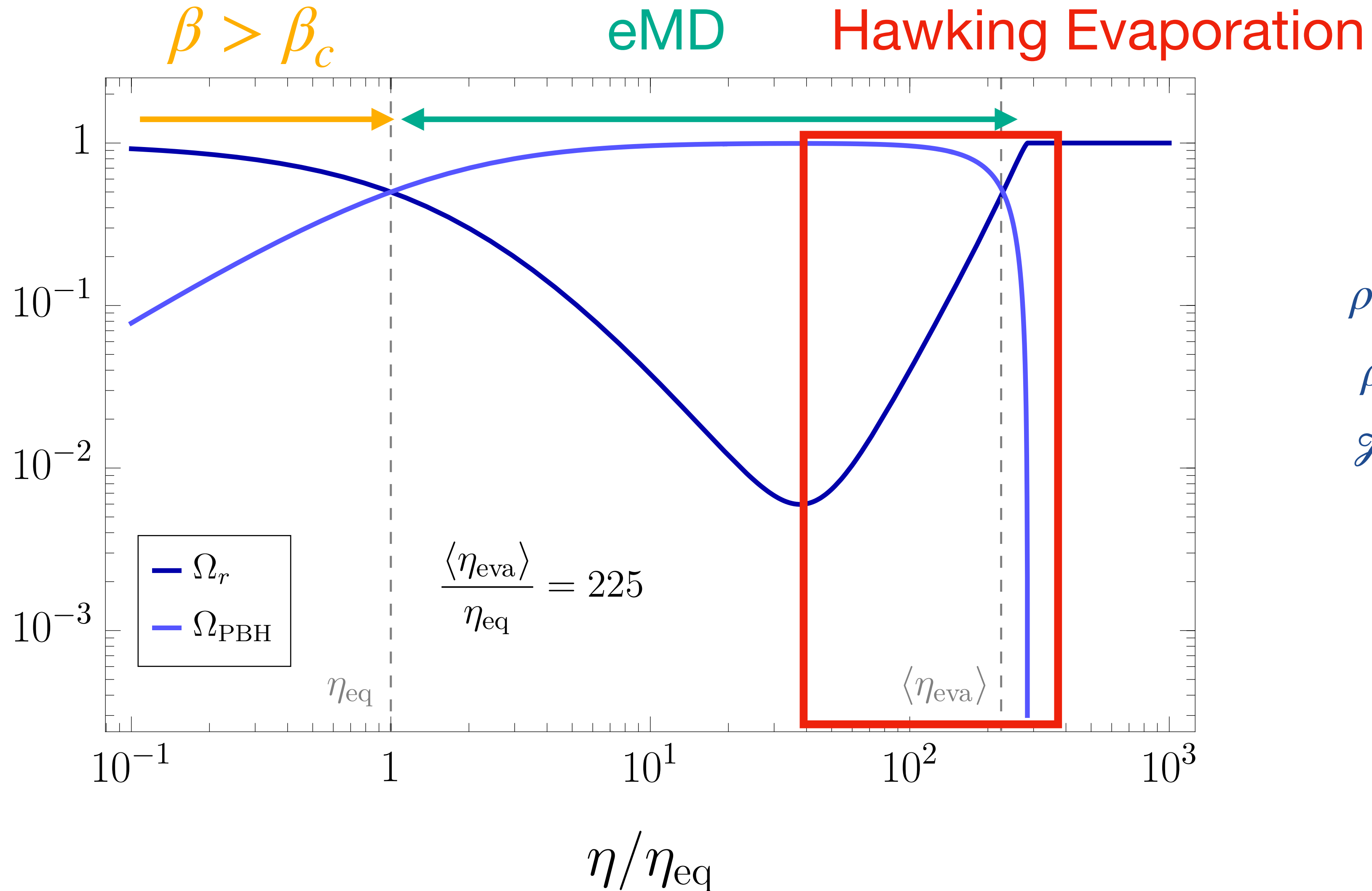


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SOLVING PERTURBATIONS

Cosmological perturbation theory

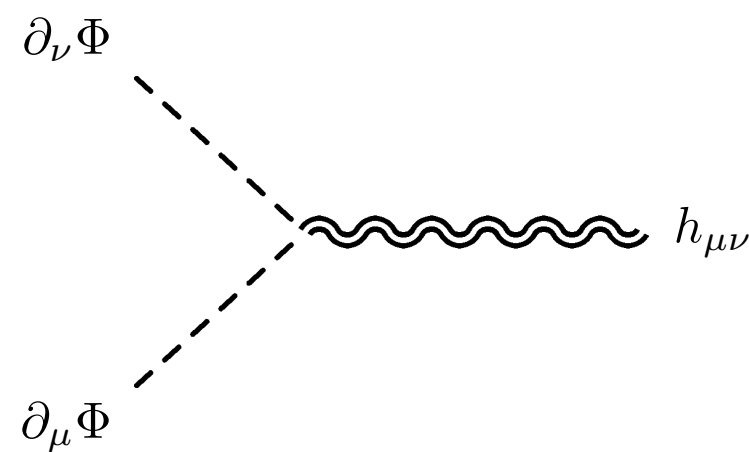
$$ds^2 = a^2(\eta) \left[(1 + 2\Psi) d\eta^2 - (1 - 2\Phi) \delta_{ij} dx^i dx^j + h_{ij} dx^i dx^j \right]$$

In Newtonian gauge and with out anisotropic stress ($\Phi = -\Psi$)

At 1st order in PT: no scalar-tensor mixing

At 2nd order in PT: SIGWs

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \partial_k \partial^k h_{ij} = \mathcal{P}^{ab}_{ij} \{T_{ab}\} \approx \mathcal{P}^{ab}_{ij} \{4\partial_a \Phi \partial_b \Phi + 2\partial_a \delta\varphi \partial_b \delta\varphi\}$$



$$\mathcal{P}_h \propto h^2 \propto \Phi^4$$

SOLVING PERTURBATIONS

Cosmological perturbation theory

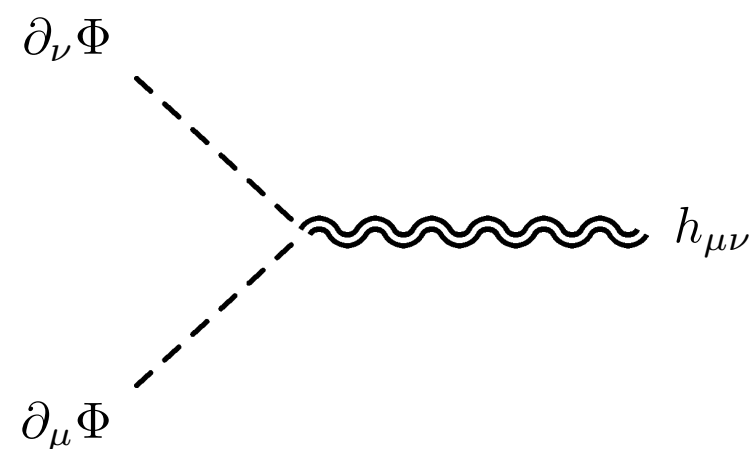
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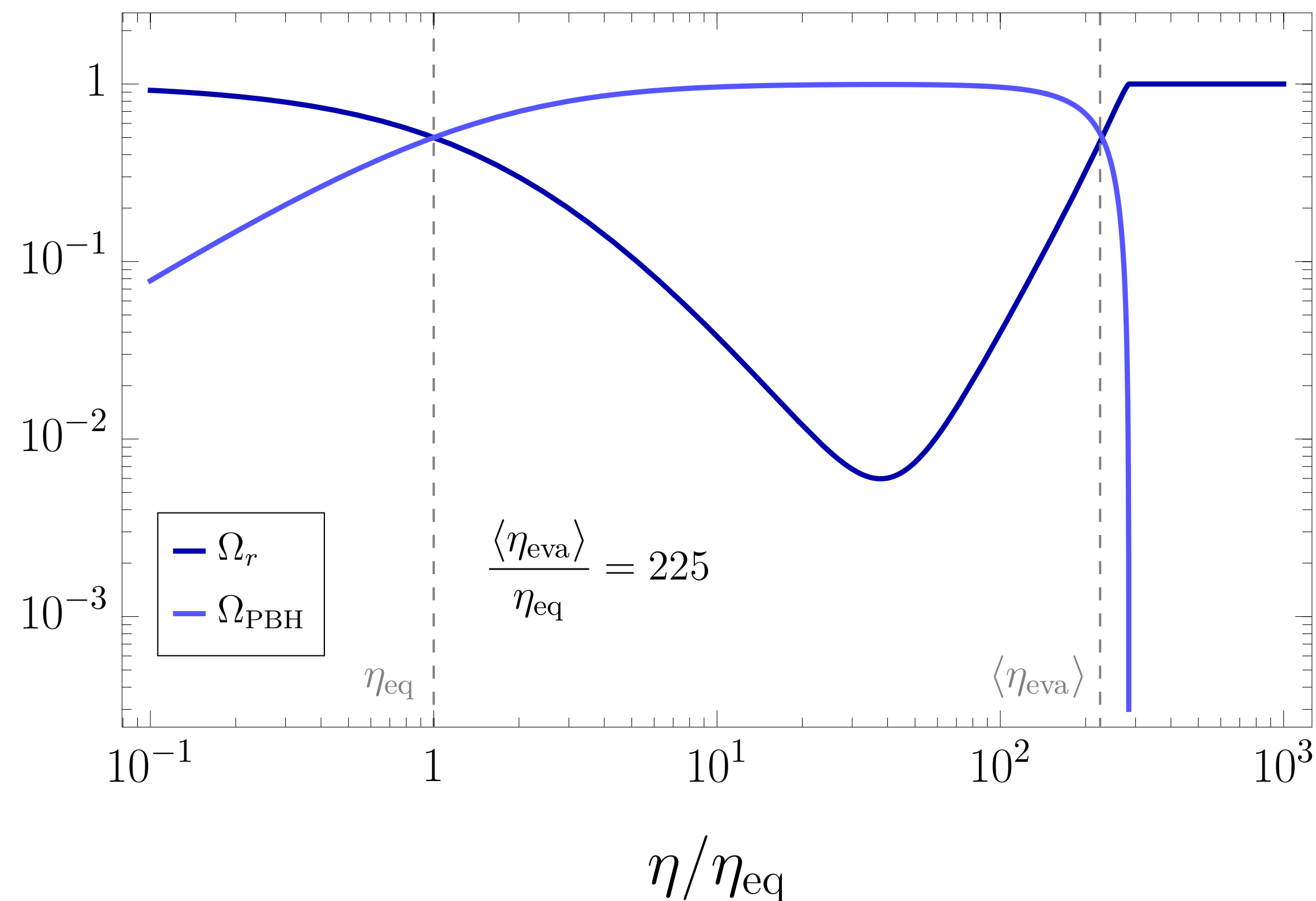
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$$\mathcal{P}_h \propto h^2 \propto \Phi^4$$

$$\delta\phi \sim \Phi + \frac{\Phi'}{\mathcal{H}}$$

SOLVING PERTURBATIONS



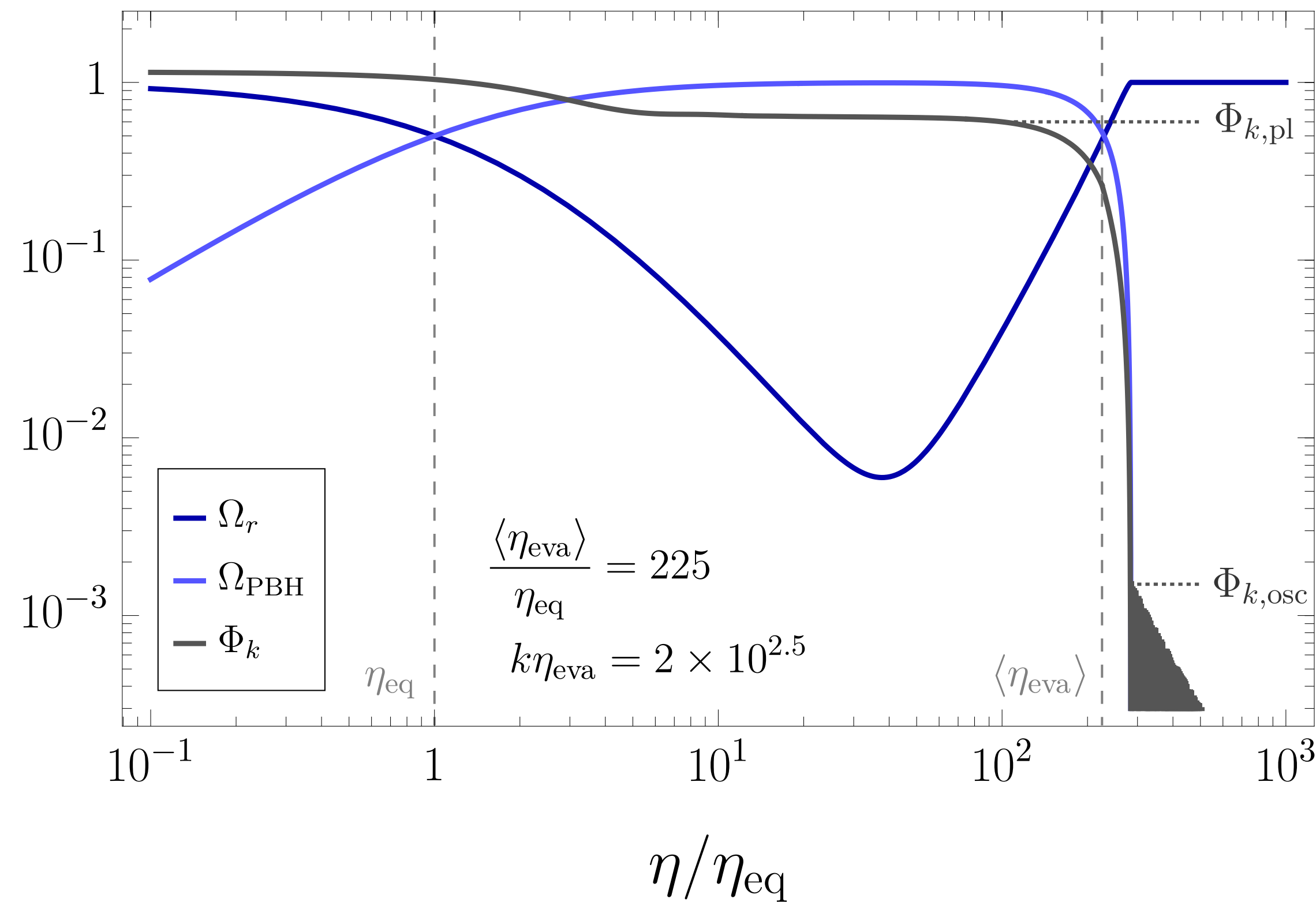
$$\mathcal{P}_h \propto \Phi_{\text{osc}}^4$$

Combine:

1. **Transfer function** $\mathcal{T}(k)$:
RD-to-MD transition
2. **Suppression factor** $\mathcal{S}(k)$:
MD-to-RD transition

Effects decouple

SOLVING PERTURBATIONS



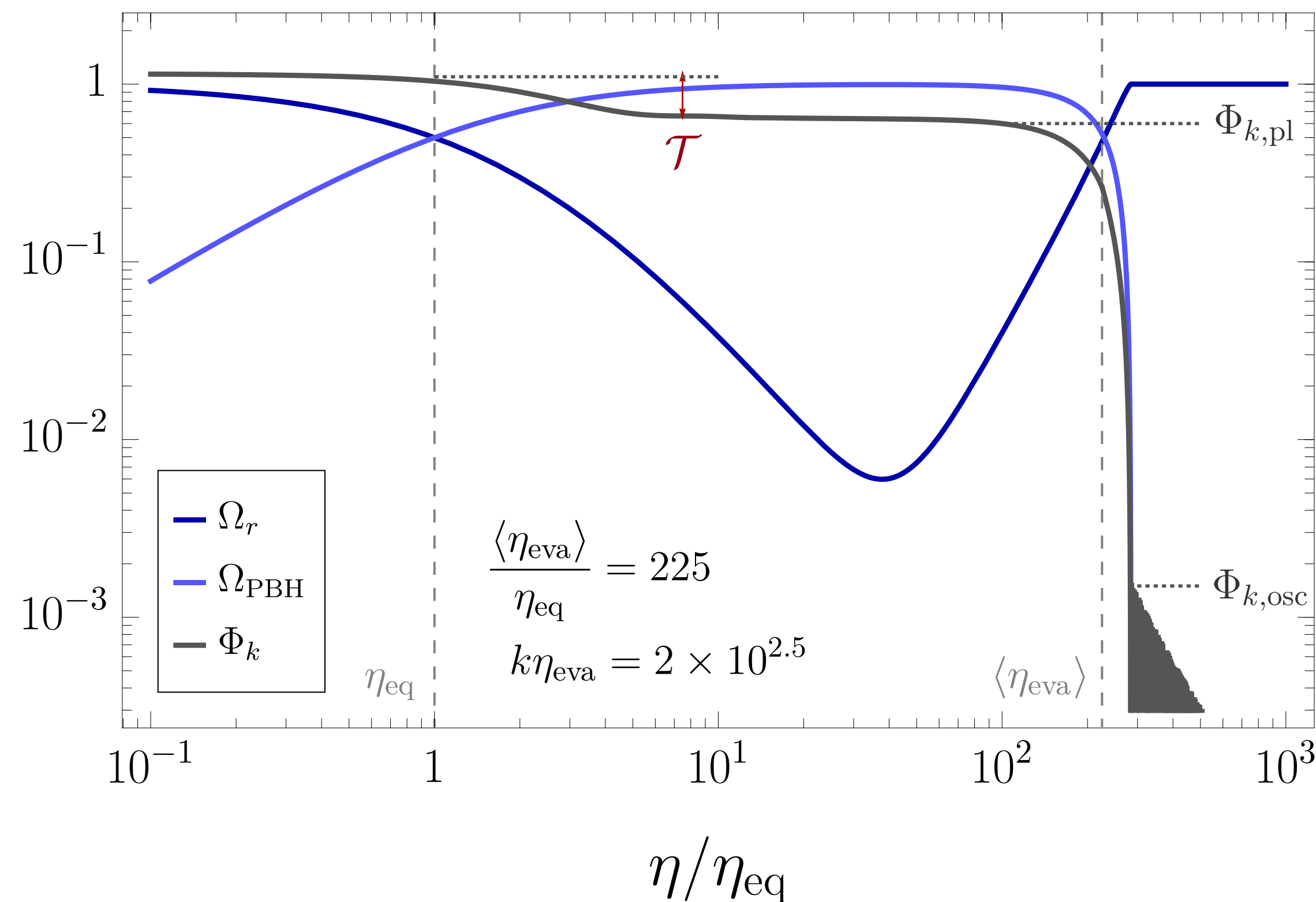
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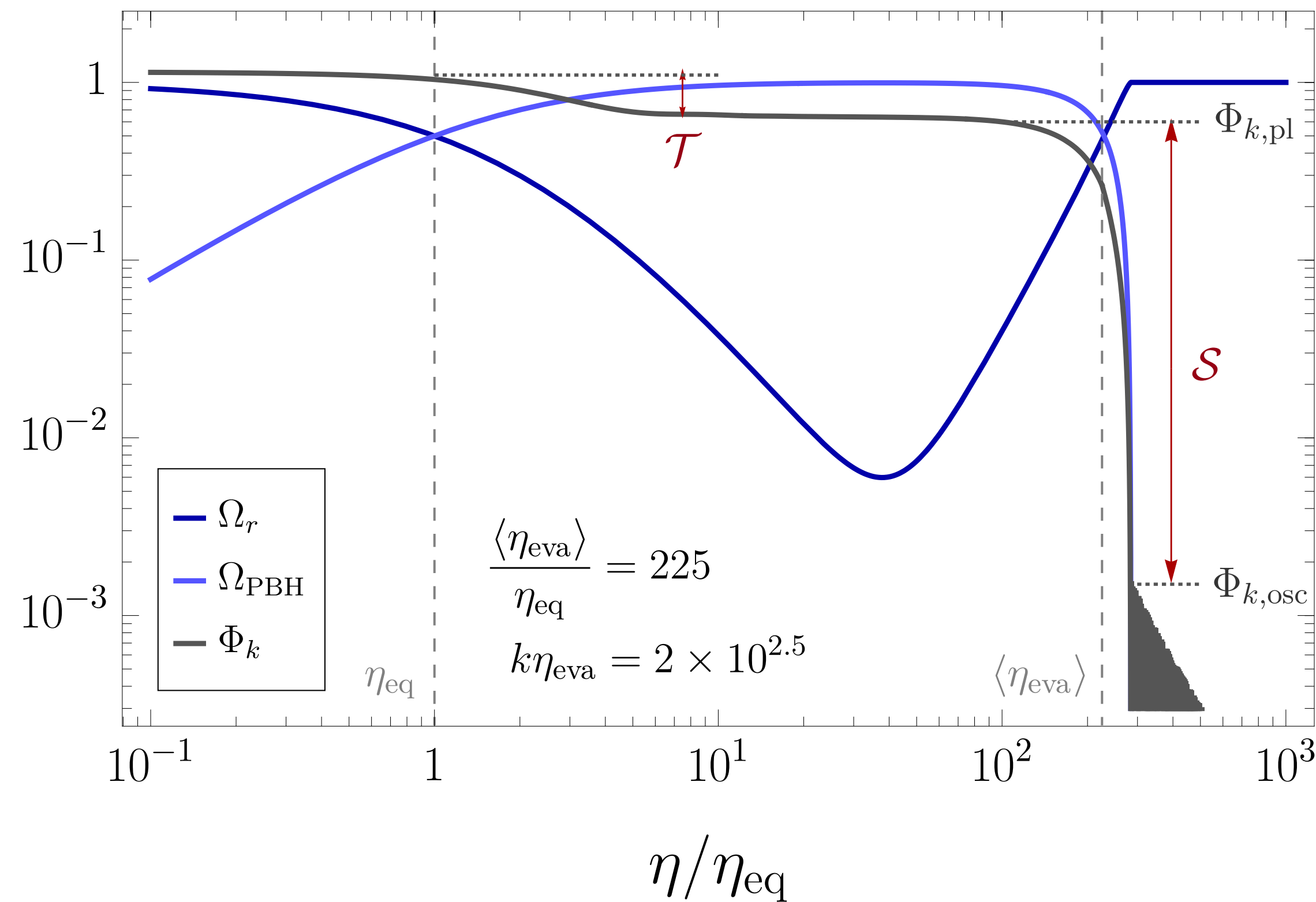
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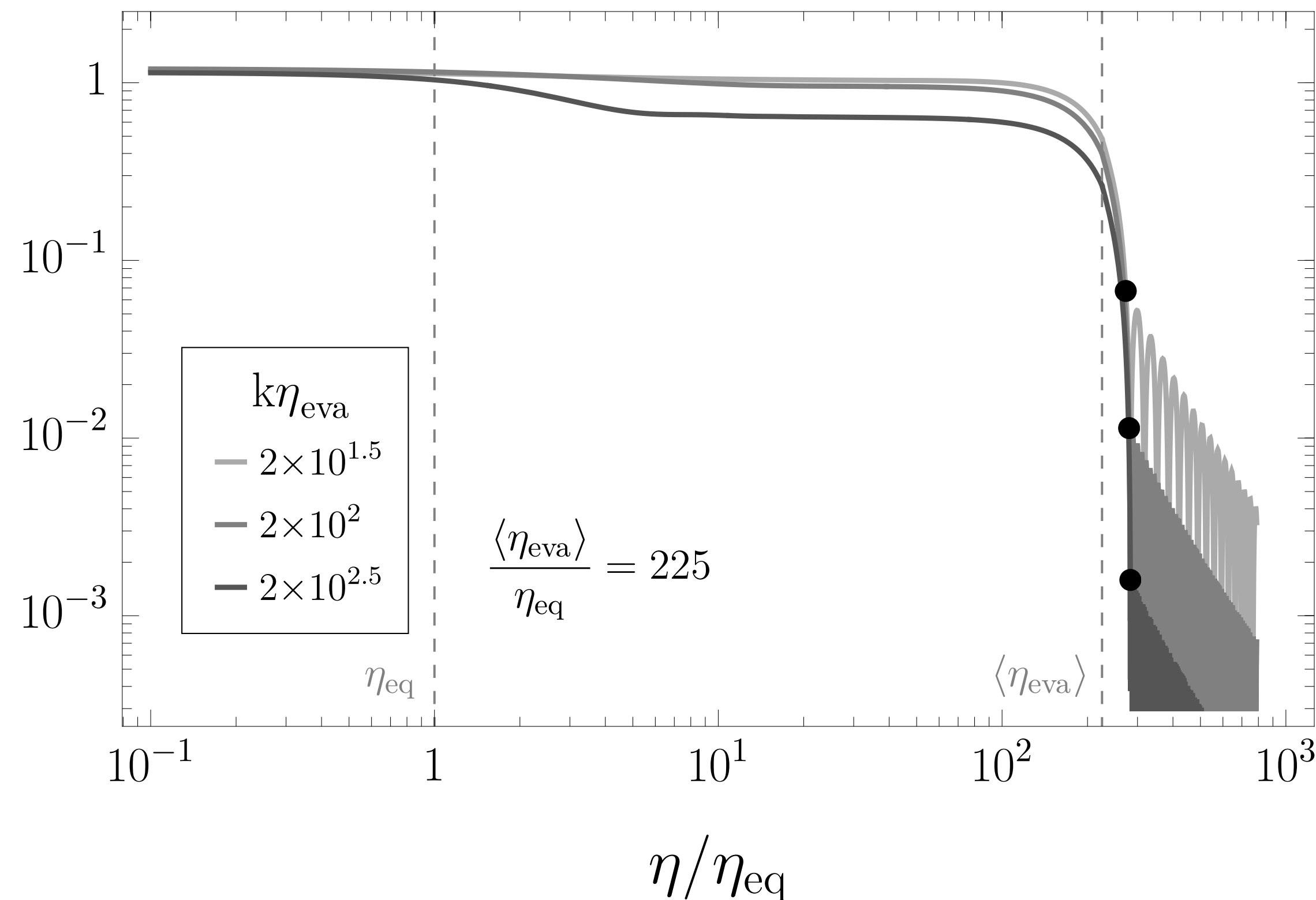
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SOLVING PERTURBATIONS

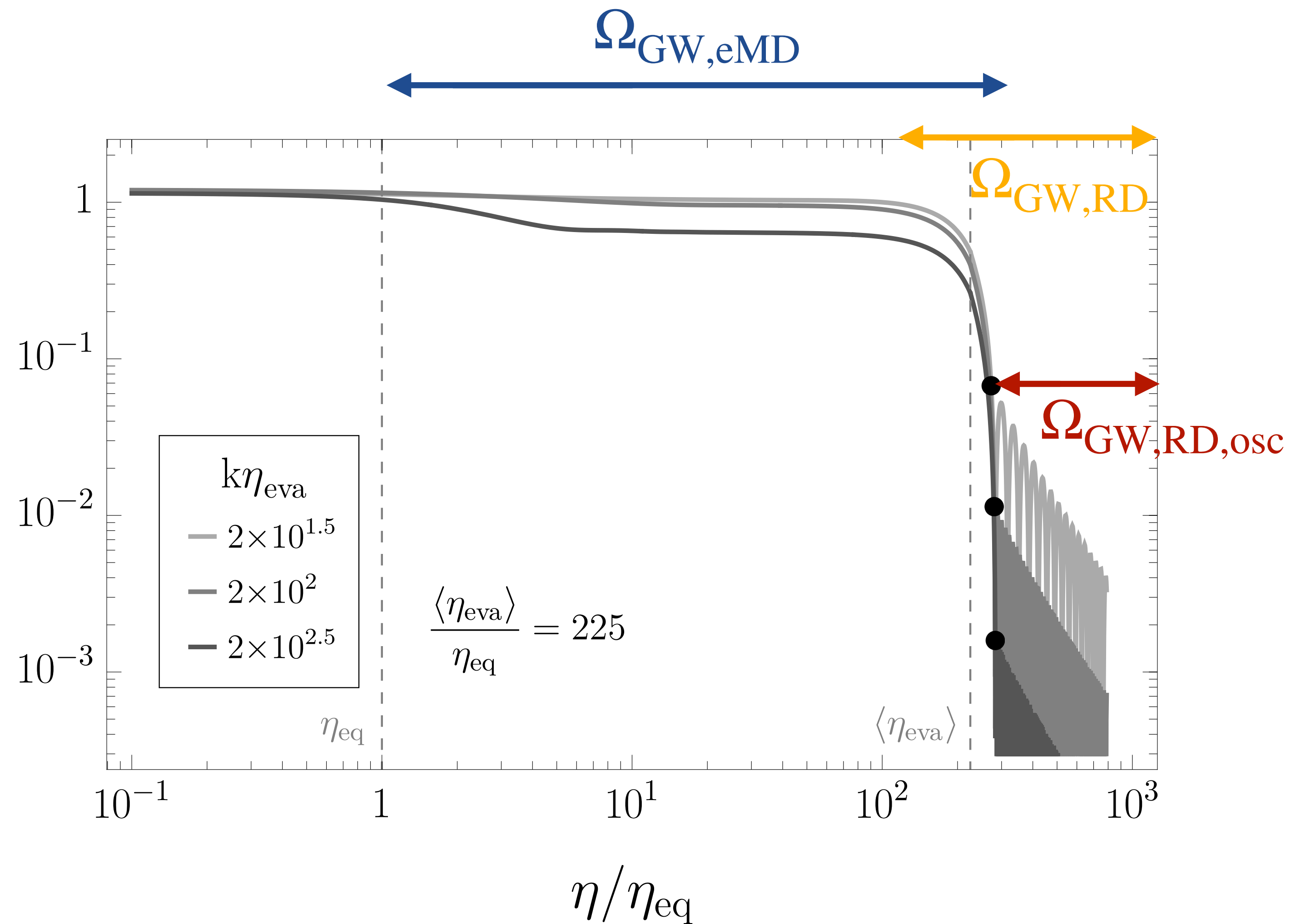


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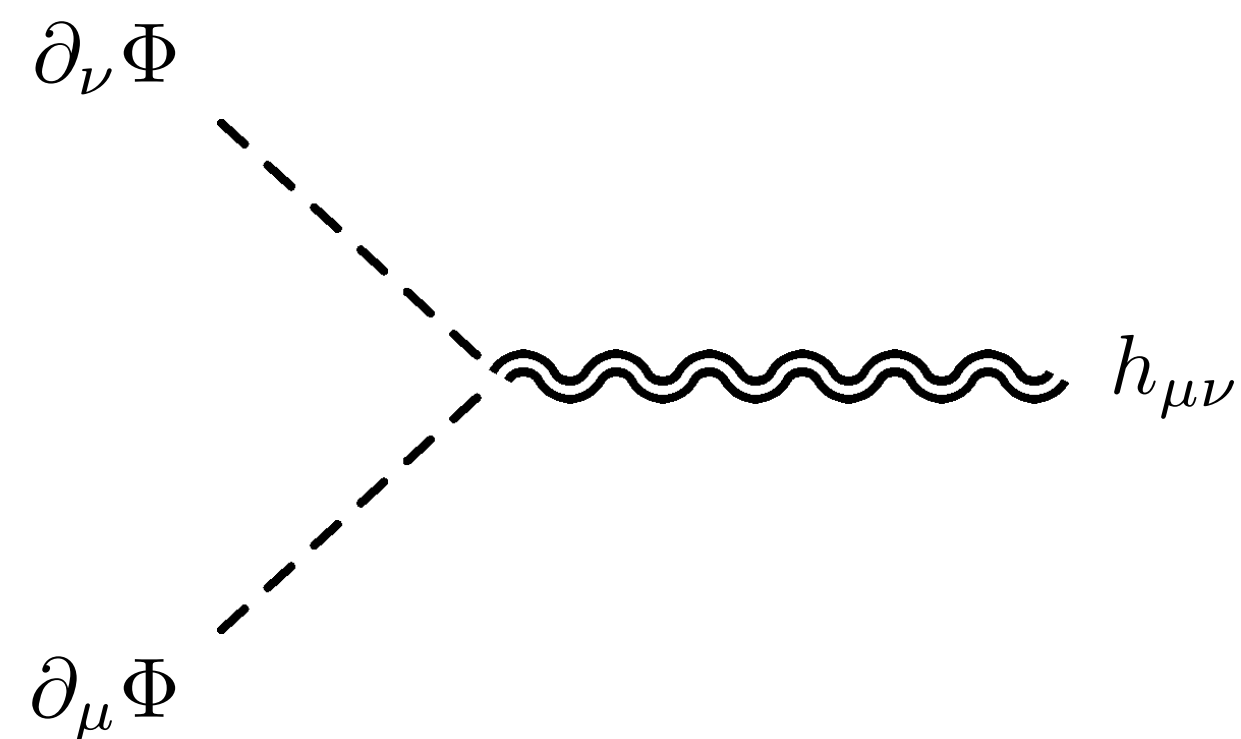
Effects decouple



$$\mathcal{P}_h \subset \Phi^4, \left(\frac{\Phi'}{\mathcal{H}} \right)^4$$

$$\Omega_{\text{GW}}(k) = \frac{k^2}{12\mathcal{H}^2} \overline{\mathcal{P}_{h,\text{RD}}}$$

$$\begin{aligned} \overline{\mathcal{P}_{h,\text{RD}}}(k, \eta, \bar{x} \gg 1) &\sim \int_0^\infty dv \int_{|1-v|}^{1+v} du (4v^2 - (1 + v^2 - u^2)^2)^2 \\ &\times \mathcal{P}(uk) \mathcal{P}(vk) \mathcal{T}^2(uk) \mathcal{T}^2(vk) \mathcal{S}^2(uk) \mathcal{S}^2(vk) \overline{\mathcal{F}_{\text{osc}}^2}(\bar{x}, u, v), \end{aligned}$$



$$\overline{\mathcal{P}}_{h,\text{RD}}(k, \eta, \bar{x} \gg 1) \sim \int_0^\infty dv \int_{|1-v|}^{1+v} du (4v^2 - (1 + v^2 - u^2)^2)^2 \\ \times \mathcal{P}(uk) \mathcal{P}(vk) \mathcal{T}^2(uk) \mathcal{T}^2(vk) \mathcal{S}^2(uk) \mathcal{S}^2(vk) \overline{\mathcal{F}}_{\text{osc}}^2(\bar{x}, u, v)$$

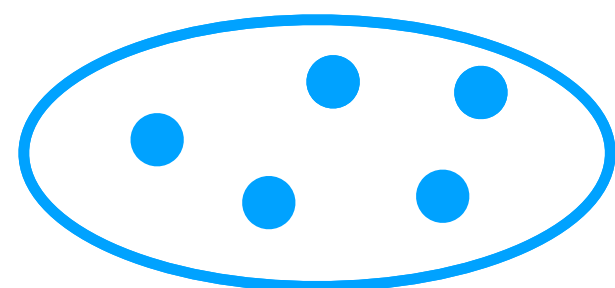
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SEED

1. Adiabatic



2. Isocurvature



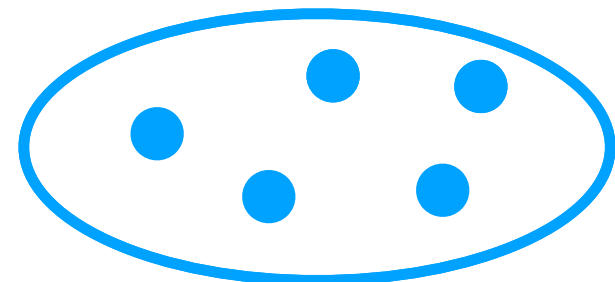
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SEED

1. Adiabatic



2. Isocurvature



TRANSFER

RD-MD
transition

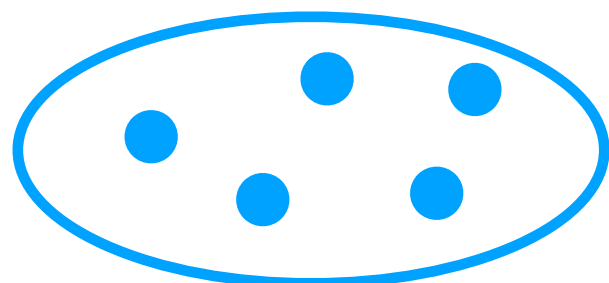
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SEED

1. Adiabatic



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TRANSFER

RD-MD
transition

SUPPRESSION

Evaporation
with finite
width

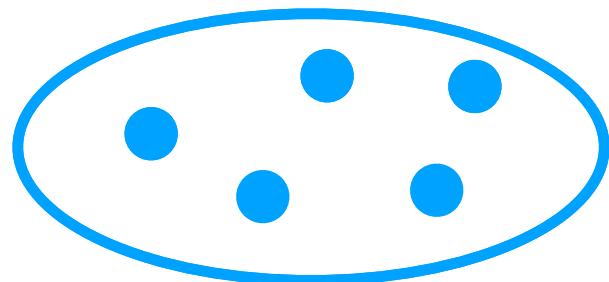
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TRANSFER

RD-MD
transition

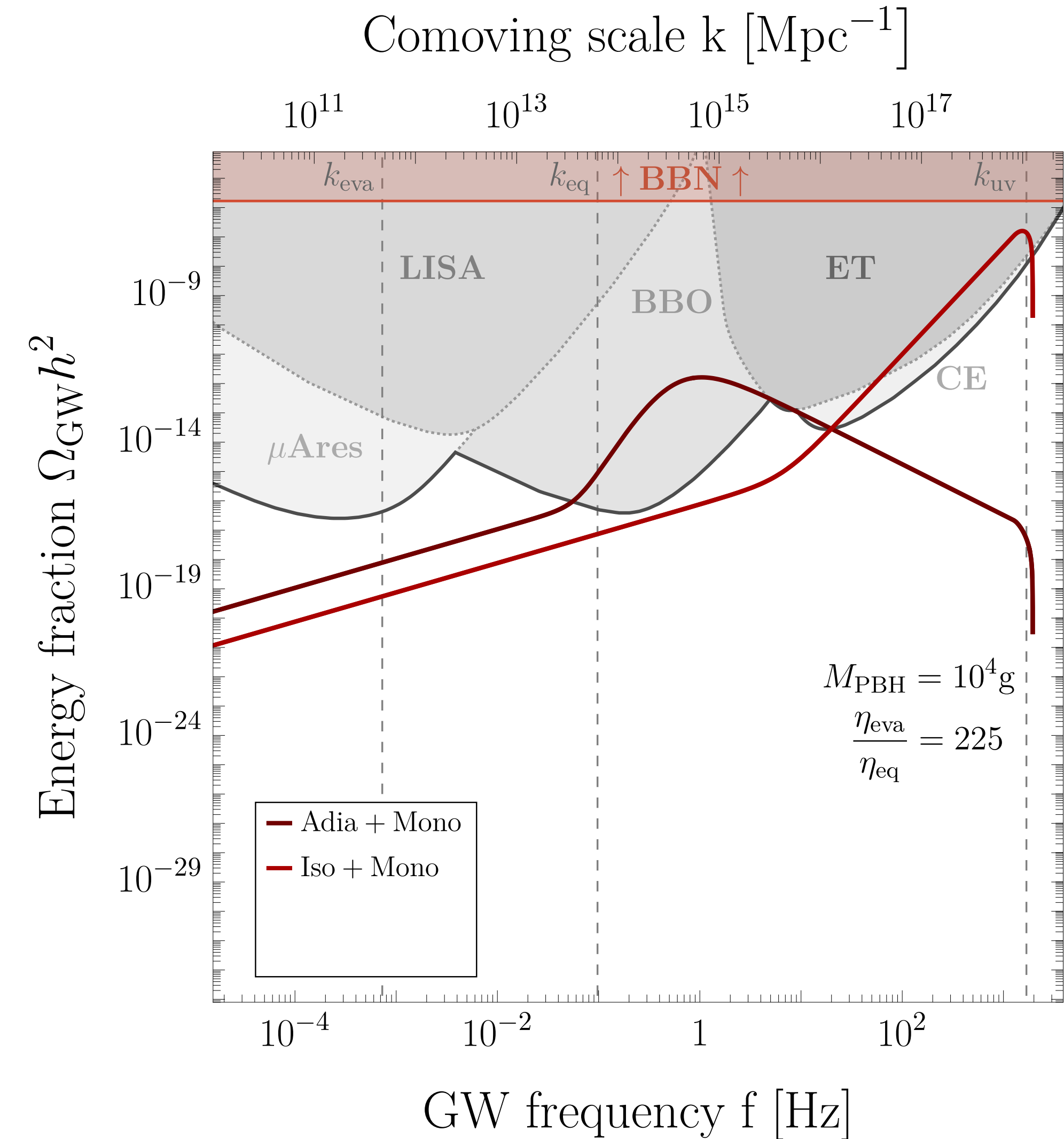
SUPPRESSION

Evaporation
with finite
width

KERNEL

GW
propagation

SIGW



$$\Omega_{\text{GW}}(k) = \frac{k^2}{12\mathcal{H}^2} \overline{\mathcal{P}_{h,\text{RD}}}$$

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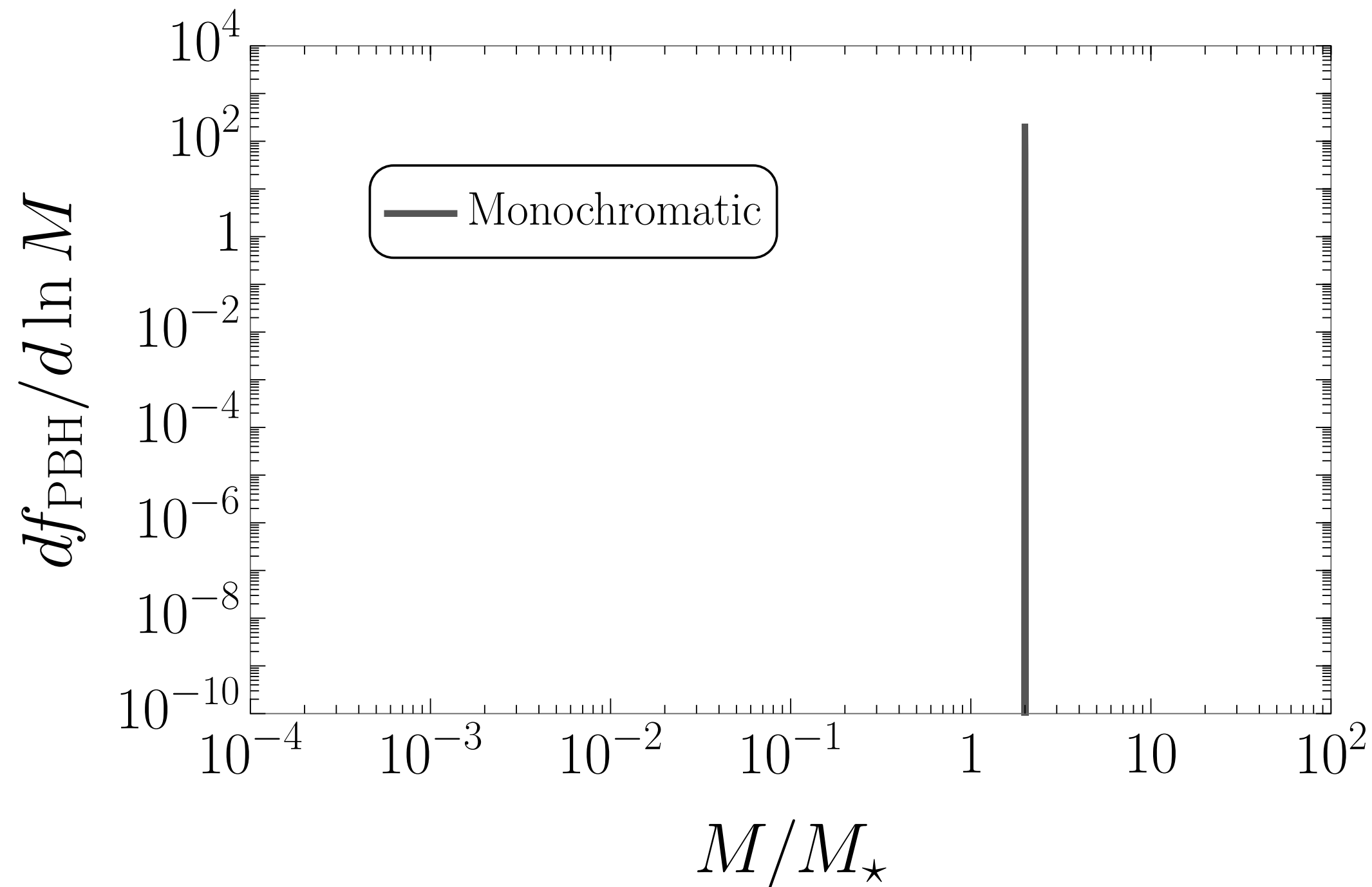
$$\mathcal{P}_{\text{Adia}}(k) = A_s \left(\frac{k}{k_*} \right)^{n_s-1} \Theta(k_{\text{UV}} - k) \Theta(k_{k-\text{IR}})$$

$$\mathcal{P}_{\text{Iso}}(k) = \frac{2}{3\pi} \left(\frac{k}{k_*} \right)^3 \Theta(k_{\text{UV}} - k)$$

PART II:

Our new results.

SUPERHORIZON COLLAPSE



So far:

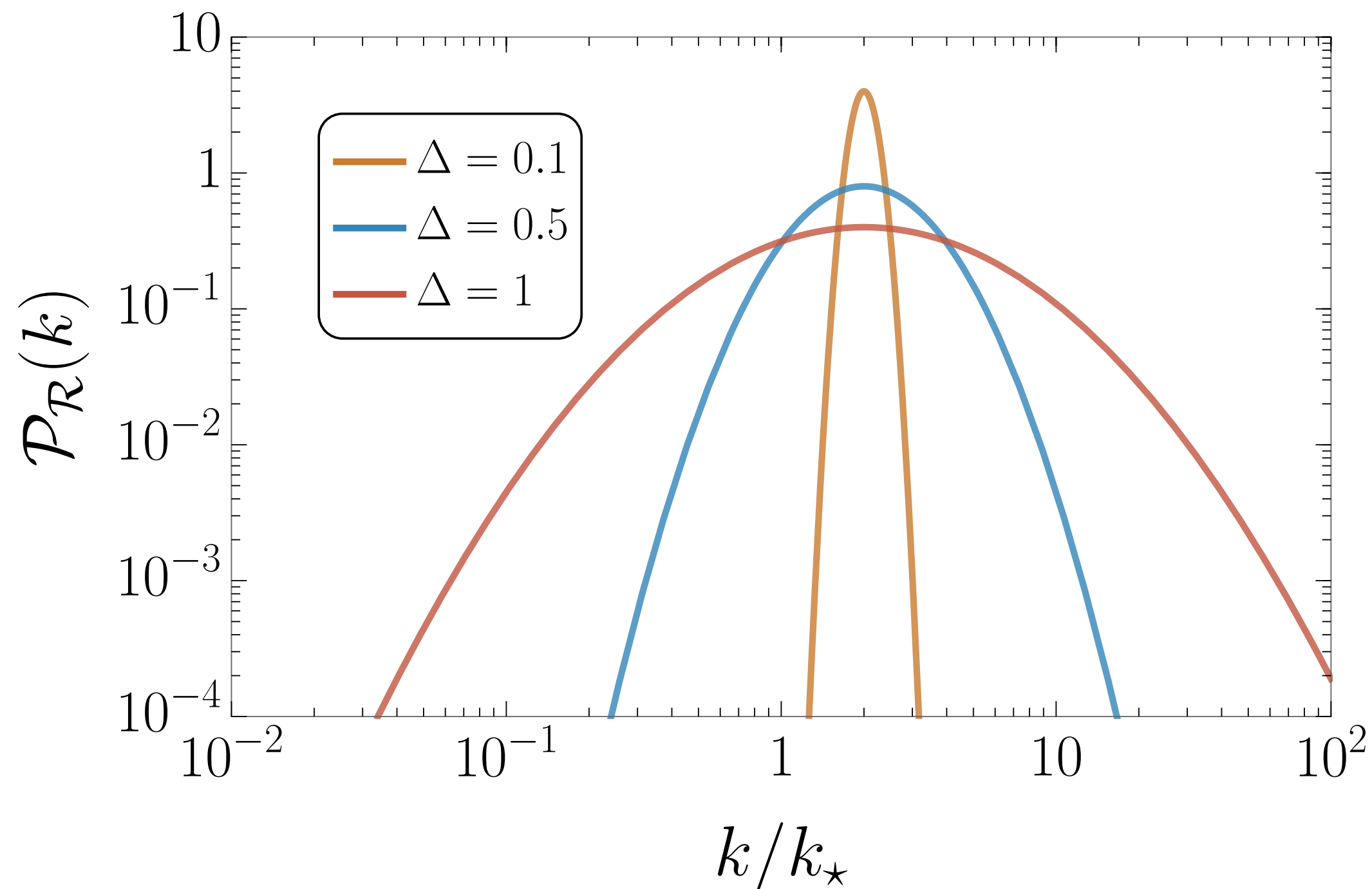
1. Assumes monochromatic^{1,2,3} or (narrow) log-normal¹ mass distribution
2. Fast reheating

¹*Poltergeist* mechanism: Inomata et al. (2020)

²Domenech et. al (2021)

³Domènech and Tränkle (2025)

SUPERHORIZON COLLAPSE



¹Choptuik (1993)

² Press and Schechter (1974)

- Superhorizon gravitational collapse:

1. Critical scaling¹

$$M(\delta_m) = \kappa M_k (\delta_m - \delta_c)^\gamma$$

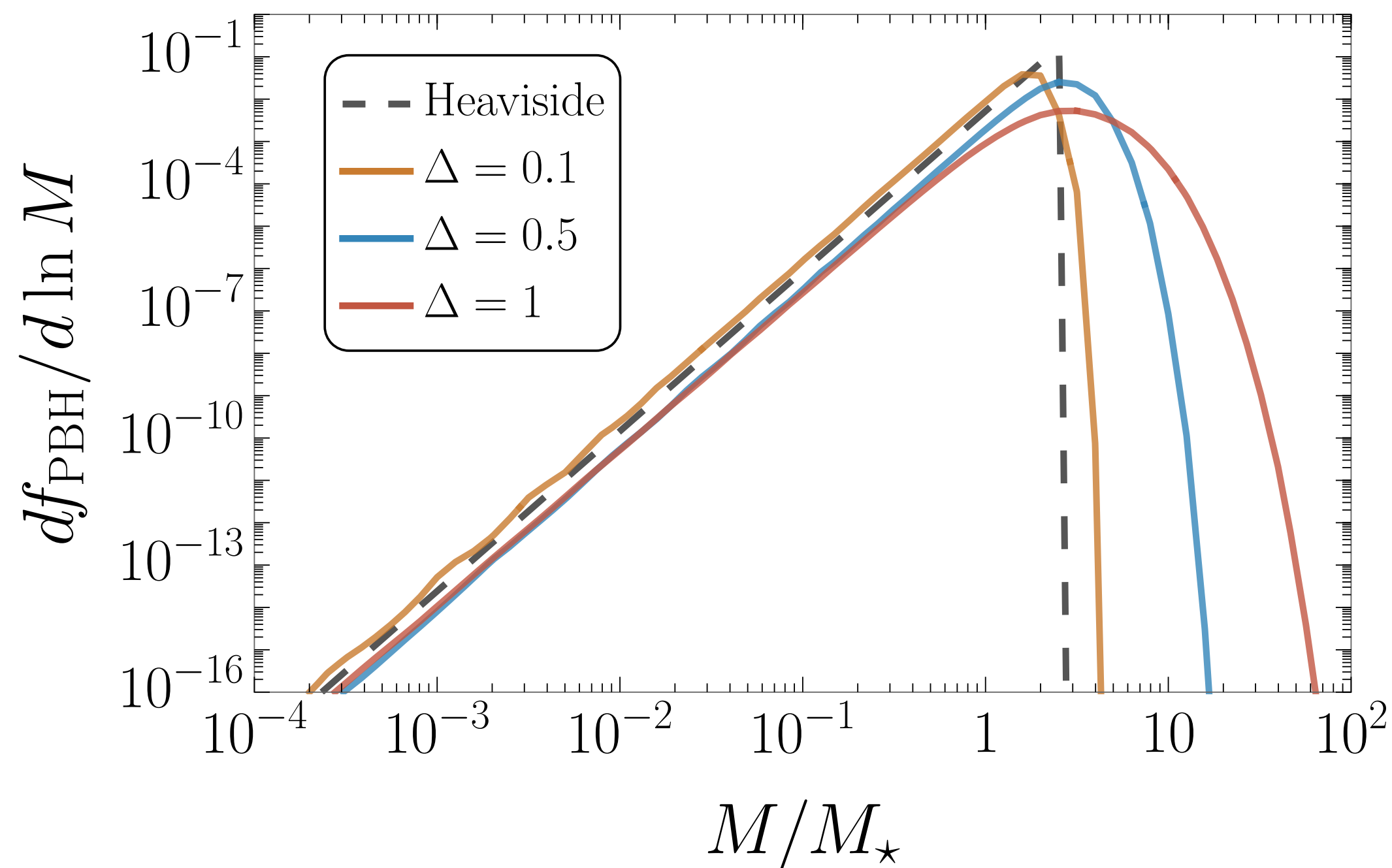
2. Press-Schechter formalism²

$$\frac{df_{\text{PBH}}}{d \log M} \propto M^{1+1/\gamma} e^{-c_1 (M/\langle M \rangle)^{c_2}}$$

- c_1, c_2 depend on curvature power spectrum. Instead:

$$\frac{df_{\text{PBH}}}{d \log M} \propto M^{1+1/\gamma} \theta(M_{\text{cut}} - M)$$

SUPERHORIZON COLLAPSE



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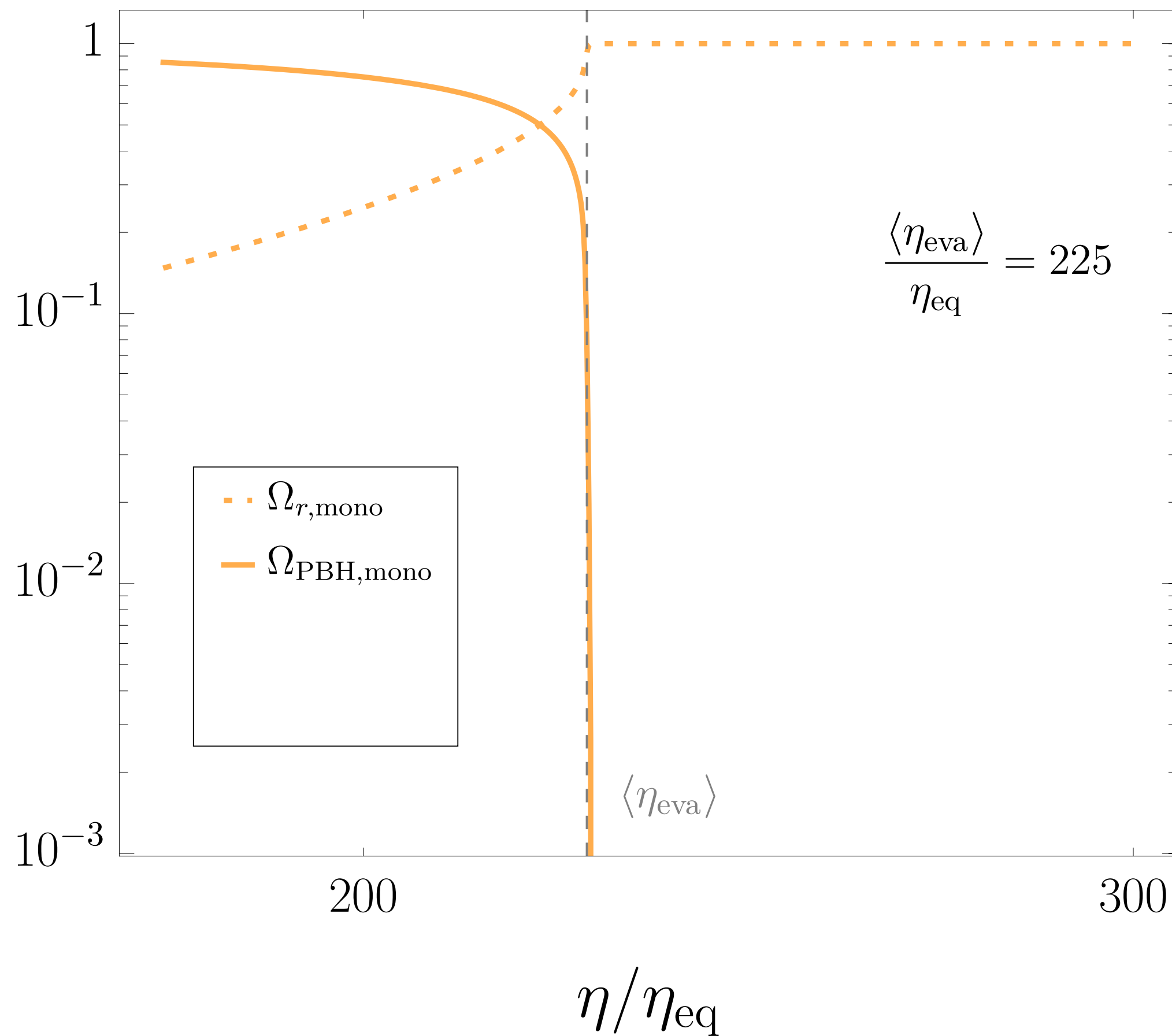
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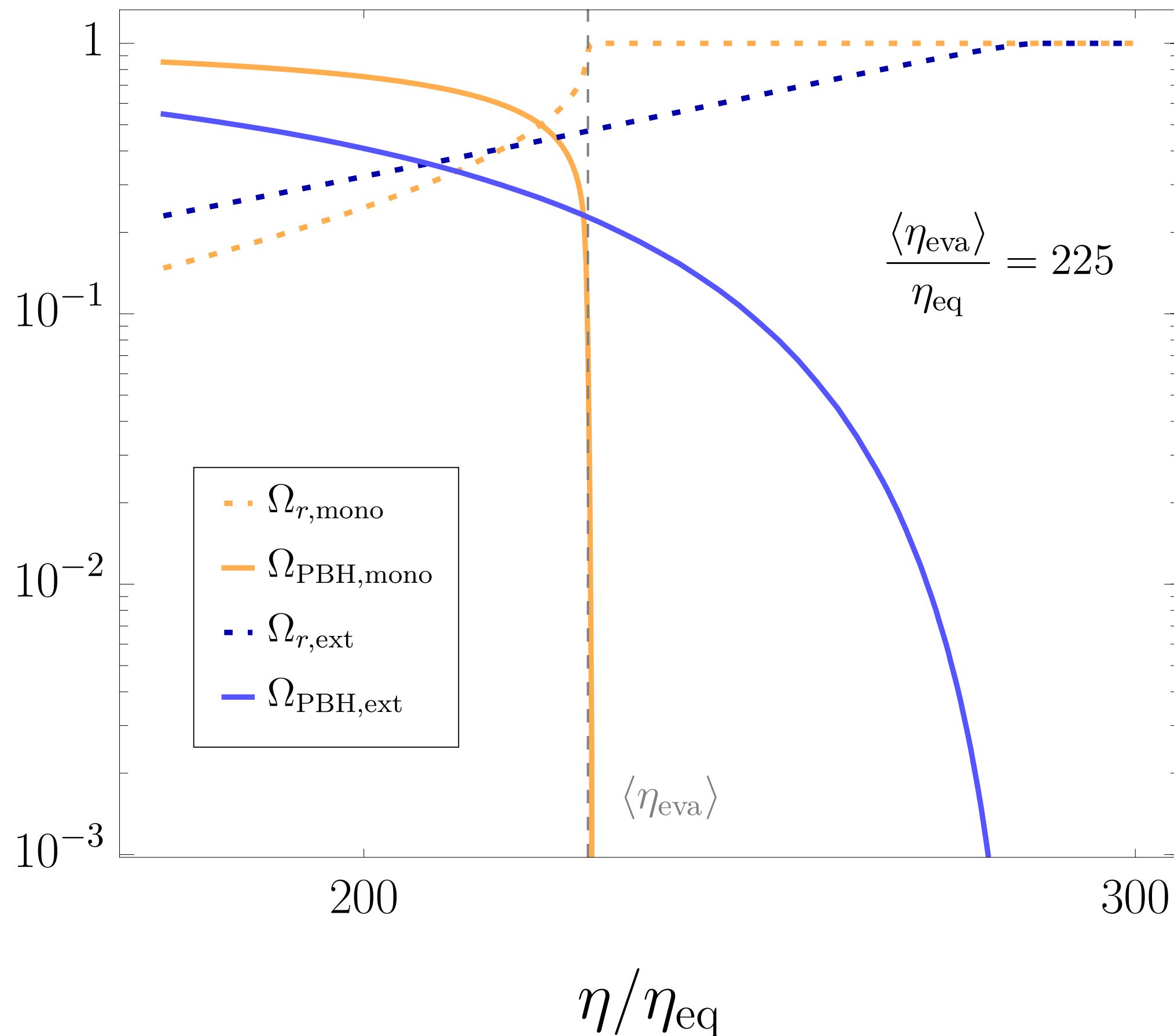
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SUPERHORIZON COLLAPSE



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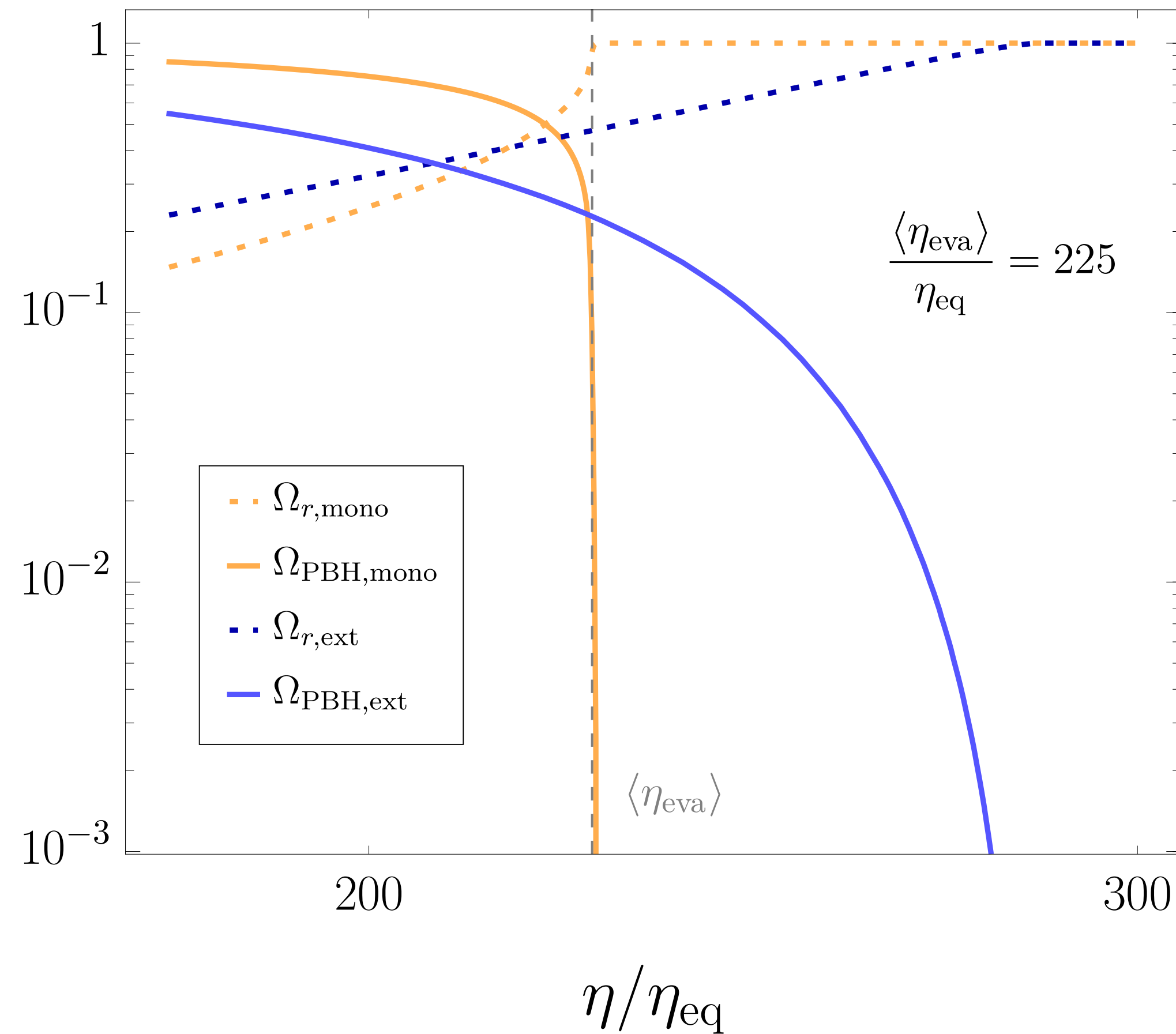
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SUPERHORIZON COLLAPSE

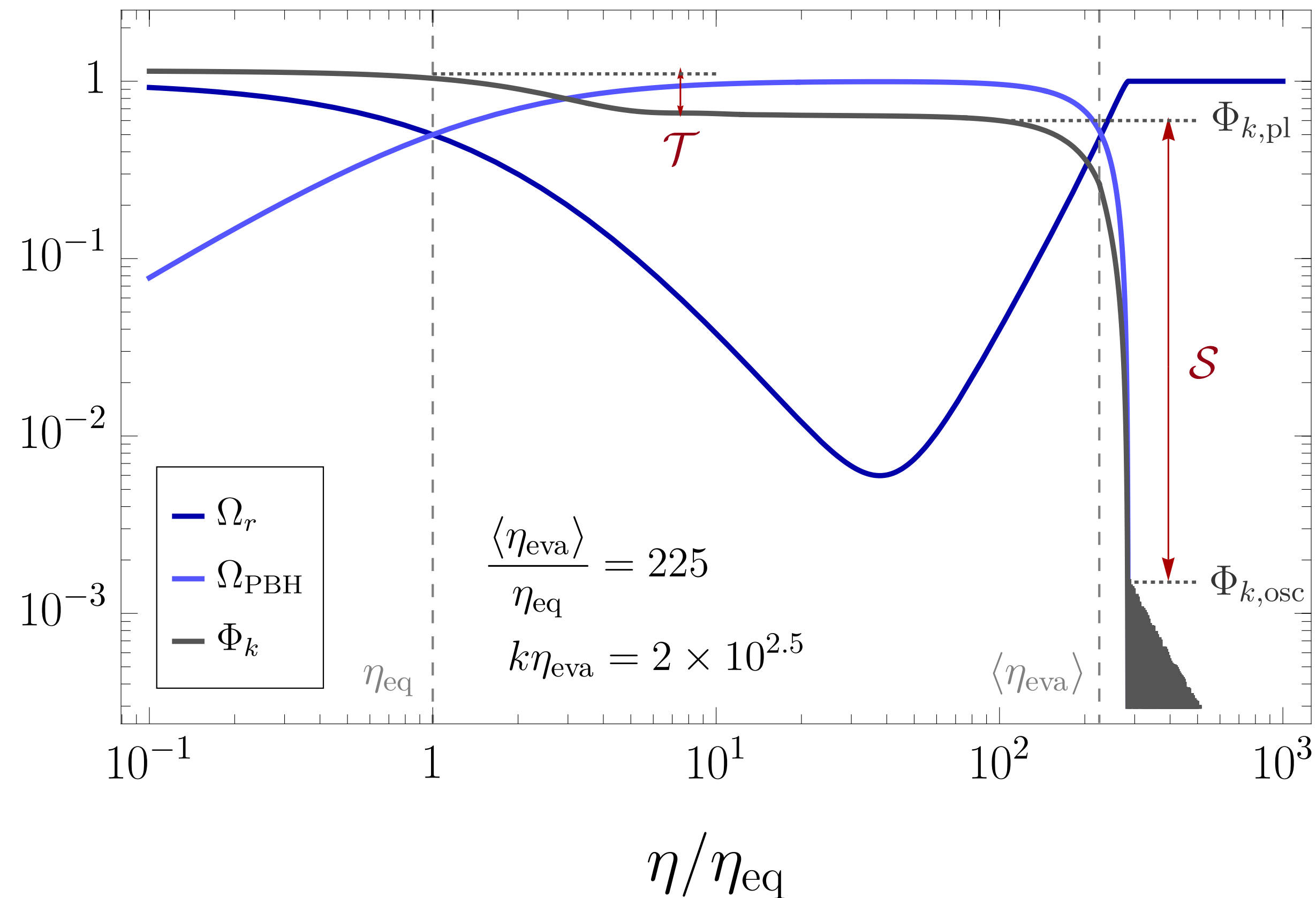


$$\rho_m \rightarrow \langle \rho_m \rangle = \int \rho_m(M) f_{\text{PBH}}(M) d \log M$$

$$\rho_r \rightarrow \langle \rho_r \rangle = \int \rho_r(M) f_{\text{PBH}}(M) d \log M$$

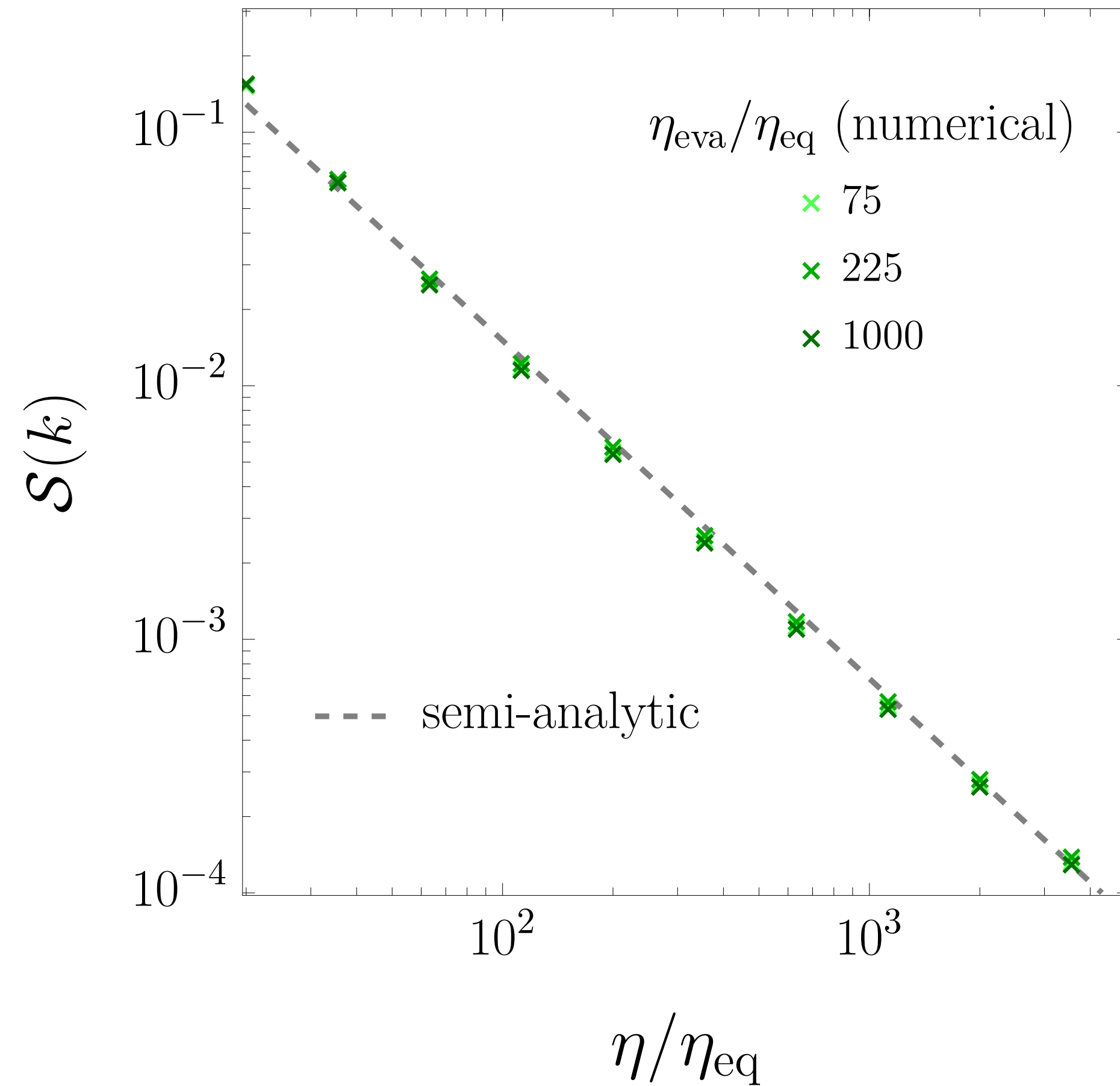
$$\Gamma \rho_m \rightarrow \langle \Gamma \rho_m \rangle = \int \Gamma(M) \rho_m(M) f_{\text{PBH}}(M) d \log M$$

SUPPRESSION FACTOR



Suppression factor: $\mathcal{P}_h \propto \Phi_{\text{osc}}^4 \propto \mathcal{S}^4(k)$

SUPPRESSION FACTOR



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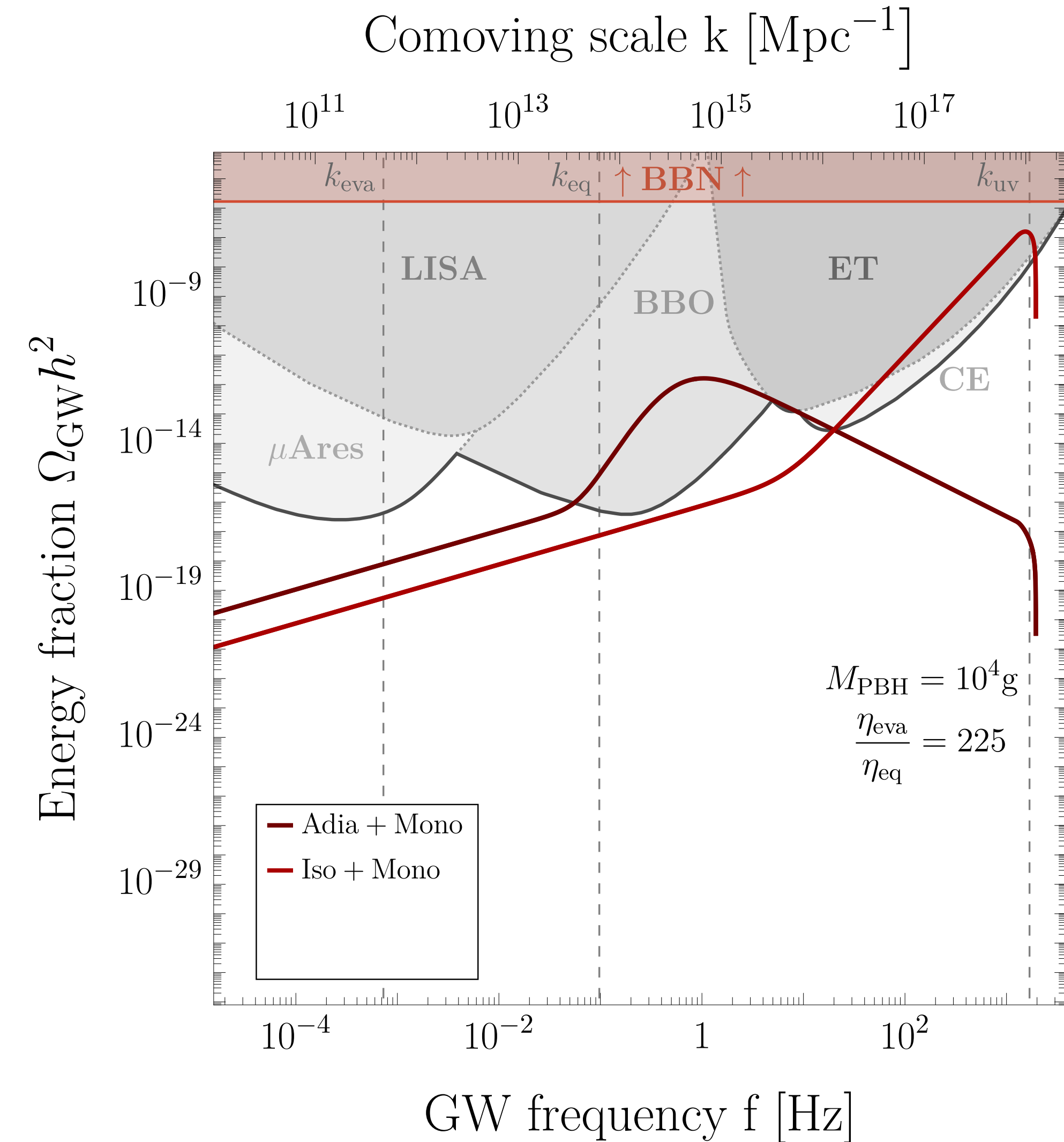
Good agreement numerical and analytical treatment:

$$\mathcal{S}_{\text{ext}}(k) \simeq 7 \left(\frac{k}{k_{\text{eva}}} \right)^{-4/3}$$

Previously:

$$\mathcal{S}_{\text{mono}}(k) \simeq \left(\sqrt{\frac{2}{3}} \frac{k}{k_{\text{eva}}} \right)^{-1/3}$$

SIGW



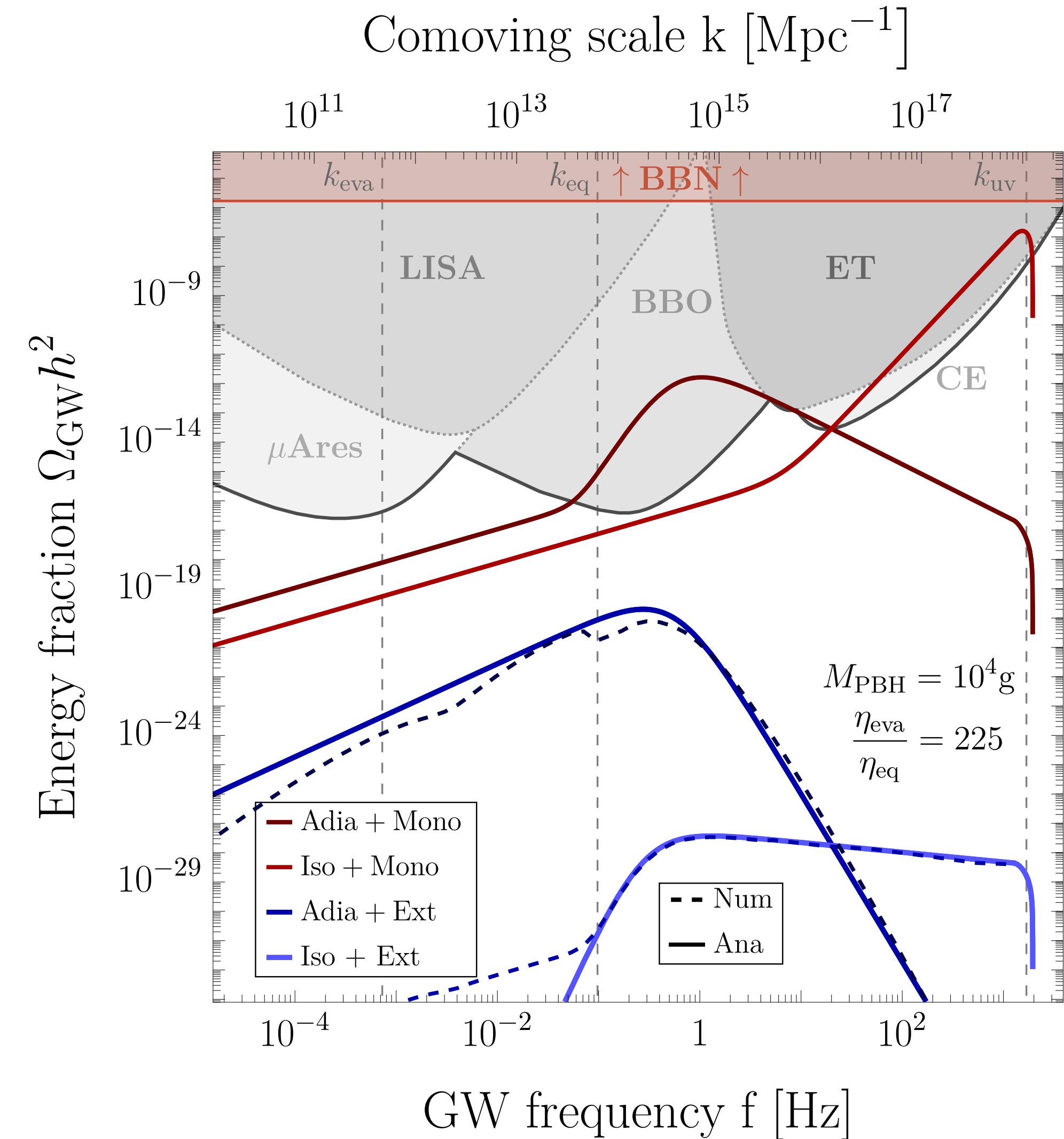
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SIGW



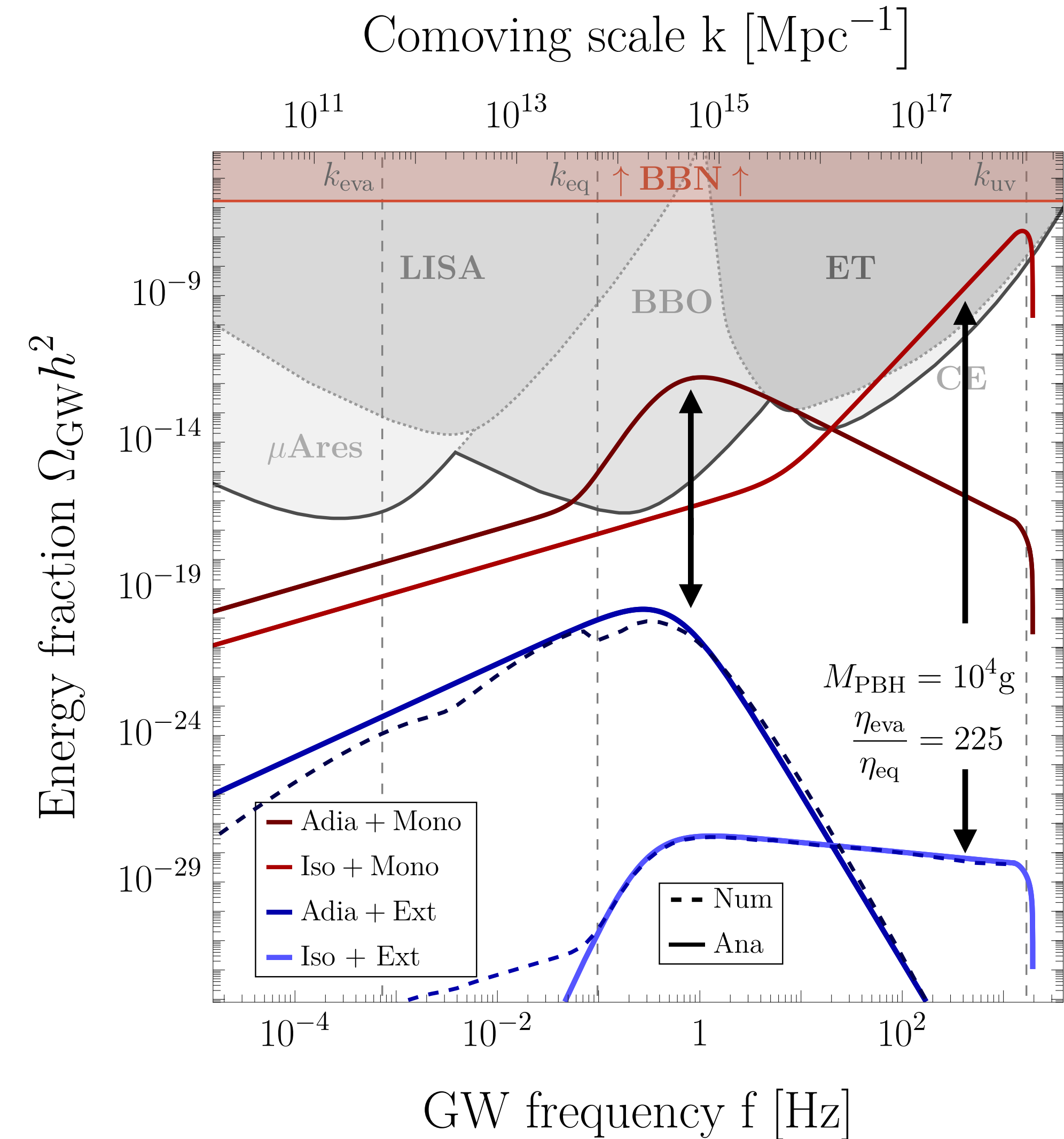
$$\Omega_{\text{GW}}(k) = \frac{k^2}{12\mathcal{H}^2} \overline{\mathcal{P}_{h,\text{RD}}}$$

$$\overline{\mathcal{P}_{h,\text{RD}}}(k, \eta, \bar{x} \gg 1) \sim \int_0^\infty dv \int_{|1-v|}^{1+v} du (4v^2 - (1 + v^2 - u^2)^2)^2 \overline{\mathcal{F}_{\text{osc}}^2}(\bar{x}, u, v) \\ \times \mathcal{P}(uk) \mathcal{P}(vk) \mathcal{S}^2(uk) \mathcal{S}^2(vk) \mathcal{T}^2(uk) \mathcal{T}^2(vk),$$

$$\mathcal{P}_{\text{Adia}}(k) = A_s \left(\frac{k}{k_*} \right)^{n_s-1} \Theta(k_{\text{UV}} - k) \Theta(k_{k-\text{IR}})$$

$$\mathcal{P}_{\text{Iso}}(k) = \frac{2}{3\pi} \left(\frac{k}{k_*} \right)^3 \Theta(k_{\text{UV}} - k)$$

SIGW



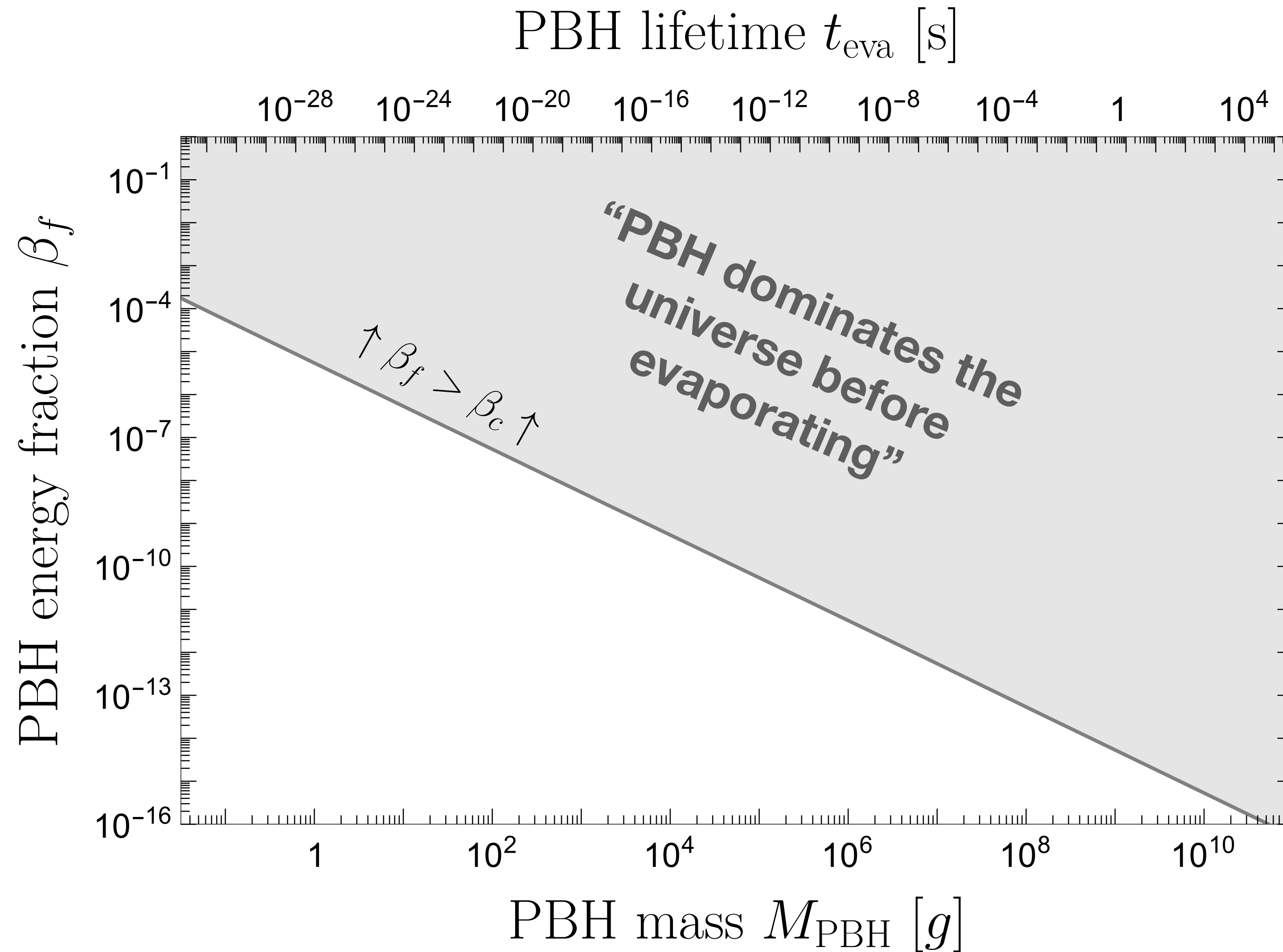
$$\Omega_{\text{GW}}(k) = \frac{k^2}{12\mathcal{H}^2} \overline{\mathcal{P}_{h,\text{RD}}}$$

$$\begin{aligned} \overline{\mathcal{P}_{h,\text{RD}}}(k, \eta, \bar{x} \gg 1) &\sim \int_0^\infty dv \int_{|1-v|}^{1+v} du (4v^2 - (1 + v^2 - u^2)^2)^2 \overline{\mathcal{F}_{\text{osc}}^2}(\bar{x}, u, v) \\ &\times \mathcal{P}(uk) \mathcal{P}(vk) \mathcal{S}^2(uk) \mathcal{S}^2(vk) \mathcal{T}^2(uk) \mathcal{T}^2(vk), \end{aligned}$$

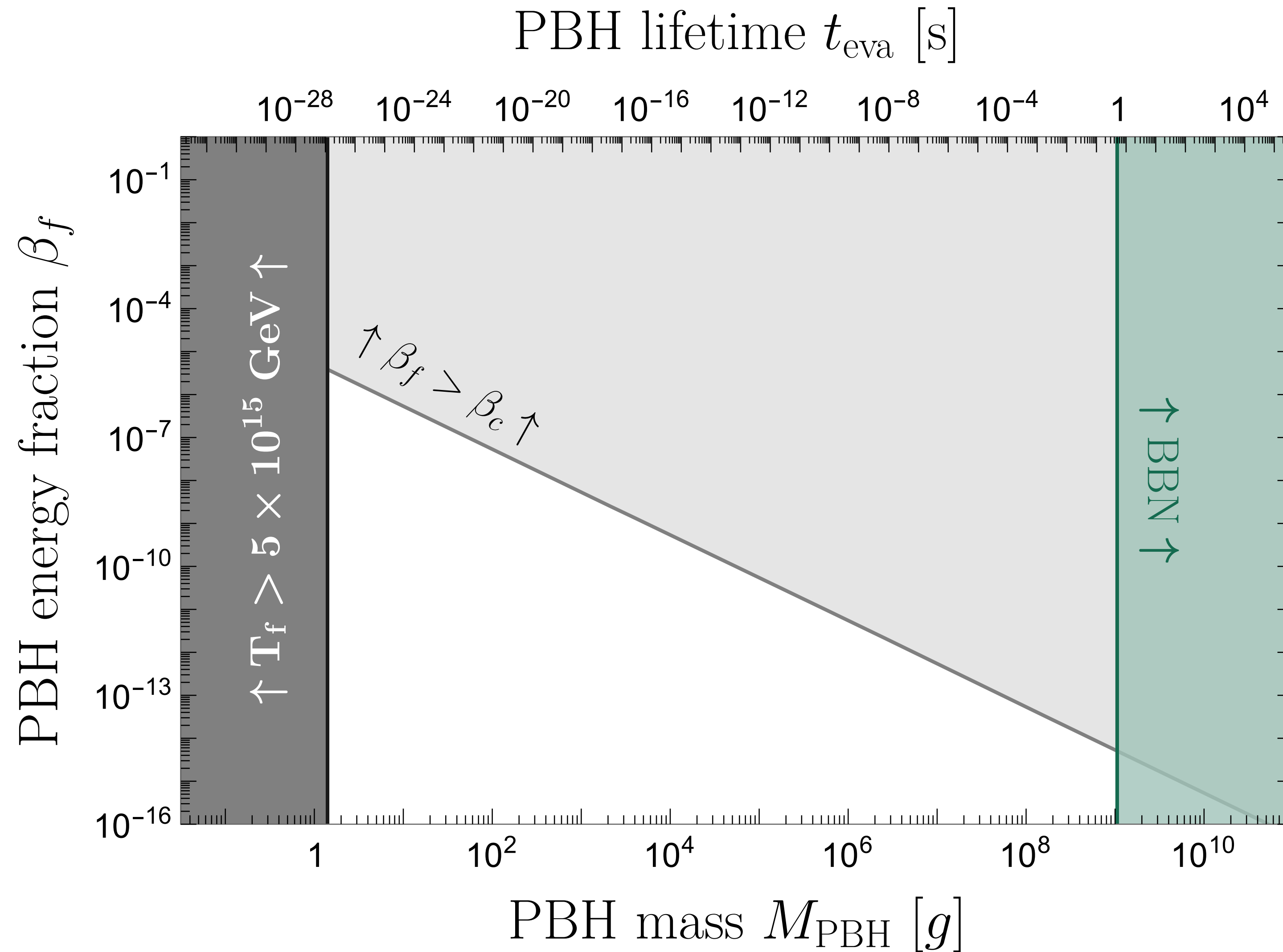
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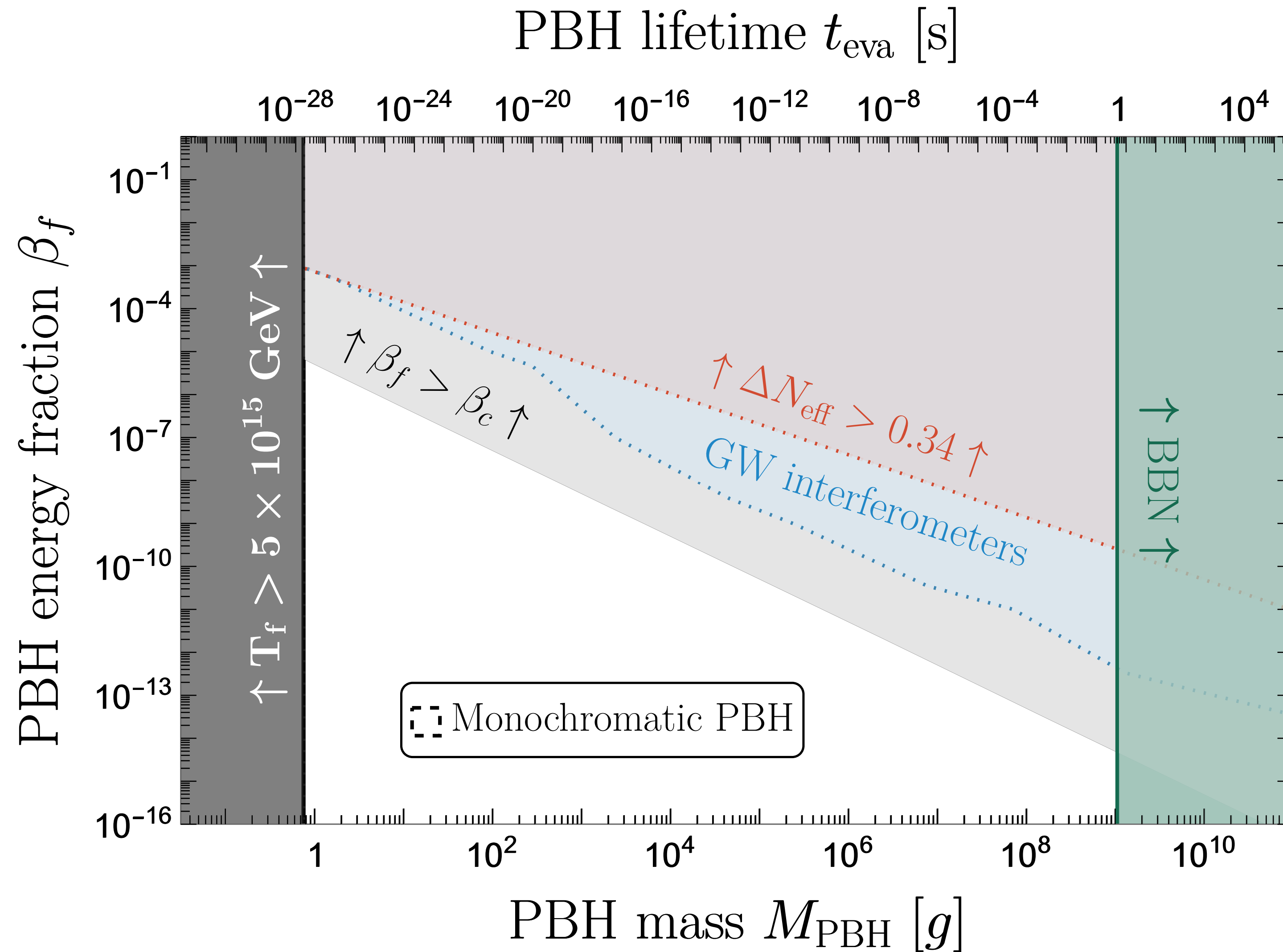
IMPLICATIONS FOR PBH



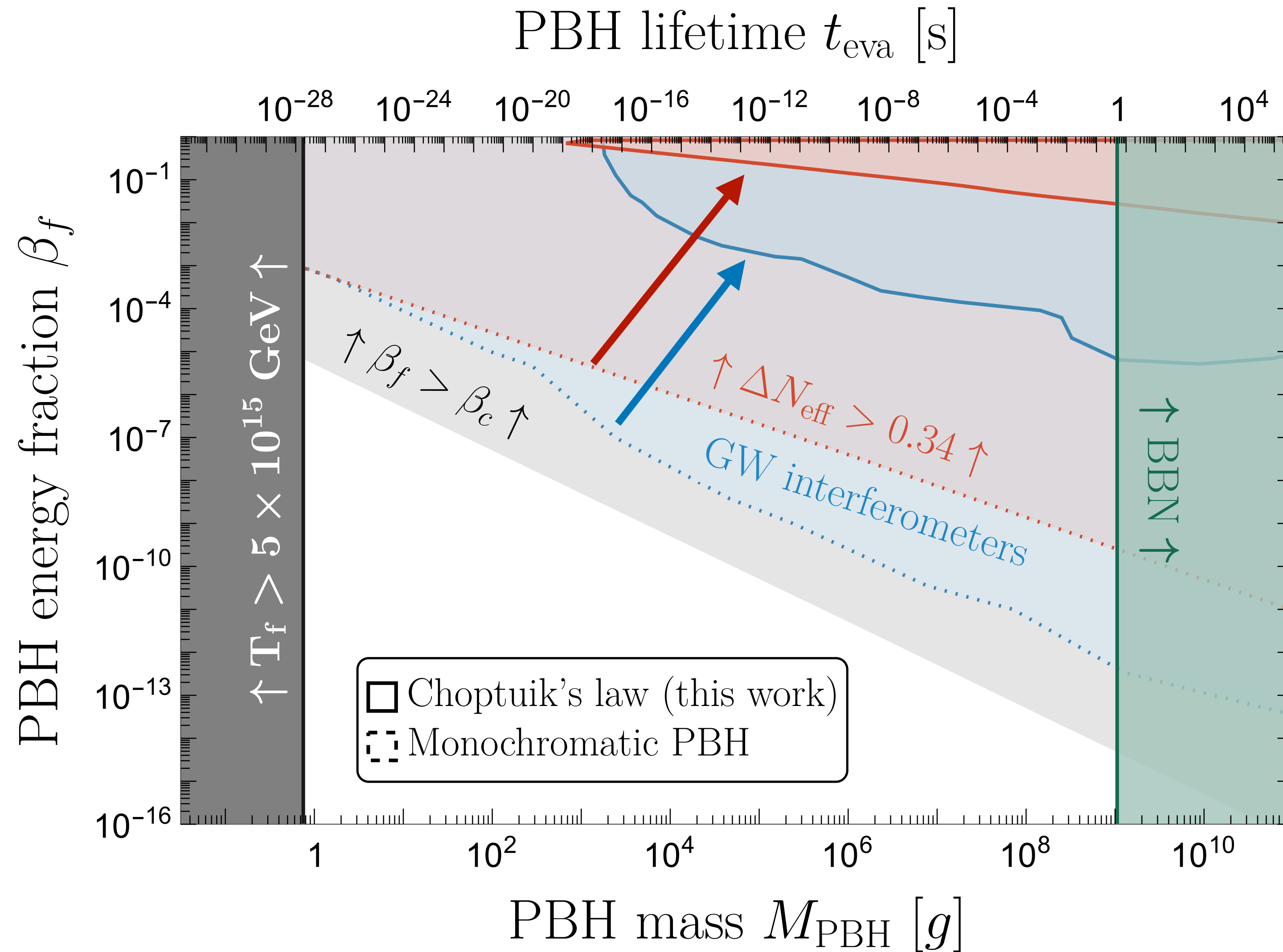
IMPLICATIONS FOR PBH



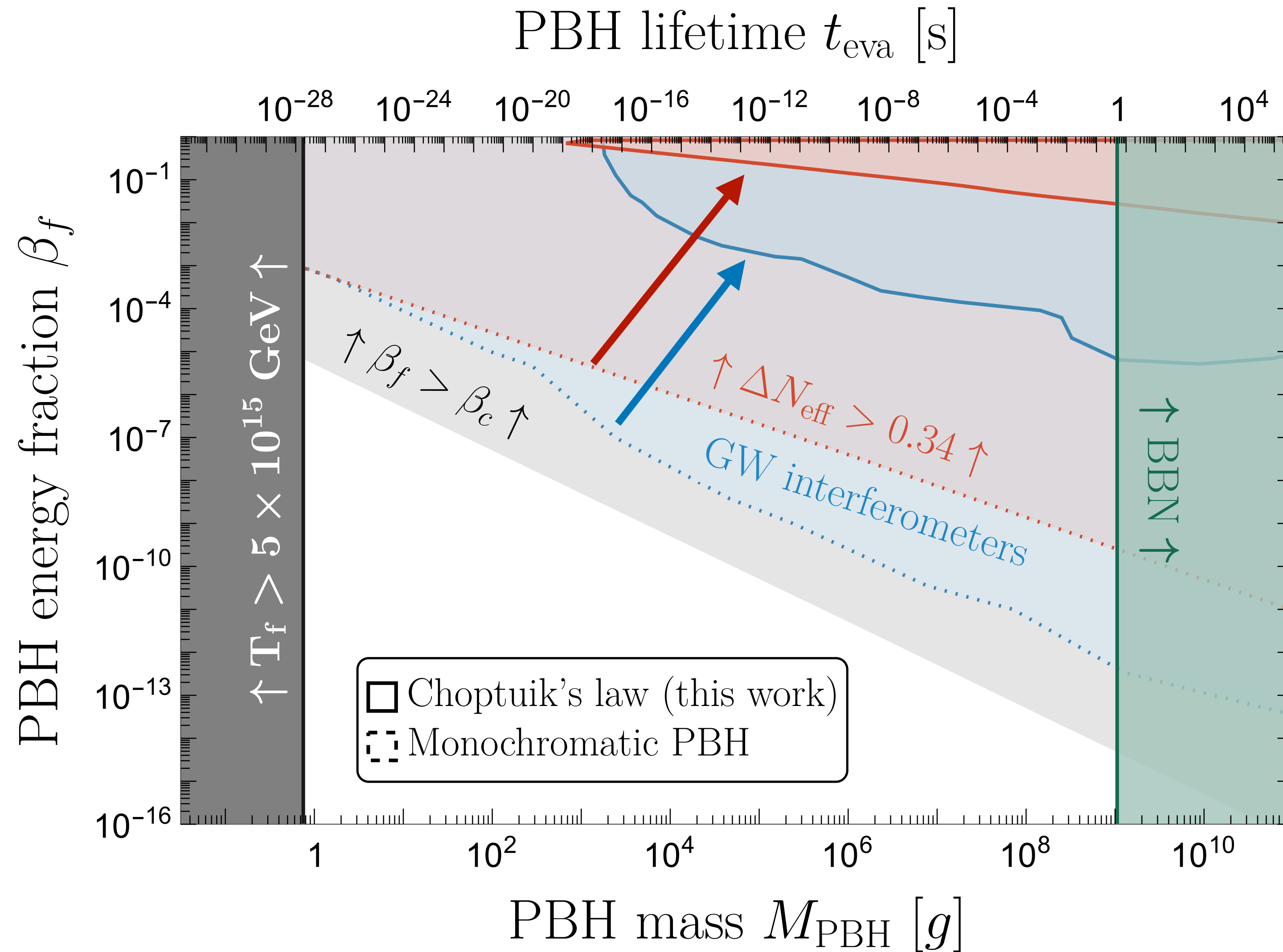
IMPLICATIONS FOR PBH



IMPLICATIONS FOR PBH



IMPLICATIONS FOR PBH

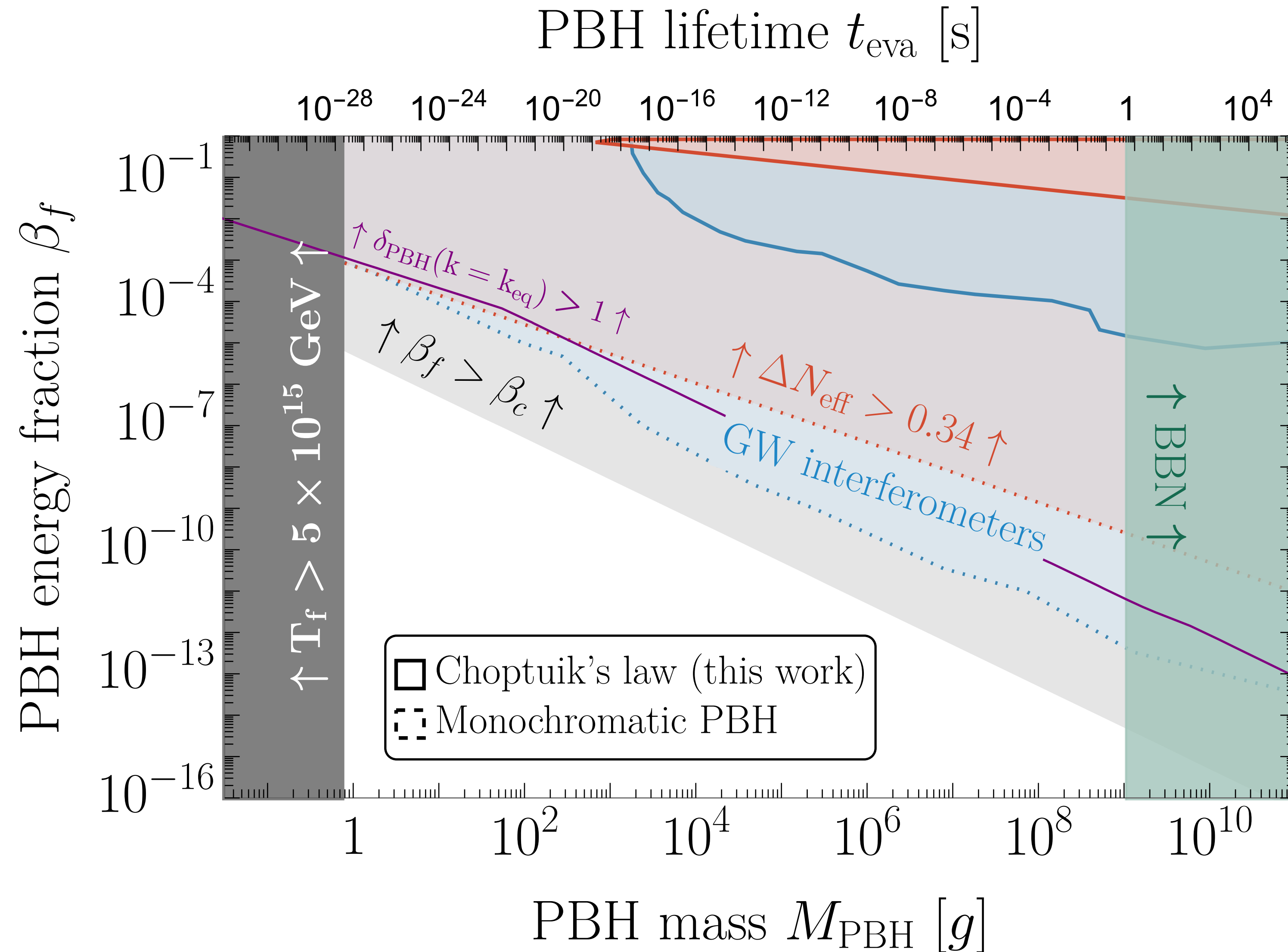


We checked:

1. Graviton emission
2. Binary induced GWs

do not
contribute to
 ΔN_{eff}

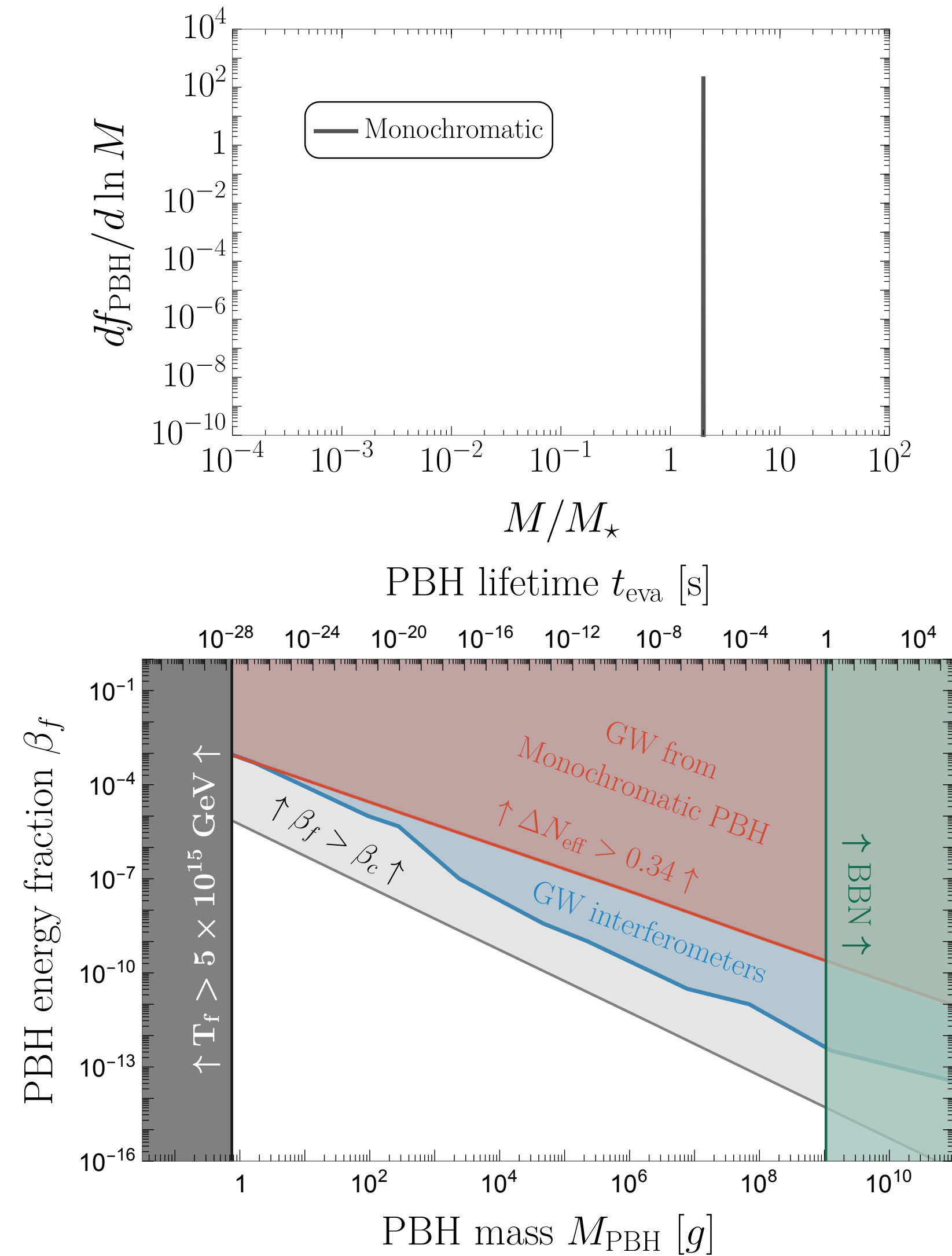
IMPLICATIONS FOR PBH



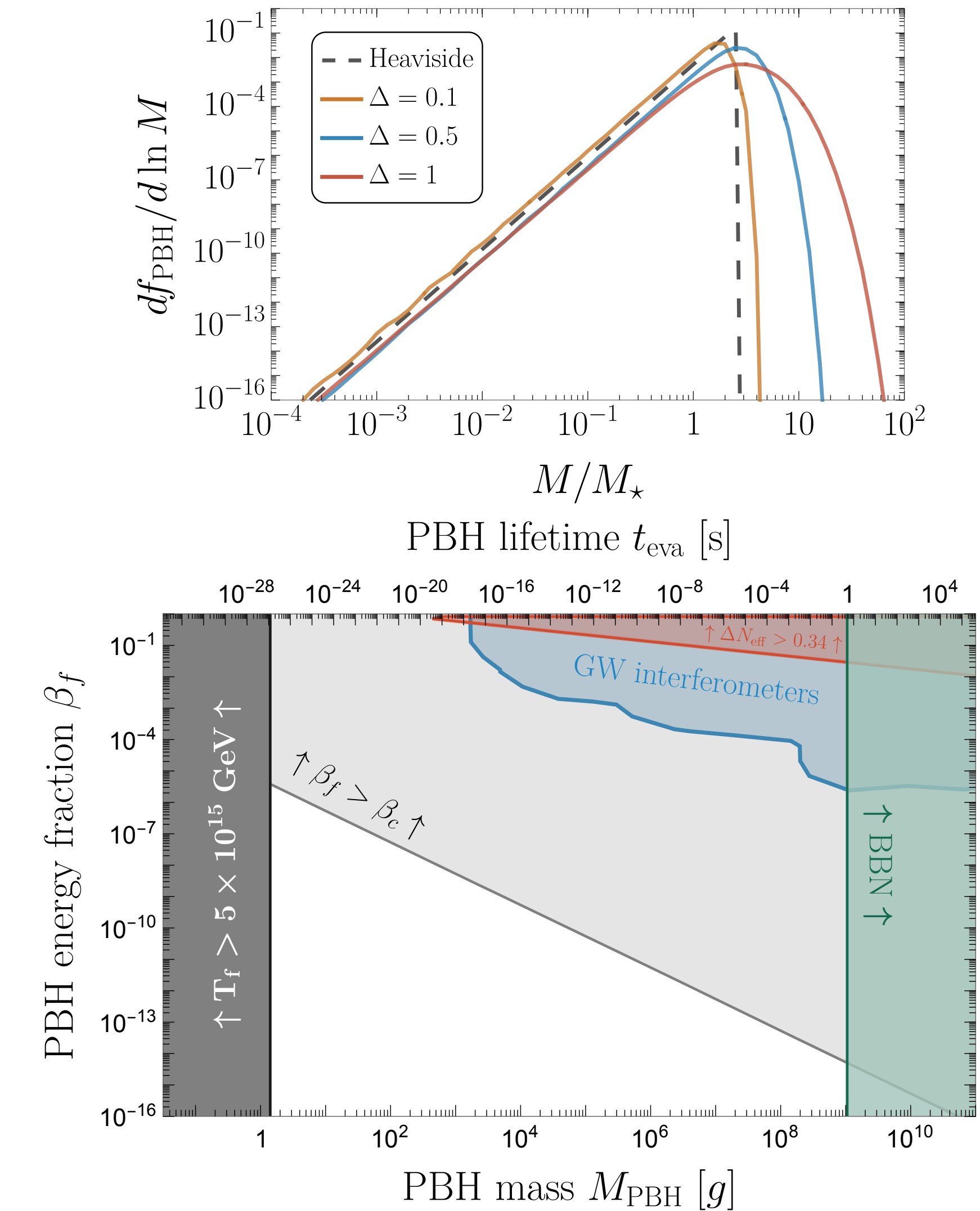
Non-linearities

1. Breakdown of PT
2. Probably overestimates signal

Monochromatic



Choptuik Scaling



BACK-UP

BACK-UP

Cosmological perturbation theory

$$ds^2 = a^2(\eta) \left[(1 + 2\Psi) d\eta^2 - (1 - 2\Phi) \delta_{ij} dx^i dx^j + h_{ij} dx^i dx^j \right]$$

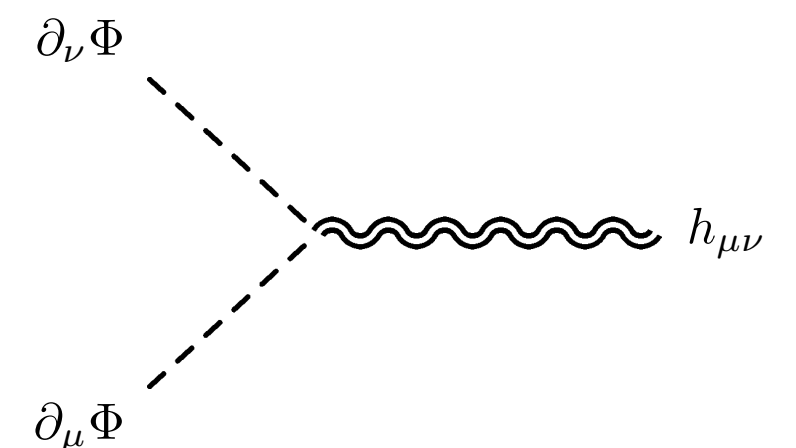
In Newtonian gauge and with out anisotropic stress ($\Phi = -\Psi$)

Switching to **synchronous gauge**

$$ds^2 = a^2 \left(d\eta^2 - H_{ij} dx^i dx^j \right) \quad \text{with} \quad H_{ij} = \delta_{ij} + \hat{k}_i \hat{k}_j \gamma + \left(\hat{k}_i \hat{k}_j + \frac{1}{3} \delta_{ij} \right) \epsilon$$

Translating back

$$\Phi_k = \epsilon - \mathcal{H} \frac{(6\epsilon + \gamma)'}{2k^2}.$$



BACK-UP

$$\Omega_{\text{GW}}(k) = \frac{k^2}{12\mathcal{H}^2} \overline{\mathcal{P}_{h,RD}}$$

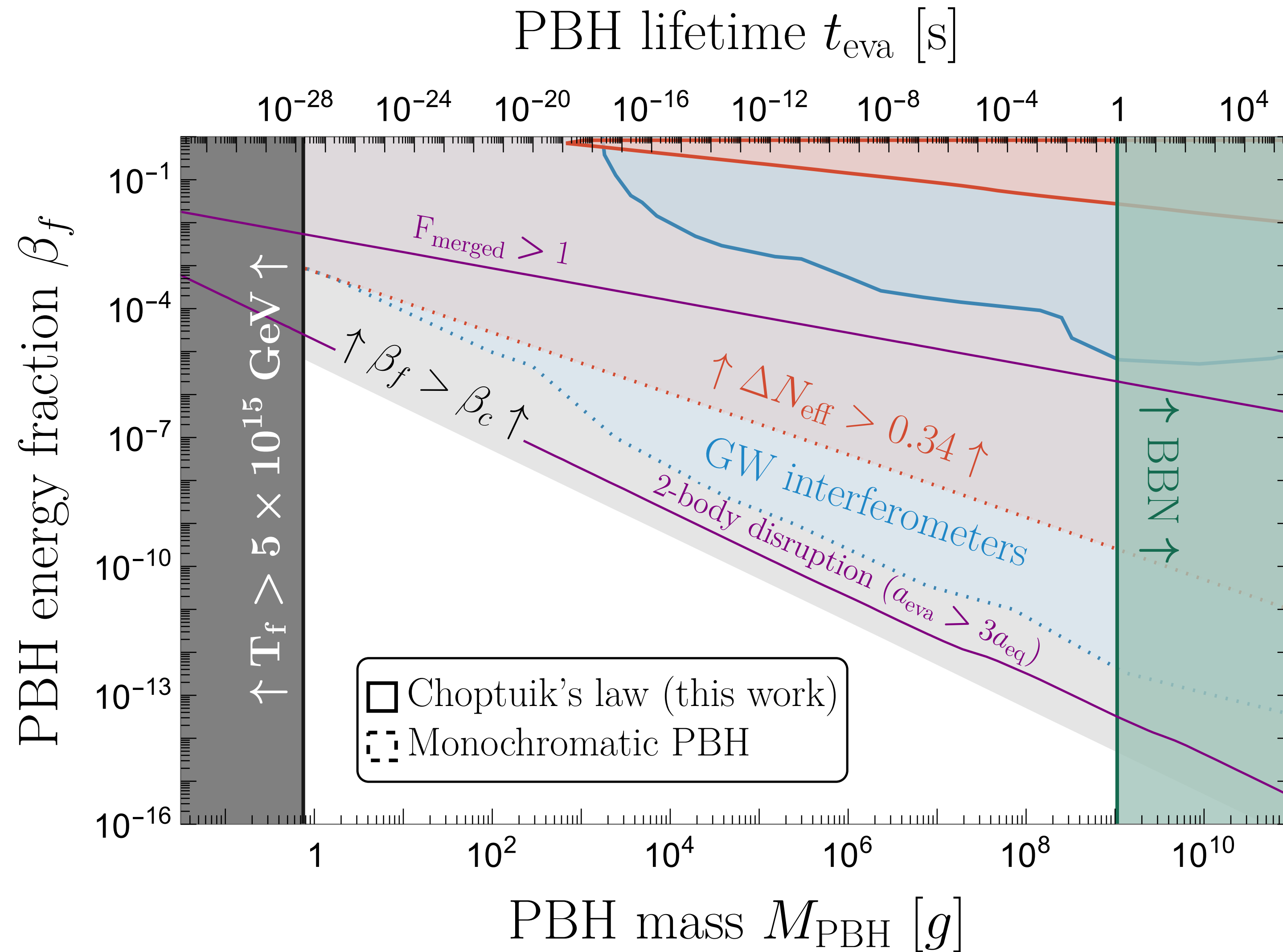
$$\begin{aligned} \overline{\mathcal{P}_{h,RD}}(k, \eta, \bar{x} \gg 1) \simeq & \frac{c_s^4 x_{\text{eva}}^8}{\bar{x}^2} \int_0^\infty dv \int_{|1-v|}^{1+v} du (4v^2 - (1 + v^2 - u^2)^2)^2 \overline{\mathcal{F}_{\text{osc}}^2}(\bar{x}, u, v) \\ & \times \mathcal{P}(uk) \mathcal{P}(vk) \mathcal{S}_{\text{eva}}^2(uk) \mathcal{S}_{\text{eva}}^2(vk) \mathcal{T}_{\text{eva}}^2(uk) \mathcal{T}_{\text{eva}}^2(vk), \end{aligned}$$

$$\overline{\mathcal{F}_{\text{osc,res}}^2}(\bar{x}, u, v) = \frac{1}{32} \text{Ci}(|1 - c_s(u + v)x_{\text{eva}}/2|)^2,$$

$$\overline{\mathcal{F}_{\text{osc,LV}}^2}(\bar{x}, u, v) = \frac{1}{8} \frac{k^2}{k_{\text{eva}}^2}.$$

In the resonant case, one can treat $\text{Ci}(|1 - c_s(u + v)x_{\text{eva}}/2|)^2$ as a delta distribution and reduce the double integral to a one-dimensional one for $s = u - v$.

BACK-UP



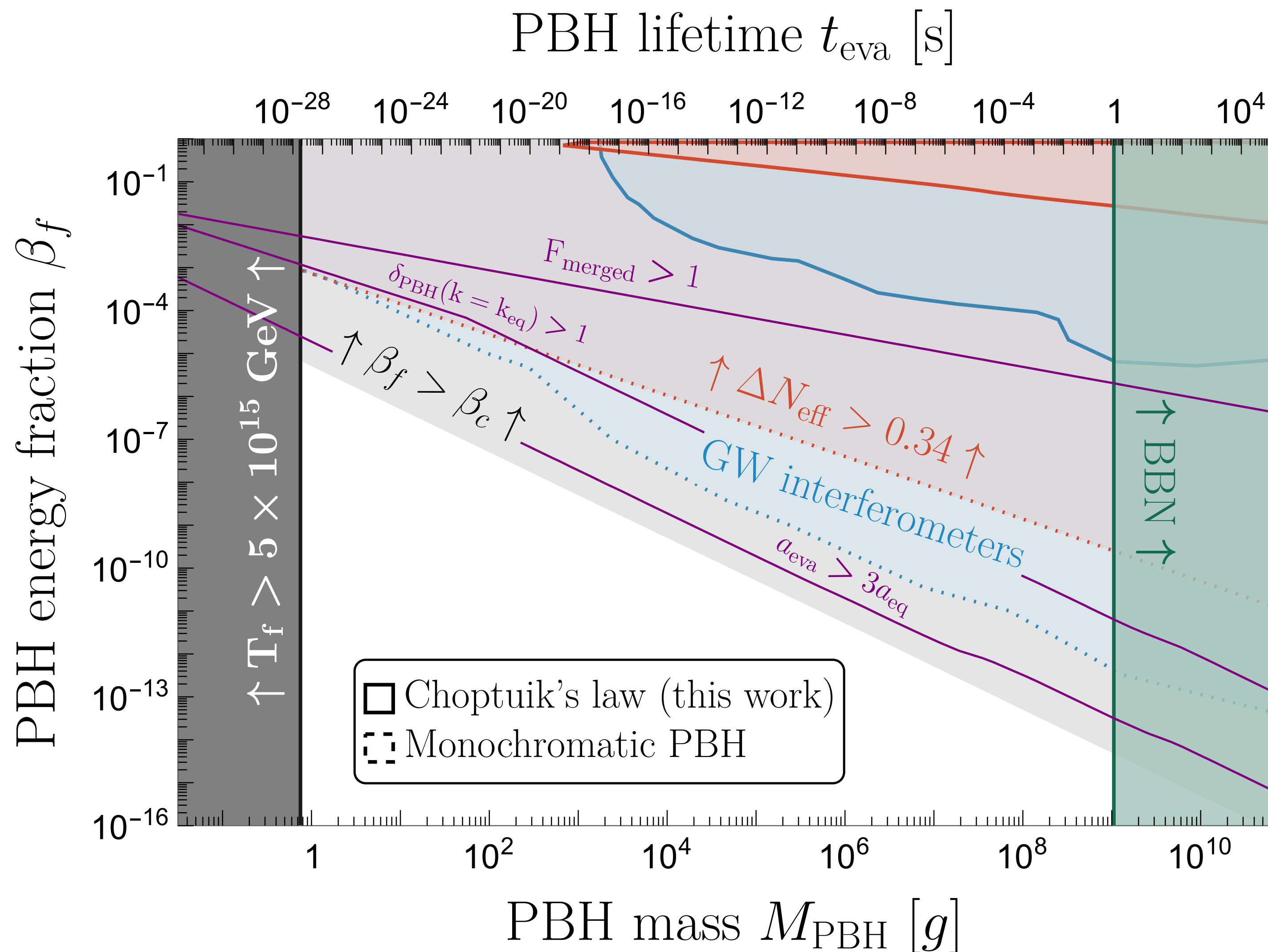
Binary formation threshold:

1. Cluster Formation
2. Major modification of mass distribution (elongation)

BACK-UP

Non-linearities

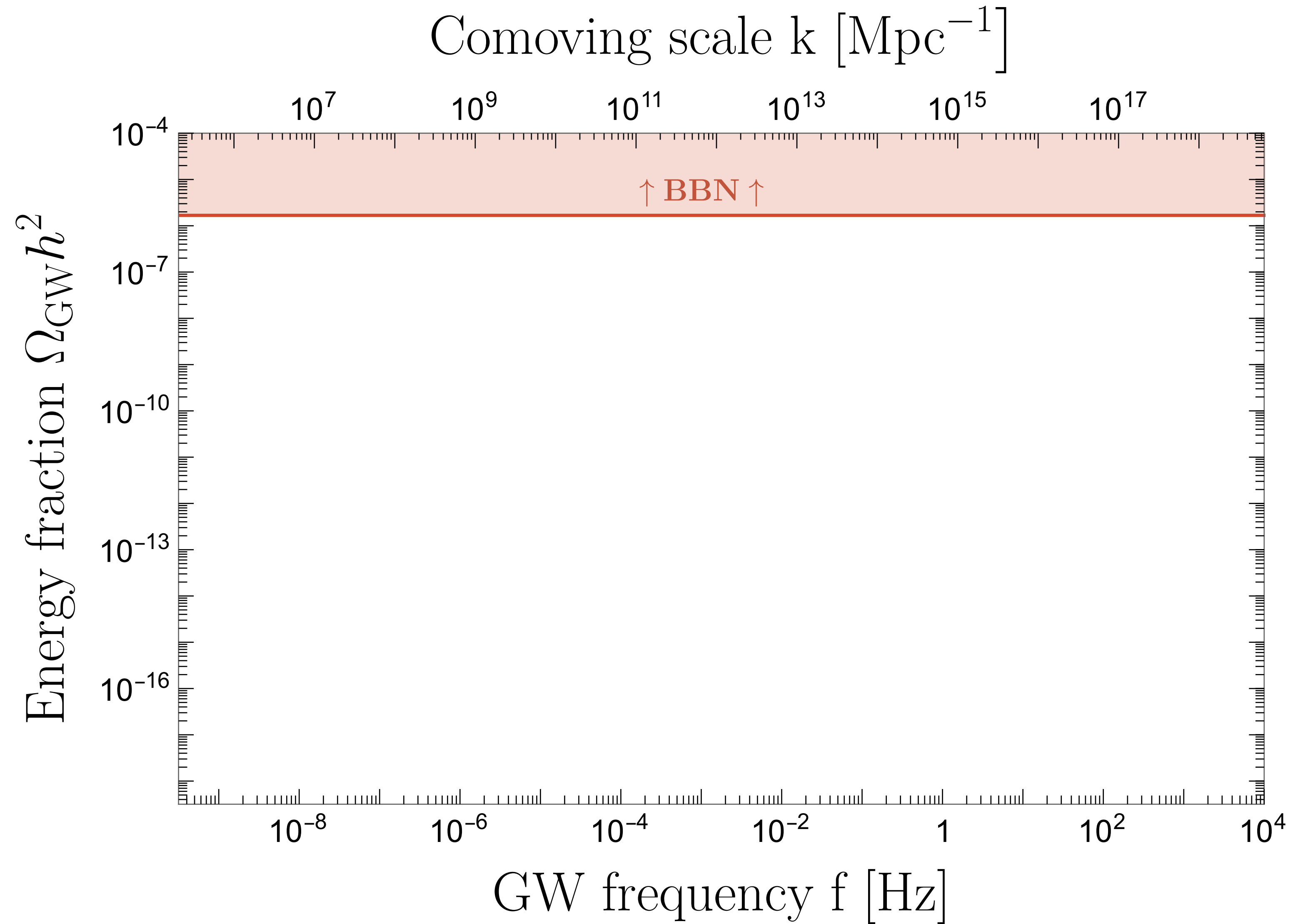
1. Breakdown of PT
2. Probably overestimates signal



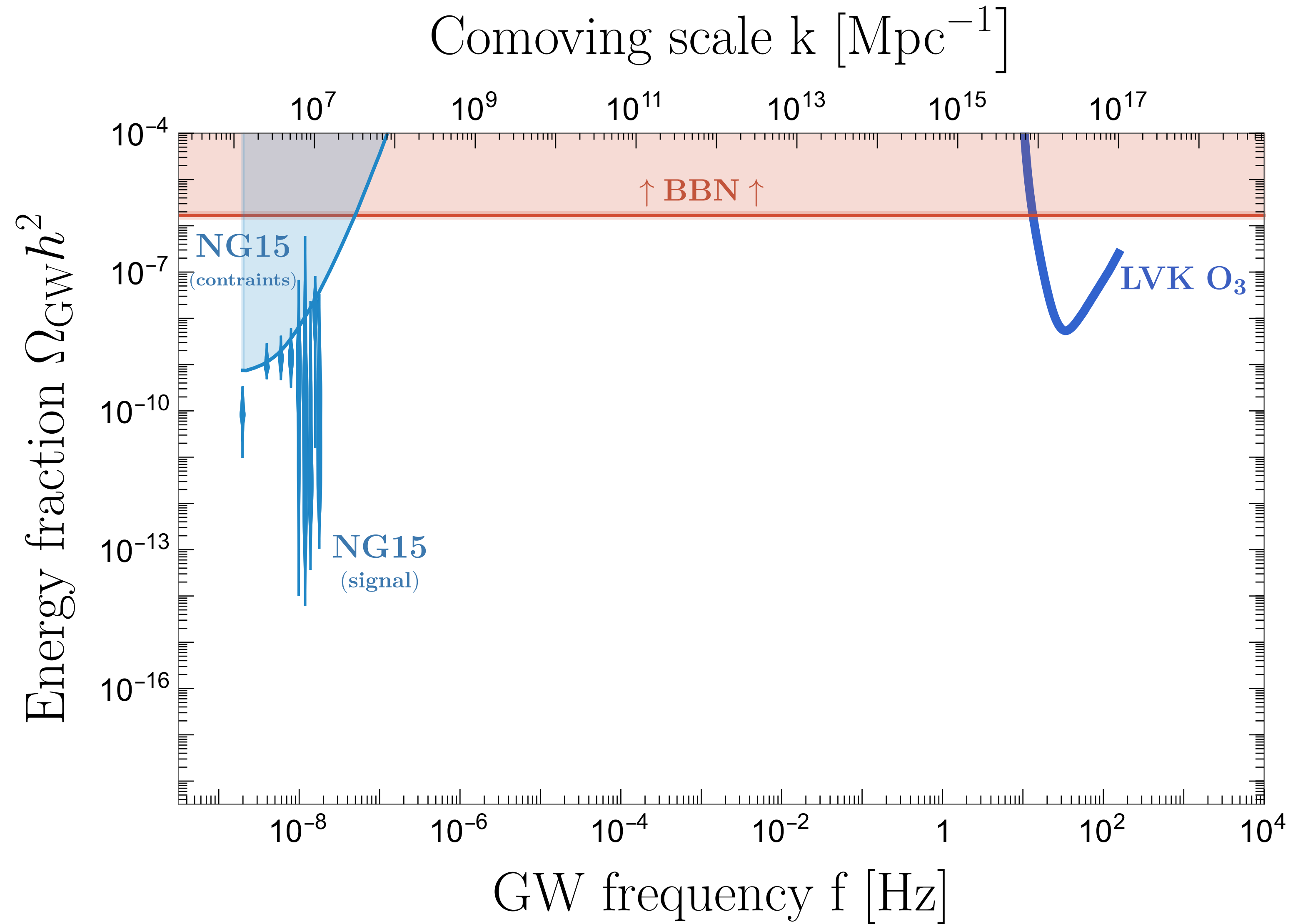
Binary formation threshold:

1. Cluster Formation
2. Major modification of mass distribution (elongation)

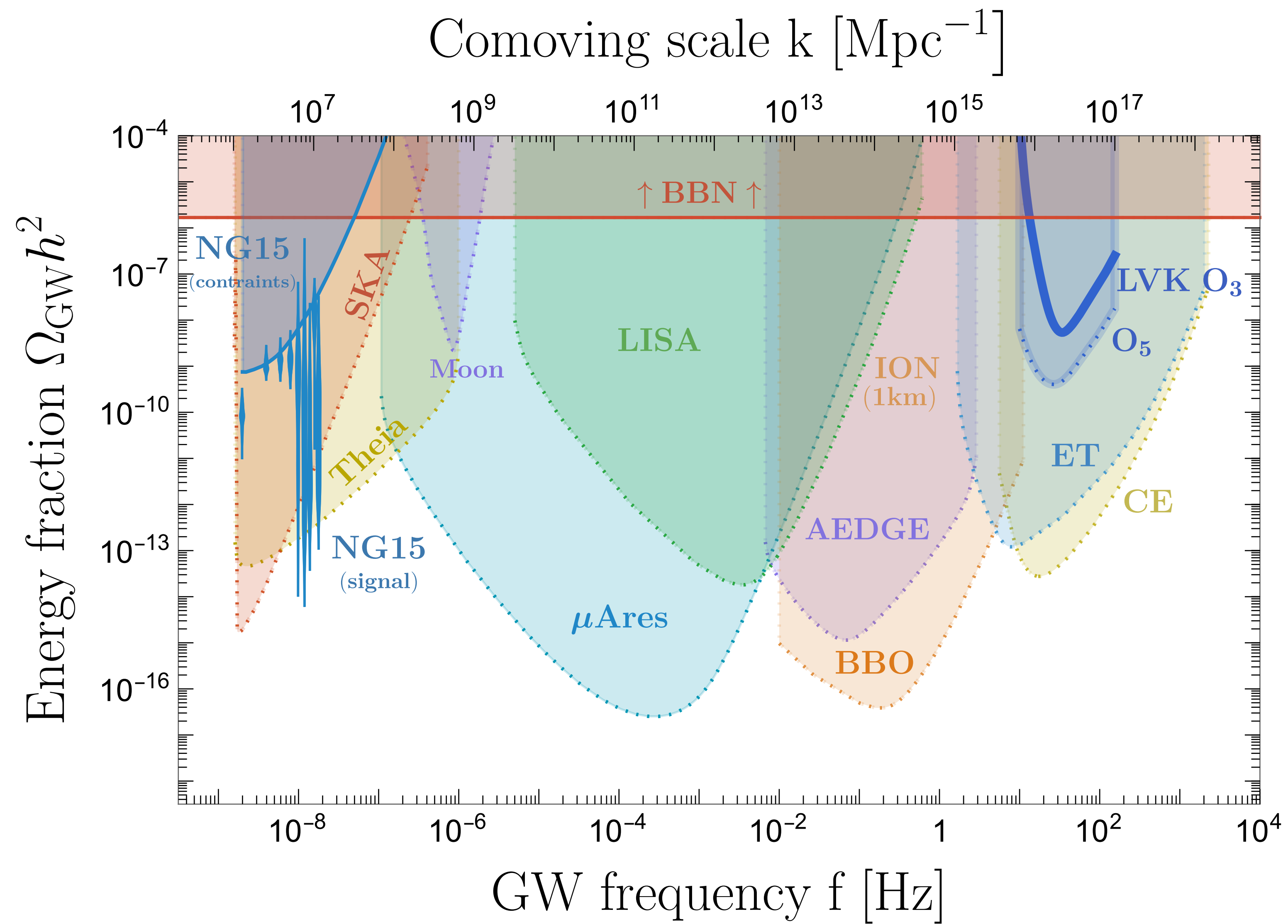
BACK-UP



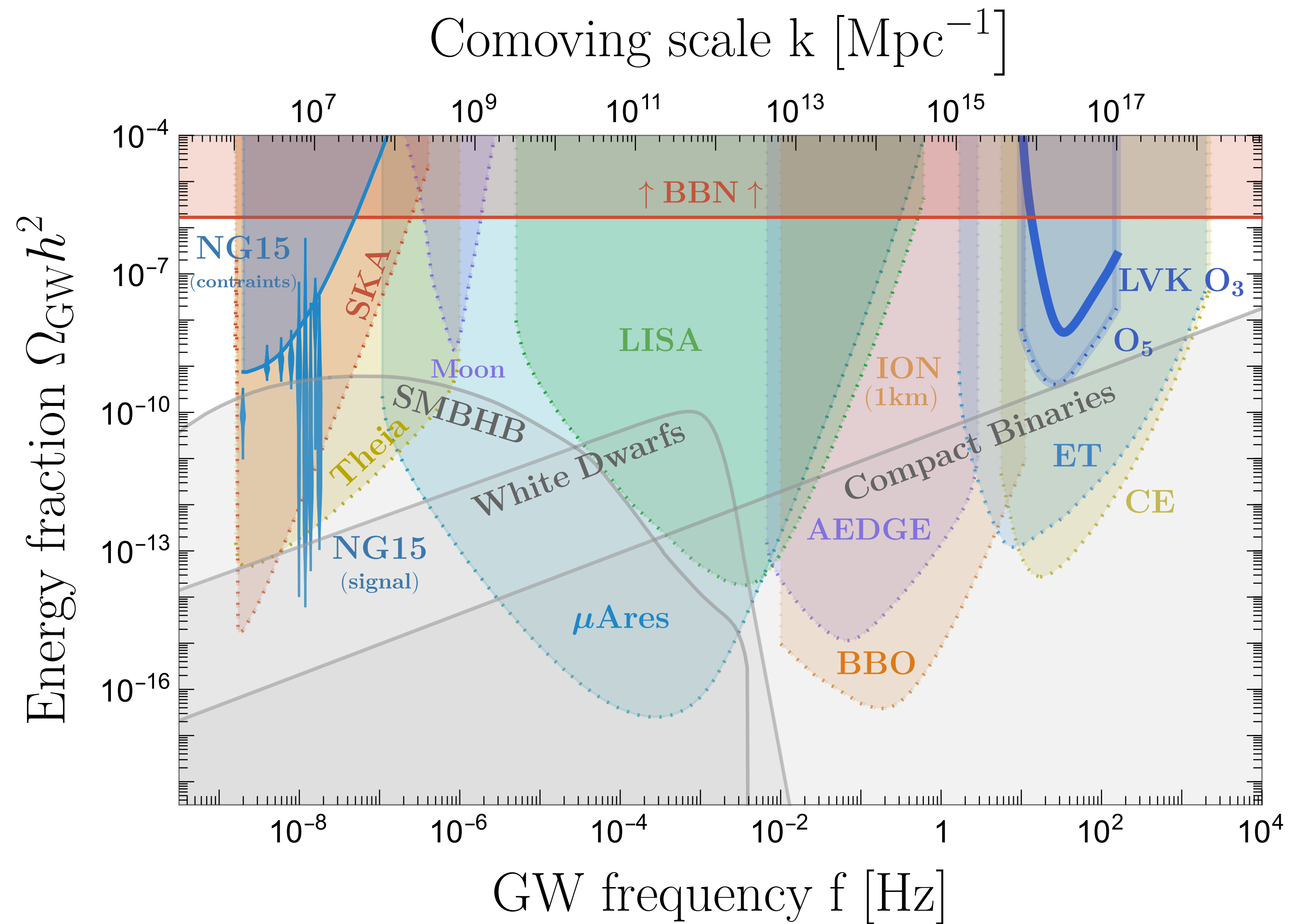
BACK-UP



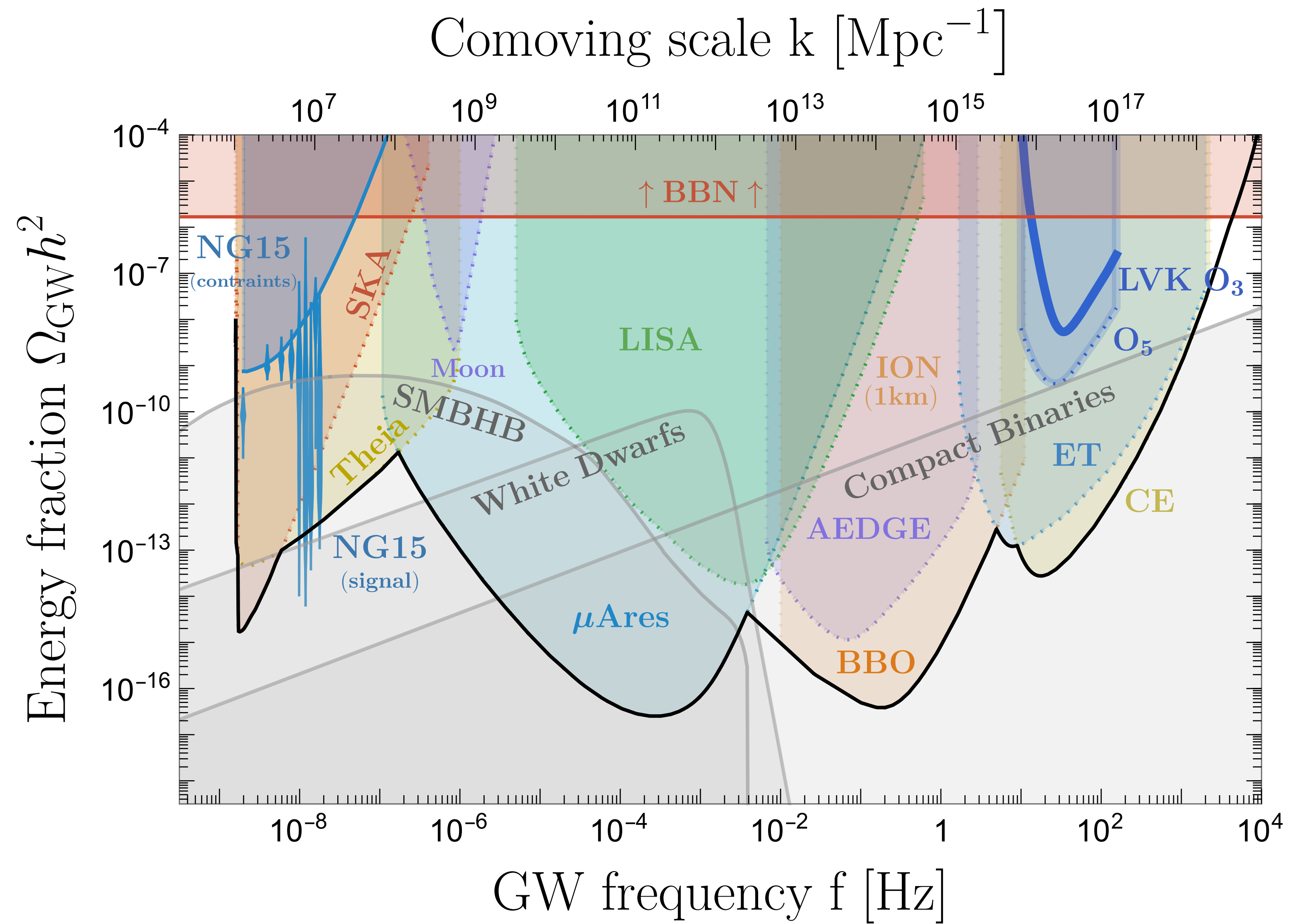
BACK-UP



BACK-UP



BACK-UP



BACK-UP

