Testing Primordial Black Holes

MPA Summer School 2025

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Based on works with Yann Gouttenoire, Antonio Iovino,
Christopher Gerlach and Pedro Schwaller

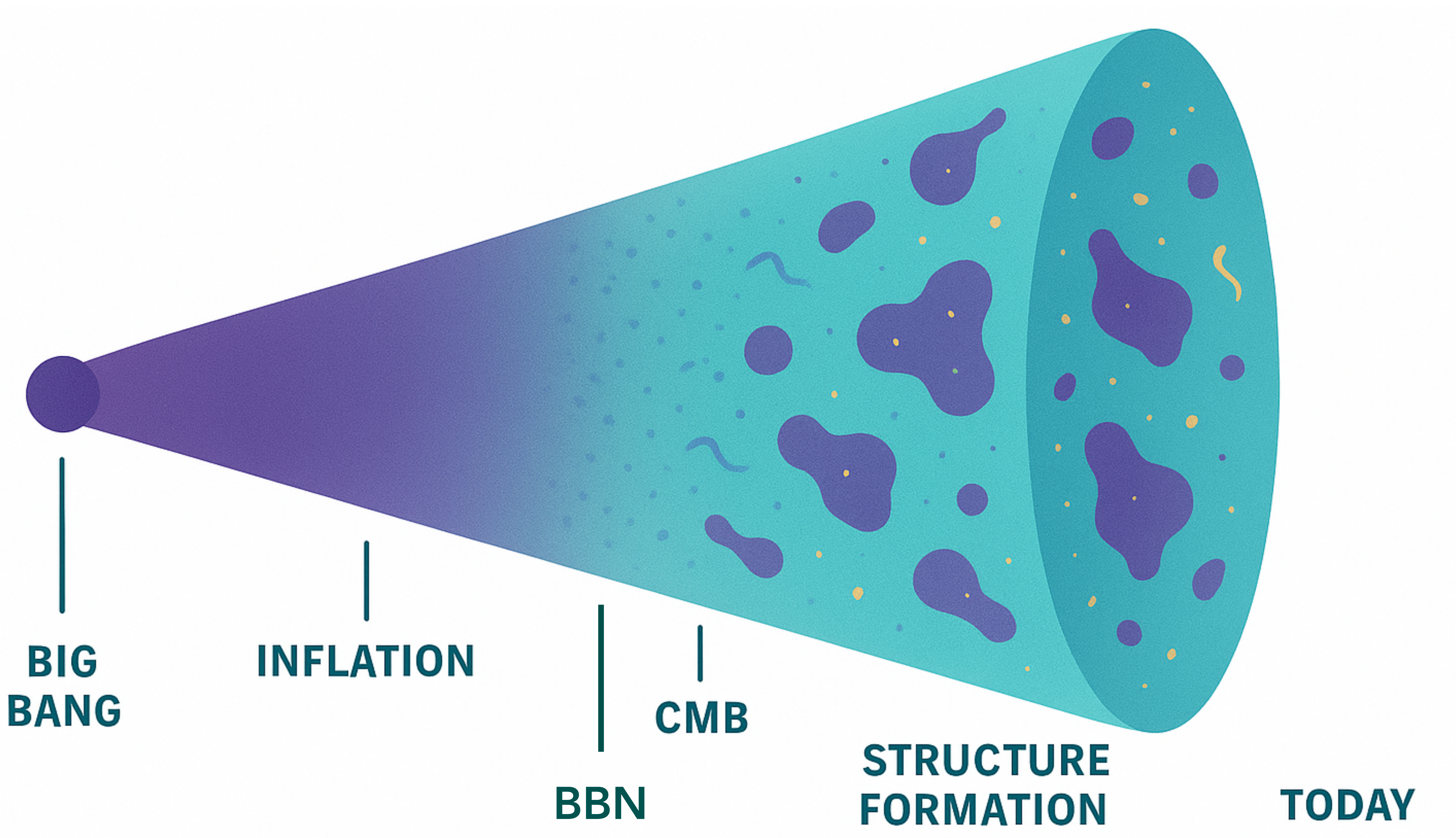
JG|U

MPA MAINZ PHYSICS ACADEMY

Cluster of Excellence PRISMA+

Studienstiftung des deutschen Volkes

EARLY UNIVERSE



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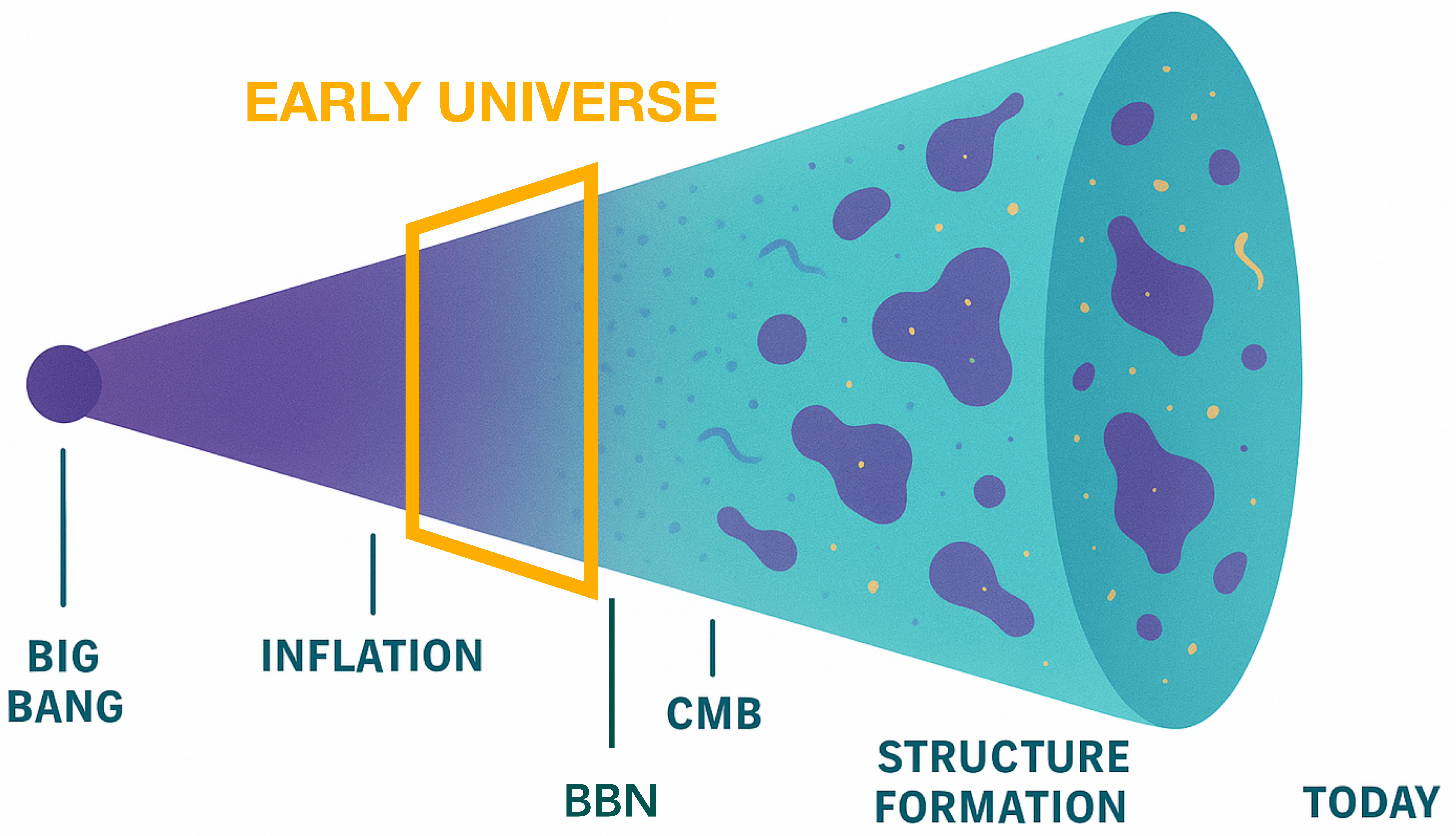
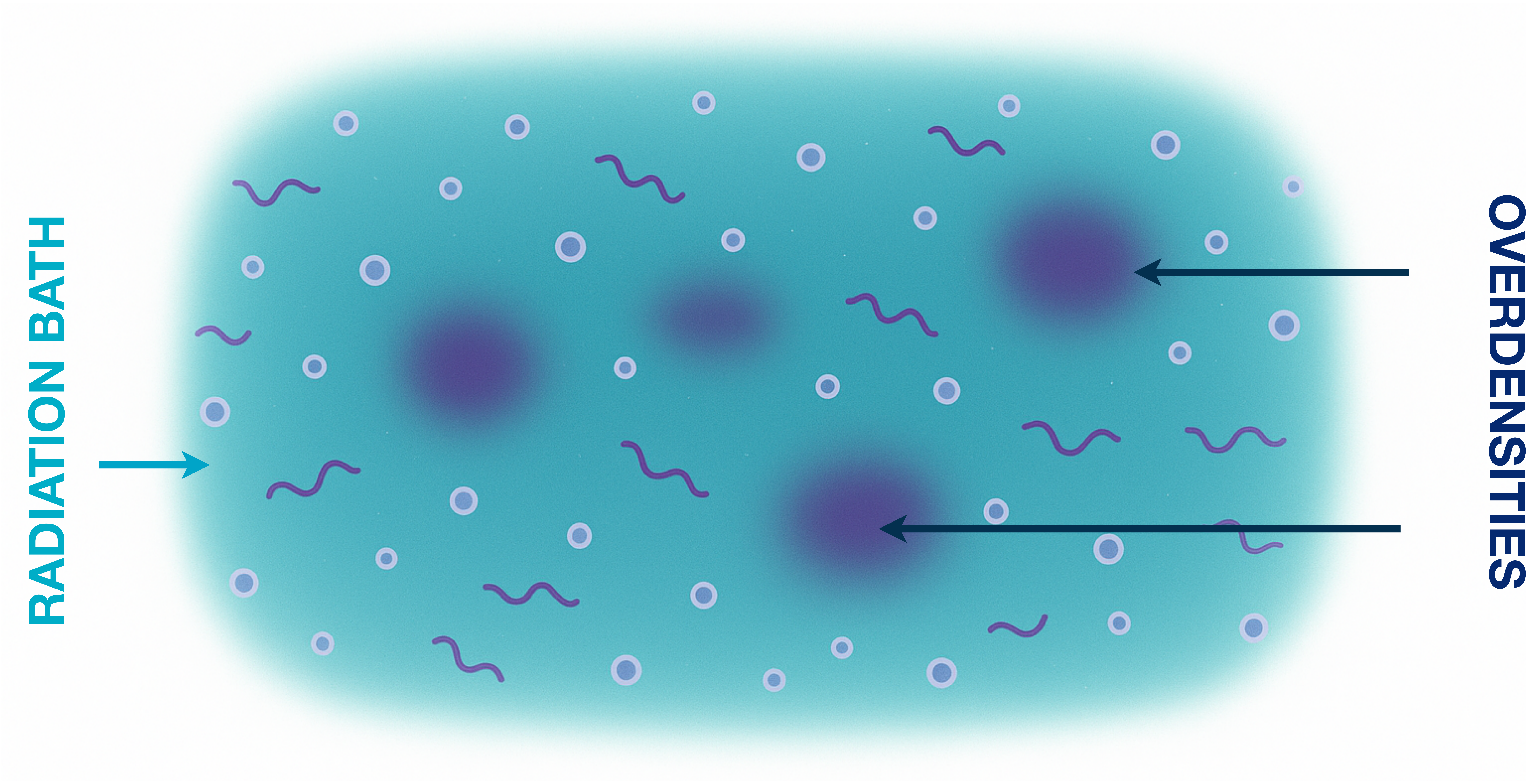


PRIMORDIAL BLACK HOLES



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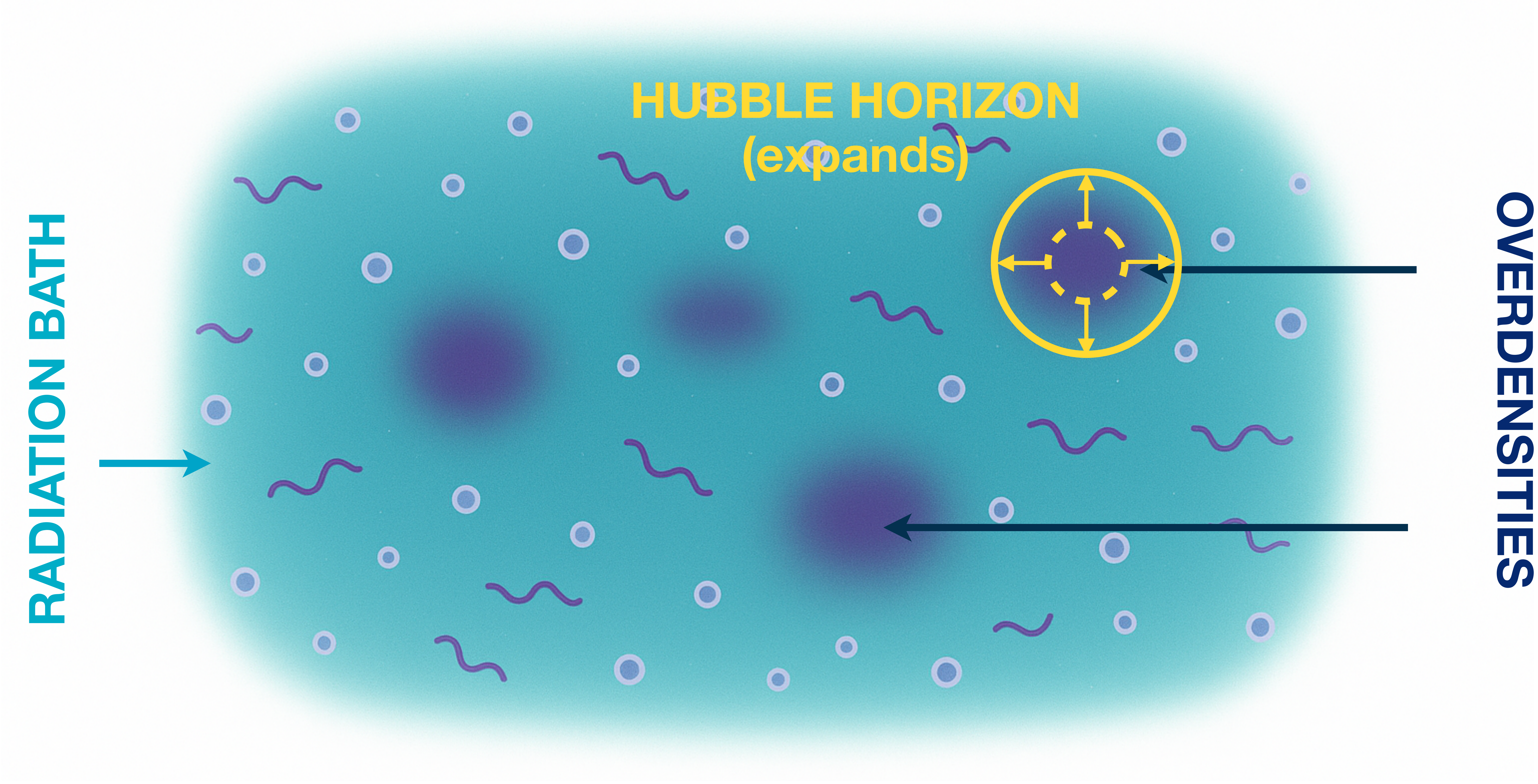

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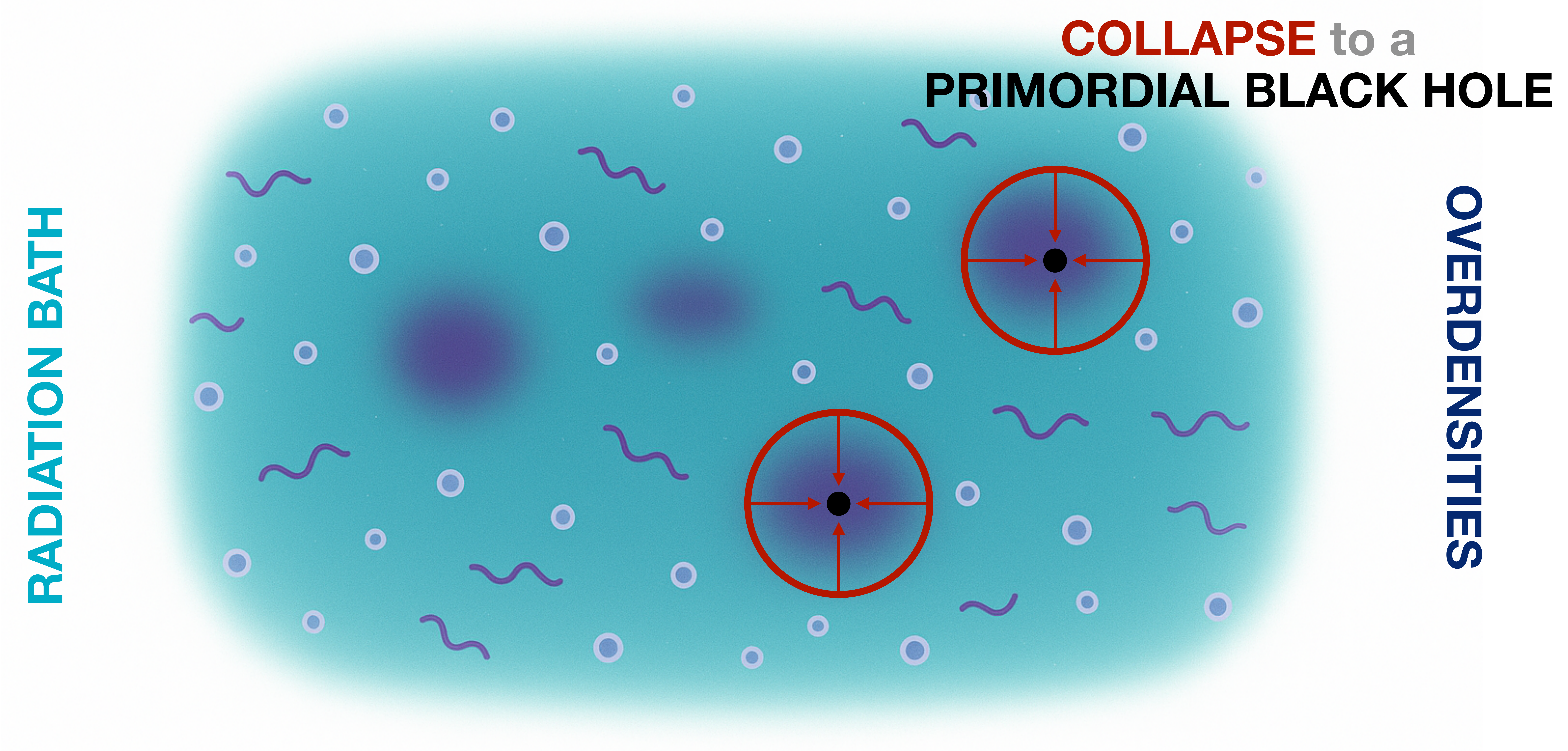

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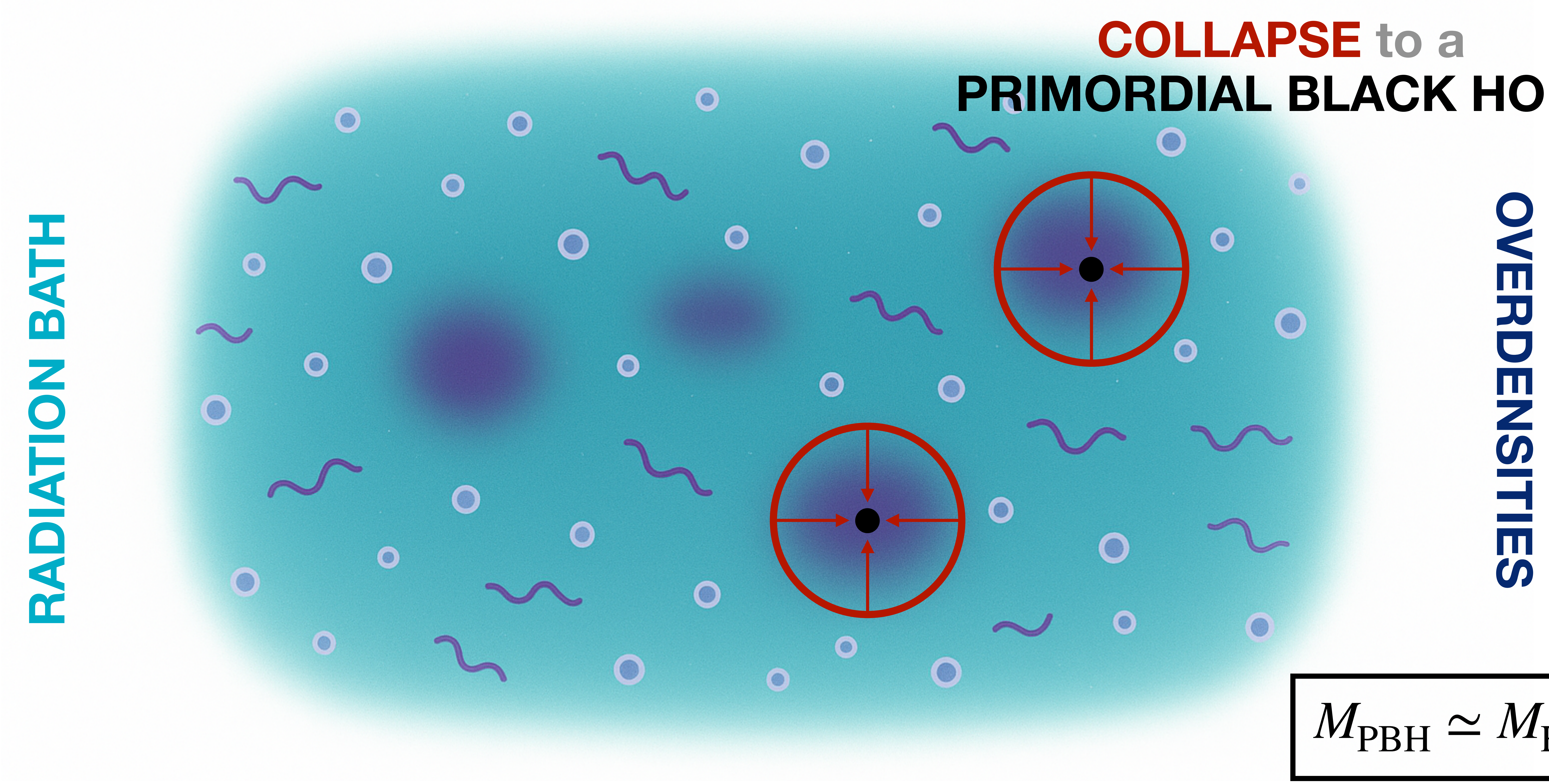
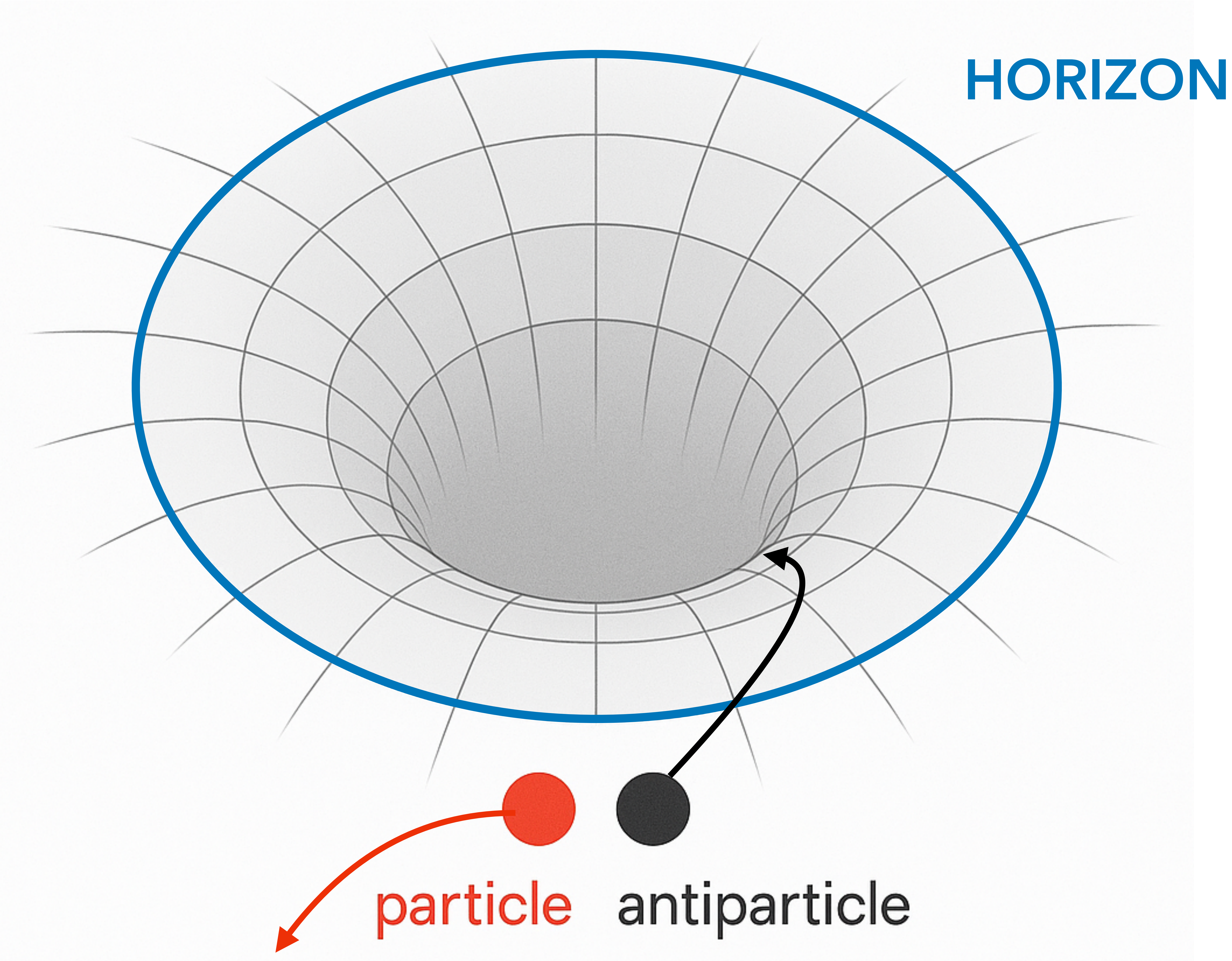


$$\boxed{M_{\mathrm{PBH}} \simeq M_{\mathrm{Horizon}}}$$

HAWKING EVAPORATION



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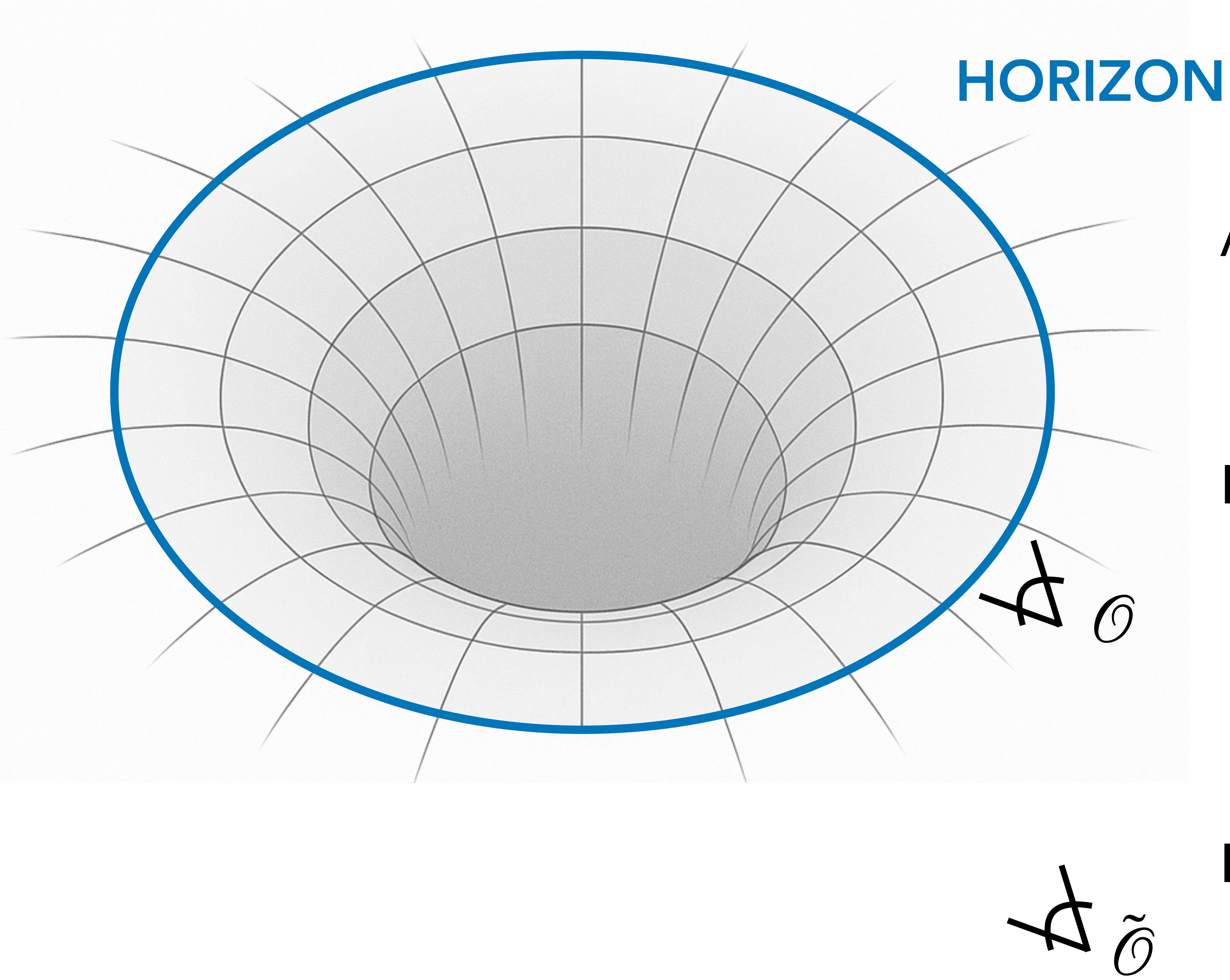


$$\Phi \simeq \int \frac{\mathrm{d}^3 k}{(2\pi)^3 2k} \left(\hat{a}_k e^{-ikx} + \hat{b}_k^\dagger e^{ikx} \right)$$

A. Minkowski space (global killing vector)
Unambiguous vacuum:

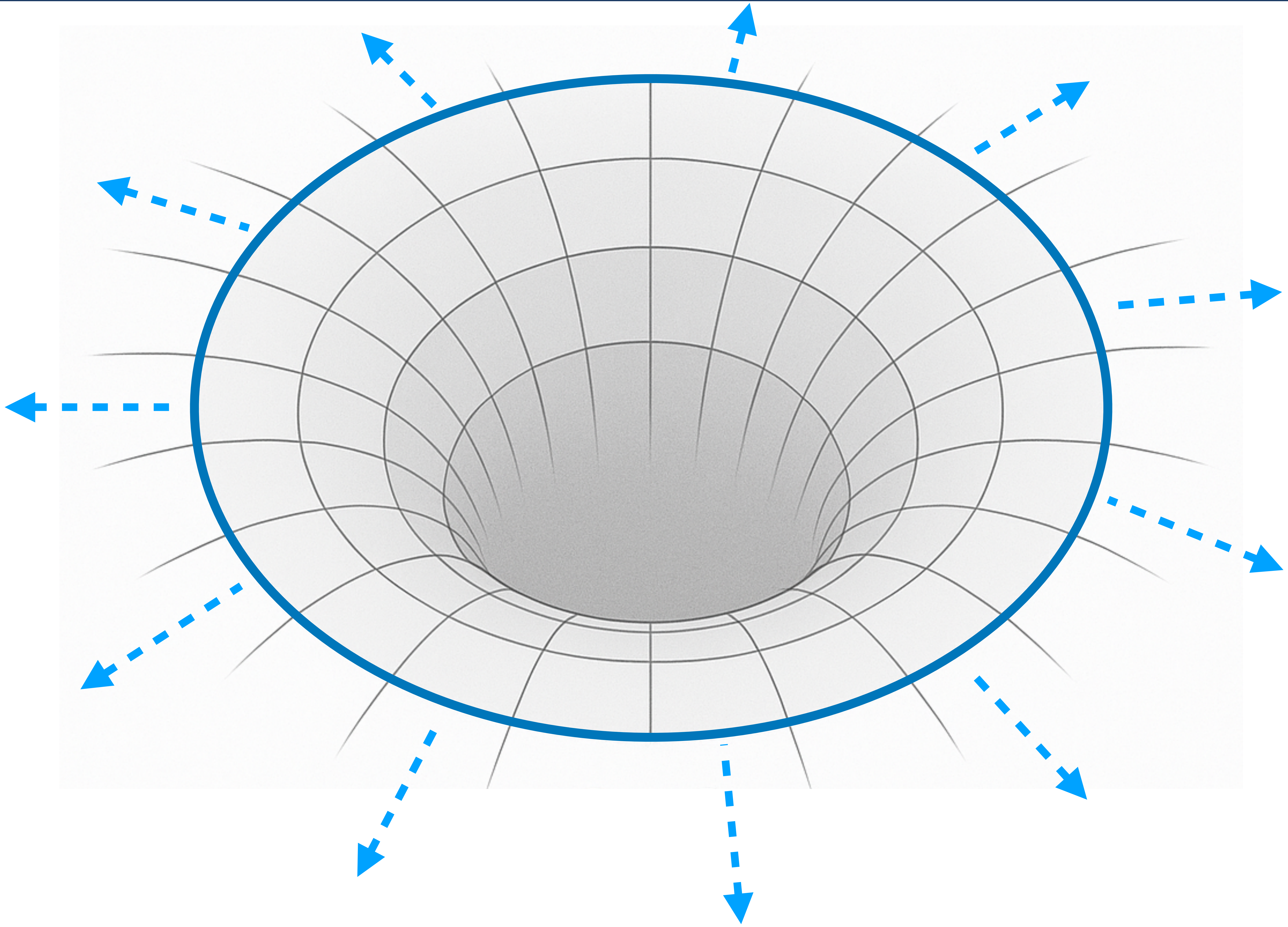
$$\hat{a}_k |0\rangle = \hat{b}_k |0\rangle = 0$$

B. Generel coordinates: Bogolyubov transformations

$$\begin{pmatrix} \tilde{\Phi} \\ \tilde{\Phi}^* \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \beta^* & \alpha^* \end{pmatrix} \begin{pmatrix} \Phi \\ \Phi^* \end{pmatrix}$$

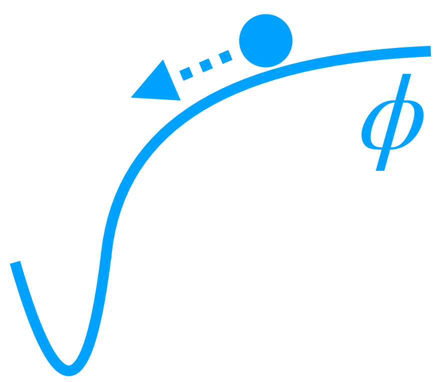
PARTICAL PRODUCTION

HAWKING EVAPORATION

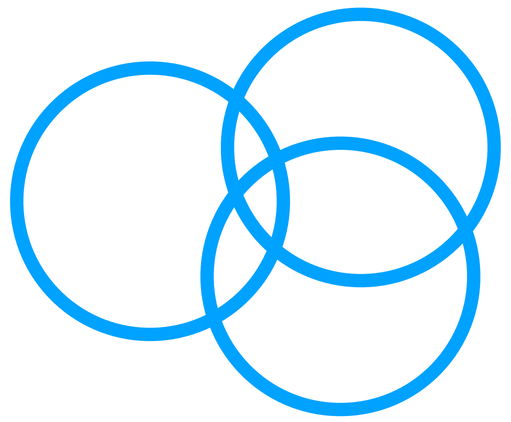


BLACKHOLES EVAPORATE (DECAY)

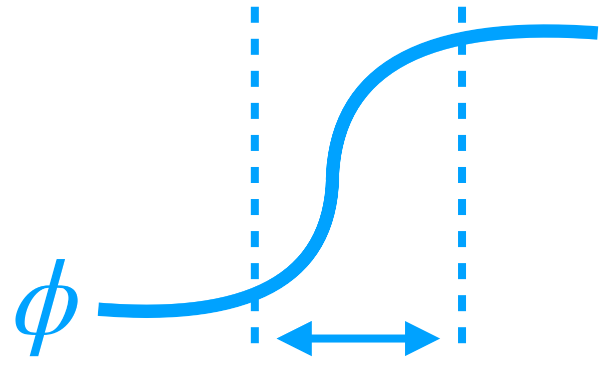
MOTIVATION



INFLATION

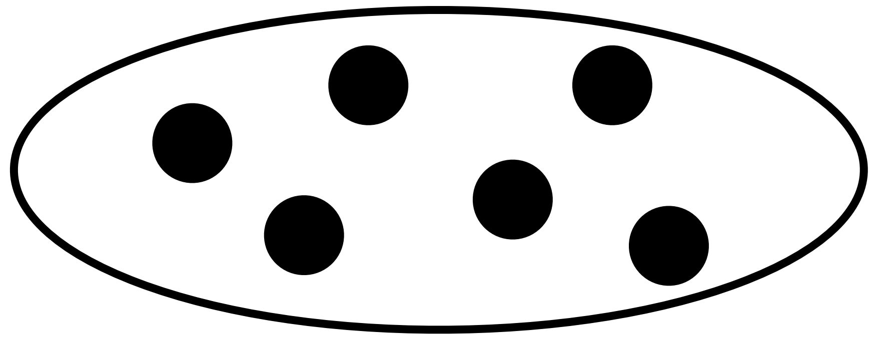


FOPT

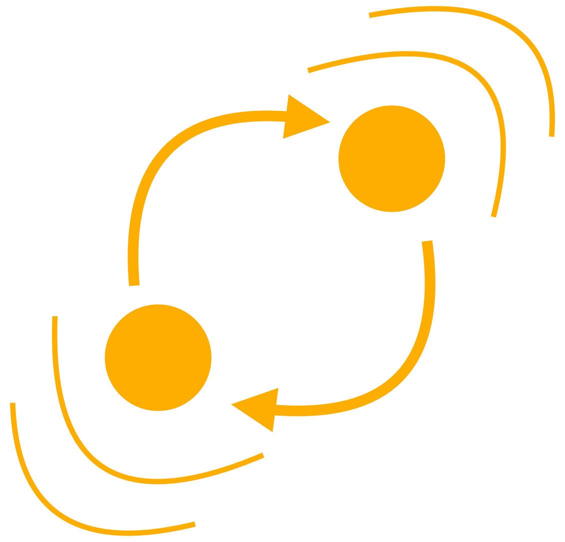


DWs

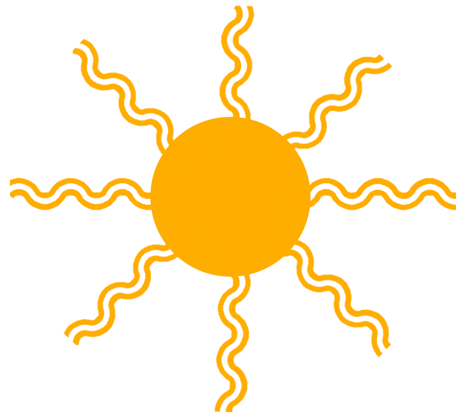
PRIMORDIAL BLACK HOLES



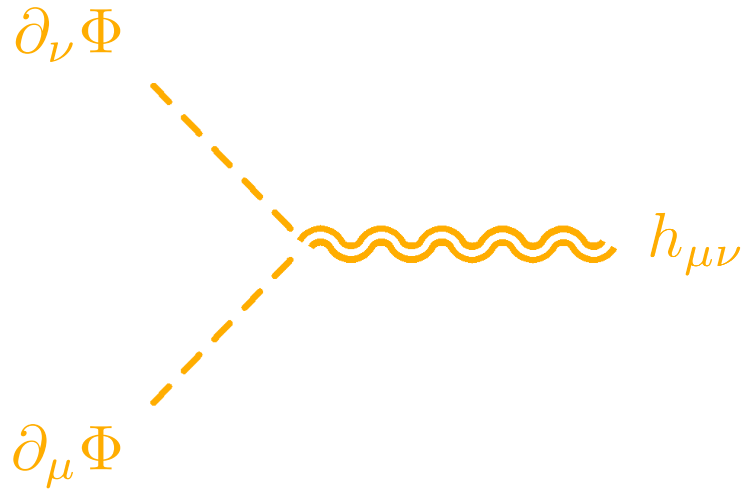
BINARIES



GRAVITONS



SCALAR-INDUCED



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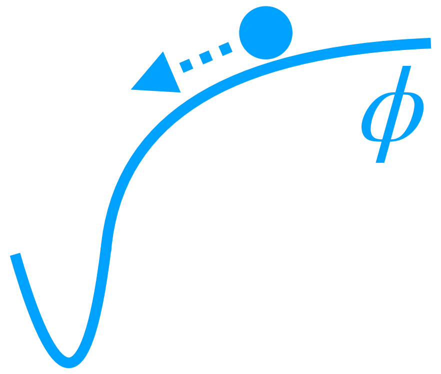

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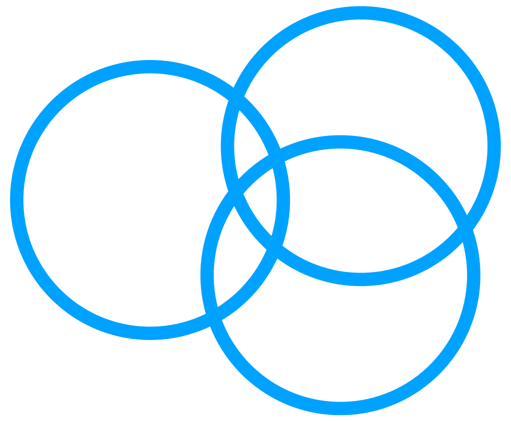
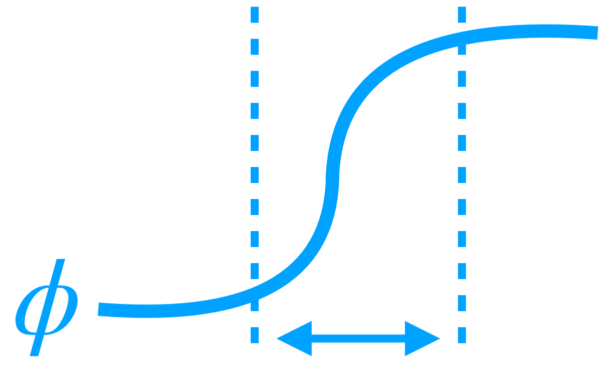


FOPT



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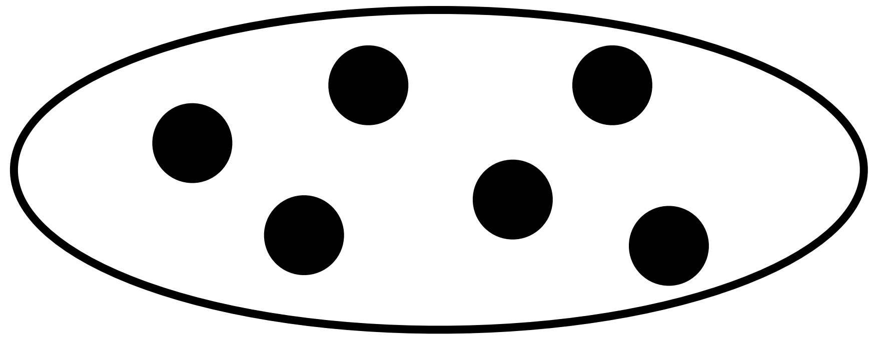

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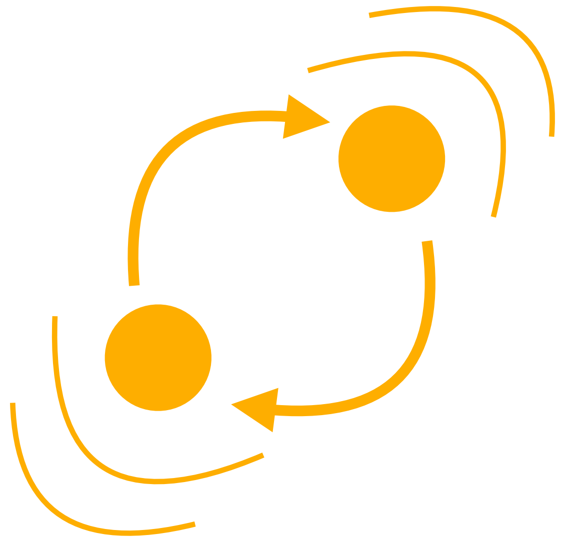

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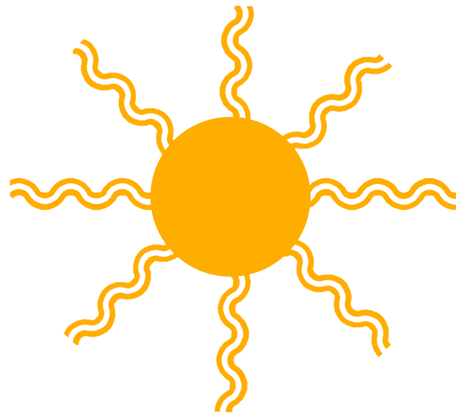

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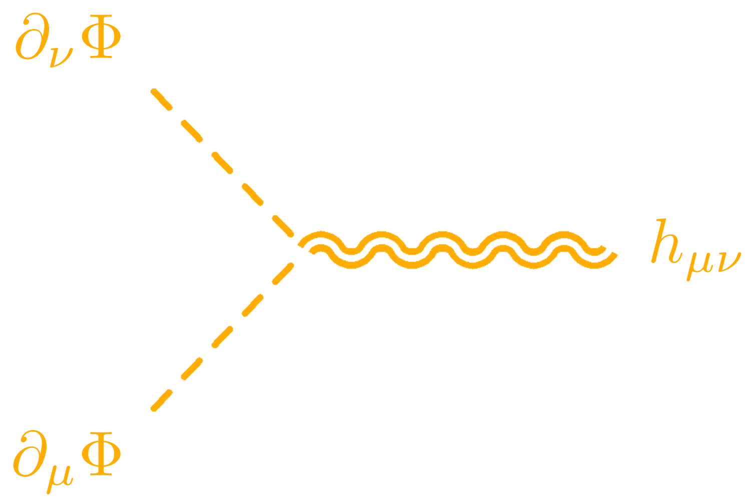
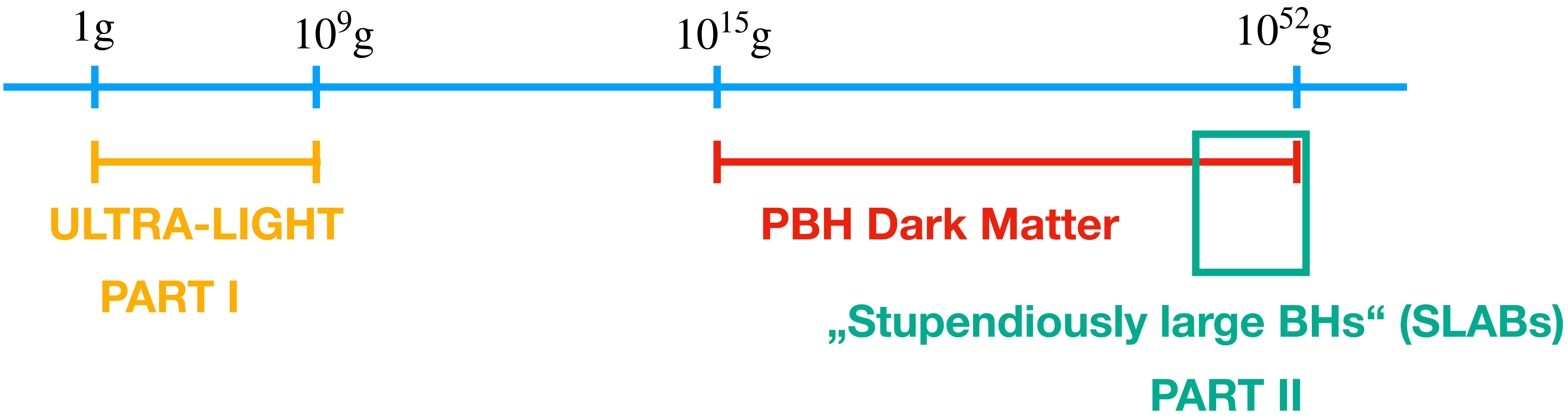


PARAMETER SPACE

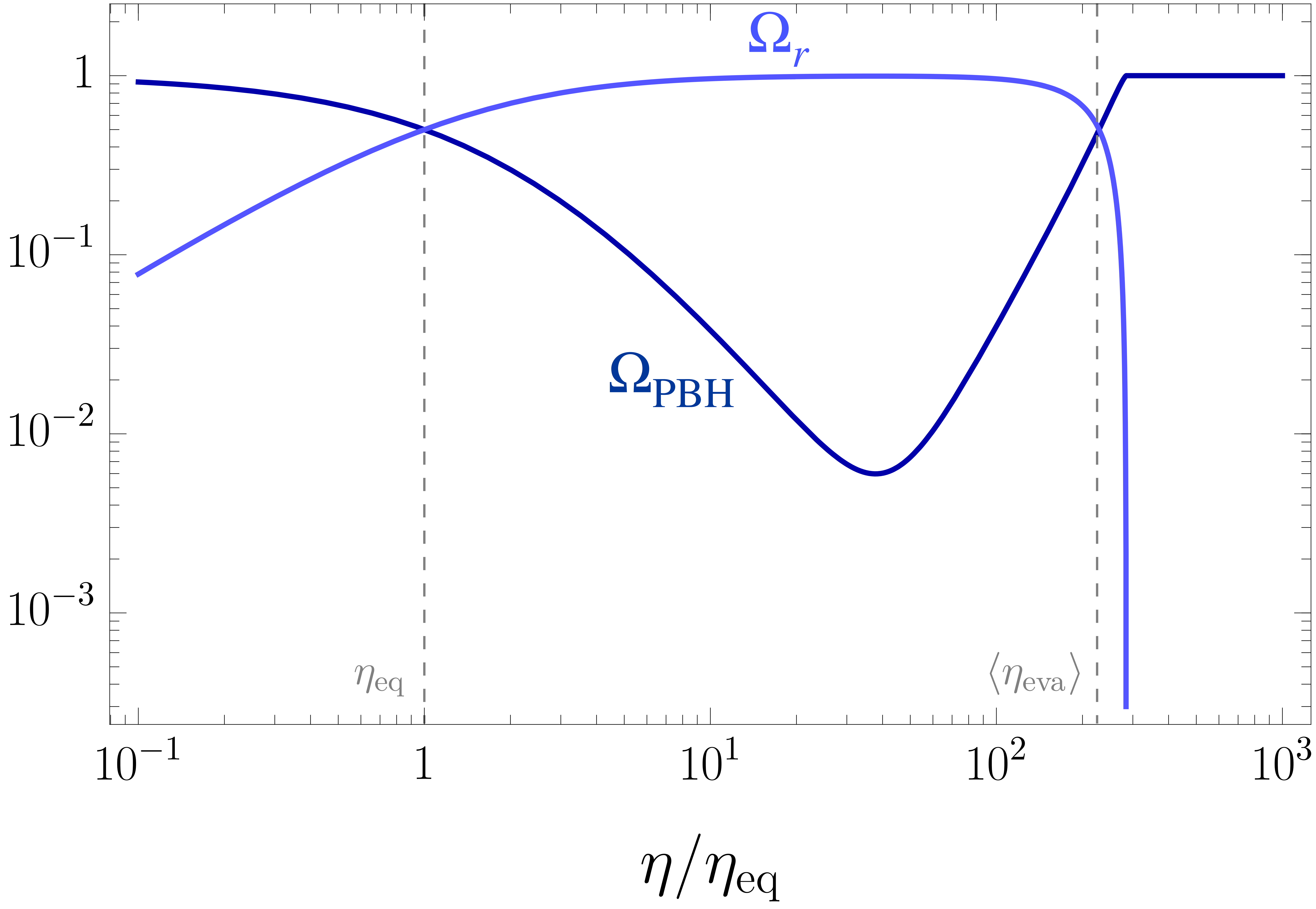


$$\boxed{M_{\rm PBH} \simeq M_{\rm Horizon}}$$

PART I:

ULTRA LIGHT PBHs

PRIMORDIAL BLACK HOLES

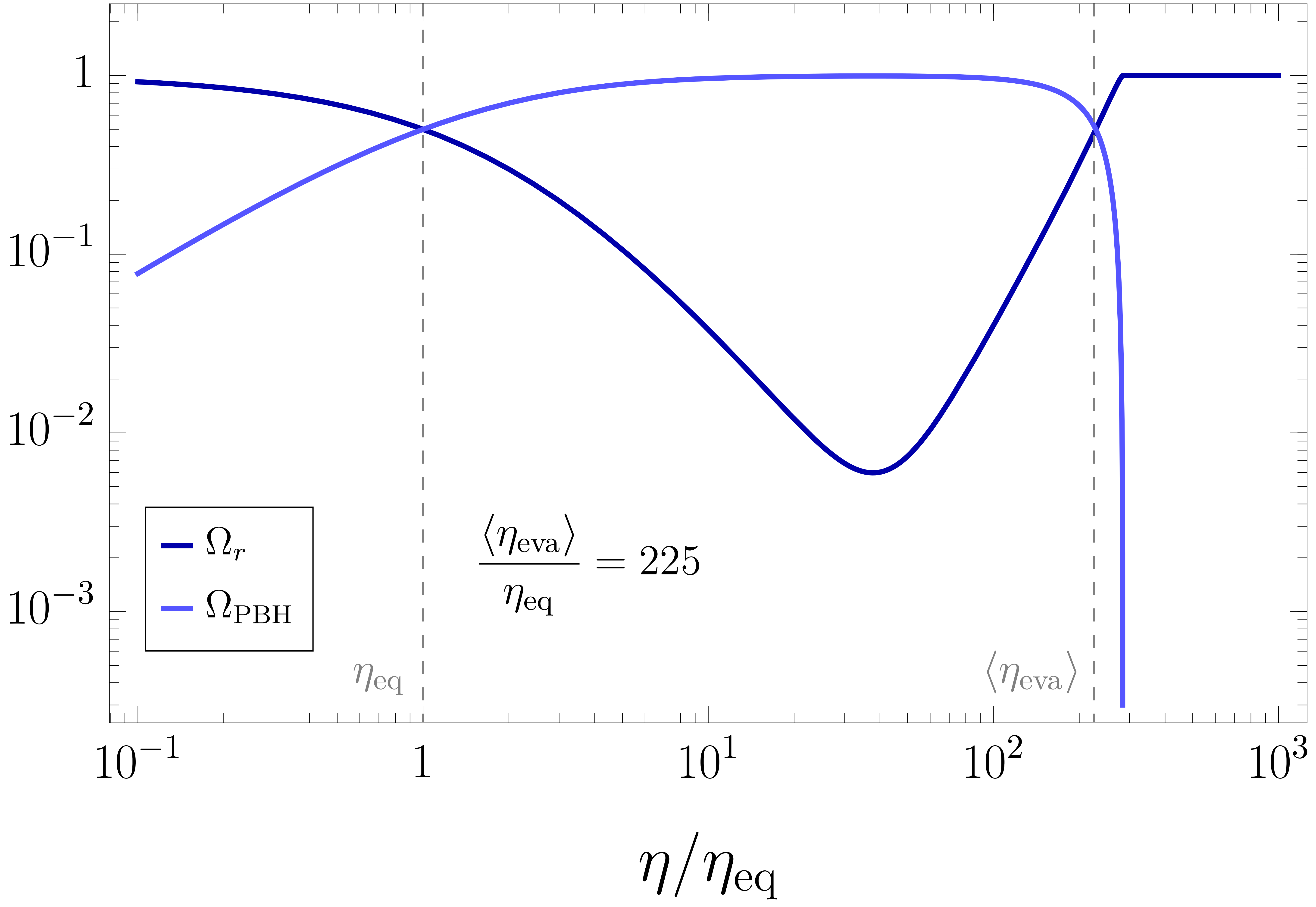


$$\rho_m' = -(3\mathscr{H} + \Gamma)\rho_m$$

$$\rho_r' = -4\mathscr{H}\rho_r + \Gamma\rho_m$$

$$\mathscr{H} = \frac{a}{\sqrt{3}M_{\rm pl}}\sqrt{\rho_{\rm tot}}$$

PRIMORDIAL BLACK HOLES



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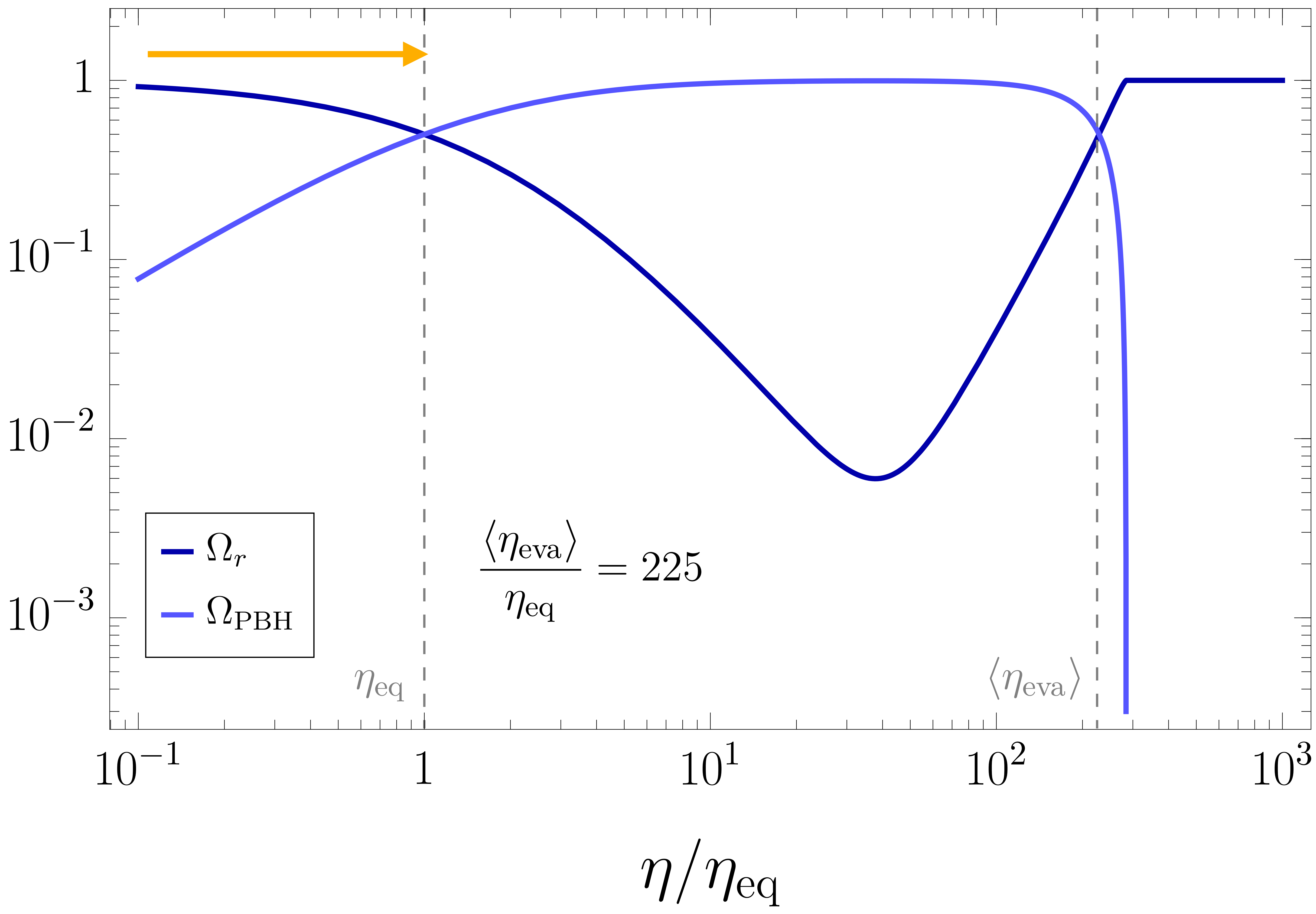
PRIMORDIAL BLACK HOLES

$\beta > \beta_c$



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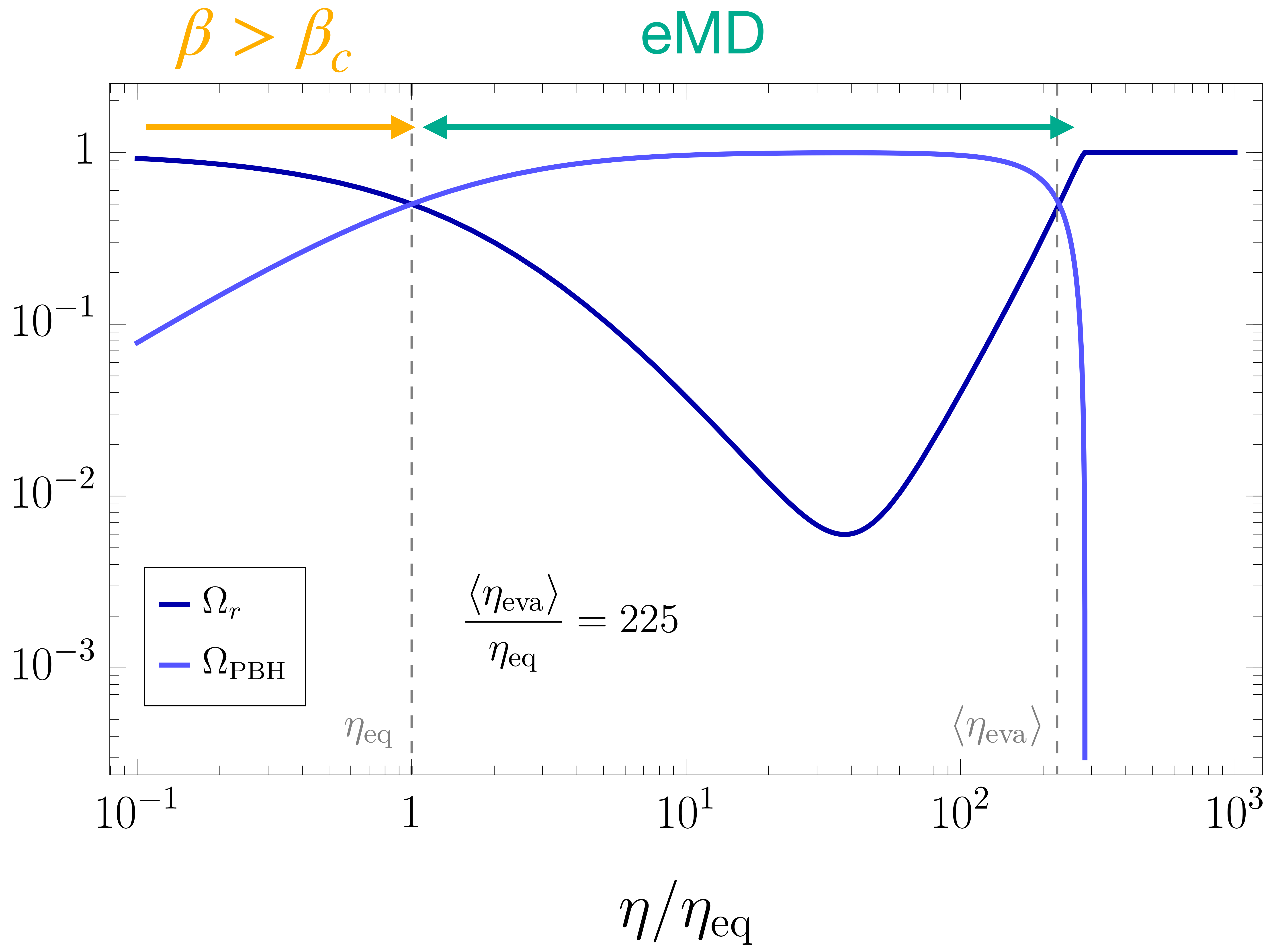

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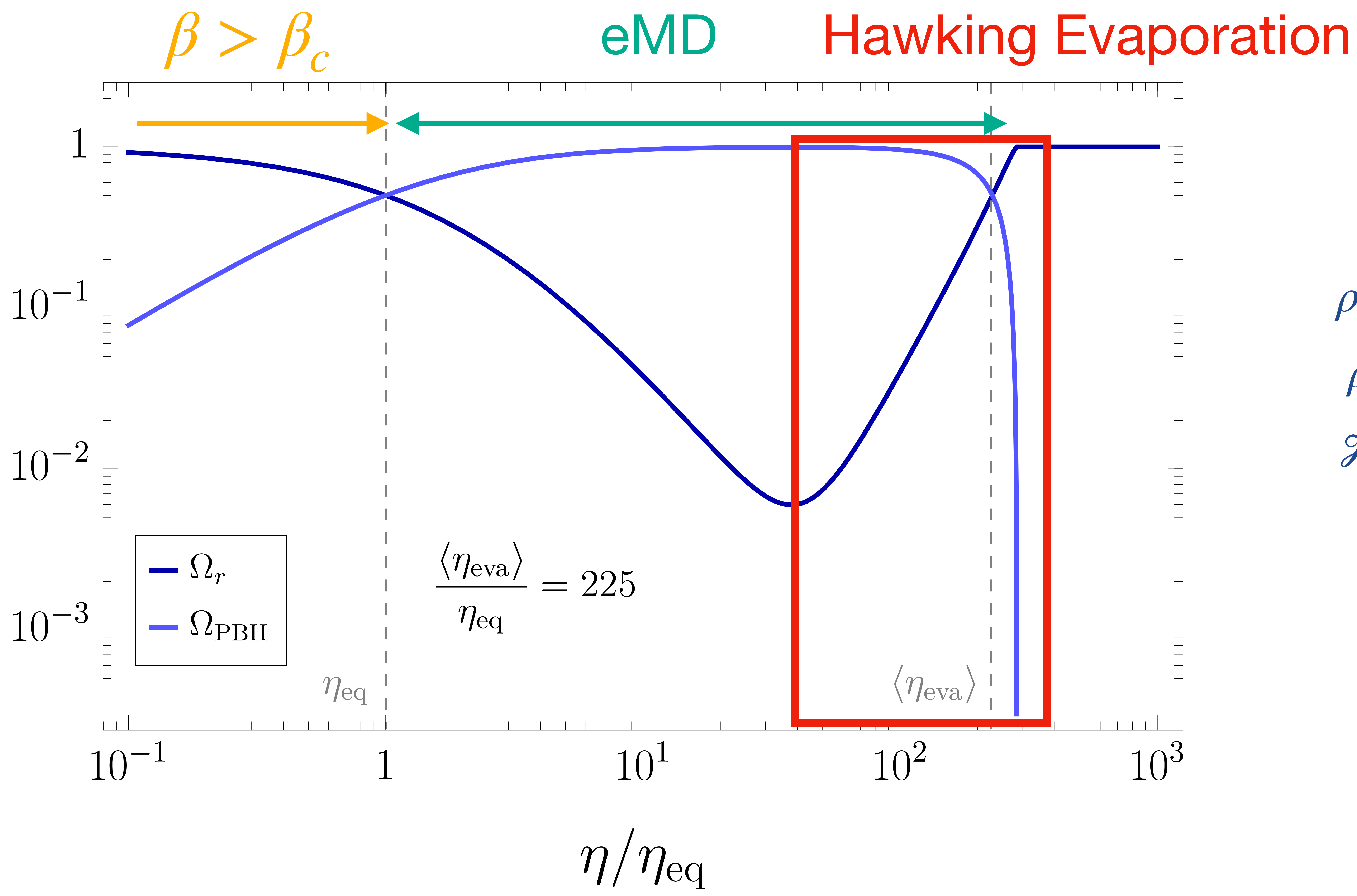

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$$\mathscr{H} = \frac{a}{\sqrt{3}M_{\rm pl}}\sqrt{\rho_{\rm tot}}$$

SOLVING PERTURBATIONS

Isotropic + homogeneous universe

$$\mathrm{d}s^2 = a^2(\eta)\left[\mathrm{d}\eta^2 - \delta_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j\right]$$

SOLVING PERTURBATIONS

Cosmological perturbation theory

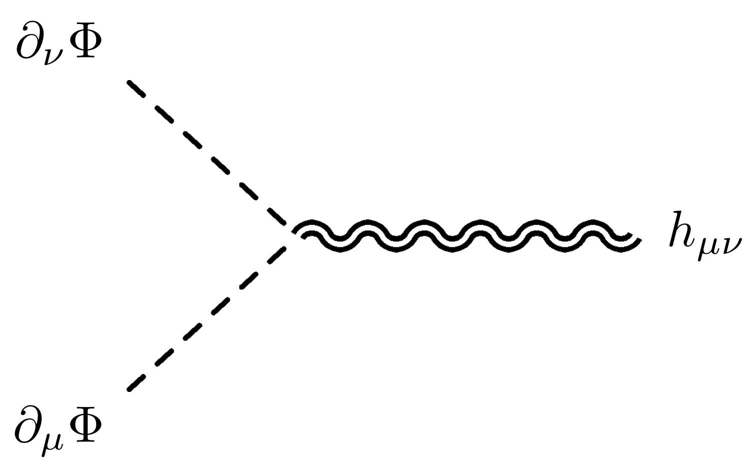
$$\mathrm{d}s^2 = a^2(\eta)\Big[(1+2\Psi)\mathrm{d}\eta^2 - (1-2\Phi)\delta_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j + h_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j\Big]$$

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

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



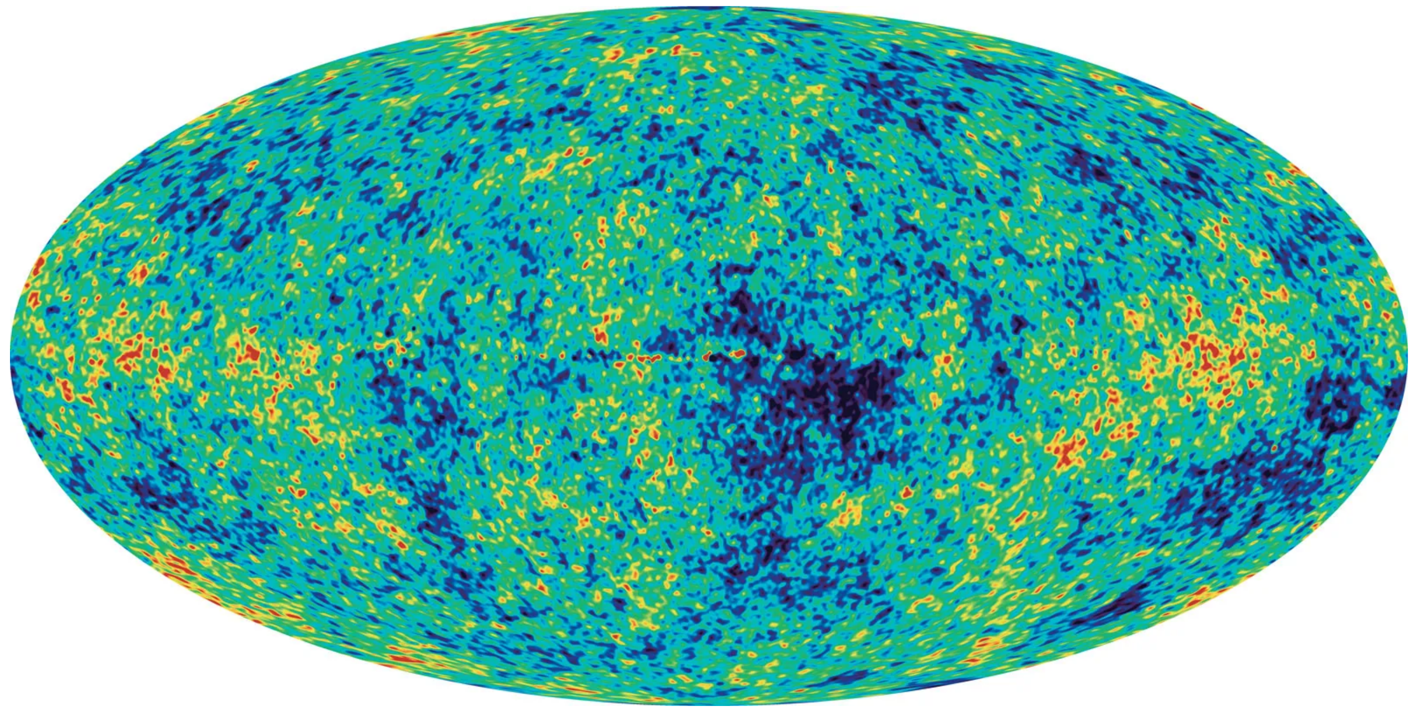
$$\mathcal{P}_h \propto h^2 \propto \Phi^4$$

SOLVING PERTURBATIONS

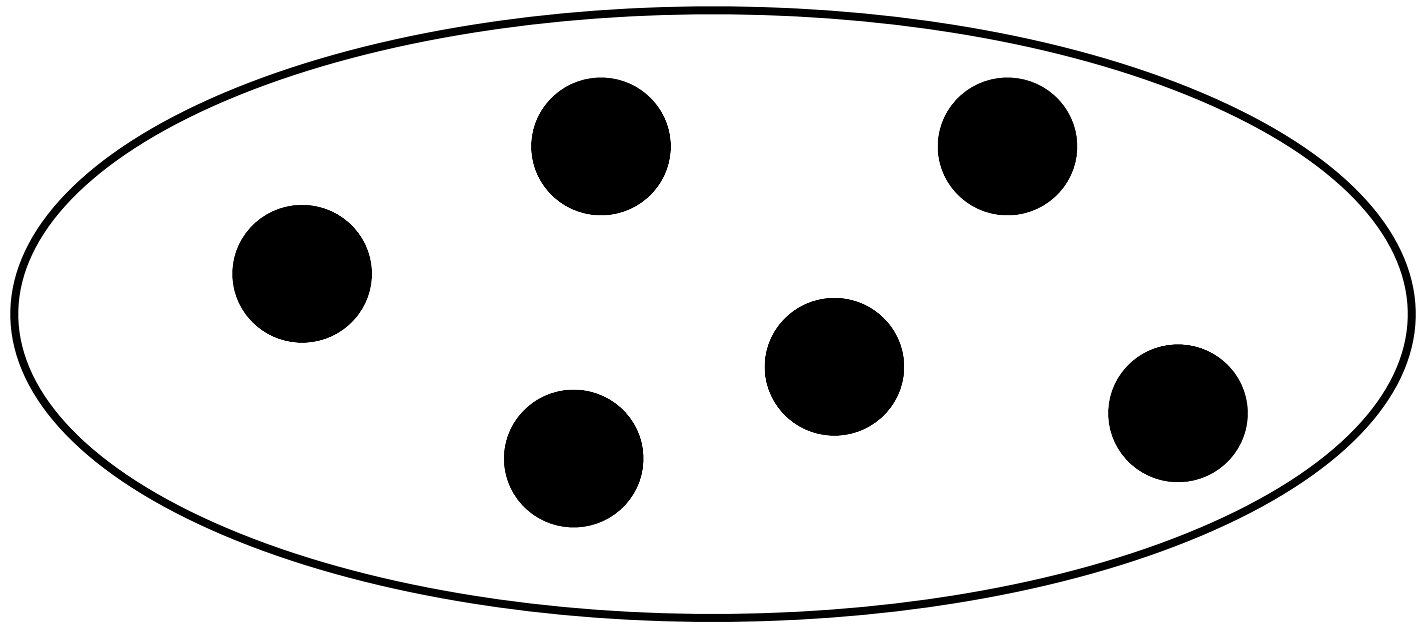
Cosmological perturbation theory

$$\mathrm{d}s^2 = a^2(\eta)\left[(1-2\Phi)\mathrm{d}\eta^2 - (1-2\Phi)\delta_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j + h_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j\right]$$

Primordial Scalar Perturbations Φ



+



Adiabatic Perturbations (Inflation)

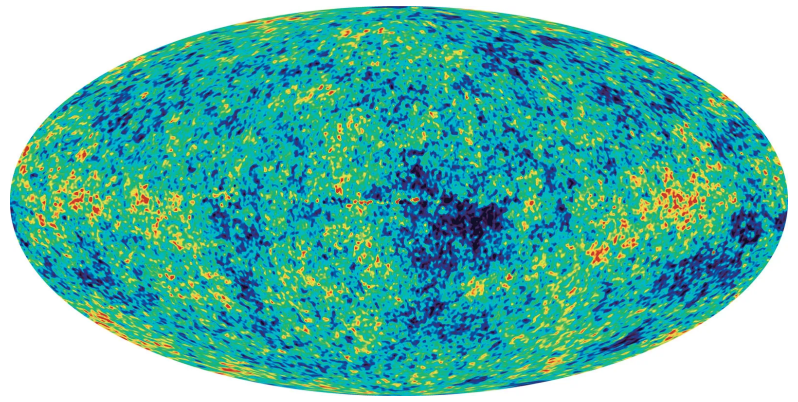
PBH Isocurvature

SOLVING PERTURBATIONS

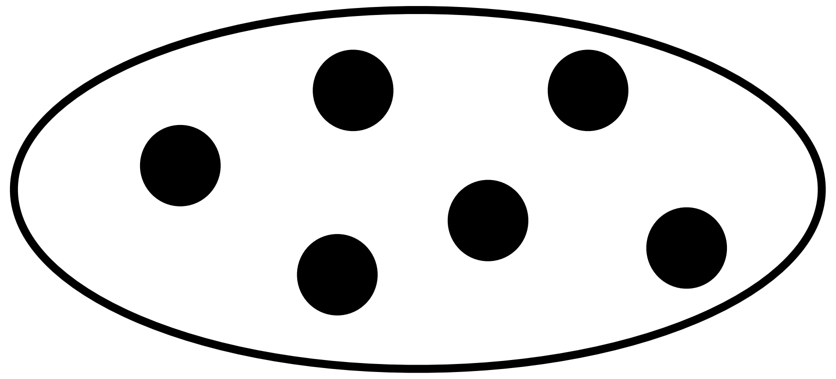
Cosmological perturbation theory

$$\mathrm{d}s^2 = a^2(\eta)\left[(1-2\Phi)\mathrm{d}\eta^2 - (1-2\Phi)\delta_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j + h_{ij}\,\mathrm{d}x^i\,\mathrm{d}x^j\right]$$

Primordial Scalar Perturbations Φ

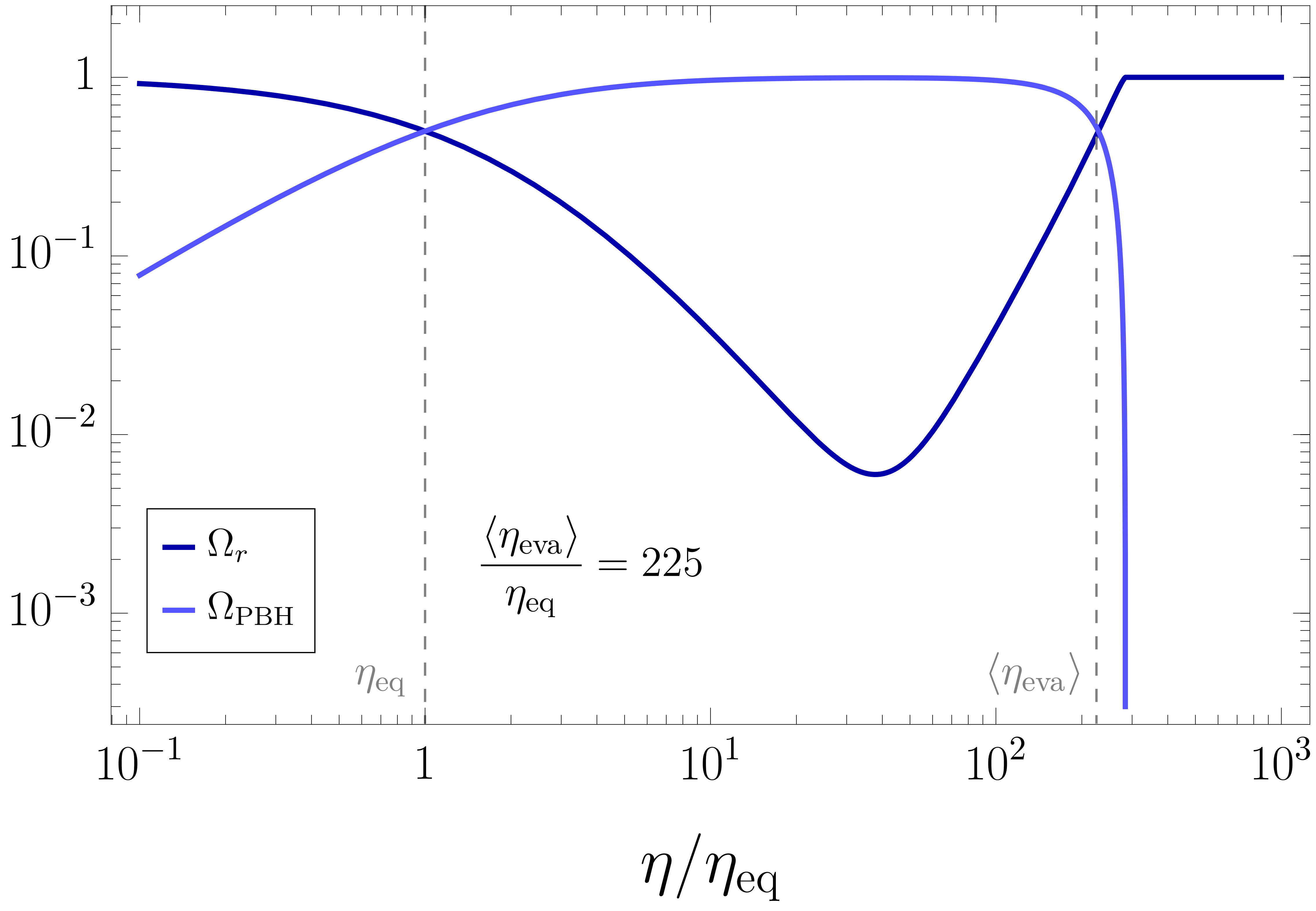


$$\mathscr{P}_\Phi \propto \langle \Phi_k \Phi_{k'} \rangle$$



Two point correlators can be predicted from inflation + Poisson statistics of PBH gas

SOLVING PERTURBATIONS



$$\boxed{\mathscr{P}_h \propto \Phi^4_{\rm osc}}$$

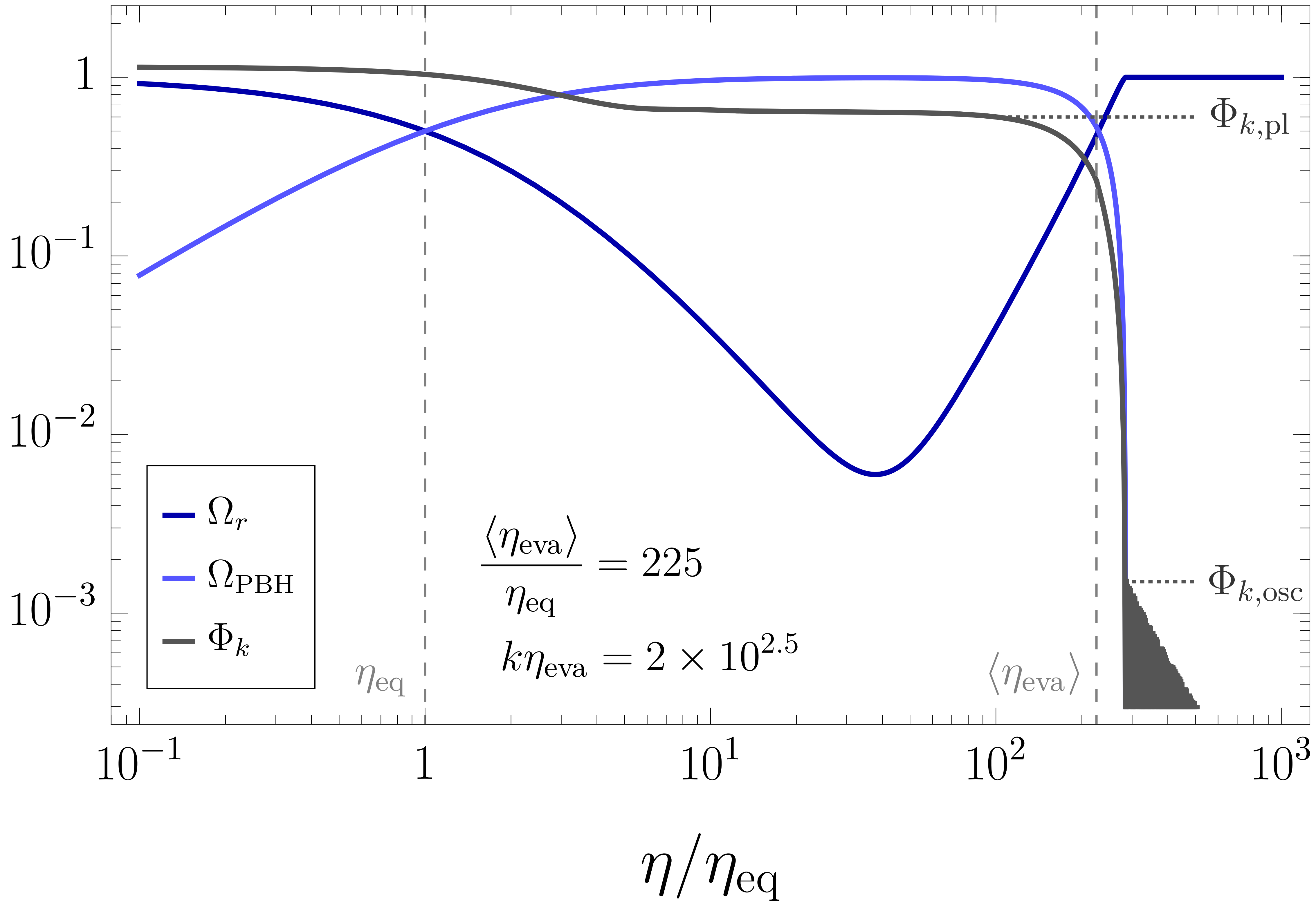
Combine:

1. **Transfer function** $\mathscr{T}(k)$:
   RD-to-MD transition

2. **Suppression factor** $\mathscr{S}(k)$
   MD-to-RD transition

Effects decouple

SOLVING PERTURBATIONS



$$\boxed{\mathscr{P}_h \propto \Phi_{\rm osc}^4}$$

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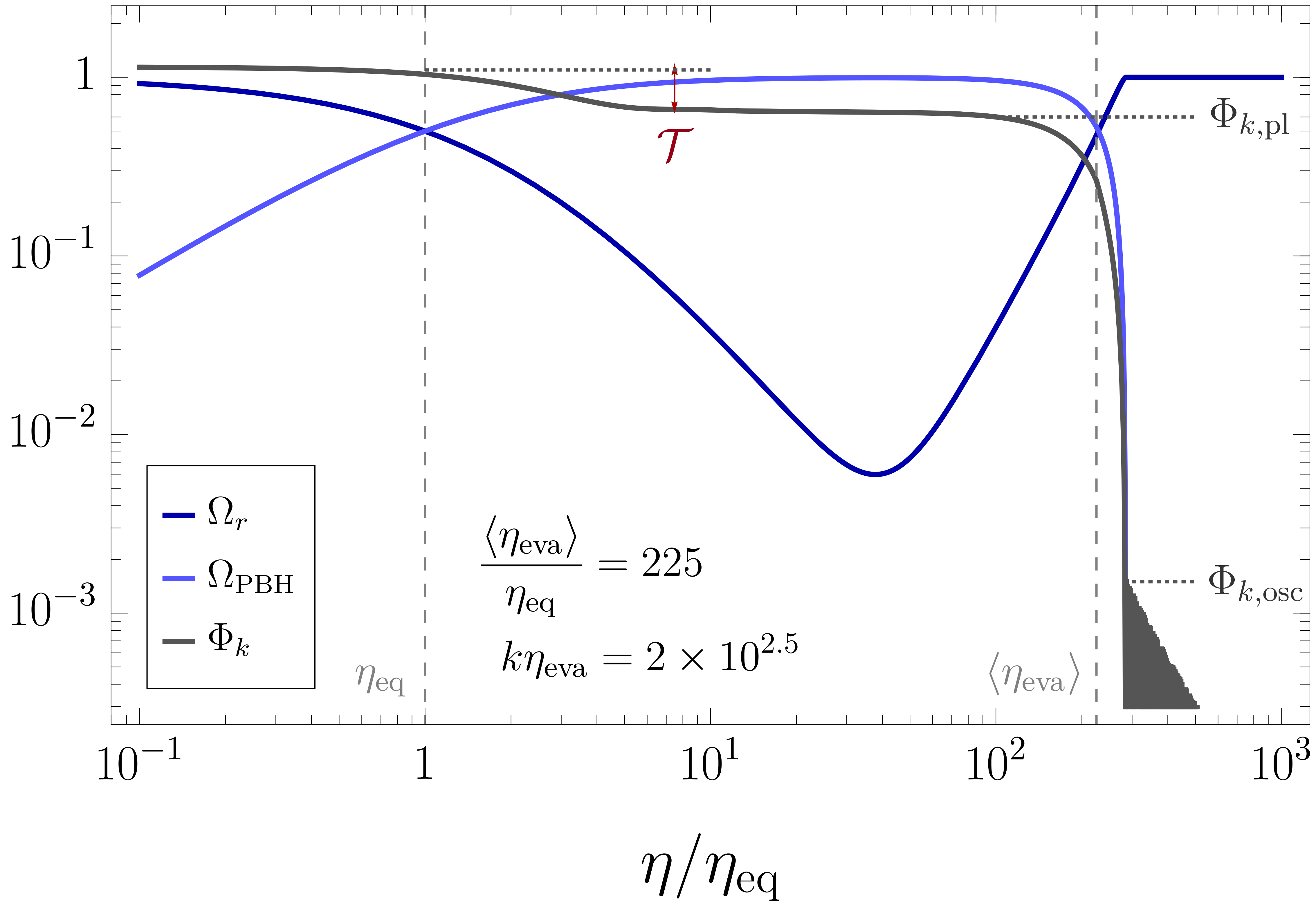
SOLVING PERTURBATIONS



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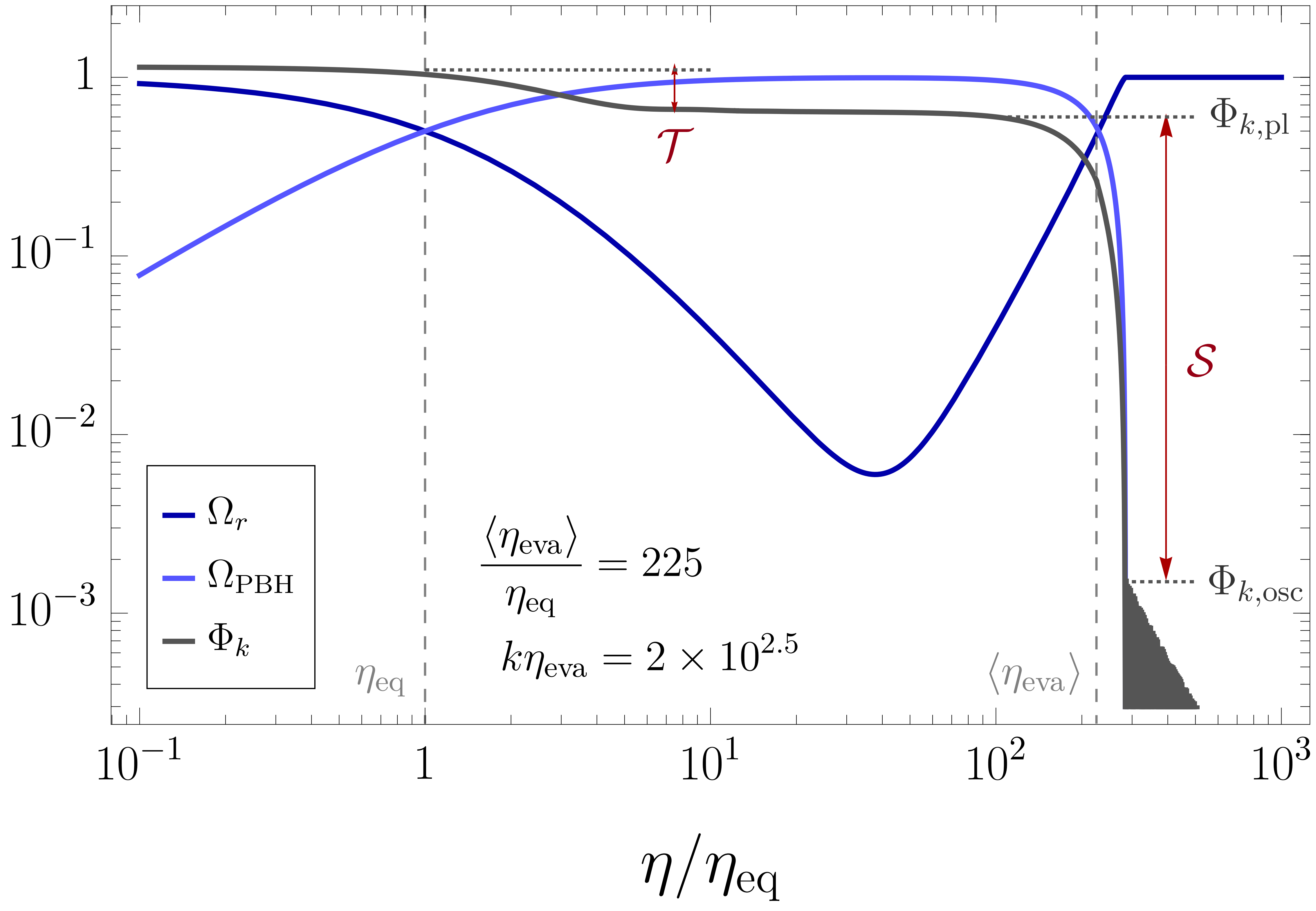

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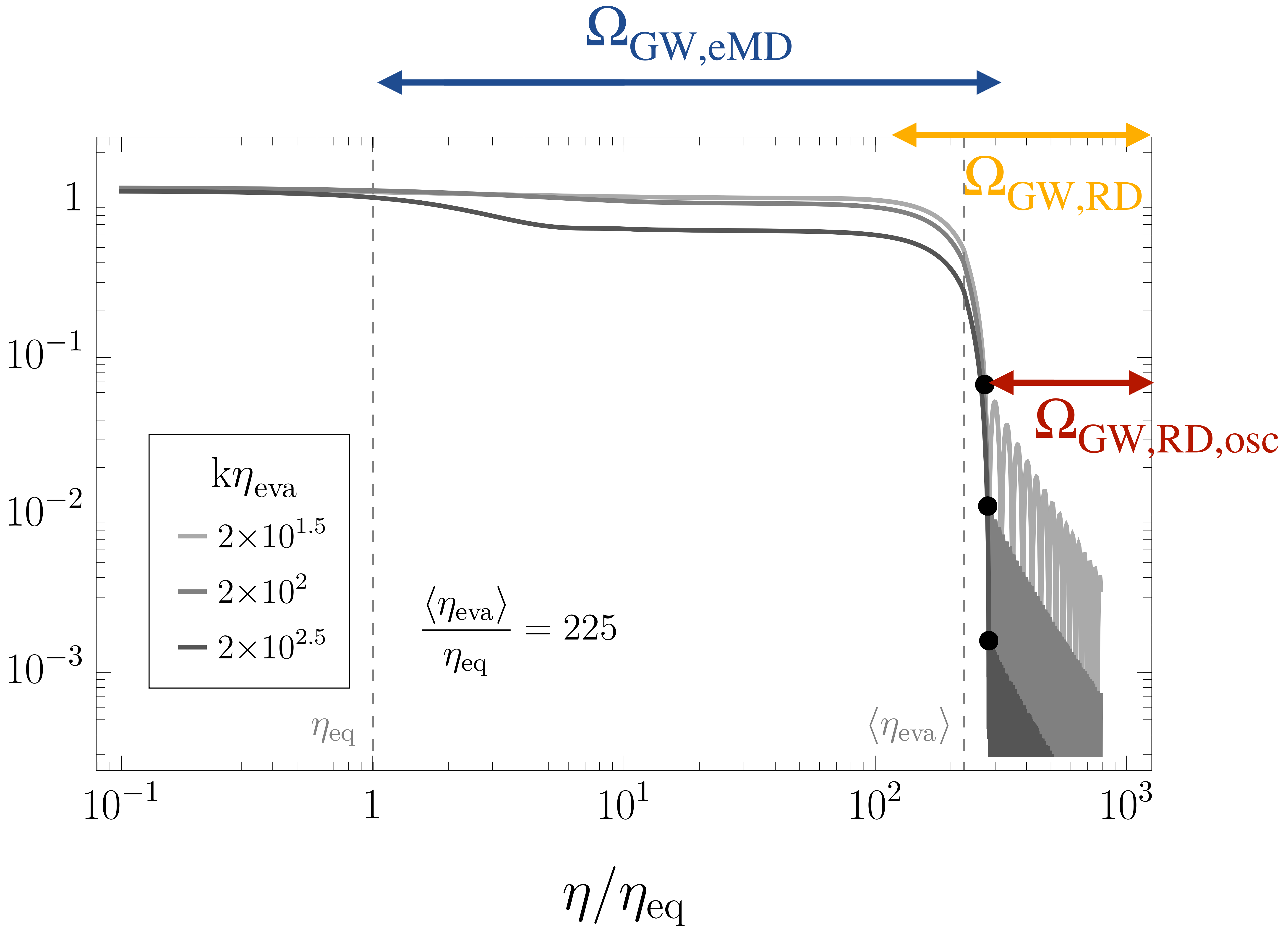
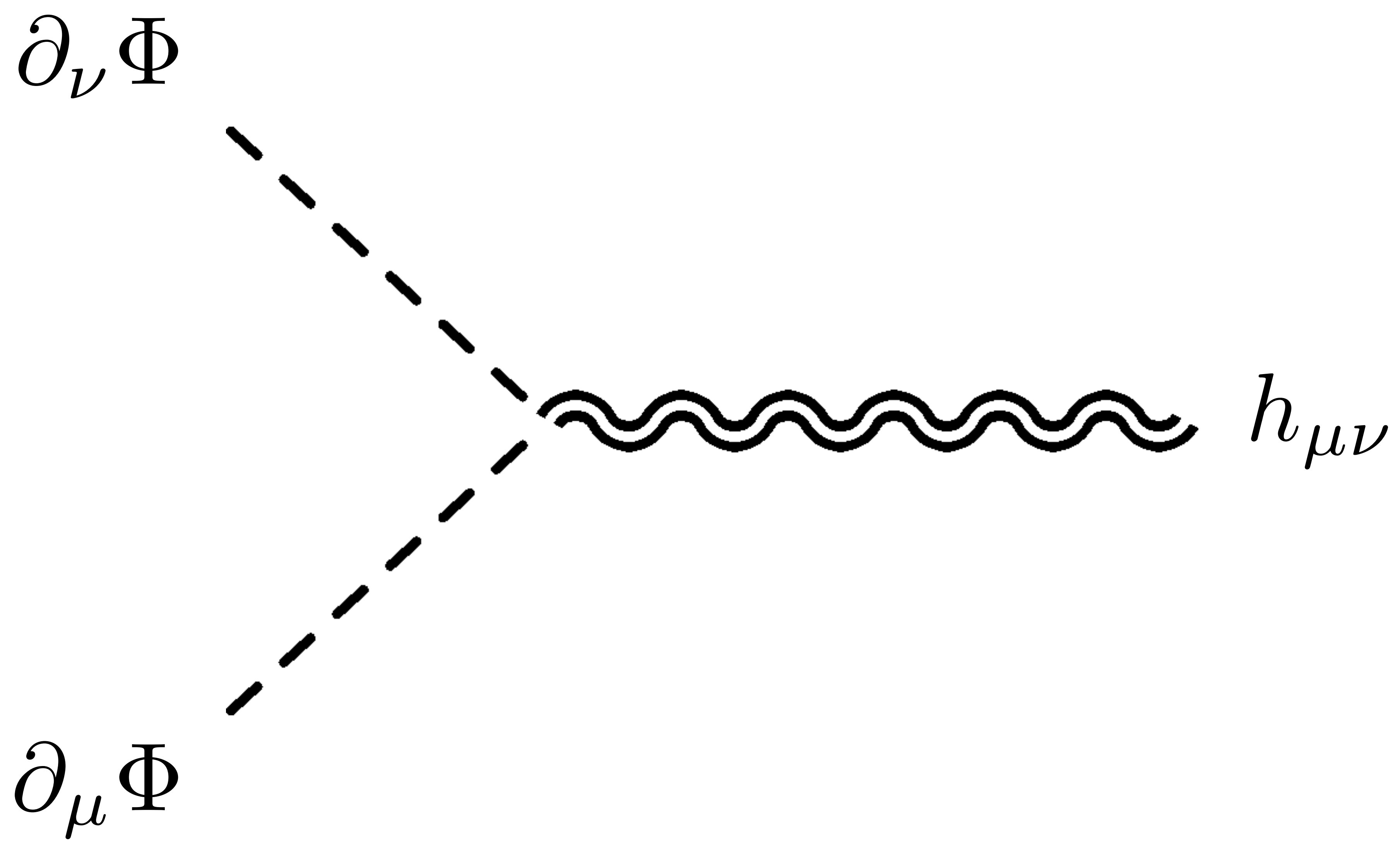
SIGW



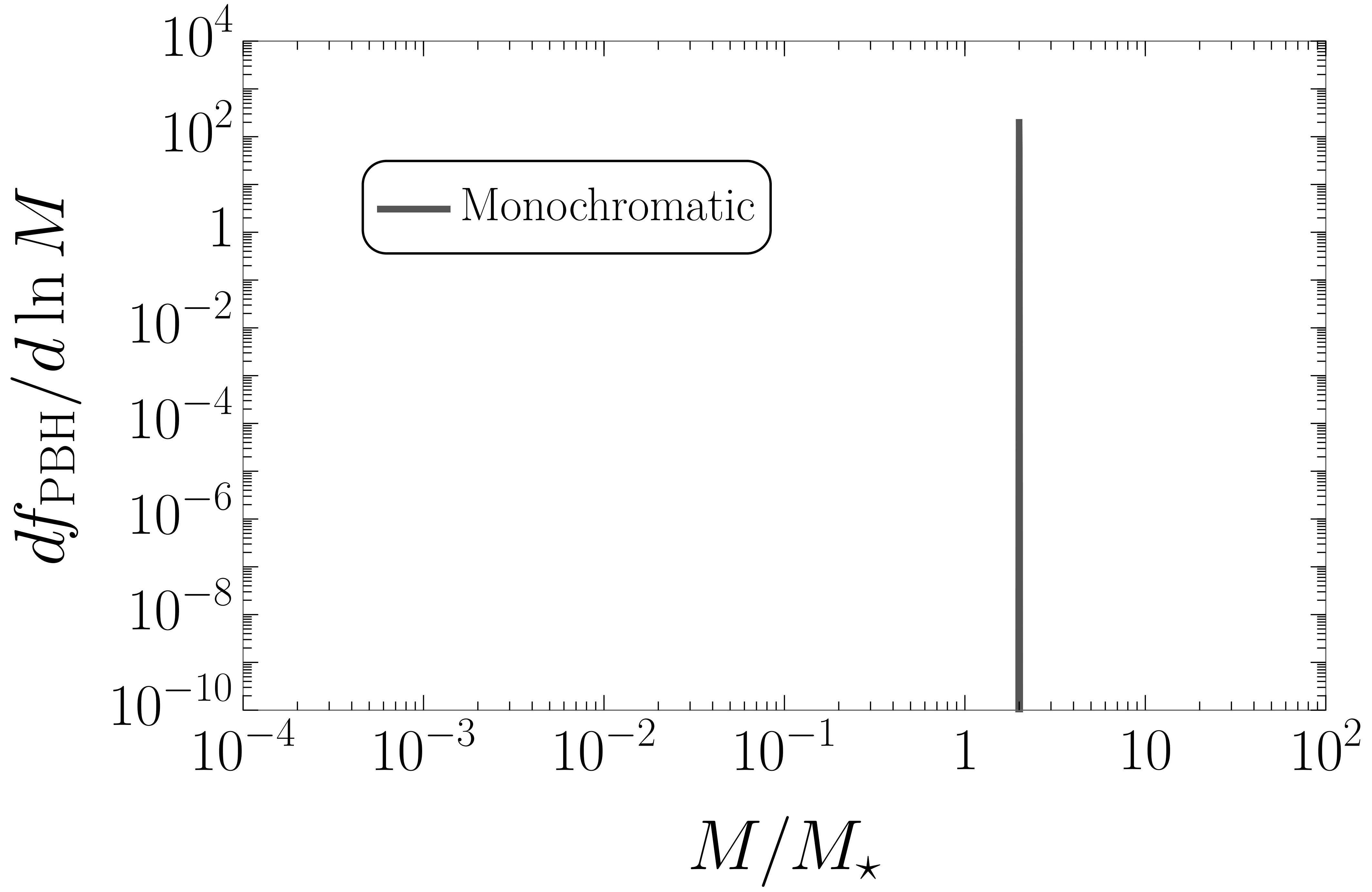
$$\mathscr{P}_h \subset \Phi^4, \ \left(\frac{\Phi'}{\mathscr{H}}\right)^4$$

SIGW

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



SUPERHORIZON COLLAPSE

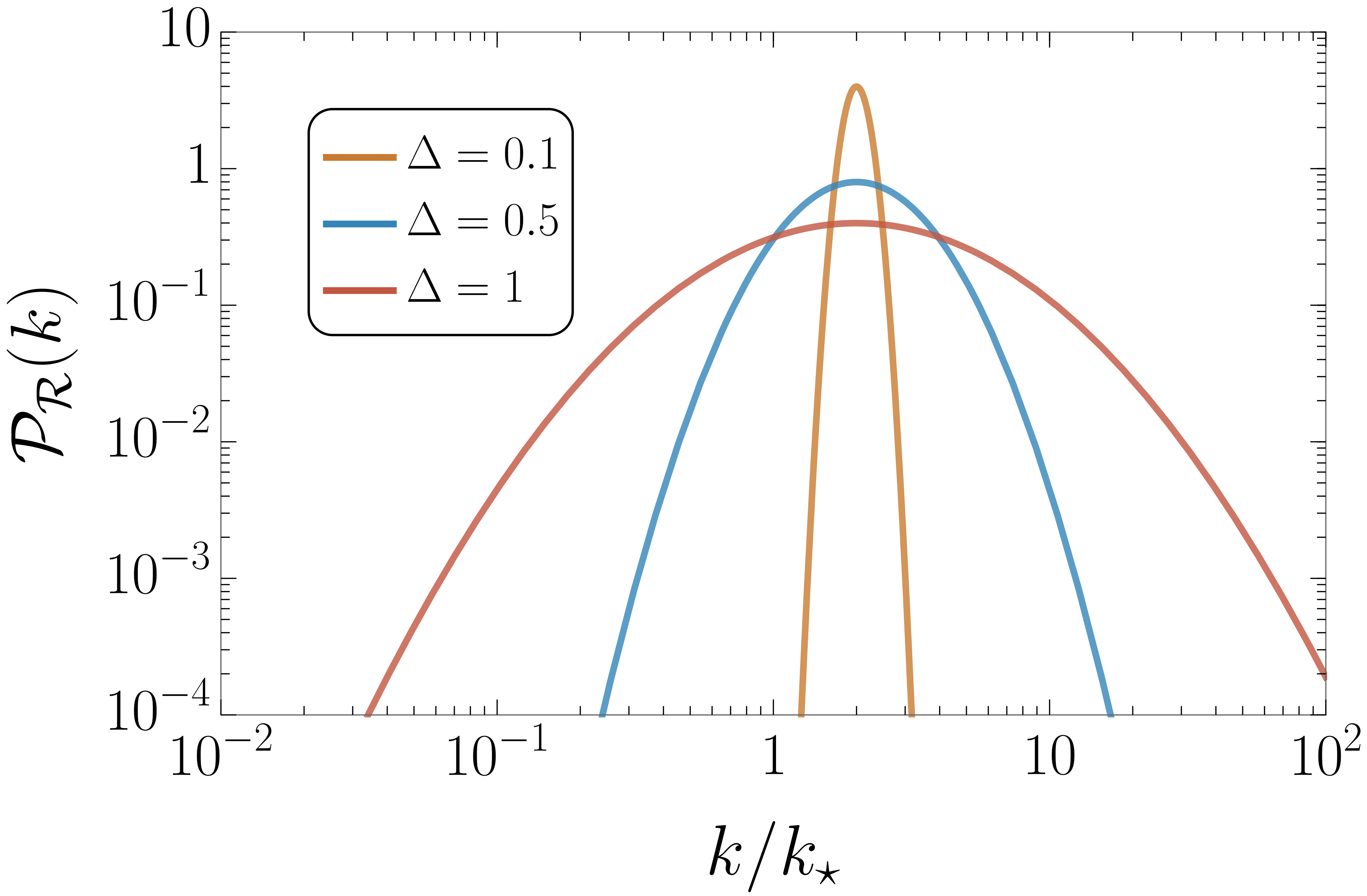


So far:

1. Assumes monochromatic[1,2,3] or (narrow) log-normal[1] mass distribution
2. Fast reheating

[1]*Poltergeist* mechanism: Inomata et al. (2020)
[2]Domenech et. al (2021)
[3]Domènech and Tränkle (2025)

SUPERHORIZON COLLAPSE



- Superhorizon gravitational collapse:

  1. **Critical scaling**[1]

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

  2. **Press-Schechter** formalism[2]

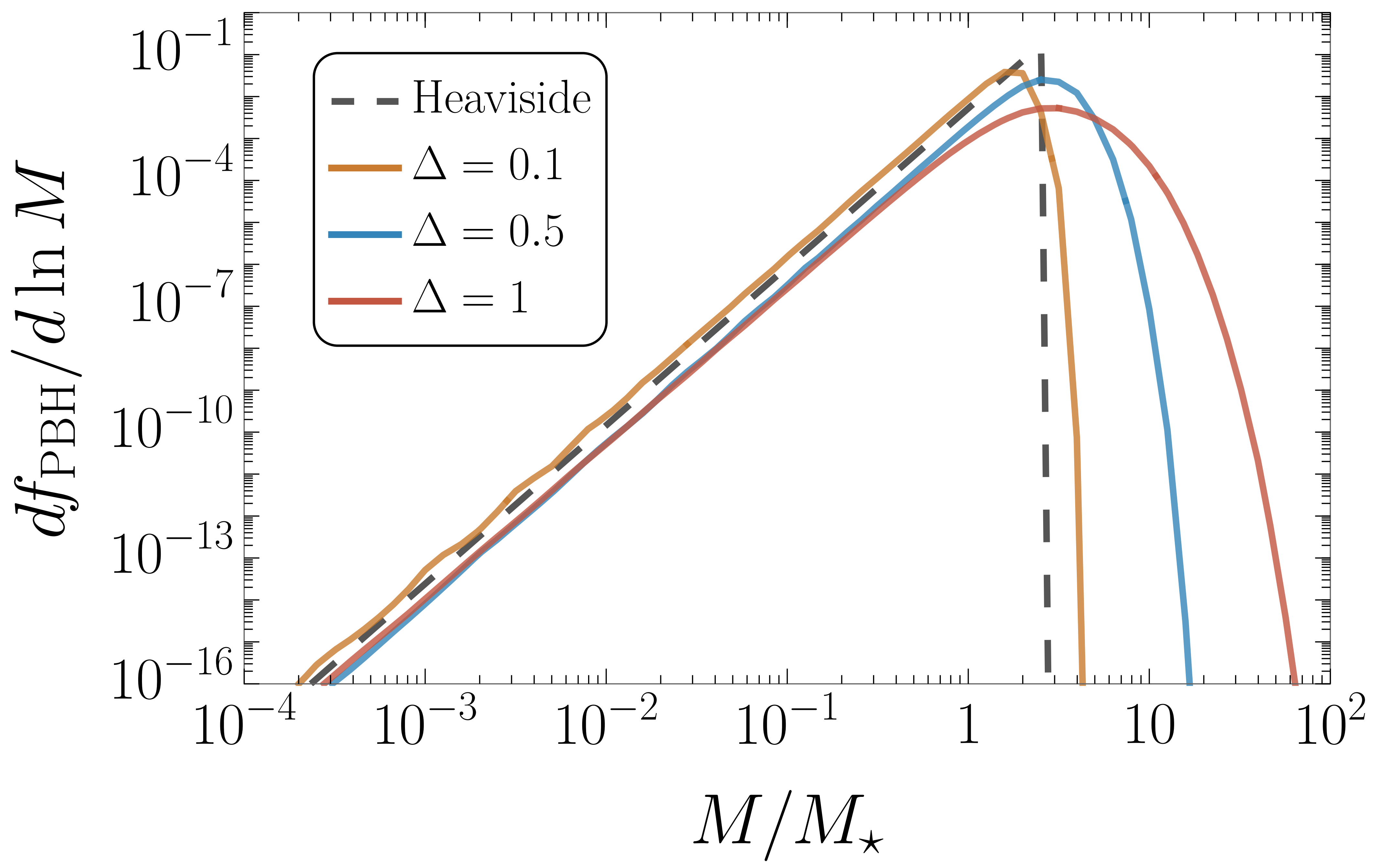
  $$\frac{\mathrm{d}f_{\mathrm{PBH}}}{\mathrm{d}\log M} \propto M^{1+1/\gamma} e^{-c_1(M/\langle M\rangle)^{c_2}}$$

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

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

[1]Choptuik (1993)
[2] Press and Schechter (1974)

SUPERHORIZON COLLAPSE



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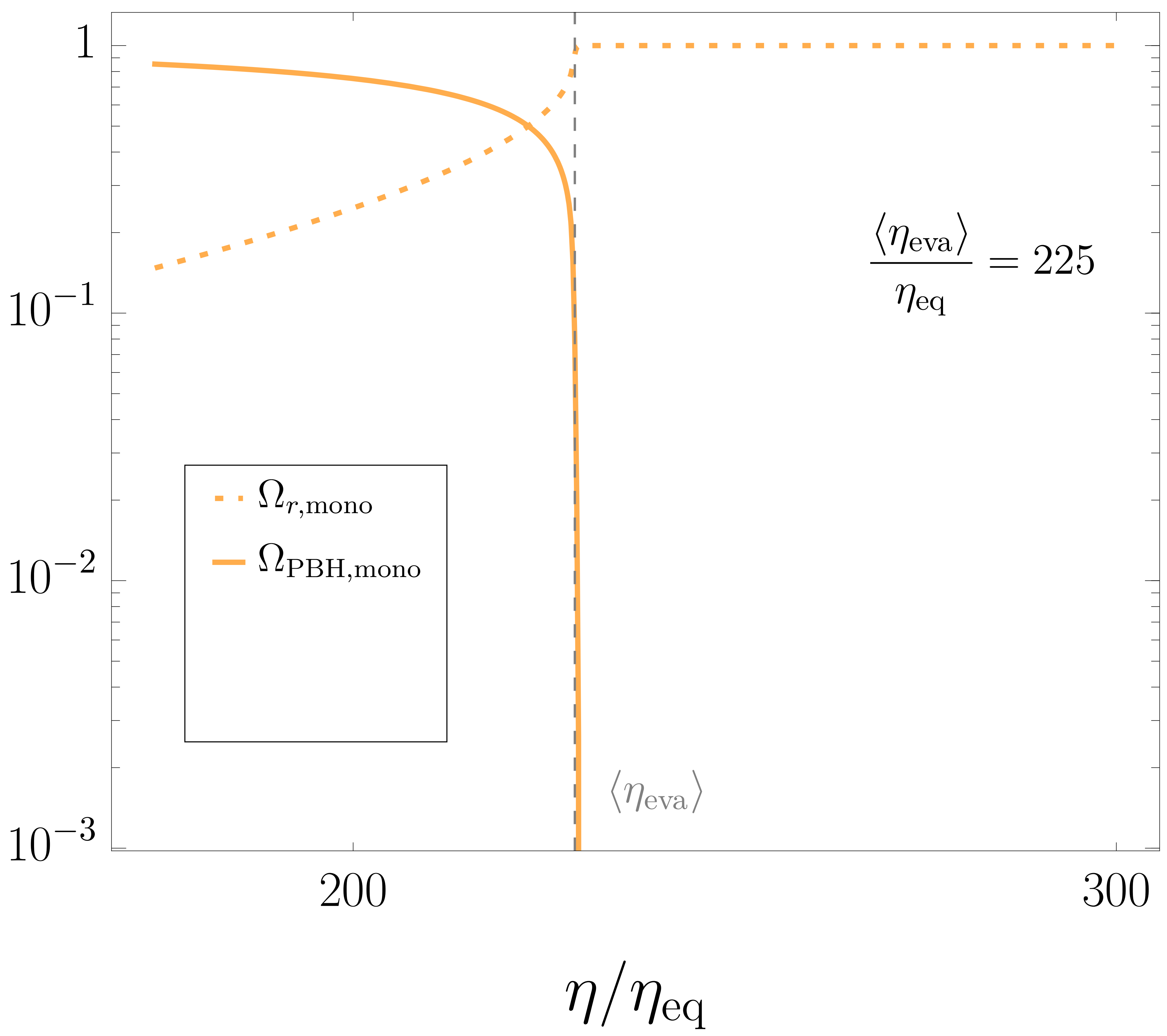

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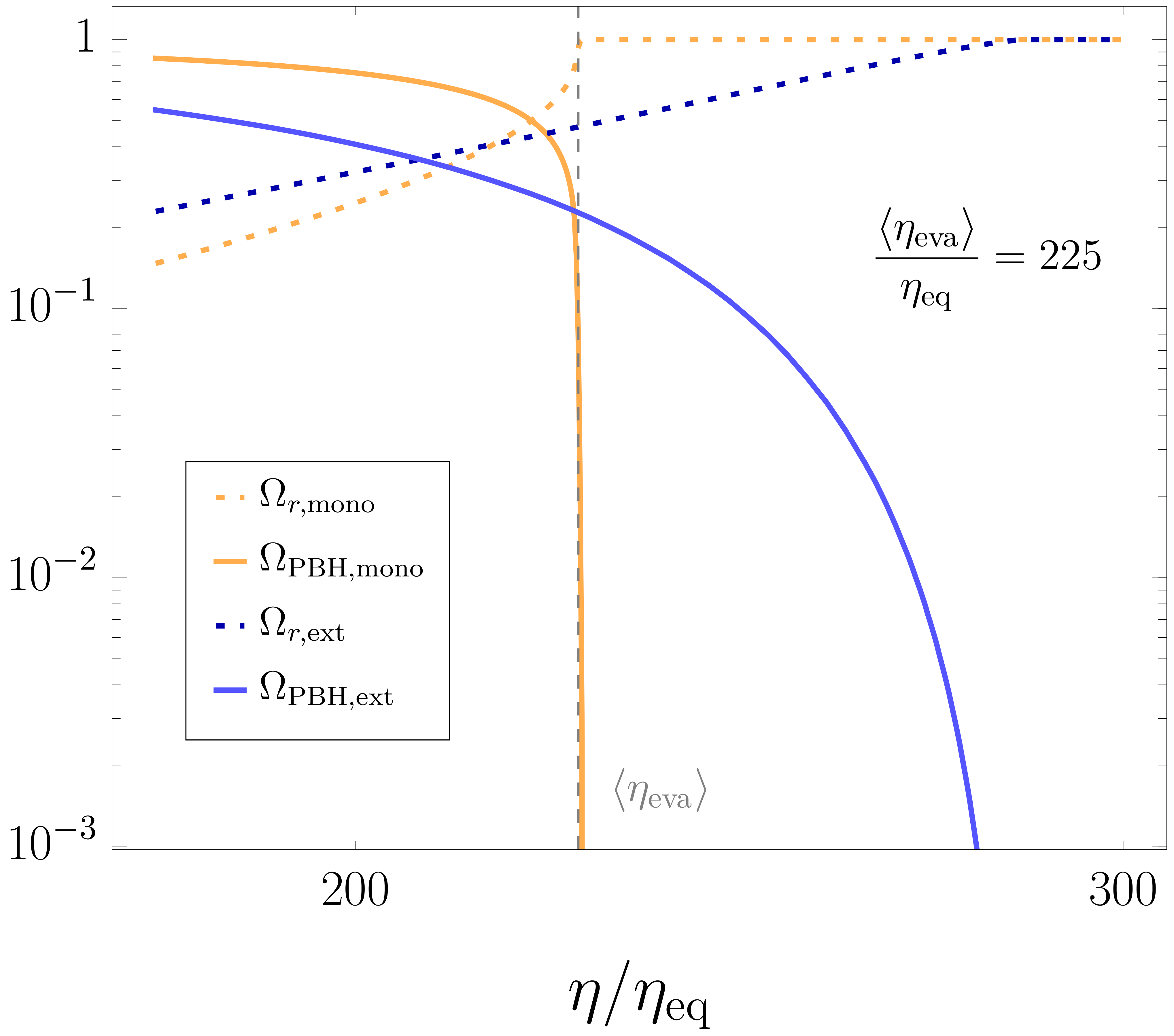

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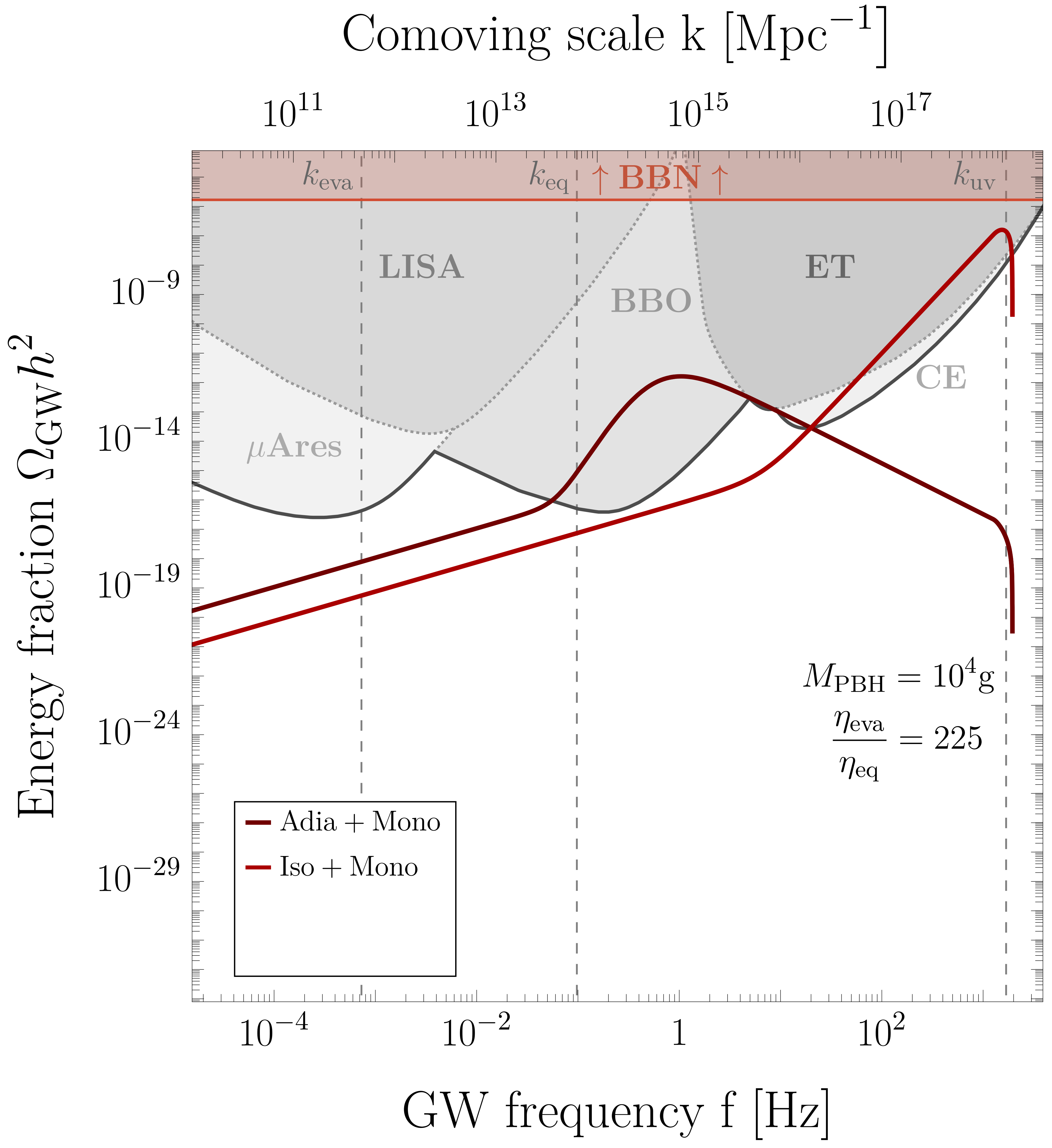
SIGW



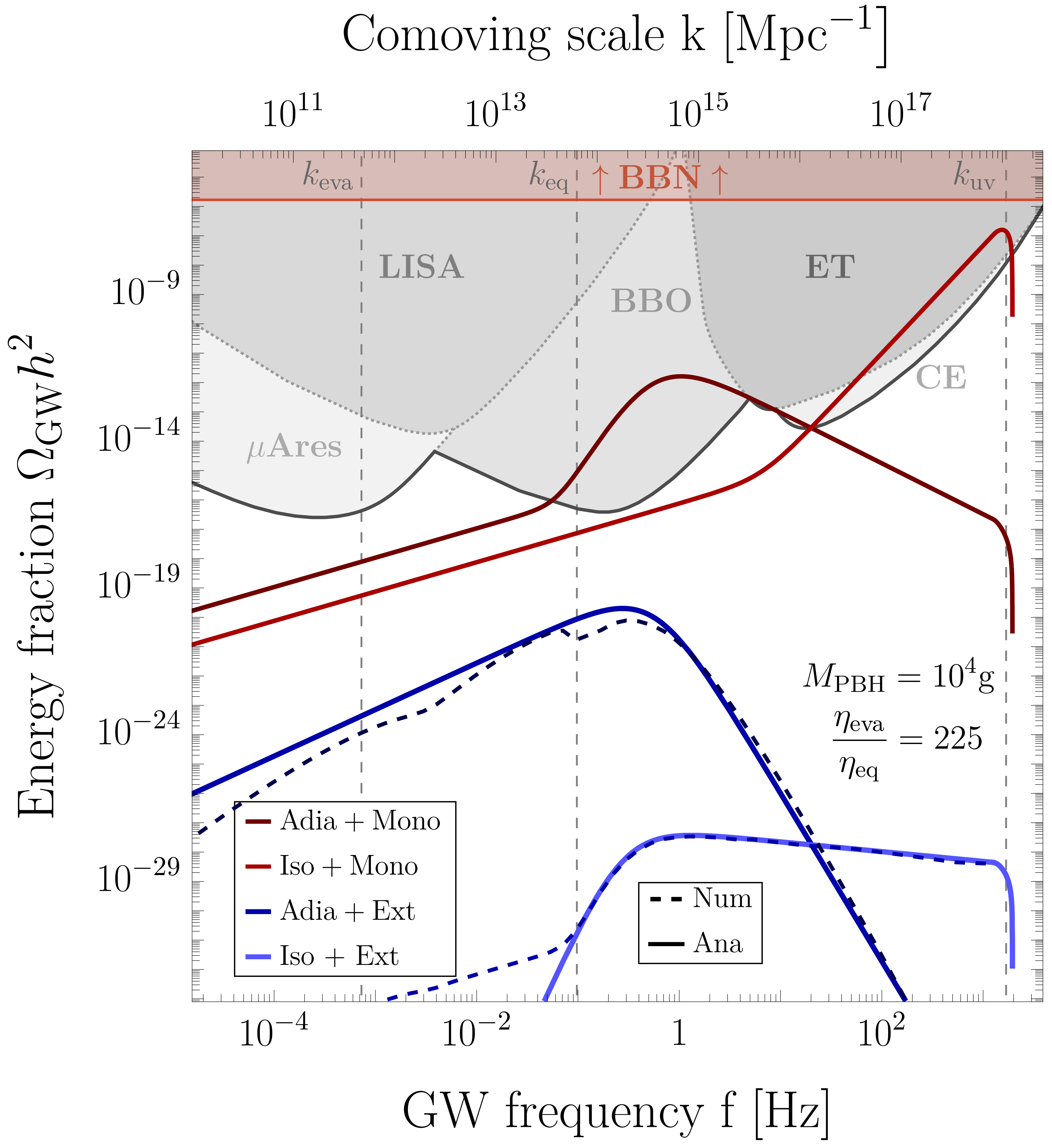
$$\Omega_{\rm GW}(k) = \frac{k^2}{12\mathscr{H}^2}\overline{\mathscr{P}_{h,\rm RD}}$$

$$\boxed{\begin{aligned}\overline{\mathscr{P}_{h,\rm RD}}(k,\eta,\bar{x}\gg 1) \sim \int_0^\infty \mathrm{d}v \int_{|1-v|}^{1+v} \mathrm{d}u\ (4v^2-(1+v^2-u^2)^2)^2\overline{\mathscr{I}^2_{\rm osc}}(\bar{x},u,v) \\ \times \mathscr{P}(uk)\mathscr{P}(vk)\mathscr{S}^2(uk)\mathscr{S}^2(vk)\mathscr{T}^2(uk)\mathscr{T}^2(vk),\end{aligned}}$$

$$\mathscr{P}_{\rm Adia}(k) = As\left(\frac{k}{k_*}\right)^{n_s-1}\Theta(k_{\rm UV}-k)\Theta(k_{k-\rm IR})$$

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

SIGW



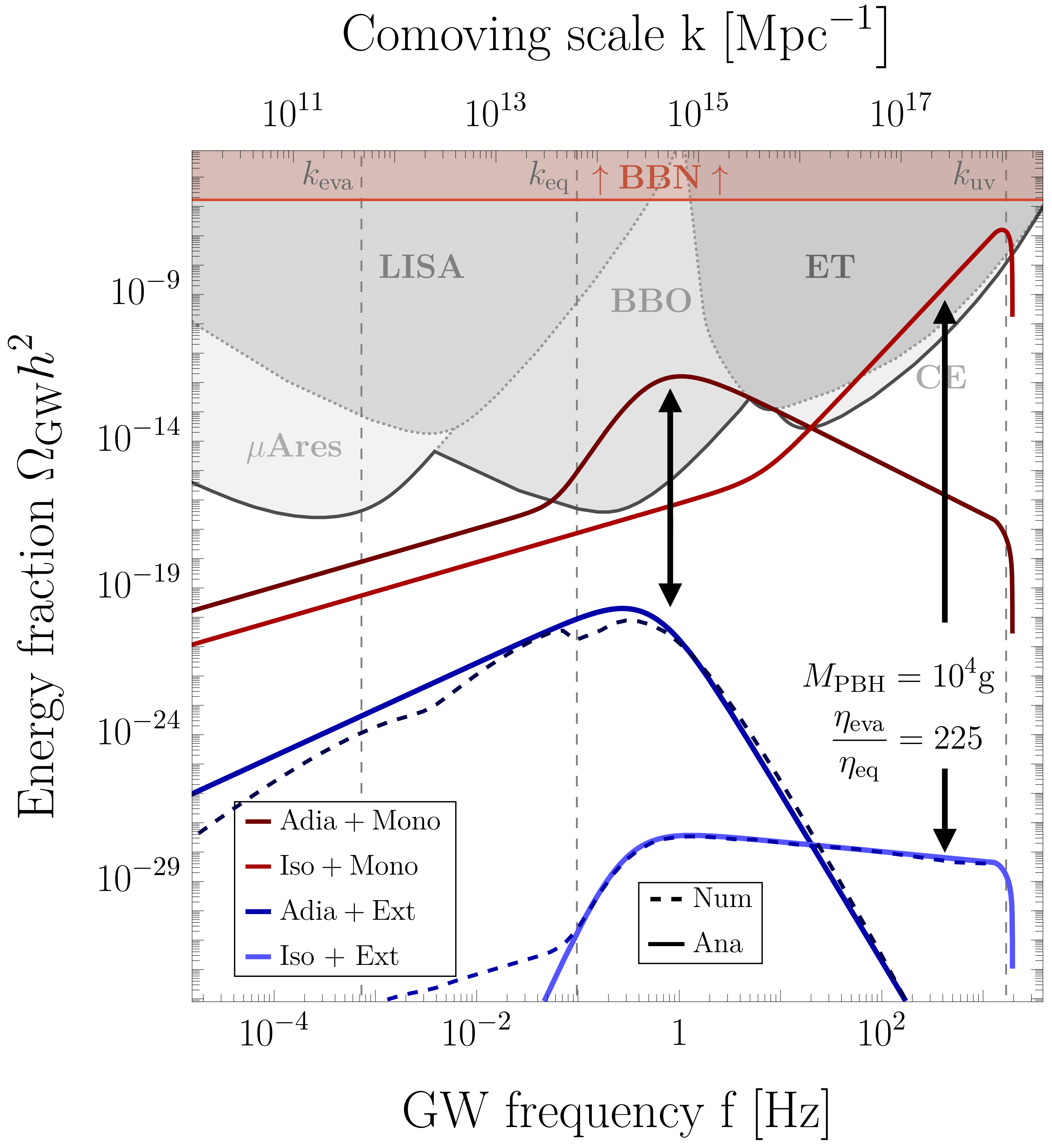
$$\Omega_{\rm GW}(k) = \frac{k^2}{12\mathcal{H}^2}\overline{\mathcal{P}_{h,\rm RD}}$$

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

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

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

SIGW



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

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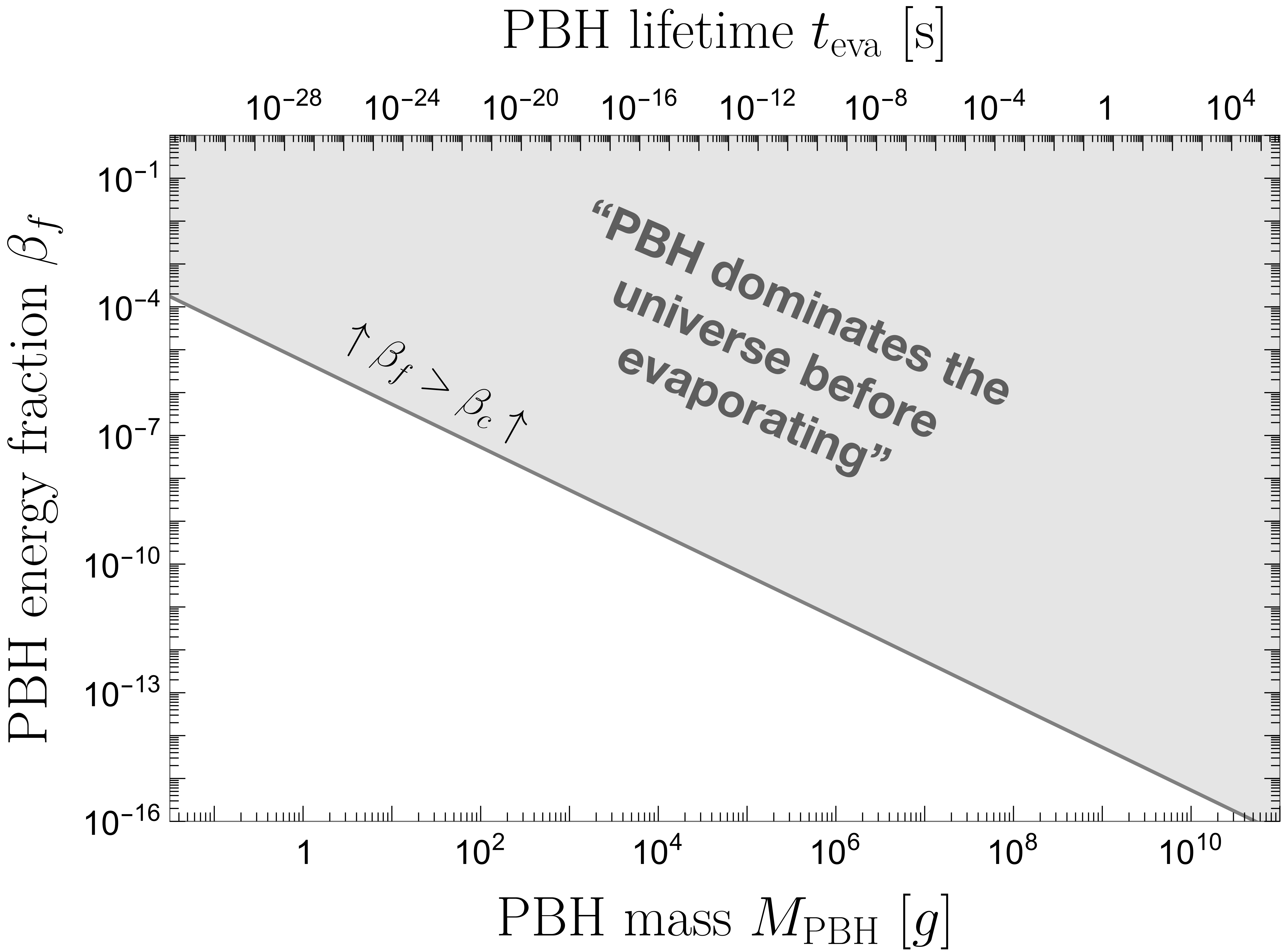
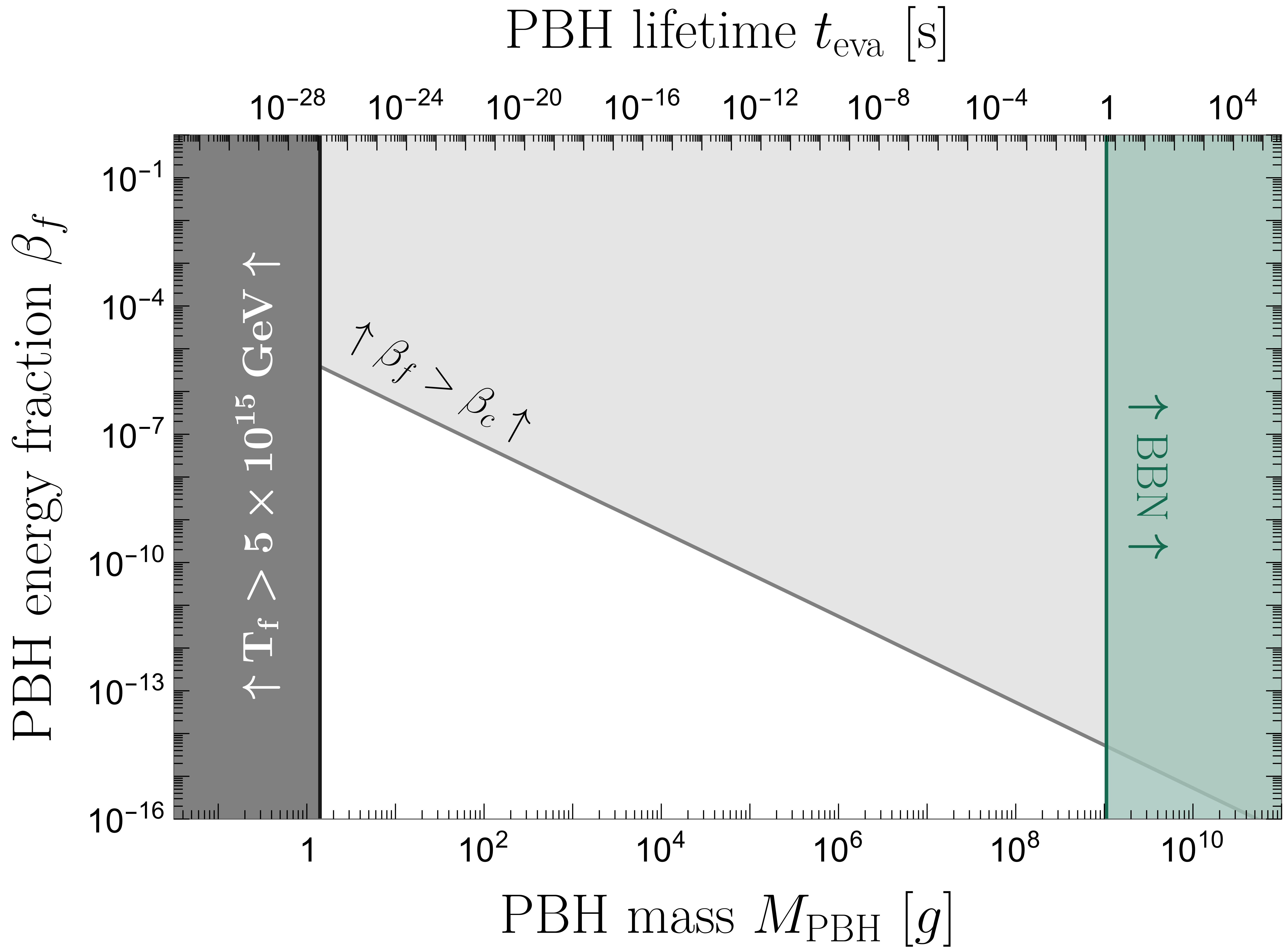
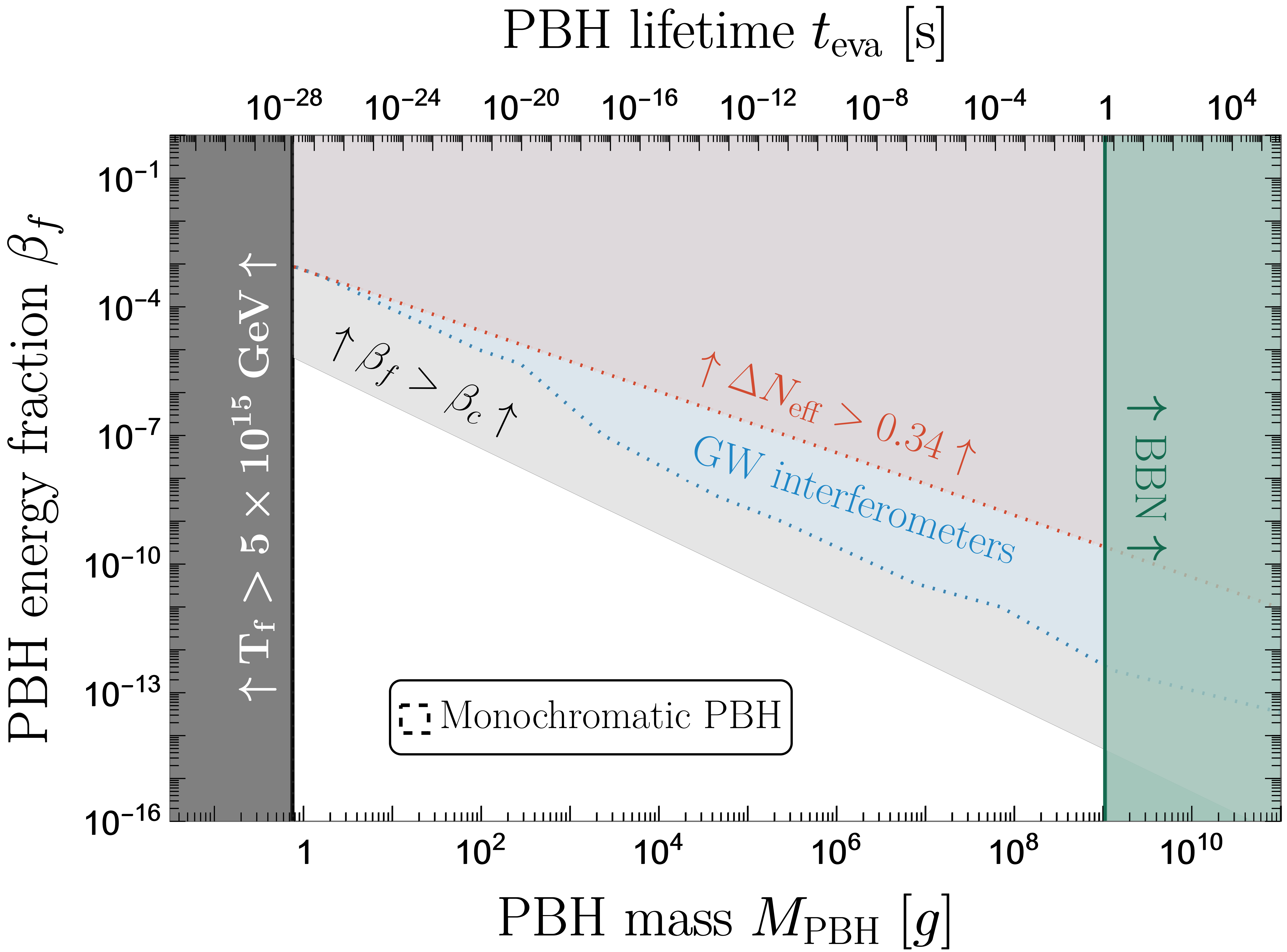
IMPLICATIONS FOR PBH



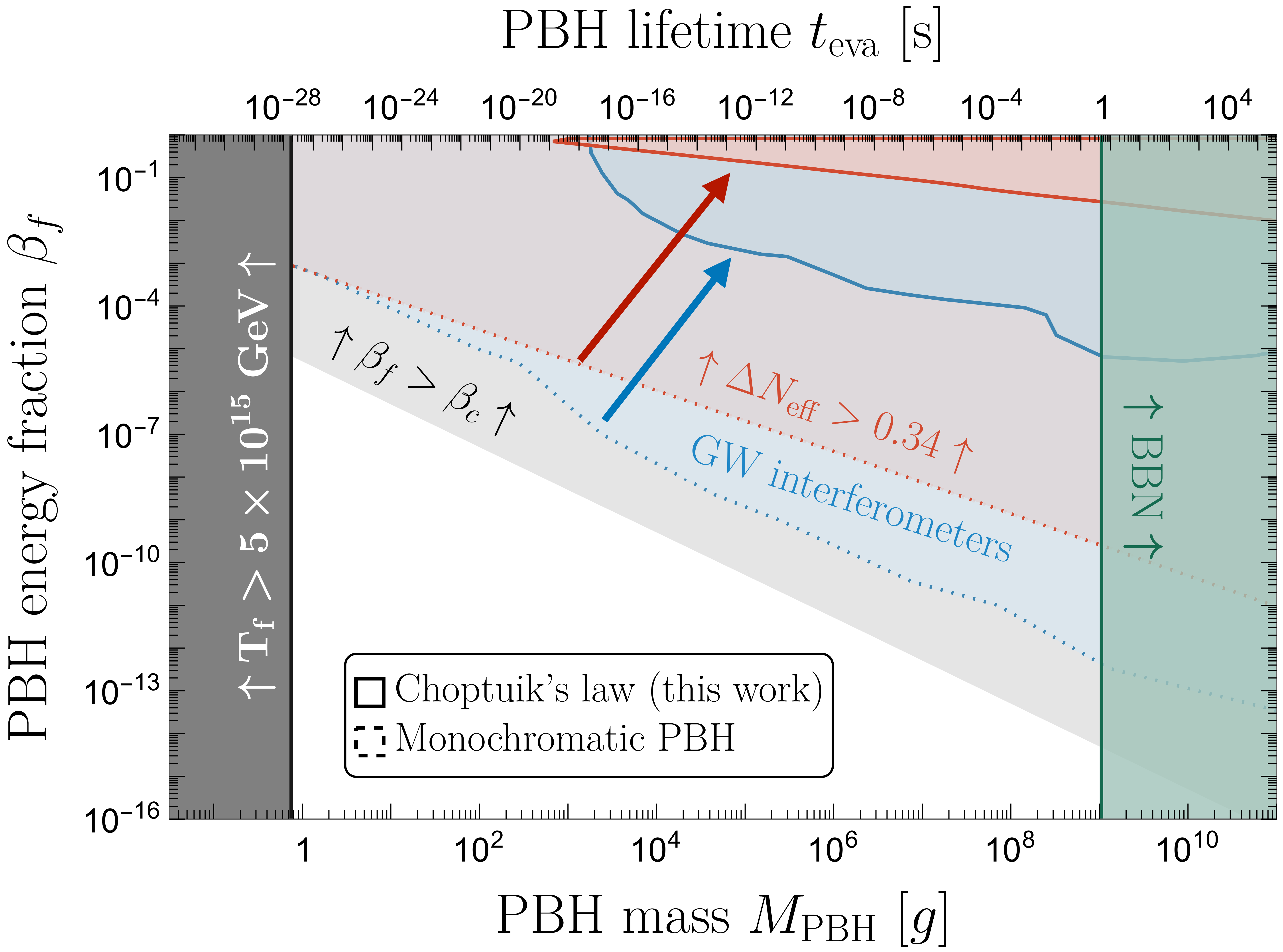
IMPLICATIONS FOR PBH



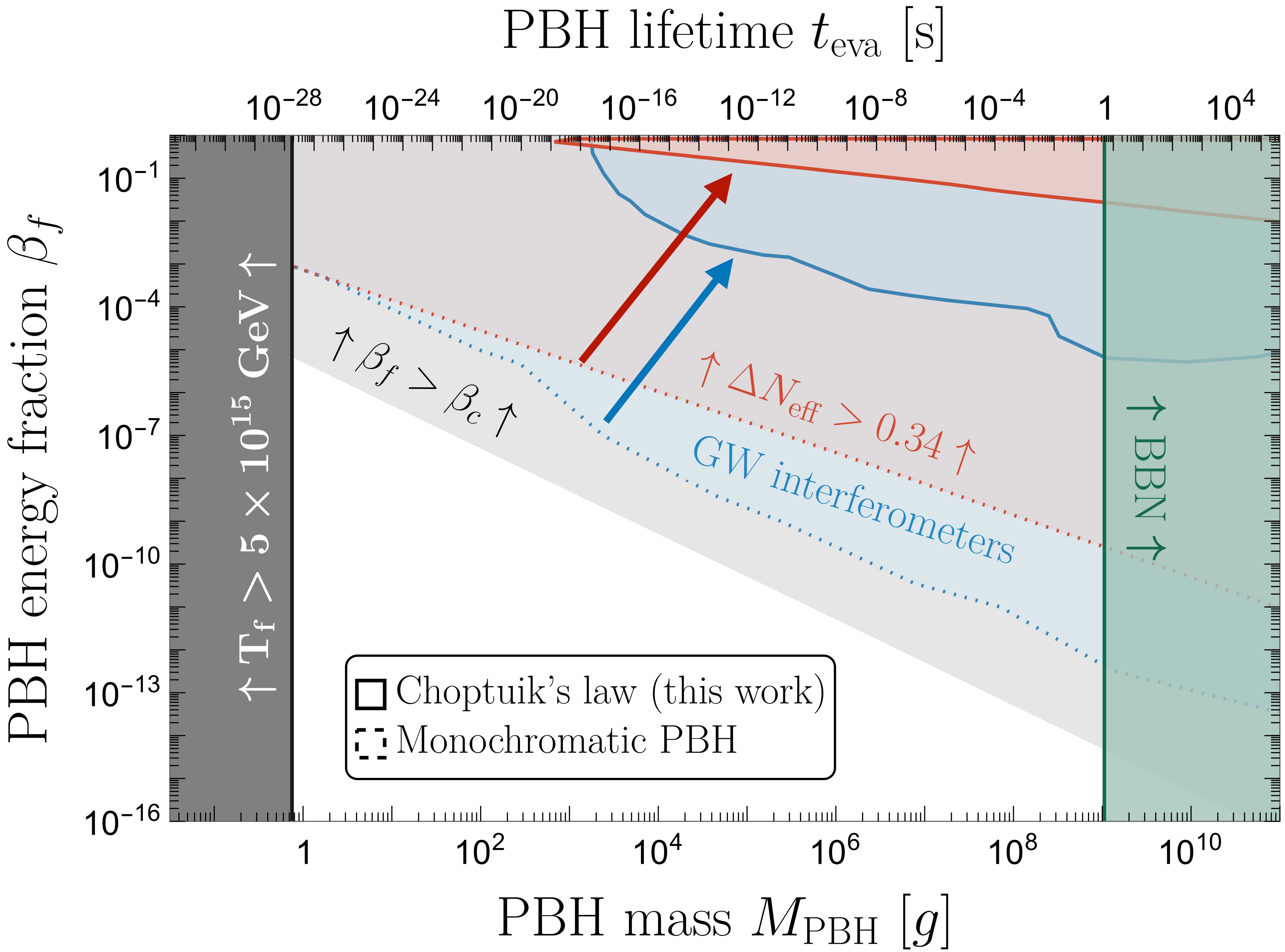
IMPLICATIONS FOR PBH



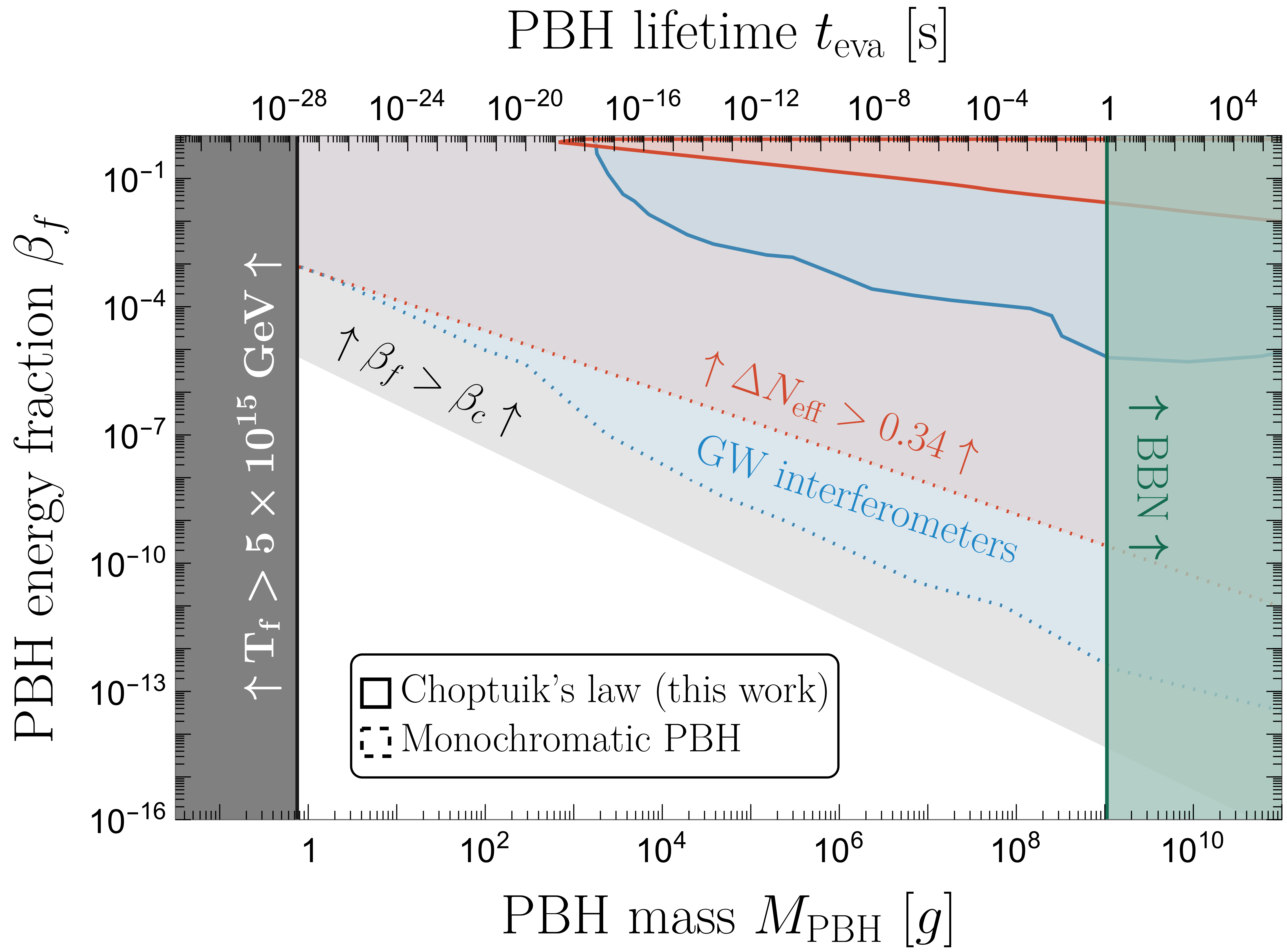
IMPLICATIONS FOR PBH



IMPLICATIONS FOR PBH



IMPLICATIONS FOR PBH



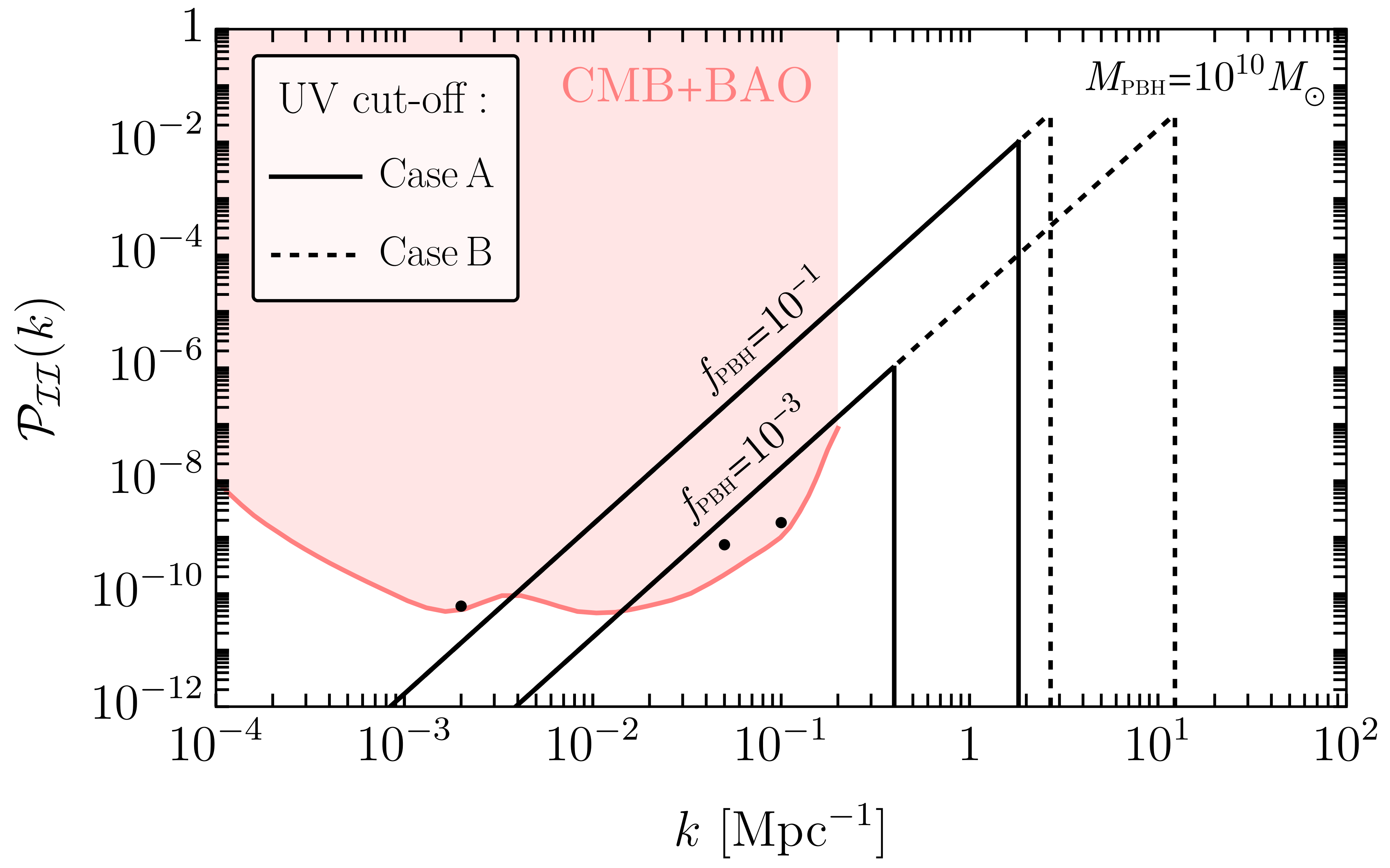
Other Sources

1. PBH binaries
2. Graviton Emission during evaporation
3. PBH Formation (curvature power enhancement)

PART II:

STUPENDIOUSLY LARGE PBHs (SLABs)

ISOCURVATURE



ISOCURVATURE:

$$\mathcal{I}_{\rm DM} = \delta_{\rm DM} - \frac{3}{4}\delta_{\rm r}$$

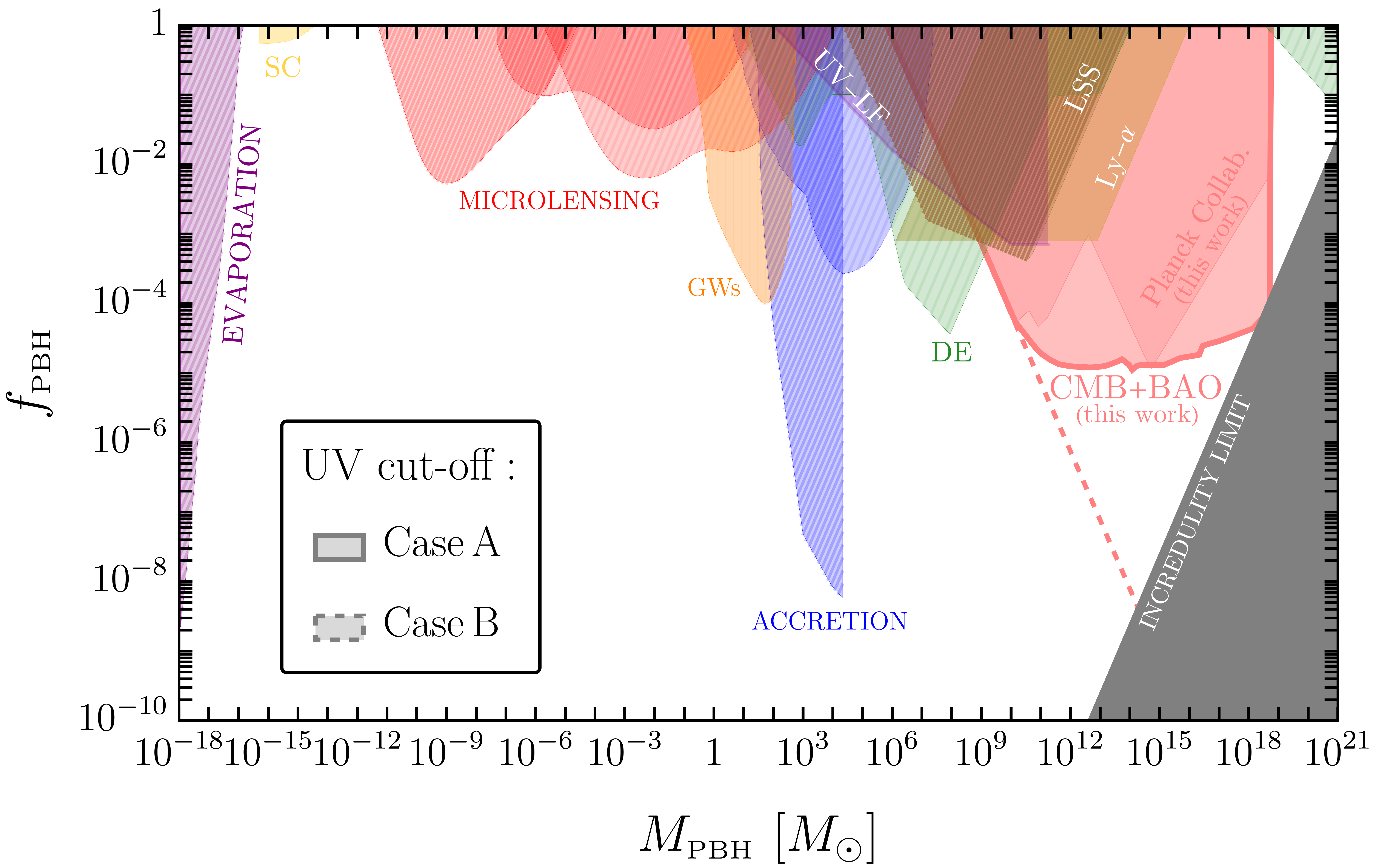
PBH gas follows Poisson statistics:

$$\langle \delta_k \delta_{k'} \rangle \simeq k^3 \delta^{(3)}(k - k')$$

Contribution to Isocurvature Power Spectrum (Planck):

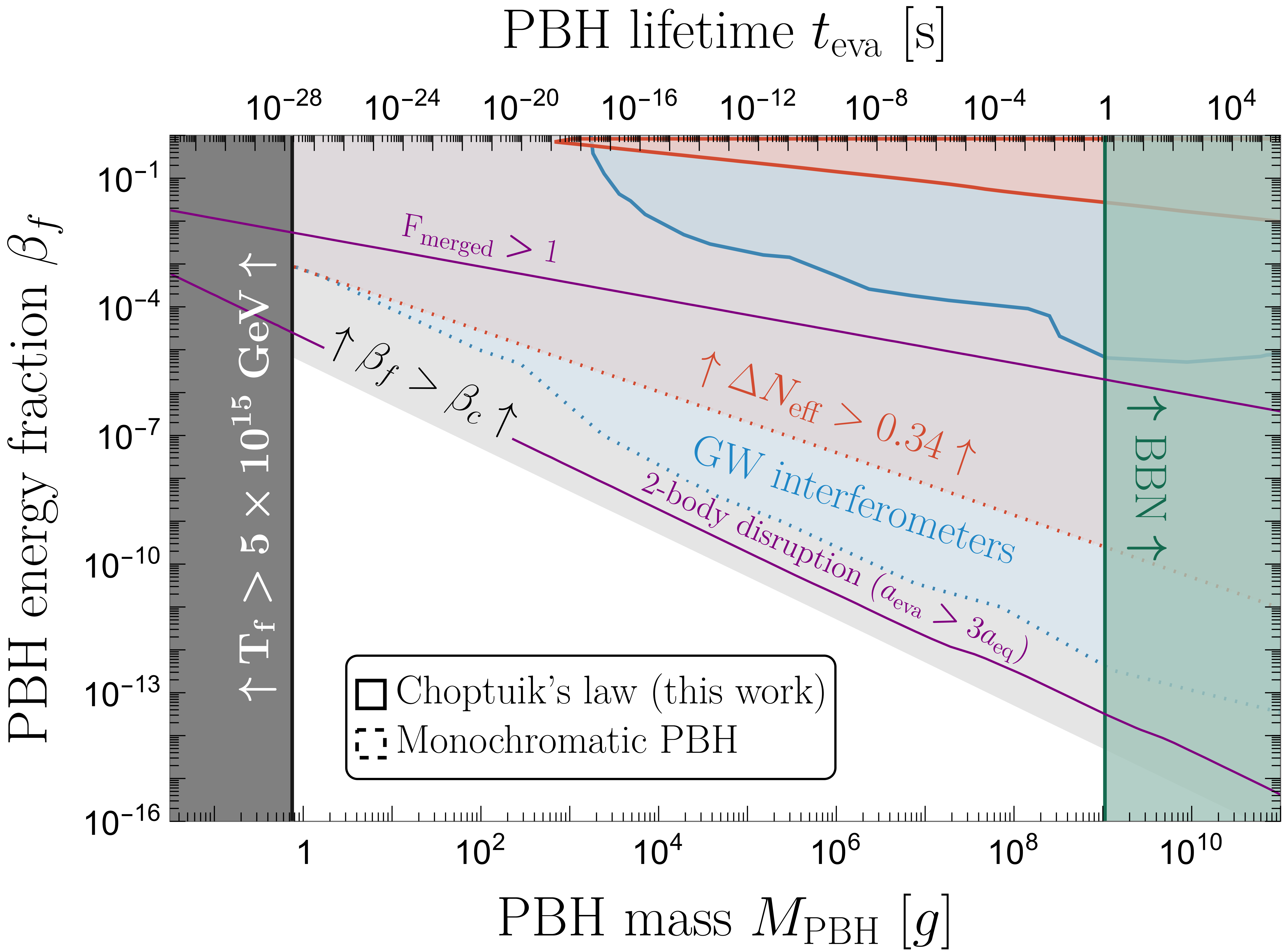
$$\mathcal{P}_{\mathcal{I}\mathcal{I}} \simeq f_{\rm PBH}^2 k^3$$

ISOCURVATURE



BACK-UP

BACK-UP



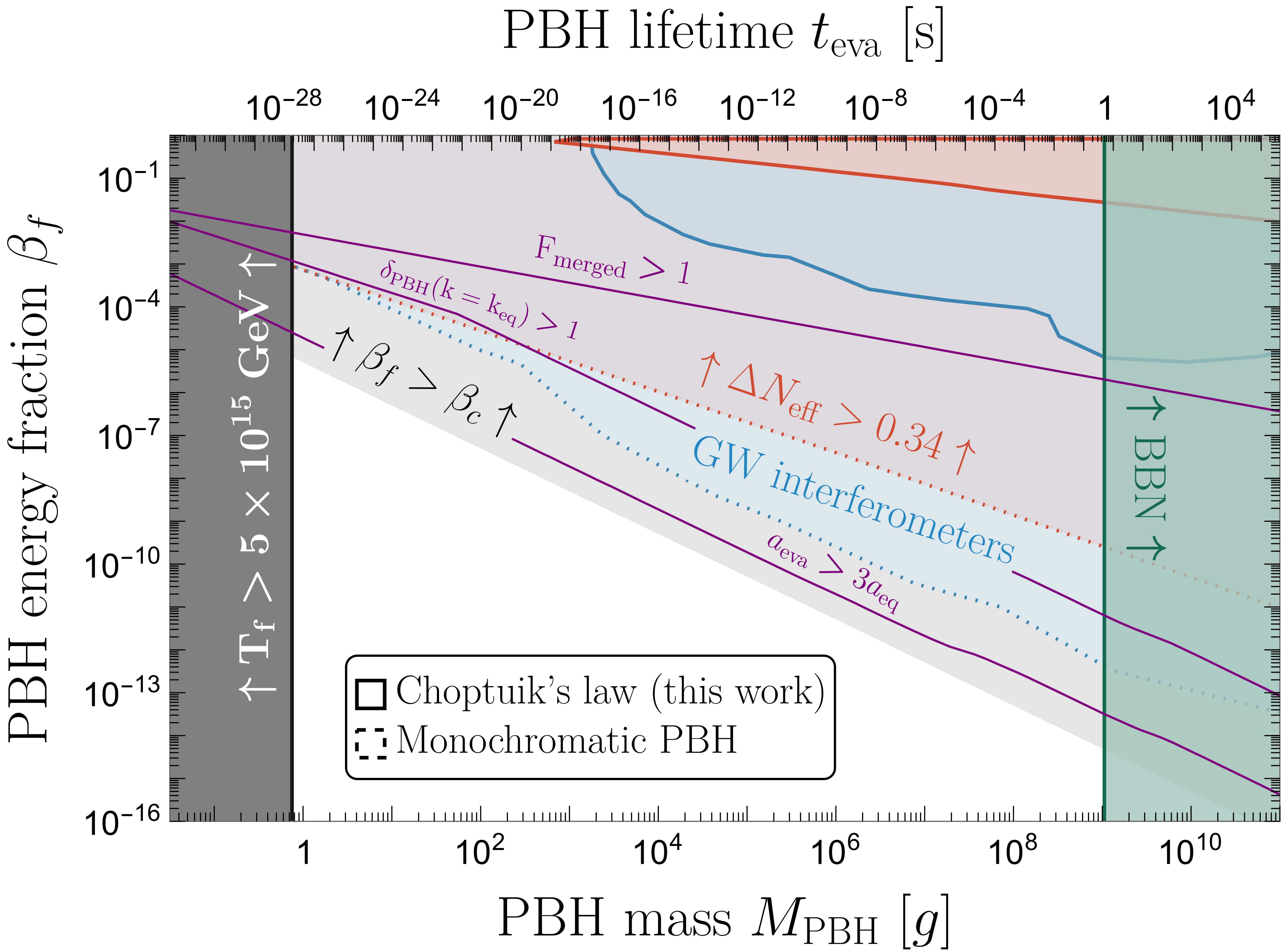
Binary formation threshold:

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:

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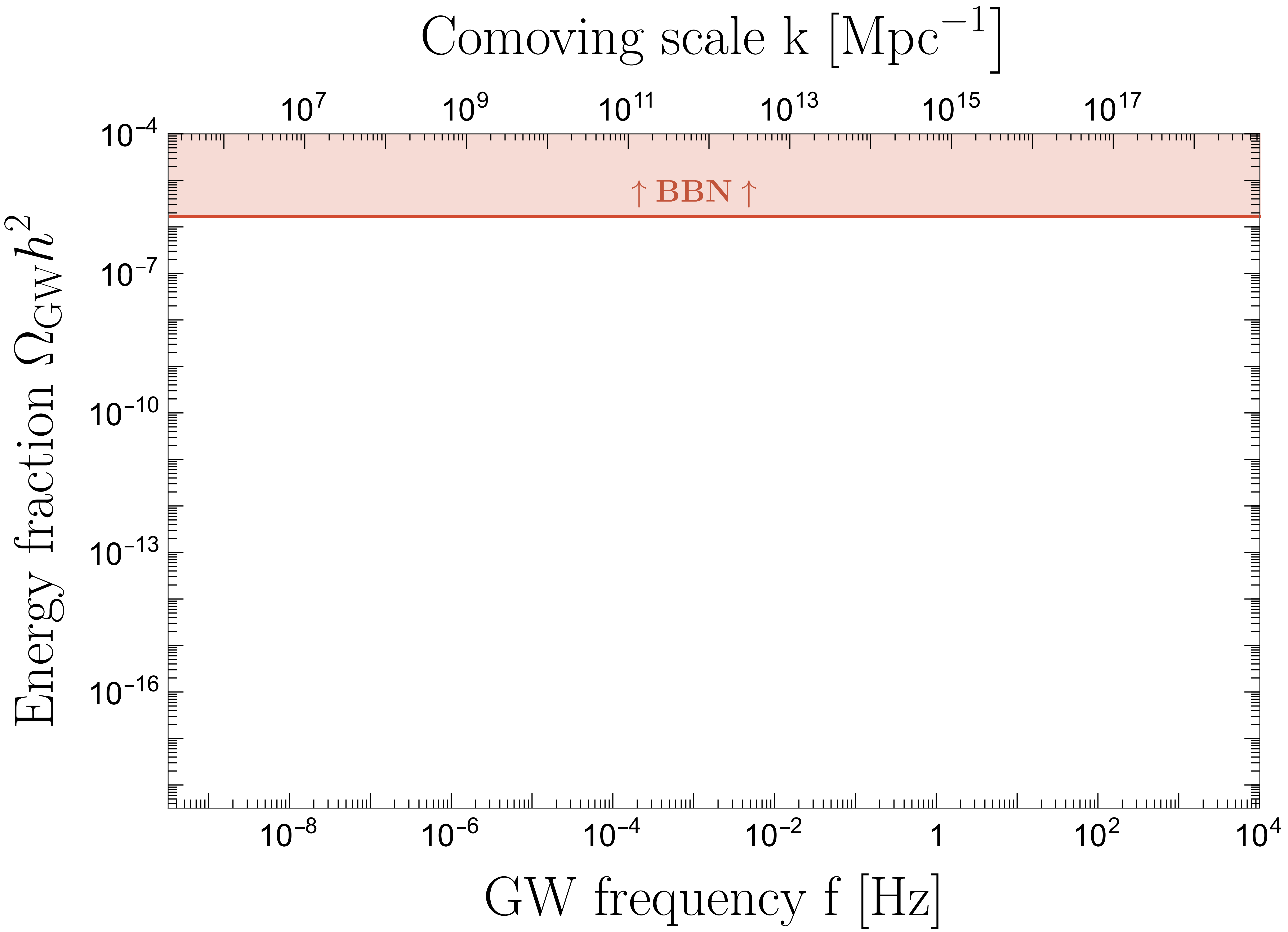
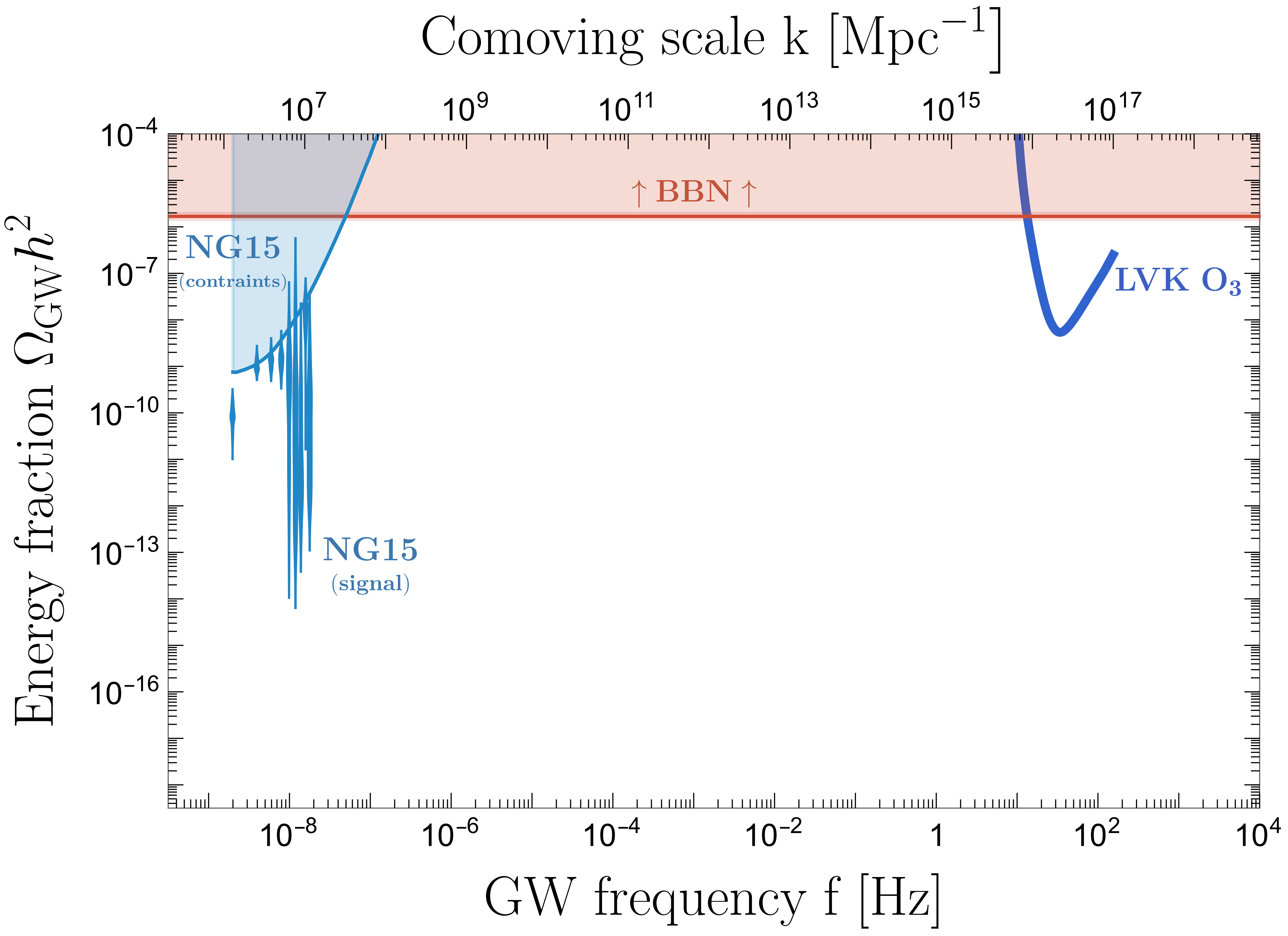

Comoving scale k [Mpc^{-1}]
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}
↑ BBN ↑
Energy fraction $\Omega_{\rm GW}h^2$
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
GW frequency f [Hz]

BACK-UP



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10^{13}
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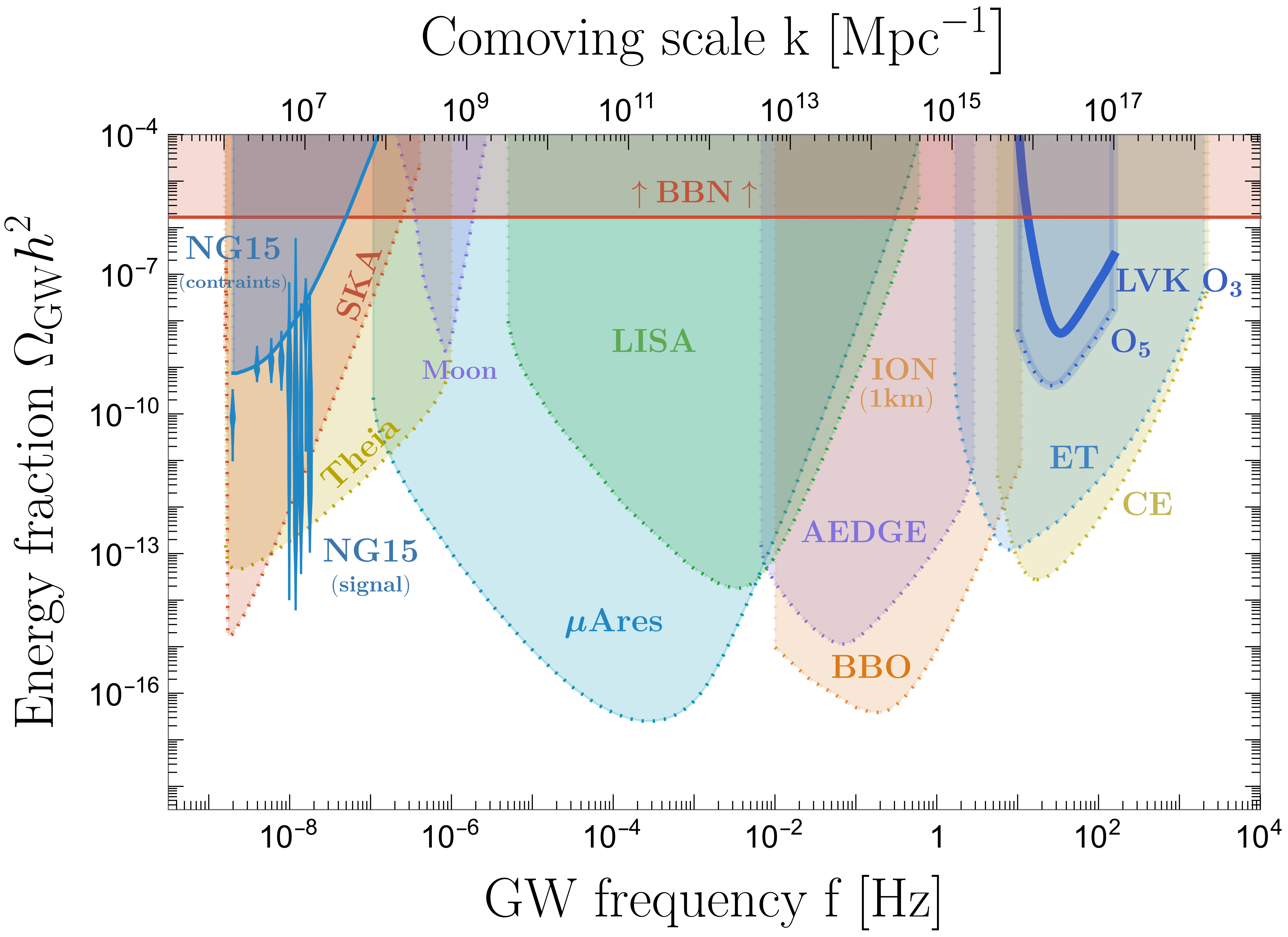
10^{17}
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
↑ BBN ↑
NG15
(contraints)
NG15
(signal)
LVK O_3
Energy fraction $\Omega_{GW}h^2$
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
10^{4}
GW frequency f [Hz]

BACK-UP



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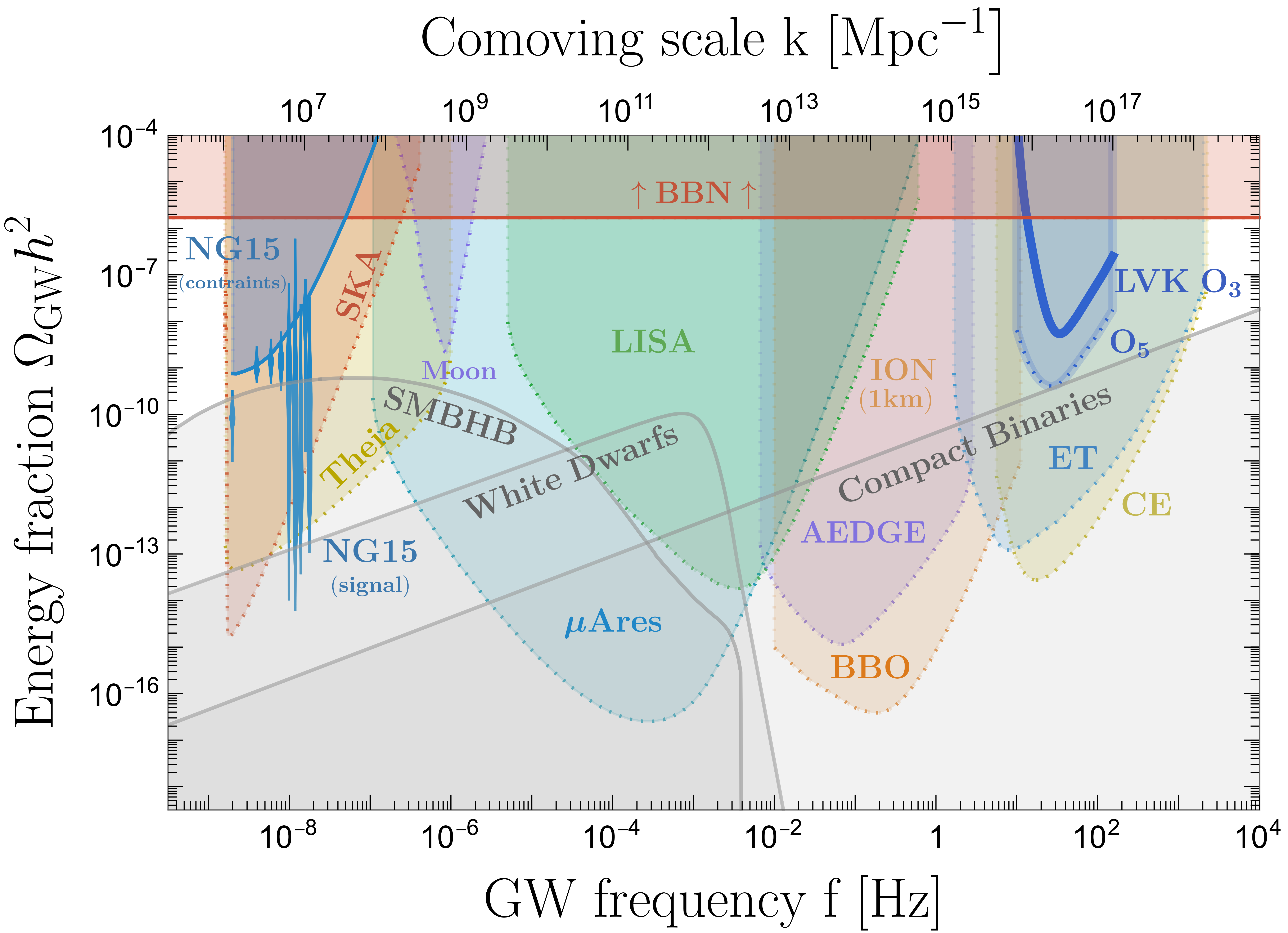
↑ BBN ↑
NG15
(contraints)
SKA
LISA
Moon
ION
(1km)
LVK O_3
O_5
ET
CE
Theia
AEDGE
NG15
(signal)
μAres
BBO
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^2
10^4
GW frequency f [Hz]

BACK-UP



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ION
(1km)
AEDGE
BBO
Compact Binaries
LVK O_3
O_5
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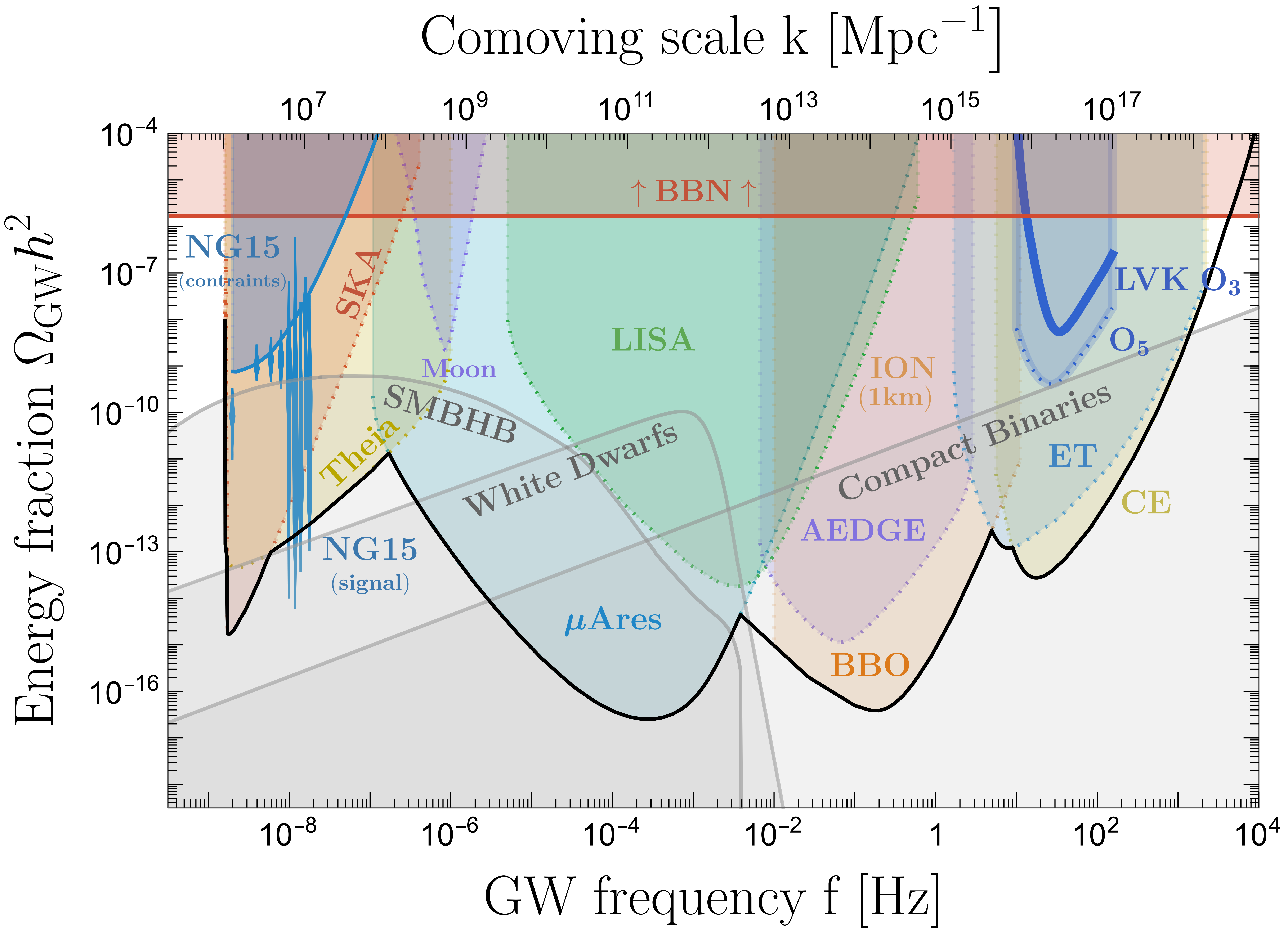
10^2
10^4
GW frequency f [Hz]

BACK-UP



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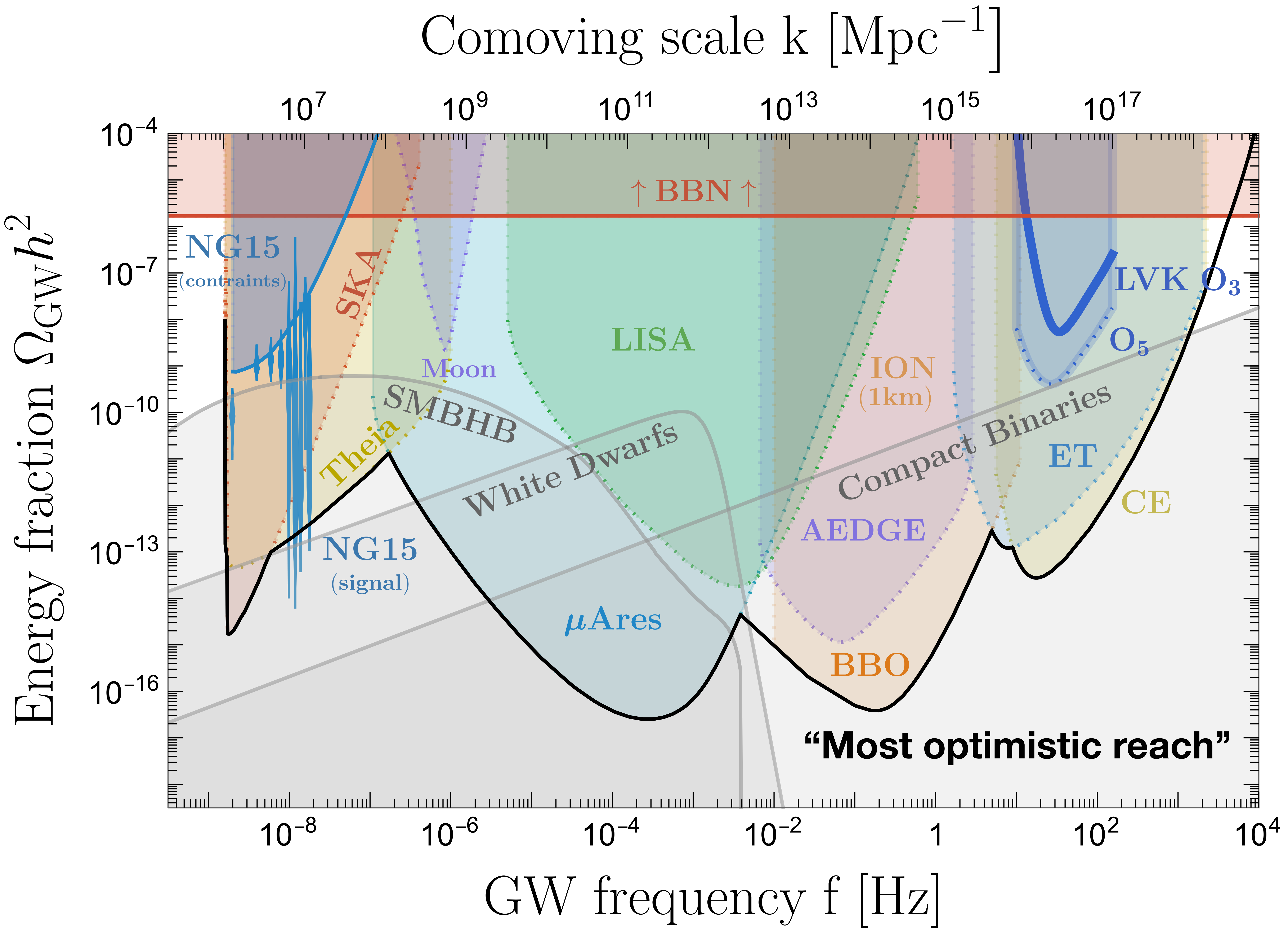
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BBO
"Most optimistic reach"
10^{-8}
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10^{-4}
10^{-2}
1
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10^{4}
GW frequency f [Hz]