Induced gravitational wave probes of the primordial black hole reheating scenario

JAN TRÄNKLE (ITP HANNOVER U.), 22.05.2025

NEHOP'25 WORKSHOP, BRUSSELS

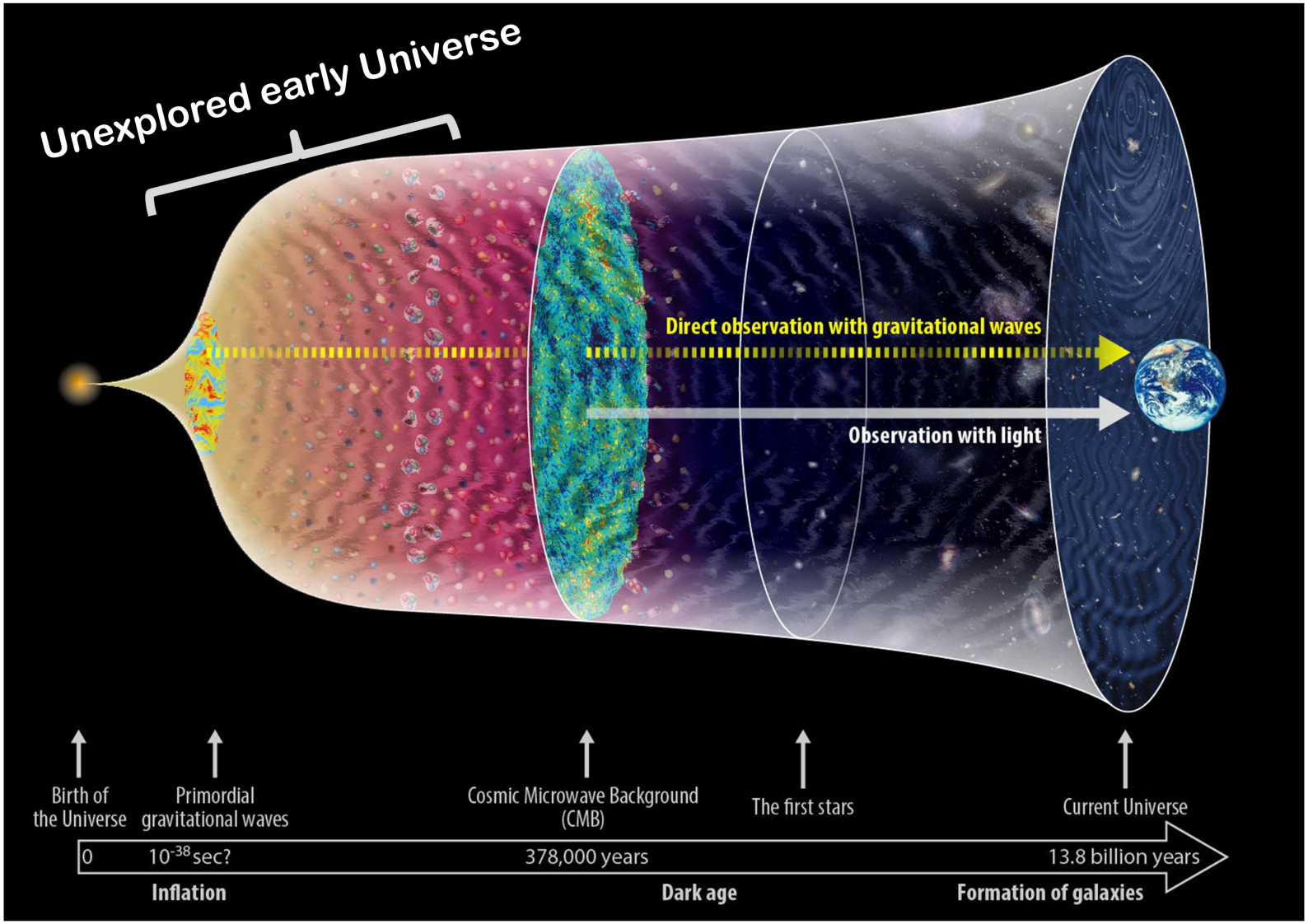
BASED ON: PHYS.REV.D 111 (2025) 6, 063528 [2409.12125]

WITH G. DOMÈNECH

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Leibniz Universität Hannover



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Motivation

- unknown expansion history between end of inflation and radiation domination

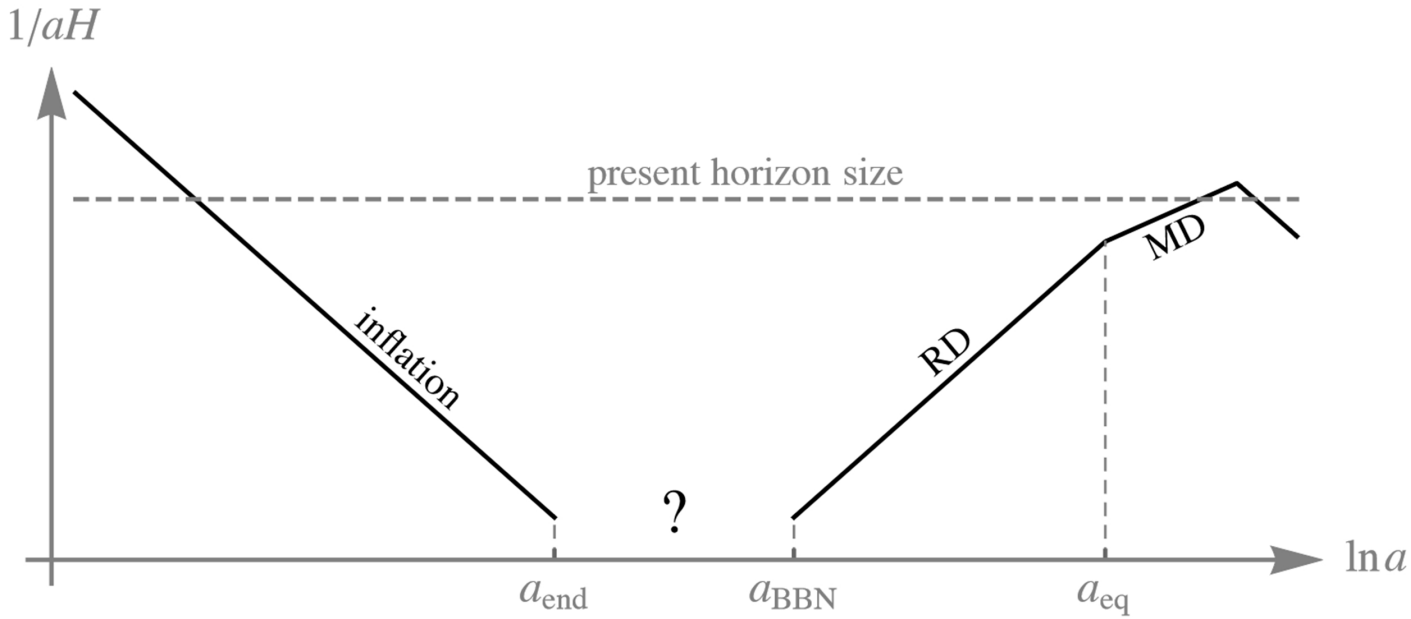

Figure: [1] Allahverdi et al. [2006.16182]

Motivation

- unknown expansion history between end of inflation and radiation domination
- EoS parameter

$$w = P/\rho$$

$w = 0$ (dust)

$w = 1$ (kination)

$w = 1/3$ (radiation)

$$w = \frac{n-1}{n+1}$$

$(V(\phi) \propto \phi^{2n})$

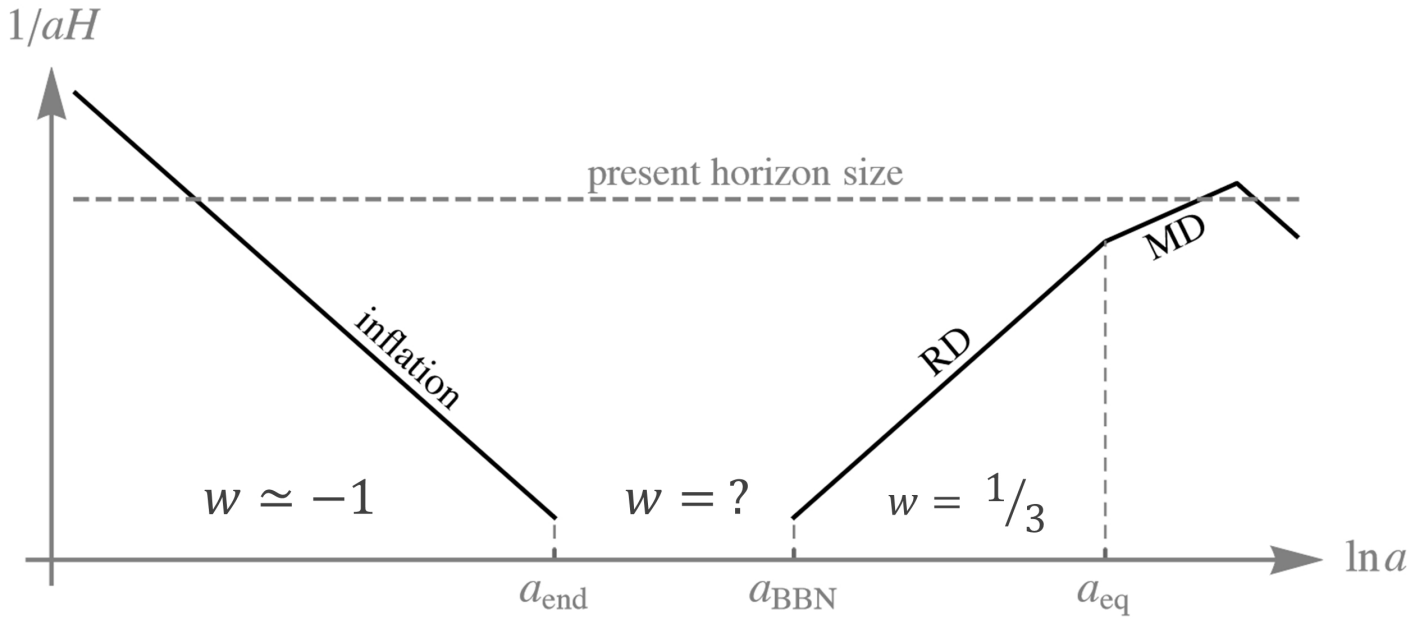

Figure: [1] Allahverdi et al. [2006.16182]

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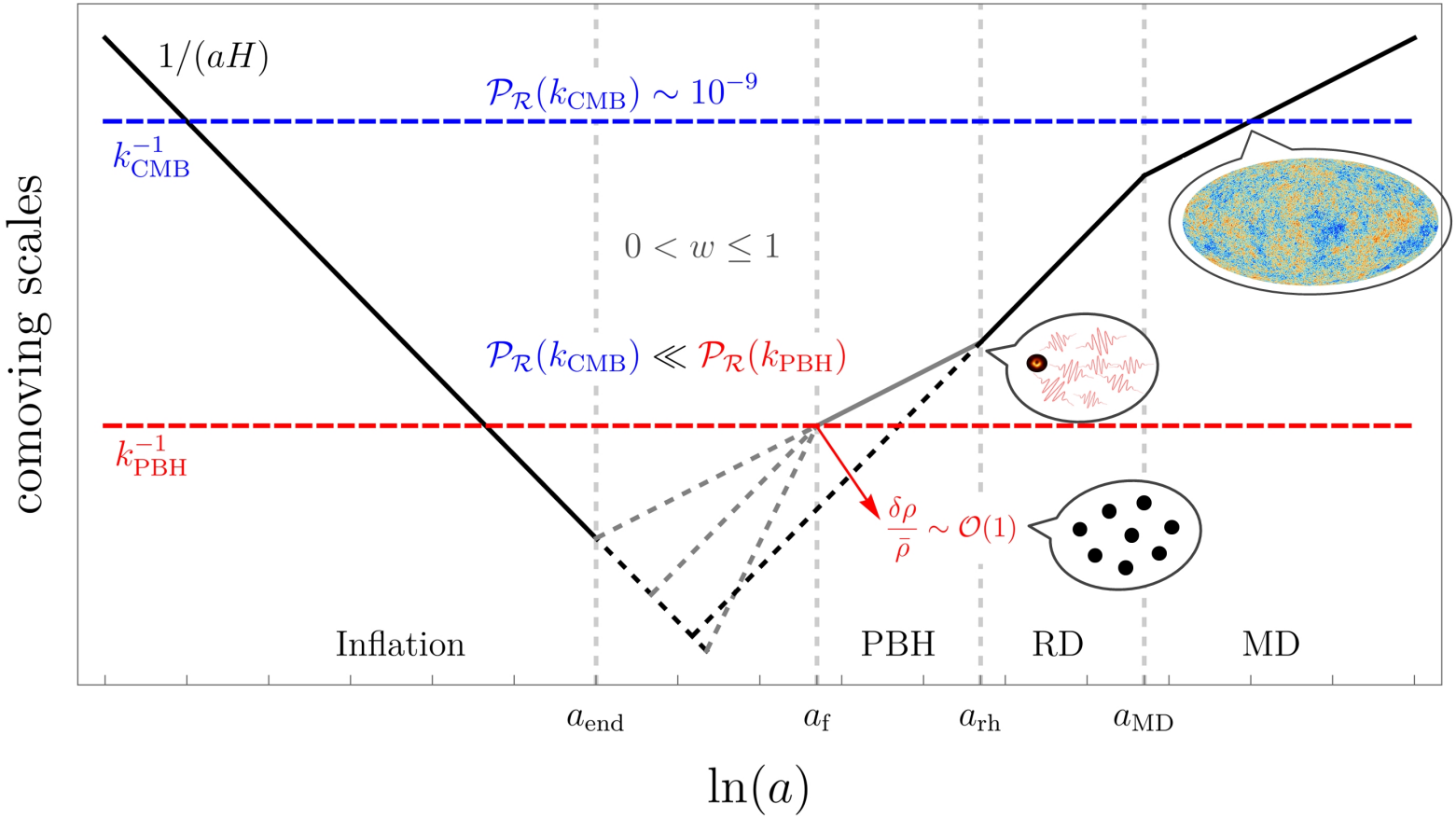
Primordial Black Holes (PBHs)



Light PBHs probe:

- small scales $k_{\rm PBH} \gg k_{\rm CMB}$
- reheating epoch
- DM production, leptogenesis, …

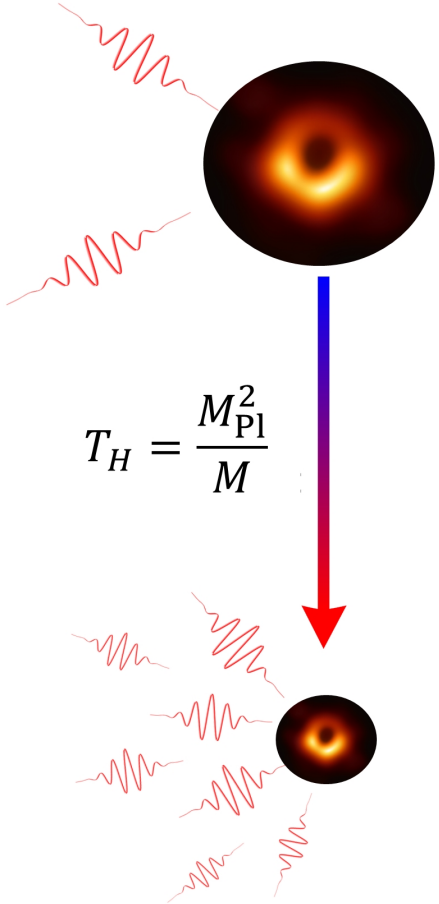
Figure adapted from: [1] Özsoy, Tassinato [2301.03600]

PBH reheating scenario

- PBH formed in post-inflationary, w-dominated epoch
- Hawking radiation $\longrightarrow M_i \ll 10^{10} g$ PBHs evaporate before BBN

$$t_{\rm eva}(M_i = 1 M_\odot) \approx 10^{55} \times 14\,{\rm Gyr}$$

$$t_{\rm eva}(M_i = 1{\rm g}) \approx 4 \times 10^{-28}{\rm s}$$



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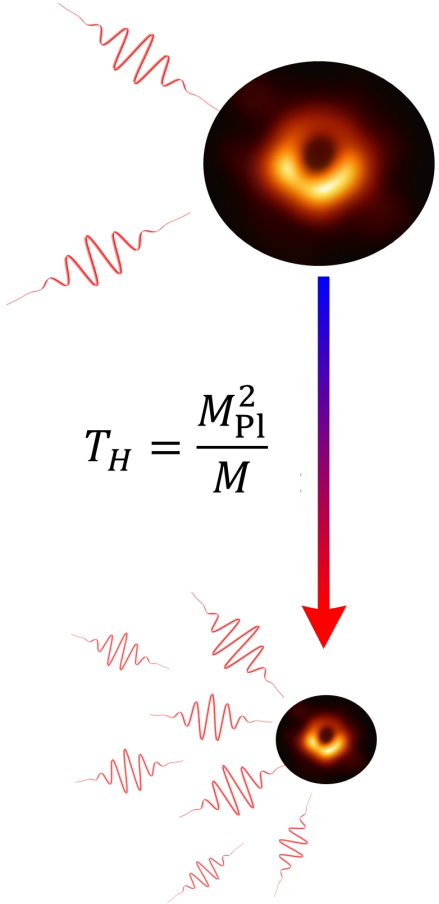
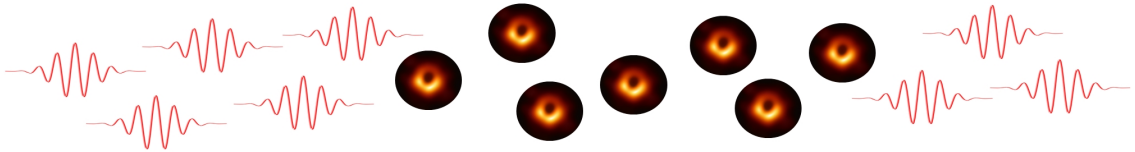
- specified by initial mass and energy fraction: $\left(M_i, \beta = \Omega_{{\rm PBH},i}\right)$
- unique signature in induced gravitational waves (GWs)



[1] Inomata et al. [2003.10455]
[2] Papanikolaou et al. [2010.11573]
[3] Domènech et al. [2012.08151]

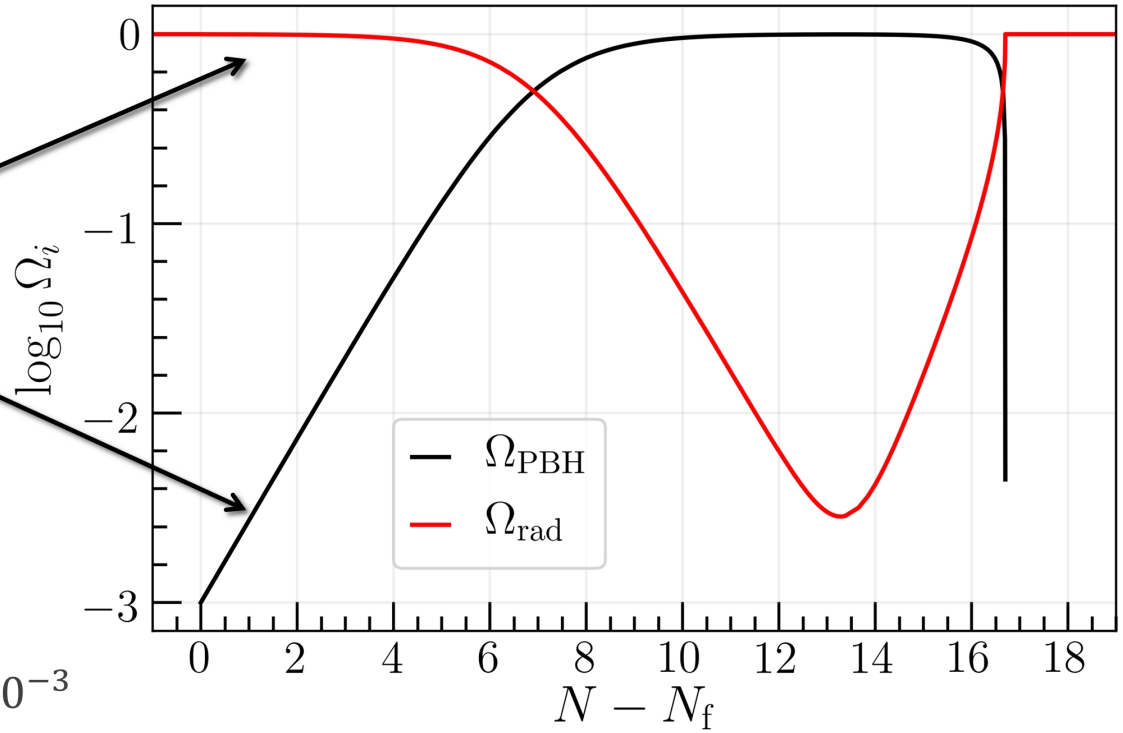
PBH reheating - standard scenario

$w = 1/3$



$\rho_{\rm rad} \propto a^{-4}$

$\rho_{\rm PBH} \propto a^{-3}$



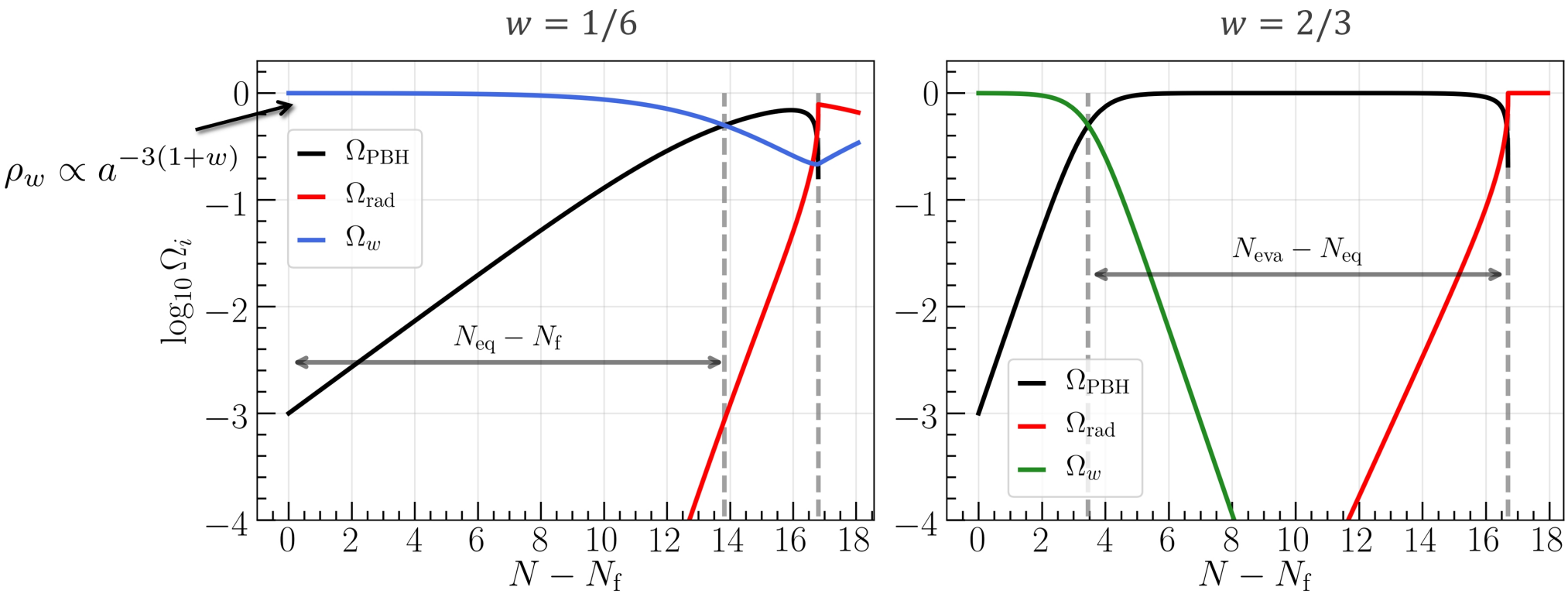
$M_i = 10g, \beta = 10^{-3}$

- reheating temperature:

$$T_{\rm eva} \sim 10^4 {\rm GeV} \left(\frac{M_i}{10^4 {\rm g}}\right)^{-3/2}$$

[1] B. Carr (1976)

PBH reheating - general w background



$M_i = 10g, \beta = 10^{-3}$

$\longrightarrow$ Duration of PBH dominated phase altered

Induced gravitational wave probes of the primordial black hole reheating scenario

Induced Gravitational Waves (iGWs)

PBH number density fluctuations $\delta_{PBH} \Longrightarrow$ curvature perturbation $\Phi \Longrightarrow$ induced GWs

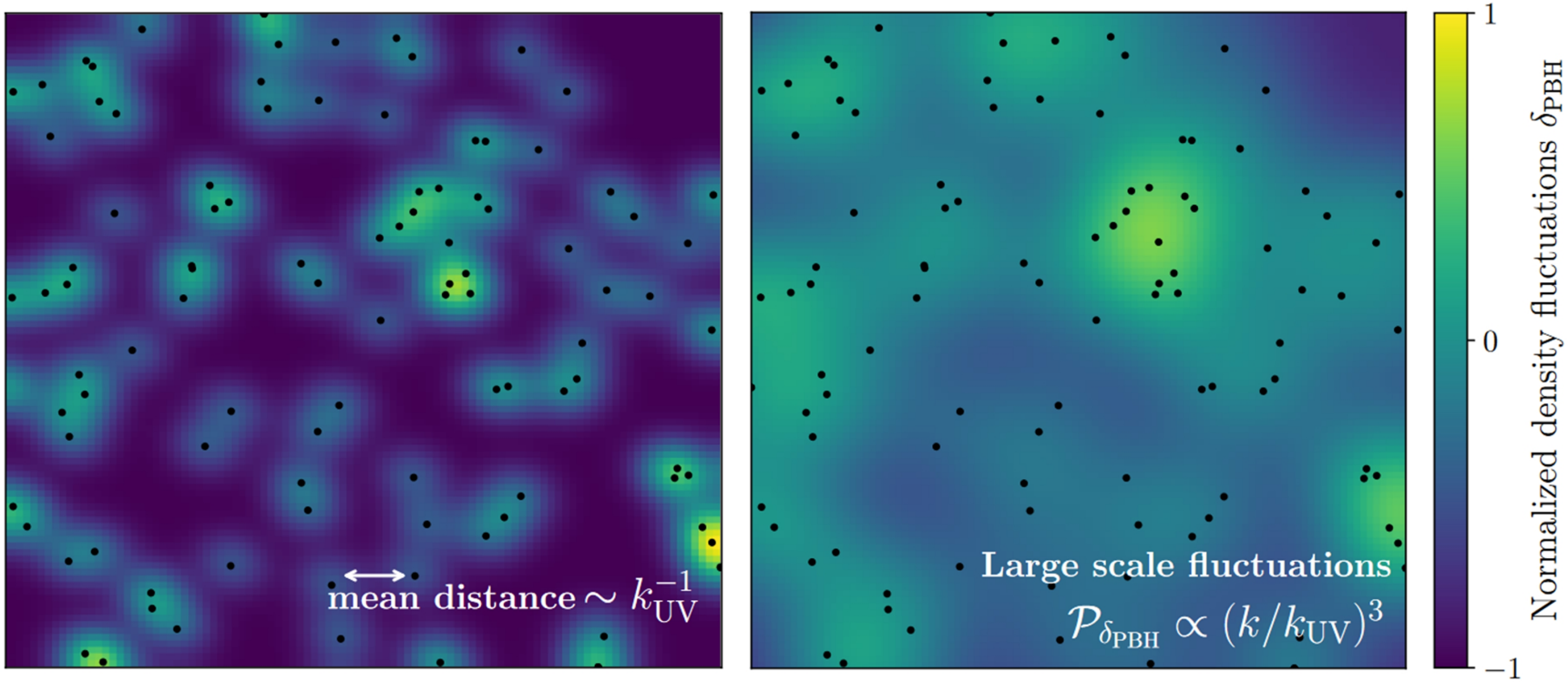


Figure: [1] G. Domènech, [2402.17388]

Induced Gravitational Waves

- Tensor perturbations at 2nd order

$$h_k''(\tau) + 2\mathcal{H}h_k'(\tau) + k^2 h_k(\tau) \propto (\Phi + \Phi'/\mathcal{H})^2$$

- Spectral GW energy density

$$\Omega_{\rm GW}(k) \sim \langle h_{ij}h_{ij}\rangle \sim \int dv \int du\, \overline{I^2}(k\tau, u, v)\, \langle \Phi\Phi\rangle(uk)\langle \Phi\Phi\rangle(vk)$$

[1] Domènech et al. [2112.10163]

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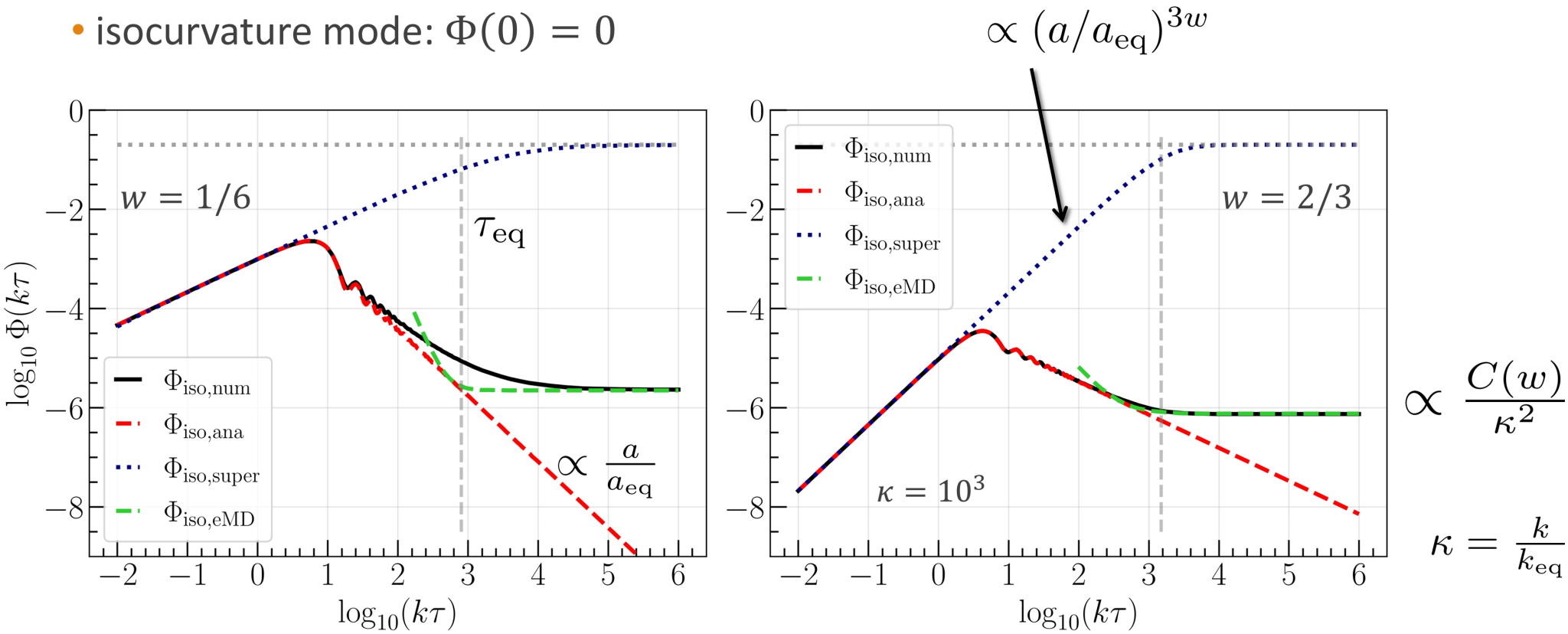
- largest contribution to GWs from rapid transition $w = 0 \longrightarrow 1/3$ right after PBH evaporation (Poltergeist mechanism)

[1] Domènech et al. [2112.10163]
[2] Inomata et al. [1904.12879]

Evolution of curvature perturbation

- isocurvature mode: $\Phi(0) = 0$



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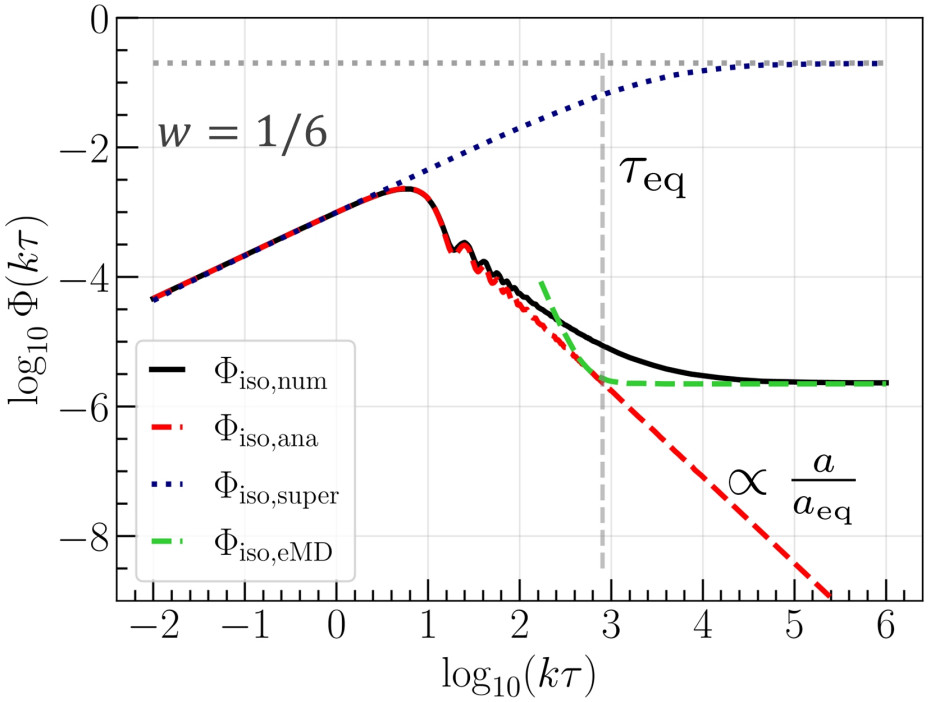
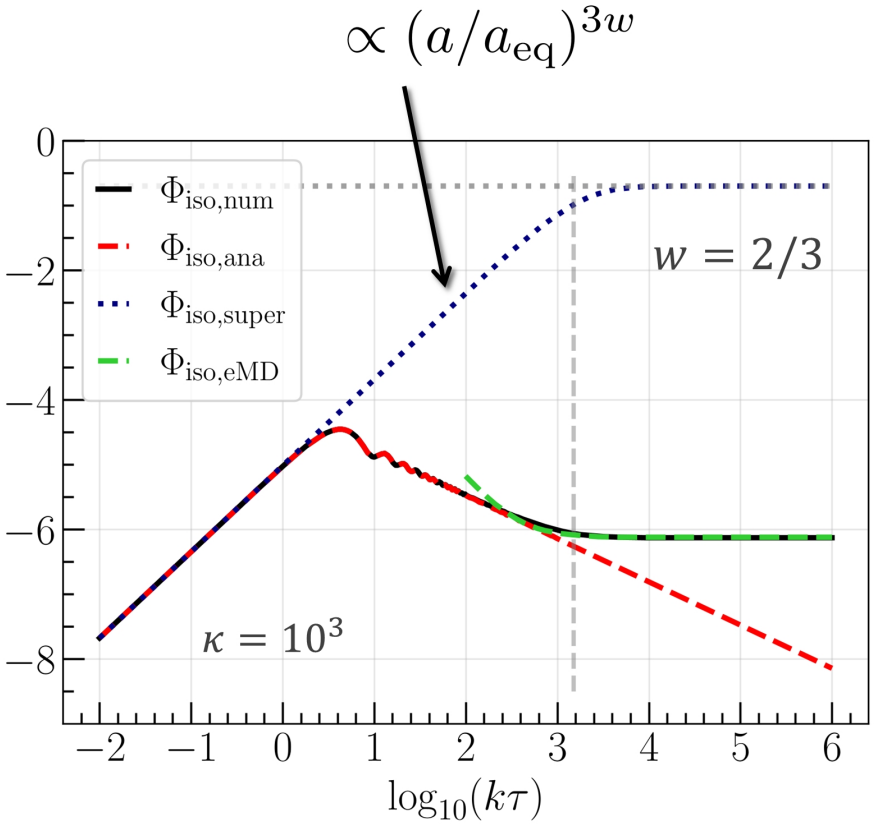




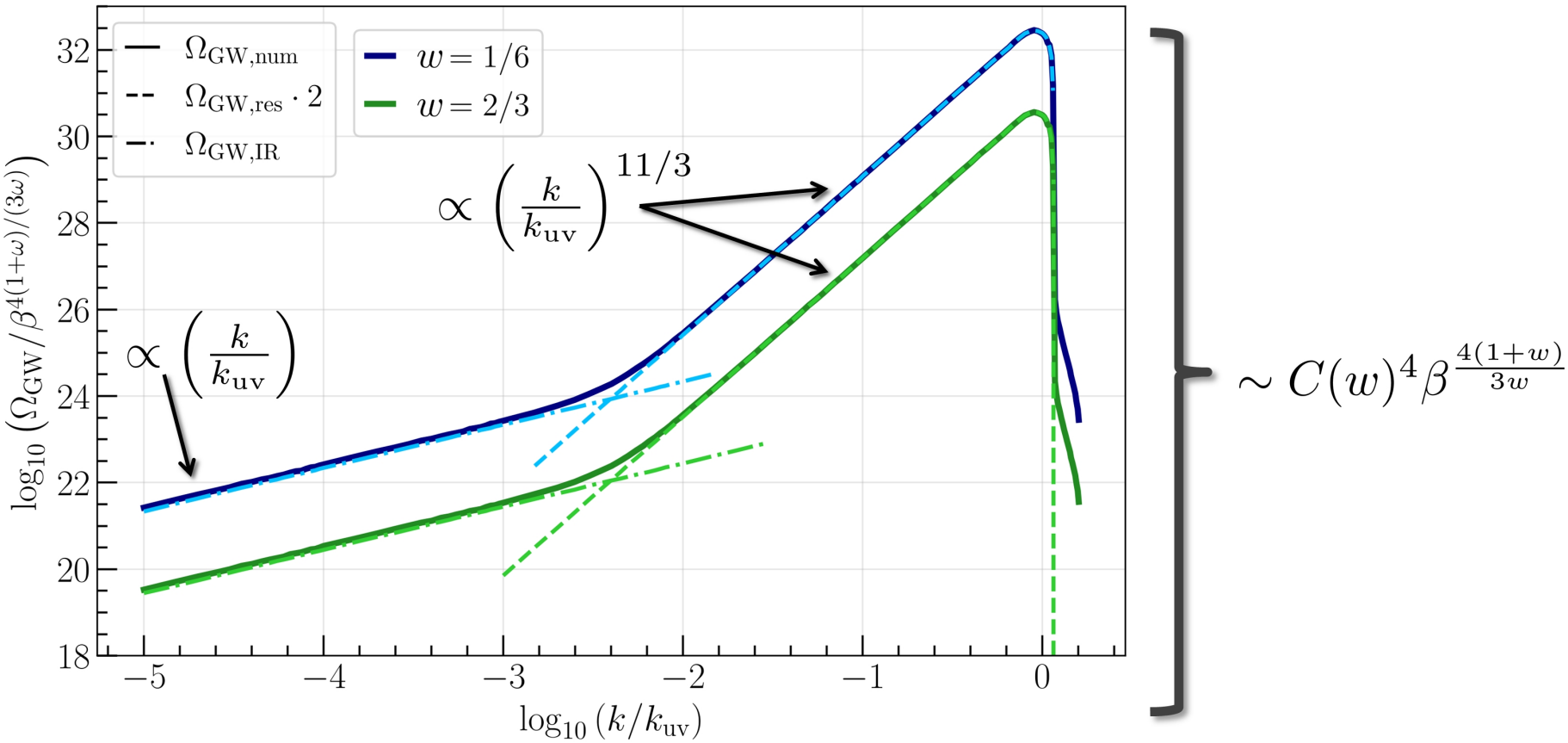
Poisson eq.

$k^2\Phi \propto \delta_{\rm PBH}$

$\propto \frac{C(w)}{\kappa^2}$

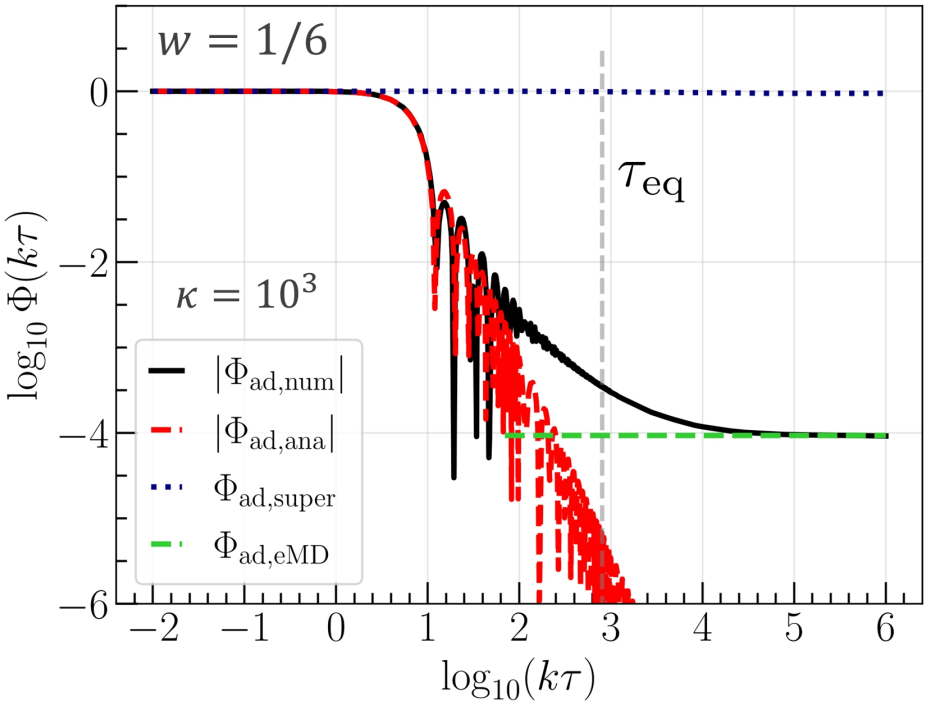
$\kappa = \frac{k}{k_{\rm eq}}$

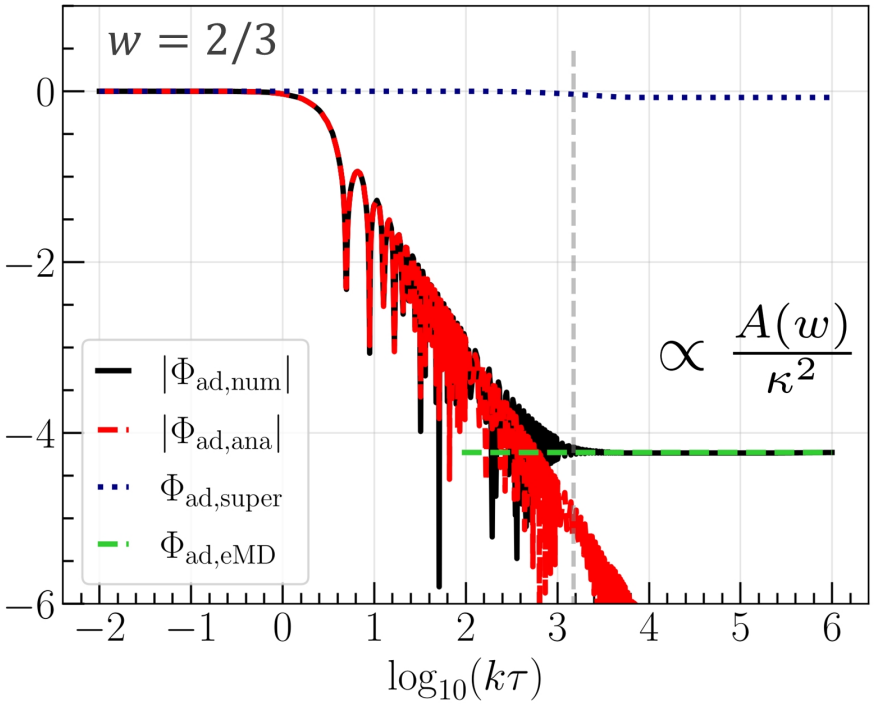
Isocurvature iGWs – effect of w



Evolution of curvature perturbation

- adiabatic mode: $\Phi(0) = \Phi_0$





$$\propto \frac{A(w)}{\kappa^2}\left(\frac{\alpha\kappa^{-b}-1}{b}\right)$$

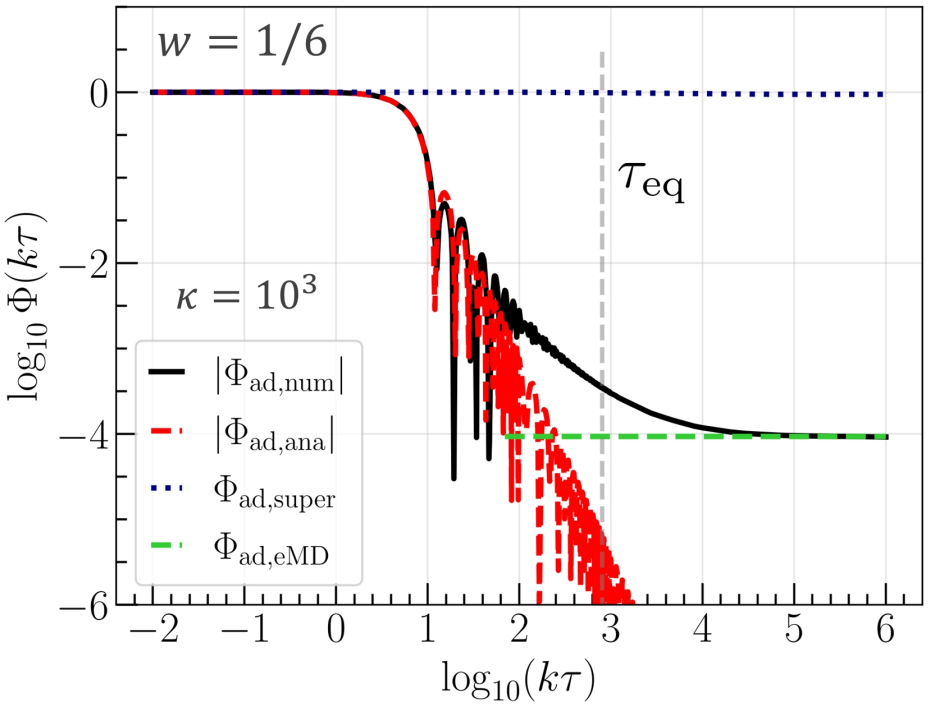
$$b = \frac{1-3w}{1+3w}$$

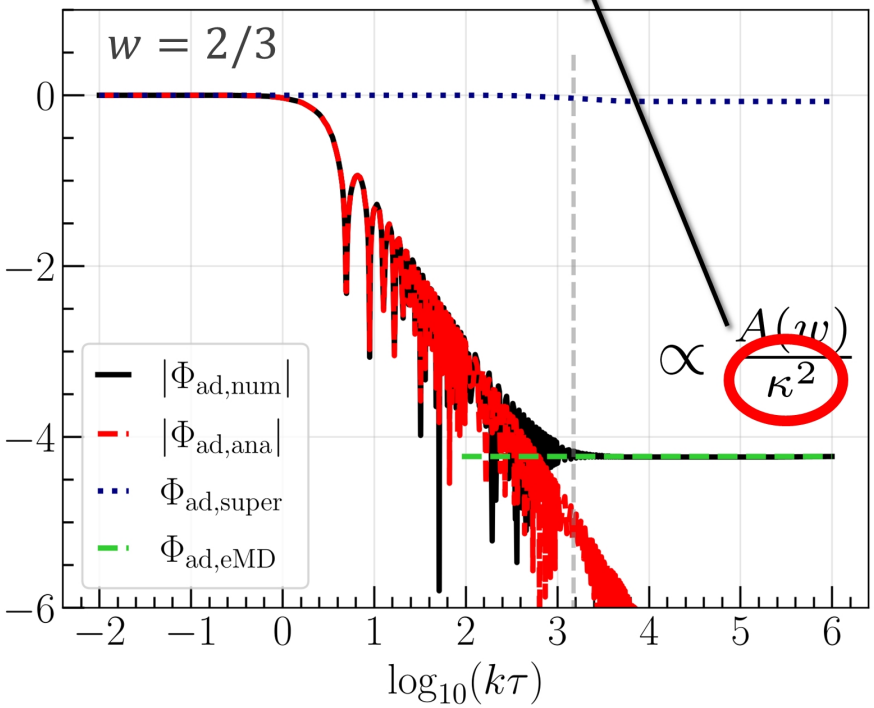
Evolution of curvature perturbation

- adiabatic mode: $\Phi(0) = \Phi_0$

Poisson eq.
$k^2\Phi \propto \delta_{\rm PBH}$

Φ_0 sources density contrast
$\delta_{\rm PBH} \propto (k\tau)^{-b}$

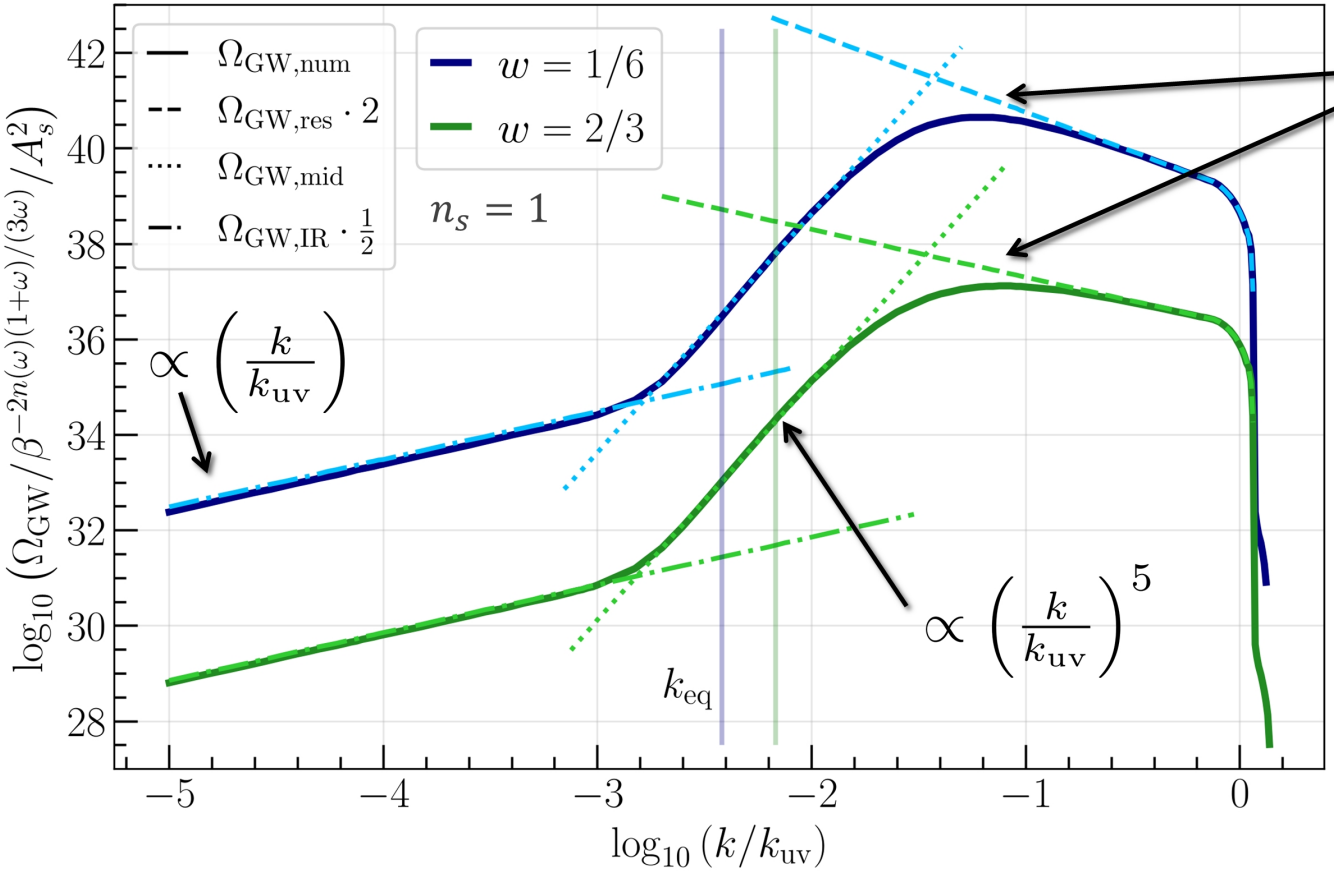




$$\propto \frac{A(w)}{\kappa^2}\left(\frac{\alpha\kappa^{-b}-1}{b}\right)$$

$$b = \frac{1-3w}{1+3w}$$

Adiabatic iGWs – effect of w



$$\propto \left(\frac{k}{k_{\rm uv}}\right)^{2n_{\rm eff}(w)+7}$$

$$n_{\rm eff} = 2n(w) + n_s - \frac{5}{3}$$

$$\sim A_s^2 A(w)^4 \beta^{-\frac{2n(w)(w+1)}{3w}}$$

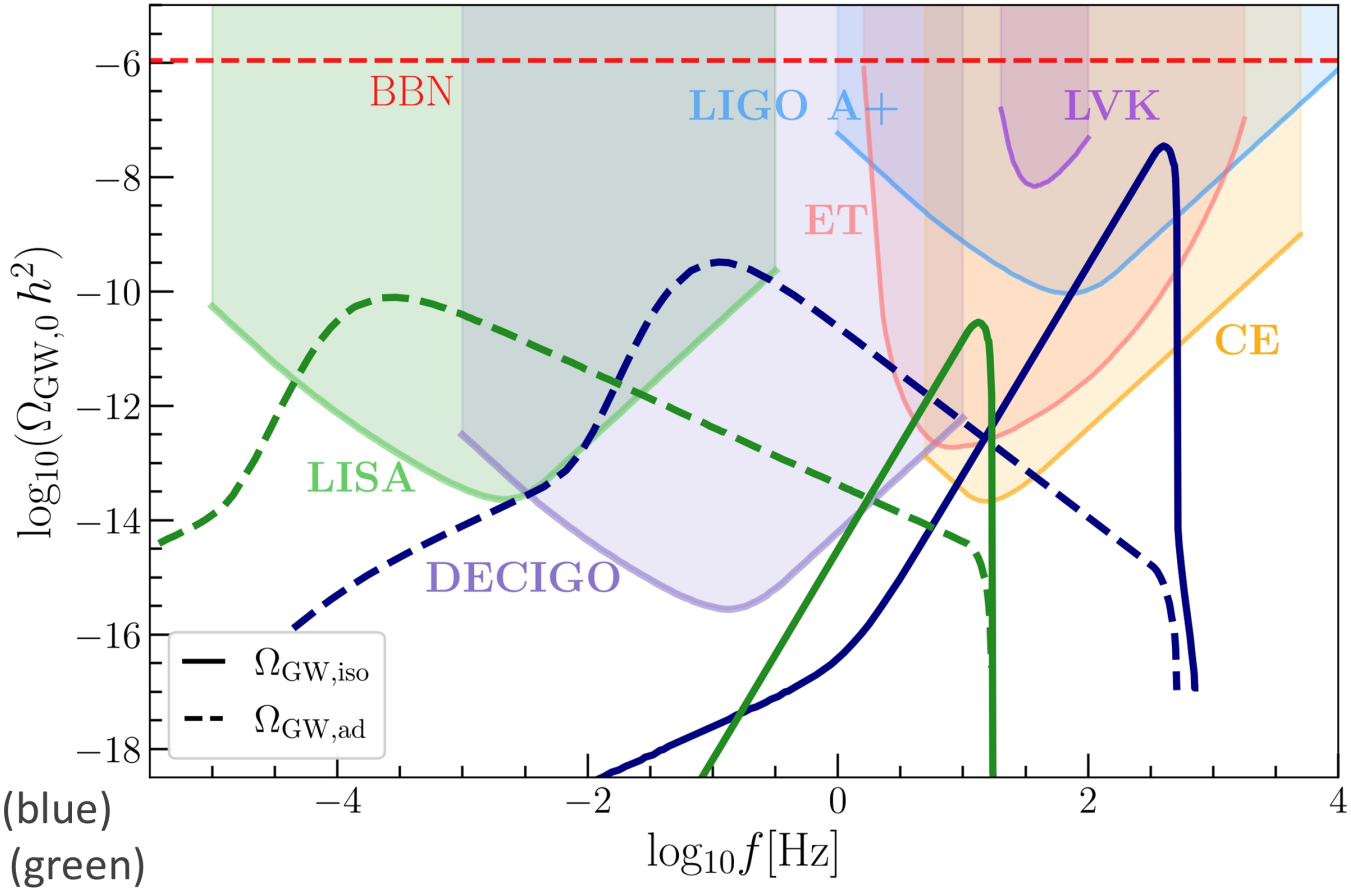
iGWs – observational prospects

- peak frequency
  - Isocurvature iGW

$$f_{\rm peak} \sim 0.3{\rm Hz} - 7{\rm MHz}$$

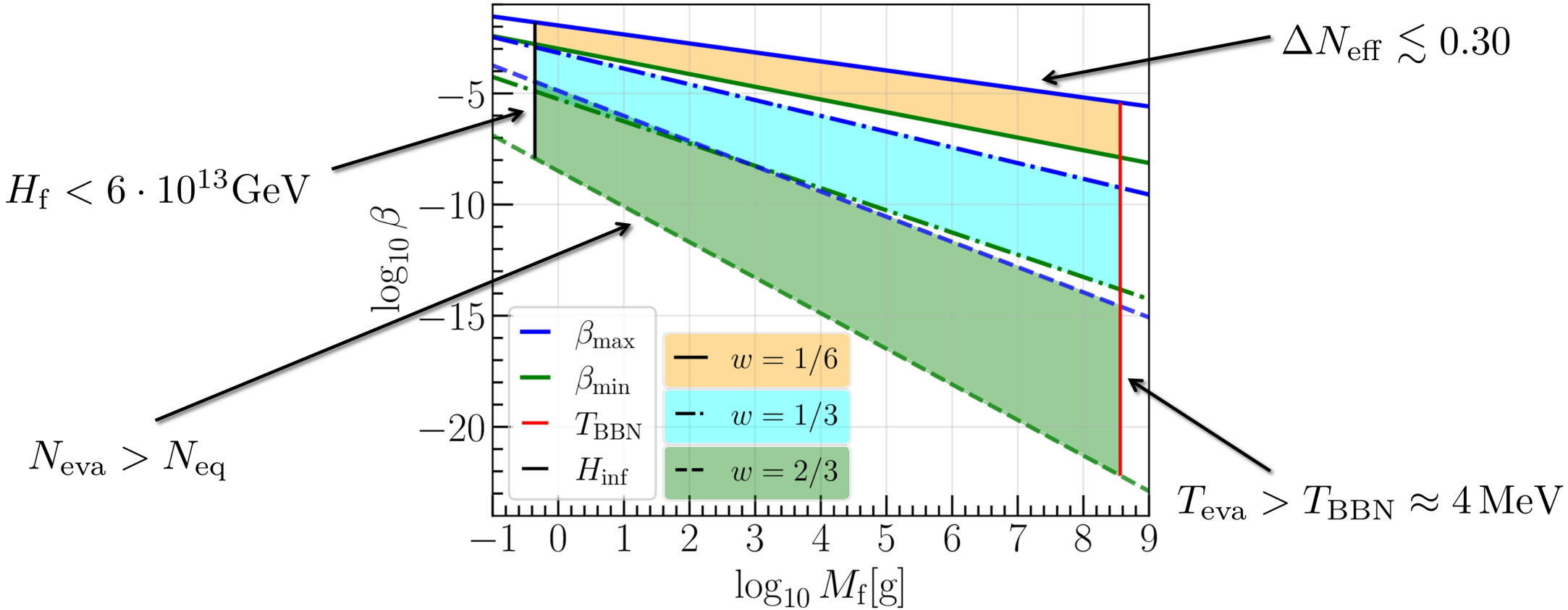
  - Adiabatic iGW

$$f_{\rm eq} \sim \beta^{\frac{1+w}{6w}} f_{\rm peak}$$



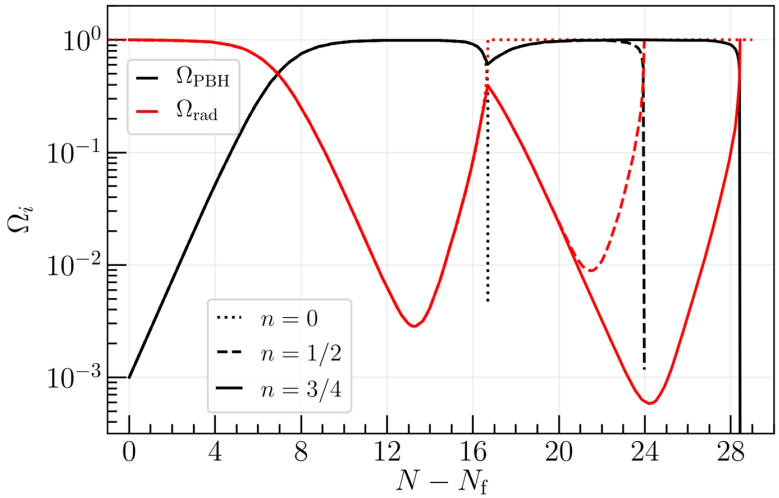
$A_s = 2.1 \times 10^{-9}, n_s = 1$
$M_i = 5 \times 10^4 g,\ \beta = 9 \times 10^{-5},\ w = 1/6$ (blue)
$M_i = 3 \times\ 10^6 g,\ \beta = 2 \times 10^{-14},\ w = 2/3$ (green)

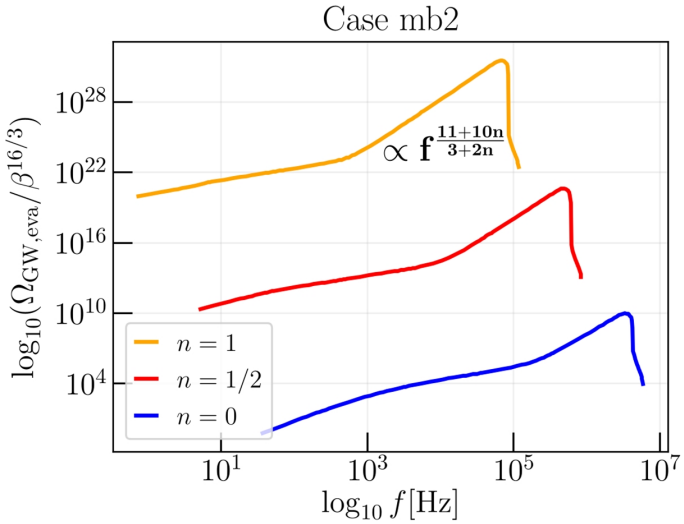
Constraints on (β, M_i)

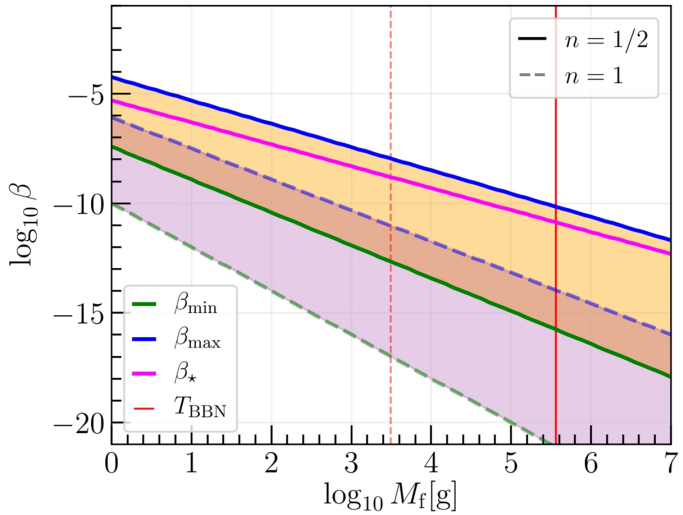


Remark: Effect of memory burden

- MB: longer PBH dominated phase ⟹ enhanced iGWs ⟹ stronger constraints







$$\frac{dM}{dt} \propto -\frac{M_{\rm pl}^4}{M^2} \times \begin{cases} 1 & (\text{for } M \geq M_{\rm mb}) \\ S^{-n}(\mathcal{M}) & (\text{for } M < M_{\rm mb}) \end{cases}$$

Probing modified Hawking evaporation with gravitational waves from the primordial black hole dominated universe

Shyam Balaji, Guillem Domènech, Gabriele Franciolini, Alexander Ganz and Jan Tränkle

Published 19 November 2024 • © 2024 The Author(s) JCAP11(2024)026, arXiv:[2403.14309]

Summary

- Ultra-light evaporating PBH can dominate & reheat early Universe
- Duration of PBH domination & evolution of curvature perturbation depend on w
- Induced GWs probe PBH reheating & preceding epoch of PBH formation
- EoS $w \neq 1/3$ opens new parameter space for ultra-light PBHs to reheat Universe

- *Caveats*: effect of non-linear scales, broad mass function ?
- *Outlook*: isocurvature iGWs at horizon entry

Thank you for your attention!

Questions?