Induced gravitational wave probes of the primordial black hole reheating scenario

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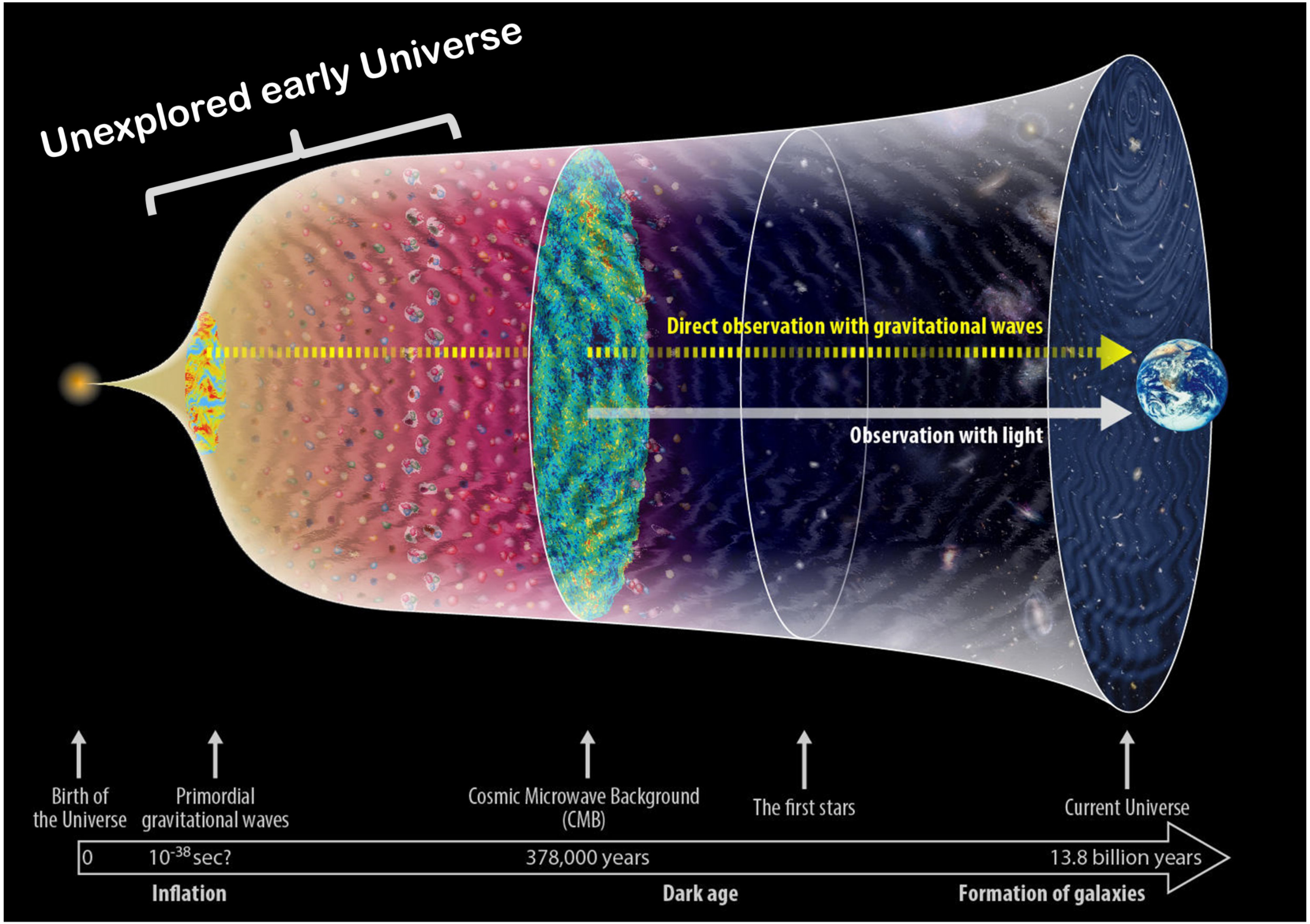
BASED ON ARXIV:2409.12125 WITH G. DOMÈNECH

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

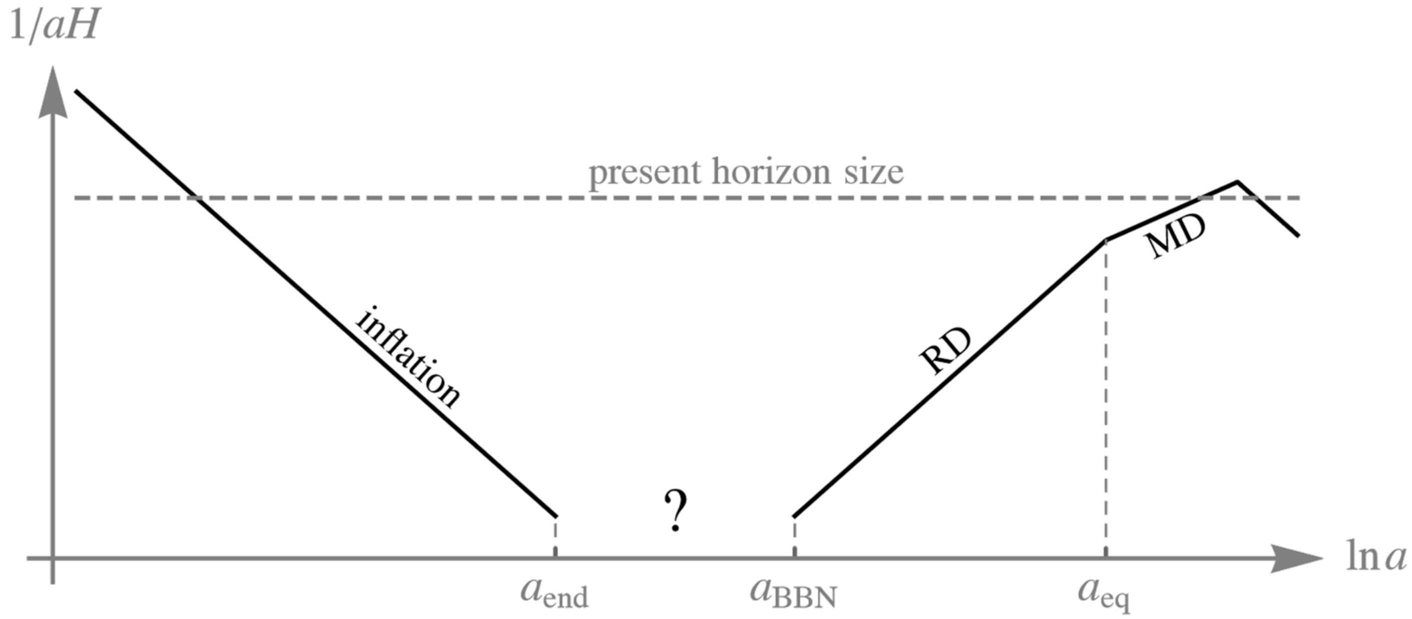
Leibniz Universität Hannover



[1] © NAOJ, https://gwpo.nao.ac.jp/en/gallery/000061.html

Motivation

- unknown expansion history between end of inflation and radiation domination



[1] Allahverdi et al. [2006.16182]

Motivation

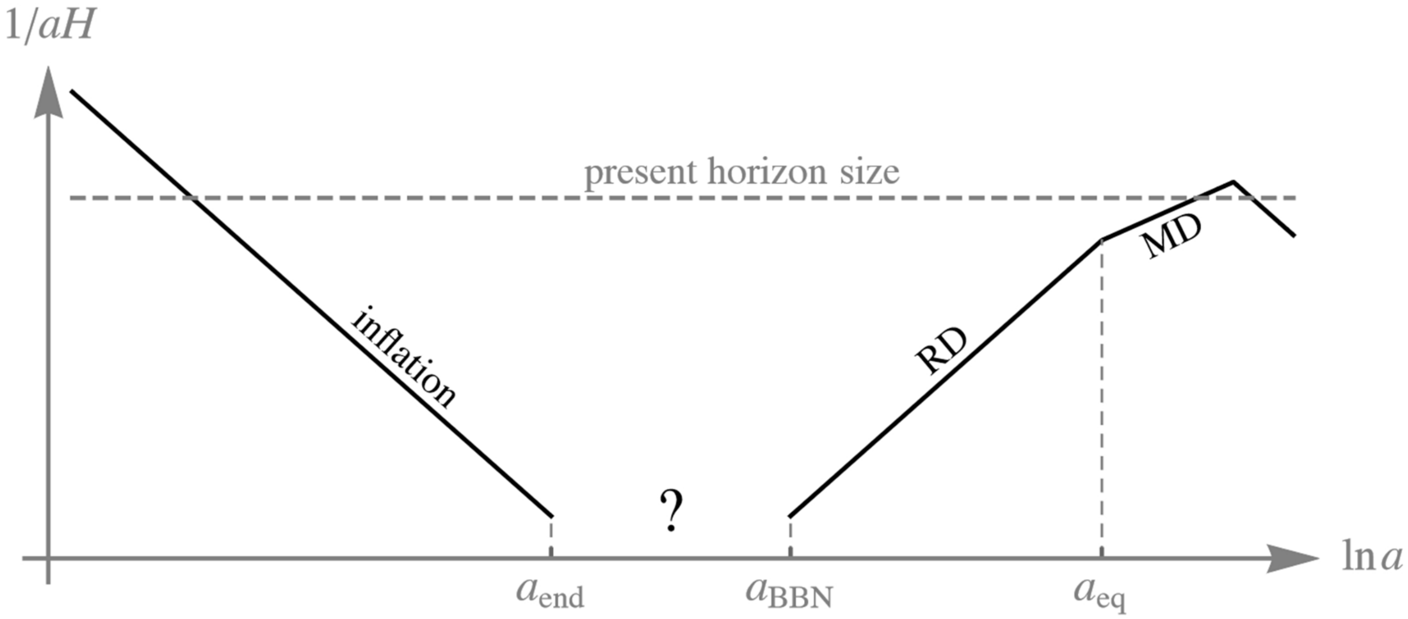
- unknown expansion history between end of inflation and radiation domination
- EoS parameter

$$w = P/\rho$$

$w = 0$ (matter)

$w = 1/3$ (radiation)

$w = 1$ (kination)



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Black Hole Evaporation

Particle Creation by Black Holes

S. W. Hawking

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

Received April 12, 1975

- black holes radiate particles at Hawking temperature: $T_H = \frac{M_{Pl}^2}{M}$
- lifetime: $t_{\rm eva} \propto M_i^3 \approx \begin{cases} 4 \times 10^{-28}\mathrm{s} & M_i = 1\mathrm{g} \\ 10^{55} \times 14\,\mathrm{Gyr} & M_i = 1 M_\odot \sim 10^{33}\mathrm{g} \end{cases}$
- consider ultra-light PBHs ($M_i \ll 10^{10} g$) $\longrightarrow$ evaporate before BBN

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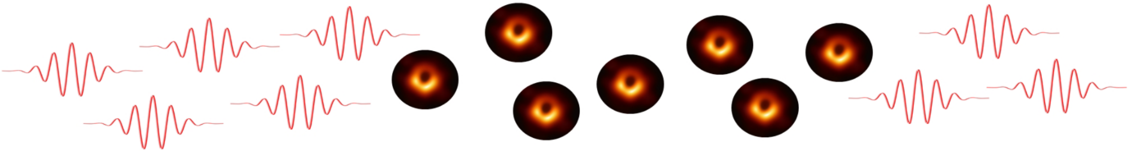
- consider ultra-light PBHs ($M_i \ll 10^{10} g$) $\longrightarrow$ evaporate before BBN
- unique signature in induced gravitational waves (GWs)
- model specified by initial mass and energy fraction: $(M_i, \beta = \Omega_{PBH,i})$

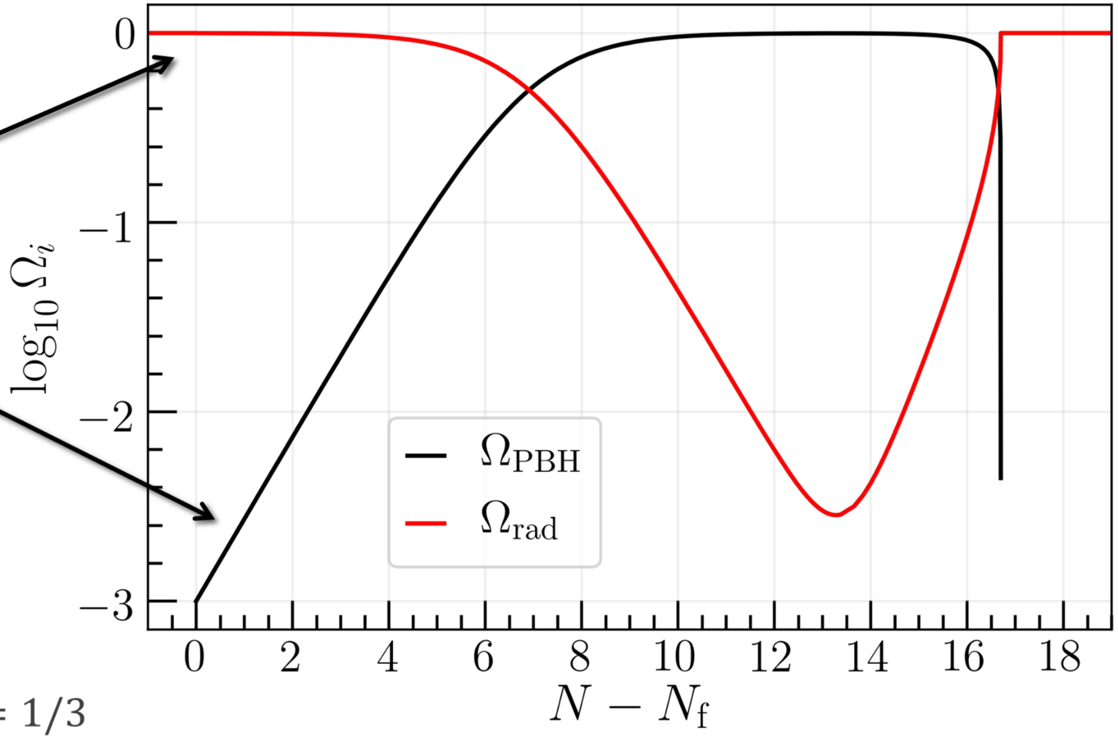
[1] Inomata et al. [2003.10455]
[2] Papanikolaou et al. [2010.11573]
[3] Domènech et al. [2012.08151]

PBH reheating - standard scenario



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

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

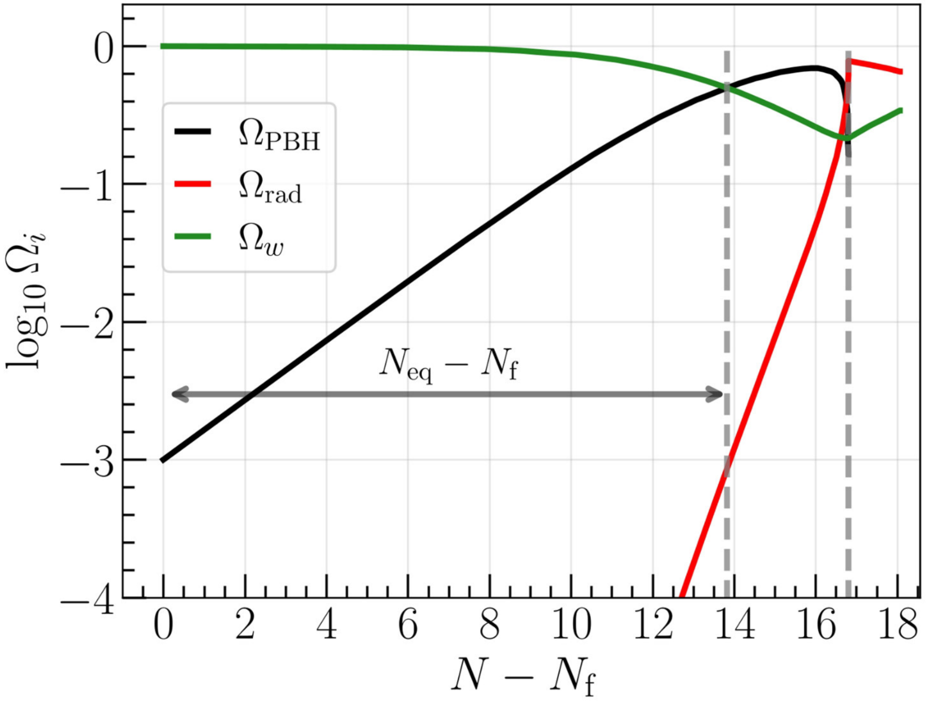


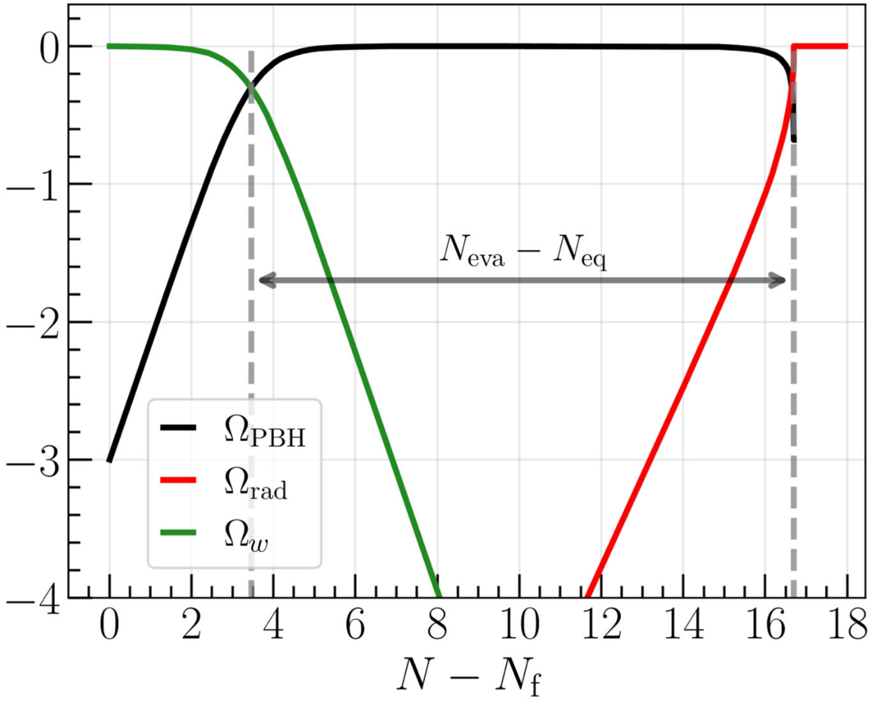
$$T_{\rm eva} \sim 10^4 {\rm GeV} \left(\frac{M_i}{10^4 {\rm g}}\right)^{-3/2}$$

$M_i = 10g, \beta = 10^{-3}, w = 1/3$

[1] B. Carr (1976)

PBH reheating - general w background





$\longrightarrow$ Duration of PBH dominated phase altered

$M_i = 10g, \beta = 10^{-3}, w = 1/6$ (l) ; $w = 2/3$ (r)

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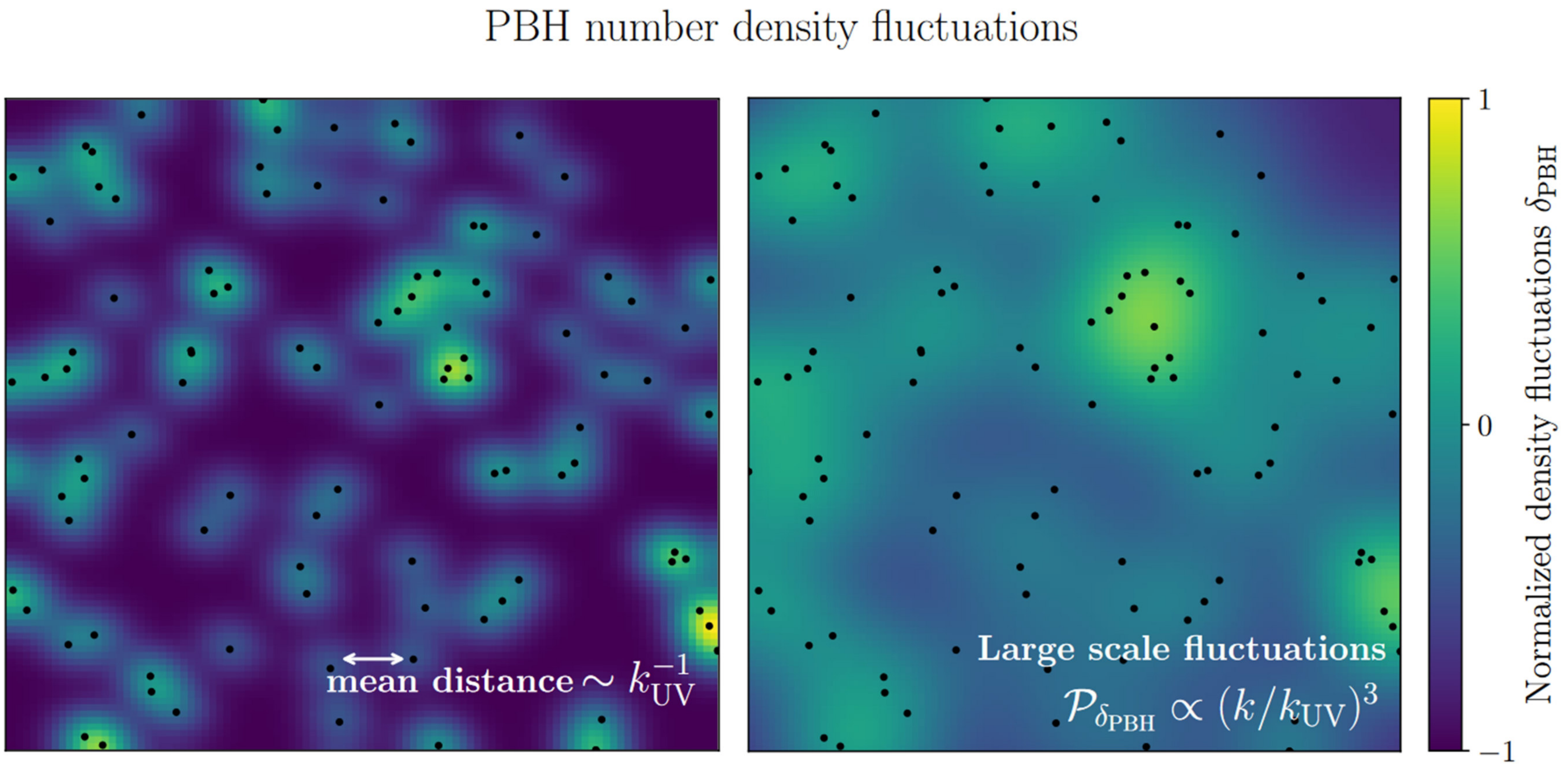
Induced Gravitational Waves (iGWs)



[1] G. Domènech, [2402.17388]

Induced Gravitational Waves

- Perturbed FLRW metric (Newton gauge)

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

- spectral GW energy density

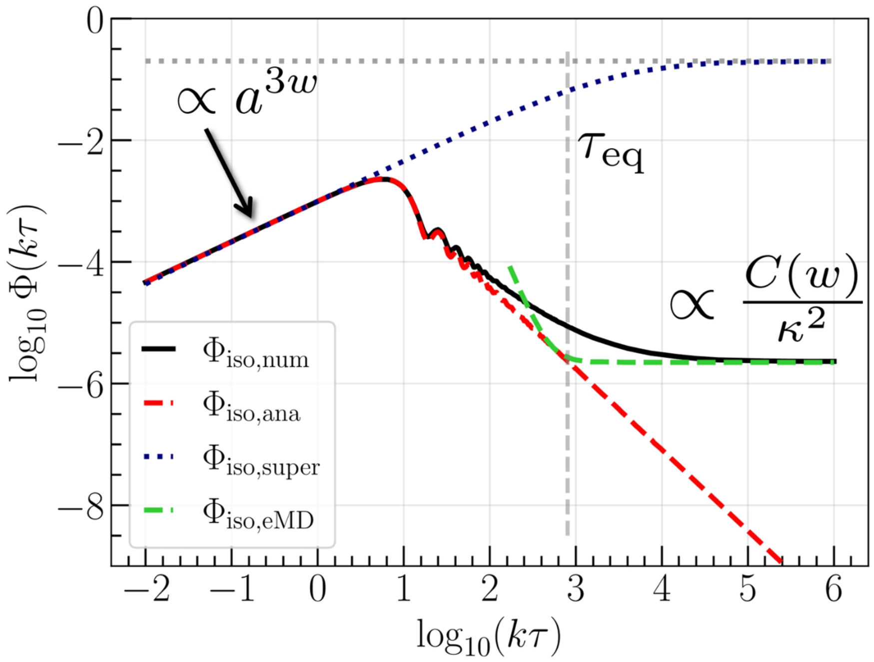
$$\Omega_{\mathrm{GW}}(k) \sim \langle h_{ij}h_{ij}\rangle \sim \int dv \int du\, \overline{I^2}(k\tau, u, v)\,\langle\Phi\Phi\rangle(uk)\langle\Phi\Phi\rangle(vk)$$

- PBH density fluctuations source gravitational potential $\delta_{\mathrm{PBH}} \Longrightarrow \Phi$

[1] G. Domènech [2109.01398]
[2] Inomata et al. [1904.12879]

Evolution of curvature perturbations

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

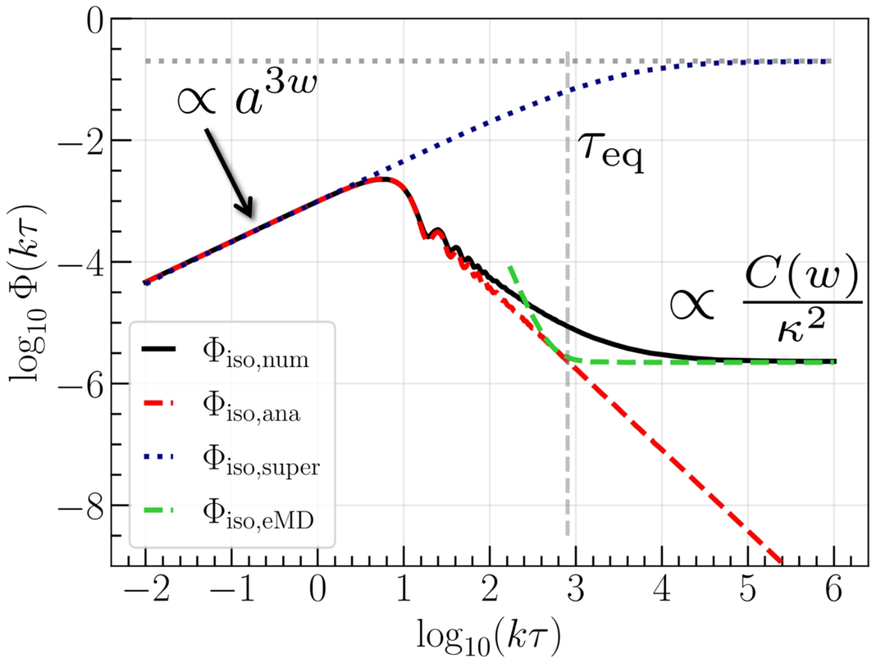


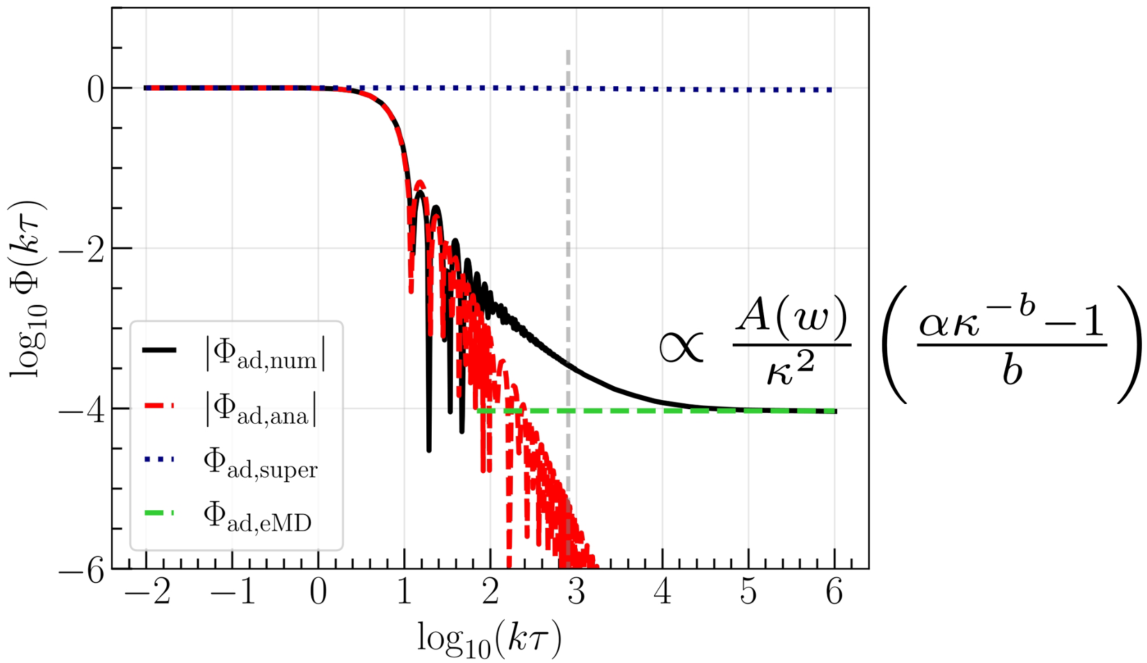
[1] Kodama, Sasaki (1987)

$k/k_{eq} = 10^3, w = 1/6$

Evolution of curvature perturbations

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

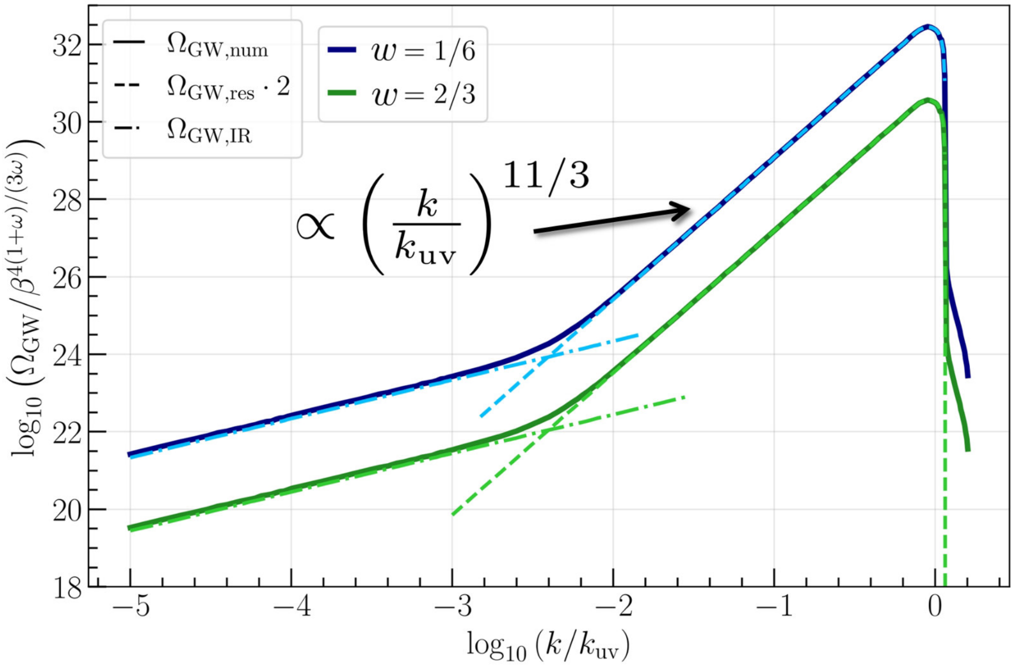




$k/k_{eq} = 10^3, w = 1/6$

Induced GWs – effect of w

- isocurvature iGWs



$$\sim C(w)^4 \beta^{\frac{4(1+w)}{3w}}$$

Induced GWs – effect of w

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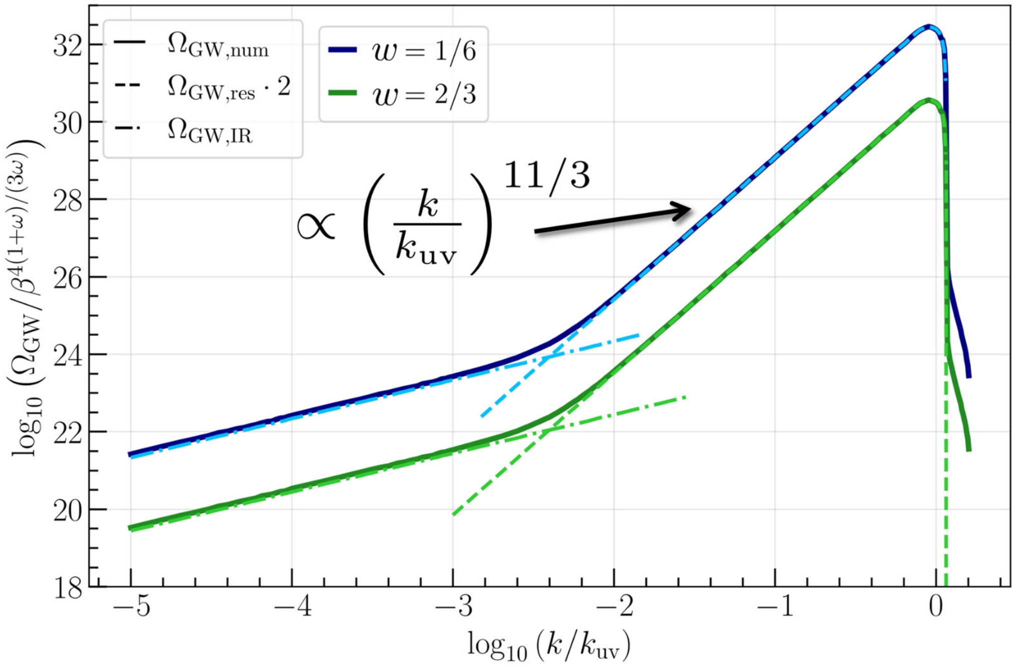
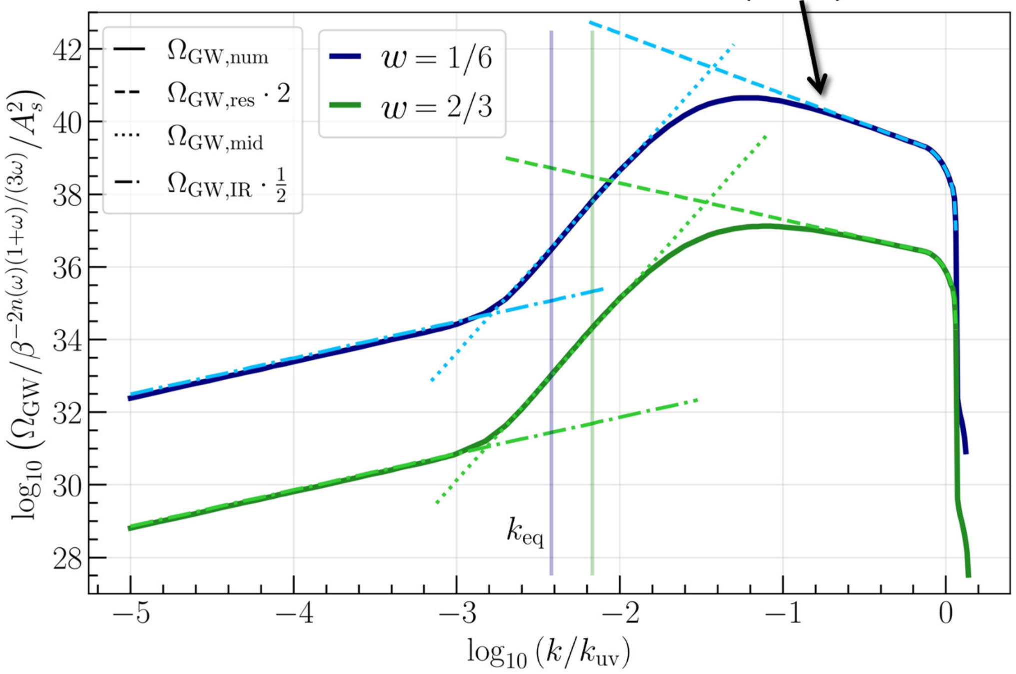


$$\sim C(w)^4 \beta^{\frac{4(1+w)}{3w}}$$

- adiabatic iGWs

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



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

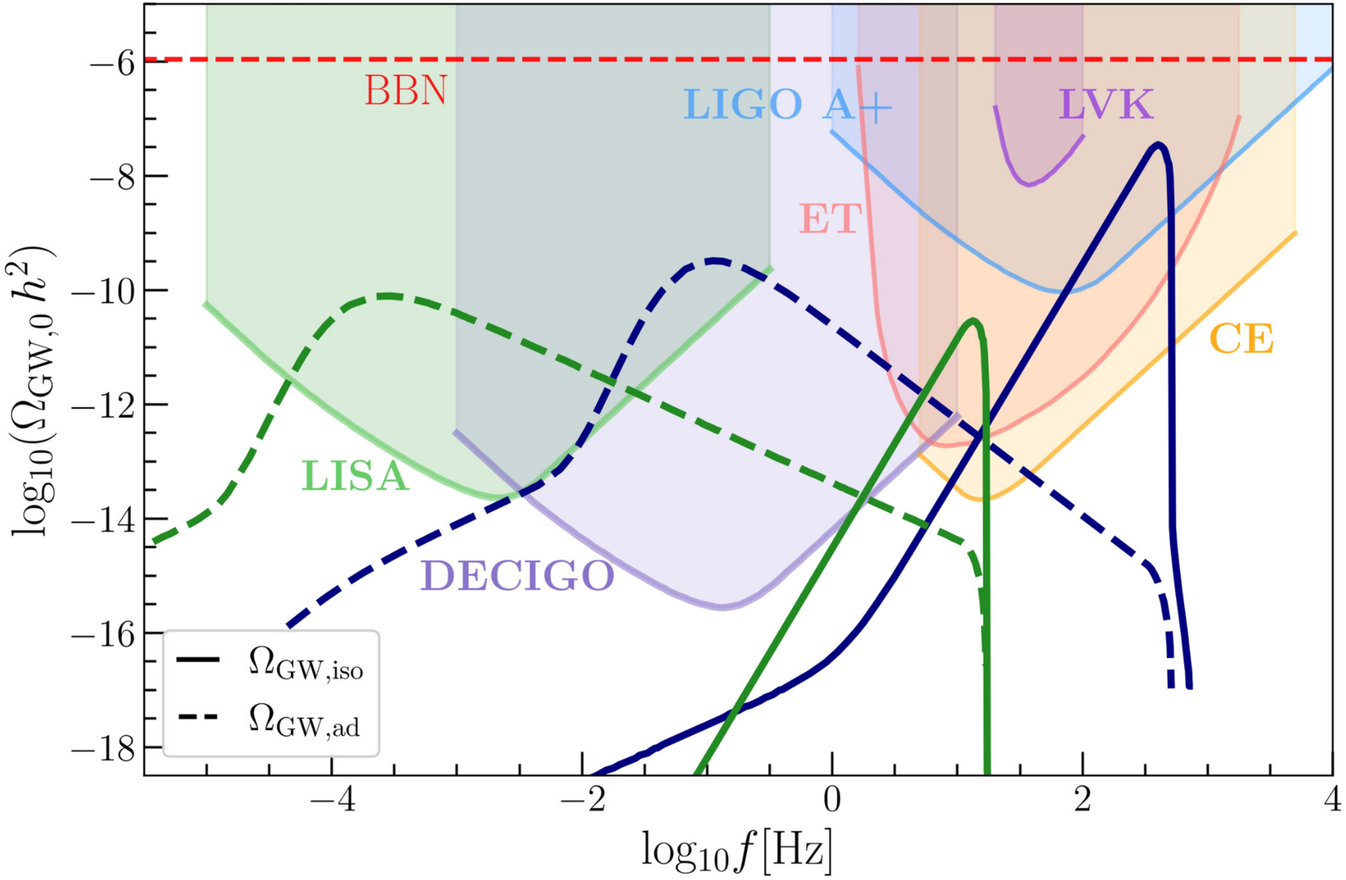
iGWs – observational prospects

- peak frequency
  - Isocurvature iGW

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

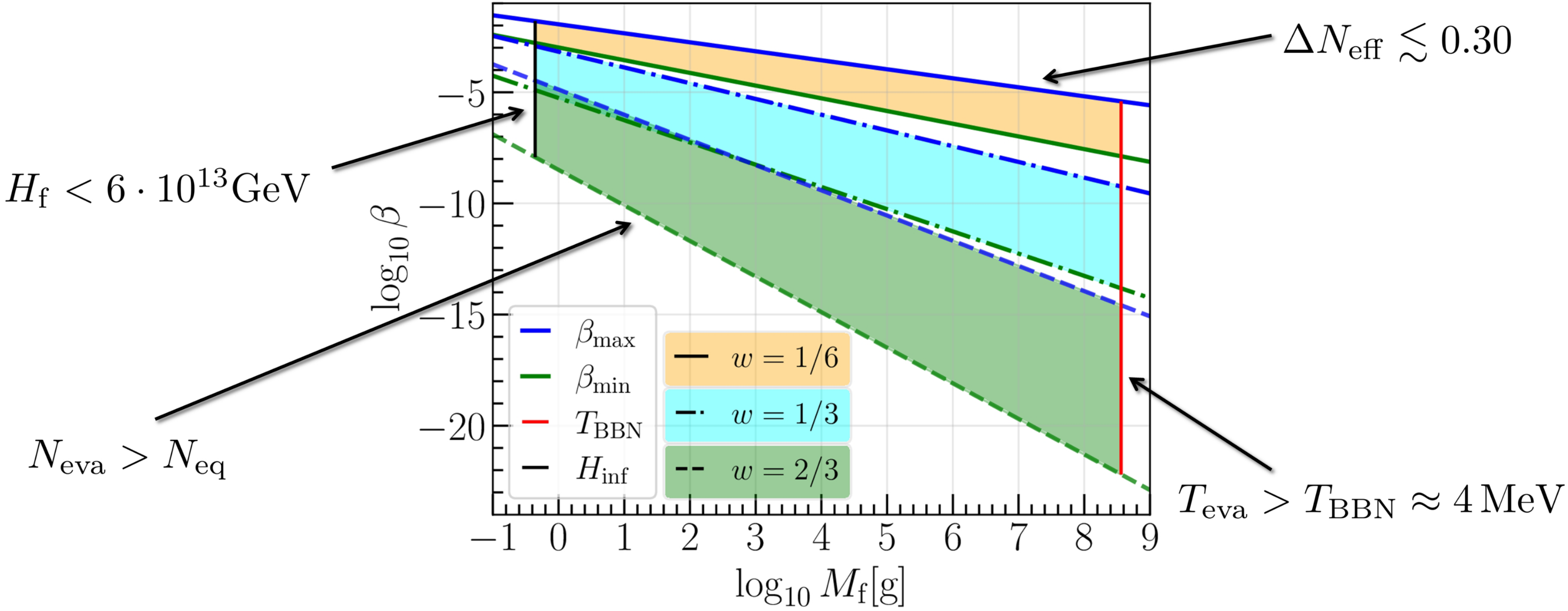
  - Adiabatic iGW

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

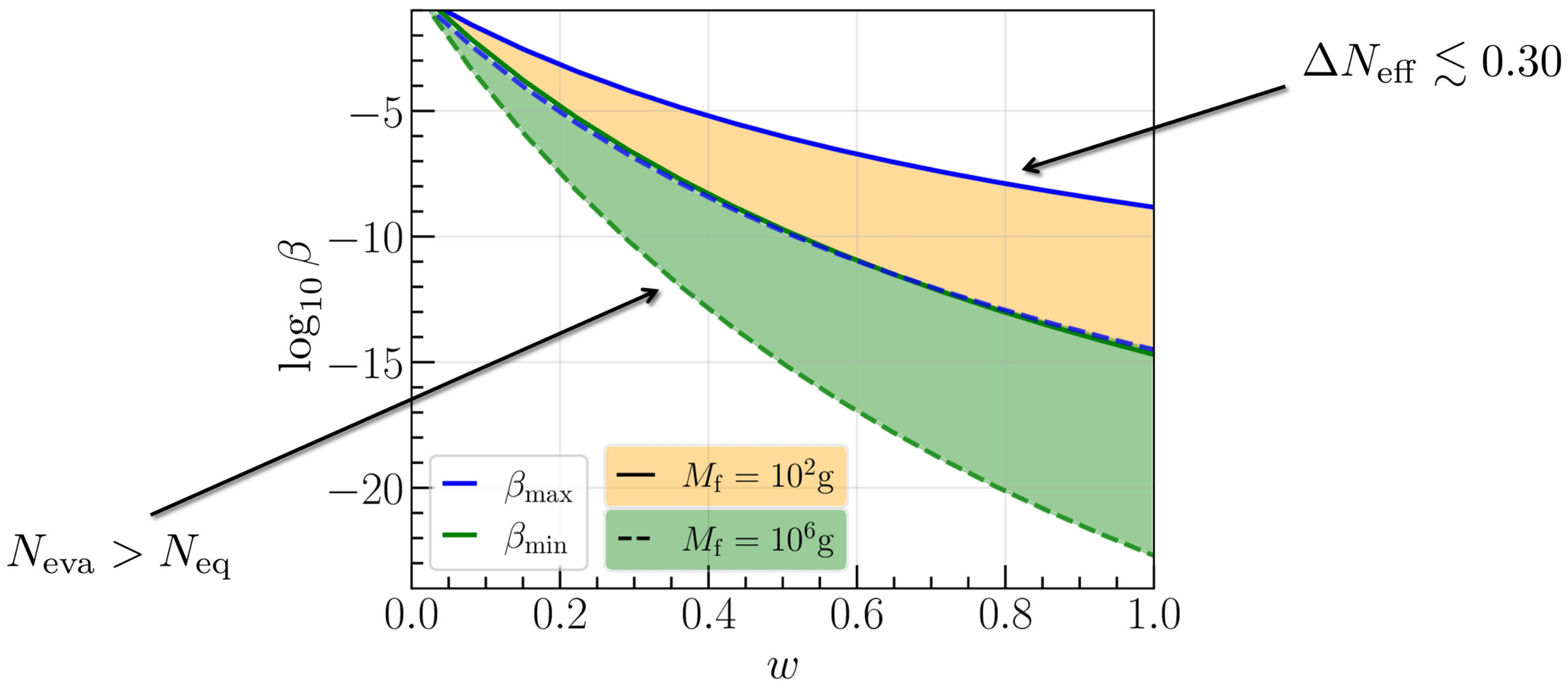


$M_i = 5 \times 10^4 g,\ \beta = 9 \times 10^{-5},\ w = 1/6$ (blue)
$M_i = 3 \times\ 10^6 g,\ \beta = 2 \times 10^{-14},\ w = 2/3$ (green)
$A_s = 2.1 \times 10^{-9}, n_s = 1$

Constraints on (β, M_i)



Constraints on (β, w)



Summary

- EoS $w \neq 1/3$ opens new parameter space for ultra-light PBHs to reheat Universe
- Duration of PBH domination & evolution of curvature perturbation depend on w
- Induced GWs probe PBH reheating & preceding epoch of PBH formation
- Adiabatic & isocurvature iGWs in reach of observations

- *Outlook*: effect of non-linear scales, extended mass function

Thank you for your attention!

Questions?