# Spectroscopy of Particle Couplings with Gravitational Waves

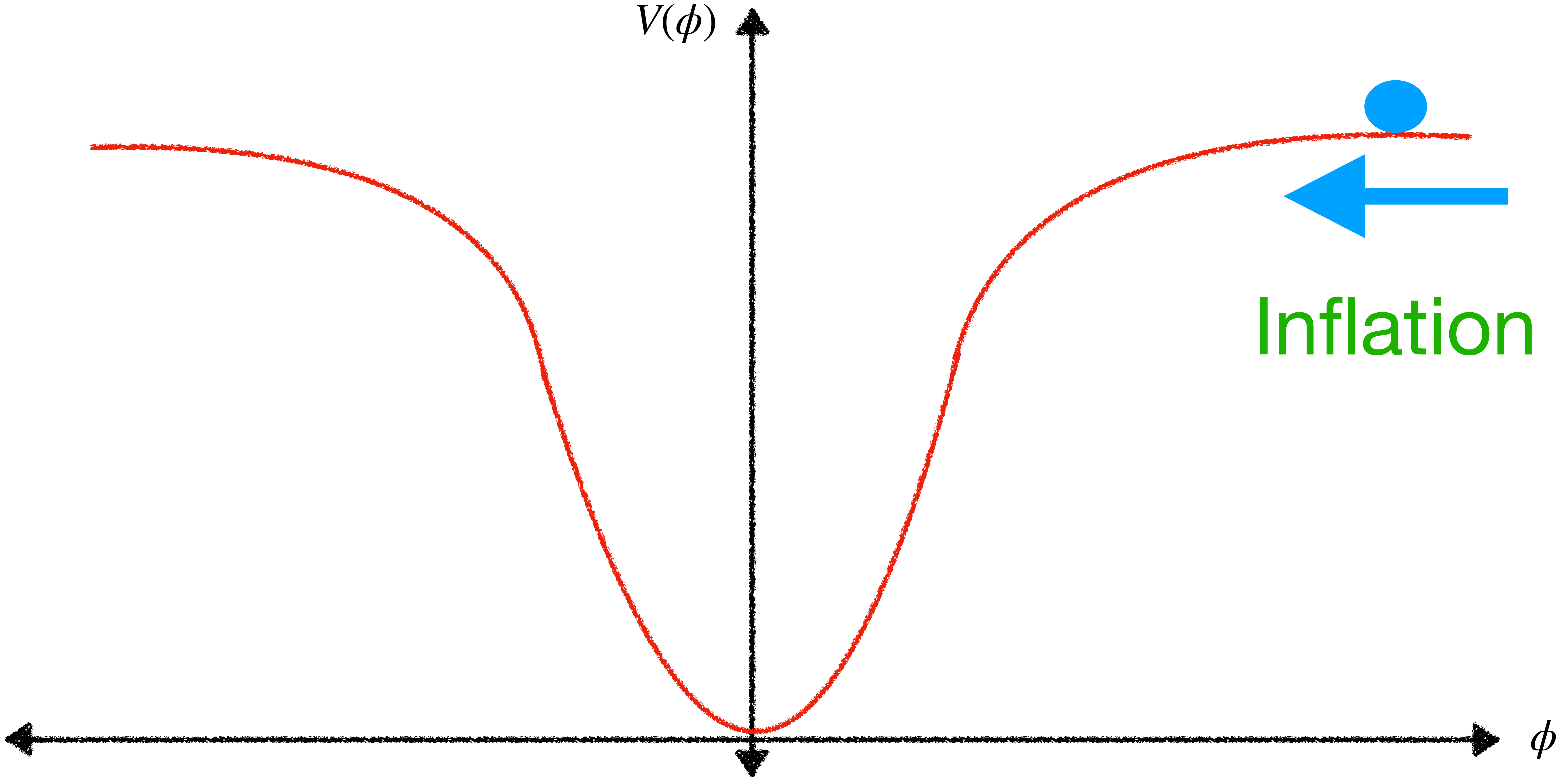
**Nicolás Loayza Romero (IFIC, Valencia, Spain)**

with: Daniel G. Figueroa, Adrien Florio and Mauro Pieroni

Based on: https://arxiv.org/pdf/2202.05805.pdf

# Preheating Scenario

$$V(\phi, \{\chi_j\}) = \frac{\Lambda^4}{2} \tanh^2\left(\frac{\phi}{M}\right) + \frac{1}{2} g_j^2 \chi_j^2 \phi^2$$




**Inflationary model: *$\alpha$-attractor***

Kallosh, Linde '13

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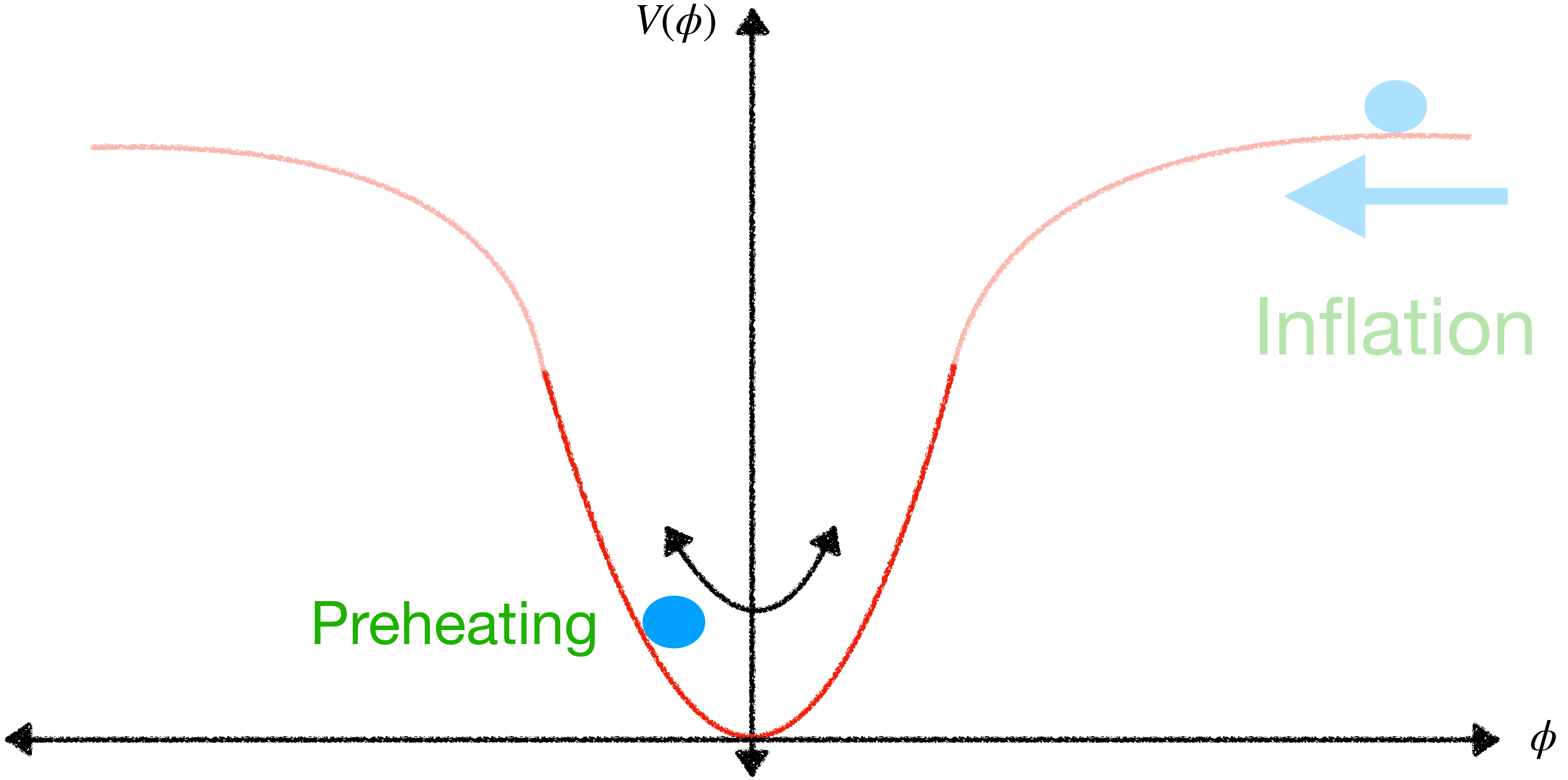


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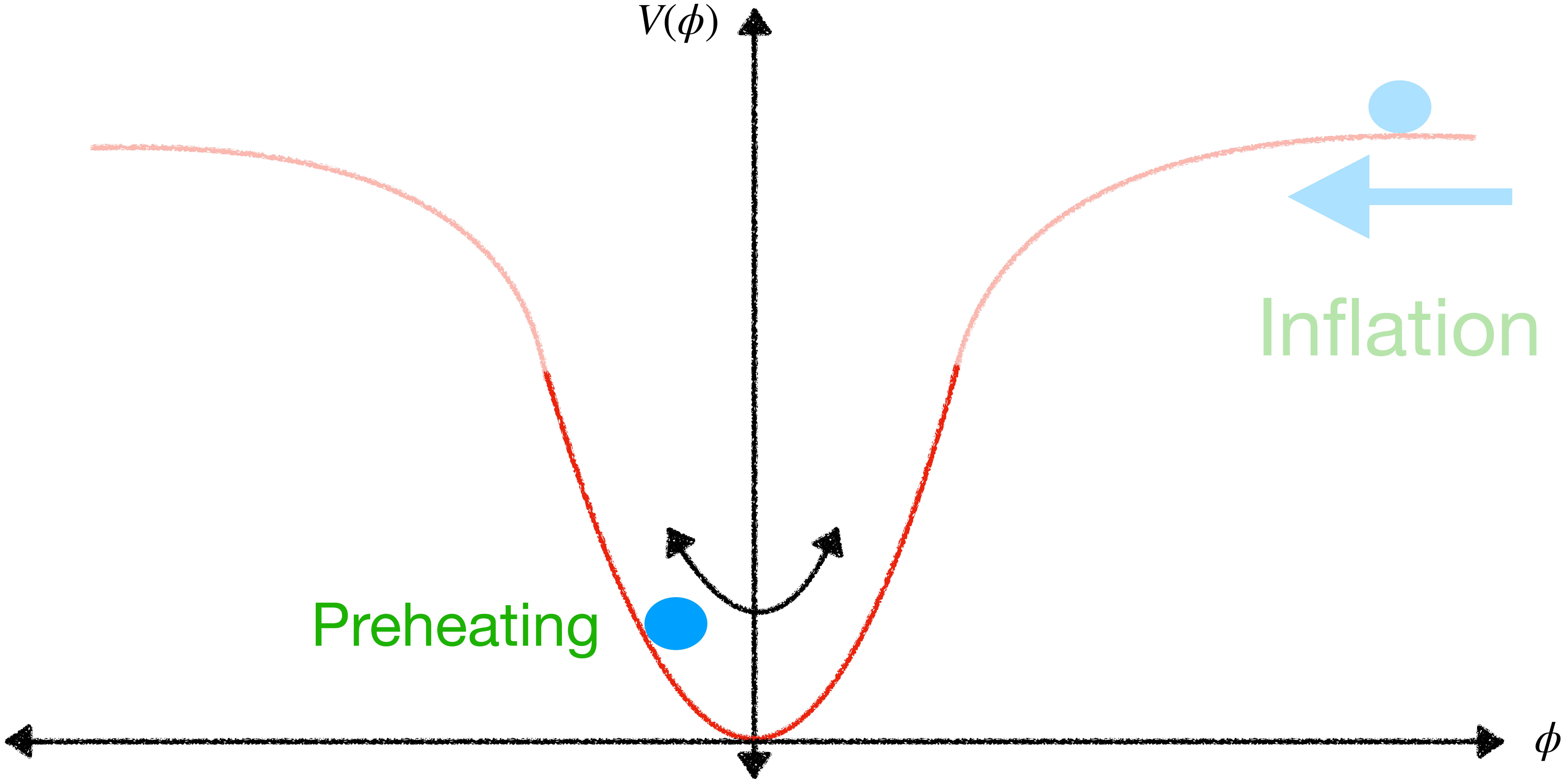


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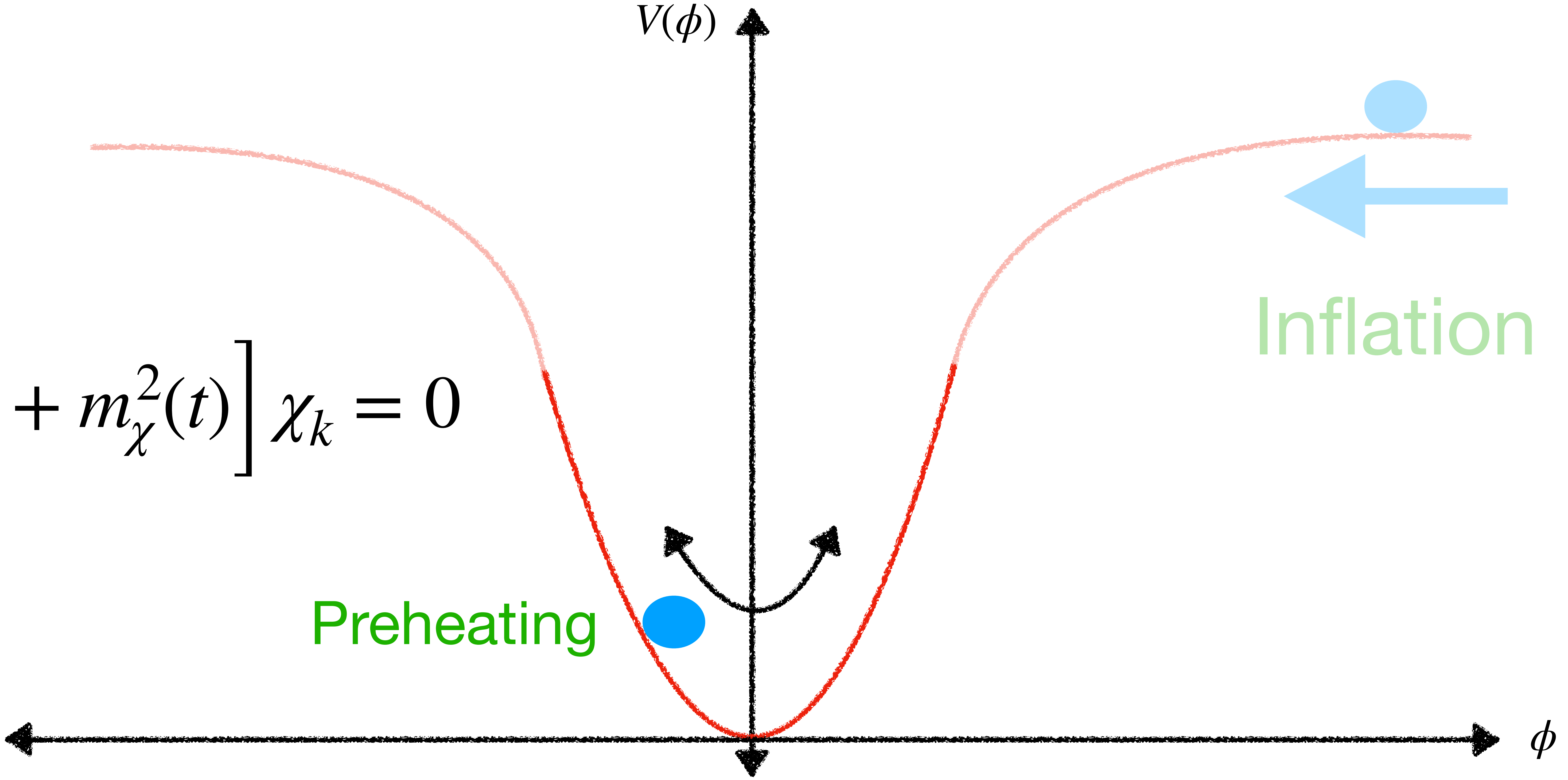
$$\ddot{\chi}_k + \left[\kappa^2 + m_\chi^2(t)\right]\chi_k = 0$$

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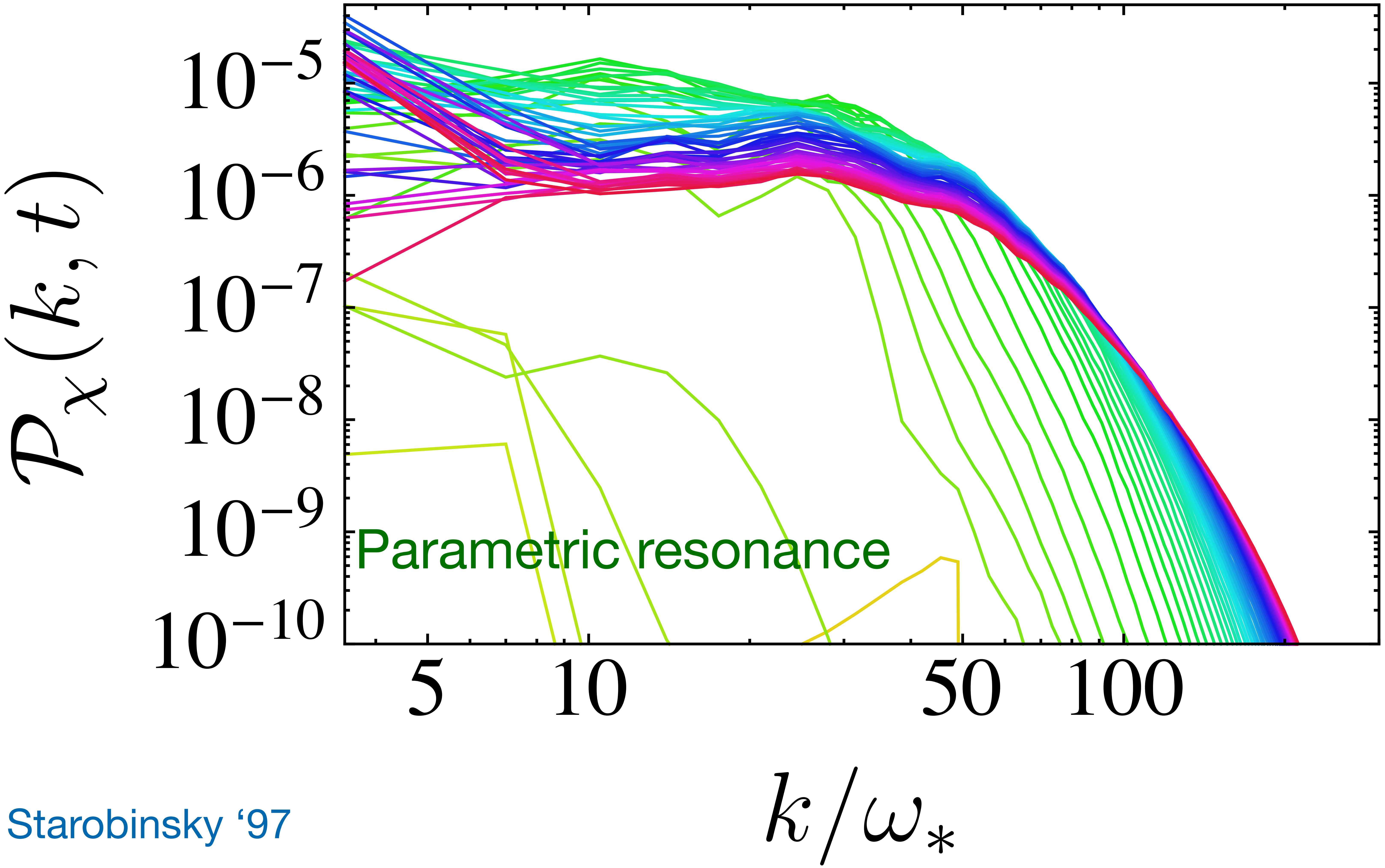


$$q = \frac{g^2 \phi_*^2}{\omega_*^2}$$

Kofman, Linde, Starobinsky '97

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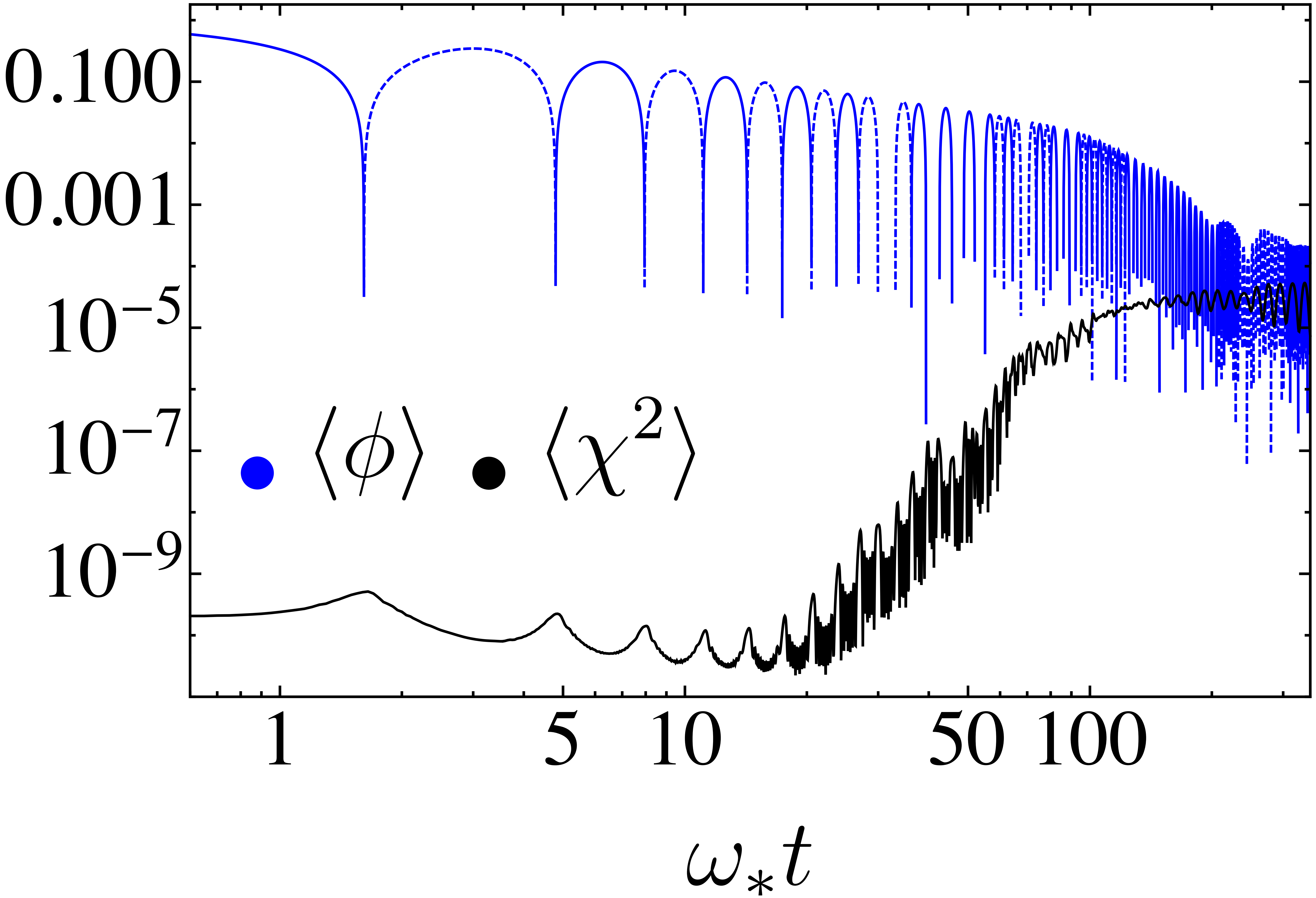

# Gravitational waves

FLRW background + tensor perturbations

$$ds^2 = -dt^2 + a(t)^2(\delta_{ij} + h_{ij})dx_i dx_j \quad \Rightarrow \quad h_{ii} = \partial_i h_{ij} = 0$$

Equation of Motion

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} + \frac{\nabla^2}{a^2}h_{ij} = \frac{2}{m_p^2 a^2}\{\partial_i\phi\partial_j\phi + \partial_i\chi\partial_j\chi\}^{TT}$$

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Transverse-Traceless

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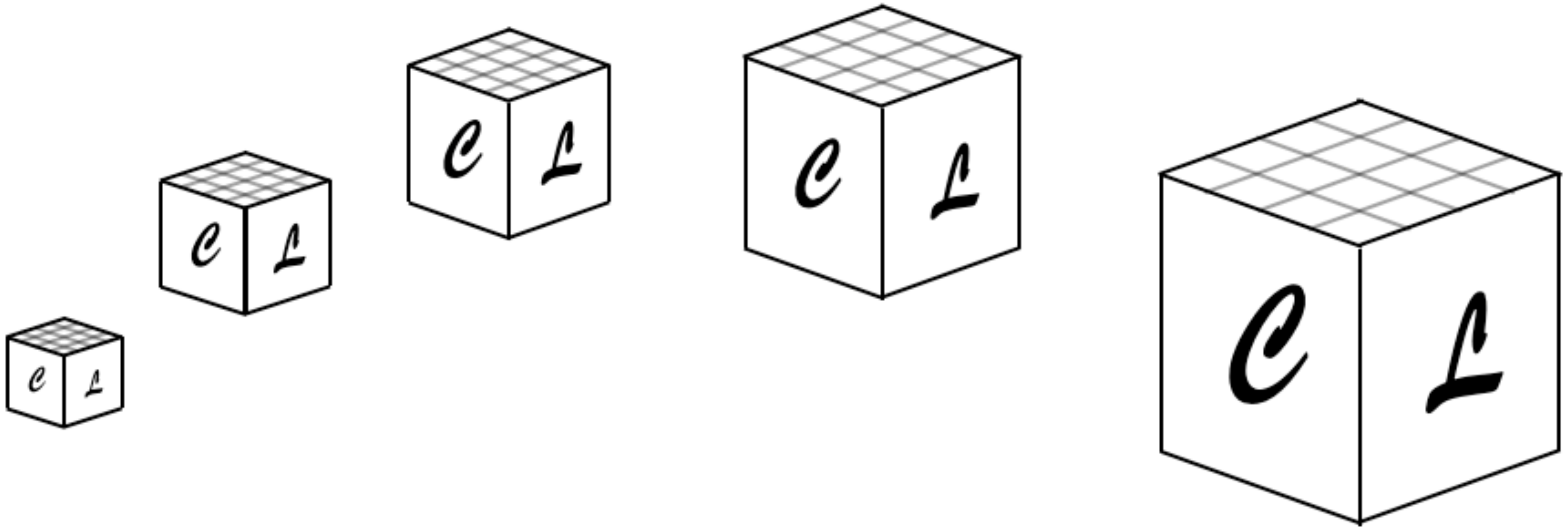
# Lattice Simulations

## CosmoLattice

Figueroa, Florio, Torrenti & Valkenburg ‘20

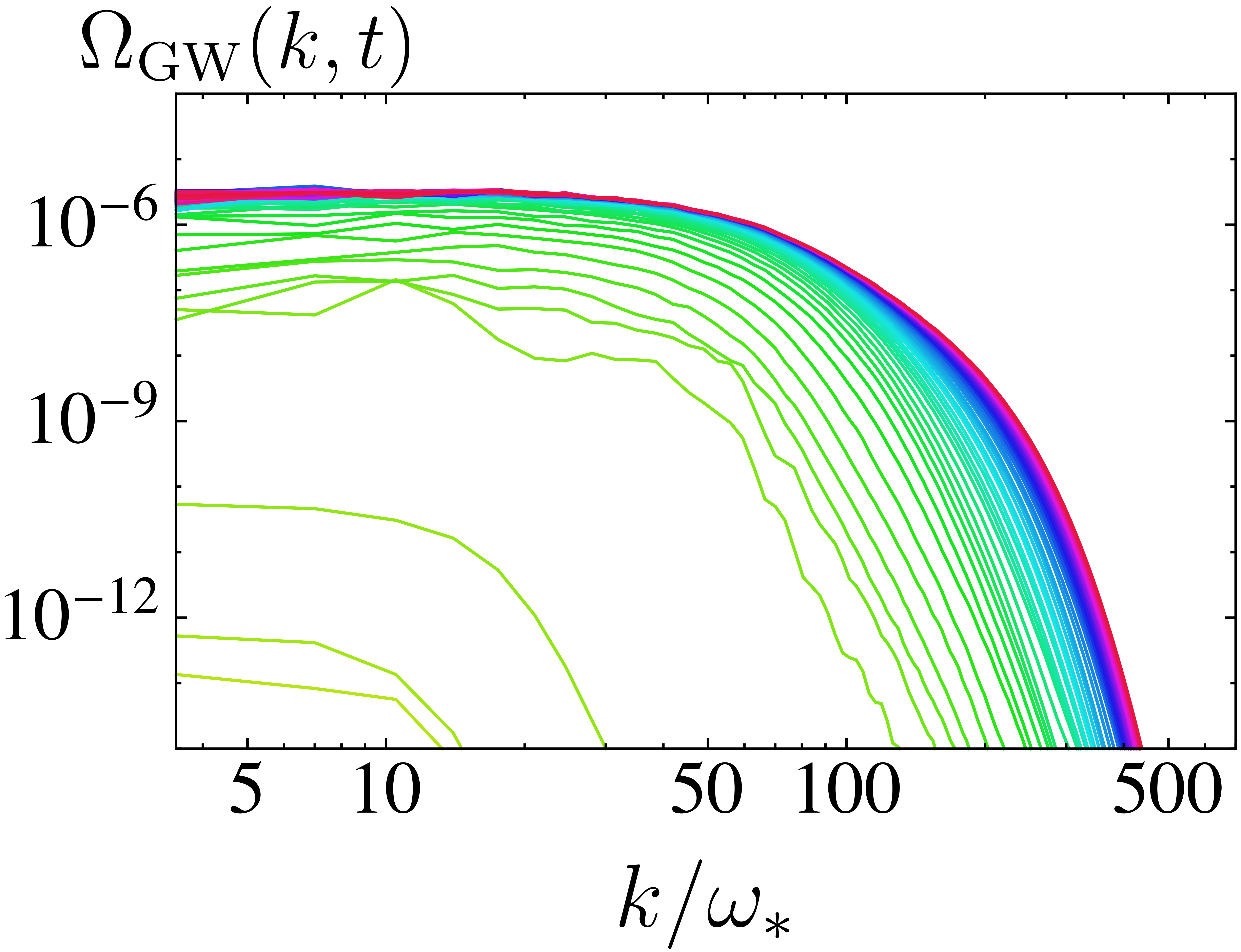



https://cosmolattice.net

**Version 1.1: New GWs Module**

Baeza-Ballesteros & NL ’22

# Stochastic Gravitational Wave Background (SGWB)

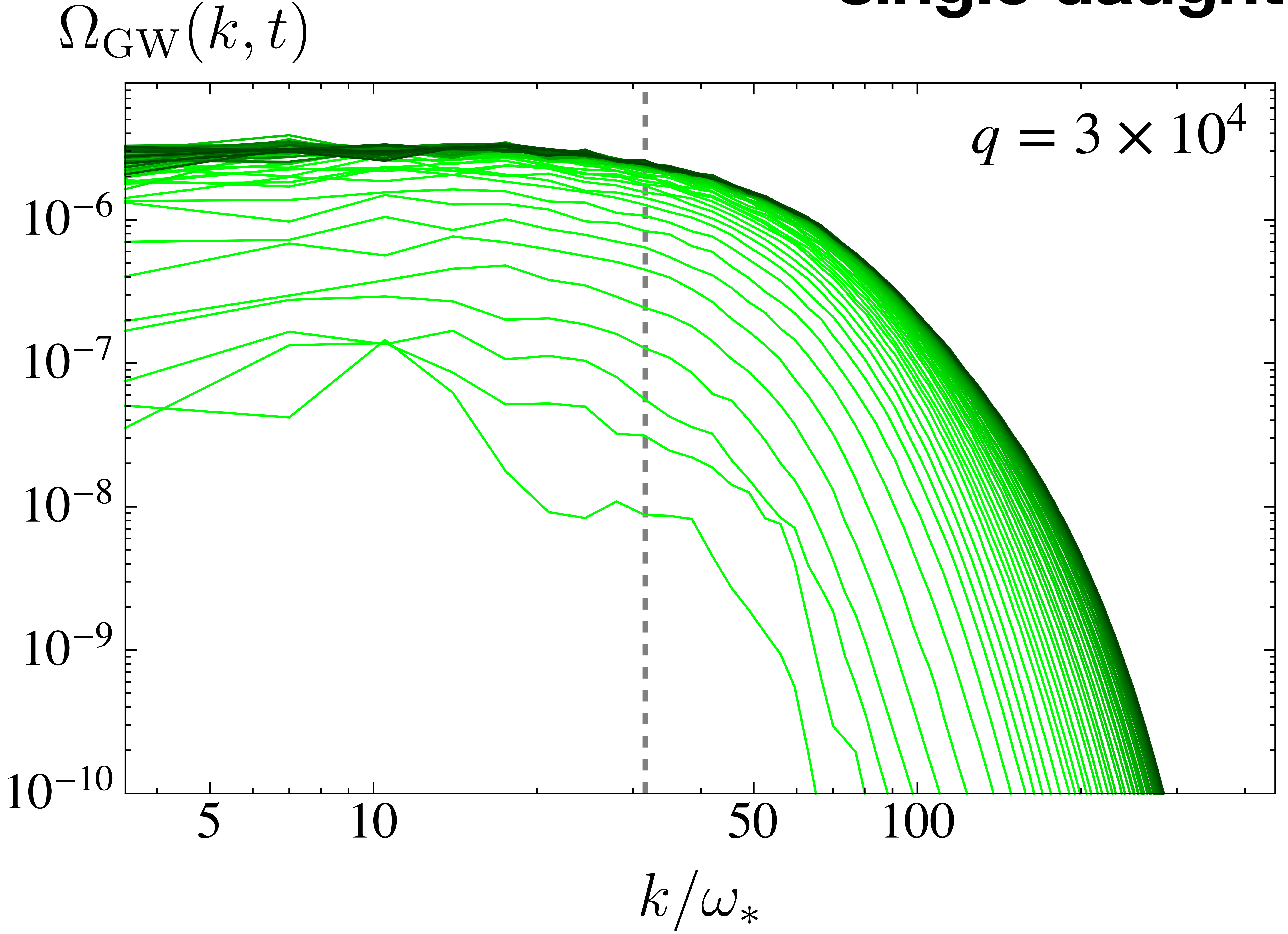



$$\Omega_{\rm GW}(k,t) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\log k}$$

$$\frac{d\rho_{\rm GW}}{d\log k} = \frac{k^3}{(4\pi)^3 GV}\int \frac{d\Omega_k}{4\pi}\dot{h}_{ij}(\mathbf{k},t)\dot{h}^*_{ij}(\mathbf{k},t)$$

Khlenbnikov, Tkachev ’97
Easther, Giblin, Lim ’06 - ‘08
Figueroa, García-Bellido, et al ’07 - ‘10
Kofman, Dufaux, et al ’07 - ‘09

# GW spectrum parametrization of single daughter field




Peak position parameter dependence

$$\frac{k_p(q)}{\omega_*} = (21.22 \pm 7.64)\left(\frac{q}{10^4}\right)^{0.52\pm0.08}$$

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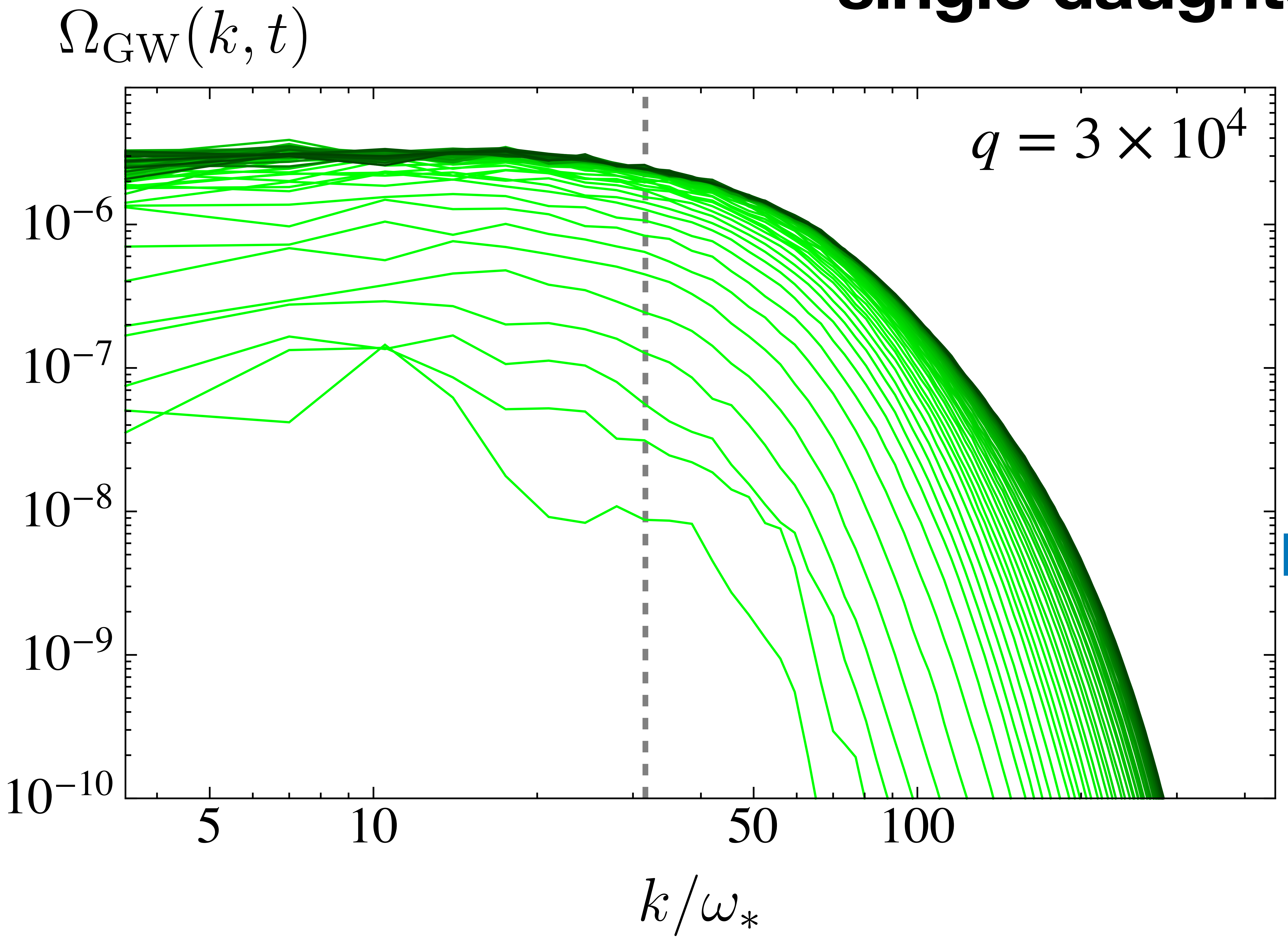



Peak position parameter dependence

$$\frac{k_p(q)}{\omega_*} = (21.22 \pm 7.64)\left(\frac{q}{10^4}\right)^{0.52\pm0.08}$$

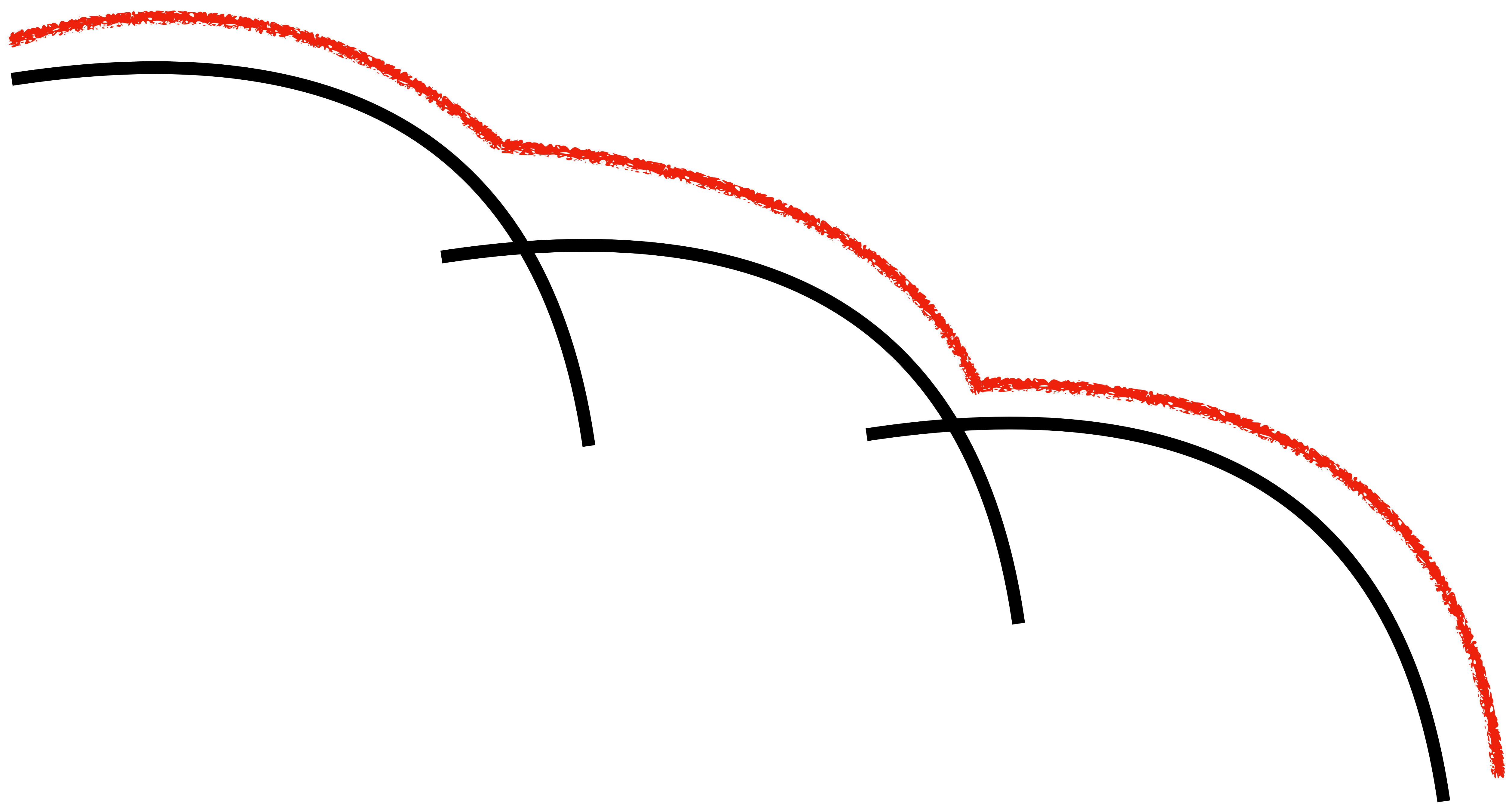
Peak amplitude parameter dependence

$$\Omega_{\rm GW}^{(p)}(q) = (1.2 \pm 0.7)\times 10^{-5}\left(\frac{q}{10^4}\right)^{-1.1\pm0.12}$$

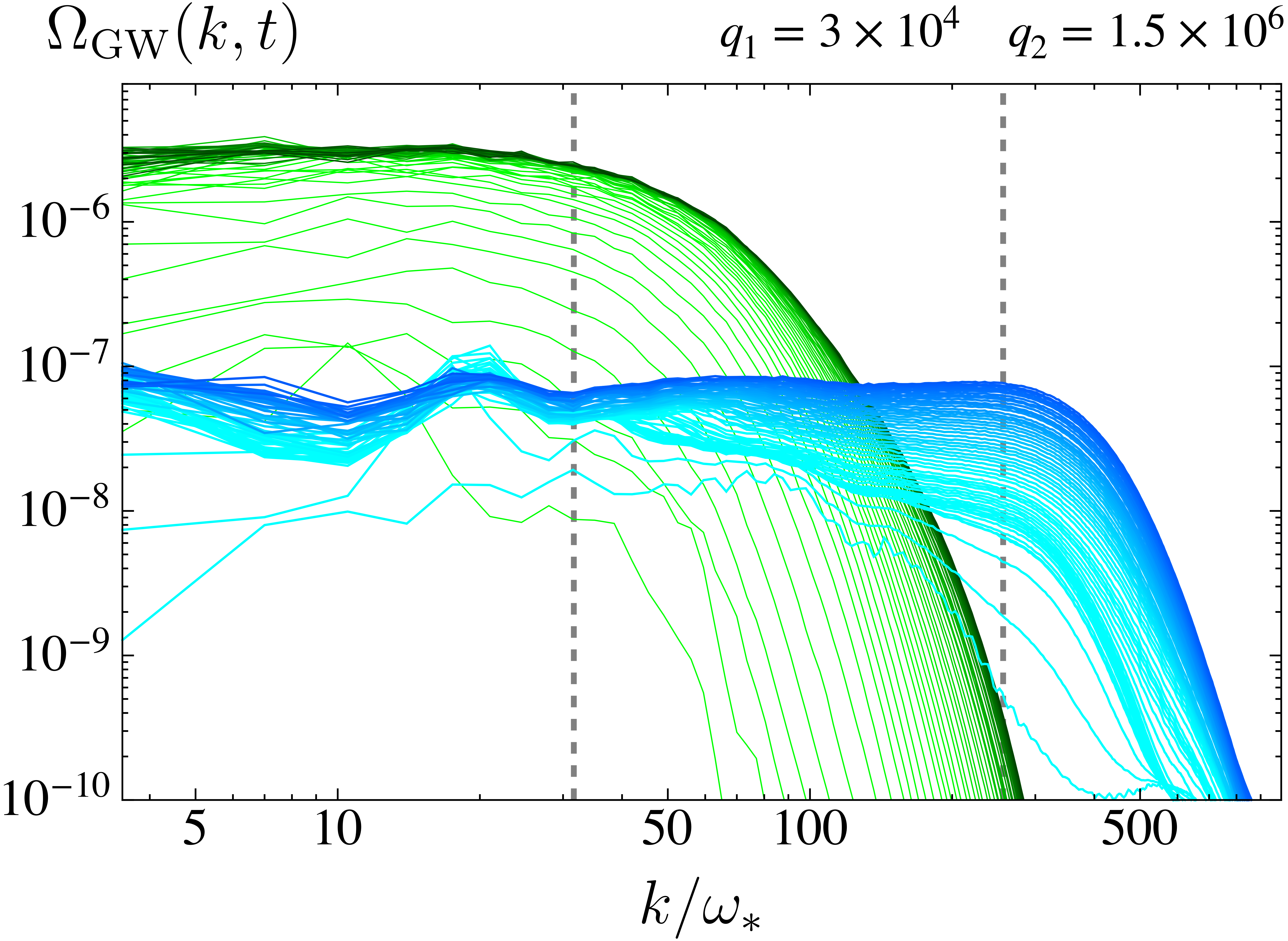
# What if multiple daughter fields?

## Multipeak Spectra?

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} + \frac{\nabla^2}{a^2}h_{ij} = \frac{2}{m_p^2 a^2}\left\{\partial_i\phi\partial_j\phi + \sum_n \left(\partial_i\chi_n\partial_j\chi_n\right)\right\}^{TT}$$



# Preheating scenario with 2 daughter fields



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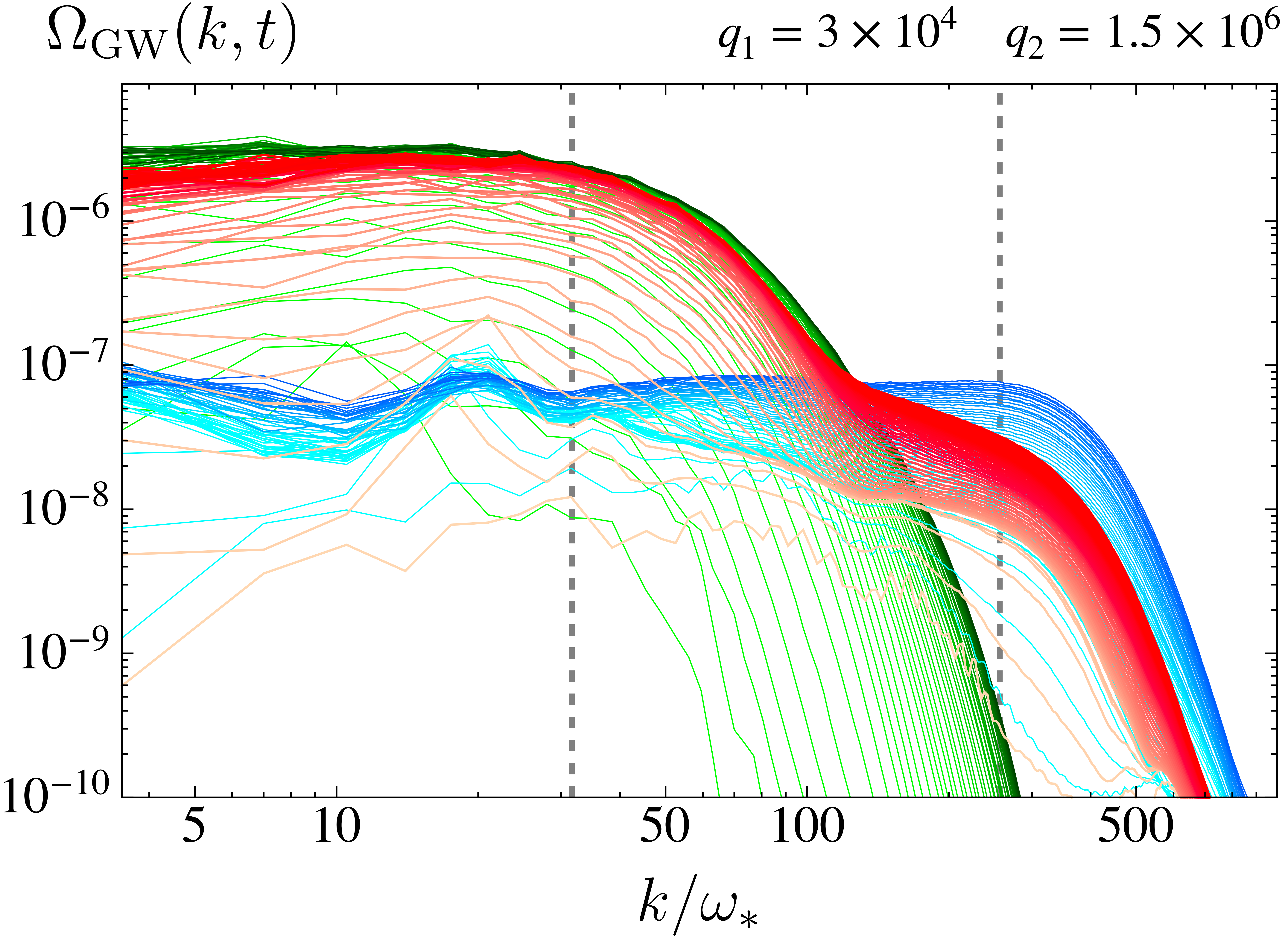

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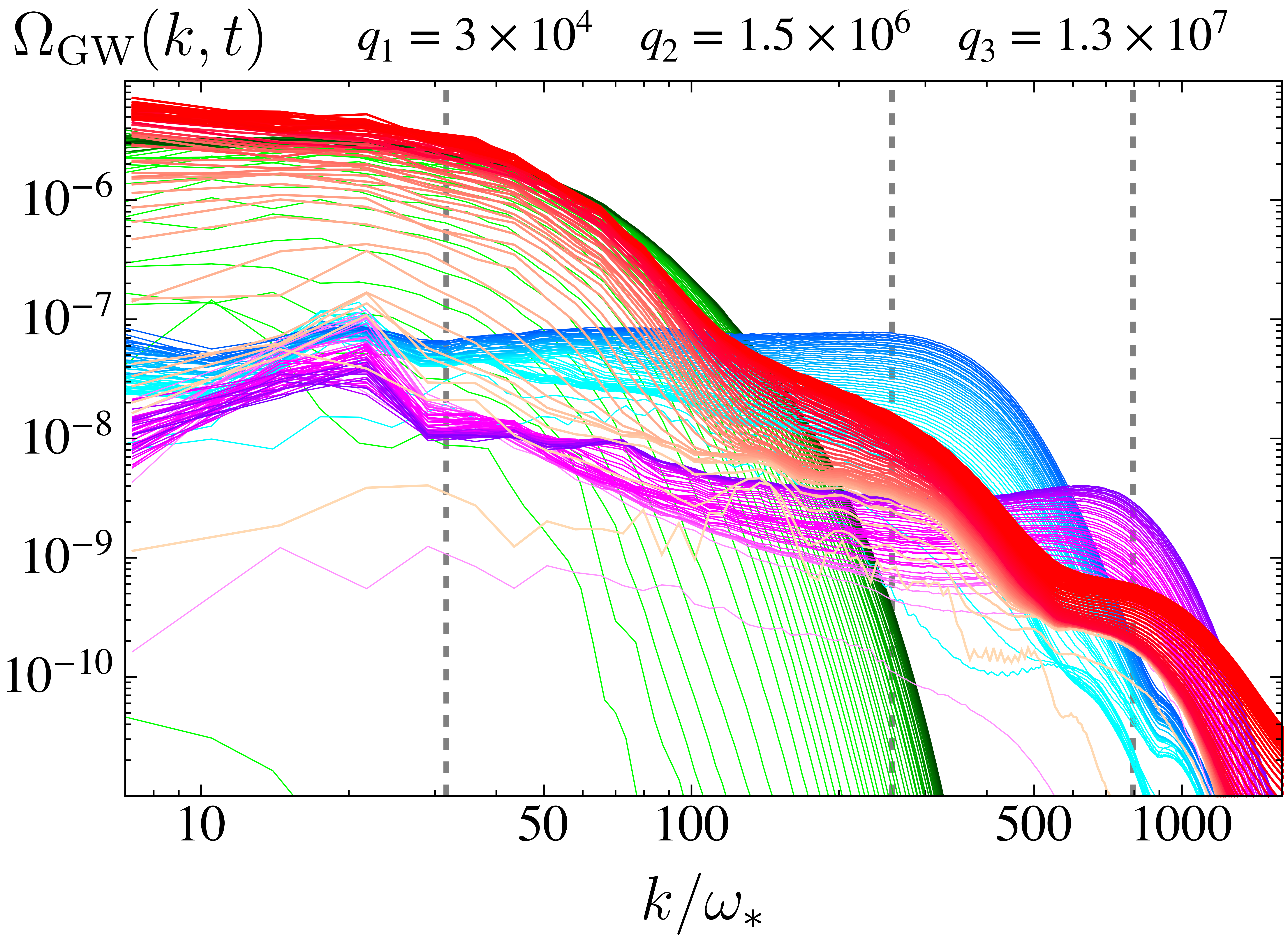

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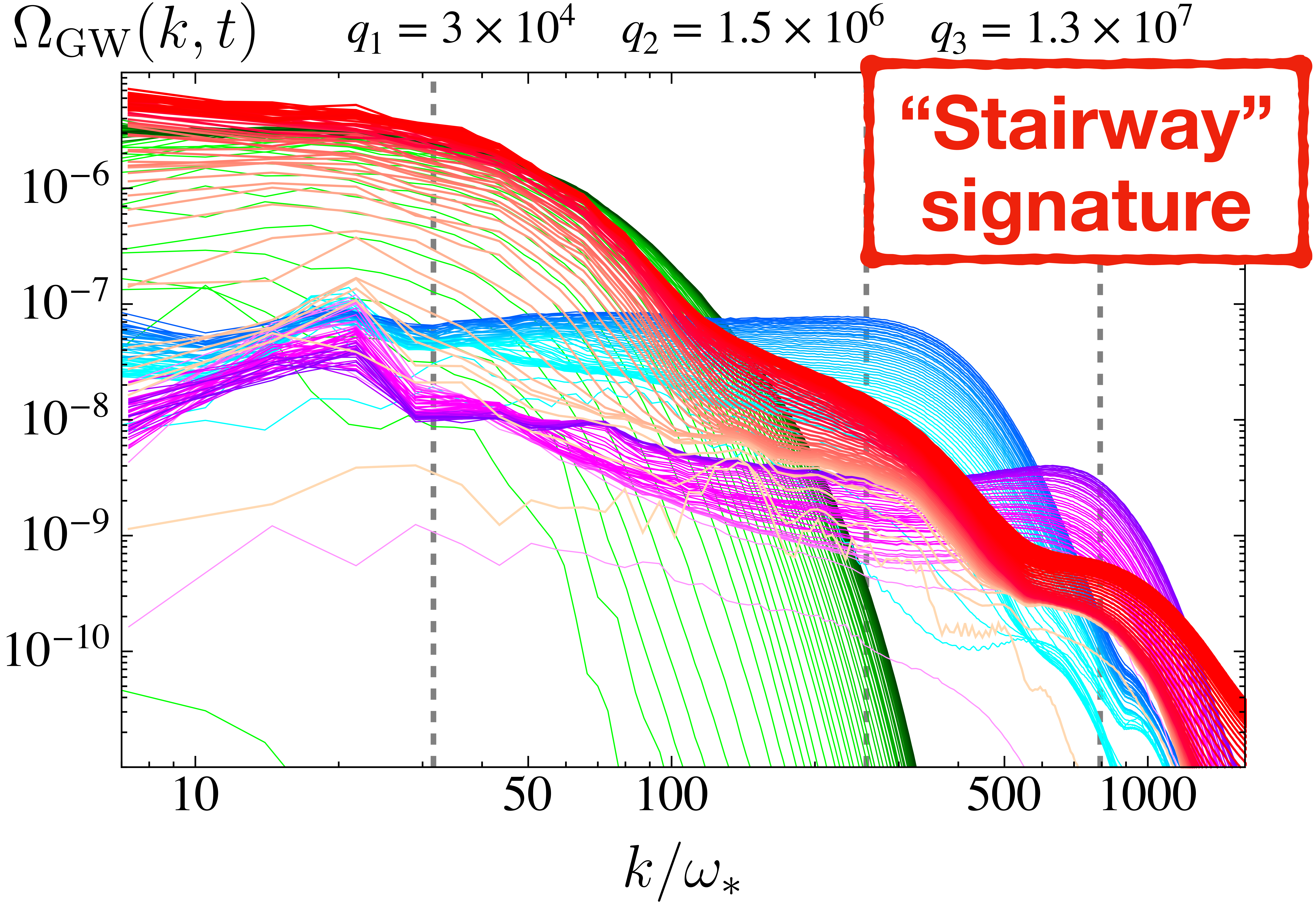

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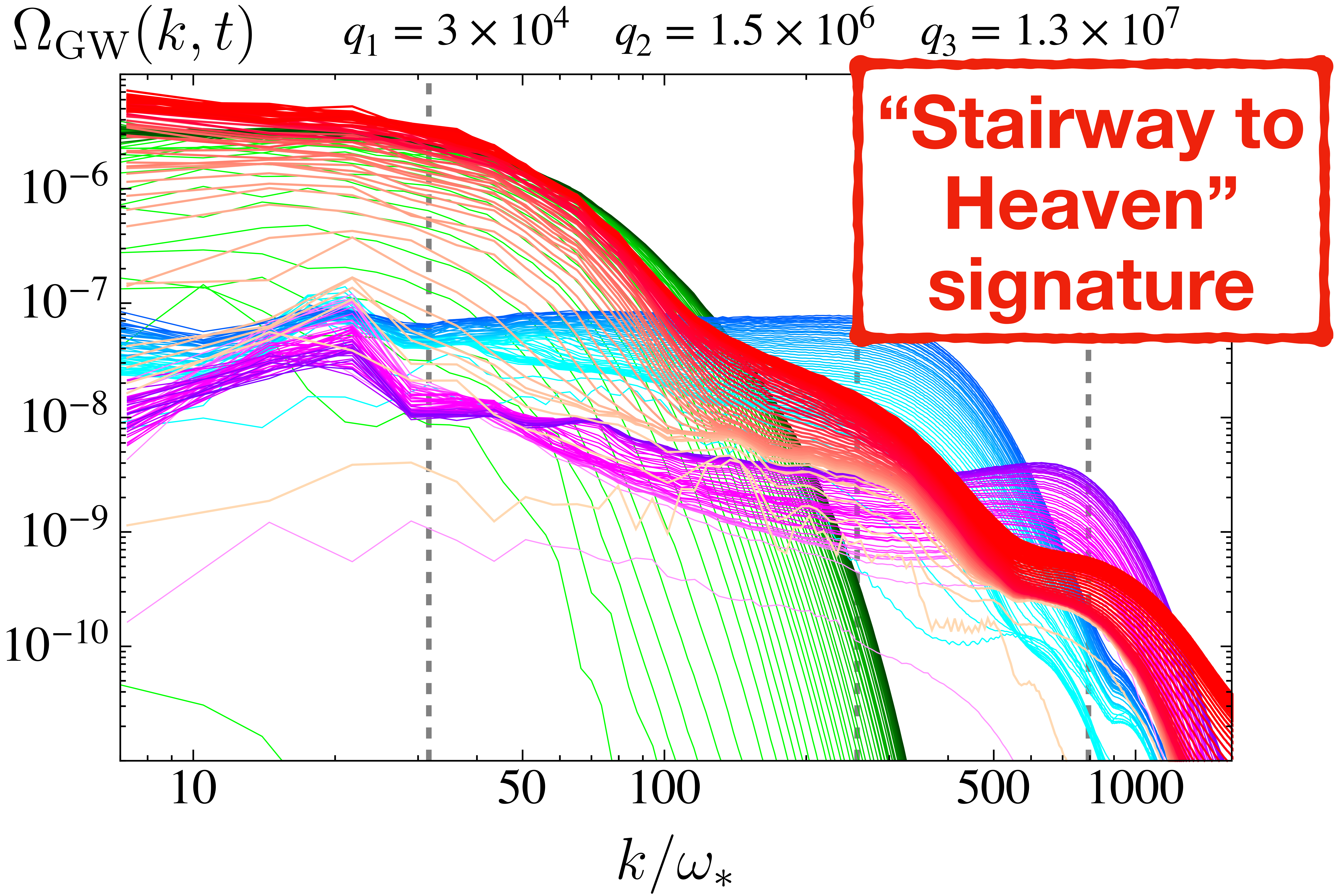
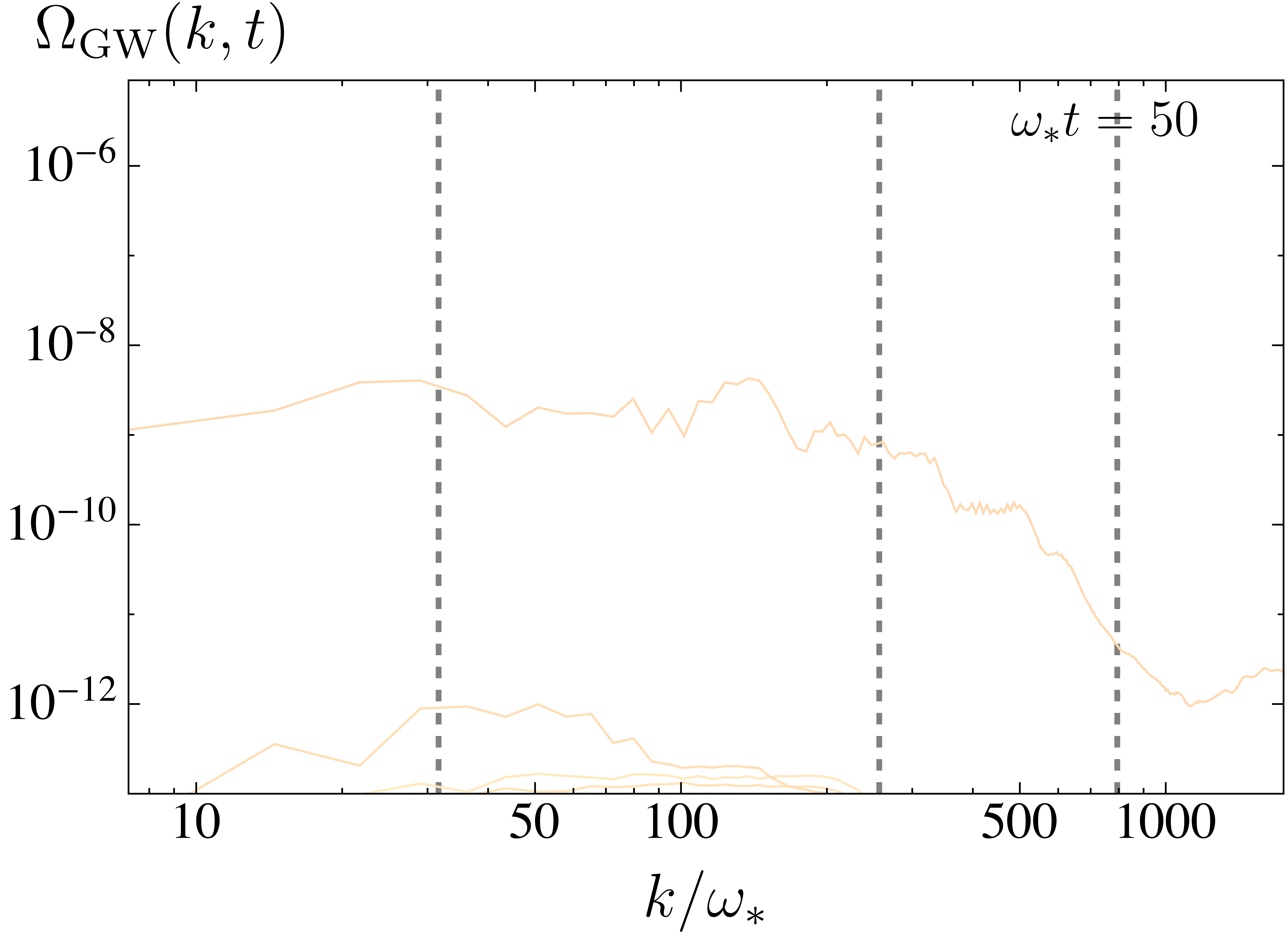
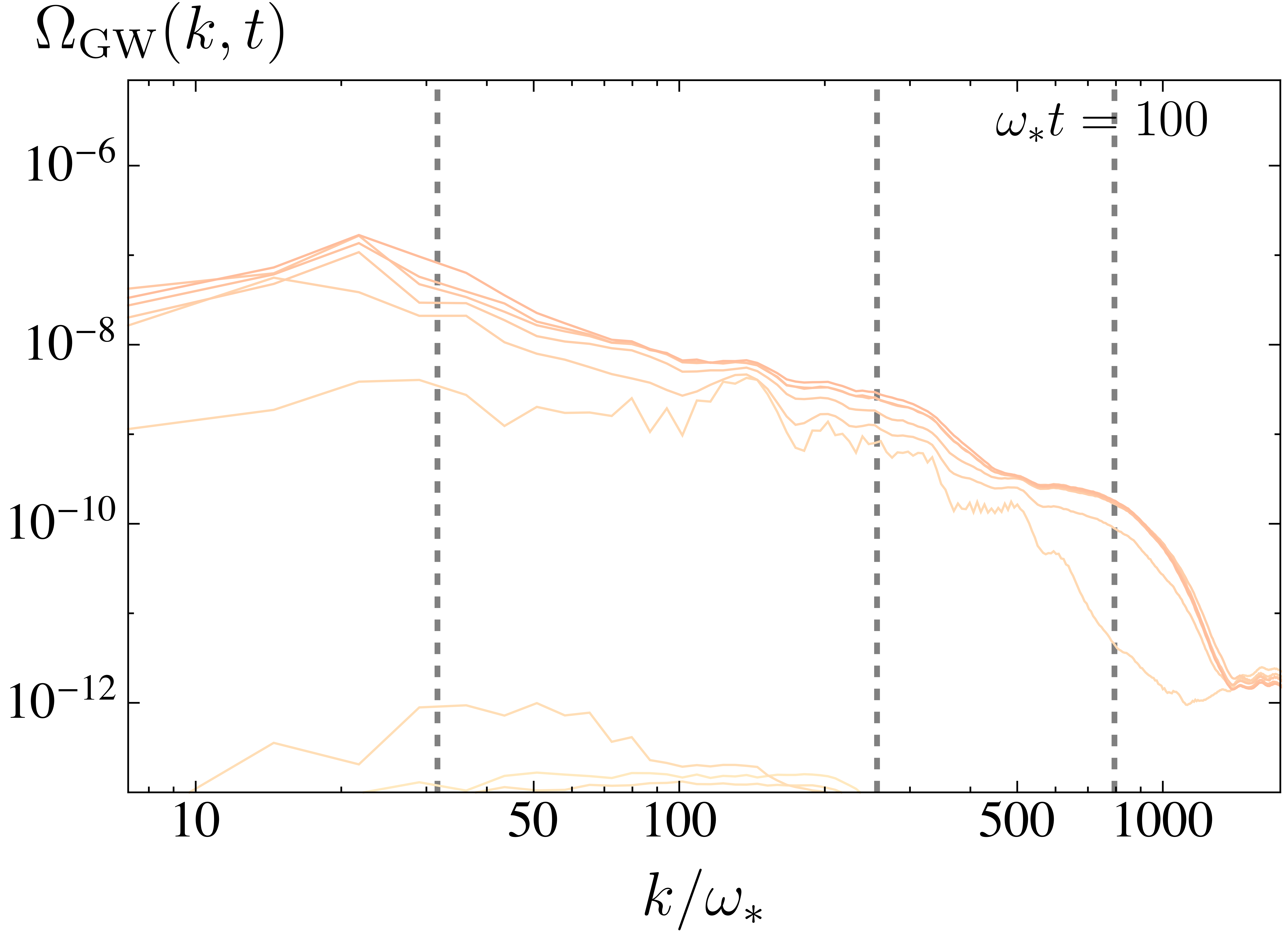
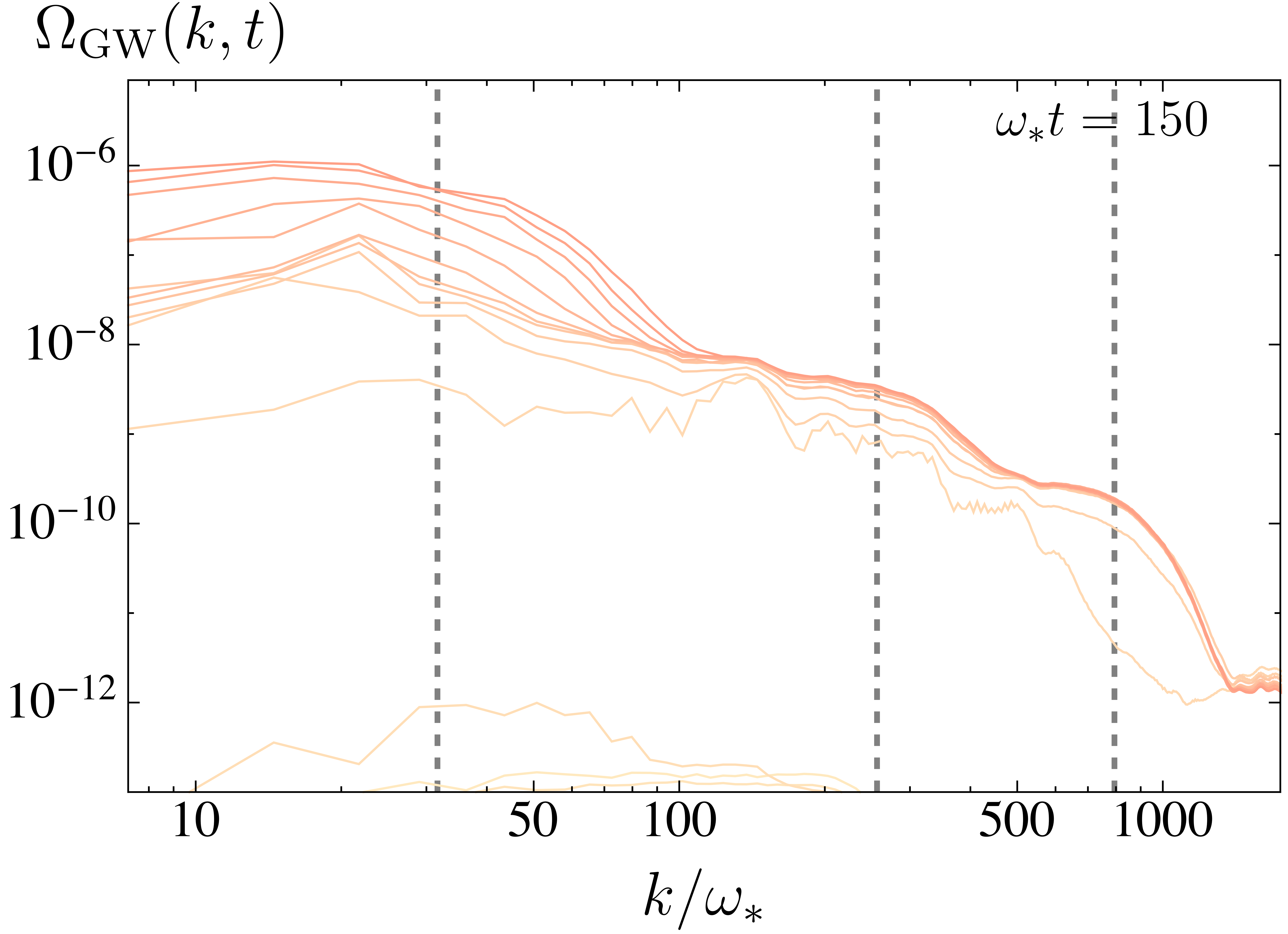




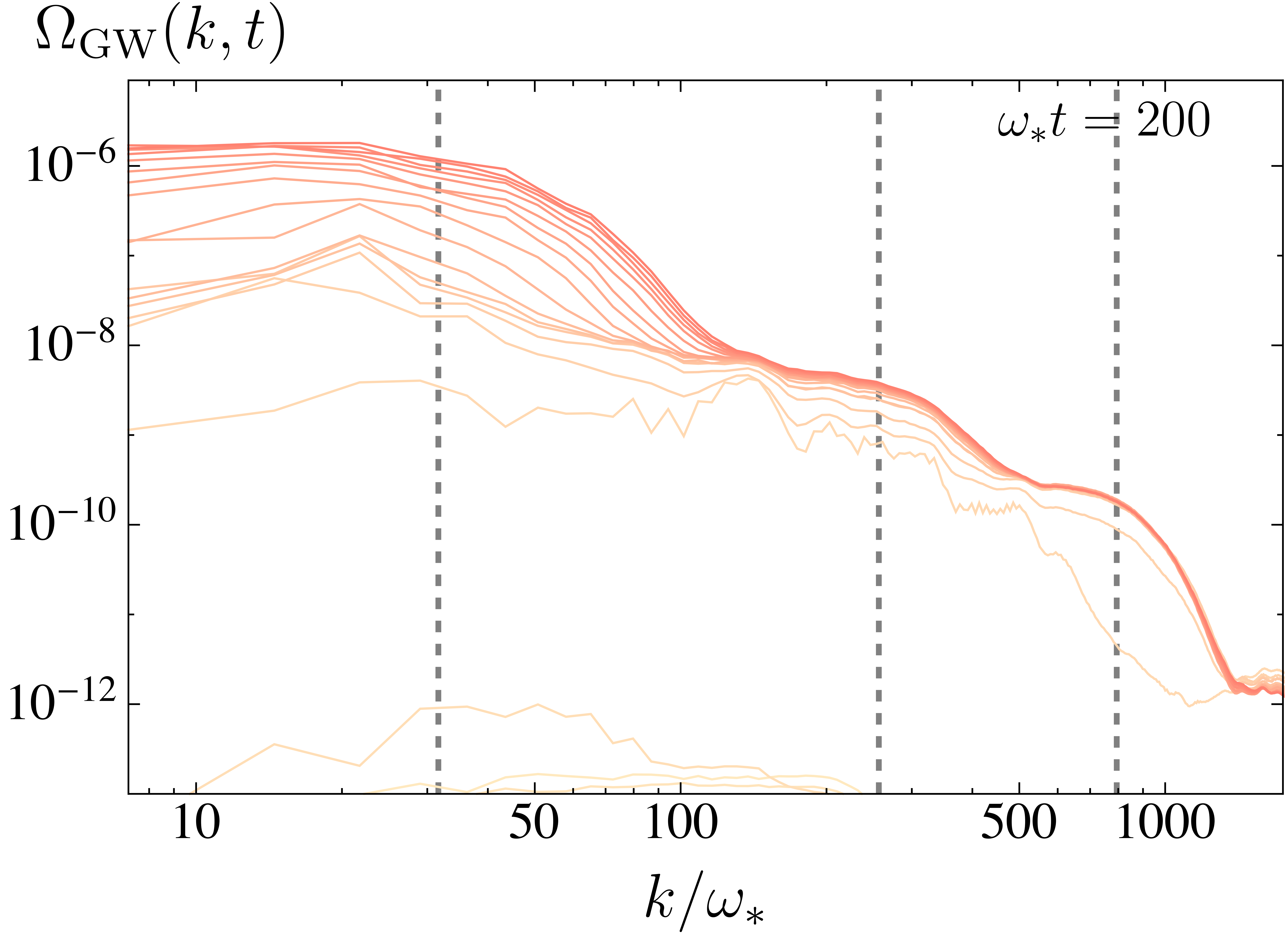
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 50$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



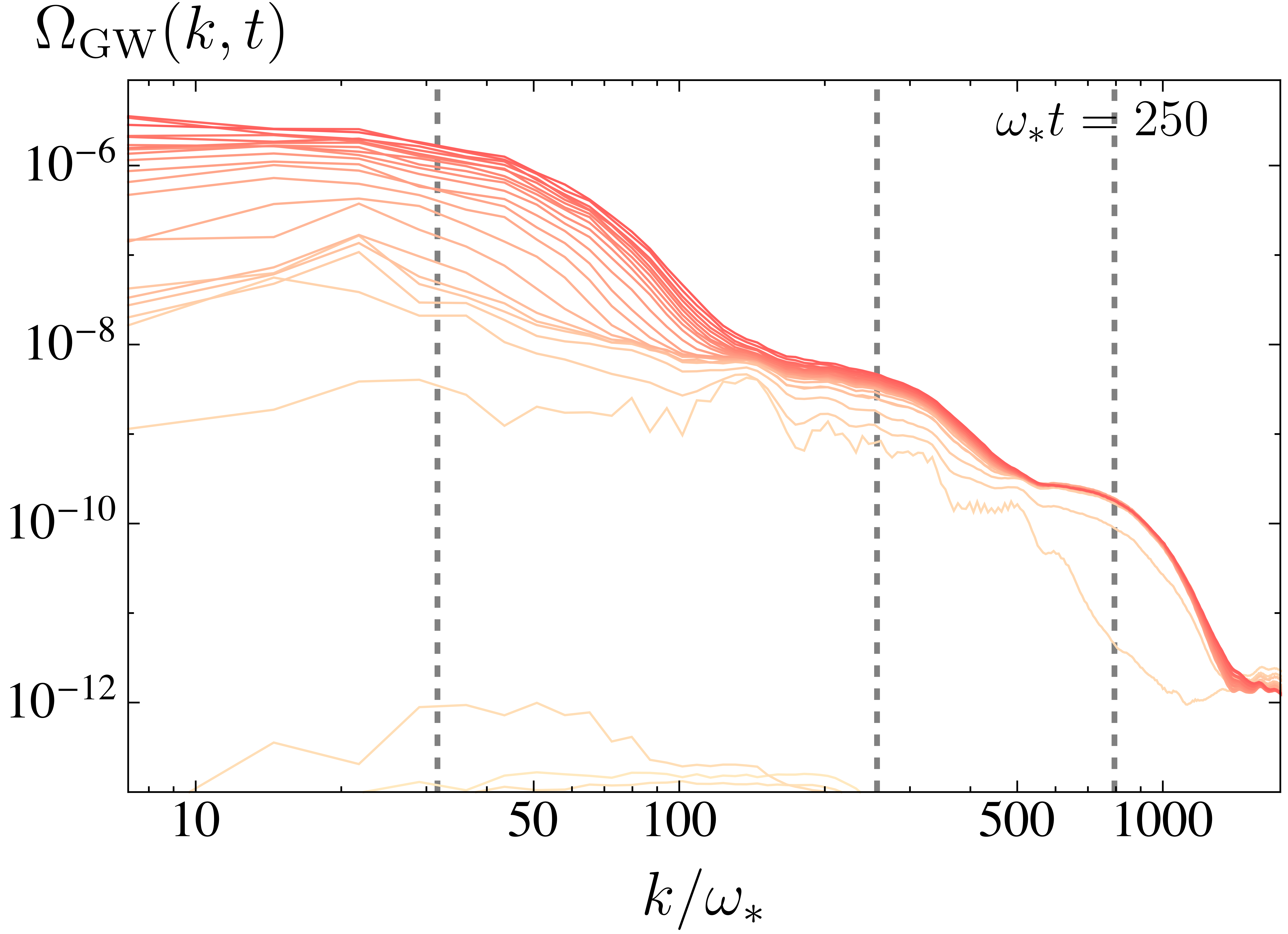
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 100$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



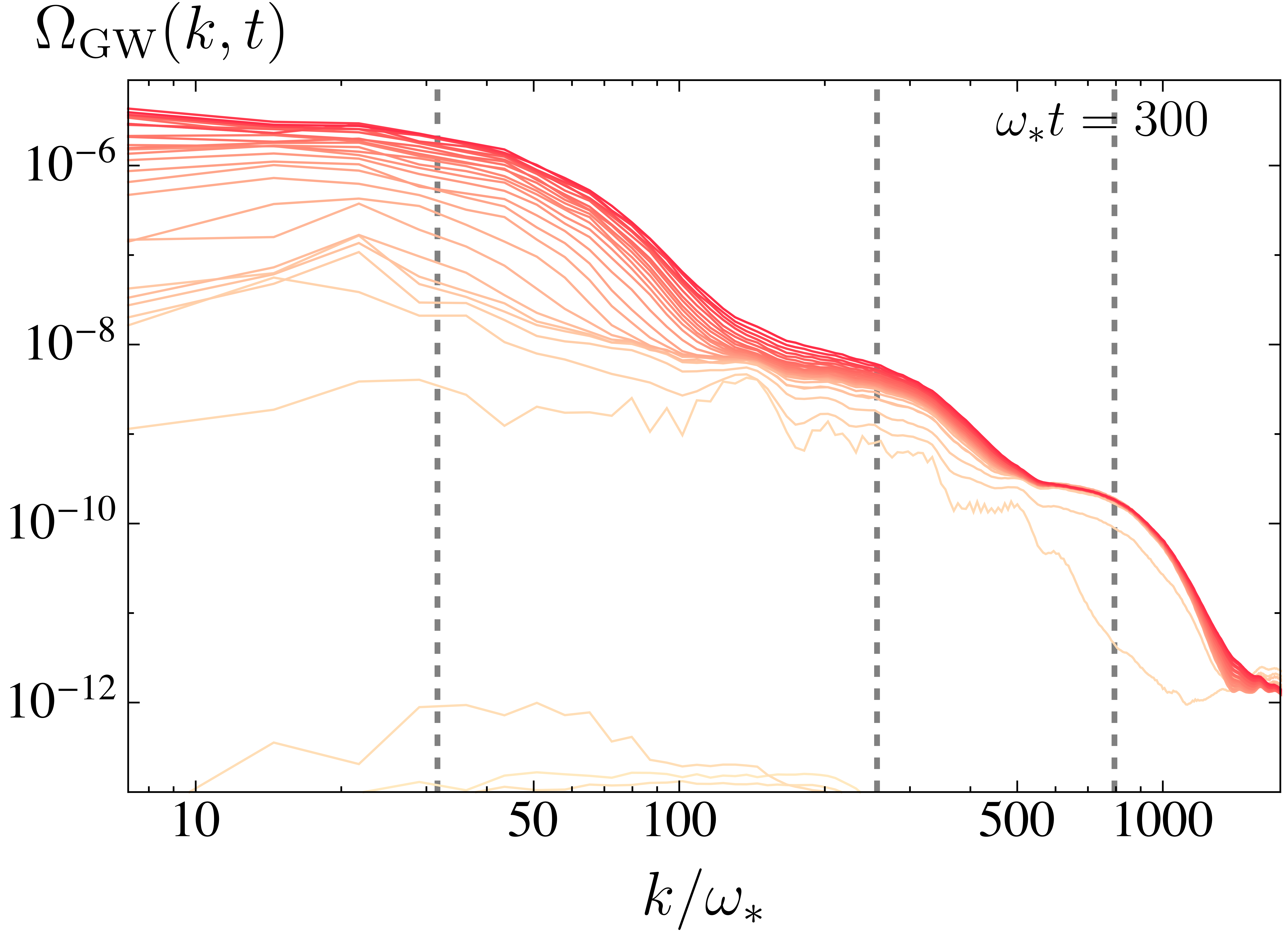
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 150$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



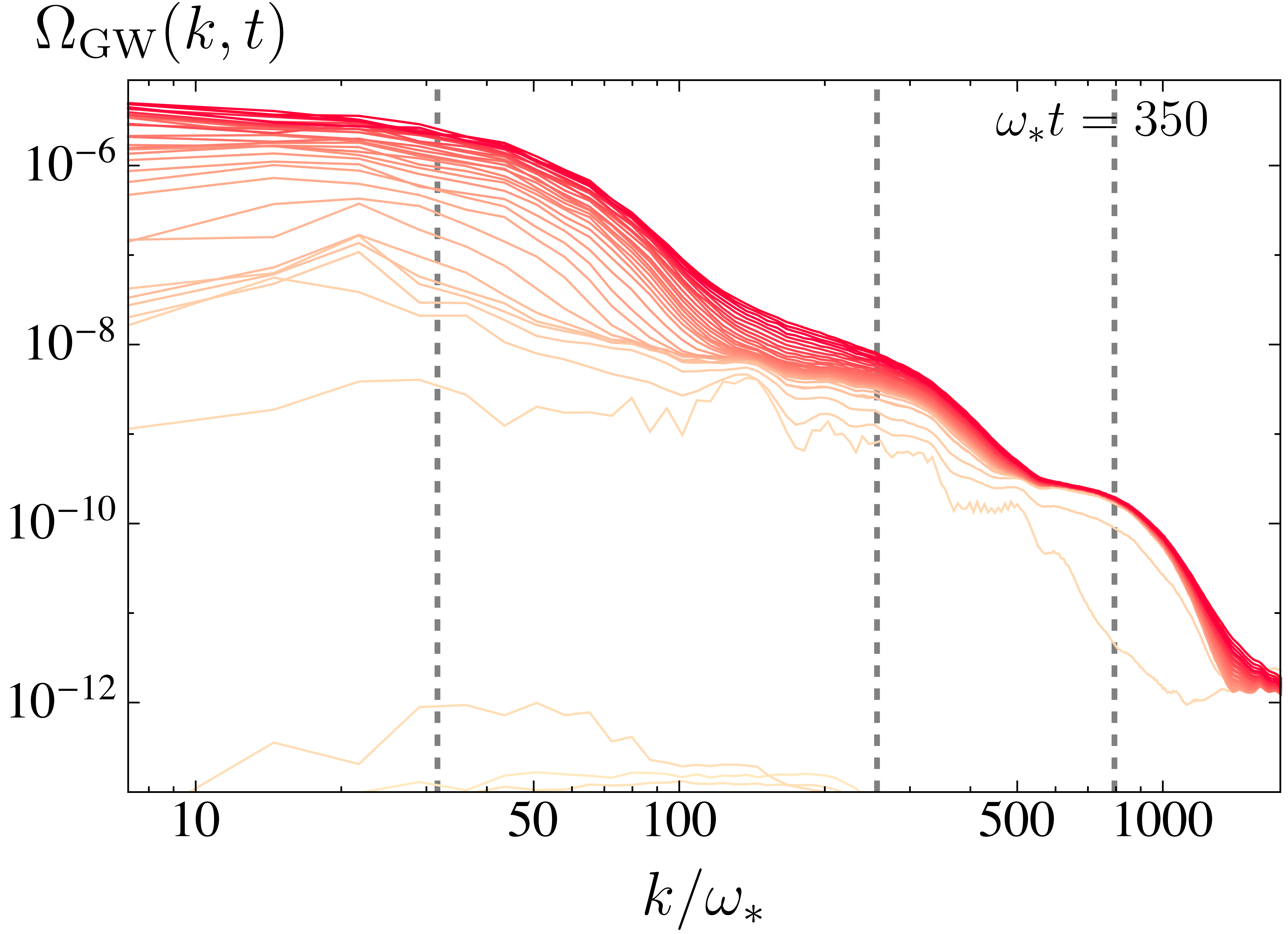
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 200$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



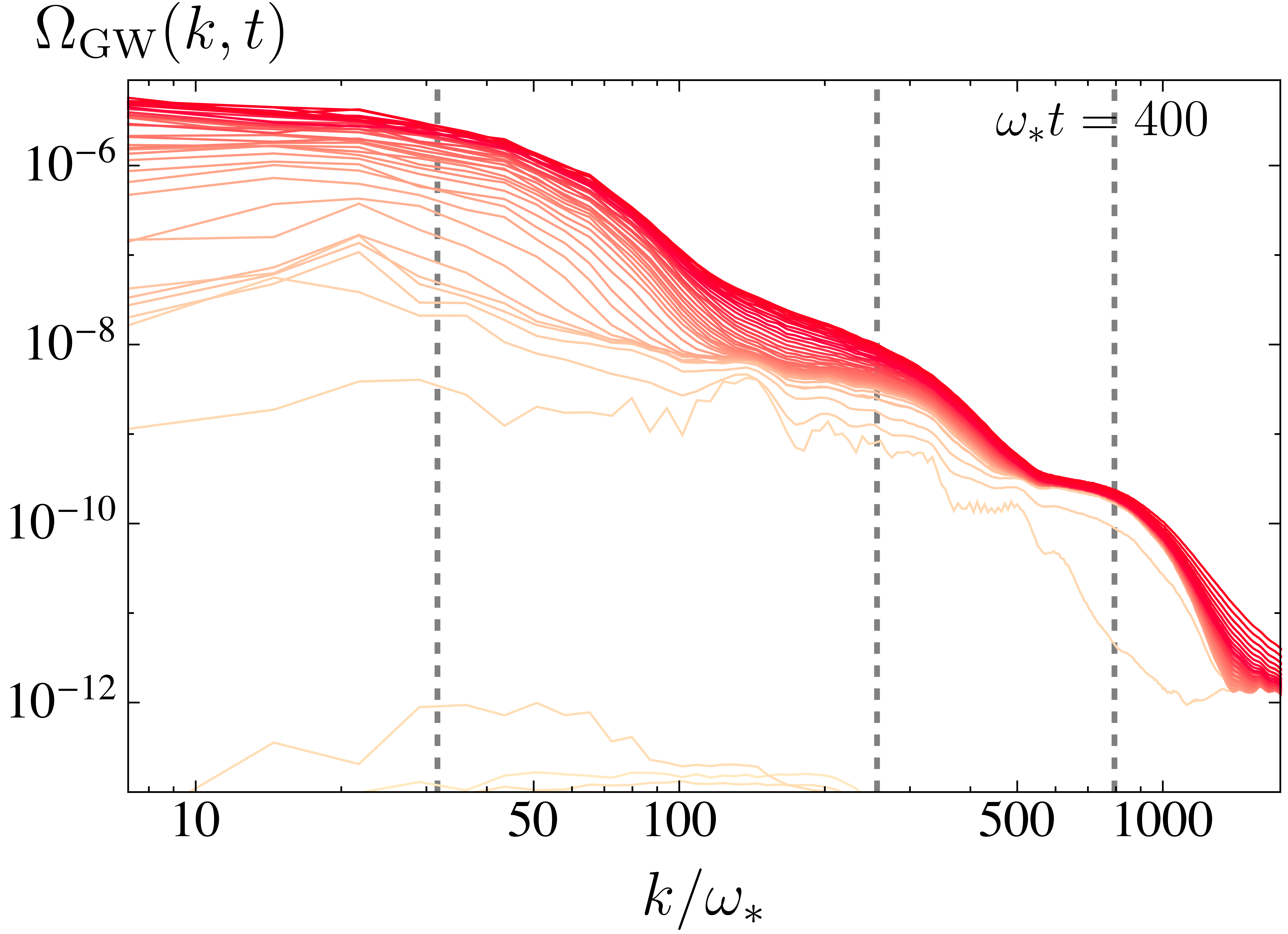
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 250$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



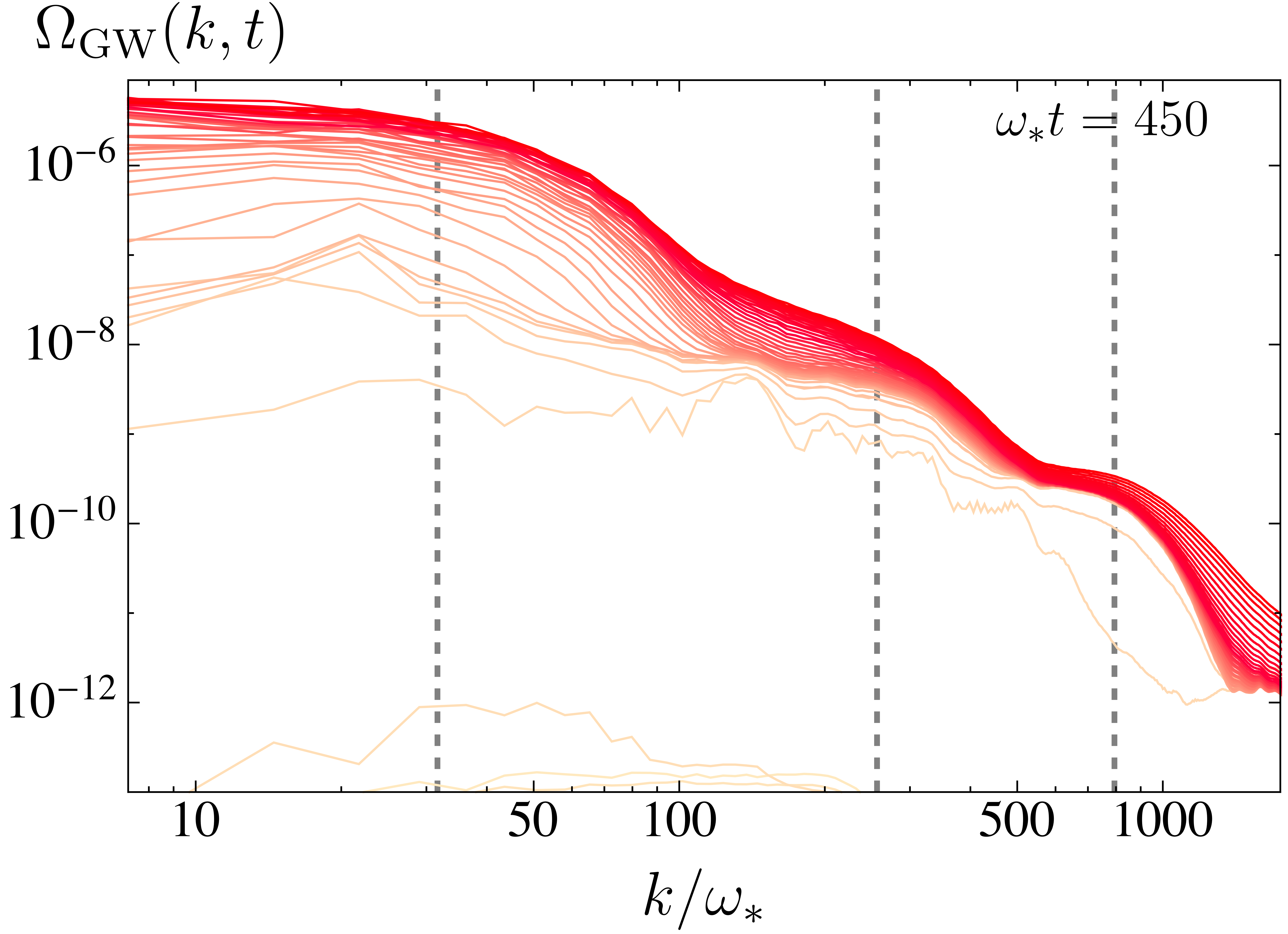
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 300$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



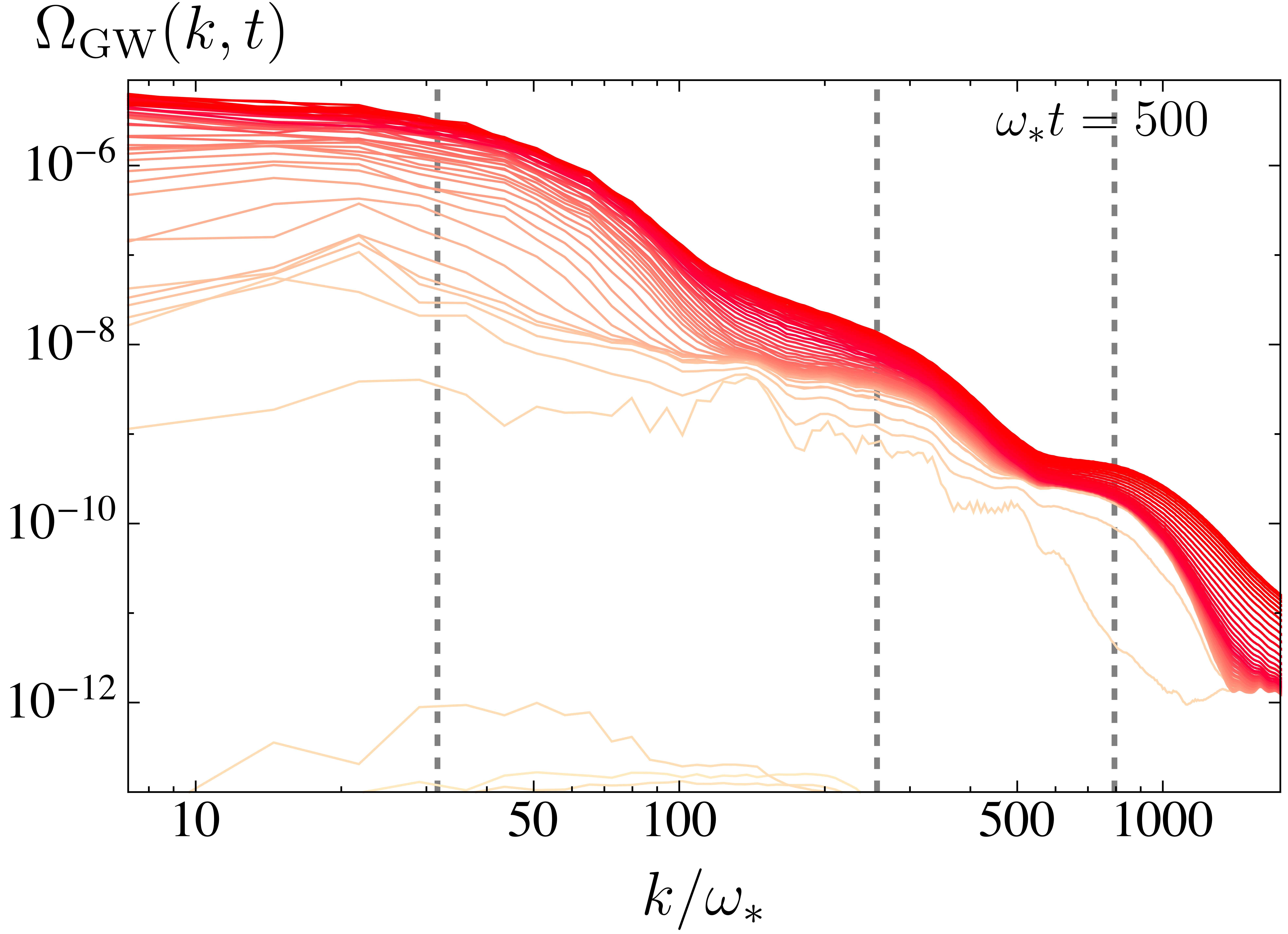
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 350$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



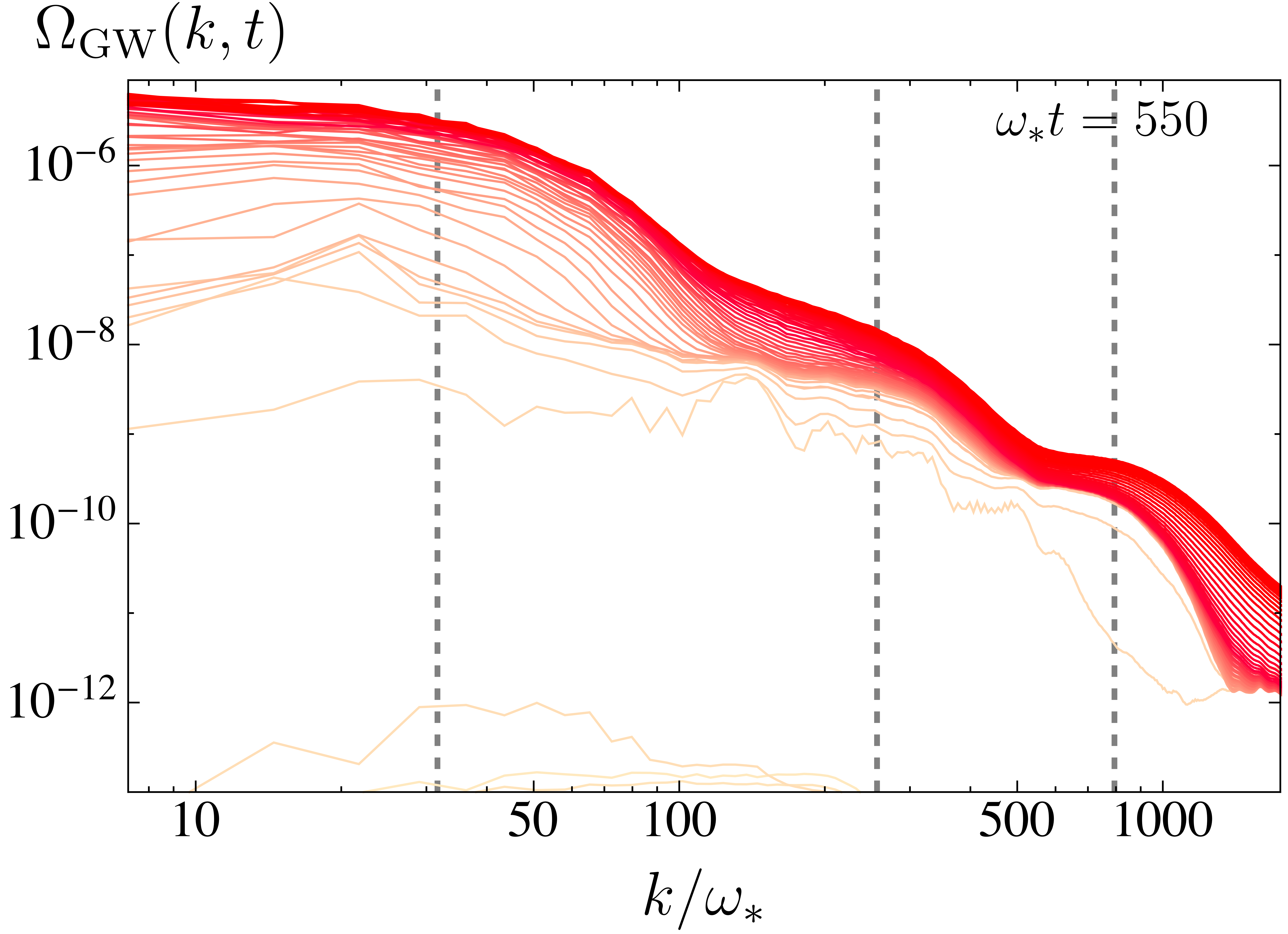
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 400$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



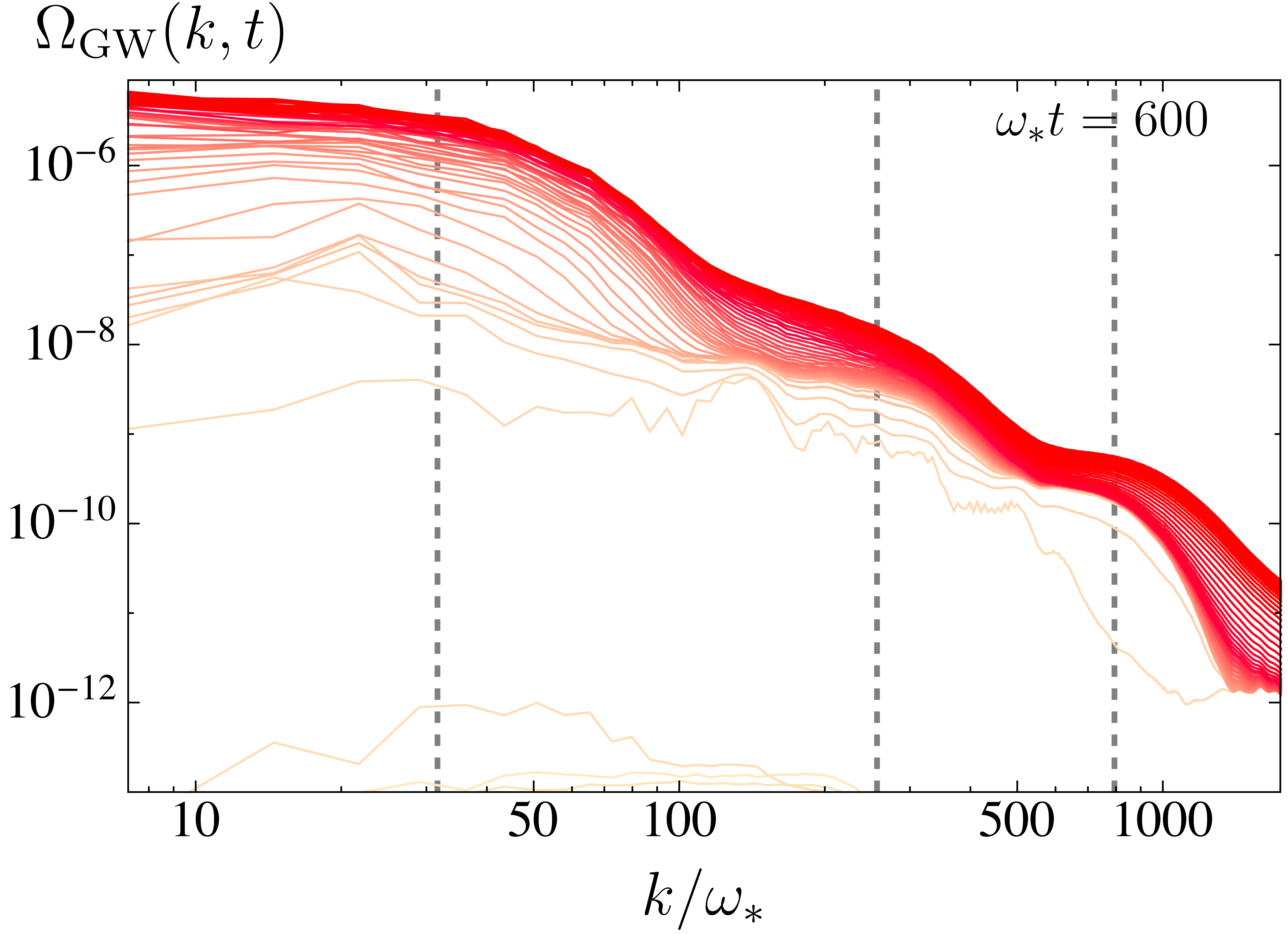
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 450$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



$\Omega_{\rm GW}(k,t)$
$\omega_* t = 500$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



$\Omega_{\rm GW}(k,t)$
$\omega_* t = 550$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$



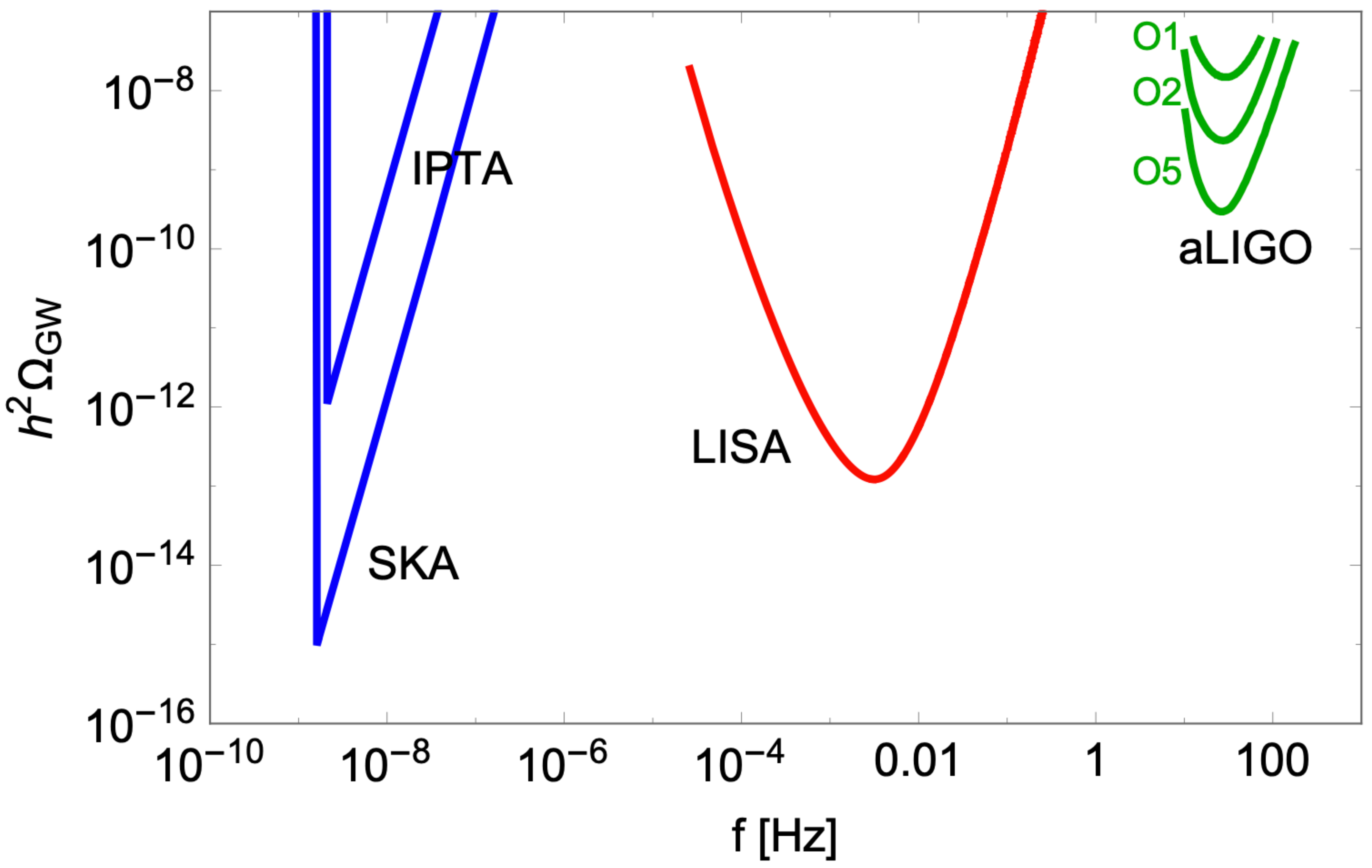
$\Omega_{\rm GW}(k,t)$
$\omega_* t = 600$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
10
50
100
500
1000
$k/\omega_*$

# Is the signal detectable?

## Today's frequency and Amplitude

$$h_0^2 \Omega_{\rm GW}^{(0)}\Big|_{\rm peak} \simeq 1.92 \times 10^{-10} \left(\frac{q}{10^4}\right)^{-1.1}$$

Large amplitude!




Caprini & Figueroa '18

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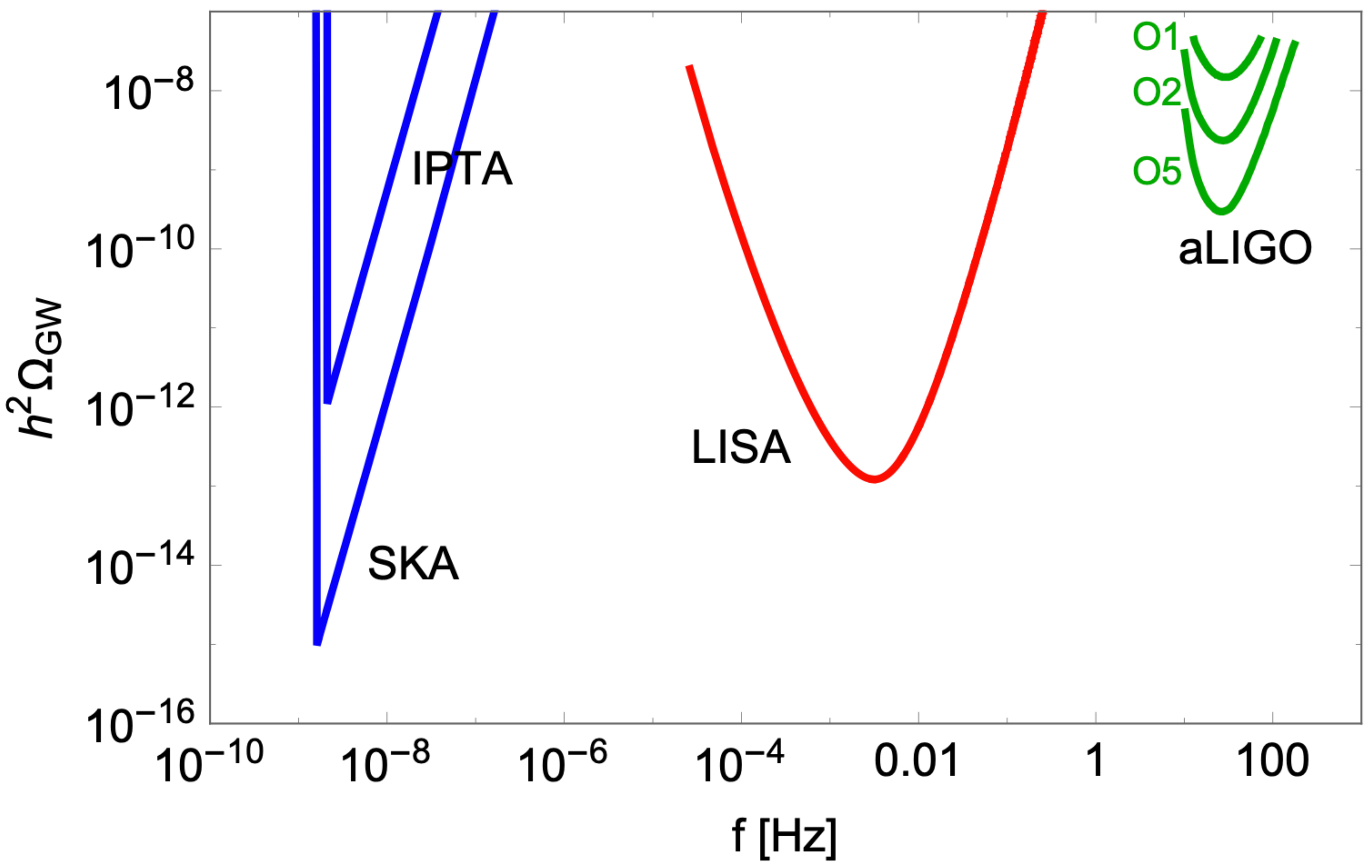
$$f_p \simeq 1.64\times10^{9}\left(\frac{q}{10^4}\right)^{0.52}\ \text{Hz}$$

High Frequency!

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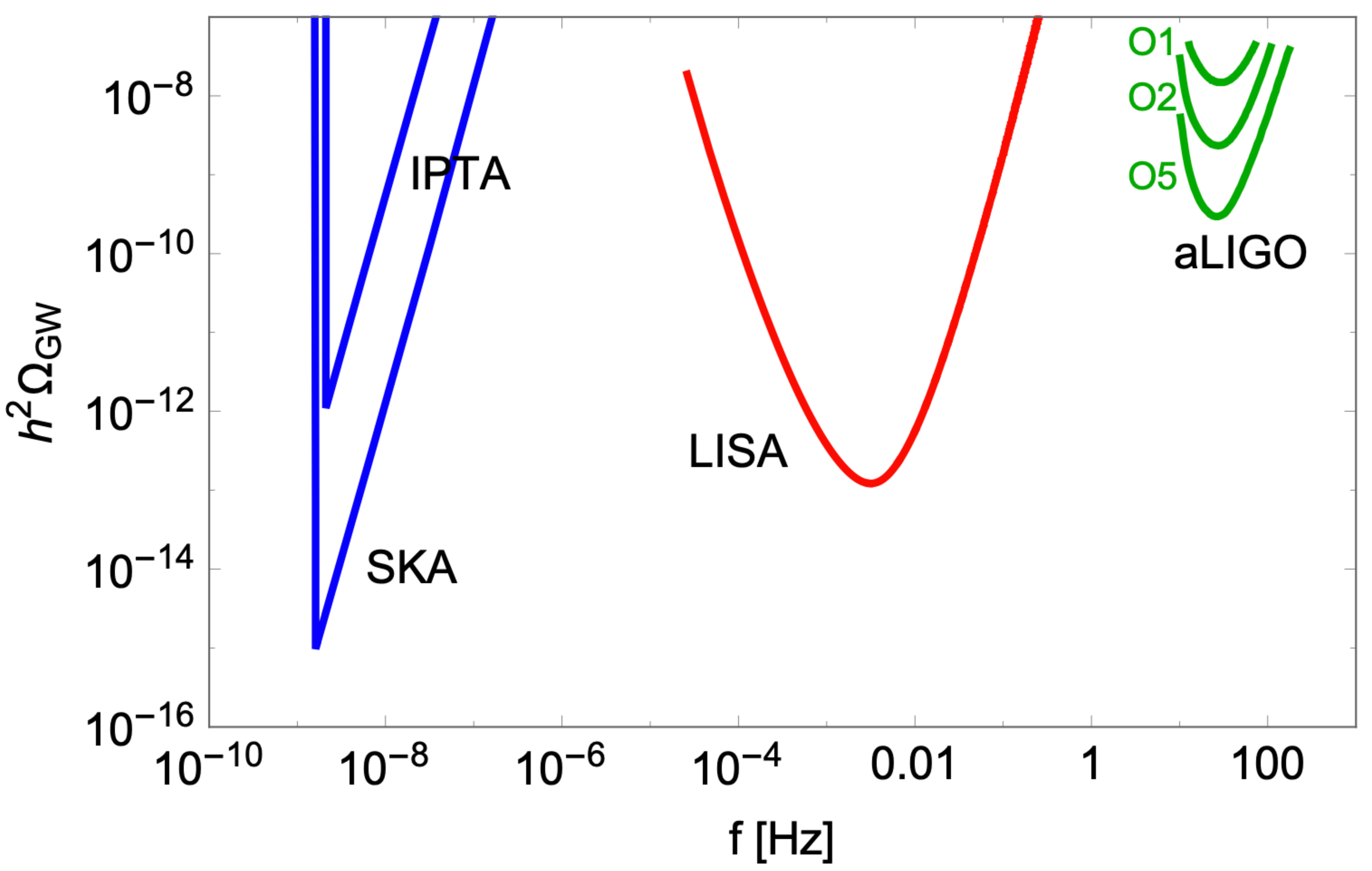



Caprini & Figueroa '18

→ Signal not detectable by current/future observatories!

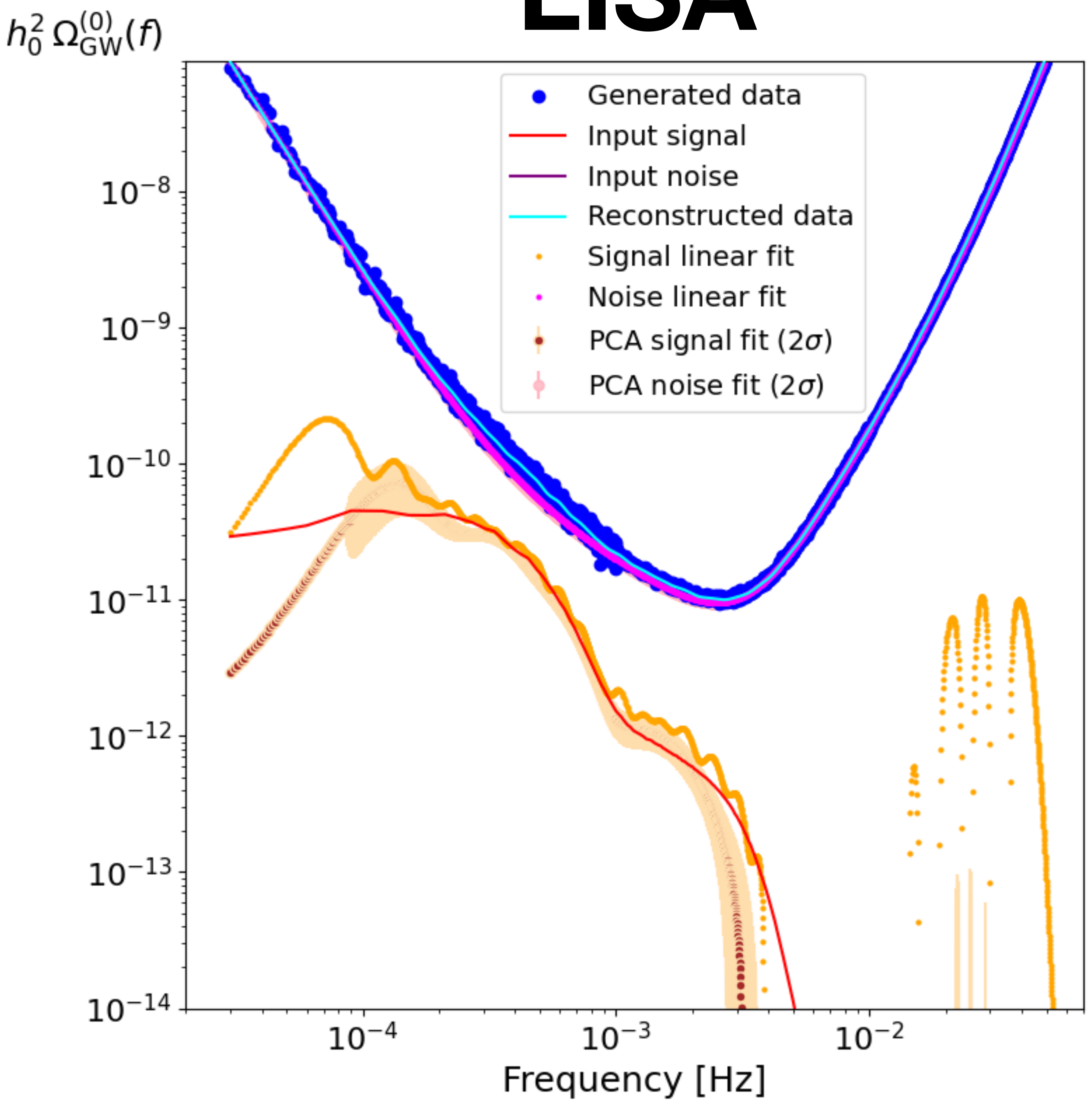
# Signal Reconstruction

Shift by hand to frequency window of
LISA, BBO
High Frequency Experiment (HFE)

Signal template

$$h^2\Omega_{GW} = \sum_{i=1}^{n} 10^{\ln(h^2\Omega_i^*)} \frac{2\left(\frac{f}{f_i^*}\right)^{n_i}}{1+\exp\left\{\frac{\delta_i(f-f_i^*)}{f_i^*}\right\}}$$

## LISA



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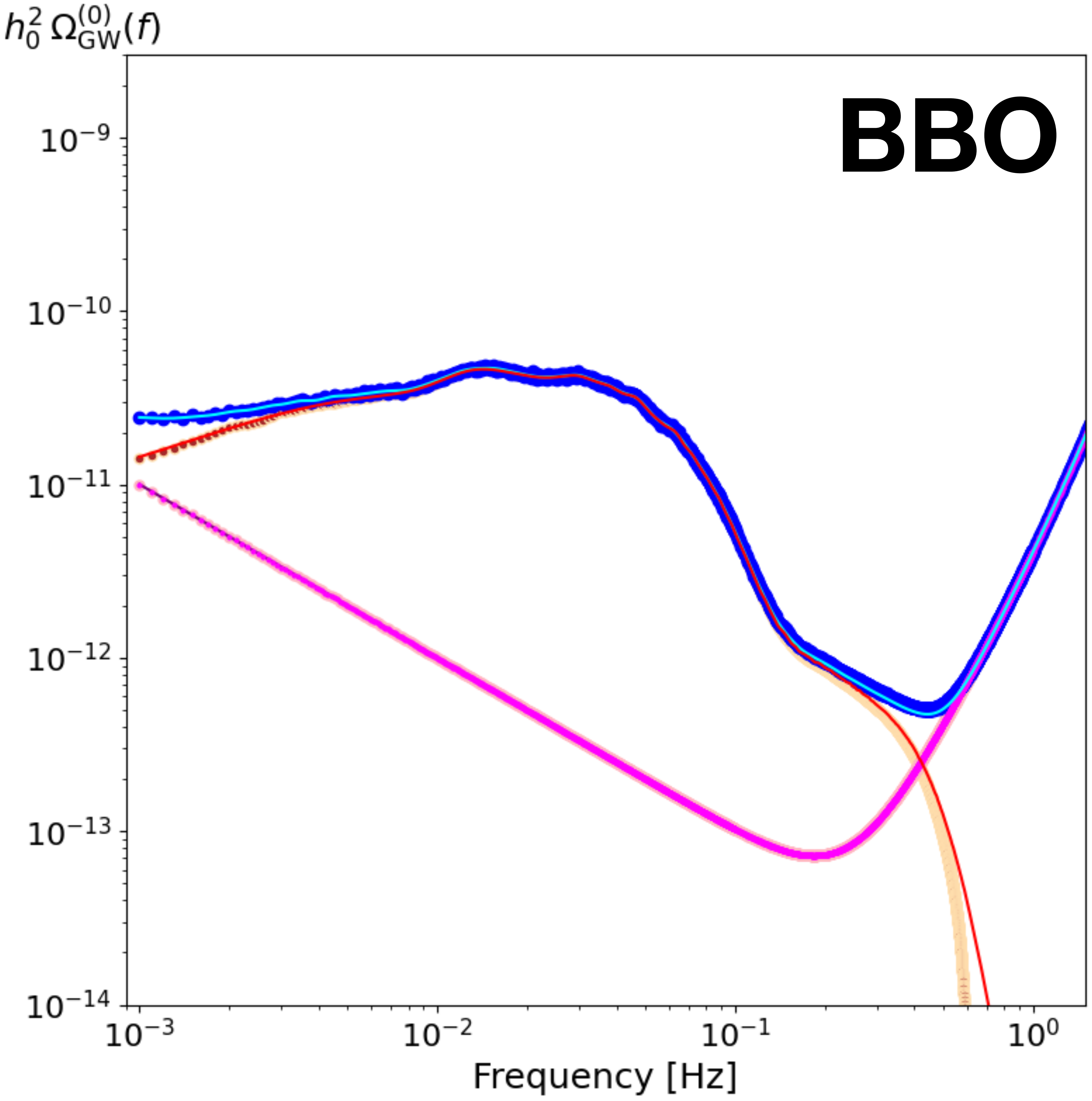

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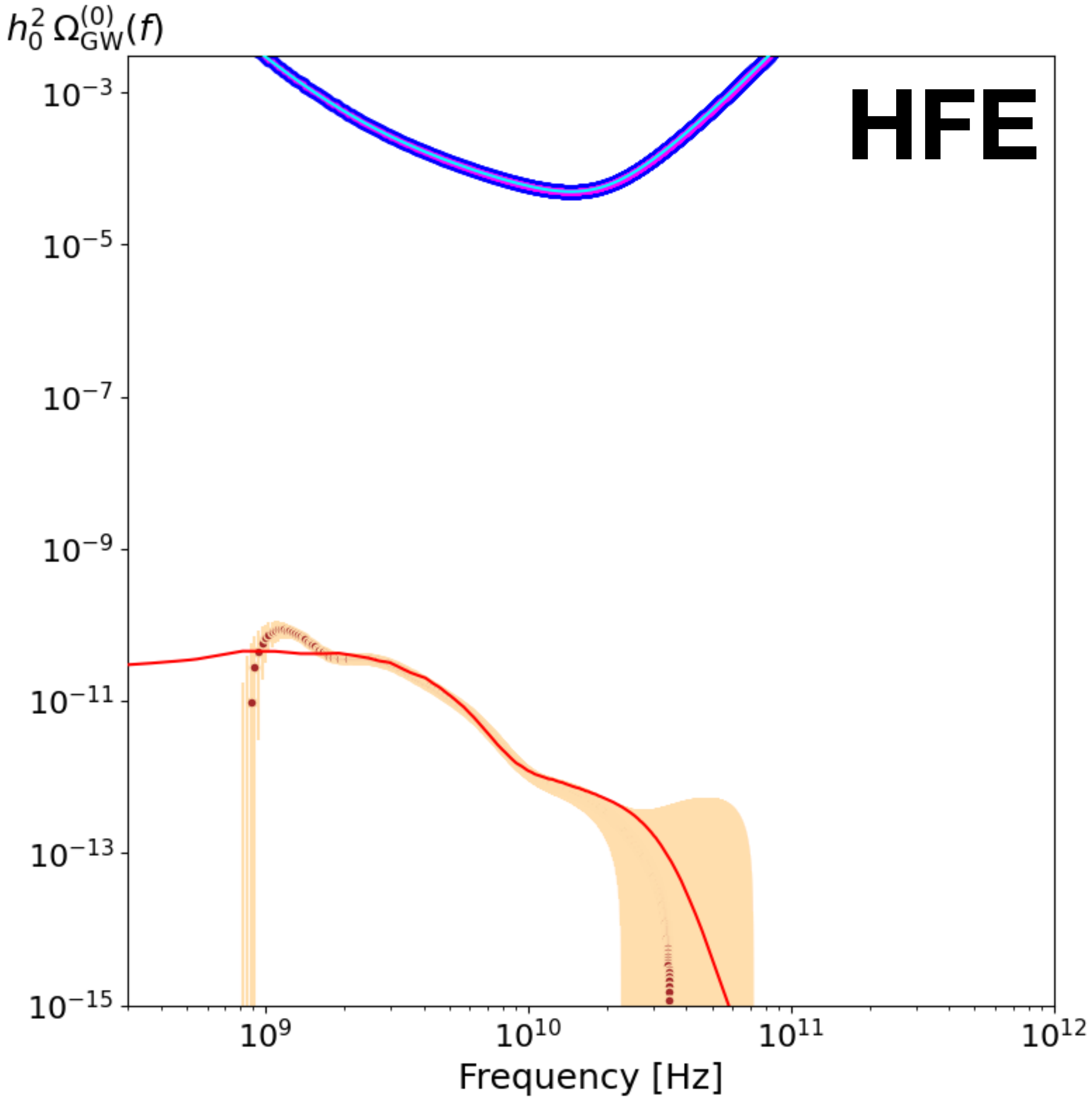
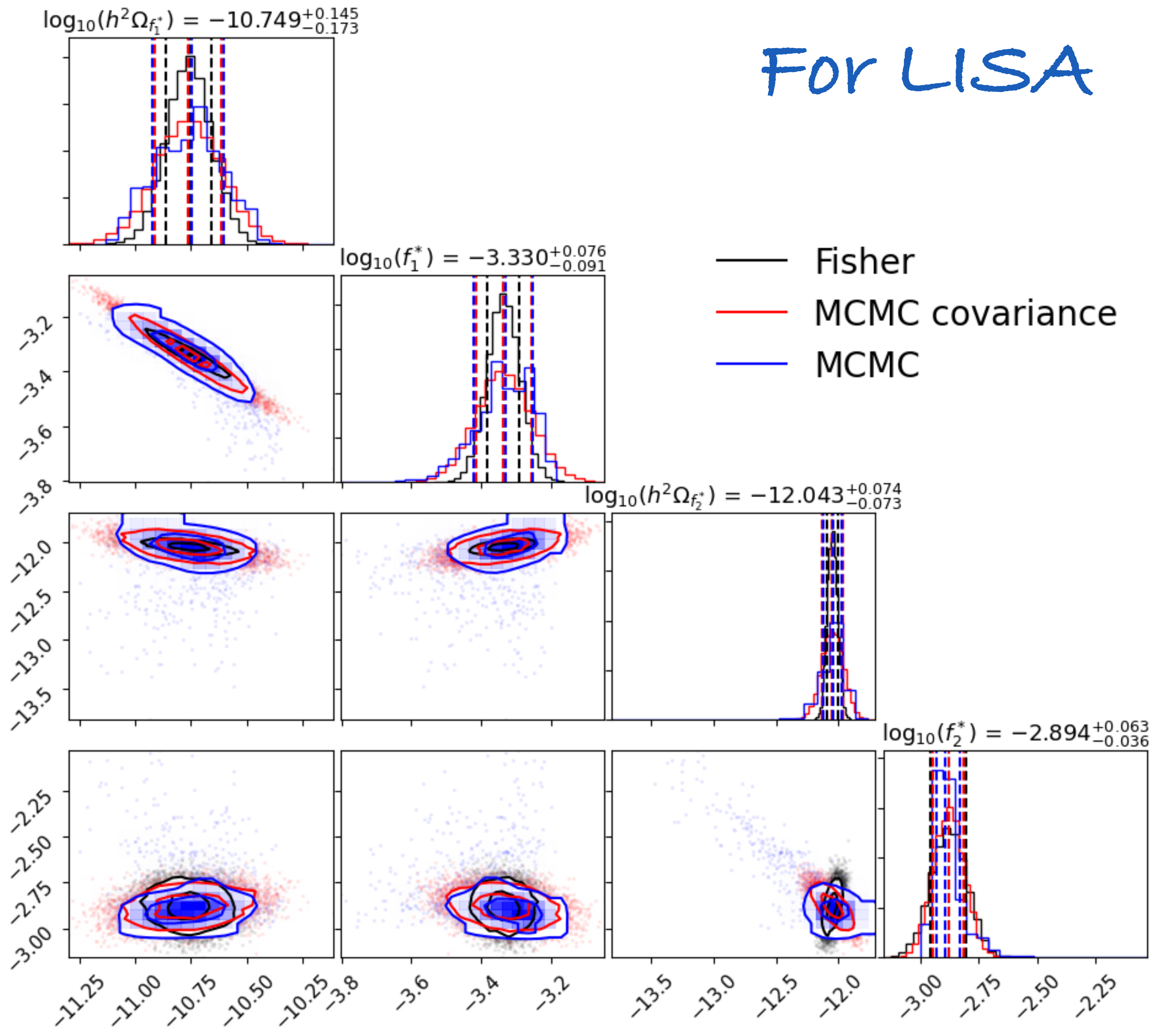


# Coupling reconstruction



# Coupling reconstruction

| | **LISA** | **BBO** | **HFE** |
|---|---|---|---|
| $\log_{10}(f_1^*[\mathrm{Hz}])$ | $-3.33^{+0.08}_{-0.09}$ | $-1.539^{+0.002}_{-0.002}$ | $9.45^{+0.15}_{-0.15}$ |
| $q_1 = 3 \cdot 10^4$ | $6.14^{+29.86}_{-4.10} \cdot 10^4$ | $1.28^{+2.45}_{-0.62} \cdot 10^4$ | $2.83^{+17.88}_{-2.06} \cdot 10^4$ |
| $g_1 = 1.16 \cdot 10^{-3}$ | $1.66^{+4.01}_{-0.55} \cdot 10^{-3}$ | $0.76^{+0.73}_{-0.18} \cdot 10^{-3}$ | $1.13^{+3.56}_{-0.41} \cdot 10^{-3}$ |
| $\log_{10}(f_2^*[\mathrm{Hz}])$ | $-2.89^{+0.06}_{-0.04}$ | $-0.496^{+0.001}_{-0.001}$ | $10.4^{+0.4}_{-0.4}$ |
| $q_2 = 1.5 \cdot 10^6$ | $0.43^{+2.8}_{-0.3} \cdot 10^6$ | $1.3^{+7.42}_{-0.89} \cdot 10^6$ | $1.9^{+108.65}_{-1.78} \cdot 10^6$ |
| $g_2 = 8.2 \cdot 10^{-3}$ | $4.39^{+14.3}_{-1.53} \cdot 10^{-3}$ | $7.64^{+21.8}_{-2.61} \cdot 10^{-3}$ | $9.23^{+263.9}_{-4.32} \cdot 10^{-3}$ |

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Realistic Early Universe scenarios have of multiple fields.

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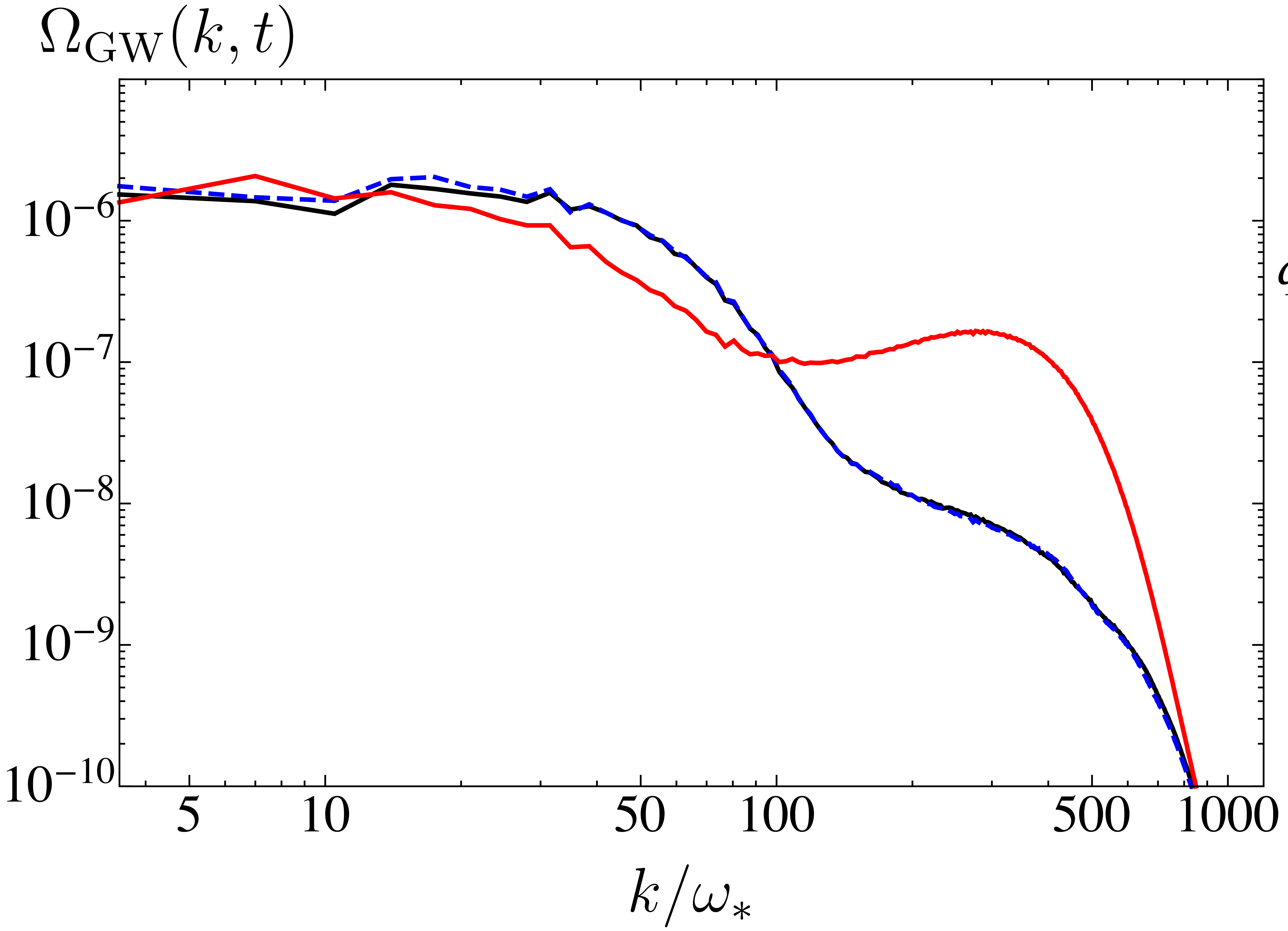
GWs are an ideal probe of early universe physics.

Coupling Reconstruction gives order of magnitude and is precise at $1\sigma$.

Realistic Early Universe scenarios have of multiple fields.

Similar “stairway” effect expected in tachyonic preheating, axion preheating or geometric preheating.

# !Thank you¡




nonzero coupling among daughters species

$q_1 = 3\times 10^4 \quad q_2 = 1.5\times 10^6 \quad q_{12} = 0$

$q_1 = 3\times 10^4 \quad q_2 = 1.5\times 10^6 \quad q_{12} = 0.01\cdot q_1$

$q_1 = 3\times 10^4 \quad q_2 = 1.5\times 10^6 \quad q_{12} = 10\cdot q_2$

$$\sim \frac{1}{2} g_{12}^2 \chi_1^2\,\chi_2^2$$