Emission of gravitational waves by cosmic domain walls with constant tension

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Introduction

- Pulsar timing arrays: NANOGrav, EPTA with InPTA, PPTA, and Chinese PTA →
- stochastic gravitational waves background
- supermassive black hole binaries are the most likely source
- primordial sources are also possible
- we focus on domain walls

- CosmoLattice computer code – Figueroa et al., 2021

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{\lambda}{4}\left(\phi^2 - \eta^2\right)^2$$

Scaling regime

- One domain wall per horizon
- Distance between walls = Hubble radius

$$\rho_{wall} \sim \frac{H^{-2}\sigma_{wall}}{H^{-3}} \sim \sigma_{wall}/t$$

$$\xi_{dw} = \frac{\rho_{wall}}{\sigma_{wall}}t$$ - scaling parameter

$$\sigma_{dw} = \frac{2\sqrt{2\lambda}\eta^3}{3}$$ - tension of domain walls

$$\Delta^2 = \frac{2}{\lambda\eta^2}$$ - domain wall width

Scaling regime

$$P \sim \dddot{Q}_{ij}^2 / \left(40\pi M_{Pl}^2\right) \quad Q_{ij} \sim M_{wall}/H^2 \qquad M_{wall} \sim \sigma_{wall}/H^2$$

$$\rho_{gw} \sim PtH^3 \sim \frac{\sigma_{wall}^2}{40\pi M_{Pl}^2}$$

Hiramatsu et al., 2013

$$k\tau \ll 1$$

Caprini et al., 2009

$$\frac{d\rho_{gw}}{d\ln k} \propto k^3$$

Initial conditions

$$\langle\phi(\mathbf{k})\phi(\mathbf{q})\rangle = A(k)\delta(\mathbf{k}+\mathbf{q})$$

$$\langle\dot{\phi}(\mathbf{k})\dot{\phi}(\mathbf{q})\rangle = B(k)\delta(\mathbf{k}+\mathbf{q})$$

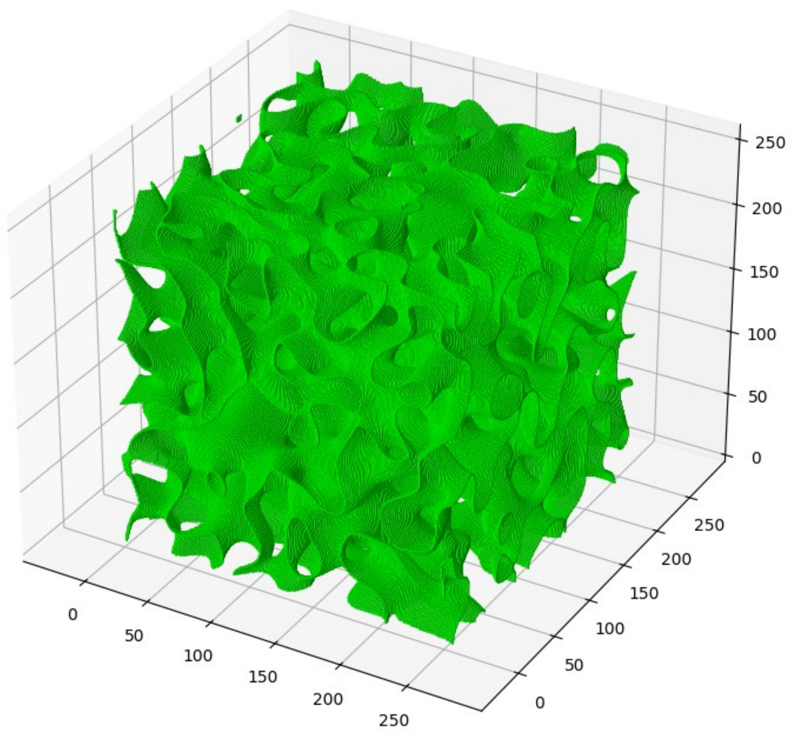
Vacuum:

$$A(k) = \frac{1}{2k} \qquad B(k) = \frac{k}{2}$$

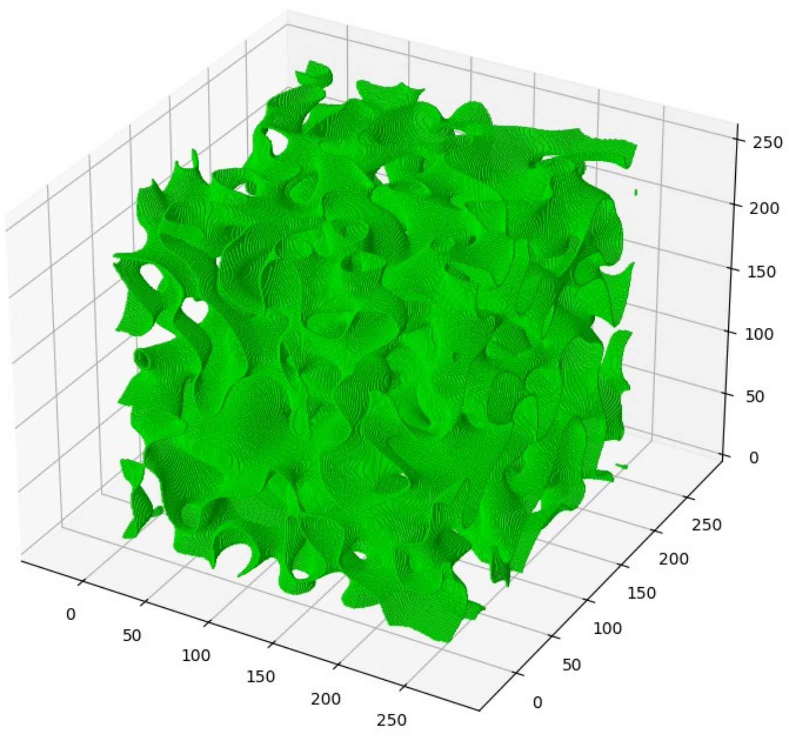
Thermal:

$$A(k) = \frac{1}{k\cdot\left(e^{\frac{k}{T}}-1\right)} \qquad B(k) = \frac{k}{e^{\frac{k}{T}}-1}$$

Evolution of DW network

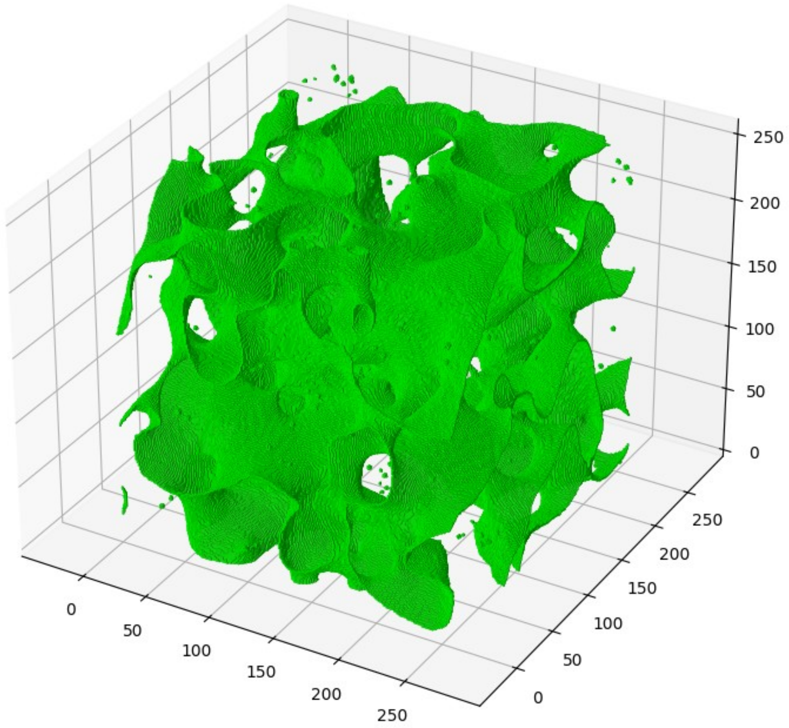


τ = 1

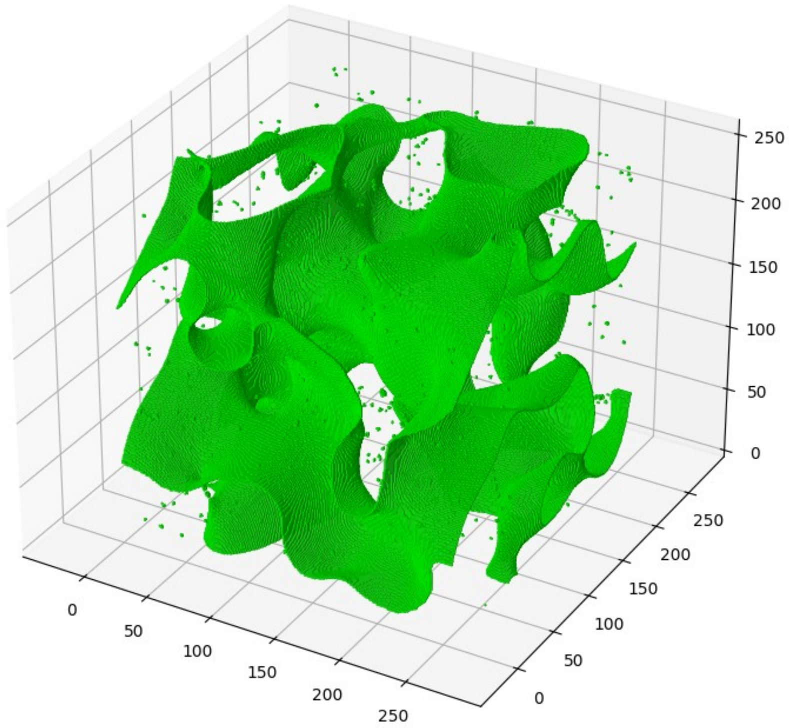


τ = 5

Evolution of DW network

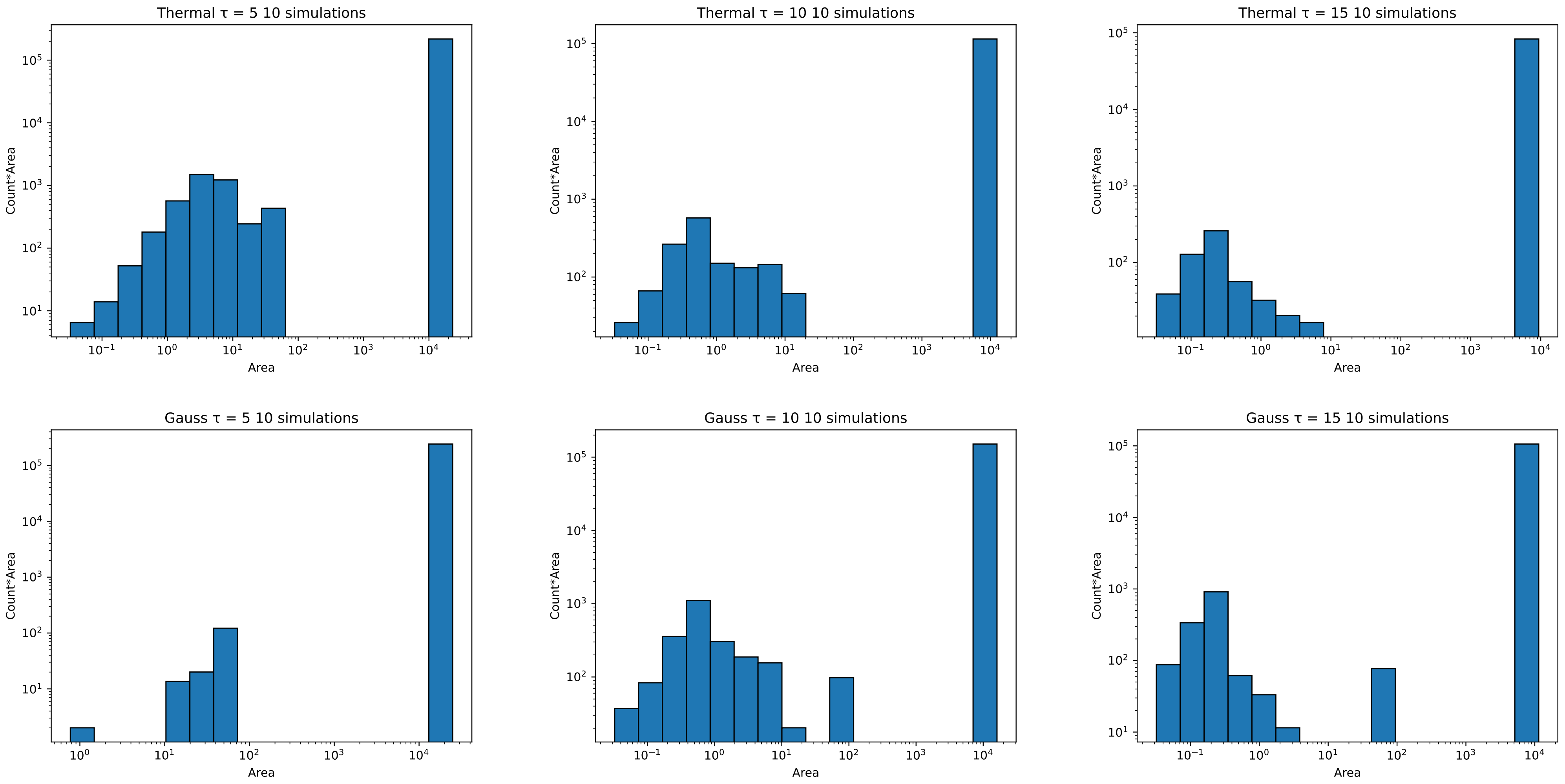


τ = 10

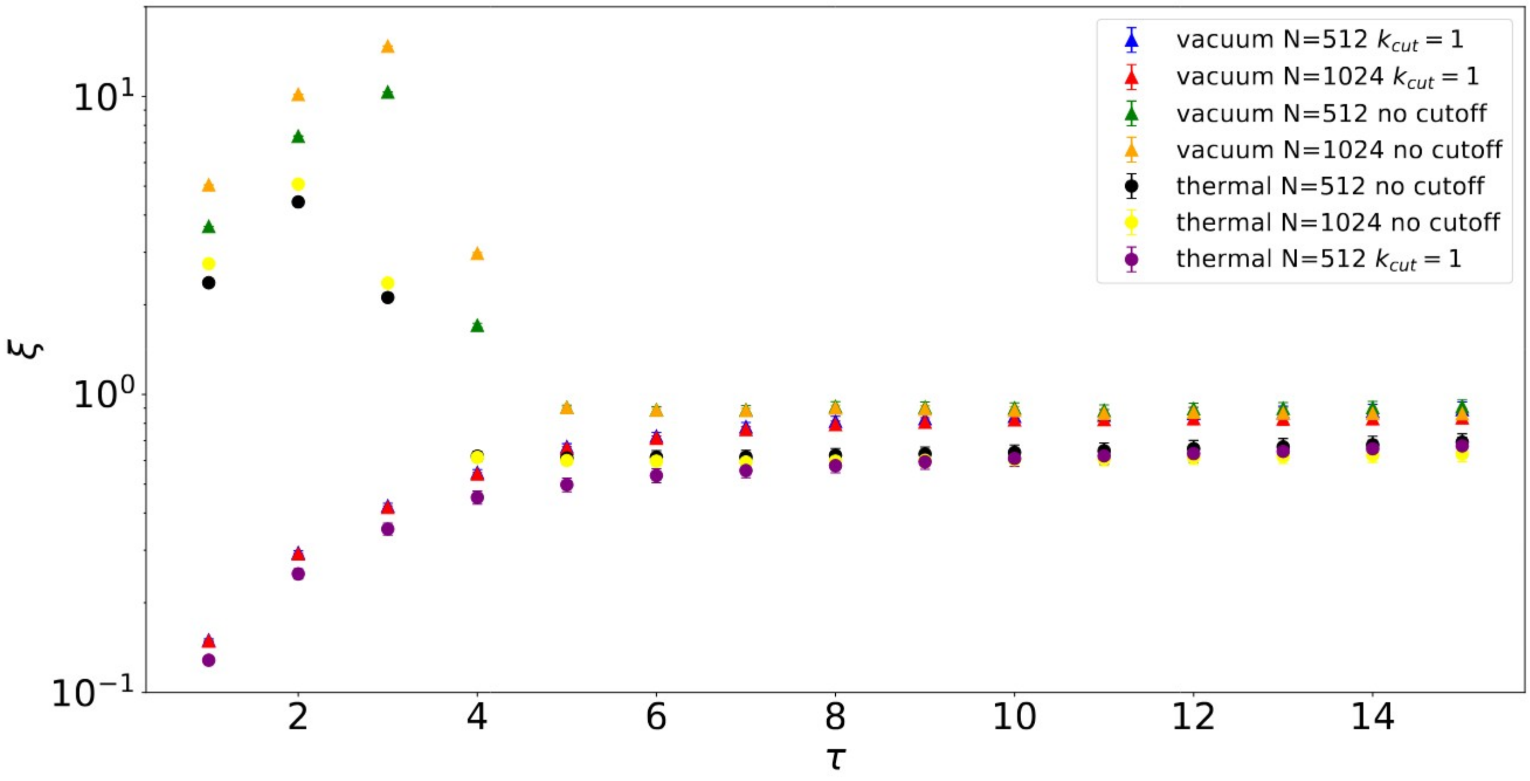


τ = 15

Distribution over areas



Scaling parameter



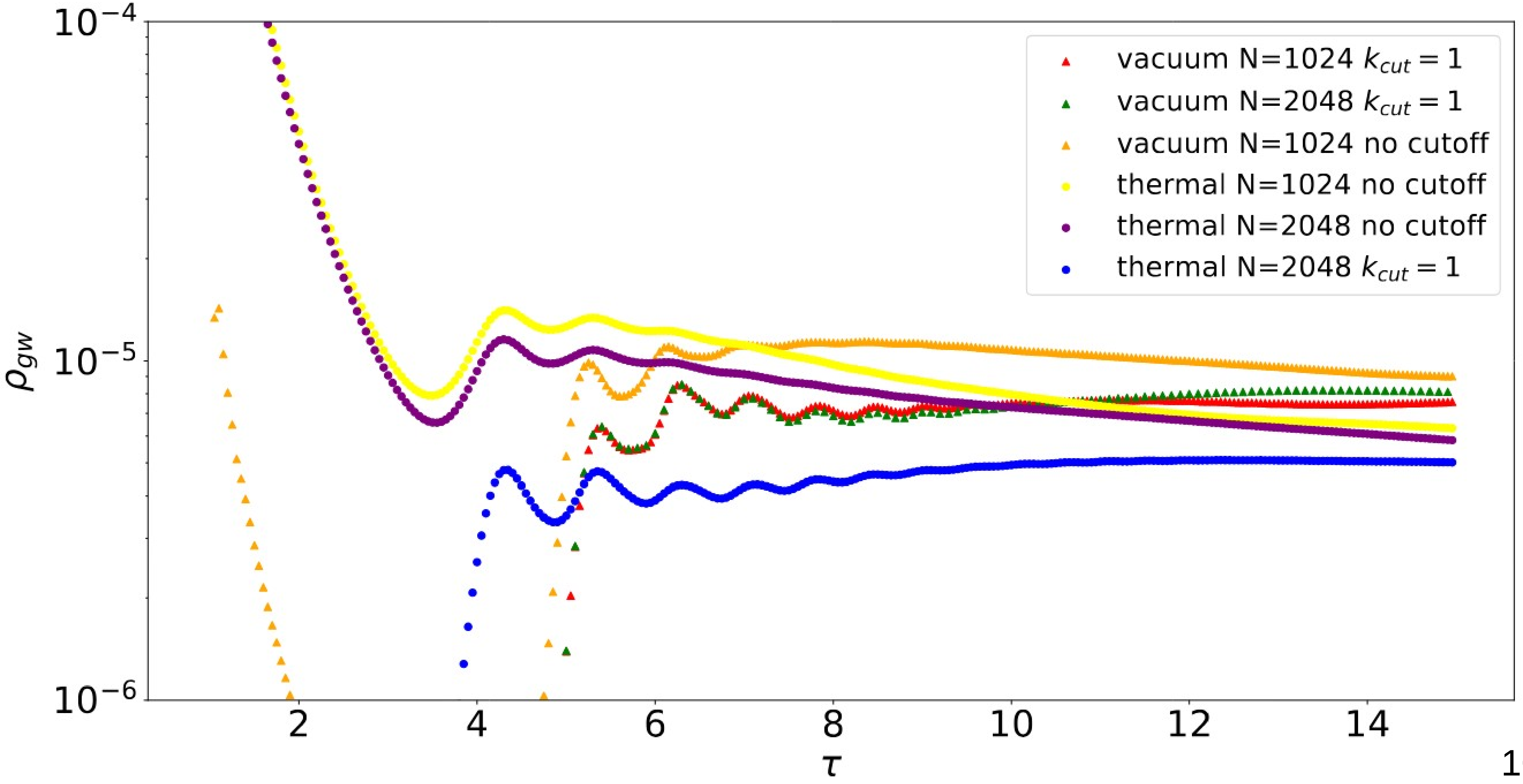
$$\tau_f \simeq \frac{5}{\sqrt{\lambda}\eta}$$

$$\delta_w \simeq 0.06H^{-1}$$

$\xi \approx 0.8$ - vacuum

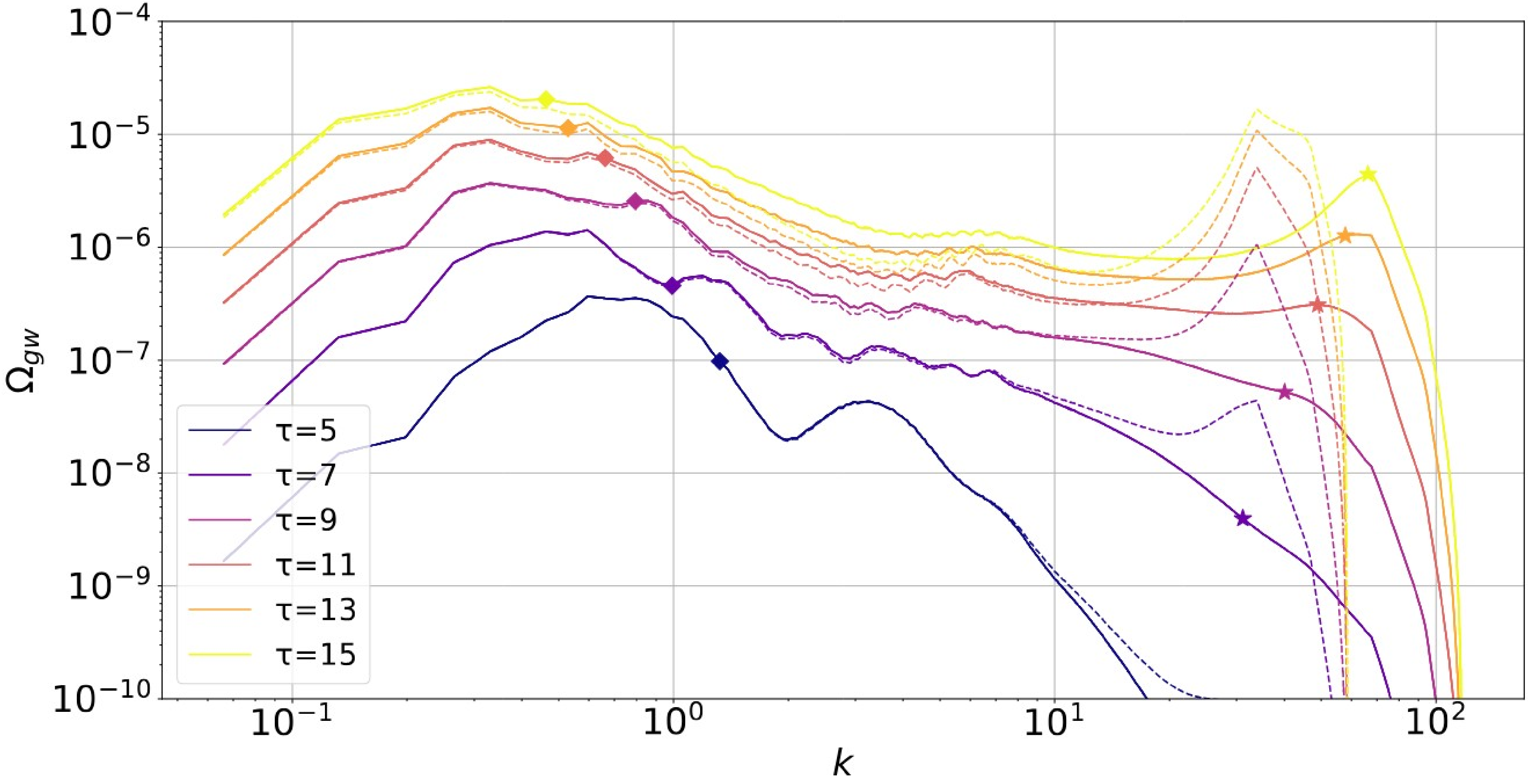
$\xi \approx 0.6$ - thermal

Energy density of GW

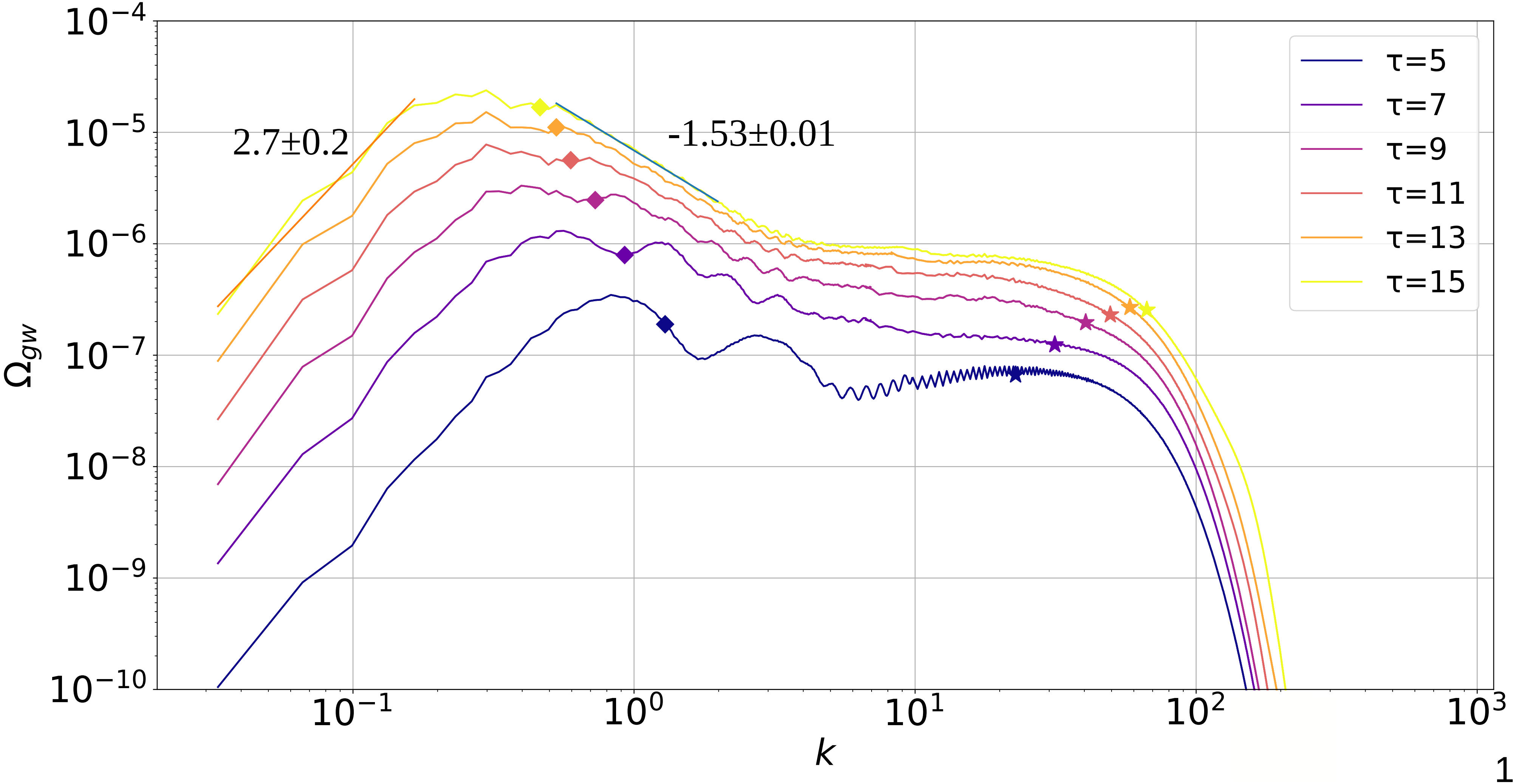


$$\Omega_{\rm GW} \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm dln}k}$$

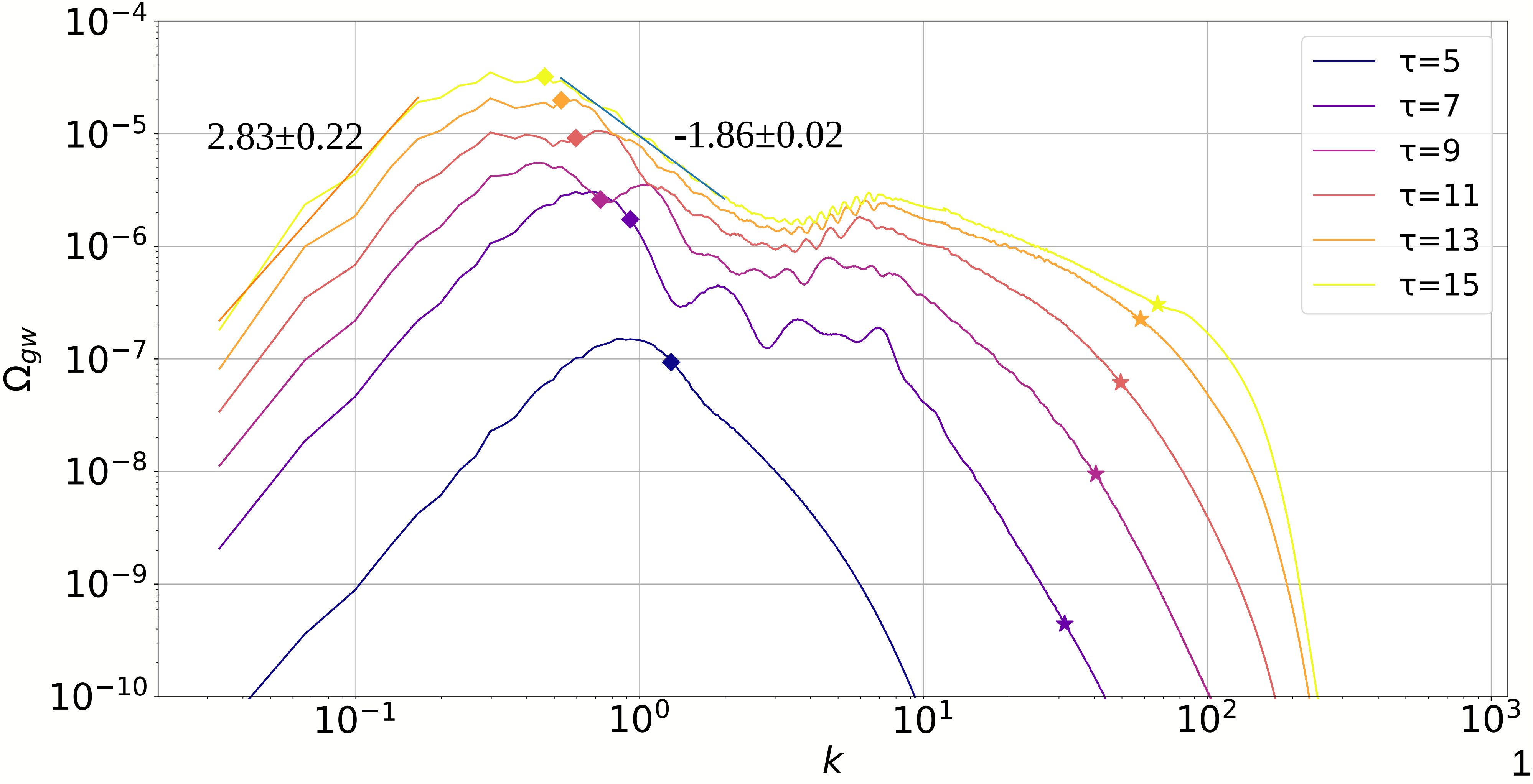
Numerical artifact



GW spectrum: thermal conditions



GW spectrum: vacuum conditions



Results

$$\Omega_{gw,peak}(\tau) \approx 4.6\ (7.7) \times 10^{-10} \cdot \left(\frac{H_i}{H(\tau)}\right)^2 \cdot \left(\frac{\eta}{6 \cdot 10^{16}\ \mathrm{GeV}}\right)^4 \qquad \text{thermal (vacuum)}$$

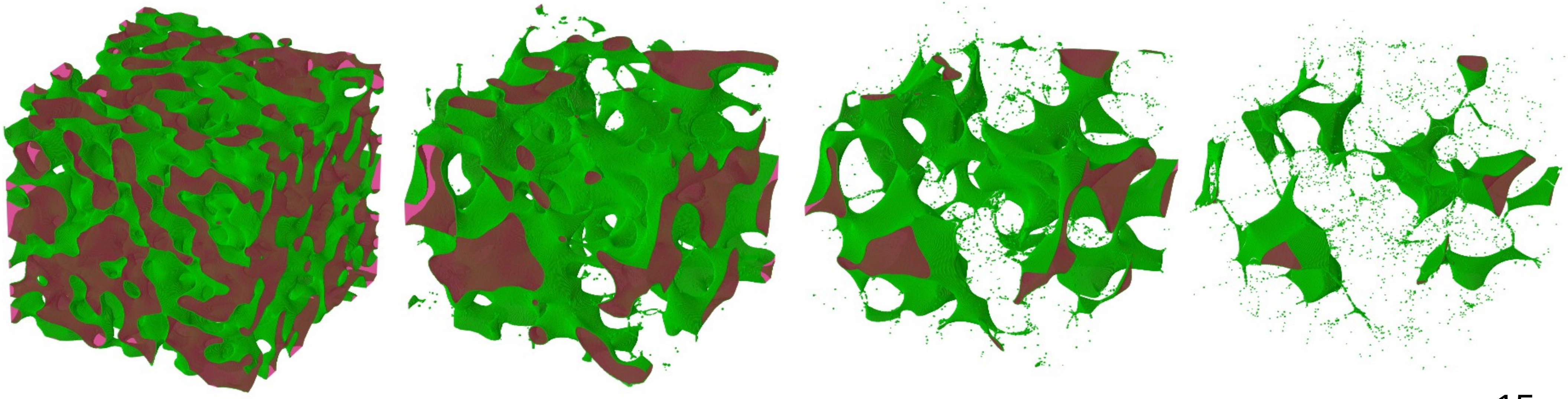
$$\Omega_{gw,peak} h_0^2 \simeq 0.6\ (1) \cdot 10^{-10} \cdot \left(\frac{100\ \mathrm{MeV}}{T_{dec}}\right)^4 \cdot \frac{\sigma_{wall}^2}{(100\ \mathrm{TeV})^6} \cdot \left(\frac{10}{g_*(T_{dec})}\right)^{4/3} \qquad \text{thermal (vacuum)}$$

$$f_{peak} = F_{peak} \cdot \frac{a_{dec}}{a_0} \simeq 0.7\ H_{dec} \cdot \frac{a_{dec}}{a_0} \simeq 0.4\ \mathrm{nHz} \left(\frac{T_{dec}}{100\ \mathrm{MeV}}\right) \cdot \left(\frac{10}{g_*(T_{dec})}\right)^{1/3}$$

Work in progress: potential bias

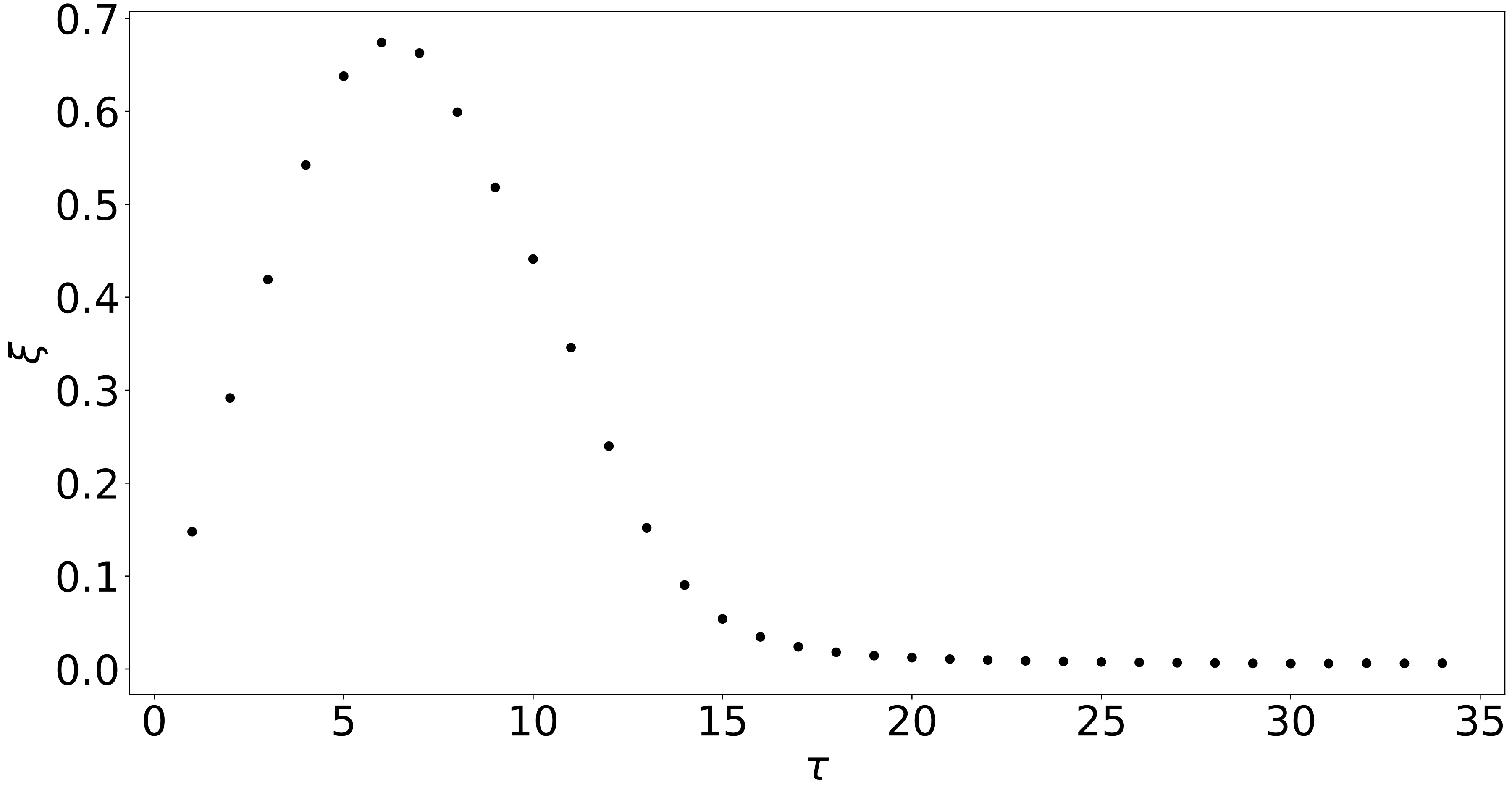
$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{4} \cdot \lambda(\chi^2 - v^2)^2 - V_{breaking} \right]$$

$$V_{breaking} = \epsilon \chi^3 \qquad V_{bias} = V_{breaking}(\chi \approx v) - V_{breaking}(\chi \approx -v) \approx 2\epsilon v^3$$

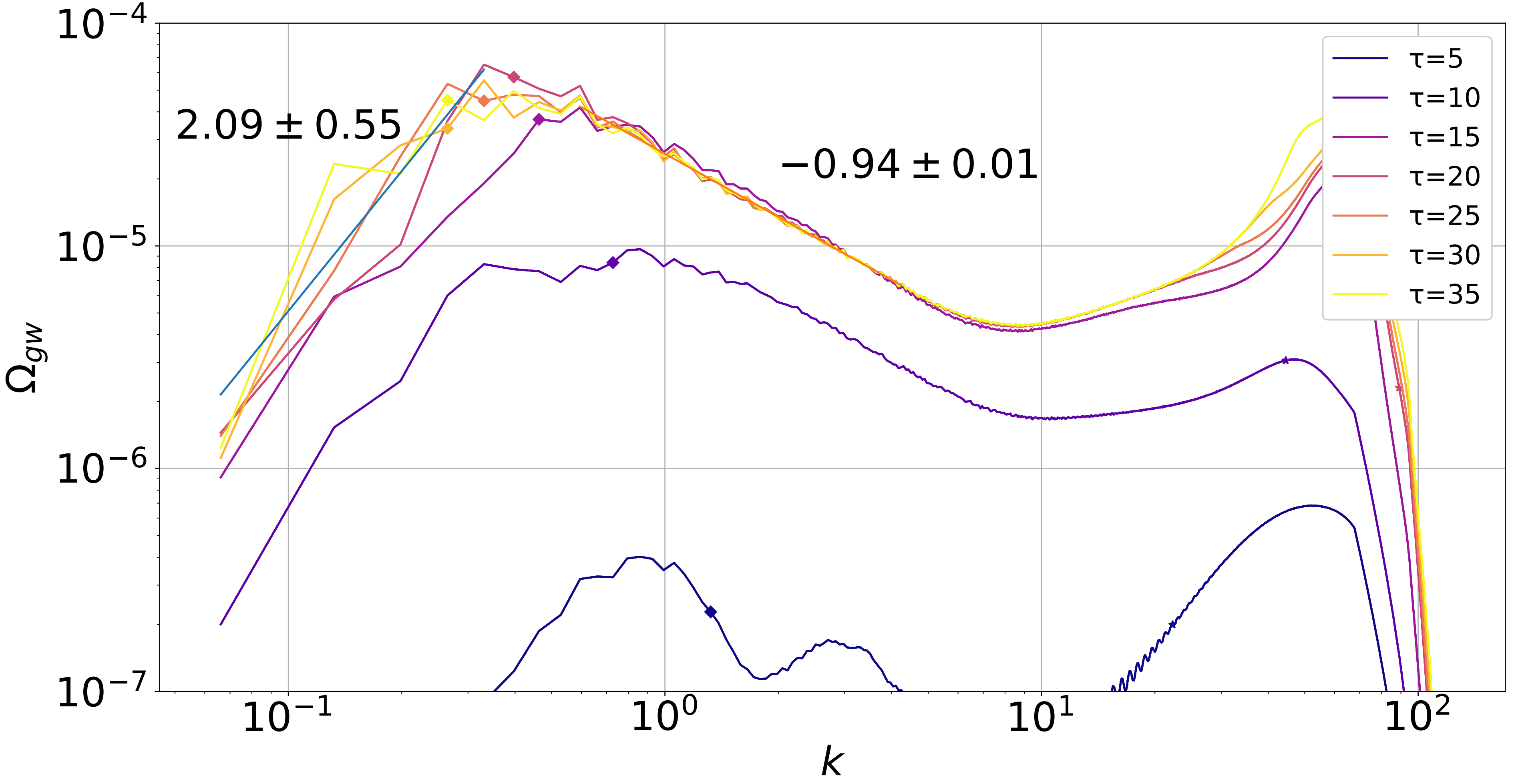


τ = 5 τ = 10 τ = 15 τ = 20

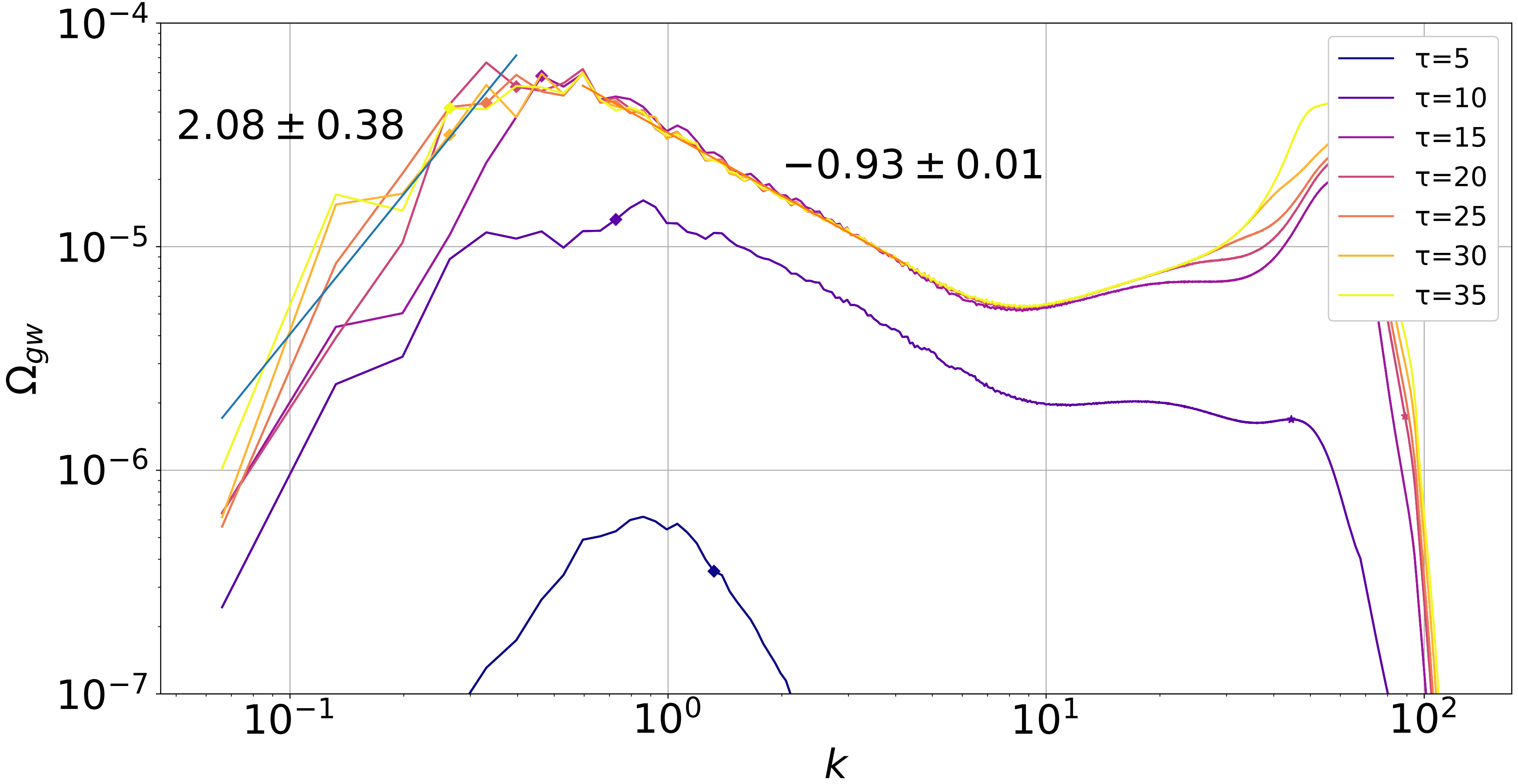
Work in progress: potential bias
Scaling parameter



Work in progress: potential bias
GW spectrum: thermal conditions



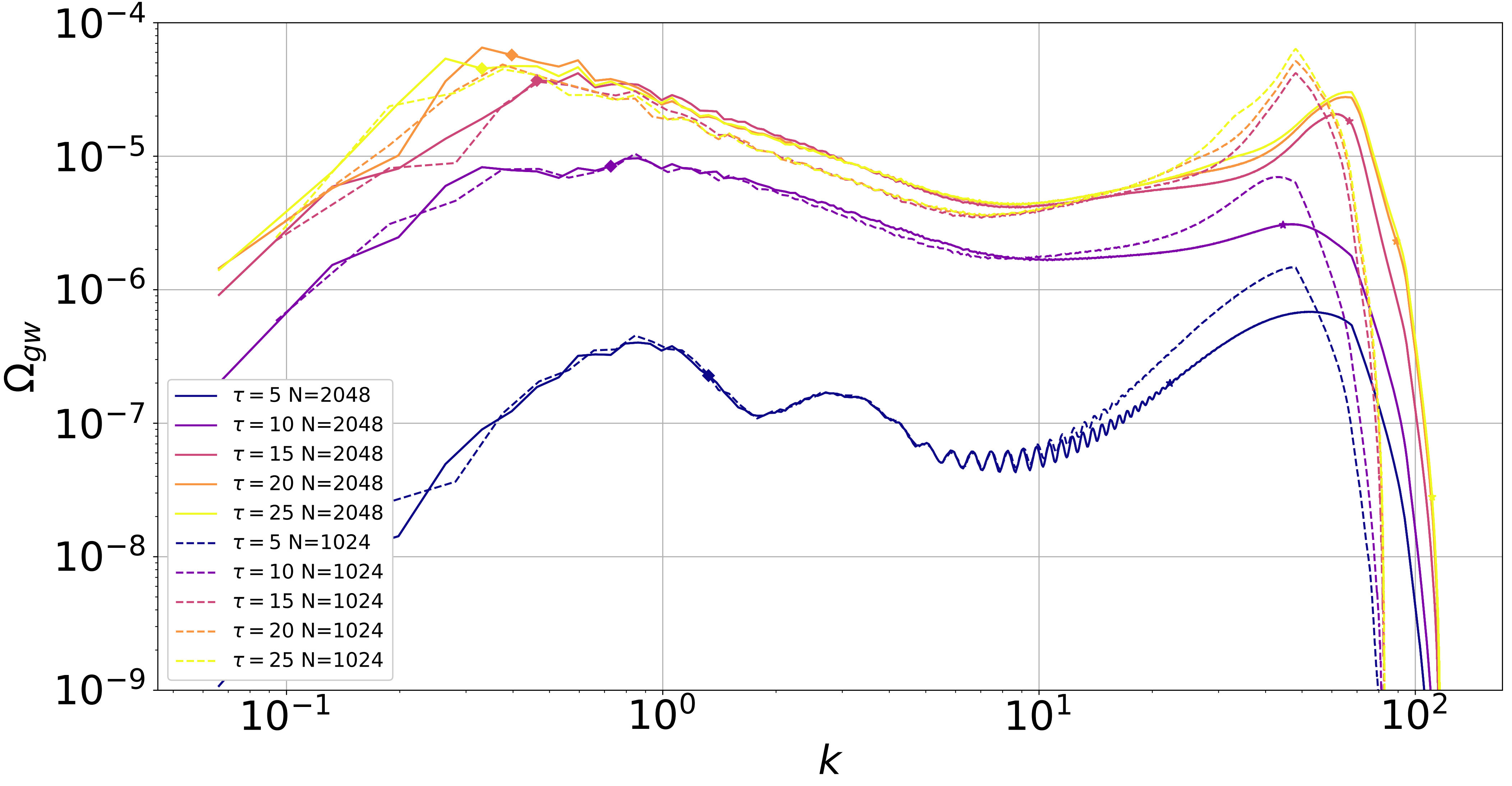
Work in progress: potential bias
GW spectrum: vacuum conditions



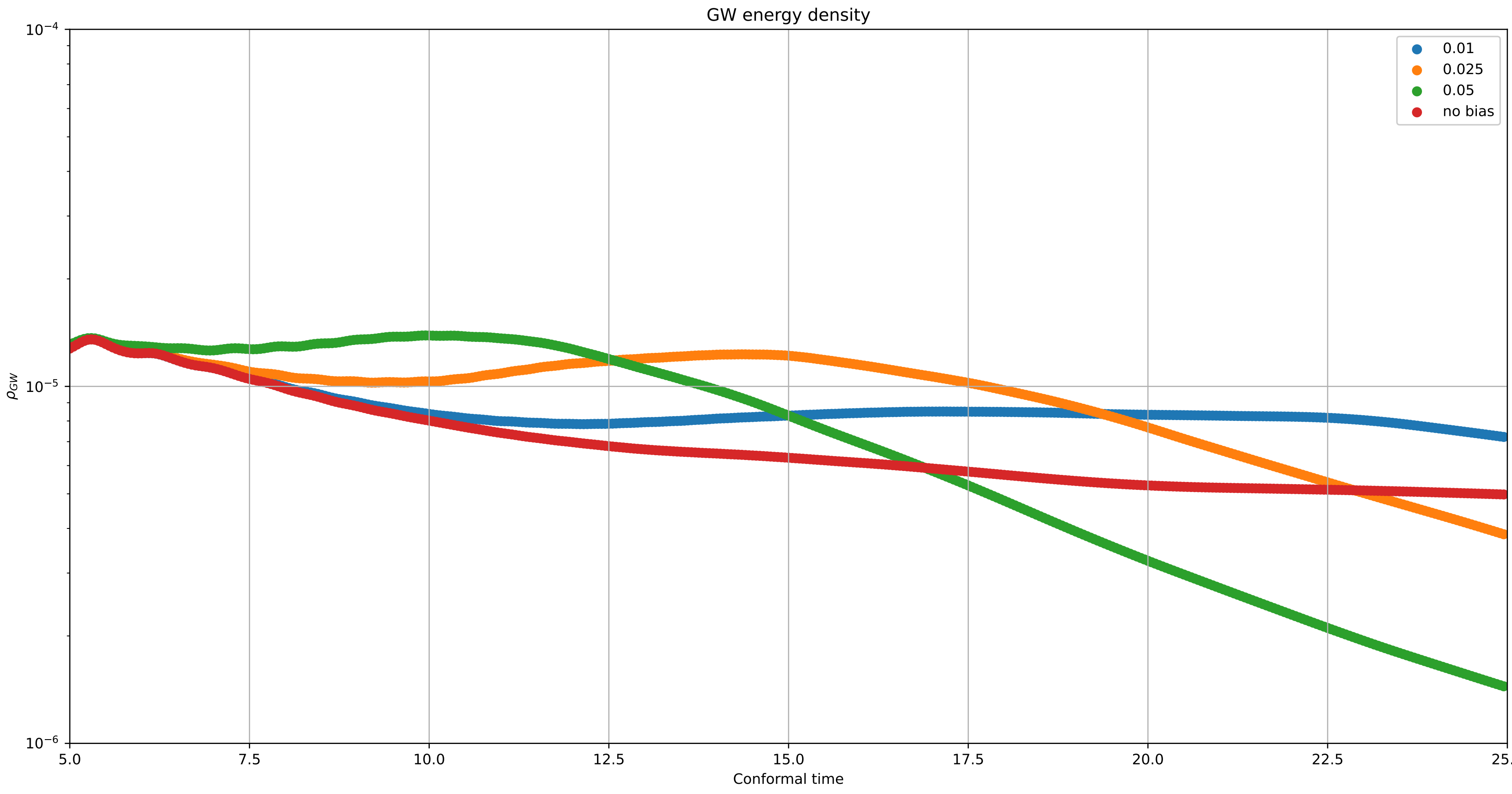
Summary

- Domain wall network settles to scaling regime: ξ and energy density of GW are constant
- Different value of ξ in the cases of thermal and vacuum conditions may have physical origin
- It is possible to get rid of numerical artifact in the UV part of the spectrum
- Potential bias does not significantly affect the GW spectra

Thank you for your attention!



10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Ω_{gw}
10^{-1}
10^{0}
10^{1}
10^{2}
k
$\tau = 5$ N=2048
$\tau = 10$ N=2048
$\tau = 15$ N=2048
$\tau = 20$ N=2048
$\tau = 25$ N=2048
$\tau = 5$ N=1024
$\tau = 10$ N=1024
$\tau = 15$ N=1024
$\tau = 20$ N=1024
$\tau = 25$ N=1024



GW energy density
10^{-4}
10^{-5}
10^{-6}
ρ_{GW}
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
Conformal time
0.01
0.025
0.05
no bias