名古屋大学
NAGOYA UNIVERSITY

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

International Workshop on
“Gravitational Waves and the Early Universe:
Accelerated Expansion, Dynamical Inhomogeneity, and Beyond”
March 12–14, 2026,

Challenges in Modelling Domain Walls and their Gravitational Wave Emission

Alexander Vikman

13.03.2026

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MINISTRY OF EDUCATION, YOUTH AND SPORTS

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Very Useful Papers

- On the estimation of gravitational wave spectrum from cosmic domain walls
  Takashi Hiramatsu, Masahiro Kawasaki, Ken'ichi Saikawa
  `e-Print: 1309.5001, JCAP`

- Stability of domain walls with inflationary fluctuations under potential bias, and gravitational wave signatures
  Naoya Kitajima, Junseok Lee, Fuminobu Takahashi, Wen Yin
  `e-Print: 2311.14590, JCAP`

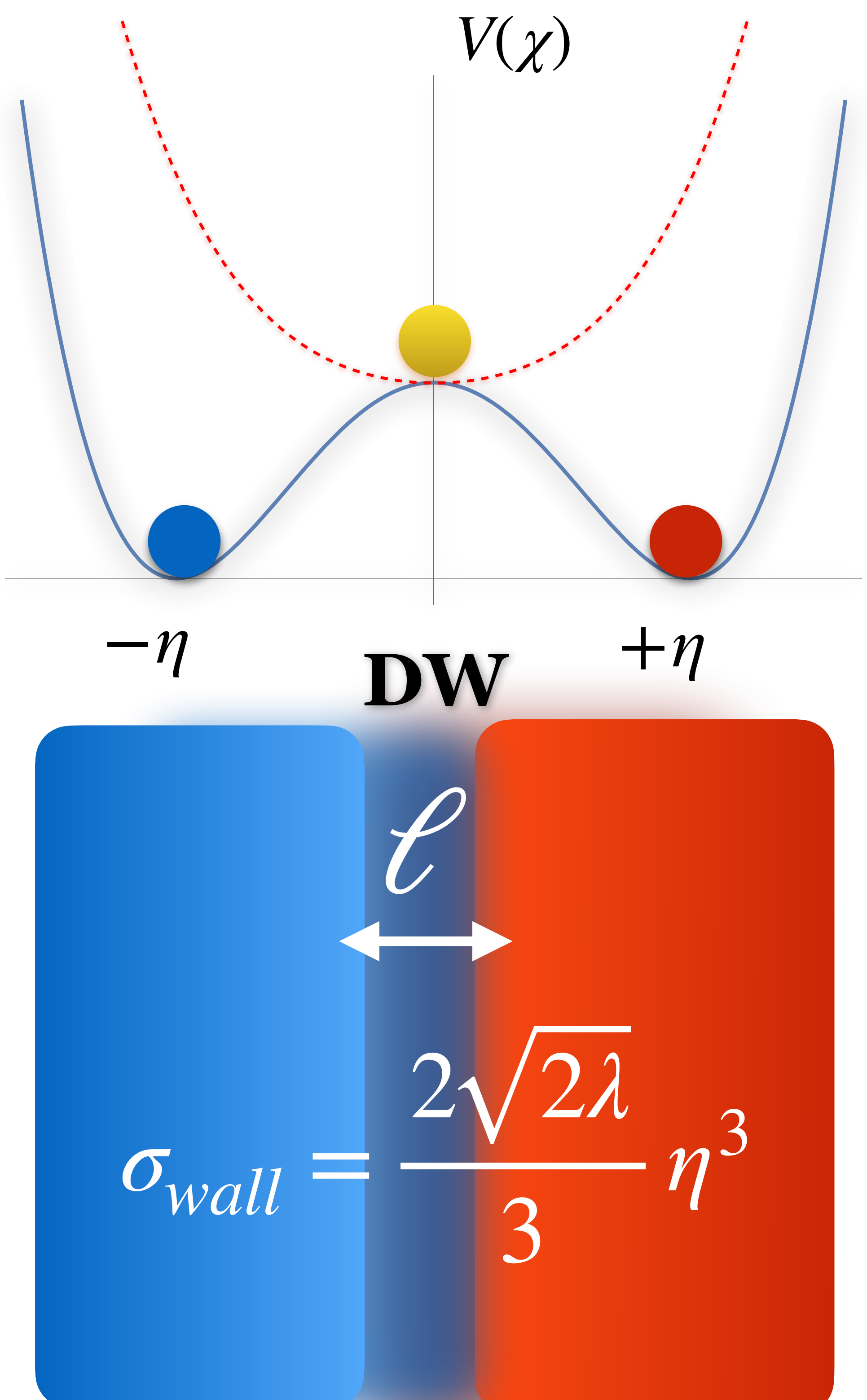
This talk is based on

- Beyond freeze-in: dark matter via inverse phase transition and gravitational wave signal
  `e-Print: 2104.13722, Phys.Rev.D`
- Gravitational shine of dark domain walls
  `e-Print: 2112.12608, JCAP`
- NANOGrav spectral index γ=3 from melting domain walls
  `e-Print: 2307.04582, Phys.Rev.D`
- Revisiting evolution of domain walls and their gravitational radiation with CosmoLattice
  `e-Print: 2406.17053, JCAP`
- Biased domain walls: faster annihilation, weaker gravitational waves
  `e-Print: 2504.07902, JCAP`
- Cosmic domain walls on a lattice: Illusive effects of initial conditions
  `e-Print: 2509.25367, Phys.Rev.D`

Eugeny Babichev (IJCLab, Orsay)
Ivan Dankovsky (Moscow State U. and INR)
Dmitry Gorbunov (INR and MIPT, Moscow)
Sabir Ramazanov (ITMP, Moscow State U.)
Rome Samanta (INFN & SSM, Naples)
Alexander Vikman (CEICO, FZU Prague)

Domain Walls (DW) and Spontaneous Breaking of Discrete Symmetry

Z_2 -symmetric scalar field χ



$$V = \frac{\lambda}{4}\left(\chi^2 - \eta^2\right)^2$$

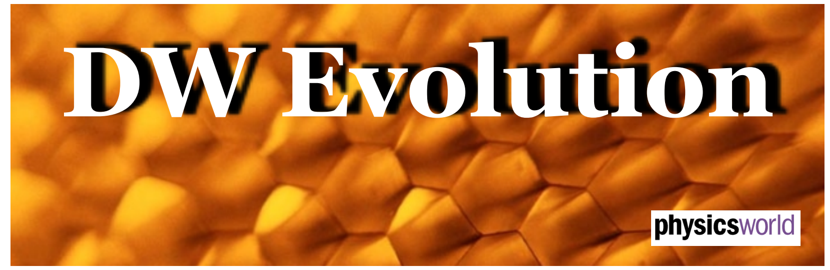
$$\varepsilon = \frac{1}{2}\left(\nabla\chi\right)^2 + V$$

Minimising energy per surface

$$\sigma \simeq \varepsilon\ell \simeq \left(\frac{\eta}{\ell}\right)^2 \ell + \lambda\eta^4\ell$$

$$\ell \simeq 1/\sqrt{\lambda}\eta \qquad \sigma \simeq \sqrt{\lambda}\eta^3$$

$$\simeq m^{-1}$$



THE ASTROPHYSICAL JOURNAL, 347: 590–604, 1989 December 15

DYNAMICAL EVOLUTION OF DOMAIN WALLS IN AN EXPANDING UNIVERSE

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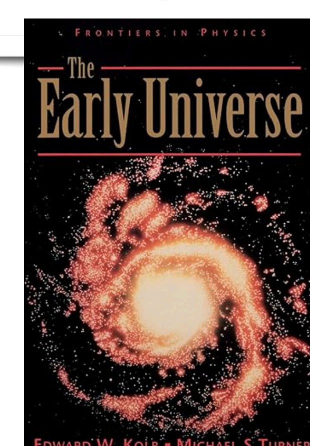
Received 1989 April 7; accepted 1989 June 17

ABSTRACT

Whenever the potential of a scalar field has two or more separated, degenerate minima, then domain walls form as the universe cools. We calculate the evolution of the resulting network of domain walls, for the case of two potential minima, by direct numerical integration of the partial differential equations of the scalar field, in two and three dimensions, thus including wall annihilation, crossing, and reconnection (intercommutation) effects. Three dimensional simulations were run on a 200 × 200 × 200 mesh, while two-dimensional simulations (three-dimensional equations but slab symmetry in one coordinate) were run on a mesh of 1024 × 1024. We find that the nature of the evolution is largely independent of the rate at which the universe expands, if time is measured in conformal units so that the wave operator in comoving space does not depend on the expansion. This means that our results should apply to walls both inside and outside the particle horizon. We find that, unlike cosmic strings, wall evolution does not leave behind many fragments or other topological detritus. Wall annihilation and reconnection occurs almost as fast as causality allows, so that the horizon volume is "swept clean" and contains, at any time, only about one, fairly smooth, wall. Quantitative statistics are given. The rms velocity of walls is $\sim 0.4c$. Wall "bubbles" or "bags" are rare and collapse almost immediately, radiating away their energy as field excitations (schizons). Up to a logarithmic correction (discussed in some detail and related to the critical behavior of self-avoiding random walks in two-dimensions) the total (comoving) area of wall per (comoving) volume decreases as the first power of (conformal) time. In a matter dominated universe, this implies $\rho_{\rm wall} \propto a^{-3/2}$. The relative slowness of this decrease, along with the fact that the wall is smooth on the horizon scale, makes it impossible for walls (if they move freely and if they survive to the present) both to generate large-scale structure and to be consistent with quadrupole microwave background anisotropy limits.
Subject headings: cosmic background radiation — cosmology — galaxies: clustering

$$M_{wall} \sim \sigma_{wall}/H^2$$

$$\rho_{wall} \sim M_{wall}H^3 \sim \sigma_{wall}\, H \propto T^2$$



"Apparently, domain walls are cosmological bad news…"

Simple Challenges

- physical DW thickness $\ell \simeq const$ lattice resolution $\propto a$

↓

- simulation cannot resolve DW at late times

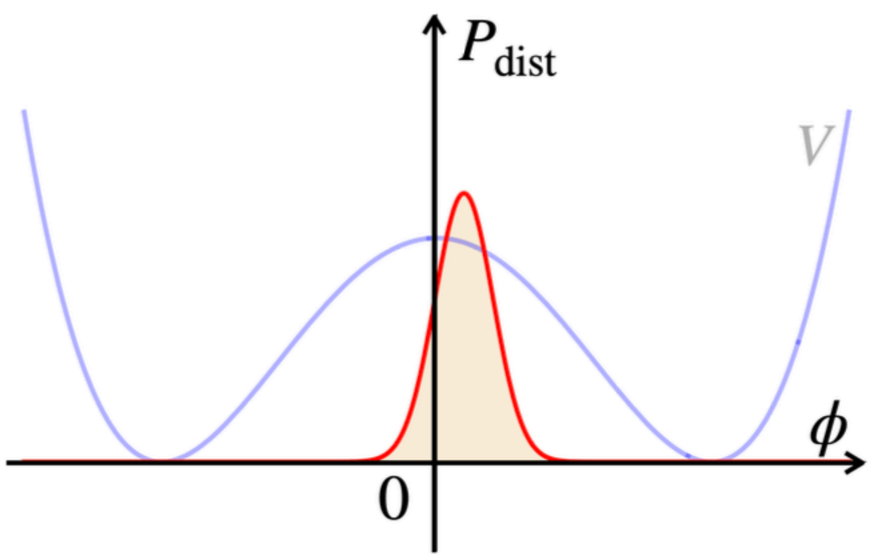
- scaling regime implies one DW per Hubble volume $H^{-3} \propto a^6$ simulation box grows as a^3

↓

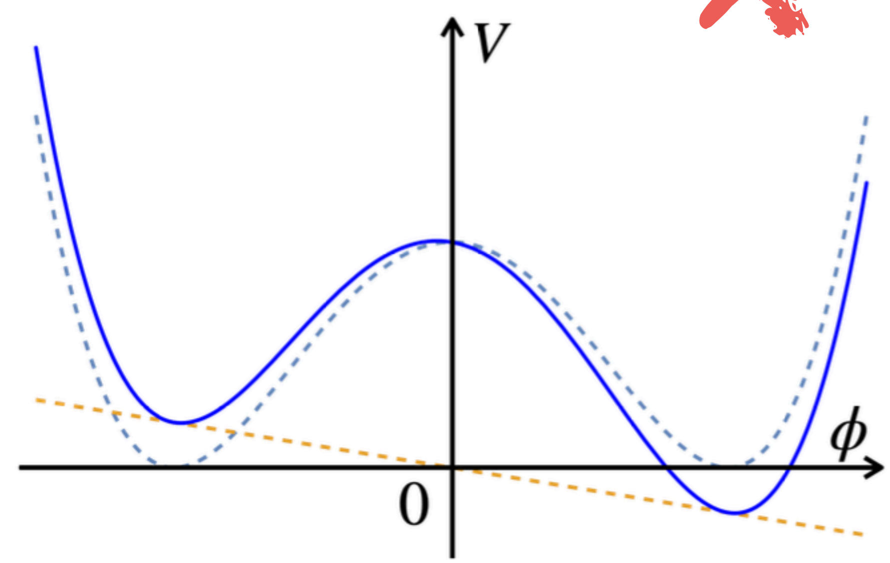
- simulation box is too small to contain even one DW at late times

Why isn't the news that bad?
DW are easy to kill

population bias

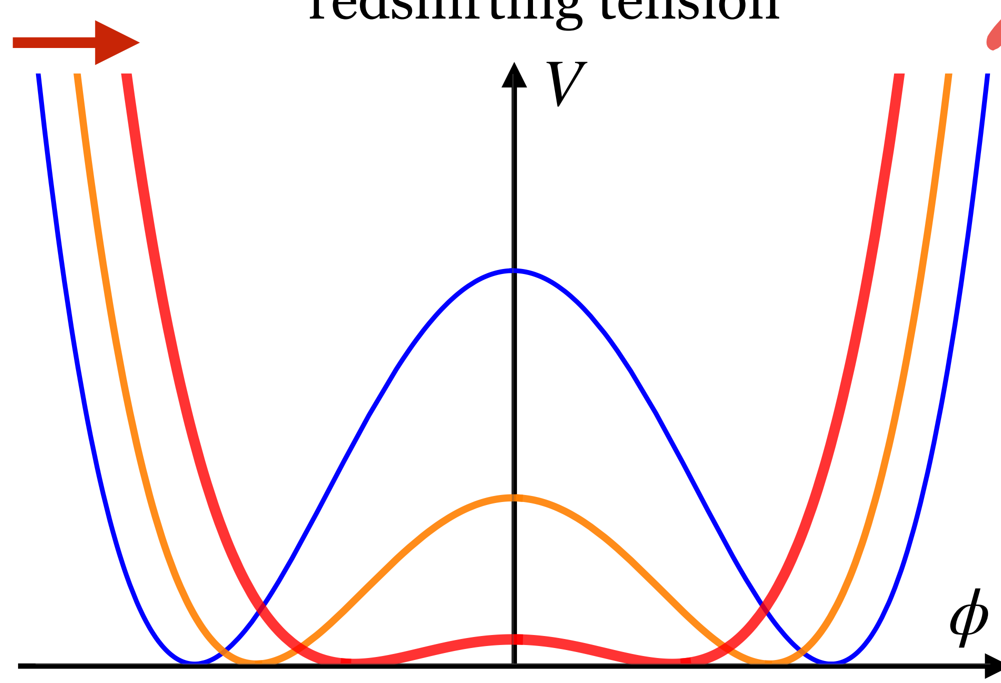


potential bias



Above Pictures are from Kitajima, Lee, Murai, Takahashi, Yin (2023)

melting -
redshirting tension



Vilenkin (1980)

Babichev, Gorbunov, Ramazanov, Vikman (2021)

Why is the news good?

Cosmological DW have “quadrupole” evolving in time / TT part of stress tensor

Gravitation Waves Emission!

The New York Times

The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find

June 28, 2023

Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.

Share full article 362

The Very Large Array on the Plains of San Agustin, N.M., one of three radio telescopes that worked with a global consortium to detect the timing of pulsars. NRAO/AUI/NSF

The Washington Post

In a major discovery, scientists say space-time churns like a choppy sea

The mind-bending finding suggests that everything around us is constantly being roiled by low-frequency gravitational waves

By Joel Achenbach and Victoria Jaggard

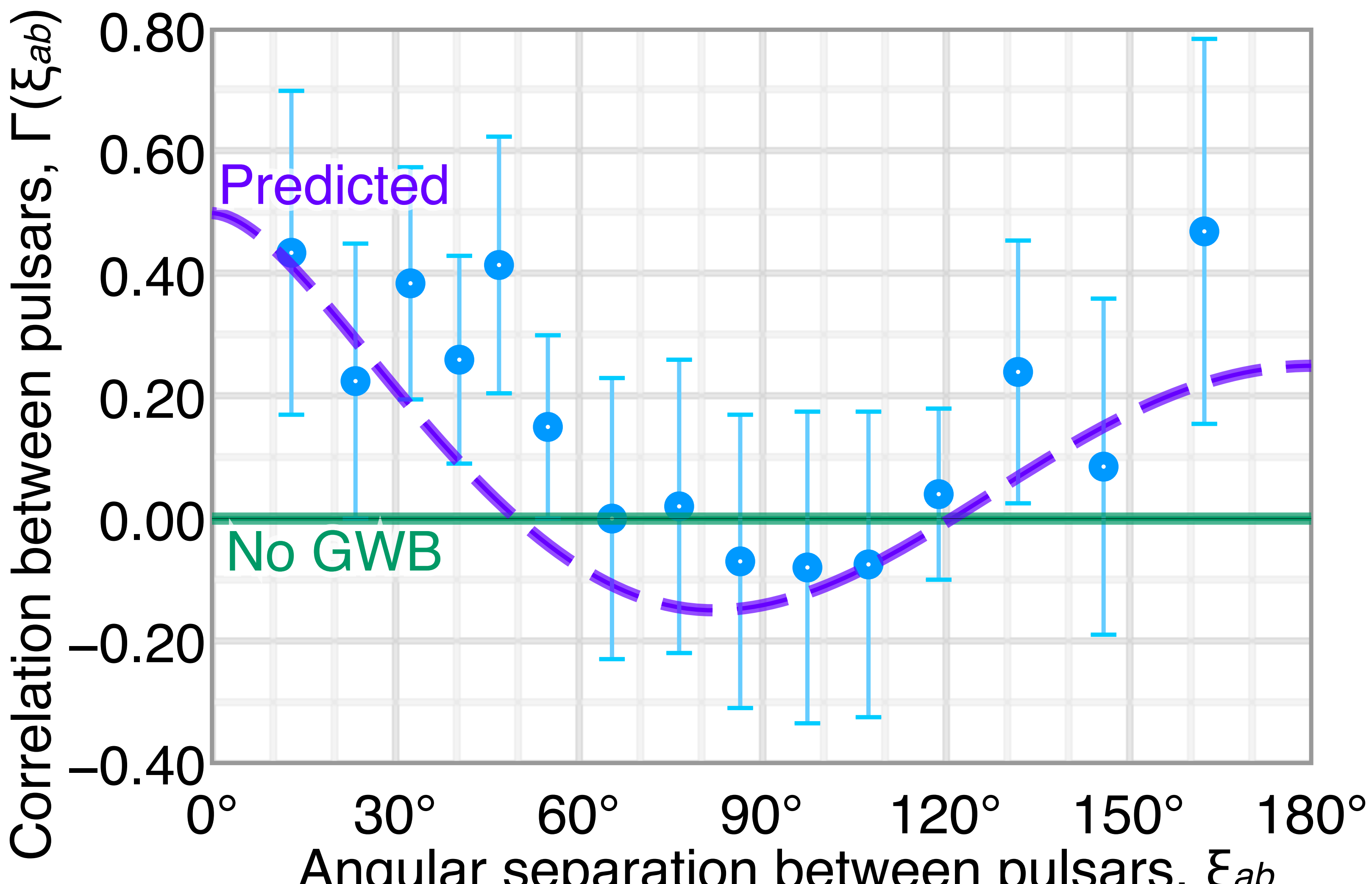
June 28, 2023 at 8:00 p.m. EDT

The Green Bank Observatory in Green Bank, W.Va., was among the observatories used to track pulsars as a way of detecting low-frequency gravitational waves. (Michael S. Williamson/The Washington Post)

NANOGrav:
15 year of observations of 68 millisecond pulsars,
GW on 10^{-9} Hz (nHz)

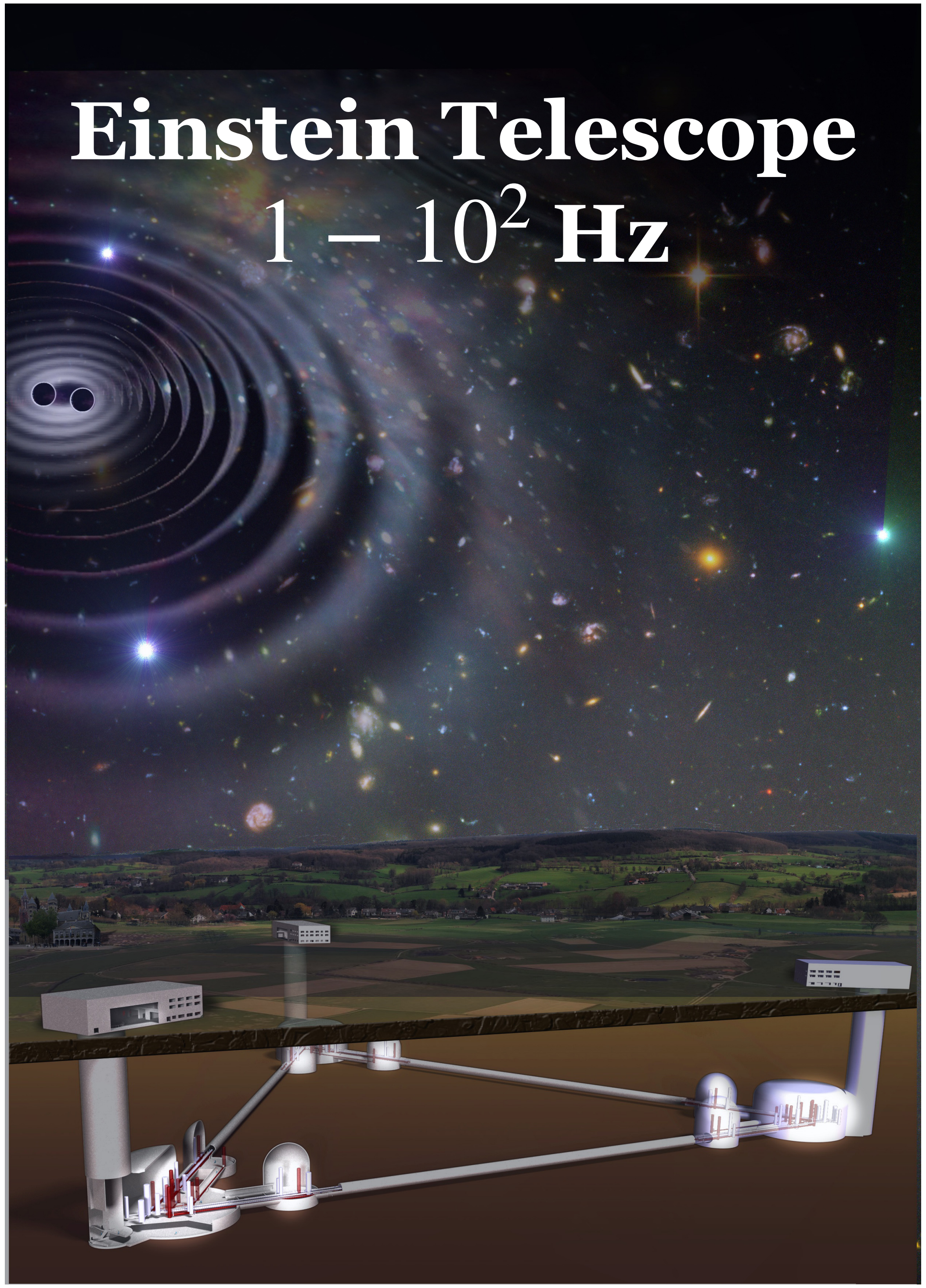
For example, J0437–4715 has a period of
0.005757451936712637 s
with an error of 1.7×10^{-17} s

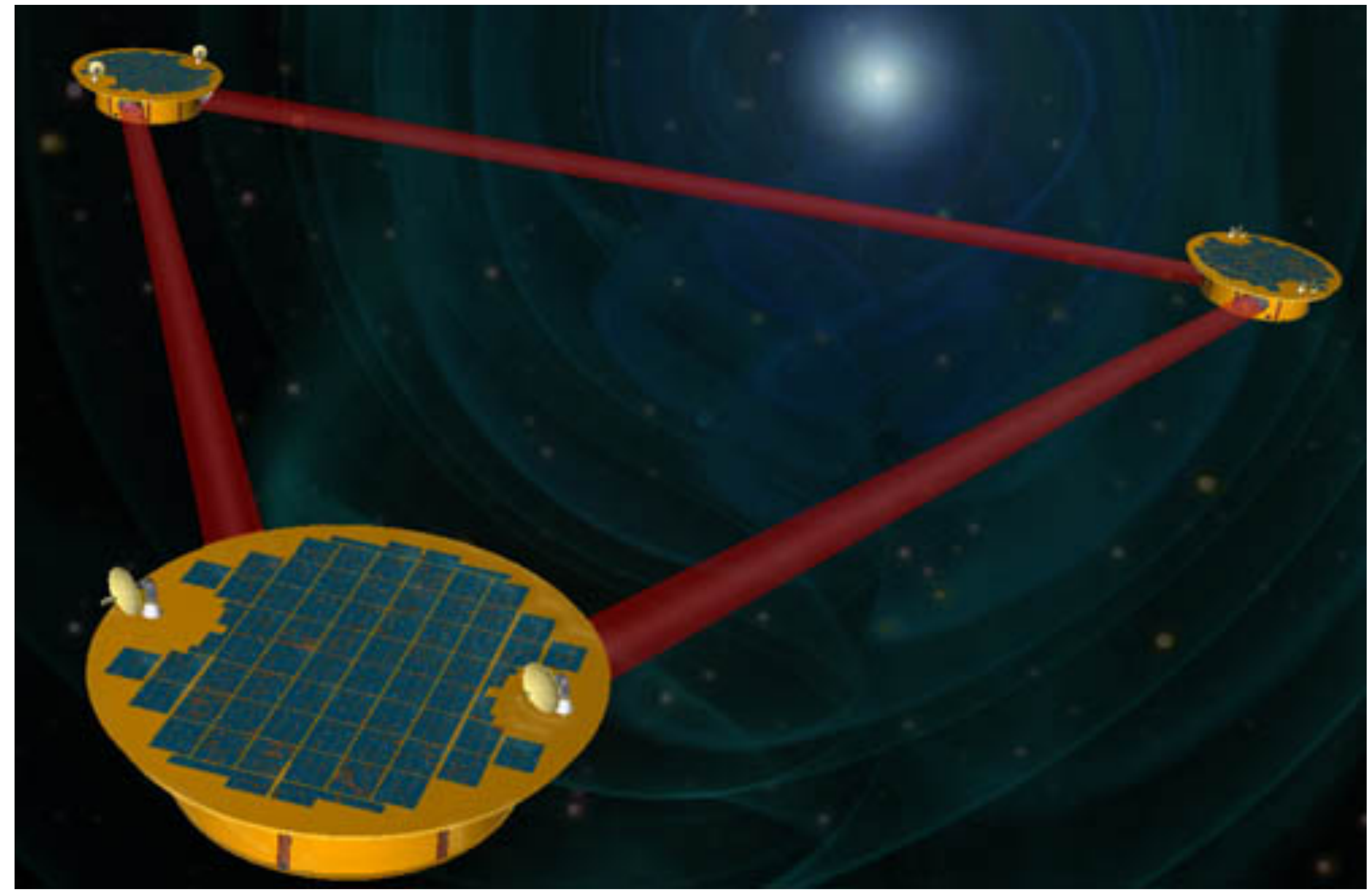
Hellings–Downs curve



NANOGrav 15-year data set

DW are also interesting as a source for Future Observatories





LISA/Taiji/TianQin

$10^{-4} - 1$ **Hz**

Gravitational Waves

$$ds^2 = dt^2 - a^2(t)\left(\delta_{ik} + h_{ik}\right) dx^i dx^k \qquad h_i^i = \partial_i h^{ik} = 0$$

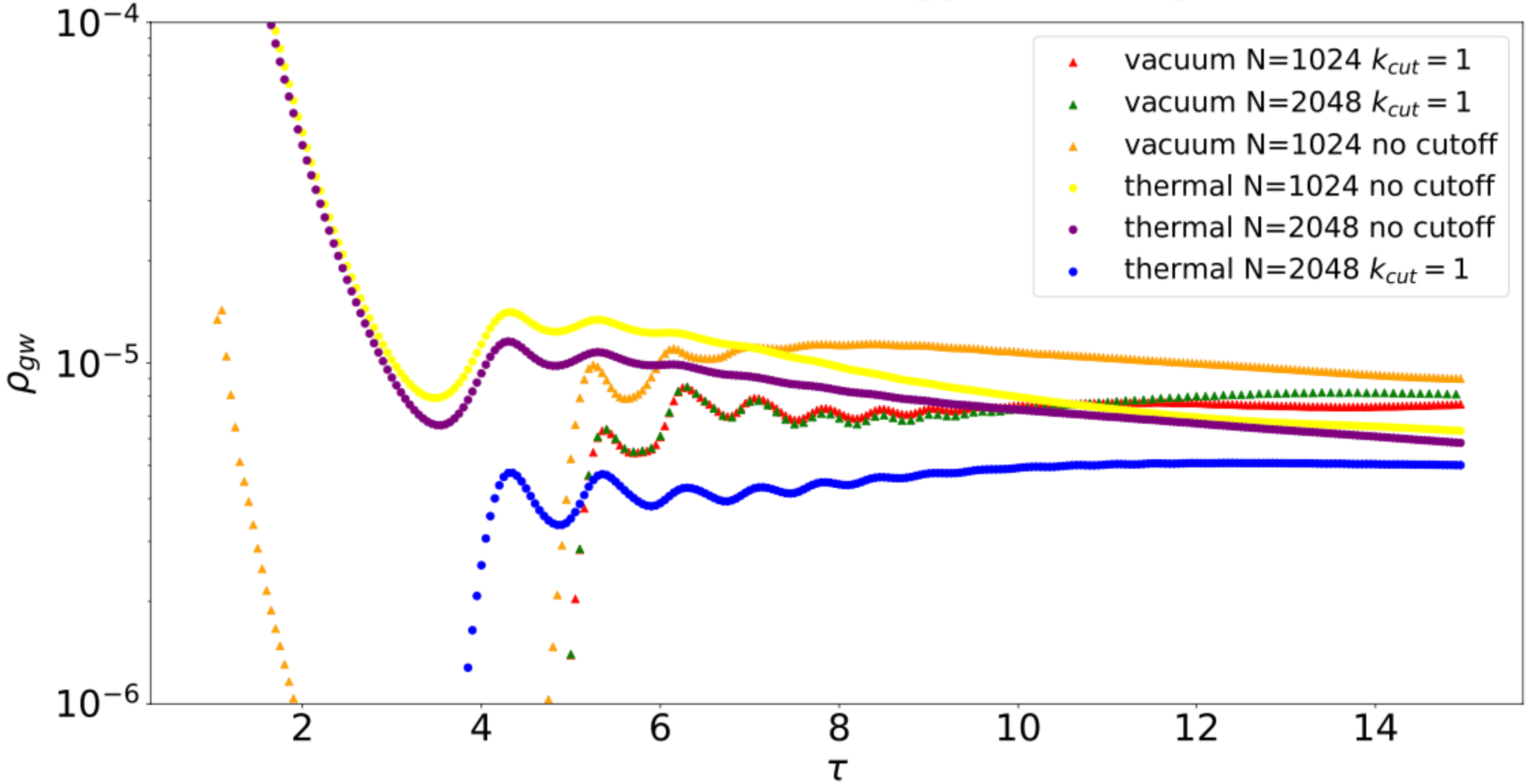
$$\ddot{h}_{ik} + 3H\dot{h}_{ik} - \frac{\Delta}{a^2} h_{ik} = \frac{2}{a^2}\delta T_{ik}^{TT} \sim \frac{\partial_i\phi\partial_k\phi}{a^2}$$

$$\sim \frac{\ell H^{-2}}{H^{-3}}\left(\frac{\eta}{\ell}\right)^2 \sim H\sqrt{\lambda}\eta^3 \sim H\sigma_{wall}$$

$$\ddot{h} + 3H\dot{h} \sim H\sigma_{wall} \quad \Rightarrow \quad \dot{h} \sim \sigma_{wall}$$

Energy density $\rho_{gw} = \frac{1}{4}\left\langle \dot{h}_{ik}\dot{h}_{ik} \right\rangle \sim \sigma_{wall}^2$

GW energy density



Figueroa, Florio, Torrenti, Valkenburg

CosmoLattice

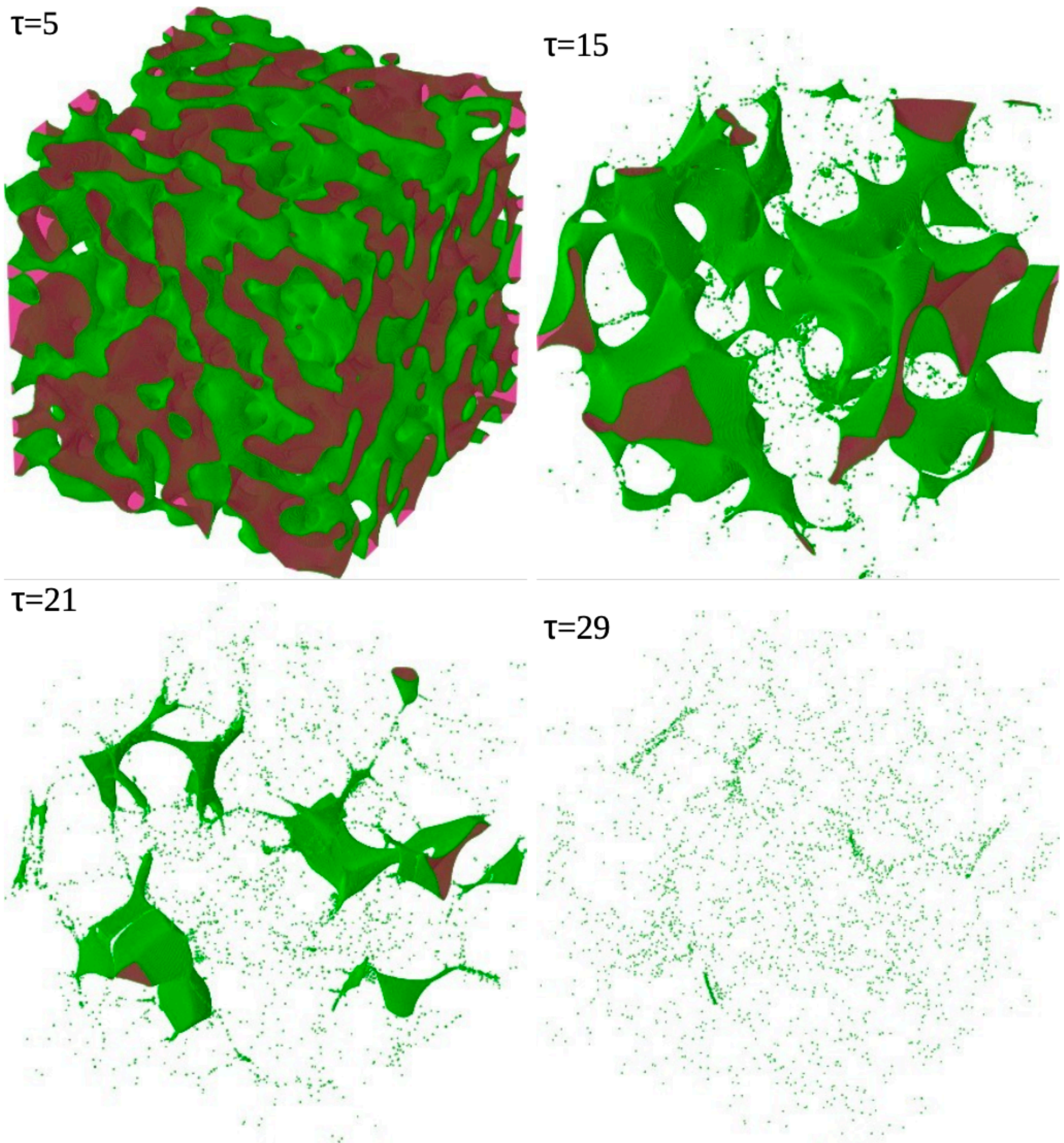
Figure 6: The energy density of GWs in units of $\lambda\eta^4$ emitted by the domain wall network is obtained from numerical simulations on lattices with the grid numbers $N = 1024$ and $N = 2048$ starting from vacuum and thermal initial conditions with and without cutoffs. Conformal time τ is in units of $\frac{1}{\sqrt{\lambda}\eta}$. The expectation value η is set at $\eta = 6 \cdot 10^{16}$ GeV. Rescaling to arbitrary η is achieved by multiplying the energy density ρ_{gw} by $(\eta/6 \cdot 10^{16}\ \text{GeV})^2$.

Dankovsky, Babichev, Gorbunov, Ramazanov, Vikman (2024)

Domain Walls with Bias

$$V(\chi) = \frac{\lambda}{4}\left(\chi^2 - v^2\right)^2 + \epsilon\chi^3$$

$$\epsilon \rightarrow \frac{\epsilon}{\lambda v}$$



Figueroa, Florio, Torrenti, Valkenburg

CosmoLattice

"vacuum" initial conditions

$$\left\langle \chi(\mathbf{k})\chi^*(\mathbf{k}')\right\rangle = \frac{1}{2k}\delta(\mathbf{k}-\mathbf{k}')$$

$$\left\langle \dot\chi(\mathbf{k})\dot\chi^*(\mathbf{k}')\right\rangle = \frac{k}{2}\delta(\mathbf{k}-\mathbf{k}')$$

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman, 2504.07902

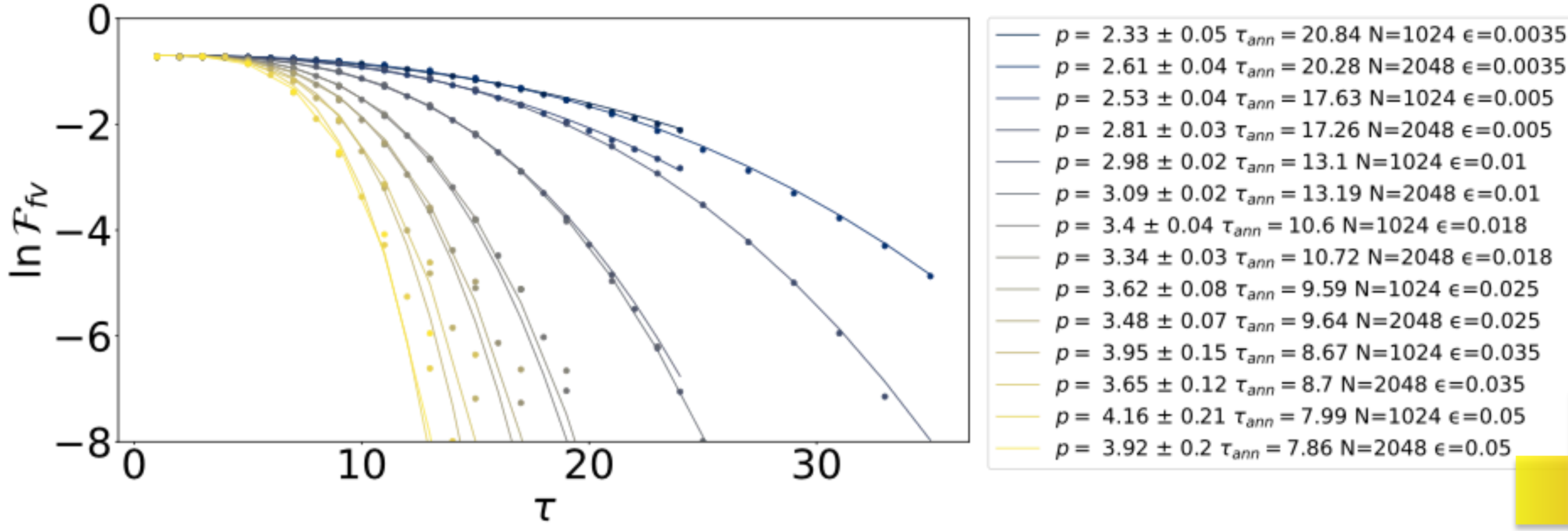
$$\langle \chi(\mathbf{k})\chi^*(\mathbf{k}')\rangle = (2\pi)^3 A(k)\,\delta(\mathbf{k}-\mathbf{k}')$$

$$\langle \dot\chi(\mathbf{k})\dot\chi^*(\mathbf{k}')\rangle = (2\pi)^3 B(k)\,\delta(\mathbf{k}-\mathbf{k}')$$

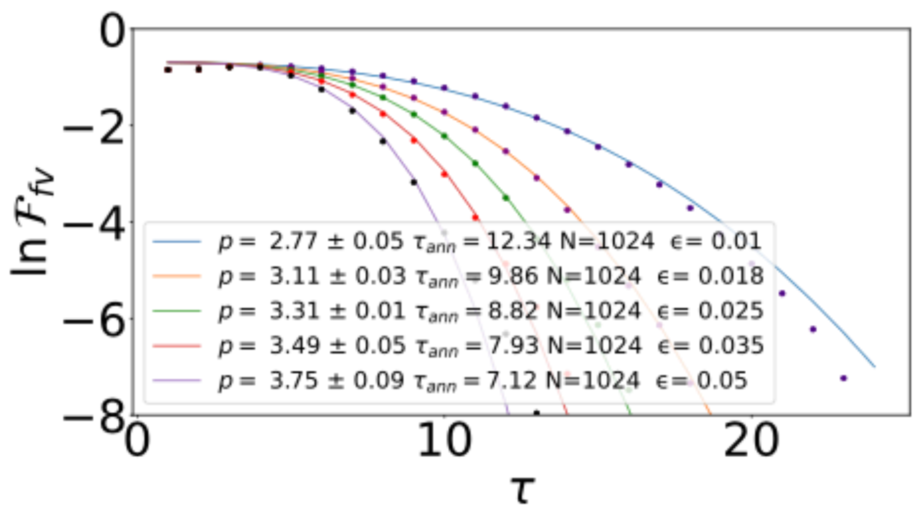
$$A(k) = \frac{e^{-k_{IR}^2/k^2}\cdot\theta\left(k_{UV}-k\right)}{k\left(e^{k/T}-1\right)^{\alpha}} \qquad B = k^2 A$$

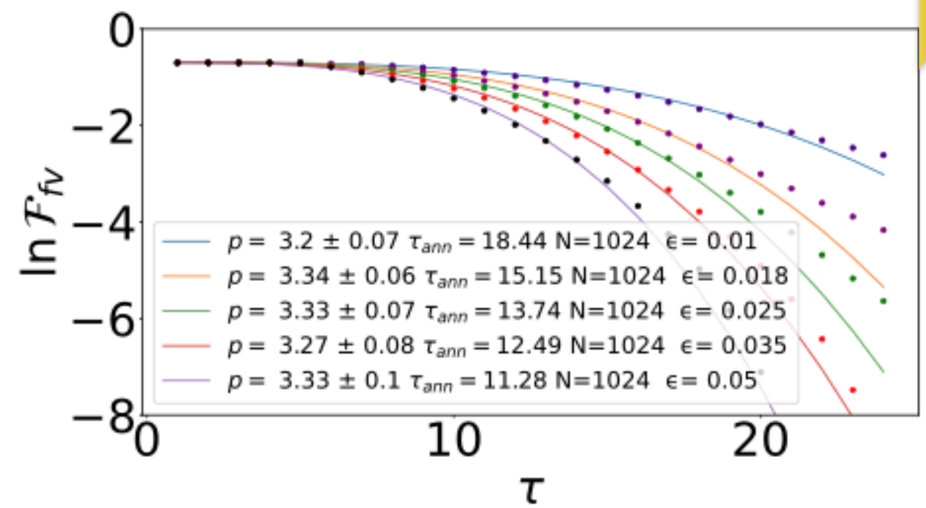
Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman, 2509.25367

Decay of the DW network



$$t_{ann} \simeq V_{bias}^{-2/3}$$





$p = 3?$

Fraction of the false vacuum

$$\mathcal{F}_{fv} = \frac{1}{2} \exp\left[-\left(\frac{\tau}{\tau_{ann}}\right)^p\right]$$

$$V_{bias} = V(+v) - V(-v) \simeq 2\epsilon v^3$$

Standard estimation $V_{bias} \simeq \sigma_{wall} H$ → $t_{ann} \simeq V_{bias}^{-1}$

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman, 2504.07902

Scaling Parameter Evolution

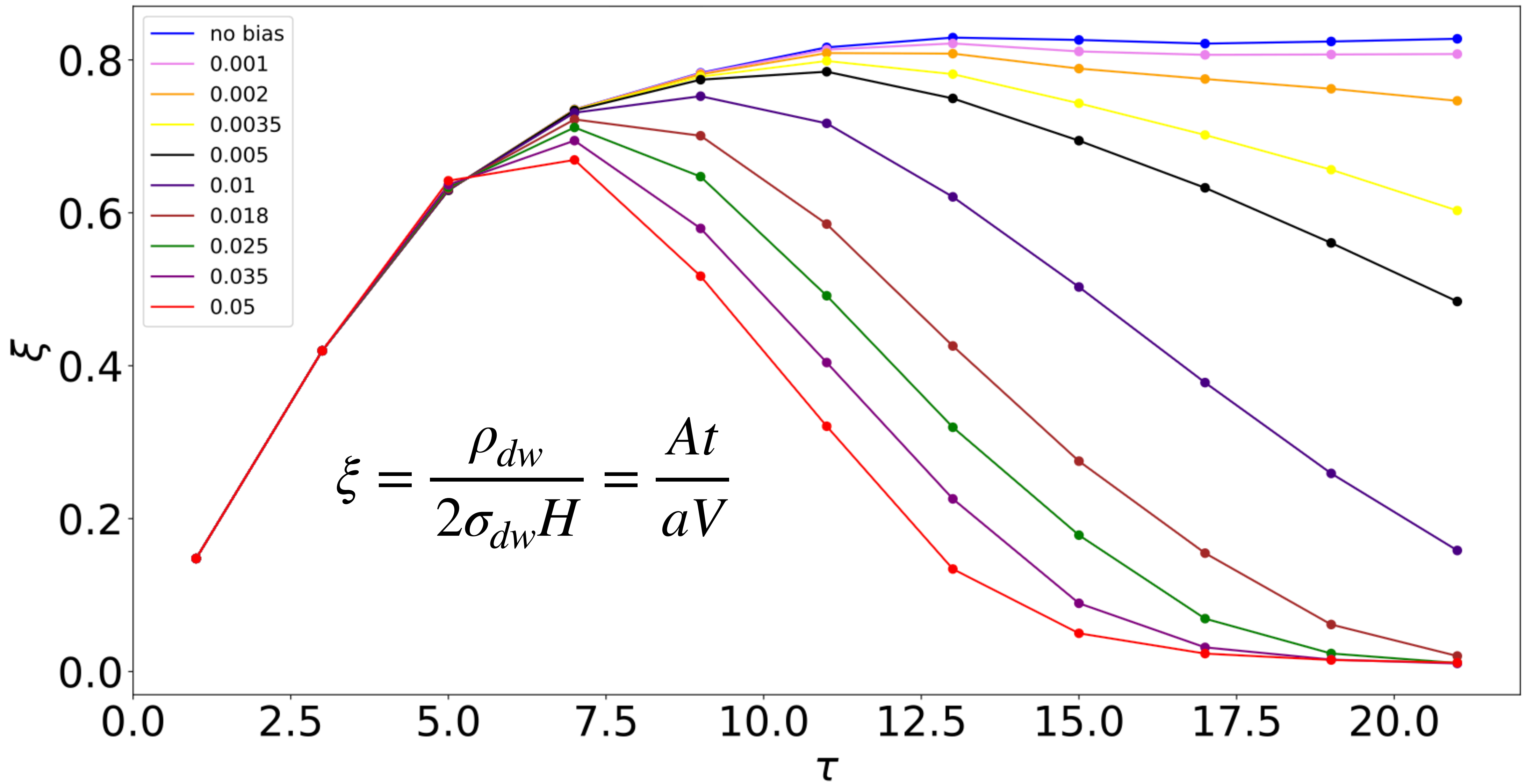


Figure 3: Scaling parameter ξ defined in Eq. (24) is shown for different values of the bias parameter ϵ. Simulations have been carried out with 1024^3 lattice.

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman 2504.07902

Boundary / Initial Conditions $\xi = 1.2$? No Bias

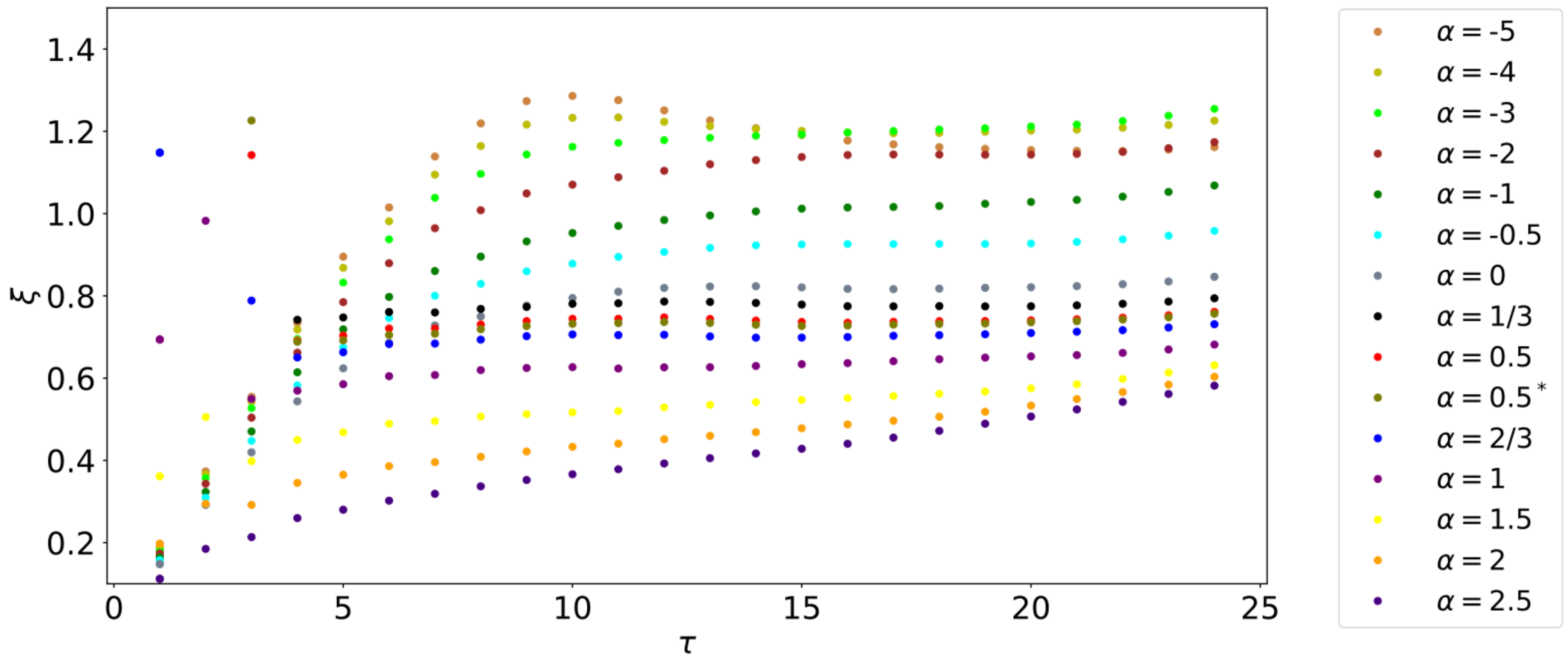
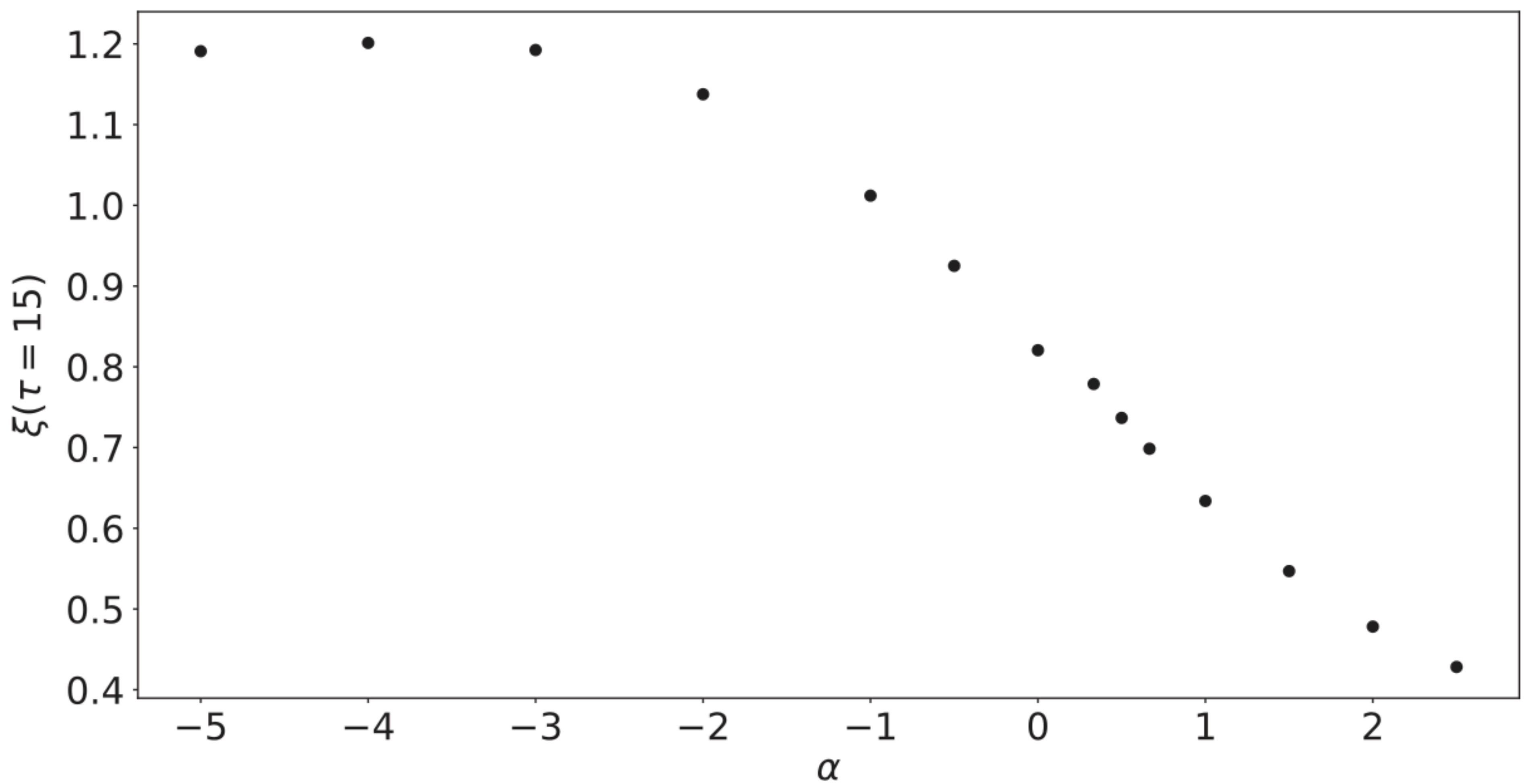


FIG. 1. Evolution of the area parameter ξ for different choices of the parameter α characterizing initial conditions in Eq. (9). An exception is the case $\alpha = 0.5$ marked with an asterisk, in which case the rhs of Eq. (9) is multiplied by a factor of 2, i.e., we have assumed doubled power of the initial scalar spectrum. The IR cutoff is set to $k_{\rm IR} = 0$. No UV cutoff is set for $\alpha > 0$, while for $\alpha \leq 0$ it is set to $k_{\rm UV} = 1$. Simulations have been carried out using a 1024^3 lattice with the box size L given by Eq. (15).

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman, 2509.25367

Boundary / Initial Conditions $\xi = 1.2$? No Bias



Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman, 2509.25367

GW from Domain Walls with Bias

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman (2025)

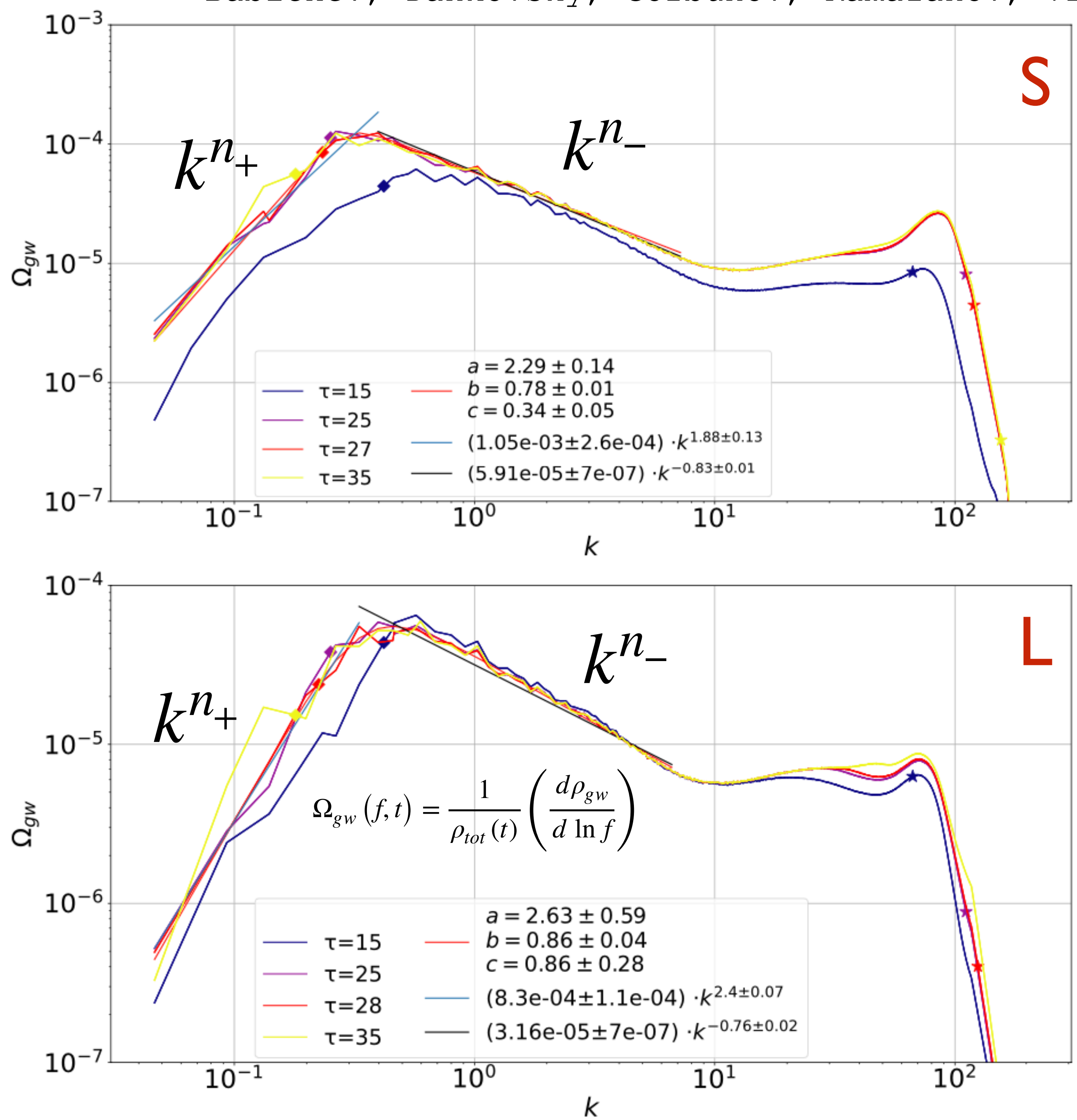


Figure 7: GW spectra obtained with the 2048^3 lattice for the bias parameter $\epsilon = 0.025$ (top panel) and $\epsilon = 0.05$ (bottom panel) starting with vacuum initial conditions and momentum cutoff $k_{cut} = 1$. Shown also are power-law fits and the fit described by Eq. (33).

$\tau_{gw} \simeq 1.8\, \tau_{ann}$

Figueroa, Florio, Torrenti, Valkenburg

CosmoLattice

"vacuum" initial conditions

$$\langle \chi(\mathbf{k}) \chi^*(\mathbf{k}') \rangle = \frac{1}{2k} \delta(\mathbf{k} - \mathbf{k}')$$

$$\langle \dot{\chi}(\mathbf{k}) \dot{\chi}^*(\mathbf{k}') \rangle = \frac{k}{2} \delta(\mathbf{k} - \mathbf{k}')$$

S

$$n_+(27) = 1.88 \pm 0.13$$

$$n_-(35) = -0.83 \pm 0.01$$

L

$$n_+(28) = 2.4 \pm 0.07$$

$$n_-(35) = -0.76 \pm 0.02$$

$$\frac{k_{peak}}{2\pi a_{ann}} \simeq 0.6 H_{ann}$$

GW peak dependence on initial conditions

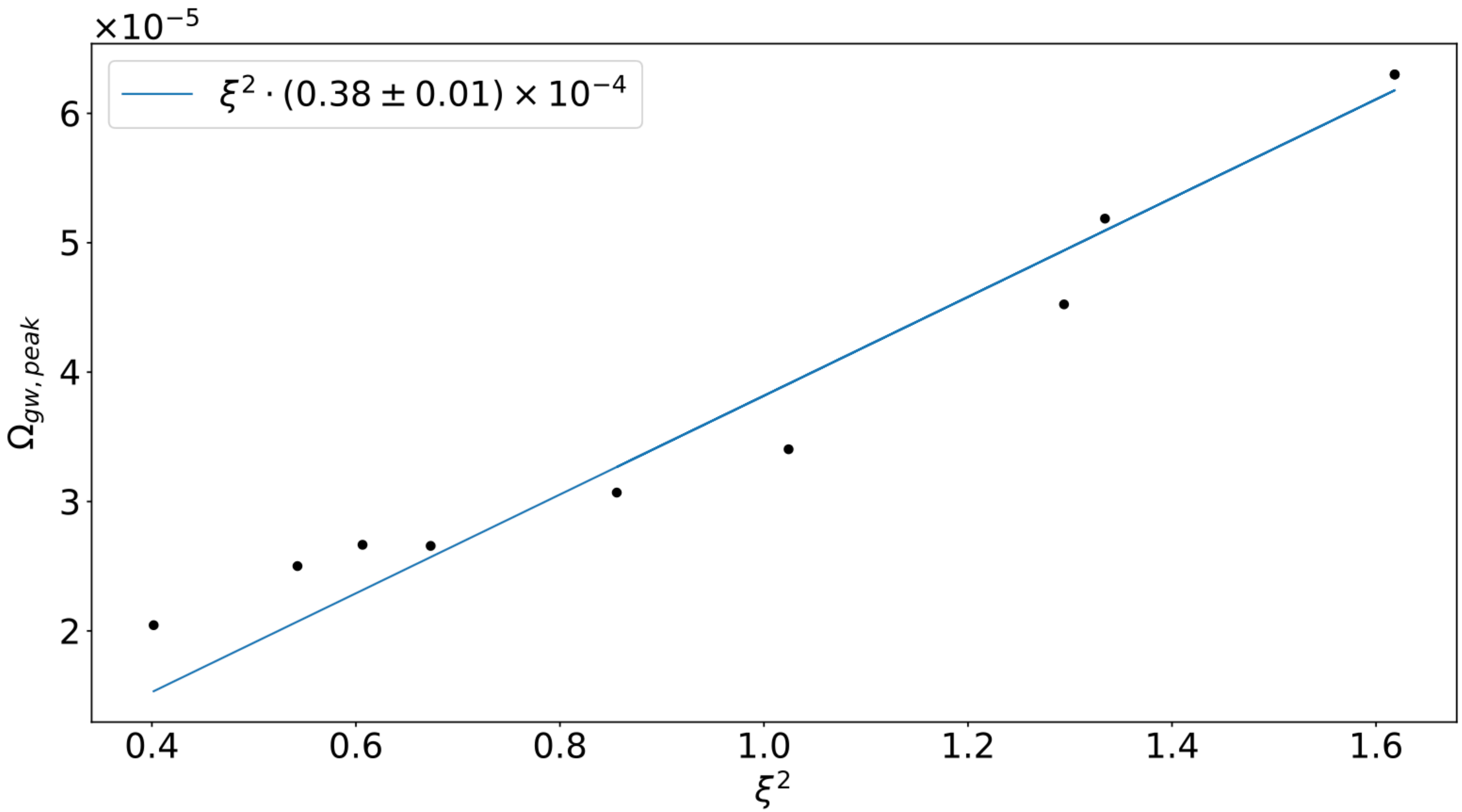


FIG. 7. Fractional energy density of GWs at peak $\Omega_{\text{gw,peak}}$ is shown as a function of ξ^2 at the conformal time $\tau = 15$. Initial conditions for the scalar field χ described by $\alpha = -3, -2, -1, -0.5, 0, 1/3, 0.5, 1$ in Eq. (9) have been assumed. The cutoff $k_{\text{UV}} = 1$ (and $k_{\text{IR}} = 0$) on the initial scalar spectrum has been imposed in the case $\alpha < 0$. In the case $\alpha = 0$, we have considered two choices: $(k_{\text{IR}}, k_{\text{UV}}) = (0, 1)$ and $(k_{\text{IR}}, k_{\text{UV}}) = (1, 2)$. In all the other cases no IR or UV cutoff has been set.

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman, 2509.25367

GW

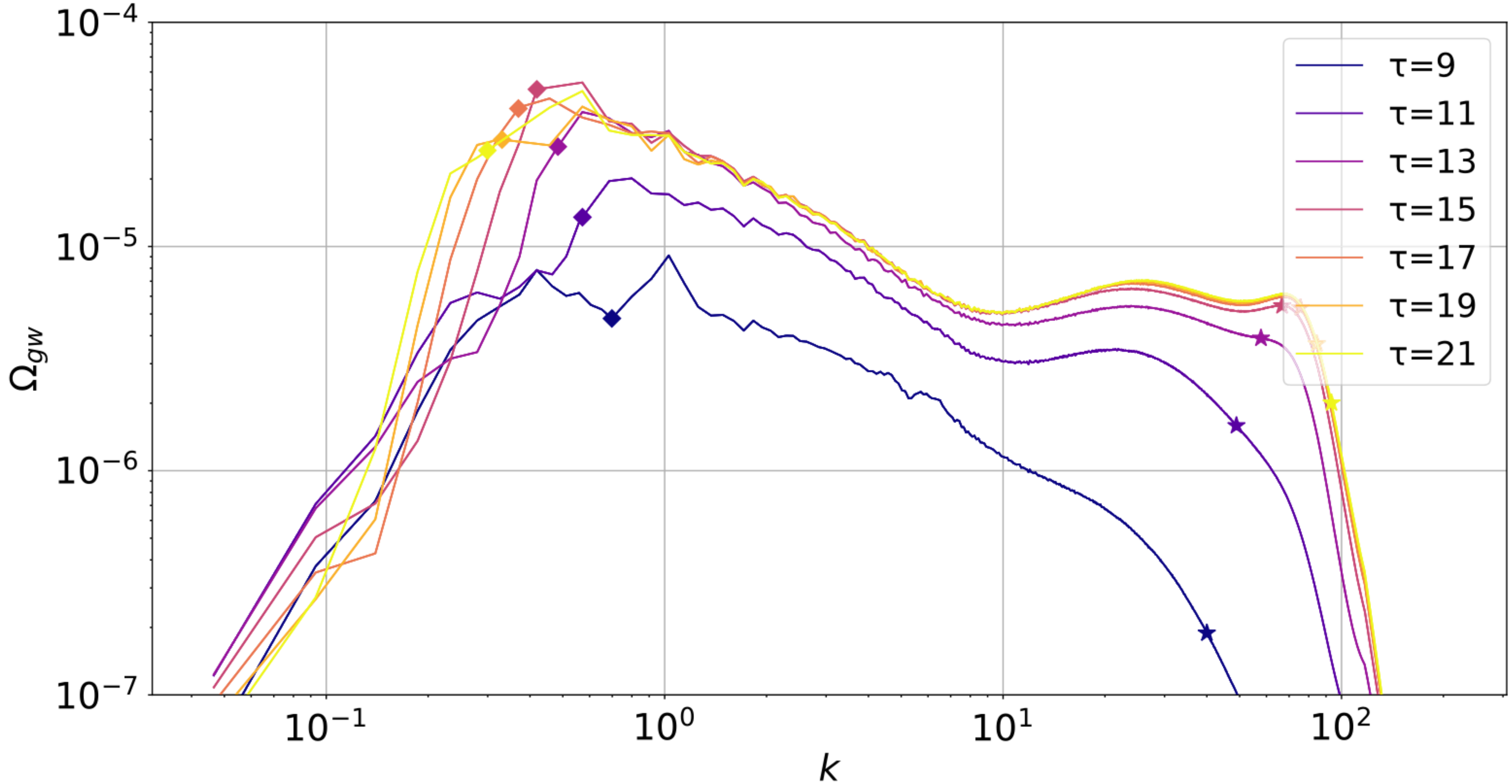


FIG. 10. Spectra of GWs from biased DWs at different conformal times τ. The bias parameter ϵ has been set to $\epsilon = 0.025$. The spectra have been obtained using a 2048^3 lattice. Initial conditions with $\alpha = -3$, $k_{\rm IR} = 0$, $k_{\rm UV} = 1$ in Eq. (9) have been assumed. Stars and diamonds indicate the positions of the DW width and Hubble parameter in conformal variables, i.e., $k = 2\pi a/\delta_{\rm wall}$ and $k = 2\pi aH$, at the given cosmic times.

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman, 2509.25367

TABLE II. Spectral indices $n_{\rm IR}$ and $n_{\rm UV}$ describing power-law fits to IR and UV slopes of GW spectra from biased DWs, respectively, are demonstrated in the case of initial conditions characterized by $\alpha = -3$, $k_{\rm IR} = 0$, $k_{\rm UV} = 1$, and $\alpha = 0$, $k_{\rm IR} = 1$, $k_{\rm UV} = 2$. For each choice of initial conditions, the results are shown at two different conformal times after GW production from DWs has reached saturation.

α	-3	-3	0	0
τ	15	19	15	19
$n_{\rm IR}$	2.81 ± 0.23	2.93 ± 0.32	2.96 ± 0.36	3.09 ± 0.34
$n_{\rm UV}$	-0.83 ± 0.02	-0.78 ± 0.02	-0.64 ± 0.04	-0.73 ± 0.03

Substantially weaker GW !

$$f_{peak} \simeq 8 \text{ nHz}\, \lambda^{1/4} \cdot \left(\frac{\epsilon}{10^{-36} \cdot \lambda v}\right)^{1/3} \cdot \sqrt{\frac{v}{100 \text{ TeV}}} \cdot \left(\frac{100}{g_*(T_{ann})}\right)^{1/12} ,$$

$$\Omega_{gw,peak} h_0^2 \simeq 1 \cdot 10^{-10} \cdot \left(\frac{v}{100 \text{ TeV}}\right)^4 \cdot \left(\frac{10^{-36} \cdot \lambda v}{\epsilon}\right)^{4/3} \cdot \left(\frac{100}{g_*(T_{ann})}\right)^{1/3}$$

$$\Omega_{gw,peack} \propto \frac{1}{\epsilon^{4/3}}$$

Babichev, Dankovsky, Gorbunov, Ramazanov, Vikman (April 2025)

instead of "usual"

$$\Omega_{gw,peack} \propto \frac{1}{\epsilon^2}$$

Cyr, Cotterill, Battye(2025); Notari, Rompineve, Torrenti(2025); Ferreira, Notari, Pujolas, Rompineve (2024)

PHYSICAL REVIEW D VOLUME 9, NUMBER 12 15 JUNE 1974

Gauge and global symmetries at high temperature*

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 19 February 1974)

It is shown how finite-temperature effects in a renormalizable quantum field theory can restore a symmetry which is broken at zero temperature. In general, for both gauge symmetries and ordinary symmetries, such effects occur only through a temperature-dependent change in the effective bare mass of the scalar bosons. The change in the boson bare mass is calculated for general field theories, and the results are used to derive the critical temperatures for a few special cases, including gauge and nongauge theories. In one case, it is found that a symmetry which is unbroken at low temperature can be broken by raising the temperature above a critical value. An appendix presents a general operator formalism for dealing with higher-order effects, and it is observed that the one-loop diagrams of field theory simply represent the contribution of zero-point energies to the free energy density. The cosmological implications of this work are briefly discussed.

PHYSICAL REVIEW D VOLUME 23, NUMBER 4 15 FEBRUARY 1981

Gravitational field of vacuum domain walls and strings

Alexander Vilenkin
Department of Physics, Tufts University, Medford, Massachusetts 02155
(Received 10 October 1980)

The gravitational properties of vacuum domain walls and strings are studied in the linear approximation of general relativity. These properties are shown to be very different from those of regular massive planes and rods. It is argued that the domain walls are gravitationally unstable and collapse at a certain time $\sim t_c$ after their creation. If the vacuum walls ever existed, they must have disappeared at $t < t_c$.

Z_2 -symmetric DM scalar field χ coupled to
ϕ - a multiplet of N *thermal* degrees of freedom

portal coupling

$$V = \frac{1}{2}\left(M^2 - g^2\phi^\dagger\phi\right)\cdot\chi^2 + \frac{\lambda}{4}\chi^4 + \frac{\lambda_\phi}{4}\left(\phi^\dagger\phi\right)^2$$

tachyonic thermal mass

$$\mu^2 = g^2\langle\phi^\dagger\phi\rangle \simeq \frac{Ng^2T^2}{12}$$

increasing during preheating,
then red-shifting

potential bounded from below

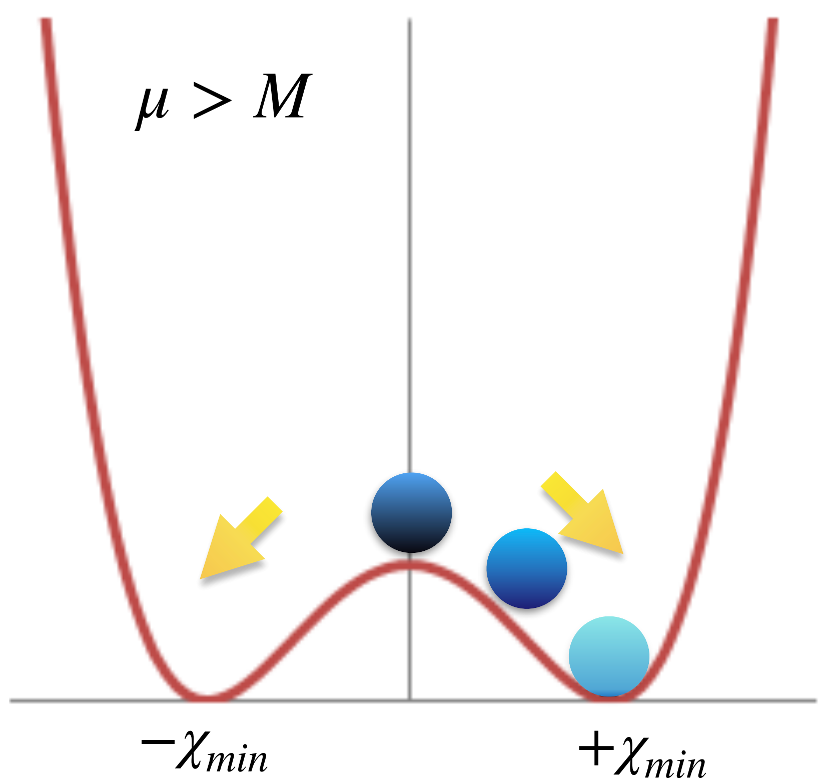
$$\beta = \frac{\lambda}{g^4} \geq \frac{1}{\lambda_\phi} \geq 1$$

potential bounded from below

weak coupling

Direct Phase Transition

Early universe spontaneously Broken Phase



Domain Walls!

Avoid too much friction to start rolling

$$\mu \gtrsim H$$

$$\sqrt{\frac{N}{12}} g T_i \simeq \sqrt{\frac{\pi^2 g_*}{90}} \frac{T_i^2}{M_{pl}}$$

$$T_i \simeq g\, M_{Pl} \sqrt{\frac{N}{g_*(T_i)}} \times \frac{1}{\sqrt{B}}$$

Correction taking into account time to get to the minimum

$$V_{eff} \simeq \frac{\lambda \cdot \left(\chi^2 - \eta^2\right)^2}{4} \qquad \eta(T) \simeq g\sqrt{\frac{N}{12\lambda}}\, T$$

Tension/energy per unit surface $\sigma_{wall} = \frac{2\sqrt{2\lambda}}{3}\eta^3(T)$ melting away as $\propto T^3$!

In the **scaling regime** one domain wall per Hubble volume:

$$\rho_{wall} \sim \sigma_{wall} H \propto T^5$$

Usual Constant tension DW $\rho_{wall} \propto T^2$

Evolution is effectively in Minkowski spacetime $s = a\chi$

$$s'' - \partial_i^2 s + s\left(s^2 - 1\right) = 0$$

Melting Walls

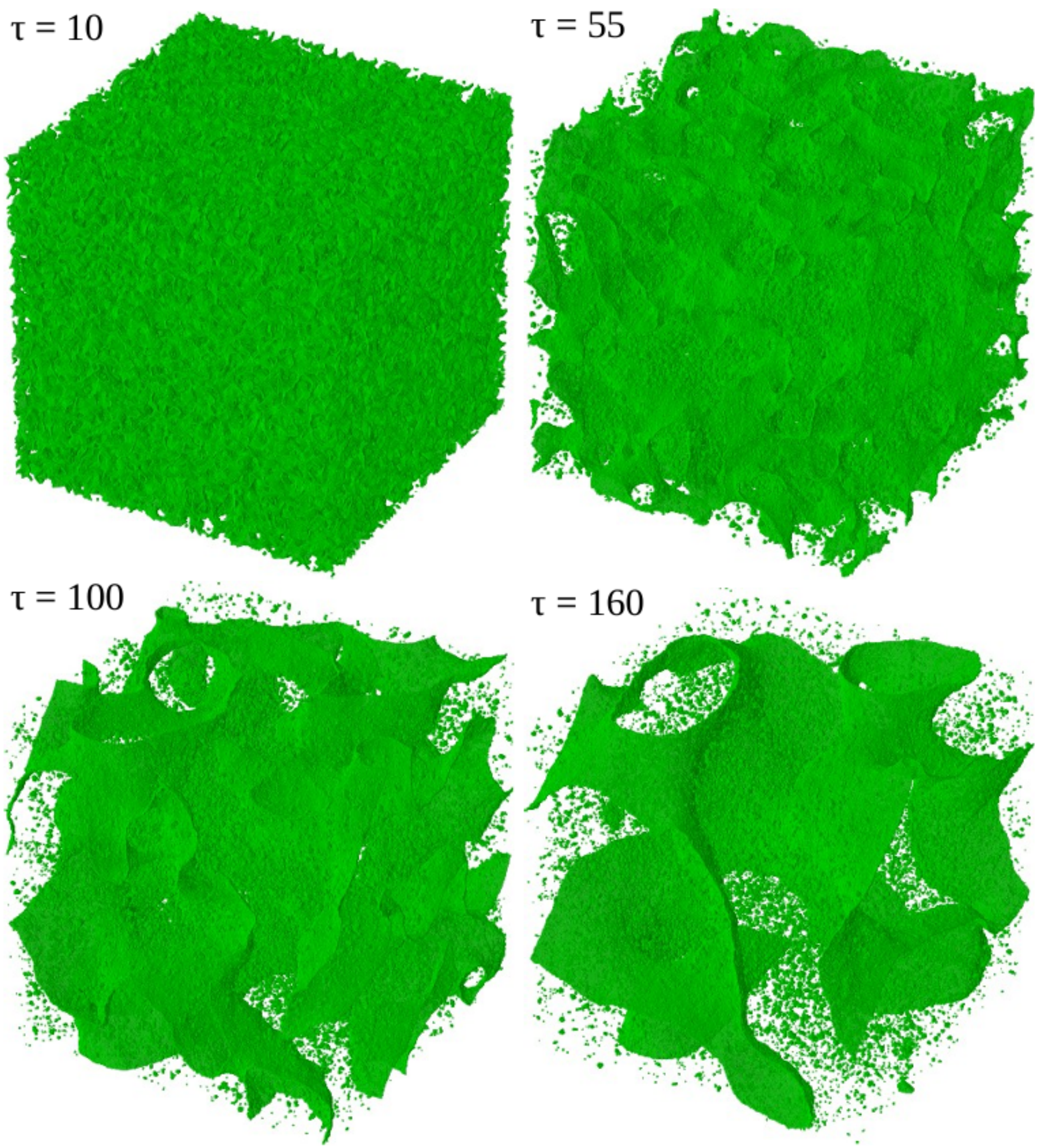


Figure 1: Snapshots of melting DW evolution obtained with the 1024^3 lattice in the case of vacuum initial conditions with $k_{cut} = 1$. We use dimensionless units of Eq. (35).

Figueroa, Florio, Torrenti, Valkenburg

CosmoLattice

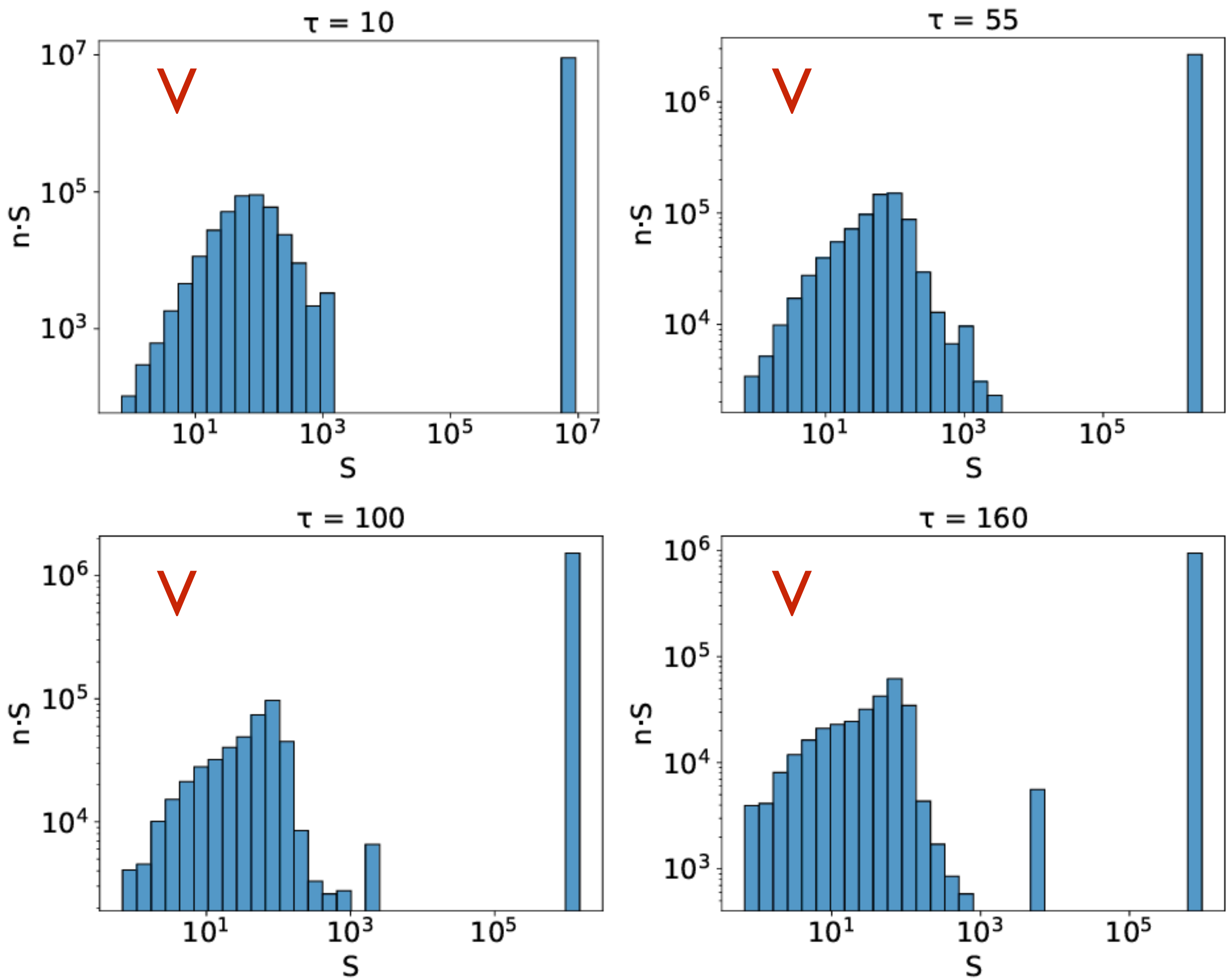
'vacuum" initial conditions

$$\left\langle \chi(\mathbf{k}) \chi^*(\mathbf{k}') \right\rangle = \frac{1}{2k} \delta(\mathbf{k} - \mathbf{k}')$$

$$\left\langle \dot{\chi}(\mathbf{k}) \dot{\chi}^*(\mathbf{k}') \right\rangle = \frac{k}{2} \delta(\mathbf{k} - \mathbf{k}')$$

Dankovsky, Babichev, Gorbunov, Ramazanov, Vikman (October 2024)

Melting Walls,
to scale or not to scale!



Figueroa, Florio,
Torrenti, Valkenburg

CosmoLattice

Dankovsky,
Babichev,
Gorbunov,
Ramazanov,
Vikman
(October 2024)

$$r = \frac{S\left(closed\, walls\right)}{S(long\, wall)} \simeq 0.3$$

Closed walls are important!

Gravitational Waves, Melting Walls

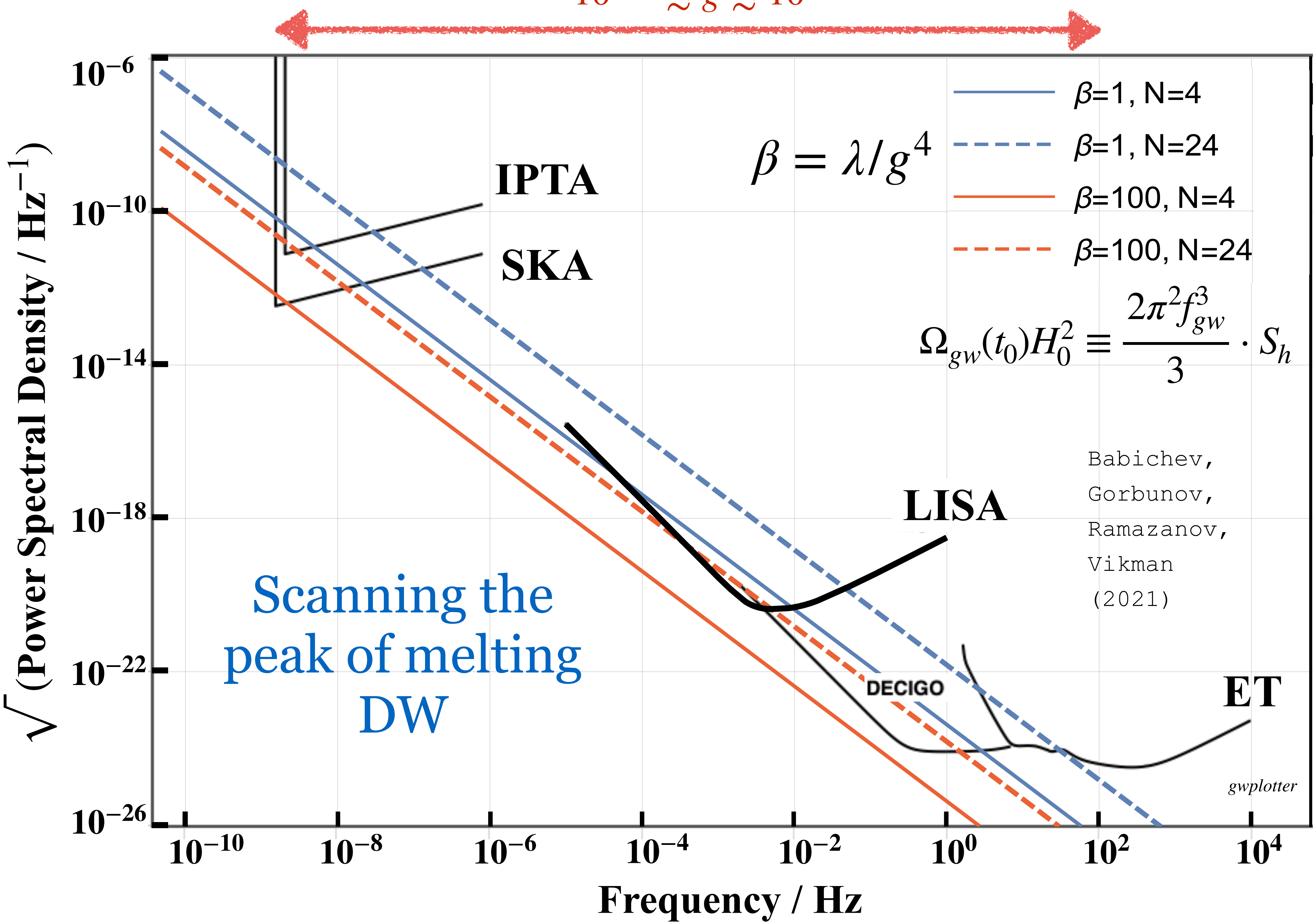
At the scaling peak

$$\Omega_{gw}(f_0) = \frac{1}{\rho_{tot}(t)}\left(\frac{d\rho_{gw}}{d\ln f}\right) \sim \frac{\sigma_{wall}^2}{T^4} \sim T^2 \sim f_0^2$$

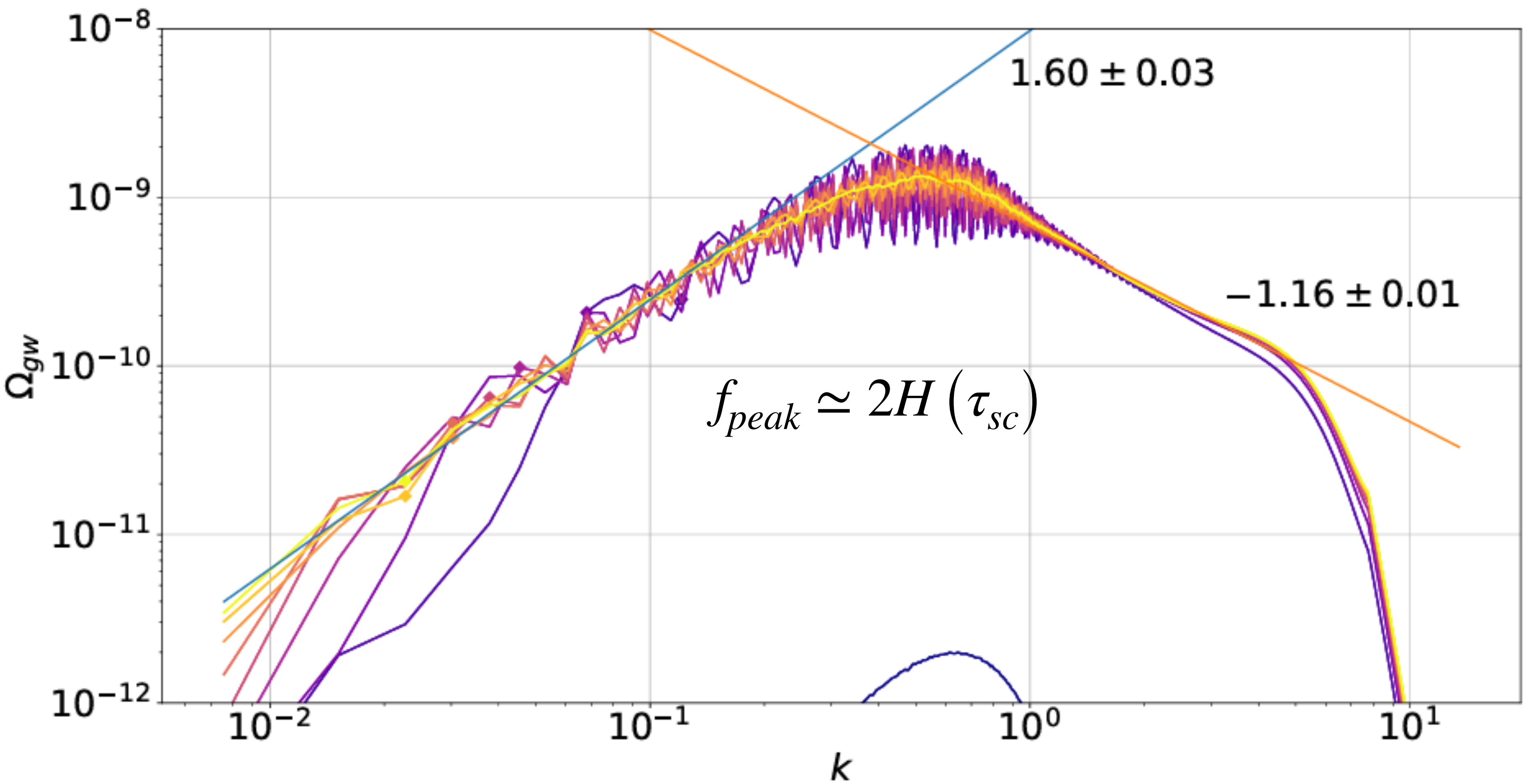
$$f_{peak} \simeq 6\ \text{nHz} \cdot \sqrt{N} \cdot \frac{g}{10^{-18}} \cdot \left(\frac{100}{g_*(T_i)}\right)^{1/3}$$

$$\Omega_{gw} h^2(t_0) \simeq \frac{4 \cdot 10^{-14} \cdot N^4}{\beta^2} \cdot \left(\frac{100}{g_*(T_i)}\right)^{7/3}$$

$$10^{-18} \lesssim g \lesssim 10^{-8}$$



GW from Melting Domain Walls



Figueroa, Florio, Torrenti, Valkenburg

CosmoLattice

Figure 7: Spectrum of GWs produced by the network of melting DWs in the case of vacuum initial conditions with the cutoff $k_{cut} = 1$ in dimensionless units defined in Eq. (35). One simulation is performed on 2048^3 lattice. Brighter colors correspond to the spectrum at later times. The initial and final conformal times of the simulation are set at $\tau_i = 1$ and $\tau = 405$ (shown with the yellow line), respectively. Straight lines demonstrate slopes of GW spectrum in its close-to-maximum infrared and ultraviolet parts at $\tau = 405$; corresponding spectral indices are also shown. We have set $\alpha = 1$, $\lambda_\chi = 0.03$, $g_*(T_{sc}) = 100$, and $T_i \approx 1.3 \cdot 10^{17}$ GeV, when performing simulations. For arbitrary α, λ_χ, $g_*(T_{sc})$, and T_i, one should multiply values on the plot by $\alpha^6 \cdot (\lambda_\chi/0.03) \cdot (T_i/1.3 \cdot 10^{17}\ \text{GeV})^2 \cdot (100/g_*(T_{sc}))$, see Eq. (52).

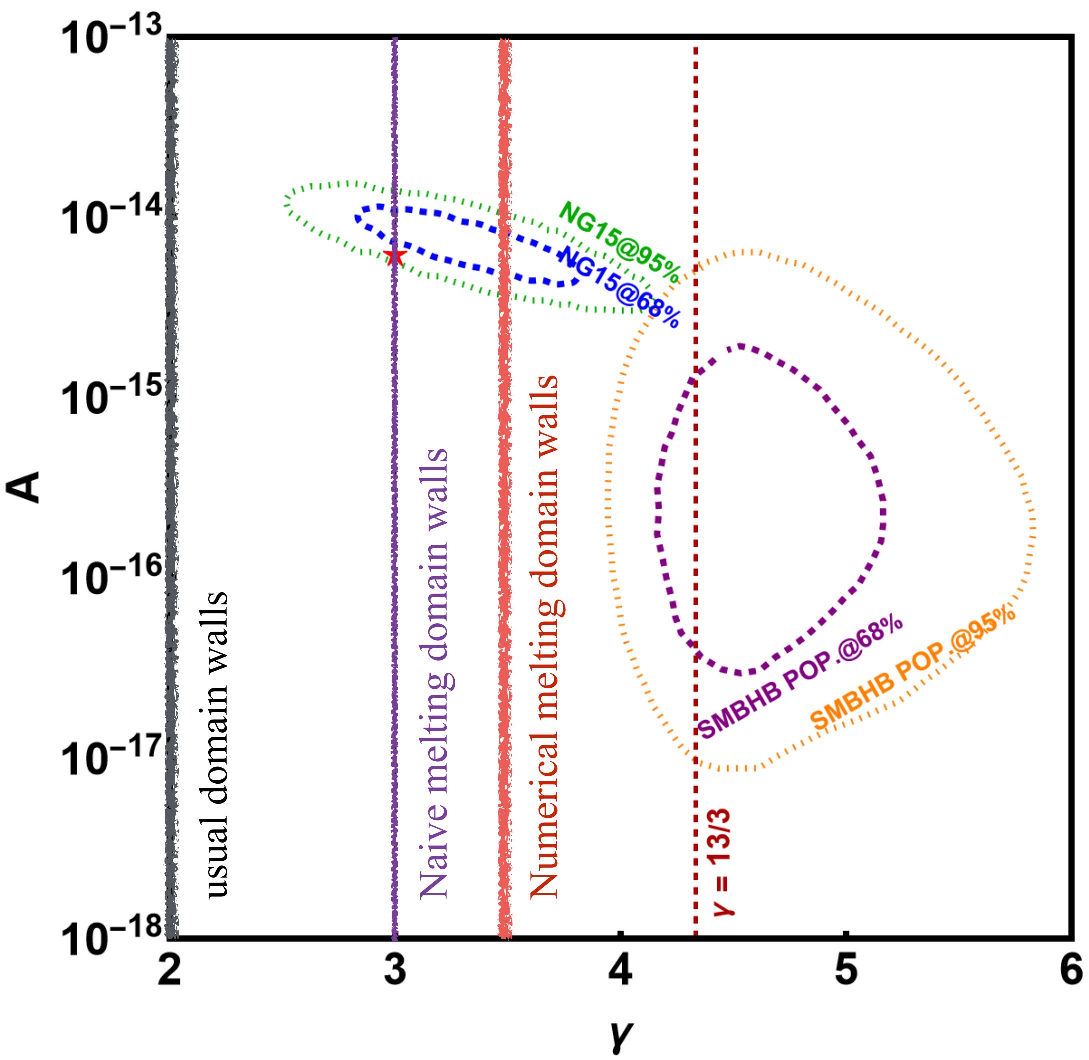
Dankovsky, Babichev, Gorbunov, Ramazanov, Vikman (October 2024)

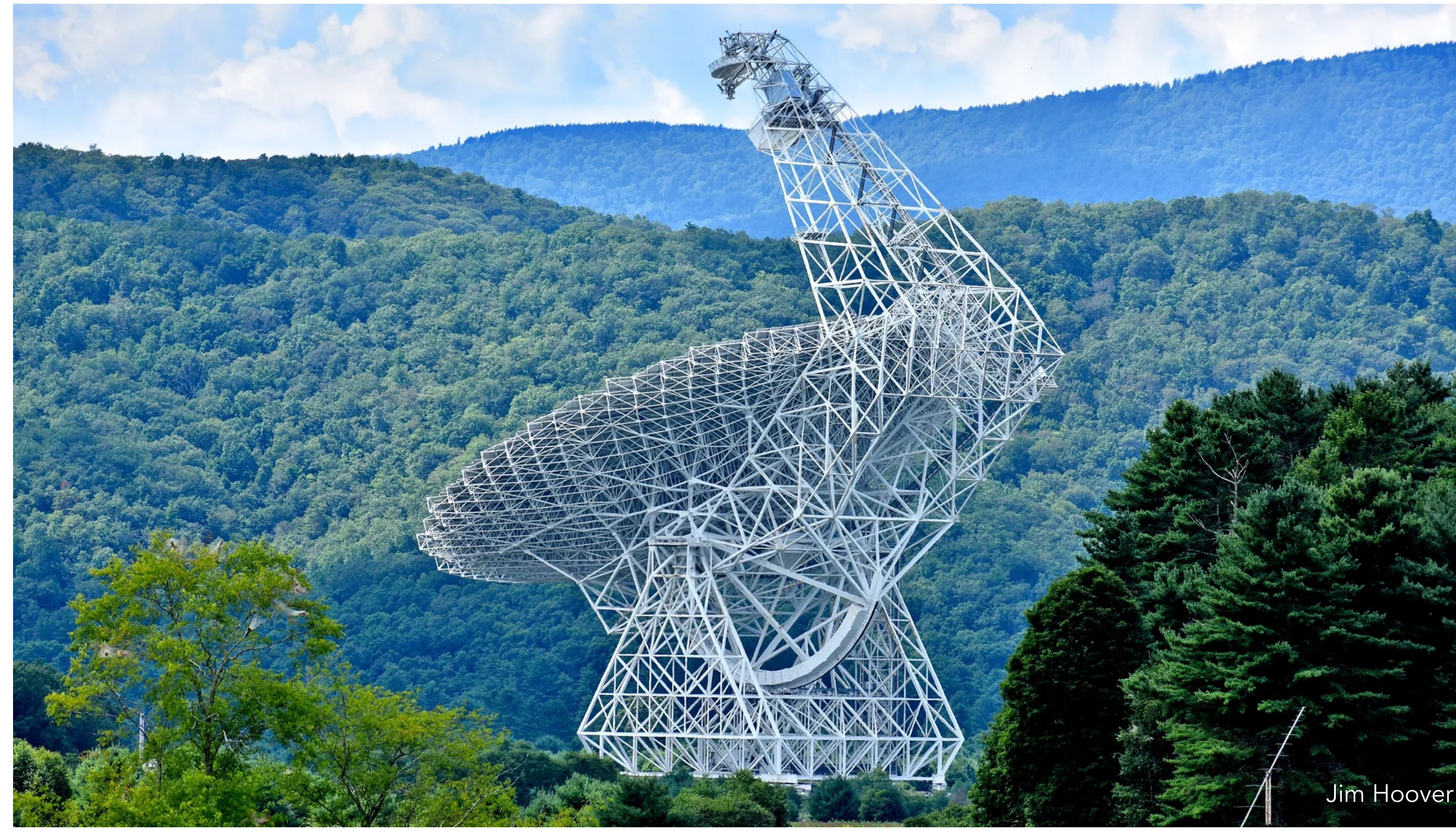
Perfect for NANOGgrav

$$\Omega_{\rm GW}(f) = \Omega_{yr}\left(f/f_{\rm yr}\right)^{5-\gamma},$$

$$f_{yr} = 32\,\mathrm{nHz}$$

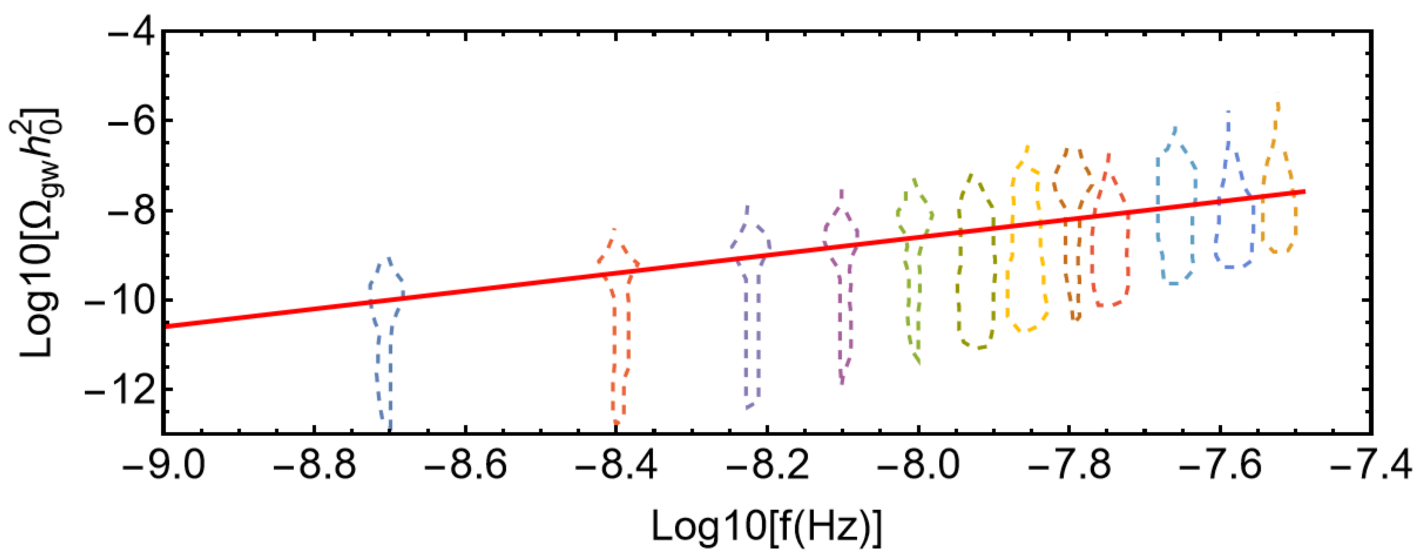
$$\Omega_{yr} = \frac{2\pi^2}{3H_0^2}A^2 f_{yr}^2$$





The 100-meter Green Bank Telescope, the world's largest fully steerable telescope and a core instrument for pulsar timing array experiment.

parameters $g = 10^{-18}$, $\beta = \lambda/g^4 = 1$, $N = 24$, $g_* = 75$

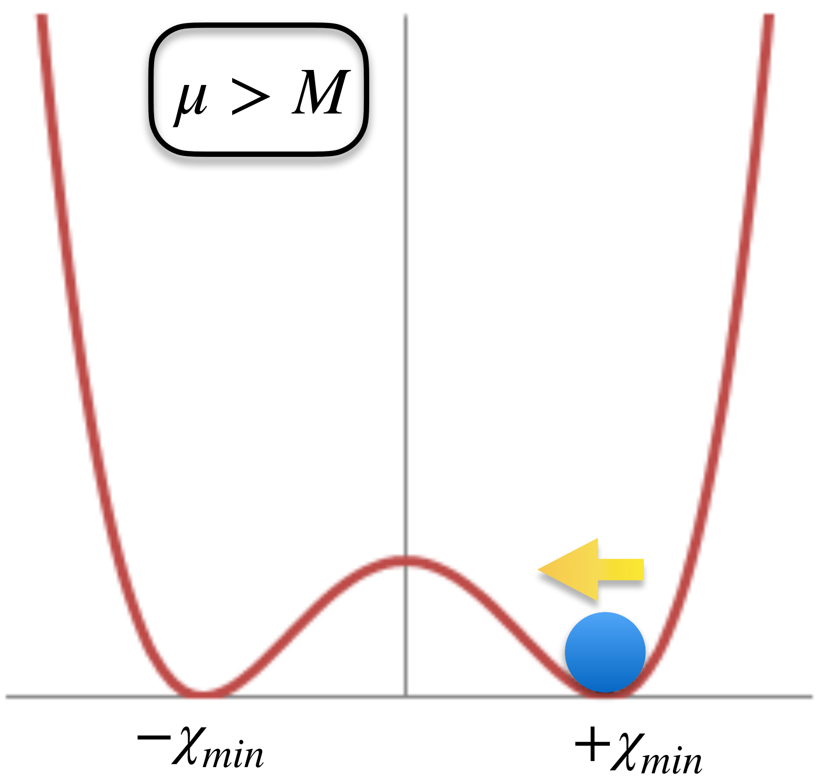


Inverse Phase Transition At Meltdown

$$\mathscr{L} = \frac{(\partial\chi)^2}{2} - \frac{\left(M^2 - \mu^2(t,\mathbf{x})\right)\cdot\chi^2}{2} - \frac{\lambda\chi^4}{4}$$

Early Universe

spontaneously Broken Phase with VEV slowly moving

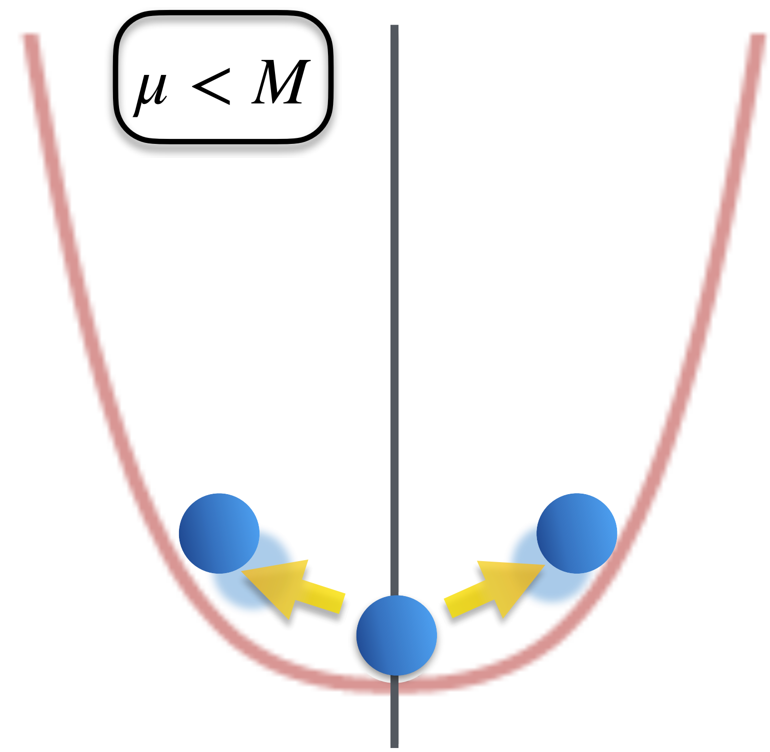


Tachyonic mass $\mu(t)$
slowly decreases /
redshifts
due to cosmological
expansion

Late Universe

DW melt down and disappear

then oscillations around restored symmetric vacuum



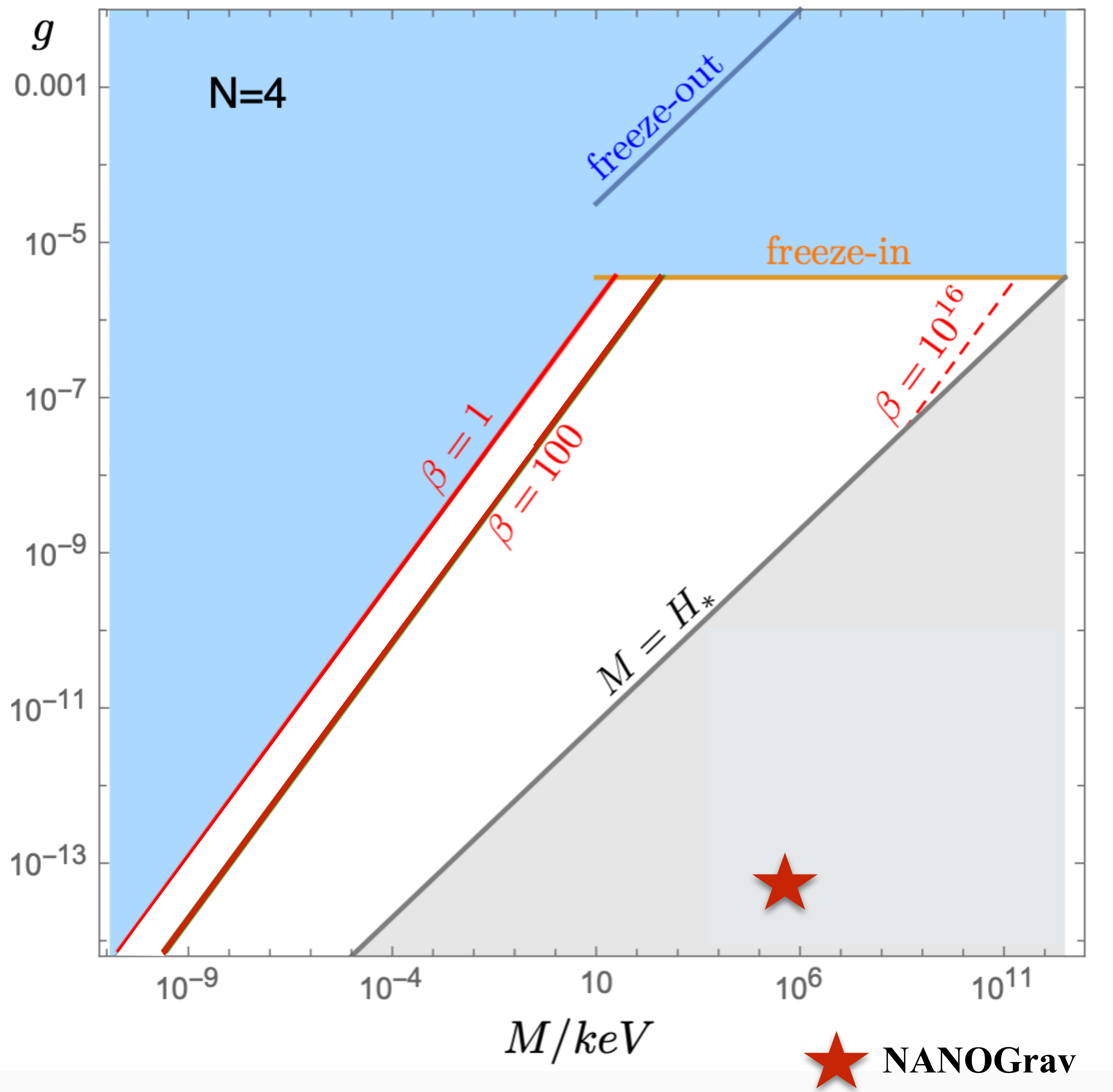
for Hubble parameter

$H < M$

scalar field traces vacuum $\chi_{min}(t) = \sqrt{\dfrac{\mu^2(t) - M^2}{\lambda}}$ as long as $\left|\dfrac{\dot{M}_{eff}}{M^2_{eff}}\right| \ll 1$

Allowed Parameter Space

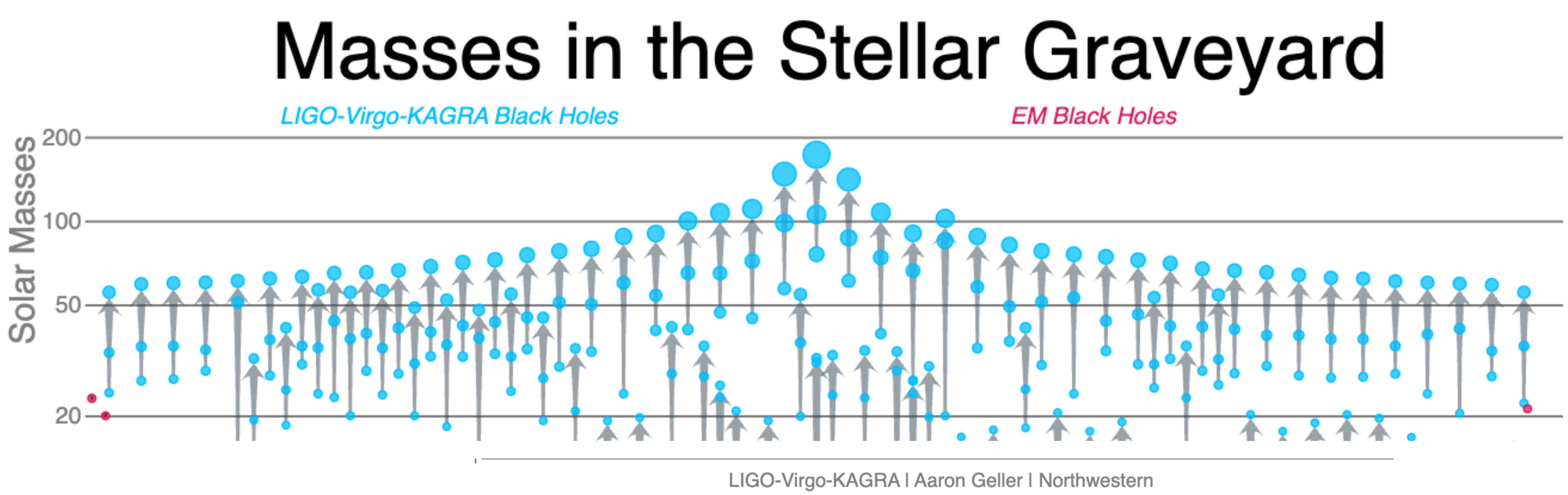
$$M \simeq 10^{-13}\ \text{eV} \cdot \frac{\beta^{3/5}}{\sqrt{N}} \cdot \left(\frac{g_*(T_*)}{100}\right)^{2/5} \cdot \left(\frac{g}{10^{-18}}\right)^{7/5}$$



A bridge between NANOGrav and LIGO!

$$M_\chi \simeq 10^{-12}\ \mathrm{eV} \cdot B^{9/20} \cdot \left(\frac{g_*(T_{sym})}{100}\right)^{1/5} \cdot \left(\frac{g_*(T_i)}{100}\right)^{1/20} \cdot \left(\frac{m_\phi}{10\ \mathrm{MeV}}\right)^{1/2} \times \left(\frac{f_{peak}}{30\ \mathrm{nHz}}\right)^{6/5} \cdot \left(\frac{10^{-8}}{\Omega_{gw,peak} h_0^2}\right)^{3/20}$$

Superradiance for $M_{BH} \simeq 10^2 M_\odot$ → Just on on edge of LIGO!



Scalar fields around black hole binaries in LIGO-Virgo-KAGRA

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Light scalar particles arise naturally in many extensions of the Standard Model and are well-motivated dark matter candidates. Gravitational interactions near black holes can trigger the growth of dense scalar configurations that, if sustained during inspiral, alter binary dynamics and imprint signatures on gravitational-wave signals. Detecting such effects would provide a novel probe of fundamental physics and dark matter. Here we develop a semi-analytic waveform model for binaries in scalar environments, validated against numerical relativity simulations, and apply it in a Bayesian analysis of the LIGO–Virgo–KAGRA catalog. Our results set physically meaningful upper bounds on scalar environments around compact binaries. When superradiance priors are included, we find tentative evidence for such an environment in GW190728 with $\ln \mathcal{B}^{\rm env}_{\rm vac} \approx 3.5$, which would correspond to the existence of a light scalar field with mass $\sim 10^{-12}$ eV.

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Thanks a lot for attention!