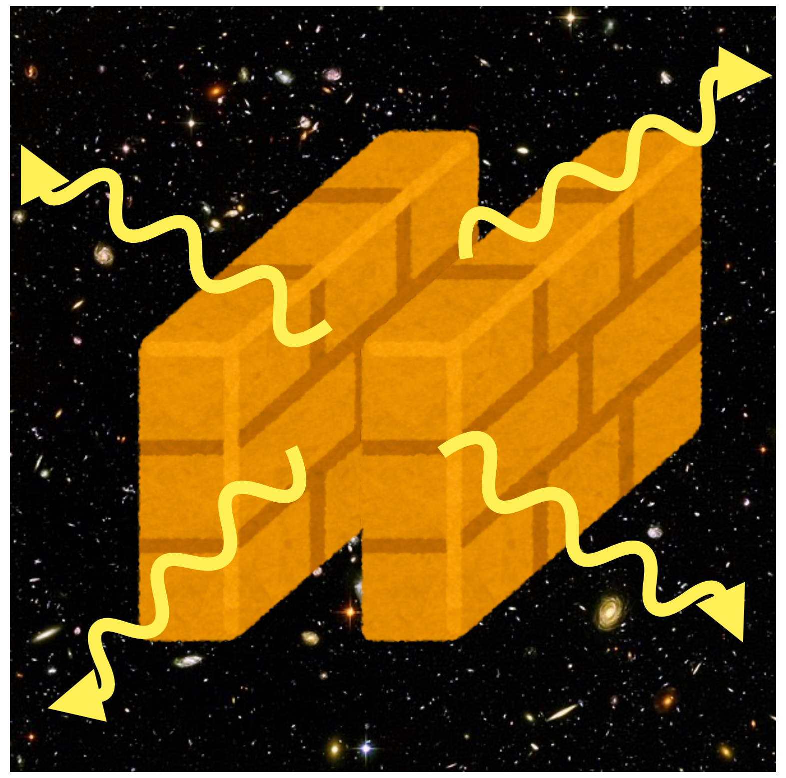
QCDと結合するドメインウォールによるnHz重力波

September 1, 2023
@PPP2023



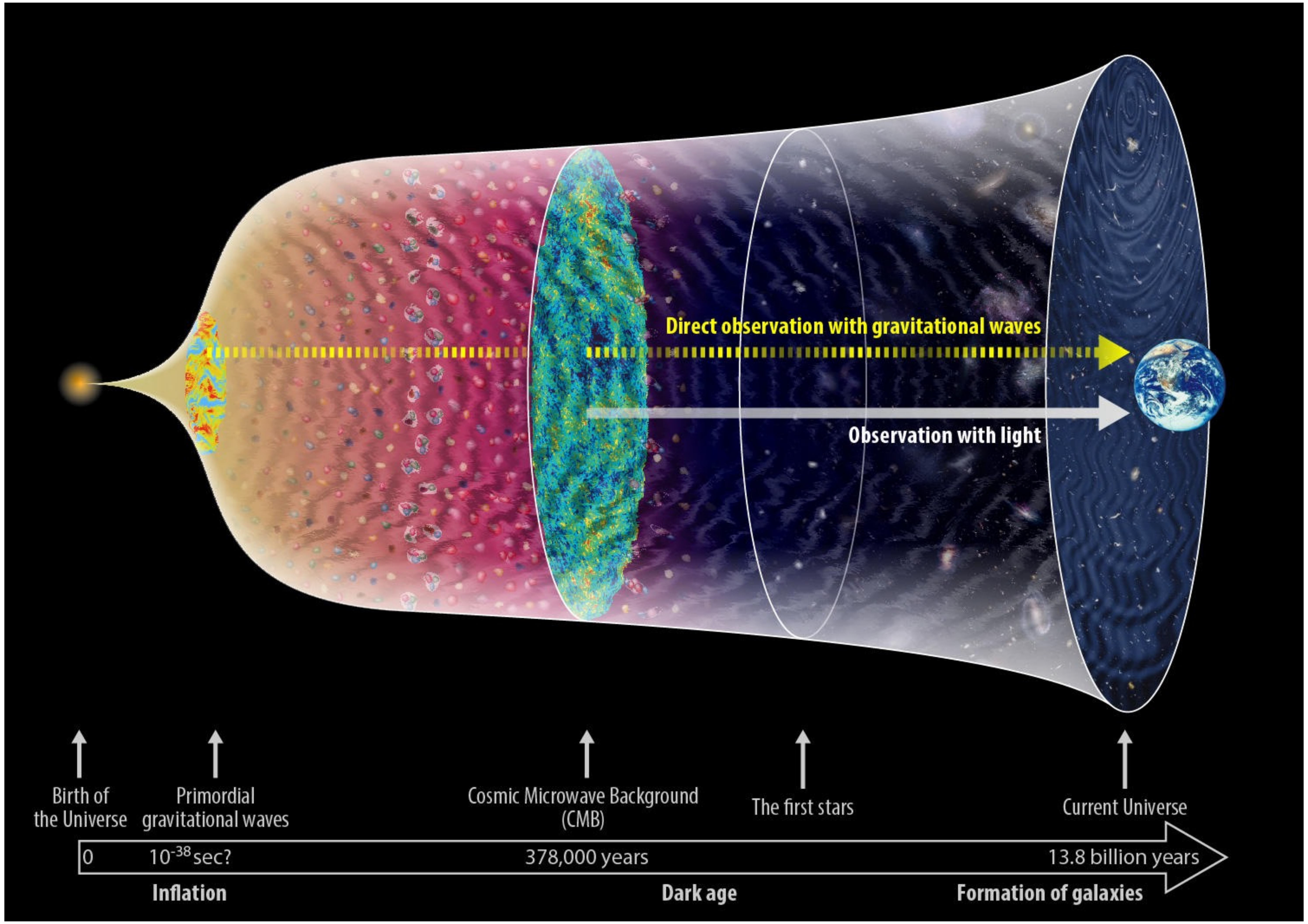
李　俊錫 / Junseok Lee（東北大学）

Based on 2306.17146

in collaboration with Naoya Kitajima, Kai Murai, Fuminobu Takahashi, and Wen Yin

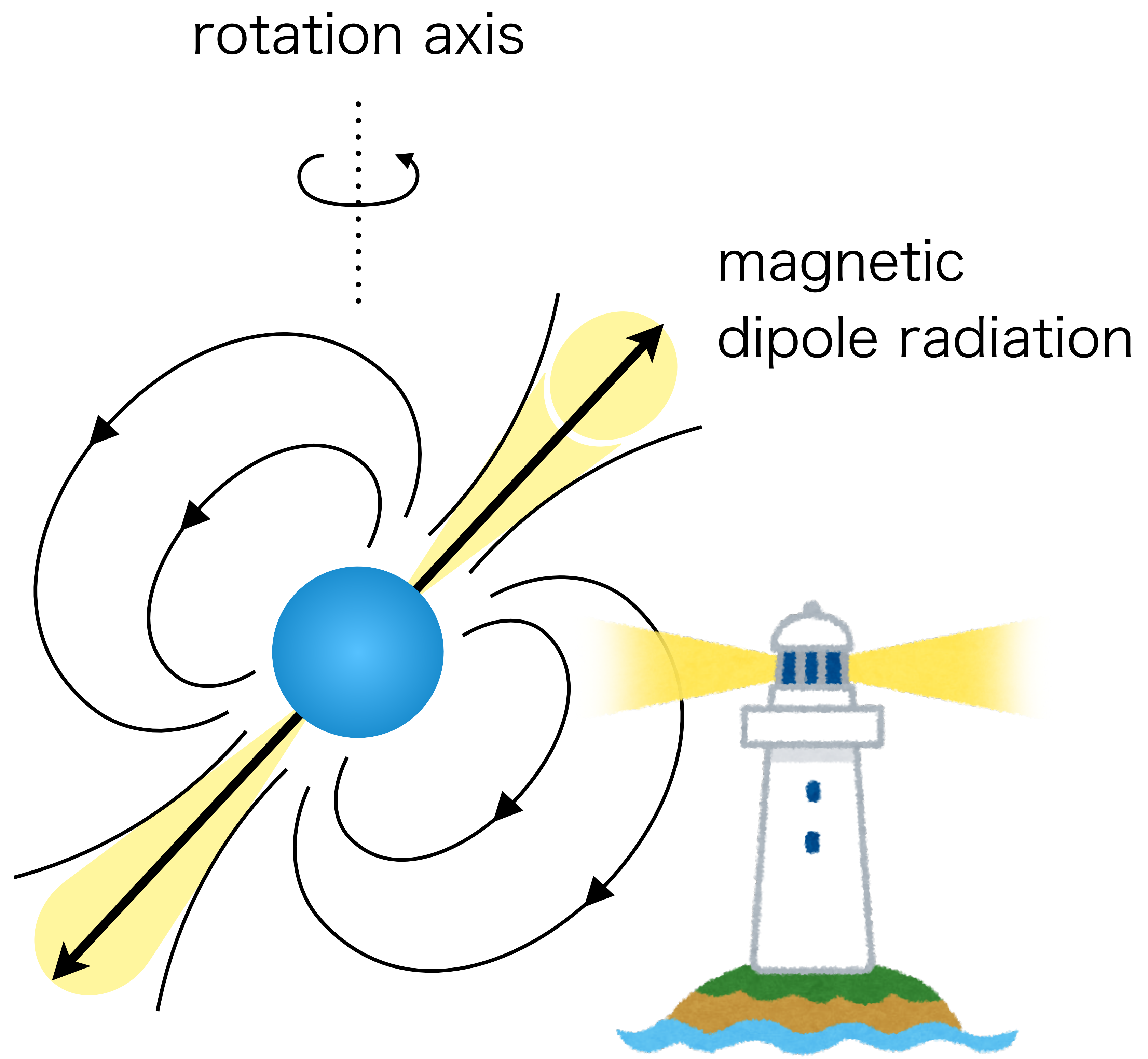
1. Introduction

Gravitational waves can carry the information about the very early universe.



(C) NAOJ

Pulsar Timing Array (PTA)

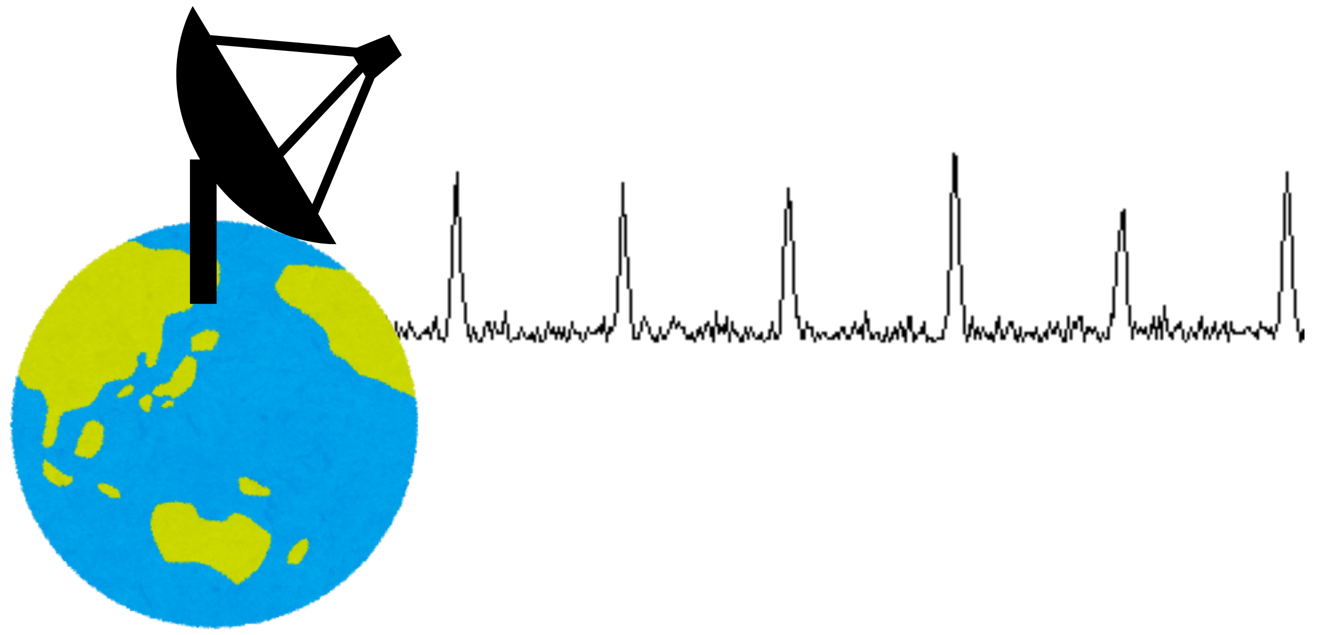


Millisecond pulsars rotate on their own axes with $\mathcal{O}(1-10)$ ms periods.

→ A stable pulse profiles can be obtained even in a few minutes.

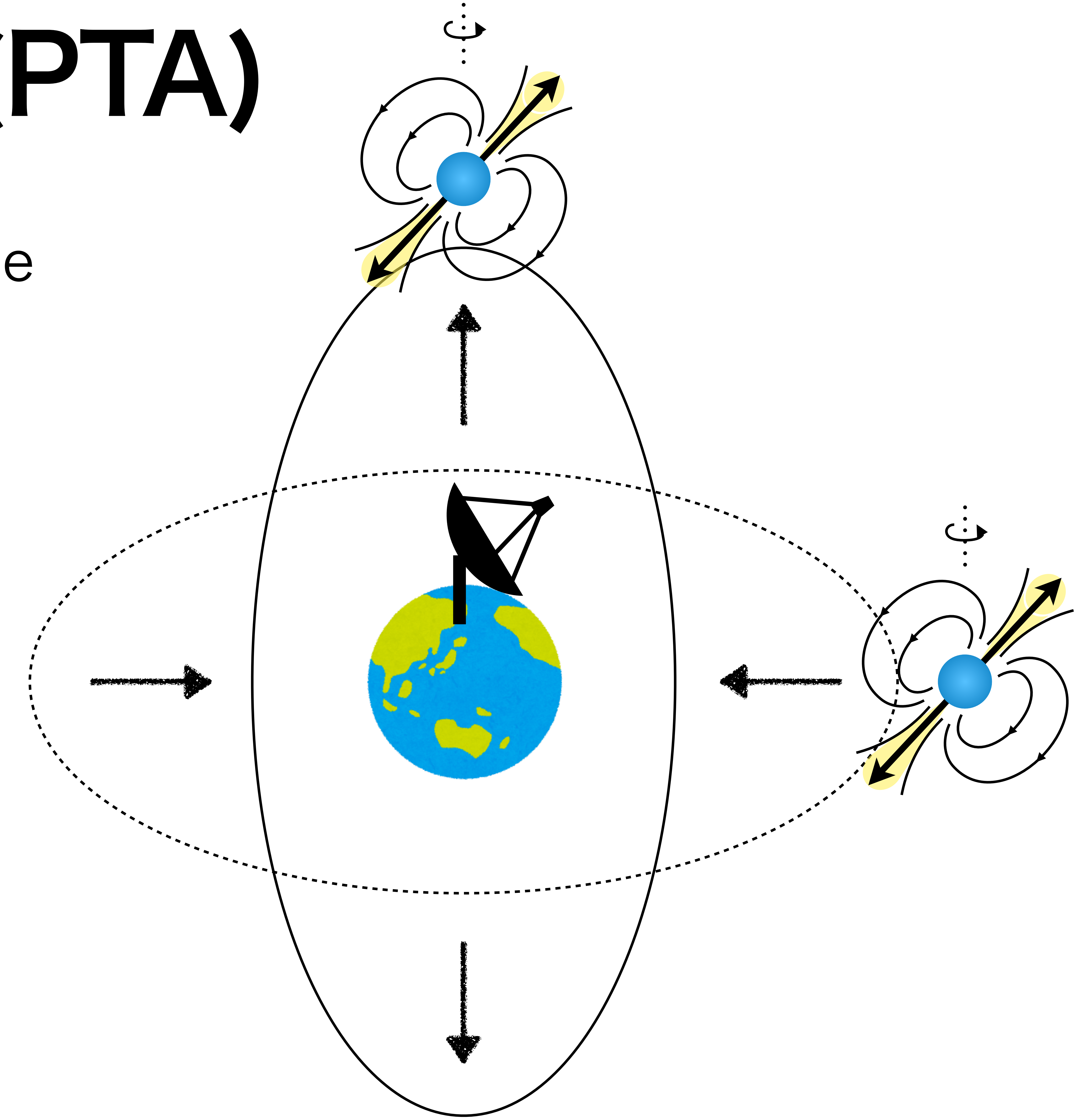
(Typical observing frequency is $\mathcal{O}(1)$ GHz)

: extremely precise clock



Pulsar Timing Array (PTA)

- GW creates a strain that slightly shifts the pulse-arrival time by a specific angular correlations. (Hellings and Downs curve)



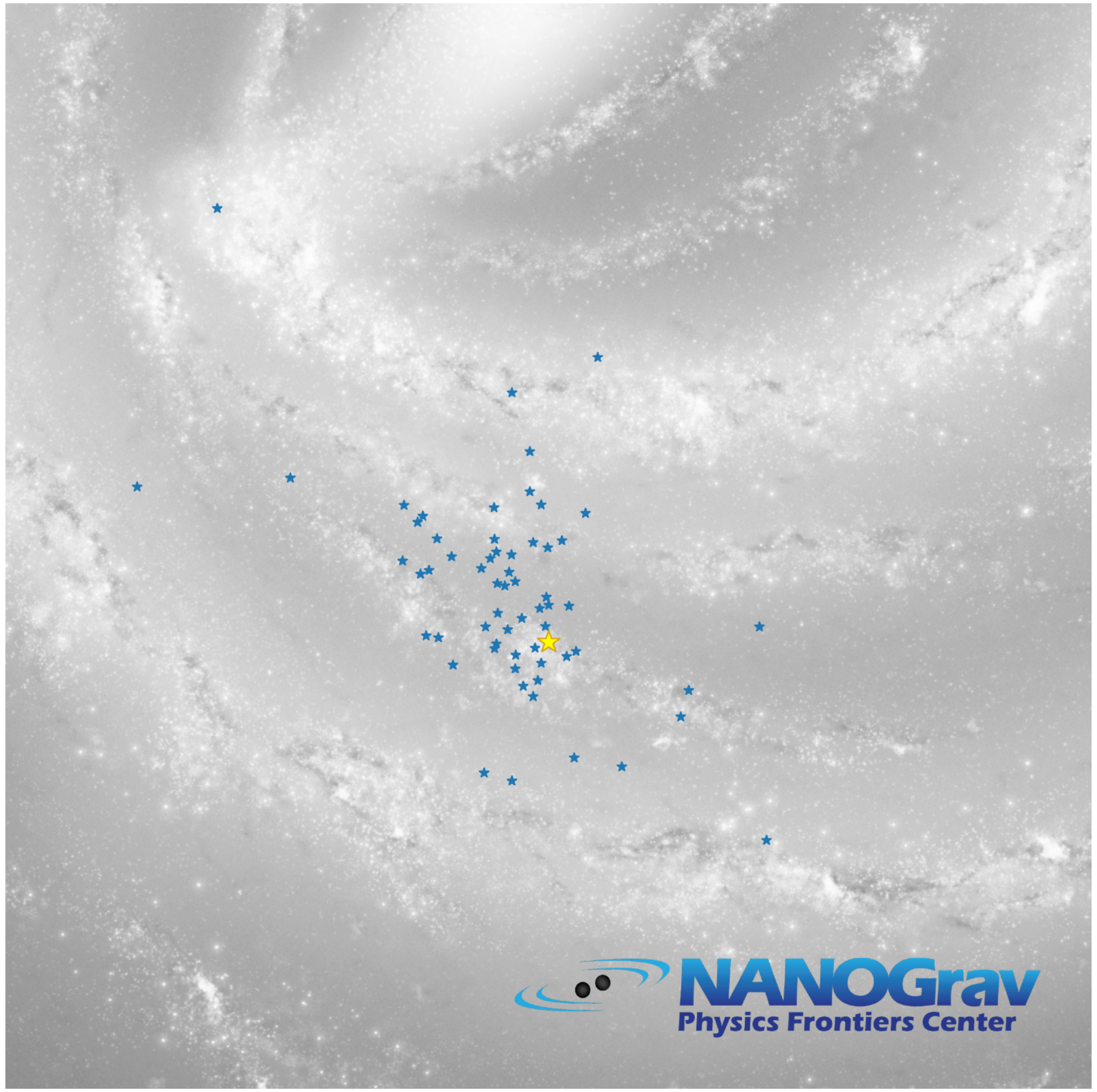
Pulsar Timing Array (PTA)

- GW creates a strain that slightly shifts the pulse-arrival time by a specific angular correlations. (Hellings and Downs curve)

- **A set of millisecond pulsars** can be a galaxy-size probe to measure the strain.

- Its sensitivity is highest at the frequency $f \sim 1/T$ where T is the observation time.

$(10\ \mathrm{yr})^{-1} \sim 3\ \mathrm{nHz}$



yellow : solar system

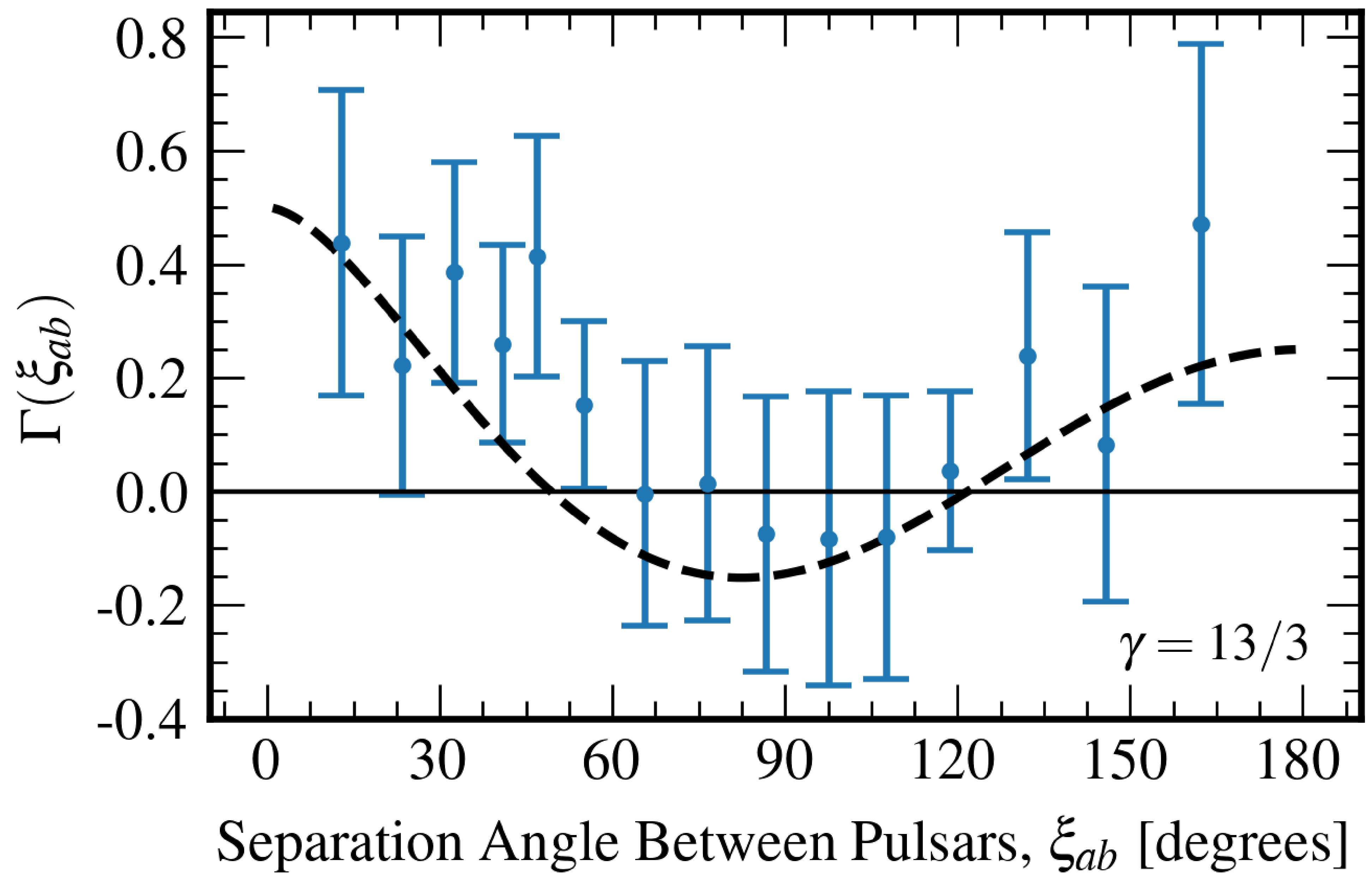
blue : millisecond pulsars NANOGrav uses

Recent results of PTAs

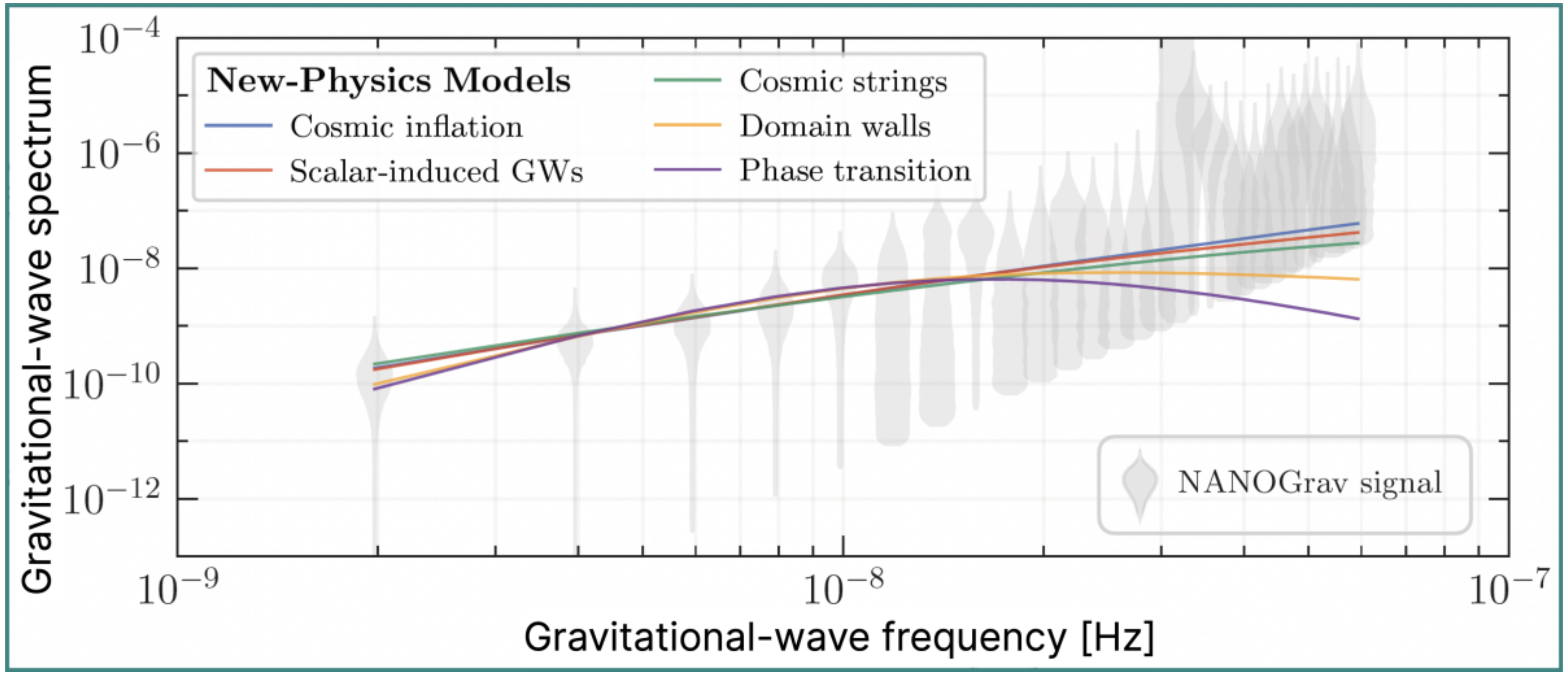
Recently, the existence of stochastic gravitational waves (GWs) in the **nanohertz region** was reported by PTA teams :

NANOGrav, EPTA, PPTA, and CPTA

The NANOGrav Collaborations, arXiv : 2306.16213



https://nanograv.org/15yr/Summary/NewPhysics



Sources of the nHz GWs

Leading candidate

- Supermassive black hole binaries

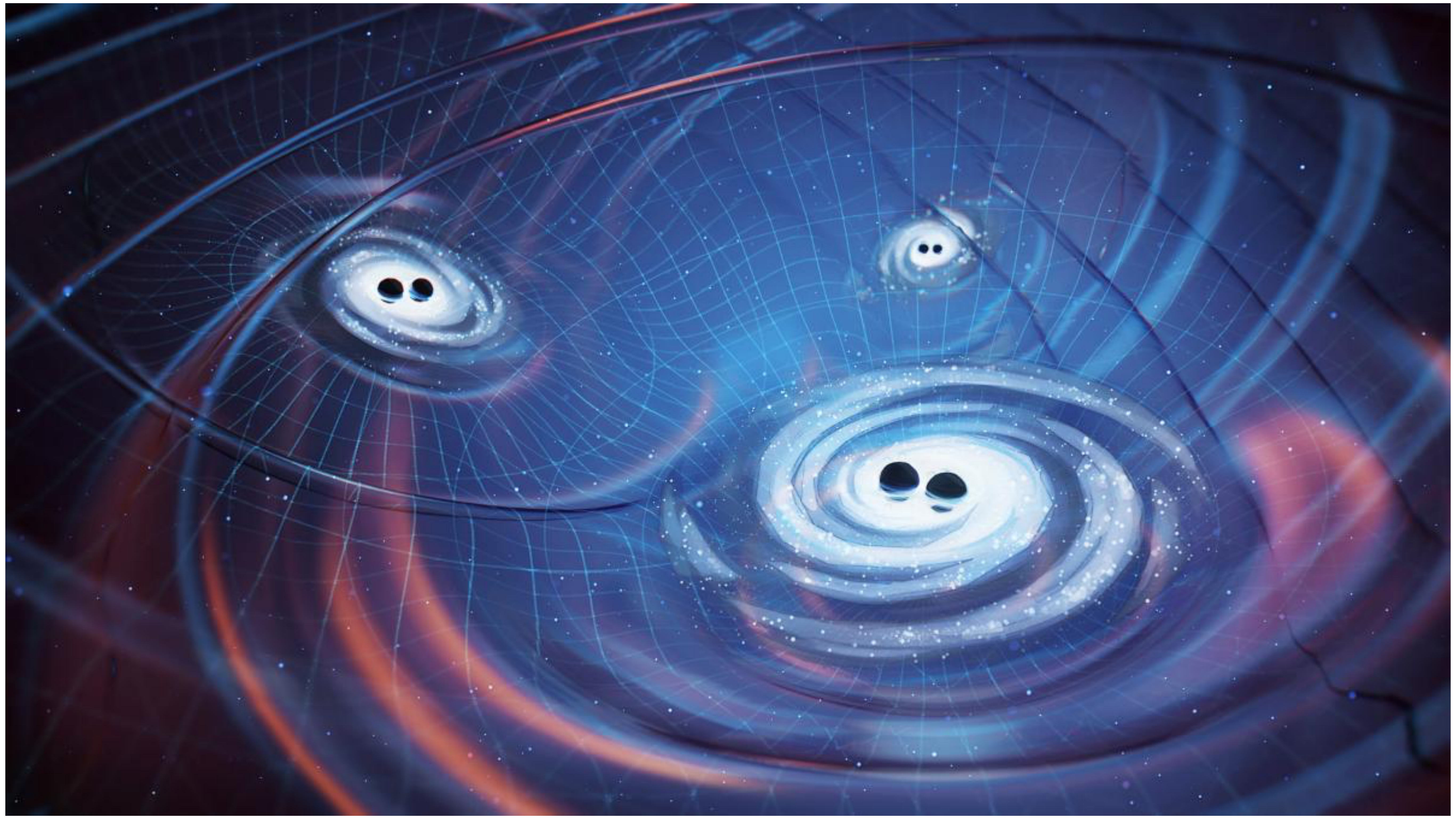


Illustration: Olena Shmahalo

Sources of the gravitational wave

Leading candidate

- Supermassive black hole binaries

New Physics ?

- First order phase transition
- Scalar-induced GW See also the poster by T. Terada
- Topological defects (cosmic strings, domain walls, ⋯)

See also the talk by Y. Hamada, N. Kitajima, and the poster by Y. Kanda

PTA as the signals of new physics

The NANOGrav Collaborations, arXiv : 2306.16219

Abstract

The 15 yr pulsar timing data set collected by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) shows positive evidence for the presence of a low-frequency gravitational-wave (GW) background. In this paper, we investigate potential cosmological interpretations of this signal, specifically cosmic inflation, scalar-induced GWs, first-order phase transitions, cosmic strings, and domain walls. We find that, with the exception of stable cosmic strings of field theory origin, all these models can reproduce the observed signal. When compared to the standard interpretation in terms of inspiraling supermassive black hole binaries (SMBHBs), many cosmological models seem to provide a better fit resulting in Bayes factors in the range from 10 to 100. However, these results strongly depend on modeling assumptions about the cosmic SMBHB population and, at this stage, should not be regarded as evidence for new physics. Furthermore, we identify excluded parameter regions where the predicted GW signal from cosmological sources significantly exceeds the NANOGrav signal. These parameter constraints are independent of the origin of the NANOGrav signal and illustrate how pulsar timing data provide a new way to constrain the parameter space of these models. Finally, we search for deterministic signals produced by models of ultralight dark matter (ULDM) and dark matter substructures in the Milky Way. We find no evidence for either of these signals and thus report updated constraints on these models. In the case of ULDM, these constraints outperform torsion balance and atomic clock constraints for ULDM coupled to electrons, muons, or gluons.

PTA as the signals of new physics

The NANOGrav Collaborations, arXiv : 2306.16219

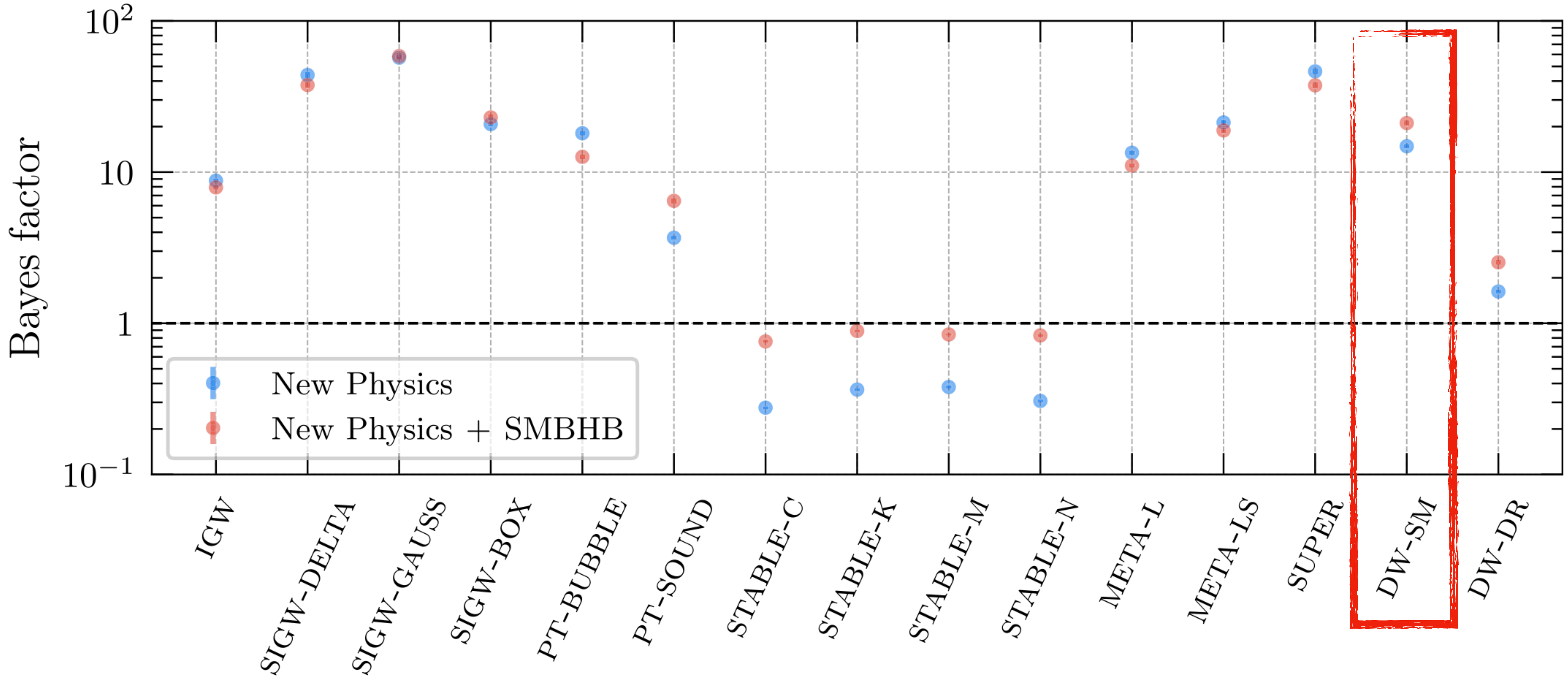
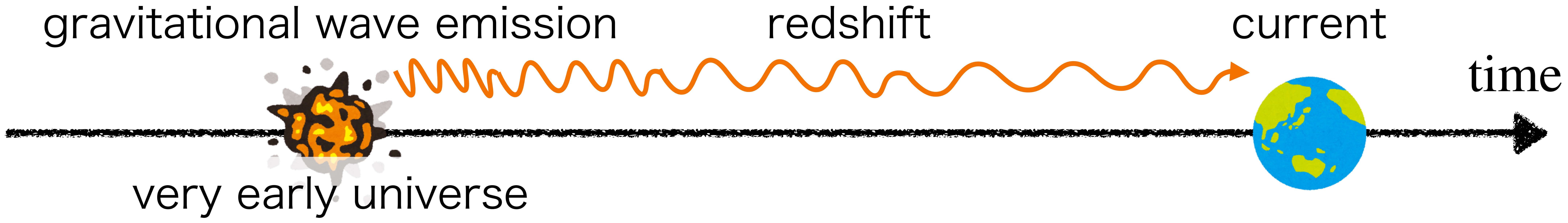


Figure 2. Bayes factors for the model comparisons between the new-physics interpretations of the signal considered in this work and the interpretation in terms of SMBHBs alone. Blue points are for the new physics alone, and red points are for the new physics in combination with the SMBHB signal. We also plot the error bars of all Bayes factors, which we obtain following the bootstrapping method outlined in Section 3.2. In most cases, however, these error bars are small and not visible.

Emission time to accommodate PTAs



$$f_{\text{emission}} = \frac{T_{\text{emission}}}{T_{\text{current}}} f_{\text{current}}$$

$$\begin{cases} f_{\text{current}} \sim \text{nHz} \sim 10^{-24}\ \text{eV} \\ T_{\text{current}} \sim 2.7\ \text{K} \sim 10^{-4}\ \text{eV} \end{cases}$$

$$f_{\text{emission}} \sim H_{\text{emission}} = \frac{{T_{\text{emission}}}^2}{M_{pl}}$$

QCD scale

$$T_{\text{emission}} \sim f_{\text{current}} \times T_{\text{current}} \times M_{pl} \sim 100\ \text{MeV}$$

Axion domain wall coupled to QCD can be a good candidate

2. Model and Expectation

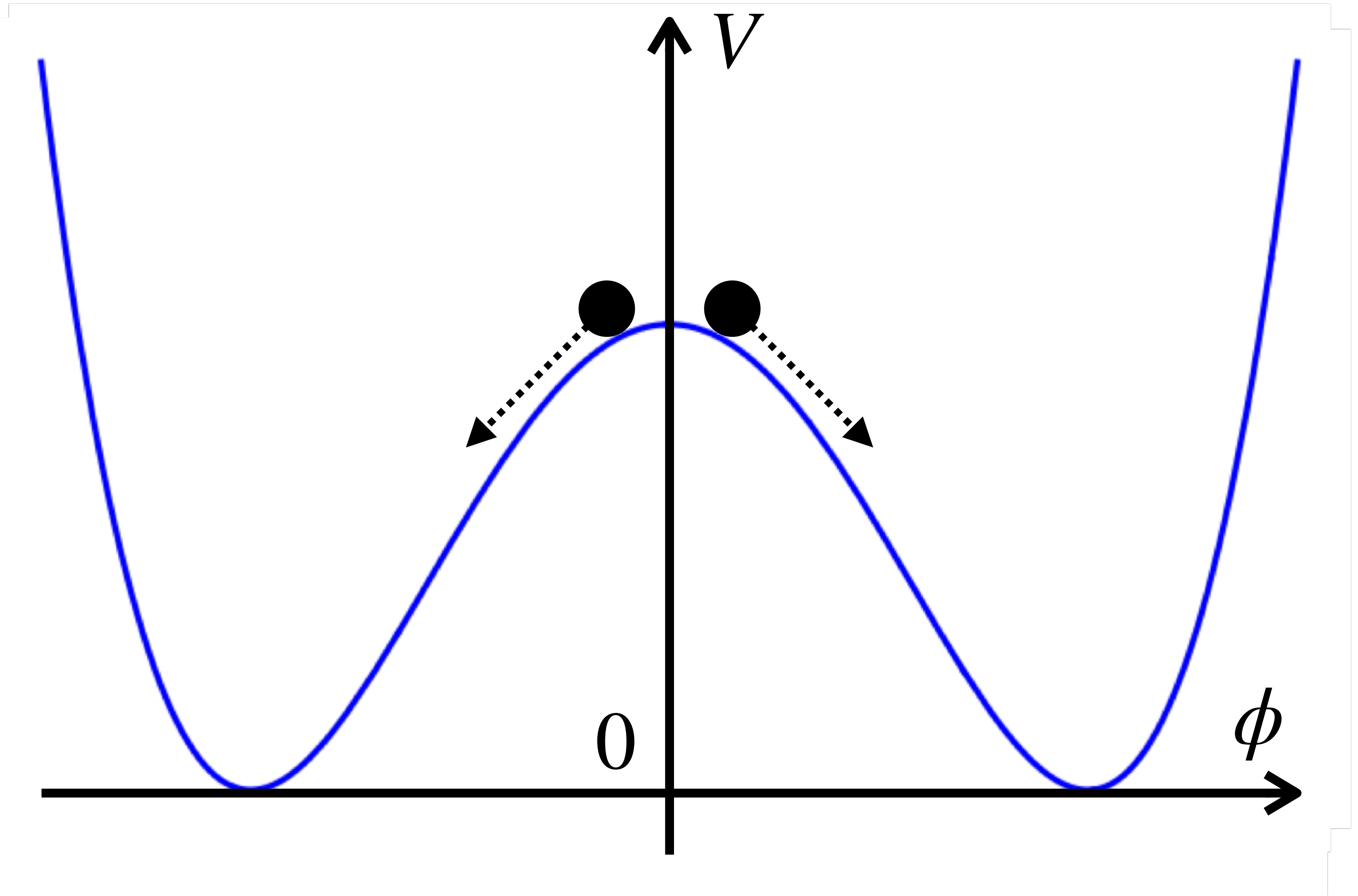
Cosmological domain wall

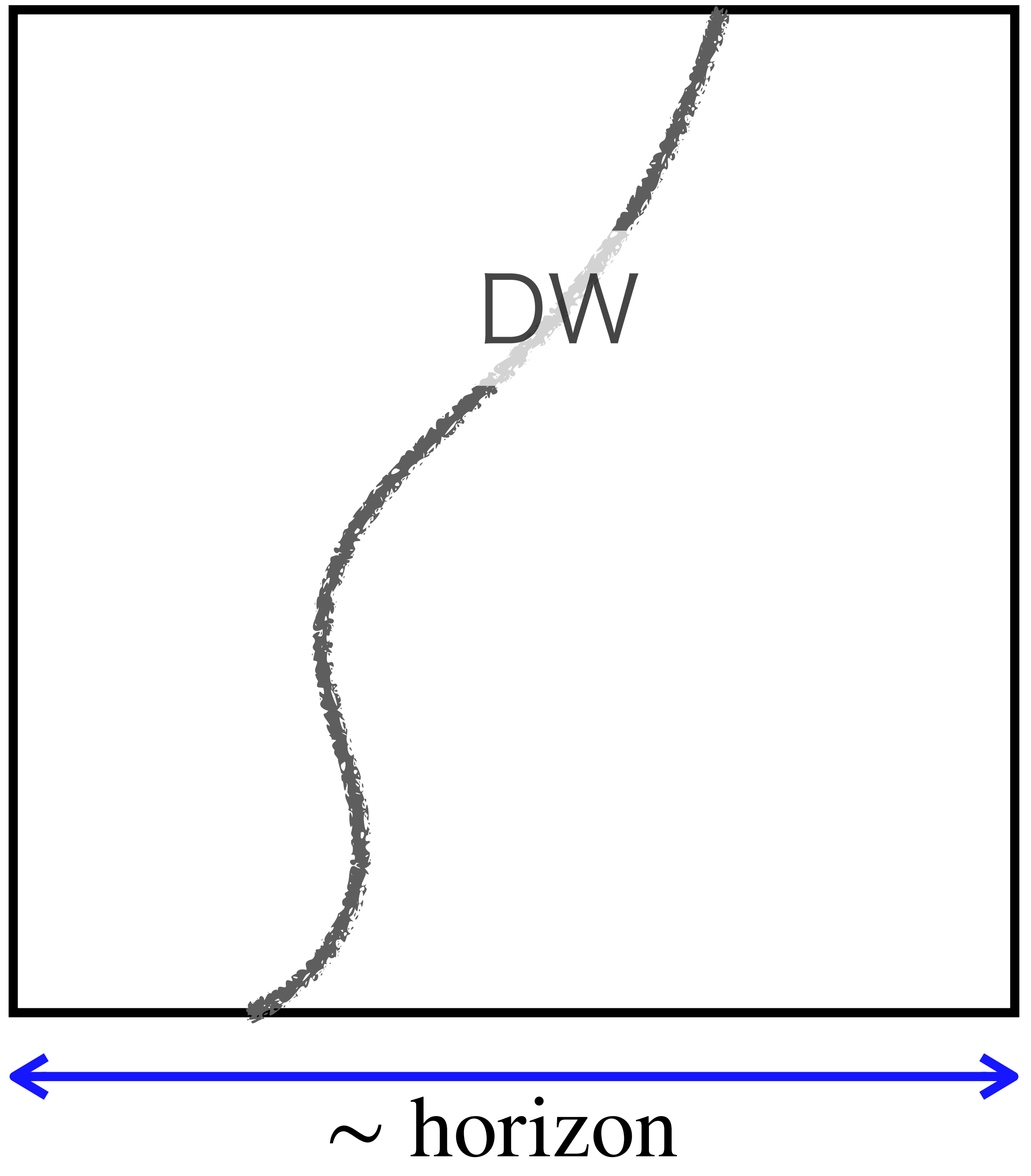
If there are multiple disconnected degenerate vacua, **domain walls (DW)**, a type of topological defects, appear during the phase transition.

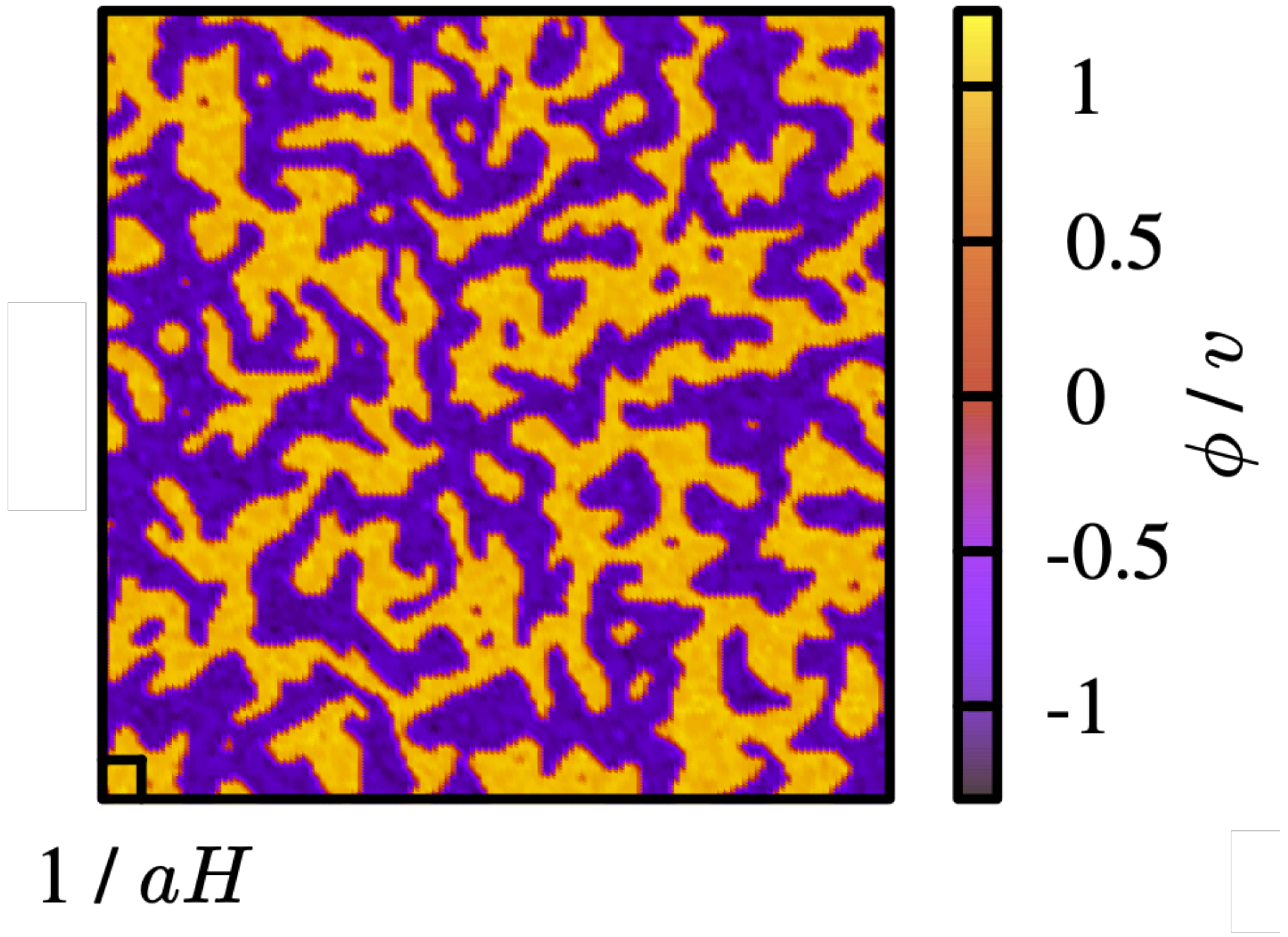
Zel'dovich, Kobzarev, Okun `74, Kibble `76, ⋯

Each Hubble horizon (H^{-1}) contains $\mathcal{O}(1)$ DW, known as **the scaling solution**.

Sikivie `82, Vilenkin `85, Press, Ryden, Spergel `89, ⋯







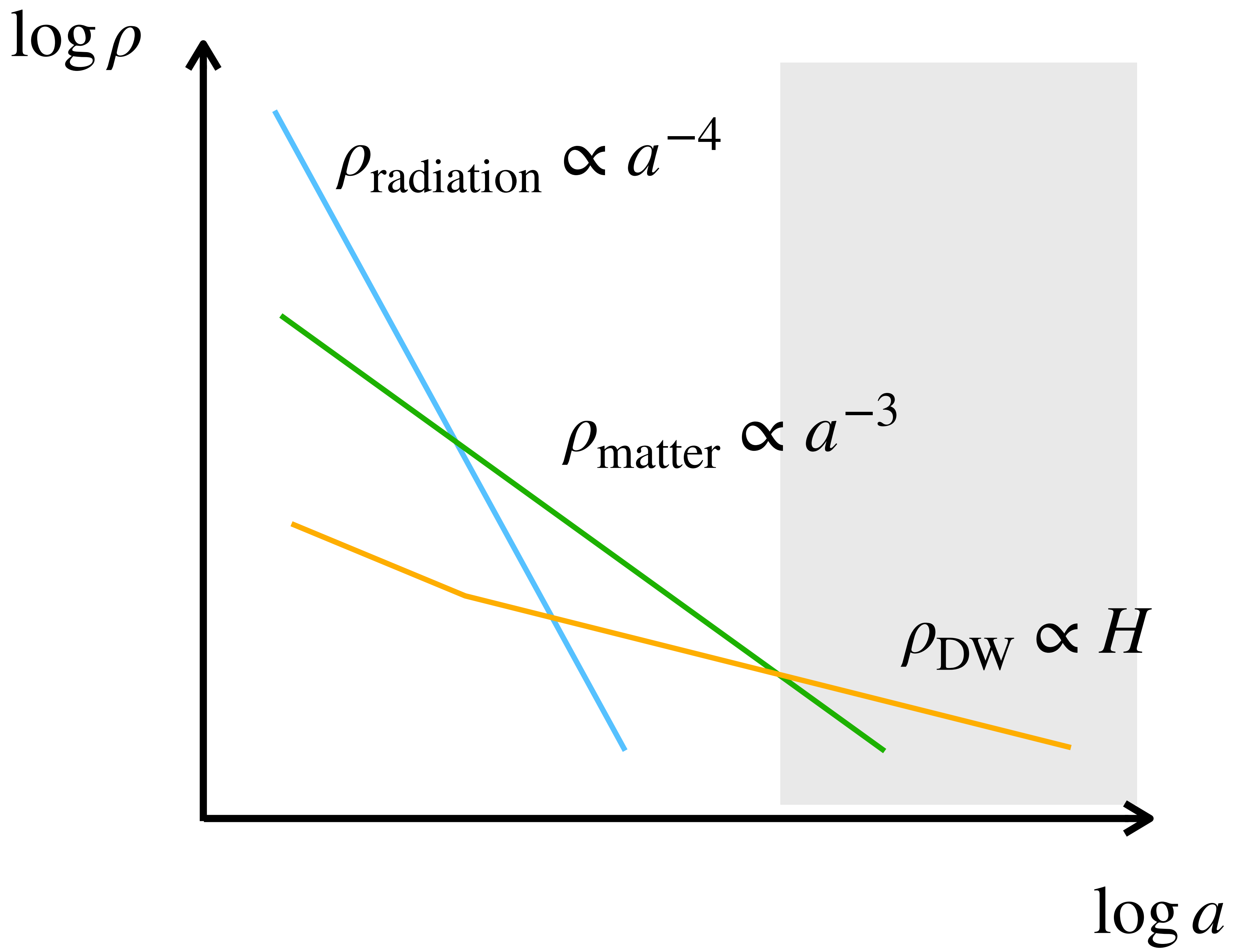
Cosmological domain wall problem

Zel'dovich, Kobzarev, Okun `74

The energy density of DW network falls slowly compared to other components as the universe expands.

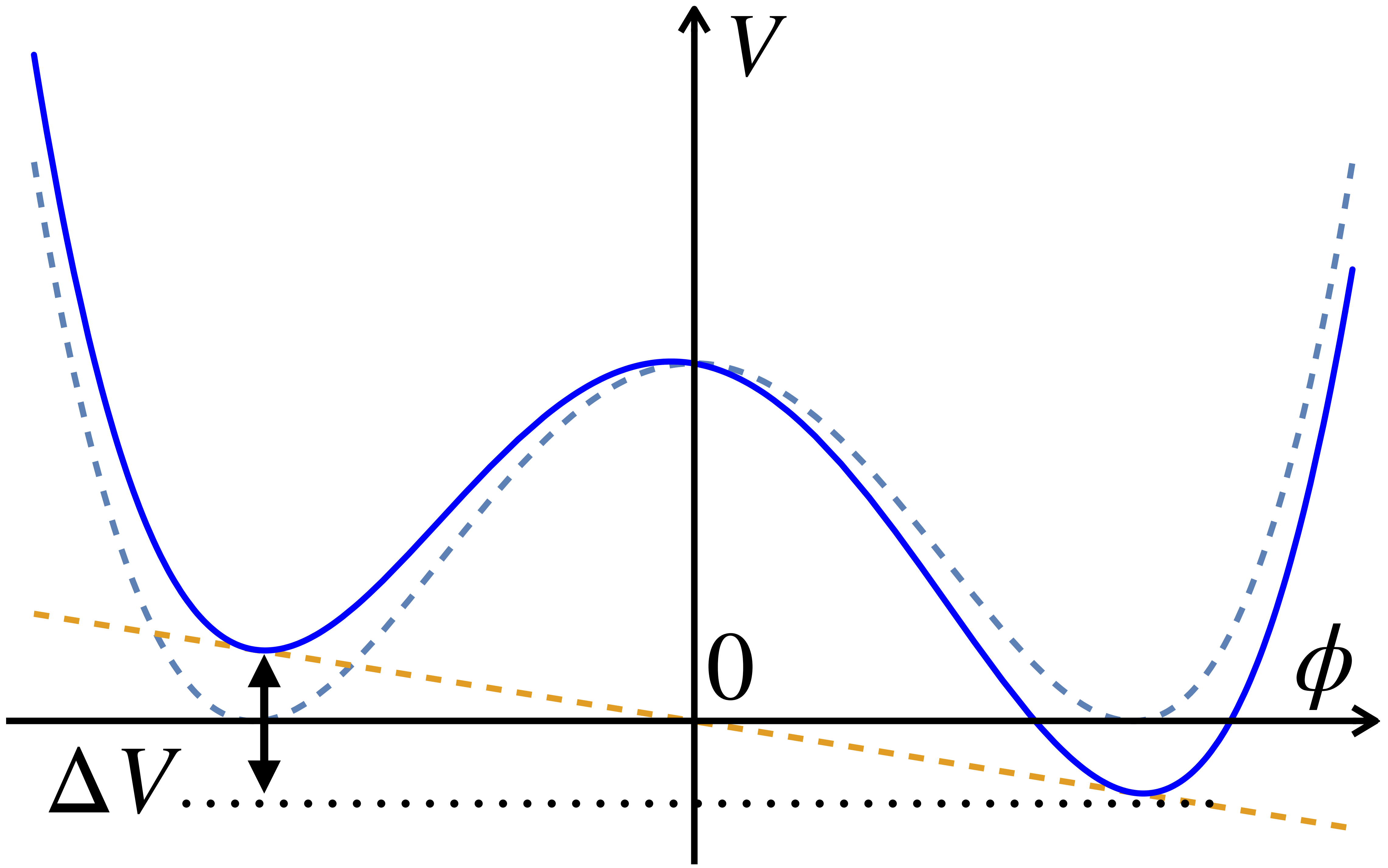
$$\rho_{\rm DW} = \frac{\sigma H^{-2}}{H^{-3}} = \sigma H$$

This easily makes DWs to dominate the universe which contradicts the isotropy of CMB observations.



We need small DW tension $\sigma < ({\rm MeV})^3$ or **asymmetry which makes DW unstable**.

Cosmological domain wall problem



Coulson, Lalak, Ovrut `96, Larsson, Sakar, White `97, Correia, Leite, Martins `14, Kitajima, JL, Takahashi, Yin (on going) …

Breaking the degeneracy of vacuum destabilizes DW network.

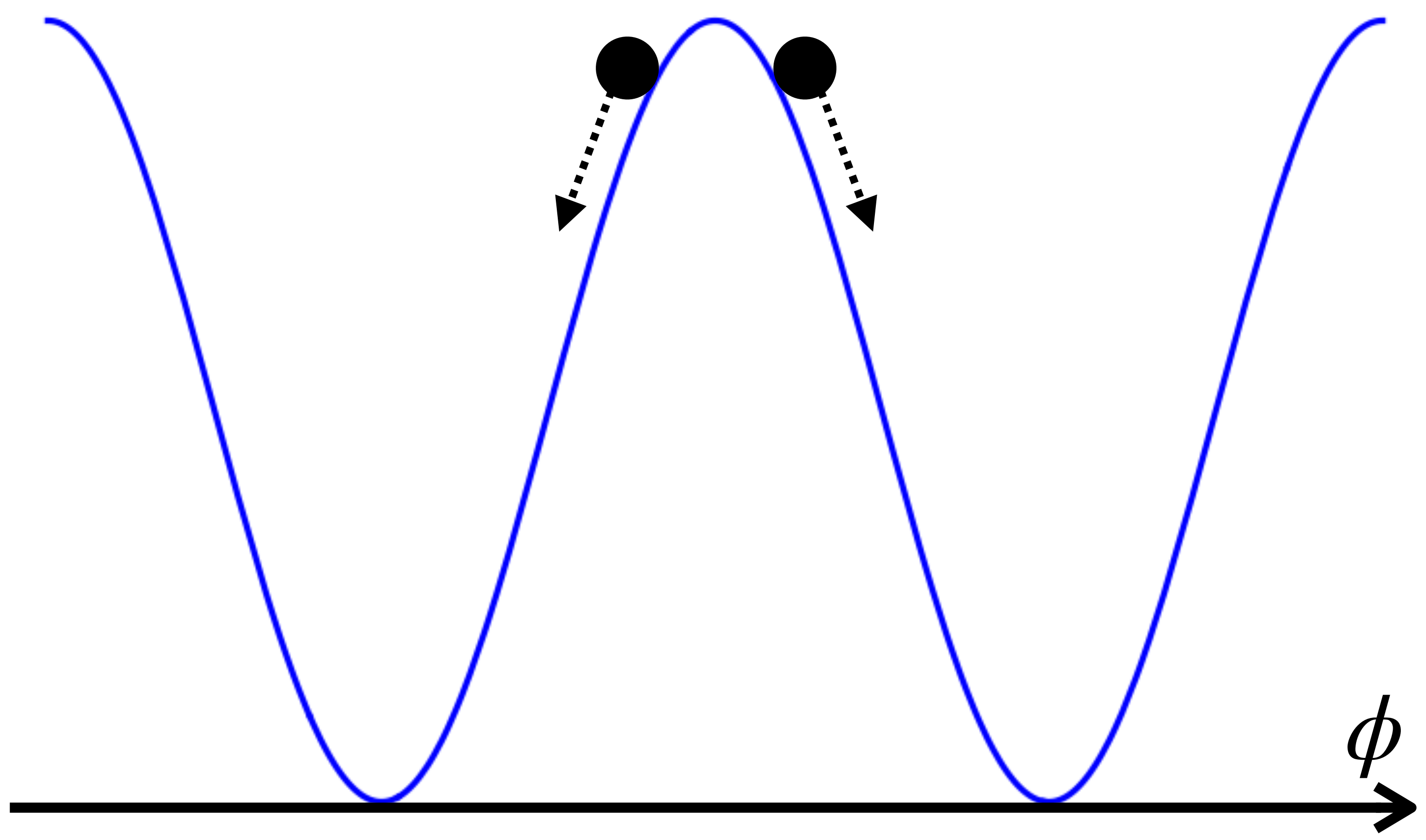
Hiramatsu, Kawasaki, Saikawa `13, …

The DW annihilation releases a large amount of GW.

Axion DW

Axion ϕ with cosine form potential

$$V(\phi) = \frac{m_\phi^2 f_\phi^2}{n^2}\left[1 - \cos\left(n\frac{\phi}{f_\phi}\right)\right] \qquad (Z_n \text{ domain wall})$$



After $H \lesssim m_\phi$, the axion starts to oscillate, and this potential could have DW configurations

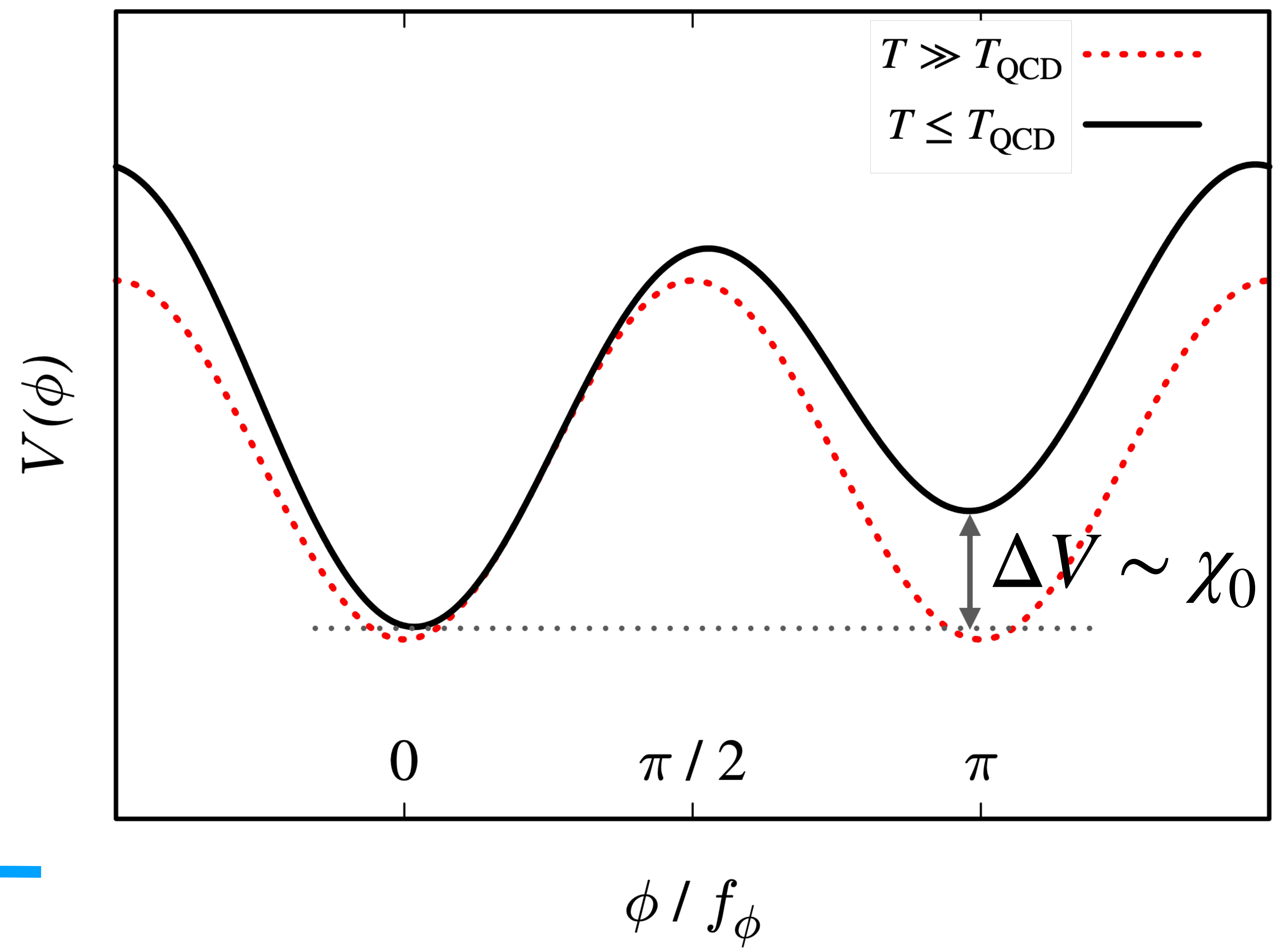
This DW has a **tension** $\sigma = \frac{8}{n^2} m_\phi {f_\phi}^2$.

Axion DW coupled to QCD

Axion ϕ with cosine form potential

$$V(\phi) = \frac{m_\phi^2 f_\phi^2}{n^2}\left[1 - \cos\left(n\frac{\phi}{f_\phi}\right)\right] \qquad (Z_n \text{ domain wall})$$

We assume $n_{\rm mix} = 1,\ n = 2$

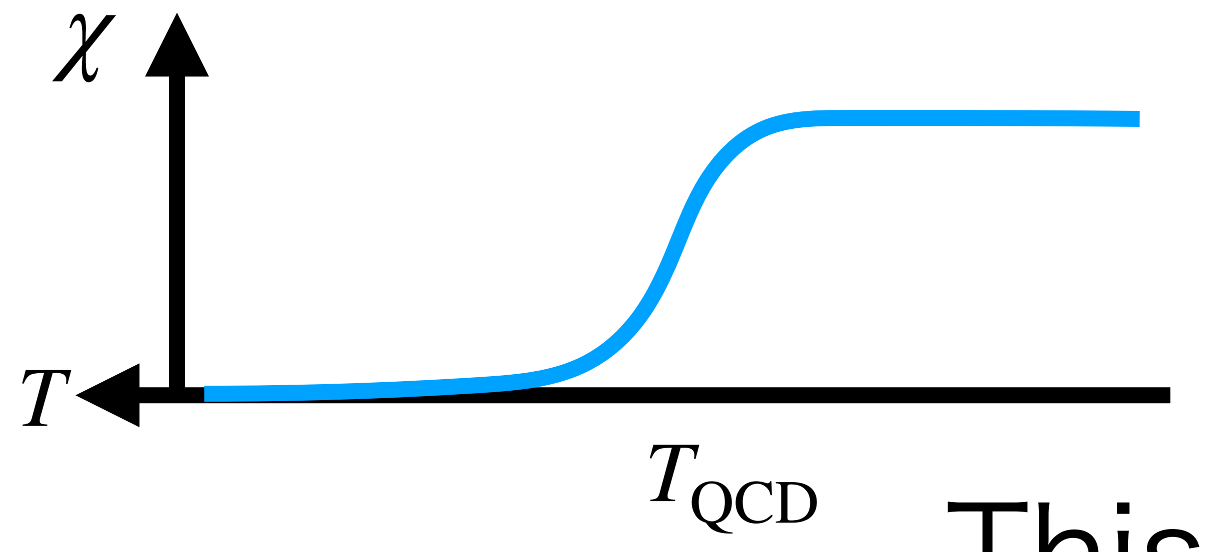


+ coupling to gluons $\mathscr{L} \supset -\frac{\alpha_s}{8\pi}\left(n_{\rm mix}\frac{\phi}{f_\phi} + \theta\right) G^a_{\mu\nu}\tilde{G}^{a\mu\nu},$

$$V_{\rm QCD}(\phi) = \chi(T)\left[1 - \cos\left(n_{\rm mix}\frac{\phi}{f_\phi} + \theta\right)\right]$$

: acts as potential bias

$$\chi(T) = \begin{cases} \chi_0 & (T < T_{\rm QCD}) \\ \chi_0\left(\dfrac{T}{T_{\rm QCD}}\right)^{-8.16} & (T \geq T_{\rm QCD}) \end{cases}$$



This gives a **pressure** on DW.

GWs from DW collapse

Hiramatsu, Kawasaki, Saikawa `13, ⋯

Before the DW network collapsed, it was in the scaling regime.

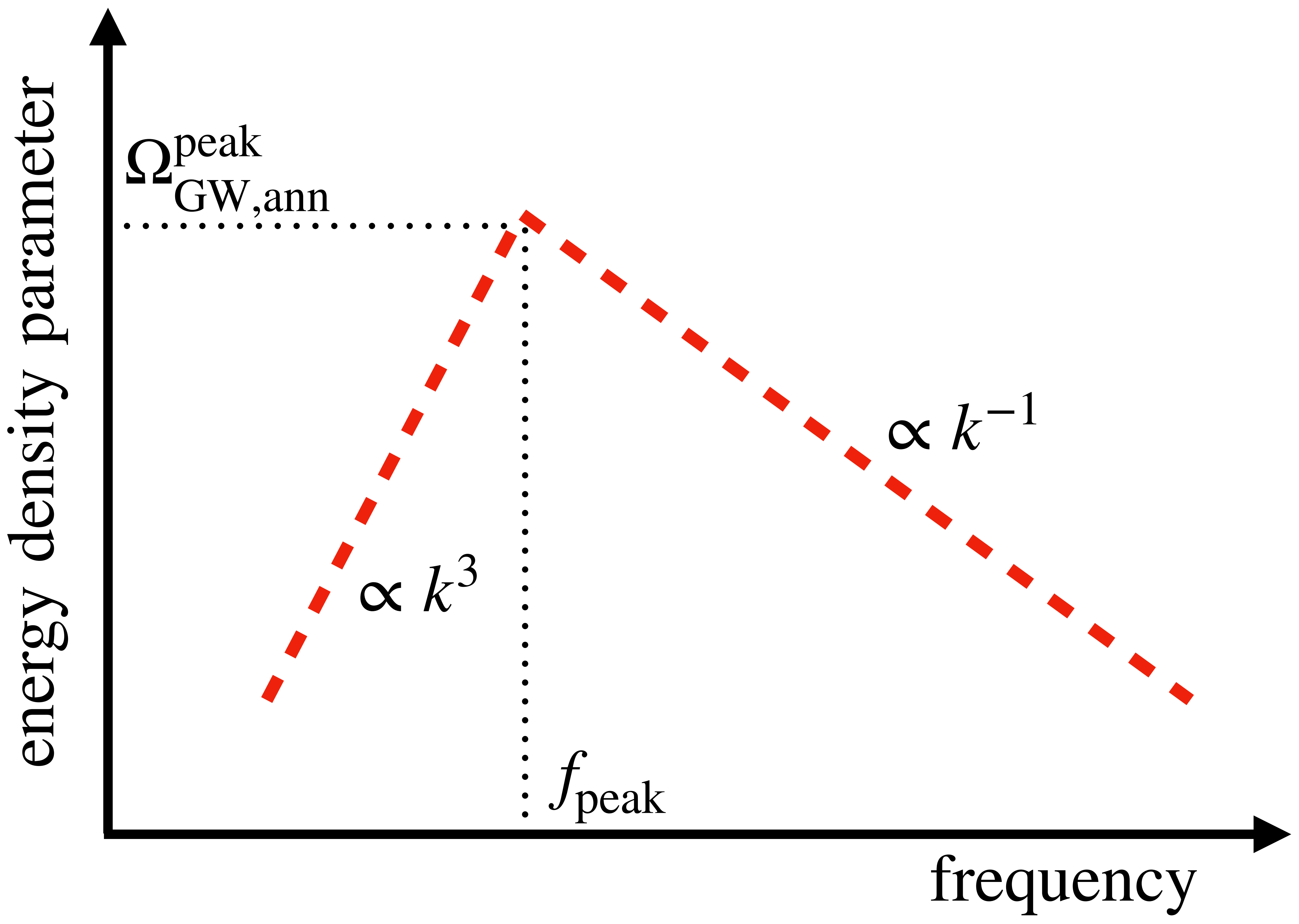
→ Sources are distributed on the Hubble horizon scale.

$$f_{\rm peak} \sim H(T_{\rm eq})$$

Stored gravitational energy

$\propto$ (DW area × tension)^2

$$\Omega_{\rm GW,ann}^{\rm peak} = \left.\frac{\tilde{\epsilon}_{\rm GW}\mathcal{A}^2\sigma^2}{24\pi M_{\rm pl}^4 H^2}\right|_{T=T_{\rm eq}} = \left.\frac{\xi^2\chi^2}{24\pi M_{\rm pl}^4 H^4}\right|_{T=T_{\rm eq}}$$



* $T_{\rm eq}$ is defined as $\chi(T_{\rm eq}) = \sigma H(T_{\rm eq})$

* Each Hubble patch contains $\mathcal{A}$ sheets of walls.

* $\tilde{\epsilon}_{\rm GW} = \mathcal{O}(1)$

* ξ is parameter including various numerical factors

GWs from DW collapse

Hiramatsu, Kawasaki, Saikawa `13, …

Before the network collapses, it is in the scaling regime.

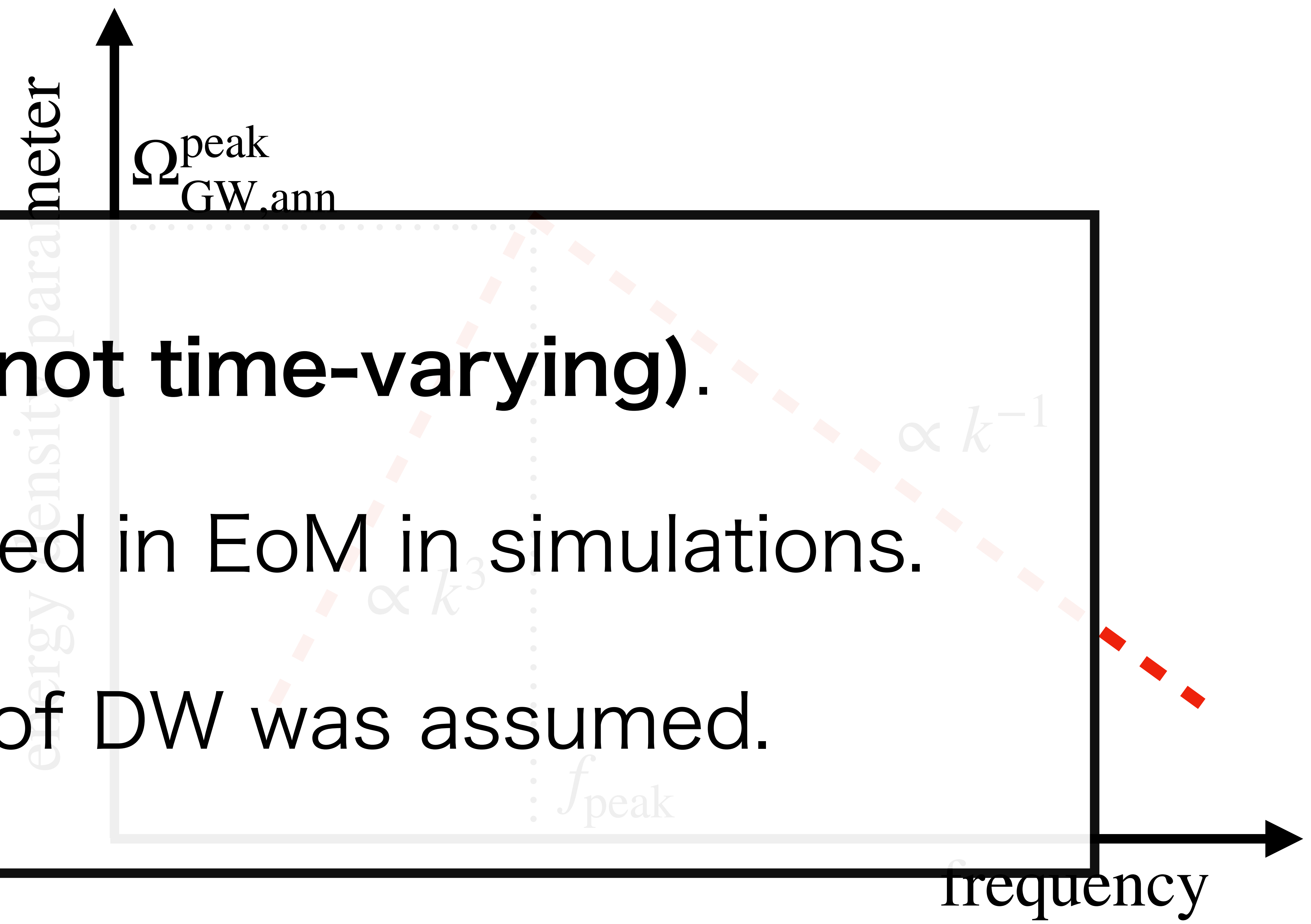
→ Sources are distributed in Hubble horizon scale

$f_{\rm peak} \sim H(T_{\rm eq})$

Stored gravitational energy

$\propto$ (DW area × tension)^2

- **The bias is constant (not time-varying).**
- The bias was not included in EoM in simulations.
- **Instantaneous decay** of DW was assumed.



$$\Omega^{\rm peak}_{\rm GW,ann} = \left.\frac{\tilde{\epsilon}_{\rm GW}\mathcal{A}^2\sigma^2}{24\pi M_{\rm pl}^4 H^2}\right|_{T=T_{\rm eq}} = \left.\frac{\xi^2\chi^2}{24\pi M_{\rm pl}^4 H^4}\right|_{T=T_{\rm eq}}$$

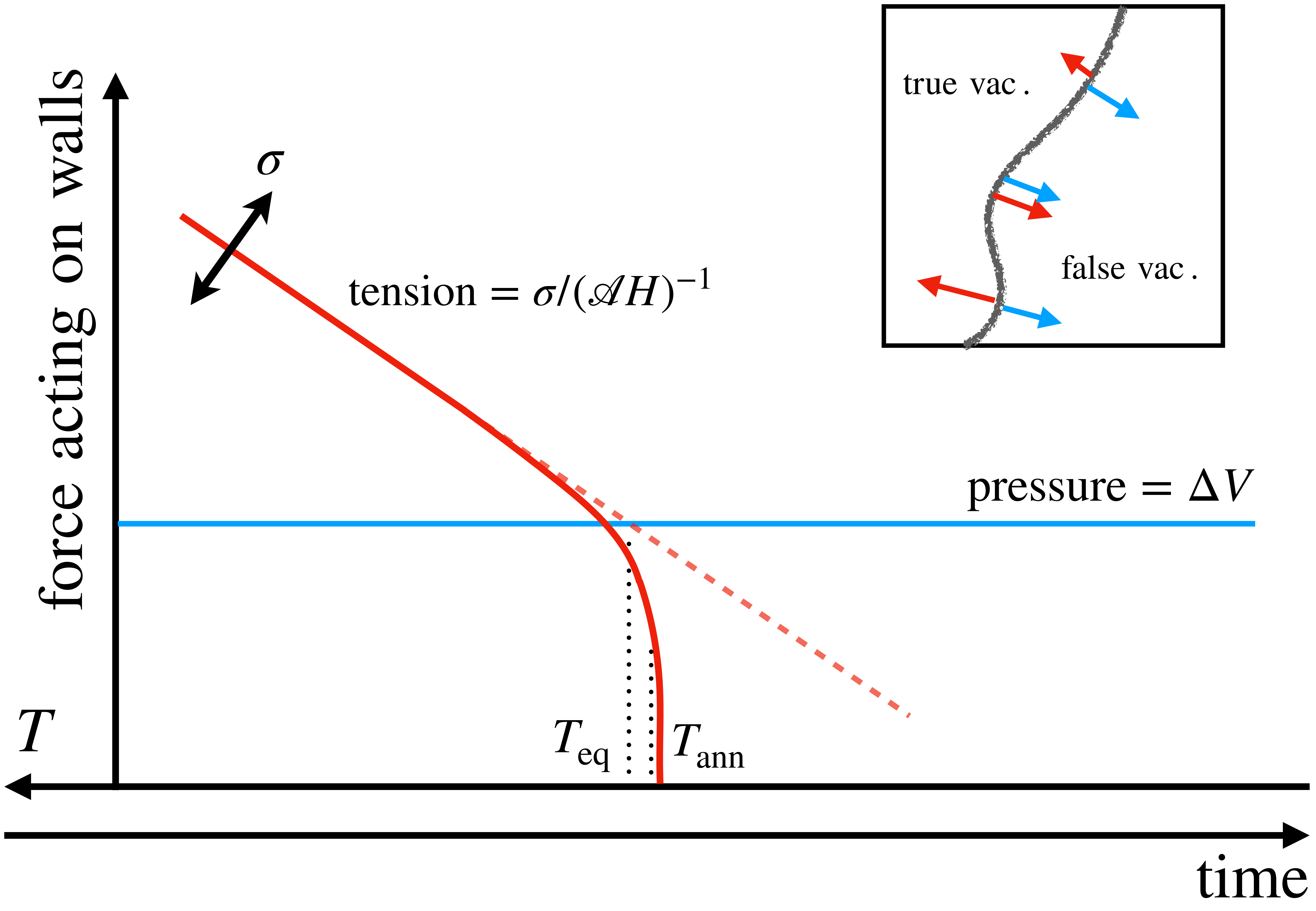
* $T_{\rm eq}$ is defined as $\chi(T_{\rm eq}) = \sigma H(T_{\rm eq})$

* Each Hubble patch contains $\mathcal{A}$ sheets of walls.

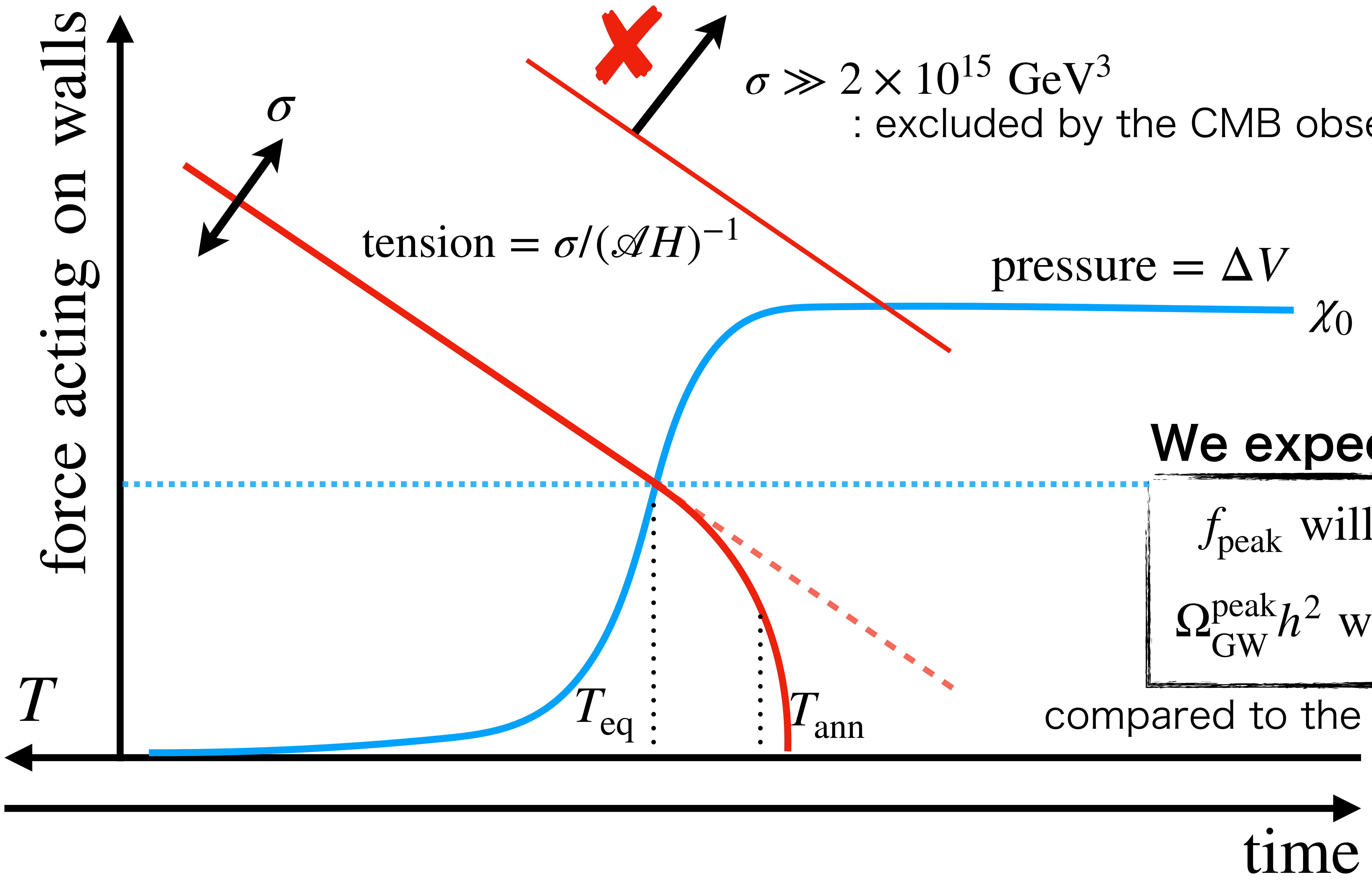
* $\tilde{\epsilon}_{\rm GW} = \mathcal{O}(1)$

* ξ is parameter including various numerical factors

In the case of the constant bias



Constant bias → Temperature-dependent bias



We expect

f_{peak} will decrease
$\Omega_{\mathrm{GW}}^{\mathrm{peak}} h^2$ will increase

compared to the constant bias case

3. Numerical Results

Numerical simulations

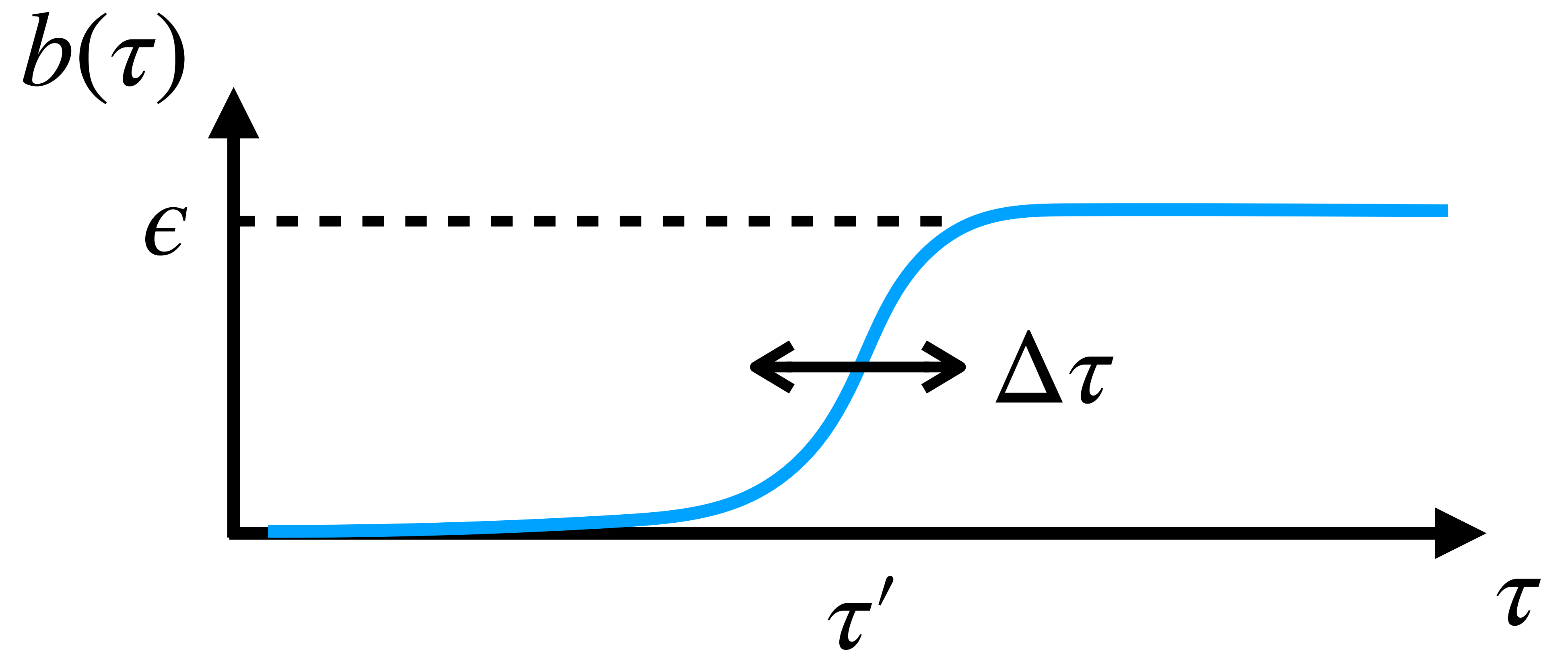
- 3D 1024^2 lattice simulations
- Periodic boundary condition
- Radiation dominated universe
- White noise initial condition

We approximated the cosine potential of the axion using a simple ϕ^4 potential. To emulate the QCD potential, we introduced a time-dependent potential bias.

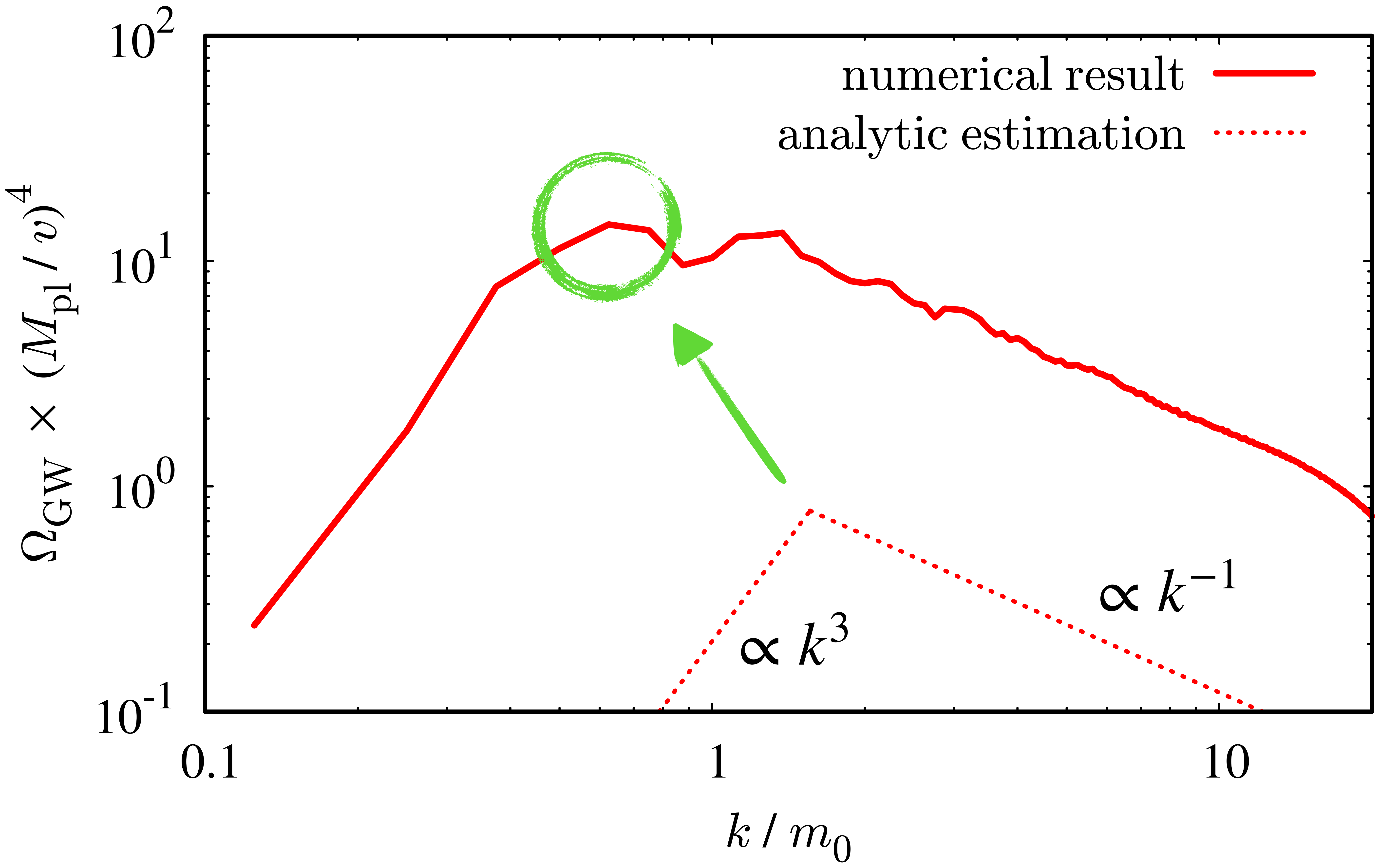
$$\text{EoM}: \begin{cases} \ddot{\phi} + 3H\dot{\phi} - \frac{1}{a^2}\Delta\phi + \frac{\partial V}{\partial \phi} = 0 \\ \ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\Delta h_{ij} = \frac{2}{M_{\rm pl}^2}\Lambda_{ij}^{\ kl}T_{kl} \end{cases}$$

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 - b(\tau)\lambda v^3\phi$$

$$b(\tau) \equiv \frac{\epsilon}{1 + e^{-2(\tau-\tau')/\Delta\tau}}$$



Numerical results



We found

$$\begin{cases} \text{the peak frequency is reduced by a factor of } \sim 0.4 \\ \text{the abundance is increased by a factor of } \sim 19 \end{cases}$$

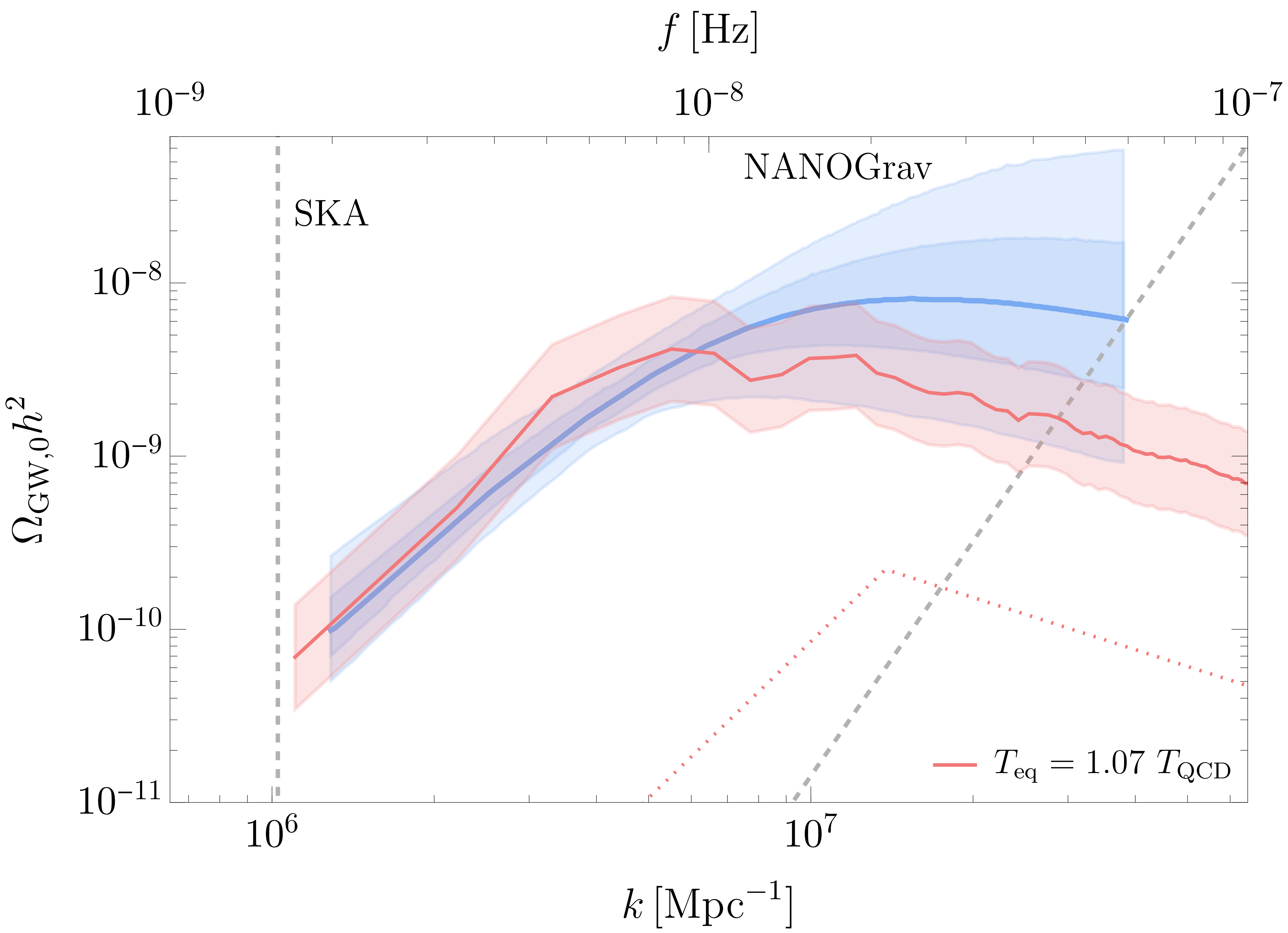
Comparison with the NANOGrav results

After the DW decayed, the GW spectrum keeps its form and red shifts.

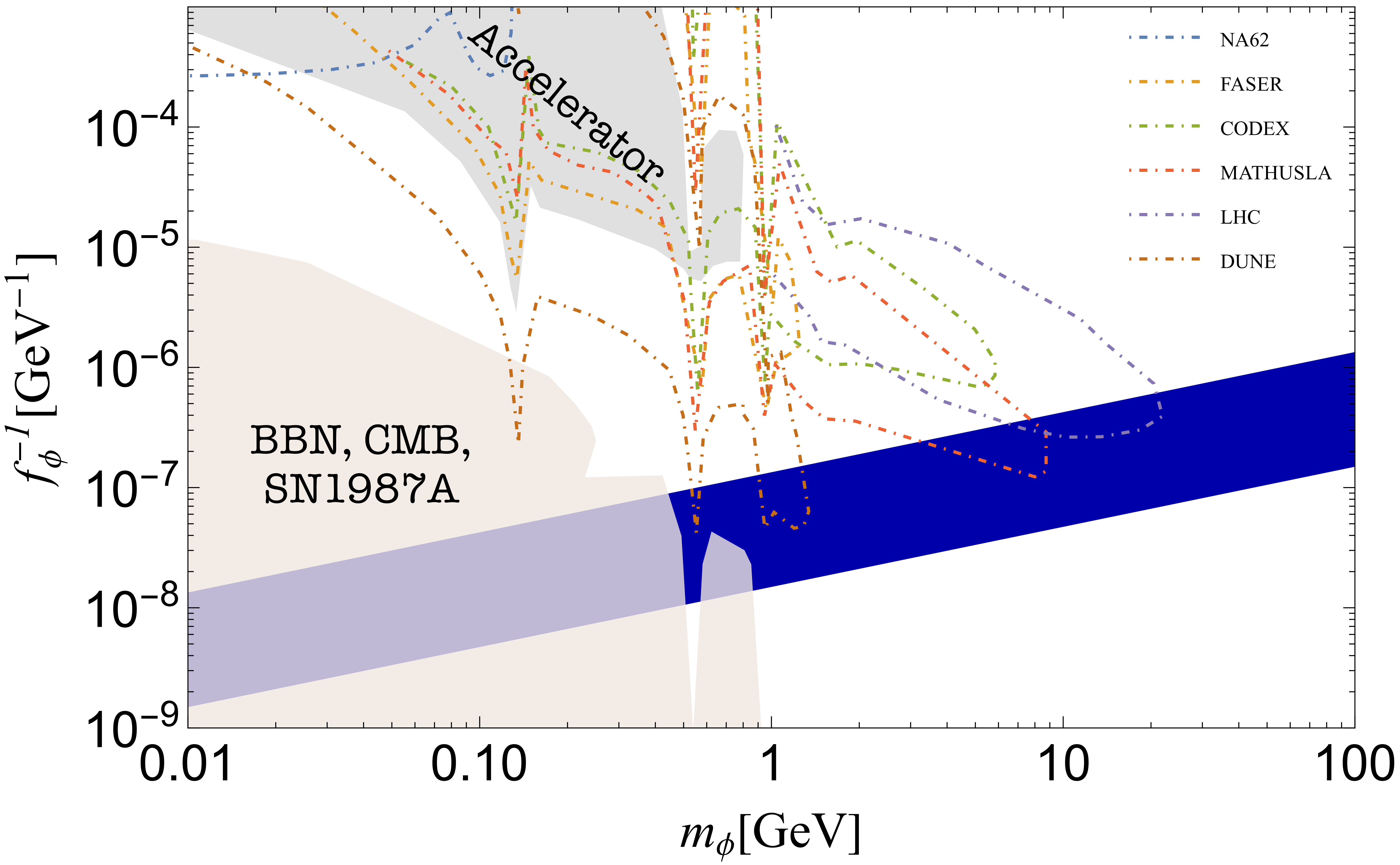
$$f_{\rm peak,0} \simeq 13\,{\rm nHz} \times \left(\frac{g_\star(CT_{\rm eq})}{20}\right)^{1/6} \left(\frac{CT_{\rm eq}}{0.1\,{\rm GeV}}\right)$$

$$\Omega^{\rm peak}_{\rm GW,0}h^2 = \Omega_r h^2 \frac{g_\star(T_{\rm eq})}{g_{\star,0}} \left(\frac{g_{\star s,0}}{g_{\star s}(T_{\rm eq})}\right)^{4/3} \Omega^{\rm peak}_{\rm GW,ann}$$

Considering $\Omega_r h^2 \sim 10^{-5}$, we predict $\sigma \sim 10^{15}\ {\rm GeV}^3$ for our scenario.



Experimental search for the axion



Summary

- The recent NANOGrav results may imply the new physics.
- We explored **GWs resulting from the collapse of axion DWs coupled to QCD**. These waves stem from the temperature-dependent potential bias generated by the QCD phase transition.
- The GW spectrum naturally peaks at the nHz frequency, to which the PTA is sensitive.
- We simulated the GW emission from the DW network **with time-varying bias** due to the QCD effect, and compared it with the recent NANOGrav data. The DW tension NANOGrav implies is $\sigma \sim 10^{15}\ \mathrm{GeV}^3$, for which the axion can be probed in the future/recent accelerator experiments.