GW signatures of domain walls

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Outline

- Defects in field theory
- Formation in the early Universe
- Domain walls as seeds for bubble nucleation
- Domain walls as GW sources:
    - Impact of particle friction
    - Improved understanding of the scaling regime

Defects in field theory

- Topological defects are non-trivial (space dependent) solutions of the EOM.

- Their classification is based on the topological properties of the vacuum manifold $\mathscr{M}$:

Symmetry group G broken to subgroup $H \Rightarrow \mathscr{M} = G/H$ (coset).

- The type of defects that are supported depends on the non trivial homotopy group of $\mathscr{M}$

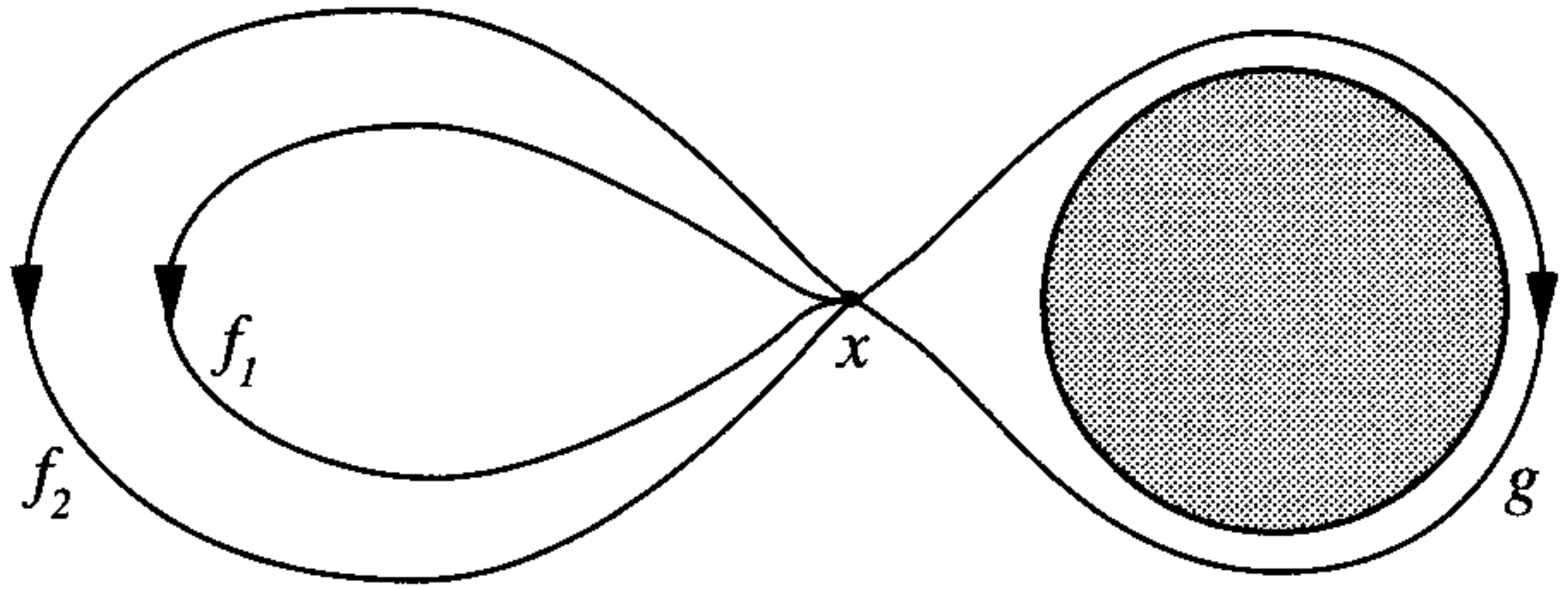

Fig. from Vilenkin & Shellard

Space equivalent to $\mathscr{M} = S^1$ with non trivial $\pi_1(S^1) = \mathbb{Z}$

Defects in field theory

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Strings

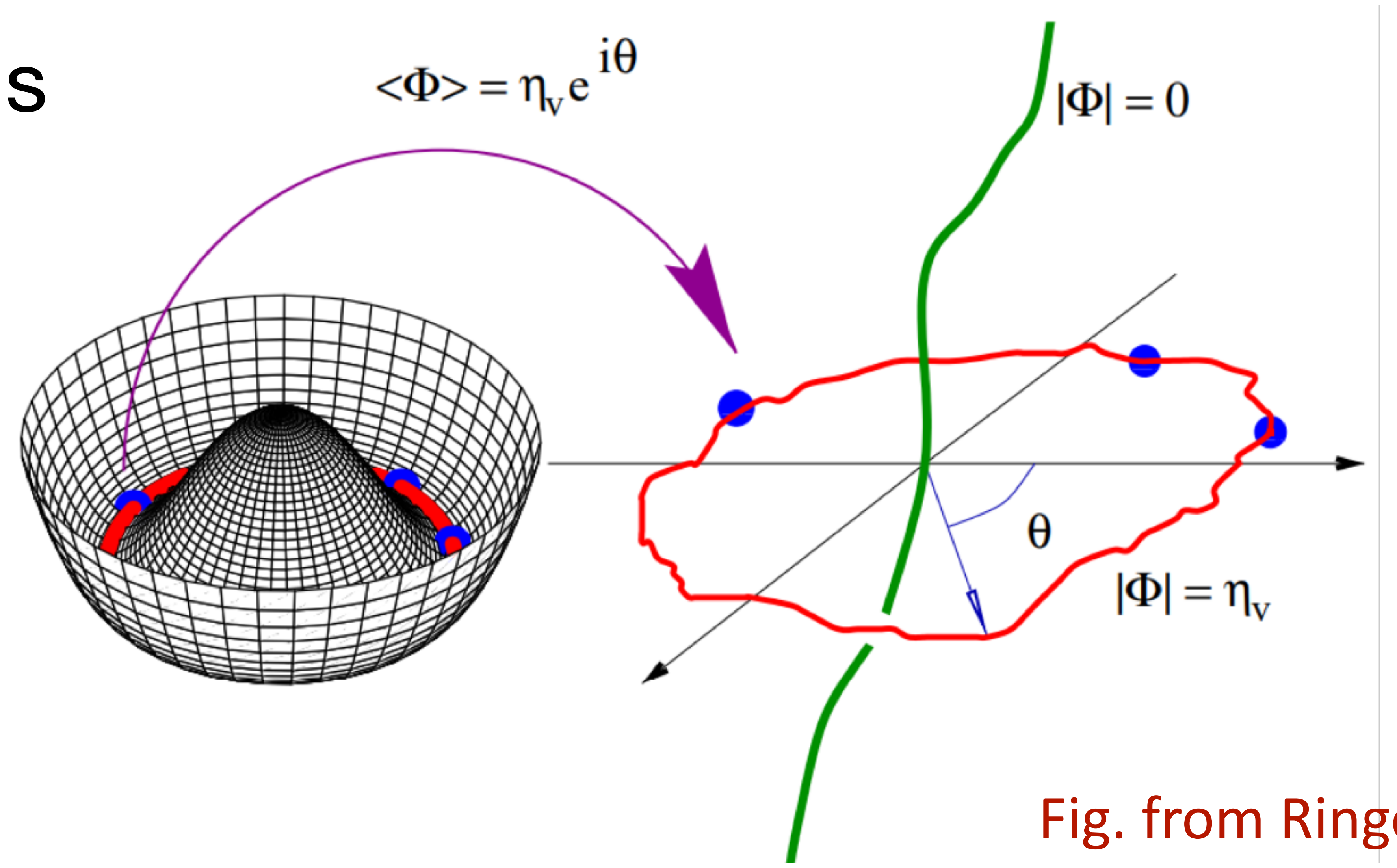


Fig. from Ringeval 2010

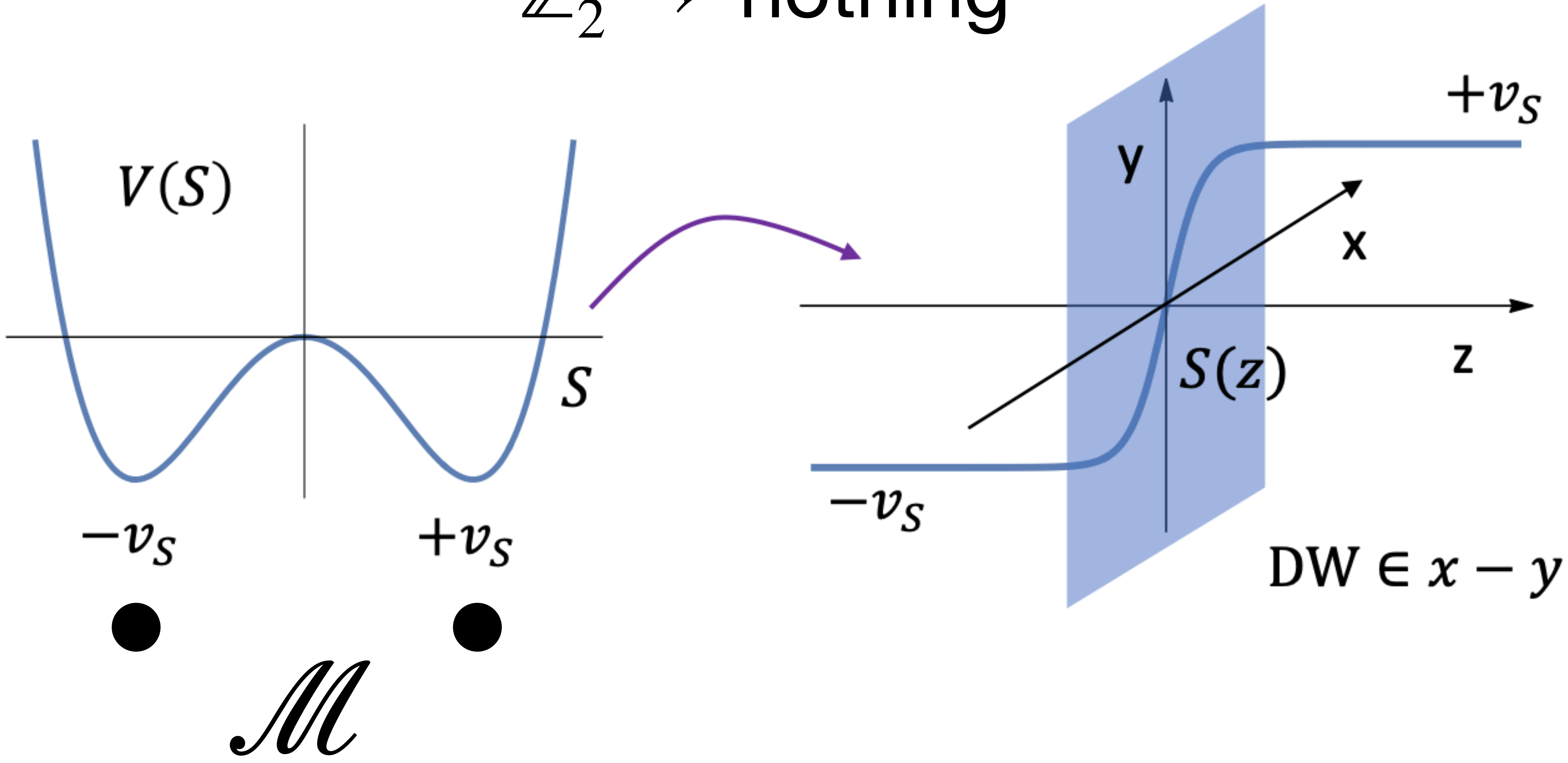
Defects in field theory

- Domain walls correspond to disconnected vacuum manifolds: breaking of discrete symmetries

Defects in field theory

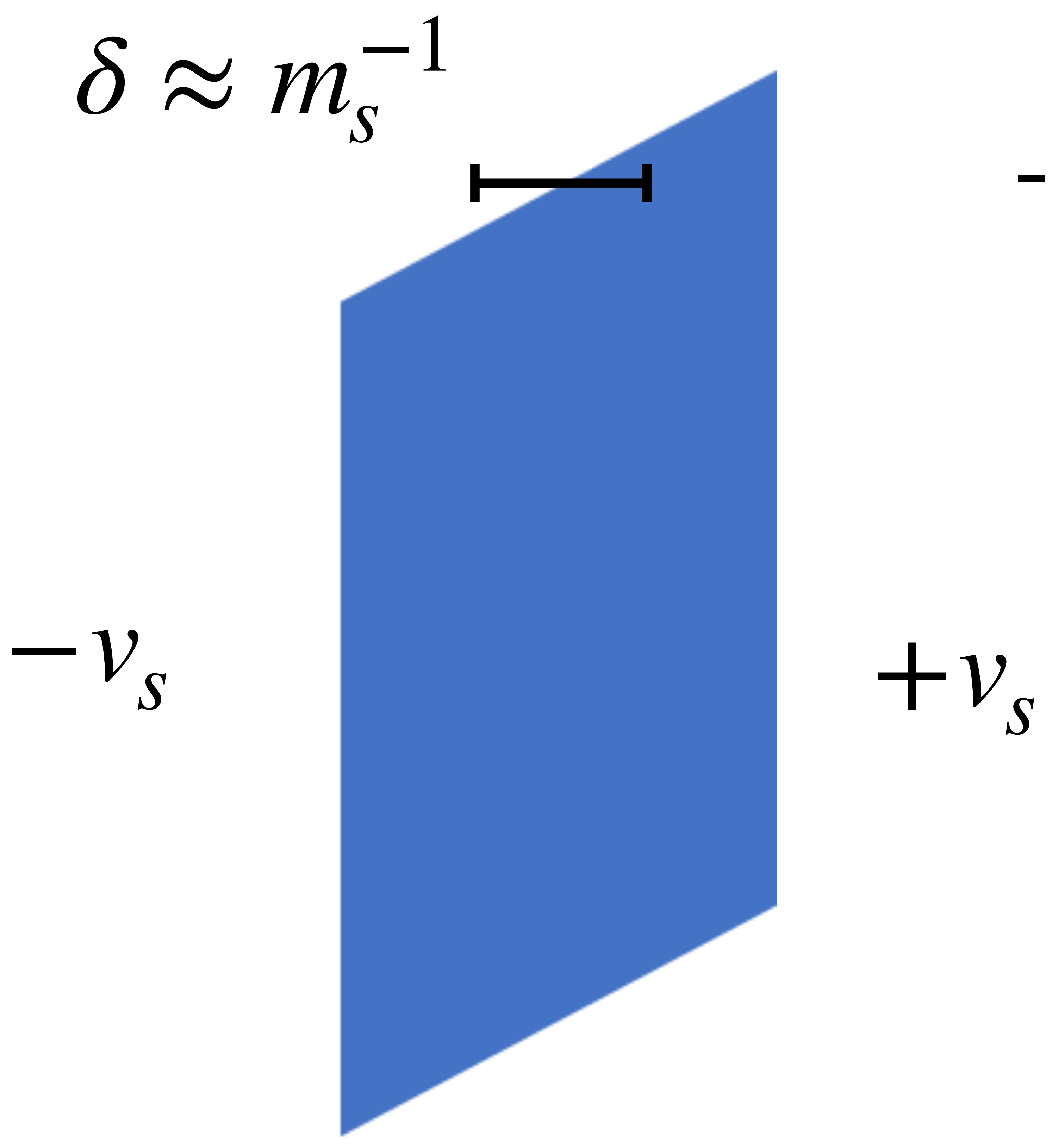
- Domain walls correspond to disconnected vacuum manifolds: breaking of discrete symmetries

$\mathbb{Z}_2 \to$ nothing



Defects in field theory

- A domain wall solution is characterized by the tension σ of the wall and its width δ



- Domain wall mass per unit surface:

$$\sigma \approx m_s v_s^2$$

Formation of the network

- Domain walls form according to the Kibble mechanism:
    - Fluctuations of scalar field around T_c have finite correlation length $\xi(T) < d_H$
    - Uncorrelated patches will generally select different points of vacuum manifold $\mathscr{M}$

Zeldovich et al. 1975
Kibble 1976

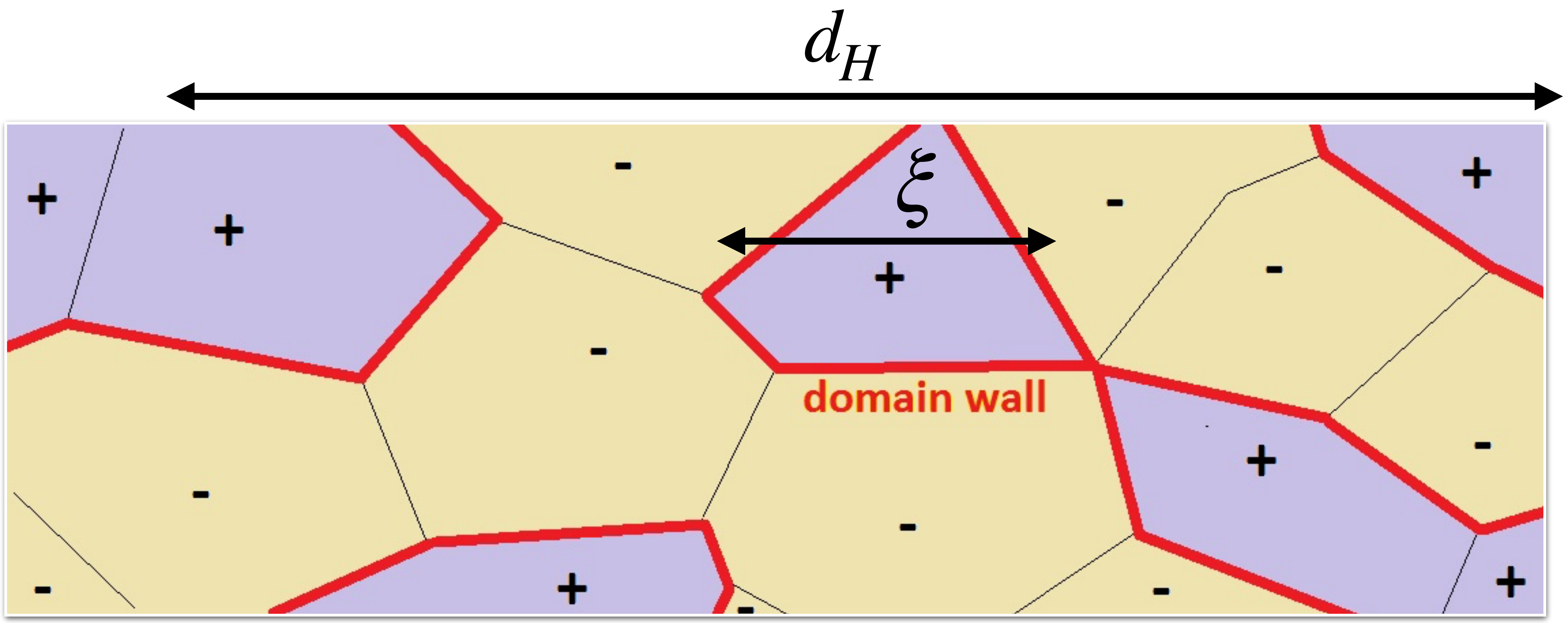
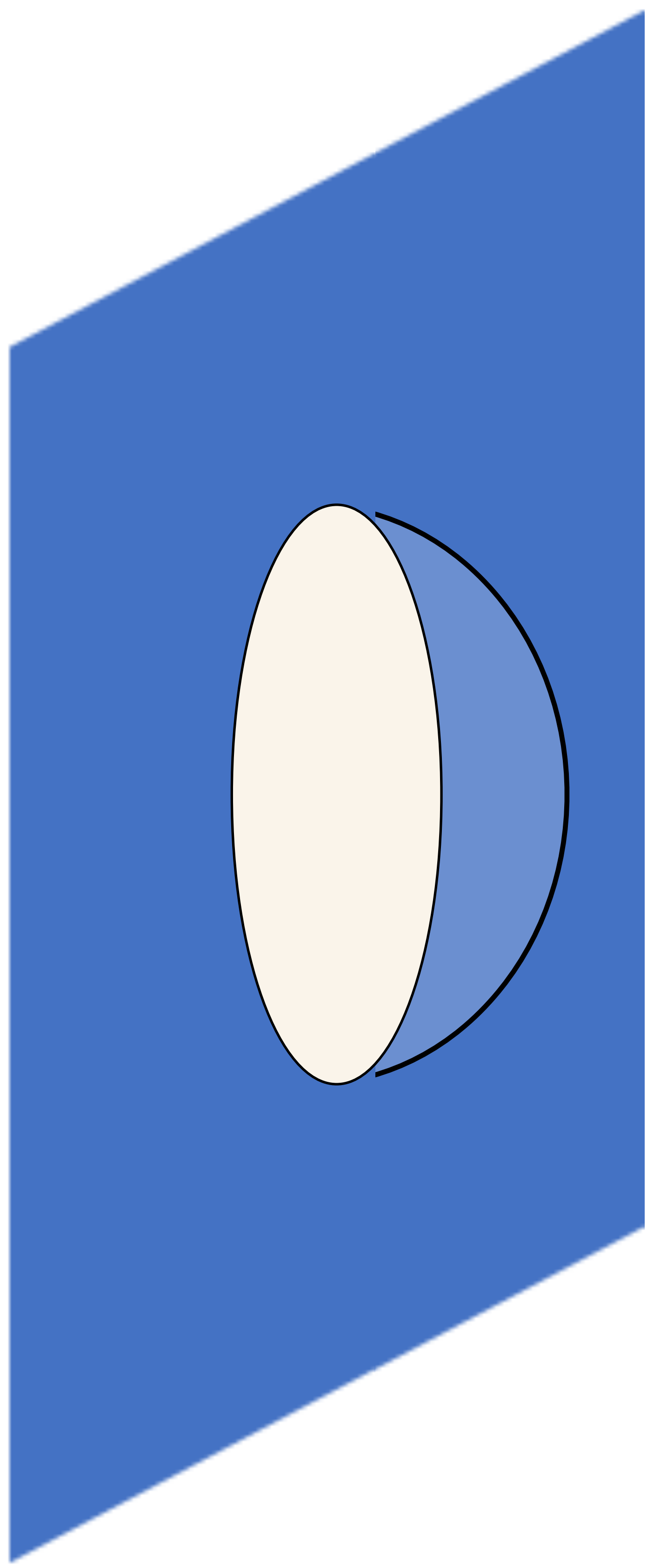


Fig. From MIT edu

Walls as impurities

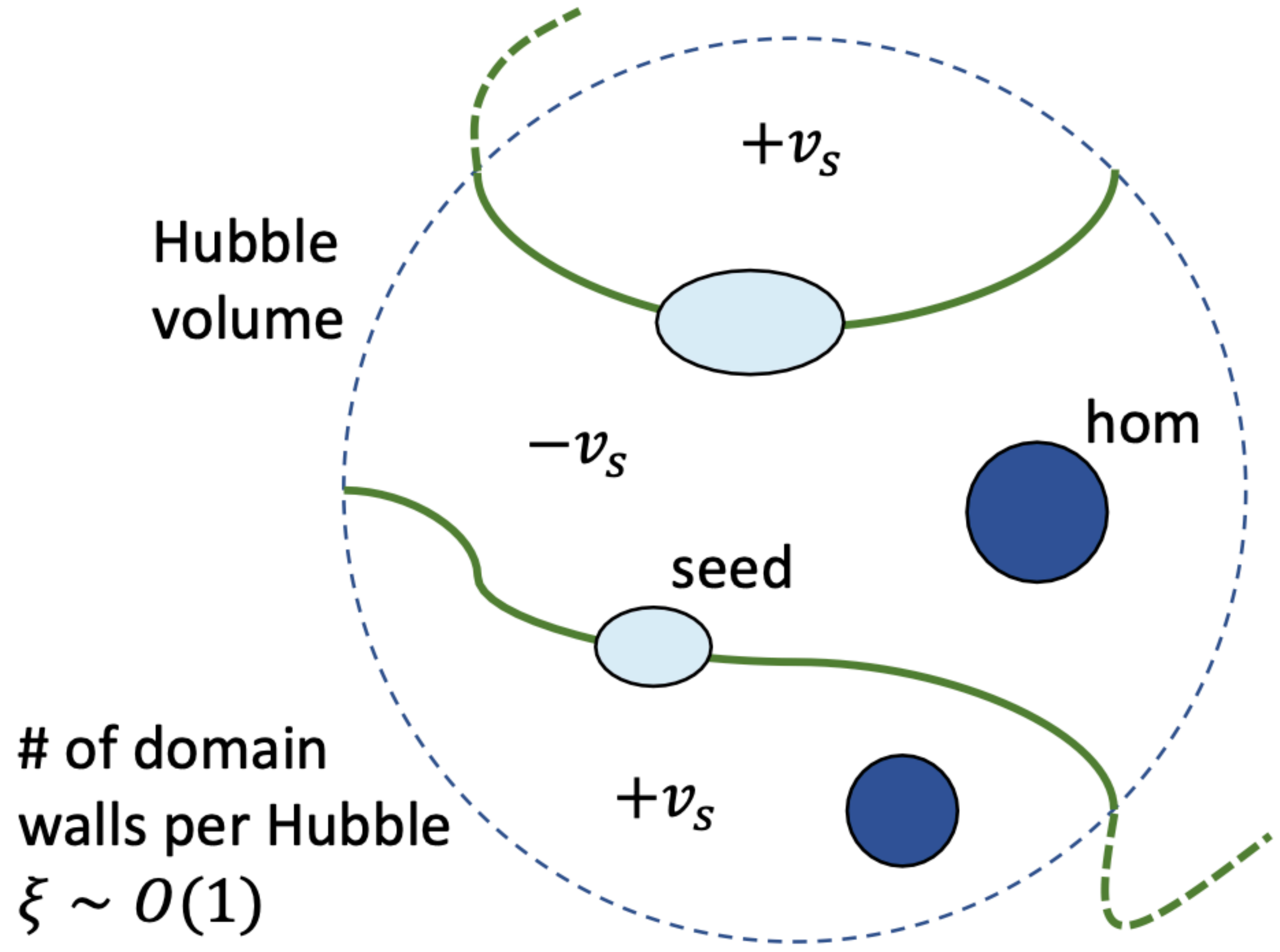
- The presence of domain walls at the time of a first order phase transition can induce exponentially enhanced nucleation on the surface



Seeded critical bubble

SB, Mariotti [2203.16450], PRL

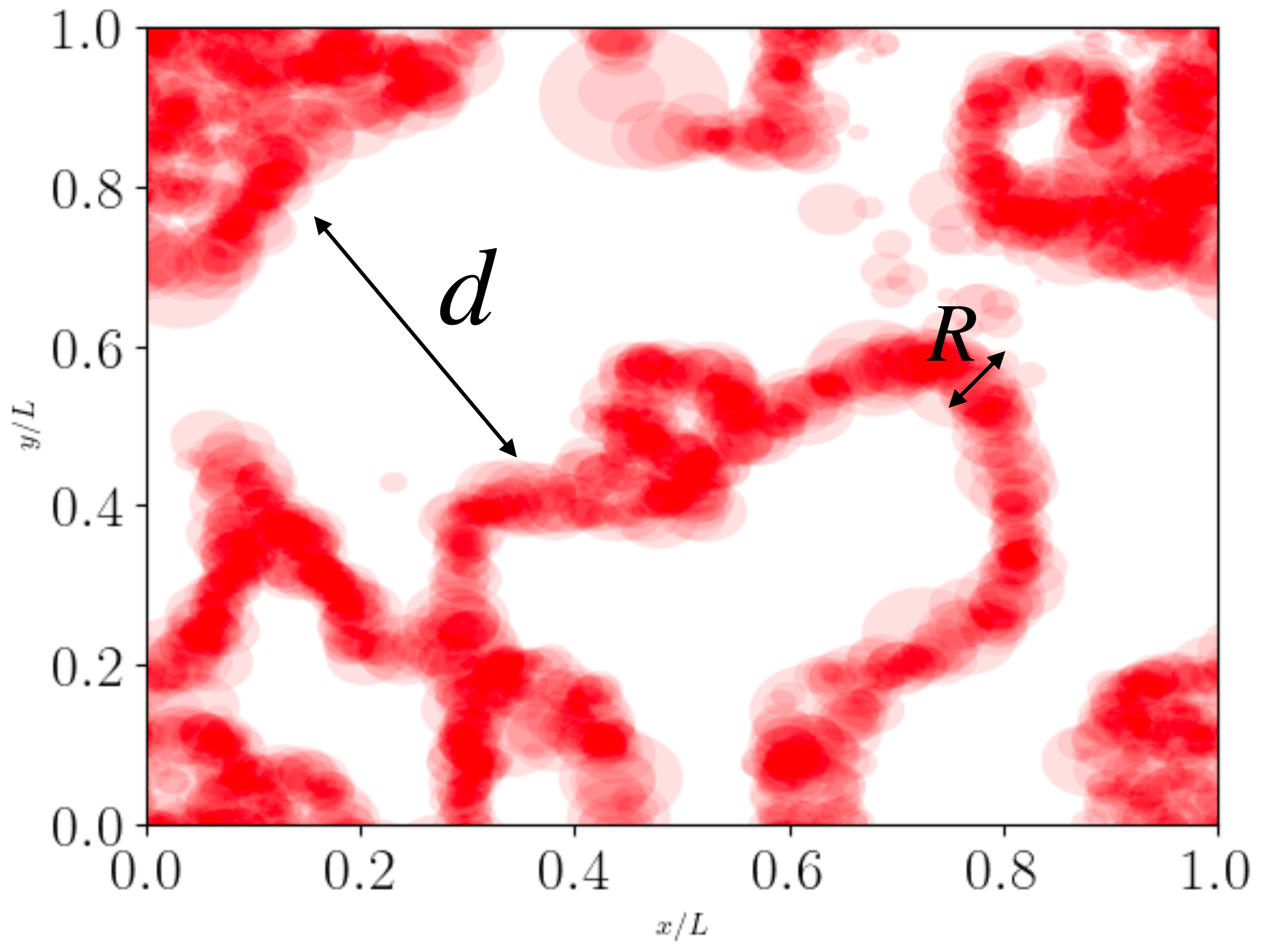
Agrawal, **SB**, Mariotti, Nee [2312.06749], JHEP



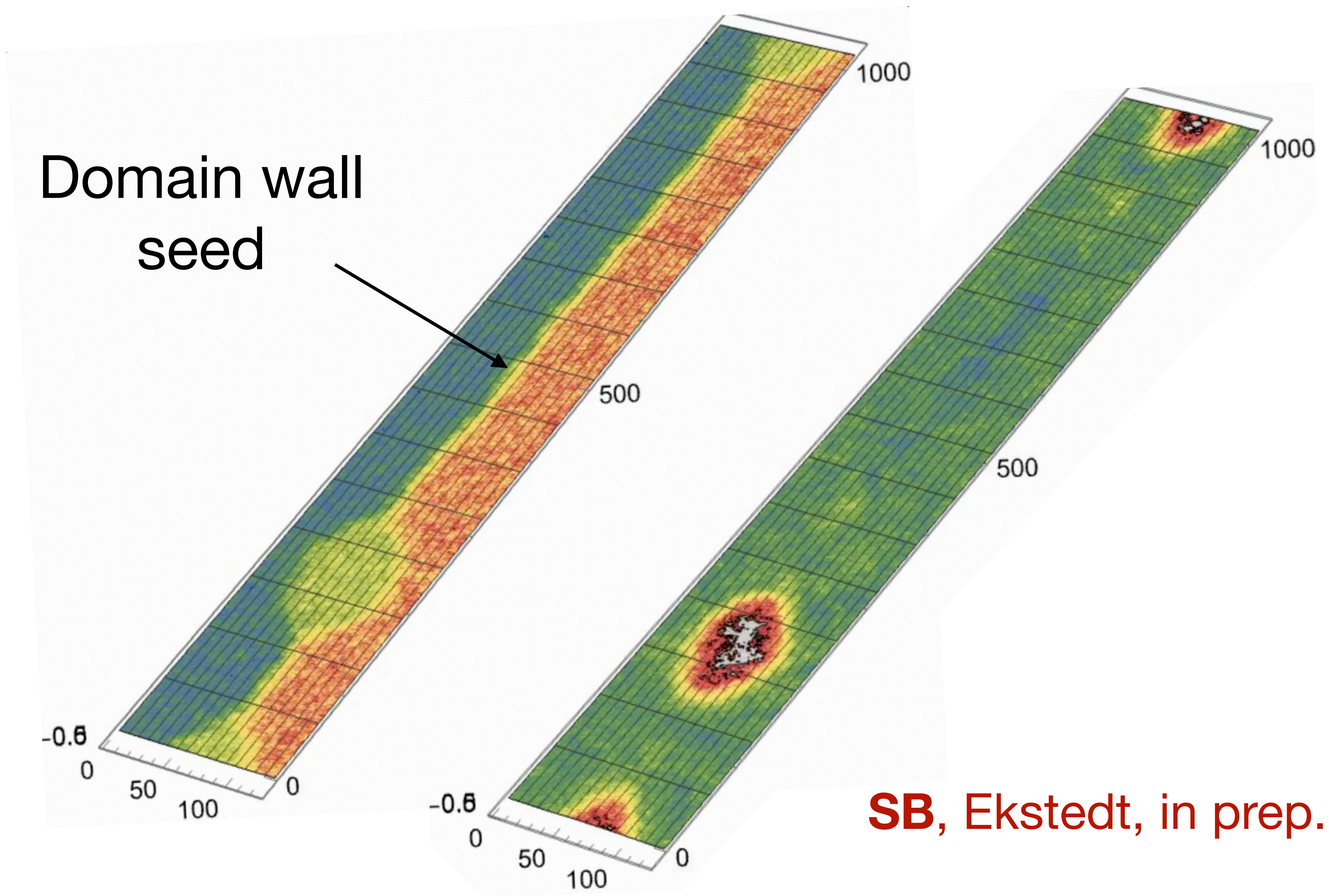
Same catalyzing effect can occur from axion strings: **SB**, Mariotti, [2405.08060]

Walls as impurities

- This scenario can be simulated from the hydrodynamical point of view, as well as real time seeded nucleation (Langevin approach)



SB, Jinno, Konstandin, Rubira, Stomberg, JCAP [2302.06952]



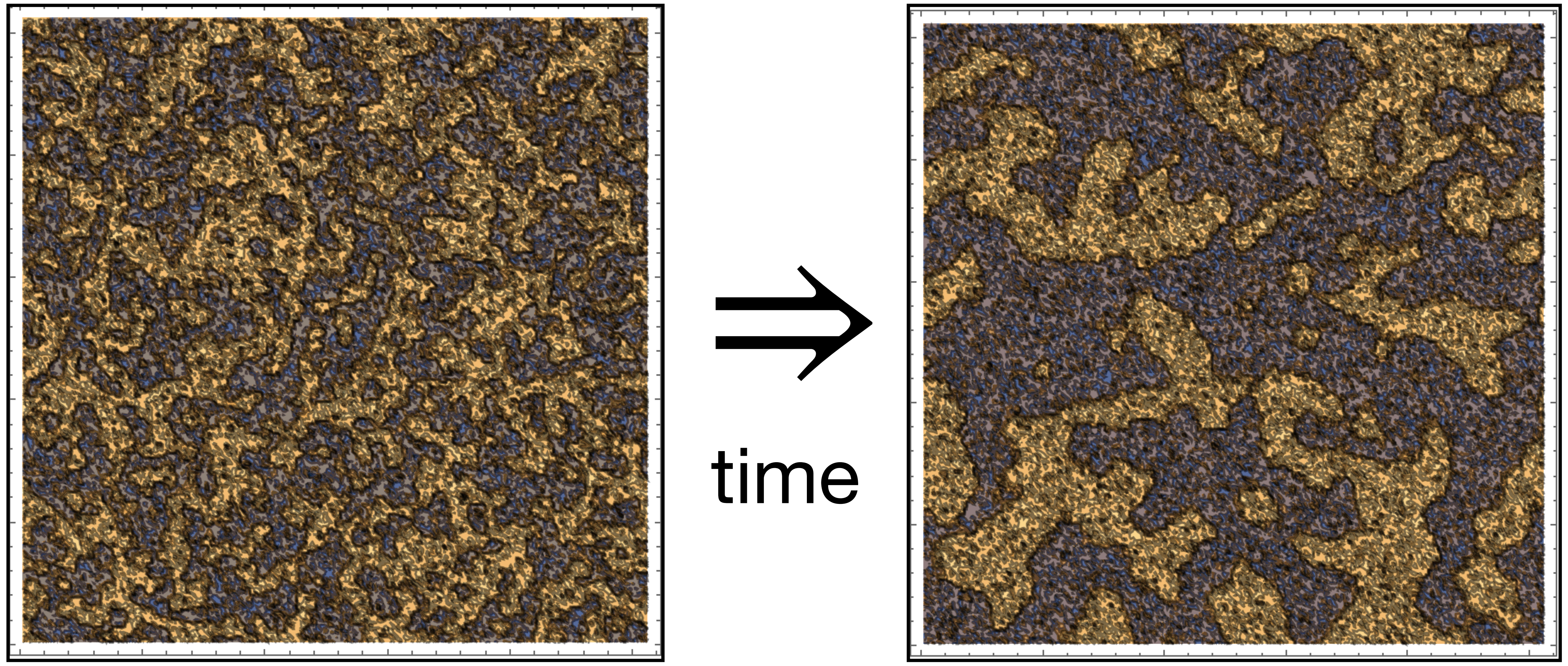
SB, Ekstedt, in prep.

Scaling regime

- After formation, the network reaches a dynamical attractor solution known as the scaling regime, with $\mathcal{O}(1)$ domain walls per Hubble volume at any time

- In scaling, the energy density of the network grows compared to the critical density

- This “domain wall problem” can be solved by a small energy or population bias that eventually annihilates the network

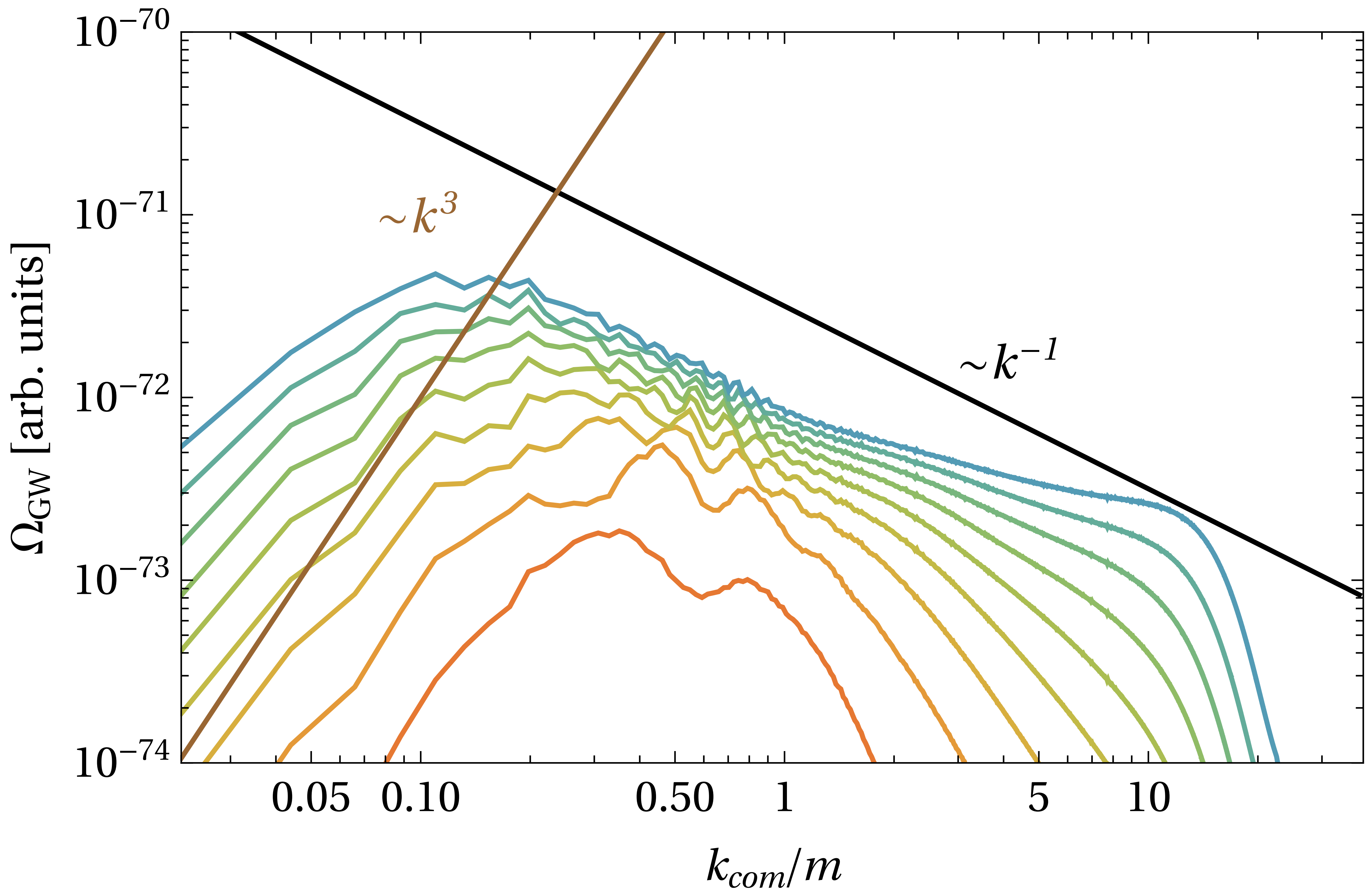


$$\frac{\rho_{\rm DW}}{\rho_c} \sim G\,\sigma\,t$$

GWs from the scaling regime

- GWs are radiate by the domain walls during:
  - the scaling the regime (long-lasting source, dominated by later times)
  - the final phase of collapse and annihilation
- Assuming scaling ends at $T = T_*$:

$$\Omega_{\text{peak}} \sim 10^{-6}\,\alpha_*^2\,,\quad f_{\text{peak}} \sim H(T_*)$$



Friction domination

- Domain wall motion from the Nambu-Goto action

$$S = -\sigma \int d^3\zeta \sqrt{\gamma}$$

- Parameterize a possible friction force by

$$F^\nu = \boxed{\frac{\sigma}{\ell_\mathrm{f}}} (u^\nu - x^\nu_{,a}\gamma^{ab}x^\mu_{,b}\, g_{\mu\sigma}u^\sigma)$$

- Equation of motion for the surface:

$$\ddot{x} + \boxed{\left(3\frac{\dot{a}}{a^2} + \frac{1}{\ell_\mathrm{f}}\right)} (1-\dot{x}^2)a\dot{x} = \textit{Curvature}$$

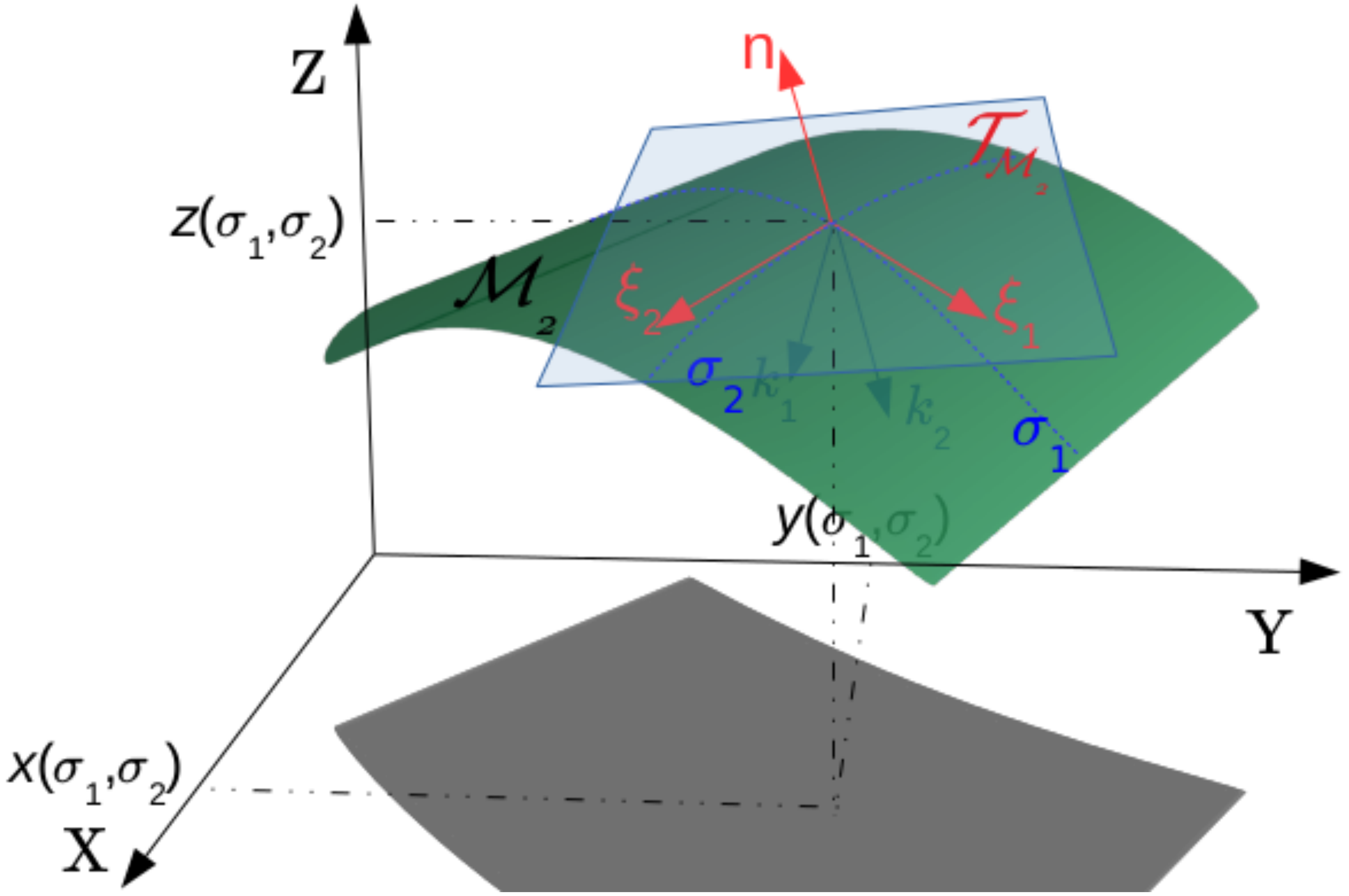


Fig. from Martins, Rybak, Avgoustidis, Shellard [1602.01322]

Friction domination

- Define a total damping length given by:

$$\frac{1}{\ell_{\mathrm{d}}} = 3H + \frac{1}{\ell_{\mathrm{f}}}$$

Scaling regime

Friction domination

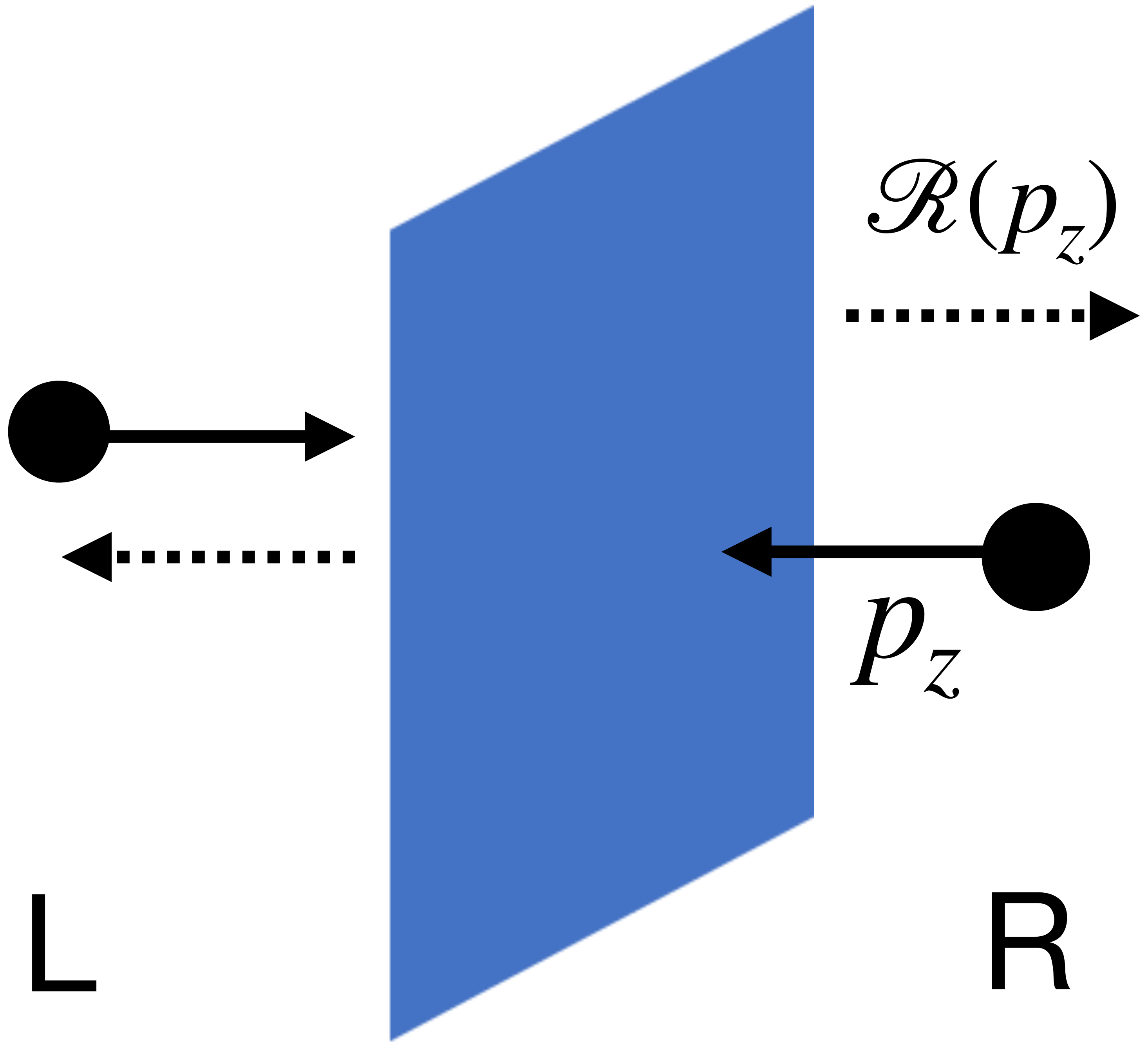
Friction domination

- The friction length can be evaluated given a particle physics model

$$\Delta P = P_{\rm R} - P_{\rm L} = 2\int \frac{{\rm d}^2 p}{(2\pi)^3}\int_0^\infty {\rm d}p_z [f(-v) - f(v)]\frac{p_z^2}{E}\boxed{\mathcal{R}(p)}$$

Right and *Left* particle distribution in the wall frame

Reflection coefficient



$$\boxed{\frac{1}{\ell_{\rm f}} = \frac{\Delta P}{\sigma\gamma(v)v} \simeq \frac{\Delta P}{\sigma v}}$$

Friction domination

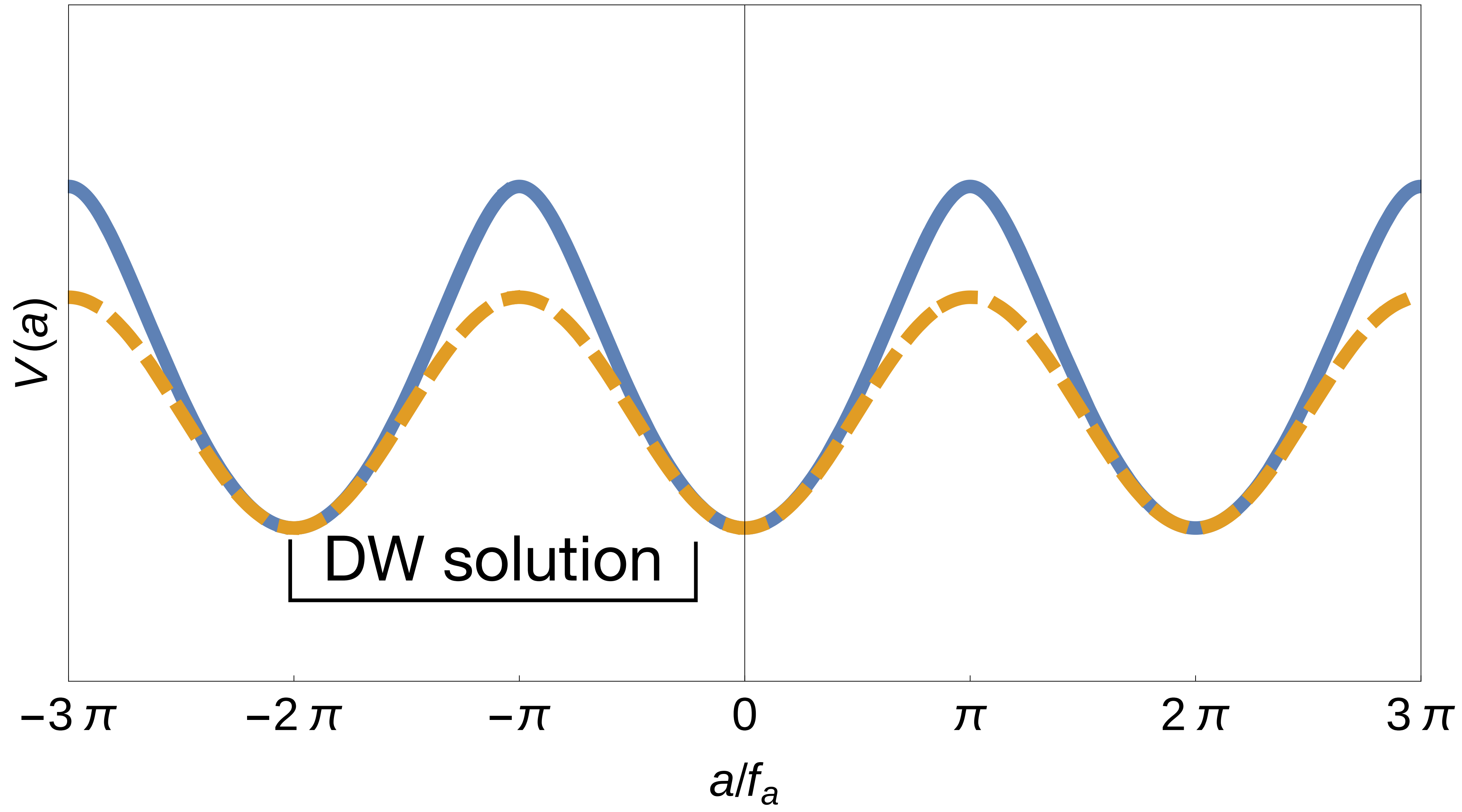
- Consider the case of fermions derivatively coupled to an axion-like-particle (ALP)

$$\mathcal{L}_{a\psi} = \frac{\kappa}{2N_{\rm DW} f_a} \partial_\mu a \, \bar{\psi}\gamma^\mu \gamma_5 \psi + \bar{\psi}(i\partial\!\!\!/ - m_f)\psi$$

- Scattering off ALP domain walls:

$$V(a) = \Lambda^4 \left[1 - \cos\left(\frac{a N_{\rm DW}}{v_a}\right)\right]$$

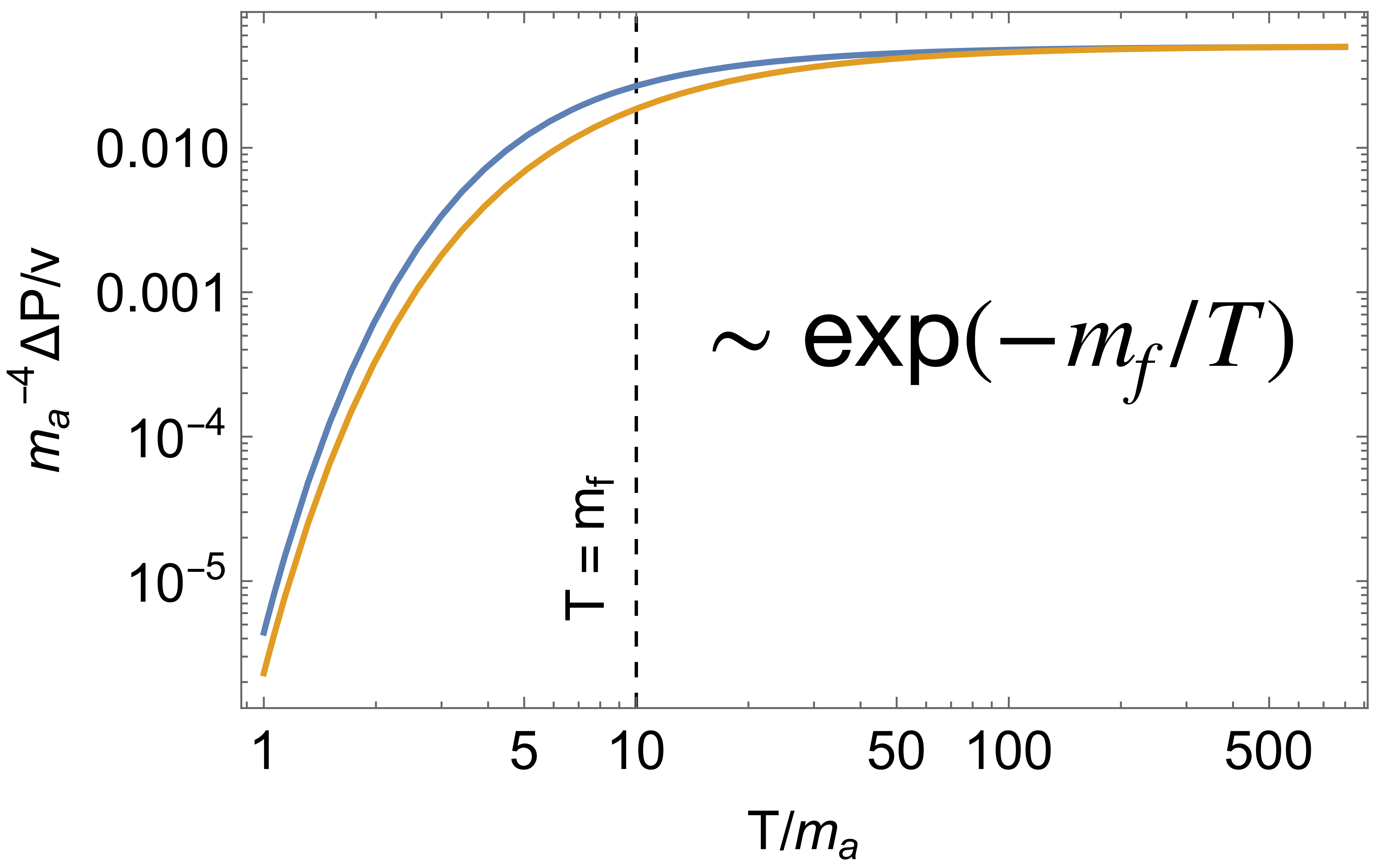
$$a(z) = 4 f_a \arctan\left(e^{m_a z}\right)$$



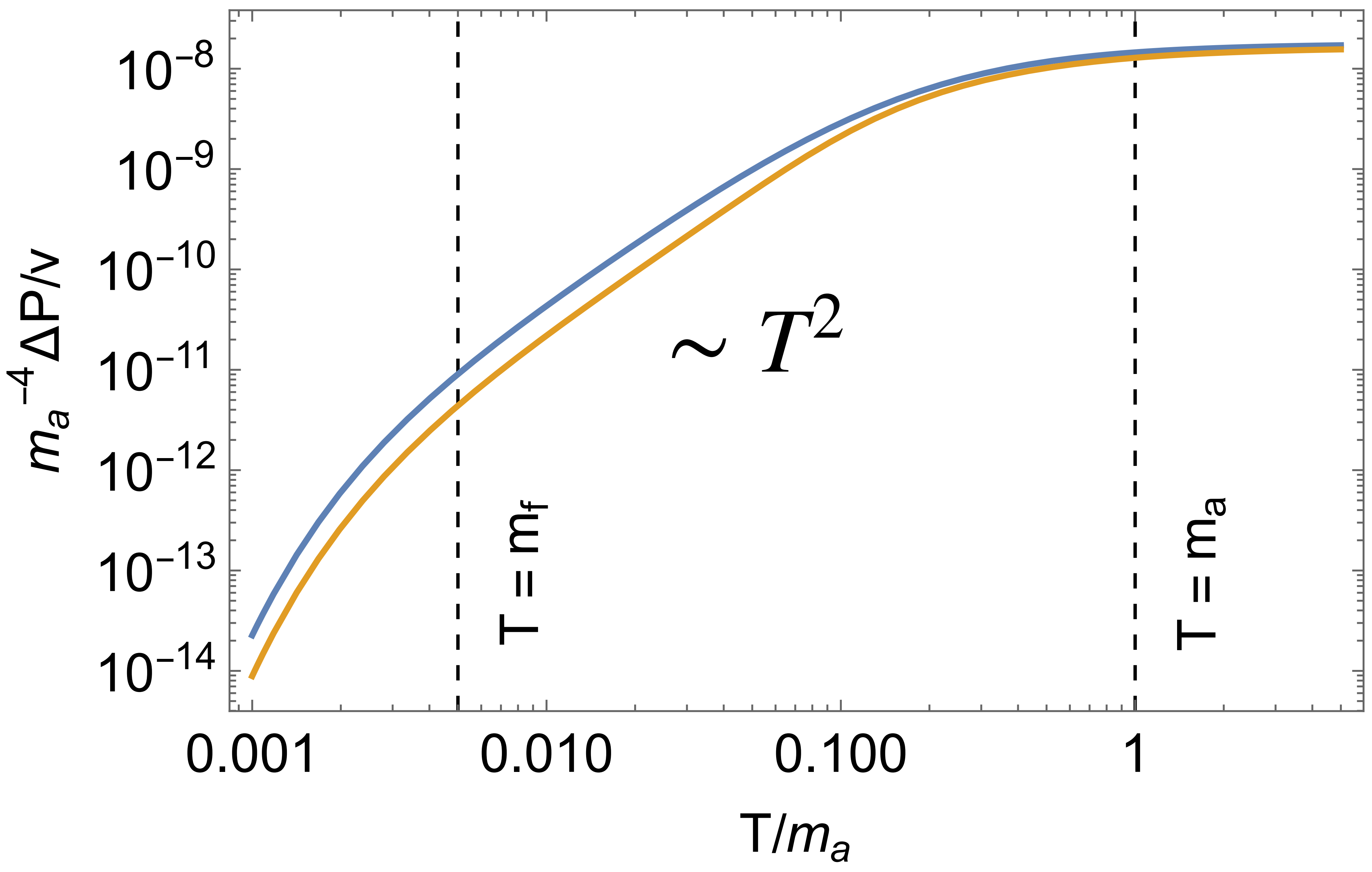
Friction domination

- Determine the reflection coefficient for the fermion scattering via Dirac equation

$m_f \gg m_a$



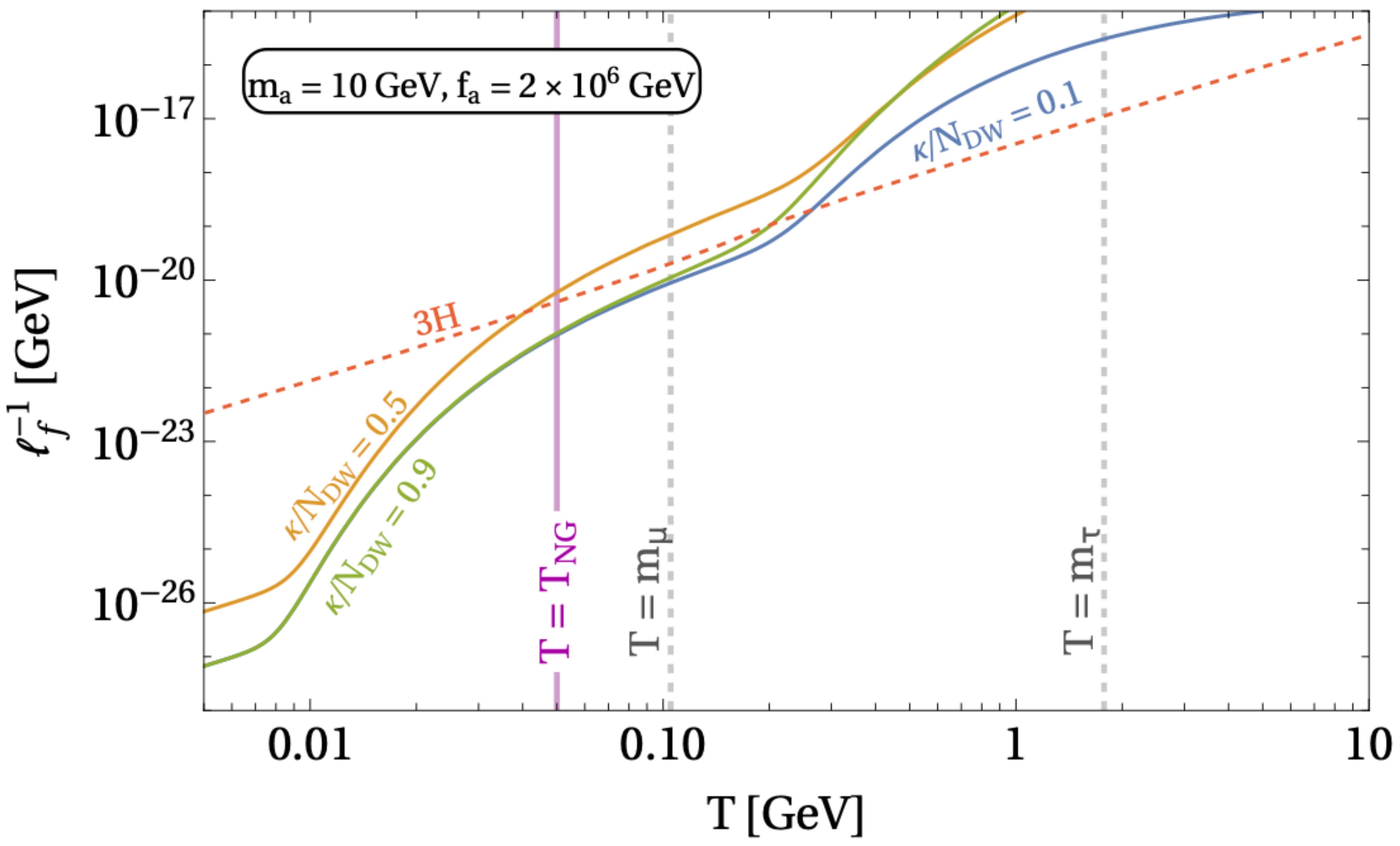
$m_f \ll m_a$

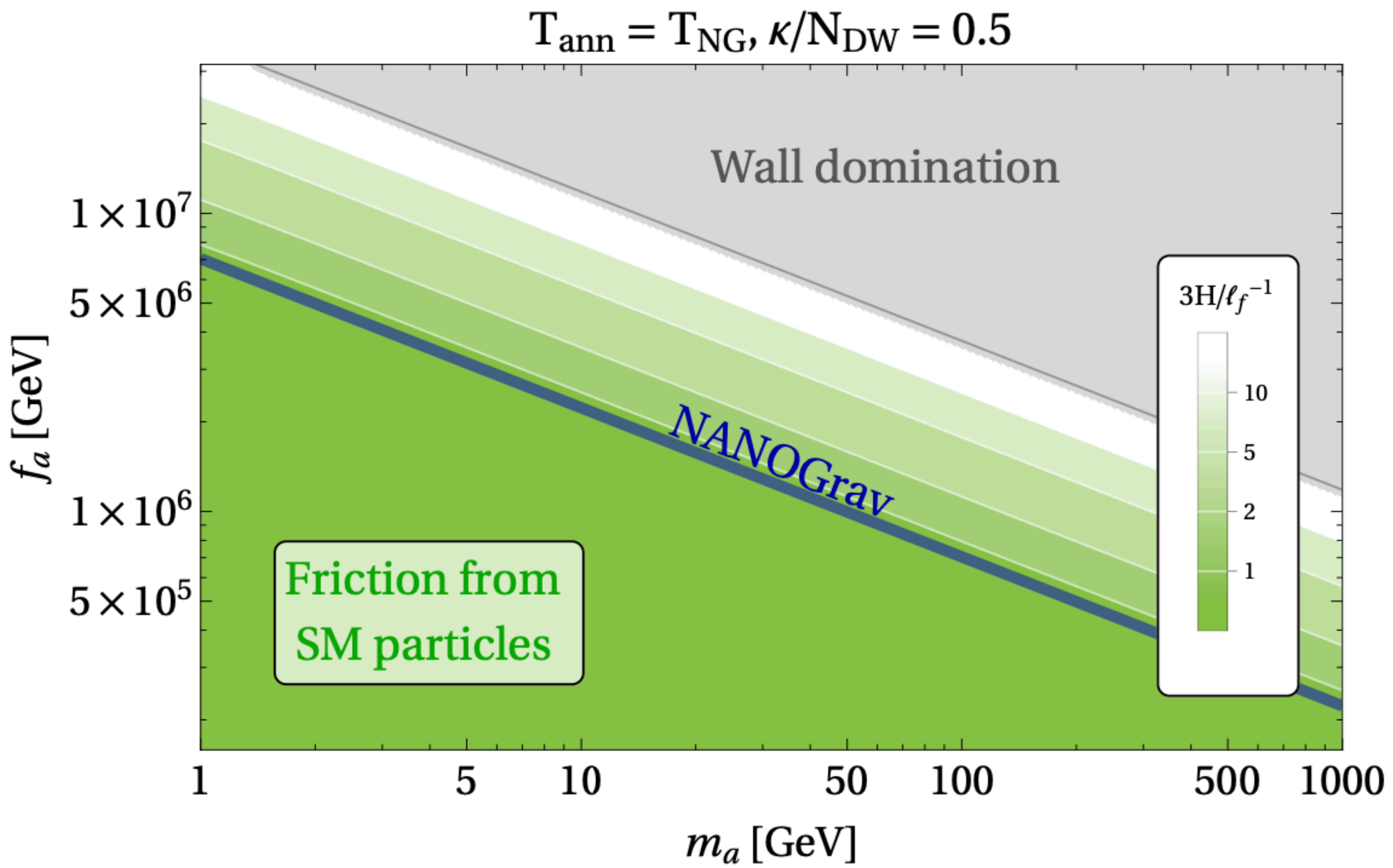


Friction domination

- ALPs coupled to **SM leptons** with strength $\sim 1/f_a$

SB, Mariotti, Rase, Sevrin, Turbang, [2210.14246], JCAP



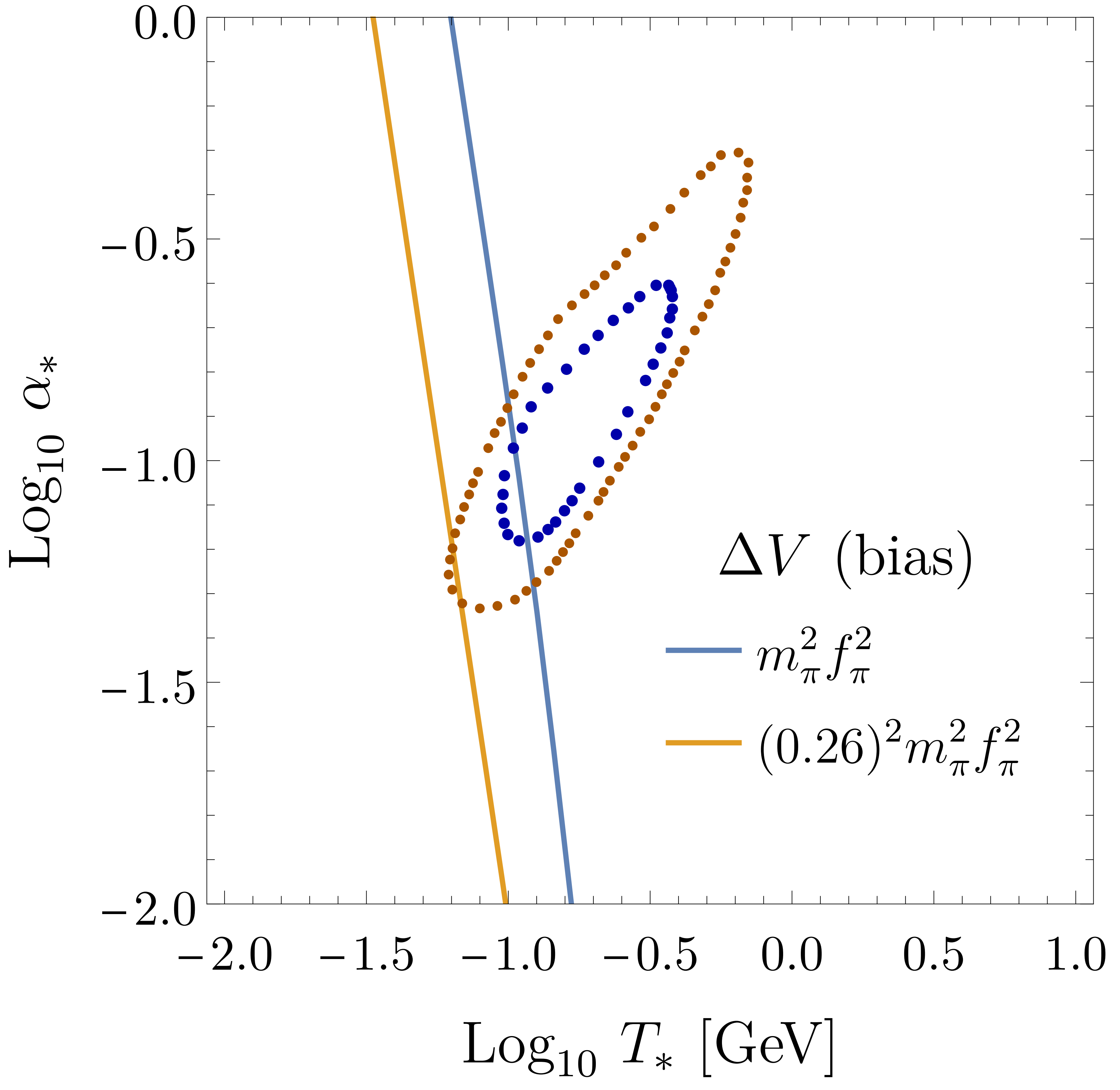


Friction domination

- ALP domain walls destroyed by QCD bias: natural annihilation at $T_* \sim 100\,\mathrm{MeV}$
  - Introduce a coupling of the ALP to the gluons:

$$\mathcal{L}_a \supset \frac{\alpha_s}{4\pi}\frac{N_c}{v} G\tilde{G}$$

  - This will generate a potential which will act as a bias for the pre-existing DW network



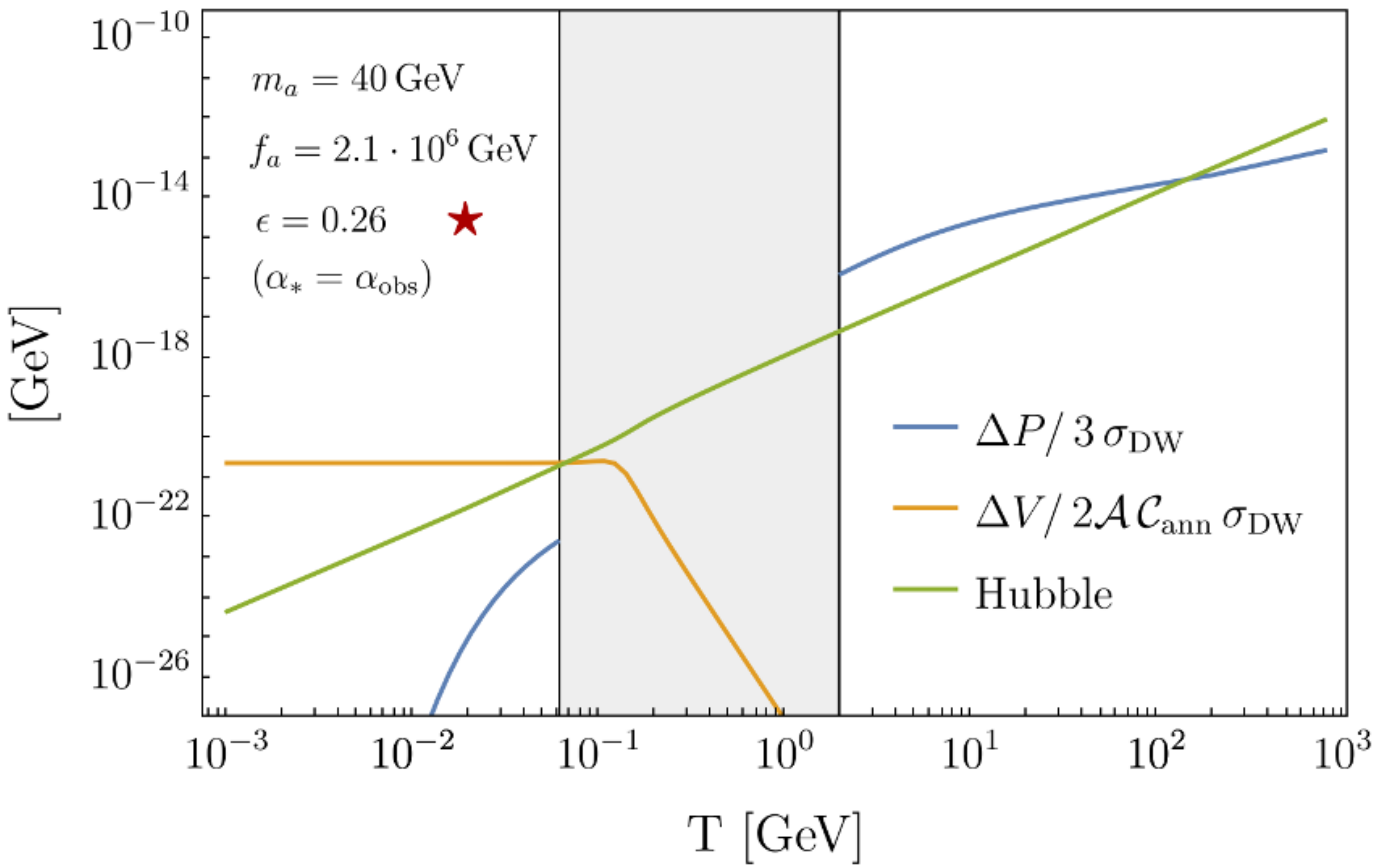
Friction domination

- Does this coupling with the QCD sector also induce friction from the ALP domain walls around the time of collapse?

  - Crude approximations:

    - Gluon scattering for $T > 2\,\mathrm{GeV}$

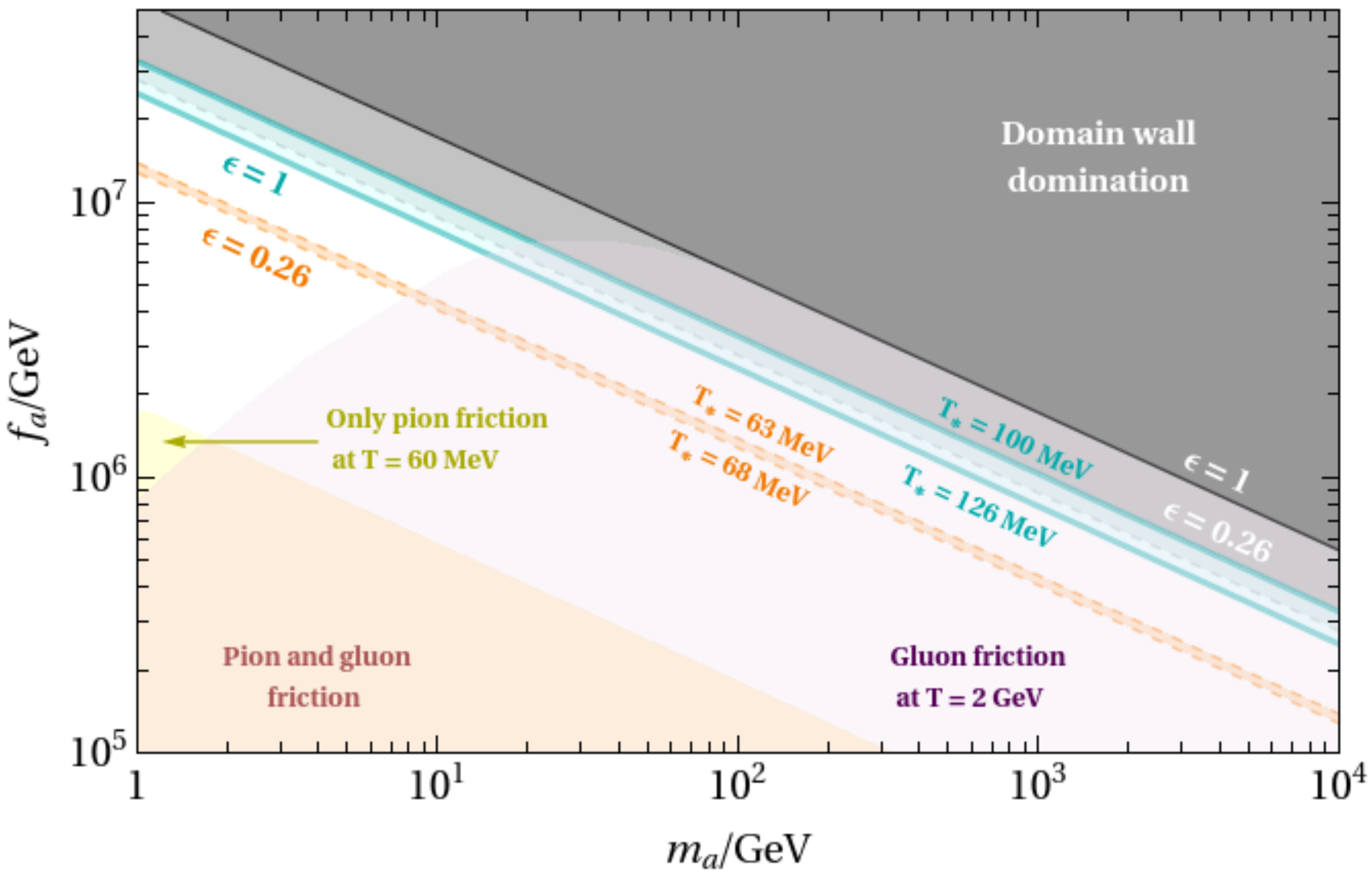
    - Pion scattering for $T < 60\,\mathrm{MeV}$



SB, Mariotti, Rase, Sevrin, [2302.06952], JCAP

Friction domination

- Summary plot for the NANOGrav 15yr parameter space of ALP domain walls:



Friction domination

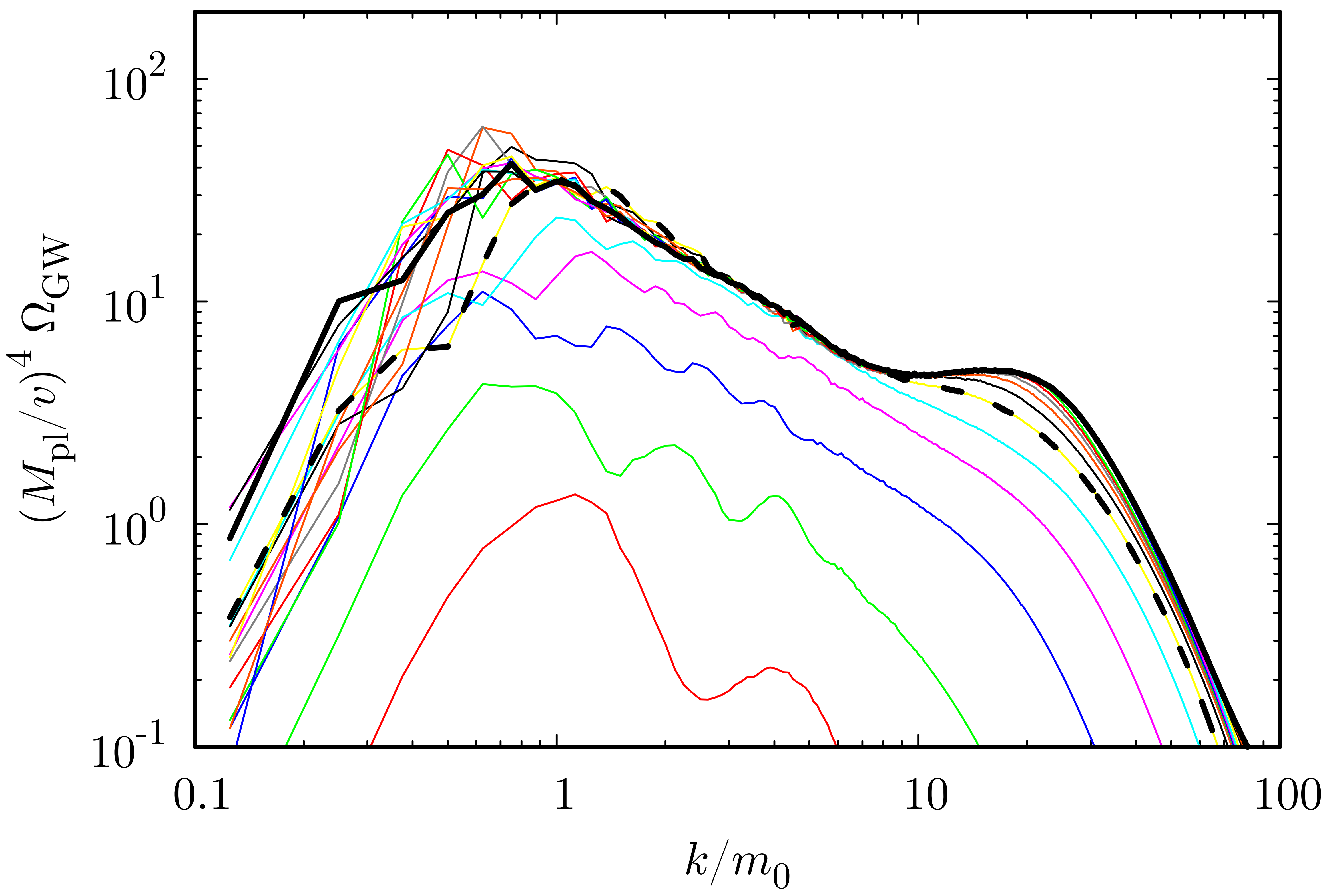
- Friction can be relevant also for the late dynamics of the domain wall network
- The corresponding implications for the GW emission have been studied within the velocity-one-scale model implying a suppressed amplitude, no actual numerical simulation so far
- When friction is relevant, possible new contribution to the GWs from the plasma?

GWs from the network collapse

- So far GW spectrum as given by the last moment of scaling prior to collapse
- Additional contribution from the actual phase of annihilation is expected
- This contribution can enhance the GW peak by 1-2 orders of magnitude

Kitajima, Lee, Murai, Takahashi, Yin, PLB [2306.17146]

Ferreira, Notari, Pujolàs, Rompineve, JCAP [2401.14331]



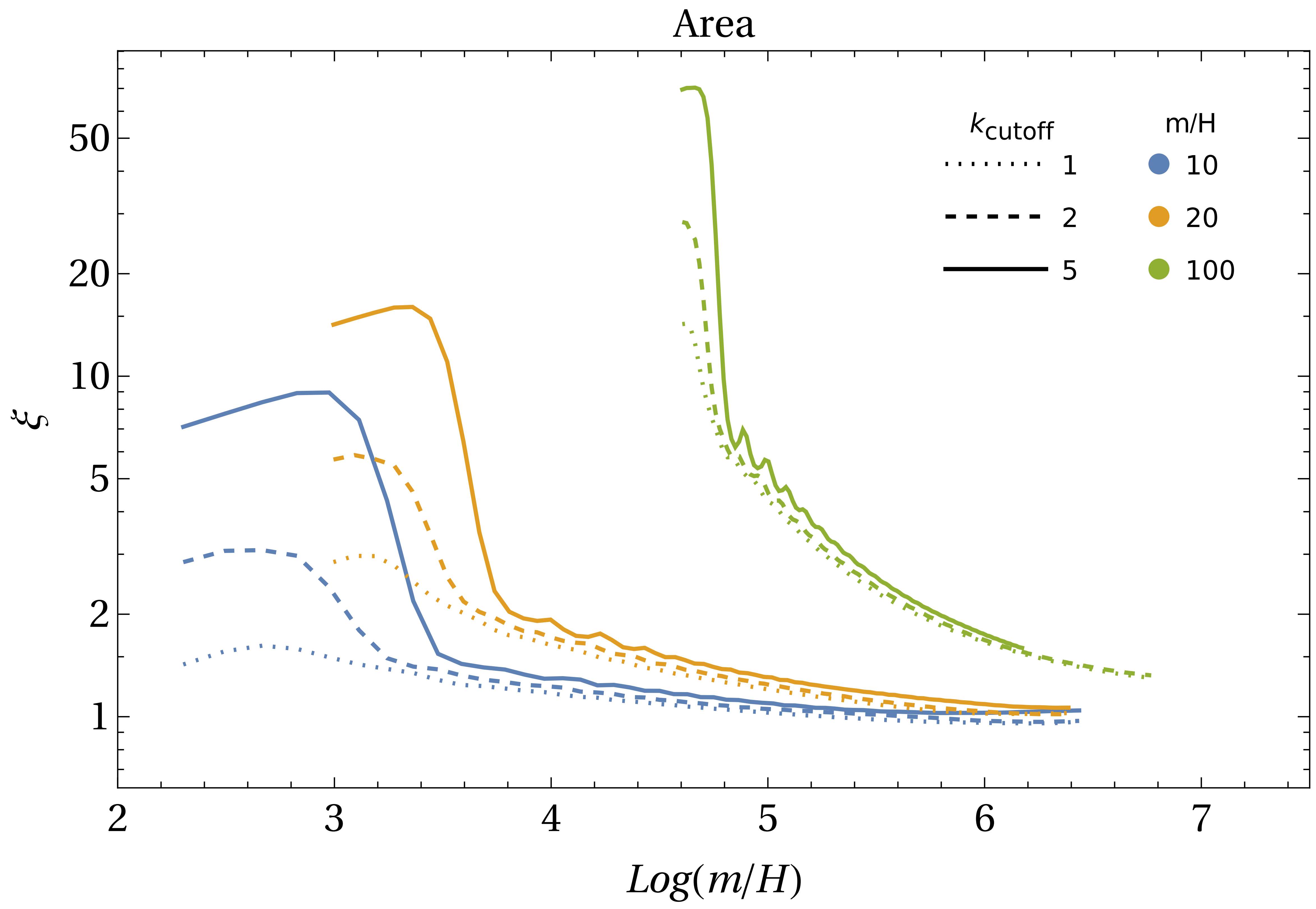
Scaling regime

- Simulations of domain wall networks support the scaling regime, but no systematic study of initial conditions (many simulations start with less than one wall per Hubble volume)

  - Systematic study in terms of initial fluctuations and $m_s/H(T_i)$

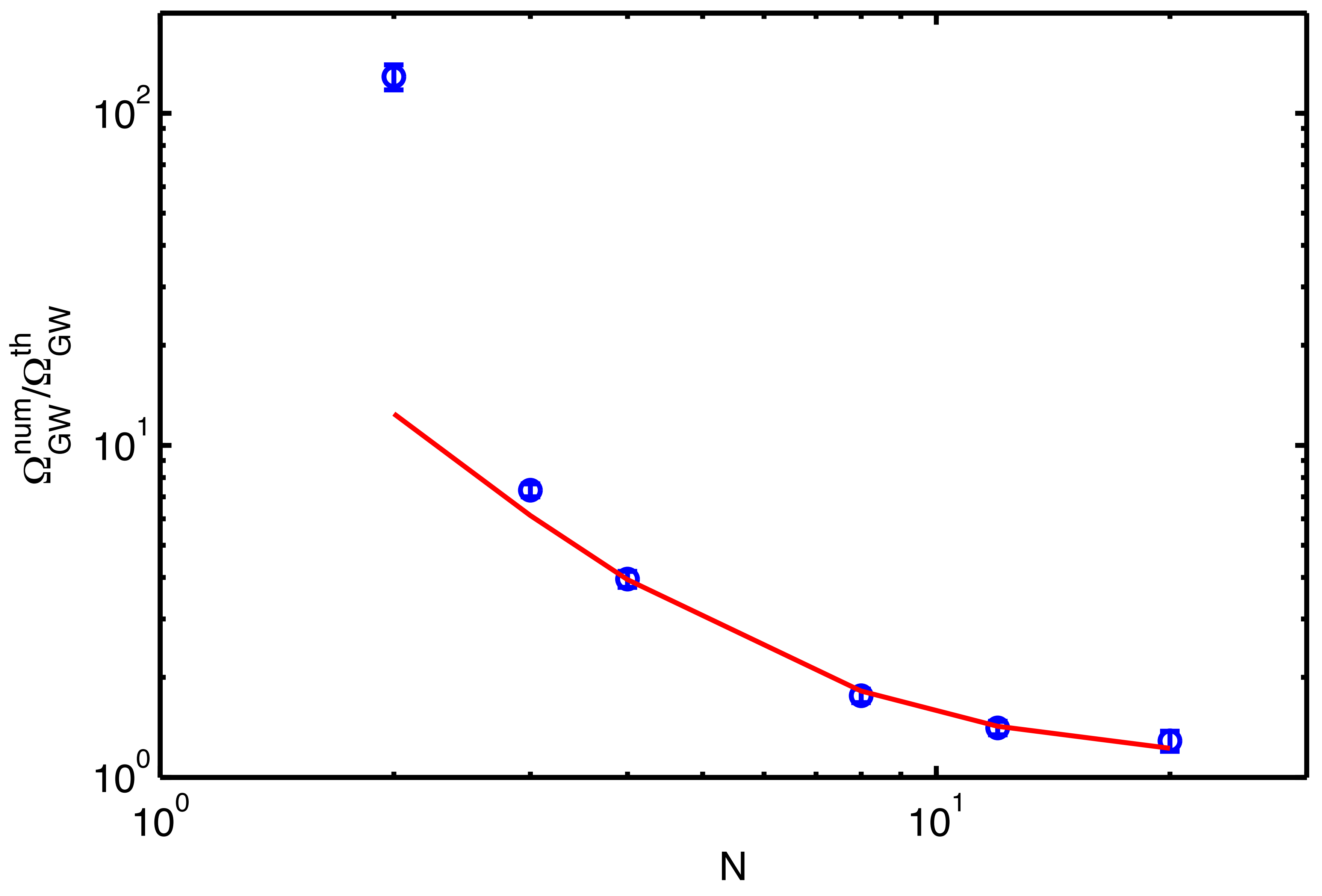
  - Infer the time evolution of ξ during the approach to scaling

Fig. From **SB**, Mariotti, Rase, Vanvlasselaer, in prep.

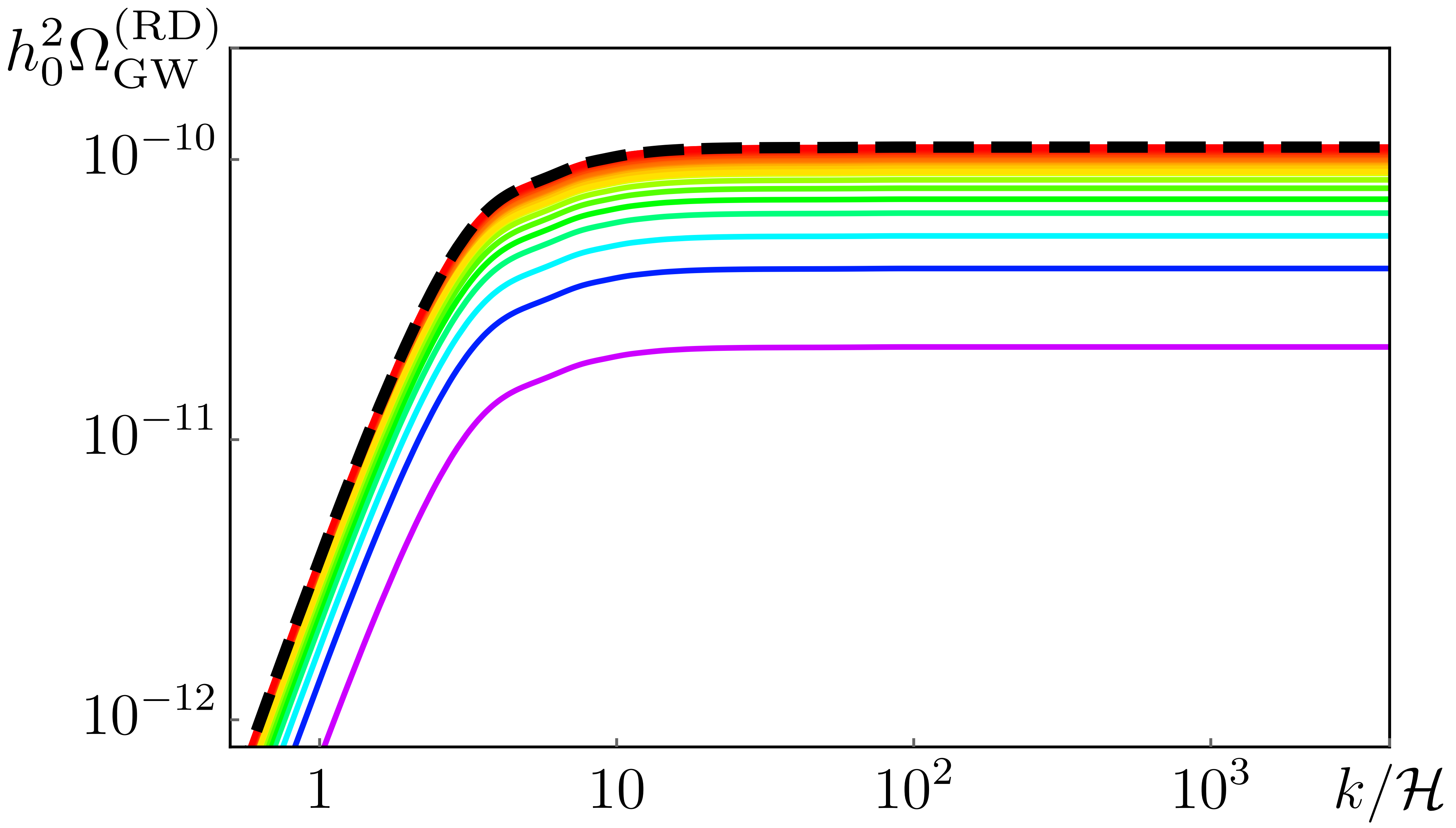


Scaling properties of the UETC

- A scaling network is characterized by a single scale set by the horizon size
- This argument has been used to prove the flat spectrum from scaling defects during radiation domination, and compared to explicit results from models with $O(N) \to O(N-1)$



Figueroa, Hindmarsh, Urrestilla, PRL [1212.5458]



Figueroa, Hindmarsh, Lizarraga, Urrestilla, PRD [2007.03337]

Scaling properties of the UETC

- The argument is based on dimensional analysis on the UETC of the stress-energy tensor:

$$\langle \Pi_{ij}^{\mathrm{TT}}(\mathbf{k},t)\Pi_{ij}^{\mathrm{TT}*}(\mathbf{k}',t')\rangle = (2\pi)^3\Pi^2(k,t,t')\delta_D(\mathbf{k}-\mathbf{k}')$$

- If the source is scaling Π^2 can only depend on $x_i = \kappa\, t_i$ up to trivial factors,

$$\Pi^2(k,t_1,t_2) = \frac{4v^4}{\sqrt{t_1 t_2}}\, C^T(x_1,x_2)$$

- The GW spectrum then reads:

$$\frac{d\rho_{\mathrm{GW}}}{d\log k}(x,t) = \Omega_{\mathrm{rad}}\frac{4}{\pi}\frac{M_P^2 H_0^2}{a(t)^4}\left(\frac{v}{M_P}\right)^4 \boxed{F^T(x)}$$ **= const.**

Scaling properties of the UETC

- Apply the same procedure to domain walls and study the scaling property of the UETC
- A similar (naive) ansatz for domain walls does not work:

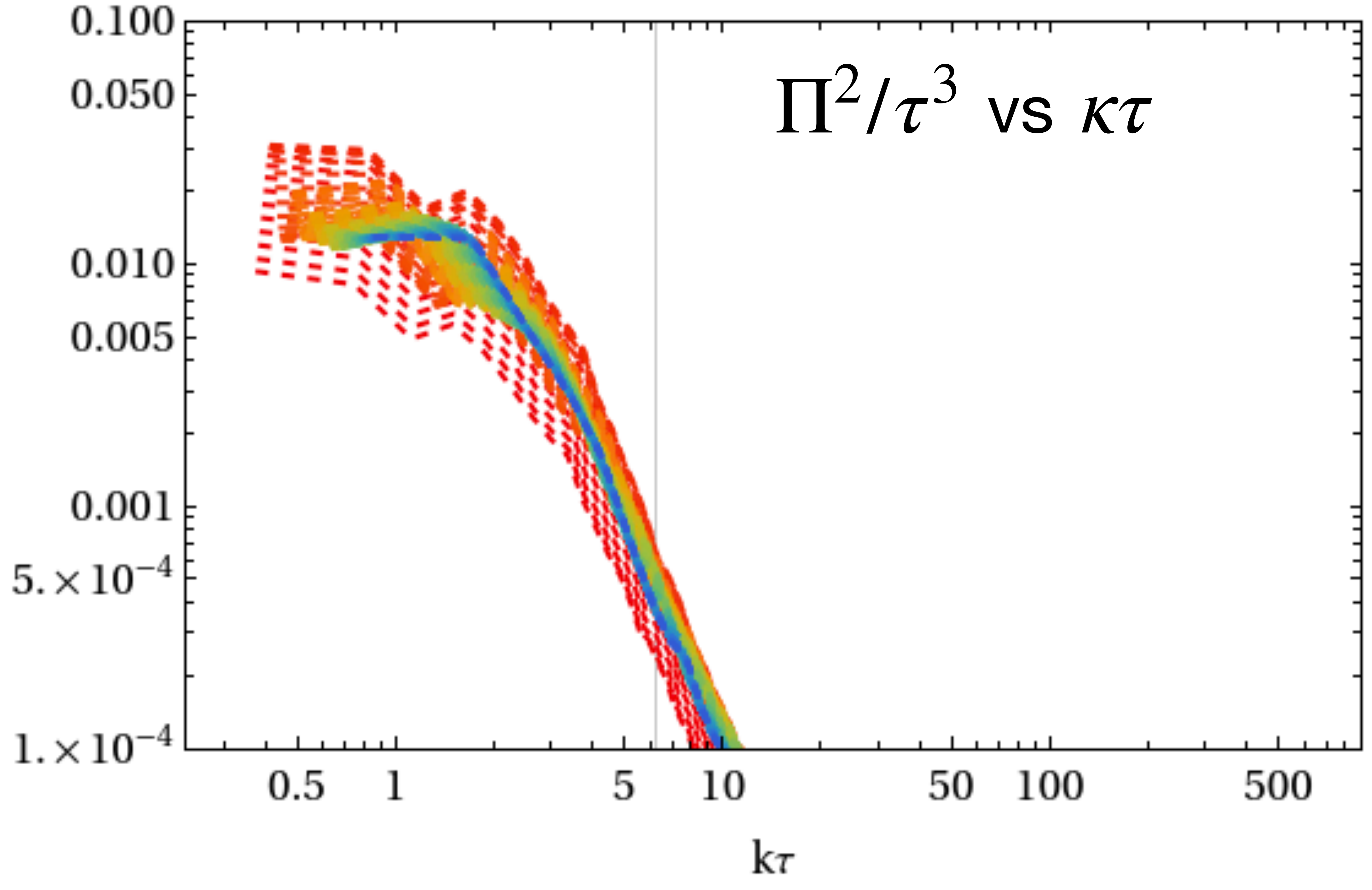
$$\Pi^2(k,\tau_1,\tau_2) = \sigma^2(\tau_1\tau_2)^{1/2}C(x_1,x_2), \quad x = k\tau$$

  - Need to include powers of the scale factor in the ansatz to account for the scaling in the DW network energy density

See also [2406.17053]

Scaling properties of the UETC

- Extract the scaling properties of the (equal time) Π^2 from the simulation, possibly determine the k^{-1} spectrum



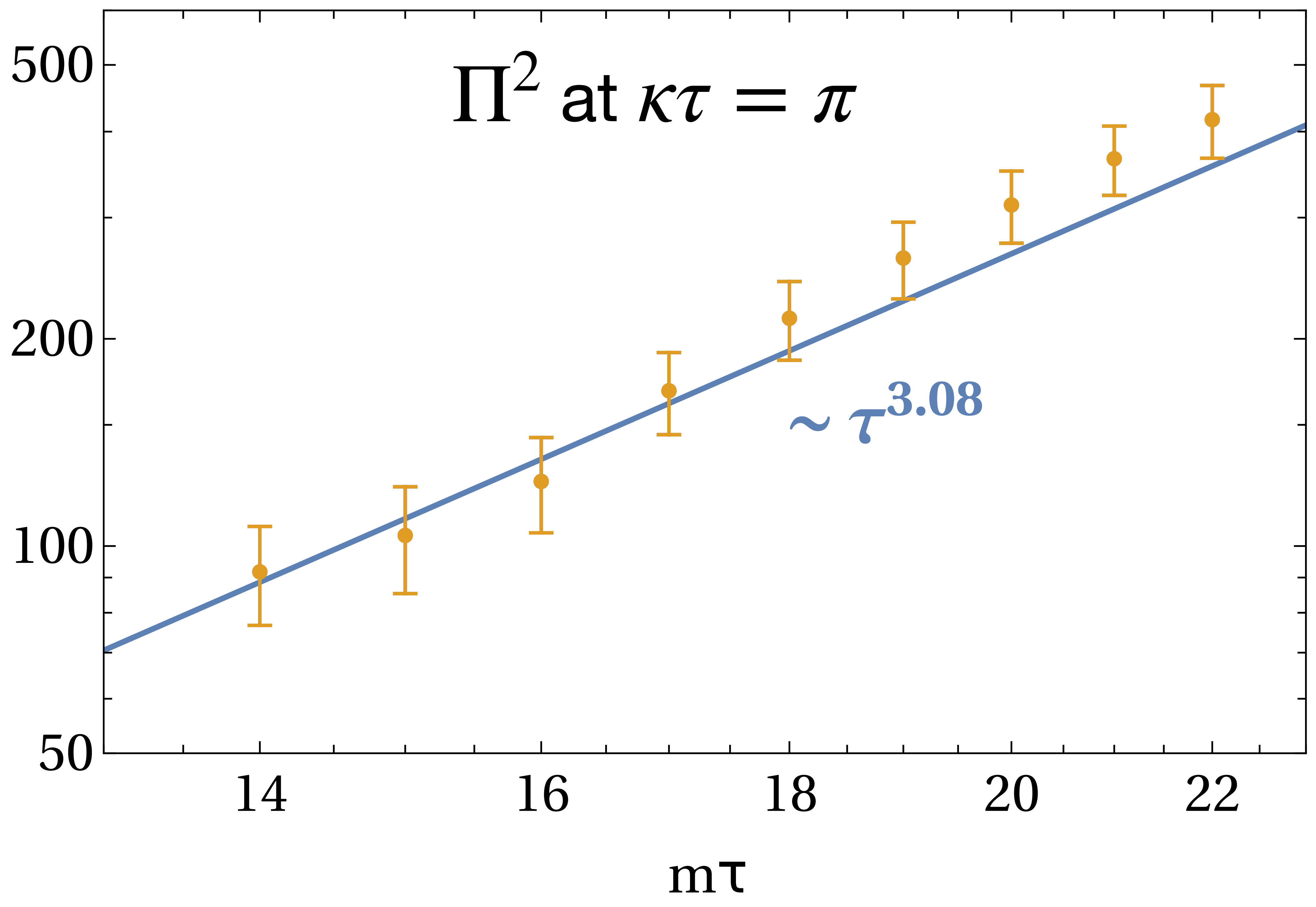


Fig. From **SB**, Mariotti, Rase, Vanvlasselaer, in prep.

Summary

- Domain walls can be themselves a powerful source of gravitational waves, and can also act as seeds for catalyzed bubble nucleation
- Friction with the plasma can be relevant at late times. This regime has not been studied with simulations, no clear indication for the GW spectrum so far
- Still room to improve the understanding of the scaling regime: systematic study of the approach to scaling and semi-analytical studies of the UETC.

Thank you!