Cold baryogenesis revisited

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Based on:

Bhusal, **SB**, Cataldi, Chatrchyan, Gorghetto, Servant, to appear

Nordita, 06.08.2025

The SM

- It allows for non-trivial field configurations (which play a role in $U(1)_B$ violation)

$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) - \frac{1}{2}\mathrm{Tr}(D^\mu\Phi)^\dagger D_\mu\Phi - \frac{\lambda}{4}\left[\mathrm{Tr}(\Phi^\dagger\Phi) - v^2\right]^2$$

SU(2) only for simplicity

$$\Phi(\mathbf{x},t) = \begin{pmatrix} \varphi_2^* & \varphi_1 \\ -\varphi_1^* & \varphi_2 \end{pmatrix}$$

Higgs doublet

$$\Phi(\mathbf{x},t) = U(\mathbf{x},t)\sigma(\mathbf{x},t), \quad \sigma^2 = \mathrm{Tr}\left(\Phi^\dagger\Phi\right)$$

$U \in \mathrm{SU}(2)$

In vacuum: $\sigma^2 = v^2 =$ const.

The SM

- Higgs winding number:

$$N_H(t) = w[U] = \frac{1}{24\pi^2} \int d^3x\, \epsilon^{ijk} \mathrm{Tr}[U^\dagger \partial_i U U^\dagger \partial_j U U^\dagger \partial_k U]$$

$U(x,t)$ defined iff $\sigma \neq 0$

$N_H(t) \in \mathbb{N}$ with $U \to \mathbf{1}_{2\times 2}$ at $r = \infty$

- On the vacuum manifold $\sigma^2 = v^2$ the topological charge is conserved
- $N_H(t)$ can however jump by an integer when $\sigma^2 = 0$ somewhere

See e.g. Turok, Zadrozny, NPB 1991

The SM

- Chern-Simons number:

$$N_{CS}(t) = \frac{g^2}{32\pi^2}\int d^3x\,\epsilon^{ijk}\mathrm{Tr}\left(A_i\partial_j A_k + \frac{2}{3}igA_iA_jA_k\right)$$

$N_{\mathrm{CS}}(t) \notin \mathbb{N}$ away from the vacuum

- $\Delta N_{\mathrm{CS}} = N_{\mathrm{CS}}(t) - N_{\mathrm{CS}}(0)$ gauge invariant, related to non-conservation of $U(1)_B$:

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = N_f \frac{g_W^2}{32\pi^2} W_{\mu\nu}\tilde{W}^{\mu\nu}, \qquad \Delta B = \Delta L = N_f\,\Delta N_{\mathrm{CS}}$$

See e.g. Turok, Zadrozny, NPB 1991

The SM

- $\delta N = N_H(t) - N_{CS}(t)$ is gauge invariant, in terms of Goldstone-Wilczek current:

$$\delta N = \frac{1}{24\pi^2}\int d^3x\,\epsilon^{ijk}\,\mathrm{Tr}\left[U^\dagger D_i U\,U^\dagger D_j U\,U^\dagger D_k U + \frac{3}{2} ig\,U^\dagger F_{ij} D_k U\right]$$

- In the vacuum, $D_\mu\Phi = 0$ and one trivially has $\delta N = 0$

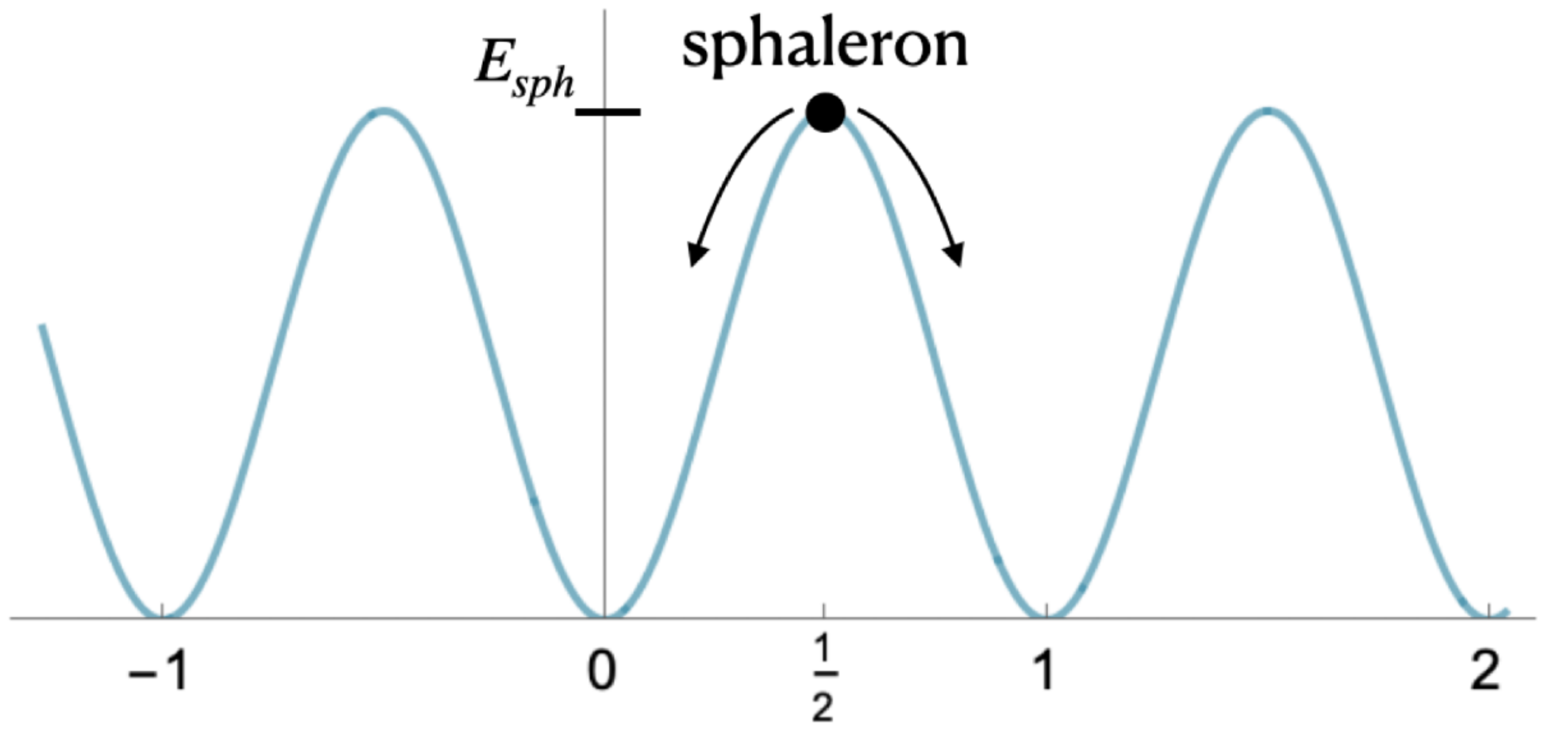
Example: pure gauge $\quad \Phi = \frac{v}{\sqrt{2}}U, \quad A_\mu = \frac{1}{ig}U^\dagger \partial_\mu U$

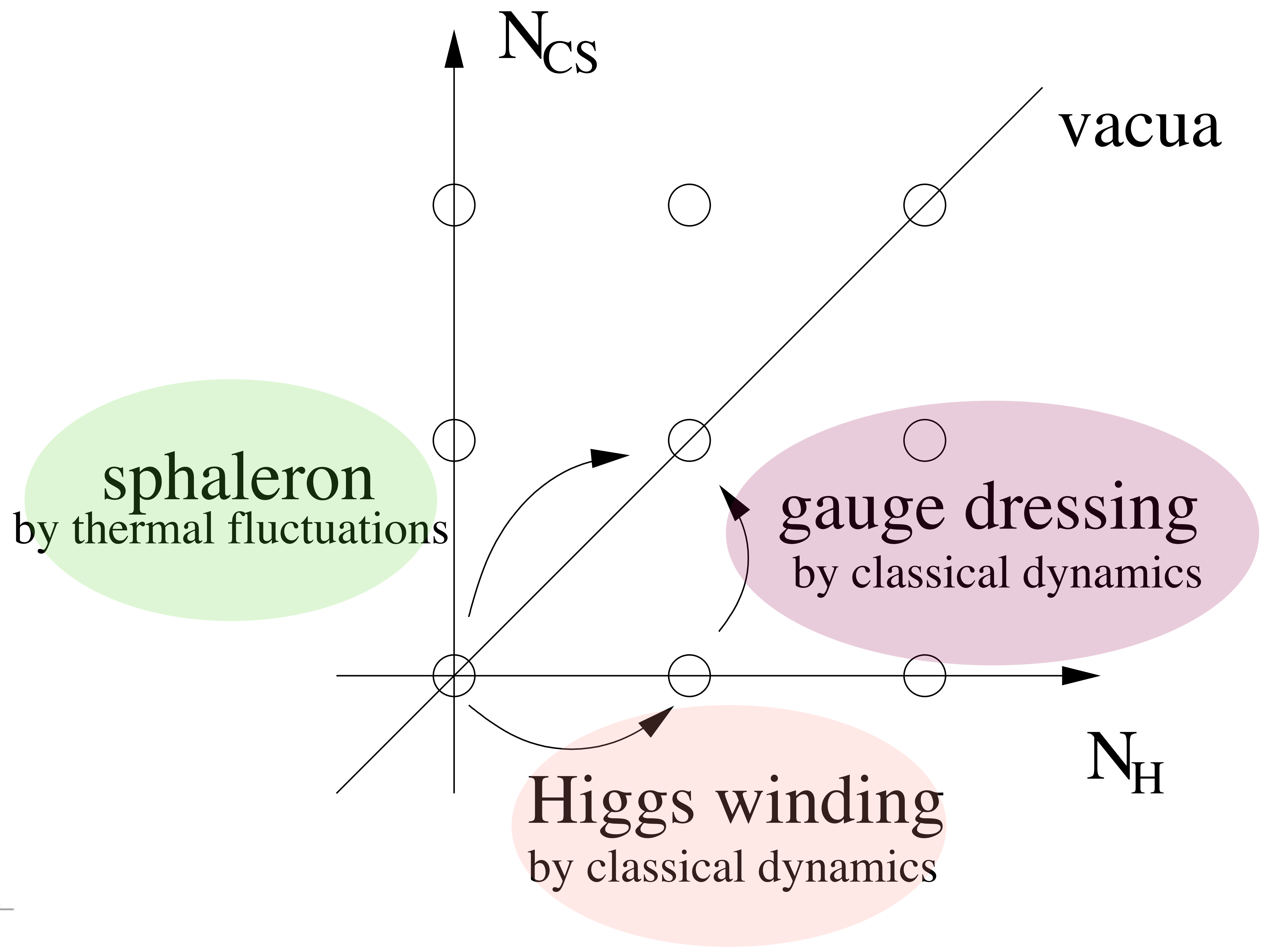
See e.g. Turok, Zadrozny, NPB 1991

The SM

Sphaleron: static, spherically symmetric, unstable, gauge-Higgs configuration:

$$E_{\rm sph} = \frac{m_W}{\alpha_w} B(\lambda/g^2)$$

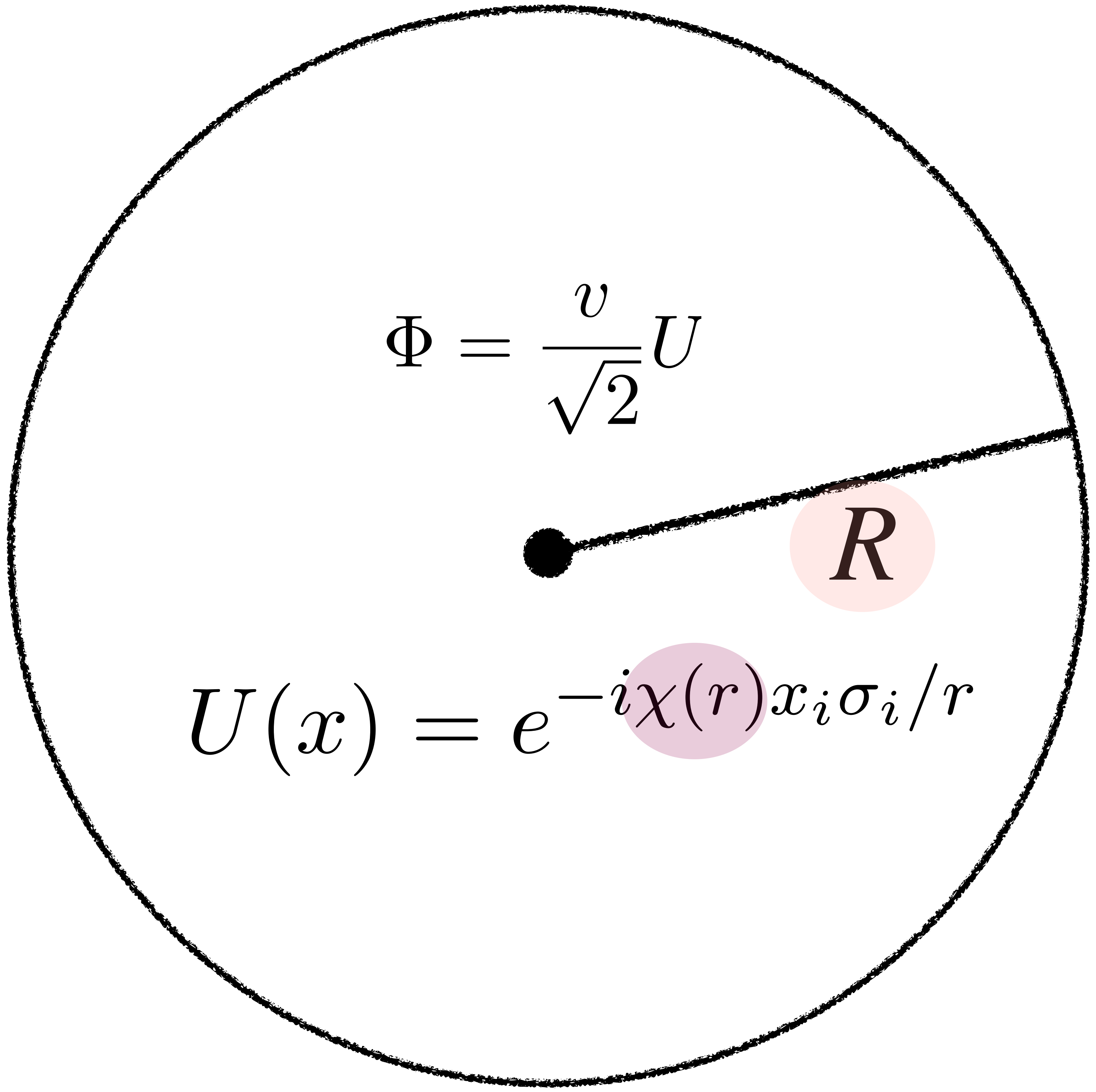




Cartoon from Konstandin, Servant [1104.4793] JCAP

Texture dynamics

- Collapse of a spherical texture with $N_H = 1$ and no gauge fields ($g = 0$)



Initial conditions ($t = 0$)

Field always within the vacuum manifold, but non-zero energy due to scalar field gradients: $E_T \sim c \cdot 4\pi v^2 R$

$$\chi(r) = \pi \left[1 - \tan^{-1}(r/R)\right]$$

$$N_H = \frac{1}{\pi}\left[\chi(r=0) - \chi(r=\infty)\right] = 1$$

Texture dynamics

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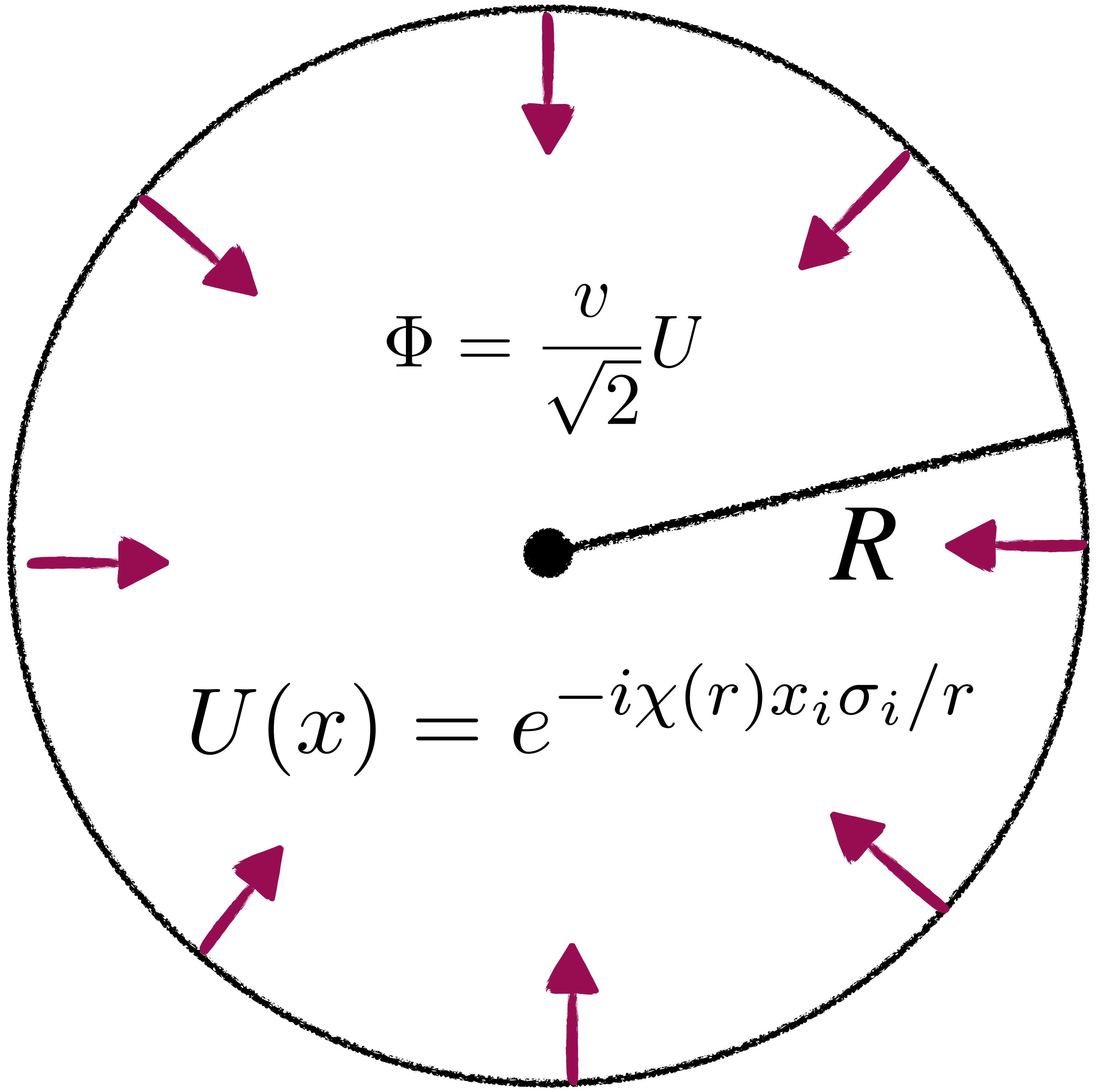

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Field always within the vacuum manifold, but non-zero energy due to scalar field gradients: $E_T \sim c \cdot 4\pi v^2 R$

General param. for subsequent evolution:

$$\Phi(r,t) = \left(\mu(r,t) + \frac{x_i \sigma_i}{r} \nu(r,t) \right) \Phi_0, \qquad \mu^2 + \nu^2 \neq 1$$

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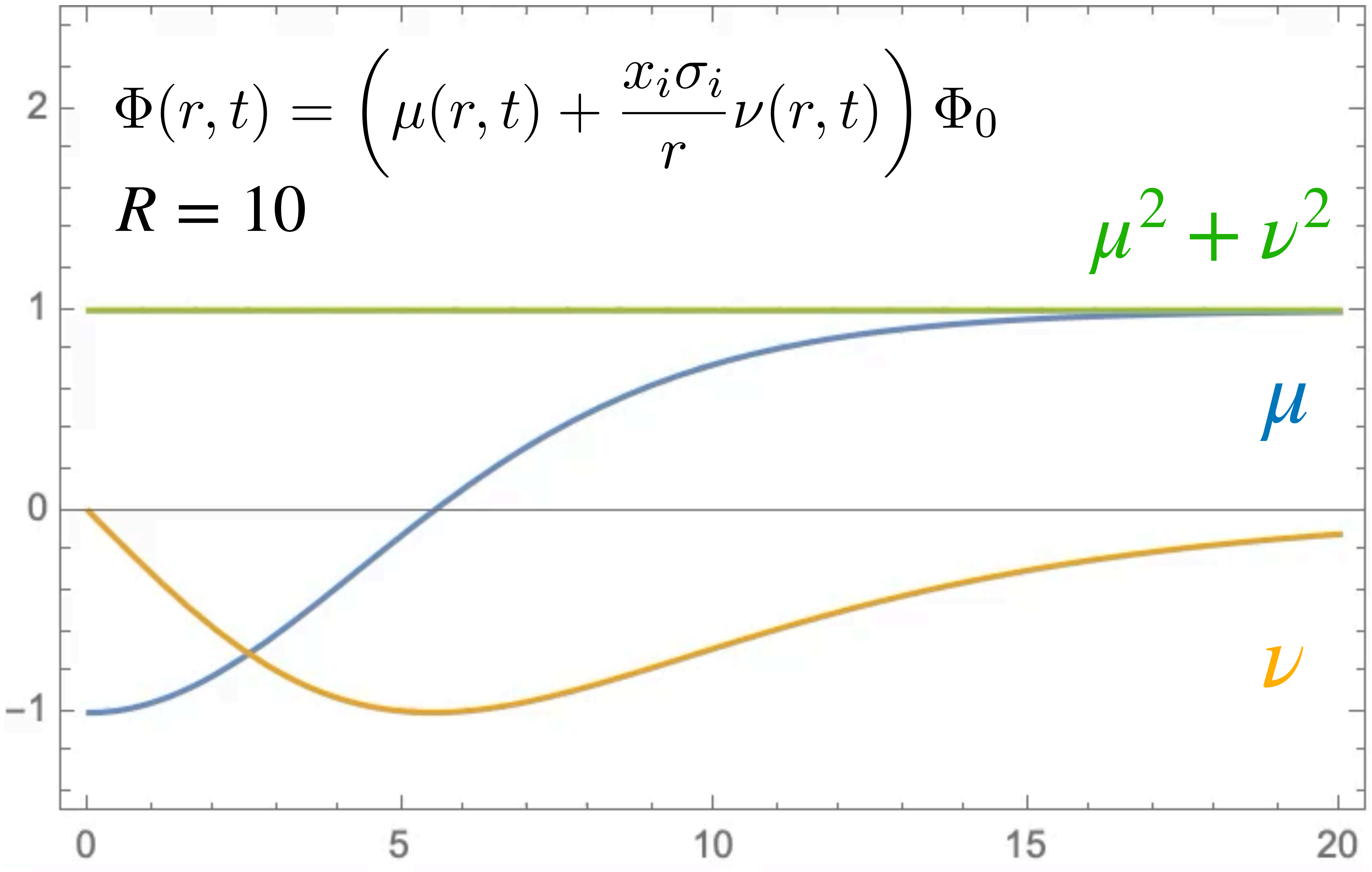
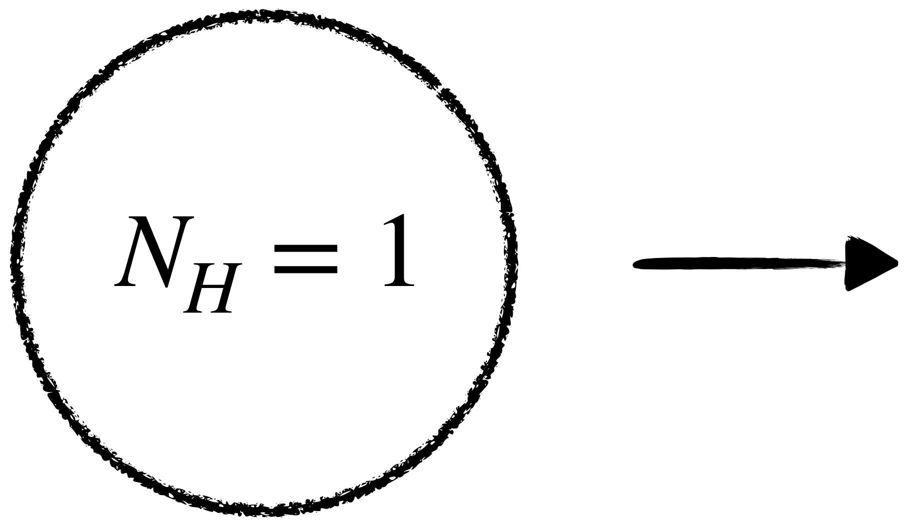


Higgs texture collapses and **unwinds** by crossing the false vacuum $\Phi = 0$



$N_H = 0$

+ Higgs and Goldstone radiation

Texture dynamics

- Collapse of a spherical texture with $\delta N = 1$ **and gauge fields** $(g \neq 0)$

$\delta N = 1$ → $\delta N = 0$
+ Higgs and massive gauge radiation

Gauge fields turn on and cancel $D_\mu = \partial_\mu - igA_\mu$

$$R_c \sim m_W^{-1}$$

$\mathrm{I}: \; R < R_c$

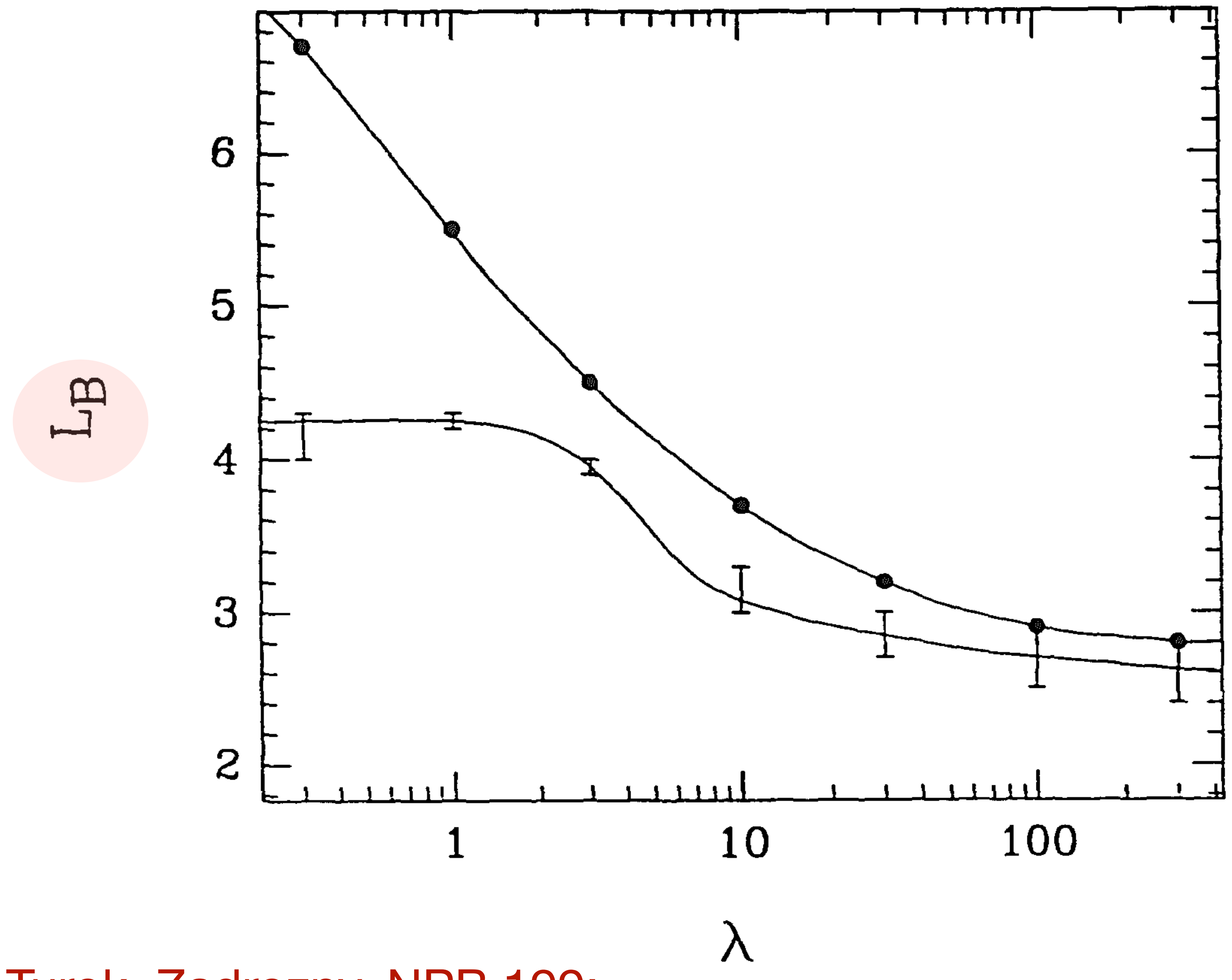
“Unwinding” :
$\Delta N_H = -1, \quad \Delta N_{\mathrm{CS}} = 0$

$\mathrm{II}: \; R > R_c$

“Dressing” :
$\Delta N_H = 0, \quad \Delta N_{\mathrm{CS}} = -1$

Texture dynamics

- Determination of the critical size (bifurcation scale) and impact of CP violation



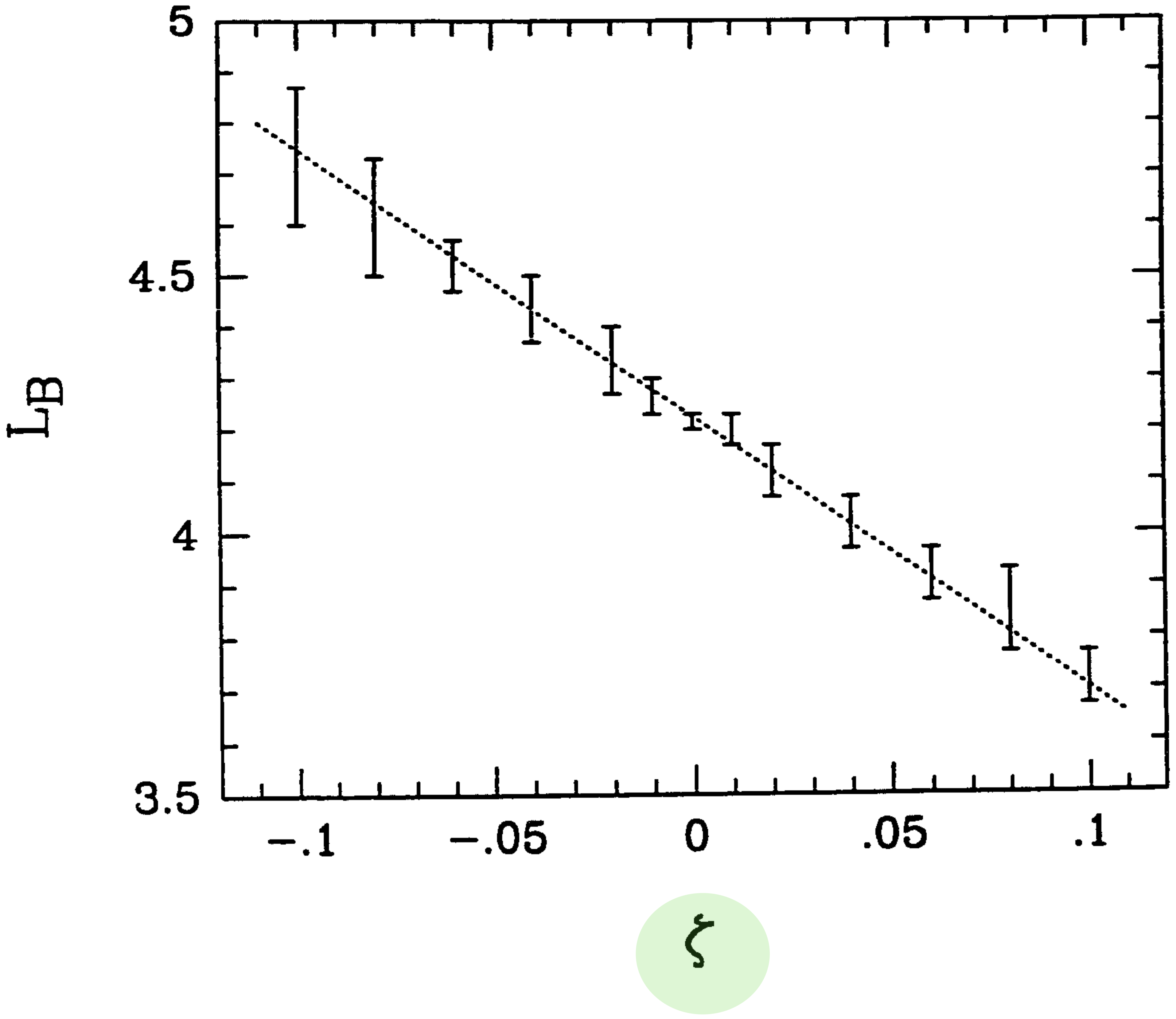


Fig. from Turok, Zadrozny, NPB 199;
See also Lue, Rajagopal, Trodden, PRD 1997 “Life is complicated”

Texture dynamics

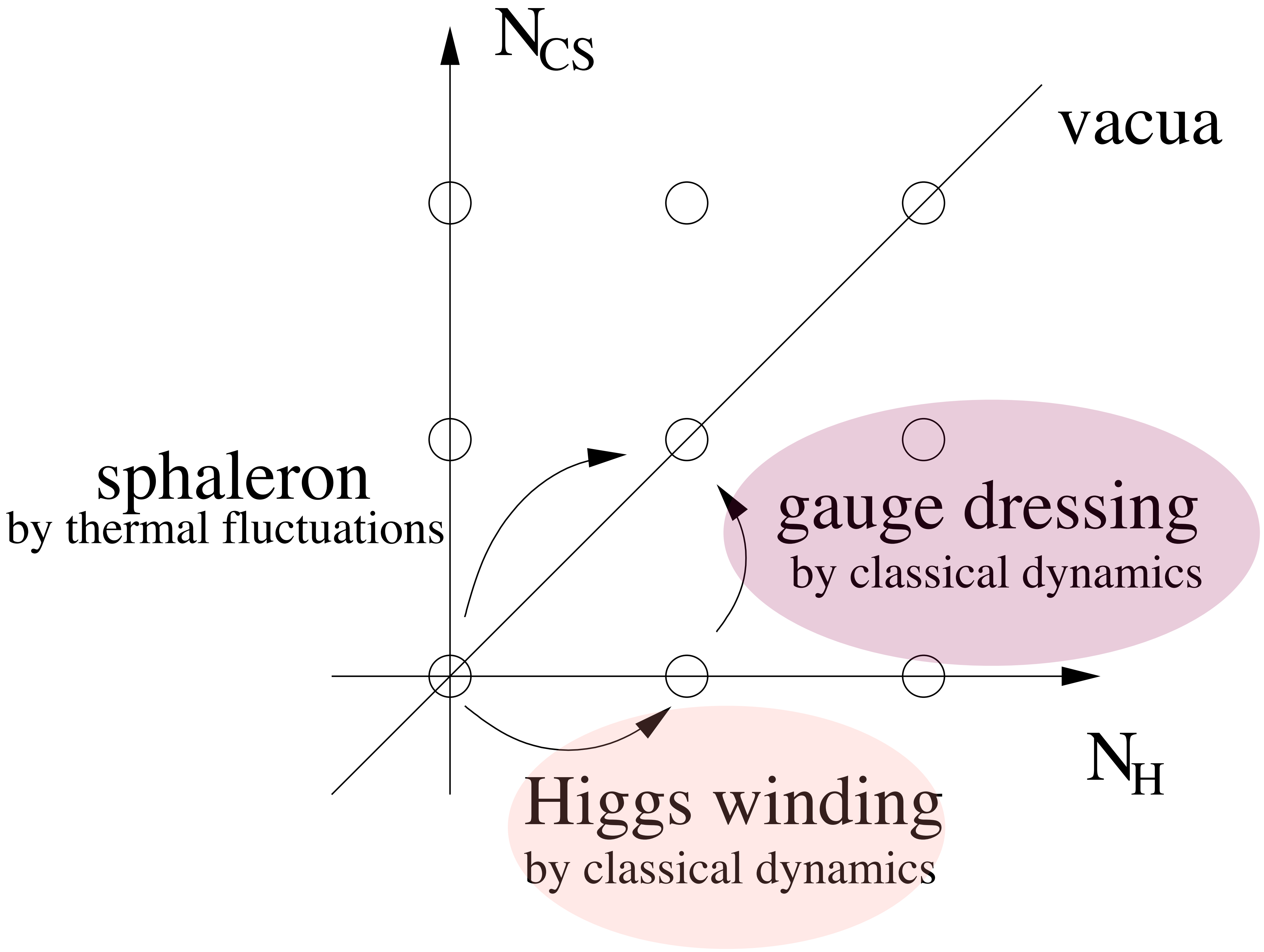
- In addition to thermal sphalerons, there exists another mechanism (dressing of SM textures) that can operate even at $T = 0$

- Which dynamics in the early Universe can **generate Higgs windings** in the first place?

Spinodal (tachyonic) electroweak phase transition

↓

“Cold baryogenesis”



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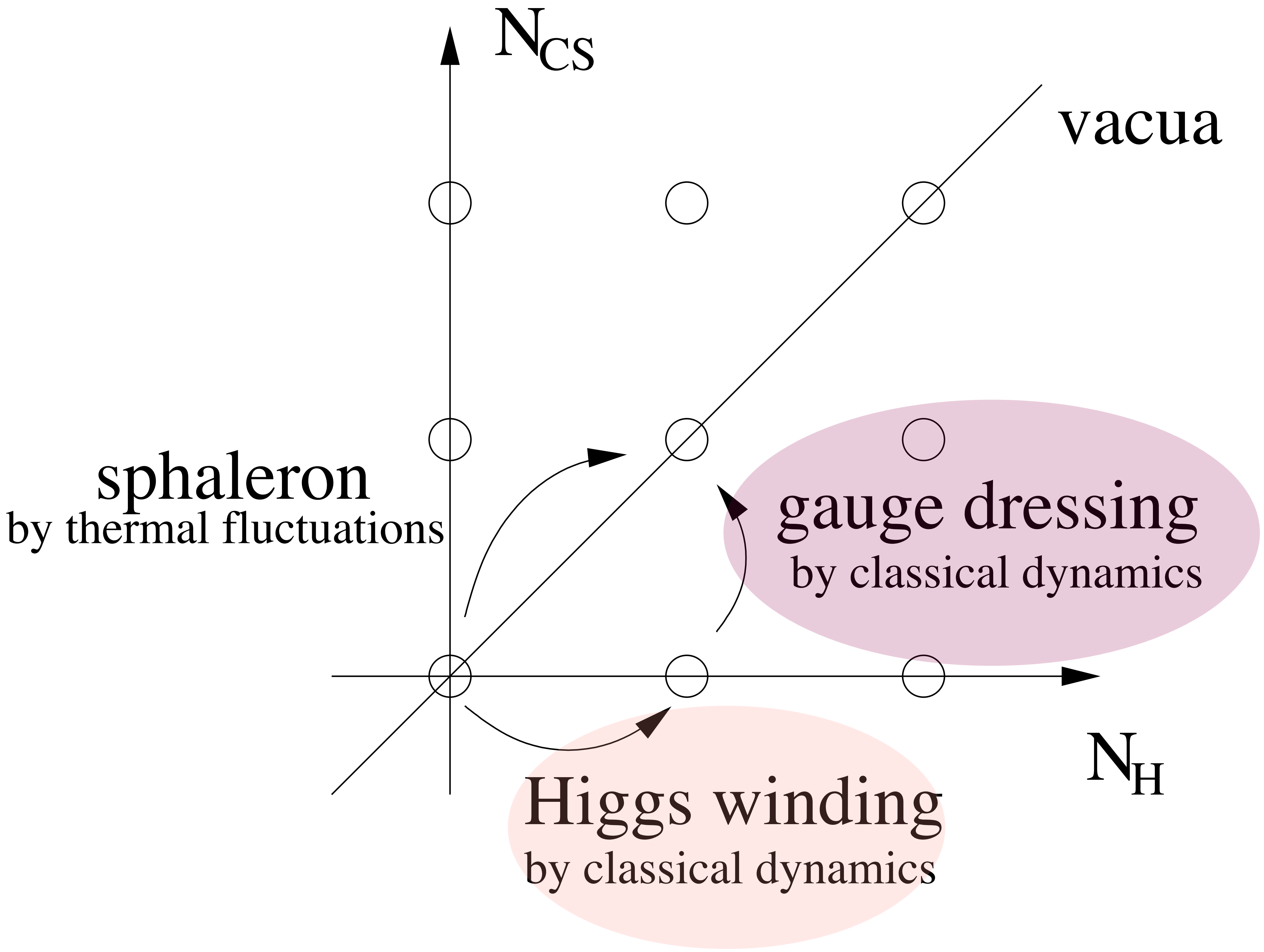

Spinodal (tachyonic) electroweak phase transition

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Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, PRD 1990

Smit, Tranberg [hep-ph/0211243] JHEP 2002

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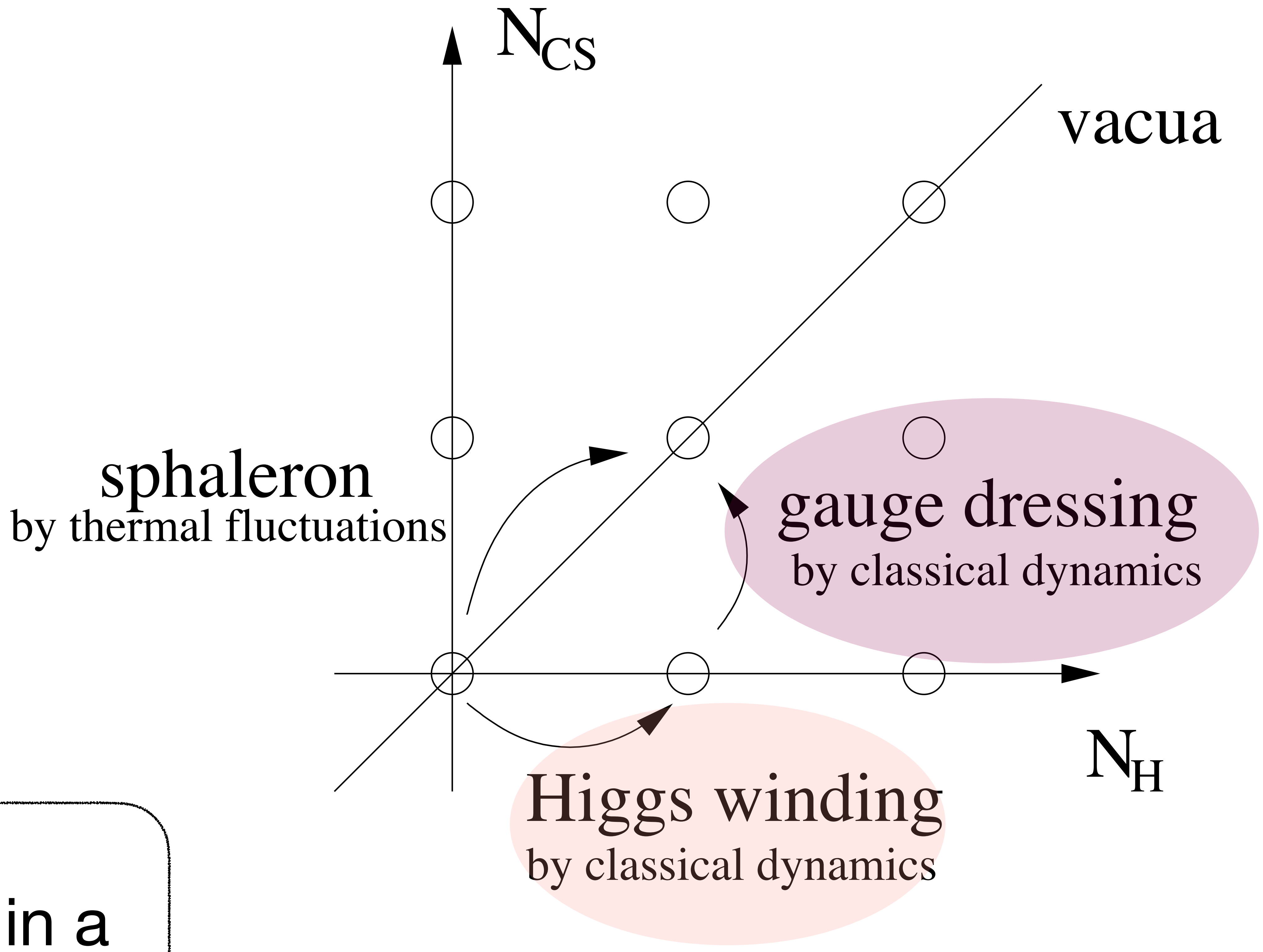

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Bubble collisions in a first order electroweak phase transition

See also Konstandin, Servant [1104.4793] JCAP; Servant [1407.0030] PRL

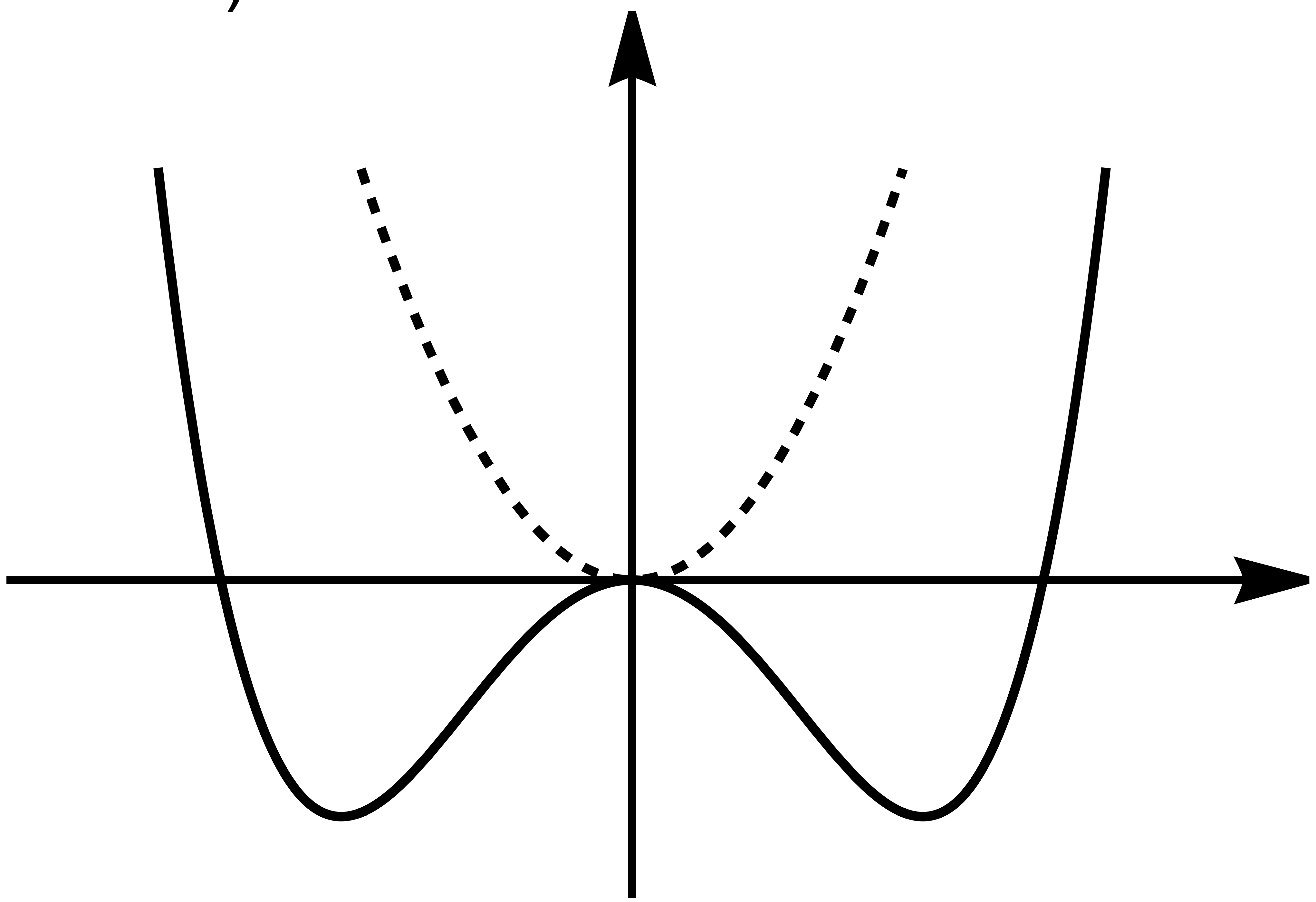
Smit, Tranberg [hep-ph/0211243] JHEP 2002

Tachyonic instability

- Higgs mass changes from positive (stable minimum) to negative (spinodal instability)

$$\partial_t^2 \phi - \nabla^2 \phi + \mu_{\rm eff}^2(t)\phi = 0$$

$$\mu_{\rm eff}^2(t) = -\mu^2 + \kappa\, \sigma^2(t)$$



- IR modes experience exponential growth until back reaction: inhomogeneous field

Tachyonic instability

- Higgs IR modes reach local thermal equilibrium at high temperature:

$$n_k = \frac{1}{\exp(\omega_k/T) - 1} \approx \frac{T_{\rm eff}}{\omega_k} \gg 1$$

- Full thermalization takes much longer: out of equilibrium dynamics

- To avoid wash out:

$$T_{\rm RH} < T_{\rm sph\, f.o.}$$

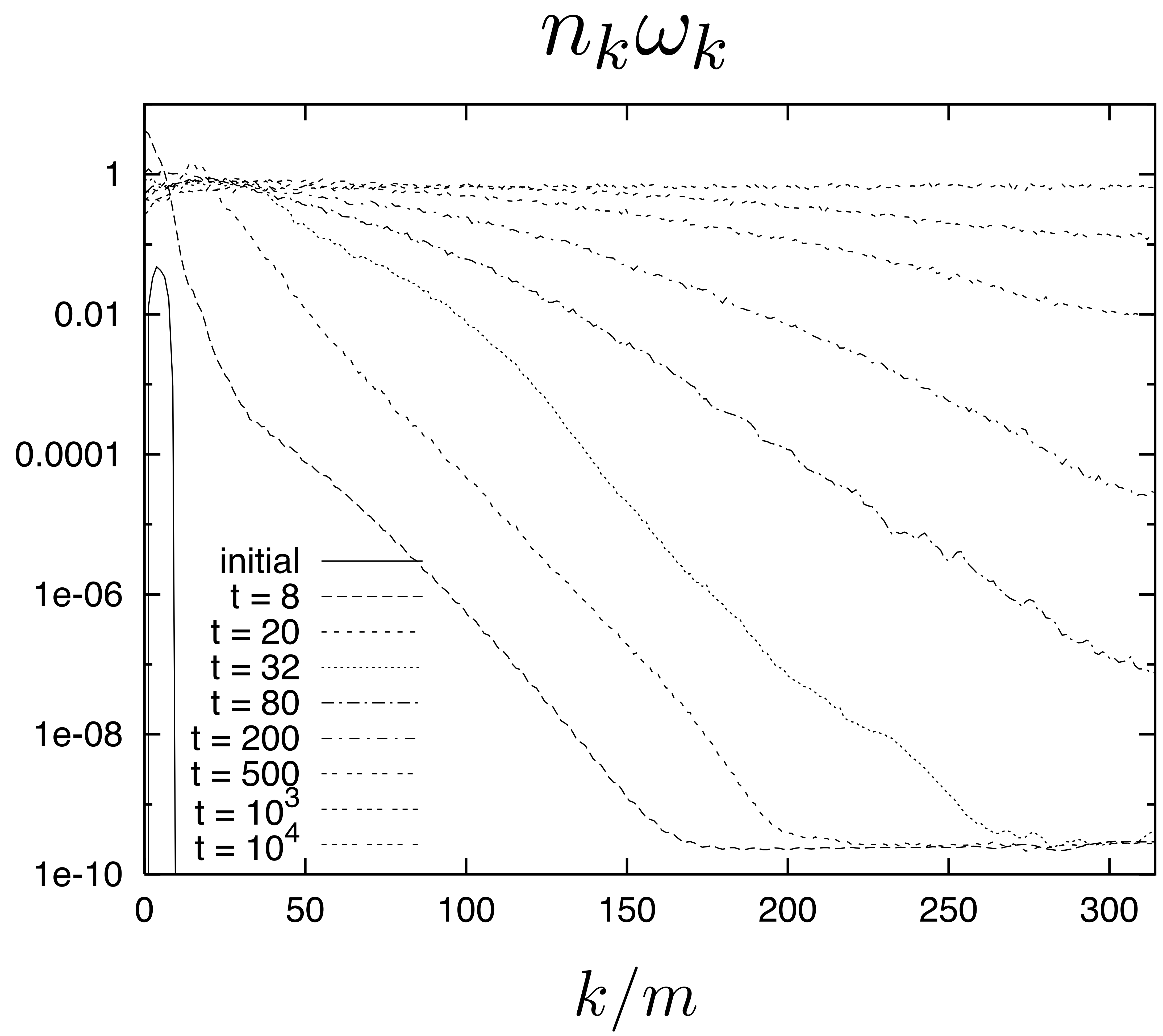
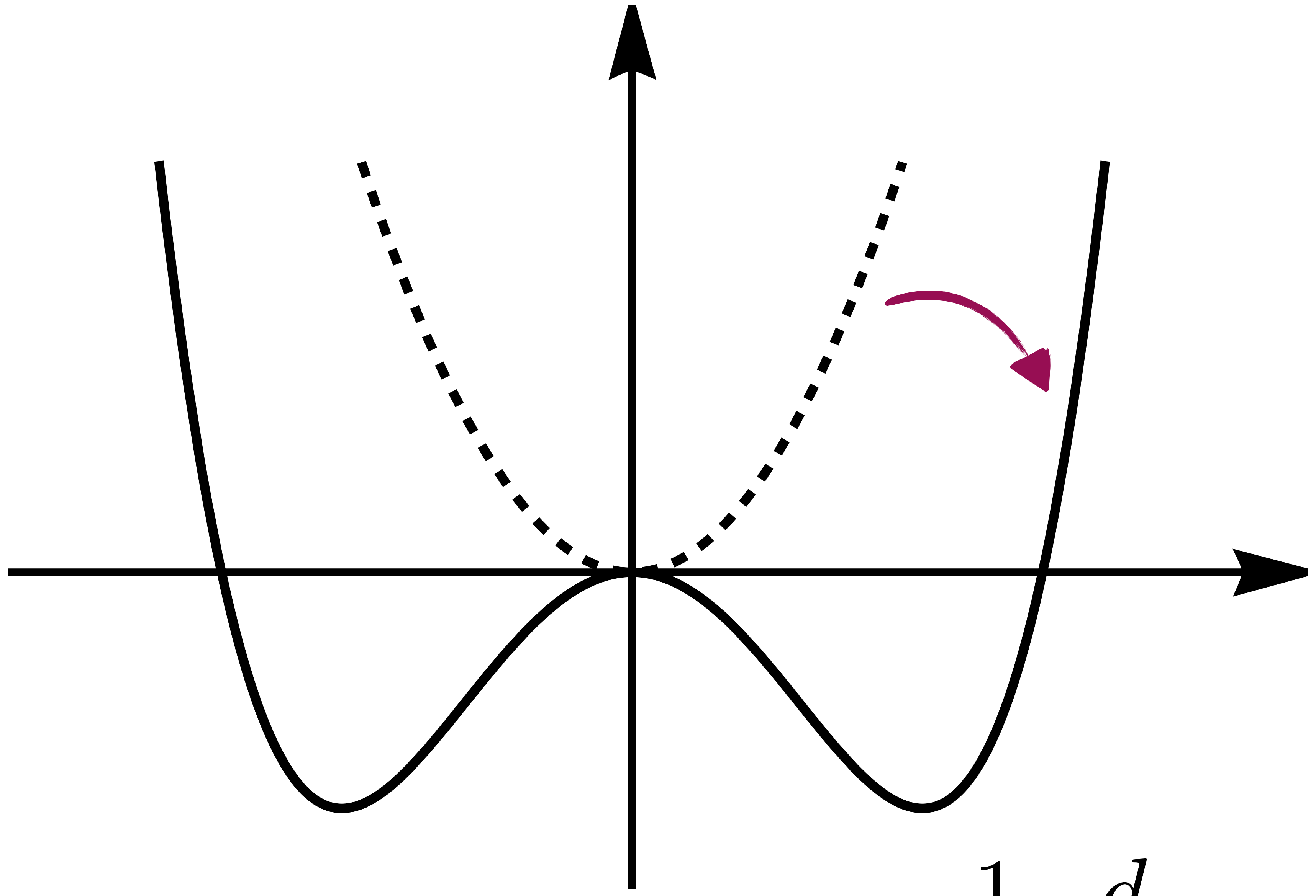


Fig. from Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, PRD 1990

Tachyonic instability

- Formation of Higgs and CS windings depending on the “quench speed”



$$v_q = \frac{1}{m_h^3}\frac{d}{dt}\mu_{\rm eff}^2(t)\Big|_{t=t_Q}$$

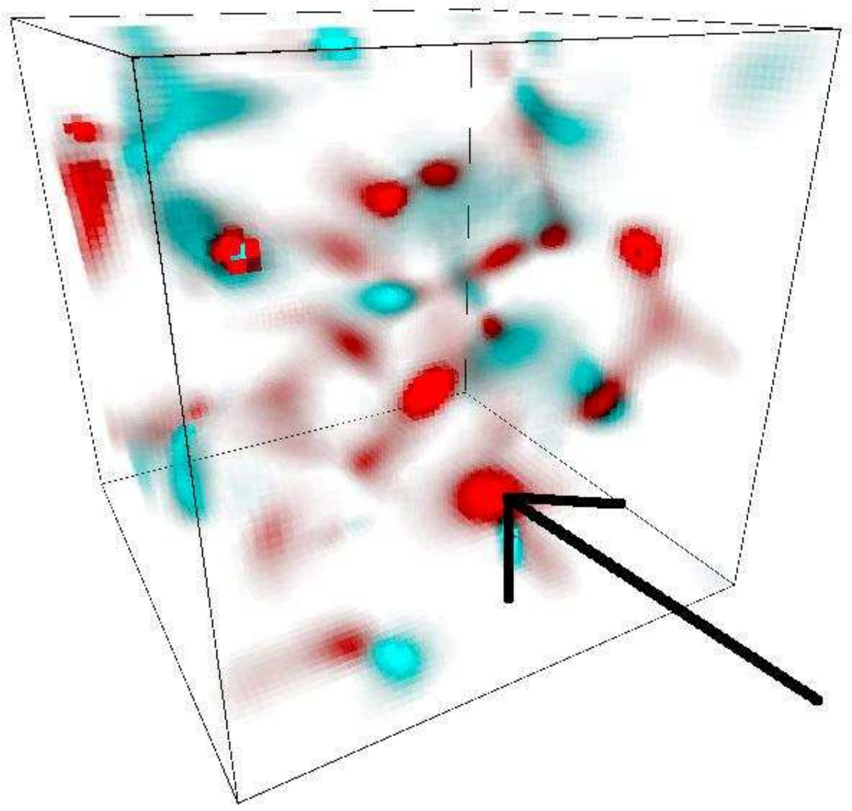
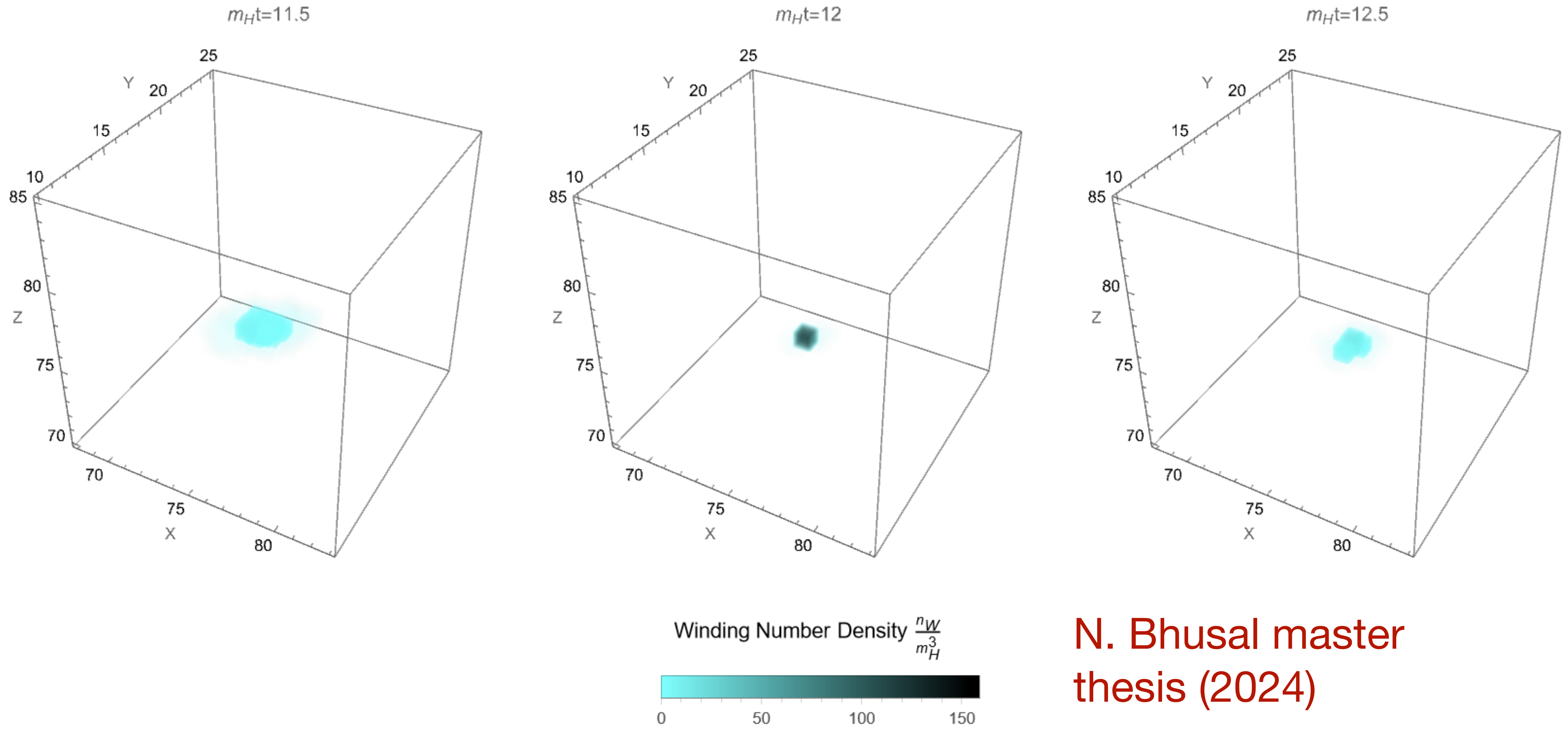


Fig. from Van der Meulen, Sexty, Smit, Tranberg [hep-ph/0511080], JHEP



N. Bhusal master thesis (2024)

A package for simulating real time field dynamics in an CosmoLattice expanding Universe, including scalar and gauge interactions + our own code

Tachyonic instability

- Statistics of Higgs windings:

$$\left(v_q^{\mathrm{SM}} \sim \frac{T_{\mathrm{EW}}}{M_{\mathrm{Pl}}} \right)$$

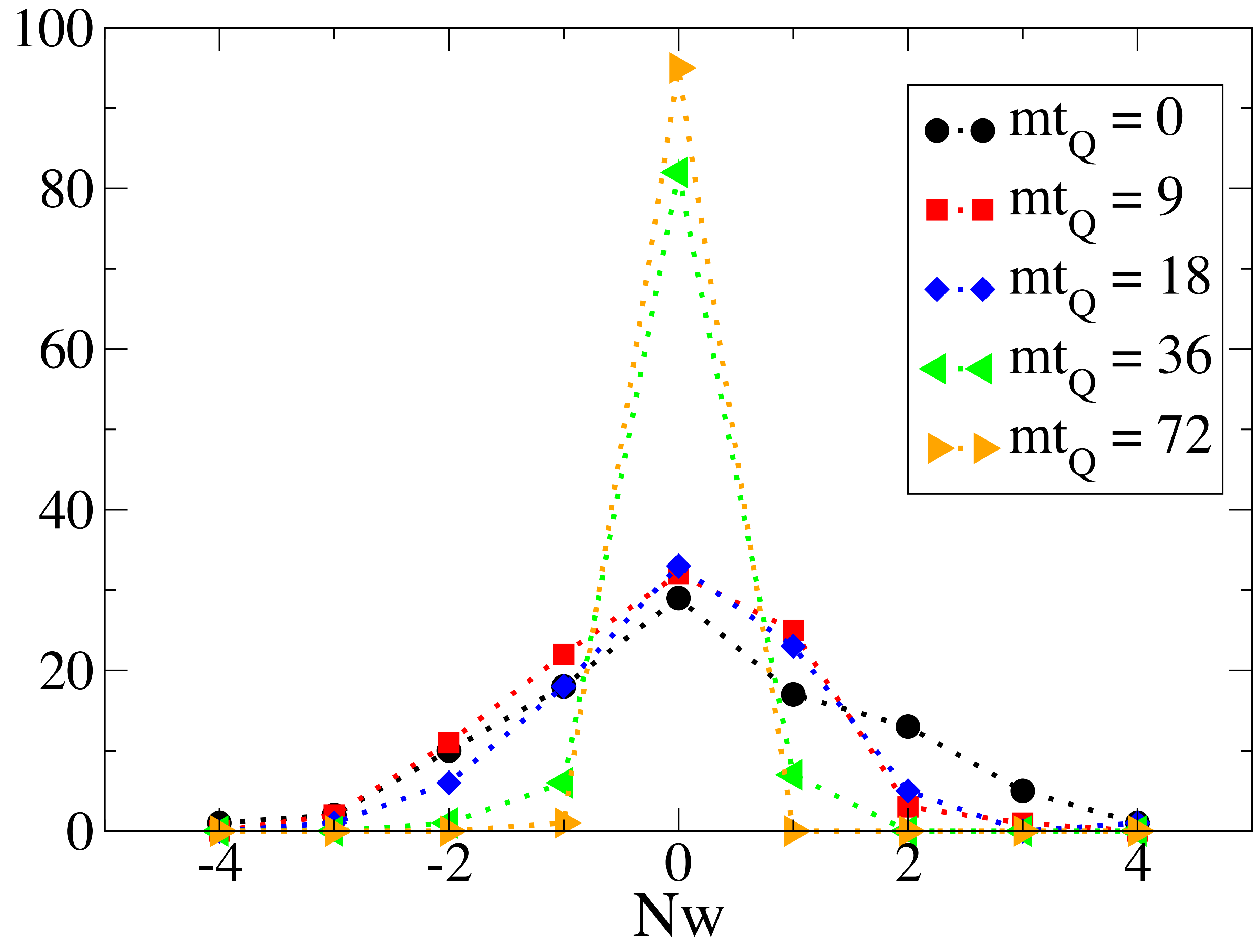


Fig. from Tranberg, Smit, Hindmarsh [hep-ph/0610096] JHEP

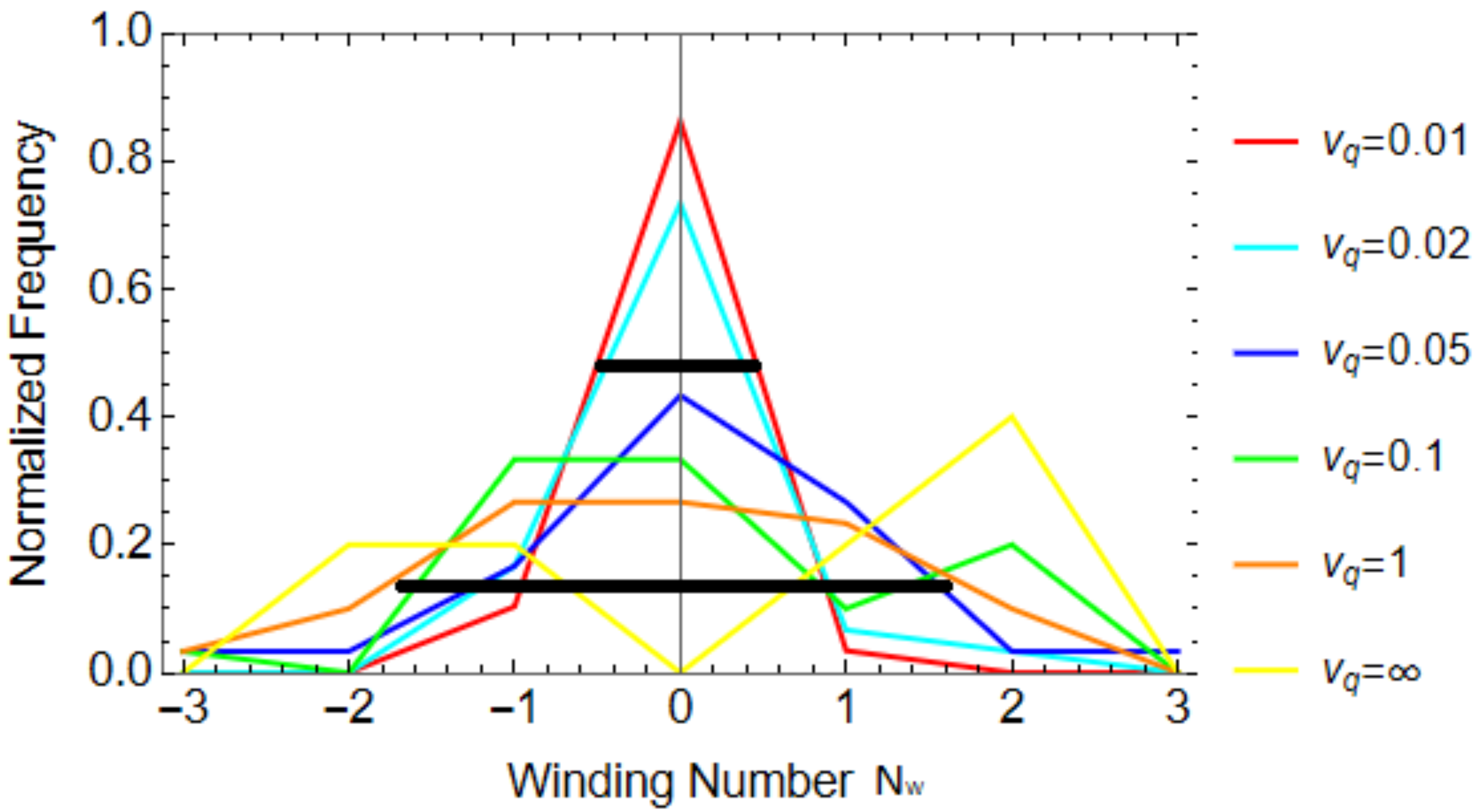


Fig. from N. Bhusal master thesis (2024)

Tachyonic instability

- Chern-Simons variance:

$$\Gamma \equiv \lim_{L,t\to\infty} \frac{\langle N_{\rm CS}^2(t)\rangle - \langle N_{\rm CS}(t)\rangle^2}{L^3 t}$$

CS diffusion determines
effective sphaleron rate

Tachyonic instability

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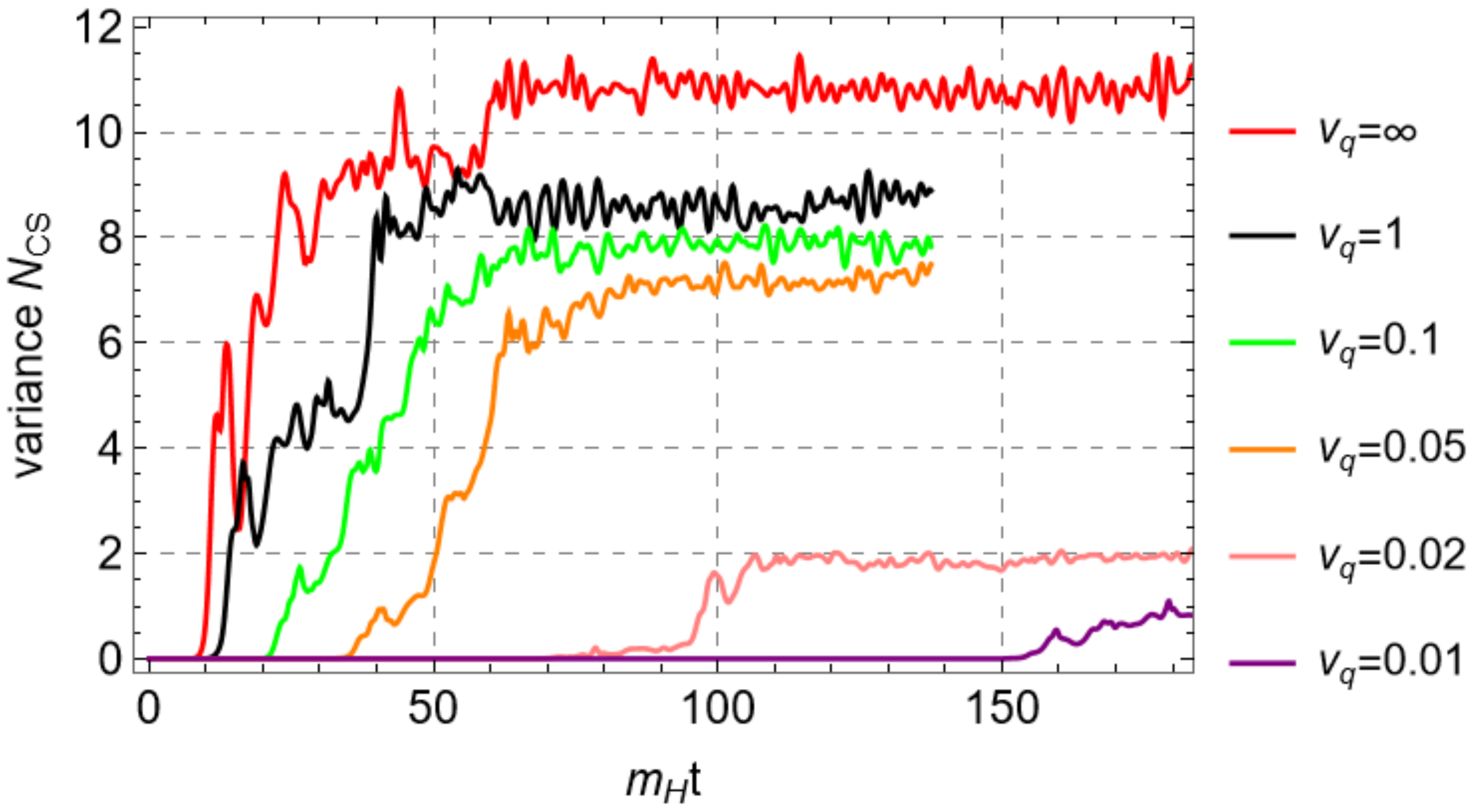

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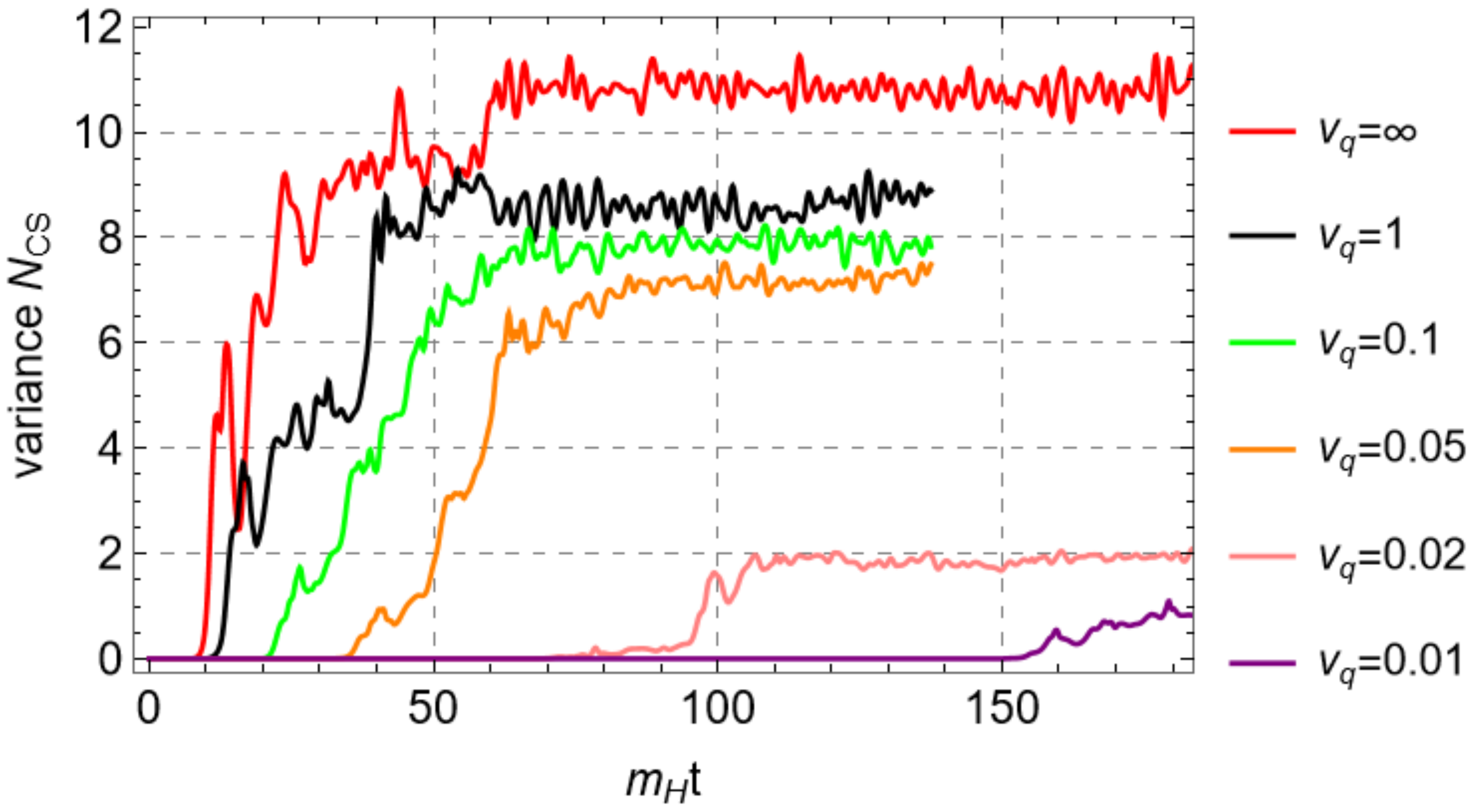
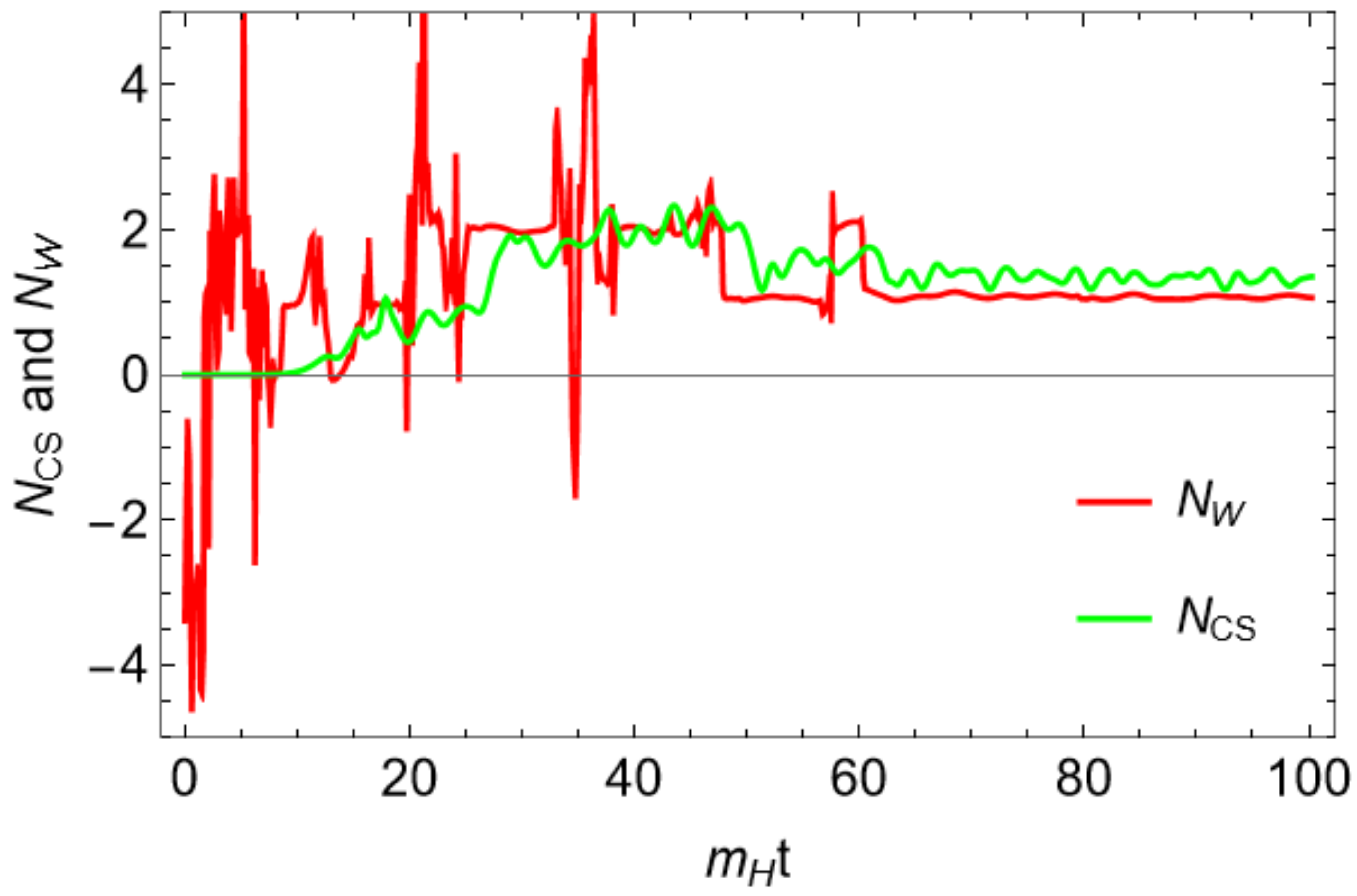


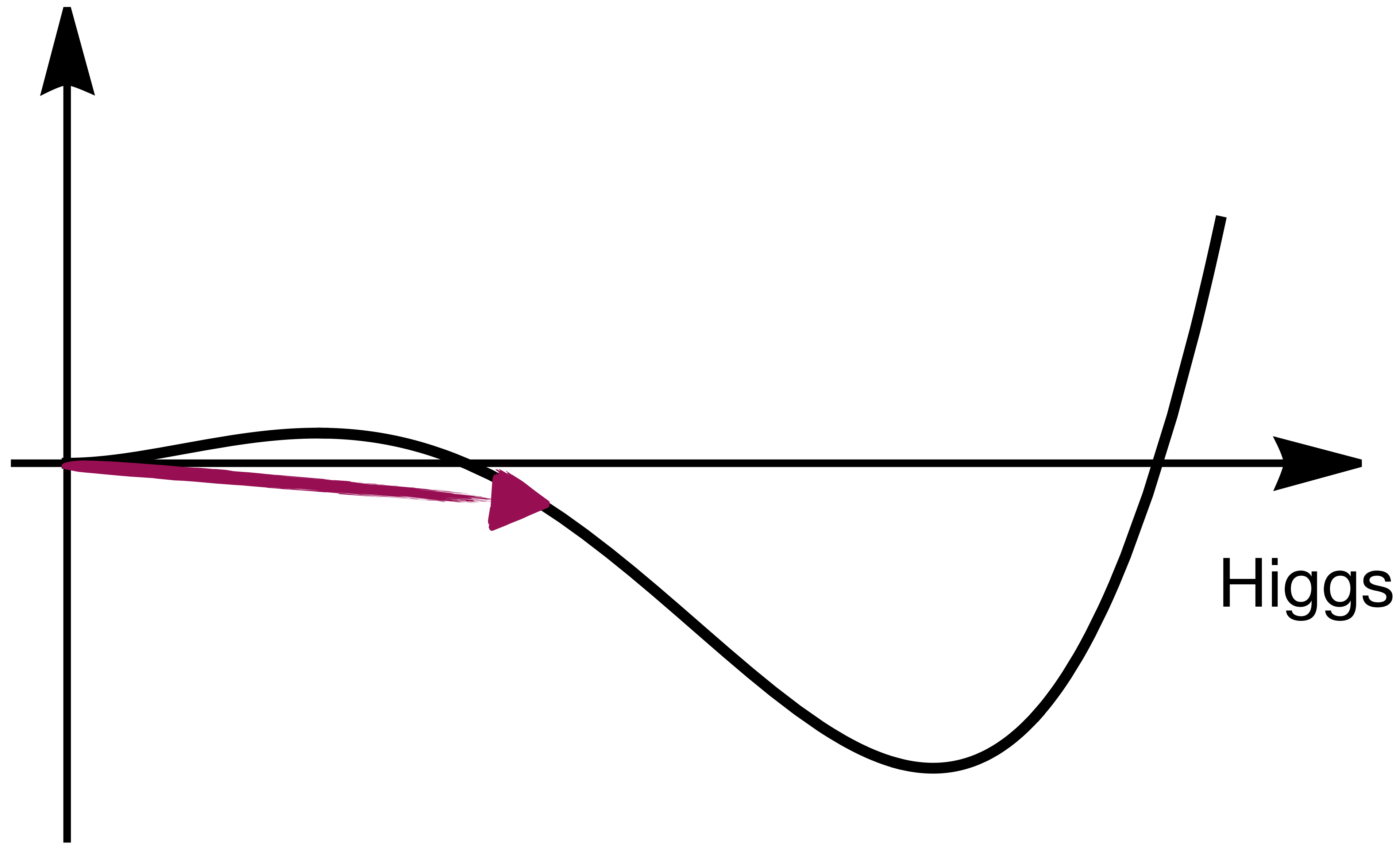
- System in the vacuum at late times:



Figures from N. Bhusal master thesis (2024)

Realizations

- Explicit realizations of a spinodal (tachyonic) electroweak phase transition are mostly based on reheating after (hybrid) inflation
- Another possibility would be a first order phase transition: **1)** a time-dependent barrier such that nucleation is basically a roll-over



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See also Konstandin, Servant [1104.4793] JCAP; Servant [1407.0030] PRL

Requires **fully 3d simulations** of bubble collisions with **non-abelian gauge fields**

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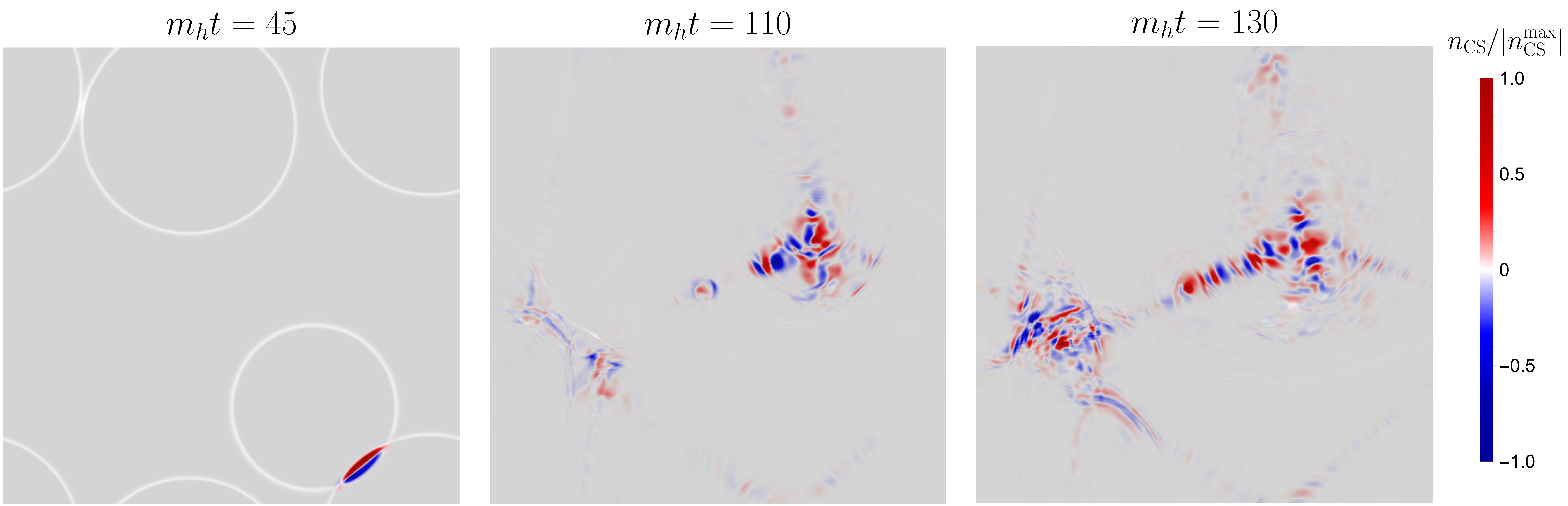

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Chern-Simons from bubble collisions

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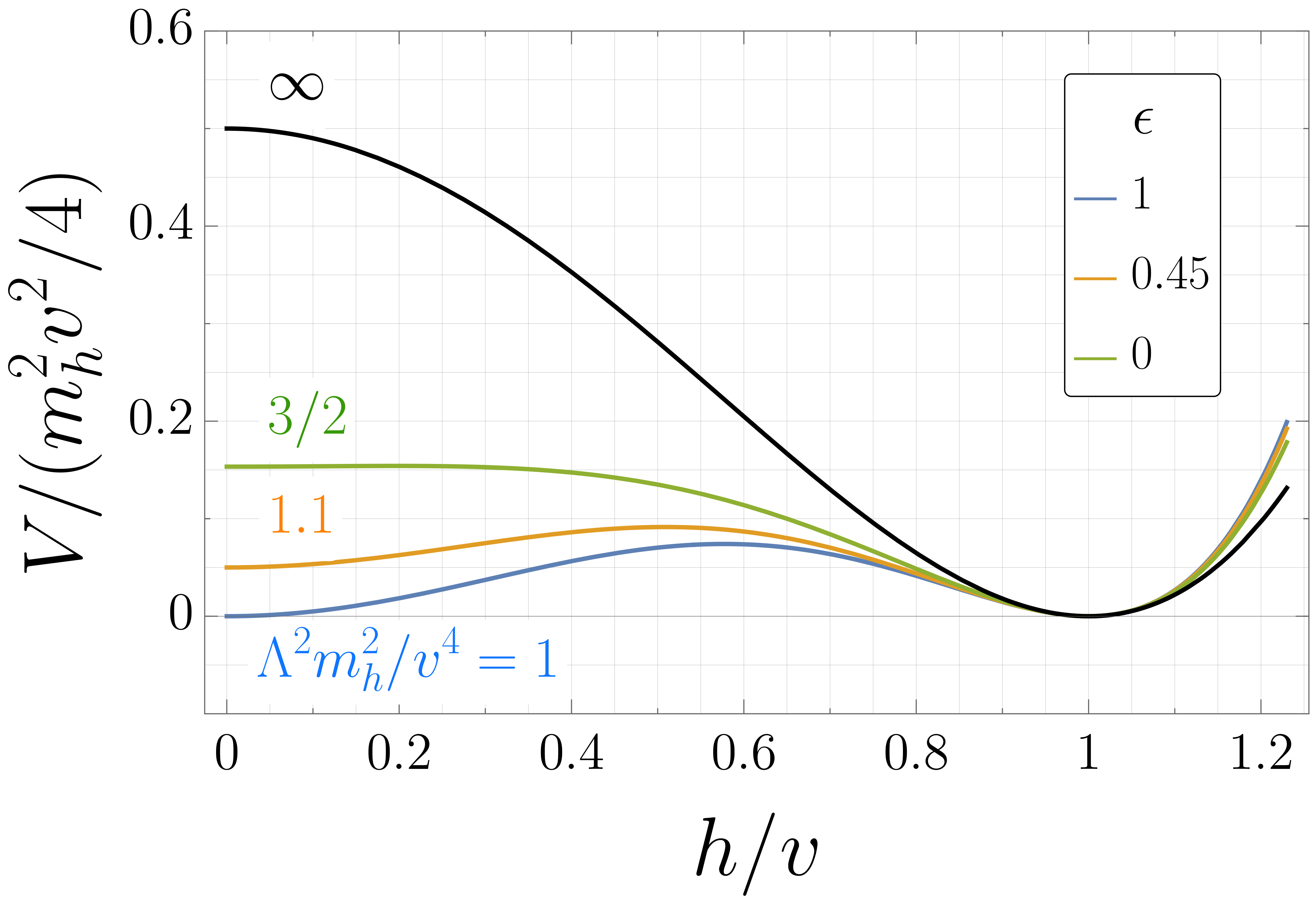
- We vary the shape of the Higgs potential, as this controls wall—wall collisions
- We vary the size of bubbles at collision (γ_*) for extrapolation to the physical point
- We have tried $\mathscr{C}\mathrm{osmo}\mathscr{L}\mathrm{attice}$ for the FOPT as well, but eventually used our code

Shape of the Higgs potential

- Bubble collision dynamics controlled by:

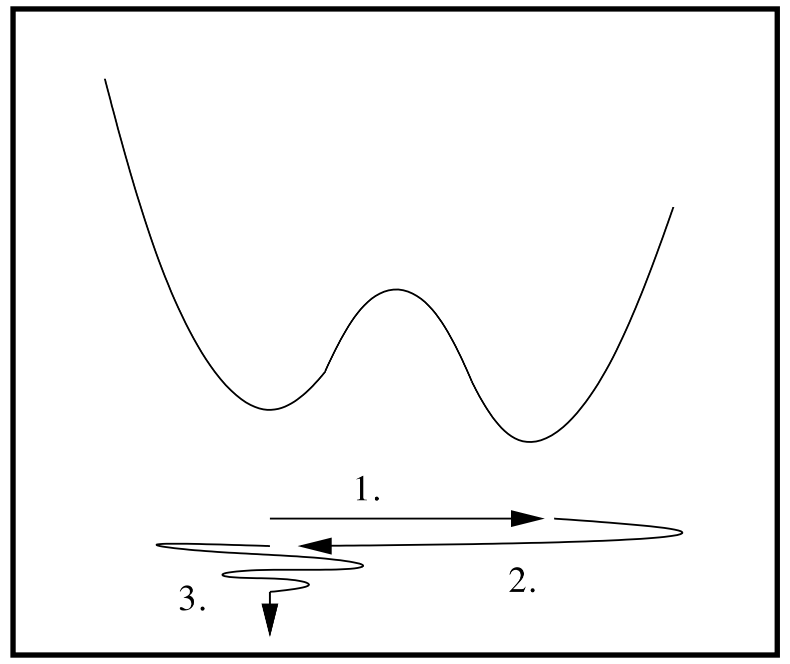
$$\epsilon = \frac{(\text{barrier height}) - (\text{false vacuum height})}{(\text{barrier height}) - (\text{true vacuum height})}$$

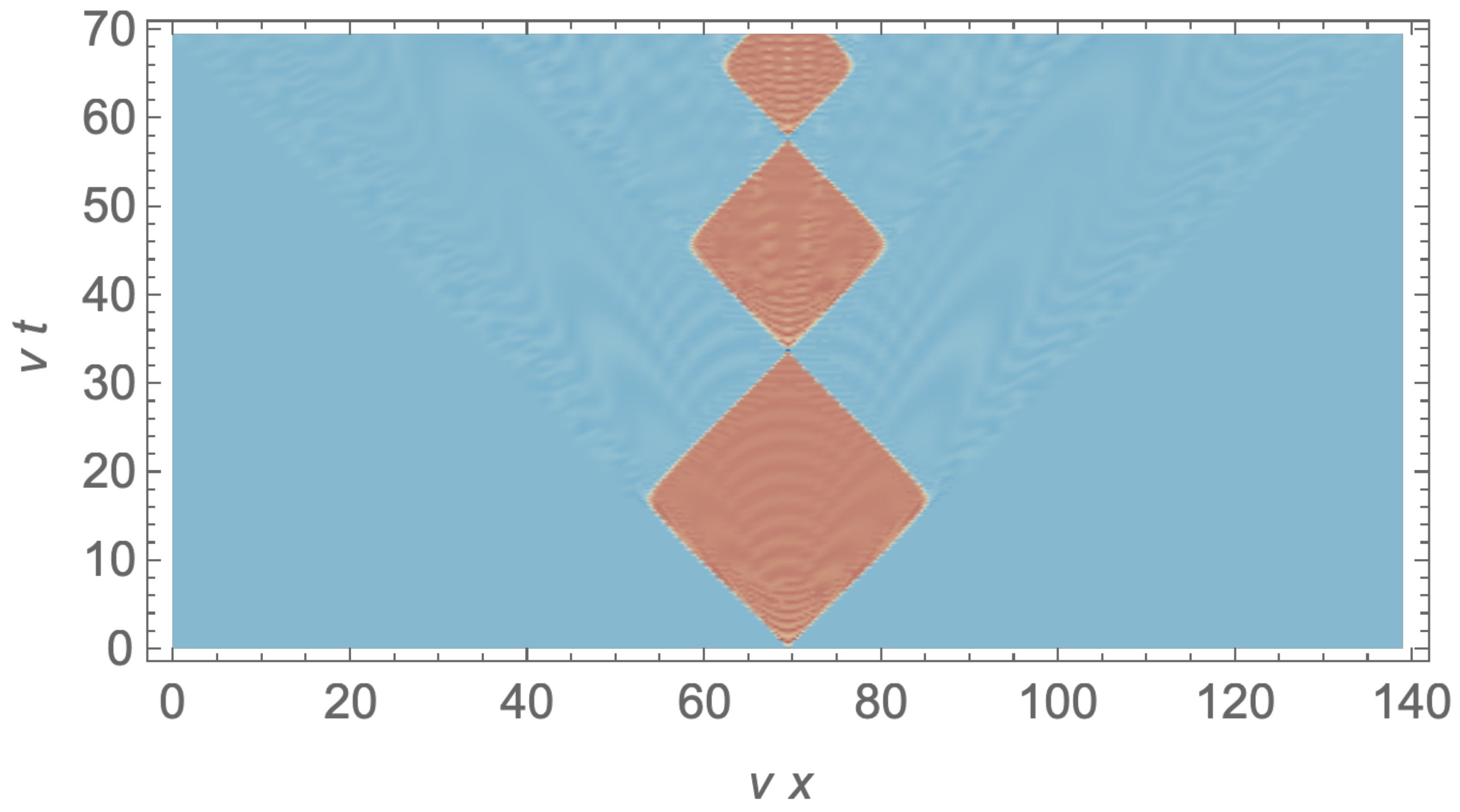
Jinno, Konstandin, Takimoto
[1906.02588] JCAP

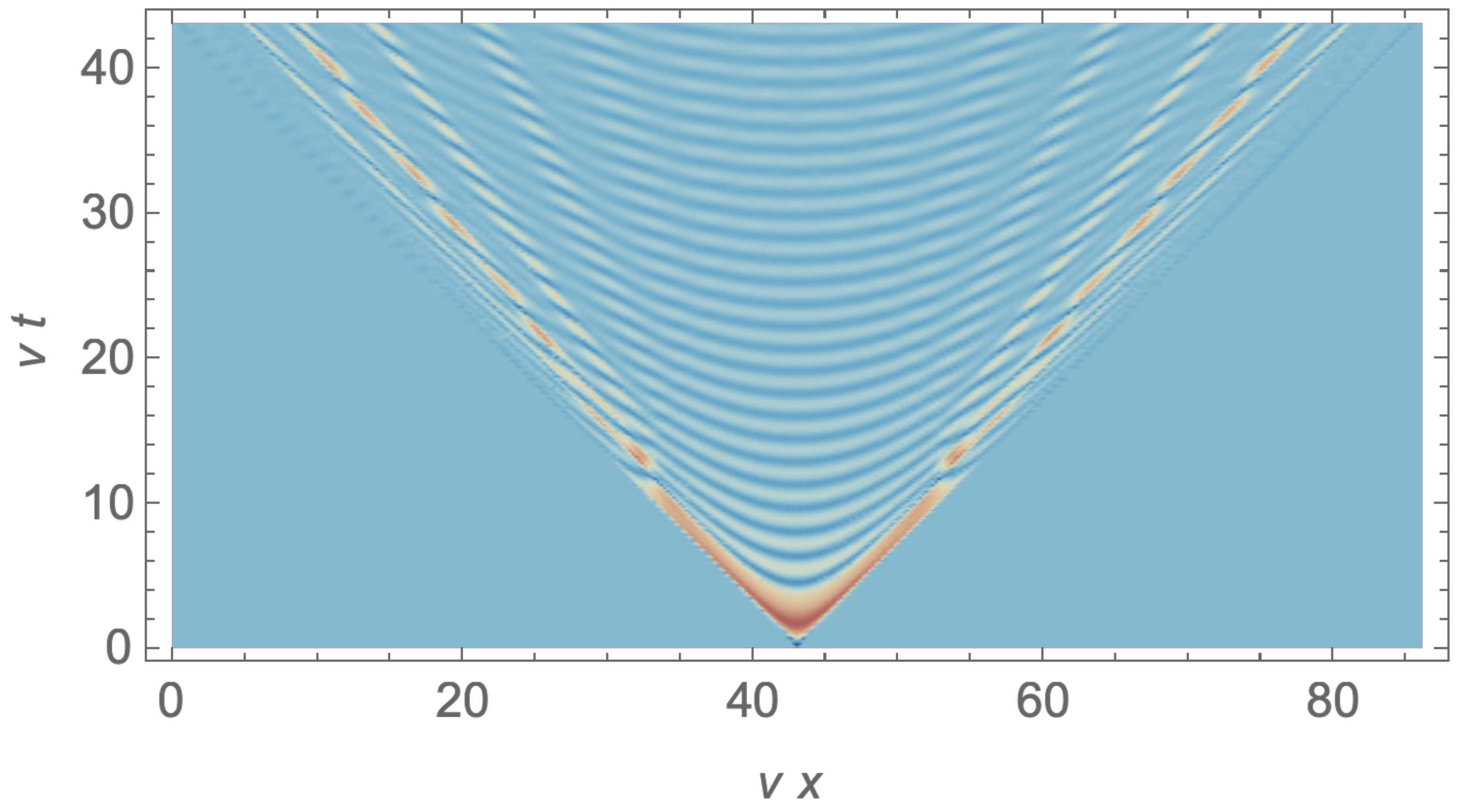


Shape of the Higgs potential

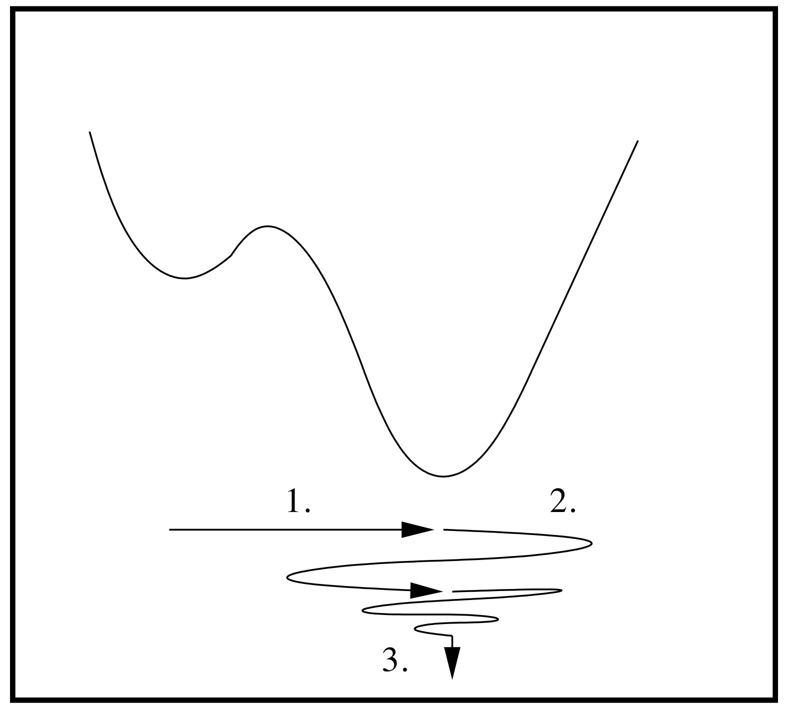
$\epsilon = 0.5$

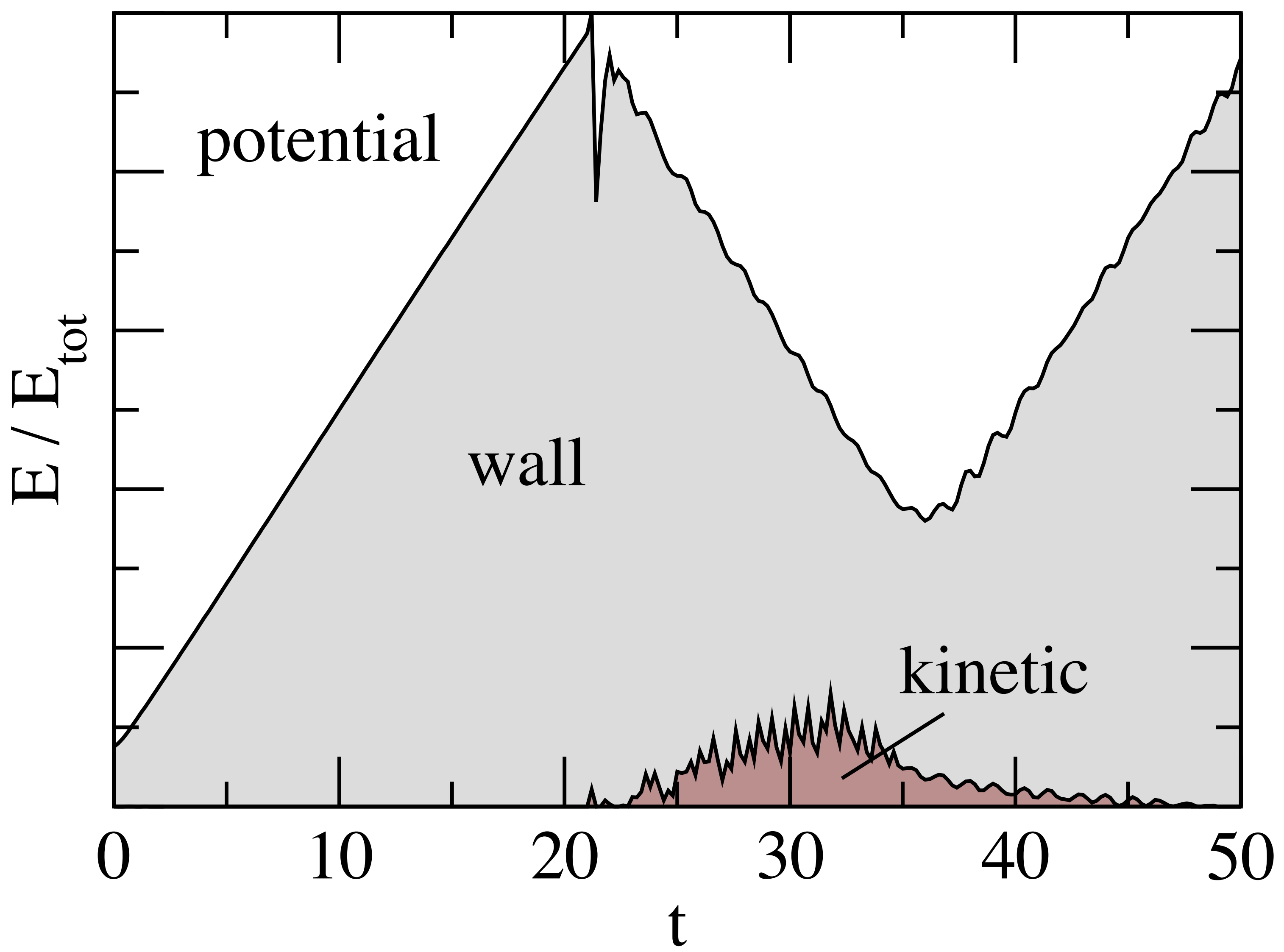


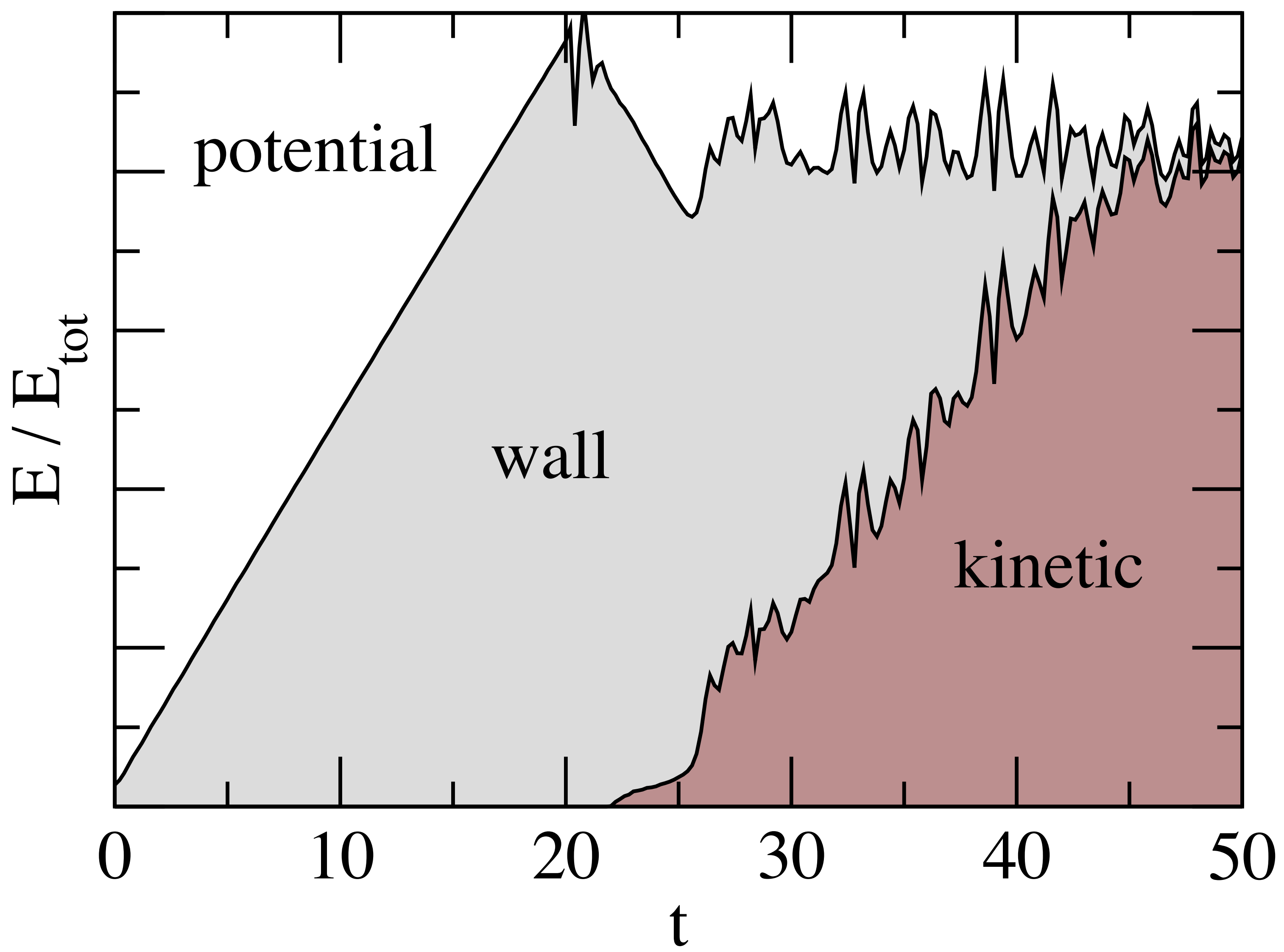




$\epsilon \ll 1$







Jinno, Konstandin, Takimoto
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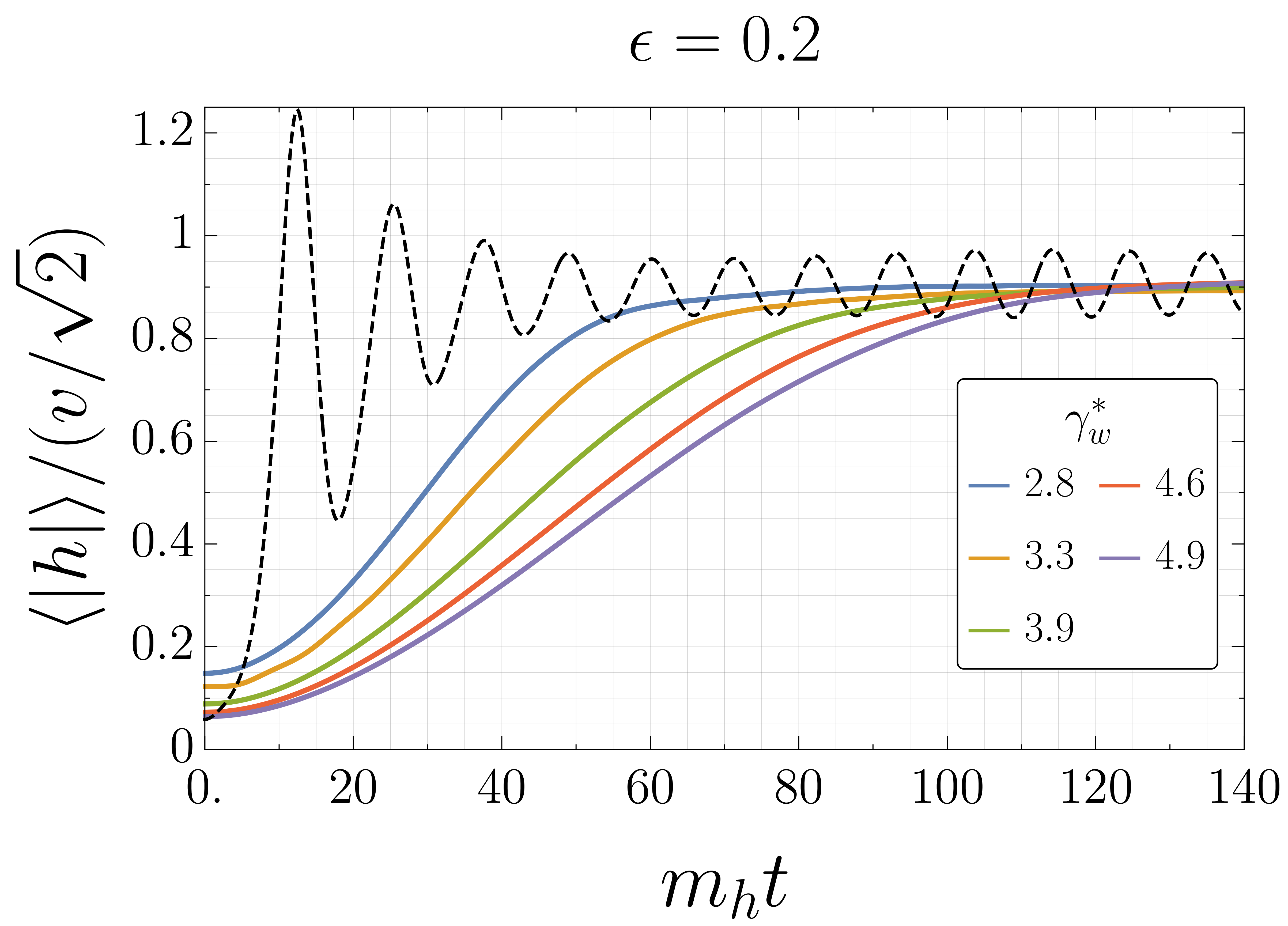
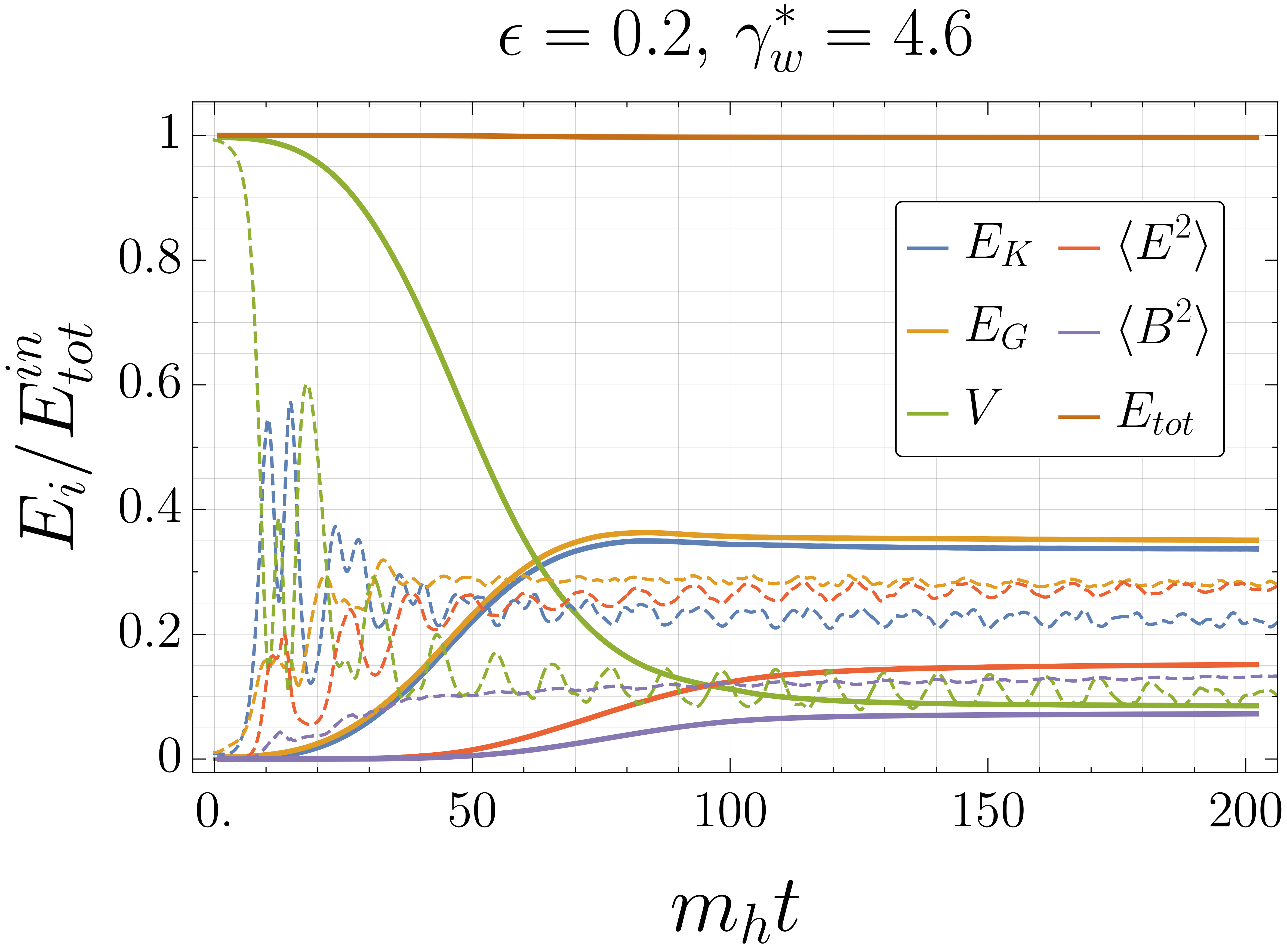
Konstandin, Servant
[1104.4793] JCAP

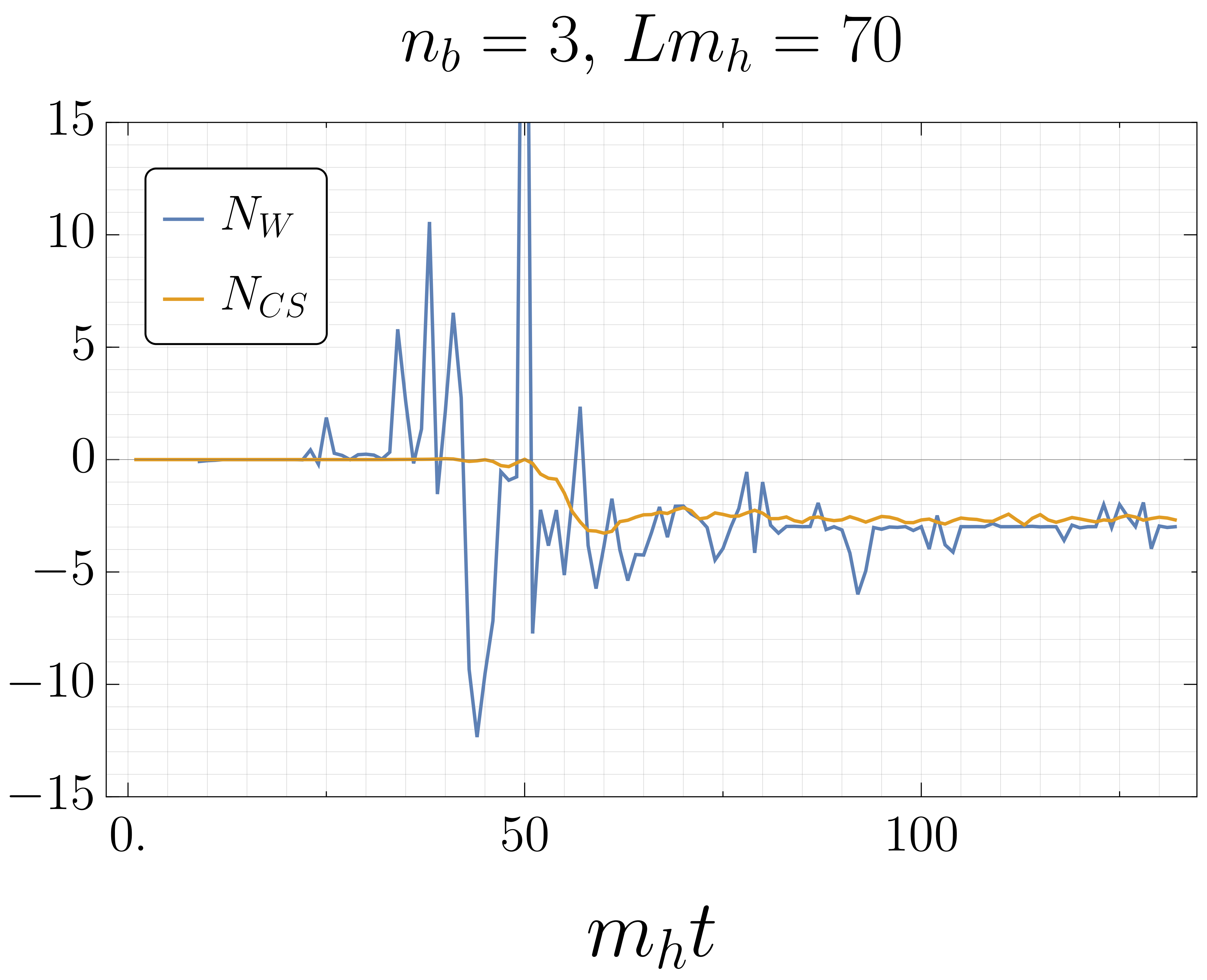
Time scale and energy budget

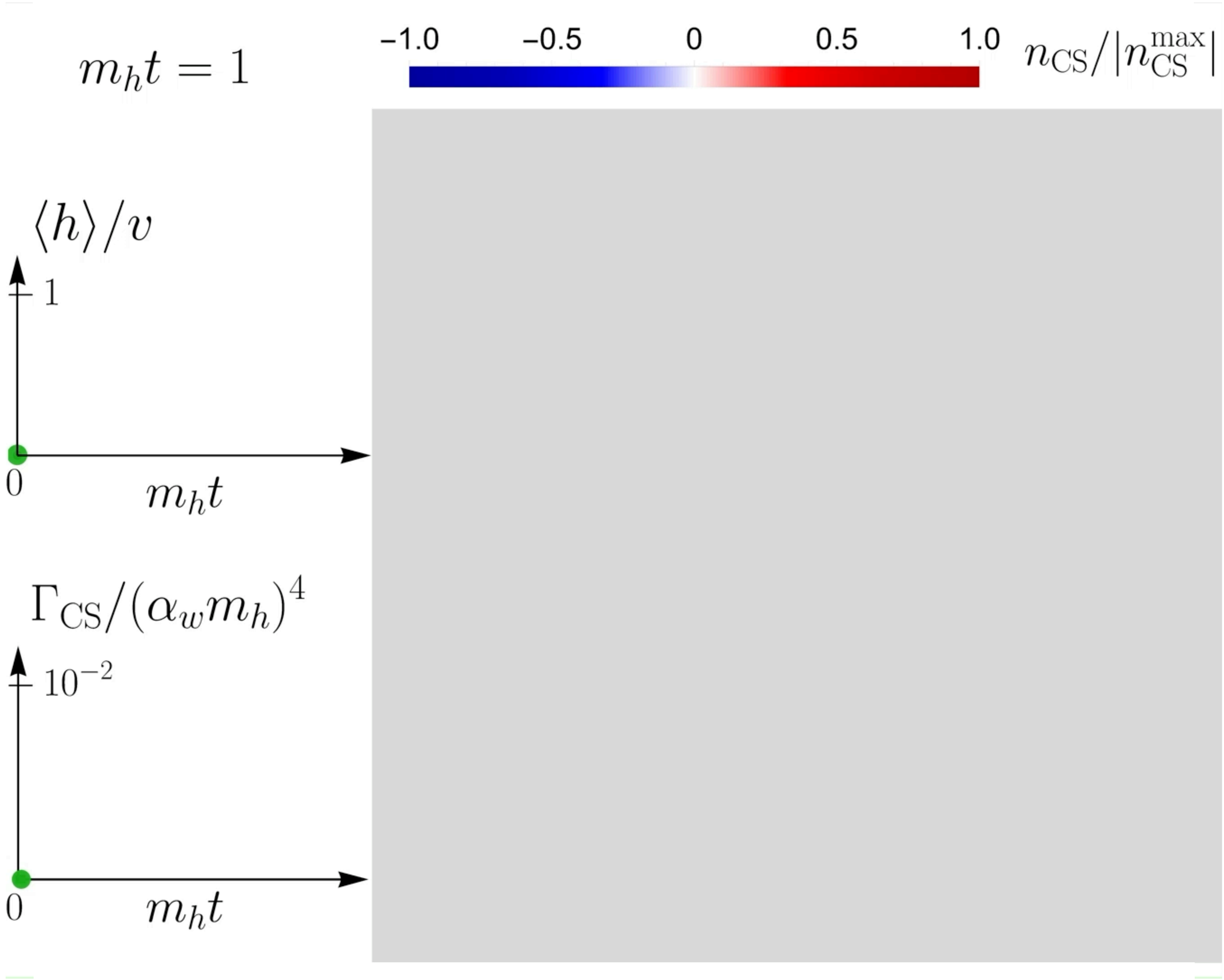




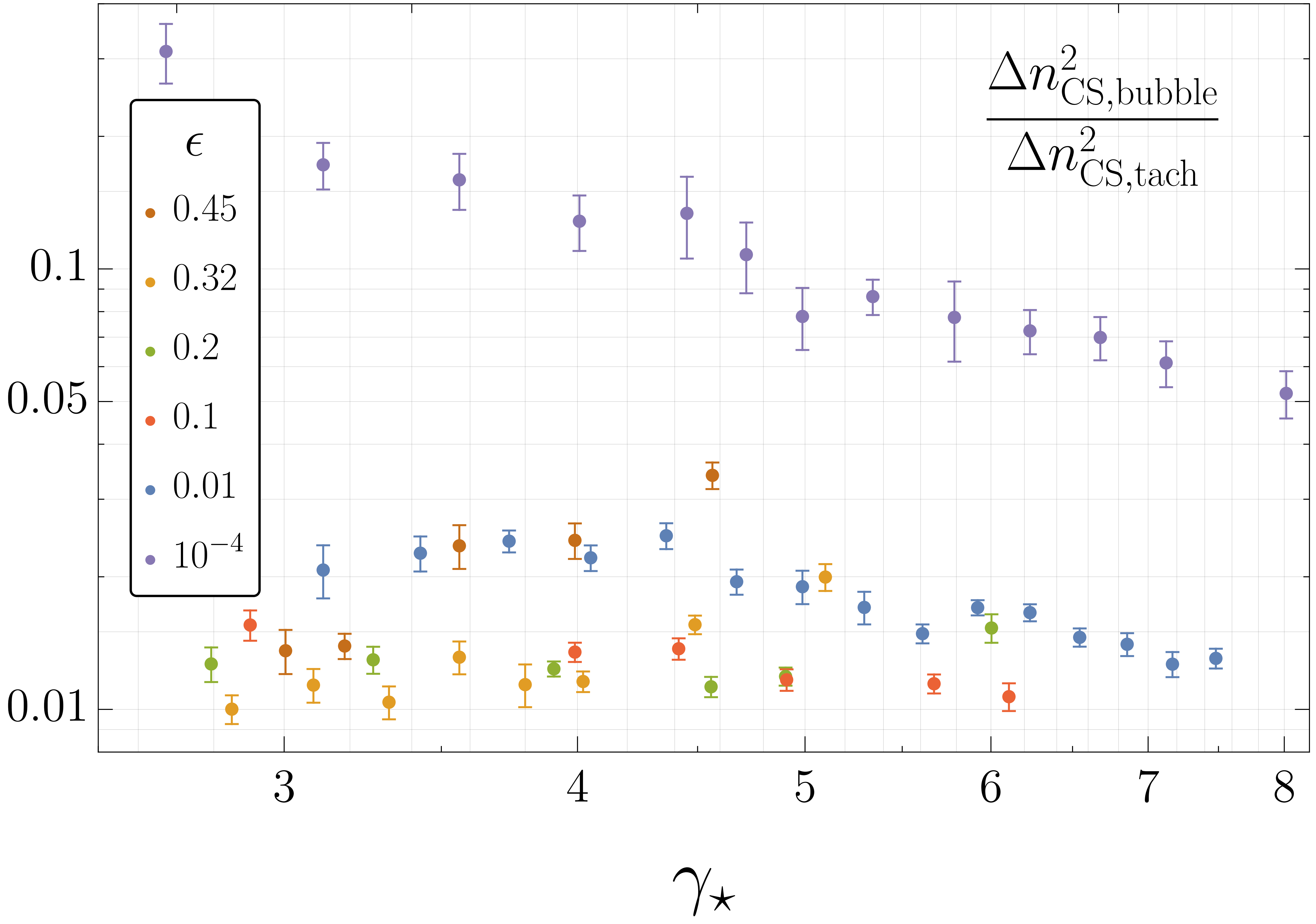
Cross-checks

- Convergence of Higgs winding and CS number observed also for the first order phase transition:




$m_h t = 1$
–1.0
–0.5
0
0.5
1.0
$n_{\rm CS}/|n_{\rm CS}^{\rm max}|$
$\langle h \rangle / v$
1
0
$m_h t$
$\Gamma_{\rm CS}/(\alpha_w m_h)^4$
10^{-2}
0
$m_h t$

Results 3+1

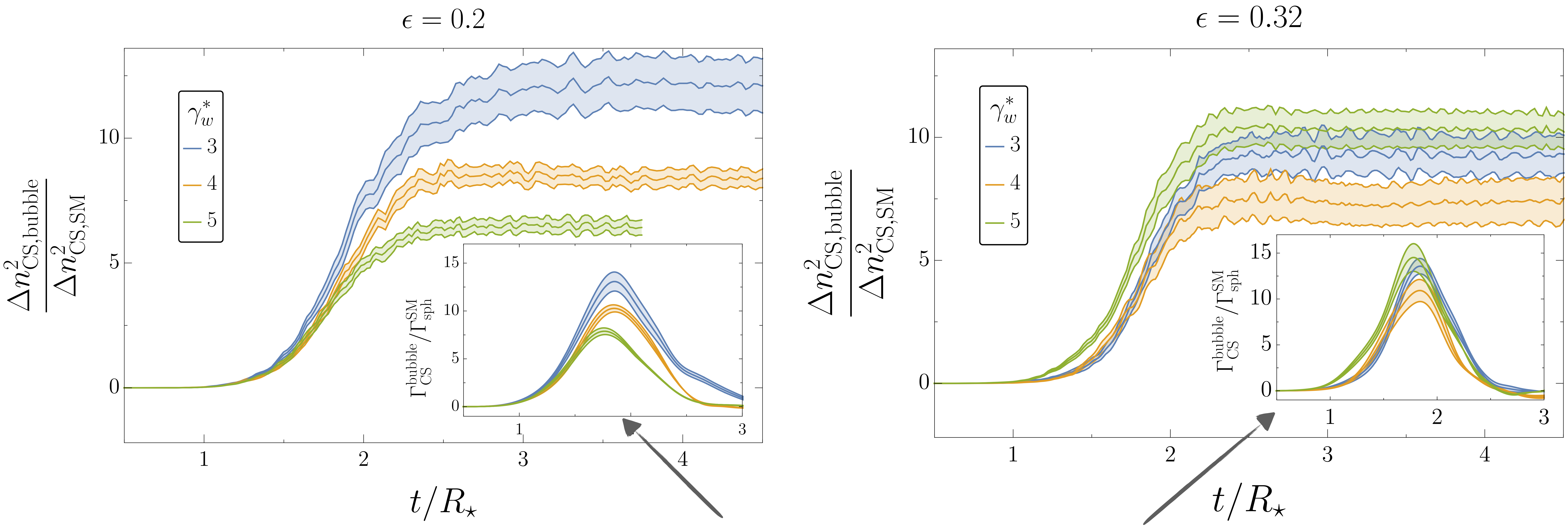


Collisions with $\epsilon \gtrsim 0.2$ show a non-decreasing CS variance at large γ_* !

May lead to successful baryogenesis depending on the source of CP violation

Bhusal, **SB**, Cataldi, Chatrchyan, Gorghetto, Servant, to appear

Results 3+1



Effective sphaleron rate

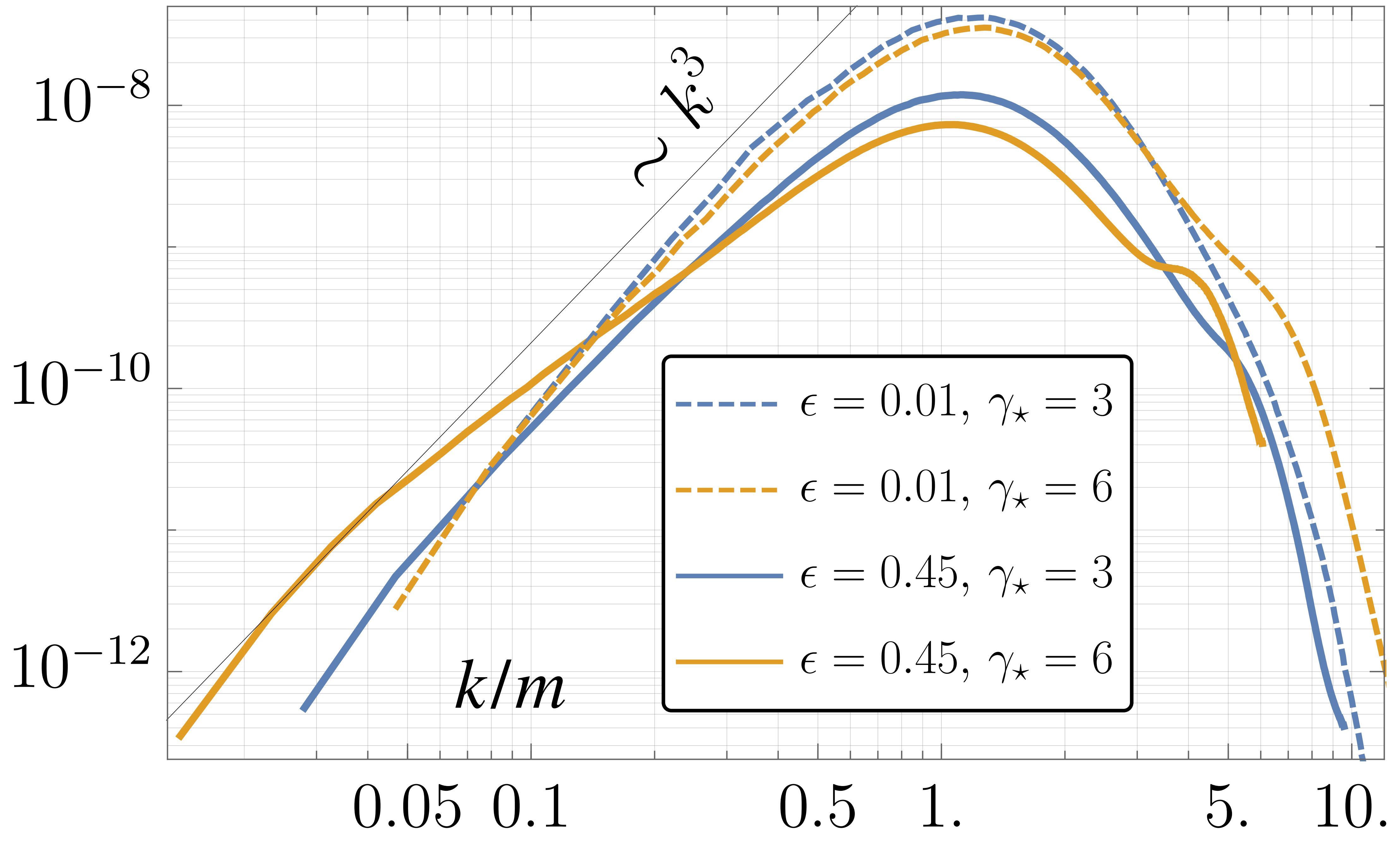
Bhusal, **SB**, Cataldi, Chatrchyan, Gorghetto, Servant, to appear

Summary and Outlook

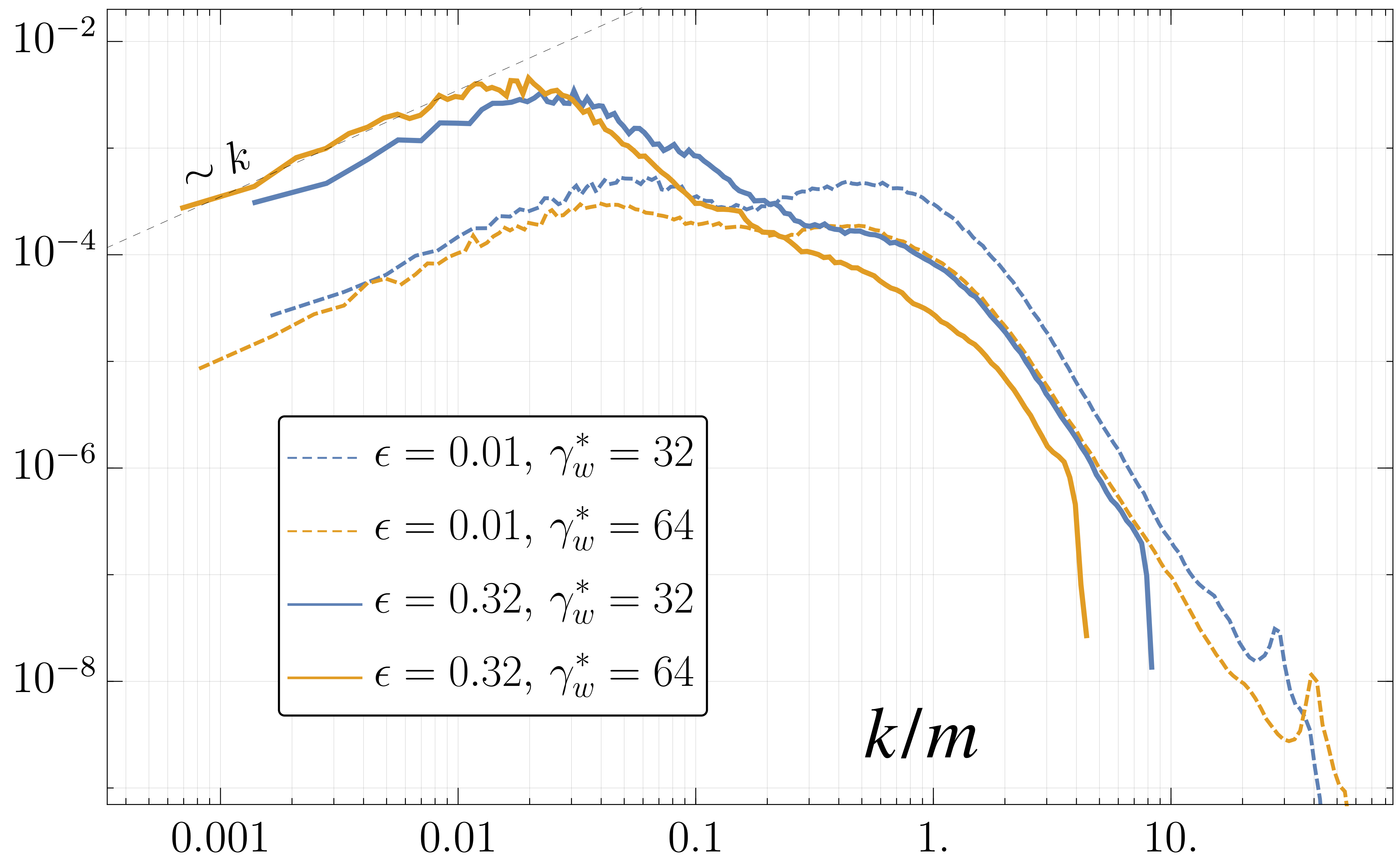
- Bubble collisions can lead to a sizable production of Chern-Simons number
- This provides an alternative realization of electroweak baryogenesis which does not rely on the existence of a thermal plasma (in the spirit of cold baryogenesis)
- A crucial role is played by the shape of the Higgs potential (controlled by ϵ)
- Implement exponential nucleation of bubbles
- Include CP violation and evaluate $\langle N_{\mathrm{CS}} \rangle \neq 0$ (directly related to B number)
- Include scalar and gauge fluctuations around the non-trivial bubble background
- Provide an explicit realization of this dynamics (e.g. Higgs + singlet)
- Consider bubble walls with terminal velocity and interaction with SM particles
- Extract the gravitational wave spectrum

Chern-Simons power spectra

3+1



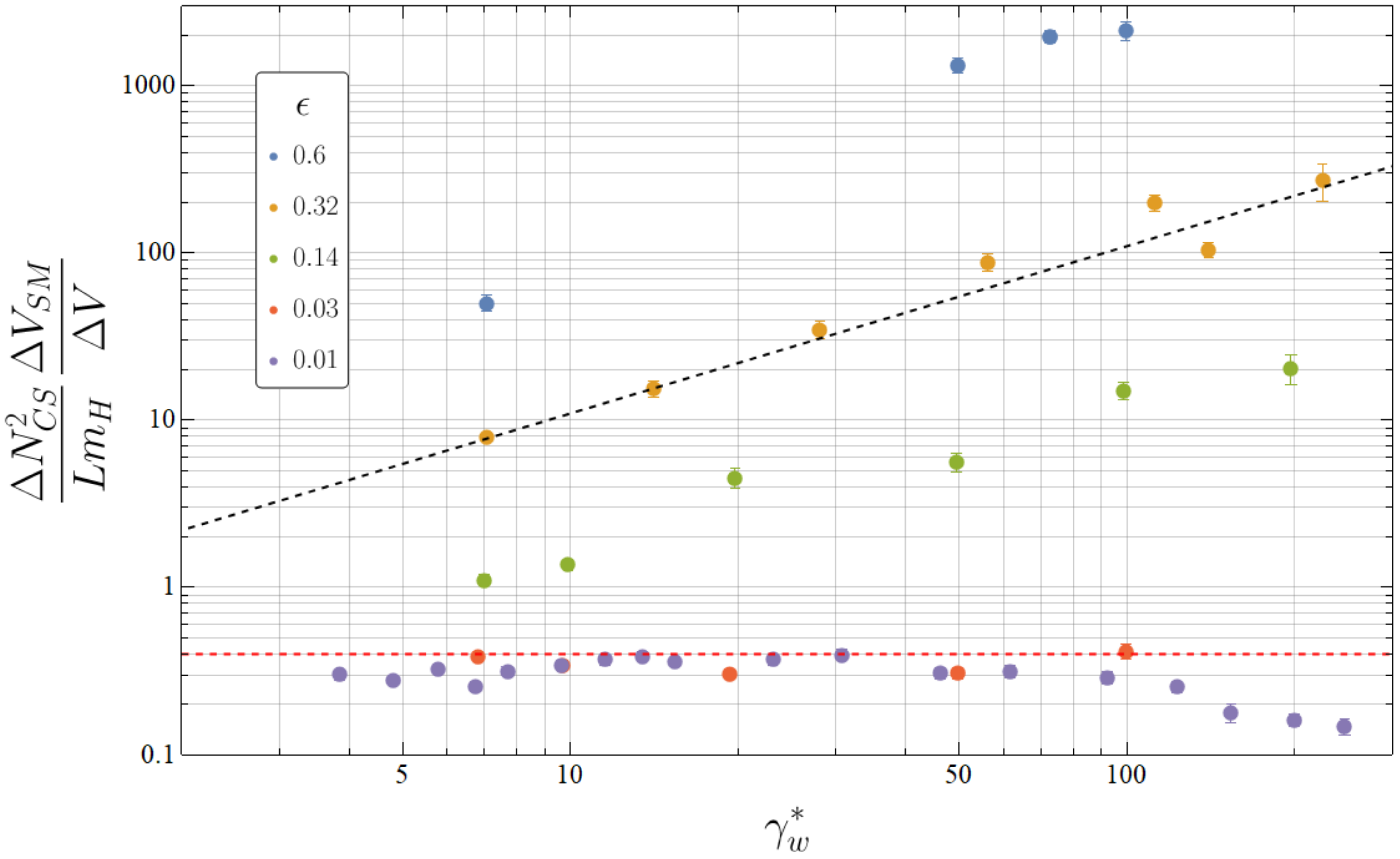
1+1



$$\langle \tilde{n}(k)\tilde{n}(k')\rangle = (2\pi)^d \delta^d(k-k')\frac{1}{k^d} P_{\rm CS}(k)$$

Results 1+1

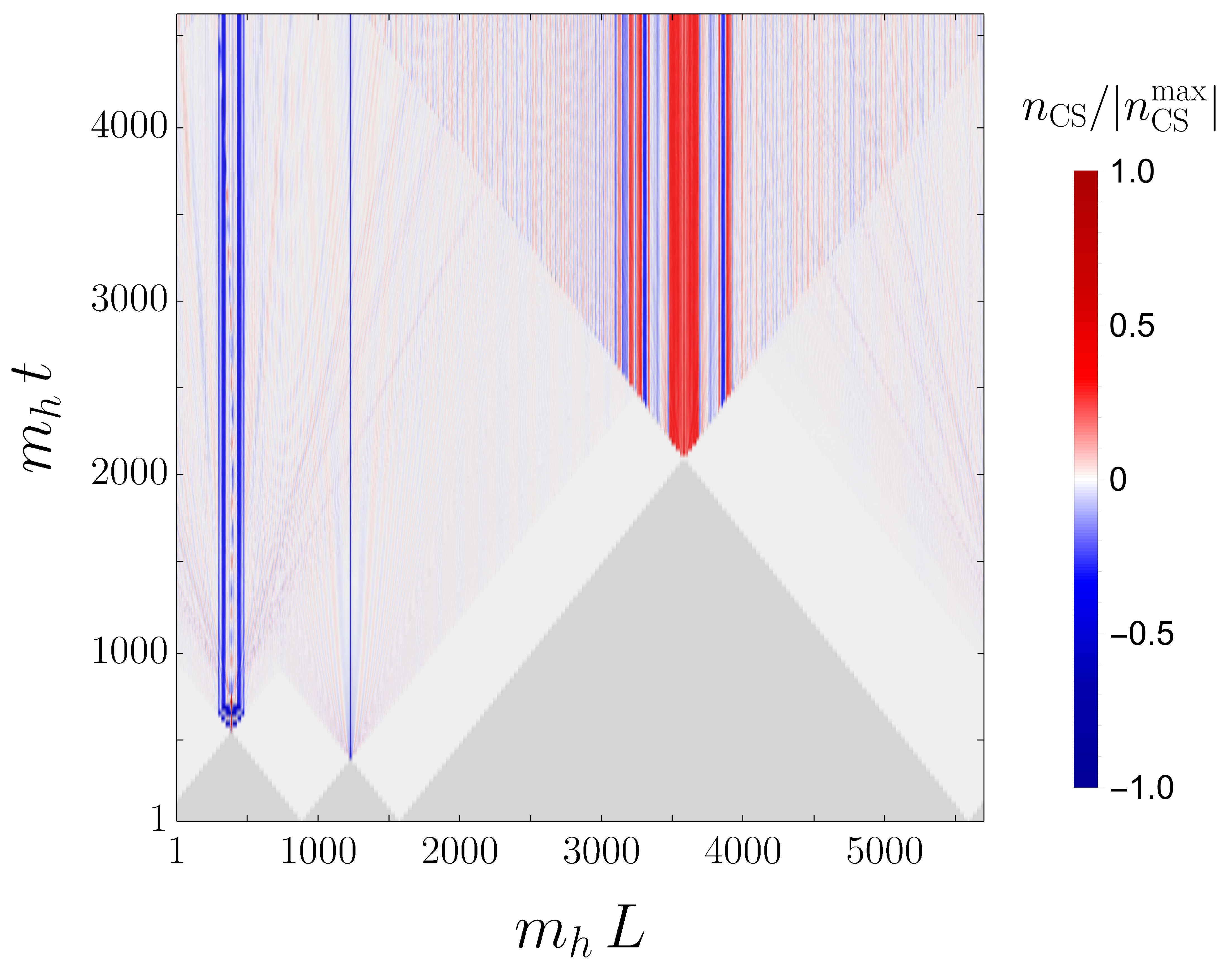
- Chern-Simons variance:



Tachyonic instability

Results 1+1

$\epsilon = 0.32$



$\epsilon = 0.01$