Cold baryogenesis from Higgs Bubble Collisions

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Based on: *Phys. Rev. Lett.* 136 (2026) 241803 [2508.21825] + ongoing work with Blasi, Gorghetto, Servant

Strong and Electro-Weak Matter 2026

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Helsinki, Finland

20/08/2026

In a nutshell

Novel realization of cold electroweak baryogenesis via:

Yesterday's talk by N. Bhusal

- *Effective* sphaleron rate from Higgs bubble collisions in a first-order EWPT [2508.21825]

Cold = it takes place at low temperatures, lower than O(100) GeV, and it does not rely on thermal sphalerons

Cold baryogenesis from Higgs Bubble Collisions

1) low reheat temperature

$T_{rh} < T_{sph\ f.o.} \simeq 132\ \mathrm{GeV}$
thermal sphalerons suppressed

2) efficient at large (supersonic) bubble wall velocity

$v_w > v_s$

First idea of Cold Baryogenesis in a FOPT in

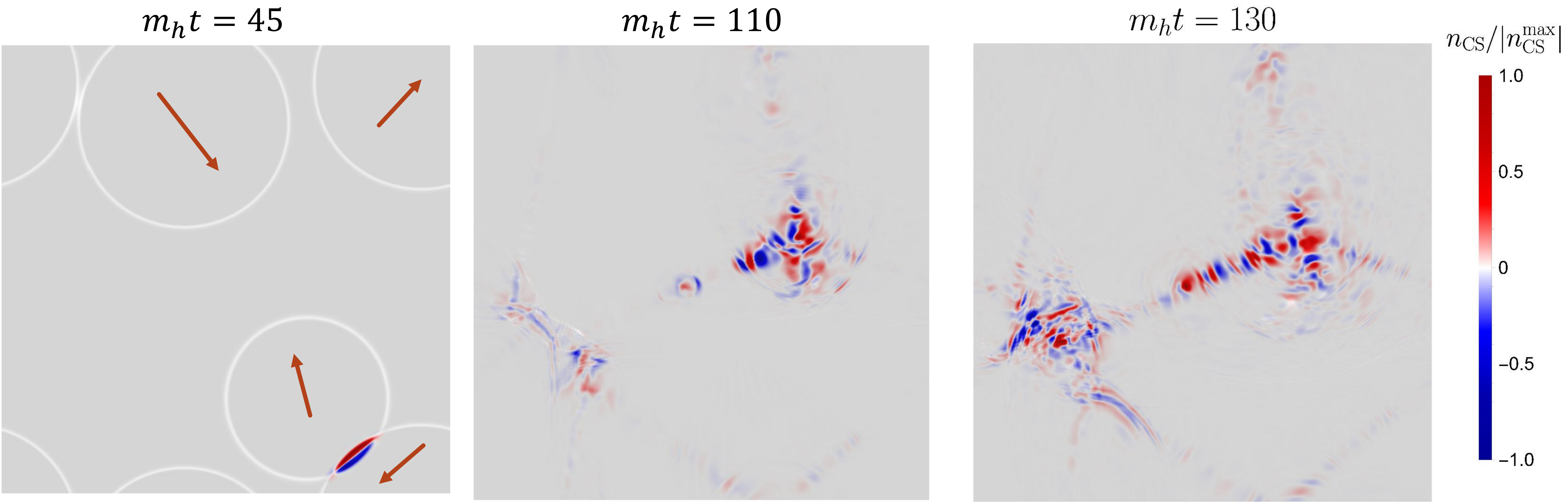
Konstandin, Servant, JCAP07(2011)024
Servant, Phys. Rev. Lett. 113, 171803 (2014)

→ New possibilities for EW baryogenesis in models with a supercooled first-order EWPT, for which conventional EW baryogenesis via charge-transport is not efficient

Baryon number violation at zero temperature

Yesterday's talk by N. Bhusal

Non-thermal activation of SM baryon number violation via out-of-equilibrium classical gauge-field dynamics, induced by decay of *SU(2)-gauge textures*



$\Delta N_{CS} \neq 0$ In contrast with thermal sphalerons, baryon production even at zero temperature!

Phys. Rev. Lett. 136 (2026) 241803

In a nutshell

Novel realization of cold electroweak baryogenesis via:

- *Effective* sphaleron rate from Higgs bubble collisions in a first-order EWPT [2508.21825]

- CP-violating source, namely

$$\boxed{\mathcal{O}_{\text{CP}} = \frac{g^2}{32\,\pi^2\Lambda^2}\,\phi^\dagger\phi\; Tr[W_{\mu\nu}\widetilde{W}^{\mu\nu}]}$$

This CP-violating operator induces an effective chemical potential $\mu = \frac{d}{dt}\,\phi^\dagger\phi$, thus biasing the baryon number production.

Note: New physic scale is constrained from electron EDM, $\Lambda > 6\,TeV$

In a nutshell

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This talk!

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Plan of this talk

1) General set up

2) Numerical results from (1+1)D lattice simulations

3) (3+1)D lattice implementation with SU(2)-gauge fields & preliminary results

Setup

→ Directly measure $\langle N_{CS} \rangle$ (averaged over a statistical ensemble of different realizations) from real-time lattice simulations of first-order EWPT at zero temperature

→ Discretization of action via conventional lattice gauge-invariant techniques (gauge links and plaquettes)

→ Initial conditions: critical bubble profile + simultaneous nucleation

→ Bubbles showing a runaway regime (expansion in vacuum)

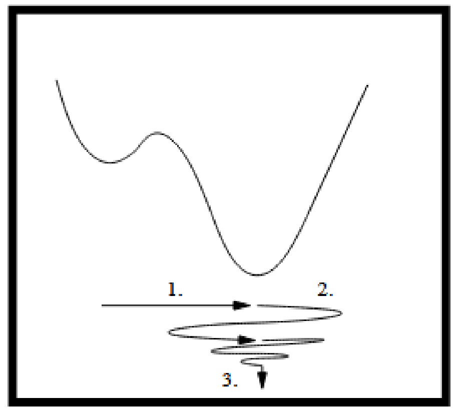
Setup

→ Study of dependence Chern-Simons number transitions on:

1) Scalar potential's shape, controlled by the degeneracy parameter

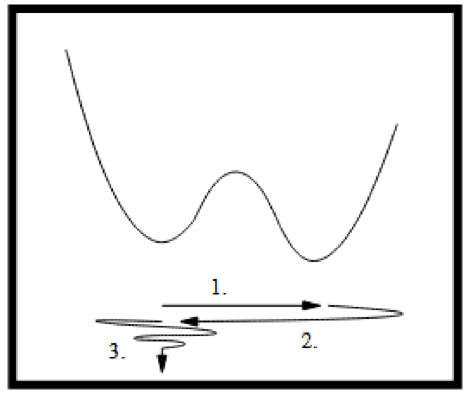
$$\boxed{0 \le \epsilon = \frac{V_{barr}}{V_{barr}+|\Delta V|} \le 1}$$

Inelastic collision



non-degenerate

Elastic collision



almost degenerate

2) Lorentz-boost factor of bubble walls at collision $\boxed{\gamma_\star = \frac{R_\star}{R_c}}$

Adding a *CP*-violating source on the lattice

Adding a *CP*-violating source: (1+1)D lattice simulations

(1+1)D Abelian Higgs model with U(1)-gauge fields: $$L = -\left|D_\mu \phi\right|^2 - \frac{1}{4} F_{\mu\nu}F^{\mu\nu} - V(\phi) - k\,|\phi|^2\epsilon_{\mu\nu}F^{\mu\nu}$$

effective CP-violating operator*

with EoM $$D_\mu D^\mu \phi = \partial_{\phi^*} V(\phi) + k\,\phi\epsilon_{\mu\nu}F^{\mu\nu}$$

$$\partial_\nu F^{\mu\nu} = 2g\,Im[\phi^*\, D^\mu \phi] - 2k\epsilon^{\mu\nu}\,\partial_\nu|\phi|^2$$

*it actually generates a C-asymmetry, since it is C- and P-odd

See Carena, et al. Phys. Rev. D 113 (2026) 014502

Adding a *CP*-violating source: (1+1)D lattice simulations

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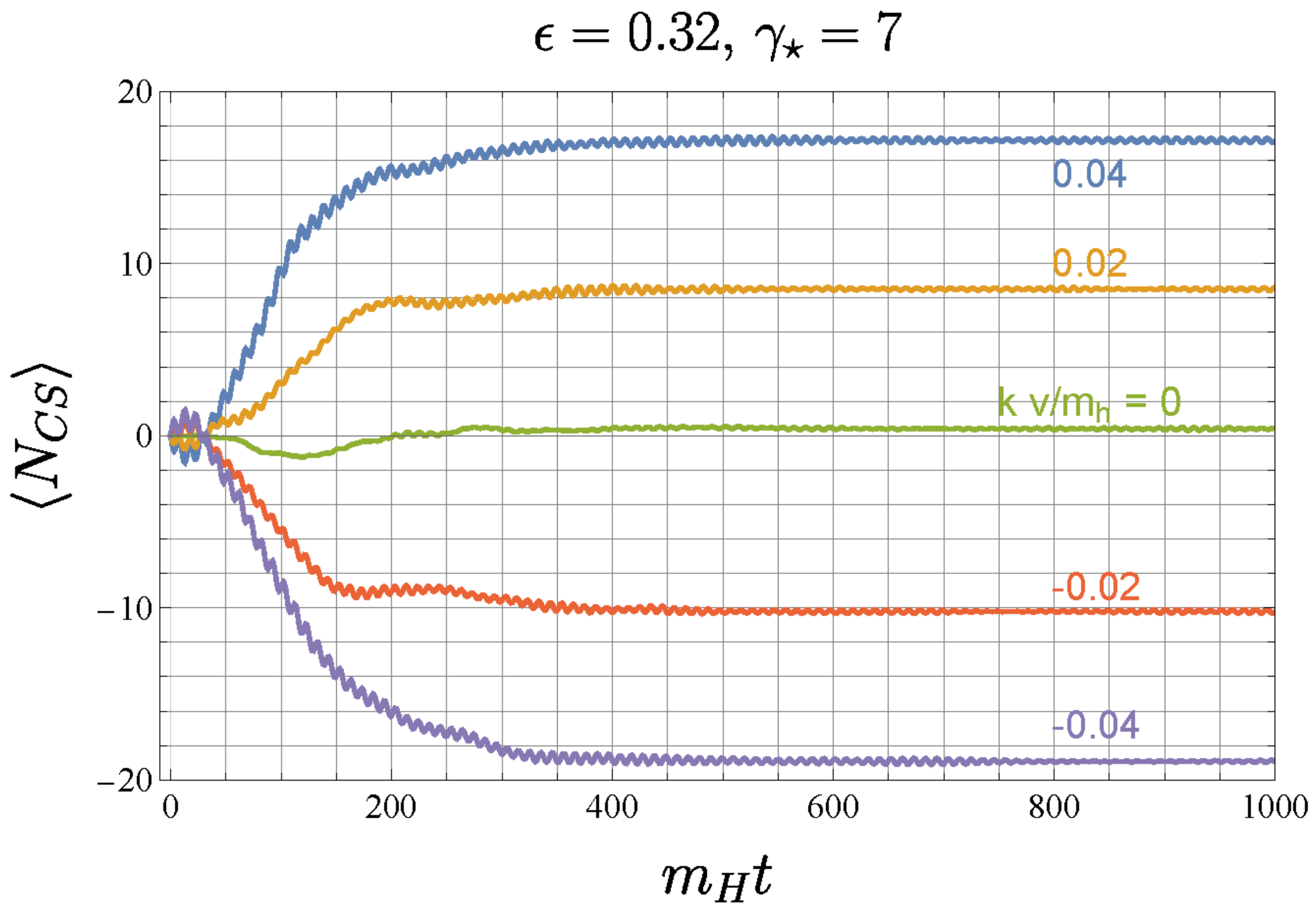
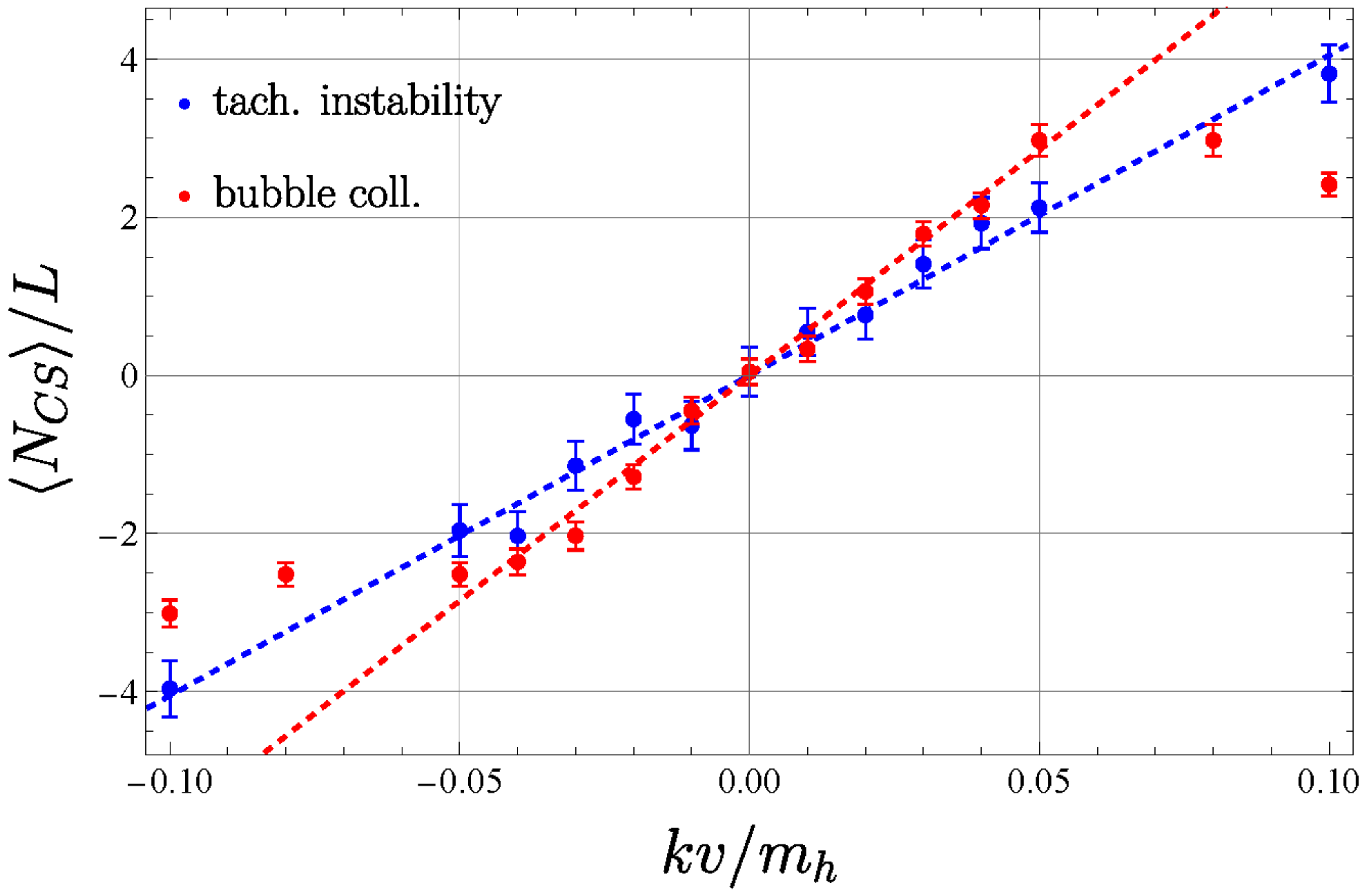
This toy model has been used in first works on original cold baryogenesis from a quenched EW crossover

Garcia-Bellido, et al. Phys. Rev. D 60 (1999) 123504
Tranberg, Smit, JHEP 12 (2002) 020

It allows us to simulate a larger parameter space, in particular $\gamma_* < 200$

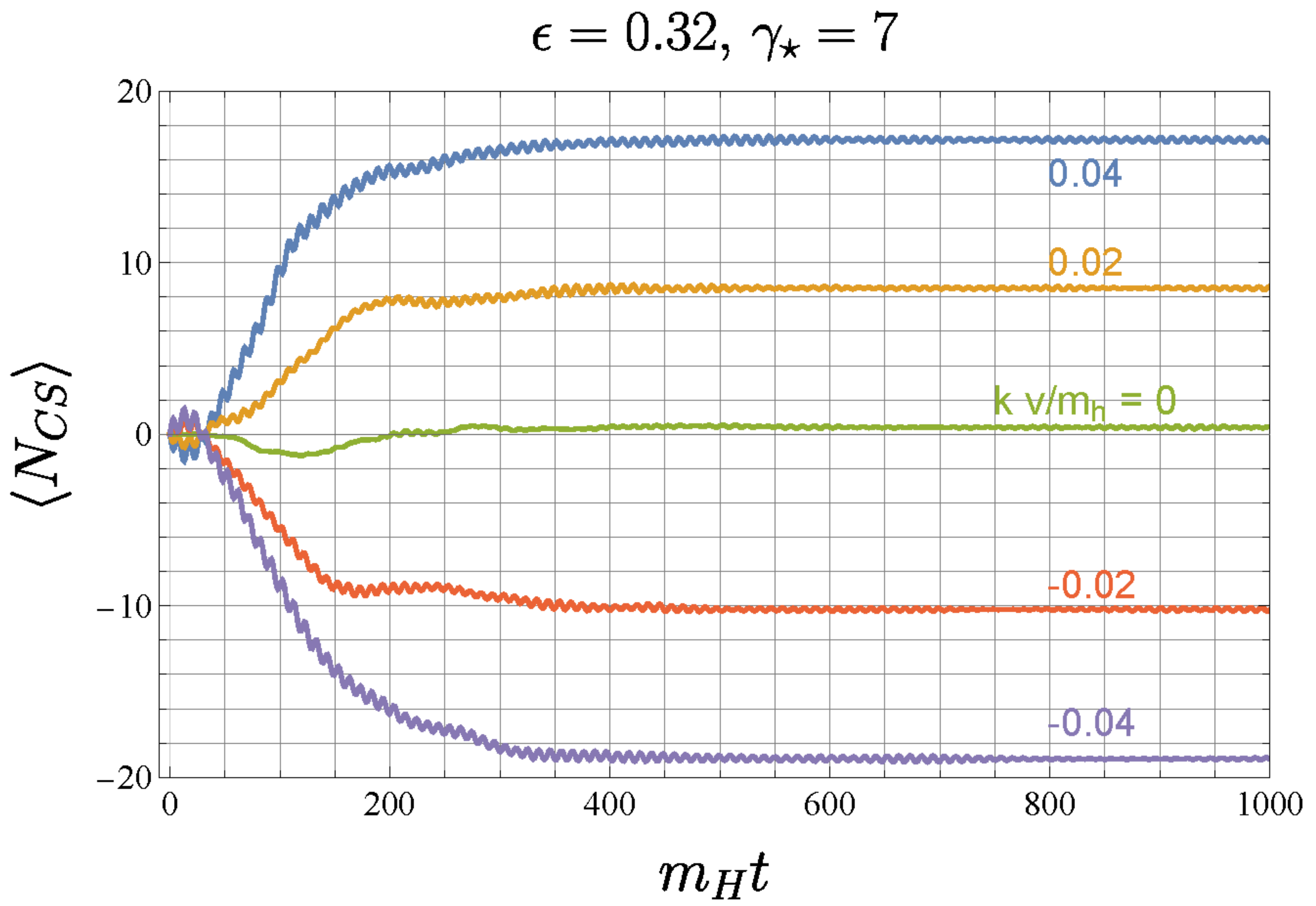
Dependence of Chern-Simons number on *k*

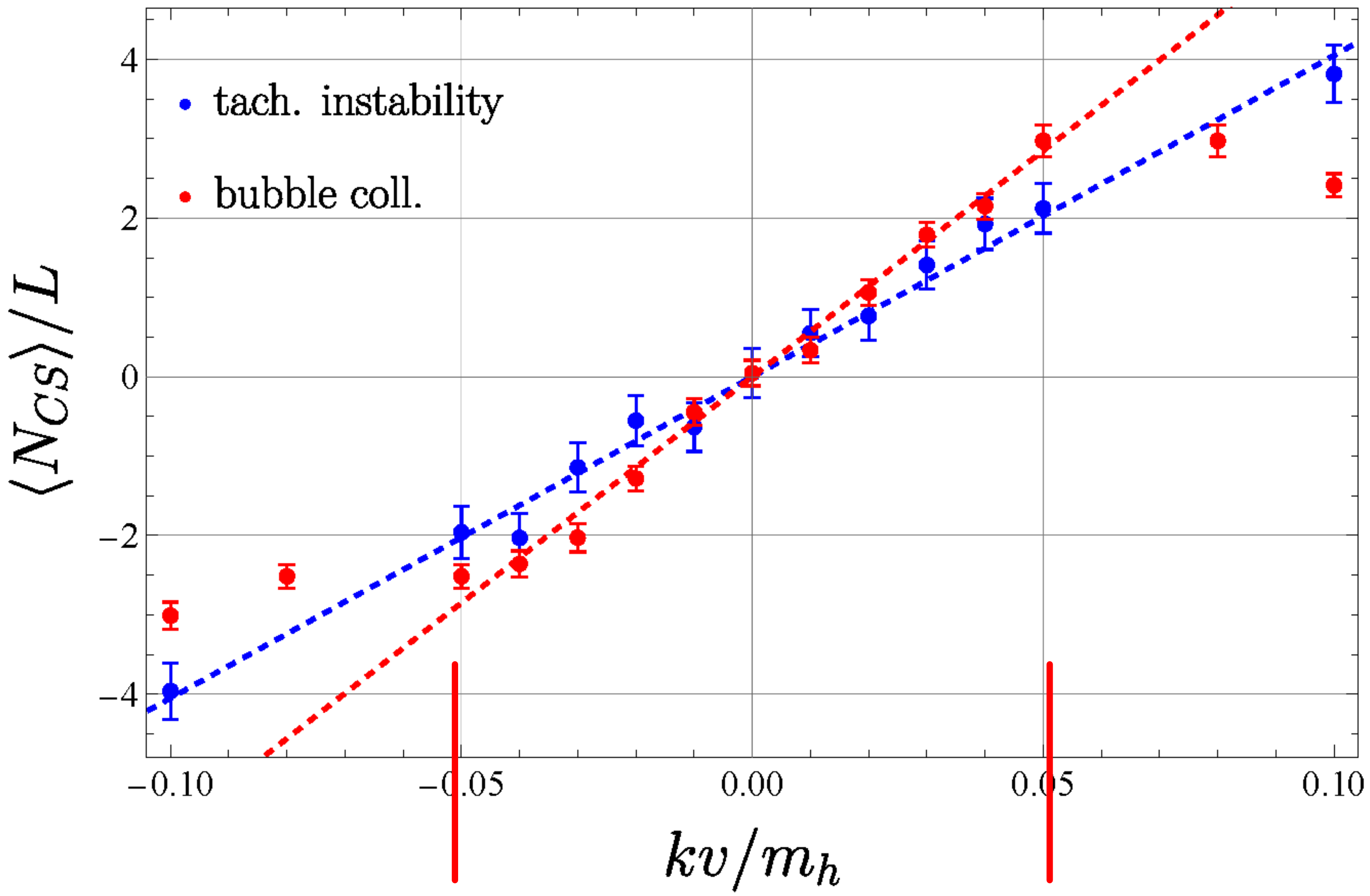




Blasi, MC, Gorghetto, Servant, *In preparation*

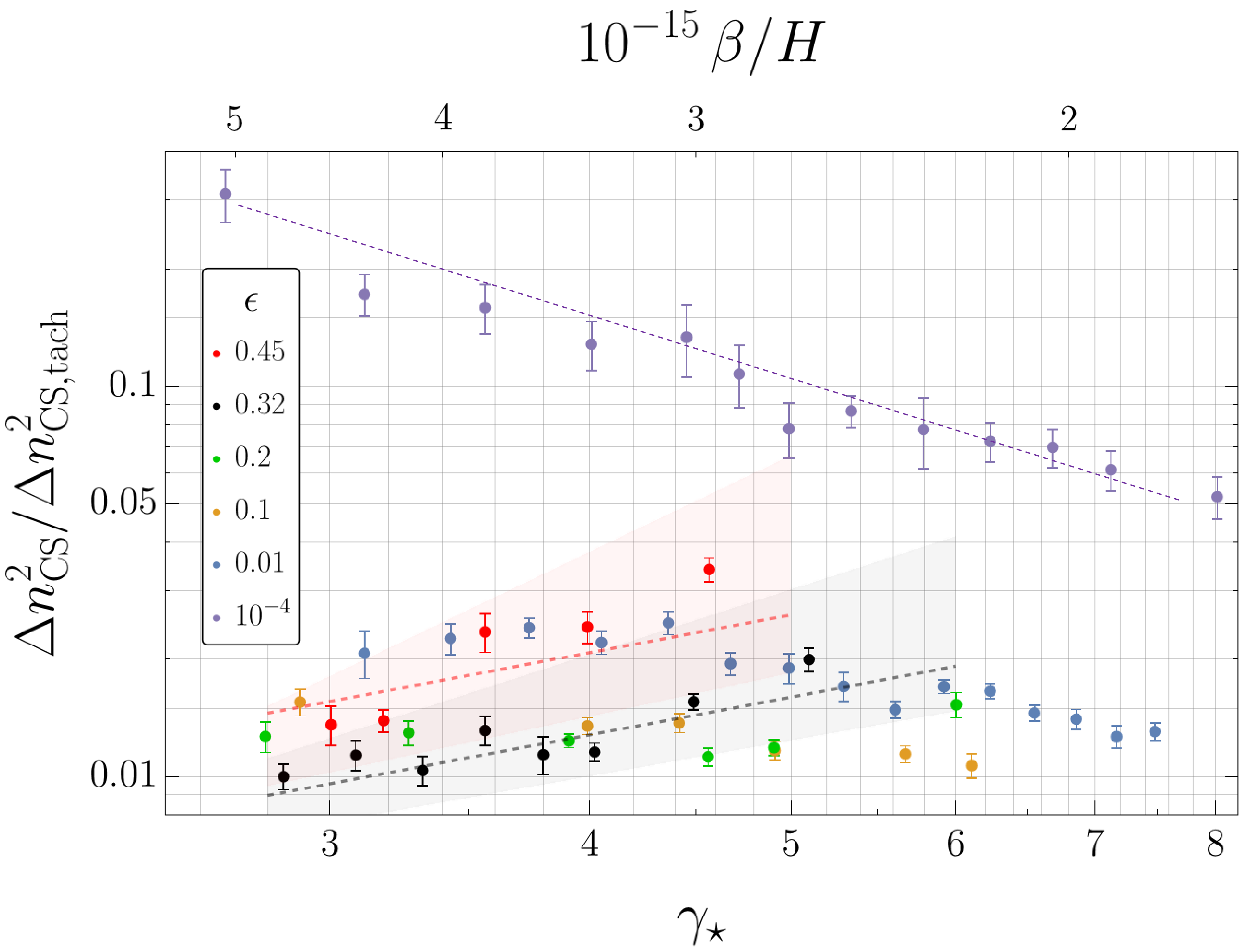
Dependence of Chern-Simons number on k





Blasi, MC, Gorghetto, Servant, *In preparation*

CP-preserving simulations: results on Chern-Simons variance



Yesterday's talk by N. Bhusal

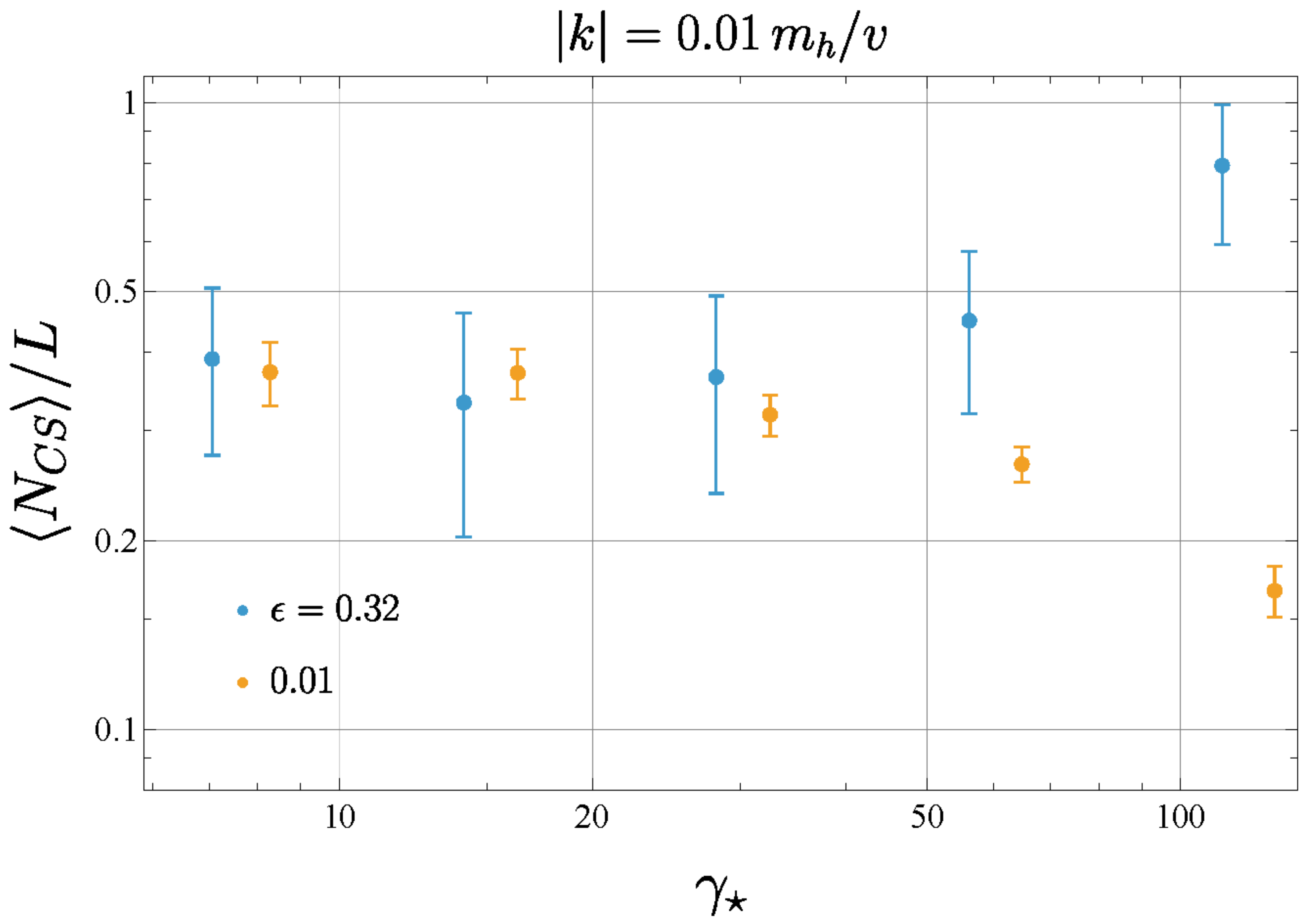
Dependence on potential's shape (ϵ)

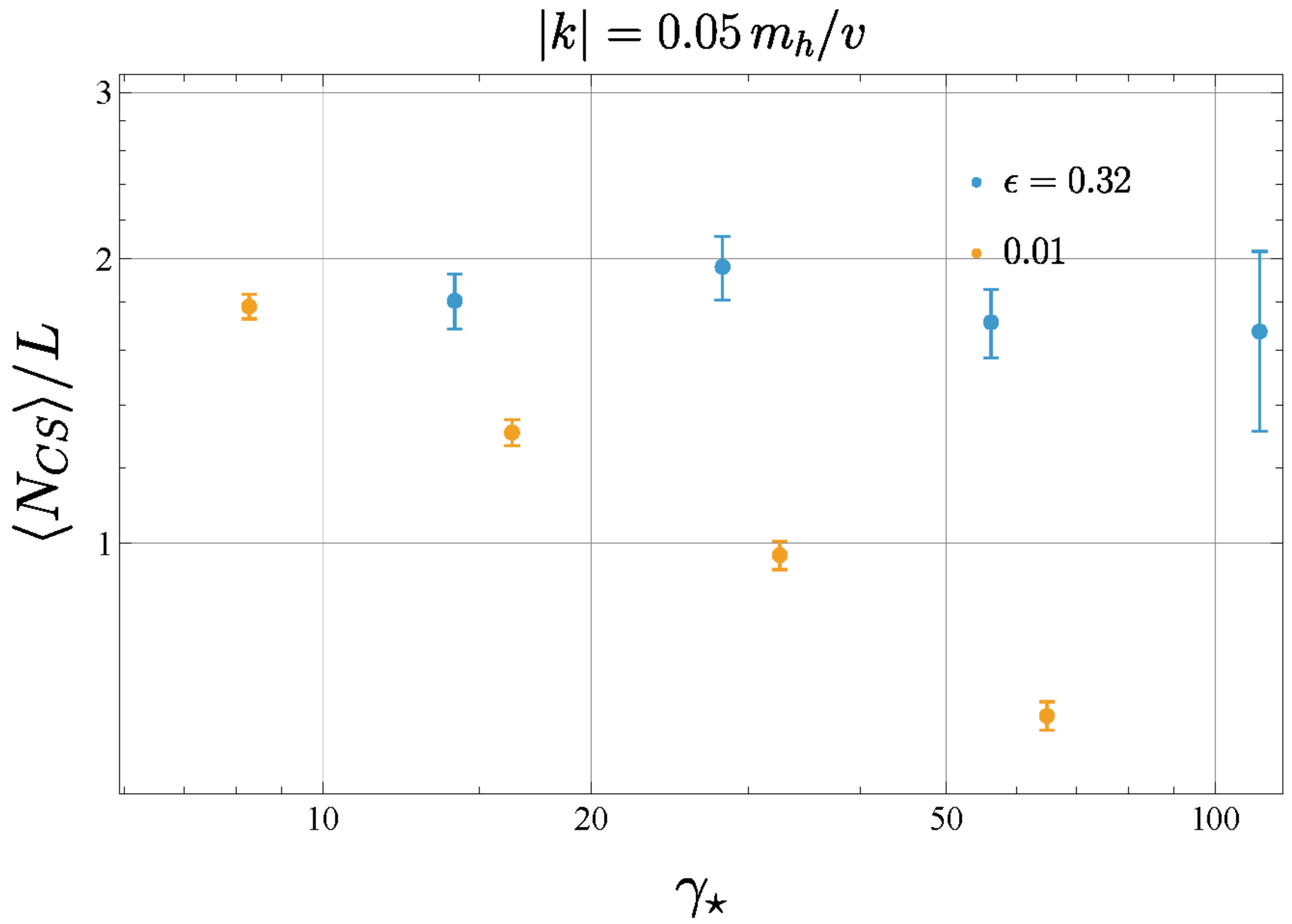
Sizeable baryon number production at large ϵ

Phys. Rev. Lett. 136 (2026) 241803 [2508.21825]

Dependence of Chern-Simons number on $\gamma_\star$ and ϵ

Extrapolation to physical scales, i.e. large Lorentz boost factor at collision $\gamma_\star \to \infty$





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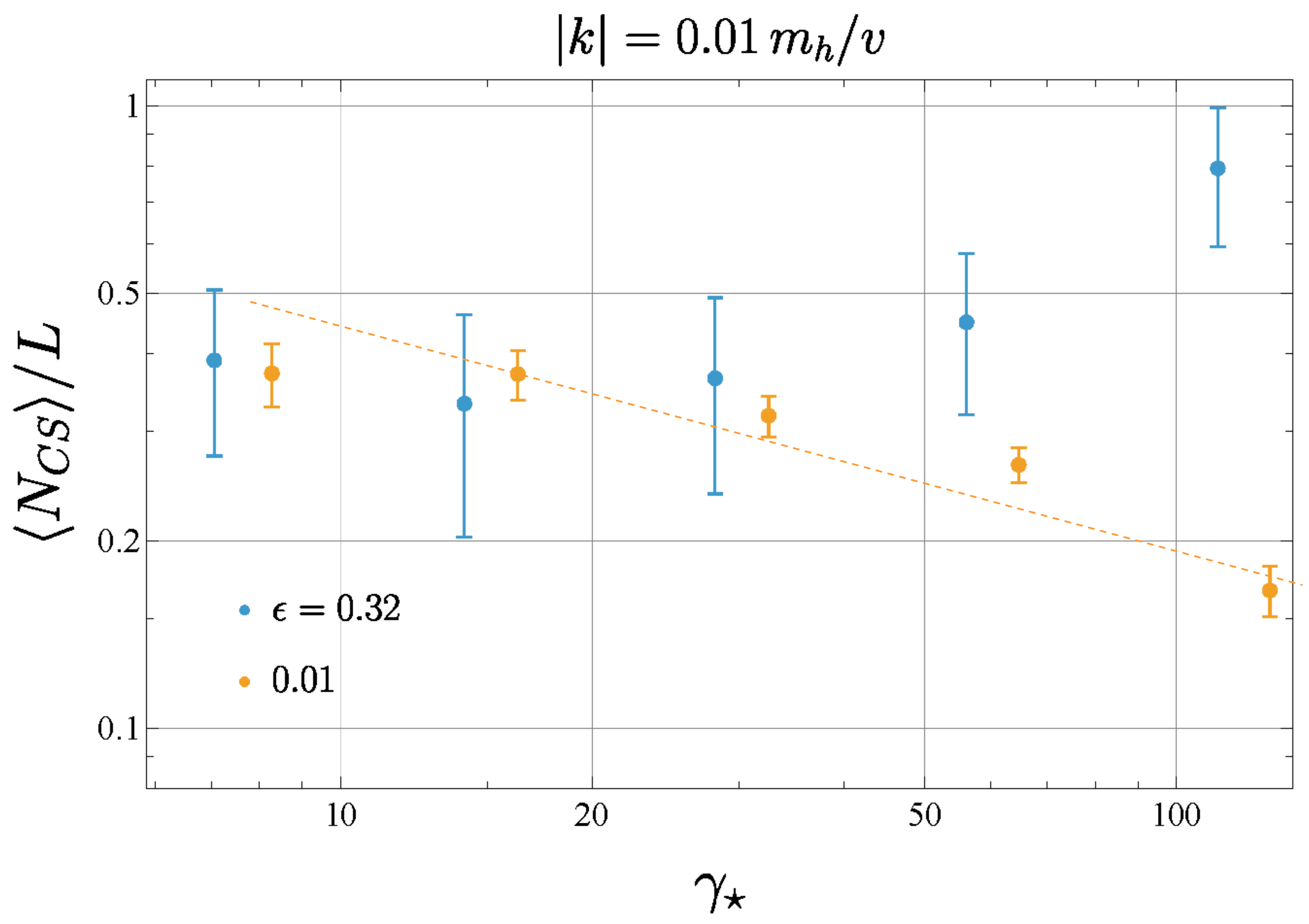
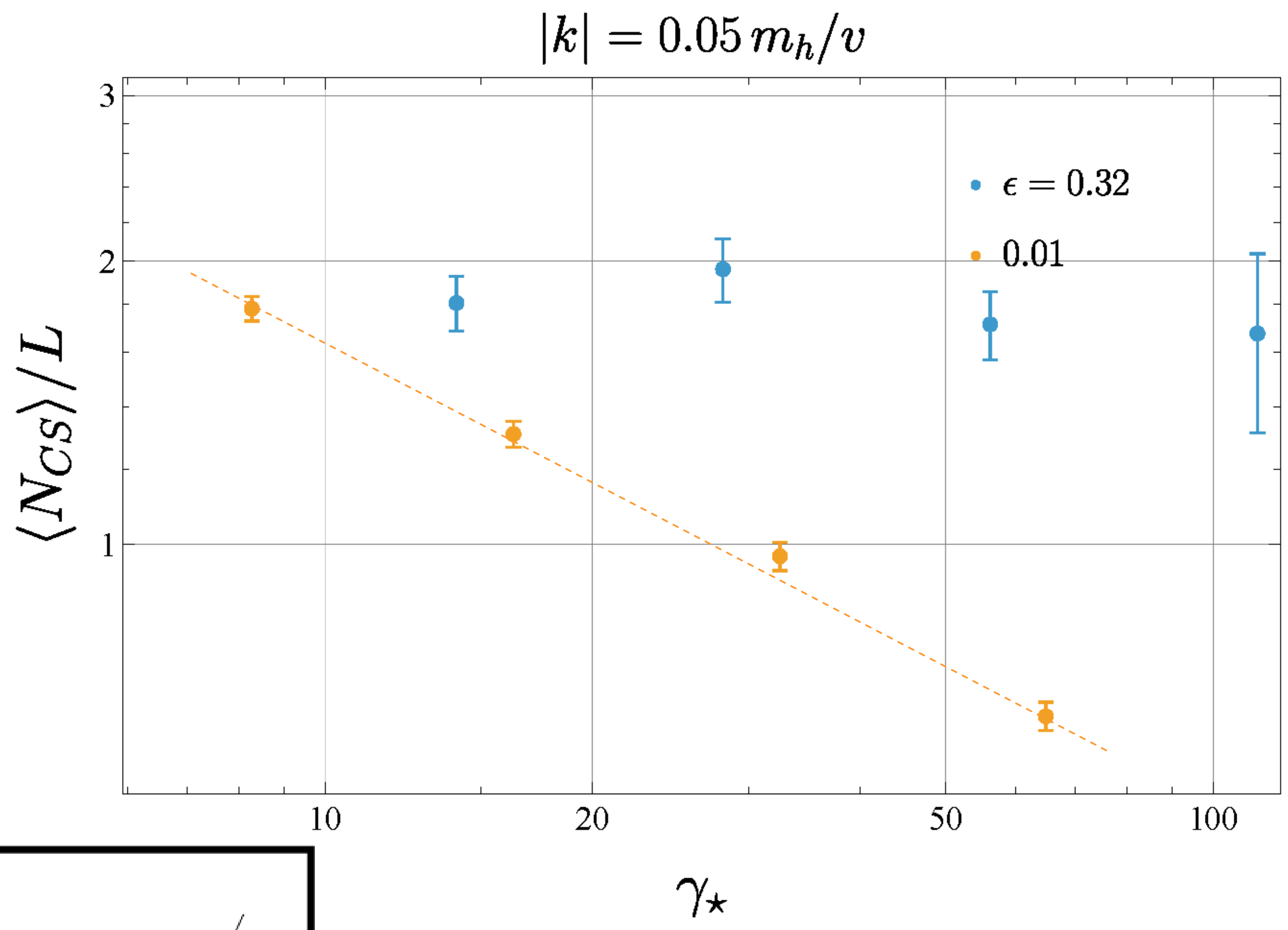
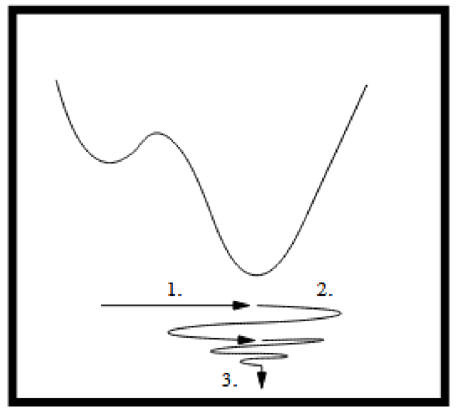




Small ϵ : decreasing Chern-Simons number density



non-degenerate

Blasi, MC, Gorghetto, Servant, *In preparation*

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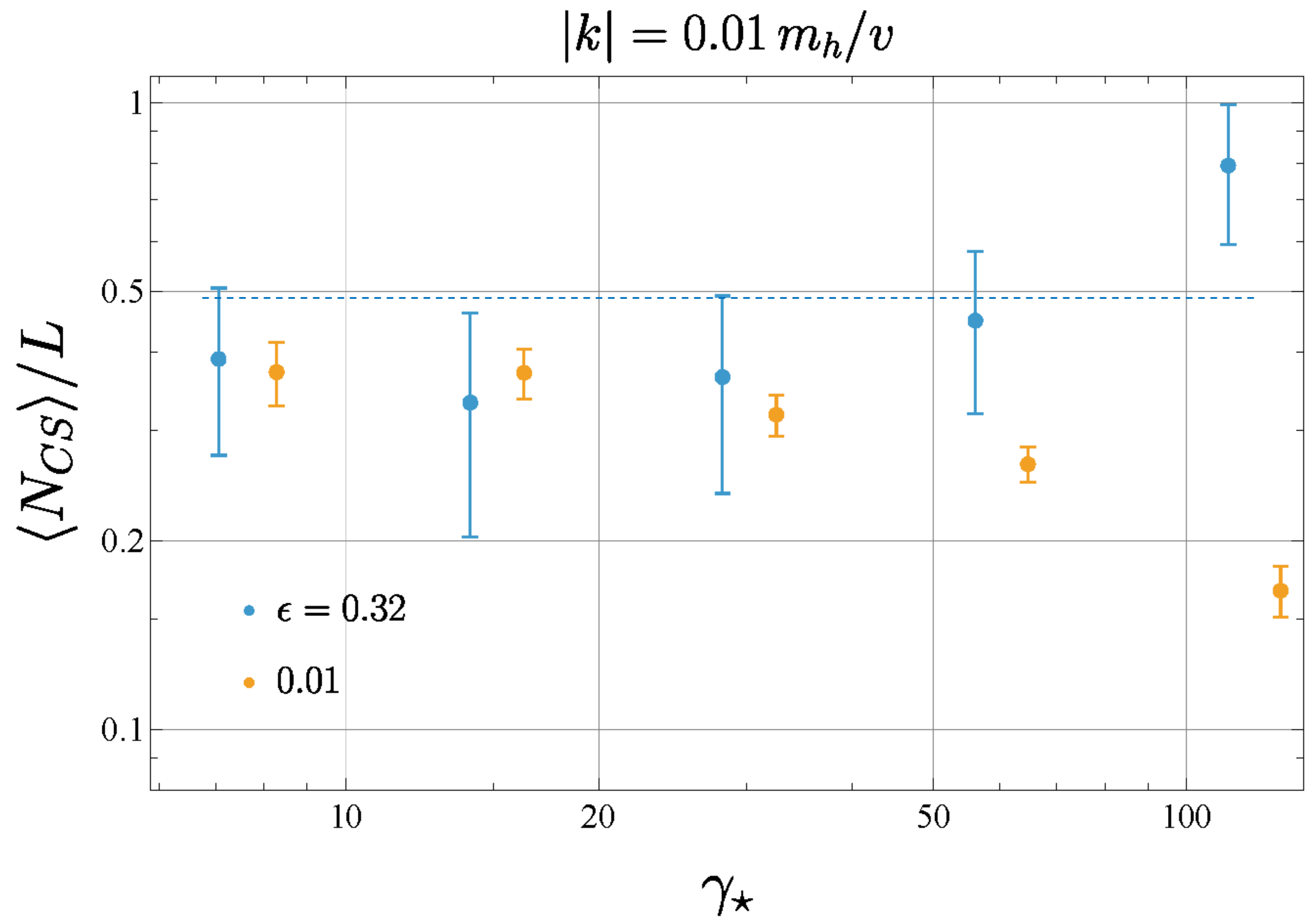
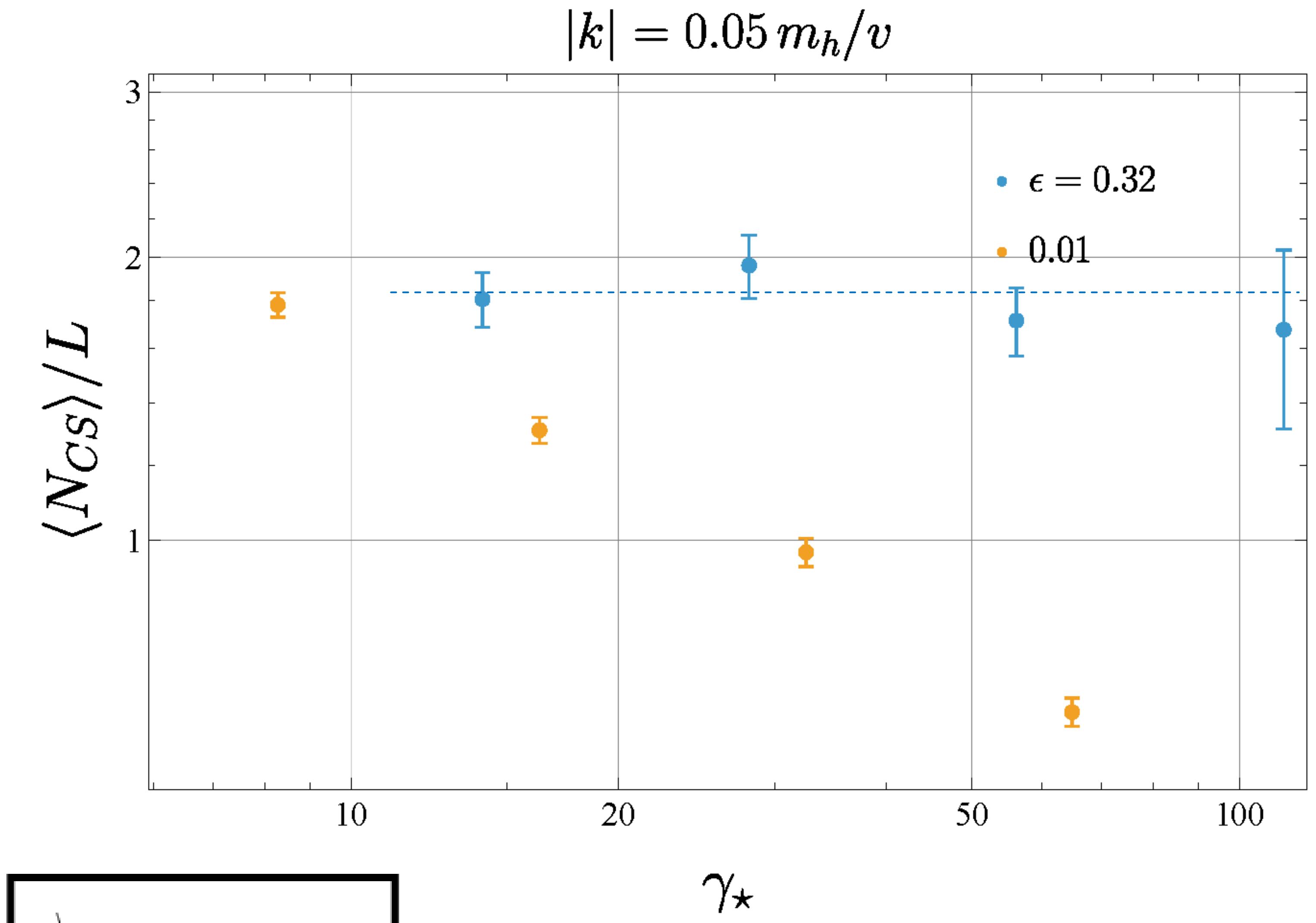
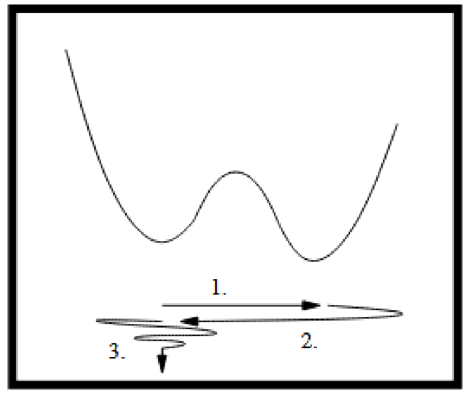




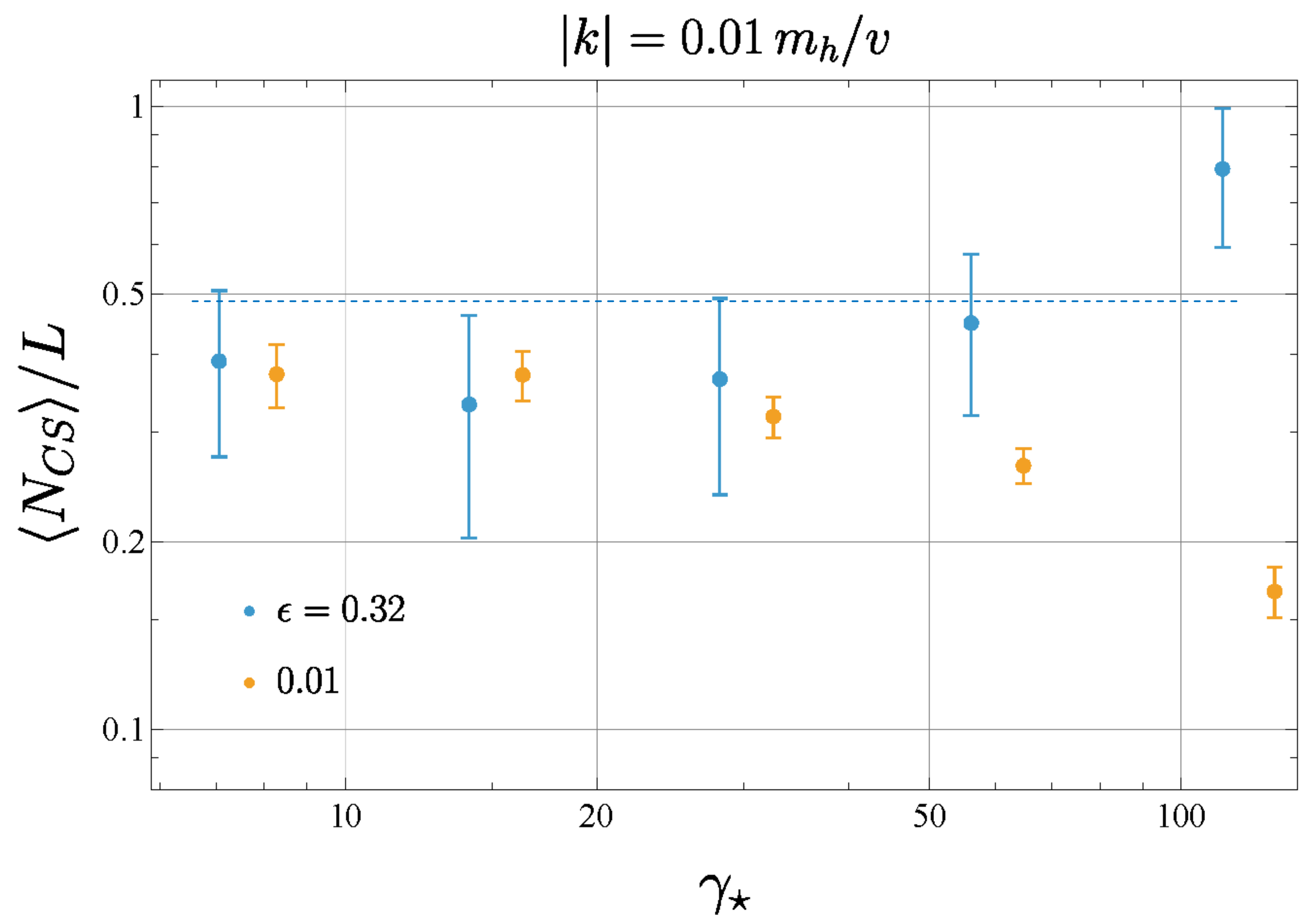
Large ϵ :   constant Chern-Simons number density

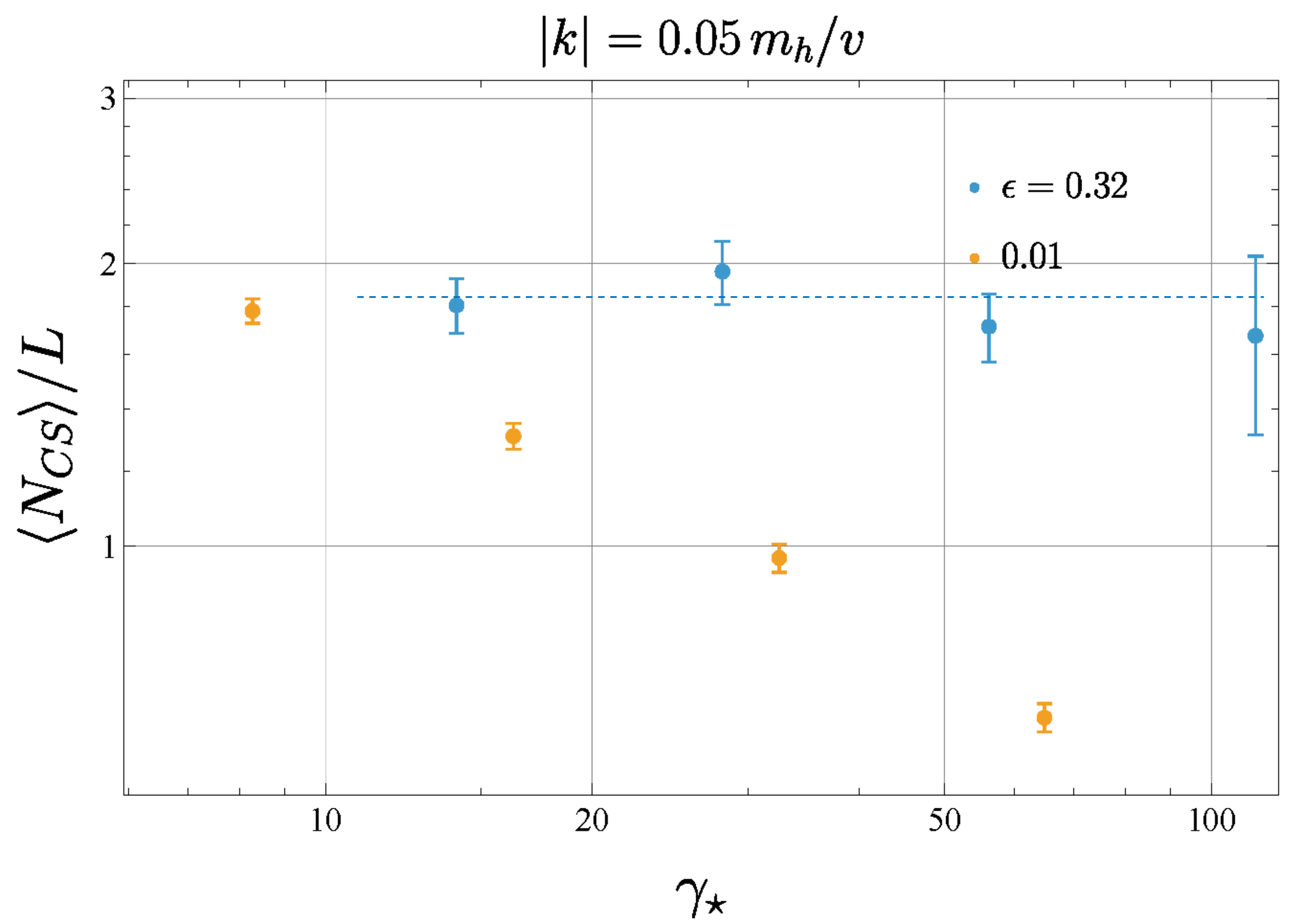


almost degenerate

Blasi, MC, Gorghetto, Servant, *In preparation*

C(P)-violation: (1+1)D with *U(1)*-gauge field





It confirms our results from CP-preserving simulations and it is promising for successful baryogenesis.

However, ultimate test to validate our mechanism of cold baryogenesis: (3+1)D simulations with SU(2)-gauge fields

Blasi, MC, Gorghetto, Servant, *In preparation*

Adding a *CP*-violating source: (3+1)D lattice simulations

Simulations of Higgs doublet and SU(2)-gauge fields:

CP-violating coefficient $k = \frac{g^2}{32\,\pi^2\Lambda^2}$

$$L = -\left|D_\mu\, \phi\right|^2 - \frac{1}{2}\, Tr\left[W_{\mu\nu}W^{\mu\nu}\right] - V(\phi)\ - k\ \phi^\dagger\phi\ Tr[W_{\mu\nu}\widetilde{W}^{\mu\nu}]$$

with EoM

$$D_\mu D^\mu \phi = \partial_{\phi^*} V(\phi) + k\ \phi\ Tr[W_{\mu\nu}\widetilde{W}^{\mu\nu}]$$

$$D_\nu (W^{\mu\nu} + 2k\ \phi^\dagger\phi\ \widetilde{W}^{\mu\nu}) = J_a^\mu\ T_a, \qquad J_a^\mu = 2g\ Im[\phi^\dagger\, T_a\, D^\mu \phi]$$

Blasi, MC, Gorghetto, Servant, *In preparation*

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$$D_\mu D^\mu\phi = \partial_{\phi^*}V(\phi) + k\;\phi\;Tr[W_{\mu\nu}\widetilde{W}^{\mu\nu}]$$

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Implementation of a non-Abelian topological term Tr$[W_{\mu\nu}\,\widetilde{W}^{\mu\nu}]$ is not trivial:

$$\frac{g^2}{32\,\pi^2\Lambda^2}Tr\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] = \partial_\mu\,J_{CS}^\mu$$

In the continuum

See e.g. Moore Nucl.Phys. B 480 (1996) 657-688,
Moore Phys.Rev. D 59 (1999) 014503

Blasi, MC, Gorghetto, Servant, *In preparation*

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with EoM $\quad D_\mu D^\mu\phi = \partial_{\phi^*}V(\phi) + k\,\phi\ Tr[W_{\mu\nu}\widetilde{W}^{\mu\nu}]$

$$D_\nu(W^{\mu\nu}+2k\,\phi^\dagger\phi\,\widetilde{W}^{\mu\nu}) = J^\mu_a\,T_a, \qquad J^\mu_a = 2g\,Im[\phi^\dagger\,T_a\,D^\mu\phi]$$

Implementation of a non-Abelian topological term Tr$[W_{\mu\nu}\,\widetilde{W}^{\mu\nu}]$ is not trivial:

$$\boxed{\frac{g^2}{32\,\pi^2\Lambda^2}Tr\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] \neq \partial_\mu\,J^\mu_{CS}}$$

On the lattice

No local operator reproducing an exact total derivative!

See e.g. Moore Nucl.Phys. B 480 (1996) 657-688,
Moore Phys.Rev. D 59 (1999) 014503

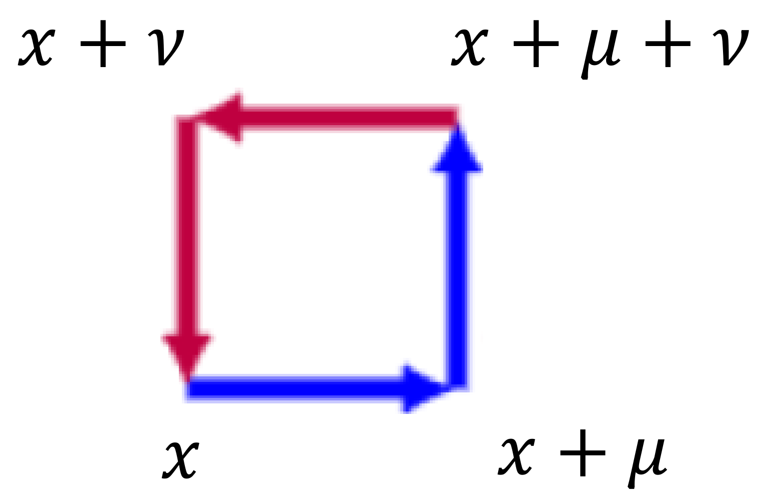
Blasi, MC, Gorghetto, Servant, *In preparation*

Technical details

$$- k\, \phi^{\dagger} \phi\, Tr\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] = 2\, k\, \phi^{\dagger} \phi\, E_i^a B_i^a \longrightarrow 2\, k\, \phi^{\dagger} \phi\, (E_i^a B_i^a)_{Latt}$$

Naïve discretization of the electric and magnetic fields: large discretization errors, large lattice artifacts

Plaquette $\quad U_{\mu\nu} \equiv$



$= U_{\mu}(x)\mathrm{U}_{\nu}(\mathrm{x}+\mu)\mathrm{U}_{\mu}^{\dagger}(\mathrm{x}+\nu)\mathrm{U}_{\nu}^{\dagger}(\mathrm{x}) \in SU(2)$

Smallest Wilson loop on the lattice

Blasi, MC, Gorghetto, Servant, *In preparation*

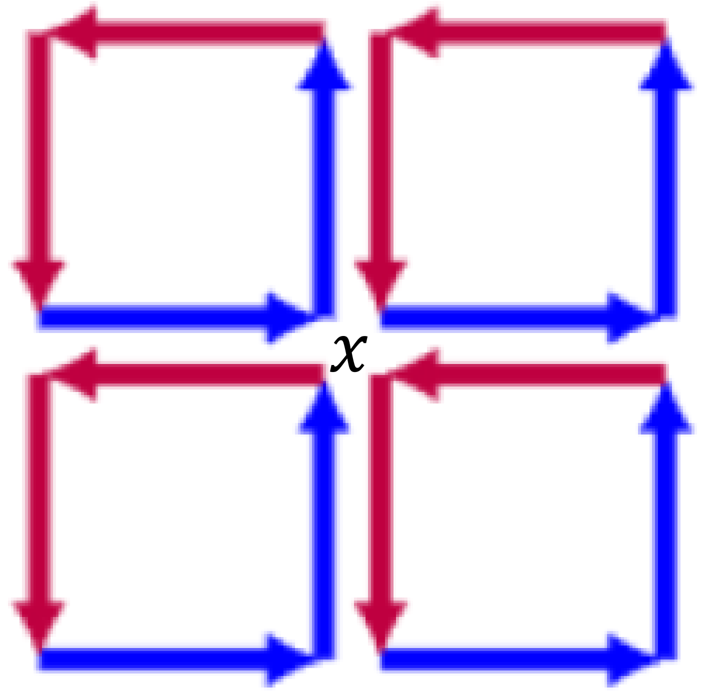
Technical details

$$- k\,\phi^{\dagger}\phi\, Tr\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] = 2\,k\,\phi^{\dagger}\phi\, E_i^a B_i^a \longrightarrow 2\,k\,\phi^{\dagger}\phi\,(E_i^a B_i^a)_{Latt}$$

Improved discretization of the electric and magnetic fields: smaller discretization errors, scaling as $O(dx^2)$

Clover

$\bar{U}_{\mu\nu} \equiv$



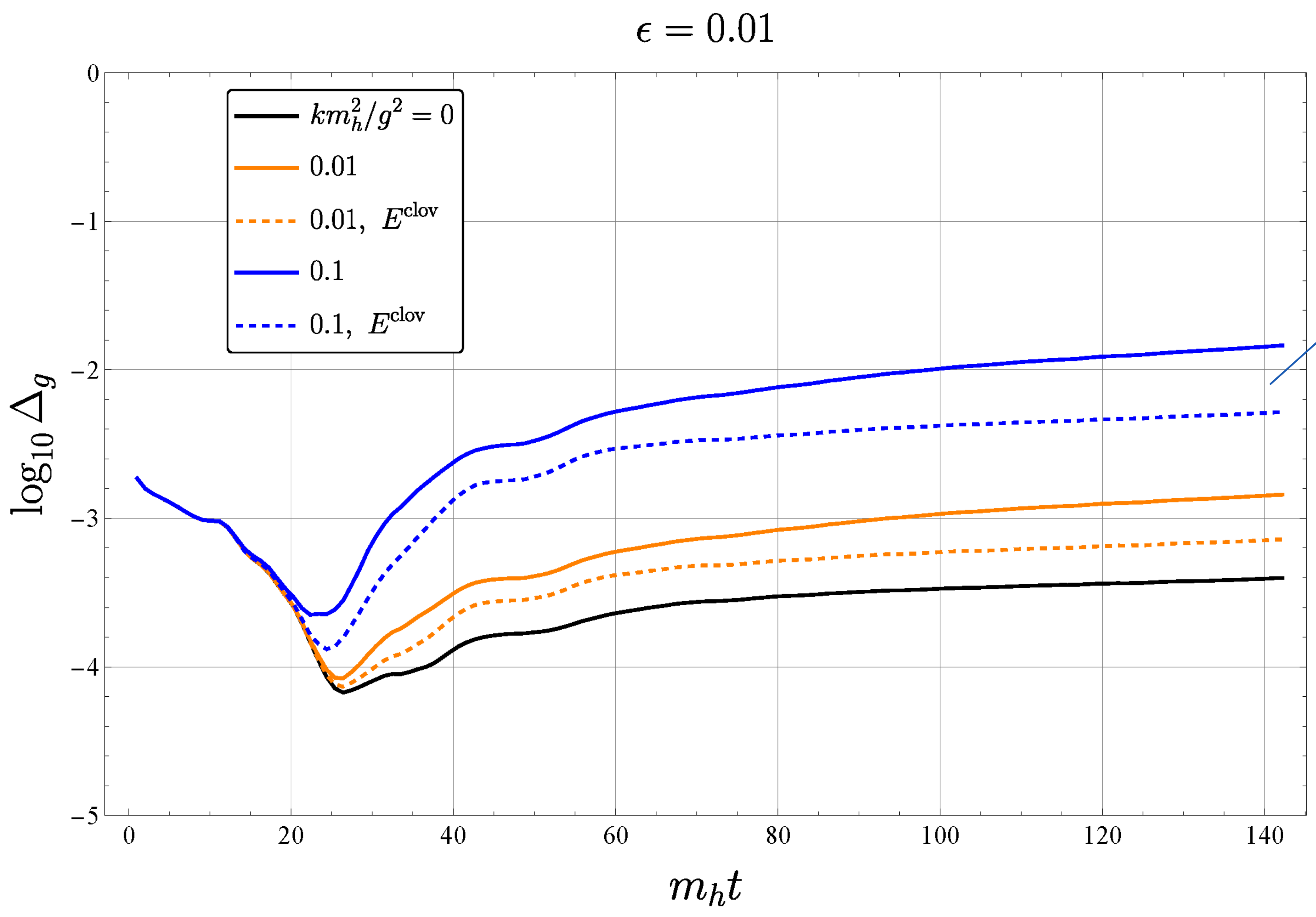
$= \frac{1}{4}\left(U_{\mu\nu} + U_{-\nu\mu} + U_{\nu-\mu} + U_{-\nu-\mu}\right)$

Centered at x

Blasi, MC, Gorghetto, Servant, *In preparation*

Adding a *CP*-violating source: Gauss constraint

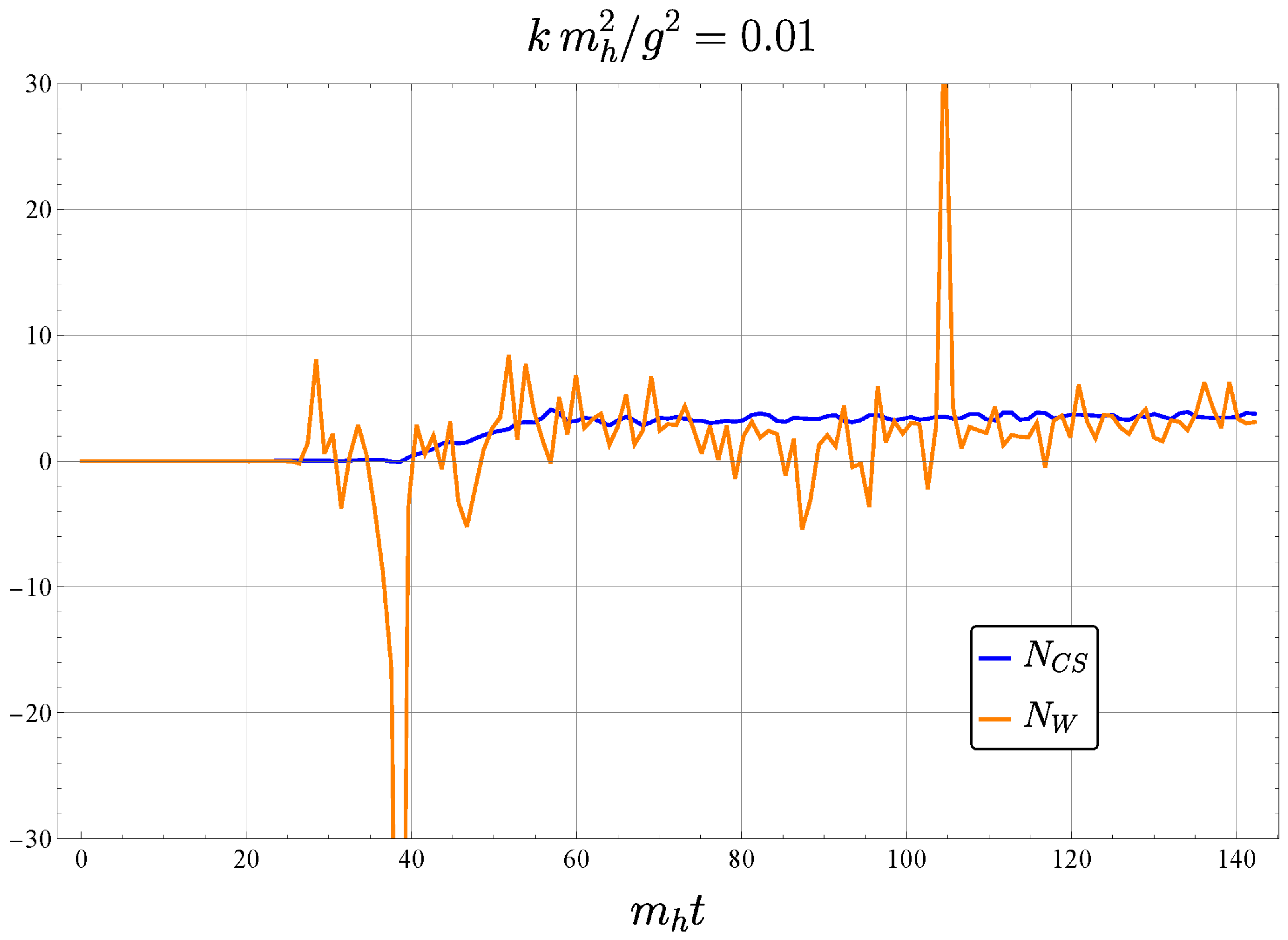
$$-k\,\phi^{\dagger}\phi\,Tr\left[W_{\mu\nu}\widetilde{W}^{\mu\nu}\right] = 2\,k\,\phi^{\dagger}\phi\,E_i^a B_i^a \longrightarrow 2\,k\,\phi^{\dagger}\phi\,(E_i^a B_i^a)_{Latt} = 2\,k\,\phi^{\dagger}\phi\,(E_i^{clov,a}\,B_i^{clov,a})$$



Clover configuration improves the conservation of the Gauss law

Blasi, MC, Gorghetto, Servant, *In preparation*

Convergence of N_{CS} and N_W



Blasi, MC, Gorghetto, Servant, *In preparation*

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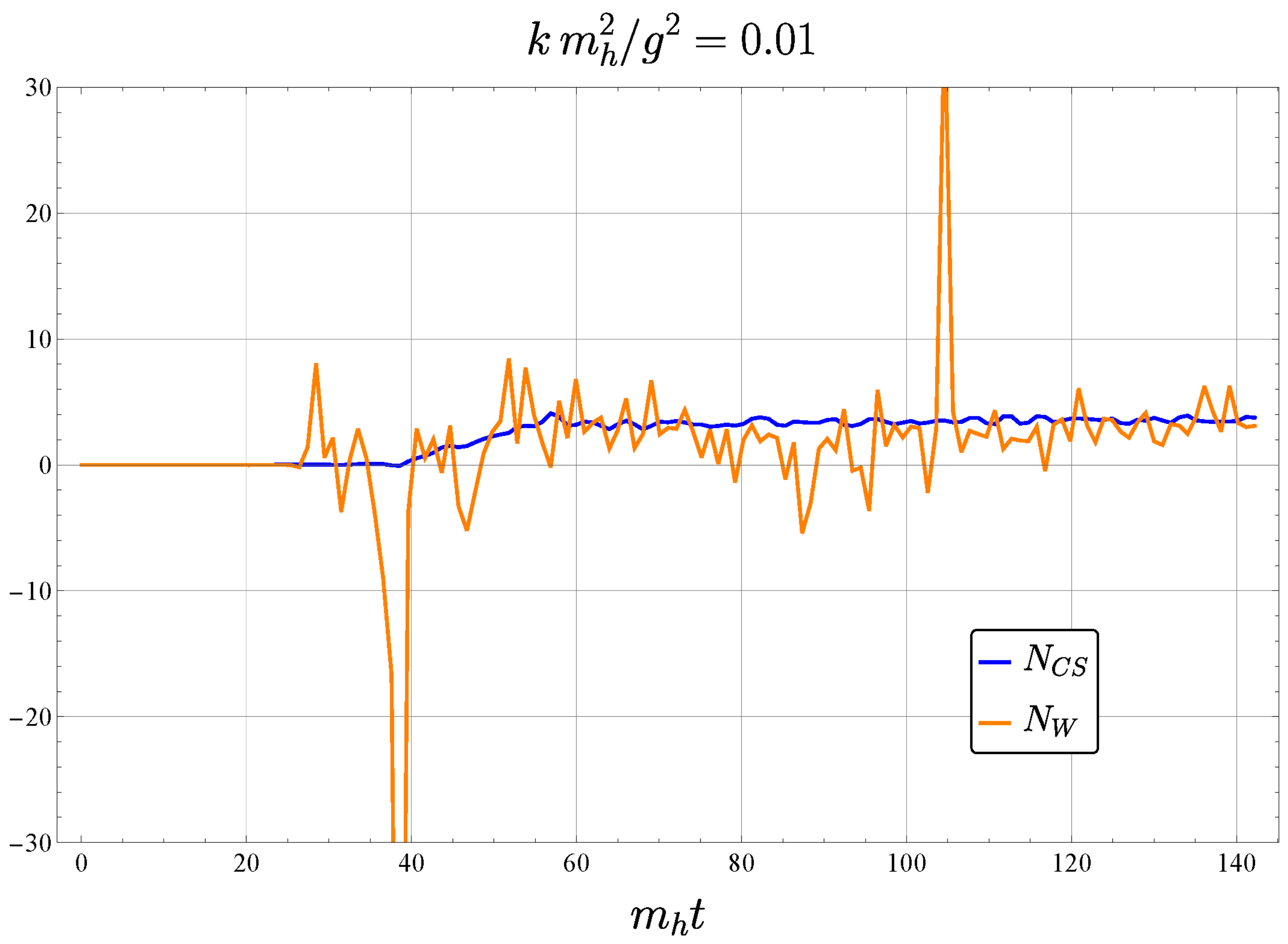


Ongoing: scan of the parameter space + dependence of Chern-Simons number density on k

Blasi, MC, Gorghetto, Servant, *In preparation*

Summary and outlook

- Novel realization of cold electroweak baryogenesis (i.e. at zero temperature) from Higgs Bubble Collisions in a strongly First Order ElectroWeak Phase Transition

- New possibilities of *electroweak baryogenesis* for models of EWPT with low reheat temperature and large bubble wall velocity

- Promising results from toy model in (1+1)D, with a relevant baryon number production for large $\epsilon > 0.2$

- Preliminary results from (3+1)D simulations with SU(2)-gauge fields

Next:

- Parameter scan of $\langle N_{CS} \rangle / L^3$ in (3+1)D
- Other sources of CP-violation
- Bubble walls with terminal velocities
- Multi-messenger cosmological signals (GWs and primordial magnetic fields)

Backup slides

A Mexican standoff

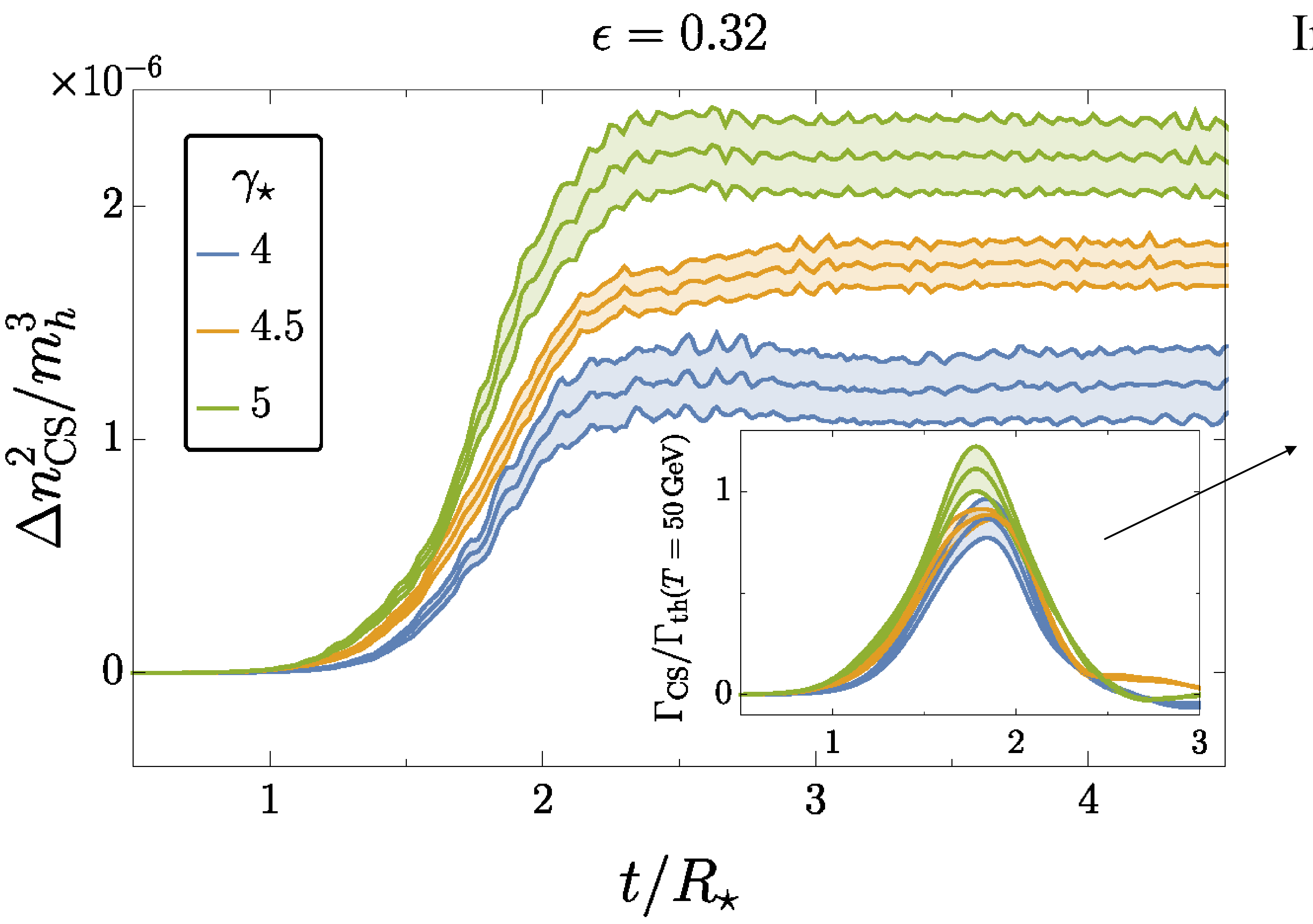
Original cold baryogenesis	*Cold baryogenesis from Higgs bubble collisions*	*EWB via charge transport*
quenched EW crossover	first-order PT	first-order PT
local	local	non-local
tachyonic instability	bubble collisions	bubble expansion
cold	cold	hot (thermal plasma)
EW-scale hybrid inflation	supercooled first-order EWPT	strong first-order EWPT

Adding a CP-violating source

→ Strongly First Order EW Phase Transition (runaway regime)

$$L = -\left|D_\mu \phi\right|^2 - \frac{1}{2} Tr\left[W_{\mu\nu}W^{\mu\nu}\right] - V(\phi) + CP \quad \text{with toy potential} \quad V(\phi) = \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 + \frac{1}{8\Lambda^2}\phi^6$$

Chern-Simons variance and rate



Increase $R_\star$ to extrapolate to cosmological scales $\gamma_\star \gg 1$

Effective sphaleron rate:

1) for $t \sim R_\star$

2) same order of magnitude as thermal sphaleron rate in the symmetric phase

Baryon number violation in the SM

In the SM, B and L are global accidental symmetries.

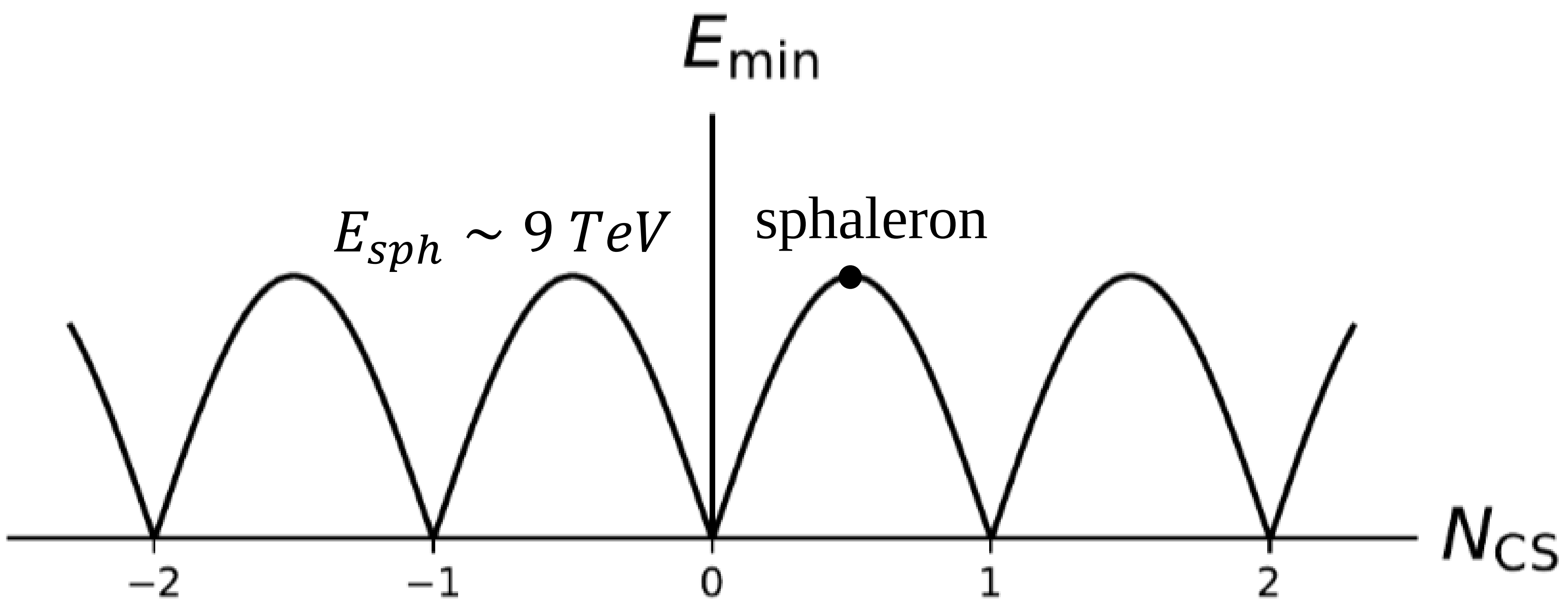
Both B and L are violated at the quantum level by the chiral anomaly: $\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = N_F \frac{g^2}{32\,\pi^2}\, Tr[W_{\mu\nu}\widetilde{W}^{\mu\nu}]$

Chern-Simons number of the *SU(2)*-gauge fields: $\Delta N_{CS} = \int d^3x\; J^0_{CS} = \frac{g^2}{32\,\pi^2} \int d^3x\; Tr[W^{\mu\nu}\,\widetilde{W}_{\mu\nu}]$

ΔN_{CS} related to $U(1)_B$ violation via $\Delta B = \Delta L = N_F\, \Delta N_{CS}$

$\boldsymbol{B - L}$ conserved

$\boldsymbol{B + L}$ violated when processes changing N_{CS}



Electroweak sphalerons

D'Onofrio, et al., Phys. Rev. Lett. 113, 141602 (2014)

T

EW **symmetric** phase

$\Gamma_{th} \sim 25\, \alpha_w^5 T^4$

$T_c \simeq 160\,\text{GeV}$

$\Gamma \sim T^4 e^{-E_{sph}(T)/T}$

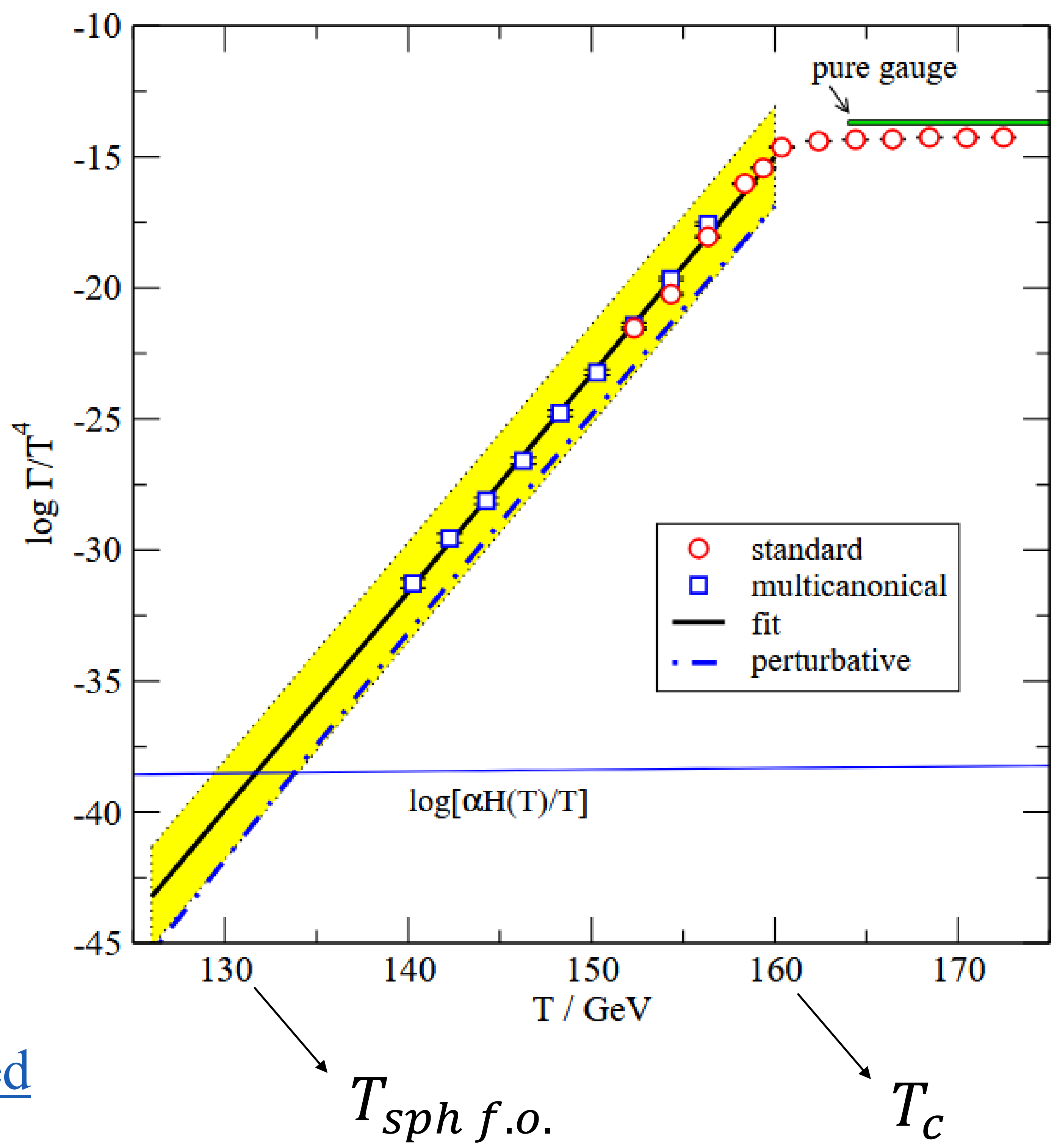
EW **broken** phase

$E_{sph}(T) = m_W(T)/\alpha_W \propto \langle \phi(T) \rangle$

Chern-Simons transitions suppressed

when T $< \langle \phi(T) \rangle$

$T_{sph\ f.o.} \simeq 130$ GeV



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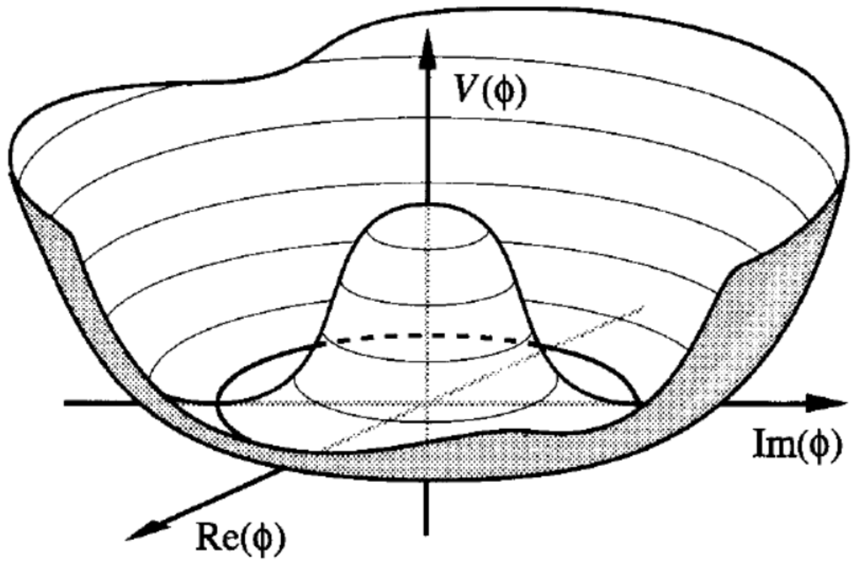
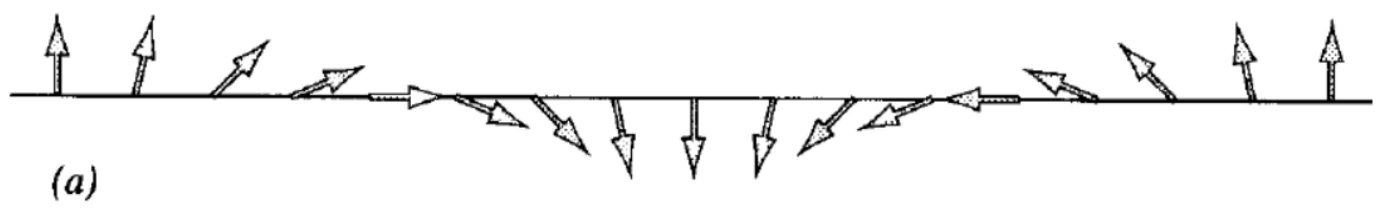
Baryons from *SU(2)* textures

EW symmetry breaking allows for non-trivial Higgs field configurations which play a role in $U(1)_B$ violation

Textures = field configuration where ϕ is in the vacuum manifold M everywhere but maps non-trivially space onto M

<u>*In 1+1d:*</u> $M = U(1) \simeq S^1$





$N_W = 1$

Vilenkin, '94

$\pi_1(S^1) = \mathbb{Z}$

Textures labeled by integer Higgs winding number: $N_W = \dfrac{1}{2\,\pi} \displaystyle\int dx \;\; \partial_x \, Arg\, \phi$

Energy due to field gradient only → texture collapses to minimize it

Baryons from *SU(2)* textures

EW symmetry breaking allows for non-trivial Higgs field configurations which play a role in $U(1)_B$ violation

Textures = field configuration where ϕ is in the vacuum manifold M everywhere but maps non-trivially space onto M

<u>*In 1+3d:*</u> $M = SU(2) \times U(1)/U(1) \simeq S^3$ in the SM

$$N_W = \frac{1}{24\,\pi^2} \int d^3x \;\; \epsilon_{ijk} Tr[(\partial_i U)U^\dagger(\partial_j\, U)U^\dagger(\partial_k U)U^\dagger]$$

$$U = \frac{(i\,\sigma^2\,\phi^*, \phi)}{\phi^\dagger \phi} \in SU(2)$$

$\Delta N_W(t)$ gauge invariant

$\mathrm{N_W}(t) - N_{CS}(t)$ gauge invariant

$U(x,t)$ defined iff $\phi^\dagger \phi \neq 0$

$$\pi_3(S^3) = \mathbb{Z}$$

Gauge textures labeled by $N_W - N_{CS} \neq 0$

Martina Cataldi

Baryons from *SU(2)* textures

Turok, Zadrozny, NPB, '91

Gauge textures collapse into minimal energy (vacuum) configuration where $\boxed{D_\mu \phi = 0 \;\Leftrightarrow\; N_{CS} = N_W}$

$$\underset{N_W - N_{CS} \neq 0}{\text{Gauge textures}} \xrightarrow{\textit{collapse}} \underset{N_W - N_{CS} = 0}{\text{Vacuum configuration}}$$

If **large** texture: $R > R_c \sim m_W^{-1}$ $\longrightarrow$ Dressing: $\Delta N_W = 0, \quad \Delta N_{CS} \neq 0$ $\longrightarrow$ Baryon production!

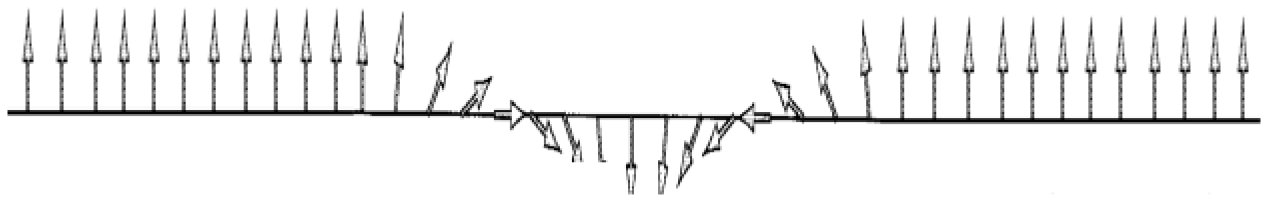
$\longrightarrow$ In addition to thermal sphalerons, there exists another mechanism (dressing of SM textures) operating even at $T < T_{sph\ f.o.} = 130$ GeV

Baryons from *SU(2)* textures

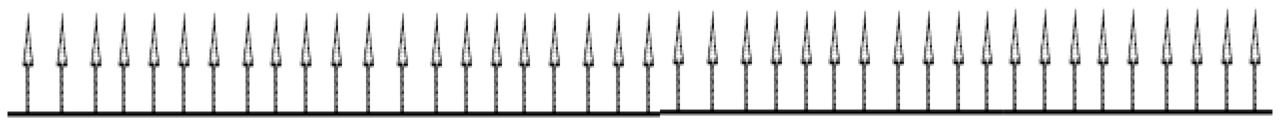
Turok, Zadrozny, NPB, ‘91

Gauge texture with $N_W - N_{CS} = 1$

Small texture: $R < R_c \sim m_W^{-1}$



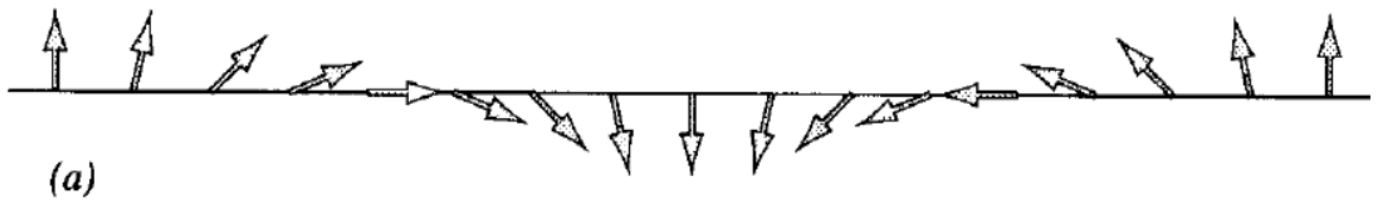
$\boldsymbol{R}$ $\boldsymbol{m_W^{-1}}$



Unwinding:

$\Delta N_W = -1, \qquad \Delta N_{CS} = 0$

Large texture: $R > R_c \sim m_W^{-1}$



$\boldsymbol{R}$ $\boldsymbol{m_W^{-1}}$

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

Dressing:

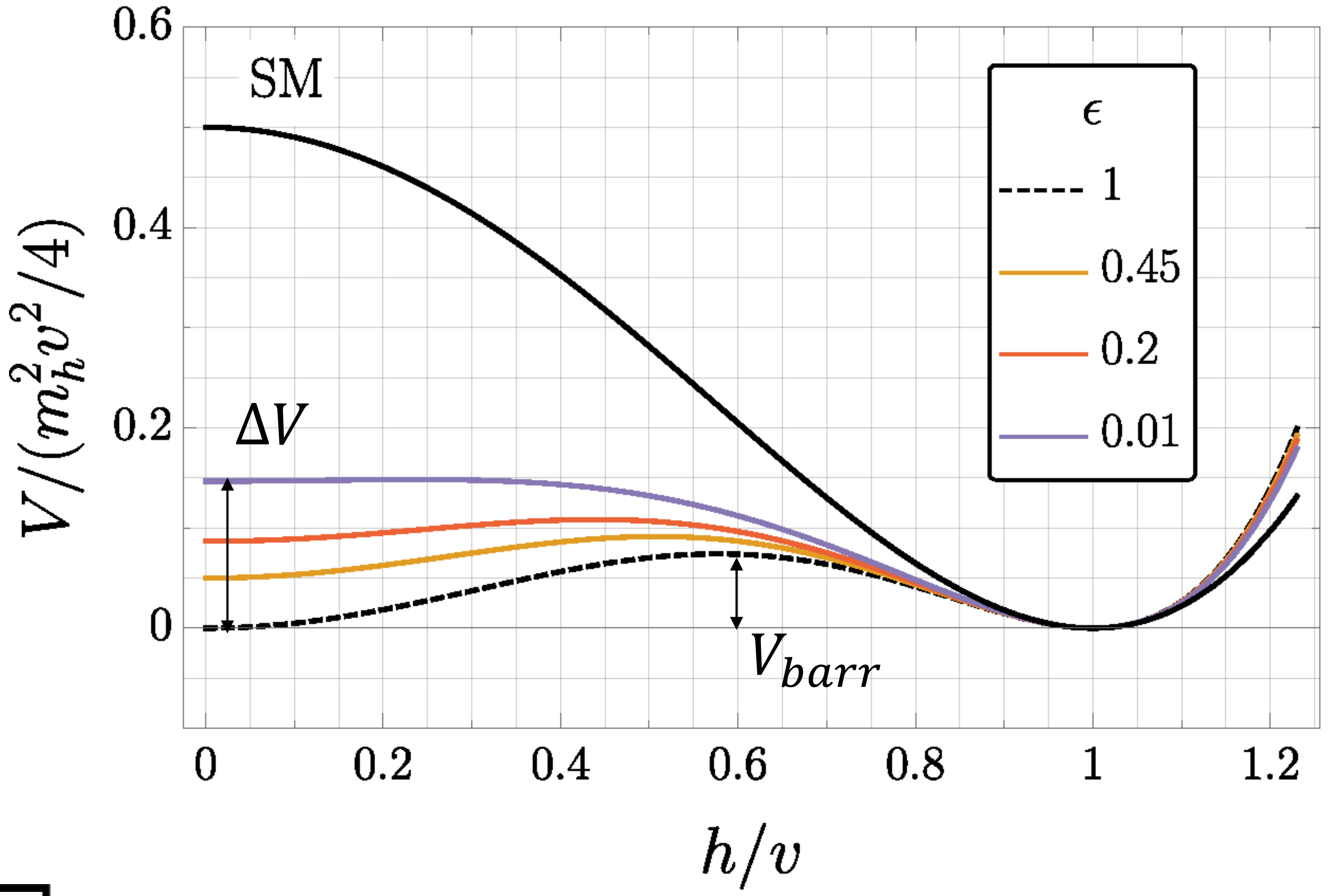
$\Delta N_W = 0, \qquad \Delta N_{CS} = 1$

Baryon production!

1) Degeneracy parameter

$$\boxed{\epsilon = \frac{V_{barr}}{V_{barr} + |\Delta V|} \in (0,1)}$$

Jinno et al., 1906.02588

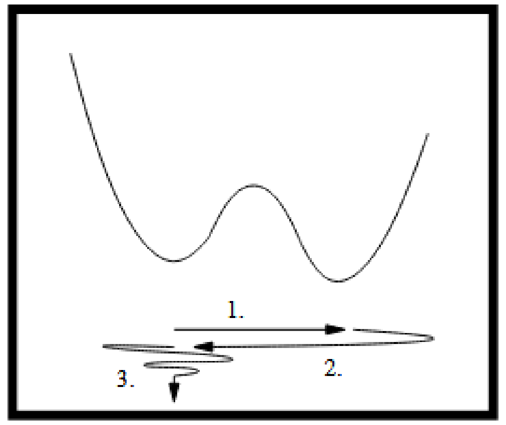


We vary the potential shape, since this controls the dynamics of wall-wall collisions

For $\epsilon \to 1$

- shallow potential with large barrier
- likely to restore false vacuum after collision

elastic bubble collisions



almost degenerate

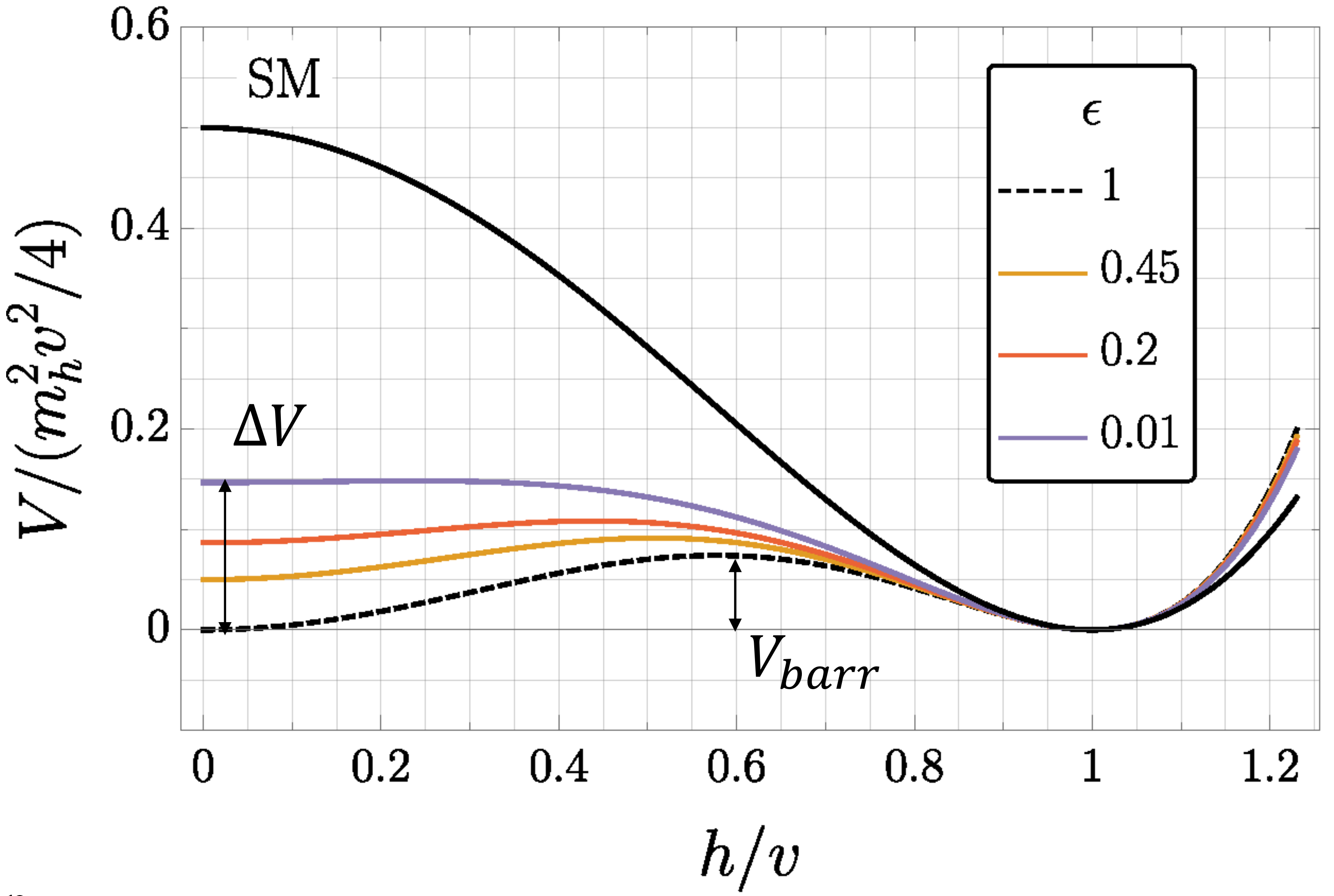
Konstandin, Servant, JCAP07(2011)024

Martina Cataldi

1) Degeneracy parameter

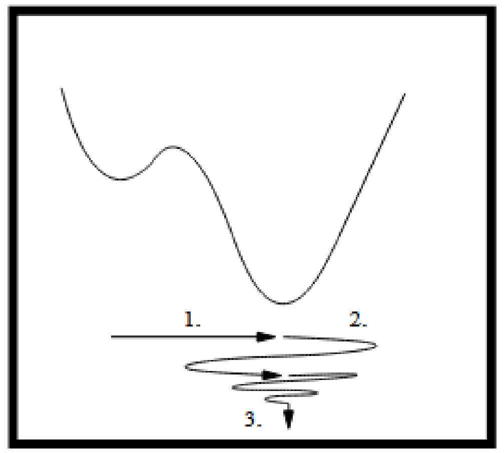
$$\boxed{\epsilon = \frac{V_{barr}}{V_{barr} + |\Delta V|} \in (0,1)}$$

Jinno et al., 1906.02588



We vary the potential shape, since this controls the dynamics of wall-wall collisions

For $\epsilon \to 0$



non-degenerate

- deep potential with small barrier
- not likely to restore false vacuum after collision

inelastic bubble collisions

Konstandin, Servant, JCAP07(2011)024

Martina Cataldi

2) Boost factor of bubble walls at collision

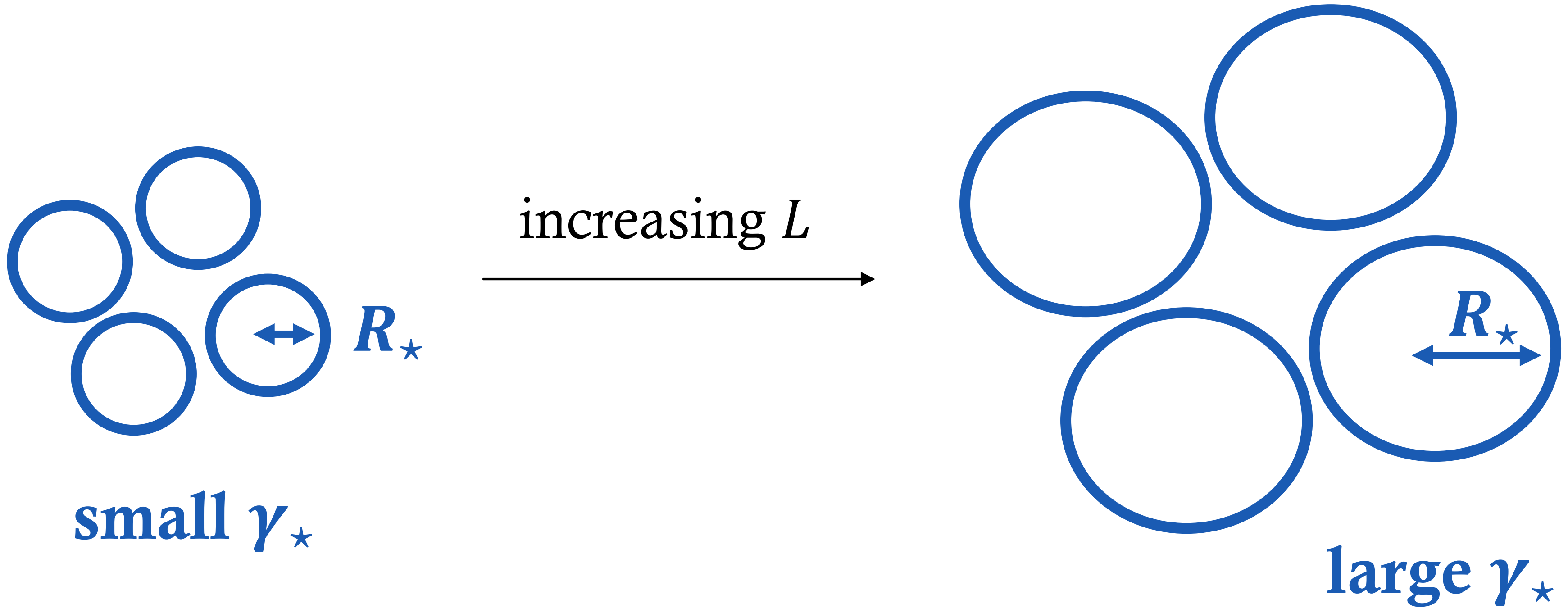
bubble size at collision

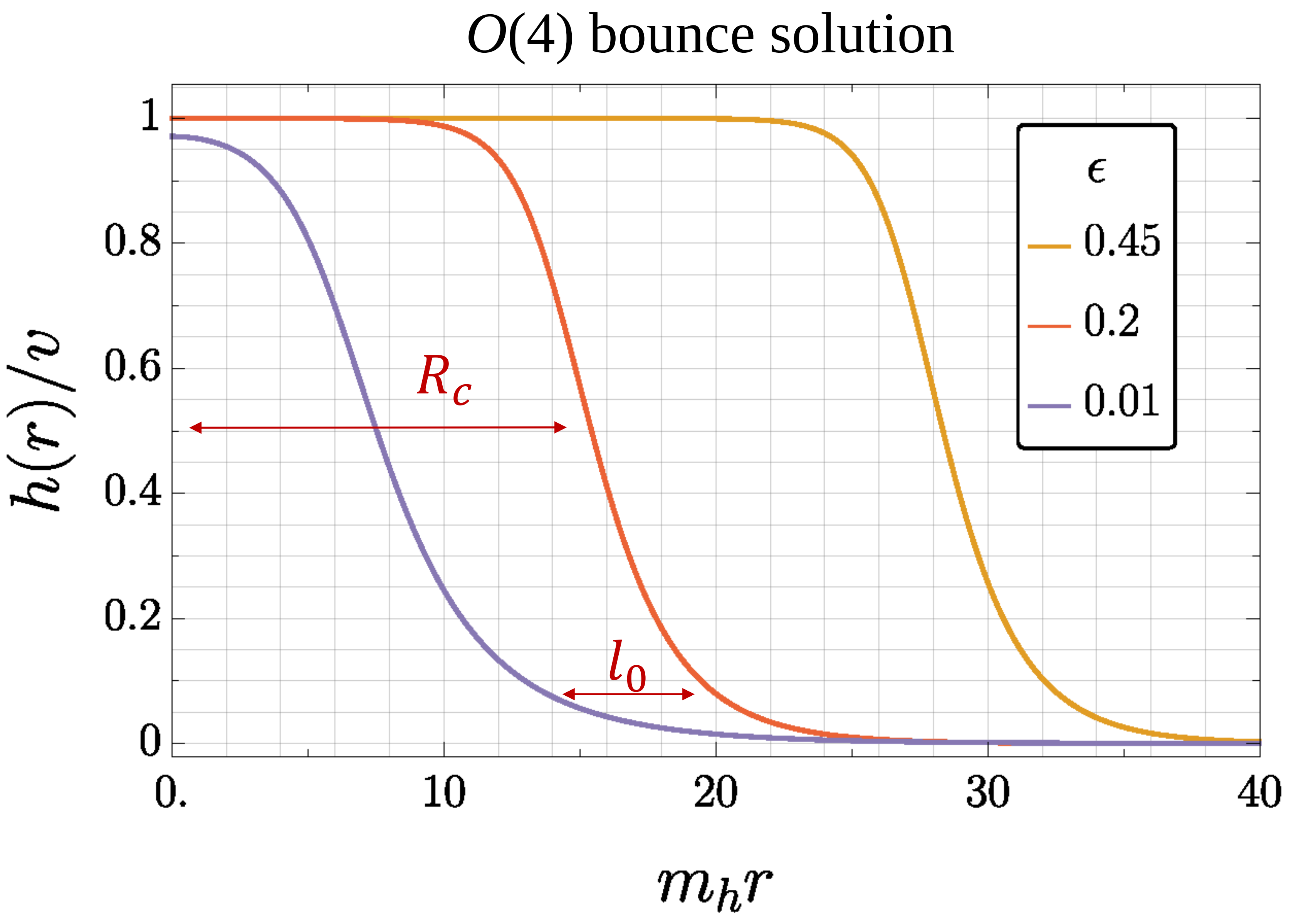
box length

$$\boxed{\gamma_\star = \frac{R_\star}{R_c} \sim \frac{L}{R_c}\,(N_{bubble})^{-\frac{1}{3}}}$$

number of bubbles

resolving the wall on the lattice $\quad \Delta x \ll l_\star = \frac{l_0}{\gamma_\star}$





physical limit $\gamma_\star \to \infty$

Martina Cataldi

Convergence of N_W and N_{CS}

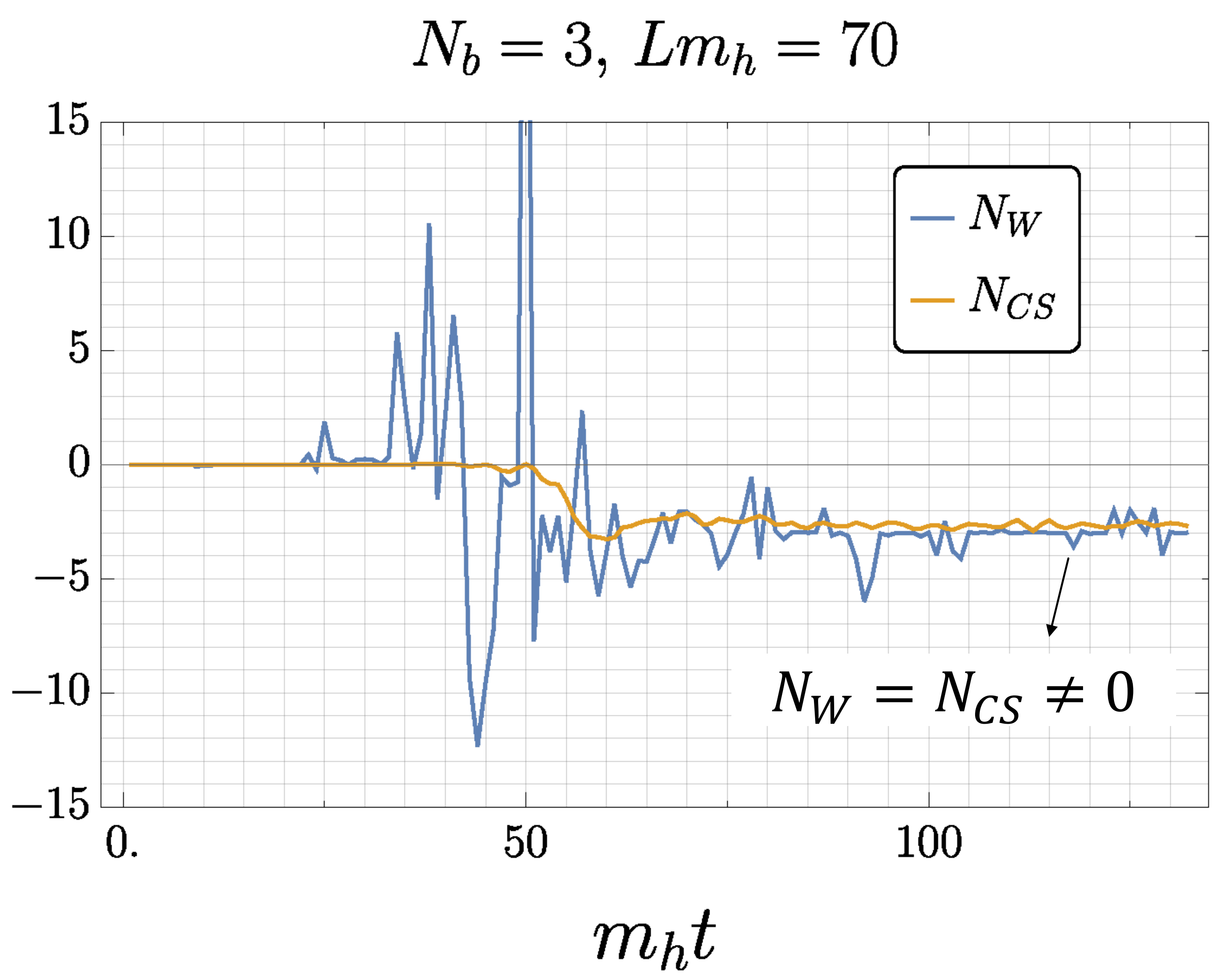
→ N_{CS} asymptotically relaxes to N_W
(in the vacuum $N_{CS} = N_W$)

→ It can produce Chern-Simons number transitions

effective sphaleron rate

→ **Non-zero Chern-Simons rate**

$$\boxed{\Gamma_{CS} = \frac{1}{L^3}\frac{d\Delta N_{CS}^2(t)}{dt} \equiv \frac{d\Delta n_{CS}^2(t)}{dt}}$$



with Chern-Simons variance (averaged over many realizations) $\Delta N_{CS}^2(t) \equiv \langle N_{CS}(t)^2\rangle - \langle N_{CS}(t)\rangle^2$

Backup – Baryon asymmetry estimate

Boltzmann equation for baryon number density:

$$\frac{\partial}{\partial t} n_b = \Gamma(\xi - \cancel{A\, n_b})$$

washout

effective chemical potential $\xi \equiv \frac{\mu}{T}$

CP-violating source via dim-6 operator

$$O = \frac{g^2}{32\,\pi^2\,\Lambda^2}\,\phi^\dagger\phi W^a_{\mu\nu}\widetilde{W}^{\mu\nu,a}$$

generating an effective chemical potential $\quad \mu = N_F^{-1}\,\frac{d}{dt}\,\langle\phi^\dagger\phi\rangle$

Given the parametrization $\Delta n^2_{CS} \propto \gamma_\star^a$ (thus $\Gamma_{CS} \propto \gamma_\star^{a-1}$), the baryon yield to entropy density ratio can be estimated as

$$\frac{n_b}{s} = \frac{1}{s}\int dt\,\Gamma_{CS}(t)\,\frac{\mu(t)}{T_{eff}(T)} \simeq 10^{-10}\,\gamma_\star^{\frac{3(a-1)}{4}}\left(\frac{30\,GeV}{T_{rh}}\right)^3\left(\frac{10\,TeV}{\Lambda}\right)^2$$

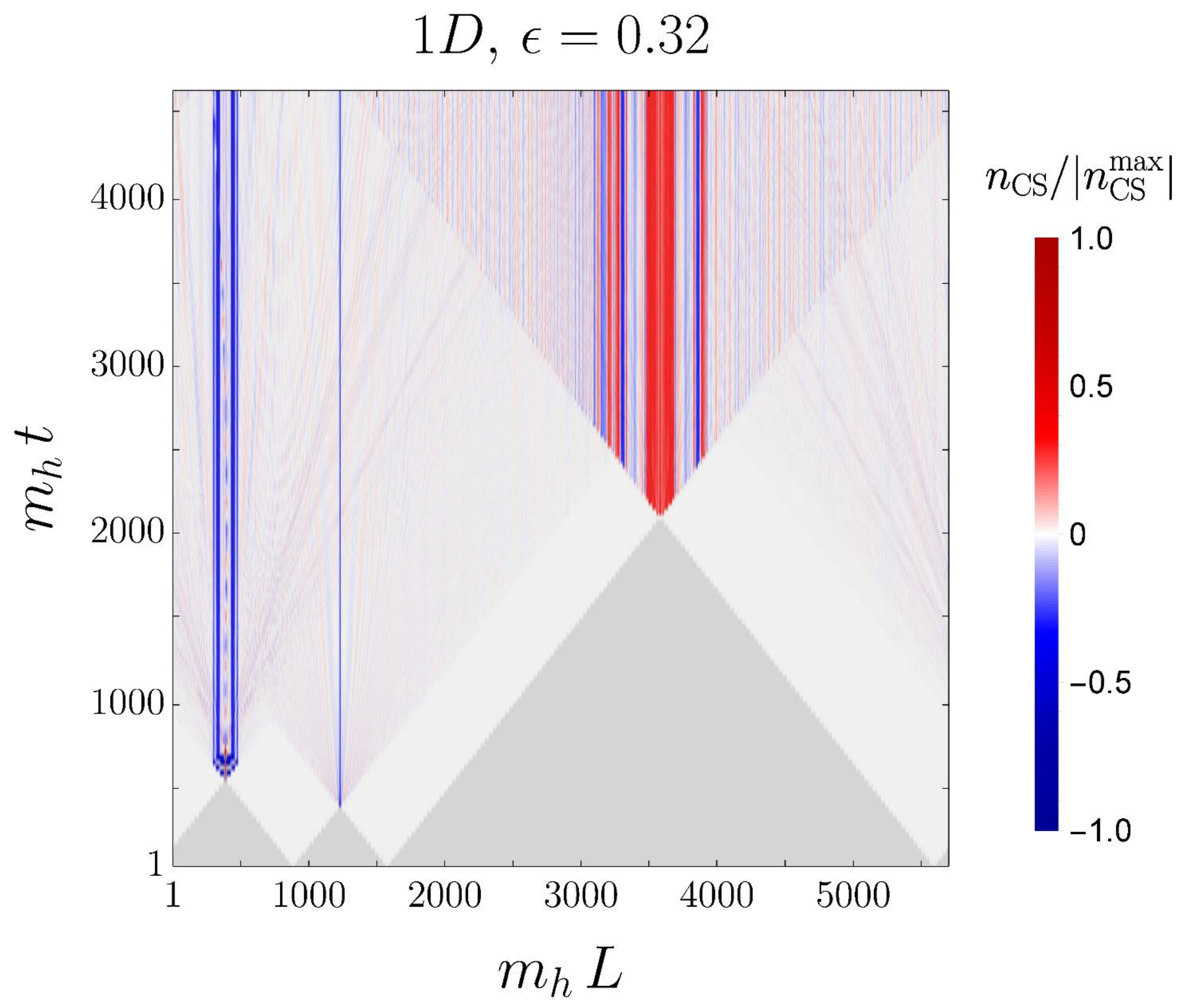
Note: $\Lambda > 6\,TeV$ from electron EDM constraints

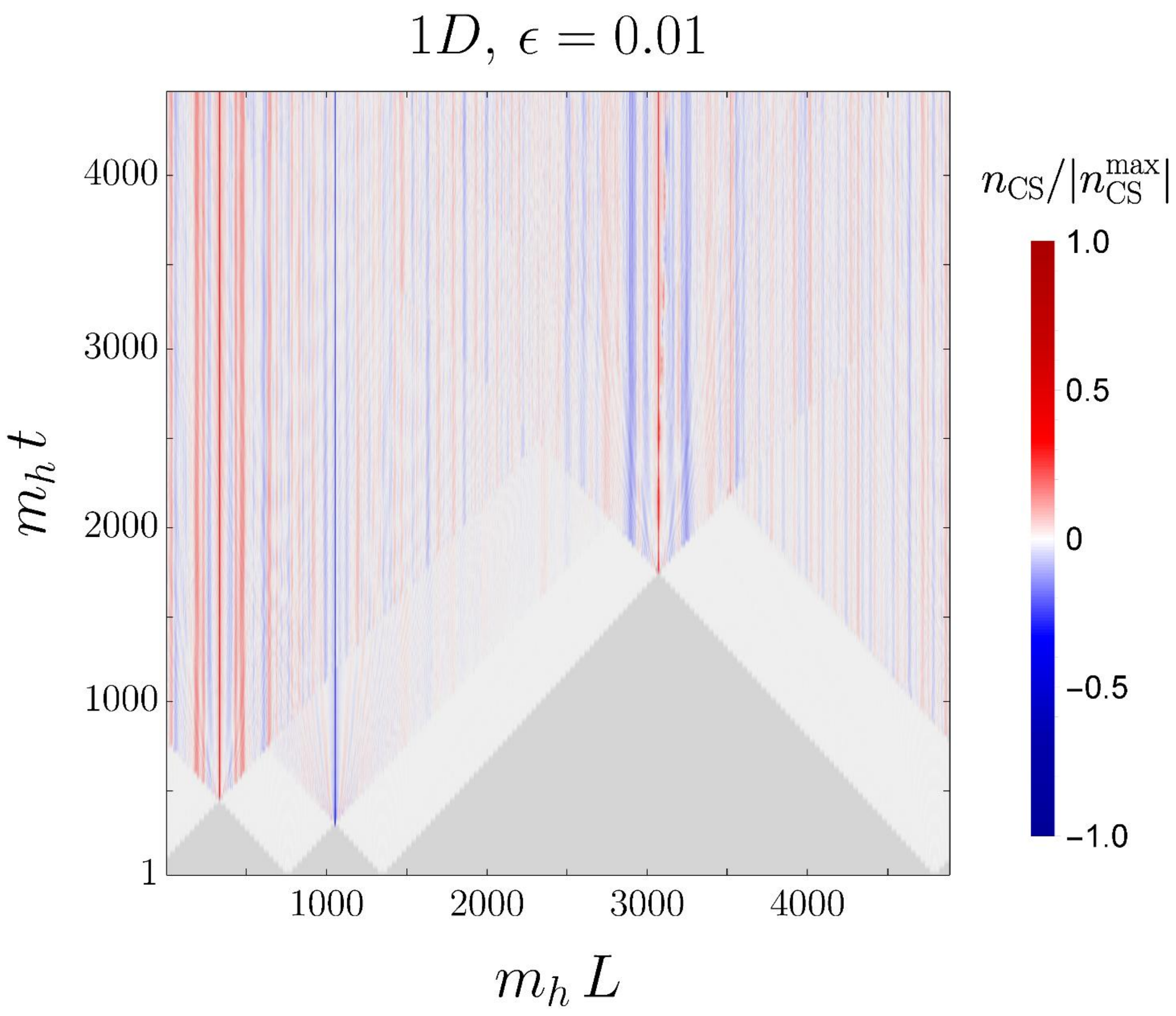
→ However, need of implement *CP*-violation to ultimately establish viable parameter space

Backup – (1+1)D case with *U(1)*-gauge field

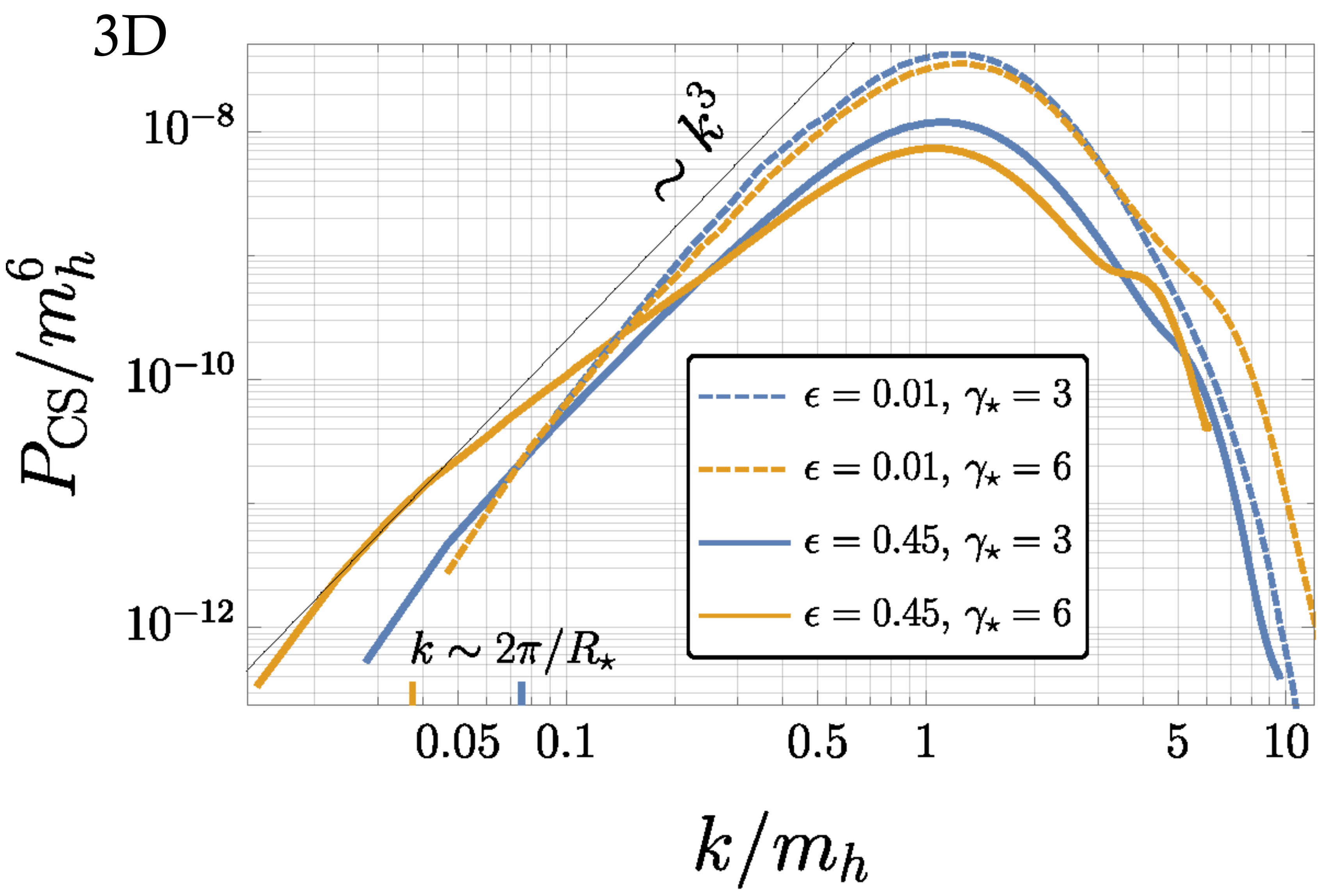
$$N_W = 1/(2\pi) \int dx\, \partial_x \mathrm{Arg}[\psi]$$

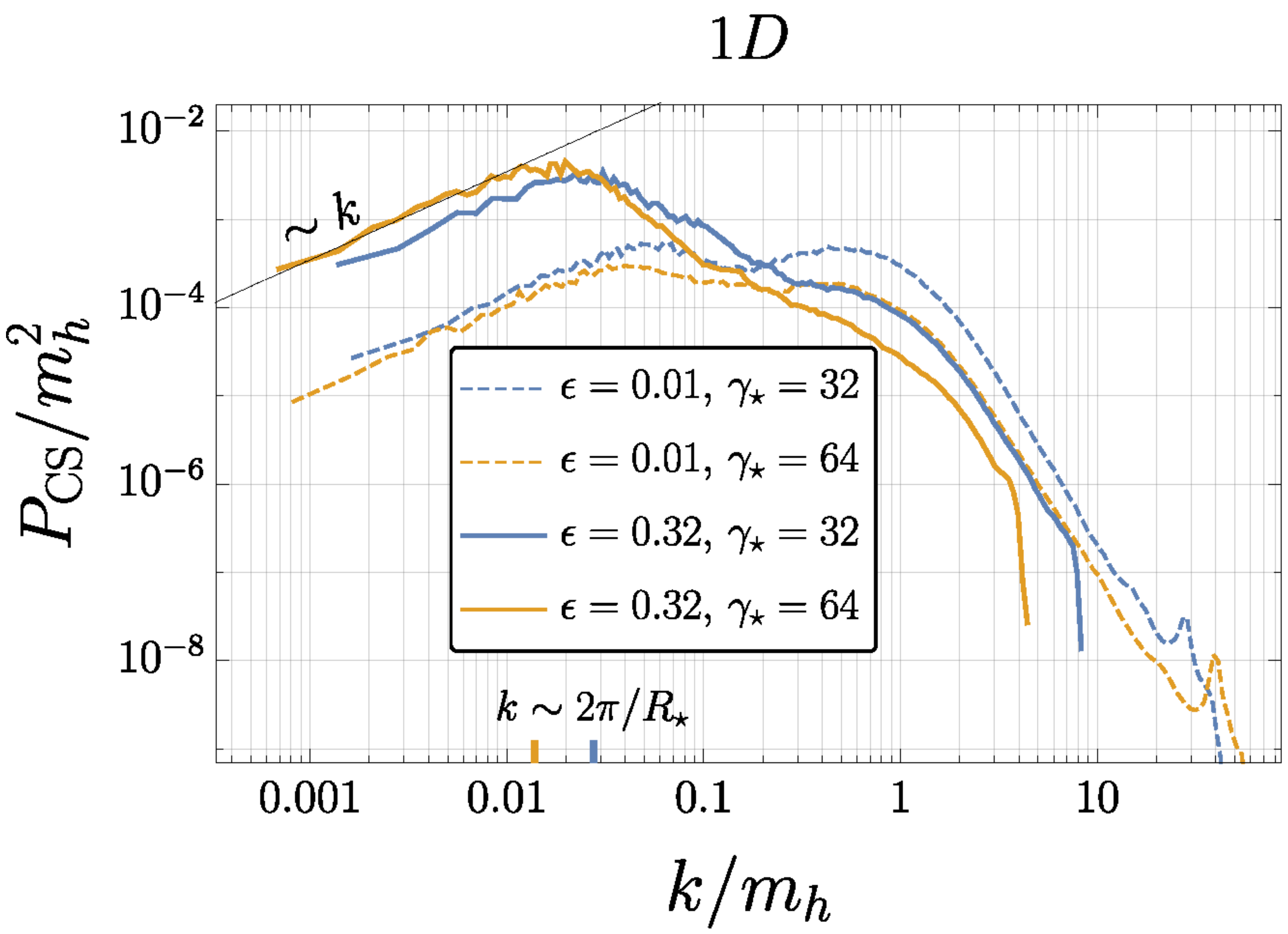
$$N_{CS} = g/(2\pi) \int dx\, A_1$$



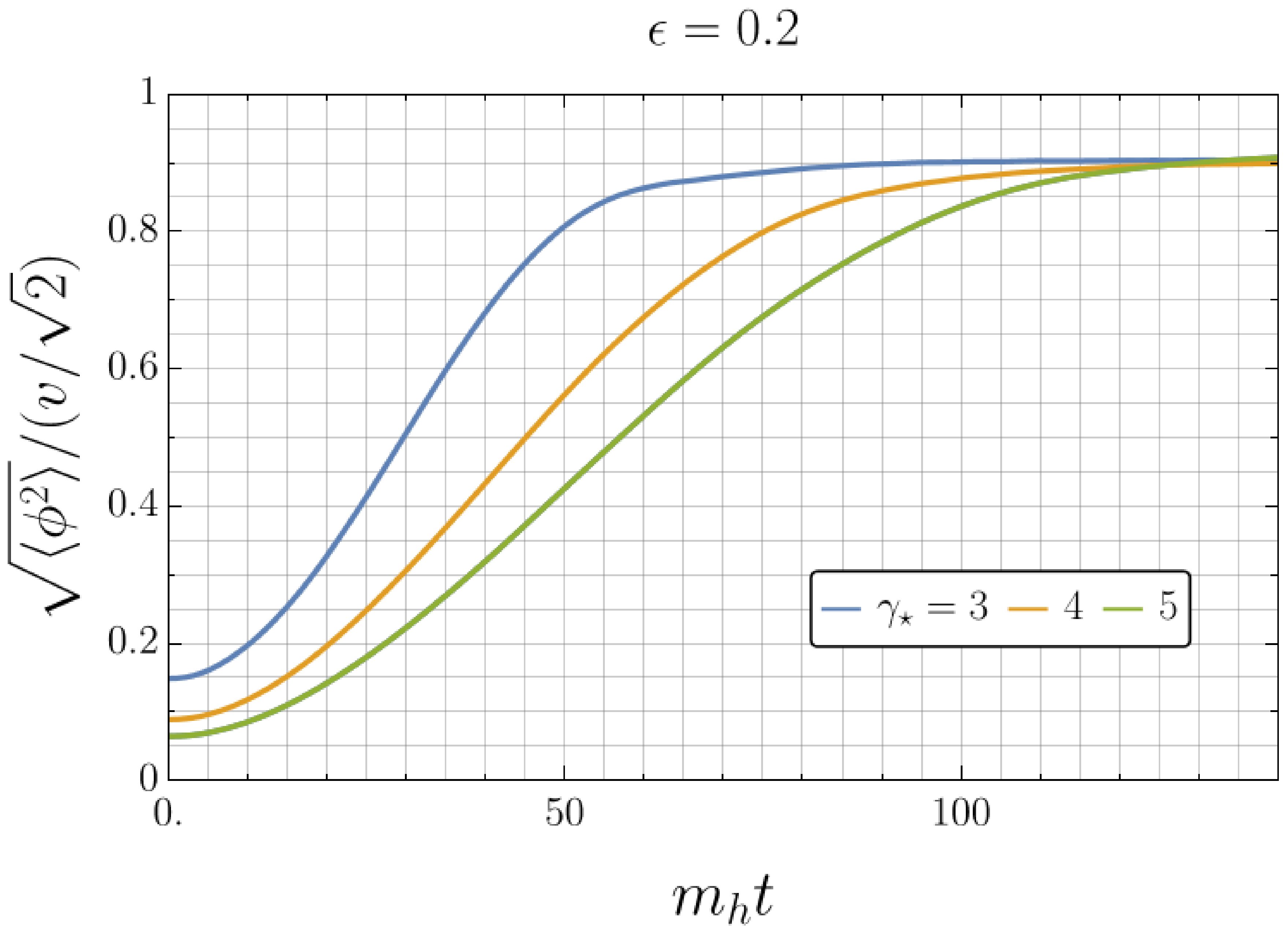


Backup – Chern-Simons Spectra

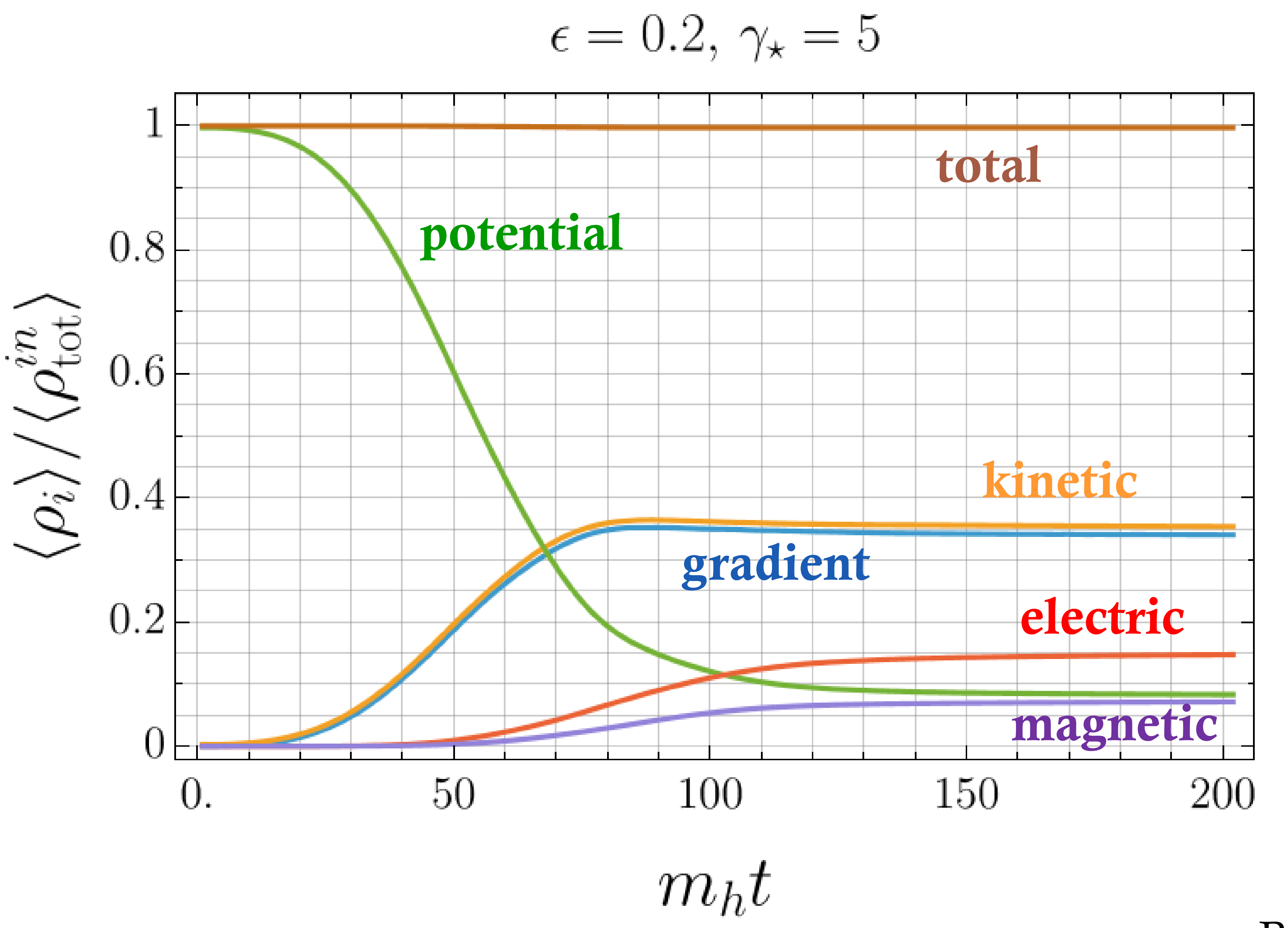




Higgs field evolution



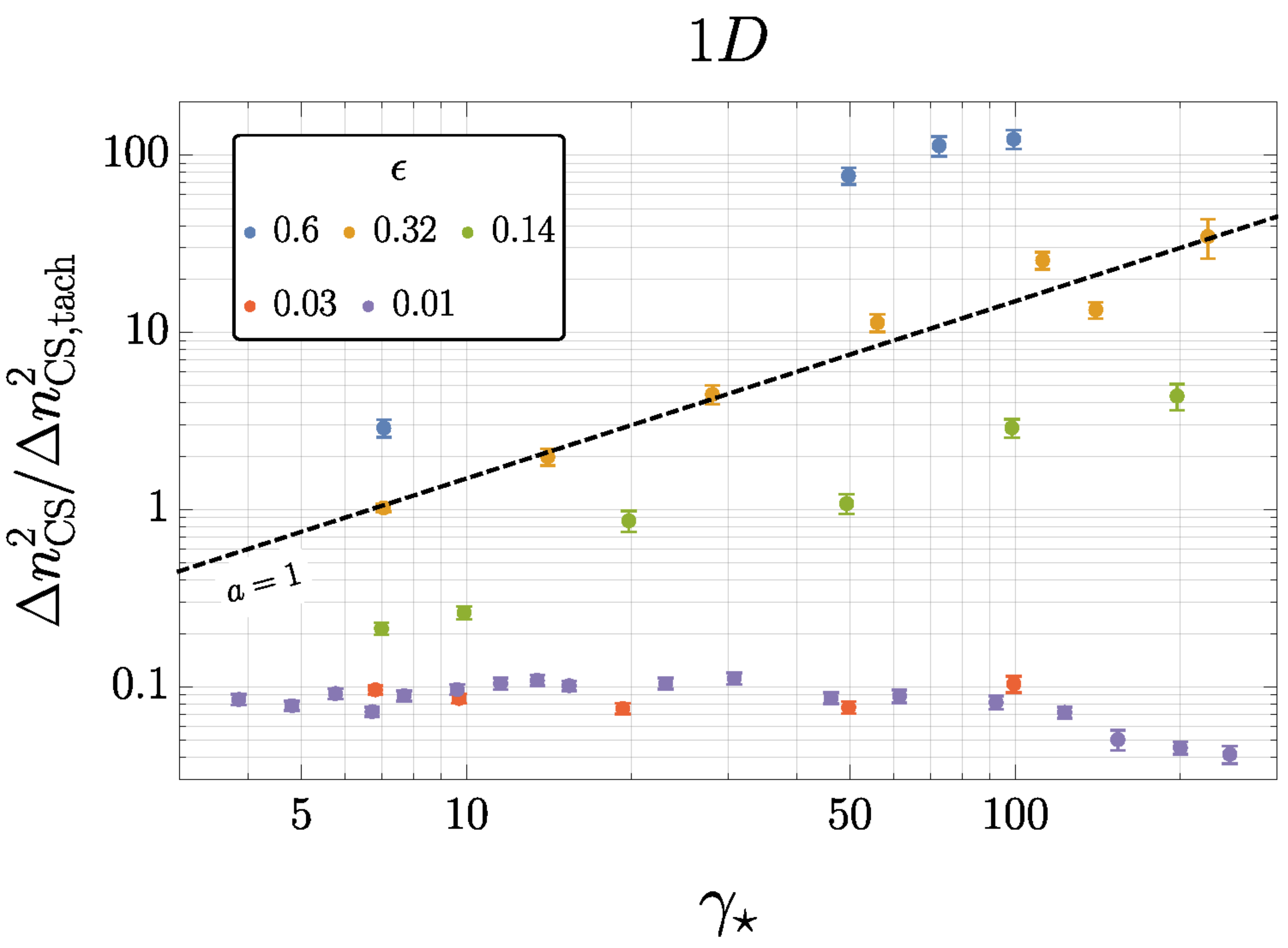
Energy budget

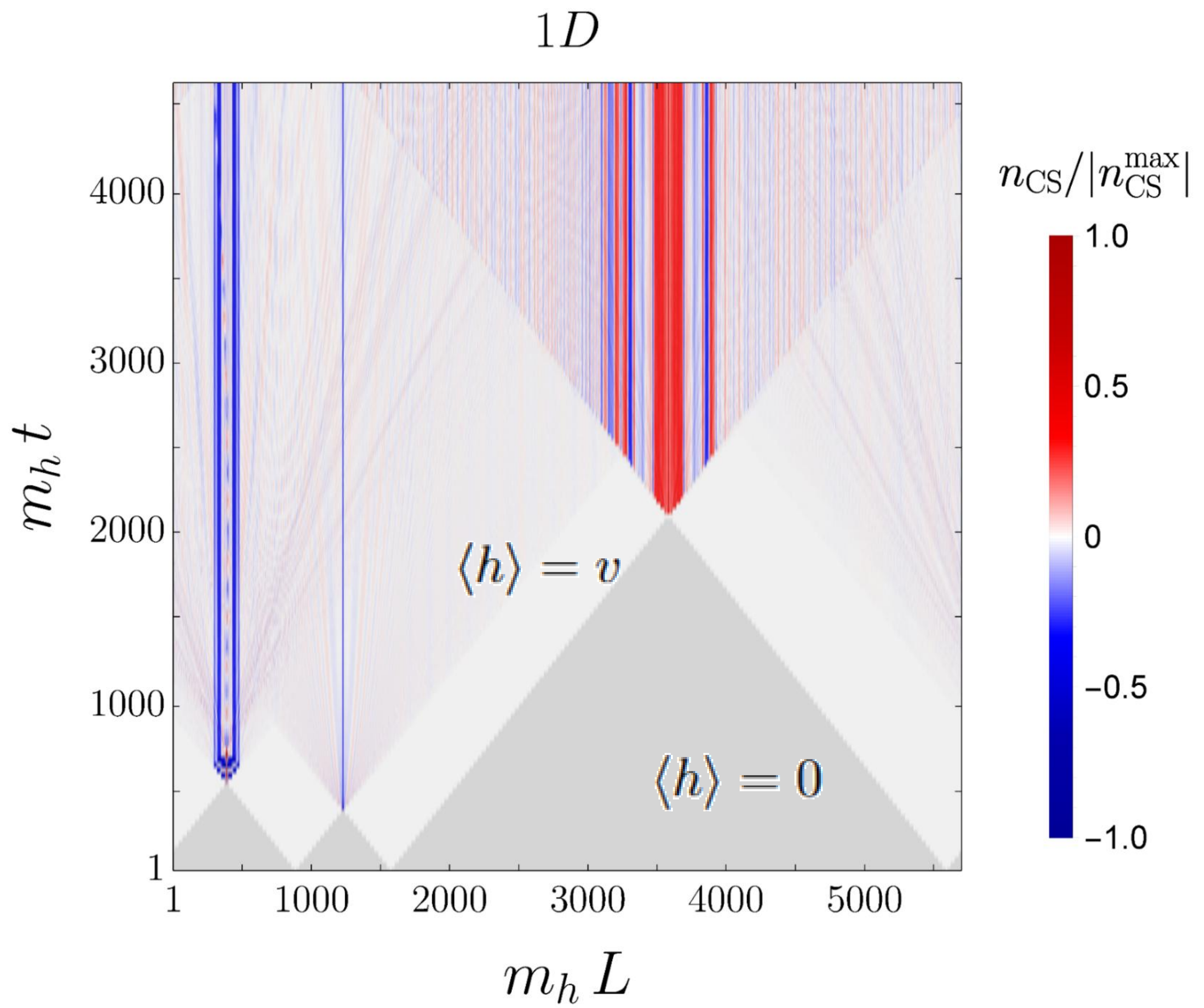


(1+1)D with *U(1)*-gauge field

Probe larger ϵ and $\gamma_\star$

$\epsilon = 0.32$





Clear hint for linear dependence for large ϵ in the (1+1)D case with *U(1)*-gauge field!

Backup – Runaway regime

Pressure contributions: $\mathcal{P}_{LO} \sim \frac{1}{24} m^2 T^2$ and $\mathcal{P}_{NLO} \sim \alpha_w \gamma_w m_V T^3$

Terminal velocity of bubble wall reached when $\mathcal{P}_{NLO} = \Delta V$

We impose $\frac{R_t}{R_*} \gtrsim 1$ to attain runaway regime for an EWPT

$$\longrightarrow \quad \frac{\beta}{H} \geq 0.1 \left(\frac{T_n}{MeV} \right)^3$$

Adding a *CP*-violating source: (1+1)D lattice simulations

Gauss constraint
$$\sum_i \frac{\pi_{A,i}(t,x) - \pi_{A,i}(t,x-\hat{i})}{dx} = 2g\mathrm{Im}[\varphi^*(t,x)\pi_\varphi(t,x)] - \frac{2k}{dx}\sum_i \left[|\varphi(t,x)|^2 - |\varphi(t,x-\hat{i})|^2\right]$$

Initial conditions (preserving the Gauss law): $A_i = 0\,, \quad \pi_\varphi = 0\,, \quad \pi_{A,i} = -2k|\varphi|^2$

Adding a *CP*-violating source: (3+1)D lattice simulations

Local-in-time expression of the Chern-Simons number

$$N_{CS}(t) = \int d^3x \, \frac{g^2}{16\pi^2} \epsilon^{ijk} \, \mathrm{Tr}\left[W_i W_{jk} + \frac{2}{3} i g W_i W_j W_k \right]$$

with discrete expression

$$N_{CS}(t) = dx^3 \sum_x n_{\rm CS} = \sum_x \frac{1}{64\pi^2} \epsilon^{ijk}$$
$$\times \mathrm{Tr}\left[(U_i - U_i^\dagger) \left((U_{jk} - U_{jk}^\dagger) - \frac{1}{3} (U_j - U_j^\dagger)(U_k - U_k^\dagger) \right) \right] + \mathcal{O}(dx^3).$$

Adding a *CP*-violating source: (3+1)D lattice simulations

Sum-in-time expression of the Chern-Simons number $\Delta N_{\text{CS}} = N_{\text{CS}}(t) - N_{\text{CS}}(0) = \frac{g^2}{16\pi^2}\int_0^t dt' \int d^3x \text{Tr}[W_{\mu\nu}\tilde{W}^{\mu\nu}]$

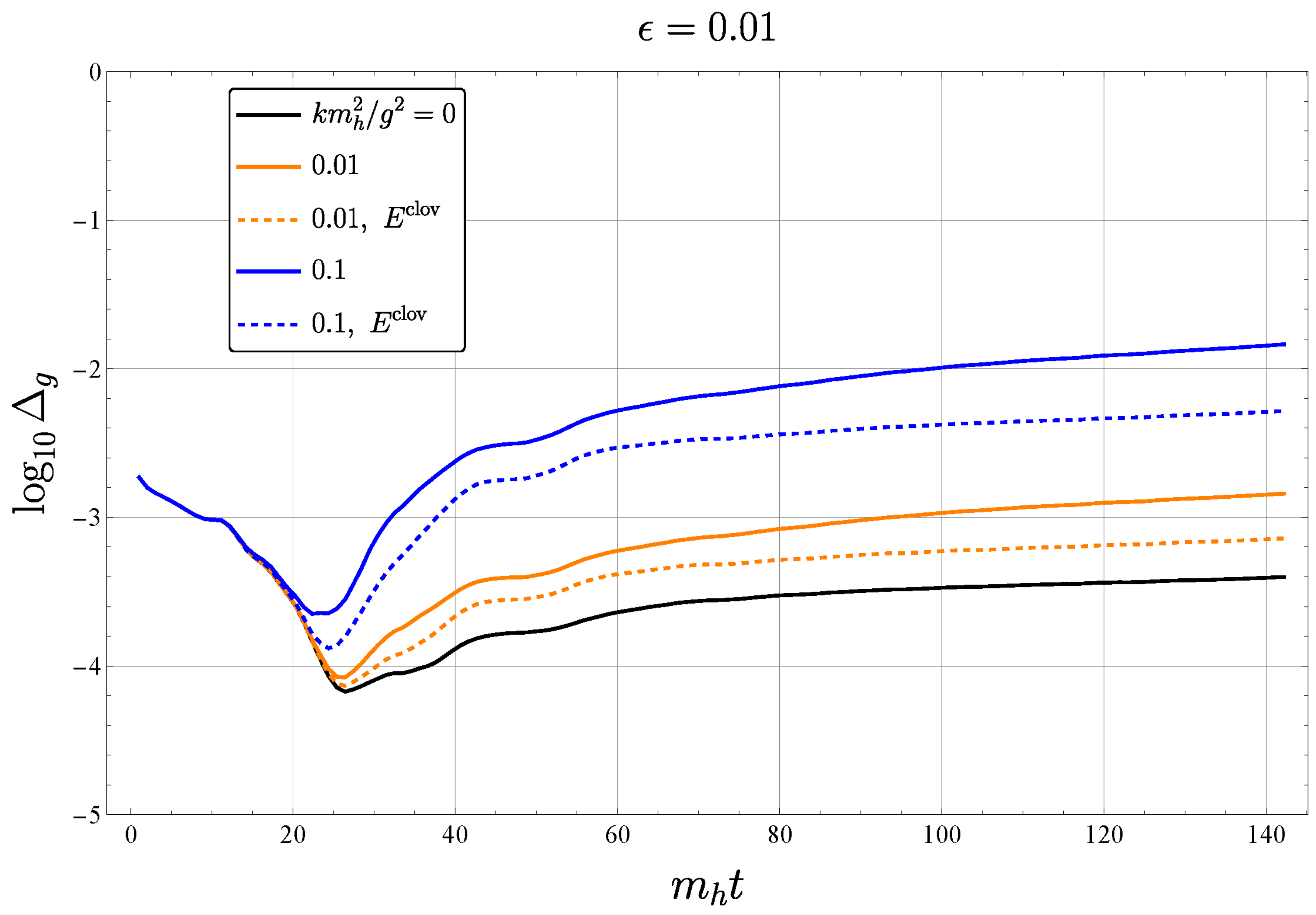
with discrete expression $\Delta N_{\text{CS}} = N_{\text{CS}}(t) - N_{\text{CS}}(0) = \frac{g^2}{8\pi^2} dt\, dx^3 \sum^{t} \sum \left(\sum E_i^a B_i^a \right)_{\text{Latt}}$

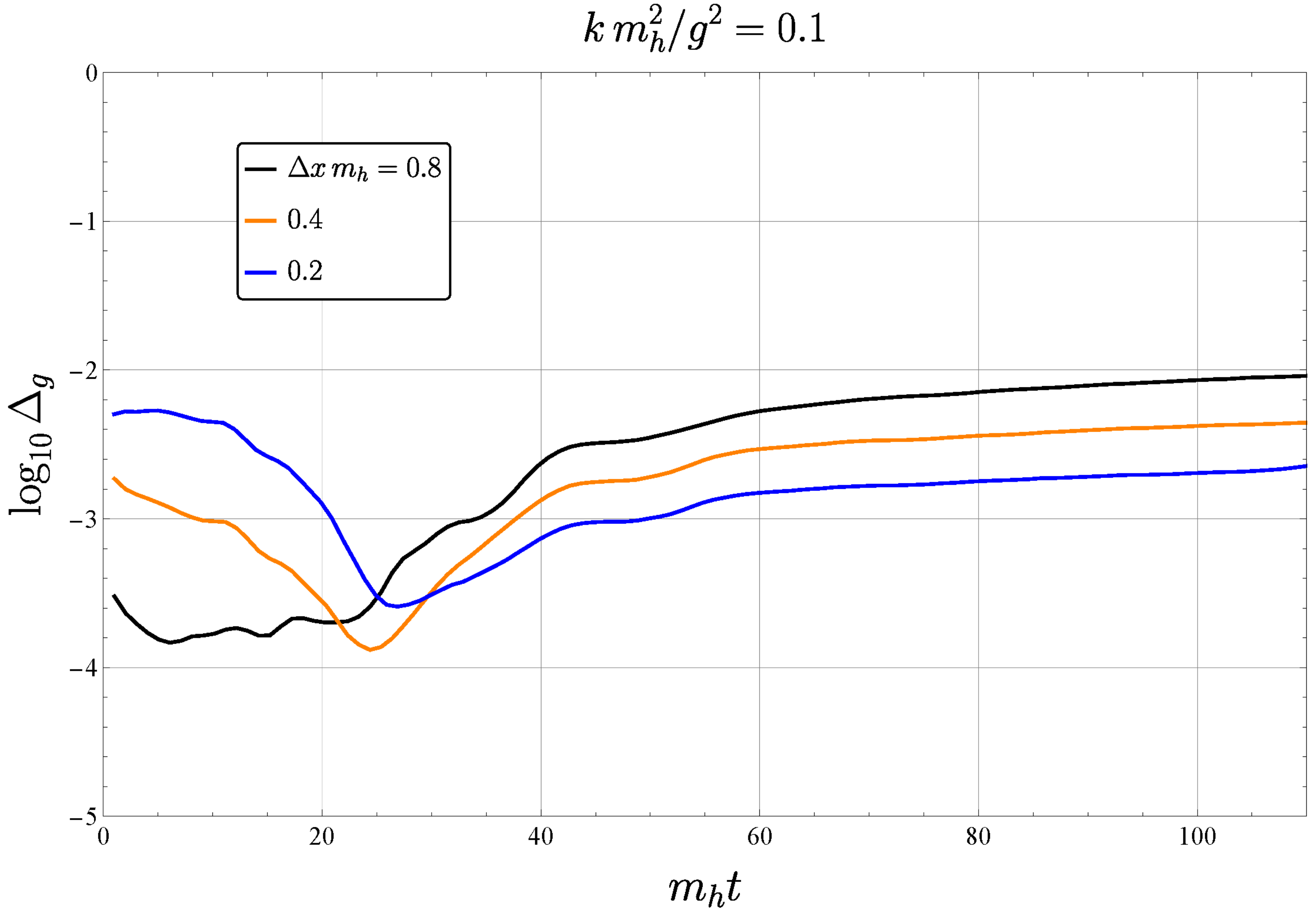
$$\sum_i \frac{\pi_{A,i}(t,x) - \pi_{A,i}(t,x-\hat{\imath})}{dx} = 2g\text{Im}[\varphi^*(t,x)\pi_\varphi(t,x)] - \frac{2k}{dx}\sum_i \left[|\varphi(t,x)|^2 - |\varphi(t,x-\hat{\imath})|^2\right]$$

Adding a *CP*-violating source: Gauss constraint

$$\sum_i \frac{\Pi_i(t,x) - U^\dagger_{i,-i}(t)\Pi_i(t,x-\hat{i})U_{i,-i}(t)}{dx} = 2g\mathrm{Im}[\phi^\dagger(t,x)T_a\pi_\phi(t,x)]T_a$$

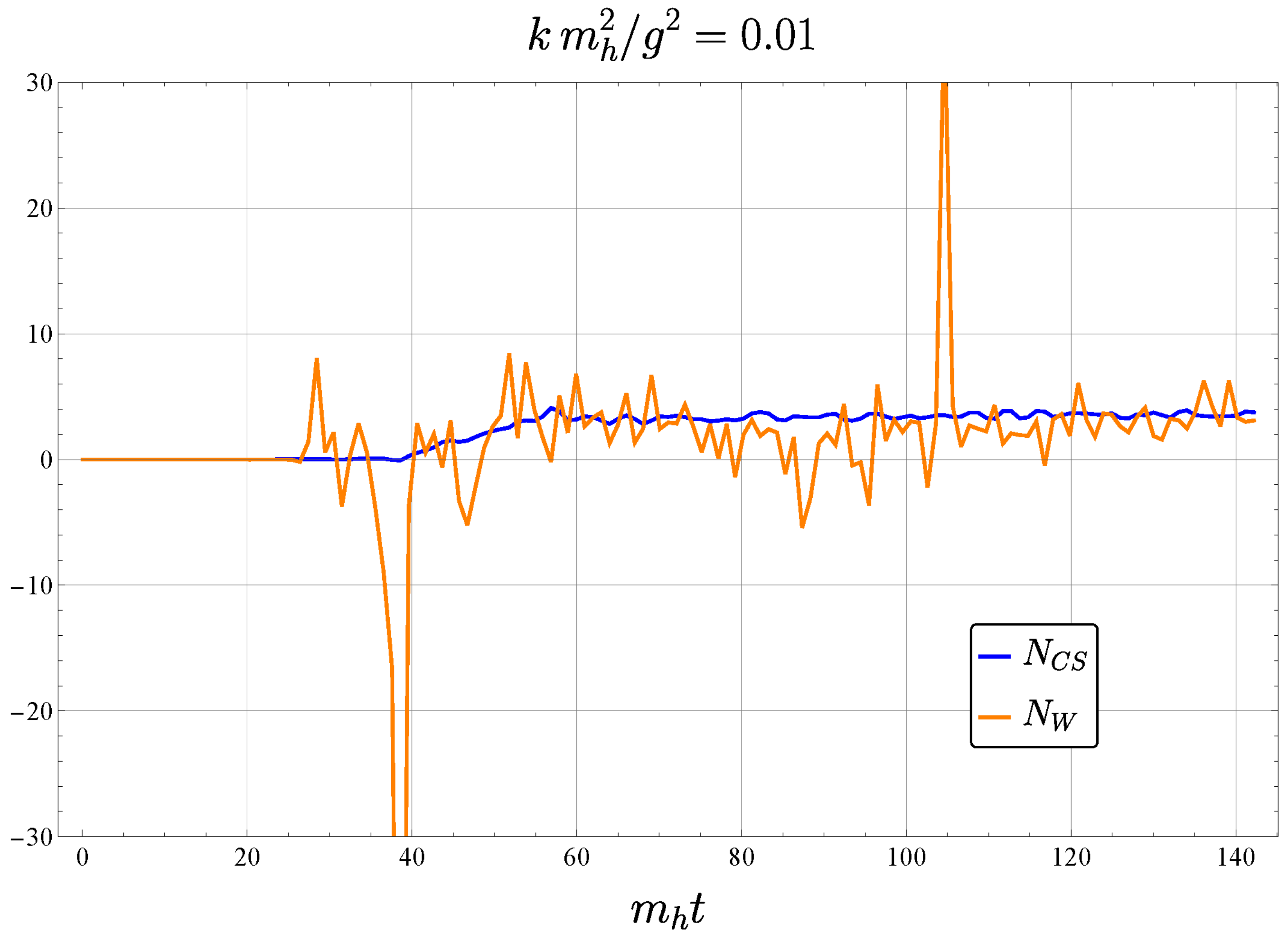
$$\Delta_g \equiv \frac{\langle|\mathrm{RHS} - LHS|\rangle_V}{\langle|\mathrm{RHS} + \mathrm{LHS}|\rangle_V}$$

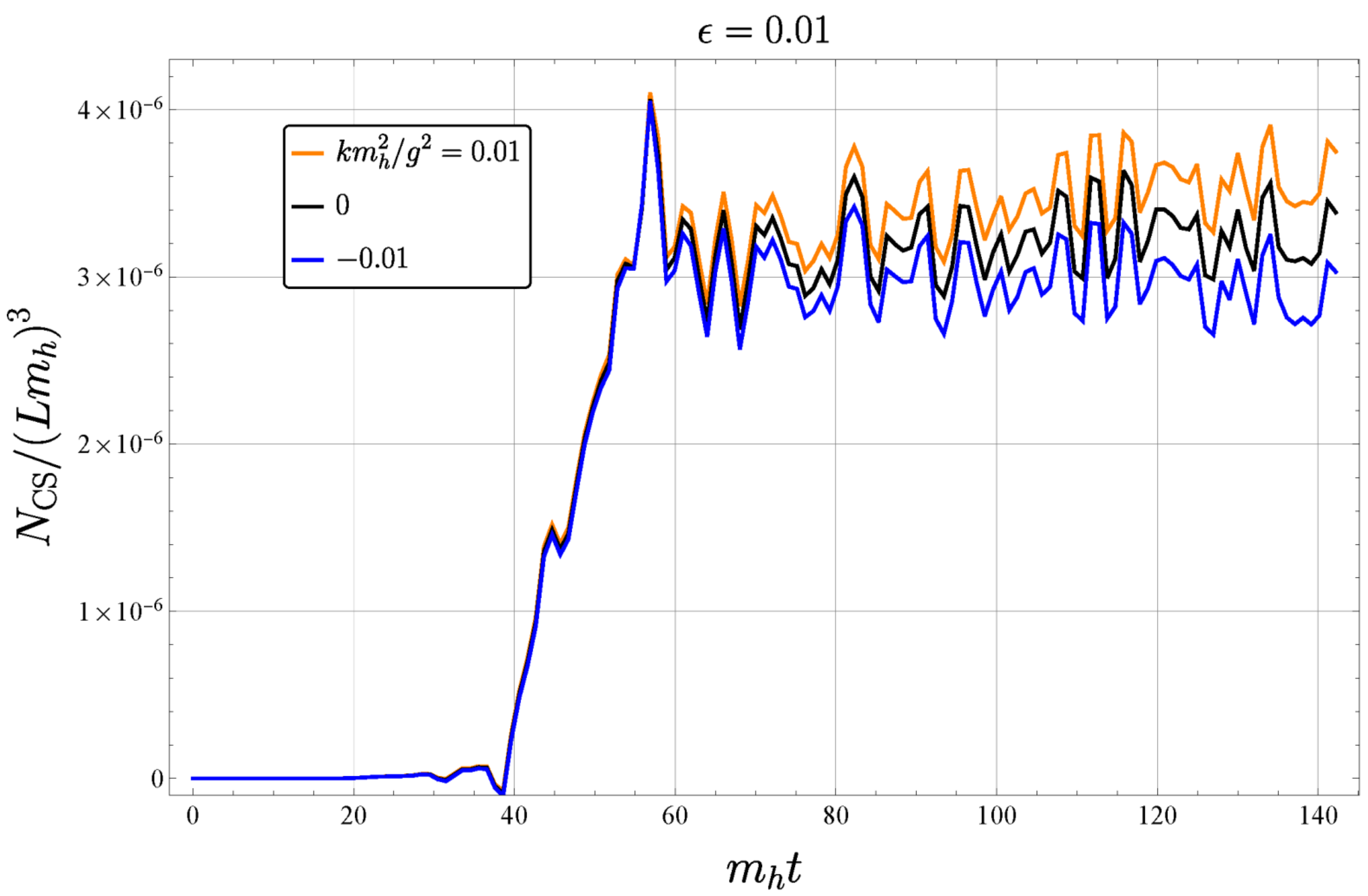




Blasi, MC, Gorghetto, Servant, *In preparation*

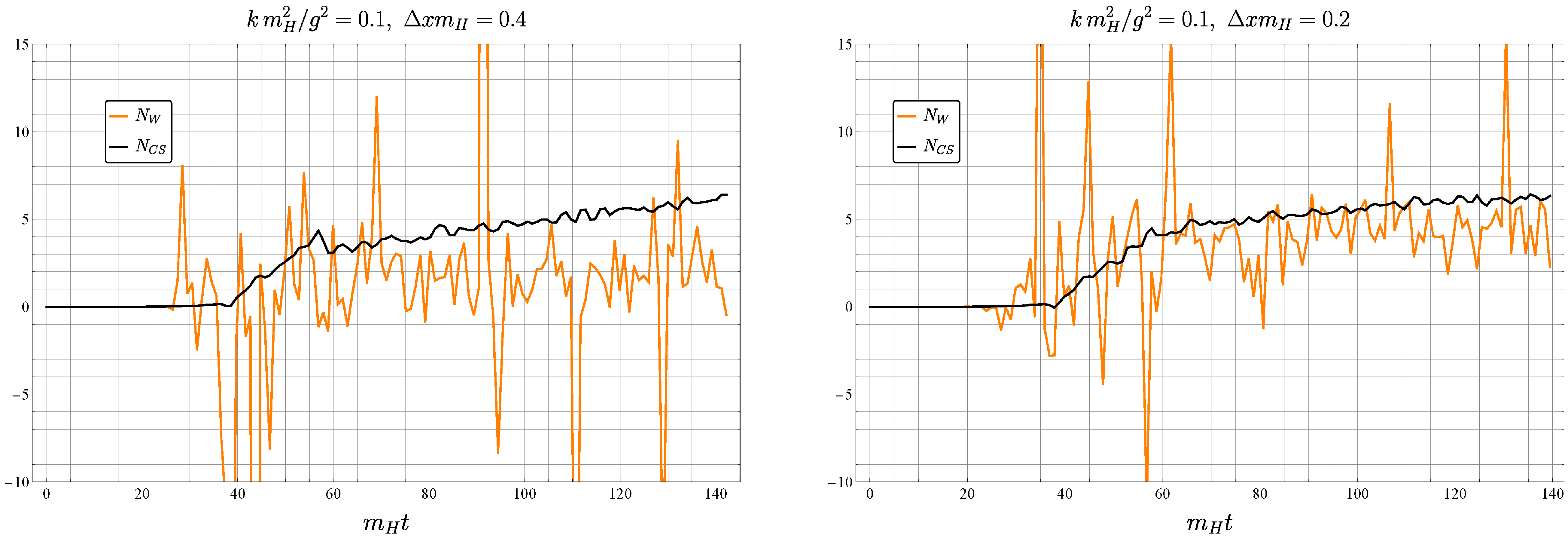
Preliminary results





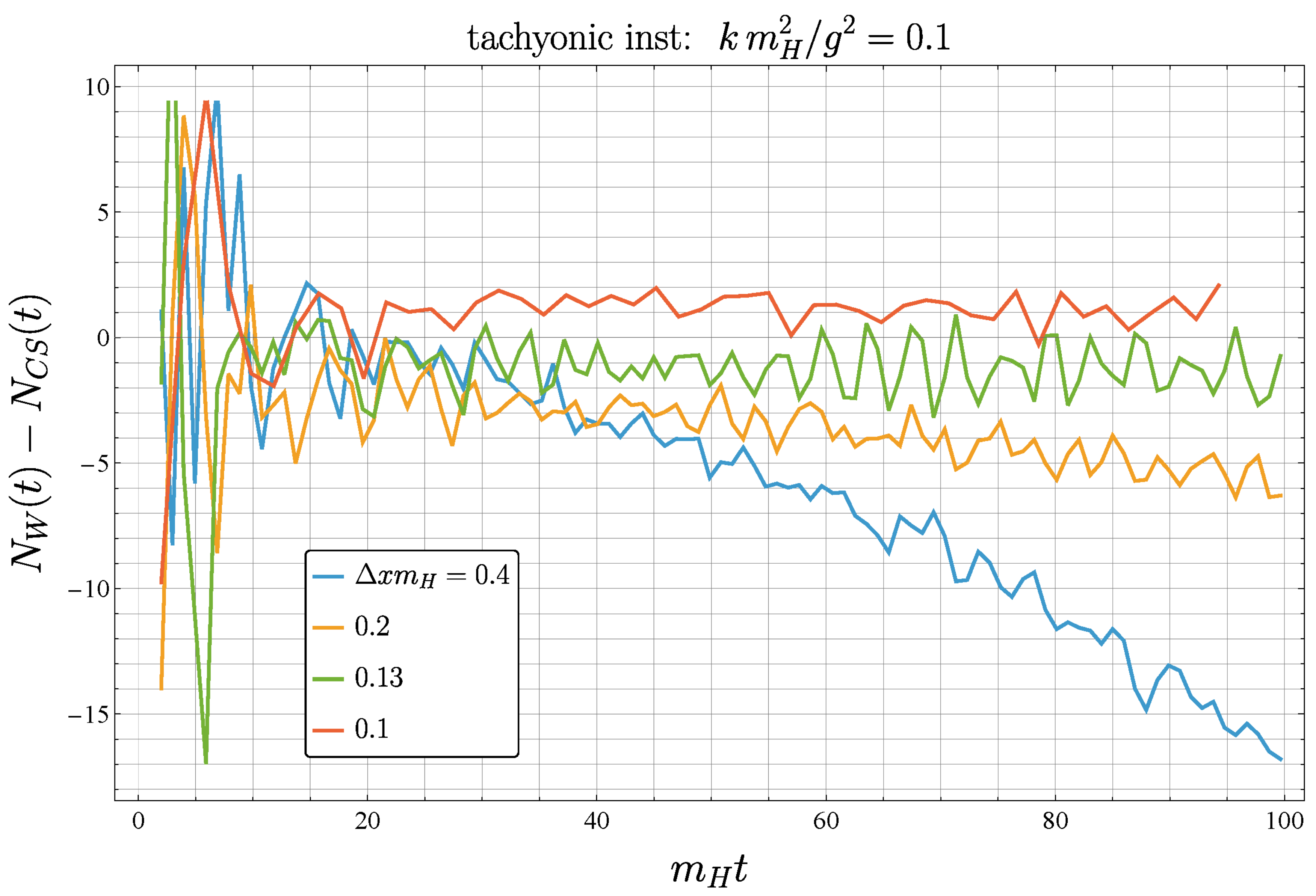
Blasi, MC, Gorghetto, Servant, *In preparation*

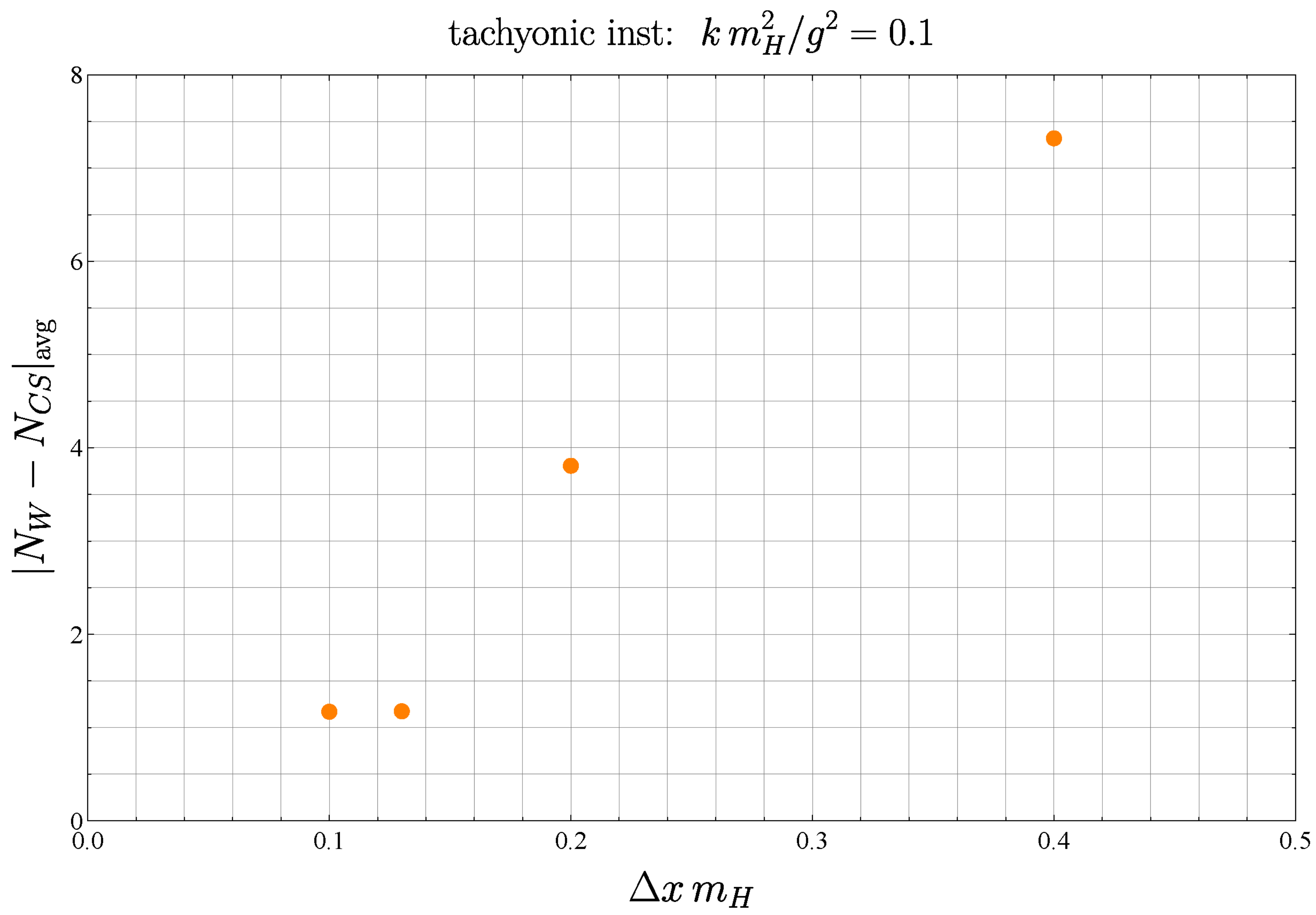
Continuum extrapolation of $N_{CS} - N_W$: FOPT



Blasi, MC, Gorghetto, Servant, *In preparation*

Continuum extrapolation of $N_{CS} - N_W$: tachyonic transition





Blasi, MC, Gorghetto, Servant, *In preparation*

Adding a *CP*-violating source: (3+1)D lattice simulations

Discretized EoM:

$$\ddot{\Phi}(t) = \frac{1}{dx^2}\sum_i (U_i\Phi_{+i} - 2\Phi + U_{-i}\Phi_{-i}) - \partial_{\Phi^*}V(\Phi) + 2k\Phi\sum_{i,a} E_i^{\mathrm{clov},a} B_i^{\mathrm{clov},a}$$

$$\dot{U}_i(t) = -igdxE_iU_i$$

$$\dot{\Pi}_i^a(t) = \frac{2i}{g\,dx^3}\,\mathrm{Tr}\left[\left(U_{ji} - U^\dagger_{j,-j}U_{ji,-j}U_{j,-j}\right)T_a\right] + \frac{2g}{dx}\,\mathrm{Im}\left[\Phi^\dagger T_a U_i \Phi_{+i}\right]$$
$$- \frac{2k}{8dx}\sum_{j,k}\epsilon_{ijk}\,\Theta^a_{ijk}(\Phi, E_i^{\mathrm{clov}}, U)$$
$$- 2ig\,dx\,k\,\left(\Phi^\dagger\Phi\right)_{+i}\,\mathrm{Tr}\left[T^a\left(E_iU_iB^{\mathrm{clov},a}_{i,+i}U_i^\dagger - U_iB^{\mathrm{clov},a}_{i,+i}U_i^\dagger E_i\right)\right]\,.$$

We followed both Ref. [2601.09784] (axion coupling with non-Abelian gauge fields) and [hep-ph/0310342] (Higgs with non-Abelian in tachyonic EW phase transition)

Kernels show dependence on field momenta: iterative leapfrog or Runge-Kutta at second order as evolution scheme

Blasi, MC, Gorghetto, Servant, *In preparation*

Adding a *CP*-violating source: (3+1)D lattice simulations

Lattice action:

$$S_L = -\Delta t \Delta x^3 \sum_{n_0} \sum_{\mathbf{n}} \left(\sum_{\mu} \frac{(\Phi^\dagger U_\mu \Phi_{+\mu} - 2\Phi^\dagger\Phi + \Phi^\dagger_{+\mu} U^\dagger_\mu \Phi)}{(dx^\mu)^2} + \sum_{\mu,\nu} \frac{\mathrm{Tr}[1 - U_{\mu\nu}]}{g^2(dx^\mu dx^\nu)^2} + V(\Phi^\dagger\Phi) \right)$$

plus

$$\mathcal{L}^{\mathrm{CP}}_{\mathrm{Latt}} = 2k\, \Phi^\dagger\Phi \left(\sum_{i,a} E^a_i B^a_i \right)_{\mathrm{Latt}} = k\, \Phi^\dagger\Phi \sum_{i,a} \left(E^{\mathrm{clov},a}_i + E^{\mathrm{clov},a}_{i,-0} \right) B^{\mathrm{clov},a}_i$$

$$E^{\mathrm{clov}}_i \equiv E^{\mathrm{clov}}_i(t + \hat{0}/2, \mathbf{x}) = \frac{E_i + U^\dagger_{i,-i} E_i(x - \hat{i}) U_{i,-i}}{2}$$

$$B^{\mathrm{clov}}_i \equiv B^{\mathrm{clov}}_i(t, \mathbf{x}) = \frac{1}{2}\epsilon_{ijk} \langle W^{jk}(\mathbf{x}) \rangle \qquad \langle W^{jk}(\mathbf{x}) \rangle = \frac{i}{8dx^2 g} \left(U_{jk} + U_{k-j} + U_{-j-k} + U_{-kj} - U_{kj} - U_{-jk} - U_{-k-j} - U_{j-k} \right)$$

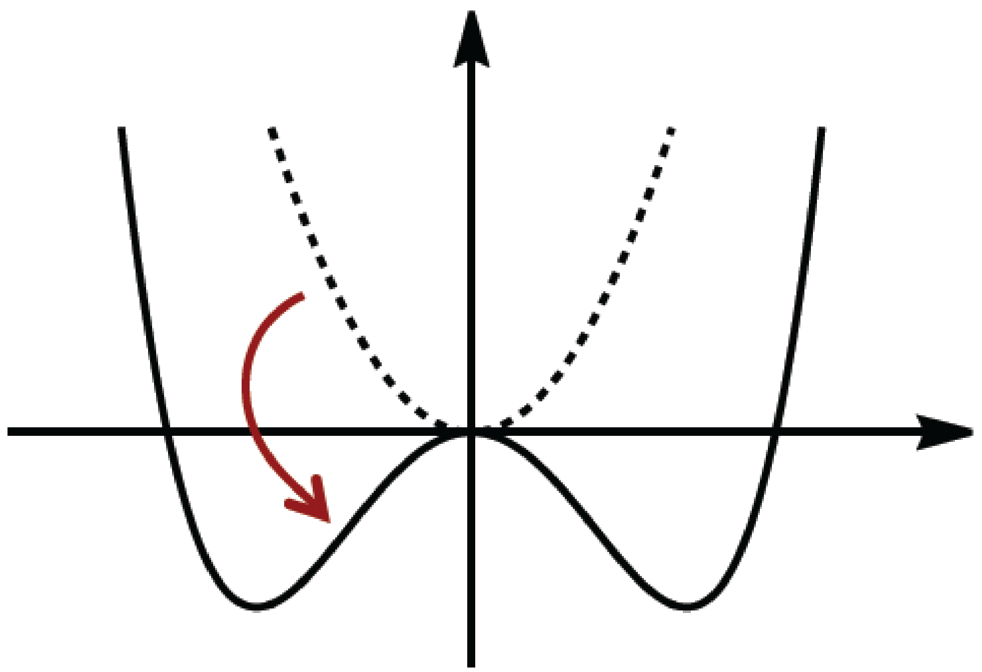
Blasi, MC, Gorghetto, Servant, *In preparation*

(Original) Cold baryogenesis via a quenched EW crossover

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

$$\Box\phi + \mu_{eff}^2(\mathrm{t})\phi = 0$$

$$\mu_{eff}^2(\mathrm{t}) = -\mu^2 + k\sigma^2(t)$$



- IR modes grow exponentially:
  inhomogeneous Higgs field with different *SU(2)* orientations
  Electroweak texture configurations

Krauss, Trodden, Phys. Rev. Lett. 83 (1999) 1502
Garcia-Bellido, et al. Phys. Rev. D 60 (1999) 123504
E. J. Copeland, et al. Phys. Rev. D 64 (2001) 043506
Tranberg, Smit, JHEP 0311 (2003) 016

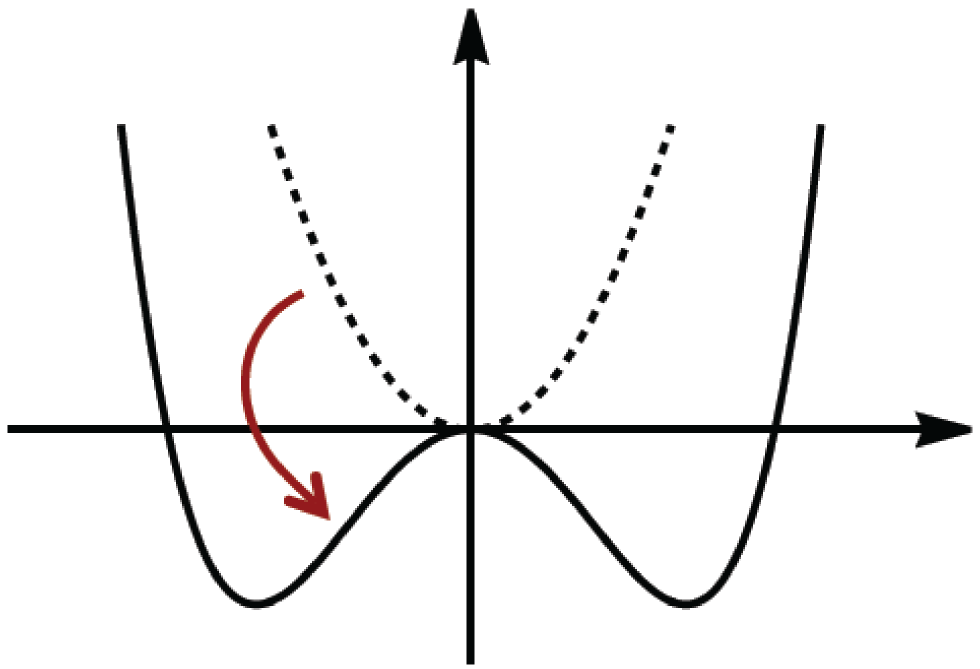
- To avoid washout:

$T_{rh} < T_{sph\ f.o.} \simeq 130$ GeV   Sphaleron processes are out-of-equilibrium

(Original) Cold baryogenesis via a quenched EW crossover

→ Realized in models of EW-scale hybrid inflation, with the Higgs as waterfall field

Ad-hoc assumptions:
significant amount of tuning in the inflaton sector + hierarchy problem due to a fundamental light scalar inflaton



→ We propose a different realization in the context of a supercooled first-order EWPT, particularly motivated in Composite Higgs models with a light dilaton

Krauss, Trodden, Phys. Rev. Lett. 83 (1999) 1502
Garcia-Bellido, et al. Phys. Rev. D 60 (1999) 123504
E. J. Copeland, et al. Phys. Rev. D 64 (2001) 043506
Tranberg, Smit, JHEP 0311 (2003) 016