News on Cold Baryogenesis: $\not{B}$ from SM *SU(2)*-textures induced by Higgs bubble collisions at T≈0

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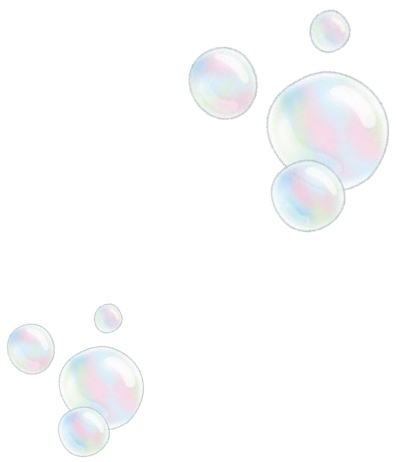

Based on hep-ph/2506.xxxxx

Bhusal, Blasi, MC, Chatrchyan, Gorghetto, Servant

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What is it?

Very first 3D lattice computation of Standard Model baryon number violation at T≈0 from Higgs bubble collisions

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What is it?

→ Study dynamics of Chern-Simons number in First Order ElectroWeak Phase Transition by numerical lattice simulations of the Higgs doublet and *SU(2)*-gauge fields

→ Relevant for FOEWPT with $T_{\rm reh}$ below sphaleron freeze-out temperature $T_{sph} \simeq 130$ GeV

Outline of this talk

1) Motivation
2) Key observables: Standard Model *SU(2)*-gauge textures, Higgs winding number N_W and Chern-Simons number N_{CS}
3) Chern-Simons production from bubble collisions in a FOEWPT
4) Baryon asymmetry estimate

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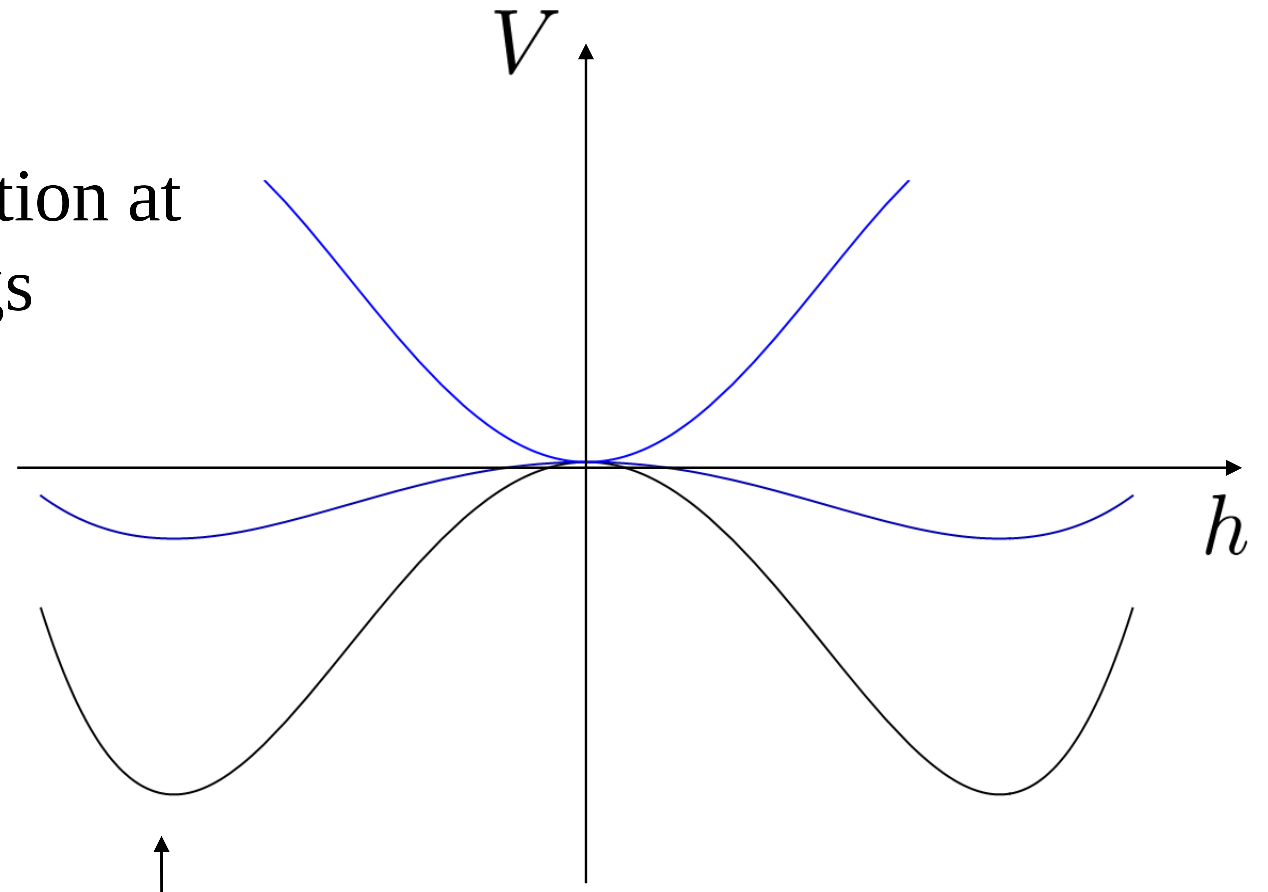
Motivation



→ In previous works by Tranberg et al., Standard Model baryon number violation at T≈ 0 has been studied on the lattice, from tachyonic Electroweak PT (Higgs quenching), assuming low-scale inflation

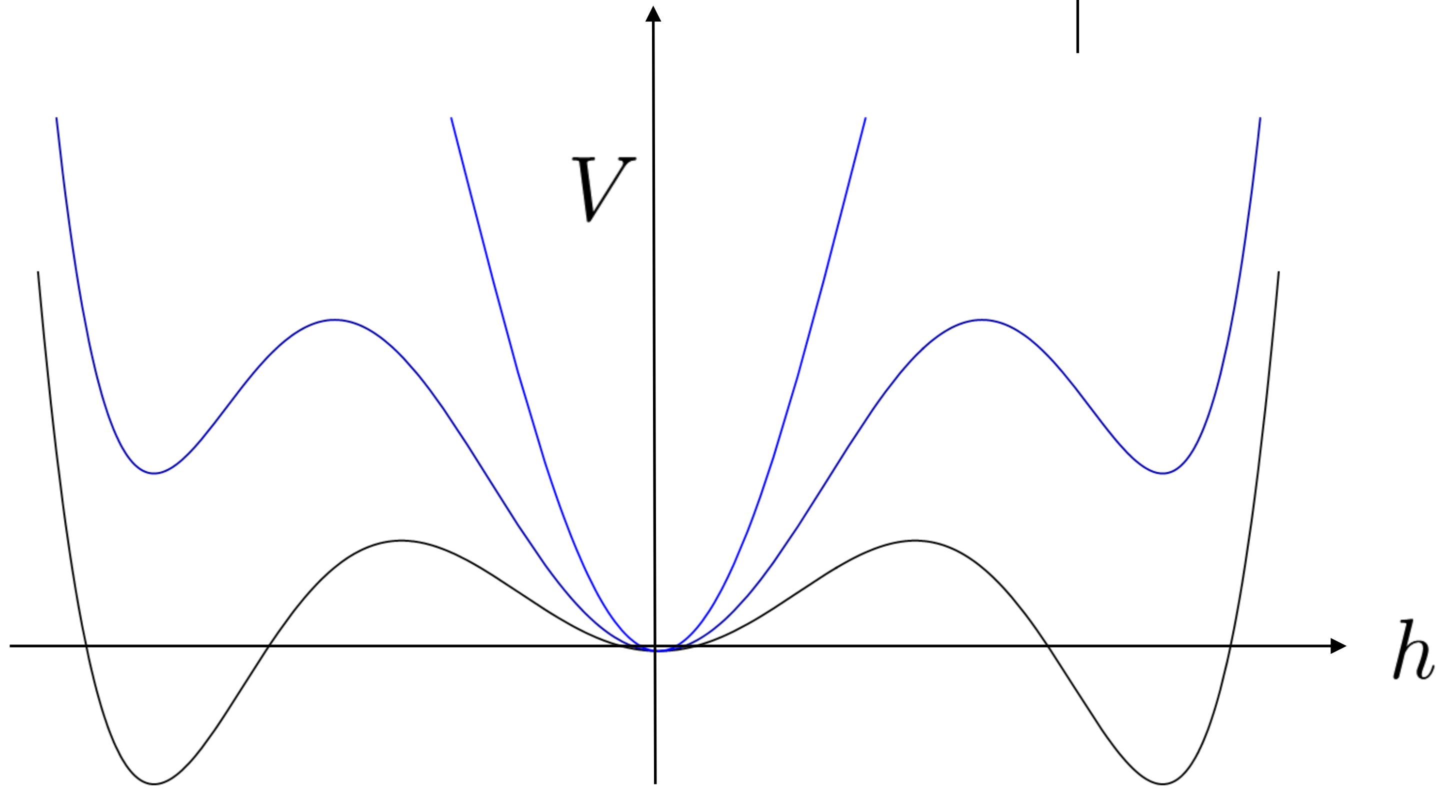
(no bubbles)

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

→ First idea: Cold Baryogenesis in the context of FOPT

Planar bubble walls without gauge fields

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



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Key Observables

→ Chern-Simons number of *SU(2)*-gauge field $N_{CS}(t) - N_{CS}(0) = \frac{1}{16\pi^2}\int_0^t dt \int d^3x \,\mathrm{Tr} F^{\mu\nu}\tilde{F}_{\mu\nu}$

Chern-Simons variance $\Delta N^2_{CS}(t) \equiv \langle N_{CS}(t)^2\rangle - \langle N_{CS}(t)\rangle^2$

Chern-Simons rate $\Gamma_{CS} = \frac{1}{L^3}\frac{d\Delta N^2_{CS}(t)}{dt}$

→ Baryon number

$B(t) = 3\,\langle N_{CS}(t) - N_{CS}(0)\rangle$

→ Higgs winding number $N_W = \frac{1}{24\pi^2}\int d^3x\, \epsilon_{ijk}\mathrm{Tr}(\partial_i U)U^\dagger(\partial_j U)U^\dagger(\partial_k U)U^\dagger\,, \qquad U = \frac{(i\tau^2\phi^*, \phi)}{\phi^\dagger\phi}$

characterizing *SU(2)*-gauge textures

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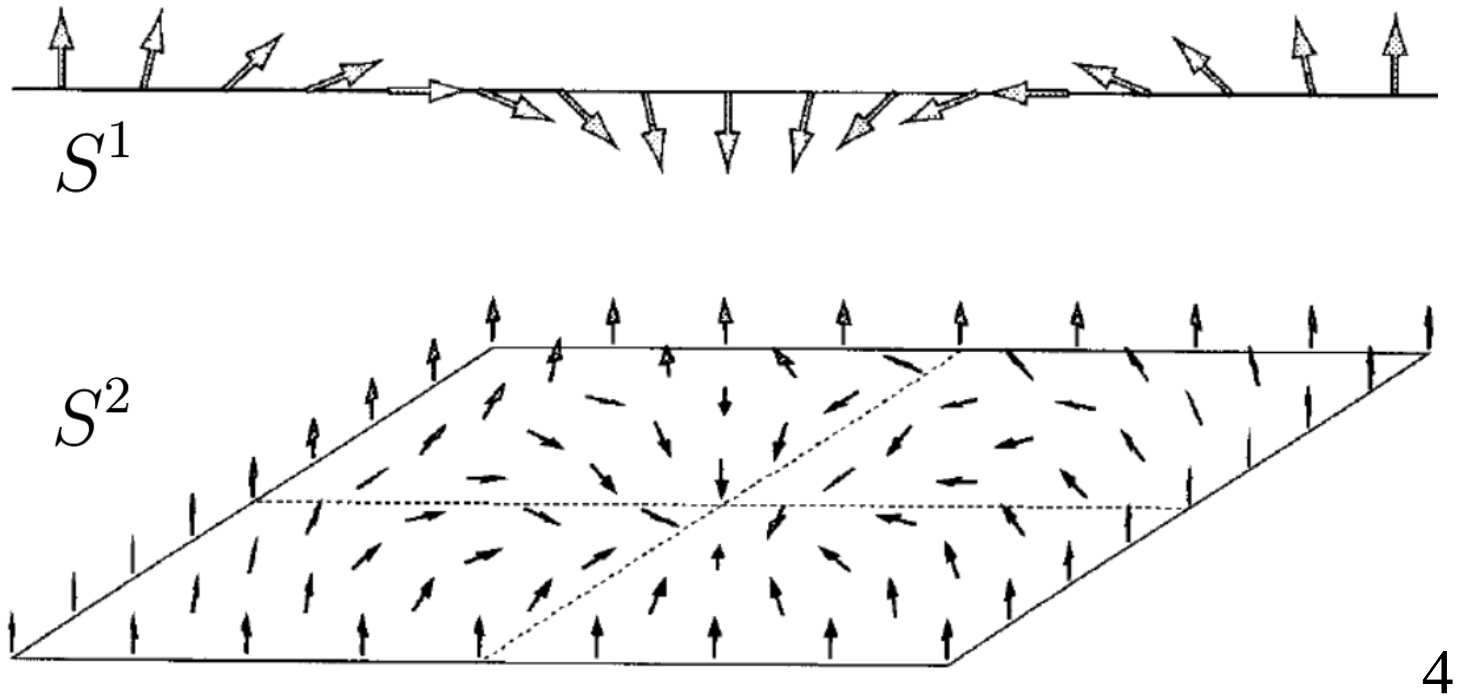
topologically non-trivial Higgs field configurations
associated to SM gauge group

S^3



Vilenkin, 1994

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Baryons from *SU(2)*-gauge texture dynamics

EW symmetry breaking → *SU(2)*-orientation of Higgs field is inhomogeneous in space → production of gauge textures $N_{CS} - N_W \neq 0$

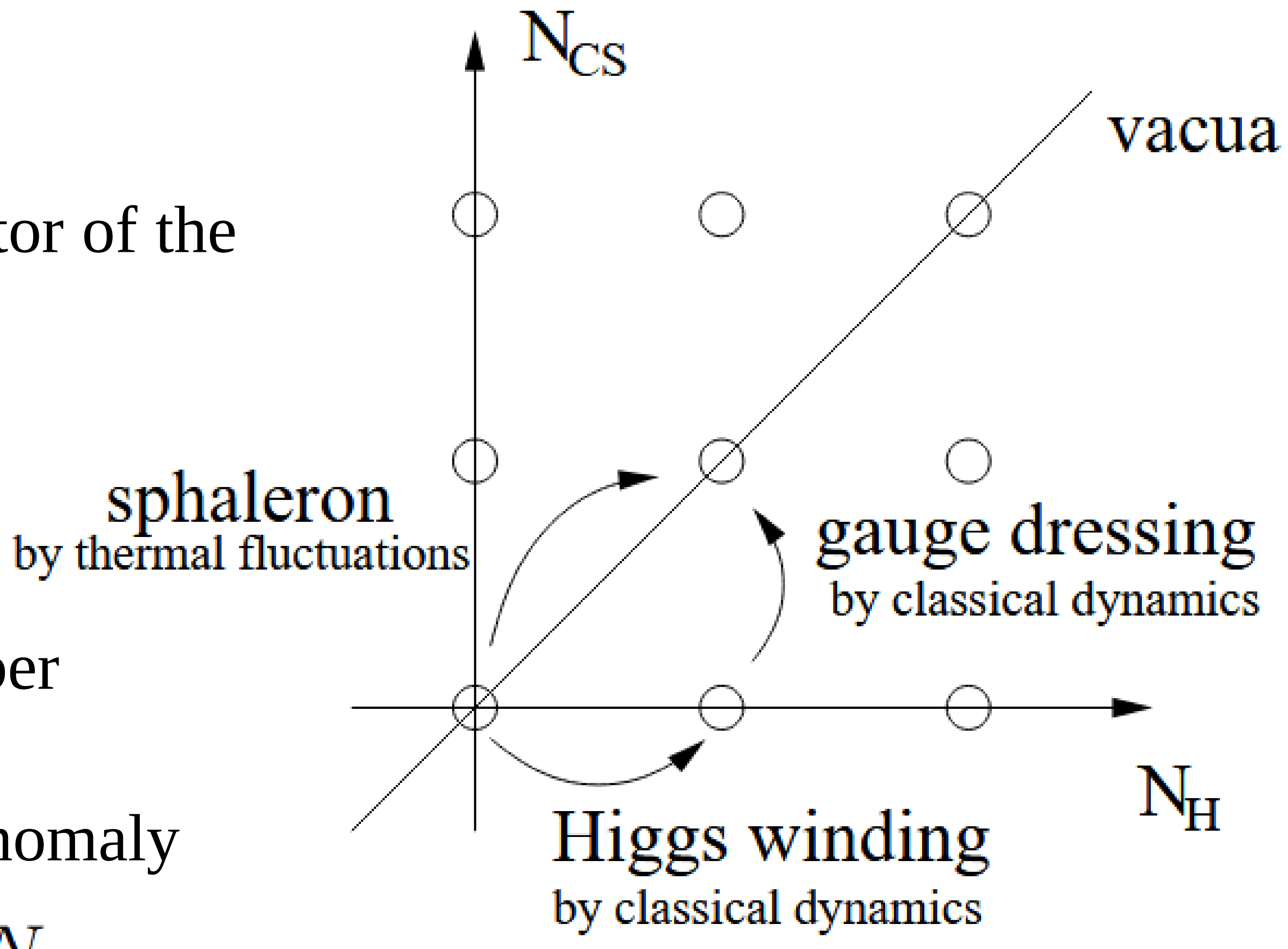
Note: $N_{CS} - N_W$ is gauge invariant and $N_{CS} = N_W$ in vacuum

Cold Baryogenesis is based on dynamics gauge textures of the EW sector of the SM:

If typical size $< m_W^{-1}$ → N_W relaxes to N_{CS}

typical size $> m_W^{-1}$ → N_{CS} relaxes to N_W, N_W dressed by gauge fields → Baryon number violation via quantum anomaly

$$\Delta B = 3\Delta N_{CS}$$



Konstandin, Servant, JCAP07(2011)024

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Set up

→ Strong First Order Electroweak Phase Transition
(runaway regime)

One free parameter λ

→ Degeneracy parameter $\epsilon = \frac{V_{barr} - V_F}{V_{barr} - V_T} = \frac{V_{barr}}{V_{barr} - \Delta V}$

Jinno et al., 1906.02588

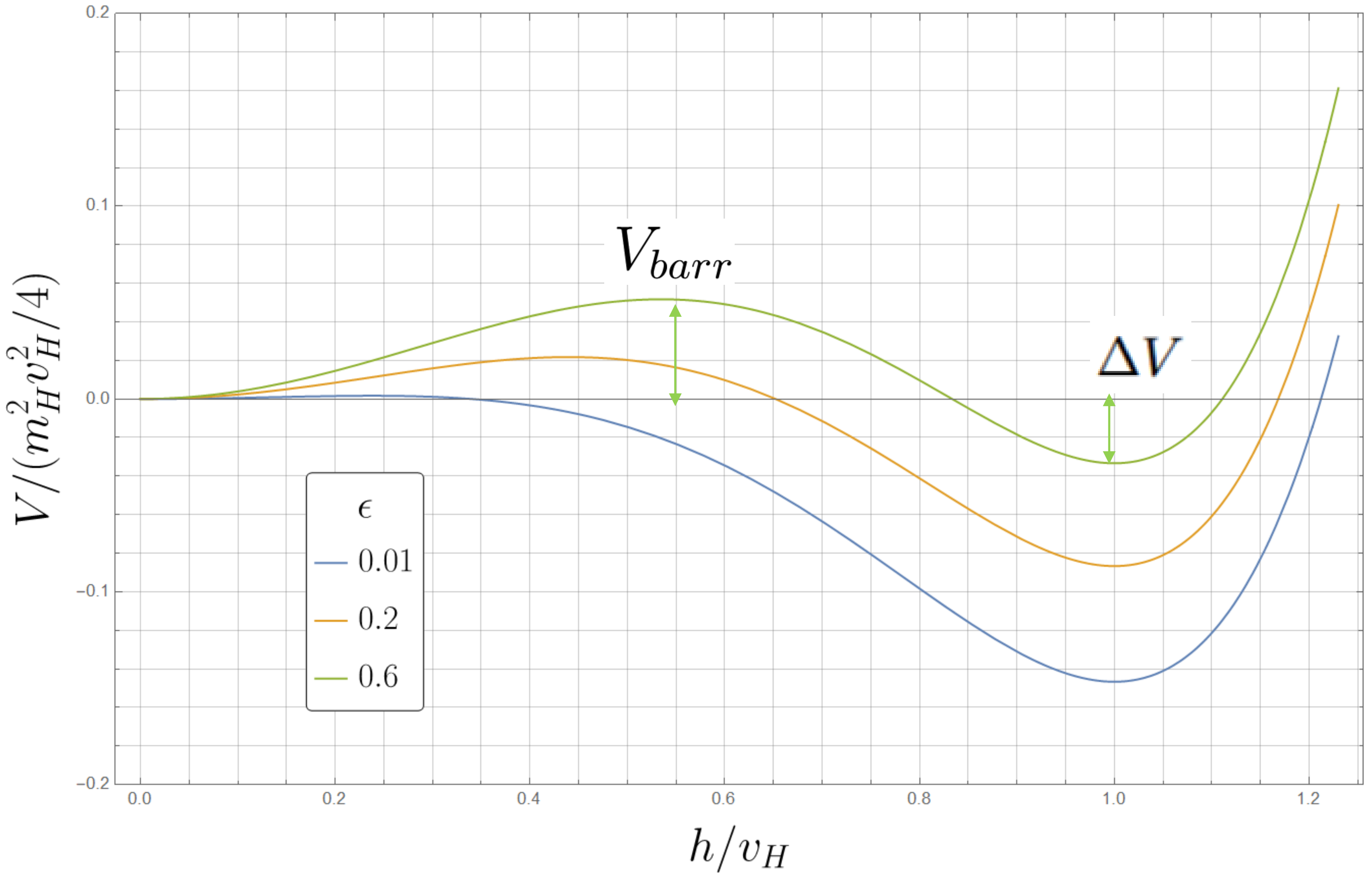
For $\epsilon \to 0$ $\quad |\Delta V| \gg V_{barr}$ → Inelastic bubble collisions

For $\epsilon \to 1$ $\quad |\Delta V| \ll V_{barr}$ → Elastic bubble collisions; False vacuum trapping

$$V = \frac{1}{2}\mu^2 h^2 - \frac{1}{4}\lambda h^4 + \frac{1}{8\Lambda^2} h^6$$

Higgs mass and vev reproduced when

$$\Lambda = \frac{\sqrt{3}v^2}{2\sqrt{\lambda v^2 - \mu^2}}, \qquad \mu = \frac{1}{2}\sqrt{2\lambda v^2 - m_h^2}$$



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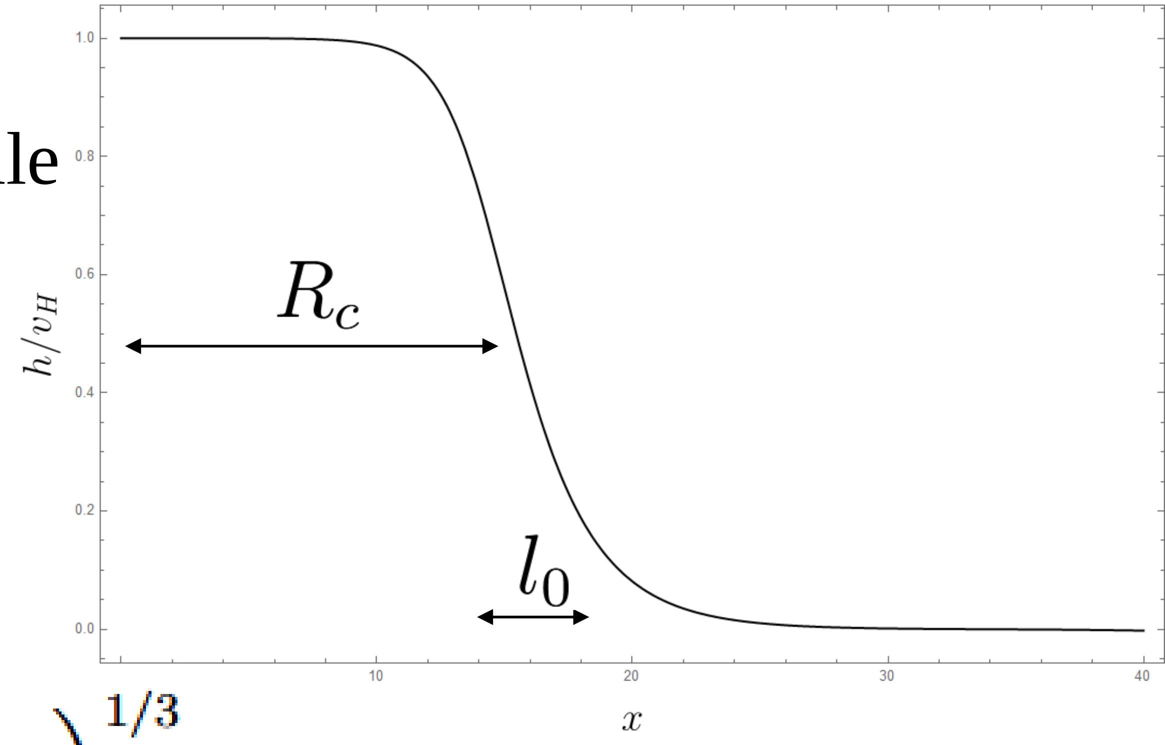
Extensive Lattice Simulations



- Implementation of Higgs doublet and *SU(2)*-gauge fields and critical bubble profile

$$\mathcal{L} \sim \mathrm{Tr}[F_{\mu\nu}F^{\mu\nu}] + |D_\mu \mathcal{H}|^2 - V(h)$$

$O(4)$ bounce solution

Bubbles of true vacuum are initialized in simulation box with random positions and random Higgs orientations

- Lorentz-boost factor at collision can be estimated as $\gamma_w^* \sim \frac{R_*}{R_c} \sim \frac{L m_H}{R_c m_H} \frac{\sqrt{3}}{2} \left(\frac{3}{4\pi n_b}\right)^{1/3}$ $\quad n_b$ = number of bubbles

  with mean bubble collision radius $R_* = \frac{\sqrt{3}}{2} L \left(\frac{3}{4\pi n_b}\right)^{1/3}$

- 2 scales: wall width l_* and R_* resolving the wall width means $\Delta x m_H \ll l_* m_H = \frac{l_0 m_H}{\gamma_w^*}$

- *SU(2)*-gauge field simulations (quantities averaged over many runs, large γ_w^*)

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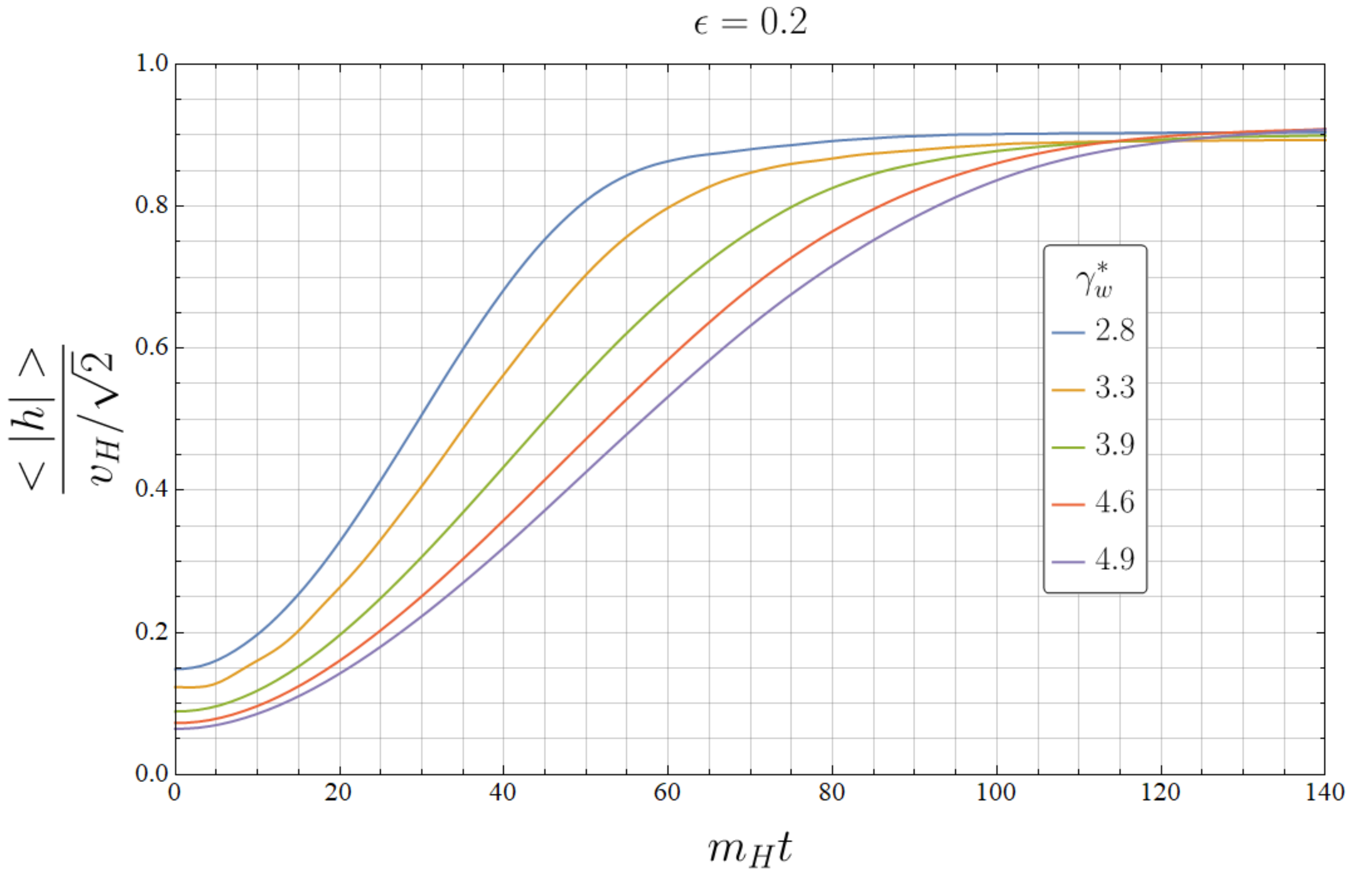
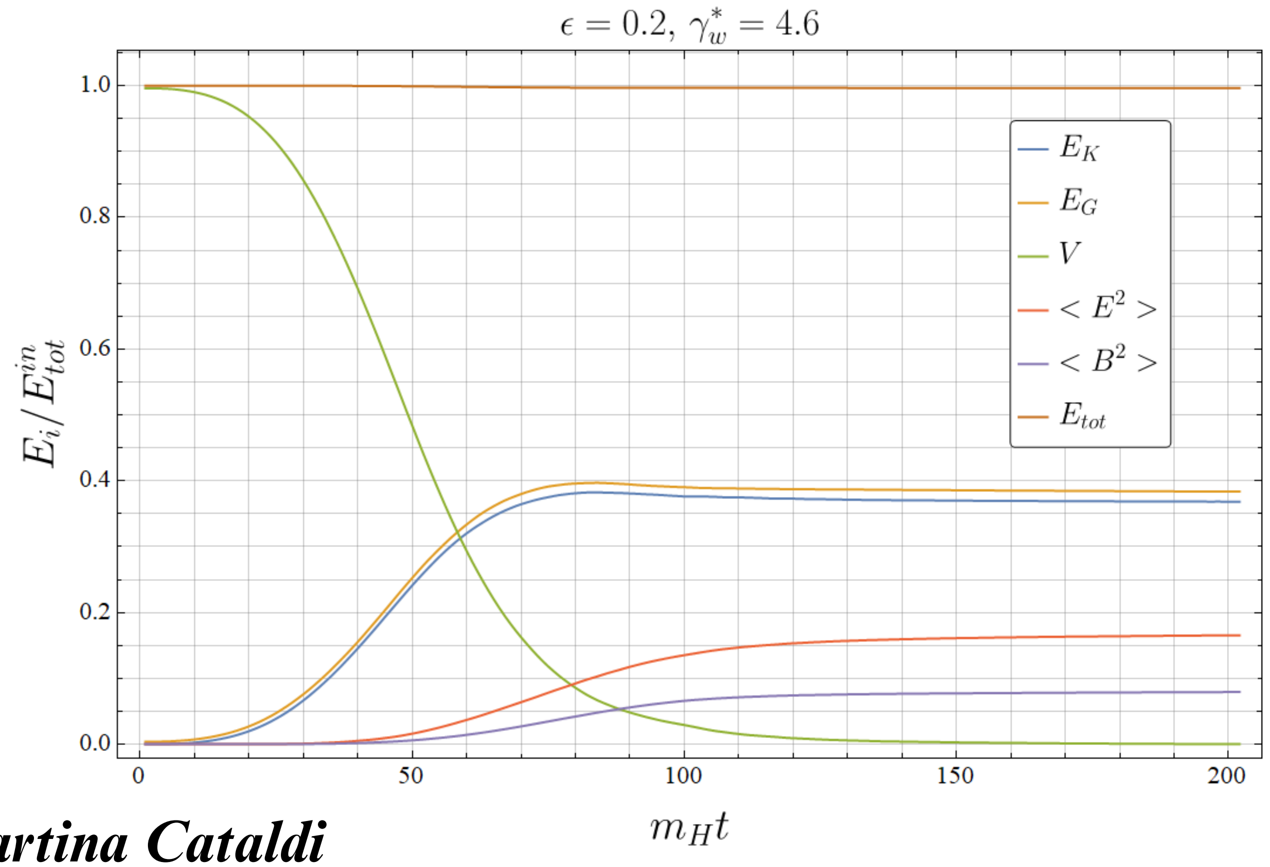
3D-Numerical results

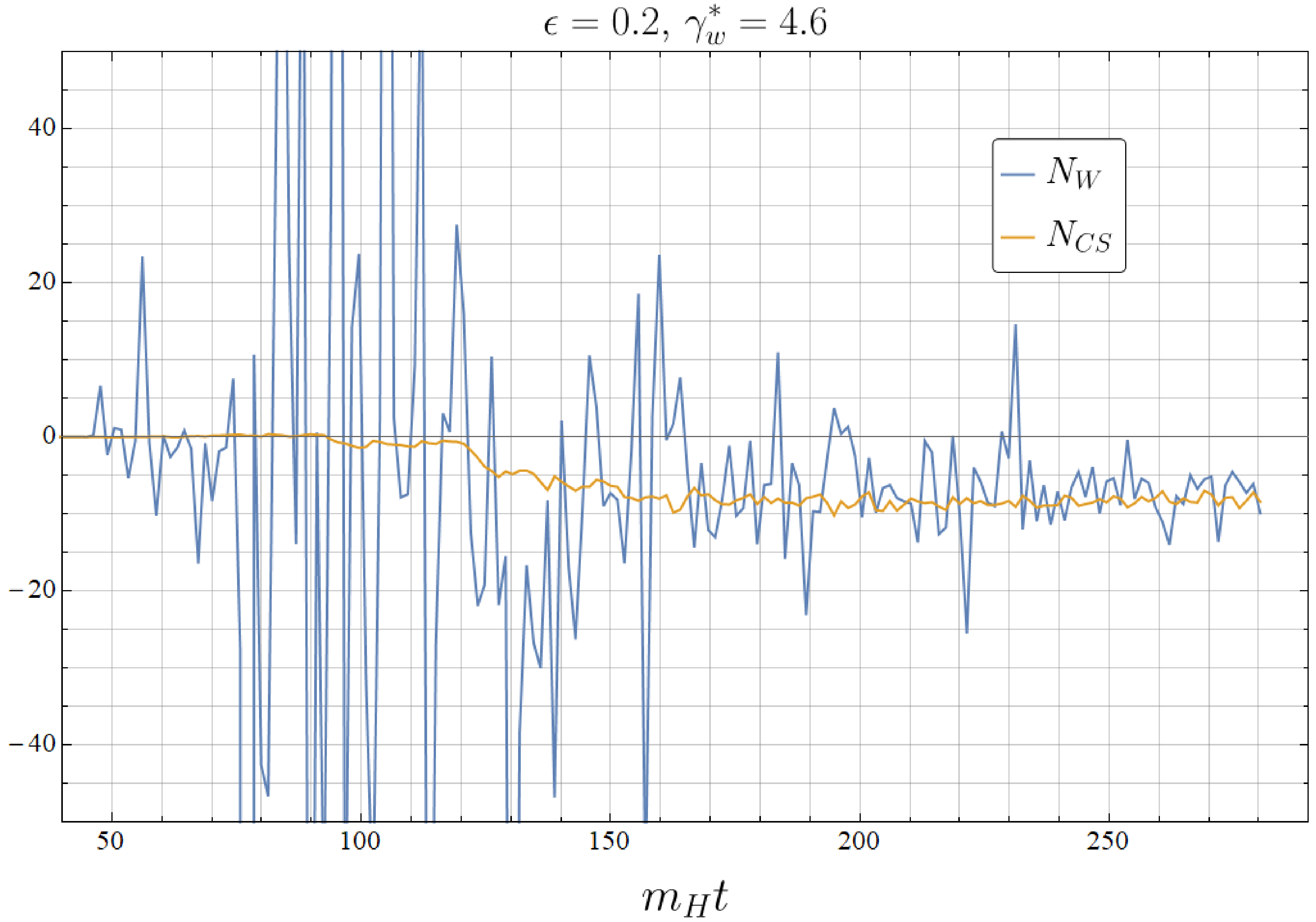


Volume-averaged Higgs norm



Energy distribution

Higgs winding and Chern-Simons number time evolution



We checked numerically that:

1) 2-bubble collision gives $N_W = 0$, due to spherical/cylindrical symmetry
2) Bubbles with same *SU(2)*-phase orientations give $N_W = 0$

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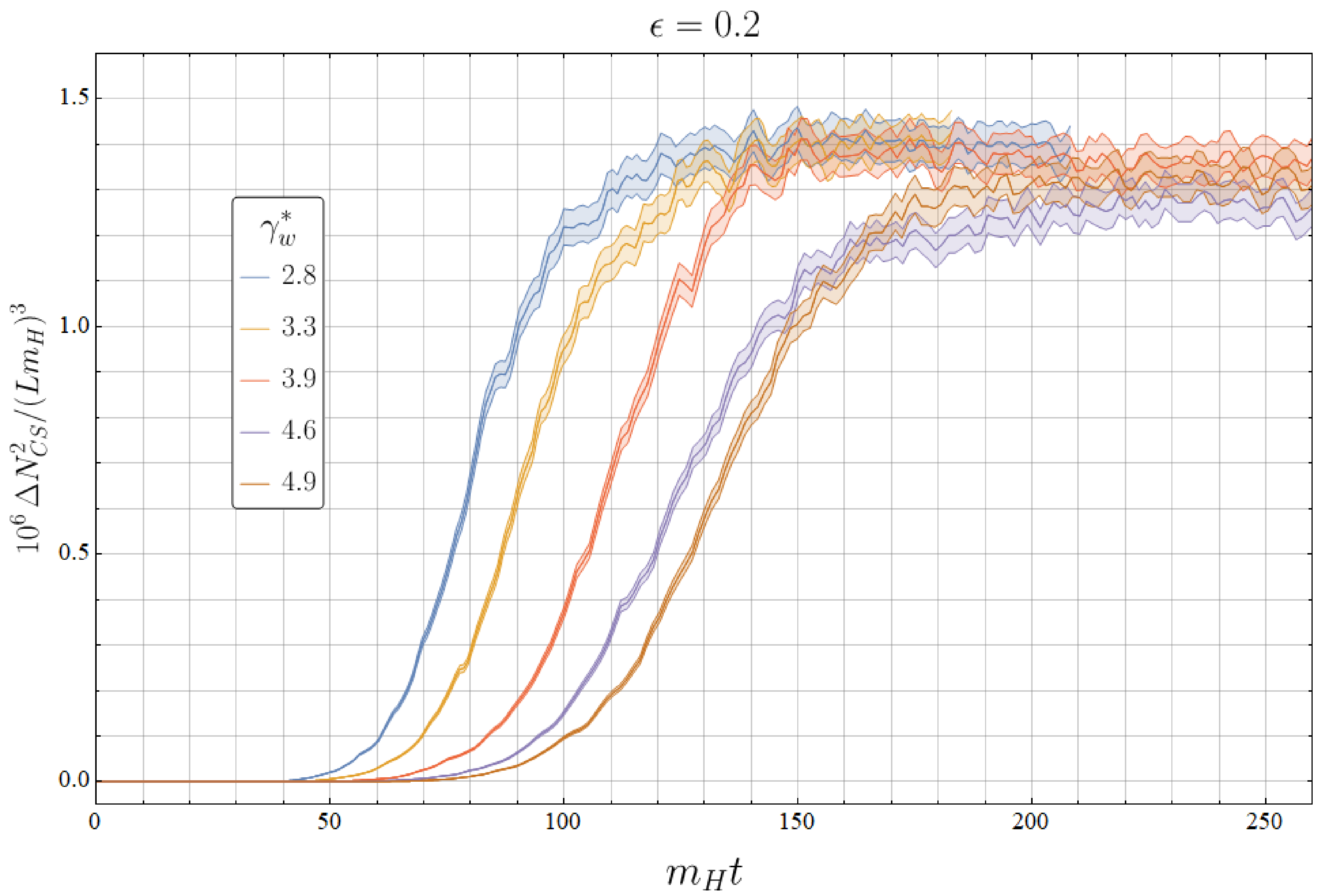
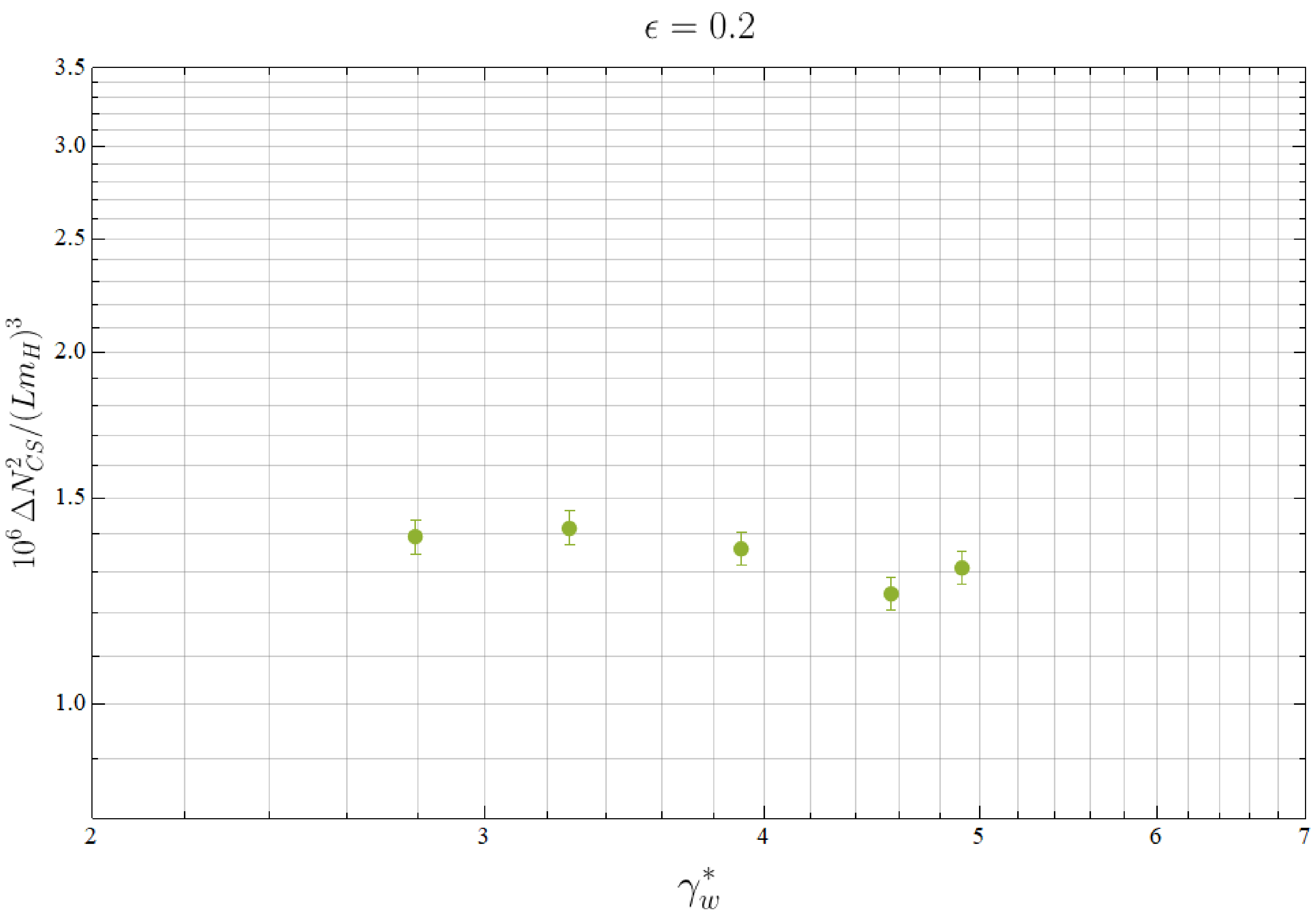
For ε = 0.2

Time evolution of Chern-Simons variance



$$\Delta N_{CS}^2(t) \equiv \langle N_{CS}(t)^2\rangle - \langle N_{CS}(t)\rangle^2$$

Asymptotic value of Chern-Simons variance vs boost factor at collision



Averaged over 100 simulations for each point, 10 bubbles per volume

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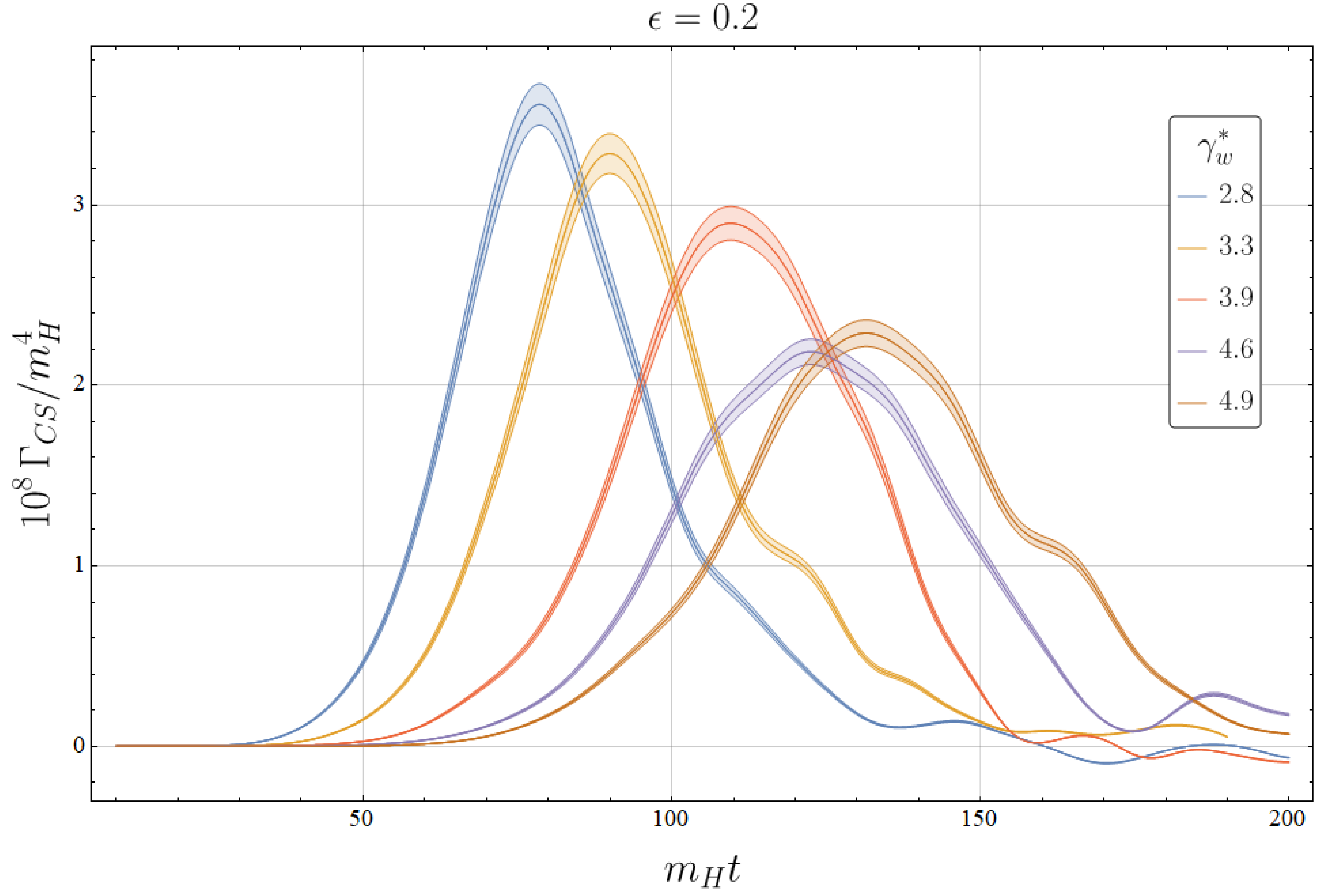
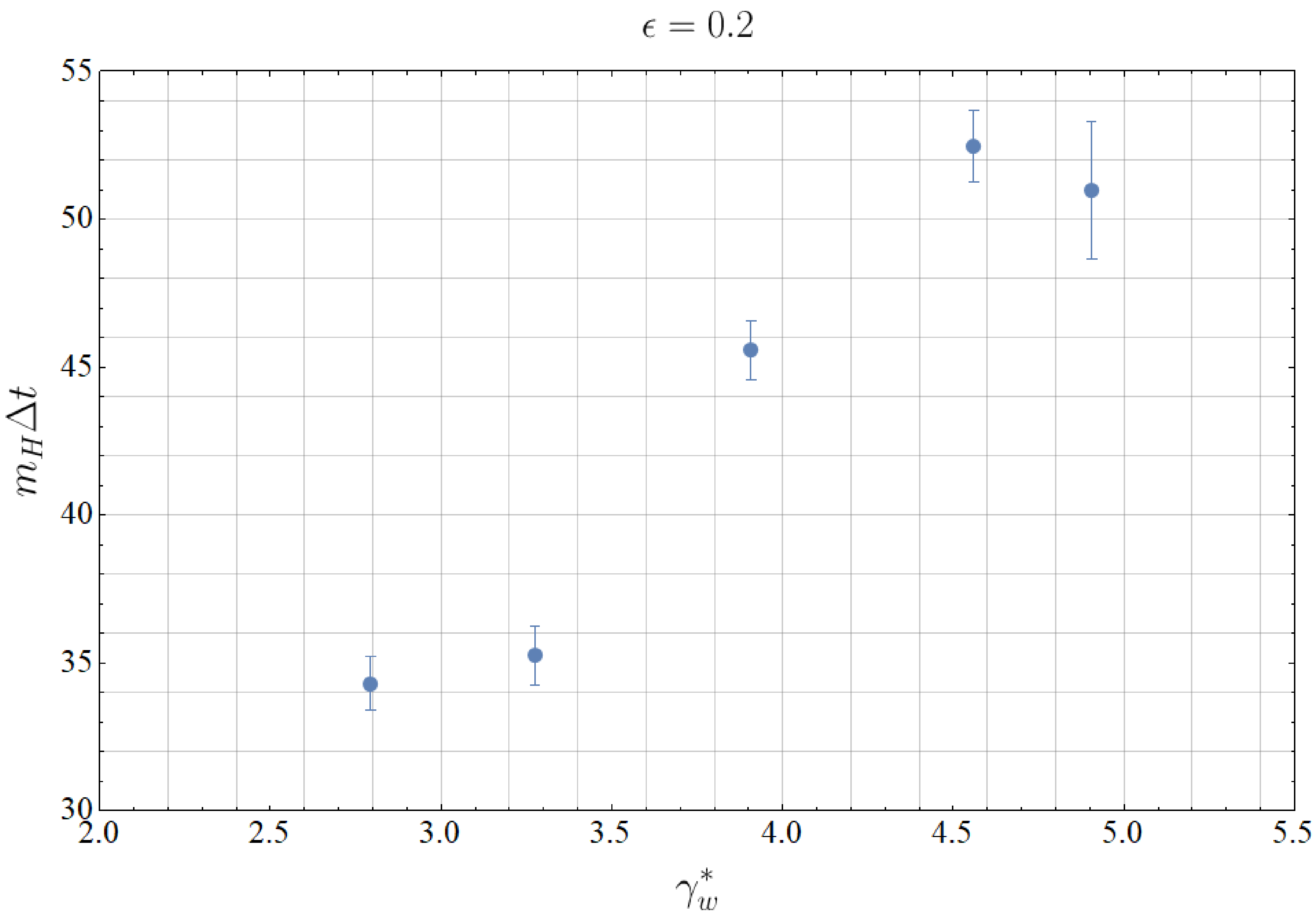
For ε = 0.2

$$\Gamma_{CS} = \frac{1}{L^3}\frac{d\Delta N^2_{CS}(t)}{dt}$$

Chern-Simons rate



Time duration of PT



In our mechanism, peak of the CS rate gets smaller while the time duration of the PT gets larger with boost factor

For $\epsilon = 0.2$, integrated Chern-Simons rate $\int dt\Gamma_{CS} = \frac{\Delta N^2_{CS}}{L^3} \simeq const$

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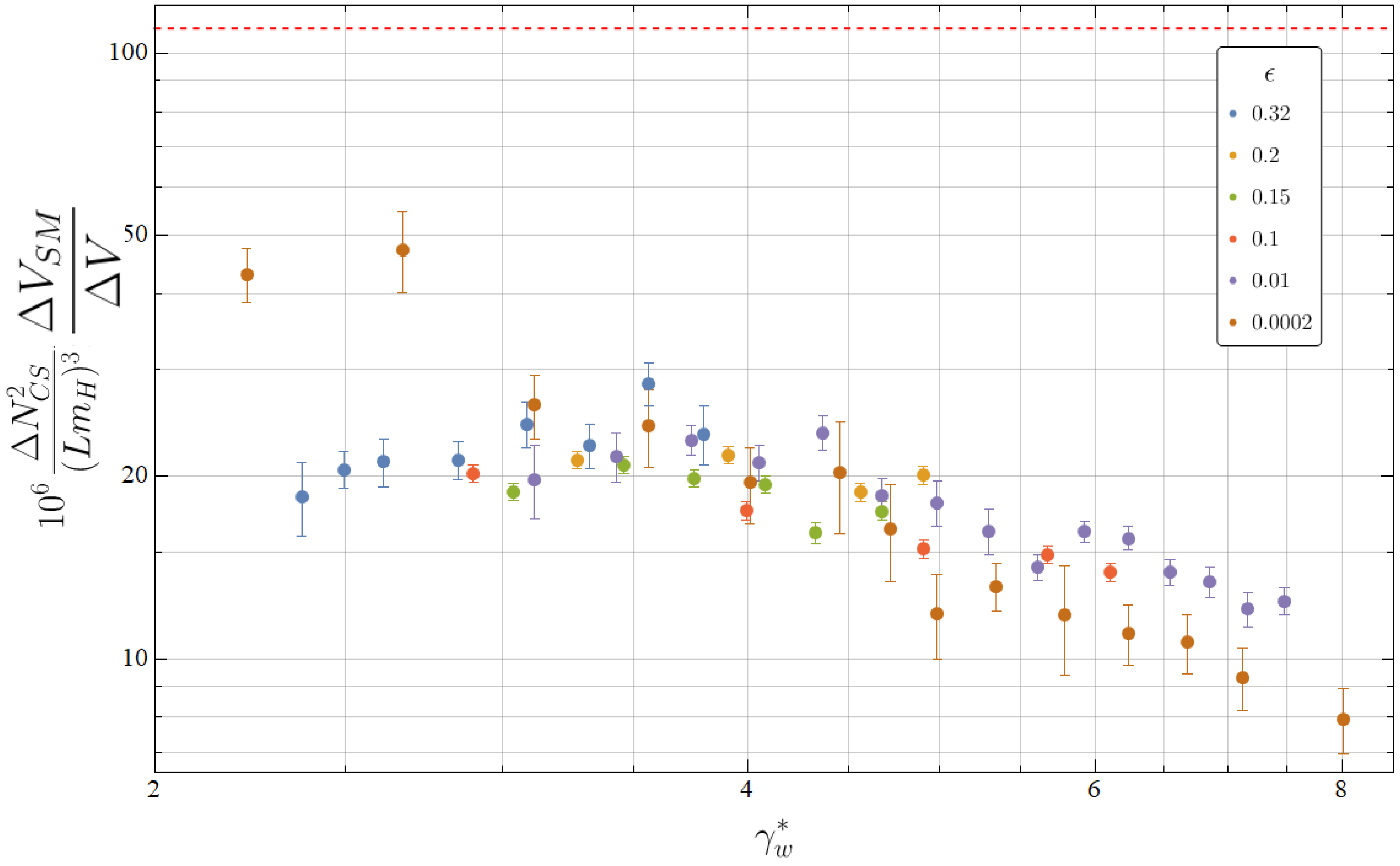
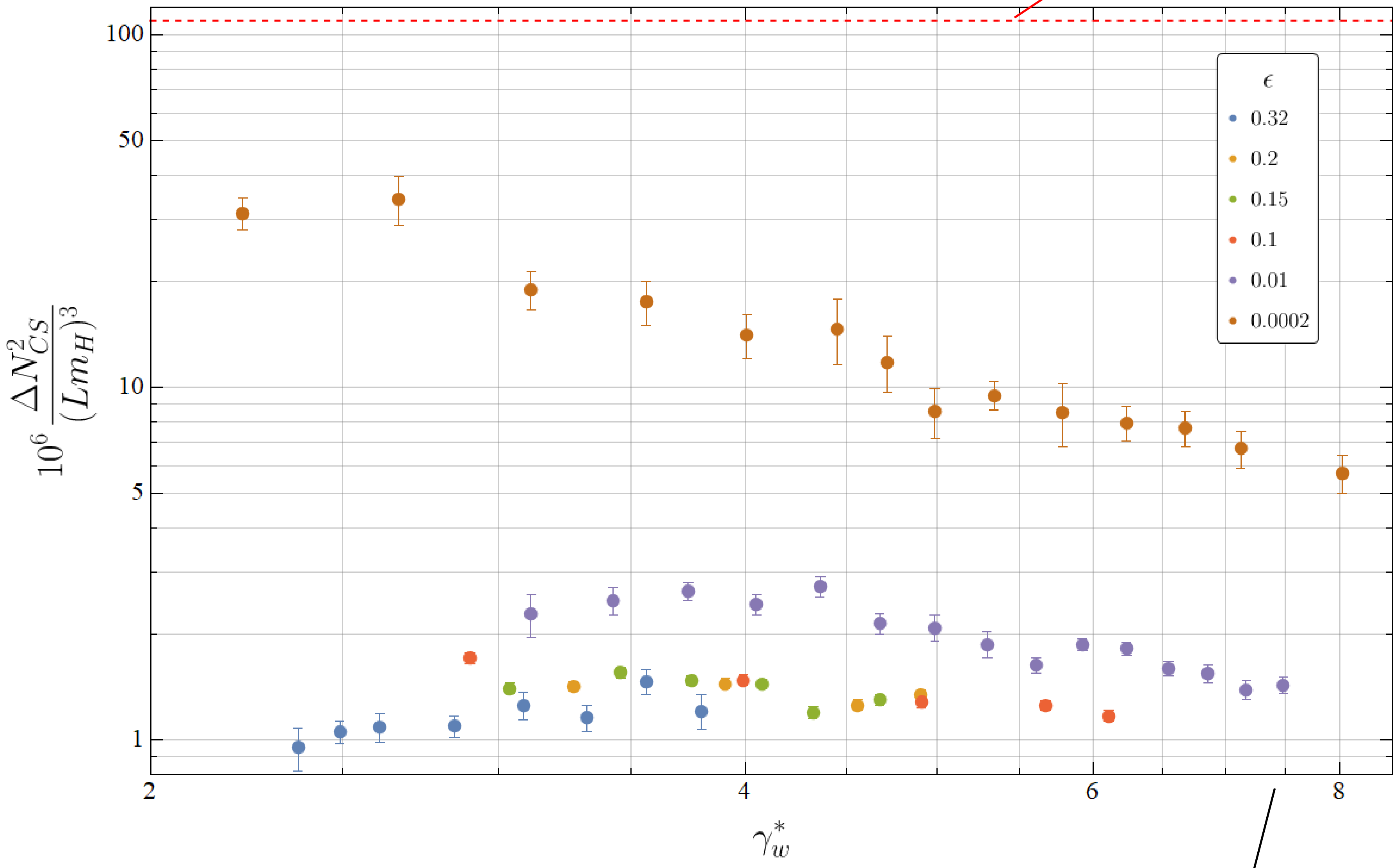
Dependence of CS variance on ε

Normalized by ΔV



Tachyonic instability value



For $\epsilon \ll 0.2$ → CS production decreases with γ_w^*

For $\epsilon \gtrsim 0.2$ → CS production is (at least) constant with γ_w^*

Pushing towards technical limits

Most extensive lattice simulations with *SU(2)*-gauge fields!!

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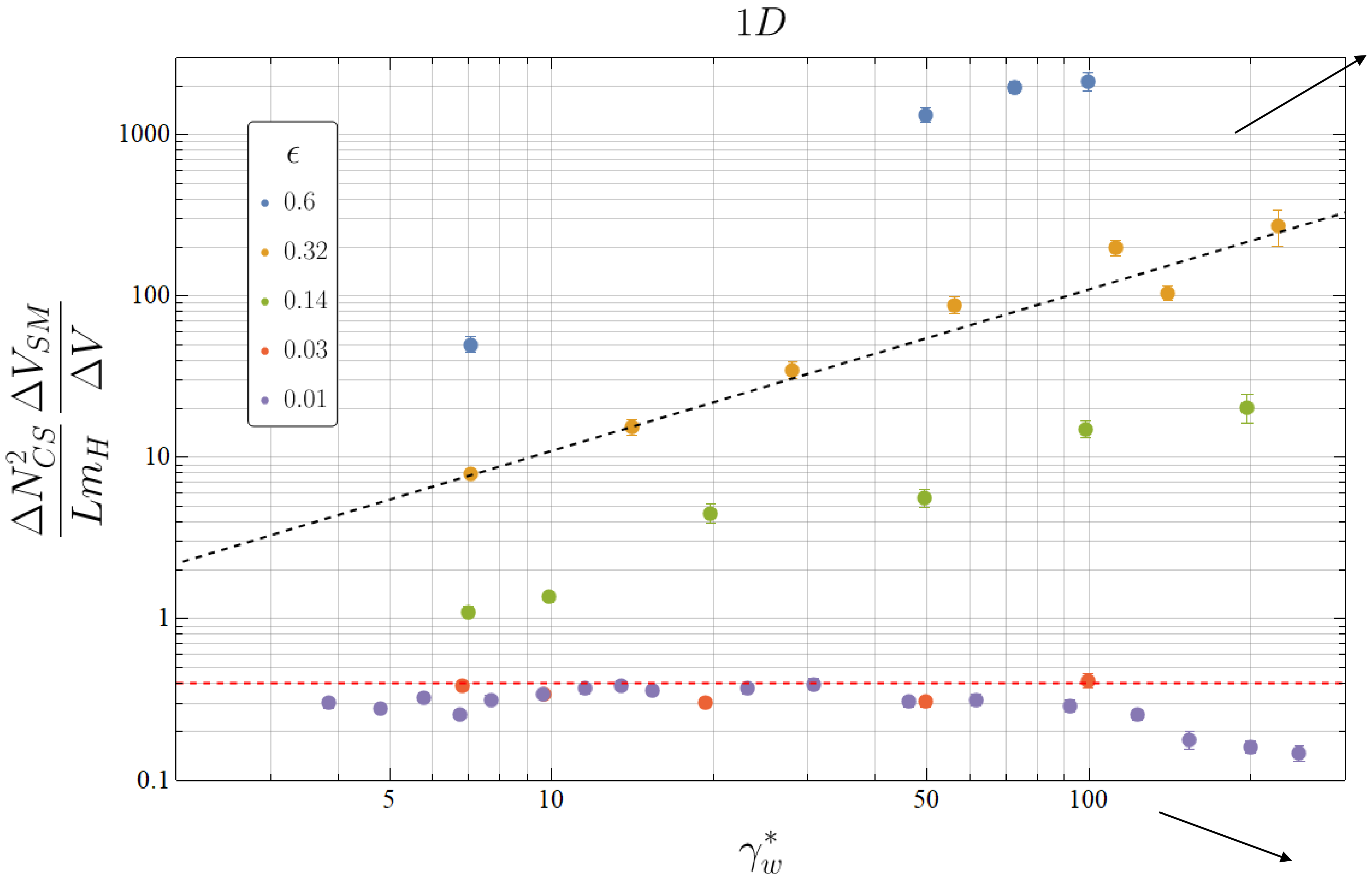
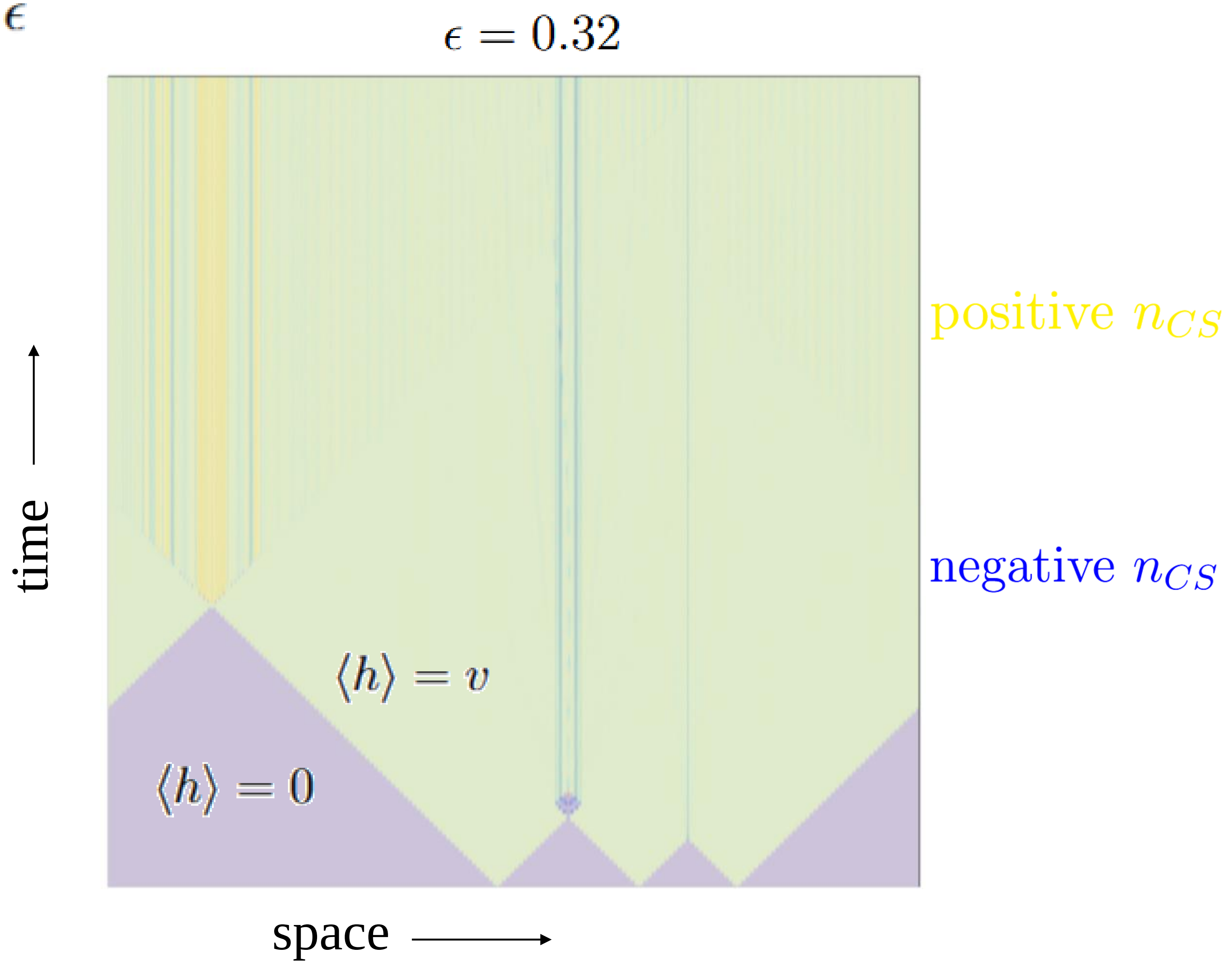
Dependence of CS variance on ε : (1+1)D case with U(1) gauge field



Probe higher ϵ

Probe higher γ_w^*



→ CS production changes behaviour

For $\epsilon \sim 0.1$

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Baryon asymmetry estimate

→ Baryon number density from Higgs bubble collisions at T=0

$$n_B = 3n_{CS} = \frac{3}{L^3}\int_0^{L^3} d^3x \int_0^{\Delta t} dt \frac{\Gamma_{CS}(x,t)}{L^3}\delta_{CP} = 3\delta_{CP}\left(\frac{\Delta N_{CS}^2}{L^3}\right)$$

with dimensionless *CP*-asymmetry parameter δ_{CP}
(no *CP*-violating term simulated)

→ Baryon asymmetry today

$$Y_{\Delta B} = \frac{n_B}{s} = \frac{45}{2\pi^2}\frac{3\delta_{CP}}{g_*(T_{reh})T_{reh}^3}\left(\frac{\Delta N_{CS}^2}{L^3}\right) = 2.97 g_*^{-1/4}(T_{reh})\frac{\delta_{CP}}{\Delta V^{3/4}}\left(\frac{\Delta N_{CS}^2}{L^3}\right)$$

L^3 = Hubble volume

Δt = duration of PT

ΔV = released Higgs potential energy

$T_{reh} \sim \Delta V^{1/4} \simeq \mathcal{O}(30)$ GeV

→ For a preliminary estimate, consider the lower bound on CS production given by $\epsilon = 0.2$

$$Y_{\Delta B} = 8.2 \times 10^{-6}\delta_{CP}$$ reproducing observed baryon asymmetry for $\delta_{CP} \simeq 10^{-5}$

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Mexican standoff

Tachyonic Cold Baryogenesis	*First Order Electroweak Baryogenesis*	*Cold Baryogenesis by Higgs bubble collisions*
Cold	Hot (thermal sphaleron)	**Cold**
Microscopic time duration	**Macroscopic time duration**	**Macroscopic time duration**
Every point in volume	**Eventually sweeping whole volume**	**Eventually sweeping whole volume**
Low scale inflation	**Strong FOEWPT**	**Strong FOEWPT**
Tachyonic transition	Bubble wall interface	***SU(2)*-textures from Higgs bubble wall collisions**

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Summarising

→ Novel realization of Cold Baryogenesis, which relies on

1) **Out-of-Equilibrium** dynamics from strong First Order Electroweak Phase Transition

2) Production and decay of *SU(2)*-gauge textures leading to **baryon number violation**

→ Extensive lattice simulations to compute Standard Model baryon number violation at T=0 from Higgs bubble collisions

→ Potentials with $\epsilon \to 1$, i.e. false-vacuum trapping regions after collisions, seem to be favoured for the Chern-Simons production mechanism

→ Able to reproduce observed baryon asymmetry for reasonable value of *CP*, i.e $\delta_{CP} \simeq 10^{-5}$

Backup

(1+1)D case with U(1) gauge field

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D_\mu\psi|^2 - V(\psi)\,, \qquad D_\mu\psi = \partial_\mu\psi - igA_\mu\psi,$$

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

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

Backup

Runaway regime for EWPT: supercooling

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

Thus, $\frac{\beta}{H} \frac{(10^{-8}\mathrm{GeV}^3)}{T_n^3} \gtrsim 1$ $\longrightarrow$ $\beta/H = (10^5 - 10^8)$ for $T_n \lesssim (0.1 - 1)\mathrm{GeV}$