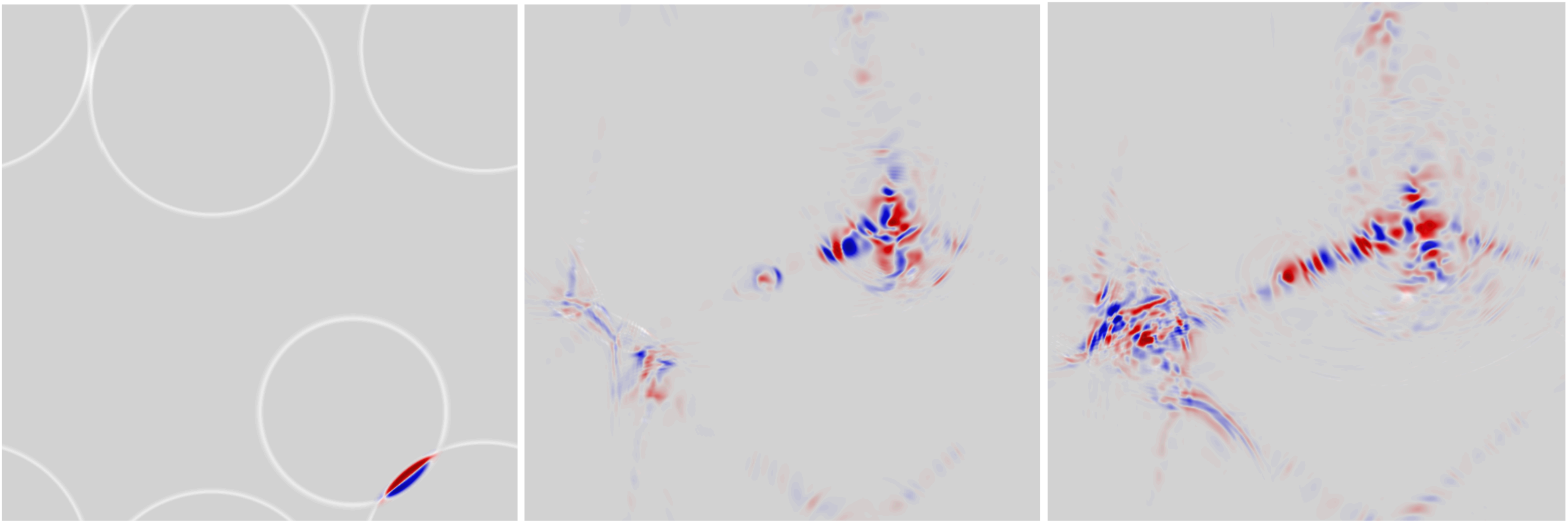
Standard Model Baryon number Violation at T=0 from Higgs Bubble Collisions



Marco Gorghetto

DESY.

Alexander von Humboldt
Stiftung / Foundation

Based on: [2508.21825] **Bushal, Blasi, Cataldi, Chatrchyan, MG, Servant**

Main Result

- We identified a **new source of baryon number violation** during a first-order electroweak (EW) phase transition, active at $T = 0$

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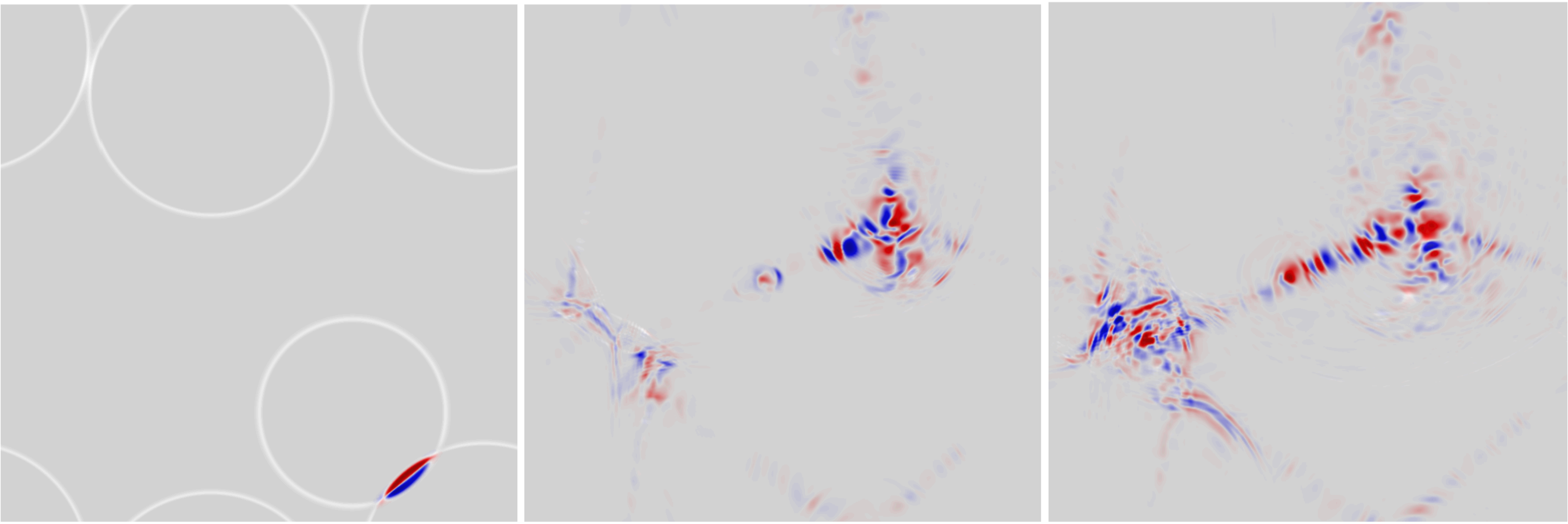
- We identified a **new source of baryon number violation** during a first-order electroweak (EW) phase transition, active at $T = 0$

- Bubble collisions generate EW gauge bosons, producing an **effective sphaleron rate** similar in magnitude to electroweak sphalerons in the symmetric phase



- Opens up new possibilities for **baryogenesis** in a **supercooled** phase transition

Review of baryon number violation in the SM

- B and L are **global accidental symmetries** of the SM, at the classical level

- Their violation has **never been measured** experimentally

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- However, they **must have been violated** in the early Universe to account for the observed baryon asymmetry of our Universe

- In the SM both B and L **are violated** at the quantum level by the chiral anomaly

- From the anomaly: $\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = N_f \frac{\alpha_w}{8\pi} \mathrm{Tr}\, F\tilde{F} \neq 0$

EW field strength

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$\mathrm{Tr}\, F\tilde{F}$ → $\partial_\mu J^\mu_{\mathrm{CS}}$ total derivative

$\mathrm{Tr}\, F\tilde{F}$ ← EW field strength

$$\Delta B = \Delta L = N_f \, \Delta N_{\mathrm{CS}}$$

$$N_{\mathrm{CS}} = \int d^3x \, J^0_{\mathrm{CS}} \sim \int d^3x \, \epsilon^{ijk} \, \mathrm{Tr}\big(W_i F_{jk} + W_i W_j W_k\big)$$

Chern-Simons (CS) number

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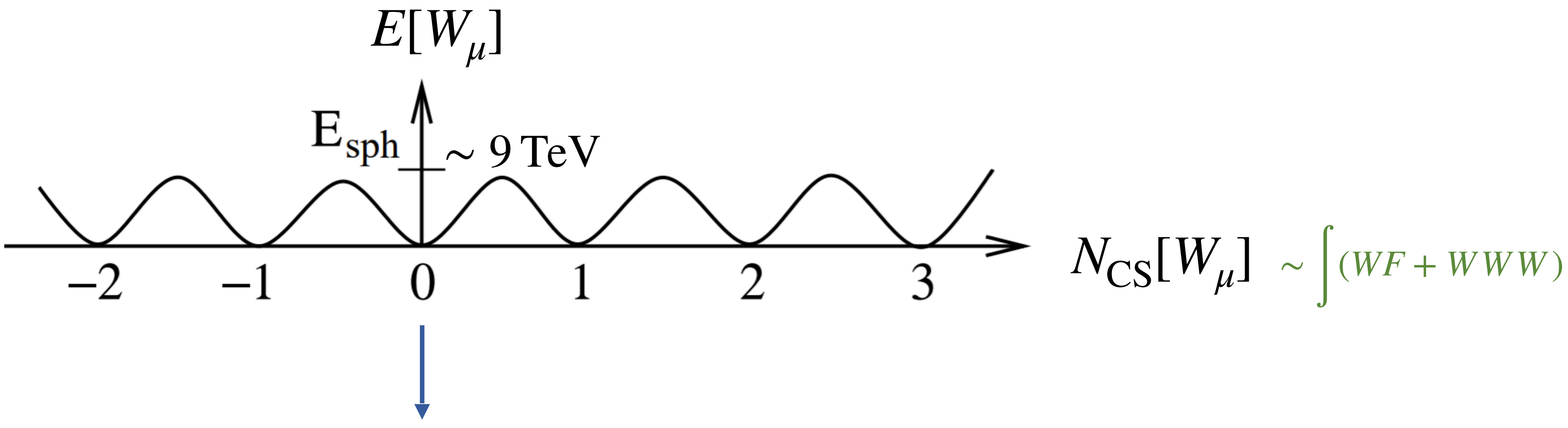
Chern-Simons (CS) number

- $B - L$ **is conserved**

- Processes changing N_{CS} also lead to a change to $B + L$

Energy of a gauge field configuration



E **minima (vacua):** $F_{\mu\nu} = 0$ $\quad W_\mu = 0$

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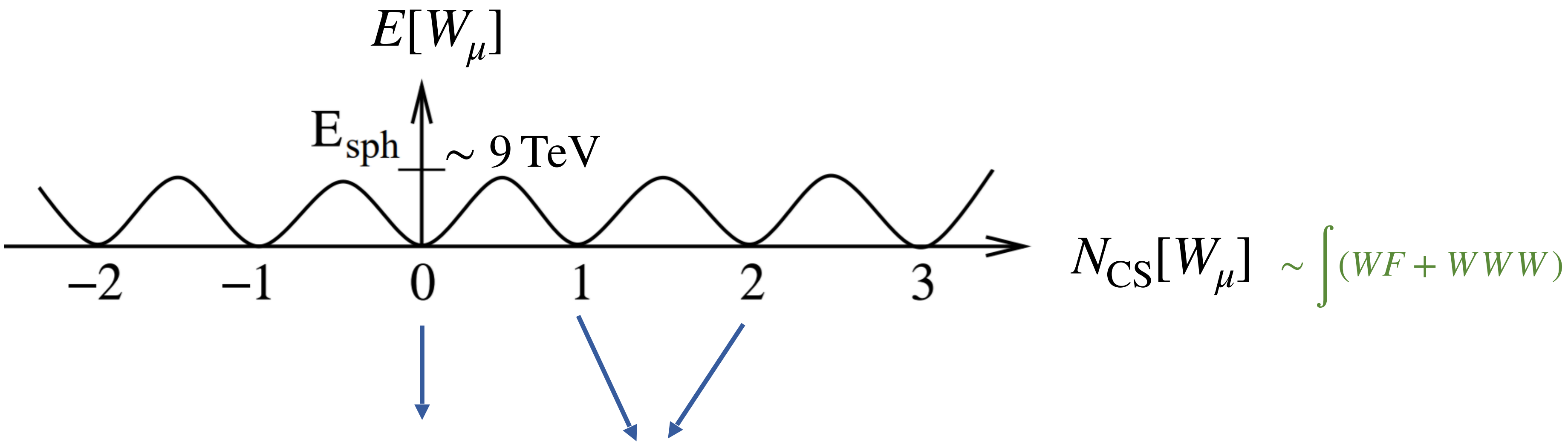

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$S^3 \to SU(2)$

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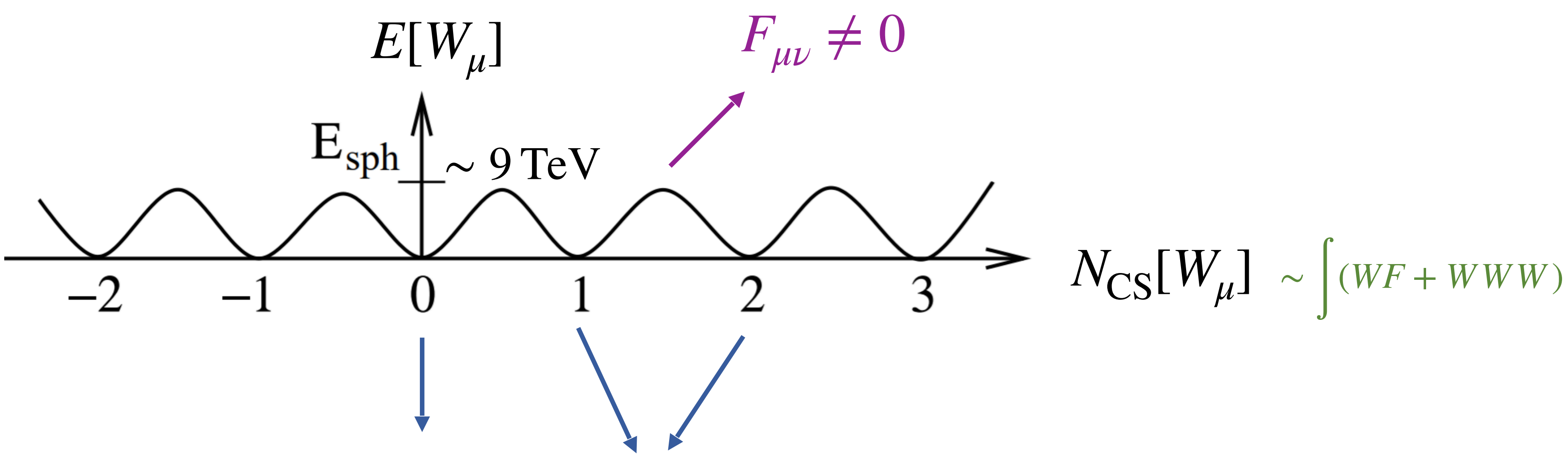

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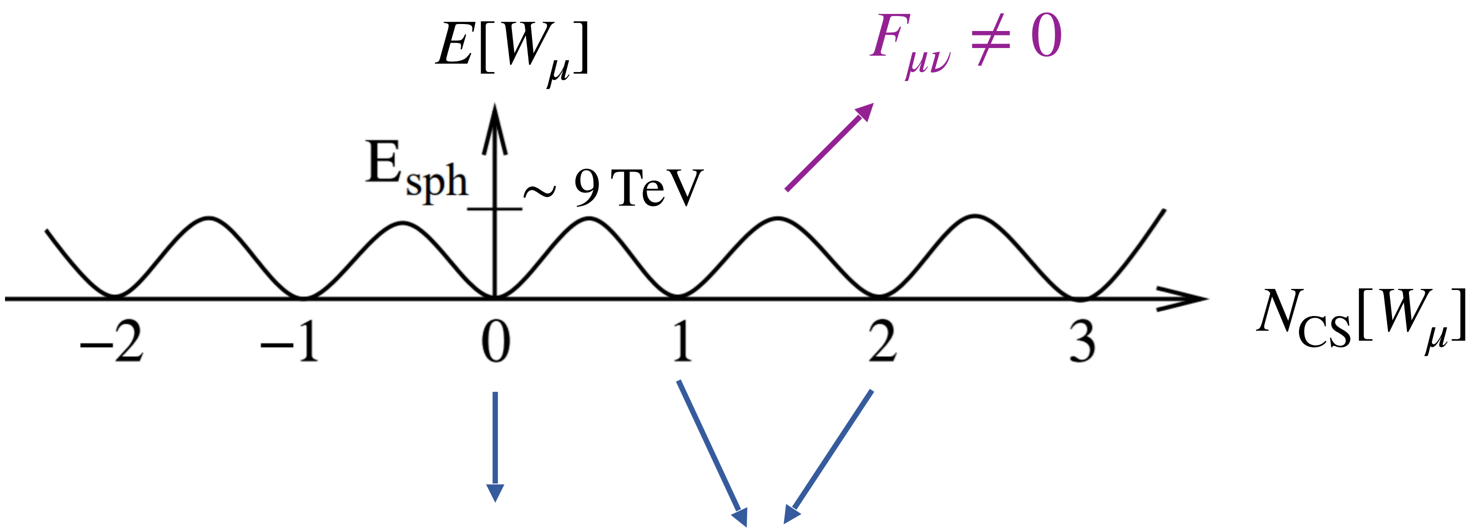

$\sim \int (WF + WWW)$

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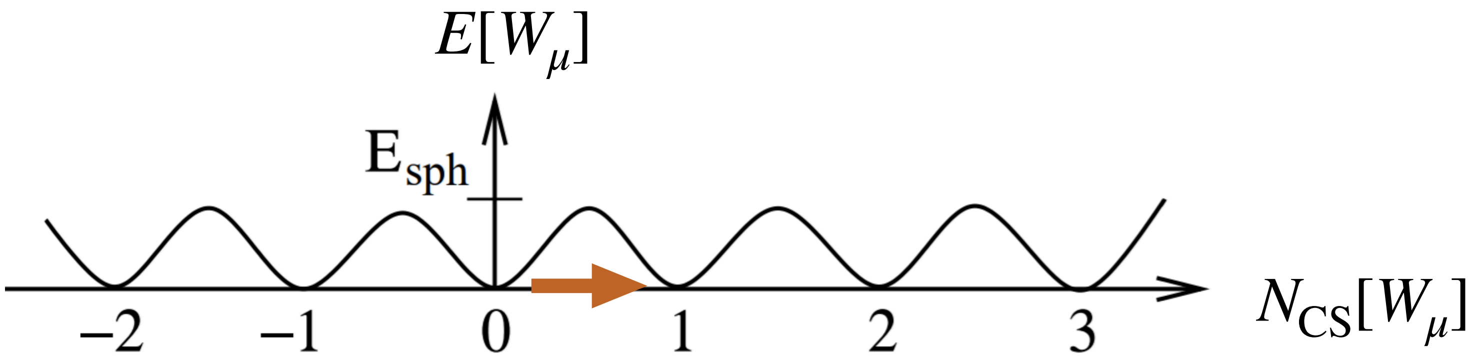
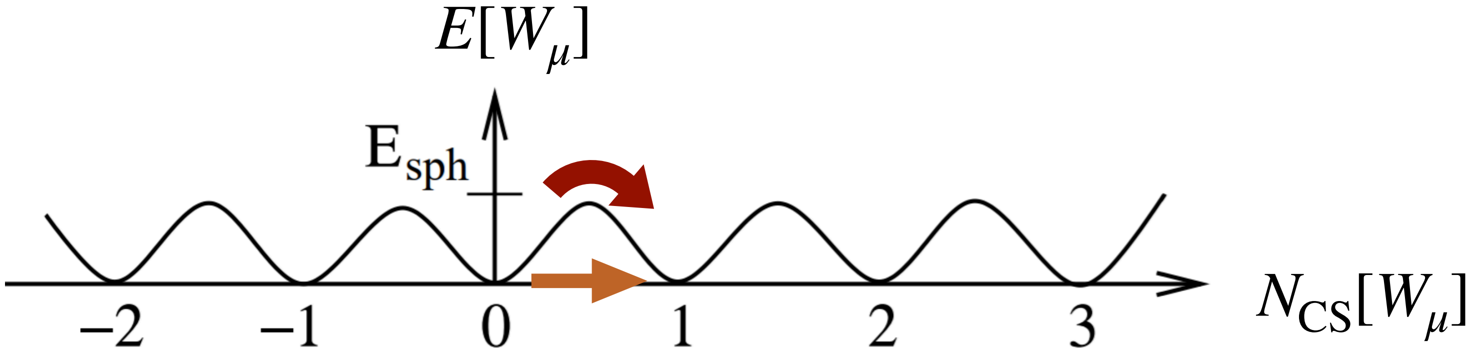
$\Delta B = N_f \, \Delta N_{CS} \implies$ Baryons created by transitions between topologically distinct vacua of the SU(2) gauge field



- **Quantum** tunnelling rate per unit time and volume: $\Gamma \sim e^{-4\pi/\alpha_w} \sim 10^{-165}$

$$\alpha_w \sim 1/30$$



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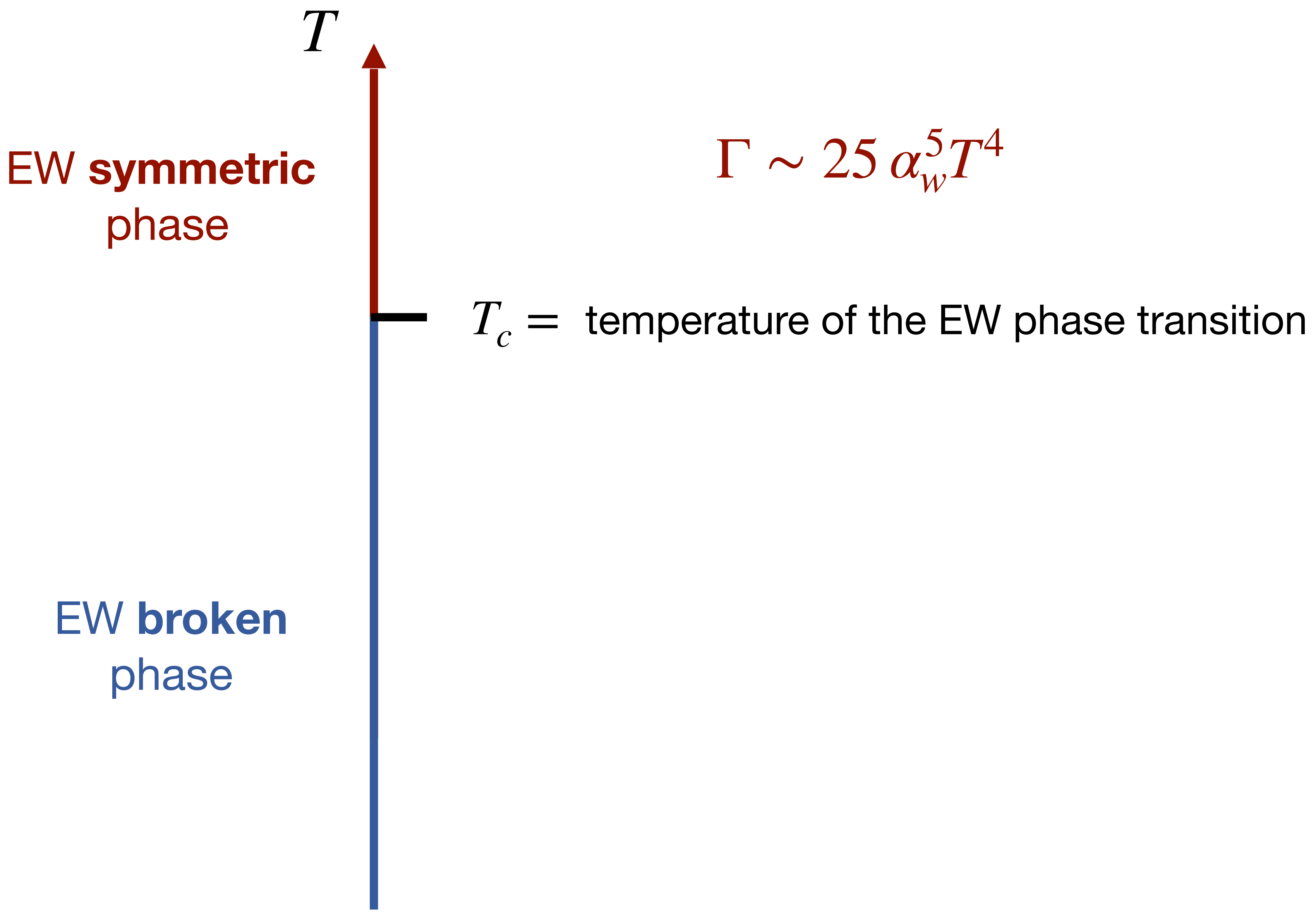
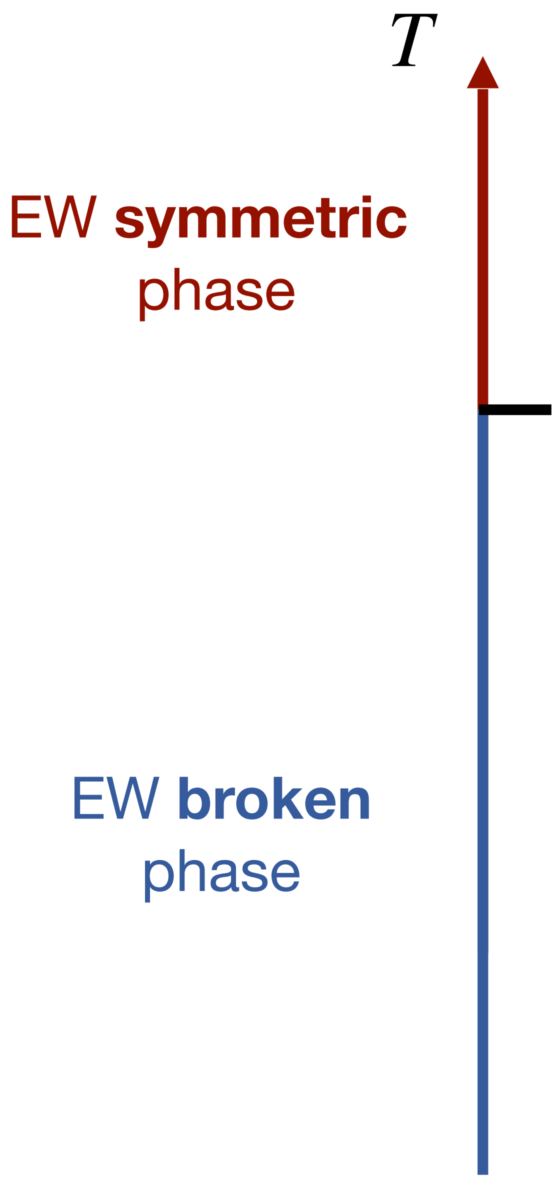
- Γ sizeable at high T: it is possible to go over the barrier via **thermal fluctuations**


T
EW **symmetric** phase
$\Gamma \sim 25\, \alpha_w^5 T^4$
$T_c =$ temperature of the EW phase transition
EW **broken** phase



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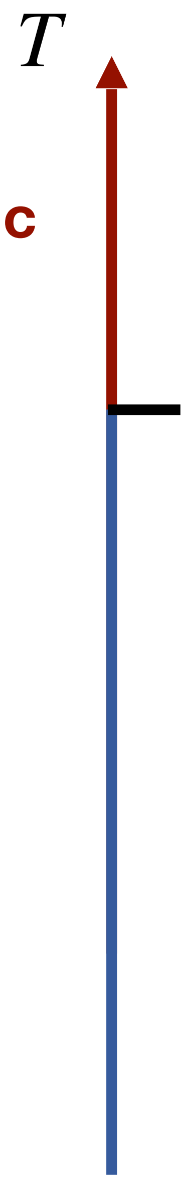
$$\Gamma \sim v^4 e^{-E_{\rm sph}(T)/T} \qquad E_{\rm sph}(T) = M_W(T)/g_w \propto \langle \phi(T) \rangle$$



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EW **broken** phase

CS number transitions suppressed when $T \lesssim \langle \phi(T) \rangle$

e.g. in **supercooled** phase transitions, nucleation temperature $T_n \ll T_c$

(in addition, bubble walls are too fast)

Baryons from SU(2) texture dynamics

1) bubble collisions produce $SU(2)$ **textures**

2) textures decay **producing** CS number transitions

Turok, Zadrozny, NPB 1991
Lue, Rajagopal, Trodden, 1996

Texture = field configuration where:

ϕ is in the **vacuum** manifold M everywhere but maps nontrivially space onto M

Vilenkin, Shellard '94

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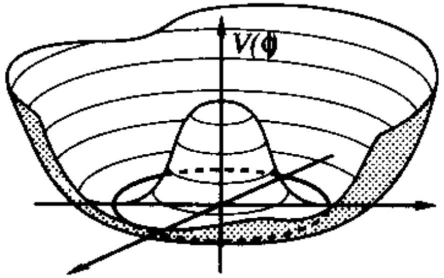
Example: $M = U(1) \simeq S^1$ in 1+1d



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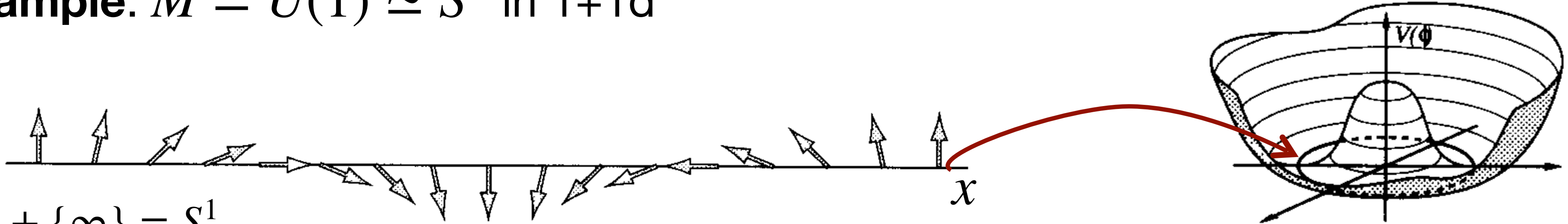

$\mathbb{R}^1 + \{\infty\} = S^1$

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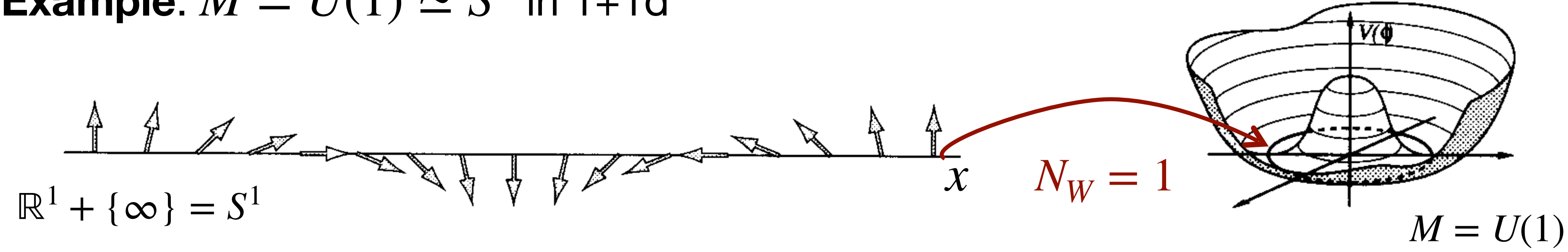
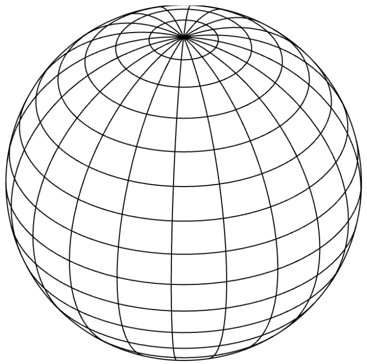


→ labelled by the integer Higgs winding number: $N_W = \dfrac{1}{2\pi}\displaystyle\int dx\, \partial_x \mathrm{Arg}\, \phi$ $\quad [\, \pi_1(S^1) = \mathbb{Z}\,]$

→ energy due to the field gradient only → (global) texture collapses to minimize it

Vilenkin, Shellard ‘94

Example: $M = S^2$ in 1+2d



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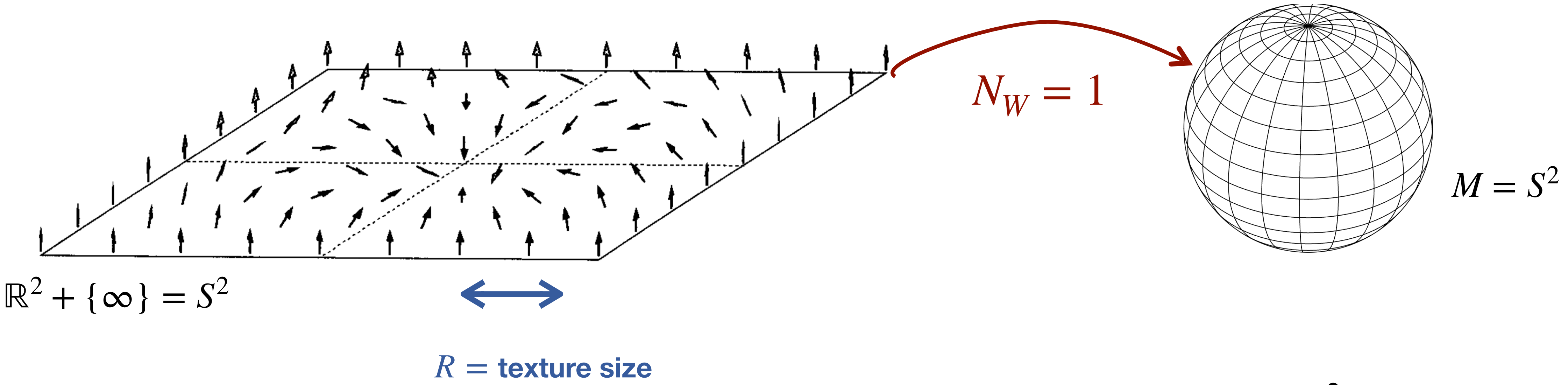

$[\ \pi_2(S^2) = \mathbb{Z}\ ]$

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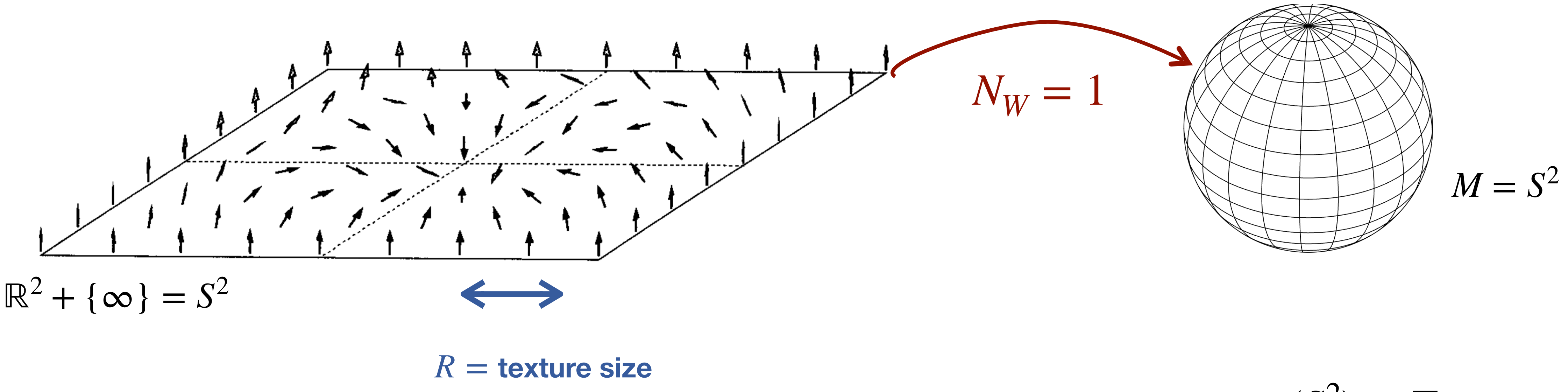

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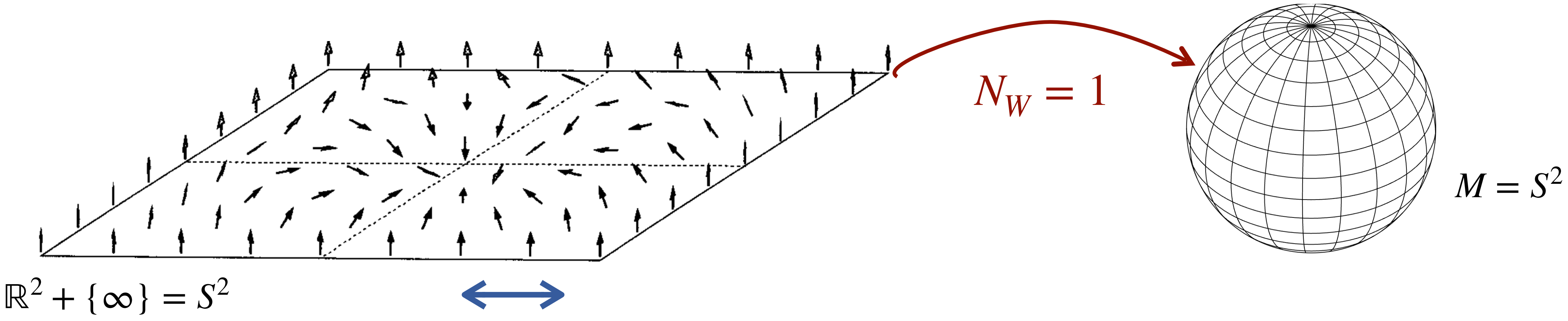

R = **texture size**

$[\ \pi_2(S^2) = \mathbb{Z}\ ]$

The SM: $M = SU(2) \times U(1)/U(1) \simeq SU(2) \simeq S^3$ in 1+3d — obvious generalization

- Gauge textures **collapse** into the **vacuum** where $D_\mu \Phi = 0 \iff N_W = N_{CS}$

How do textures with $N_W - N_{\mathrm{CS}} = 1$ **and gauge fields** collapse to the vacuum $N_W - N_{\mathrm{CS}} = 0$?

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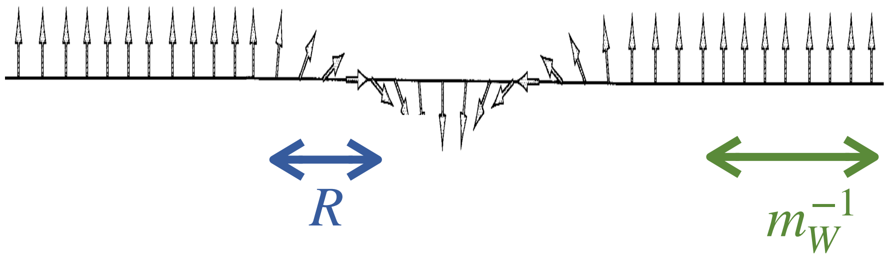

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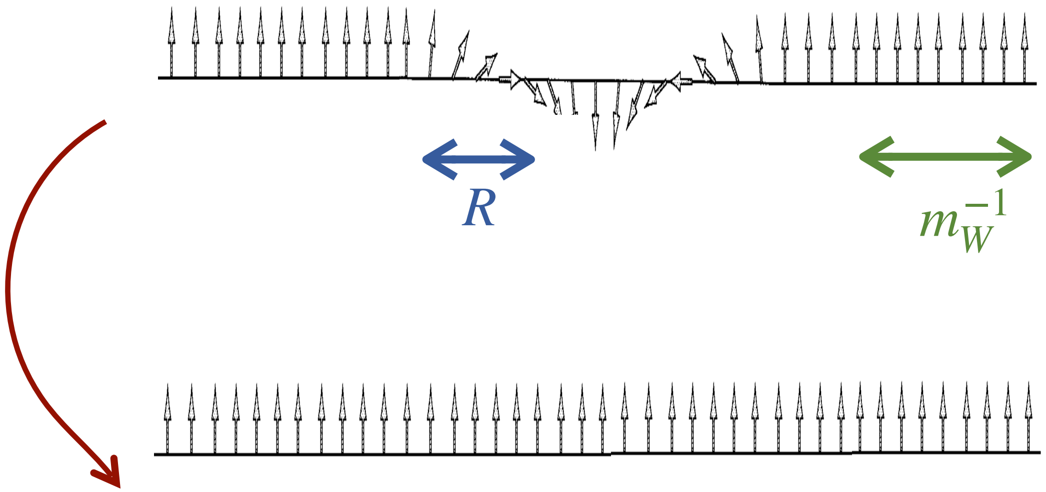

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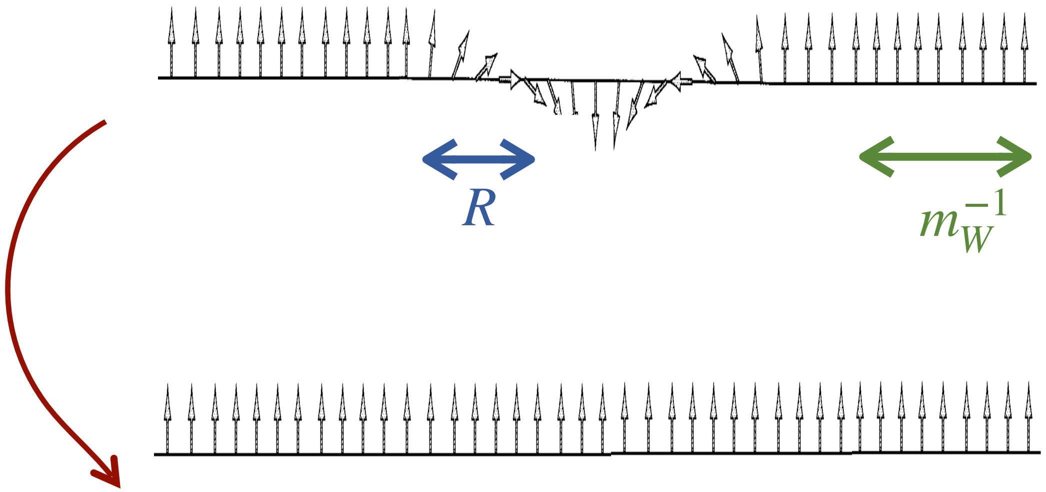

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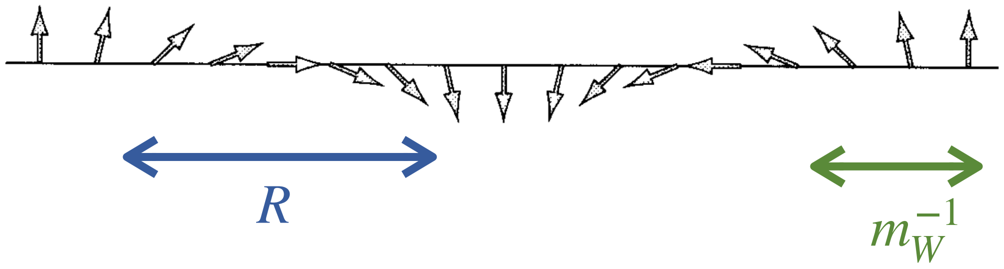

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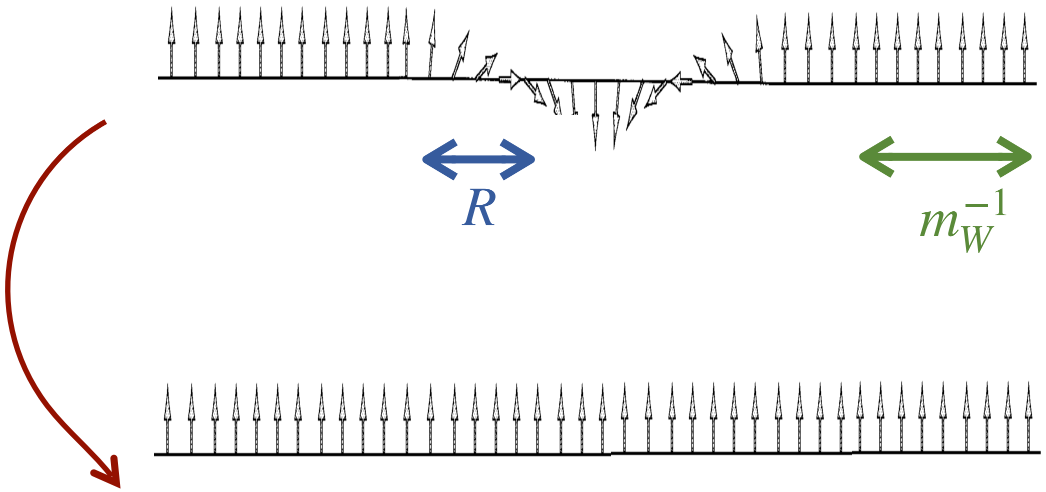

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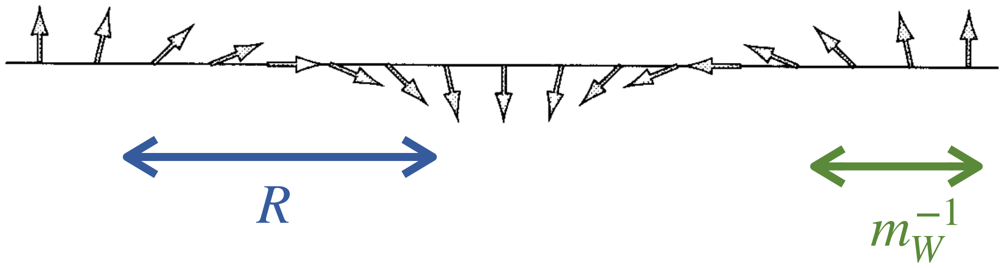

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"Dressing" :

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

Baryons **produced**! $\Delta B = N_f \Delta N_{CS}$

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

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

1) Tachyonic instability

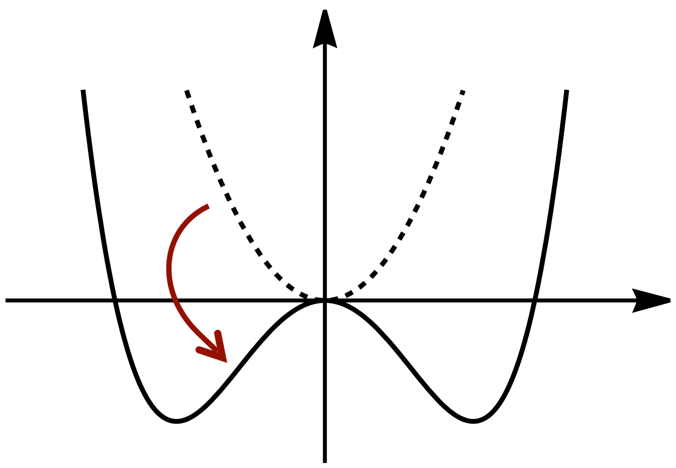
Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, PRD 1990

Smit, Tranberg JHEP 2002

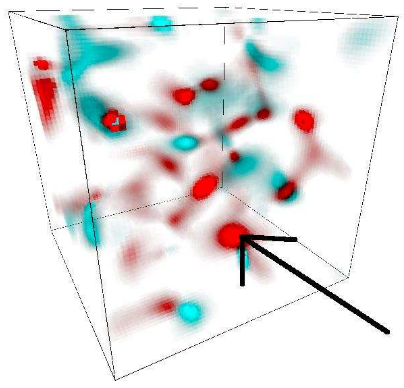
- Higgs mass changes from **positive** (stable minimum) to **negative** (spinodal instability)

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

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



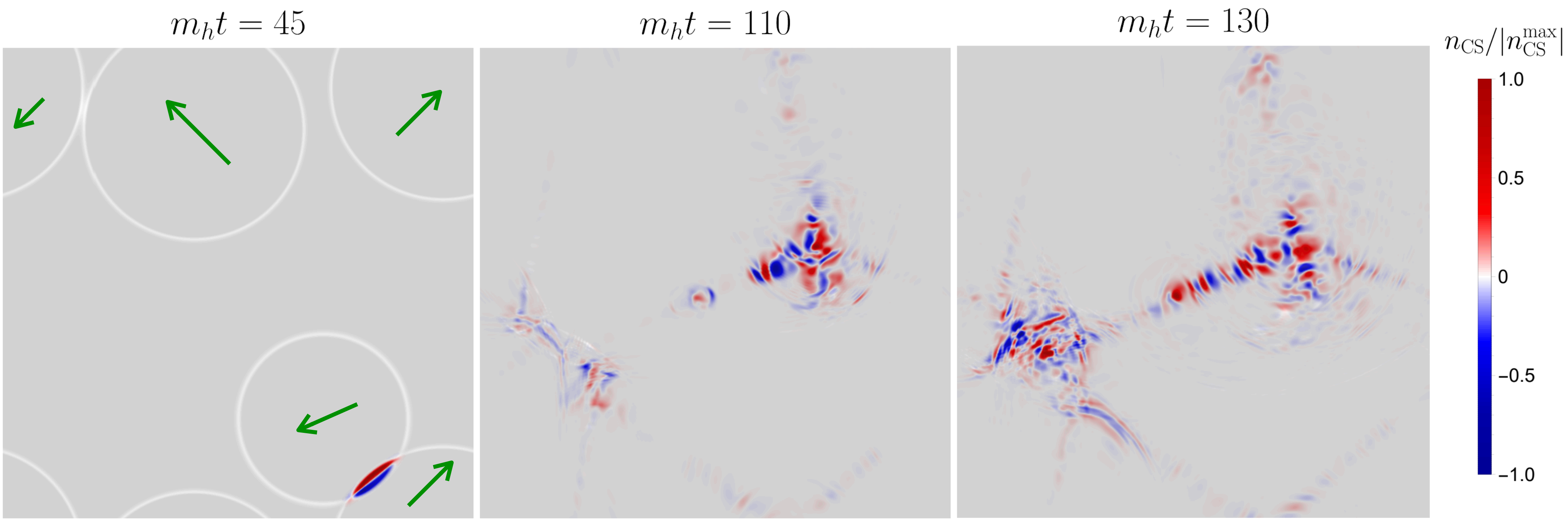
- IR modes grow exponentially growth: **inhomogeneous Higgs field** with different $SU(2)$ orientations *'Cold Baryogenesis'*



Van der Meulen+ '05

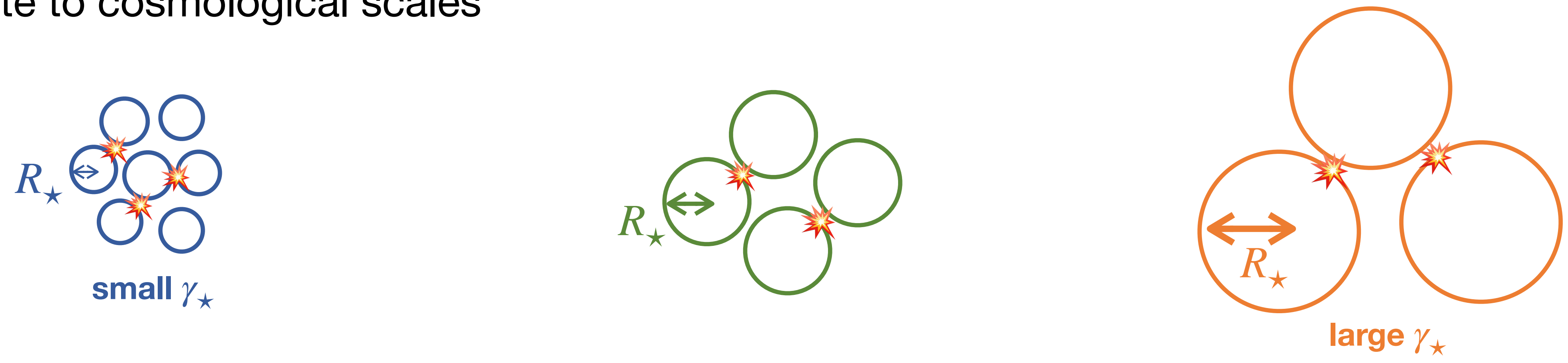
2) Bubble collisions (this work)

- We study run-away bubbles of broken EW symmetry in 3+1 (and 1+1)
- Initial condition: critical $O(4)$ bubble + simultaneous nucleation
- Each bubble nucleated with **random $SU(2)$ orientation** of the Higgs field



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

1) **Boost factor** of the walls at collision is $\gamma_\star \gg 1$, so we vary the bubble radius $R_\star$ at collision to extrapolate to cosmological scales



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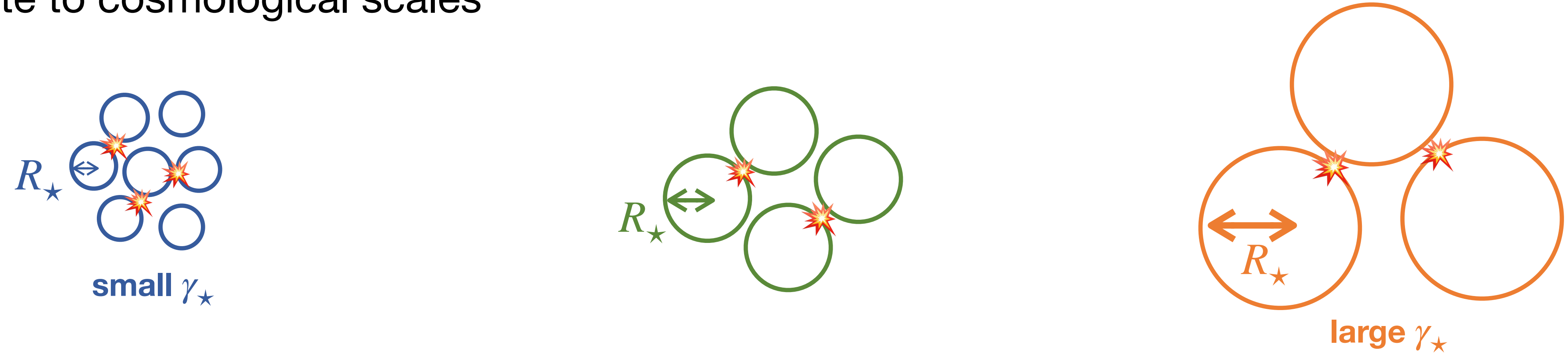

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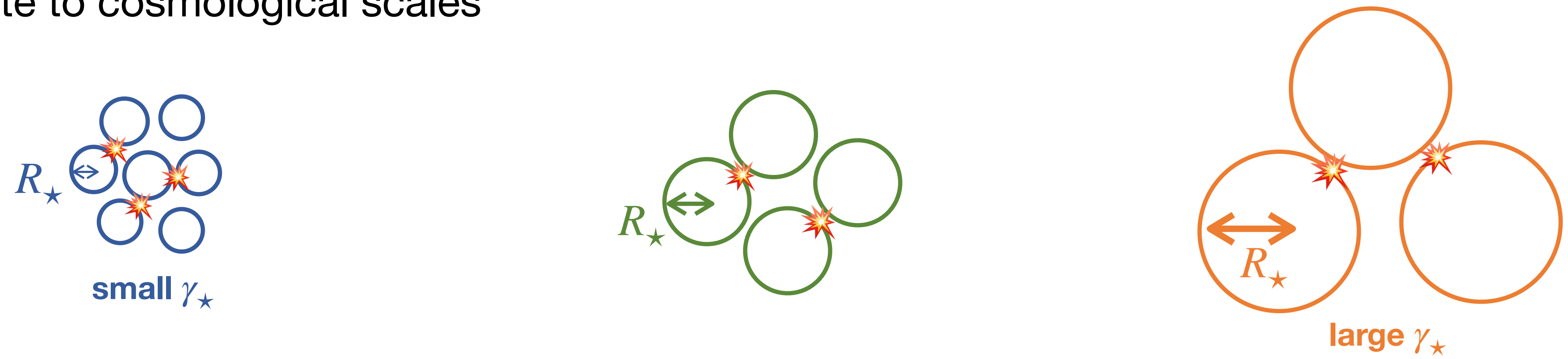

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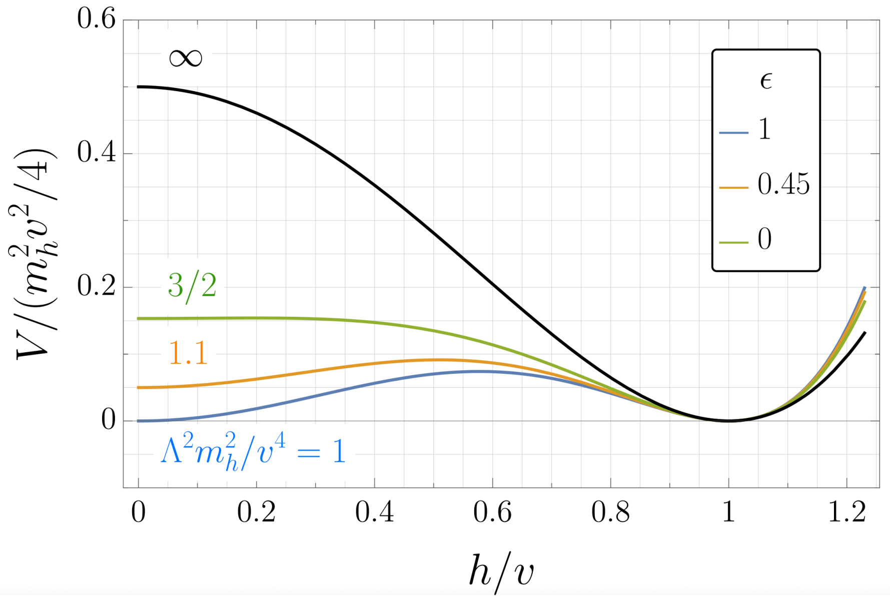
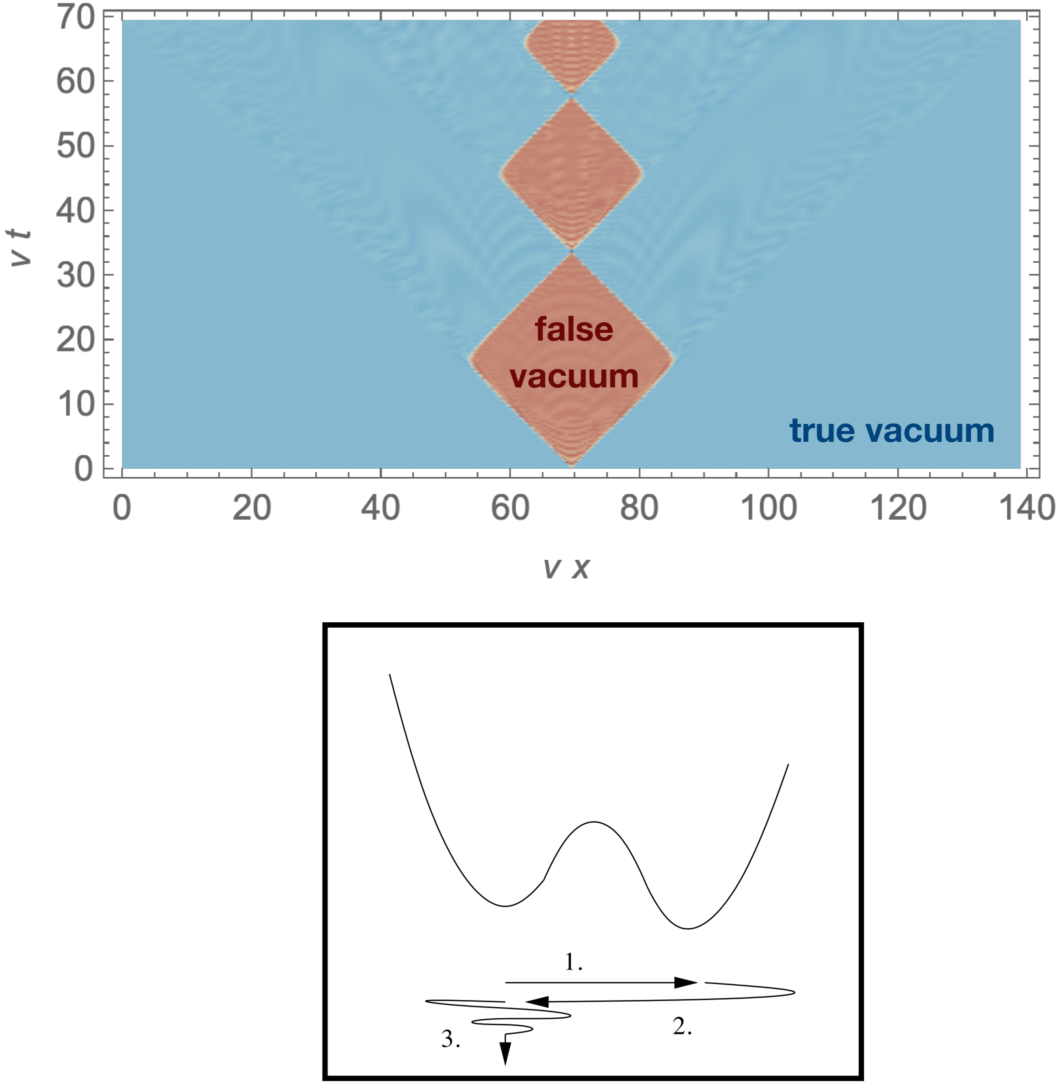
2) We vary the **potential shape**, as this controls wall—wall collisions

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

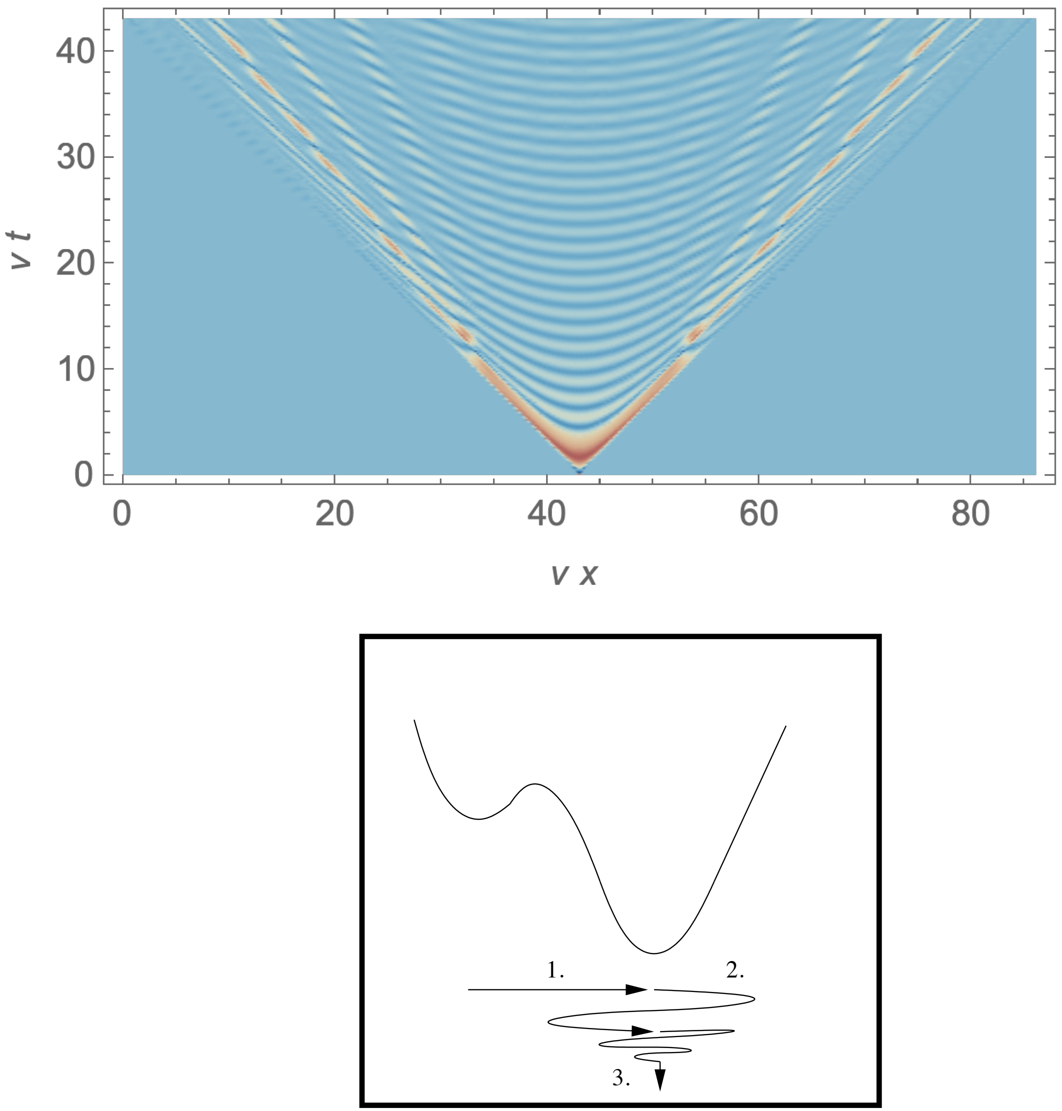


$\epsilon = 0.5$



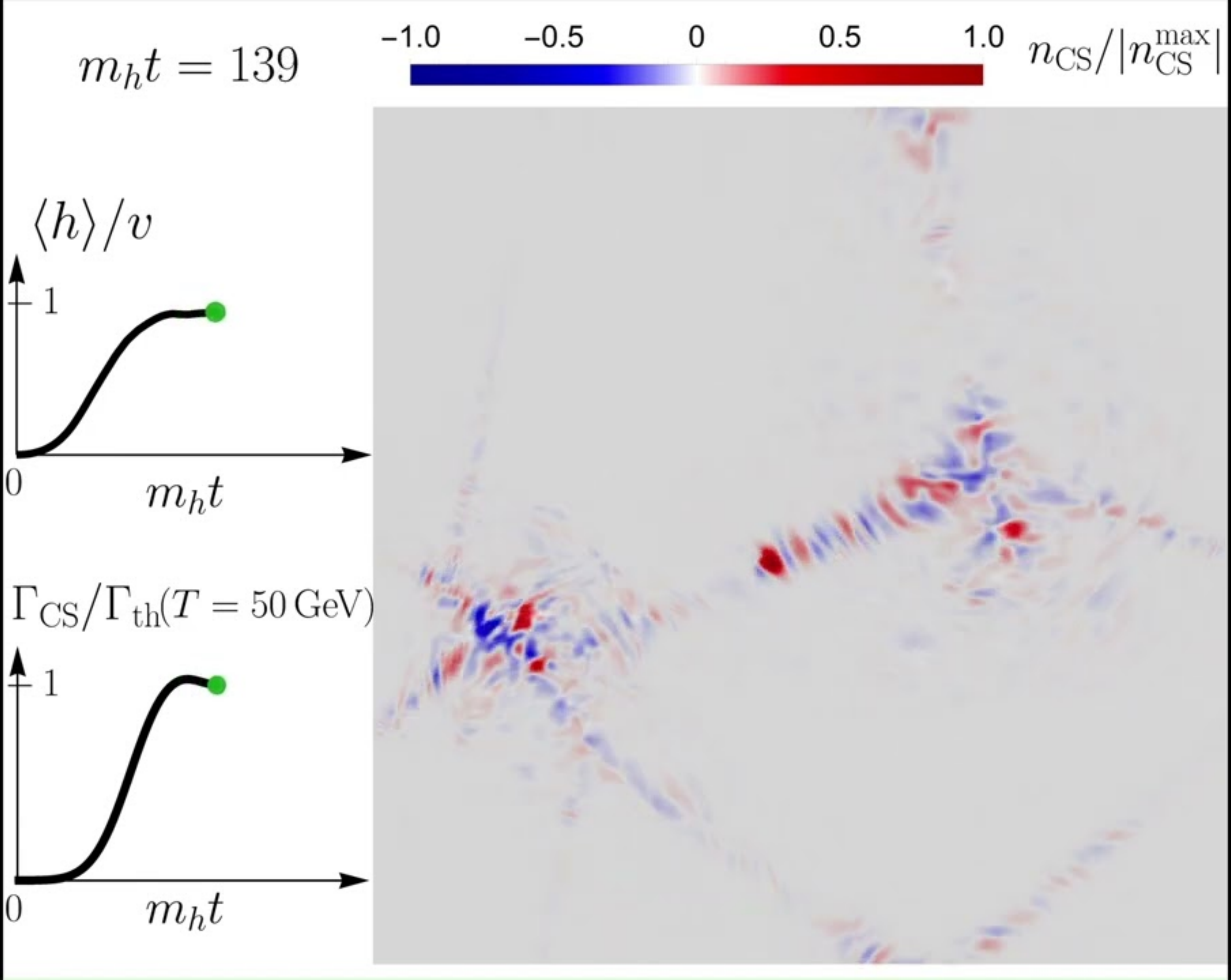
almost degenerate

$\epsilon \ll 1$



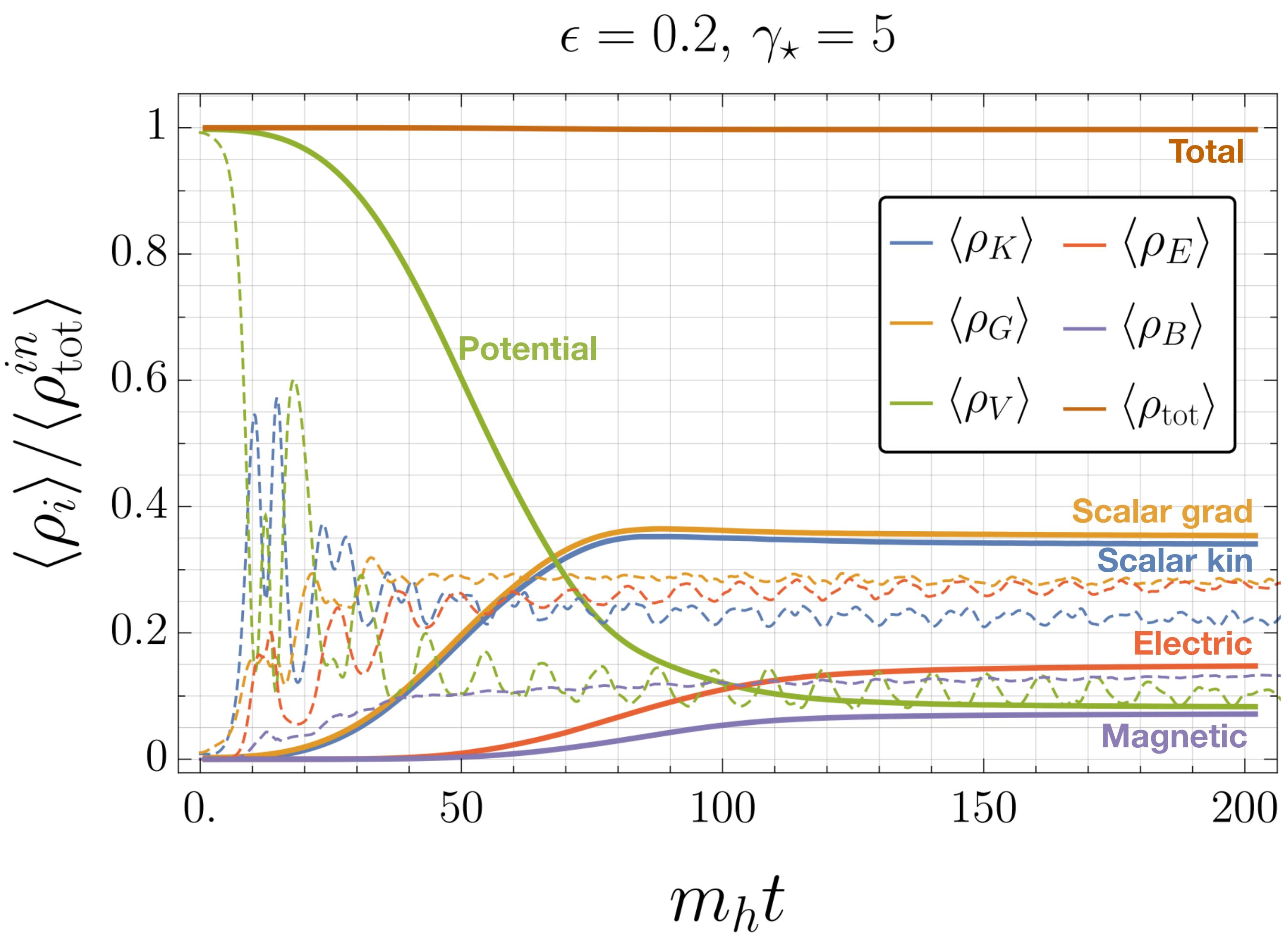
non-degenerate

Jinno, Konstandin, Takimoto [1906.02588] JCAP

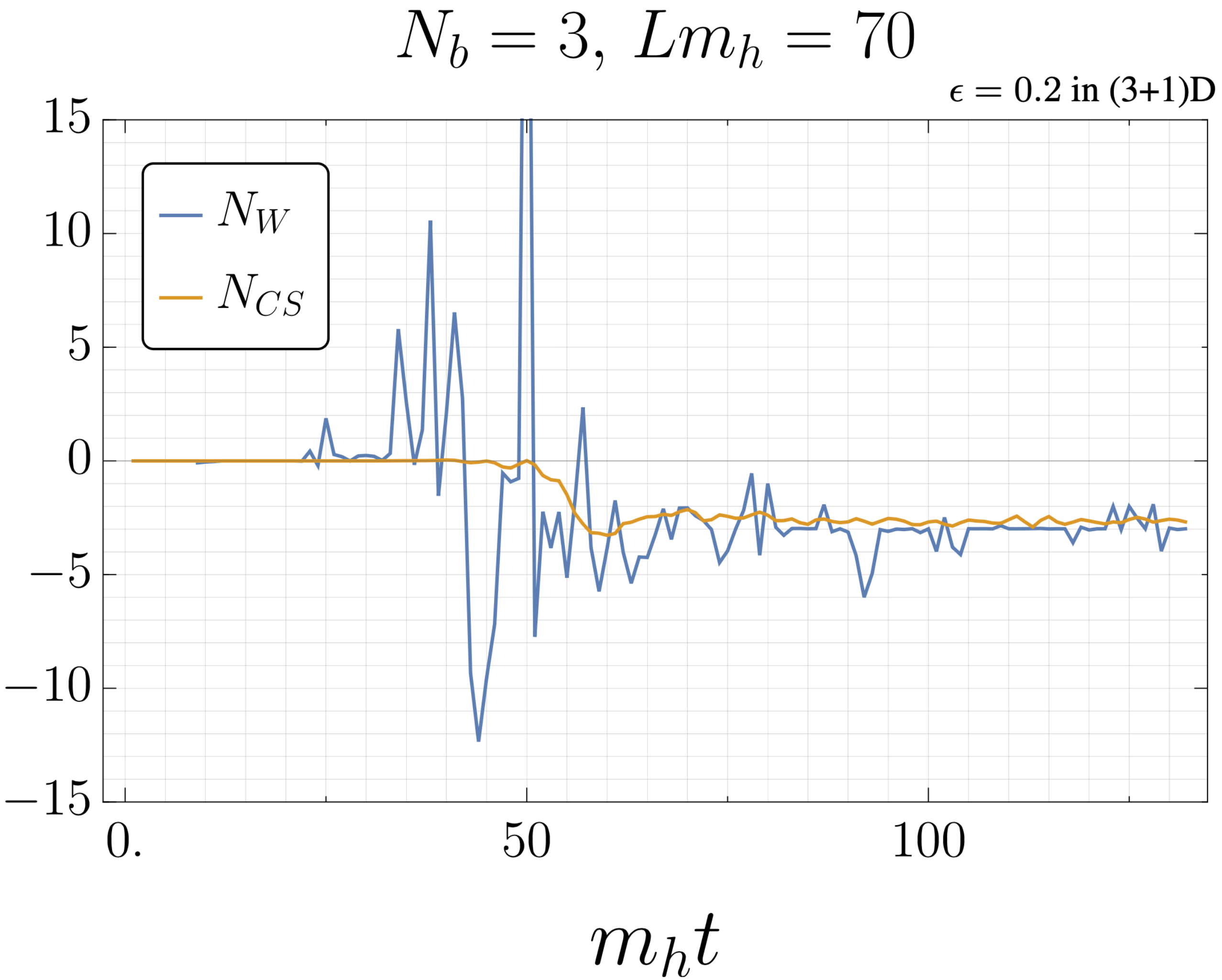


$m_h t = 139$
−1.0
−0.5
0
0.5
1.0
$n_{\rm CS}/|n_{\rm CS}^{\rm max}|$
$\langle h \rangle / v$
1
0
$m_h t$
$\Gamma_{\rm CS}/\Gamma_{\rm th}(T = 50\,{\rm GeV})$
1
0
$m_h t$

Energy budget

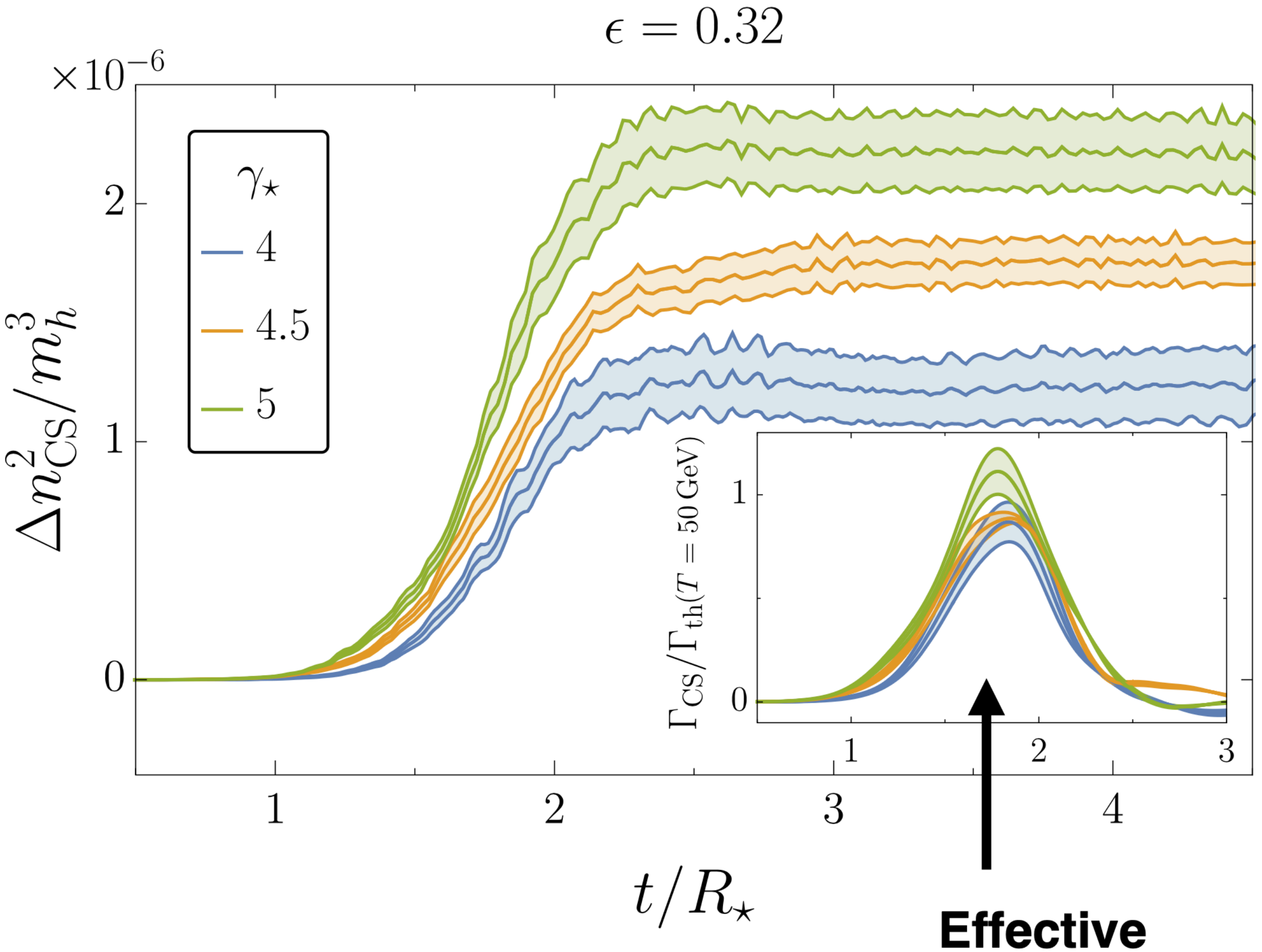


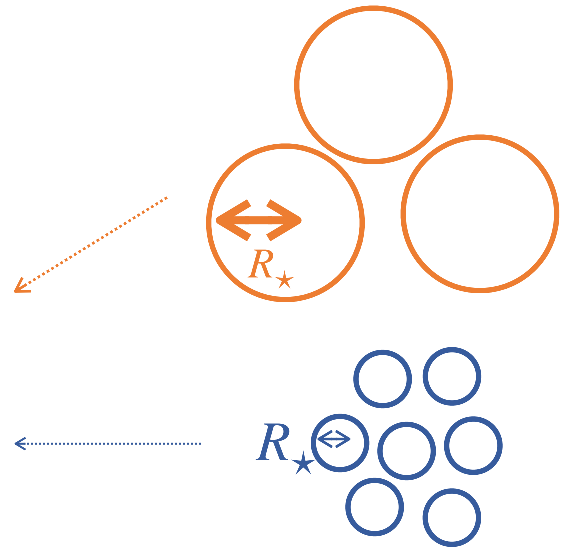
Convergence of N_W and N_{CS}



N_{CS} asymptotically relaxes to the produced N_W (remember: in the vacuum $N_W = N_{\text{CS}}$)

Chern—Simons variance and rate





Effective sphaleron rate

1) for $t \sim R_\star$

2) similar to Γ_{therm} !

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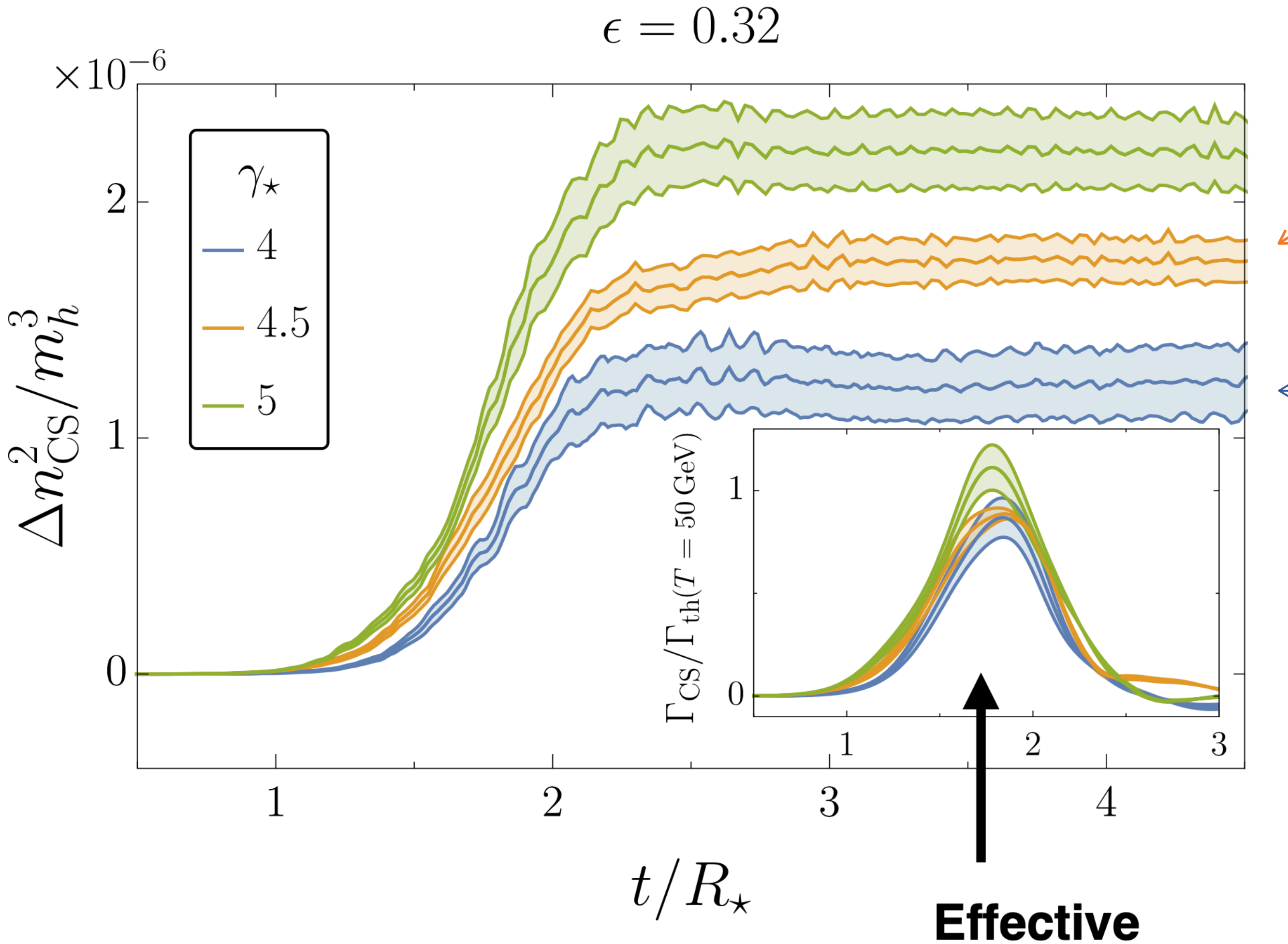

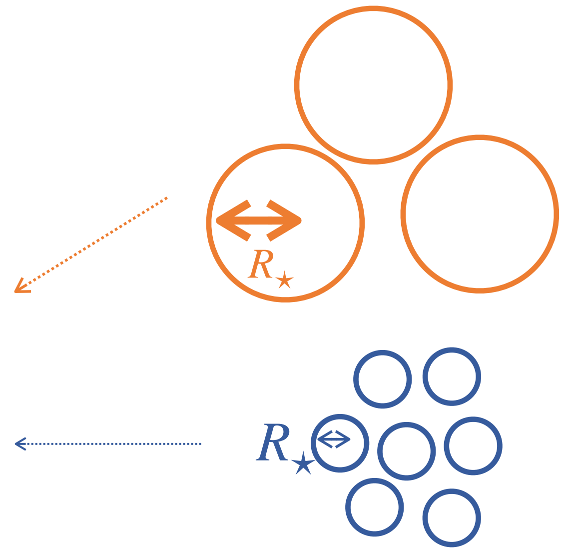

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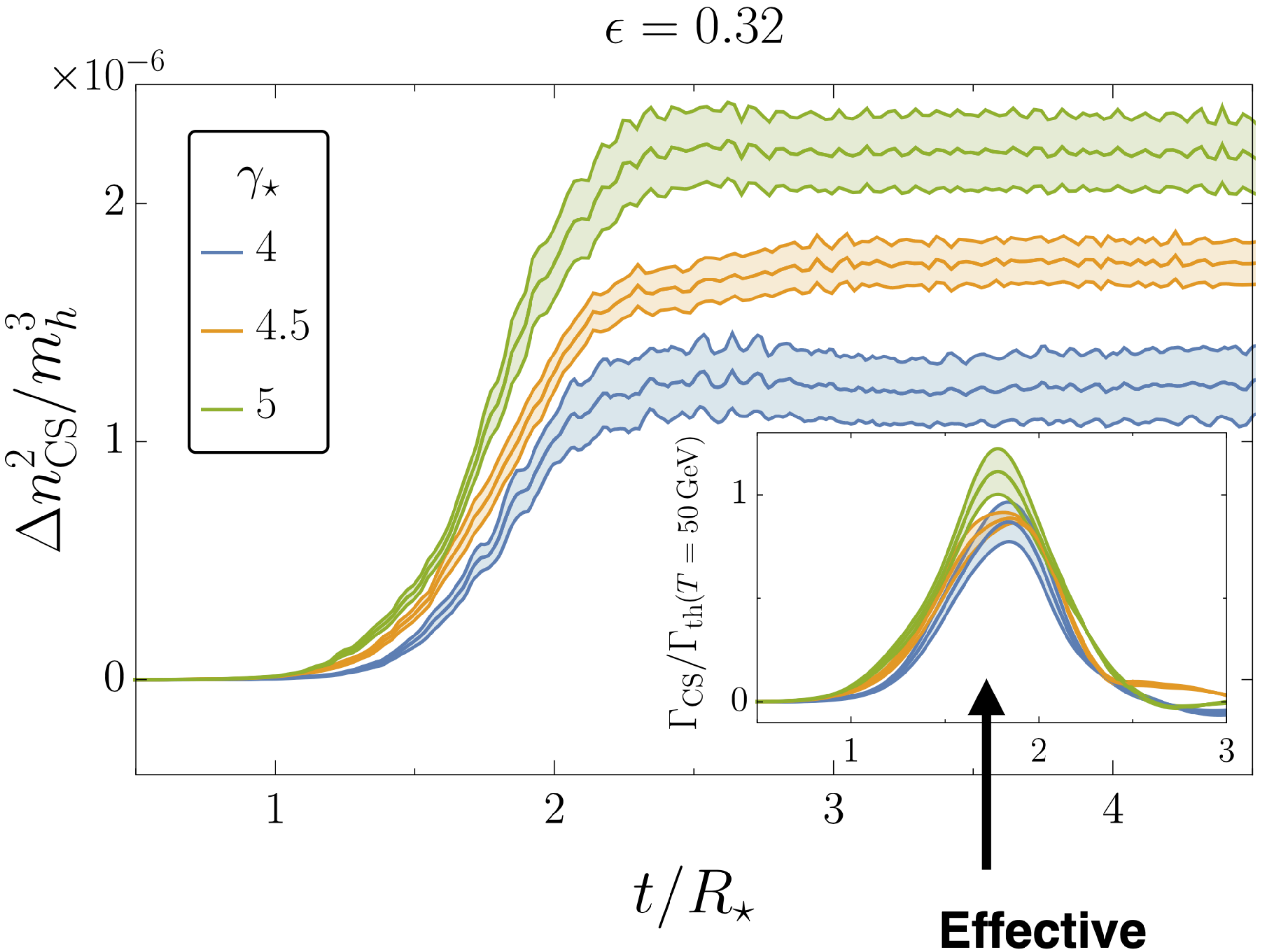

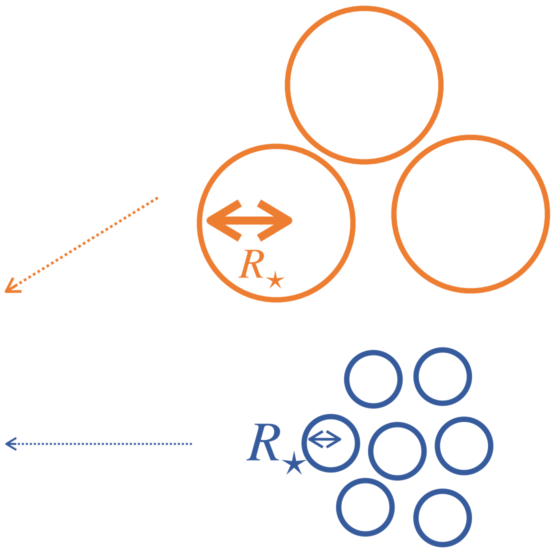

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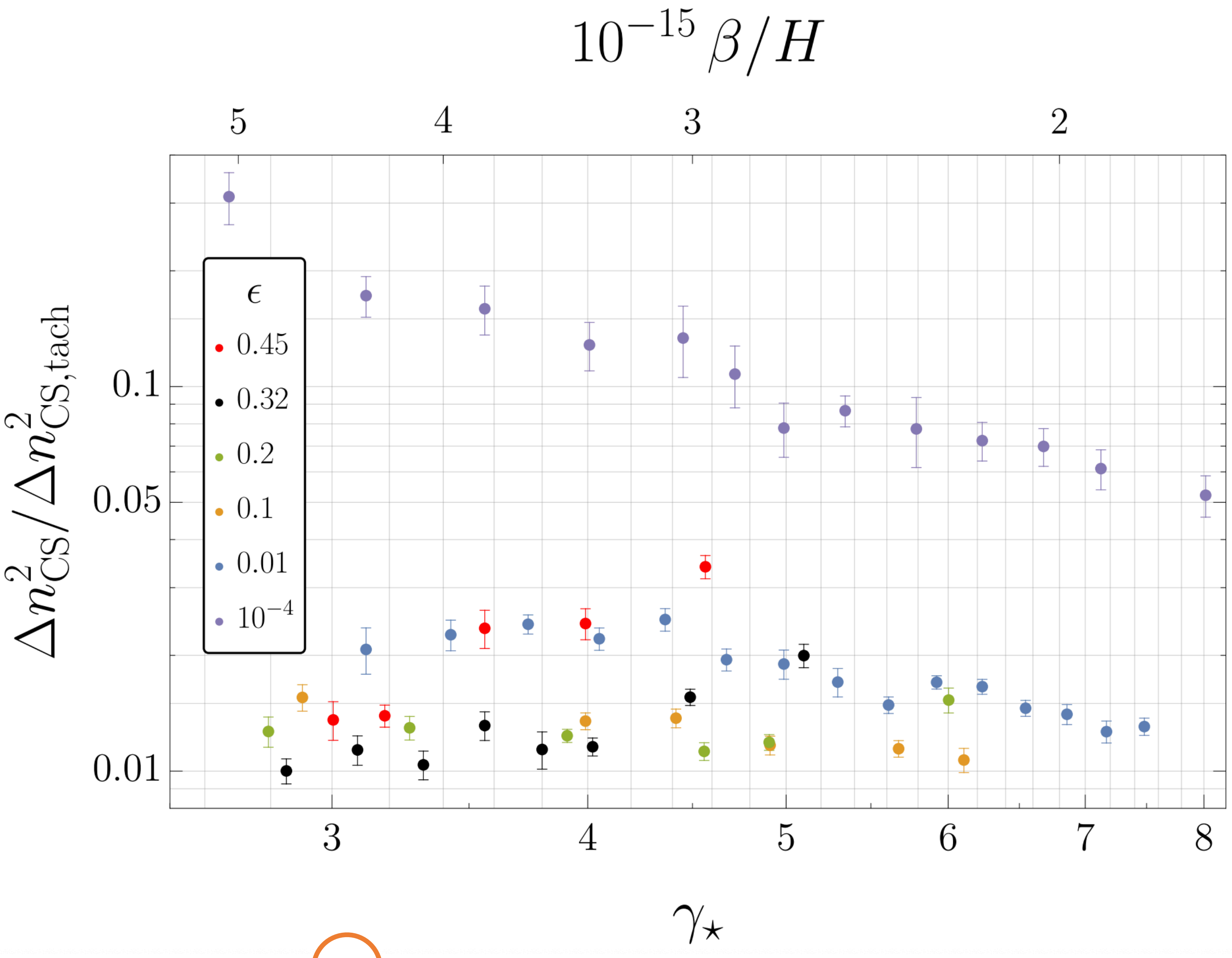
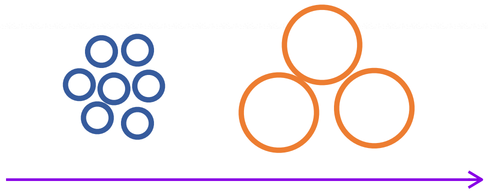
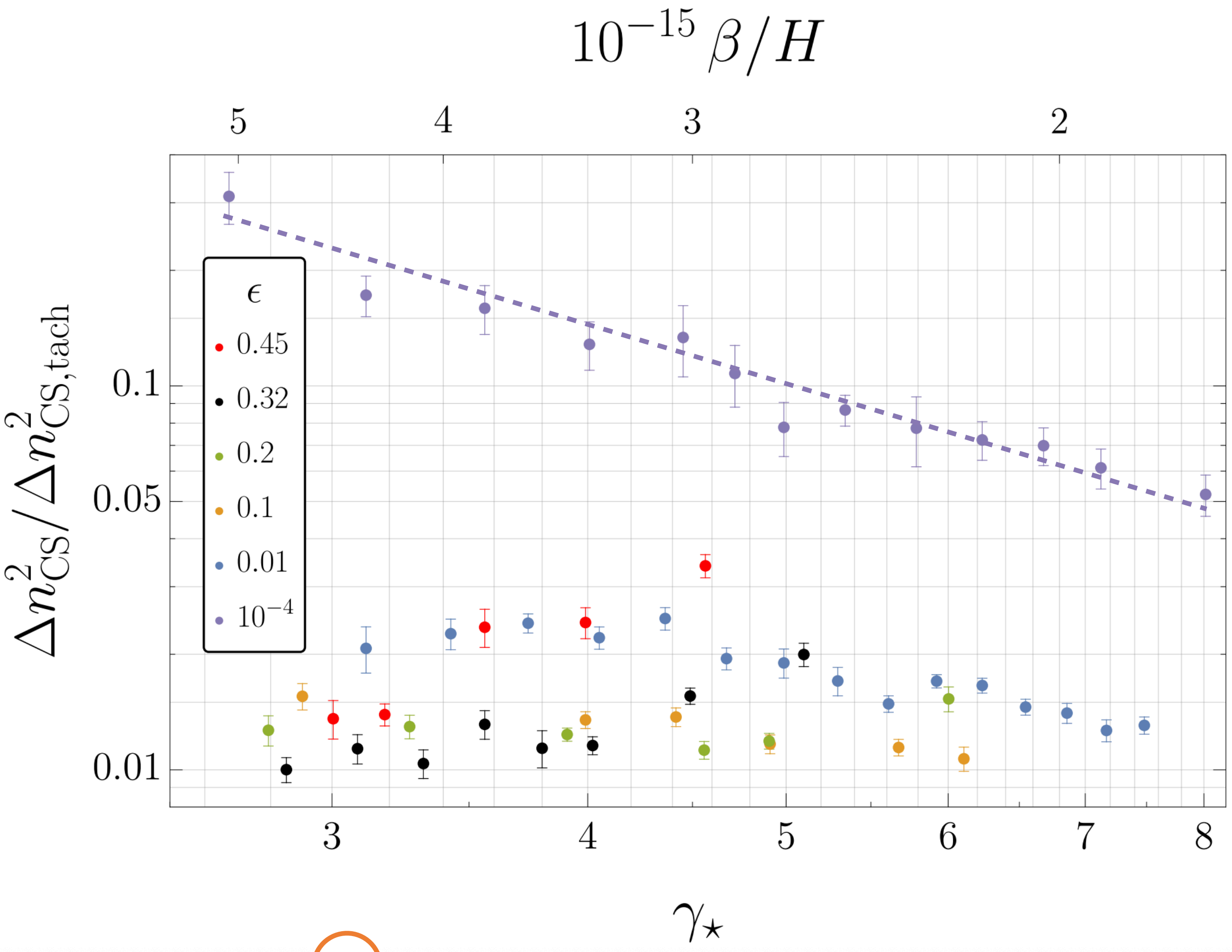
Asymptotic value of the CS variance vs $\gamma_\star$

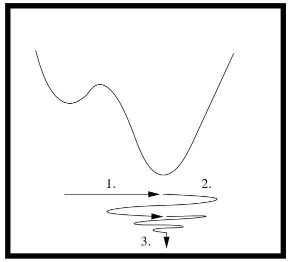




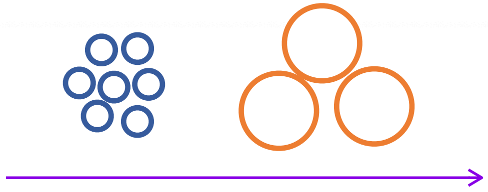
$\gamma_\star$ (at physical point, $\gamma_\star \gg 8$)

Asymptotic value of the CS variance vs $\gamma_\star$





non-degenerate



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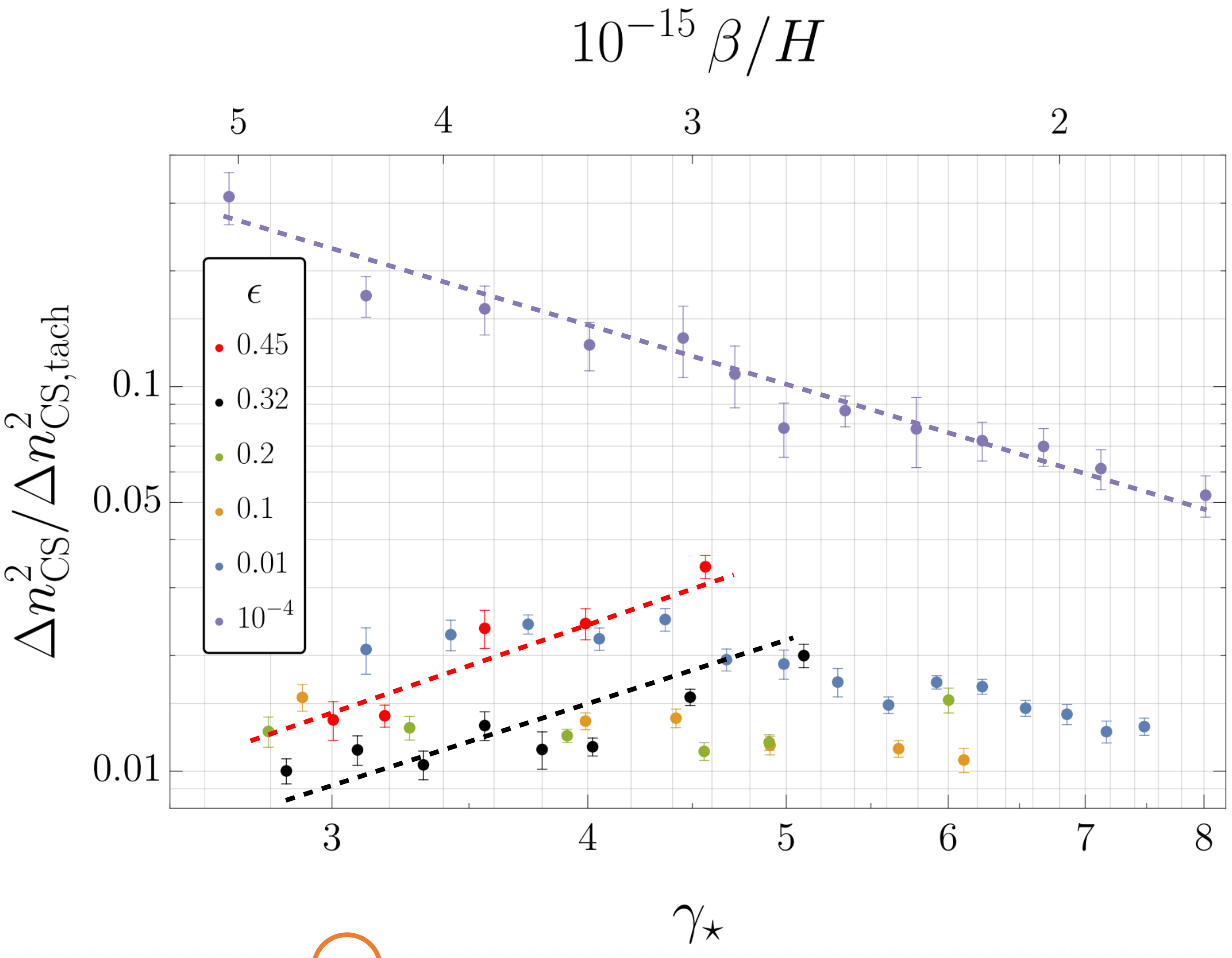

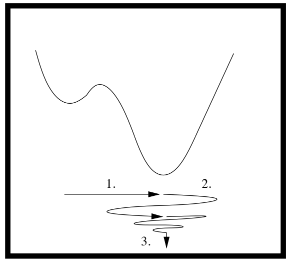

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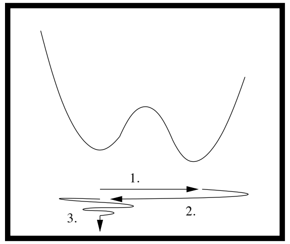
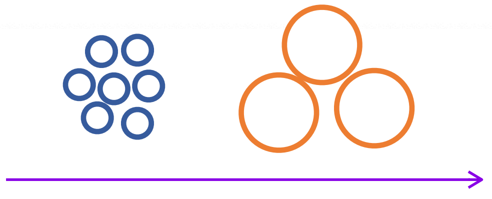


almost degenerate



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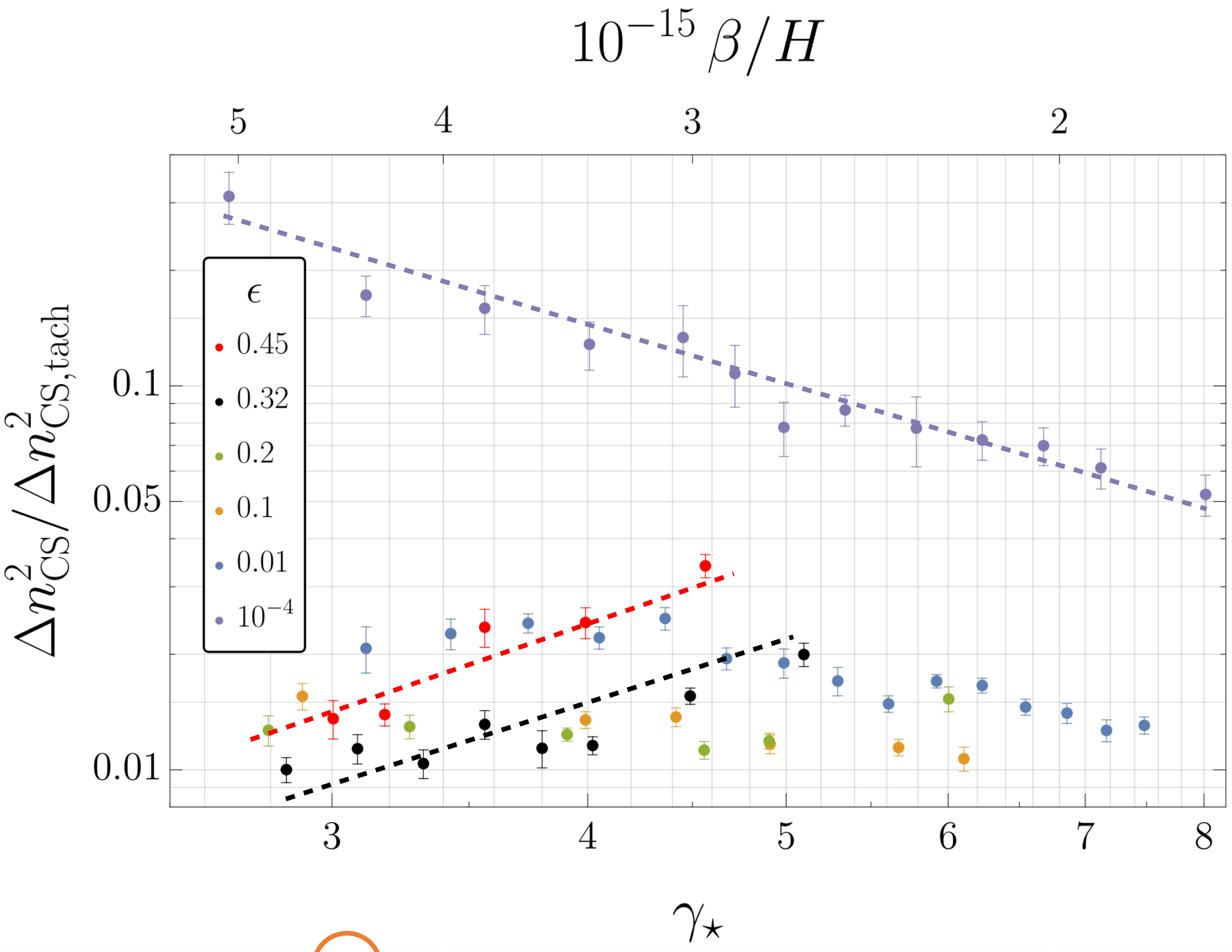

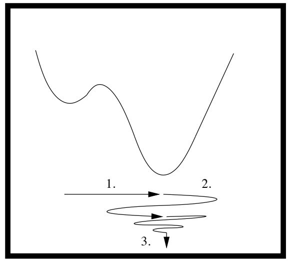

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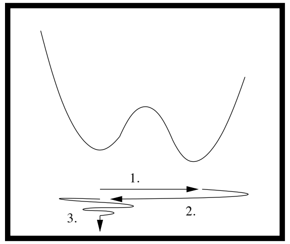
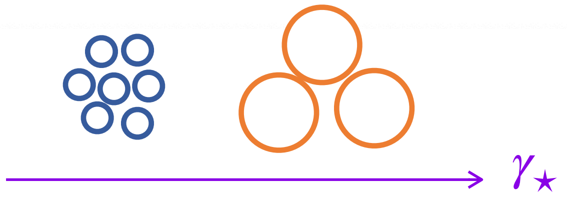


almost degenerate

Collisions with large ϵ show a non-decreasing CS variance at large γ_*

May lead to successful baryogenesis



(at physical point, $\gamma_\star \gg 8$)

Summary and Outlook

- Bubble collisions provide a **new sizeable source of Chern—Simons number**
- Chern—Simons rate sensitive to the **shape** of the potential (ϵ) driving the phase transition
- Possibility for new EW baryogenesis in models where the reheat temperature of the EWPT never exceeds the 130 GeV sphaleron freeze-out temperature

Summary and Outlook

- Bubble collisions provide a **new sizeable source of Chern—Simons number**

- Chern—Simons rate sensitive to the **shape** of the potential (ϵ) driving the phase transition

- Possibility for new EW baryogenesis in models where the reheat temperature of the EWPT never exceeds the 130 GeV sphaleron freeze-out temperature

- **Include CP violation**, e.g. via $|\phi|^2 F\tilde{F}$, and evaluate $\langle N_{CS} \rangle$, related to actual B asymmetry
- Bubble walls with **terminal velocity** and interactions with SM
- …

Thanks!

Backup

- We solve the equations of motion with $N_x^3 = 500^3 - 1500^3$ points:

$$D_\mu D^\mu \phi - \partial_{\phi^*} V(\phi) = 0\,,$$

$$D_\nu W^{\mu\nu} = J_a^\mu T_a\,, \qquad J_a^\mu = 2g\mathrm{Im}[\phi^\dagger T_a D^\mu \phi]$$

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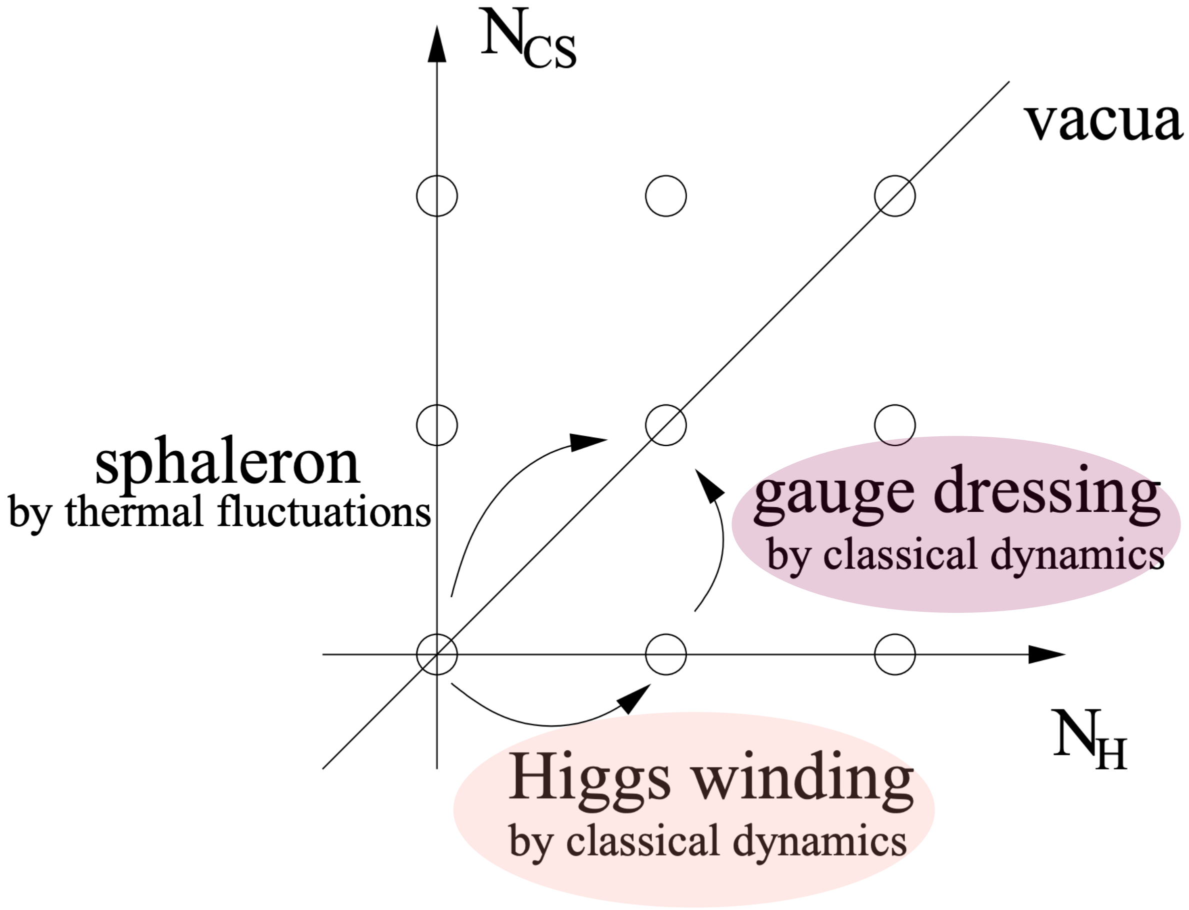
- We calculate:

  — Higgs winding number N_W

  — CS diffusion rate (effective sphaleron rate):

$$\Gamma_{\rm CS} = \frac{1}{L^3}\frac{d\Delta N_{\rm CS}^2(t)}{dt} \qquad \Delta N_{\rm CS}^2(t) \equiv \left\langle N_{\rm CS}^2(t)\right\rangle - \left\langle N_{\rm CS}(t)\right\rangle^2$$

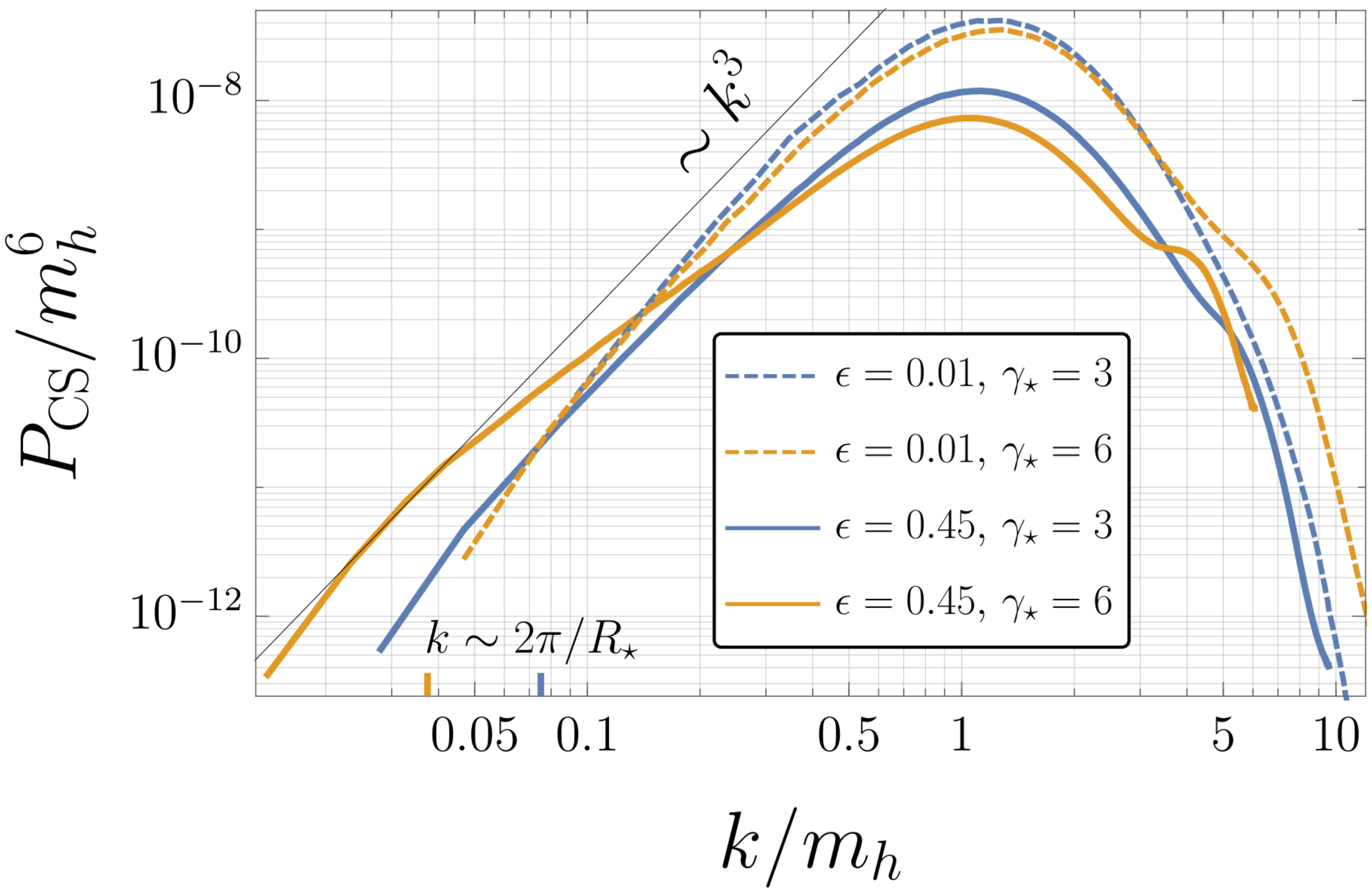
- In addition to thermal sphalerons, there exists another mechanism (dressing of SM textures) that can operate even at $T = 0$



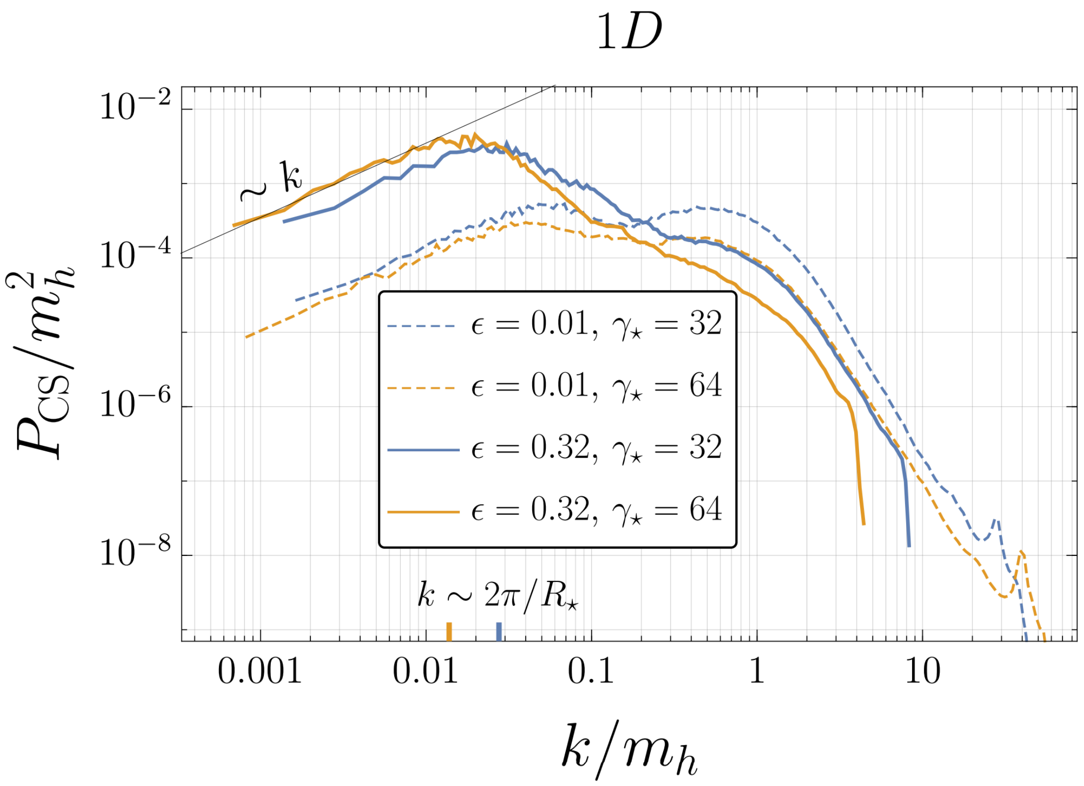
- What dynamics in the early Universe can **generate Higgs windings** in the first place?

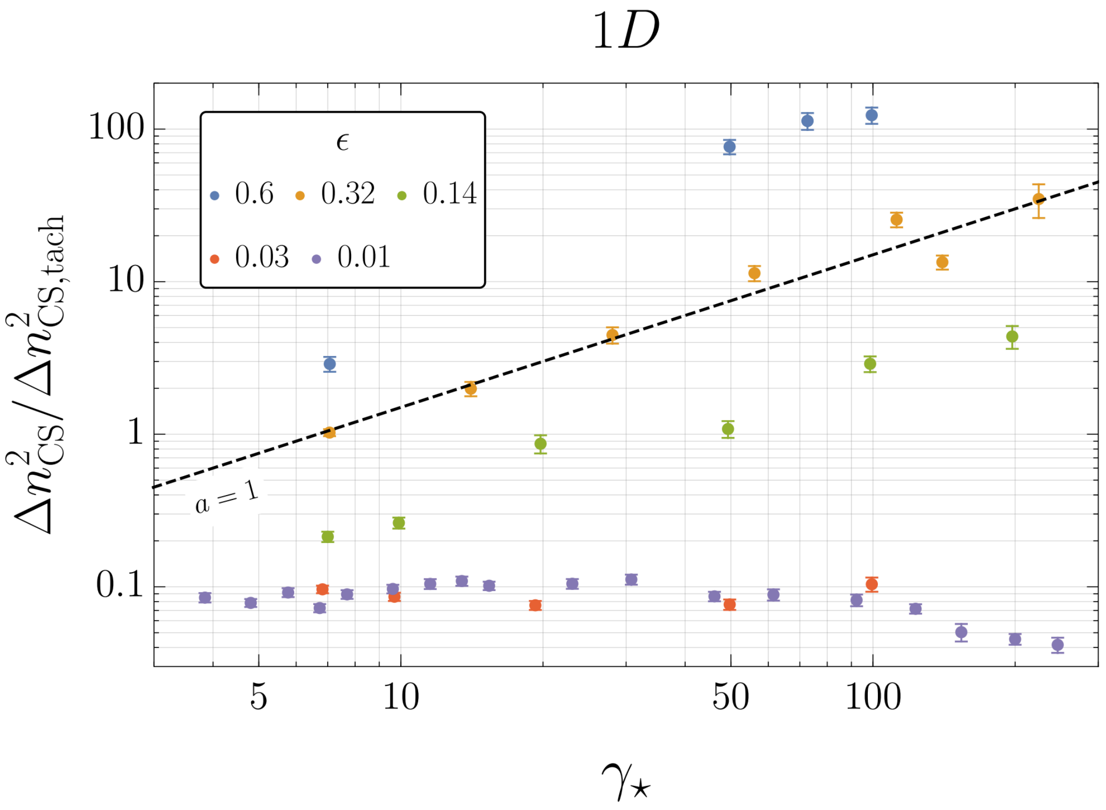
CS number density spectrum

$$\langle n_{\rm CS}(k) n^*_{\rm CS}(k')\rangle = (2\pi)^3\delta^3(k - k')\frac{2\pi^2}{k^3}P_{\rm CS}(k)$$

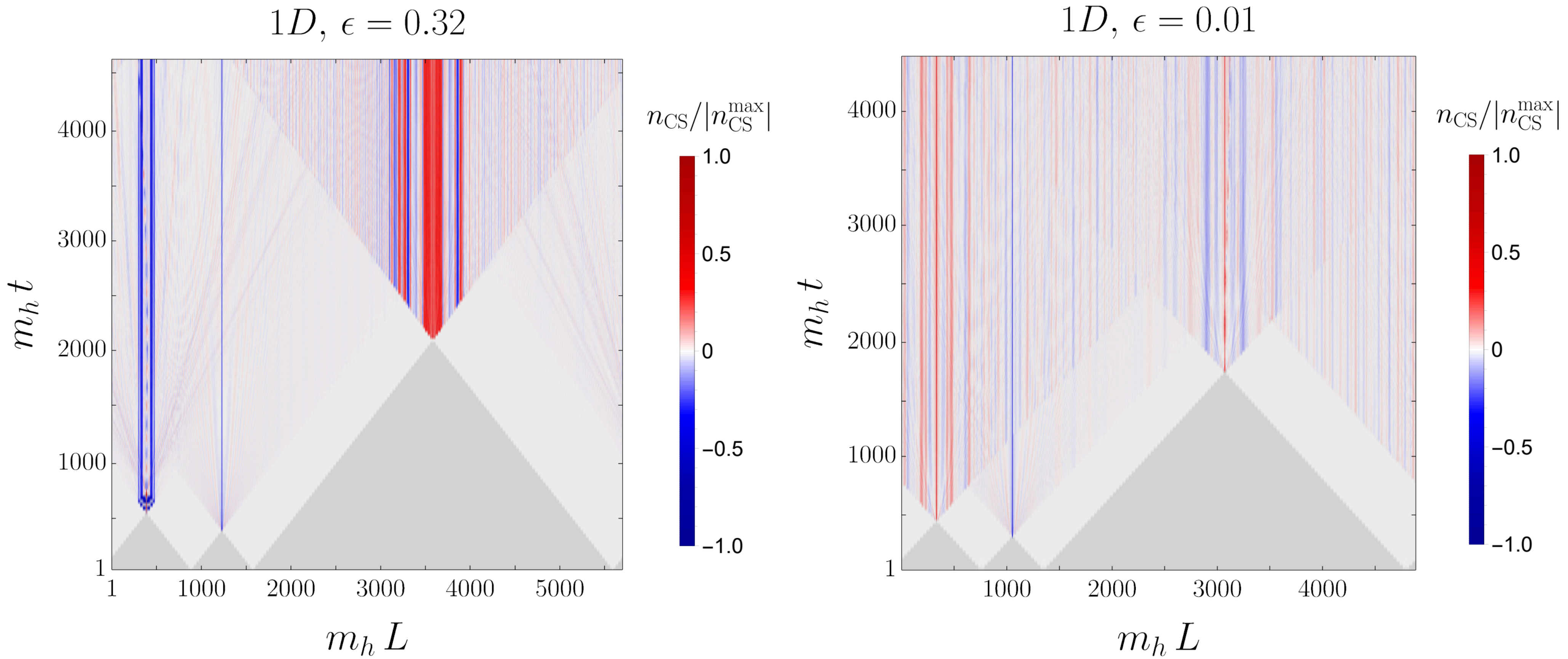


(3+1)d trend confirmed by (1+1)d simulations





N_{CS} density in (1+1)d



EW baryogenesis in a supercooled EW phase transitions?

- Motivated by models with near-conformal dynamics

  (e.g. composite Higgs with a light dilaton)

Bruggisser et al, 1804.07314, 2212.11953, 2212.00056

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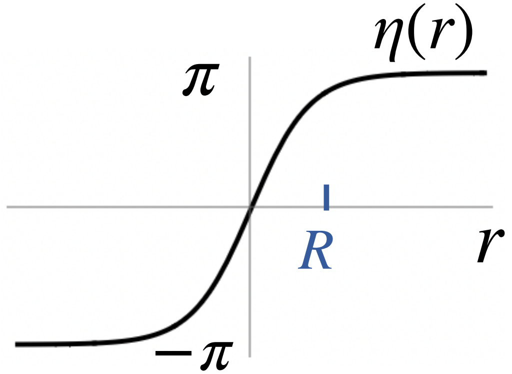
- **Bubble collisions** themselves produce CS number transitions

  $\rightarrow$ new source of B violation at low T (no thermal sphalerons)

The SM: $M = S^3$ in 1+3d

$$\phi(x) = e^{-i\eta(r)\hat{r}\cdot\vec{\sigma}}(0, v)$$



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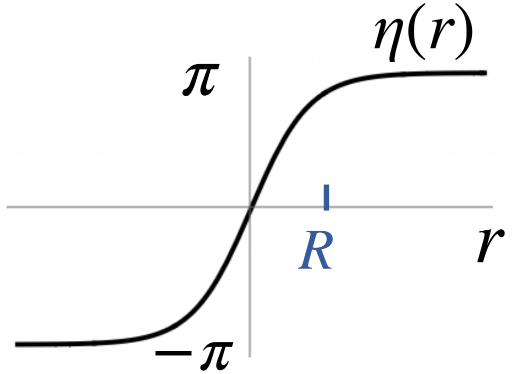

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- Higgs winding number integer, $\pi_3(S^3) = \mathbb{Z}$:

$$N_W \sim \int d^3x\, \epsilon_{ijk} \mathrm{Tr}[(\partial_i\Phi)\Phi^\dagger(\partial_j\Phi)\Phi^\dagger(\partial_k\Phi)\Phi^\dagger]$$

$$\Phi = \frac{(i\sigma_2\phi^*, \phi)}{|\phi|^2} \in SU(2)$$

$[\, N_W = 1 \,]$

- In fact, in a **gauge theory** $(g \neq 0)$ only the **difference** $N_W - N_{\rm CS}$ is gauge invariant

$$\delta N \equiv N_W - N_{\rm CS} \sim \int d^3x\, \epsilon^{ijk}\, {\rm Tr}\Big[\Phi^\dagger D_i\Phi\, \Phi^\dagger D_j\Phi\, \Phi^\dagger D_k\Phi + \Phi^\dagger F_{ij} D_k \Phi\Big]$$

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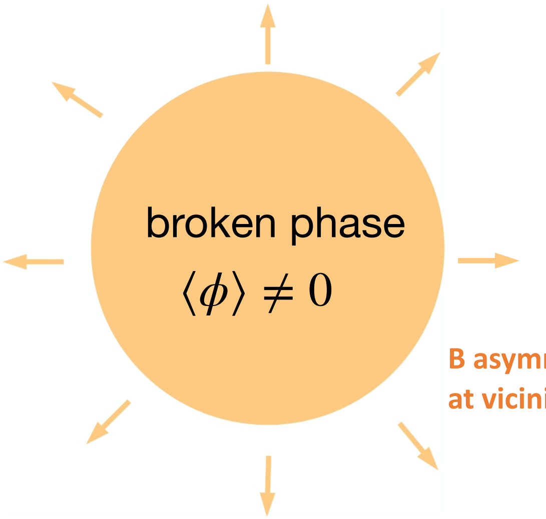
- The **vacuum** has $D_\mu \Phi = 0$

- Textures **collapse** into the vacuum where trivially $\delta N = 0$ $\rightarrow$ $N_W = N_{\rm CS}$
emitting scalar/vector radiation

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

Standard Electroweak Baryogenesis



symmetric phase

$\langle \phi \rangle = 0$

B asymmetry created
at vicinity of CPV wall

$T_n =$ nucleation temperature

Kuzmin, Rubakov, Shaposhnikov ’85
Cohen, Kaplan, Nelson ’91

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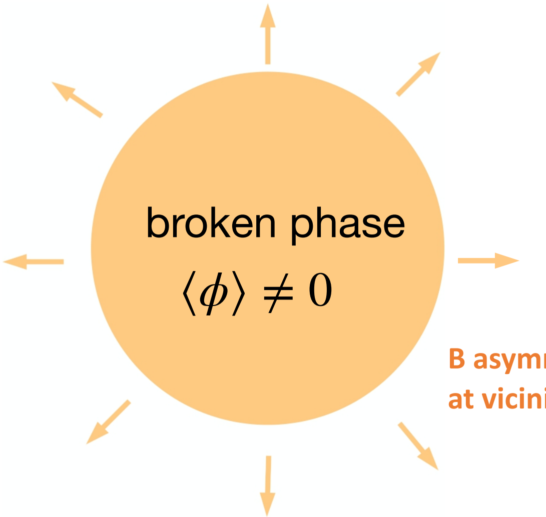

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Requires: $\left.\frac{\langle \phi(T) \rangle}{T}\right|_{T_n} \simeq 1$ **strong** EW phase transition

If $\left.\frac{\langle \phi(T) \rangle}{T}\right|_{T_n} \ll 1 \quad \rightarrow$ B washout

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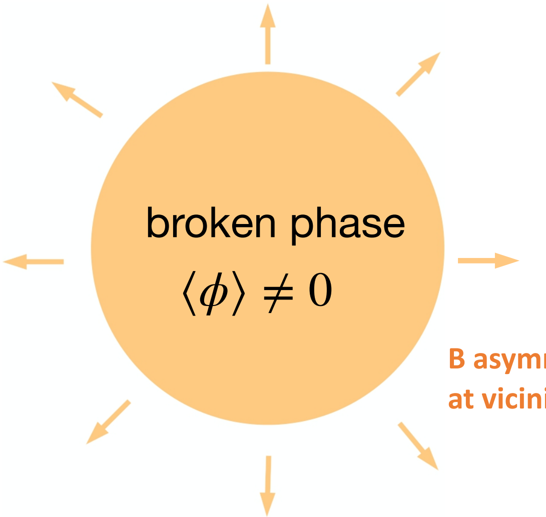

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If $\left.\frac{\langle \phi(T) \rangle}{T}\right|_{T_n} \gg 1 \quad \rightarrow$

- Walls are too fast
- Thermal CS transitions suppressed

includes supercooled phase transitions, $T_n \ll T_c$

Kuzmin, Rubakov, Shaposhnikov '85
Cohen, Kaplan, Nelson '91

Runaway condition

$$\mathcal{P} < \Delta V$$

Pressure from friction — **Latent energy**

$\mathcal{P}_{LO} \sim \frac{1}{24} m^2 T^2$ **Due to particles crossing the wall, negligible for T<v**

$\mathcal{P}_{NLO} \sim \alpha_w \gamma_w m_V T^3$ **Due to transition radiation of gauge bosons**

Condition for the bubbles to collide before reaching their terminal velocity $\frac{\beta}{H} \frac{(10^{-8}\mathrm{GeV}^3)}{T^3} \gtrsim 1$

i.e. for β/H **~ O(100)** $T_n \lesssim 10$ **MeV**

Highly supercooled EW phase transition

Estimate of baryon asymmetry

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

$$\Lambda \gtrsim 6\,\text{TeV.}$$

$$\frac{\partial}{\partial t}n_b(x,t) = \Gamma\left(\xi - \mathcal{A}\, n_b\right)$$

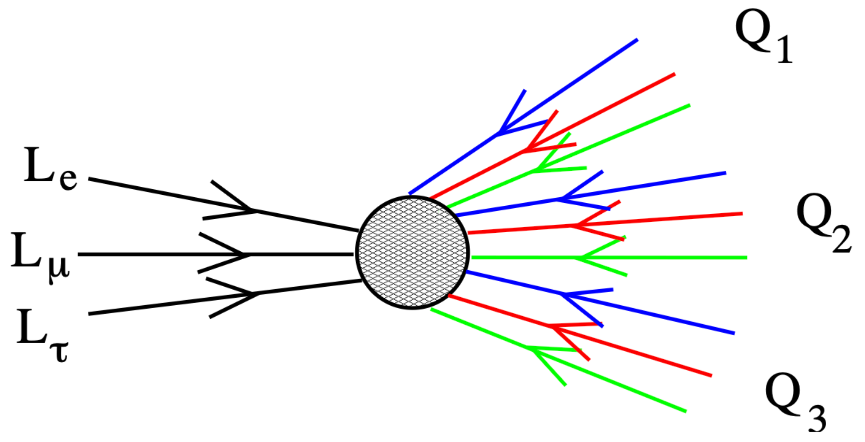
$$\xi \equiv \mu/T \qquad \mu = N_F^{-1}\frac{1}{\Lambda^2}\frac{d}{dt}\langle\phi^\dagger\phi\rangle$$

$$n_b = \int dt\, \Gamma_{\rm CS}(t)\mu(t)/T_{\rm eff}(t)$$

$$T_{\rm eff} = \Gamma_{\rm CS}^{1/4}/\alpha_w$$

$$n_b/s \simeq 10^{-10}\gamma_\star^{3(a-1)/4}\left(\frac{30\,\text{GeV}}{T_{\rm rh}}\right)^3\left(\frac{10\,\text{TeV}}{\Lambda}\right)^2$$

Determinant in all baryogenesis mechanisms whatever their energy scale



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

Each transition creates 9 LH-quarks and 3 LH leptons.