



Baryon number violation from Standard Model Higgs bubble collisions

Nabeen Bhusal

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In collaboration with: S. Blasi, M. Cataldi, A. Chatrchyan, M. Gorghetto and G. Servant



How does the Standard Model (SM) violate Baryon (B) Number

Motivation

The **SM violates $B+L$** , but conventional sphaleron transitions become inefficient below the electroweak scale.

Can a first-order transition generate B violation through a different mechanism?

How does the Standard Model (SM) violate Baryon (B) Number

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In the SM, Baryon and Lepton number is violated by the chiral anomaly

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = N_F \frac{g^2}{32 \pi^2} \text{Tr}[W_{\mu\nu} \tilde{W}^{\mu\nu}]$$

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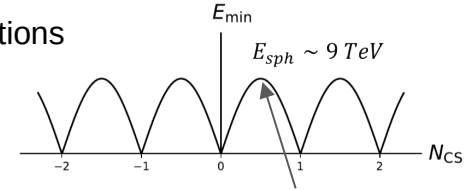
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Sphaleron transitions



$$N_{CS}(t) = \int d^3x J_{CS}^0 = \frac{g^2}{32 \pi^2} \int d^3x \text{Tr}[W^{\mu\nu} \tilde{W}_{\mu\nu}]$$

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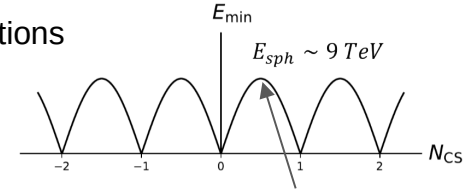
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$$\Delta B = \Delta L = N_F \Delta N_{CS}$$

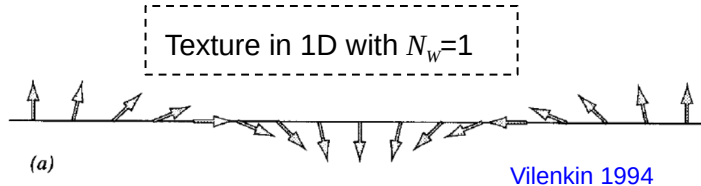
Changing N_{CS} is the key to baryon-number violation

How does the Standard Model (SM) violate Baryon (B) Number

Textures: Higgs topology

$$M = SU(2) \times U(1)/U(1) \simeq S^3$$

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



Textures are labelled by Higgs Winding number :

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

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

In the presence of gauge fields, the gauge invariant quantity: $(N_W - N_{CS})$

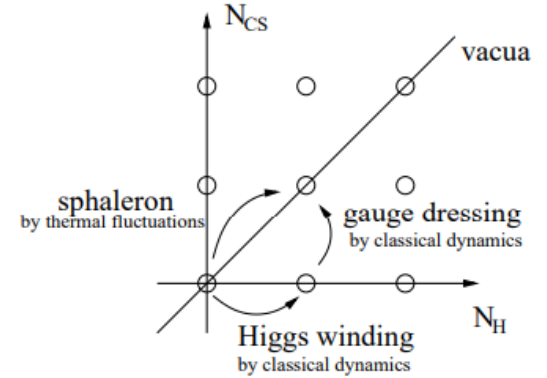
A texture is simply a Higgs configuration with a non-trivial winding.

ΔB from Textures

See e.g. Turok, Zdrozny, NPB 1991

- Gauge textures are unstable and collapse into the vacuum configuration

$$D_\mu \phi = 0 \Leftrightarrow N_{CS} = N_W$$



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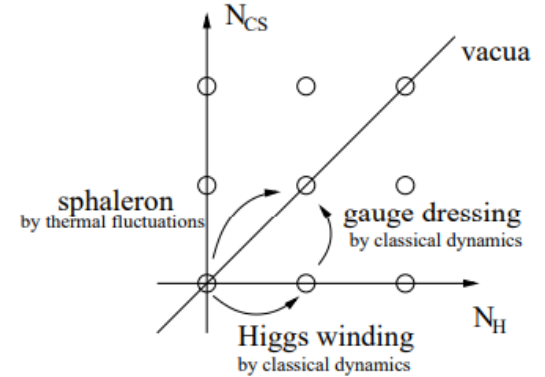
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→ How do textures with $N_W - N_{CS} = 1$ and gauge fields collapse to the vacuum $N_W - N_{CS} = 0$?



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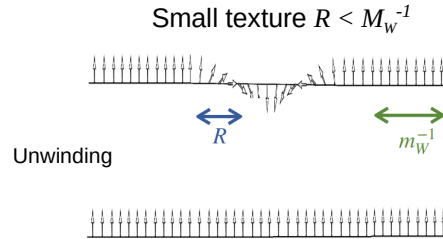
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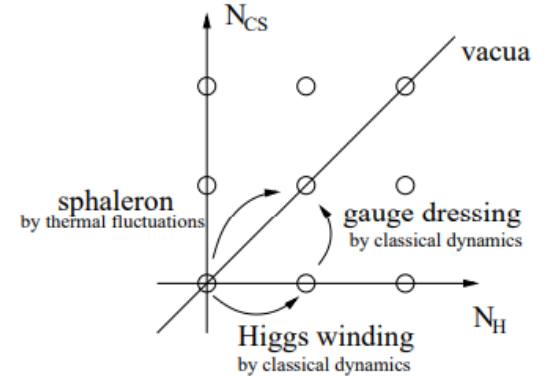
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$$\Delta N_W = -1, \Delta N_{CS} = 0$$



Konstantin, Servant,
JCAP07(2011)024

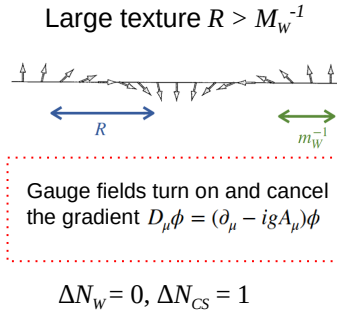
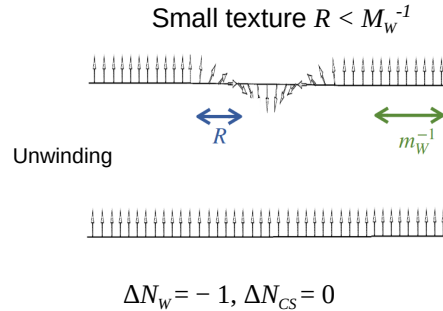
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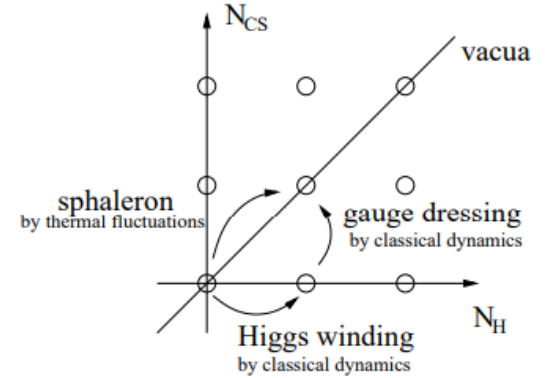
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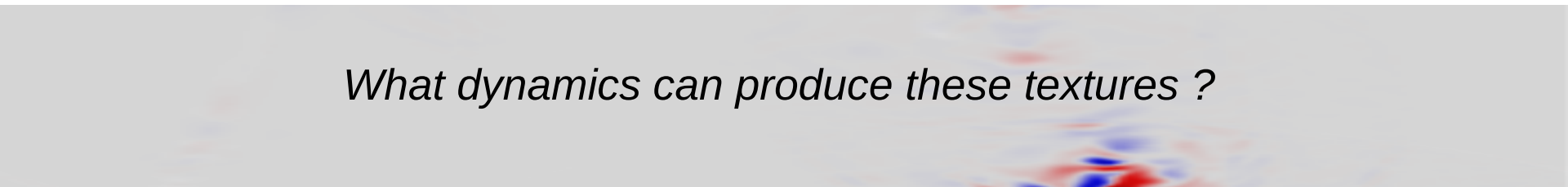
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Produces Baryons !



Konstantin, Servant,
JCAP07(2011)024

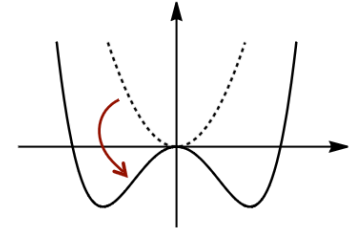


What dynamics can produce these textures ?

Recap: B violation from Tachyonic transition

Garcia-Bellido, Grigoriev, Kusenko,
Shaposhnikov, PRD 1990
Smit, Tranberg JHEP 2002

- Higgs $SU(2)$ symmetry broken rapidly (quenched crossover phase transition)
 - Kibble mechanism leads to formation of Textures dressed by gauge fields
 - Textures decay via changing N_{CS}



- Rate of change of N_{CS} is equivalent to rate of B violation.
 - If transition is delayed : B violation at $T \sim 0$ GeV [The original “Cold Baryogenesis”]

First-Order Phase Transition (FOPT)

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

- Use the same principle of Texture formation and decay but through bubble nucleation and collision

Toy Model

$$L = -|D_\mu \phi|^2 - \frac{1}{2} \text{Tr}[W_{\mu\nu}W^{\mu\nu}] - V(\phi)$$

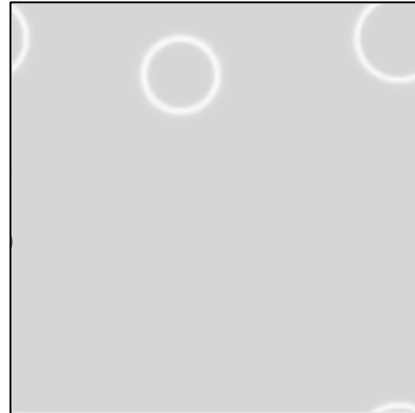
$$V(\phi) = \frac{1}{2}\mu^2\phi^2 - \frac{1}{4}\lambda\phi^4 + \frac{1}{8\Lambda^2}\phi^6$$

Initial Condition

- N bubbles
- Random $SU(2)$ orientation
- Critical bubble profile (sets limit on simulation size)

Geometry

$3+1$ D lattice

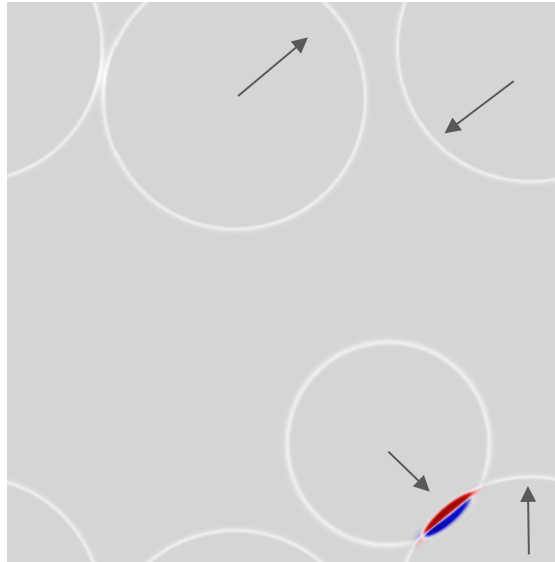


2D slice at
simulation time $t=0$

Bubble collisions create non-trivial Higgs configurations

We simulate runaway bubbles of the Electroweak phase transition

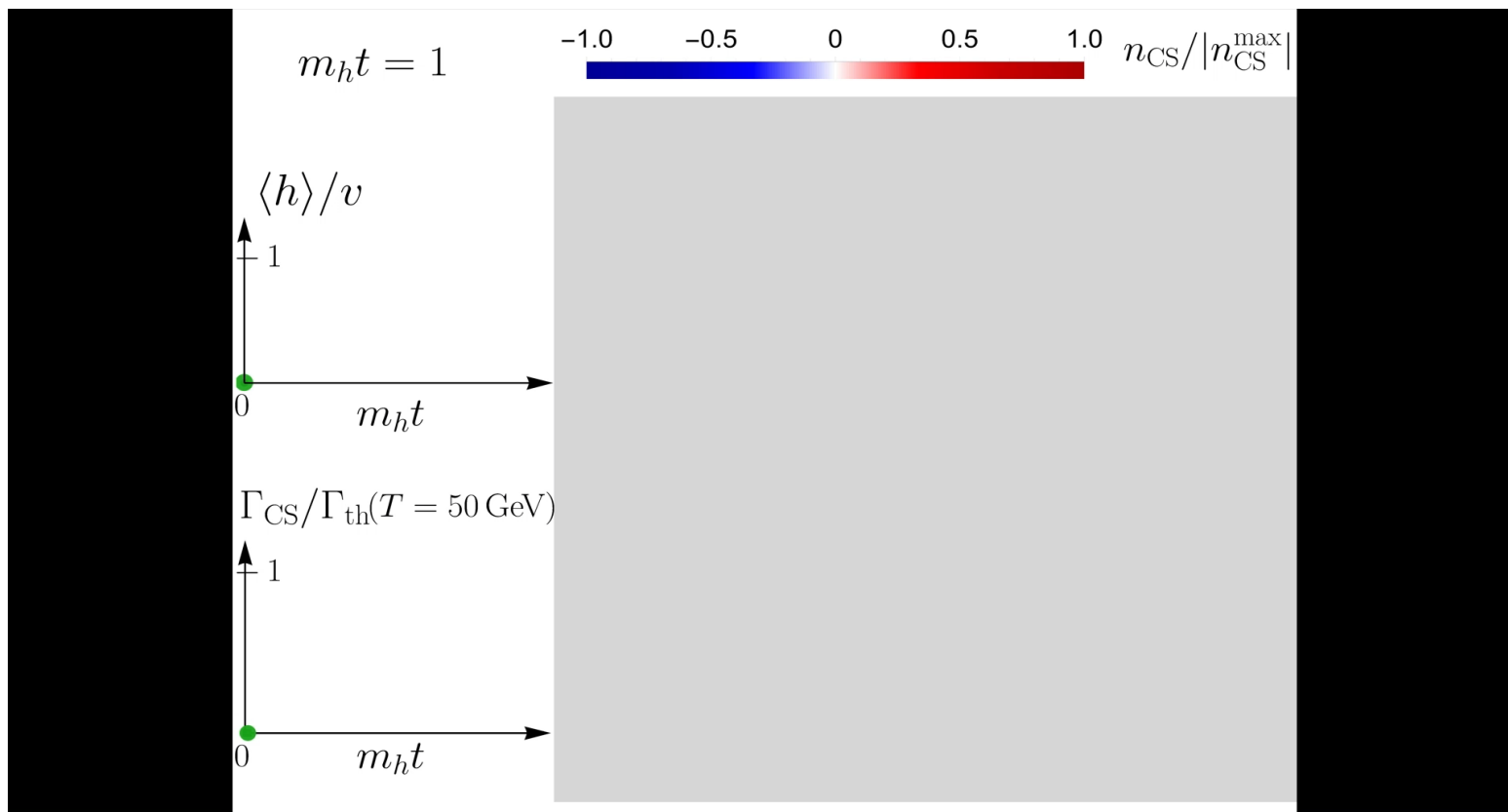
Random $SU(2)$
configuration



Collisions

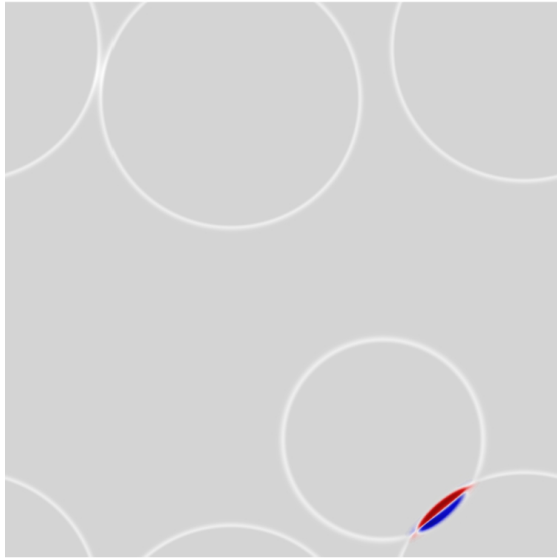
Higgs gradients $\rightarrow$ gauge-field excitation

Can bubble collisions produce gauge
textures ?

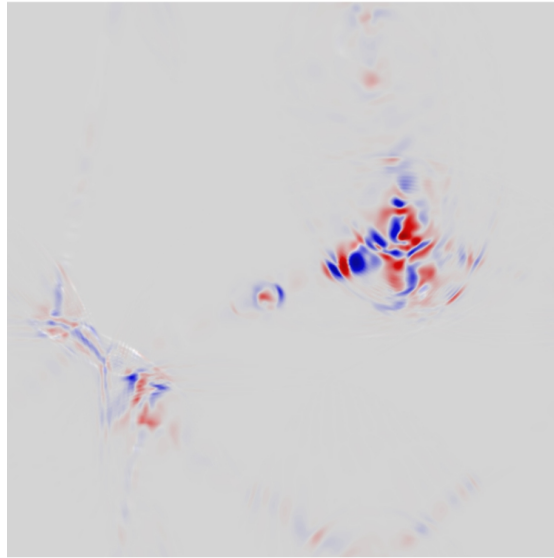


Bubble collisions to N_{CS}

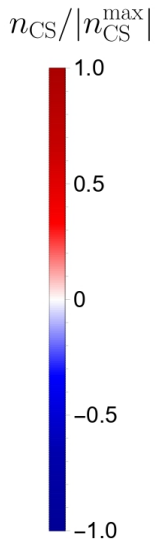
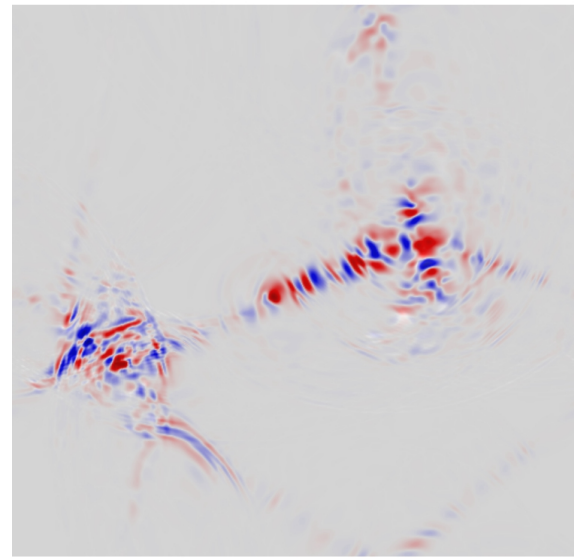
$m_h t = 45$



$m_h t = 110$

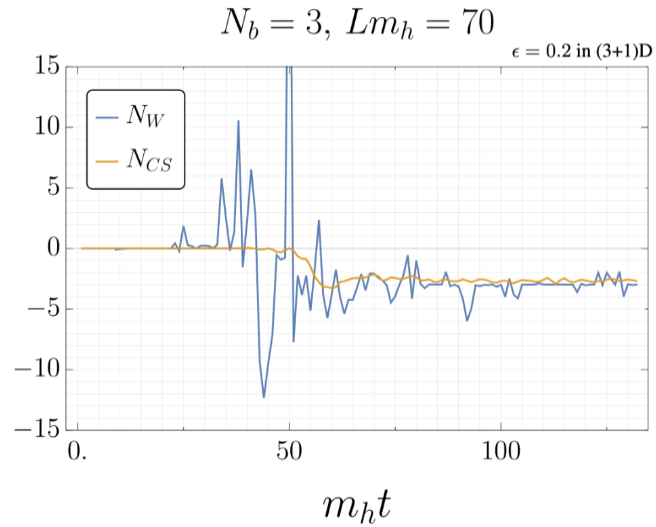


$m_h t = 130$



Bubble collisions produce $SU(2)$ gauge textures which then decay, leading to B violation

Convergence of N_{CS} and N_W



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

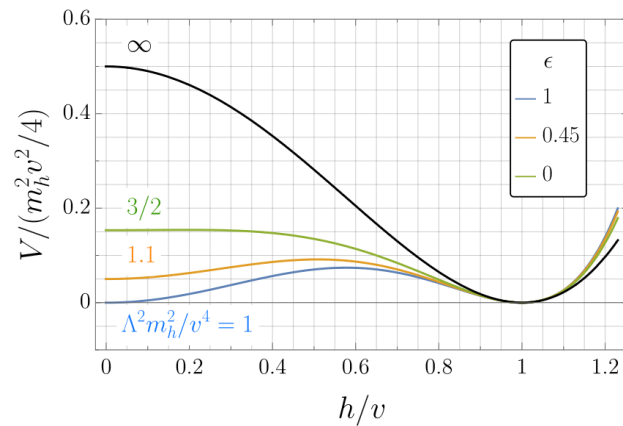
Results from the Lattice

N_{CS} from Bubble Collisions

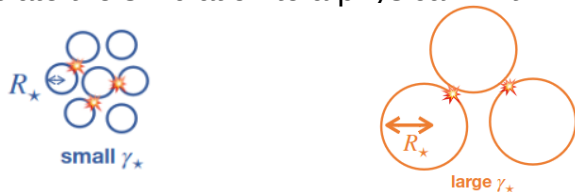
We study the dependence of the N_{CS} on:

- Shape of the Higgs potential $\epsilon = \frac{V_{barr}}{V_{barr} + |\Delta V|} \in (0,1)$
 - $\epsilon \rightarrow 1$: Nearly degenerate vacua $\rightarrow$ **likely** to restore false vacuum
 - $\epsilon \rightarrow 0$: Non-degenerate vacua $\rightarrow$ **unlikely** to restore false vacuum

*Jinno, Konstandin, Takimoto [1906.02588] JCAP

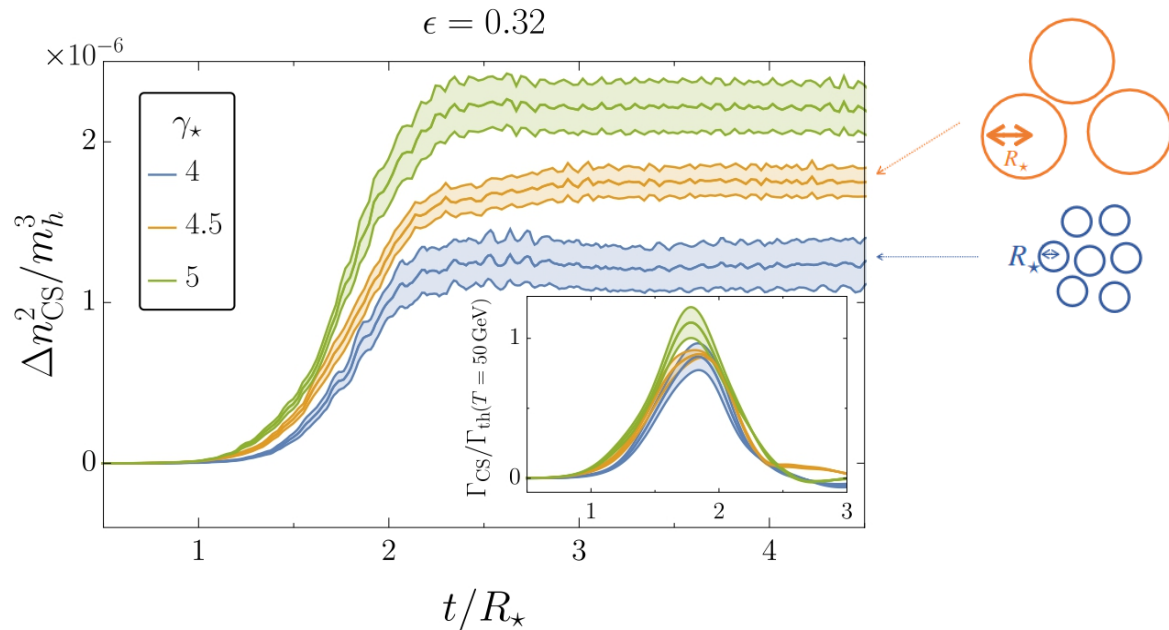


- Lorentz-boost factor gamma of the bubble walls at collision γ_*
 - Since we have to extrapolate the simulation to a physical limit



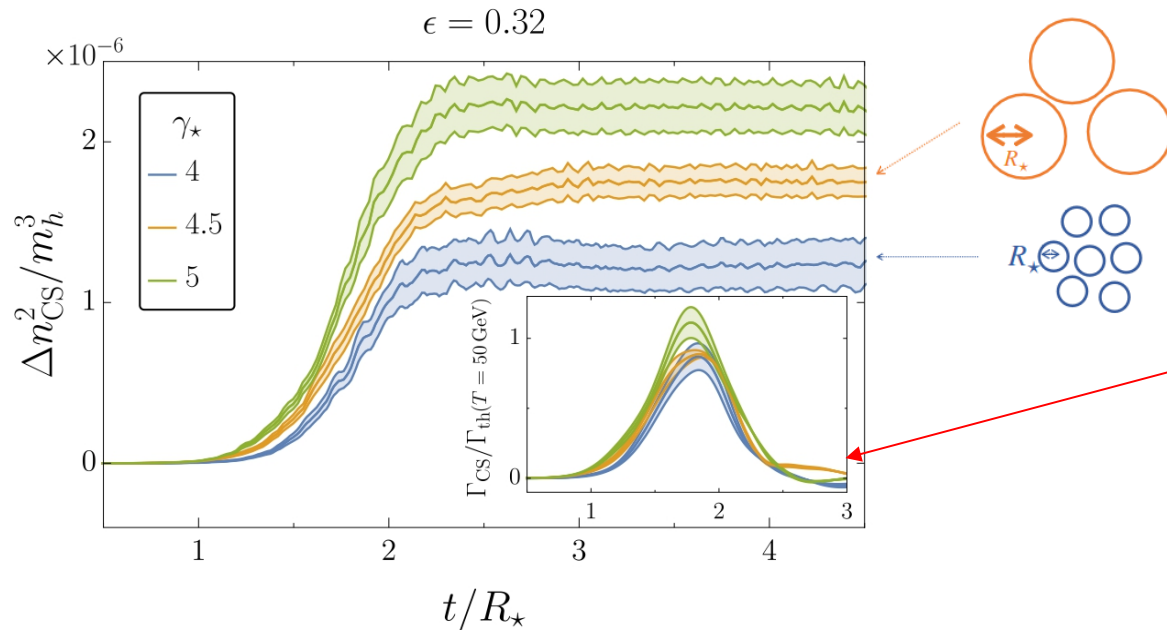
Variance and rate of N_{CS}

- We measure the “amount” of N_{CS} produced through the statistical quantity “variance” averaged over ensembles $\Delta N_{CS}^2(t) \equiv \langle N_{CS}(t)^2 \rangle - \langle N_{CS}(t) \rangle^2$



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- And the corresponding rate via

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

Rate is of order of “thermal” sphaleron rate !

From lattice simulations to physical scales

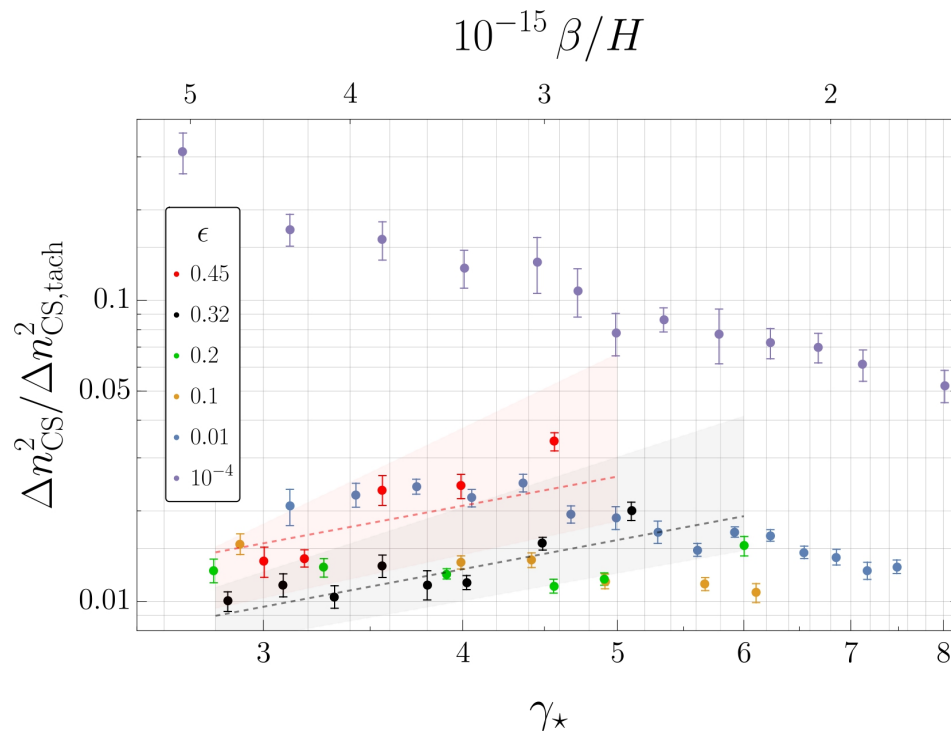
What we simulate:

- Different ϵ
- Different γ_* Different bubble sizes (at collision)

→ Extrapolate to physical scale

We measure our variance in units of the variance from the tachyonic phase transition case

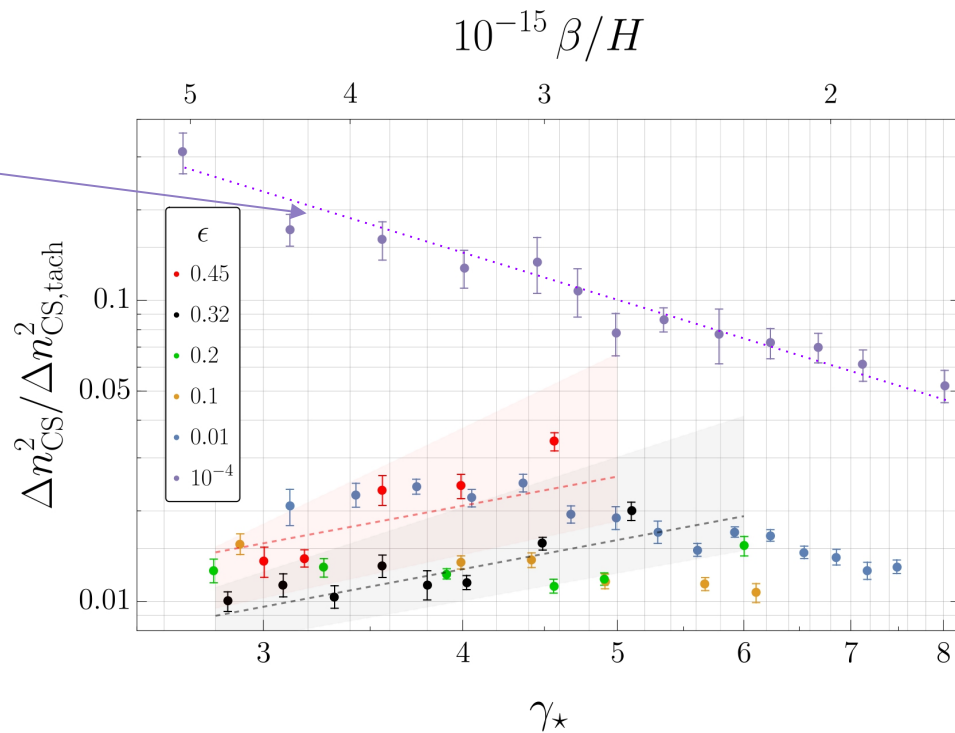
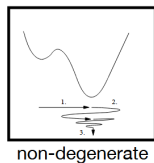
$$\Delta n_{CS,tach}^2 = 10^{-4} m_h^3$$



From lattice simulations to physical scales

1. For $\epsilon < 0.2$

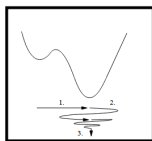
Variance $\rightarrow 0$



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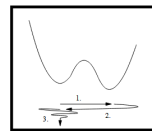
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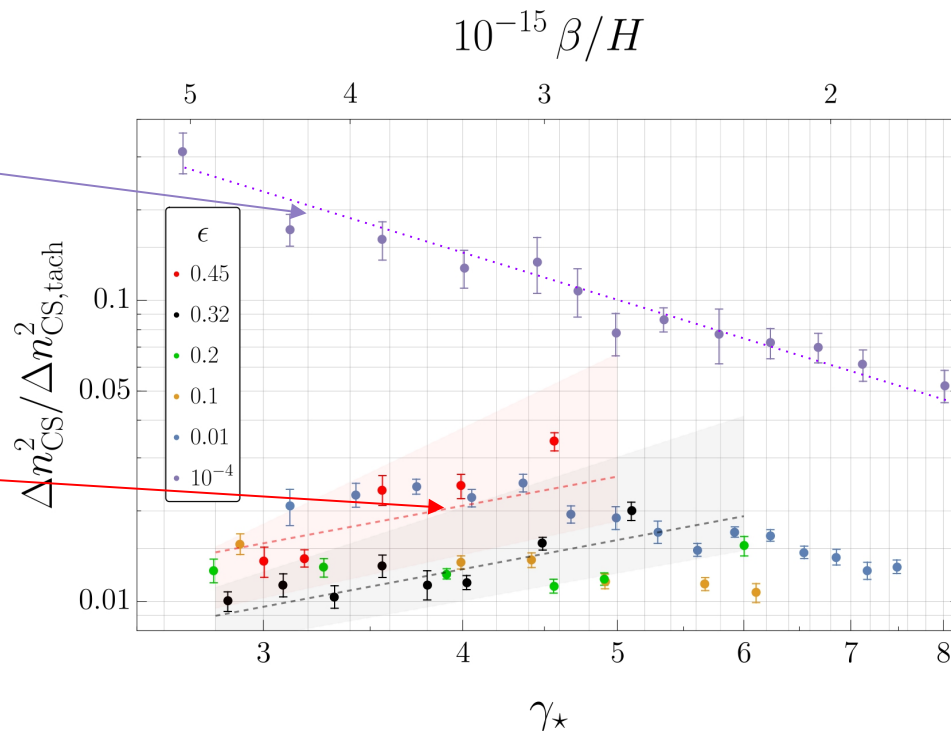


1. For $\epsilon > 0.2$

Variance $\rightarrow$ increases



- Collisions with large ϵ show non decreasing N_{CS} variance
 $\rightarrow$ **A sizeable B violation rate potentially to do Baryogenesis !!!**



Conclusion

- Bubble collisions provide a new sizeable source of Chern—Simons number
- Dependence on shape of the potential and size of bubbles at collision

First-order Higgs bubble collisions provide a non-thermal source of baryon-number violation, distinct from thermal sphaleron transitions.

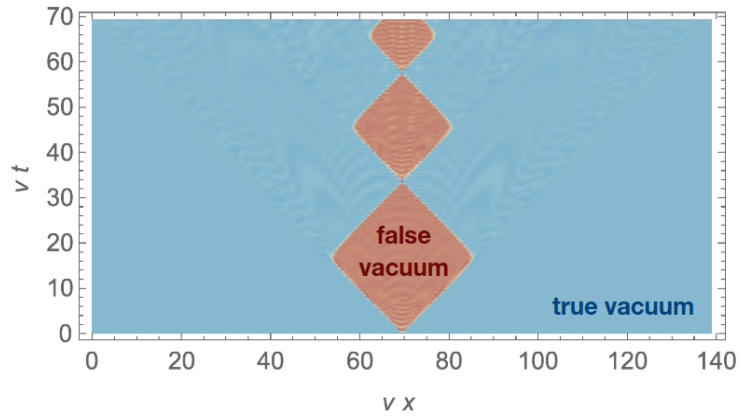
→ **COLD BARYOGENESIS ?** (Find out more on the next episode by Martina tomorrow)

[illegible][illegible][illegible]

1+1D

*Jinno, Konstandin, Takimoto [1906.02588] JCAP

$$\epsilon = 0.5$$



$$\epsilon \ll 1$$

