Pushing up the temperature of the electroweak phase transition.

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MITP virtual Workshop
"Shaping the Universe: Frameworks & Footprints of Cosmological Phase Transitions",
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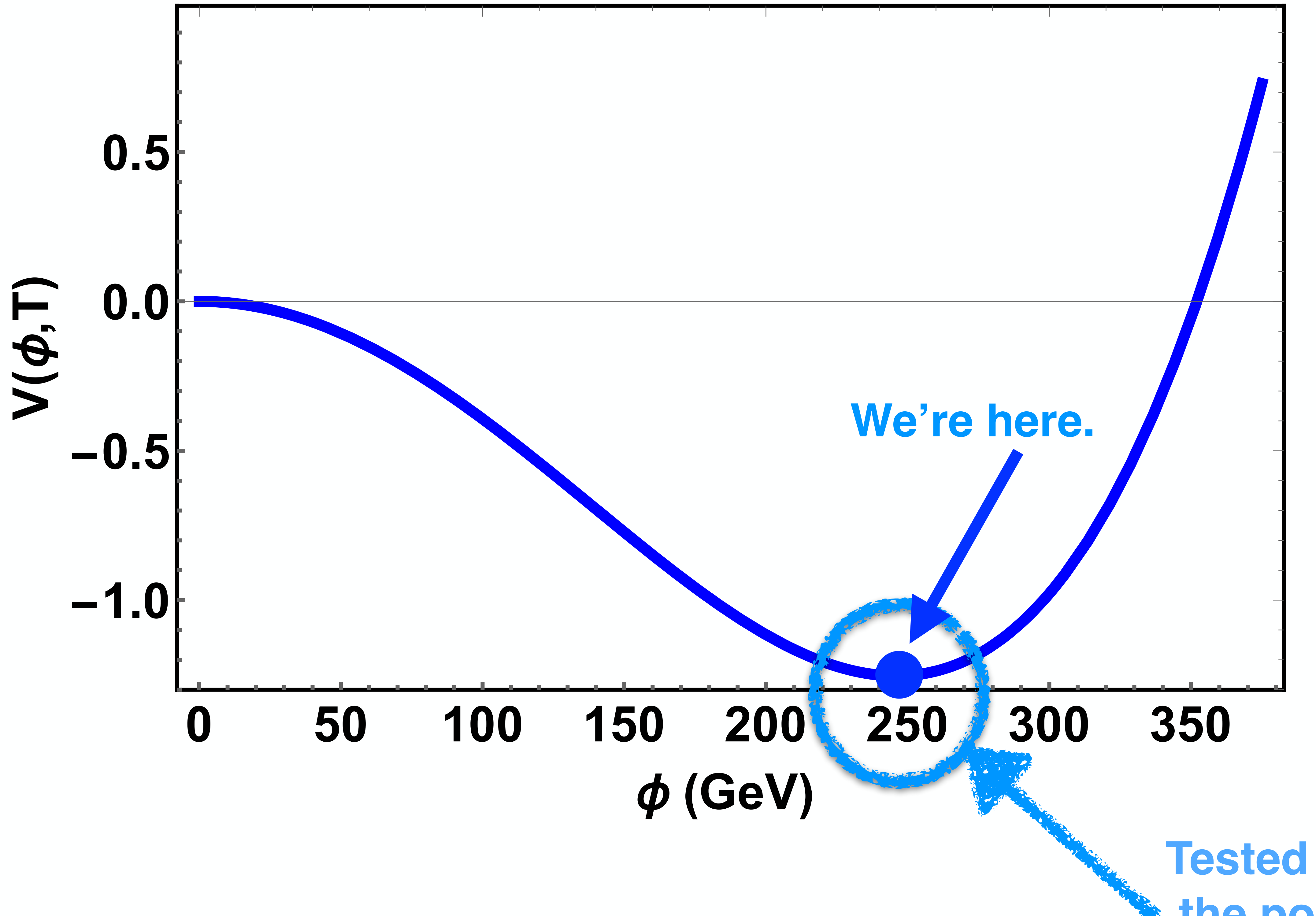
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Universität Hamburg

THE HIGGS POTENTIAL .

TODAY, T=0

$$V_0(\phi) = -\mu^2\phi^2/2 + \lambda\phi^4/2$$



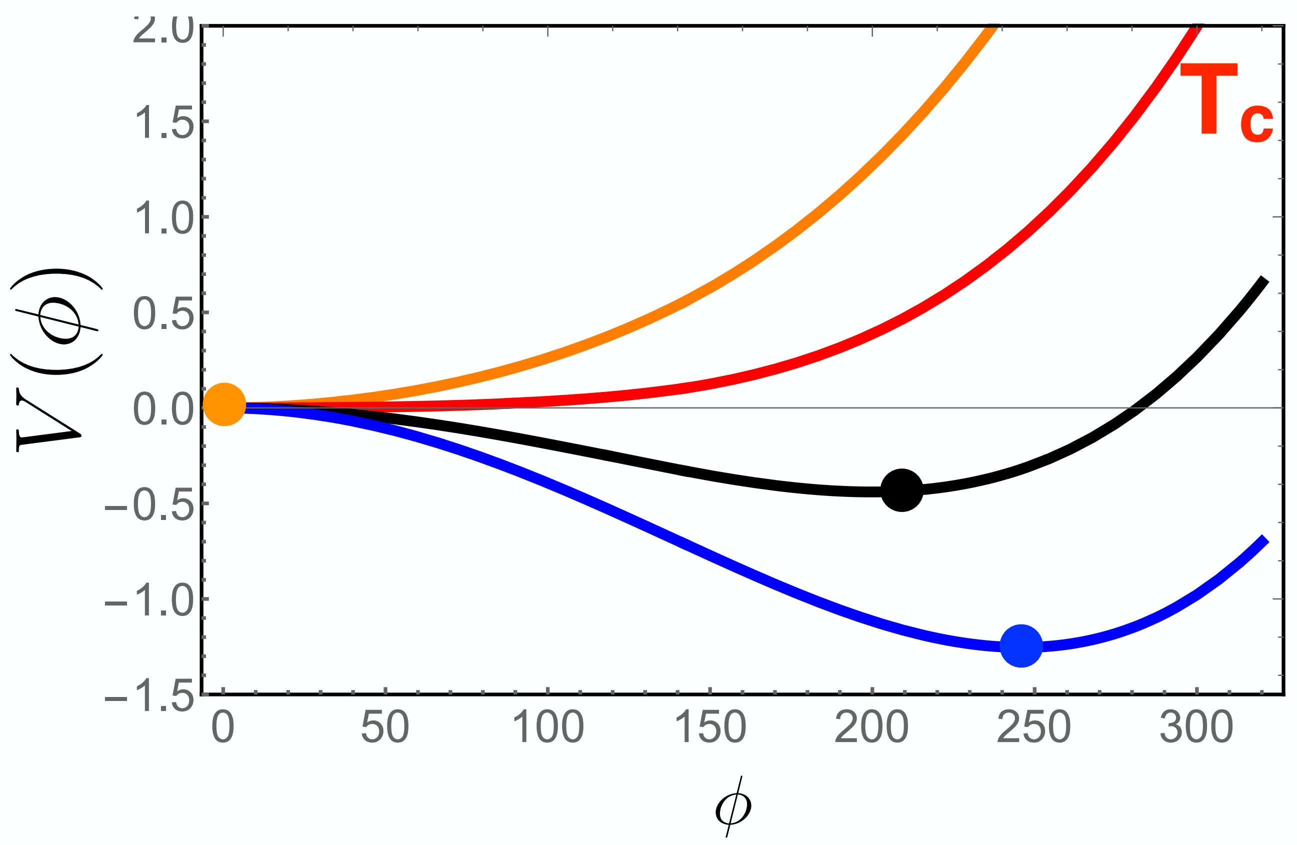
We’re here.

Tested part of the potential

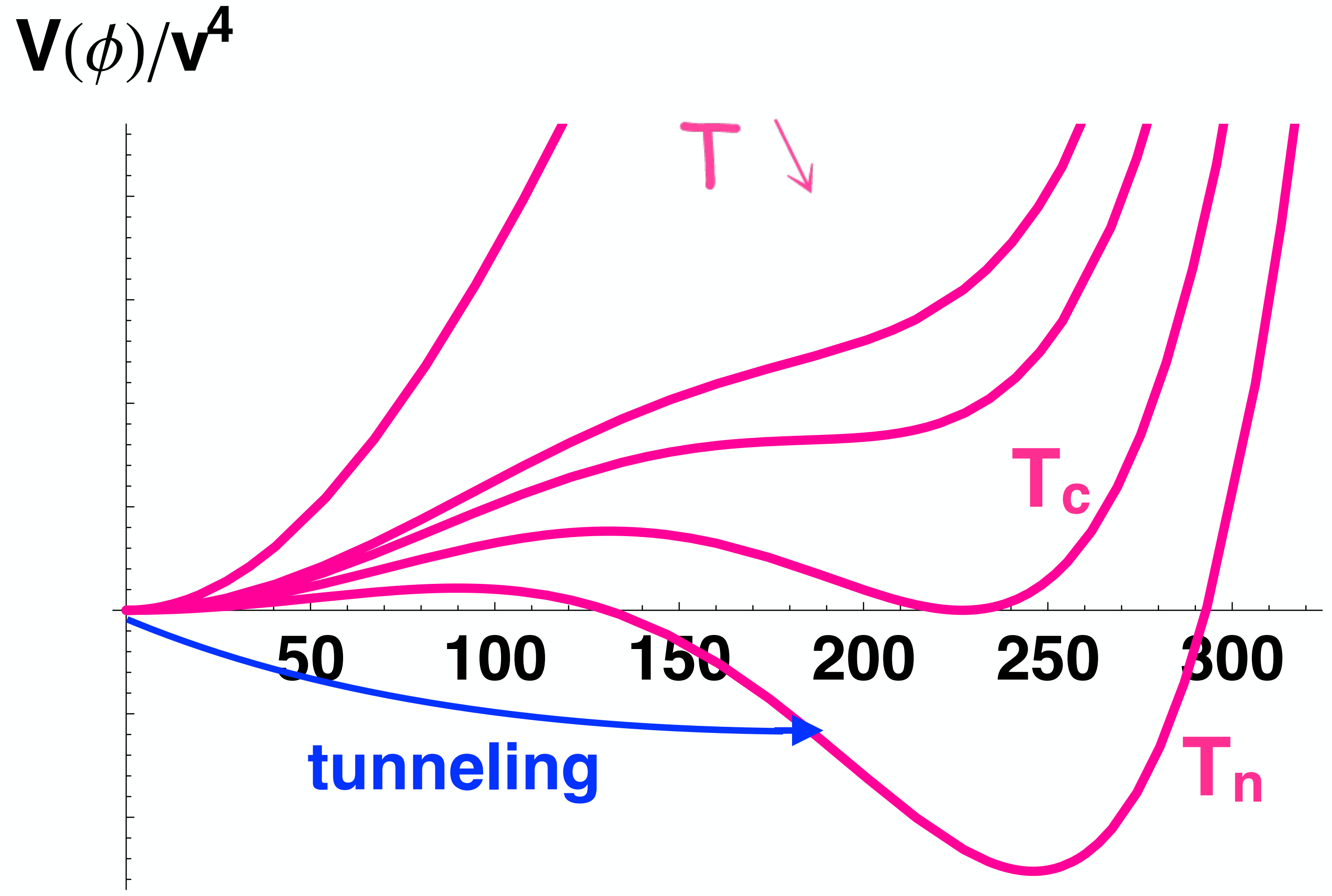
> How did we end up here ?

The EW phase transition

Standard Model crossover

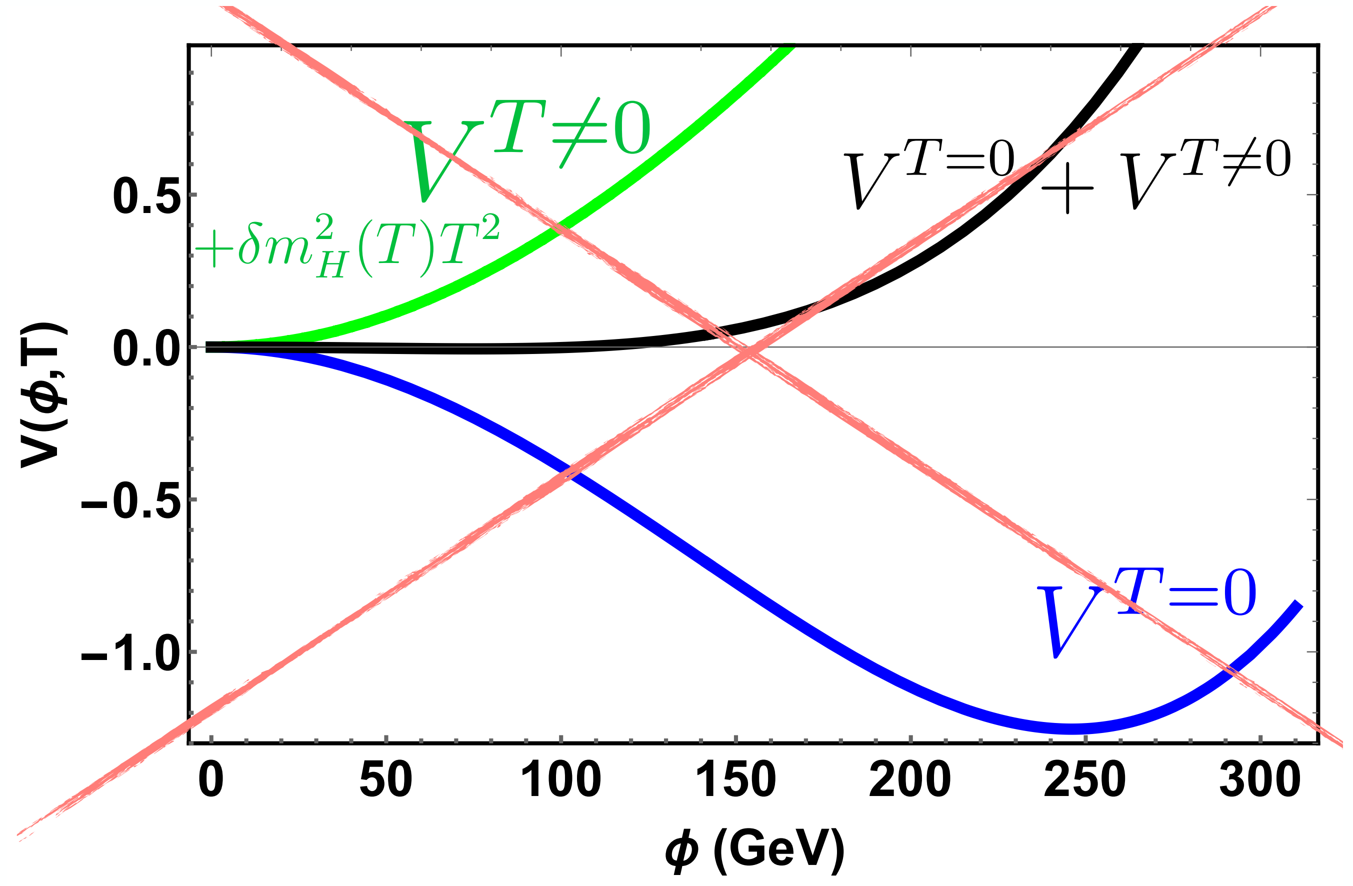


1st-order EW phase transition



∃ new EW-mass scalars (light for strong PT)

No EW phase transition or happening at scale>>v



∃ new EW-mass (<~300 GeV) singlets

LHC has huge potential to explore all this

A universe in which EW symmetry was always broken always had its sphalerons shutoff, which is challenging to explain baryogenesis.

Baryon Number Violation Standard Model

due to chirality + topology of electroweak theory

From the anomaly

$$\partial_\mu j^\mu_B = N_F \frac{\alpha_W}{8\pi} Tr F \tilde{F}$$

EW field strength

$$B = \int d^3x\, j^0_B$$

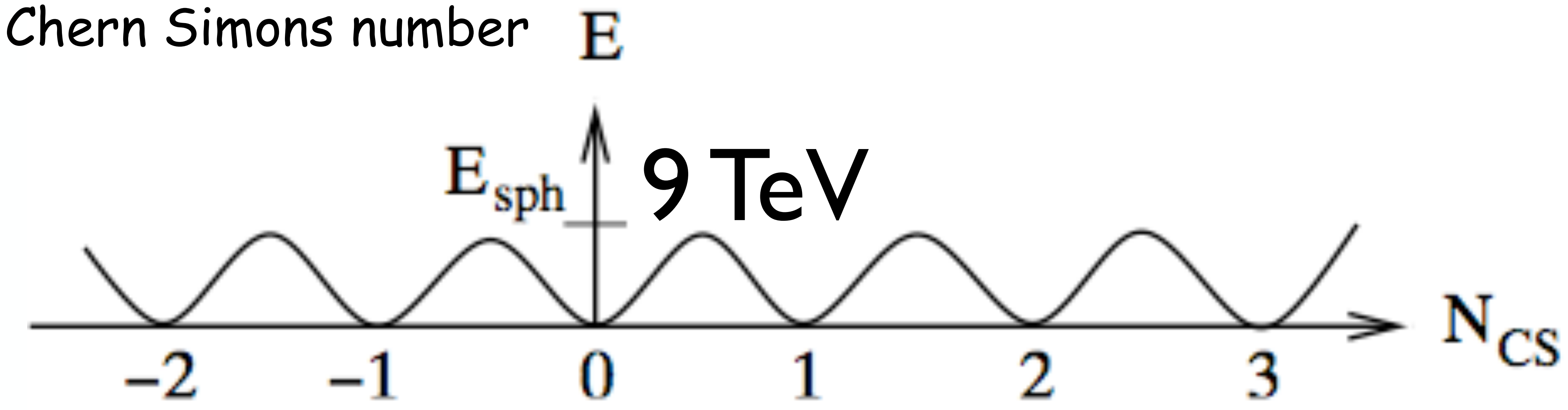
$$\Delta B = \Delta L = N_F \Delta N_{CS}$$

N_{CS}: Chern-Simons number

B-L is conserved

Baryon Number Violation Standard Model

Energy of gauge field configuration as a function of Chern Simons number



barrier height proportional to Higgs VEV

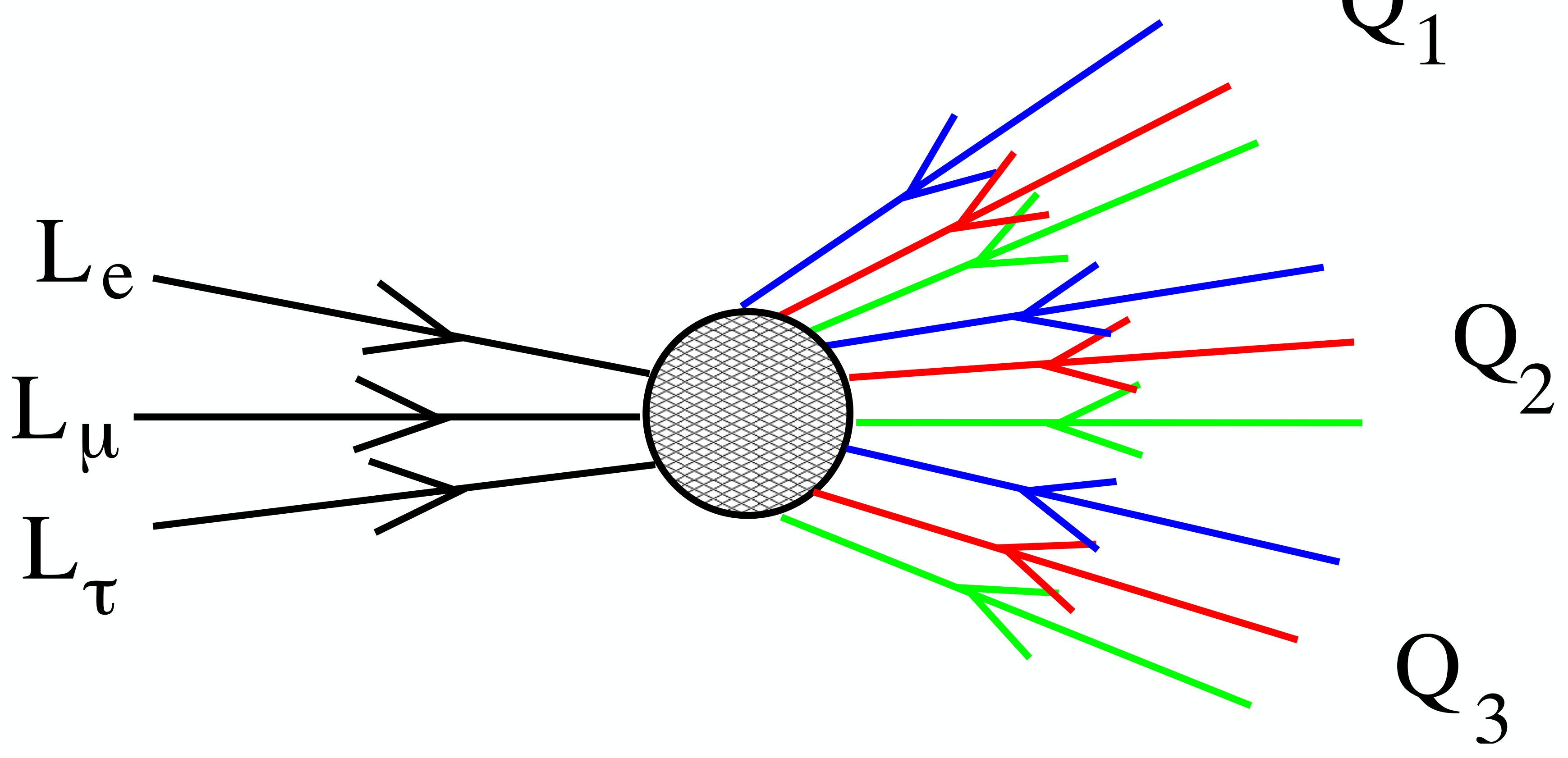
$$\Delta B = \Delta L = N_F \Delta N_{CS}$$

Baryons are created by transitions between topologically distinct vacua of the SU(2)$_L$ gauge field

$$N_{CS}(t) \; - \; N_{CS}(0) \;\; = \;\; \frac{g^2}{16\pi^2} \int_0^t dt \int d^3x \, \mathbf{Tr}[W^{\mu\nu}\tilde{W}_{\mu\nu}]$$

Sphalerons !

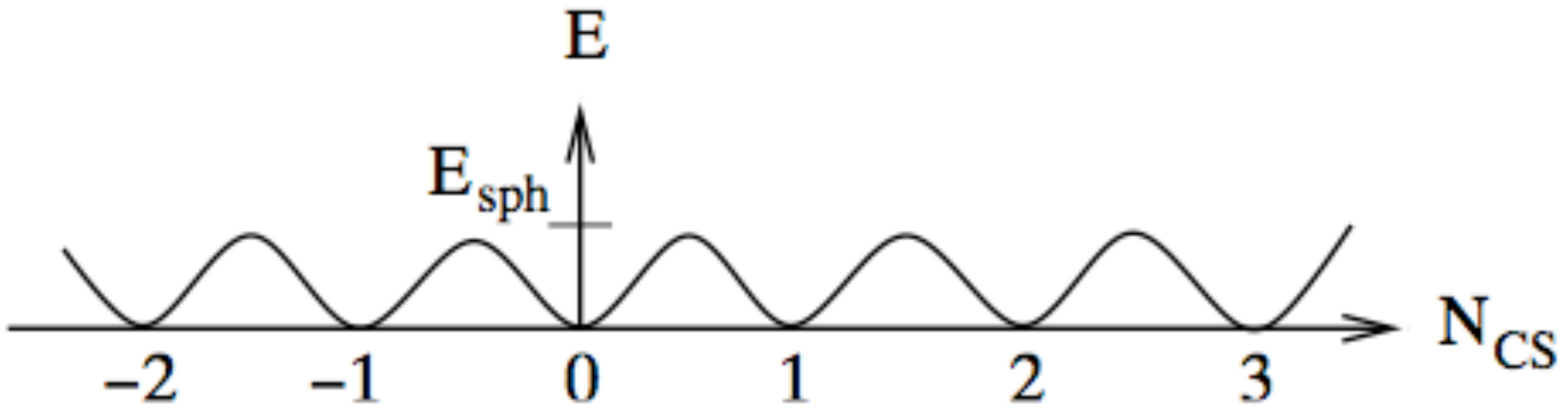
Determinant in almost all baryogenesis mechanisms whatever their energy scale



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

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

Rate of B-violation through sphalerons at T=0



↑ barrier height proportional to Higgs VEV

Quantum Tunneling rate: $\Gamma \sim e^{-4\pi/\alpha_W} \sim 10^{-165}$

$\alpha_W \sim 1/30$

⇒ Baryon number violation is totally suppressed in the SM at zero temperature

However, is sizeable at high temperatures, as it becomes possible to go over the barrier via thermal fluctuations

Rate of B-violation in the Standard Model .

The Higgs VEV sets the scale of B-violation

Two very ≠ rates depending whether $T>T_c$ or $T<T_c$

T_c: Temperature of the EW phase transition

- **In the EW symmetric phase, $T>T_c$** $\Gamma \sim \alpha_W^4 T^4$
- **In the EW broken phase, $T<T_c$** $\Gamma \sim v^4 e^{-E_{\rm sph}/T}$ **where** $E_{\rm sph} \propto \langle \phi \rangle$

Relating Baryon and Lepton number asymmetries at T>T$_c$

$$B = \sum_i (2\mu_{q_i} + \mu_{u_i} + \mu_{d_i})$$

$$L = \sum_i L_i, \quad L_i = 2\mu_{\ell_i} + \mu_{e_i}$$

At high temperature in the plasma, all processes at equilibrium give rise to constraints among the chemical potentials of quarks, leptons and Higgs.

At thermal equilibrium, one finds that B, L and B-L are related by:

$$\boxed{\mathbf{B} = \underbrace{\frac{8N_f+4}{22N_f+13}}_{c_s=28/79}\ \mathbf{(B\text{-}L)}}$$

$$L = (c_s - 1)(B\text{-}L)$$

Therefore, at thermal equilibrium (when sphalerons are active), B relaxes to (B-L). In the SM, B-L=0 so any primordial baryon asymmetry produced at early times gets erased by sphalerons in a theory which conserves B-L.

Baryon number violation in the Standard Model due to sphalerons at finite temperature

T_{EWPT}: Temperature of the EW phase transition

- In the EW symmetric phase, $T>T_{EWPT}$

out-of-equilibrium if: $\boxed{T > 10^{12}\ \text{GeV}}$

- In the EW broken phase, $T<T_{EWPT}$

out-of-equilibrium if: $\boxed{\langle\phi\rangle/T > 1}$

$\langle\phi\rangle$: Higgs vacuum expectation value

At equilibrium:

$$\boxed{B = \frac{8N_f+4}{22N_f+13}\,(B-L)}$$

Sphalerons' implications

2 main possibilities for baryogenesis:

1) B-L= 0 theory

(this talk)

Baryogenesis must take place at the EWPT.

Advantage: connected to EW physics, testable

2) B-L≠ 0 theory

High-scale baryogenesis possible.

Disadvantage: typically difficult to test

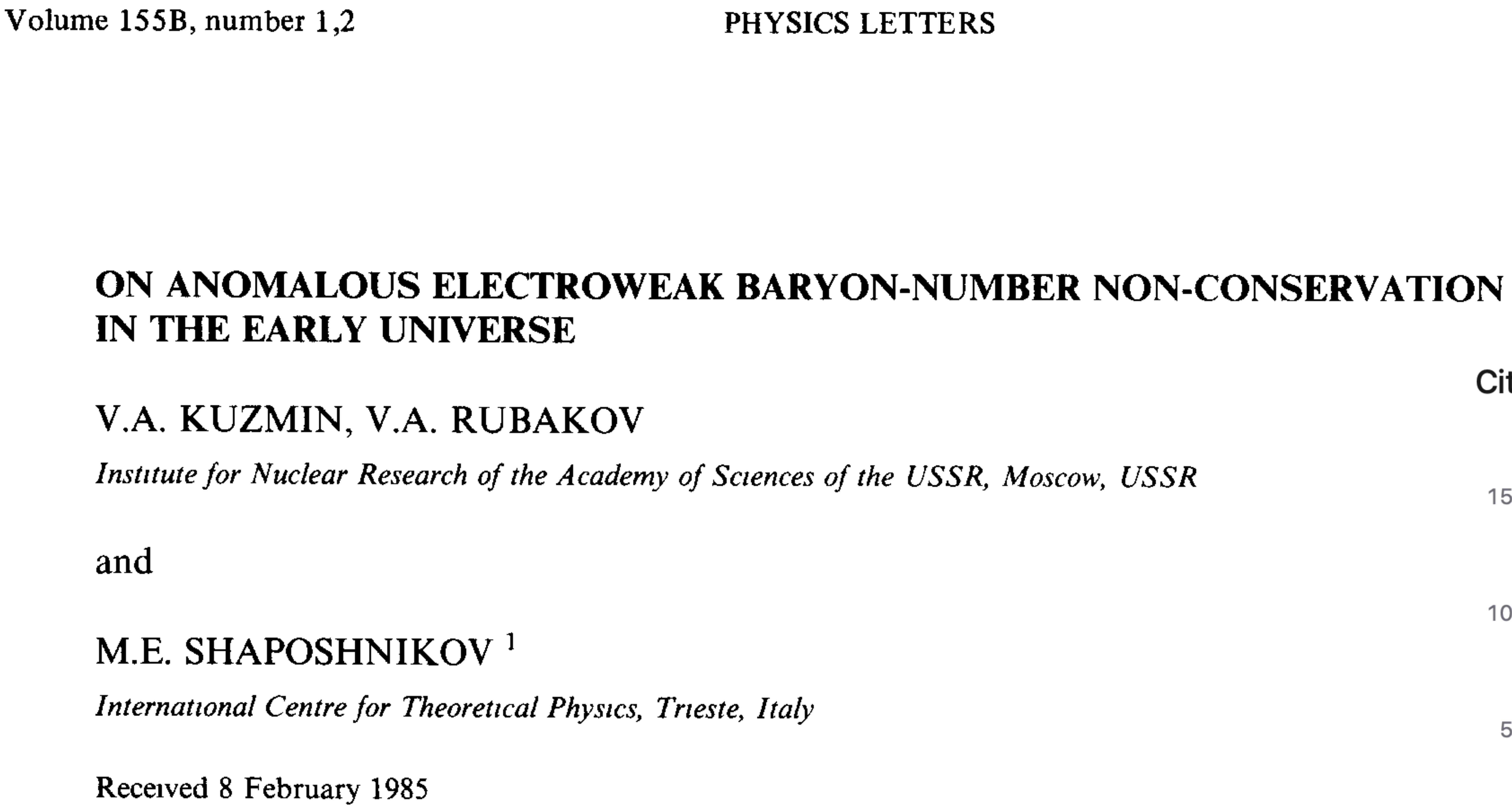
Create B-L ≠0, e.g through out-of-equilibrium decays, which then gets converted into B by sphalerons.
Popular example: Leptogenesis

—> Only way to achieve baryogenesis in minimal (B-L) conserving theory:

At the electroweak phase transition:

Electroweak baryogenesis

EW baryogenesis: 40 years old and still attractive



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ON ANOMALOUS ELECTROWEAK BARYON-NUMBER NON-CONSERVATION IN THE EARLY UNIVERSE

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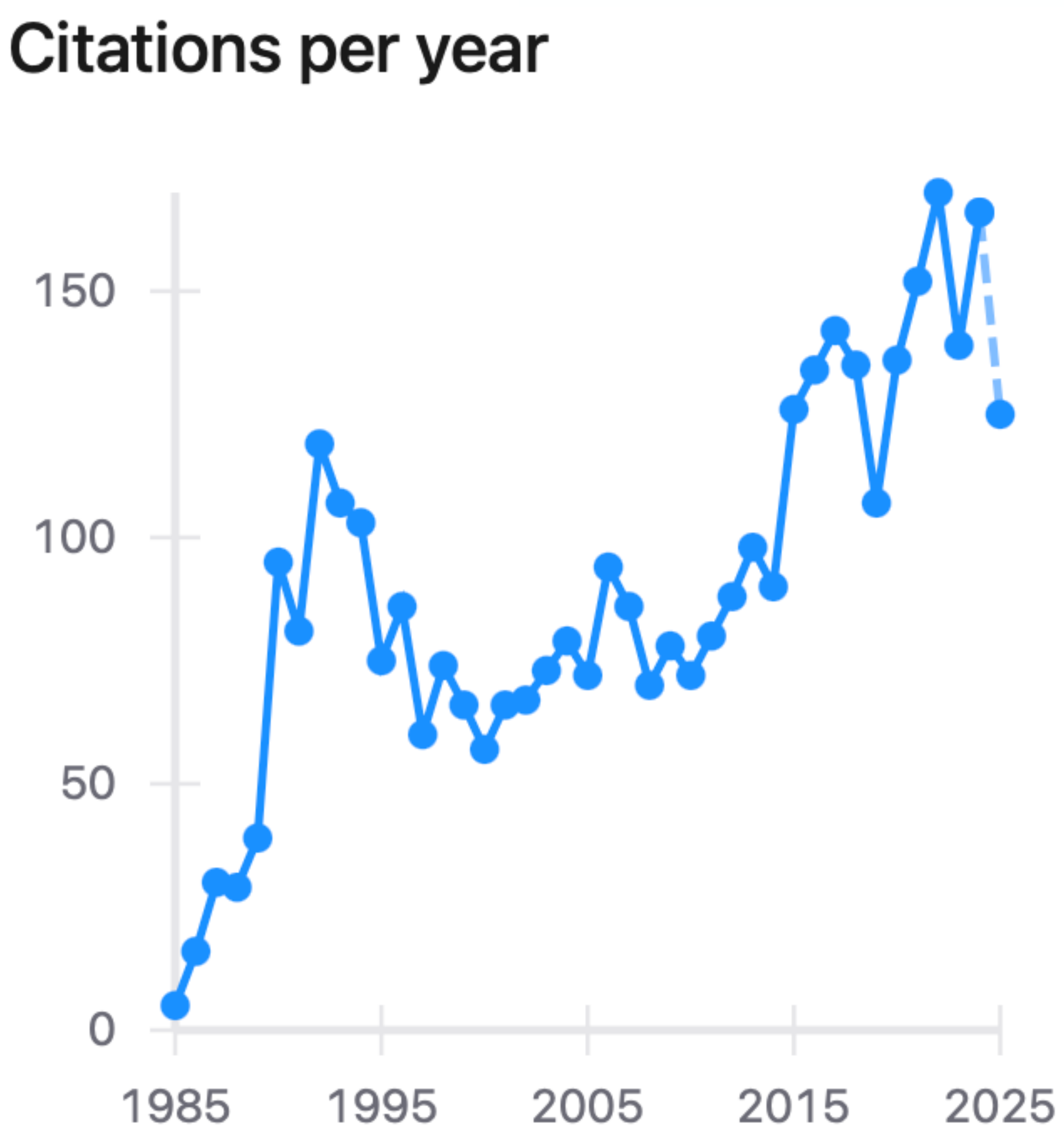
Received 8 February 1985



Citations per year

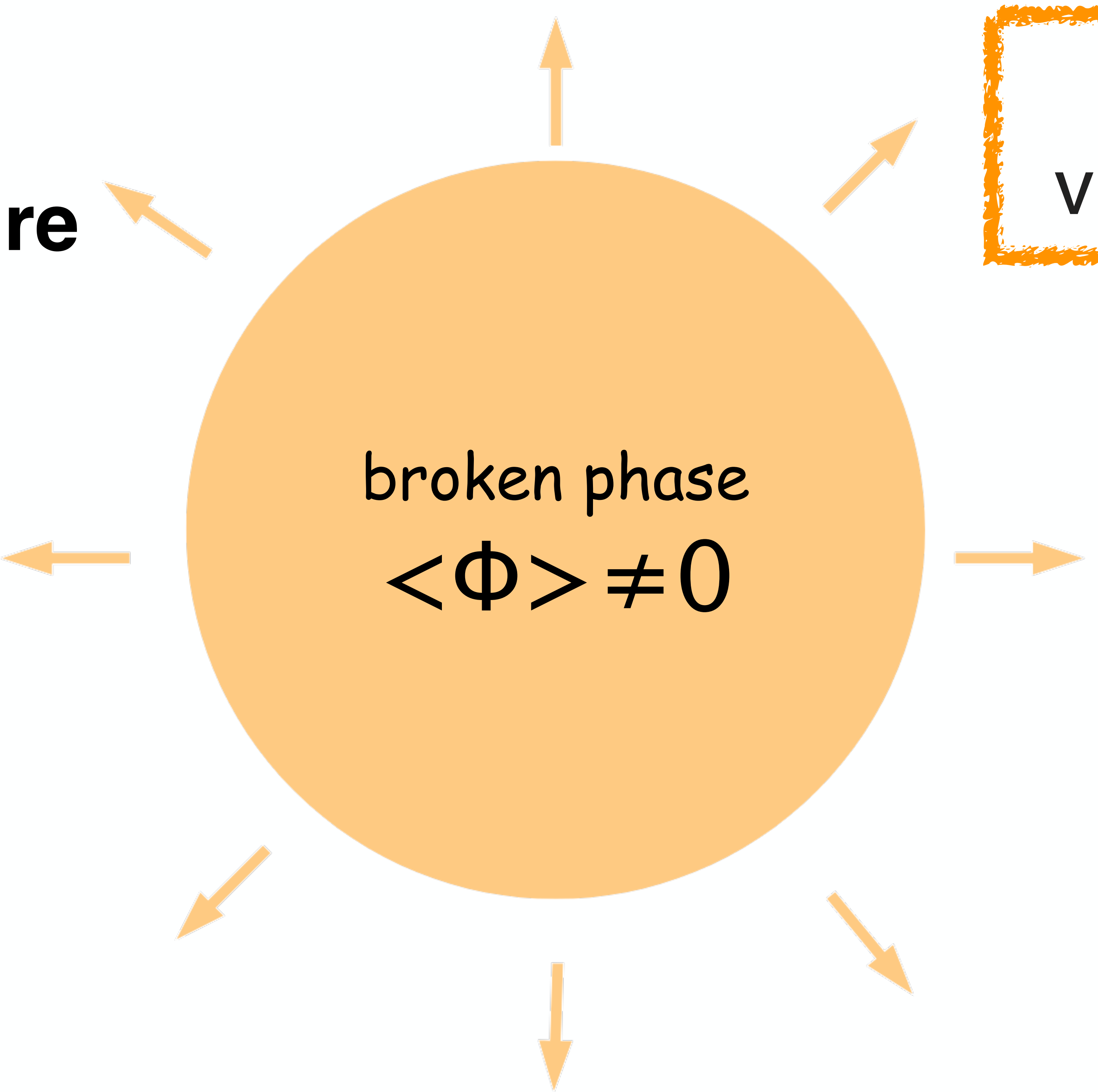
Standard EW baryogenesis during a first-order EW phase transition

Kuzmin, Rubakov, Shaposhnikov'85

Cohen, Kaplan, Nelson'91

Baryon asymmetry created at vicinity of CP-violating bubble wall.

$T_n \equiv$ **nucleation temperature**



broken phase

$<\Phi>\neq 0$

symmetric phase

$<\Phi>=0$

Fine-tuned?

Requires $\left.\frac{\langle\phi\rangle}{T}\right|_{T_n} \sim \mathcal{O}(1)$

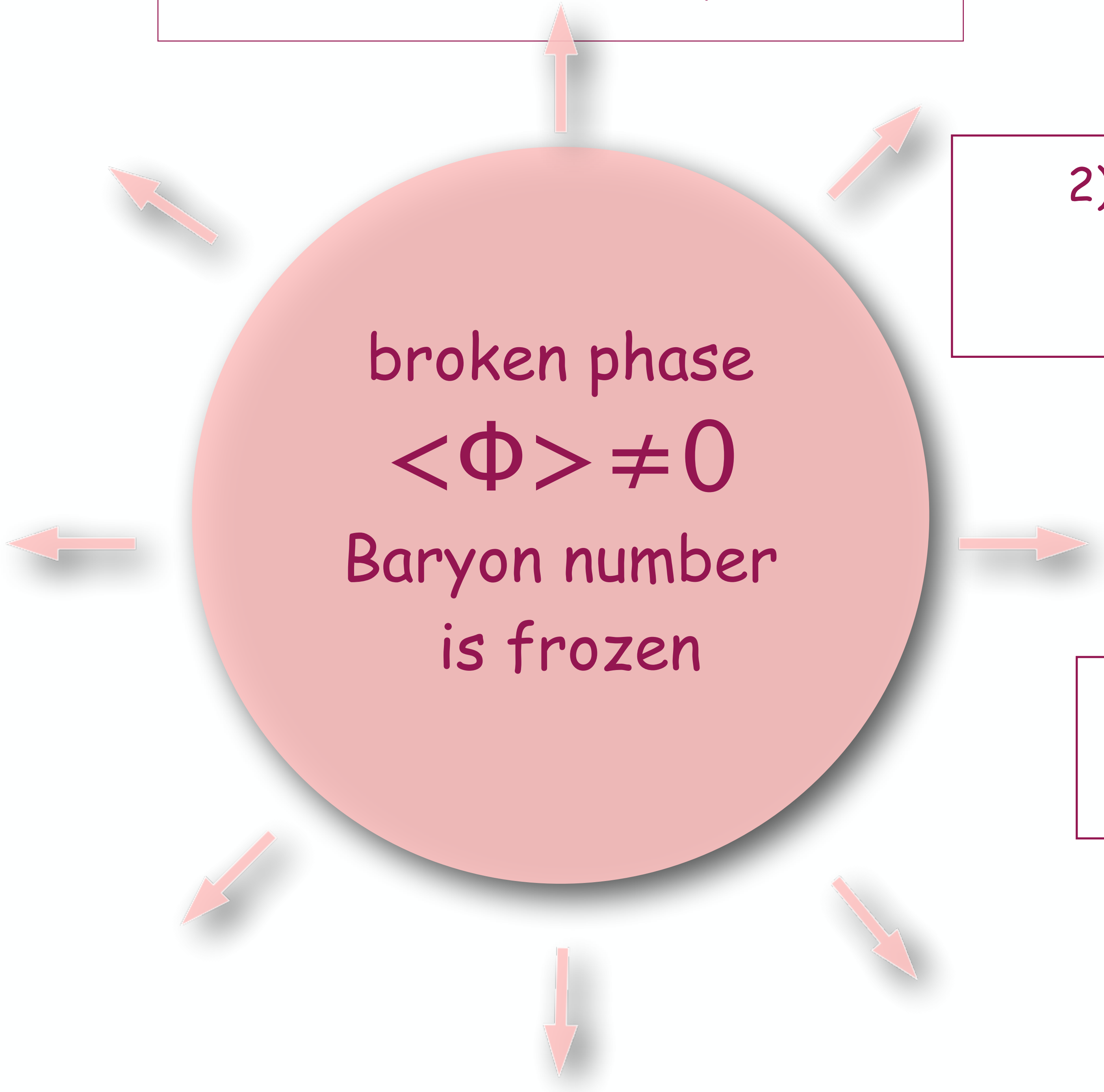
If $\left.\frac{\langle\phi\rangle}{T}\right|_{T_n} \ll 1$ **–>** **Washout**

If $\left.\frac{\langle\phi\rangle}{T}\right|_{T_n} \gg 1$ **–>** **Too-fast wall, no time for diffusion**

EW baryogenesis during a first-order EW phase transition .

Kuzmin, Rubakov, Shaposhnikov'85

Cohen, Kaplan, Nelson'91



1) nucleation and expansion of bubbles of broken phase

broken phase

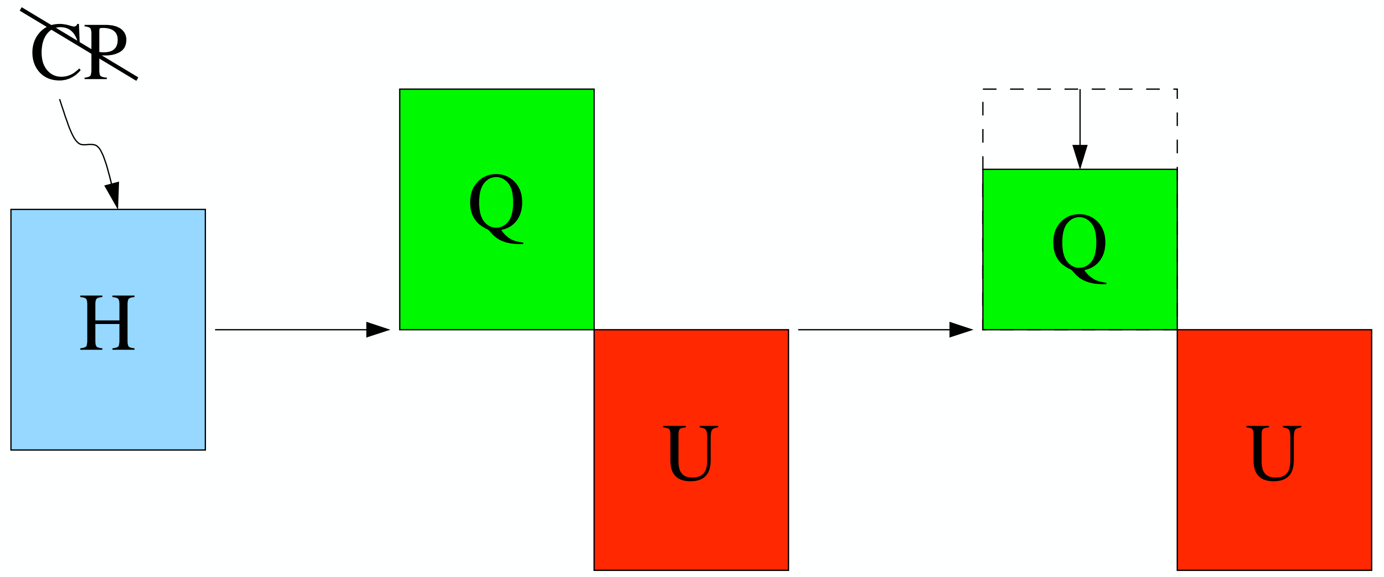
$<\Phi>\neq 0$

Baryon number is frozen

2) CP violation at phase interface responsible for mechanism of charge separation

Chirality Flux in front of the wall

3) In symmetric phase, $<\Phi>=0$, very active sphalerons convert chiral asymmetry into baryon asymmetry



Strength of EW phase transition $\equiv \dfrac{\langle\Phi(T_n)\rangle}{T_n} \gtrsim 1$

T_n ≡ nucleation temperature

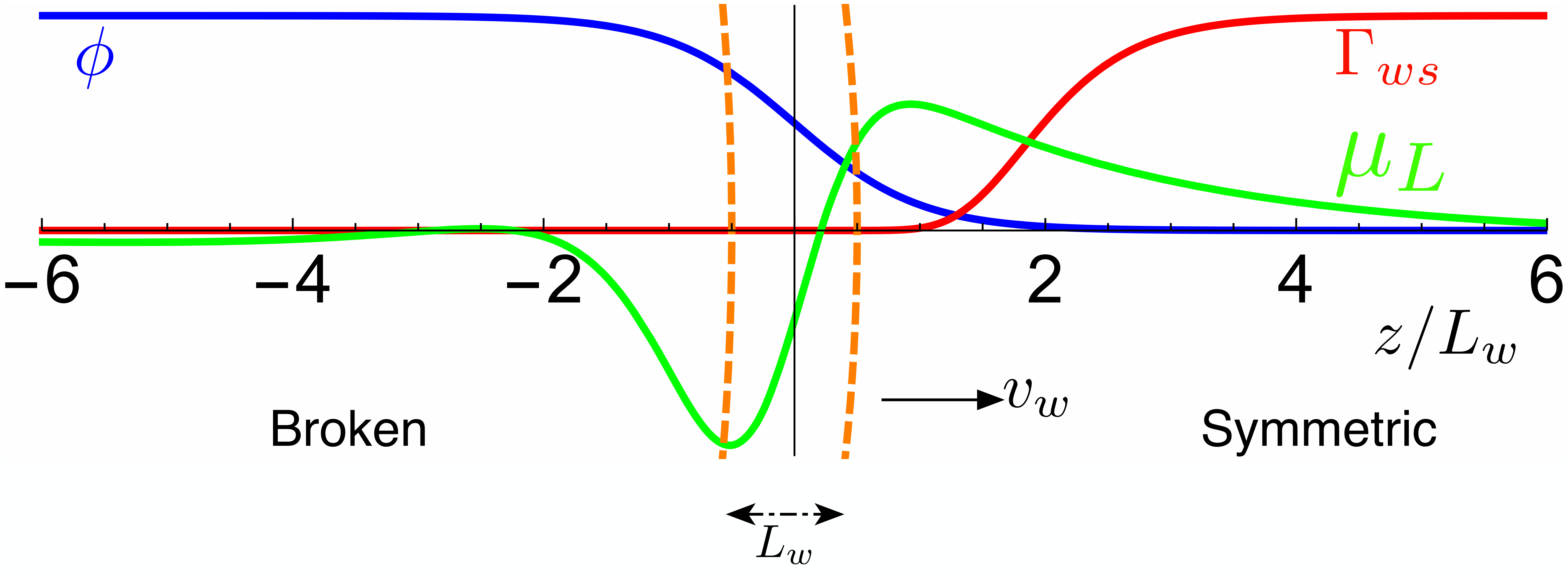
The EW baryogenesis miracle .

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} \mathrm{d}z\ \Gamma_{ws}\ \mu_L\ \mathrm{Exp}\left[-\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} \mathrm{d}z_0 \Gamma_{ws}\right]$$

bubble wall velocity

$$\Gamma_{ws} = 10^{-6}\ T\ e^{-\frac{E_{sph}}{T}\frac{\phi(T)}{v}}$$

: sphaleron rate



bubble wall

We will hear about EW baryogenesis in this workshop.

Alternative question raised in this talk:

Was the EW symmetry ever restored?

What kind of BSM would lead to EW symmetry non-restoration (SNR) at high temperature?

This is relevant:

Sphalerons mediate efficient Baryon number
violation at high-temperature in the EW symmetric phase.

If there was never any phase of EW symmetry restoration at high temperature,
we would need to do baryogenesis without relying on sphalerons

At high temperature, the Higgs effective potential can be obtained from the free energy of the plasma of particles getting their mass from the Higgs, which is, in the non-interacting gas approximation

$$\mathcal{F} = V_0 + T \int \frac{d^3p}{(2\pi)^3} \sum_i \pm g_i \log\left[1 \mp e^{-E_i/T}\right]$$

T=0 potential

internal dof

-/+ : for bosons/fermions

$$E_i^2 = p^2 + m_i^2$$

φ-dependent

$$\mathcal{F} = \underset{\downarrow}{V_0} + \underbrace{\frac{T^4}{2\pi^2}\sum_i \pm g_i Y_{b/f}(\frac{m_i}{T})}_{\blacktriangledown}$$

T=0 potential **T≠ 0 potential called** $V_1(\phi, T)$

with the thermal bosonic/fermionic function defined as

$$Y_{b/f}(x) = \int_0^\infty dy\ y^2 \log\left[1 \mp e^{-\sqrt{x^2+y^2}}\right]$$