EW Baryogenesis from dynamical Yukawa couplings

Sebastian Bruggisser

In collaboration with:
T. Konstandin & G. Servant

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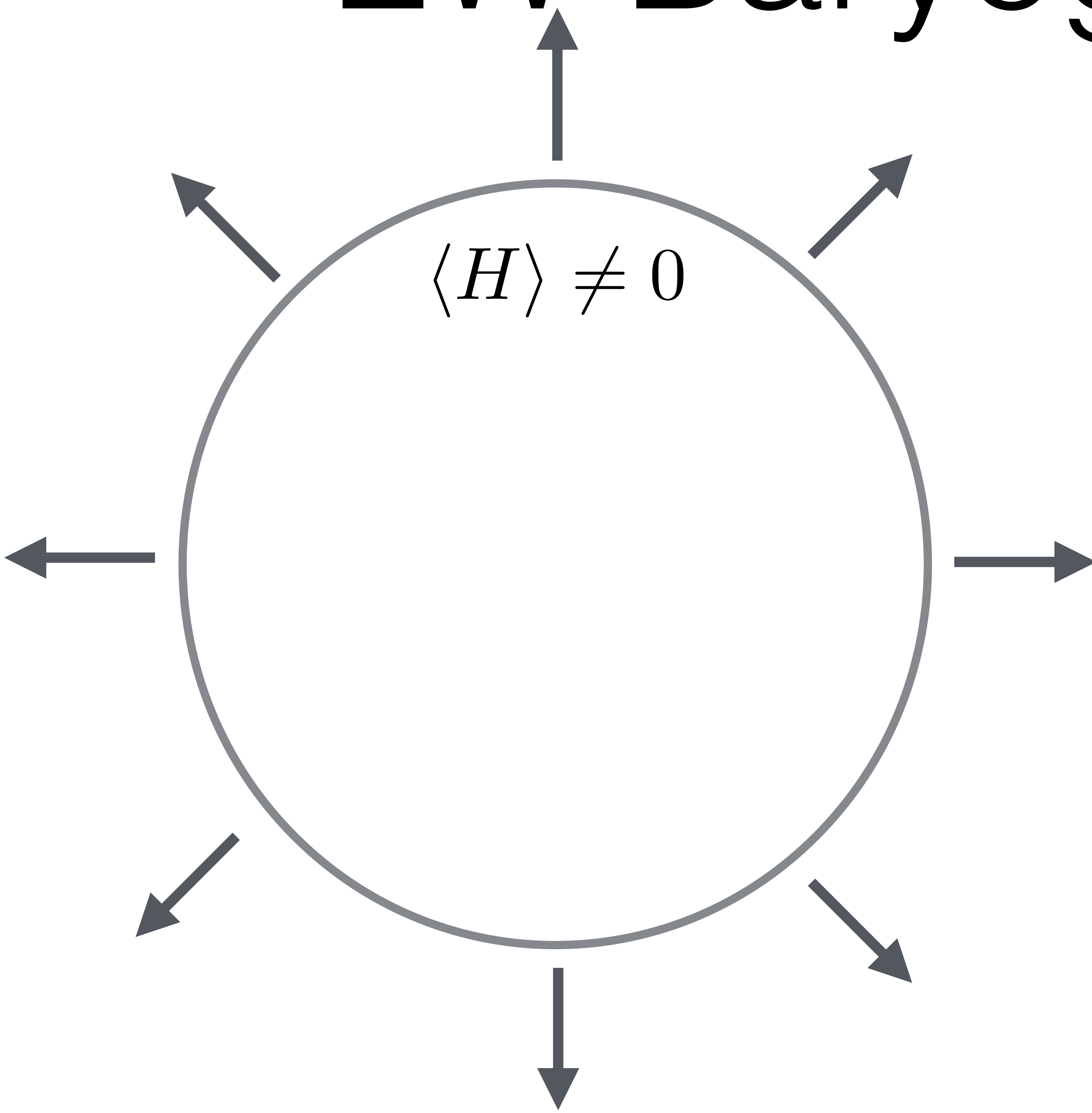
See talk tomorrow morning

DESY

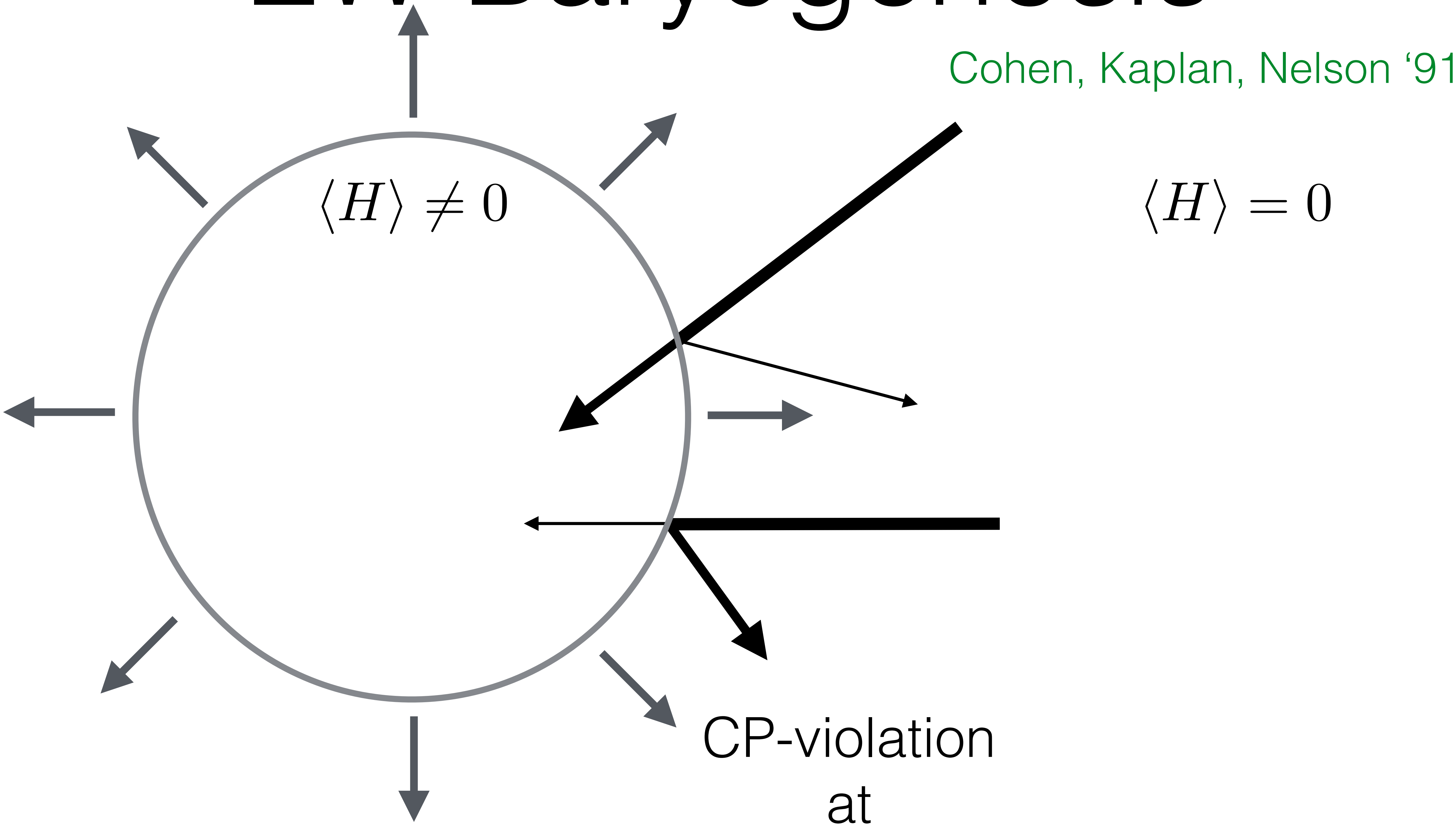
EW Baryogenesis

Cohen, Kaplan, Nelson ‘91



$\langle H \rangle = 0$

EW Baryogenesis



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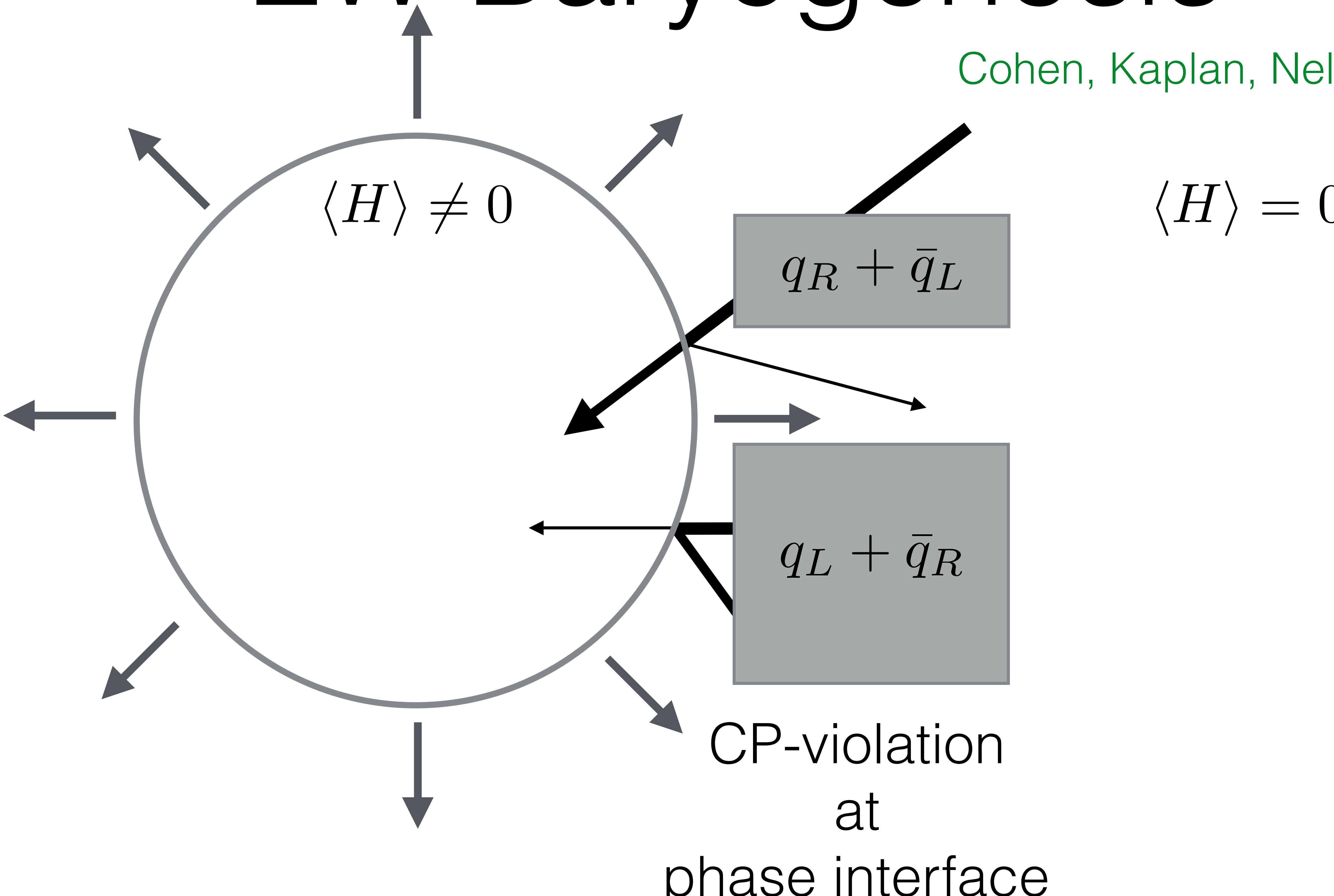

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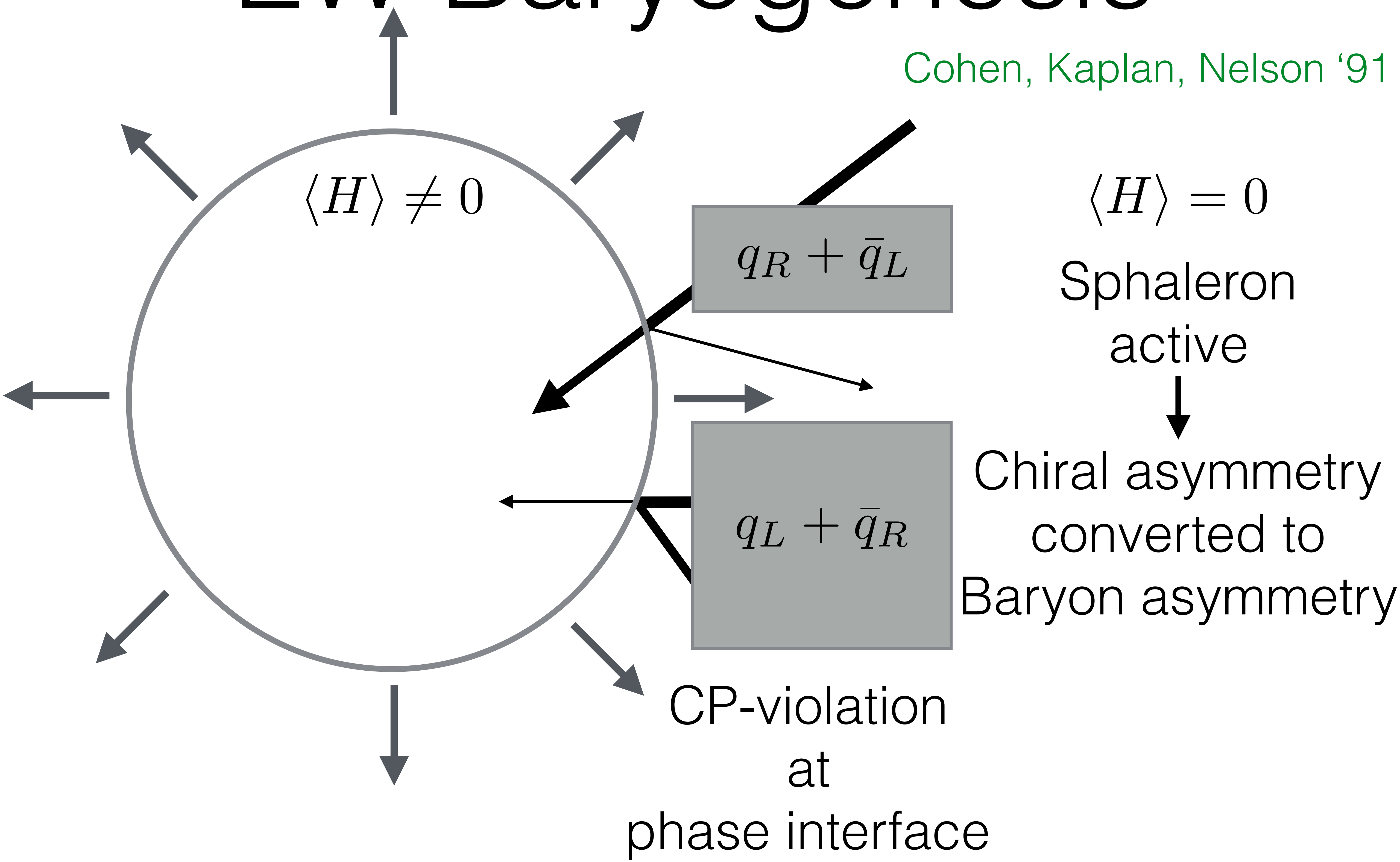

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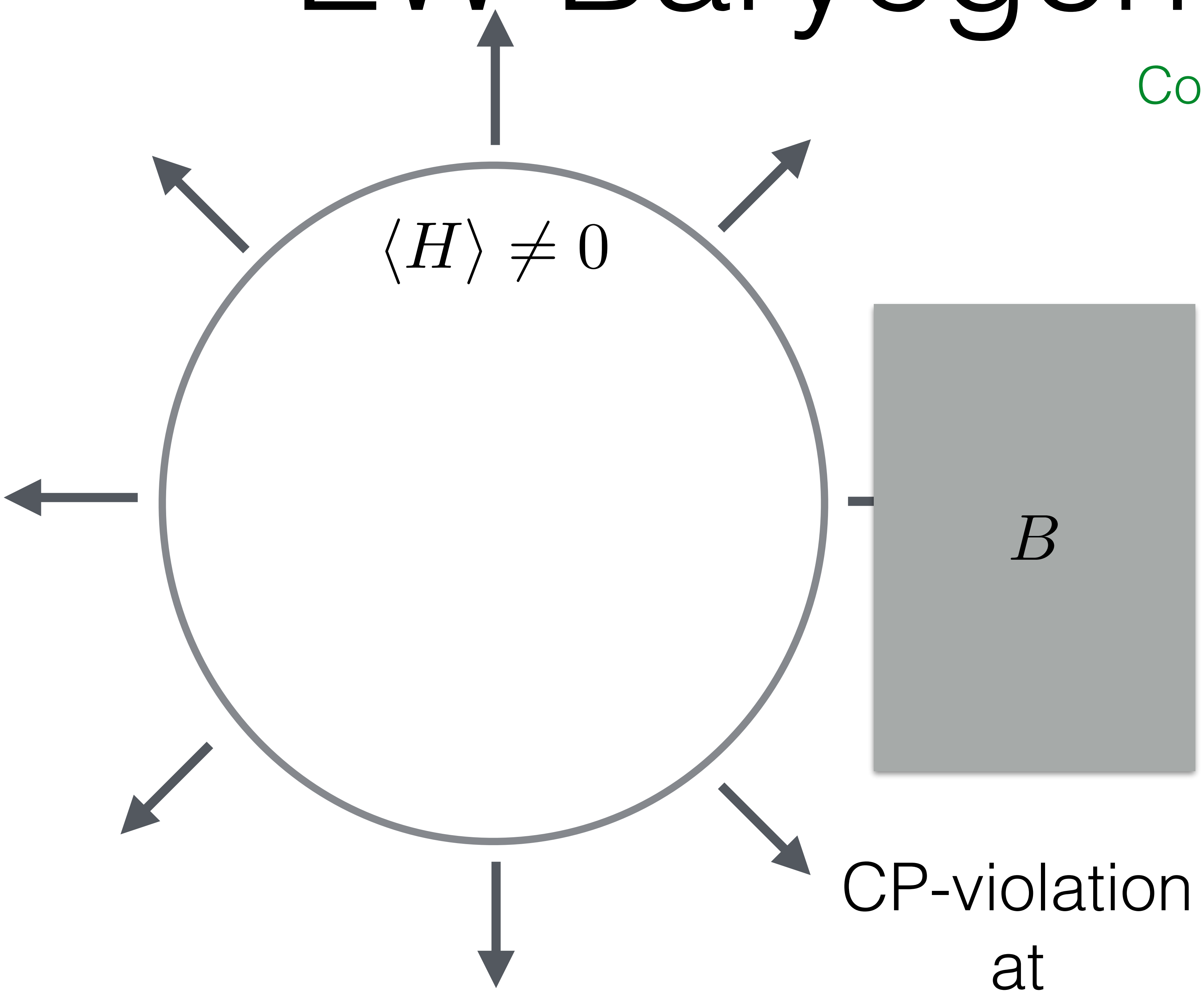


$\langle H \rangle = 0$

Sphaleron active

$\downarrow$

Chiral asymmetry converted to Baryon asymmetry

CP-violation at phase interface

EW Baryogenesis

Cohen, Kaplan, Nelson '91

$\langle H \rangle \neq 0$

Sphaleron inactive

$\downarrow$

Baryon number frozen

B

$\langle H \rangle = 0$

Sphaleron active

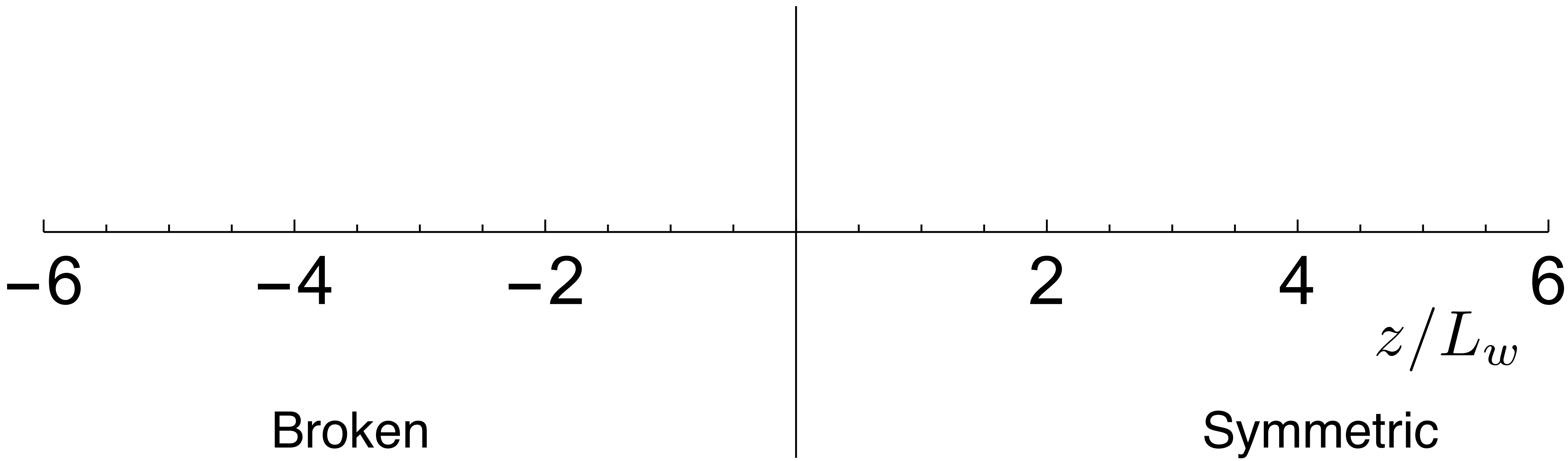
$\downarrow$

Chiral asymmetry converted to Baryon asymmetry

CP-violation at phase interface

Baryon asymmetry

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



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2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

Baryon asymmetry

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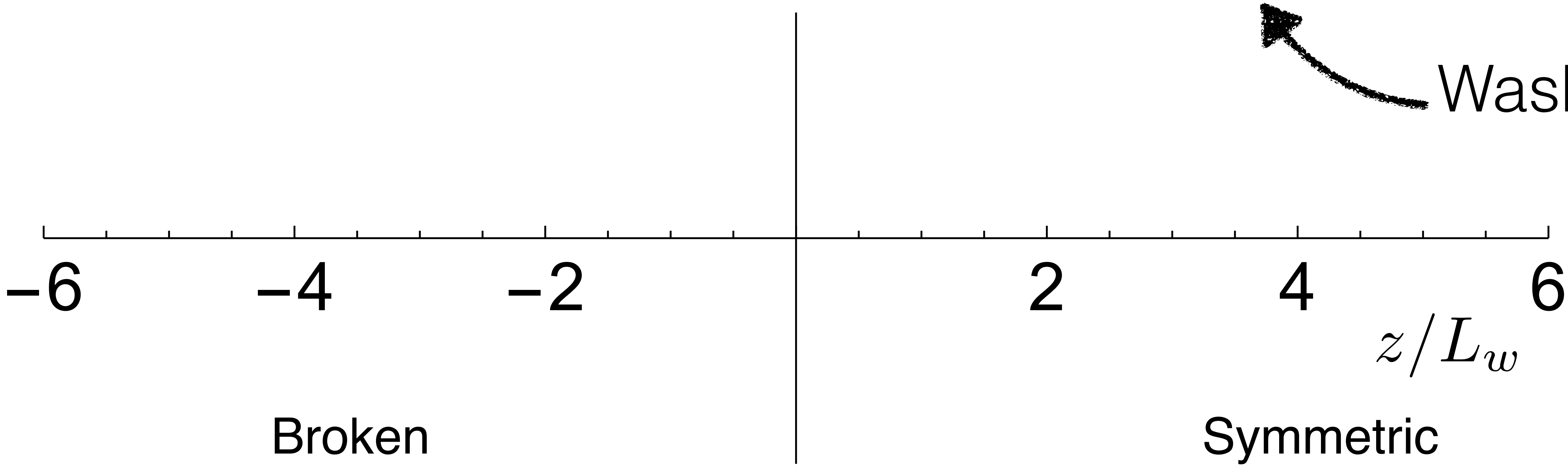
Washout



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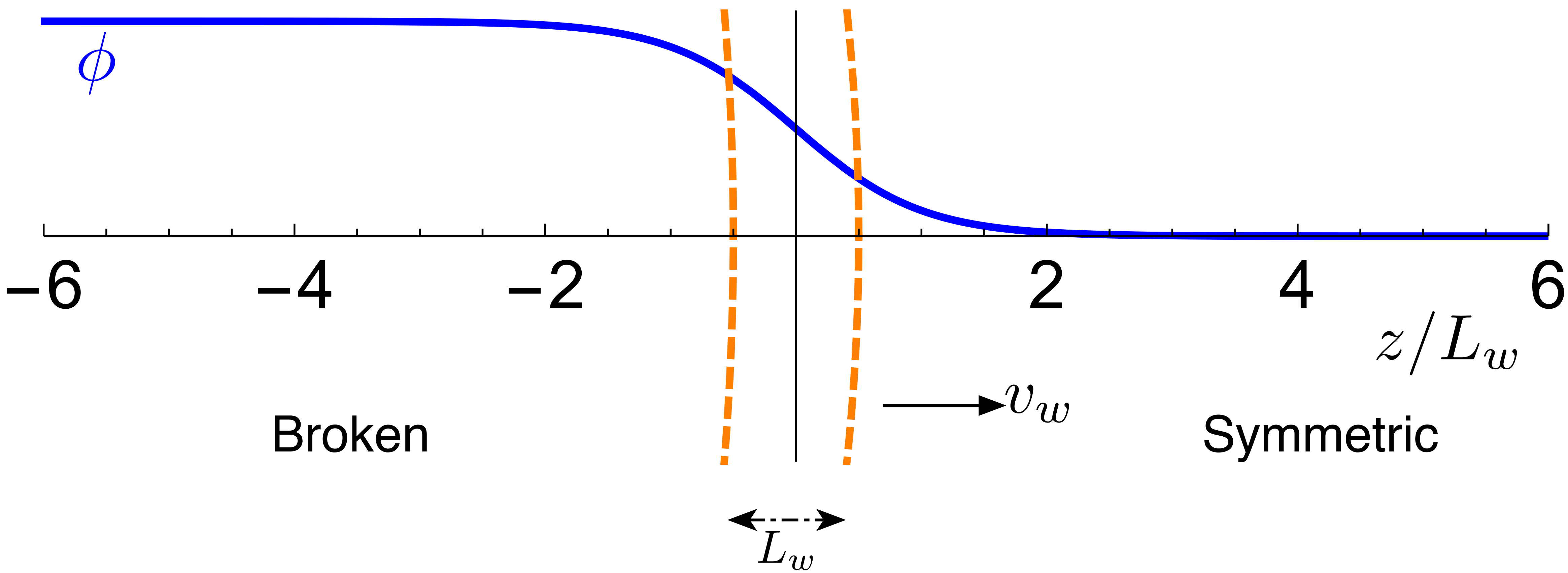

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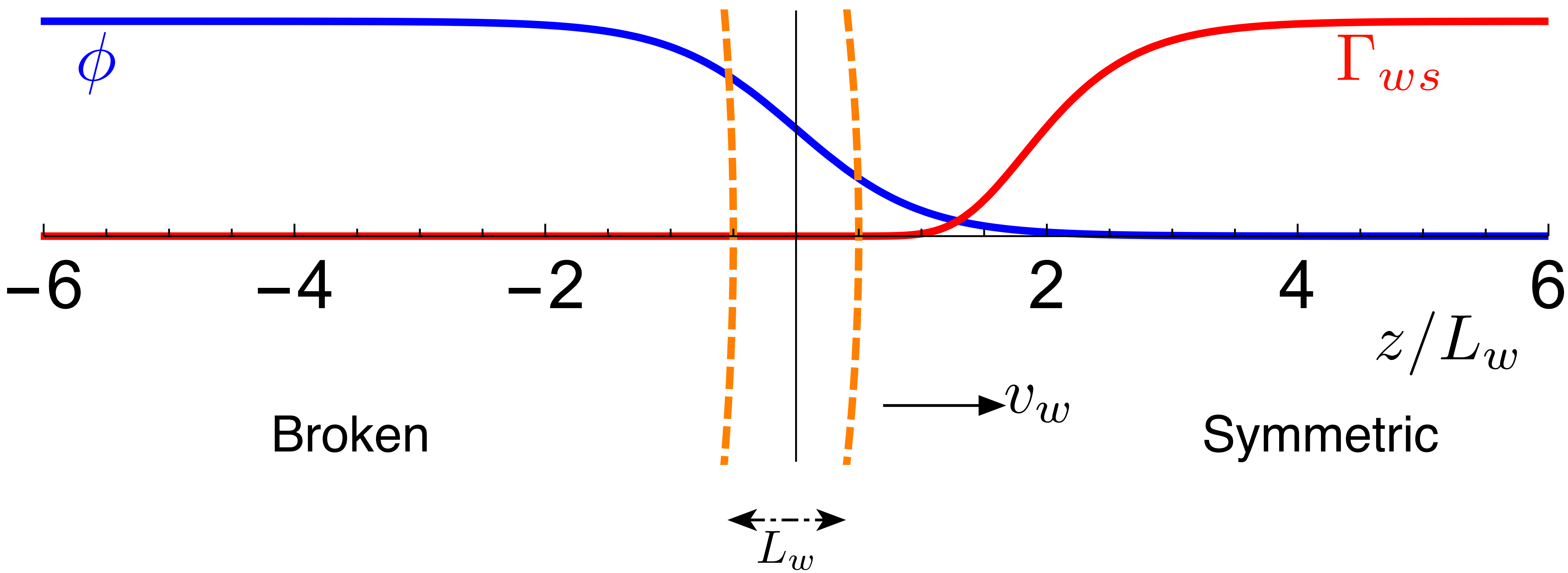

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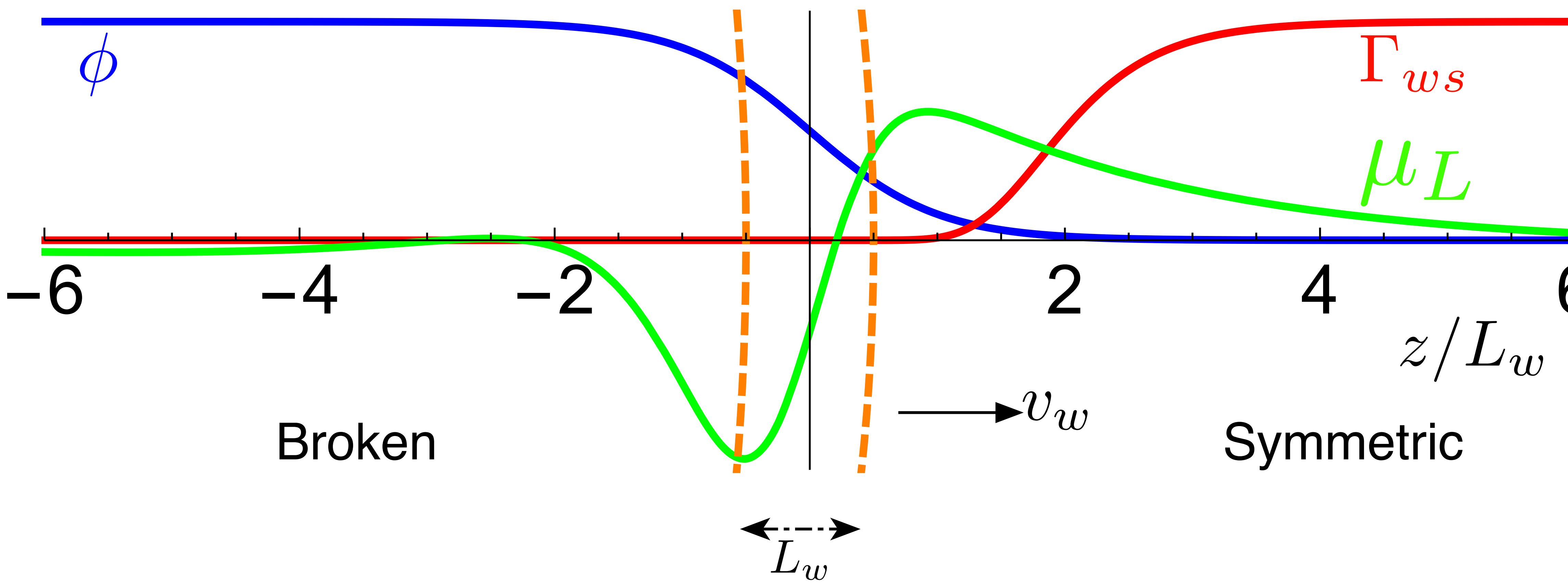

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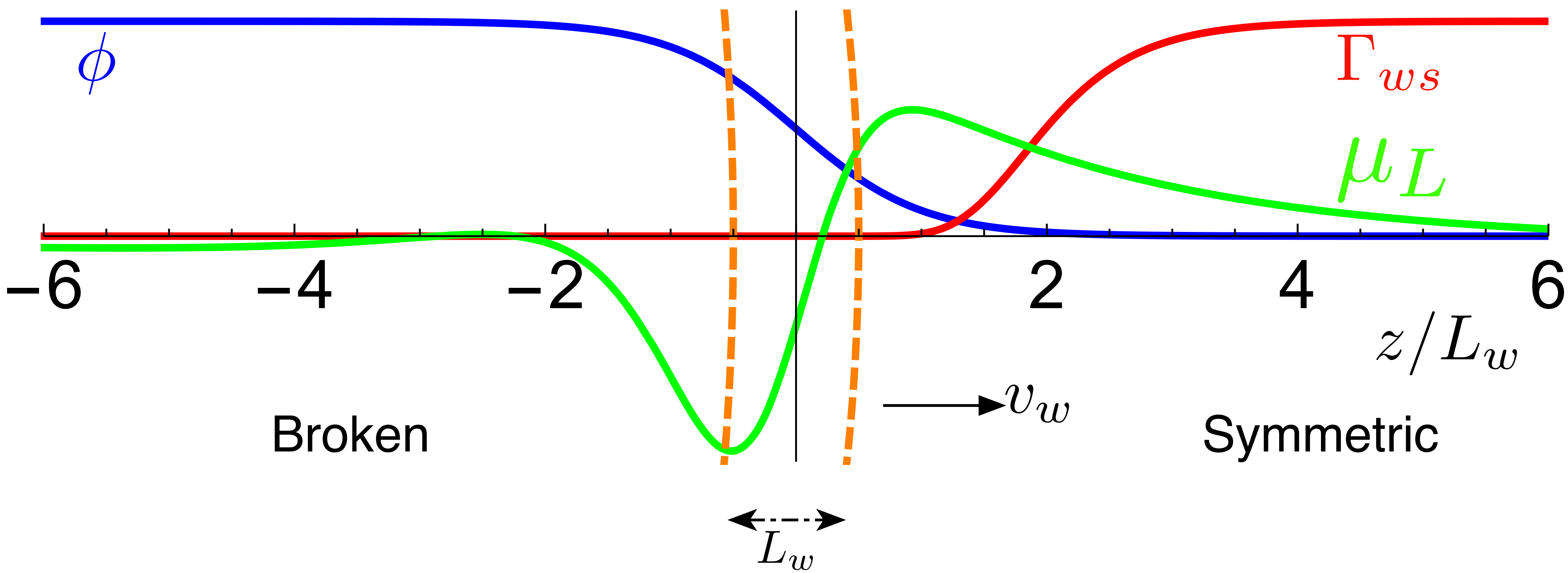

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CP-violation in the SM and beyond

In the SM: $\eta_B \lesssim 10^{-2}\Delta_{CP}$ Farrar, Shaposhnikov '93

$$\Delta_{CP} \sim \left(M_W^6 T_c^6\right)^{-1} \prod_{\substack{i>j \\ u,c,t}} \left(m_i^2 - m_j^2\right) \prod_{\substack{i>j \\ d,s,b}} \left(m_i^2 - m_j^2\right) J_{CP}$$

Gavela, *et al.* '93
Huet, Sather '94

Jarlskog constant

Based solely on
reflection coefficients

CP-violation in the SM and beyond

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F... ...poshnikov '93

$$\Delta_{CP} \sim \left(M_W^6 T_c^6\right)^{-1} \prod_{\substack{i>j \\ u,c,t}} \left(m_i^2 - m_j^2\right) \prod$$

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Much too small!

(measured: η_B~8.9 10^{-11})

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Based solely on reflection coefficients

Models with diffusion

2 Higgs doublet Cohen, Kaplan, Nelson ‘94

MSSM Cline, Joyce, Kainulainen ‘97

Calculate CP-violating source, inject to Boltzmann equation

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Jarlskog constan…

Based solely on reflection coefficients

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MSSM Cline, Joyce, Kainulainen ‘97

Calculate CP-violating source, inject to Boltzmann equation

CP-violation and diffusion equation from first principles (Kadanoff-Baym)

Prokopec, Schmidt, Weinstock ’03

Source for μ in SM

$$S \sim \mathrm{Im}\left[V_{CKM}^{\dagger} m^{\dagger}{}'' m V_{CKM}\right]$$

$$m = y(z) \cdot \frac{\phi(z)}{\sqrt{2}}$$

Source for μ in SM

$$S \sim \mathrm{Im}\left[V_{CKM}^{\dagger} {m^{\dagger}}'' m V_{CKM}\right]$$

For constant y:

$$m = y(z) \cdot \frac{\phi(z)}{\sqrt{2}}$$

$$S \sim \underbrace{\mathrm{Im}\left[V_{CKM}^{\dagger} y^{\dagger} y V_{CKM}\right]}_{=0} \phi'' \phi$$

Source for μ in SM

$$S \sim \mathrm{I}m\left[V_{CKM}^{\dagger} m^{\dagger\,\prime\prime} m V_{CKM}\right]$$

$$m = y(z) \cdot \frac{\phi(z)}{\sqrt{2}}$$

For constant y:

$$S \sim \underbrace{\mathrm{I}m\left[V_{CKM}^{\dagger} y^{\dagger} y V_{CKM}\right]}_{=0} \phi^{\prime\prime}\phi$$

EW scale flavour physics

$\Rightarrow$ z dependent Yukawas $\left\{ \begin{array}{l} \text{Froggatt-Nielsen} \\ \text{Randall-Sundrum} \\ \dots \end{array} \right.$

Network equations

Fluide type Ansatz:

$$f_i = \frac{1}{e^{\beta(\omega_i + v_w k_z - \mu_i)} \pm 1} + \delta f_i \qquad u \equiv \left\langle \frac{k_z}{\omega_0} \delta f \right\rangle$$

CP-odd Energy-Momentum average, linear in: μ_i, u_i and v_w :

$$v_w\, K_1\, \mu' + v_w (m^2)'\, K_2\, \mu + u' - \langle \mathbf{C} \rangle = 0$$

$$-K_4\, \mu' + v_w\, \tilde{K}_5\, u' + v_w (m^2)'\, \tilde{K}_6\, u - \left\langle \frac{k_z}{\omega_{0i}} \mathbf{C} \right\rangle = \pm v_w K_8\, \mathrm{Im}\left[V^\dagger m^{\dagger\prime\prime} m V \right]$$

Interactions

Source

System and Kernel

$$A(z)\, v'(z) + B(z)\, v(z) = S(z)$$

Unknowns

$$(\mu_{t_{R/L}}, \mu_{b_{R/L}}, \mu_{s_{R/L}}, \mu_{c_{R/L}}, \mu_h$$
$$u_{t_{R/L}}, u_{b_{R/L}}, u_{s_{R/L}}, u_{c_{R/L}}, u_h)$$

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$$\mu(z) = \int_{-\infty}^{+\infty} \mathrm{d}z_0\, G(z, z_0)\, S(z_0)$$

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$$\eta_B = \int_{-\infty}^{+\infty} \mathrm{d}z\, \#\Gamma_{ws}(z)\, e^{-\#z}\, \mu_L(z)$$

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$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0\, K_i(z_0)\, S_i(z_0)$$

Kernel

- Weak Sphaleron
- Interactions (GF)
- Numerical factors

Source

- CP-violation

Varying Yukawas across the wall

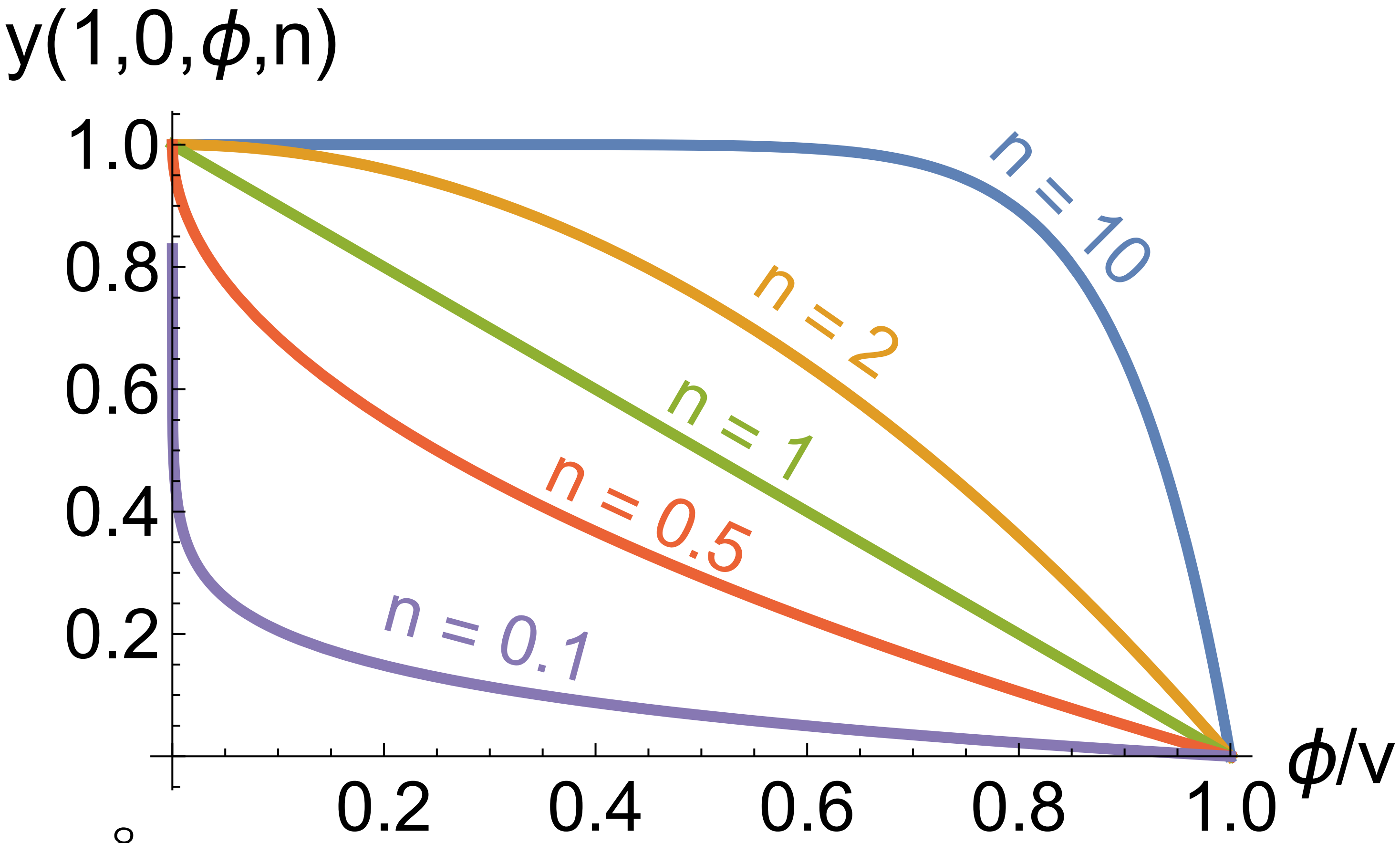
Effective description following from Flavon-Higgs coupling

Broken phase Free parameter Higgs vev in broken phase

$$y(y_0, y_1, \phi, n) = (y_0 - y_1)\left[1 - \left(\frac{\phi}{v}\right)^n\right] + y_1$$

Symmetric phase

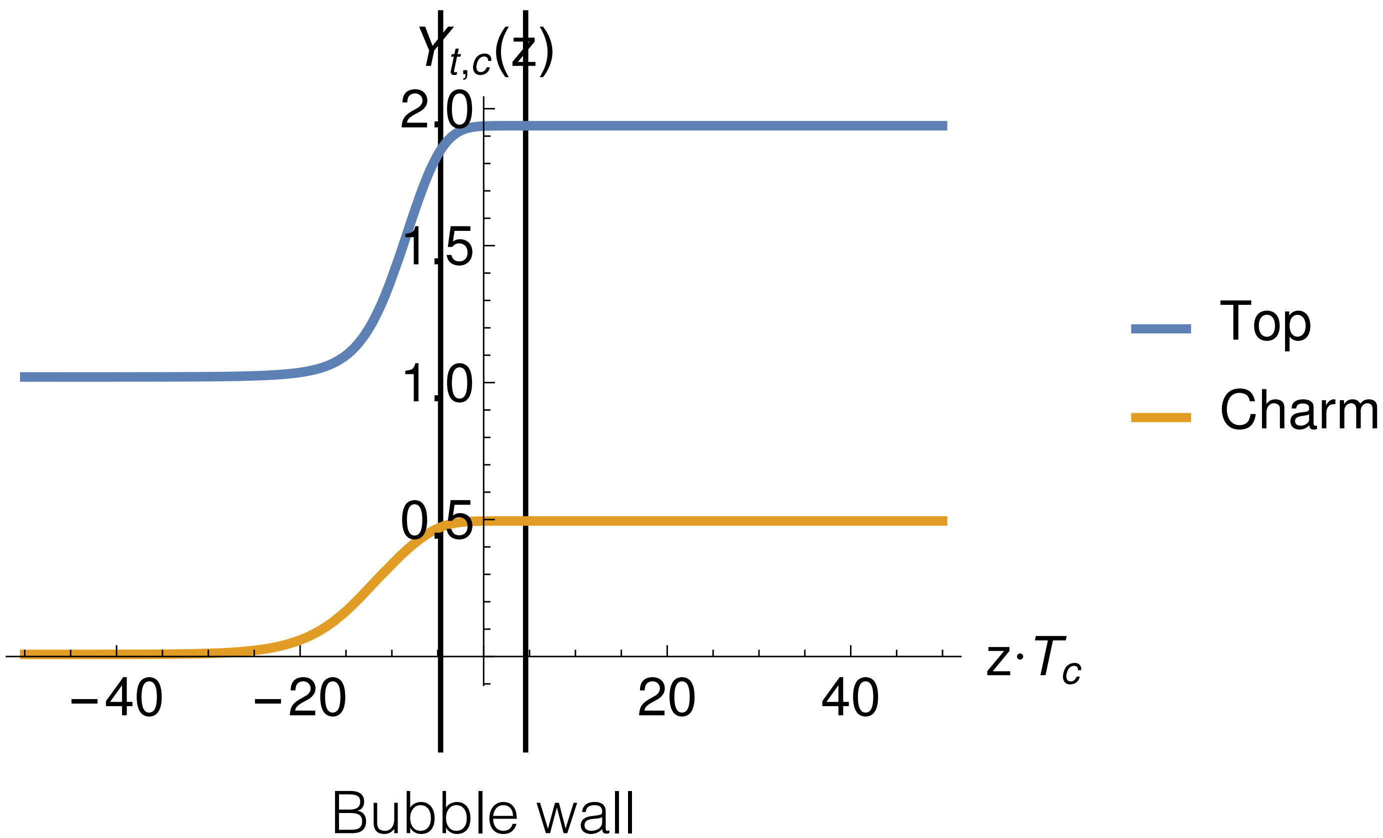
Higgs vev



Baldes, Konstandin, Servant '16
1608.03254 & 1604.04526

Yukawas

$$Y_{tc}(z,n) = \begin{pmatrix} e^i y(1, 0.008, \phi(z), n) & y(1, 0.04, \phi(z), n) \\ y(1, 0.2, \phi(z), n) & y(1, 1, \phi(z), n) \end{pmatrix}$$



$n = 10$

Broken phase

Symmetric phase

Yukawas

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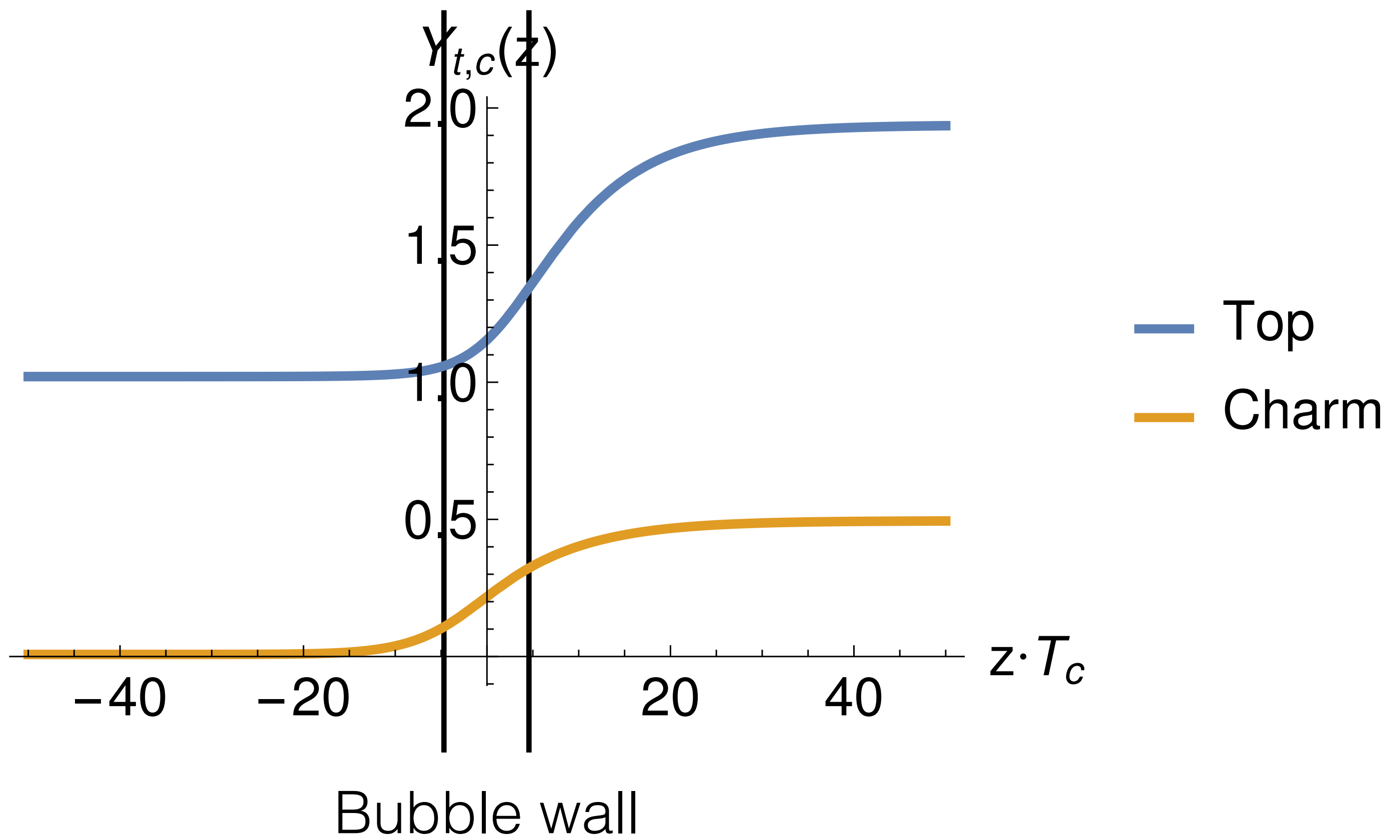
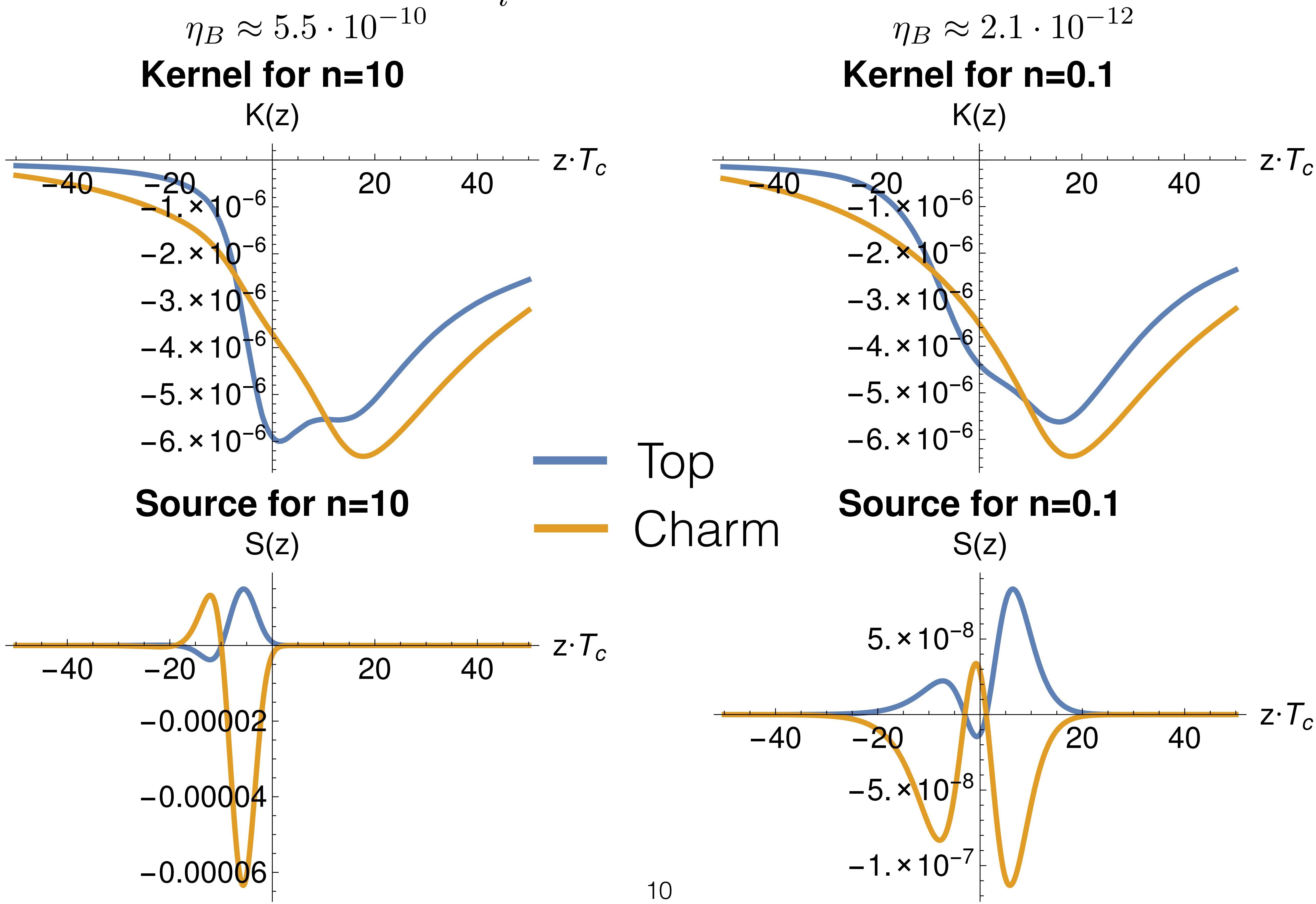


$$n = 0.5$$

Broken phase Symmetric phase

$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0\, K_i(z_0)\, S_i(z_0)$$

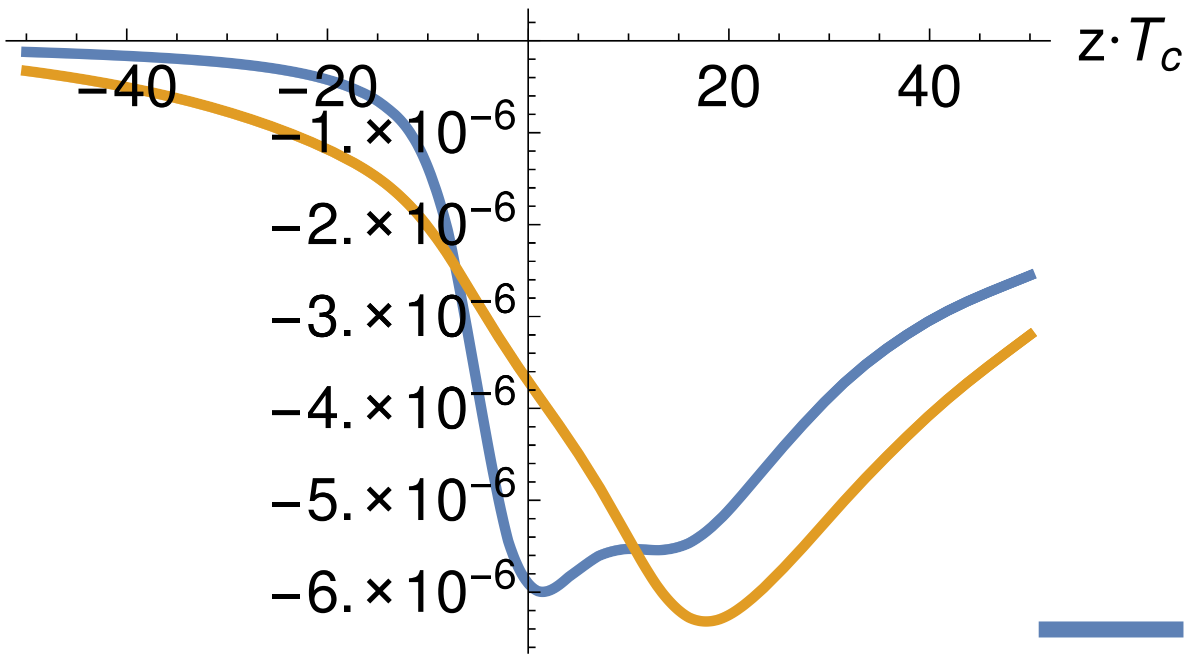


$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0 \, K_i(z_0) \, S_i(z_0)$$

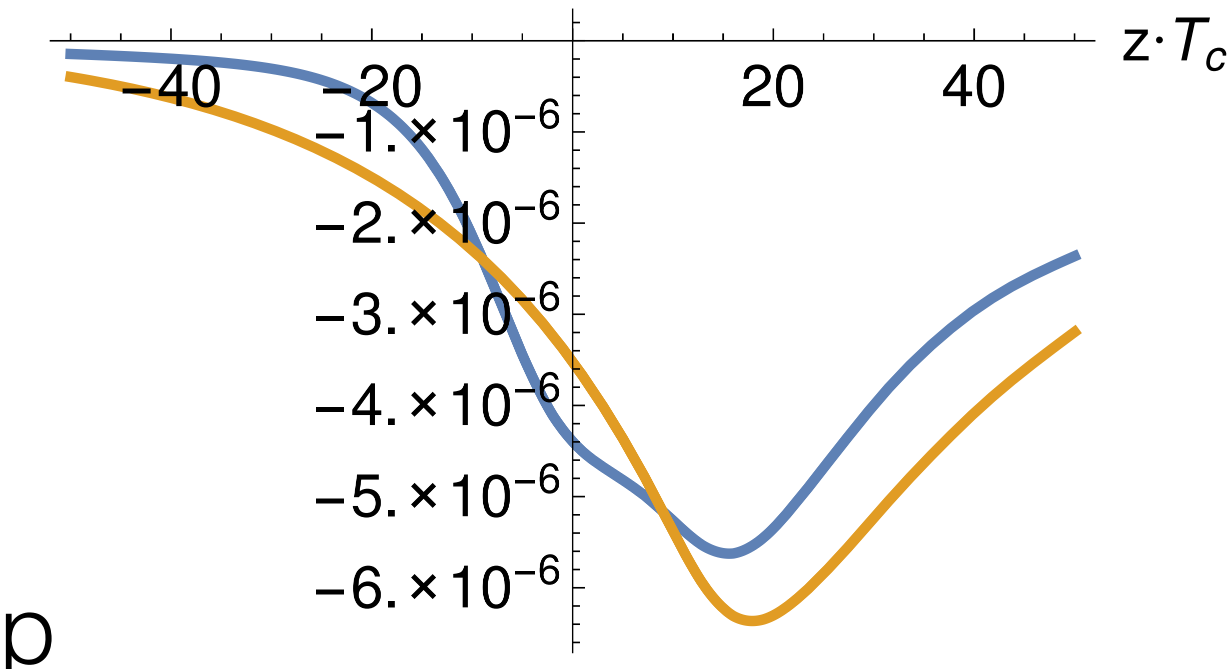
$\eta_B \approx 5.5 \cdot 10^{-10}$

$\eta_B \approx 2.1 \cdot 10^{-12}$

Kernel for n=10



Kernel for n=0.1



Source for n=10

Source for n=0.1

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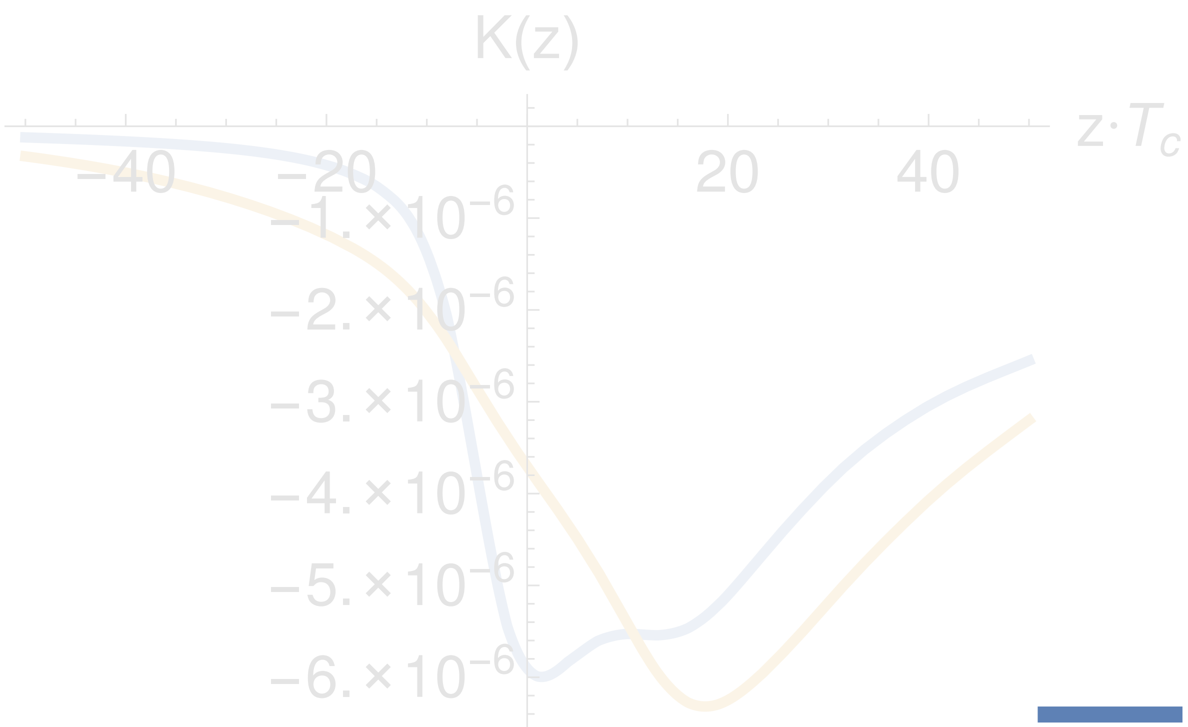
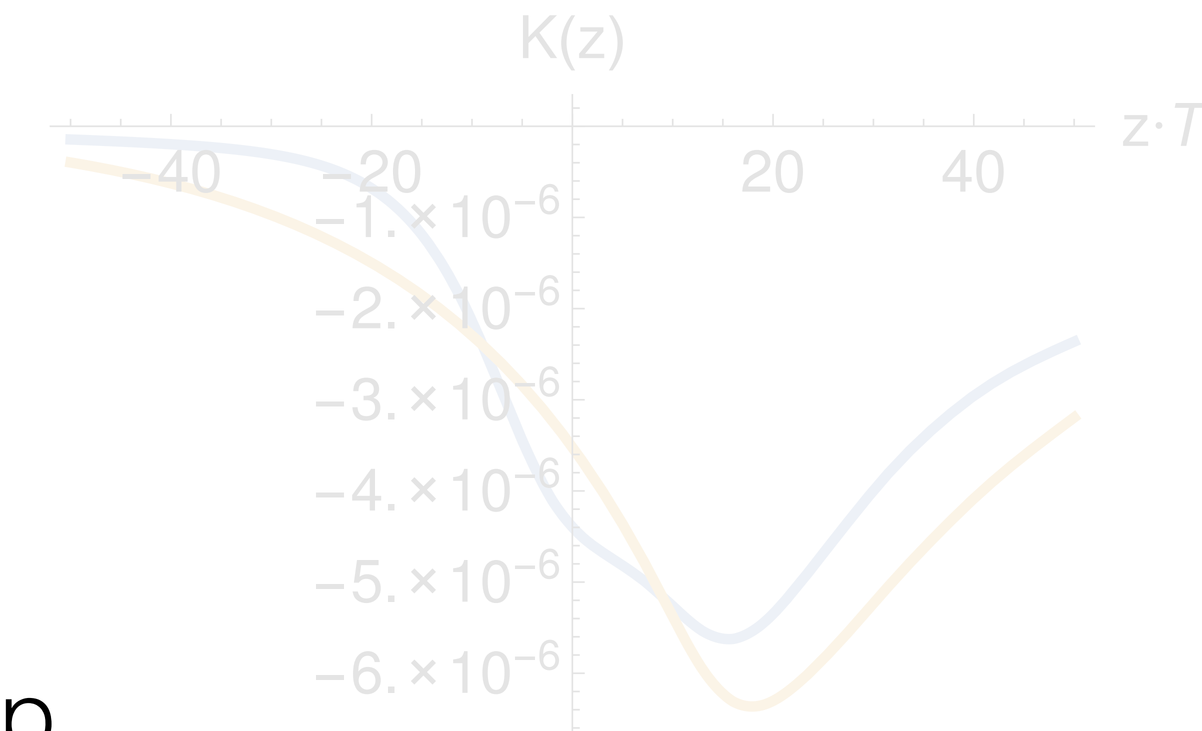
$\eta_B \approx 5.5 \cdot 10^{-10}$

Kernel for n=10

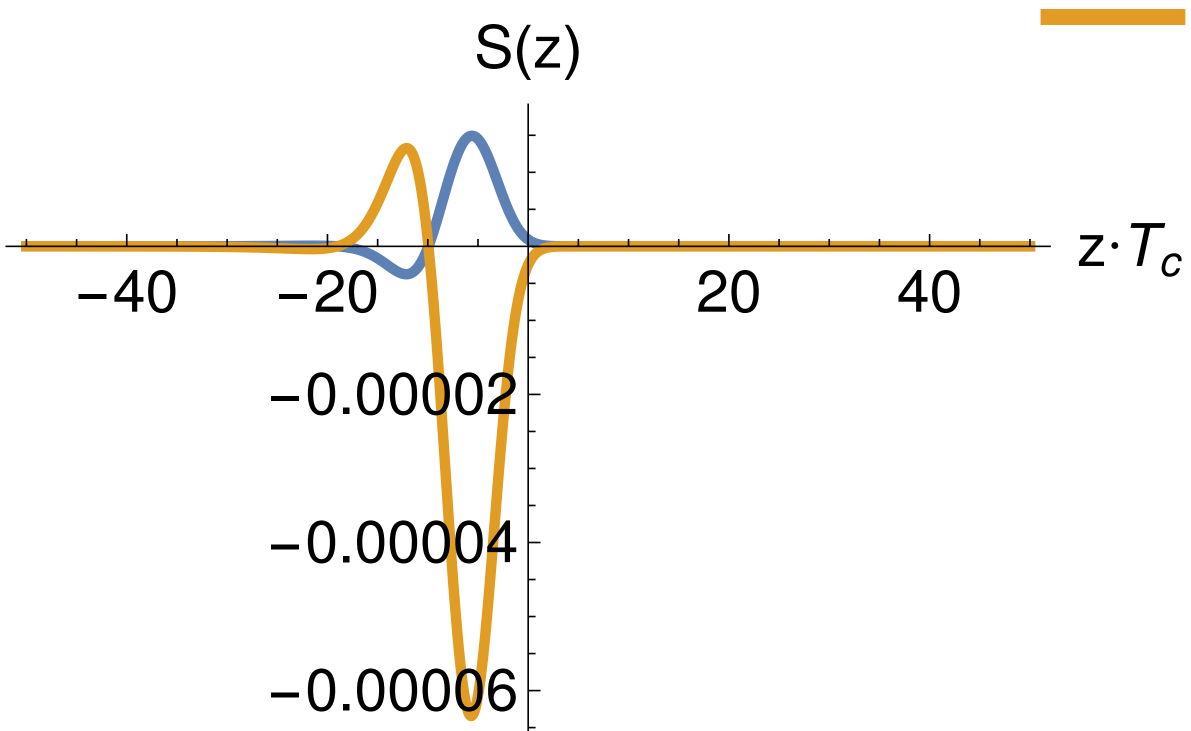


$\eta_B \approx 2.1 \cdot 10^{-12}$

Kernel for n=0.1



Source for n=10



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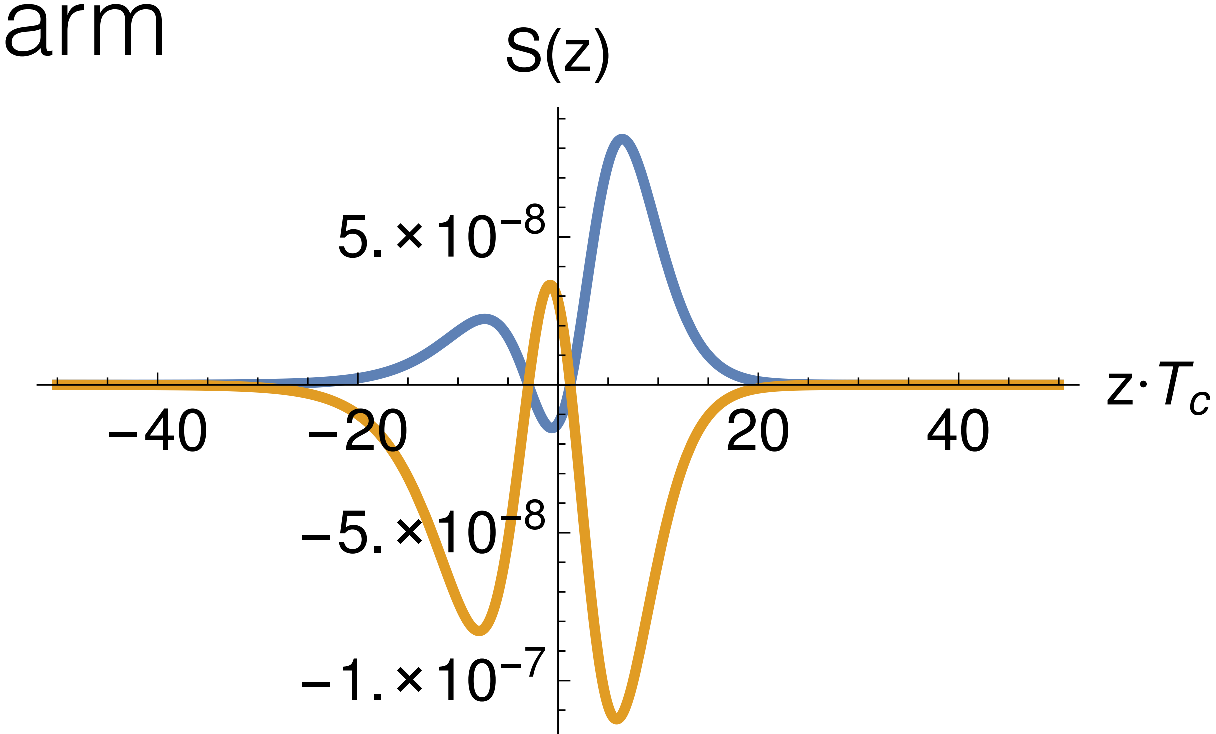

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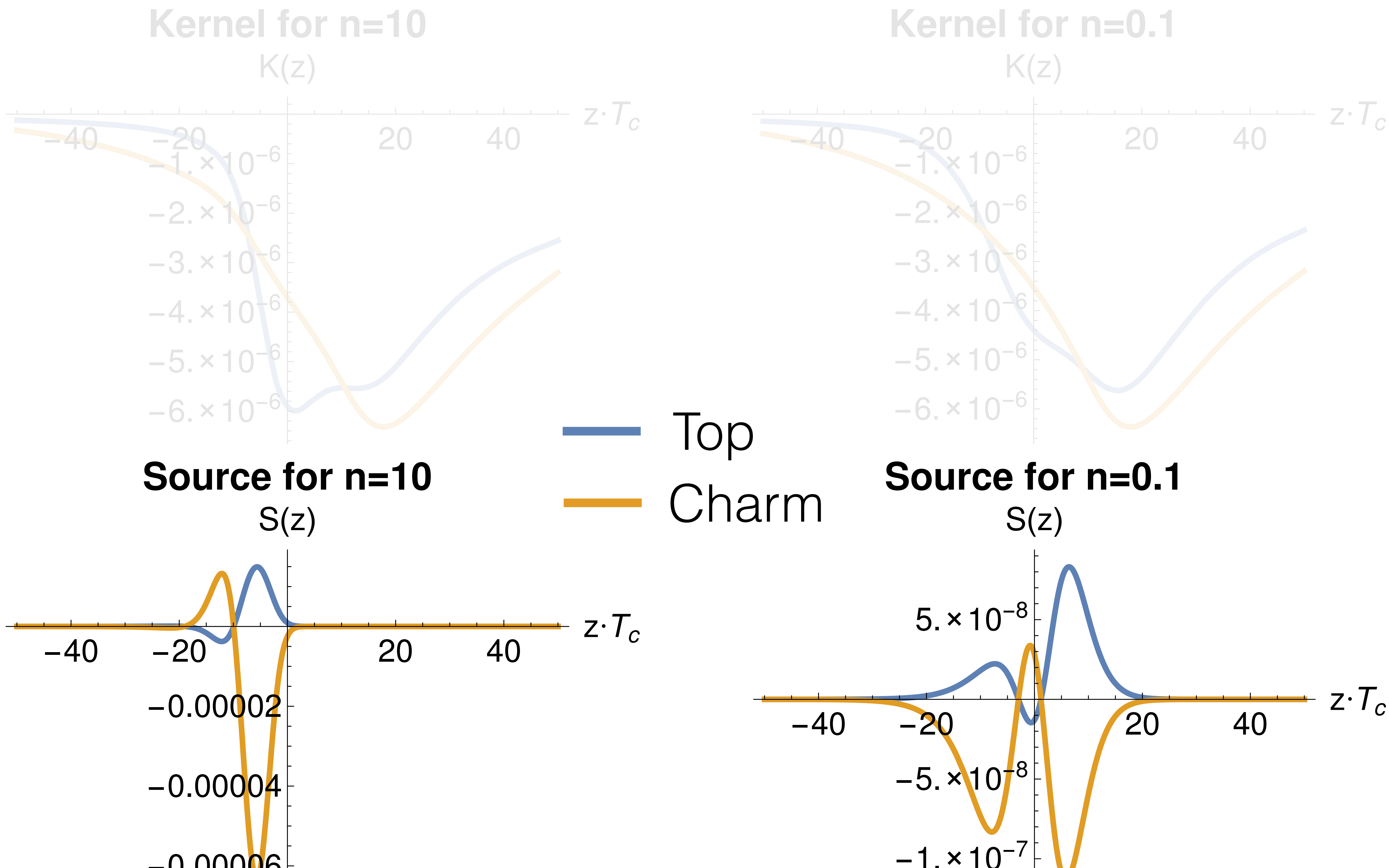

Summary

- Framework for CP-violation and diffusion for z-dependent Yukawas.
- Fully consistent and general formalism (diffusion and CP-violation from first principle).
- Application possible to low-scale flavour physics (Froggatt-Nielsen, Randall-Sundrum, etc.)

Baldes, Konstandin, Servant '16
1604.04526 & 1608.03254

Von Harling, Servant '16
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1612.02447

See talk by B. von Harling after the break in the theory session

Special case: 1 flavour

$$m = |m|e^{i\theta}$$

$$S \propto \mathrm{Im}\left[V^\dagger {m^\dagger}'' m V\right] = \left(|m|^2\theta'\right)'$$

Agrees with semi-classical treatment

θ has to be space dependent!

This is not the case for two mixing flavours.

Froggat-Nielsen

$U(1)_{FN}$ with two FN fields χ, σ

Charge assignment

$$Q_{FN}(\sigma) = Q_{FN}(\chi) = -1$$

$$\begin{array}{lll} \bar{Q}_3\ (0) & \bar{Q}_2\ (+2) & \bar{Q}_1\ (+3) \\ U_3\ (0) & U_2\ (+1) & U_1\ (+4) \\ D_3\ (+2) & D_2\ (+2) & D_1\ (+3) \end{array}$$

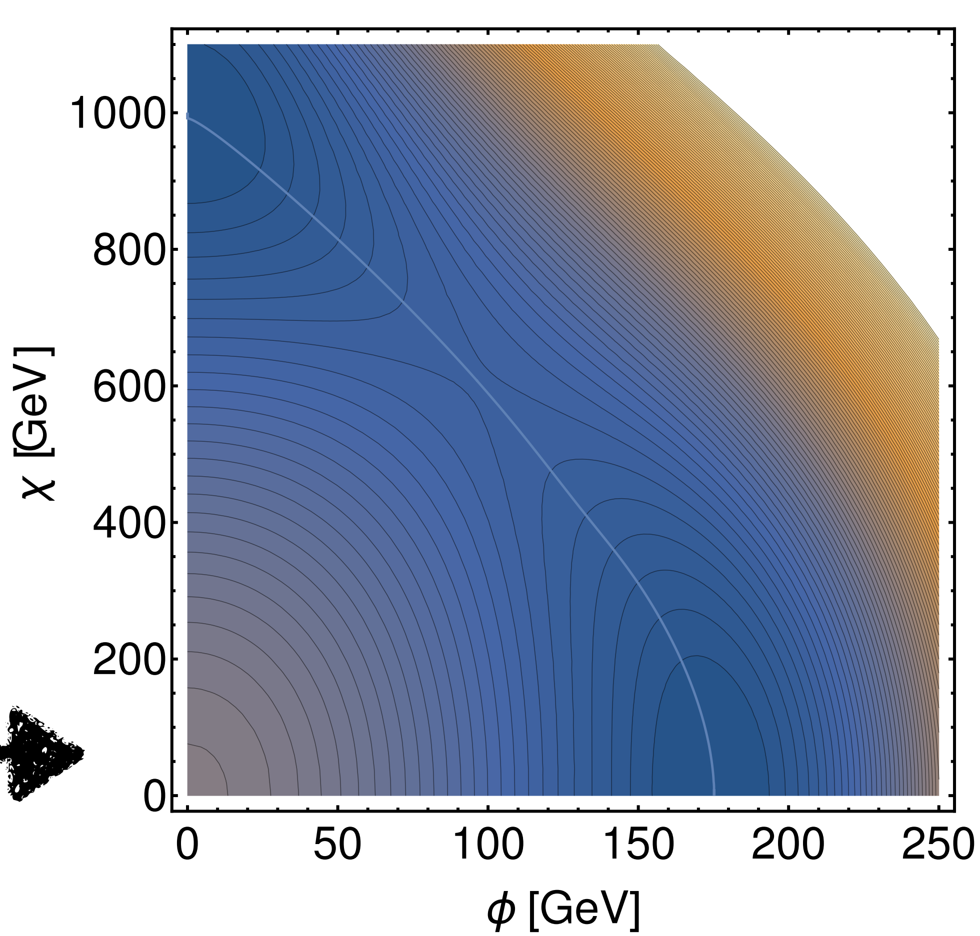
Yukawa type interactions after SSB

$$\mathcal{L} \supset \tilde{y}_{ij} \left(\frac{\langle\chi\rangle}{\Lambda_\chi}\right)^{\tilde{n}_{ij}} \bar{Q}_i \tilde{\phi} U_j + y_{ij} \left(\frac{\langle\chi\rangle}{\Lambda_\chi}\right)^{n_{ij}} \bar{Q}_i \phi D_j$$
$$+\tilde{Y}_{ij} \left(\frac{\langle\sigma\rangle}{\Lambda_\sigma}\right)^{\tilde{n}_{ij}} \bar{Q}_i \tilde{\phi} U_j + Y_{ij} \left(\frac{\langle\sigma\rangle}{\Lambda_\sigma}\right)^{n_{ij}} \bar{Q}_i \phi D_j$$

VEVs during EWSB

$$\phi : 0 \to v_\phi \quad \sigma : \Lambda_\sigma/5 \to \Lambda_\sigma/5 \quad \chi : \Lambda_\chi \to 0$$

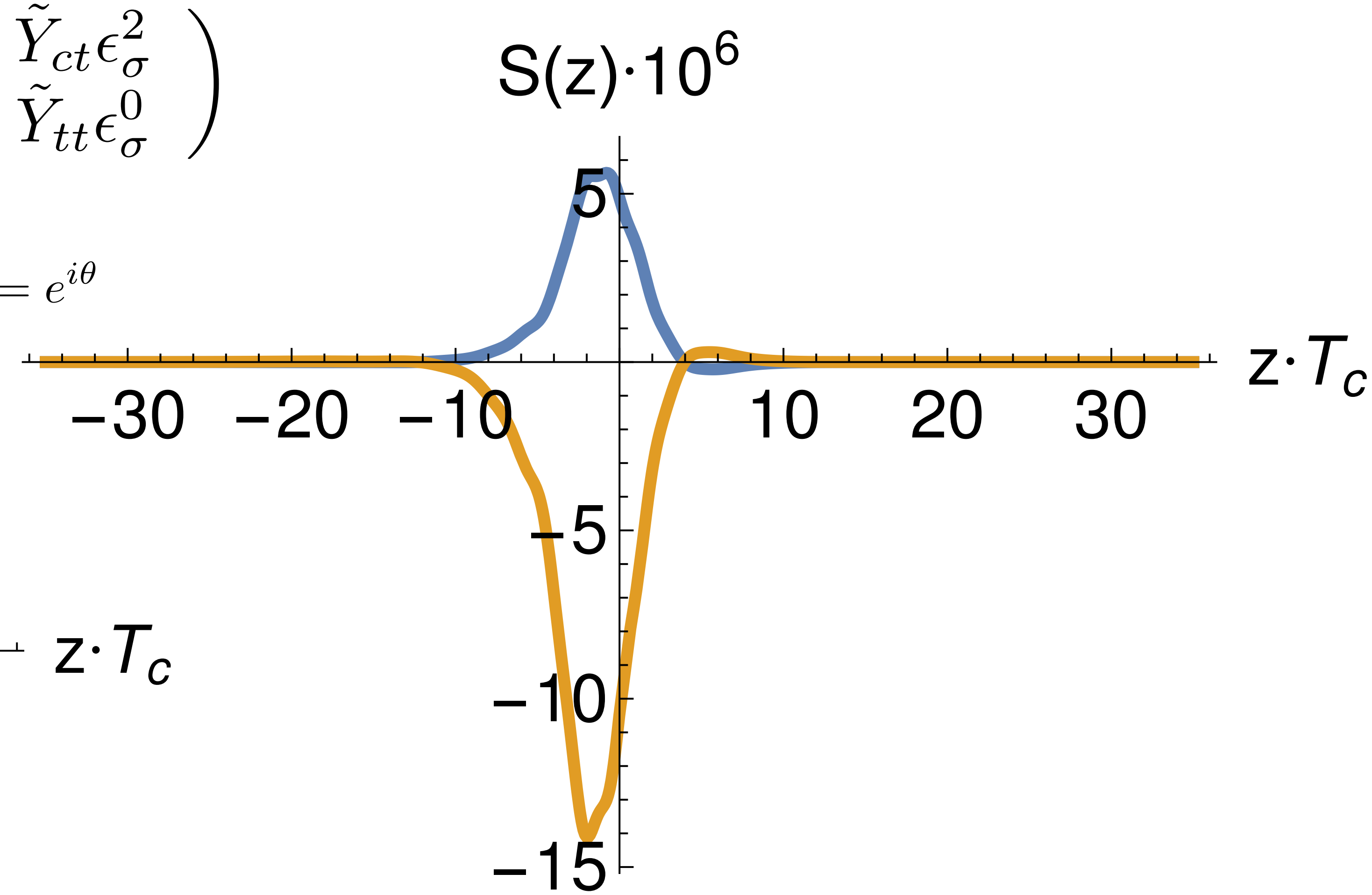
$\chi - \phi$ -Potential

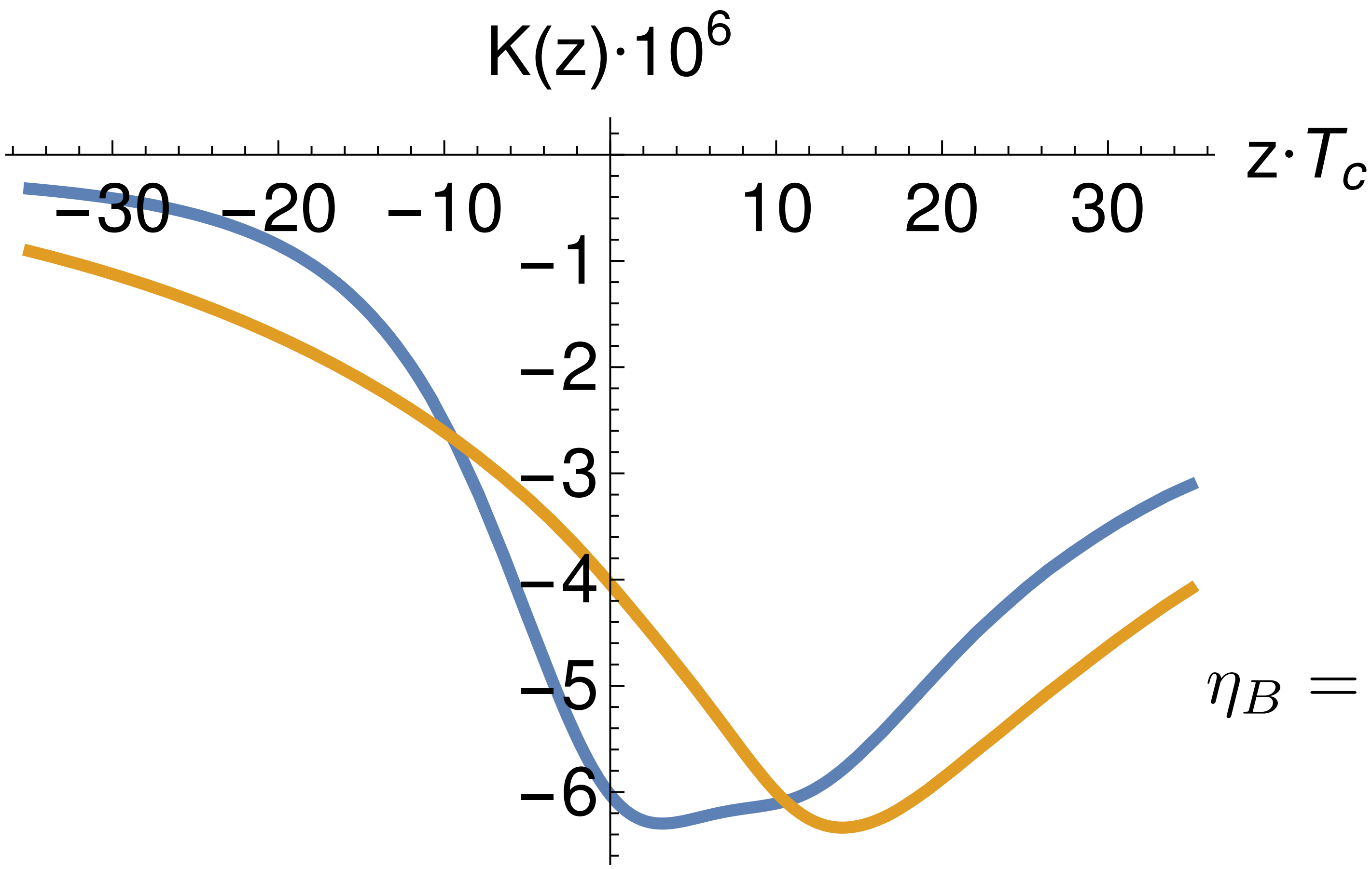


Froggat-Nielsen

$$Y_{t-c} = \begin{pmatrix} \tilde{y}_{cc}\epsilon_\chi^3 & \tilde{y}_{ct}\epsilon_\chi^2 \\ \tilde{y}_{tc}\epsilon_\chi^1 & \tilde{y}_{tt}\epsilon_\chi^0 \end{pmatrix} + \begin{pmatrix} \tilde{Y}_{cc}\epsilon_\sigma^3 & \tilde{Y}_{ct}\epsilon_\sigma^2 \\ \tilde{Y}_{tc}\epsilon_\sigma^1 & \tilde{Y}_{tt}\epsilon_\sigma^0 \end{pmatrix}$$

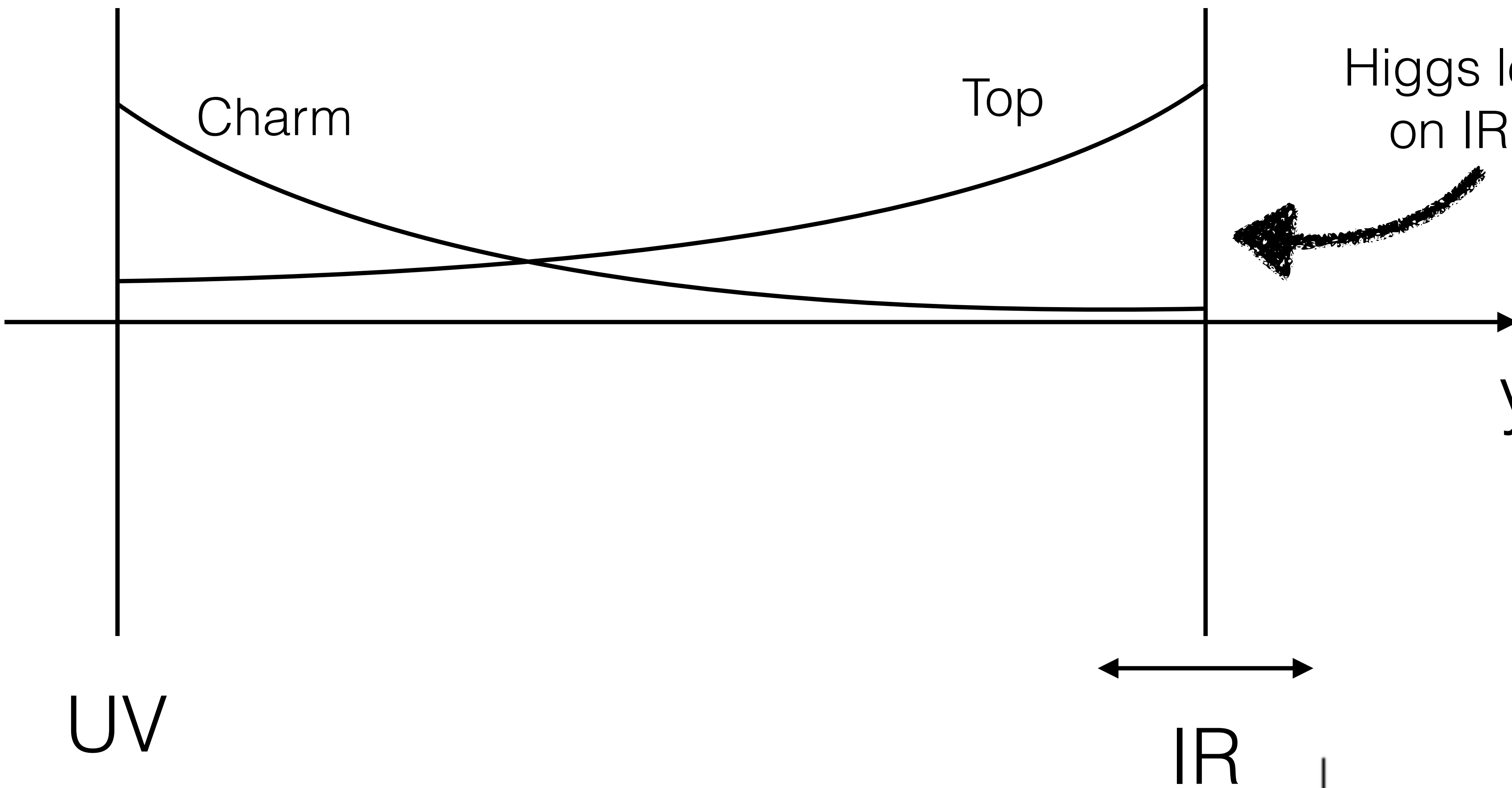
$$\tilde{y}_{i\neq j} = \tilde{Y}_{i\neq j} = 1 \qquad \tilde{y}_{tt} = \tilde{Y}_{tt} = 1/2 \qquad \tilde{y}_{cc} = \tilde{Y}_{cc} = e^{i\theta}$$





$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0\, K_i(z_0)\, S_i(z_0) \simeq 1.15 \cdot 10^{-10}$$

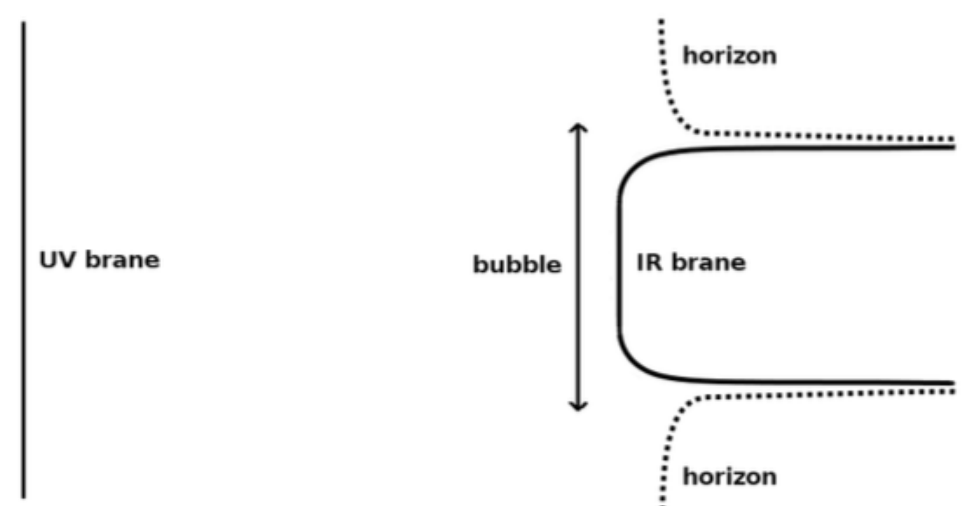
Randall-Sundrum



Higgs localised on IR brane

5^{th} dimension

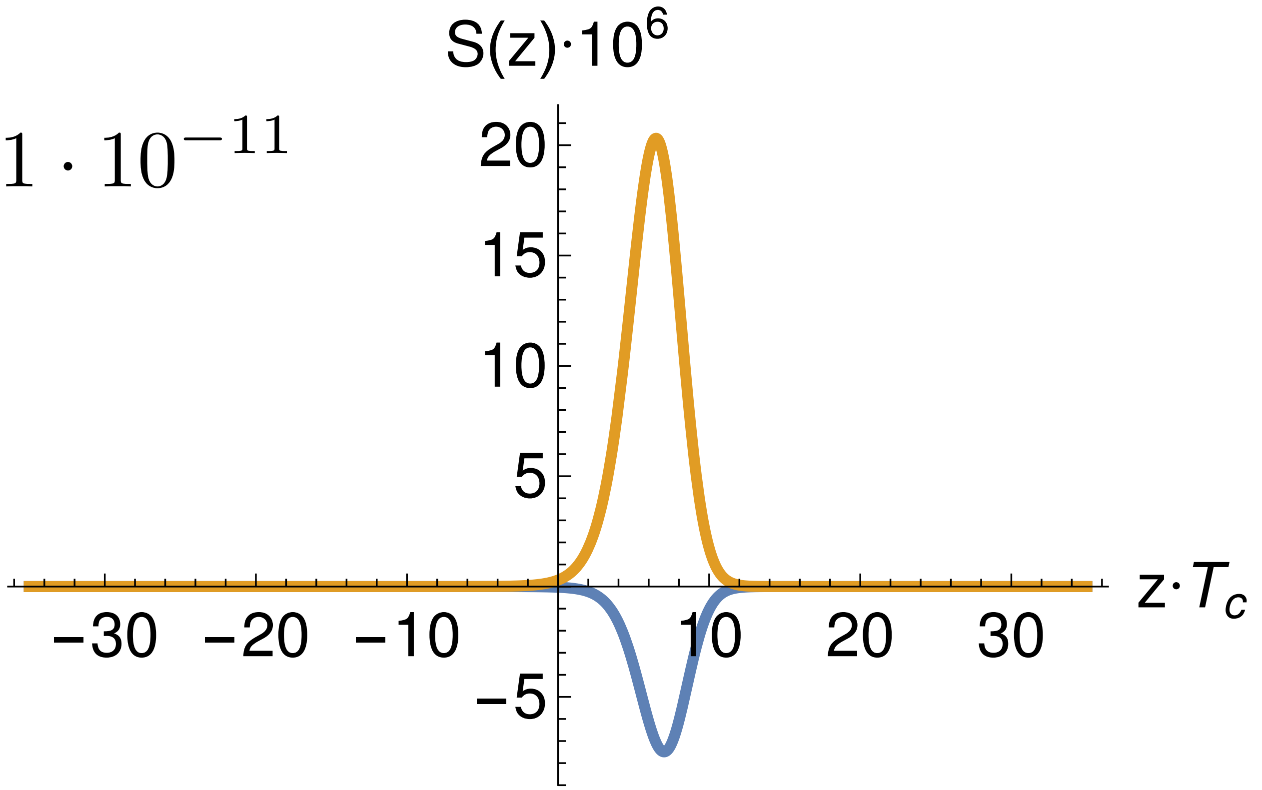
At high temp. -> AdS-Schwarzschild
Low temp. -> RS metric
—> “Brane Nucleation”

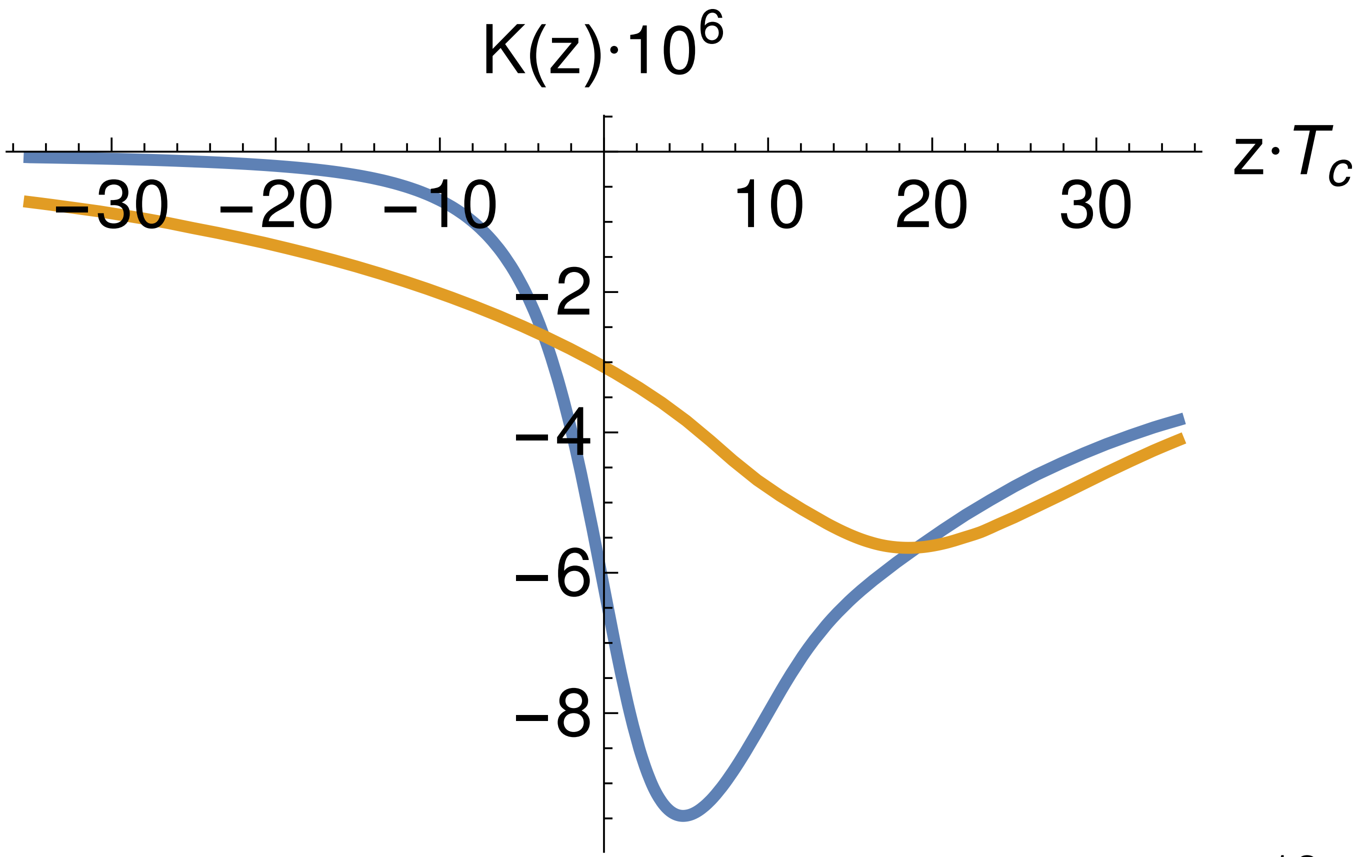


Von Harling, Servant ‘16
1612.02447

Randall-Sundrum

$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0 \, K_i(z_0) \, S_i(z_0) \simeq 9.81 \cdot 10^{-11}$$





Deriving the equations

- Hermitian part of the Kadanoff-Baym equations
- Expand to second order in gradients (smooth background) and at tree level
- Neglect off-diagonals (fast flavour oscillations)
- Fluid type Ansatz for particle densities:

$$f_i = \frac{1}{e^{\beta(\omega_i + v_w k_z - \mu_i)} \pm 1} + \delta f_i$$

- Take different momenta and average over energy and momentum

Kinetic equations

$$\left(k_z\partial_z - \frac{1}{2}\left(\left[V^\dagger \left(m^\dagger m\right)' V\right]\right)_{ii}\partial_{k_z}\right) f_{L,i} \approx \mathbf{C} + \mathcal{S}$$

$$\left(k_z\partial_z - \frac{1}{2}\left(\left[V^\dagger \left(m^\dagger m\right)' V\right]\right)_{ii}\partial_{k_z}\right) f_{R,i} \approx \mathbf{C} - \mathcal{S}$$

Collision term

CP-violating source term:

$$\mathcal{S} \equiv \frac{\mathrm{sign}[k_z]}{2\tilde{k}}\mathrm{Im}\left[V^\dagger m^{\dagger\prime\prime} m V\right]_{ii}\partial_{k_z} f_{L/R,i}$$

(V are the Eigenvectors of $m^\dagger m$)

Source depends on *m*

$\Downarrow$

link to

Yukawa couplings

Collision term

$$\langle \mathbf{C} \rangle = \Gamma^{\mathrm{inel}} \sum_i \mu_i \,, \qquad \left\langle \frac{k_z}{\omega_{0i}} \mathbf{C} \right\rangle = -\Gamma^{\mathrm{tot}} u$$

Collision term

$$\langle \mathbf{C} \rangle = \Gamma^{\rm inel} \sum_i \mu_i \,, \qquad \left\langle \frac{k_z}{\omega_{0i}} \mathbf{C} \right\rangle = -\Gamma^{\rm tot} u$$

- Yukawa interactions e.g. $t_L \leftrightarrow t_R + h$ $\quad \Gamma_{y,q} = 4.2 \times 10^{-3}\, y_q^2\, T$

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$$\Gamma_{m,q} = \frac{m_q^2}{63T}$$

- Helicity flip $\quad \text{e.g. } t_L \leftrightarrow t_R$

Collision term

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- Yukawa interactions   e.g. $t_L \leftrightarrow t_R + h$ $\Gamma_{y,q} = 4.2 \times 10^{-3} \, y_q^2 \, T$
- Helicity flip   e.g. $t_L \leftrightarrow t_R$ $\Gamma_{m,q} = \frac{m_q^2}{63T}$
- W-scattering   e.g. $t_L \leftrightarrow b_L$ $\Gamma_W = \frac{T}{60}$

Collision term

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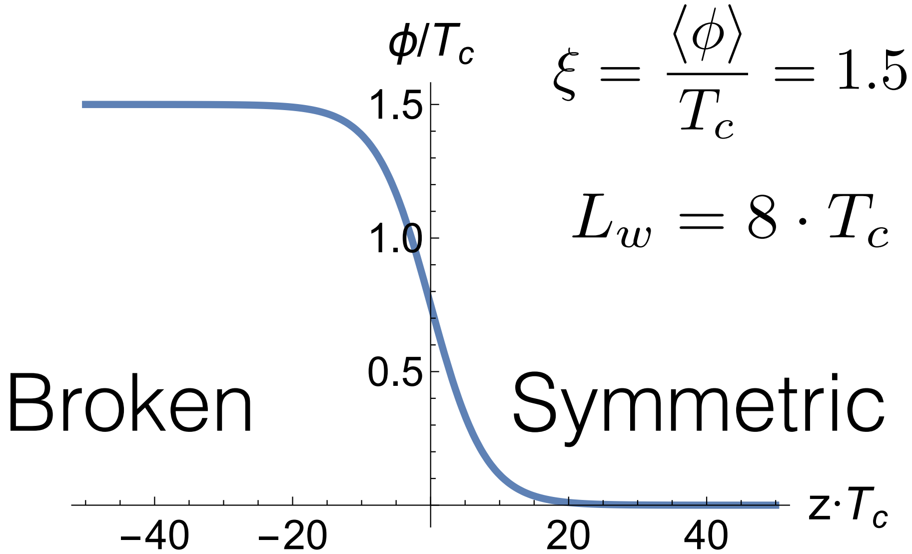
- Higgs number violation $h \leftrightarrow 0$ $\quad \Gamma_h = \frac{m_W^2}{50T}$
- Strong sphaleron $\text{all L} \leftrightarrow \text{all R}$ $\quad \Gamma_{ss} = 4.9 \times 10^{-4} T$

$$\phi(z) = \frac{1}{2}\left(1 - \mathrm{Tanh}\frac{z}{L_w}\right)$$



$$\xi = \frac{\langle\phi\rangle}{T_c} = 1.5$$

$$L_w = 8 \cdot T_c$$

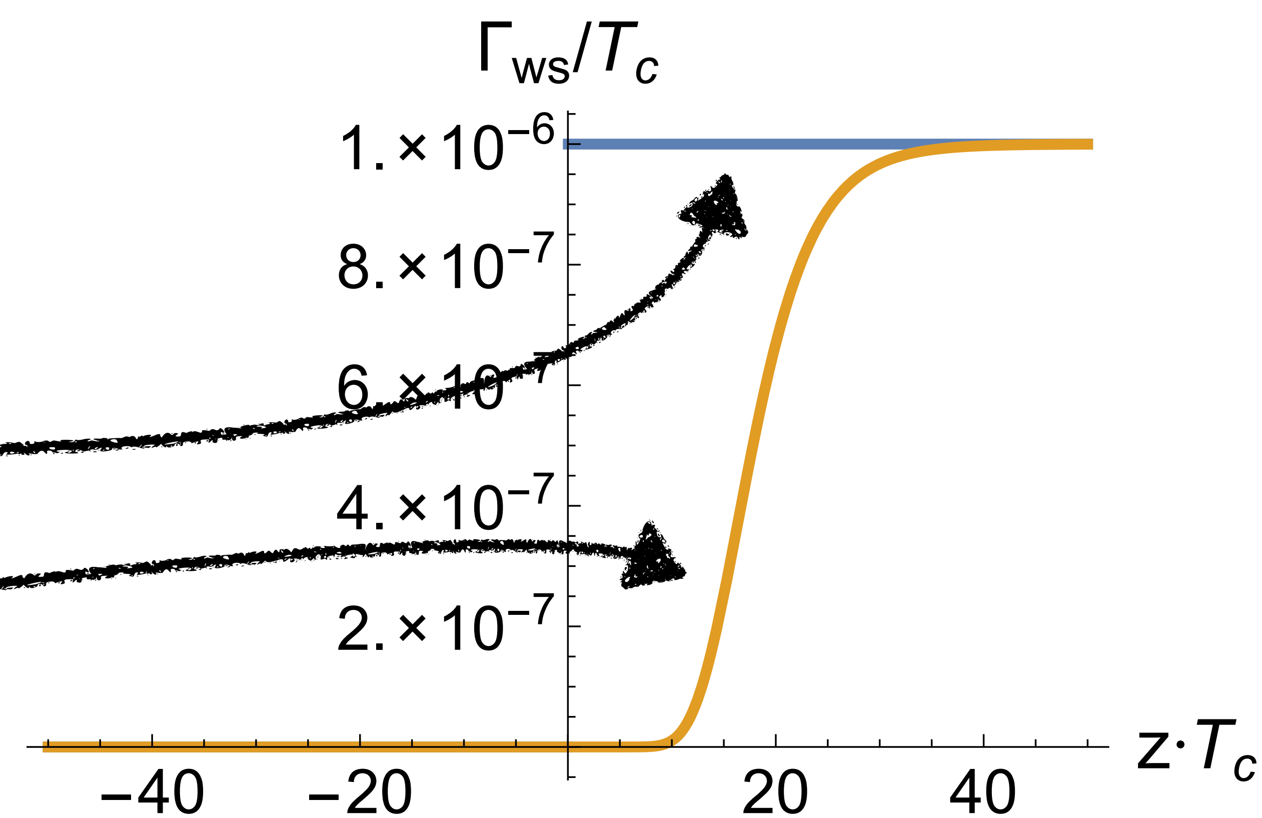
$$\Gamma_{ws} = 10^{-6}\, T\, \exp(-a\phi(z)/T)$$

$$a \approx 40$$

NEW

Rate
in Literatur

Our rate



$$v_w\, K_1\, \mu' + v_w (m^2)'\, K_2\, \mu + u' - \Gamma^{\rm inel} \sum_i \mu_i = 0$$

$$-K_4\, \mu' + v_w\, \tilde{K}_5\, u' + v_w (m^2)'\, \tilde{K}_6\, u + \Gamma^{\rm tot} u = \pm v_w K_8\, \mathrm{Im}\left[V^\dagger {m^\dagger}'' m V\right]$$

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Source

$$m = y(z) \cdot \frac{\phi(z)}{\sqrt{2}}$$

$$v_w\, K_1\, \mu' + v_w (m^2)'\, K_2\, \mu + u' - \Gamma^{\text{inel}} \sum_i \mu_i = 0$$

$$-K_4\, \mu' + v_w\, \tilde{K}_5\, u' + v_w (m^2)'\, \tilde{K}_6\, u + \Gamma^{\text{tot}} u = \pm v_w K_8\, \mathrm{Im}\left[V^\dagger m^{\dagger\prime\prime} m V\right]$$

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Source

$$m = y(z) \cdot \frac{\phi(z)}{\sqrt{2}}$$

e.g. Fromme, Huber '06
hep-ph/0604159

Interactions:
Couple different particle species together

- Yukawa interactions e.g. $t_L \leftrightarrow t_R + h$ $\qquad \Gamma_{y,q} = 4.2 \times 10^{-3}\, y_q^2\, T$
- Helicity flip e.g. $t_L \leftrightarrow t_R$ $\qquad \Gamma_{m,q} = \frac{m_q^2}{63T}$
- W-scattering e.g. $t_L \leftrightarrow b_L$ $\qquad \Gamma_W = \frac{T}{60}$
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