

# EW Baryogenesis from dynamical Yukawa couplings

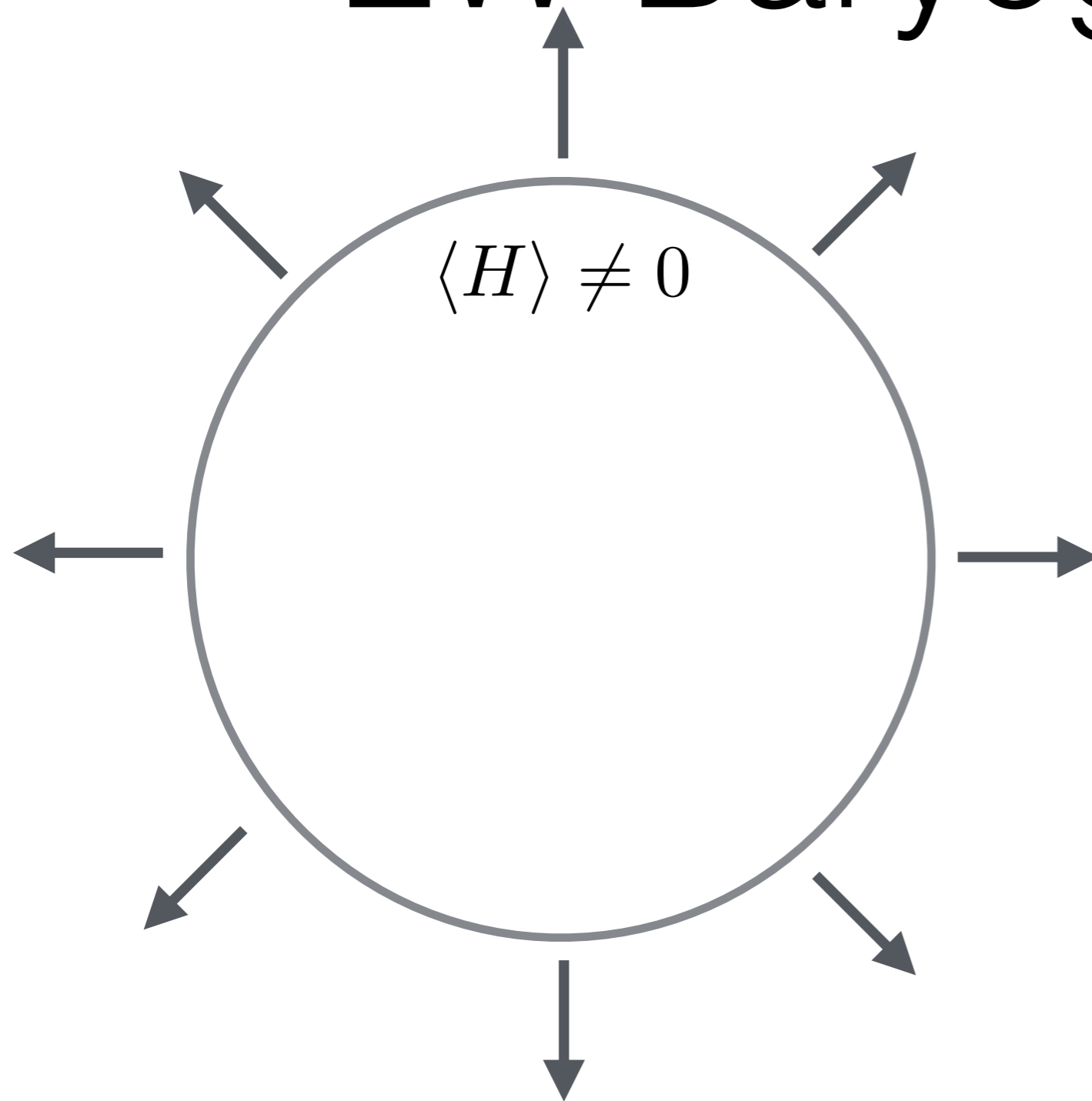
Sebastian Bruggisser

In collaboration with:  
T. Konstandin & G. Servant



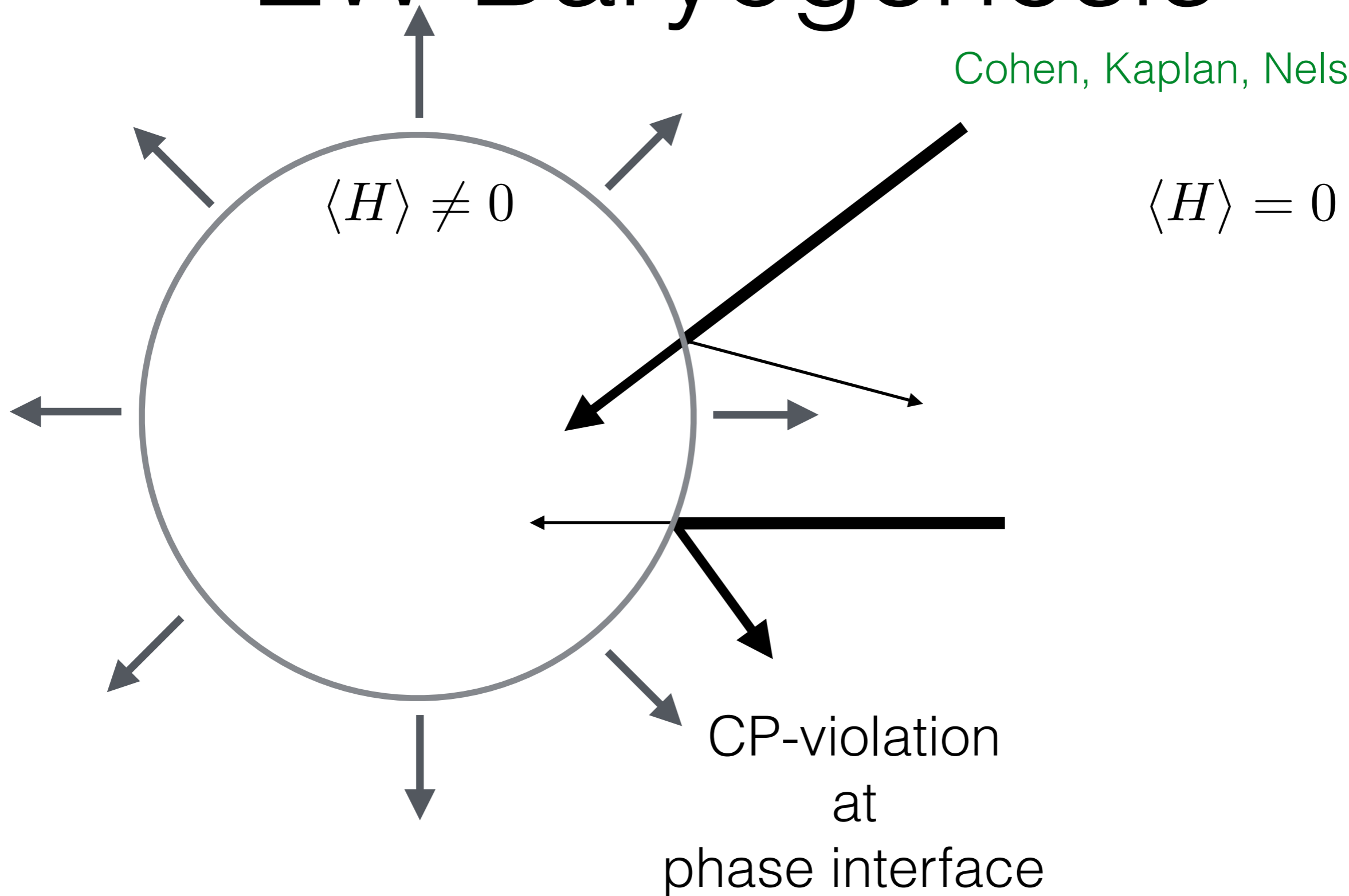
# EW Baryogenesis

Cohen, Kaplan, Nelson '91



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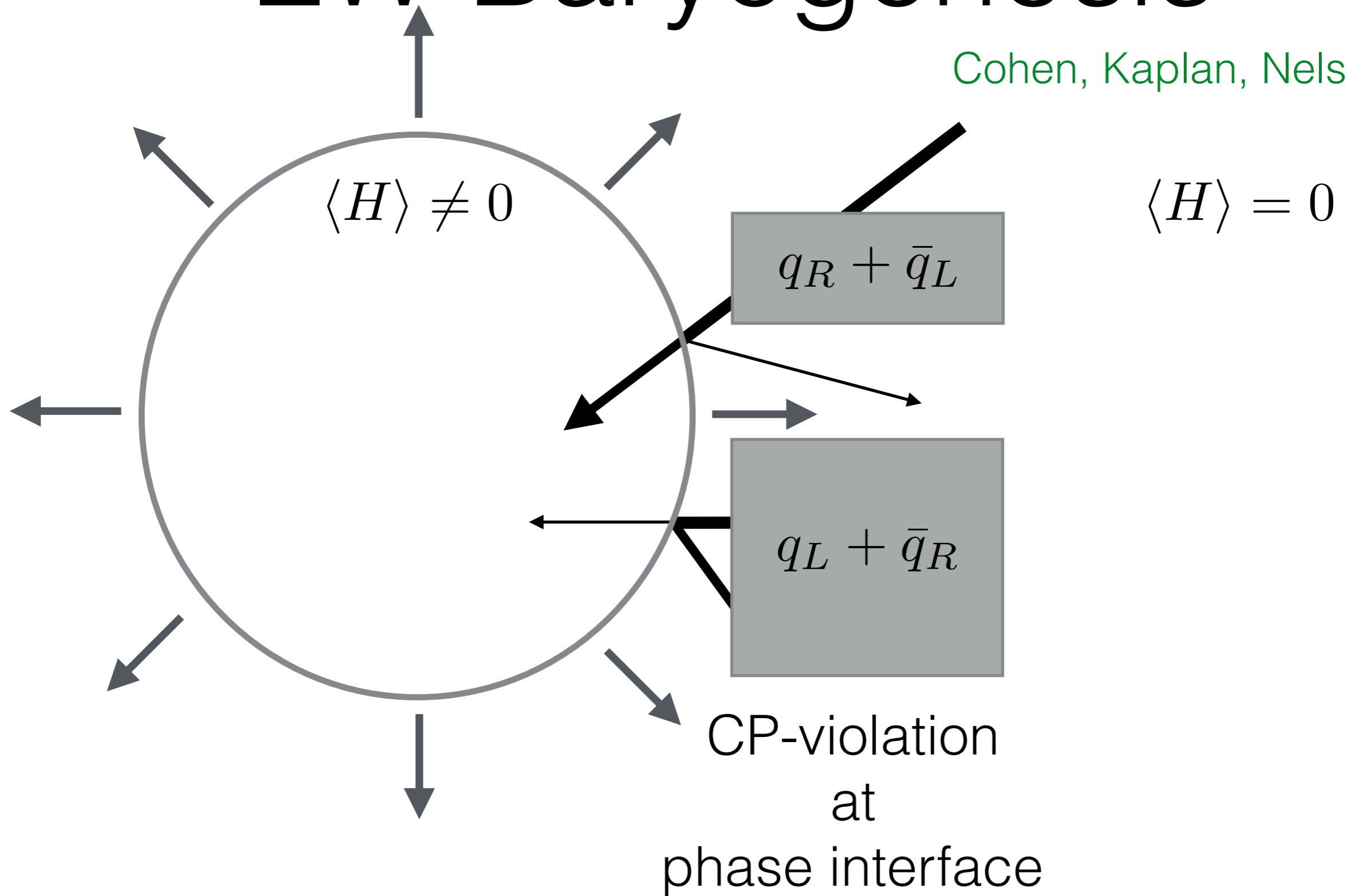
Cohen, Kaplan, Nelson '91





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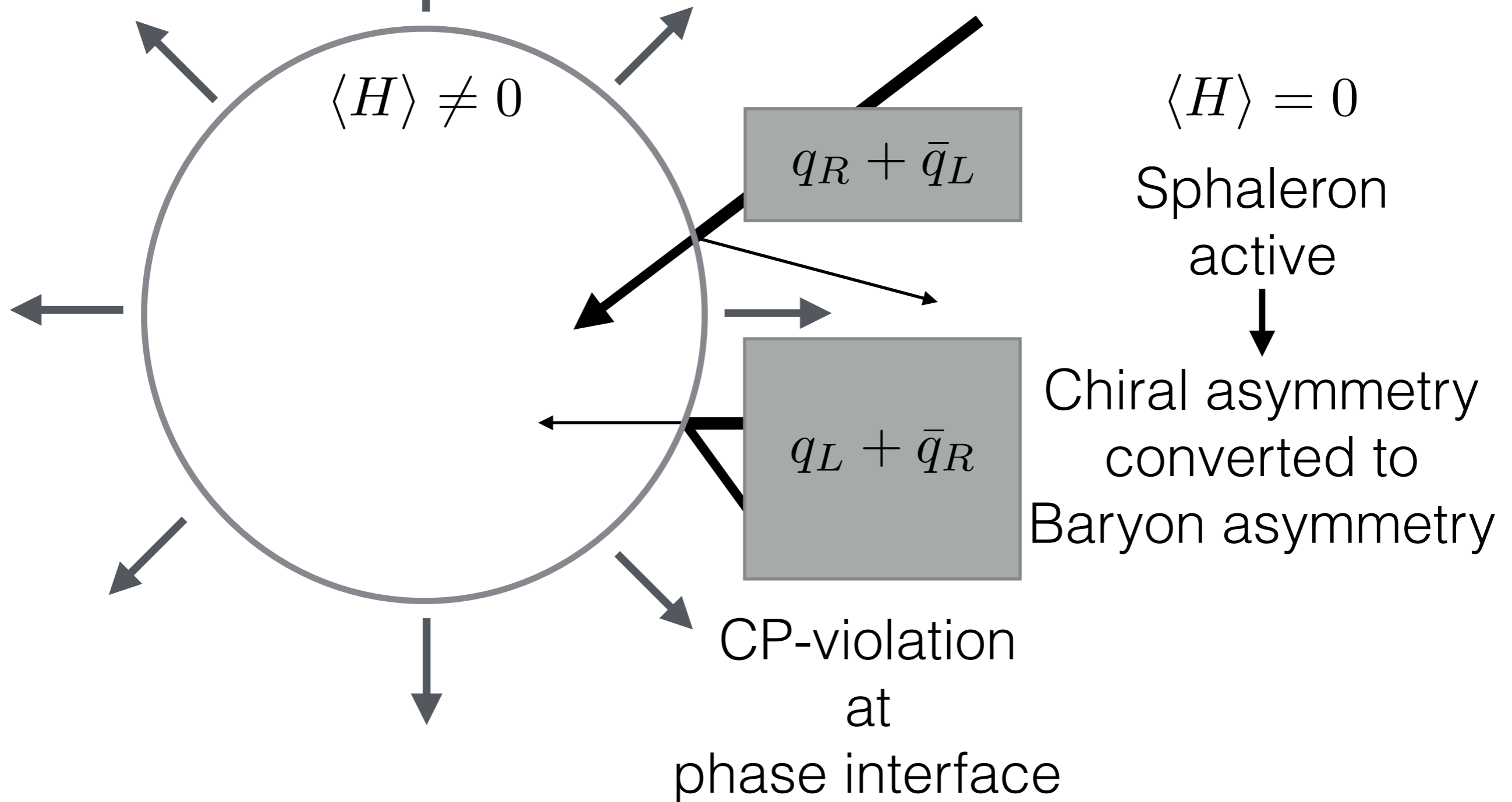
Cohen, Kaplan, Nelson '91





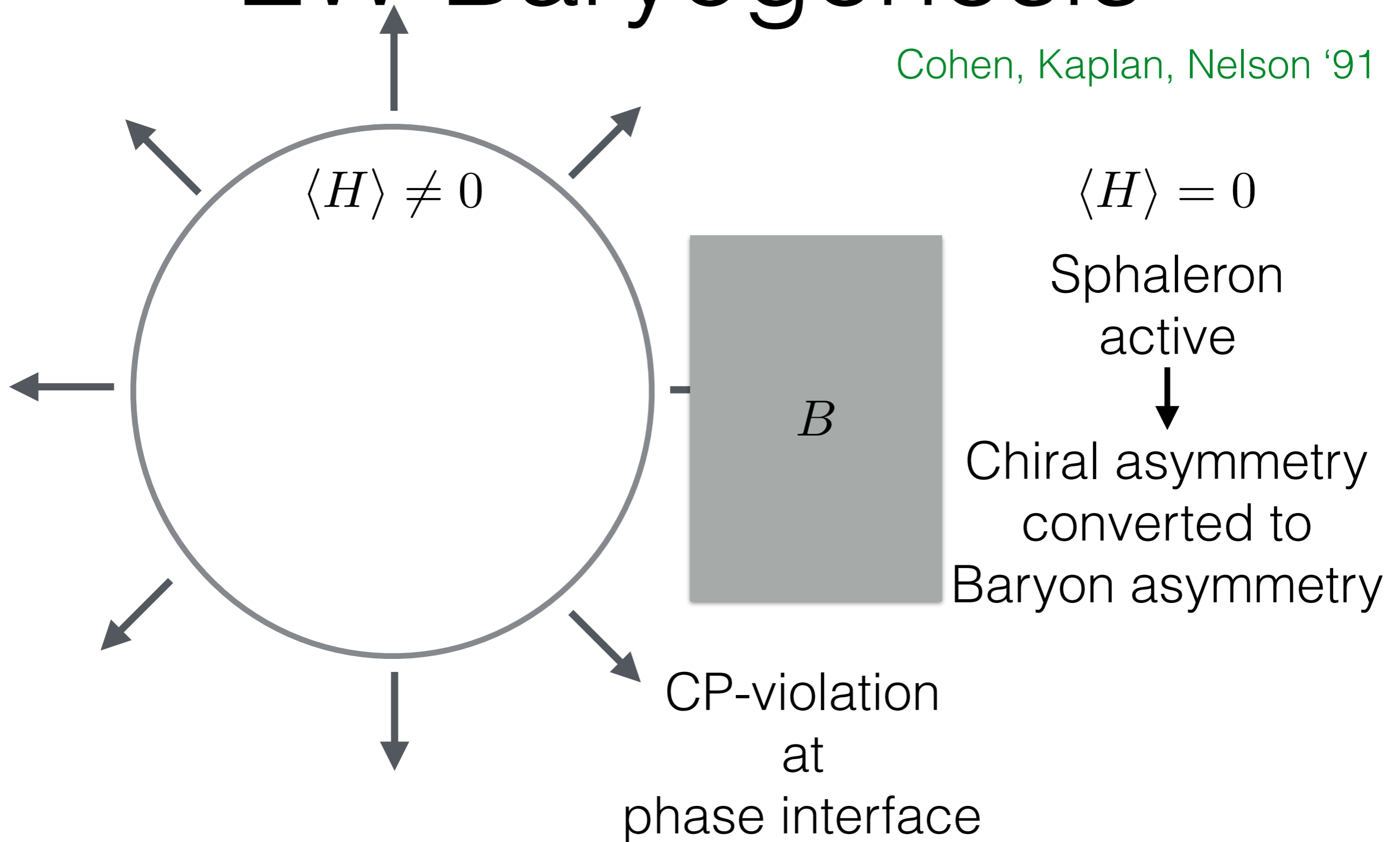
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Cohen, Kaplan, Nelson '91



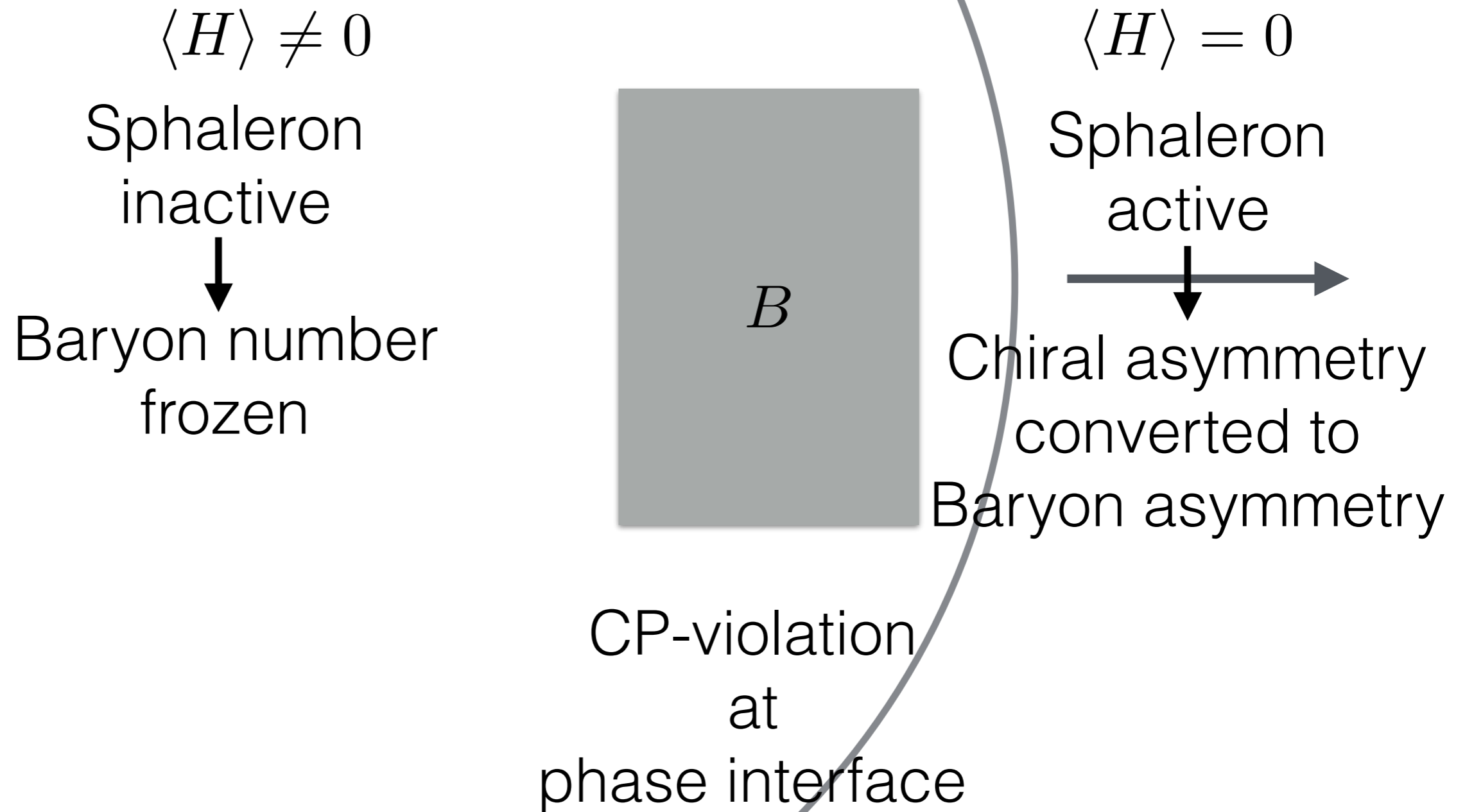
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# CP-violating source in SM

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

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

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EW scale flavour physics

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



# Special case: 1 flavour

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

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

$\theta$  has to be space dependent!

Agrees with semi-classical treatment

Source strong enough only for heavy flavour, i.e. the top.

This is not the case for two mixing flavours.

# 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.)

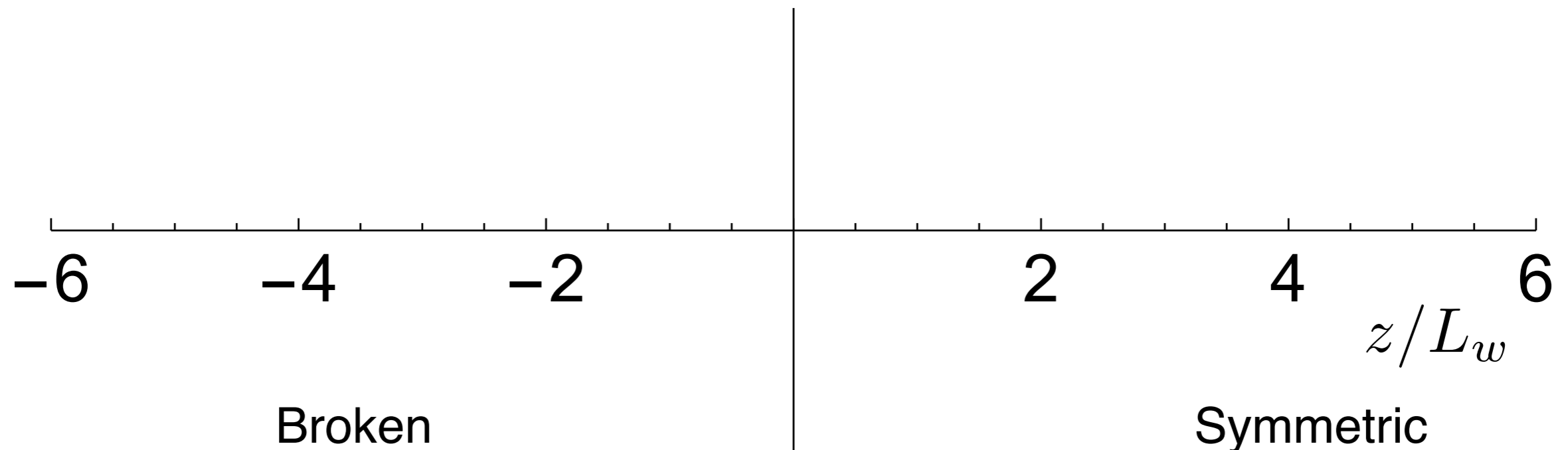
Baldes, Konstandin,  
Servant '16

1604.04526 & 1608.03254

Von Harling, Servant '16  
1612.02447

# Baryon asymmetry

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135 N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} dz \Gamma_{ws} \mu_L \text{Exp} \left[ -\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^z dz_0 \Gamma_{ws} \right]$$

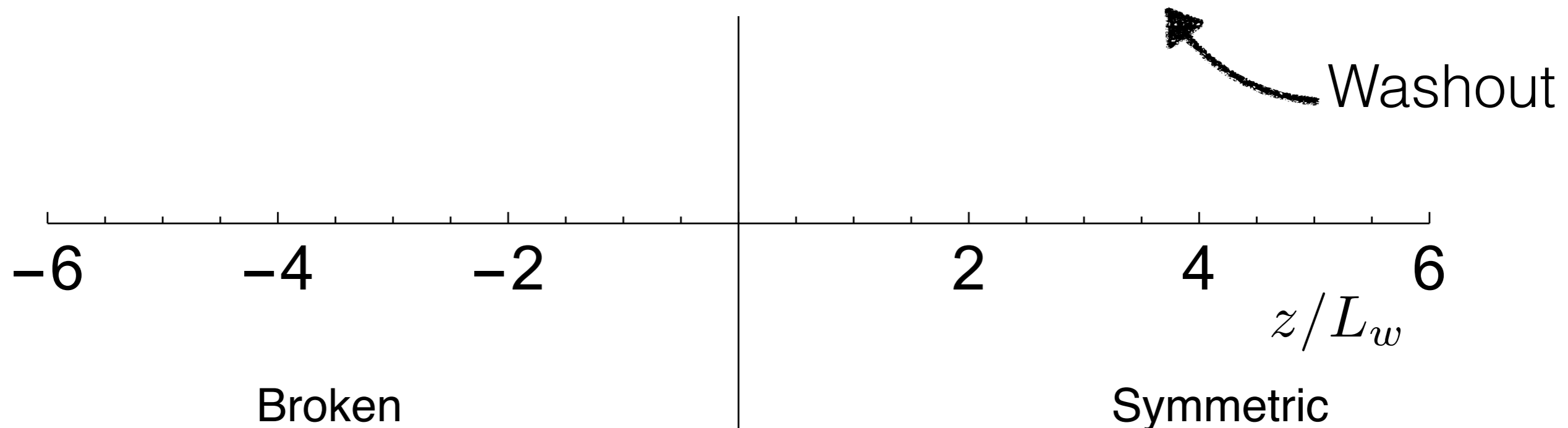


1. Sakharov condition (B-violation)
2. Sakharov condition (CP-violation)
3. Sakharov condition (out of equilibrium)



# Baryon asymmetry

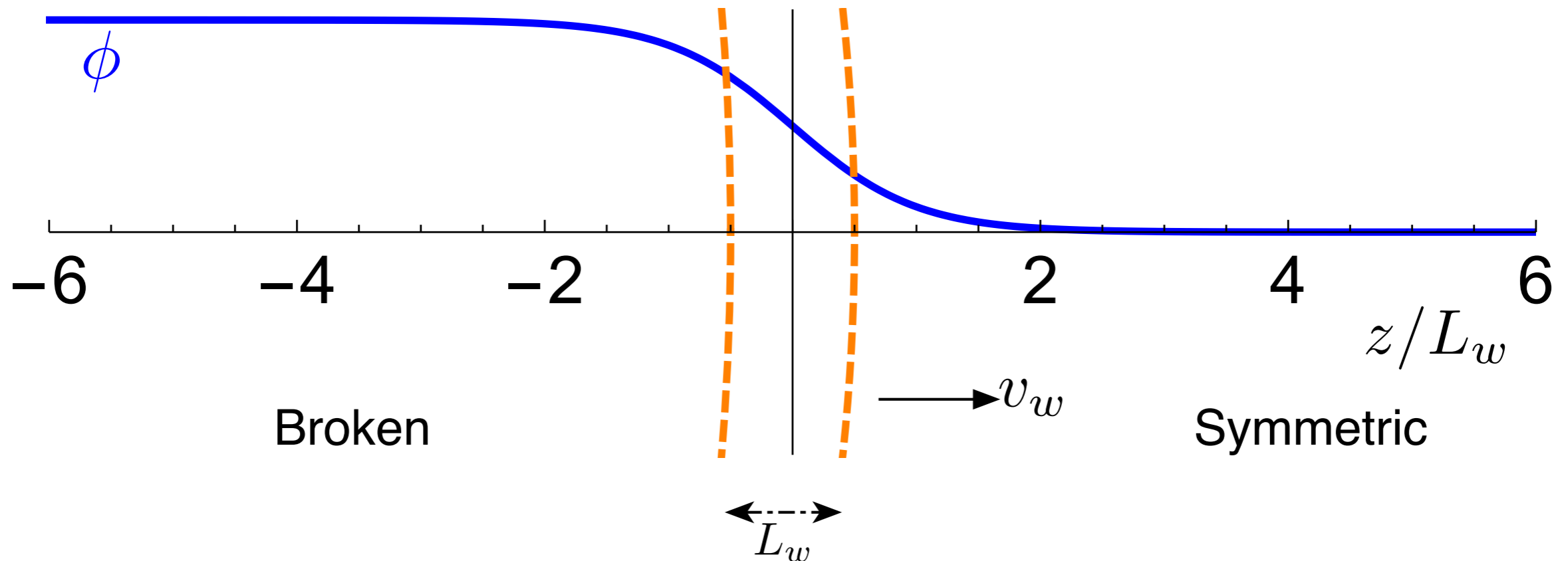
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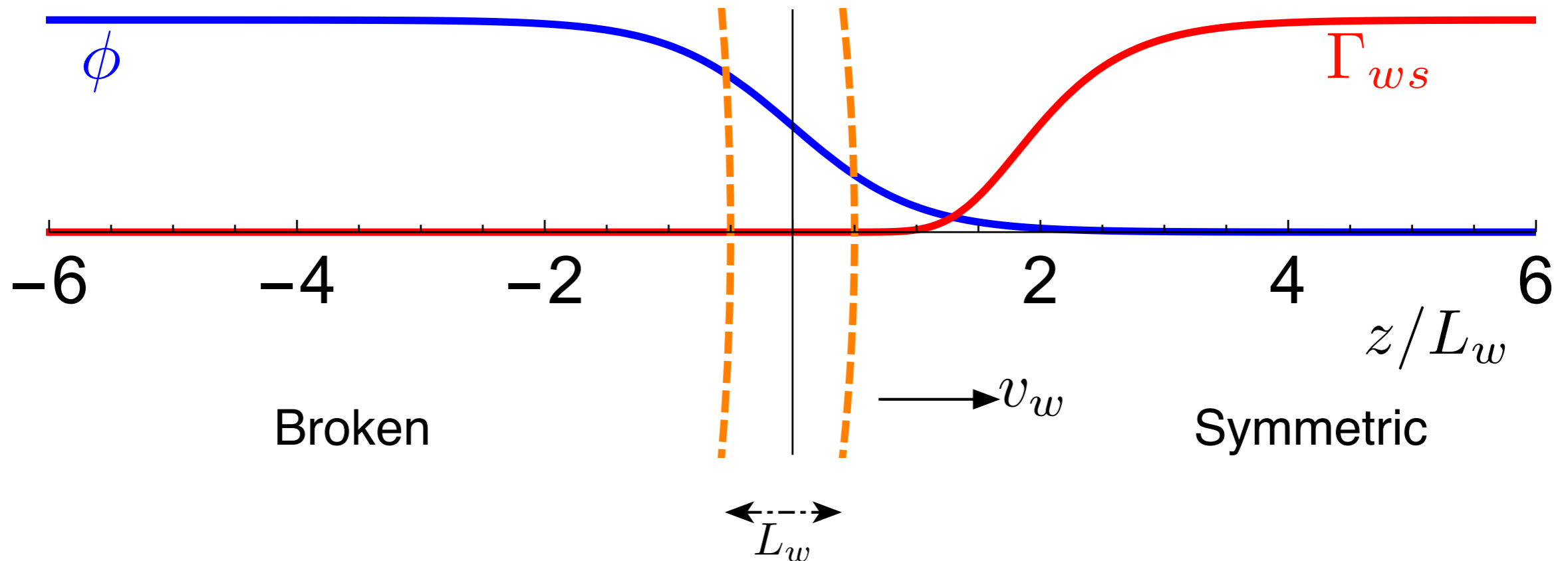
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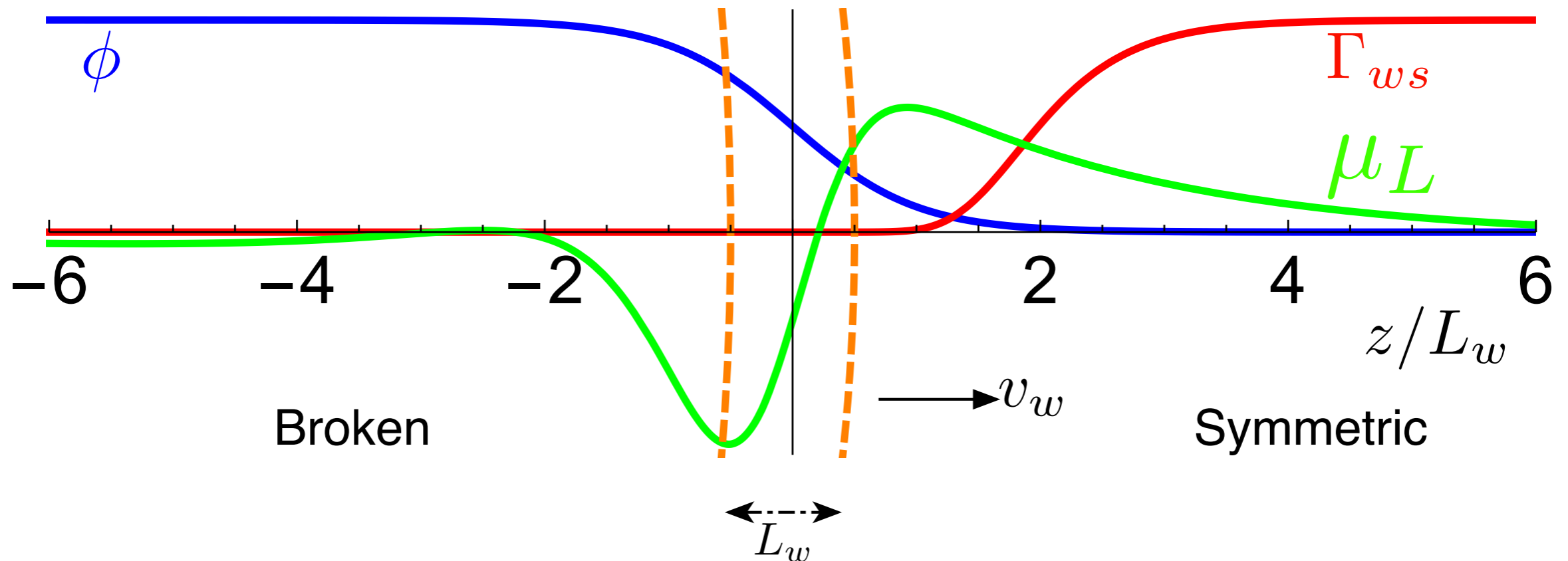
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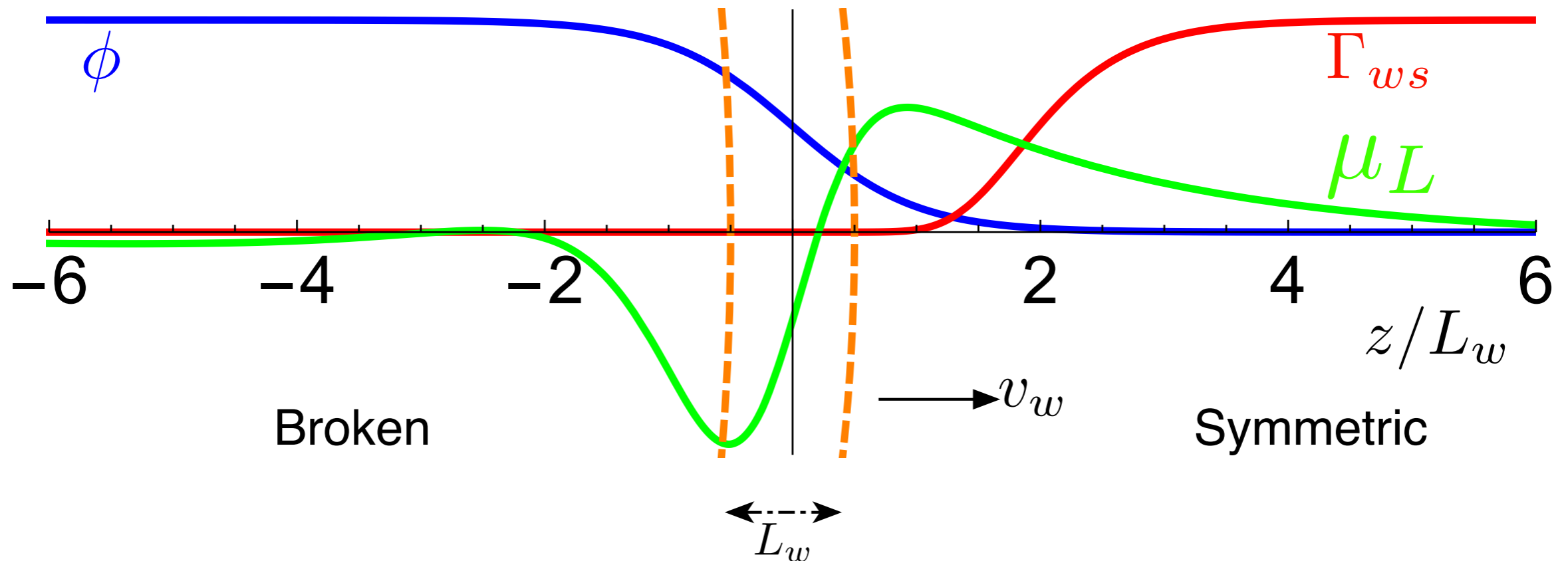
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# CP-violation in the SM and beyond

In the SM:  $\eta_B \lesssim 10^{-2} \Delta_{CP}$

Farrar, Shaposhnikov '93

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

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

Jarlskog constant

Based solely on  
reflection coefficients



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**Much too small!**  
(measured:  $\eta_B \sim 8.9 \cdot 10^{-11}$ )

Gavela, *et al.* '93  
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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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Yoshinikov '93

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Calculate CP-violating source,  
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CP-violation and diffusion equation  
 from first principles (Kadanoff-Baym)

Prokopec, Schmidt,  
 Weinstock '03

# Network equations

Fluide type Ansatz:

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

CP-odd Energy-Momentum average, linear in:  $\mu_i$ ,  $u_i$  and  $v_w$  :

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

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

**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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$$\mu(z) = \int_{-\infty}^{+\infty} dz_0 G(z, z_0) S(z_0)$$

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

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$$\eta_B = \sum_i \int_{-\infty}^{+\infty} dz_0 K_i(z_0) S_i(z_0)$$

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

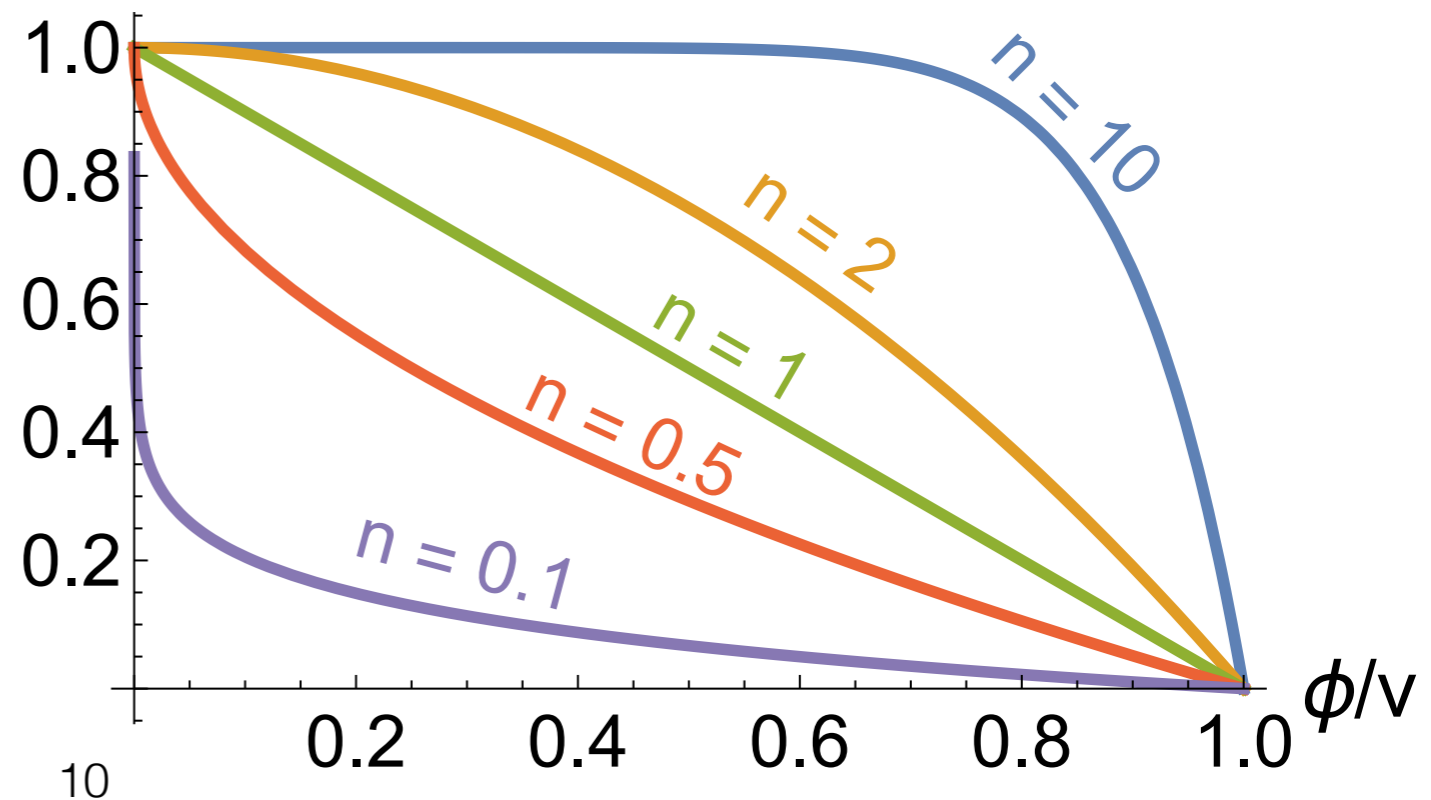
Higgs vev in broken phase

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

Symmetric phase

Higgs vev

$y(1,0,\phi,n)$

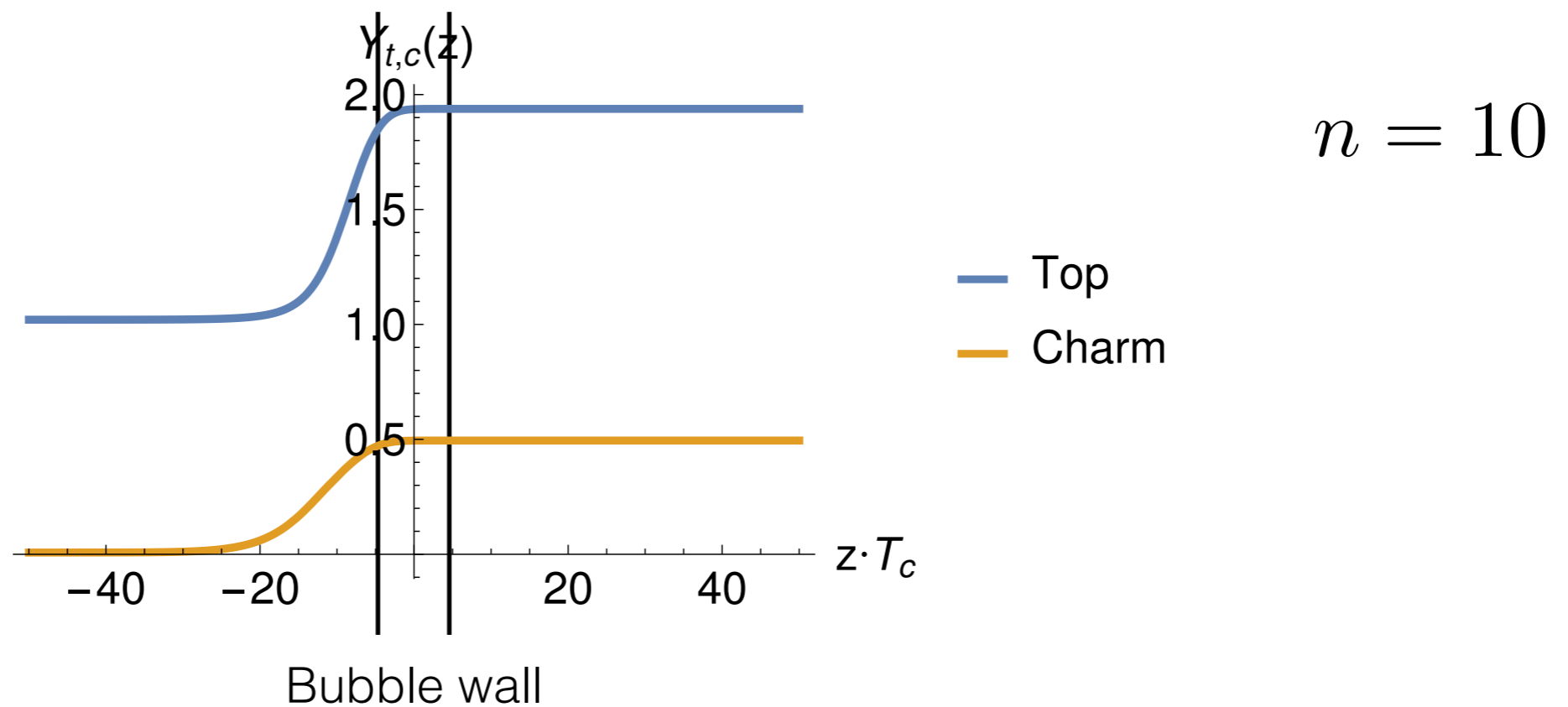


Baldes, Konstandin,  
Servant '16

1608.03254 & 1604.04526

# Yukawas

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



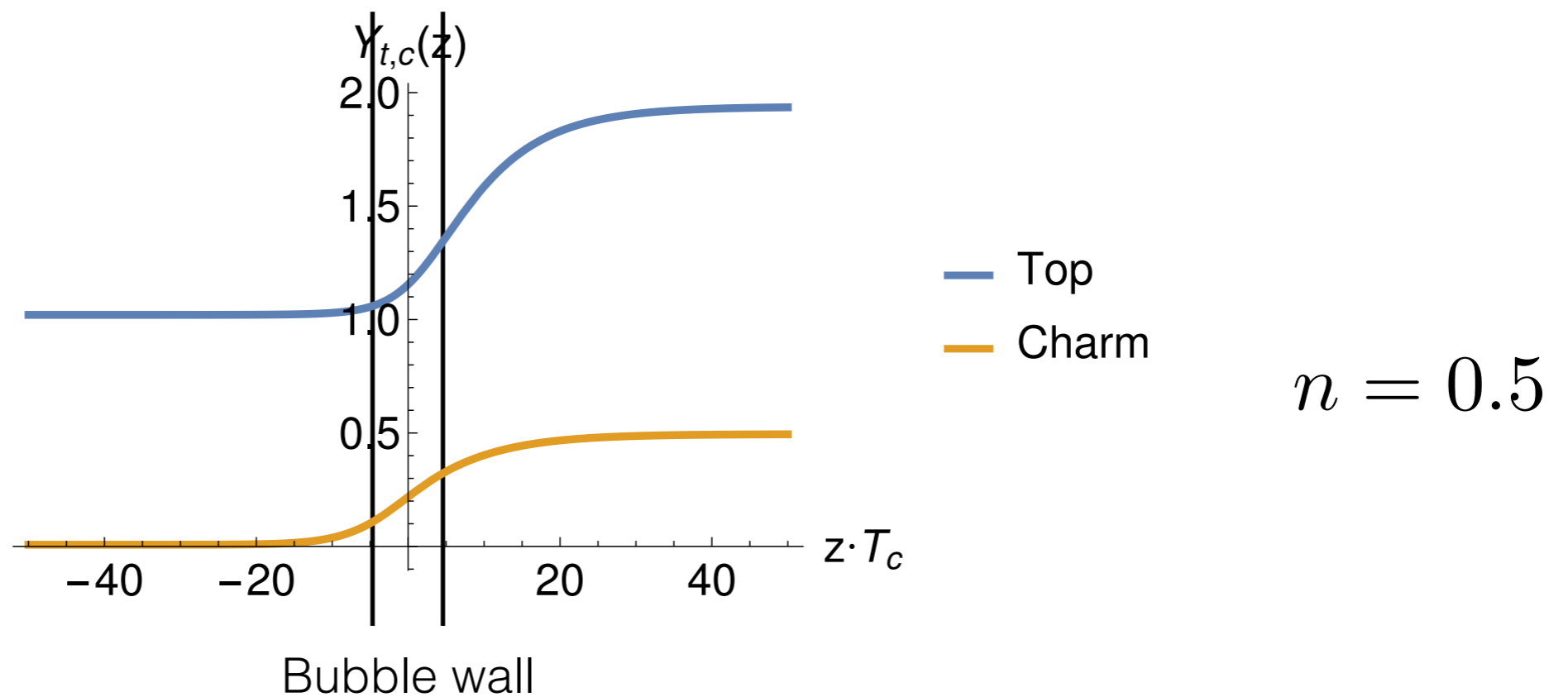
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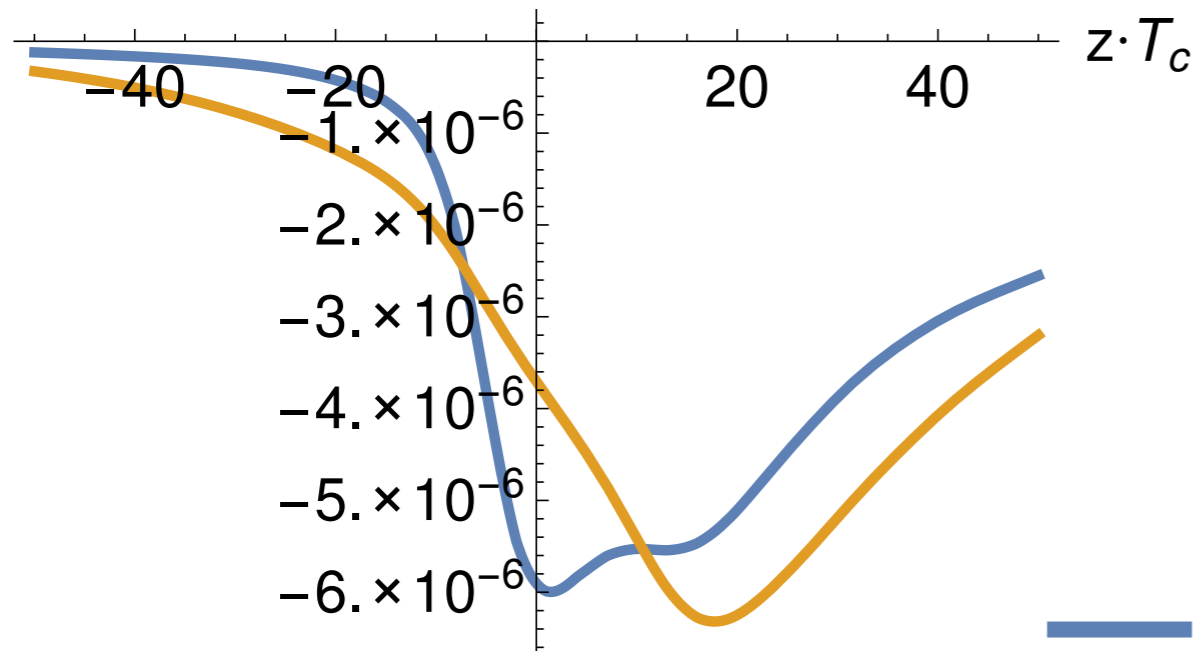
Symmetric phase →

$$\eta_B = \sum_i \int_{-\infty}^{+\infty} dz_0 K_i(z_0) S_i(z_0)$$

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

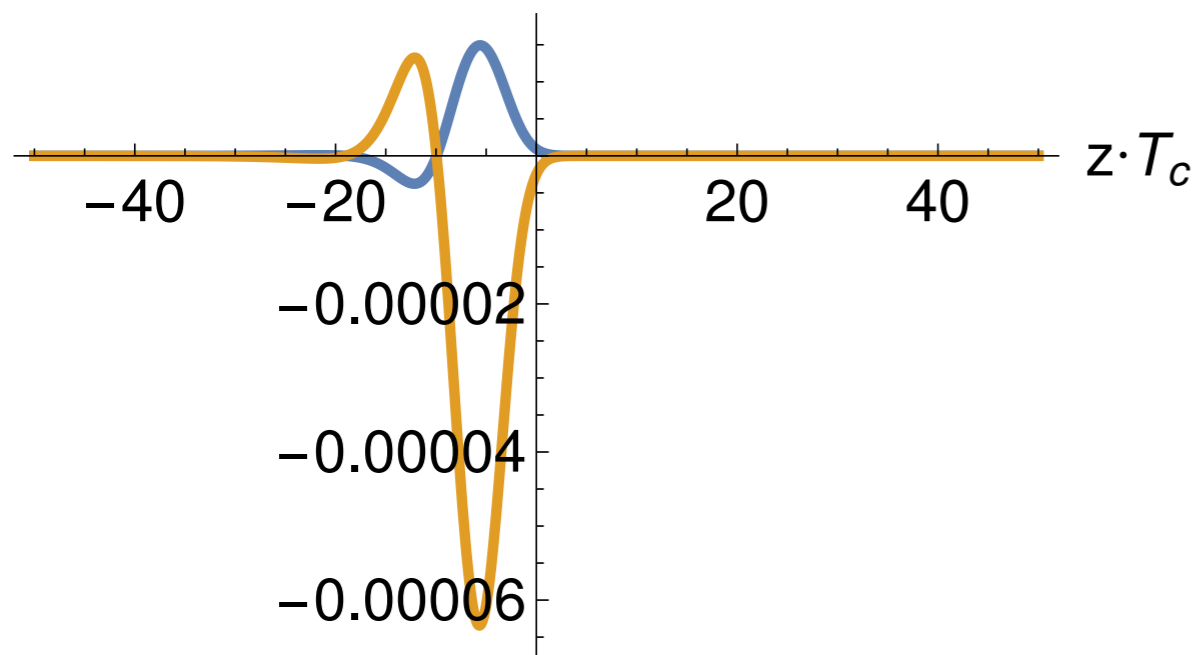
**Kernel for n=10**

K(z)



**Source for n=10**

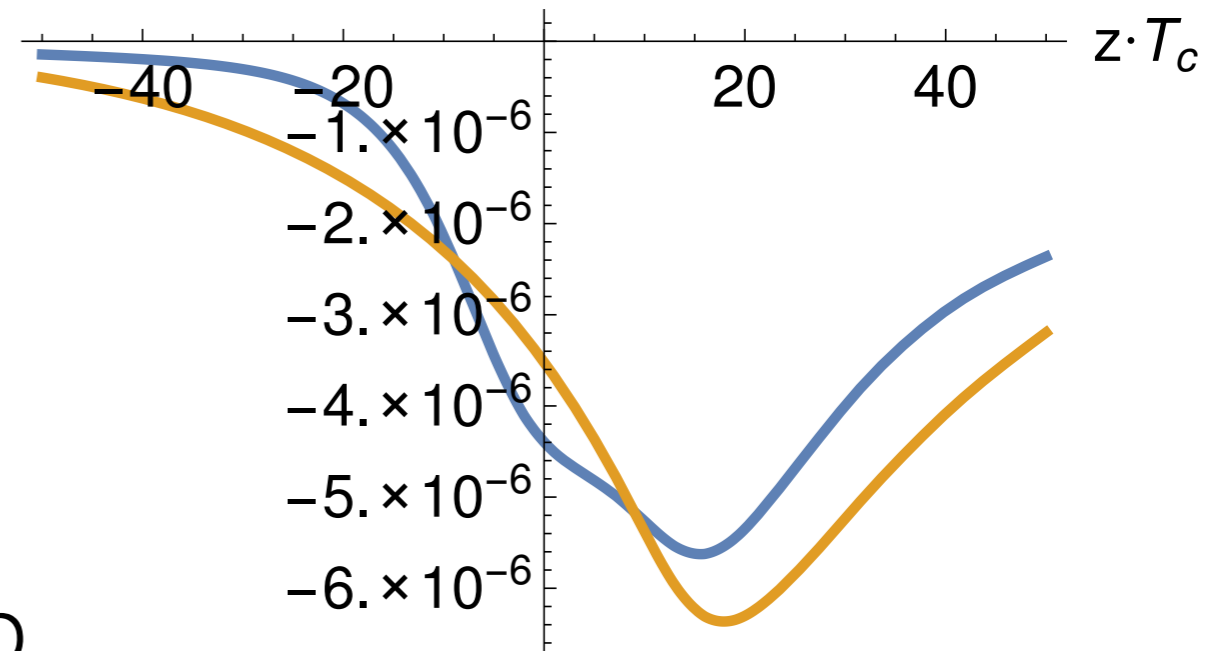
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$$\eta_B \approx 2.1 \cdot 10^{-12}$$

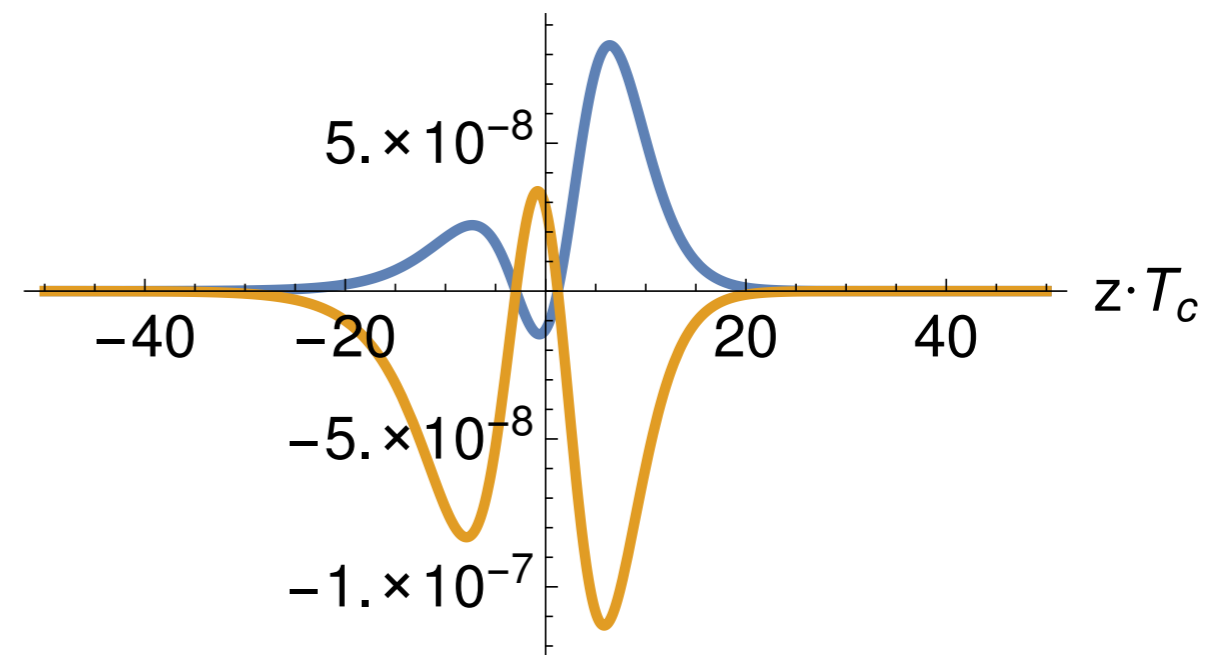
**Kernel for n=0.1**

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**Source for n=0.1**

S(z)



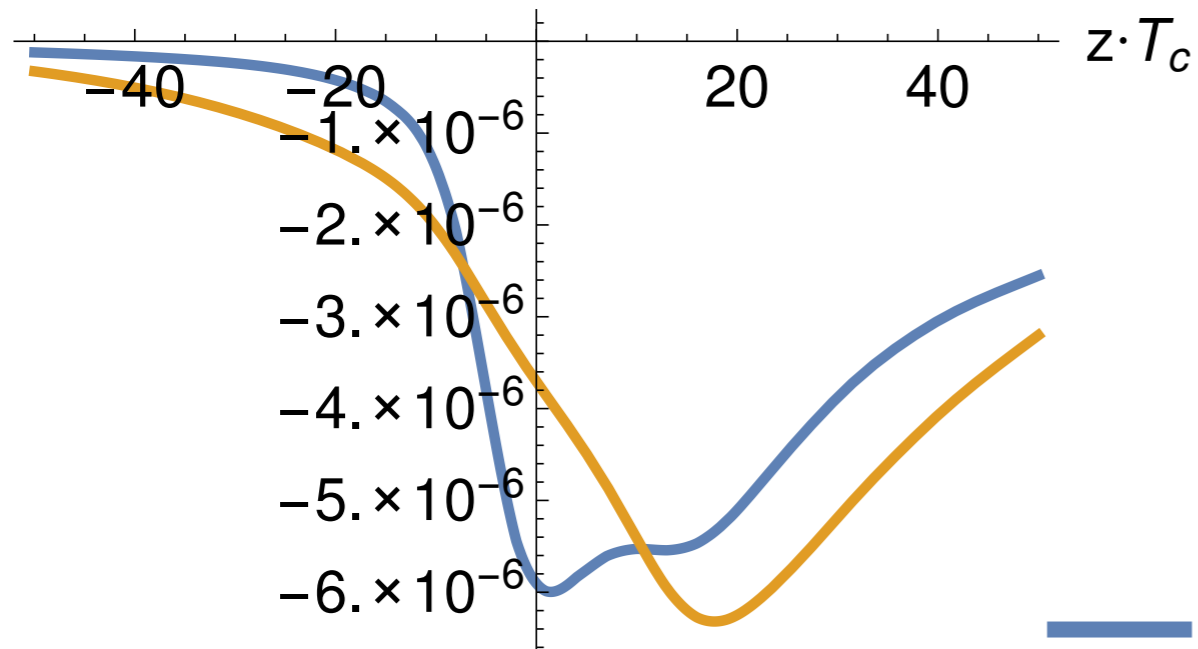
— Top  
— Charm

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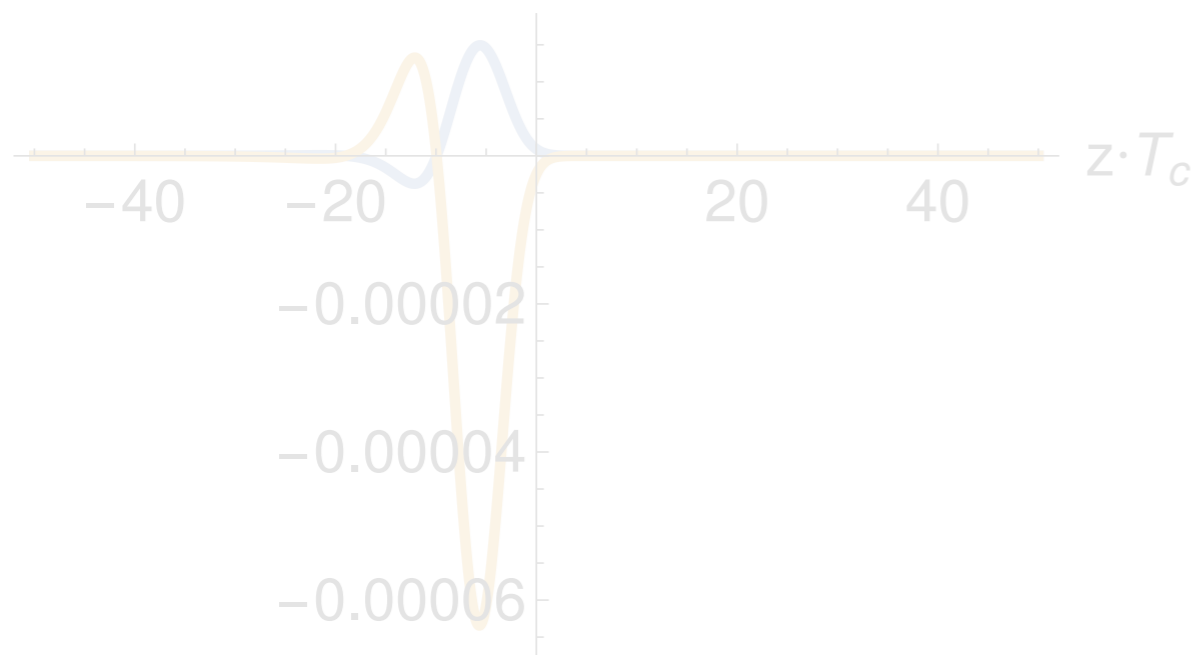
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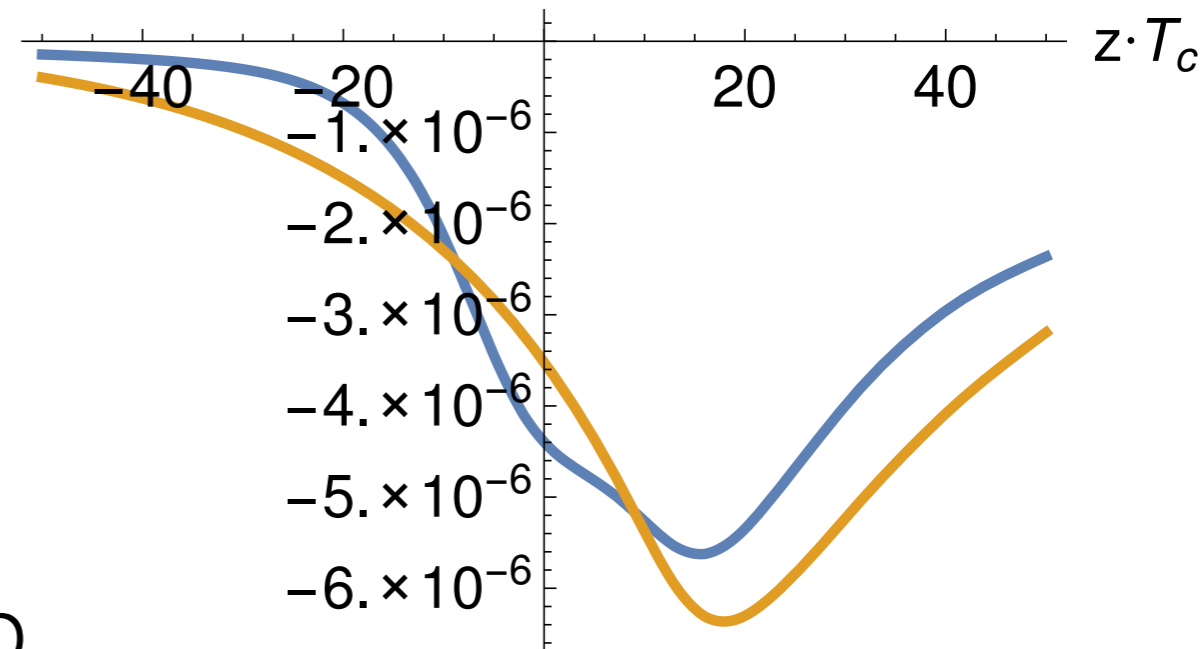
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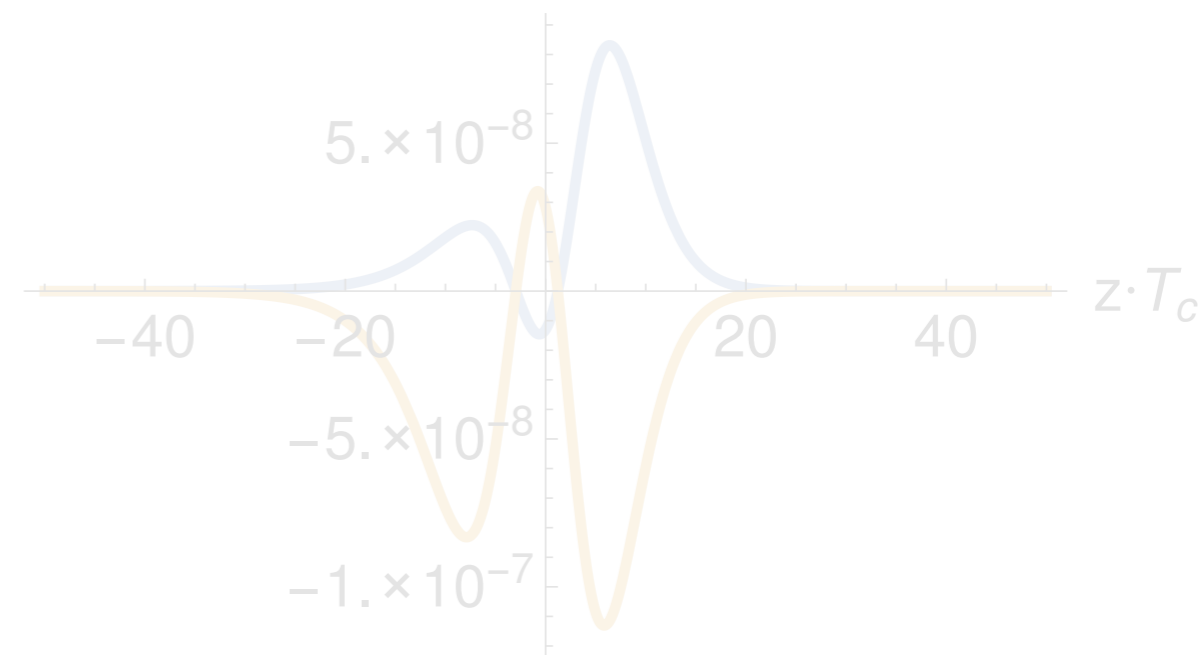
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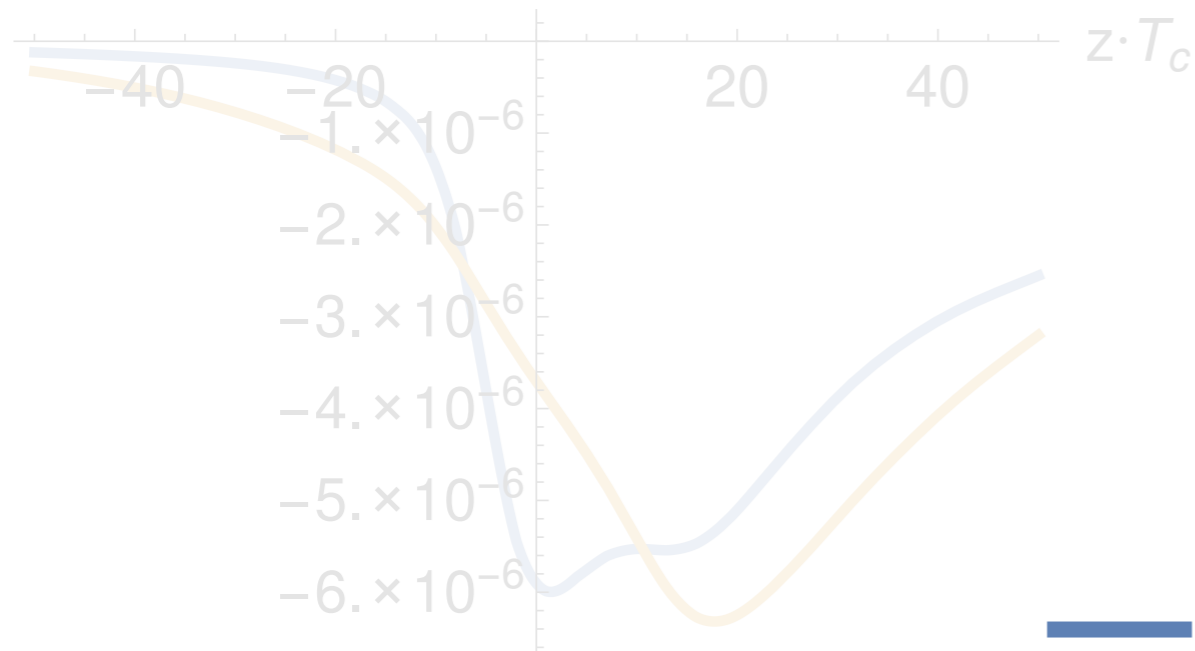
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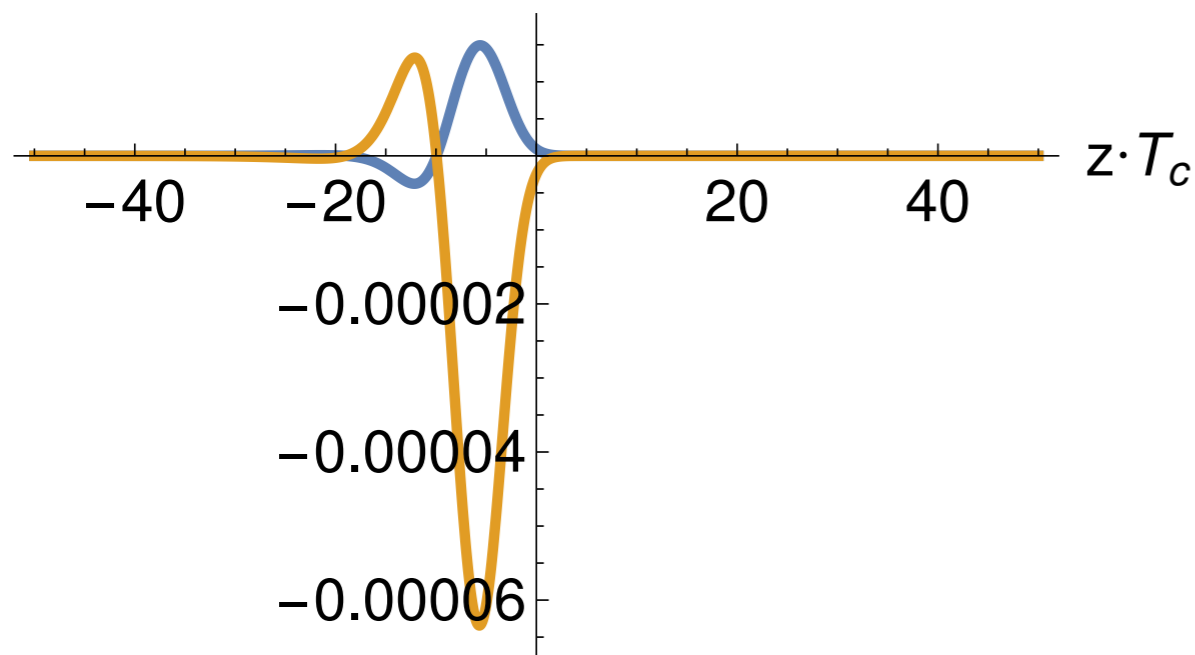
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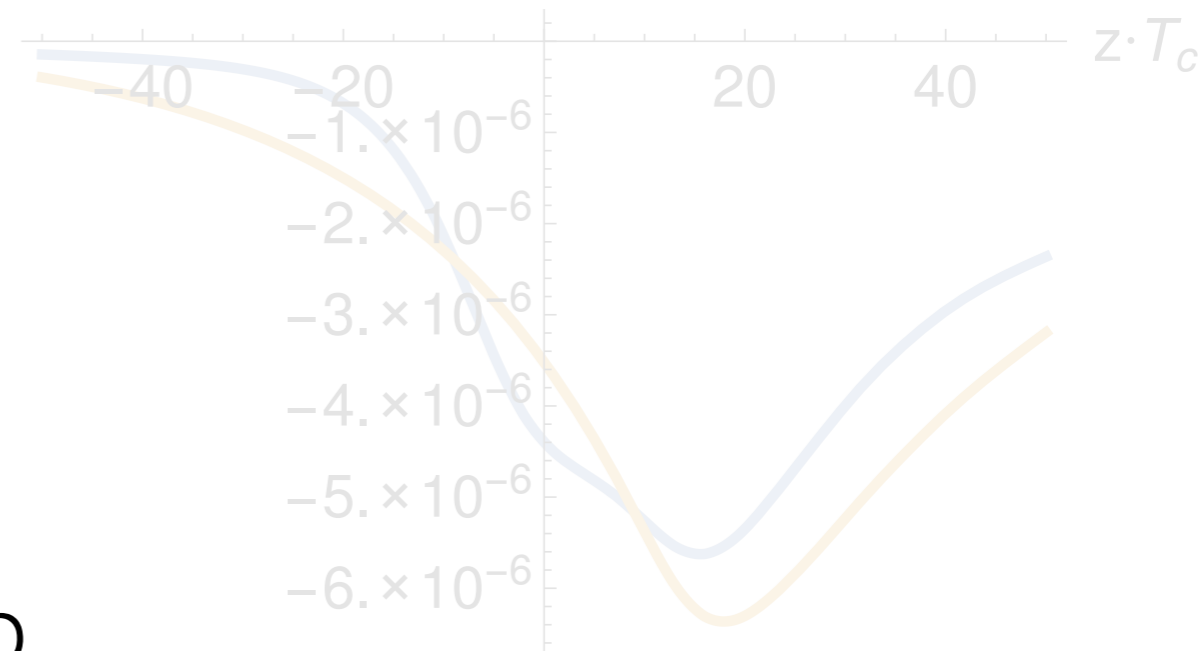


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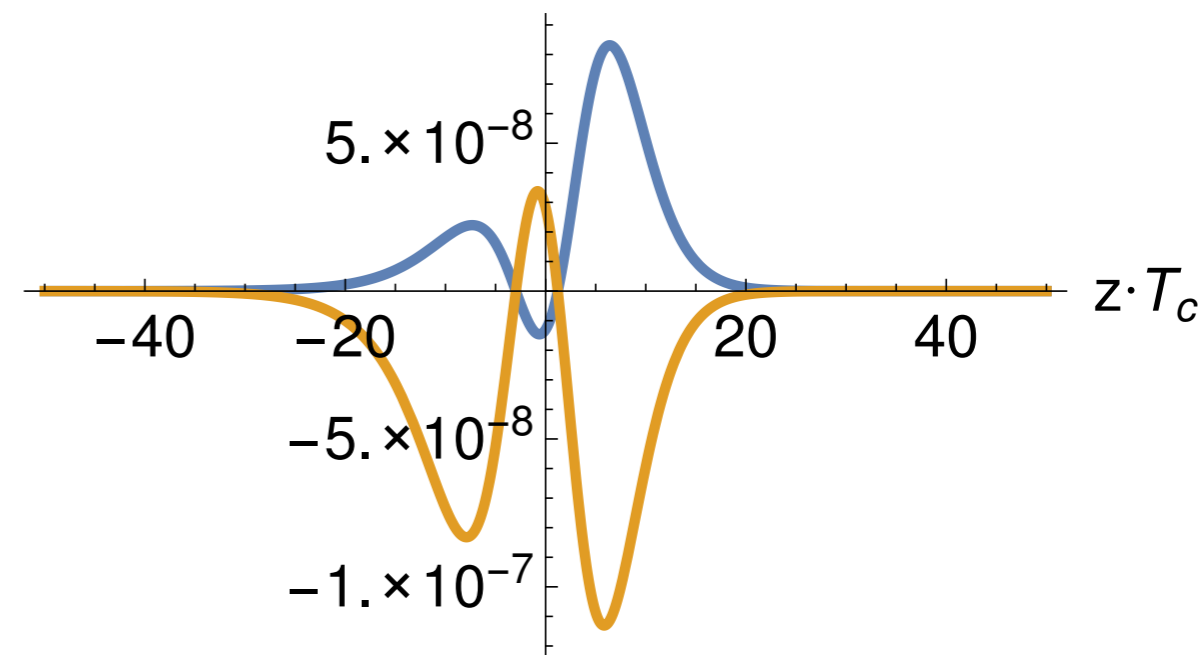
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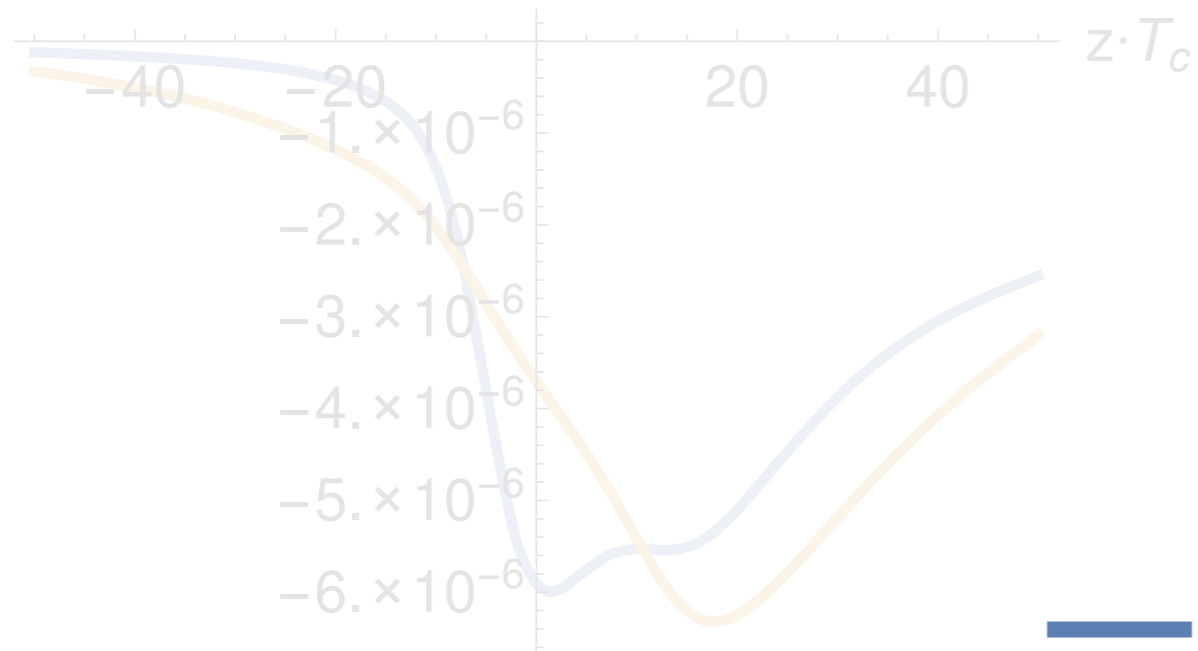


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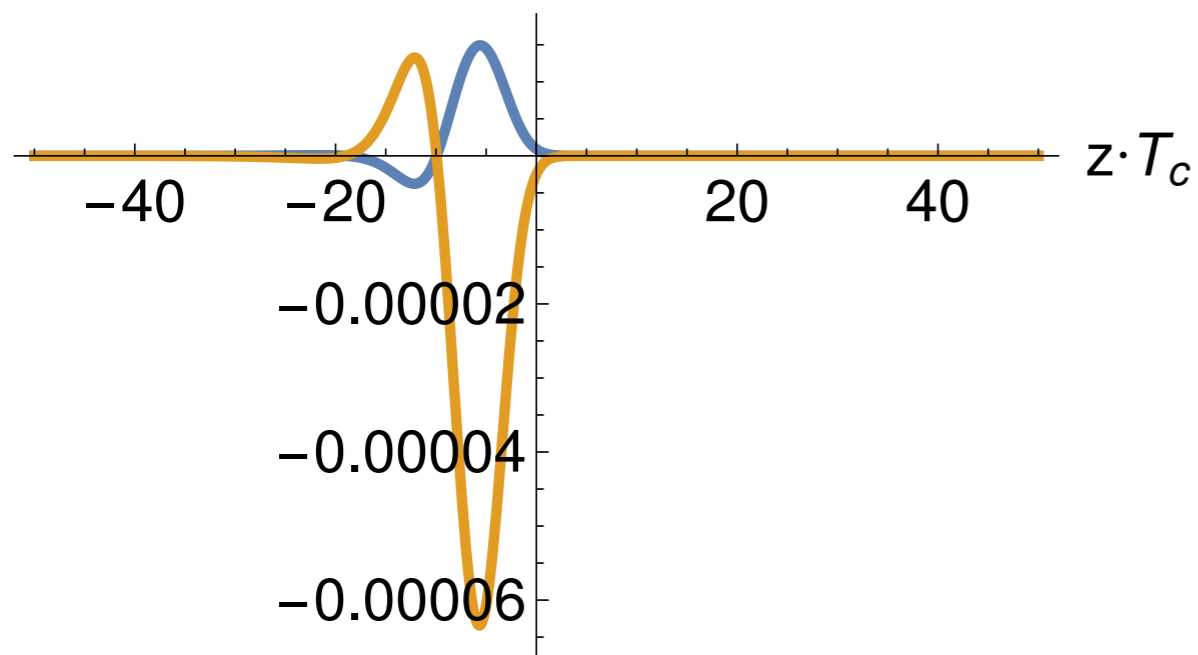
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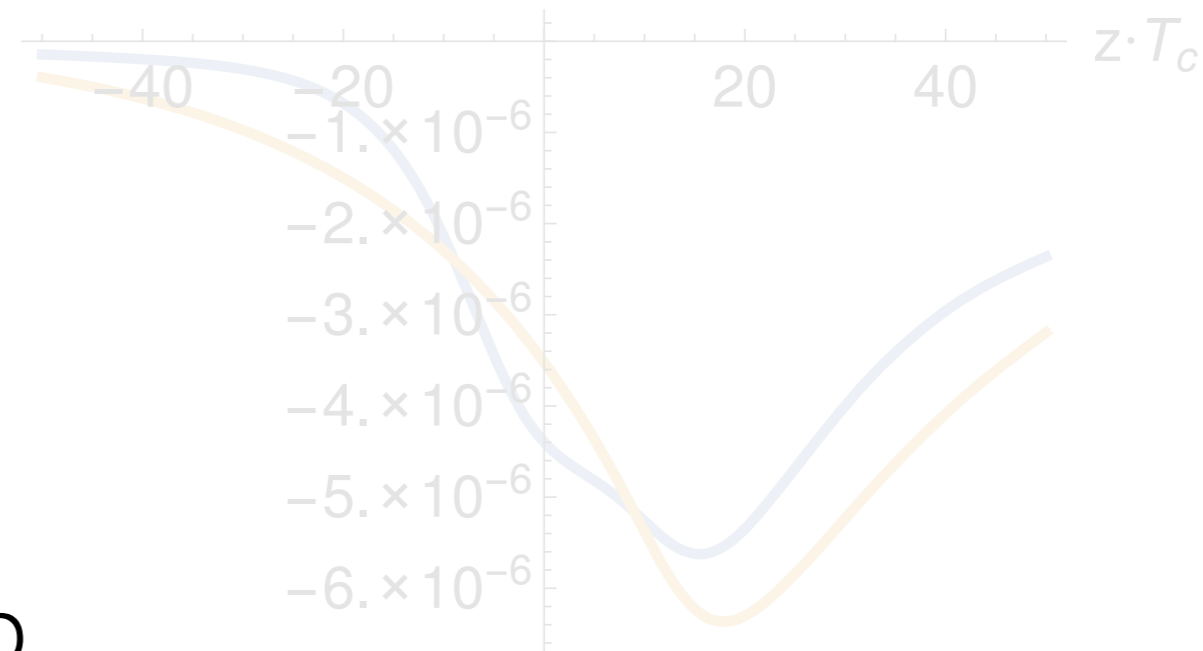


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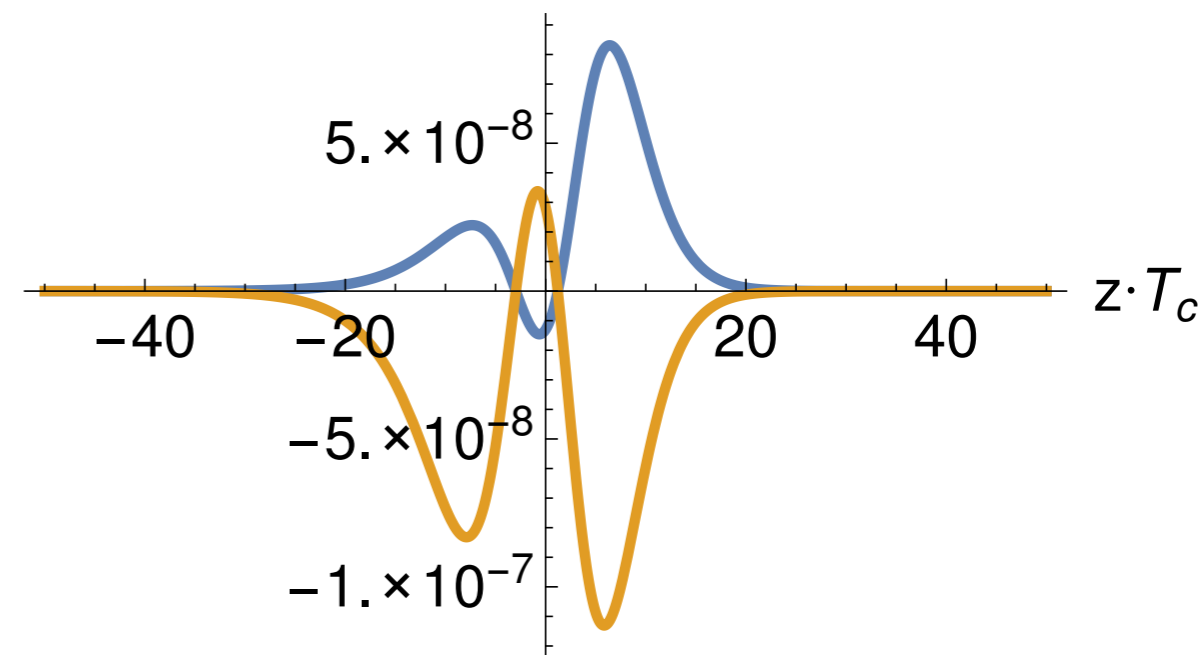
Kernel for n=0.1

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Source for n=0.1

S(z)



# Froggat-Nielsen

$U(1)_{FN}$  with two FN fields  $\chi, \sigma$

Charge assignment

Yukawa type interactions after SSB

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

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

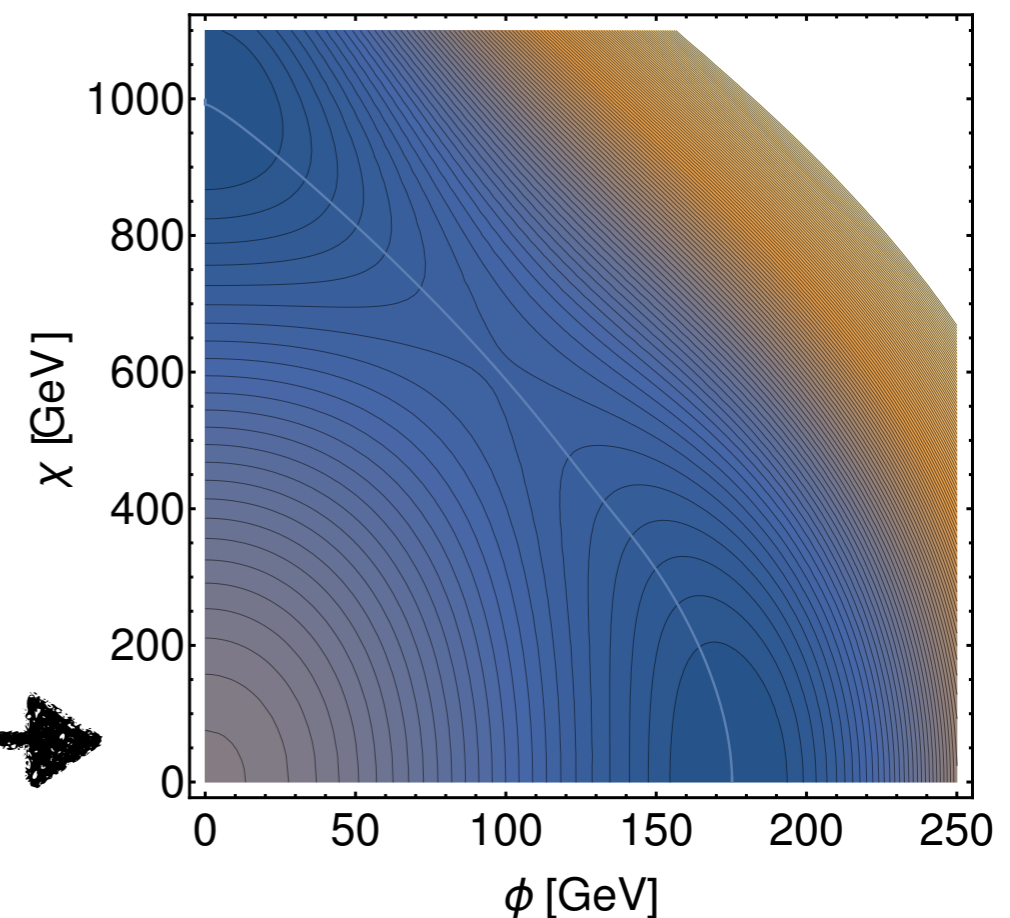
$$Q_{FN}(\sigma) = Q_{FN}(\chi) = -1$$

$\bar{Q}_3$ (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)

VEVs during EWSB

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

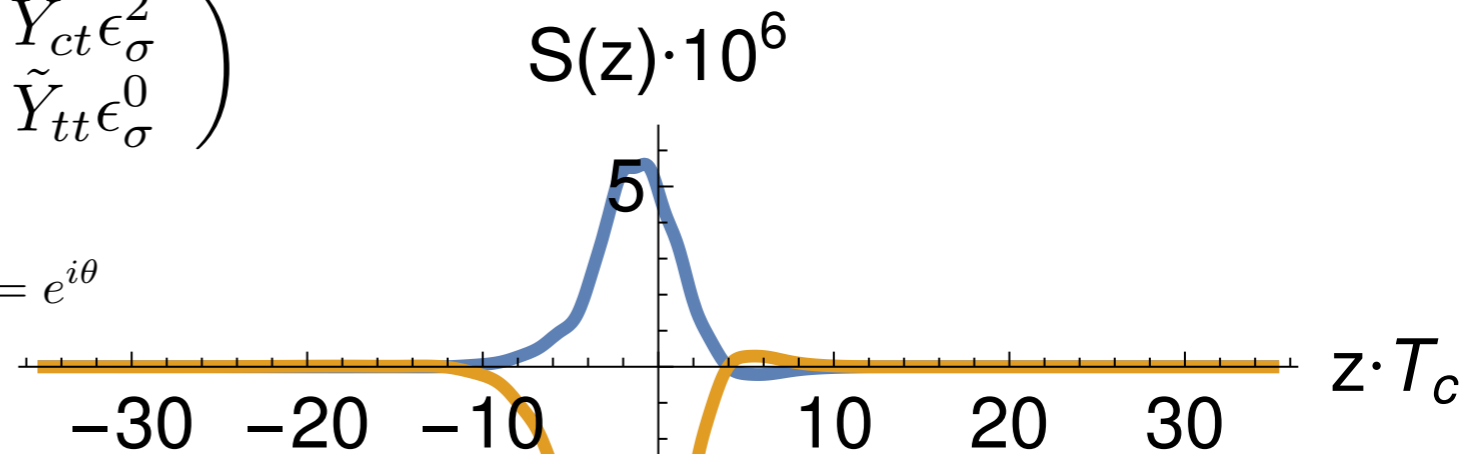
$\chi - \phi$  -Potential  $\rightarrow$



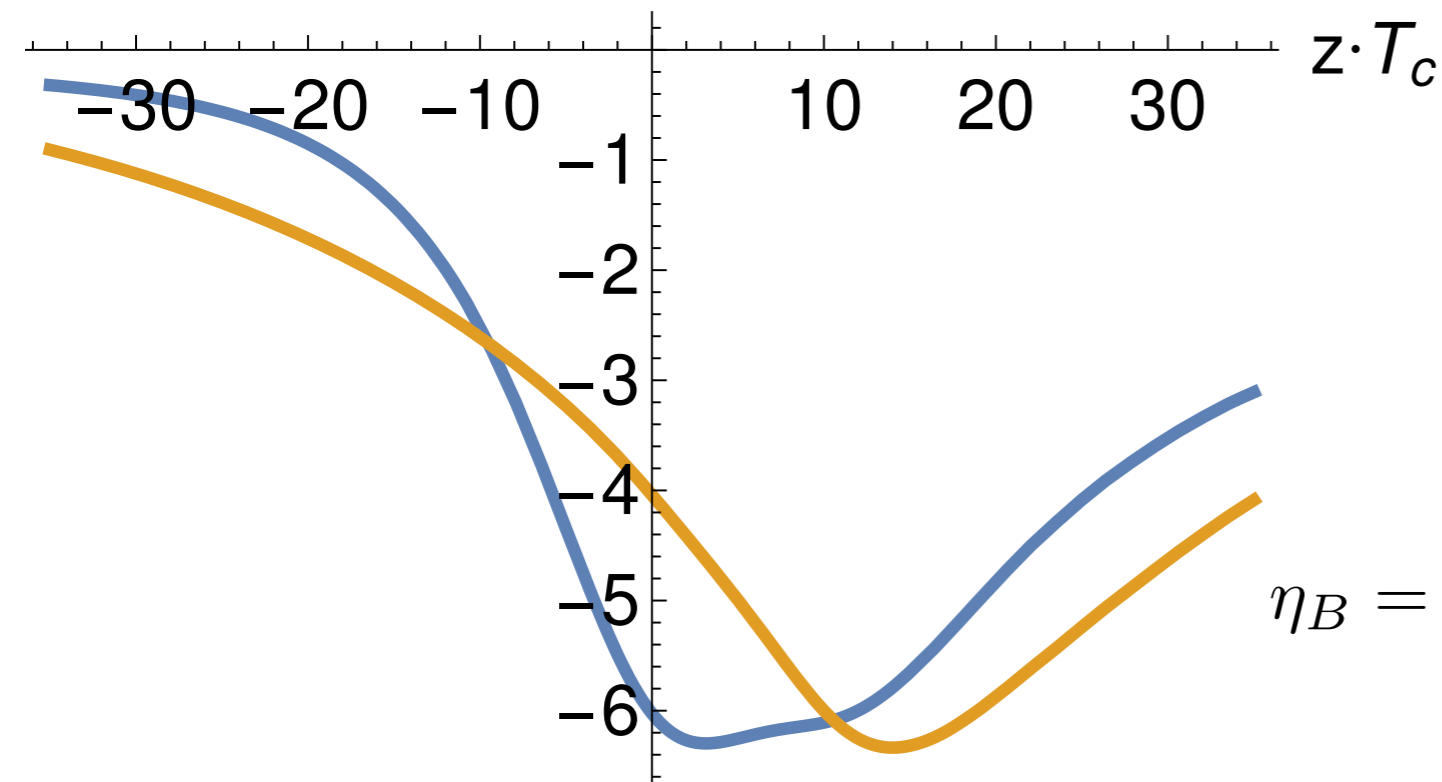
# Froggat-Nielsen

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

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

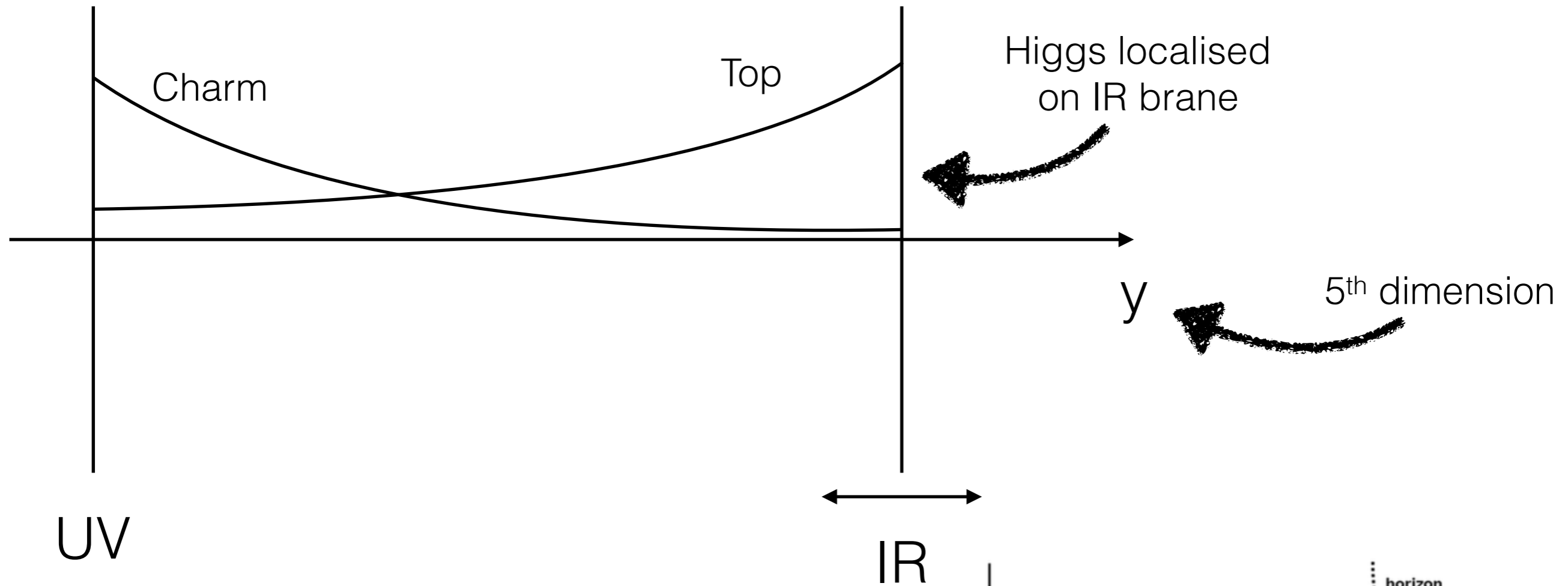


$$K(z) \cdot 10^6$$

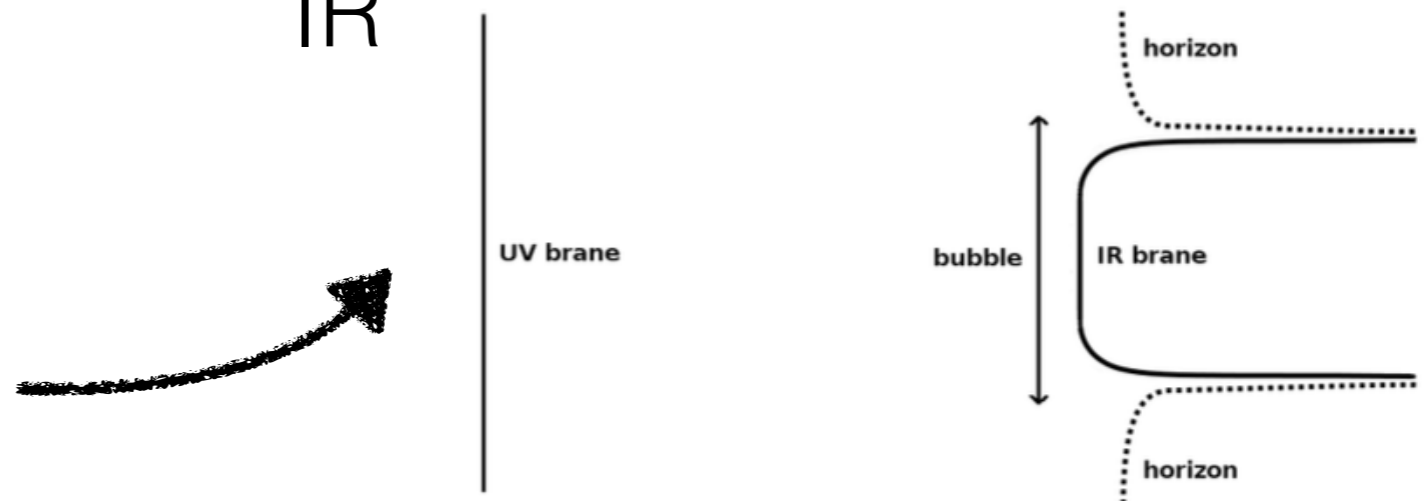


$$\eta_B = \sum_i \int_{-\infty}^{+\infty} dz_0 K_i(z_0) S_i(z_0) \simeq 1.15 \cdot 10^{-10}$$

# Randall-Sundrum



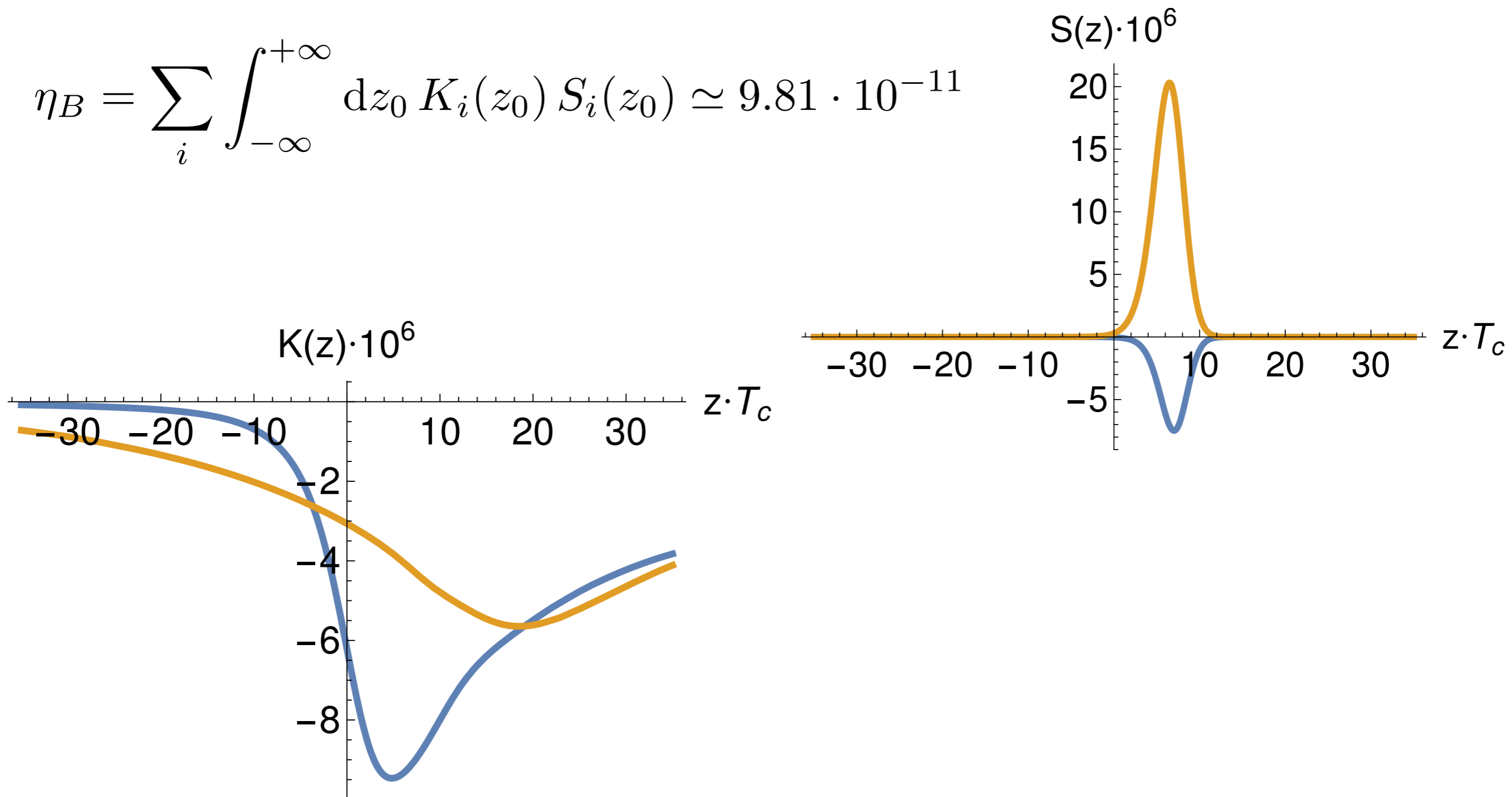
At high temp. -> AdS-Schwarzschild  
 Low temp. -> RS metric  
 —> “Brane Nucleation”





# Randall-Sundrum

$$\eta_B = \sum_i \int_{-\infty}^{+\infty} dz_0 K_i(z_0) S_i(z_0) \simeq 9.81 \cdot 10^{-11}$$



# 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

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

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

Collision term

CP-violating source term:

Source depends on  $m$



link to

Yukawa couplings

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

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

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

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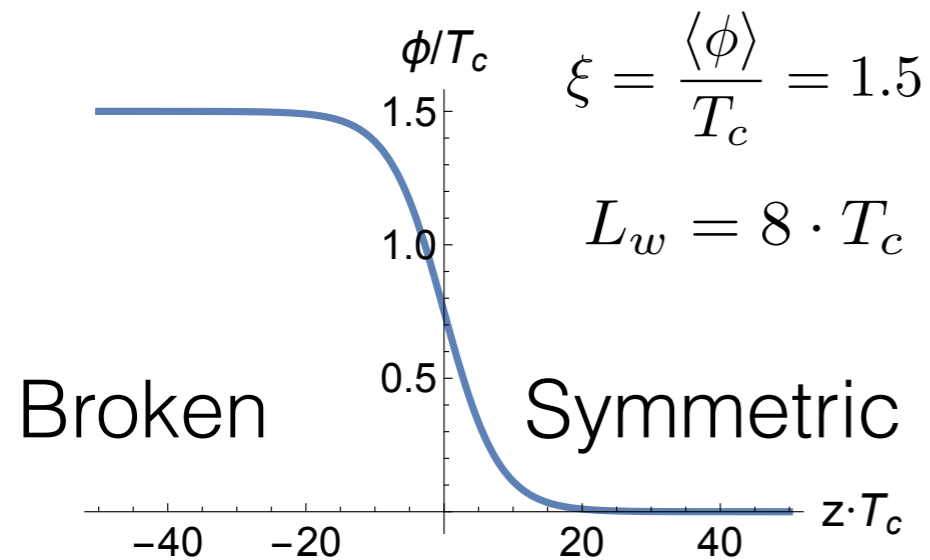


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- Strong sphaleron all L  $\leftrightarrow$  all R  $\Gamma_{ss} = 4.9 \times 10^{-4} T$

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



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

$a \approx 40$       **NEW**

