EW Baryogenesis through varying Yukawas in Composite Higgs models

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In collaboration with:
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& G. Servant & B. von Harling

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1803.08546, 1804.07314

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Conditions for Baryogenesis

Sakharov ‘67

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- Baryon number violation

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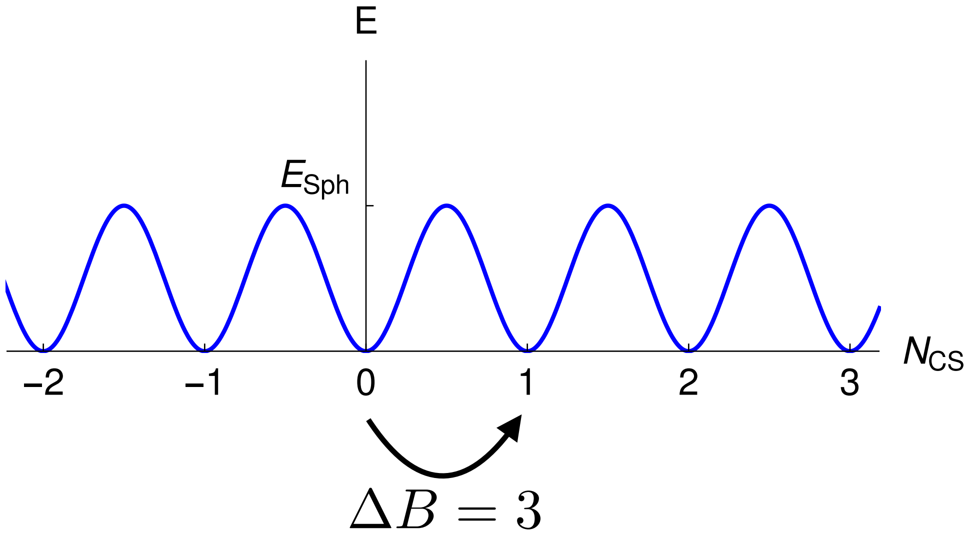
  ➡ Electroweak Sphaleron



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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

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Supersymmetric CP violation:

- Chargino/Neutralino sector
- Sfermion sector

Carena et al. ’97, ’00, ‘02
Konstandin, Prokopek, Schmidt, Seco ‘05
Cirigliano, Li, Profumo, Ramsey-Musolf ‘09
Chung, Garbrecht, Ramsey-Musolf ‘09
Kozaczuk, Profumo, Ramsey-Musolf ‘12

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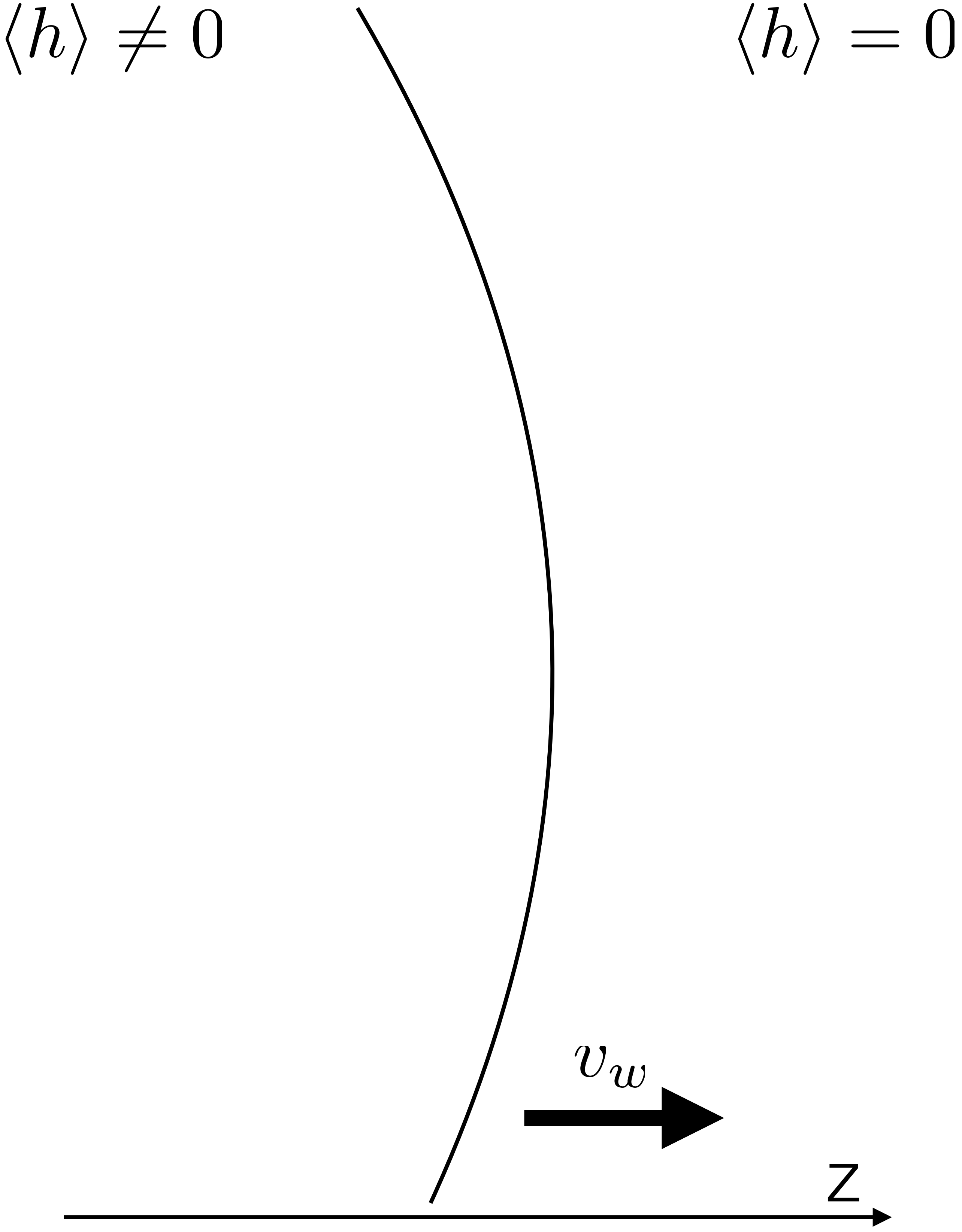
- Out-of-equilibrium
  - ➡ Strong first-order electroweak phase transition

Electroweak baryogenesis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$\langle h \rangle = 0$
v_w
z

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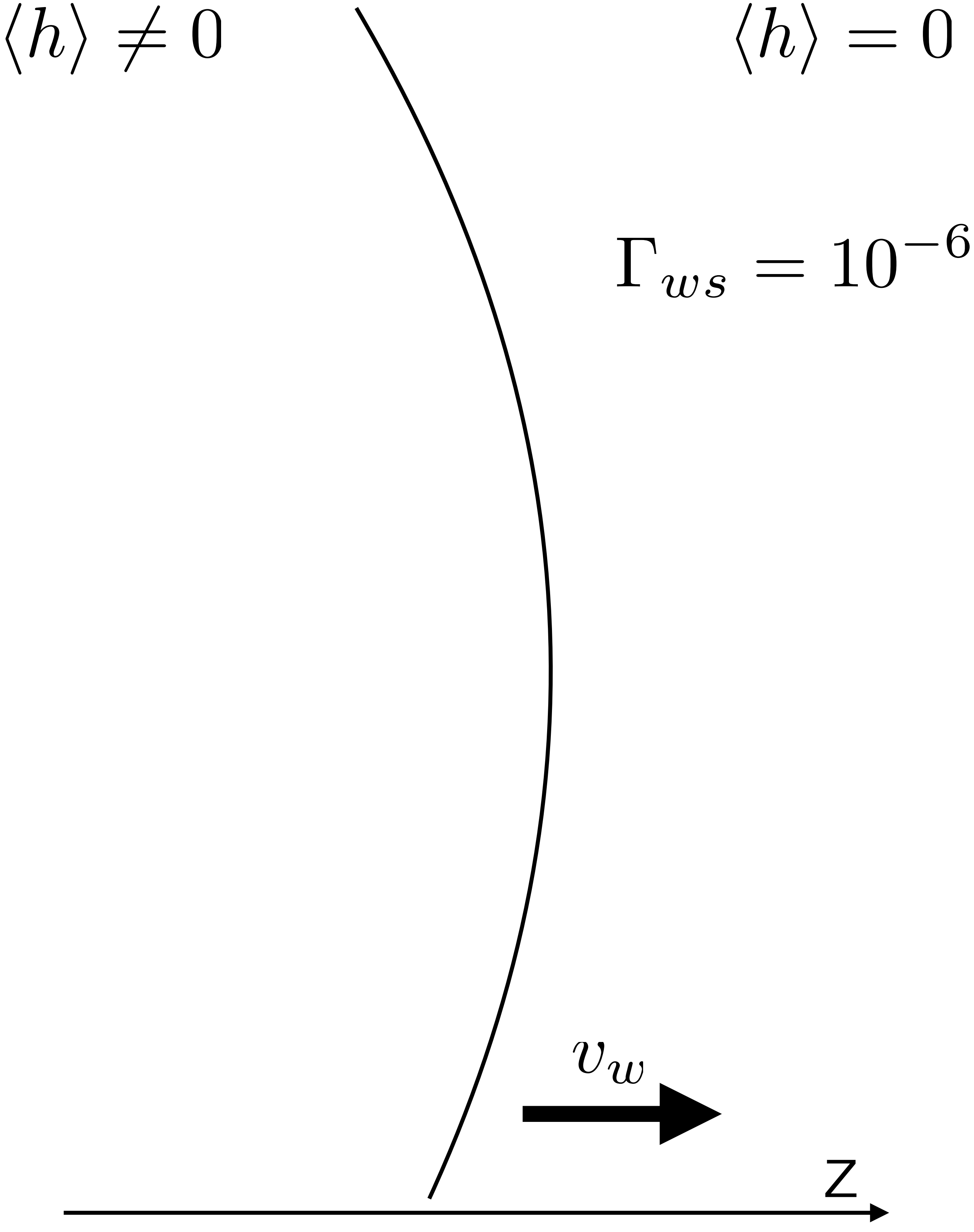
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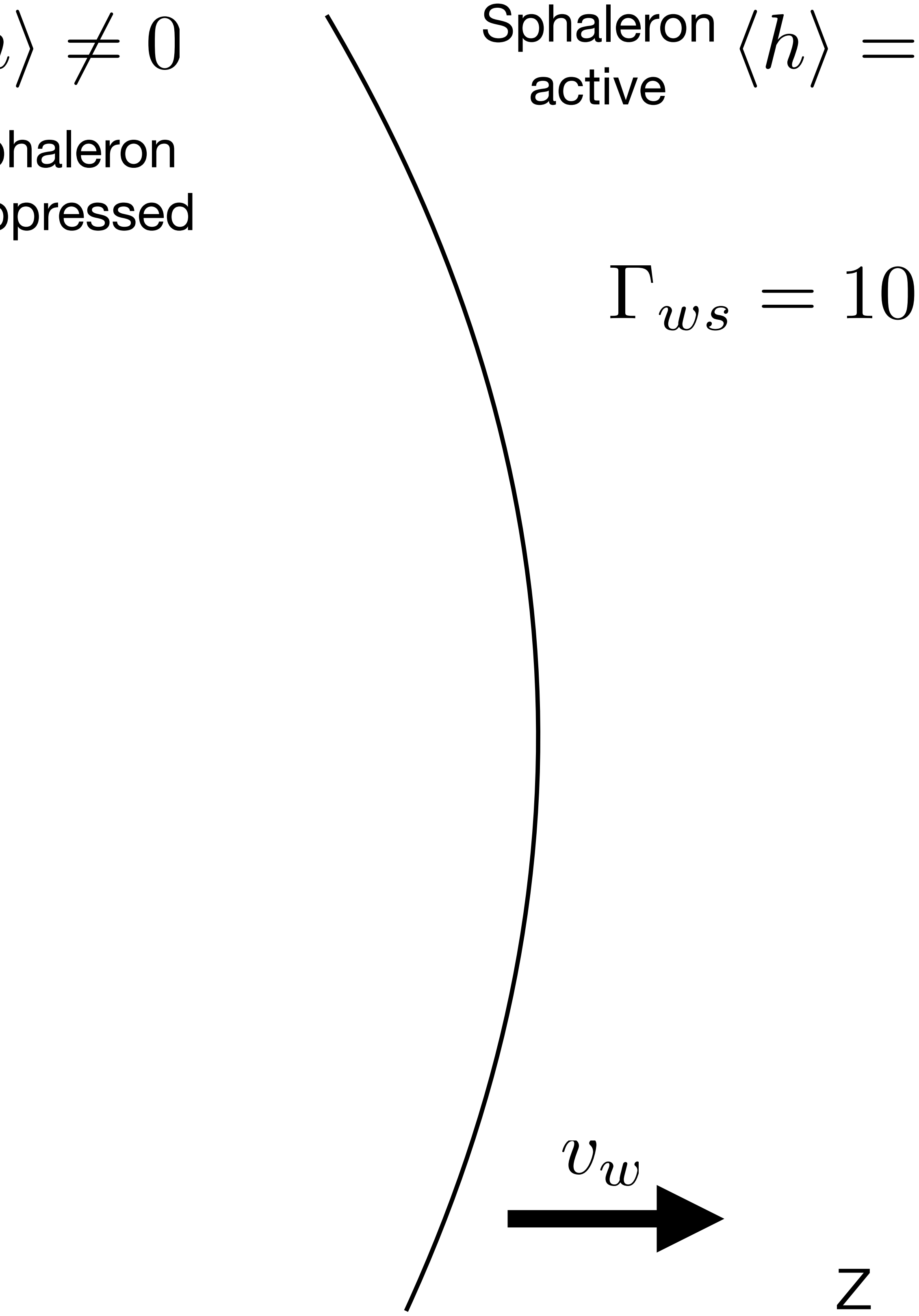

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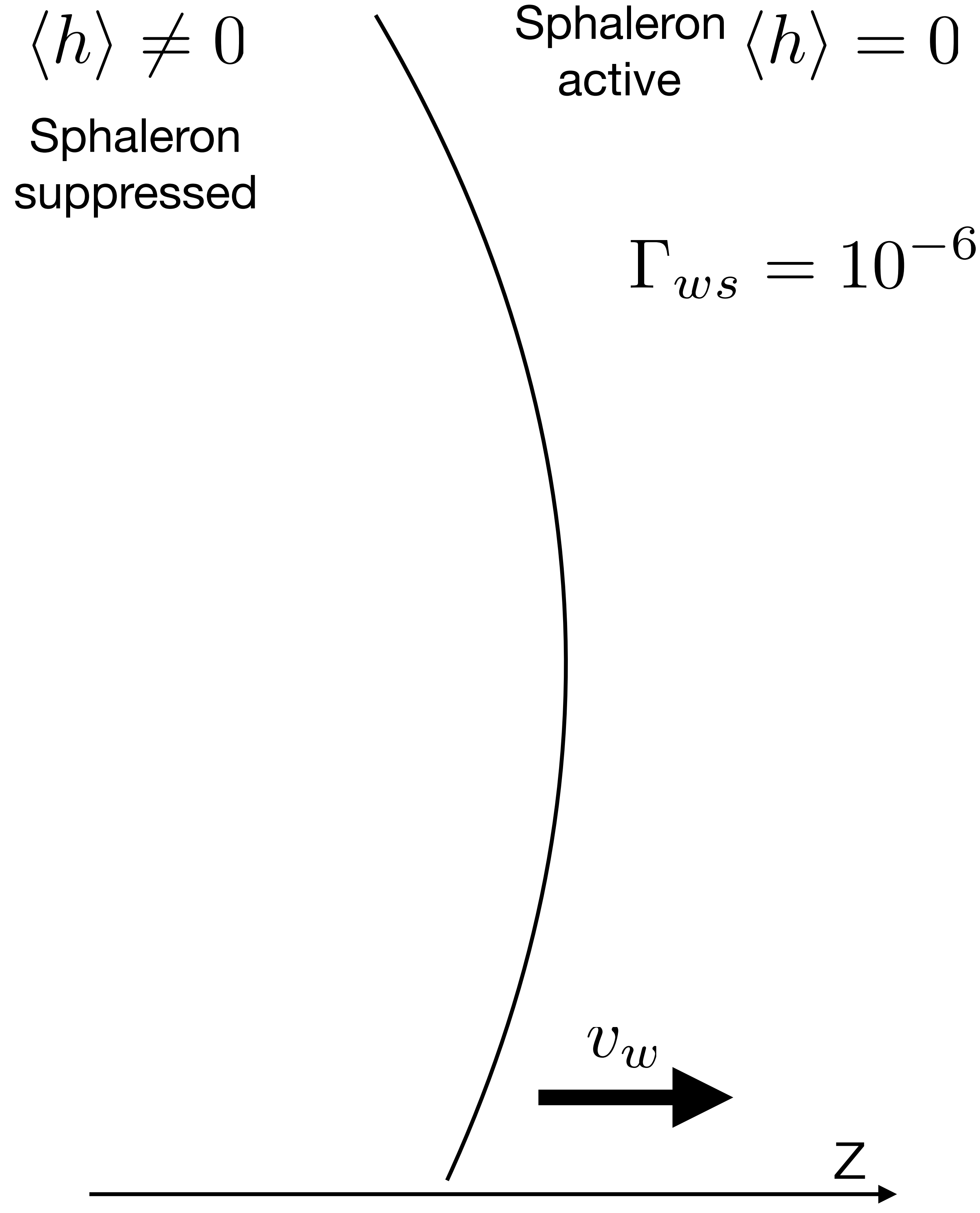

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$$\Downarrow$$

$$\frac{h(-\infty)}{T} \geq 1$$

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z

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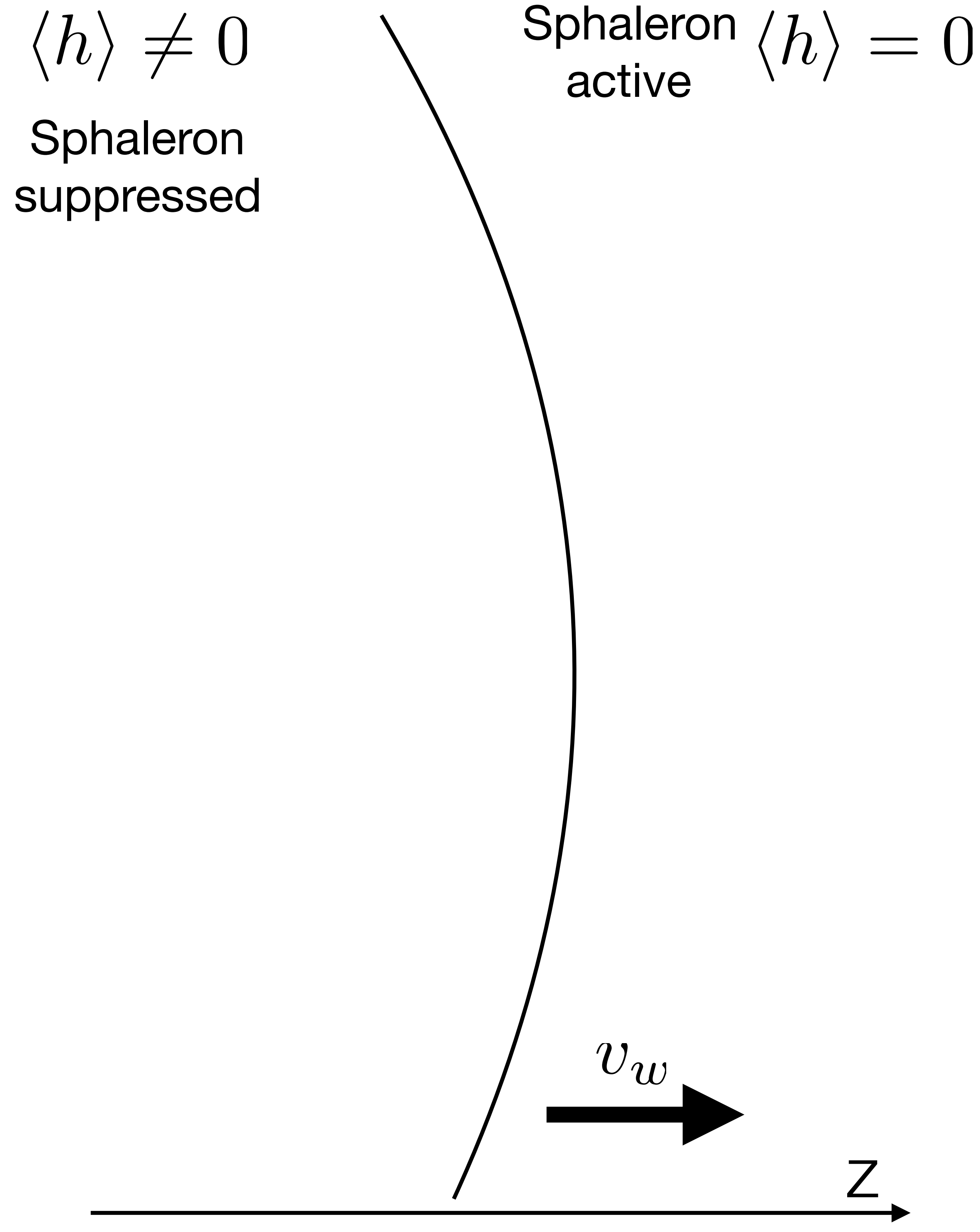

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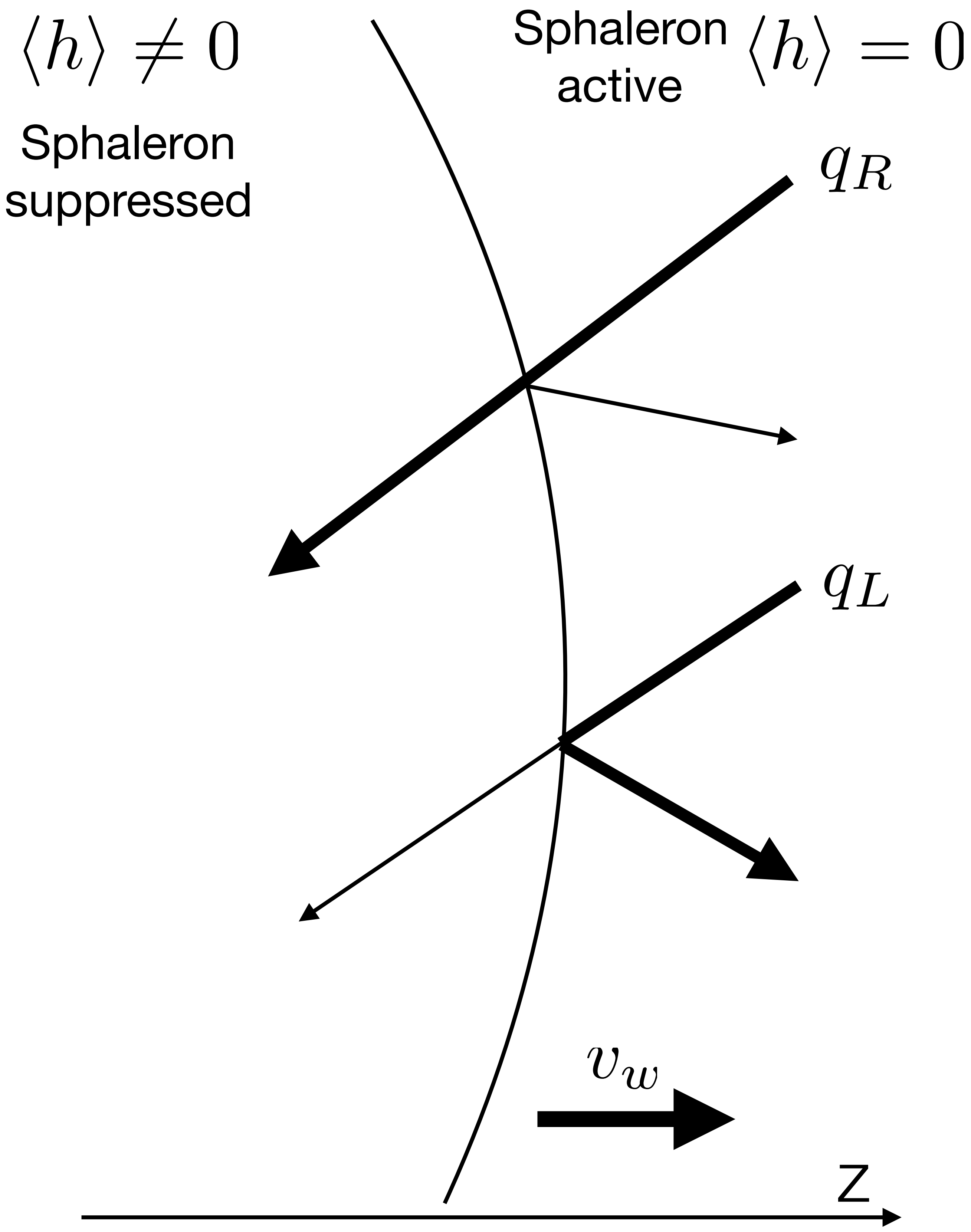
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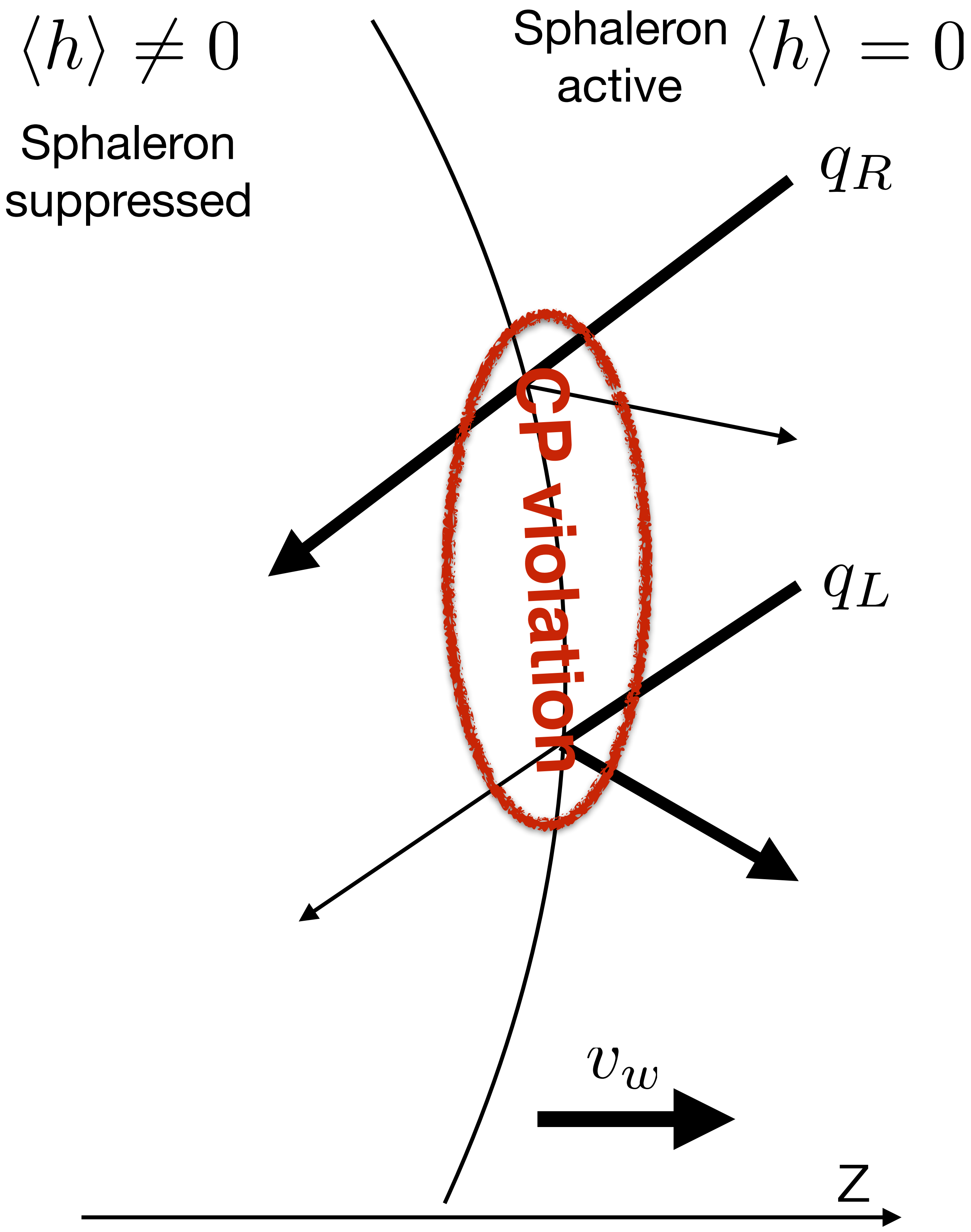
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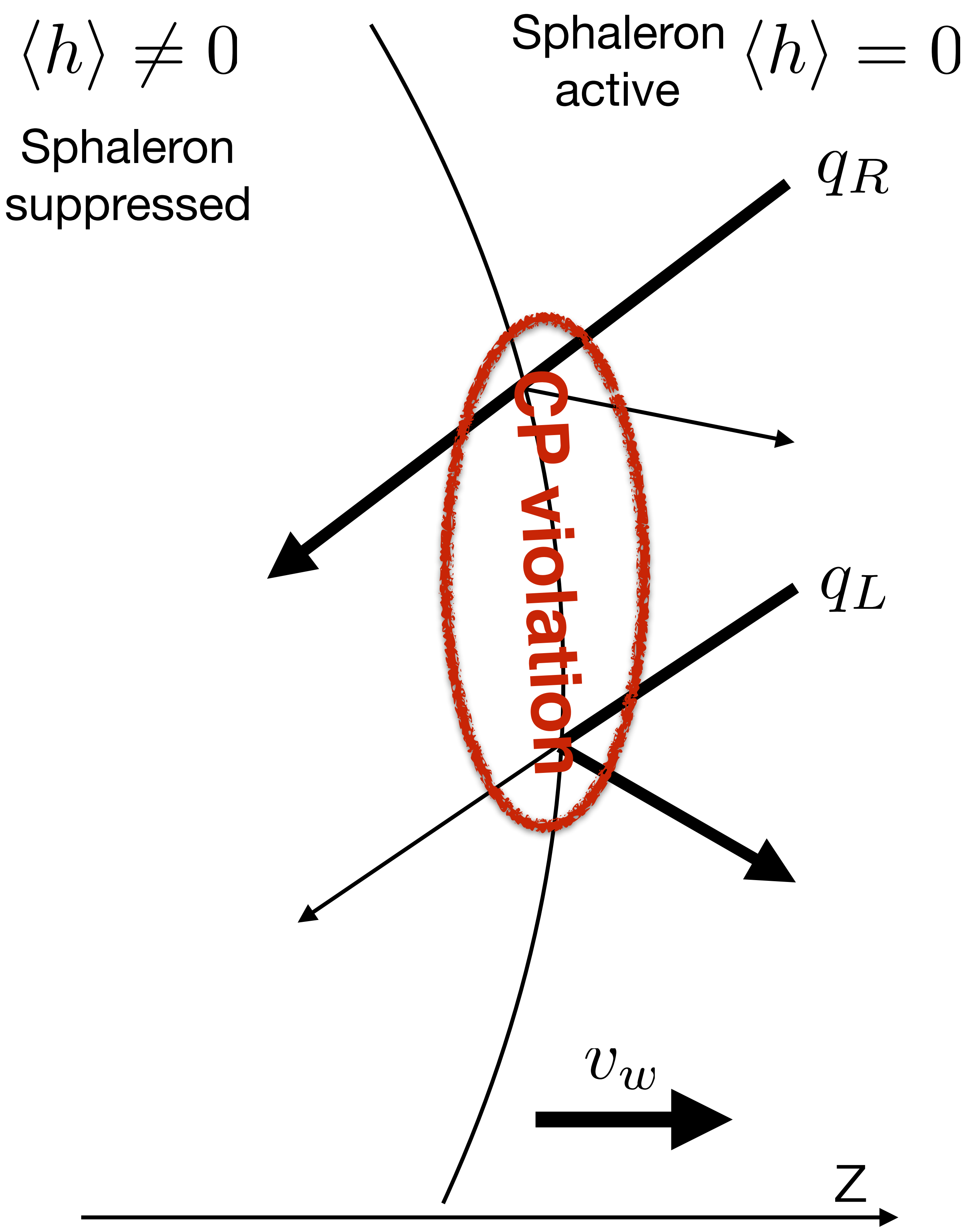
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where V s.t. $V^\dagger m^\dagger m V$ is diagonal

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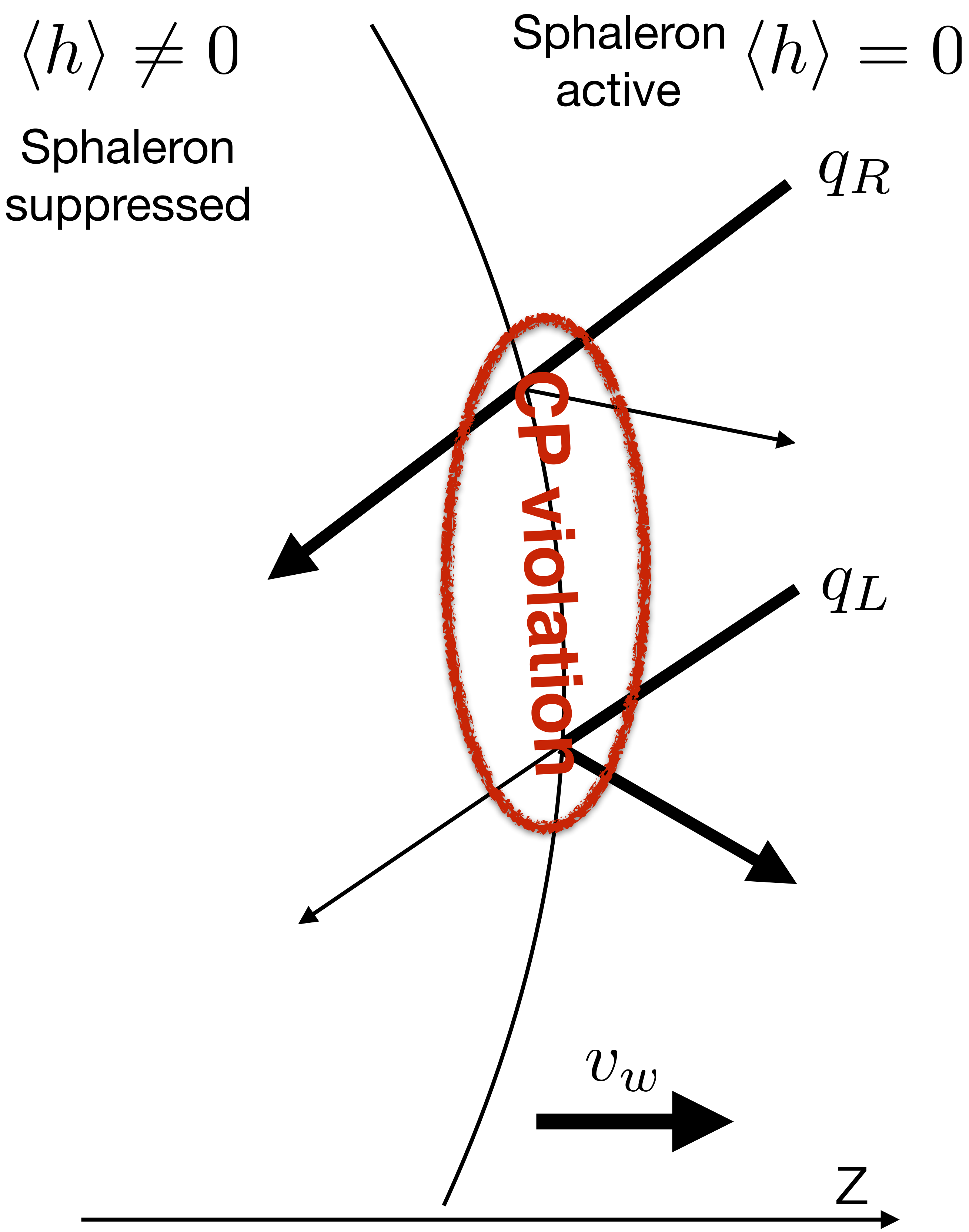
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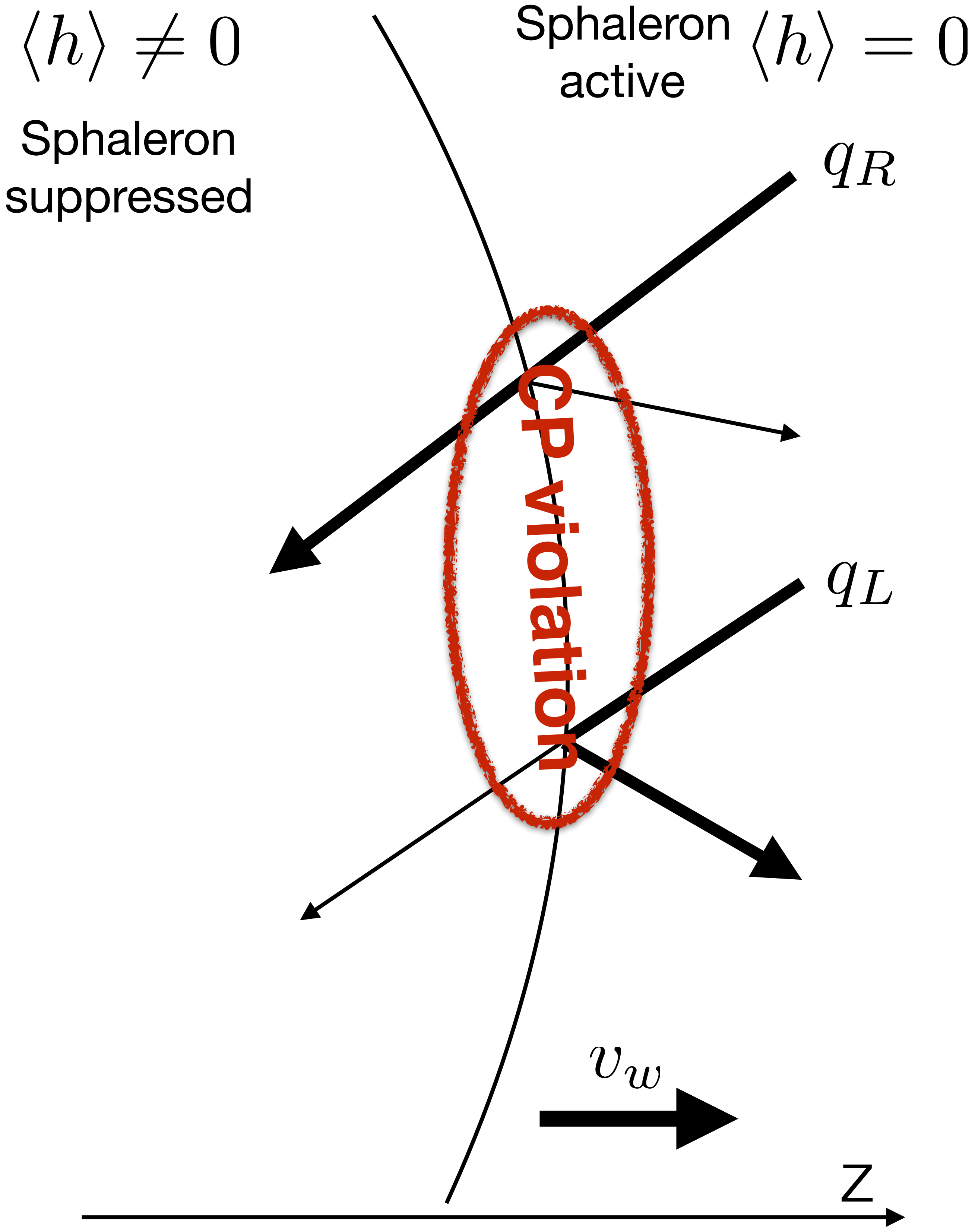
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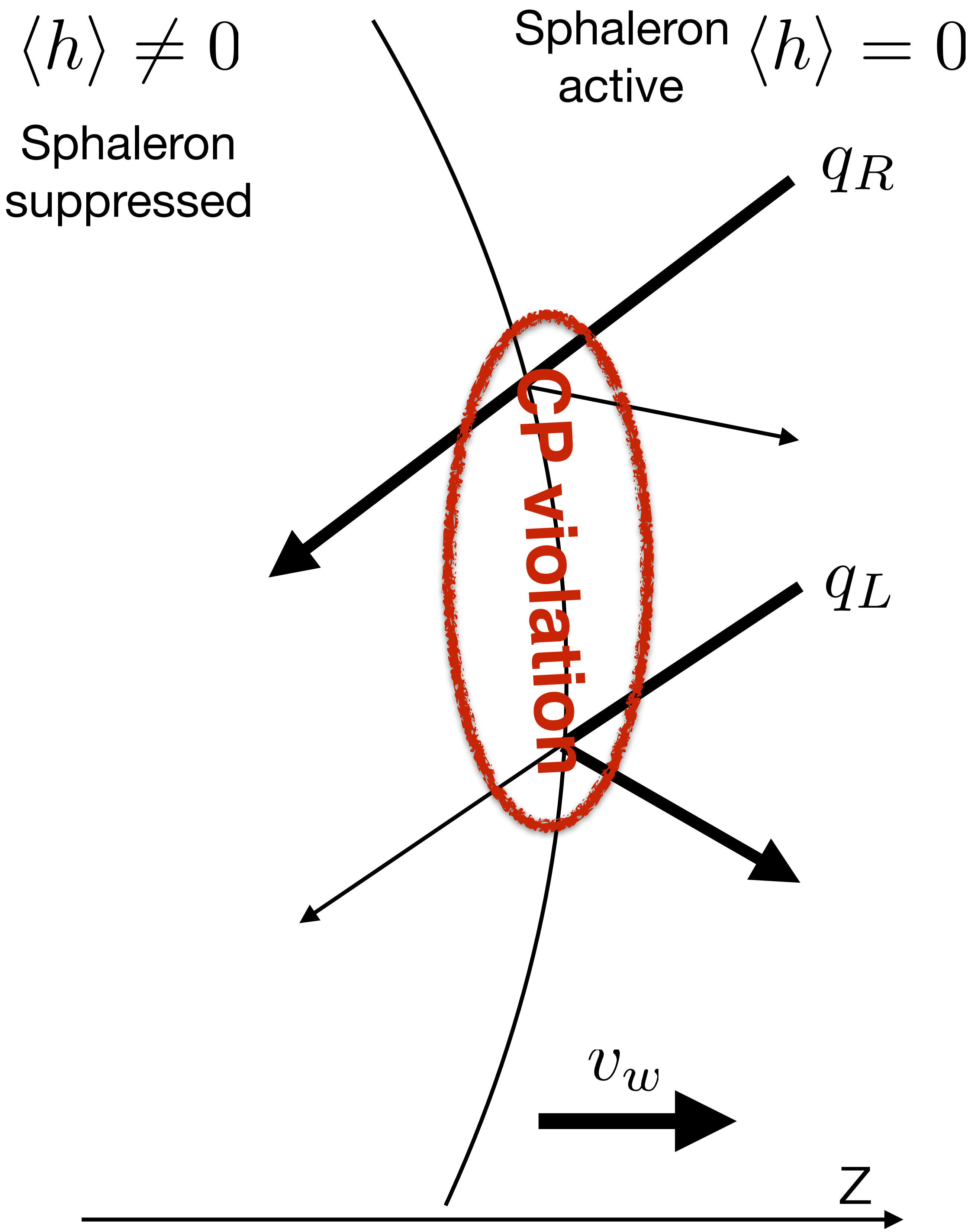
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- Only active during the variation of Yukawas
- Connection between flavour and Higgs physics: Froggat-Nielsen, Randall-Sundrum, Composite Higgs, …

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- Mass gap: Higgs is a PNGB of symmetry breaking $\mathcal{G}/\mathcal{H}$

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Variation of Yukawa couplings for CP-violation

Strong first-order electroweak phase transition

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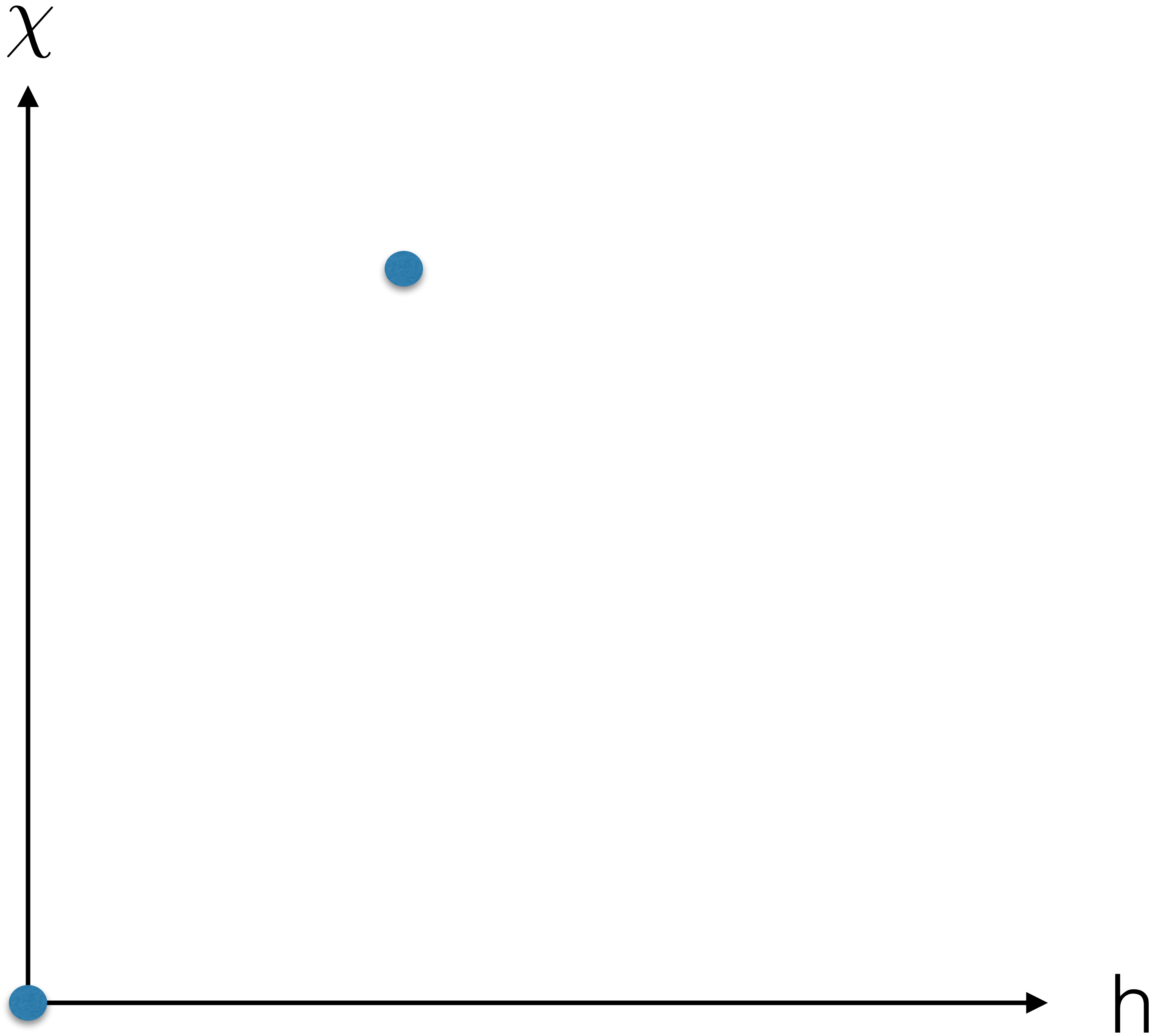
Strong first-order electroweak phase transition

- What CH naturally provides:

Varying Yukawas through partial compositeness

Joint confinement-electroweak phase transition

Studying the phase transition in the Dilaton-Higgs potential



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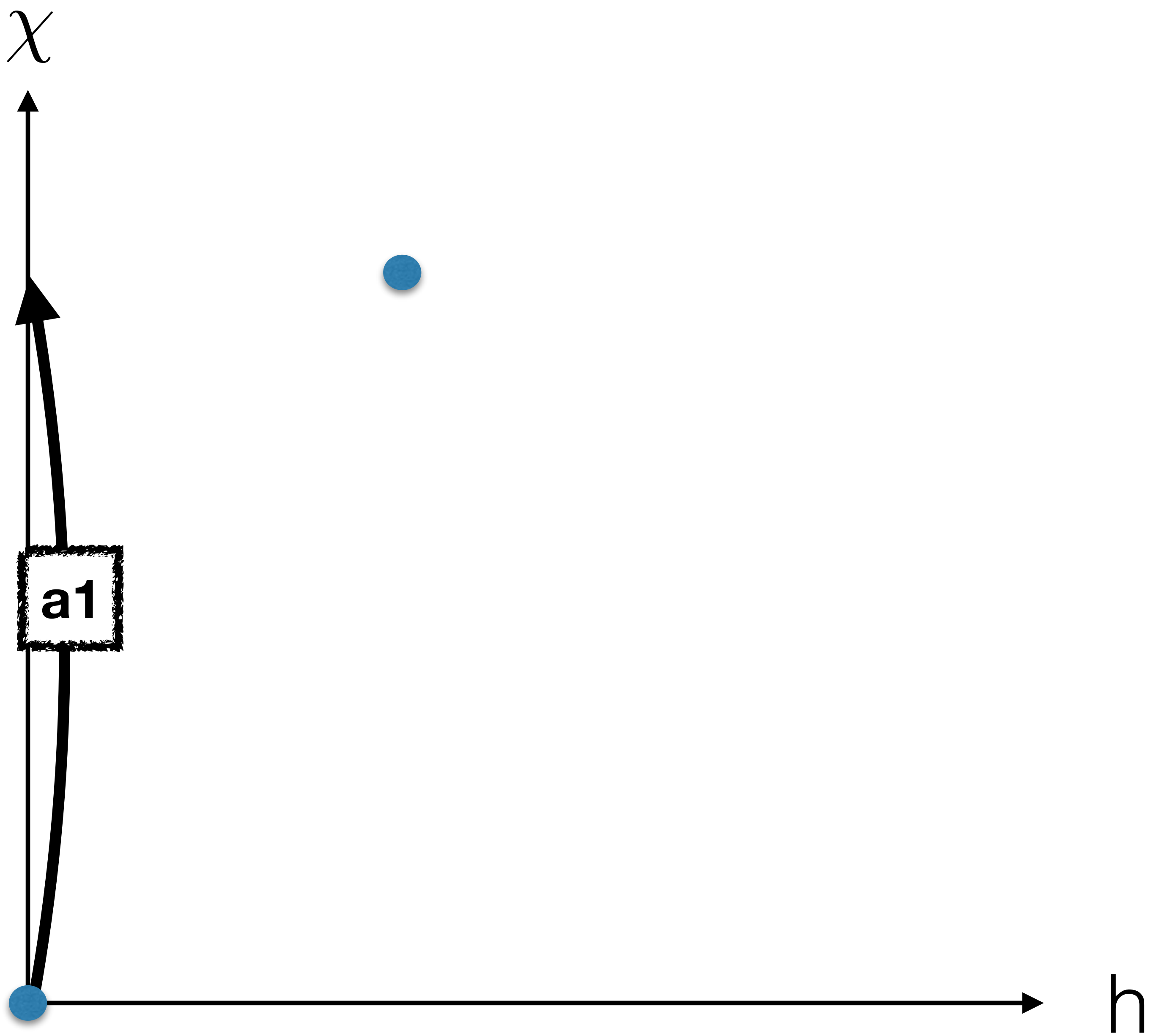

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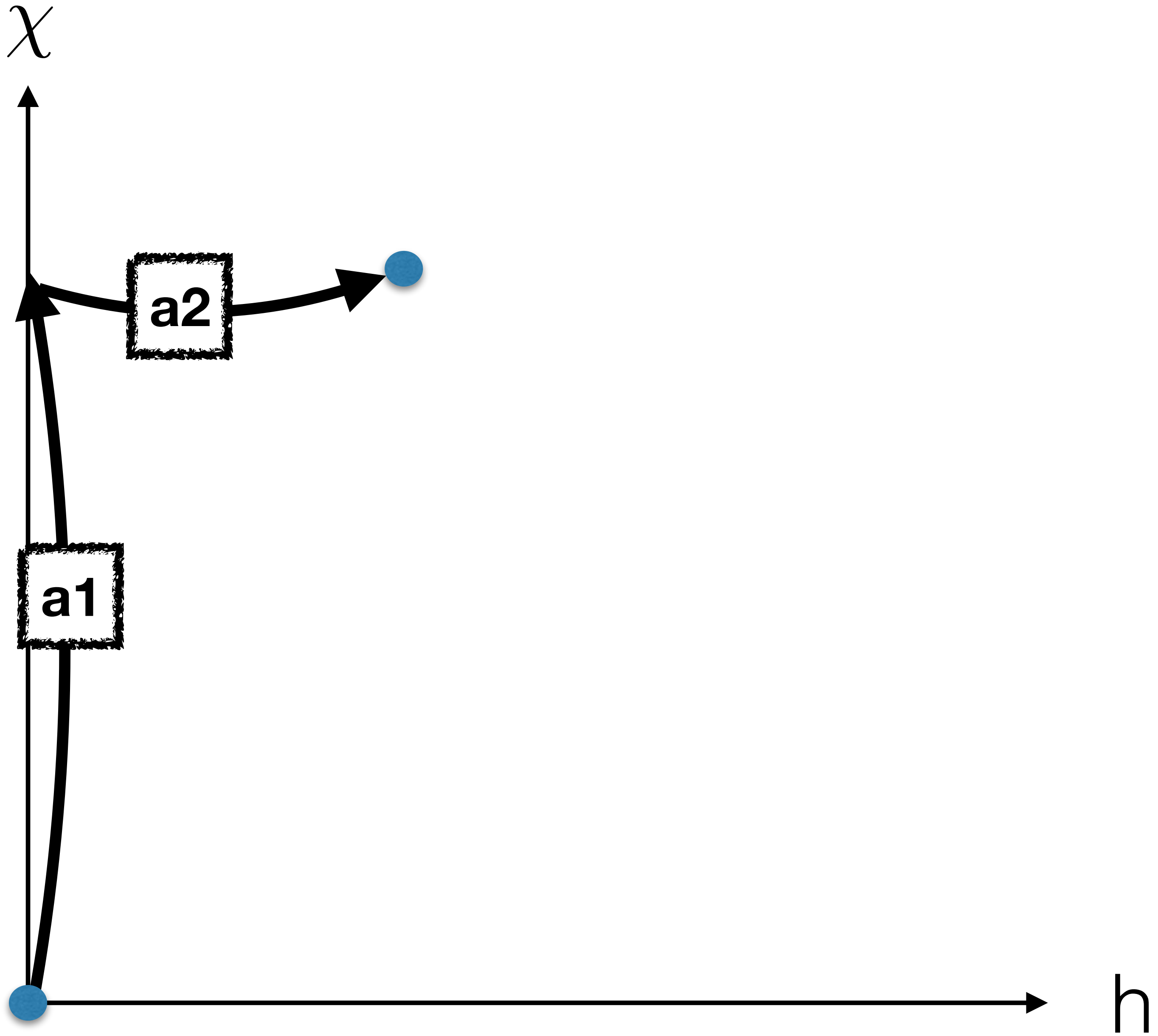

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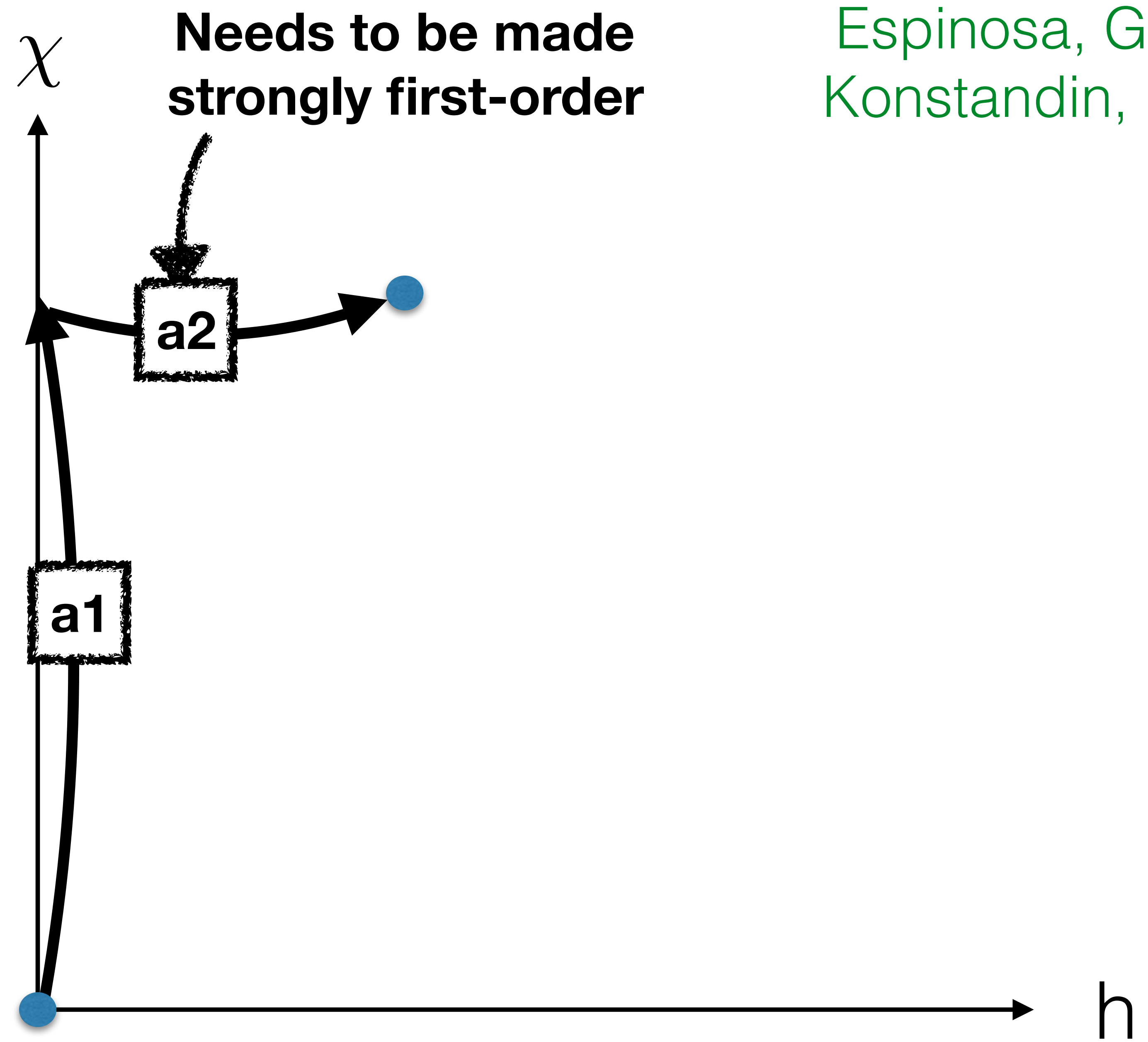
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Espinosa, Gripaios,
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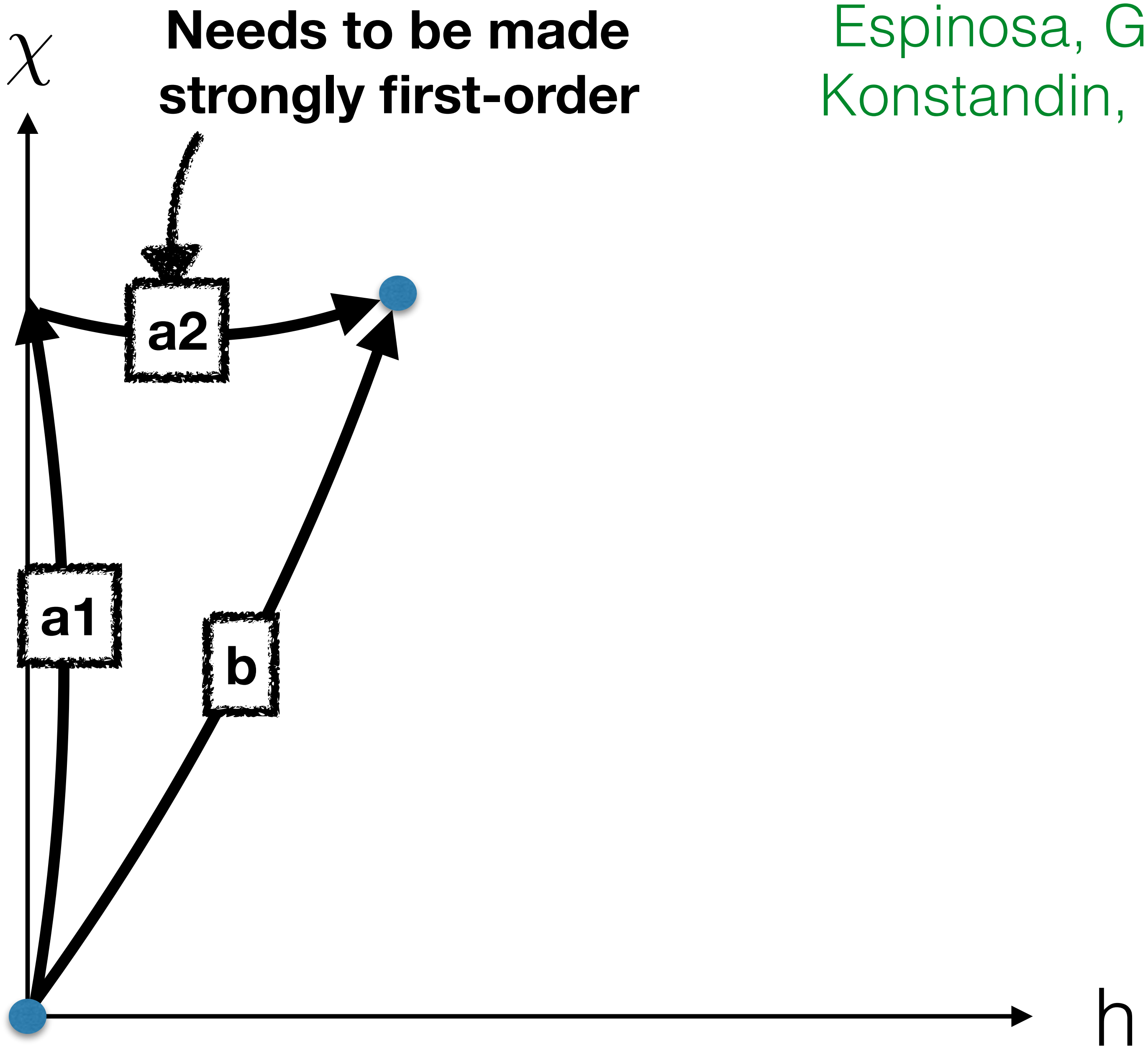
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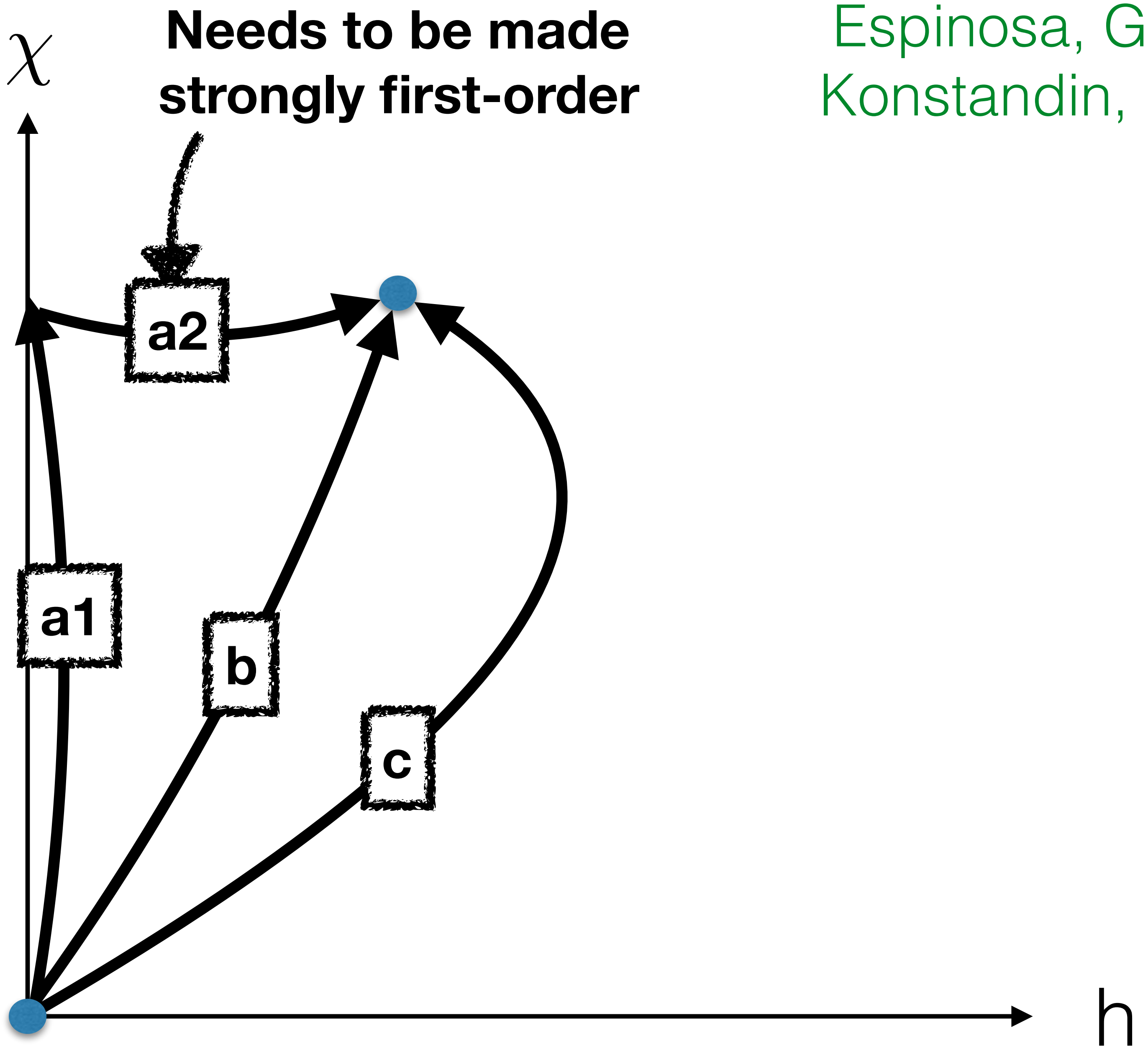
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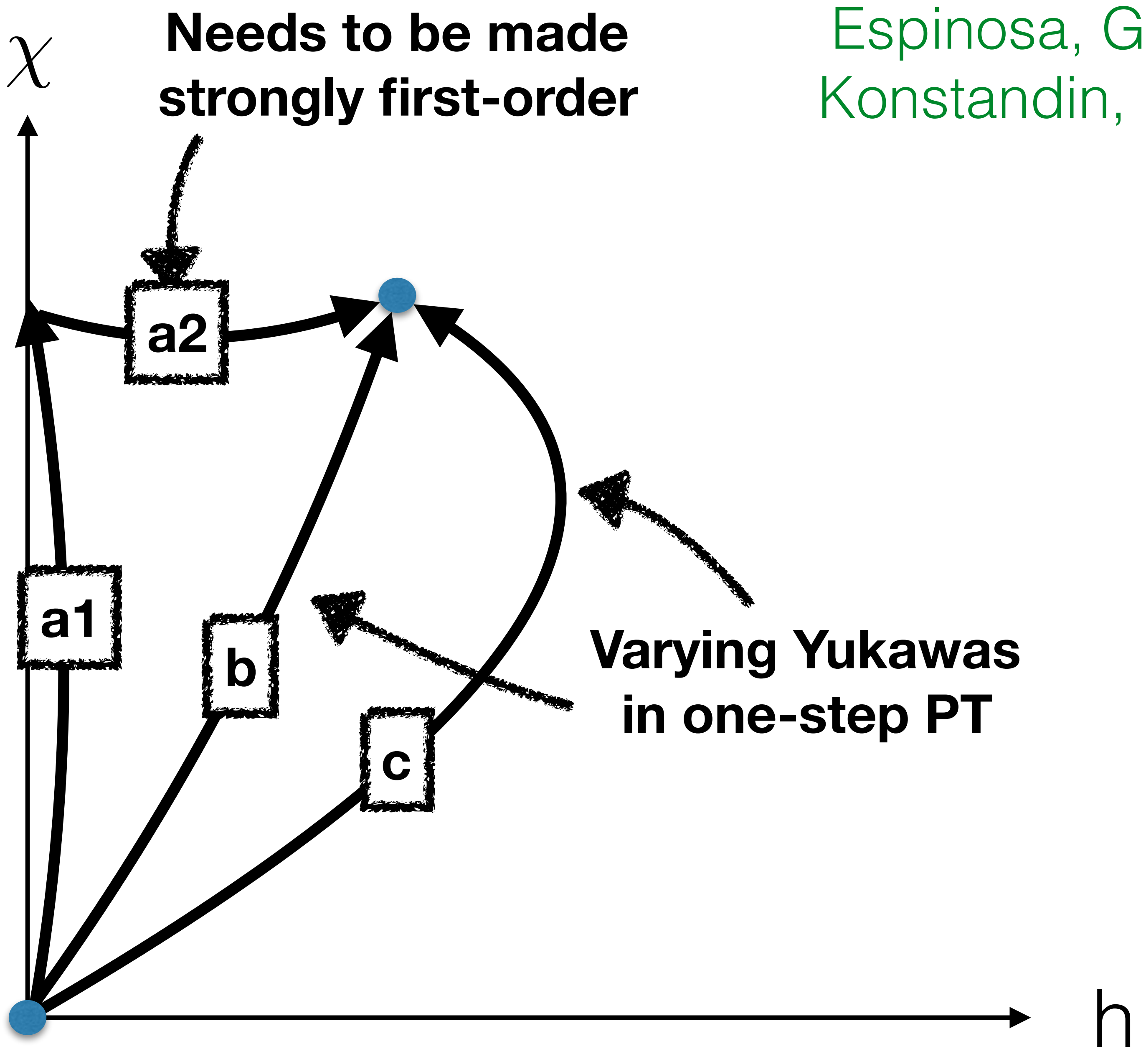
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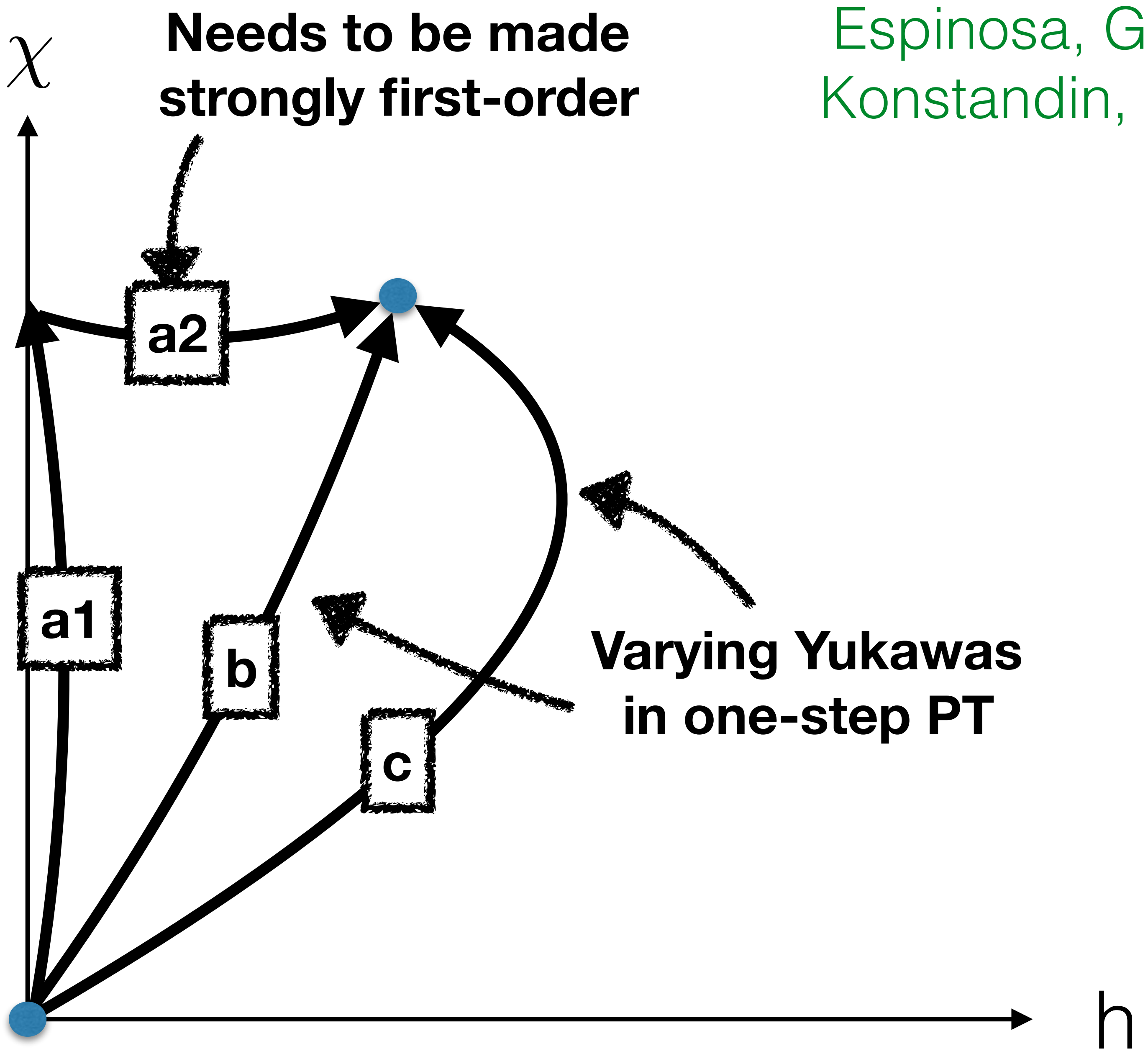
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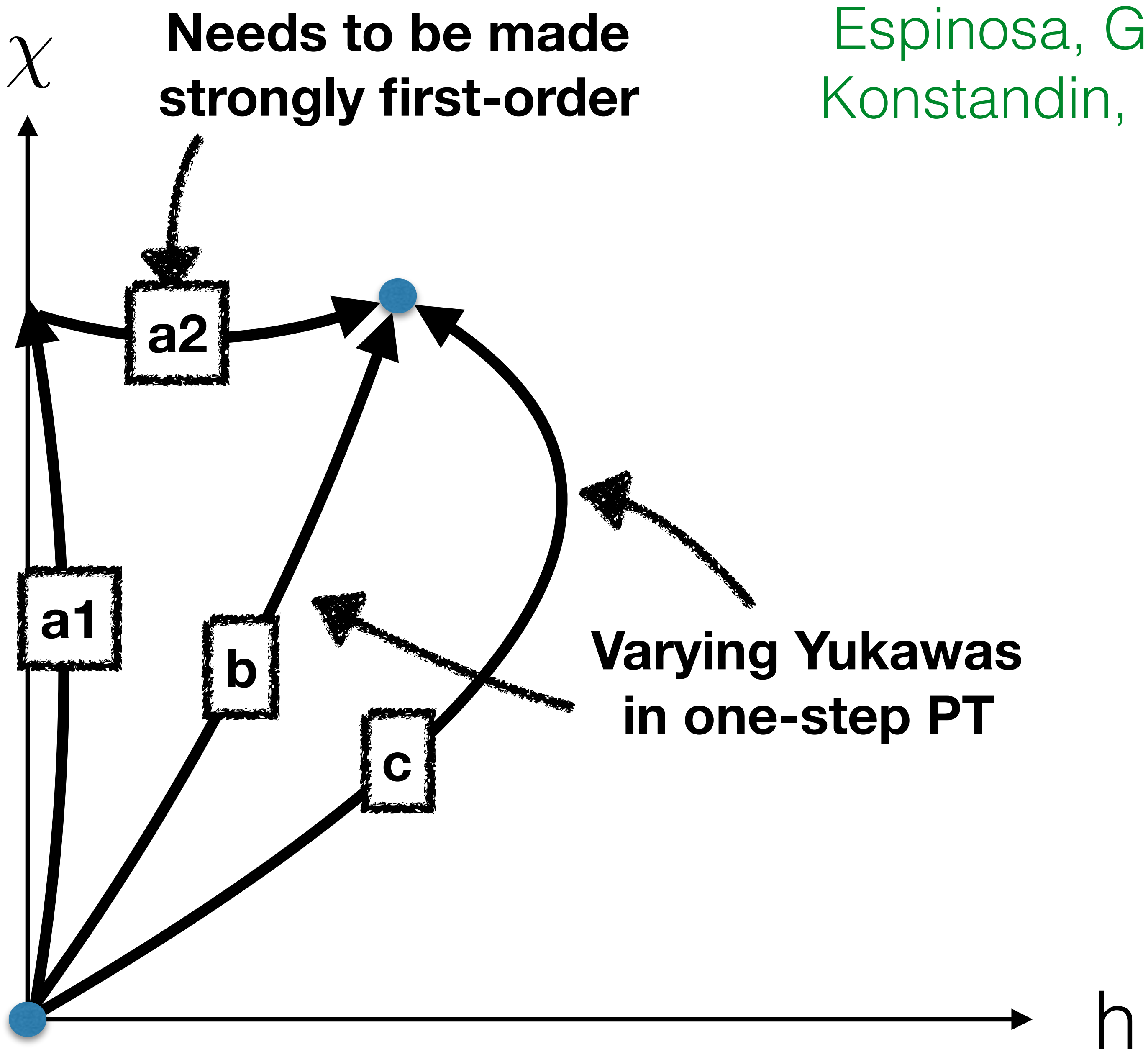
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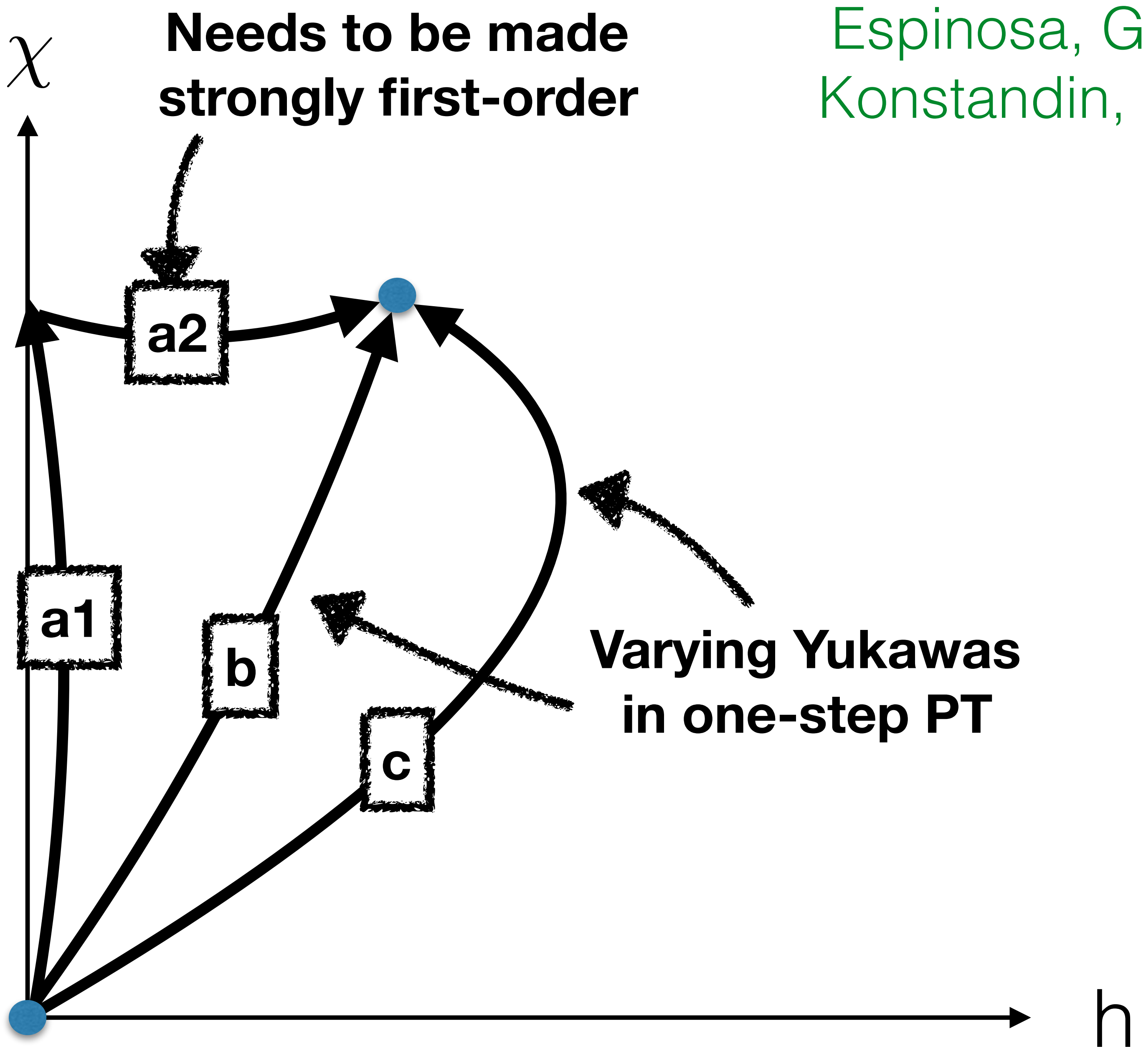
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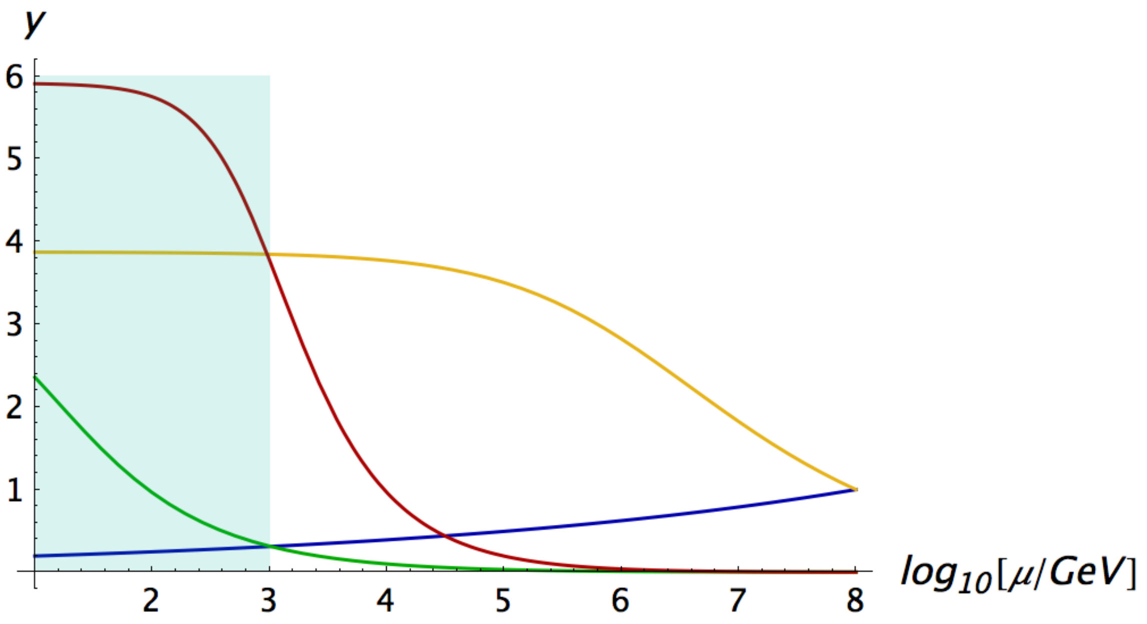

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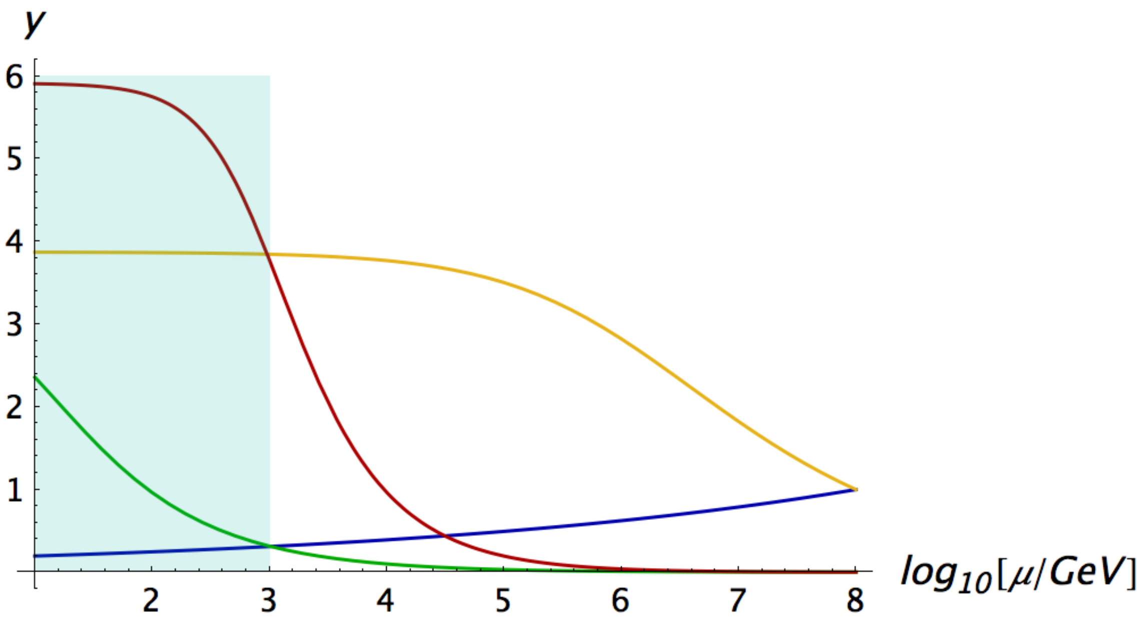

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$\alpha, \beta < 0 \quad \Rightarrow$ **valley along** $h/\chi \sim \pi/2$ **Trajectory c**

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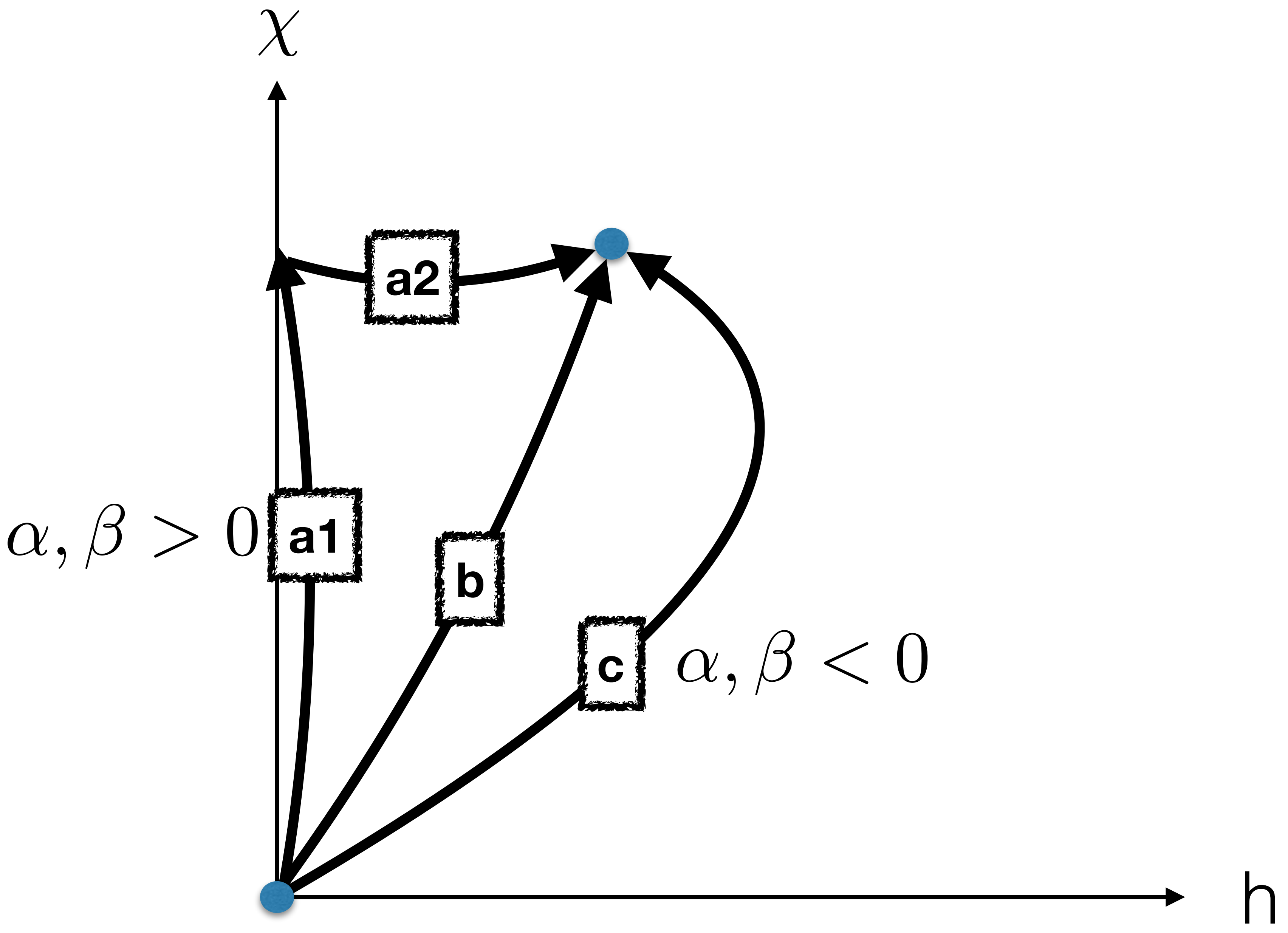
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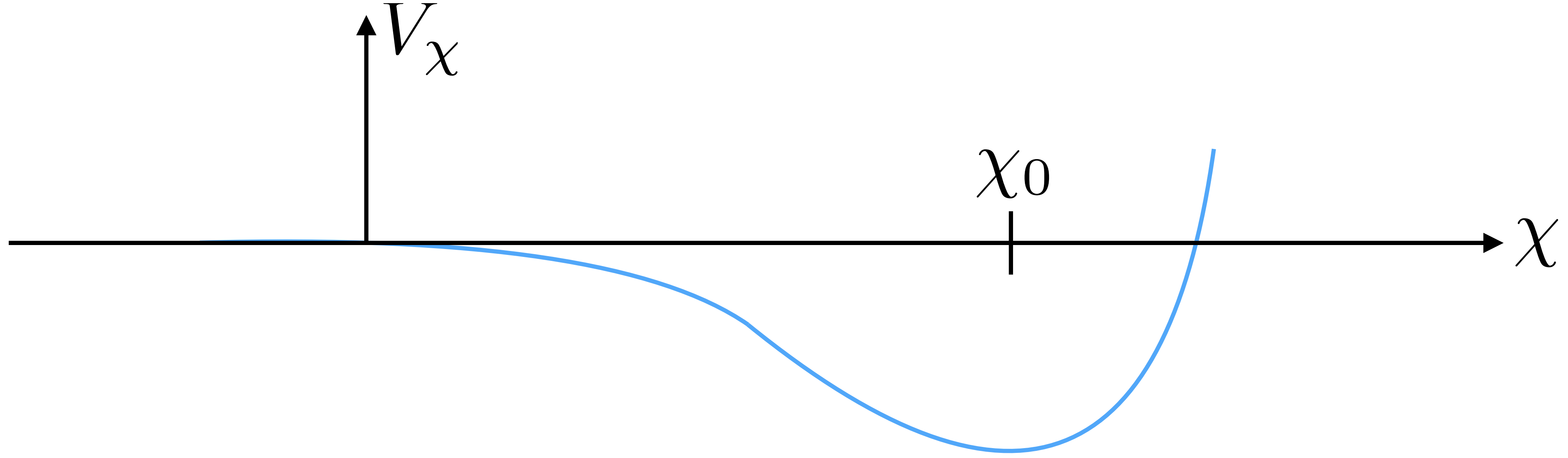
Conformal symmetry breaking

The vev of the dilaton sets the scale of the strong sector:

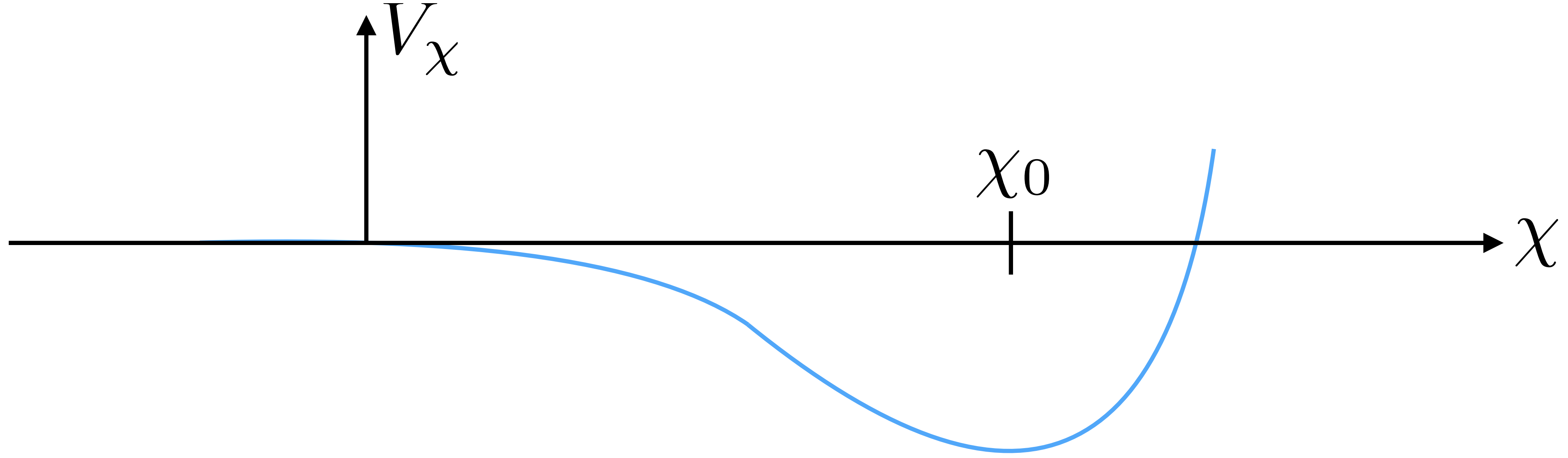


Need small explicit breaking of conformal symmetry

$$V_\chi = c_\chi g_\chi^2 \chi^4 \;.$$

Conformal symmetry breaking

The vev of the dilaton sets the scale of the strong sector:



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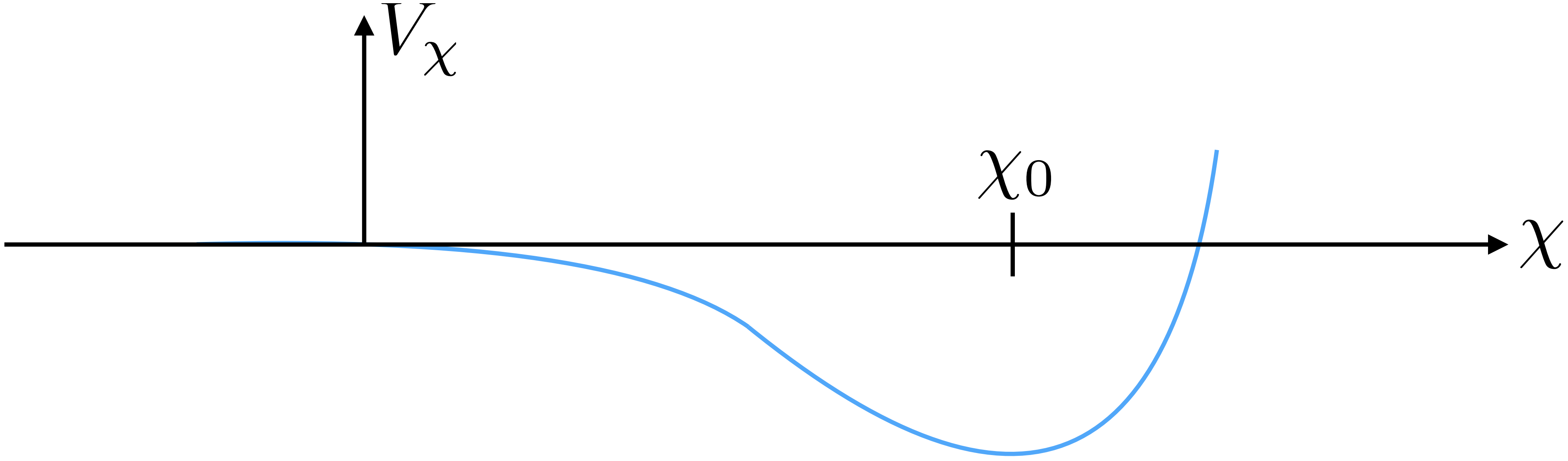

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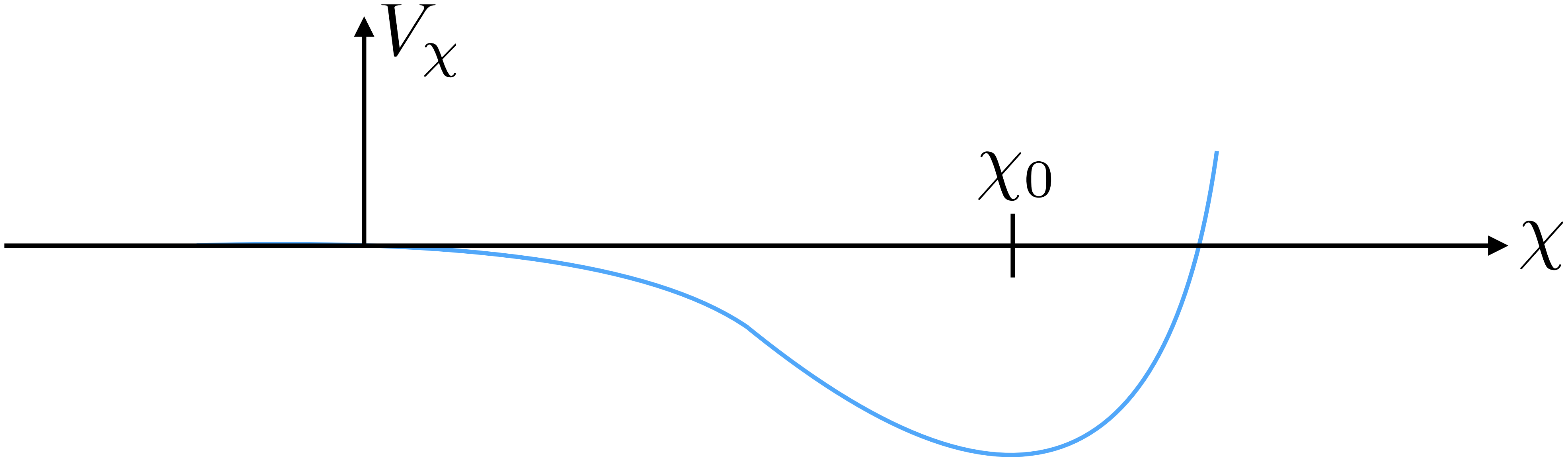

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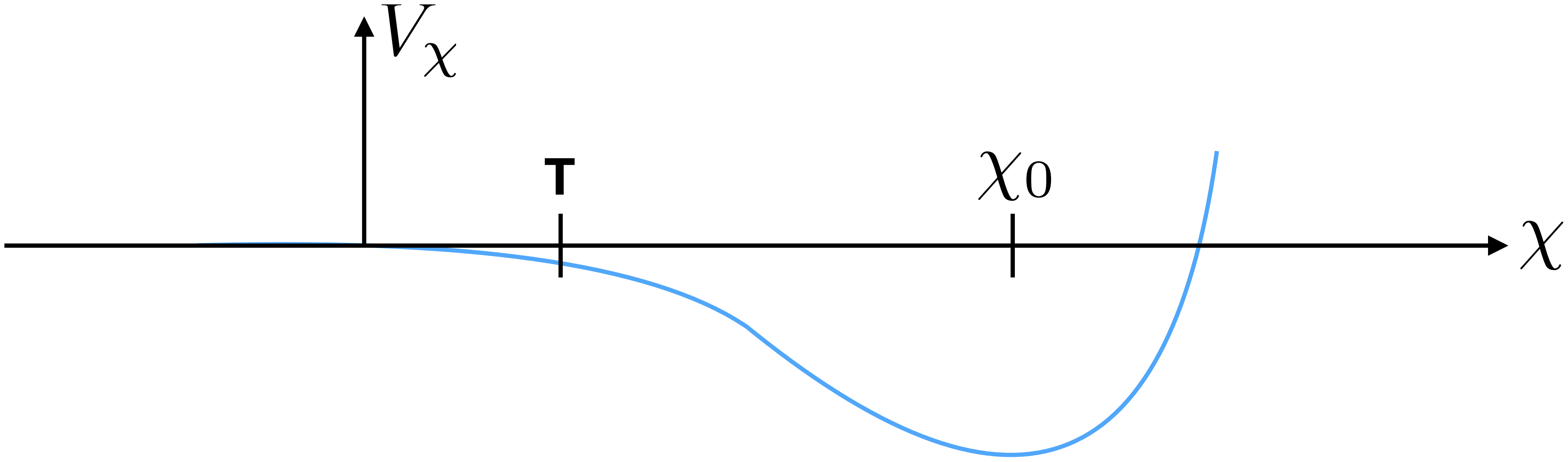

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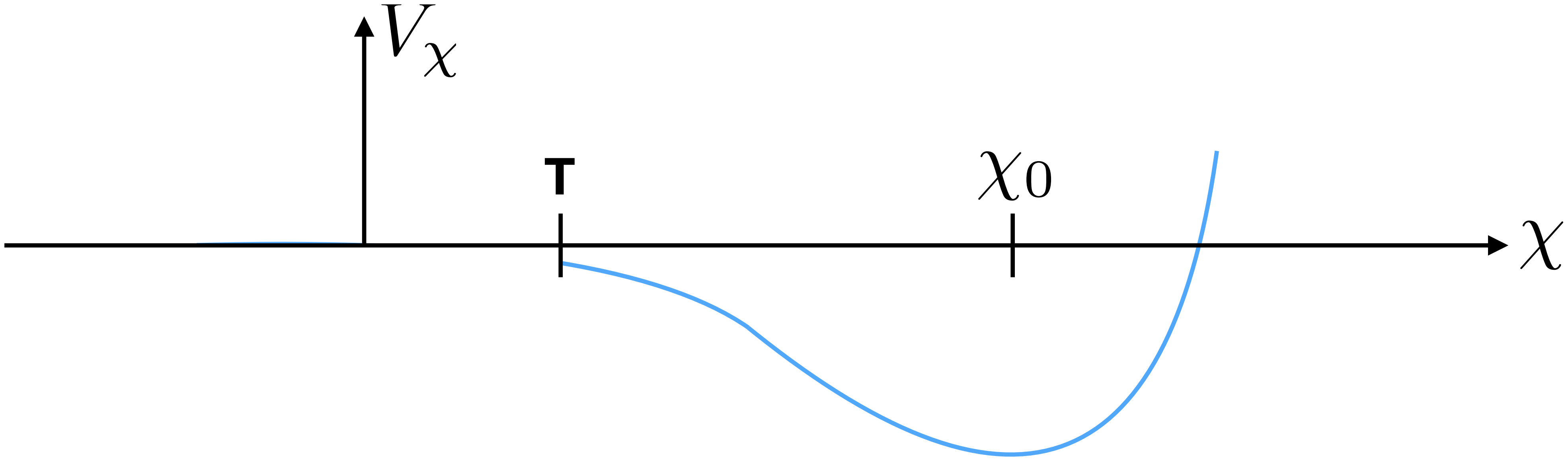

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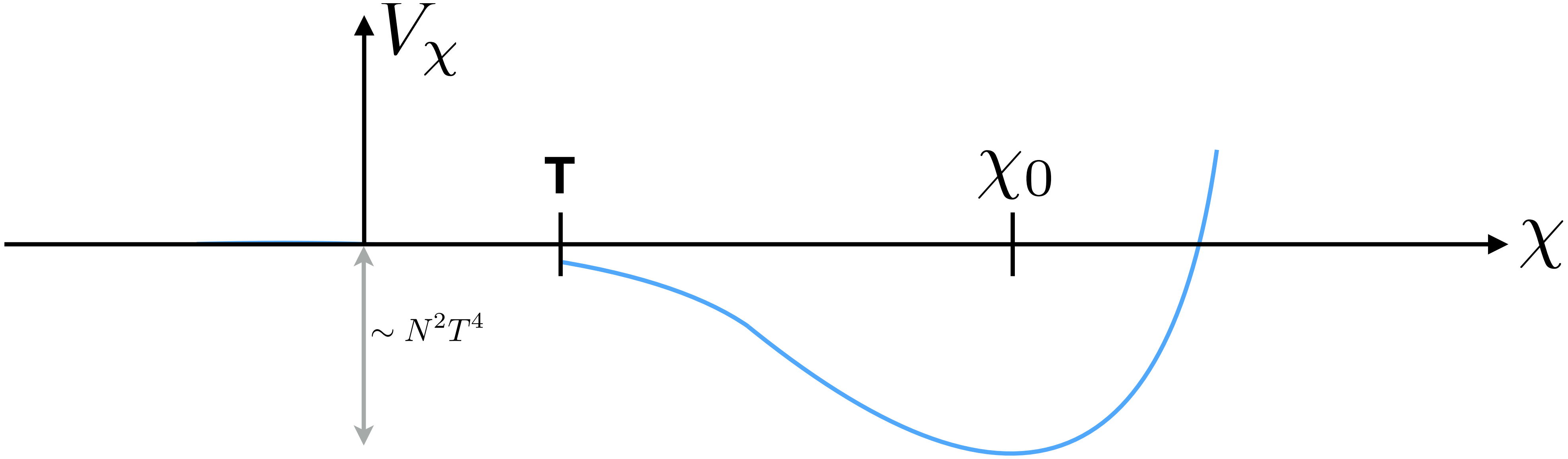

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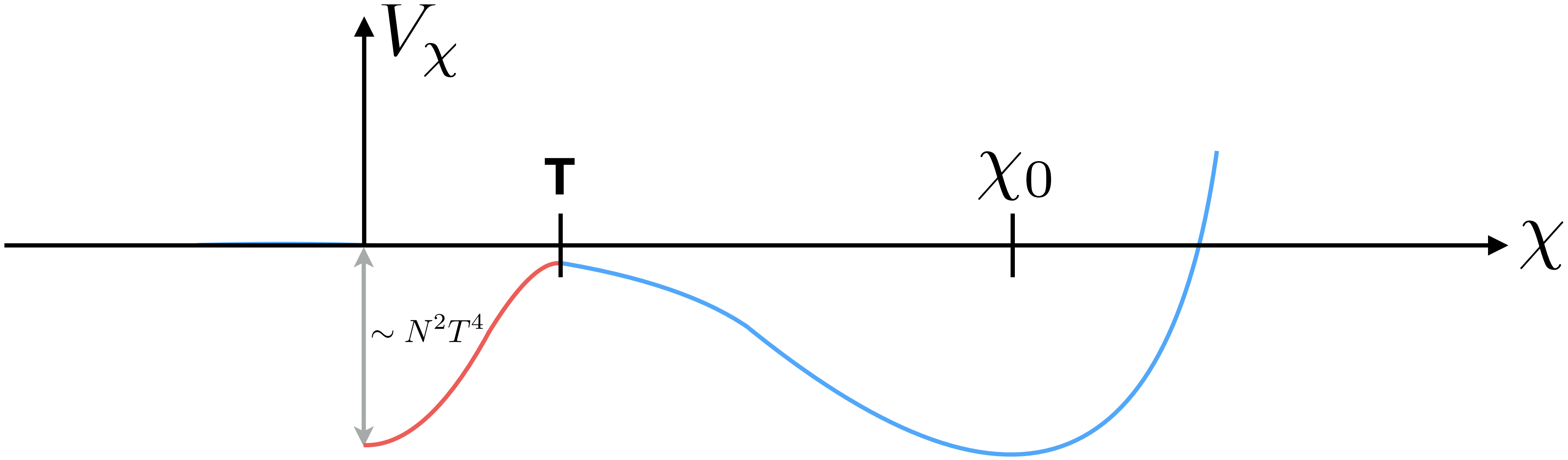

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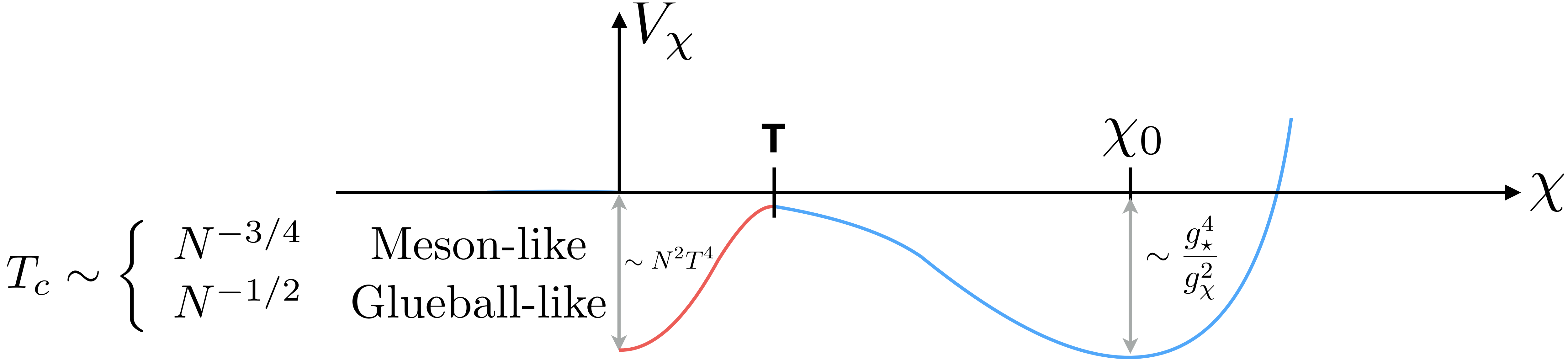

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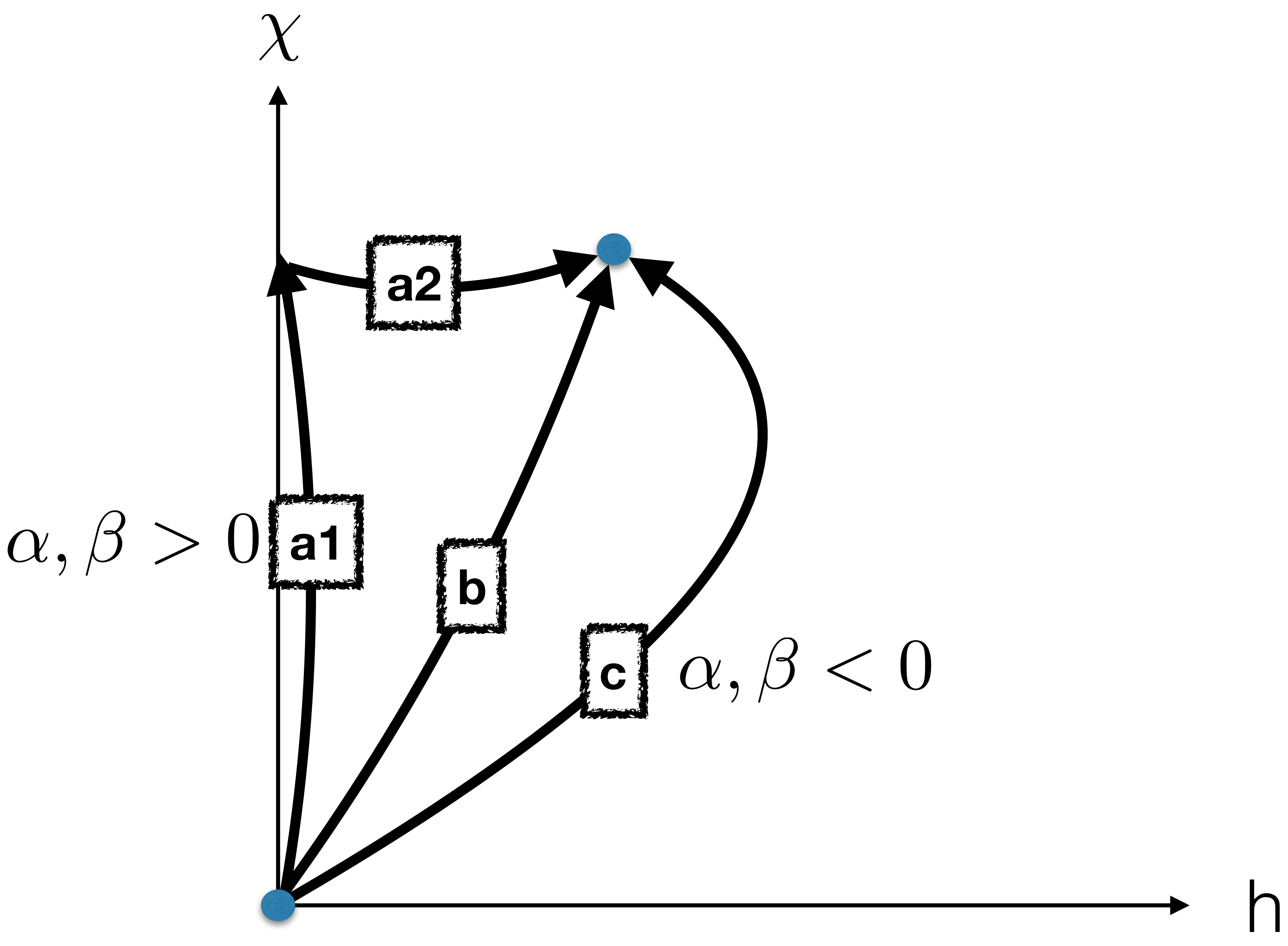
Studying the phase transition in the Dilaton-Higgs potential


χ
a2
a1
$\alpha, \beta > 0$
b
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h

- What are the conditions for trajectories b & c? ✓
- Is the confinement PT strongly first-order? ✓
- Is there enough CP violation along the trajectories b & c?

CP violation

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

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

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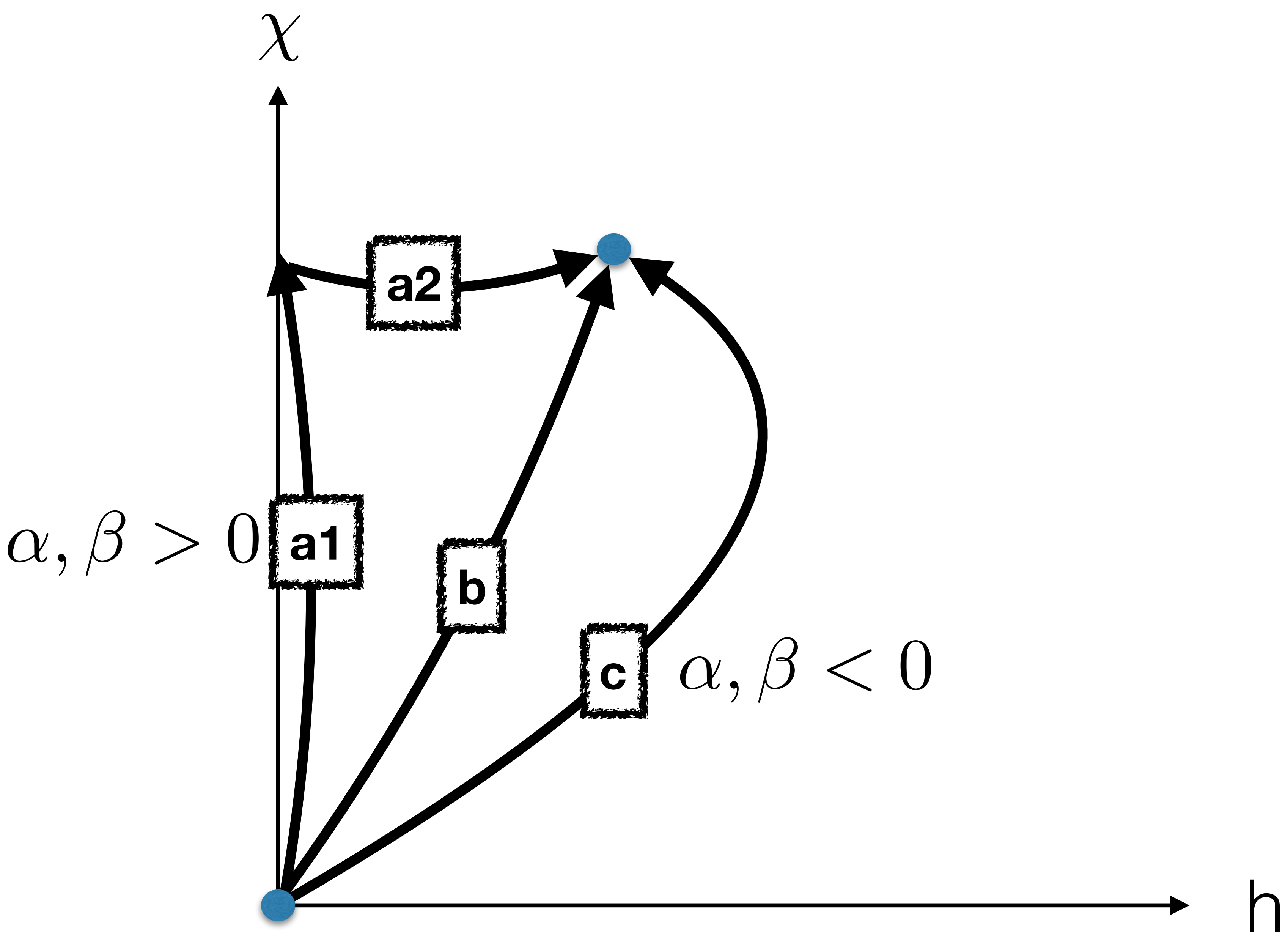
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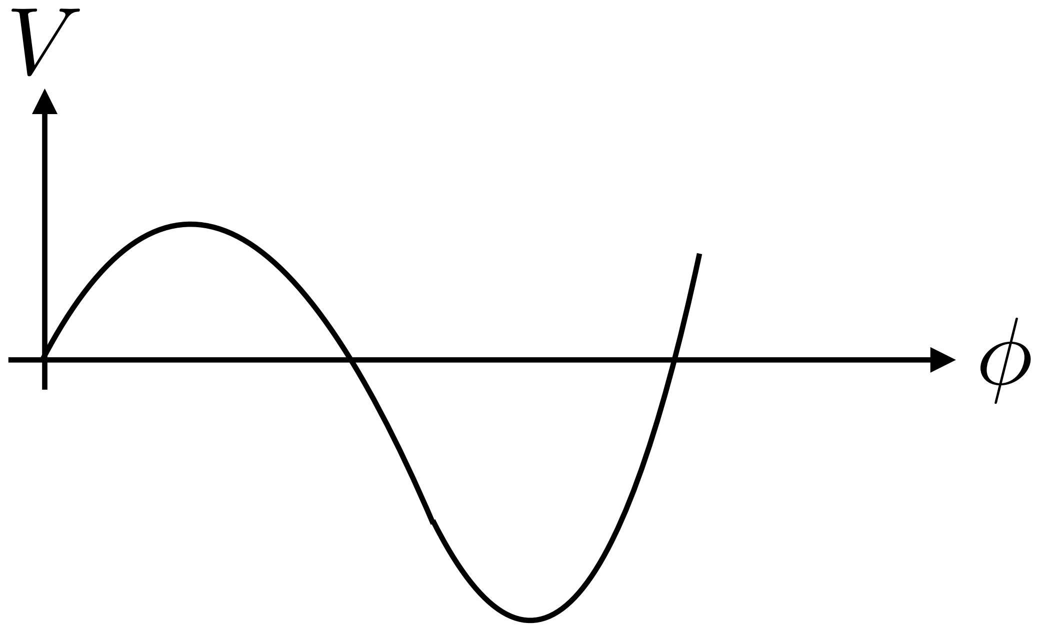
Two field tunneling

One field

$$S_E \sim 140$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{dr}^2} + \frac{\alpha}{r}\frac{\mathrm{d}\phi}{\mathrm{dr}} = V'(\phi)$$



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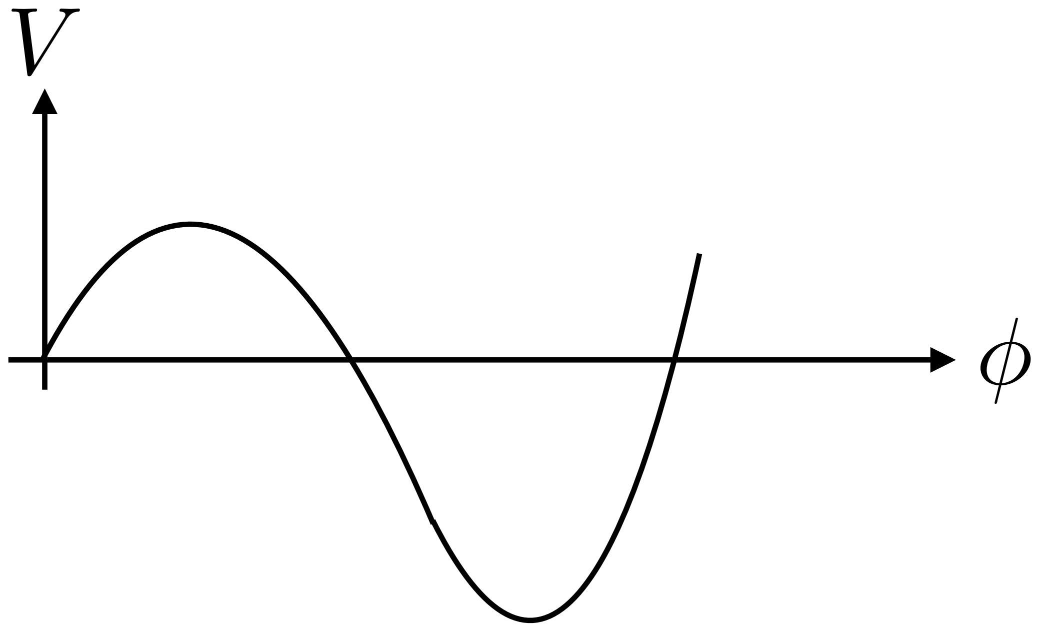

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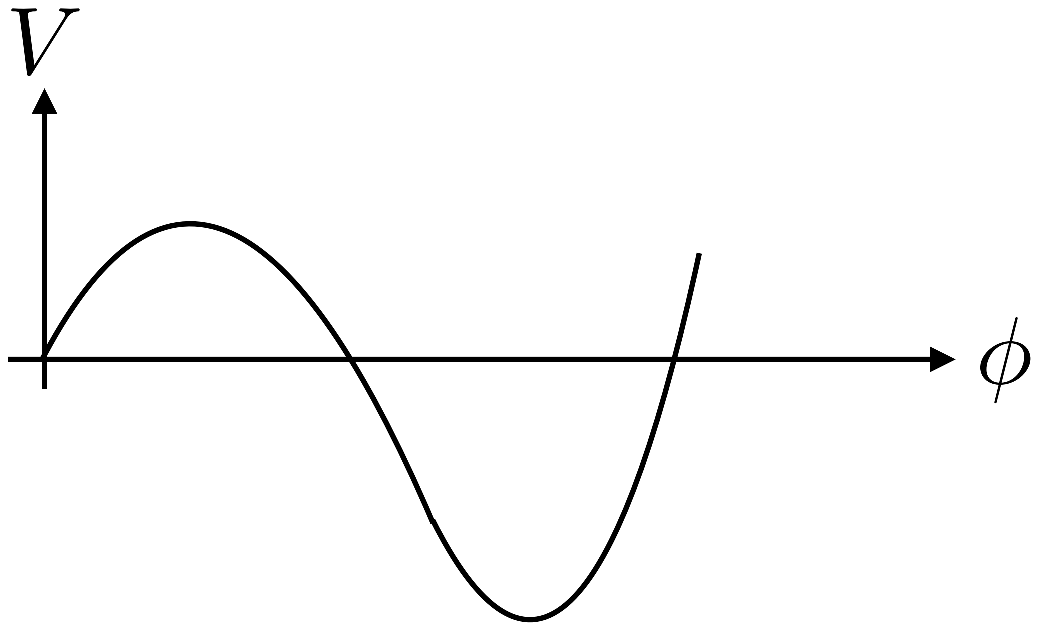

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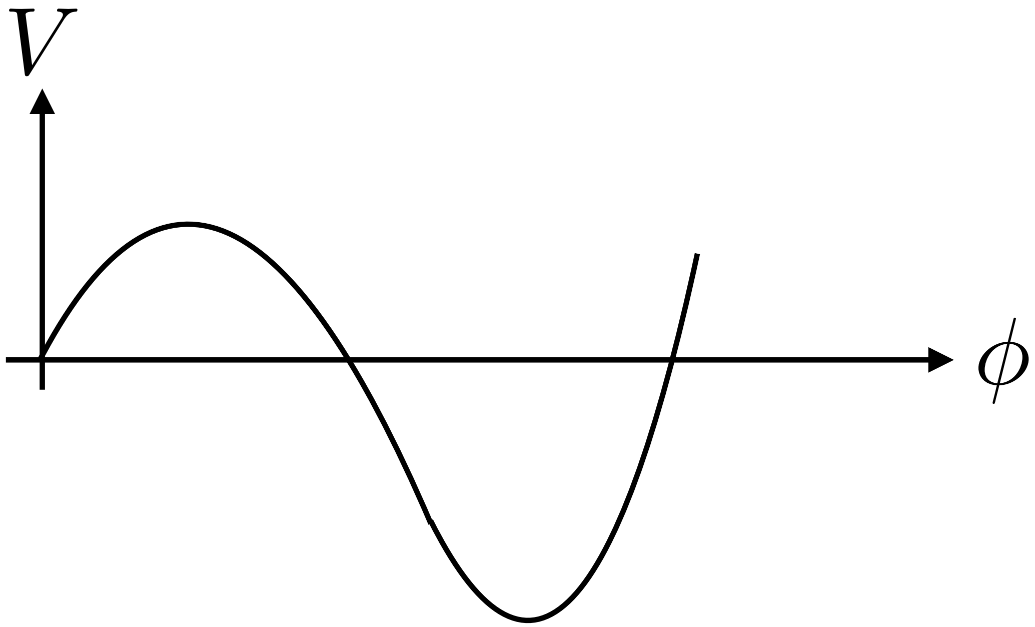

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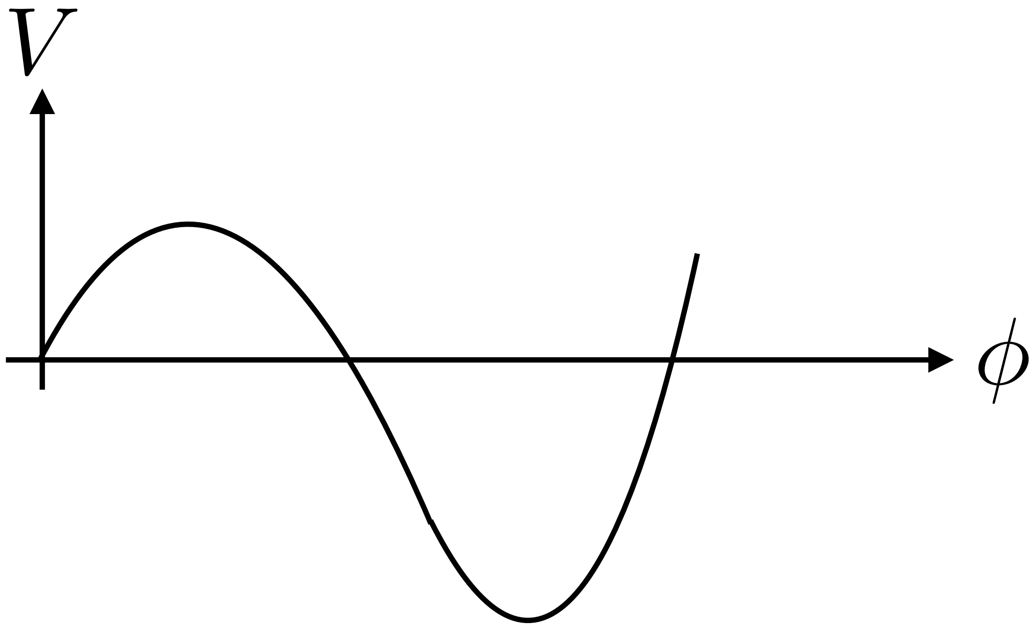

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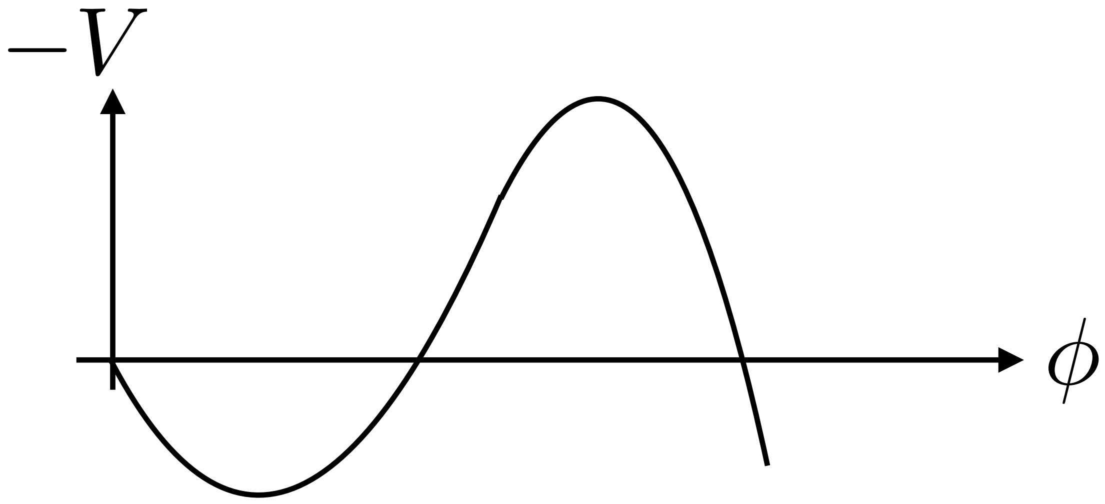

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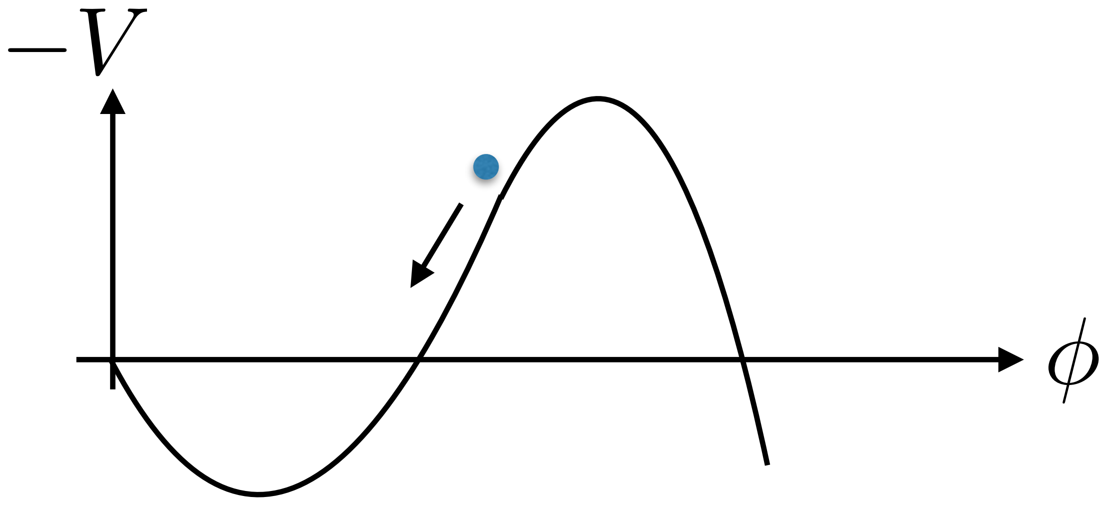

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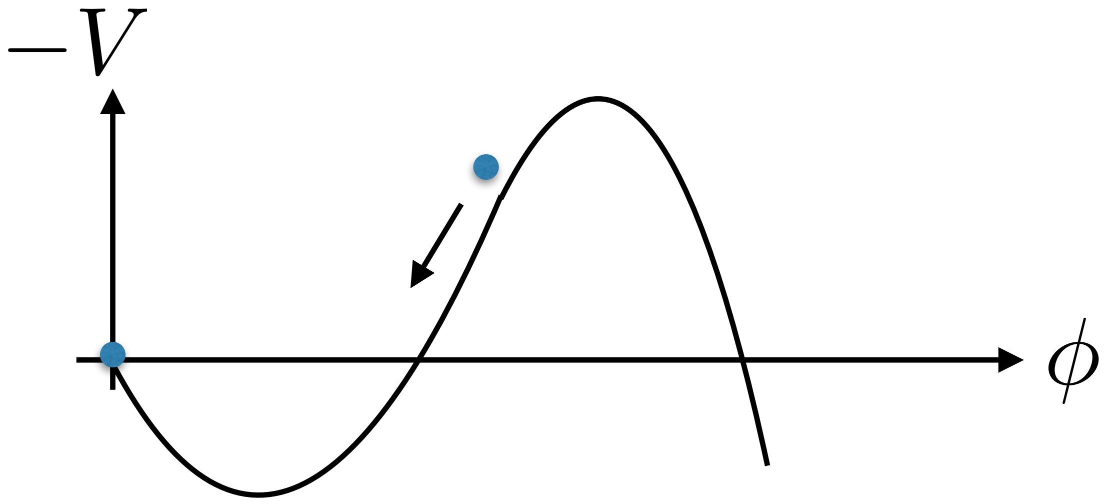

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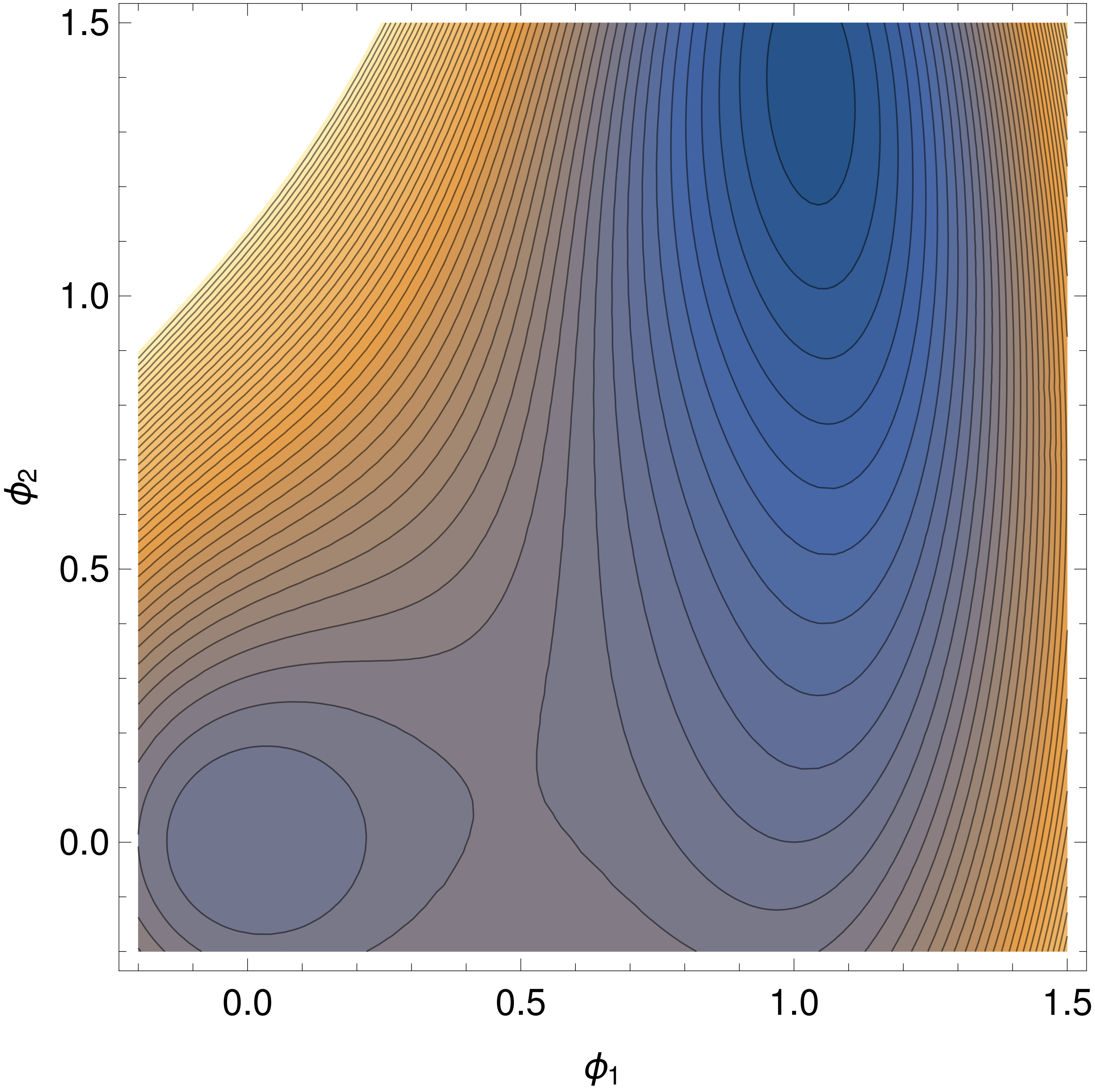

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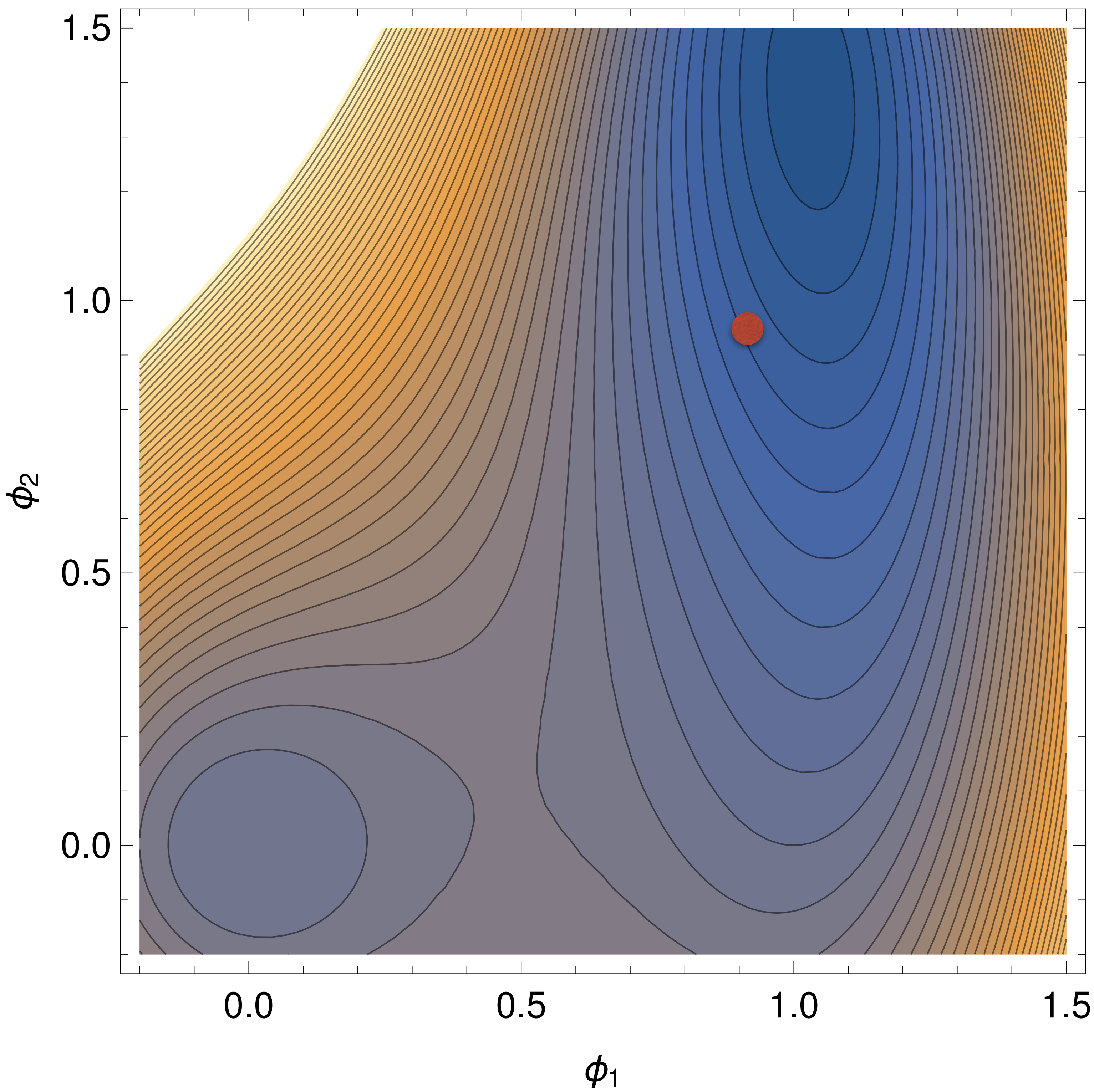

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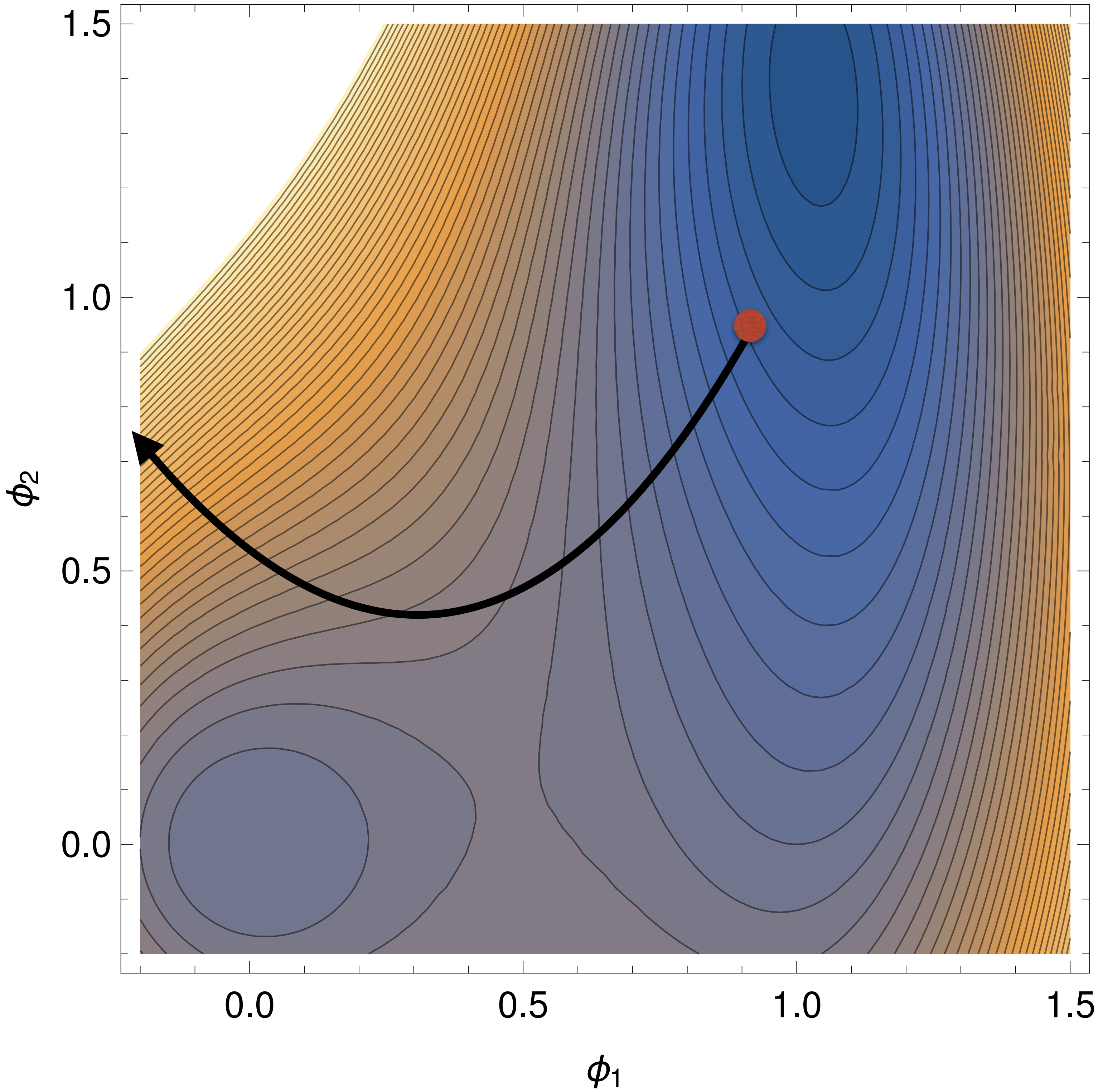

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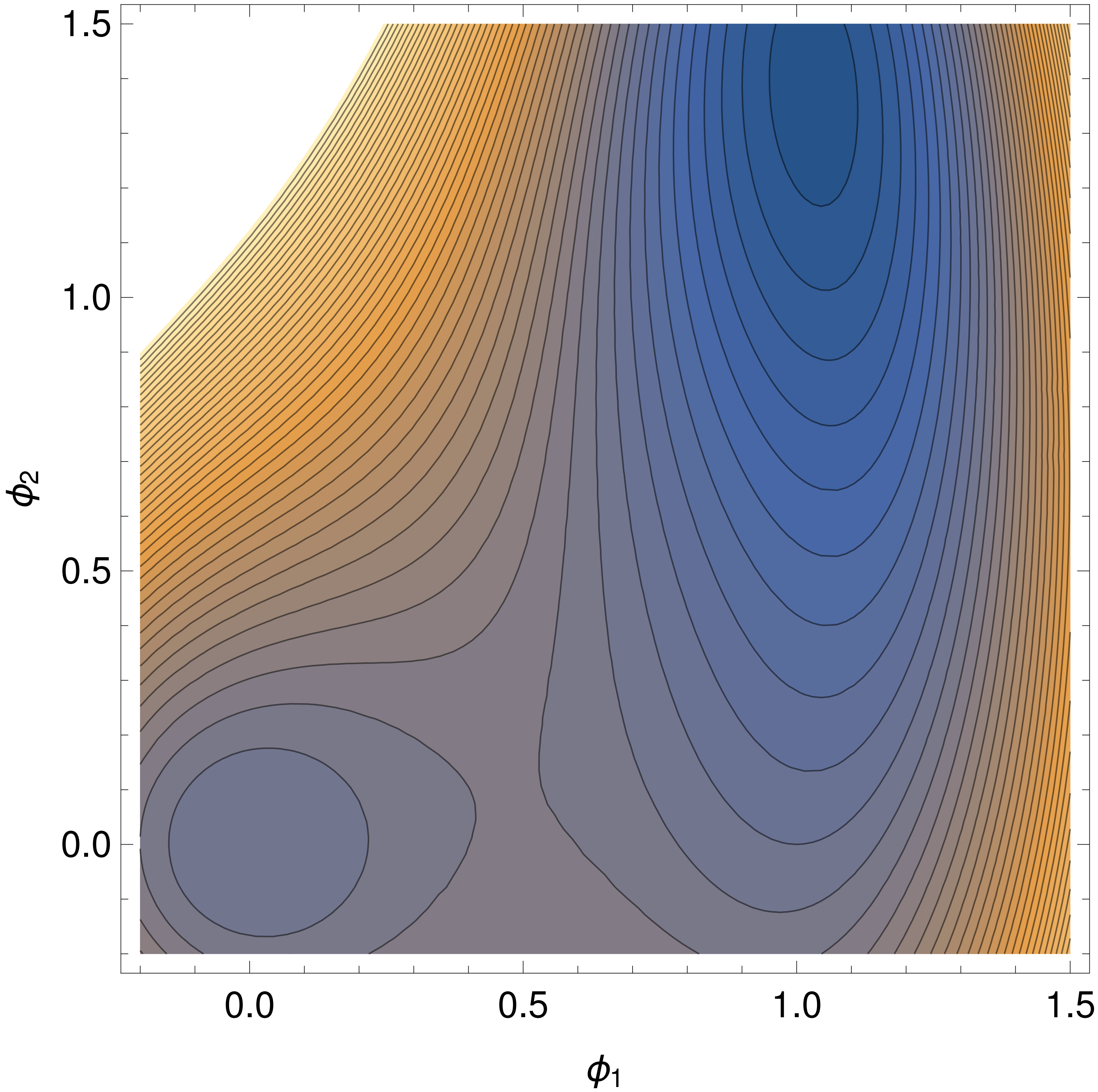

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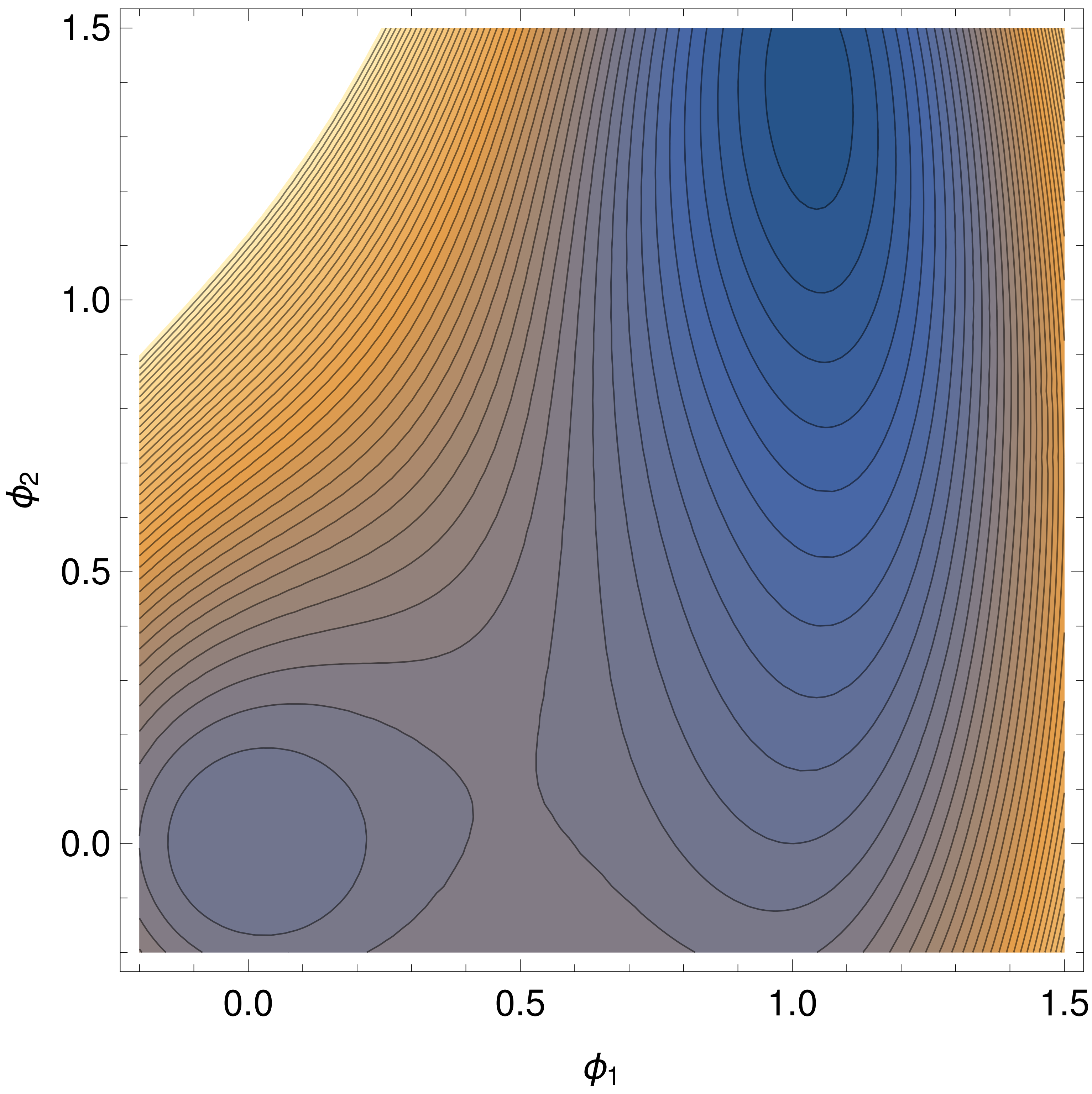

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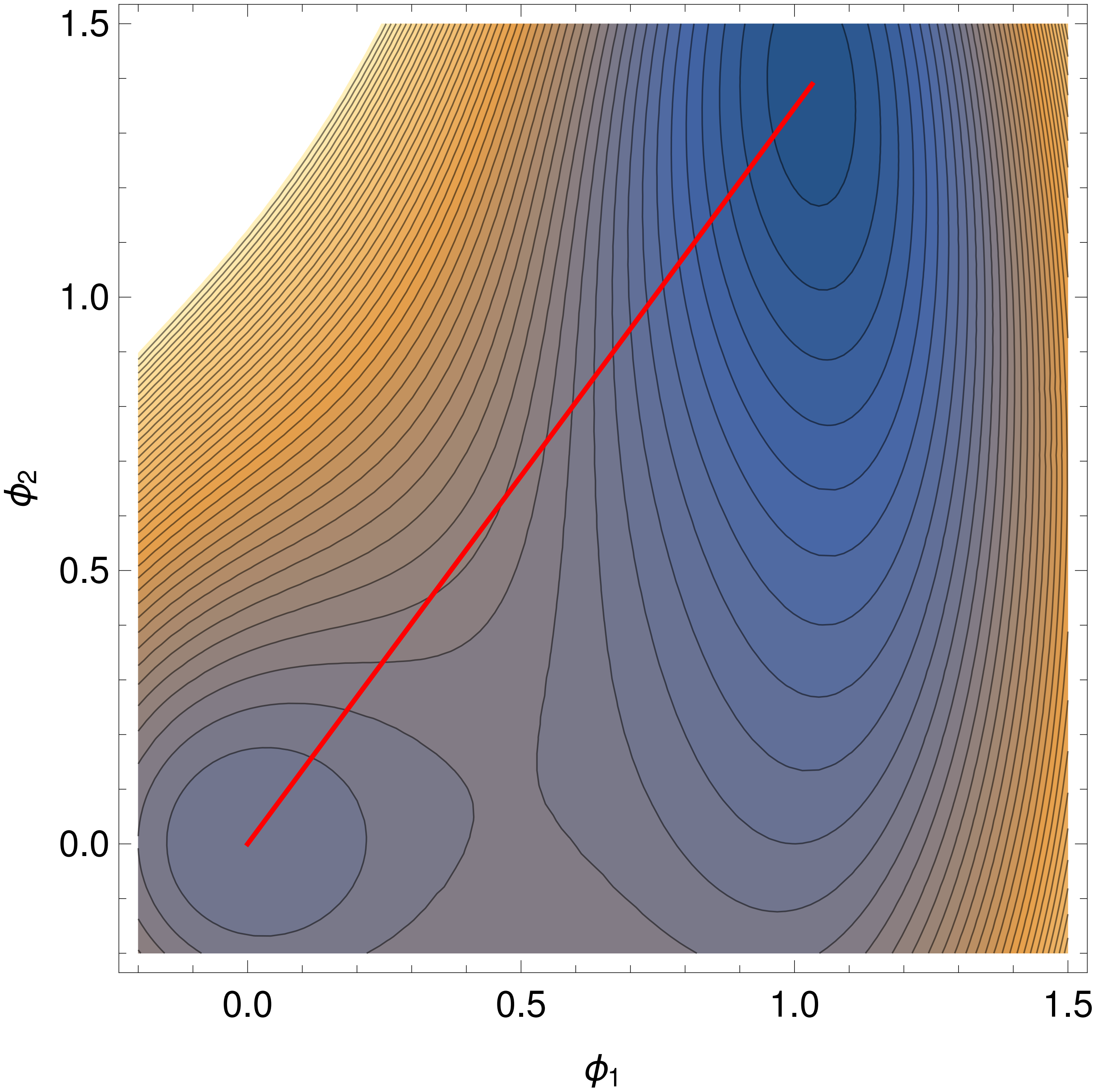

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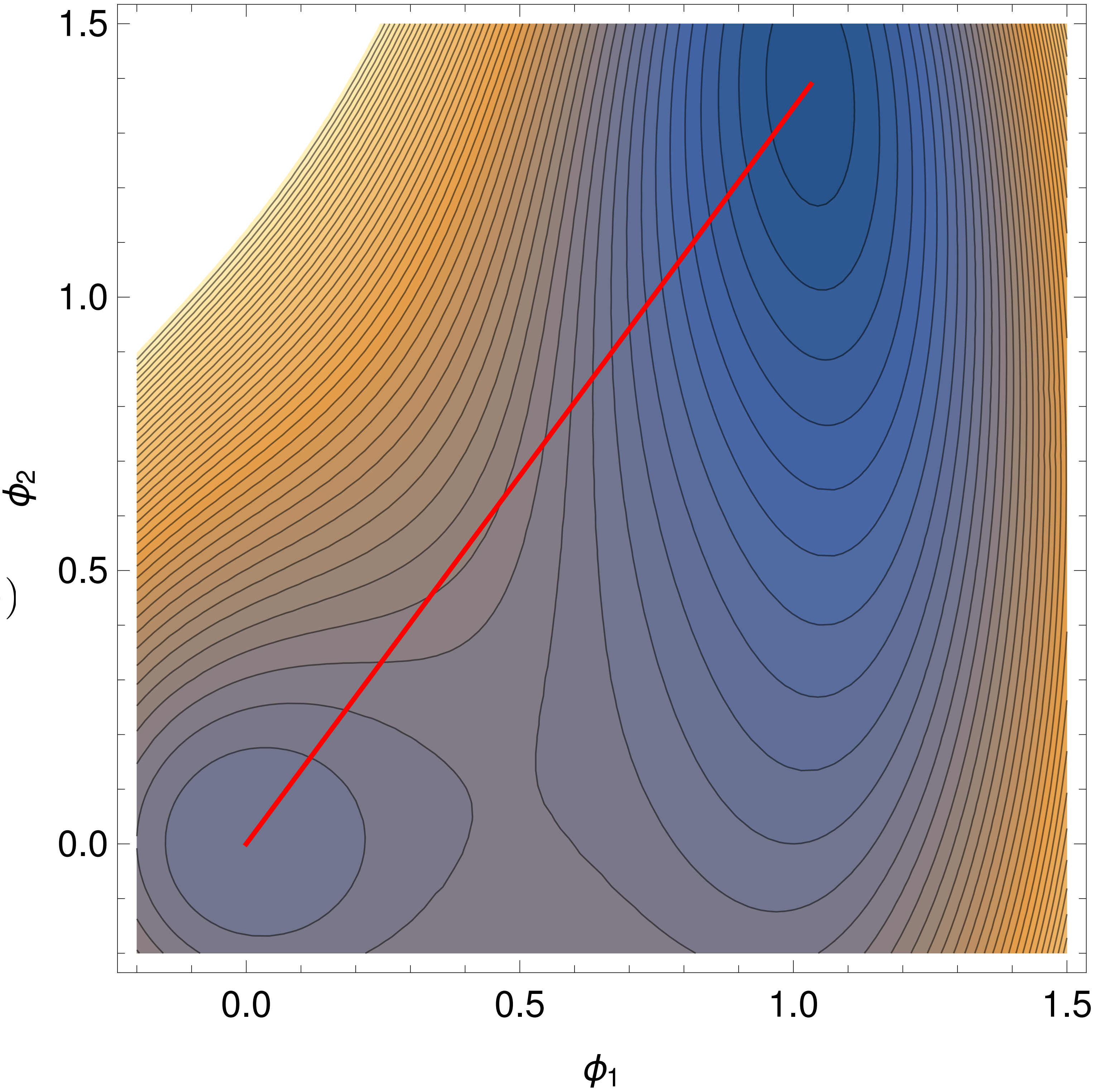

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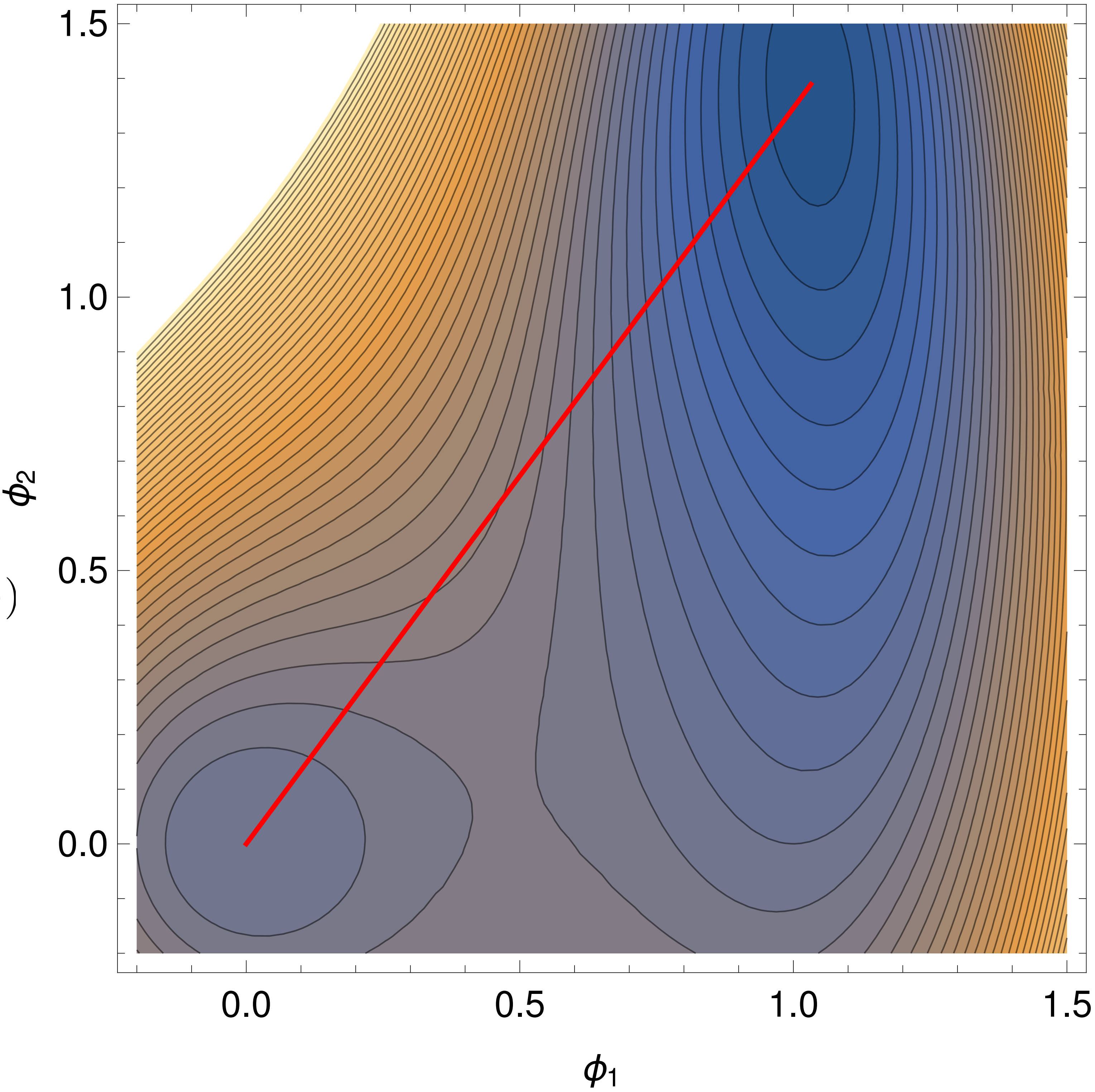

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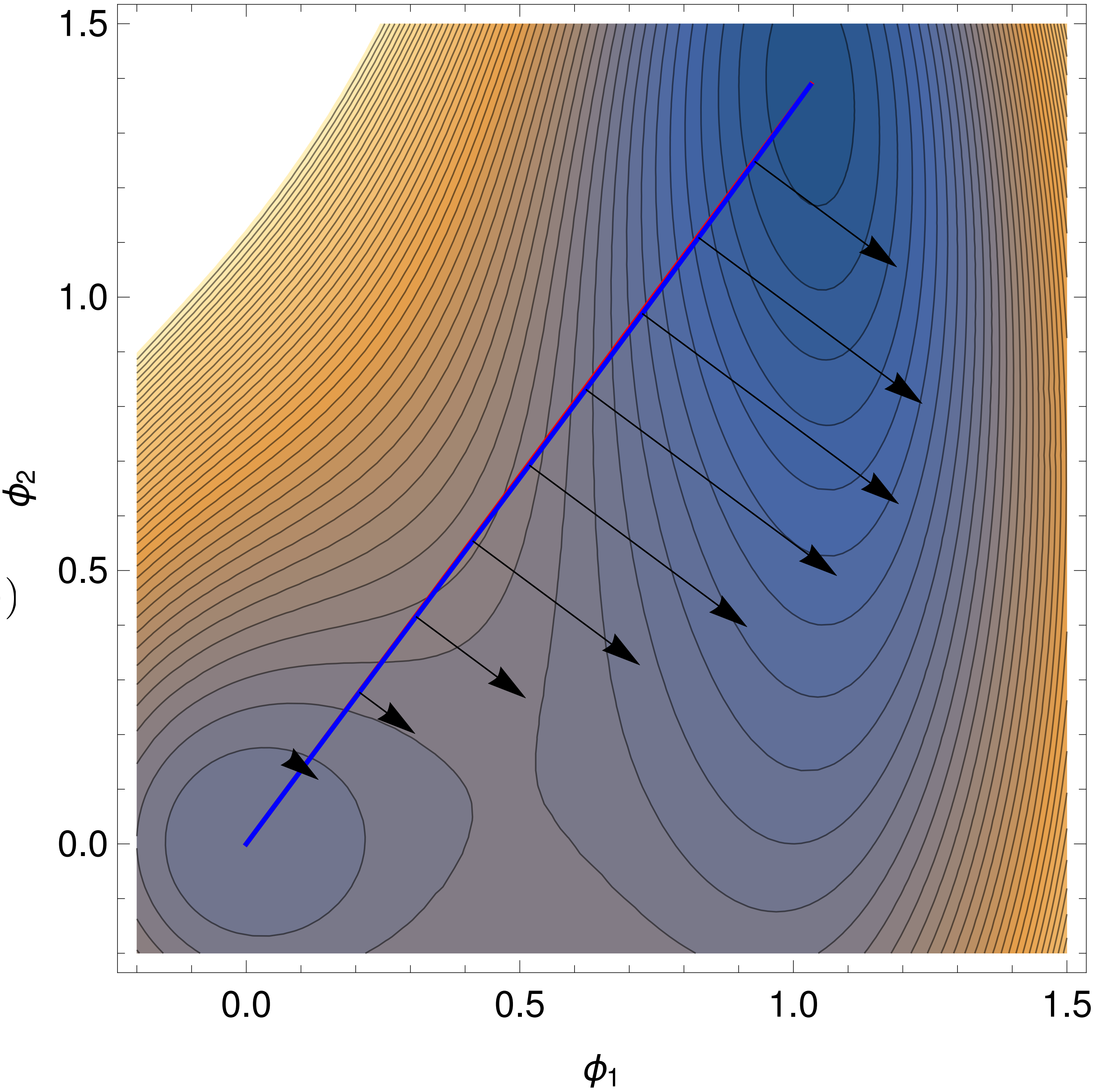

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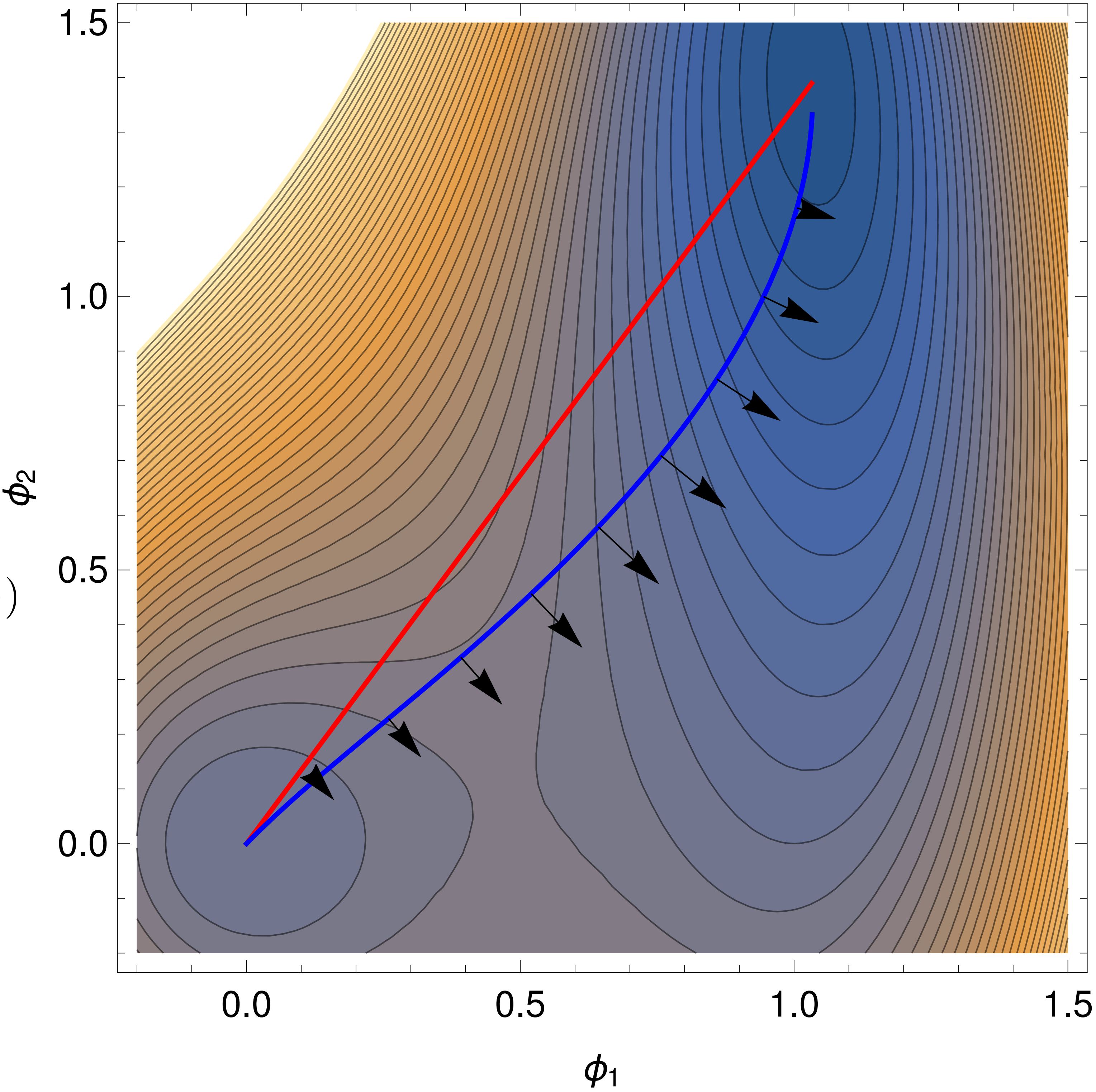

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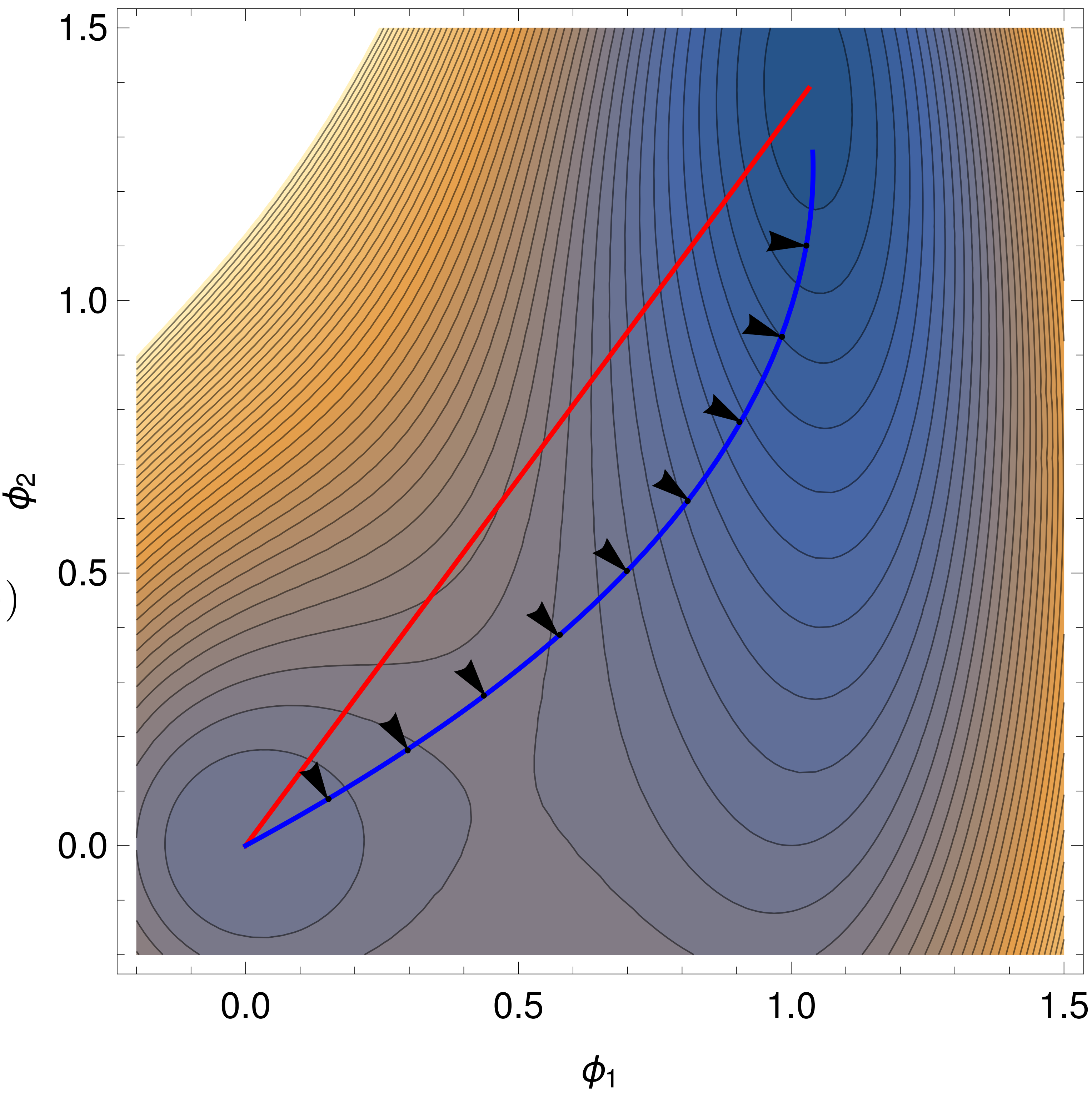

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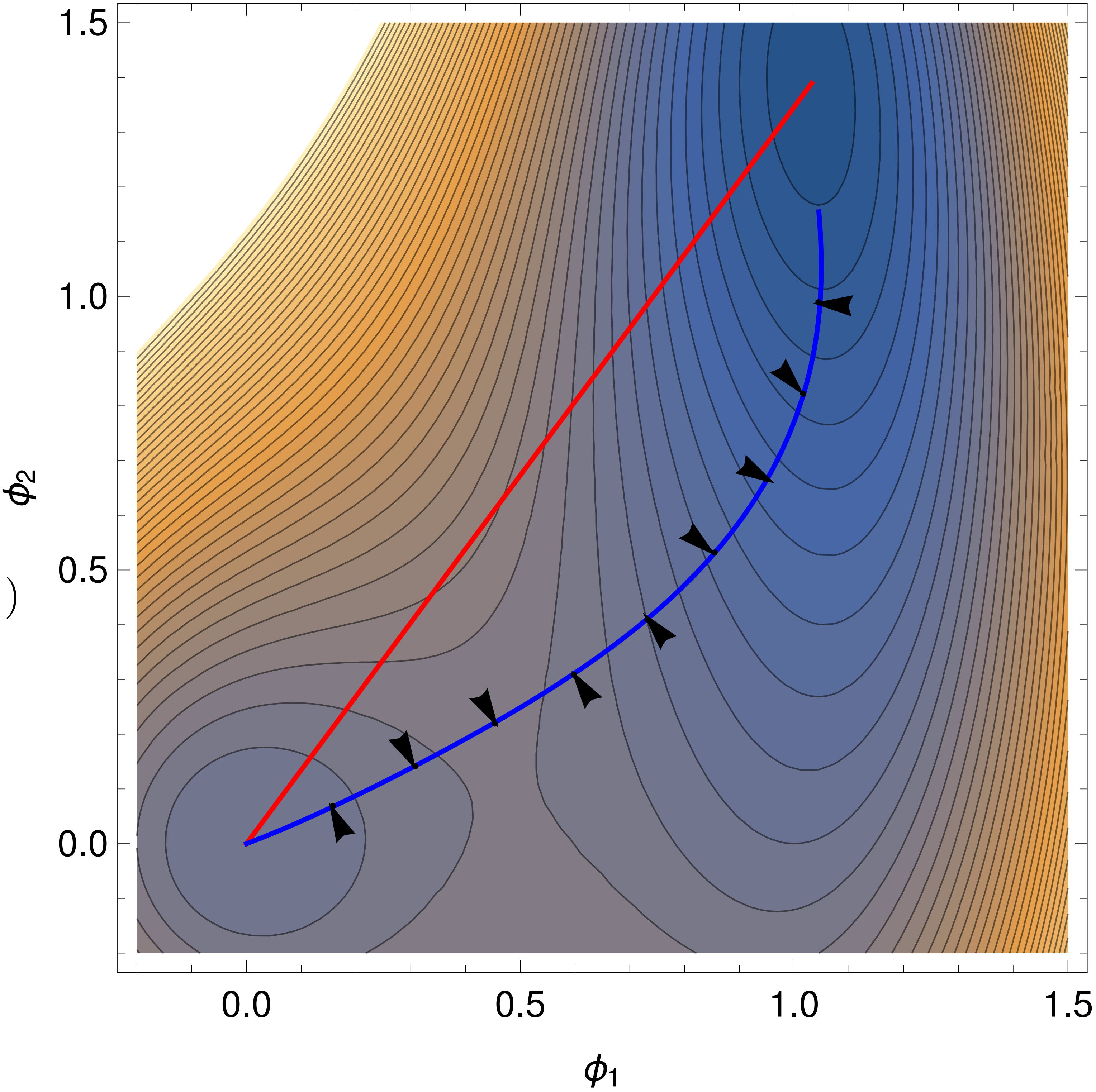

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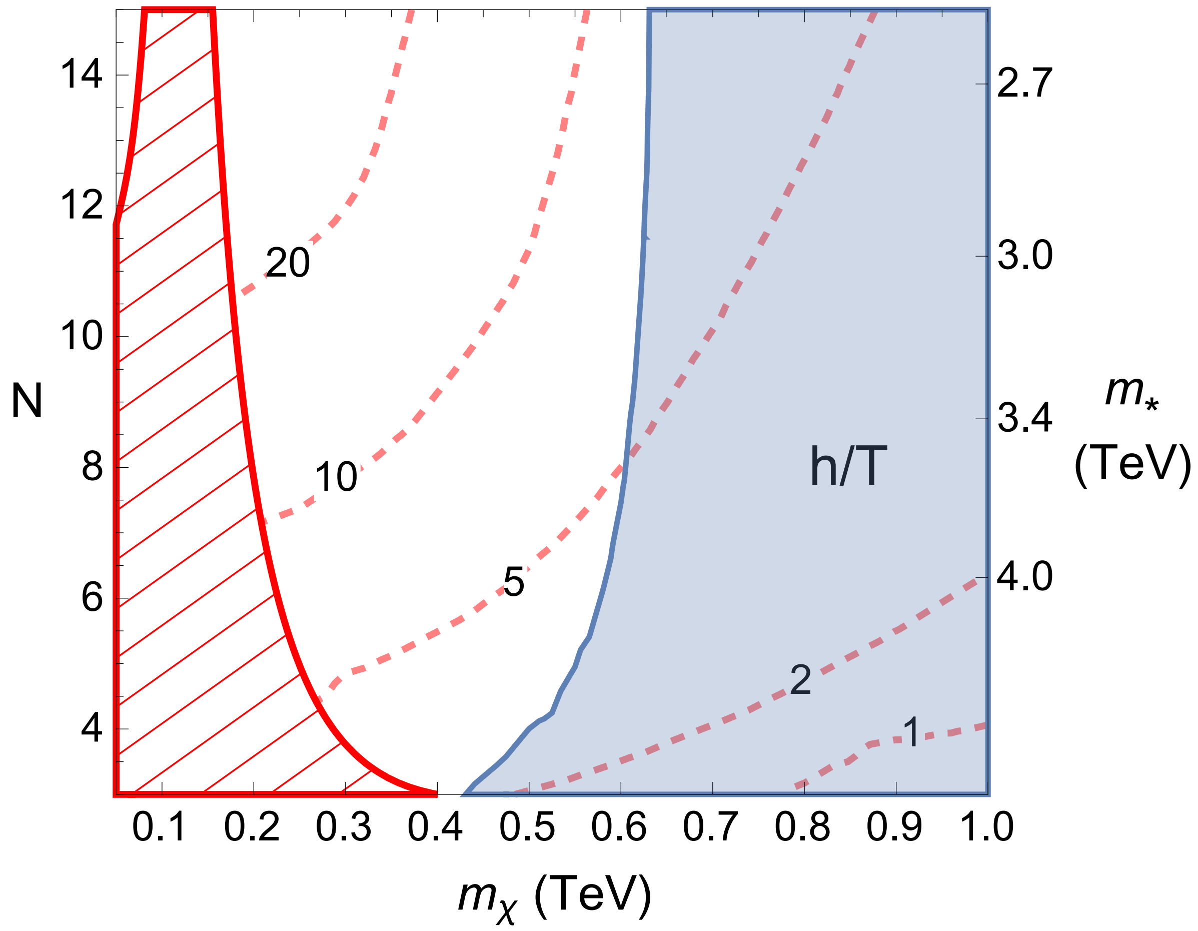

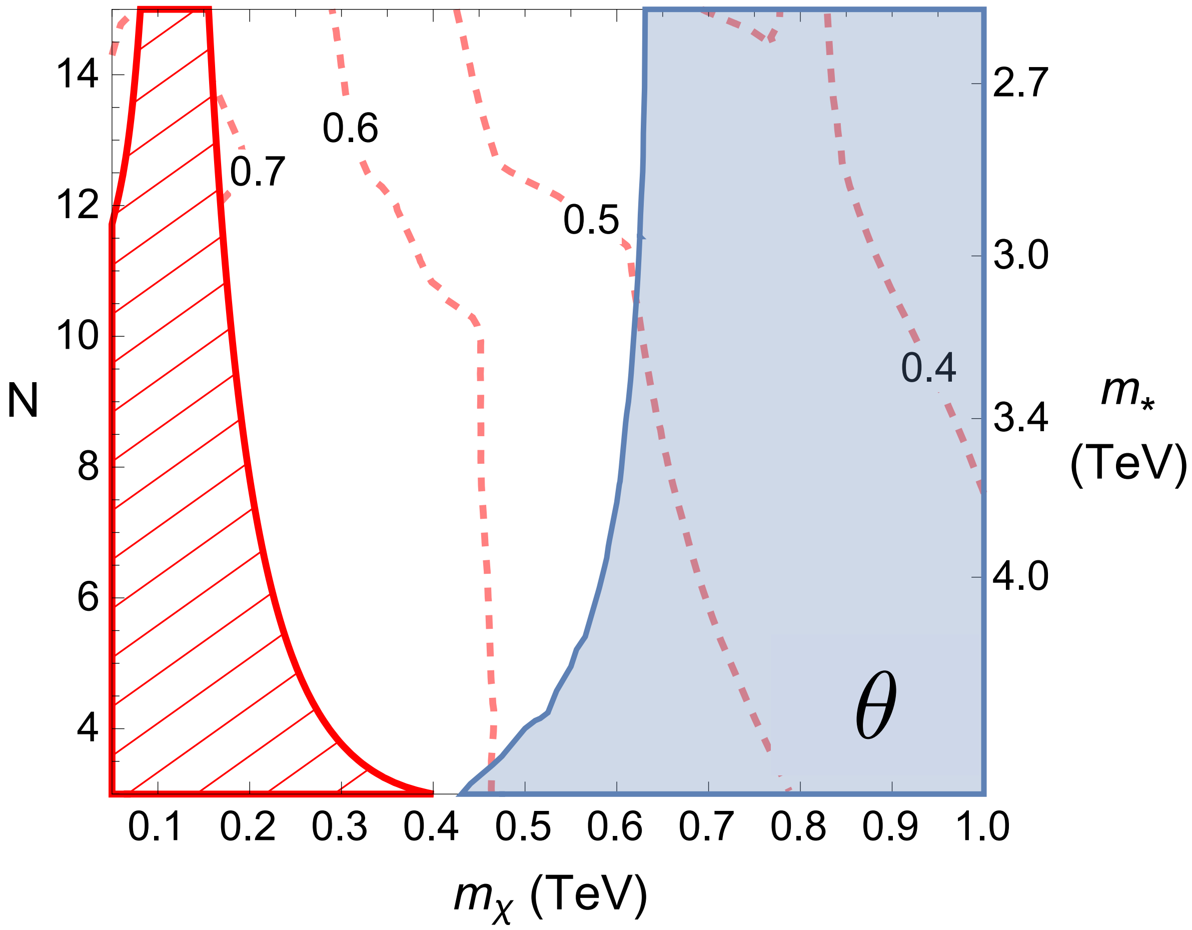

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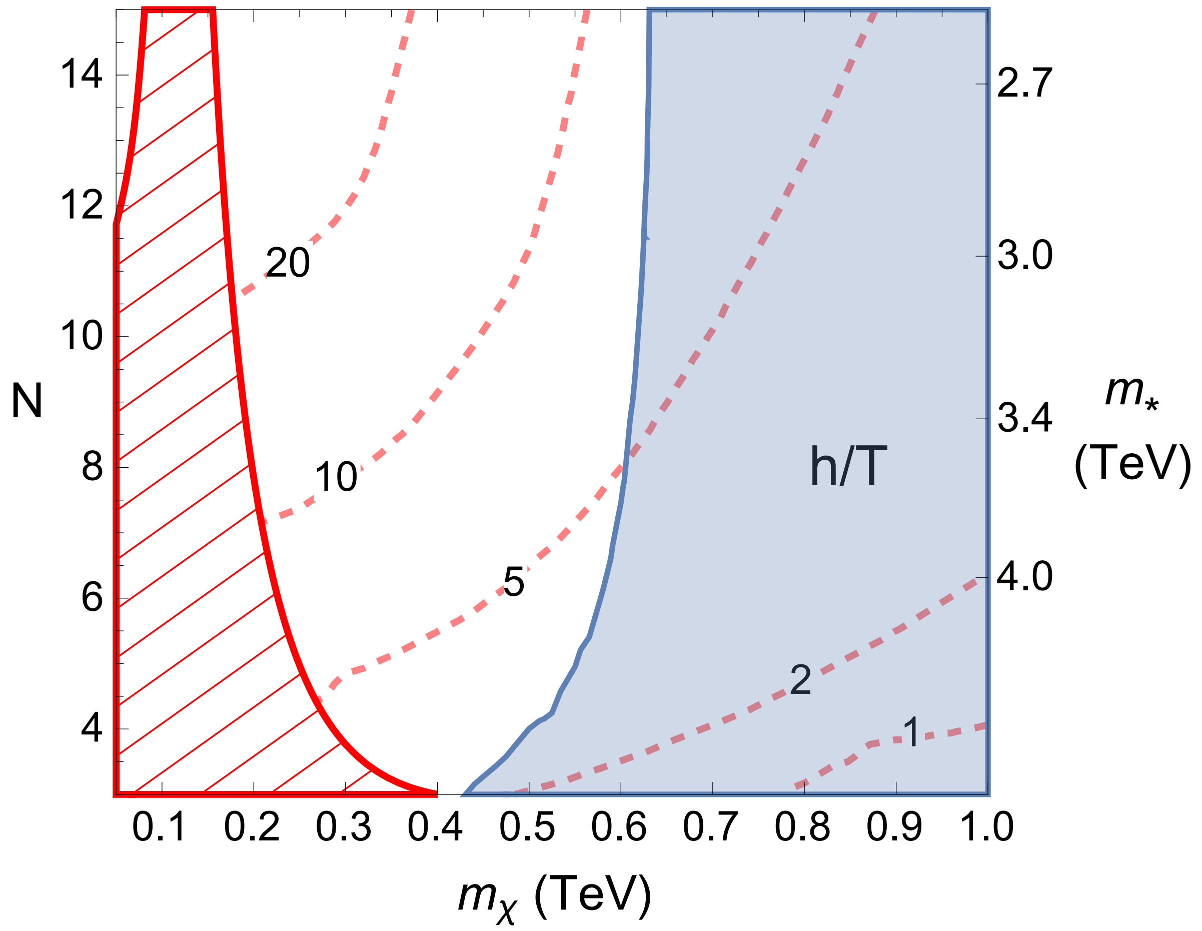
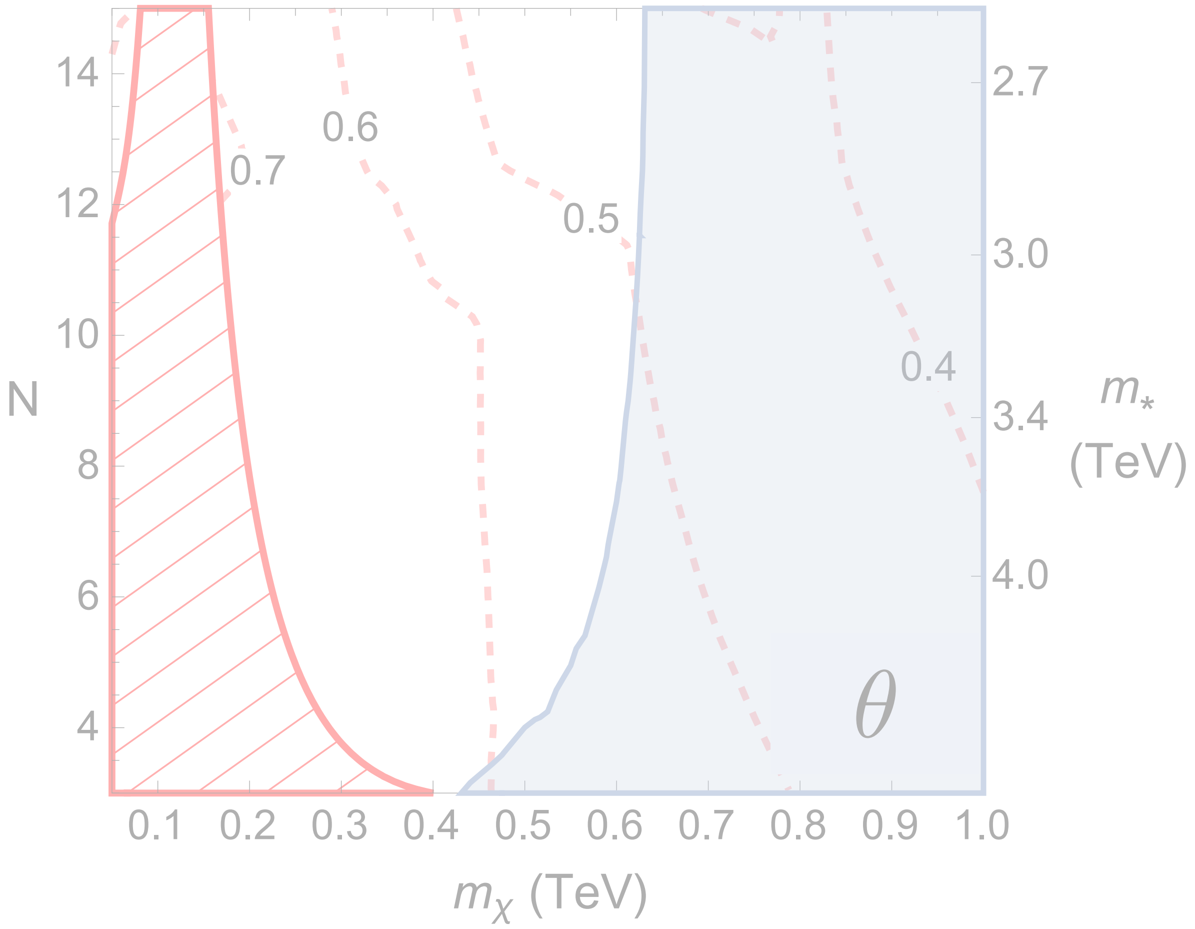
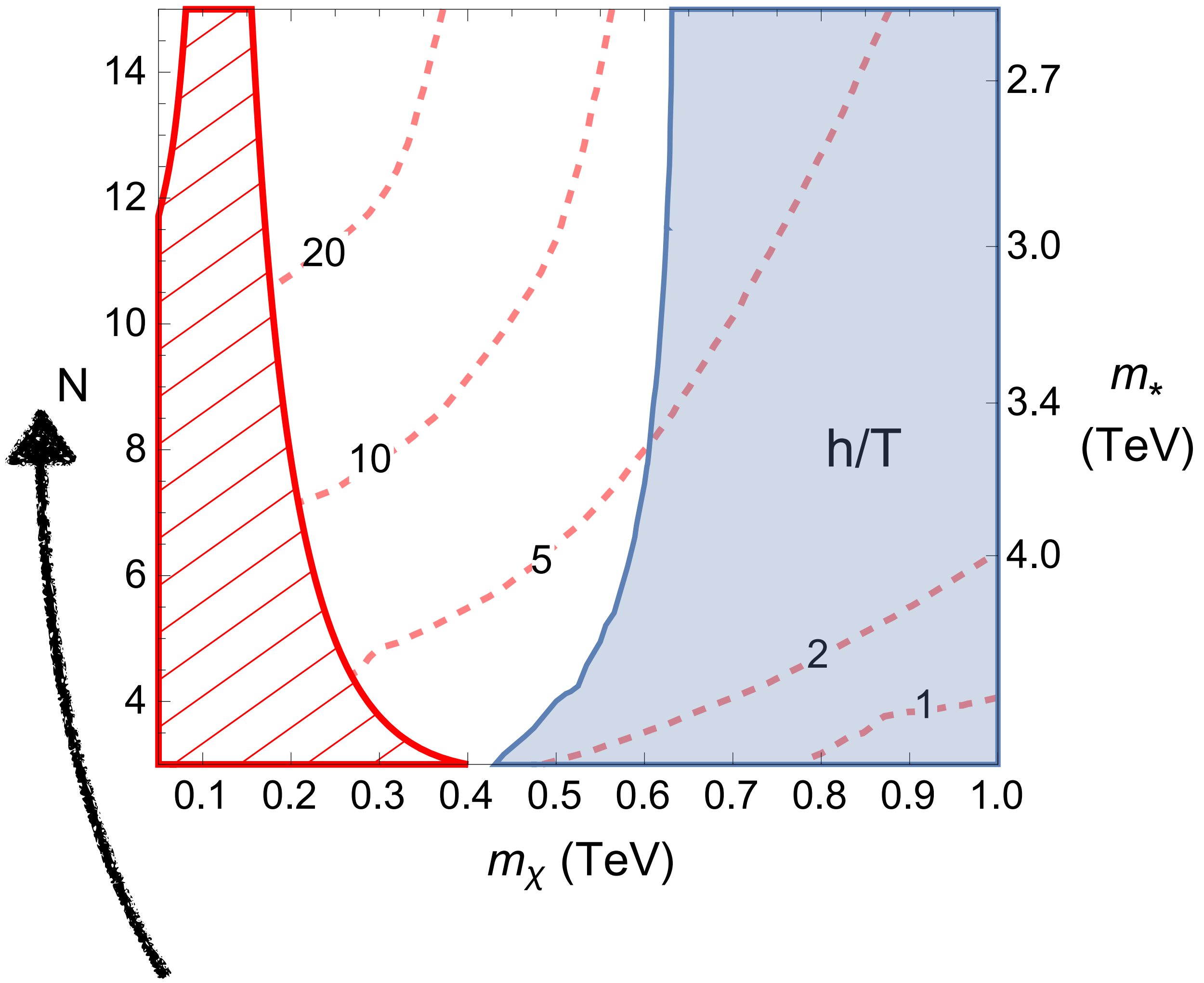
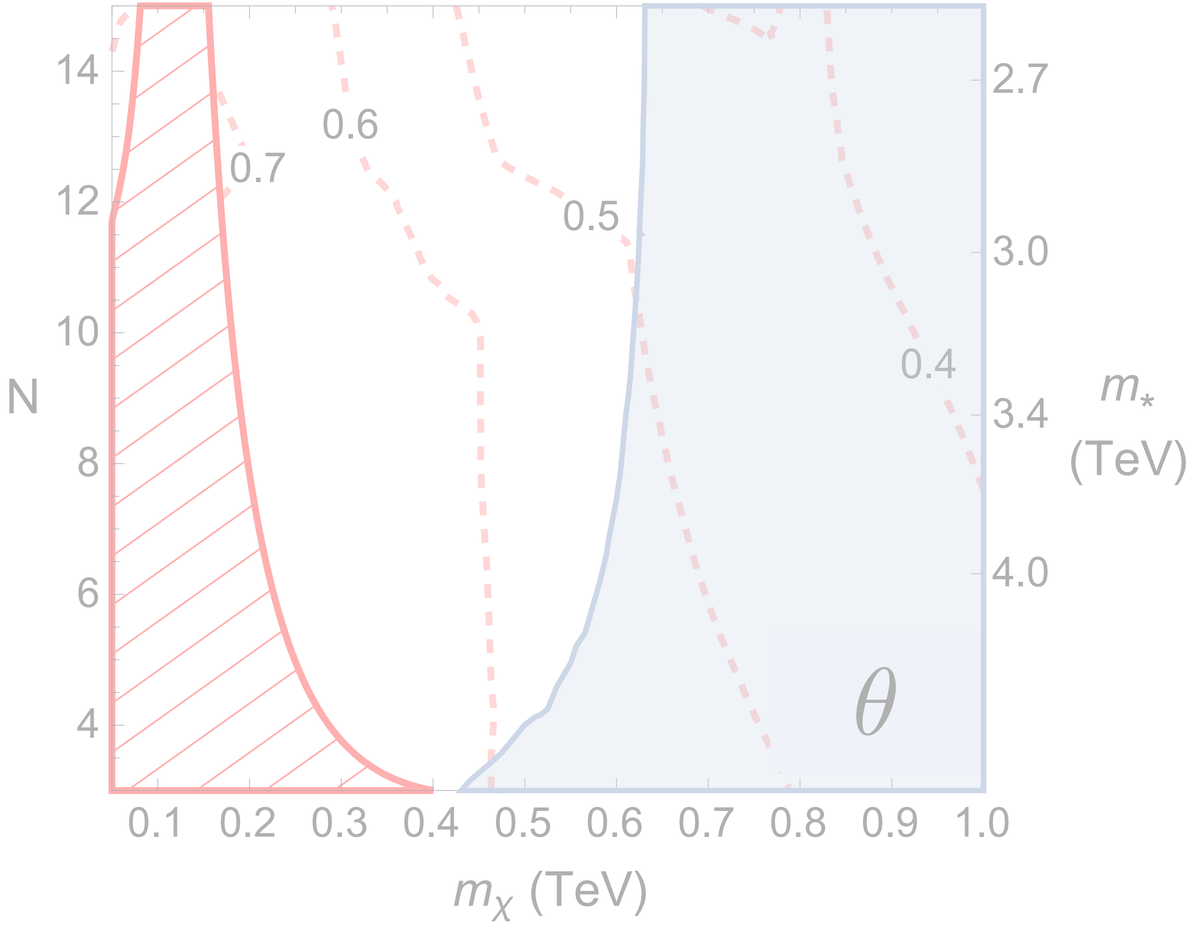




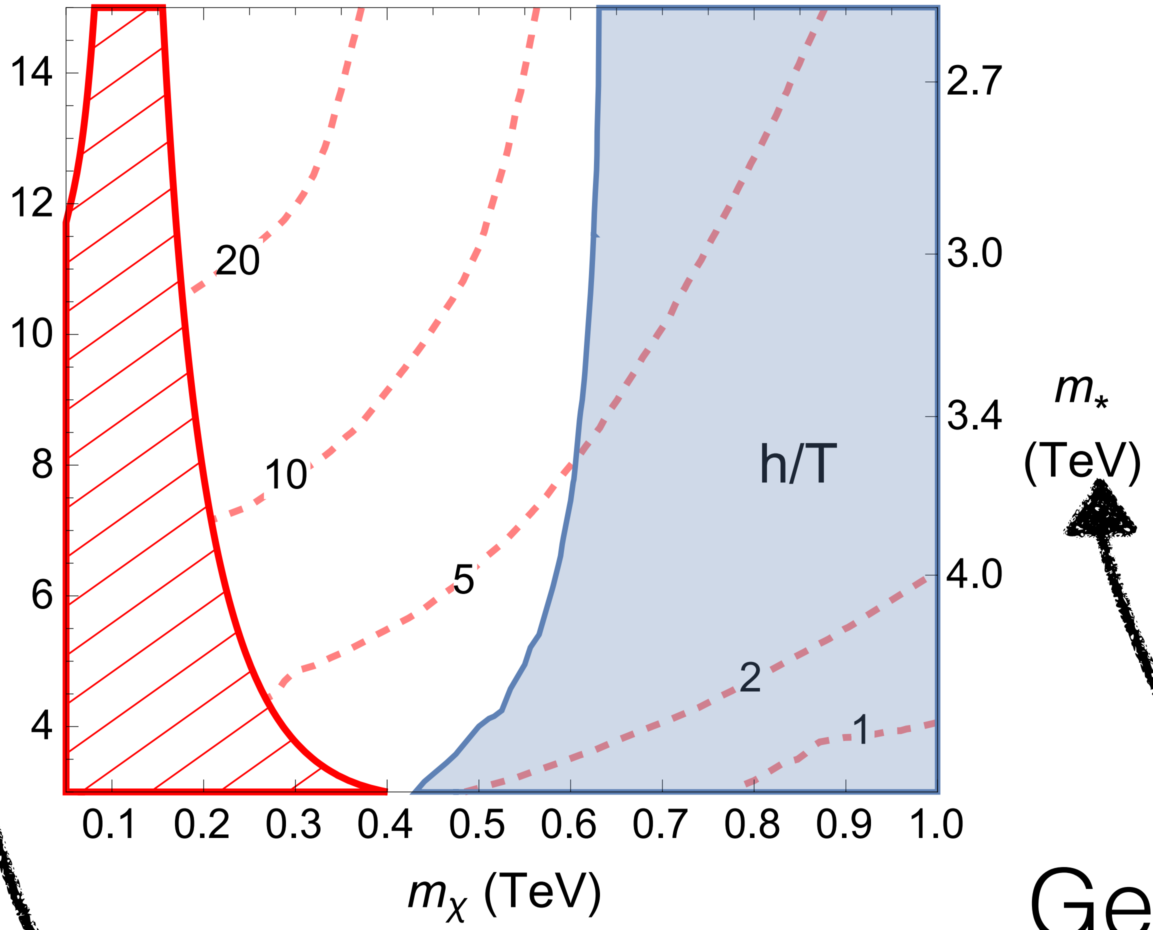
The phase transition

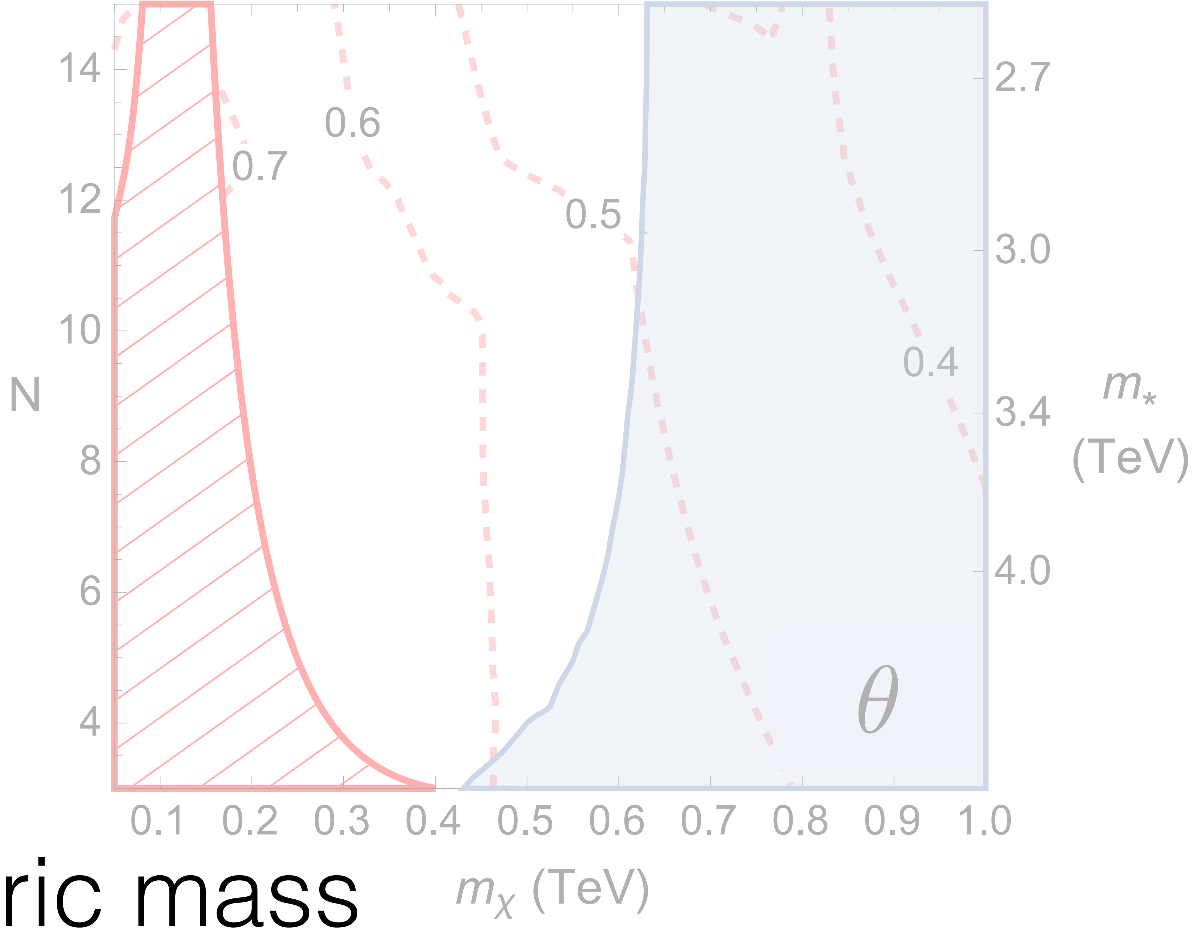




# colours in CFT, used in large N expansion

The phase transition



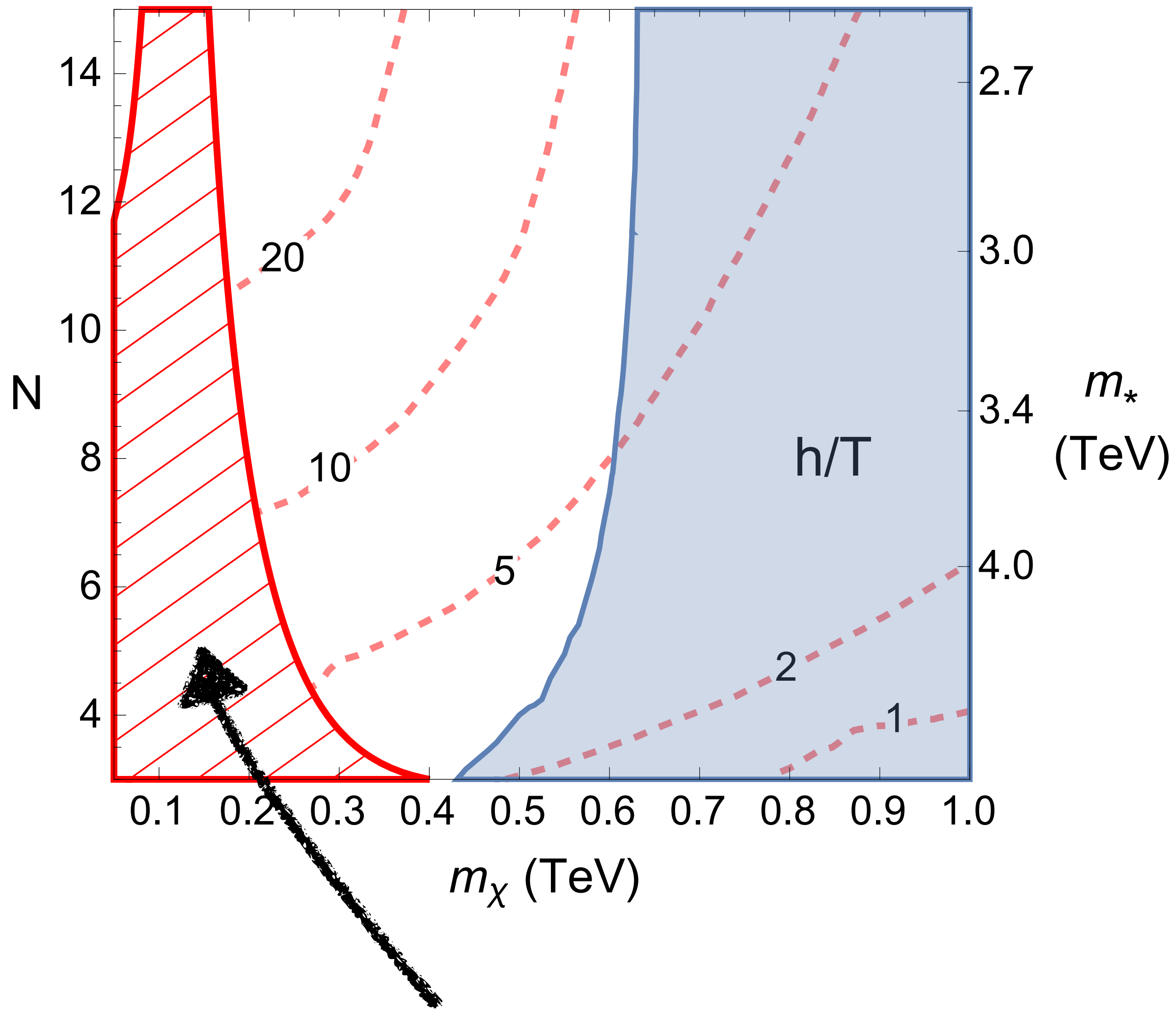


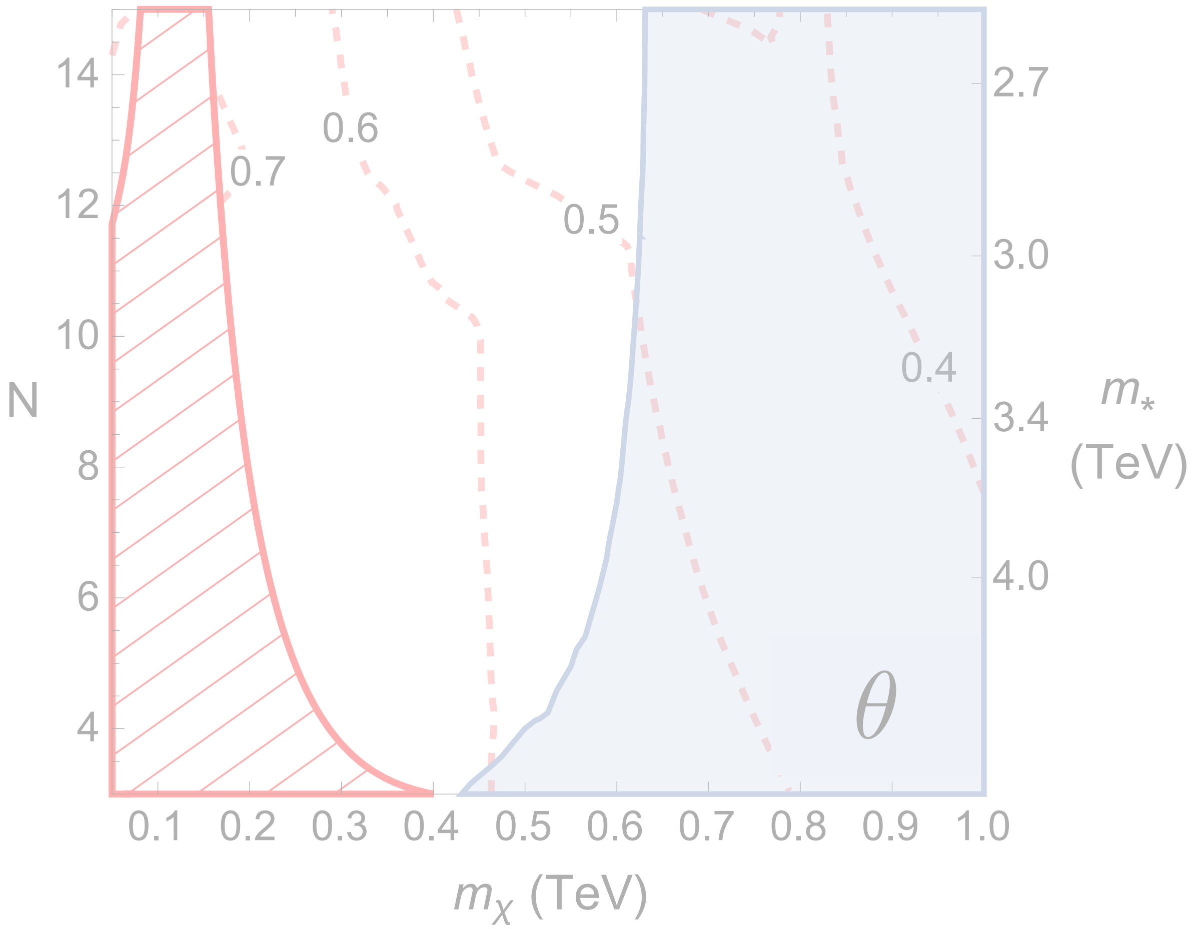
# colours in CFT, used in large N expansion

Generic mass of composite resonances

$$m_\star = g_\star f$$

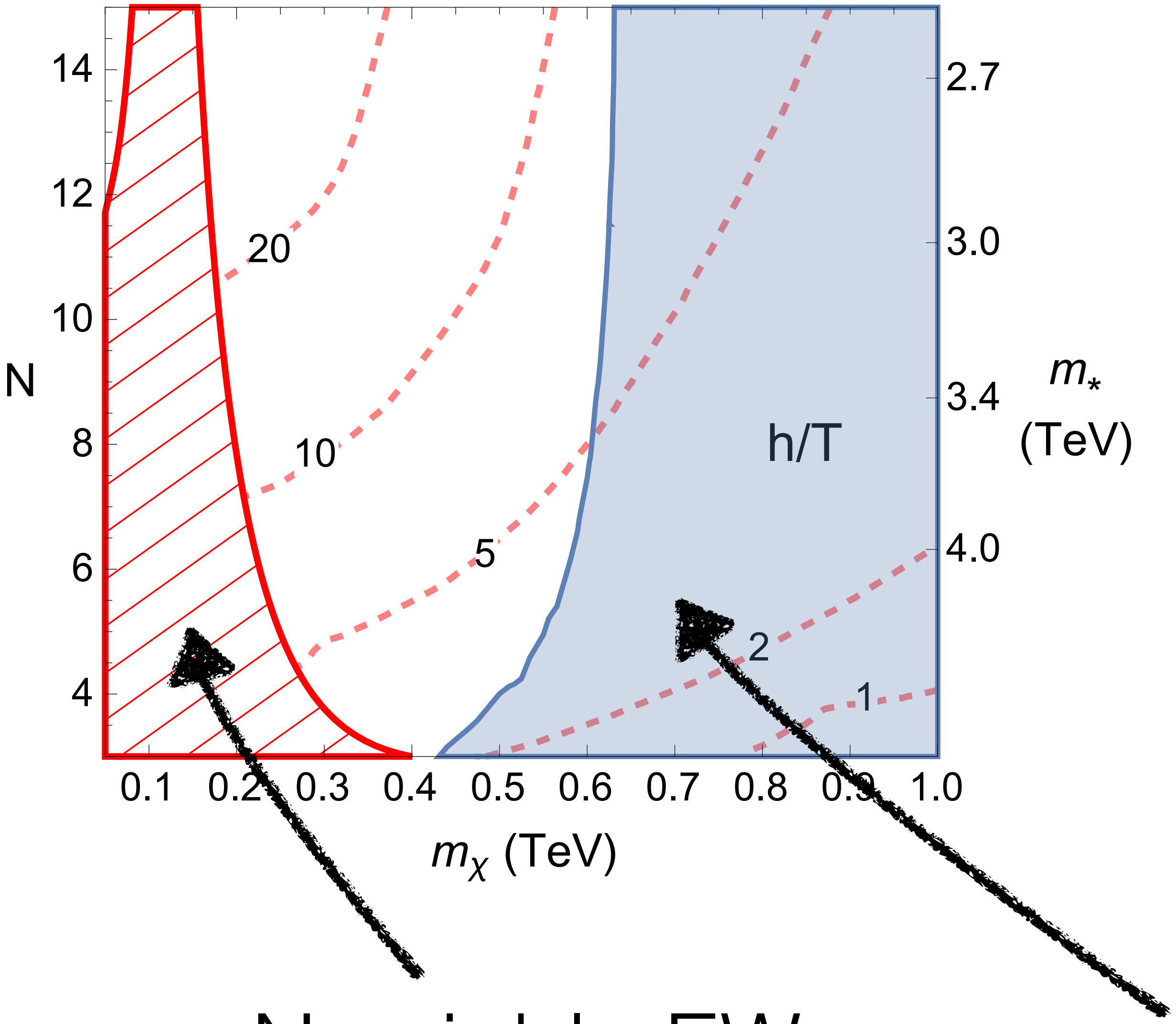
The phase transition

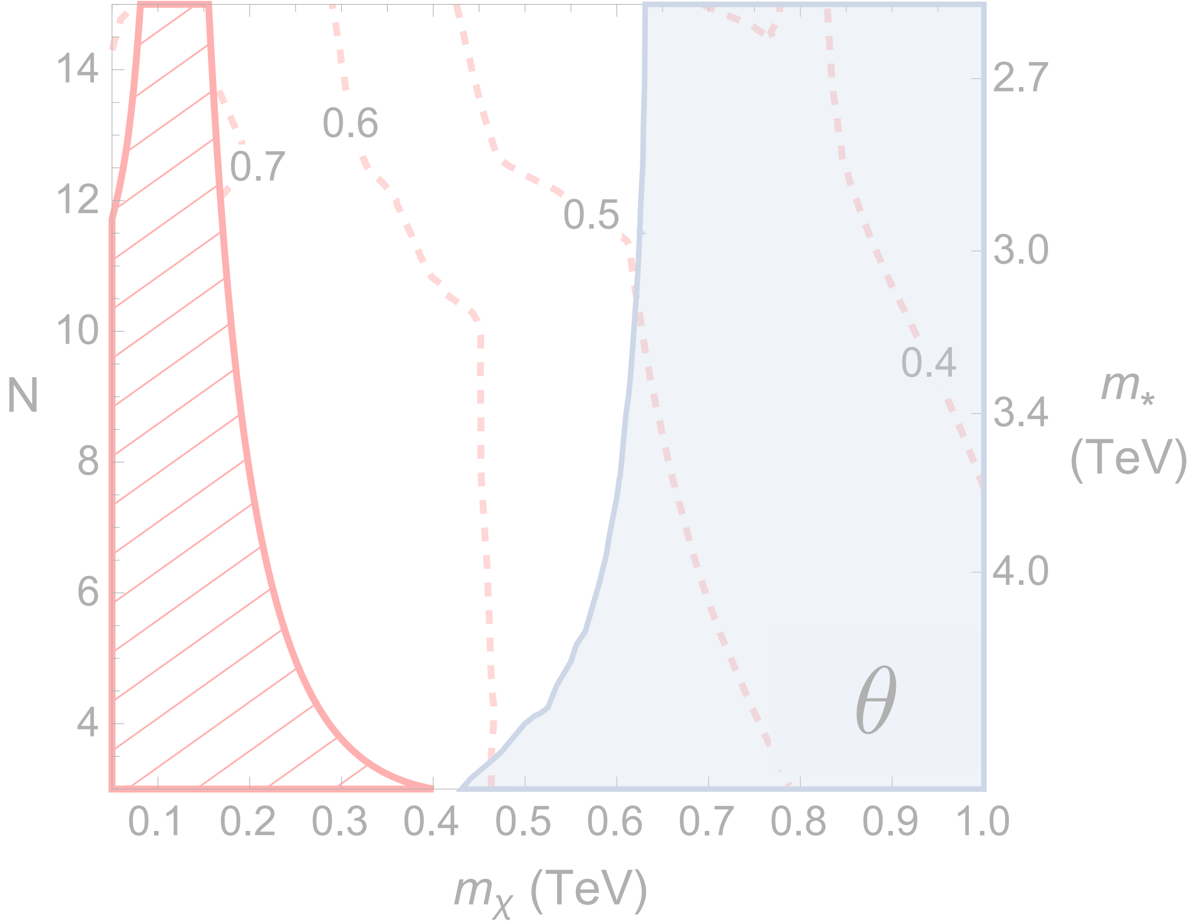




No viable EW
Minimum found

The phase transition

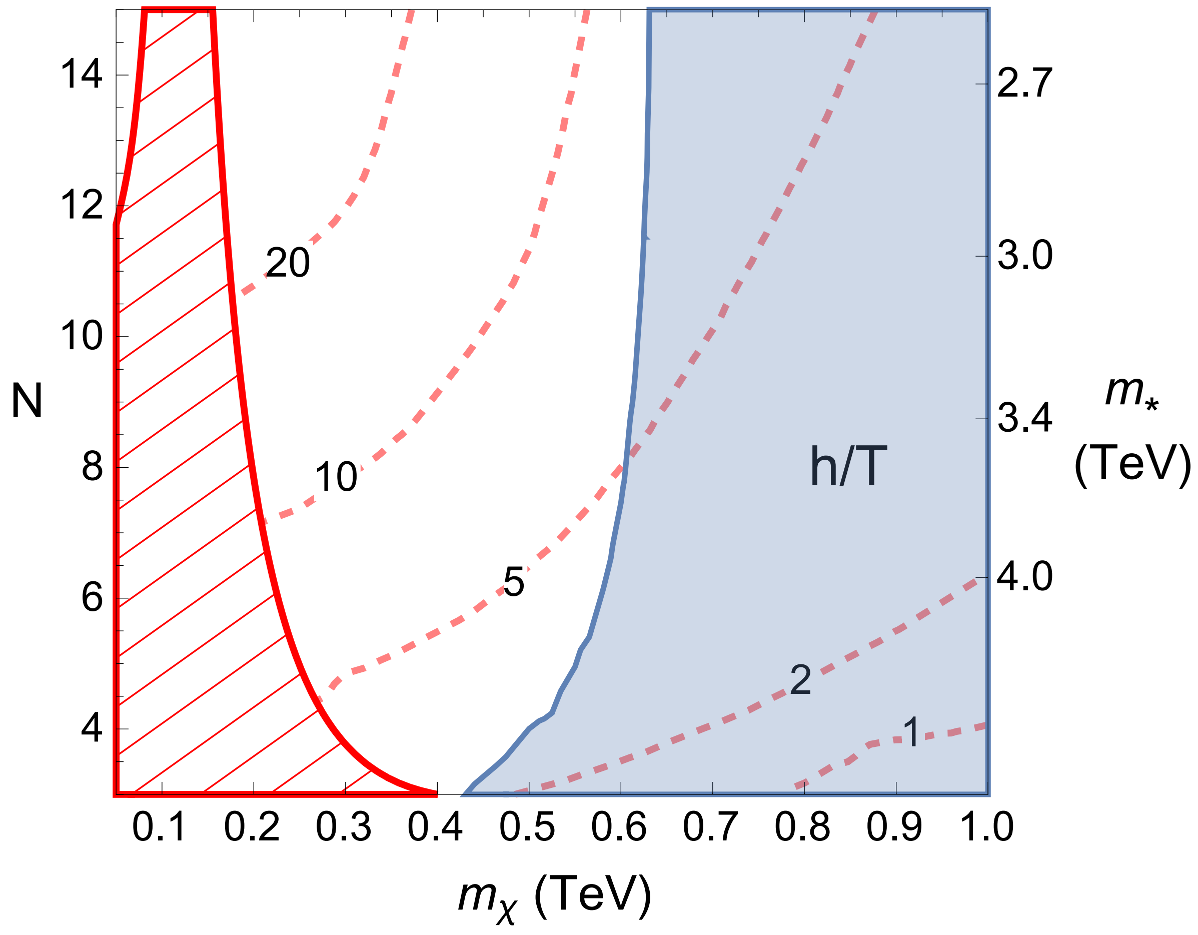


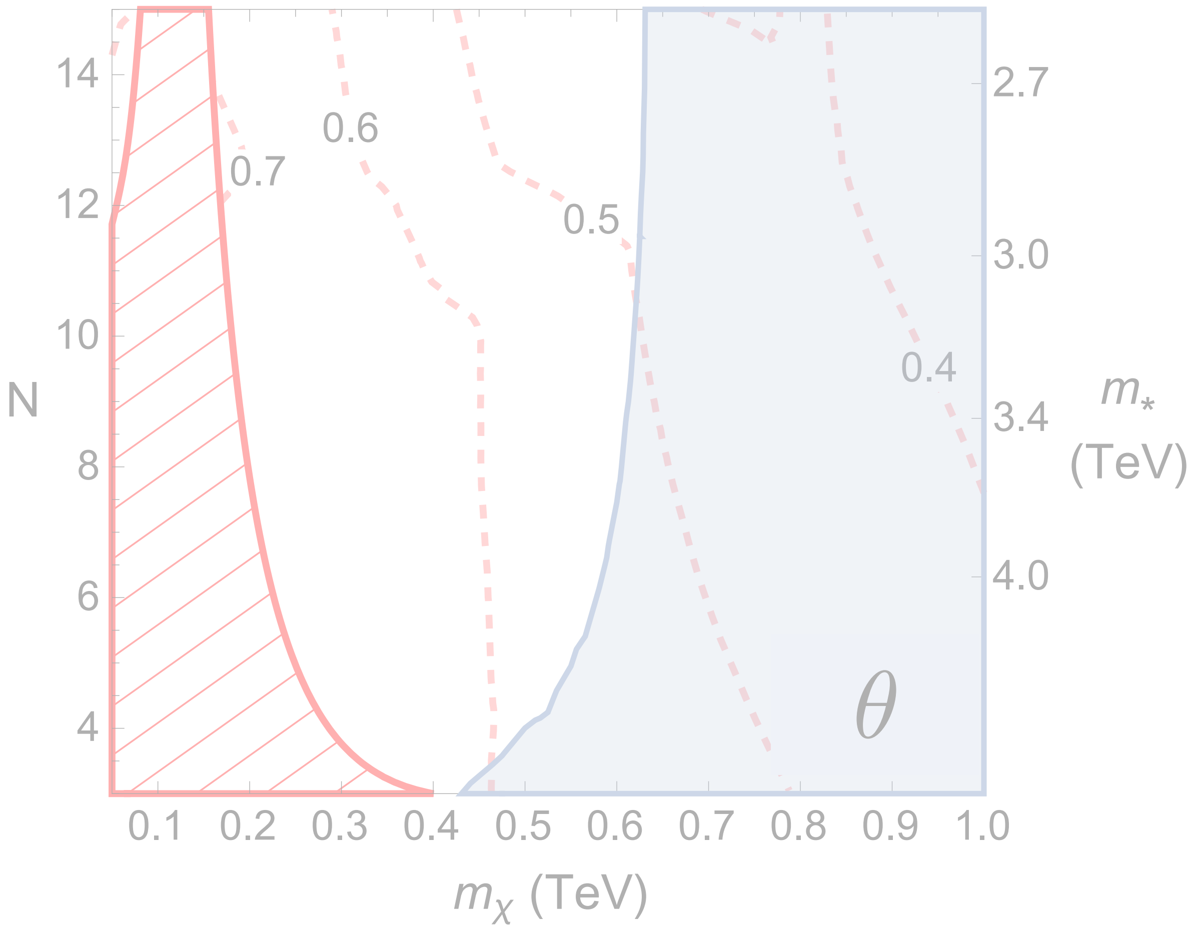


No viable EW
Minimum found

Reheating temperature
s.t. h/Treheat<1

The phase transition

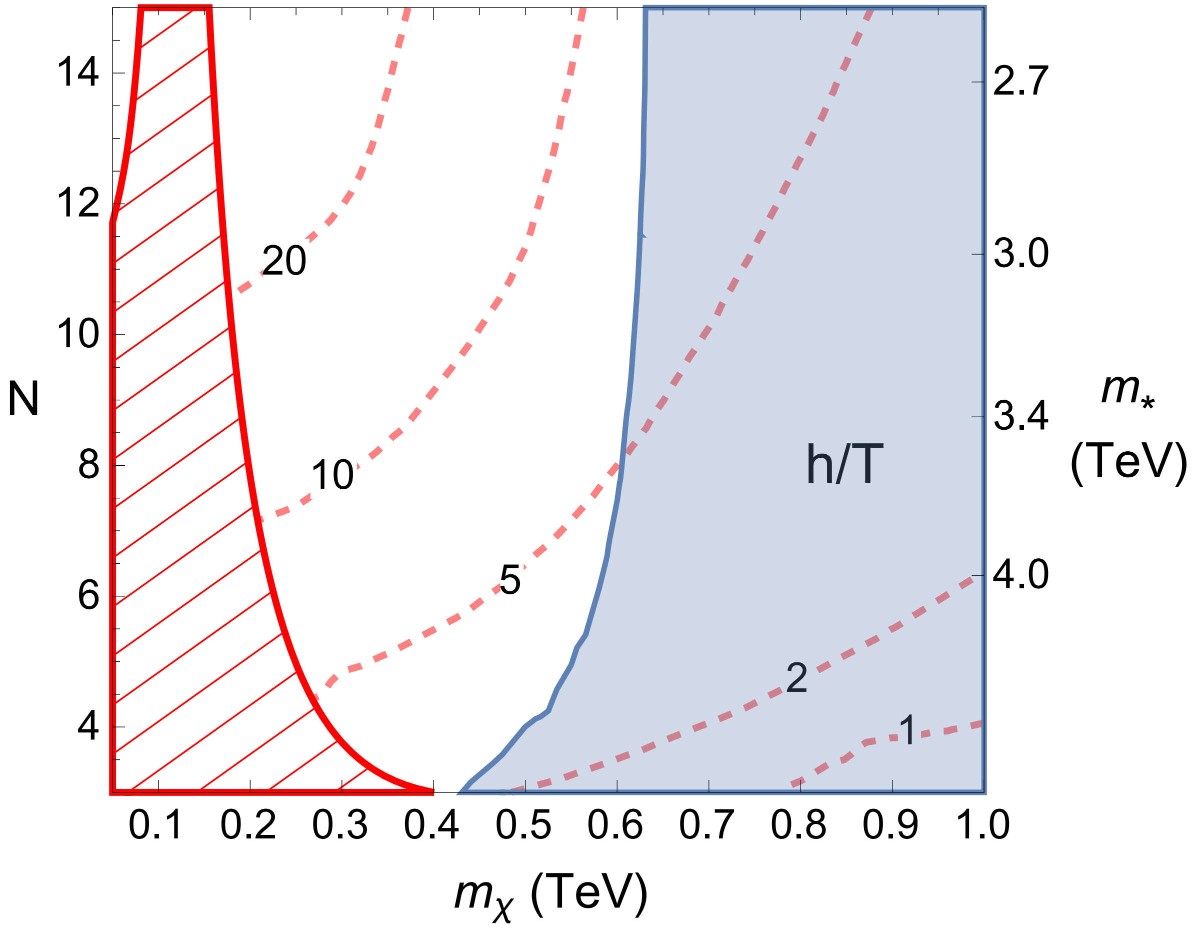


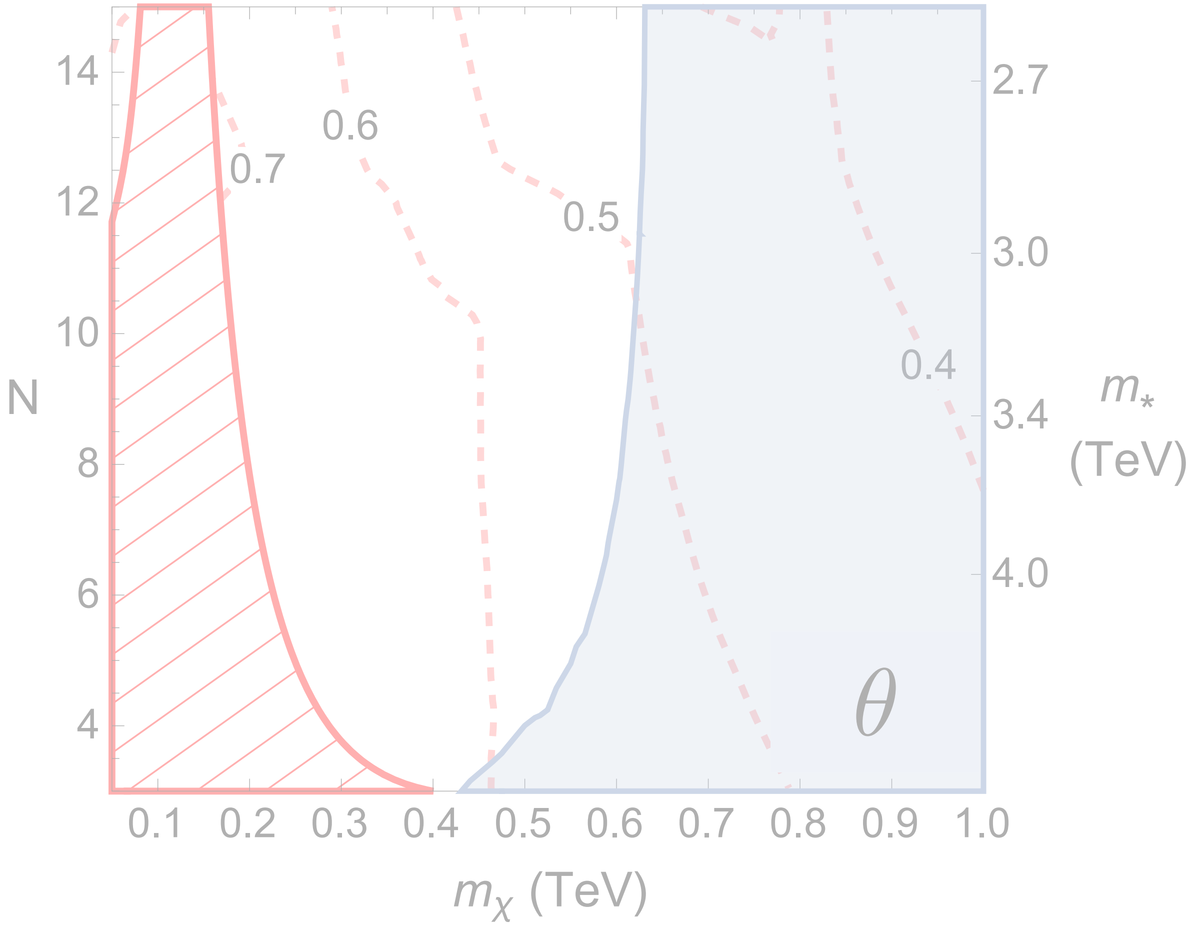


The phase transition

Meson-like dilaton

$$g_\chi = \frac{4\pi}{\sqrt{N}}$$

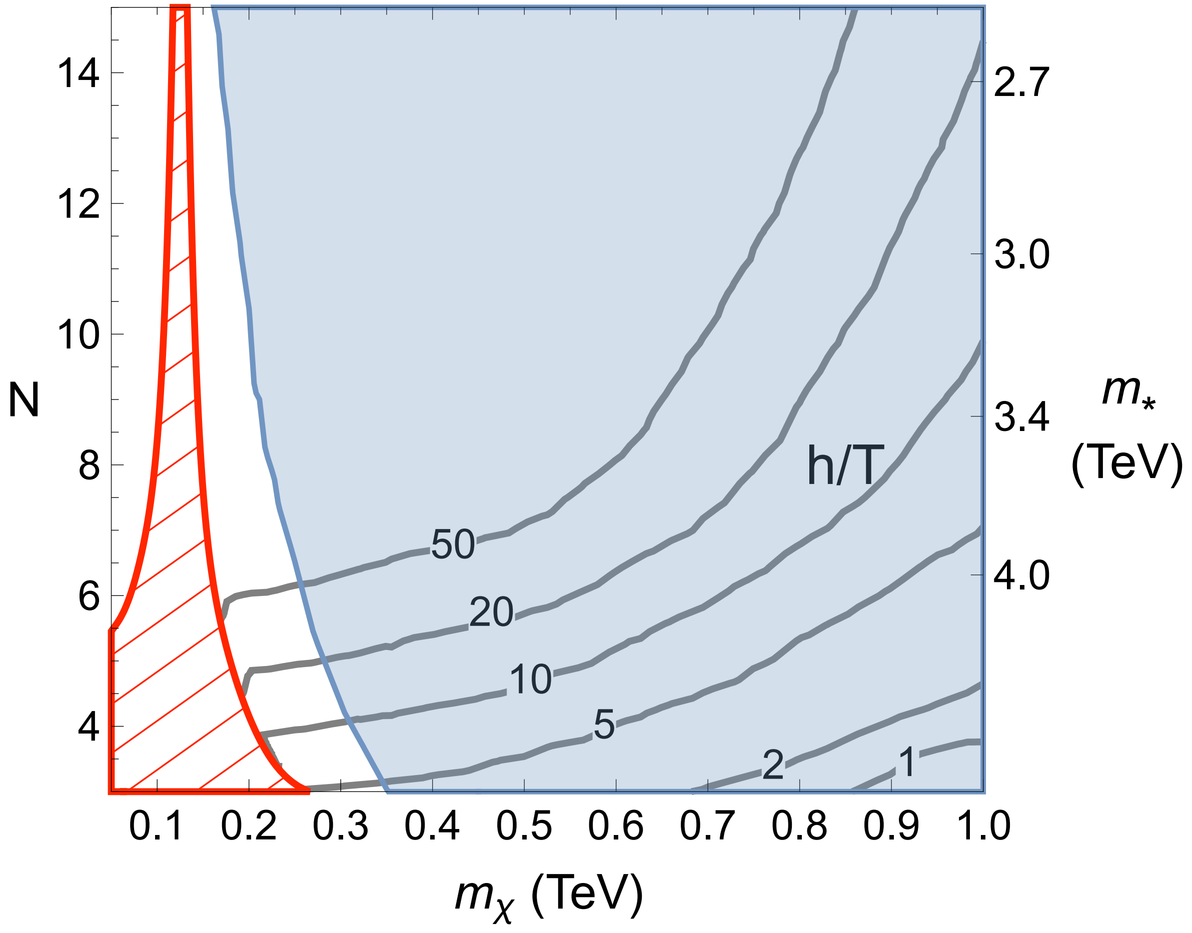


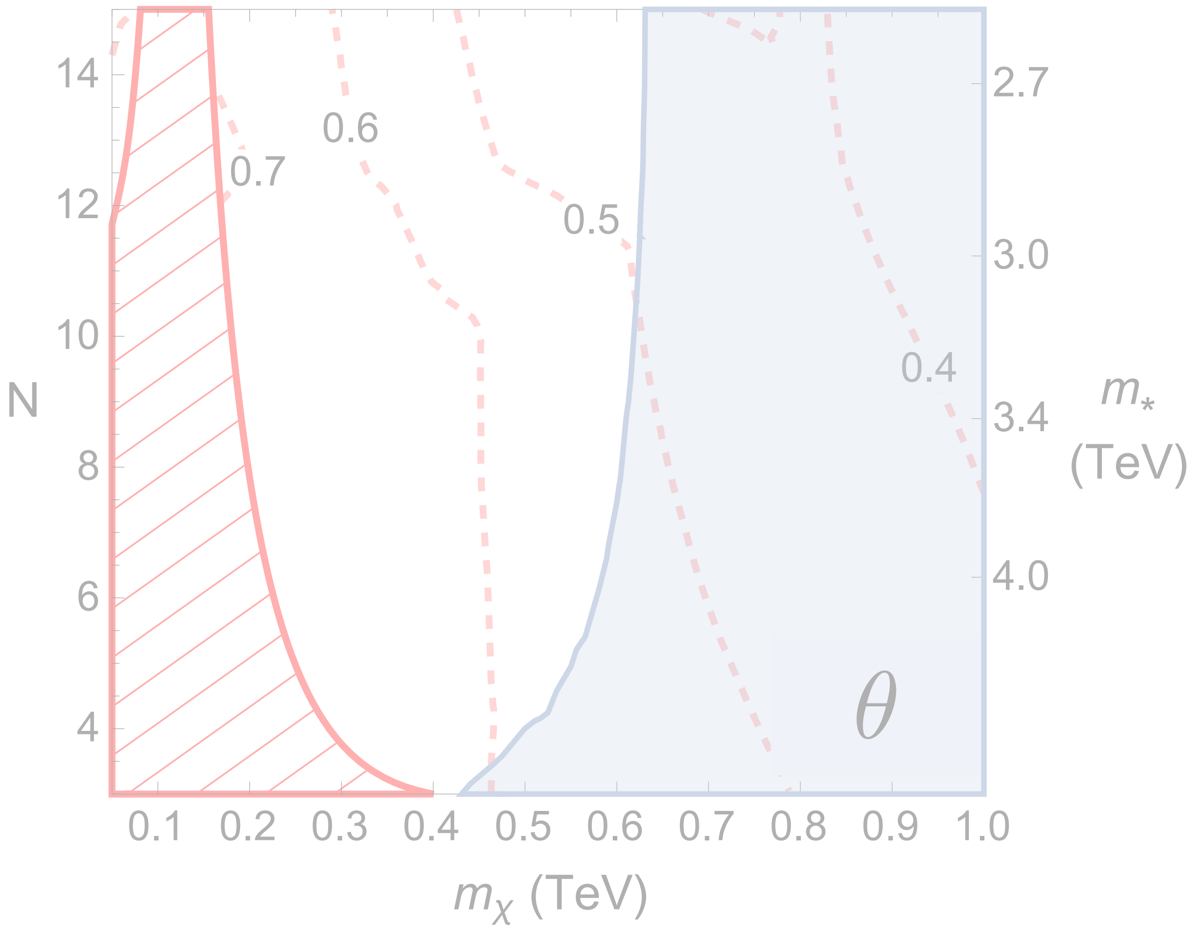


The phase transition

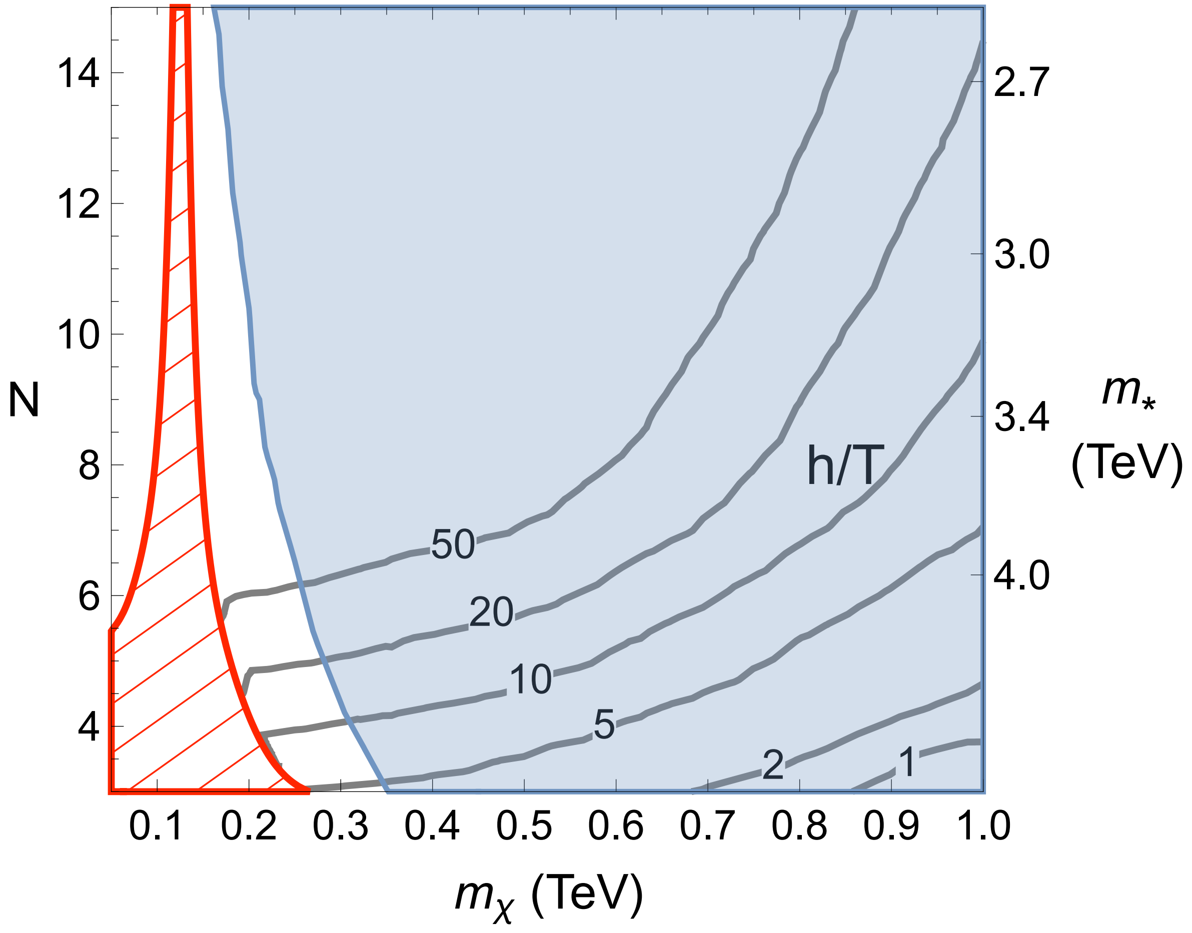
Glueball-like
dilaton

$$g_\chi = \frac{4\pi}{N}$$





The phase transition



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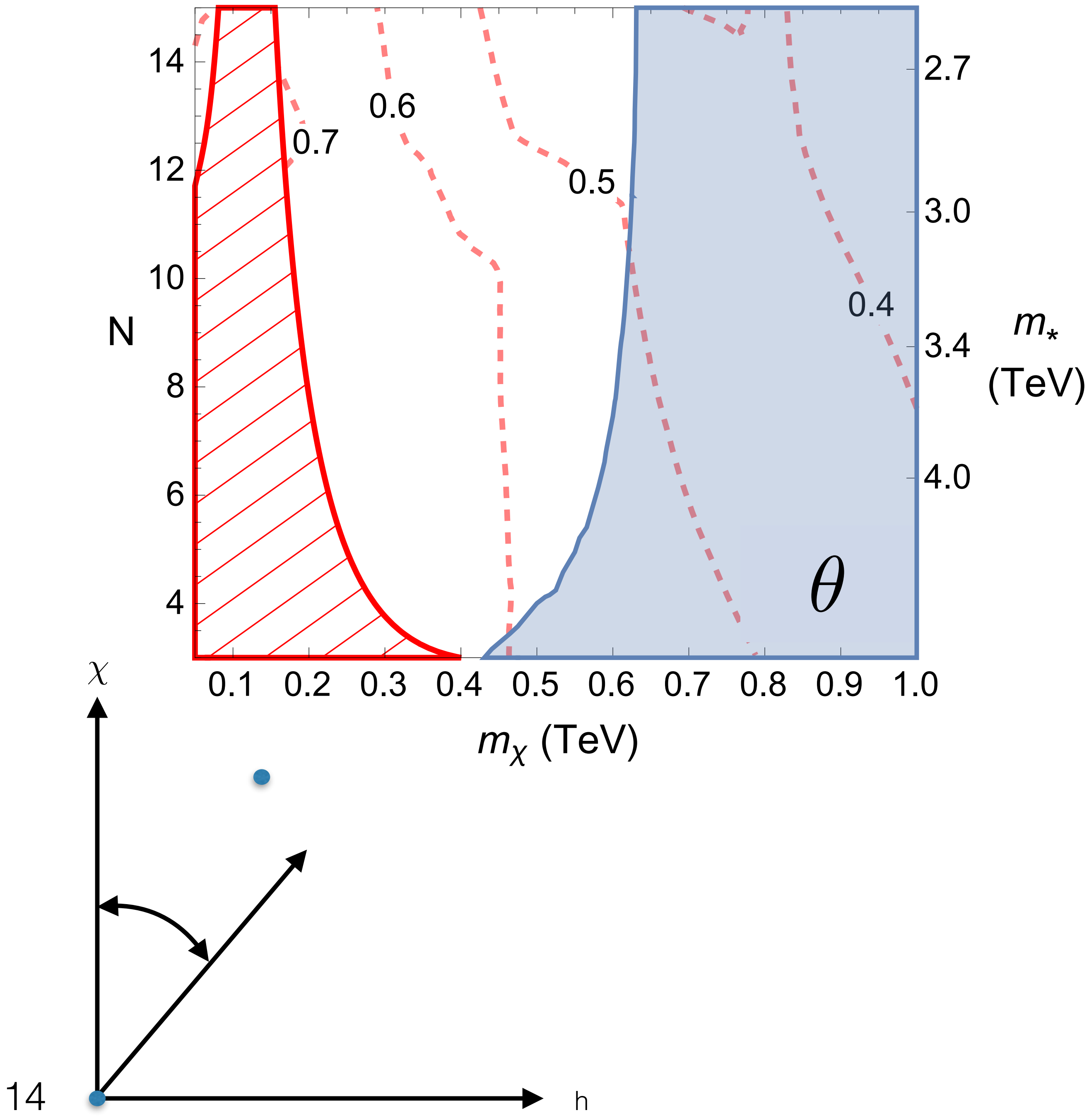

The phase transition

Glueball-like
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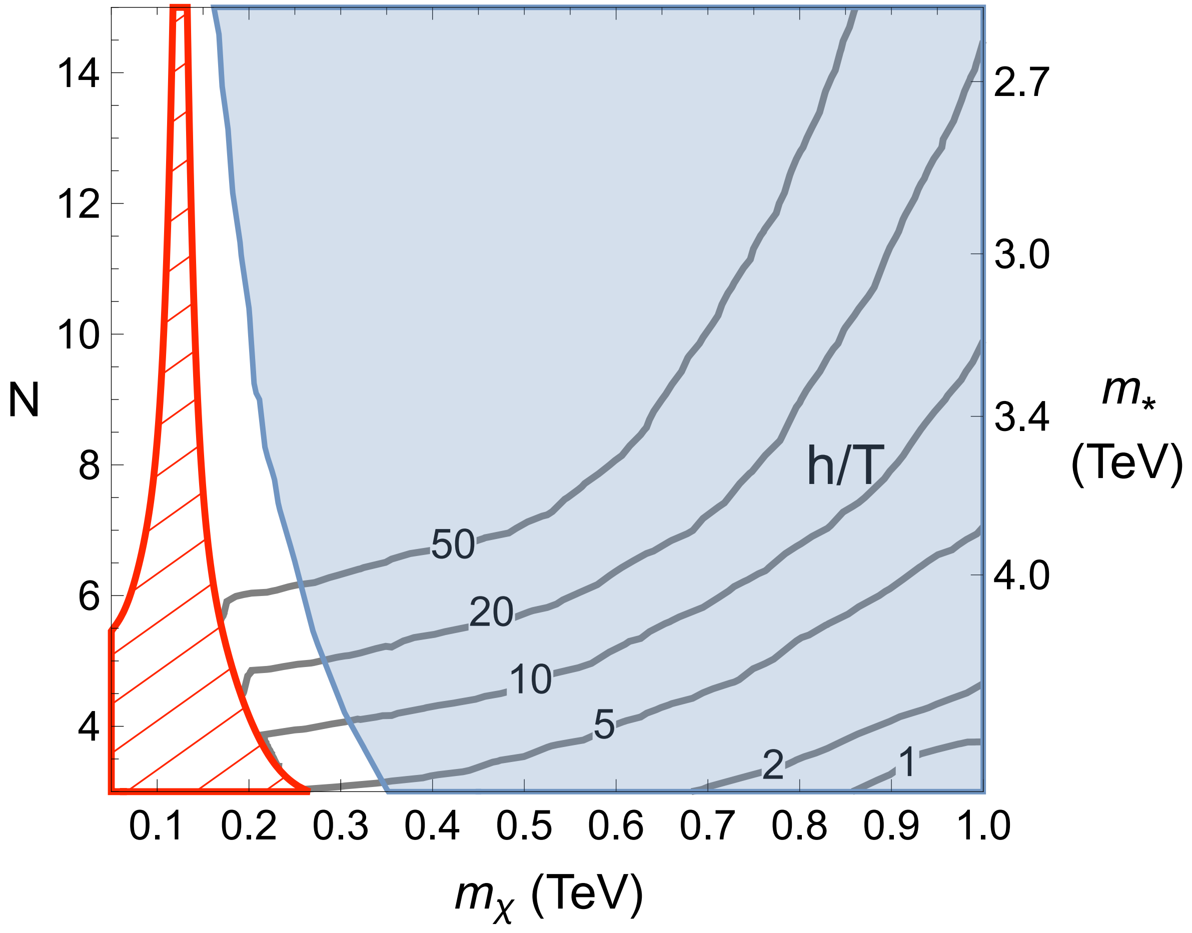

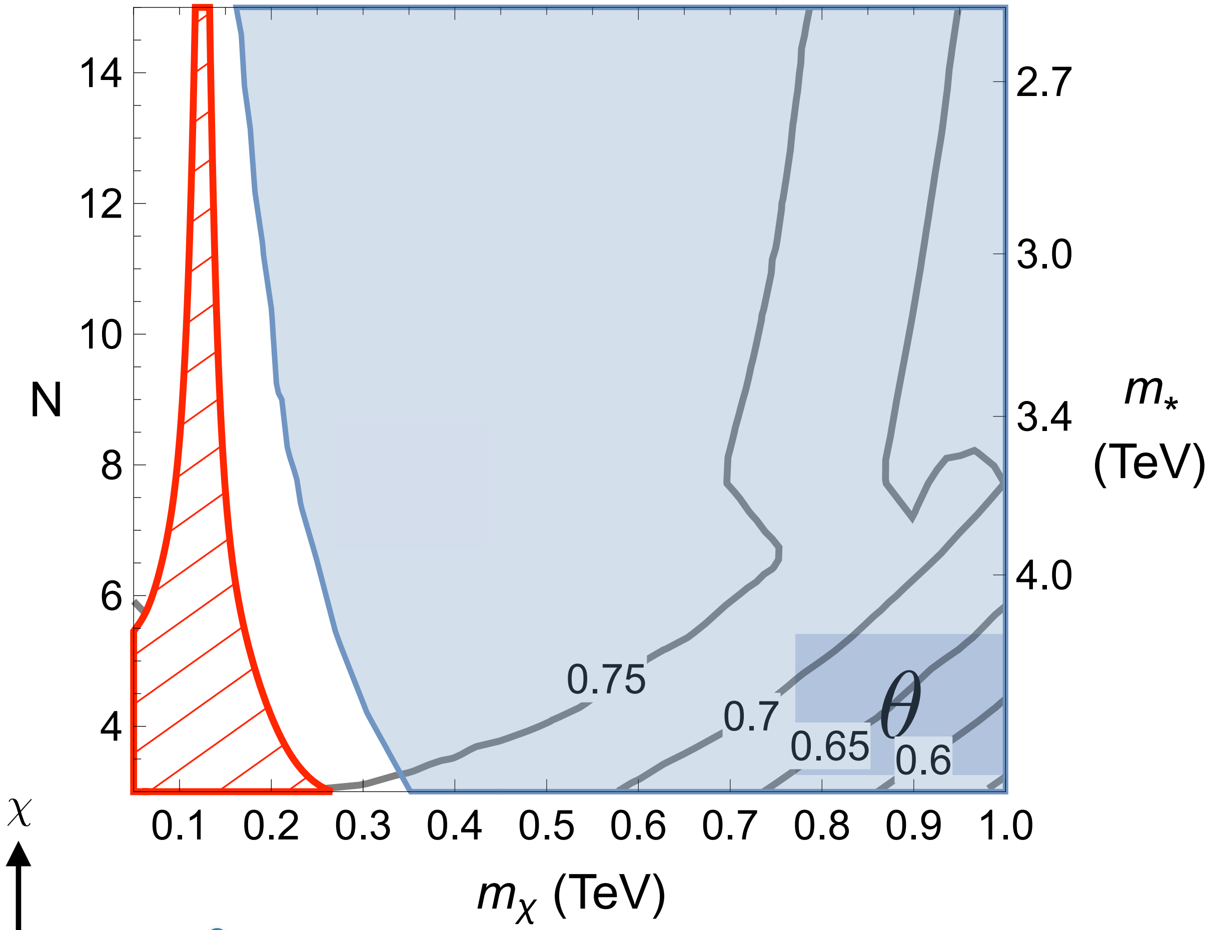

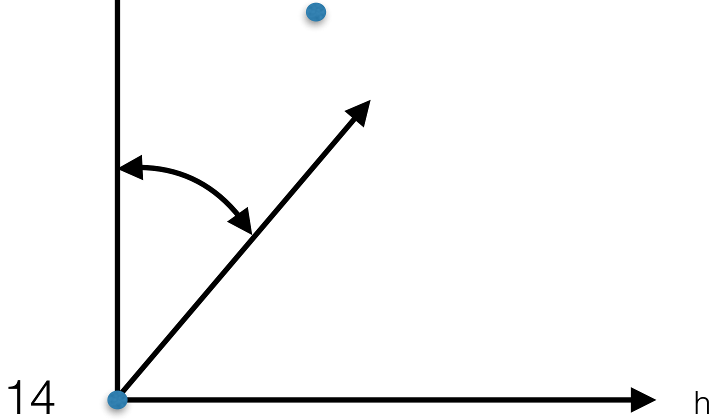

Experimental signatures

Experimental signatures

- Light dilaton

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- Light dilaton
- Modification of Yukawa coupling

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    - Real part: Measurable at LHC and future linear colliders

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    - Imaginary part: electron and neutron EDMs

Experimental signatures

- Light dilaton
- Modification of Yukawa coupling
    - Real part: Measurable at LHC and future linear colliders
    - Imaginary part: electron and neutron EDMs
- Gravitational waves in LISA spectrum

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, Composite Higgs etc.)

Baldes, Konstandin,
Servant '16
1604.04526 & 1608.03254

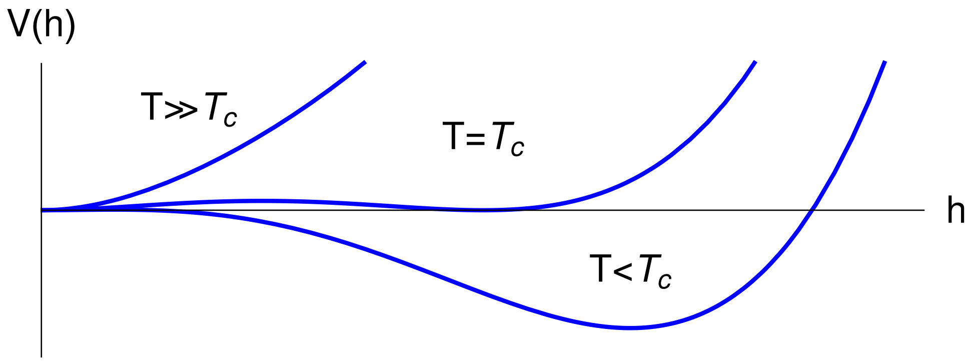
Von Harling, Servant '16
1612.02447

SB, Matsedonskyi,
Von Harling, Servant
1803.08546, 1804.07314

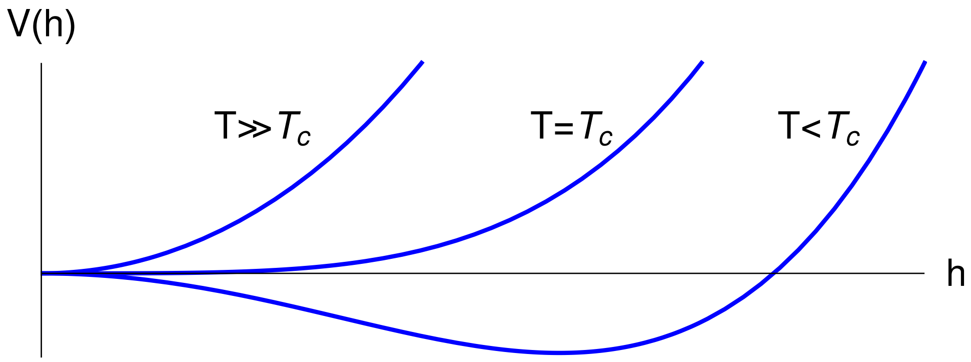
Summary

- Composite Higgs is a prime model for EWBG with varying Yukawas
  - Strong first-order PT from combined confinement-EWPT
  - Varying Yukawas from partial compositeness
  - Detectable signal in gravitational waves
  - Detection possible in electron/neutron EDM

Phase transitions

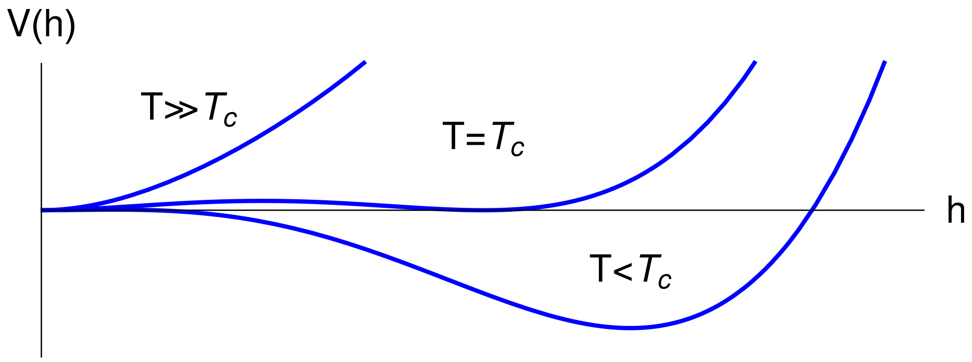


First-order phase transition

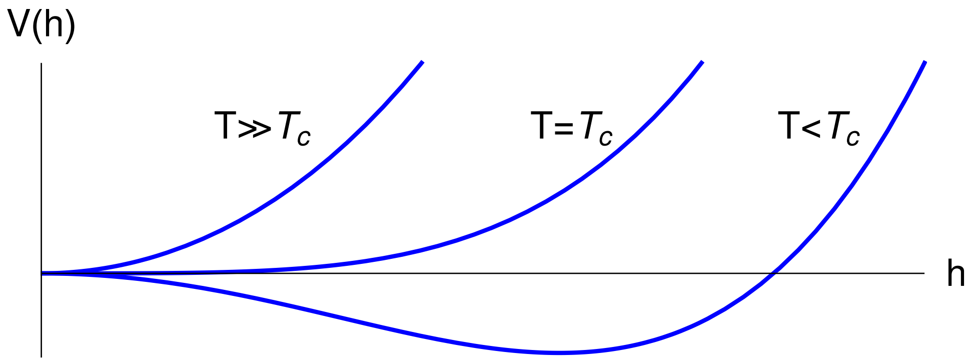


Higher order phase transition

Phase transitions



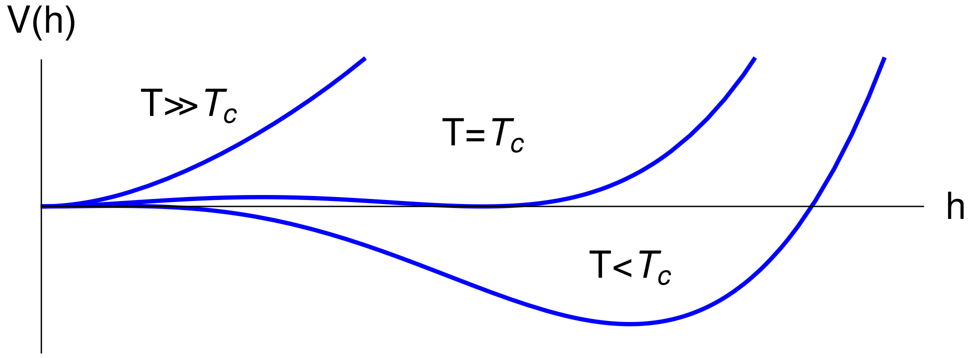
First-order phase transition



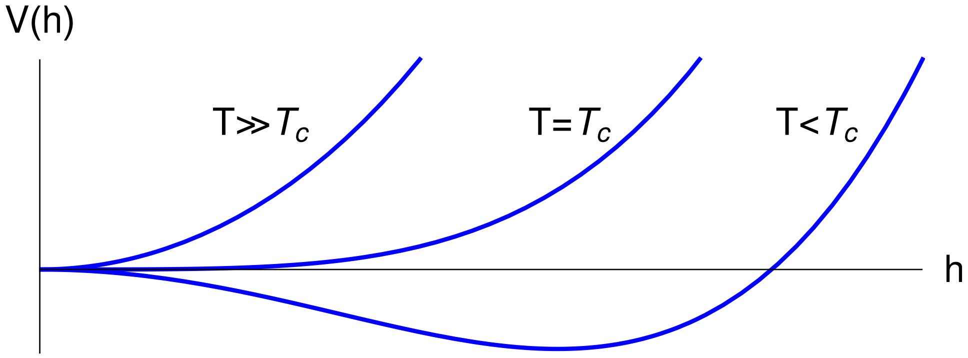
Higher order phase transition

In the SM: not first order

Phase transitions


V(h)
T≫T_c
T=T_c
T<T_c
h

First-order phase transition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h

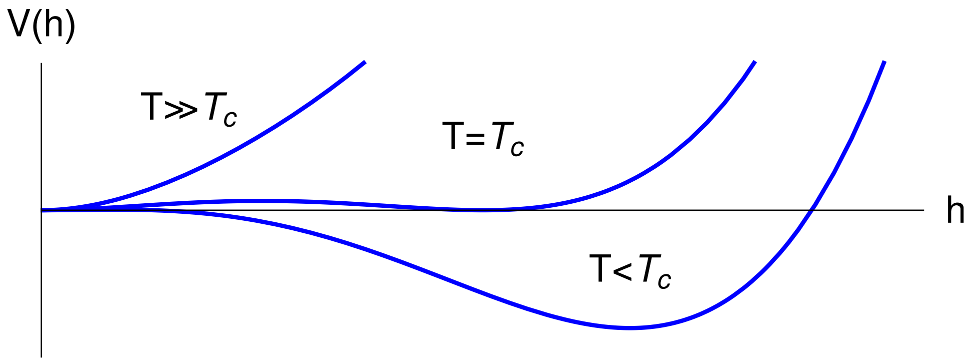
Higher order phase transition

In the SM: not first order

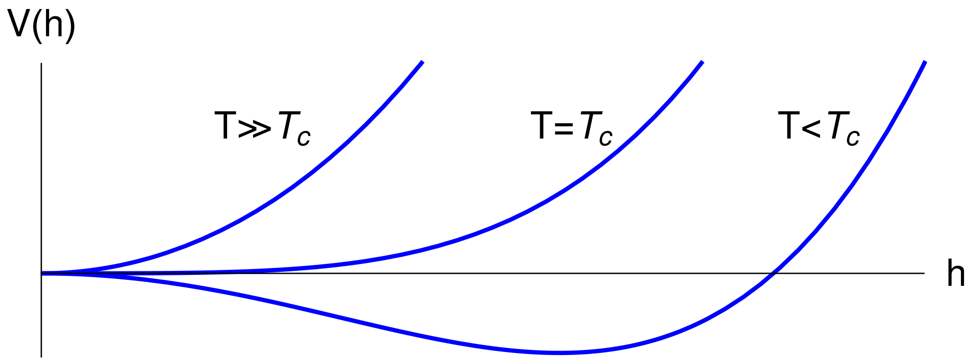
Yukawa variation:

Baldes, Konstandin, Servant ‘16

Phase transitions



First-order phase transition



Higher order phase transition

In the SM: not first order

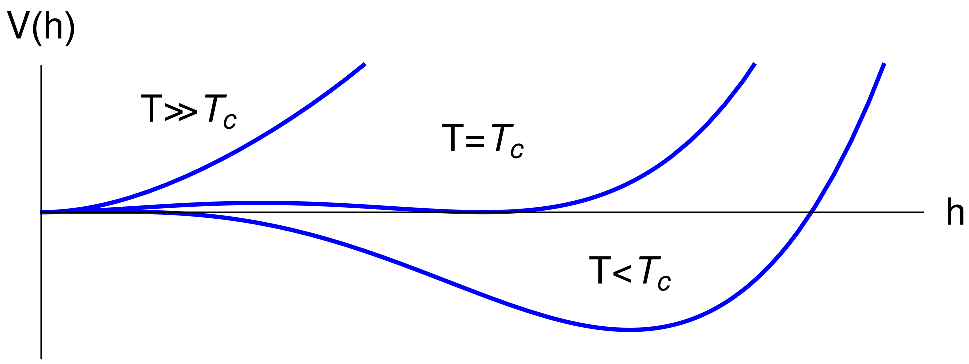
Yukawa variation:

Baldes, Konstandin, Servant '16

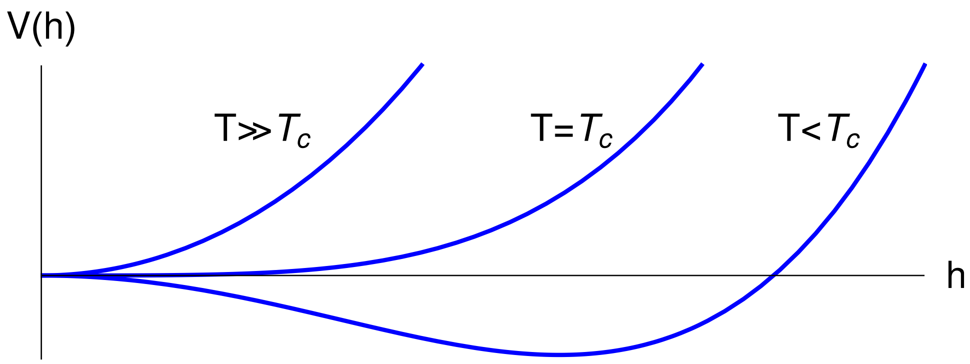
Singlet extensions:

Espinosa, Gripaios,
Konstandin, Riva '11

Phase transitions



First-order phase transition



Higher order phase transition

In the SM: not first order

Yukawa variation: Baldes, Konstandin, Servant ‘16

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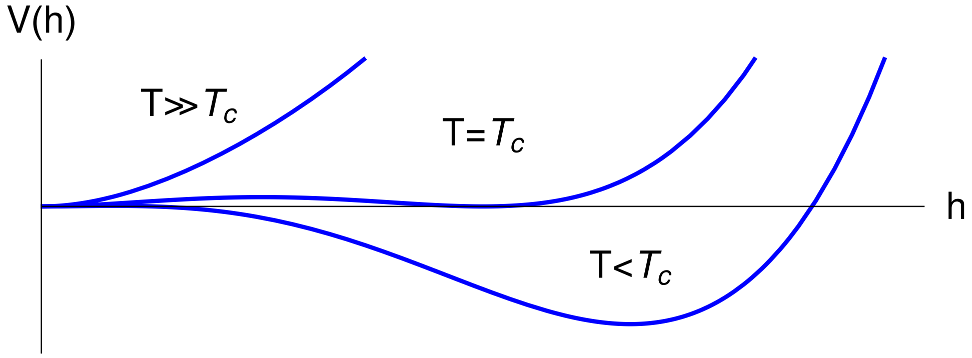
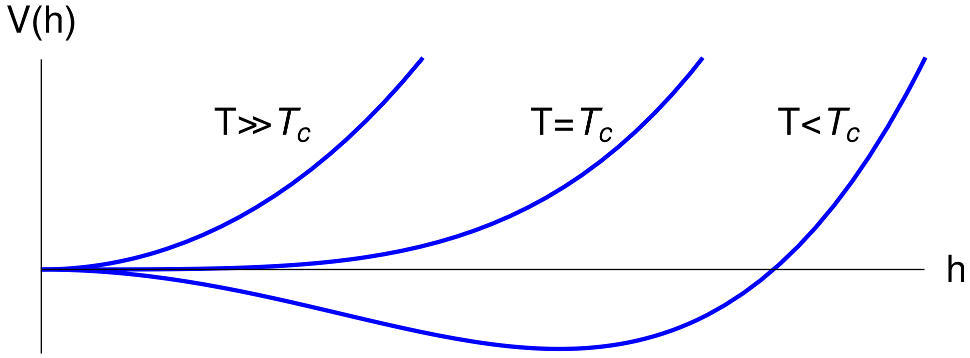
Higher order operators: Delaunay, Grojean, Wells ‘07 Grinstein, Trott ‘08

Phase transitions



First-order phase transition



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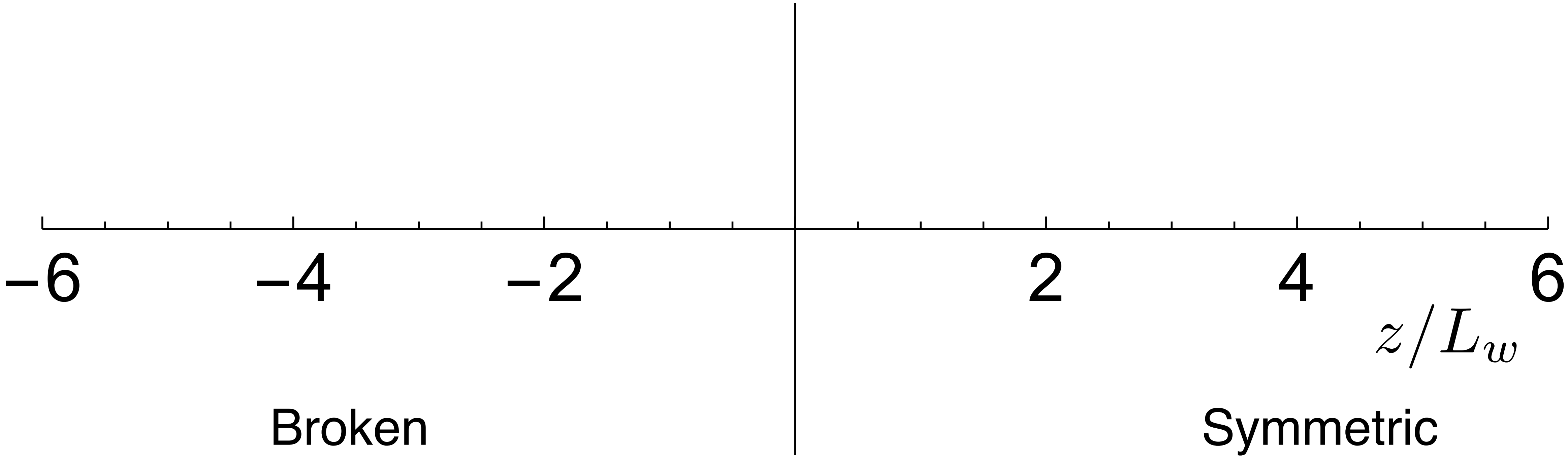
Grinstein, Trott ‘08

Joint confinement-electroweak phase transition: stay tuned

Baryon asymmetry

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



1. Sakharov condition (B-violation)

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

Baryon asymmetry

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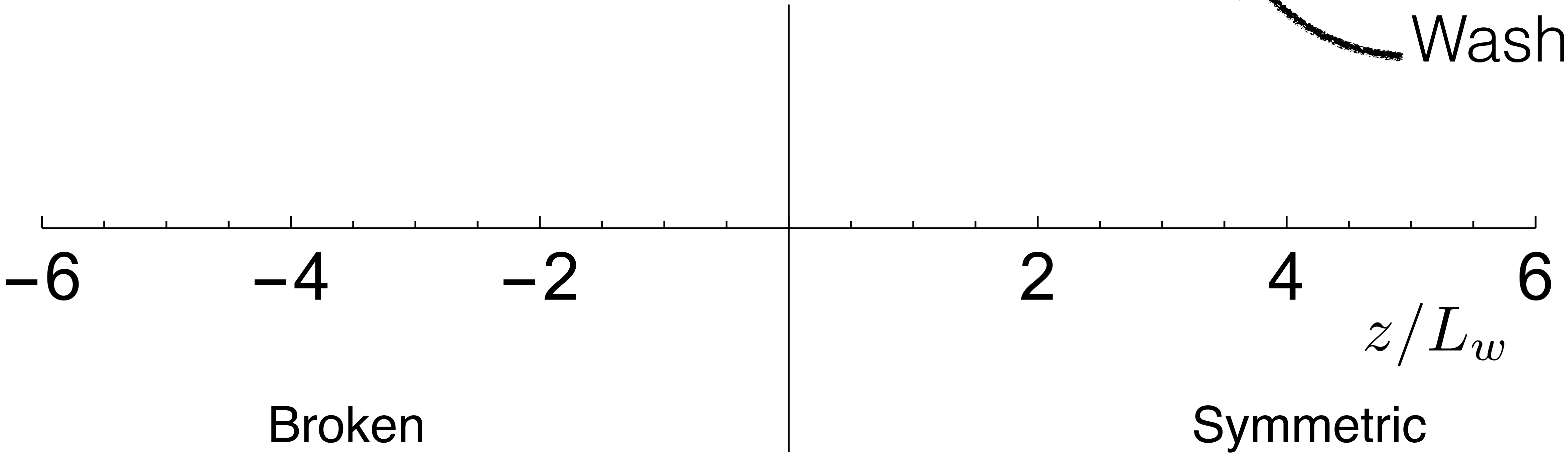
Washout



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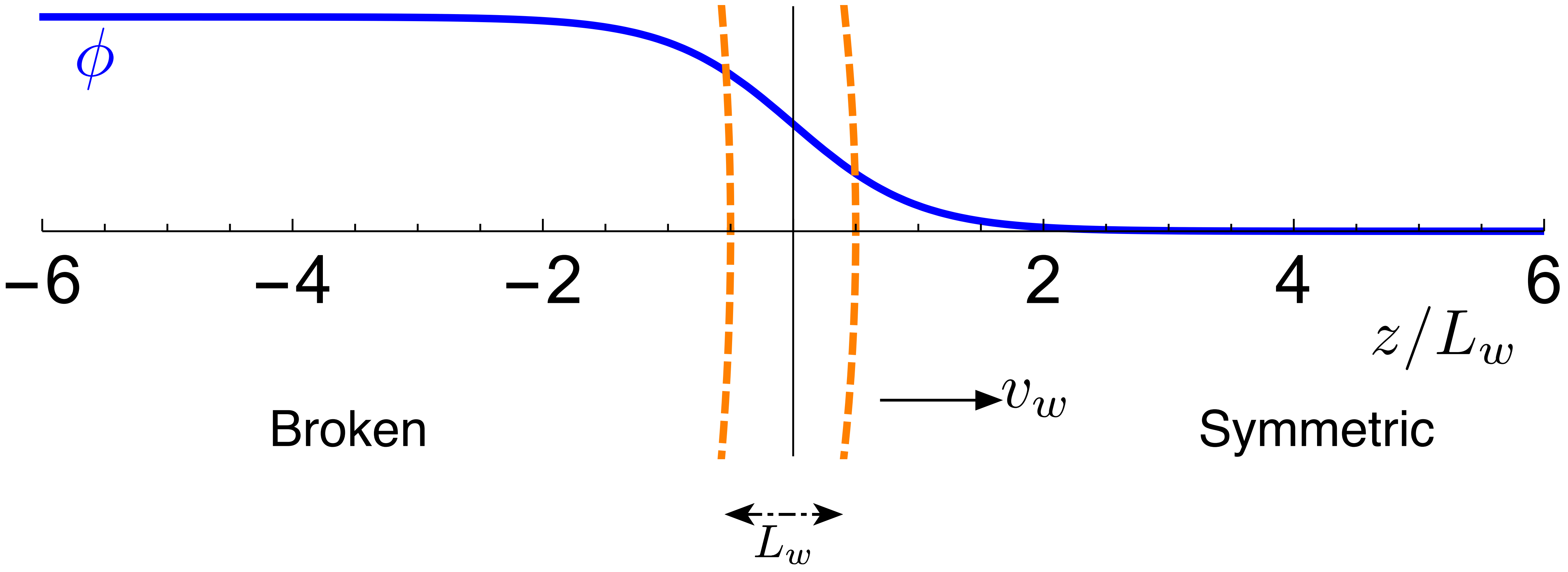

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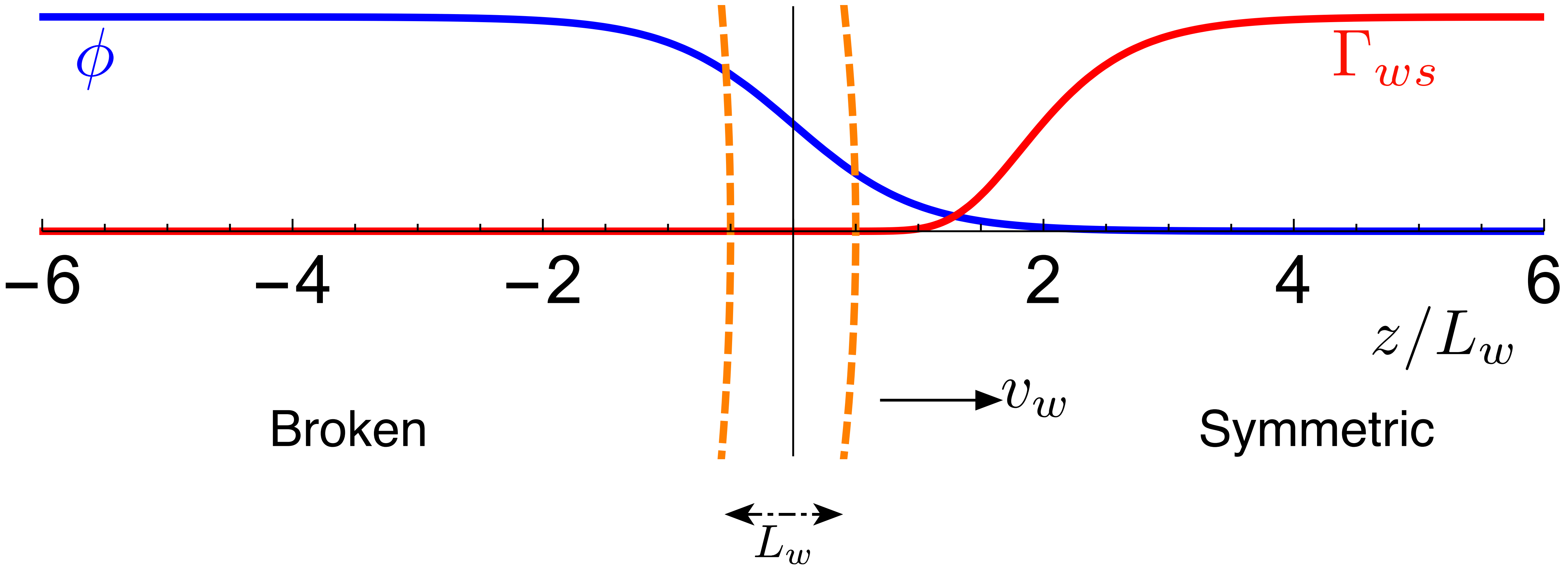

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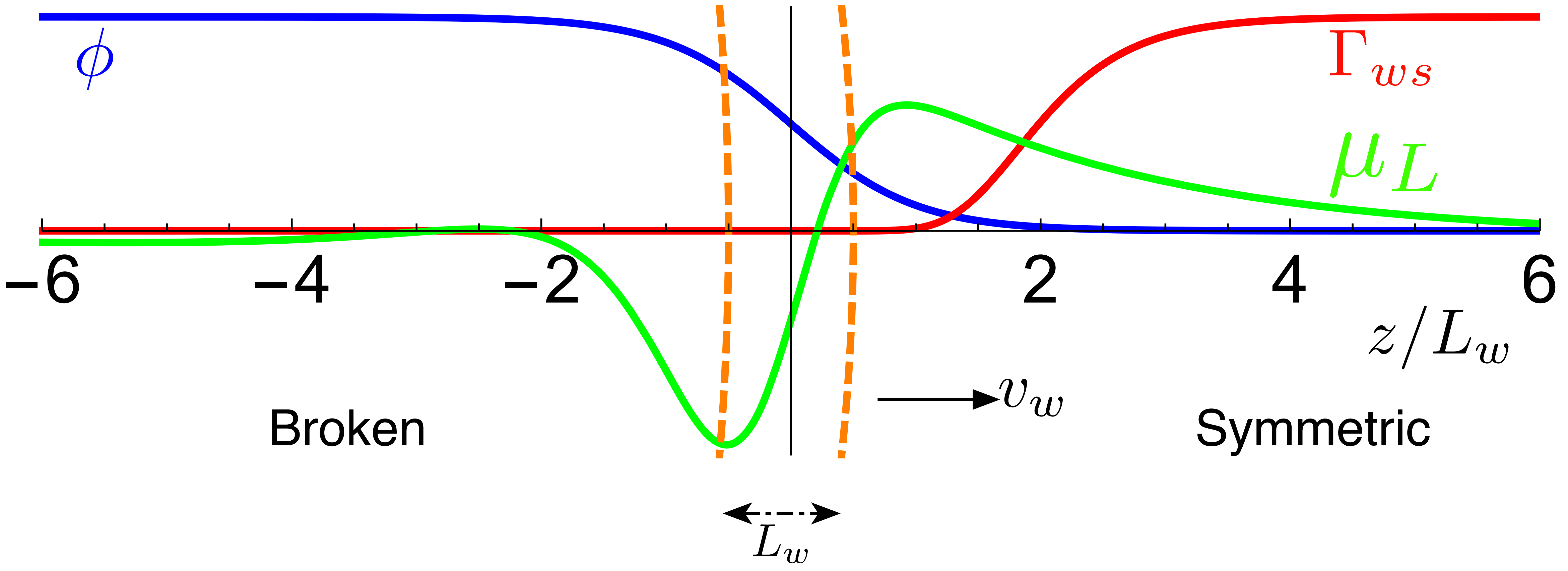

1. Sakharov condition (B-violation)

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

System and Kernel

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

Unknowns

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

$$u_{t_{R/L}}, u_{b_{R/L}}, u_{s_{R/L}}, u_{c_{R/L}}, u_h)$$

System and Kernel

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

System and Kernel

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

Unknowns

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

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

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

System and Kernel

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

Unknowns

$$(\mu_{t_{R/L}}, \mu_{b_{R/L}}, \mu_{s_{R/L}}, \mu_{c_{R/L}}, \mu_h$$
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$$\eta_B = \int_{-\infty}^{+\infty} \mathrm{d}z\, \#\Gamma_{ws}(z)\, e^{-\# z}\, \mu_L(z)$$

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

Kernel

- Weak Sphaleron
- Interactions (GF)
- Numerical factors

Source

- CP-violation

Varying Yukawas across the wall

Effective description following from Flavon-Higgs coupling

Broken phase

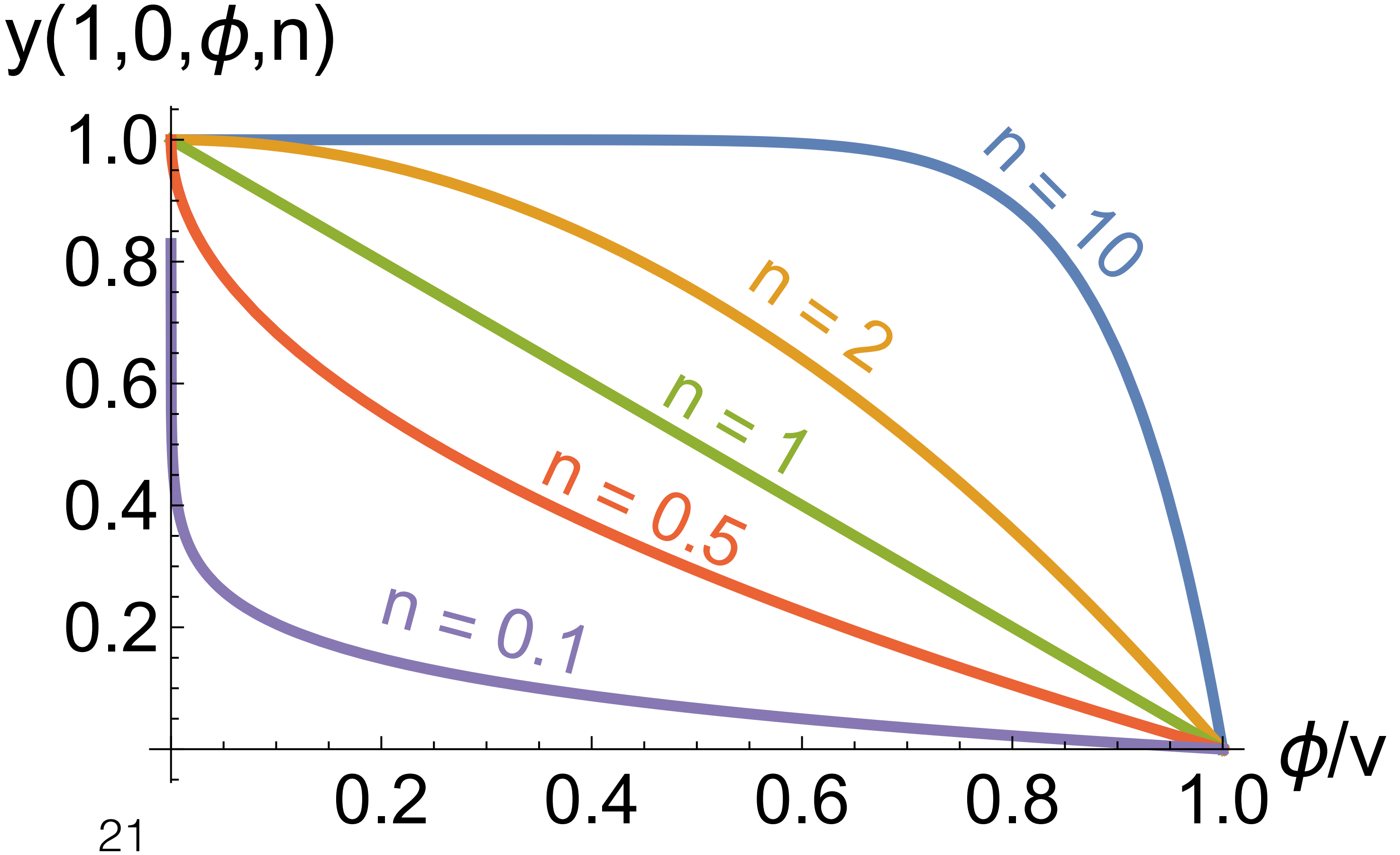
Free parameter

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

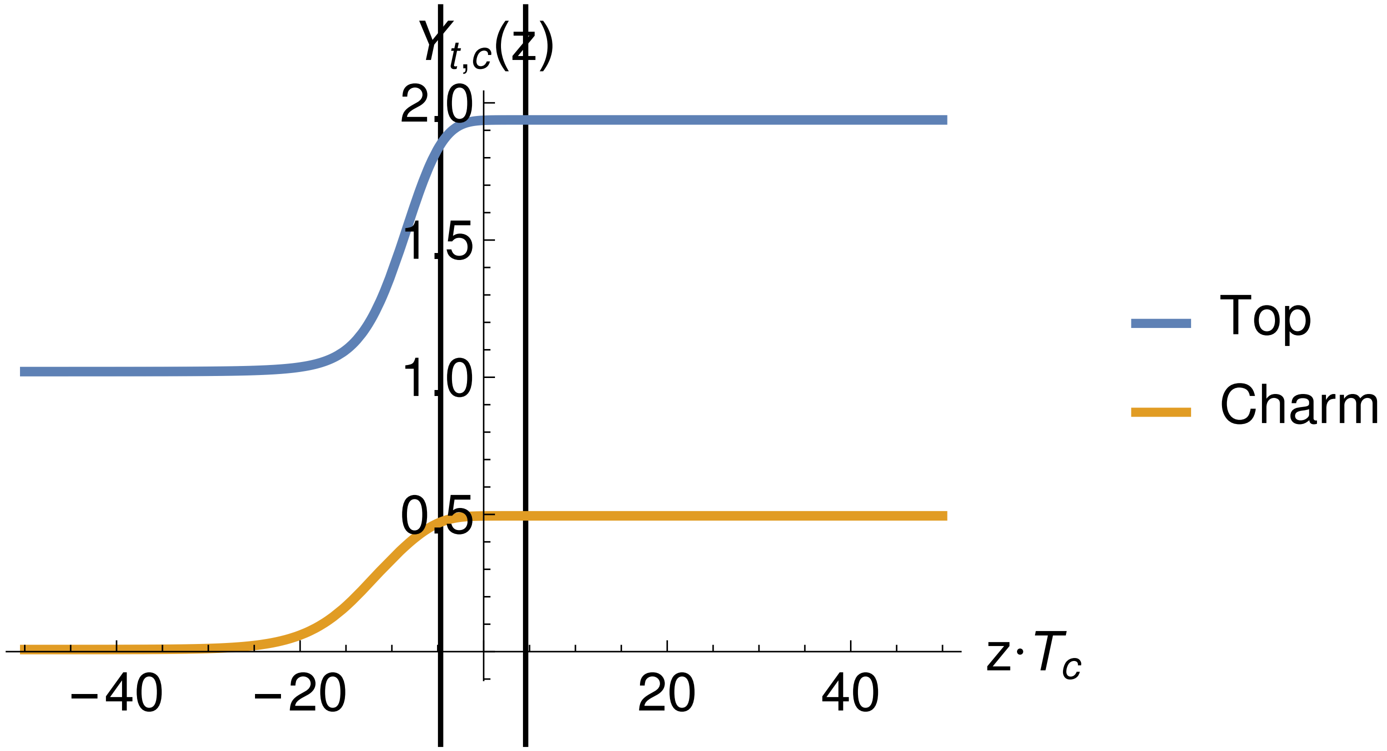
Higgs vev



Baldes, Konstandin, Servant ’16
1608.03254 & 1604.04526

Yukawas

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



$n = 10$

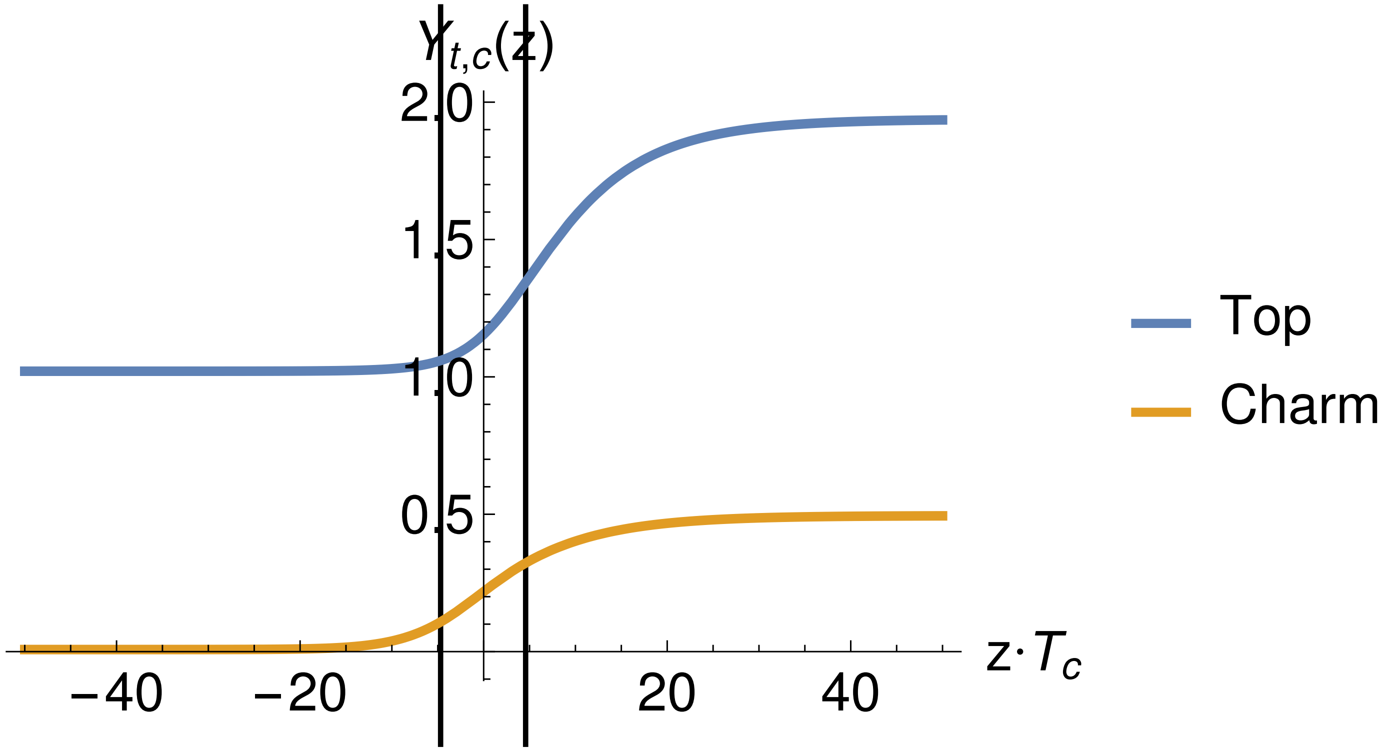
Bubble wall

← Broken phase

Symmetric phase →

Yukawas

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



Bubble wall

$$n = 0.5$$

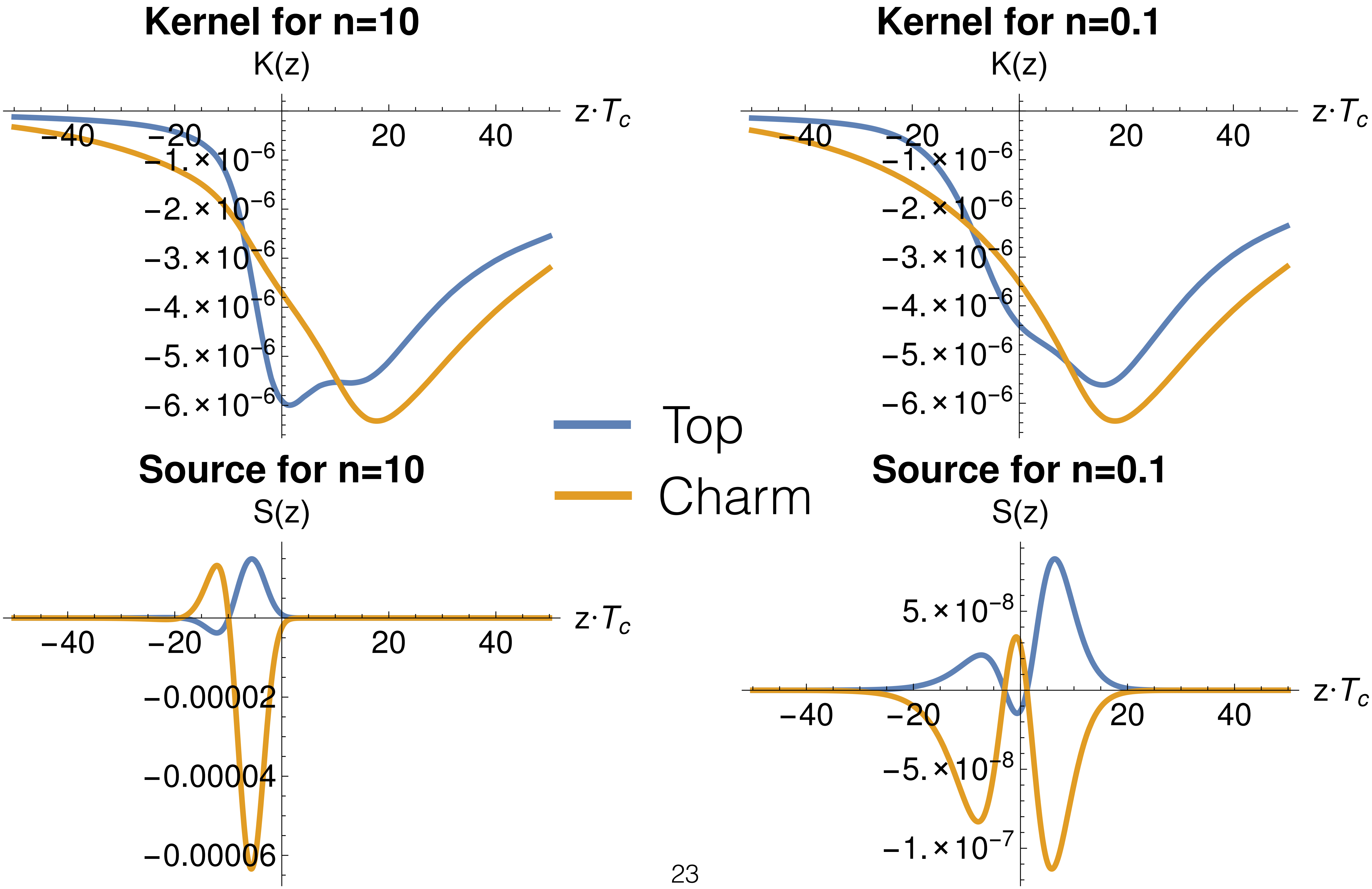
← Broken phase

Symmetric phase →

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

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

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



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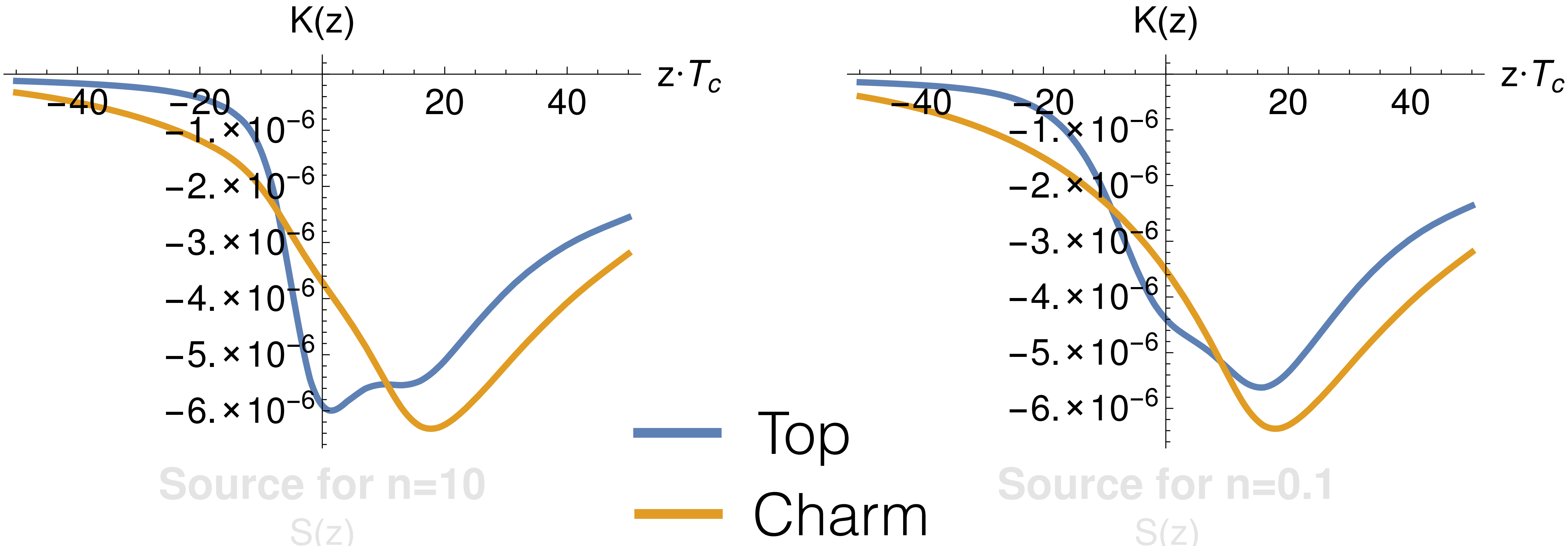
$\eta_B \approx 5.5 \cdot 10^{-10}$

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

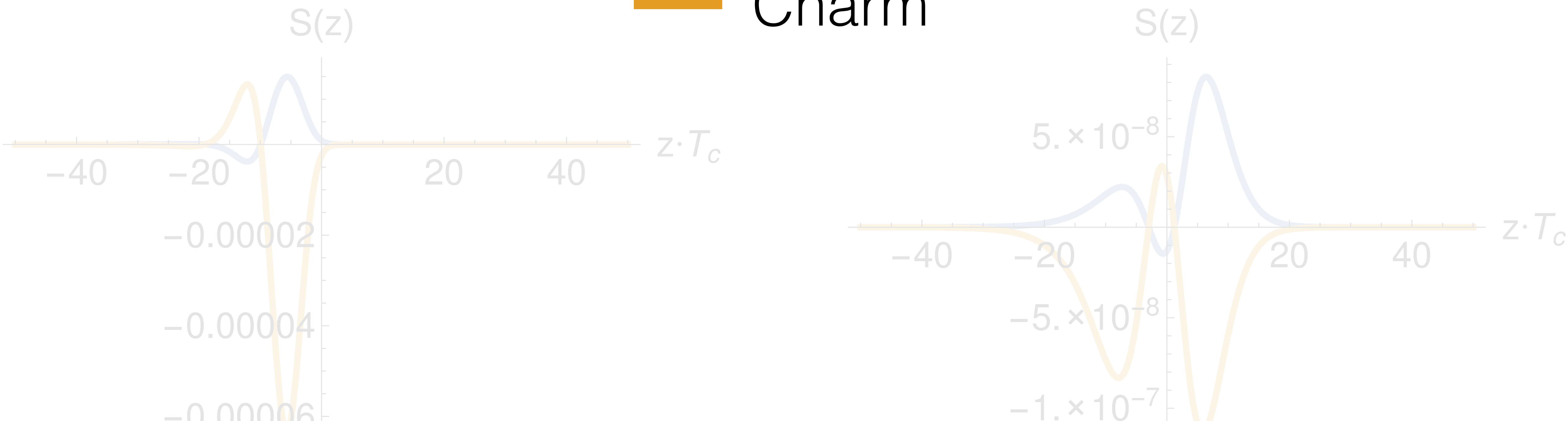
Kernel for n=10

Kernel for n=0.1



Source for n=10

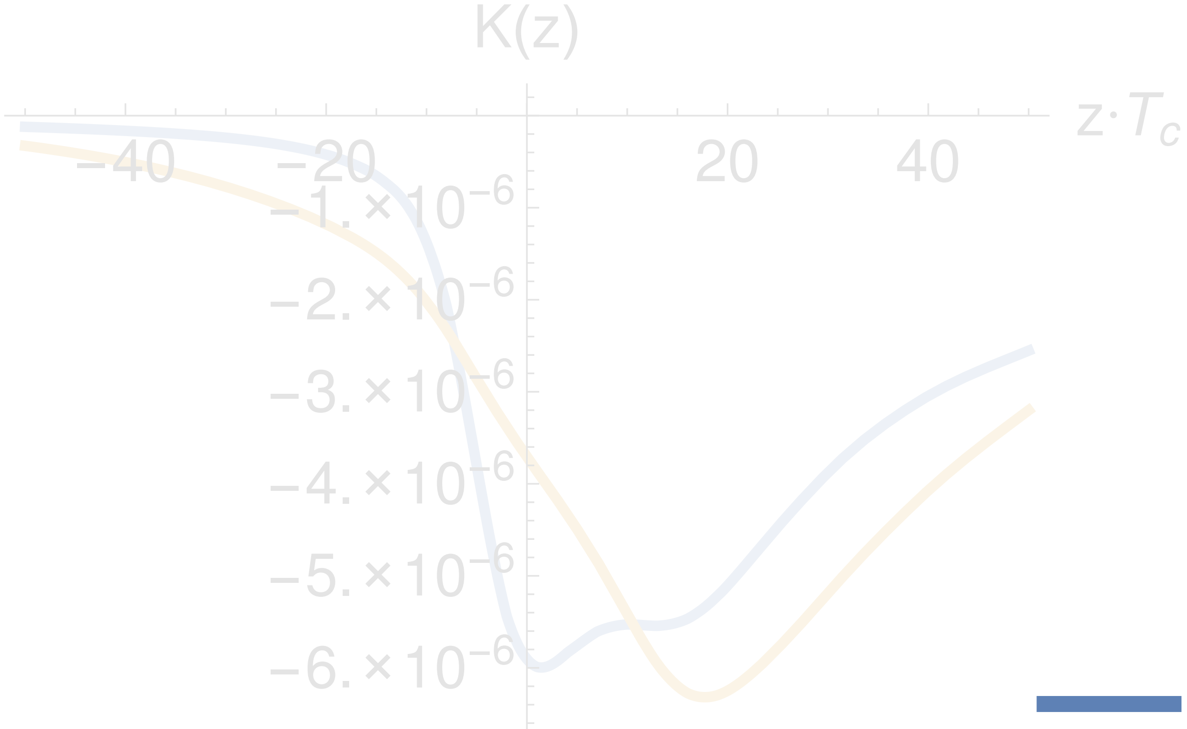
Source for n=0.1



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

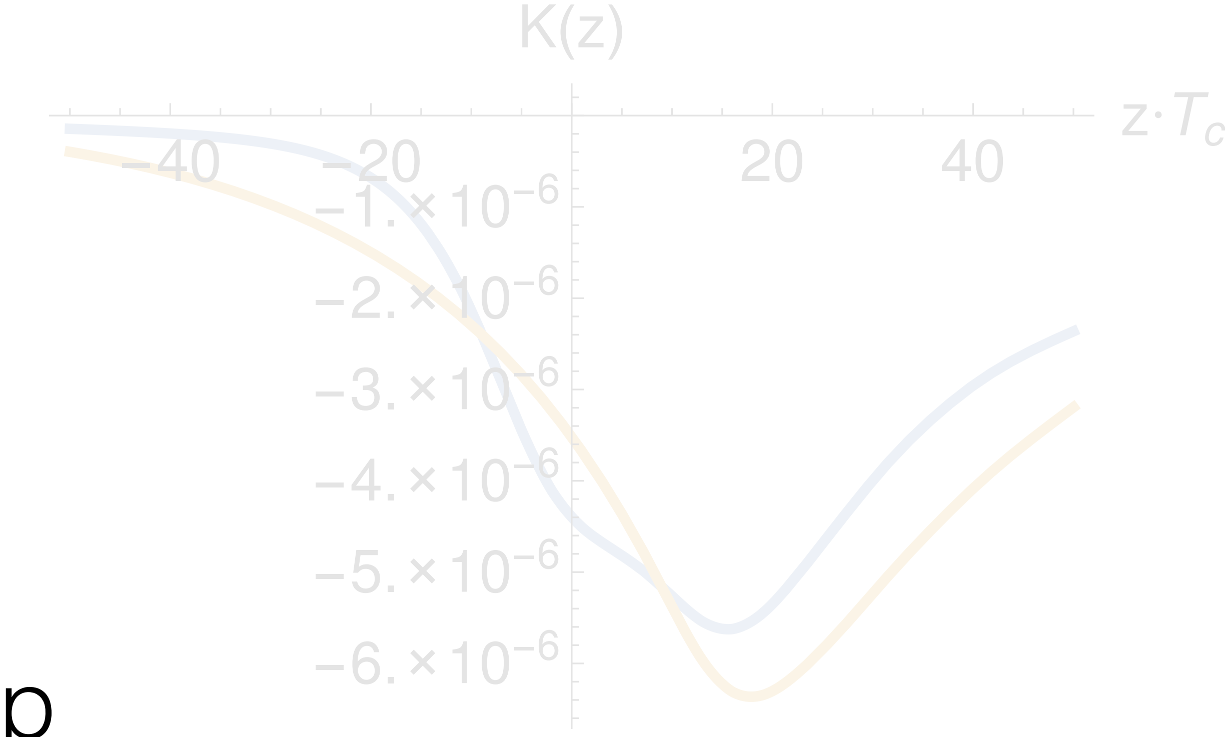
$\eta_B \approx 5.5 \cdot 10^{-10}$

Kernel for n=10



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

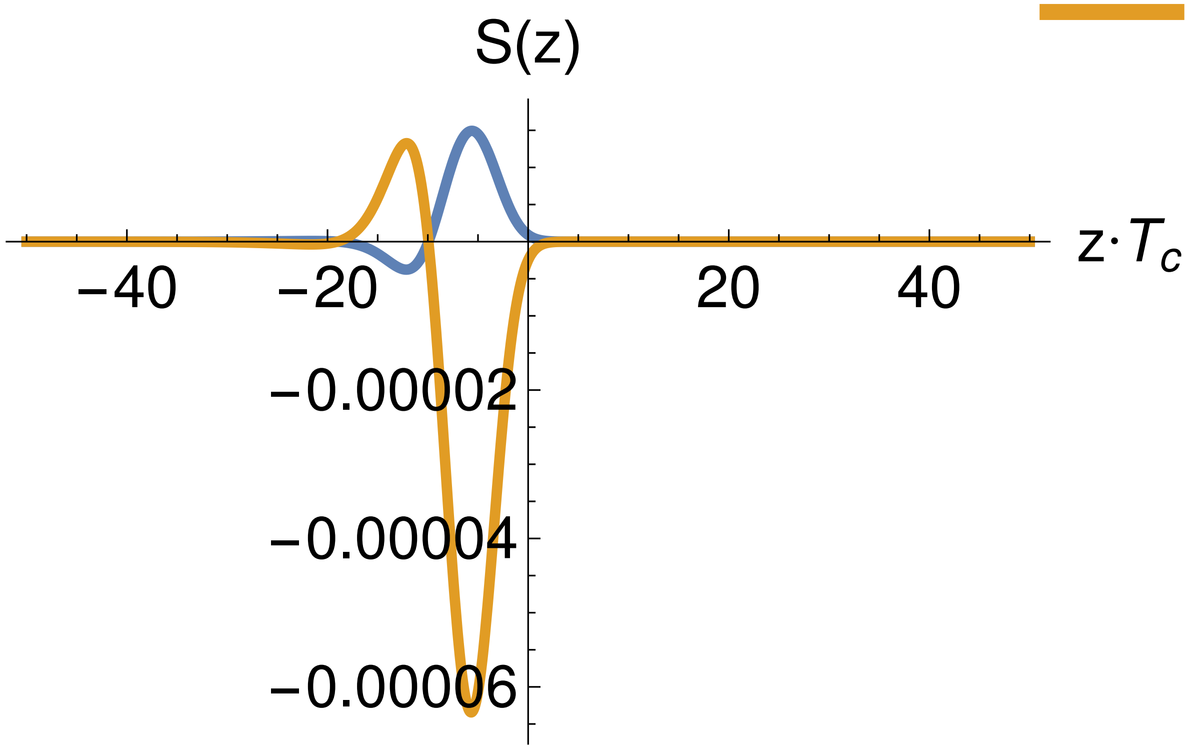
Kernel for n=0.1



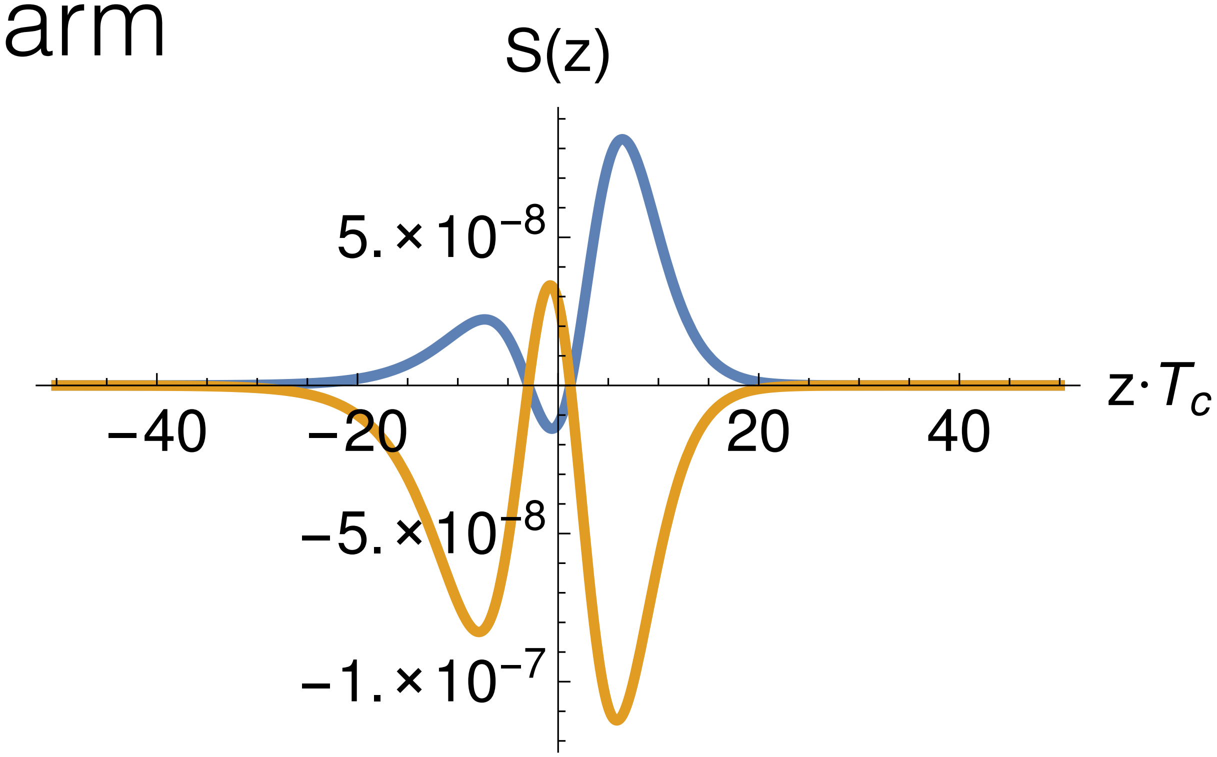
▬ Top

▬ Charm

Source for n=10



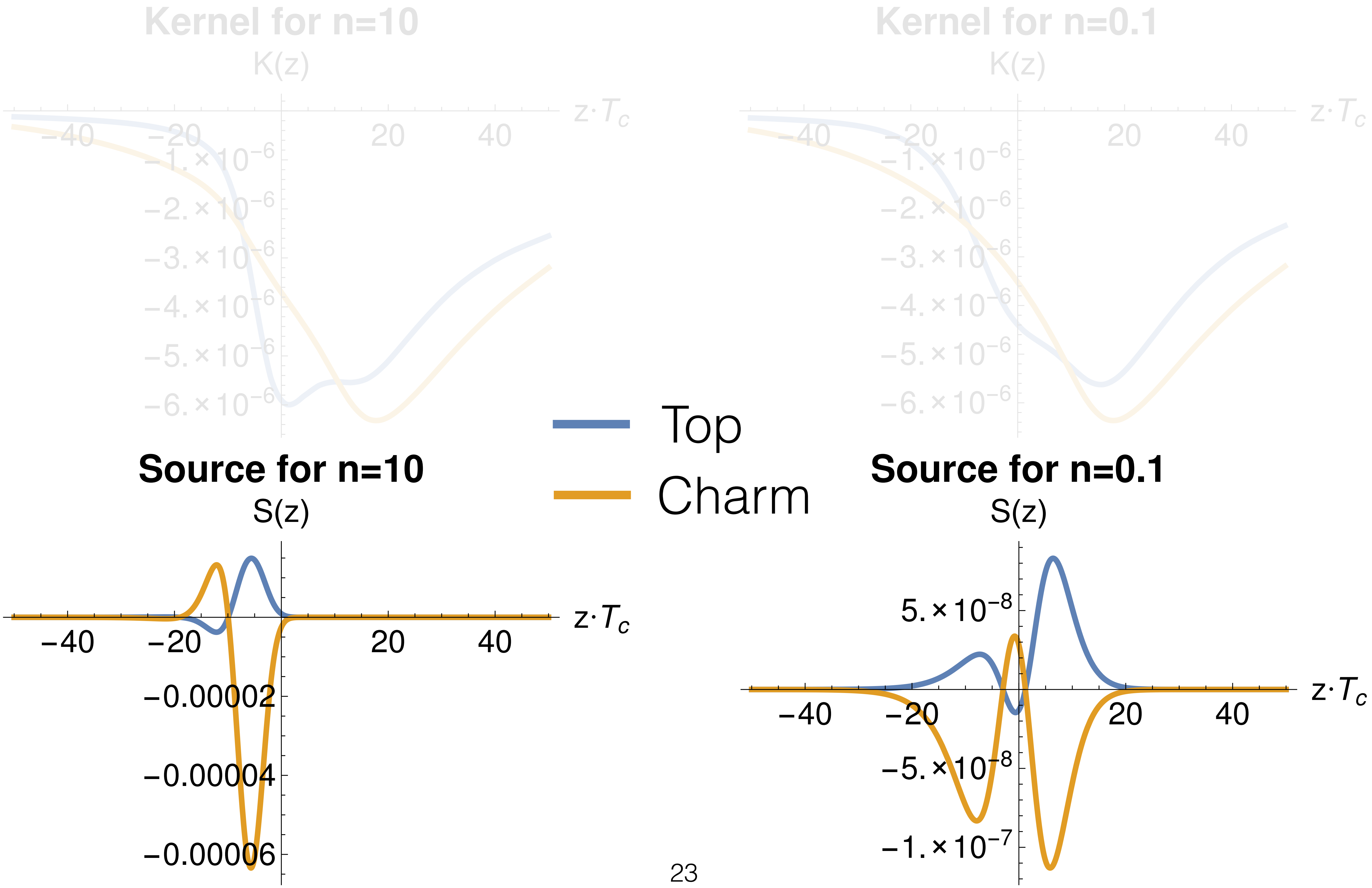
Source for n=0.1



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

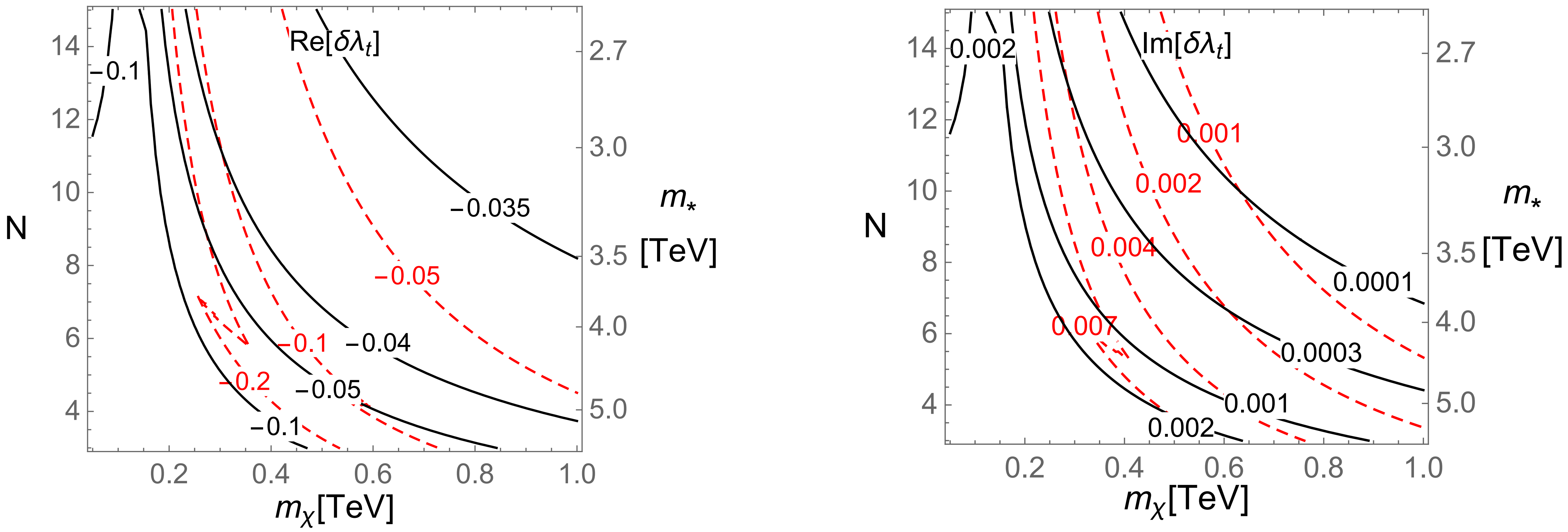
$\eta_B \approx 5.5 \cdot 10^{-10}$

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



Experimental signatures

$$\Gamma_{qqh} \sim -\beta_{\lambda_q} s_\delta \sin[v/f] + \lambda_q (c_\delta \cos[v/f] - s_\delta \sin[v/f])$$



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Beta function of Yukawa
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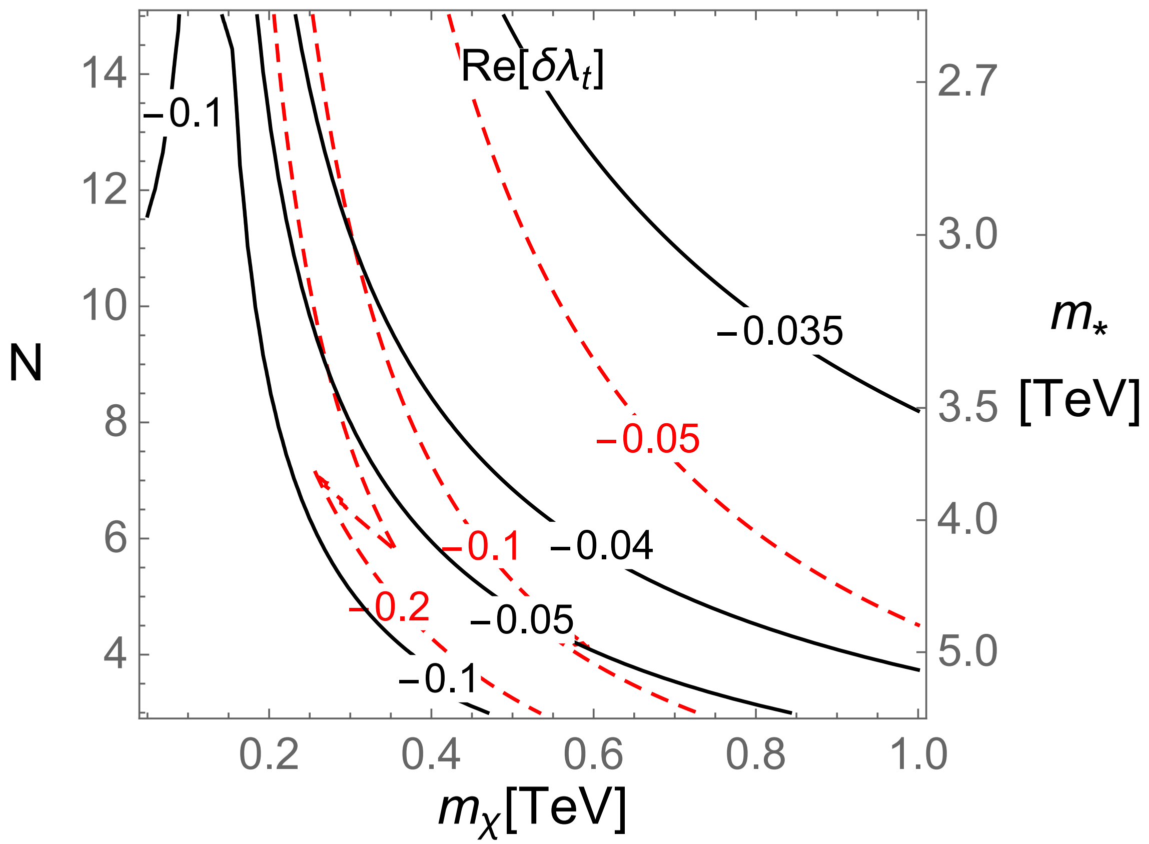

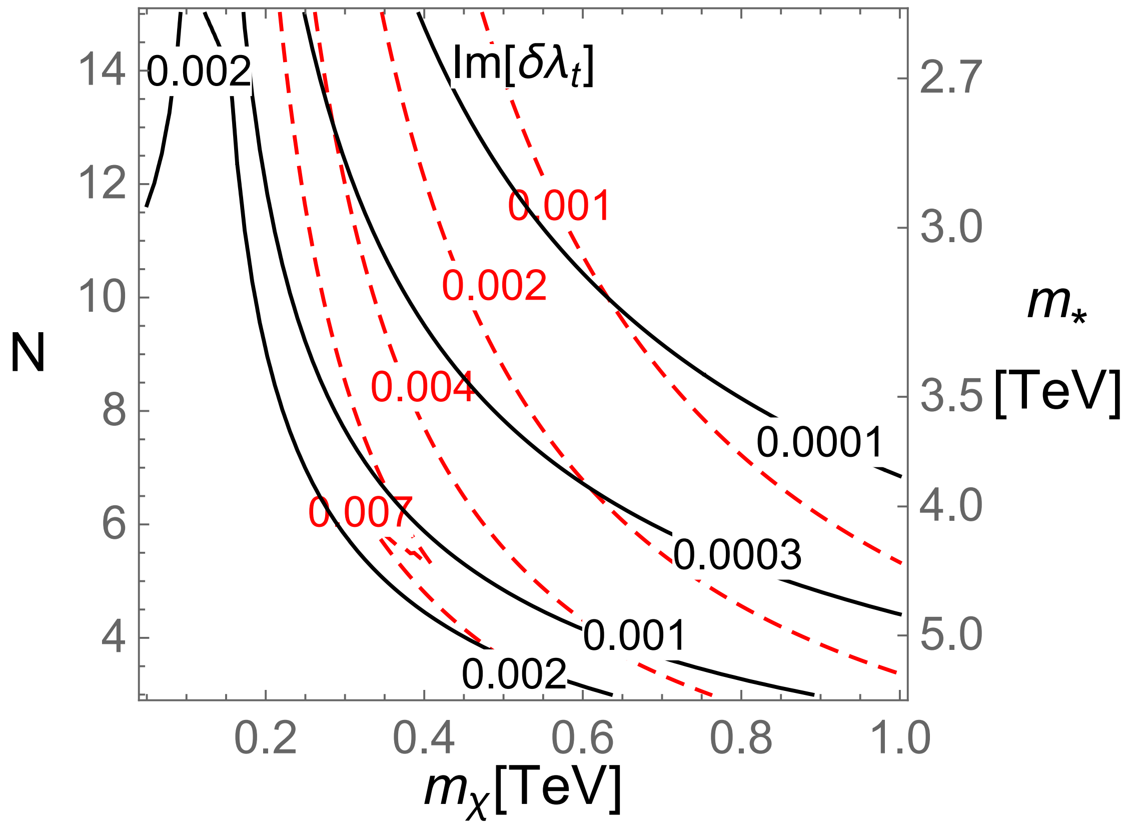

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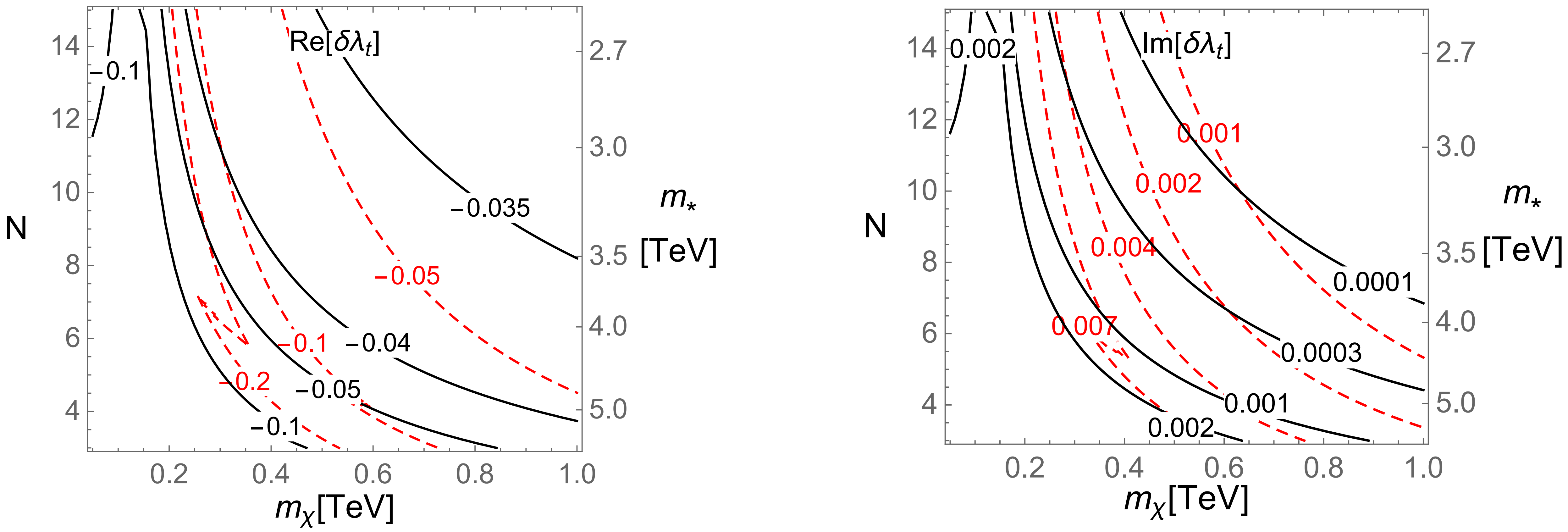

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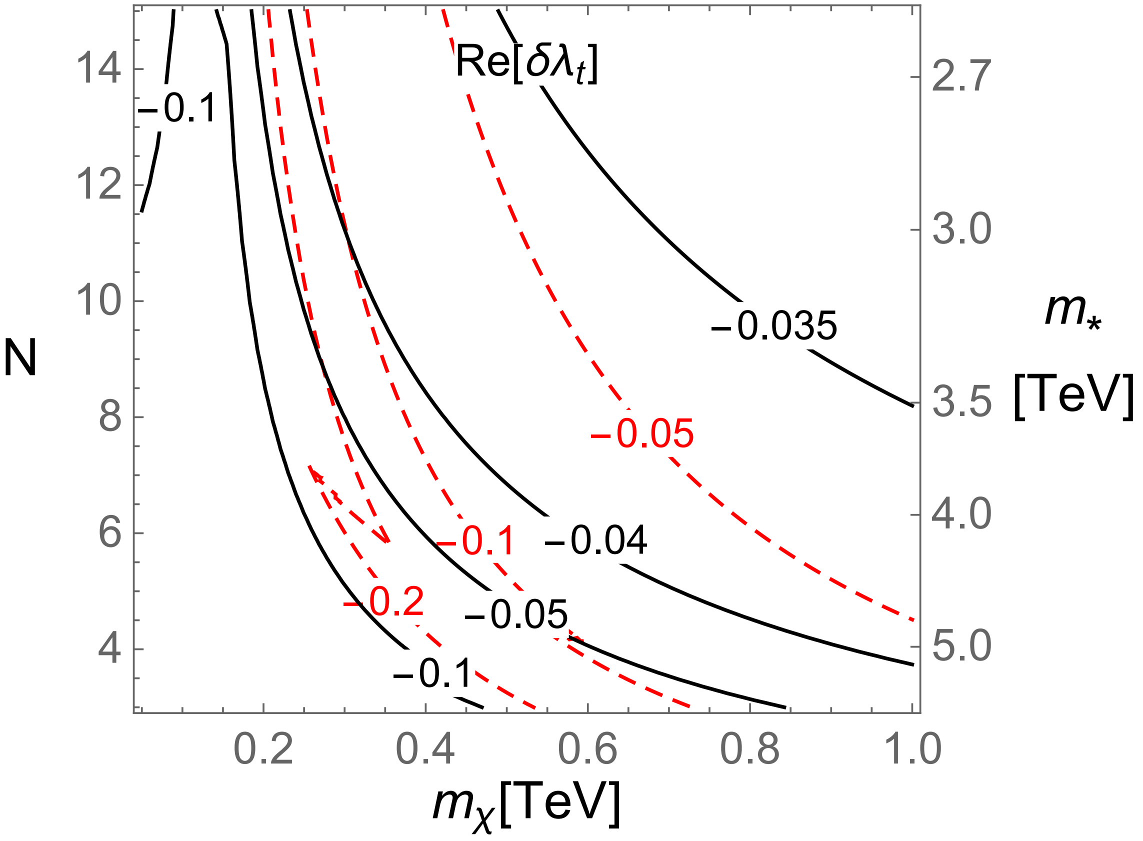
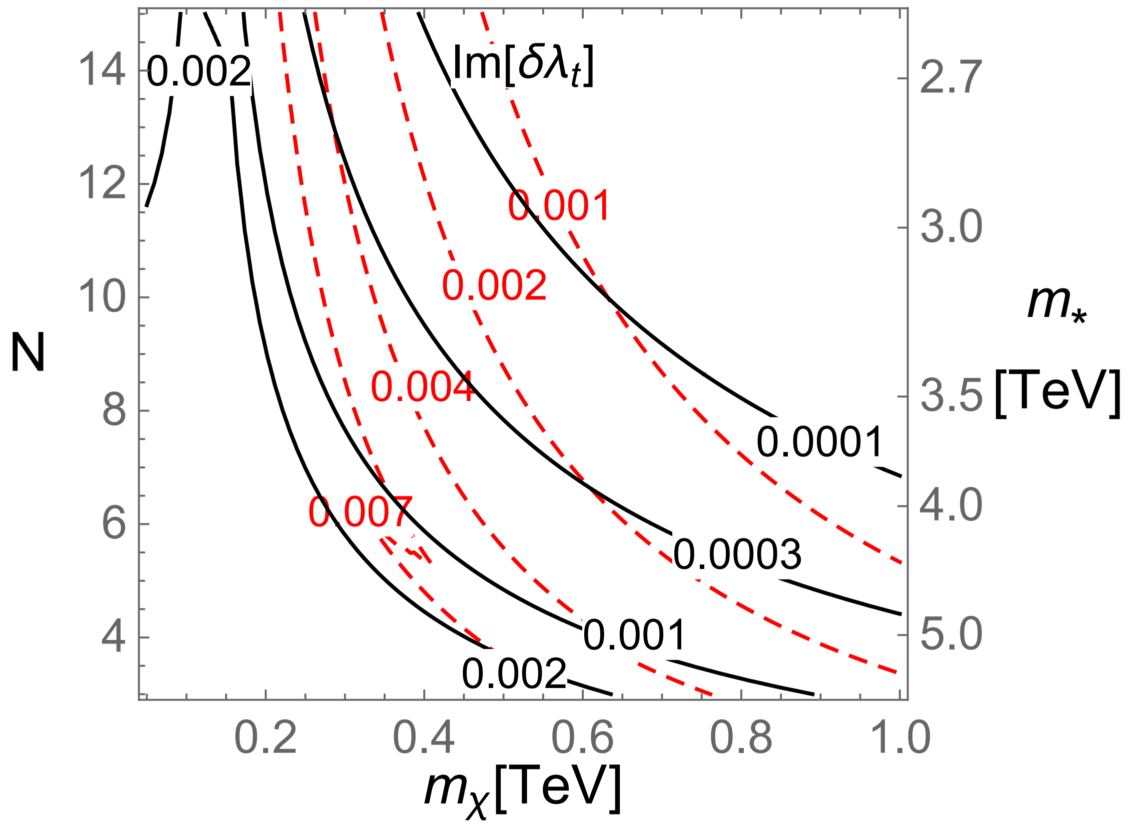


CLIC sensitivity on $\mathrm{Re}\left[\delta\lambda_t\right] \sim 4\%$ at 1σ

Abramowicz et al. ‘13

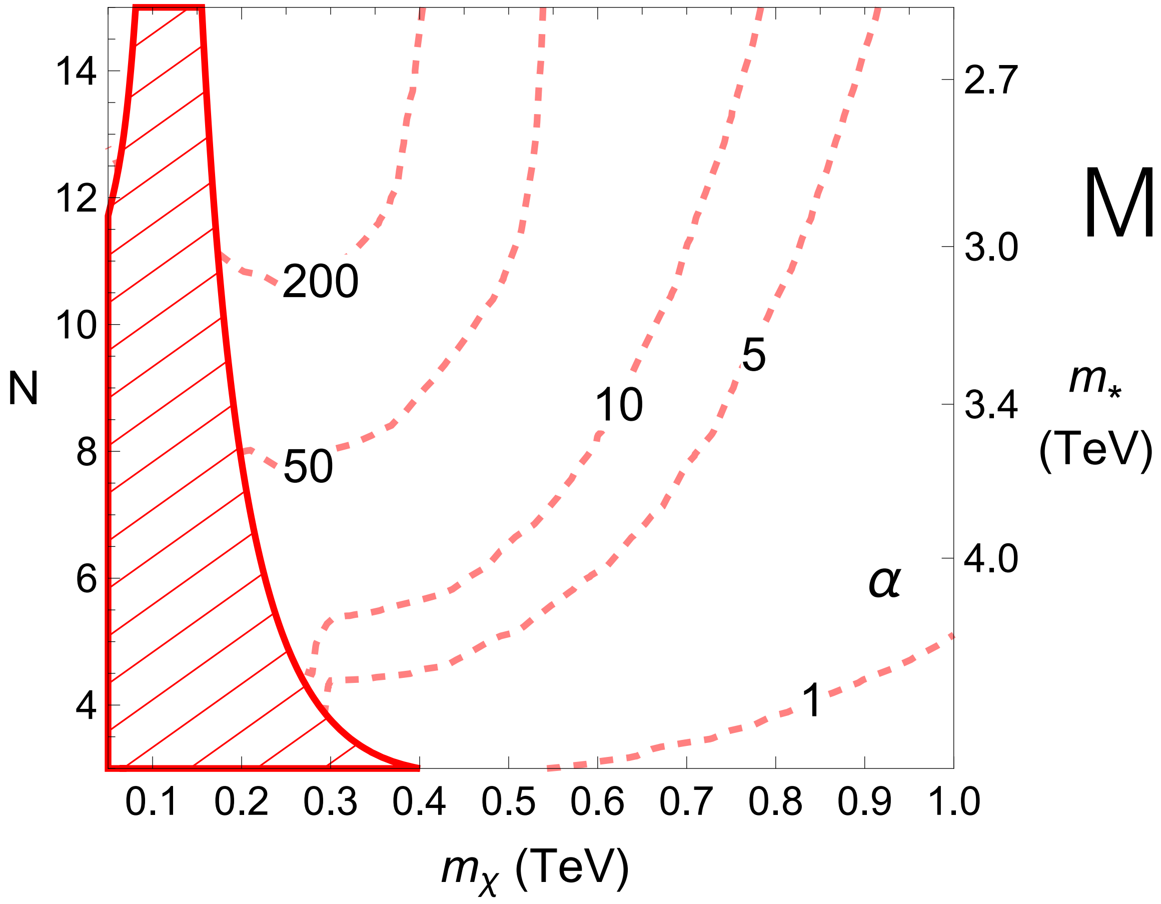


$\mathrm{Im}\left[\delta\lambda_t\right] \lesssim 0.018$ @ 90%CL

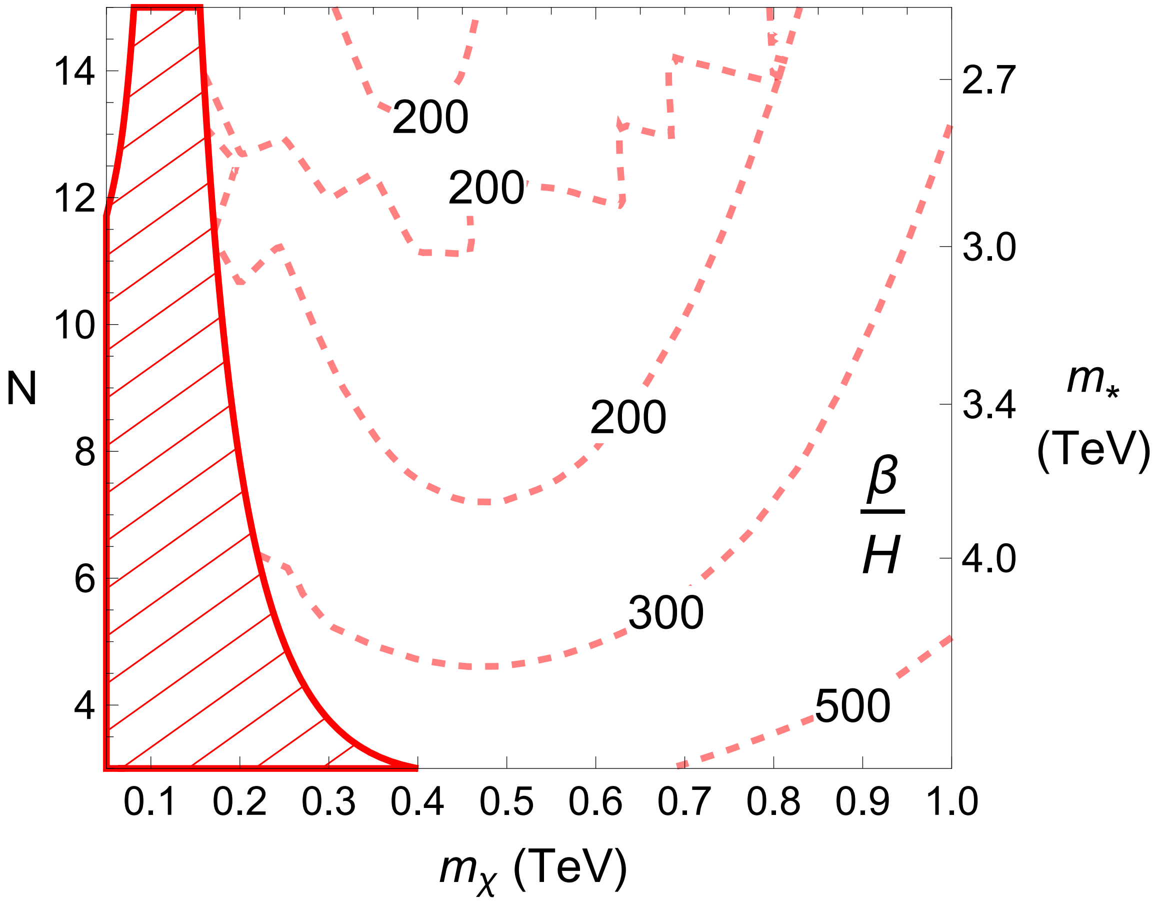
Cirigliano, Dekens,
de Vries, Mereghetti ‘16

Experimental signatures

$$\alpha = \frac{\epsilon}{\rho_{\mathrm{rad}}} \simeq \frac{\left(V_{\mathrm{tot}}\left[0,0\right] - V_{\mathrm{tot}}\left[v,\chi_0\right]\right)_{T_n}}{3\pi^2 N^2 T_n^4/8}\,, \qquad \frac{\beta}{H} \simeq T_n \frac{\mathrm{d}S_E}{\mathrm{d}T}\bigg|_{T_n}$$



Meson



LISA: $\alpha \gtrsim 0.1 \quad \& \quad 1 \lesssim \beta/H \lesssim 10^4$

Grojean, Servant '06

Caprini et al. '15

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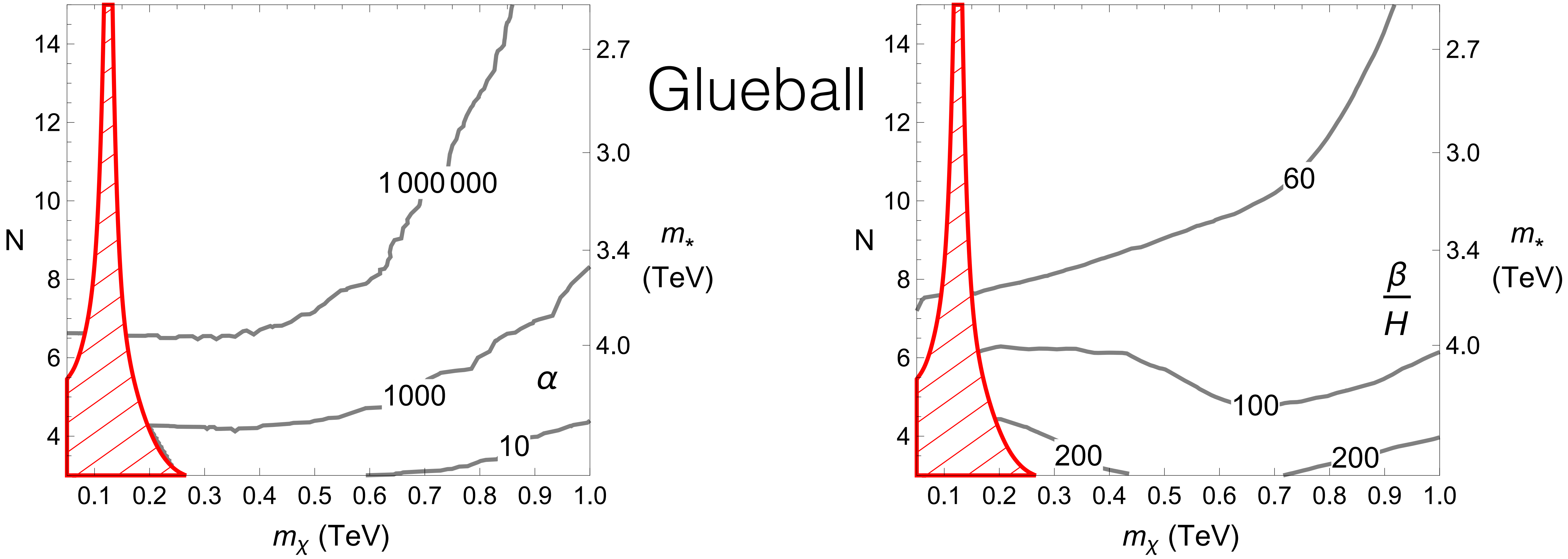

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CP Violation

$$S_i^{CPV} \sim \mathrm{Im}\left[V^\dagger \left(m^\dagger\right)'' m V\right]_{ii}$$

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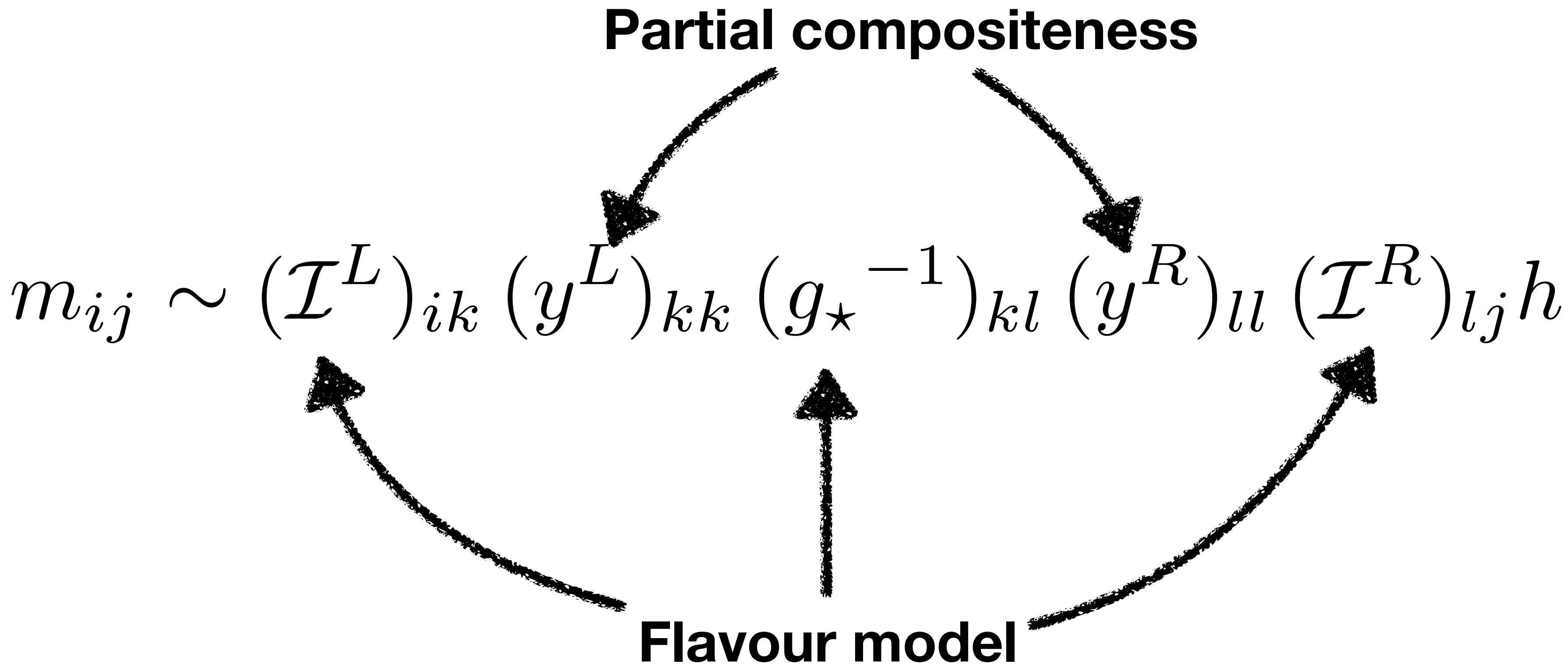

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Flavour model

CP-Violation

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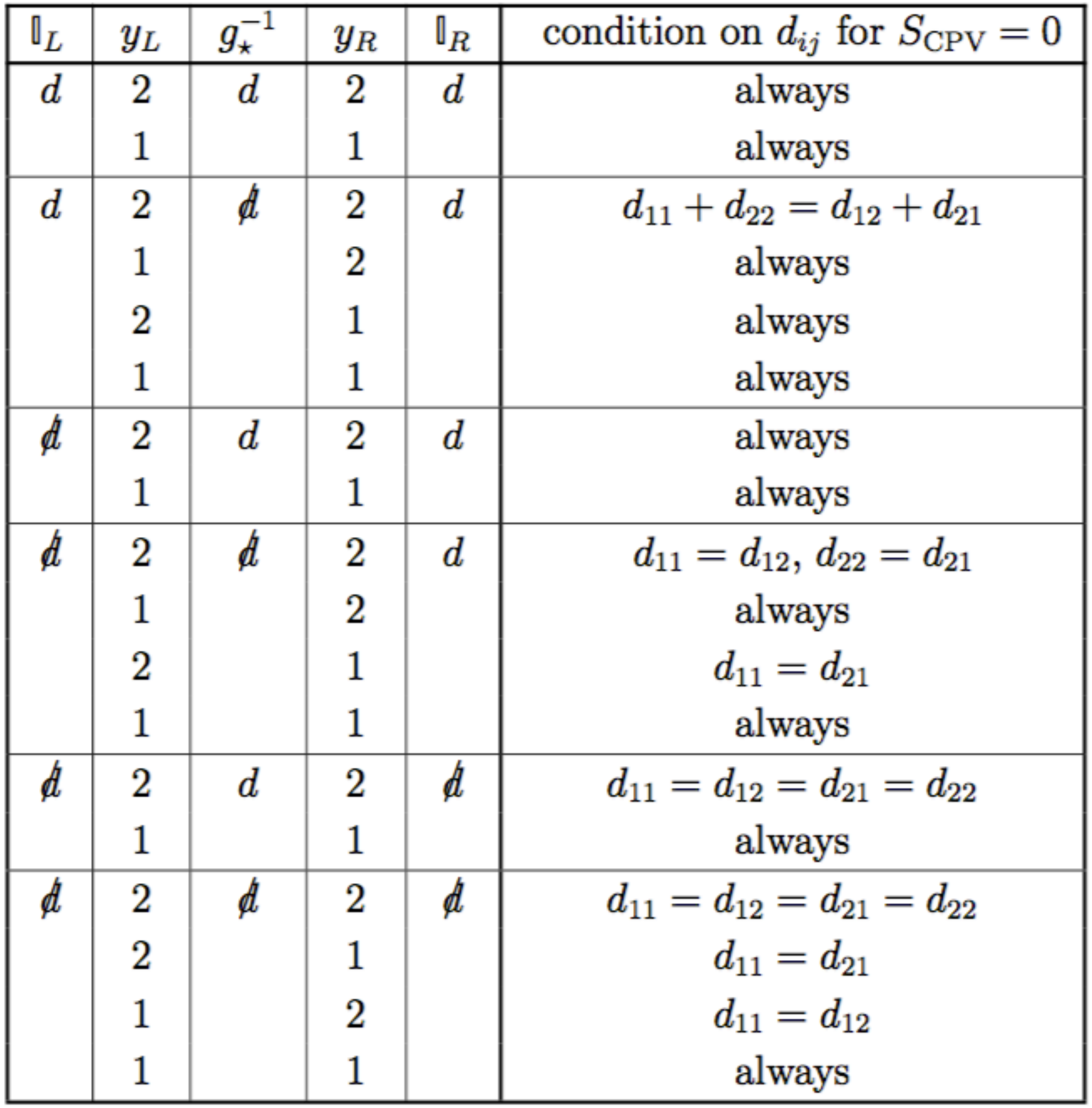

$\mathbb{I}_L$	y_L	$g_\star^{-1}$	y_R	$\mathbb{I}_R$	condition on d_{ij} for $S_{\text{CPV}} = 0$
d	2	d	2	d	always
	1		1		always
d	2	$\not{d}$	2	d	$d_{11} + d_{22} = d_{12} + d_{21}$
	1		2		always
	2		1		always
	1		1		always
$\not{d}$	2	d	2	d	always
	1		1		always
$\not{d}$	2	$\not{d}$	2	d	$d_{11} = d_{12}$, $d_{22} = d_{21}$
	1		2		always
	2		1		$d_{11} = d_{21}$
	1		1		always
$\not{d}$	2	d	2	$\not{d}$	$d_{11} = d_{12} = d_{21} = d_{22}$
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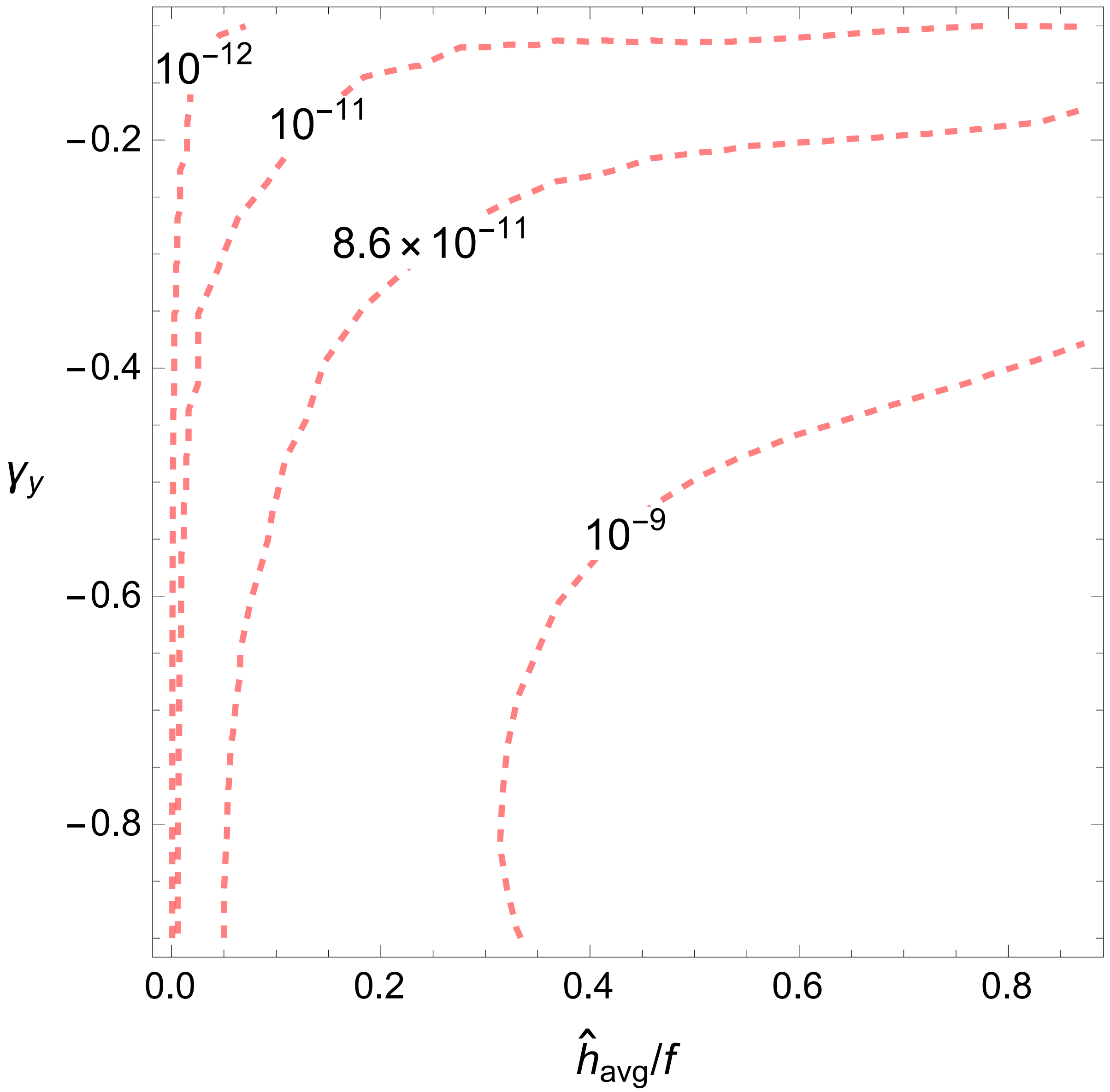
	2		1		$d_{11} = d_{21}$
	1		2		$d_{11} = d_{12}$
	1		1		always

Baryon asymmetry: multi-flavour case with U(1) flavour symmetries

$$m_{ij} \sim (y^L)_{ii}\,({g_\star}^{-1})_{ij}\,(y^R)_{jj}\,\sin\left(\frac{h}{f}\right)\cos\left(\frac{h}{f}\right) f$$

Csaki, Falkowski,
Weiler '08



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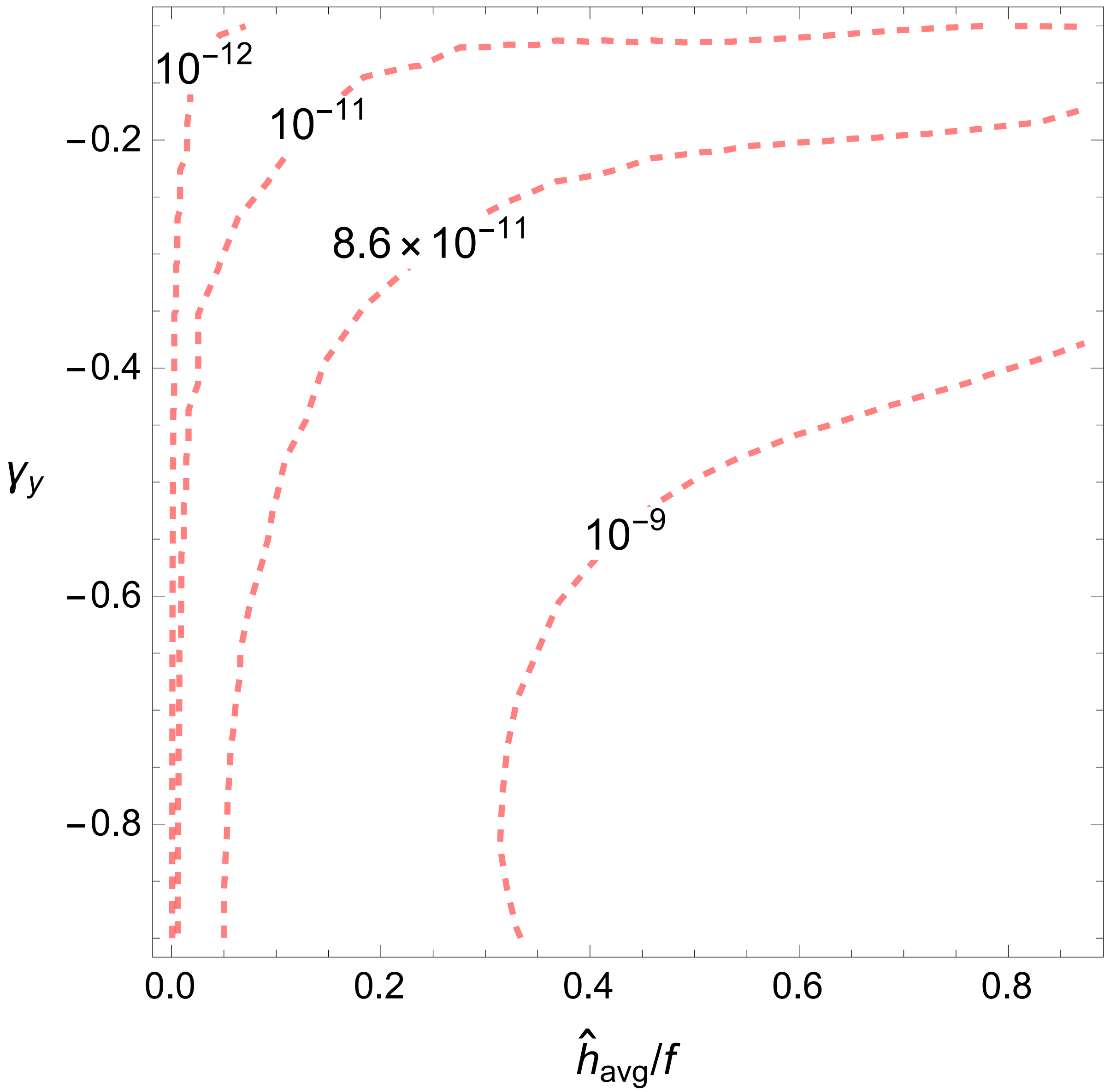
Csaki, Falkowski, Weiler ‘08

Anarchic



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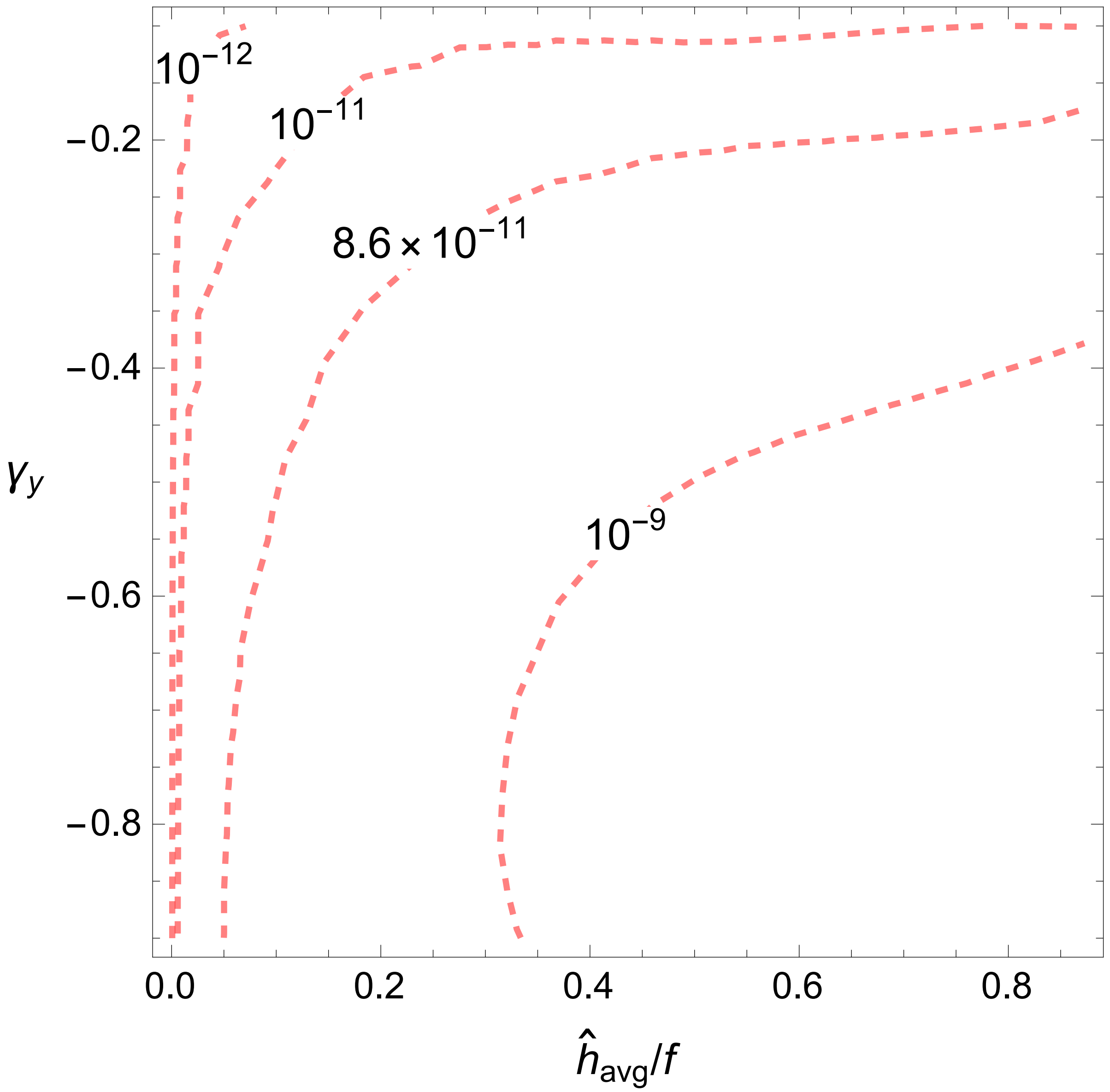
Csaki, Falkowski,
Weiler ‘08

Anarchic

Two large entries



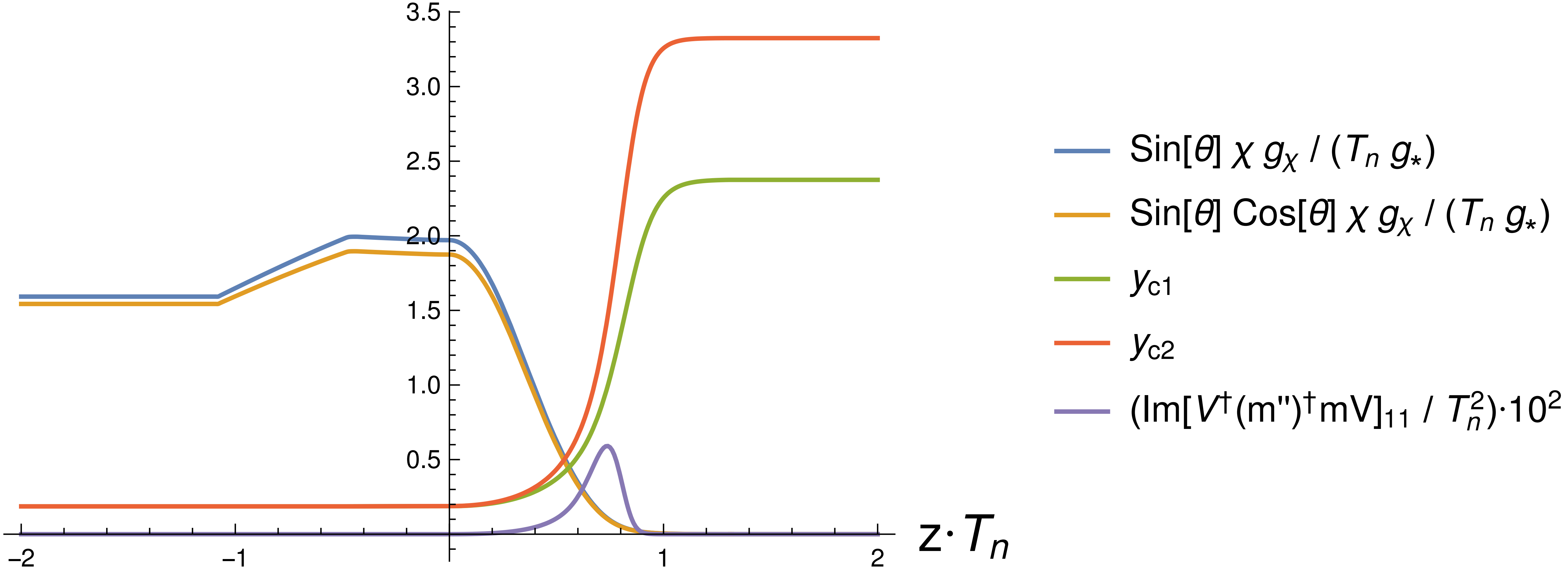
Baryon asymmetry: top-only case

$$\mathcal{L} \supset y_L \bar{t}_L \mathcal{O}_L + y_R^1 \bar{t}_R^1 \mathcal{O}_R^1 + y_R^2 \bar{t}_R^2 \mathcal{O}_R^2$$

$$\Big\Downarrow$$

$$\lambda_t\left[\chi\right] \sim \frac{y_L\left[\chi\right]\left(y_R^1\left[\chi\right] + y_R^2\left[\chi\right]\right)}{g_\star}$$

Baryogenesis



Dimensional Analysis and large N

Idea: restore dimensions of $\hbar$

$$[V] = \frac{[\hbar]}{L^4}, \quad [\phi] = [f] = \frac{\sqrt{[\hbar]}}{L}, \quad [g] = \frac{1}{\sqrt{[\hbar]}}, \quad [\partial_\mu] = \frac{1}{L}$$

$$\Downarrow$$

$$V \sim g^2 \phi^4 \quad \text{or} \quad V \sim g^2 f^4$$

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Large N expansion: for a meson like Higgs $g_\star \sim \dfrac{4\pi}{\sqrt{N}}$

Canonically normalised fields

$$\frac{1}{2}(\partial_\mu h)^2$$

$h \to h + 2\pi f k \ (k \in \mathbb{Z})$ for constant f

$h \to h + 2\pi \chi k \ (k \in \mathbb{Z})$ for dynamical χ

$$\theta = h/\chi : \quad \theta \to \theta + 2\pi k \qquad \mathcal{L} = \frac{1}{2}\chi^2(\partial_\mu \theta)^2 + \frac{1}{2}(\partial_\mu \chi)^2$$

We need canonically normalised fields for vacuum tunneling:

$$\chi_1 = \chi \sin\theta, \quad \chi_2 = \chi \cos\theta$$

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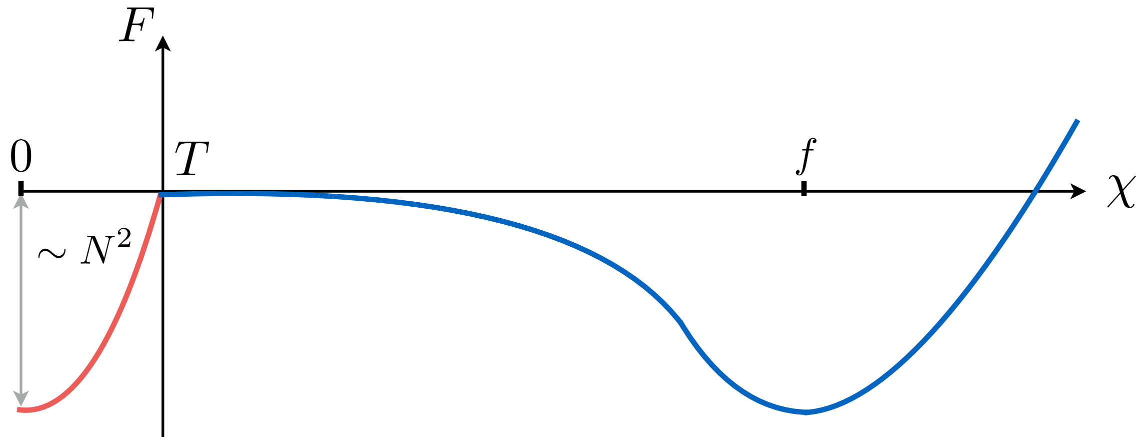
Temperature Corrections

- Hard to compute in the symmetric phase
- From dimensional analysis and large-N counting:

  $F_{CFT}[\chi = 0] \simeq -cN^2T^4$ where c depends on the number of d.o.f. per color in the strong sector

- For definiteness we use a 5-D estimate to fix c:

$$F_{CFT}[\chi = 0] \simeq -\frac{\pi^2 N^2}{8} T^4$$



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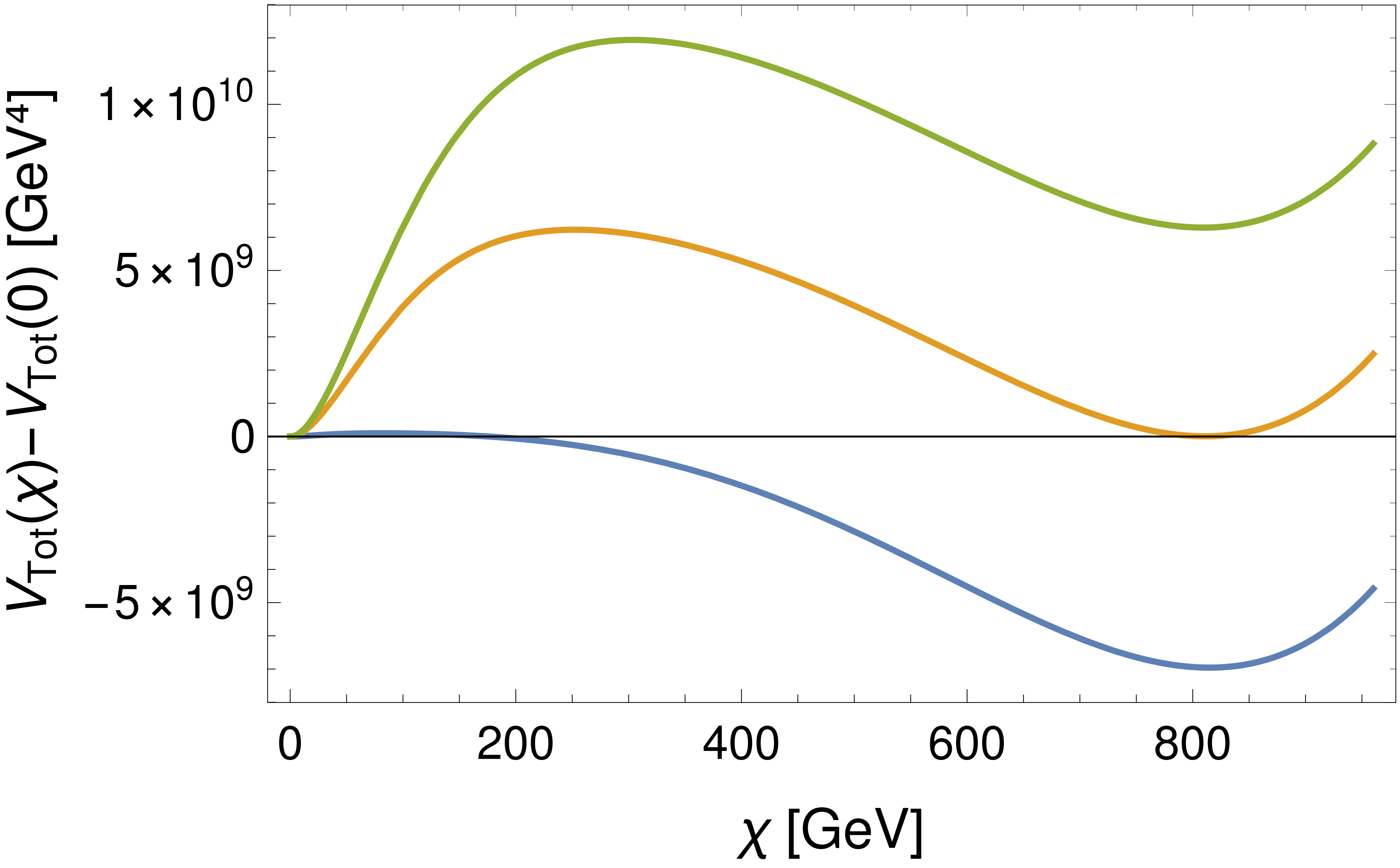
$$\Delta V^T_{1-loop} = \sum_{\text{bosons}} \frac{nT^4}{2\pi^2} J_b\left[\frac{m^2}{T^2}\right] - \sum_{\text{fermions}} \frac{nT^4}{2\pi^2} J_f\left[\frac{m^2}{T^2}\right]$$

$$J_b[x] = \int_0^\infty \mathrm{d}k\ k^2 \log\left[1 - e^{-\sqrt{k^2+x}}\right] \quad \text{and} \quad J_f[x] = \int_0^\infty \mathrm{d}k\ k^2 \log\left[1 + e^{-\sqrt{k^2+x}}\right]$$

$$\sum_{\text{CFT bosons}} n + \sum_{\text{CFT fermions}} n = \frac{45N^2}{8\pi^2}$$

Temperature Evolution



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Higgs-Dilaton mass mixing.
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Depend on parameters of potential.

Froggat-Nielsen

$U(1)_{FN}$ with two FN fields χ, σ

Charge assignment

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

$\bar{Q}_3$ (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 $(+3)$

Yukawa type interactions after SSB

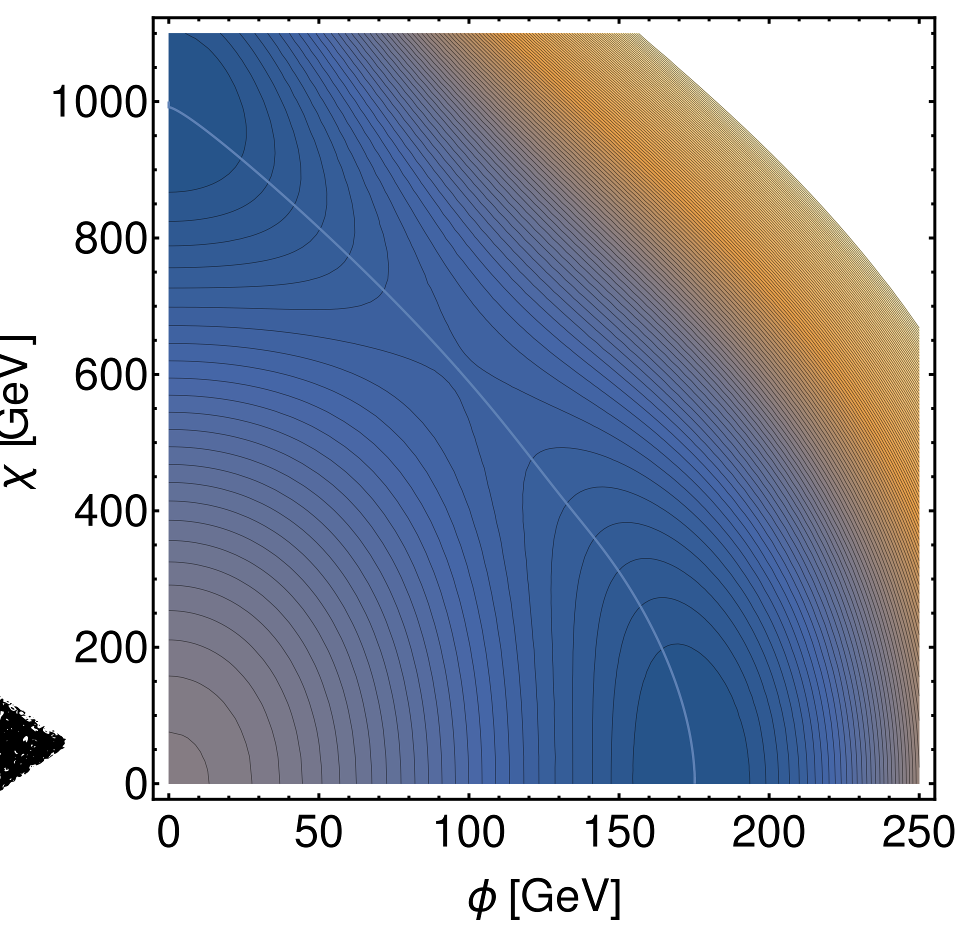
$$\mathcal{L} \supset \tilde{y}_{ij} \left(\frac{\langle\chi\rangle}{\Lambda_\chi}\right)^{\tilde{n}_{ij}} \bar{Q}_i \tilde{\phi} U_j + y_{ij} \left(\frac{\langle\chi\rangle}{\Lambda_\chi}\right)^{n_{ij}} \bar{Q}_i \phi D_j$$

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

VEVs during EWSB

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

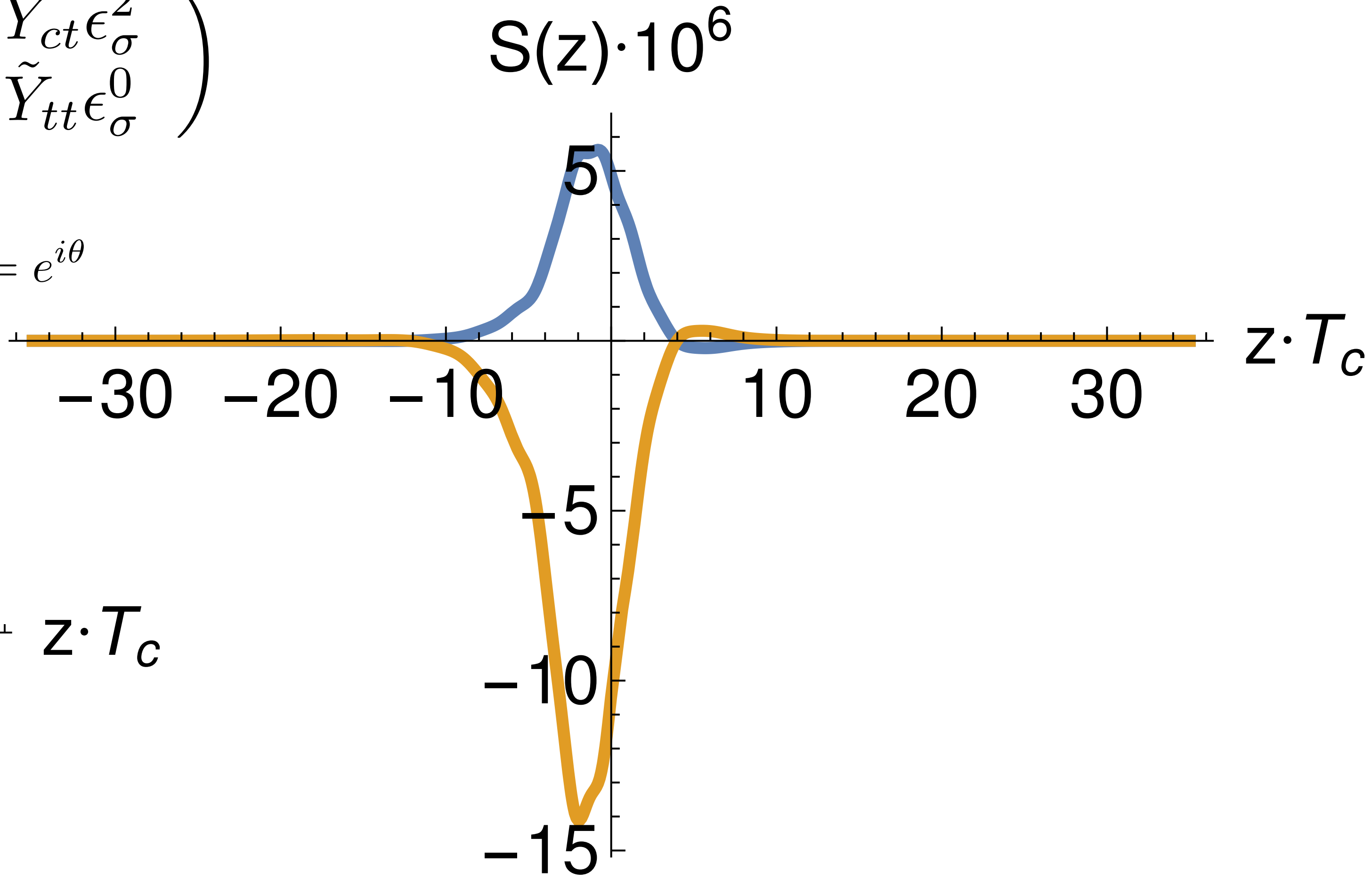
$\chi - \phi$ -Potential

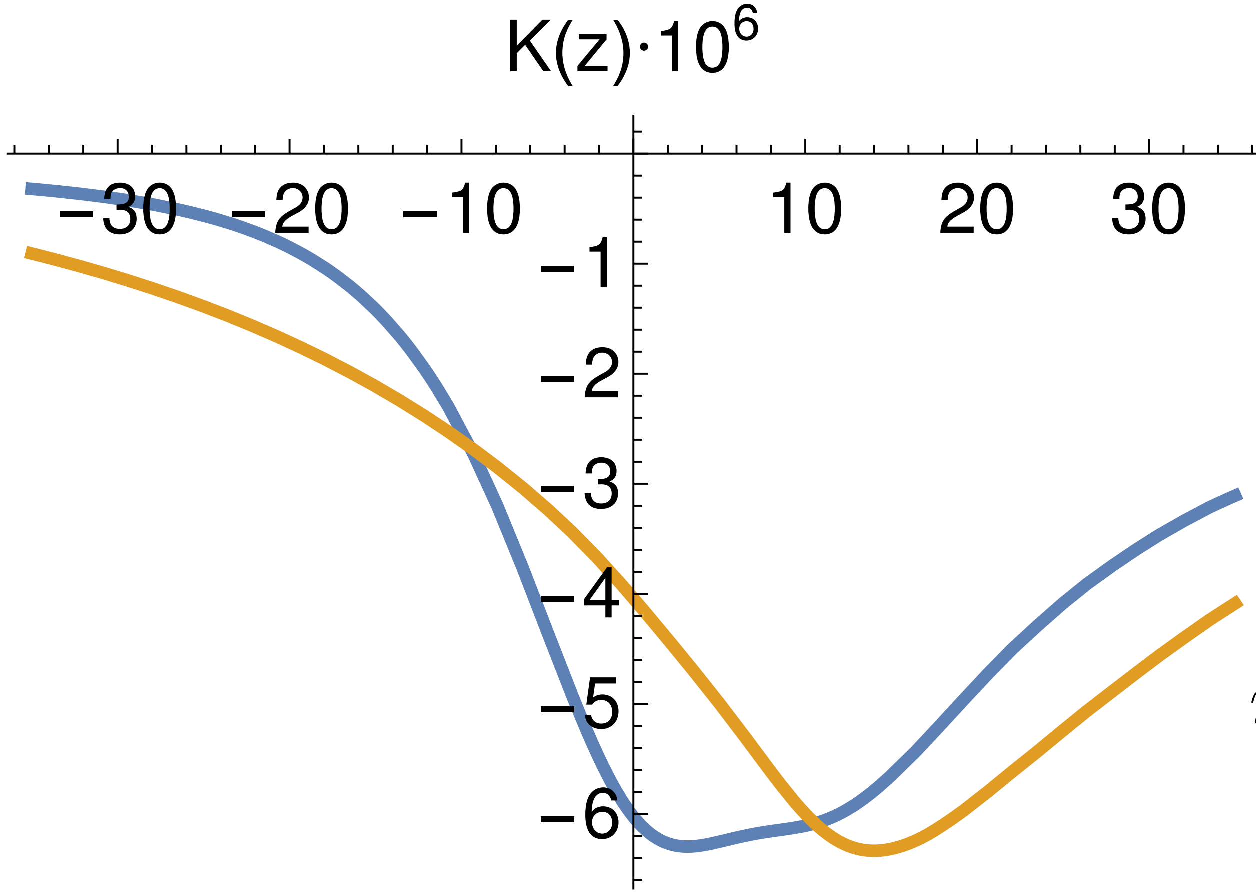


Froggat-Nielsen

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

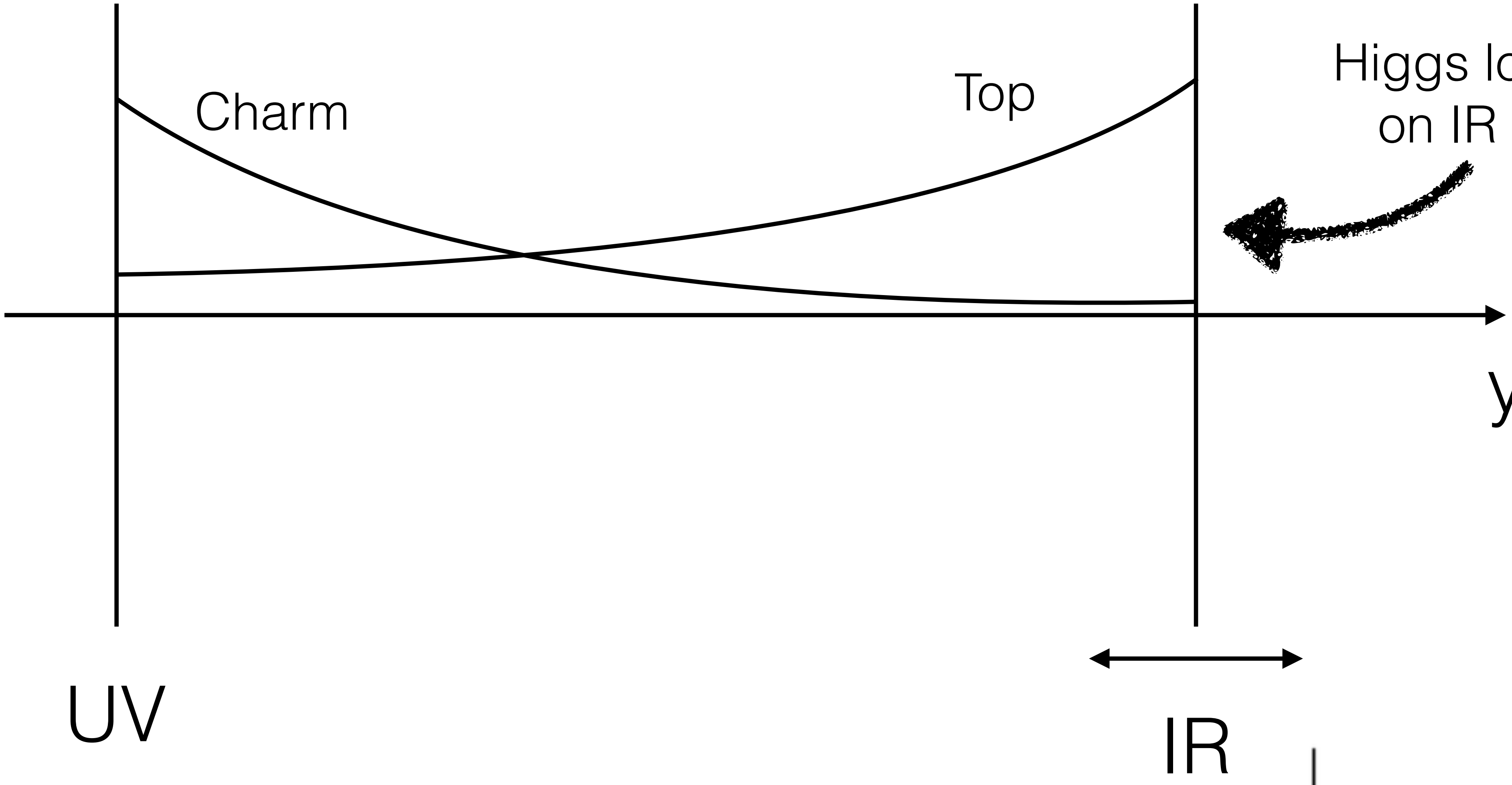
$$\tilde{y}_{i\neq j} = \tilde{Y}_{i\neq j} = 1 \qquad \tilde{y}_{tt} = \tilde{Y}_{tt} = 1/2 \qquad \tilde{y}_{cc} = \tilde{Y}_{cc} = e^{i\theta}$$





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

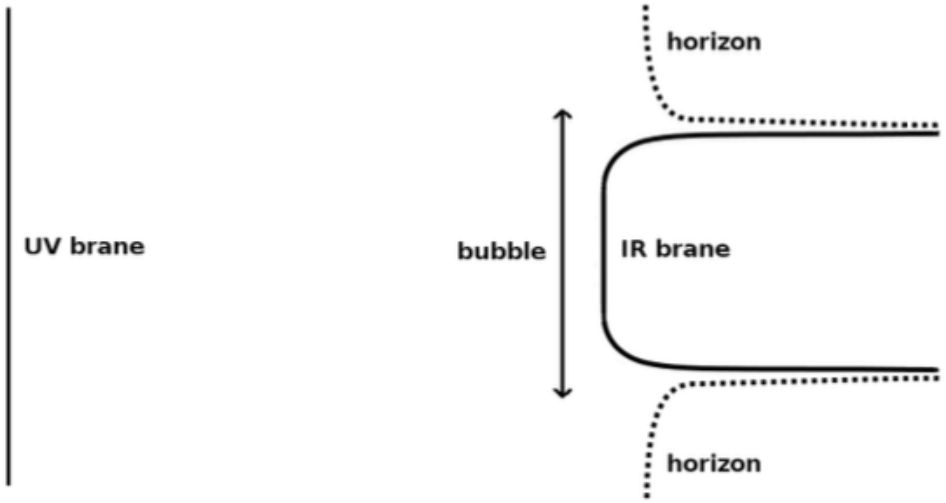
Randall-Sundrum


Charm
Top
y
UV
IR

Higgs localised on IR brane

5th dimension

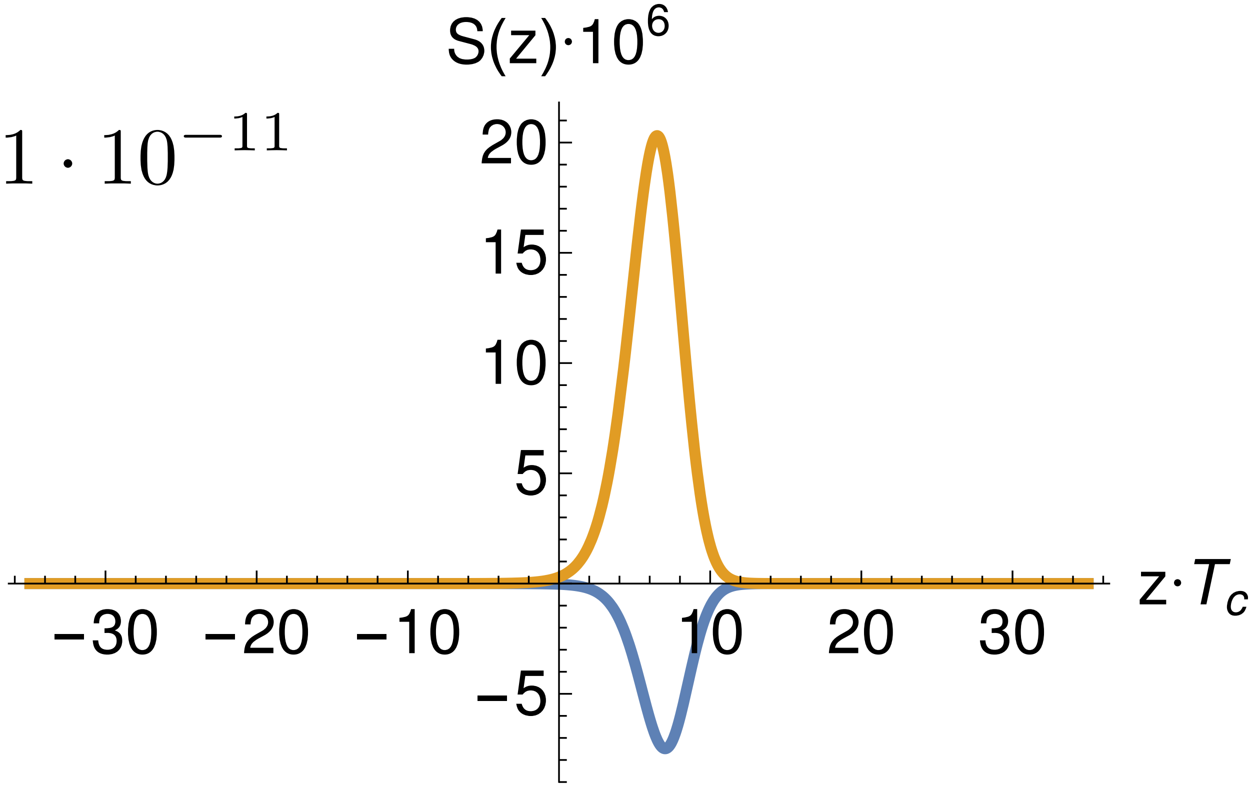
At high temp. -> AdS-Schwarzschild
Low temp. -> RS metric
—> “Brane Nucleation”

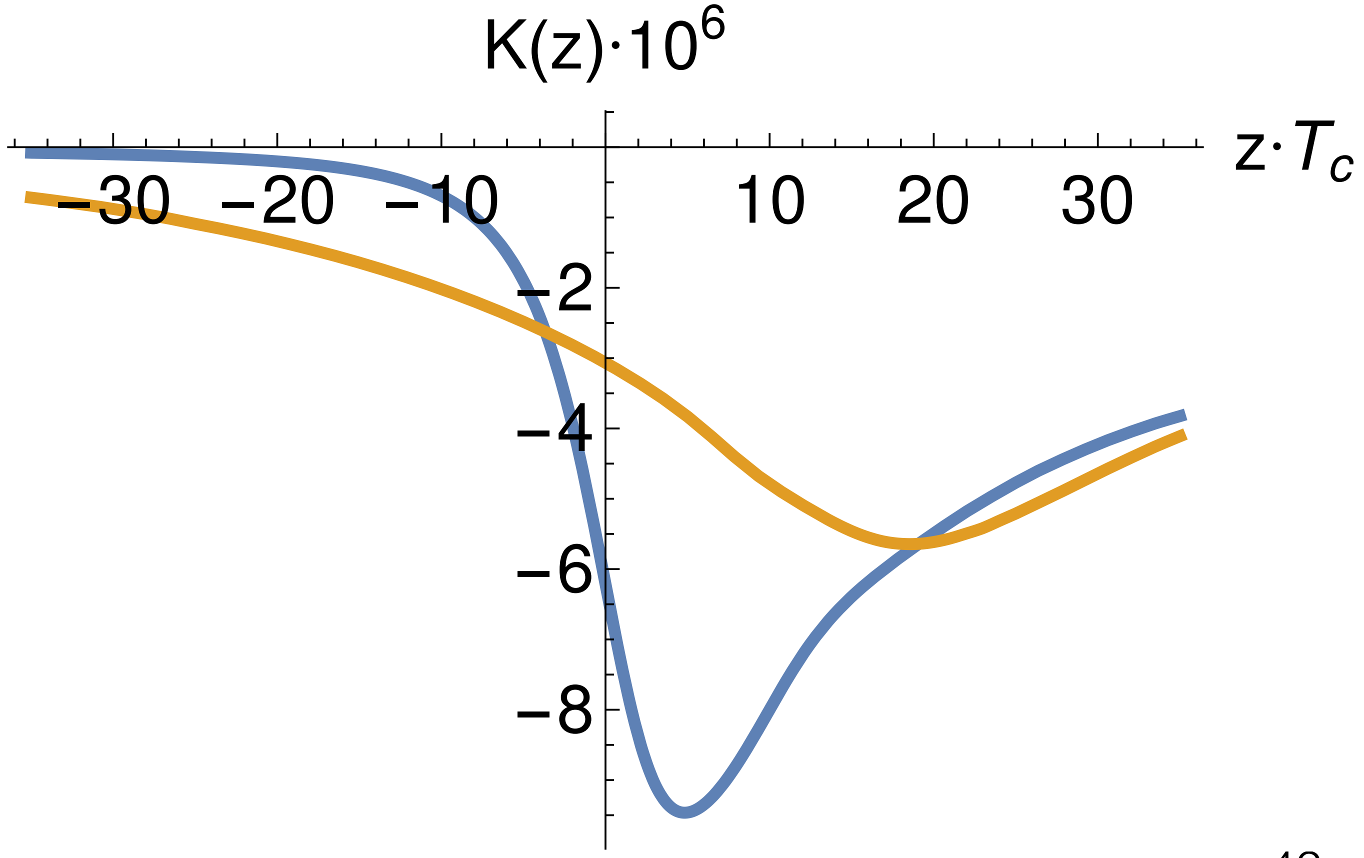

UV brane
horizon
bubble
IR brane
horizon

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:

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

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

Source depends on *m*

⇓

link to
Yukawa couplings

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

Network equations

Fluide type Ansatz:

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

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Interactions

Source

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

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

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

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e.g. Fromme, Huber ’06
hep-ph/0604159

Interactions:
Couple different particle species together

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

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

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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. $t_L \leftrightarrow b_L$ $\qquad \Gamma_W = \frac{T}{60}$
- Higgs number violation $h \leftrightarrow 0$ $\qquad \Gamma_h = \frac{m_W^2}{50T}$
- Strong sphaleron $\text{all L} \leftrightarrow \text{all R}$ $\qquad \Gamma_{ss} = 4.9 \times 10^{-4} T$

Collision term

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

- Yukawa interactions e.g. $t_L \leftrightarrow t_R + h$ $\quad \Gamma_{y,q} = 4.2 \times 10^{-3} \, y_q^2 \, T$
- Helicity flip e.g. $t_L \leftrightarrow t_R$ $\quad \Gamma_{m,q} = \frac{m_q^2}{63T}$
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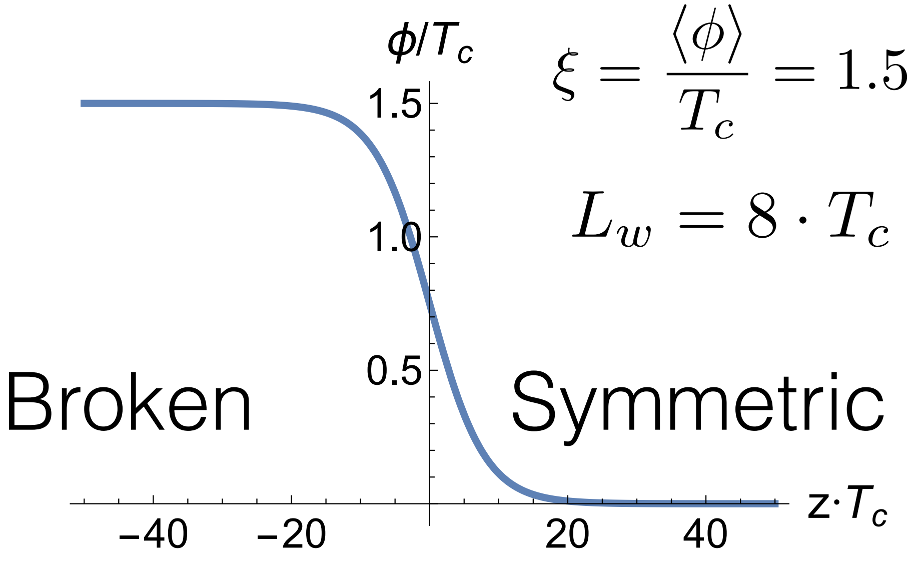
- Higgs number violation $h \leftrightarrow 0$ $\quad \Gamma_h = \frac{m_W^2}{50T}$
- Strong sphaleron all L ↔ all R $\quad \Gamma_{ss} = 4.9 \times 10^{-4} T$

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



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

$$L_w = 8 \cdot T_c$$

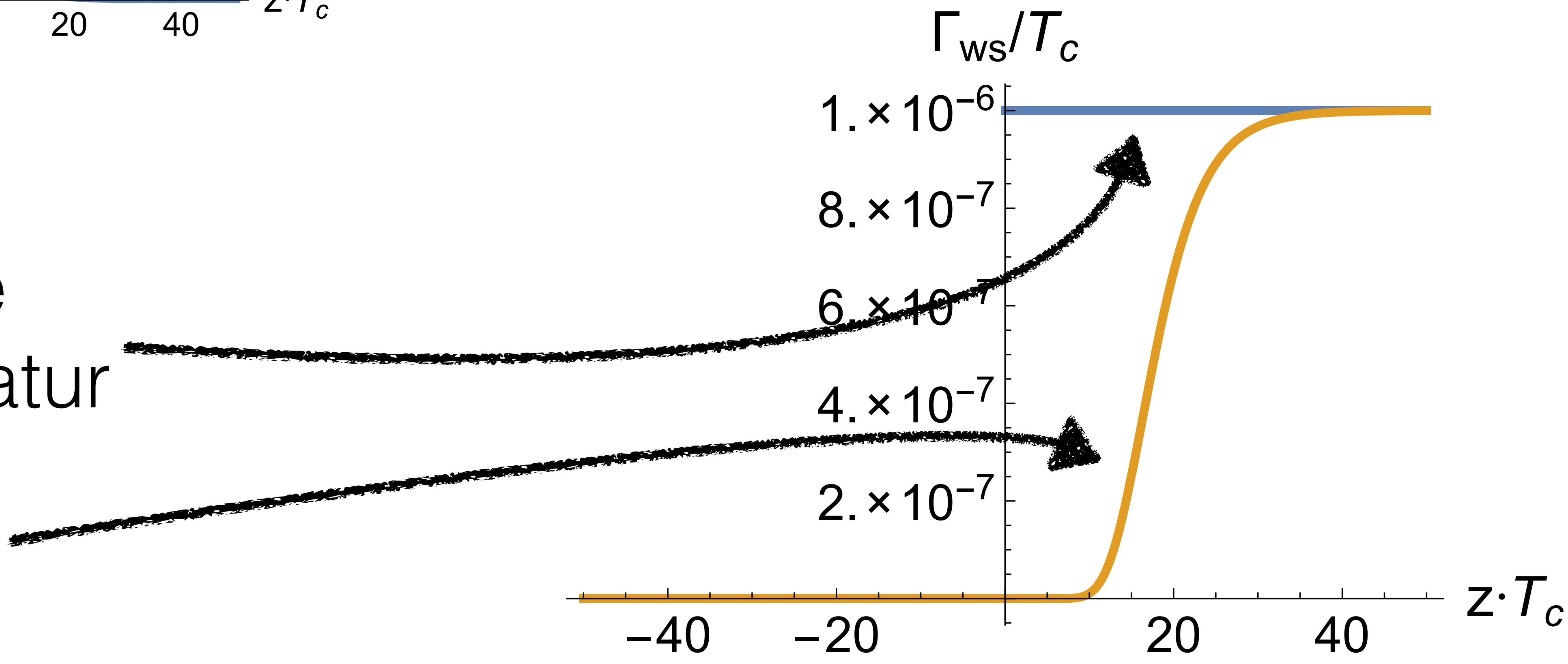
$$\Gamma_{ws} = 10^{-6}\, T\, \exp(-a\phi(z)/T)$$

$$a \approx 40$$

NEW

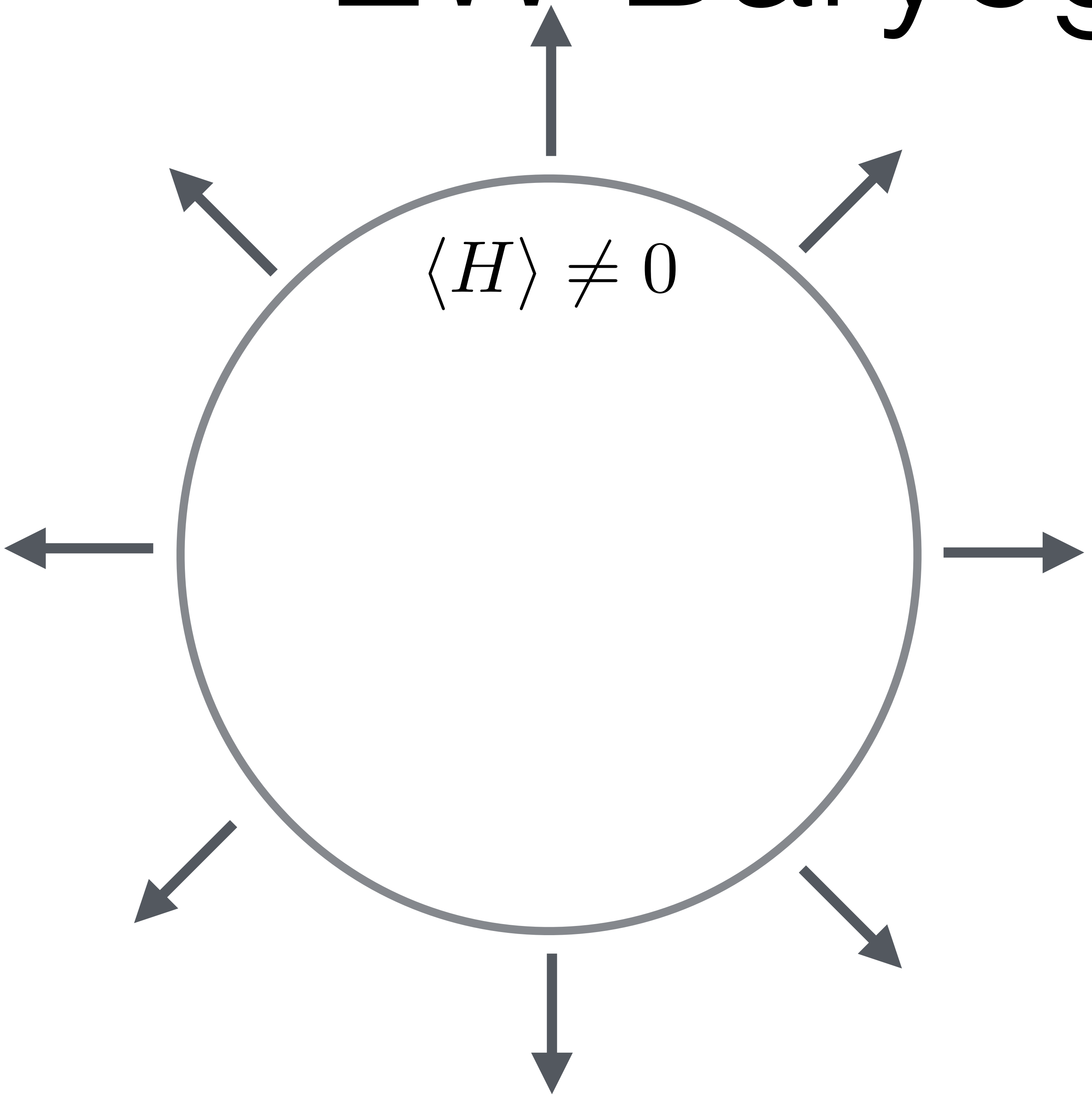
Rate in Literatur

Our rate



EW Baryogenesis

Cohen, Kaplan, Nelson ‘91



$\langle H \rangle \neq 0$

$\langle H \rangle = 0$

EW Baryogenesis

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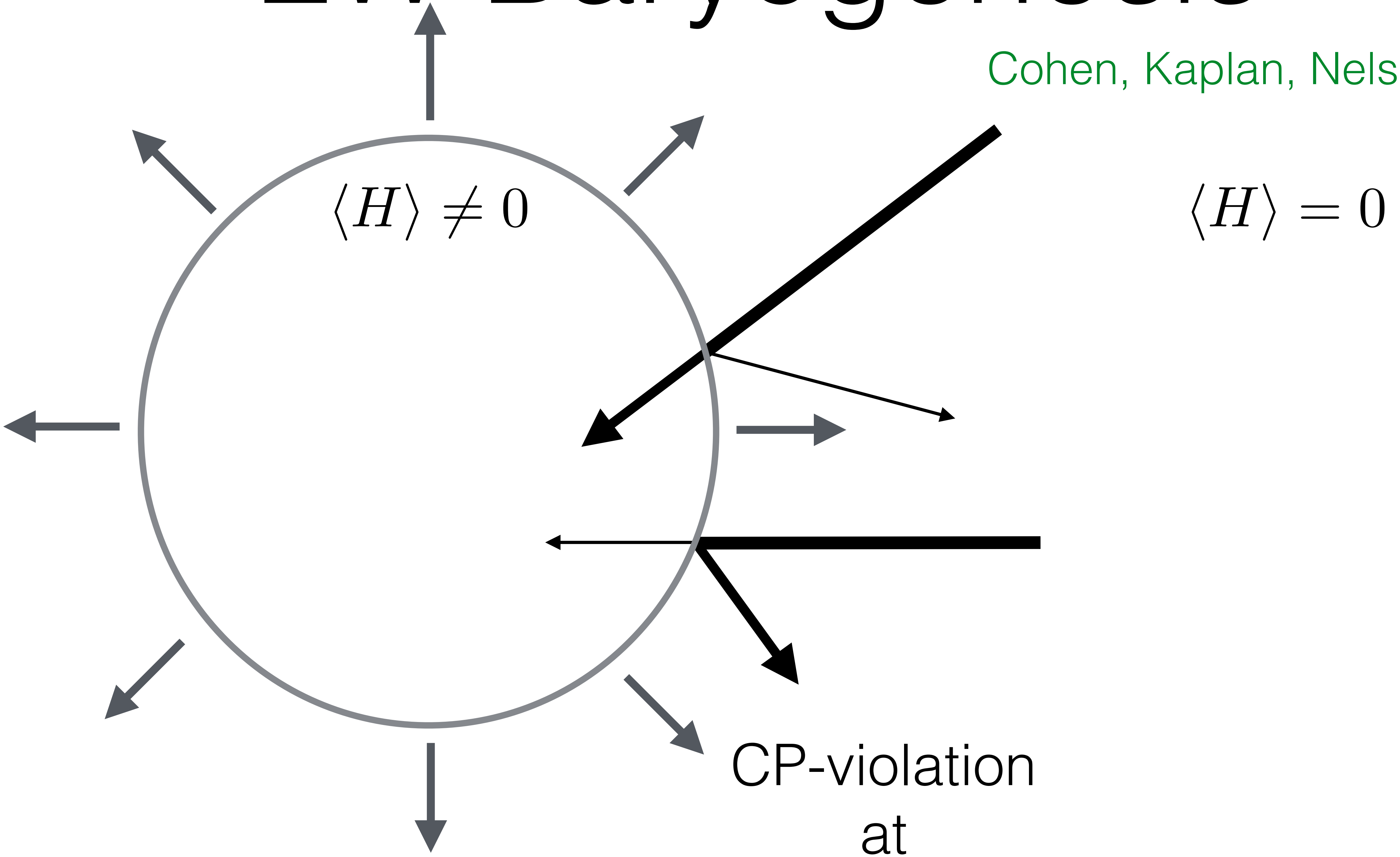
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CP-violation
at
phase interface

EW Baryogenesis

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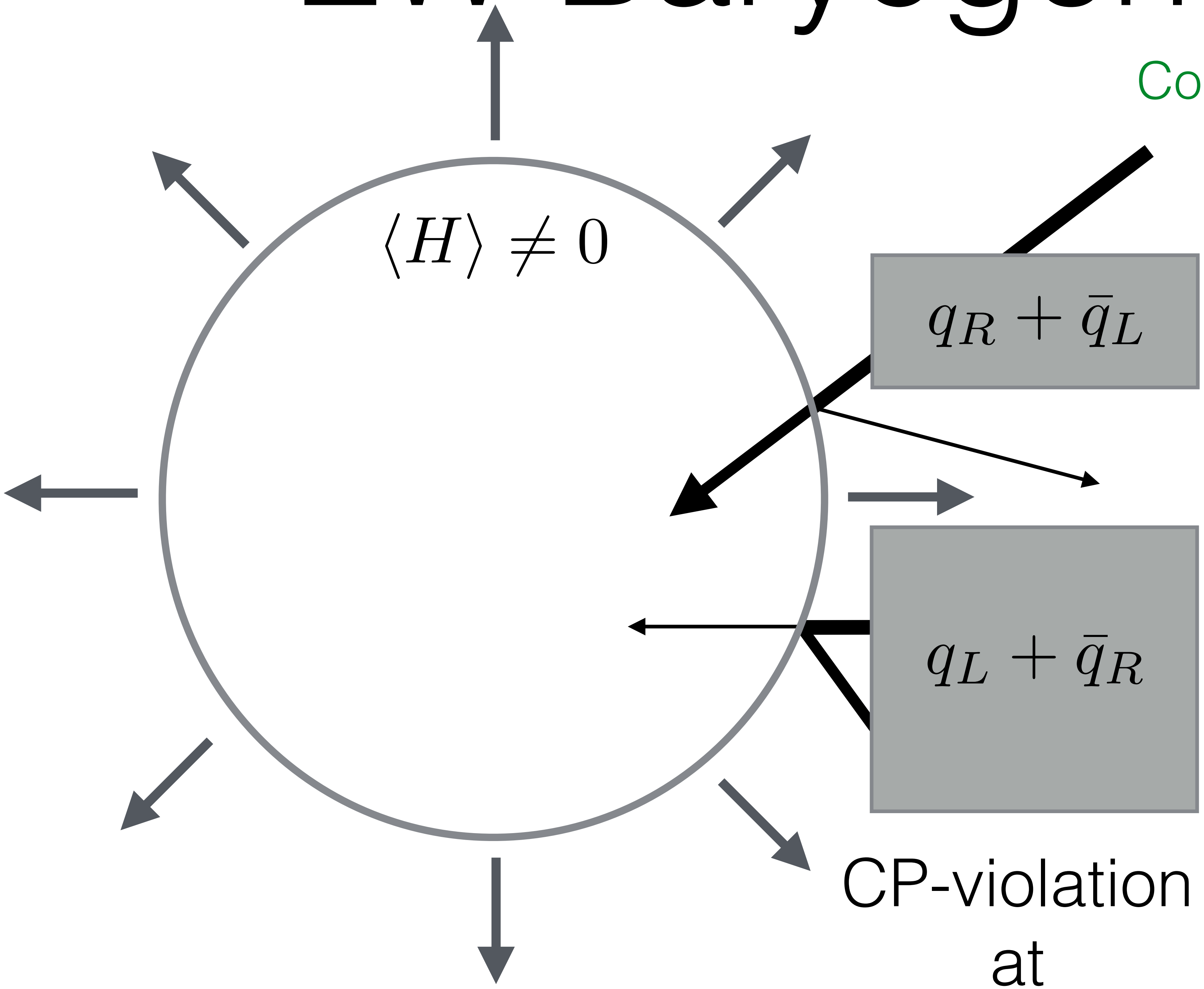

$\langle H \rangle \neq 0$

$q_R + \bar{q}_L$

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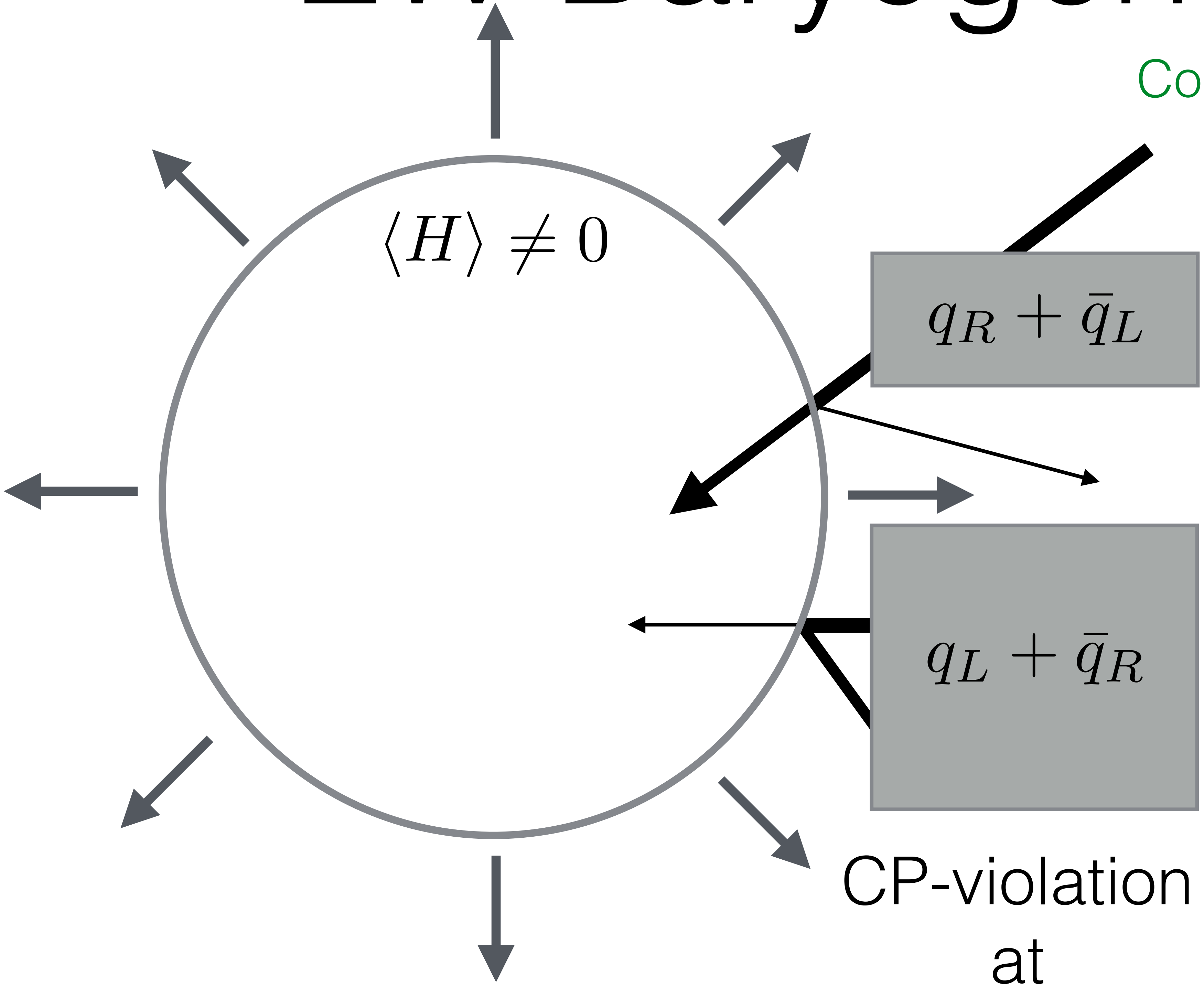

$\langle H \rangle \neq 0$
$q_R + \bar{q}_L$
$q_L + \bar{q}_R$

$\langle H \rangle = 0$

Sphaleron active

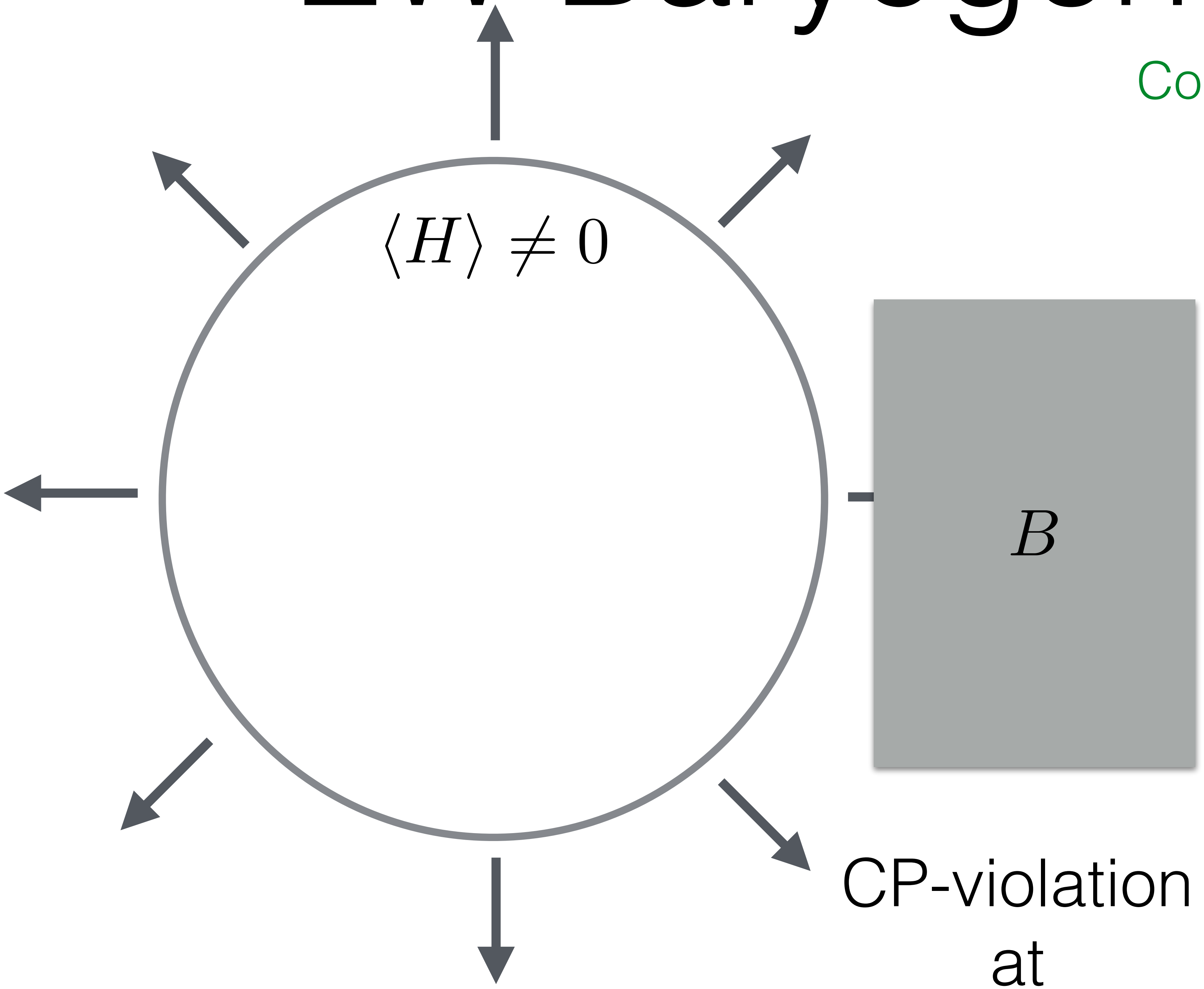
↓

Chiral asymmetry converted to Baryon asymmetry

CP-violation at phase interface

EW Baryogenesis

Cohen, Kaplan, Nelson ‘91


$\langle H \rangle \neq 0$
B

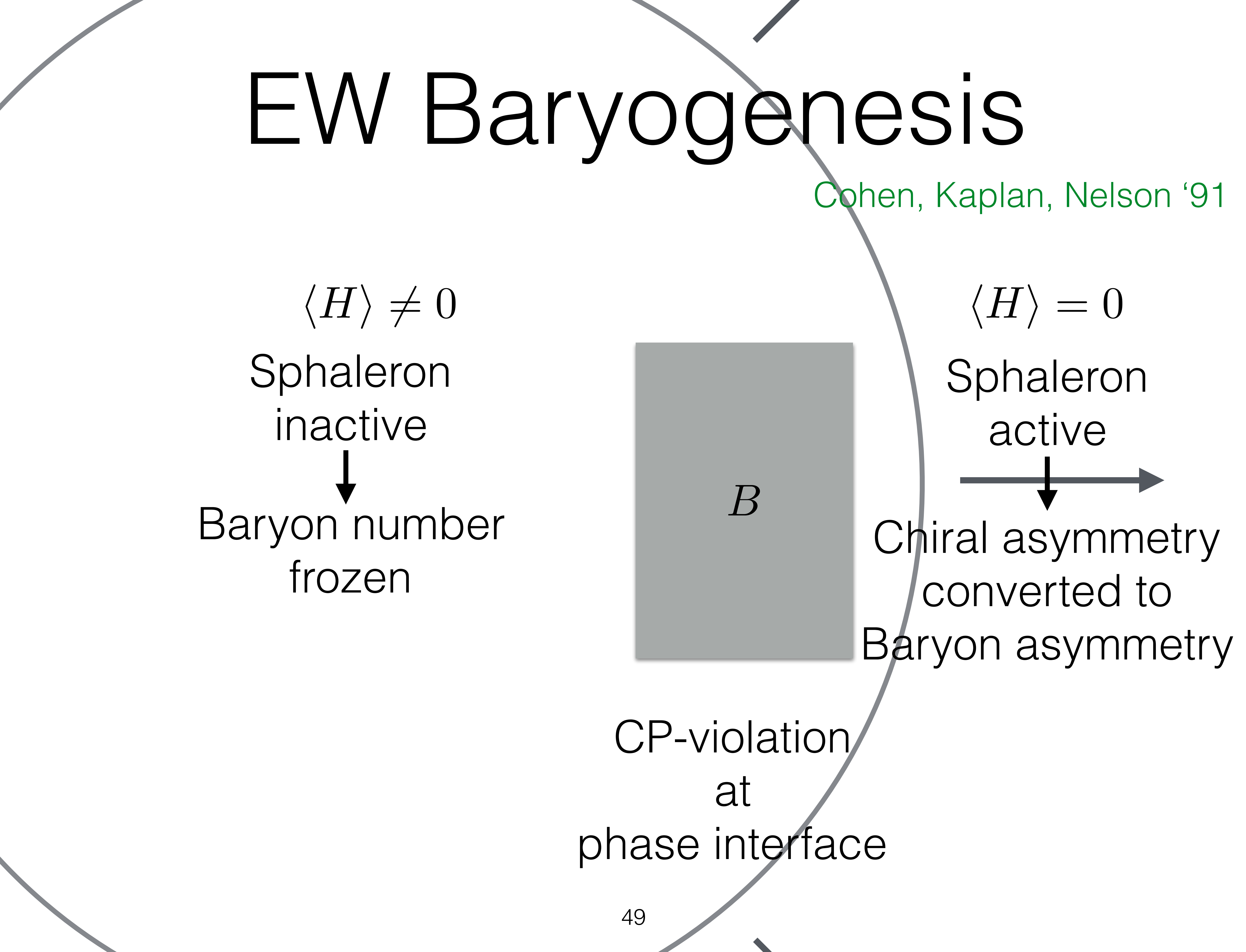
$\langle H \rangle = 0$

Sphaleron
active
↓
Chiral asymmetry
converted to
Baryon asymmetry

CP-violation
at
phase interface

EW Baryogenesis

Cohen, Kaplan, Nelson ‘91



$\langle H \rangle \neq 0$

Sphaleron
inactive

↓

Baryon number
frozen

$\langle H \rangle = 0$

Sphaleron
active

↓

Chiral asymmetry
converted to
Baryon asymmetry

CP-violation
at
phase interface

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

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

poshnikov ‘93

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

Much too small!

(measured: η_B~8.9 10^{-11})

Gavela, *et al.* ’93
Huet, Sather ’94

Jarlskog constan

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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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Based solely on
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2 Higgs doublet Cohen, Kaplan, Nelson ‘94

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

$$S \sim \Im\left[V^{\dagger} m^{\dagger\prime\prime} m V\right]$$

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

Source for μ in SM

$$S \sim \Im\left[V^\dagger {m^\dagger}'' m V\right]$$

For constant y:

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

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

Source for μ in SM

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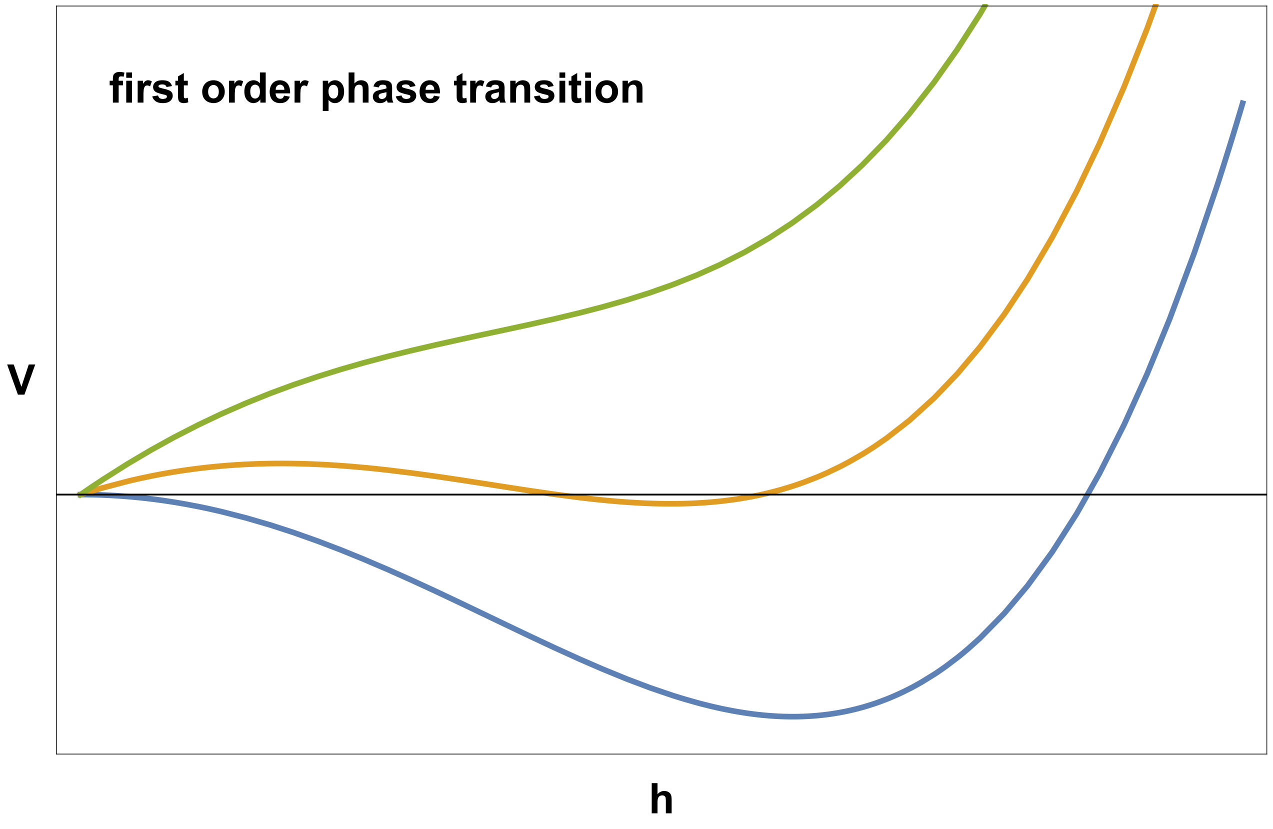
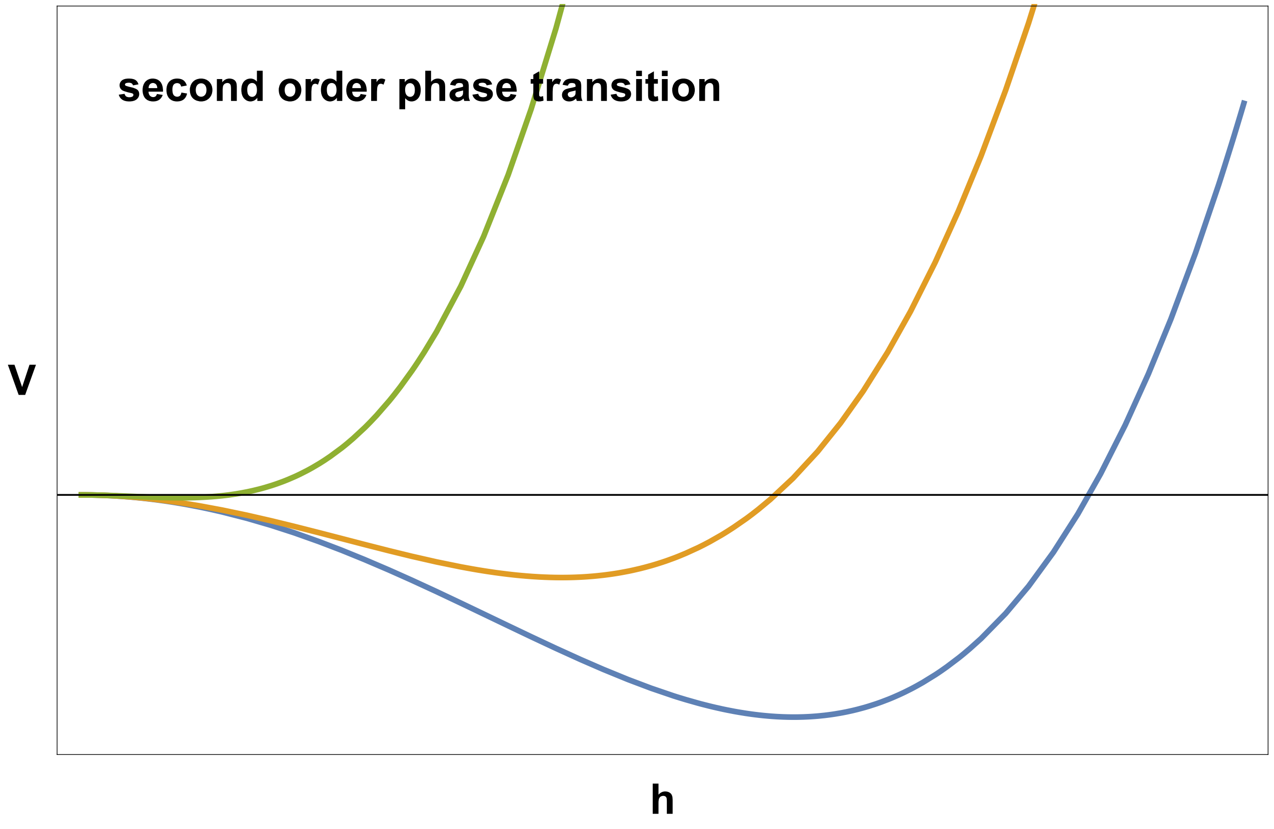
EW scale flavour physics

⇒ z dependent Yukawas

- Composite Higgs
- Froggatt-Nielsen
- Randall-Sundrum
- …

The phase transition in the SM and beyond





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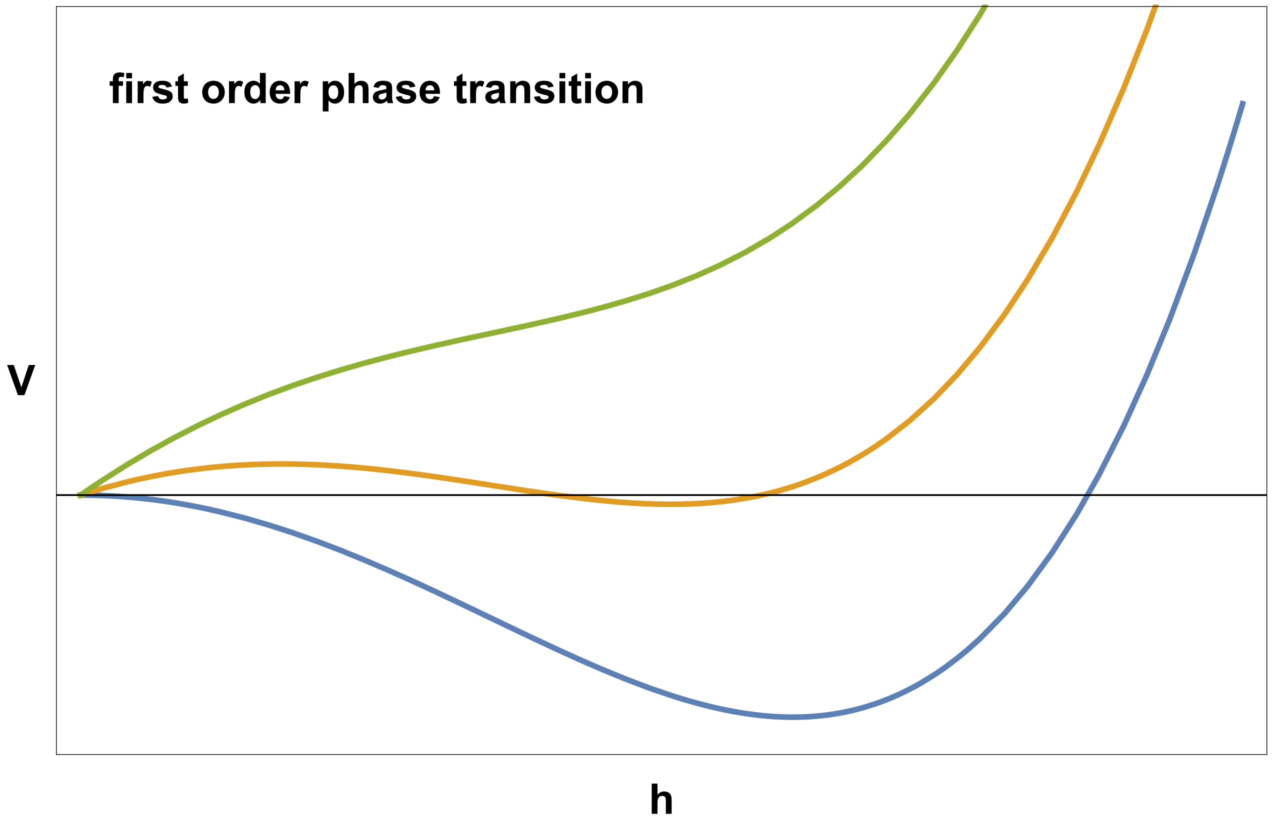
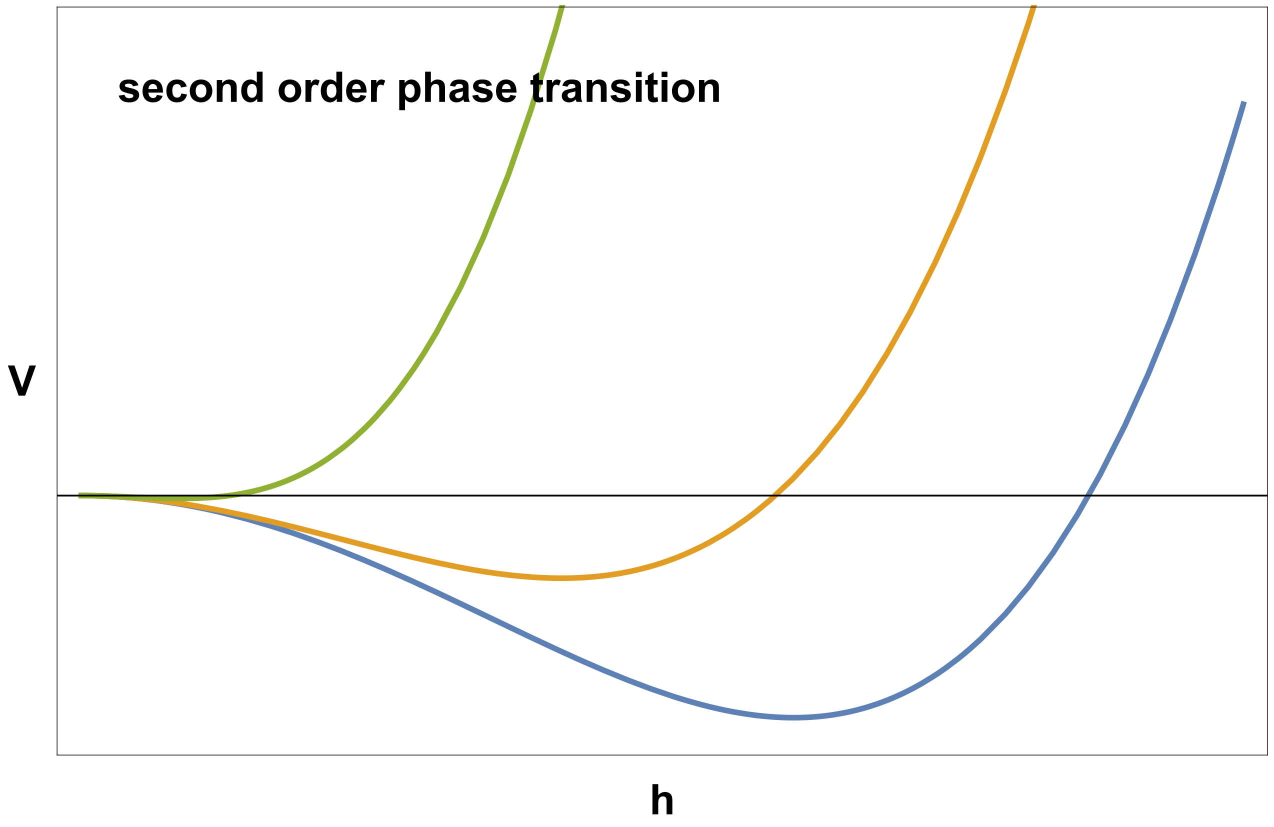
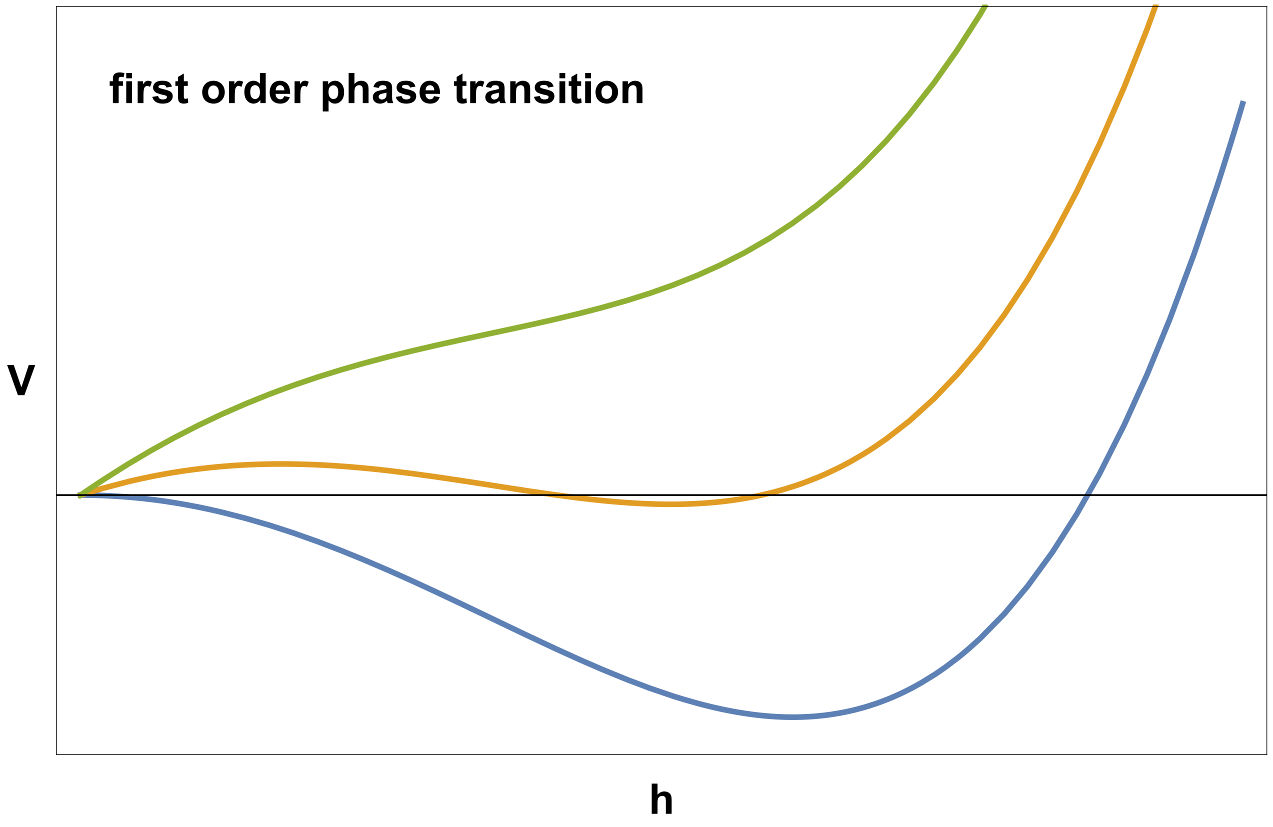
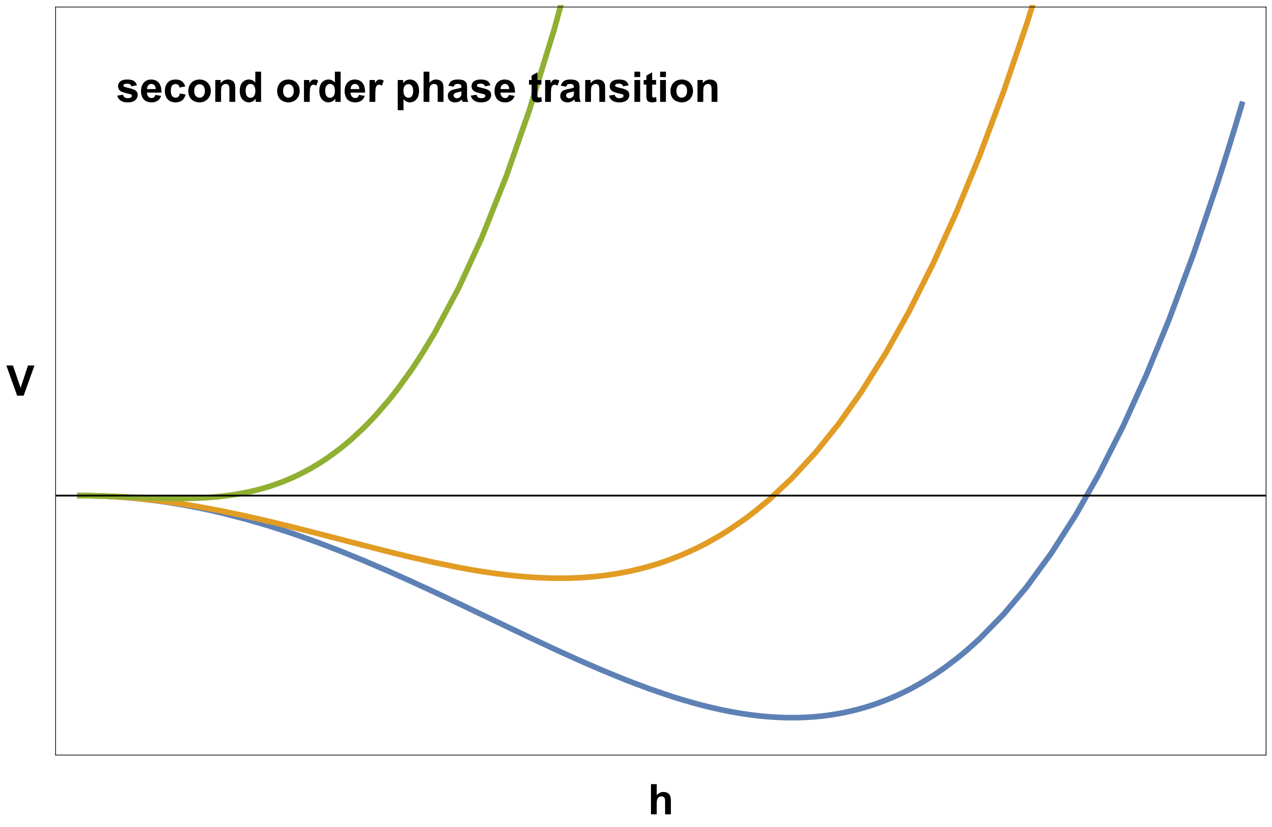




In the SM: not first order

The phase transition in the SM and beyond



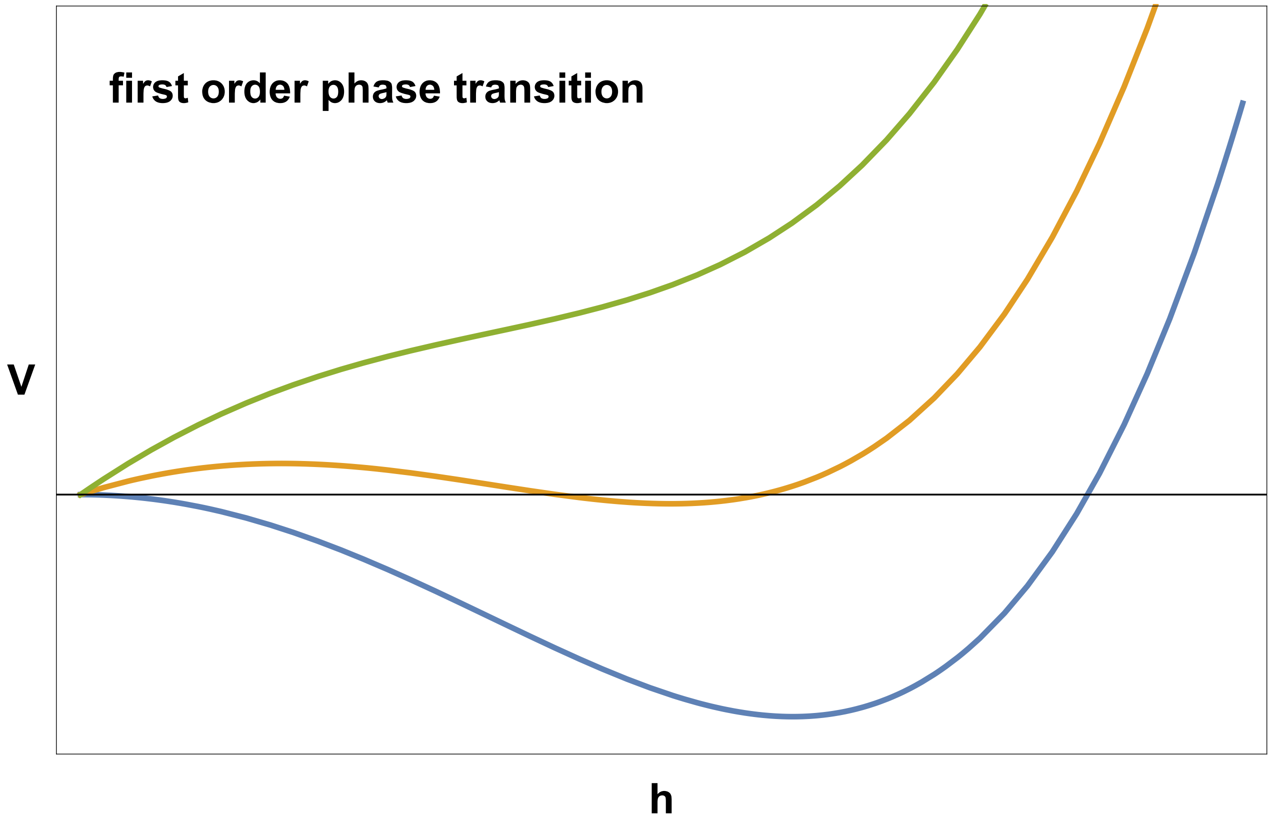


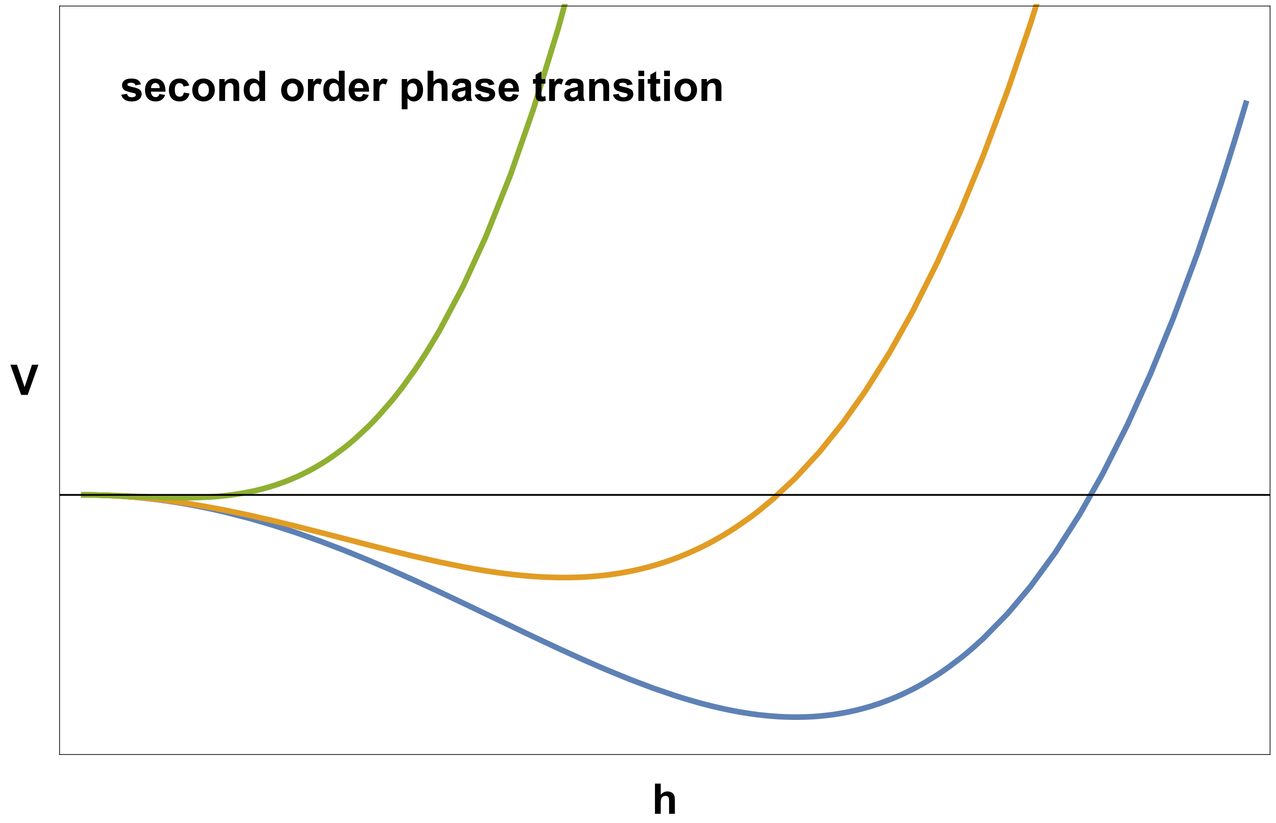
In the SM: not first order

Yukawa variation:

Baldes, Konstandin, Servant ‘16

The phase transition in the SM and beyond



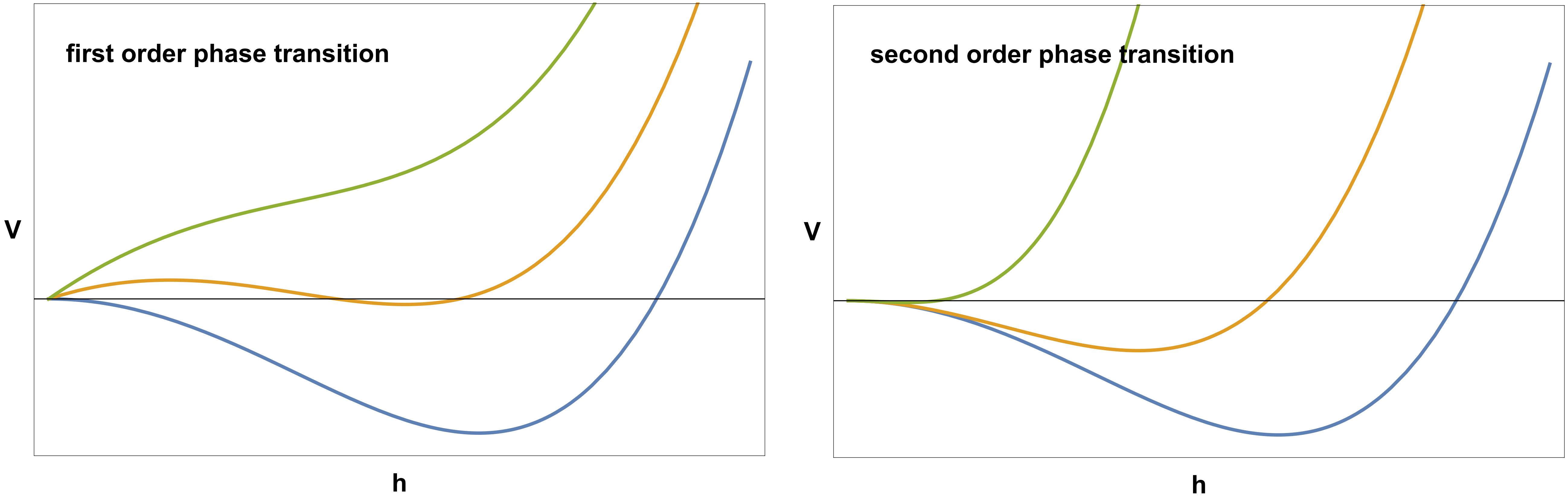


In the SM: not first order

Yukawa variation: Baldes, Konstandin, Servant ‘16

Singlet extensions: Espinosa, Gripaios, Konstandin, Riva ‘11

The phase transition in the SM and beyond



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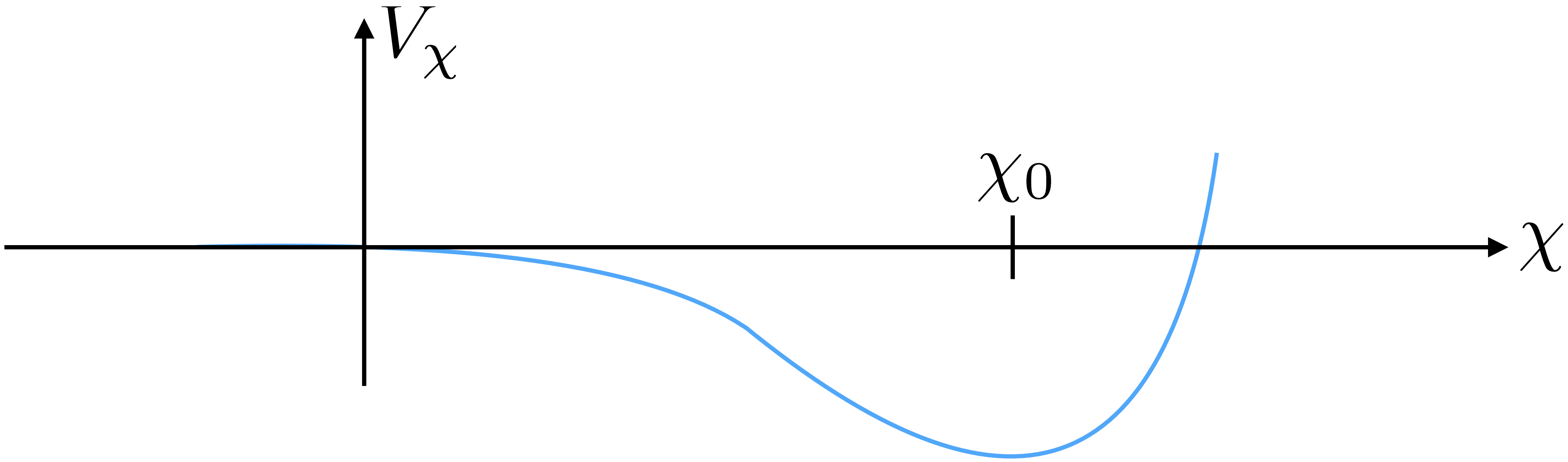
Minimal Composite Higgs: Up next

Conformal symmetry breaking

The vev of the dilaton sets the scale of the strong sector:



Need small explicit breaking of conformal symmetry

$$V_\chi = c_\chi g_\chi^2 \chi^4 \ .$$

Conformal symmetry breaking

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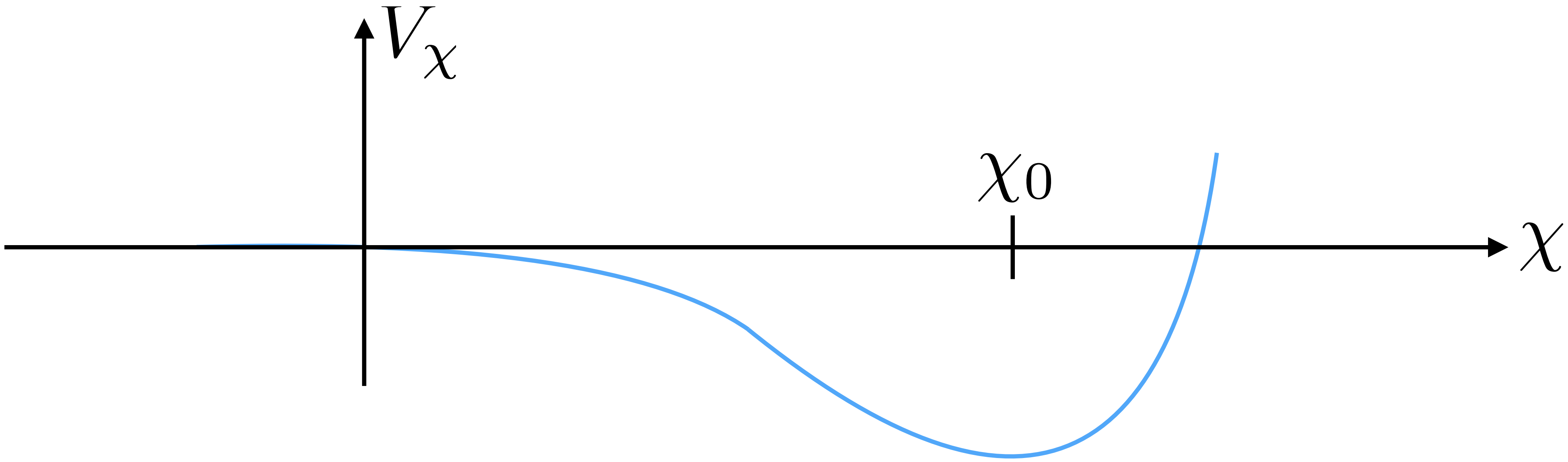

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$$V_\chi = c_\chi g_\chi^2 \chi^4 - \epsilon[\chi]\chi^4 + \ldots$$

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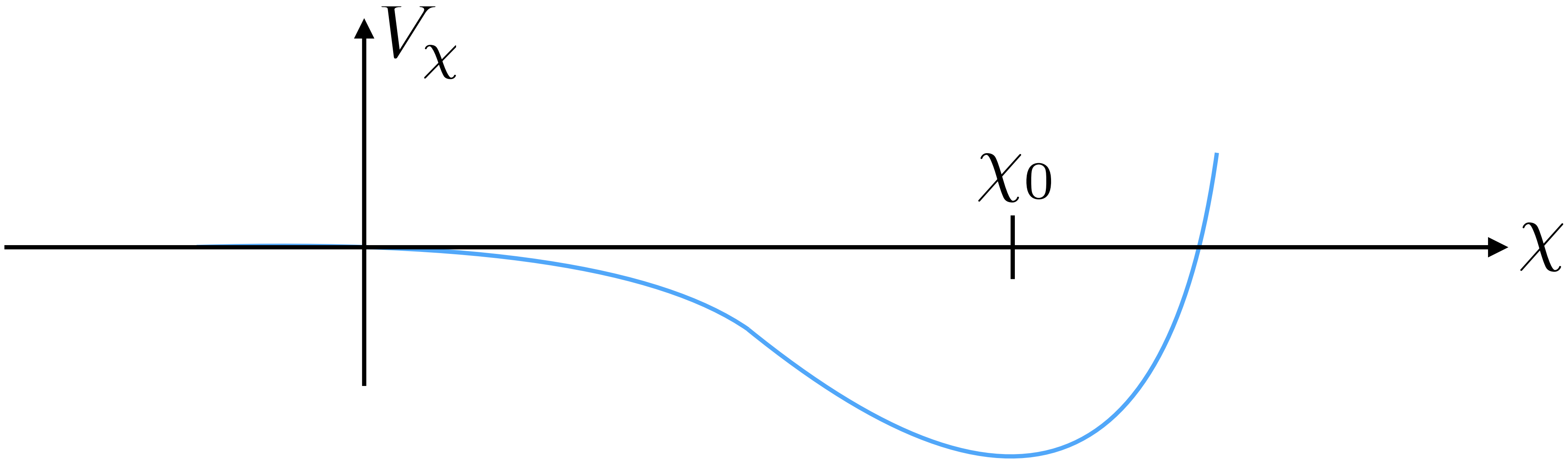

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All scales in the strong sector (including *f*) are determined by χ $\Rightarrow$ Yukawas vary as χ varies

Conformal symmetry breaking

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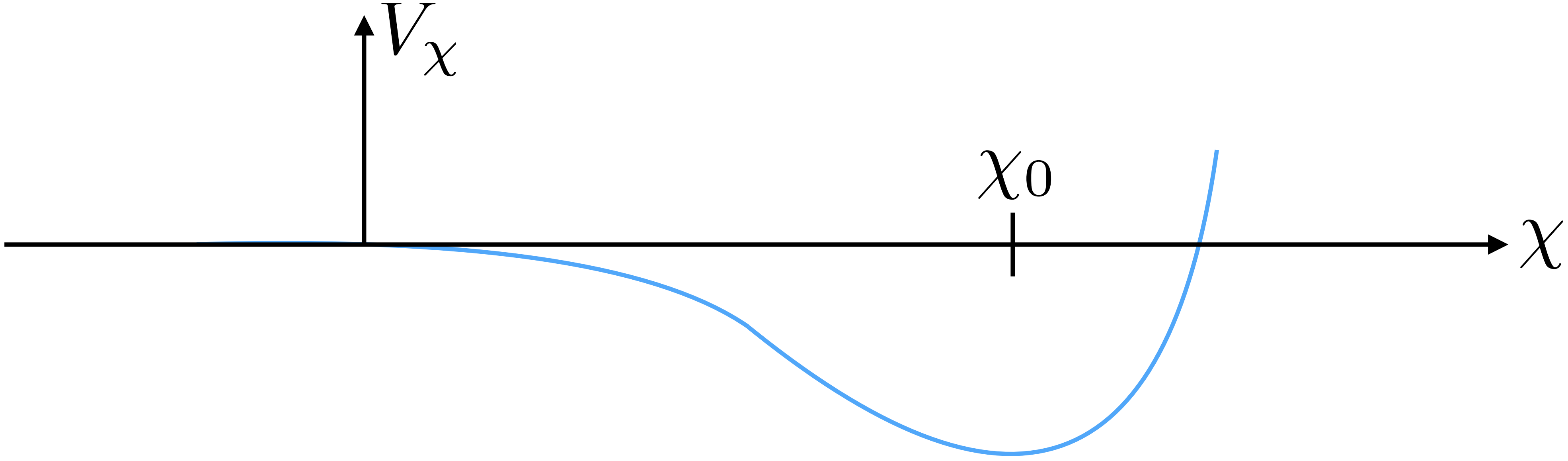

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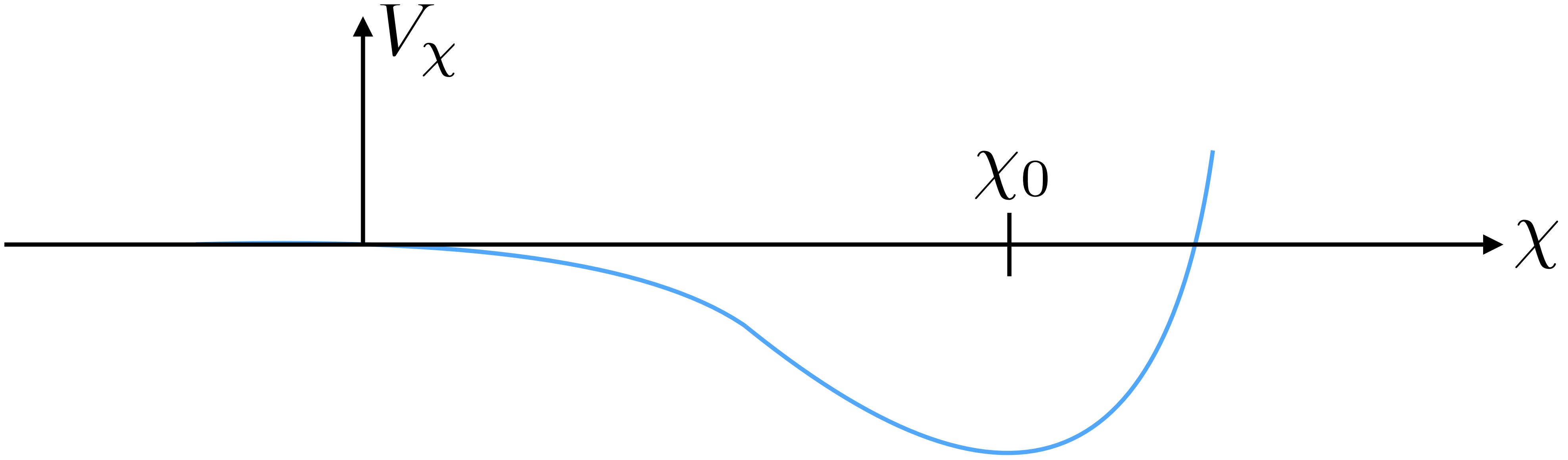

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Typical coupling of the dilaton:

Meson-like dilaton: $g_\chi \sim N^{-1/2}$

Glueball-like dilaton: $g_\chi \sim N^{-1}$

Conformal symmetry breaking

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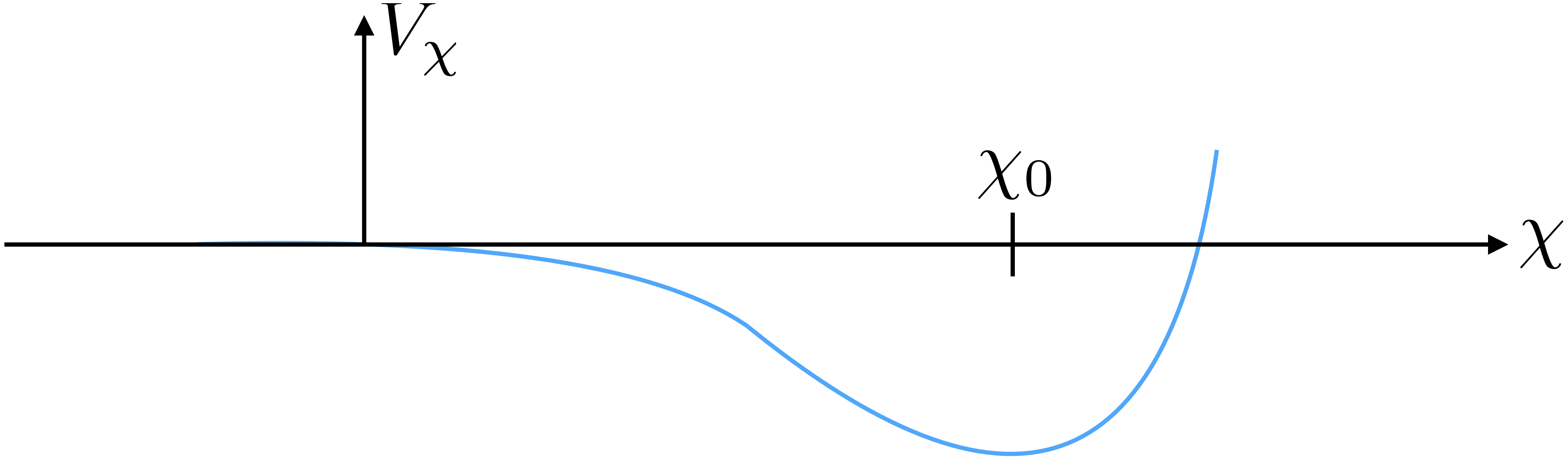

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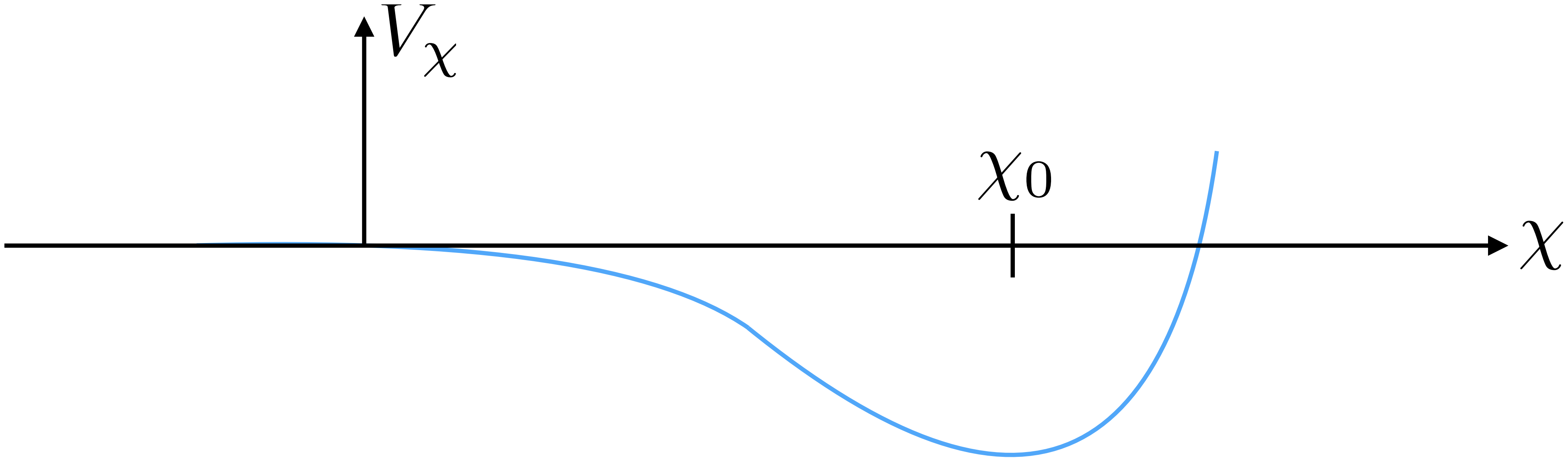

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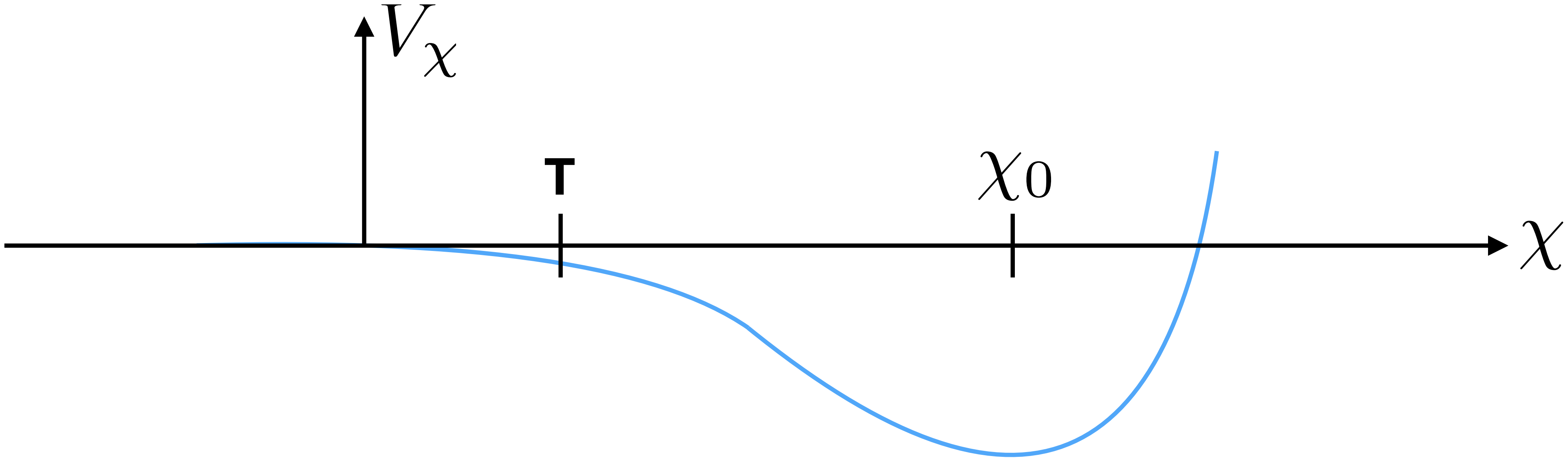

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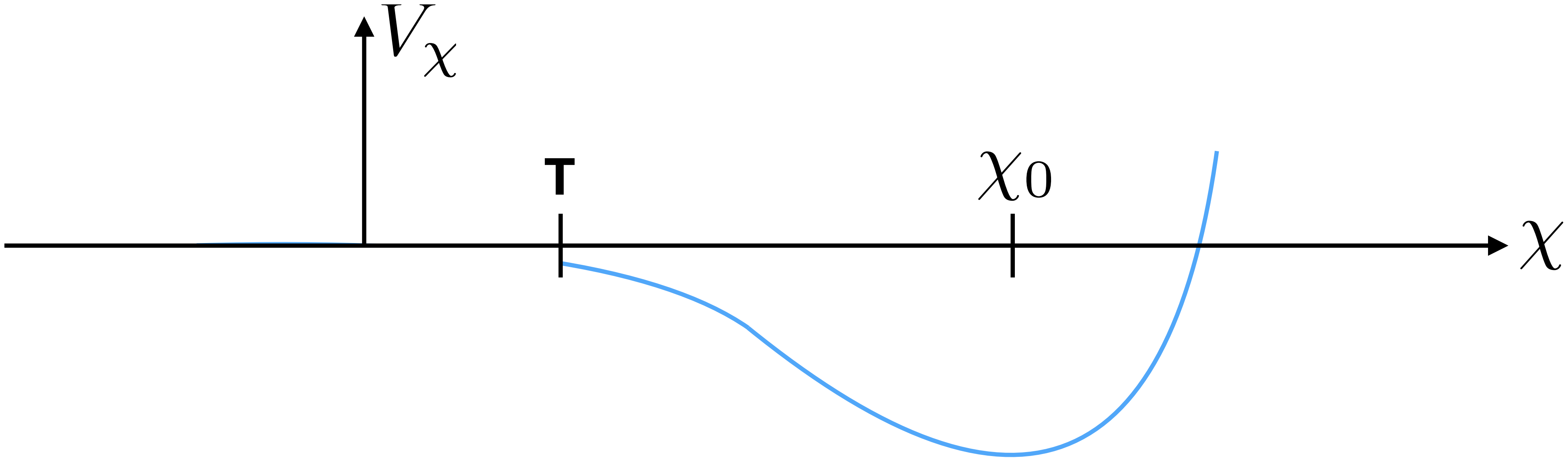

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- For $T \ll \chi$ use 0-Temperature potential

Conformal symmetry breaking

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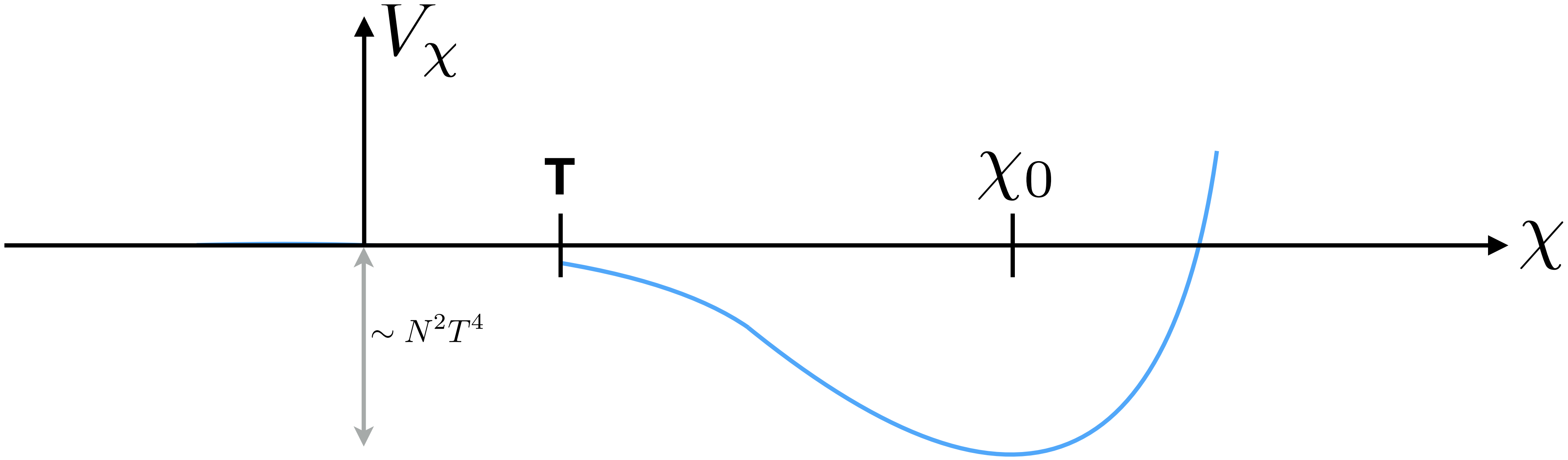

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- From dimensional analysis and large-N counting: $F_{CFT}[\chi=0] \simeq -cN^2T^4$

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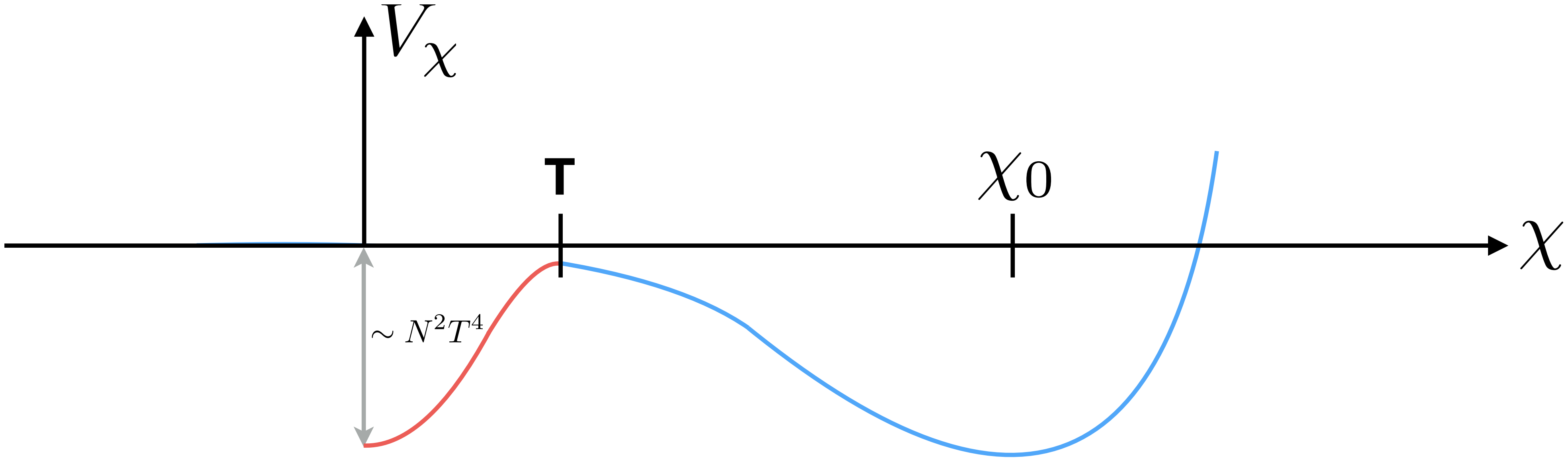

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- Use $\frac{45N^2}{4}$ strong sector bosons to reproduce $\mathcal{N} = 4$ SYM result for *c*.

Conformal symmetry breaking

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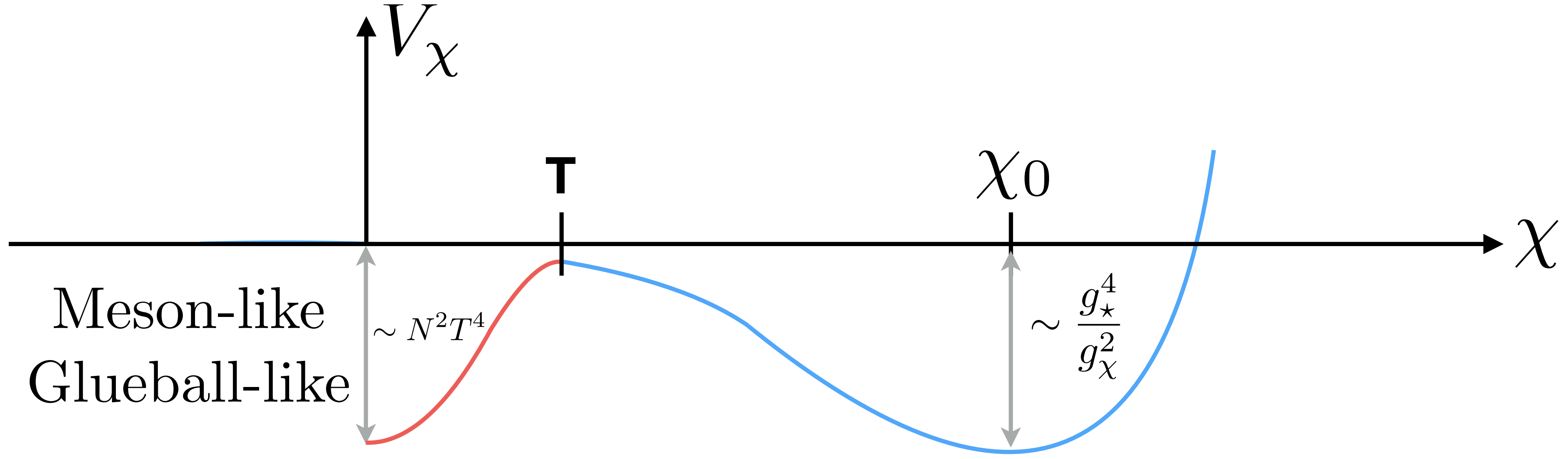

$$T_c \sim \begin{cases} N^{-3/4} & \text{Meson-like} \\ N^{-1/2} & \text{Glueball-like} \end{cases}$$

Need small explicit breaking of conformal symmetry

$$V_\chi = c_\chi g_\chi^2 \chi^4 - \epsilon[\chi]\chi^4 + \dots$$

- For $T \ll \chi$ use 0-Temperature potential
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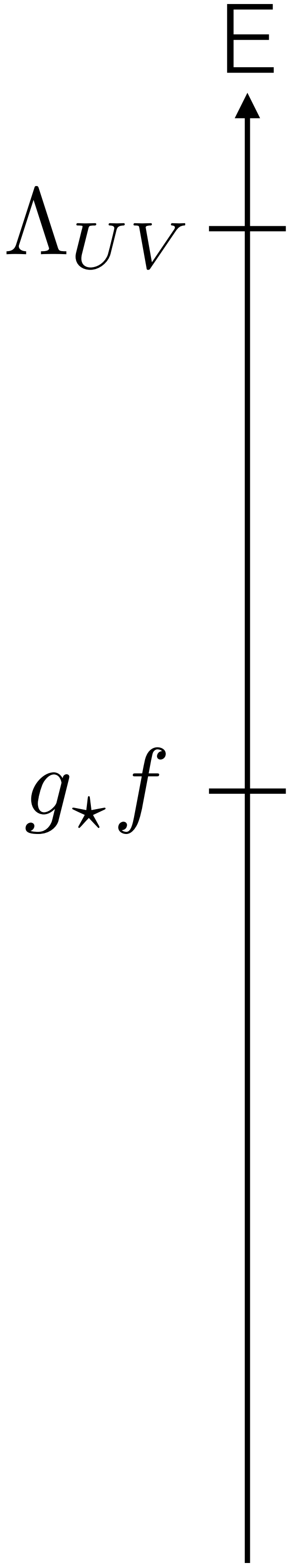
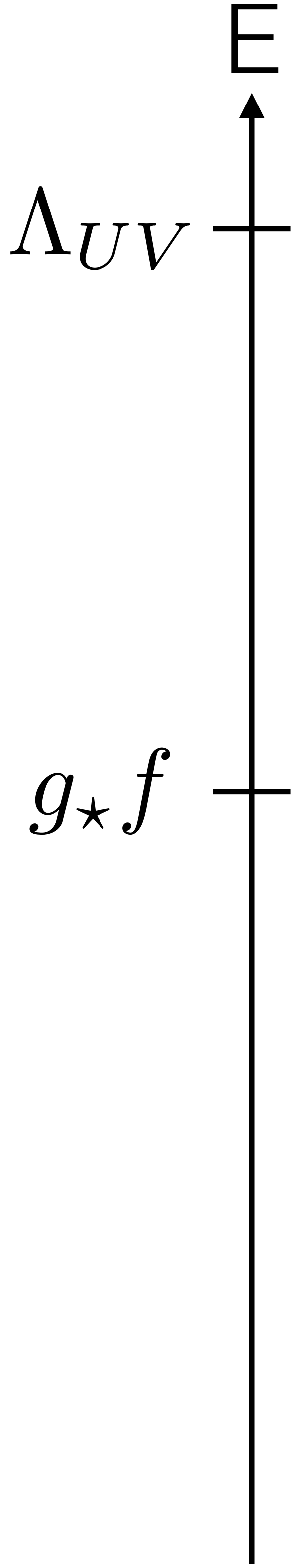
Quark masses in Composite Higgs through partial compositeness


E
Λ_{UV}
$g_\star f$

Quark masses in Composite Higgs through partial compositeness

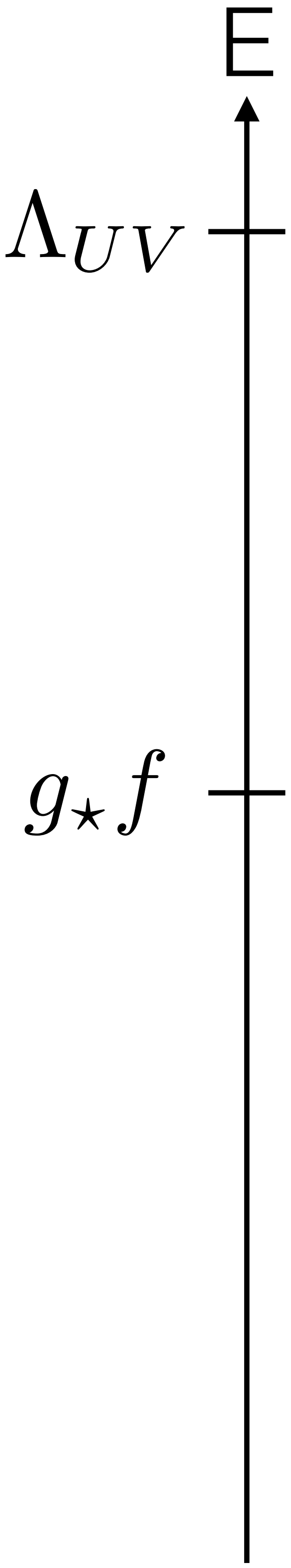


$$\mathcal{L} \supset y_i \bar{q}_i \mathcal{O}_i$$

Fermionic operators
of the strong sector, e.g:

$$\mathcal{O}_i \sim \psi \bar{\psi} \psi$$

Quark masses in Composite Higgs through partial compositeness



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Fermionic operators
of the strong sector, e.g:

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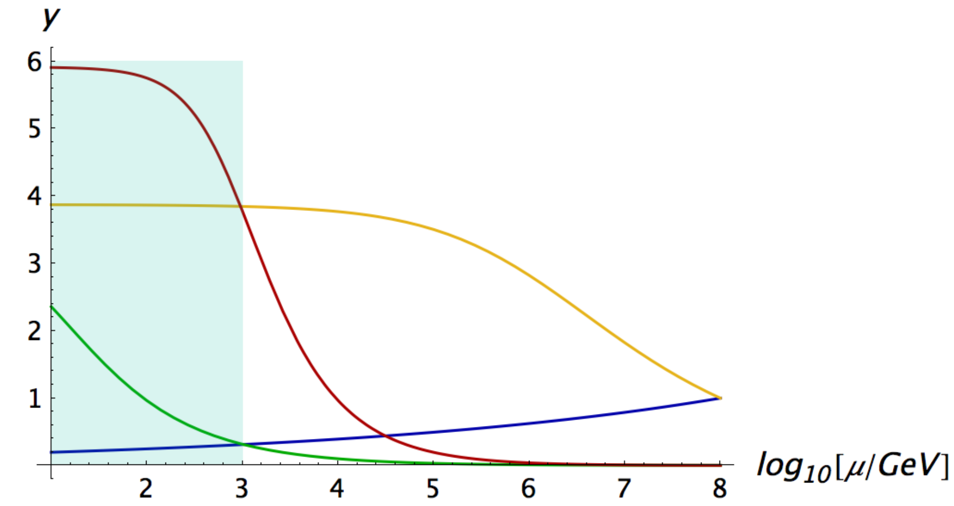
$$\frac{\partial y_i}{\partial \log \mu} = \gamma_i y_i + c_i \frac{y_i^3}{g_\star^2} + \ldots$$



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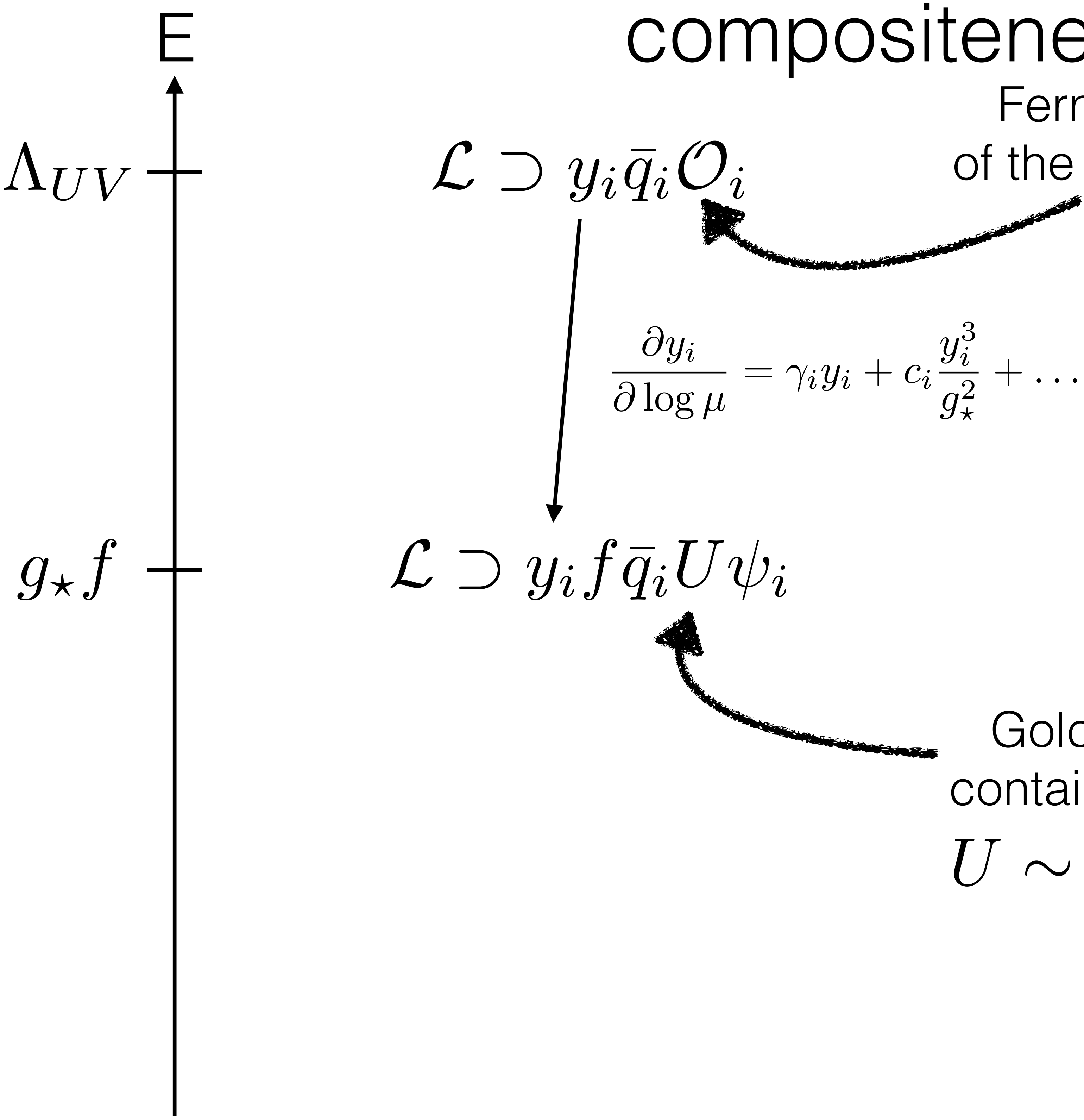

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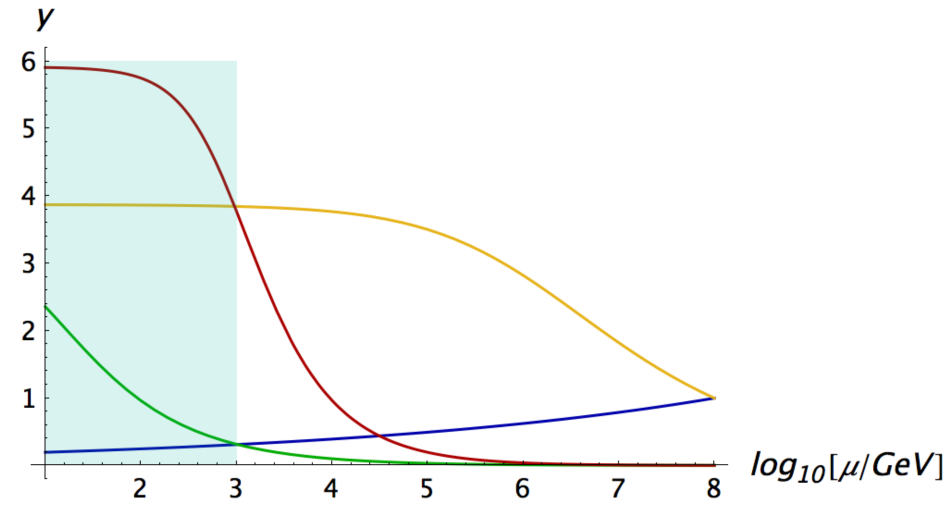

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Goldstone matrix containing the Higgs

$$U \sim \exp[ih/f]$$

Quark masses in Composite Higgs through partial compositeness

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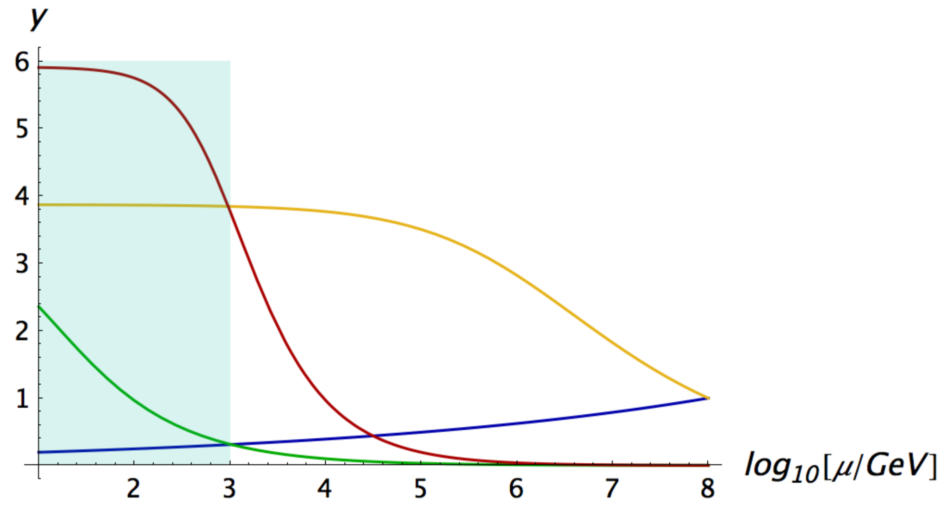

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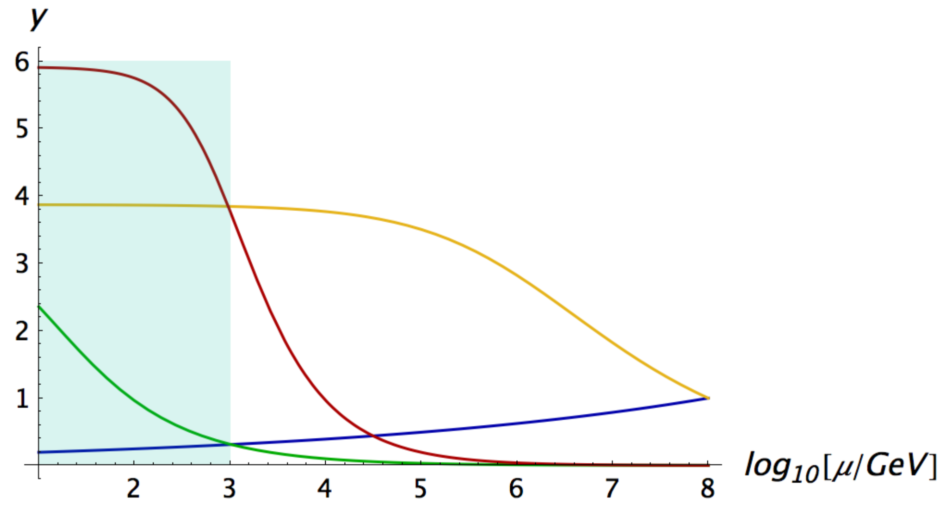

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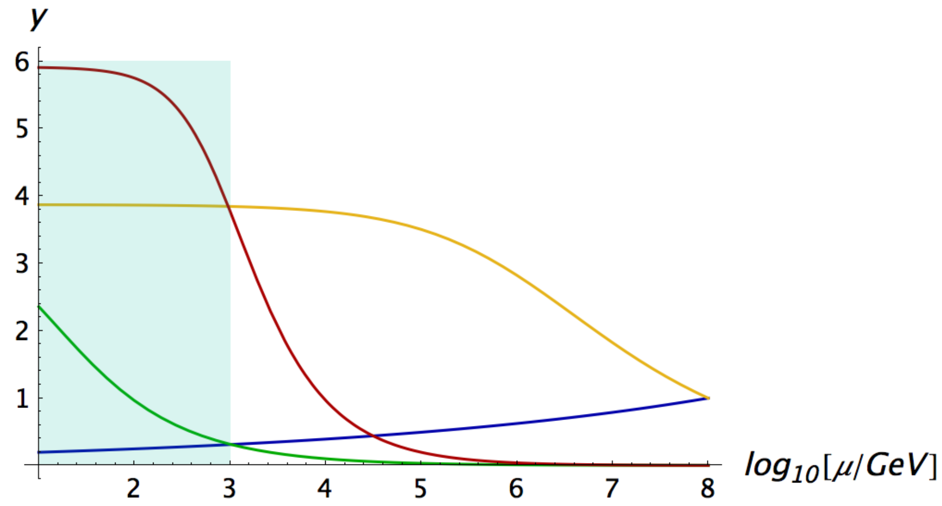

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Mass hierarchy generated by order one differences in the scaling dimensions of $\mathcal{O}_i$

The Higgs potential

The Higgs potential

Explicit breaking of *G* through elementary-composite couplings:

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SM-fermions don't
fill complete multiplets of *G*

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$$f \sim \langle \chi \rangle$$

Tuning of the Higgs potential

$$V_h = g_\star^2 \chi^4 \frac{y^2}{(4\pi)^2} \sum_i c_i \left(\frac{y}{g_\star}\right)^{p_i} \mathcal{I}_i\left(\frac{h}{\chi}\right)$$

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Full potential

$$V = V_\chi + (\chi/f)^4 V_h^0 + \left(V_h^{NDA}[y] - V_h^{NDA}[y_0]\right)$$

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$\alpha, \beta < 0 \quad \Rightarrow$ **valley along** $h/\chi \sim \pi/2$ **Trajectory c**