EW Baryogenesis in Composite Higgs models

Sebastian Bruggisser

In collaboration with:
T. Konstandin & O. Matsedonskyi
& G. Servant & B. von Harling

arXiv: 1706.08534, 1803.08546
1804.07314

Requirements for Baryogenesis

Requirements for Baryogenesis

- Baryon number violation

Requirements for Baryogenesis

- Baryon number violation
  - ➡ Electroweak Sphaleron

Requirements for Baryogenesis

- Baryon number violation
  - ➡ Electroweak Sphaleron
- CP violation

Requirements for Baryogenesis

- Baryon number violation
  - ➡ Electroweak Sphaleron
- CP violation
  - ➡ Dynamical CP violation from varying Yukawas

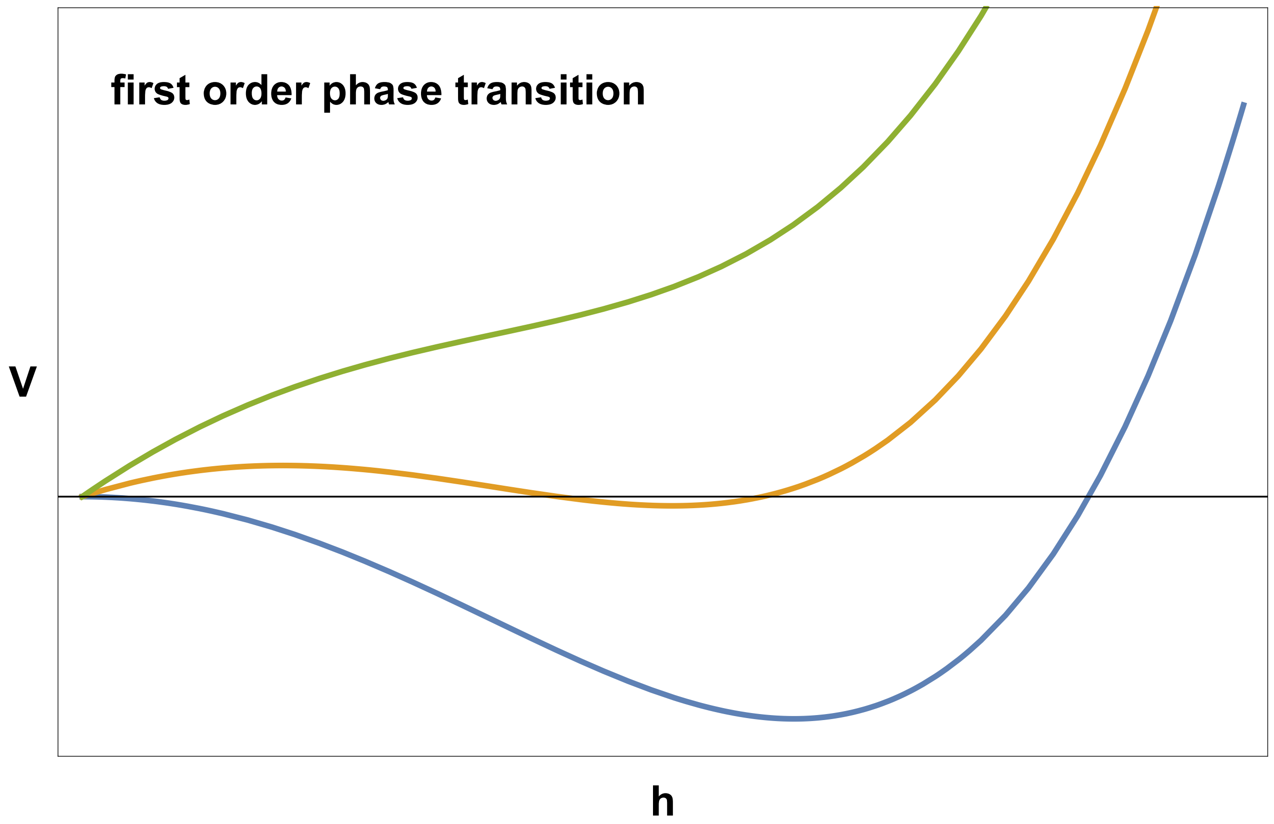
Requirements for Baryogenesis

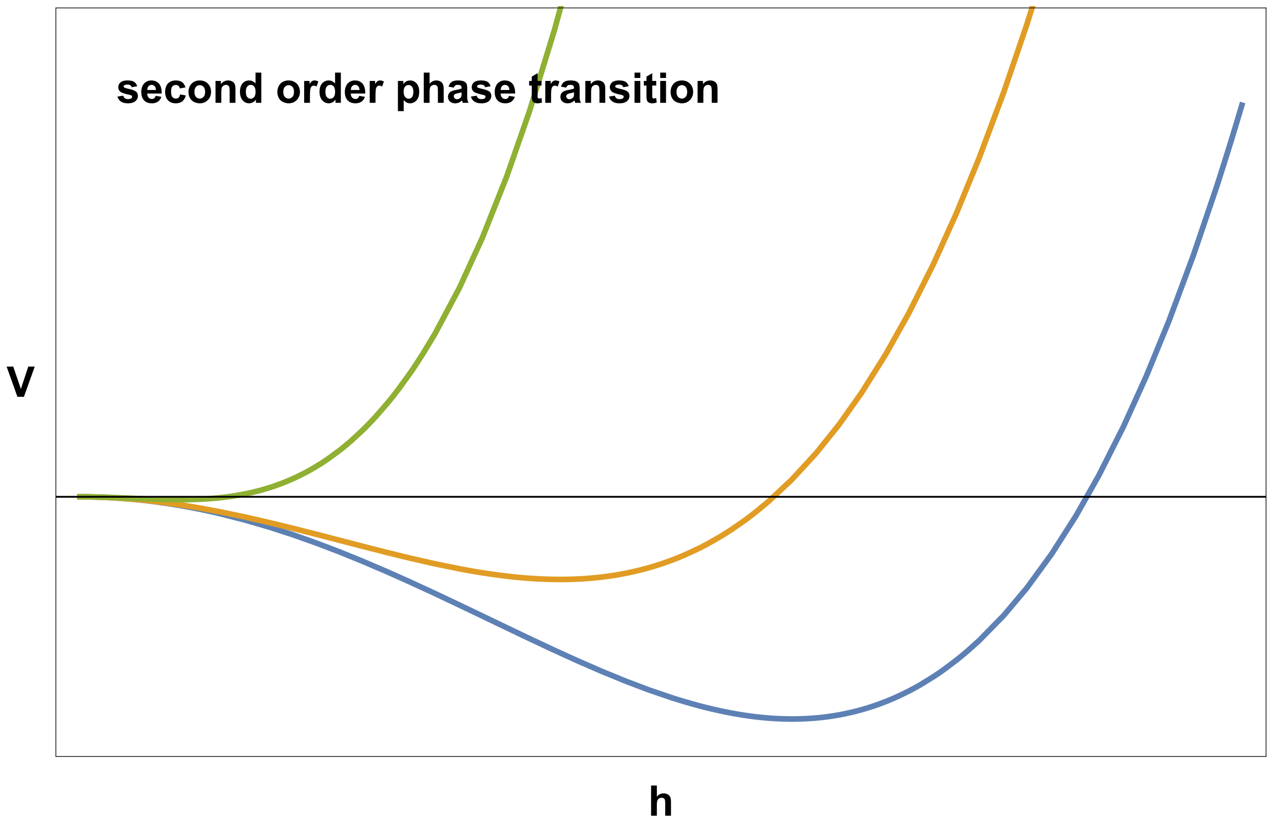
- Baryon number violation
  - ➡ Electroweak Sphaleron
- CP violation
  - ➡ Dynamical CP violation from varying Yukawas
- Out-of-equilibrium

Requirements for Baryogenesis

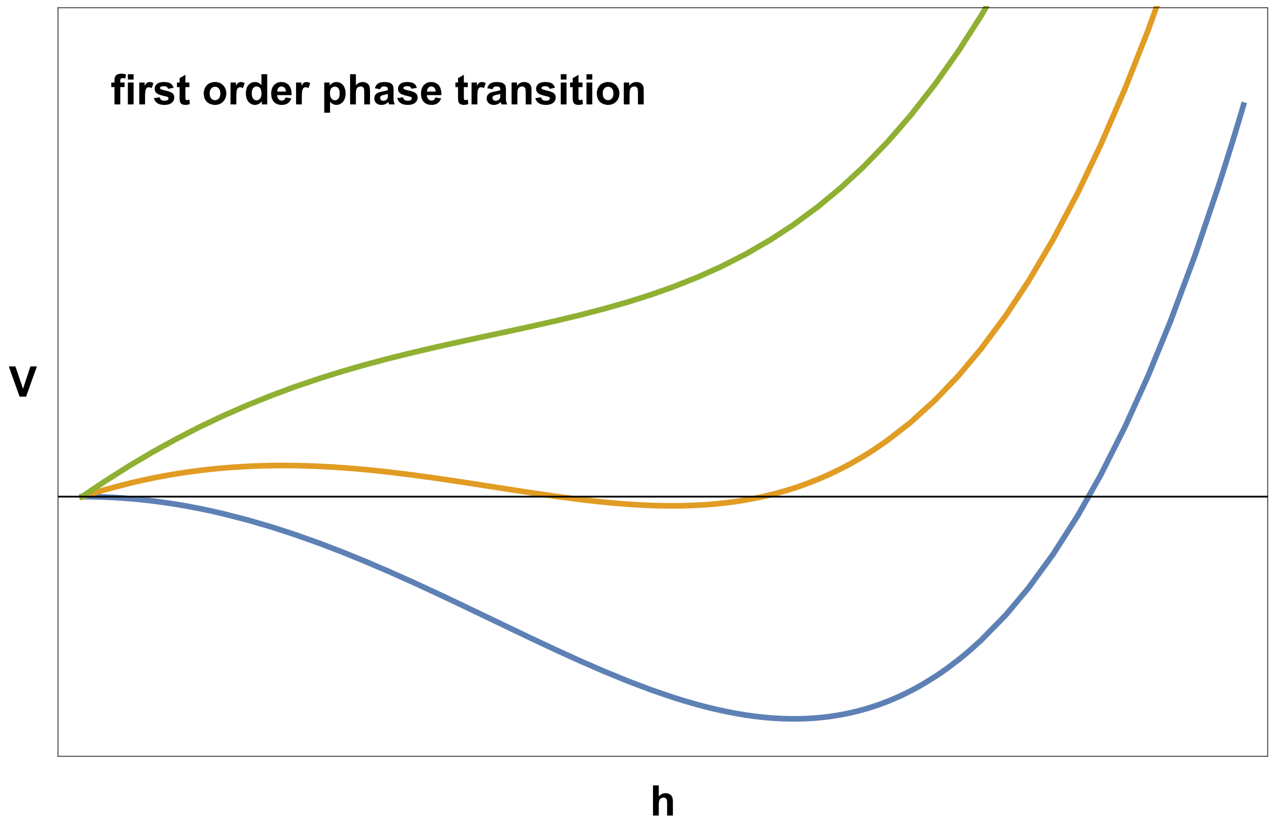
- Baryon number violation
  - ➡ Electroweak Sphaleron
- CP violation
  - ➡ Dynamical CP violation from varying Yukawas
- Out-of-equilibrium
  - ➡ Strong first-order electroweak phase transition

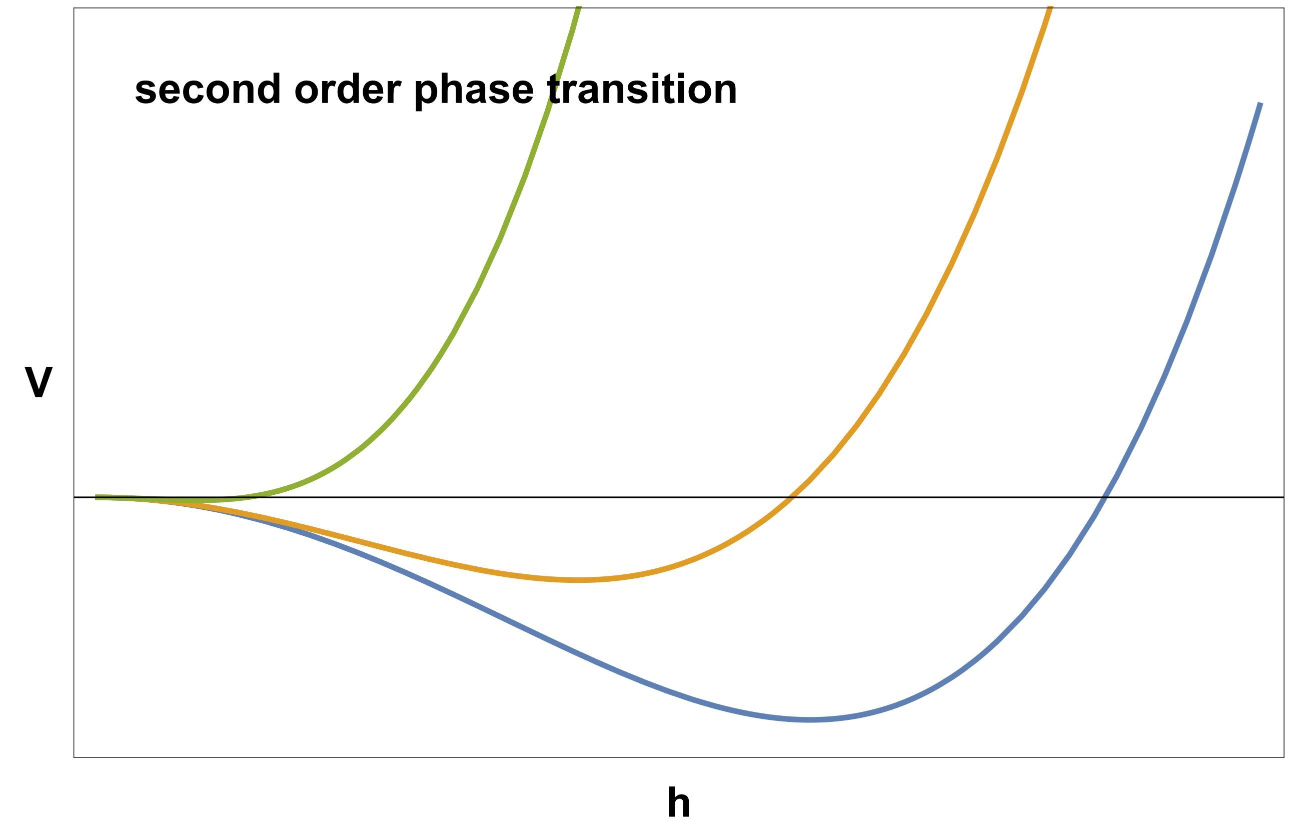
The phase transition in the SM and beyond





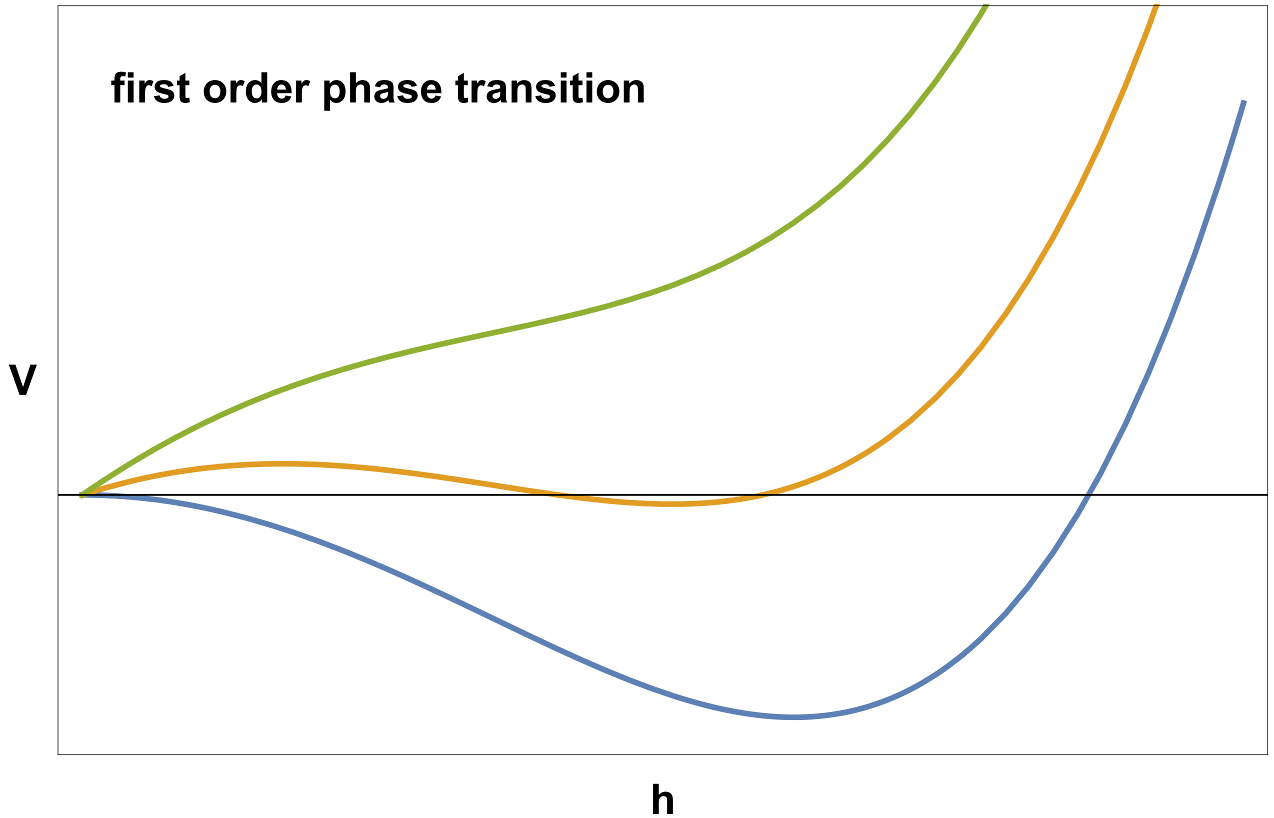
The phase transition in the SM and beyond

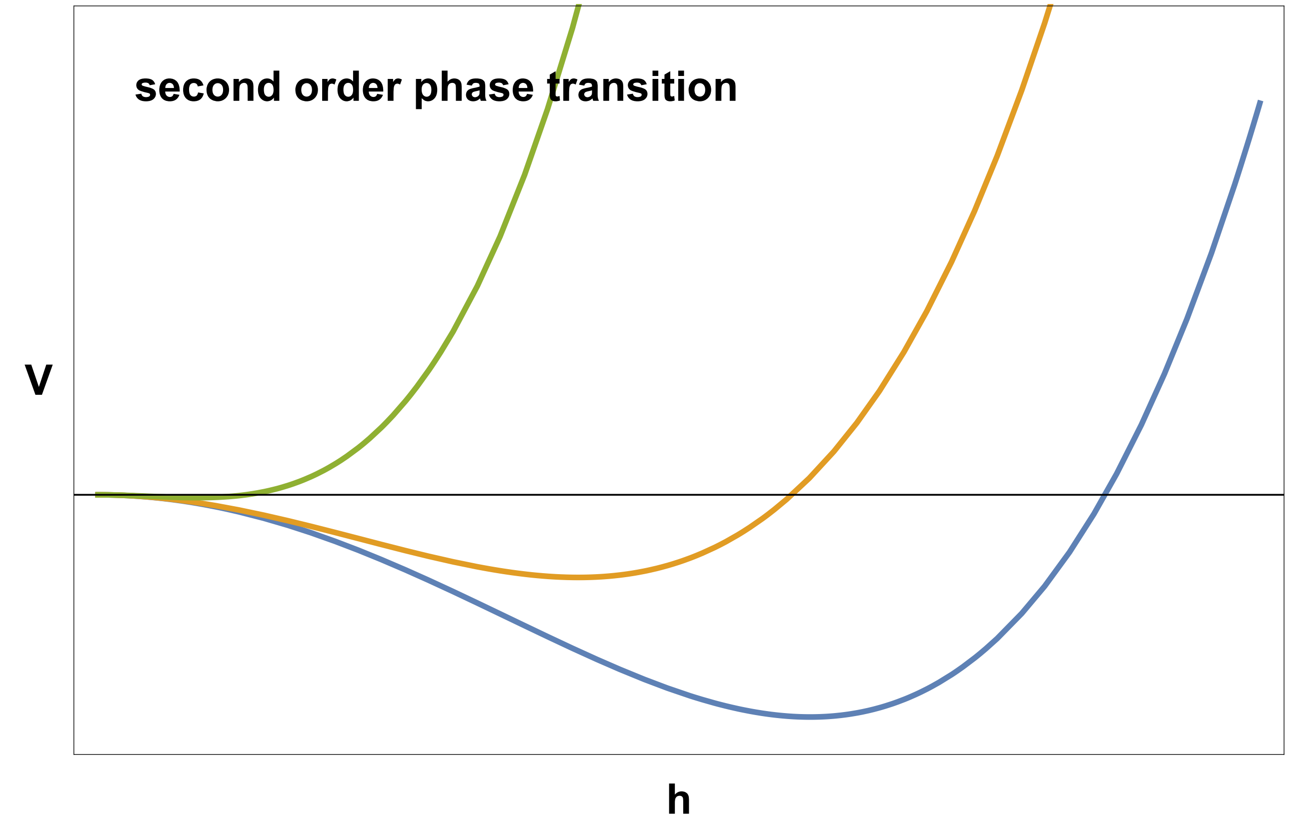




In the SM: not first order

The phase transition in the SM and beyond

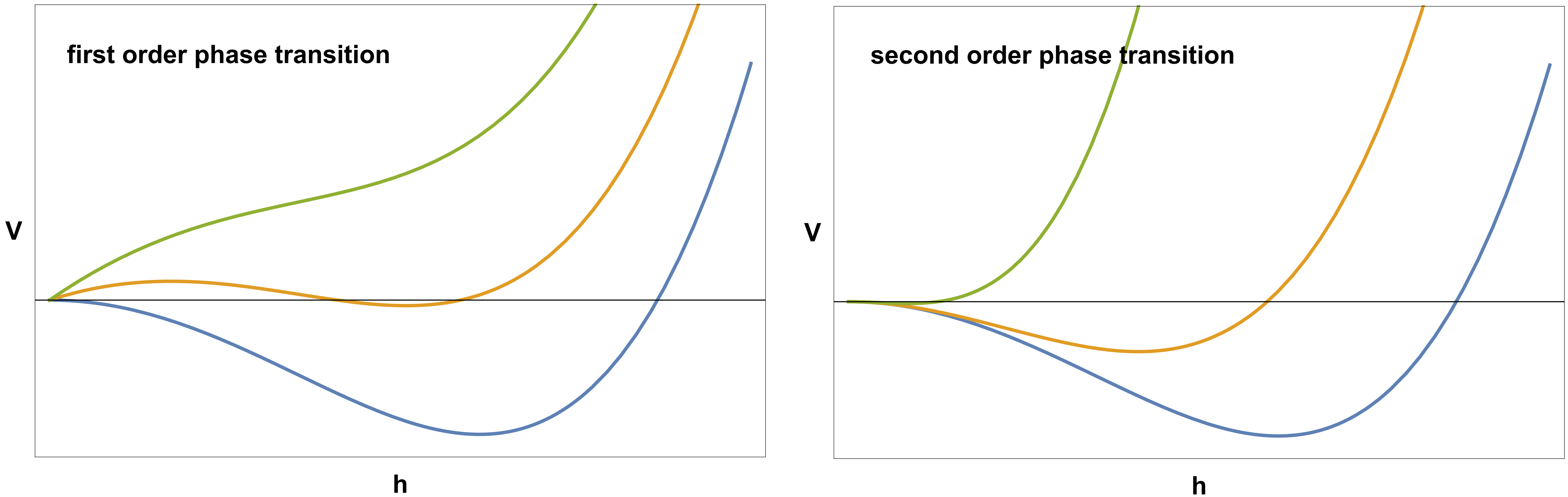




In the SM: not first order

Yukawa variation: Baldes, Konstandin, Servant ‘16

The phase transition in the SM and beyond

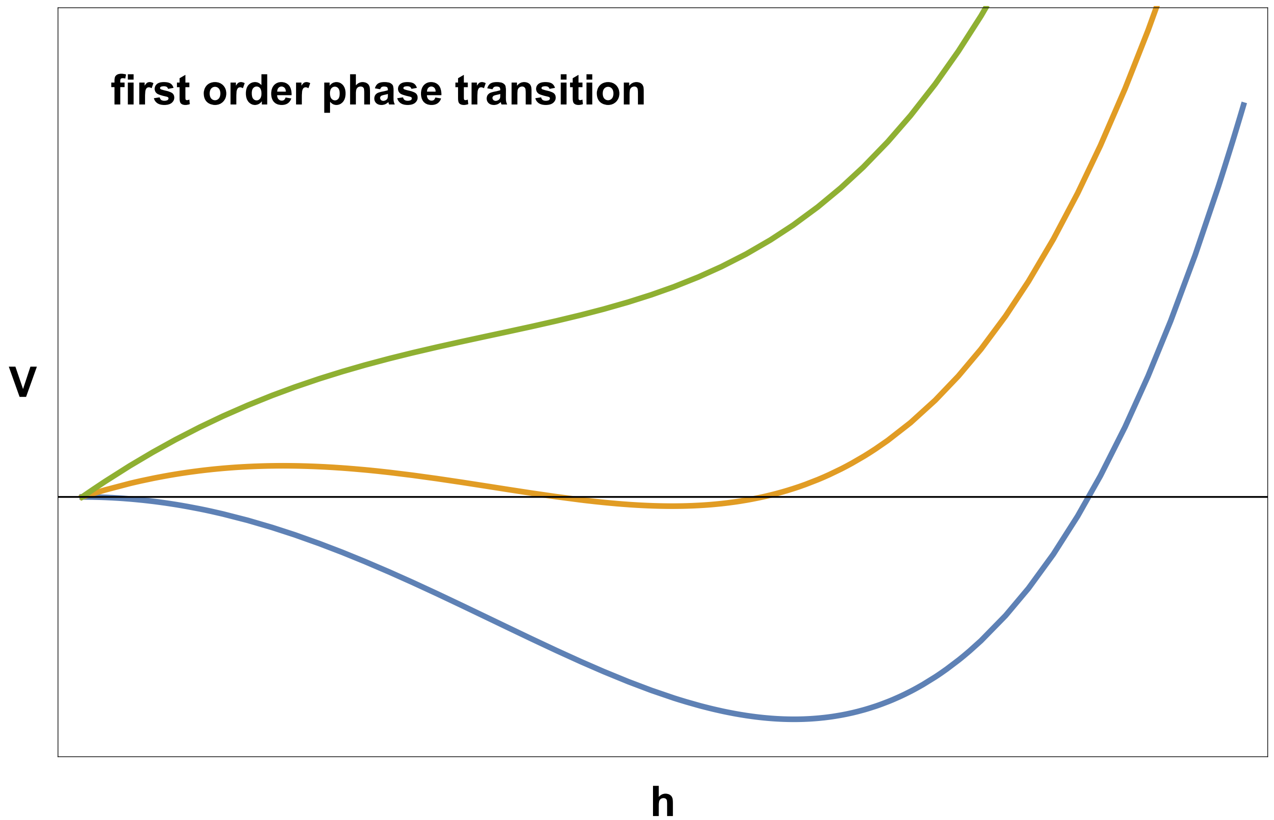


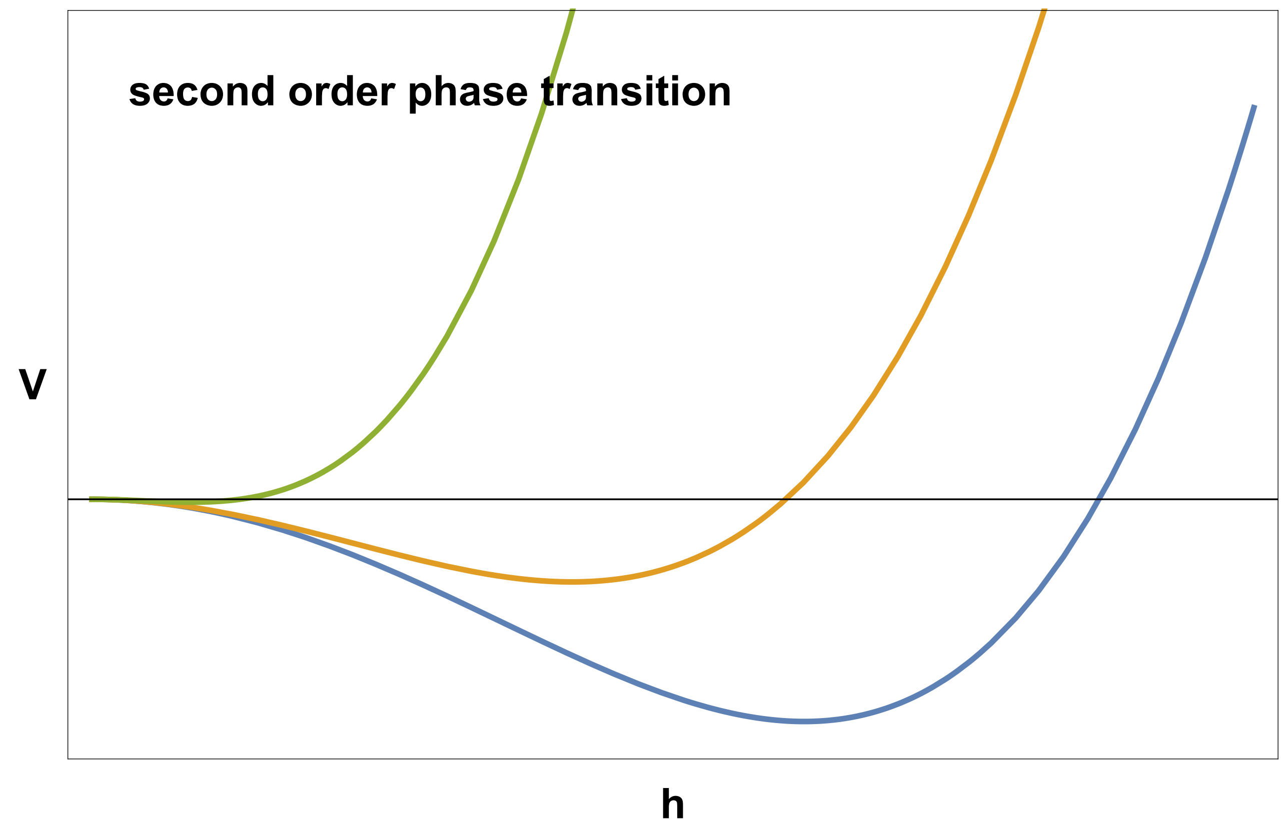
In the SM: not first order

Yukawa variation: Baldes, Konstandin, Servant '16

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

The phase transition in the SM and beyond





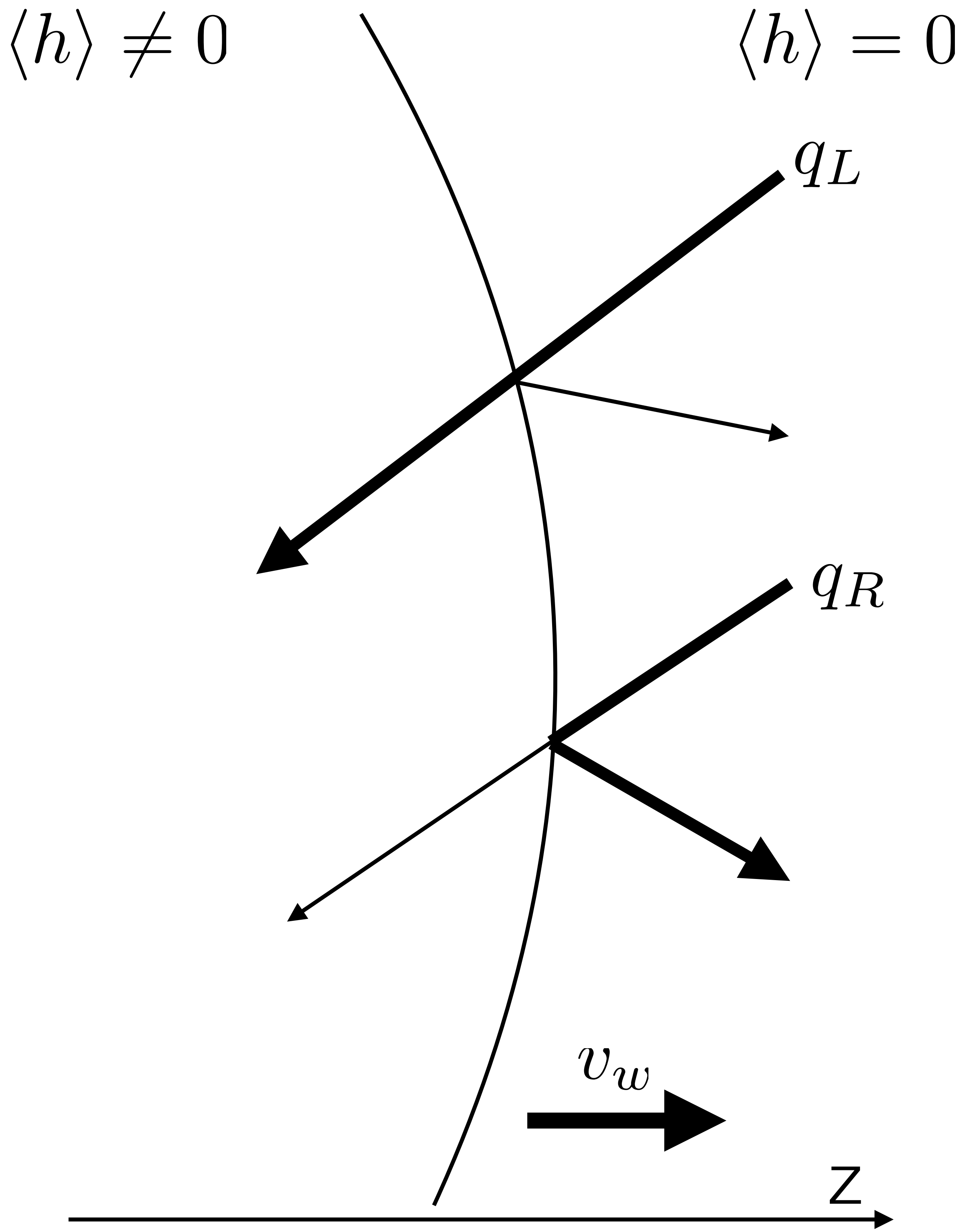
In the SM: not first order

Yukawa variation: Baldes, Konstandin, Servant '16

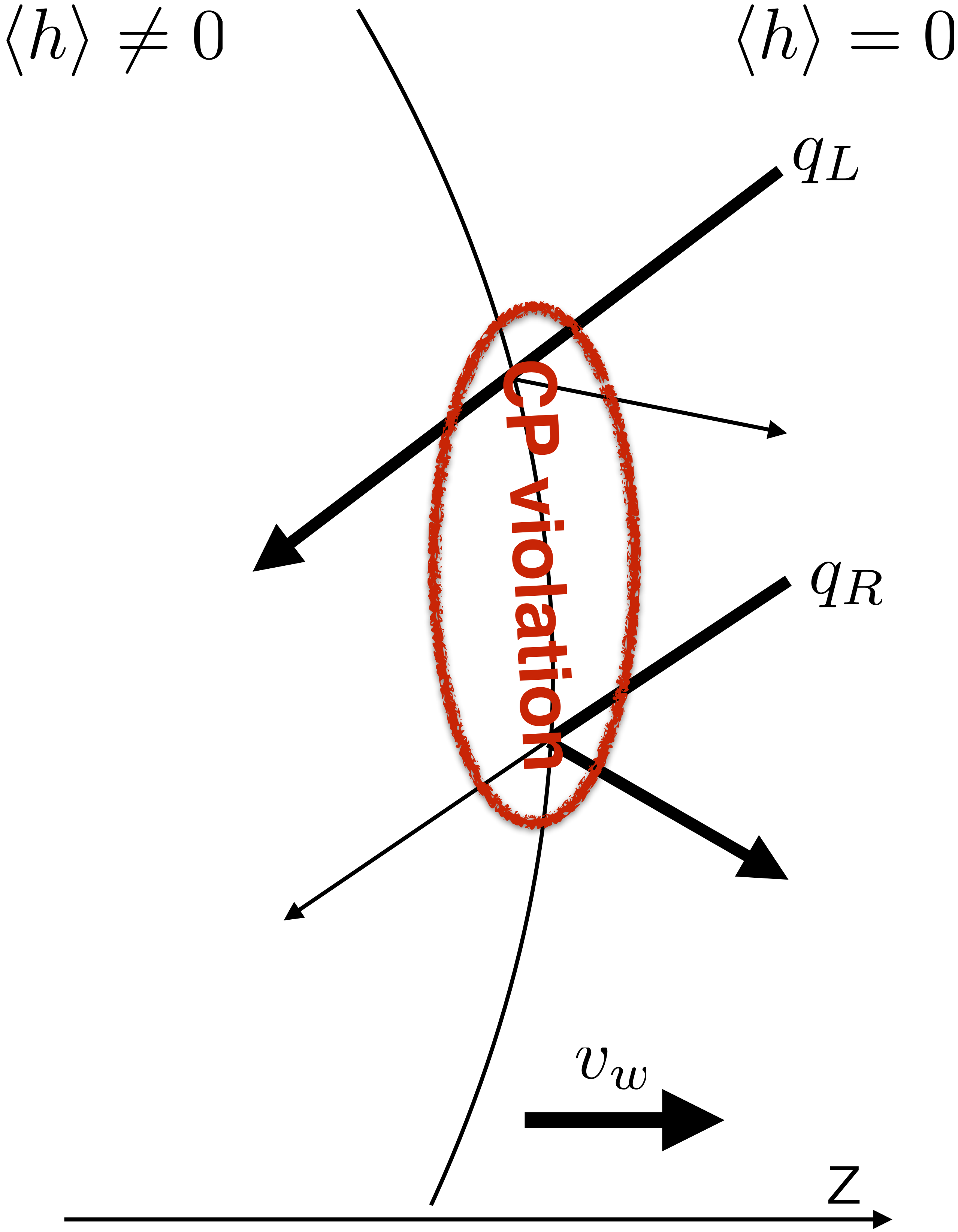
Singlet extensions: Espinosa, Gripaios, Konstandin, Riva '11

Minimal Composite Higgs: Joint confinement-electroweak phase transition

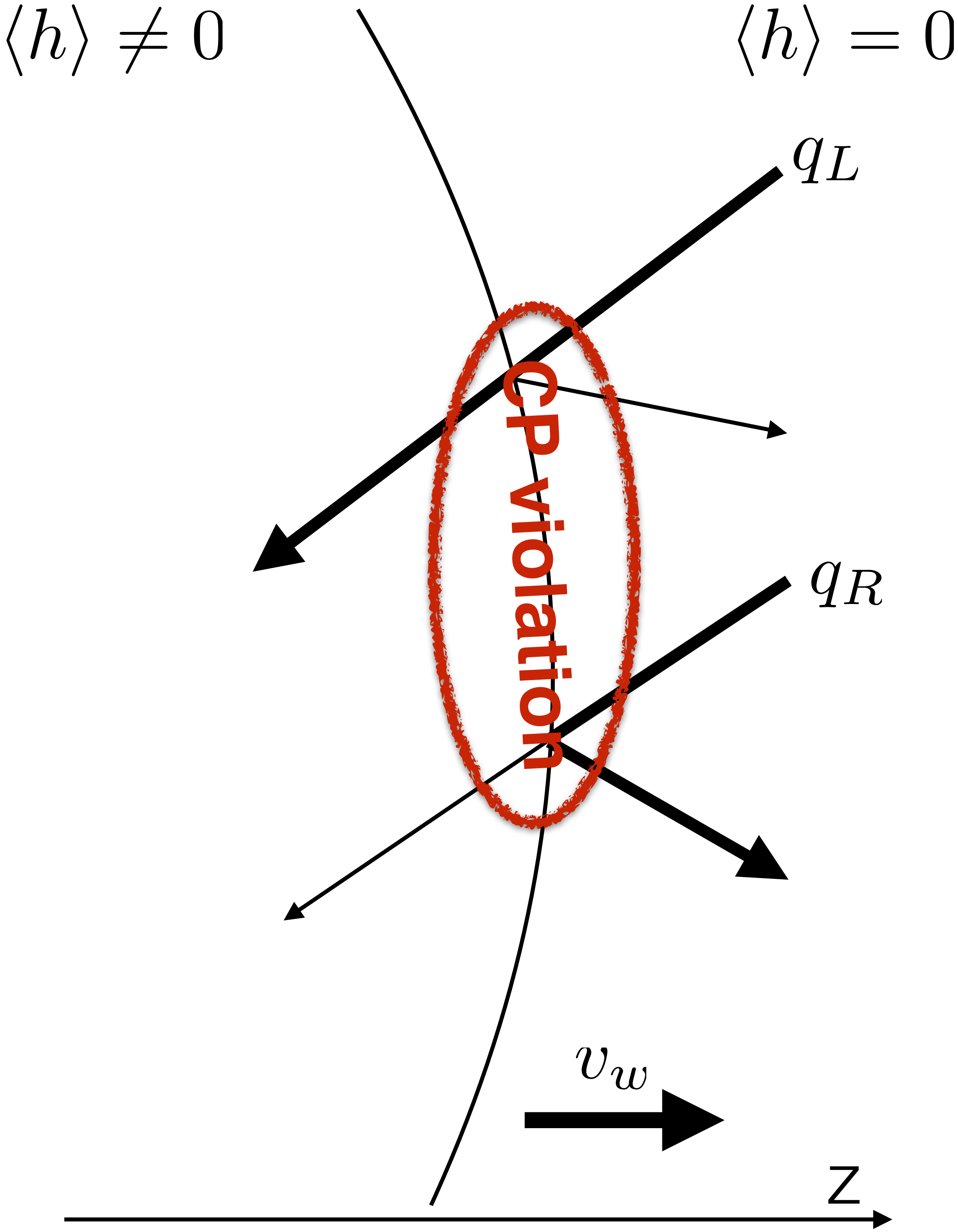
CP violation from varying Yukawas



CP violation from varying Yukawas



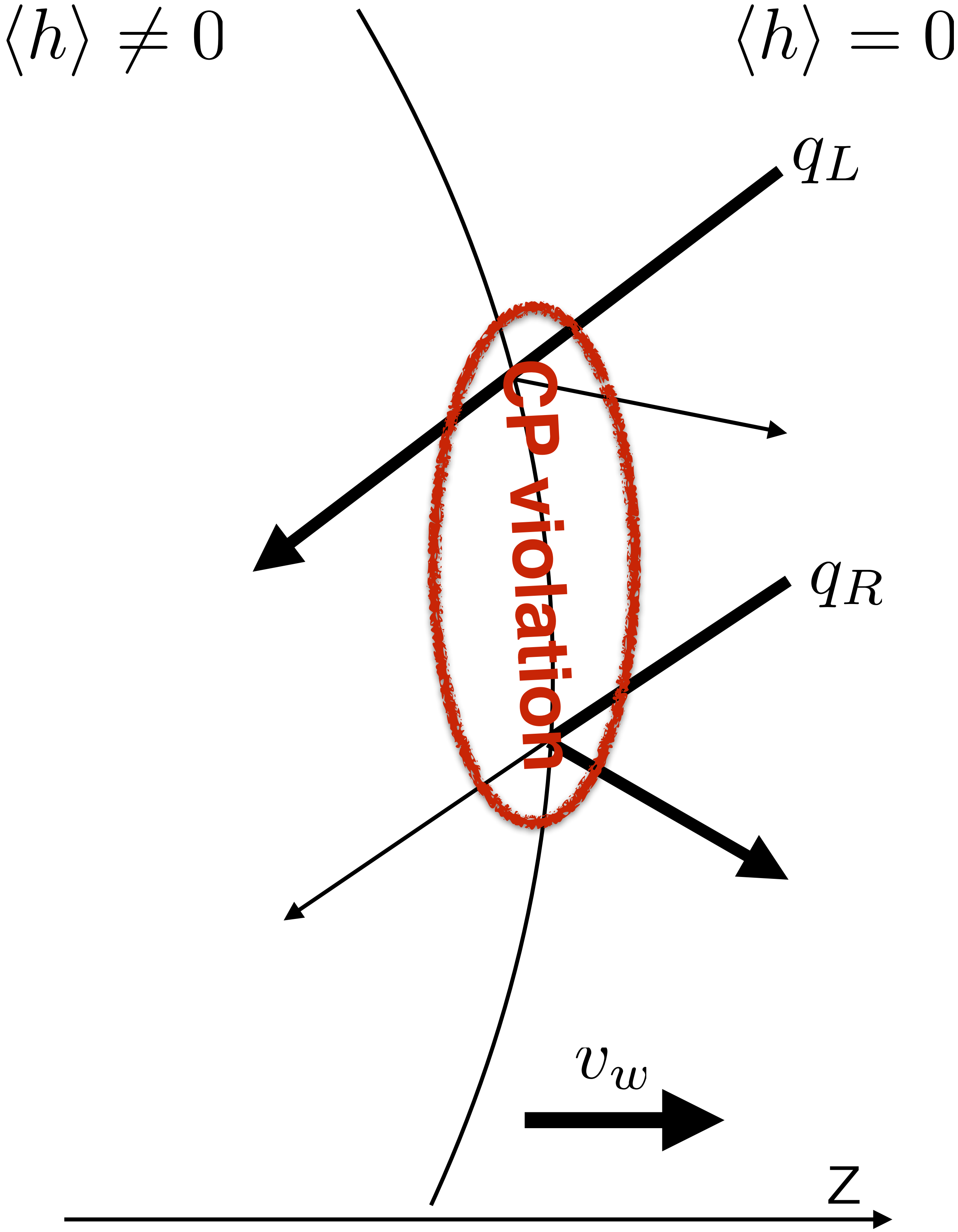
CP violation from varying Yukawas



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

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

CP violation from varying Yukawas

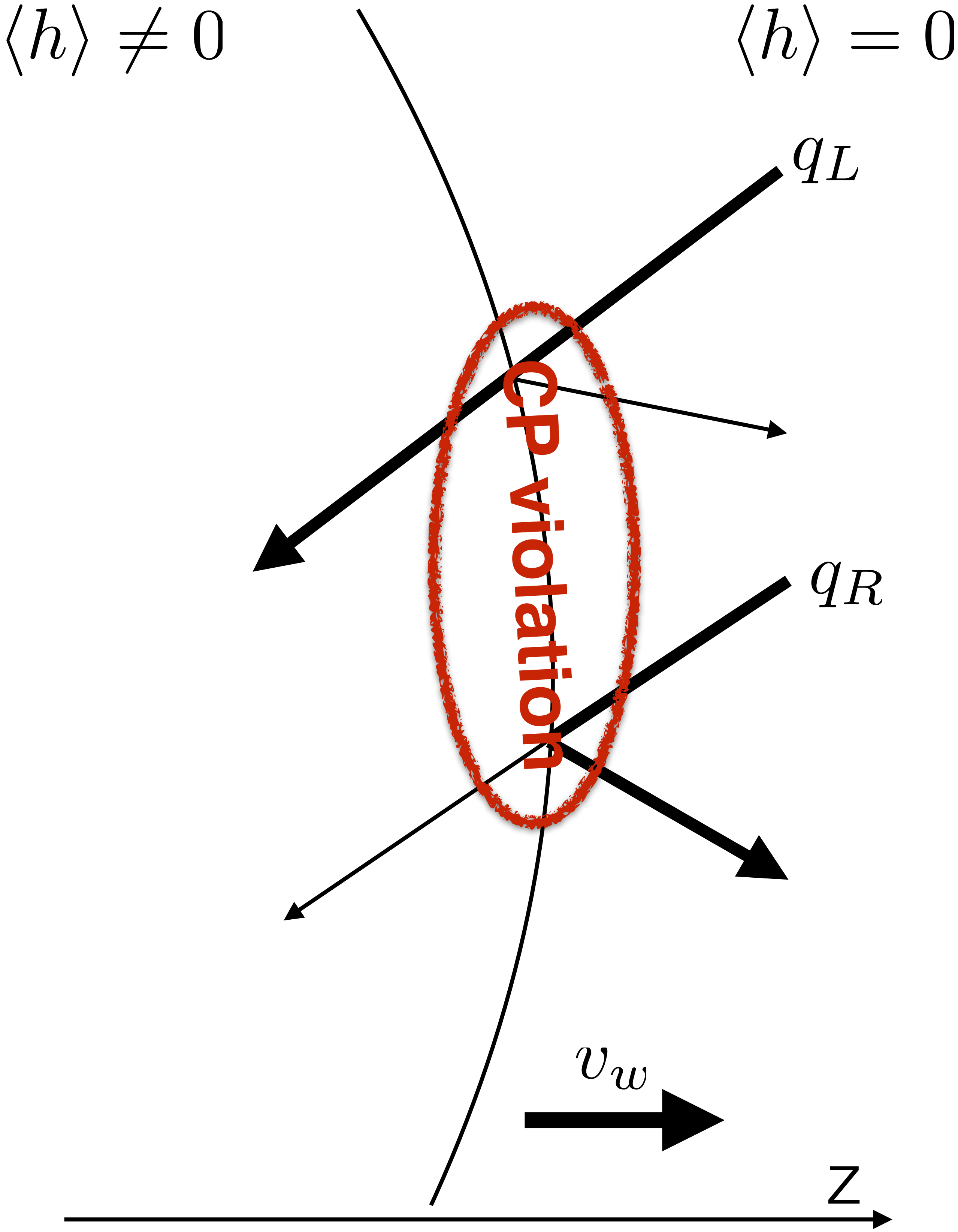


$$S_i^{CPV} \sim \mathrm{Im}\left[V^\dagger \left(m^\dagger\right)'' mV\right]_{ii}$$

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

- Zero for constant Yukawas

CP violation from varying Yukawas

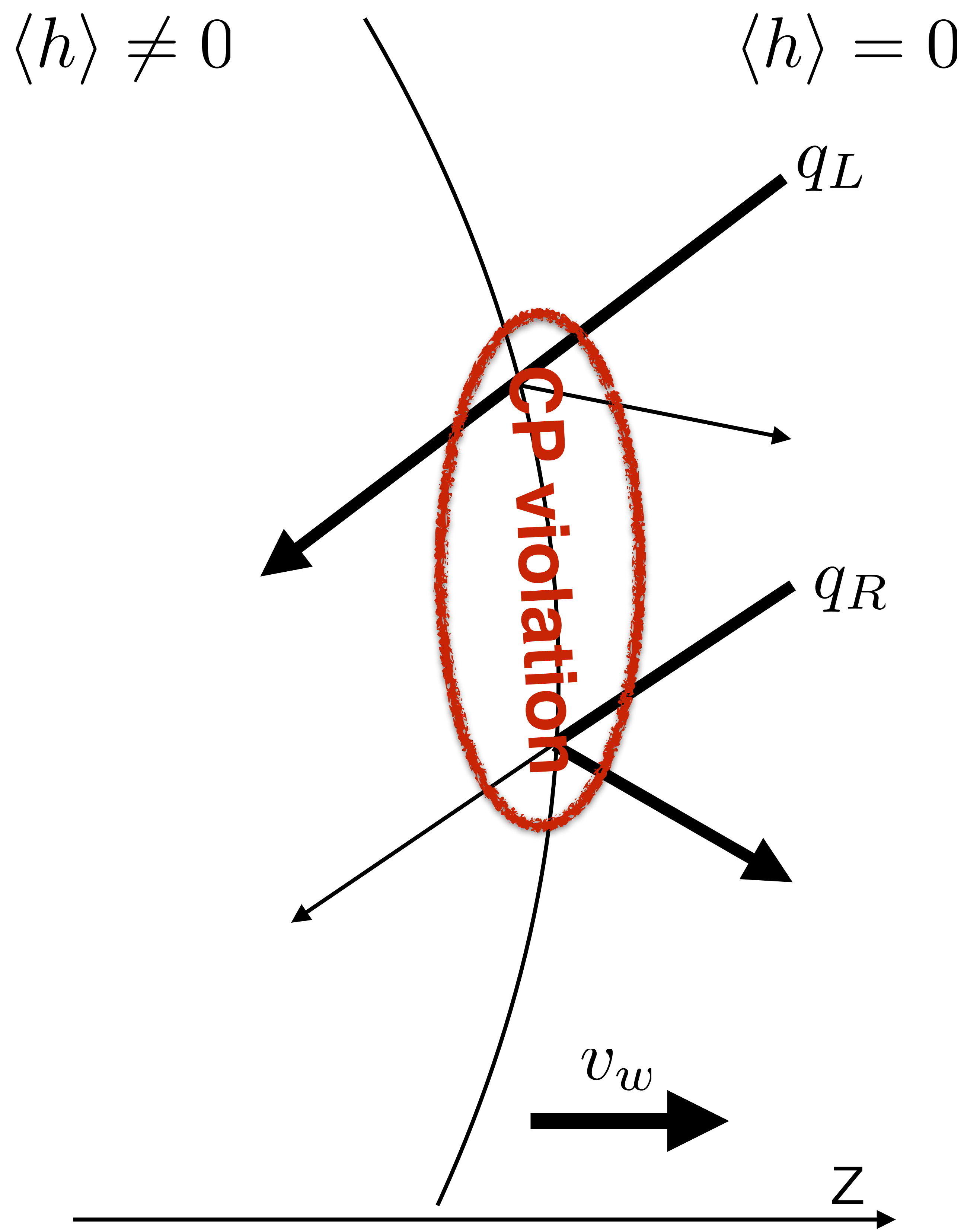


$$S_i^{CPV} \sim \text{Im}\left[V^\dagger \left(m^\dagger\right)'' m V\right]_{ii}$$

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

- Zero for constant Yukawas
- Only active during the variation of Yukawas

CP violation from varying Yukawas



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

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

- Zero for constant Yukawas
- Only active during the variation of Yukawas
- Connection to flavour model

Composite Higgs

Composite Higgs

- Higgs as pseudo-Nambu-Goldstone boson (pNGB) from symmetry breaking G/H.

Composite Higgs

- Higgs as pseudo-Nambu-Goldstone boson (pNGB) from symmetry breaking G/H.

- Fermion masses through partial compositeness

Composite Higgs

- Higgs as pseudo-Nambu-Goldstone boson (pNGB) from symmetry breaking G/H.
- Fermion masses through partial compositeness
- Composite sector needs to be almost conformal

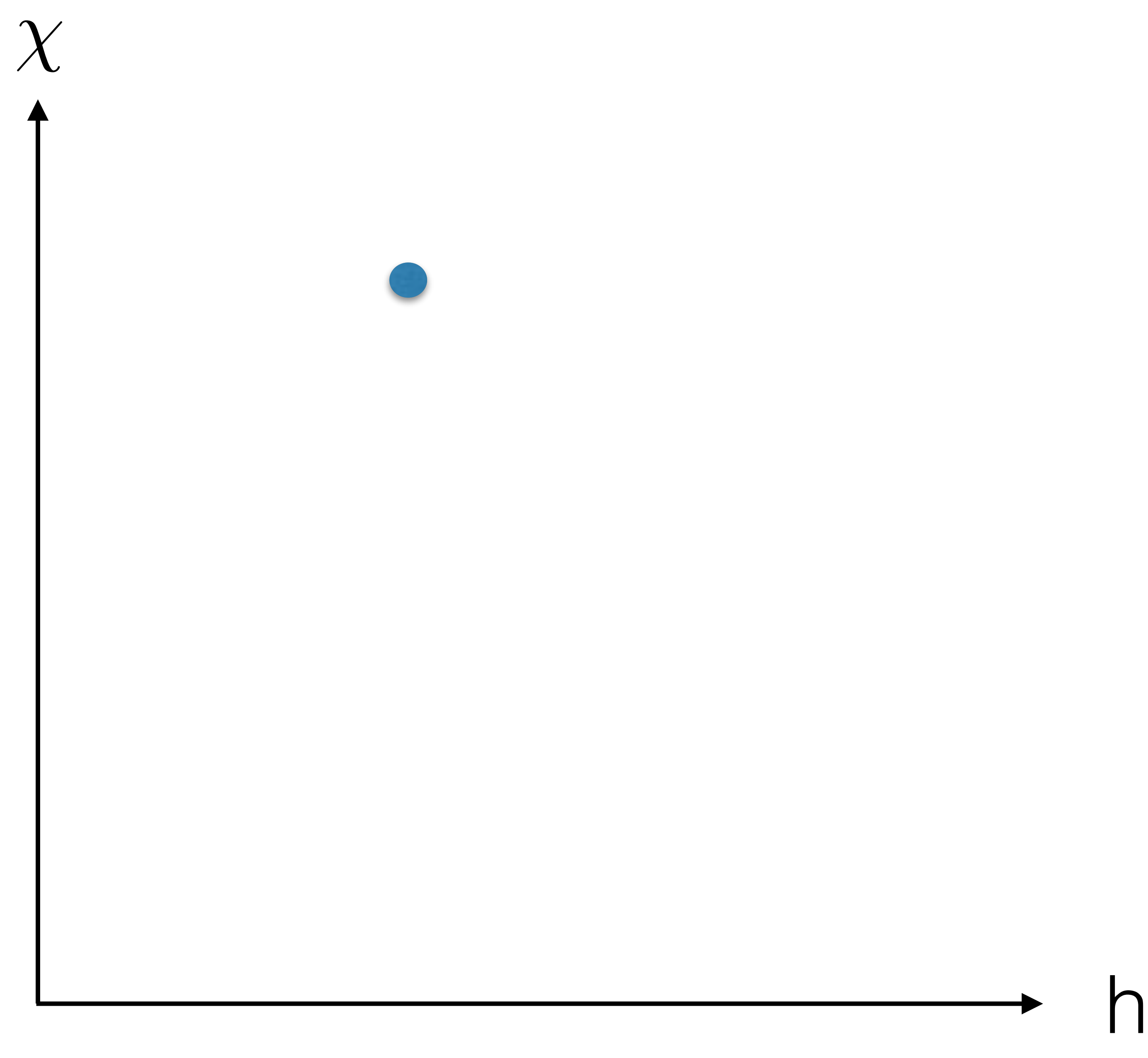
Composite Higgs

- Higgs as pseudo-Nambu-Goldstone boson (pNGB) from symmetry breaking G/H.
- Fermion masses through partial compositeness
- Composite sector needs to be almost conformal
- Confinement phase transition naturally first-order

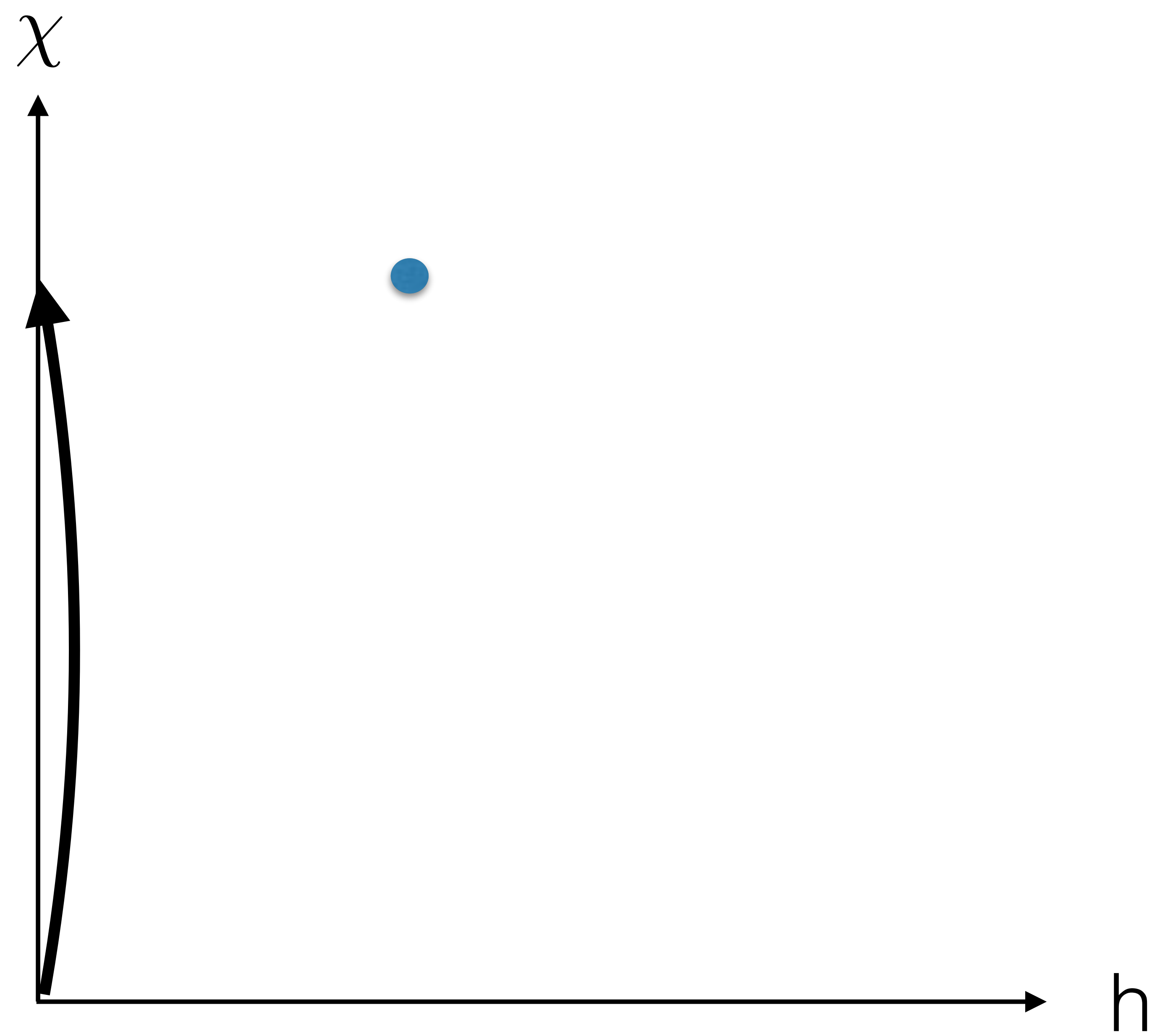
Composite Higgs

- Higgs as pseudo-Nambu-Goldstone boson (pNGB) from symmetry breaking G/H.
- Fermion masses through partial compositeness
- Composite sector needs to be almost conformal
- Confinement phase transition naturally first-order
- Joint confinement-electroweak phase transition

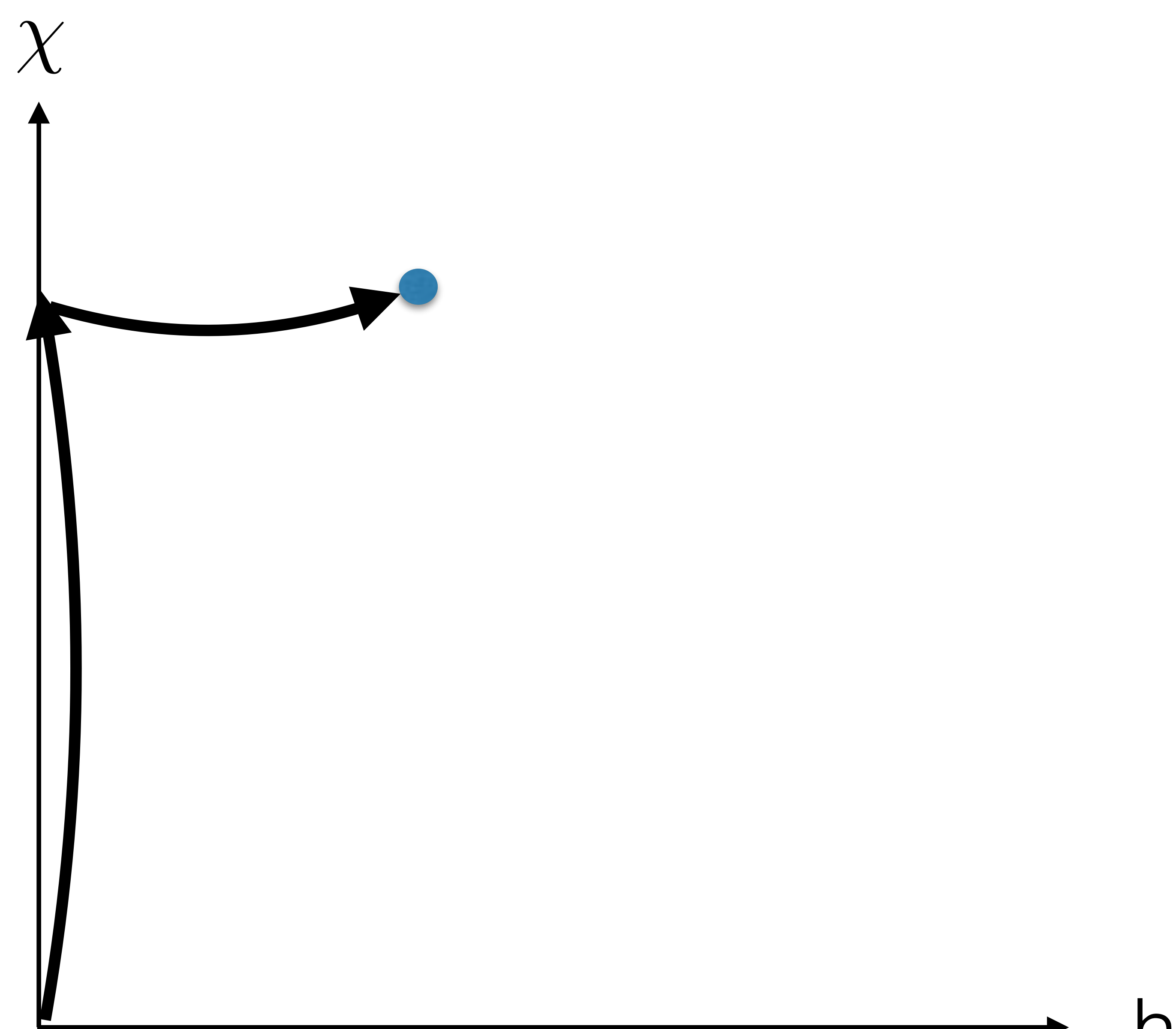
Studying the phase transition in the Dilaton-Higgs potential



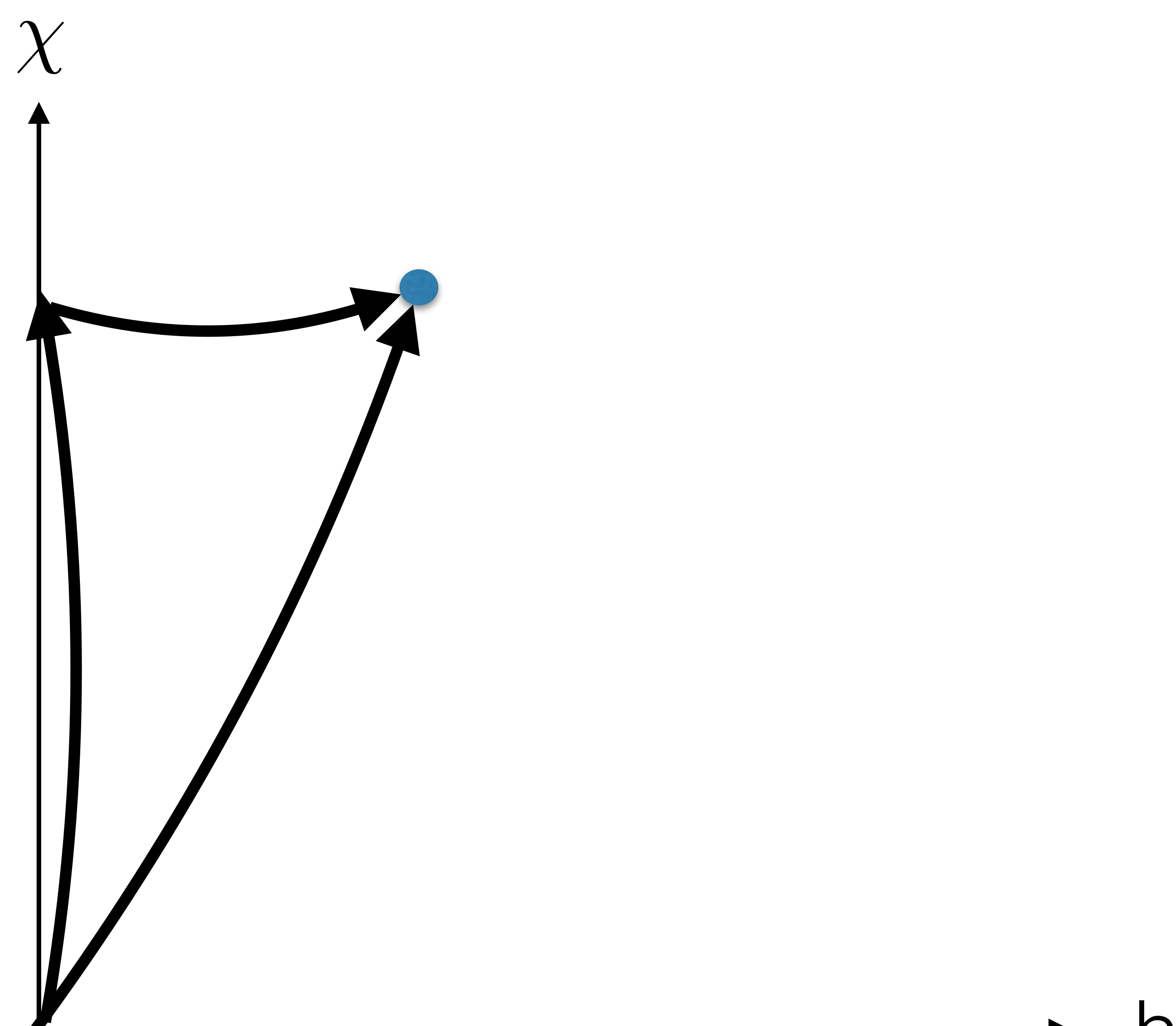
Studying the phase transition in the Dilaton-Higgs potential



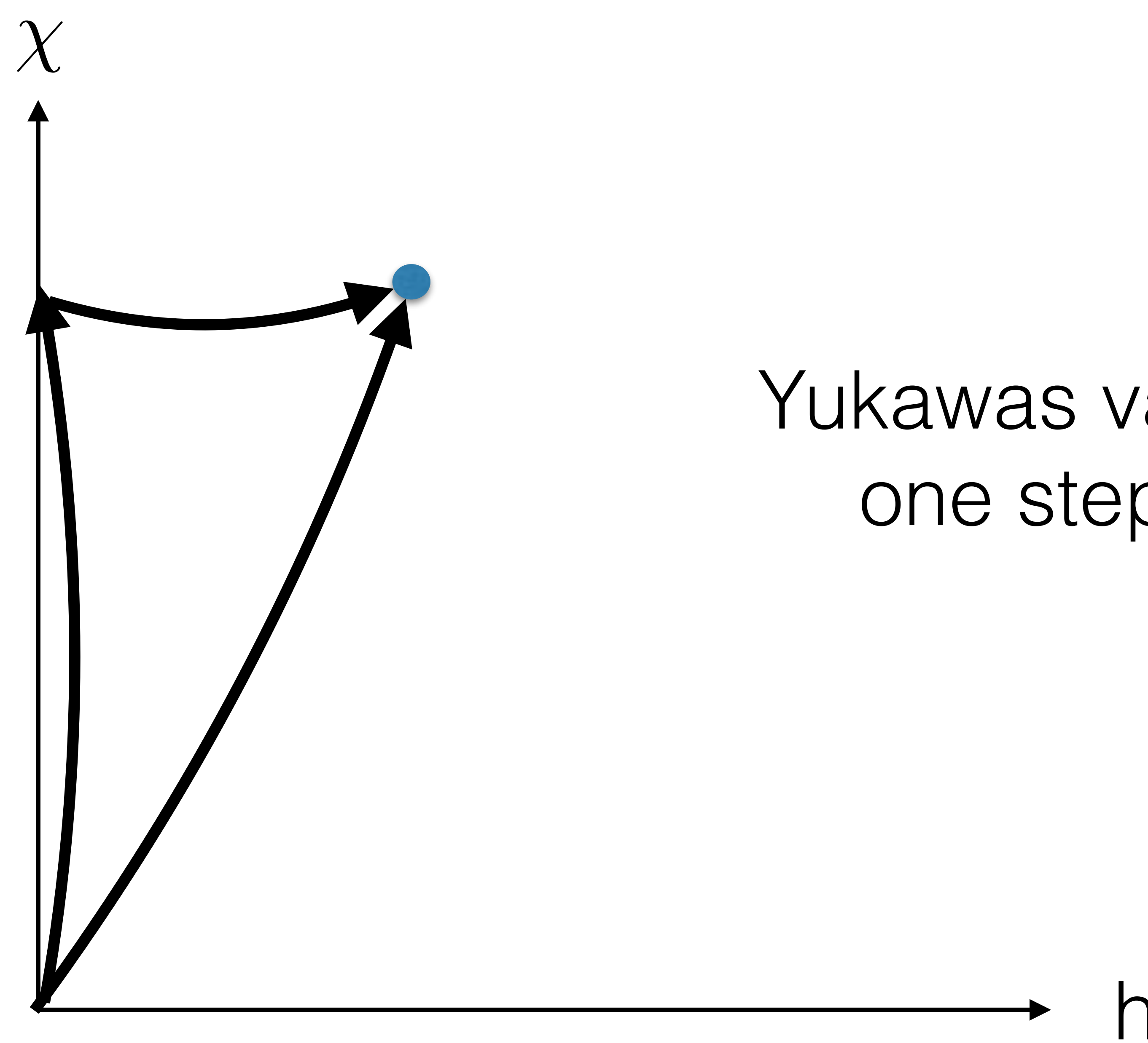
Studying the phase transition in the Dilaton-Higgs potential



Studying the phase transition in the Dilaton-Higgs potential

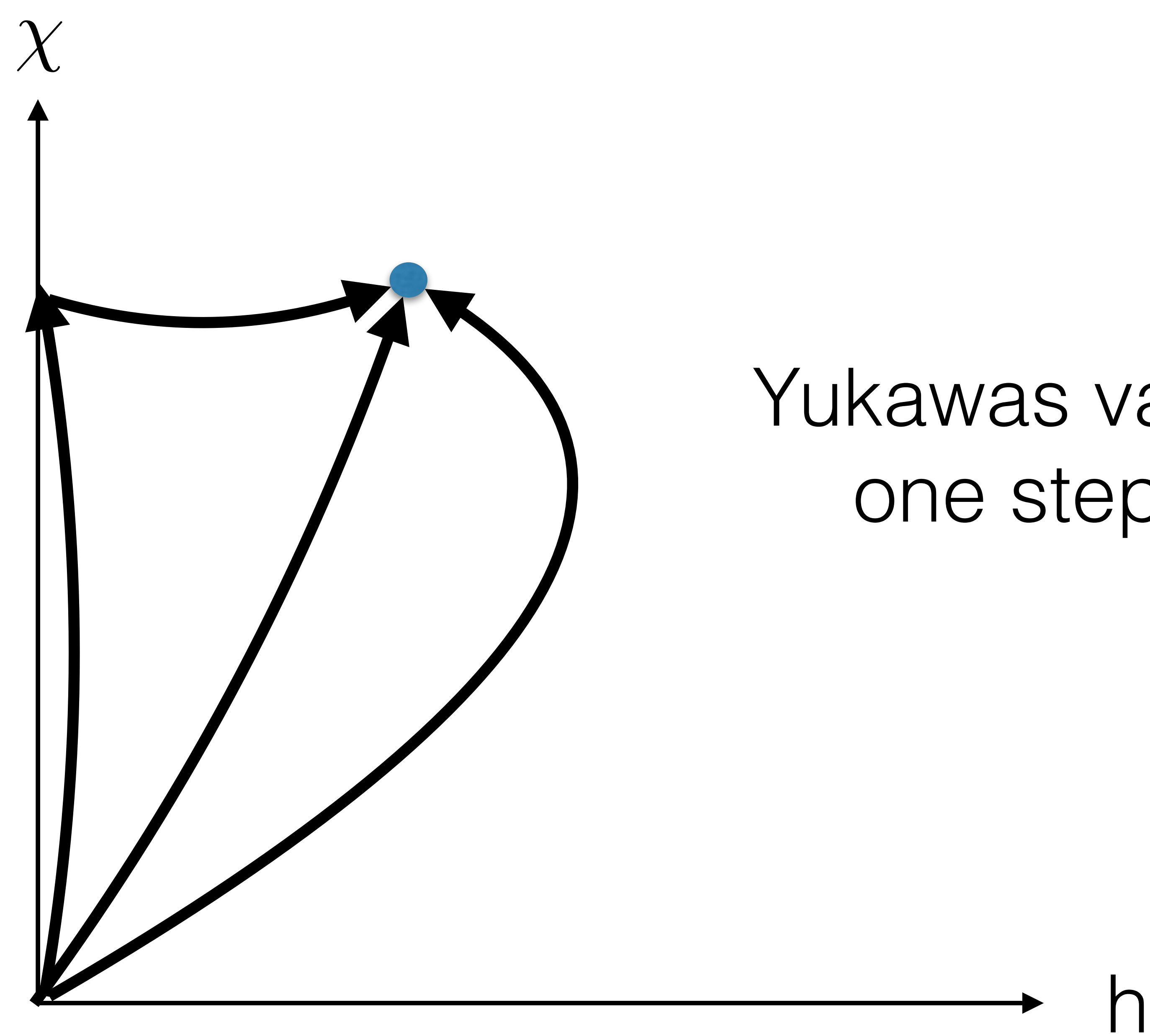


Studying the phase transition in the Dilaton-Higgs potential



Yukawas vary during one step EWPT

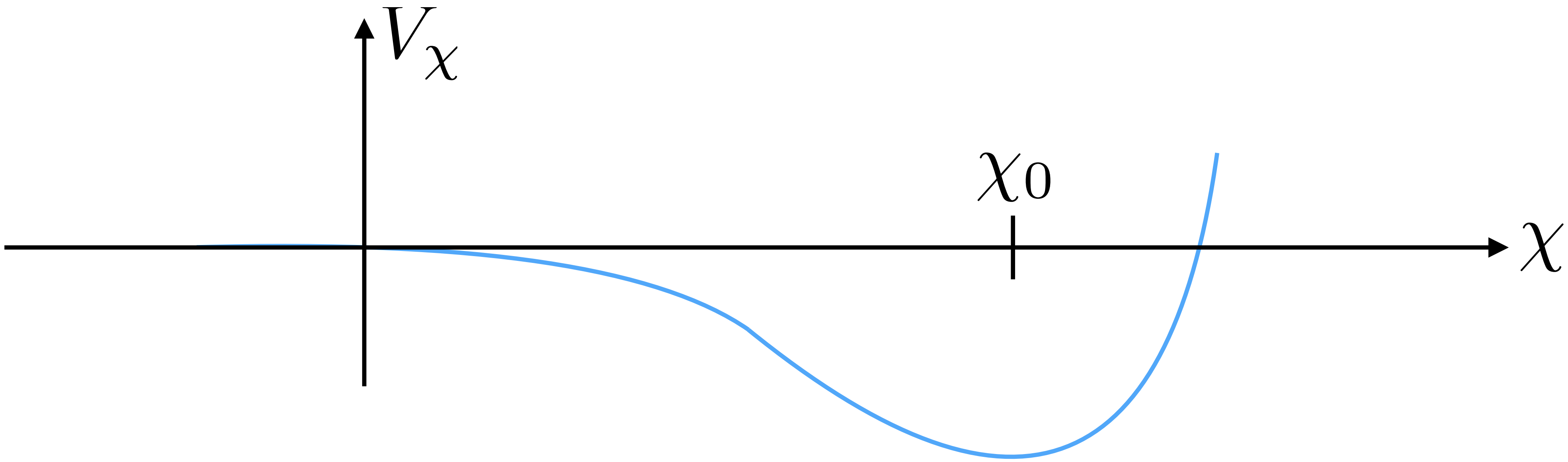
Studying the phase transition in the Dilaton-Higgs potential



Yukawas vary during one step EWPT

Conformal symmetry breaking

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

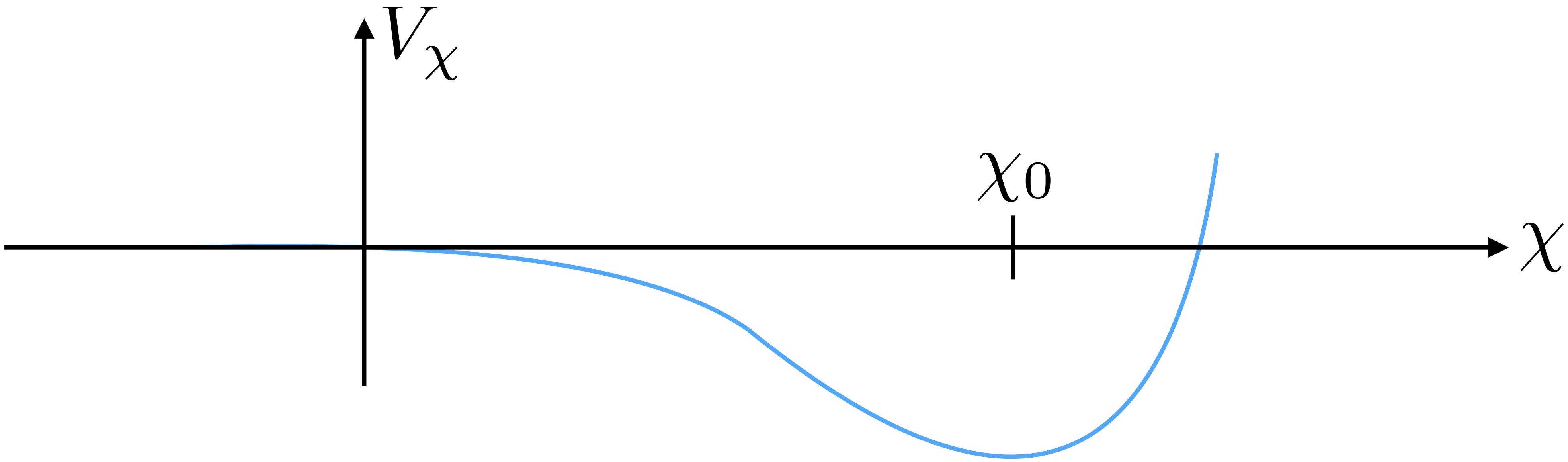


Need small explicit breaking of conformal symmetry

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

Conformal symmetry breaking

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

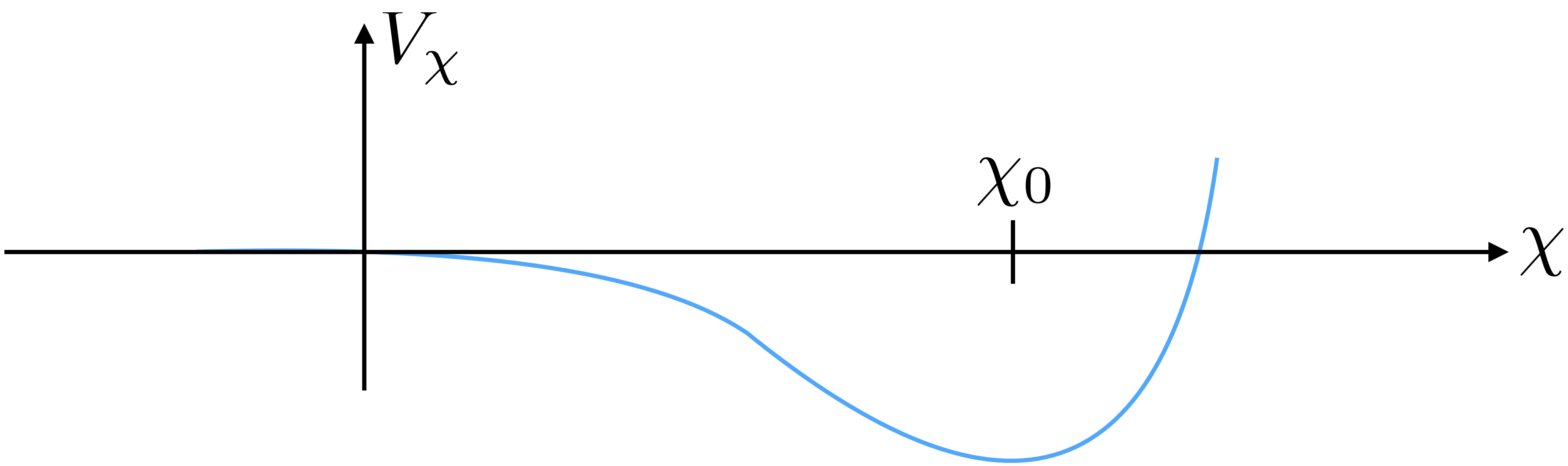


Need small explicit breaking of conformal symmetry

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

Conformal symmetry breaking

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

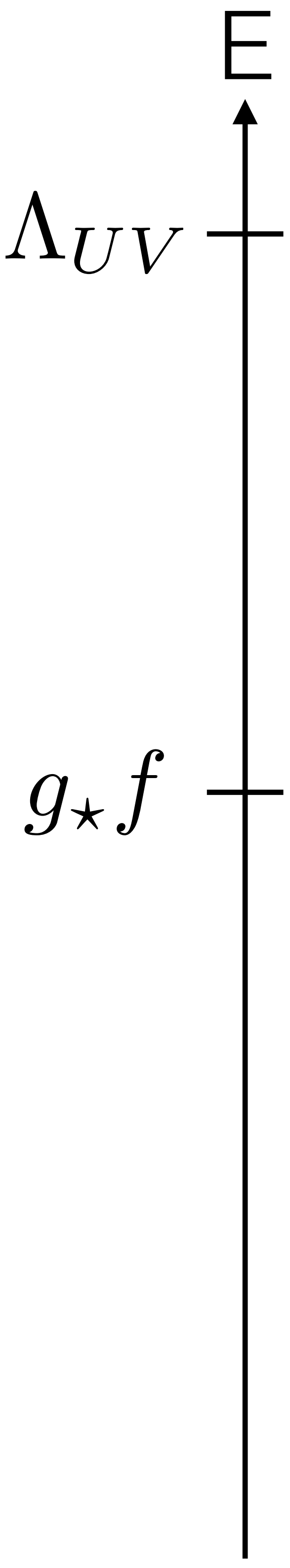


Need small explicit breaking of conformal symmetry

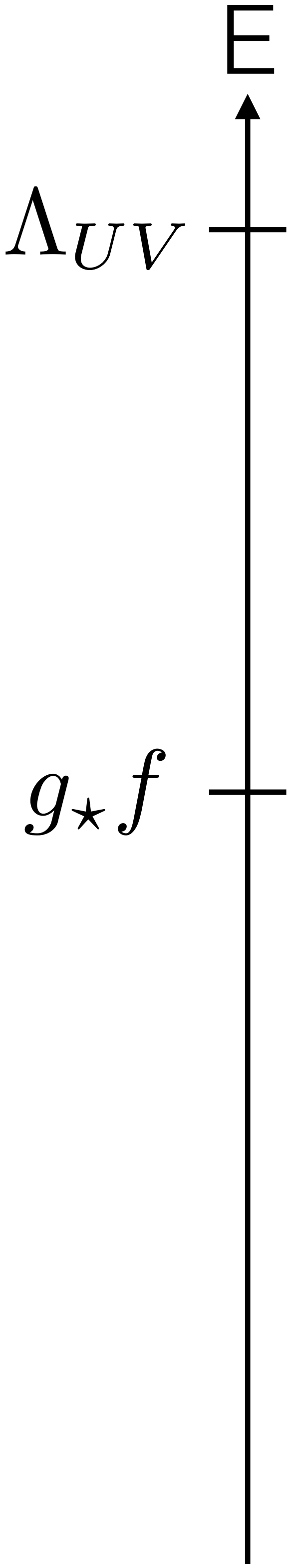
$$V_\chi = c_\chi g_\chi^2 \chi^4 - \epsilon[\chi]\chi^4 + \ldots$$

All scales in the strong sector (including *f*) are determined by χ

Quark masses in Composite Higgs through partial compositeness



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

E

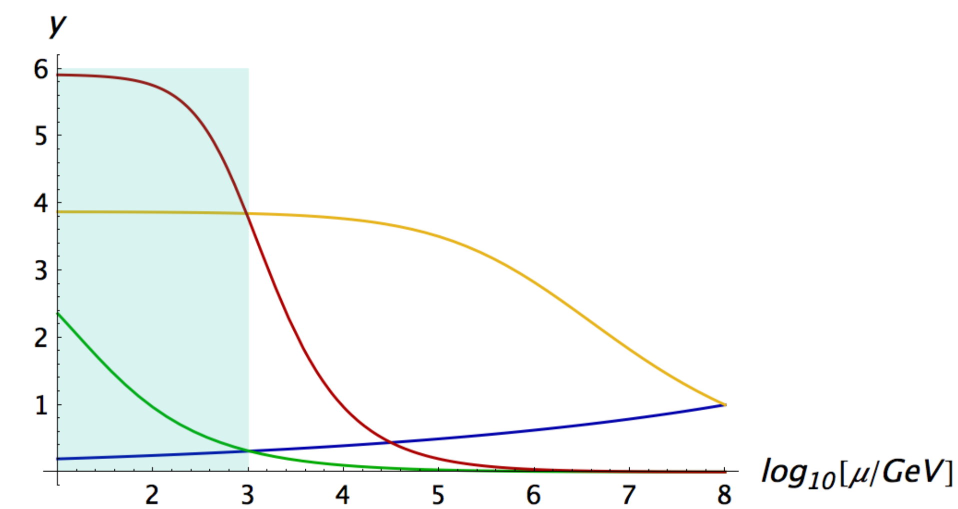
Λ_{UV}

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

Fermionic operators of the strong sector, e.g:

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

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



$g_\star f$

Quark masses in Composite Higgs through partial compositeness

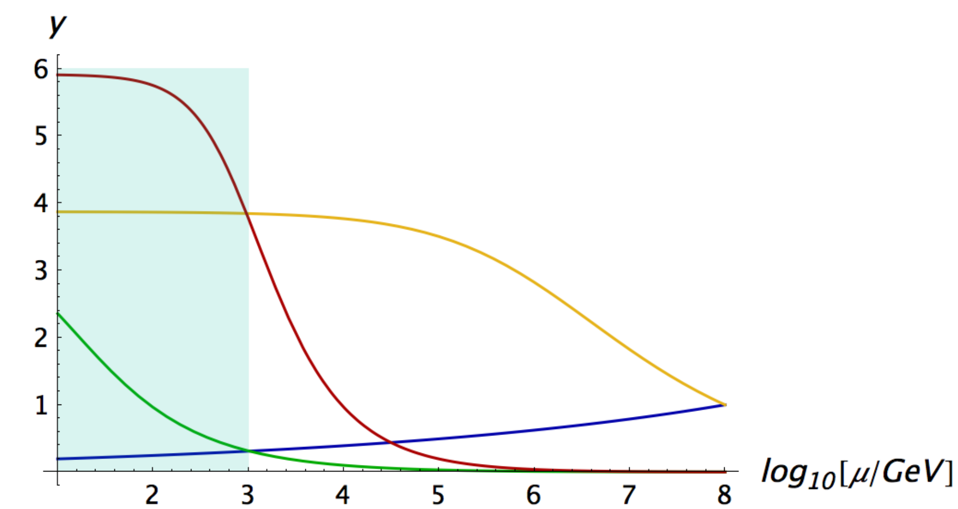
E

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

Fermionic operators of the strong sector, e.g:

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

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



$g_\star f$ — $\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$

Goldstone matrix containing the Higgs

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

Quark masses in Composite Higgs through partial compositeness

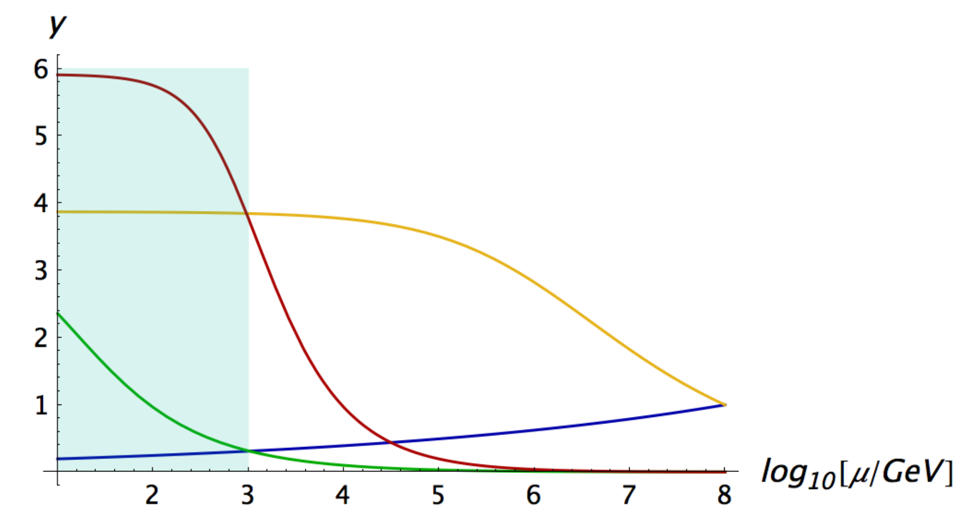
E

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

Fermionic operators of the strong sector, e.g:

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

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



$g_\star f$ — $\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$

Goldstone matrix containing the Higgs

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

Integrating out ψ_i with $m_\psi \sim g_\star f$

Quark masses in Composite Higgs through partial compositeness

E

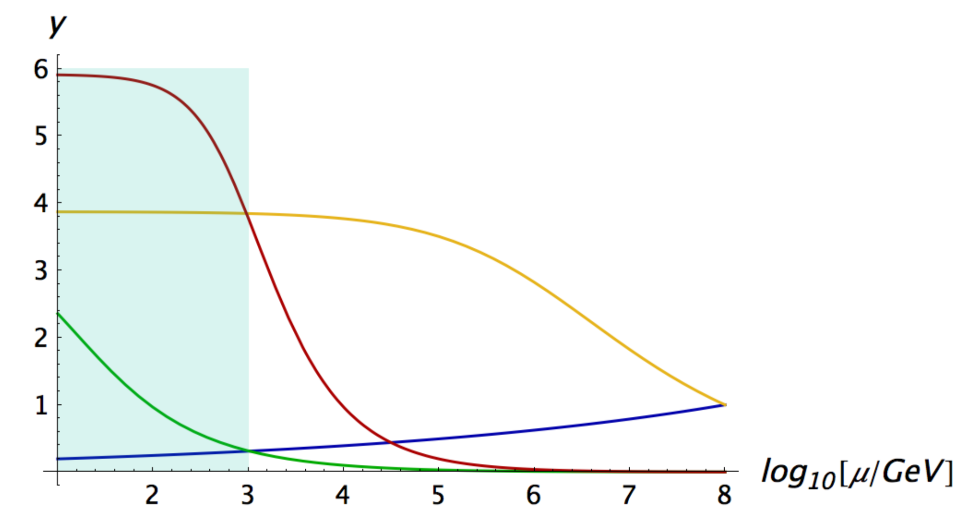
Λ_{UV}

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

Fermionic operators of the strong sector, e.g:

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

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



$g_\star f$

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

Goldstone matrix containing the Higgs

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

Integrating out ψ_i with $m_\psi \sim g_\star f$

SM Yukawas determined by the mixings at the confinement scale

$$\lambda_q \sim \frac{y_L y_R}{g_\star}$$

Quark masses in Composite Higgs through partial compositeness

E

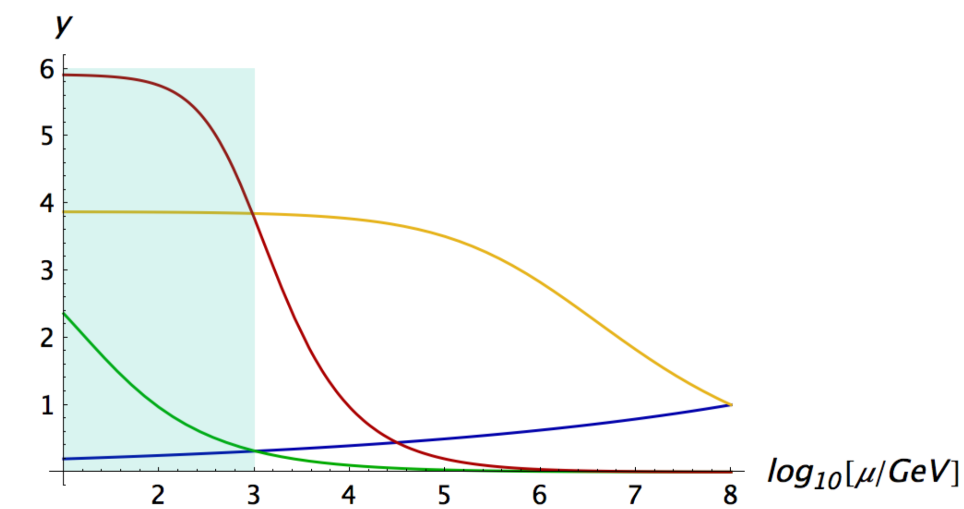
Λ_{UV}

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

Fermionic operators of the strong sector, e.g:

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

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



$g_\star f$

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

Goldstone matrix containing the Higgs

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

Integrating out ψ_i with $m_\psi \sim g_\star f$

SM Yukawas determined by the mixings at the confinement scale

$$\lambda_q \sim \frac{y_L y_R}{g_\star}$$

Yukawas naturally vary as χ varies

The Higgs potential

The Higgs potential

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

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

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

The Higgs potential

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

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

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

Higgs potential generated at one loop with SM-fermions

The Higgs potential

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

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

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

Higgs potential generated at one loop with SM-fermions

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

The Higgs potential

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

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

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

Higgs potential generated at one loop with SM-fermions

Dimensional
Analysis

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

The Higgs potential

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

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

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

Higgs potential generated at one loop with SM-fermions

Loop factor

Dimensional
Analysis

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

The Higgs potential

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

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

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

Higgs potential generated at one loop with SM-fermions

Dimensional Analysis

Loop factor

Expansion in small explicit breaking

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

The Higgs potential

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

$$\mathcal{L} \supset y_i f \bar{q}_i U \psi_i$$

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

Higgs potential generated at one loop with SM-fermions

Dimensional Analysis

Loop factor

Expansion in small explicit breaking

Trigonometric functions (Goldstone nature of Higgs)

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

Tuning of the Higgs potential

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

Chose characteristic $\mathcal{I}_i \to \sin^2, \ \sin^4$

$$V_h^0 = \alpha^0 \sin^2\left(\frac{h}{f}\right) + \beta^0 \sin^4\left(\frac{h}{f}\right)$$

Reproduce Higgs mass and vev $\Rightarrow \alpha^0 = -2\beta^0 \sin^2(v/f), \quad \beta^0 = \frac{1}{8} m_h^2 f^2/\sin^2(v/f)$

$$|\alpha^0/\beta^0| = 2\sin^2(v/f) \ll 1$$

Full potential

$V =$

Full potential

$$V = c_\chi g_\star^2 \chi^4 - \epsilon[\chi]\chi^4 + c_{\chi y} \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4$$

Full potential

$$\theta = \frac{h}{\chi}$$

$$V = c_\chi g_\star^2 \chi^4 - \epsilon[\chi]\chi^4 + c_{\chi y} \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4 + (\chi/f)^4 (\alpha^0 \sin^2\theta + \beta^0 \sin^4\theta) + \left(V_h^{NDA}[y] - V_h^{NDA}[y_0]\right)$$

$$V_h^{NDA}[y] = \left(c_\alpha \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4 \sin^2\theta + c_\beta \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4 \left(\frac{y}{g_\star}\right)^{p_\beta} \sin^4\theta \right)$$

Full potential

$$\theta = \frac{h}{\chi}$$

$$V = c_\chi g_\star^2 \chi^4 - \epsilon[\chi]\chi^4 + c_{\chi y} \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4$$

$$+ (\chi/f)^4 (\alpha^0 \sin^2\theta + \beta^0 \sin^4\theta) + \left(V_h^{NDA}[y] - V_h^{NDA}[y_0]\right)$$

$$V_h^{NDA}[y] = \left(c_\alpha \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4 \sin^2\theta + c_\beta \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4 \left(\frac{y}{g_\star}\right)^{p_\beta} \sin^4\theta \right)$$

Full potential

$$\theta = \frac{h}{\chi}$$

$$V = c_\chi g_\star^2 \chi^4 - \epsilon[\chi]\chi^4 + c_{\chi y} \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4$$
$$+ (\chi/f)^4 (\alpha^0 \sin^2\theta + \beta^0 \sin^4\theta) + \left(V_h^{NDA}[y] - V_h^{NDA}[y_0]\right)$$

$$V_h^{NDA}[y] = \left(c_\alpha \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4 \sin^2\theta + c_\beta \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2} \chi^4 \left(\frac{y}{g_\star}\right)^{p_\beta} \sin^4\theta \right)$$

Full potential

$$\theta = \frac{h}{\chi}$$

$$V = c_\chi g_\star^2 \chi^4 - \epsilon[\chi]\chi^4 + c_{\chi y} \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2}\chi^4$$
$$+ (\chi/f)^4(\alpha^0 \sin^2\theta + \beta^0 \sin^4\theta) + \left(V_h^{NDA}[y] - V_h^{NDA}[y_0]\right)$$

$$V_h^{NDA}[y] = \left(c_\alpha \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2}\chi^4 \sin^2\theta + c_\beta \sum_{n_f} g_\star^2 \frac{N_c y^2[\chi]}{(4\pi)^2}\chi^4 \left(\frac{y}{g_\star}\right)^{p_\beta} \sin^4\theta \right)$$

Valley along the diagonal in $h - \chi$ potential

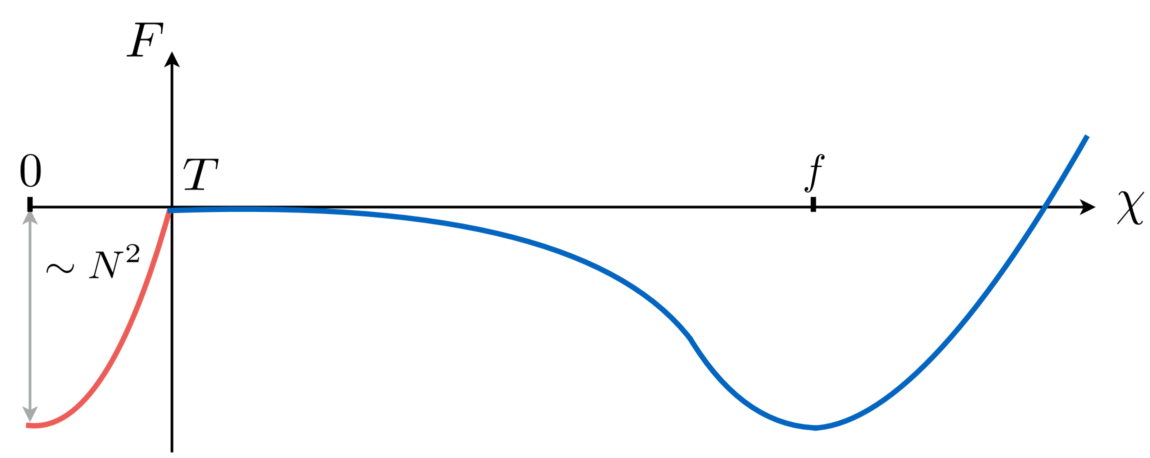
Temperature Corrections

- 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:

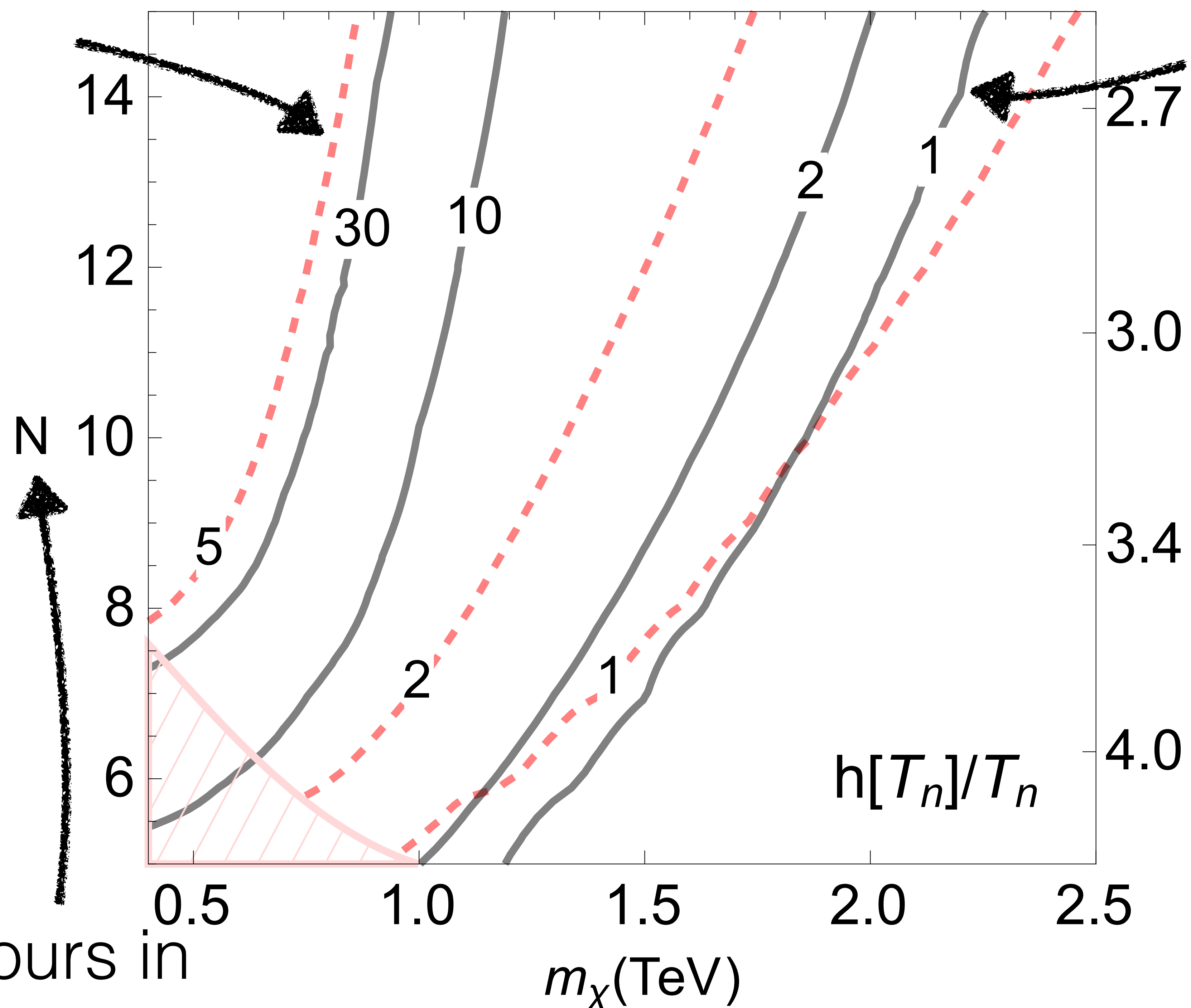
$$F_{CFT}[\chi = 0] \simeq -\frac{\pi^2 N^2}{8} T^4$$



Scan Dilaton Mass vs. N

Meson-like dilaton
$g_\chi = \frac{4\pi}{\sqrt{N}}$

Glueball-like dilaton
$g_\chi = \frac{4\pi}{N}$



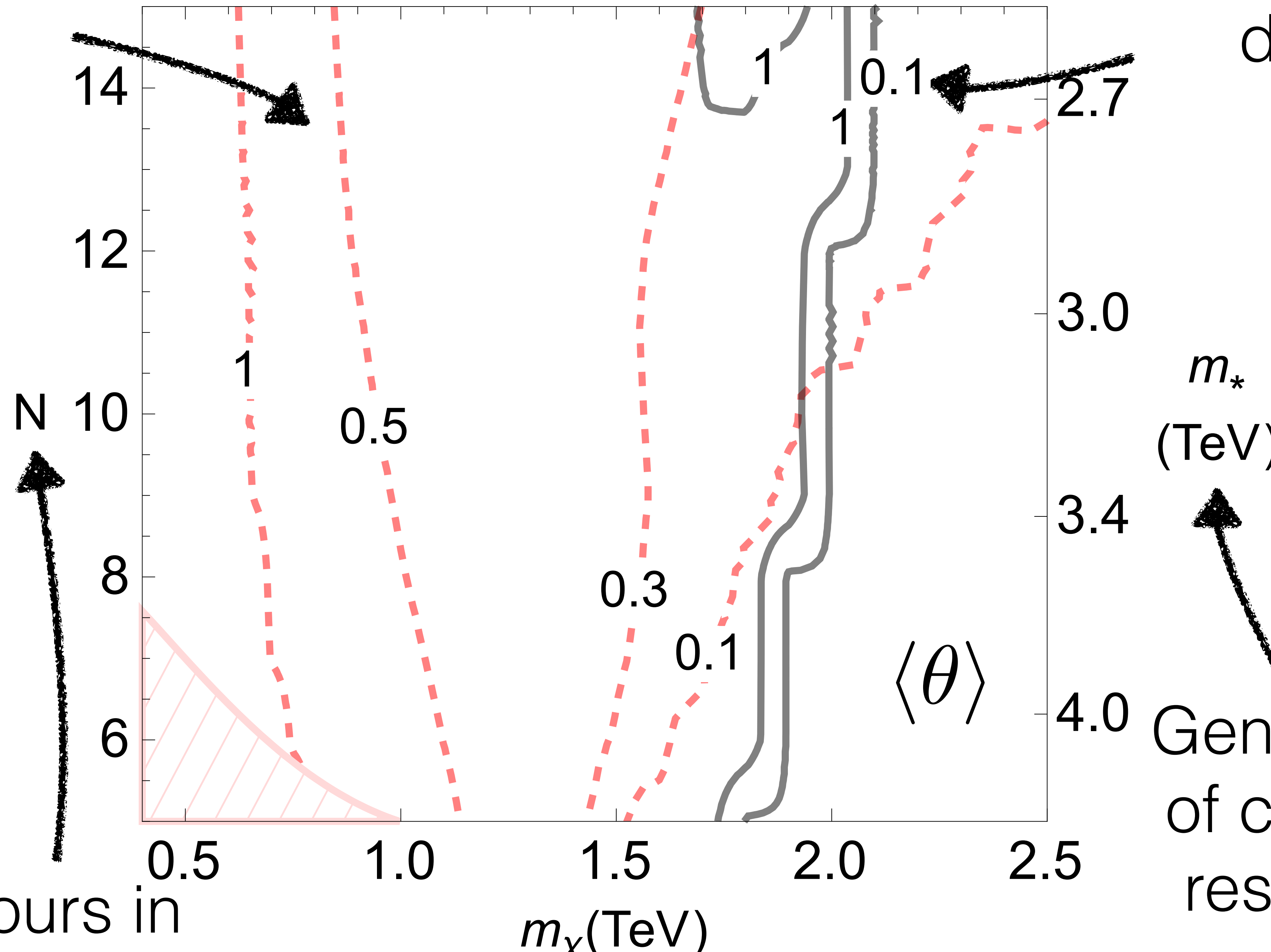
colours in CFT, used in large N expansion

Generic mass of composite resonances
$m_\star = g_\star f$

Scan Dilaton Mass vs. N

Meson-like dilaton
$g_\chi = \frac{4\pi}{\sqrt{N}}$

Glueball-like dilaton
$g_\chi = \frac{4\pi}{N}$



colours in CFT, used in large N expansion

Generic mass of composite resonances
$m_\star = g_\star f$

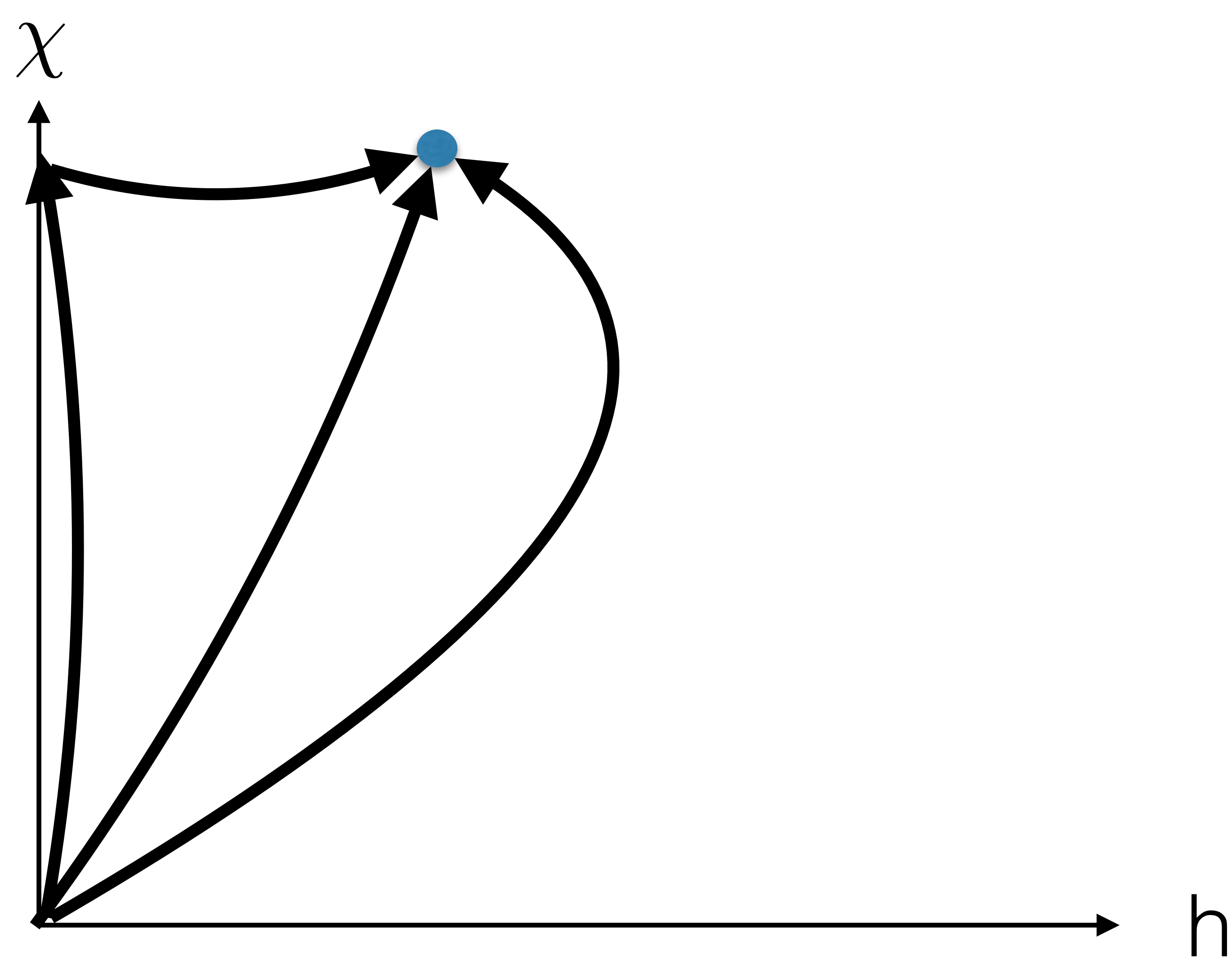
Baryon asymmetry

Baryon asymmetry

- Final baryon asymmetry depends on the direction of tunneling

Baryon asymmetry

- Final baryon asymmetry depends on the direction of tunneling



Baryon asymmetry

- Final baryon asymmetry depends on the direction of tunneling

Baryon asymmetry

- Final baryon asymmetry depends on the direction of tunneling
- Top-only case: non-vanishing CP violation requires varying complex phase in top Yukawa

Baryon asymmetry

- Final baryon asymmetry depends on the direction of tunneling
- Top-only case: non-vanishing CP violation requires varying complex phase in top Yukawa
- Multi-flavour case: CP violation depends on the flavour structure

Experimental tests and signatures

- Light dilaton
- Modified Higgs-quark coupling
- Neutron EDM through complex Higgs-top coupling
- Gravitational wave signal from strong first-order phase transition

Summary

- Composite Higgs is a prime example of varying Yukawas during the EW phase transition

- Partial compositeness explains the fermion mass hierarchy and also gives rise to a non vanishing Higgs potential

- Open parameter space for first-order phase transition and baryogenesis

- We provided strong motivation for EW baryogenesis in (even minimal) CH models

Dimensional Analysis and large N

Idea: restore dimensions of $\hbar$

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

$$\Downarrow$$

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

Dimensional Analysis and large N

Idea: restore dimensions of $\hbar$

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

$$\Downarrow$$

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

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

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

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

We need canonically normalised fields for vacuum tunneling:

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

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:

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

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:

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

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:

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

Temperature Corrections

- Use standard one loop result to interpolate between the symmetric phase and the brocken phase.

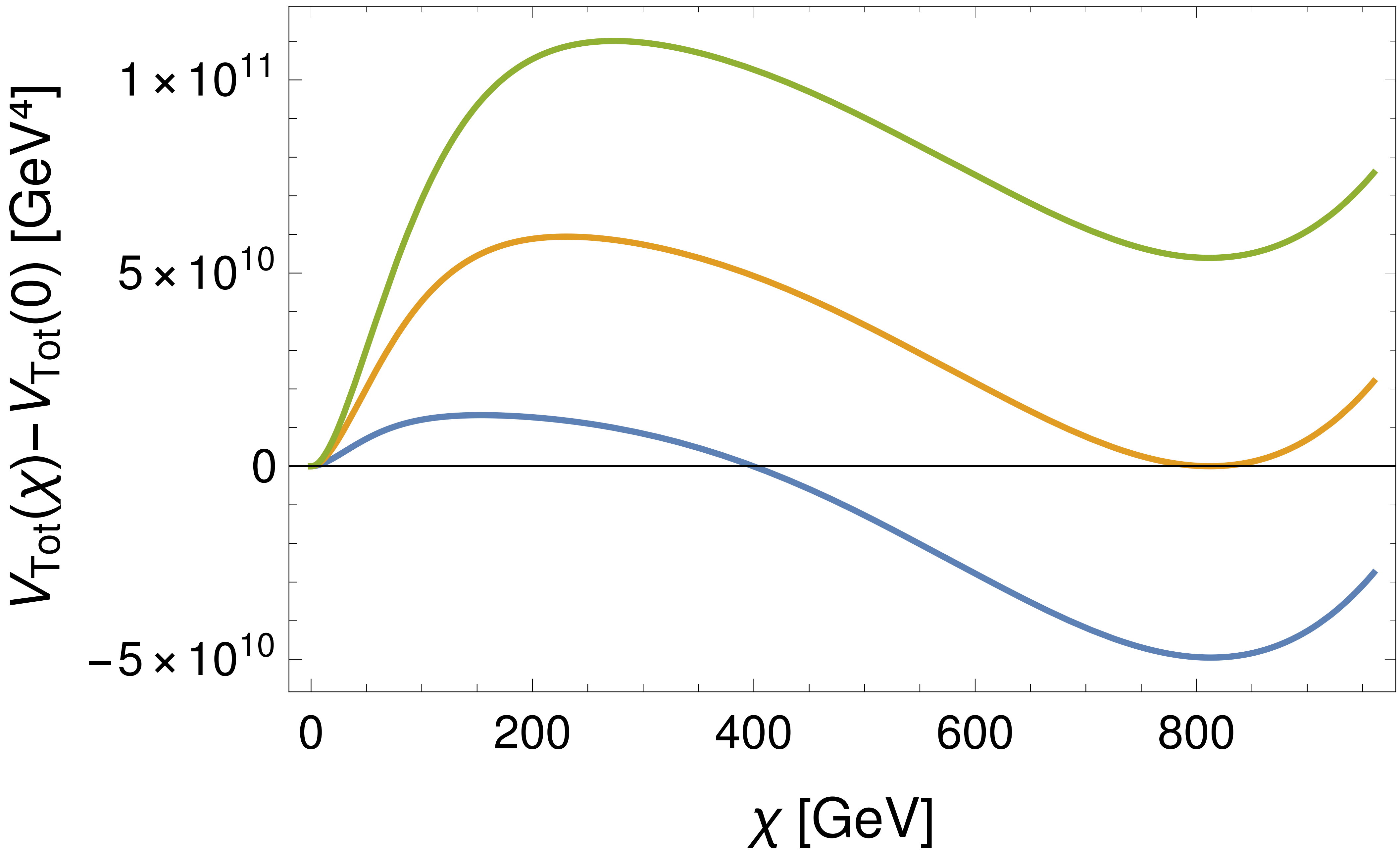
- We use standard one loop result for SM fermions

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

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

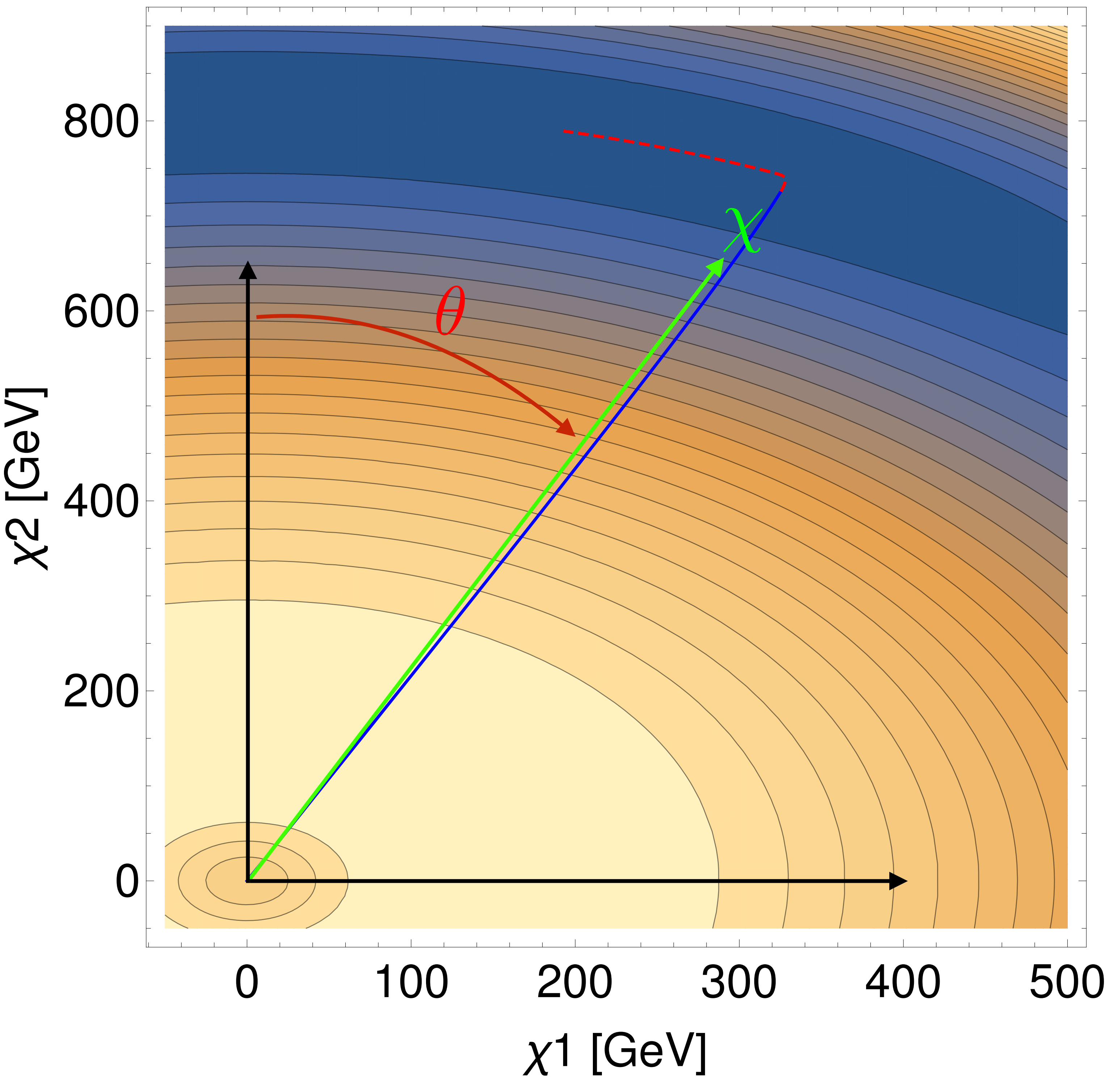
$$\sum_{\text{CFT bosons}} n + \sum_{\text{CFT fermions}} n = \frac{45N^2}{8\pi^2}$$

Temperature Evolution



Full potential

$$\theta = \frac{h}{\chi}$$



CP-Violation

Generically $y_i \bar{q}_i \mathcal{O}_i \to y_{ij} \bar{q}_i \mathcal{O}_j$

$$\Rightarrow \; m_{ij} \sim (\mathbb{I}_L)_{ik} (y_L)_{kk} (g_\star^{-1})_{kl} (y_R)^\dagger_{ll} (\mathbb{I}_R)_{lj} h$$

Define

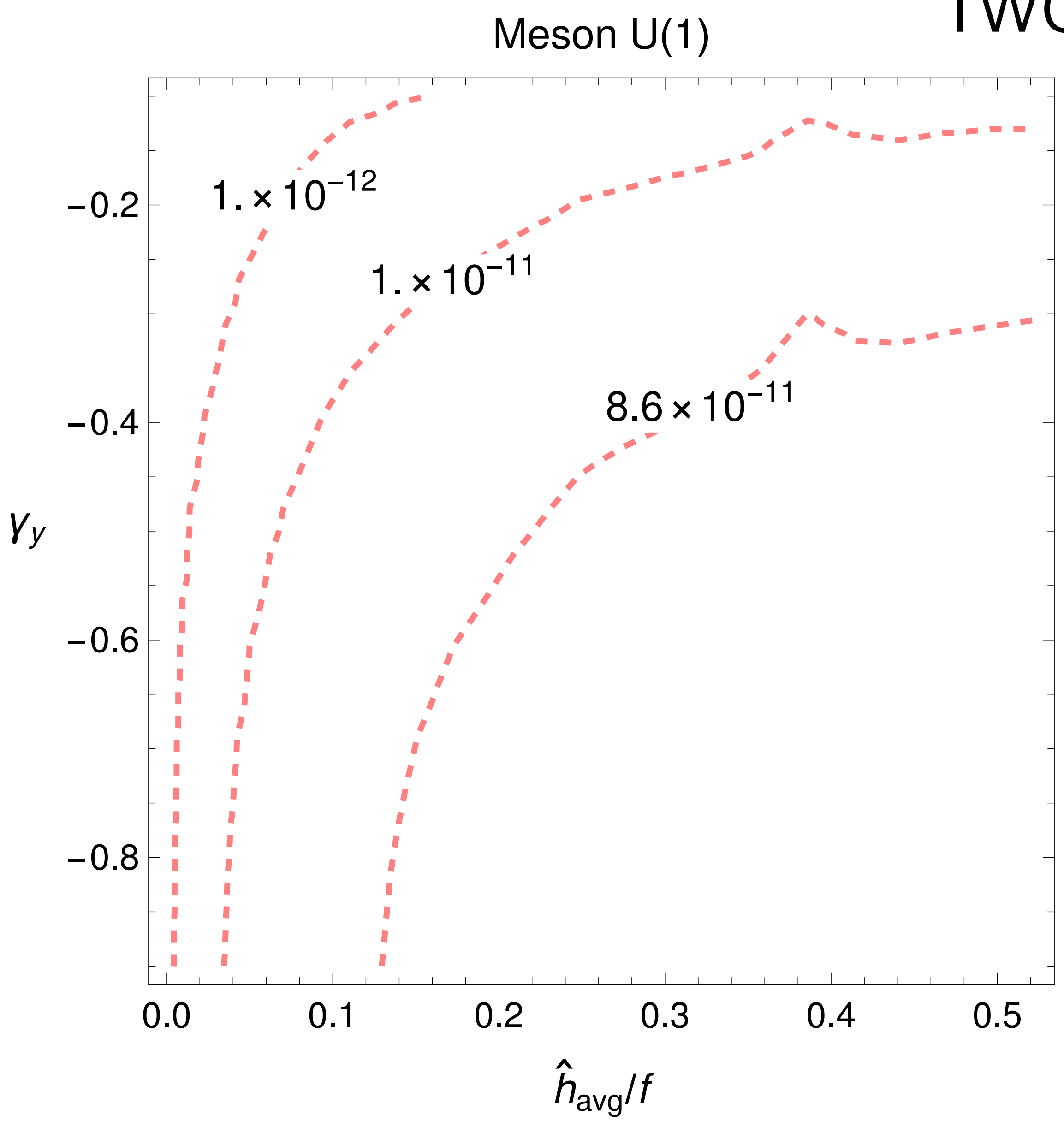
$$d_{ij} = (y_{Li} y^\star_{Rj} h)'' / (y_{Li} y^\star_{Rj} h)$$

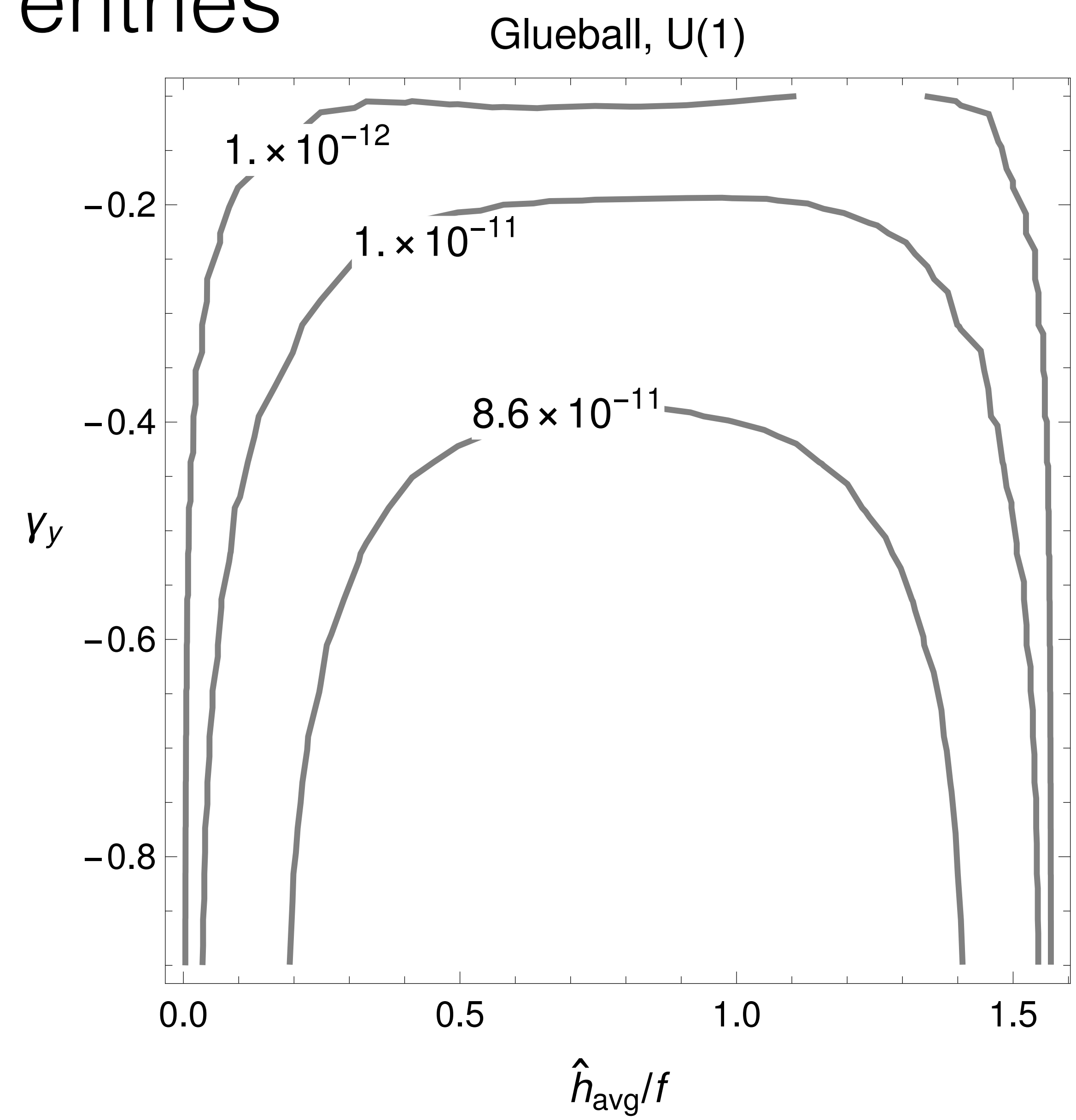
$\mathbb{I}_L$	y_L	$g_\star^{-1}$	y_R	$\mathbb{I}_R$	condition on d_{ij} for $S_{\rm CPV} = 0$
d	2	d	2	d	always
	1		1		always
d	2	$\not{d}$	2	d	$d_{11} + d_{22} = d_{12} + d_{21}$
	1		2		always
	2		1		always
	1		1		always
$\not{d}$	2	d	2	d	always
	1		1		always
$\not{d}$	2	$\not{d}$	2	d	$d_{11} = d_{12}$,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

$$m_{ij} \sim (\mathbb{I}_L)_{ik}(y_L)_{kk}(g_\star^{-1})_{kl}(y_R)^\dagger_{ll}(\mathbb{I}_R)_{lj} h$$

Diagonal — Two large entries — Anarchic — Two large entries — Diagonal





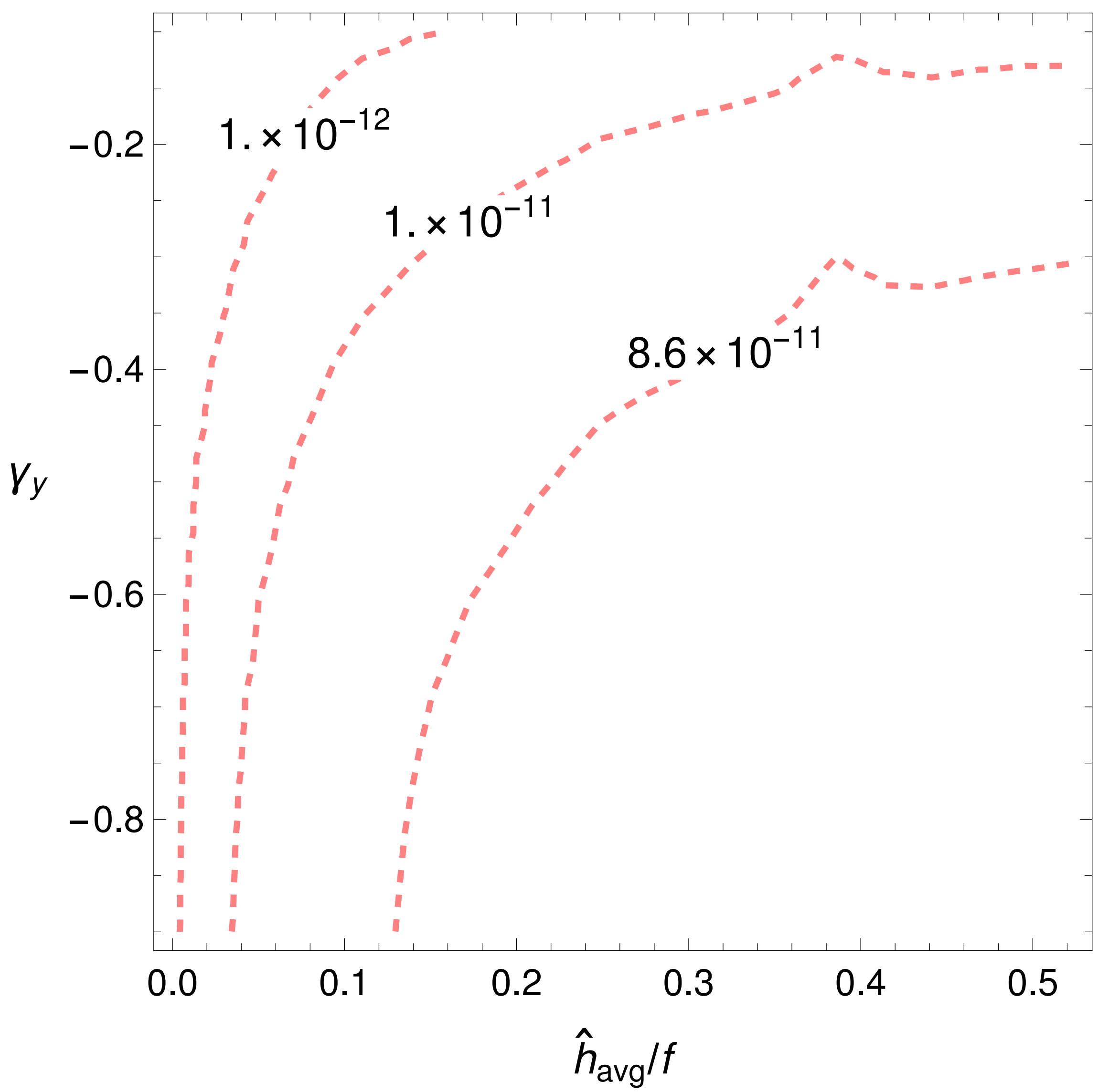
Baryon asymmetry: multi-flavour case with U(1) flavour symmetries

Csaki, Falkowski, Weiler '08

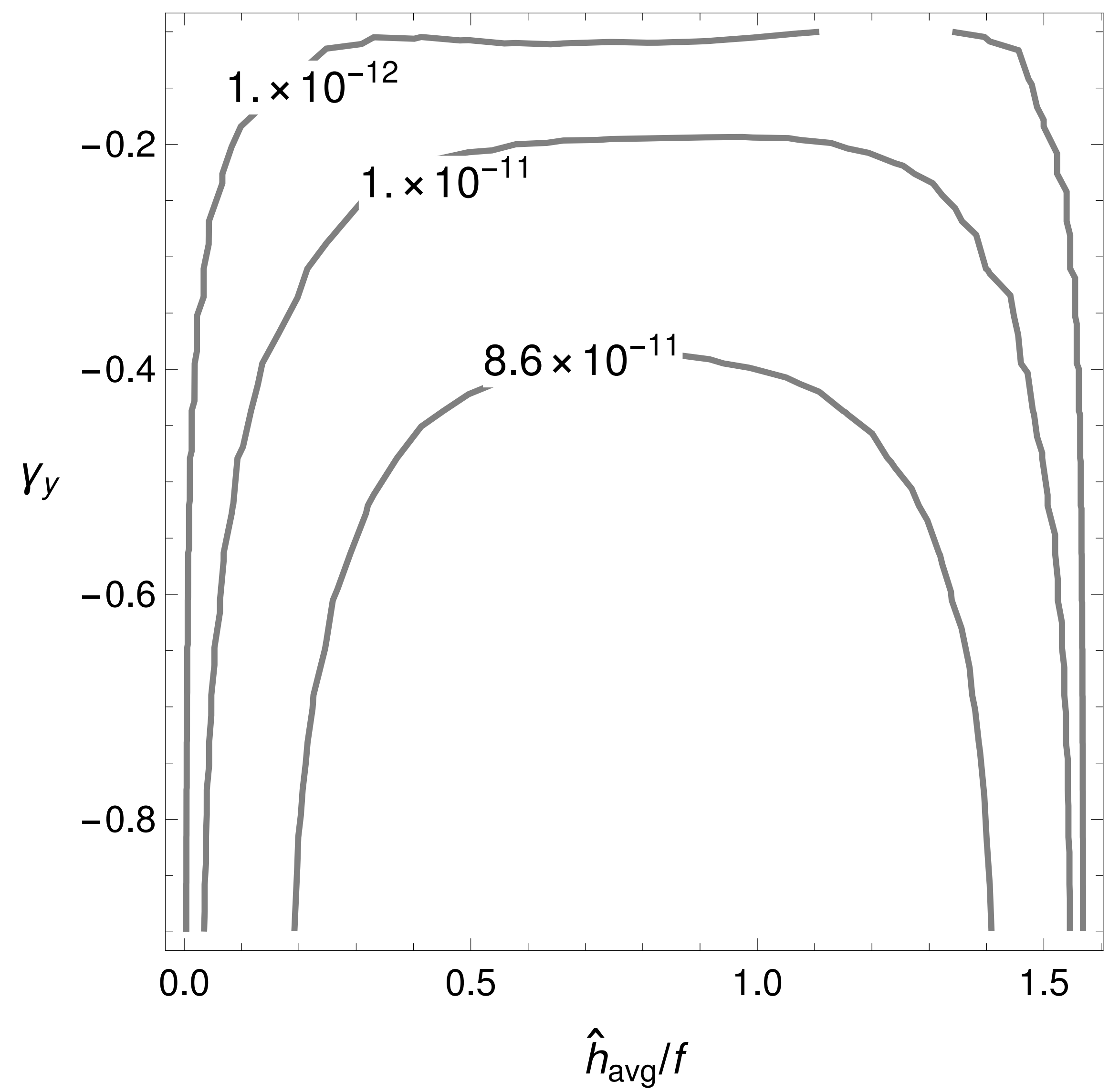
$$m_{ij} \sim (\mathbb{I}_L)_{ik}(y_L)_{kk}(g_\star^{-1})_{kl}(y_R)^\dagger_{ll}(\mathbb{I}_R)_{lj}h$$

Diagonal — Two large entries — Anarchic — Two large entries — Diagonal

Meson U(1)



Glueball, U(1)

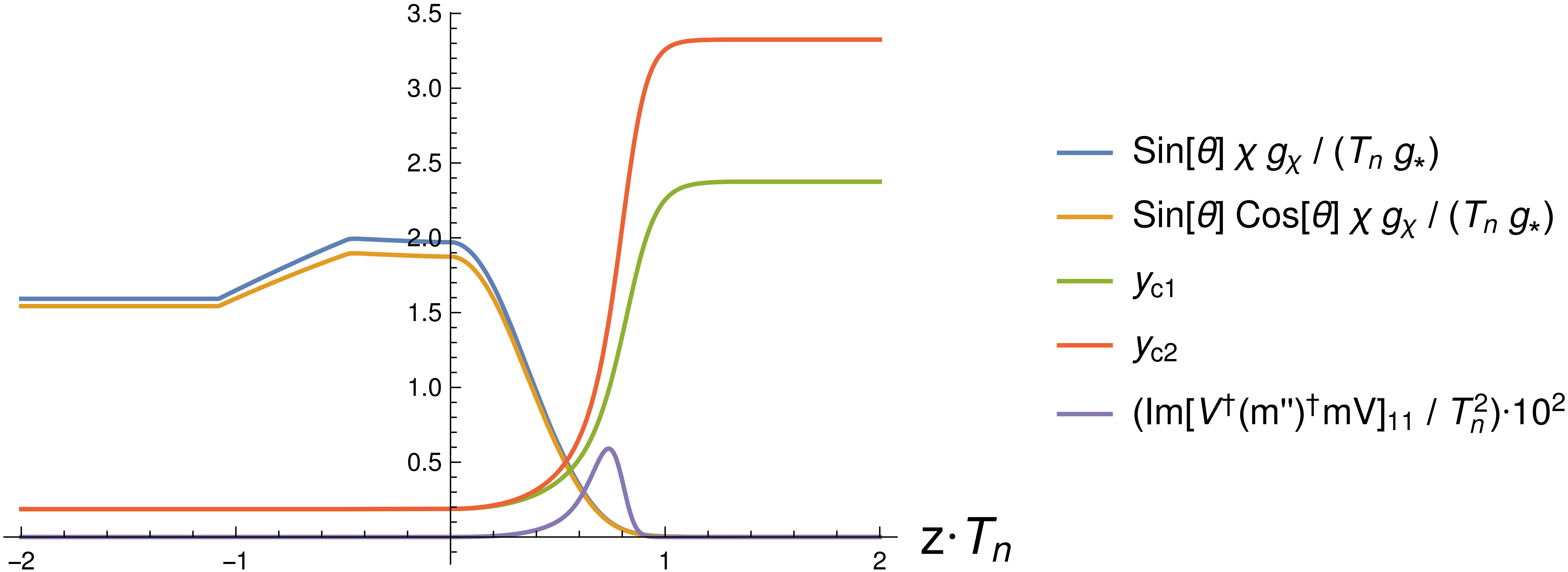


Baryon asymmetry: top-only case

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

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

Baryogenesis



Collider phenomenology

- Detect Dilaton
- Fit parameters of EFT to data
- E.g.: Dilaton quark coupling

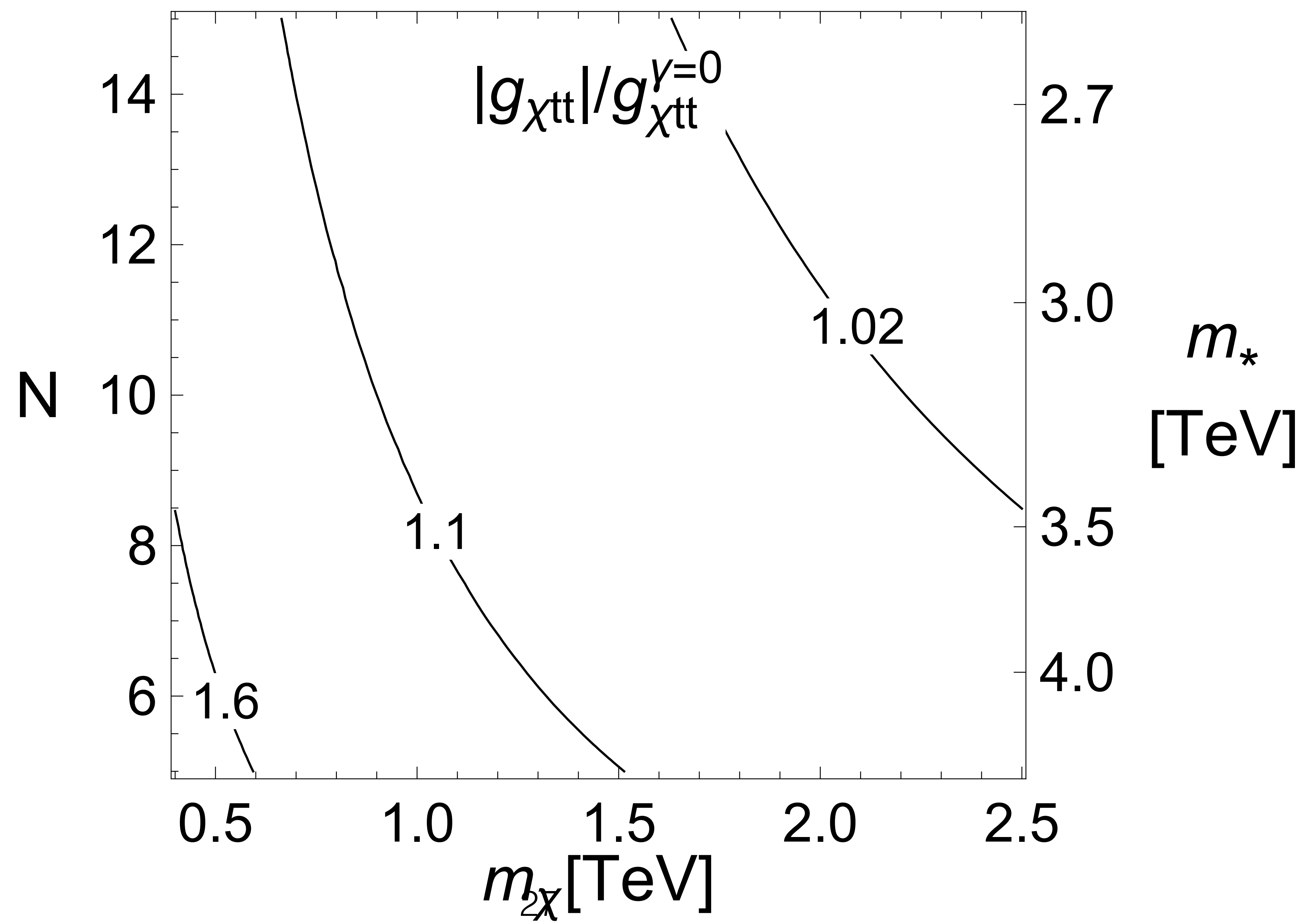
Beta function of Yukawa coupling of quark q

$$\Gamma_{qq\chi} \sim c_\delta \beta_{\lambda_q} \frac{v}{f} + c_\delta \lambda_q \frac{v}{f} + s_\delta \lambda_q$$

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

Collider phenomenology

- Detect Dilaton
- Fit parameters of EFT to data
- E.g.: Dilaton quark coupling



Collider phenomenology

- Detect Dilaton
- Fit parameters of EFT to data
- E.g.: Higgs quark coupling

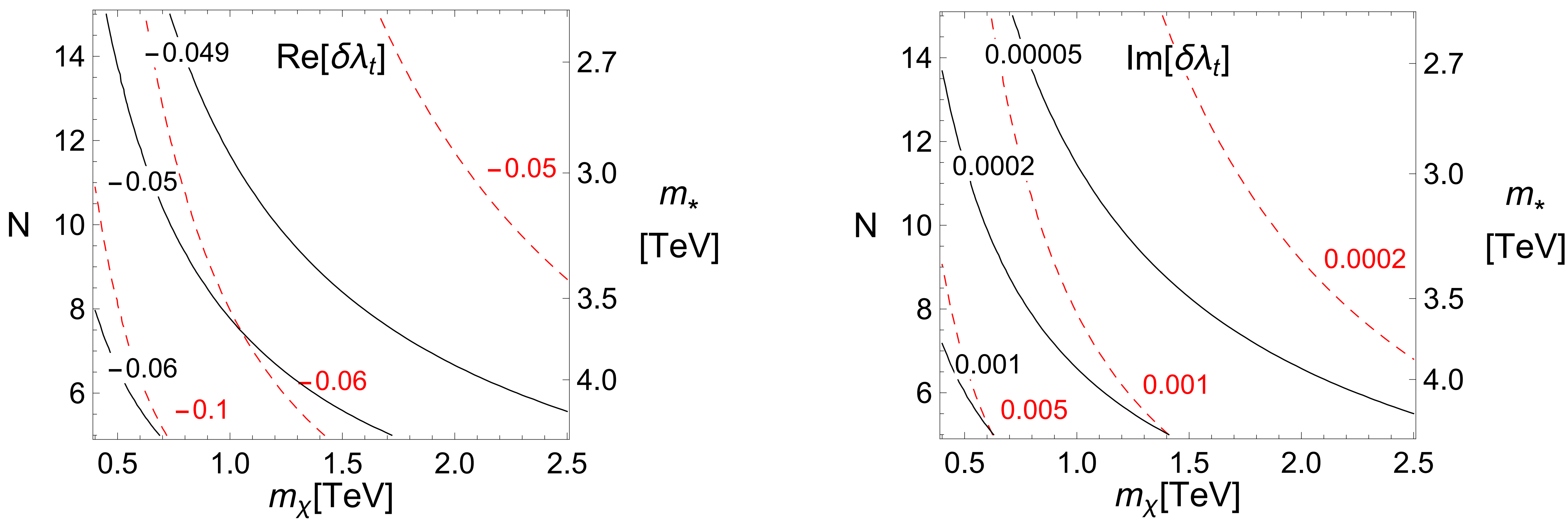
Beta function of Yukawa coupling of quark q

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

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

Collider phenomenology

- Detect Dilaton
- Fit parameters of EFT to data
- E.g.: Higgs quark coupling



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

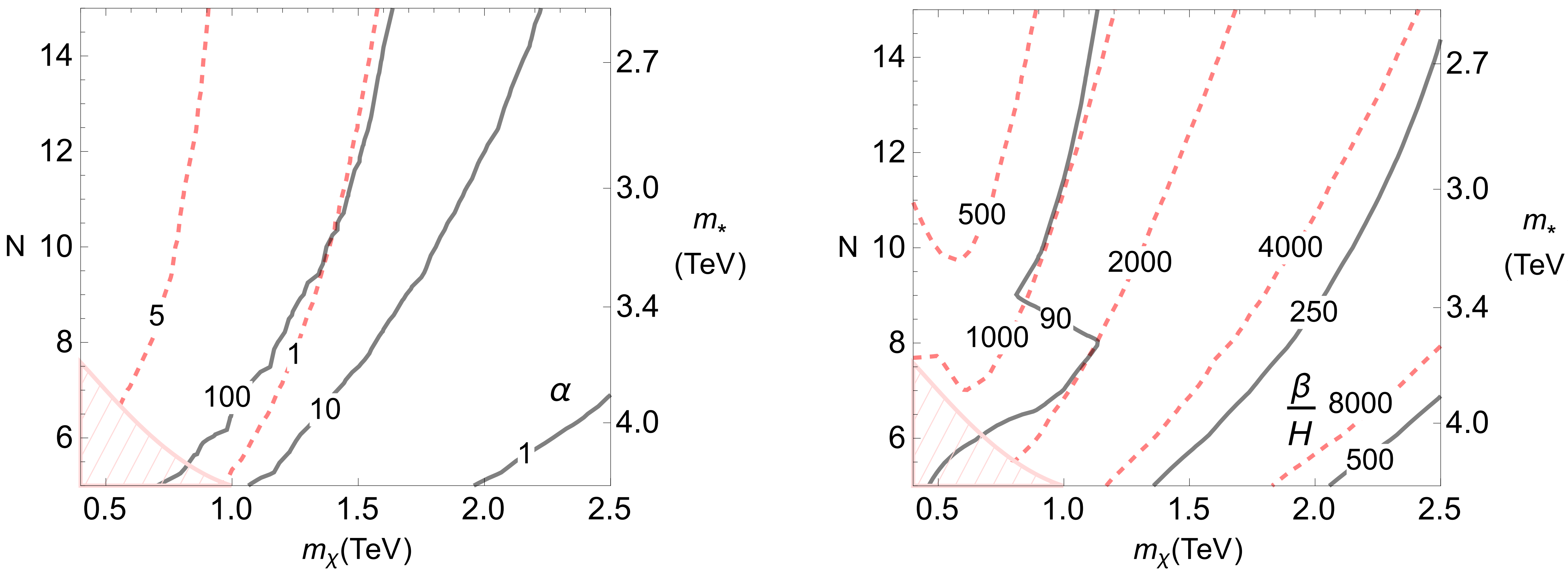
Abramowicz et al. ‘13

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

Cirigliano, Dekens, de Vries, Mereghetti ‘16

Graviational wave signal

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

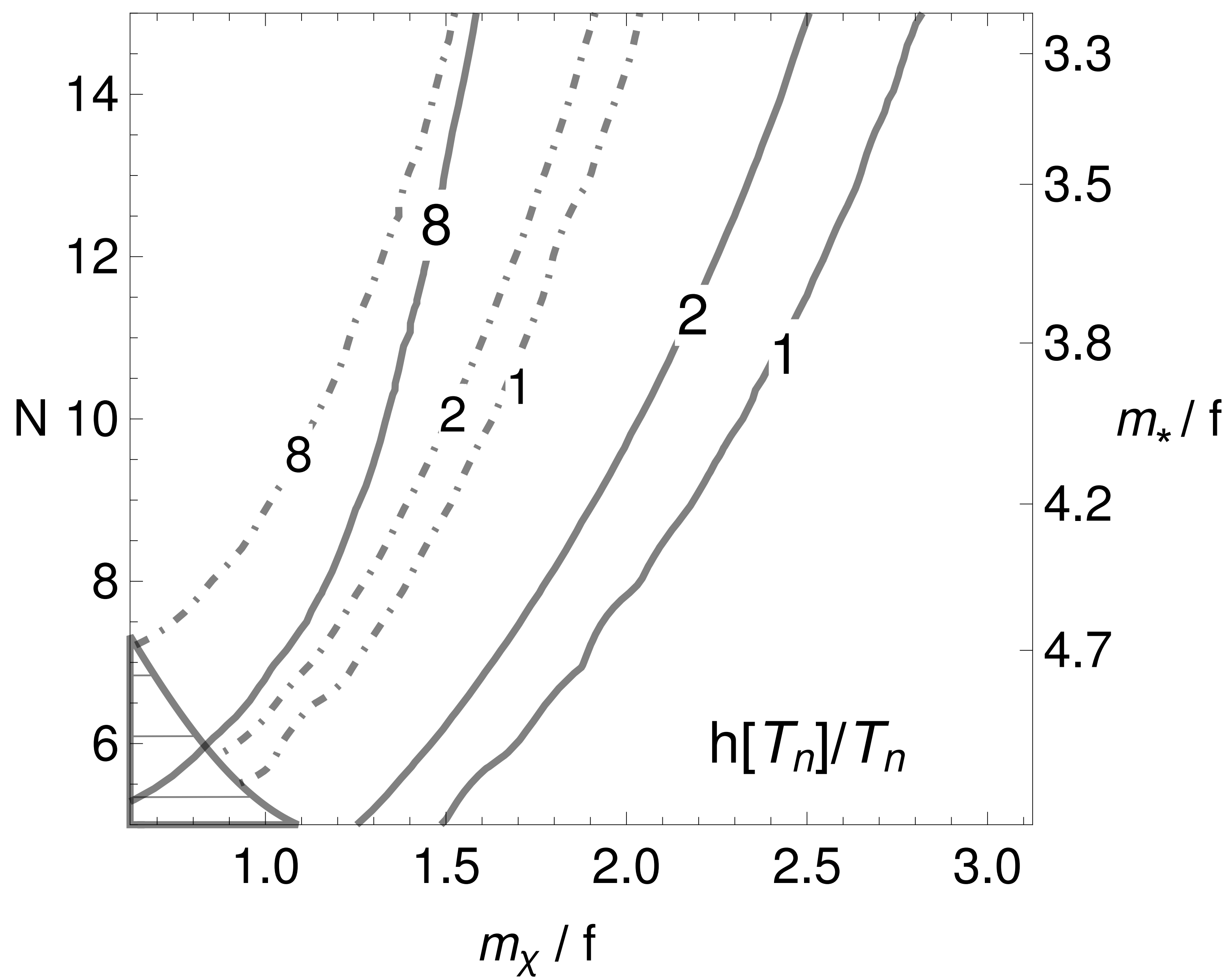


LISA: $\alpha \gtrsim 0.1 \quad \& \quad 1 \lesssim \beta/H \lesssim 10^4$

Grojean, Servant '06
Caprini et al. '15

Sensitivity to f

$$f = 0.8\,\mathrm{TeV}\ \ \text{vs.}\ \ f = 2\,\mathrm{TeV}$$



Two field tunneling

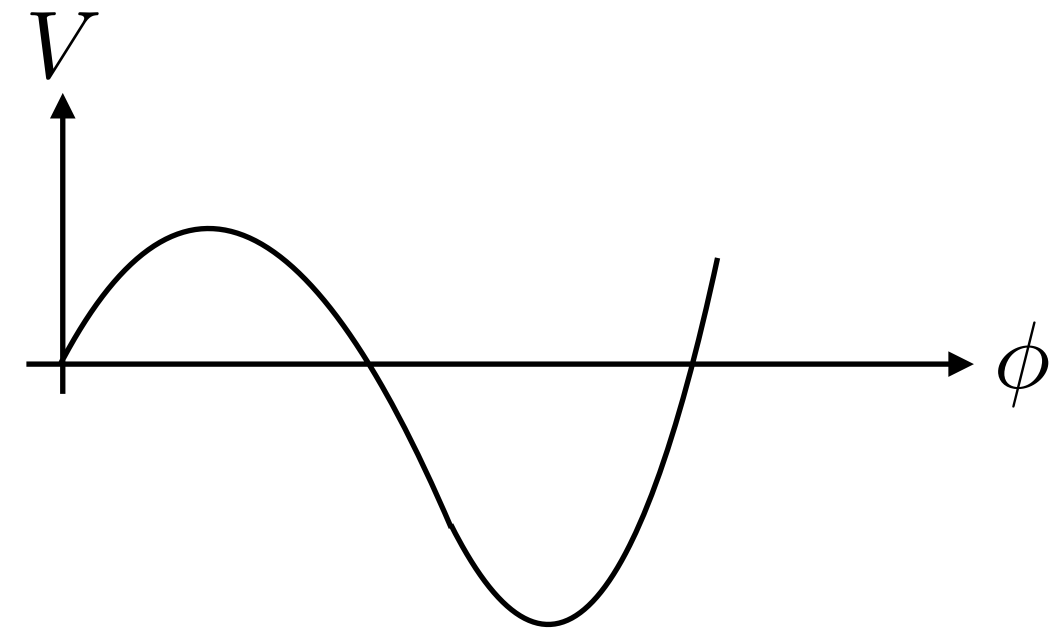
One field

$$S_E \sim 140$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{dr}^2} + \frac{\alpha}{r}\frac{\mathrm{d}\phi}{\mathrm{dr}} = V'(\phi) \qquad \alpha = \begin{cases} 3 & O(4) \\ 2 & O(3) \end{cases}$$

$$\phi(r \to \infty) = 0 \qquad r \sim \text{“time”}$$

$$\left.\frac{\mathrm{d}\phi}{\mathrm{d}r}\right|_{r=0} = 0$$



Two field tunneling

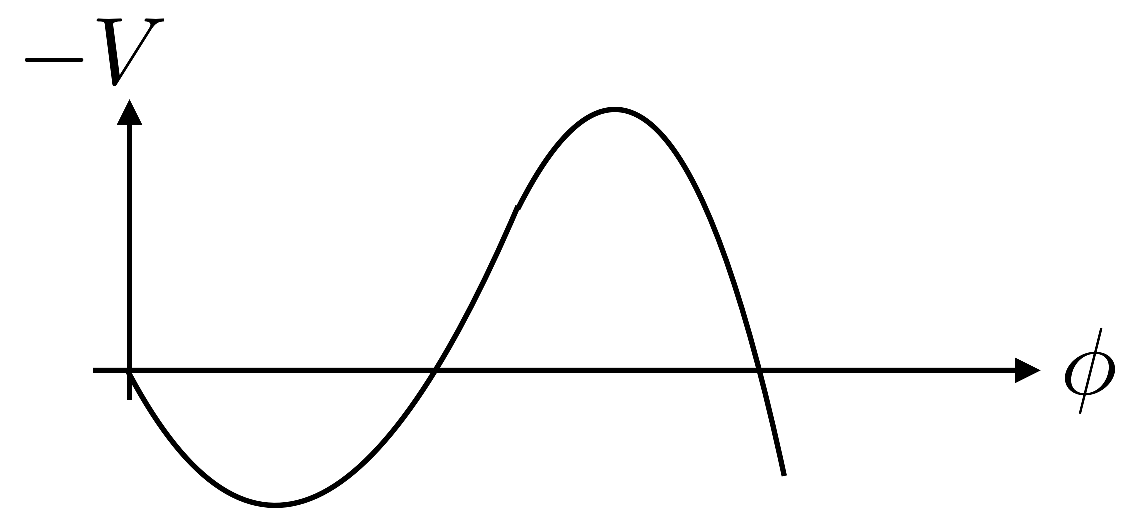
One field

$$S_E \sim 140$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{dr}^2} + \frac{\alpha}{r}\frac{\mathrm{d}\phi}{\mathrm{dr}} = V'(\phi) \qquad \alpha = \begin{cases} 3 & O(4) \\ 2 & O(3) \end{cases}$$

$$\phi(r \to \infty) = 0 \qquad r \sim \text{“time”}$$

$$\left.\frac{\mathrm{d}\phi}{\mathrm{d}r}\right|_{r=0} = 0$$



Two field tunneling

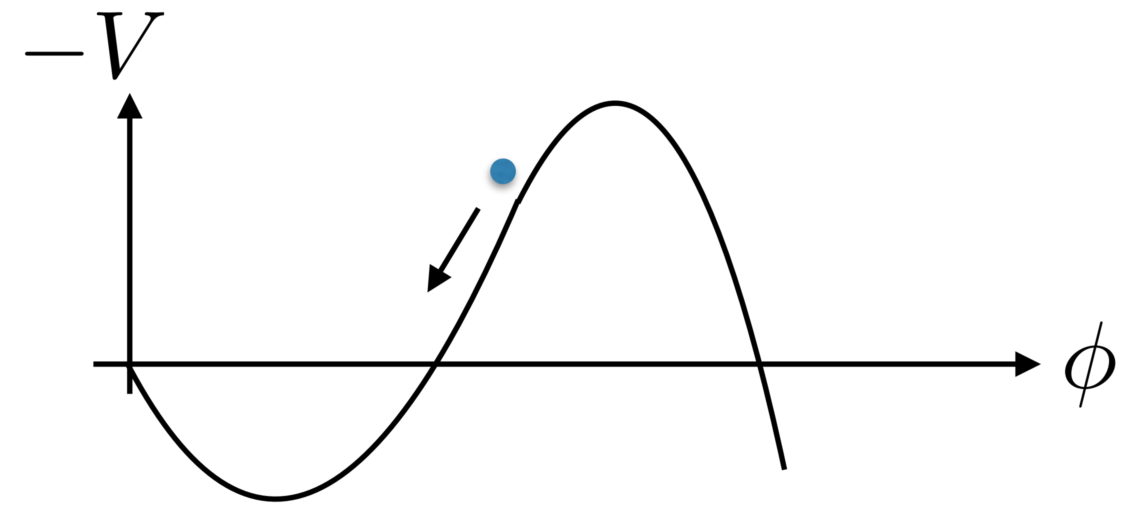
One field

$$S_E \sim 140$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} = V'(\phi) \qquad \alpha = \begin{cases} 3 & O(4) \\ 2 & O(3) \end{cases}$$

$$\phi(r \to \infty) = 0 \qquad r \sim \text{“time”}$$

$$\left.\frac{\mathrm{d}\phi}{\mathrm{d}r}\right|_{r=0} = 0$$



Two field tunneling

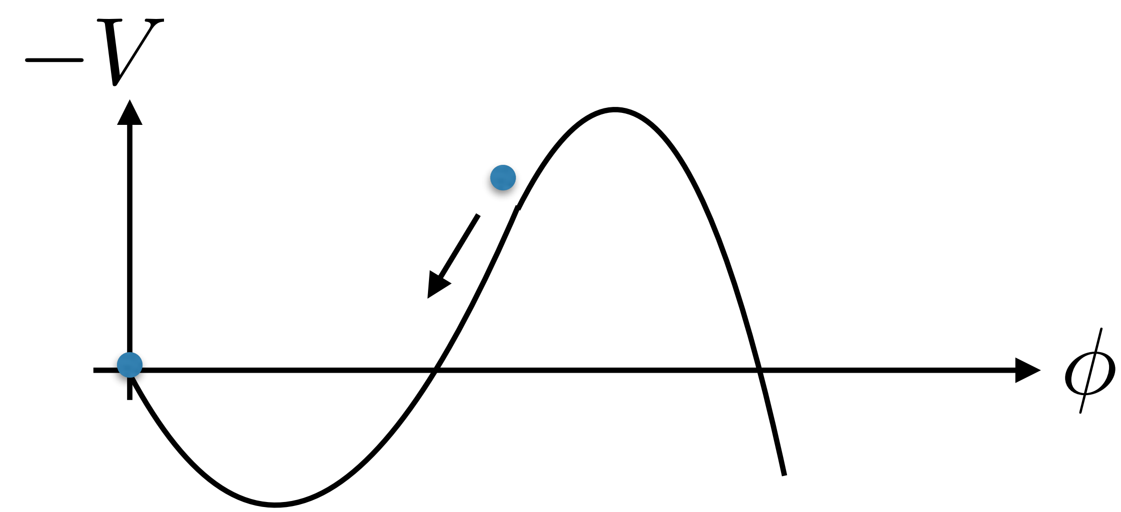
One field

$$S_E \sim 140$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{dr}^2} + \frac{\alpha}{r}\frac{\mathrm{d}\phi}{\mathrm{dr}} = V'(\phi) \qquad \alpha = \begin{cases} 3 & O(4) \\ 2 & O(3) \end{cases}$$

$$\phi(r \to \infty) = 0 \qquad r \sim \text{“time”}$$

$$\left.\frac{\mathrm{d}\phi}{\mathrm{d}r}\right|_{r=0} = 0$$



Two field tunneling

Two fields

$S_E \sim 140$

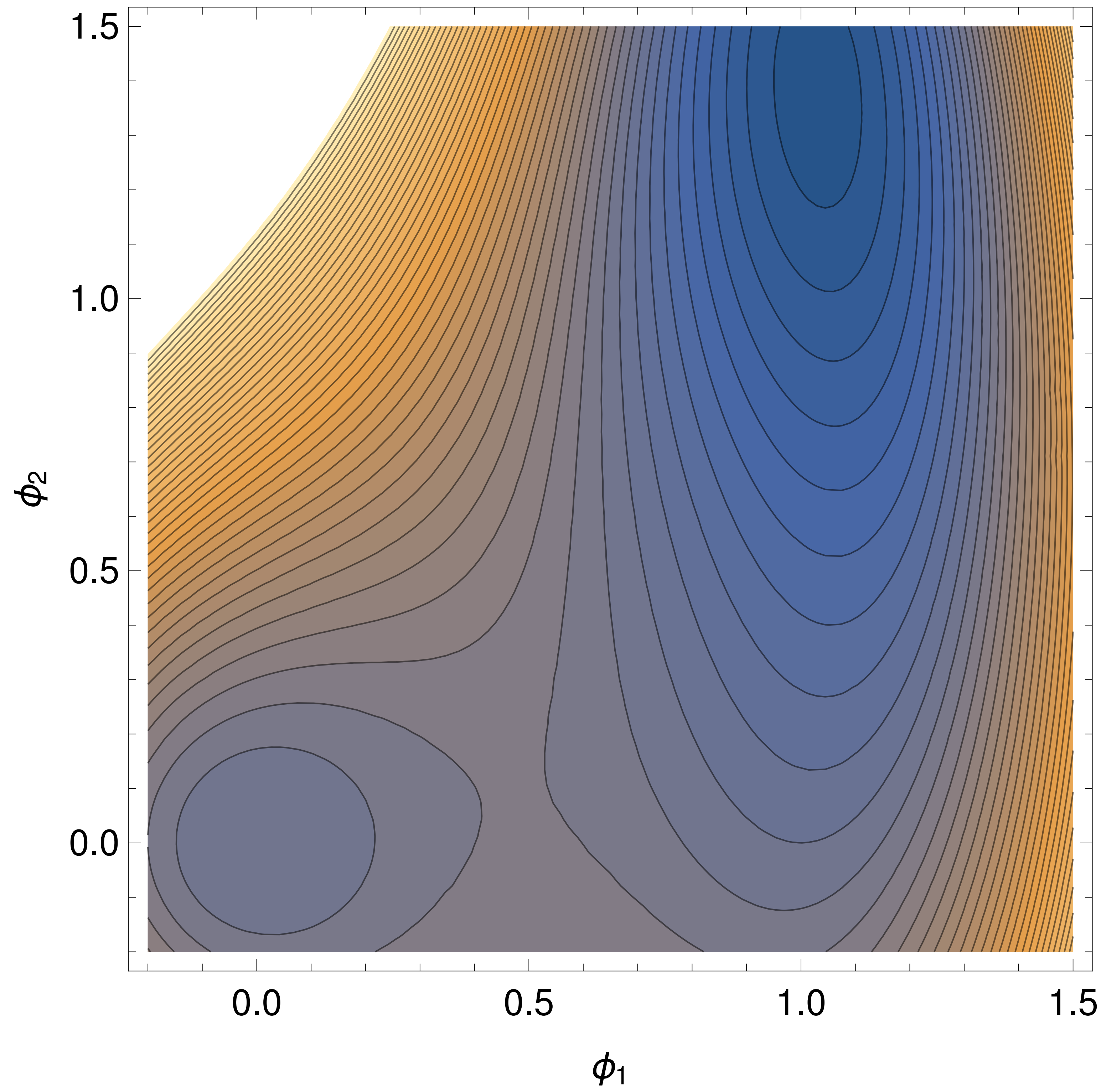
$$\frac{\mathrm{d}^2\vec{\phi}}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}\vec{\phi}}{\mathrm{d}r} = \nabla V(\vec{\phi})$$

Two field tunneling

Two fields

$$S_E \sim 140$$

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



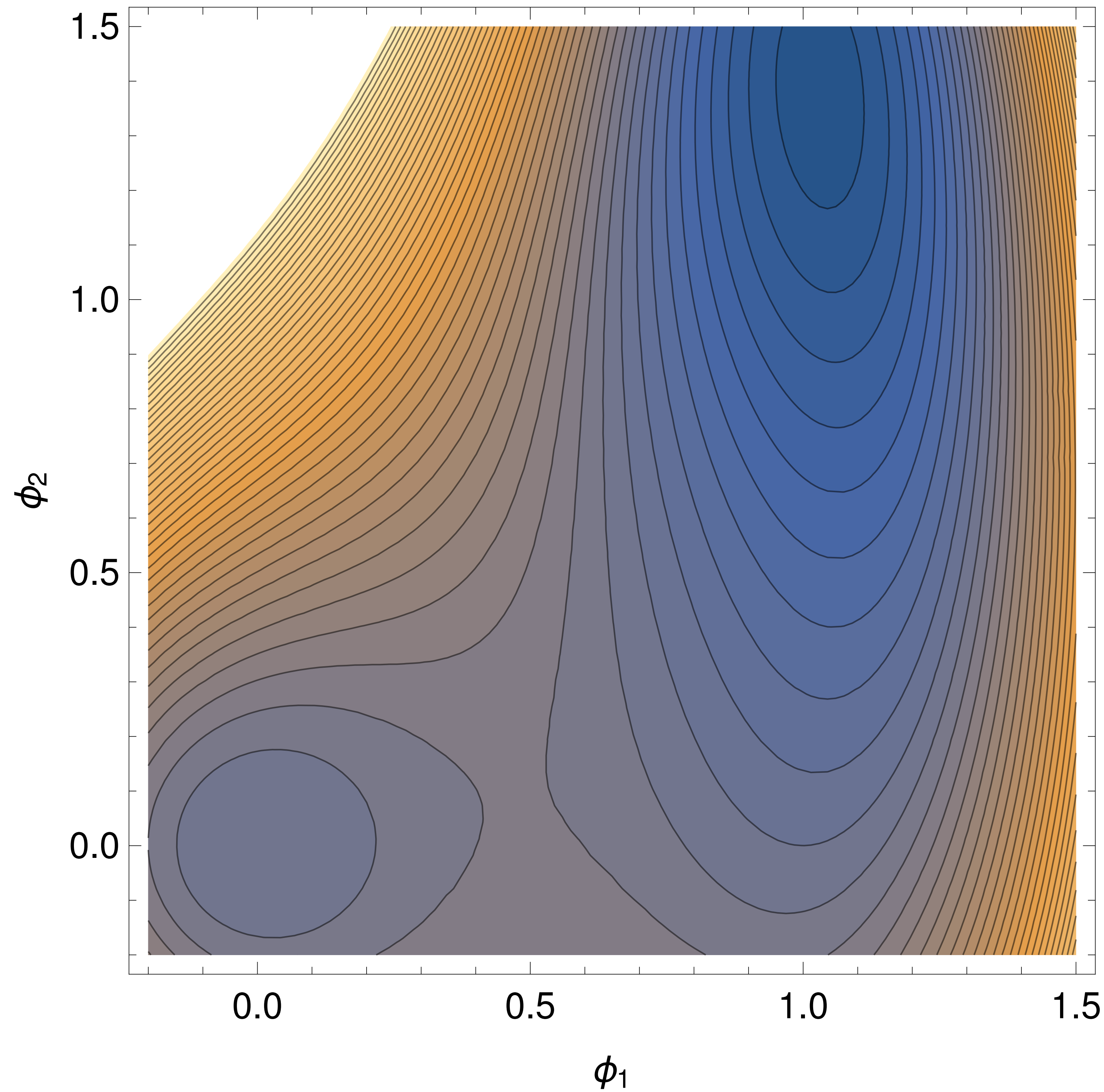
Two field tunneling

$S_E \sim 140$

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

Guess $\vec{\phi}_g(x)$

Two fields



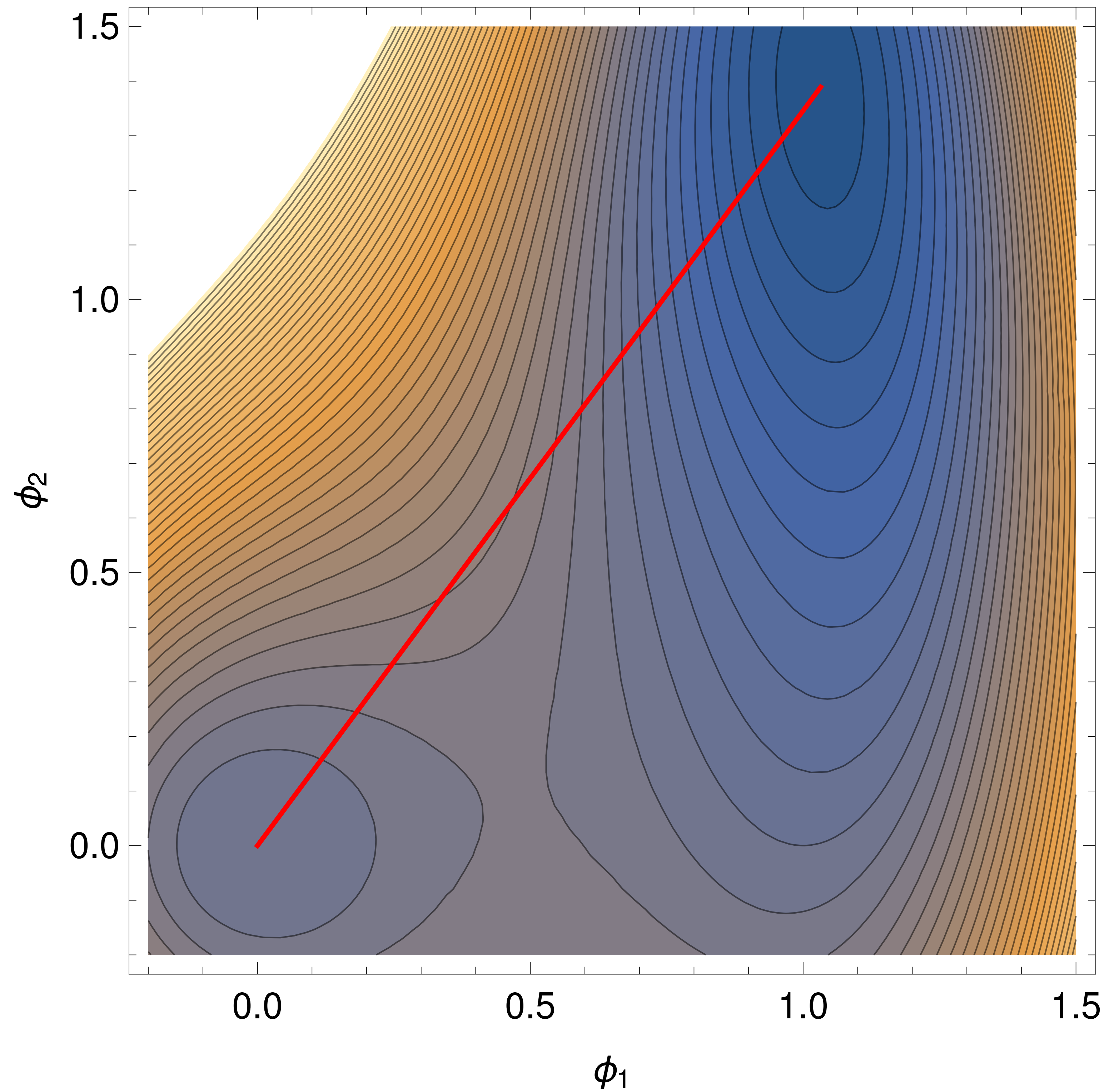
Two field tunneling

$S_E \sim 140$

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

Guess $\vec{\phi}_g(x)$

Two fields



Two field tunneling

Two fields

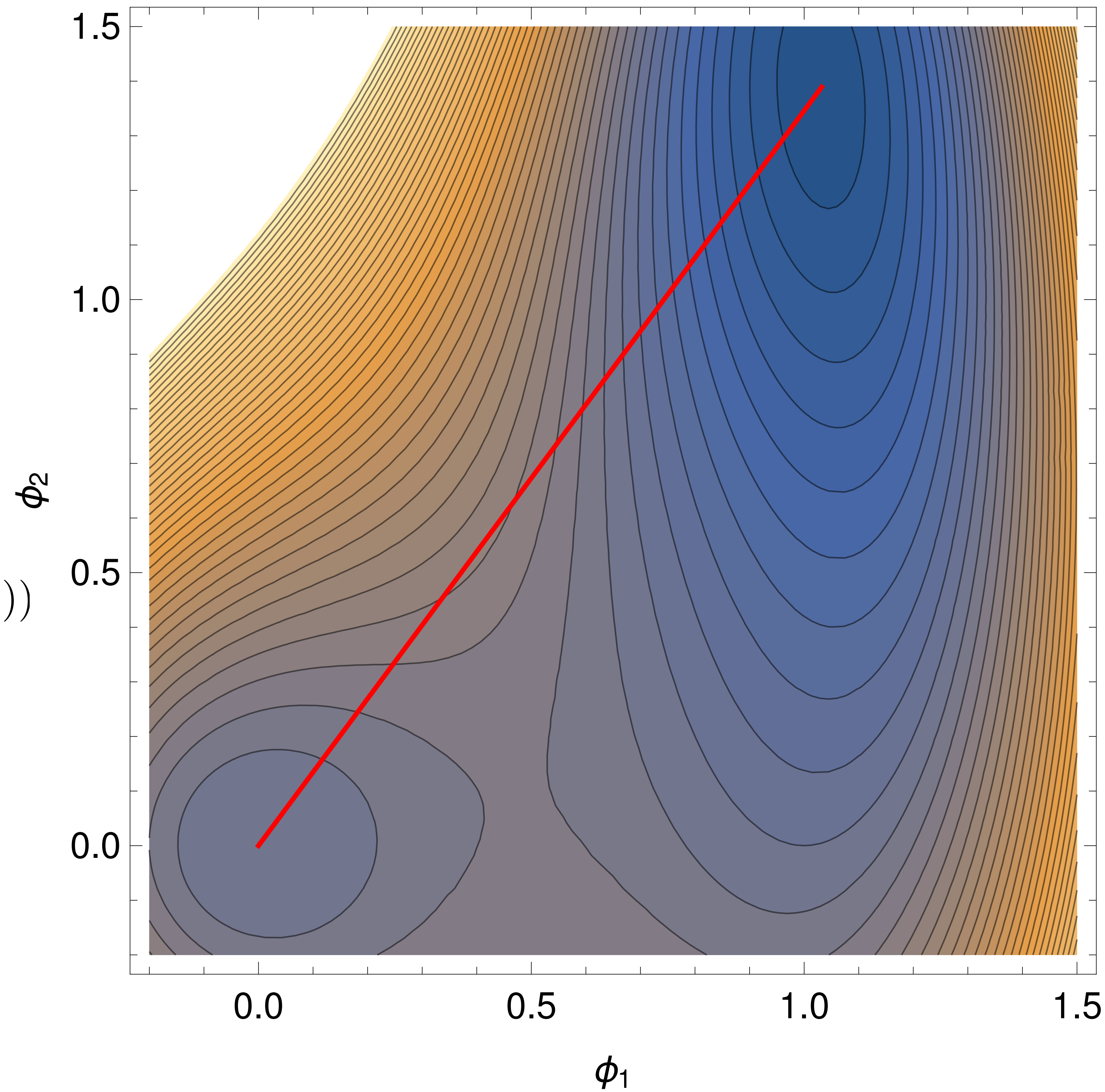
$$S_E \sim 140$$

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

Guess $\vec{\phi}_g(x)$

$$\frac{\mathrm{d}^2 x}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}x}{\mathrm{d}r} = \partial_x V(\vec{\phi}_g(x))$$

$$\frac{\mathrm{d}^2\vec{\phi}_g}{\mathrm{d}x^2}\left(\frac{\mathrm{d}x}{\mathrm{d}r}\right)^2 - \nabla_\perp V(\vec{\phi}_g(x)) = 0$$



Two field tunneling

Two fields

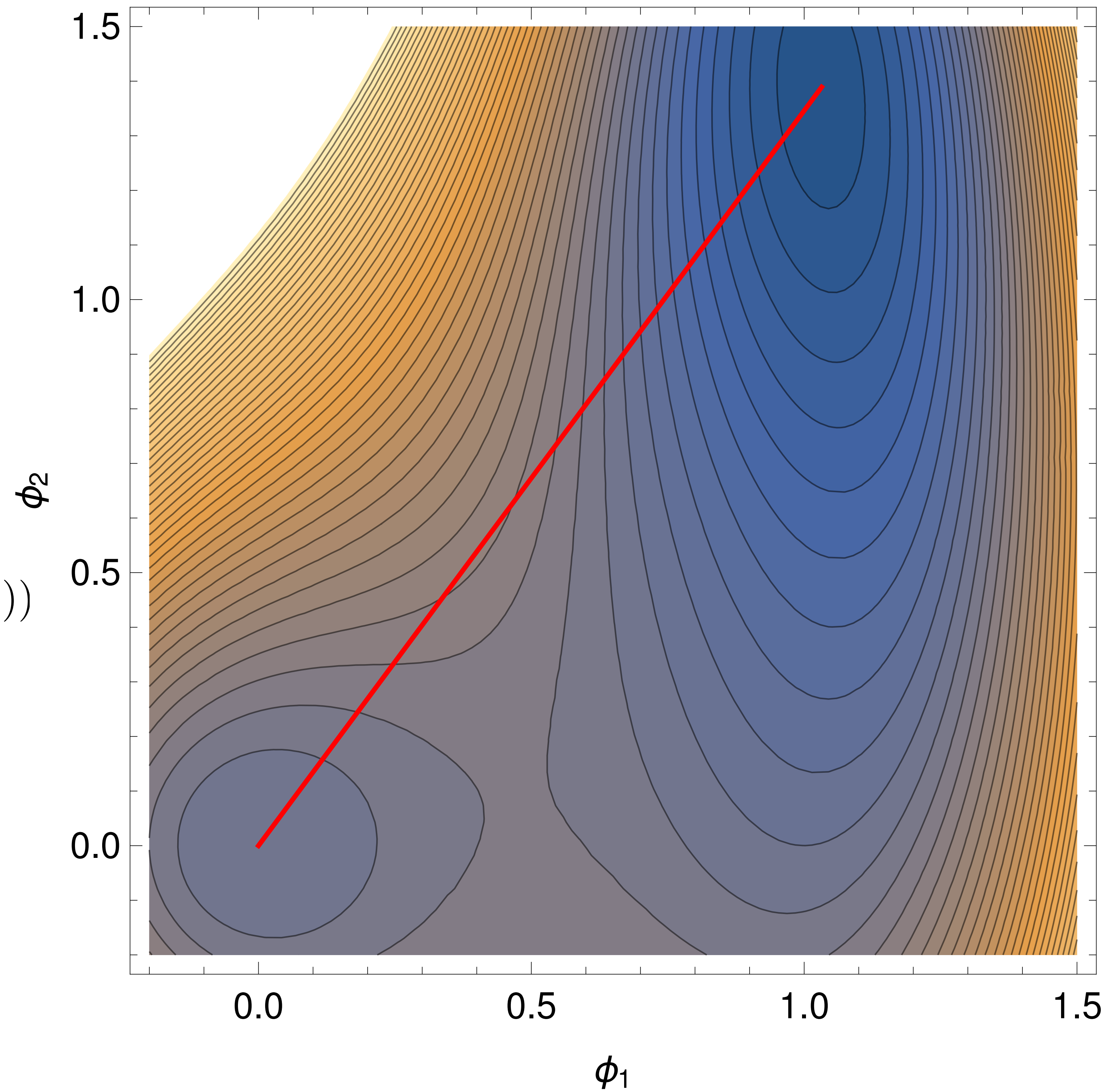
$$S_E \sim 140$$

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

Guess $\vec{\phi}_g(x)$

$$\frac{\mathrm{d}^2 x}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}x}{\mathrm{d}r} = \partial_x V(\vec{\phi}_g(x))$$

$$\underbrace{\frac{\mathrm{d}^2\vec{\phi}_g}{\mathrm{d}x^2}\left(\frac{\mathrm{d}x}{\mathrm{d}r}\right)^2 - \nabla_\perp V(\vec{\phi}_g(x))}_{\equiv \vec{N}} = 0$$



Two field tunneling

Two fields

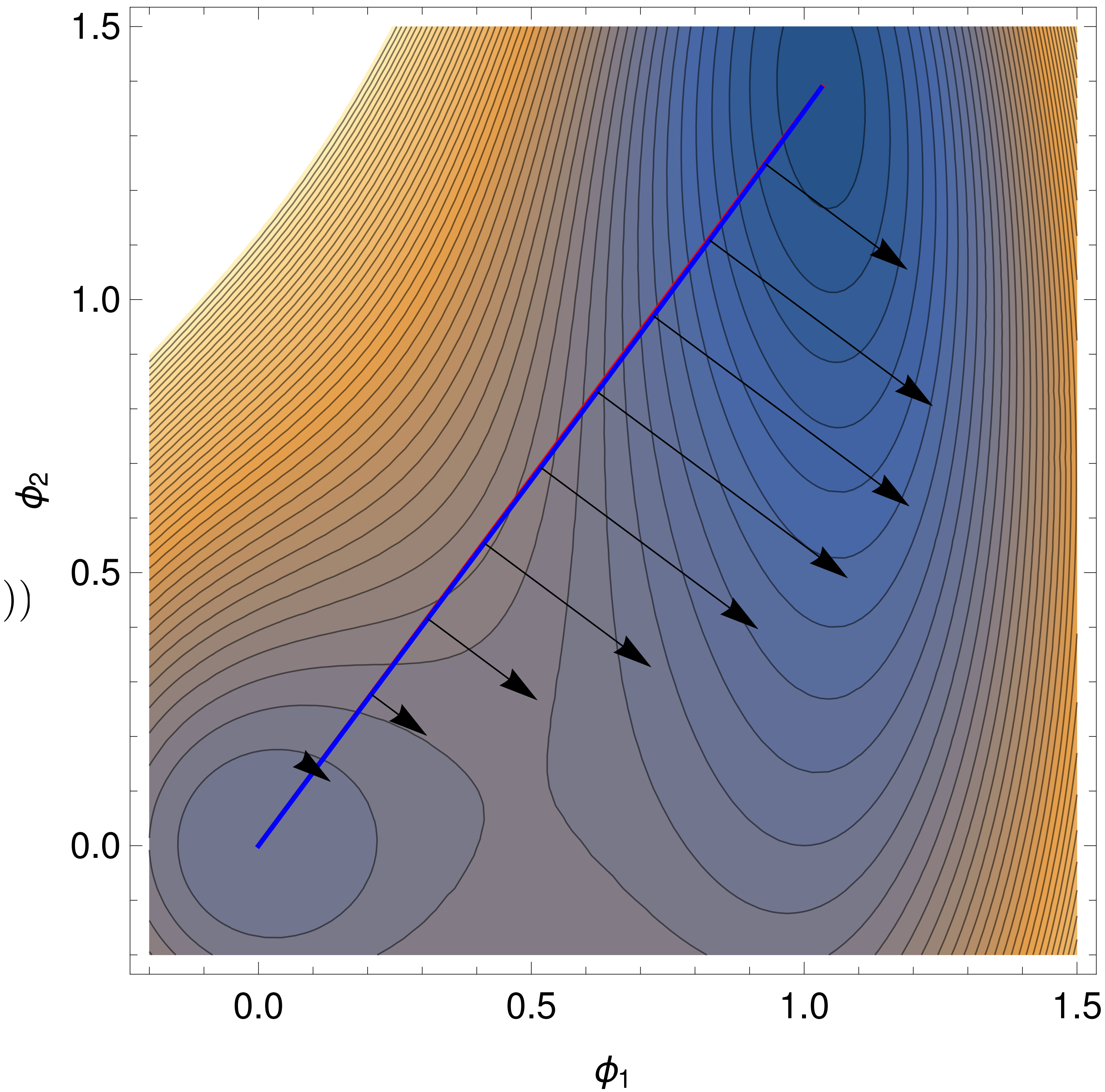
$$S_E \sim 140$$

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

Guess $\vec{\phi}_g(x)$

$$\frac{\mathrm{d}^2 x}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}x}{\mathrm{d}r} = \partial_x V(\vec{\phi}_g(x))$$

$$\underbrace{\frac{\mathrm{d}^2\vec{\phi}_g}{\mathrm{d}x^2}\left(\frac{\mathrm{d}x}{\mathrm{d}r}\right)^2 - \nabla_\perp V(\vec{\phi}_g(x))}_{\equiv \vec{N}} = 0$$



Two field tunneling

$$S_E \sim 140$$

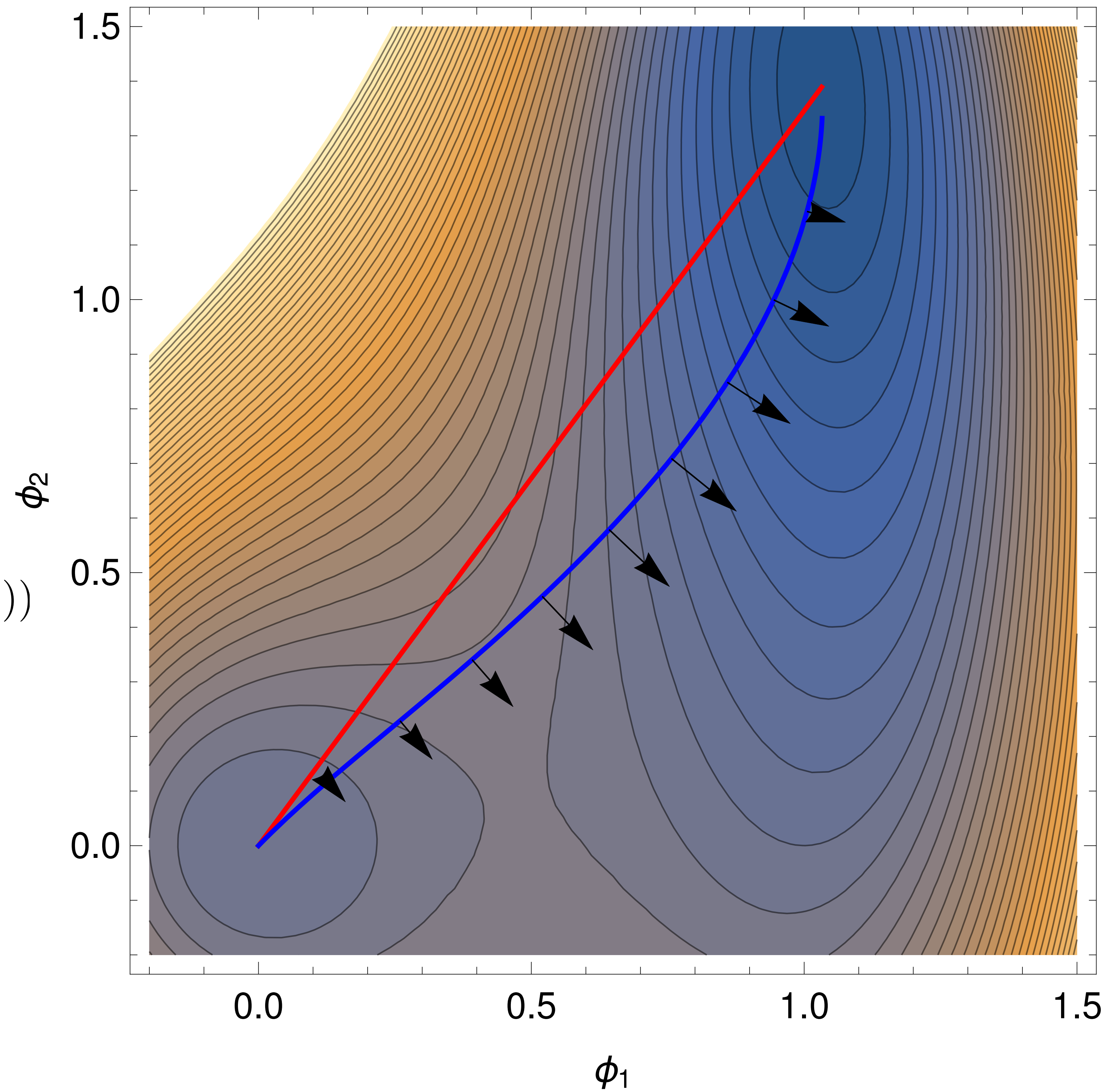
$$\frac{\mathrm{d}^2\vec{\phi}}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}\vec{\phi}}{\mathrm{d}r} = \nabla V(\vec{\phi})$$

Guess $\vec{\phi}_g(x)$

$$\frac{\mathrm{d}^2 x}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}x}{\mathrm{d}r} = \partial_x V(\vec{\phi}_g(x))$$

$$\underbrace{\frac{\mathrm{d}^2\vec{\phi}_g}{\mathrm{d}x^2}\left(\frac{\mathrm{d}x}{\mathrm{d}r}\right)^2 - \nabla_\perp V(\vec{\phi}_g(x)) = 0}_{\equiv \vec{N}}$$

Two fields



Two field tunneling

Two fields

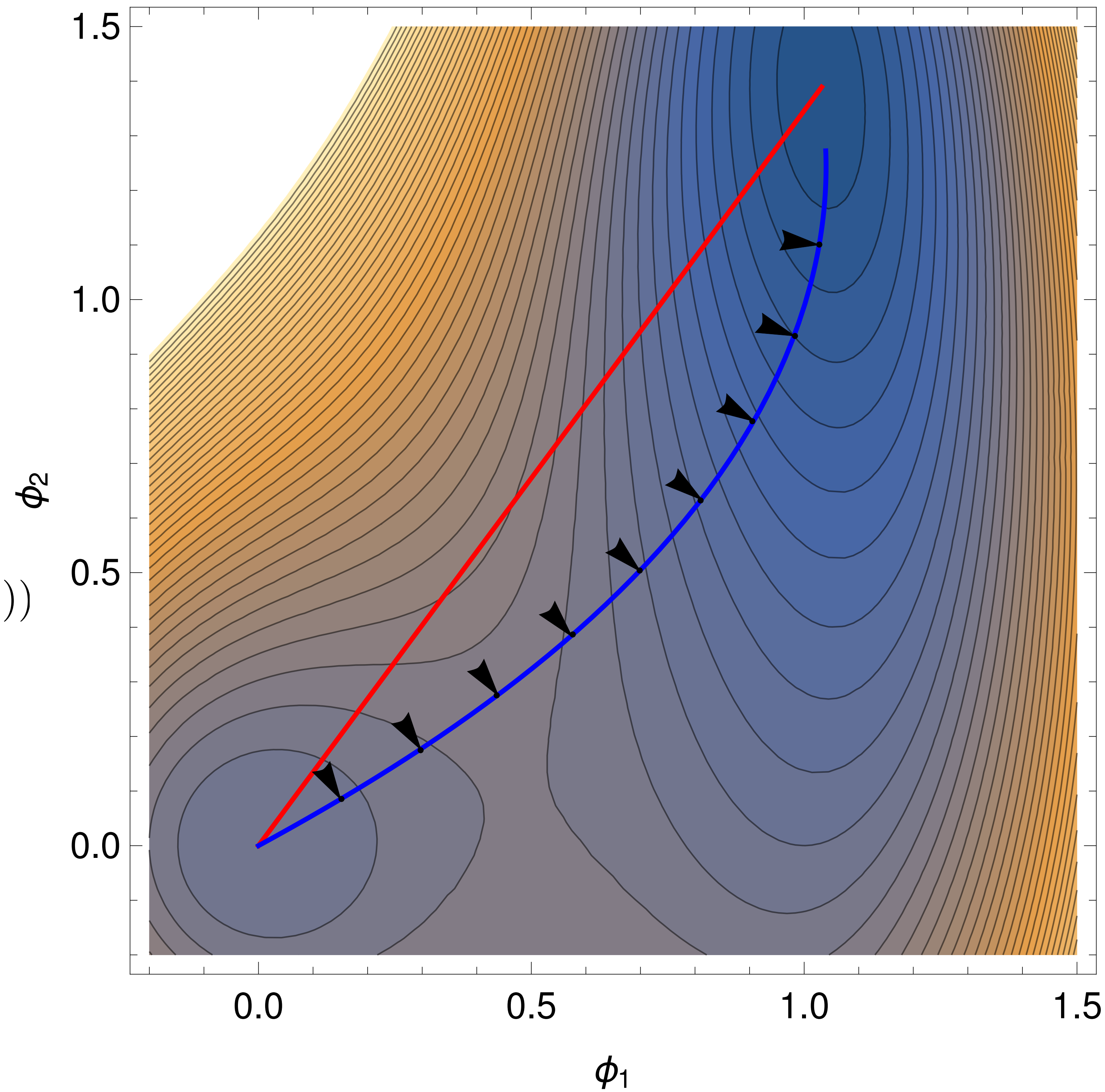
$$S_E \sim 140$$

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

Guess $\vec{\phi}_g(x)$

$$\frac{\mathrm{d}^2 x}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}x}{\mathrm{d}r} = \partial_x V(\vec{\phi}_g(x))$$

$$\underbrace{\frac{\mathrm{d}^2\vec{\phi}_g}{\mathrm{d}x^2}\left(\frac{\mathrm{d}x}{\mathrm{d}r}\right)^2 - \nabla_\perp V(\vec{\phi}_g(x)) = 0}_{\equiv \vec{N}}$$



Two field tunneling

Two fields

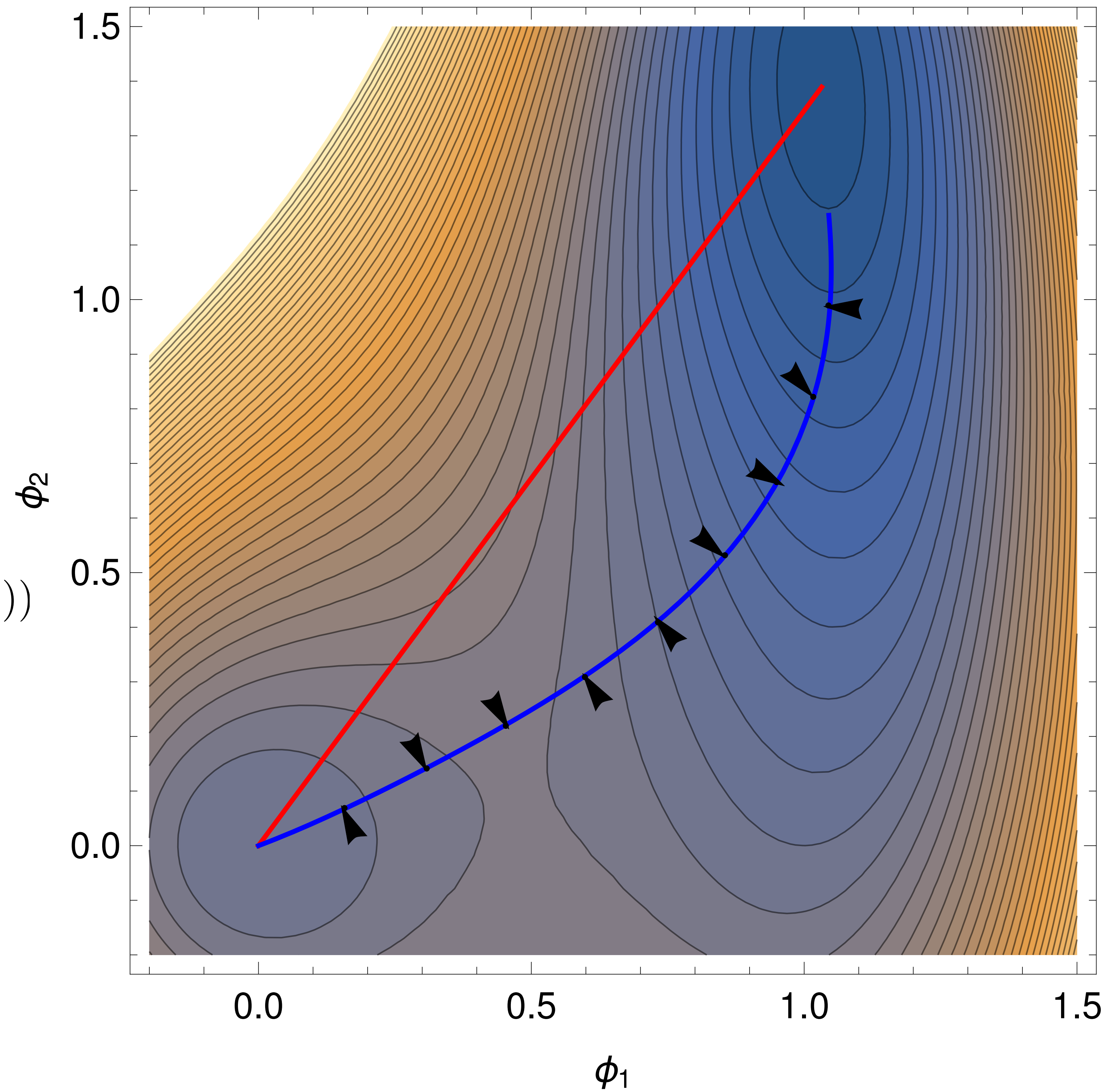
$$S_E \sim 140$$

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

Guess $\quad \vec{\phi}_g(x)$

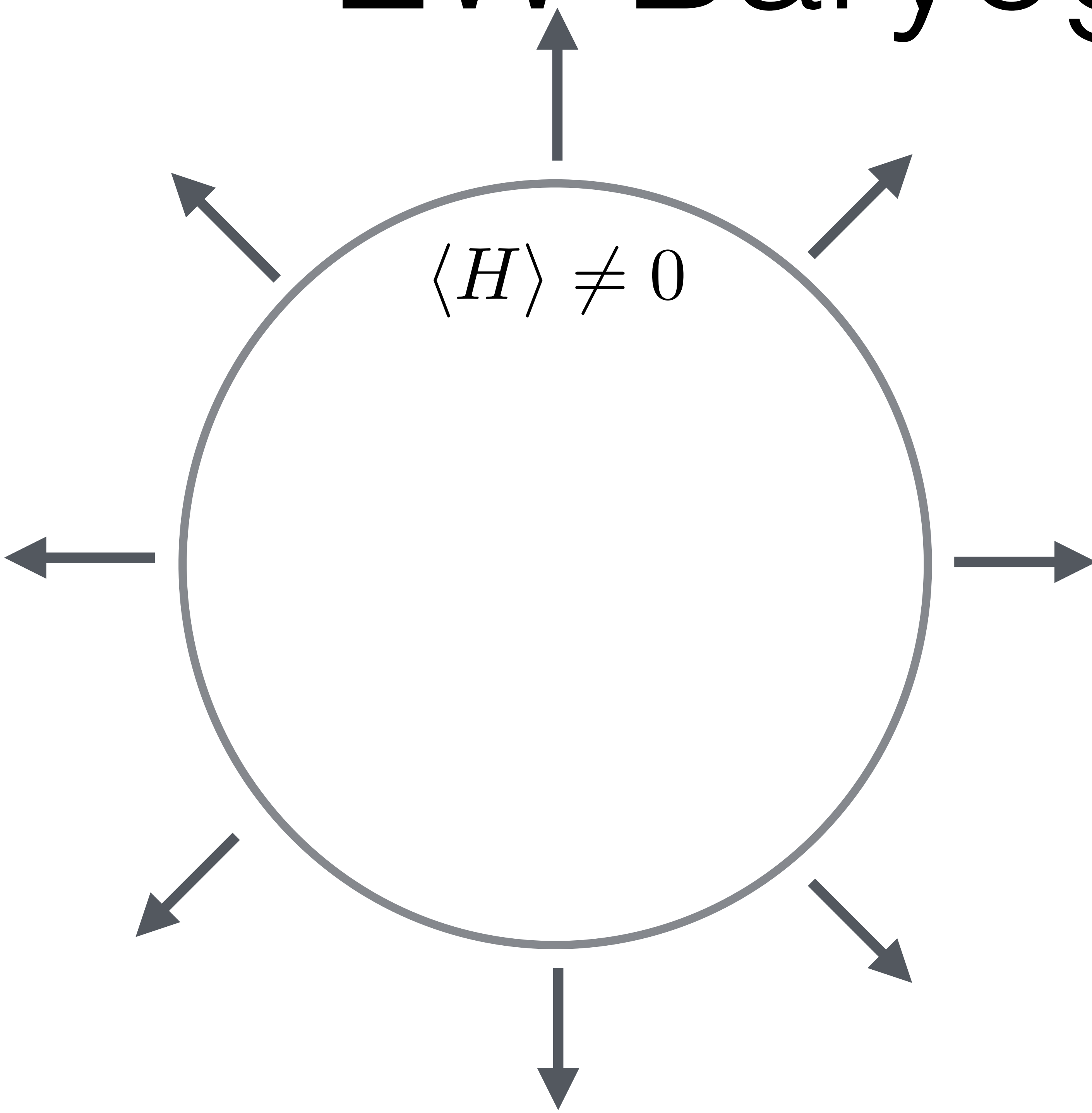
$$\frac{\mathrm{d}^2 x}{\mathrm{d}r^2} + \frac{\alpha}{r}\frac{\mathrm{d}x}{\mathrm{d}r} = \partial_x V(\vec{\phi}_g(x))$$

$$\underbrace{\frac{\mathrm{d}^2\vec{\phi}_g}{\mathrm{d}x^2}\left(\frac{\mathrm{d}x}{\mathrm{d}r}\right)^2 - \nabla_\perp V(\vec{\phi}_g(x))}_{\equiv \vec{N}} = 0$$



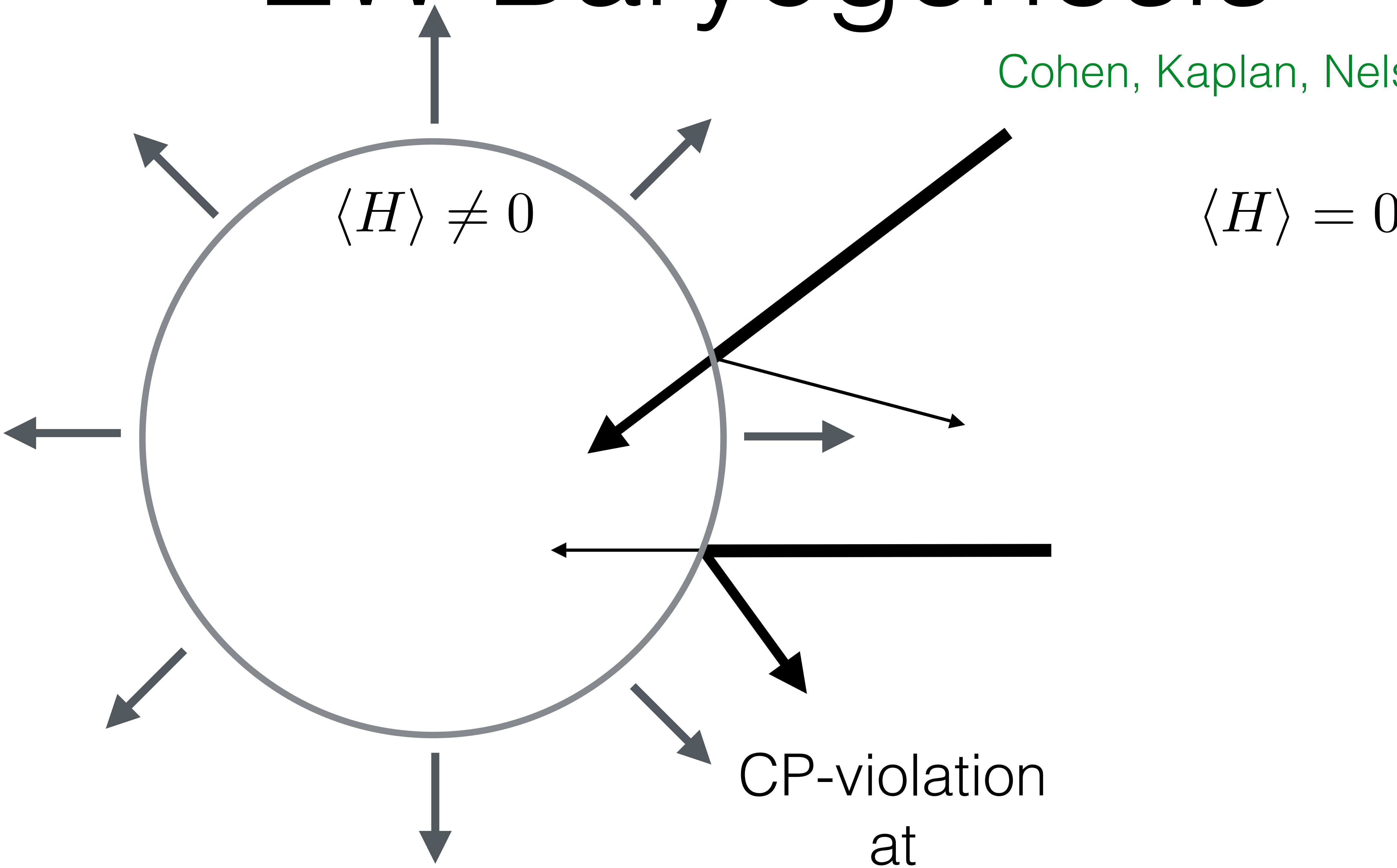
EW Baryogenesis

Cohen, Kaplan, Nelson '91



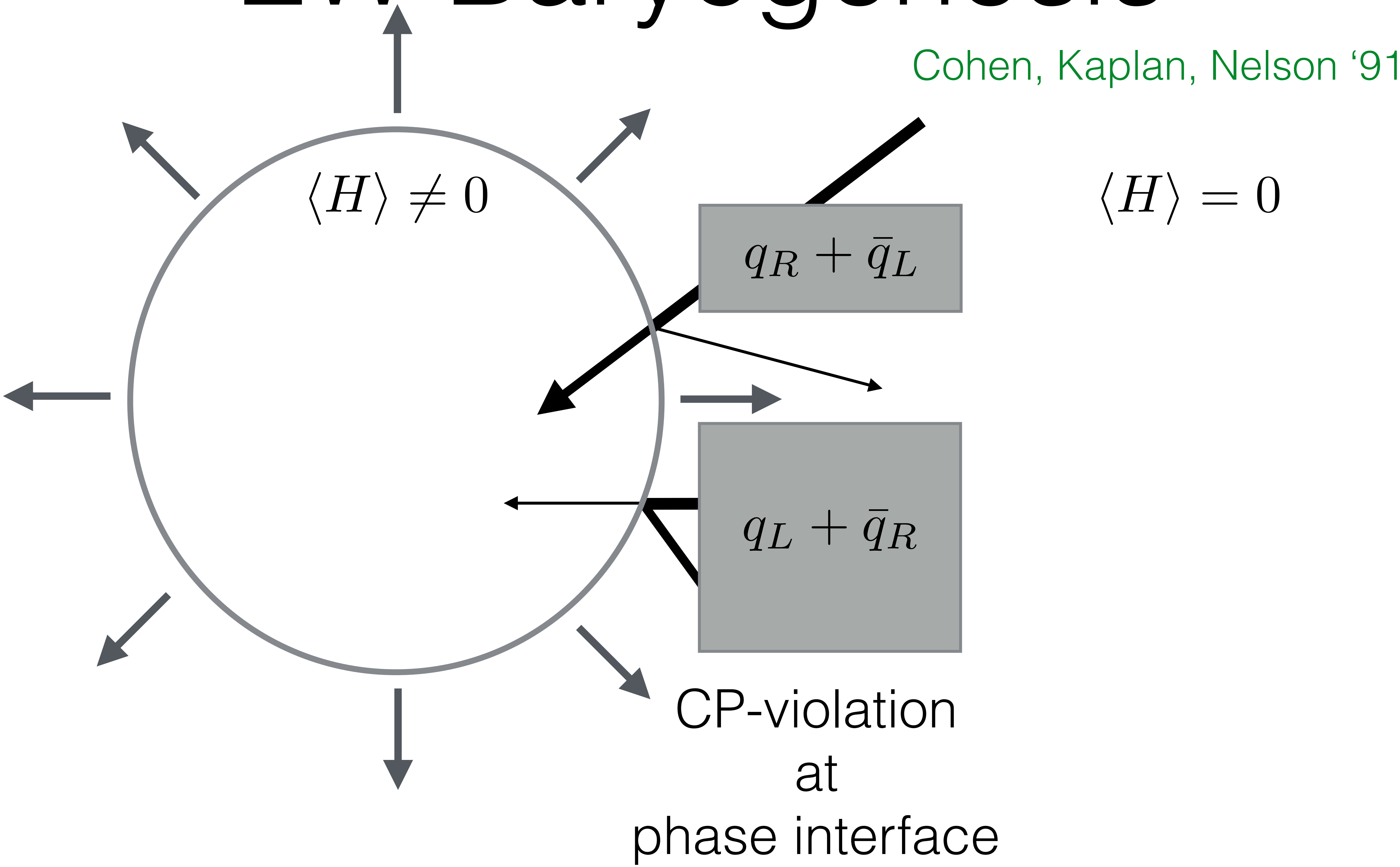
EW Baryogenesis

Cohen, Kaplan, Nelson ‘91



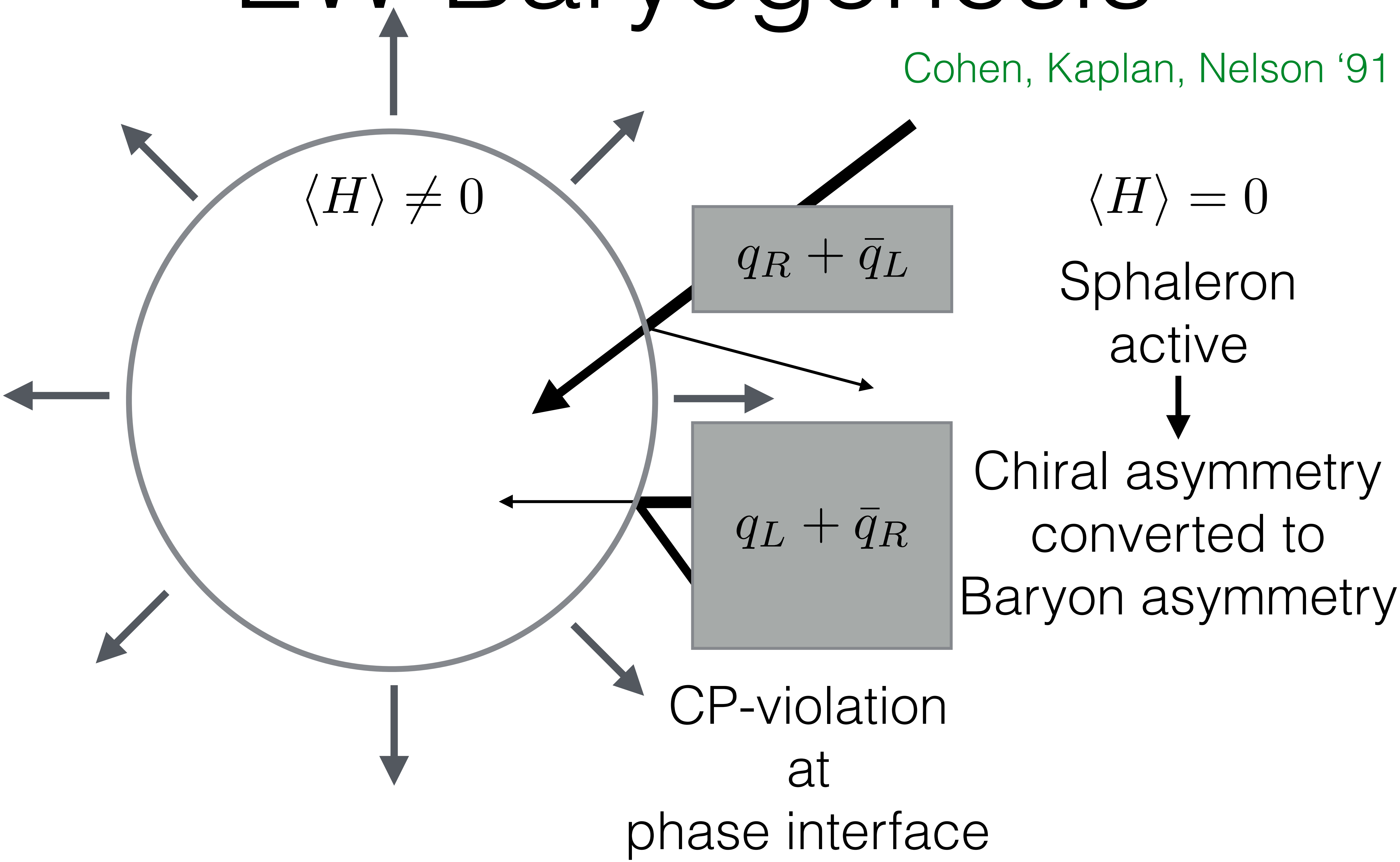
CP-violation
at
phase interface

EW Baryogenesis



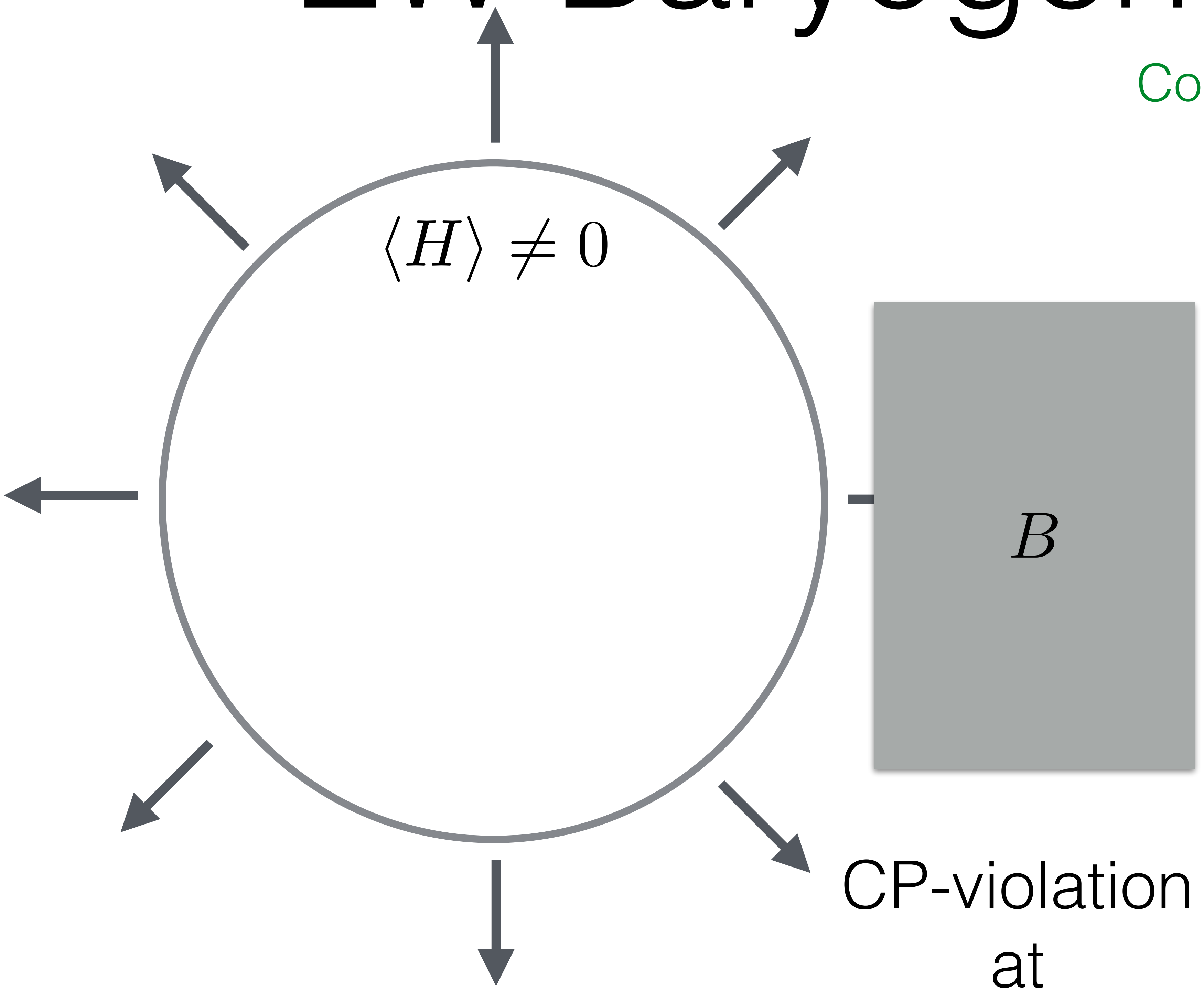
EW Baryogenesis

Cohen, Kaplan, Nelson '91



EW Baryogenesis

Cohen, Kaplan, Nelson '91



$\langle H \rangle = 0$

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

B

$\langle H \rangle = 0$

Sphaleron active

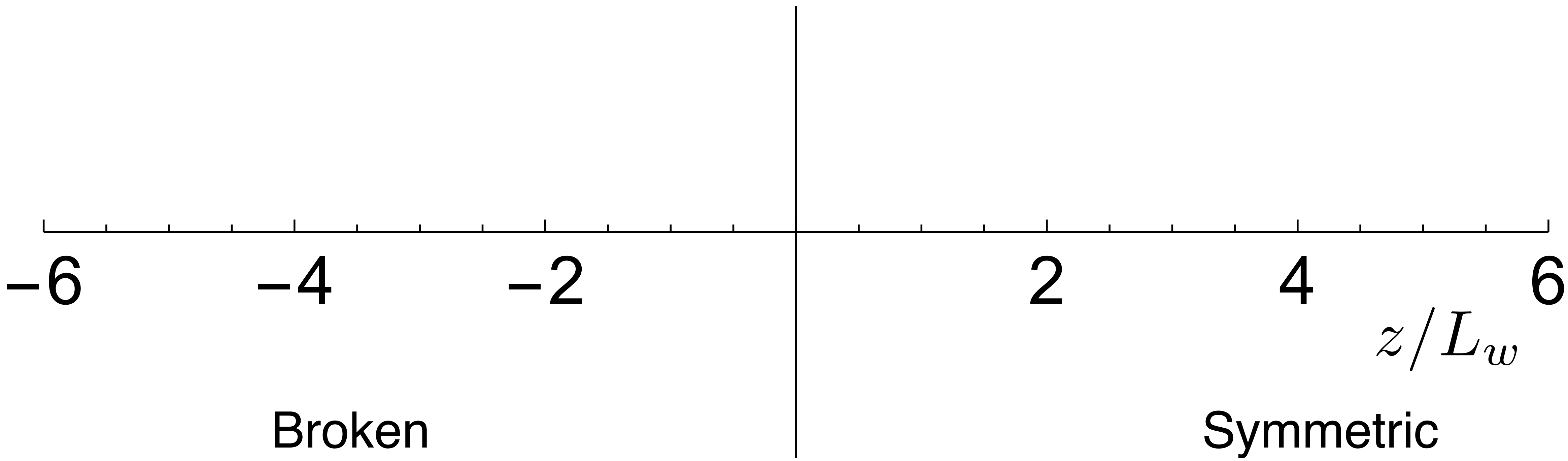
↓

Chiral asymmetry converted to Baryon asymmetry

CP-violation at phase interface

Baryon asymmetry

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



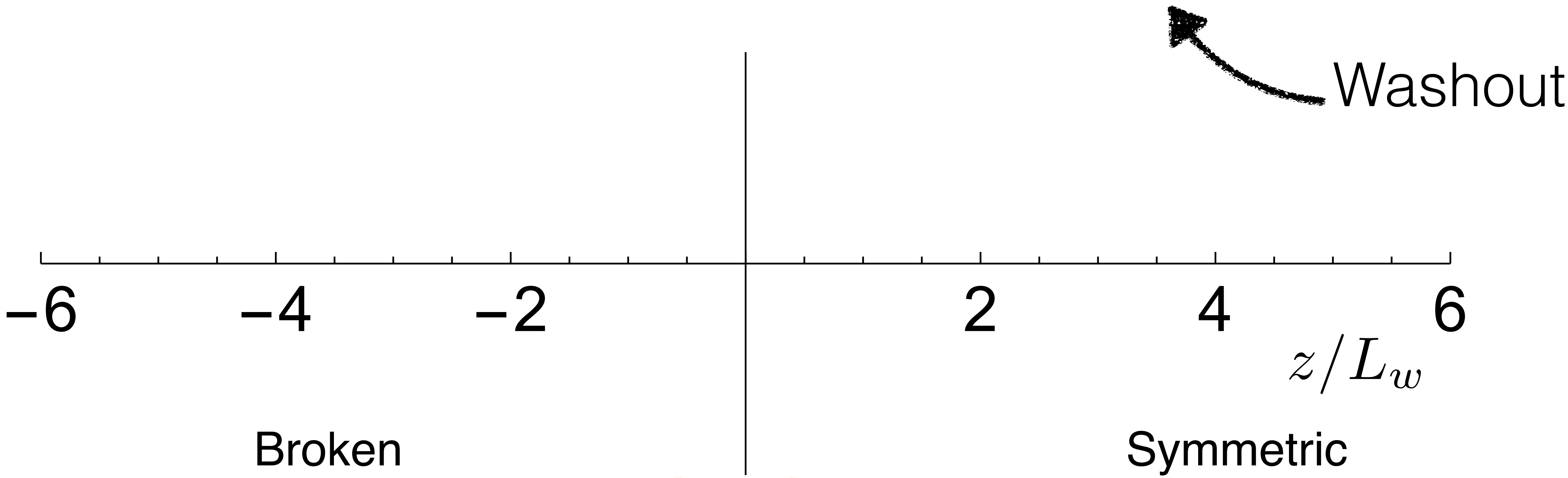
1. Sakharov condition (B-violation)

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

Baryon asymmetry

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



1. Sakharov condition (B-violation)

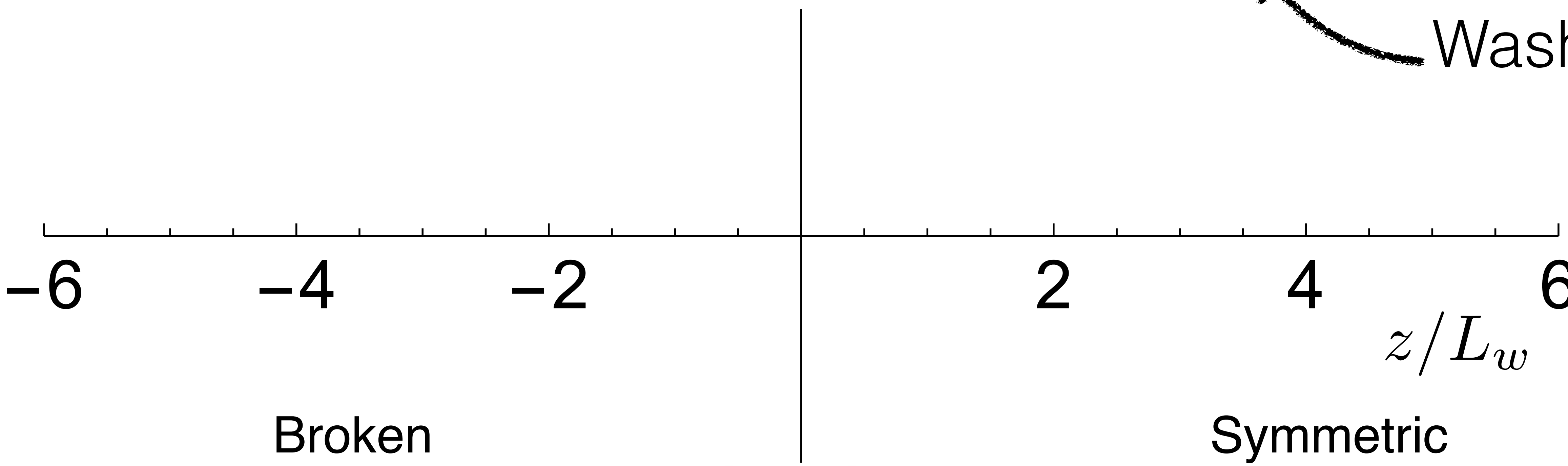
2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

Baryon asymmetry

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

Washout



1. Sakharov condition (B-violation) $\Gamma_{ws} = 10^{-6}\, T \exp(-a\phi(z)/T)$

$$\Downarrow$$

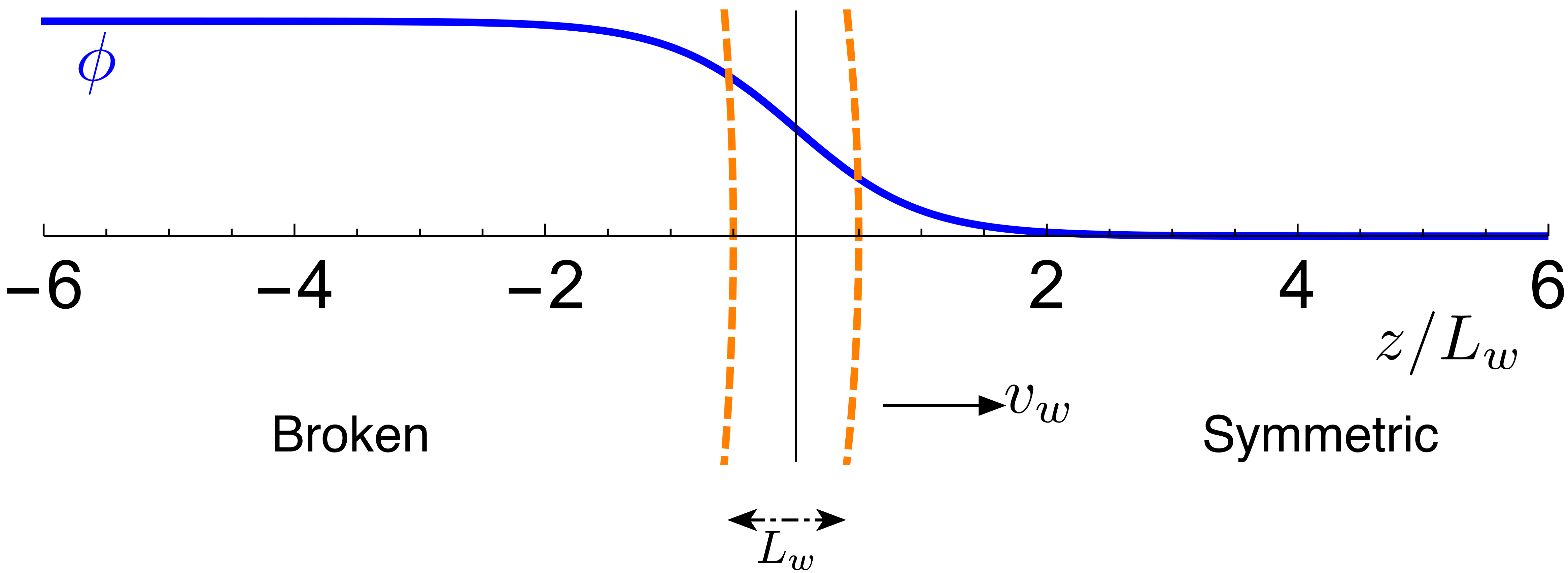
$$\frac{h}{T} \geq 1$$

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

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)

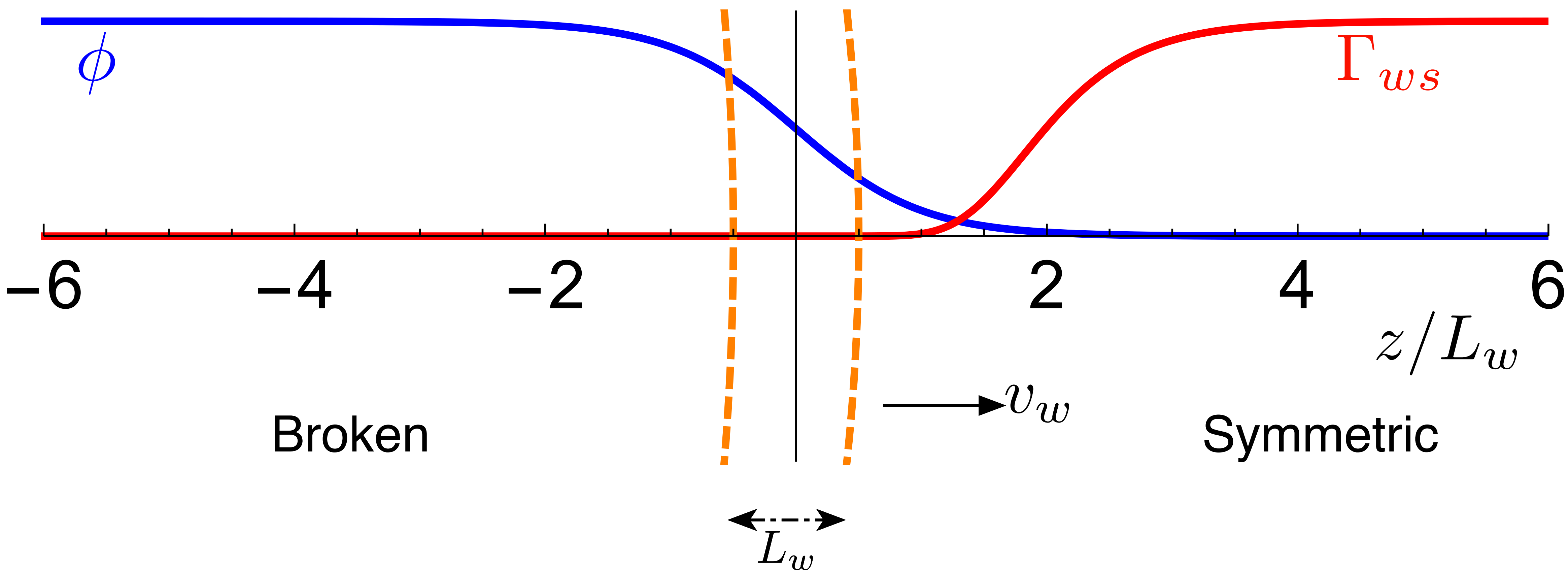
$$\Gamma_{ws} = 10^{-6}\, T\, \exp(-a\phi(z)/T)$$
$$\Downarrow$$
$$\frac{h}{T} \geq 1$$

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

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)

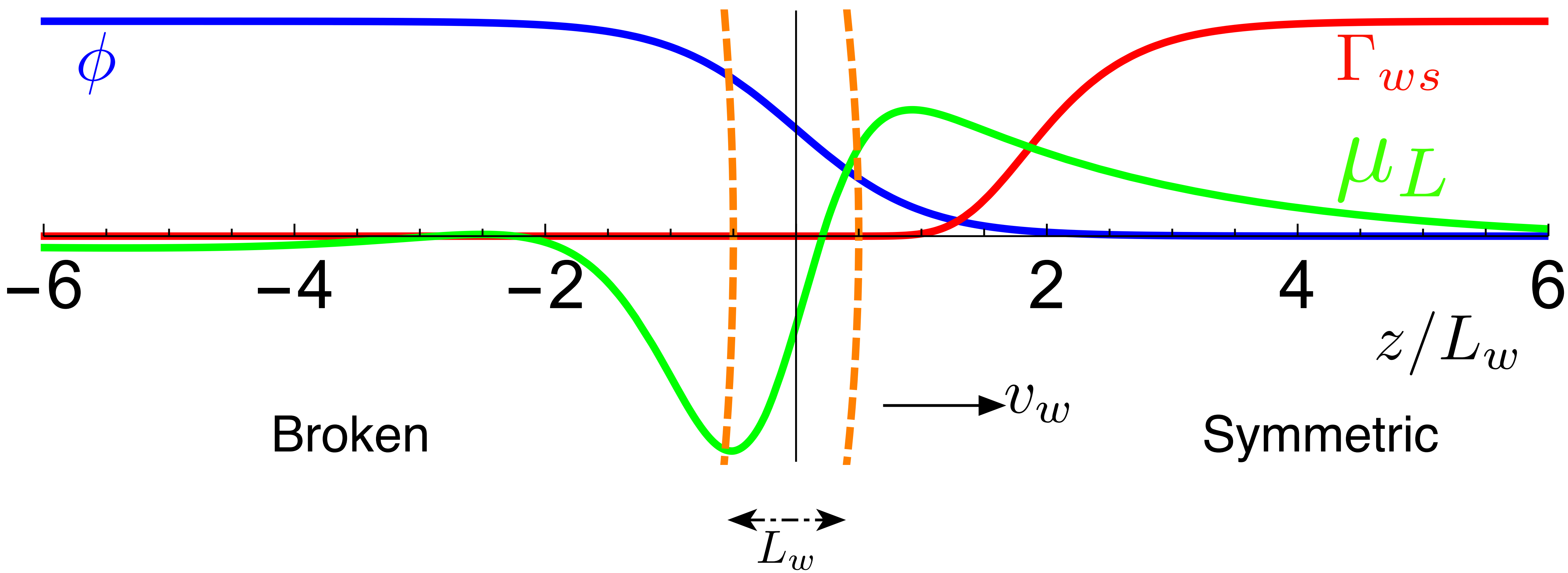
$$\Gamma_{ws} = 10^{-6}\, T \exp(-a\phi(z)/T)$$
$$\Downarrow$$
$$\frac{h}{T} \geq 1$$

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

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)

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

$$\Downarrow$$

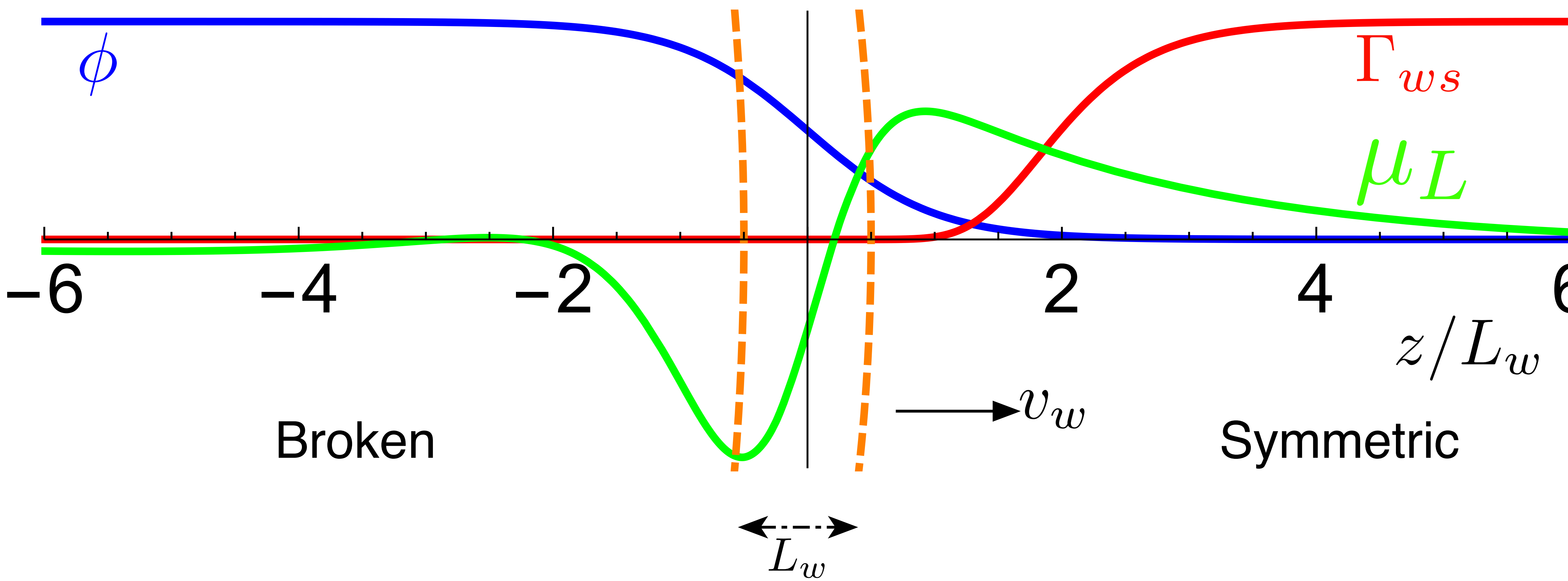
$$\frac{h}{T} \geq 1$$

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

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)

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

$$\Downarrow$$

$$\frac{h}{T} \geq 1$$

2. Sakharov condition (CP-violation)

3. Sakharov condition (out of equilibrium)

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

Much too small!

(measured: η_B~8.9 10^{-11})

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

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

Jarlskog constan…

Based solely on reflection coefficients

CP-violation in the SM and beyond

In the SM: $\eta_B \lesssim 10^{-2} \Delta_{CP}$ ... poshnikov '93

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

Much too small!

(measured: η_B~8.9 10^{-11})

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

Jarlskog constant ...

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

CP-violation in the SM and beyond

In the SM: $\eta_B \lesssim 10^{-2} \Delta_{CP}$ …poshnikov '93

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

Much too small!

(measured: η_B~8.9 10^{-11})

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

Jarlskog constan…

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

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

Prokopec, Schmidt, Weinstock '03

Source for μ in SM

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

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

For constant y:

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

EW scale flavour physics

$\Rightarrow$ z dependent Yukawas

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

Special case: 1 flavour

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

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

Agrees with semi-classical treatment

θ has to be space dependent!

This is not the case for two mixing flavours.

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

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

Unknowns

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

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

System and Kernel

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

Unknowns

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

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

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

System and Kernel

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

Unknowns

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

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

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

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

Kernel

- Weak Sphaleron
- Interactions (GF)
- Numerical factors

Source

- CP-violation

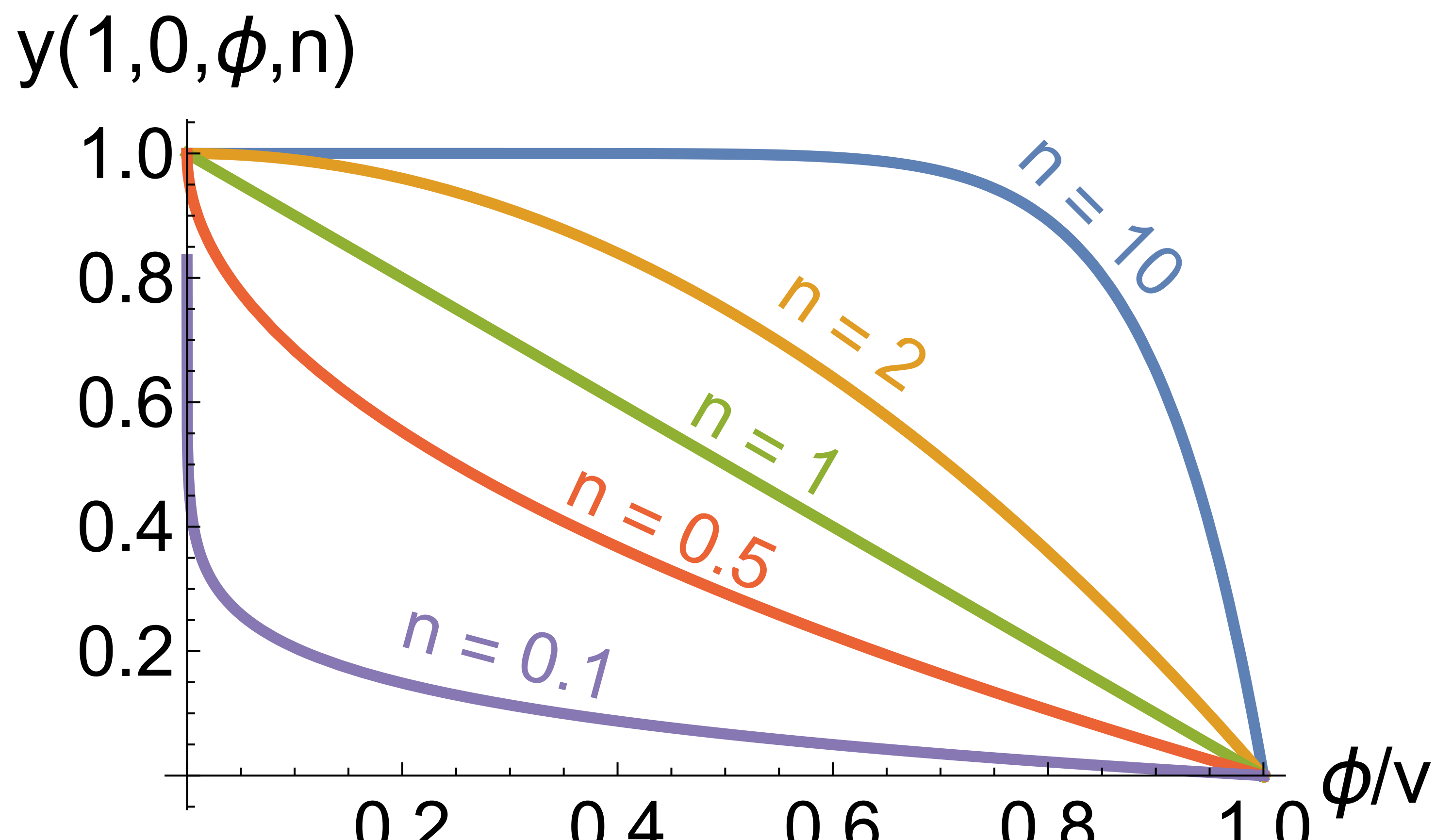
Varying Yukawas across the wall

Effective description following from Flavon-Higgs coupling

Broken phase; Free parameter; Higgs vev in broken phase

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

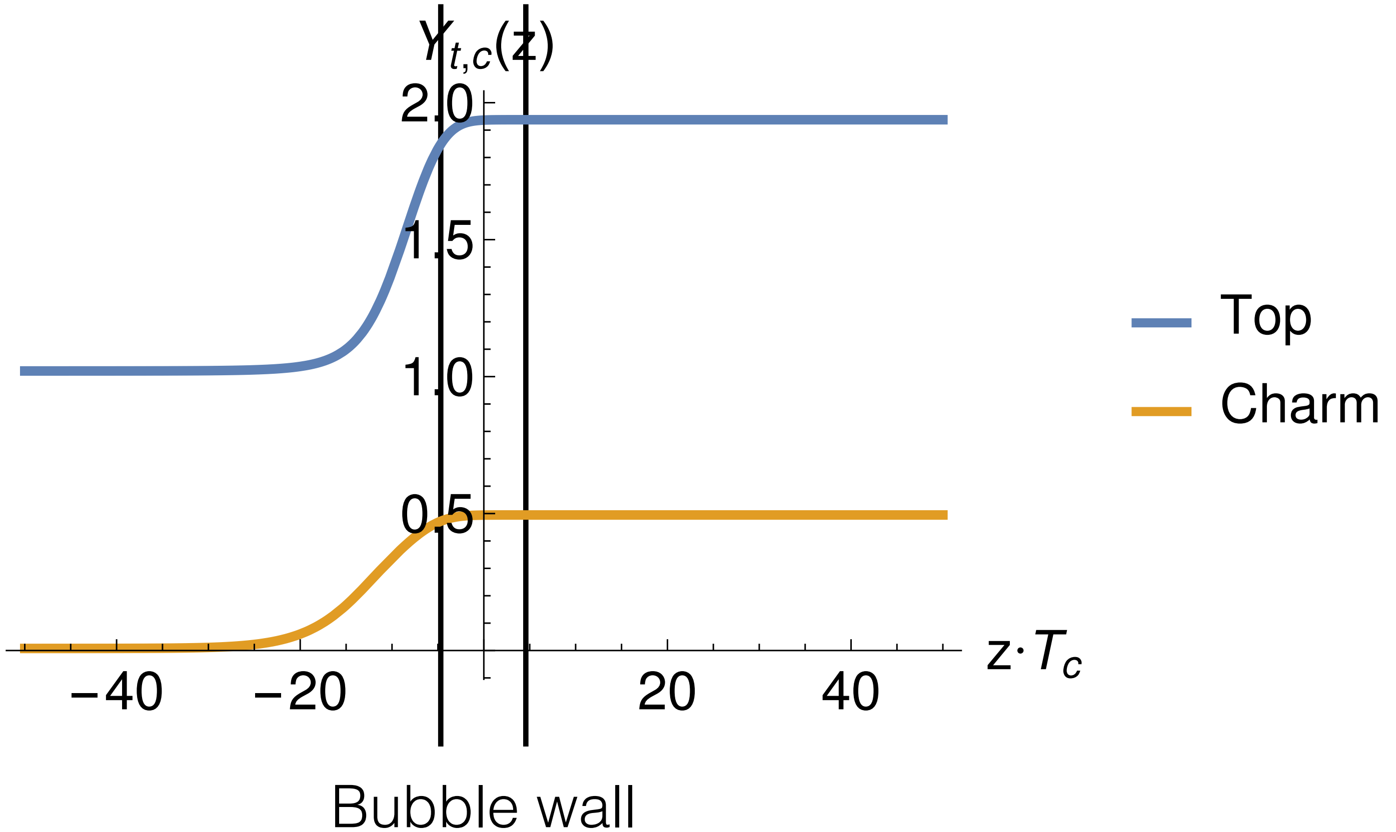
Symmetric phase; Higgs vev



Baldes, Konstandin, Servant '16
1608.03254 & 1604.04526

Yukawas

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



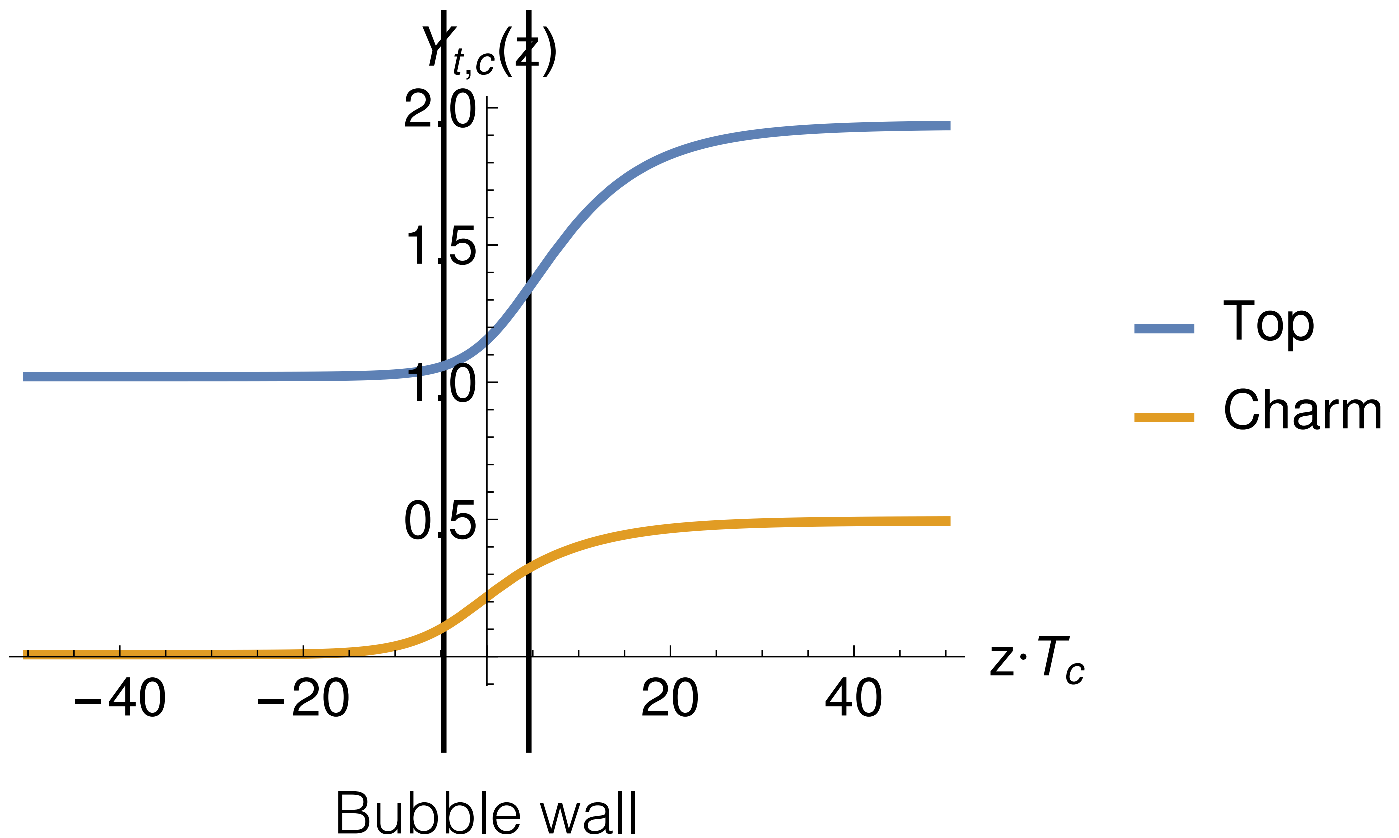
$n = 10$

← Broken phase

Symmetric phase →

Yukawas

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



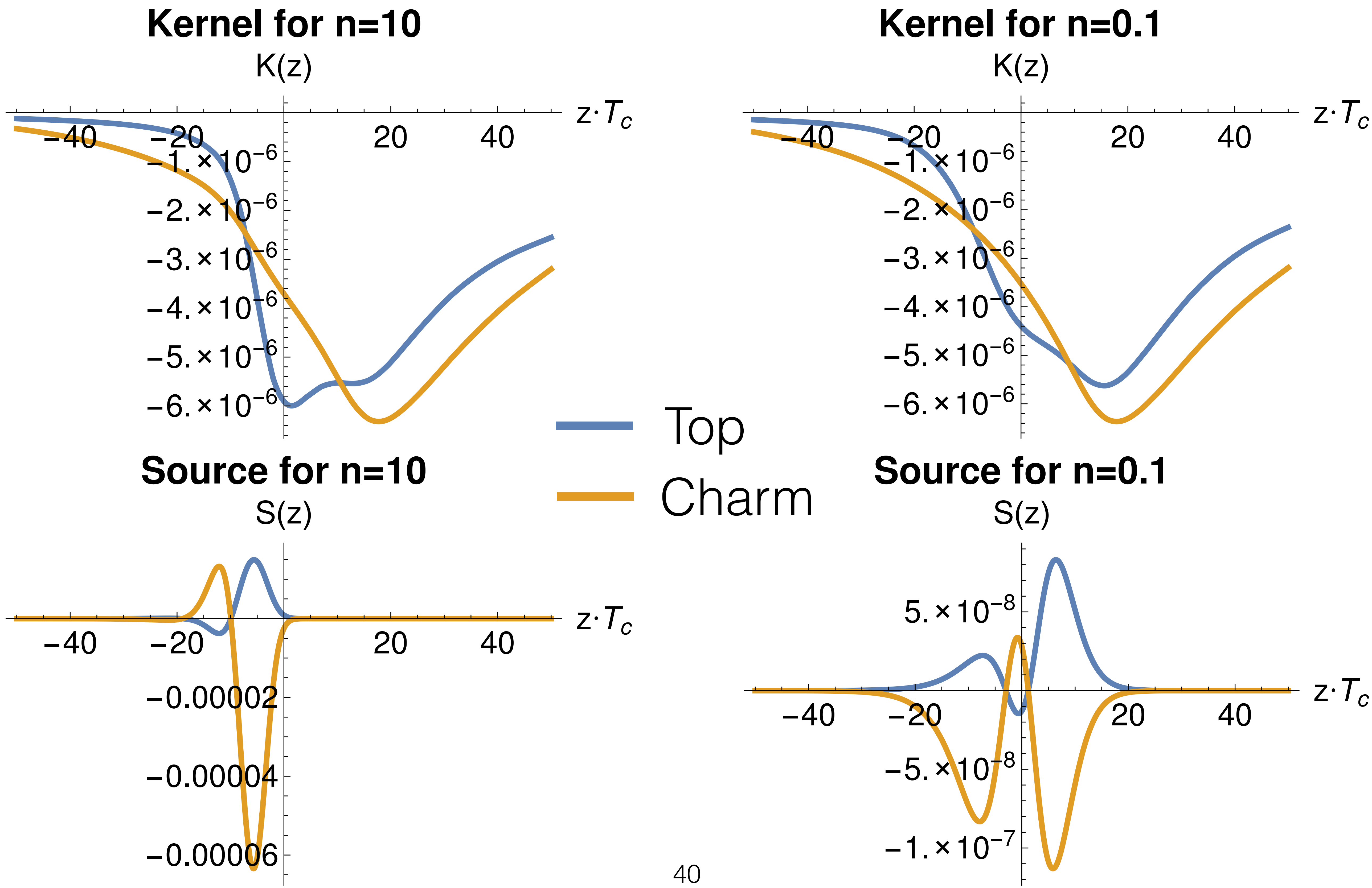
$$n = 0.5$$

Broken phase

Symmetric phase

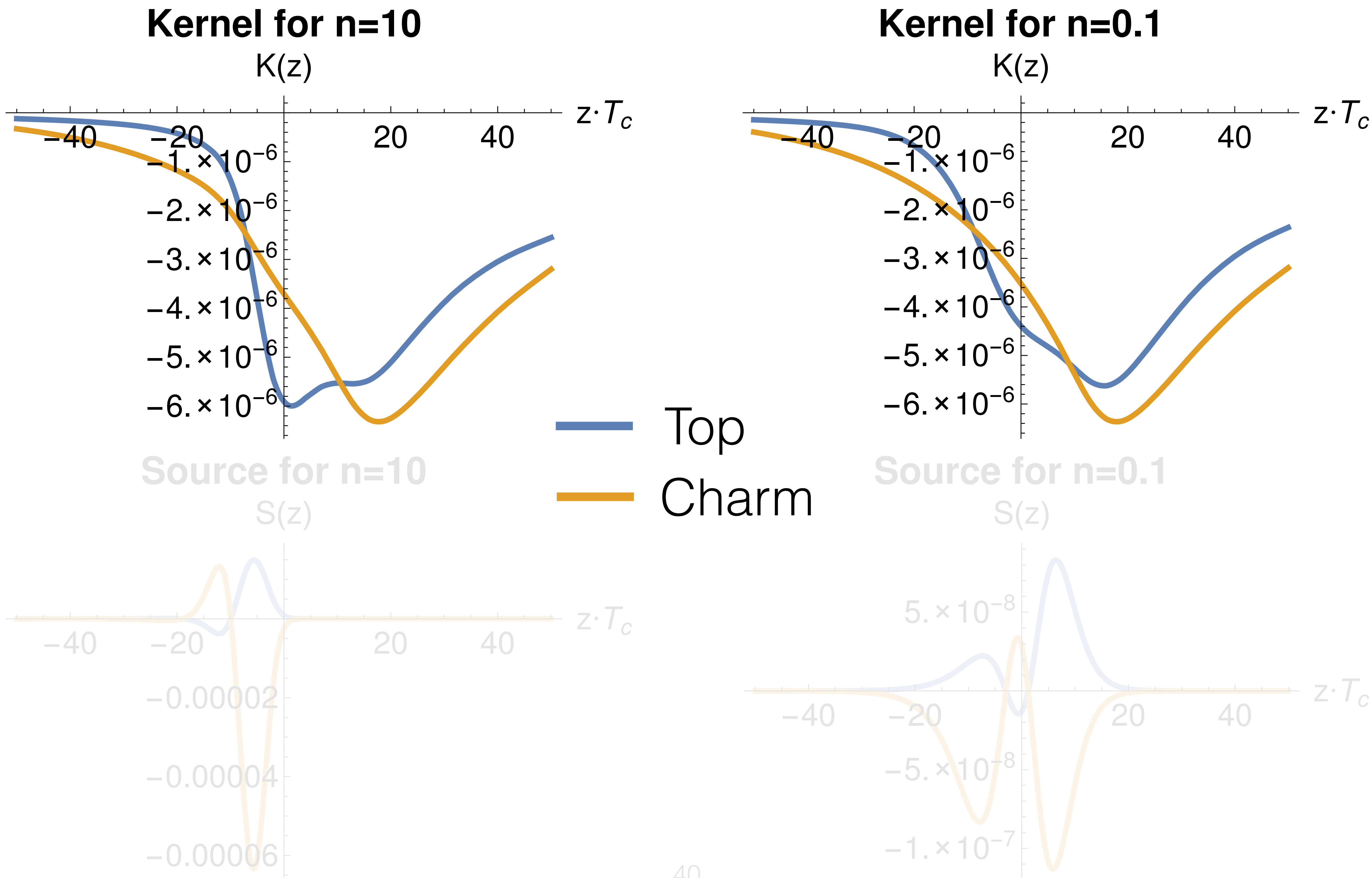
$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0\, K_i(z_0)\, S_i(z_0)$$

$\eta_B \approx 5.5 \cdot 10^{-10}$ $\eta_B \approx 2.1 \cdot 10^{-12}$

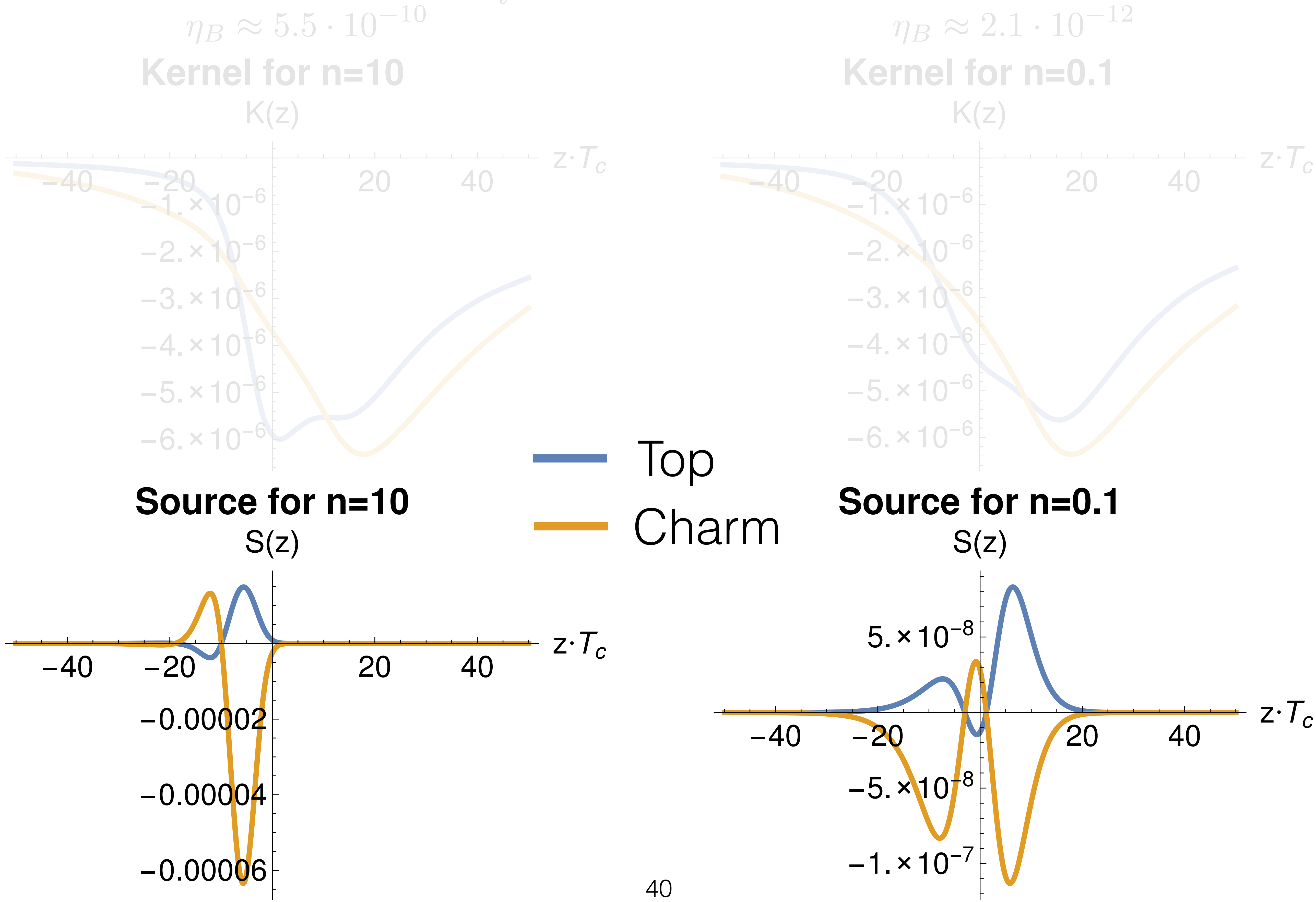


$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0\, K_i(z_0)\, S_i(z_0)$$

$\eta_B \approx 5.5 \cdot 10^{-10}$ $\eta_B \approx 2.1 \cdot 10^{-12}$

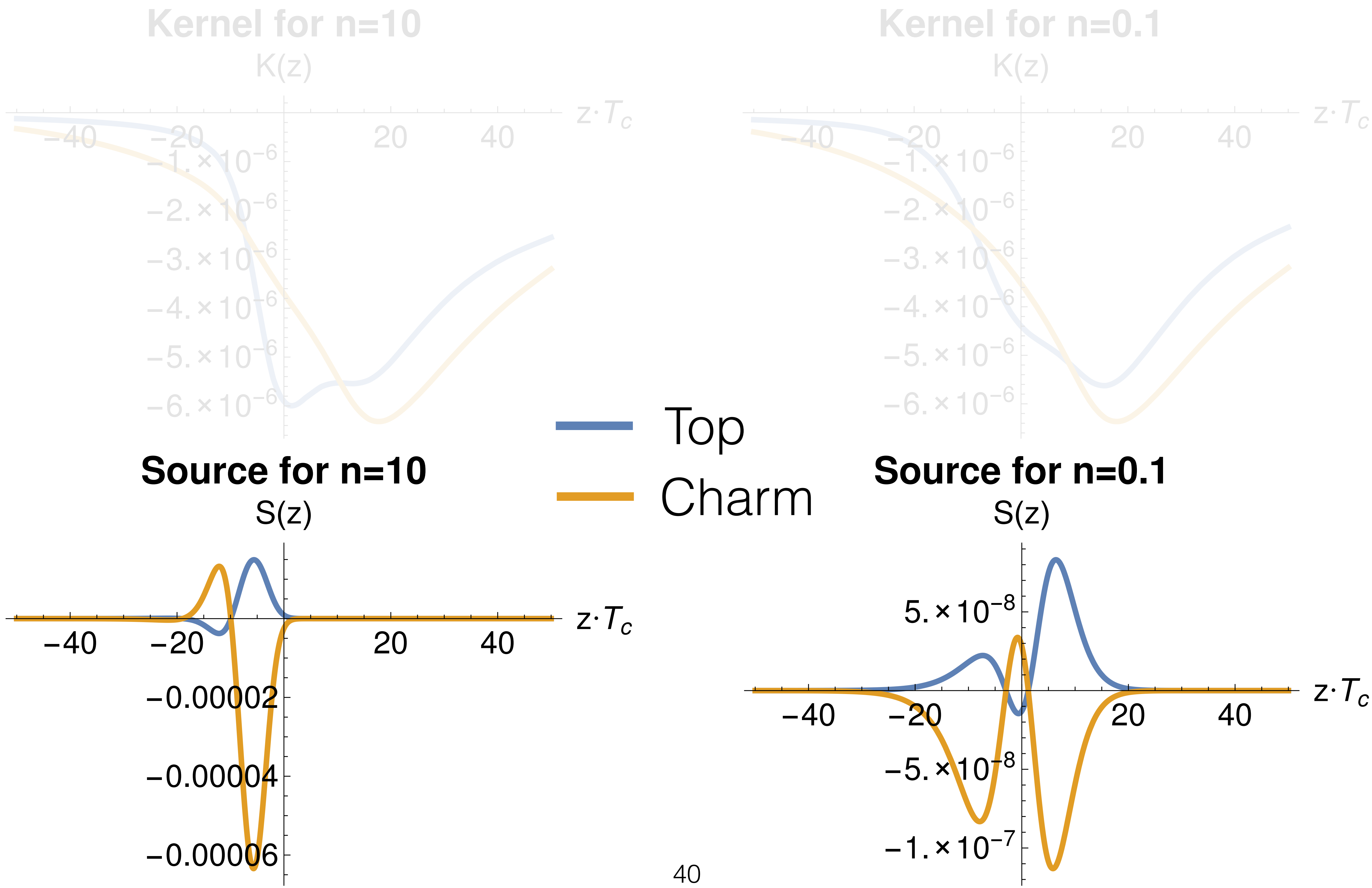


$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0 \, K_i(z_0) \, S_i(z_0)$$



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

$\eta_B \approx 5.5 \cdot 10^{-10}$ $\eta_B \approx 2.1 \cdot 10^{-12}$



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
In preparation

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

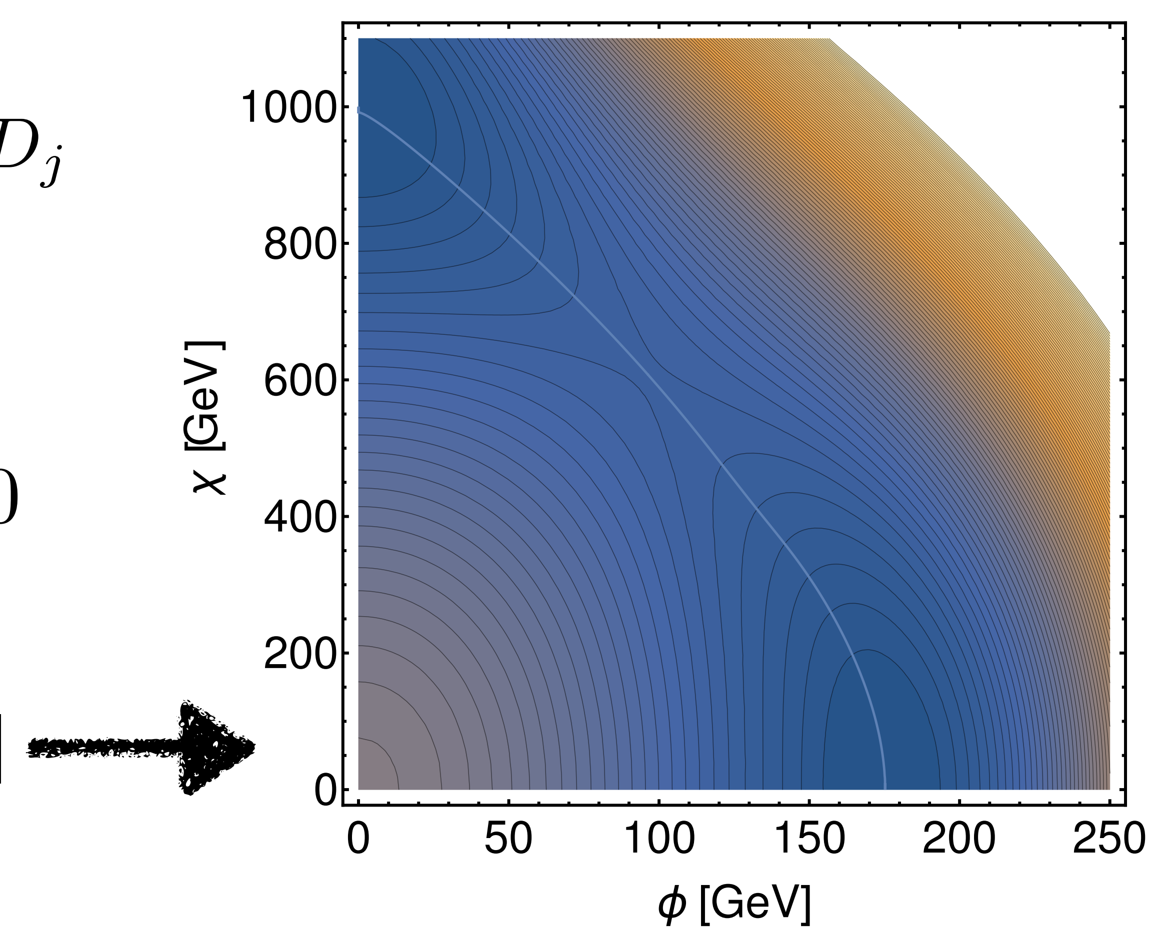
$$\mathcal{L} \supset \tilde{y}_{ij} \left(\frac{\langle \chi \rangle}{\Lambda_\chi} \right)^{\tilde{n}_{ij}} \bar{Q}_i \tilde{\phi} U_j + y_{ij} \left(\frac{\langle \chi \rangle}{\Lambda_\chi} \right)^{n_{ij}} \bar{Q}_i \phi D_j$$

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

VEVs during EWSB

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

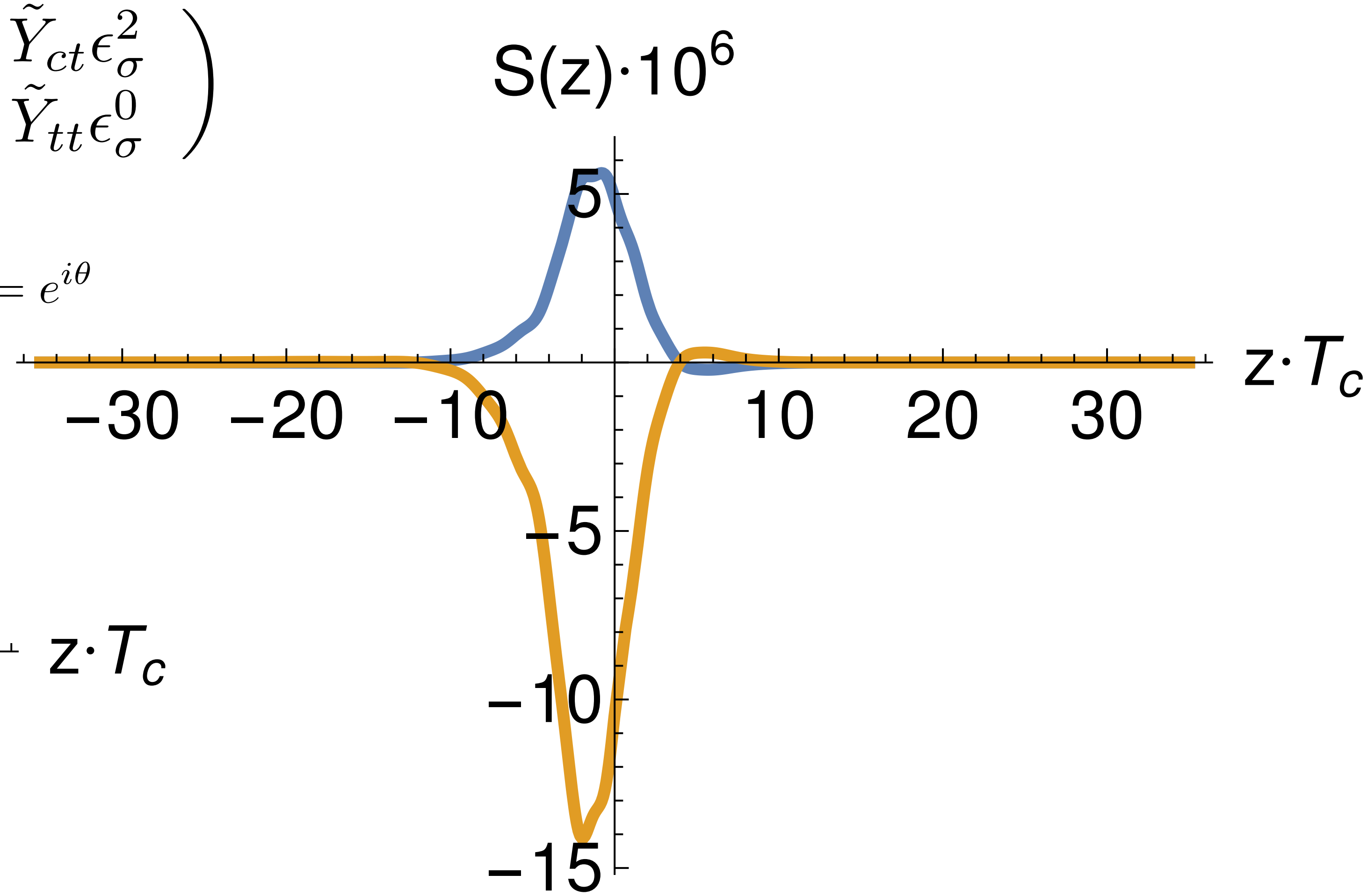
$\chi - \phi$ -Potential

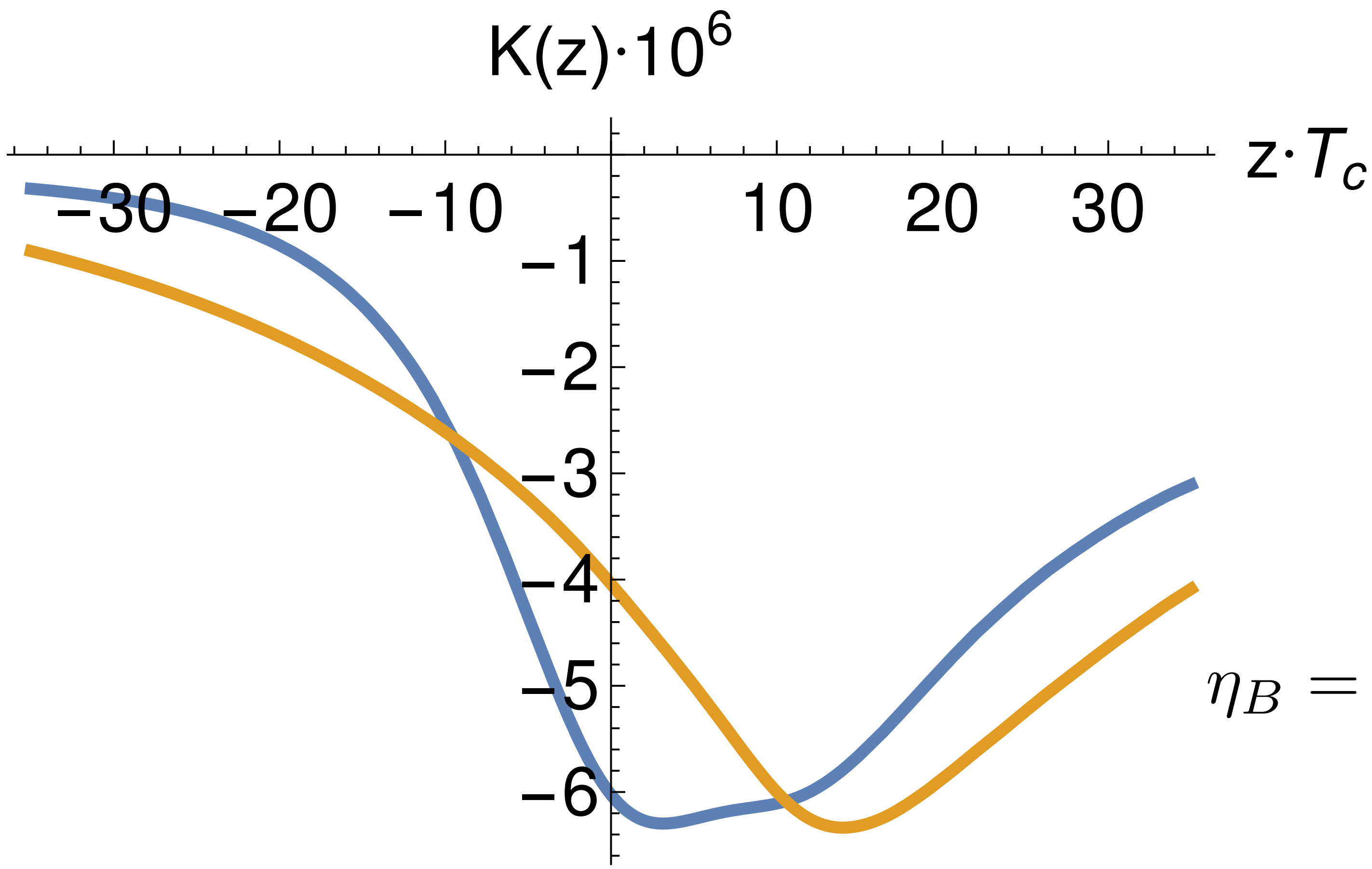


Froggat-Nielsen

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

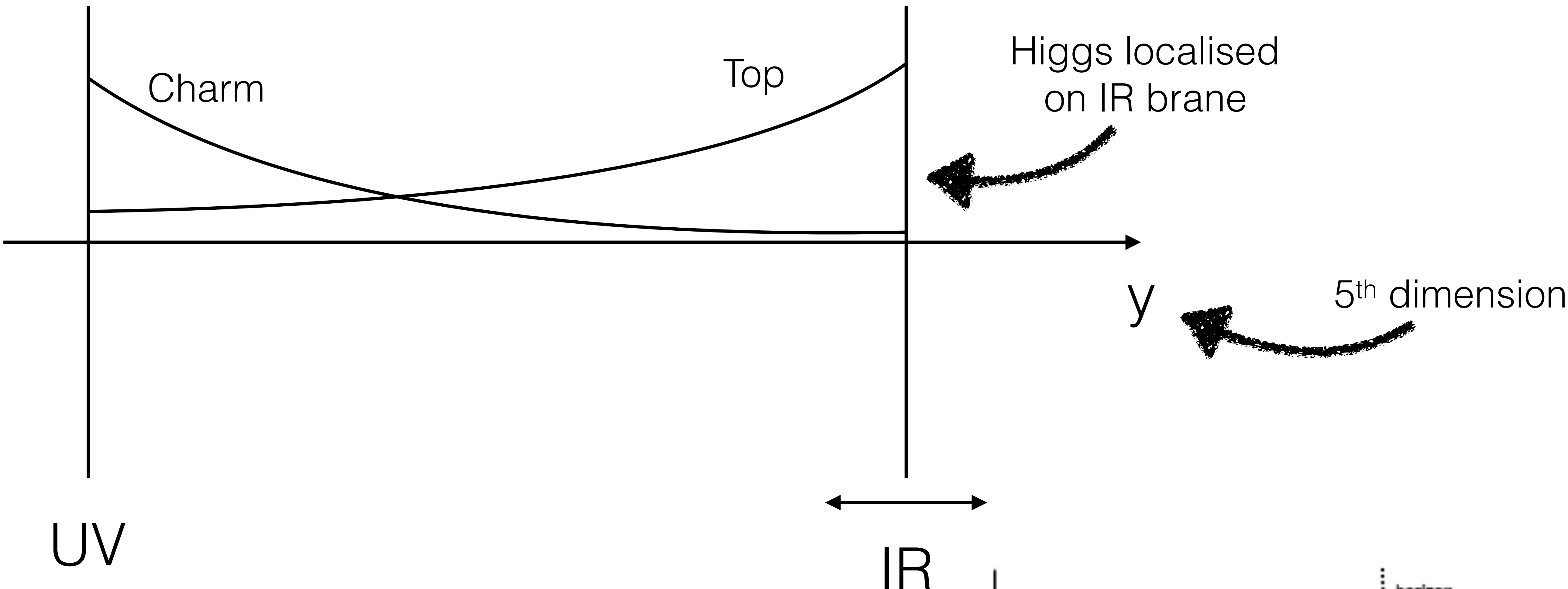
$$\tilde{y}_{i\neq j} = \tilde{Y}_{i\neq j} = 1 \qquad \tilde{y}_{tt} = \tilde{Y}_{tt} = 1/2 \qquad \tilde{y}_{cc} = \tilde{Y}_{cc} = e^{i\theta}$$



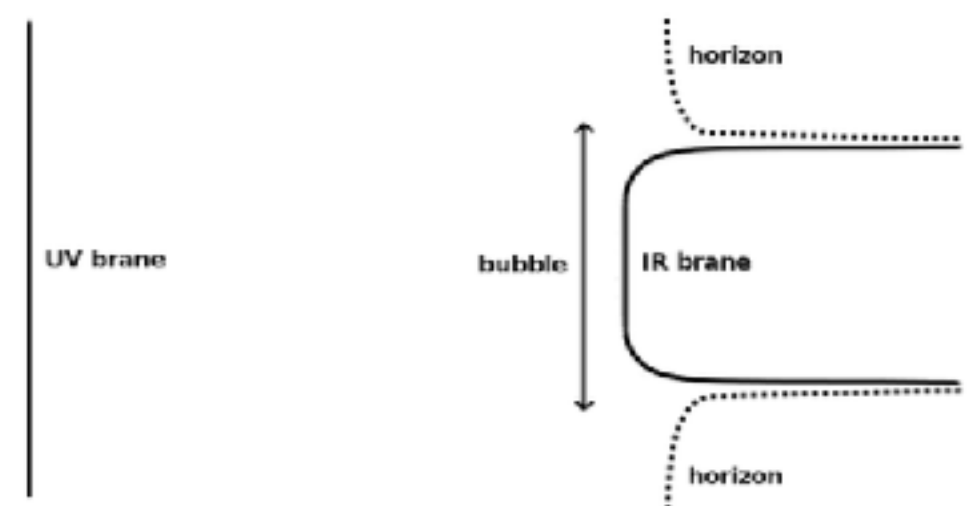


$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}z_0\, K_i(z_0)\, S_i(z_0) \simeq 1.15 \cdot 10^{-10}$$

Randall-Sundrum



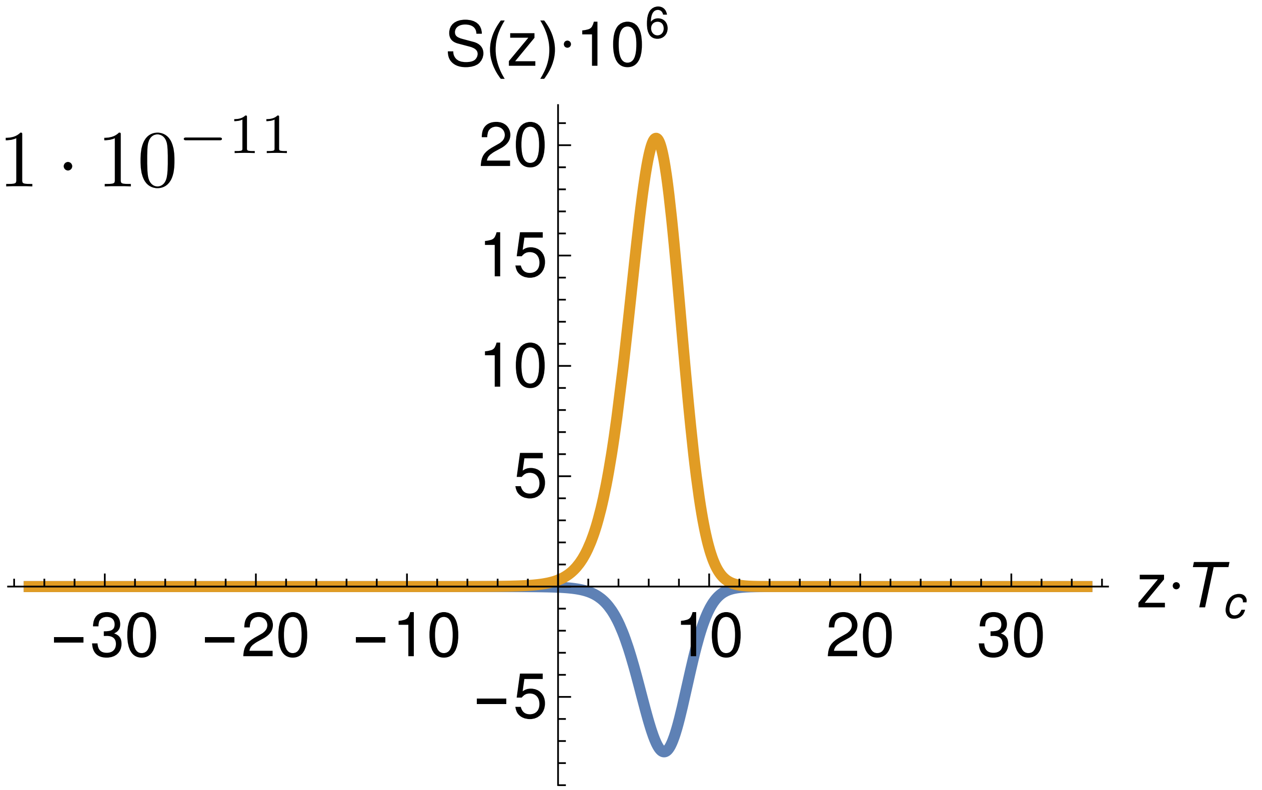
At high temp. -> AdS-Schwarzschild
Low temp. -> RS metric
—> “Brane Nucleation”

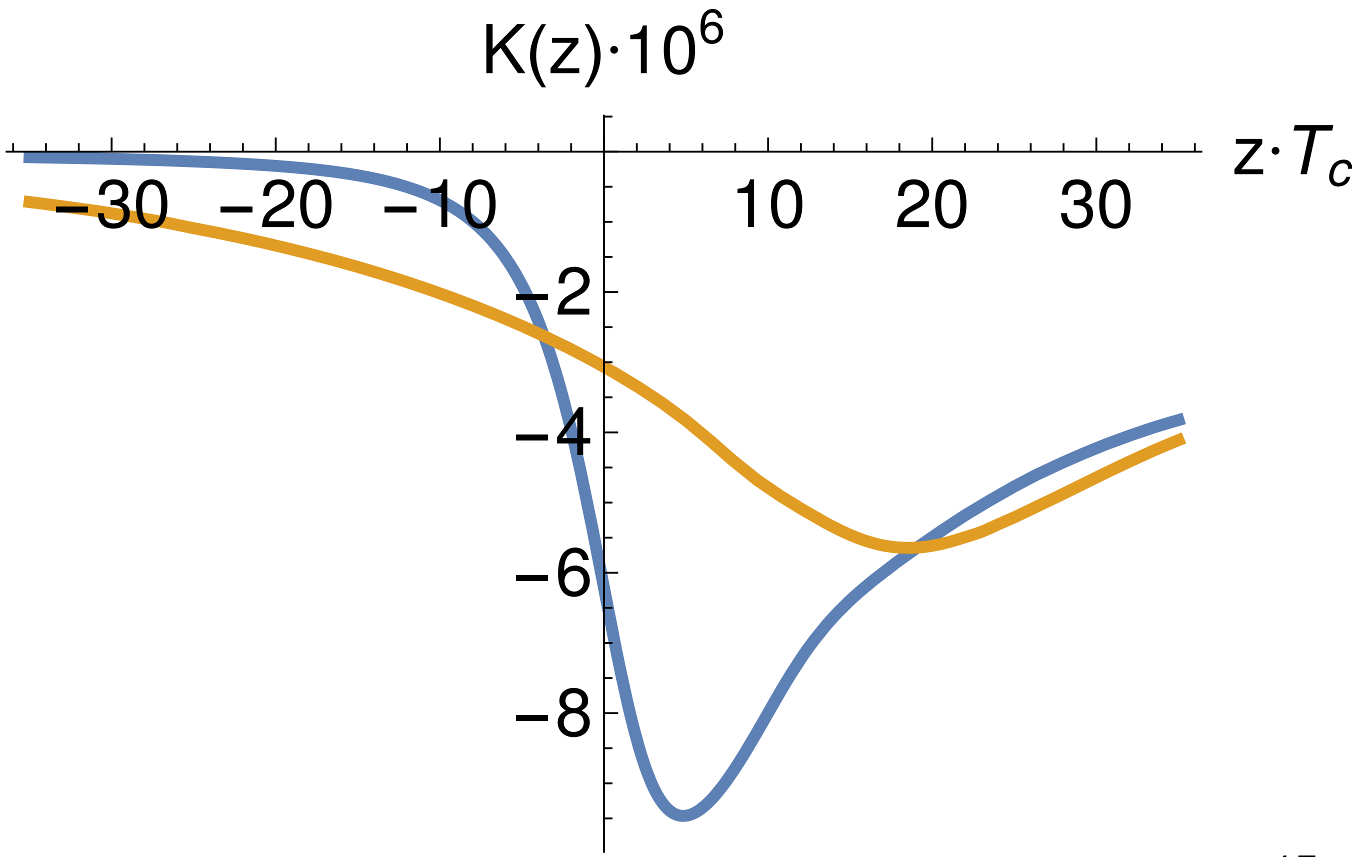


Von Harling, Servant ‘16
1612.02447

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*

⇓

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:

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

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

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

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

Interactions

Source

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

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

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

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

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

Interactions:

Couple different particle species together

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

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

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

Interactions:
Couple different particle species together

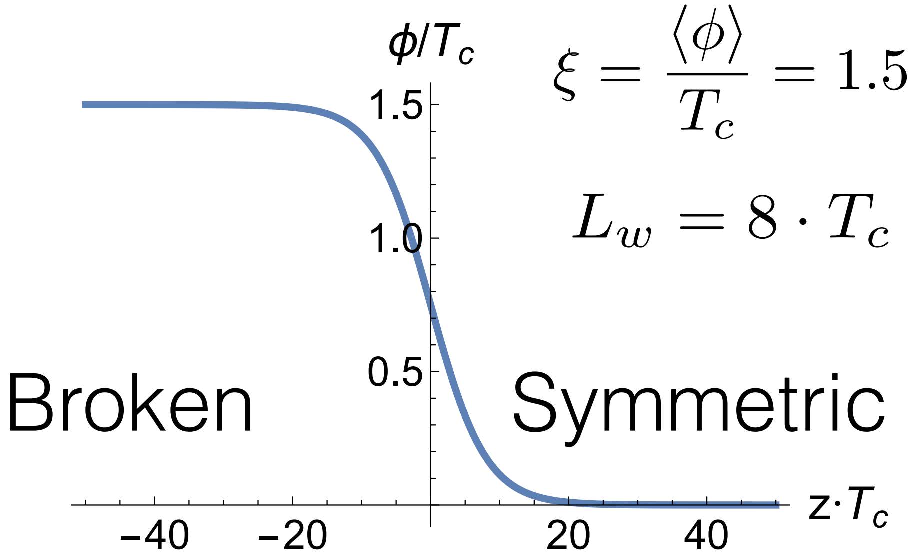
- Yukawa interactions e.g. $t_L \leftrightarrow t_R + h$ — $\Gamma_{y,q} = 4.2 \times 10^{-3}\, y_q^2\, T$
- Helicity flip e.g. $t_L \leftrightarrow t_R$ — $\Gamma_{m,q} = \frac{m_q^2}{63T}$
- W-scattering e.g. $t_L \leftrightarrow b_L$ — $\Gamma_W = \frac{T}{60}$
- Higgs number violation $h \leftrightarrow 0$ — $\Gamma_h = \frac{m_W^2}{50T}$
- Strong sphaleron all L $\leftrightarrow$ all R — $\Gamma_{ss} = 4.9 \times 10^{-4} T$

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. $t_L \leftrightarrow t_R + h$ $\quad \Gamma_{y,q} = 4.2 \times 10^{-3}\, y_q^2\, T$
- Helicity flip e.g. $t_L \leftrightarrow t_R$ $\quad \Gamma_{m,q} = \frac{m_q^2}{63T}$
- W-scattering e.g. $t_L \leftrightarrow b_L$ $\quad \Gamma_W = \frac{T}{60}$
- Higgs number violation $h \leftrightarrow 0$ $\quad \Gamma_h = \frac{m_W^2}{50T}$
- Strong sphaleron all L $\leftrightarrow$ all R $\quad \Gamma_{ss} = 4.9 \times 10^{-4} T$

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



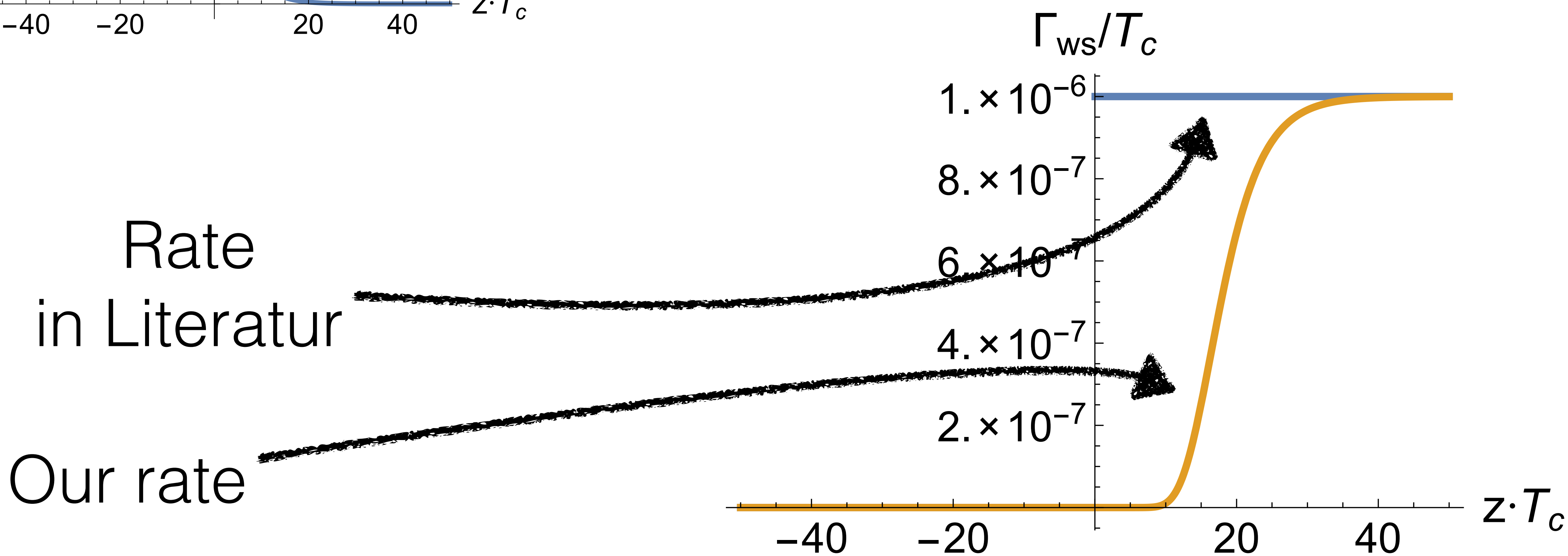
$$\xi = \frac{\langle\phi\rangle}{T_c} = 1.5$$

$$L_w = 8 \cdot T_c$$

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

$$a \approx 40$$

NEW



Overwiev

- Introduction to Electroweak Baryogenesis
- Model independent approach to Baryogenesis from varying Yukawas
    - CP-violation from varying Yukawas
    - Computation of the Baryon asymmetry
- Introducing Composite Higgs as prime example of this scenario
    - The Higgs-Dilaton potential
        - Higgs shift symmetry breaking
        - Conformal symmetry breaking
    - Two field tunneling
    - Results

What is new?

- Minimal coset $SO(5)/SO(4)$ insures custodial symmetry.

- Non-minimal cases typically contain additional singlets $\Rightarrow$ first order phase transition is easy to obtain Espinosa, Gripaios, Konstandin, Riva ‘11

- We study the dynamics of the conformal symmetry breaking at the same time as the EW symmetry breaking