Extended window for electroweak baryogenesis.

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Invisibles workshop, Bologna, 05-07-2024

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Universität Hamburg

This talk .

Conservative:

EW baryogenesis: One of the first baryogenesis proposals.

Minimal:

The only source of baryon number violation being used: Standard Model sphalerons (standard EW baryogenesis).

(≠ from the recent many models of baryogenesis during a 1st-order PT that combine bubbles + new source of B or L beyond the SM)

Motivations .

EW baryogenesis in a minimal SM extension that adresses:

-the Higgs hierarchy problem

-the flavour hierarchy

and does not require B nor L violations beyond the SM

Plan of this talk .

1- Generalities about the electroweak (EW) phase transition (EWPT)

2- High-temperature EW symmetry non-restoration effects

3- Application to EWPT in minimal Composite Higgs

Motivation .

We have to explain

Matter Anti-Matter asymmetry of the universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}$$

from BBN: $5.8<\eta_{10}<6.5$; from CMB: $6.08<\eta_{10}<6.16$

Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

(we need a process which can turn antimatter into matter)

2) C (charge conjugation) and CP (charge conjugation × Parity) violation

(we need to prefer matter over antimatter)

3) Loss of thermal equilibrium

(we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass, so no asymmetry can develop)

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$

η remains unexplained within the Standard Model

double failure:

- lack of out-of-equilibrium condition

- so far, no baryogenesis mechanism that works with only Standard Model CP violation (CKM phase)

2 out of 3 Sakharov's conditions missing

Sphalerons!

Determinant in all baryogenesis mechanisms whatever their energy scale

The Higgs VEV sets the scale of Standard Model baryon-number violation

"The" paper

Volume 155B, number 1,2 PHYSICS LETTERS 16 May 1985

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

V.A. KUZMIN, V.A. RUBAKOV

Institute for Nuclear Research of the Academy of Sciences of the USSR, Moscow, USSR

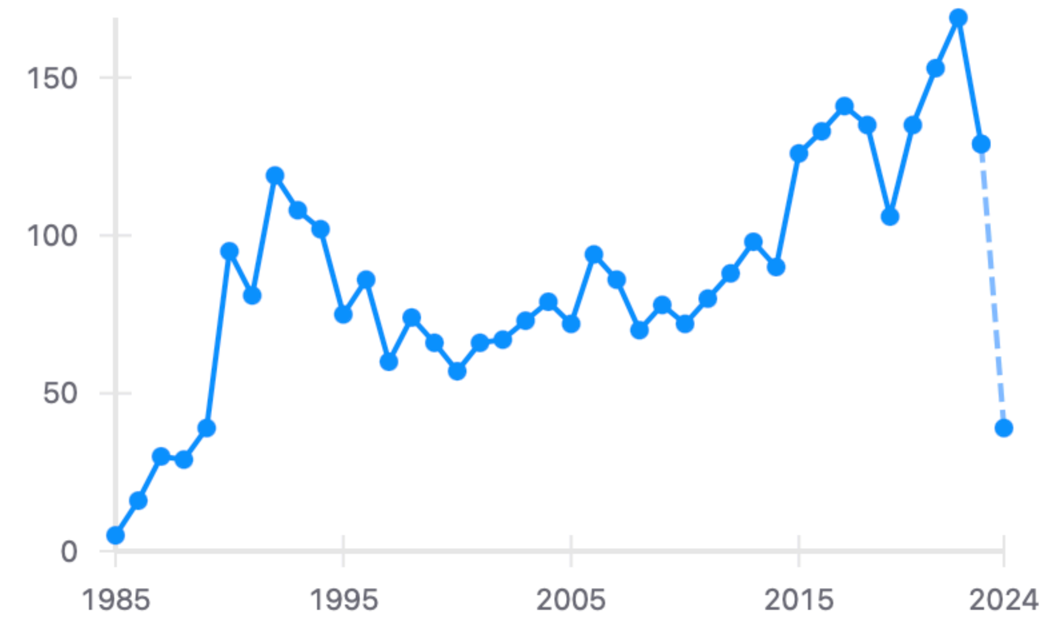
and

M.E. SHAPOSHNIKOV [1]

International Centre for Theoretical Physics, Trieste, Italy

Received 8 February 1985

Citations per year



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

T_{EWPT}: Temperature of the EW phase transition

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

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

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

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

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

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

Sphalerons' implications

2 main possibilities for baryogenesis:

1) B-L= 0 theory

(this talk)

Baryogenesis must take place at EW Phase Transition: EW baryogenesis

Advantage: connected to EW physics, testable

2) B-L≠ 0 theory

High-scale baryogenesis possible.

Disadvantage: typically difficult to test

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

This talk:

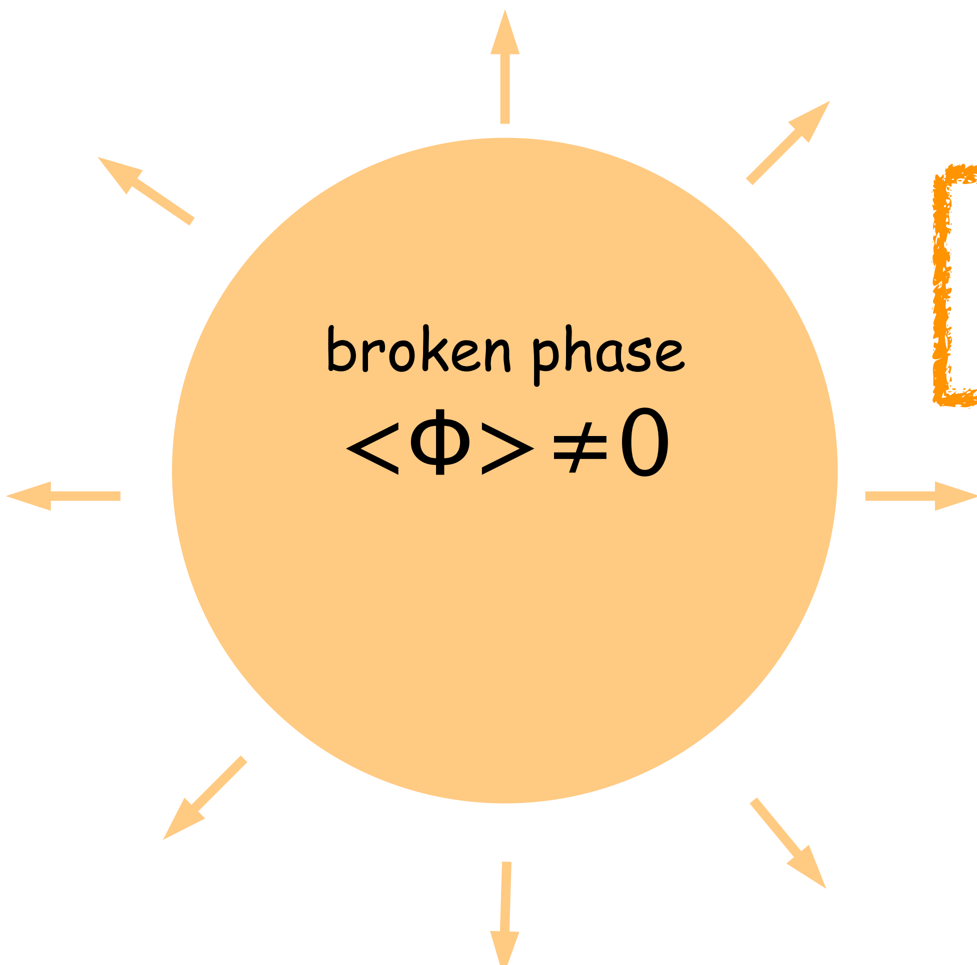
Baryogenesis at the EWPT
in a minimal B-L=0 SM extension.

To satisfy 3rd Sakharov ingredient
(departure form thermal equilibrium):

EWPT has to be 1st-order!

EW baryogenesis during a first-order EW phase transition

Kuzmin, Rubakov, Shaposhnikov'85
Cohen, Kaplan, Nelson'91



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

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

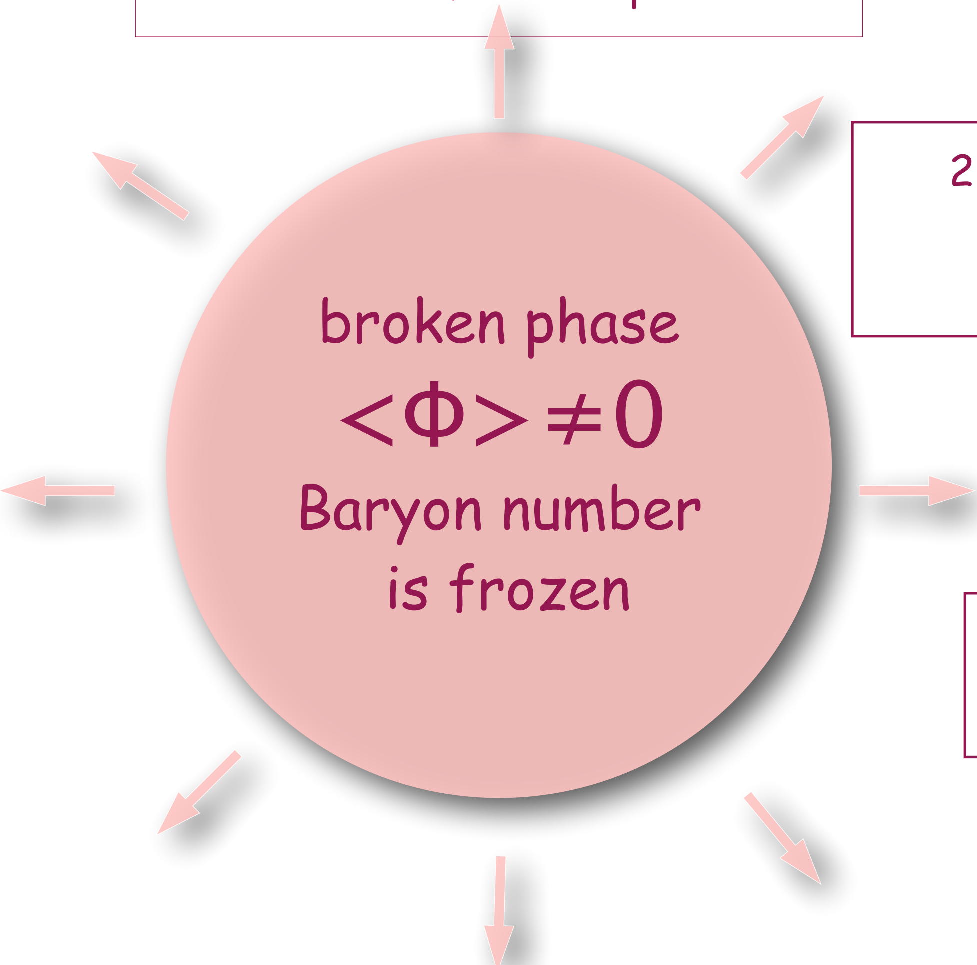
T_n $\equiv$ nucleation temperature

EW baryogenesis during a first-order EW phase transition .

Kuzmin, Rubakov, Shaposhnikov'85

Cohen, Kaplan, Nelson'91

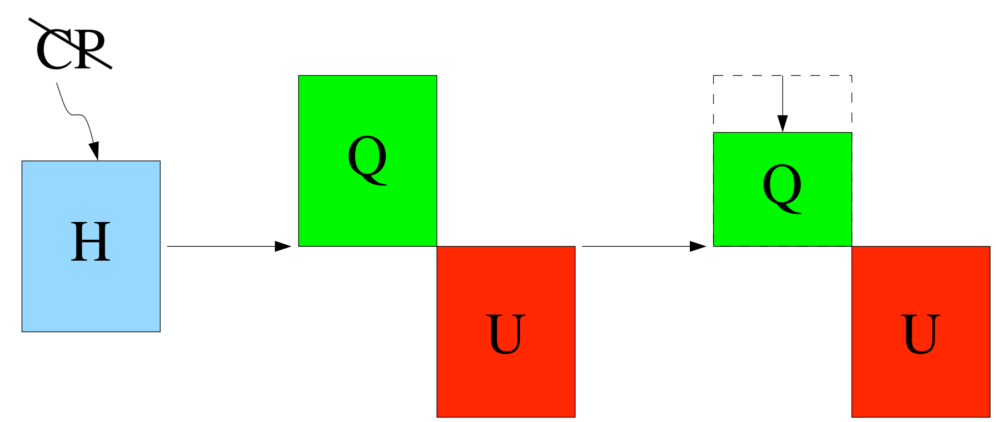
1) nucleation and expansion of bubbles of broken phase



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

Chirality Flux in front of the wall

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



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

T_n $\equiv$ nucleation temperature

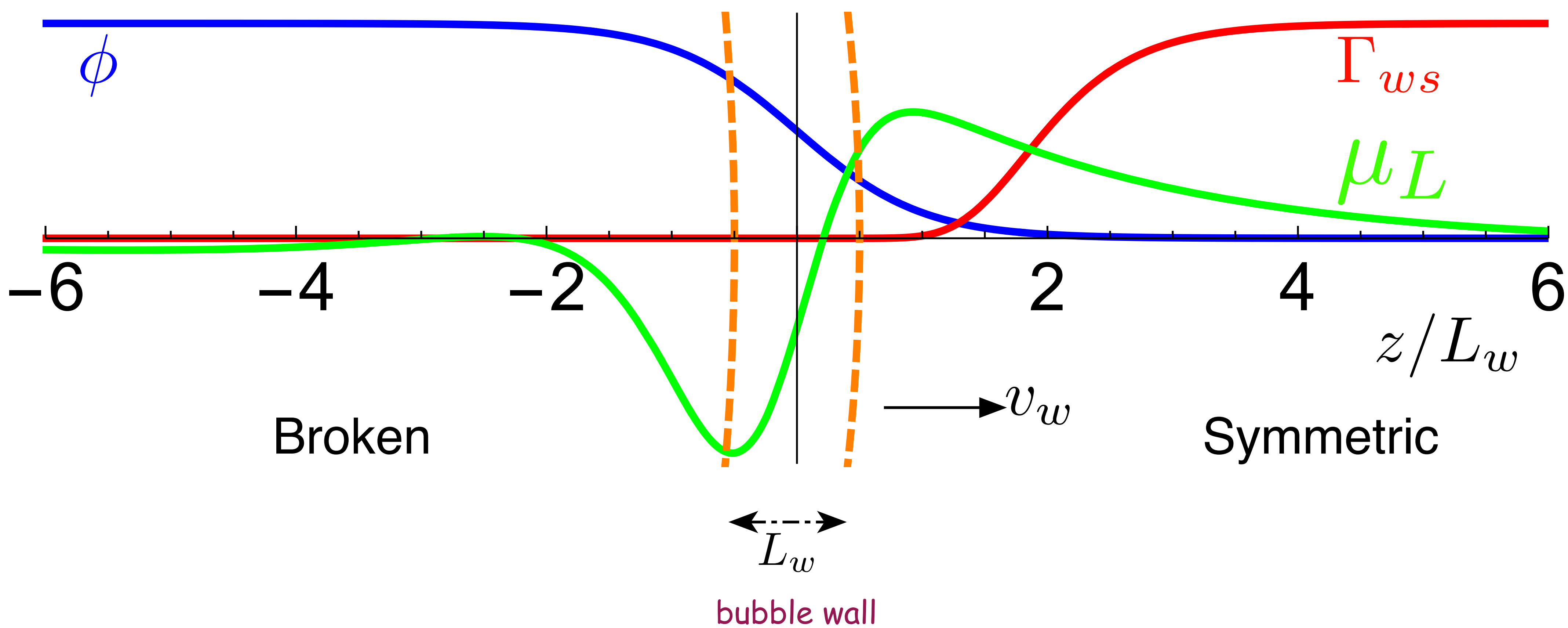
The EW baryogenesis miracle .

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

bubble wall velocity

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

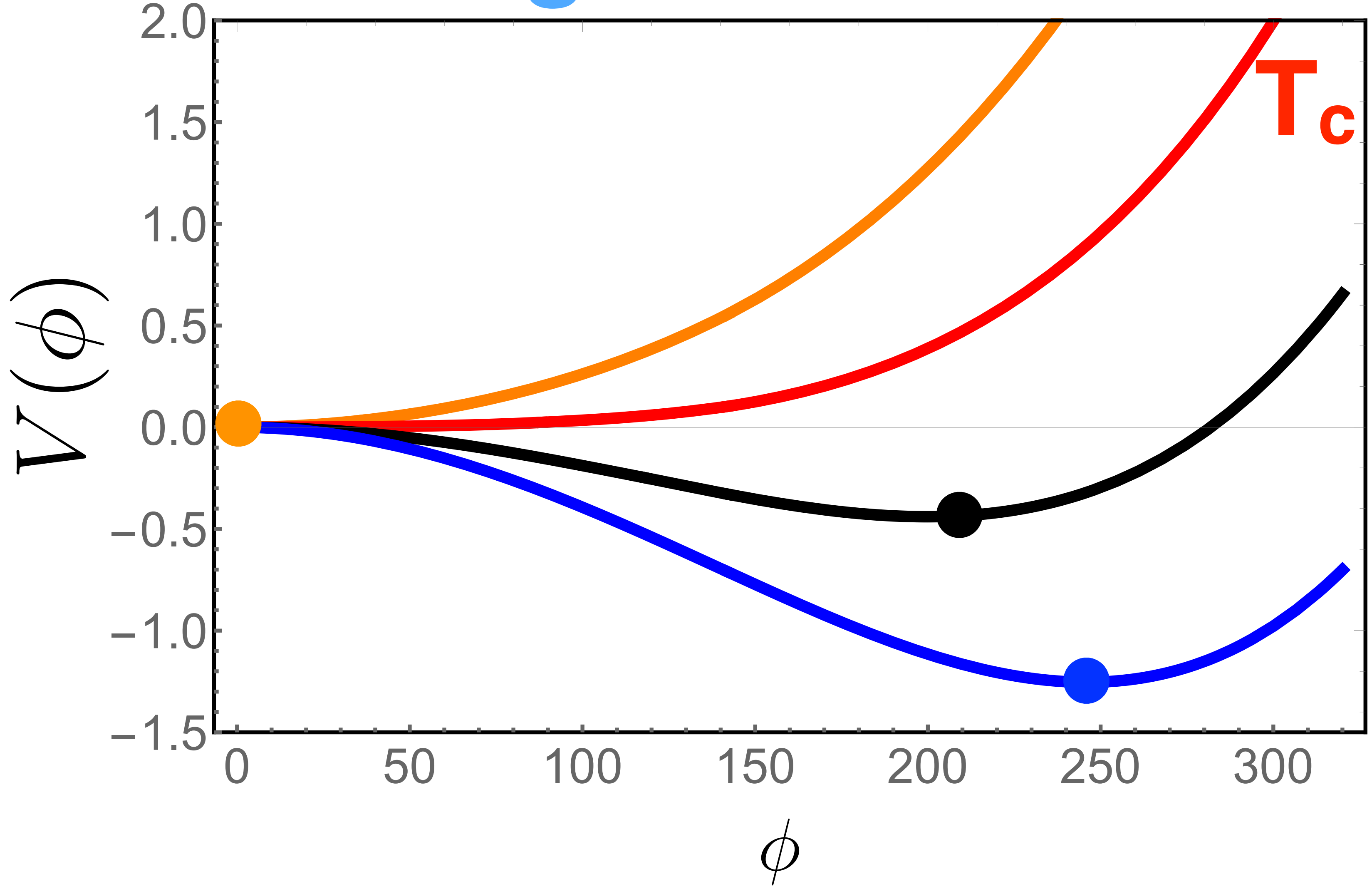
: sphaleron rate

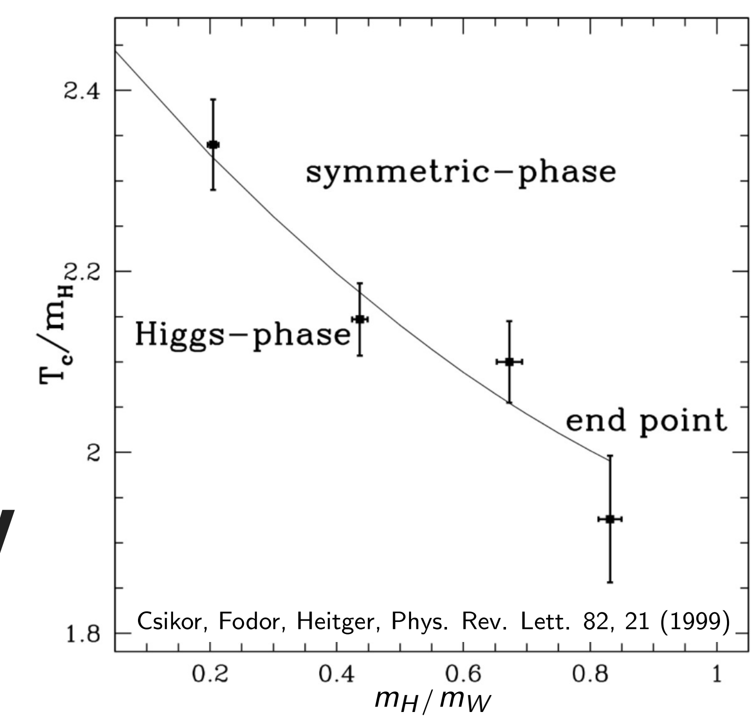


HEATING UP THE STANDARD MODEL .

EW sym. restored at T≳160 GeV***

through a smooth crossover





No departure from thermal equilibrium

It would have been different if m_H≲70 GeV

***1404.3565

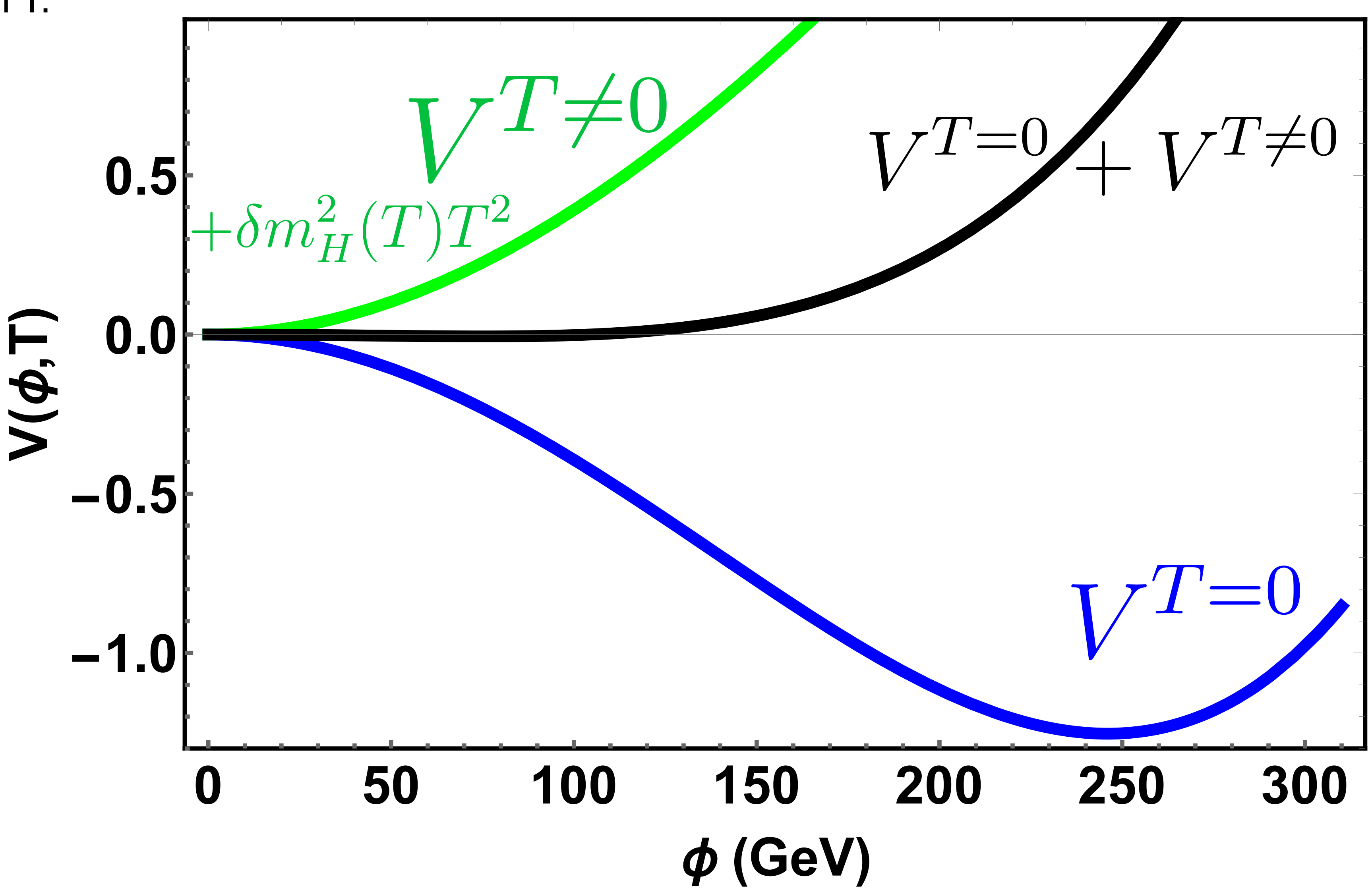
HIGH TEMPERATURE EW SYM. RESTORATION.

At one-loop:

$$V_{\text{eff}} = \boxed{V_{\text{tree}}(\phi) + V_1^0(\phi)} + \boxed{V_1^T(\phi,T) + V_{\text{Daisy}}(\phi,T)}.$$

Tree level — 1-loop T=0 — 1-loop T≠0 — Daisy resummation

At high T:



—> Symmetry restoration at Tc

HIGGS EFFECTIVE POTENTIAL AT HIGH TEMPERATURE

At one-loop:

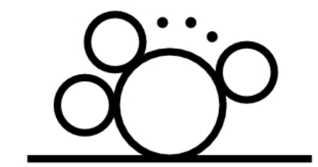
$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T).$$

Tree level

1-loop T=0

1-loop T≠0

Daisy resummation



$$V_1^T(\phi, T) = \sum_i (\Delta V_{b,i}^T + \Delta V_{f,i}^T)$$

bosons

fermions

Sum over all particles coupled to the Higgs

$$\propto T \sum_i \pm g_i \int p^2 dp \log[1 \mp e^{-\sqrt{p^2+m_i^2(\phi)}/T}]$$

For high-T, m/T<<1:

$$\Delta V_{b,i}^T \simeq -\frac{\pi^2 T^4}{90} + \frac{T^2 m_i^2(\phi)}{24}$$

$$\Delta V_{f,i}^T \simeq -\frac{7\pi^2 T^4}{180} + \frac{T^2 m_i^2(\phi)}{12}$$

depth of negative correction to $V_{\rm eff}$ at m=0

sets the thermal mass

$$\delta m_H^2(T) \simeq +T^2 \left[\frac{y_t^2}{4} + \frac{\lambda}{2} + \frac{3g^2}{16} + \frac{g'^2}{16}\right]$$

Higgs Thermal Mass in the SM

What makes the EW phase transition 1st-order ?

> O(1) modifications to the Higgs potential

> Extra **EW-scale** scalar(s) coupled to the Higgs

What makes the EW phase transition 1st-order ?

> Extra **EW-scale** scalar(s) coupled to the Higgs

2 main classes of models

1- Standard polynomial potentials, e.g extra singlet S, 2Higgs-Doublet Model… under specific choices of parameters

- -Effect of cross-quartic $\lambda_{\phi S}\phi^2 S^2$
- -Moderate strength of EW phase transition, $\frac{\phi}{T} \lesssim \ \mathrm{O}(1)$

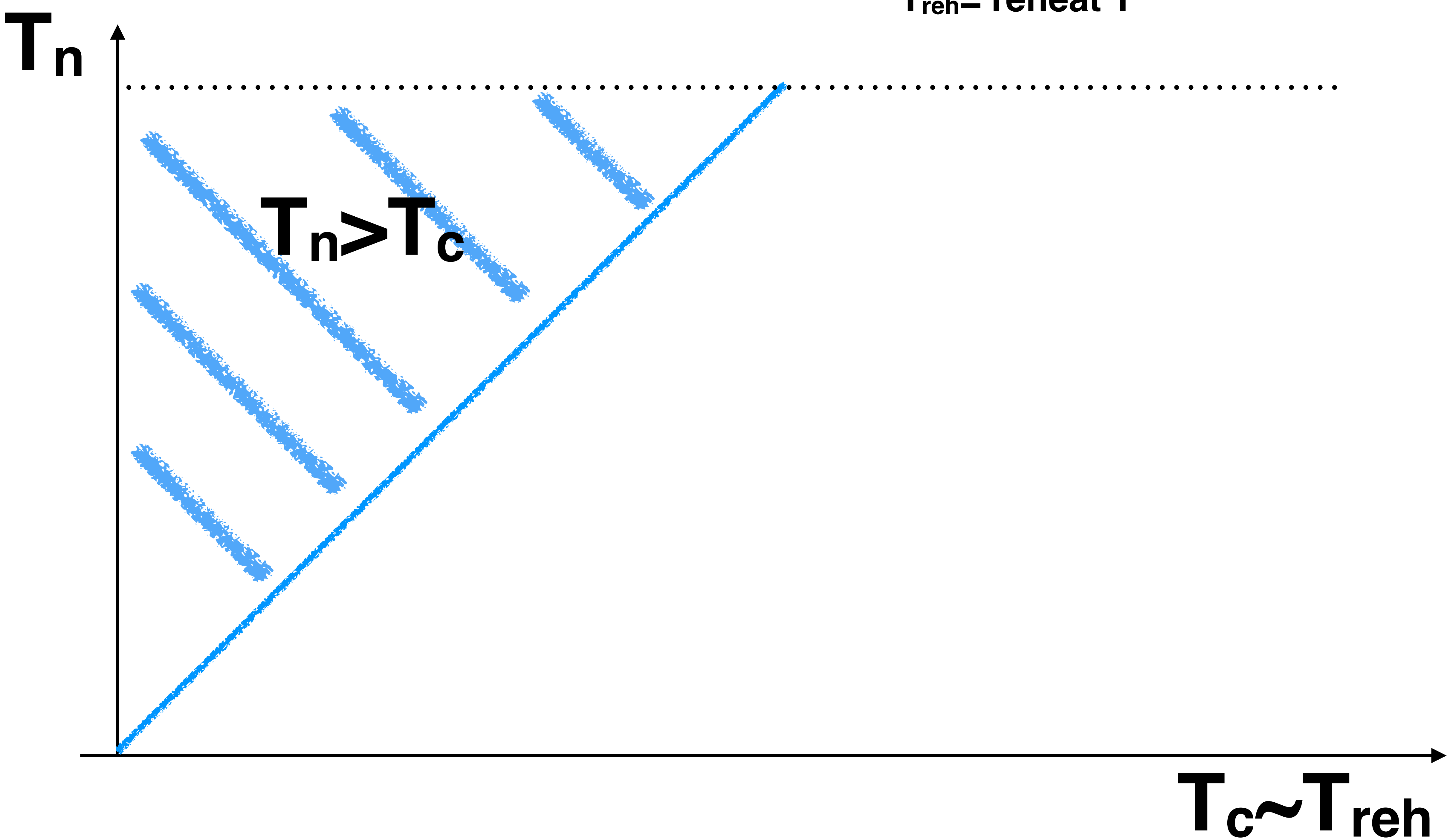
2- Higgs emerging during confinement phase transition of strongly interacting new sector.

- -Higgs potential is trigonometric function
- -Fate of the Higgs ruled by the dilaton
- -Unbounded strength, $\frac{\phi}{T}$ can naturally be >>1

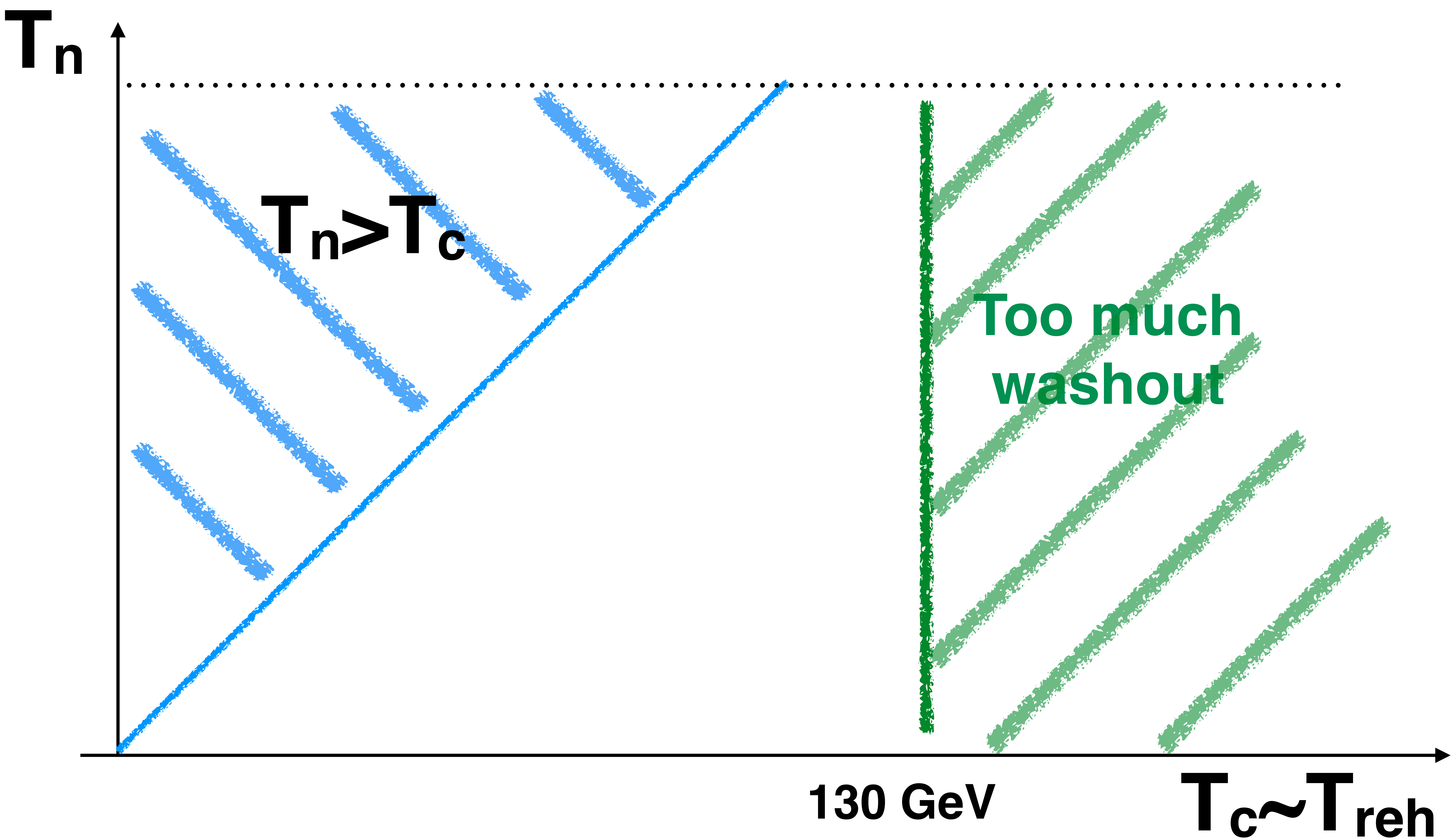
First-order EW phase transition driven by an extra scalar .

Consider the $[T_c, T_n]$ plane

T_c=critical T,
T_n= nucleation T
T_{reh}= reheat T

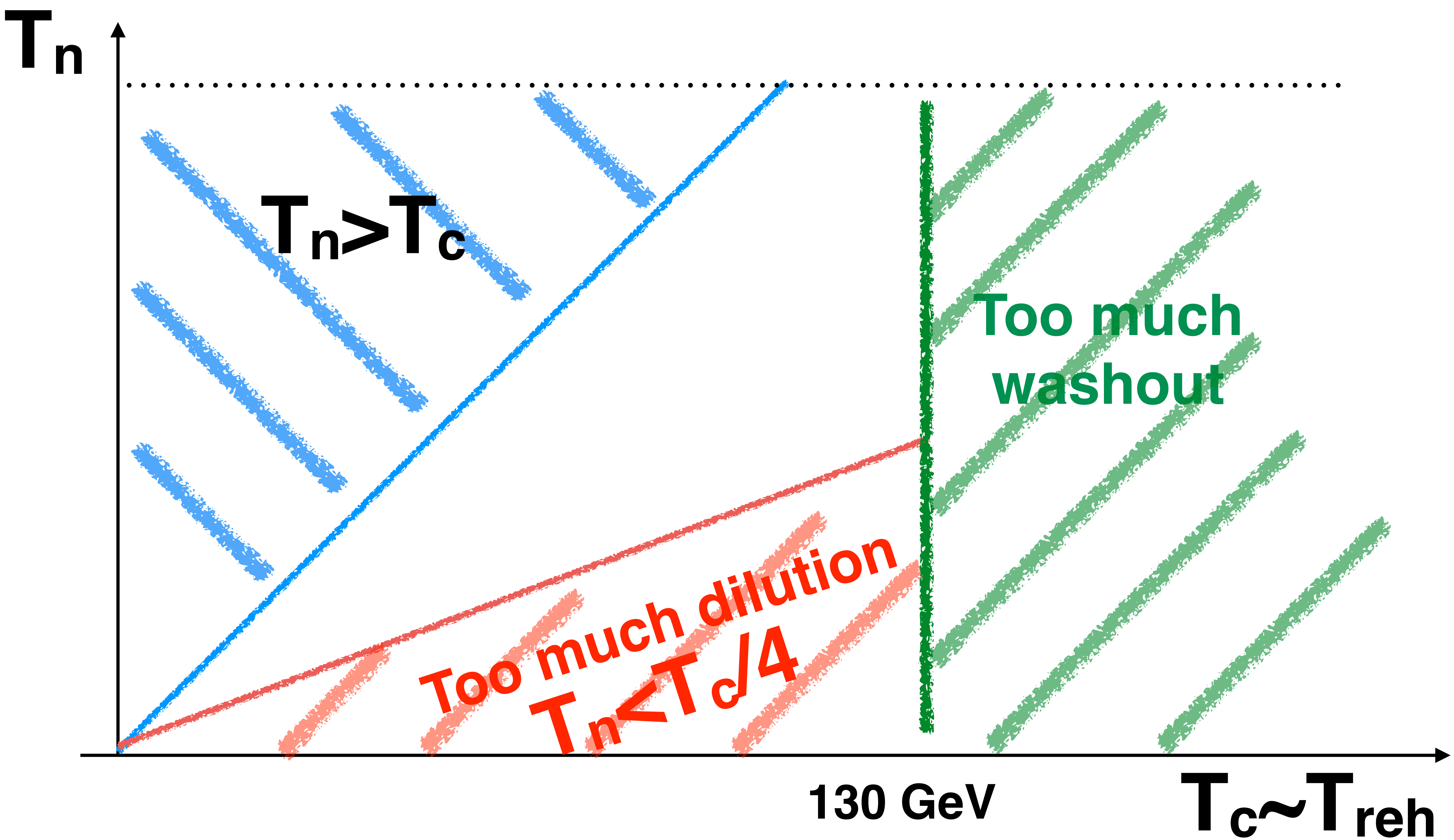


Reheating temperature from the extra scalar should be below the sphaleron washout temperature 130 GeV



➜ $m_s < m_{s,\,max}$

First-order phase transition should not be too supercooled (otherwise baryon asymmetry is diluted)



*caveat: cold baryogenesis (1104.4793, 1407.0030)

The EW baryogenesis tension

Electroweak baryogenesis requires an additional scalar S .

1- induces a 1st-order EWPT through interplayed dynamics with the Higgs

2- also plays a role in CP-violation

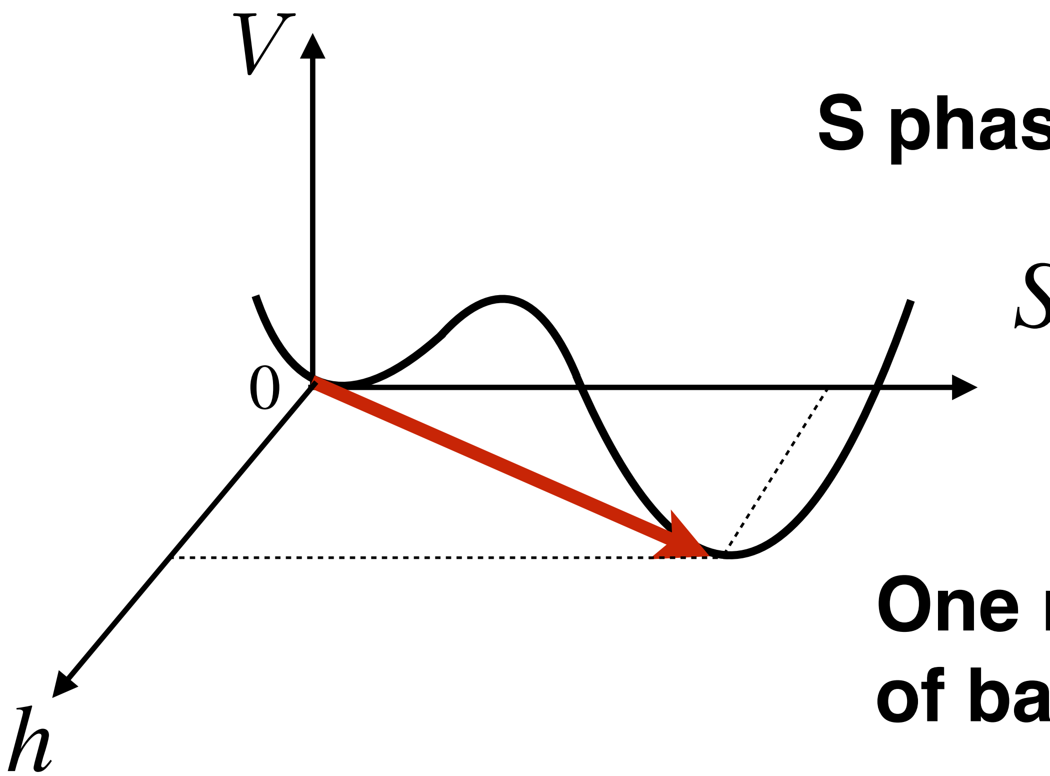
3- contributes to reheating once the transition is complete

For these 3 reasons, S must not be much heavier than the Higgs

Severely constrained by EDM bounds!

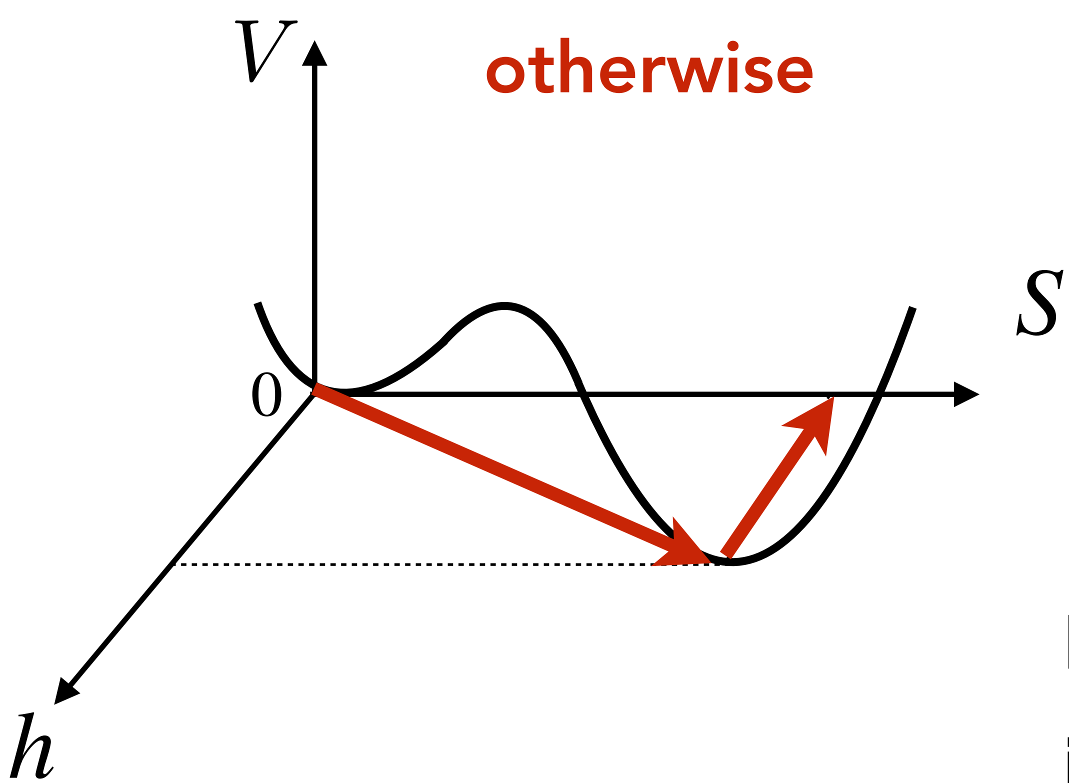
This is the EW baryogenesis tension

Electroweak baryogenesis requires an additional light scalar S .



S phase transition releases latent heat $T^4 \propto m_S^2$

One needs T <T$_{\text{EW restoration}}$ to avoid washout of baryon asymmetry



$\Rightarrow$ for T restoration ~130 GeV

$m_S \lesssim$ O(100 GeV)

Light S -> Very constrained by EDM

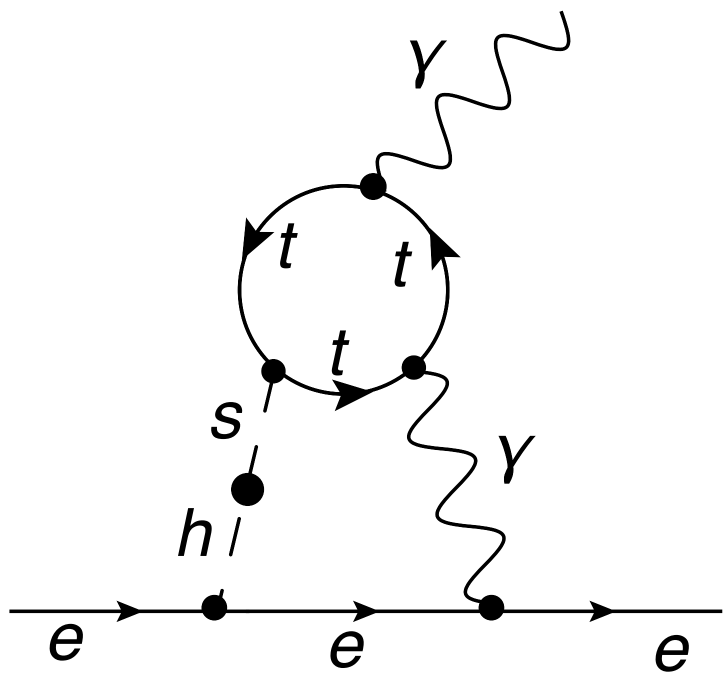
if mixes with h

The EW baryogenesis tension .

1110.2876

Well-motivated CP source for EW baryogenesis : modified Top-yukawa ("Top-transport" EW baryogenesis)

$$\frac{s}{f} H \bar{Q}_3 (a + ib\gamma_5) t + \mathrm{h.c.}$$



threatened by EDM bounds

unless the S-h mixing vanishes

EDM threat on Electroweak baryogenesis

$$|d_e| < 1.1 \cdot 10^{-29}\,\mathrm{e \cdot cm}$$

ACME II, Oct. 2018.

Evading EDM bounds for EW baryogenesis

— vanishing mixing with Higgs (extra scalar has no VEV today)

see e.g 2208.10512 (2HDM + singlet pseudoscalar a).

— Hide $\not{CP}$ in dark sector e.g:1811.09719

— $\not{CP}$ from dynamics of partial fermion compositeness

Use the dilaton in Composite Higgs models 1804.07314 2212.11953

-> search for the dilaton at LHC! 2212.00056

—Do EW baryogenesis at higher scales

Even if only up to TeV, it considerably relaxes the bounds

$\Rightarrow$ for T restoration ~1 TeV 1807.08770, 1811.11740, 2002.05174 2307.14426

$m_S \lesssim$ O(few TeV) 2008.13725, 2107.07560,2211.09147

How to release the tension ?

How to induce a 1st-order EWPT with a scalar S significantly heavier than H?

⬇

Increase the temperature of EW symmetry restoration

(to prevent washout by sphalerons at reheating)

S heavier than H —> EDM bounds weakened

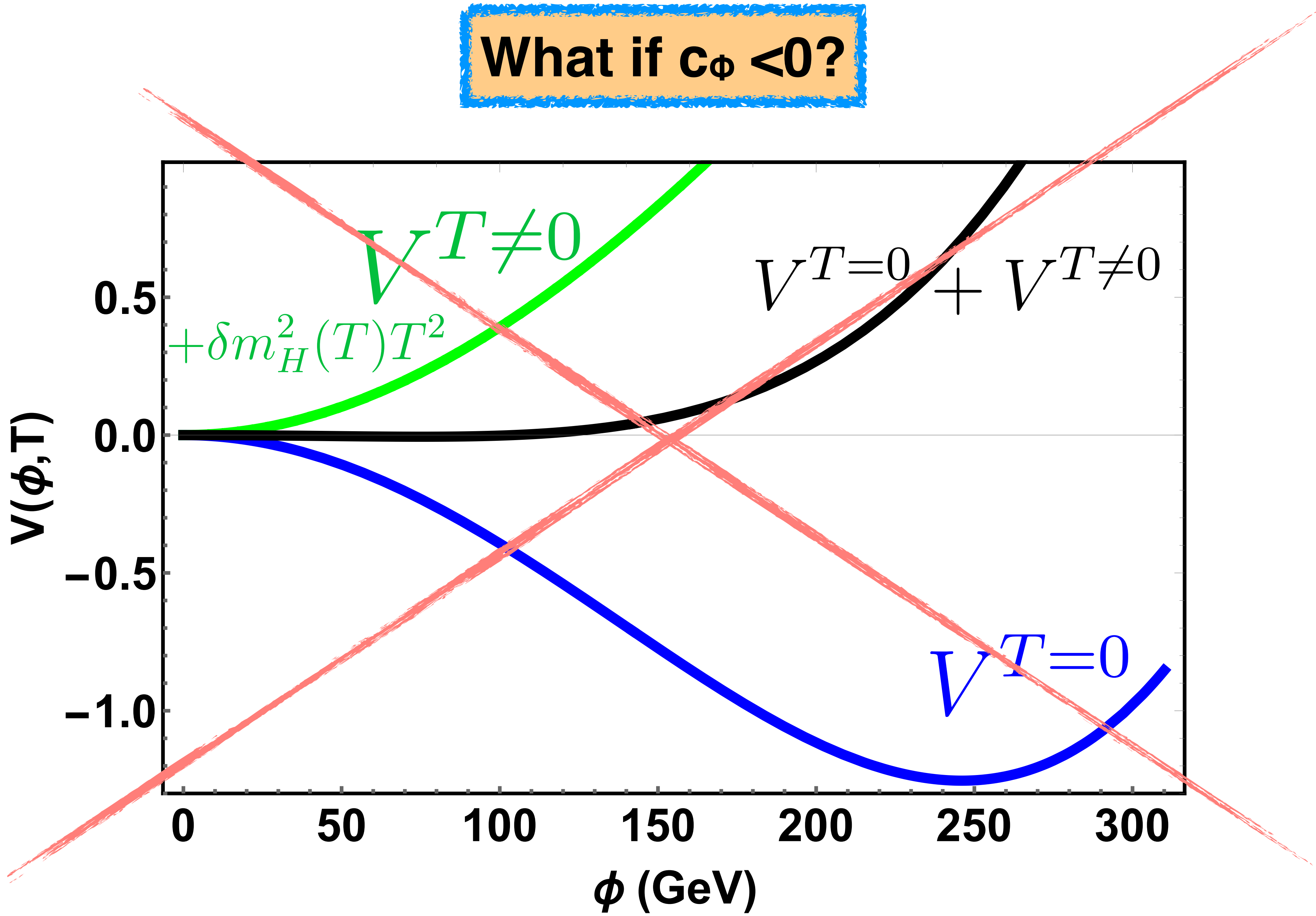
Can we push up the temperature of the EW phase transition ?

High-temperature EW symmetry non-restoration .

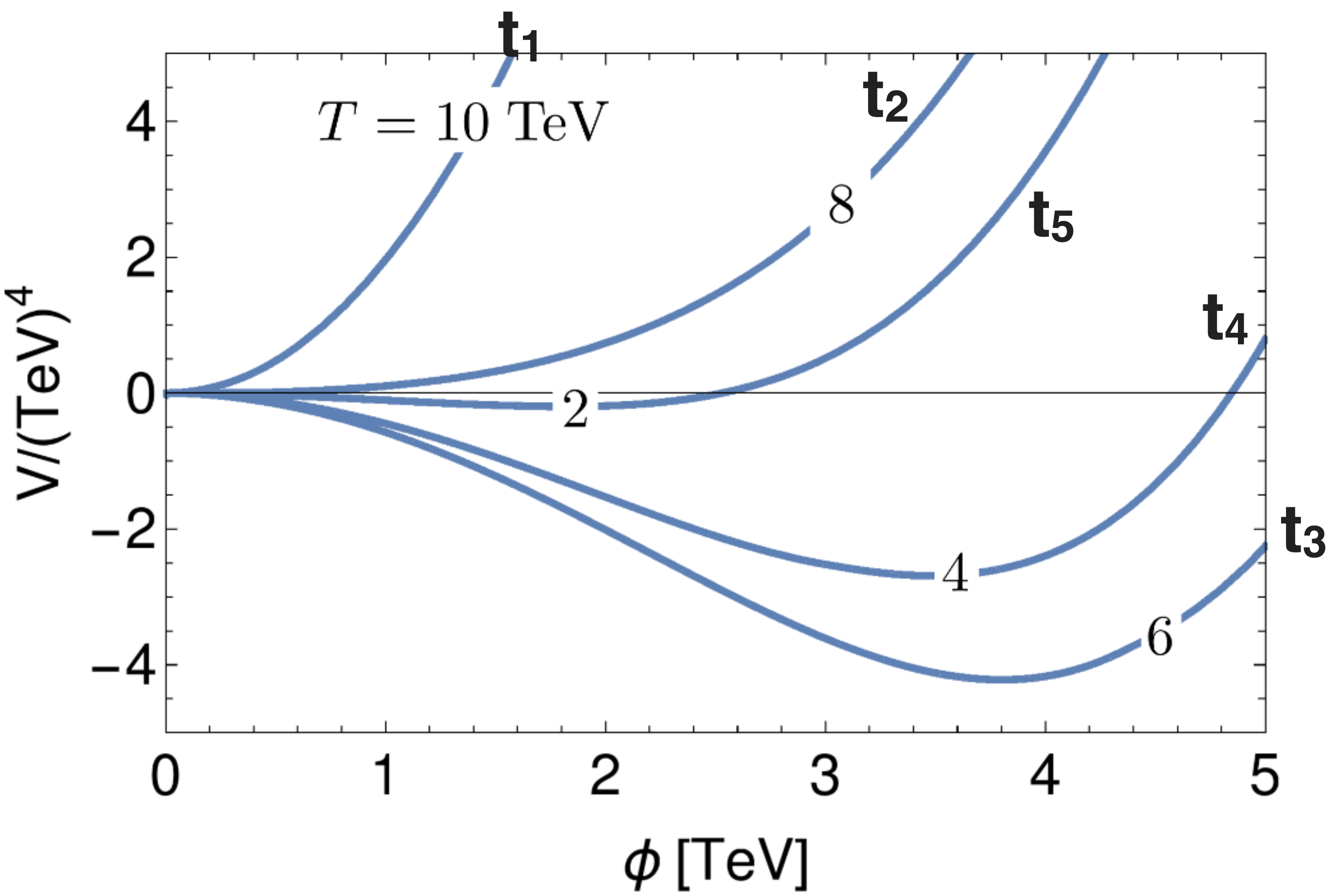
EW Symmetry restoration comes from the competition of two opposite terms in Higgs mass parameter

$$\mu_\phi^2(T) \sim -\mu_\phi^2 + c_\phi T^2$$

What if $c_\phi < 0$?



High-scale (T>TeV) EW phase transition



1807.08770

Pushing up the temperature of the EW phase transition .

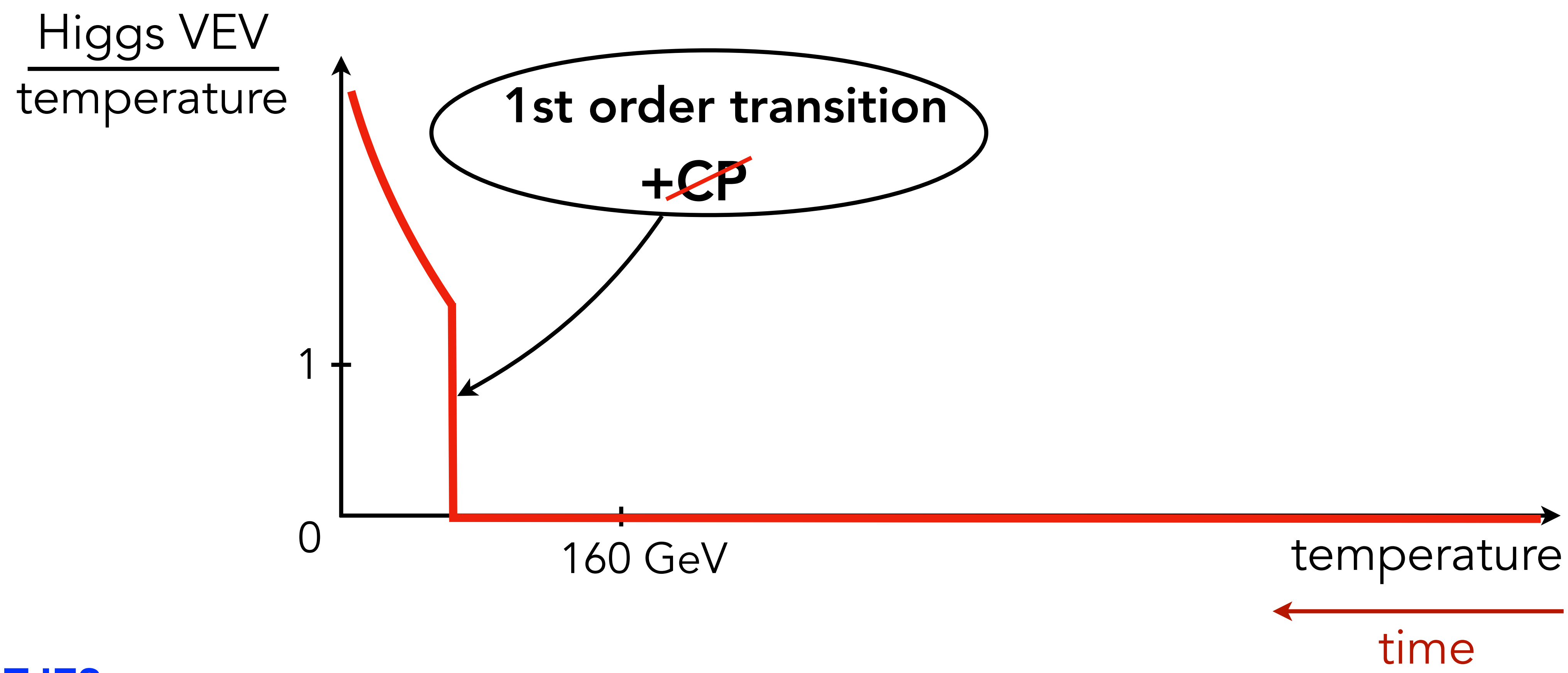
> **Motivation: EW baryogenesis using high-scale sources of CP violation, allowed by data**

> **Early baryon asymmetry safe from sphaleron wash-out even in models with B-L=0**

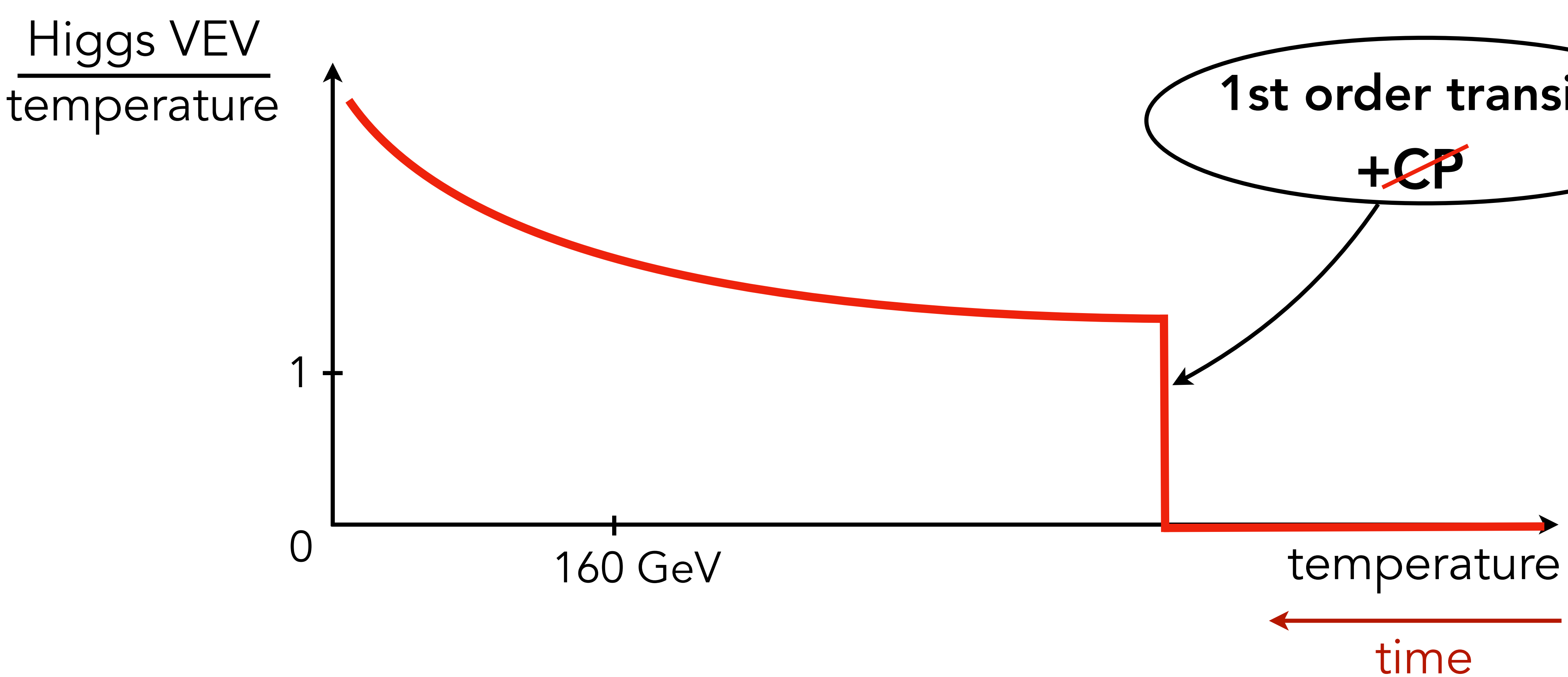
> **opens large new windows of theory space for successful EW baryogenesis even if T_{EWPT} pushed by only a few hundreds of GeV**

> **GW peak at LISA shifted to higher frequencies**

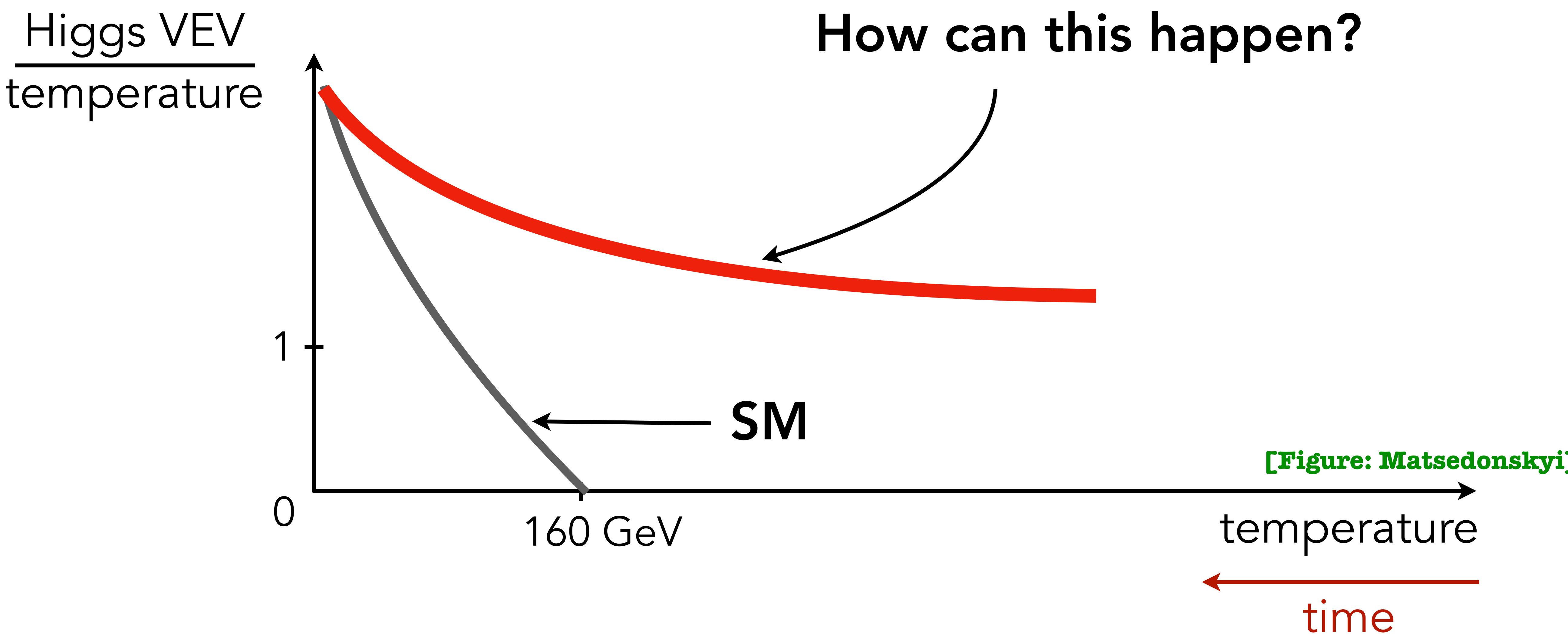
In EW baryogenesis scenario:



WHAT IF?



[Figure: Matsedonskyi]



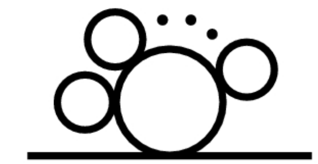
By adding new weak-scale (m<~300 GeV) singlet scalars
[1807.08770, Baldes, Servant], [1807.07578, Meade, Ramani], [1811.11740, Gliotto, Rattazzi, Vecchi]
or singlet fermions [2002.05174, Matsedonskyi, Servant]
whose mass has a non-standard dependence on Higgs VEV

See also: Matsedonskyi 2008.13725, 2107.07560 (Twin Higgs), 2211.09147 (SUSY)
Bai et al, Biekötter et al, Carena et al, (2HDM)

HIGGS EFFECTIVE POTENTIAL AT HIGH TEMPERATURE

At one-loop:

$$V_{\text{eff}} = \underbrace{V_{\text{tree}}(\phi)}_{\text{Tree level}} + \underbrace{V_1^0(\phi)}_{\text{1-loop } T=0} + \underbrace{V_1^T(\phi, T)}_{\text{1-loop } T\neq 0} + \underbrace{V_{\text{Daisy}}(\phi, T)}_{\text{Daisy resummation}}.$$



$$V_1^T(\phi, T) = \sum_i (\underbrace{\Delta V_{b,i}^T}_{\text{bosons}} + \underbrace{\Delta V_{f,i}^T}_{\text{fermions}})$$

Sum over all particles coupled to the Higgs

$$\propto T \sum_i \pm g_i \int p^2 dp \log[1 \mp e^{-\sqrt{p^2+m_i^2(\phi)}/T}]$$

For high-T, m/T<<1:

$$\Delta V_{b,i}^T \simeq -\frac{\pi^2 T^4}{90} + \frac{T^2 m_i^2(\phi)}{24}$$

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depth of negative correction to V_{eff} at m=0

sets the thermal mass

$$\delta m_H^2(T) \simeq +T^2 \left[\frac{y_t^2}{4} + \frac{\lambda}{2} + \frac{3g^2}{16} + \frac{g'^2}{16}\right]$$

Higgs Thermal Mass in the SM

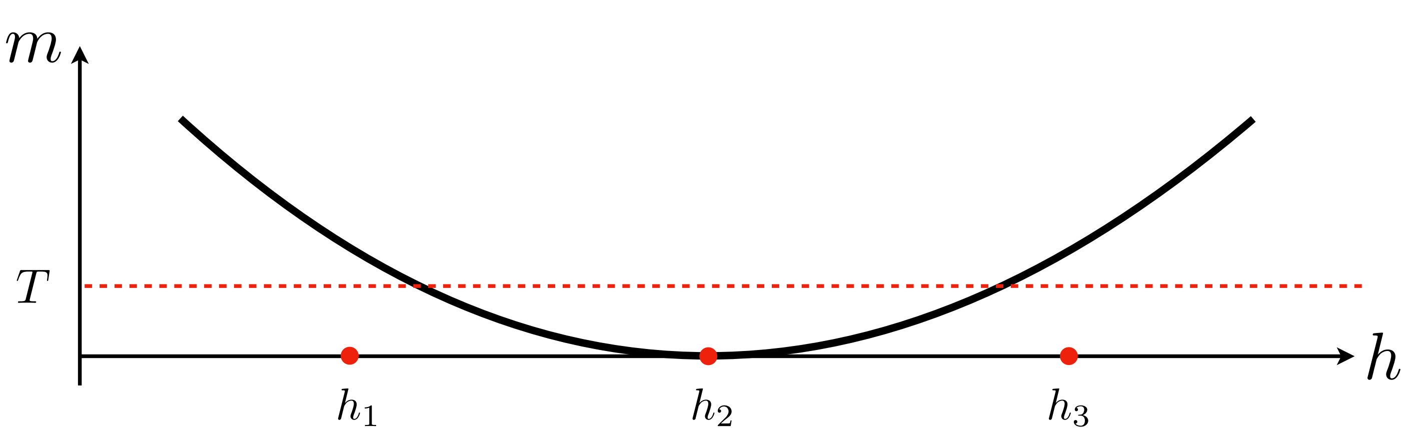
EW symmetry non-restoration at $T>M_H$

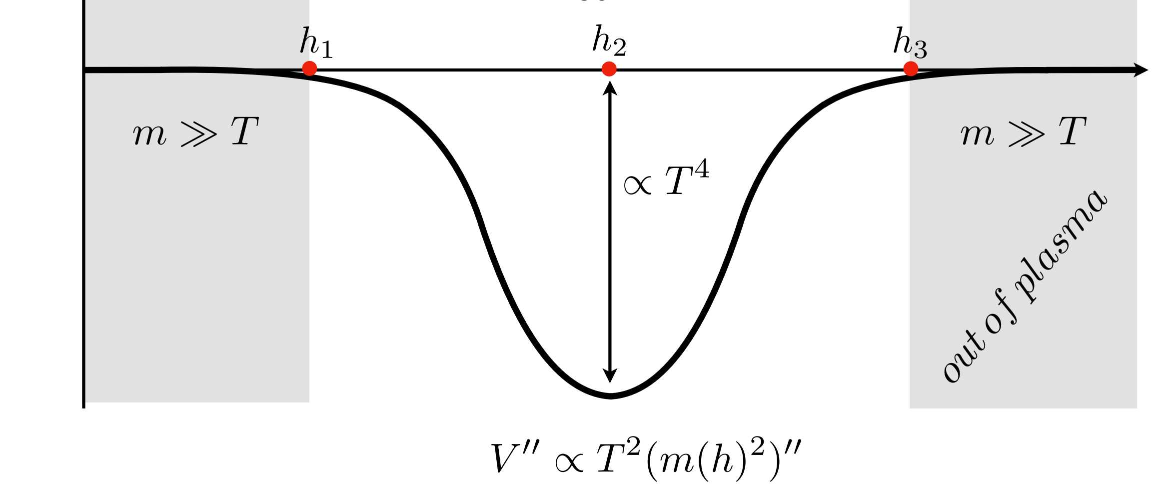
SUMMARY OF PRINCIPLE: Massless or sufficiently light (m<T) particles coupled to the Higgs produce a dip in the Higgs potential of the size ~ -T^4

$$\Delta V \propto T \sum_i \pm g_i \int p^2 dp \log[1 \mp e^{-\sqrt{p^2+m_i^2(h)}/T}]$$

for m/T<<1 :

$$\Delta V^T_{f,i} \simeq -\frac{7\pi^2 T^4}{180} + \frac{T^2\, m_i^2(h)}{12}$$





EW symmetry non-restoration at T>M$_H$.

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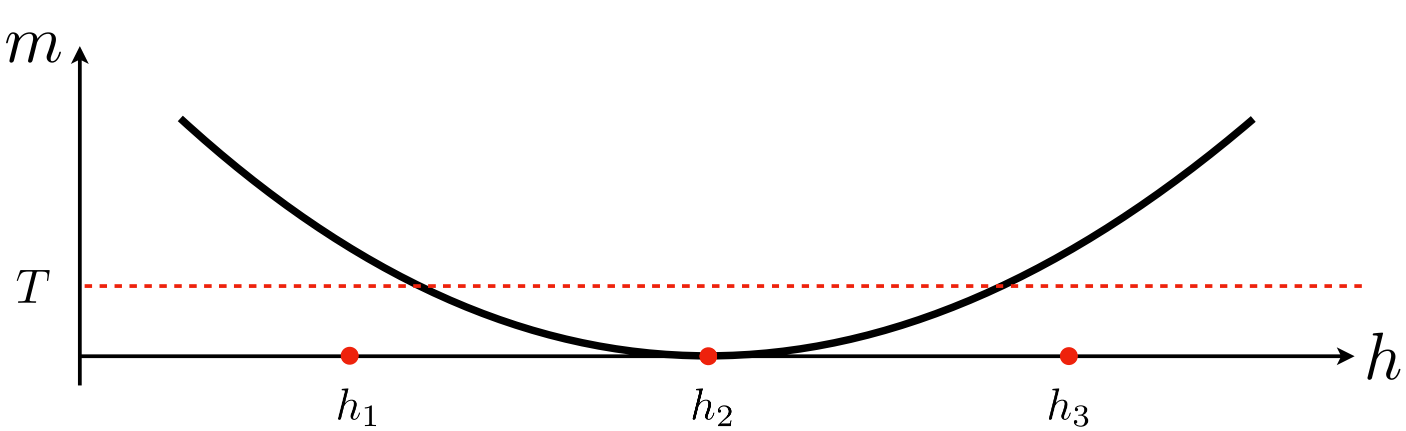
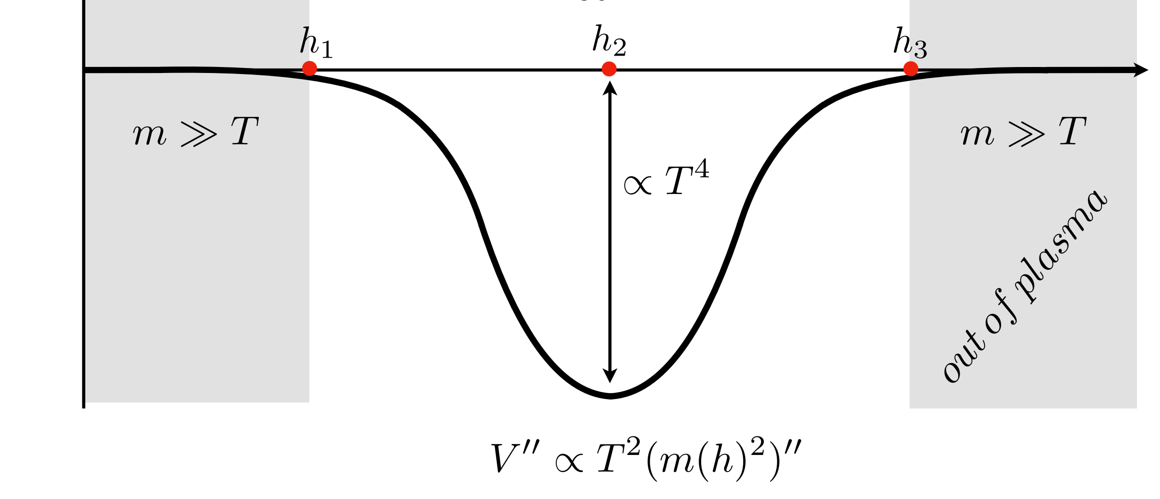


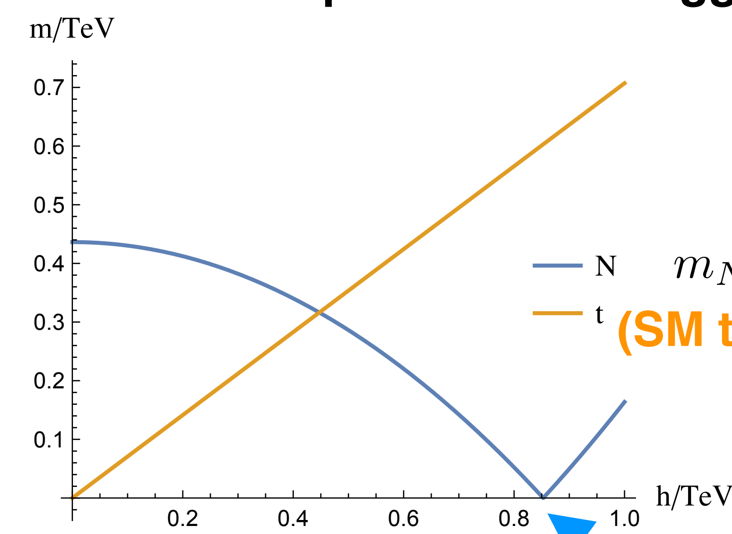


If some degree of freedom is effectively massless at a large Higgs VEV, the induced thermal negative correction at this VEV can make the Higgs field origin unstable leading to high-T EW symmetry non-restoration.

Example: Add a singlet fermion N

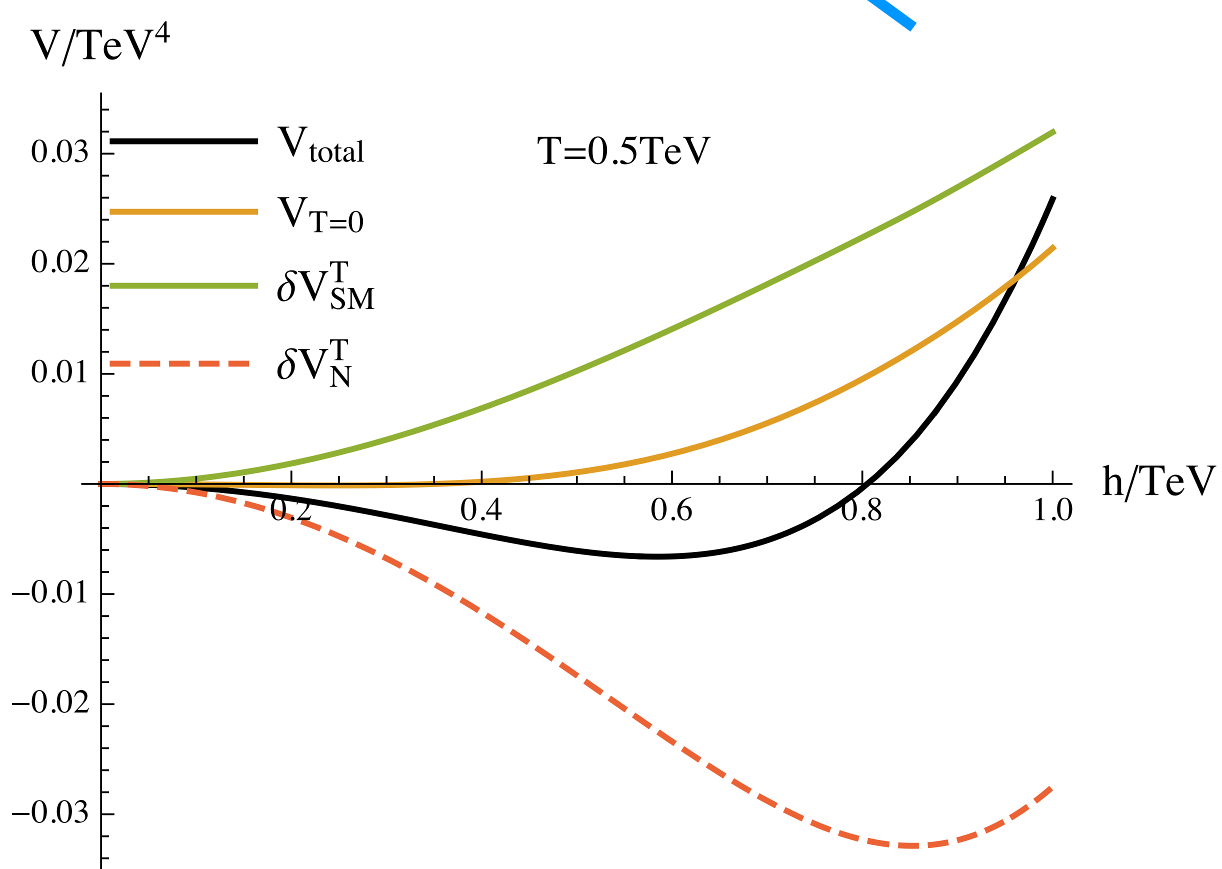
$$\mathcal{L}_N = -m_N^{(0)}\bar{N}N + \lambda_N \bar{N}N h^2/\Lambda$$

Particle mass dependence on Higgs VEV



$$m_N(h) = m_N^{(0)} - \lambda_N h^2/\Lambda = 0 \quad \longrightarrow \quad h^2 = m_N^{(0)}\Lambda/\lambda_N.$$

Responsible for a high-T minimum at large Higgs VEV!



[2002.05174]

High-scale EW phase transition from new EW-scale singlet fermions

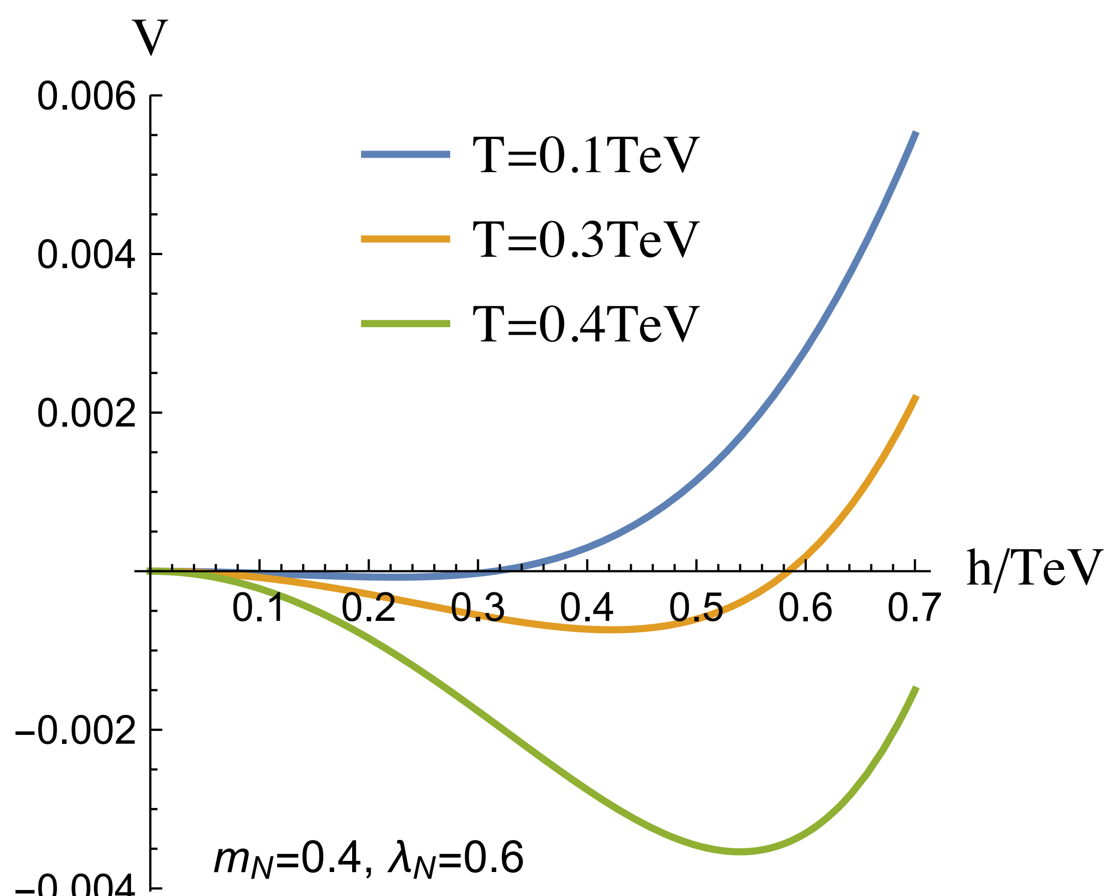
Add n new fermions N with Higgs-dependent mass contribution. Mass vanishes at <h>≠0

[2002.05174]

$$m_N(h) = m_N^{(0)} - \lambda_N h^2/\Lambda = 0 \quad \longrightarrow \quad h^2 = m_N^{(0)}\Lambda/\lambda_N,$$

$$\delta m_h^2[T] \simeq n\frac{T^2}{12}(m_N^2(h))'' = -n\lambda_N \frac{m_N^{(0)}}{3\Lambda}T^2.$$

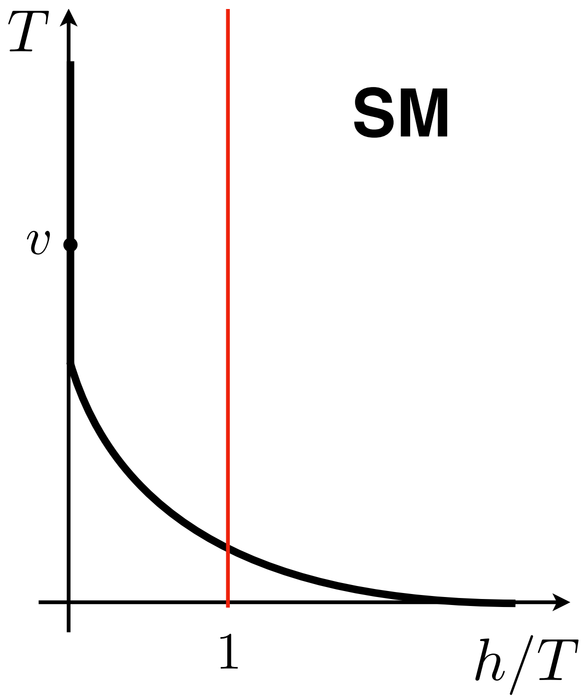
Negative thermal mass

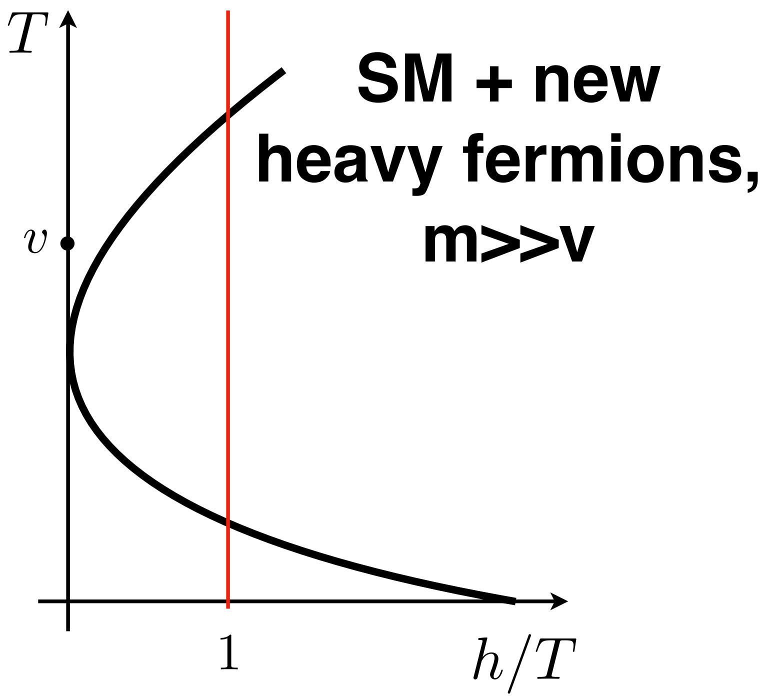


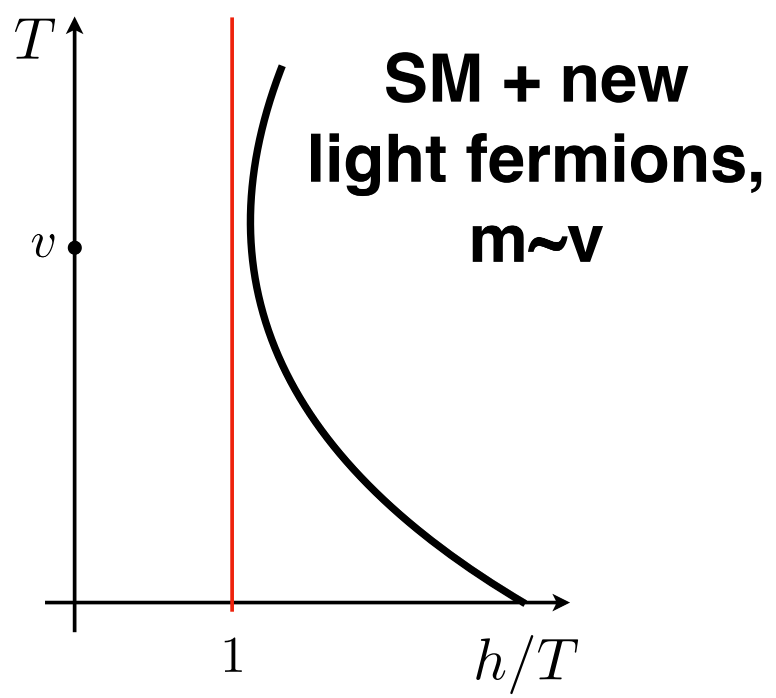
Enables to push Tc to ~ 500 GeV while keeping <h>/T>1 for T<Tc.

Why pushing up the temperature of the EW phase transition ?

[2002.05174]



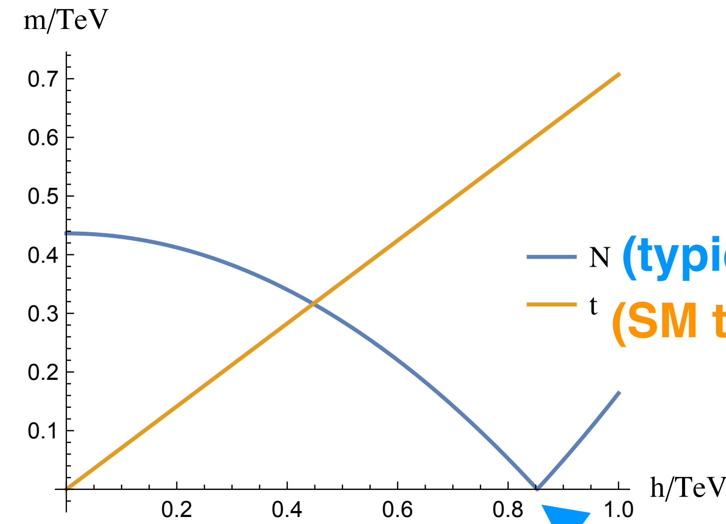




> **Baryon asymmetry produced during higher T phase transition is never washed out !**

Arises in Composite Higgs

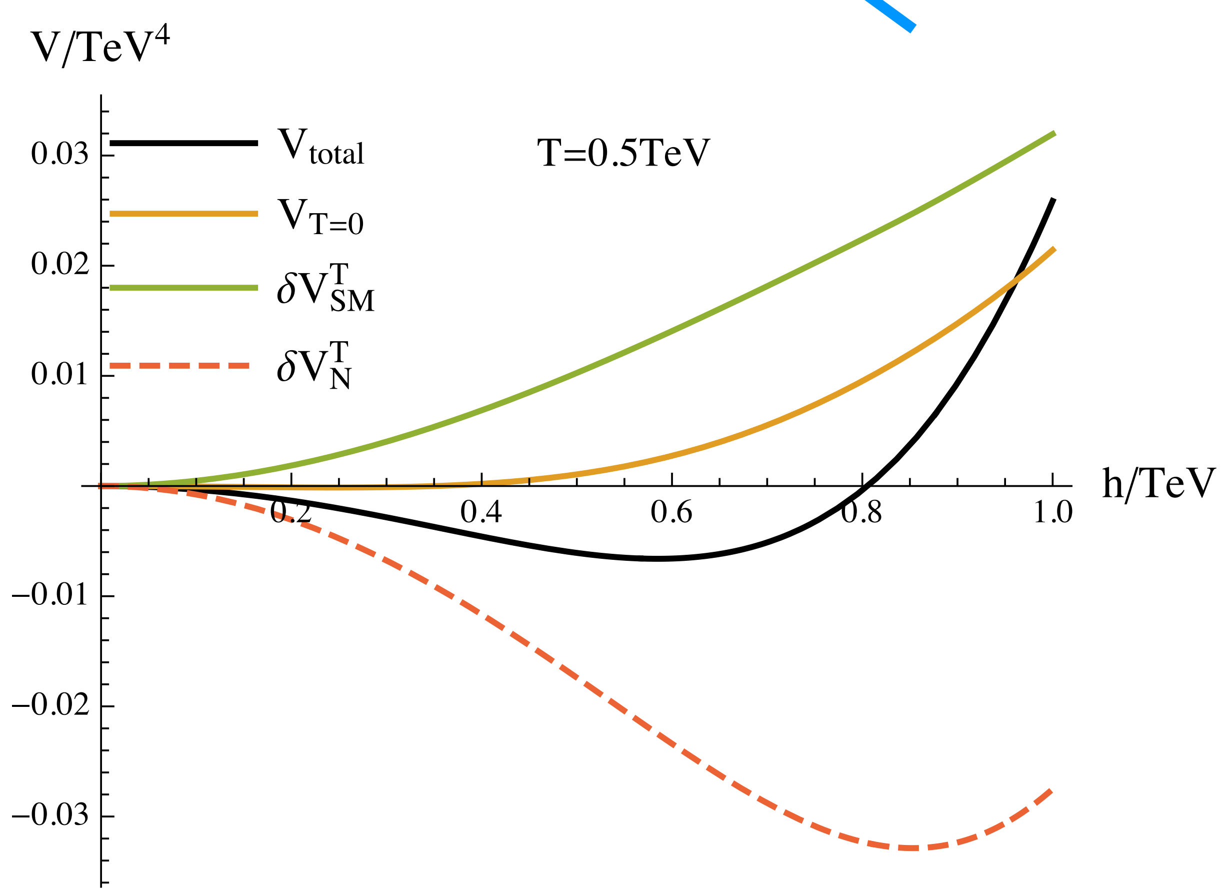
Particle mass dependence on Higgs VEV



(typical Composite Higgs model behavior)

(SM top)

Responsible for a high-T minimum at large Higgs VEV!



[2002.05174]

Illustration:

EW Phase transition in Composite Higgs Models :

Naturally strongly first-order .

Motivations .

EW baryogenesis in a minimal SM extension that adresses:

-the Higgs hierarchy problem —> Composite Higgs

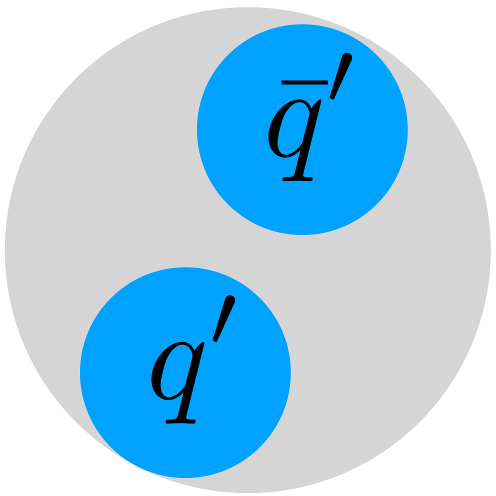
-the flavour hierarchy —> from partial fermion compositeness
CP-violation from the varying Yukawas during the EWPT

and does not require B or L violations beyond the SM

Minimality
- Extra singlet scalar is the dilaton -> substantial couplings to SM -> testable at LHC
- EFT with minimal dependence on UV completion

Composite Higgs models

Higgs is a bound state of new strong interactions confining at ~ 1 TeV

$h =$ 

Lighter than confining scale because is a PNGB of the new strongly interacting sector

Solves the hierarchy pb.

Minimal Composite Higgs .

Higgs boson : Goldstone boson associated with spontaneous global symmetry breaking SO(5) → SO(4) in new strongly interacting sector, which happens at the scale f as new sector confines.

Higgs potential generated via loops involving explicit SO(5)-breaking interactions between elementary fermions (such as the top quark) and new strongly-interacting sector.

SM electroweak gauge group is embedded in subgroup of SO(5) and a U(1)X factor.

Higgs potential in Composite Higgs models

Higgs potential emerges at E≲f

For PNGB: $$V_h \sim f^4 \left[\alpha \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right) \right]$$

f~O(TeV): confinement scale of new strongly interacting sector

Higgs potential in Composite Higgs models .

Higgs potential emerges at E≲f

For PNGB: $$V_h \sim f^4 \left[\alpha \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right)\right]$$

f~O(TeV): confinement scale of new strongly interacting sector

For fixed f and taking all phenomenological constraints into account, such potential leads to rather Standard-Model-like EW phase transition unless one tunes parameters.

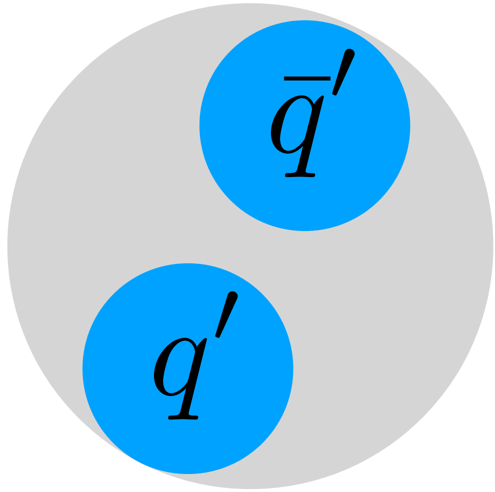
See e.g EFT approach hep-ph/0407019 and 0711.2511

This conclusion radically changes if one considers an approximate scale invariance of the composite sector

EW phase transition in Composite Higgs models .

Higgs is a bound state of new strong interactions confining at f~ 1 TeV

$h =$



solves the hierarchy pb.

The new light scalar triggering the 1st-order PT is a composite dilaton χ (PNGB of approximate conformal invariance)

We next promote f to be dynamical

Scalar potential describing the EW phase transition now depends on dilaton.

> Higgs potential emerges at E$\lesssim$f .

For PNGB: $$V_h \sim f^4 \left[\alpha \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right)\right]$$

f~O(TeV): confinement scale of new strongly interacting sector, described by VEV of dilaton field $<\chi>$

$$V = V_\chi(\chi) + V_h(\chi, h)$$

intertwinned dynamics

χ dominates the dynamics

$$\boxed{V(\chi) = \chi^4 \times f(\chi^\epsilon)}$$

$|\varepsilon|$<<1

Nearly conformal potential : T_n << f , SUPERCOOLING

1104.4791

Confinement phase transition

$$V_\chi = c_\chi g_\chi^2 \chi^4 - \epsilon[\chi]\chi^4 \, .$$

conformally invariant

Source of explicit breaking

CFT dynamics:

$$\frac{\partial \epsilon}{\partial \log \mu} = \gamma_\epsilon \epsilon - c_\epsilon \epsilon^2 / g_\chi^2 \, ,$$

ε grows as χ decreases, eventually produces a minimum

Higgs-dilaton intertwinned dynamics

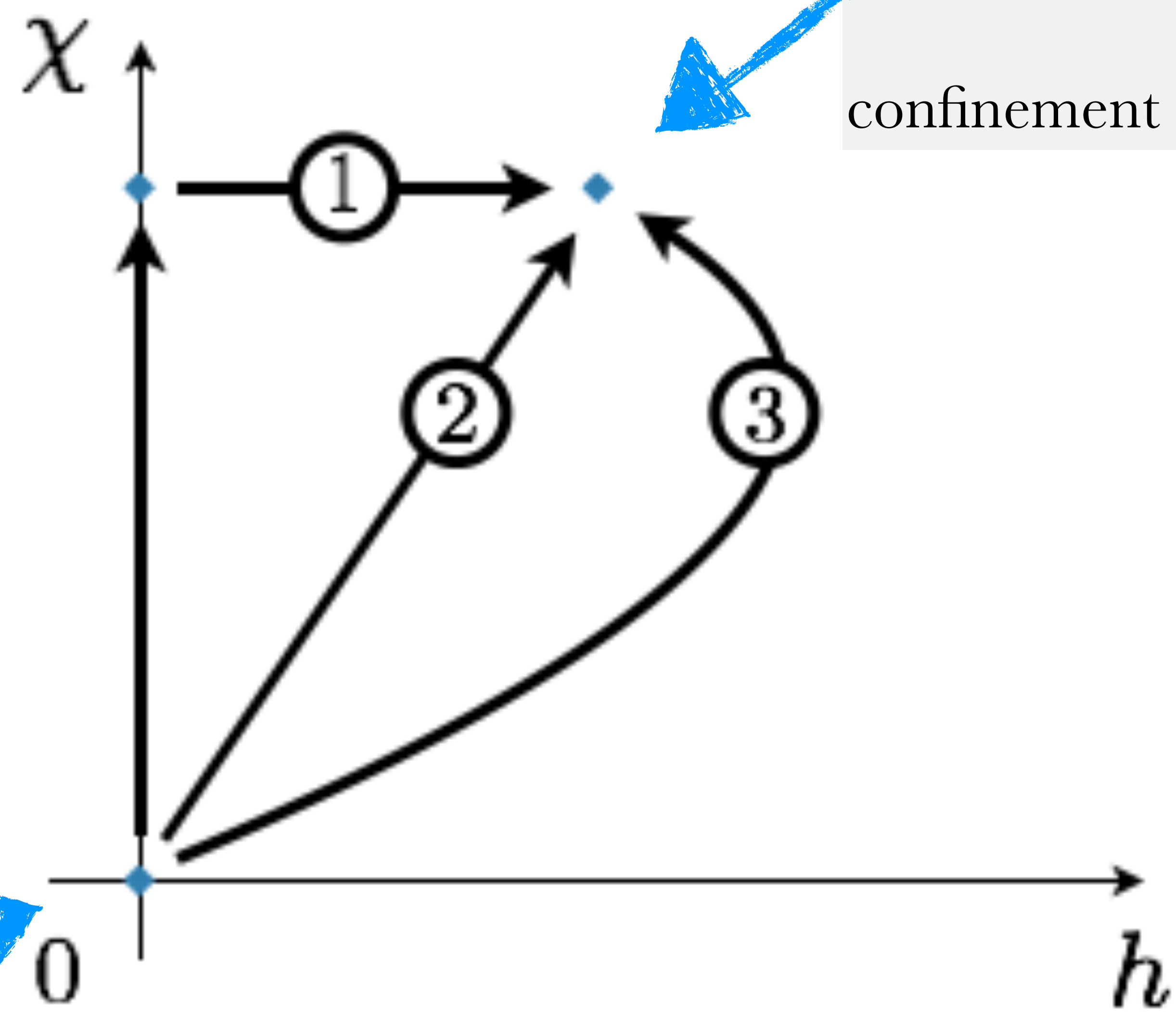
global minimum at

$T \ll f$

confinement and EWSB

Which path?

Path (1) had been assumed until 2018



global minimum at

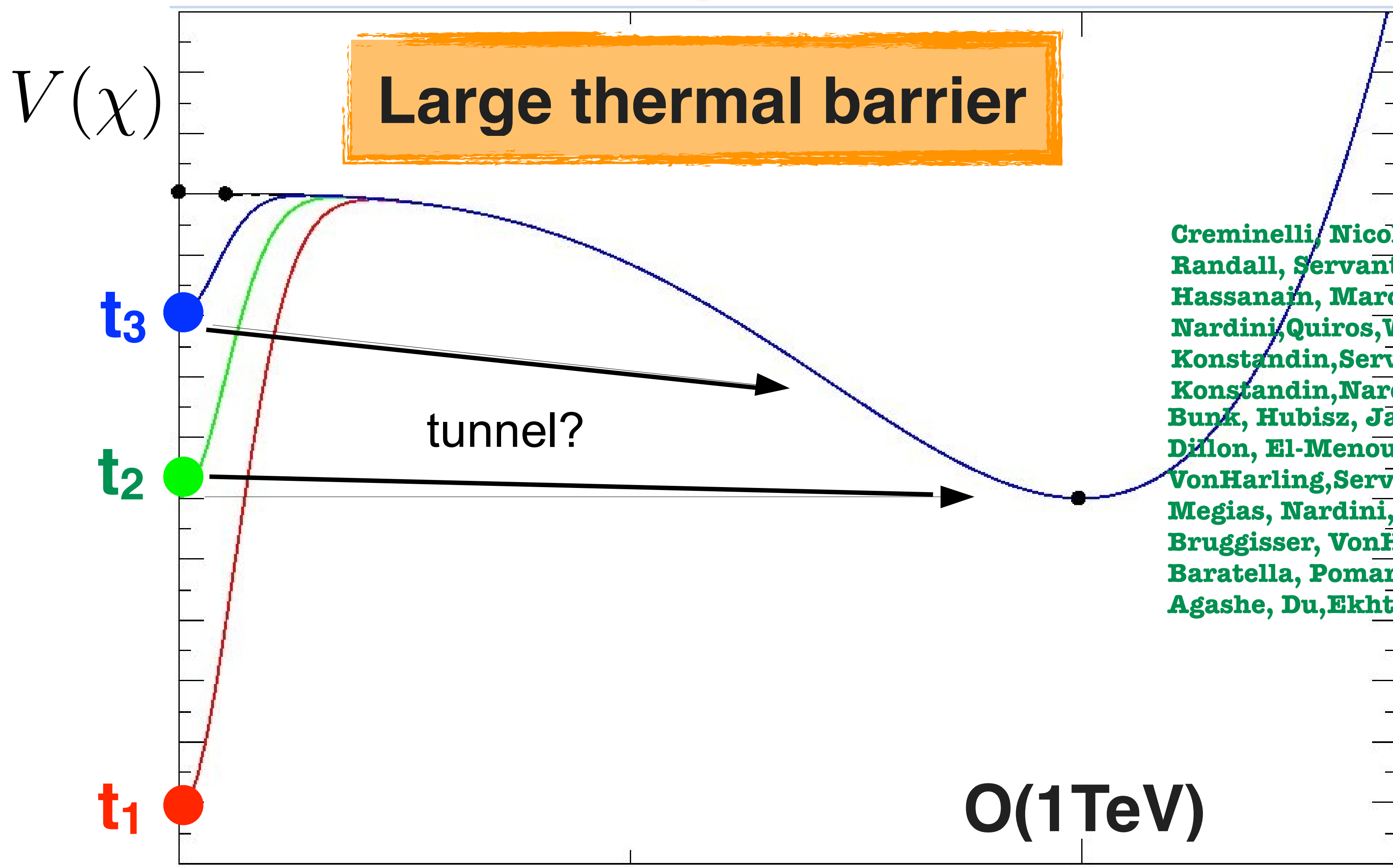
$T \gg f$

deconfined strong sector
unbroken EW symmetry

1803.08546 ,1804.07314

Strongly 1st order TeV scale confinement phase transition .

Large number of massless dof in deconfined phase + Shallow (nearly conformal) potential at T=0 with TeV minimum



Creminelli, Nicolis, Rattazzi'01
Randall, Servant'06
Hassanain, March-Russell, Schwellinger'07
Nardini,Quiros,Wulzer'07
Konstandin,Servant'11
Konstandin,Nardini,Quiros'10
Bunk, Hubisz, Jain'17
Dillon, El-Menoufi,Huber,Manuel'17
VonHarling,Servant'17
Megias, Nardini, Quiros' 18
Bruggisser, VonHarling, Matsedonskyi, Servant'18,'22,'23
Baratella, Pomarol, Rompineve'18
Agashe, Du,Ekhterrachian,Kumar,Sundrum'19,'20

Supercooled confinement phase transition

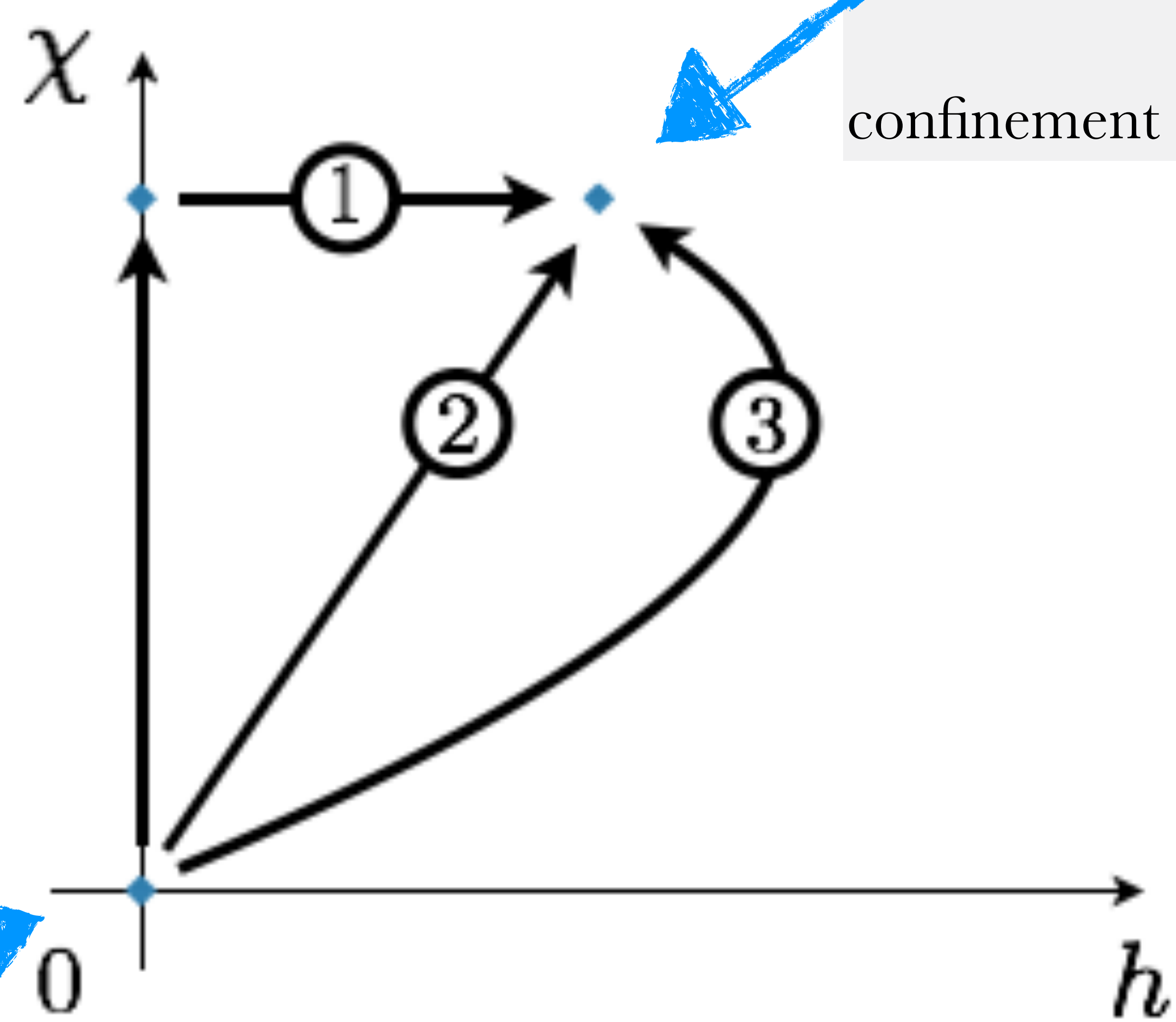
Impact on EW phase transition in Composite Higgs.

global minimum at
$T \ll f$

confinement and EWSB

(1) SM-like EW phase transition
(crossover)

(2)-(3) Joint confinement-EW phase transitions: very rich pheno for EW baryogenesis
(strongly 1st-order)



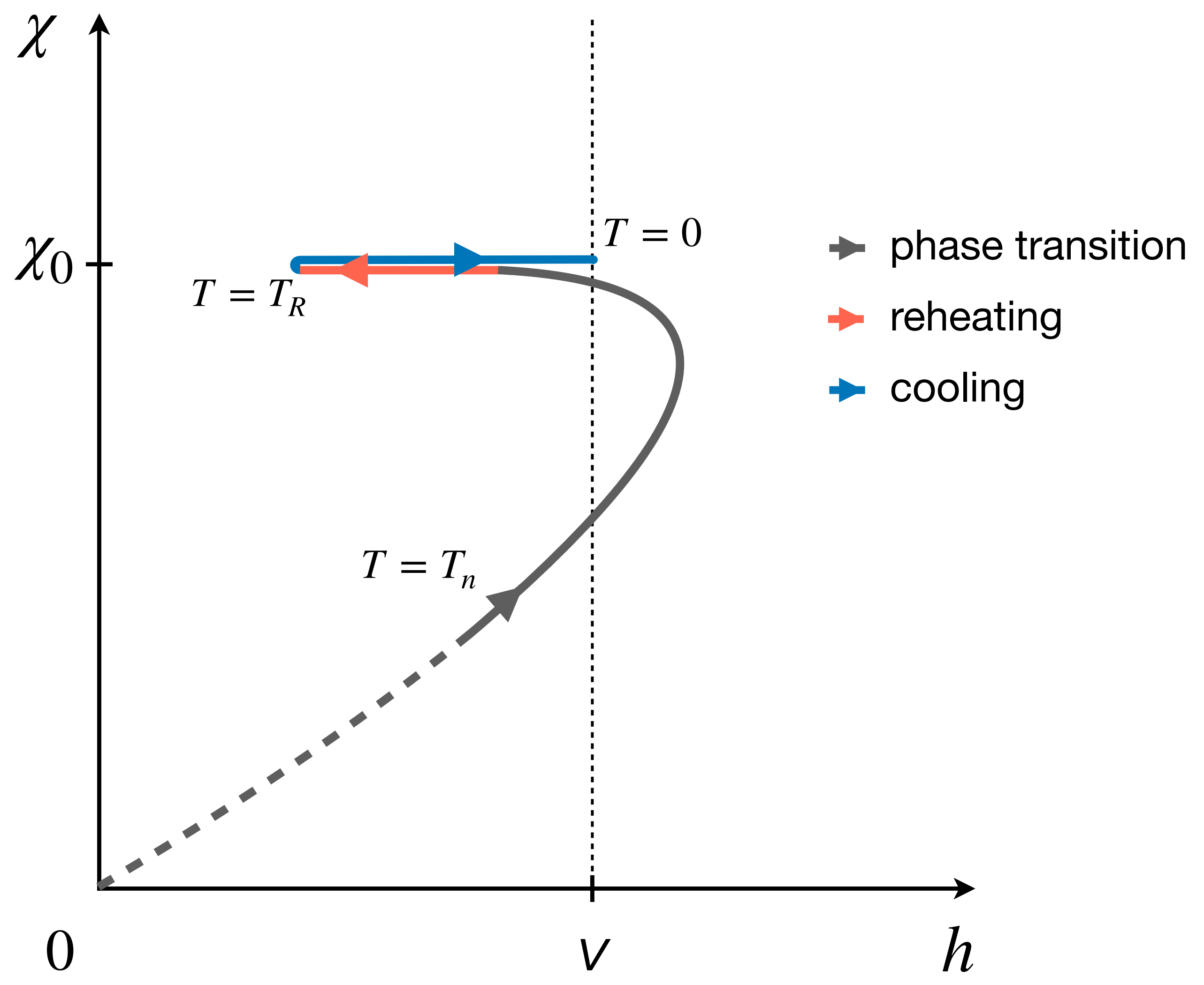
global minimum at
$T \gg f$

deconfined strong sector
unbroken EW symmetry

1804.07314

EW phase transition in Composite Higgs models .

Higgs and & dilaton evolution



h/T > 1 at any time after the phase transition.

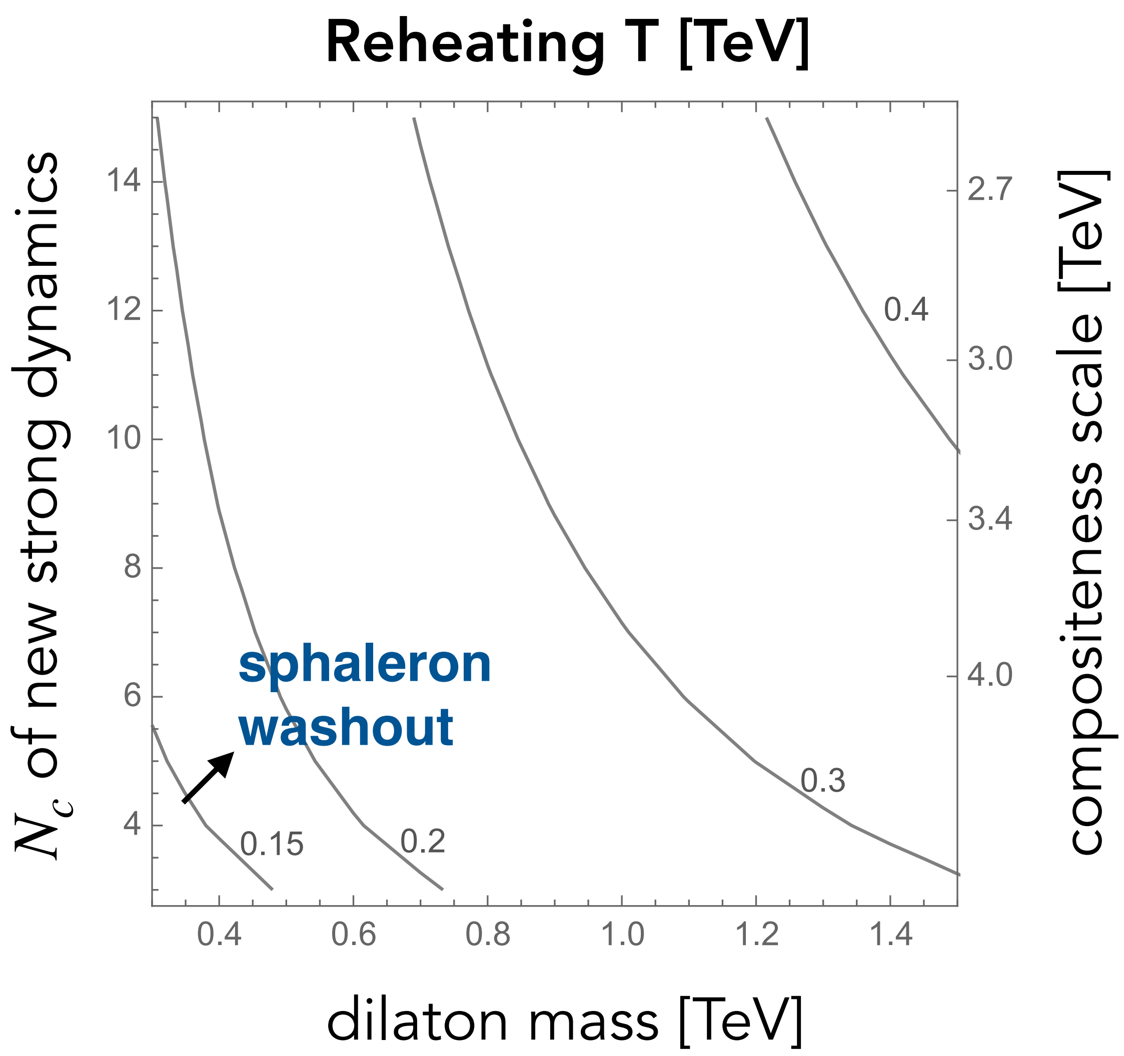
Constraints from reheating

After confining phase transition: universe may be reheated above the sphaleron freese out temperature

To preserve baryon asymmetry from washout:

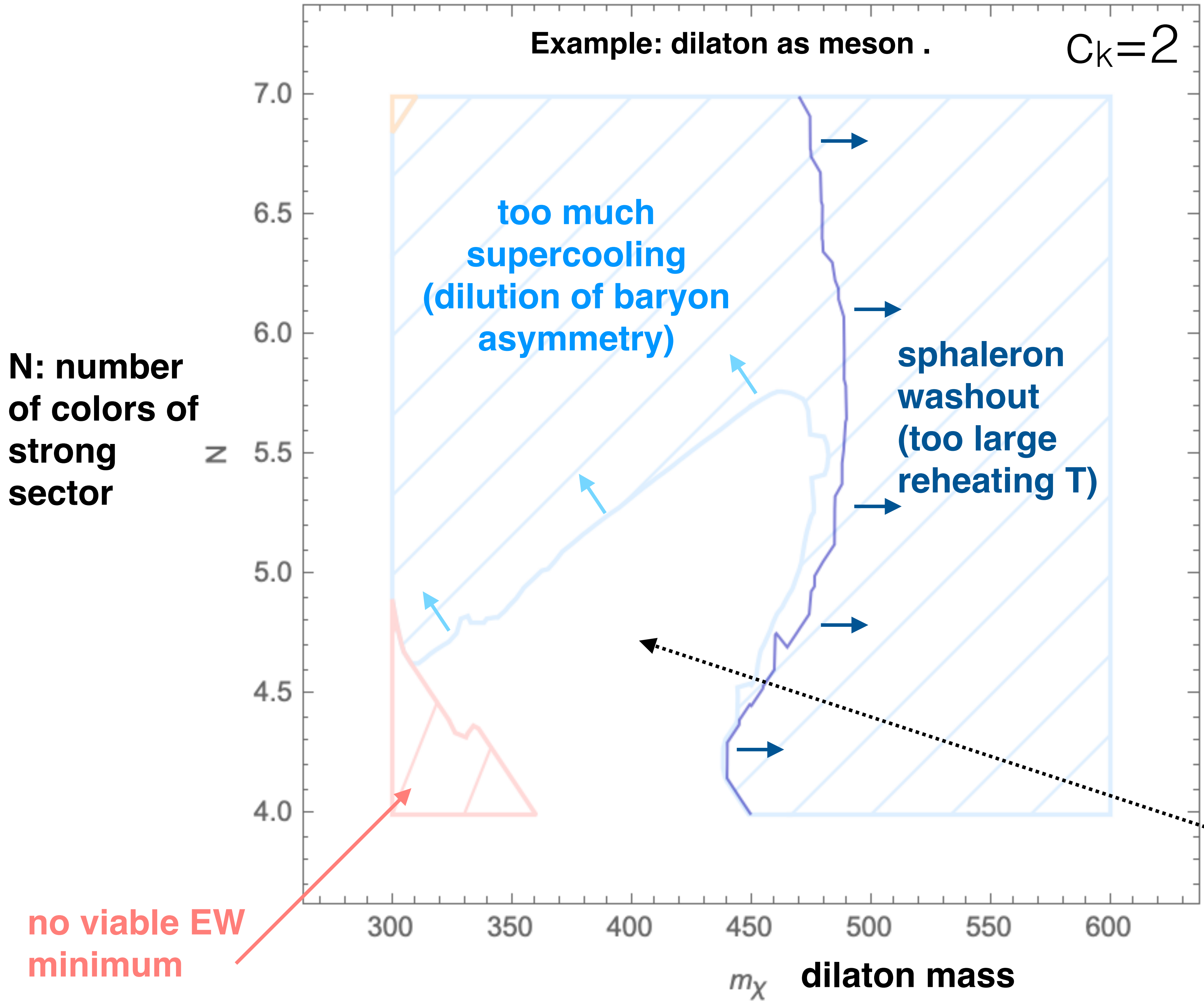
$$h(T_{reheat})/T_{reheat} \gtrsim 1$$

LIGHT DILATON WINDOW



A typical situation .

f=800 GeV



Entire viable region expected to be probed at the LHC!

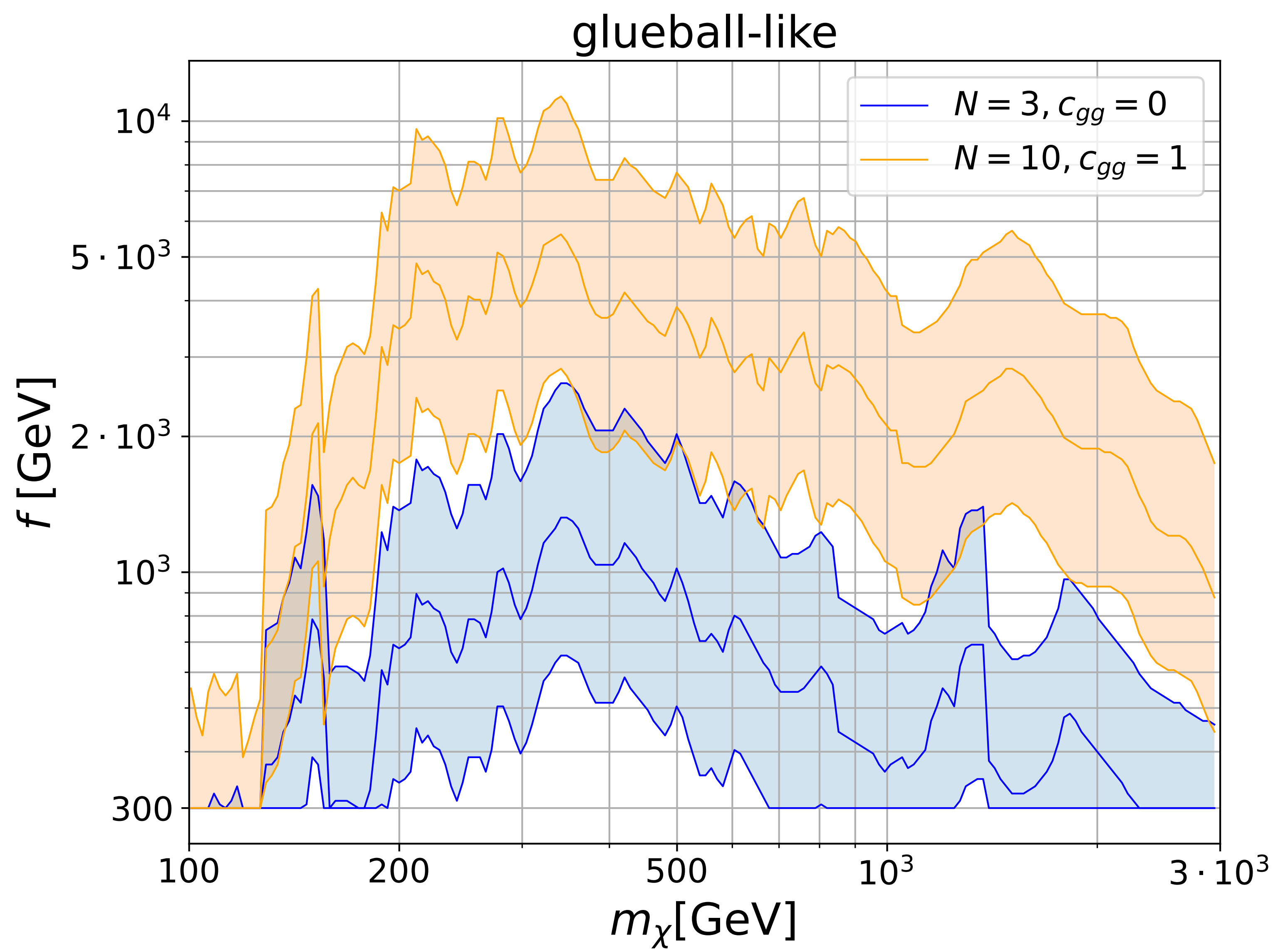
There is a series of similar plots scrutinising available regions for ≠ c_k and f values and for glue ball dilaton.

[Bruggisser et al' 2212.11953]

Collider bounds on dilaton

Higgs-like couplings suppressed by v/χ_0

Produced in gluon fusion, decays mainly into W&Z



dilaton mass

combination of LEP & LHC data

bands corresponds to variations of parameters

[Bruggisser et al' 2212.00056.]

see [Ahmed, Mariotti, Najjari] for light dilaton

Other signatures: $\delta g_{hhh}\,,\ \delta g_{Vhh}\ ,\delta g_{htt}\ ,\ \delta g_{\chi tt}$

from Higgs-dilaton mixing

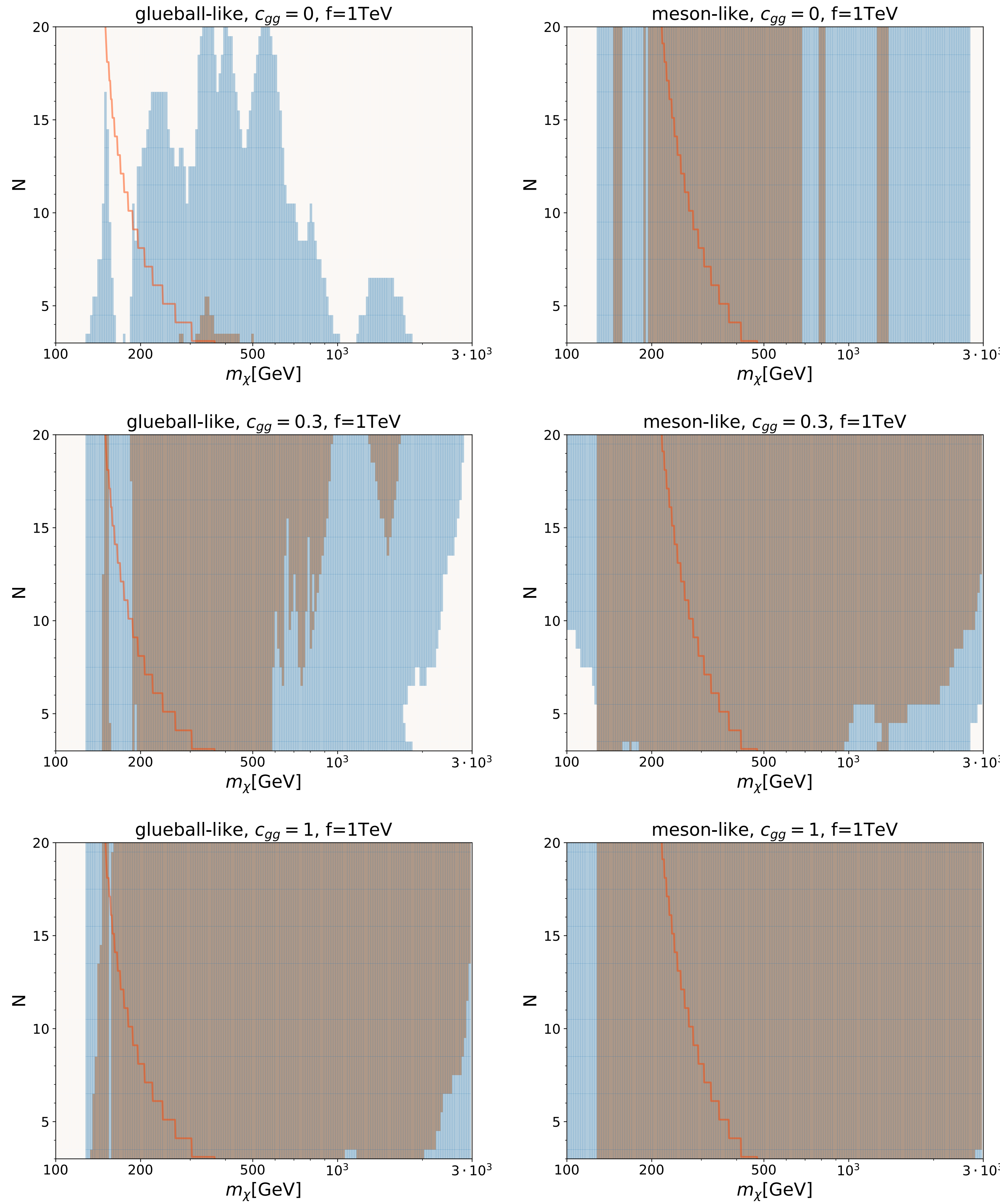
Almost all relevant region will be covered by LHC !

$$c_{gg}\frac{g_s^2}{3g_*^2}\frac{\chi}{\chi_0}G_{\mu\nu}G^{\mu\nu}$$

c_{gg} inferred from a complete UV theory of the strong sector

excluded

future sensitivity



2212.00056

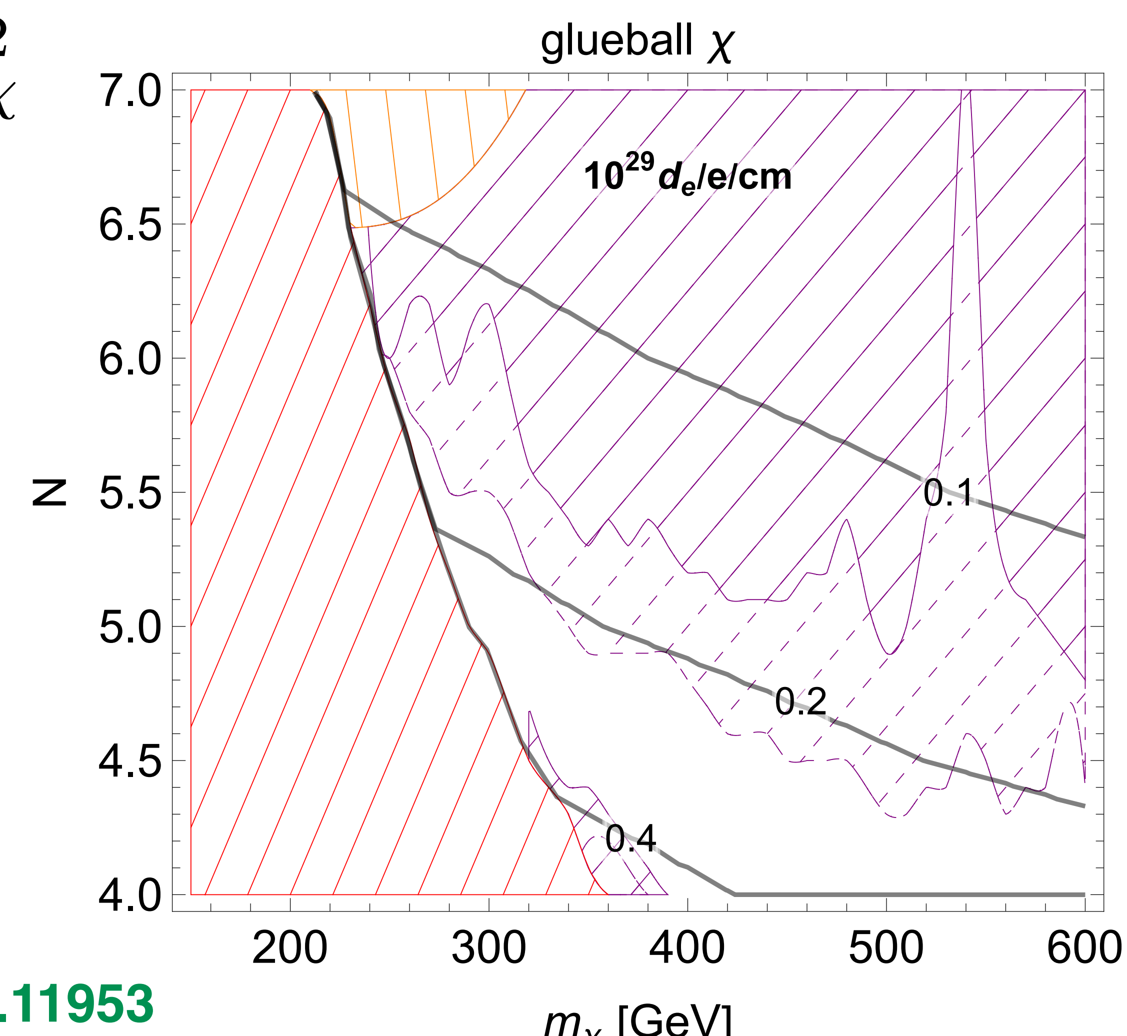
CP-violating source for baryogenesis

$$\mathcal{L}_{\rm Yuk} = -\frac{\lambda_t(\chi)}{\sqrt{2}}(g_\chi \chi/g_*)\sin\frac{h}{f}\bar{t}_L t_R + h.c. \supset -\frac{1}{\sqrt{2}}\left\{\lambda_t + \frac{\partial \lambda_t}{\partial \log\chi}\frac{\chi-\chi_0}{\chi_0}\right\} v_{\rm SM}\bar{t}_L t_R + h.c.$$

The CP violating coupling is coming from the complex part of $\partial\lambda_t/\partial\log\chi$.

$$\frac{\partial \lambda_t}{\partial \log\chi} \equiv \lambda_t[\chi_0]\gamma_t$$

EDM: $d_e/e \propto Im[\gamma_t]\dfrac{v_{\rm SM}}{\chi_0}\sin\theta \;\propto 1/m_\chi^2$

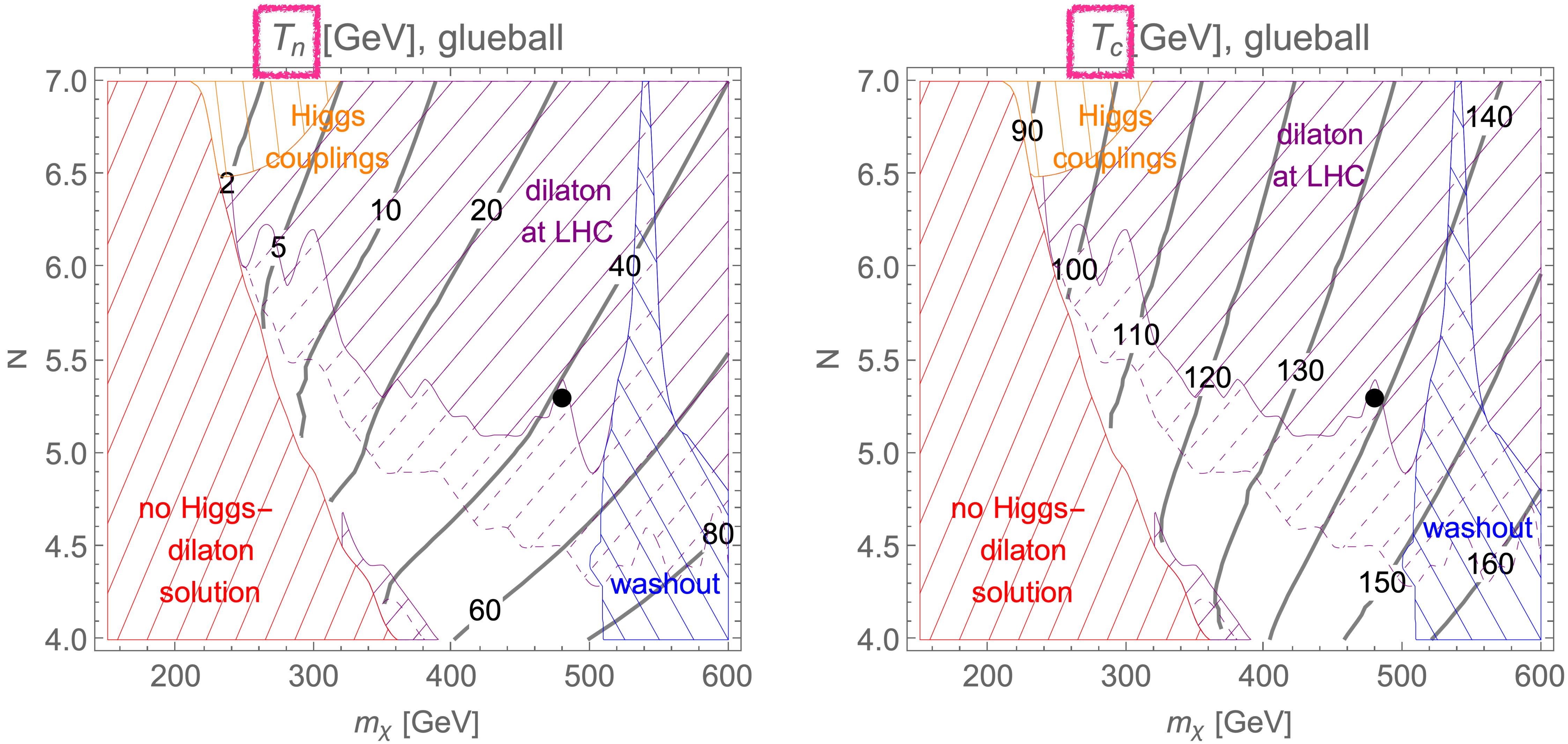


EDM bound can be evaded but
predicted EDM are close to ACME limit

$$|d_e|/e < 1.1\cdot 10^{-29}\mathrm{cm}$$

2212.11953

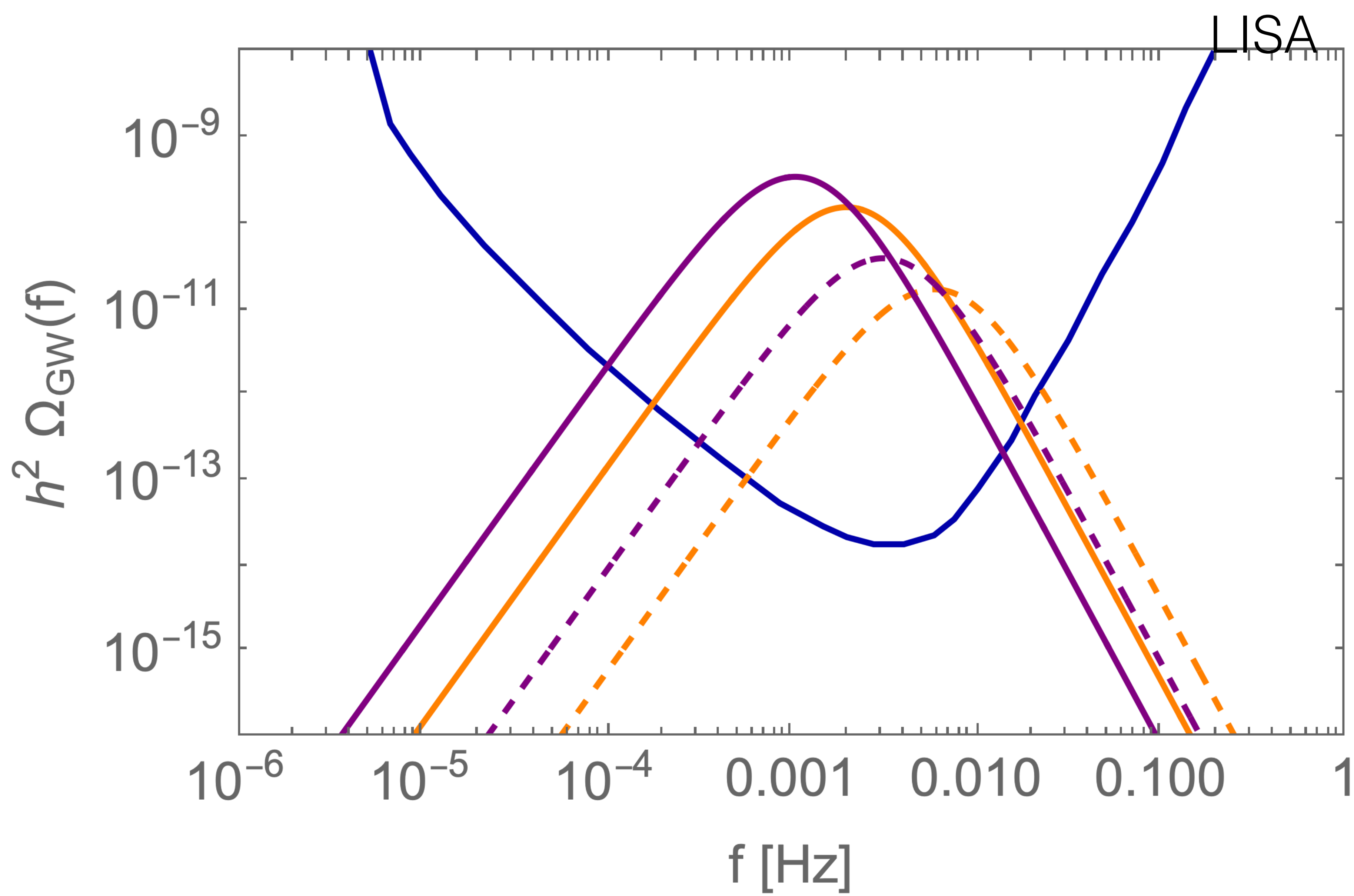
Amount of supercooling



2212.11953

-> Large Gravitational-wave signal

Large Gravitational-wave signal from the dilaton-induced EW phase transition in Composite Higgs.



[Bruggisser et al'22]

Take-away message

Top-transport typically ruled out in 2HDM and other models with polynomial potentials but still able in Composite Higgs with nearly-conformal dynamics

Finite window of viable parameter space for minimal Composite Higgs with nearly-conformal dynamics: entirely testable at high-lumi LHC

[Bruggisser et al'22]

See also de Curtis et al.,1909.07894, for the EWPT in non-minimal Composite Higgs (i.e based on SO(6)/SO(5)) & Angelescu et al., 2112.12087.

What next ?

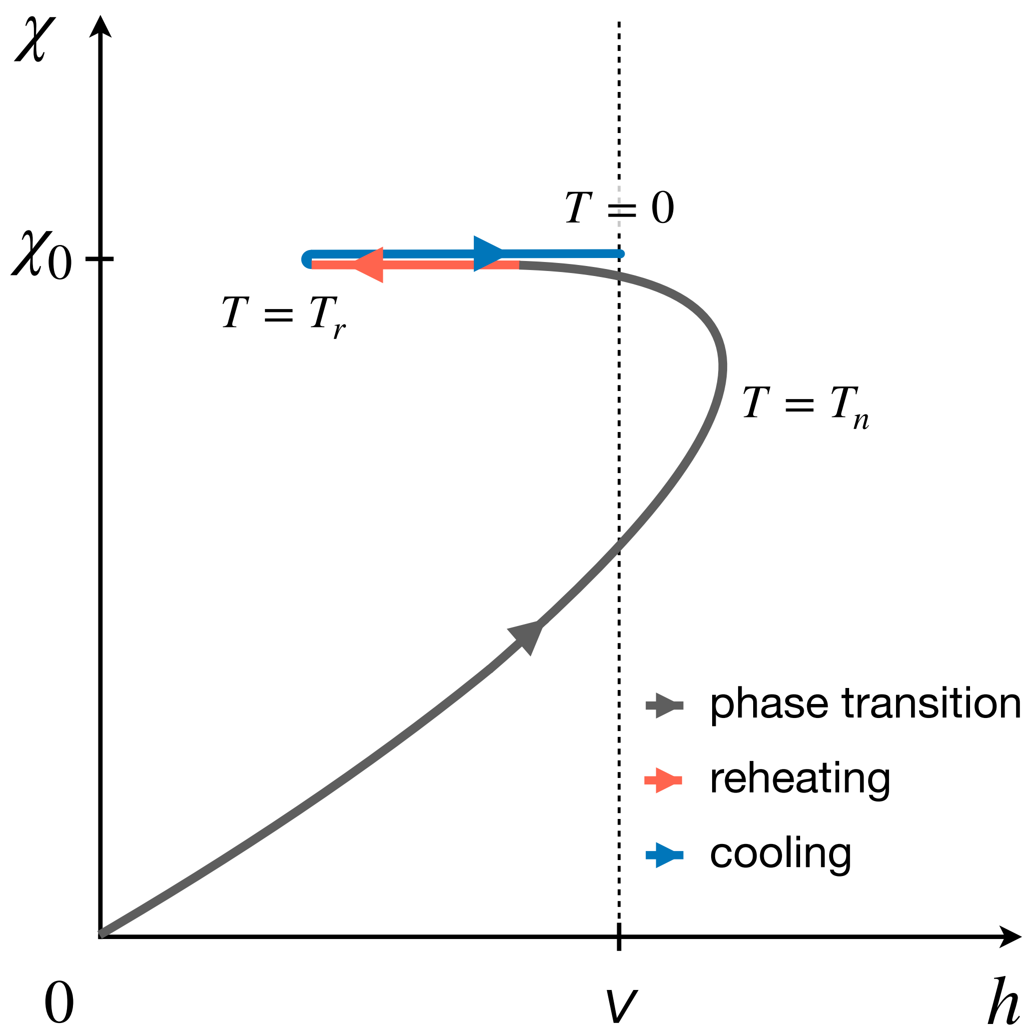
Revisit EWPT in Composite Higgs with extra singlet fermions

—> Open the heavy dilaton region!

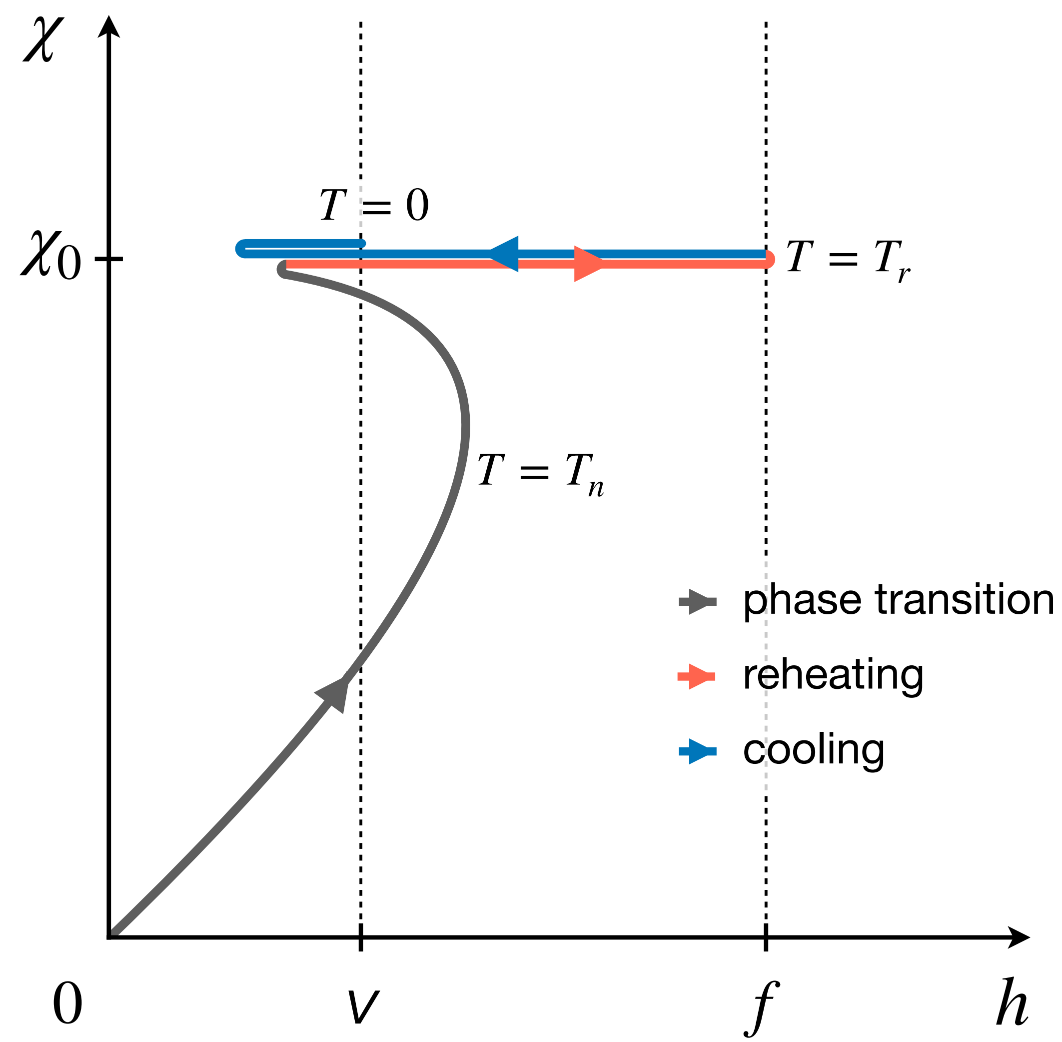
VonHarling, Matsedonskyi, Servant, 2307.14426.

Higgs & dilaton temperature evolution

Minimal setup

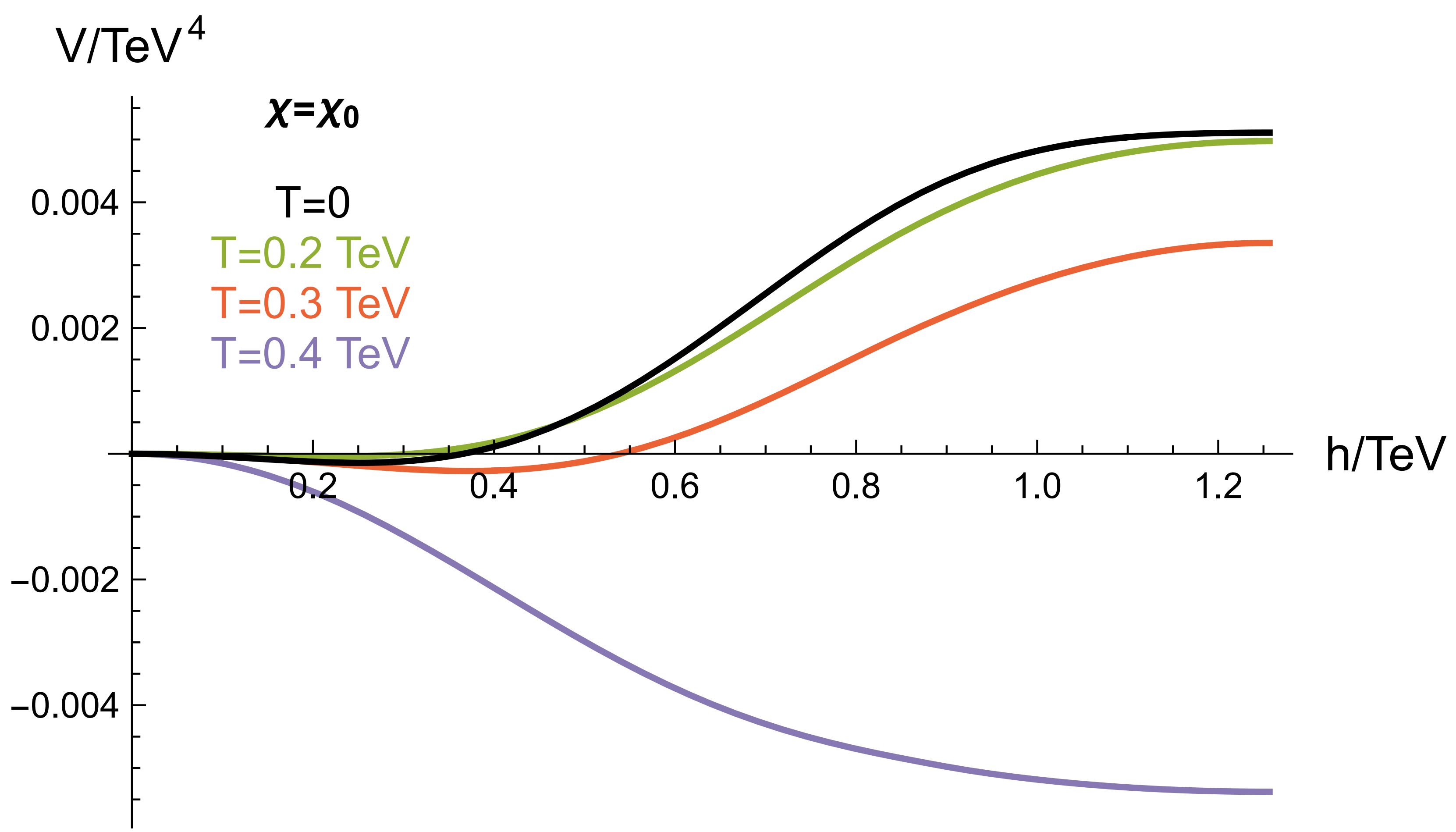


With extra singlets



2307.14426

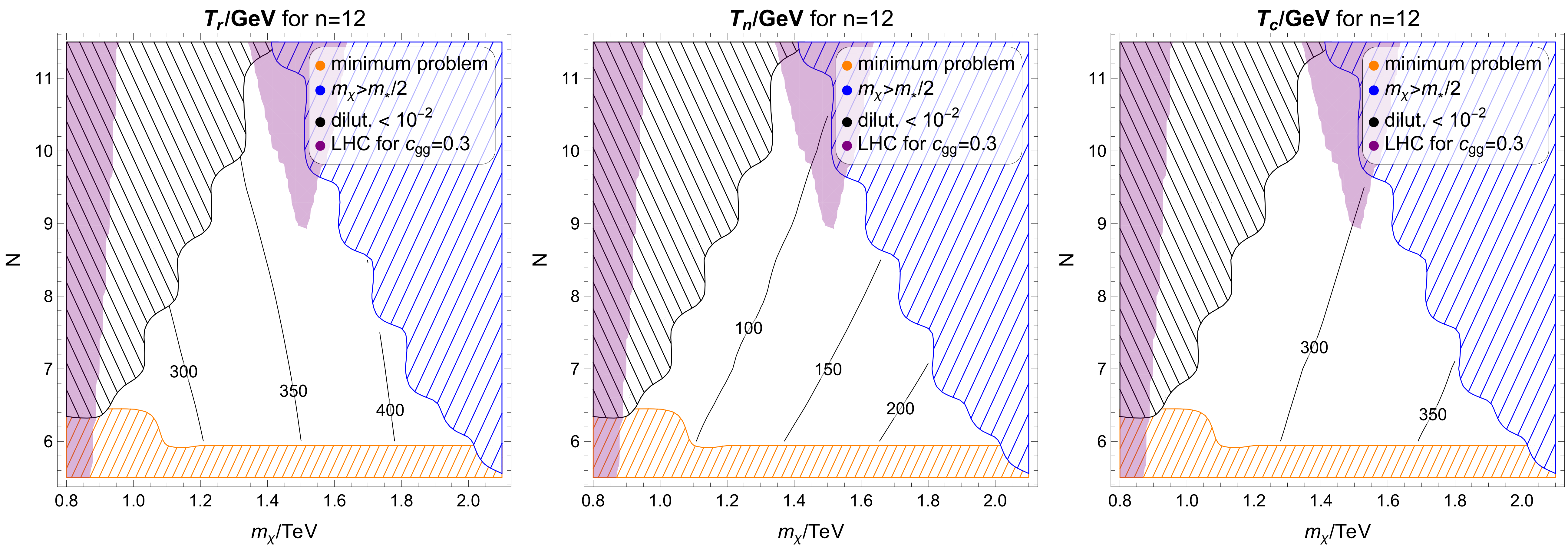
Minimal Composite Higgs potential in presence of extra singlet fermions at high temperature



from $$\mathcal{L}_{\rm SNR} = (g_\chi \chi/g_*)\,(y_{SL}\bar{S}_L\psi_R + y_{SR}\bar{S}_R\psi_L + \text{h.c.})\cos h/f - m^0_\psi\bar{\psi}\psi - m^0_S\bar{S}S$$

Mass eigen states: $$m_S[h] \simeq m^0_S - \frac{y_{SL}y_{SR}f^2}{m^0_\psi}\cos[h/f]^2\,, \qquad m_\psi[h] \simeq m^0_\psi + \frac{(y^2_{SL}+y^2_{SR})f^2}{2m^0_\psi}\cos[h/f]^2,$$

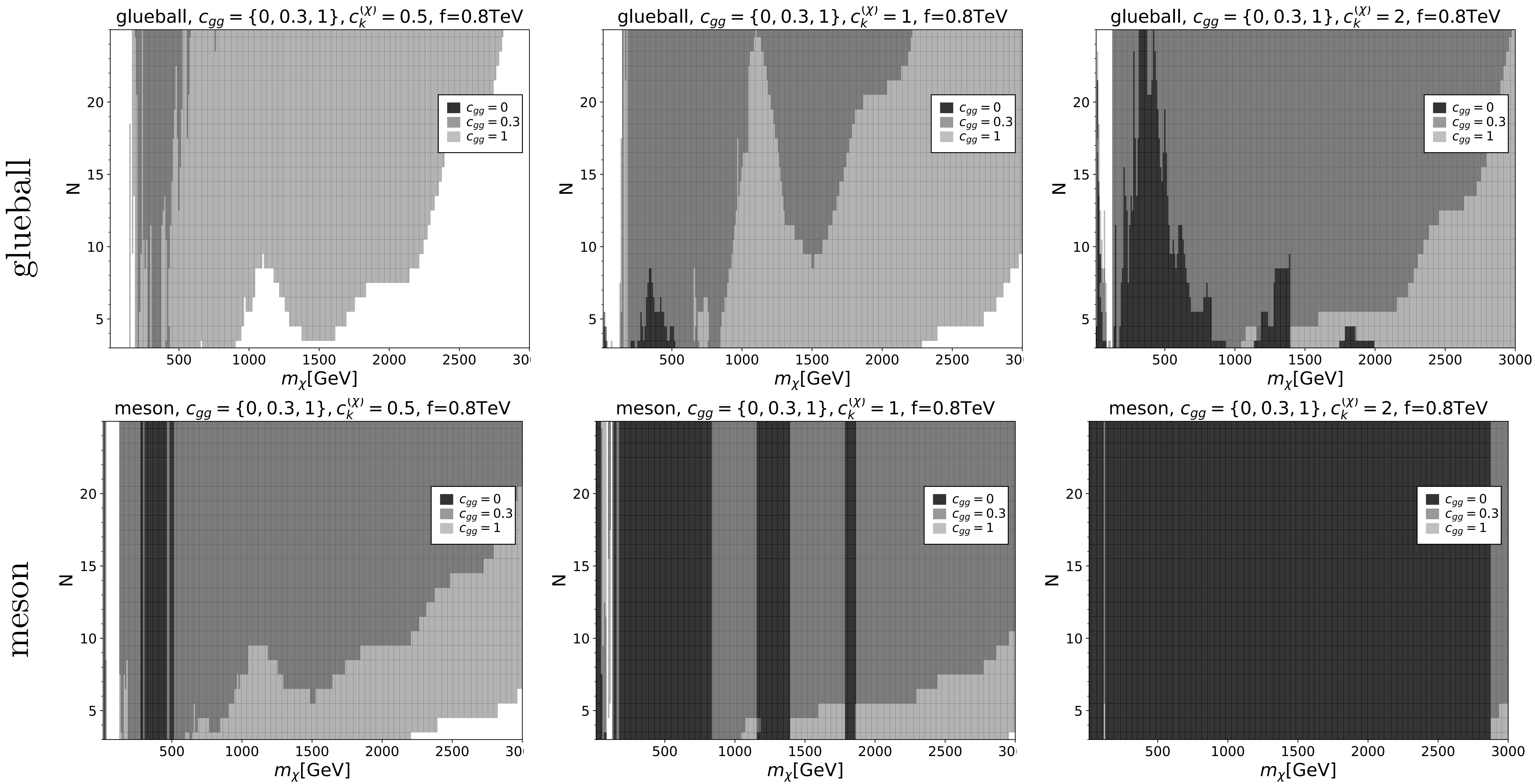
Opening the heavy dilaton window with high-temperature EW symmetry Non-restoration .



2307.14426.

Heavy dilaton window with high-temperature EW symmetry Non-restoration

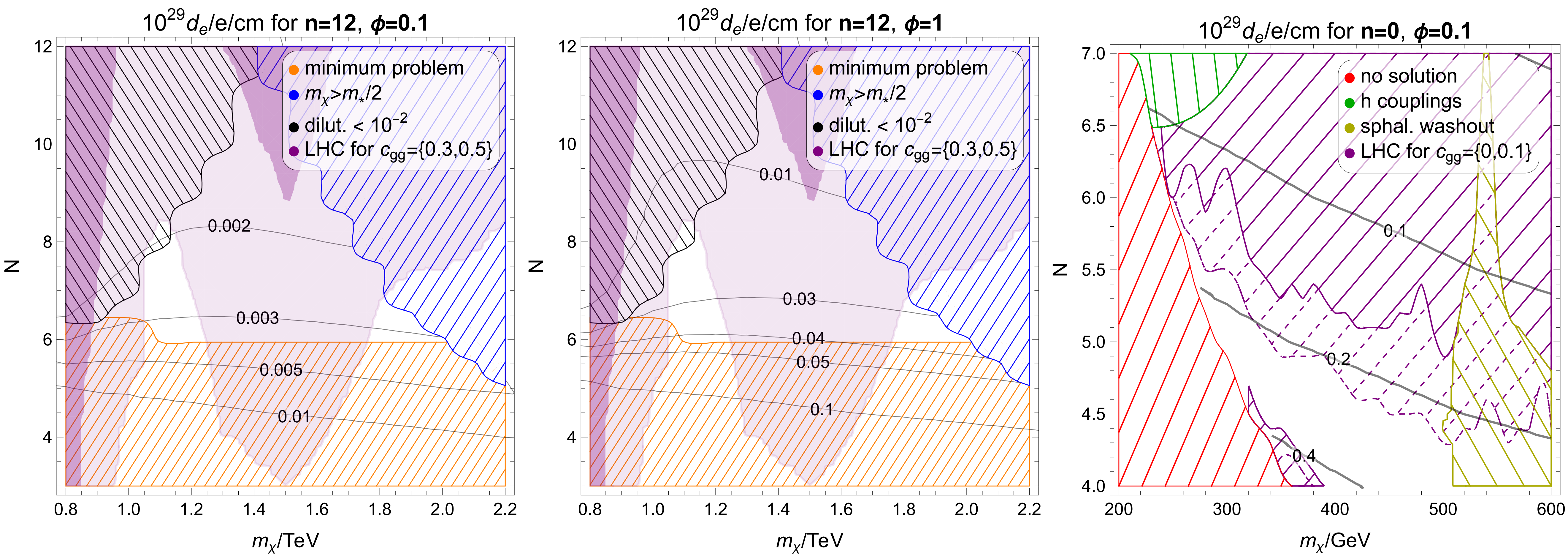
LHC bounds due to $c_{gg}\frac{g_s^2}{3g_*^2}\frac{\chi}{\chi_0}G_{\mu\nu}G^{\mu\nu}$



2307.14426.

Opening the heavy dilaton window with high-temperature EW symmetry non-restoration .

Much smaller EDMs ($\propto 1/m_\chi^2$)



2307.14426.

Summary

- **EW baryogenesis: still alive**

-e.g: Strongly 1st-order EW phase transition generic in minimal Composite Higgs with approximate scale invariance.

-Rich pheno & cosmology (*LHC, EDMs & GW signatures at LISA),* entirely t*estable at high-lumi LHC through Higgs-like scalar searches*

- **EW symmetry non-restoration effects**

-EW phase transition occurring at high temperatures >> 100 GeV, via additional singlet scalars or singlet fermions.

-Opens the large singlet mass window
(e.g. large dilaton mass window in composite Higgs)

Other applications: Twin Higgs, SUSY, 2HDM

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY THEORY WORKSHOP

WHISPERS FROM THE DARK UNIVERSE – PARTICLES & FIELDS IN THE GRAVITATIONAL WAVE ERA

HELMHOLTZ 24 - 27 September 2024 DESY Hamburg, Germany

The annual DESY Theory Workshop is organized by the elementary particle physics community in Germany. The focus is on a topical subject in theoretical particle physics and related fields. The workshop features:

> **Plenary sessions** of specialized talks by invited speakers.
> **Parallel sessions**, allowing young researchers to present their work (Wednesday and Thursday afternoon).
> The **DESY Heinrich-Hertz-Lecture on Physics** for public outreach.

Plenary Talks

P. Agrawal (Oxford U.)	J. Harz (Mainz U.)	N. Porayko (MPI Bonn)
O. Buchmueller (ICL London)	L. Heisenberg (Heidelberg U.)	R. Porto (DESY)
M. Buschmann (GRAPPA/UvA)	A. Hook (Maryland U.)	C. Prescod-Weinstein (N. Hampsh.)
A. Chou (Fermilab)	M. Kamionkowski (J. Hopkins)	E.-M. Rossi (Leiden U.)
S. Ellis (Geneva U.)	E. Lim (King's College)	K. Schutz (McGill U.)
R. Flauger (UC, San Diego)	M. Peloso (Padua U.)	X. Siemens (Oregon State U.)
G. Franciolini (CERN)		J. van de Vis (Leiden U.)

DESY Heinrich Hertz Lecture on Physics

Marc Kamionkowski (Johns Hopkins University)
Thursday, September 26, 2024, DESY Auditorium

Parallel Sessions and Convenors

Deadline for abstract submission: TODAY!!

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY
DESY Theory Group

Programme on INDICO

Andreas Ringwald Fest

Back-up .

Talk mainly based on :

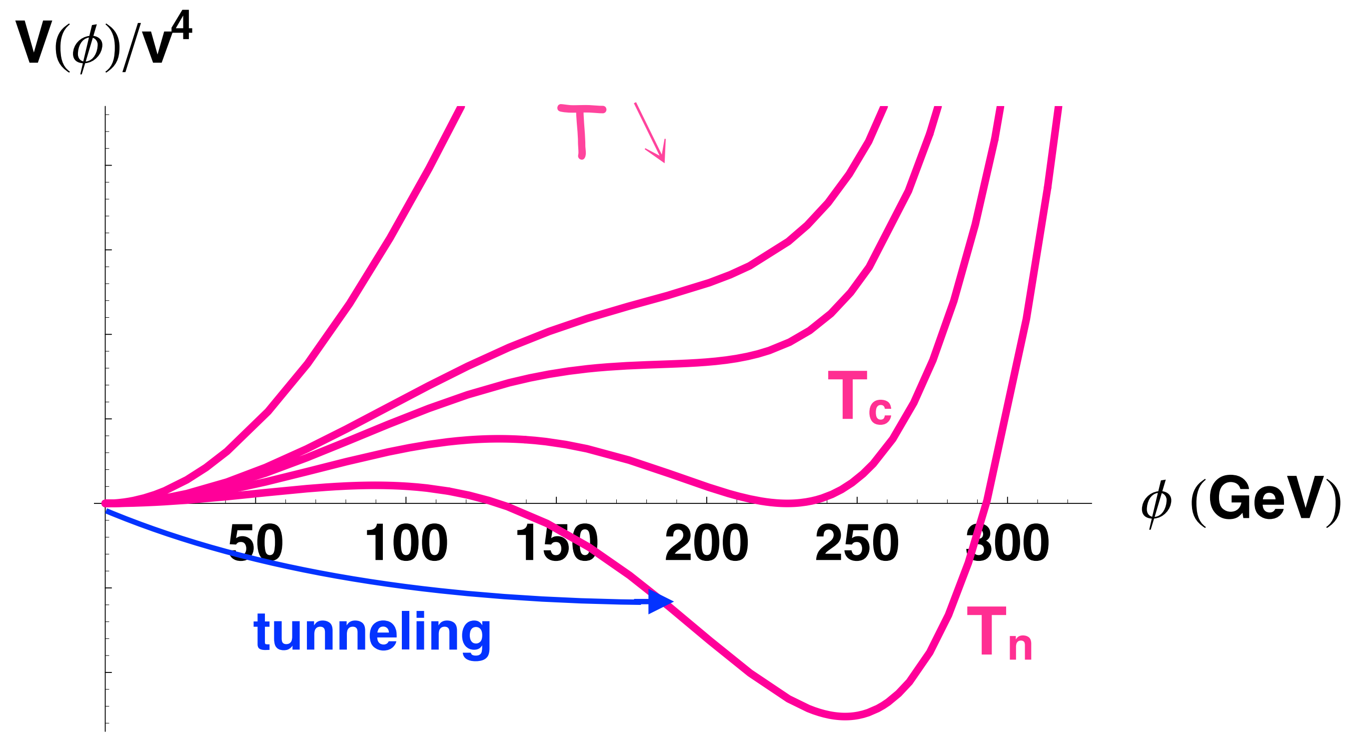
1807.08770 High temperature EW symmetry non-restoration
2002.05174

1803.08546 EW phase transition occurring *simultaneously* with confinement phase transition in composite Higgs with approximate scale-invariance in the UV.
1804.07314
2212.11953
2212.00056 Dilaton@ LHC

2307.14426 EW phase transition in minimal composite Higgs occurring at much higher temperature from high-T-symmetry-non-restoration effects

1st-order phase transition described by temperature evolution of scalar potential

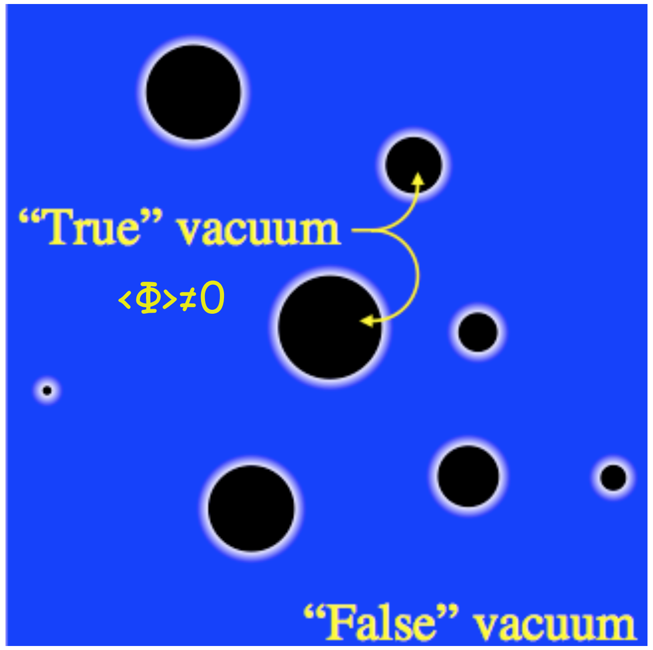
free energy of gas of particles getting a mass from φ.



Barrier separates 2 degenerate minima

2 phases can coexist

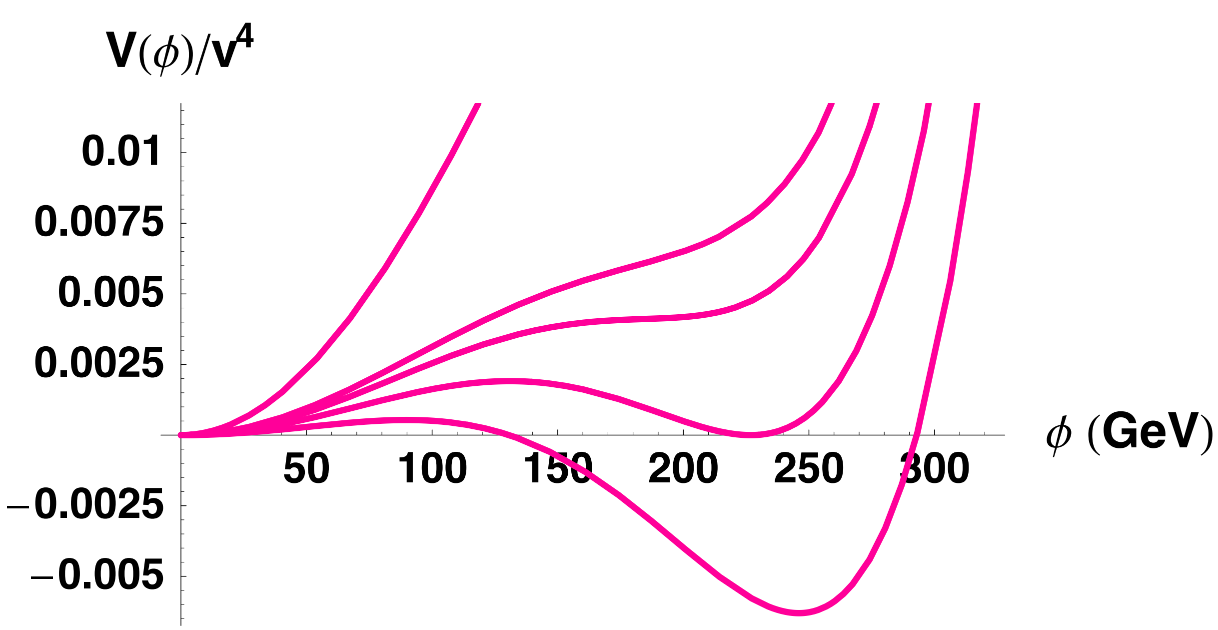
Nucleation, expansion and collision of Higgs bubbles

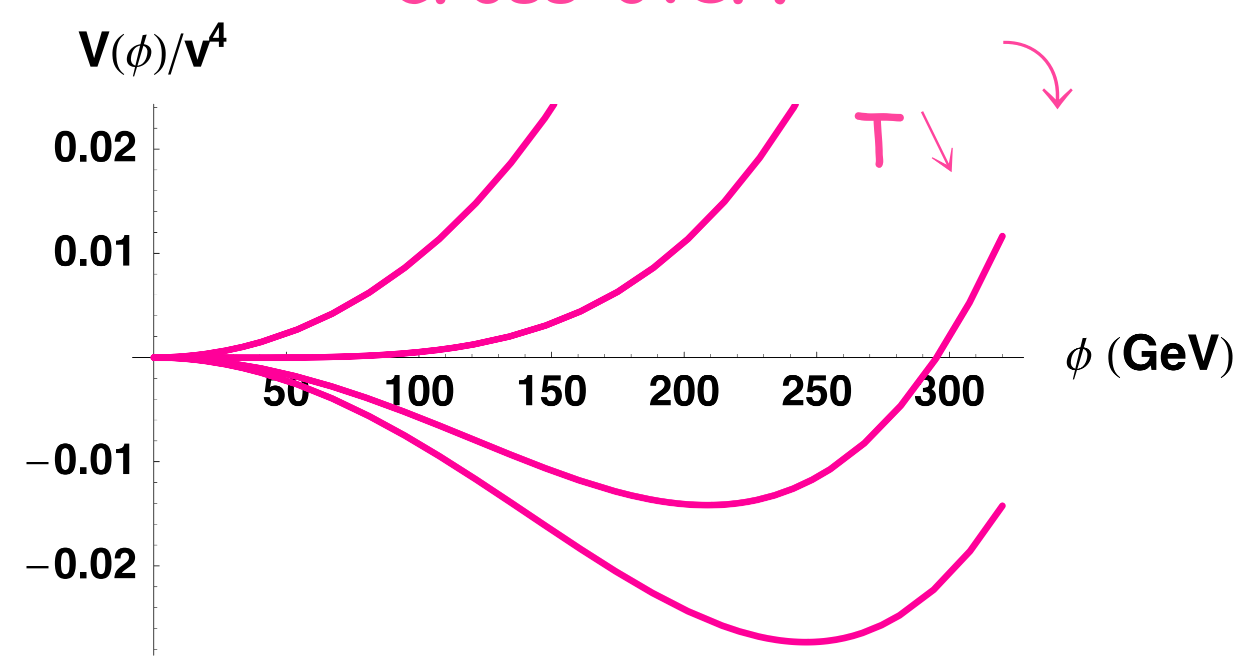


<Φ>=0

EW phase transition

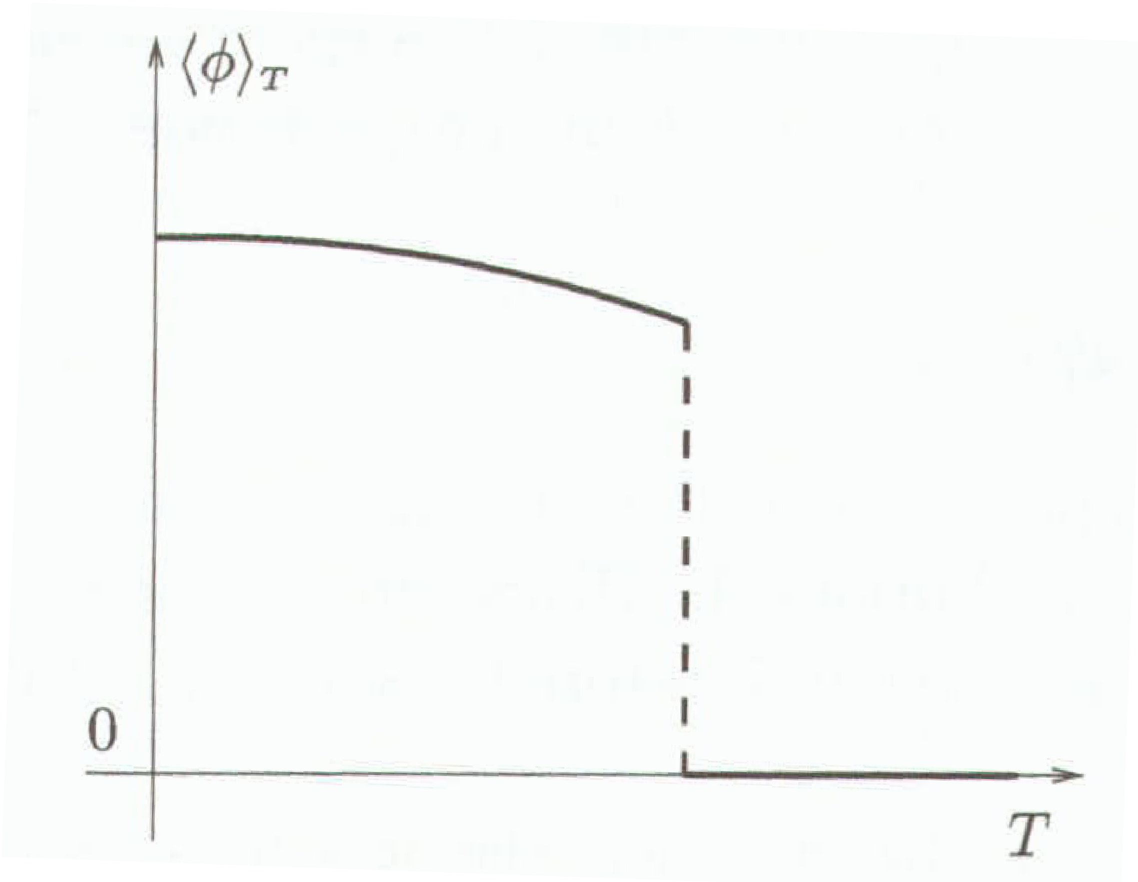
first-order or cross over?



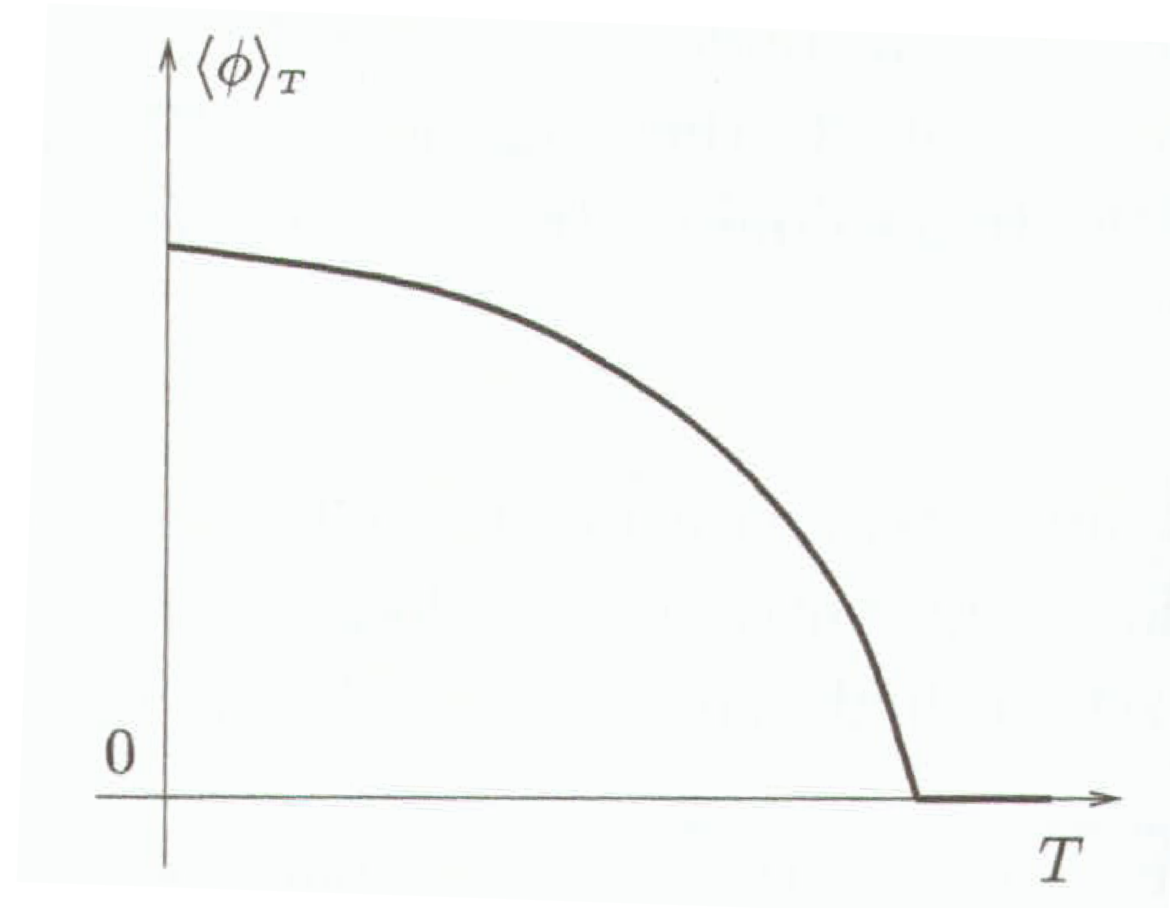


1st-order **versus** **2nd-order**

<φ(T)> discontinuous



1st derivative discontinuous



Crossover: no discontinuity in any derivative

The EW baryogenesis miracle .

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

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

$$\eta_B \sim \frac{\Gamma_{ws}\ \mu_L\ L_w}{g_*\ T}$$

$$\mu_L \sim M^{''} M \sim \frac{\delta_{CP}}{L_w^2\ T} \qquad\qquad L_w \sim \frac{1}{T}$$

$$\eta_B \sim \frac{\Gamma_{ws}\ \delta_{CP}}{g_*\ L_w\ T^2} \sim \frac{10^{-6}\ \delta_{CP}}{g_*} \sim 10^{-8}\delta_{CP}$$

All parameters fixed by EW physics. If new CP violating source of order 1 then we get just the right baryon asymmetry.

Minimal Composite Higgs with approximate scale invariance .

Assumption : theory is approximately scale-invariant in the UV, but contains operators whose coefficients slowly run with energy.

—> weak explicit breaking of scale invariance

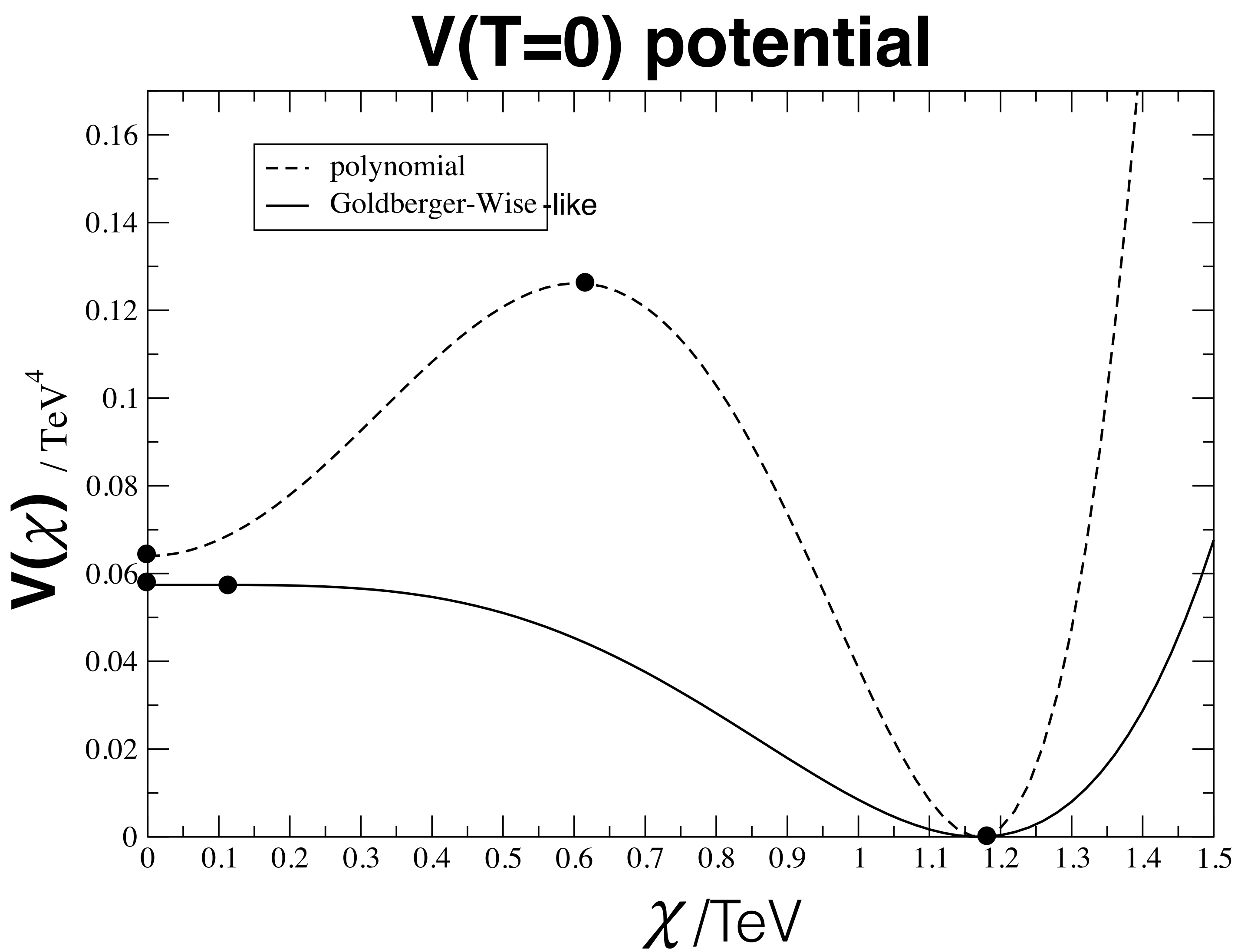
—> parametrically light dilaton, Goldstone particle associated with spontaneous breaking of conformal invariance

—> dilaton is composite state, can be meson-like or glueball-like,

—> consider an effective field theory (EFT) where no other new states are present

—> In a 4D effective description dilaton mass can be treated as a free parameter.

Generically Strong 1st order phase transition .



For shallow nearly-conformal potential, thermal corrections from the many new dof that acquire mass during the transition will naturally induce supercooling

Higgs & Dilaton phenomenology .

Assume that the underlying strongly-interacting theory is an SU(N) Yang-Mills

4D description based on a large-N expansion, dimensional analysis, conformal invariance and the approximate shift symmetry of the composite Higgs

h and χ have the following couplings

$$g_* = c_k^{(h)} \frac{4\pi}{\sqrt{N}} \qquad \text{with } c_k \sim O(1)$$

$$g_\chi = c_k^{(\chi)} \frac{4\pi}{N} (\text{glueball}) \text{ or } c_k^{(\chi)} \frac{4\pi}{\sqrt{N}} (\text{meson})$$

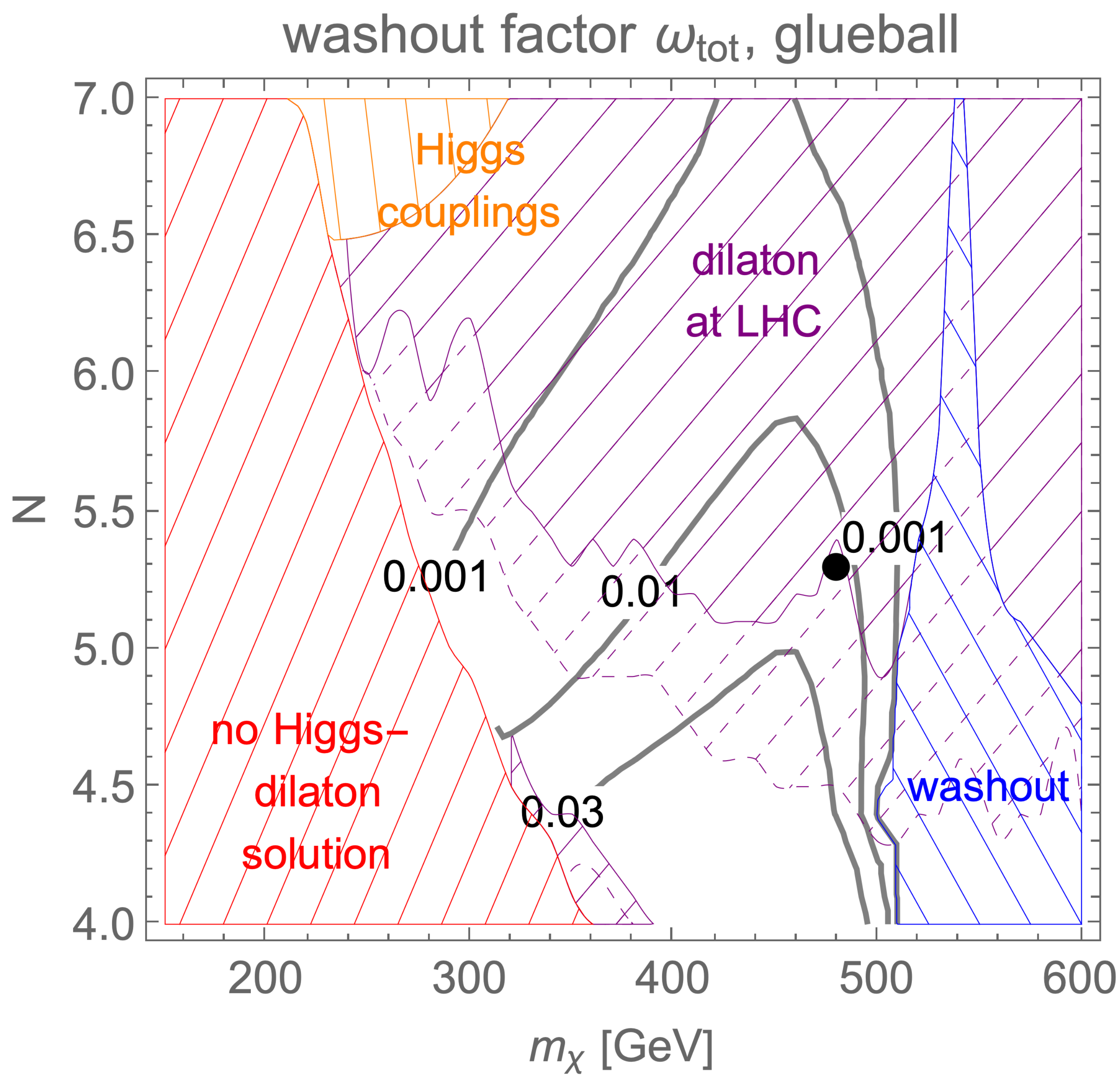
- **dilaton mass: m$_\chi$;**

- **conformal symmetry breaking scale χ_0, is related to the Higgs decay constant f ≃ 800 GeV by** $$\chi_0 = (g_*/g_\chi) f$$

- **Higgs-dilaton mixing: sin θ**

- **effective number of colors of underlying new strong dynamics: N**

Strong constraints from LHC bounds on dilaton !



2212.11953

Effect of Higgs-dilaton mixing on Higgs couplings

Possibility to access the degree of conformal- invariance breaking in the UV by measuring the Higgs couplings

$$\kappa_V^h = \cos\left(\theta + \frac{v_{\mathrm{CH}}}{f}\right).$$

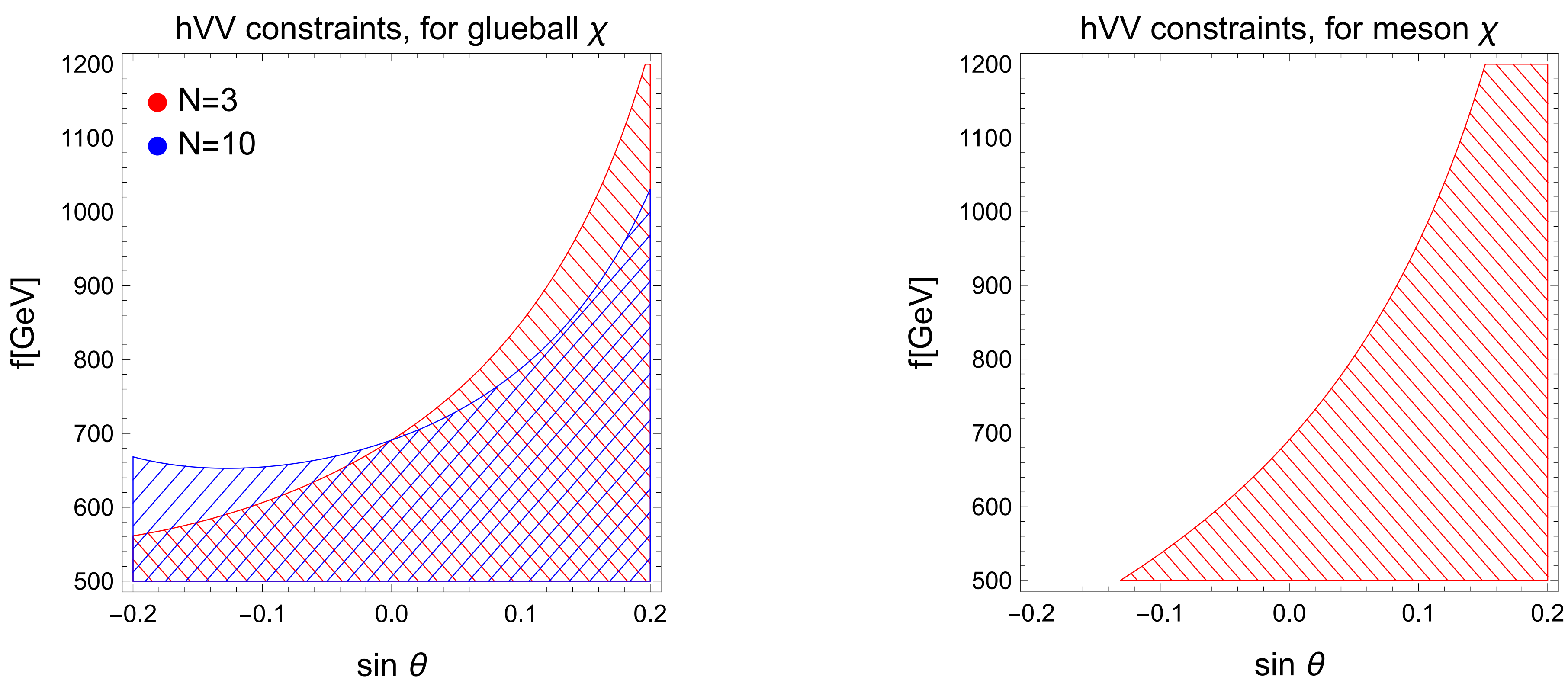


Figure 1: *Current bounds on the dilaton-Higgs mixing angle and f derived from the Higgs-EW vector boson coupling measurements.*

On LHC constraints

Even for c_{gg} = 0, a dilaton coupling to gluons is generated via top quark loops, proportional to the dilaton-top coupling

$$\mathcal{L} \supset -\frac{\lambda_t}{\sqrt{2}}\left\{ s_\theta \cos\frac{v_{\rm CH}}{f} + c_\theta (1+\gamma_t)\frac{v_{\rm SM}}{\chi_0}\right\}\bar{t}t\hat{\chi} + \text{h.c.} \equiv -\frac{\lambda_t}{\sqrt{2}}\kappa_t^\chi \bar{t}t\hat{\chi} + \text{h.c.},$$

$$\gamma_t = d\log\lambda_t / d\log\mu$$

$$\mathcal{L}_{\rm top} = -\frac{\lambda_t}{\sqrt{2}} f \sin(h/f)\bar{q}_L t_R, \qquad \lambda_t = y_{tL}(y_{tR}^{(1)} + y_{tR}^{(2)})/g_*,$$

This coupling decreases if the anomalous dimension gamma_t or the Higgs-dilaton mixing angle sin theta is negative.

In the scenario where CPV is generated by a varying top quark Yukawa coupling we indeed need gamma_t to be negative and sizeable.

This reduces the size of the second term above and thereby the gluon-dilaton coupling. Moreover, in this case a sizeable mixing sin theta is automatically

generated due to the large size of the top quark Yukawa coupling at chi=chi_0. If sin theta is negative, this results in an accidental cancellation between the two terms

and in a further reduction of the gluon-dilaton coupling. The cancellation reduces the coupling along a valley for small m,N. This produces a window in the parameter space

where the LHC bounds can be satisfied. Note also that a sizeable negative sin theta can decrease the deviations of the composite Higgs couplings to massive vector bosons & quarks from their SM predictions .

$$\kappa_V^h = c_\theta \cos\frac{v_{\rm CH}}{f} - s_\theta \frac{g_\chi}{g_*}\sin\frac{v_{\rm CH}}{f}.$$

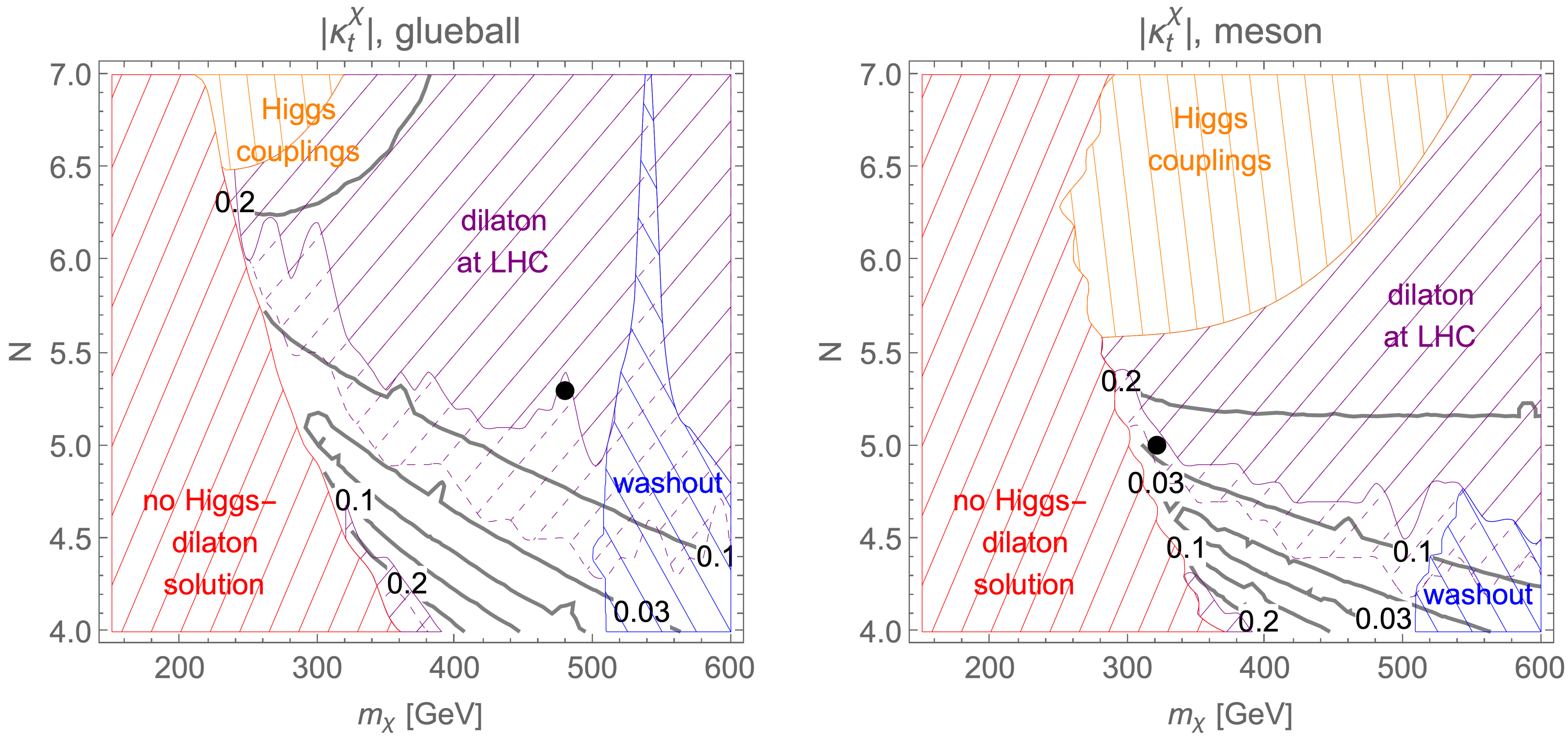
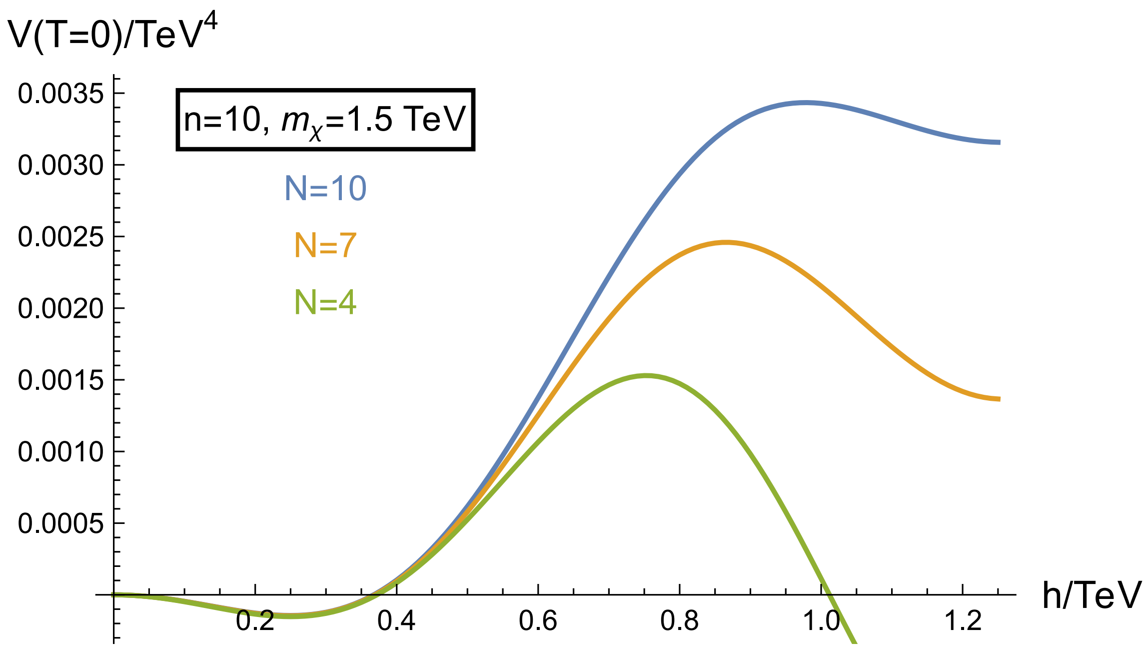
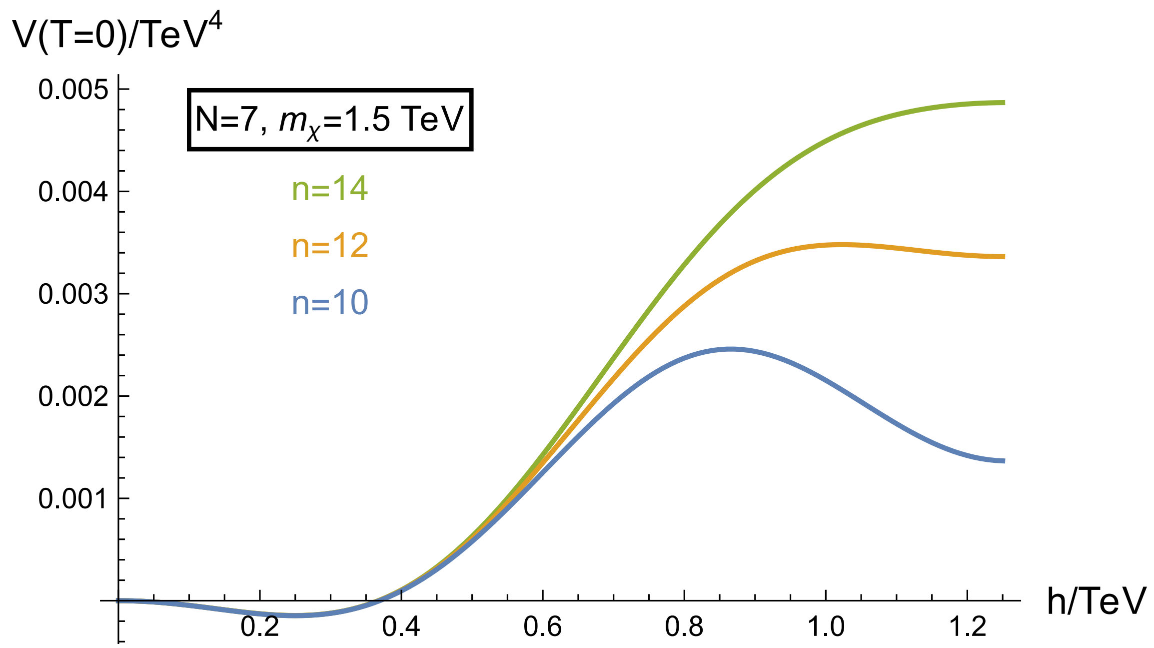


Figure 8: *Contour lines of the dilaton-top coupling κ_t^χ from Eq. (5.5) for a glueball dilaton (left panel) and a meson dilaton (right panel), both with varying top Yukawa. The color code for the hashed regions is the same as in Fig. 3.*

Minimal Composite Higgs potential in presence of extra singlet fermions

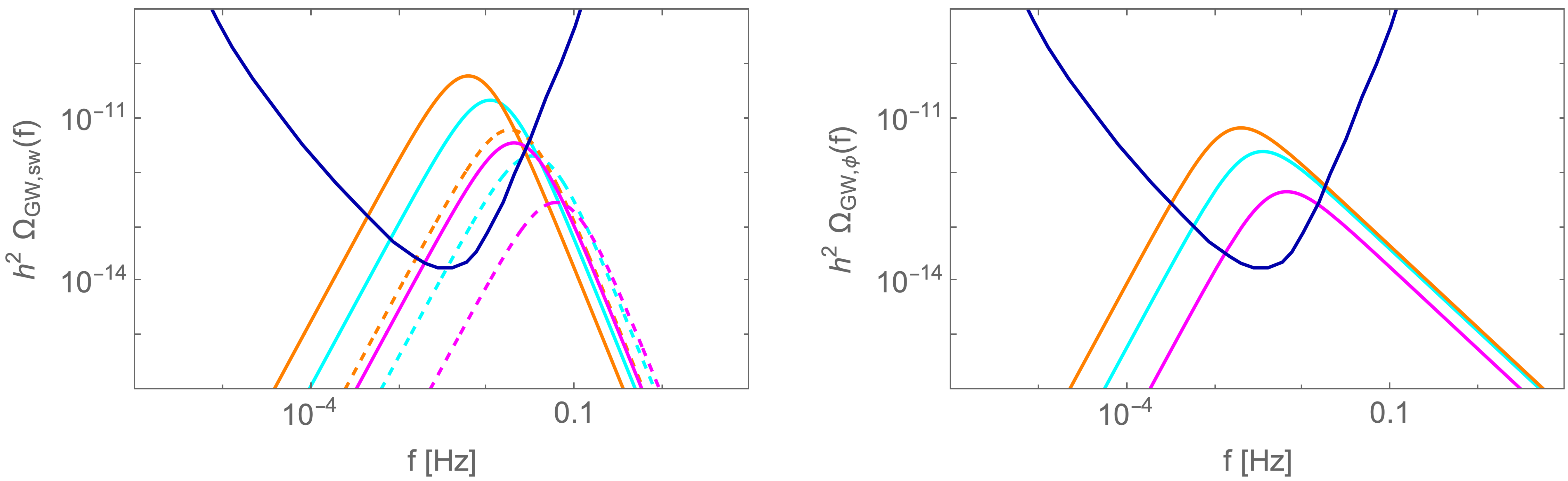
T=0



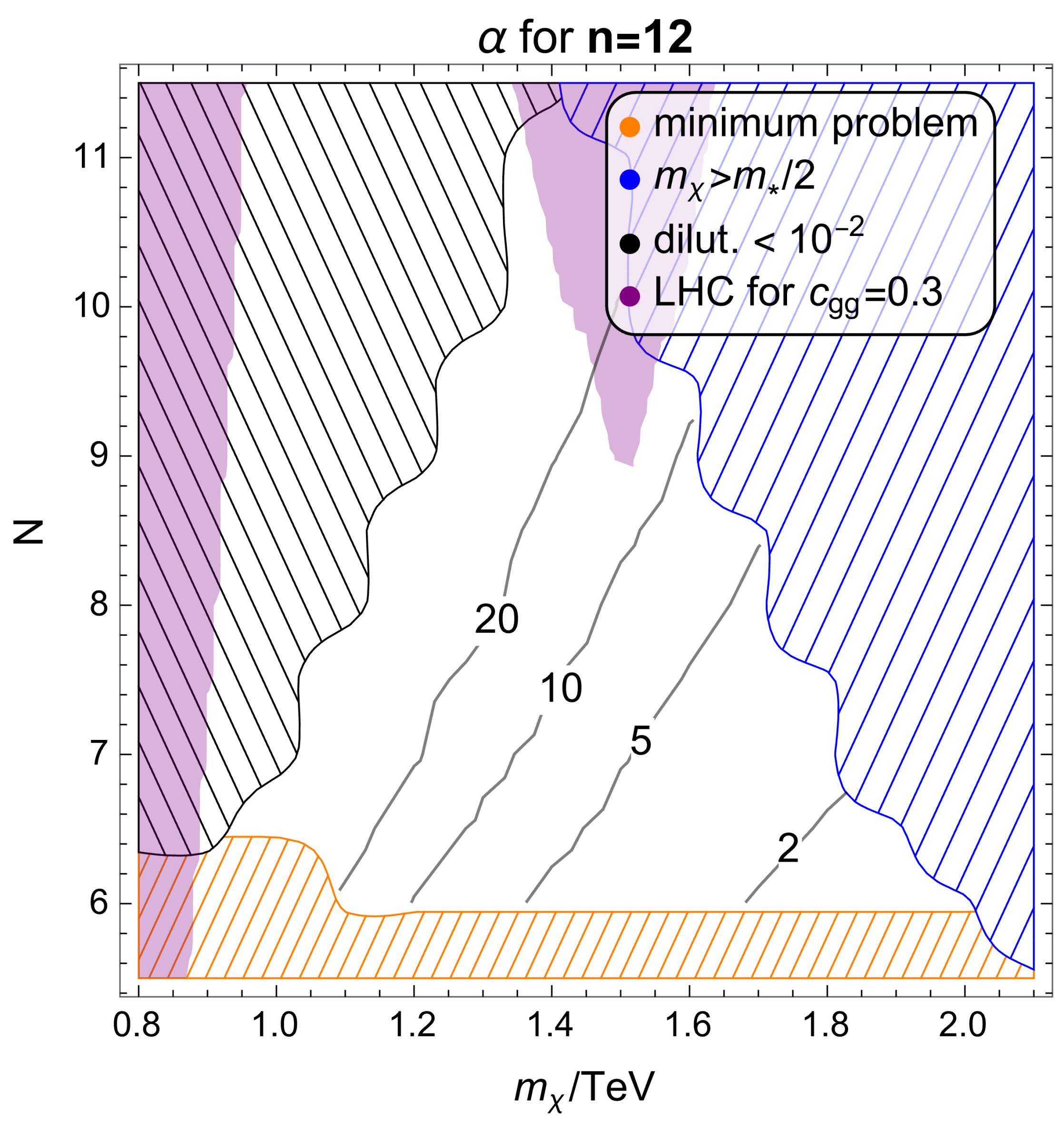


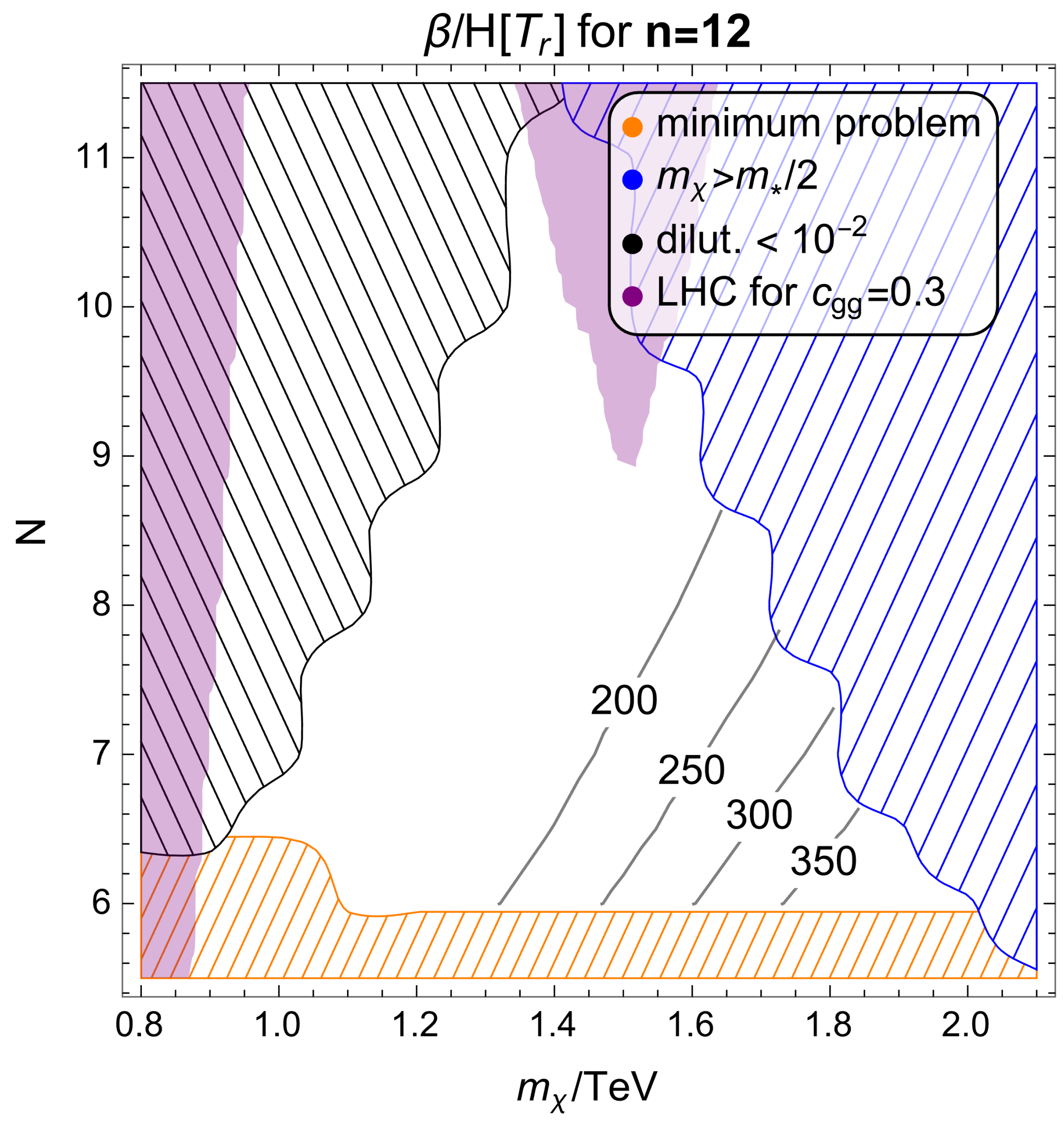
Global minimum at large Higgs VEV at low N

Gravitational-wave spectrum with SNR .



Alpha and beta for Gravitational-wave spectrum





Composite Higgs

Higgs potential: trigonometric function of h/f

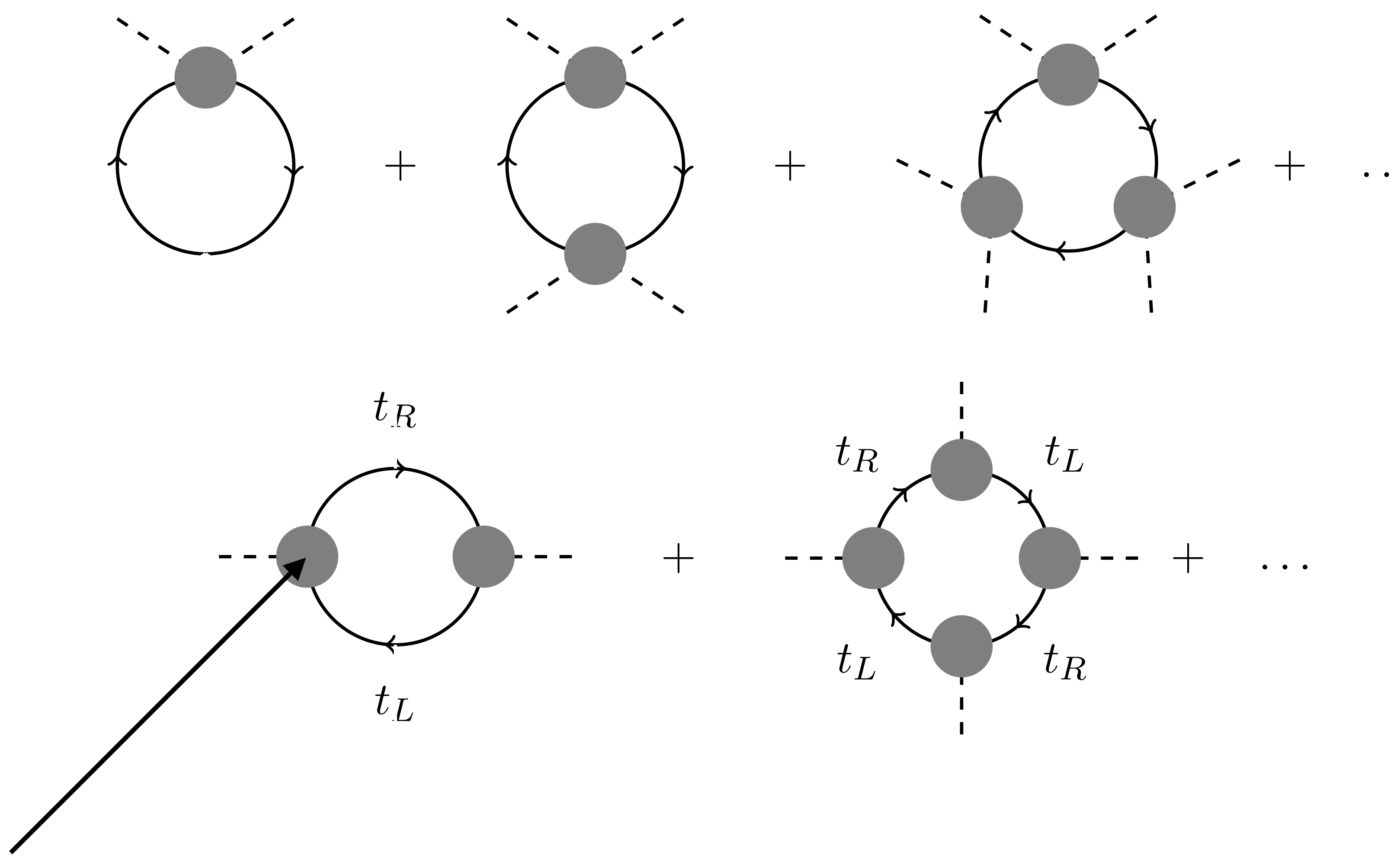
$$V^0[h] = \alpha^0 \sin^2\left(\frac{h}{f}\right) + \beta^0 \sin^4\left(\frac{h}{f}\right)$$

generated by sources of breaking of the global symmetry of the strong sector and responsible for fermion mass generation

NEW: We promote f to a dynamical field χ (the dilaton).

(with f=0.8 TeV today)

Higgs potential from fermionic loops



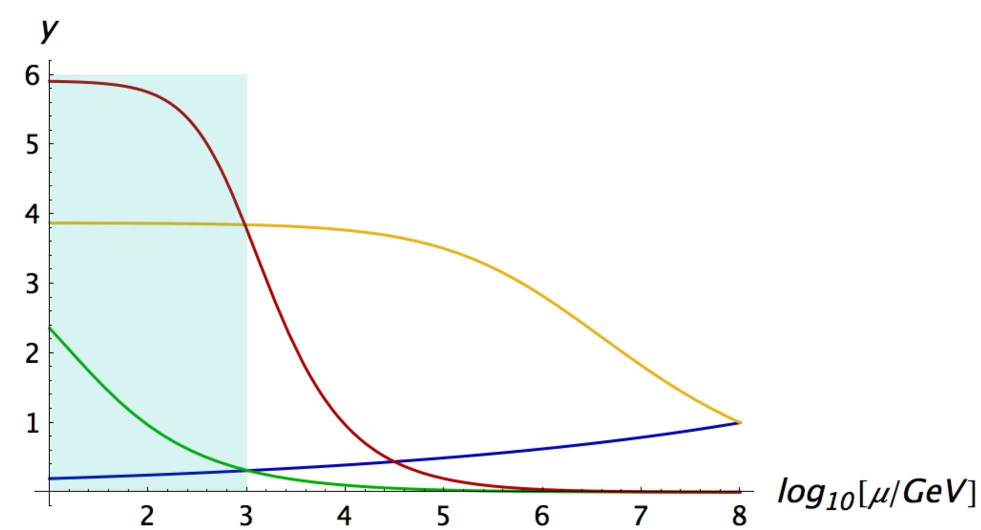
Yukawa couplings induced by composite-elementary fermion mixing.
Depend on confinement scale -> Vary during confinement phase transition.

Partial fermion compositeness

E

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

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



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

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

Goldstone matrix containing the Higgs
$U \sim \exp[ih/f]$

SM Yukawas determined by the mixings at the confinement scale

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

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

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

NEW: We promote f to a dynamical field χ (the dilaton); <χ>=f today

$$\alpha[\chi] = c_\alpha \frac{3y^2[\chi]g_*^2}{(4\pi)^2} f^4, \quad \beta[\chi] = c_\beta \frac{3y^2[\chi]g_*^2}{(4\pi)^2} f^4 \left(\frac{y[\chi]}{g_*}\right)^{p_\beta}$$

Non-trivial Higgs-dilaton interplay

Kinetic equations

Cline, Joyce, Kainulainen '00
Konstandin, Prokopec, Schmidt '04
Huber Fromme '06
Bruggisser, Konstandin, Servant '17

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

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

collisions

source

$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}y \; K_i(y) \; \bar{\mathcal{S}}_i(y)$$

diffusion effects
& sphalerons

CP-violating
source

Another way-out of EDM bounds:

Using strong CP violation from QCD axion in *COLD* baryogenesis

Servant, 1407.0030

$$\frac{a(t)}{f_a} F\tilde{F}$$

QCD axion → $a(t)$

EW field strength → $F\tilde{F}$

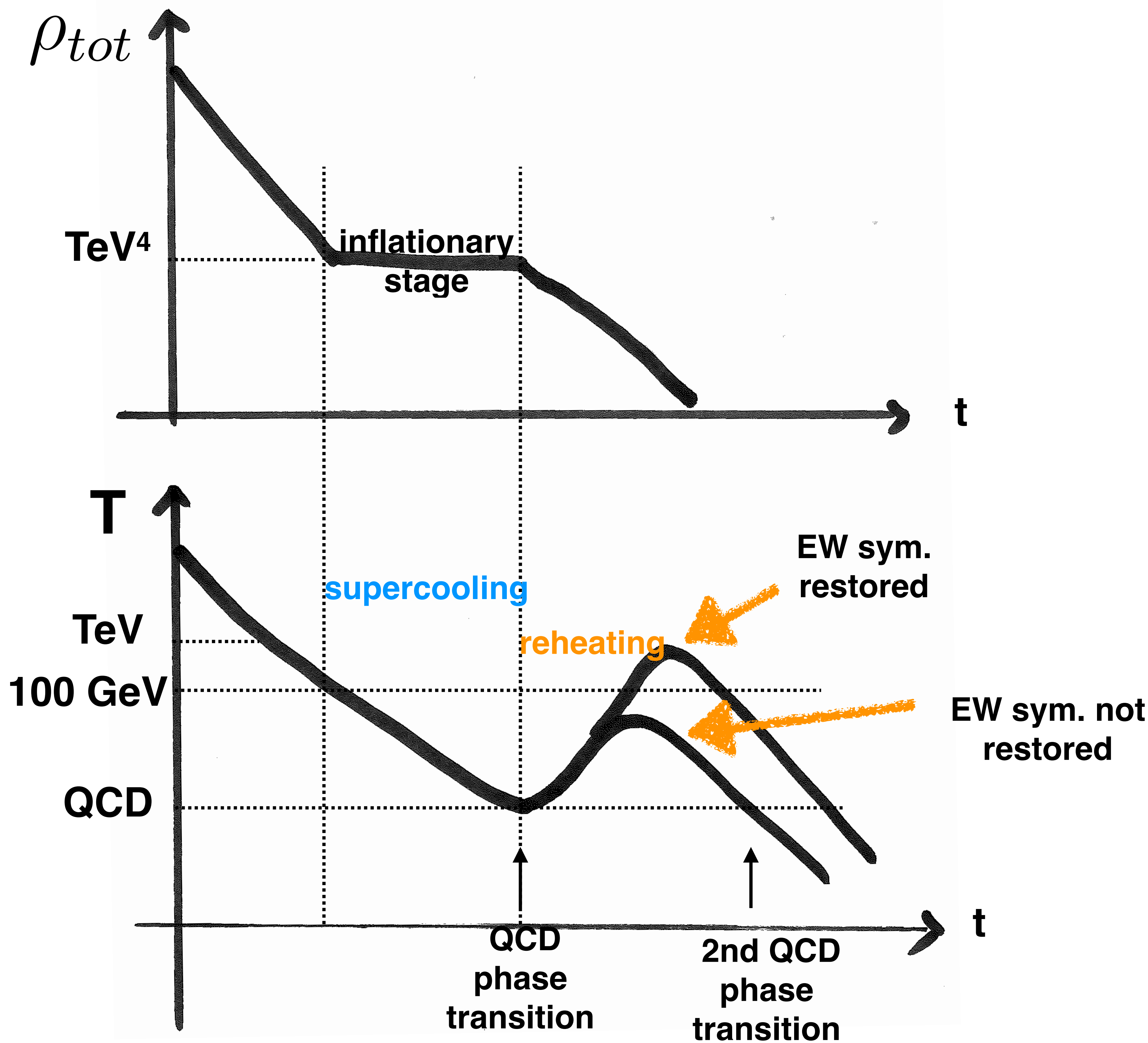
$$|\bar{\Theta}| \sim 1$$ at QCD epoch

Time variation of axion field can be large CP violating source for baryogenesis if EW phase transition is supercooled down to QCD temperatures

⟶ **Cold Baryogenesis**

requires a coupling between the Higgs and an additional light scalar: testable @ LHC & compatible with usual QCD axion Dark matter predictions

Supercooled EW phase transition induced by TeV-scale confinement phase transition .



Implications:

-> Cold EW baryogenesis using strong CP from QCD axion

1407.0030

-> Modified QCD axion relic abundance

1711.11554
1812.06996

-> Modified relic abundance of thermal dark matter

2007.08440