High-Temperature EW Symmetry Breaking.

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DESY/U.Hamburg

KAVLI IPMU workshop "New observational windows on the high-scale origin of matter-antimatter asymmetry", 10-01-2022

DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

UH
Universität Hamburg

This workshop:
“High-scale” baryogenesis

Why not “low-scale”?

Let us review the basics…

Matter-antimatter asymmetry

characterized in terms of the baryon to photon ratio

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10

The great annihilation

10 000 000 001
Matter

10 000 000 000
Anti-matter

1
(us)

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)

Baryon number violation in the Standard Model

due to chirality + topology of electroweak theory

From the Electroweak anomaly

$$\partial_\mu j^\mu_B = N_F \frac{\alpha_W}{8\pi} Tr F \tilde{F}$$

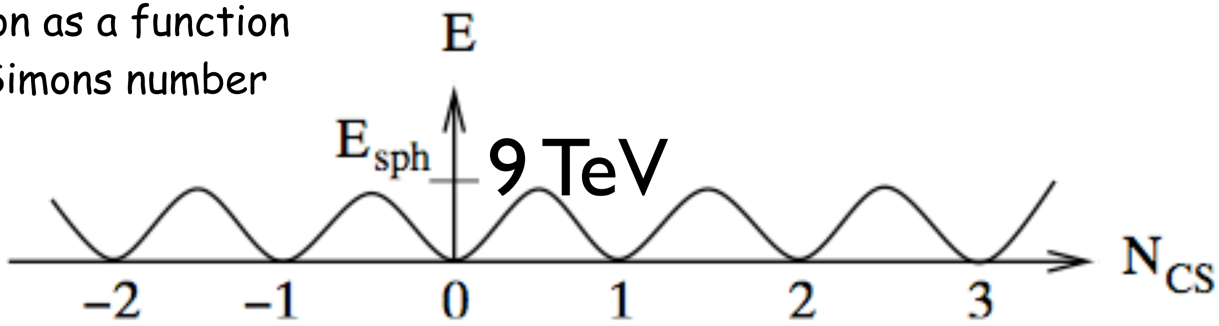
EW field strength

$$\Delta B = \Delta L = N_F \Delta N_{CS}$$

Baryon number violation in the Standard Model

due to chirality + topology of electroweak theory

Energy of gauge field configuration as a function of Chern Simons number

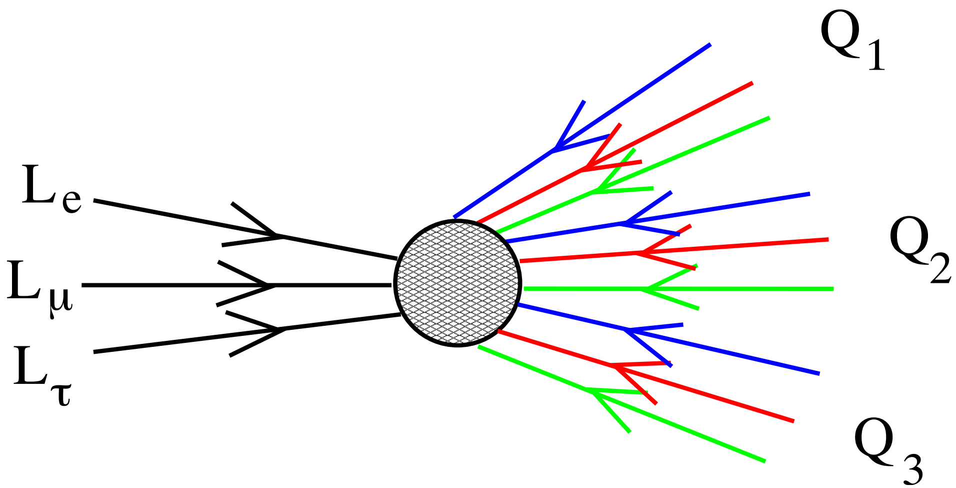


$$\Delta B = \Delta L = N_F \Delta N_{CS}$$

baryons are created by transitions between topologically distinct vacua of the $SU(2)_L$ gauge field

⇒ Baryon number violation is totally suppressed in the Standard Model at zero temperature but very efficient at high temperatures

The sphaleron



$$\Delta B = N_f \Delta N_{CS}$$

Each transition creates 9 LH-quarks and 3 LH leptons.

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

T_C: Temperature of the EW phase transition

- In the EW symmetric phase, $T>T_C$

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

- In the EW broken phase, $T<T_C$

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 EWPT.

Advantage: connected to EW physics, testable

2) B-L≠ 0 theory

High-scale baryogenesis possible.

Disadvantage: hard to test

Baryogenesis Recap

GUT Baryogenesis :

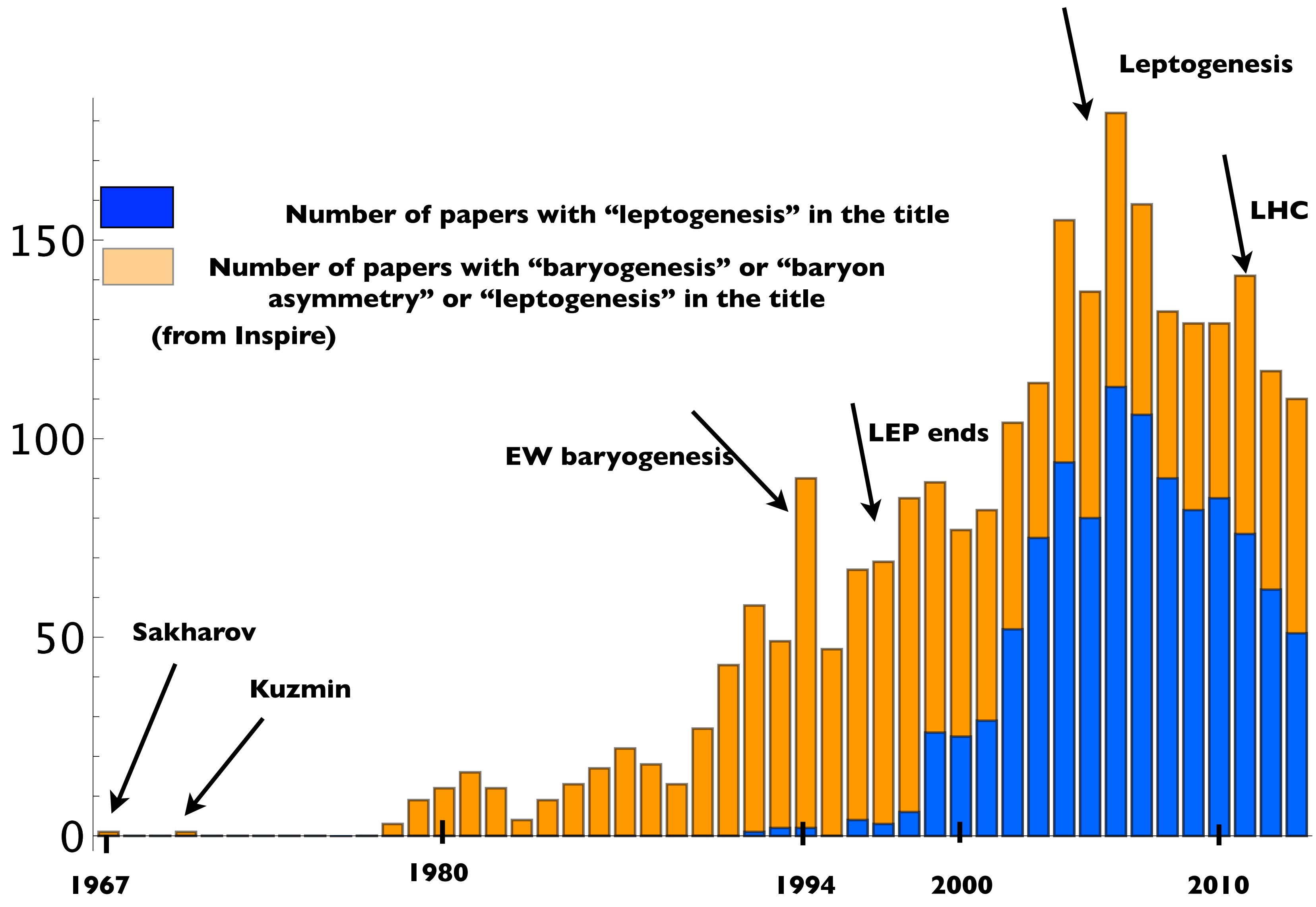
-requires too high reheat temperature
-requires (B-L) violation due to washout by sphalerons

-> **Leptogenesis** as the most viable baryogenesis through out-of equilibrium decays of heavy right-handed Majorana neutrinos (L-violating).
Appealing as it requires hardly any new physics ingredients beyond those needed to explain neutrino masses by the seesaw mechanism.

Drawback: hard to test

—> Only way to achieve baryogenesis in (B-L) conserving theory:
At the electroweak phase transition: **Electroweak baryogenesis**

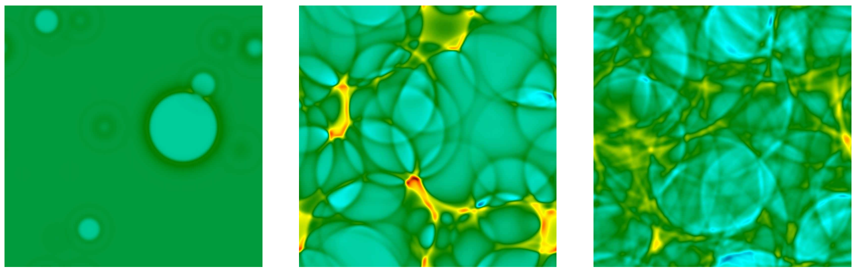
History of baryogenesis papers



Two leading candidates for baryogenesis:

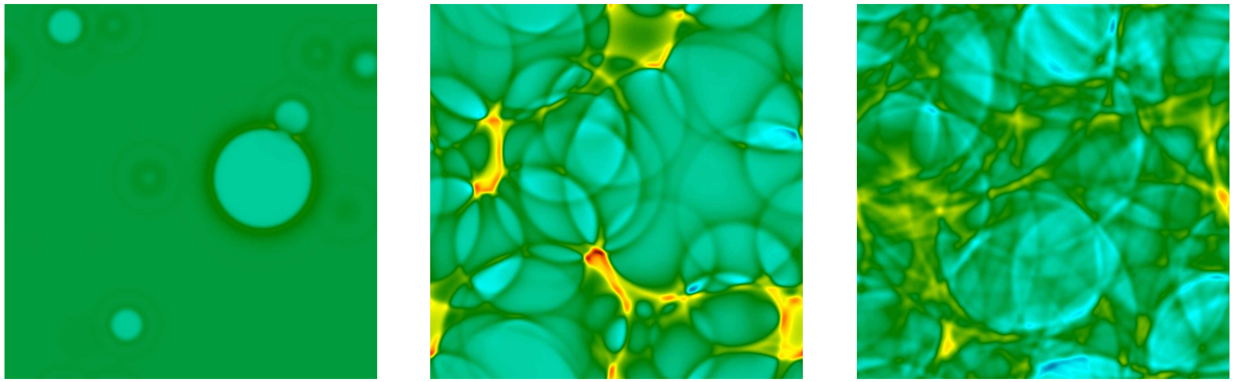
--> Leptogenesis by out of equilibrium decays of RH neutrinos before the EW phase transition

--> Baryogenesis at a first-order EW phase transition



this talk:

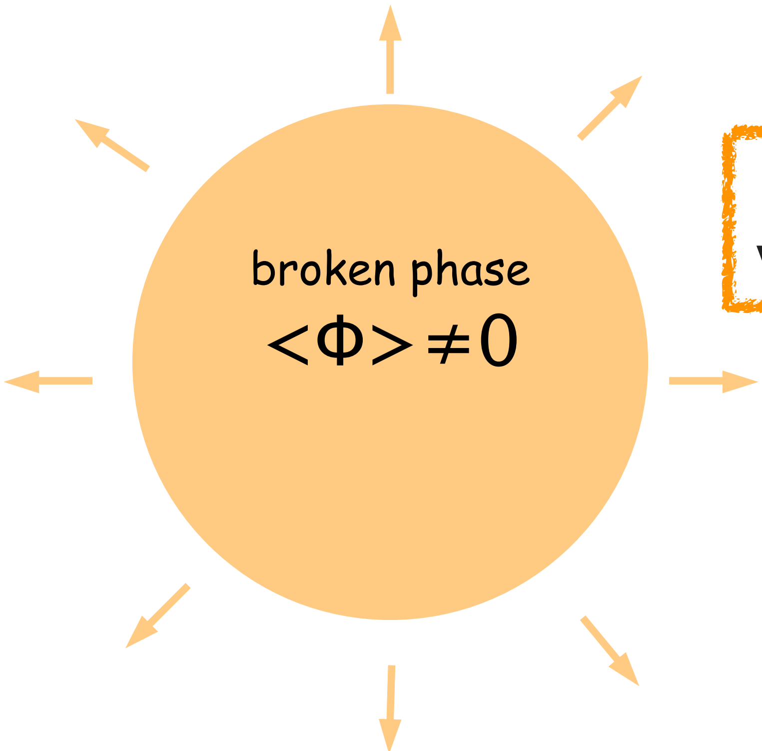
Baryogenesis at a first-order EW phase transition



[image credit:1304.2433]

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 $\equiv \quad \dfrac{\langle \Phi(T_n) \rangle}{T_n} \gtrsim 1$

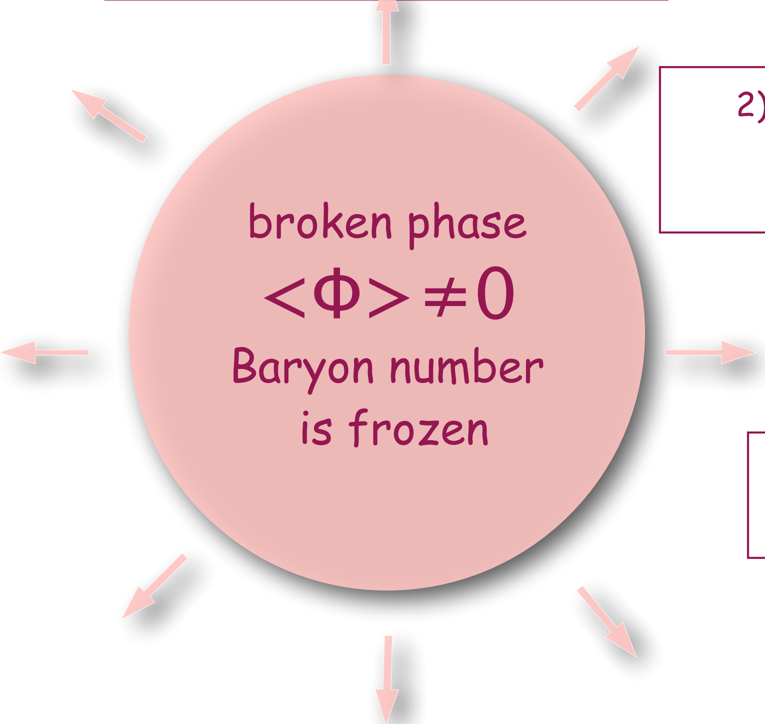
T_n $\equiv$ **nucleation temperature**

Baryon asymmetry and the EW scale

Kuzmin, Rubakov, Shaposhnikov'85

Cohen, Kaplan, Nelson'91

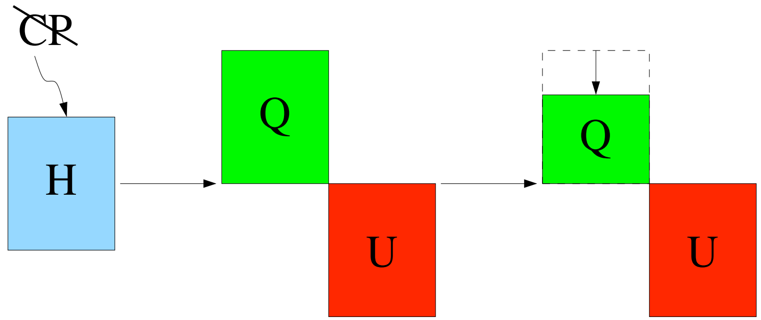
1) nucleation and expansion of bubbles of broken phase



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

Chirality Flux in front of the wall

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



Electroweak baryogenesis mechanism relies on a first-order phase transition satisfying $$\frac{\langle\Phi(T_n)\rangle}{T_n} \gtrsim 1$$

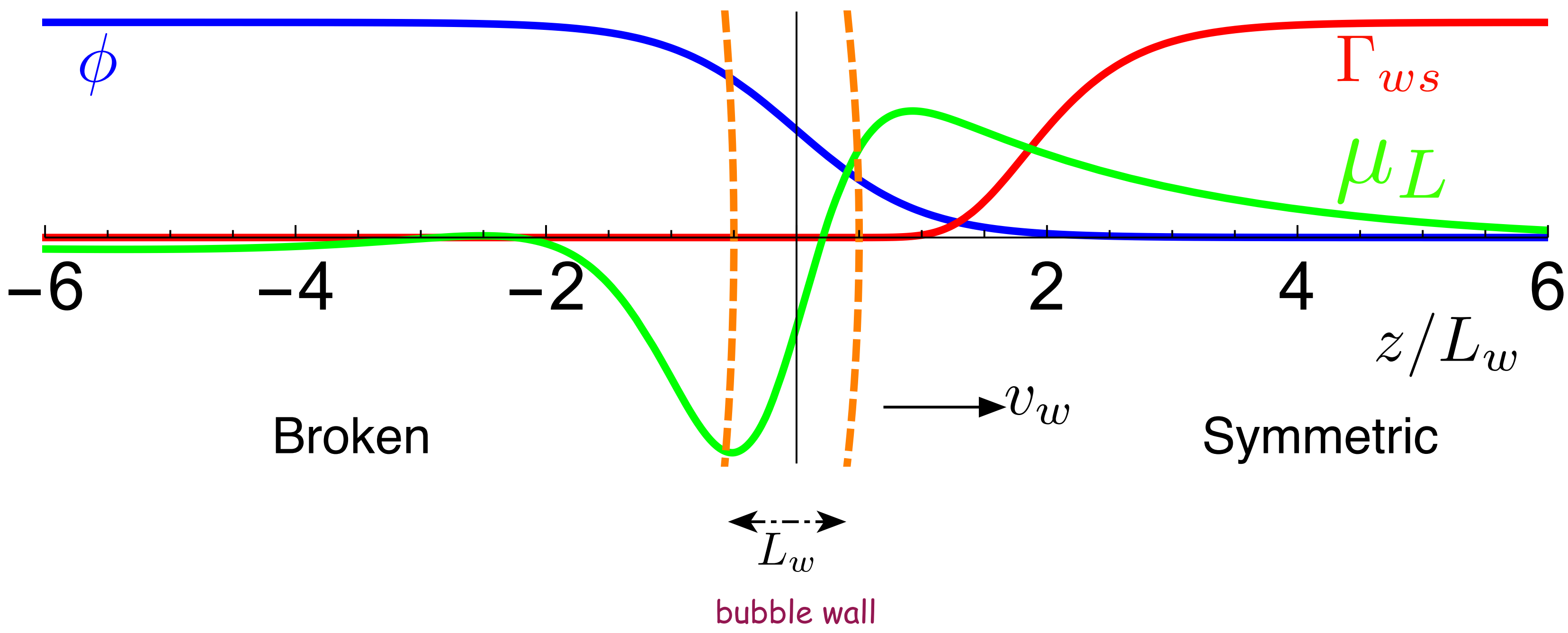
The EW baryogenesis miracle .

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

bubble wall velocity

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

: sphaleron rate



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.

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

Kinetic equations

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

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

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

Usual CP-violating sources in EW baryogenesis:

-Charginos/neutralinos/sfermions (MSSM) — **Cline et al, Carena et al, Chung et al...**

-Varying phase in effective Top quark Yukawa

SM+singlet, — **Fromme-Huber**

Composite Higgs, — **Espinosa, Gripaios, Konstandin, Riva, '11**

2-Higgs doublet model — **Konstandin et al, Cline et al**

-Varying Yukawas — **Bruggisser et al '17 + '18**

-Alternatives: strong CP QCD axion (**Servant '14**),
CP violation in Dark sector (**e.g. Cline'17**)

the CKM matrix as the CP-violating source

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

$$J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin(\delta) = (3.0 \pm 0.3) \times 10^{-5},$$

Based solely on reflection coefficients

If large masses during EW phase transition
->no longer suppression of CKM CP violation

Berkooz, Nir, Volansky '04

Varying SM Yukawas as CP violating source

Bruggisser, Konstandin, Servant '17

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

V: transformation matrix for mass diagonalization

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

For constant y:

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

1-Flavour case

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

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

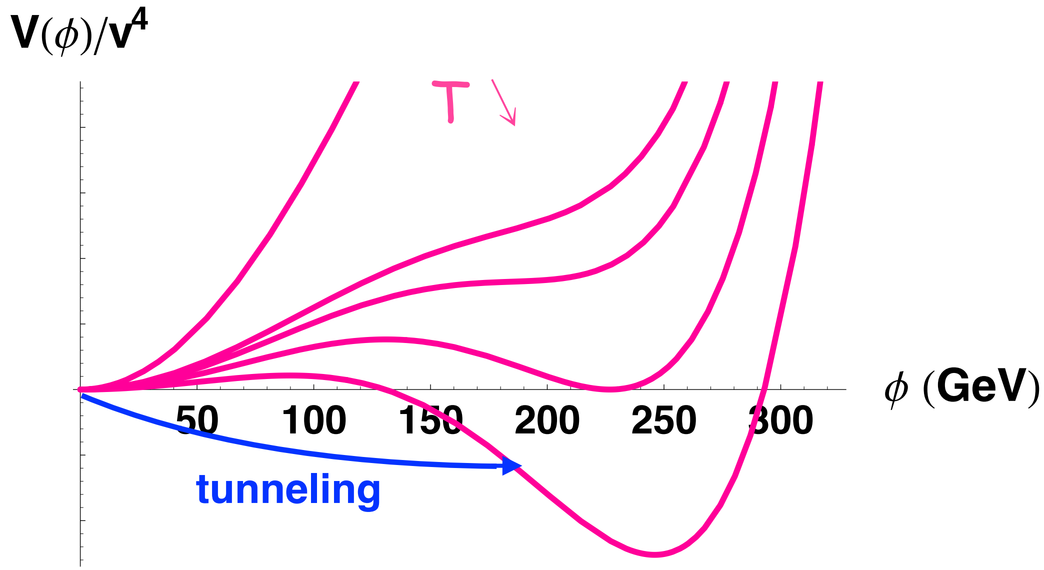
requires variation of phase

More than 1 flavour: no need for variation of phase

Bruggisser et al '17

First-order
EW Phase transition

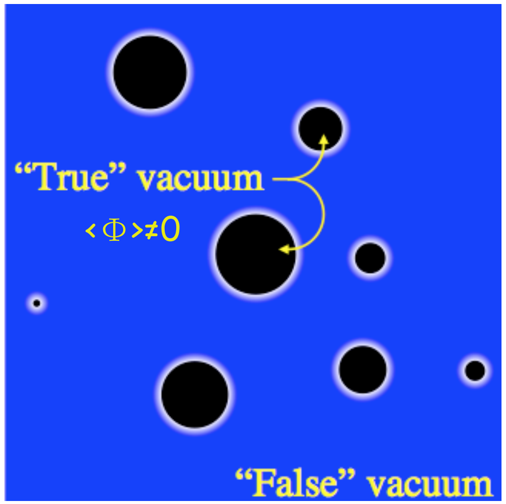
1st-order phase transition described by temperature evolution of scalar potential



Barrier separates 2 degenerate minima

2 phases can coexist

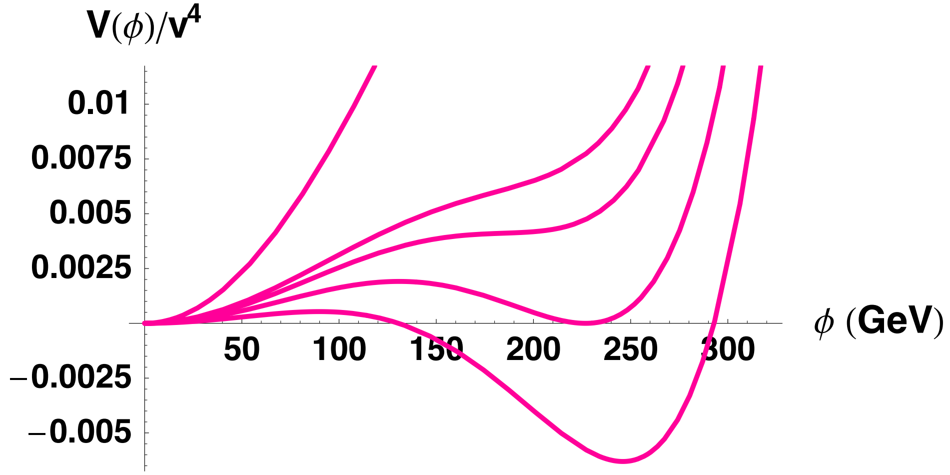
Nucleation, expansion and collision of Higgs bubbles

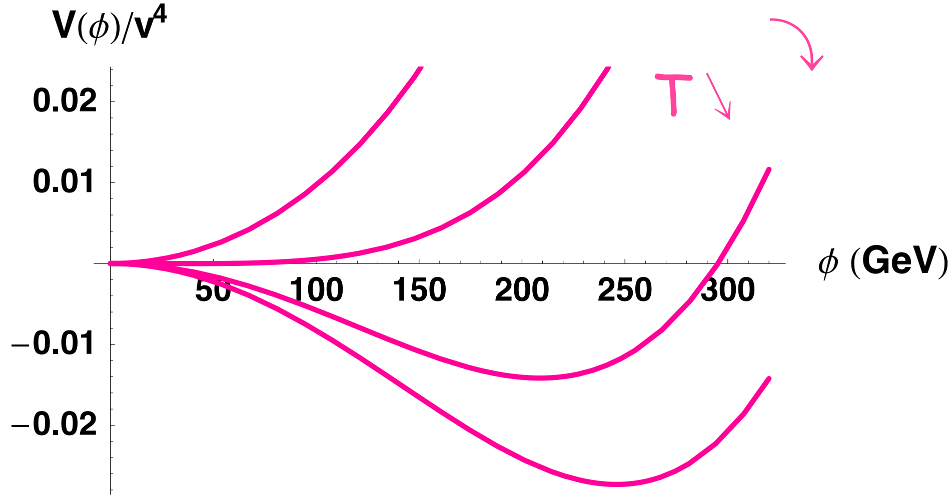


$\langle\Phi\rangle = 0$

Nature of the EW phase transition

first-order or cross over?

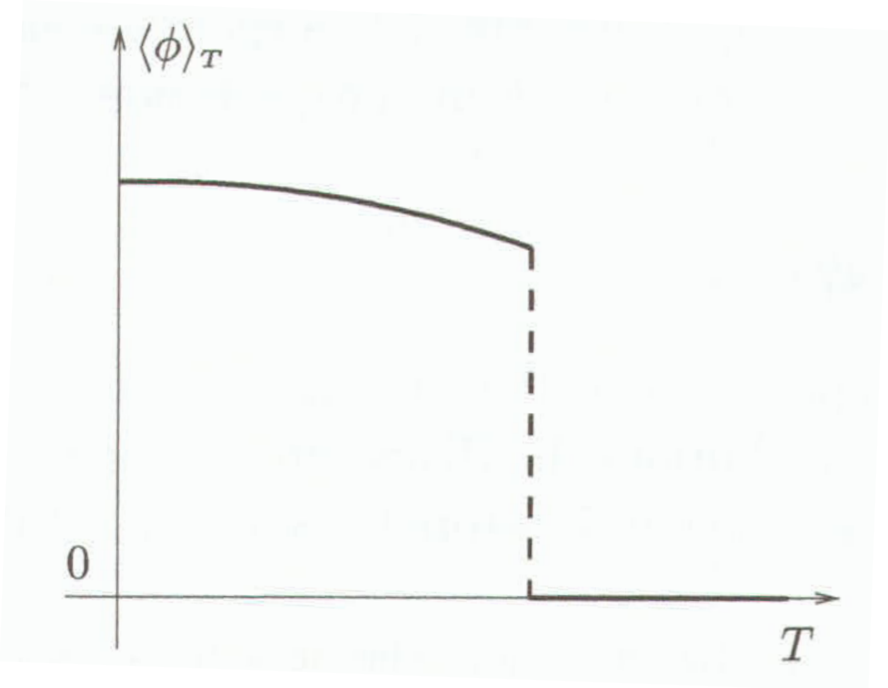


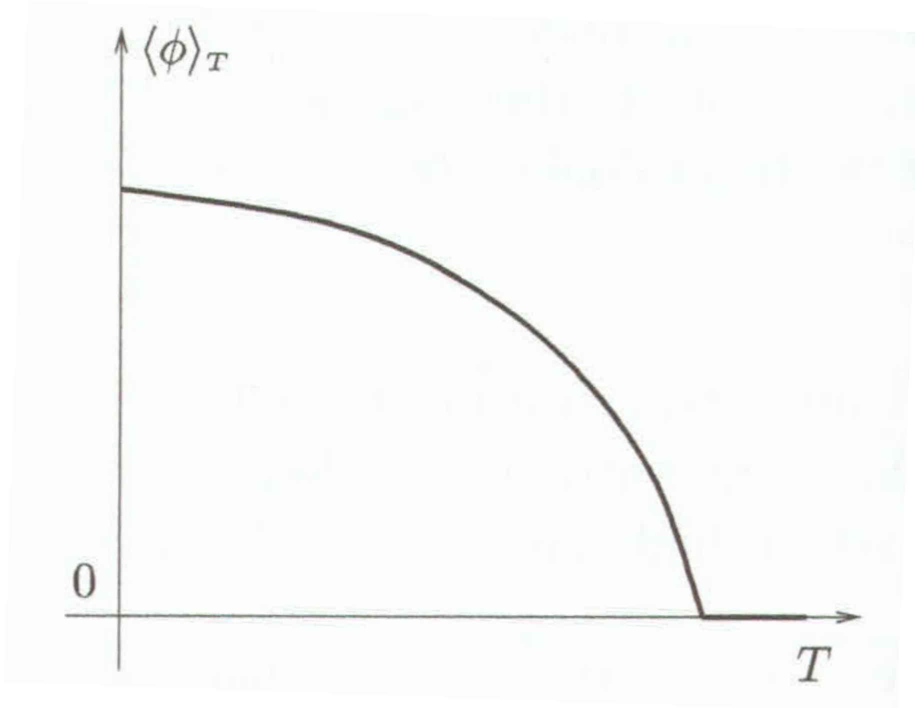


1st-order versus 2nd-order

<φ(T)> discontinuous

1st derivative discontinuous

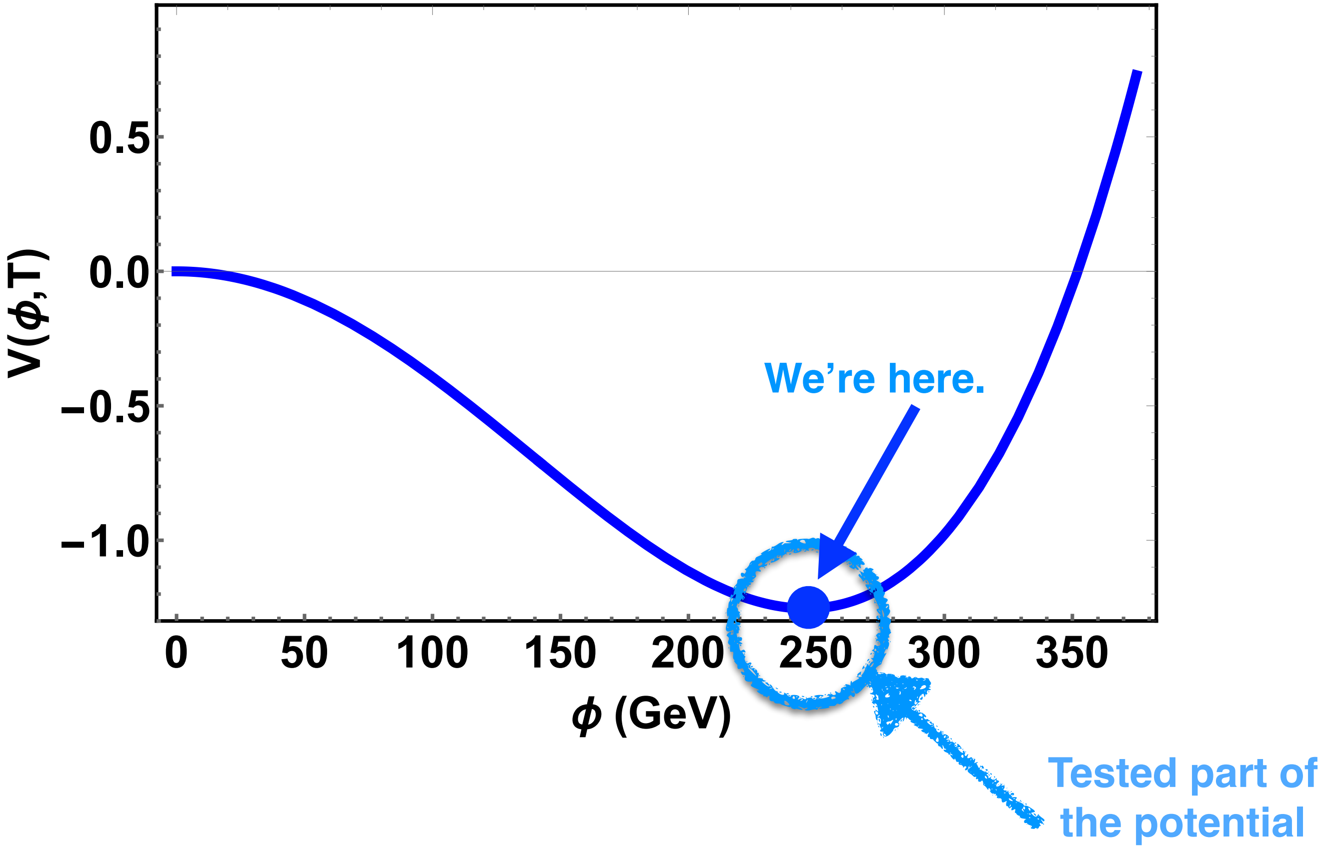




Crossover: no discontinuity in any derivative
impossible to see analytically, only on lattice

THE HIGGS POTENTIAL .

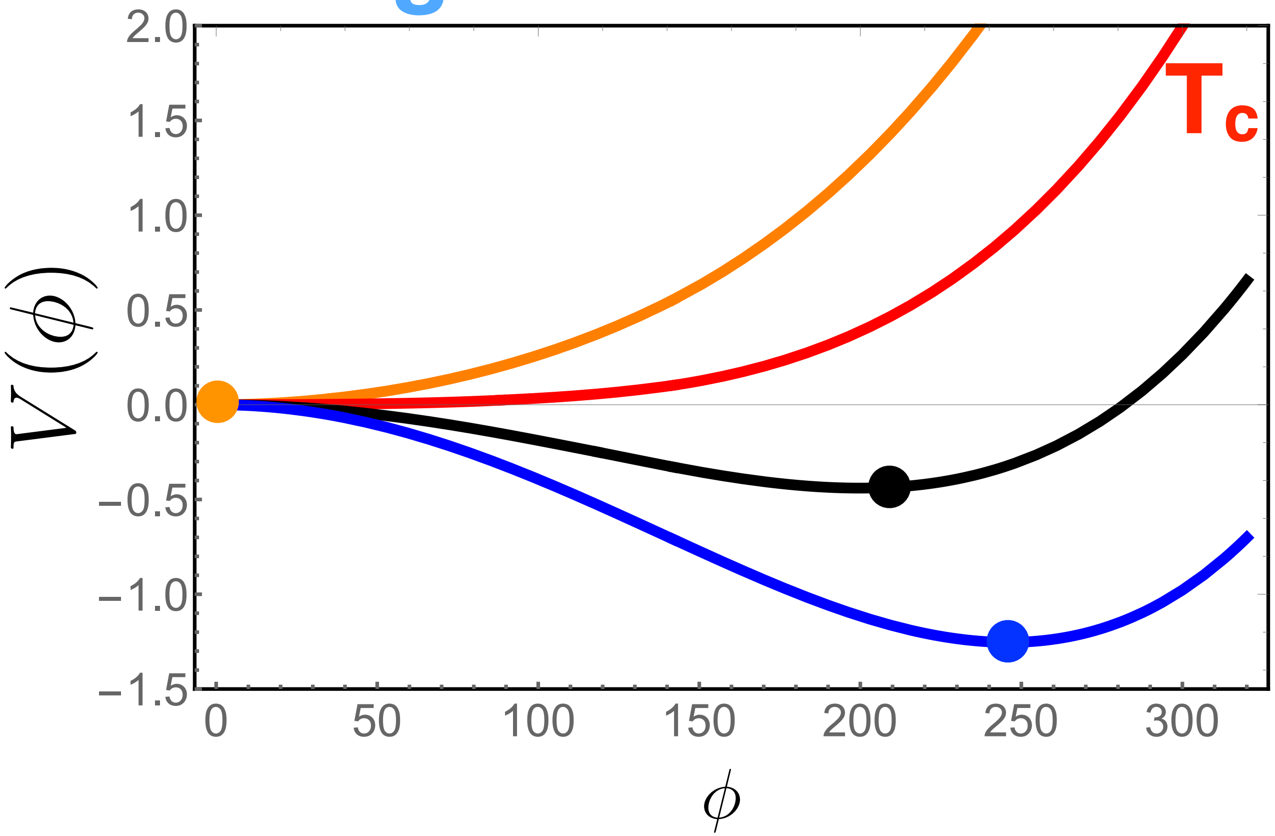
TODAY, T=0 $V_0(\phi) = -\mu^2\phi^2/2 + \lambda\phi^4/2$



> How did we end up here ?

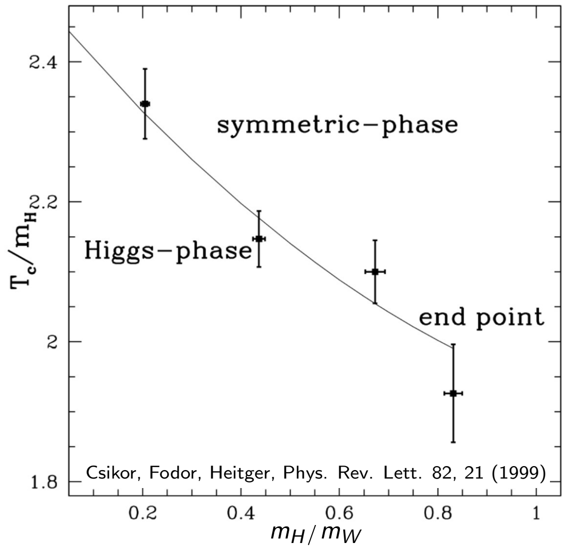
EW sym. restored at T≳160 GeV***

through a smooth crossover



No departure from thermal equilibrium

It would have been different if $m_H \lesssim 70$ GeV



***1404.3565

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

(textbook cases)

-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 after confinement phase transition of strongly interacting new sector.

(discussed in next few slides)

-Higgs potential is trigonometric function

-Fate of the Higgs ruled by the dilaton

-Unbounded strength, $\frac{\phi}{T}$ **can naturally be >>1**

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

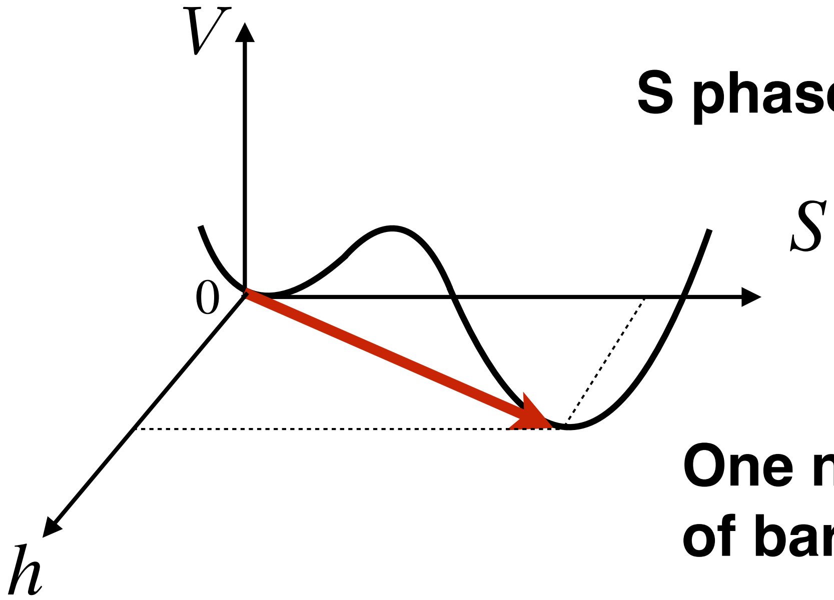
3- contributes to reheating once the transition is complete

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

Severely constrained by EDM bounds!

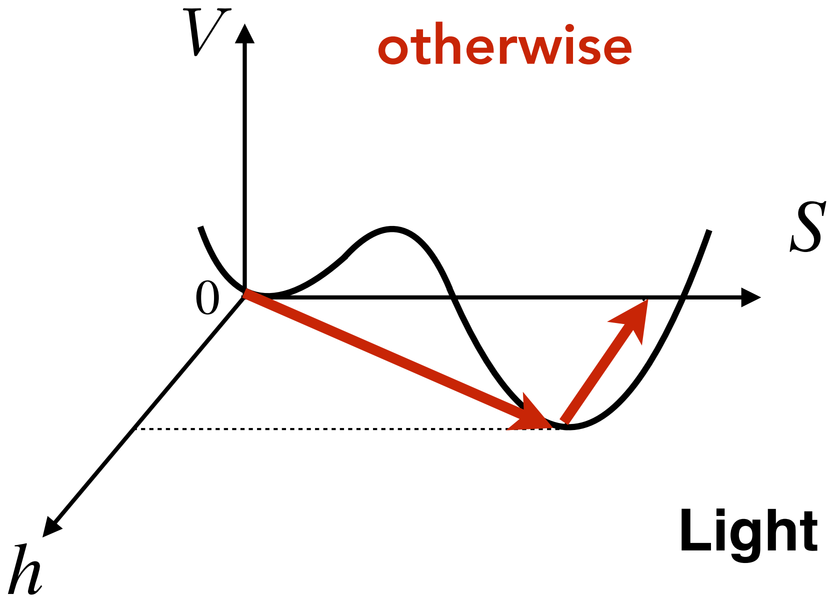
This is the EW baryogenesis tension

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)

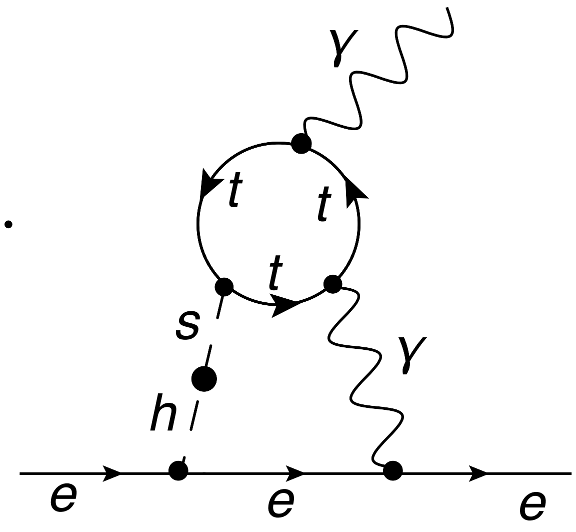
Light S -> Very constrained by EDM

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

EDM threat on Electroweak baryogenesis

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

ACME II, Oct. 2018.

Evading EDM bounds for EW baryogenesis

— Hide $\cancel{CP}$ in leptons, or dark sector

1811.11104, 1903.11255 1811.09719

— Use the dilaton in Composite Higgs models

-> search for the dilaton at LHC! 1804.07314

— 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

$m_S \lesssim$ O(few TeV)

How to release the tension ?

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

2 options

(1) Non-polynomial potential: we can have m_S>> T_n

(2) Increase the temperature of EW symmetry restoration

(to prevent washout by sphalerons at reheating)

In both cases, S heavier than H —> EDM bounds evaded

OPTION (1)

EW Phase transition in Composite Higgs Models :

Naturally strongly first-order .

EW phase transition in Composite Higgs models .

1803.08546, 1804.07314

> 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, described by VEV of dilaton field <χ>, Pseudo-Nambu-Goldstone Boson of spontaneously broken conformal symmetry of the strong sector

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

intertwinned dynamics

χ dominates the dynamics

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

|ε|<<1

Nearly conformal potential : T_n << f , SUPERCOOLING

1104.4791

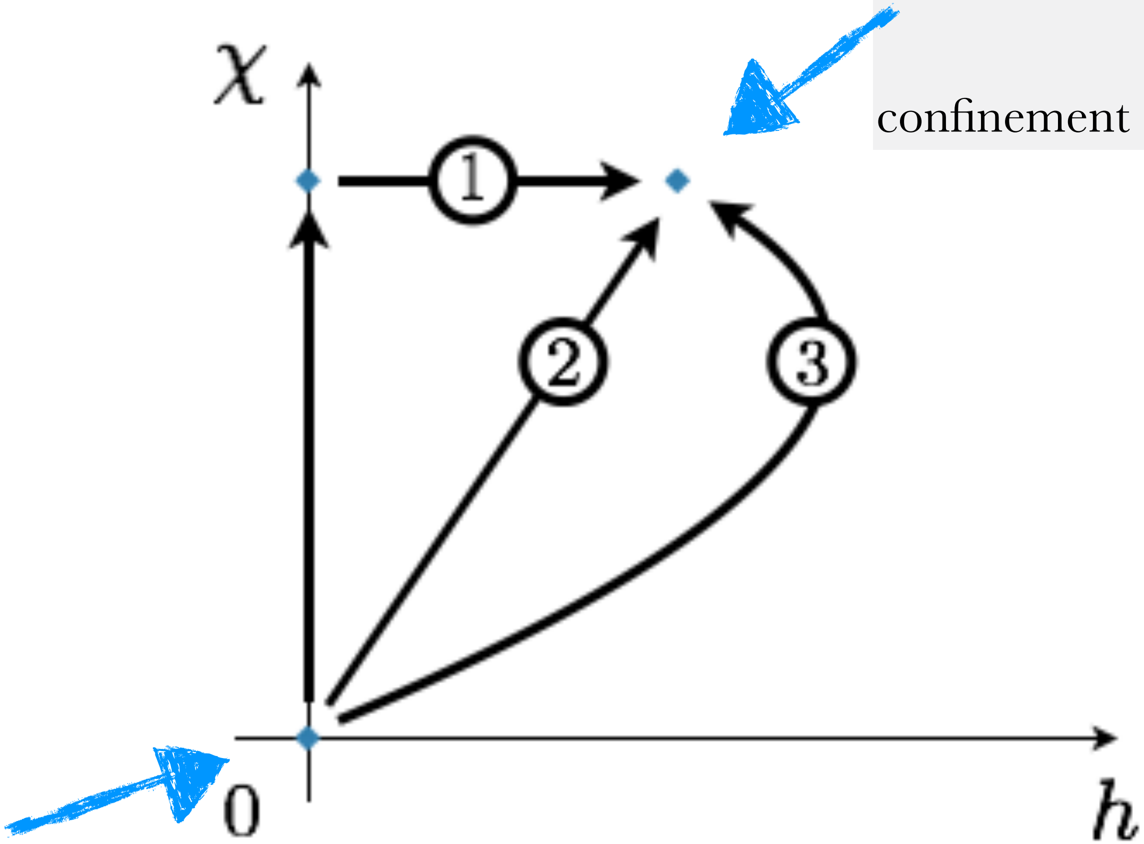
Higgs-dilaton intertwinned dynamics

global minimum at

$T \ll f$

confinement and EWSB

Which path?



global minimum at

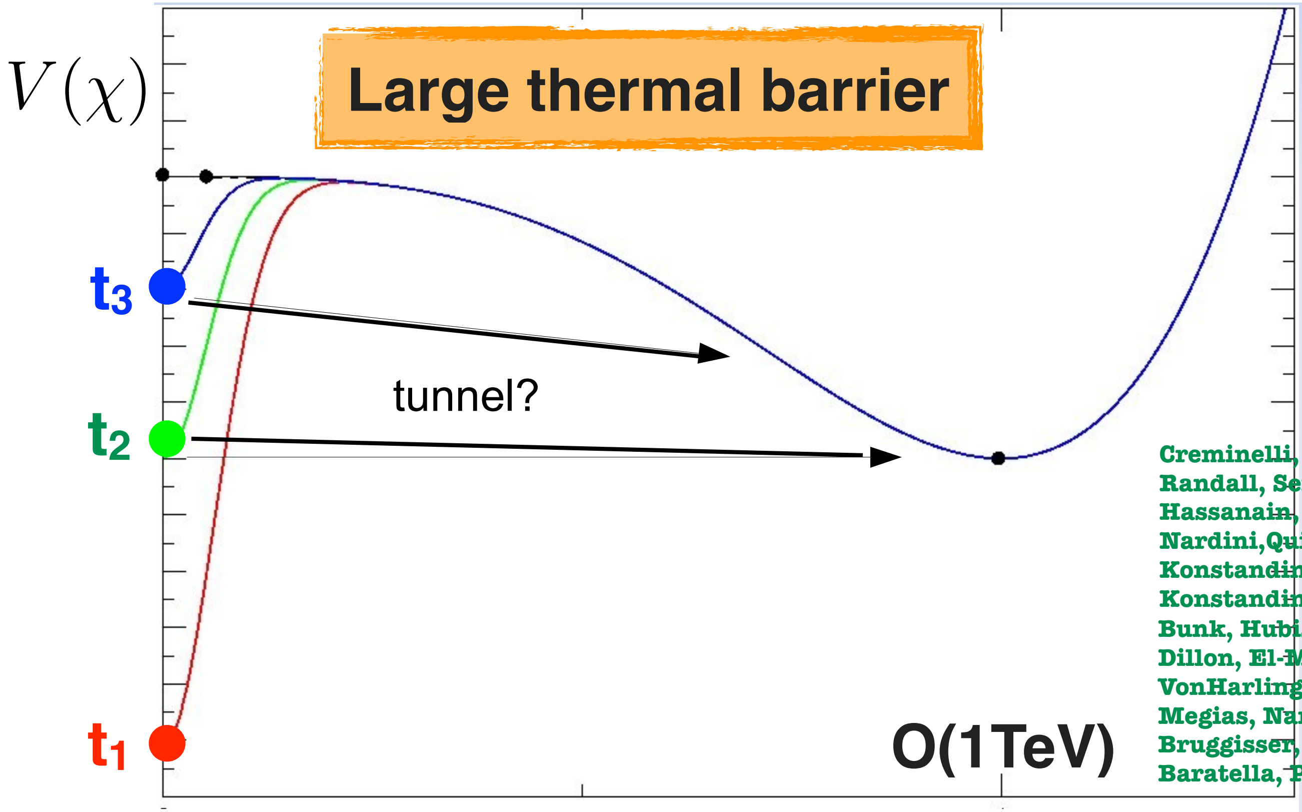
$T \gg f$

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
Baratella, Pomarol, Rompineve'18

Supercooled confinement phase transition

Impact on EW phase transition in Composite Higgs.

global minimum at
$T \ll f$

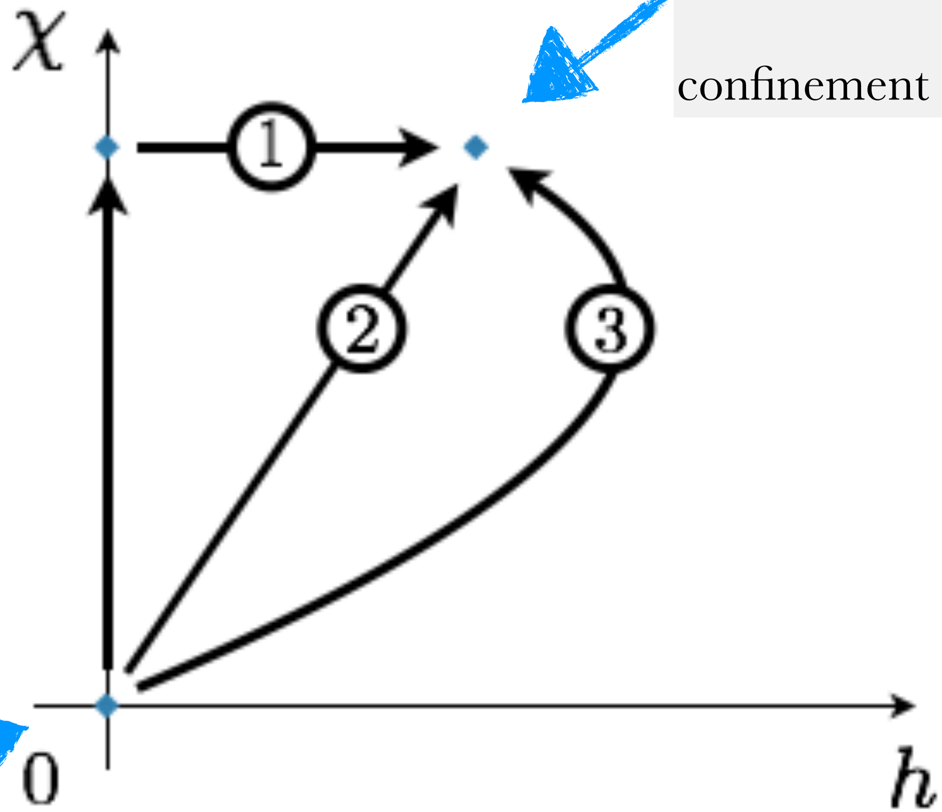
confinement and EWSB

(1) SM-like EW phase transition

(crossover)

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

(strongly 1st-order)

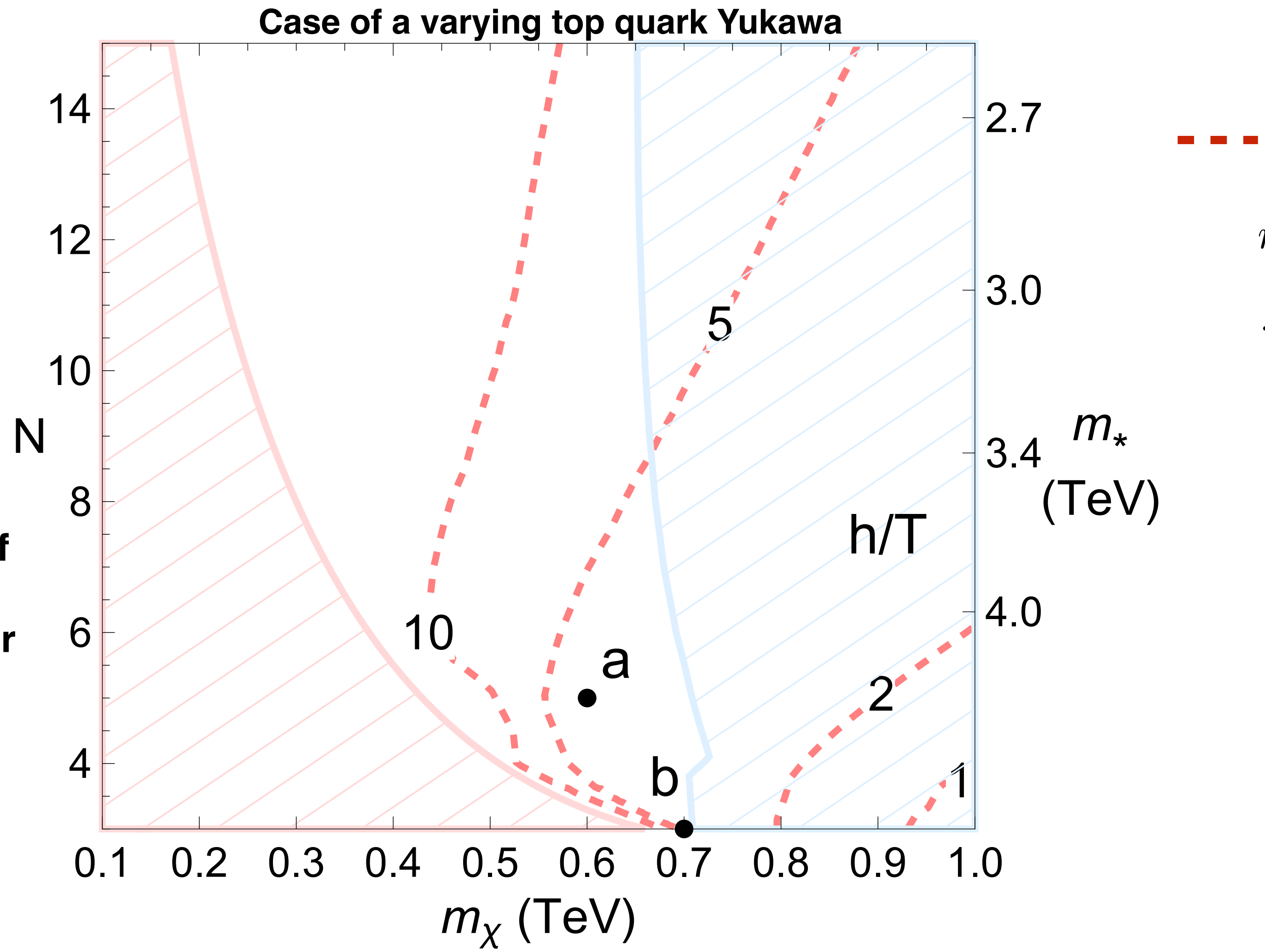


global minimum at
$T \gg f$

deconfined strong sector
unbroken EW symmetry

1804.07314

Strength of EW phase transition <h>/T



$m_\star = g_\star f$

$g_* = 4\pi/\sqrt{N}$

N: number of colors of strong sector

1804.07314

Constraints from reheating

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

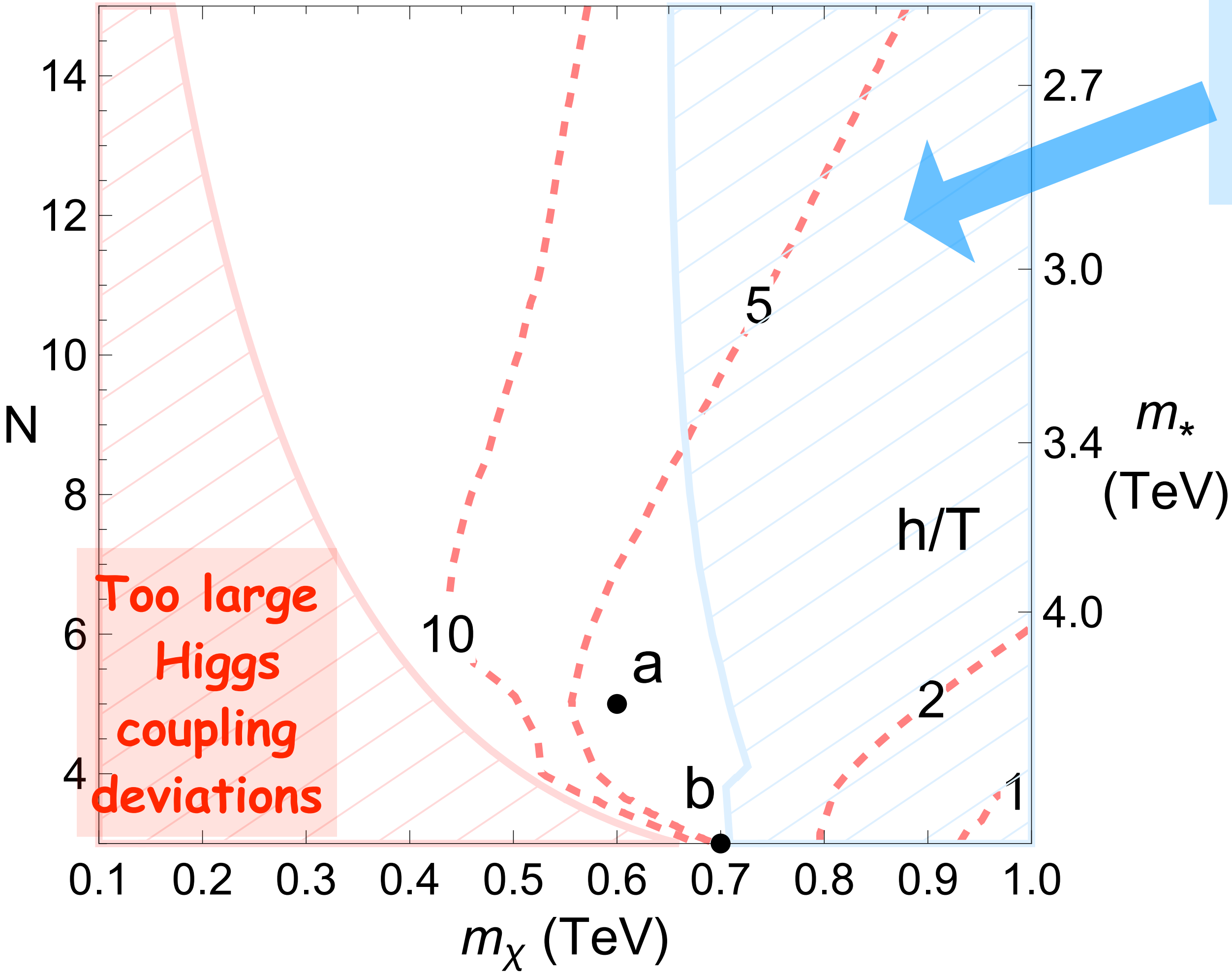
To preserve baryon asymmetry from washout:

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

LIGHT DILATON
WINDOW $\lesssim$ 700 GeV

Unavoidable? (see next...)

Constraints from reheating



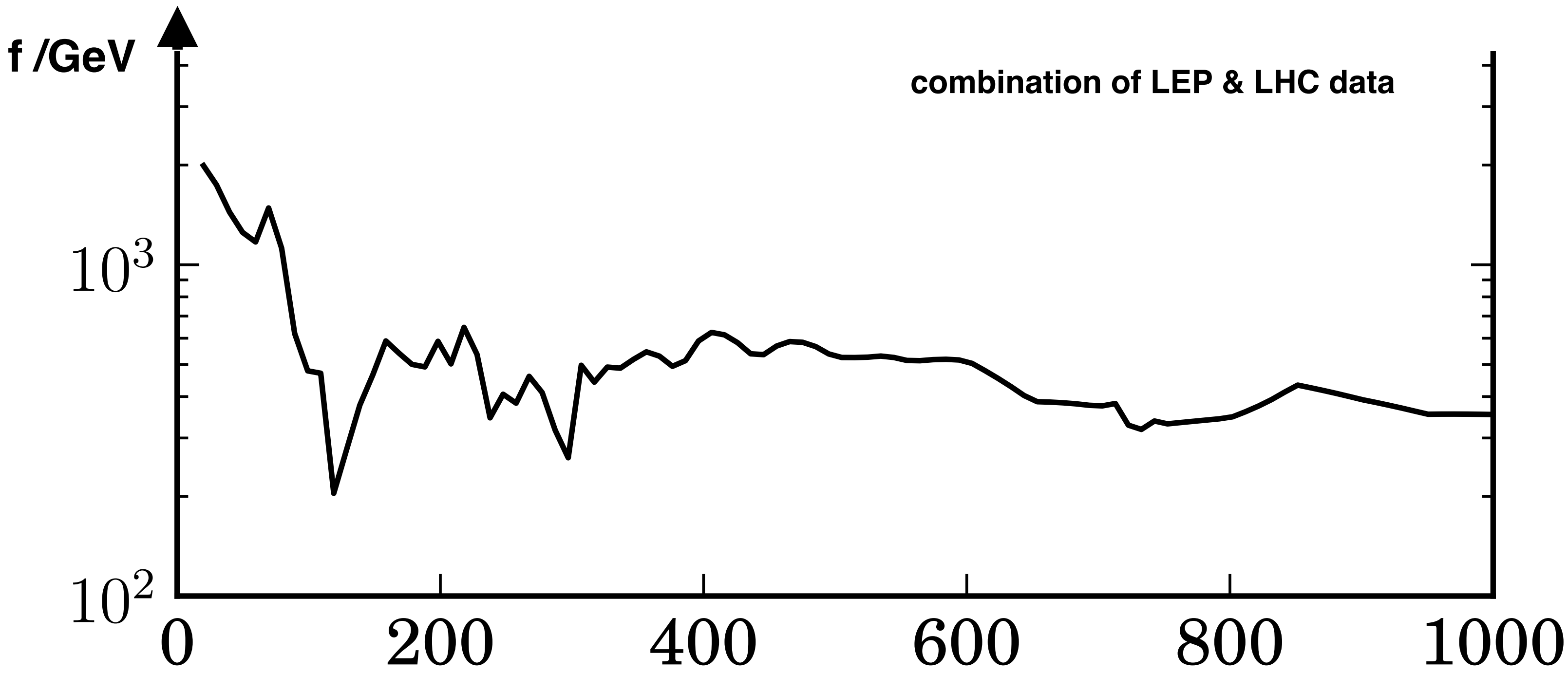
To preserve baryon asymmetry from washout: $h(T_{reheat})/T_{reheat}$ >~1

LIGHT DILATON WINDOW<~ 700 GeV

-> direct searches + Higgs physics

Collider bounds on dilaton .

Higgs-like couplings suppressed by v/f

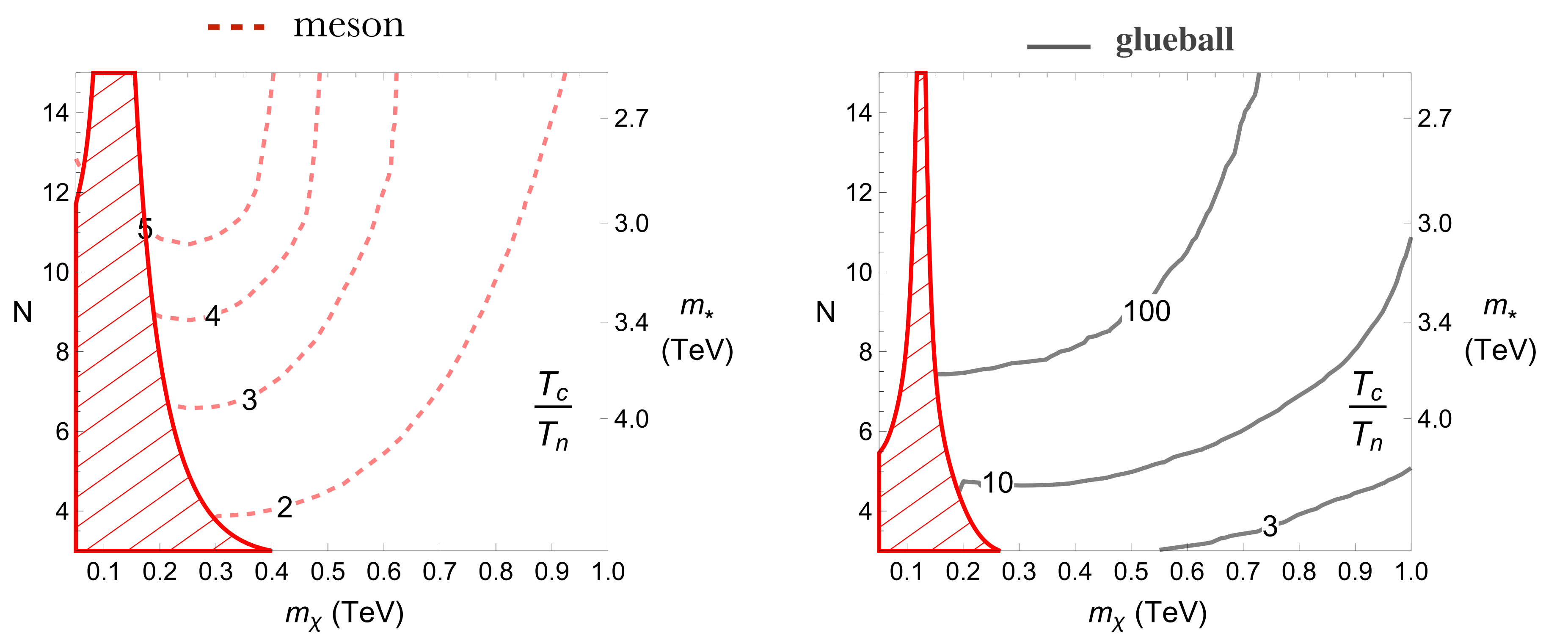


[Mikael Chala,
using HiggsBounds]

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

from Higgs-dilaton mixing

Amount of supercooling



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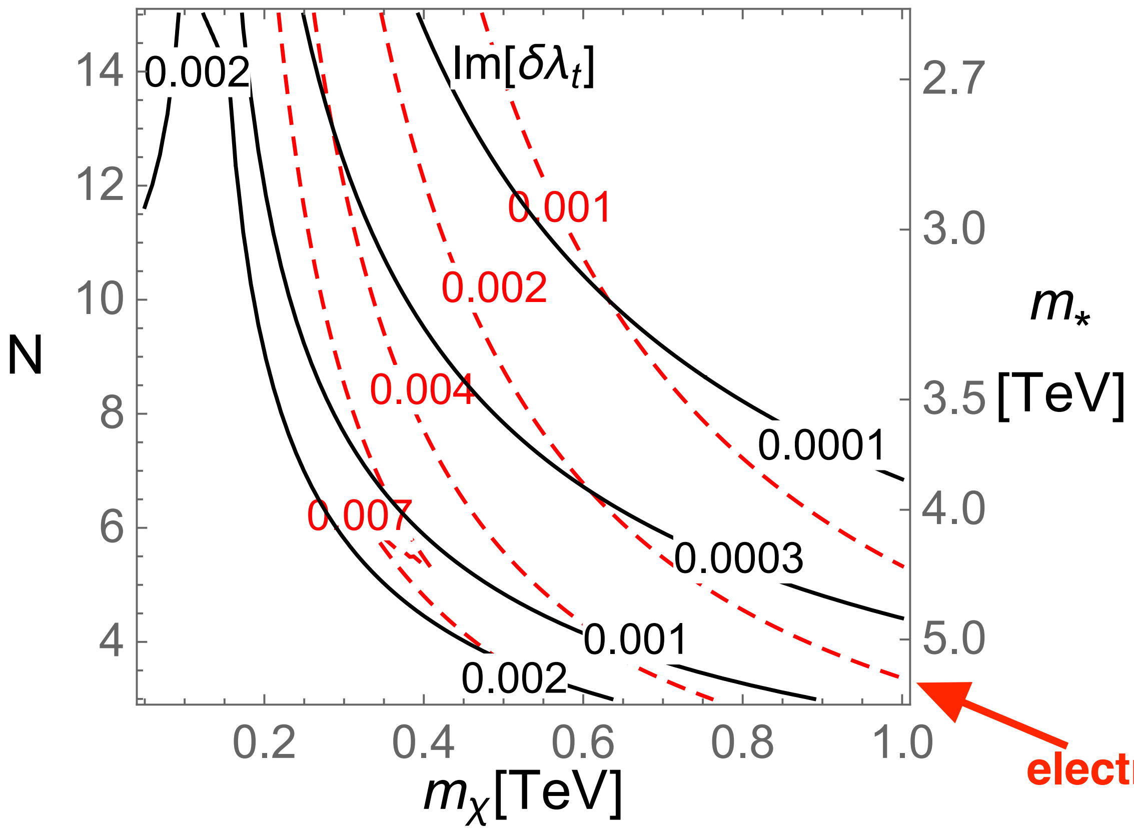
-> Large GW signal

Imaginary part of correction to Top quark Yukawa .

Number of colours in the new confining sector



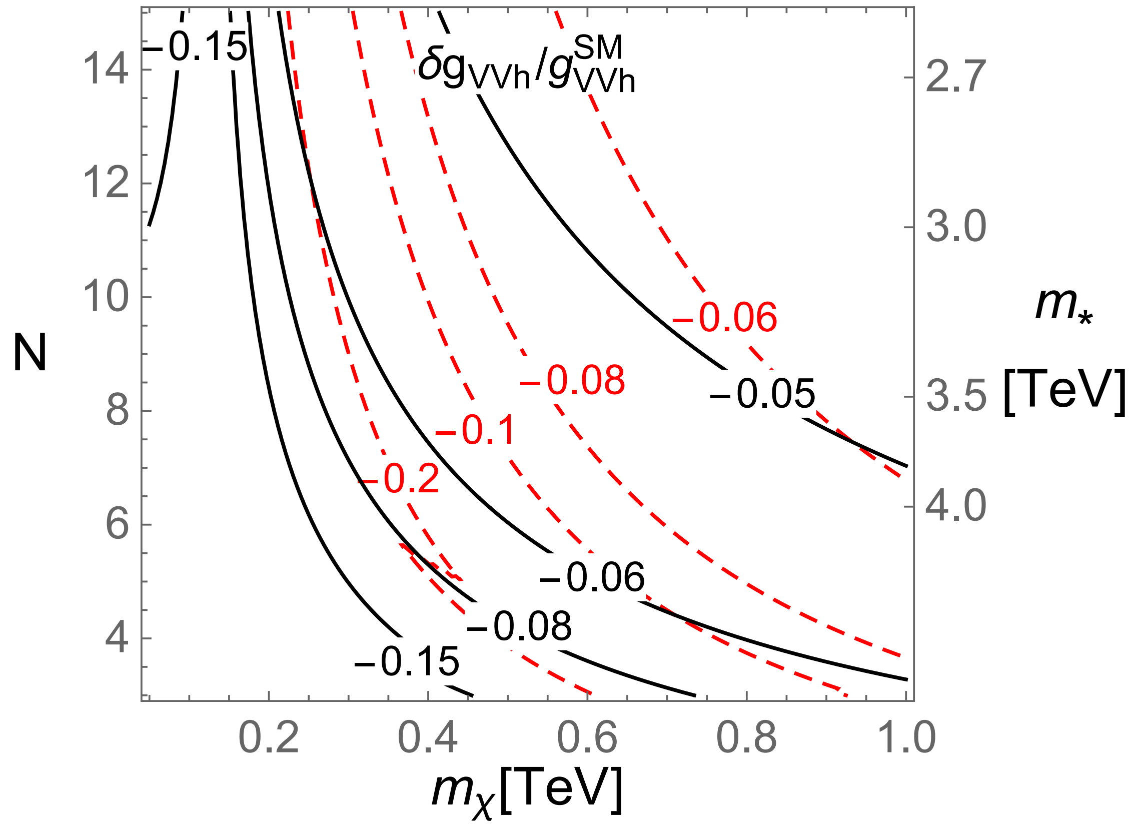
generic mass of composite states

electron EDM, ACME

dilaton mass

1804.07314

Higgs coupling deviations to W and Z .



Number of colours in the new confining sector

dilaton mass

generic mass of composite states

1804.07314

Take-away message

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

Another way-out of EDM bounds:

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

Servant, 1407.0030

QCD axion $\longrightarrow$ $$\frac{a(t)}{f_a} F\tilde{F}$$ $\longleftarrow$ EW field strength

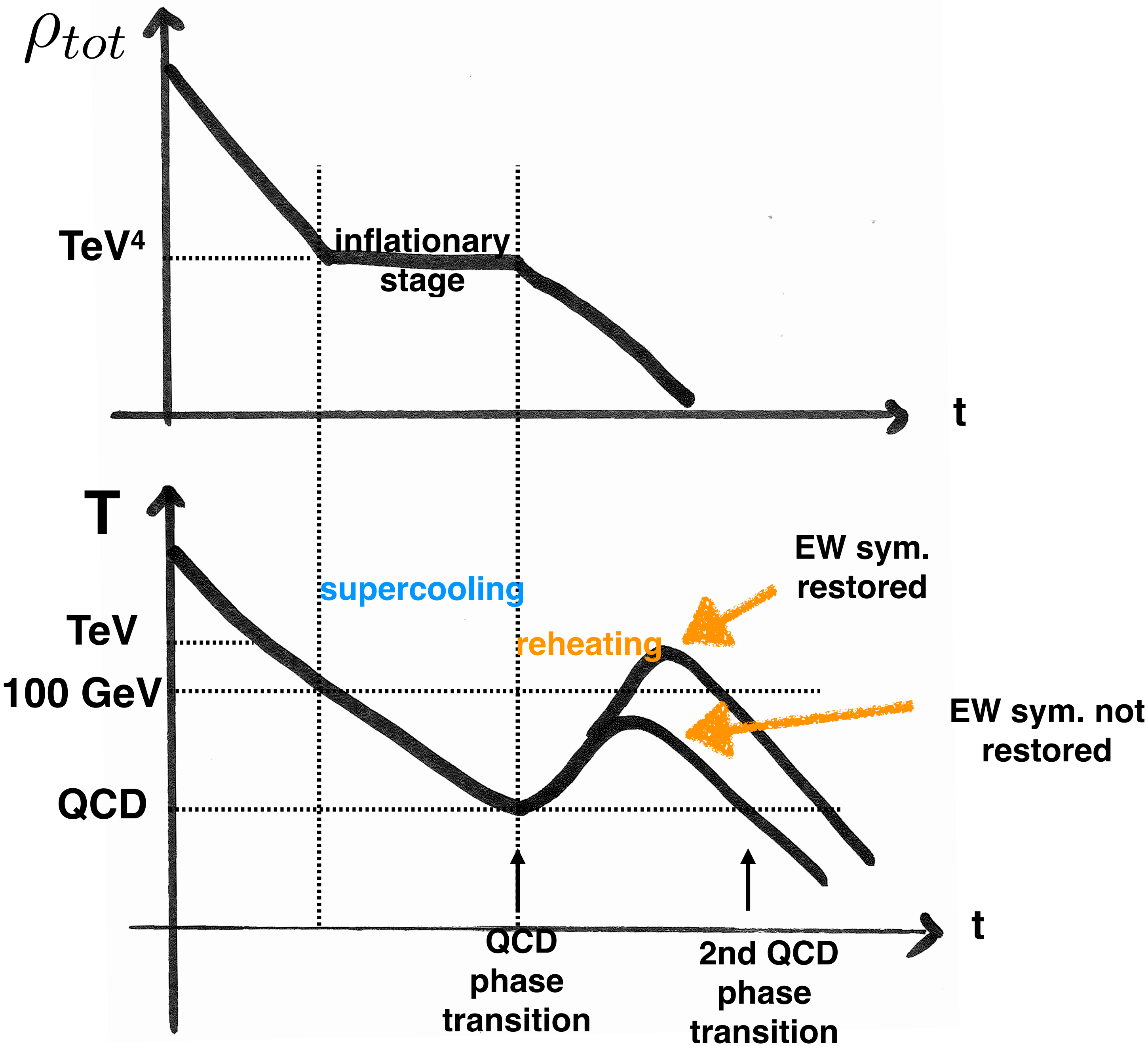
$$|\bar{\Theta}| \sim 1$$ at QCD epoch

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

$\longrightarrow$ **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

OPTION (2)

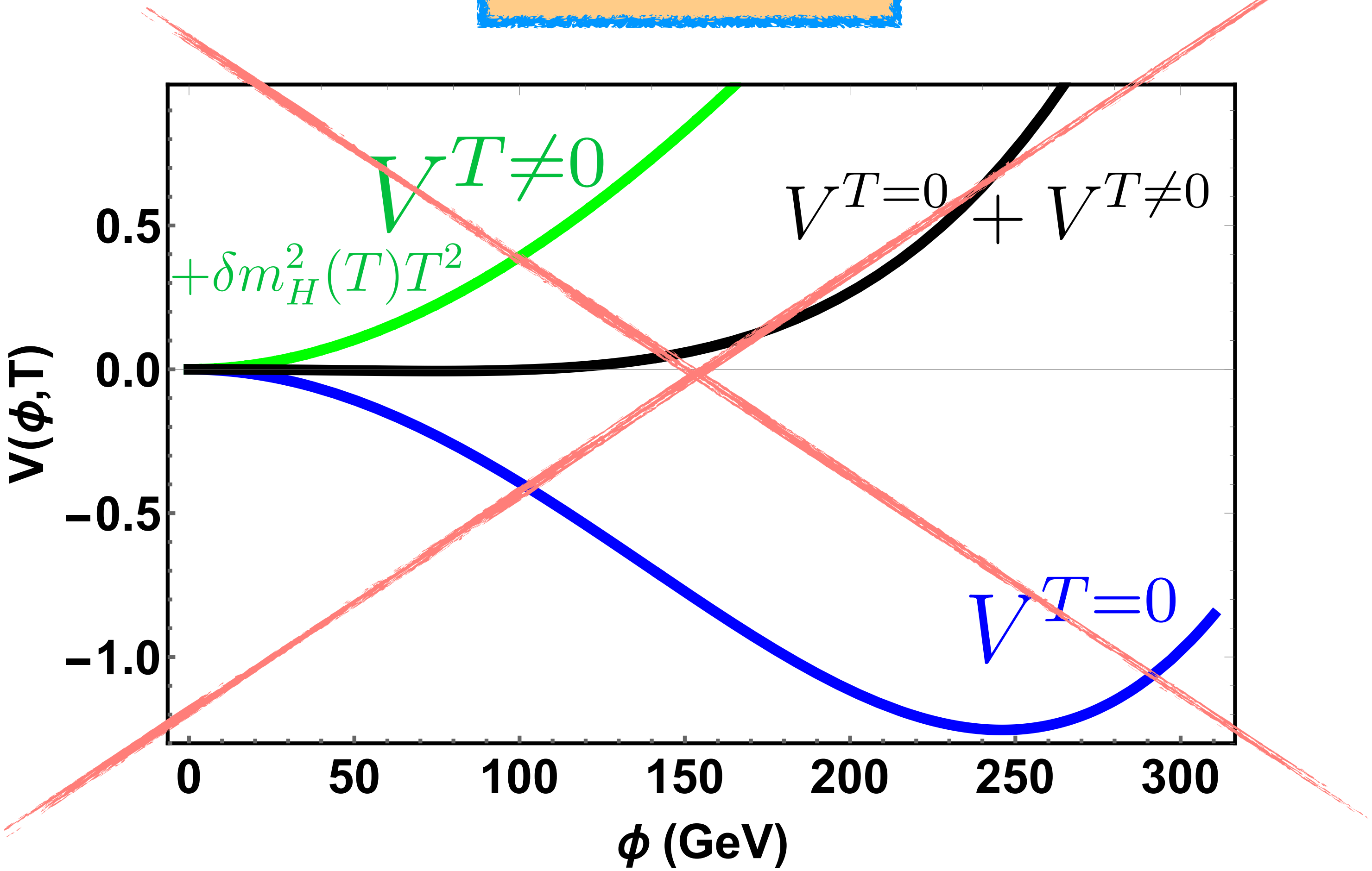
Can we push up the temperature of the EW phase transition ?

High-temperature EW symmetry non-restoration

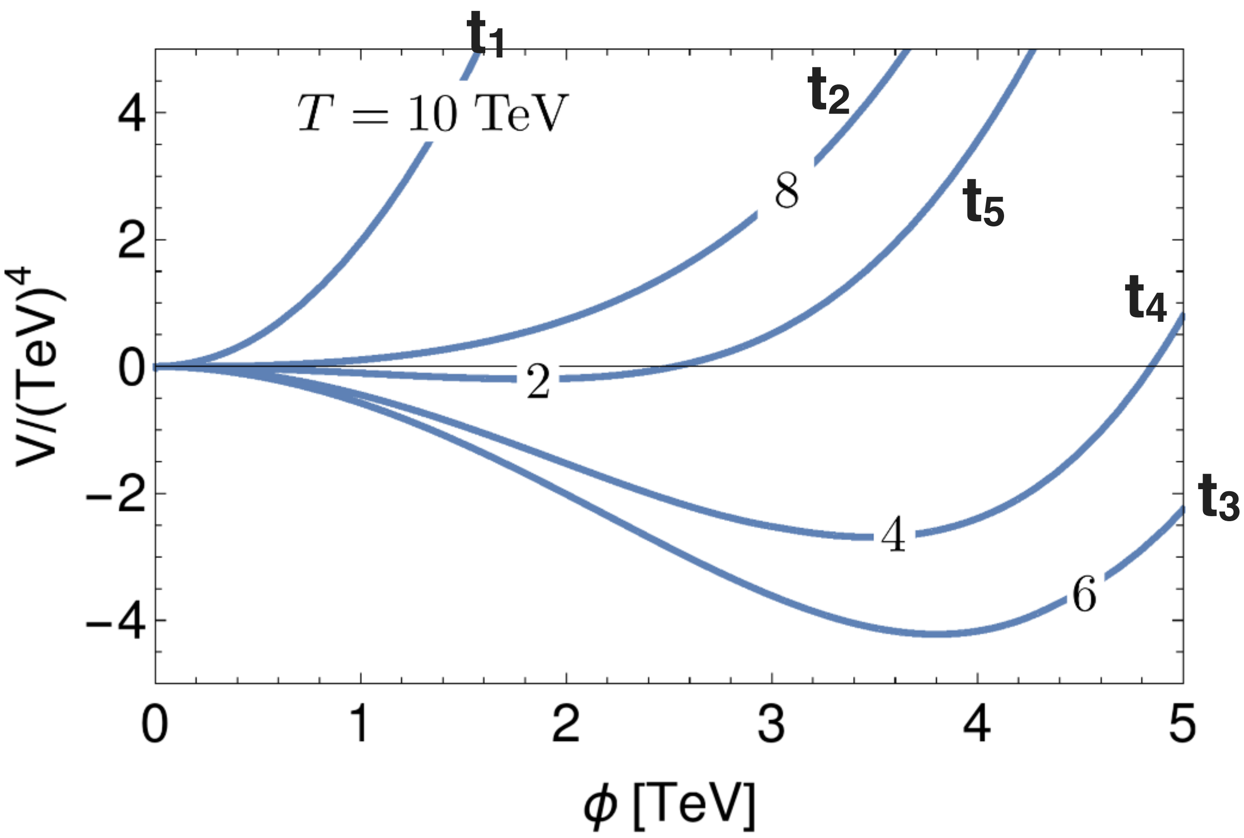
EW Symmetry restoration comes from the competition of two opposite terms in Higgs mass parameter

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

What if c_Φ <0?



High-scale (T>TeV) EW phase transition



Pushing up the temperature of the EW phase transition ?

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

> Major implications even if pushed by only a few hundreds of GeV !

> 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 !

> GW peak at LISA shifted to higher frequencies !

HIGGS EFFECTIVE POTENTIAL AT HIGH TEMPERATURE .

At one-loop:

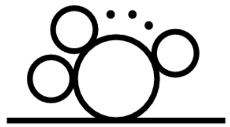
$$V_{\rm eff} = \boxed{V_{\rm tree}(\phi) + V_1^0(\phi)} + \boxed{V_1^T(\phi,T) + V_{\rm Daisy}(\phi,T)}.$$

Tree level

1-loop
T=0

1-loop
T≠0

Daisy resummation



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

bosons fermions

Sum over all particles
coupled to the Higgs

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 Veff
at m=0

sets the
thermal
mass

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

Higgs Thermal
Mass in the SM

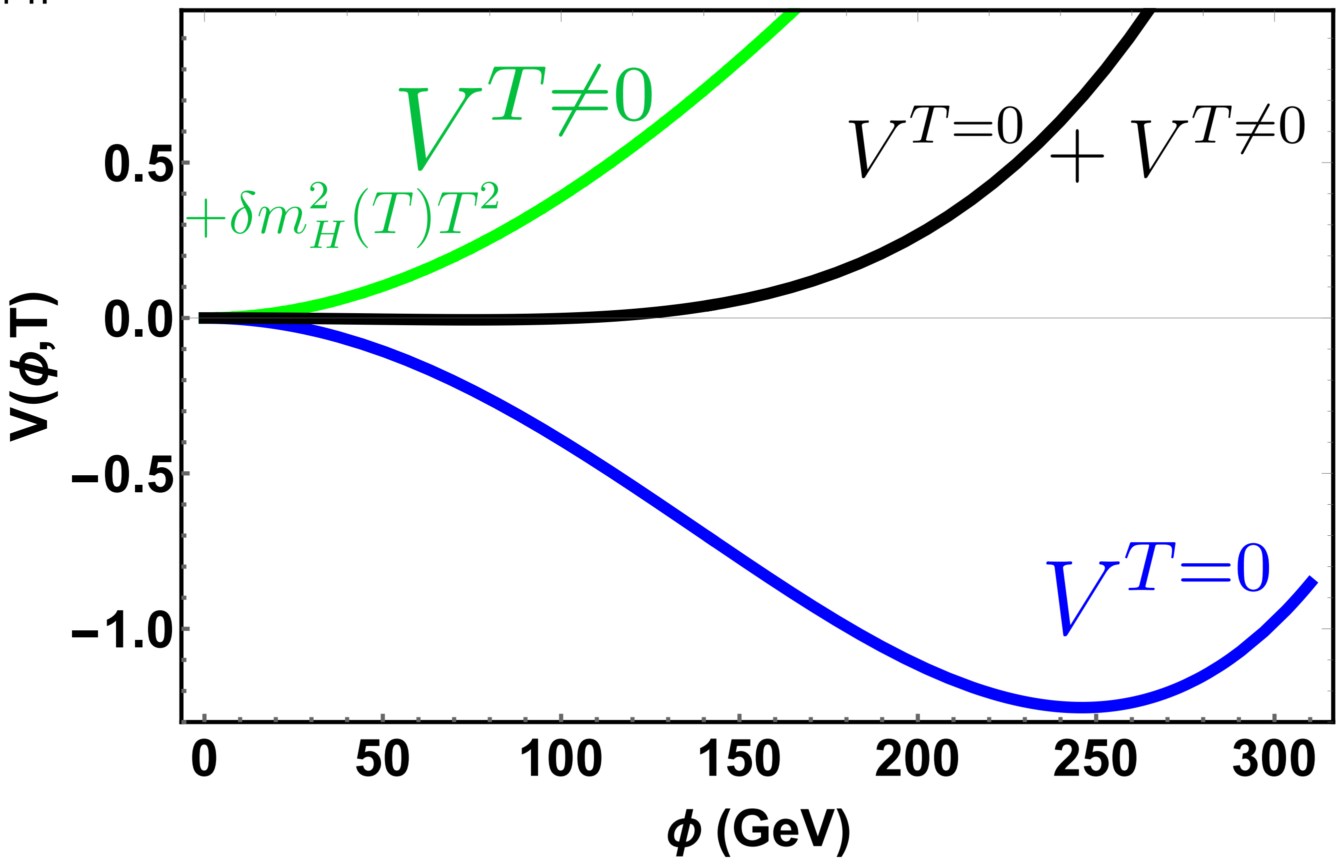
HIGH TEMPERATURE EW SYM. RESTORATION.

At one-loop:

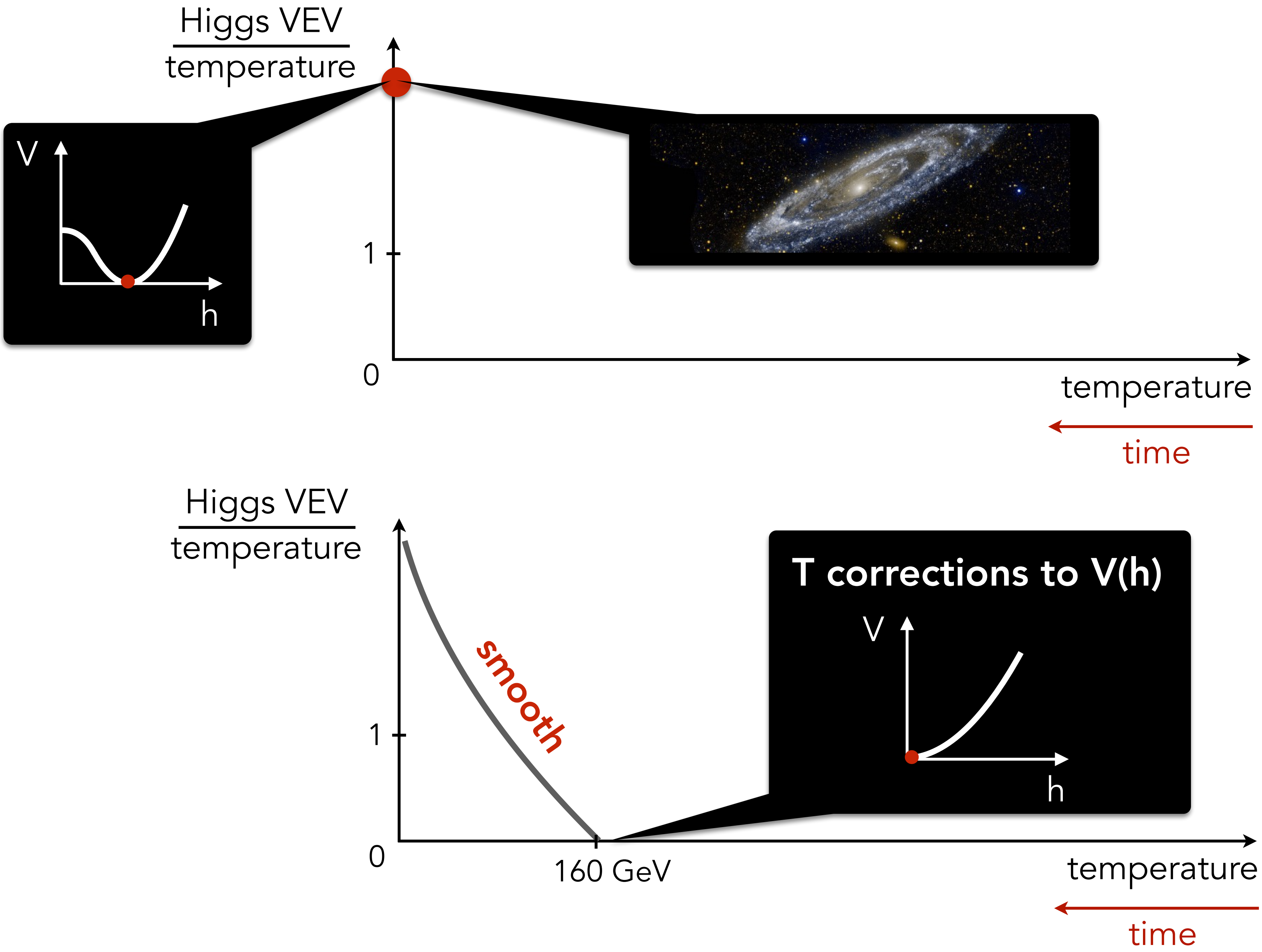
$$V_{\rm eff} = \boxed{V_{\rm tree}(\phi) + V_1^0(\phi)} + \boxed{V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T)}.$$

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

At high T:

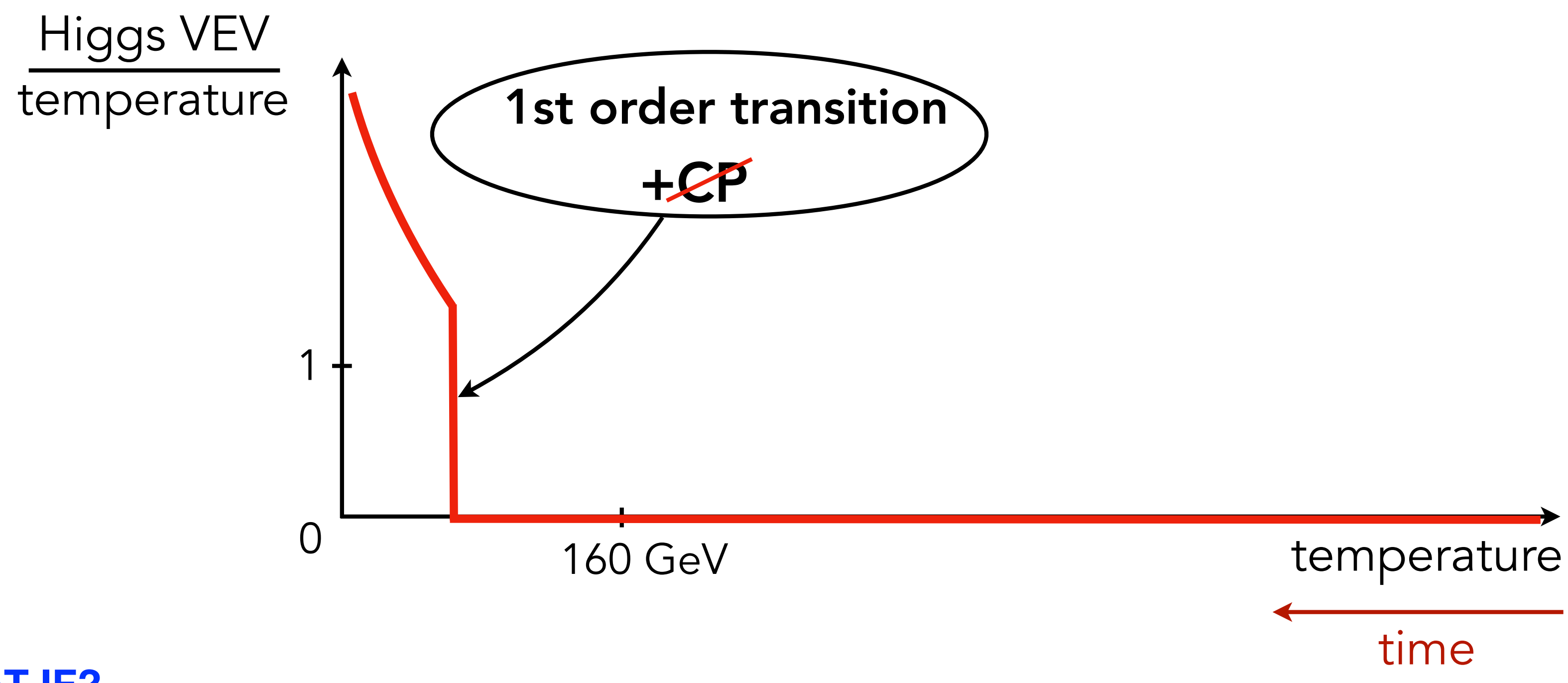


—> **Symmetry restoration at Tc**

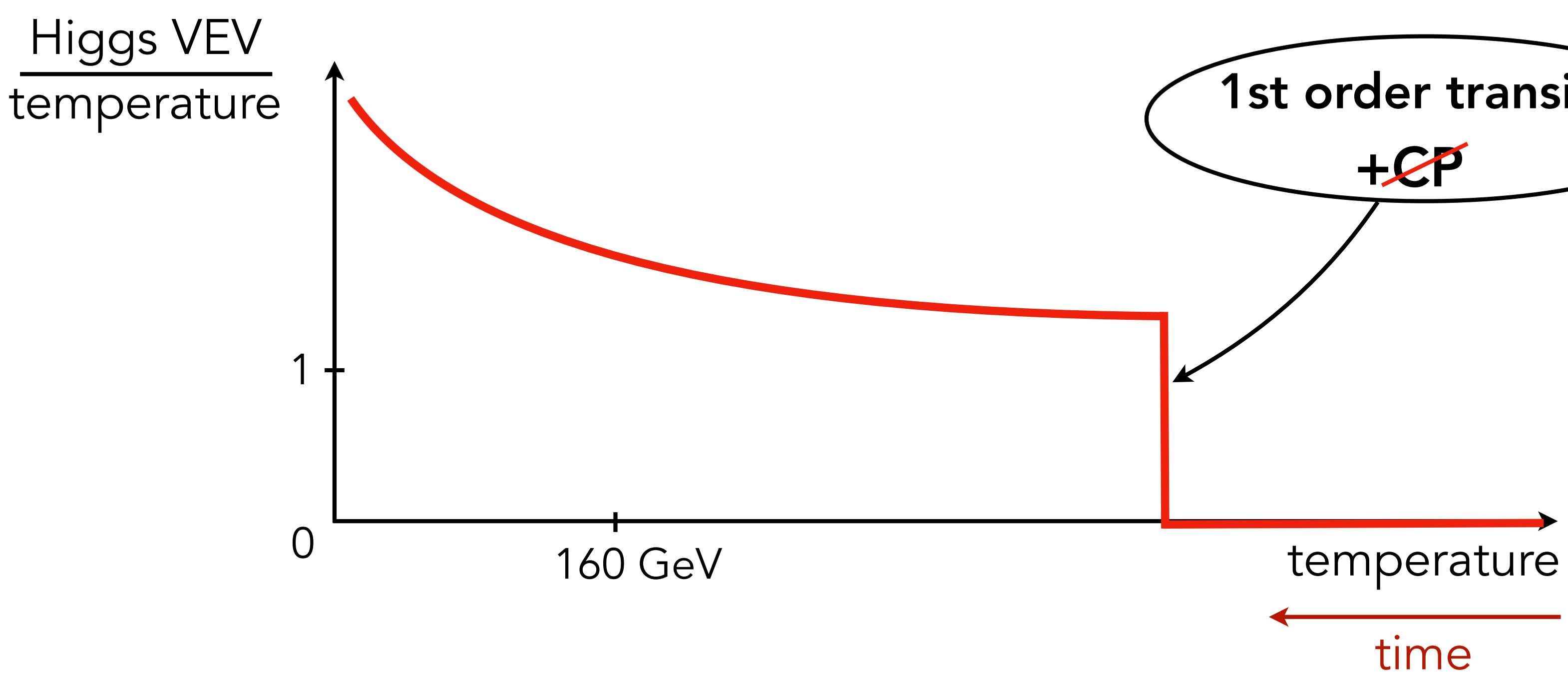


[Figure: Matsedonskyi]

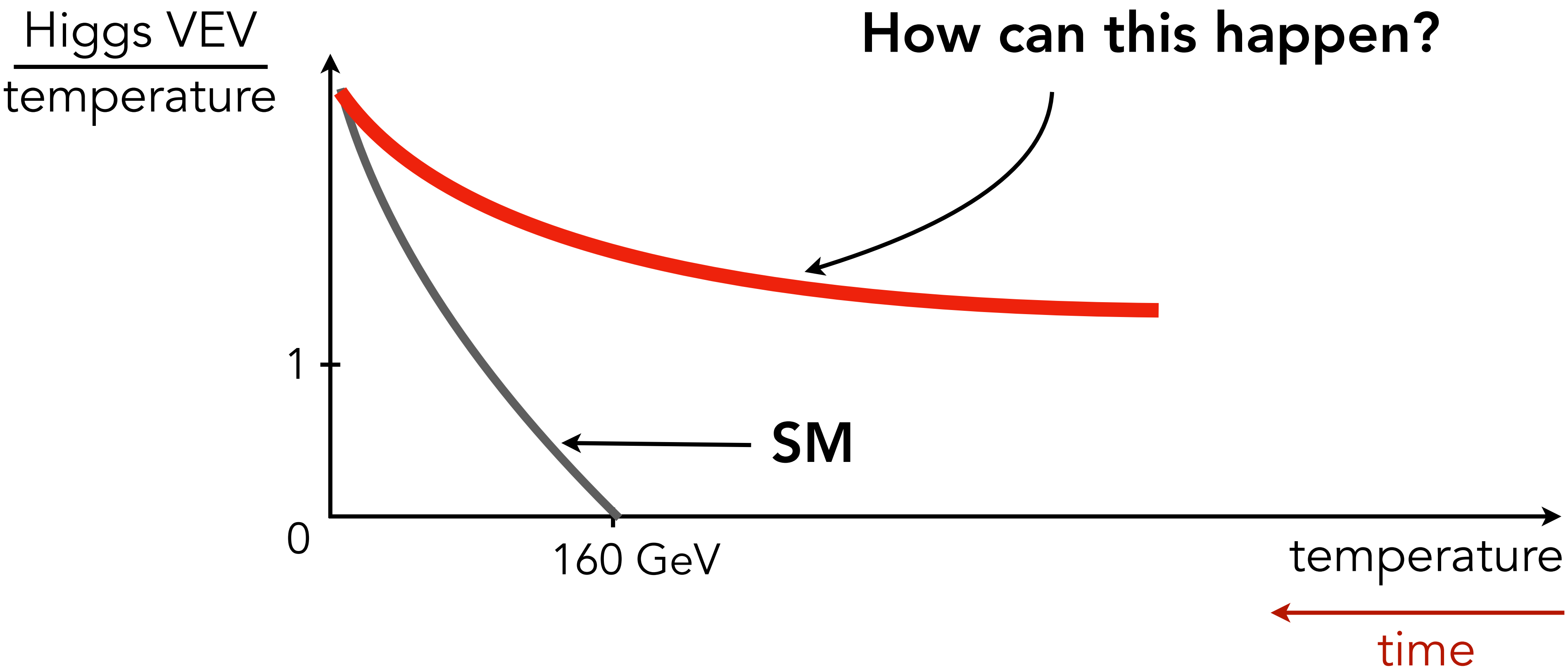
In EW baryogenesis scenario:



WHAT IF?



[Figure: Matsedonskyi]



By adding new weak-scale (m<~300 GeV) singlet scalars

[1807.08770, Baldes], [1807.07578, Meade, Ramani], [1811.11740, Gliotto, Rattazzi, Vecchi]

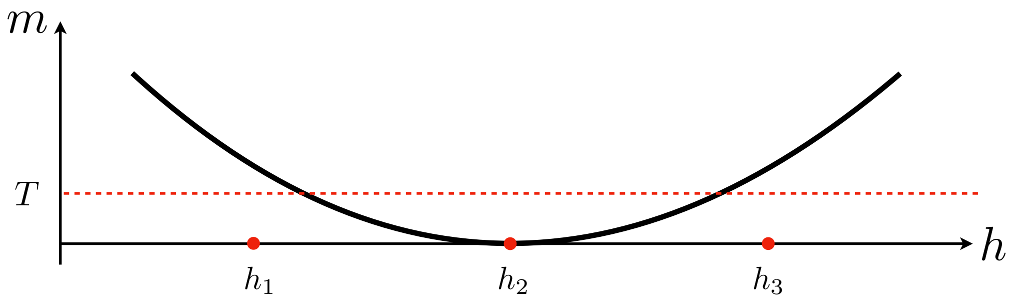
or singlet fermions [2002.05174, Matsedonskyi]

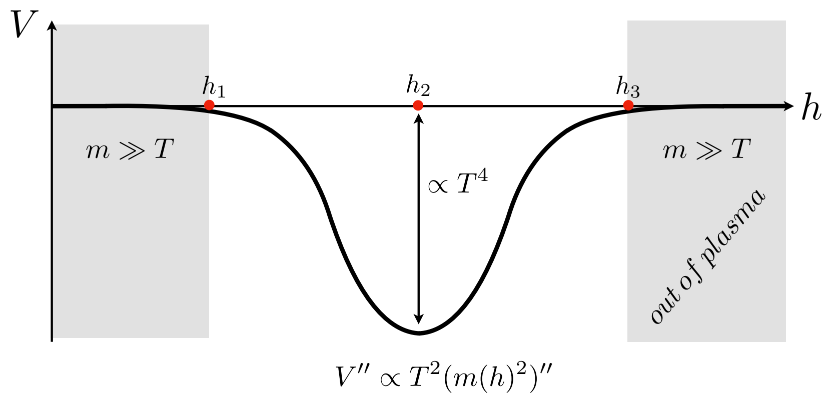
whose mass has a non-standard dependence on Higgs VEV

[Figure: Matsedonskyi]

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 !**





EW symmetry non-restoration

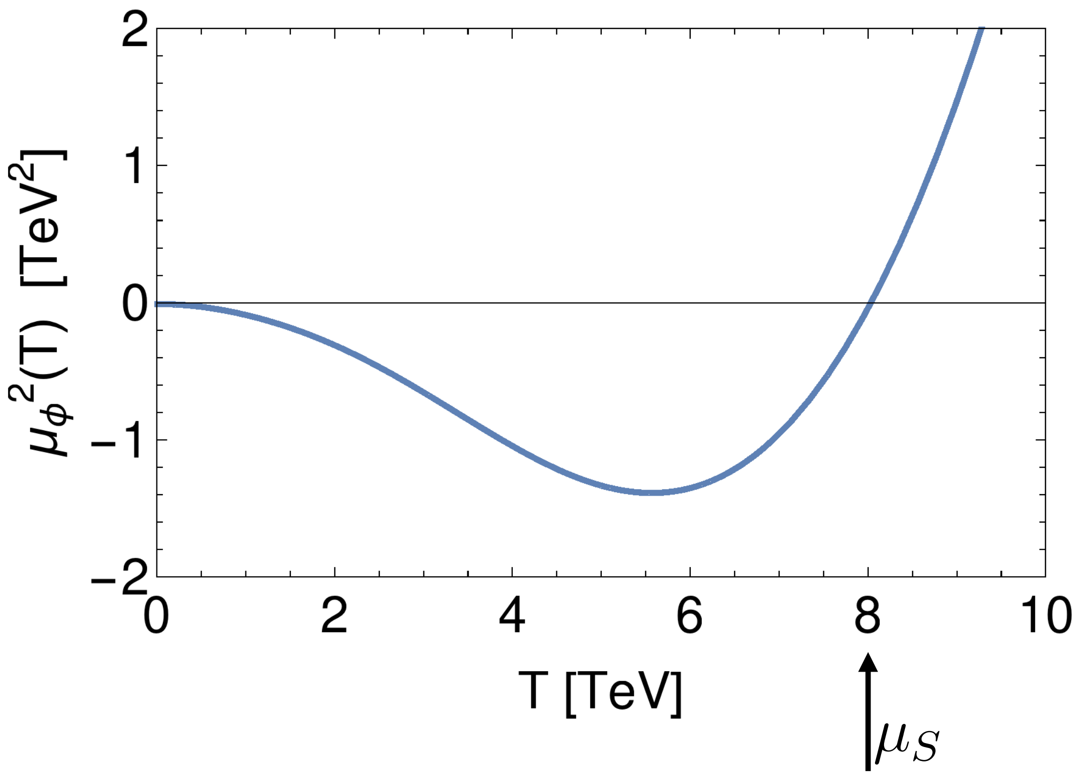
at $T>M_H$ from new scalars .

EW symmetry non-restoration at T>M_H

$$\mu_\phi{}^2(T) \sim -\mu_\phi^2 + \underbrace{c_\phi T^2}_{<0}$$

Negative thermal mass!

Maede, Ramani, 1807.07578
Baldes, Servant, 1807.08770
Gliotti, Rattazzi, Vecchi, 1811.11740



from negative Higgs cross-quartic coupling to large number of extra scalars χ

$$c_\phi T^2 \approx \begin{cases} \left([N_\phi + 2]\,\frac{\lambda_\phi}{12} + N_\chi \frac{\lambda_{\phi\chi}}{24} + N_S \frac{\lambda_{\phi S}}{24} \right) T^2 & >0 \quad \text{for } T \gtrsim \mu_S, \\ \left([N_\phi + 2]\,\frac{\lambda_\phi}{12} + N_\chi \frac{\lambda_{\phi\chi}}{24} \right) T^2 & <0 \quad \text{for } T \lesssim \mu_S. \end{cases}$$

< 0

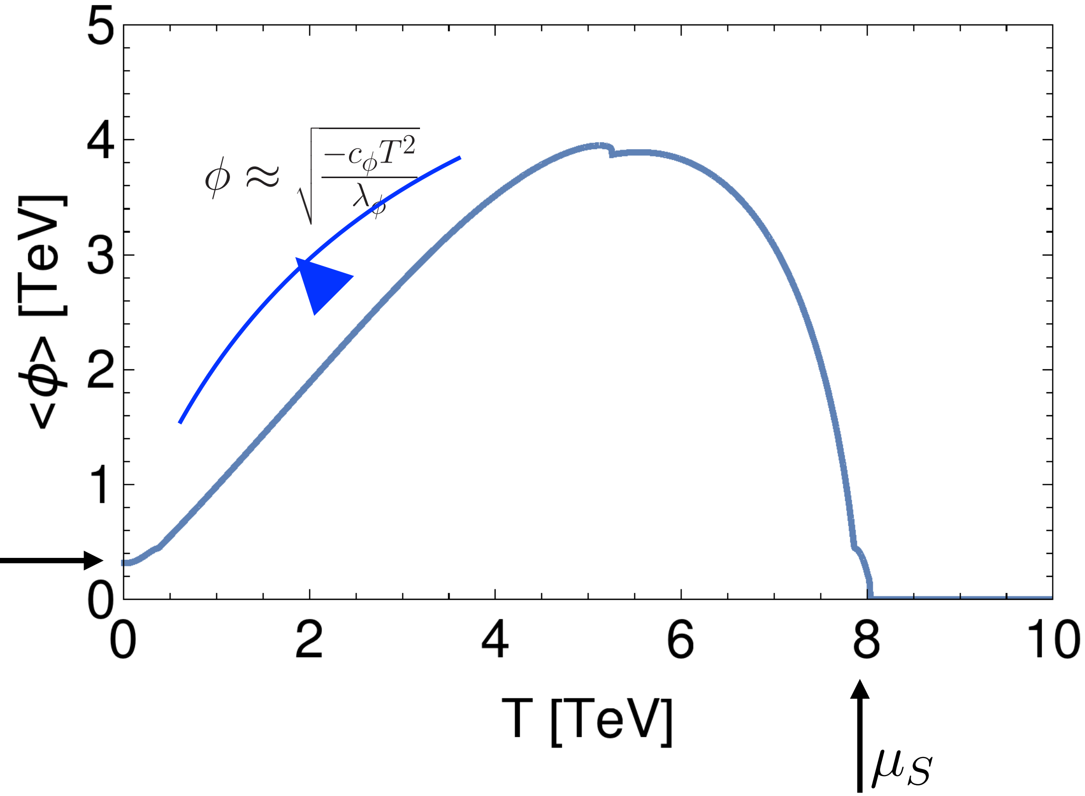
EW symmetry non-restoration at T>M$_H$

1807.07578
1807.08770
1811.11740

$$\mu_\phi{}^2(T) \sim -\mu_\phi^2 + \underbrace{c_\phi T^2}_{<0}$$

Negative thermal mass!

$$\phi \approx \sqrt{\frac{-\mu_\phi^2}{\lambda_\phi}}$$

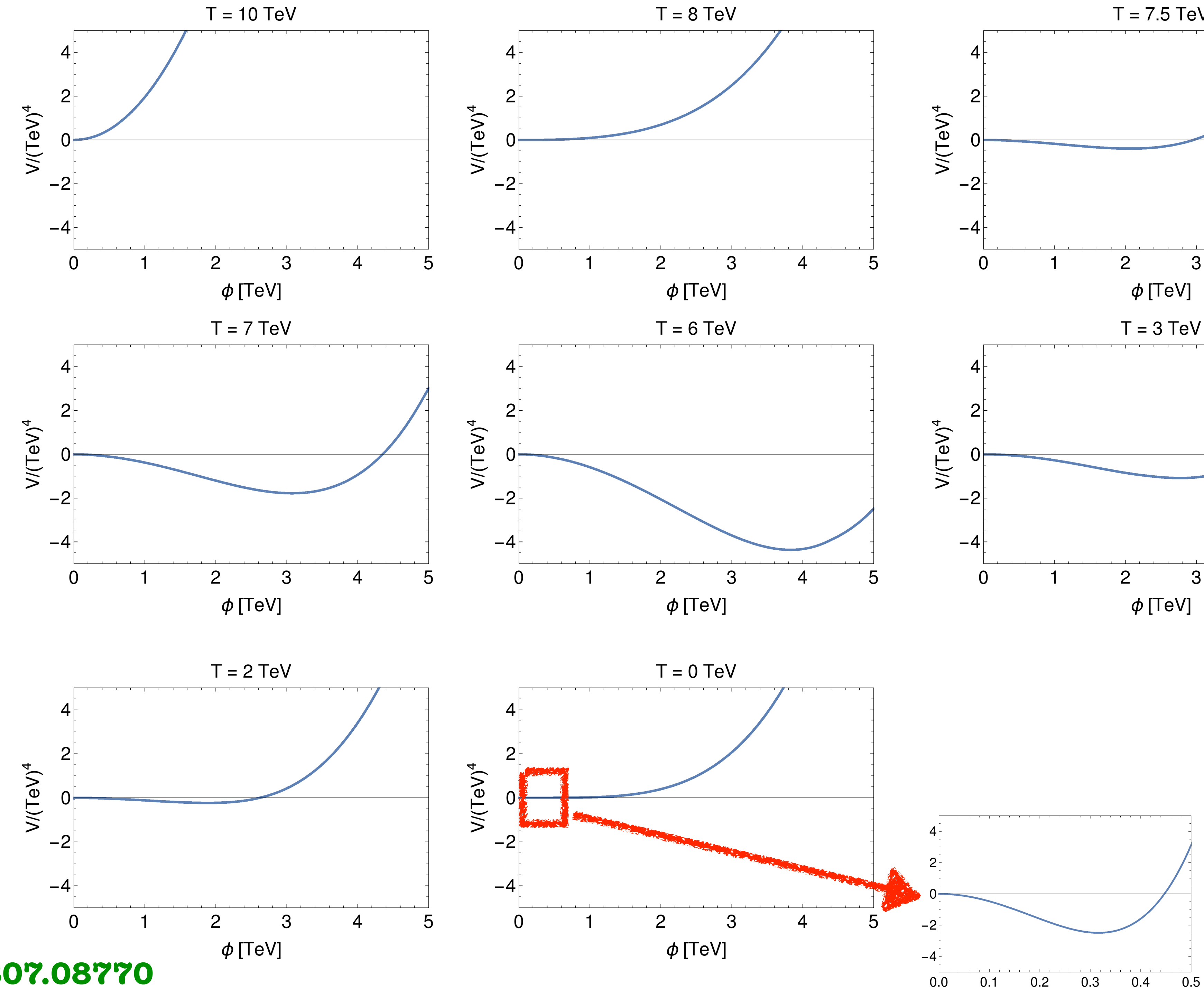


from negative Higgs cross-quartic coupling to large number of extra scalars χ

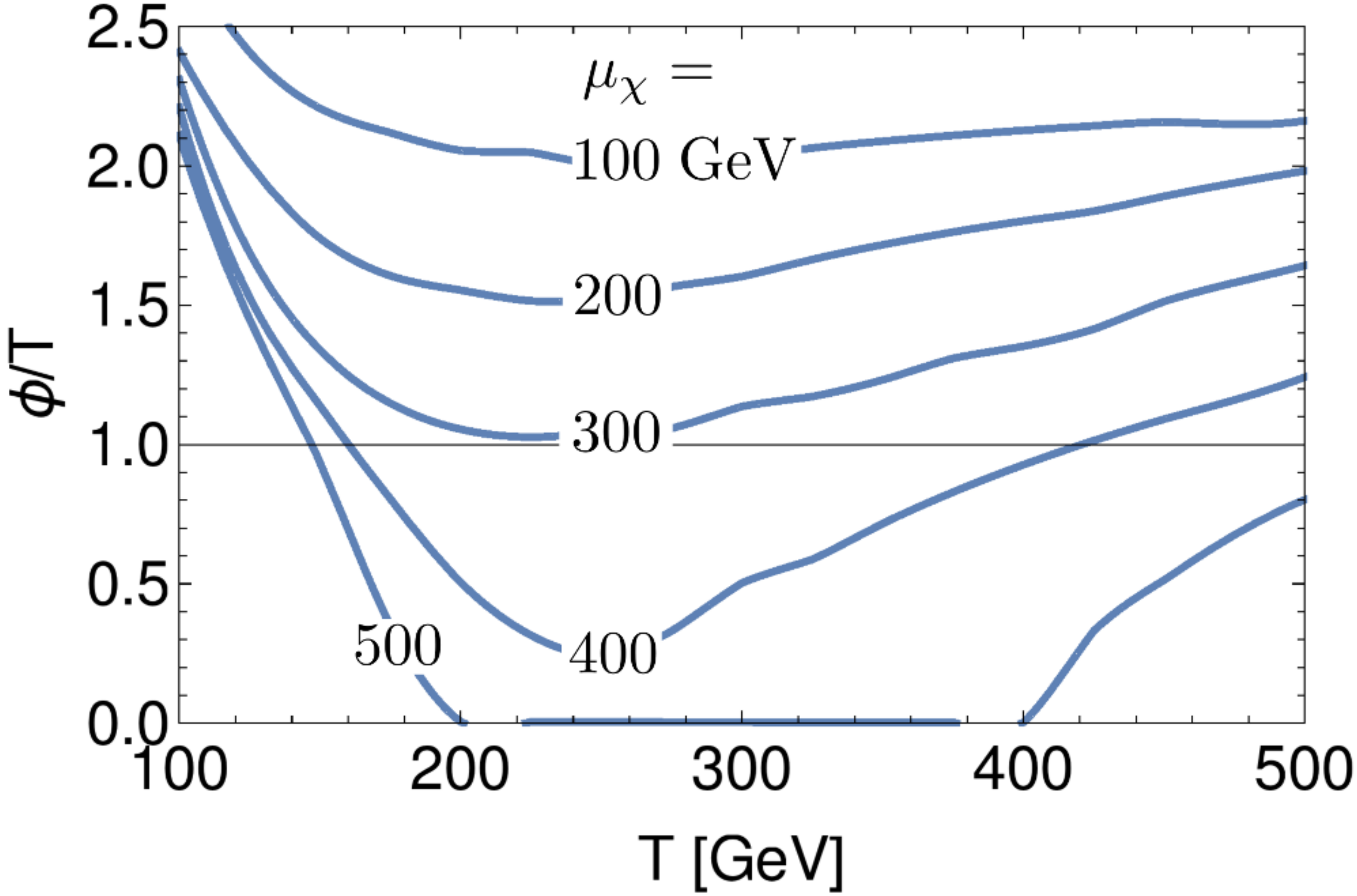
$$c_\phi T^2 \approx \begin{cases} \left([N_\phi + 2]\,\frac{\lambda_\phi}{12} + N_\chi \frac{\lambda_{\phi\chi}}{24} + N_S \frac{\lambda_{\phi S}}{24}\right) T^2 & > 0 \quad \text{for } T \gtrsim \mu_S, \\ \left([N_\phi + 2]\,\frac{\lambda_\phi}{12} + N_\chi \frac{\lambda_{\phi\chi}}{24}\right) T^2 & < 0 \quad \text{for } T \lesssim \mu_S. \end{cases}$$

< 0

High-scale (T>TeV) EW phase transition



χ's should be lighter than 300 GeV to avoid sphaleron washout of baryon asymmetry!



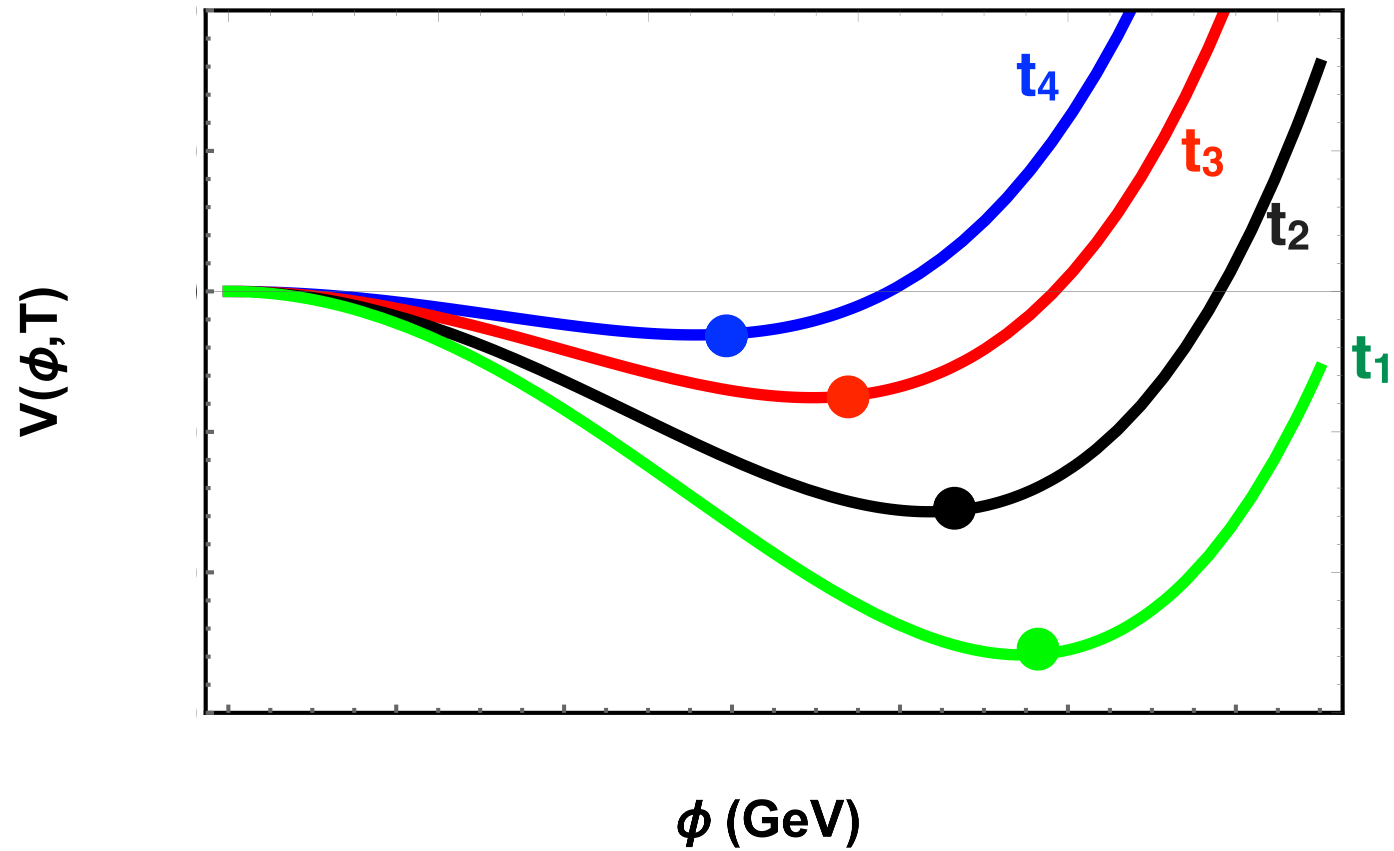
1807.08770

EW symmetry: never-restored .

1807.07578

$$-\mu^2 + c\,T^2$$

< 0, Negative thermal mass !



> No EW phase transition ! Baryogenesis without sphalerons ?

EW symmetry non-restoration at $T > M_H$ from new fermions

[2002.05174]

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

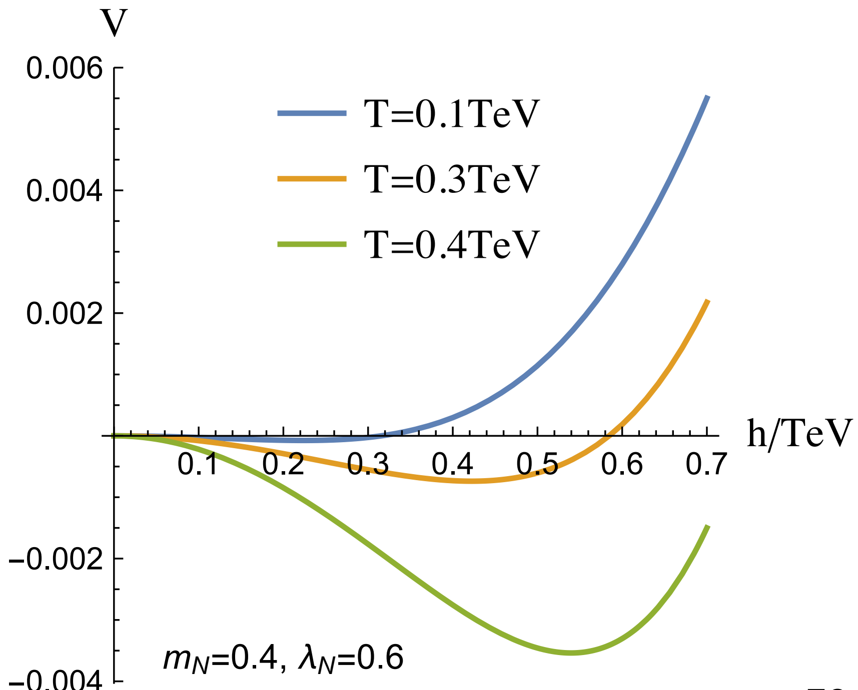
Add n new fermions N with Higgs-dependent mass contribution. Mass vanishes at <h>≠0

[2002.05174]

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

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

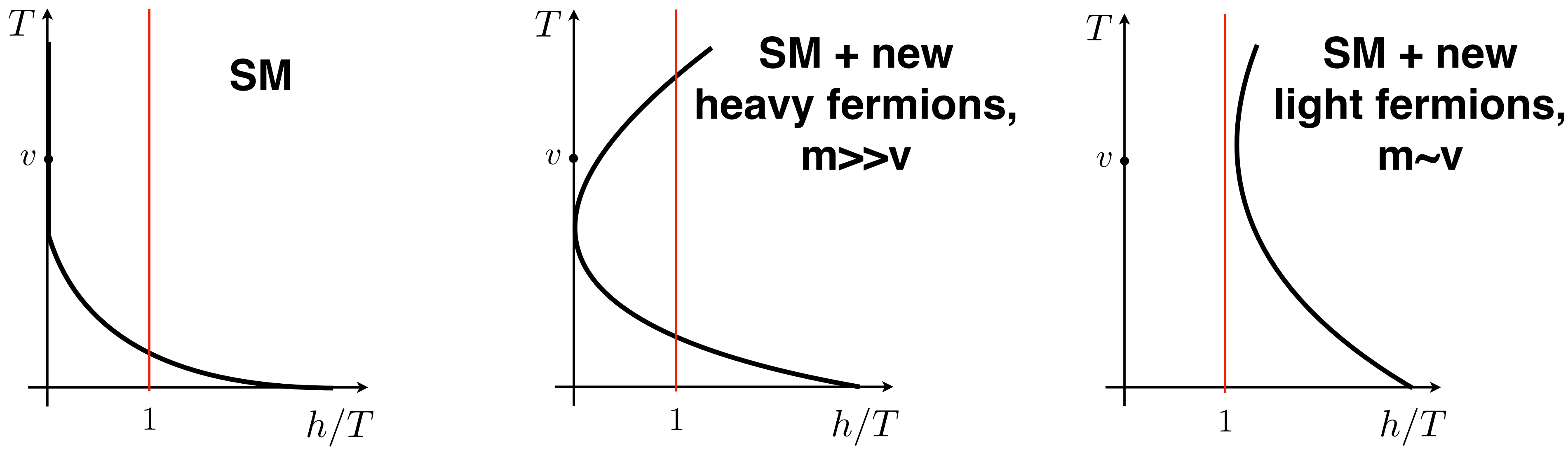
Negative thermal mass



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

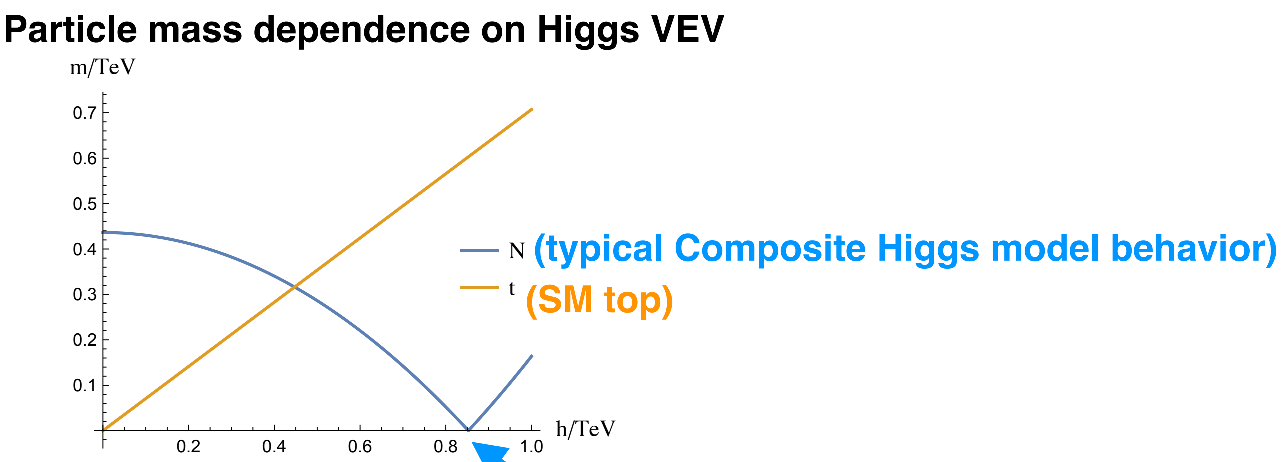
Why pushing up the temperature of the EW phase transition ?

[2002.05174]

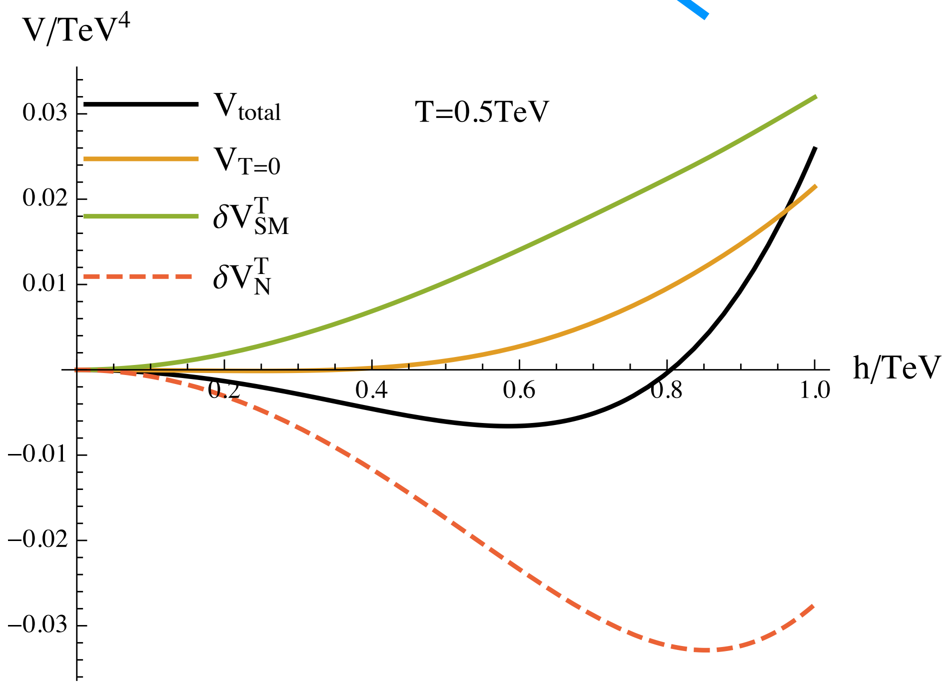


> Baryon asymmetry produced during higher T phase transition is never washed out !

Arises in Composite Higgs



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



[2002.05174]

What next ?

Revisit EWPT in Composite Higgs with extra singlet fermions

Bruggisser, VonHarling, Matsedonskyi, Servant, in prep.

—> Open the heavy dilaton region!

Another application: open the scope of cold-baryogenesis scenario

Summary

High-T Higgs behaviour: controlled by Higgs couplings

EW phase transition: a probe of the global shape of the Higgs potential

- **First-order EW phase transition: well alive and still likely**

  supercooled EW phase transition: generic in Composite Higgs, rich phenomenology and cosmology.

  Testable through dilaton signatures at LHC & GW signatures at LISA

- **EW baryogenesis: under threat by EDM bounds**

Remaining options:

- **Top transport remains open in composite Higgs.**
- **$\cancel{CP}$ in hidden sector, e.g. new leptons**
- **EW phase transition occurring at high temperatures >> 100 GeV, via additional singlet scalars or singlet fermions.**

Conclusion .

It remains open how EW symmetry got broken in early universe

Still many open exotic possibilities regarding what happened when the energy density of the universe was (EW scale)^4.

Probing the EW phase transition will keep us busy through complementarity of studies in theory, lattice, experiments in Colliders, EDMs, gravitational waves, cosmology, axions.