HIGGS cosmological history.

Géraldine SERVANT
DESY/U.Hamburg

UK Annual meeting,
Durham Dec. 17 2019

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Universität Hamburg

Higgs in the early universe :

Does the Higgs help solving any of the open problems?

- Inflation
- Dark Matter
- Matter-antimatter asymmetry

Higgs in the early universe :

Are there any imprints from the Higgs' early behaviour in cosmological observables?

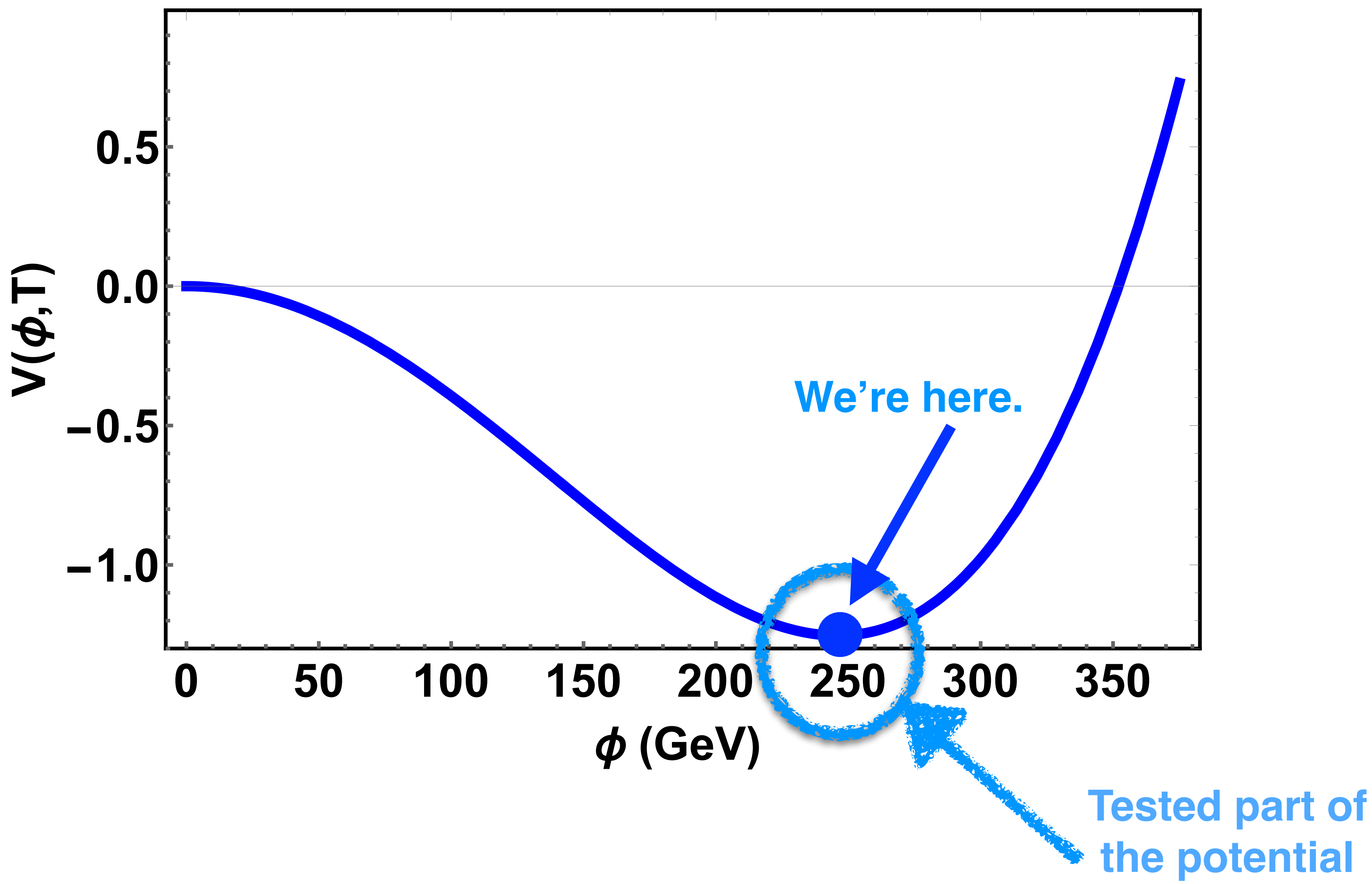
This talk :

Higgs cosmology at the EW epoch.

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

THE HIGGS POTENTIAL .

TODAY, T=0

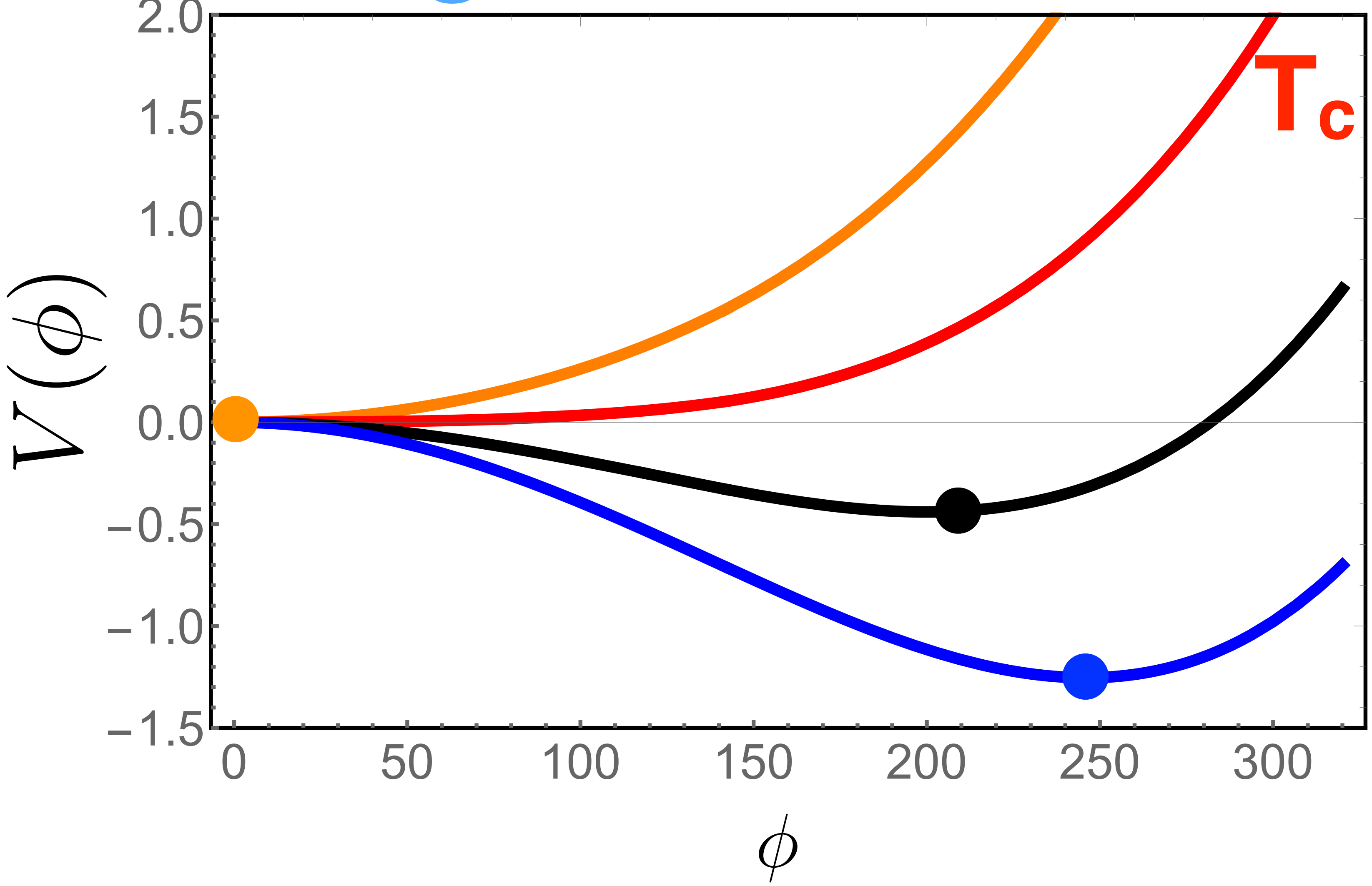


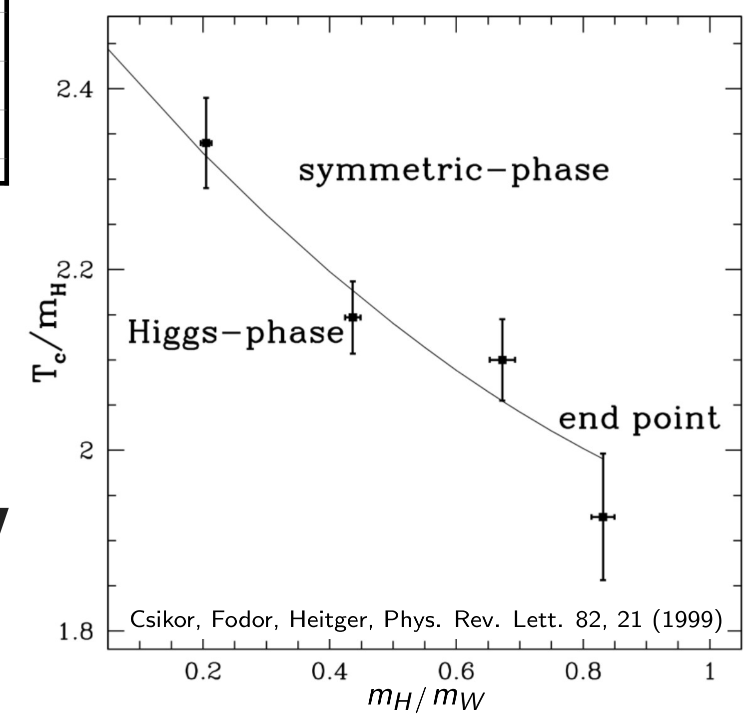
> How did we end up here ?

HEATING UP THE STANDARD MODEL .

EW sym. restored at T≳160 GeV***

through a smooth crossover





No departure from thermal equilibrium

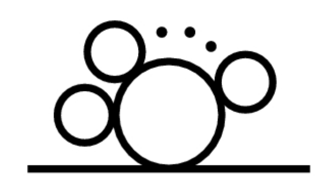
It would have been different if $m_H \lesssim 70$ GeV

***1404.3565

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

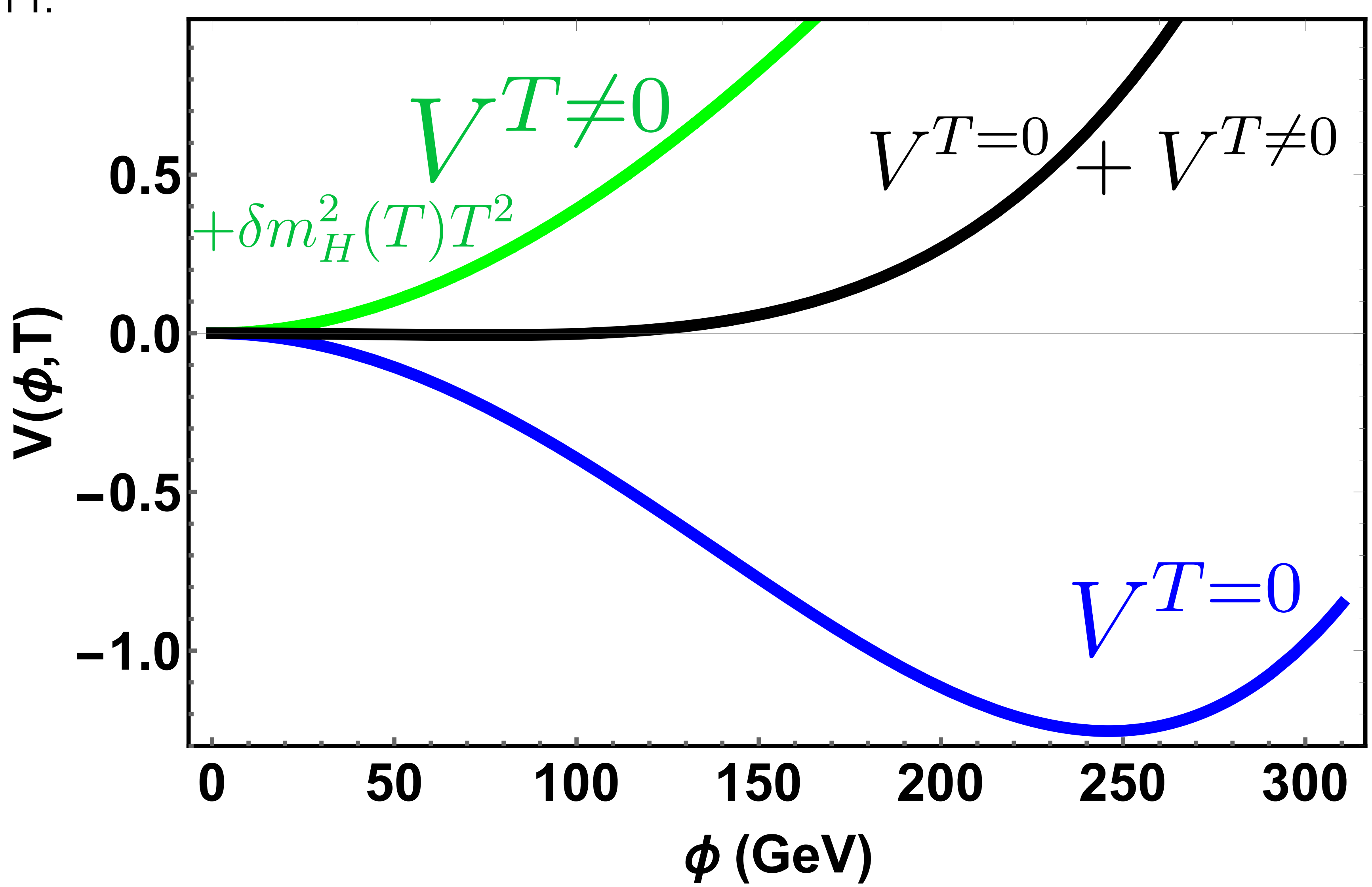
HIGH TEMPERATURE EW SYM. RESTORATION.

At one-loop:

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

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

At high T:



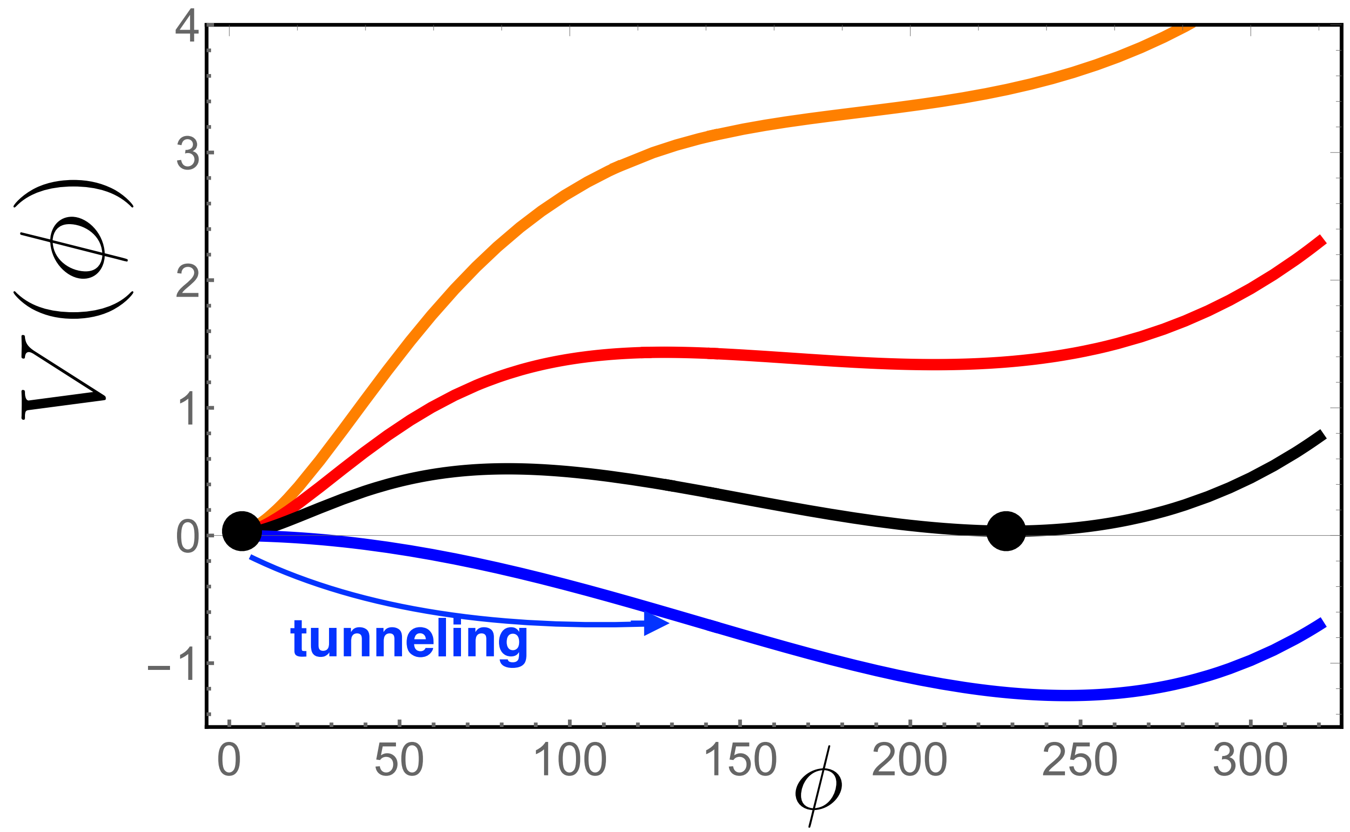
—> Symmetry restoration at Tc

WHICH ALTERNATIVE HIGGS STORIES ?

-1-

First-order EW Phase transition .

First-order EW phase transition .



Barrier separates 2 degenerate minima

2 phases can coexist

Nucleation, expansion and collision of Higgs bubbles

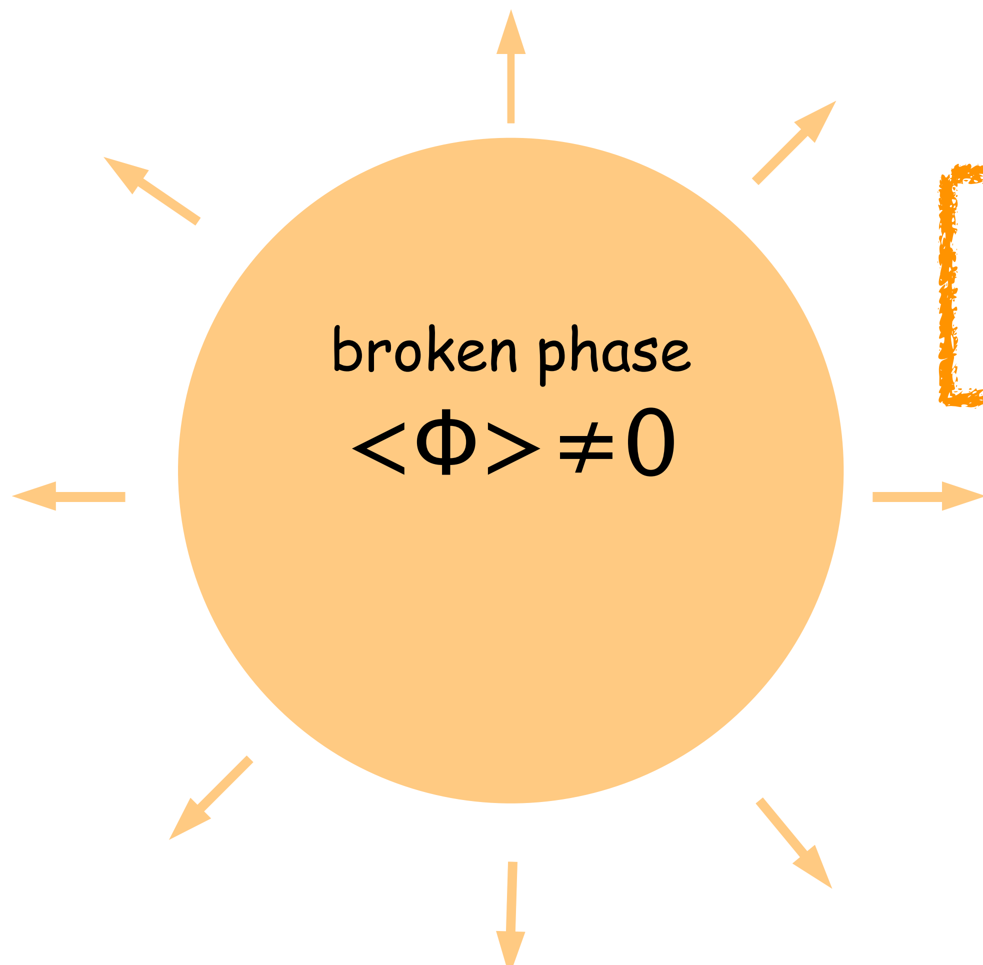
> Framework for EW baryogenesis !

> Stochastic bgd of gravitational waves detectable at LISA !

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

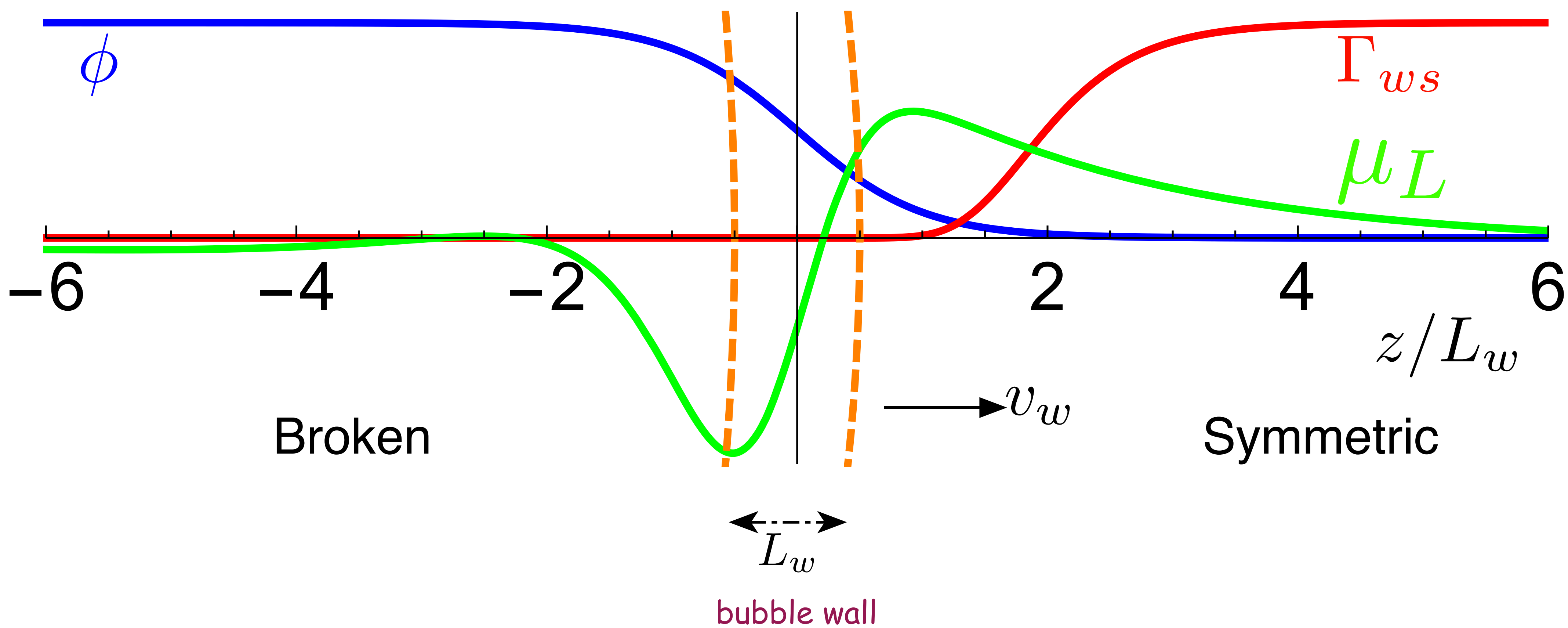
T_n $\equiv$ **nucleation temperature**

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



The EW baryogenesis miracle .

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

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

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

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

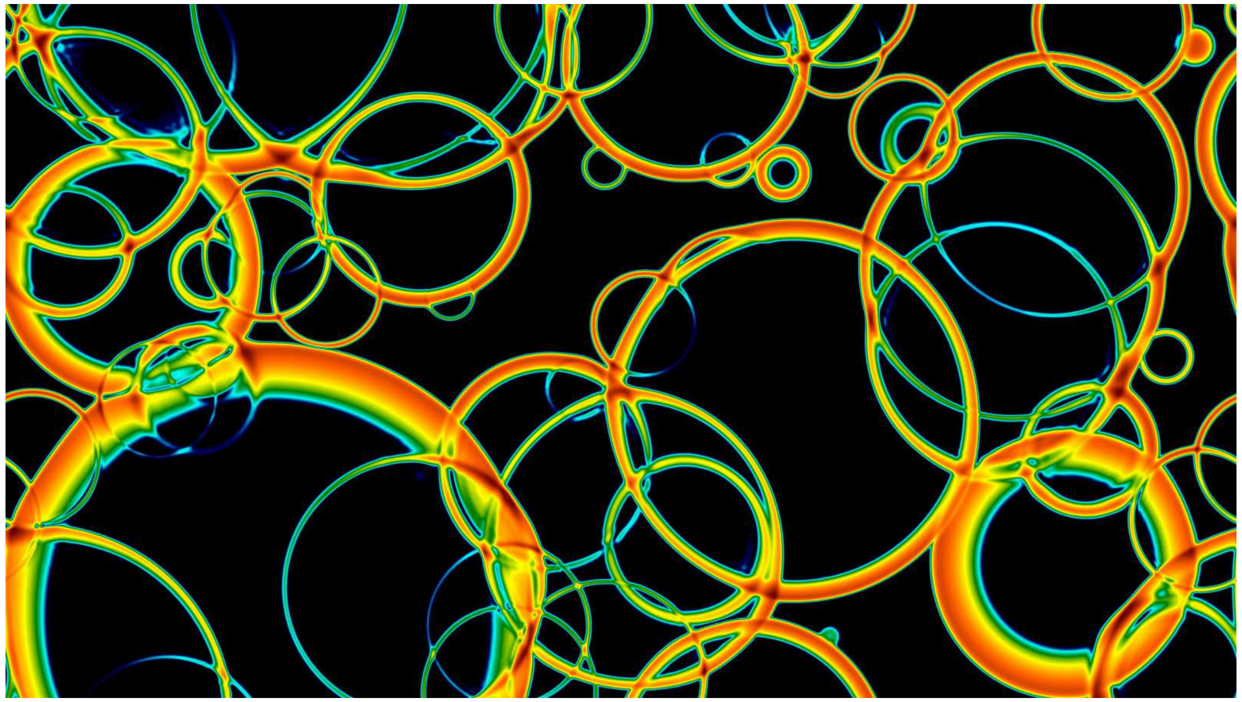
$$\eta_B \sim \frac{\Gamma_{ws}\ \delta_{CP}}{g_*\ L_w\ T^2} \sim \frac{10^{-6}\ \delta_{CP}}{g_*} \sim 10^{-8} \delta_{CP}$$

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

Gravitational Waves from a first-order phase transition .

[LISA Cosmology Working group, 1512.06239]

+ recent update 1910.13125



[Credit:David Weir]

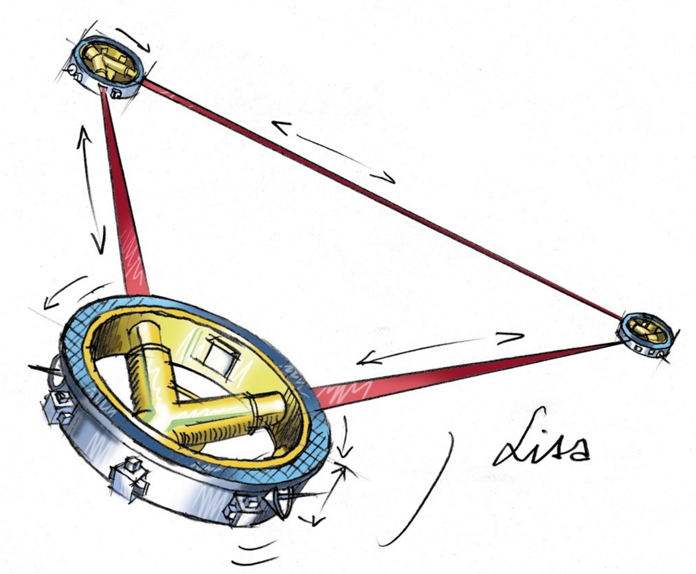
Fluid flows

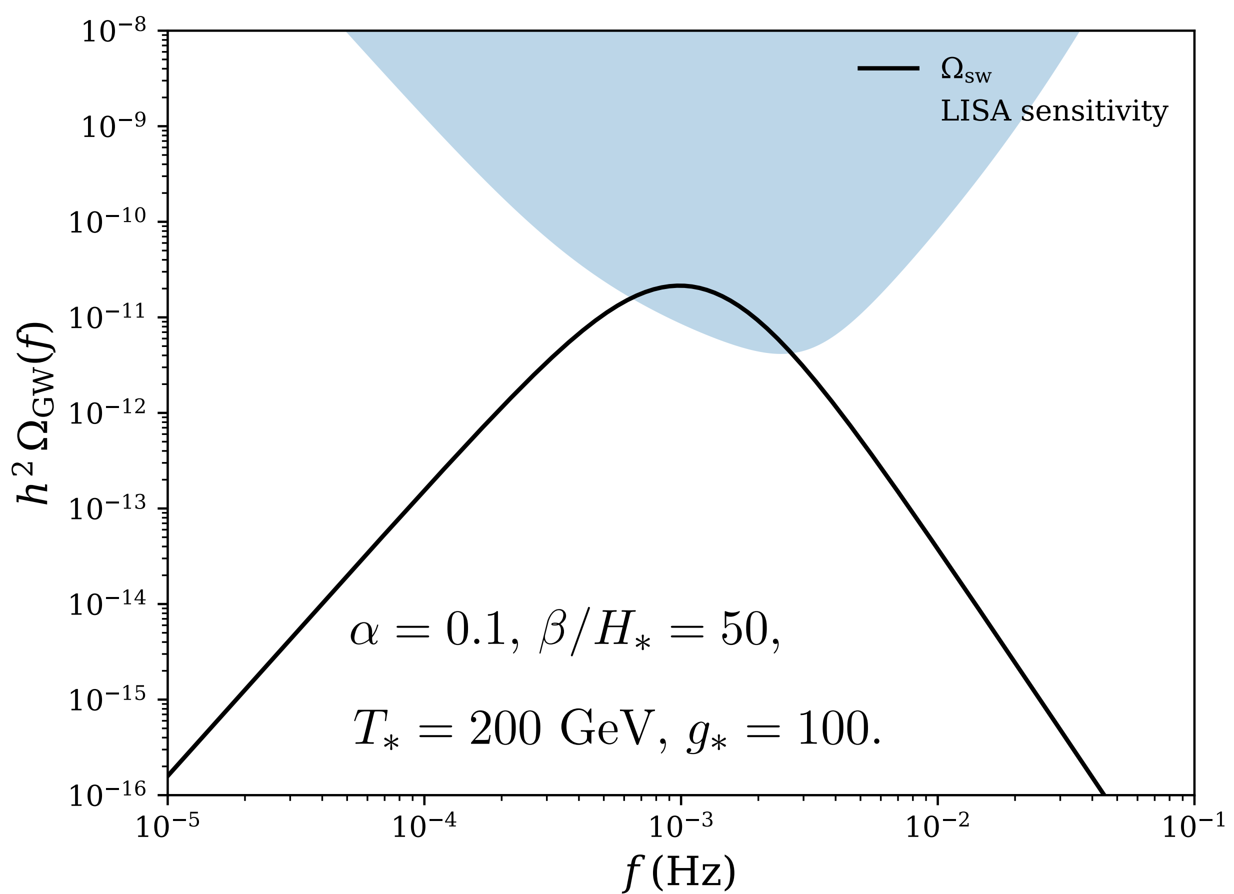
Magnetic fields

Turbulence

Stochastic bgd of gravitational radiation @ mHz

—> LISA !





What makes the EW phase transition 1st-order ?

> O(1) modifications to the Higgs potential

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

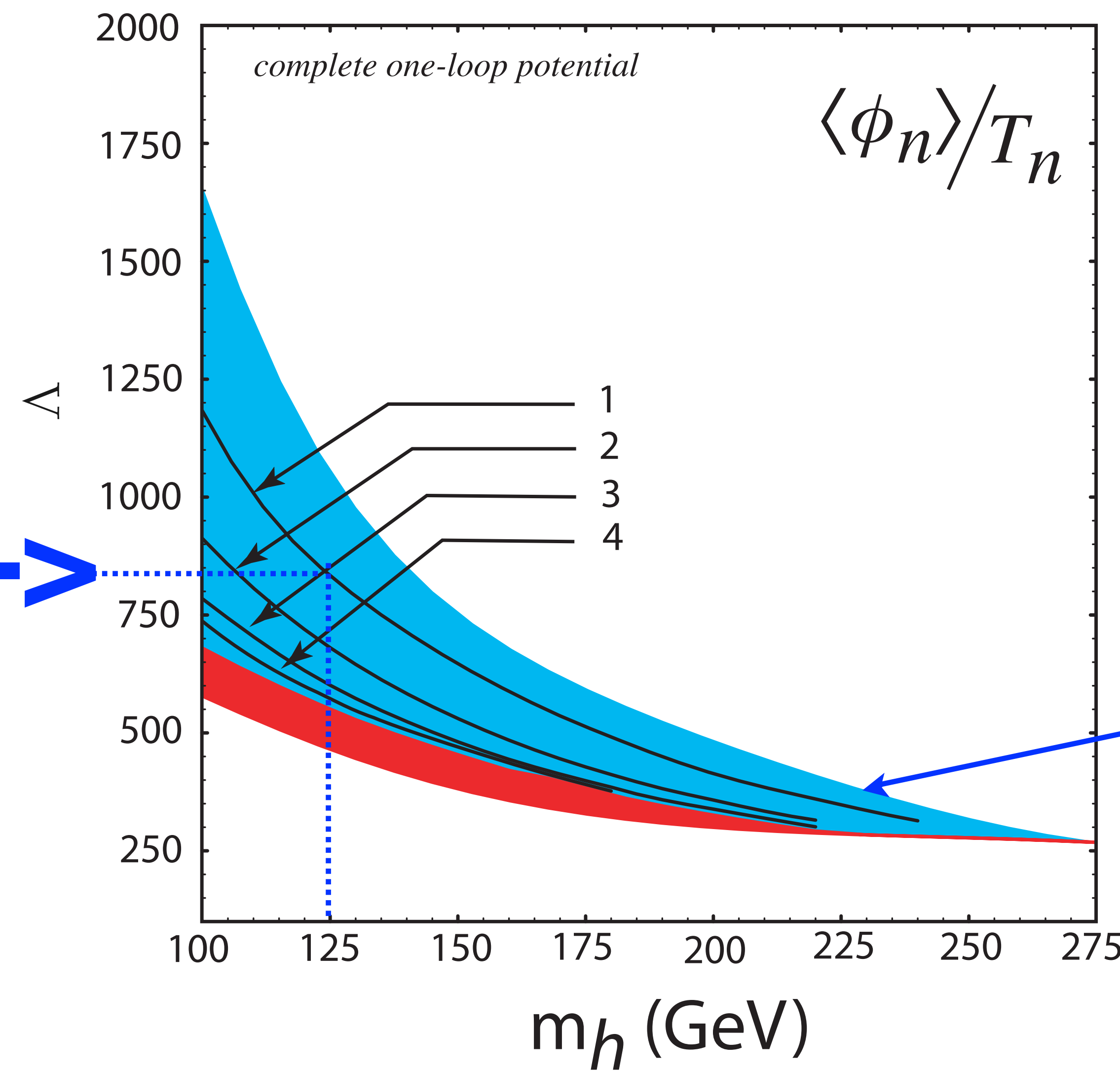
What makes the EW phase transition 1st-order ?

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

EFT approach to EW phase transition of limited use.

$$V(\phi) = -\mu_h^2|\phi|^2 - \lambda|\phi|^4 + \frac{|\phi|^6}{\Lambda^2}$$

strong enough
for EW baryogenesis
if $\Lambda \lesssim 850$ GeV



region where EW phase
transition is 1st order

hep-ph/0407019
0711.2511

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, 2HDM… 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 after 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

The most studied case: First-order EW phase transition from an extra scalar singlet .

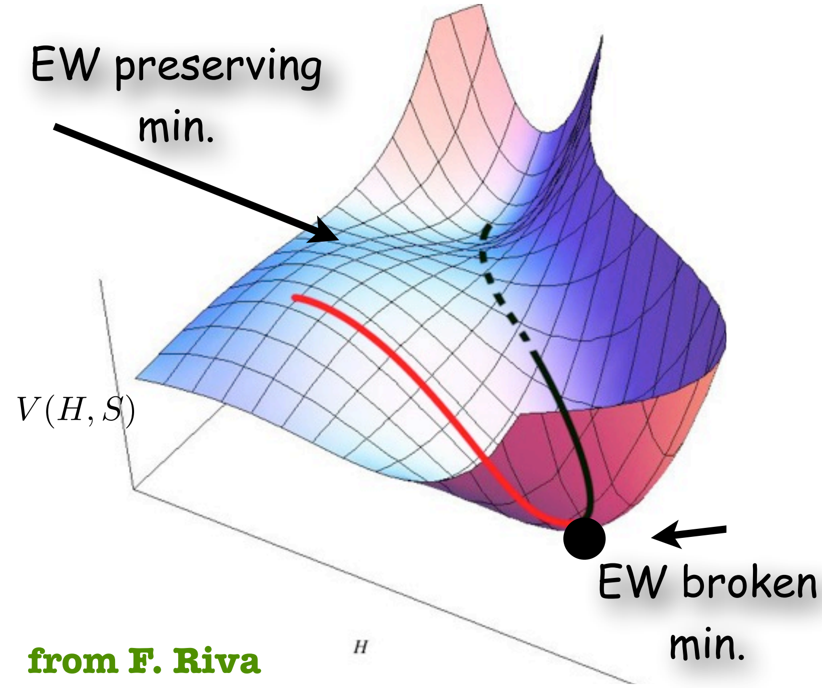
1107.5441

$$\mathbf{Z}_2 \qquad s \to -s$$

$$V = V^{\rm even} + V^{\rm odd}$$

$$V^{\rm even} \equiv -\mu_h^2|H|^2 + \lambda_h|H|^4 - \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{2}\lambda_{HS} s^2|H|^2$$

$$V^{\rm odd} \equiv \frac{1}{2}\mu_m s|H|^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$

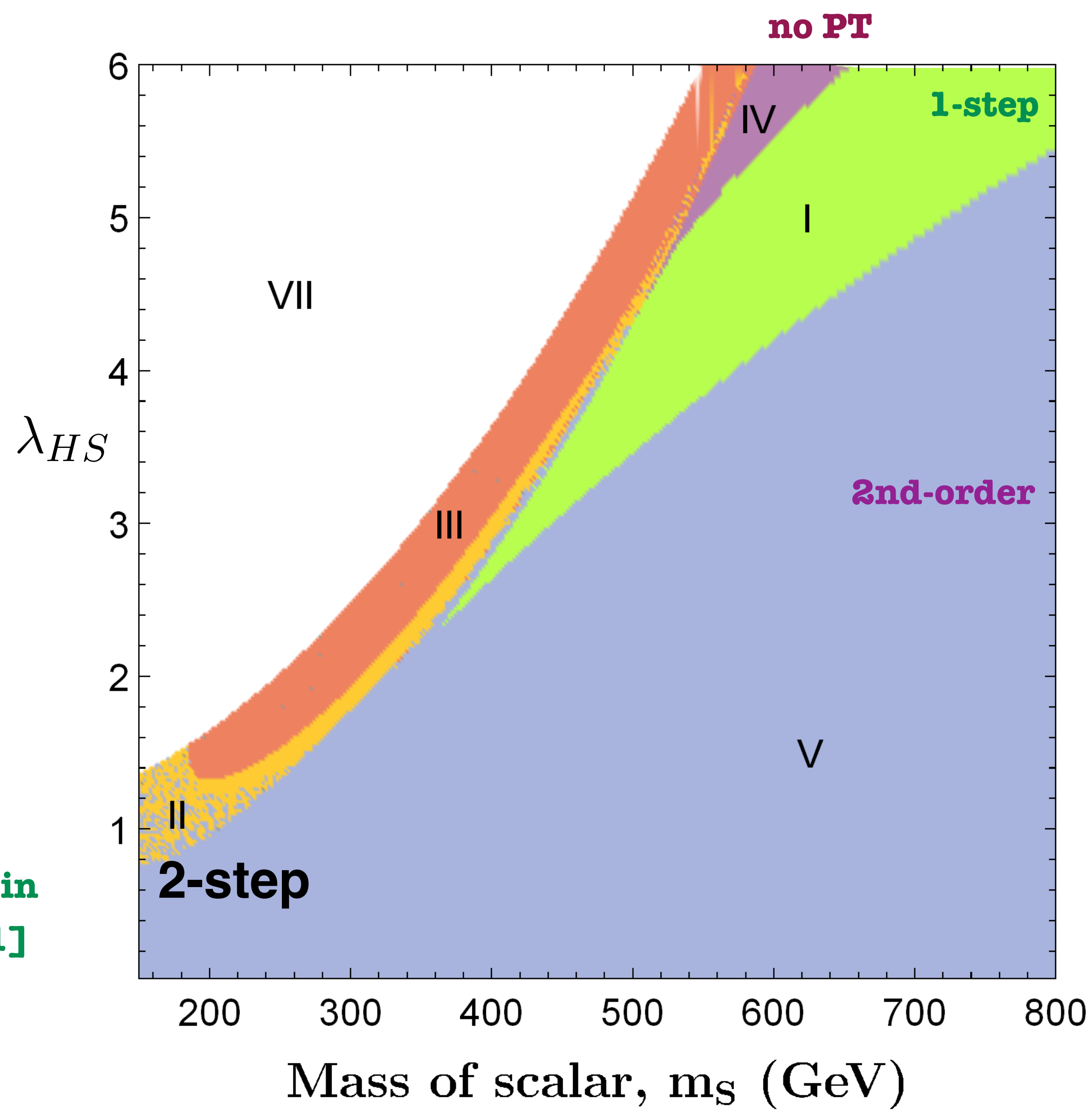


from F. Riva

- no Z_2 : <s> ≠0 today, H-s mixing —> large modif to higgs self-coupling, LHC tests

- with Z_2 : <s> ~0 today, no mixing —>nightmare scenario

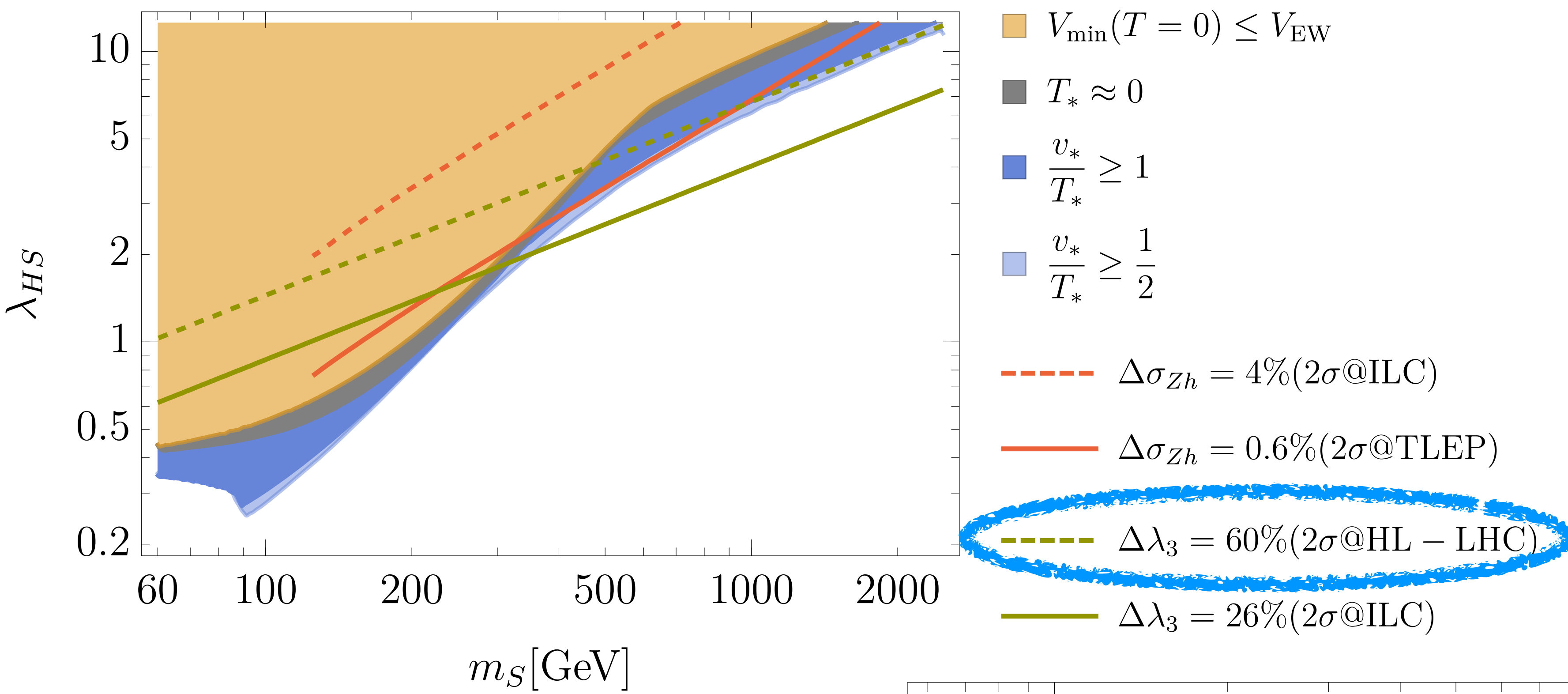
Z_2 case

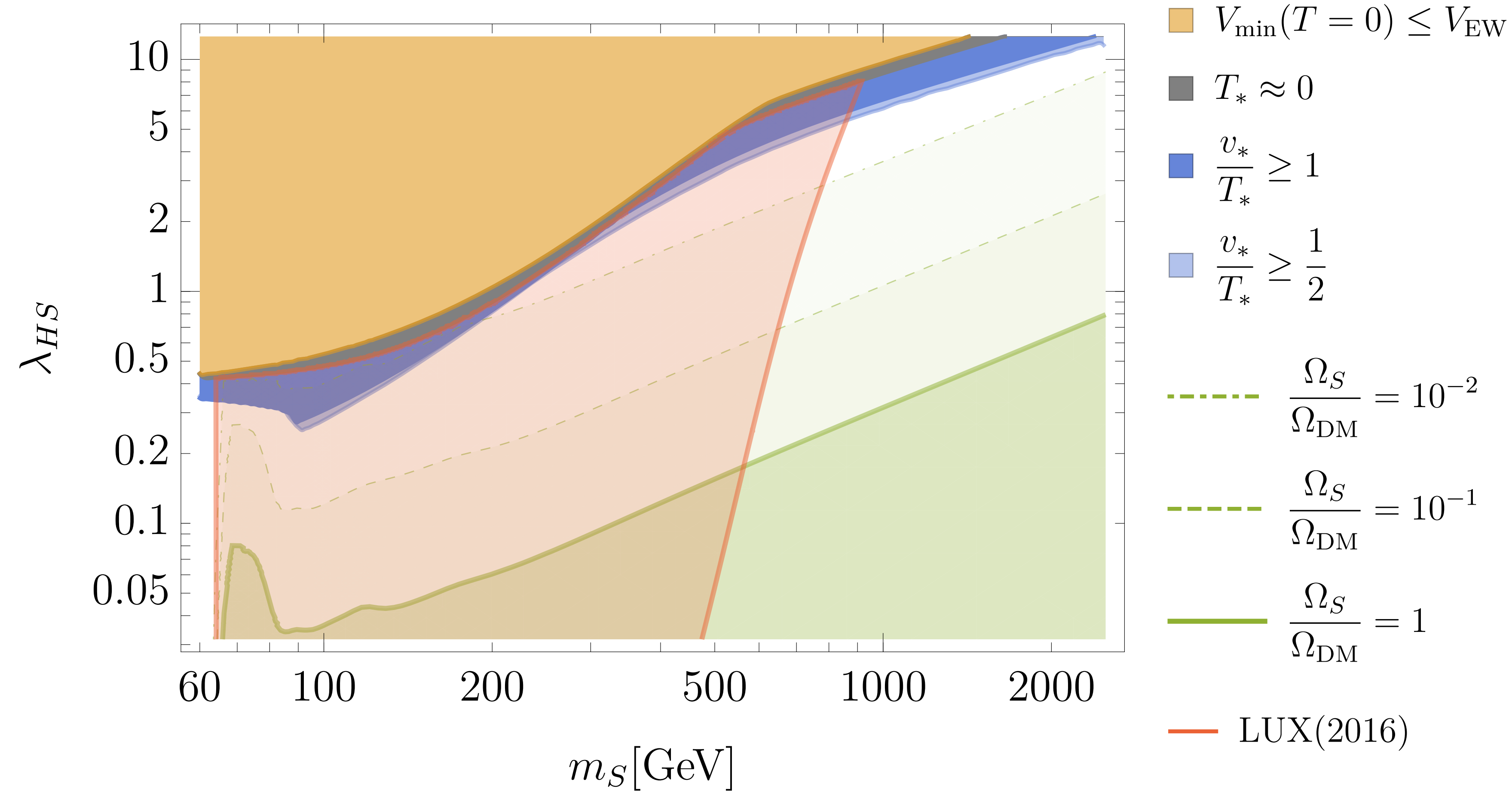


Kurup-Perelstein [1704.03381]

Z_2 case .

1702.06124





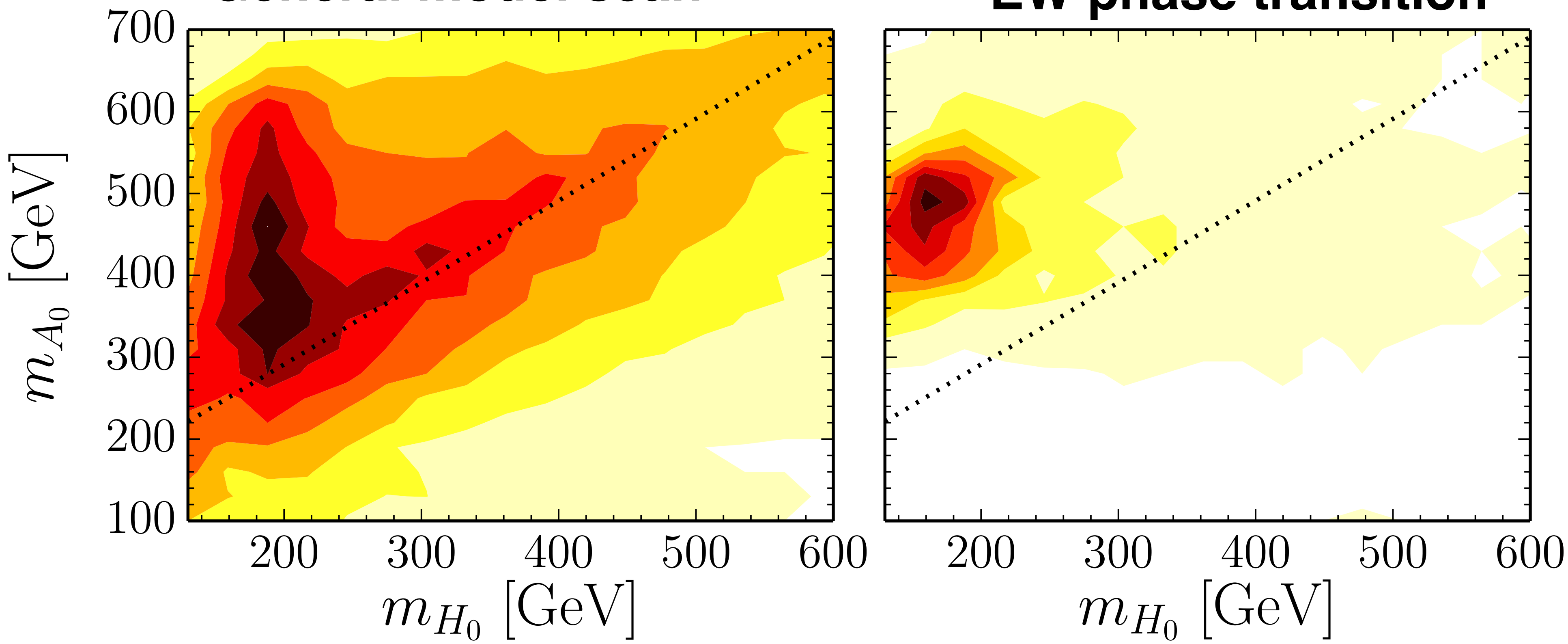
Exact Z2 case mostly excluded by direct DM searches even if S is sub-component (< 1%) of DM .

First-order EW phase transition in a 2-Higgs-doublet model .

Also requires specific parameter region

General model scan

Imposing 1st-order EW phase transition



1405.5537

(type I 2HDM)

EDM threat on EW baryogenesis

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

ACME II, Oct. 2018.

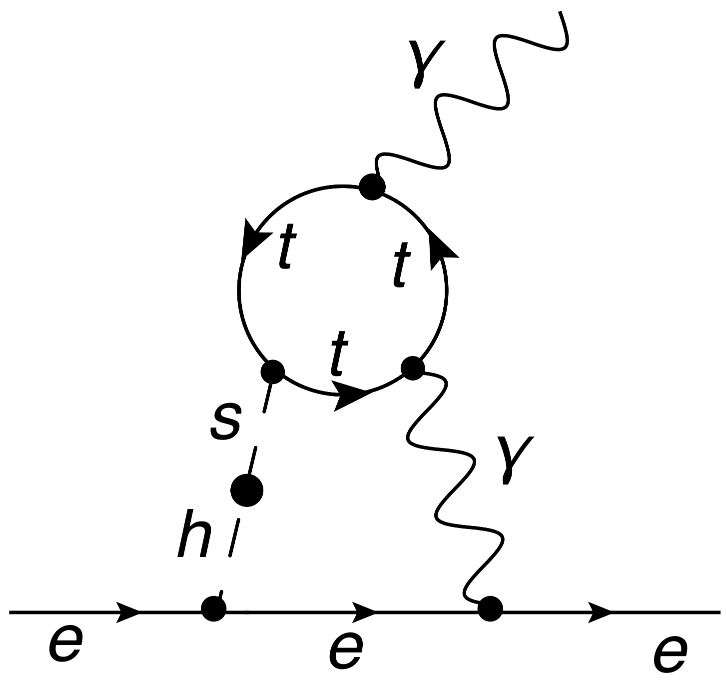
The most shaking news of the last years for EW baryogenesis practitioners!

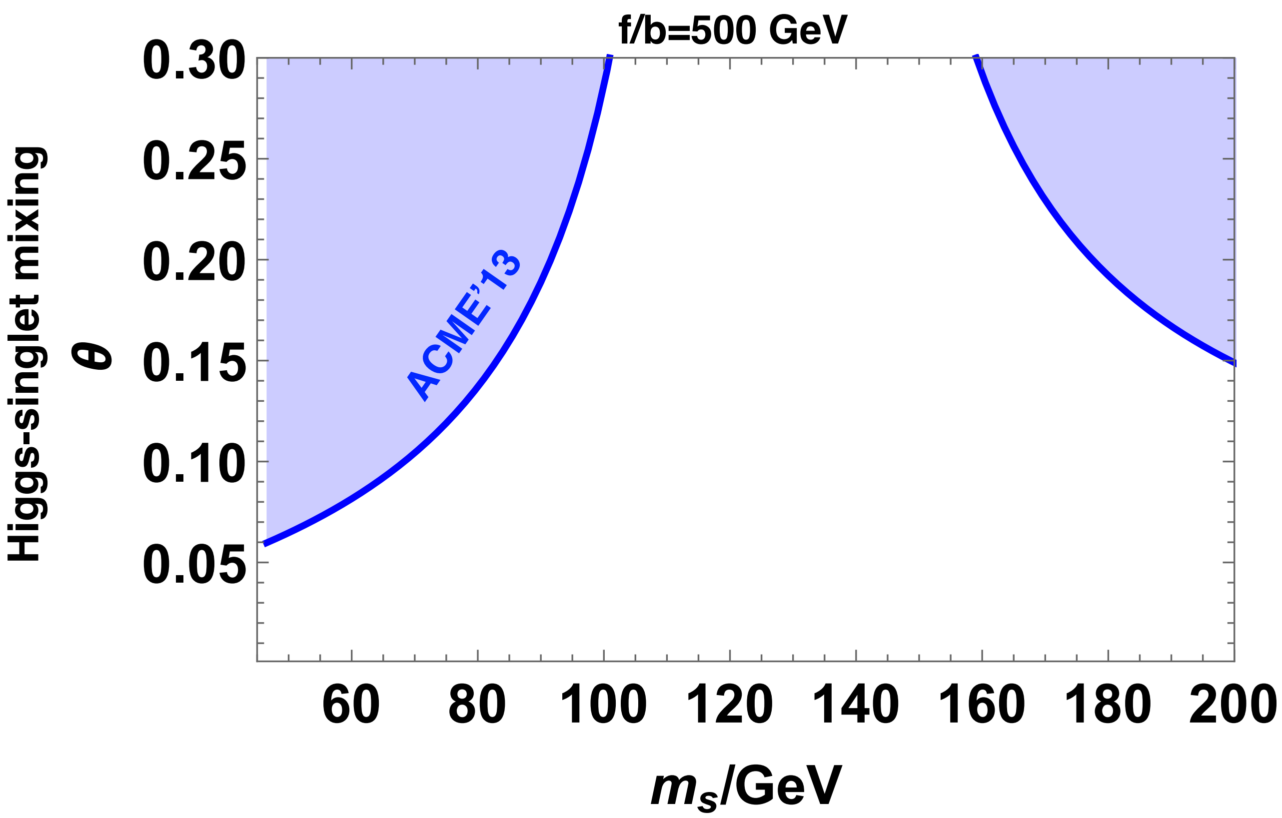
1- EW baryogenesis from extra singlet

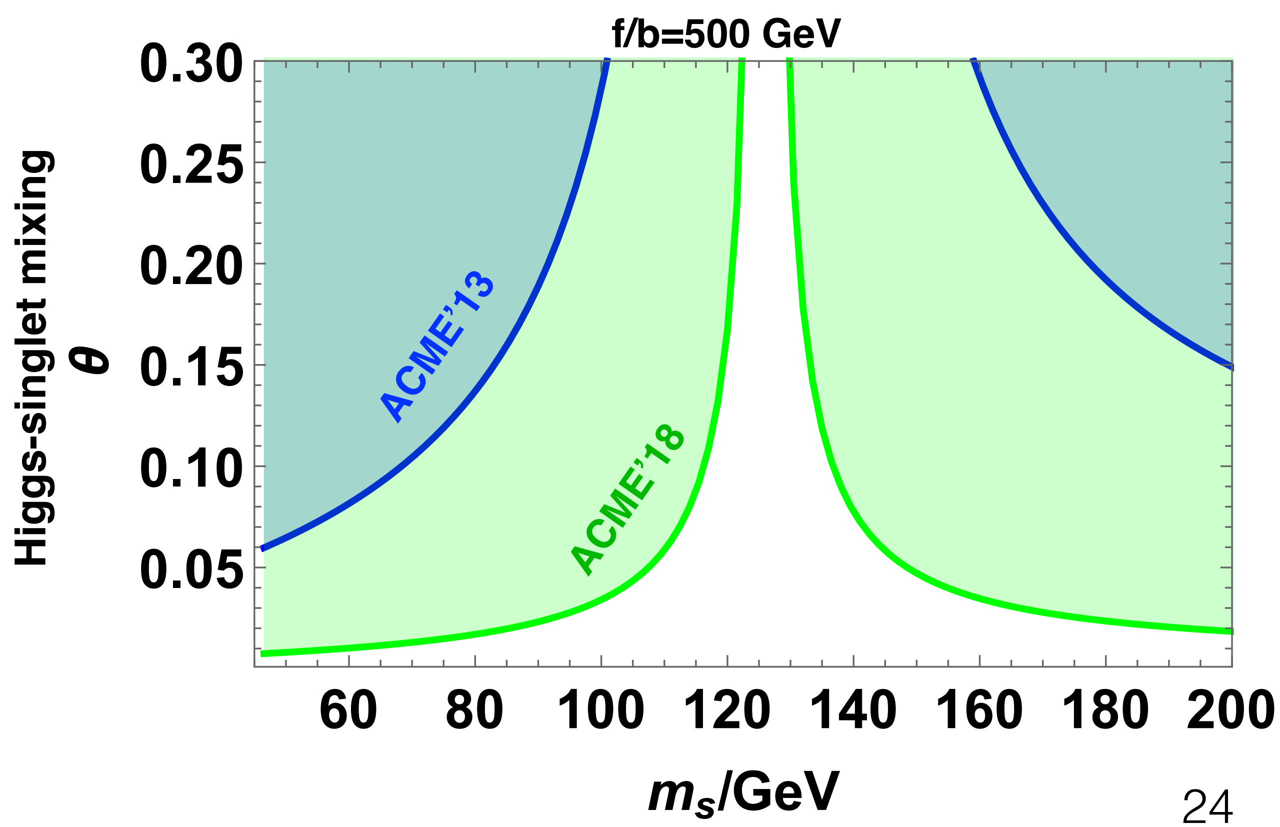
1110.2876

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

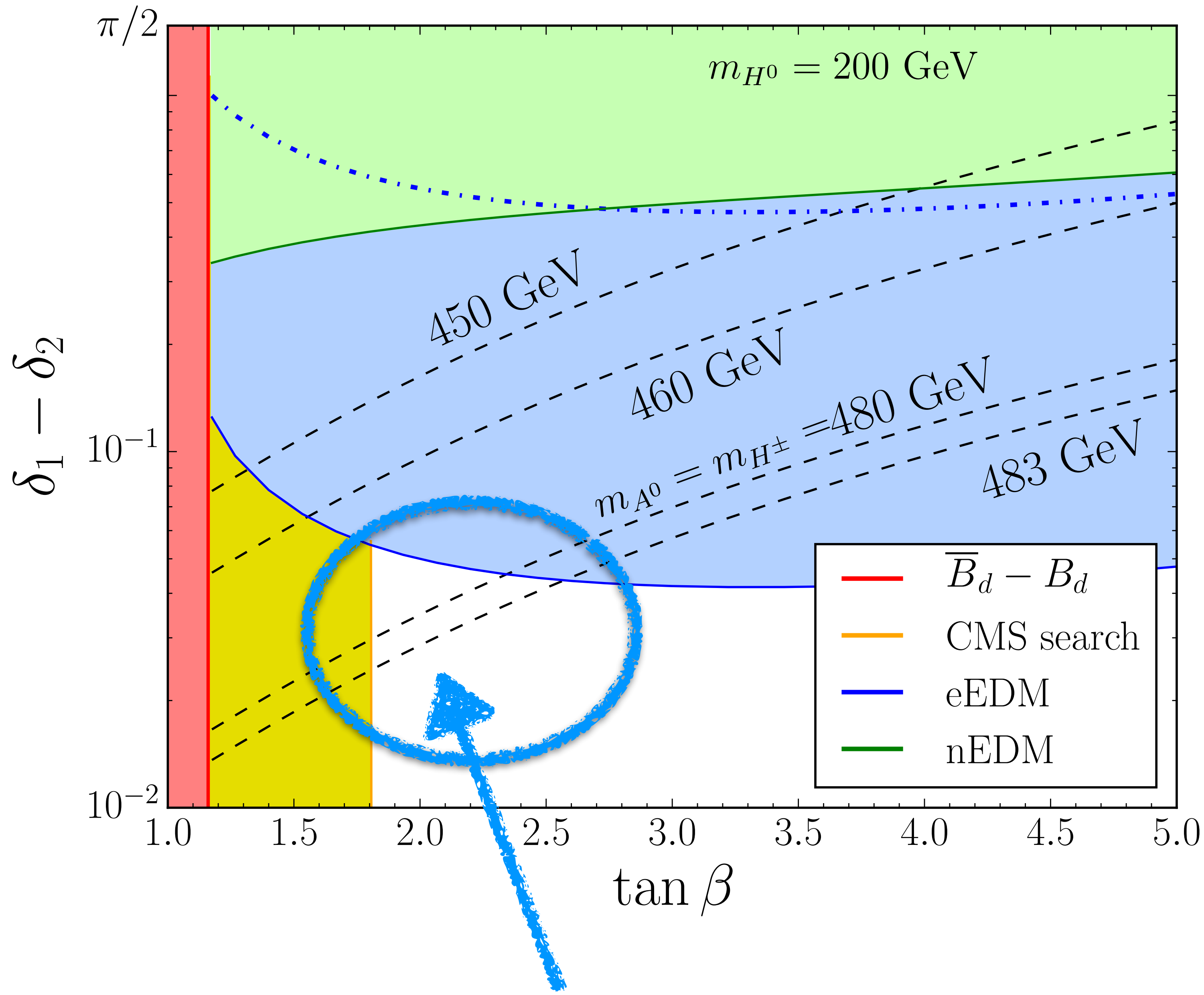
$$\frac{s}{f} H \bar{Q}_3 (a + ib\gamma_5) t + \mathrm{h.c.}$$







2- EW baryogenesis in Two-Higgs-Doublet .



Now excluded

Before ACME 18

[1611.05874]

Summary on minimally extended renormalizable scalar sectors*** .

-1- Faded motivation for EW baryogenesis with top-transport after ACME18

Ways out to evade EDM bounds: Hide $\not{CP}$ in leptons, or dark sector

1811.11104, 1903.11255 1811.09719

-2- Still, 1st-order EW phase transition possible
-> LHC & gravitational waves tests.

*** (Both S and 2HDM well-motivated in non-minimal Composite Higgs models)

-2-

EW Phase transition in Composite Higgs Models .

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

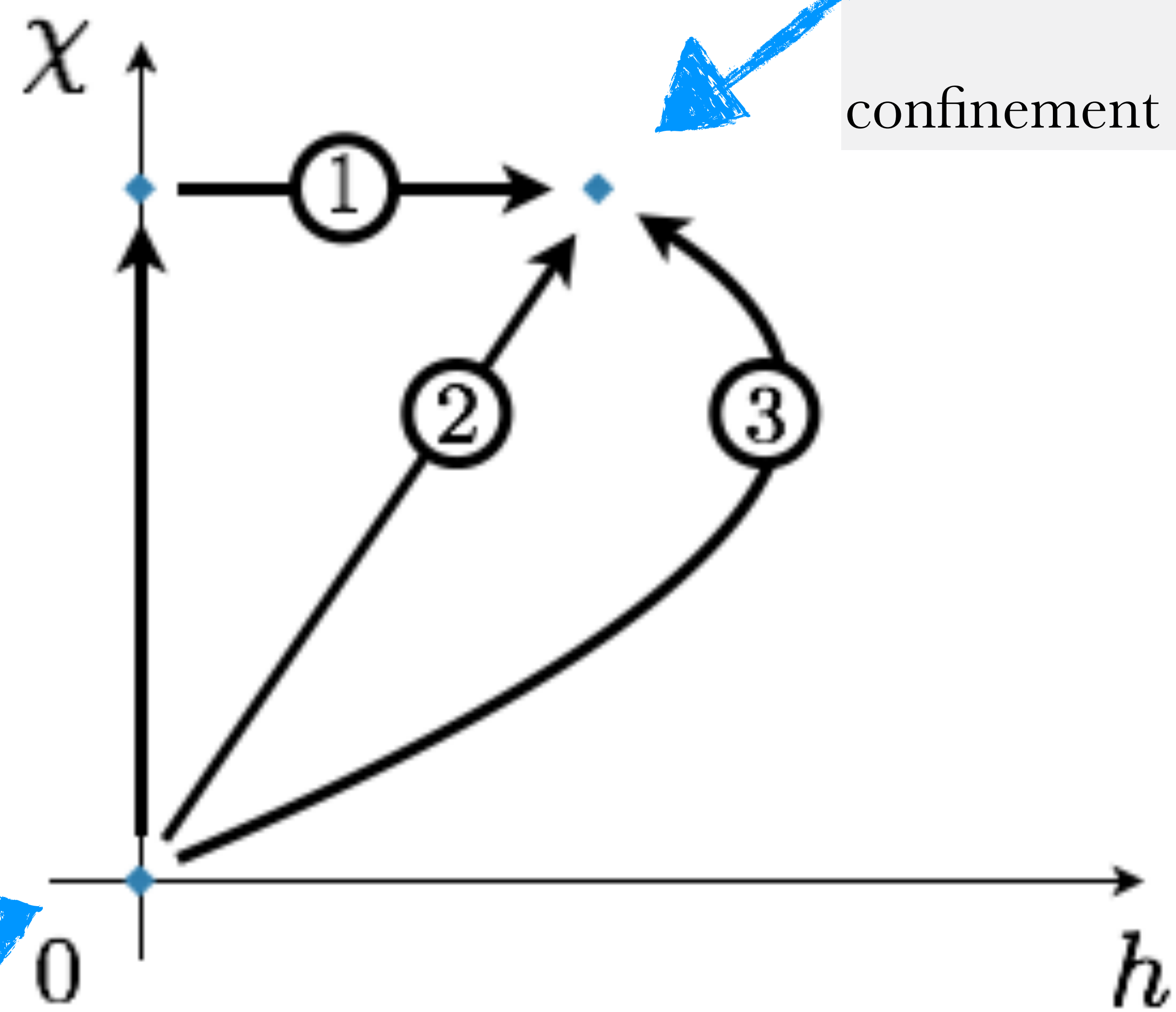
1104.4791

Higgs-dilaton intertwinned dynamics

global minimum at
$T \ll f$

confinement and EWSB

Which path?



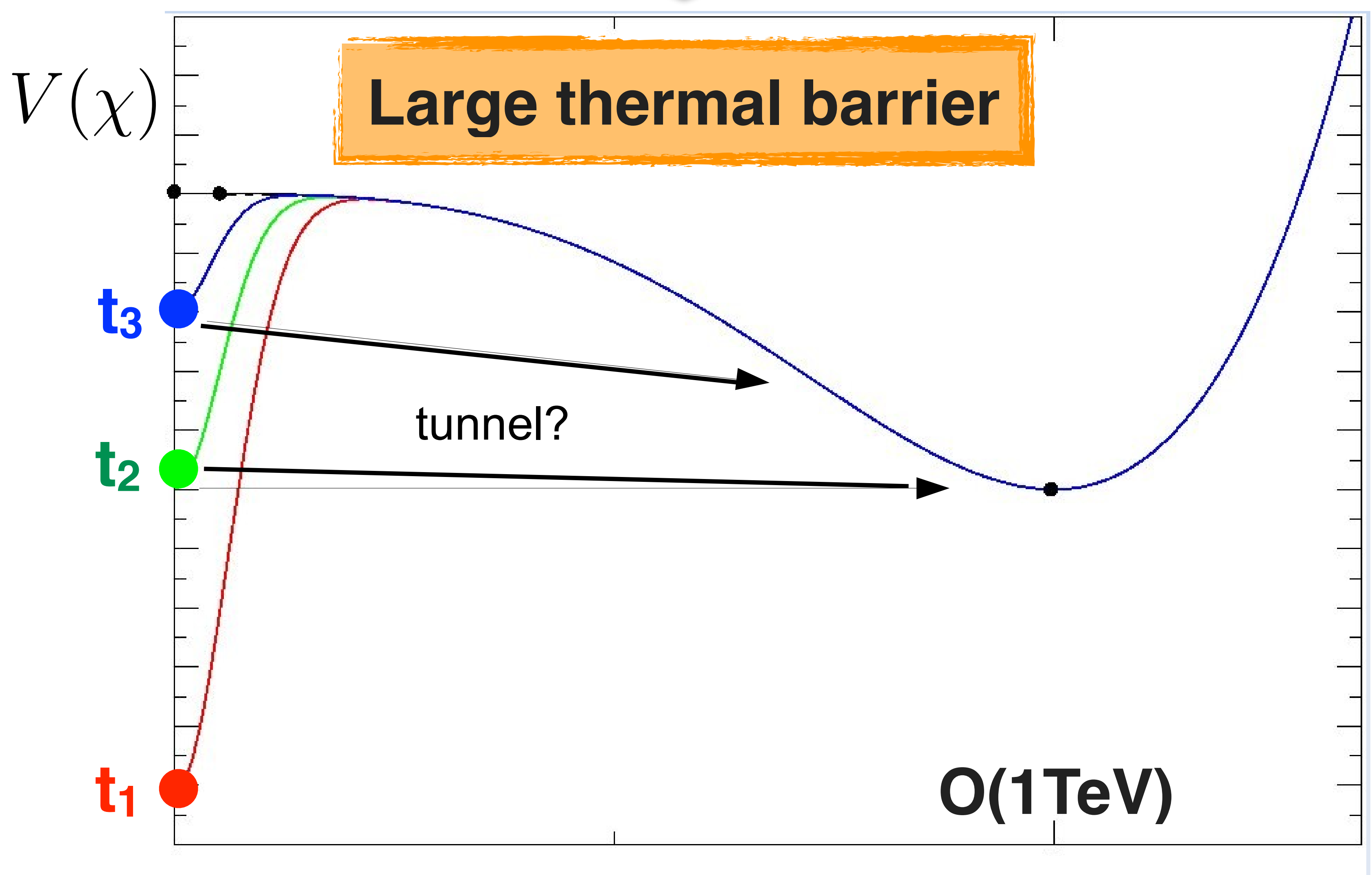
global minimum at
$T \gg f$

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



Supercooled confinement phase transition

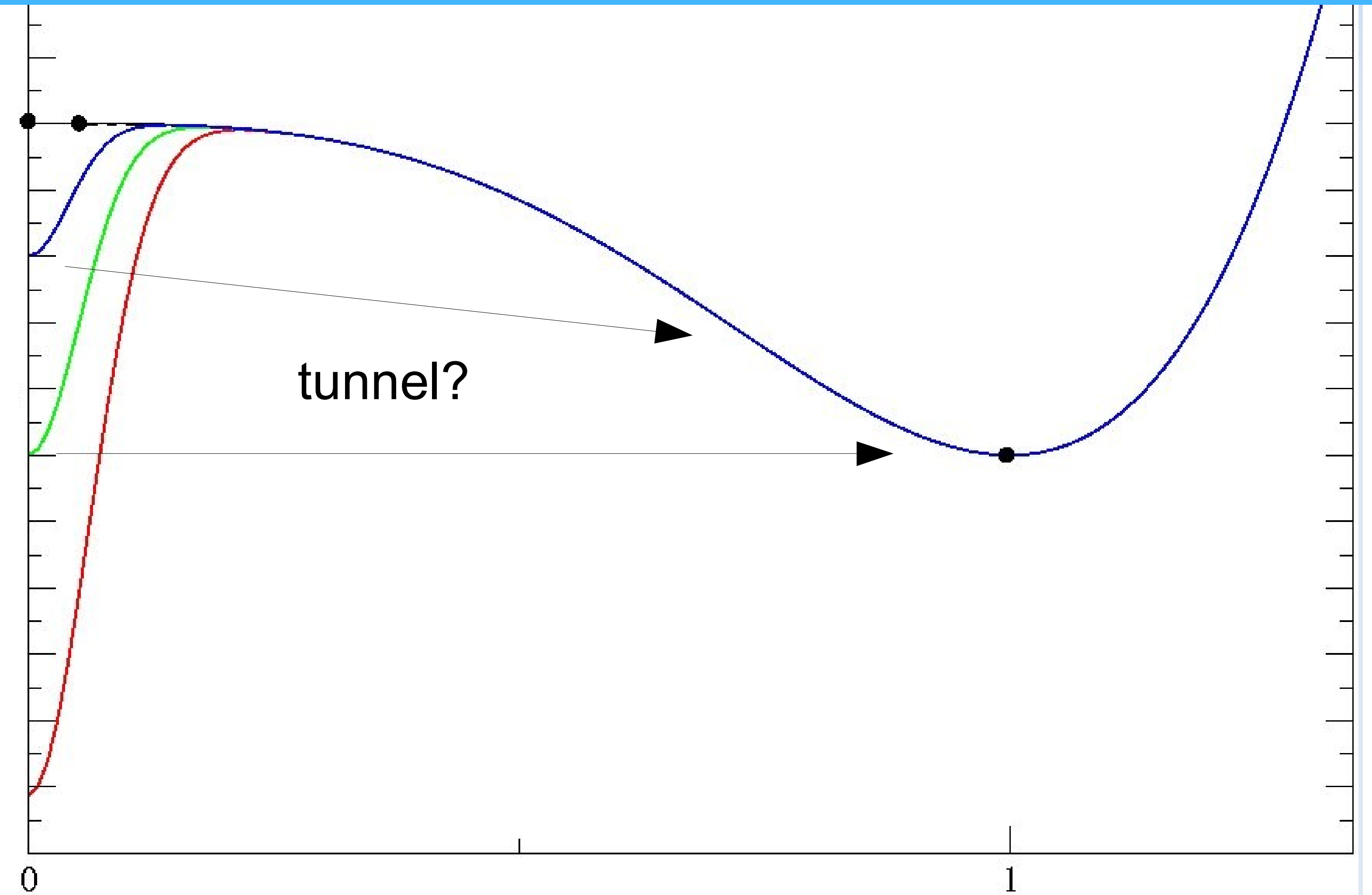
Strongly 1st order TeV scale confinement phase transition

Nearly-conformal potential with TeV minimum

+

large number of CFT states

supercooled confinement phase transition



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

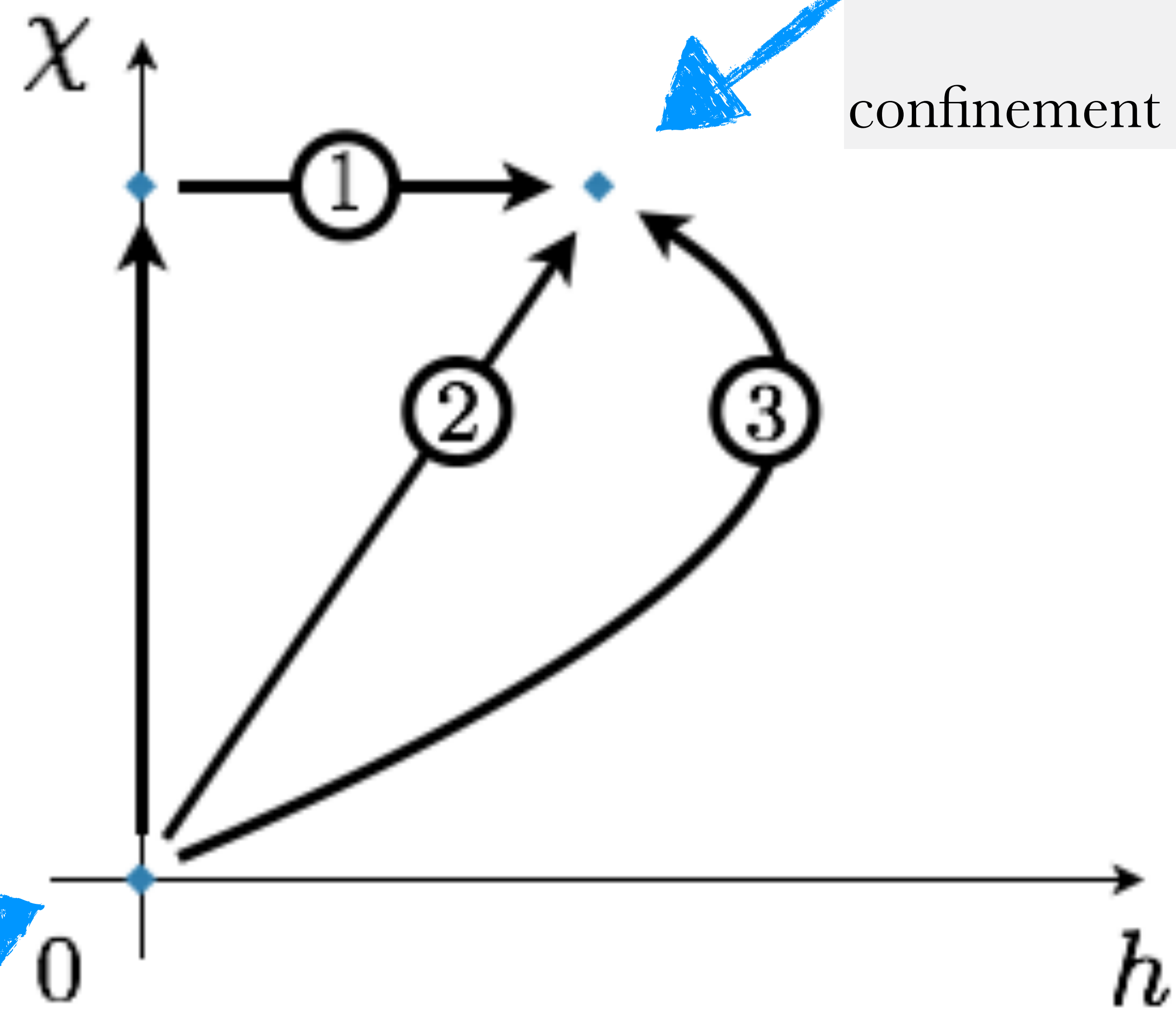
Impact on EW phase transition in Composite Higgs.

(1) SM-like EW phase transition

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

global minimum at
$T \ll f$

confinement and EWSB

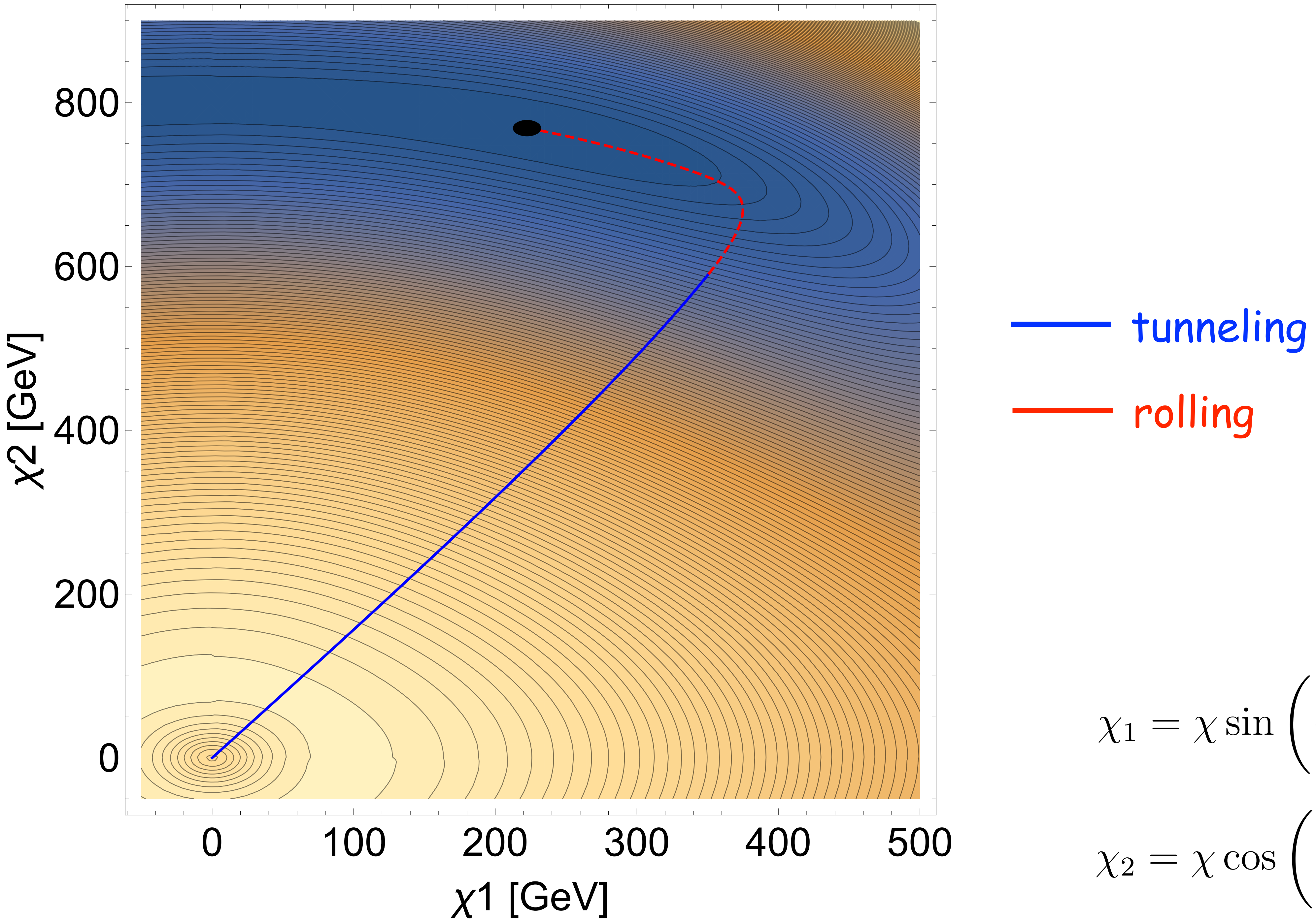


global minimum at
$T \gg f$

deconfined strong sector
unbroken EW symmetry

1804.07314

Which tunneling trajectory ?



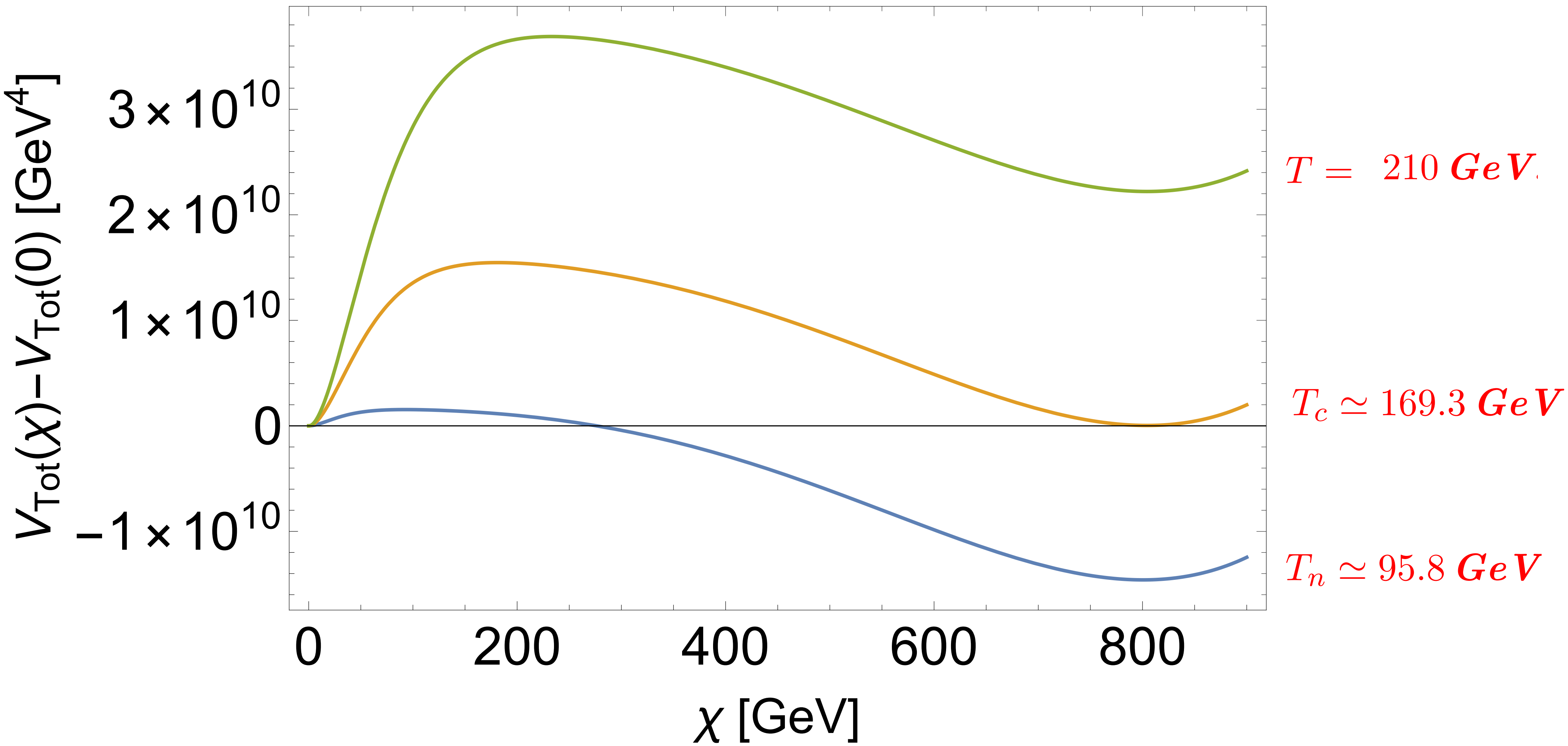
$$\chi_1 = \chi \sin\left(\frac{h}{\chi}\right)$$

$$\chi_2 = \chi \cos\left(\frac{h}{\chi}\right)$$

1804.07314

1st-order EW phase transition

Potential along the straight line trajectory:



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:

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

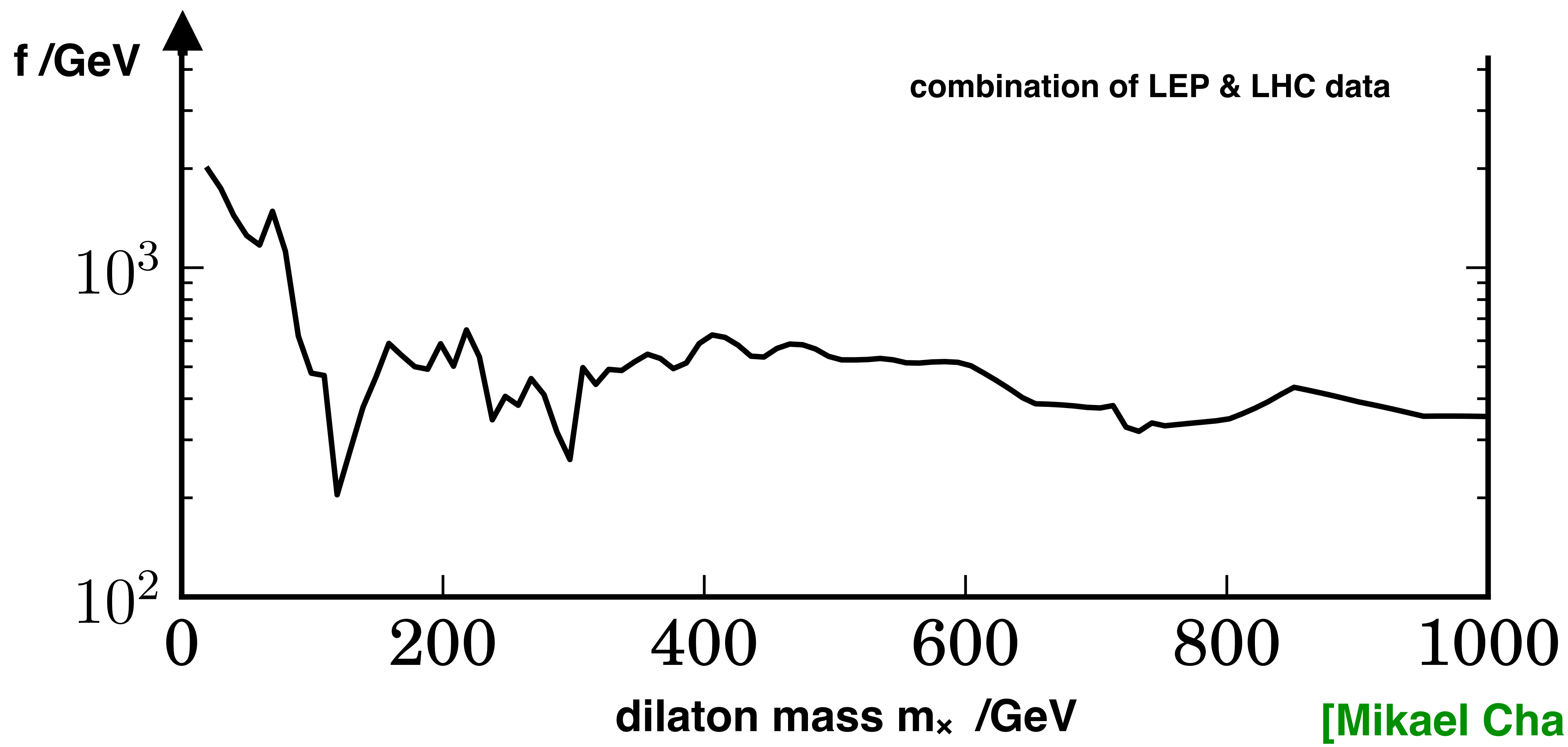
LIGHT DILATON

WINDOW <~ 700 GeV

Unavoidable? (see next...)

Collider bounds on dilaton

Higgs-like couplings suppressed by v/f

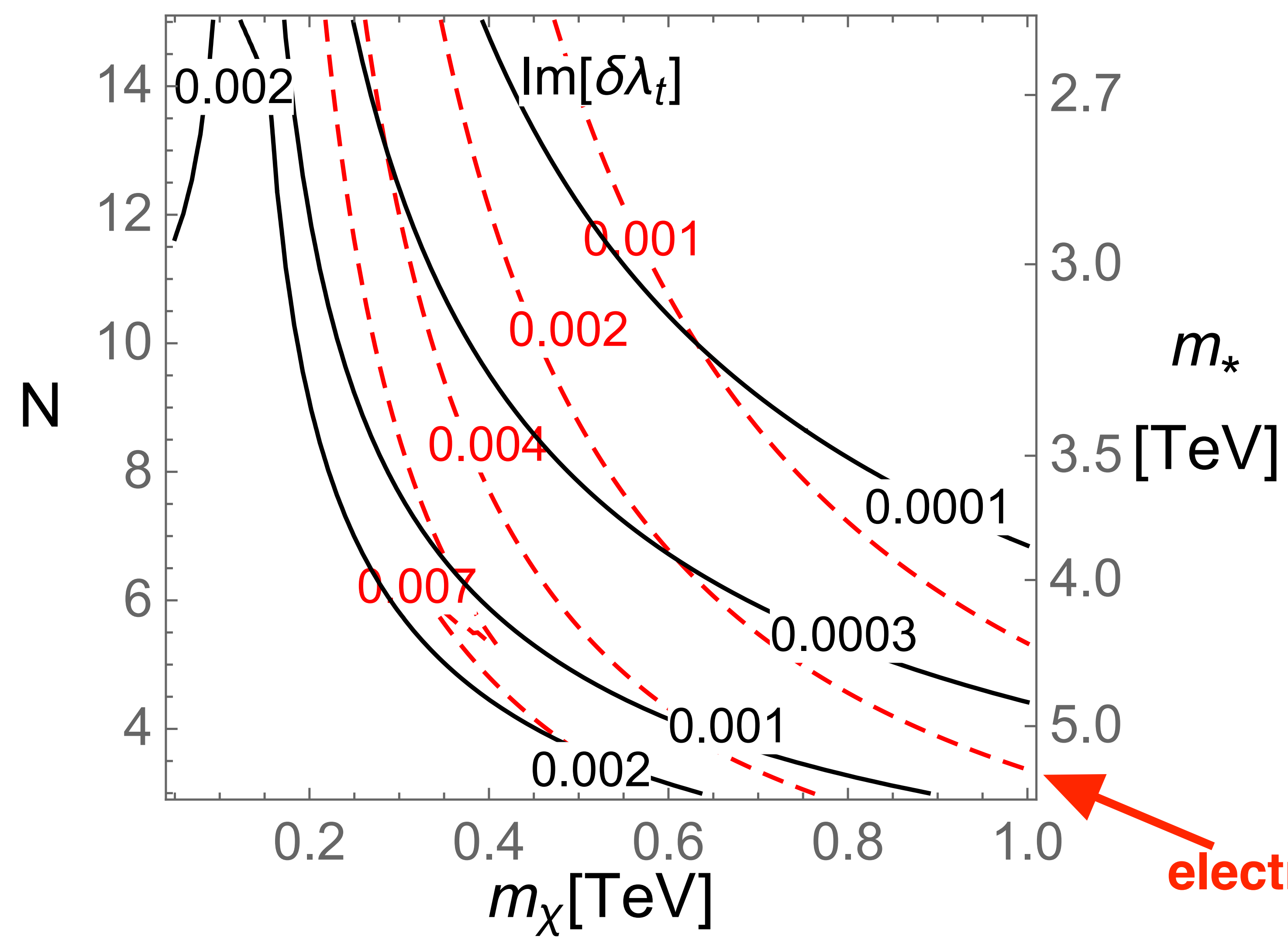


[Mikael Chala,
using HiggsBounds]

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

from Higgs-dilaton mixing

Imaginary part of correction to Top quark Yukawa



Number of colours in the new confining sector

generic mass of composite states

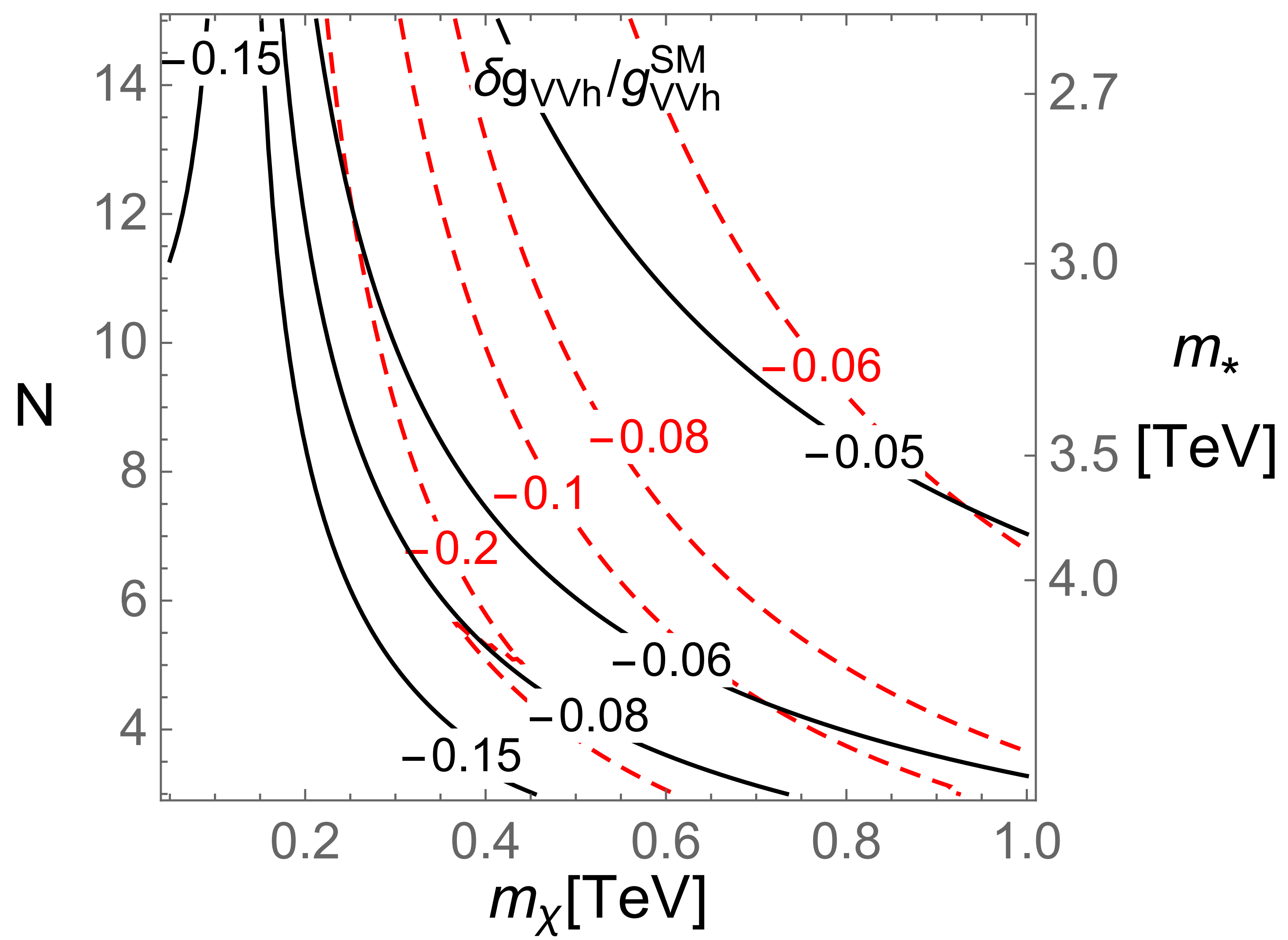
dilaton mass

electron EDM, ACME

1804.07314

Higgs coupling deviations to W and Z .

Number of colours in the new confining sector



generic mass of composite states

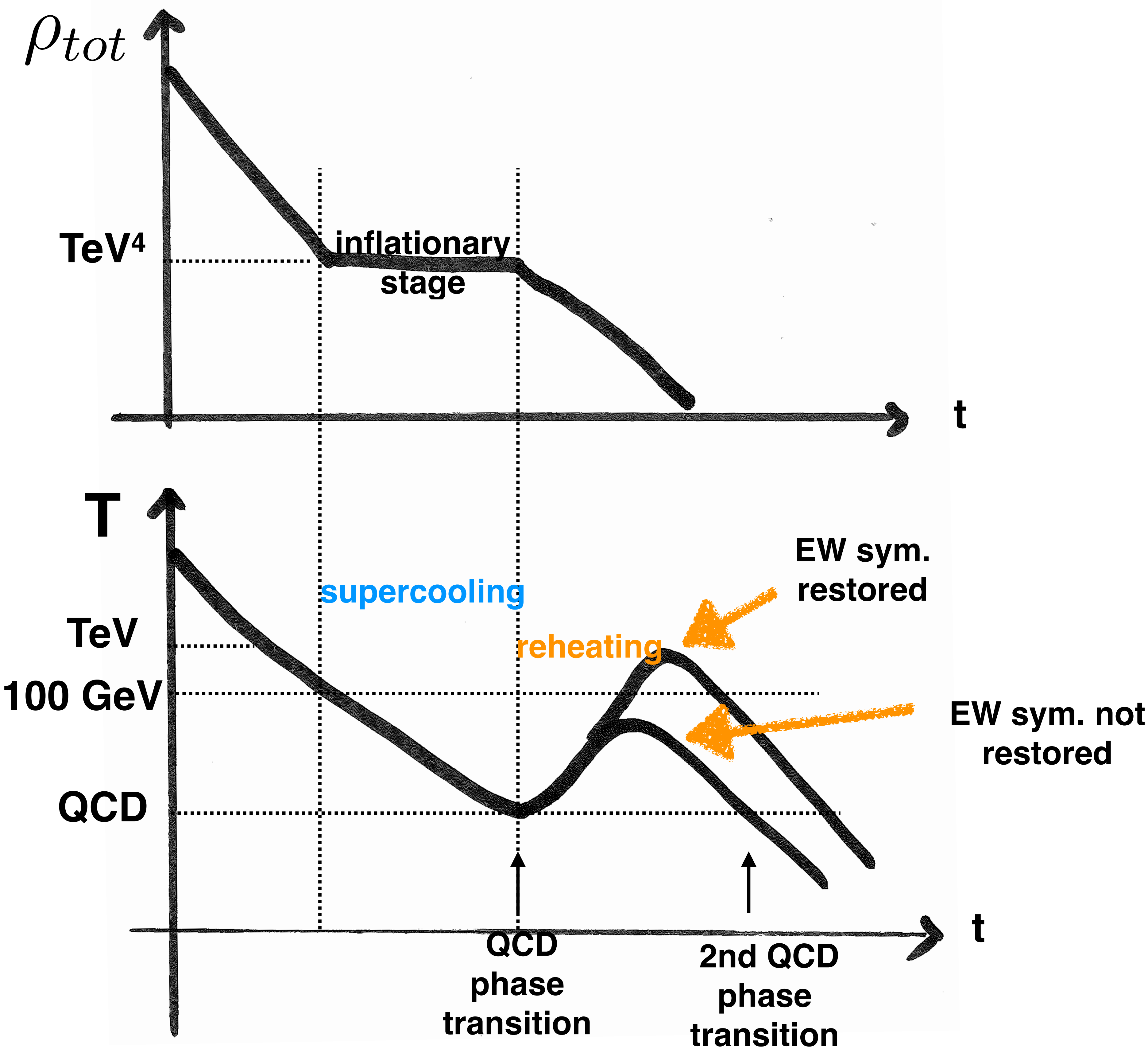
dilaton mass

1804.07314

-3-

Supercooled EW Phase transition down to QCD temperatures.

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

to appear

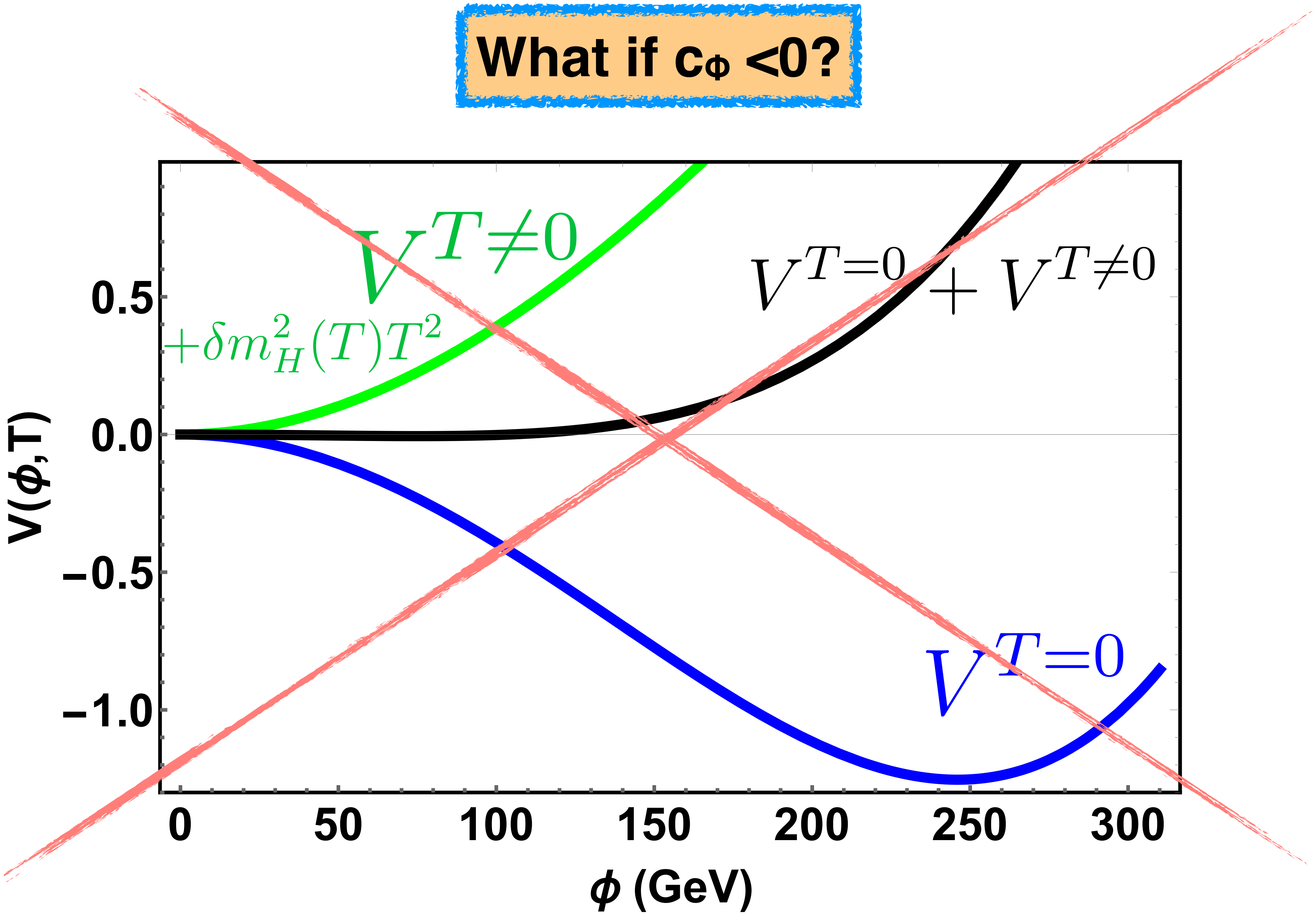
-4-

High-temperature EW symmetry non-restoration .

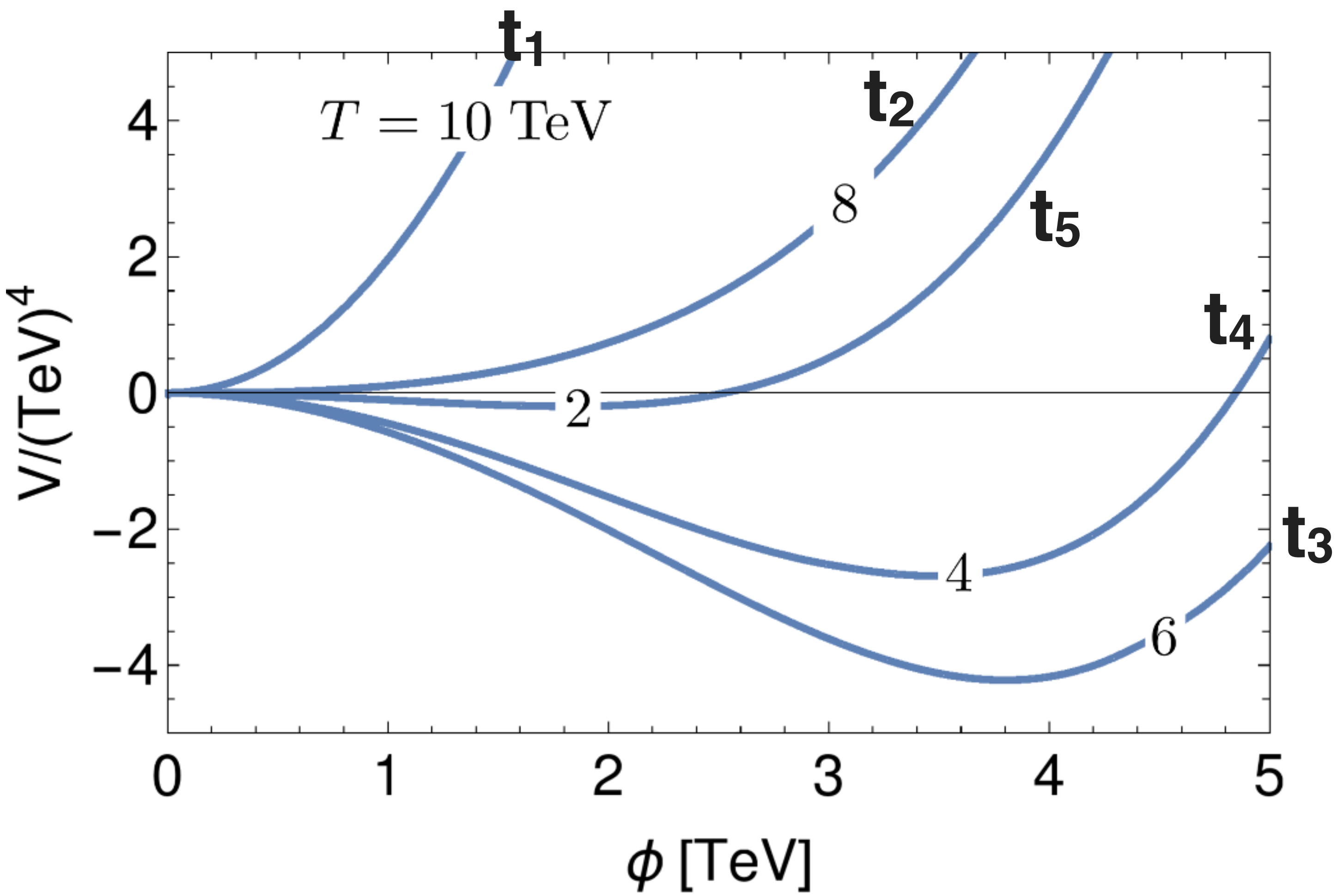
EW Symmetry restoration comes from the competition of two opposite terms in Higgs mass parameter

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

What if c_ϕ <0?



High-scale (T>TeV) EW phase transition .

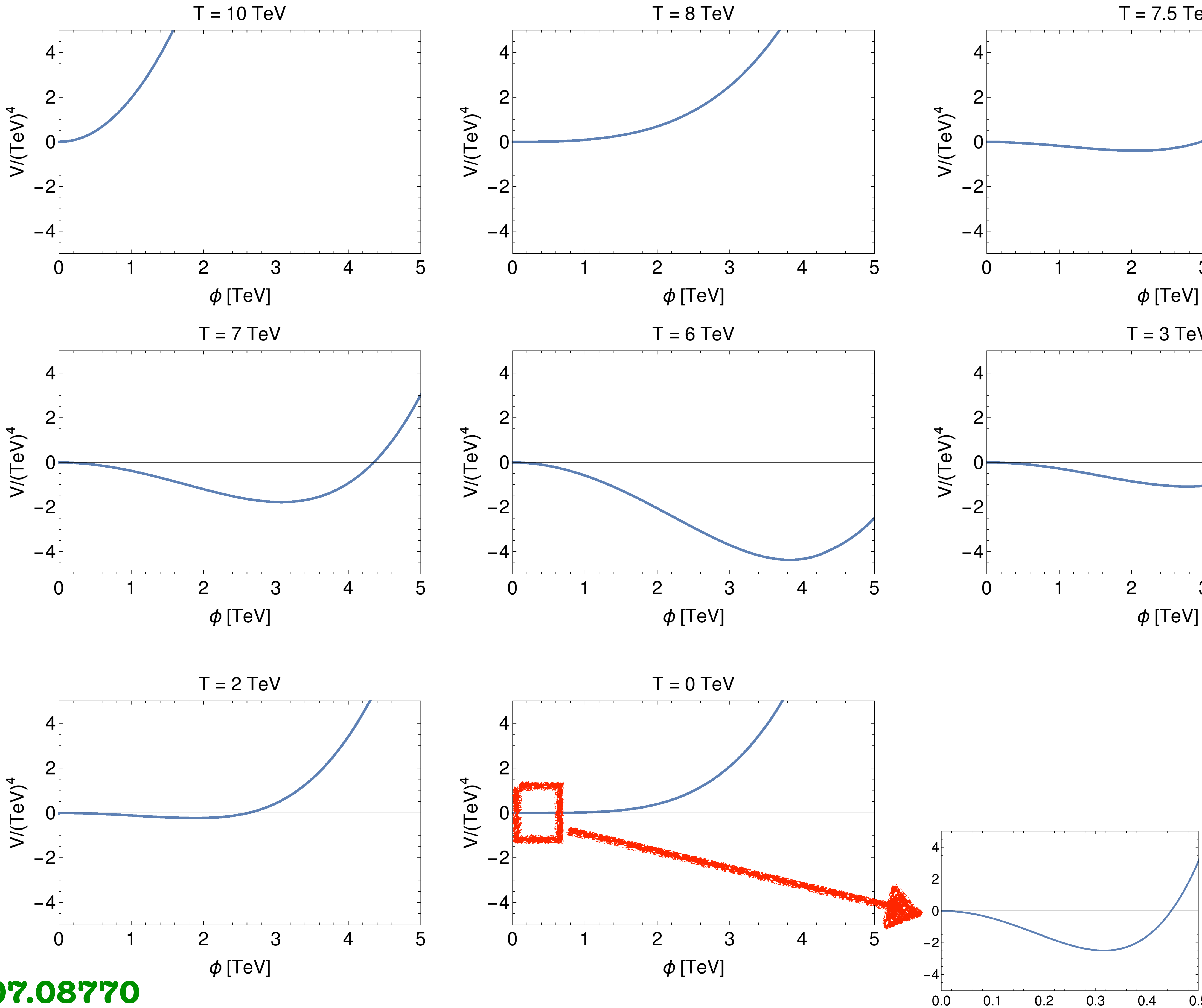


> **Motivation: EW baryogenesis using high-scale sources of CP violation, allowed by data !**

> **Prediction: Large number of new weak-scale (m<~300 GeV) scalars !**

Testable?...

High-scale (T>TeV) EW phase transition



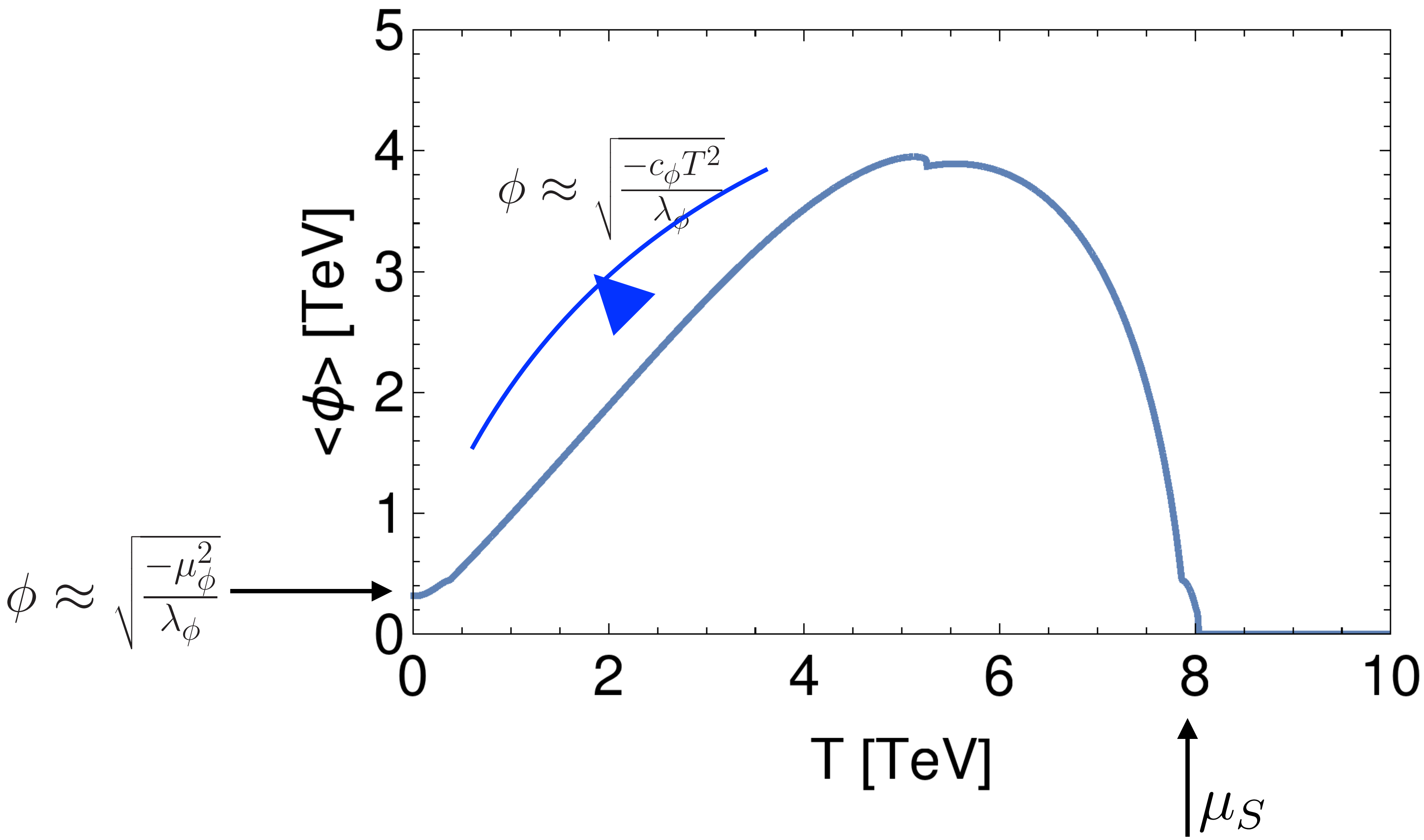
1807.08770

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!

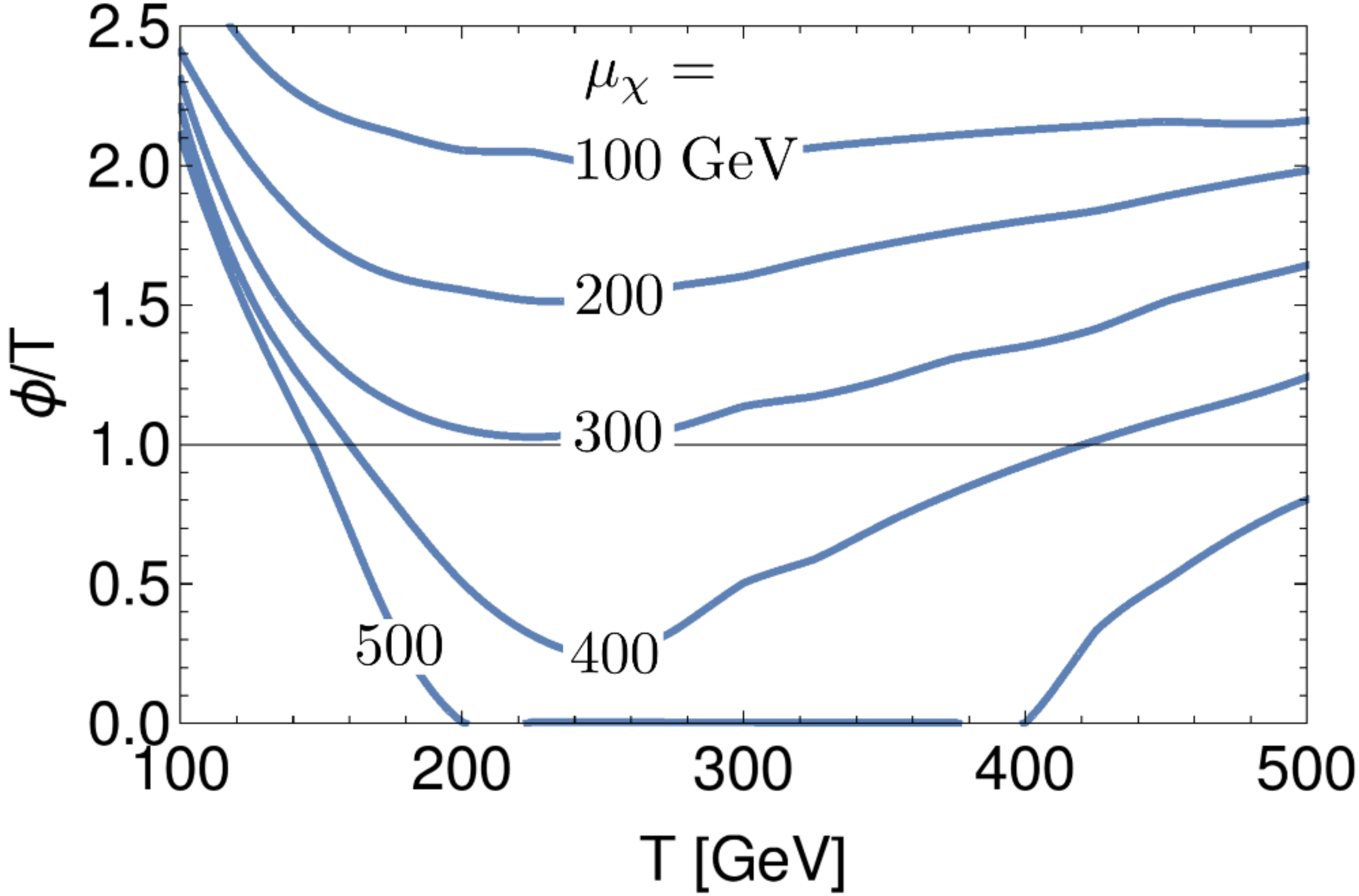


from negative Higgs cross-quartic coupling to large number of extra scalars χ

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

< 0

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



1807.08770

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

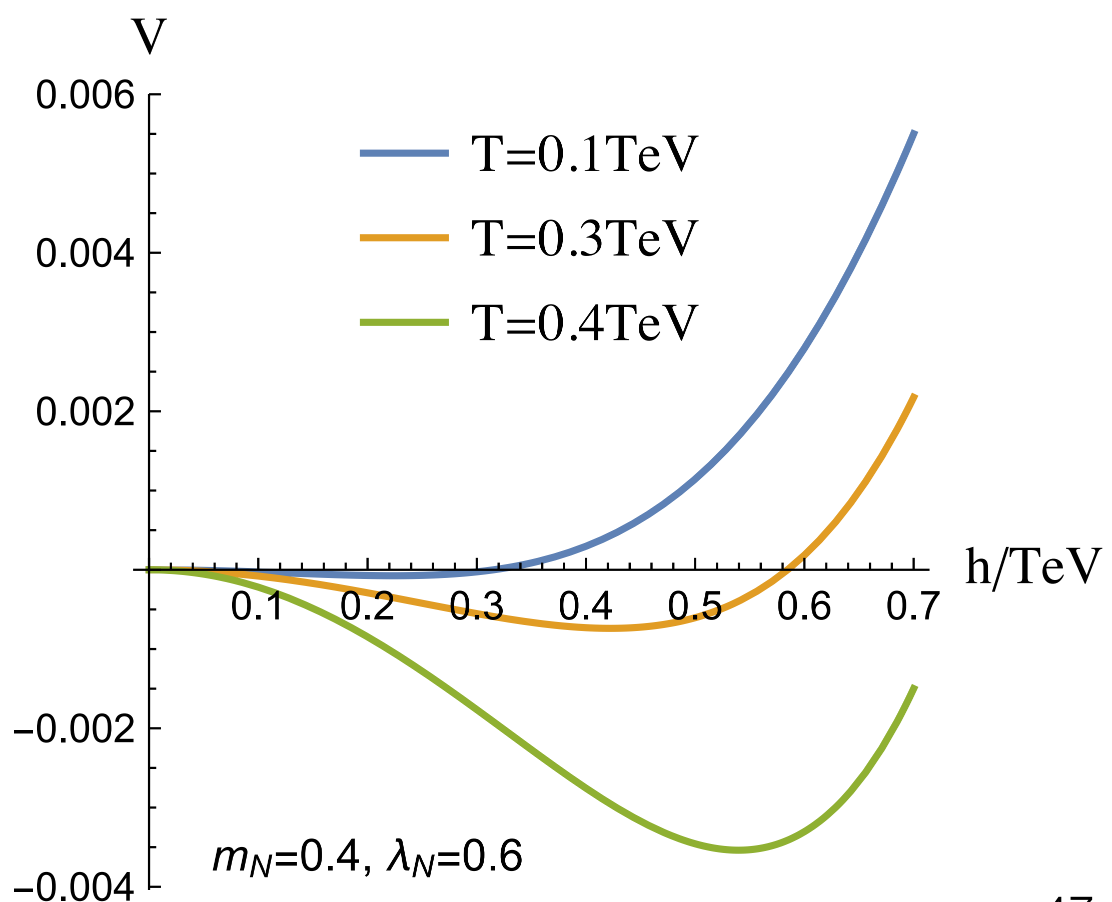
Add n new fermions N with Higgs-dependent mass contribution. Mass vanishes at <h>≠0

Matsedonskyi-Servant, to appear

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

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

Negative thermal mass



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

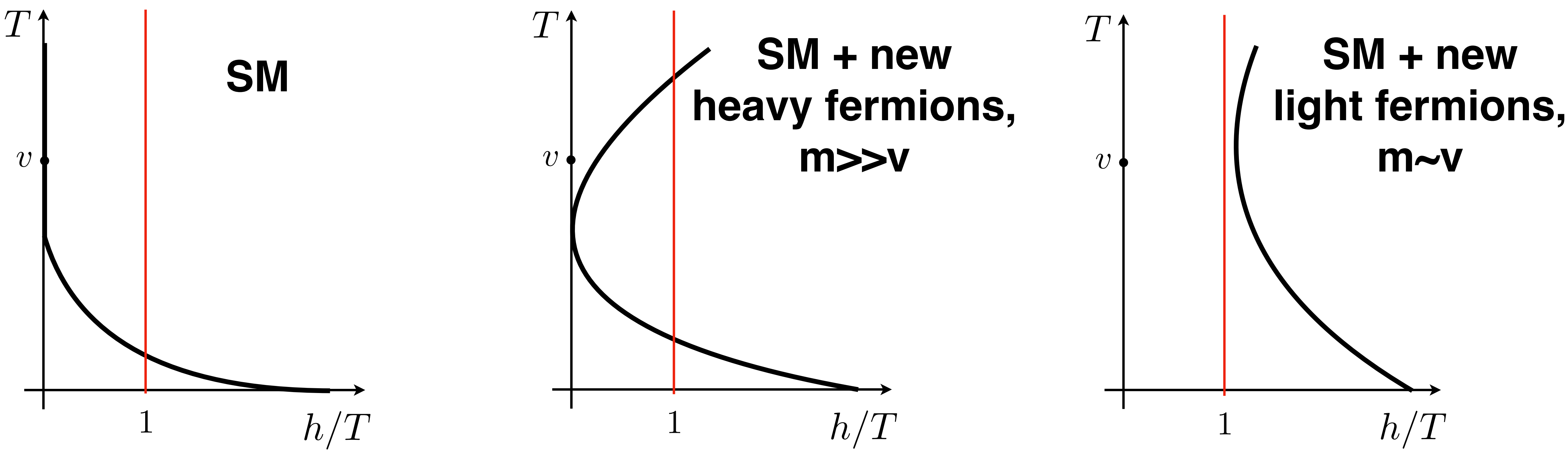
Why pushing up the temperature of the EW phase transition ?

> 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 !

Why pushing up the temperature of the EW phase transition ?



Matsedonskyi-Servant, to appear

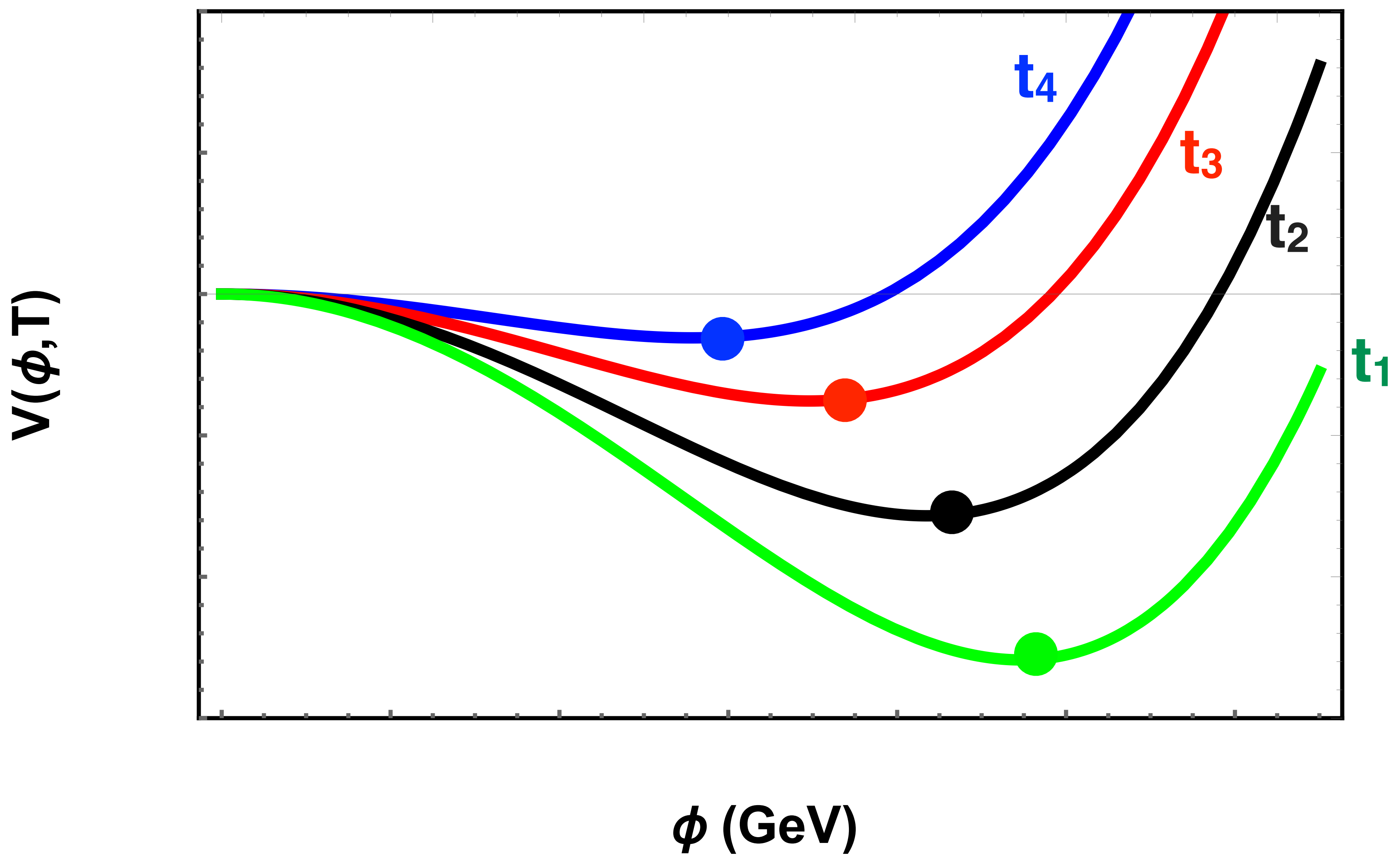
> Baryon asymmetry produced during higher T phase transition is never washed out !

EW symmetry: never-restored .

1807.07578

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

< 0, Negative thermal mass !



> No EW phase transition ! Baryogenesis without sphalerons ?

-5-

Cosmological relaxation of the EW scale .

Cosmological relaxation of the EW scale through Higgs-axion interplay.

1504.07551

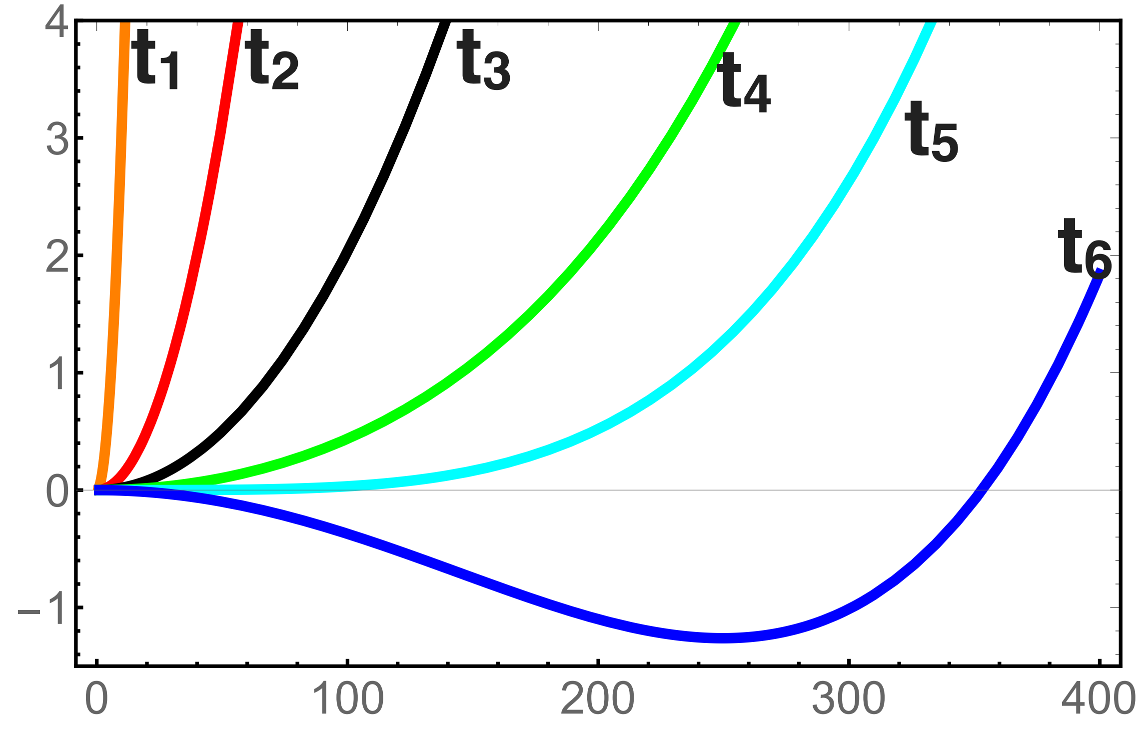
dynamical μ_H (not a temperature effect)

$$\mu_H^2 = \Lambda^2 - g\Lambda^3\phi$$

relaxion

> Start in symmetric phase

> Standard EWPT after relaxation (which is followed by reheating)



> Prediction: Very light relaxion !

Testable?...

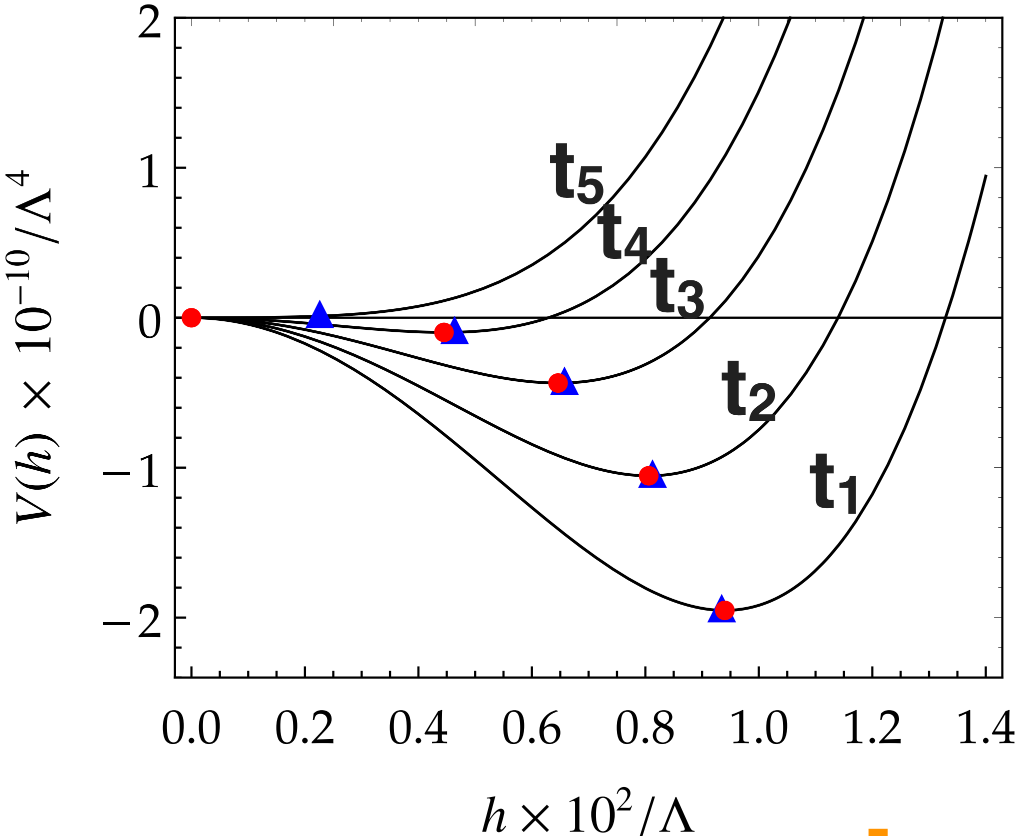
Cosmological relaxation of the EW scale a la Hook-Marques-Tavares .

1607.01786
1805.04543
1911.08473

$$\mu_H^2 = -\Lambda^2 + g\Lambda^3\phi$$

> Start in EW-broken phase at early times

> Restore EW symmetry due to reheating after relaxation

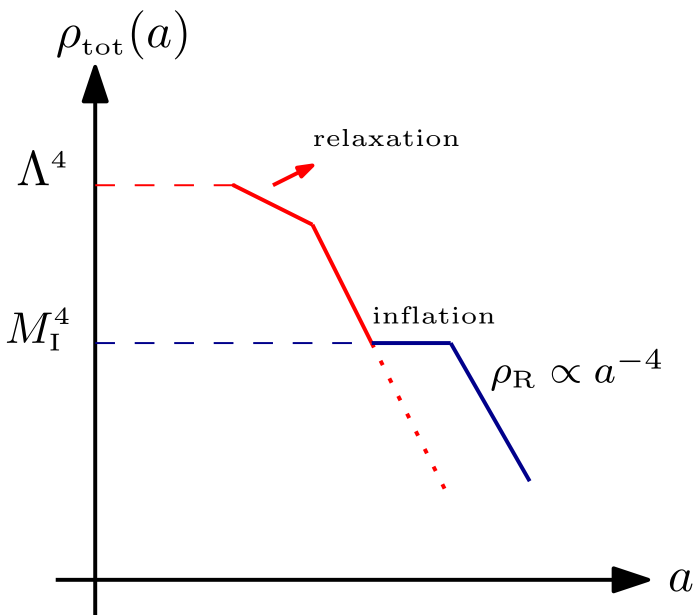


> Prediction: Very light relaxion !

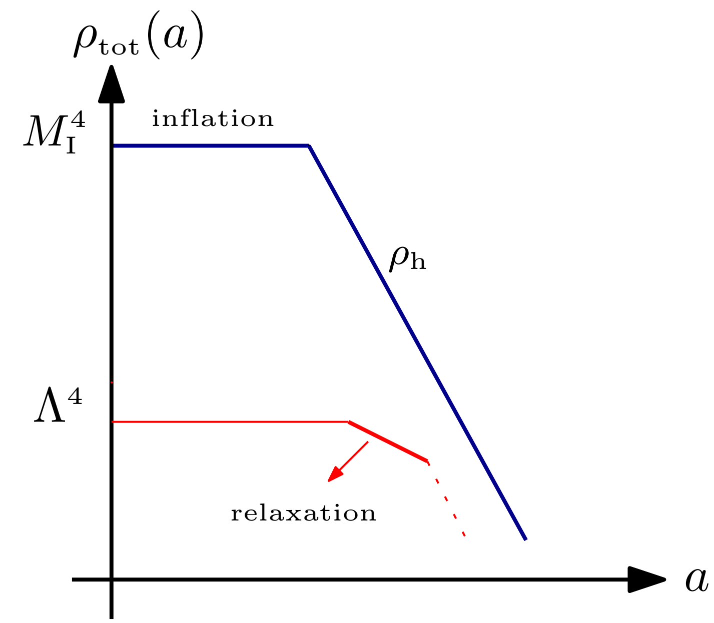
Testable?...

A whole set of different scenarios!

recent critical review:1911.08473

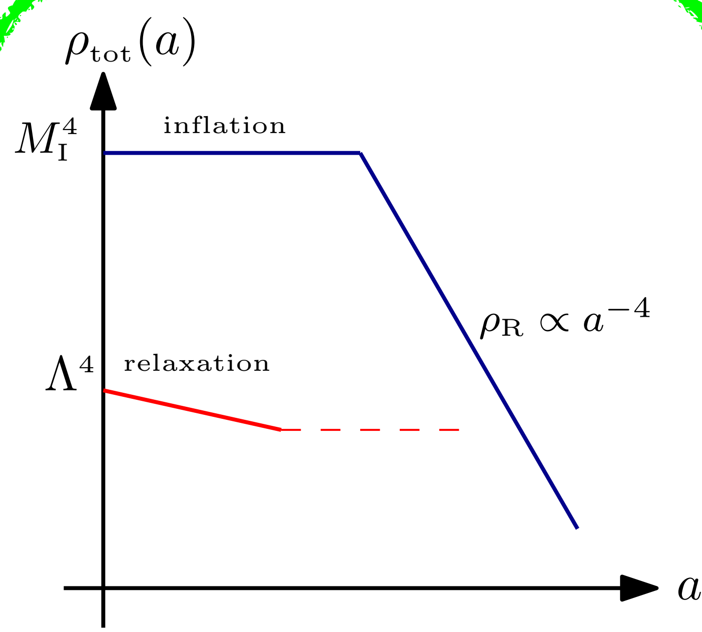


relaxation before inflation

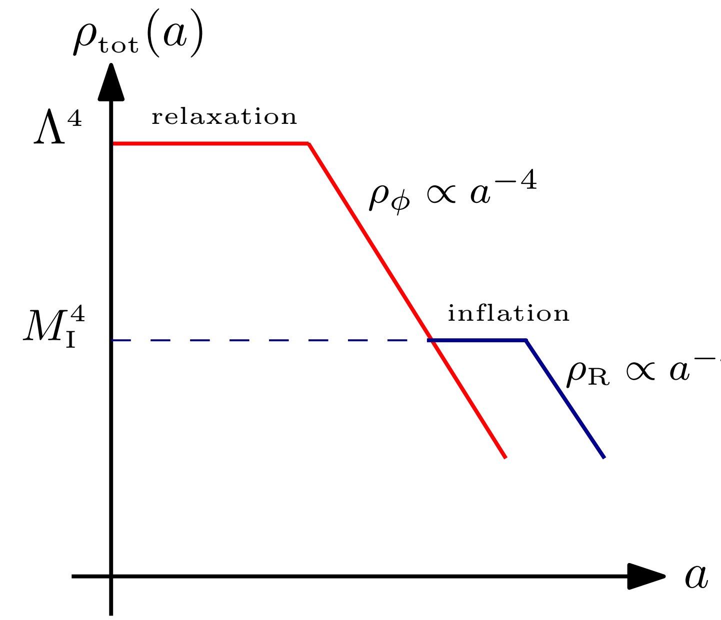


relaxation after inflation

Original proposal by Graham, Kaplan, Rajendan'15



relaxation during inflation



relaxation driving inflation

Conclusion .

It remains very open how EW symmetry got broken in early universe

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

supercooled EW phase transition: generic in Composite Higgs with light dilaton, rich pheno and cosmo.
Testable through light dilaton signatures

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

Remaining options:

- Top transport may remain open only in composite Higgs.
- $\cancel{CP}$ in hidden sector, e.g. new leptons
- EW phase transition occurring at high temperatures >> 100 GeV, via large number of new O(few100 GeV) singlet scalars or singlet fermions.

- **Broken EW sym. at early times may happen in models of EW scale cosmological relaxation (not a temperature effect) although followed by SM-like EW phase transition**

Associated predictions: light weakly coupled relaxion.
Testable signatures: not yet clear, work in progress.

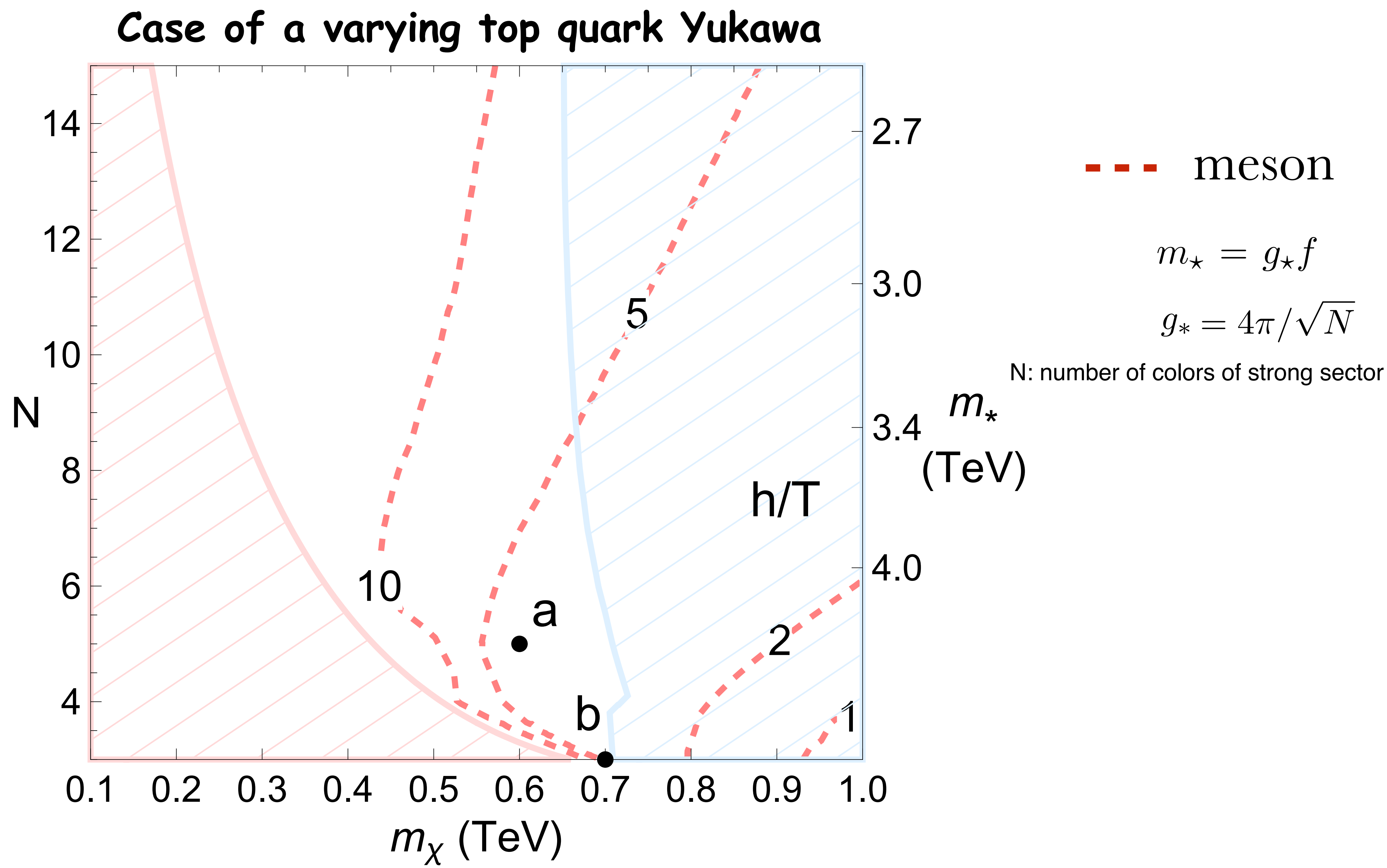
Conclusion .

It remains very open how EW symmetry got broken in early universe

Probing the EW phase transition will keep us busy for the next 2 decades through complementarity of studies in theory, lattice, experiments in Colliders, EDMs, gravitational waves, cosmology, axions.

Annexes .

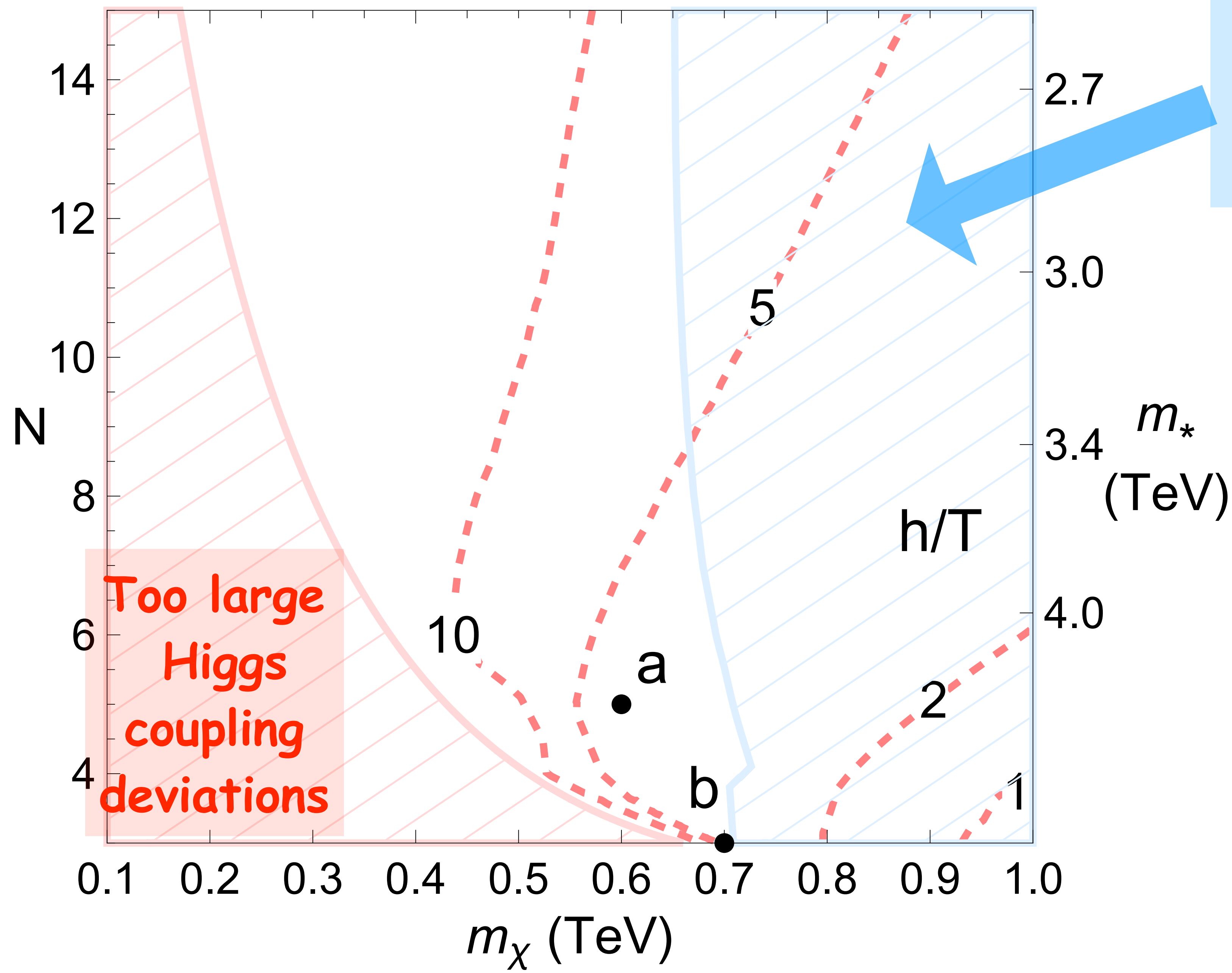
Strength of EW phase transition



~light dilaton generically needed

$\rightarrow$ direct searches+Higgs physics

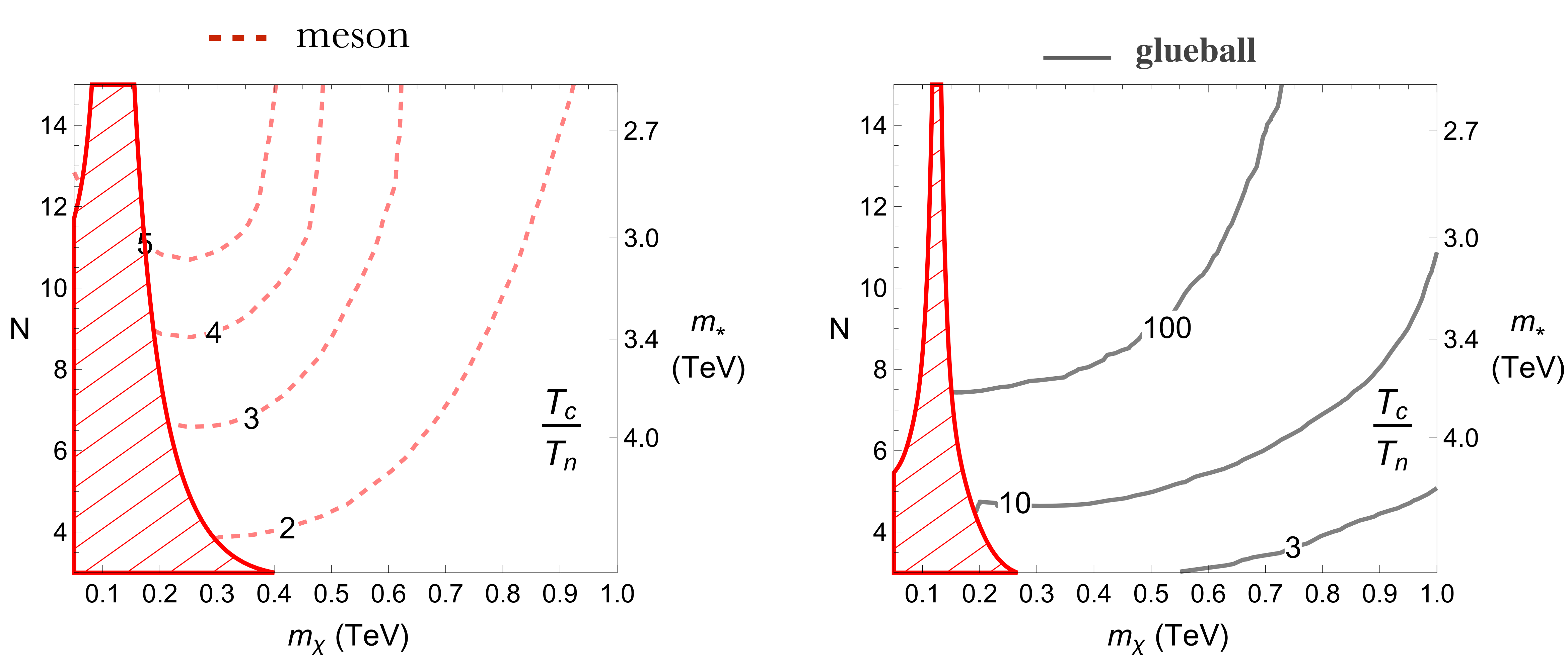
Constraints from reheating



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

LIGHT DILATON WINDOW<~ 700 GeV

Amount of supercooling in Composite Higgs



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 !**