TOP QUARK COSMOLOGY.

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Universität Hamburg

The Top Quark:
To-date heaviest fundamental particle.

Central role in the exploration of the Higgs sector.

Broad program of top-quark measurements at the LHC, at the HL-LHC and at future colliders.

Unique phenomenology: The top quark decays before it hadronizes & the information about its spin state is preserved in distributions of top-quark decay products.

Top-quark mass: a key ingredient in Electroweak (EW) precision and QCD calculations.

Top-quark couplings to Standard-Model (SM) bosons and top-quark final states are sensitive to Beyond-the-Standard-Model (BSM) particles

The Top Quark:
Directly connected to the important questions at the energy frontier.

- Origin of the Higgs potential and of the weak scale
- What keeps the Higgs light?
- Origin of the flavour structure
- What caused the primordial cosmological inflation?
- Nature of Dark Matter
- How was the matter-antimatter asymmetry produced?
- Why is CP not violated in strong interactions?

On many of these questions, the top quark has something to say

Many of these questions are related to physics in the early universe

This talk: The Top Quark & Cosmology.

1- The top quark and the metastability of the electroweak vacuum

2- The top quark and inflation

3- The top quark and dark matter

4- The top quark and the electroweak phase transition

5- The top quark and the cosmological solutions to the hierarchy problem (Relaxion)

6- The top quark and electroweak baryogenesis

7- The top quark in composite Higgs cosmology

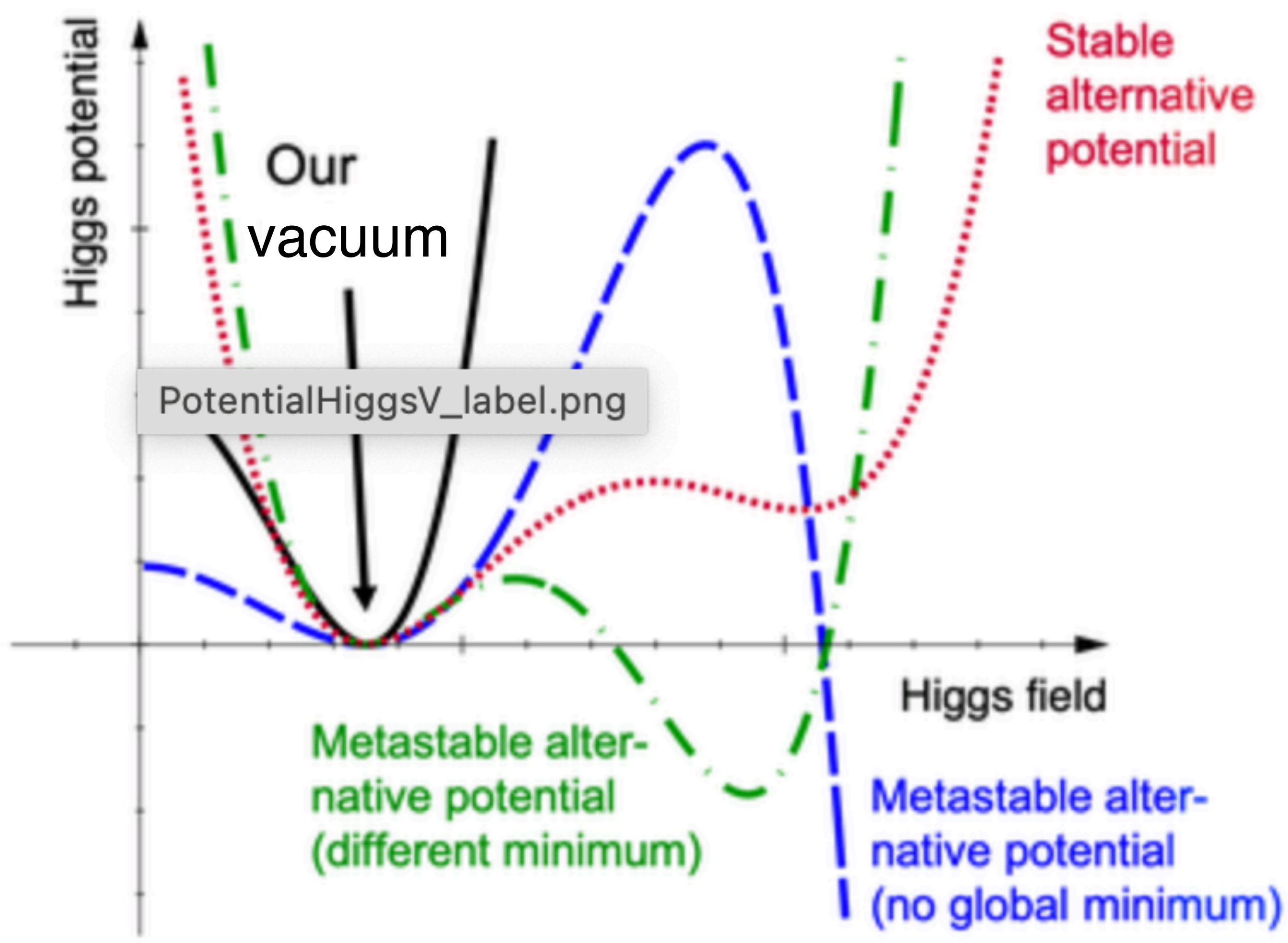
} Emphasis of this talk

1- The Top Quark & the Metastability of the EW vacuum .

See Thursday morning session on SM vacuum stability

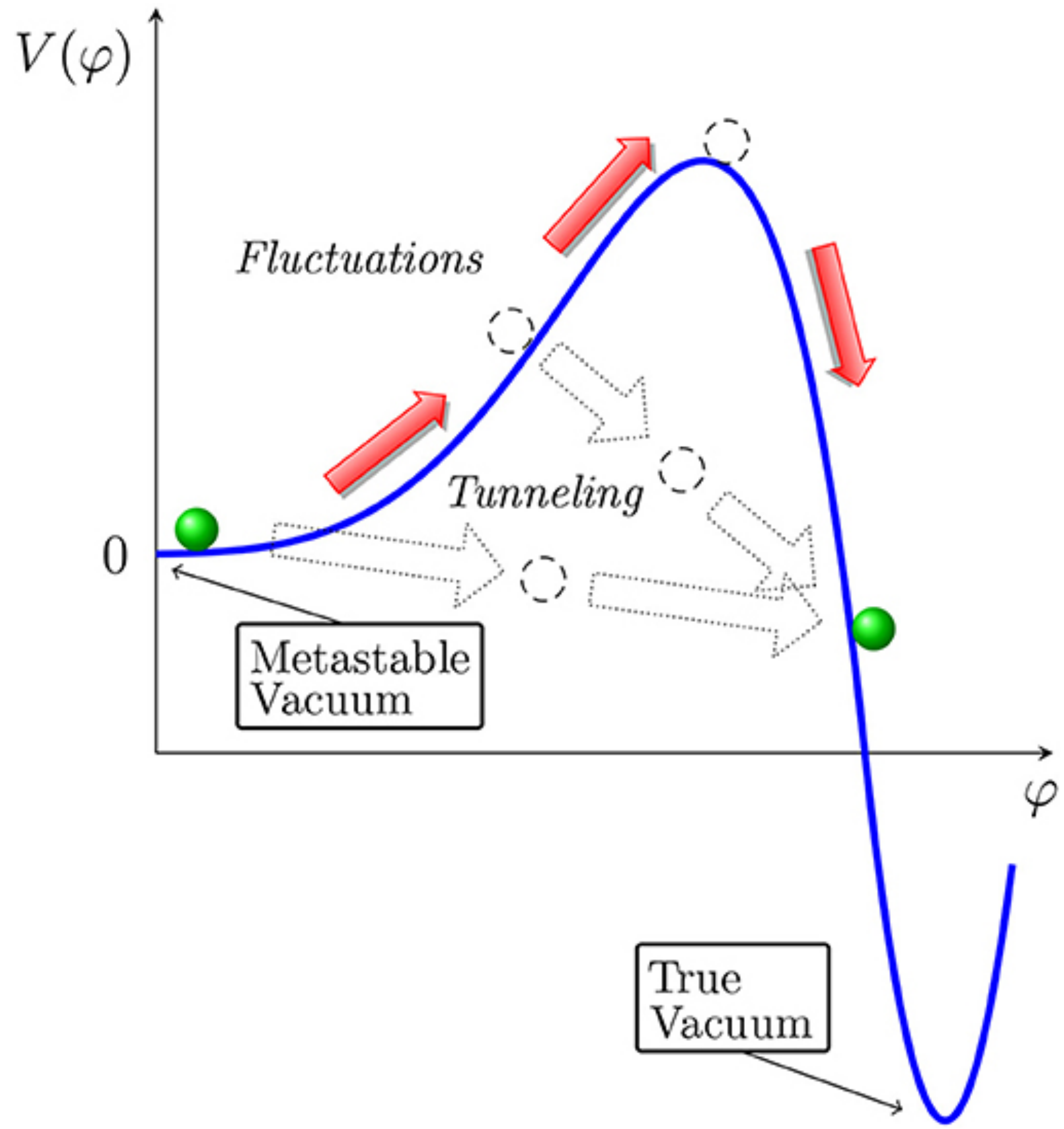
Metastability of the electroweak vacuum.

In the Standard Model, there is the possibility of having a second minimum of the Higgs potential at high energies.



Experimental data suggest that the electroweak vacuum is likely to be metastable rather than stable.

Metastability of the electroweak vacuum.



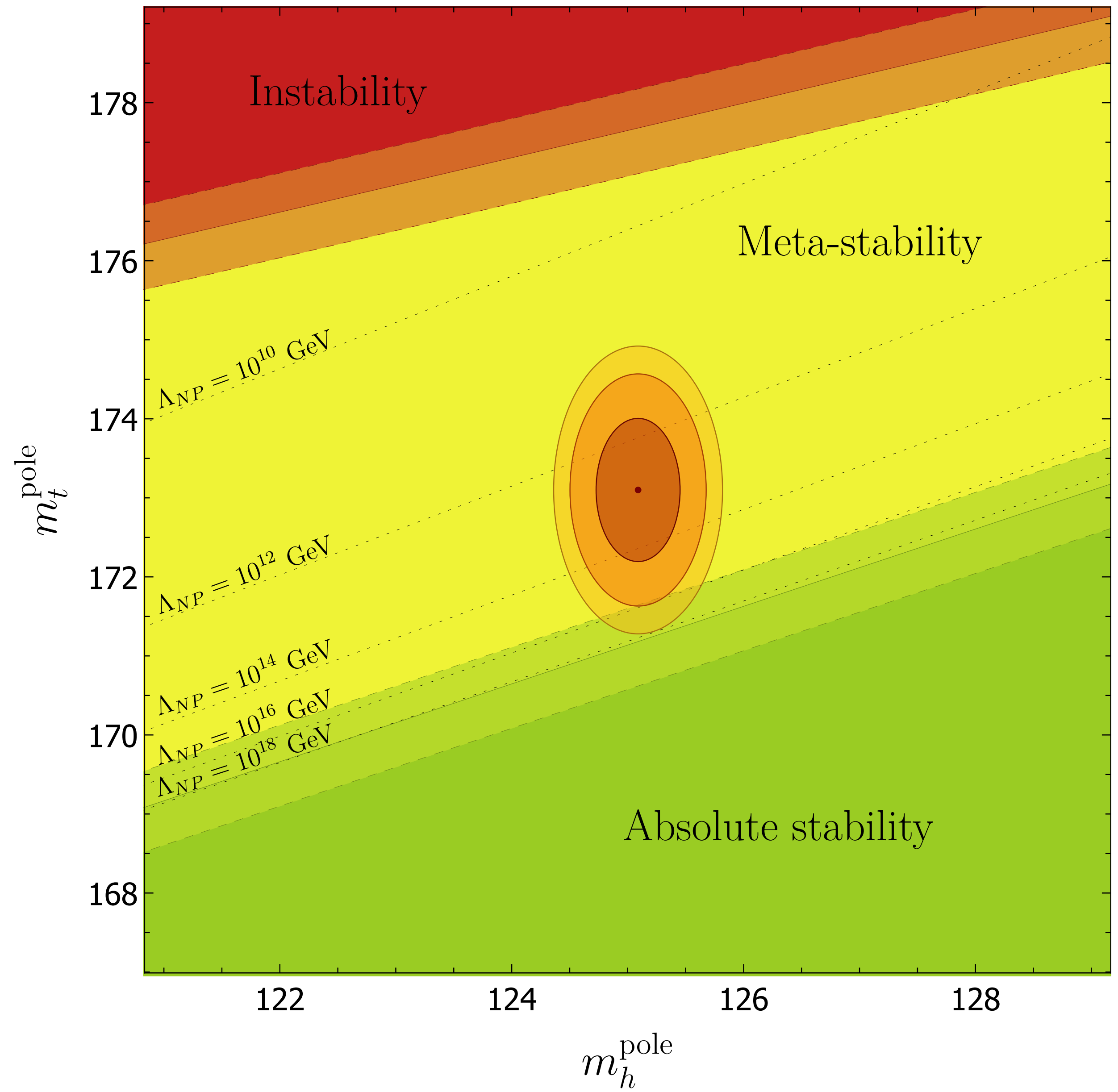
Markkanen, Rajantie, Stopyra

The vacuum can decay through quantum tunneling or classically over the barrier. In both cases, the transition happens initially locally in a small volume, nucleating a small bubble of the true vacuum.

The bubble then starts to expand, reaching the speed of light very quickly, any destroying everything in its way.

Metastability of the electroweak vacuum.

Lifetime of our universe: $\tau_{\rm SM} = 10^{161^{+160}_{-59}}$ **years**



Dotted lines indicate the scale at which the addition of higher--dimension operators could stabilize the SM

Andreassen, Frost, Schwartz

1707.08124v4

The uncertainty is part experimental uncertainty on the top quark mass and on α_S and part theory uncertainty from electroweak threshold corrections.

To rule out absolute stability to 3σ confidence, the uncertainty on the top quark pole mass would have to be pushed below 250 MeV or the uncertainty on $\alpha_S(m_Z)$ pushed below 0.00025.

Metastability of the electroweak vacuum.

The bubbles of a decaying universe expand at the speed of light: If we saw such a bubble, we would have been destroyed by it.

The probability that we should have seen a bubble of decaying universe by now is

$$P = 10^{-606^{-638}_{+239}}$$

Reassuring!

The fact that we still observe the Universe in its EW vacuum state allows us to place constraints on the cosmological history, for example the reheat temperature and the scale of inflation, and on Standard Model parameters, such as particle masses and the coupling between the Higgs field and spacetime curvature.

2- The Top Quark & Higgs Inflation

See Thursday morning session on SM vacuum stability

Higgs Inflation.

For the Higgs field to play the role of the inflaton, a region where the Higgs potential becomes sufficiently flat for large enough values of the Higgs field is required to meet the slow-roll conditions.

This can be achieved if the Higgs is non-minimally coupled to gravity, by introducing a coupling ξ between the Higgs field and the gravitational curvature scalar

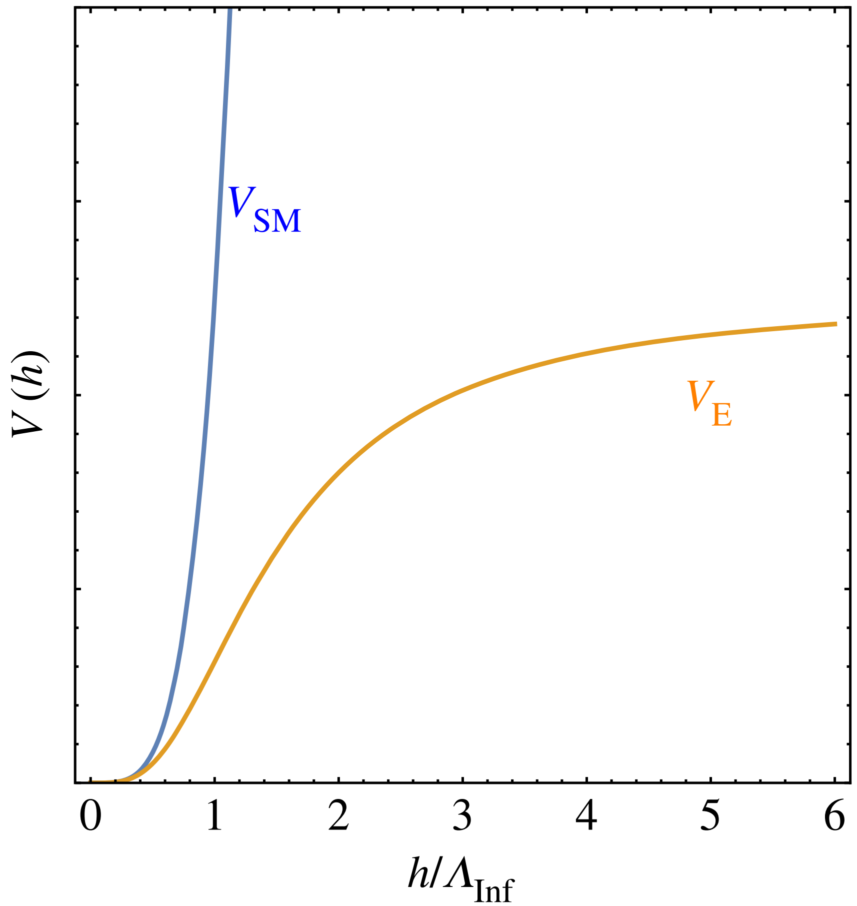
$$S = \int \mathrm{d}^4x \sqrt{-g}\left[-\frac{1}{2}m_{\mathrm{P}}^2 R + \xi |H|^2 R + \mathcal{L}_{\mathrm{SM}}\right],$$

$m_{\mathrm{P}} = 2.44 \times 10^{18}\,\mathrm{GeV}$ **: reduced Planck scale**

Higgs Inflation.

Make a rescaling of the metric to go to the Einstein frame where the Planck mass is field- independent. In this frame:

$$V_E(h) = e^{-2\sigma} V_J(h) = \frac{V_{SM}(h)}{(1 + \xi h^2/m_P^2)^2},$$



The Einstein potential develops a plateau at $h \gtrsim \Lambda_{Inf} \equiv m_P/\sqrt{\xi}$.

Promising for inflation?

Not if an instability is developed below

$$\Lambda_{Inf} \equiv m_P/\sqrt{\xi}$$

To get the right amount of scalar perturbations as required by Cosmic Microwave Background observations: $\xi \simeq 10^3, 10^4$

Higgs Inflation.

Like any other non-renormalizable effective theory, the SM with a non-minimally coupled Higgs scalar comes equipped with a cut-off scale Λ beyond which the effective theory description breaks down (breaking of perturbative unitarity)

Problem:

The cut-off scale is smaller than the scale at which the plateau develops:

$$\Lambda \equiv \frac{m_{\rm P}}{\xi} \ll \Lambda_{\rm Inf} \equiv \frac{m_{\rm P}}{\sqrt{\xi}},$$

—> existence of the plateau is questionable as it appears beyond the range of validity of the effective theory.

No-go conjecture for Higgs inflation (Barbón, Casas, Elias-Miró, Espinosa 2015):

Any UV completion of Higgs inflation that restores unitarity up to the Planck scale requires introducing a scalar field* ϕ beyond the Higgs *that ends up being the inflaton field.

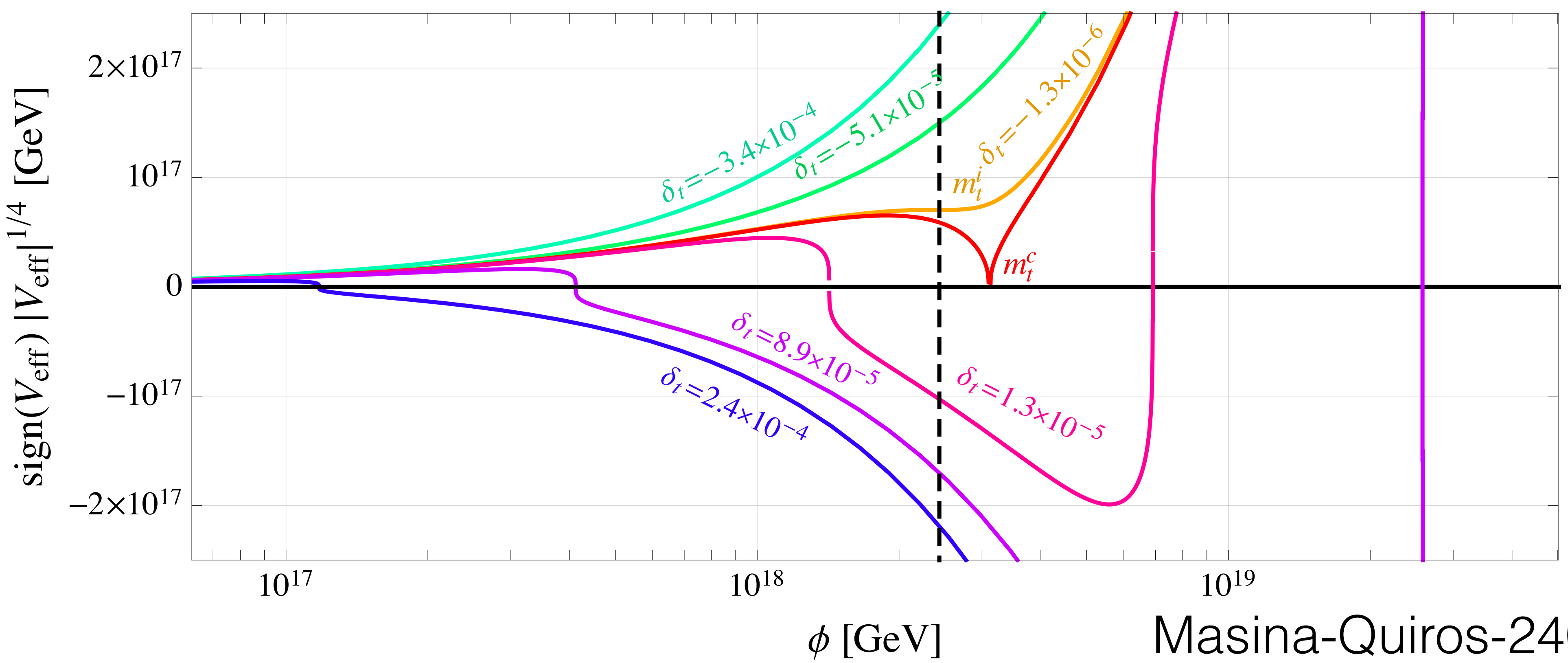
See however talk by Isabella Masina on Thursday

Higgs Inflation.

The important role of the top quark

Possible shapes of the High potential, for increasing values of the top mass,

$m_t = m^c_t\,(1 + \delta_t)$, $m^c_t \simeq 171.0588$ GeV



Masina-Quiros-2403.02461

Viability of Higgs inflation depends on future experimental measurements of the top quark mass and the strong coupling constant.

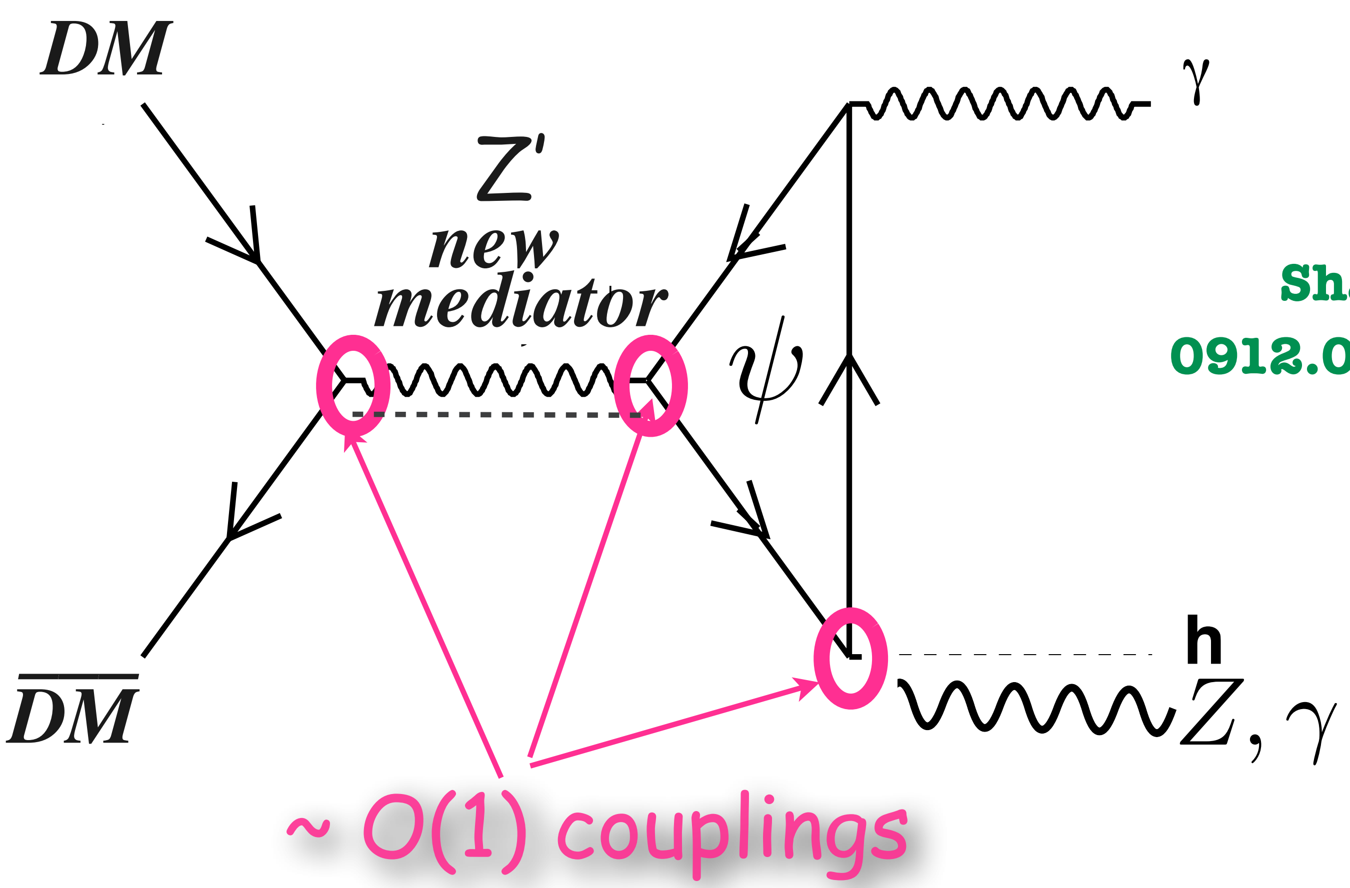
3- The Top Quark and Dark Matter .

A Top-philic Dark Matter example

Large Gamma-ray lines from top-philic dark sectors.

DM=Dark Matter

- *DM almost decouples from light SM particles while having large couplings to new heavy particles* ψ *(say top fermonic partners, motivated in Composite Higgs models)*
- *M_{DM} <* M_ψ *: tree level annihilations kinematically forbidden today (DM has small velocity in our galaxy today v/c~ 10^{-3}) but allowed in the early universe (v/c~ 10^{-1}).*
- *Virtual* ψ *close to threshold can significantly enhance loop processes producing monochromatic photons.*



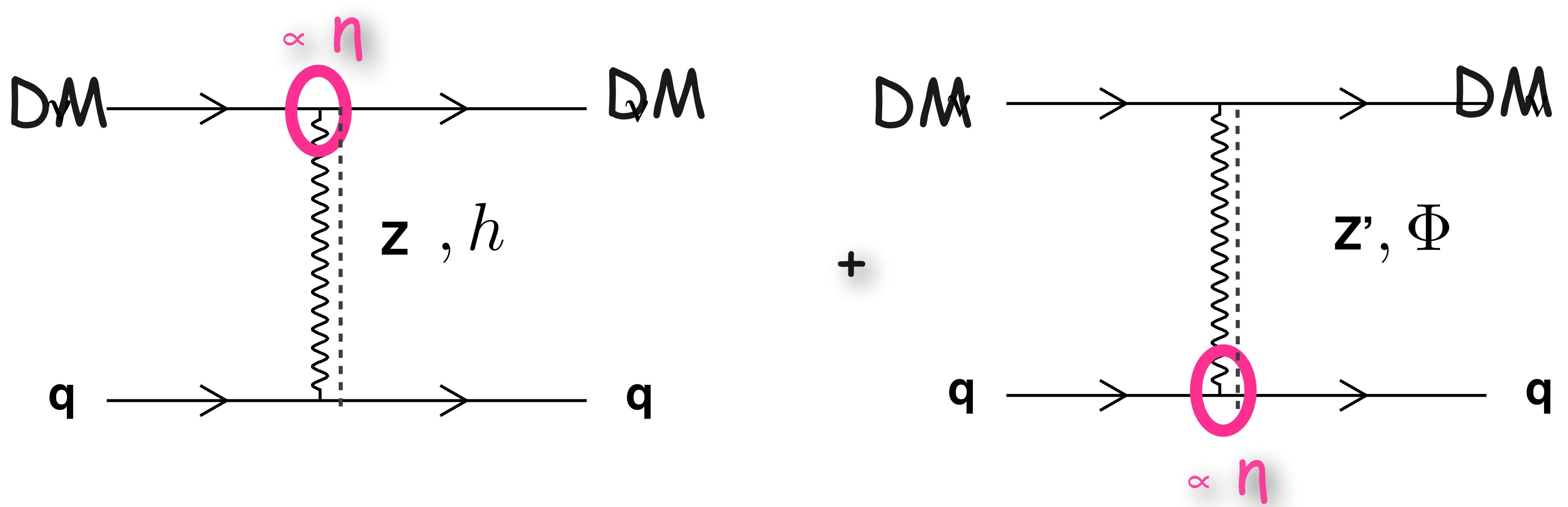
Jackson, Servant, Shaughnessy, Tait, Taoso,'09
0912.0004, 1302.1802,1303.4717

Advantage: elastic scattering and annihilations disconnected

0912.0004

a counter example to the simple relations derived in the effective field theory approach

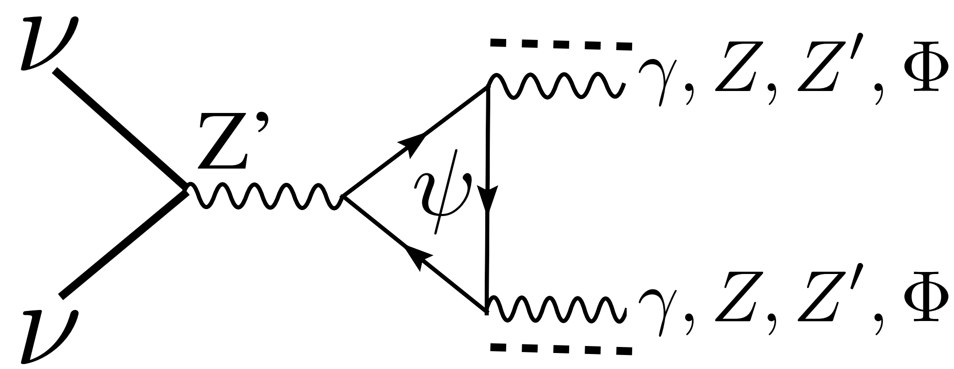
Direct detection constraints



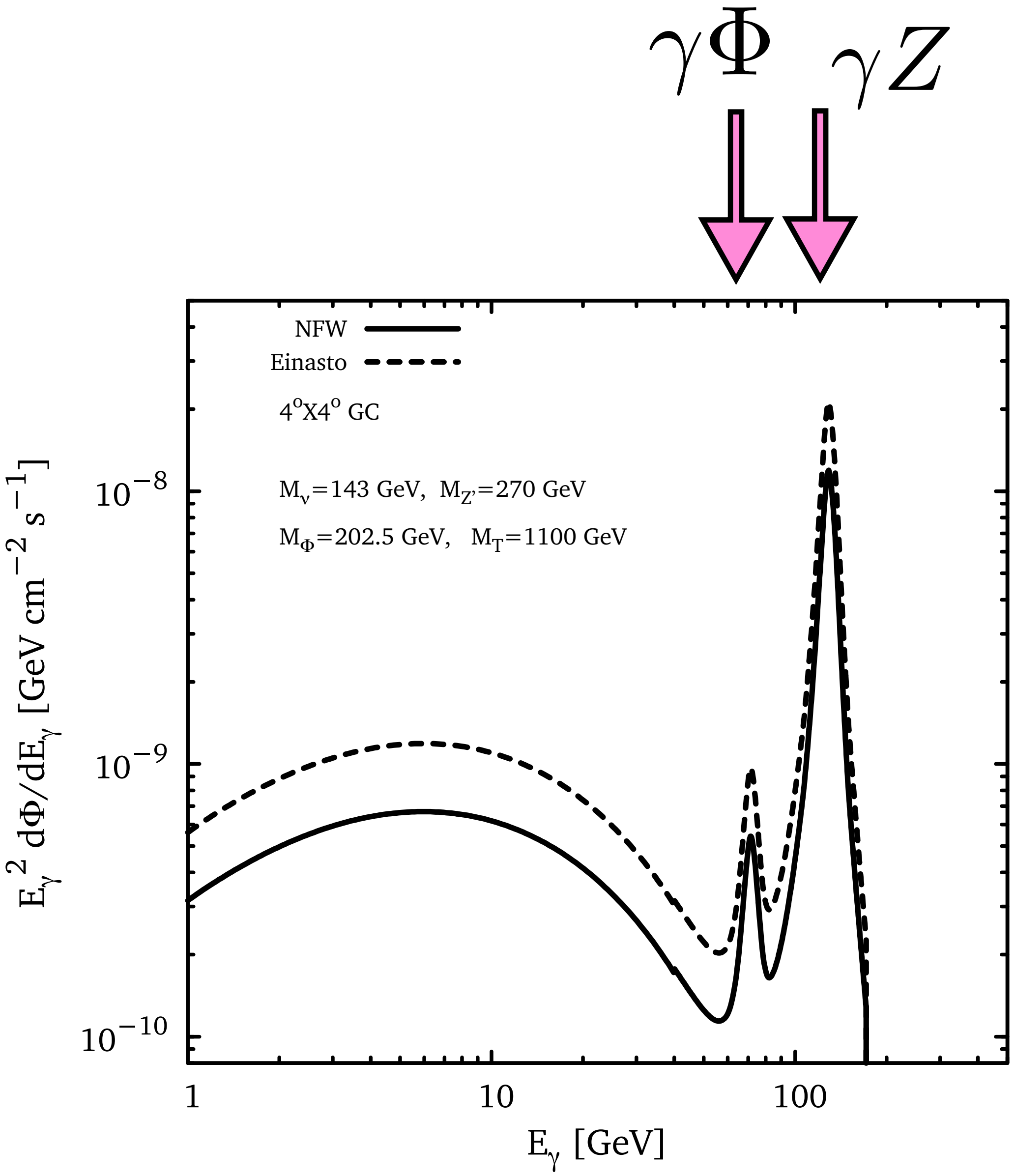
η: mixing

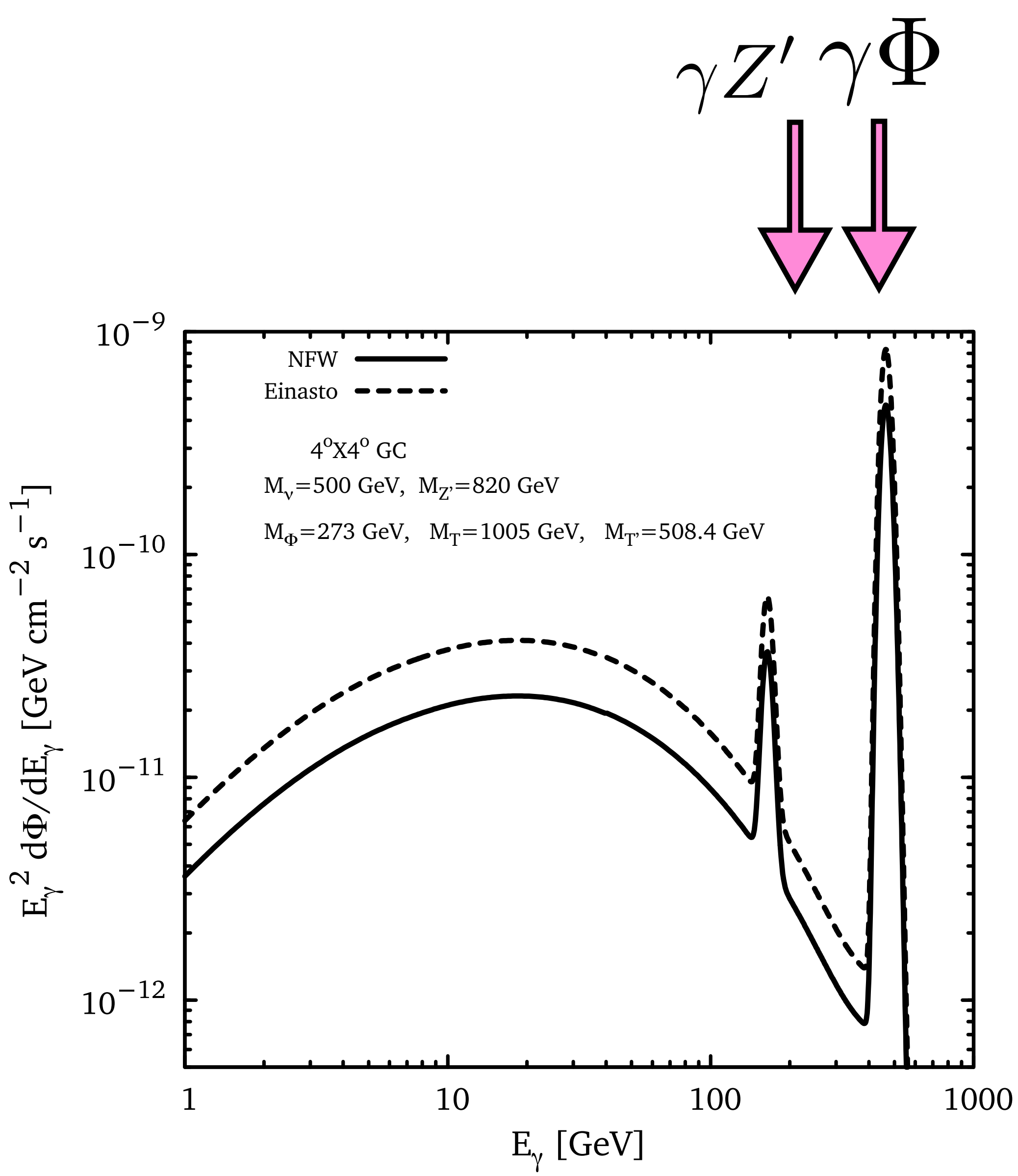
→ σ ∝ η²

Large Gamma-ray lines from top-philic dark sectors.



1303.4717
Jackson et al.



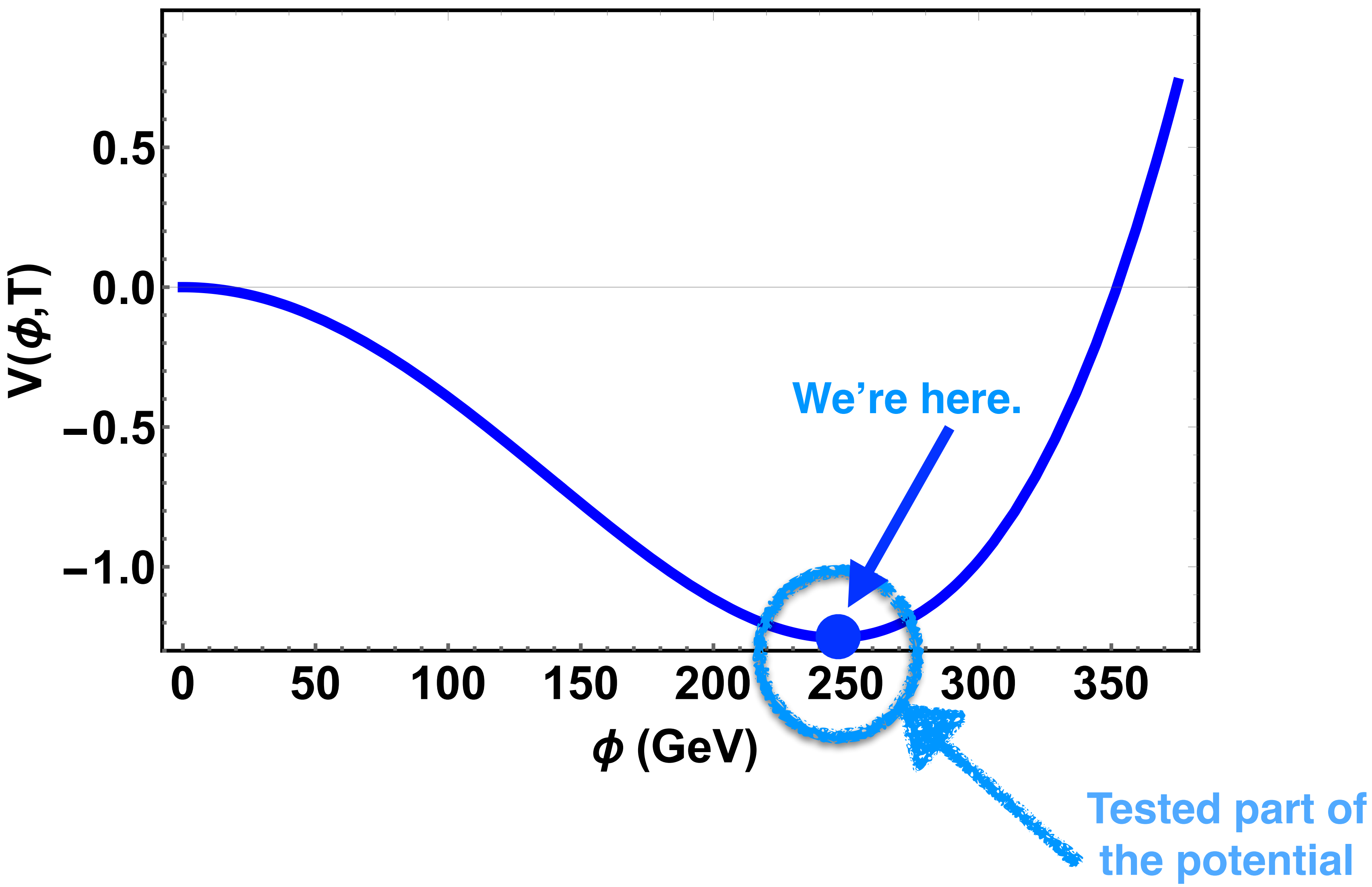


4- The Top Quark & the Electroweak Phase Transition .

High-temperature EW symmetry restoration triggered by the Top Quark

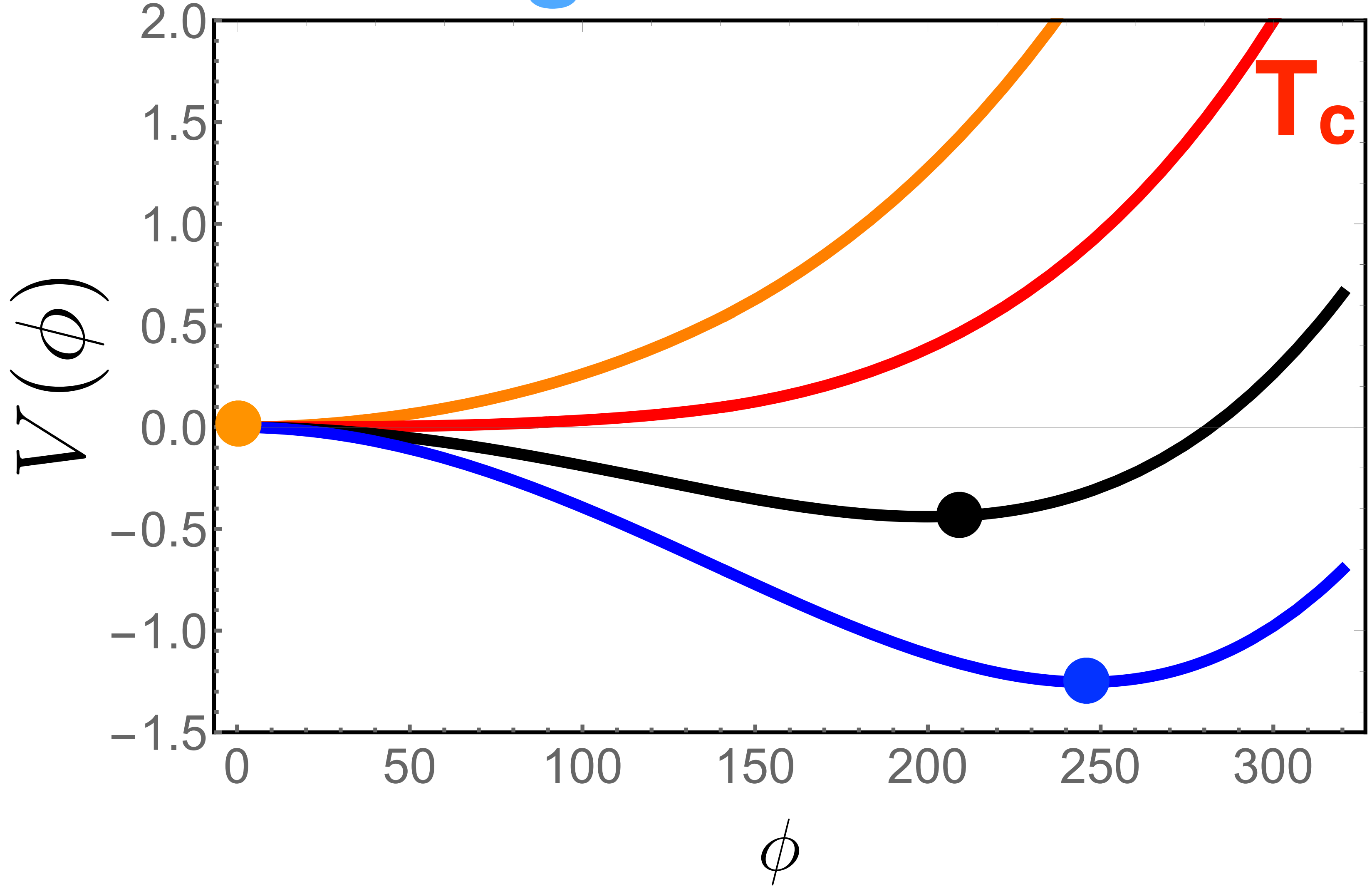
THE HIGGS POTENTIAL .

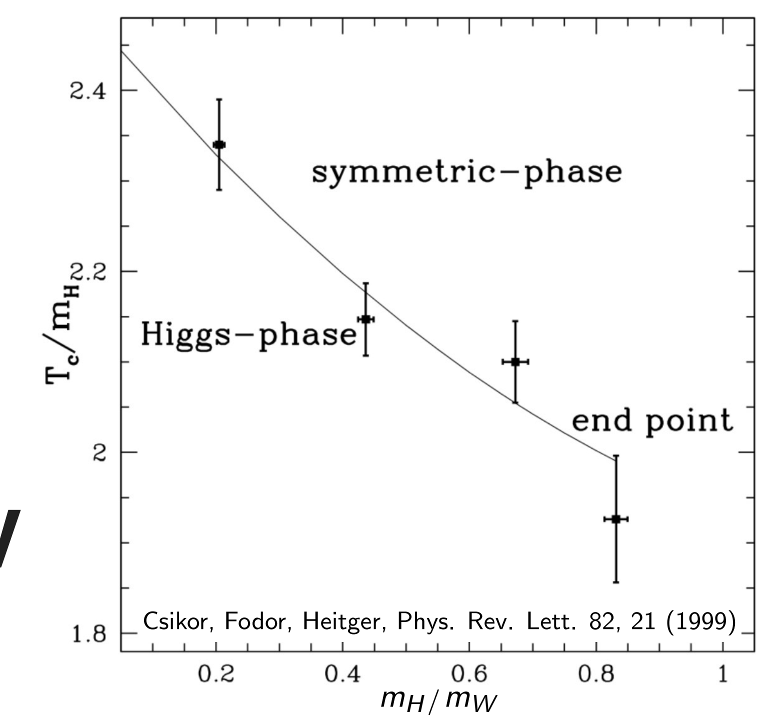
TODAY, T=0 $V_0(\phi) = -\mu^2\phi^2/2 + \lambda\phi^4/2$



> 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≲70 GeV

***1404.3565

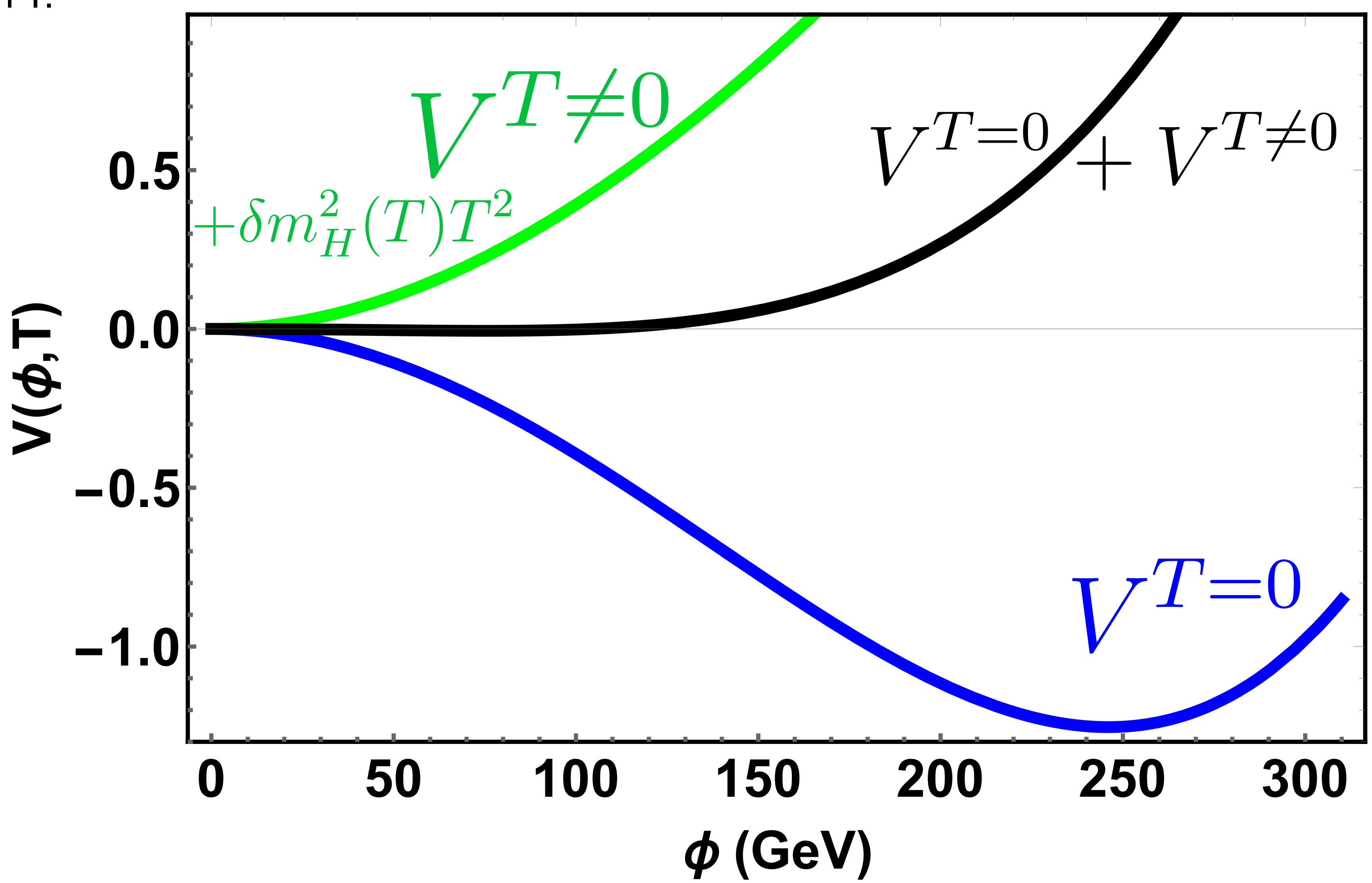
HIGH TEMPERATURE EW SYM. RESTORATION.

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

At high T:



—> Symmetry restoration at Tc

HIGGS EFFECTIVE POTENTIAL AT HIGH TEMPERATURE .

At one-loop:

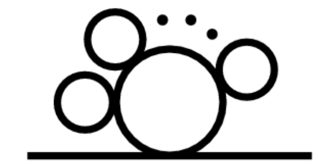
$$V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T).$$

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_{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

HIGGS THERMAL MASS .

Dominated by the top Yukawa!

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

The top Yukawa determines the temperature of the EW phase transition above which the EW symmetry is restored.

Crucial for theories of baryogeneis as it determines the temperature above which baryon number is very efficiently violated at high temperature

Exotica: A top-quark condensate triggering the EW phase transition !

1704.04955, 1711.11554

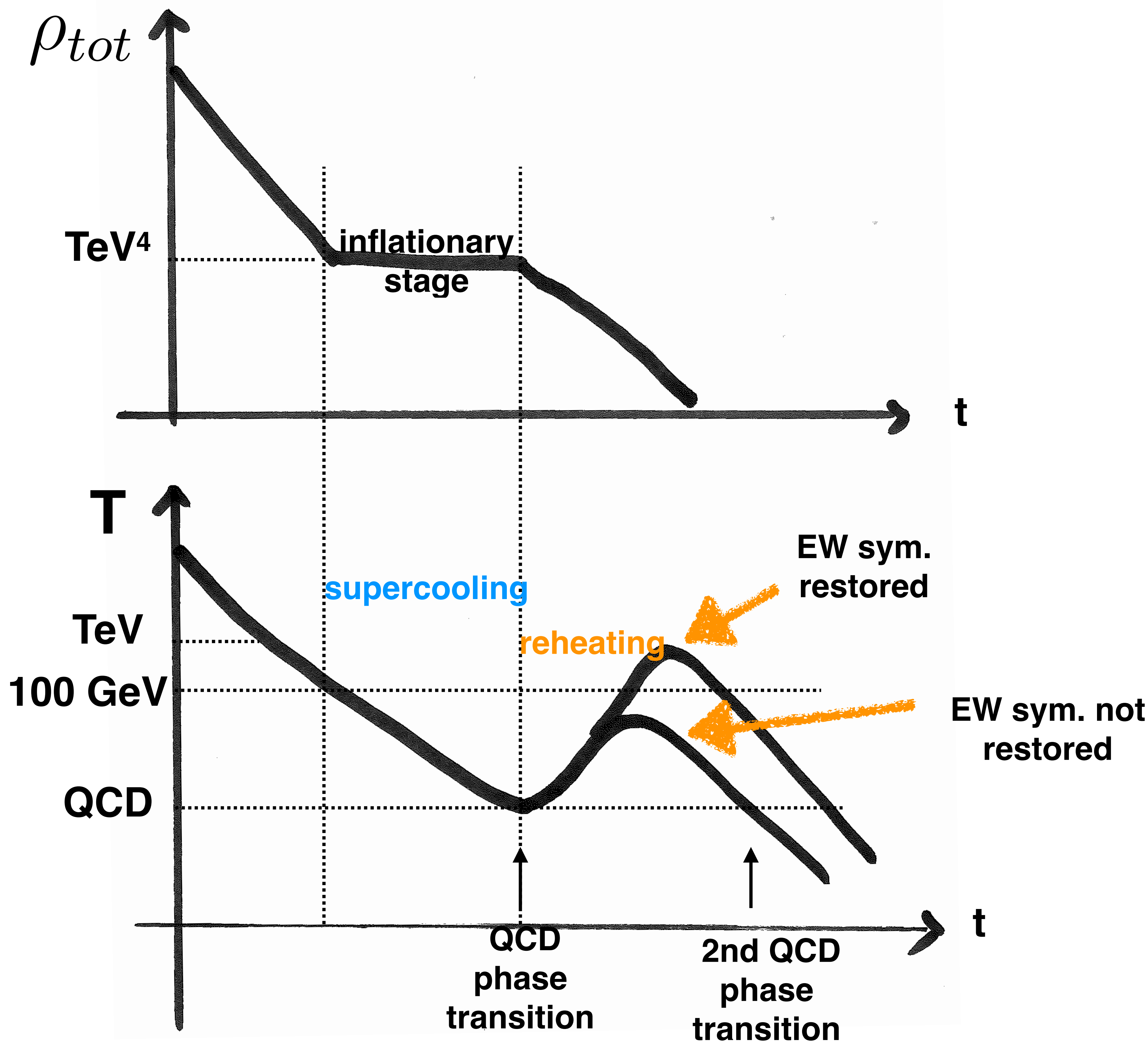
EW phase transition occurring at temperatures below the QCD scale!

QCD and the top quark condensate can trigger the EWPT !

If the Higgs is part of an approximately conformal sector, EW symmetry breaking is tied to the breaking of conformal invariance. The electroweak phase transition is then governed by a nearly conformal potential generically leading to large amounts of supercooling. This may delay the phase transition to temperatures near the QCD scale

when QCD confines and gluons and quarks form condensates. These condensates can subsequently trigger the breaking of conformal invariance and thereby induce the electroweak phase transition.

Supercooled EW phase transition induced by TeV-scale confinement phase transition in conformal sector .



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

5- The Top Quark & cosmological solutions to the hierarchy problem .

Example: The Relaxion Mechanism

The hierarchy problem.

If Standard Model is an effective field theory below M_{Planck}

$$V = m_H^2\, h^2 + \lambda\, h^4$$

Why $|m_H^2| \ll M_{Planck}^2$ **?**

Why does the Higgs vacuum reside so close to the critical line separating the phase with unbroken (<h>=0) from the phase with broken (<h> ≠0) electroweak symmetry?

Solutions to the Hierarchy Problem .

Adding a symmetry

-> Supersymmetry

-> Global symmetry …

Experimental signals: partners

Lowering the cutoff

-> Randall-Sundrum / Composite Higgs,

-> Large Extra Dimensions …

Experimental signals: resonances

Selecting a vacuum : Relaxation (dynamics),

Experimental signals: typically through cosmology

Motivation.

What if the weak scale is selected by cosmological dynamics, not symmetries?

Special point in parameter space:

$m^2_H = 0$ *not* related to a symmetry
Instead, related to early-universe dynamics!

Relaxion idea: **Higgs mass parameter is field-dependent**

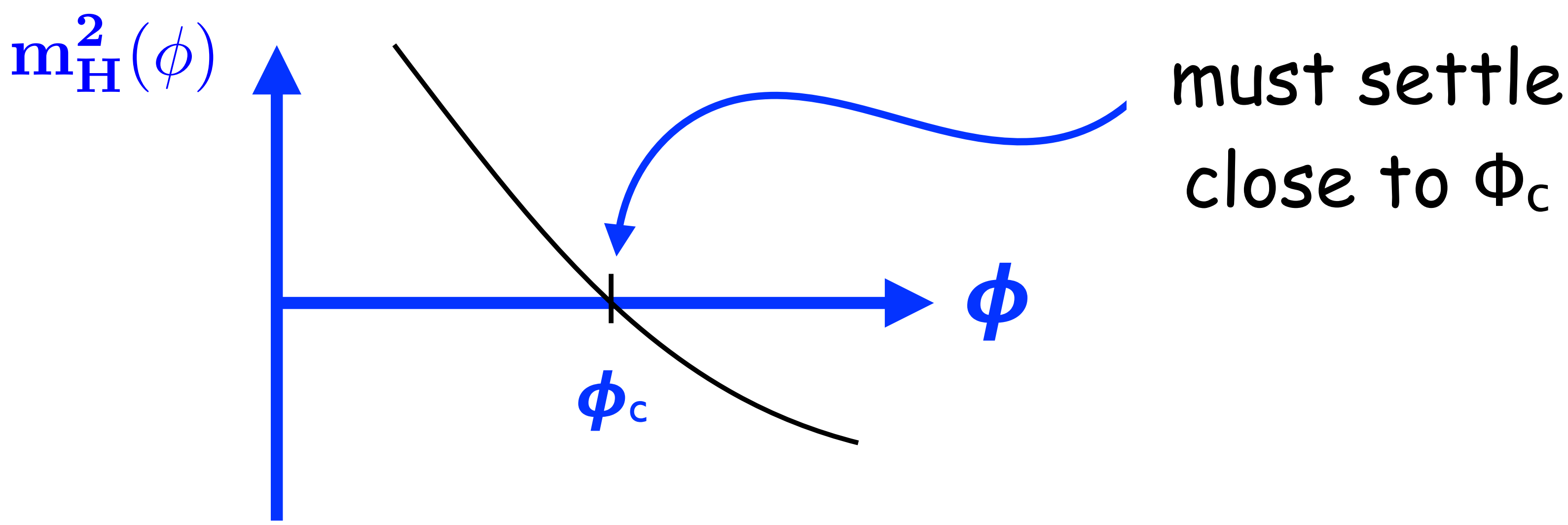
a new scalar field

$$m_{\rm H}^2 |H|^2 \to m_{\rm H}^2(\phi)|H|^2$$

Φ can get a value such that $m_{\rm H}^2(\phi) \ll \Lambda^2$

UV cutoff

from a dynamical interplay between H and Φ



m_H naturally stabilized due to back-reaction of the Higgs field after EW symmetry breaking !

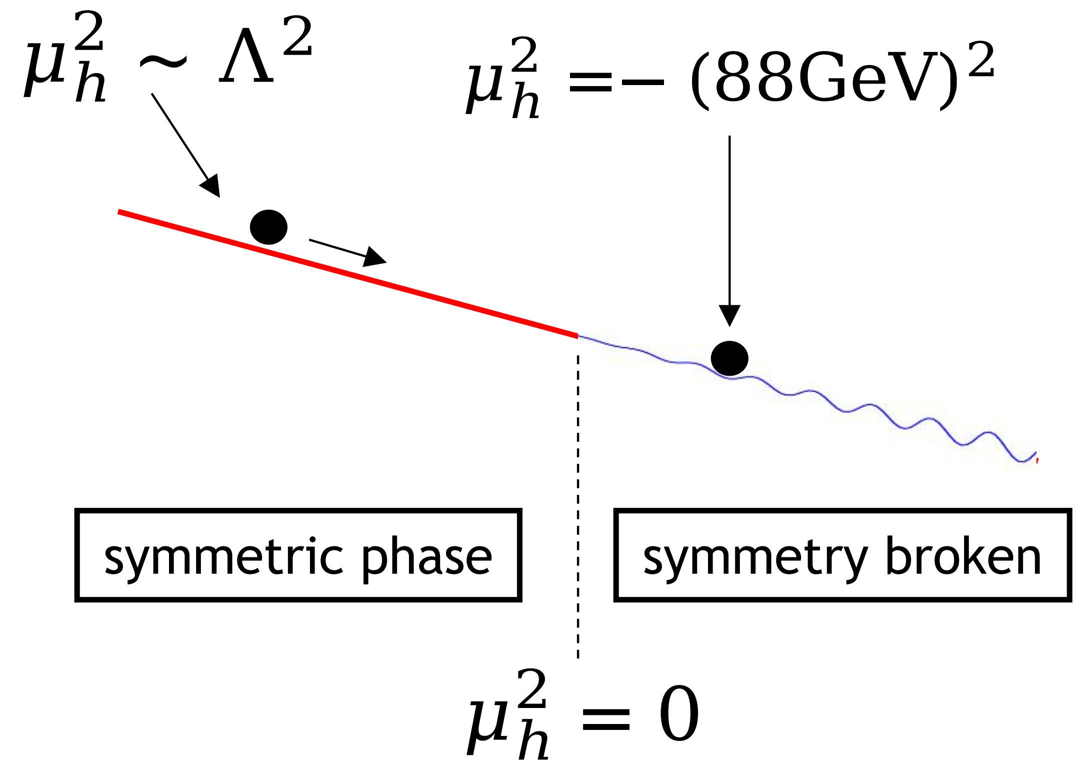
Relaxion mechanism.

[GKR: Graham, Kaplan, Rajendran '15]
inspired by Abbott's attempt to solve the Cosmological Constant problem, '85
[for a recent update see 2210.01148]

ϕ: relaxion, classically evolving pNGB.

Dynamical Higgs mass, controlled by vev of ϕ:

$$\mu_h^2 \rightarrow \mu_h^2(\phi) = \Lambda^2 - g\Lambda\phi$$



Λ: cutoff of the Higgs effective theory

Relaxion mechanism.

potential: $U(\phi) = -g\Lambda^3\phi + \Lambda_b^4(v_h)[1 - \cos(\phi/f)]$

Rolling potential

Higgs-vev-dependent barriers

stopping mechanism:

Slow-roll dynamics during inflation $\dot{\phi}_{SR} = \frac{U'}{3H_I}$

Relaxion stops near the first minimum

$$0 = V'(\phi_0) = -g\Lambda^3 + \frac{\Lambda_b^4(\phi_0)}{f}\sin\left(\frac{\phi_0}{f}\right). \longrightarrow \Lambda_b^4 \sim g\Lambda^3 f$$

Relaxion mechanism.

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inspired by Abbott's attempt to solve the Cosmological Constant problem, ’85

[for a recent update see 2210.01148]

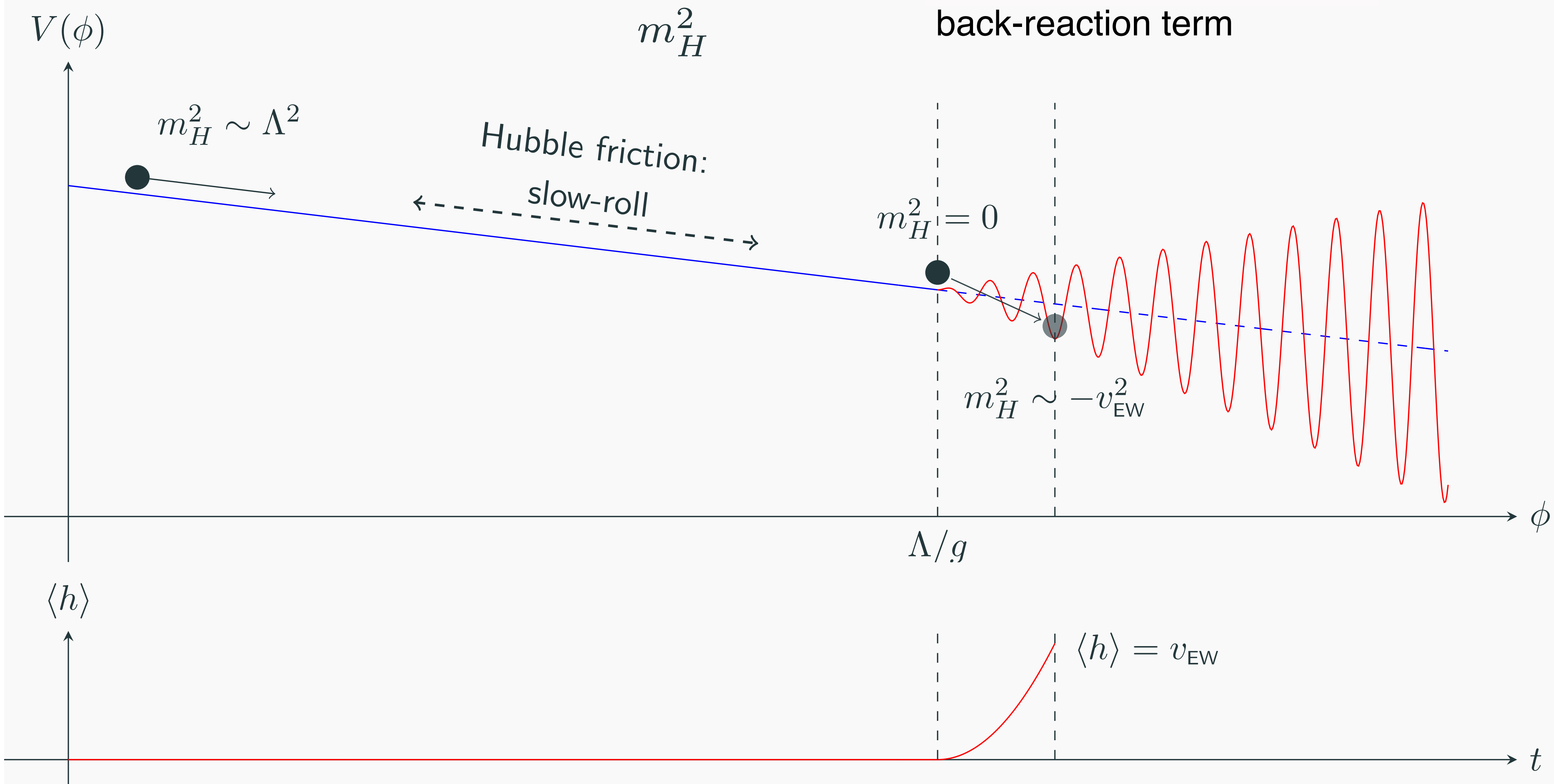
ϕ: relaxion, classically evolving pNGB.

Higgs-relaxion potential

Λ: cutoff of the Higgs effective theory

$$V(\phi,h) = -g\Lambda^3\phi + \frac{1}{2}\underbrace{(\Lambda^2 - g'\Lambda\phi)}_{m_H^2}h^2 + \Lambda_b^4(h)[1-\cos(\phi/f)] + \dots$$

back-reaction term



[figure credit: E. Morgante]

Why does this have to happen during inflation?

The responsability of the top quark:

In the standard radiation era, the Higgs acquires a large thermal mass from the top quark Yukawa coupling.

—> The relaxion would then cancel the total Higgs thermal mass^2 rather than the Higgs bare mass^2 parameter. It will stop too early when the Higgs vev is too large!

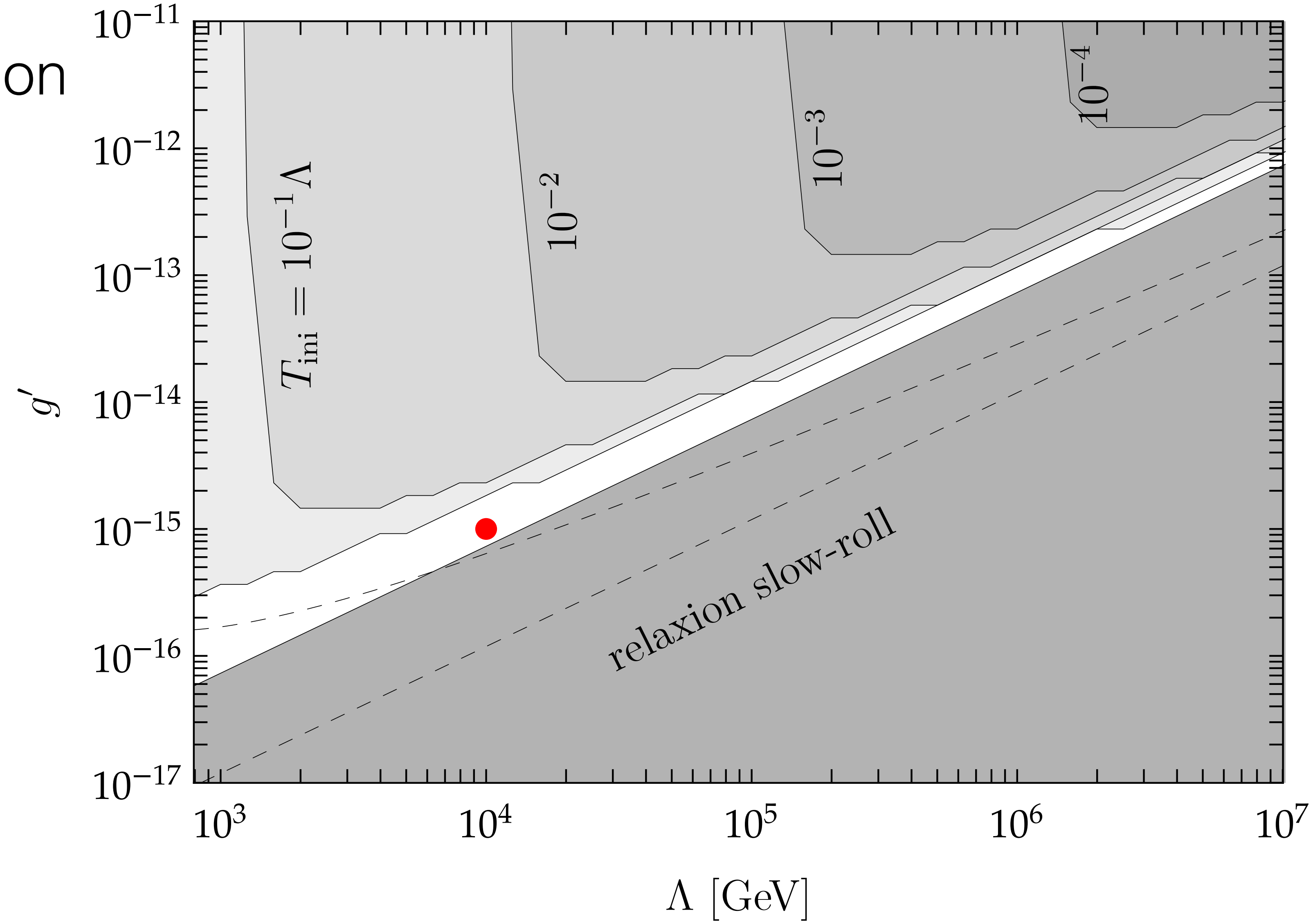
In order for the relaxion mechanism not to be spoiled by thermal effects, it is necessary that

$$|\mu_h|^2 \gtrsim y_t^2 T^2$$

$$\longrightarrow \quad g' \lesssim \frac{\Lambda}{\sqrt{3} M_{\rm Pl} \log(\Lambda/v_{\rm EW})}$$

Can the relaxion mechanism takes place during the radiation era?

Higgs-Relaxion coupling



Higgs cutoff

In white region: T is suppressed with respect to the EW scale and the relaxation lasts less than 20 e-folds. The different shades of gray show how the parameter space opens up if T_{ini} (initial temperature) is assumed to be a fraction 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4} of the cutoff scale Λ.

$$\frac{\Lambda}{20\sqrt{3}M_{\rm Pl}} \lesssim g' \lesssim \frac{\Lambda}{\sqrt{3}M_{\rm Pl}\log(\Lambda/v_{\rm EW})}$$

$\mathcal{N} \lesssim 20.$

T <~ 100 GeV

Fonseca-Morgante-Servant 1805.04543v3

The QCD and non-QCD models.

The **QCD** relaxion model

- Higgs-dependent barriers from the **QCD anomaly,**

$$\Lambda_b^4(v_h) \approx \Lambda_{QCD}^3 m_u$$

- Problem: the relaxion no longer solves the **strong CP problem!**

$$\theta_{QCD} \sim \mathcal{O}(1)$$

The **nonQCD** relaxion model

- Higgs-dependent barriers from a **hidden gauge group**

$$\Lambda_b(v_h) < \sqrt{4\pi} v_h$$

(stability of the potential)

The classical non-QCD relaxion window.

1) Vacuum energy

The **change of relaxion energy** much less compared to the **energy scale of inflation**

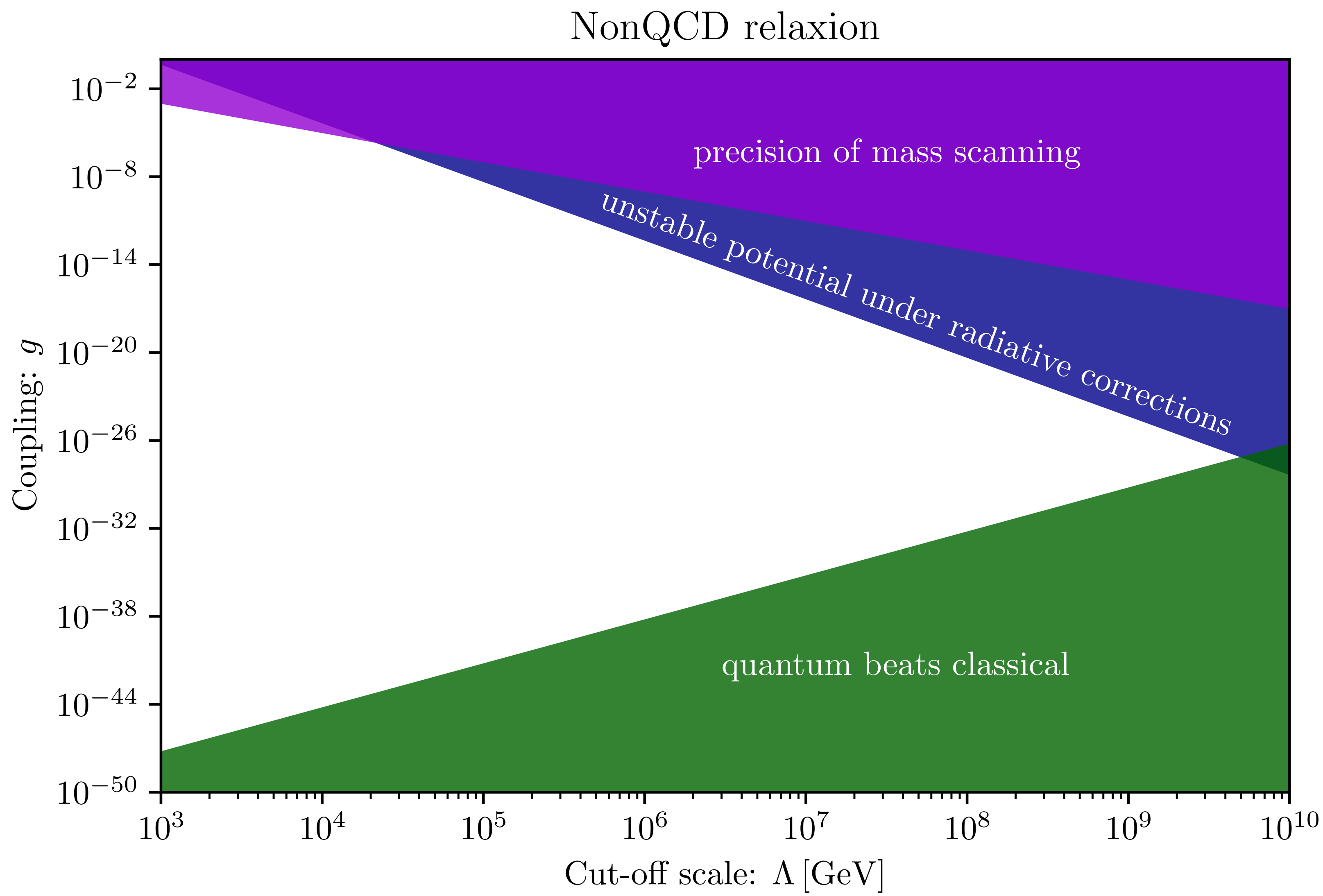
$$\Delta U \sim \Lambda^4 < H_I^2 M_{Pl}^2$$

2) Classical beats quantum

The **slow-roll** ($\dot{\phi} = g\Lambda^3/3H_I$) per unit Hubble time dominates over the random walk ($\Delta\phi \sim H_I$)

$$H_I < (g\Lambda^3)^{1/3}$$

1) + 2) ➡ $$\frac{\Lambda^2}{M_{Pl}} < H_I < g^{1/3}\Lambda$$

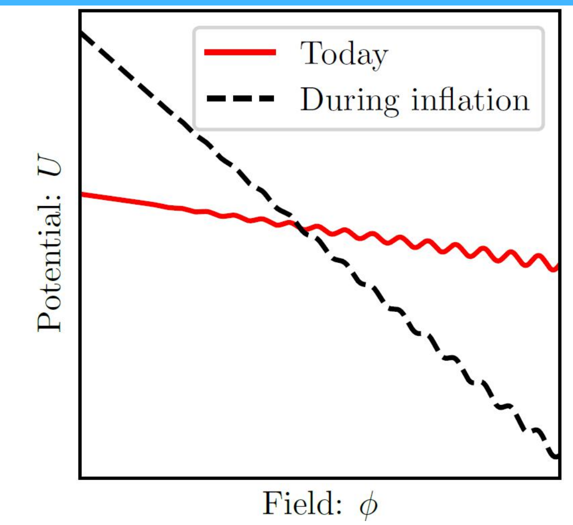


$$\Lambda < 4 \times 10^9 \mathrm{GeV} \left(\frac{\Lambda_b}{\sqrt{4\pi} v_h} \right)^{4/7}$$

The classical QCD relaxion window

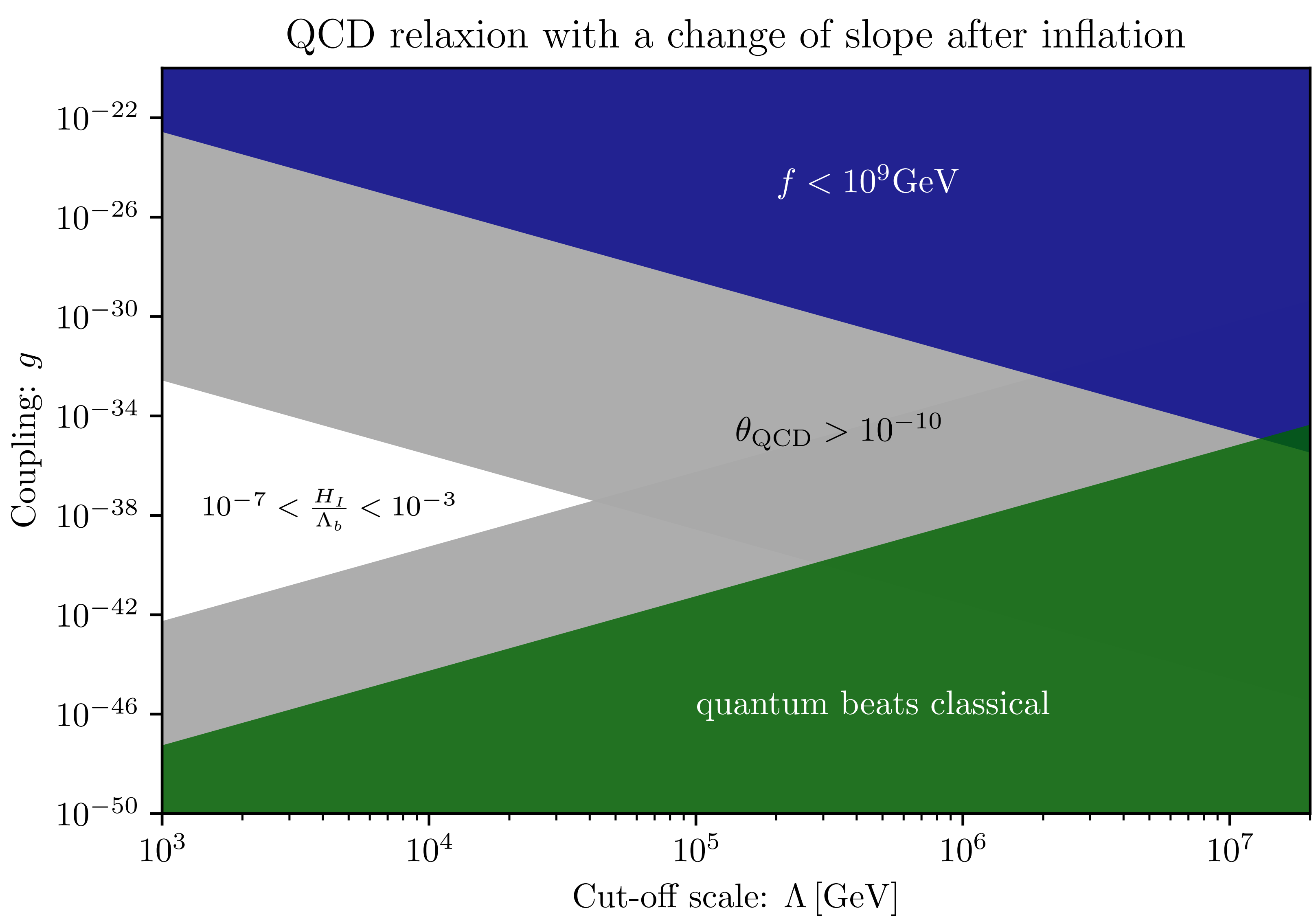
Local minima are not CP conserving

$$0 = U'(\bar\theta) = -g\Lambda^3 + \frac{\Lambda_b^4}{f}\sin\bar\theta \quad\longrightarrow\quad \bar\theta = \arcsin\left(\frac{g\Lambda^3 f}{\Lambda_b^4}\right)$$



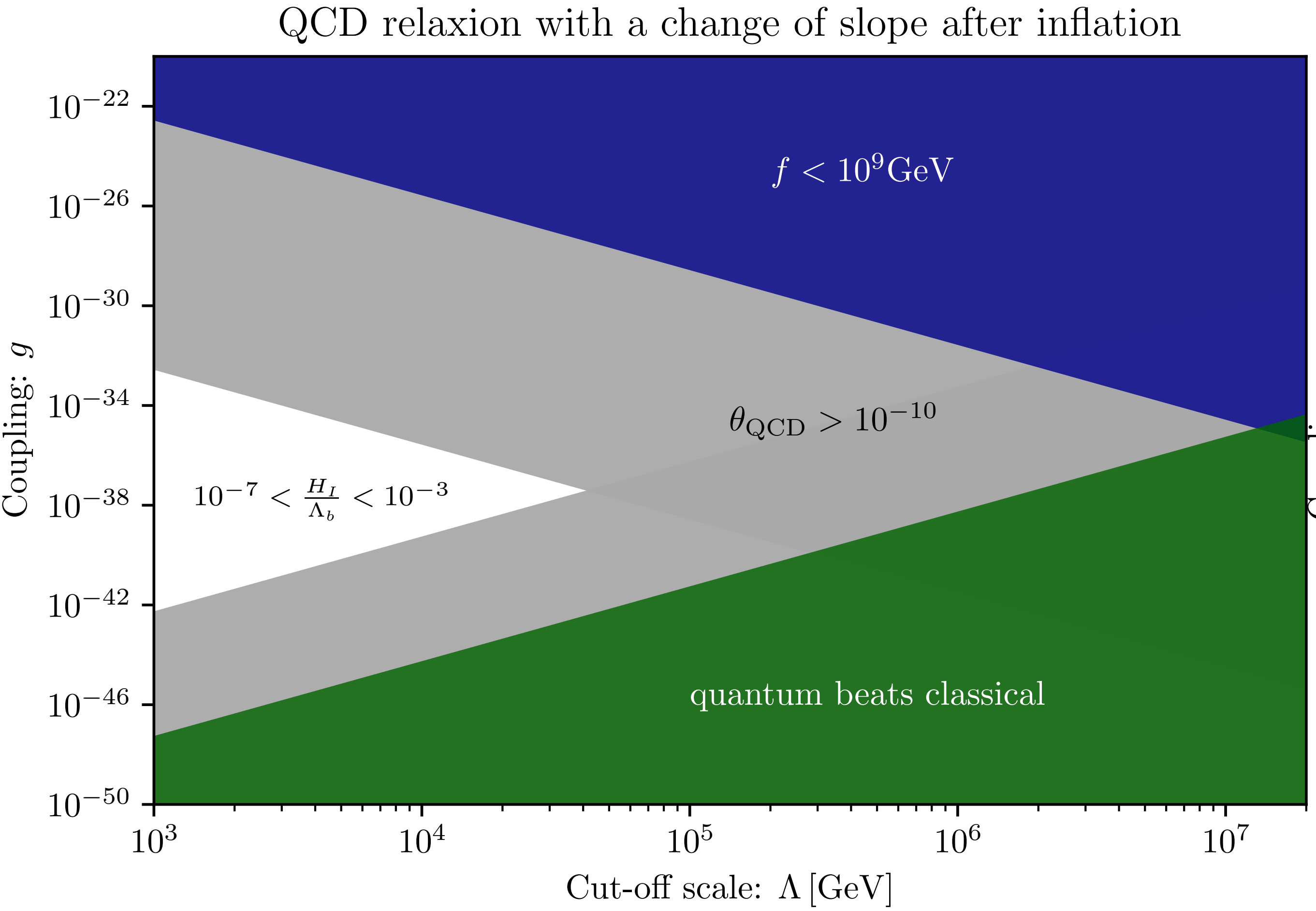
Solution: the slope of the potential drops after inflation to reduce CP violation

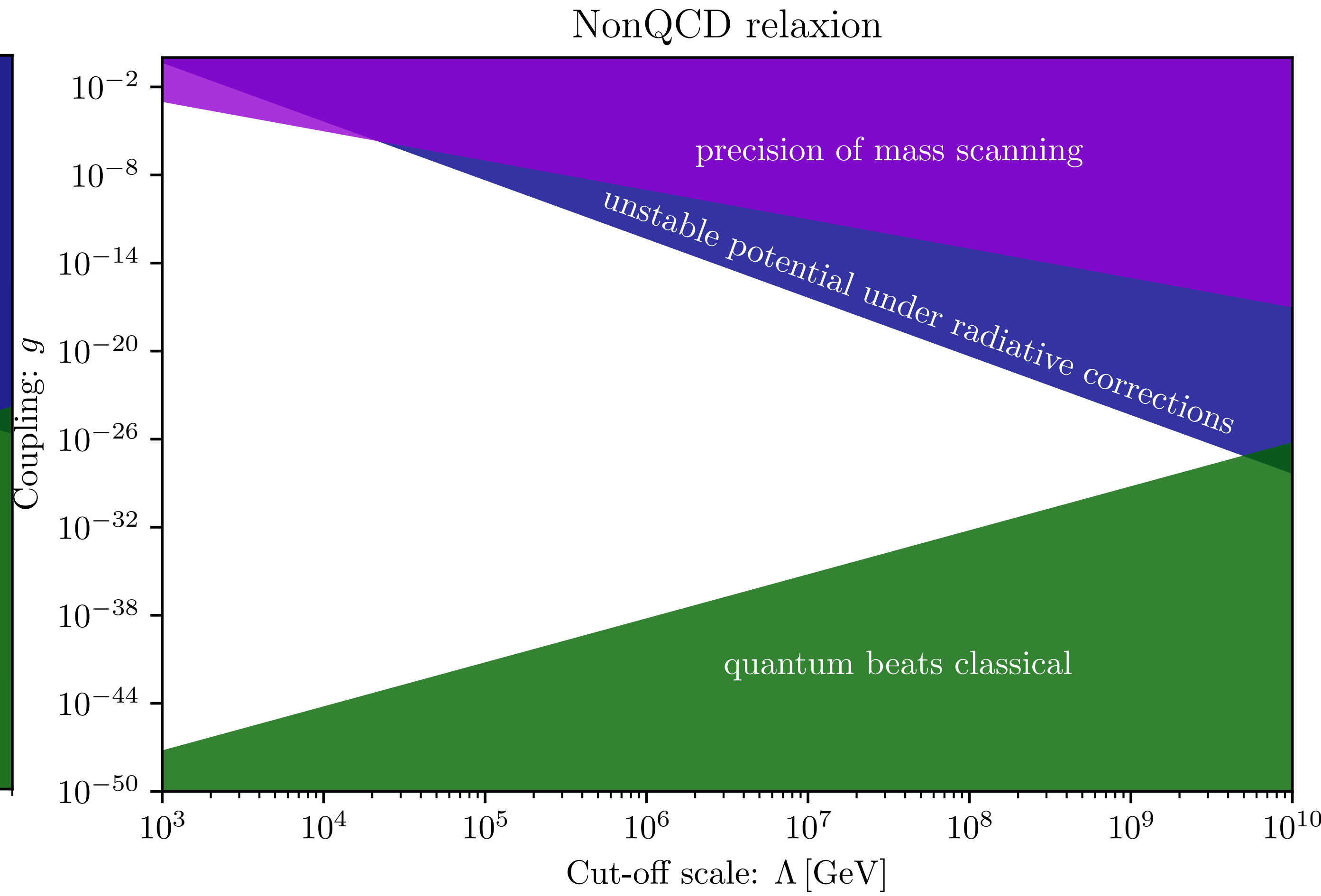
$$g = \xi g_I, \quad \xi < 10^{-10}, \qquad \bar\theta = \xi\bar\theta_I < 10^{-10}.$$



$$\Lambda < 3\times10^4\,\text{GeV}\left(\frac{10^9\,\text{GeV}}{f}\right)^{1/6}\left(\frac{\xi}{10^{-10}}\right)^{1/4}.$$

The classical relaxion windows



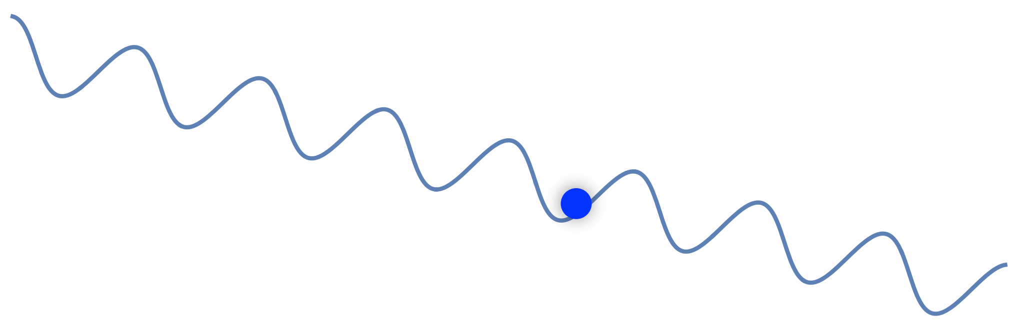


Origin of back-reaction term. Could the relaxion be the QCD axion?

From QCD condensate $\Lambda_{\mathbf{b}} = \Lambda_{QCD}$

$$\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu} \xrightarrow[\text{and replaced by}]{\text{can be rotated away}} m_u(h)\langle q\bar{q}\rangle \cos(\phi/f)$$

but leads to $\theta_{QCD} \sim 1$ **due to the tilt of the potential!**



Problem solved if the tilt disappears at the end of inflation but one can then only explain a little hierarchy:

$\Lambda \lesssim 30$ TeV

Origin of back-reaction term.

[Graham, Kaplan, Rajendran '15]

Wiggles from new strong dynamics

$$\mathcal{L} = -m_N N N^c - m_L L L^c + y H L N^c + \tilde{y} H^\dagger L^c N + \frac{\phi}{f} G\widetilde{G} + \text{h.c.}$$

$$m_L \gg 4\pi f_\pi \gg m_N$$

$$\langle N N^c \rangle = 4\pi f_\pi^3$$

should dominate

$$\Rightarrow \quad V = \left(m_N^0 + \frac{y\tilde{y}}{16\pi^2} m_L \log \frac{\Lambda}{m_L} + y\tilde{y}\frac{\langle h \rangle^2}{m_L} + \frac{y\tilde{y}}{16\pi^2}\frac{(4\pi f_\pi)^2}{m_L} \right) (4\pi f_\pi^3) \cos\frac{\phi}{f}$$

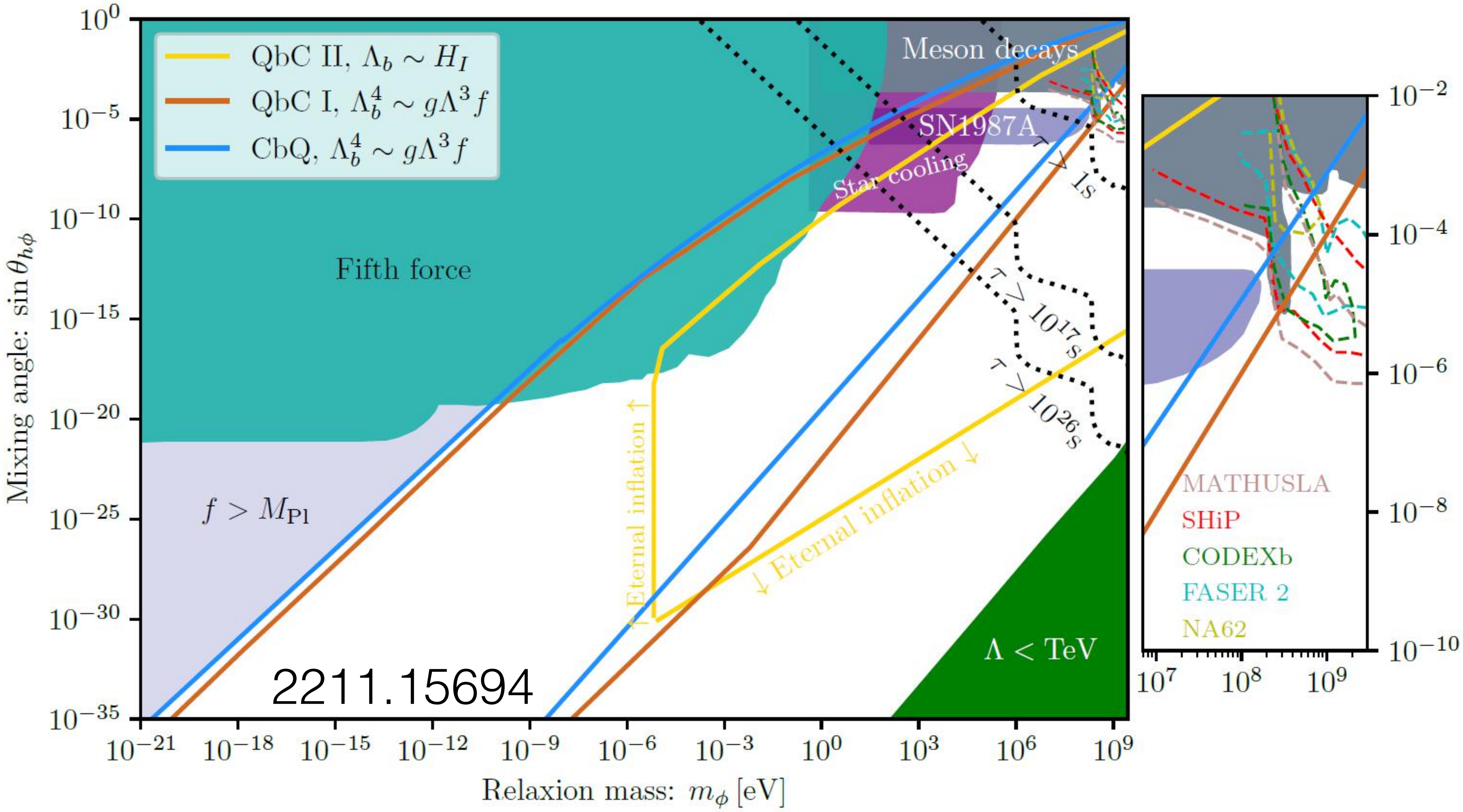
Predictions: weak-scale fermions L accessible at colliders.

Way out: By making the envelop of the oscillatory potential field-dependent, one can show that there is no need for new physics at the weak scale

J.R. Espinosa et al [1506.09217]

Interactions of the relaxion

The relaxion interacts via its mixing with the Higgs $\sin(2\theta_{h\phi}) = -\frac{2m_{h\phi}^2}{\sqrt{(2m_{h\phi}^2)^2 + (m_h^2 - m_\phi^2)^2}}.$



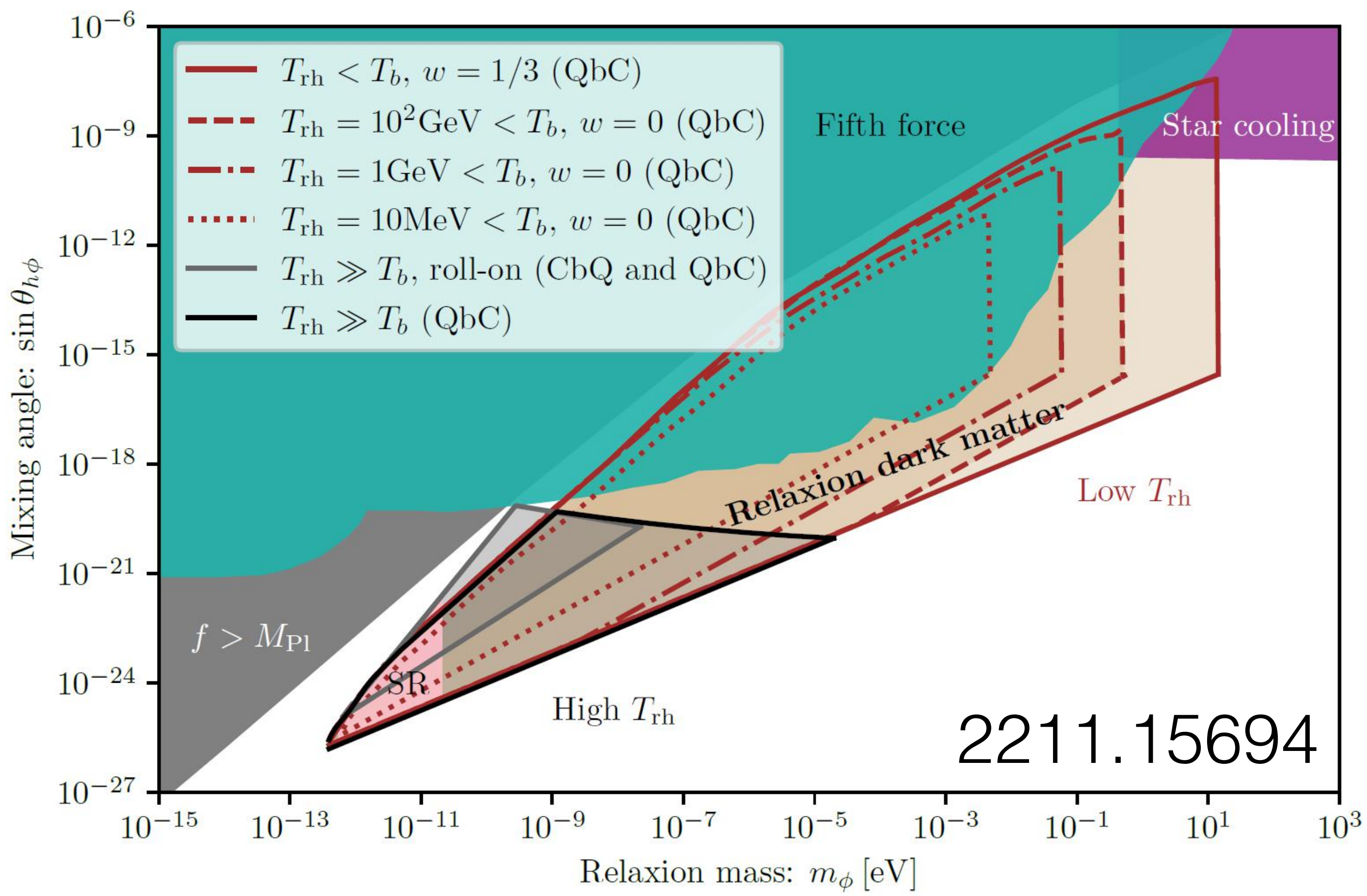
Flacke et. al., 1610.02025

Hardy et al., 1611.05852

Balaji et al., 2205.01699

Light and stable in most of the parameter space:
Can the relaxion be Dark Matter?

Relaxion dark matter window



Chatrchyan et al., 2210.01148

Brown: low reheating temperature, stochastic misalignment

Grey: high reheating temperature, misalignment from roll-on after reheating Banerjee et. al., 1810.01889

Black: high reheating temperature, stochastic misalignment

The most direct cosmological connection to collider experements:

6- The Top Quark & Electroweak Baryogenesis .

The dynamical Top Quark Yukawa coupling as the source of CP violation in baryogenesis

ELECTROWEAK BARYOGENESIS .

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).

Motivations .

EW baryogenesis in a SM extension that adresses:

-the Higgs hierarchy problem

-the flavour hierarchy

and does not require B nor L violations beyond the SM

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

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

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

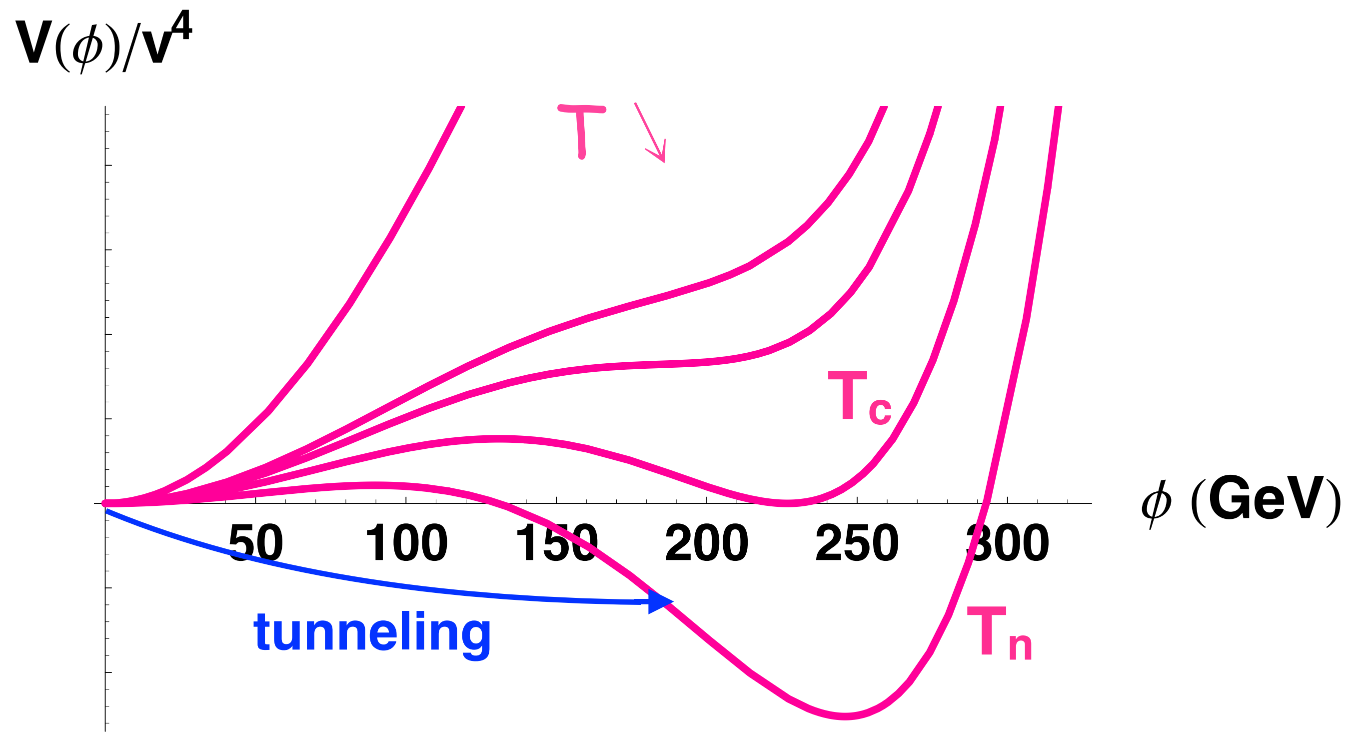
Let us focus on baryogenesis at the EWPT in a minimal B-L=0 SM extension.

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

EWPT has to be 1st-order!
—> Requires an additional weak-scale scalar beyond the Higgs

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

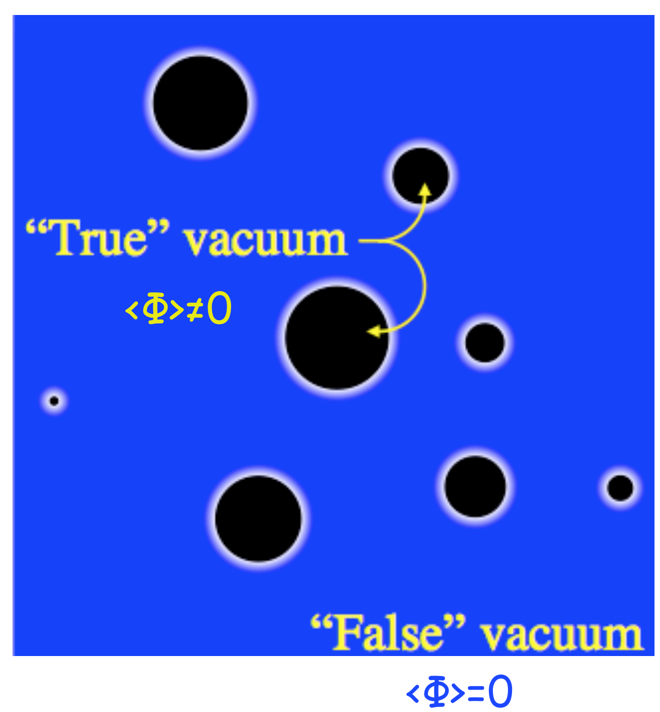
free energy of gas of particles getting a mass from φ.



Barrier separates 2 degenerate minima

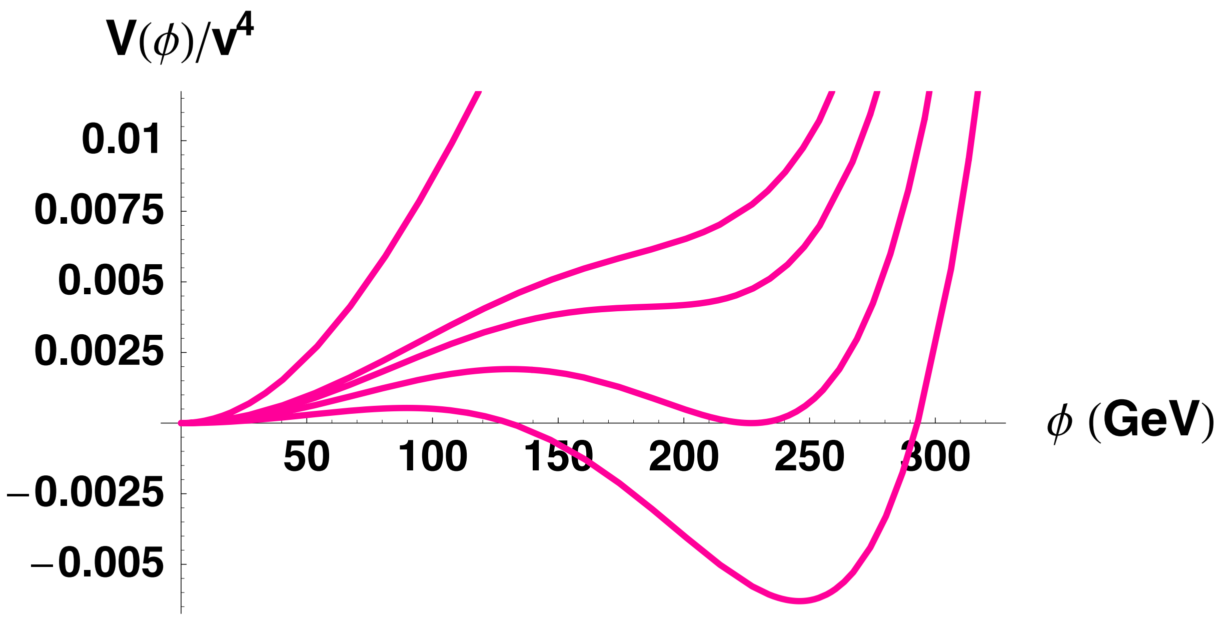
2 phases can coexist

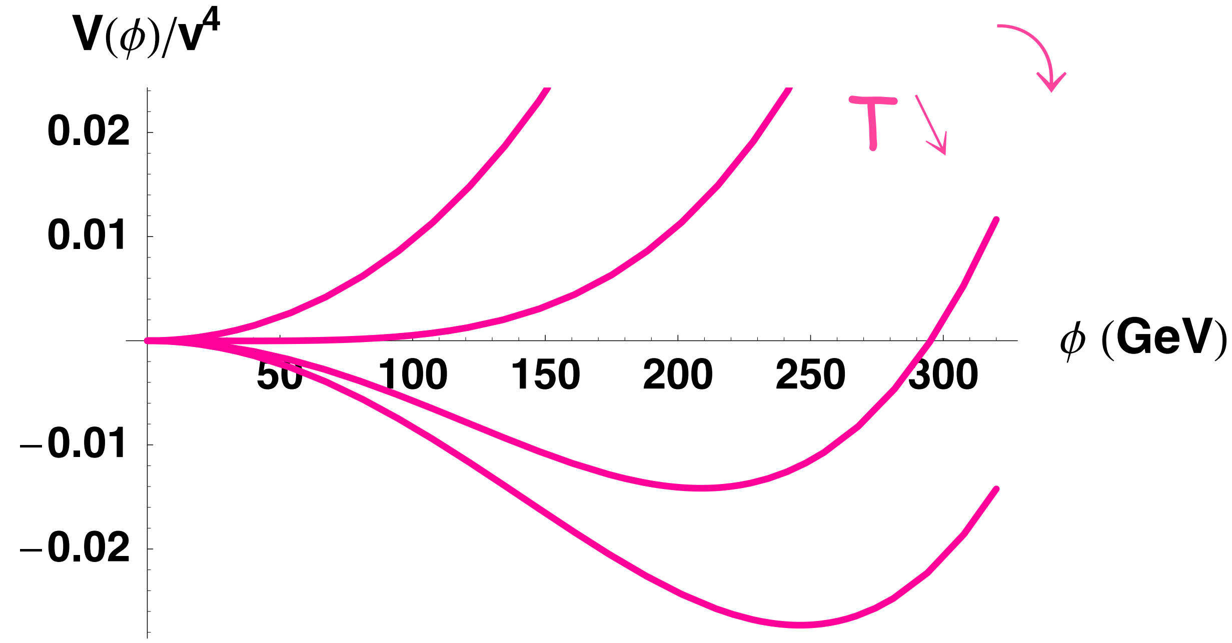
Nucleation, expansion and collision of Higgs bubbles



EW phase transition .

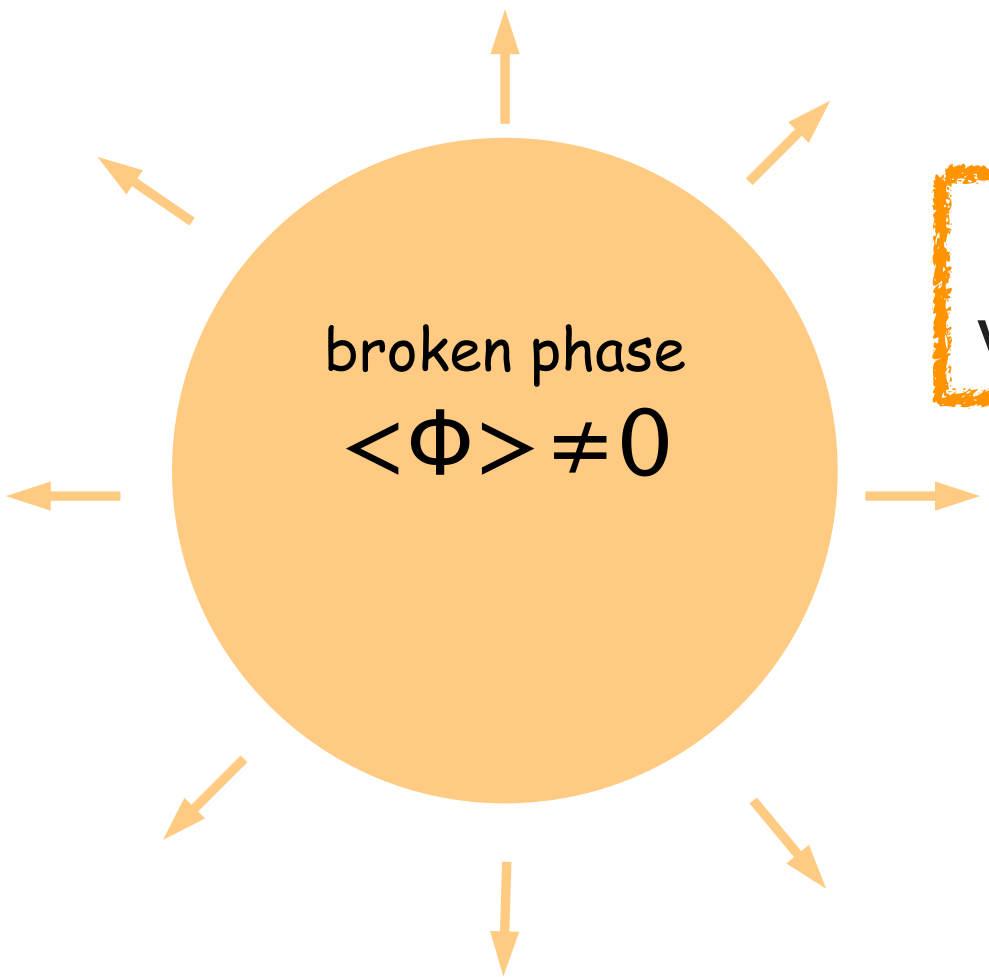
first-order or cross over?





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.

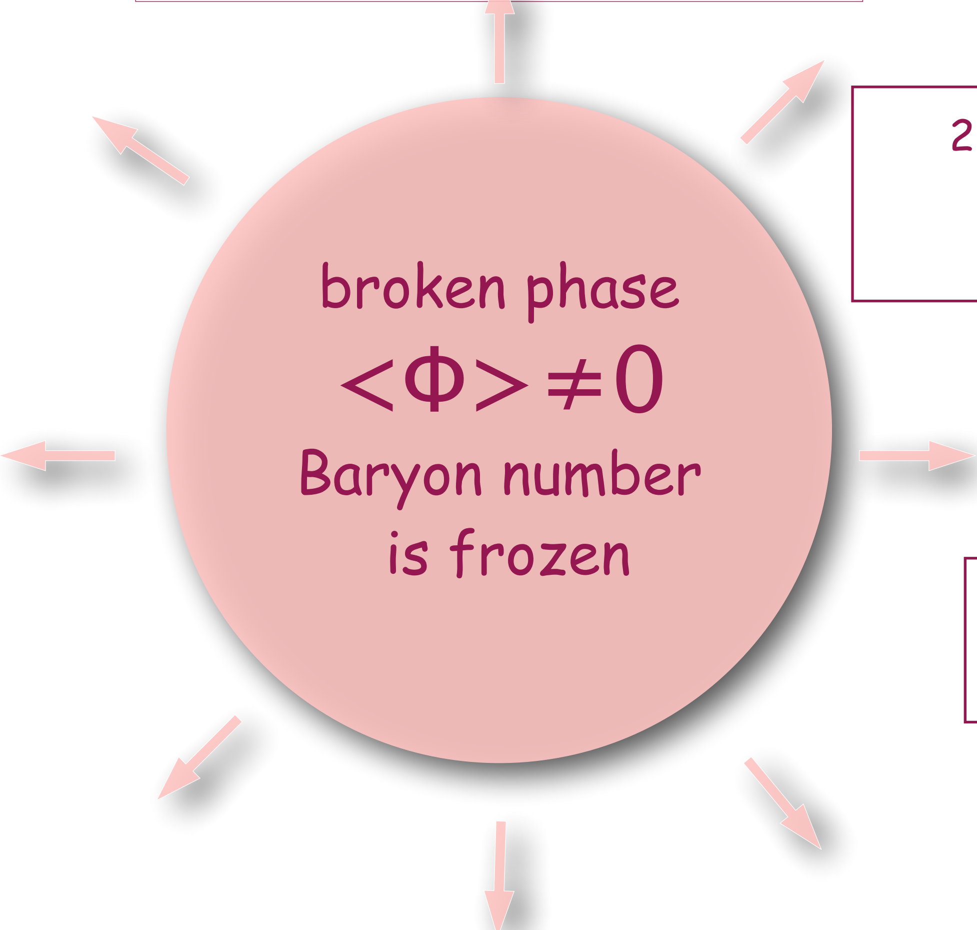
Strength of EW phase transition $\equiv \quad \frac{\langle \Phi(T_n) \rangle}{T_n} \gtrsim 1$

T_n $\equiv$ **nucleation temperature**

EW baryogenesis during a first-order EW phase transition

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

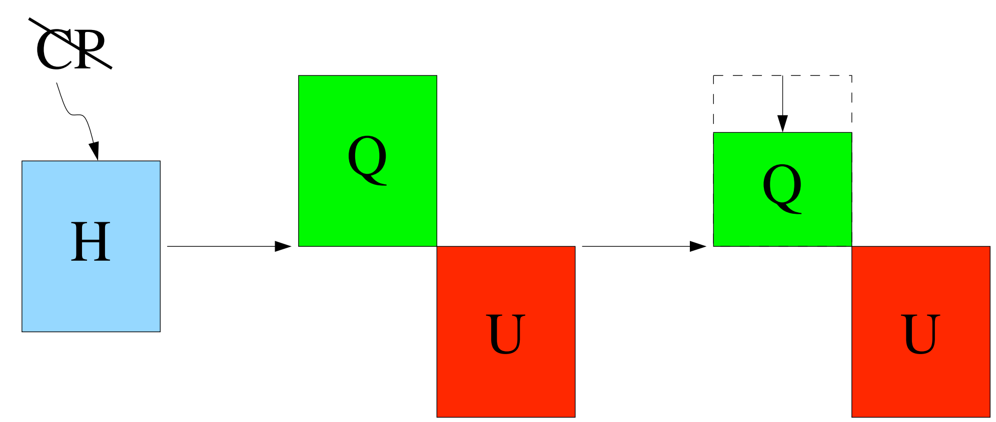
1) nucleation and expansion of bubbles of broken phase



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**

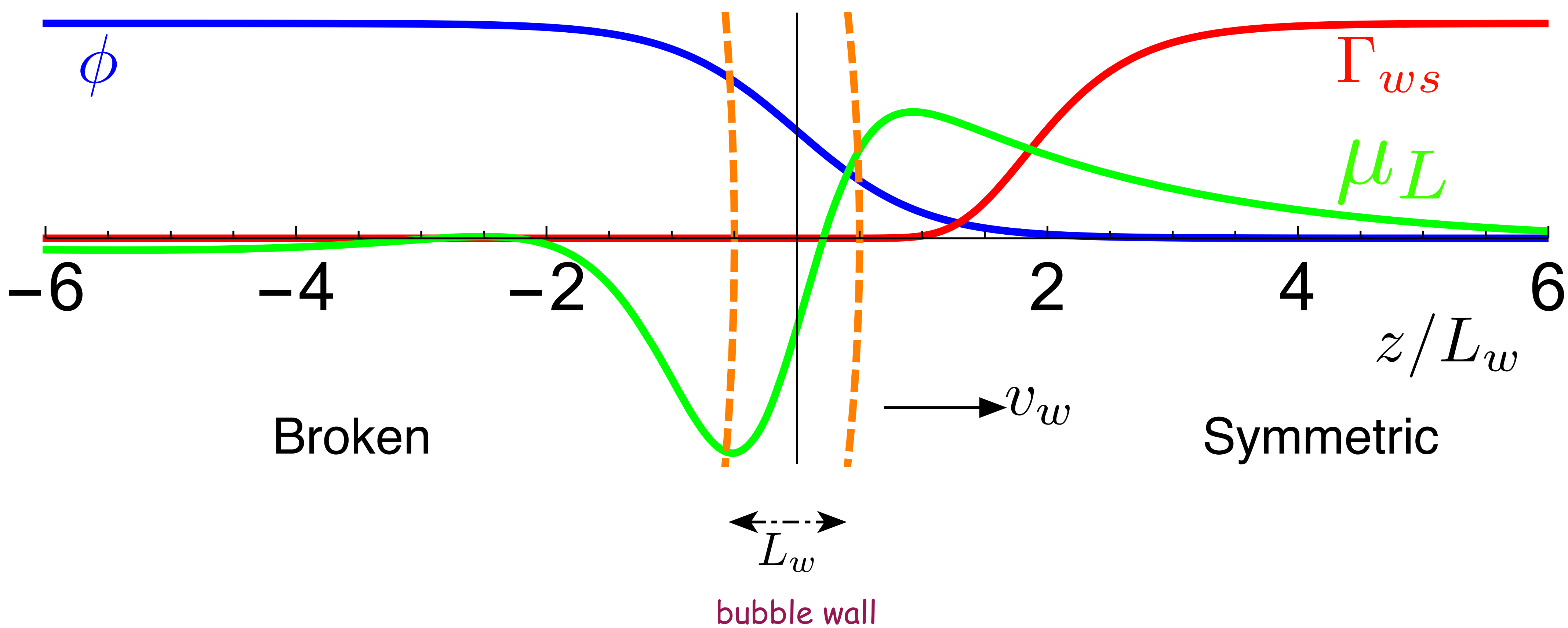
The EW baryogenesis miracle .

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

bubble wall velocity

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

: sphaleron rate



Popular CP-violating source : Varying top-quark Yukawa coupling

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.

CP violation in EW baryogenesis

In EW baryogenesis, the source of CP violation does not require 3 generations.
CP-violation is possible even with only one fermionic flavor as long as the complex phase of this mass is changing during the electroweak phase transition, a CP-violating axial current being induced due to a semi-classical force.

This source of CP violation is different from today's standard CP violation from the CKM phase which has to involve at least three flavors and accordingly are suppressed by the Jarlskog invariant J_{CP}.

The key:

Interactions with the bubble wall give rise to space- and time-dependent (top-quark) mass terms, which may contain a CP-violating phase.

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

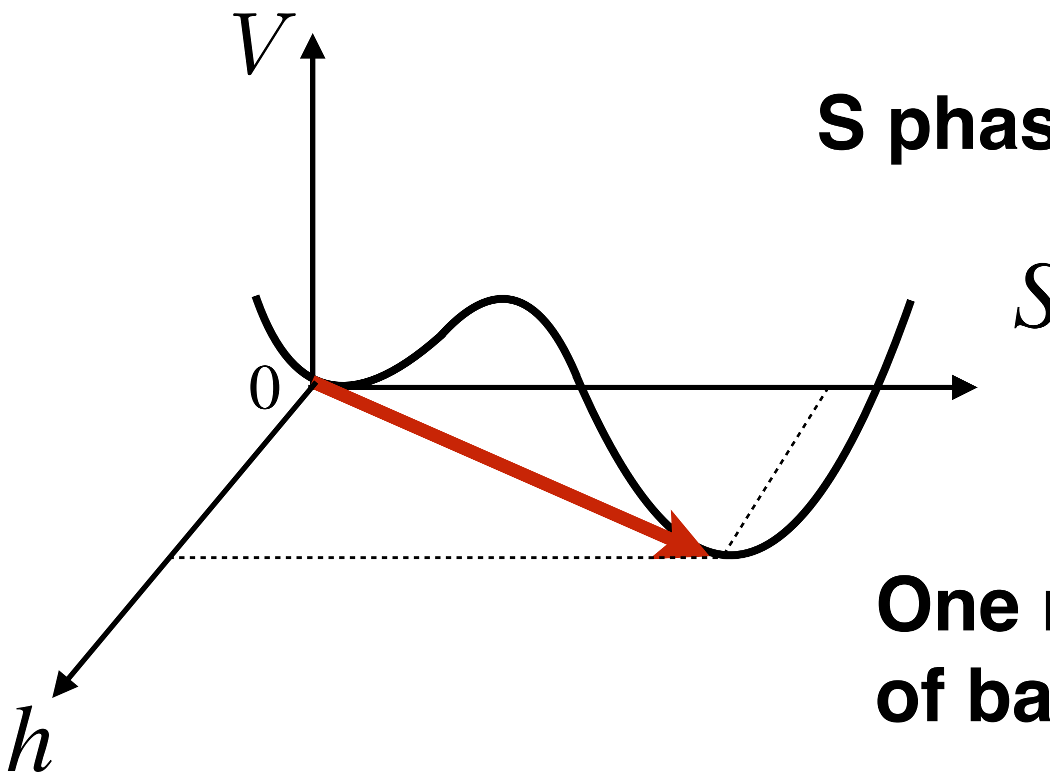
→ For these 3 reasons, S must not be much heavier than the Higgs

↓

Severely constrained by EDM bounds!

This is the EW baryogenesis tension

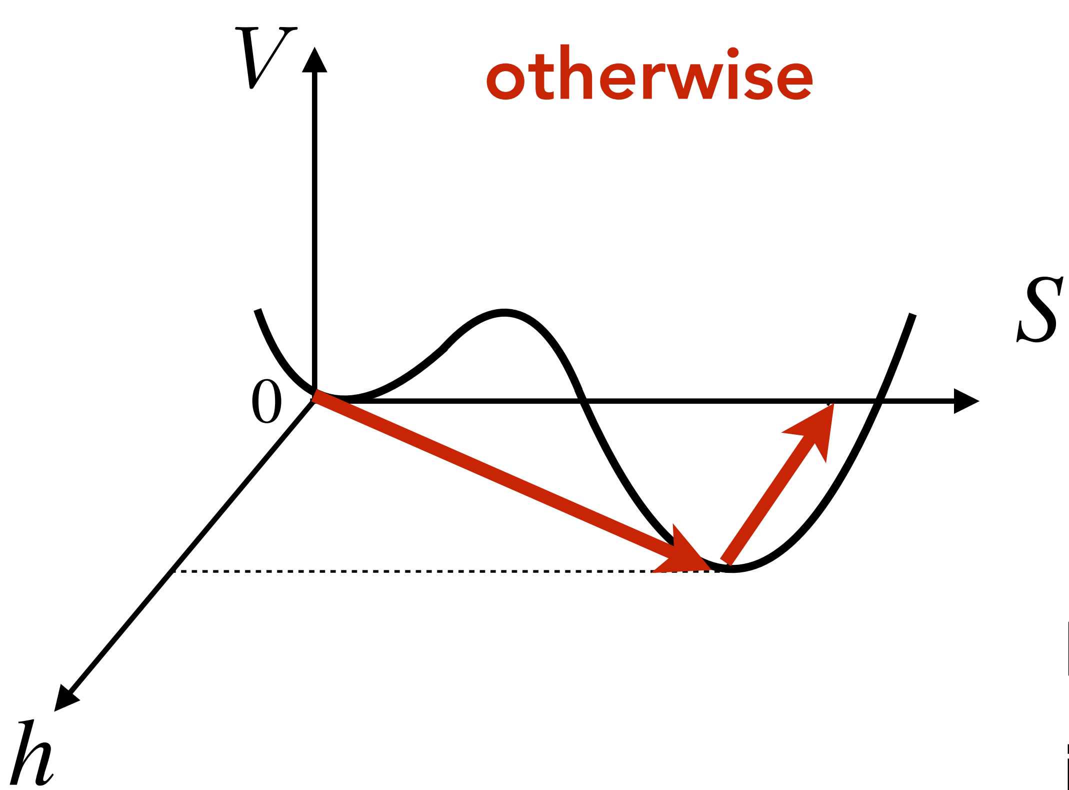
Electroweak baryogenesis requires an additional light scalar S .



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

otherwise



$\Rightarrow$ for T restoration ~130 GeV

$m_S \lesssim$ O(100 GeV)

Light S -> Very constrained by EDM

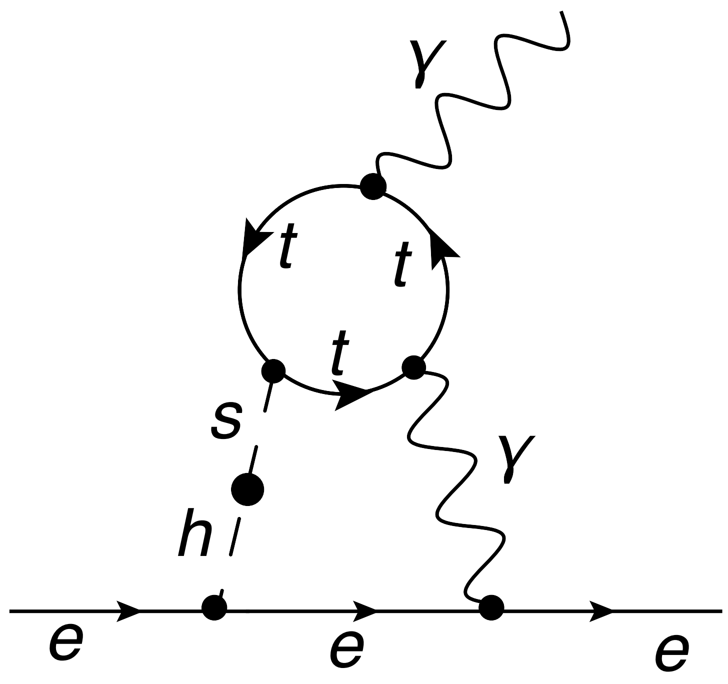
if mixes with h

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

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

ACME II, Oct. 2018.

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

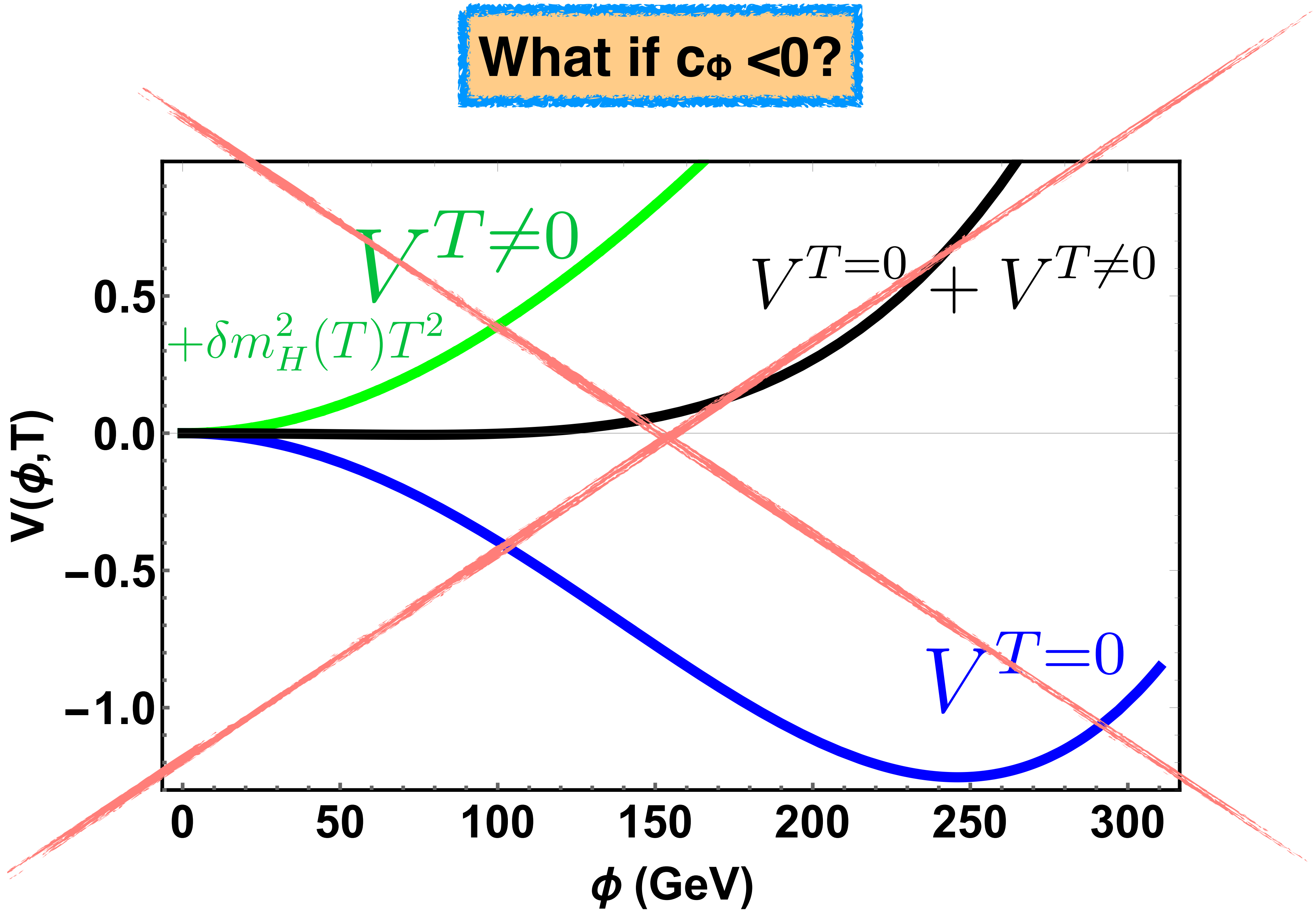
Can we push up the temperature of the EW phase transition ?

High-temperature EW symmetry non-restoration .

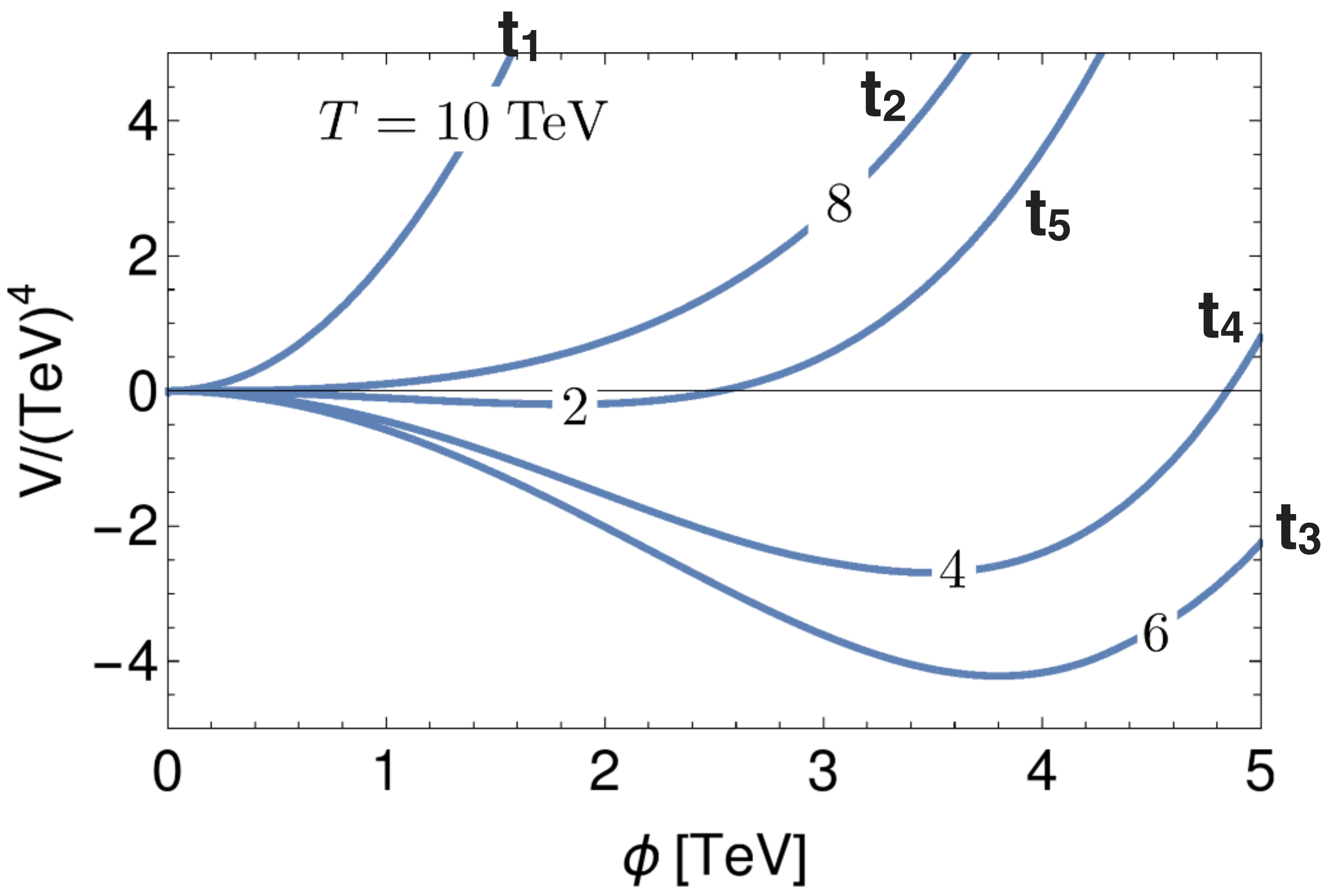
EW Symmetry restoration comes from the competition of two opposite terms in Higgs mass parameter

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

What if c_ϕ <0?



High-scale (T>TeV) EW phase transition



1807.08770

Pushing up the temperature of the EW phase transition .

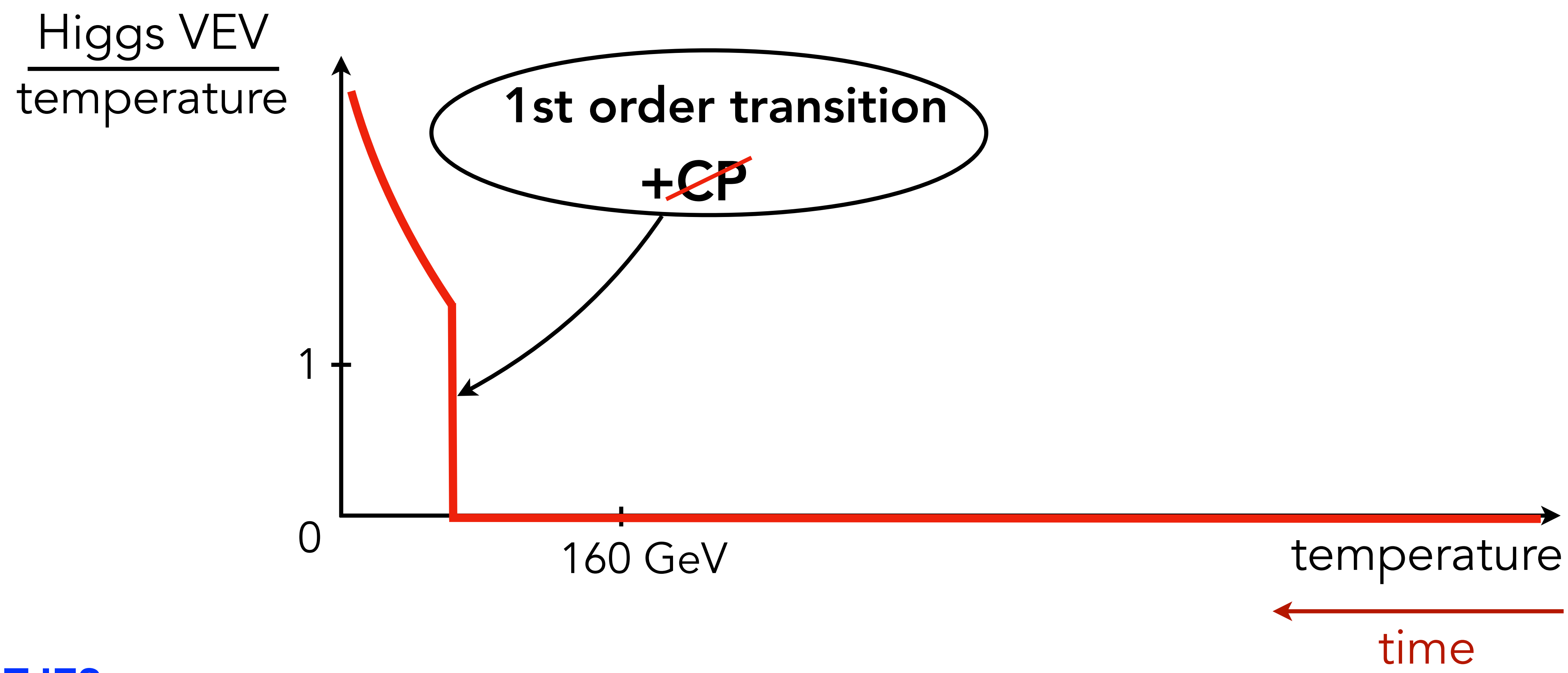
> **Motivation: EW baryogenesis using high-scale sources of CP violation, allowed by data**

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

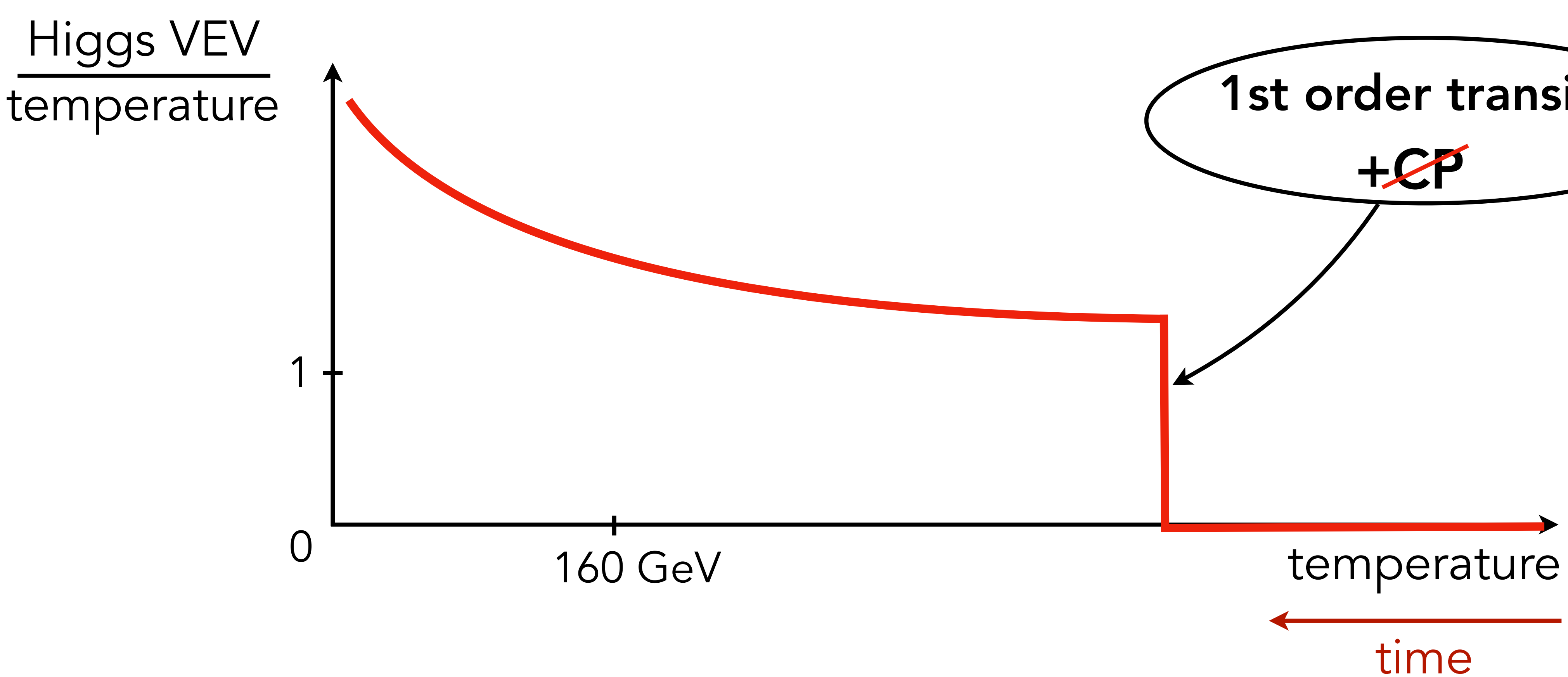
> **opens large new windows of theory space for successful EW baryogenesis even if T_{EWPT} pushed by only a few hundreds of GeV**

> **Gravitational-Wave peak at LISA shifted to higher frequencies**

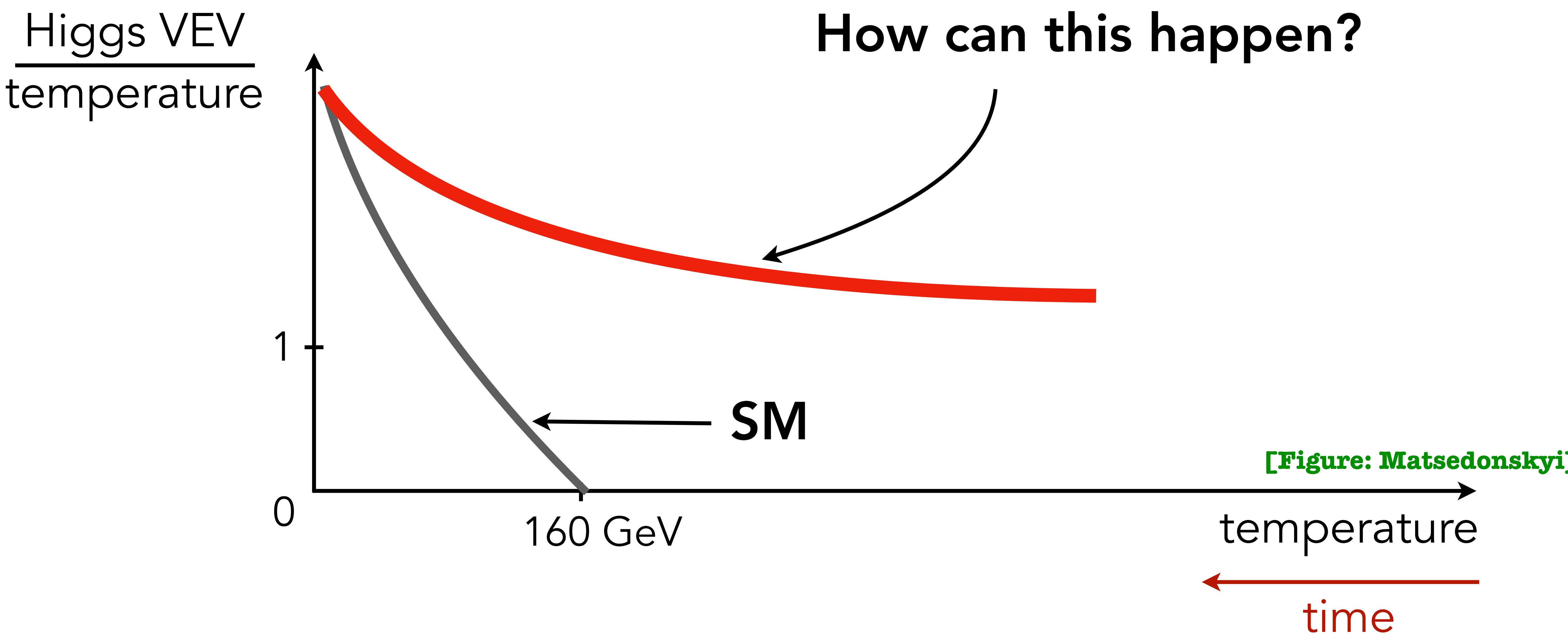
In EW baryogenesis scenario:



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)

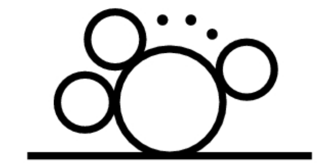
Bai et al, Biekötter et al, Carena et al, (2HDM)

HIGGS EFFECTIVE POTENTIAL AT HIGH TEMPERATURE .

At one-loop:

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

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_{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

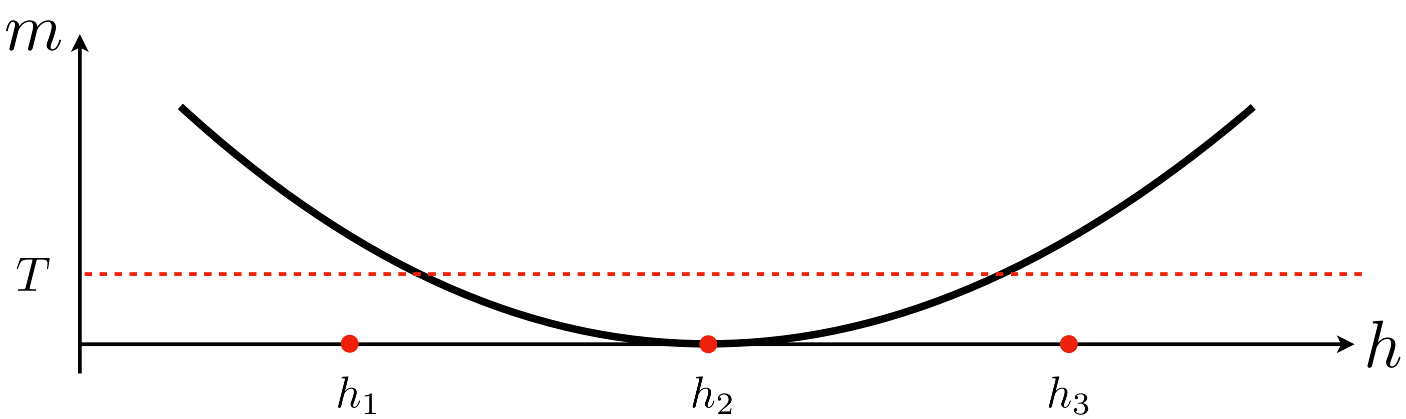
EW symmetry non-restoration at T>M_H .

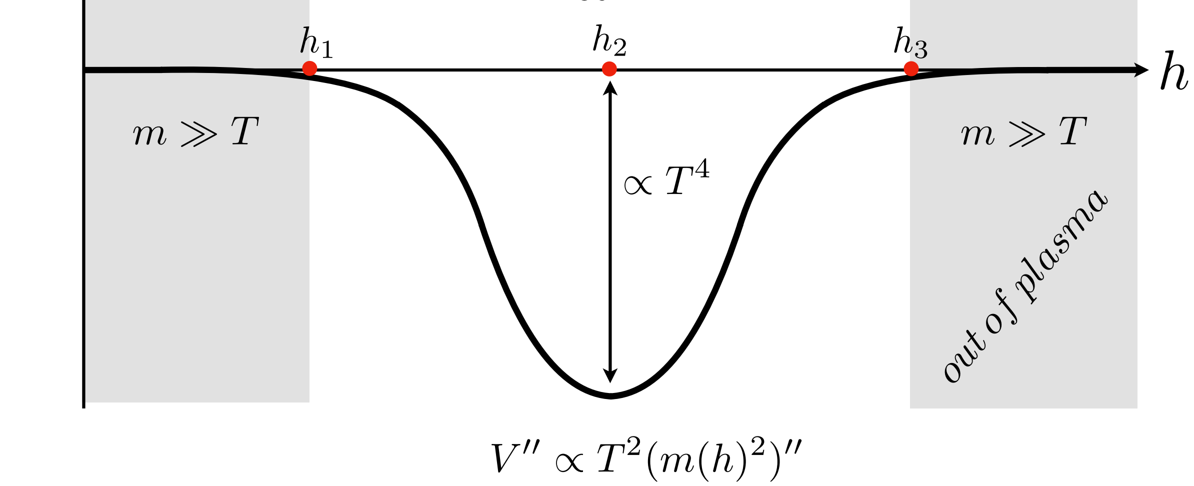
> SUMMARY OF PRINCIPLE: Massless or sufficiently light (m<T) particles coupled to the Higgs produce a dip in the Higgs potential of the size ~ -T^4

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

for m/T<<1 :

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





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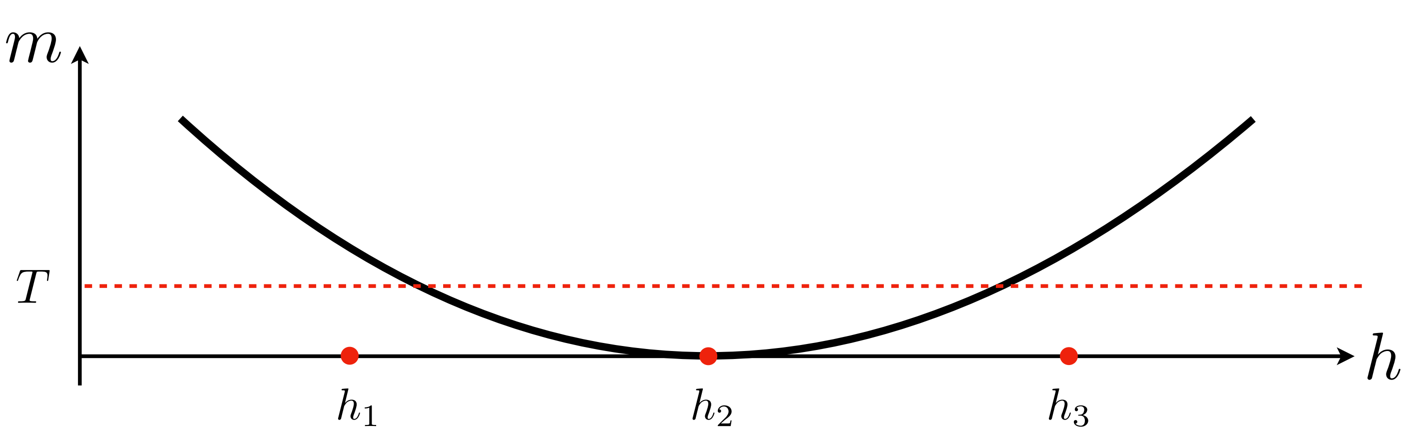
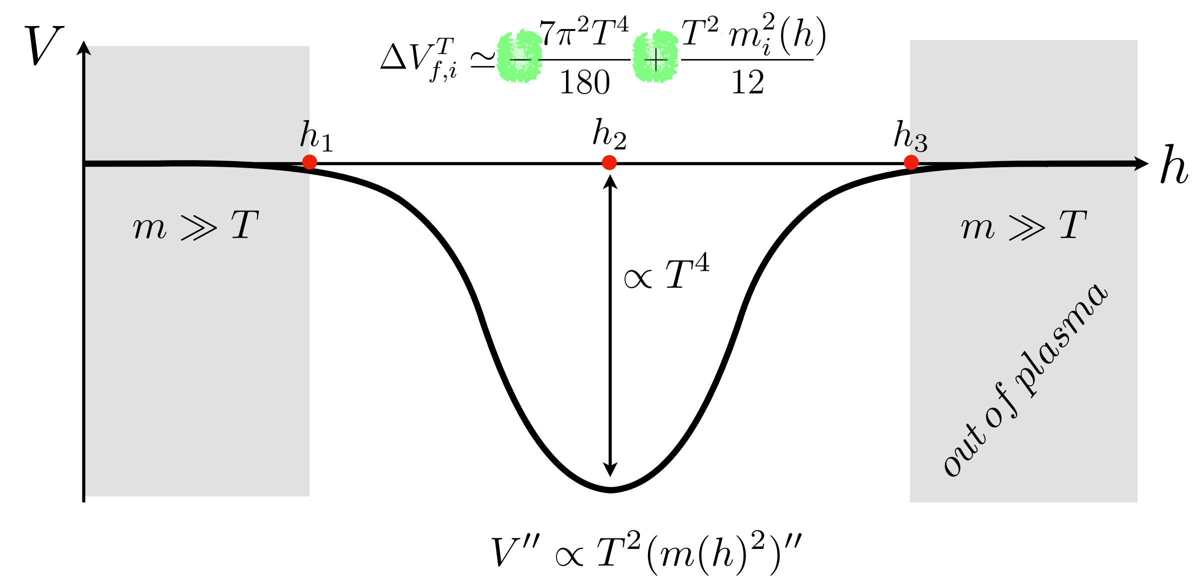


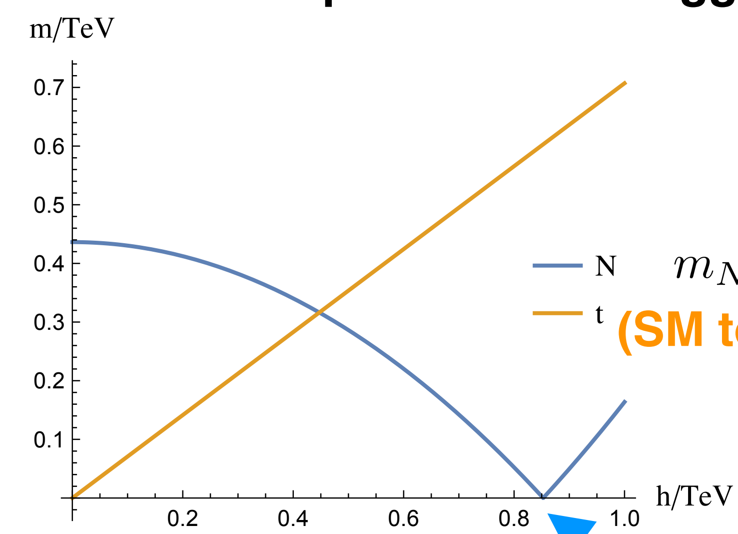


If some degree of freedom is effectively massless at a large Higgs VEV, the induced thermal negative correction at this VEV can make the Higgs field origin unstable leading to high-T EW symmetry non-restoration.

Example: Add a singlet fermion N

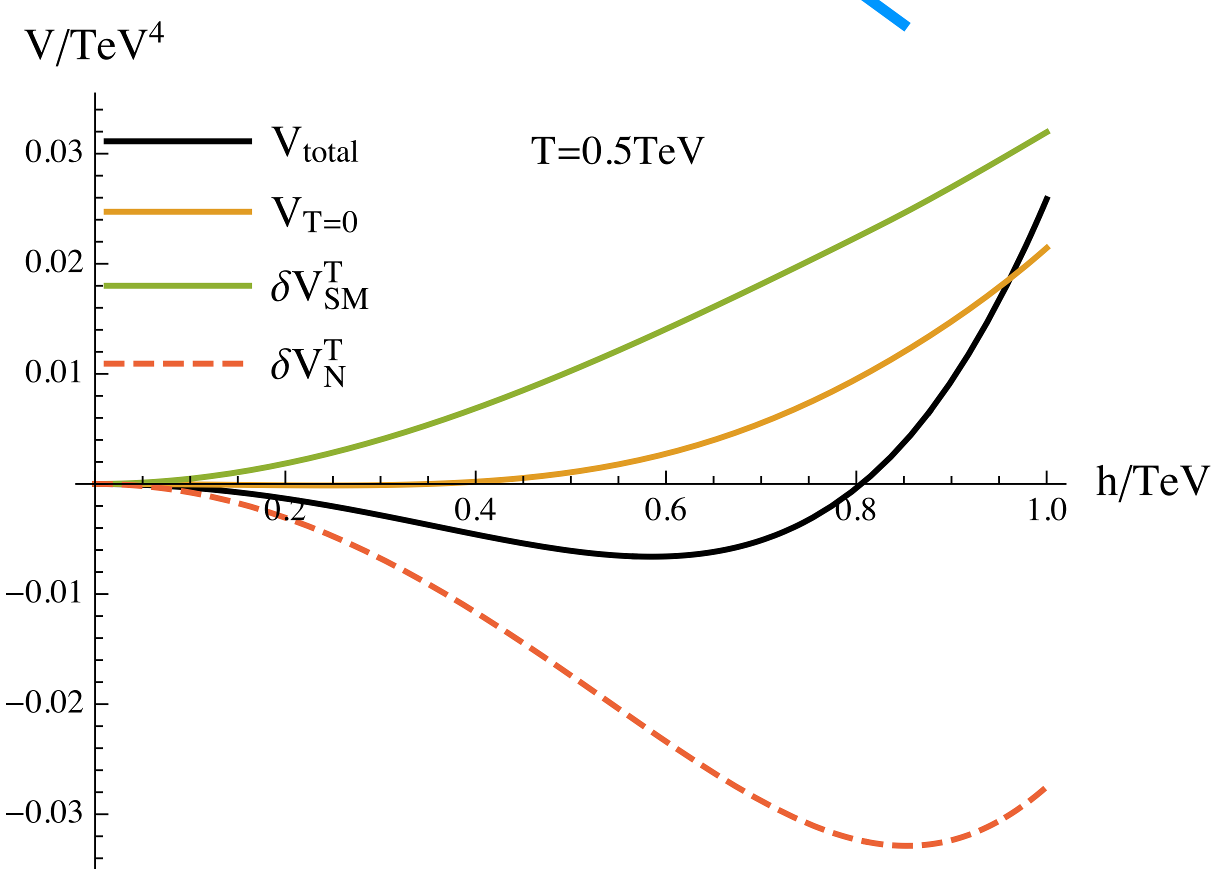
$$\mathcal{L}_N = -m_N^{(0)}\bar{N}N + \lambda_N \bar{N}Nh^2/\Lambda$$

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 .

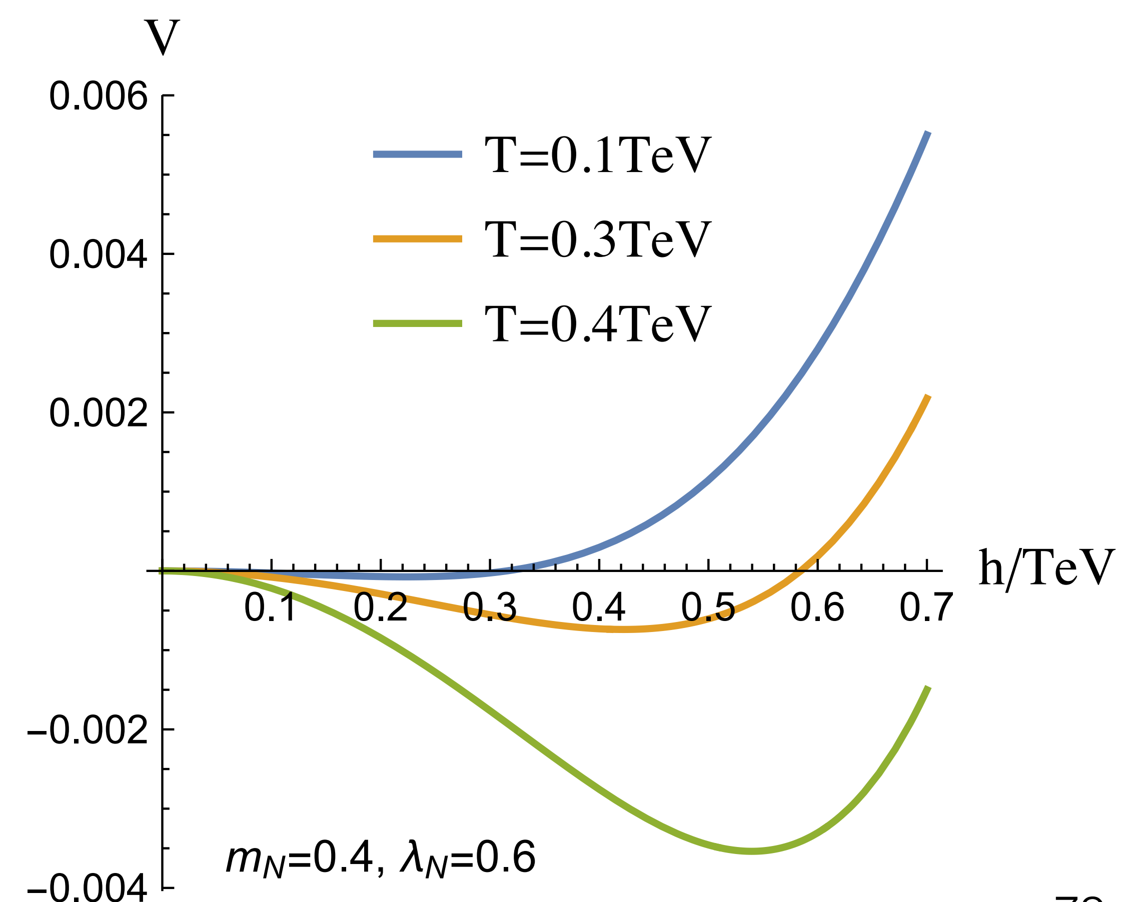
Add n new fermions N with Higgs-dependent mass contribution. Mass vanishes at <h>≠0

[2002.05174]

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

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

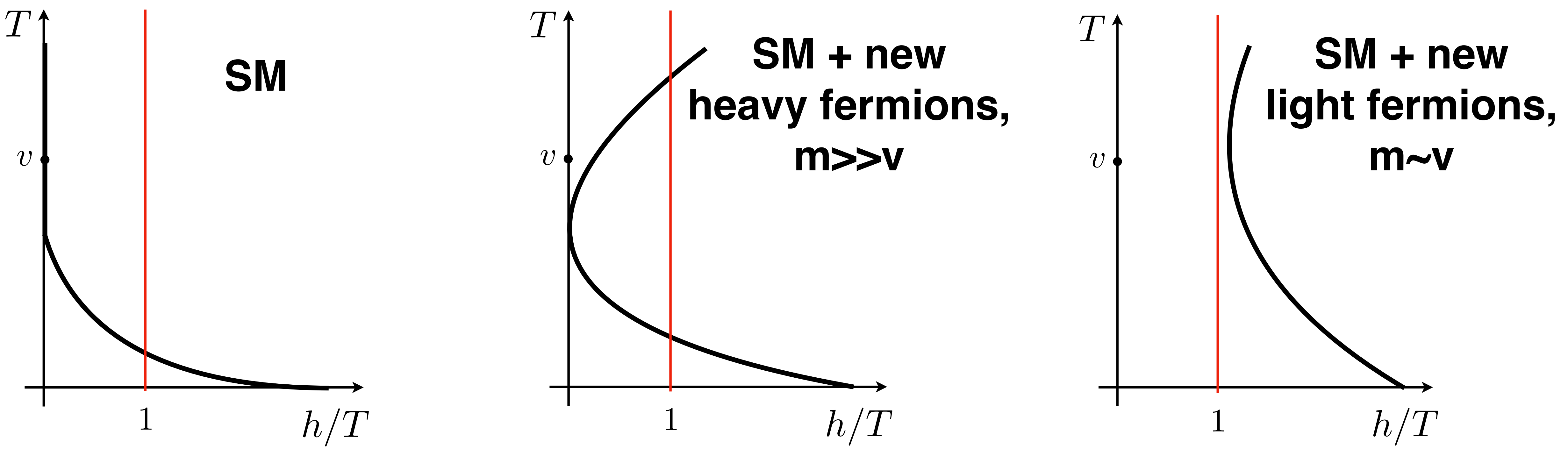
Negative thermal mass



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 !

7- The Top Quark & Composite Higgs cosmology .

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

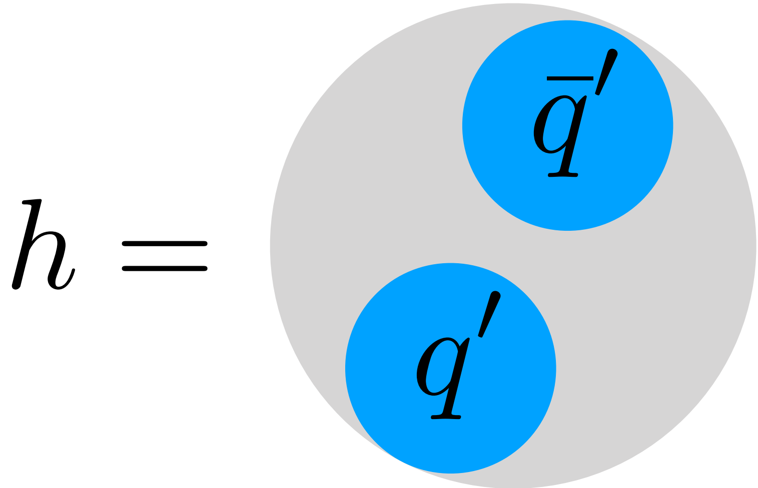
-the flavour hierarchy —> from partial fermion compositeness
CP-violation from the varying Yukawas during the EWPT

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



Lighter than confining scale because is a Pseudo Nambu Goldstone Boson 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.

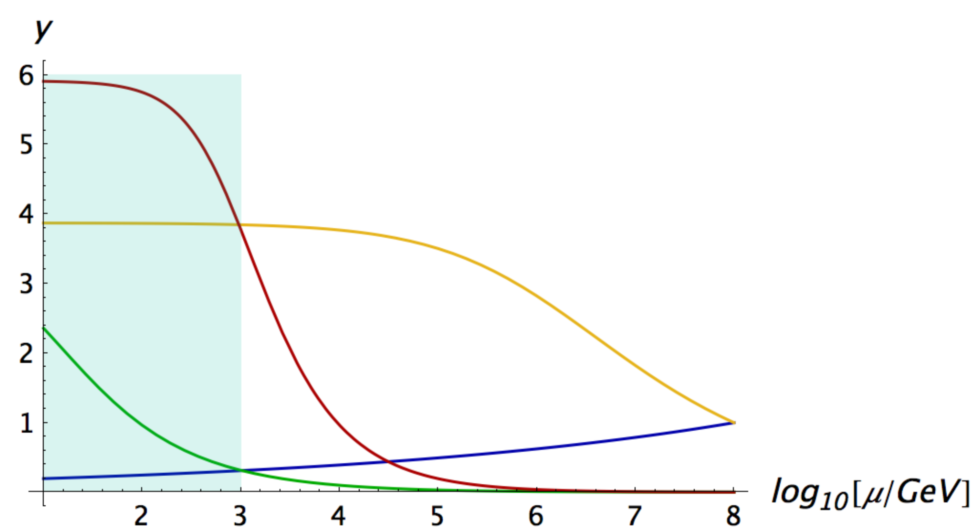
SM electroweak gauge group is embedded in subgroup of SO(5) and a U(1)X factor.

A model of Flavor:Partial fermion compositeness

E

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

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



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

Goldstone matrix containing the Higgs

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

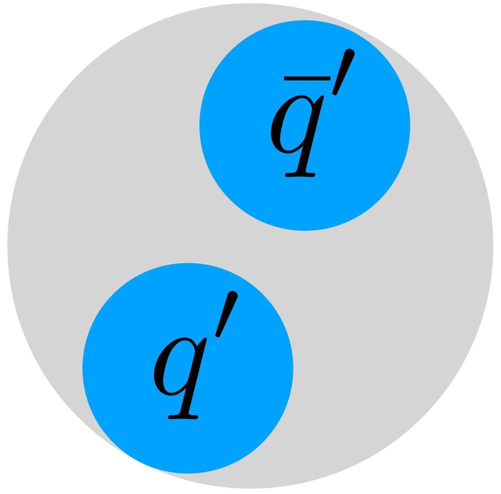
Integrating out ψ_i with $m_\psi \sim g_\star f$

SM Yukawas determined by the mixings at the confinement scale

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

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

EW phase transition in Composite Higgs models

$h =$ 

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

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

Impact on EW phase transition in Composite Higgs.

(1) SM-like EW phase transition

(crossover)

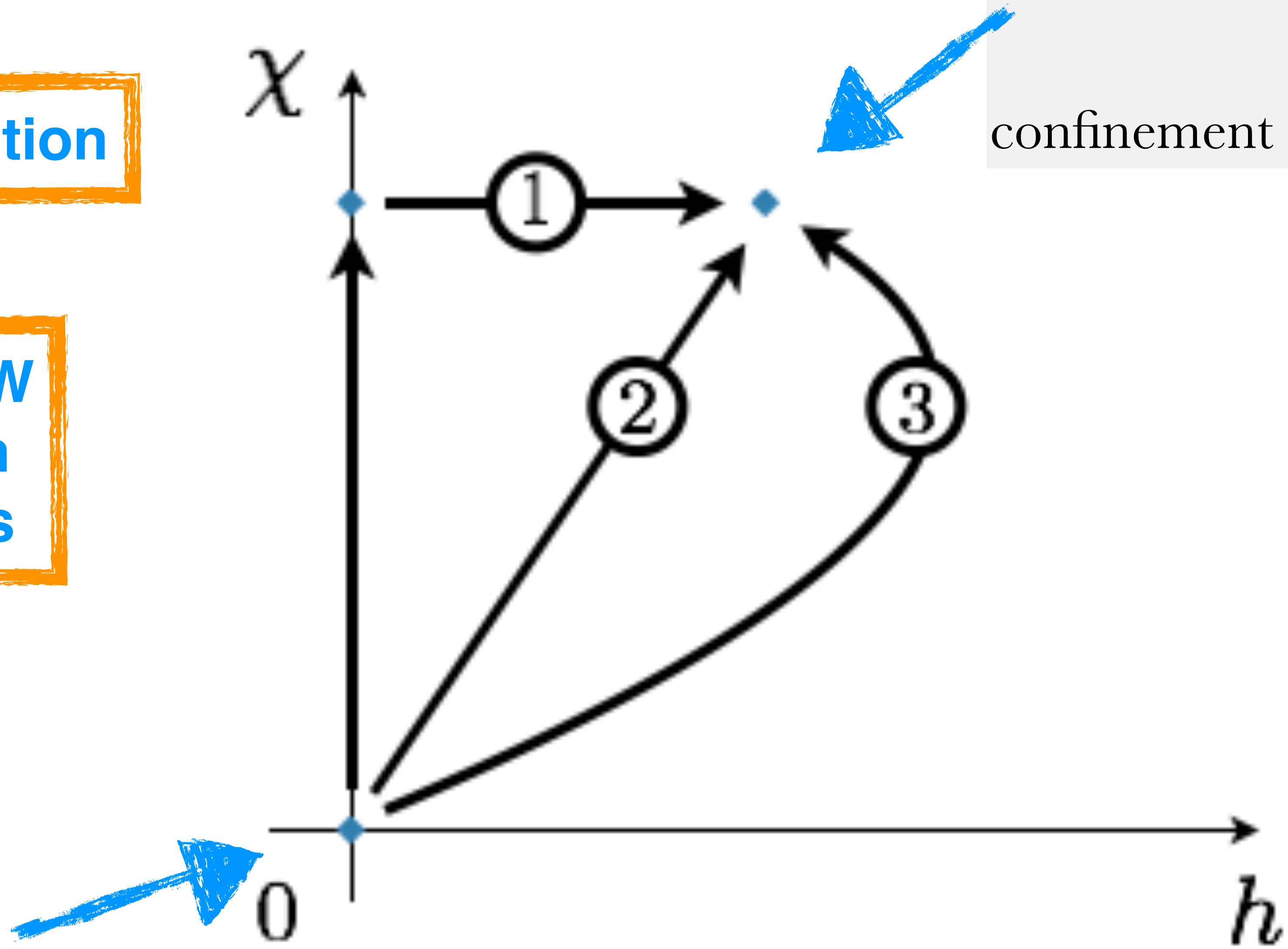
(2)-(3) Joint confinement-EW phase transitions: very rich pheno for EW baryogenesis

(strongly 1st-order)

global minimum at

$T \ll f$

confinement and EWSB



global minimum at

$T \gg f$

deconfined strong sector
unbroken EW symmetry

1804.07314

Constraints from reheating

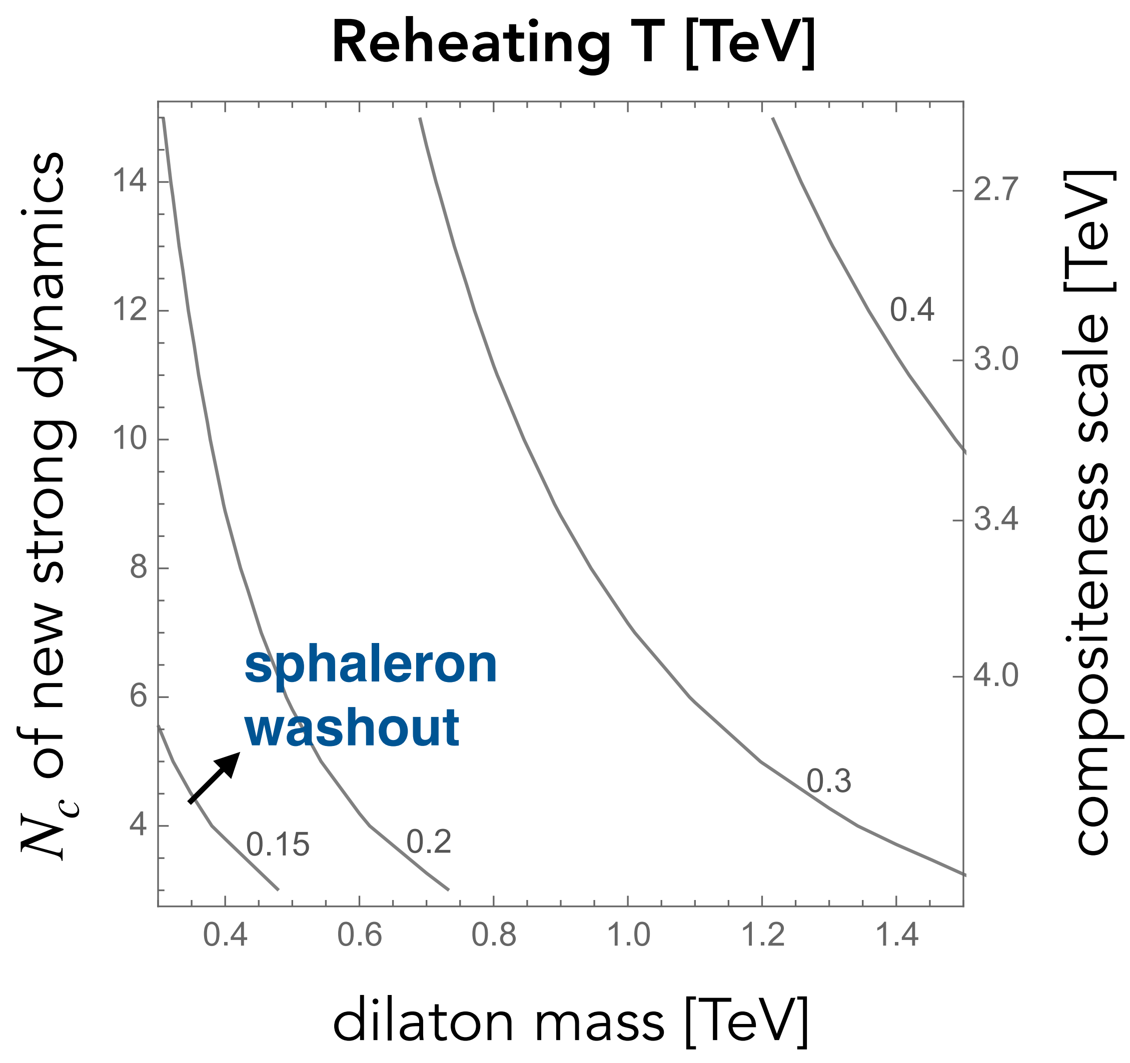
After confining phase transition: universe may be reheated above the sphaleron freese out temperature

To preserve baryon asymmetry from washout:

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

↓

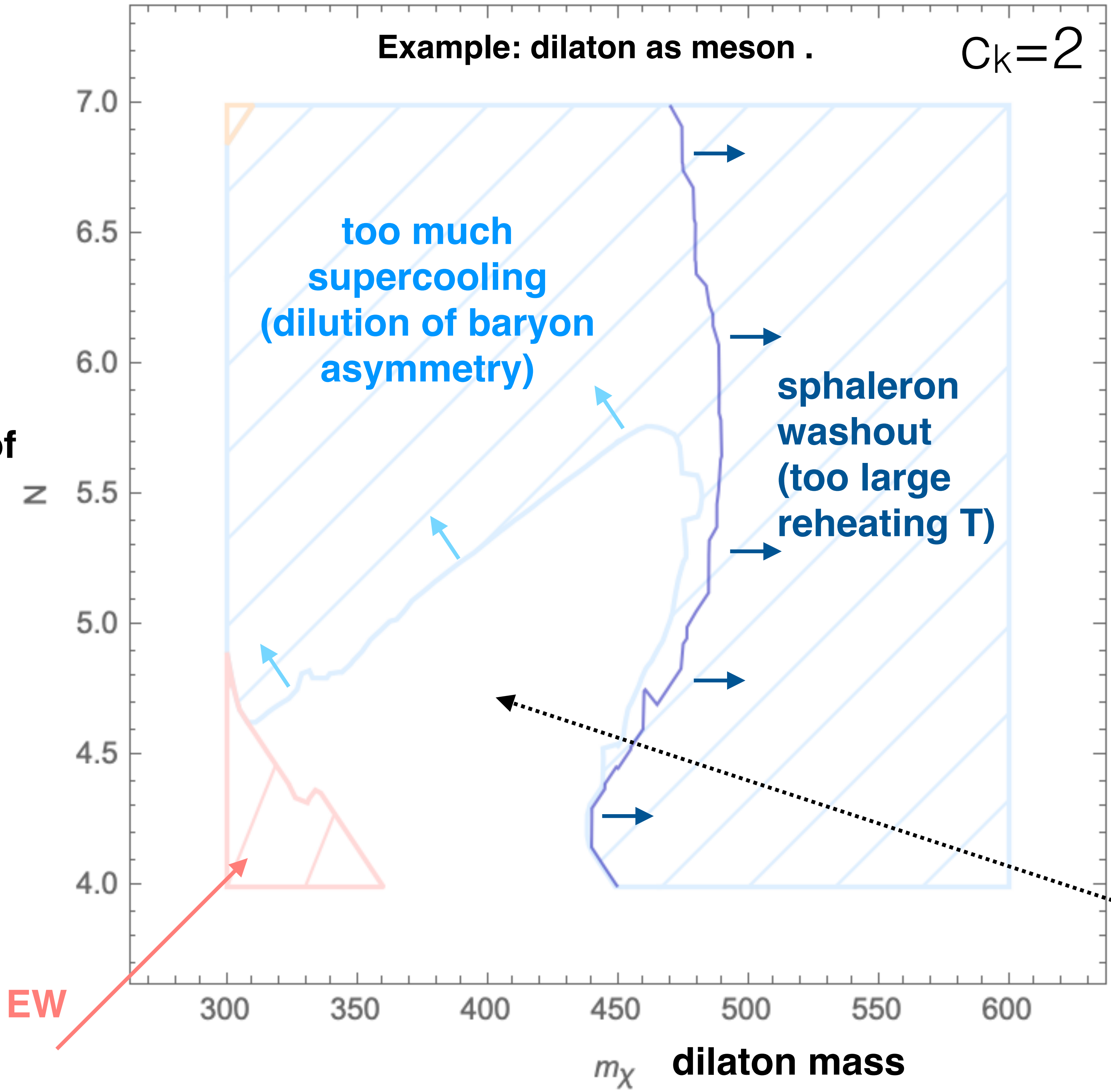
LIGHT DILATON WINDOW



A typical situation .

f=800 GeV

N: number of colors of strong sector



dilaton mass

no viable EW minimum

Entire viable region expected to be probed at the LHC!

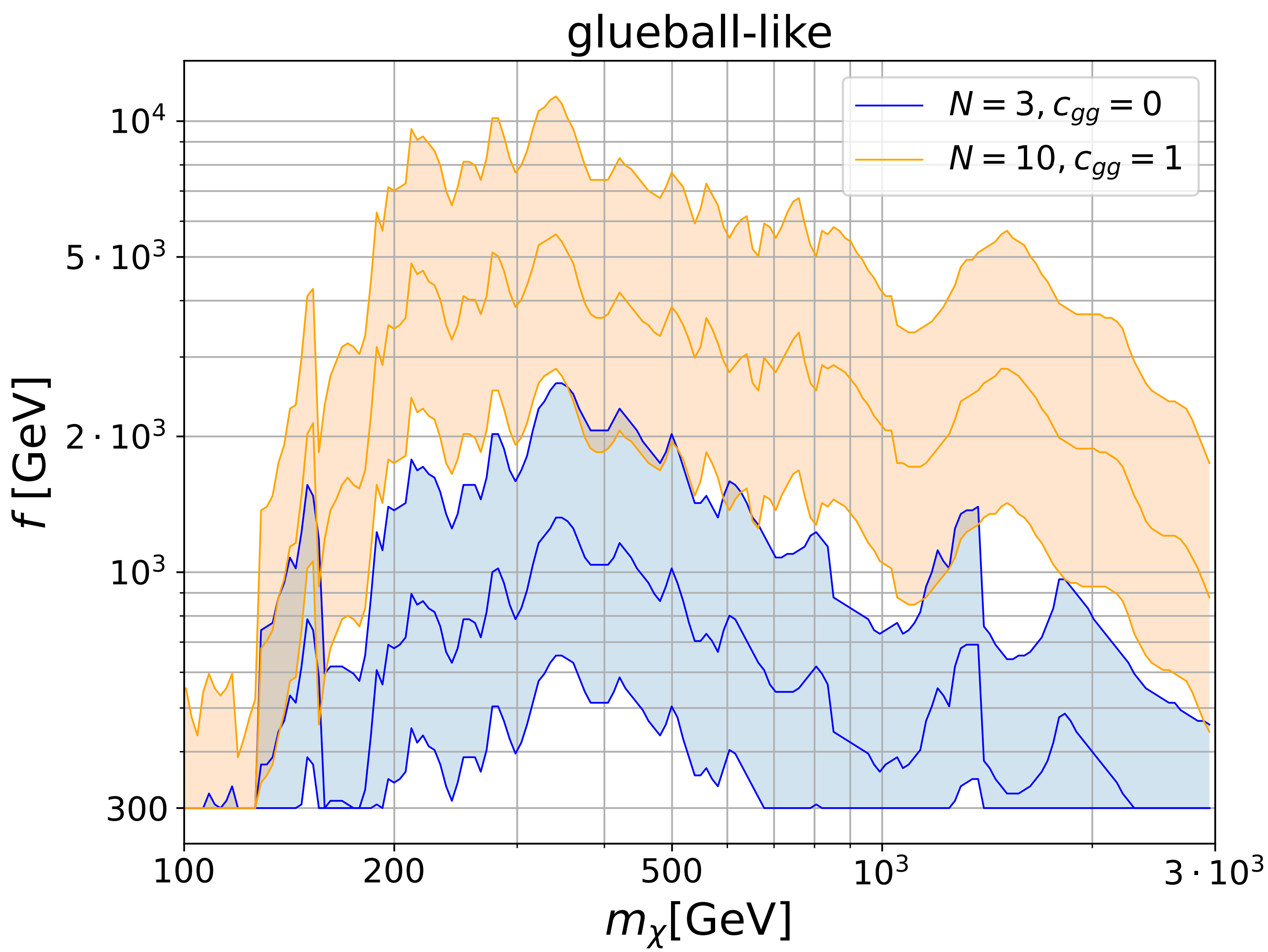
There is a series of similar plots scrutinising available regions for ≠ c_k and f values and for glue ball dilaton.

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

from Higgs-dilaton mixing

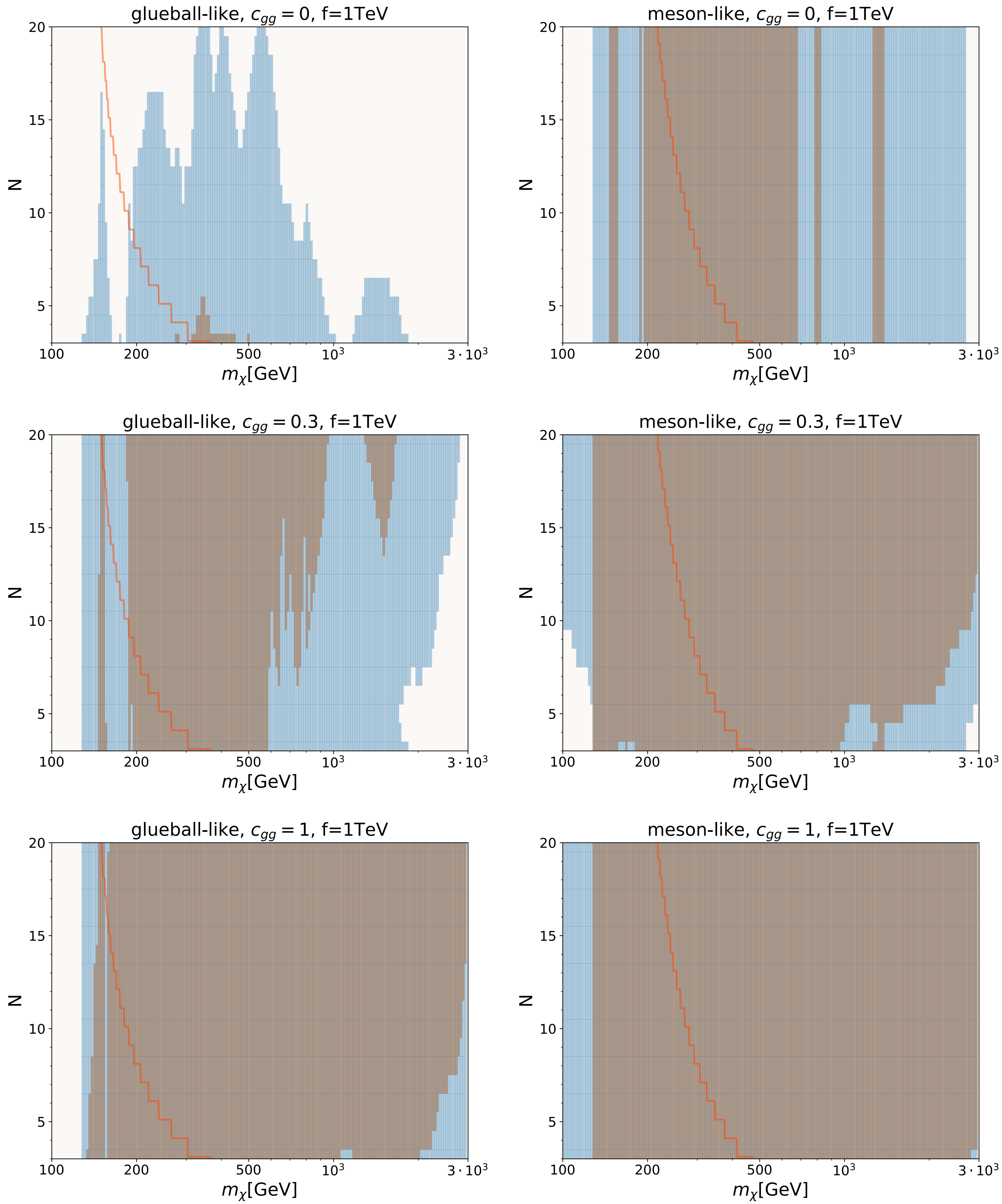
Almost all relevant region will be covered by LHC !

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

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

excluded

future sensitivity



2212.00056

CP-violating source for baryogenesis

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

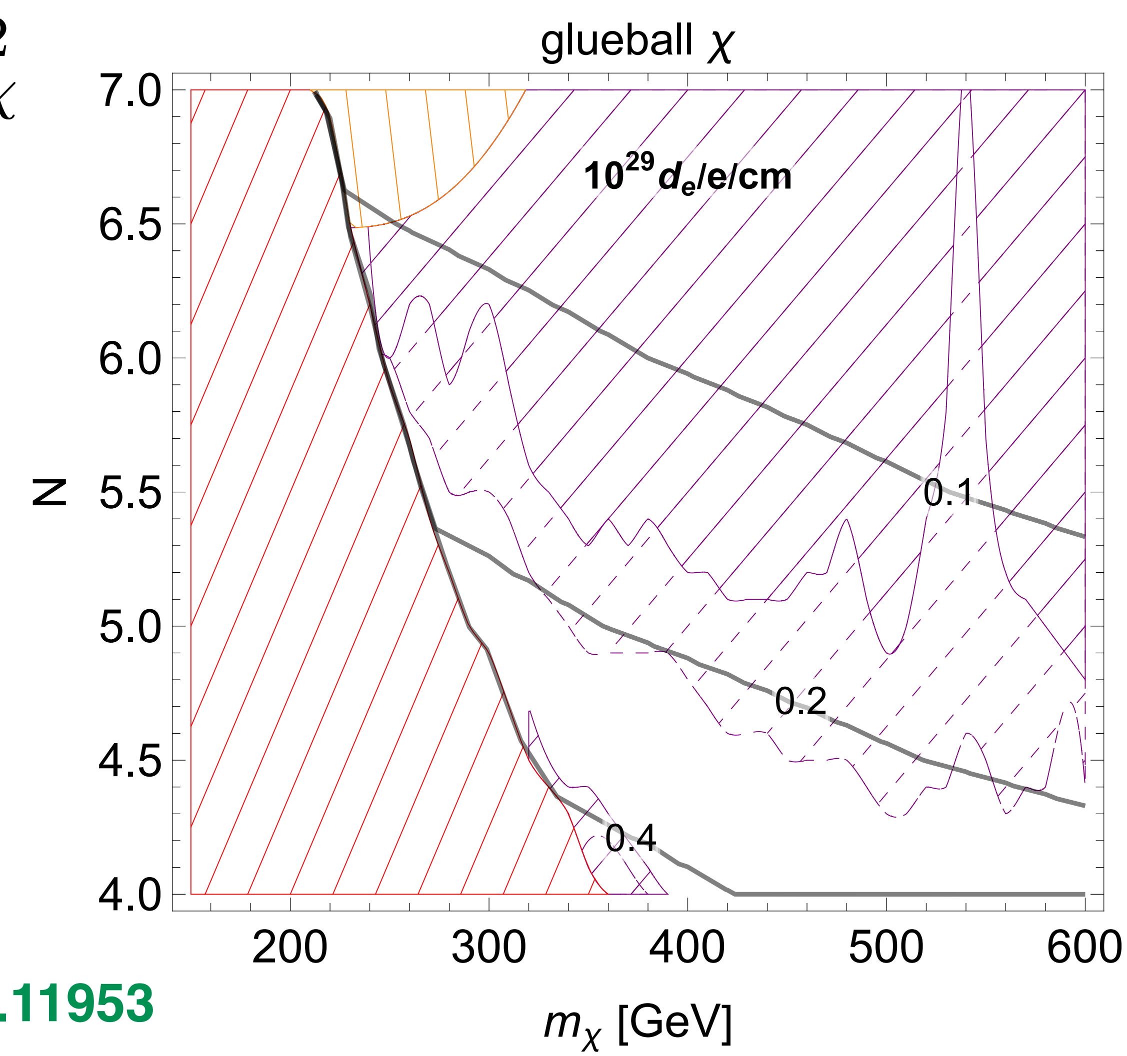
The CP violating coupling is coming from the complex part of $\partial\lambda_t/\partial\log\chi$.

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

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

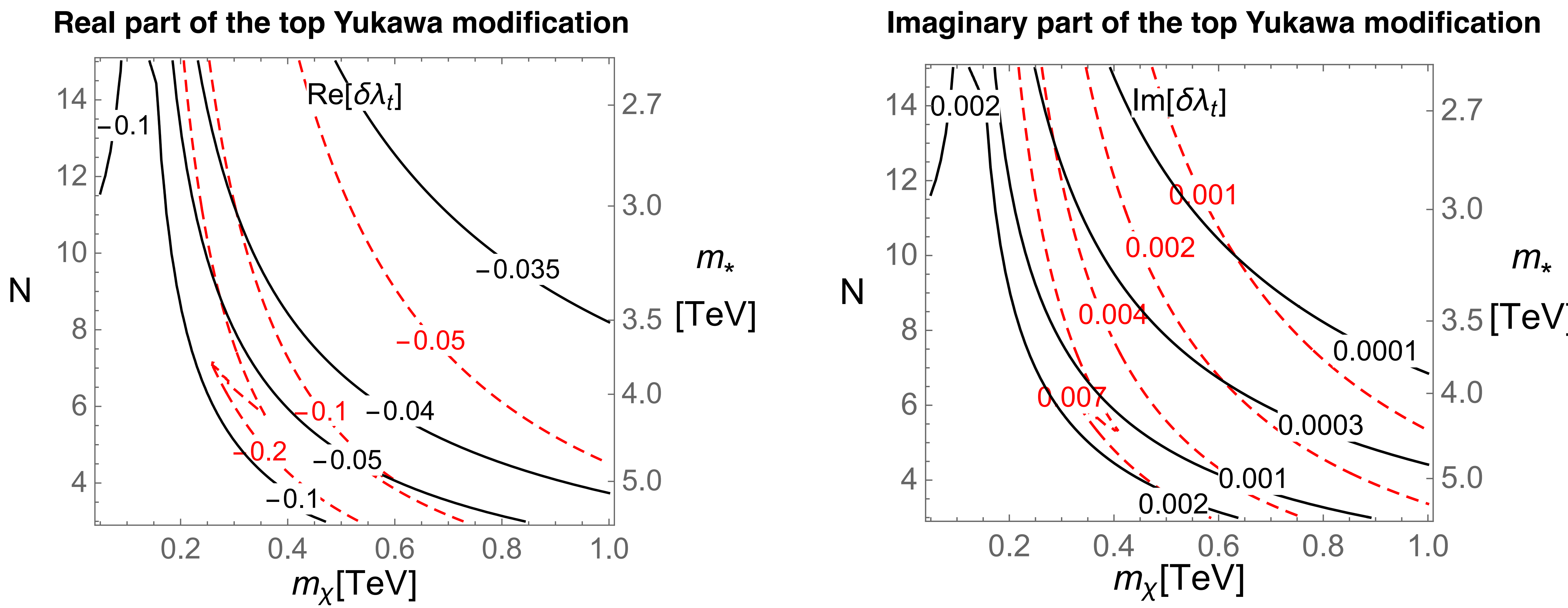
EDM bound can be evaded but
predicted EDM are close to ACME limit

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



2212.11953

Top-quark Yukawa modifications



1804.07314

- - - - - - - - - -: for a meson-like dilaton (red dashed)

__________ : a glueball-like dilaton

Dilaton-Top-quark coupling

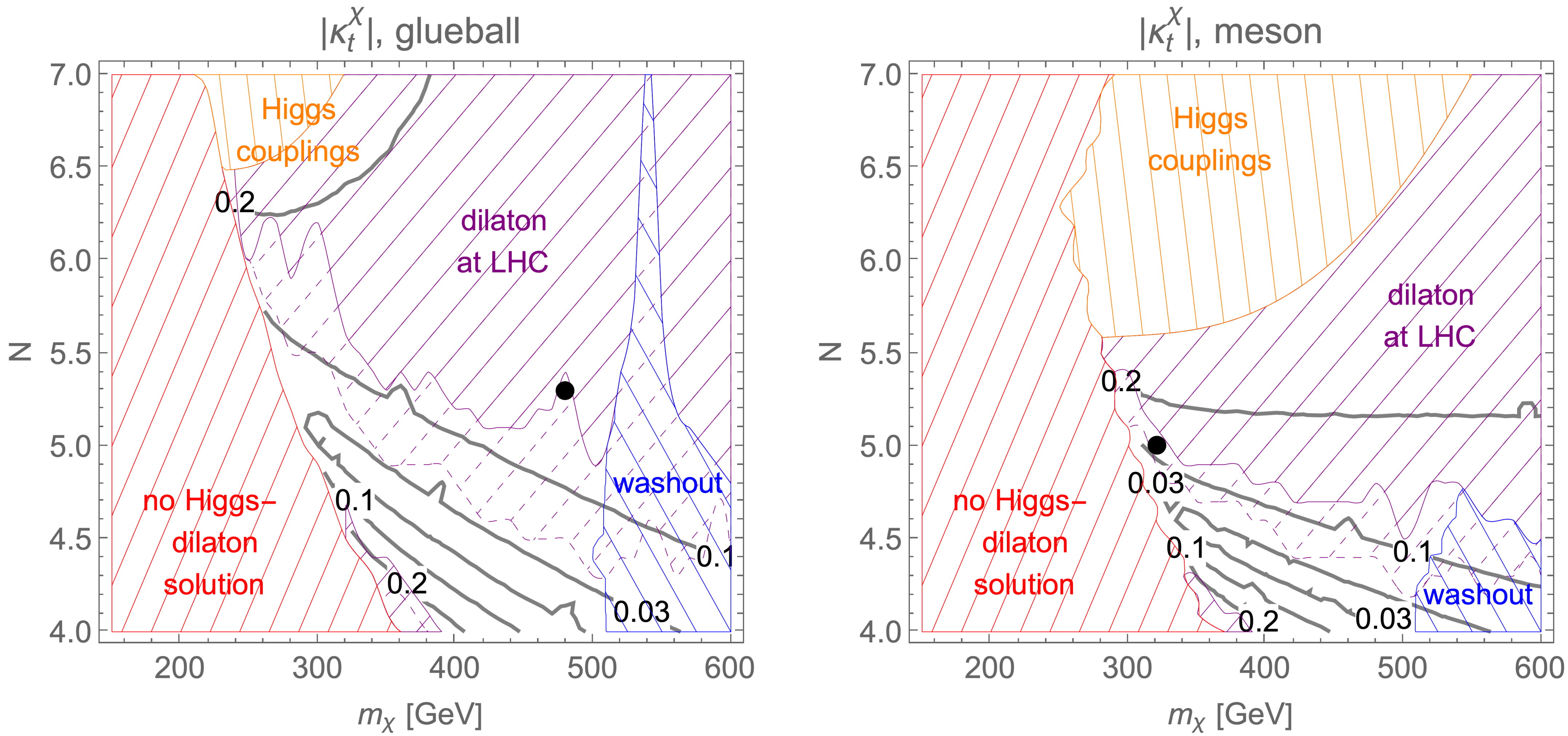
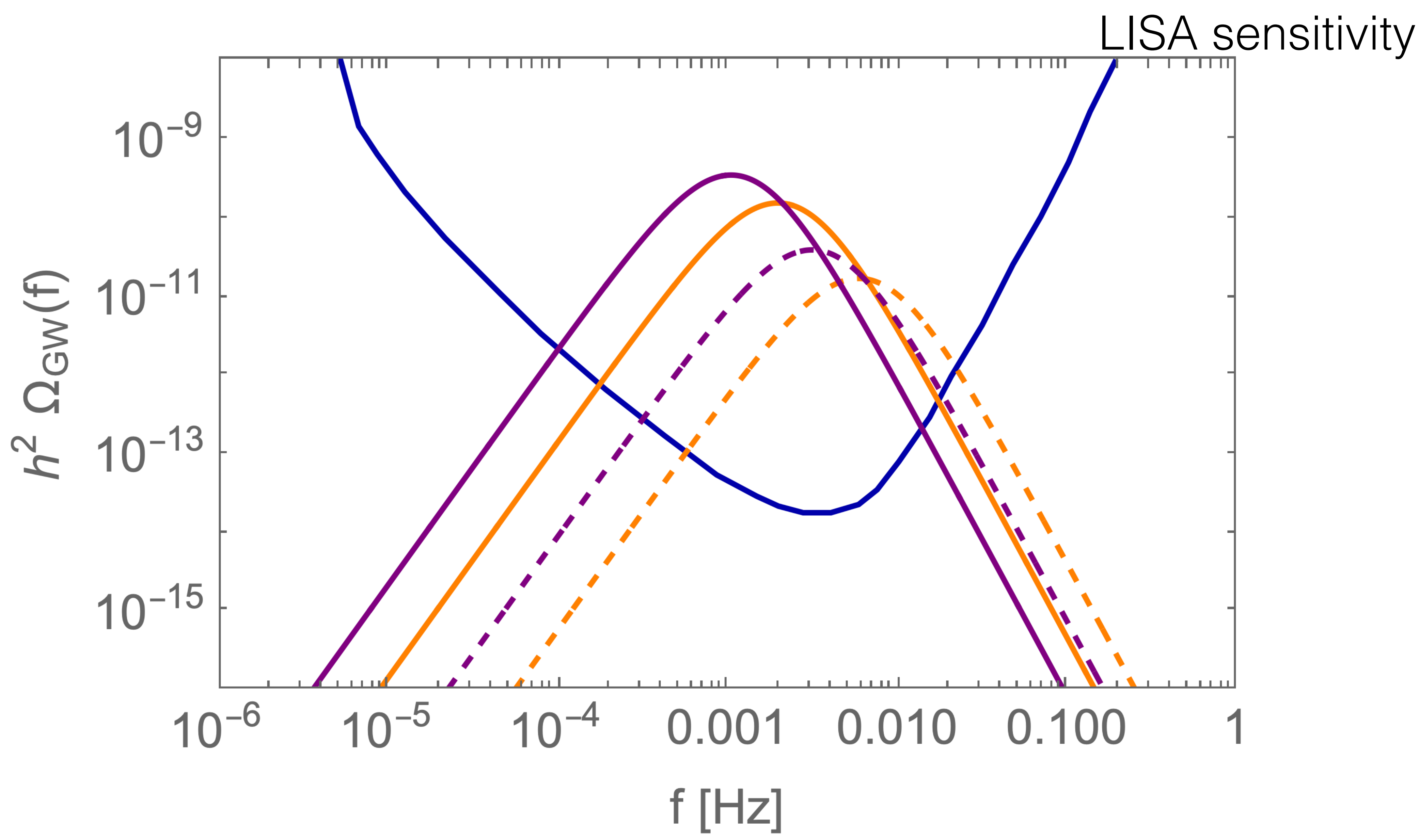


Figure 8: *Contour lines of the dilaton-top coupling κ_t^χ from Eq. (5.5) for a glueball dilaton (left panel) and a meson dilaton (right panel), both with varying top Yukawa. The color code for the hashed regions is the same as in Fig. 3.*

2212.11953

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



[Bruggisser et al'22]

Take-away message

Top-transport in EW baryogenesis still alive in Composite Higgs with nearly-conformal dynamics

Dilaton is goldstone of conformal invariance while the Higgs is goldstone of a global symmetry.

The top yukawa breaks both the Higgs shift symmetry and the conformal invariance

(it changes with energy). Mass mixing between the 2 induces the deviations in couplings.

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.

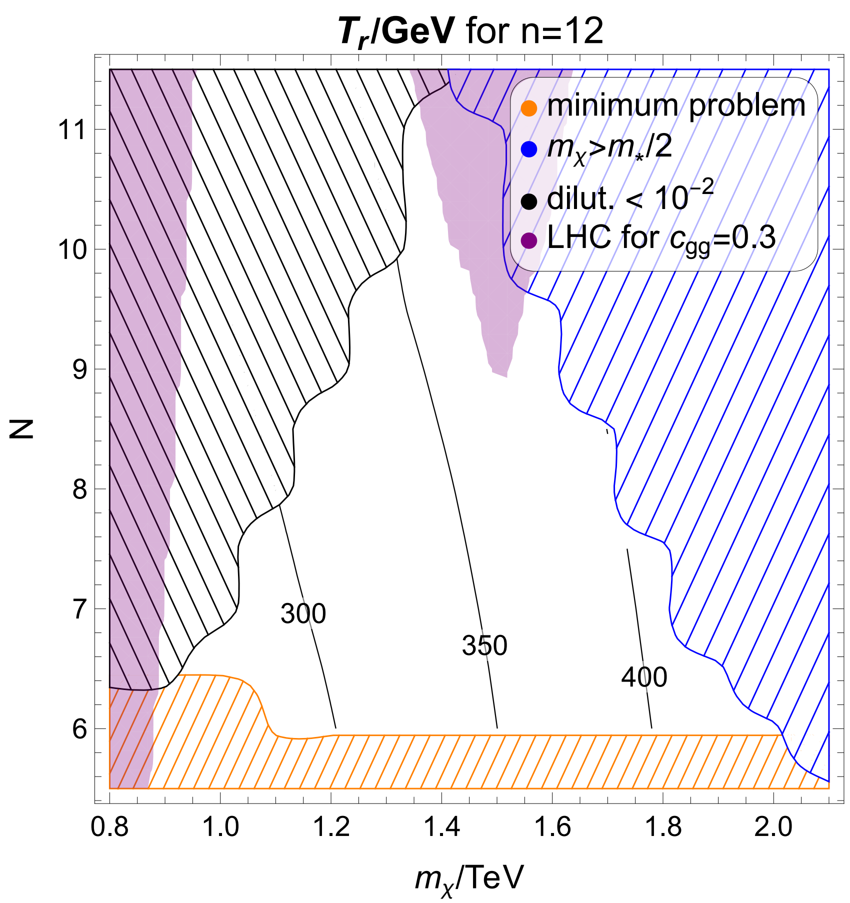
What next ?

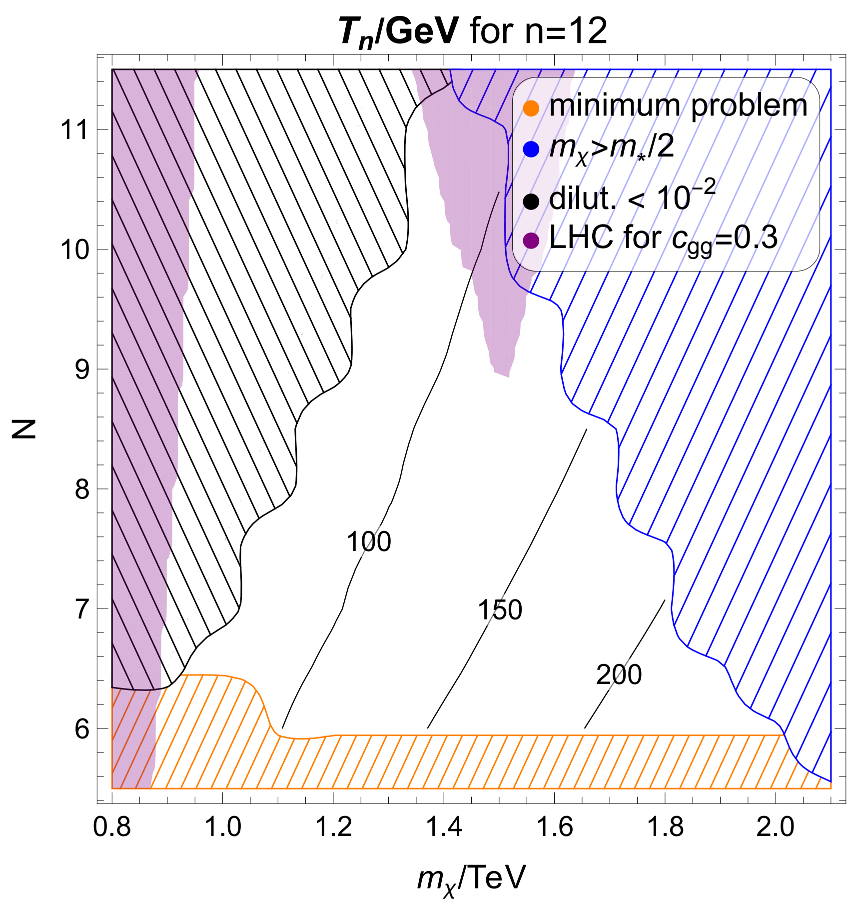
Revisit EWPT in Composite Higgs with extra singlet fermions

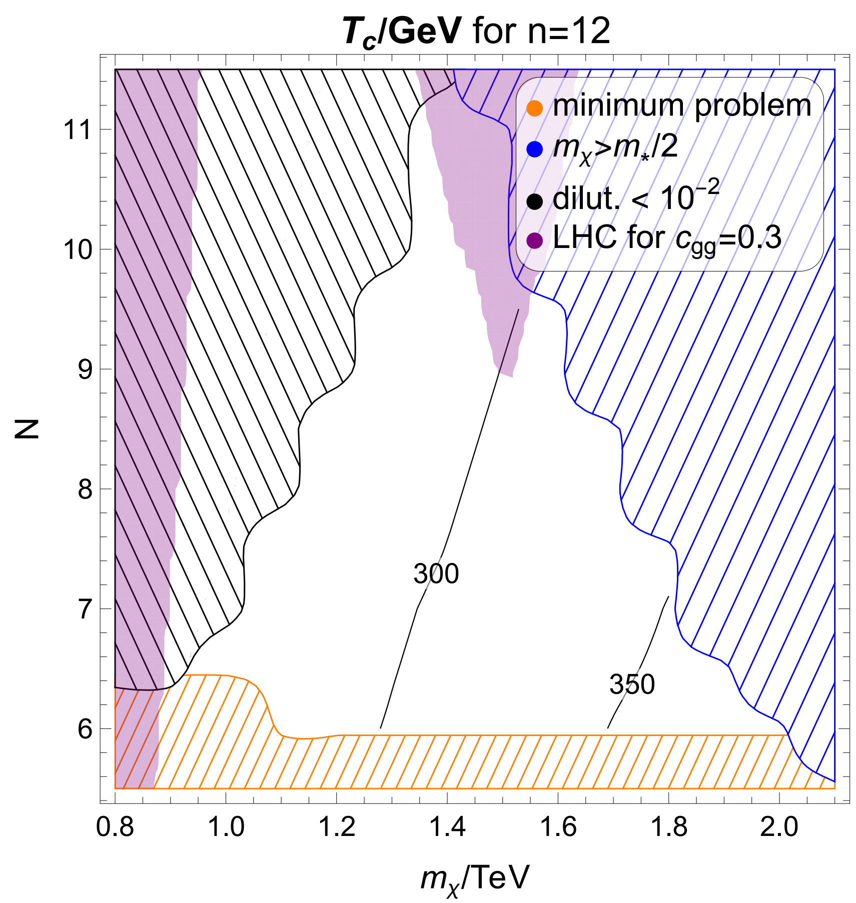
—> Open the heavy dilaton region!

VonHarling, Matsedonskyi, Servant, 2307.14426.

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



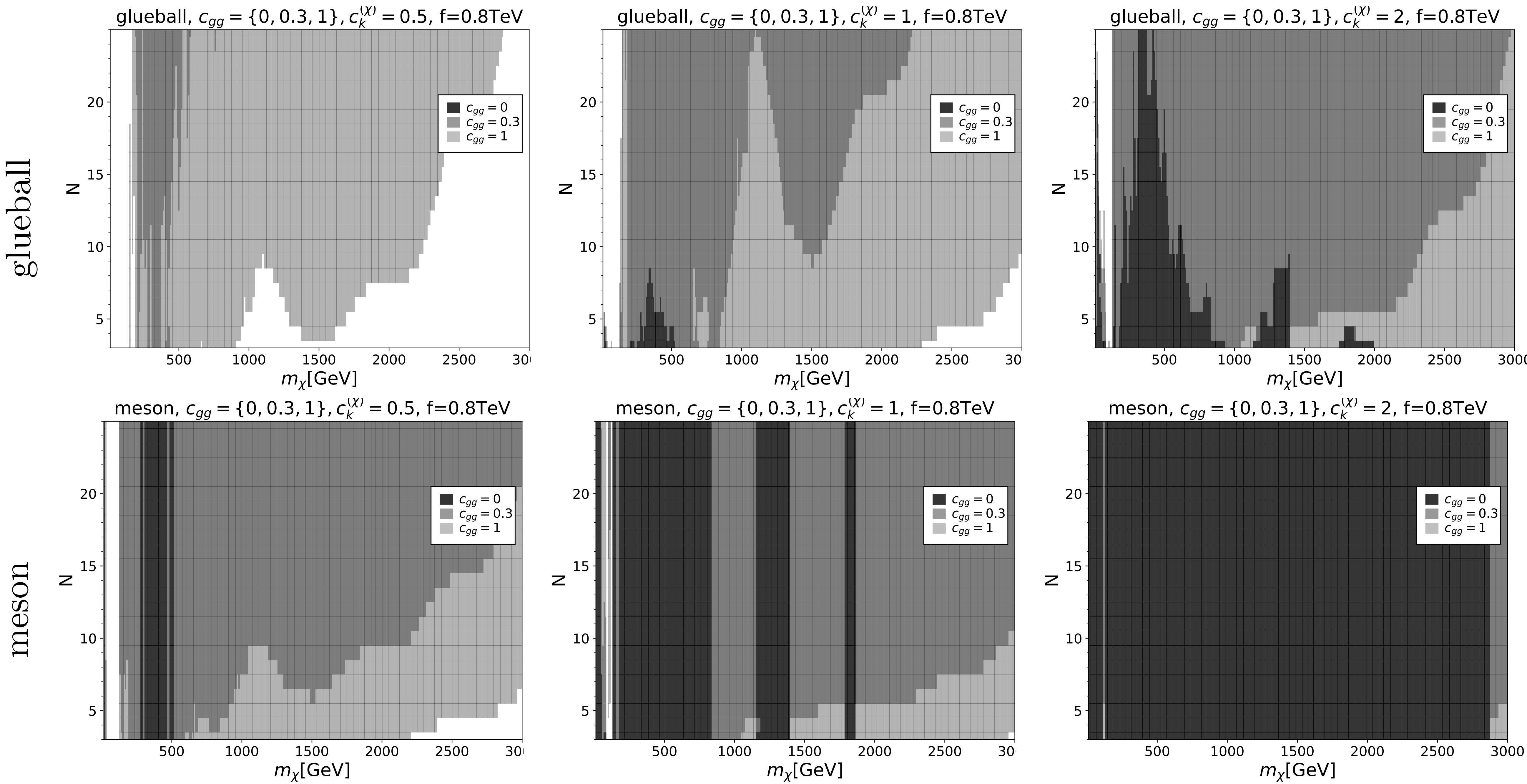




2307.14426.

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

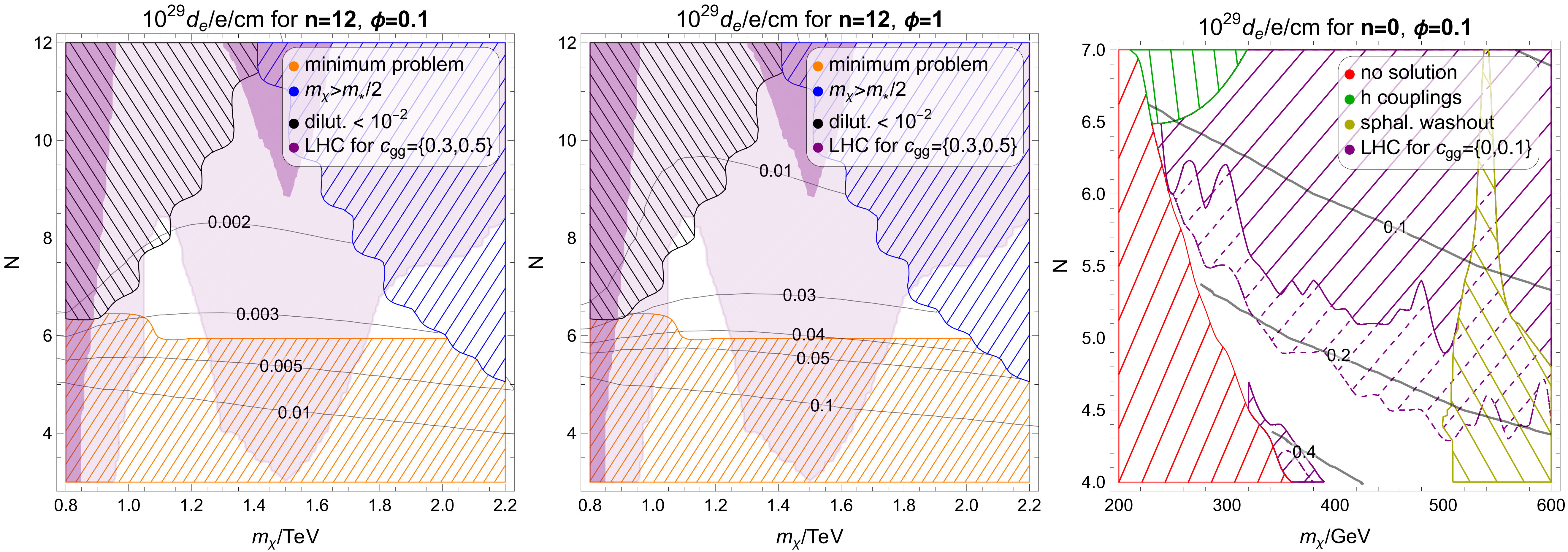
LHC bounds due to $c_{gg}\frac{g_s^2}{3g_*^2}\frac{\chi}{\chi_0}G_{\mu\nu}G^{\mu\nu}$



2307.14426.

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

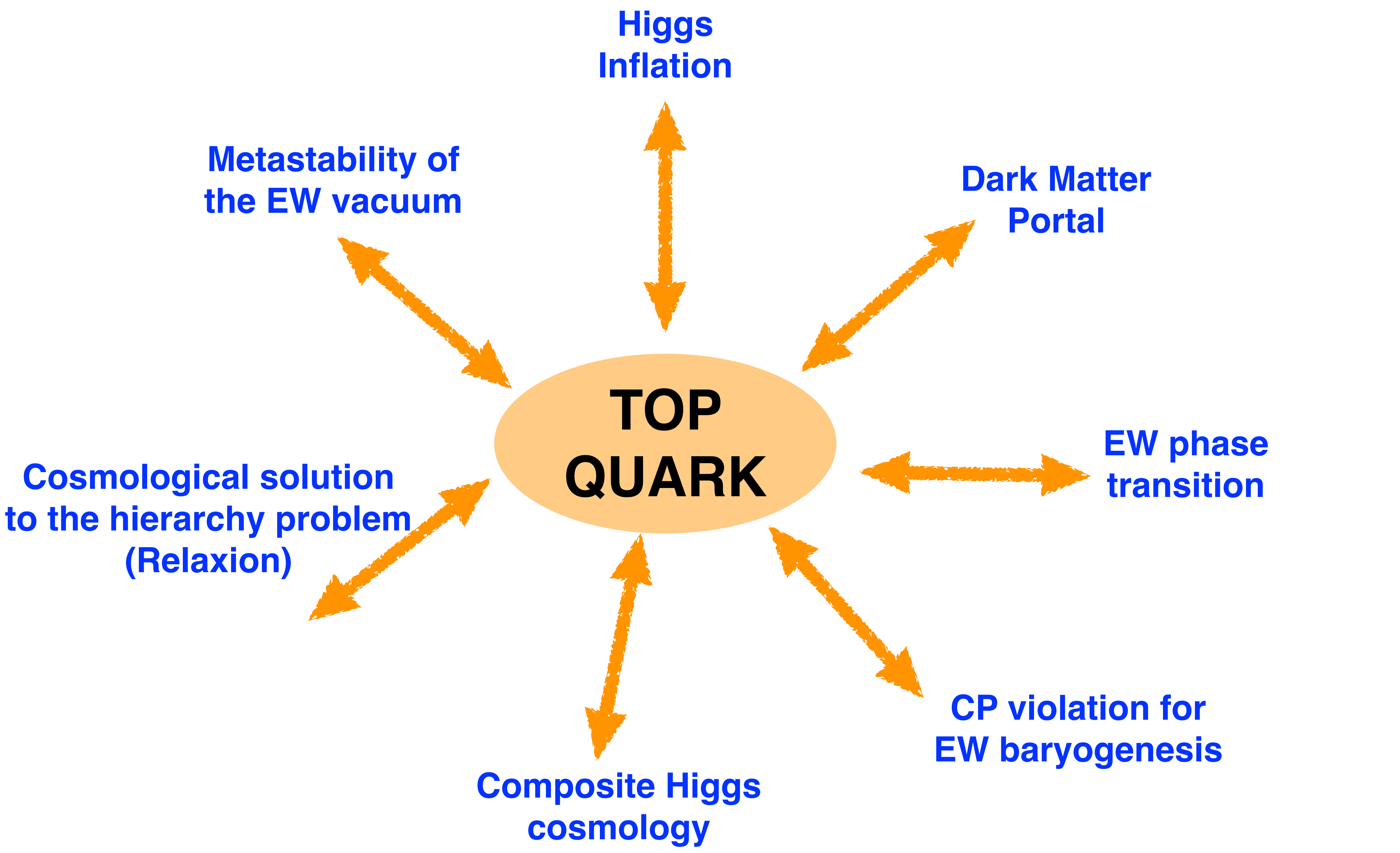
Much smaller EDMs ($\propto 1/m_\chi^2$)



2307.14426.

Summary

The Top Quark Cosmological Connections:



Back-up

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

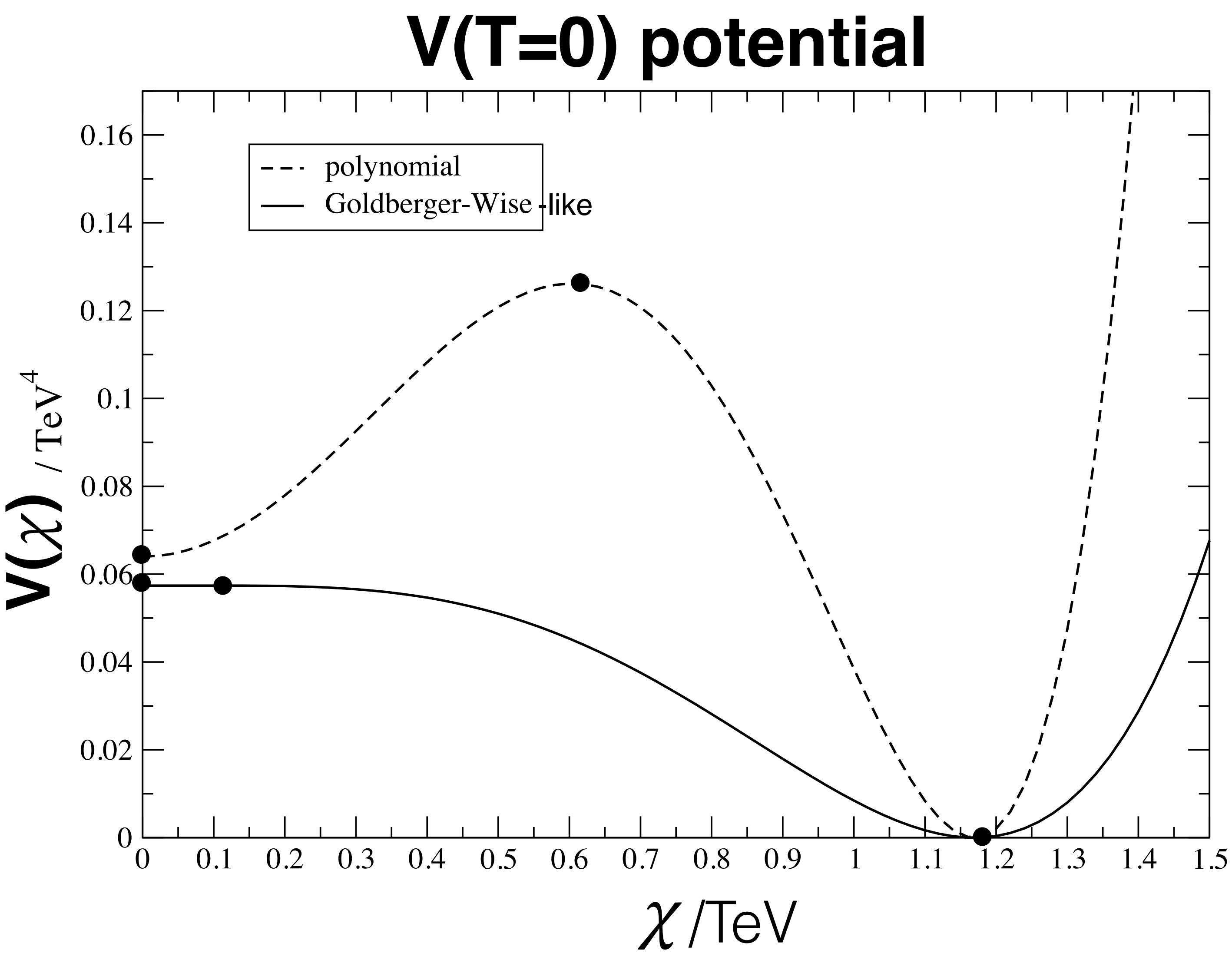
—> parametrically light dilaton, Goldstone particle associated with spontaneous breaking of conformal invariance

—> 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

$$g_* = c_k^{(h)} \frac{4\pi}{\sqrt{N}}$$

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_χ;**
- **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**

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 .

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

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

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

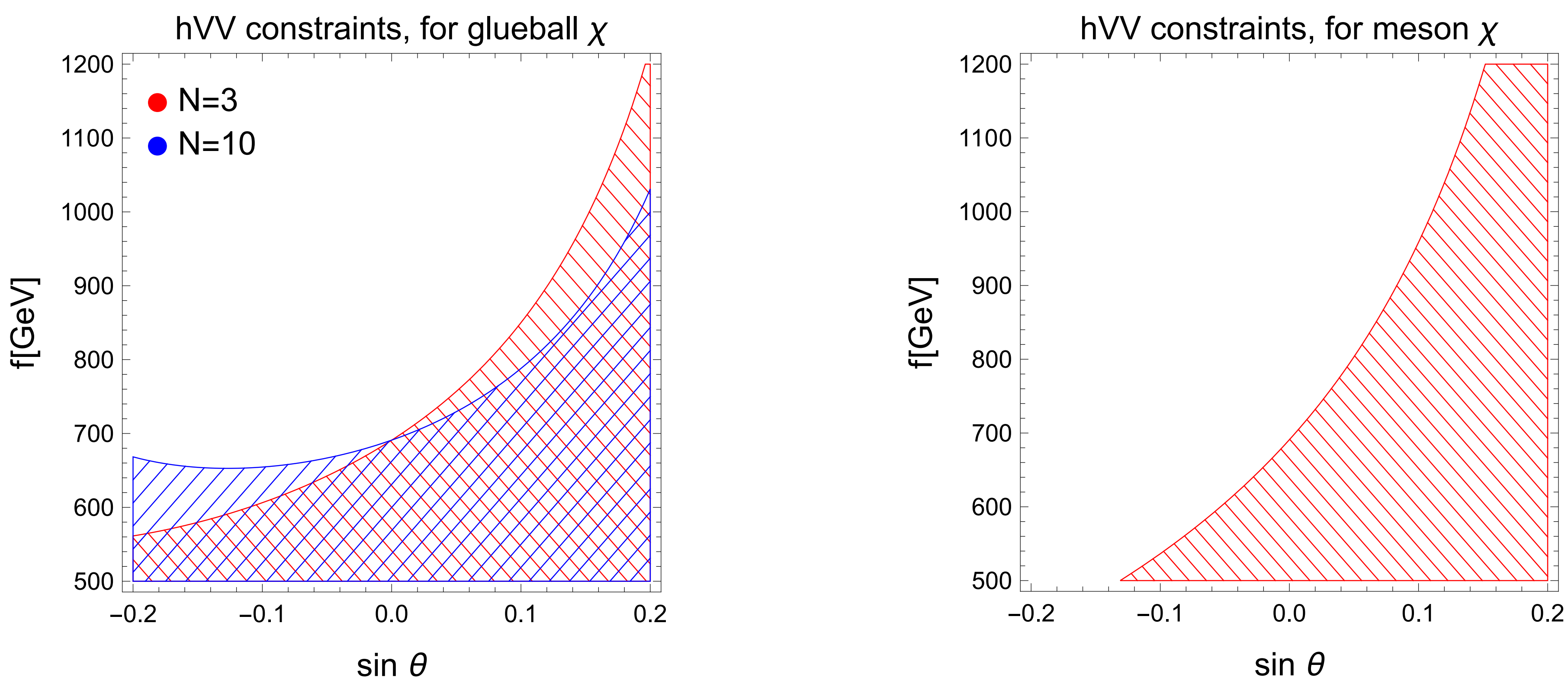
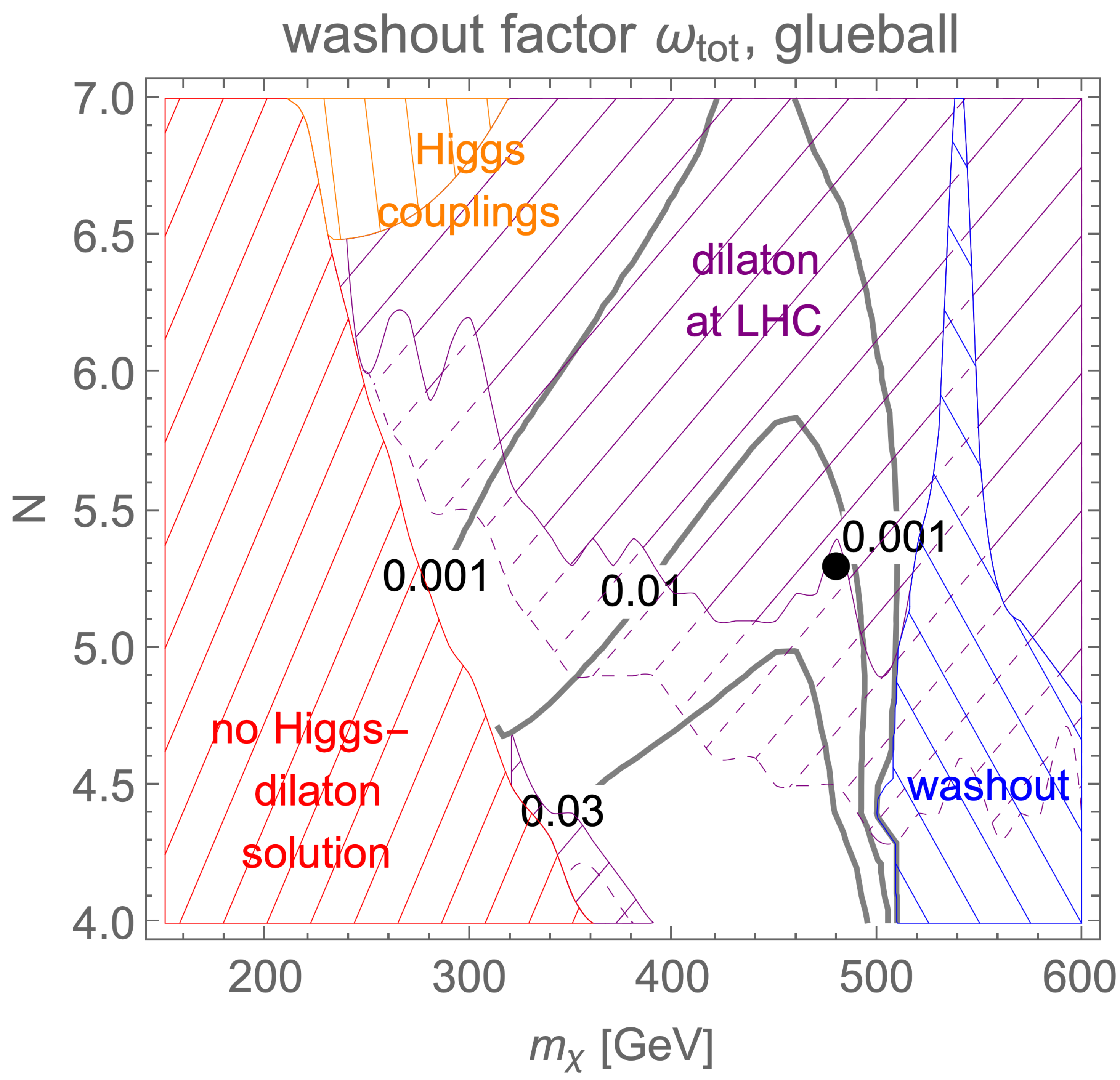


Figure 1: *Current bounds on the dilaton-Higgs mixing angle and f derived from the Higgs-EW vector boson coupling measurements.*

Strong constraints from LHC bounds on dilaton !



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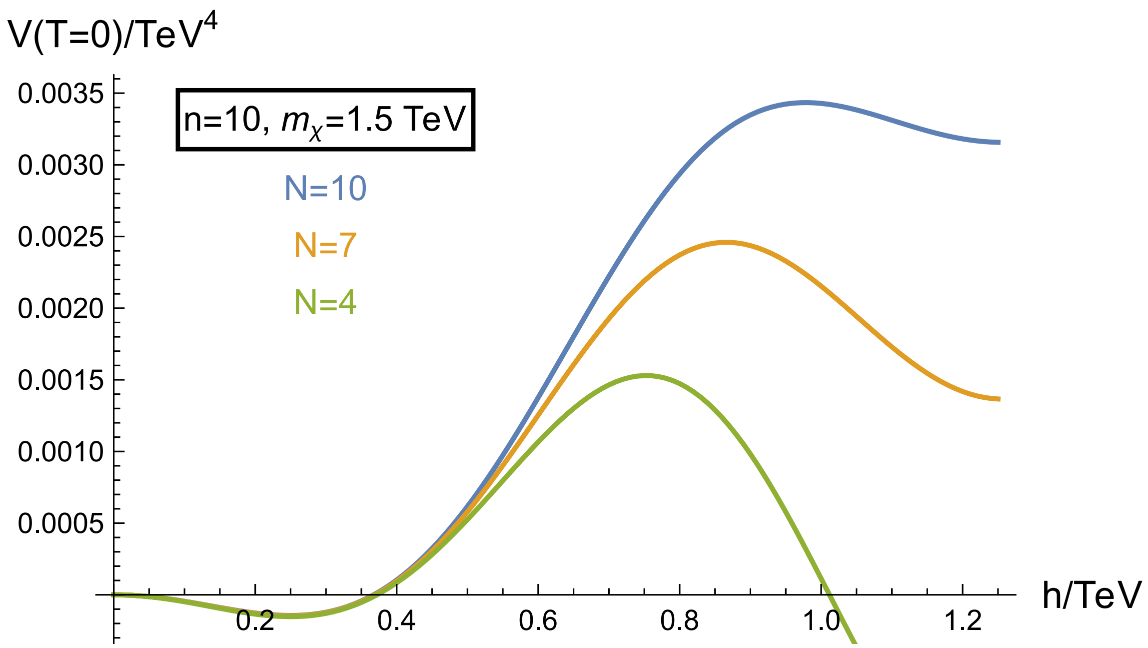
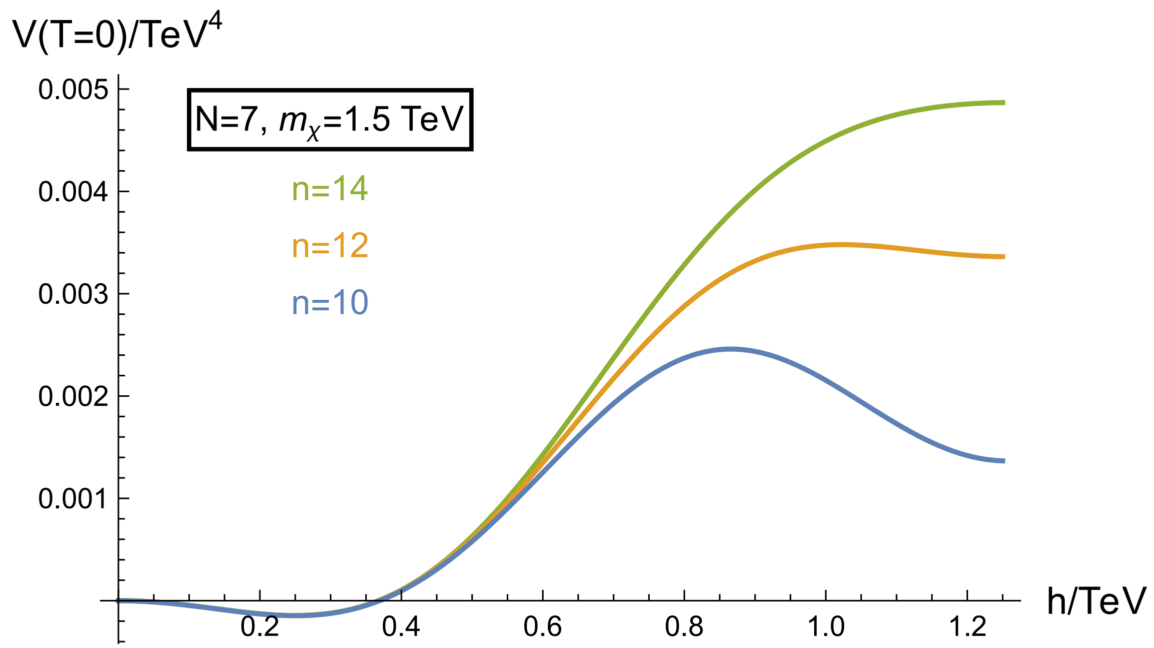
Minimal Composite Higgs potential in presence of extra singlet fermions

T=0





Global minimum at large Higgs VEV at low N

Composite Higgs

Higgs potential: trigonometric function of h/f

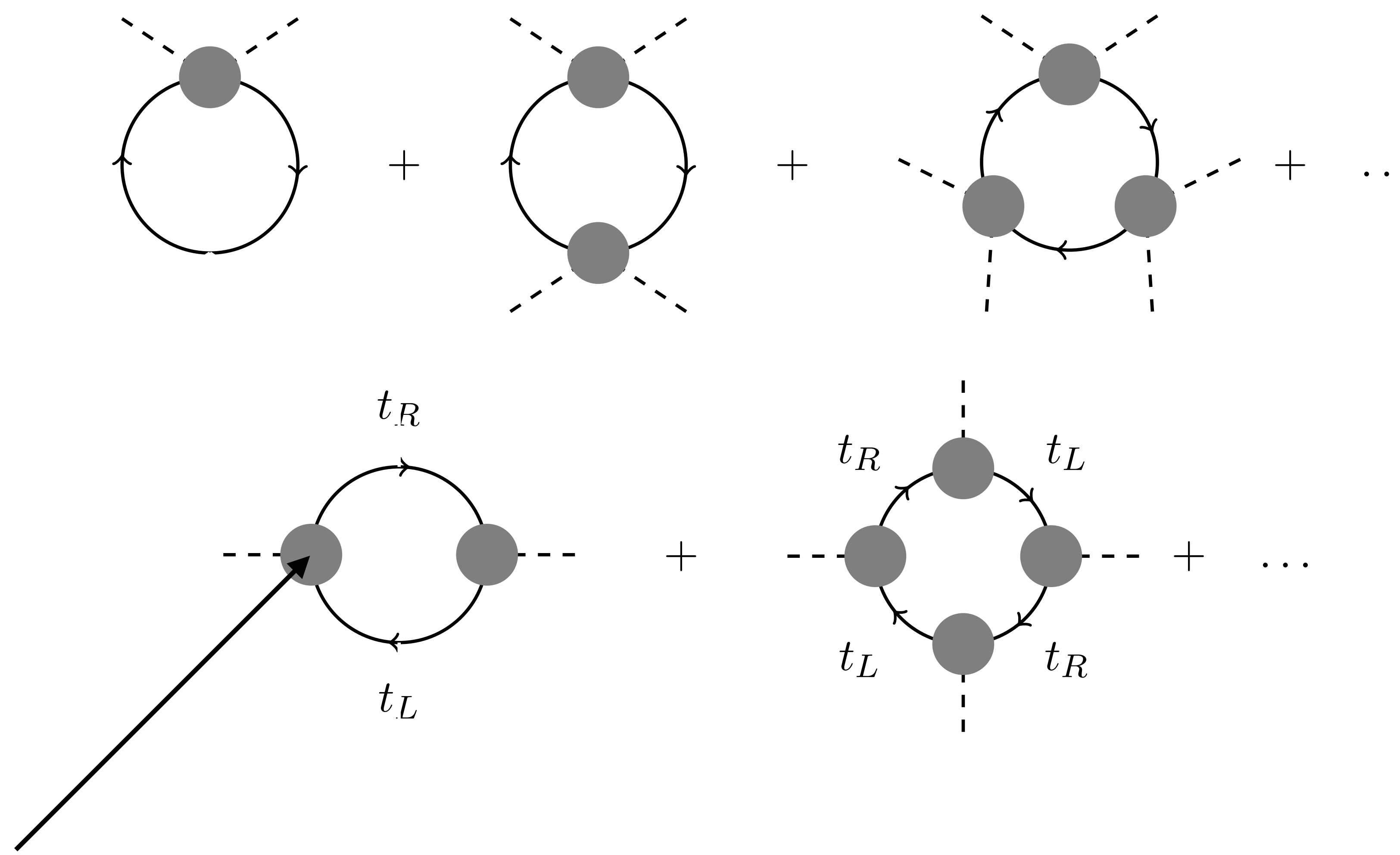
$$V^0[h] = \alpha^0 \sin^2\left(\frac{h}{f}\right) + \beta^0 \sin^4\left(\frac{h}{f}\right)$$

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.

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

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

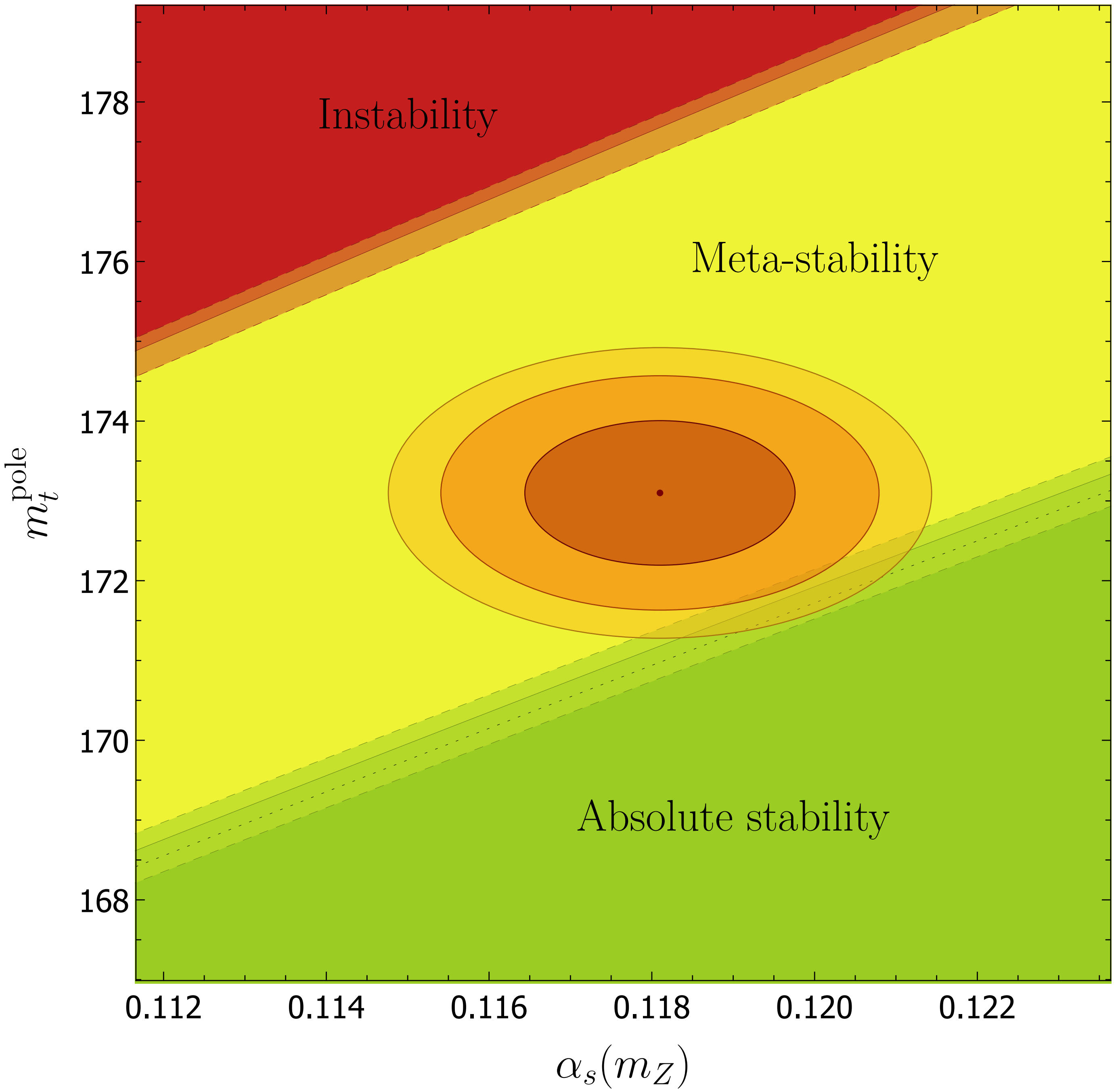
QCD axion → $\frac{a(t)}{f_a} F\tilde{F}$ ← EW field strength

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

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



Instability
Meta-stability
Absolute stability
178
176
174
172
170
168
0.112
0.114
0.116
0.118
0.120
0.122
$m_t^{\rm pole}$
$\alpha_s(m_Z)$