Electroweak Symmetry breaking & Cosmology

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Higgs Hunting 2015, Orsay
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Electroweak Symmetry breaking & Cosmology

-Electroweak Vacuum stability

-Higgs Inflation

see M. Shaposhnikov's talk @ Higgs Hunting 2014 and Espinosa's talk at CERN-TH in 04-2015

-Electroweak Baryogenesis ... and the QCD axion connection

-Asymmetric Dark Matter induced by the Higgs

-Cosmological Higgs-Axion INterplay (CHAIN)

Baryogenesis at a first-order EW phase transition

Matter Anti-matter asymmetry:

characterized in terms of the baryon to photon ratio

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

$$5.1 < \eta_{10} < 6.5 \ (95\% \ \mathrm{CL})$$

The great annihilation

10 000 000 001
Matter

10 000 000 000
Anti-matter

1
(us)

η remains unexplained within the Standard Model

double failure:

- lack of out-of-equilibrium condition

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

proven for standard EW baryogenesis

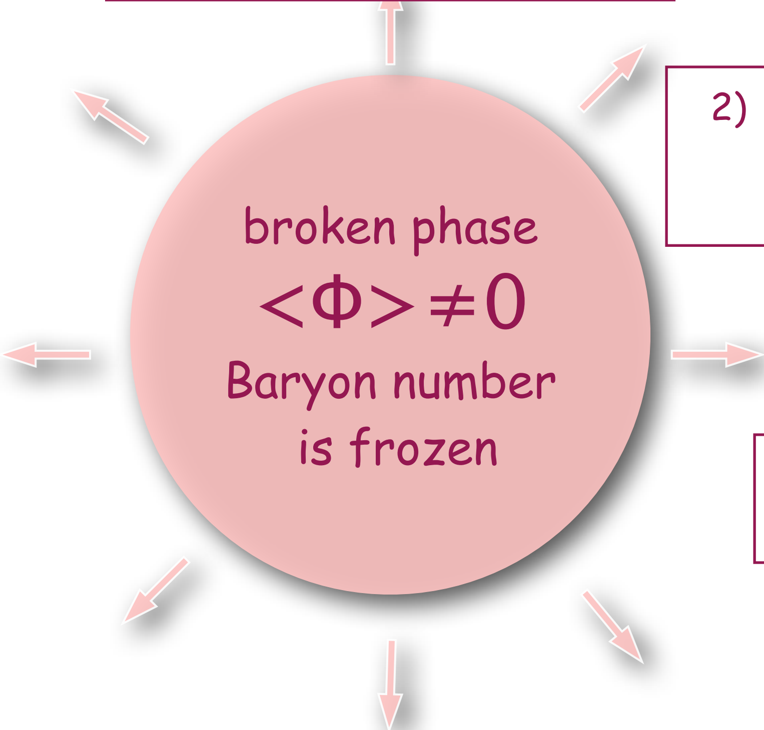
Gavela, P. Hernandez, Orloff, Pene '94
Konstandin, Prokopec, Schmidt '04

attempts in cold EW baryogenesis

Tranberg, A. Hernandez, Konstandin, Schmidt '09
Brauner, Taanila,Tranberg,Vuorinen '12

Baryon asymmetry and the EW scale

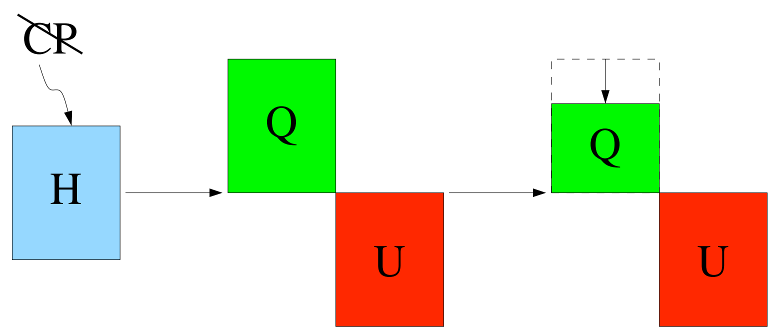
1) nucleation and expansion of bubbles of broken phase



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

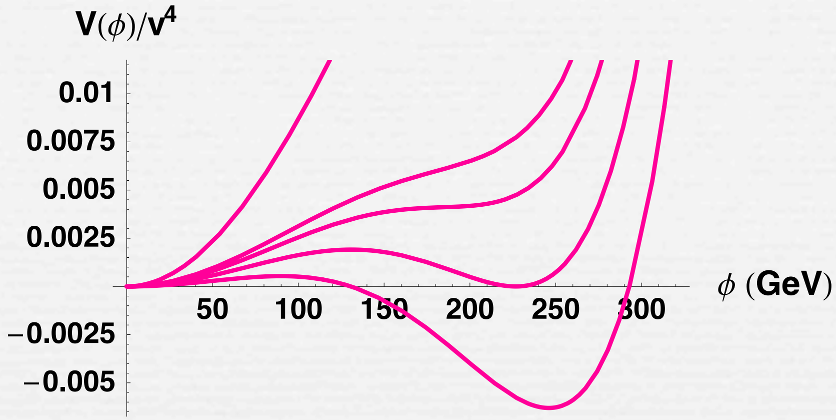
Chirality Flux in front of the wall

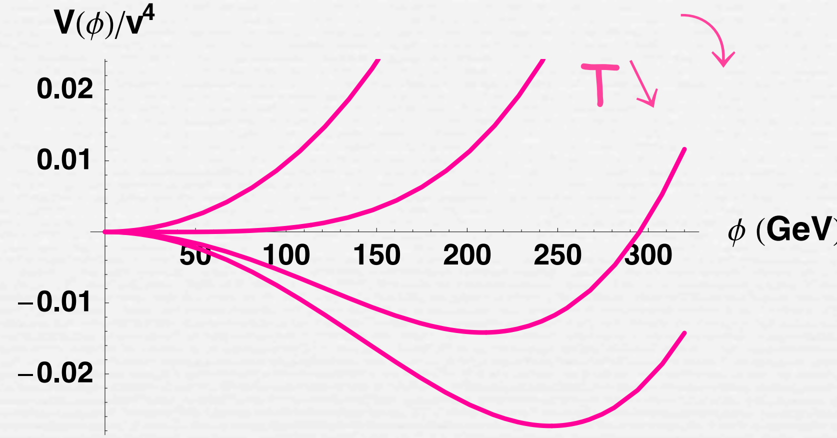
3) In symmetric phase, <Φ>=0, very active sphalerons convert chiral asymmetry into baryon asymmetry



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

first-order or second-order?





In the SM, a 1rst-order phase transition can occur due to thermally generated cubic Higgs interactions:

$$V(\phi,T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - ET\phi^3$$

$$-ET\phi^3 \subset -\frac{T}{12\pi}\sum_i m_i^3(\phi)$$

Sum over all bosons which couple to the Higgs

In the SM: $\sum_i \simeq \sum_{W,Z}$ → not enough

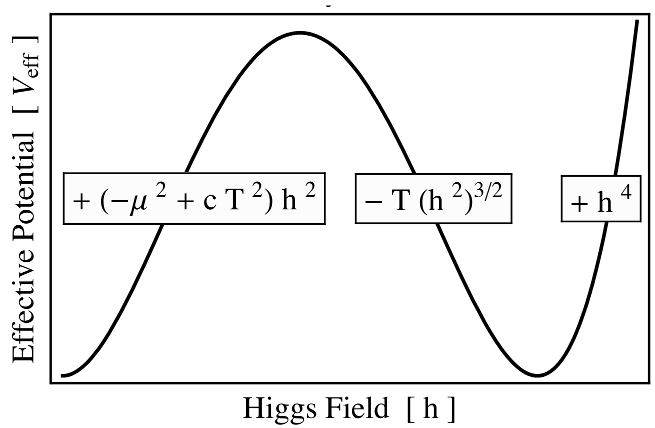
for mh>72 GeV, no 1st order phase transition

In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop

The four commonly quoted ways to obtain a strongly 1st order phase transition by inducing a barrier in the thermal effective potential

1)

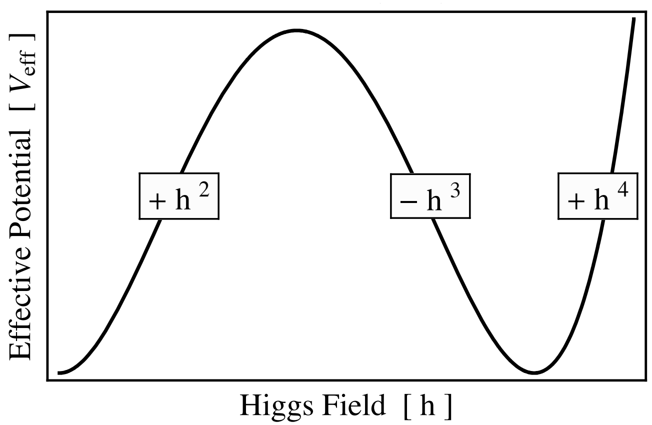


thermally driven

(thermal loop of bosonic modes)

(example:stop loop in MSSM)

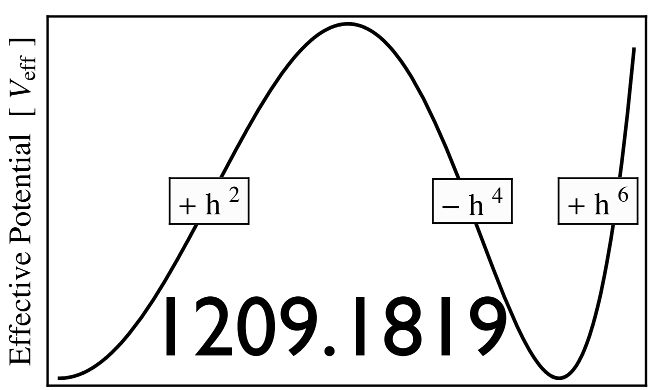
2)



tree-level driven

(competition between renormalizable operators)

3)



tree-level driven

(competition between renormalizable and non-renormalizable operators)

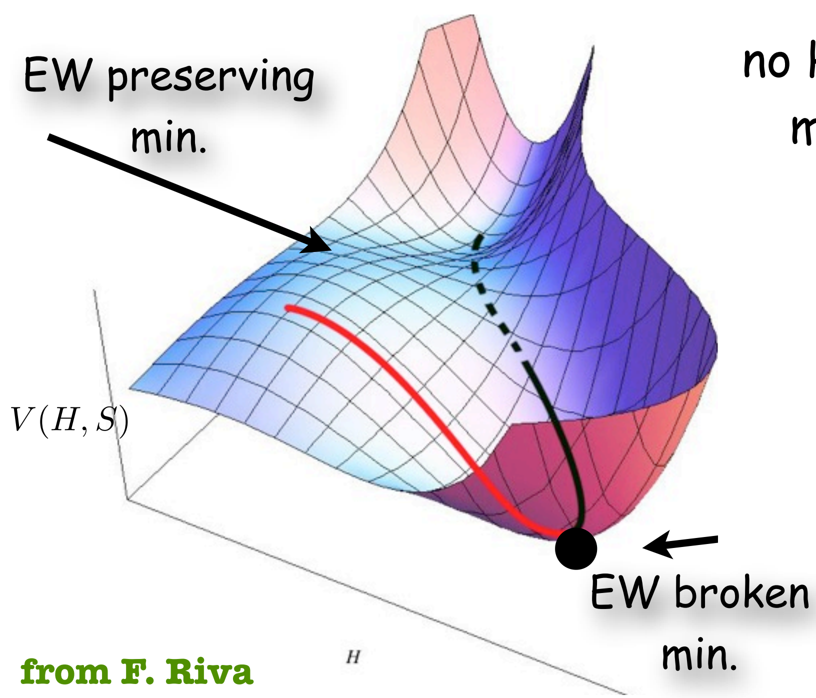
4) # Two-stage EW phase transition (tree level)

example: the SM+ a real scalar singlet

1409.0005

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2S^2 + \frac{1}{4}\lambda_S S^4.$$

S has no VEV today:
no Higgs-S mixing-> no EW precision tests , tiny modifications of higgs couplings at colliders

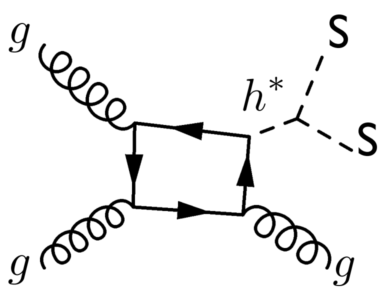


from F. Riva

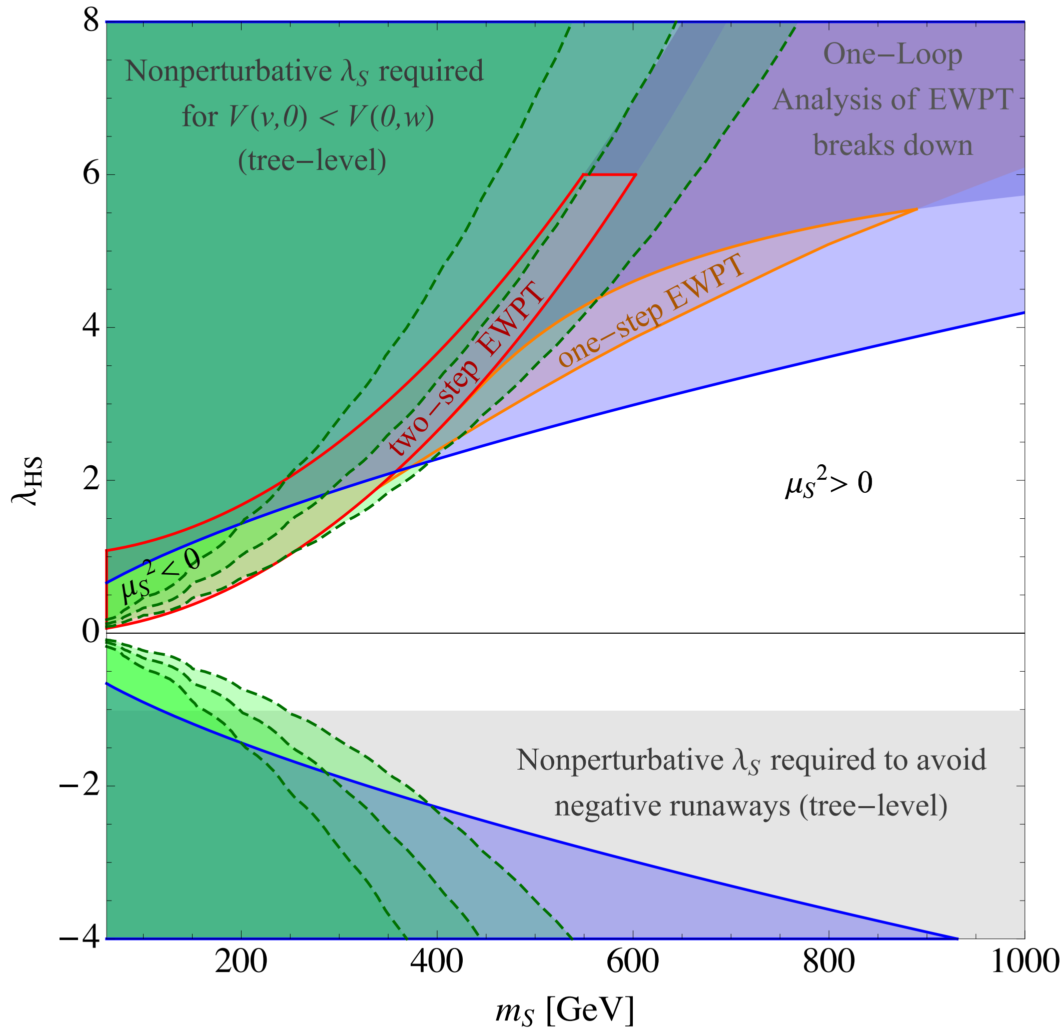
-> Espinosa et al, 1107.5441

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS}|H|^2 S^2 + \frac{1}{4}\lambda_S S^4.$$

singlet pair production via off-shell Higgs:



h*->SS testable at 100 TeV collider



higgs triple coupling deviation >16% and can be excluded at 100 TeV collider

$$\lambda_3 = \frac{m_h^2}{2v} + \frac{\lambda_{HS}^3 v^3}{24\pi^2 m_S^2} + \dots$$

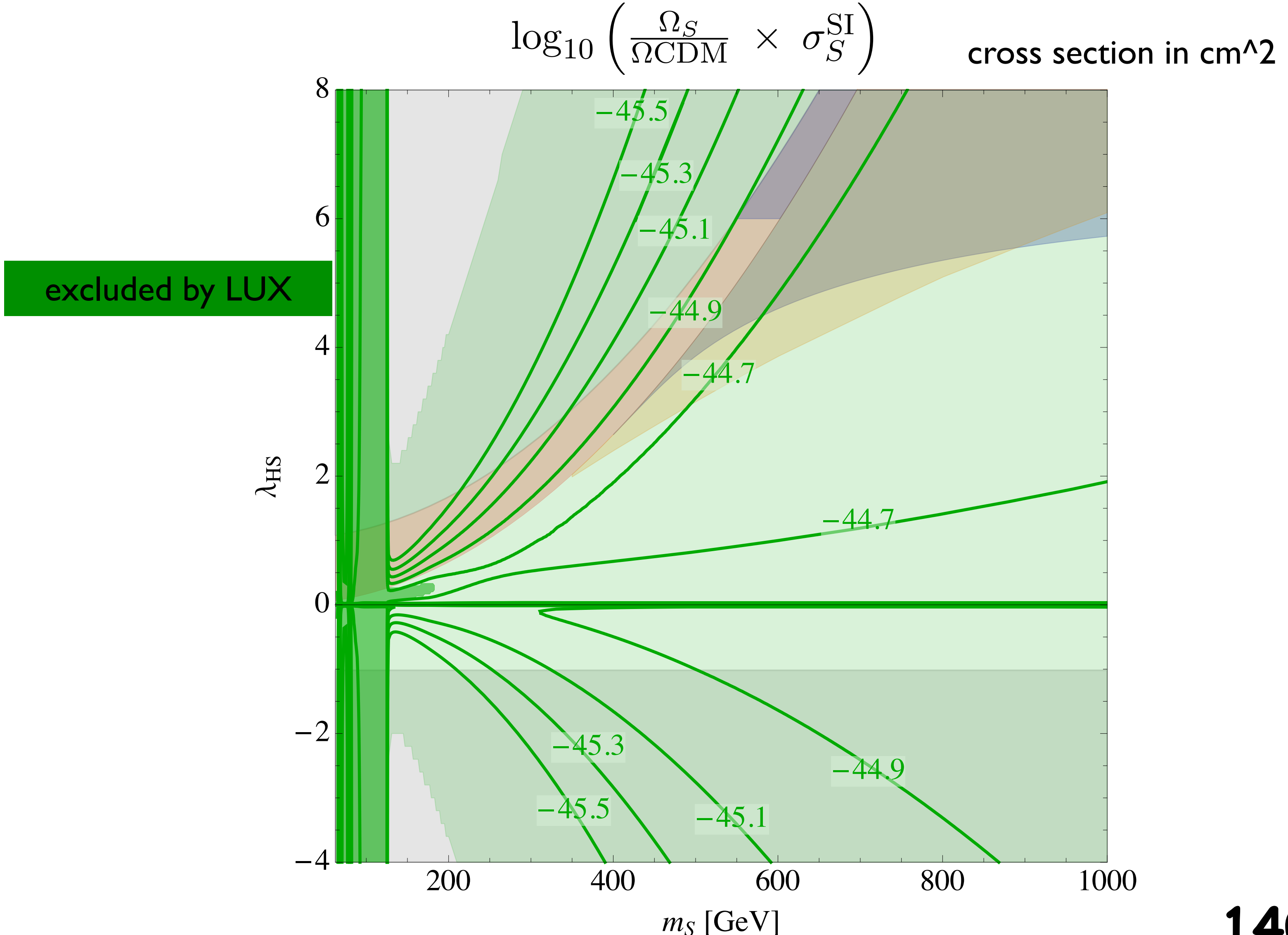
(loop level)

1409.0005

Besides: $$\delta\sigma_{Zh} = \frac{1}{2}\frac{|\lambda_{HS}|^2 v^2}{16\pi^2 m_h^2}\left[1 + F(\tau_\phi)\right]$$ <0.5% in relevant region

(at 1 loop)

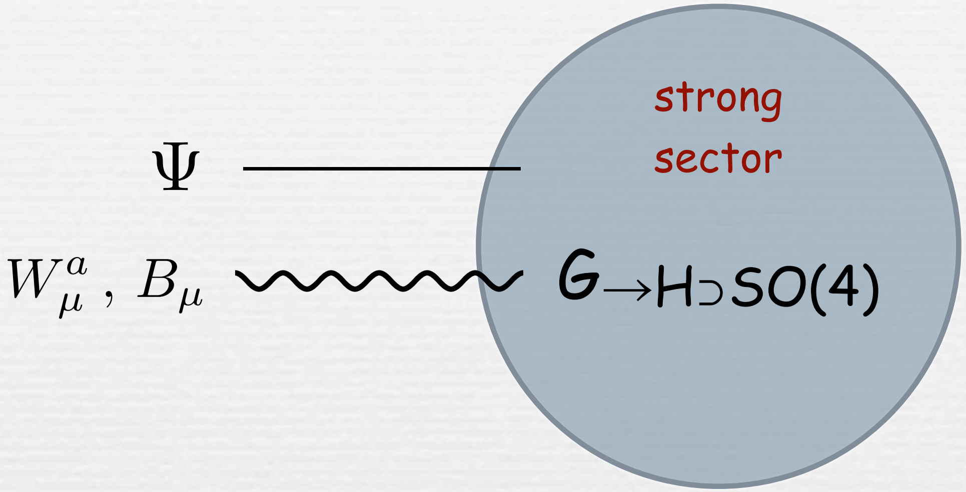
very difficult to test at colliders but Xenon 1T can test all relevant parameter space!



1409.0005

Easy to motivate additional scalars, e.g:

New strong sector endowed with a global symmetry G spontaneously broken to H
$\rightarrow$ delivers a set of Nambu Goldstone bosons



$$\mathcal{L}_{int} = A_\mu J^\mu + \bar{\Psi} O + h.c.$$

custodial SO(4)≅ SU(2)×SU(2)

to avoid large corrections to the T parameter

G	H	N_G	NGBs rep.$[H]$ = rep.[SU(2) × SU(2)]
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \mathbf{\bar{4}_{+5}} = 2 \times (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

-> **Agashe, Contino, Pomarol'05**

[Mrazek et al, 1105.5403]

5) Fifth way to get a strong 1st-order PT:

dilaton-like potential naturally leads to supercooling

Konstandin Servant '11

not a polynomial

$$V = V(\sigma) + \frac{\lambda}{4}(\phi^2 - c\sigma^2)^2$$

$$c = \frac{v^2}{\langle\sigma\rangle^2}$$

Higgs vev controlled by dilaton vev

(e.g. Randall-Sundrum scenario)

$$V(\sigma) = \sigma^4 \times f(\sigma^\epsilon)$$

a scale invariant function modulated by a slow evolution through the σ^ϵ term

for $|\epsilon| << 1$

similar to Coleman-Weinberg mechanism where a slow Renormalization Group evolution of potential parameters can generate widely separated scales

Nucleation temperature can be parametrically much smaller than the weak scale

Application:

EW baryogenesis from the QCD axion

Baryogenesis from Strong CP violation

Servant'14, 1407.0030

$$\mathcal{L} = -\bar{\Theta}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}$$

today $\quad |\bar{\Theta}| < 10^{-11} \quad$ as explained by Peccei-Quinn mechanism:

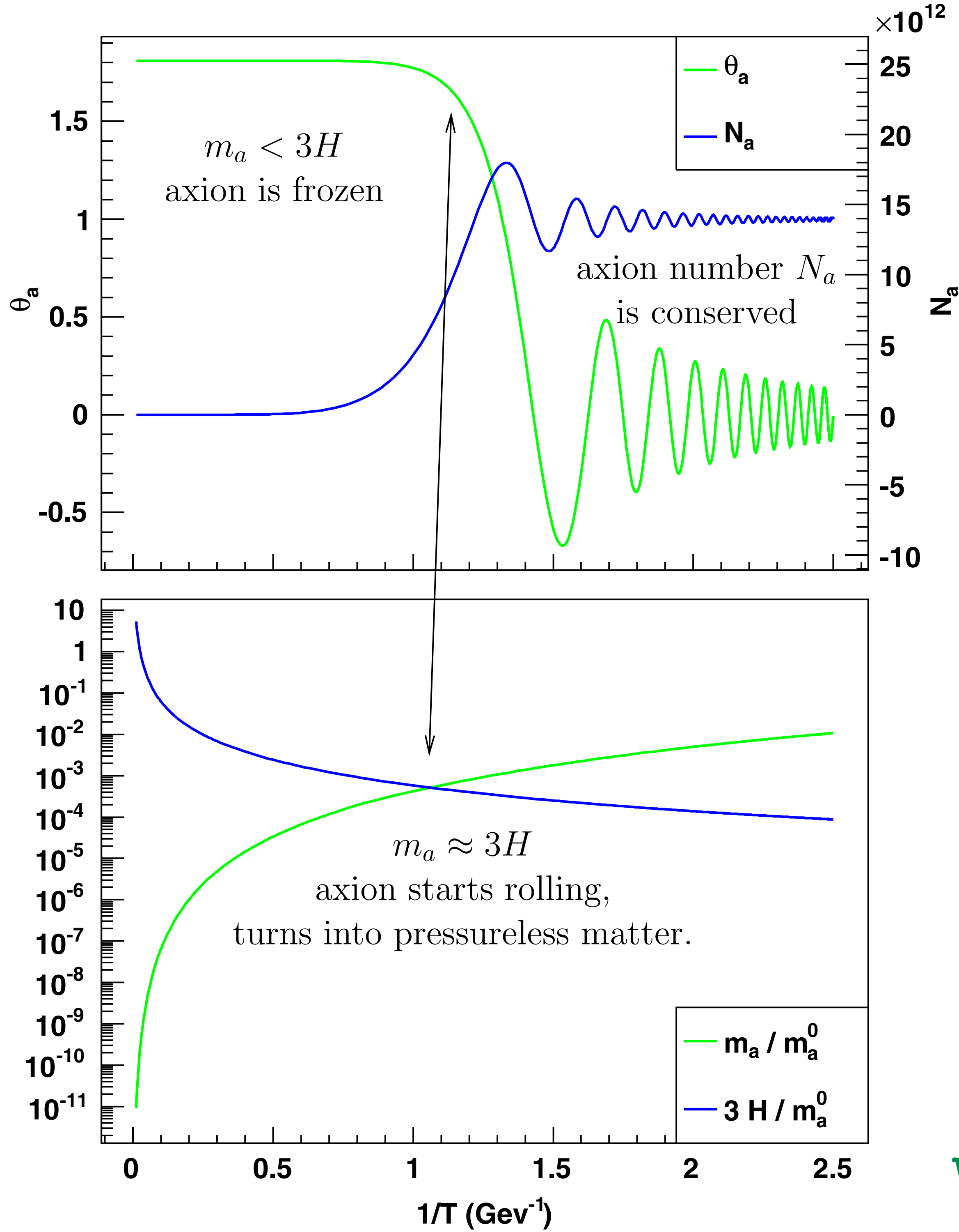
$$\bar{\Theta} \rightarrow \frac{a(x)}{f_a}$$

promoted to a dynamical field which relaxes to zero, to minimize the QCD vacuum energy.

in early universe, before the axion gets a mass around the QCD scale

$$|\bar{\Theta}| \sim 1$$

Could $\bar{\Theta}$ have played any role during the EW phase transition?



Wantz, Shellard '10

Baryogenesis from Strong CP violation

A coupling of the type ~ $\frac{a(t)}{f_a} F\tilde{F}$ ← EW field strength

will induce from the motion of the axion field a chemical potential for baryon number given by

$$\frac{\partial_t a(t)}{f_a}$$

This is non-zero only once the axion starts to oscillate after it gets a potential around the QCD phase transition.

Time variation of axion field can be CP violating source for baryogenesis only at or below the QCD phase transition

$\longrightarrow$ **Cold Baryogenesis**

Cold Baryogenesis

main idea:

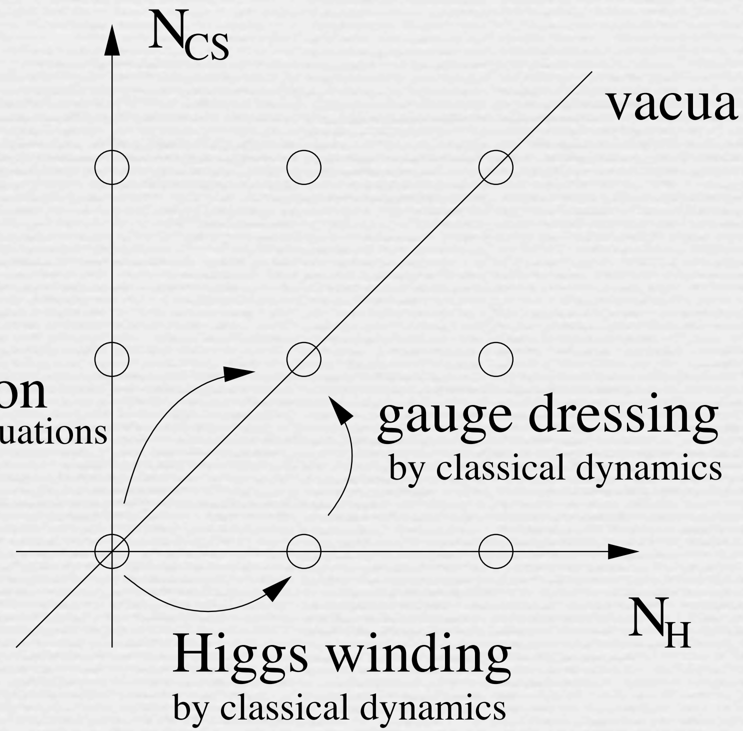
During quenched EWPT, SU(2) textures can be produced.
They can lead to B-violation when they decay.

Turok, Zadrozny '90

Lue, Rajagopal, Trodden, '96

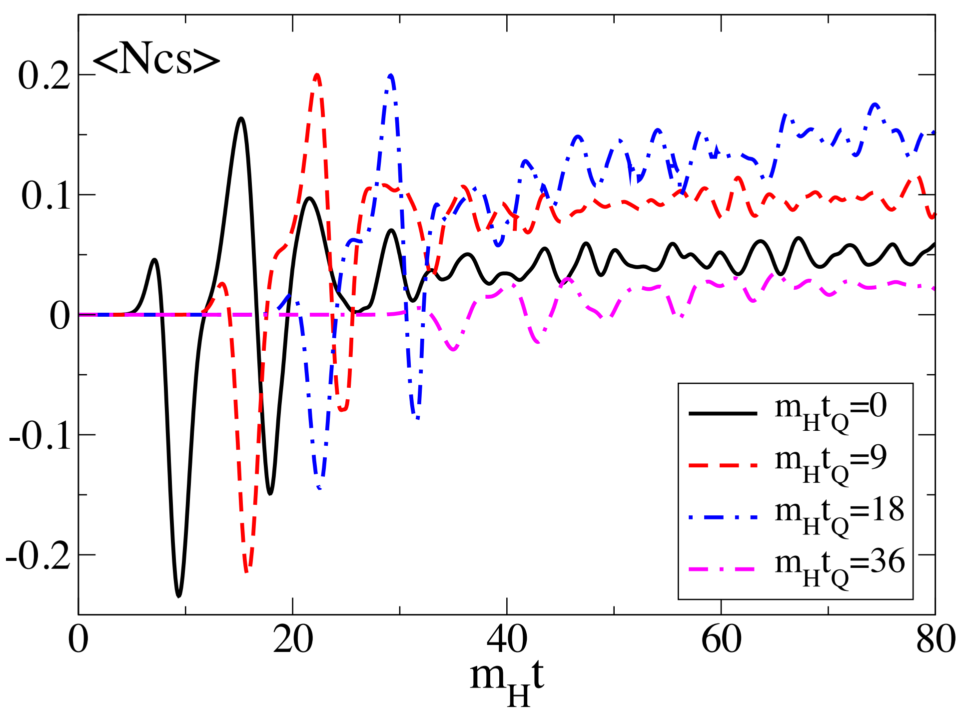
Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, '99

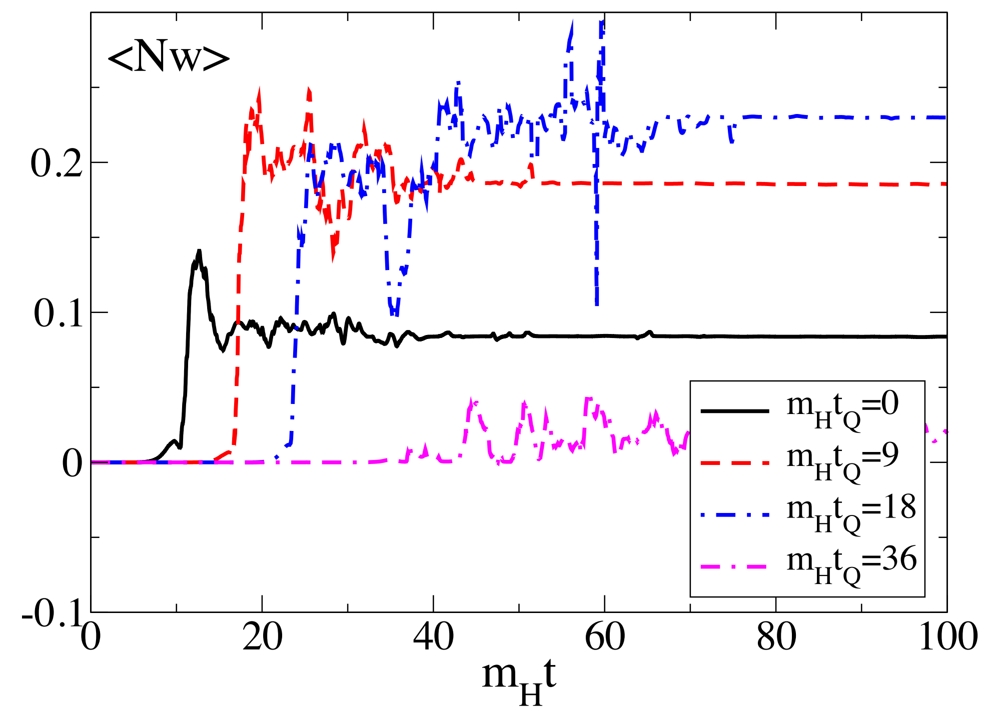
$$\Delta B = 3\Delta N_{CS}$$



Cold baryogenesis: production of baryon number at T=0 from out-of equilibrium dynamics

Cold baryogenesis has been simulated on the lattice





Tranberg, Smit, Hindmarsh, hep-ph/0610096

Motivating Cold Baryogenesis

Konstandin Servant '11

$$V = V(\sigma) + \frac{\lambda}{4}(\phi^2 - c\sigma^2)^2$$

Higgs vev controlled by dilaton vev

(e.g. Randall-Sundrum scenario)

$$V(\sigma) = \sigma^4 \times f(\sigma^\epsilon)$$

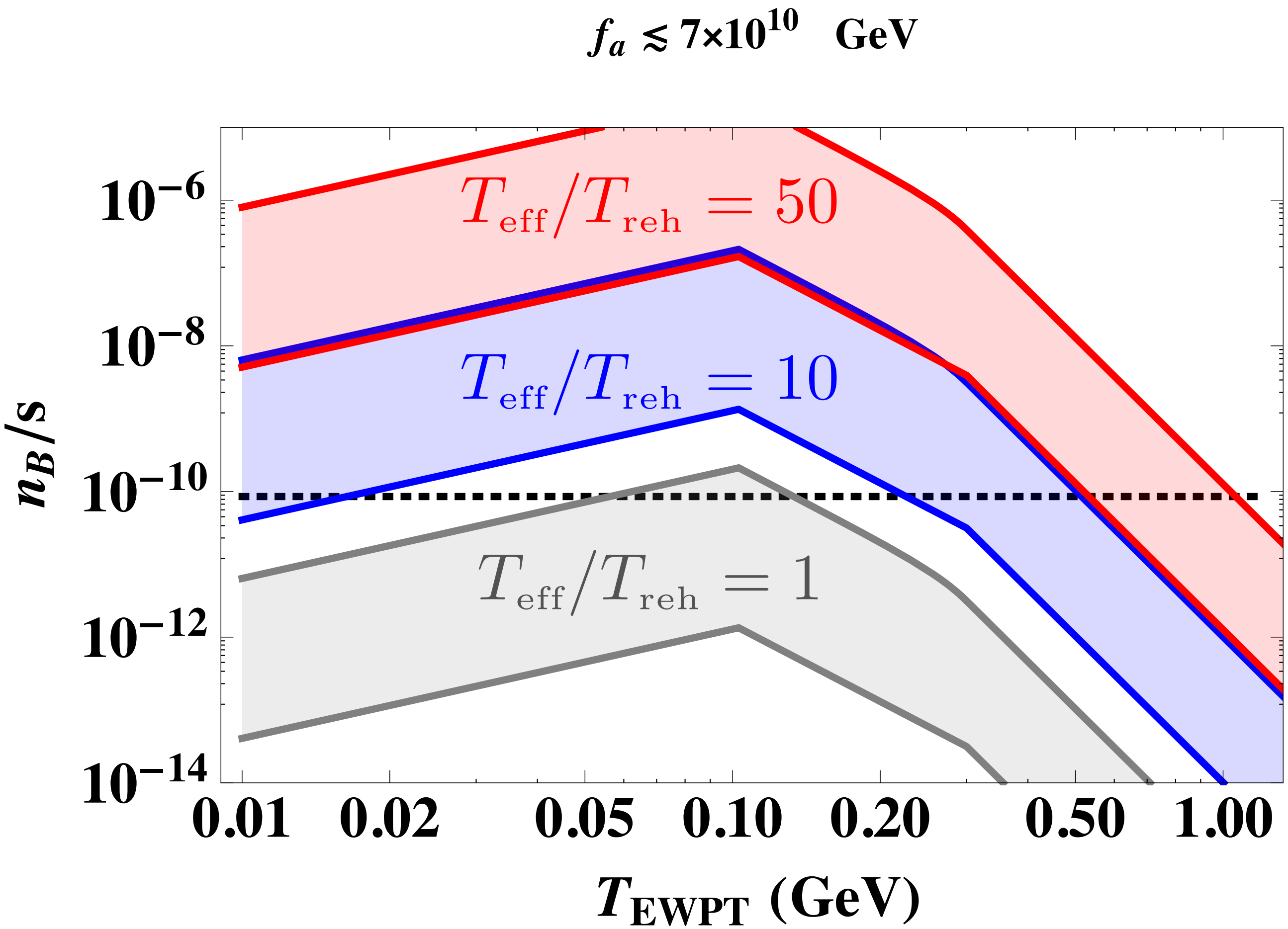
a scale invariant function modulated by a slow evolution through the σ^ϵ term

for $|\varepsilon| << 1$

similar to Coleman-Weinberg mechanism where a slow RG evolution of potential parameters can generate widely separated scales

Axion dynamics during a supercooled EW phase transition can lead to baryogenesis

Servant, 1407.0030



requires a coupling between the Higgs and an additional light scalar

Key point for the scenario to work:

Reheat temperature below sphaleron freese-out temperature to avoid washout

Bound on dilaton mass from reheating constraint

$$\frac{8\pi g_* T_{reh}^4}{30} = \Delta V \qquad \Delta V \sim m_d^2 \langle\sigma\rangle^2$$

$T_{reh} < 130 \text{ GeV}$ ~ sphaleron freese out temperature

dilaton mass ~ O(100 GeV)

-> Testable at next Run of LHC

Naturally light dilatons discussed recently in

Rattazzi et al @Planck2010

Megias, Pujolas '14

Bellazzini et al '13

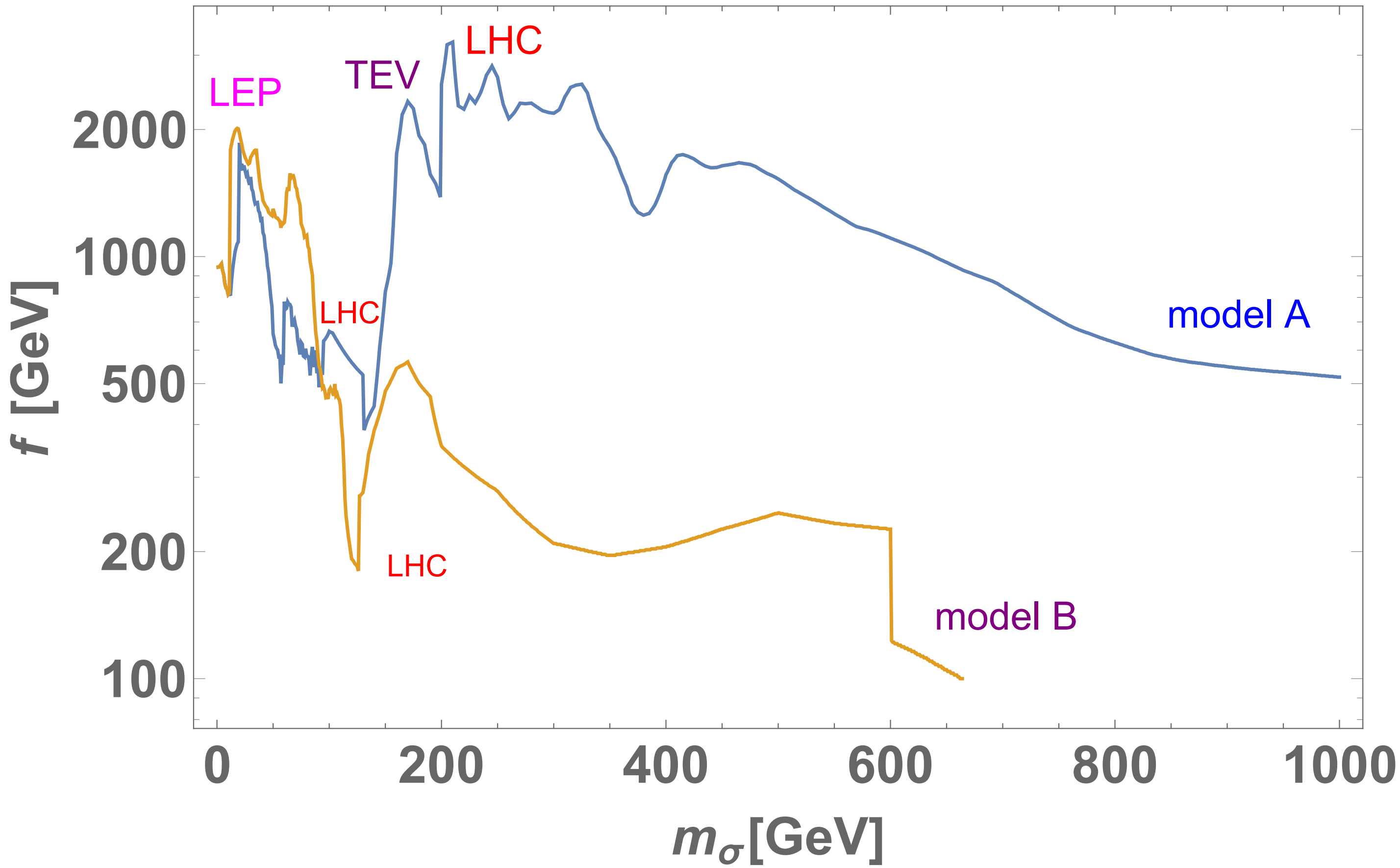
Coradeschi et al '13

Rattazzi Zaffaroni '01

cosmological consequences in

Servant-Konstandin '11

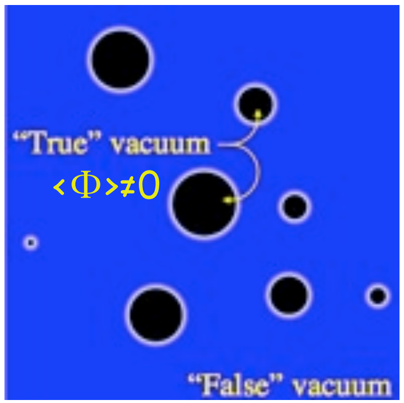
LHC constraints on the scale of conformal symmetry breaking (dilaton)



[1410.1873]

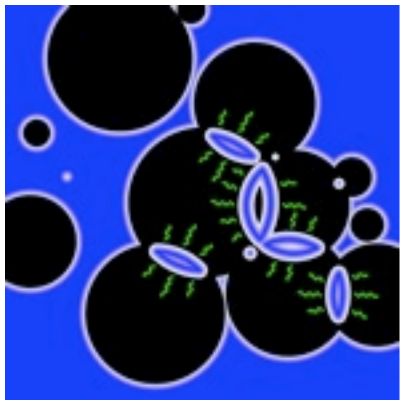
Smoking gun signature of a strongly first-order phase transition

Bubble nucleation



$\langle\Phi\rangle=0$

Bubble percolation

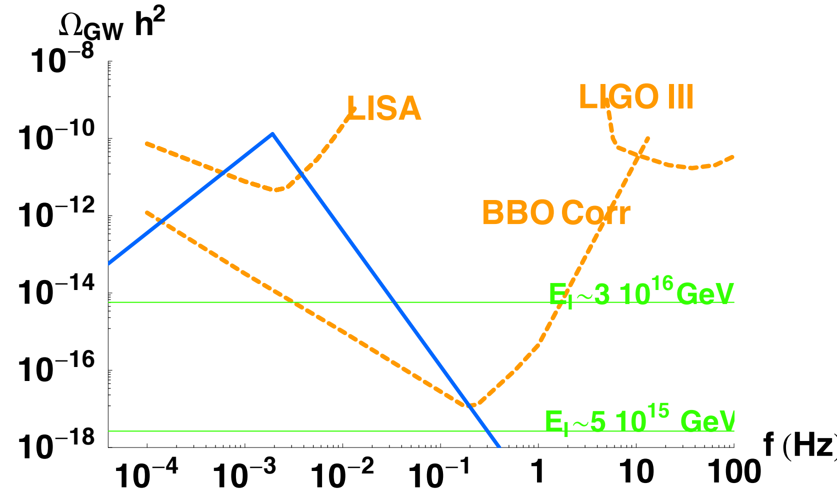


Fluid flows

turbulence

Magnetic fields

Stochastic background of gravitational radiation



$$\Omega_{GW} \sim \frac{1}{(\beta/H)^2}\kappa^2$$

characterizes amount of supercooling

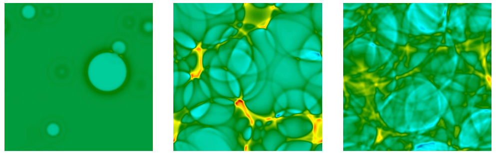
violent process if $v_b \sim O(1)$

$$f_{\rm peak} \sim 10^{-2}\ {\rm mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ {\rm GeV}}\ \frac{\beta}{H_*}$$

Grojean-Servant
hep-ph/0607107

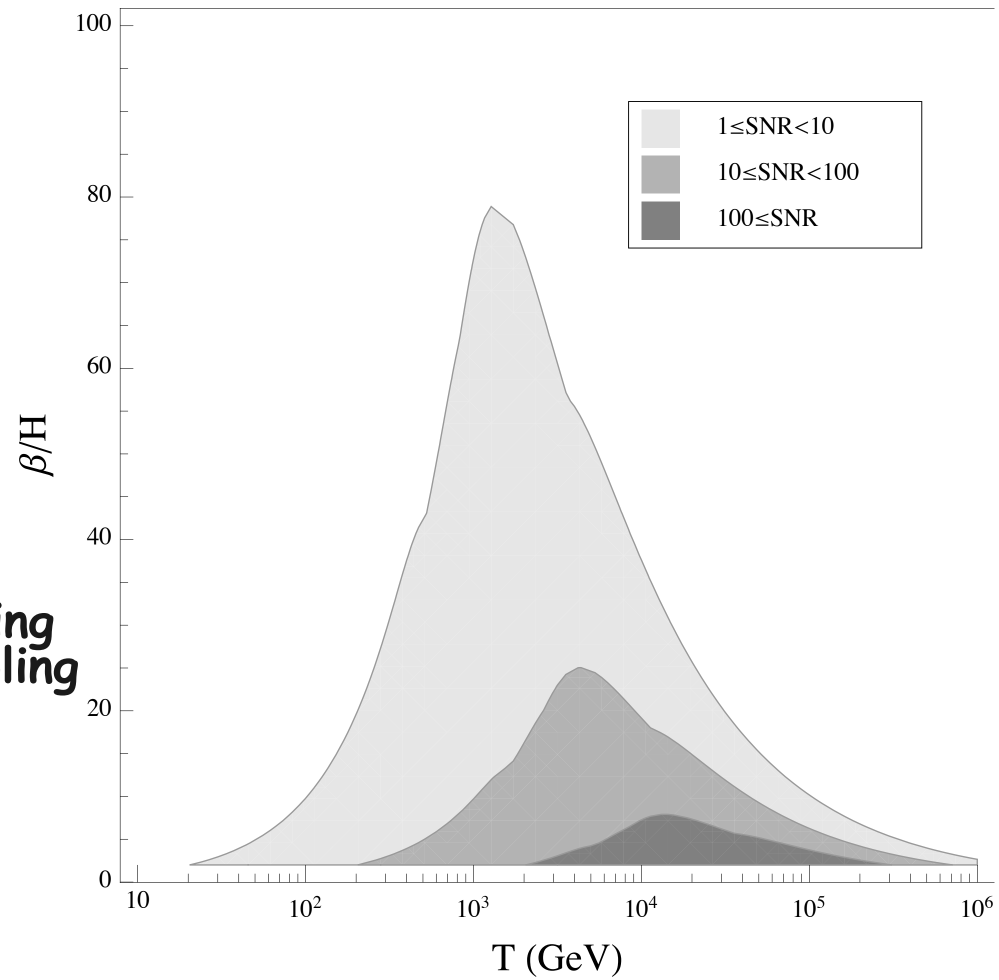
Detection of a GW stochastic background peaked in the milliHertz: a signature of near conformal dynamics at the TeV scale

Konstandin & Servant
1104.4791



Detection prospects for eLISA

increasing supercooling



Most sensitive in the region around 10TeV

It can detect GWs from strong PTs, occurring slow

detection prospects to be updated to take into account promising new results from improved numerical simulations 1304.24333 & 1504.0329

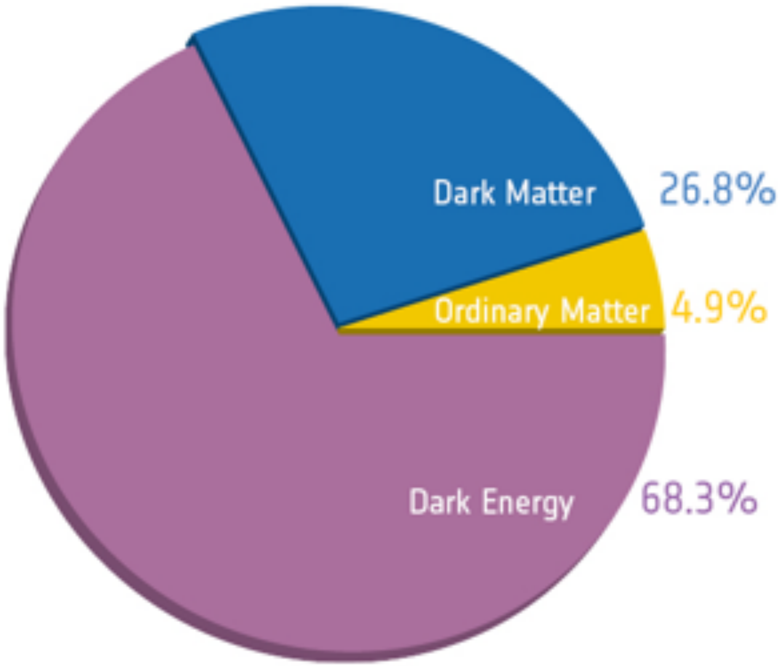
[see review by Caprini et al, 1201.0983]

Summary

- Simplest ways to get a strong 1st order EW phase transition:
  - Add a singlet -> Two-stage phase transition
  - Dilaton from Nearly conformal dynamics
- QCD axion-induced baryogenesis may follow if the EW phase transition is delayed down to the QCD scale.
- This can happen naturally if EW symmetry breaking is induced by dilaton dynamics.
- This scenario is testable at the LHC (relies on the existence of a light dilaton)
- Generic dark matter predictions of QCD axion remain mainly unaffected (although contribution from string decays may be suppressed)

Are the Dark Matter and baryon abundances related ?

$\Omega_{DM} \approx 5\ \Omega_{baryons}$

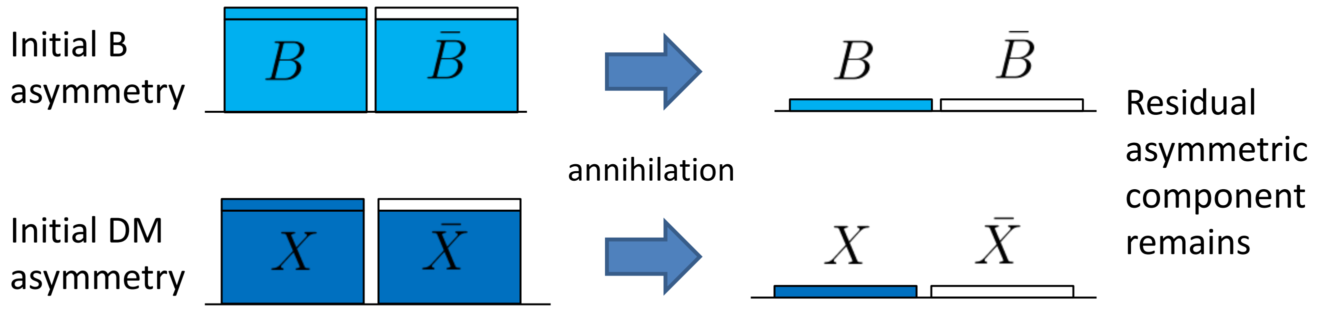


Atoms: 4.9 %

Photons: 0.0022 %

Neutrinos: 0.0016 %

natural WIMP-baryogenesis Connection: Asymmetric dark matter



and the Higgs may be responsible for the transfer of asymmetries

Servant & Tulin, PRL 111, 151601 (2013)

Minimal illustrative example

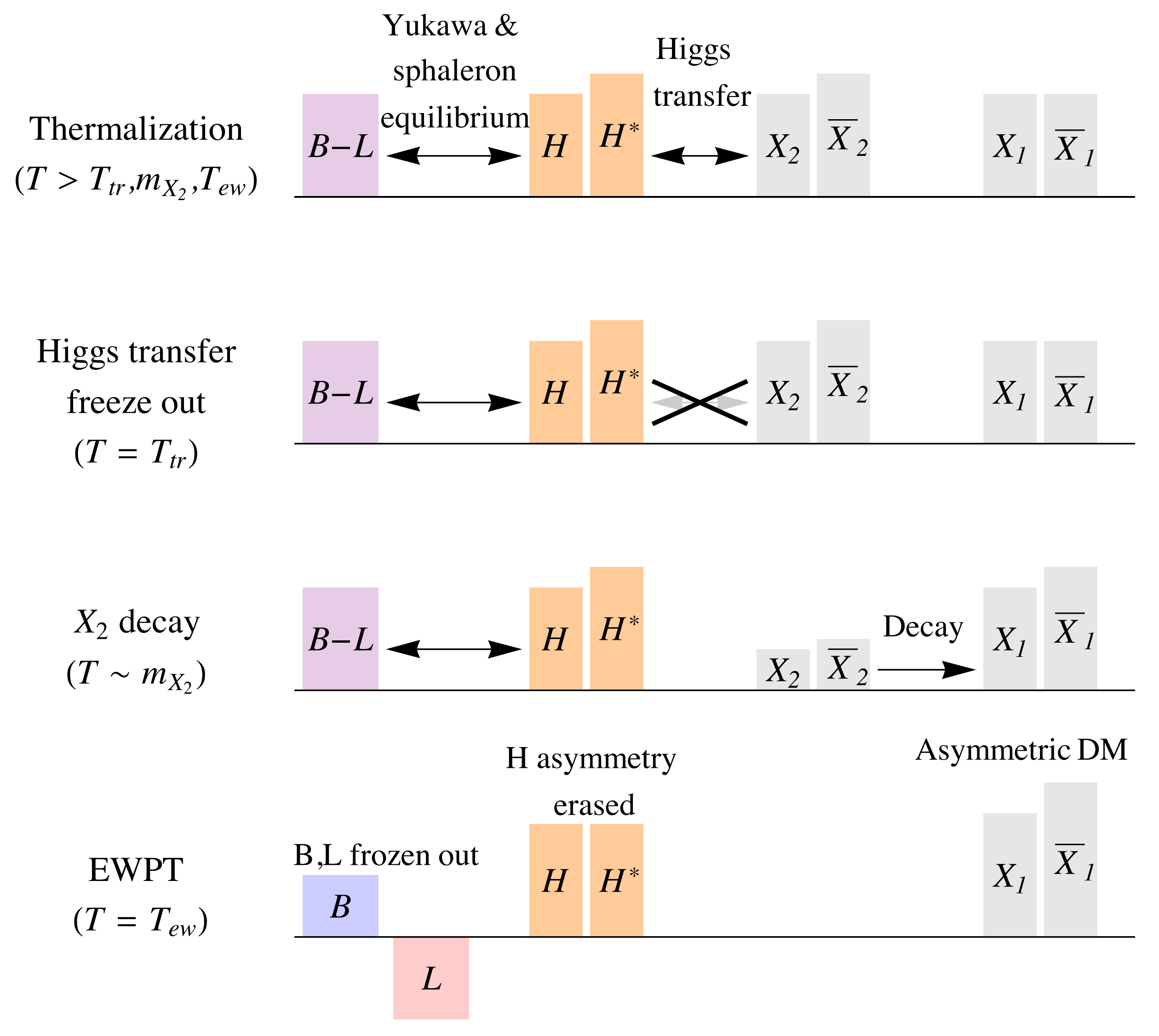
Just add to the Standard Model 2 vector-like fermions:
a singlet X_1 (Dark matter) and one EW doublet X_2 whose role is to transfer the asymmetries between the visible and dark sectors

$$\mathcal{L} \supset \frac{1}{\Lambda_2}(H^\dagger X_2)^2 + y_H \bar{X}_2 X_1 H + h.c$$

Asymmetric Wimps may follow automatically from standard leptogenesis due to Higgs couplings to the Dark sector (`Higgsogenesis idea')

Asymmetric Dark Matter from Lepto/Baryogenesis

Assume a primordial B-L asymmetry. It induces a Higgs asymmetry which flows into the dark sector



Such a scenario does not require new states that carry baryon or lepton number, unlike other Asymmetric DM models.

This is a general framework for getting asymmetric dark Matter as a natural consequence of a primordial baryon/lepton asymmetry due to coupling between the Higgs and the dark sector

One could think of many different realizations of this idea in various contexts.

Model-dependent signatures

Summary

Natural connections between dark matter and baryogenesis with the Higgs as a key player

e.g, Asymmetric Wimps from leptogenesis due to Dark Sector-Higgs couplings (`Higgsogenesis')

QCD axion-induced baryogenesis

Cosmological Higgs-Axion Interplay (CHAIN) for a Naturally small Electroweak Scale

based on 1506.09217, with
O. Pujolàs, A. Pomarol, G. Panico,
C. Grojean, J.R. Espinosa

Recent development on the Cosmology/ Weak scale Connection:

Higgs-Axion cosmological relaxation

Graham, Kaplan, Rajendran [1504.07551]

2015 Theory Highlight

Recently, a radically new approach to the Higgs Mass Hierarchy has been proposed

Graham, Kaplan, Rajendran [1504.07551]

- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe.
- The mass-squared relaxes to a small negative value.
- The electroweak symmetry breaking stops the time-dependence.
- The small electroweak scale is fixed until today.

Key Question:

Does this require new degrees of freedom at the weak scale?

This is a new proposal.

For comparison:

In Randall-Sundrum models, one can also see the Higgs mass as a time-dependent function.

m_H: given by the distance between the "TeV" brane and the "Planck brane". In 4D language, controlled by the VEV of the radion (dilaton in the CFT theory). The fact that the dilaton gets a VEV at the EW scale is a consequence of the underlying symmetries (AdS/CFT). Cosmological evolution is non-trivial (strong first-order phase transition) and imposes constraints on the parameters of the dilaton potential.

By comparison, the relaxion mechanism does not require any tuning of parameters, but instead very small numbers (g) and large field excursions. -> Change of paradigm.

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

$$m^2|H|^2 \to m^2(\phi)|H|^2$$

$$m^2(\phi) = \Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)$$

stabilized such that $m^2(\phi) \ll \Lambda^2$

Λ : cutoff of the theory

Higgs (h) and Axion-like (ϕ) interplay

3 terms:

$$V(\phi, h) = \boxed{\Lambda^3 g\phi} - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon \Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

slope for ϕ
to move forward

Higgs (h) and Axion-like (ϕ) interplay

$$V(\phi, h) = \Lambda^3 g\phi + \boxed{\frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2} + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

ϕ scans the Higgs mass

Higgs (h) and Axion-like (ϕ) interplay

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n=1,2,...

Barrier that stops ϕ when <h> turns on

periodic function for ϕ as for axion-like states generated at scale Λ_c

Higgs (h) and Axion-like (ϕ) interplay

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \boxed{\epsilon \Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)}$$

n=1,2,...

Barrier that stops ϕ
when <h> turns on

periodic function for ϕ
as for axion-like states
generated at scale Λ_c

e.g: QCD axion case: n=1, $\Lambda_c \sim \Lambda_{QCD}$

$\epsilon \sim y_u$

Higgs (h) and Axion-like (ϕ) interplay

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

g<<1, breaks the shift symmetry $\phi \longrightarrow \phi + c$

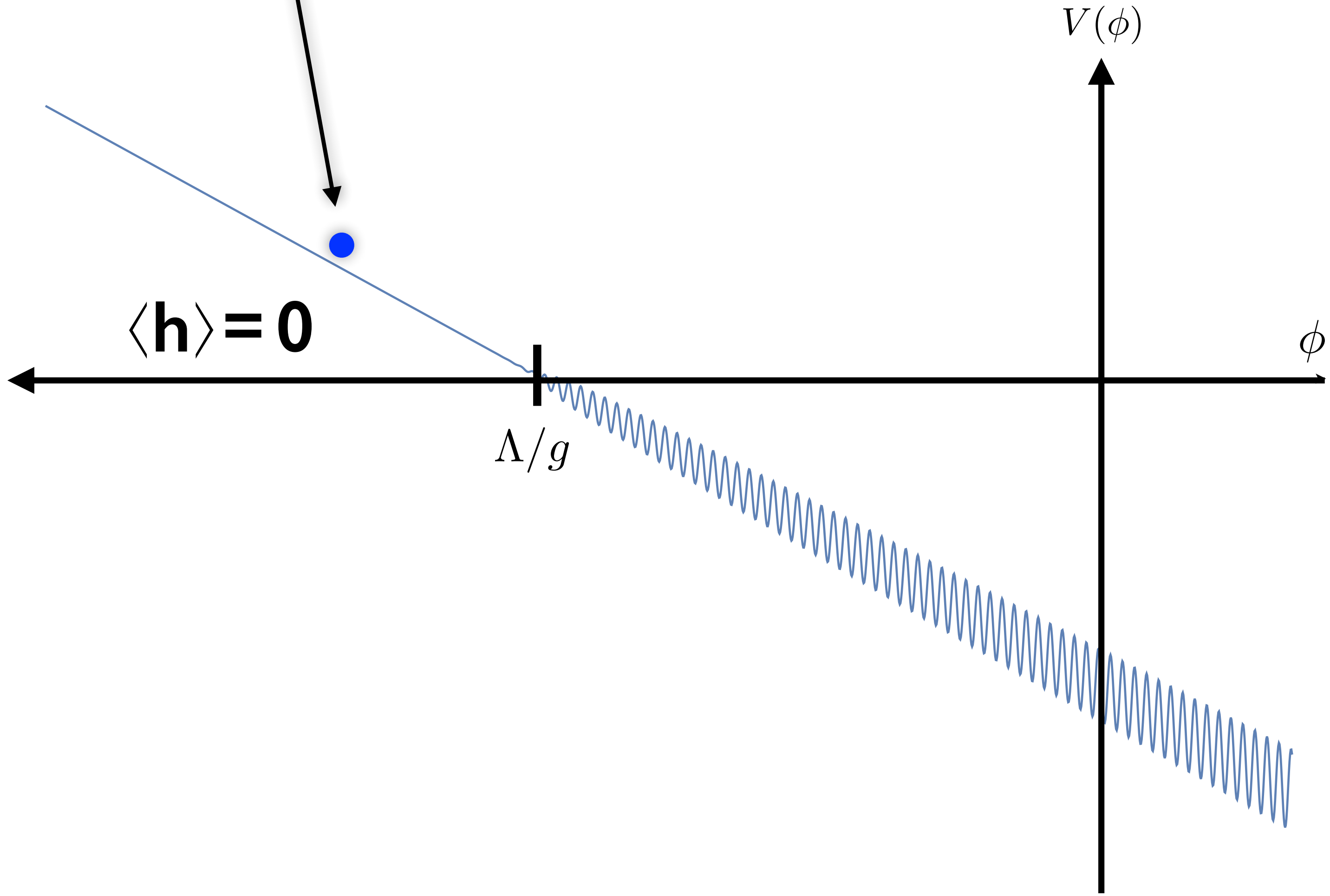
ϵ<<1, breaks the shift symmetry

respects $\phi \to \phi + 2\pi f$

$\phi \to -\phi$

Cosmological evolution

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$



Cosmological evolution

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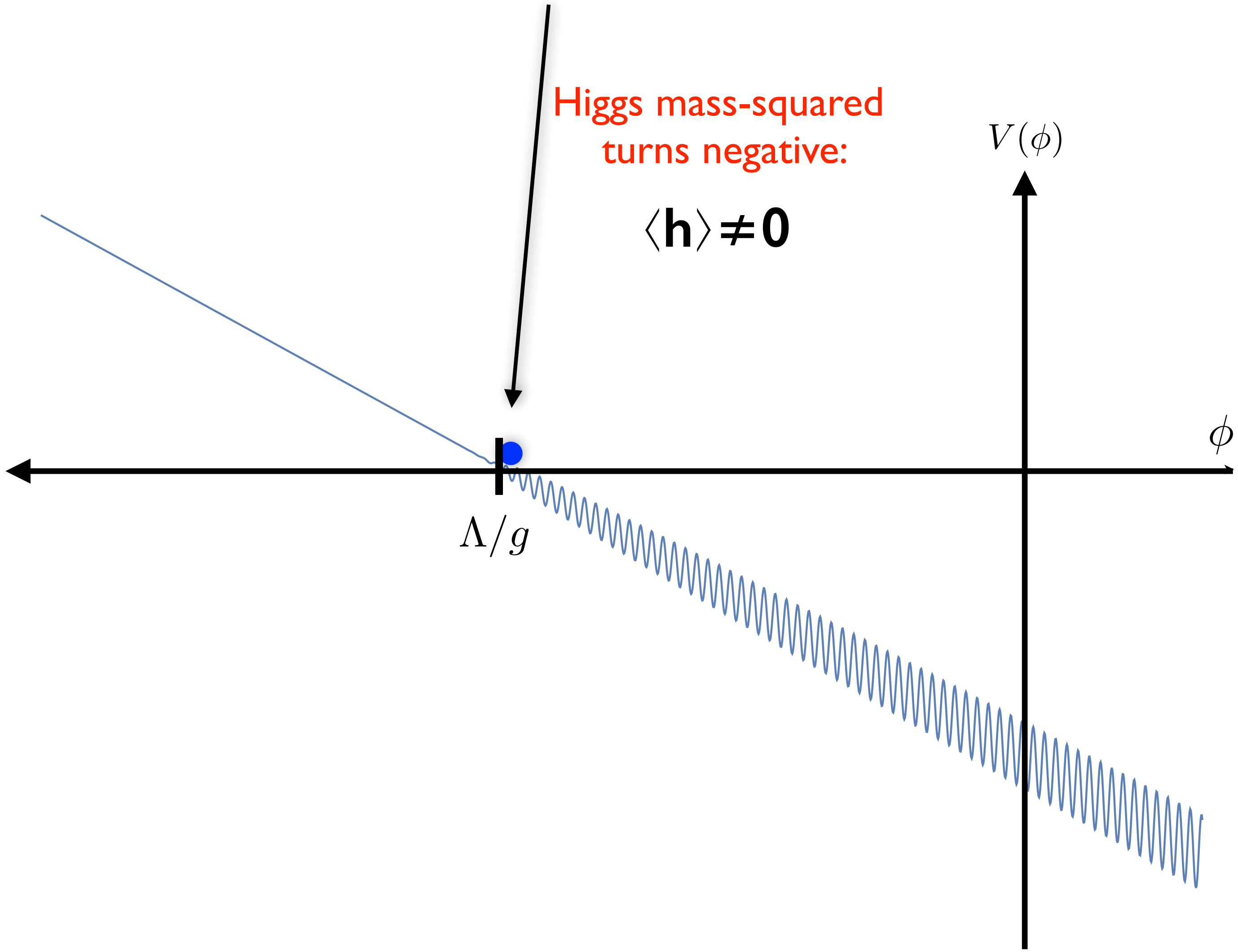
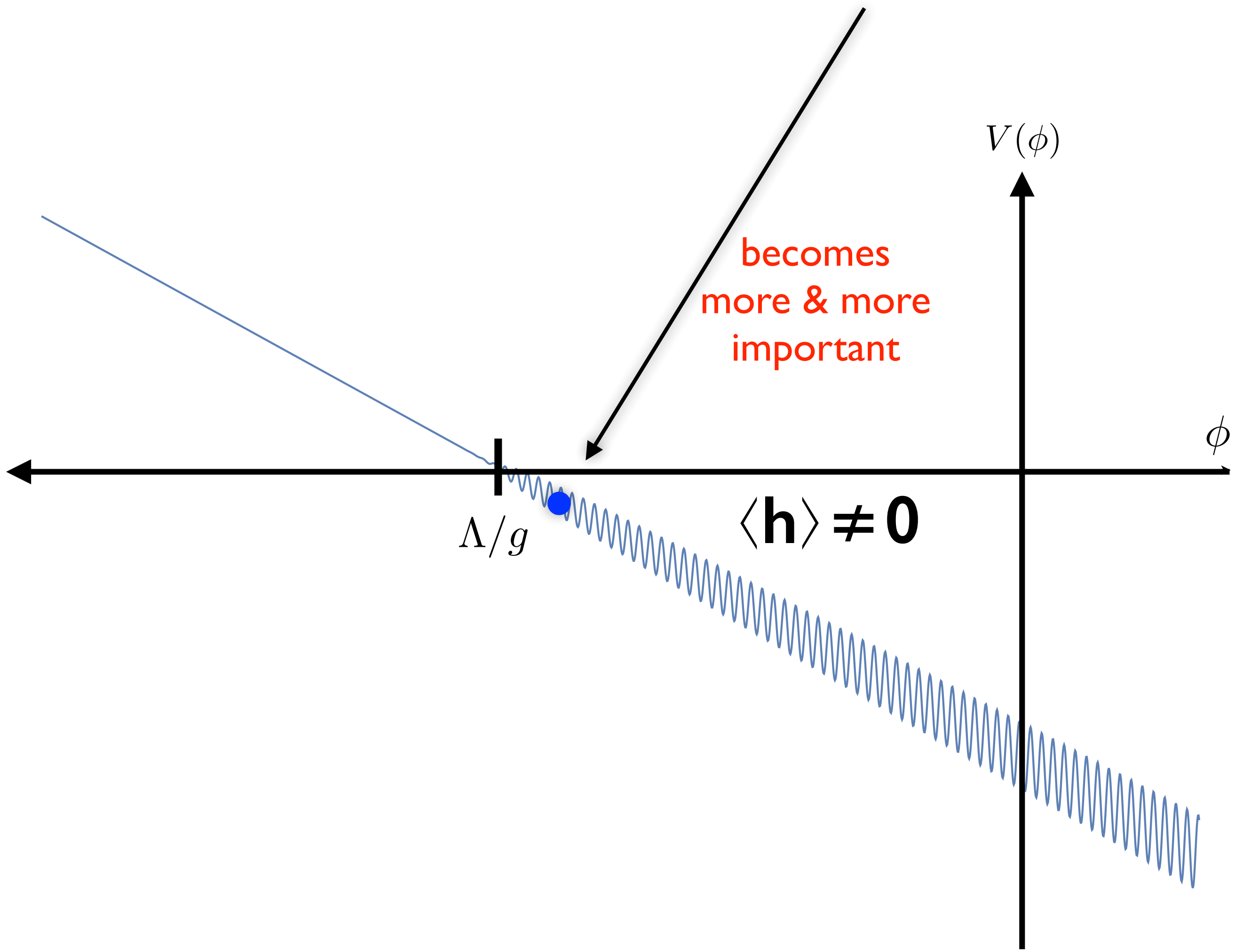


Cosmological evolution

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$



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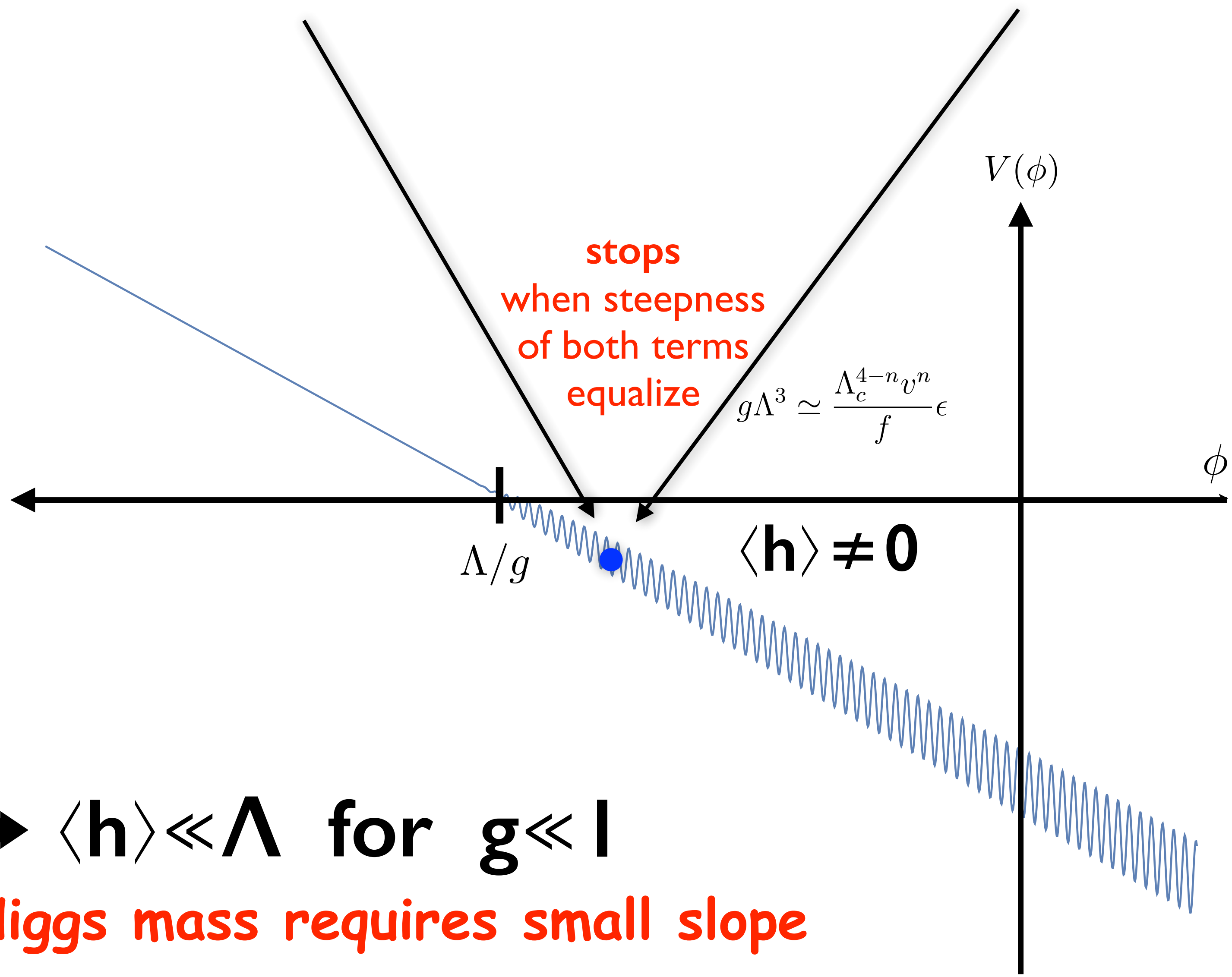


➥ $\langle h \rangle \ll \Lambda$ for $g \ll 1$

small Higgs mass requires small slope

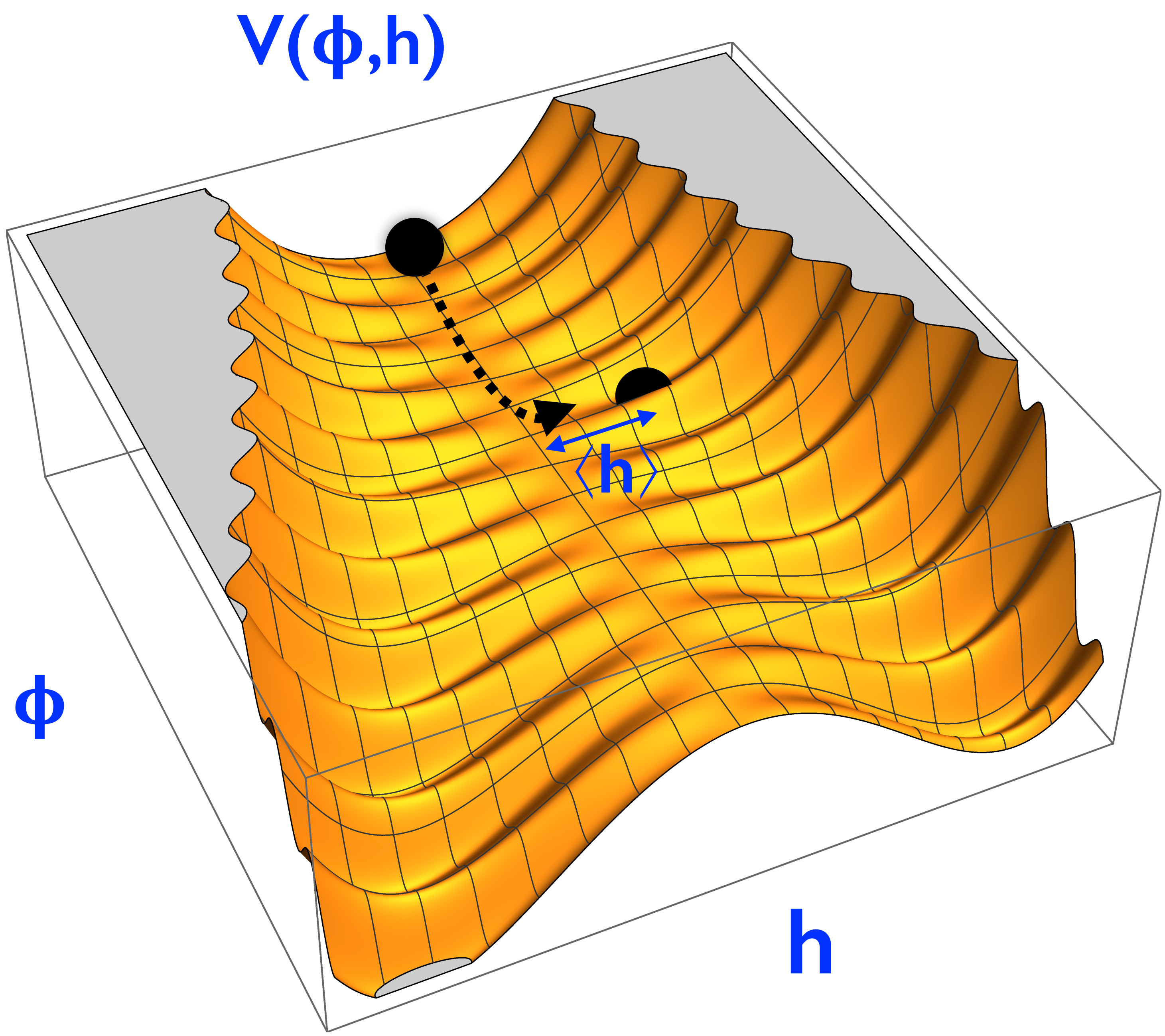
Cosmological evolution

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

Large field excursions for ϕ needed

$$\phi \sim \Lambda/g \gg \Lambda$$

No dependence on initial conditions, provided that this takes place during inflation



V(ϕ,h)
⟨h⟩
ϕ
h

Conditions:

Slow rolling:

$$H_I > \frac{\Lambda^2}{M_P}$$

from friction due to inflation

$$N_{efolds} \gtrsim \frac{H_I^2}{g^2\Lambda^2} \sim 10^{40}$$

Classical rolling

classical displacement over one Hubble time $>$ quantum fluctuation

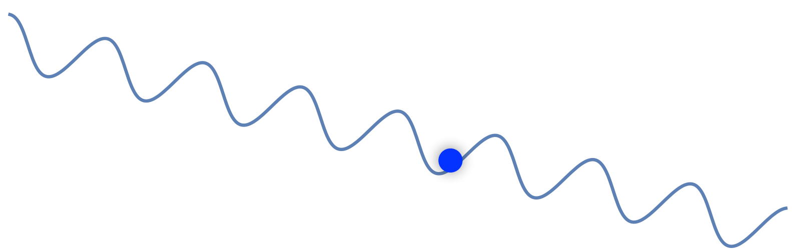
$$\frac{1}{H_I}\frac{d\phi}{dt} = \frac{1}{H_I^2}\frac{dV}{d\phi} = \frac{g\Lambda^3}{H_I^2} \qquad H_I$$

Origin of $\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)$

For n=1: From QCD condensate $\Lambda_c = \Lambda_{QCD}$

$$\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu} \longrightarrow m_u(h)\langle q\bar{q}\rangle\cos(\phi/f)$$

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



Problem solved if the tilt disappears at the end of inflation but one gets

$\Lambda \lesssim 30$ TeV

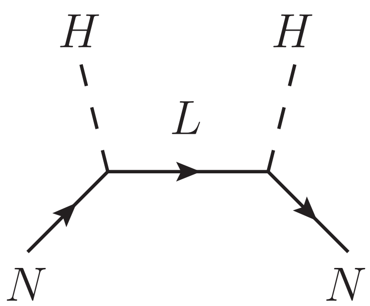
Origin of $\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)$

For n=2: $\epsilon\Lambda_c^2|H|^2\cos(\phi/f)$ **gauge invariant, no need to rely on QCD**

Similarly to QCD, the anomalous interaction term $\frac{\phi}{f}G'_{\mu\nu}\tilde{G}'^{\mu\nu}$

can be rotated away by a chiral rotation for N , and replaced by the term

$m_N e^{i\phi/f}\bar{N}N + h.c \to \Lambda^3 m_N\cos(\phi/f)$ where $\langle\bar{N}N\rangle \sim \Lambda^3$



$m_N \sim y^2|H|^2/m_L$

but $\epsilon\Lambda_c^4\cos(\phi/f)$ is generated by closing H in loop

Origin of $\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)$

For n=2: $\epsilon\Lambda_c^2|H|^2\cos(\phi/f)$ **gauge invariant, no need to rely on QCD**

but $\epsilon\Lambda_c^4\cos(\phi/f)$ is generated by closing H in loop

for the Higgs VEV to be responsible for stopping the rolling of phi, we need $\Lambda_c \lesssim v$

coincidence problem!! similar to the mu pb in the MSSM

Important drawback: weak scale is put by hand.

Our goal: Provide an existence proof of a model that generates a large mass gap between the Higgs mass and the new physics threshold, without generating a coincidence pb

J.R. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolàs, G. Servant, 1506.09217

The only new physics scale:

$$\Lambda \sim \Lambda_c \ll v$$

Our proposal:

$$A \cos(\phi / f)$$

Field-dependent amplitude

$$A(\phi, \sigma, H) \equiv \epsilon \Lambda^4 \left(\beta + \underbrace{c_\phi \frac{g\phi}{\Lambda} - c_\sigma \frac{g_\sigma \, \sigma}{\Lambda}}_{\text{the novelty with respect to Graham et al.}} + \frac{|H|^2}{\Lambda^2} \right)$$

generated at loop level

the novelty with respect to Graham et al.

generated by strong dynamics at scale Λ

σ scans the amplitude of the oscillating term

Two-scanners potential:

$$\boxed{V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right)+m^2(\phi)|H|^2+A(\phi,\sigma,H)\cos\left(\phi/f\right)}$$

key idea: at the beginning, phi is stuck during its cosmological

ALPine Cosmology

$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda}+\frac{g_\sigma\sigma}{\Lambda}\right) + m^2(\phi)|H|^2 + A(\phi,\sigma,H)\cos(\phi/f)$$

$$A(\phi,\sigma,H) \equiv \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right)$$

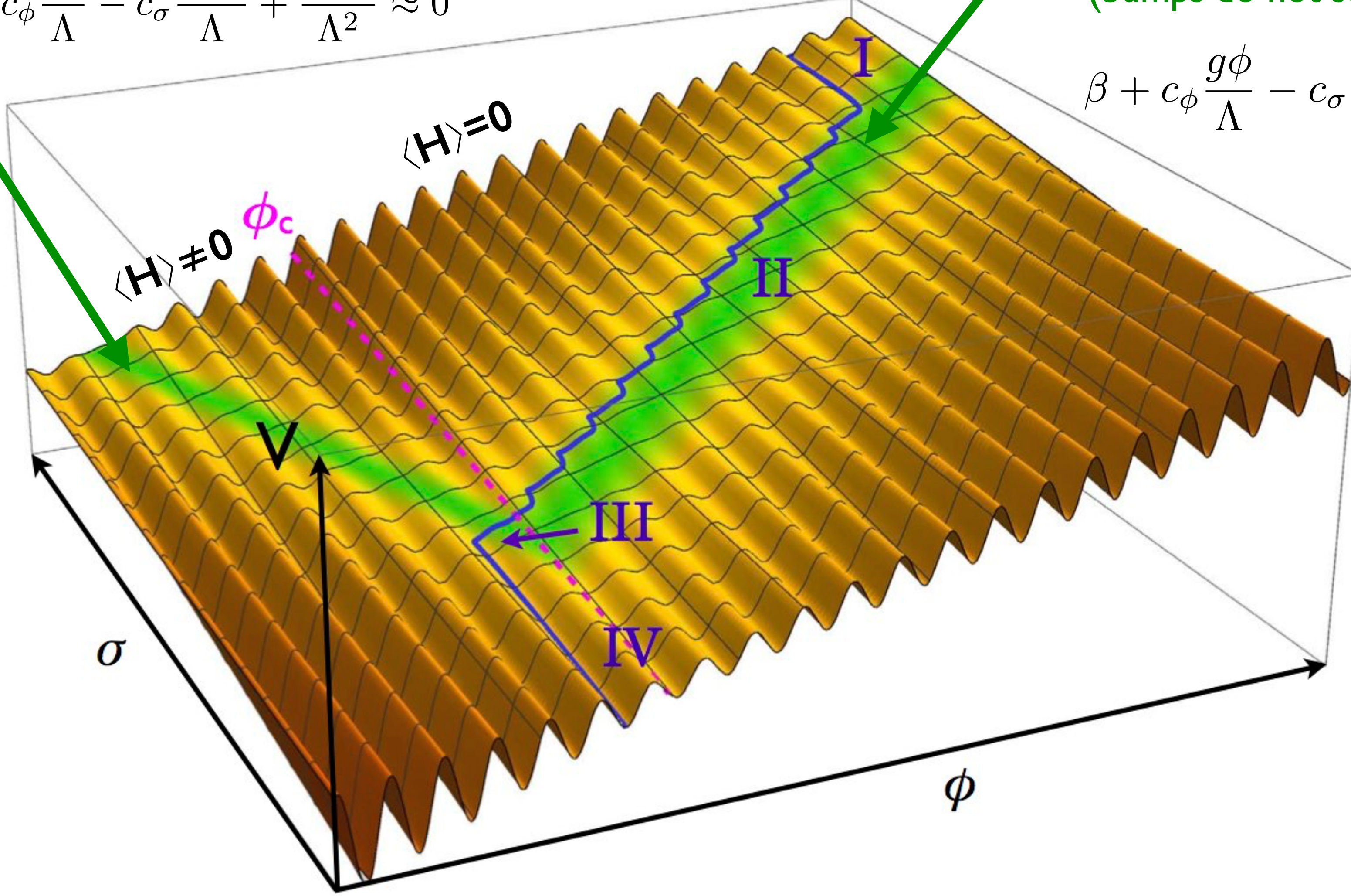
area where A≈0

$$\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2} \approx 0$$

area where A≈0

(bumps do not stop ϕ)

$$\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\,\sigma}{\Lambda} \approx 0$$



Phenomenological implications:

- Nothing at the LHC
- Only BSM below Lambda :

Two light and very weakly coupled scalars:

$m_\phi \sim 10^{-20} - 10^{2}$ GeV

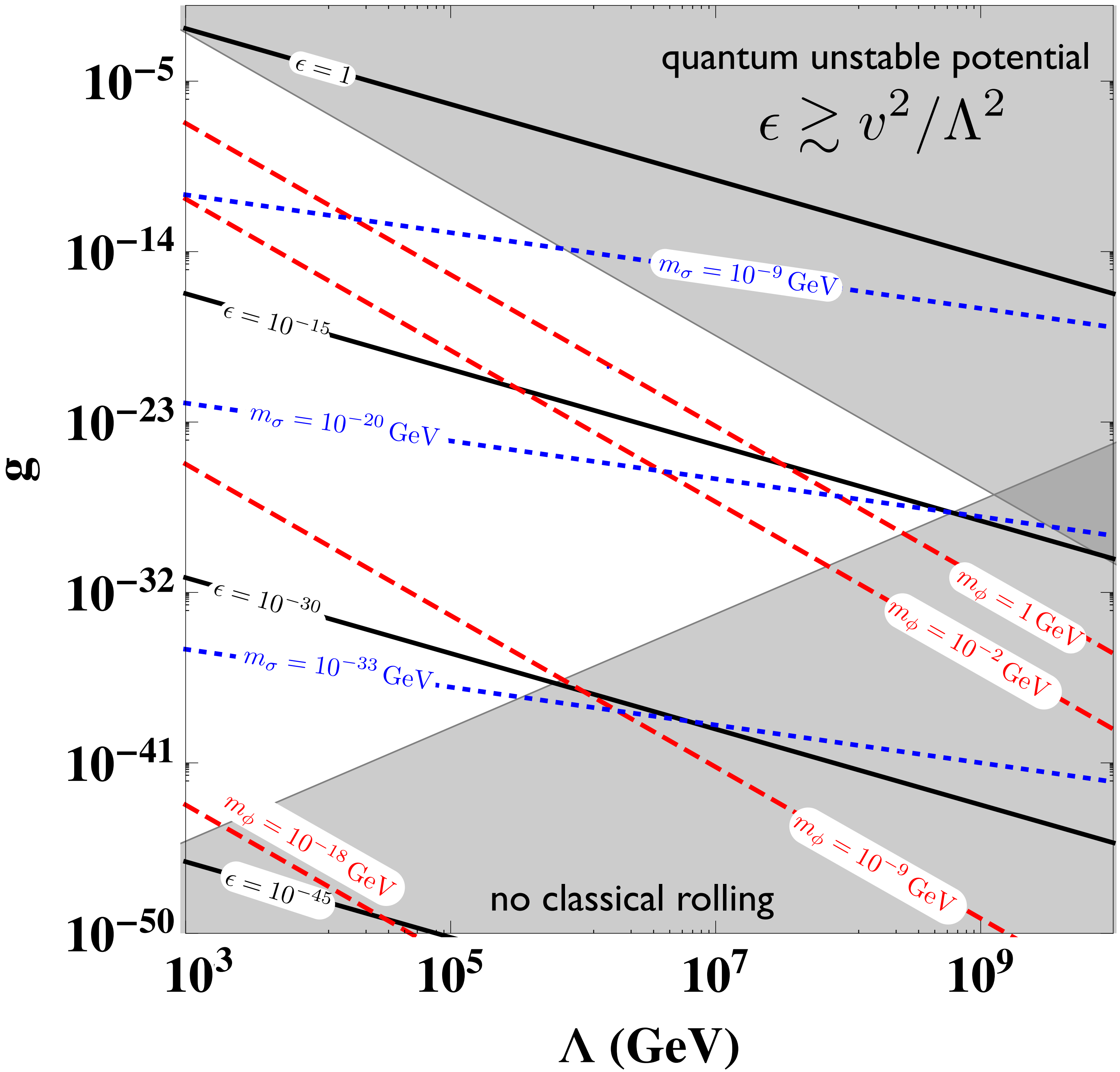
$m_\sigma \sim 10^{-45} - 10^{-2}$ GeV

Couple to the SM through their mixing with the Higgs

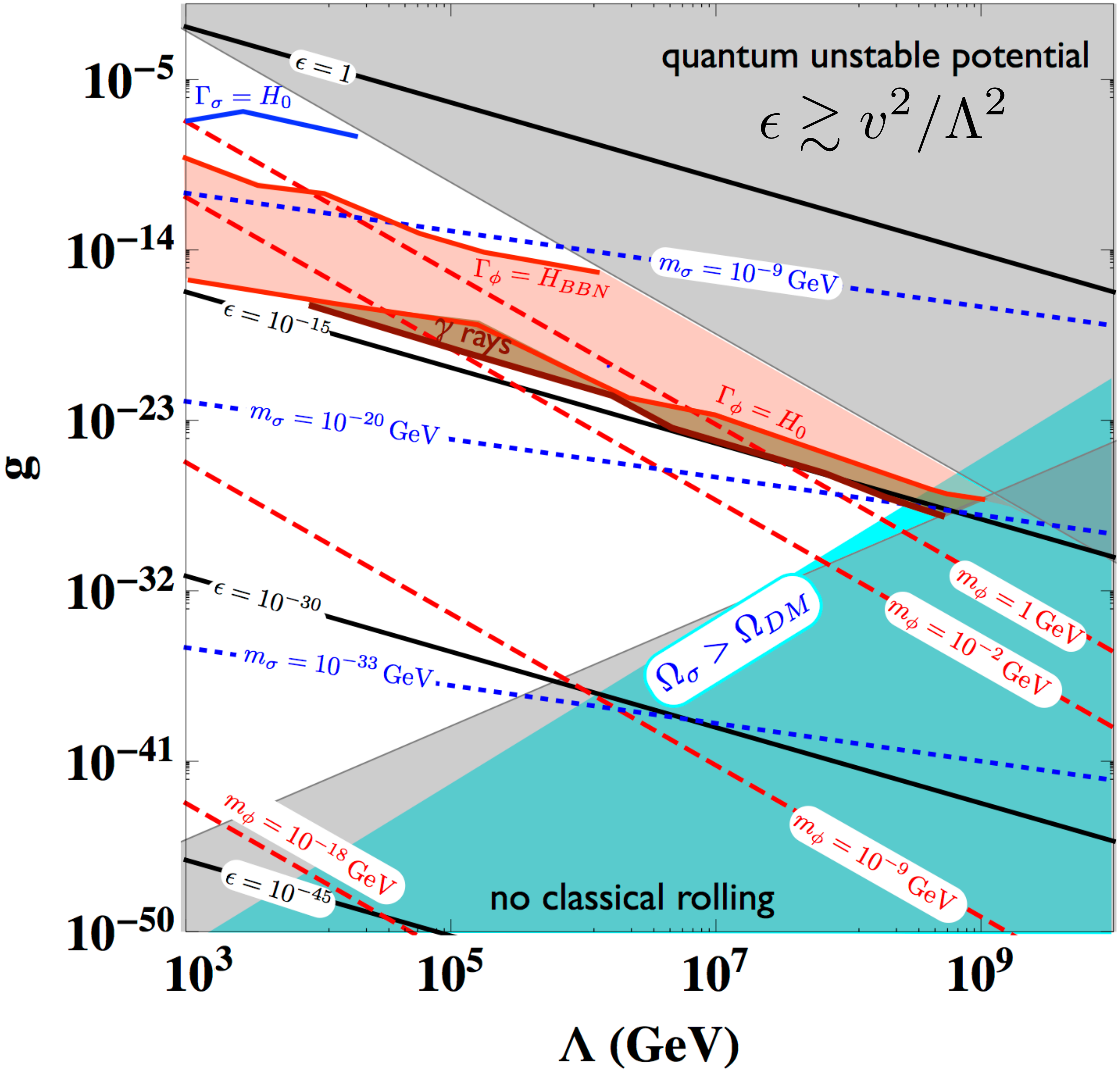
benchmark values: $\Lambda \sim 10^9$ GeV ☛ $m_\phi \sim 100$ GeV
$\theta_{\phi h} \sim 10^{-21}$
$\phi\phi$hh-coupling $\sim 10^{-14}$
$m_\sigma \sim 10^{-18}$ GeV
$\theta_{\sigma h} \sim 10^{-50}$

- **Experimental tests from cosmological overabundances, late decays, Big bang Nucleosynthesis, Gamma-rays, Cosmic Microwave Background ...**

Taking $g_\sigma \sim 0.1g$



Taking $g_\sigma \sim 0.1g$



Summary

A new paradigm for solving the hierarchy problem that connects connecting Higgs physics with inflation & (DM) axions.

Our proposal: an existence proof of a quantum stable mass gap between the weak scale and a new physics threshold Lambda

$$\Lambda < \left(v^4 M_P^3\right)^{1/7} = 3 \times 10^9\,\mathrm{GeV}$$

a solution to the hierarchy pb with no signature at the LHC nor at future collider

testable with ALPs type of signatures.

challenges:

$N_e > 10^{38}$ & super-Plankian field excursions

Annexes

master equation for EW baryogenesis:

$$\dot{n}_{CS} = -\frac{\Gamma}{T}\frac{\partial \mathcal{F}}{\partial N_{CS}} = \frac{\Gamma}{T}\mu_{CS}$$

(washout term ignored ~ $-c\Gamma\frac{n_{CS}}{T^2}$)

rate of Chern-Simons transitions

chemical potential from CP-violating source inducing a non-vanishing baryon number

$$\langle N_{CS}\rangle(t) = \frac{1}{T_{eff}}\int_0^t dt'\Gamma(t')\mu(t')$$

Operator relevant for baryogenesis:

$$\boxed{\mathcal{L}_{eff} = \frac{\alpha_W}{8\pi}\,\zeta(\varphi)\mathrm{Tr}\,F\tilde{F}}$$

EW field strength

time-varying function

$$\int d^4x \frac{\alpha_W}{8\pi}\,\zeta\,\mathrm{Tr}\,F\tilde{F} = \int d^4x\,\zeta\,\partial_\mu j^\mu_{CS} = -\int dt\,\partial_t\zeta \int d^3x j^0_{CS}$$

$$N_{CS} = \int d^3x j^0_{CS}$$

$$\mathcal{L}_{eff} = \mu\, j^0_{CS}$$

$$\boxed{\mu \equiv \partial_t \zeta}$$

the time derivative of ζ can be interpreted as a time-dependent chemical potential for Chern-Simons number

this operator has been used with $\zeta = \frac{8\pi}{\alpha_W}\frac{\Phi^\dagger\Phi}{M^2}$

This operator is a CP-violating source for baryogenesis

$$n_B = N_F \int dt \frac{\Gamma \mu}{T} \sim N_F \frac{\Gamma(T_{eff})}{T_{eff}} \Delta\zeta$$

using the sphaleron rate in the symmetric phase $\Gamma = 30\alpha_w^5 T^4 \sim \alpha_w^4 T^4$

$$\frac{n_B}{s} = N_F \alpha_w^4 \left(\frac{T_{eff}}{T_{reh}}\right)^3 \Delta\zeta \, \frac{45}{2\pi^2 g_*(T_{reh})} \sim 10^{-7} \left(\frac{T_{eff}}{T_{reh}}\right)^3 \Delta\zeta$$

in standard EW baryogenesis, $T_{eff} = T_{reh} = T_{EWPT}$

in cold EW baryogenesis, $T_{eff} \neq T_{reh}$

Baryogenesis from Strong CP violation

Therefore, we expect that a coupling of the type ~ $\dfrac{a(t)}{f_a} F\tilde{F}$

will induce from the motion of the axion field a chemical potential for baryon number given by

$$\frac{\partial_t a(t)}{f_a}$$

This is non-zero only once the axion starts to oscillate after it gets a potential around the QCD phase transition.

Baryogenesis from Strong CP violation

To see the explicit dependence on the axion mass , let us write the effective lagrangian generated by SU(3) instantons

Kuzmin, Shaposhnikov, Tkachev '92

$$\mathcal{L}_{eff} = \frac{10}{F_\pi^2 m_{\eta'}^2} \frac{\alpha_s}{8\pi} G\tilde{G} \quad \frac{\alpha_w}{8\pi} F\tilde{F}$$

A condensate for $G\tilde{G}$ induces a mass for the axion :

$$\frac{\alpha_s}{8\pi} \langle G\tilde{G} \rangle = m_a^2(T) f_a^2 \sin\theta$$

this leads to:

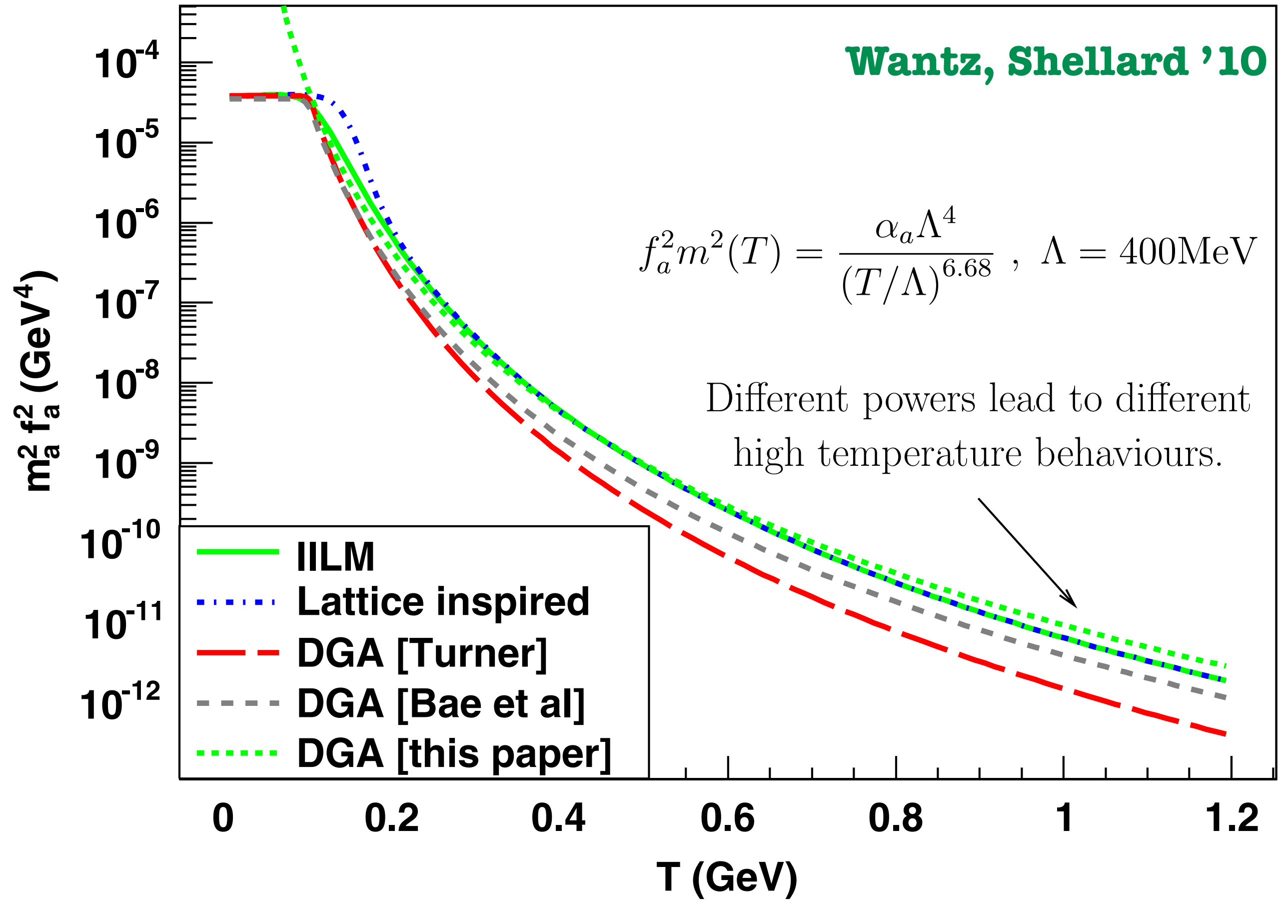
$$\mathcal{L}_{eff} = \frac{10}{F_\pi^2 m_{\eta'}^2} \sin\theta \ m_a^2(T) f_a^2 \quad \frac{\alpha_w}{8\pi} F\tilde{F}$$

$$\equiv \zeta(T)$$

time variation of axionic mass and field is source for baryogenesis

$$\boxed{\mu = \frac{d\zeta}{dt} = \frac{f_a^2}{M^4} \frac{d}{dt}[\sin\bar{\Theta} \ m_a^2(T)]}$$

Temperature dependence of axion mass



For T > T_t =0.1 GeV

$$m^2(T) = m^2(T=0) \times \left(\frac{T_t}{T}\right)^{6.68}$$

$$\delta m^2(T) \sim m^2(T)$$

$$\Delta\zeta \gtrsim 10^{-3} \to T \lesssim 0.3 \text{ GeV}$$

B-violation and time-variation of axion mass should occur at the same time...

$$n_B \propto \int dt \frac{\Gamma(T)}{T} \frac{d}{dt}[\sin \bar{\Theta}\ m_a^2(T)]$$

1) For the axion to be the source of baryogenesis, the EW phase transition should be delayed down to ~ 1 GeV. Fine ... but

$$\frac{n_B}{s} = n_f \alpha_w^4 \left(\frac{T_{eff}}{T_{reh}}\right)^3 \Delta\zeta \,\frac{45}{2\pi^2 g_*} \sim 10^{-7} \left(\frac{T_{eff}}{T_{reh}}\right)^3 \Delta\zeta \qquad \sim \bar{\Theta}(T_{eff})$$

$$\left(\frac{T_{eff}}{T_{reh}}\right)^3 \sim \left(\frac{0.1}{100}\right)^3$$ killing factor

2) and there should not be any reheating -> unacceptable as $T_{reh} \sim m_h$.

Kuzmin, Shaposhnikov, Tkachev '92

Besides, in this case, axion oscillations would start too late and would overclose the universe

Conclusion of the authors:
This kills baryogenesis from strong CP violation.

However, conclusion becomes positive if you involve Cold baryogenesis.

In 1992, the mechanism of cold baryogenesis was not yet known

Cold baryogenesis cures it all as $\frac{T_{eff}}{T_{reh}} \sim [20-30]$

--> large enough baryon asymmetry even for $\bar{\Theta}(T) \gtrsim 10^{-6}$

$$\frac{n_B}{s} \sim 10^{-8} \left(\frac{T_{eff}}{T_{reh}}\right)^3 \sin \bar{\Theta}\Big|_{EWPT}$$

key point: $T_{eff} \neq T_{EWPT}$

So even if $T_{EWPT} \lesssim \Lambda_{QCD}$ we can have $T_{eff} \gtrsim T_{reh} \sim m_H$

Cold baryogenesis arises naturally in models where EW symmetry breaking is induced by the radion/dilaton vev.

1407.0030

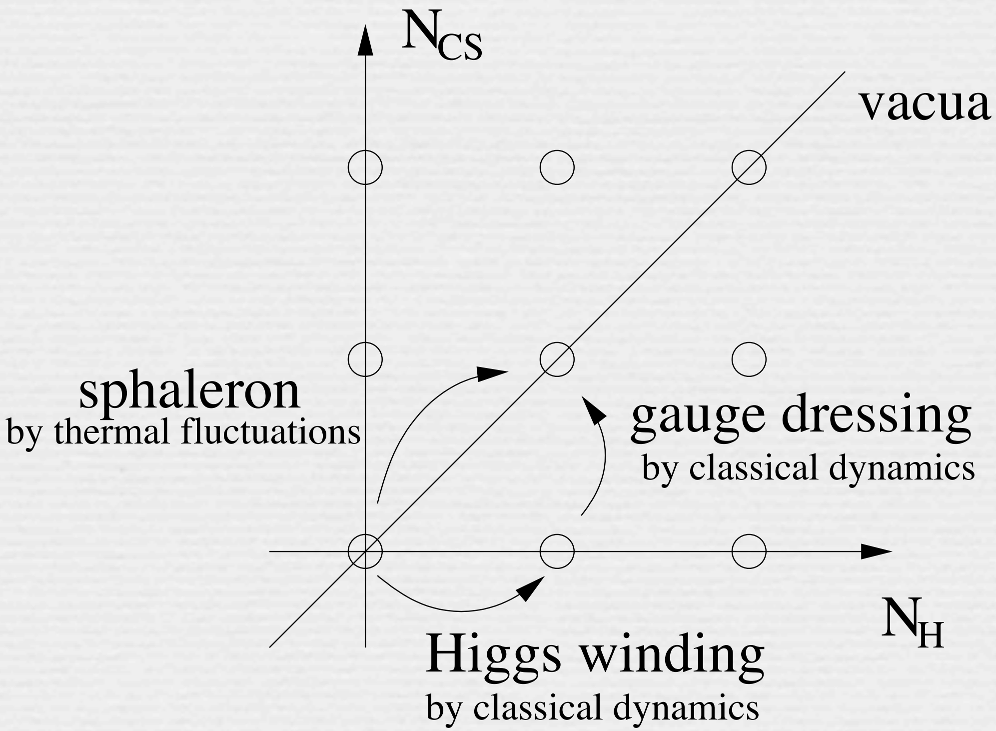
Cold Baryogenesis

main idea:

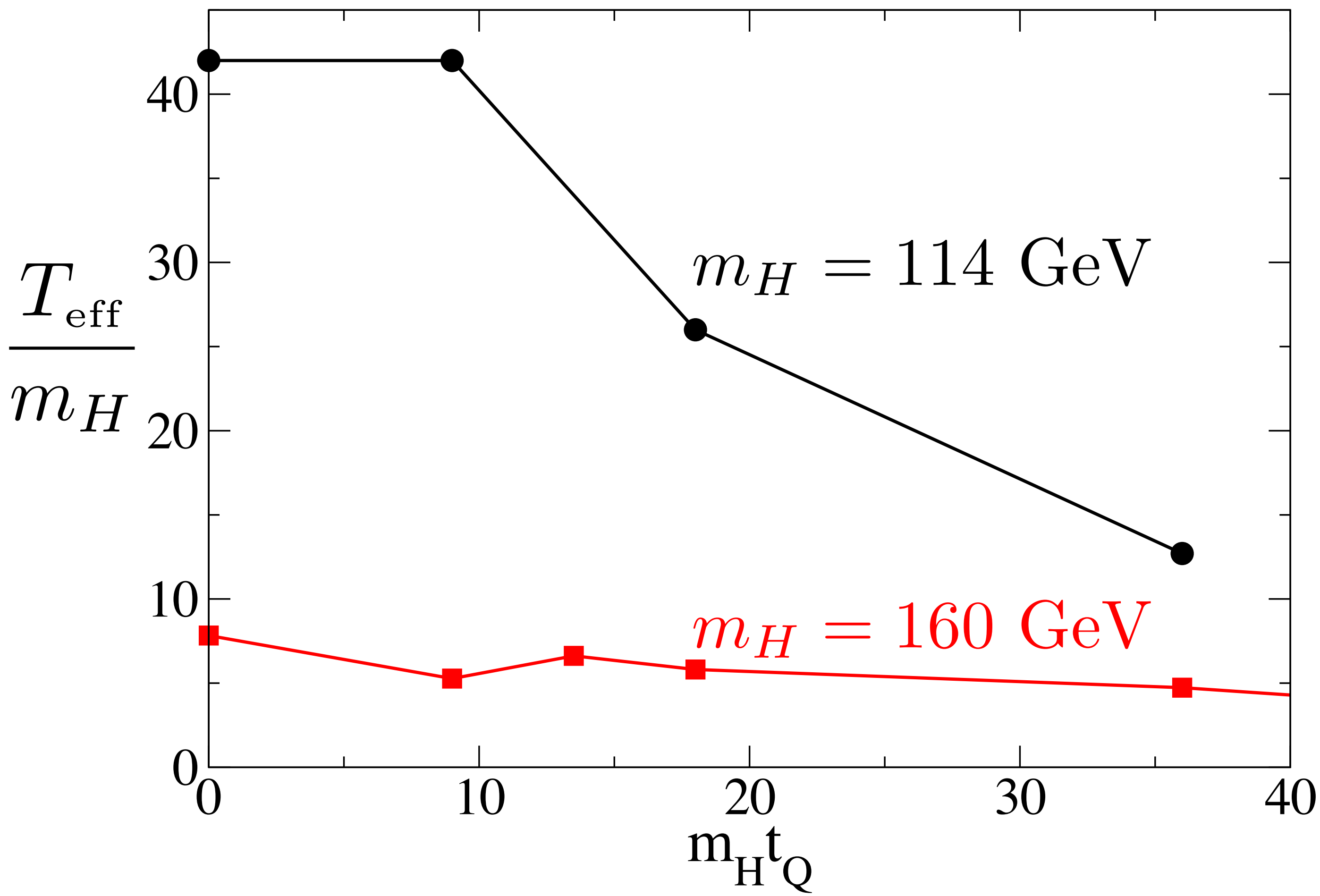
During EWPT, SU(2) textures can be produced.
They can lead to B-violation when they decay.

Turok, Zadrozny '90
Lue, Rajagopal, Trodden, '96

$$\Delta B = 3\Delta N_{CS}$$



cold baryogenesis: production of baryon number at T=0 from out-of equilibrium dynamics



Tranberg, Smit, Hindmarsh, hep-ph/0610096

Motivating Cold Baryogenesis

Konstandin Servant '11

$$V = V(\sigma) + \frac{\lambda}{4}(\phi^2 - c\sigma^2)^2$$

Higgs vev controlled by dilaton vev

(e.g. Randall-Sundrum scenario)

$$V(\sigma) = \sigma^4 \times f(\sigma^\epsilon)$$

a scale invariant function modulated by a slow evolution through the σ^ϵ term

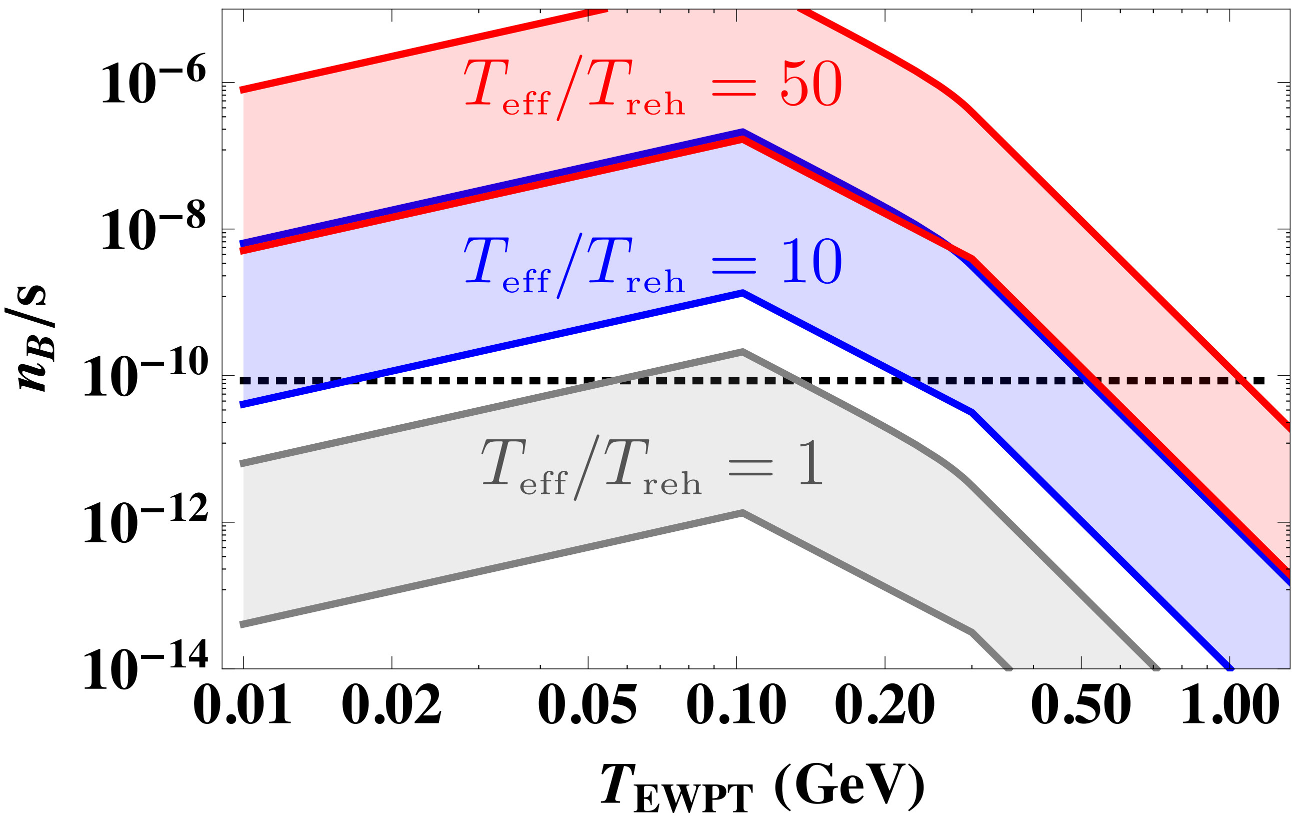
for $|\varepsilon| << 1$

similar to Coleman-Weinberg mechanism where a slow RG evolution of potential parameters can generate widely separated scales

Axion dynamics during a supercooled EW phase transition can lead to baryogenesis

Servant, 1407.0030

$f_a \lesssim 7\times10^{10}$ GeV



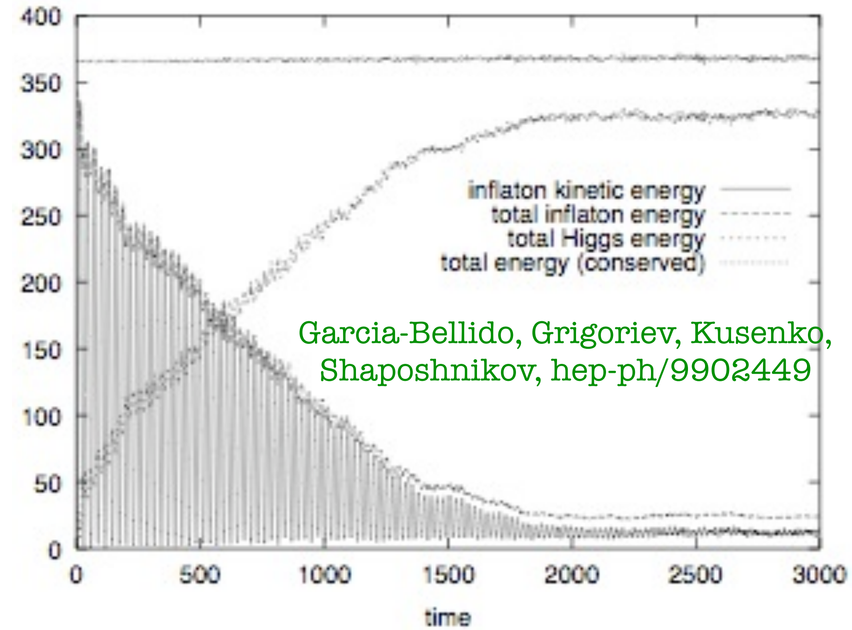
requires a coupling between the Higgs and an additional light scalar

Cold baryogenesis in a nutshell

EW symmetry breaking is triggered through a coupling of the Higgs to a rolling field

$$V(\sigma,\phi)=\frac{\lambda}{4}(\phi^2-v^2)^2+\frac{1}{2}\tilde{m}^2\sigma^2+\frac{1}{2}g^2\sigma^2\phi^2$$

Higgs



Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, hep-ph/9902449

Higgs mass squared is not turning negative as a simple consequence of the cooling of the universe but because of its coupling to another field which is rolling down its potential. The Higgs is "forced" to acquire a vev by an extra field -> Higgs quenching

It has been shown that Higgs quenching leads to the production of unstable EW field configuration which when decaying lead to Chern-Simons number transitions.

Cold Baryogenesis

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They can lead to B-violation when they decay.

Turok, Zadrozny ’90
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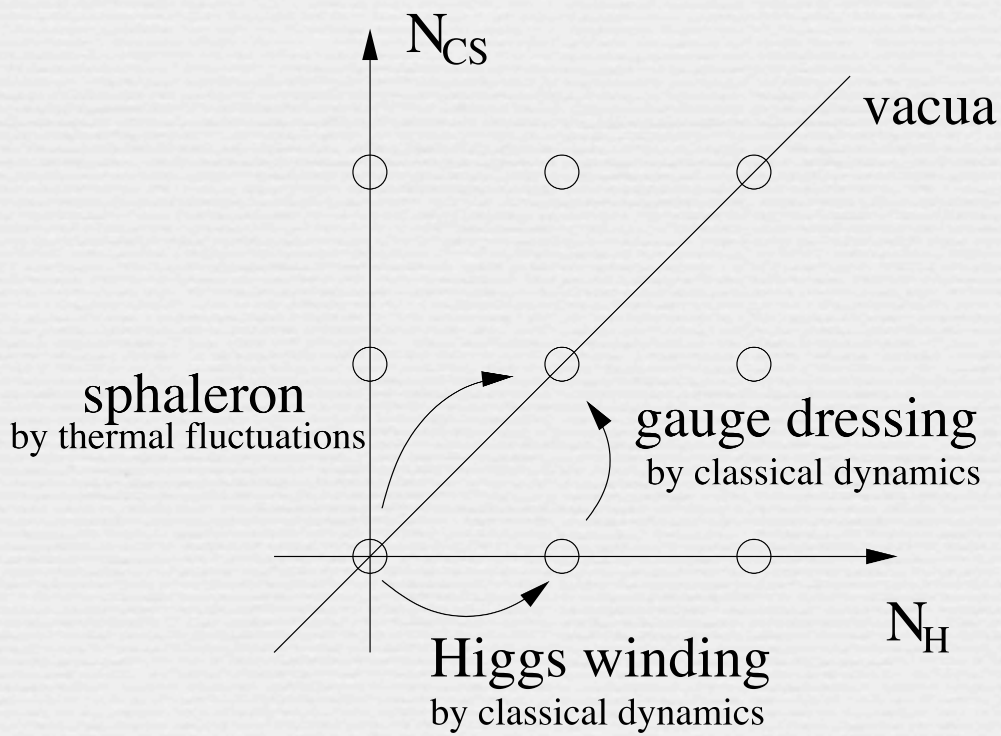


We need to produce $$\Delta B = 3\Delta N_{CS}$$

where: $$N_{CS} = -\frac{1}{16\pi^2}\int d^3x\,\epsilon^{ijk}\ \mathrm{Tr}\ \left[A_i\left(F_{jk} + \frac{2i}{3}A_jA_k\right)\right]$$

key point: The dynamics of N_{CS} is linked to the dynamics of the Higgs field via the Higgs winding number N_H:

$$N_H = \frac{1}{24\pi^2}\int d^3x\,\epsilon^{ijk}\ \mathrm{Tr}\ \left[\partial_i\Omega\Omega^{-1}\partial_j\Omega\Omega^{-1}\partial_k\Omega\Omega^{-1}\right]$$

$$\frac{\rho}{\sqrt{2}}\Omega = (\epsilon\phi^*, \phi) = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix} \quad , \quad \rho^2 = 2(\phi_1^*\phi_1 + \phi_2^*\phi_2)$$

In vacuum: $N_H = N_{CS}$

Requirements for cold baryogenesis

1) large Higgs quenching to produce Higgs winding number in the first place

2) unsuppressed CP violation at the time of quenching so that a net baryon number can be produced

3) a reheat temperature below the sphaleron freese-out temperature T ~ 130 GeV to avoid washout of B by sphalerons

Higgs quenching

The speed of the quench or quenching parameter is a dimensionless velocity parameter characterizing the rate of change of the effective Higgs mass squared at the time of quenching.

$$u \equiv \frac{1}{m_H^3} \frac{d\mu_{\text{eff}}^2}{dt}\bigg|_{T=T_q}$$

cold baryogenesis requires $u \gtrsim 0.1$

In the SM, the effective Higgs mass varies solely because of the cooling of the universe.
Using d/dt = - H T d/dT

$$u^{\text{SM}} \sim \frac{1}{\mu^3}\frac{d}{dt}(\mu^2 - cT^2)\bigg|_{T=T_q} \sim \frac{H}{\mu}\bigg|_{T_q} \sim \frac{T_{\text{EW}}}{M_{Pl}} \sim 10^{-16}$$

situation can be changed radically if the Higgs mass is controlled by the time-varying vev of an additional scalar field, e.g

$$\mu_{\text{eff}}^2(t) = \mu^2 - \lambda_{\sigma\phi}\sigma^2(t).$$

$$u \sim {\lambda_{\sigma\phi}}^{1/2}\mu^{-2}\,\dot{\sigma}\big|_{t_q}$$

From energy conservation $(\dot{\sigma})^2 \sim \mathcal{O}(V) \sim \mu^4$

quenching parameter of order 1 naturally, no longer controlled by Hubble rate

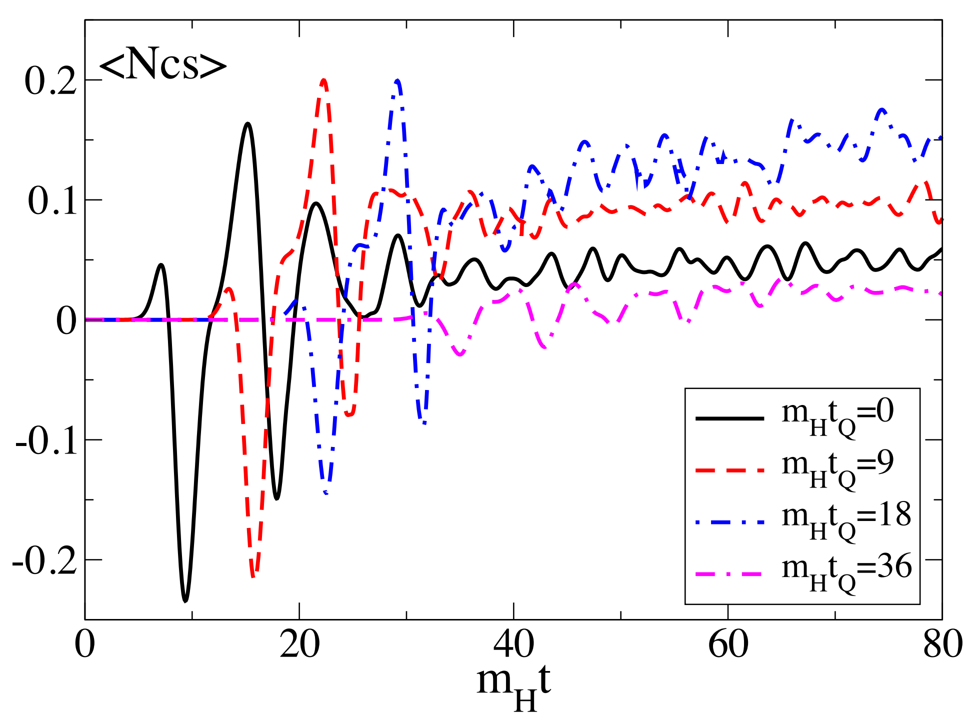
Cold baryogenesis has been simulated on the lattice where:

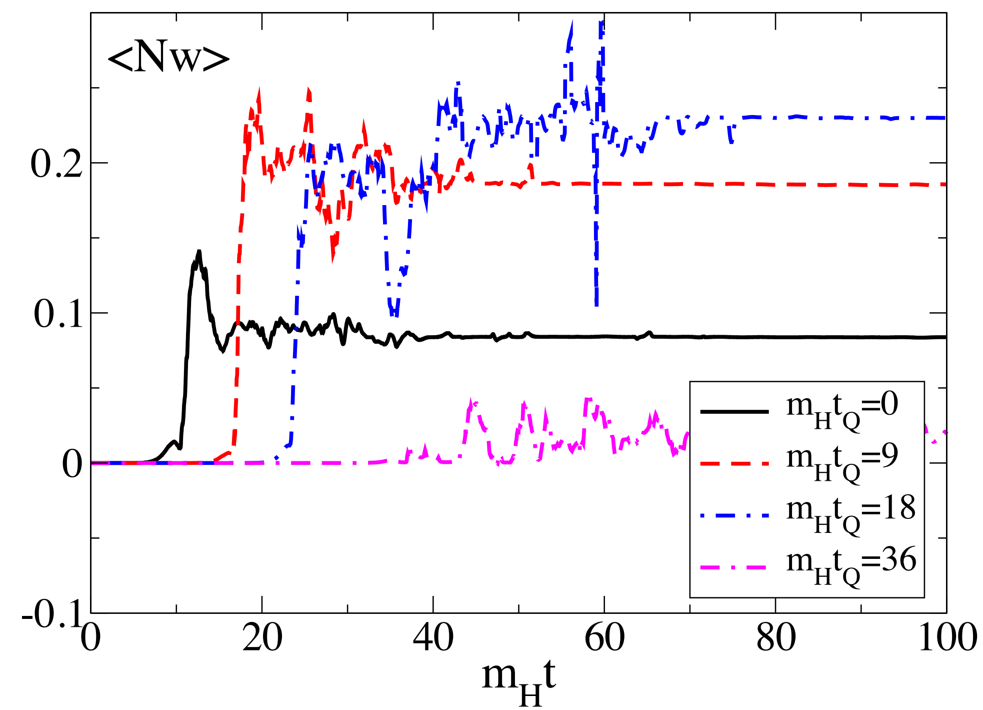
-the Higgs quenching is put by hand.
-The new CP-violating source is parametrized by the dimension-6 operator:

$$\mathcal{L}_{eff} = \frac{\alpha_W}{8\pi}\ \zeta(T)\mathrm{Tr}\ F\tilde{F}$$

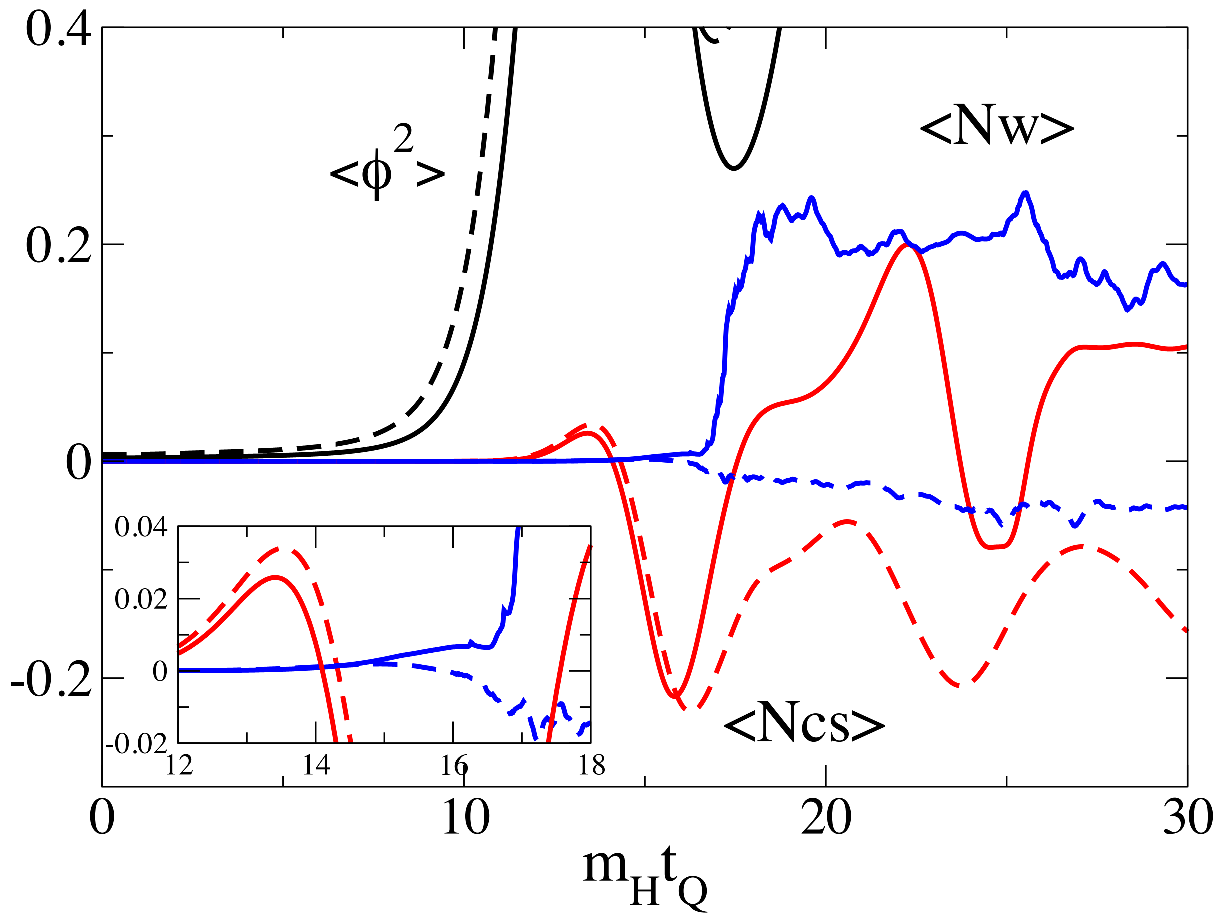
$$\zeta = \frac{8\pi}{\alpha_W}\frac{\Phi^\dagger\Phi}{M^2}$$

The latest electron EDM constraints lead to a bound of M>~ 65 TeV





Tranberg, Smit, Hindmarsh, hep-ph/0610096



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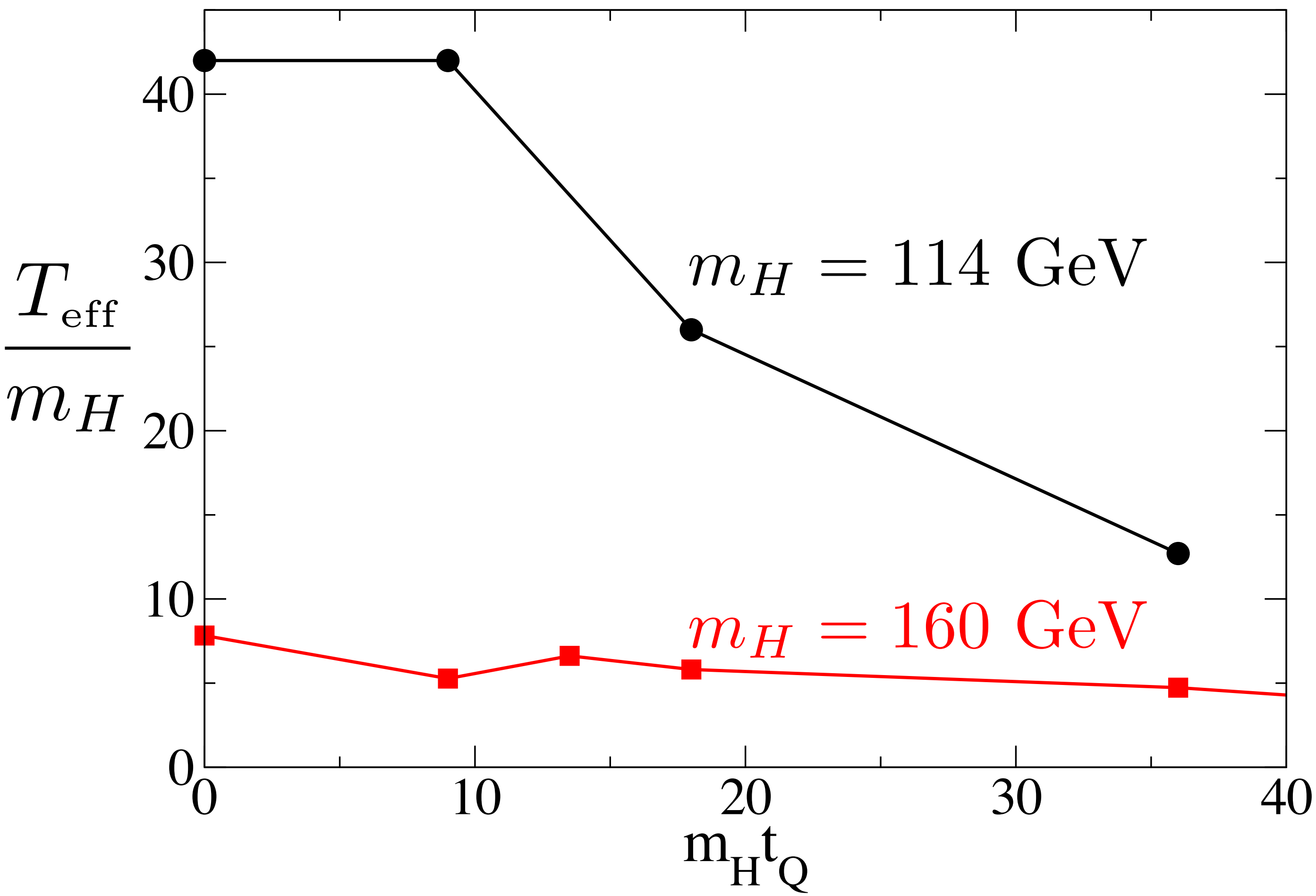

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