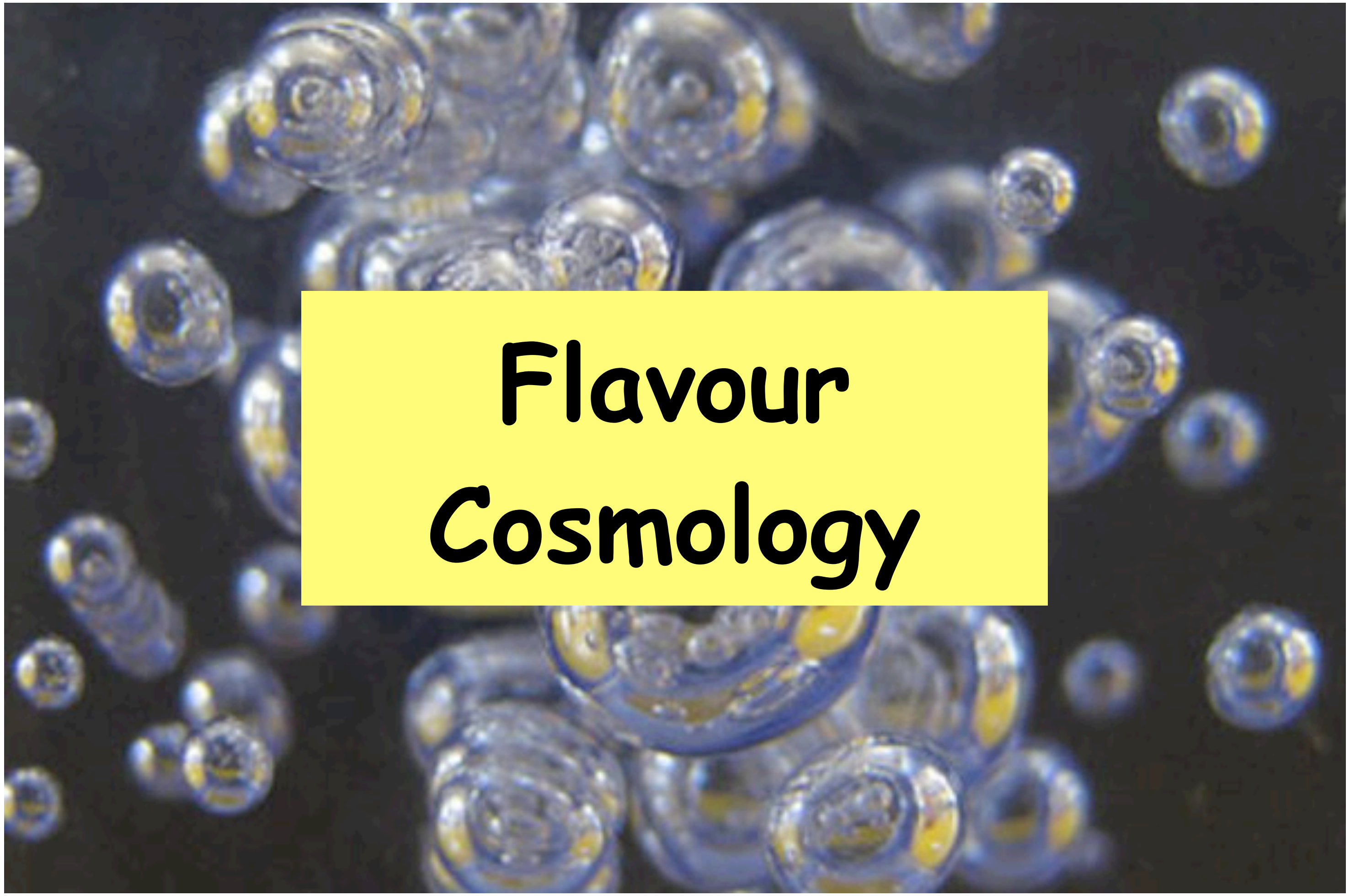


Flavour Cosmology

Géraldine SERVANT
DESY/U.Hamburg

Humboldt Kolleg conference, Kitzbühel

June 30 2016

HELMHOLTZ GEMEINSCHAFT

Universität Hamburg

DESY

Matter Anti-matter asymmetry:

characterized in terms of the baryon to photon ratio

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

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

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

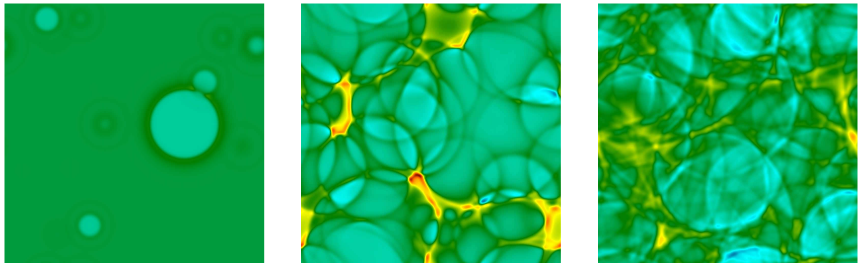
attempts in cold EW baryogenesis

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

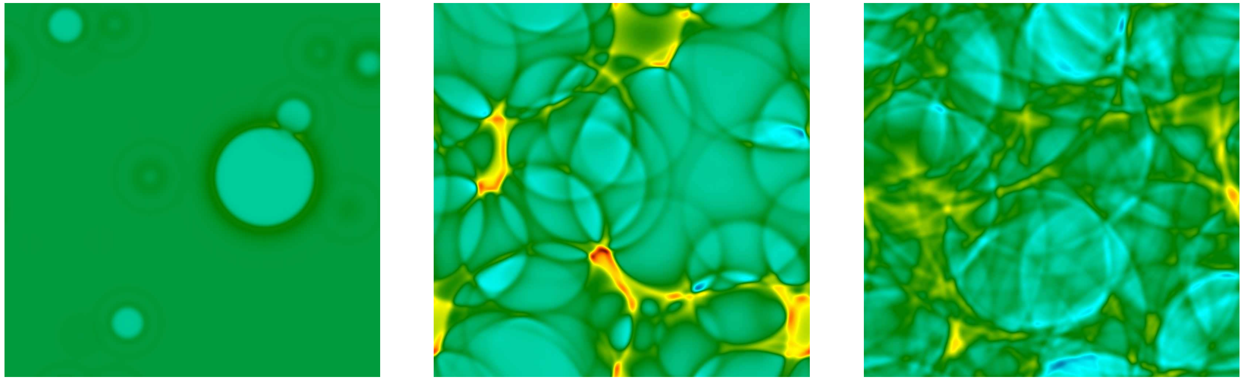
Two leading candidates for baryogenesis:

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

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



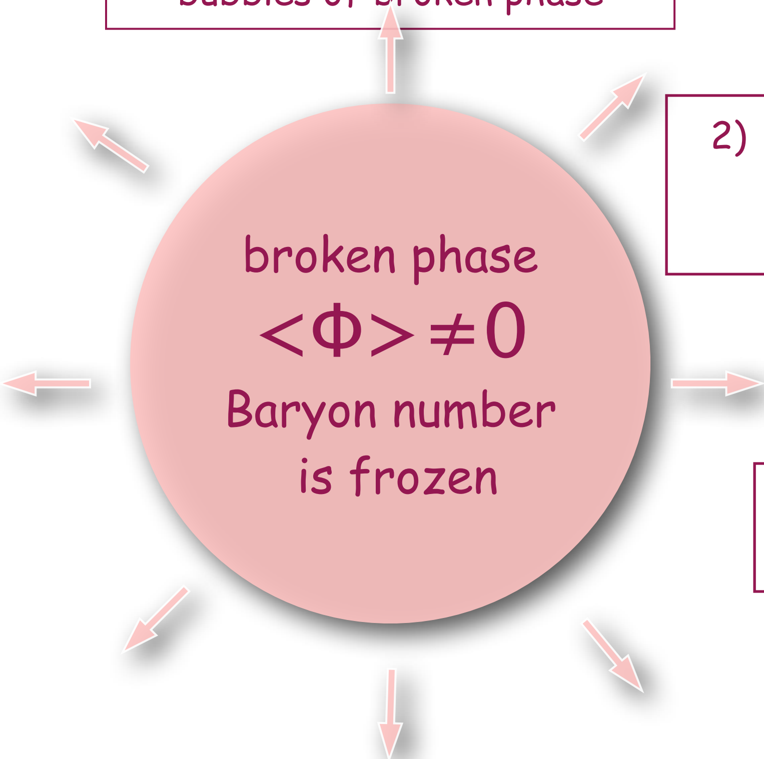
Baryogenesis at a first-order EW phase transition



Baryon asymmetry and the EW scale

Cohen, Kaplan, Nelson'91

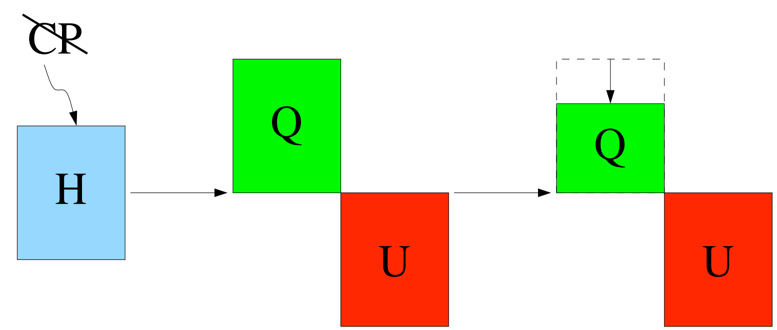
1) nucleation and expansion of bubbles of broken phase



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

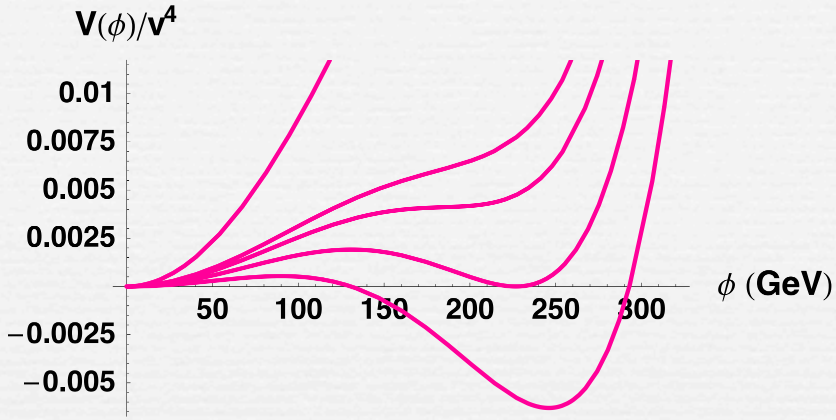
Chirality Flux in front of the wall

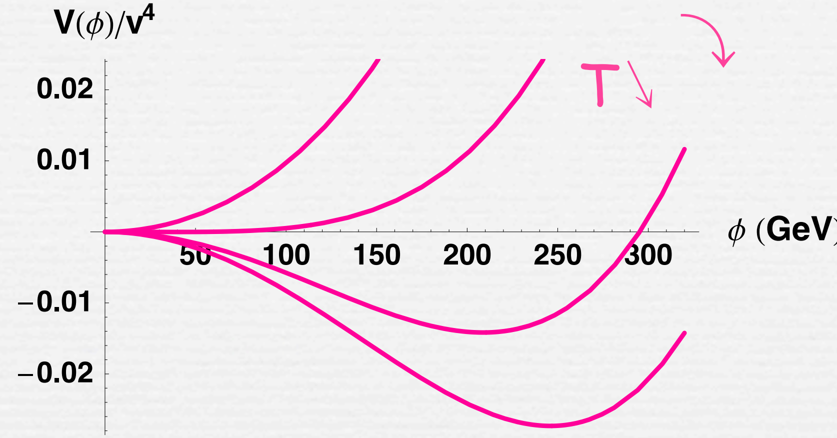
3) In symmetric phase, <Φ>=0, very active sphalerons convert chiral asymmetry into baryon asymmetry



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

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 M_H > 72 GeV, no 1st order phase transition

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

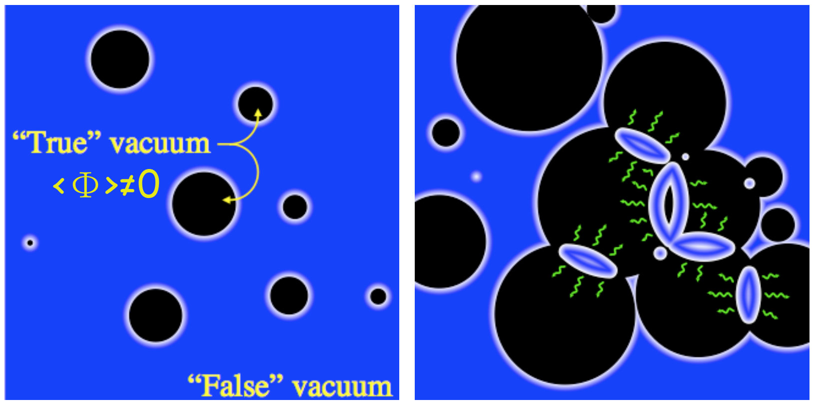
Main effect due to the stop

Gravity wave signals from 1st order cosmological phase transitions

Bubble nucleation

Bubble percolation

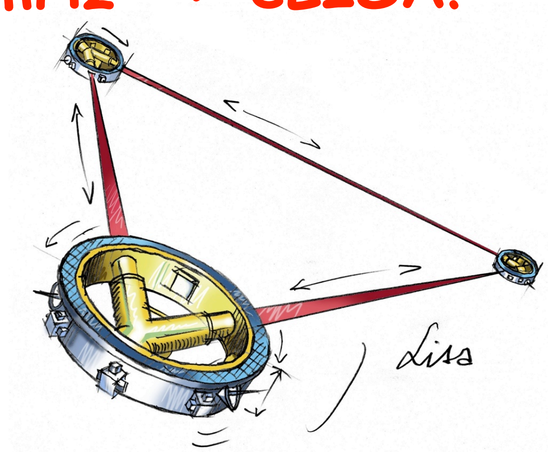
[eLISA Cosmology Working group, 1512.06239]

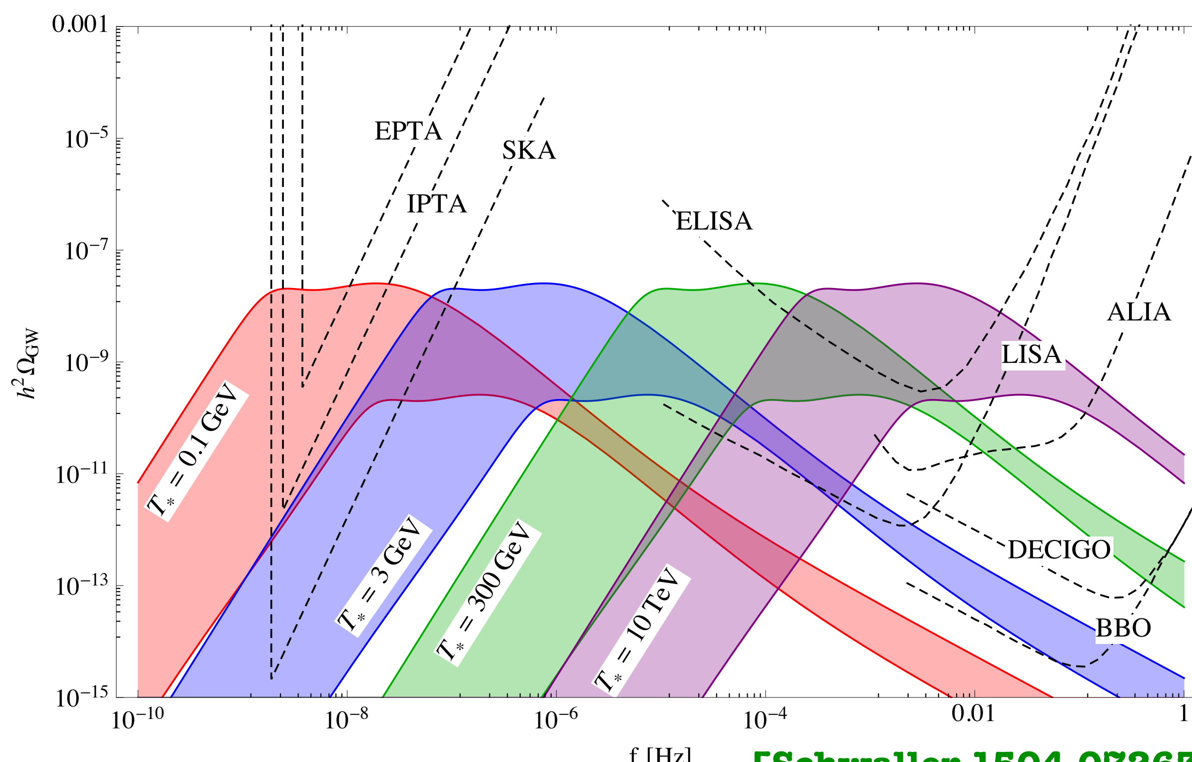


$\langle \Phi \rangle = 0$

Stochastic background of gravitational radiation

EW phase transition -> mHz -> eLISA!

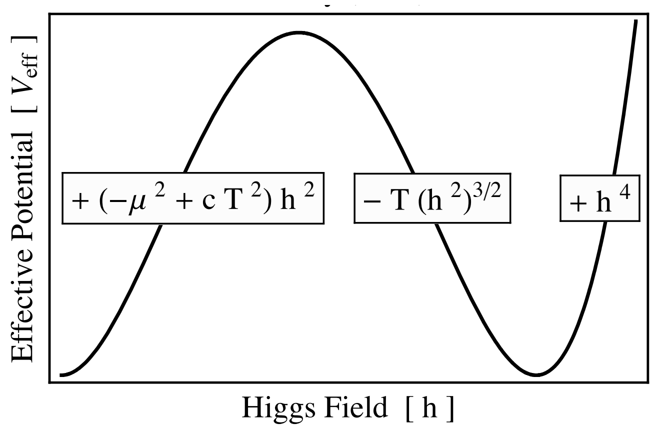




[Schwaller 1504.07263]

The most common way to obtain a strongly 1st order phase transition by inducing a barrier in the effective potential is due to thermal loops of BOSONIC modes.

One adds new scalar coupled to the Higgs



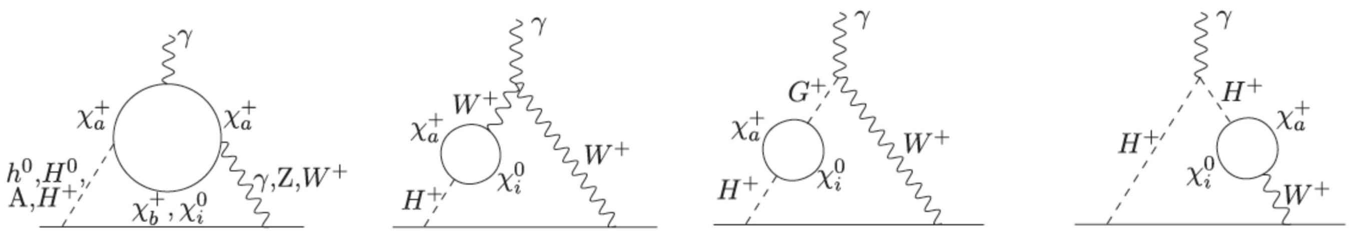
Very constrained by LHC !

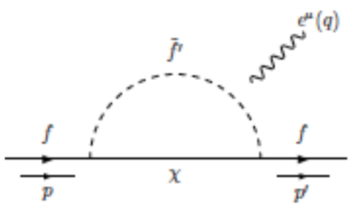
Katz, Perelstein '14

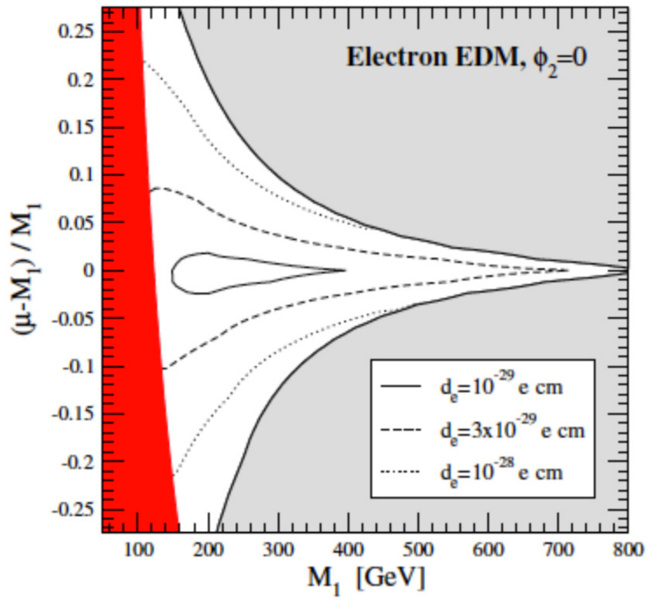
A strong 1st order PT leads to sizable deviations in hgg and $h\gamma\gamma$ couplings and therefore in Higgs production rate and decays in $\gamma\gamma$

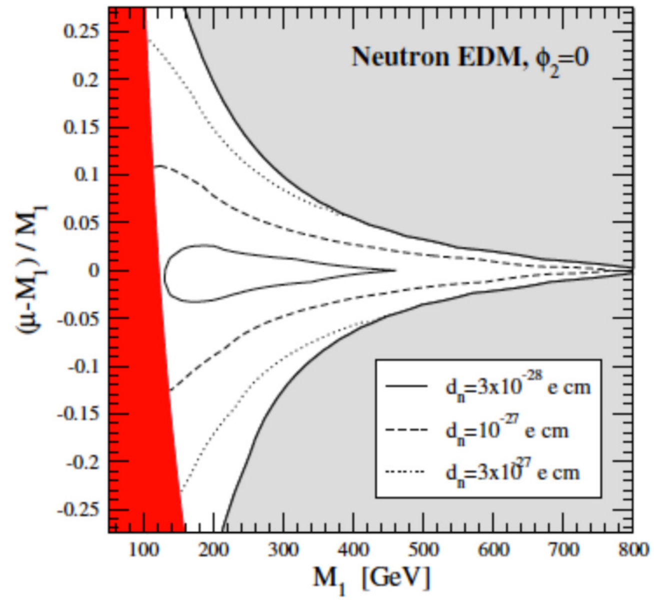
e.g: Light stop scenario in MSSM

and in addition... EDM constraints on MSSM EW baryogenesis (generic in most commonly studied scenarios of EW baryogenesis)









versus

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration*: J. Baron[1], W. C. Campbell[2], D. DeMille[3], J. M. Doyle[1], G. Gabrielse[1], Y. V. Gurevich[1,**], P. W. Hess[1], N. R. Hutzler[1], E. Kirilov[3,#], I. Kozyryev[3,†], B. R. O'Leary[3], C. D. Panda[1], M. F. Parsons[1], E. S. Petrik[1], B. Spaun[1], A. C. Vutha[4], and A. D. West[3]

$$|d_e| < 8.7 \times 10^{-29}\ e\ \mathrm{cm}$$ @ 90%CL [1310.7534]

Higgs mass measurement does not constrain the nature of the EW phase transition

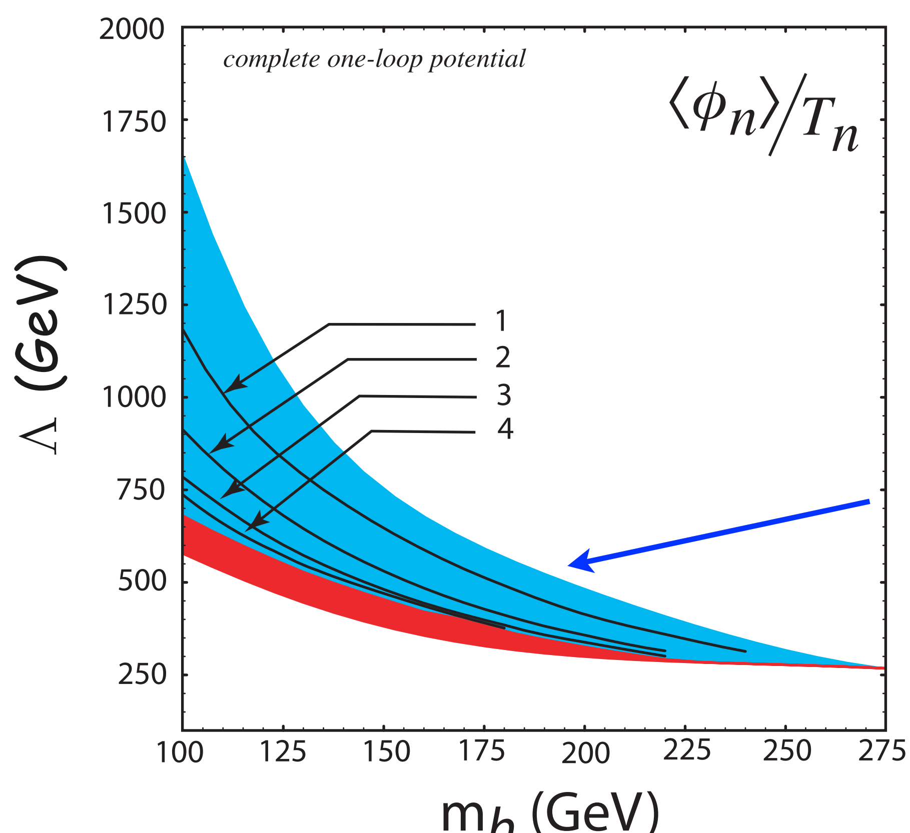
Easily seen in effective field theory approach:

Add a non-renormalizable Φ^6 term to the SM Higgs potential and allow a negative quartic coupling

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

"strength" of the transition does not rely on the one-loop thermally generated negative self cubic Higgs coupling

strong enough
for EW baryogenesis
if $\Lambda \lesssim$ 1.3 TeV



region where EW phase transition is 1st order

Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

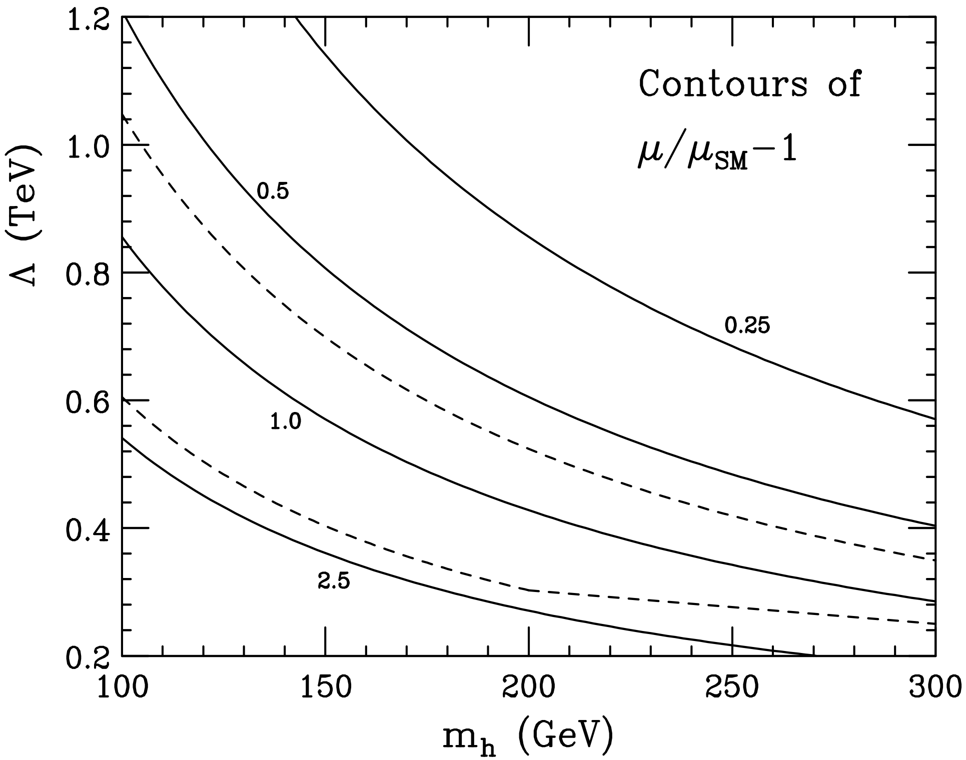
but Typically large deviations to the Higgs self-couplings

$$\mathcal{L} = \frac{m_H^2}{2} H^2 + \frac{\mu}{3!} H^3 + \frac{\eta}{4!} H^4 + \ldots$$

where

$$\mu = 3\frac{m_H^2}{v_0} + 6\,\frac{v_0^3}{\Lambda^2}$$

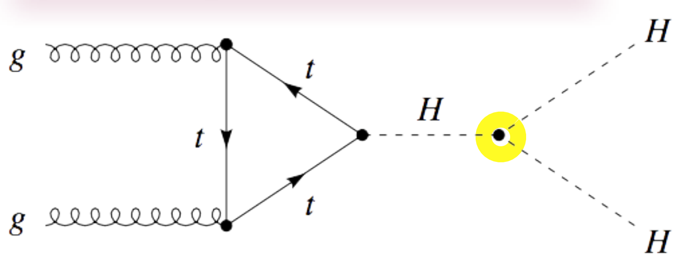
$$\eta = 3\frac{m_H^2}{v_0^2} + 36\,\frac{v_0^2}{\Lambda^2}$$



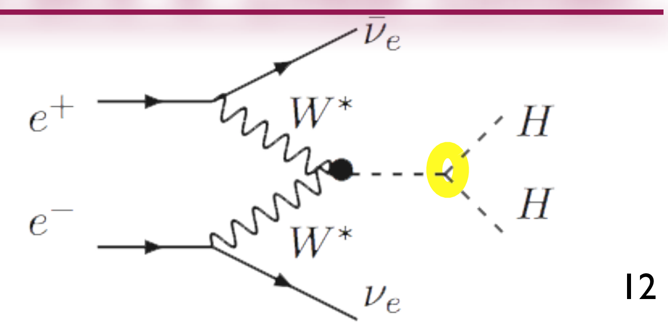
The dotted lines delimit the region for a strong 1rst order phase transition

deviations between a factor 0.7 and 2

at a Hadron Collider



at an $e^+ e^-$ Linear Collider

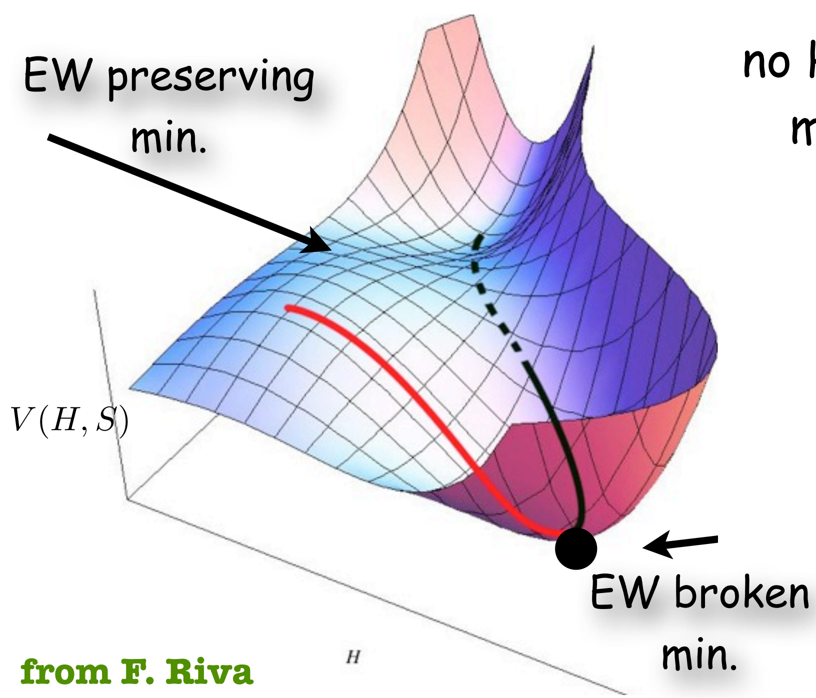


The easiest way: Two-stage EW phase transition

example: the SM+ a real scalar singlet

e.g 1409.0005

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



from F. Riva

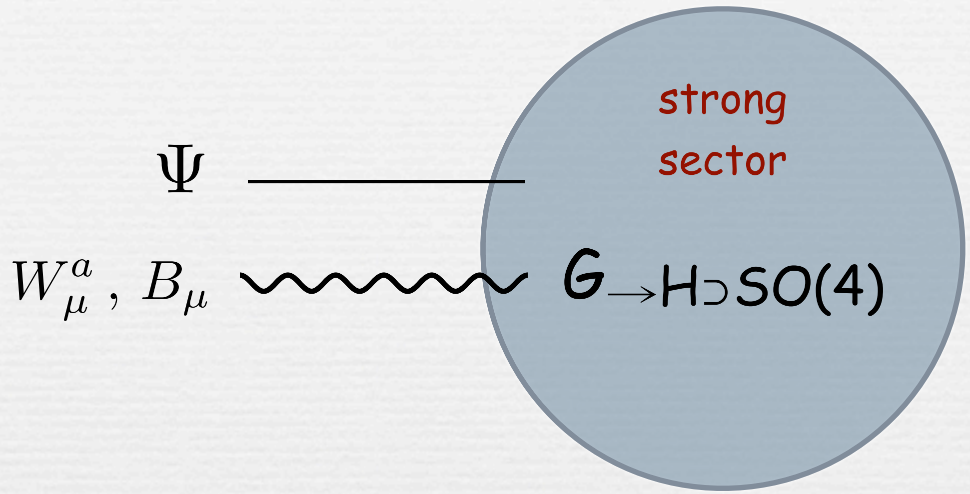
S has no VEV today:
no Higgs-S mixing-> no EW precision tests , tiny modifications of higgs couplings at colliders

Poorly constrained

-> Espinosa et al, 1107.5441

Easy to motivate additional scalars, e.g:

New strong sector endowed with a global symmetry G spontaneously broken to H → 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.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$ -> Agashe, Contino, Pomarol'05
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	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$

[Mrazek et al, 1105.5403]

Higgs scalars as pseudo-Nambu-Goldstone bosons of new dynamics above the weak scale

global symm. on u,d

strong int.

QCD: $SU(2)_L \times SU(2)_R \xrightarrow[SU(3)_c]{} SU(2)_V \supset U(1)_Q$

6 - 3 = 3 PNGB $\pi^{\pm}, \pi_0$

global symm. on techniquarks

Composite Higgs: $SO(6) \times U(1)_x \xrightarrow[SU(N_c)]{} SO(5) \times U(1)_Y \supset SU(2) \times U(1)_Y$

16 - 11 = 5 PNGB H, S

SO(5)/SO(4) -> SM
SO(6)/SO(5) -> SM + S
SO(6)/SO(4) -> 2 HDM

associated LHC tests

Another easy way to get a strong 1st-order PT:

dilaton-like potential naturally leads to supercooling

Konstandin Servant '11

not a polynomial

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

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 $|\epsilon| \ll 1$

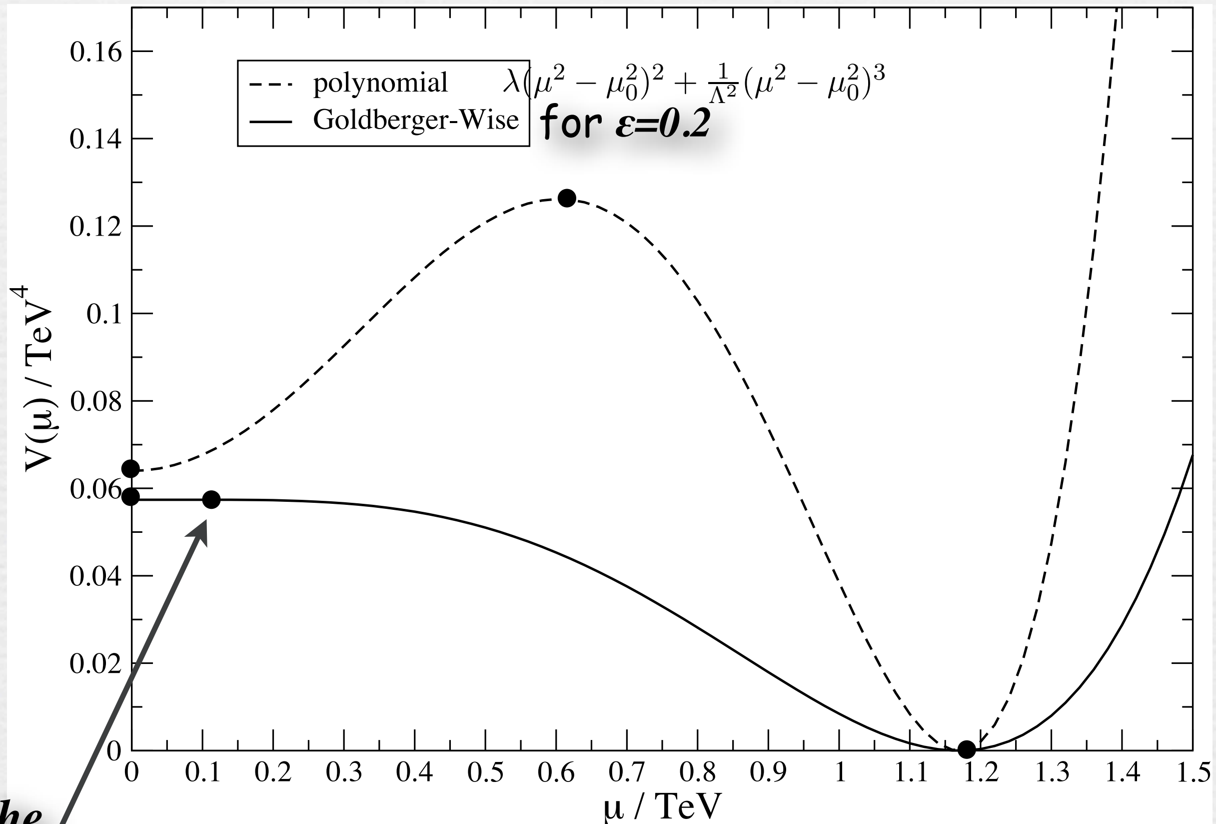
similar to Coleman-Weinberg mechanism where a slow Renormalization Group evolution of potential parameters can generate widely separated scales

Nucleation temperature can be parametrically much smaller than the weak scale

$$V(\mu) = \mu^4 P((\mu/\mu_0)^\epsilon).$$

Konstandin Servant '11

The position of the maximum μ_+ and of the minimum μ_- can be very far apart in contrast with standard polynomial potentials where they are of the same order



position of the maximum

The tunneling value μ_r can be as low as $\sqrt{\mu_+\mu_-} \ll \mu_-$

Application:

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

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

Application:

Baryogenesis from the QCD axion

EW field strength

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

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.

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

Servant, 1407.0030

→ **Cold Baryogenesis**

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

Cold Baryogenesis

main idea:

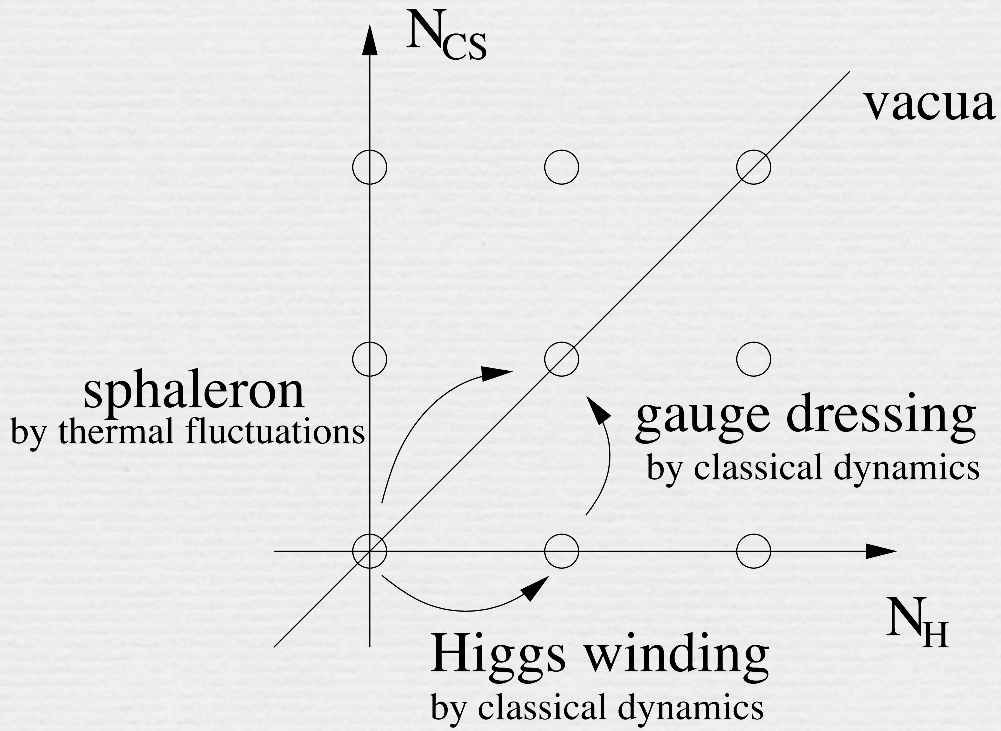
During quenched EWPT, SU(2) textures can be produced.
They can lead to B-violation when they decay.

Turok, Zadrozny '90

Lue, Rajagopal, Trodden, '96

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

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



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:

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

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

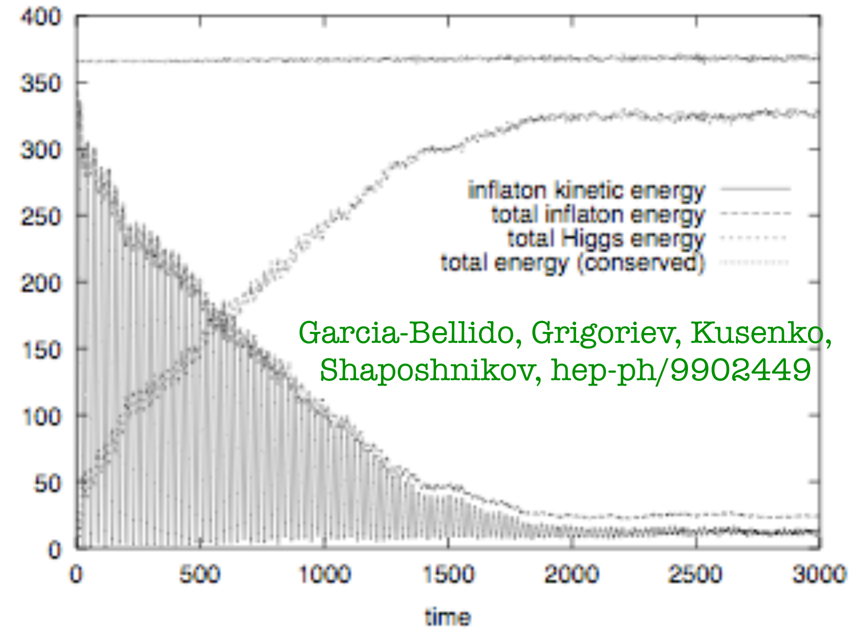
In vacuum: $N_H = N_{CS}$

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



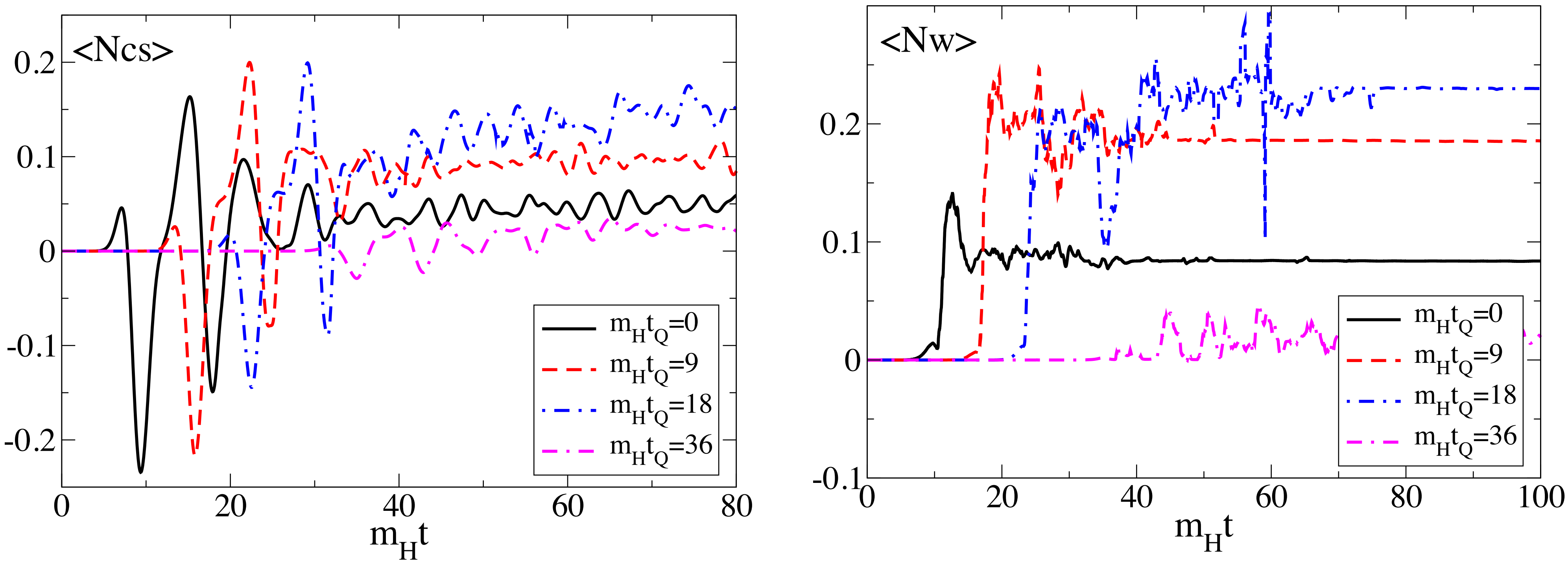
Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, hep-ph/9902449

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

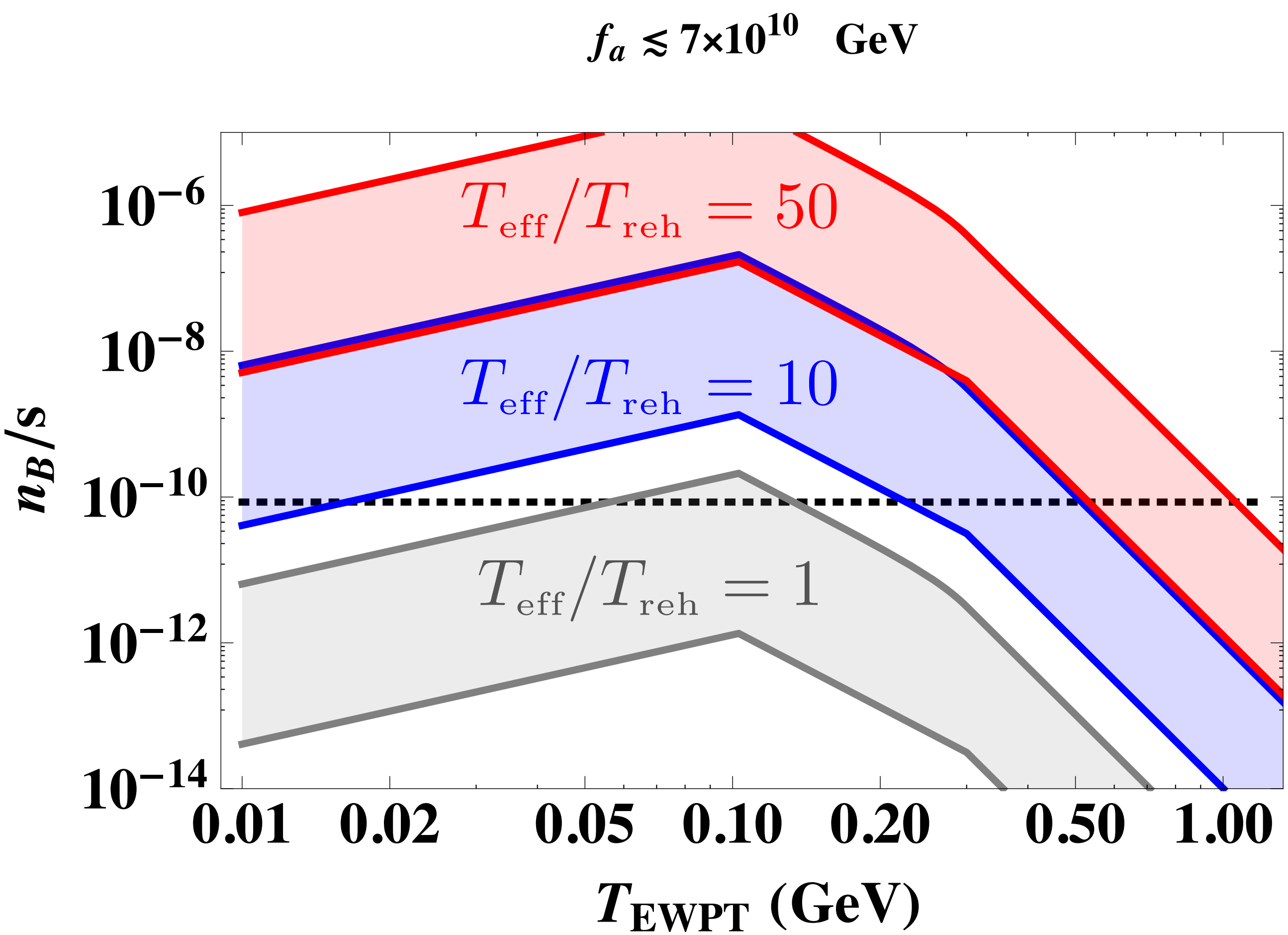
Cold baryogenesis has been simulated on the lattice



[Tranberg, Smit, Hindmarsh, hep-ph/0610096]

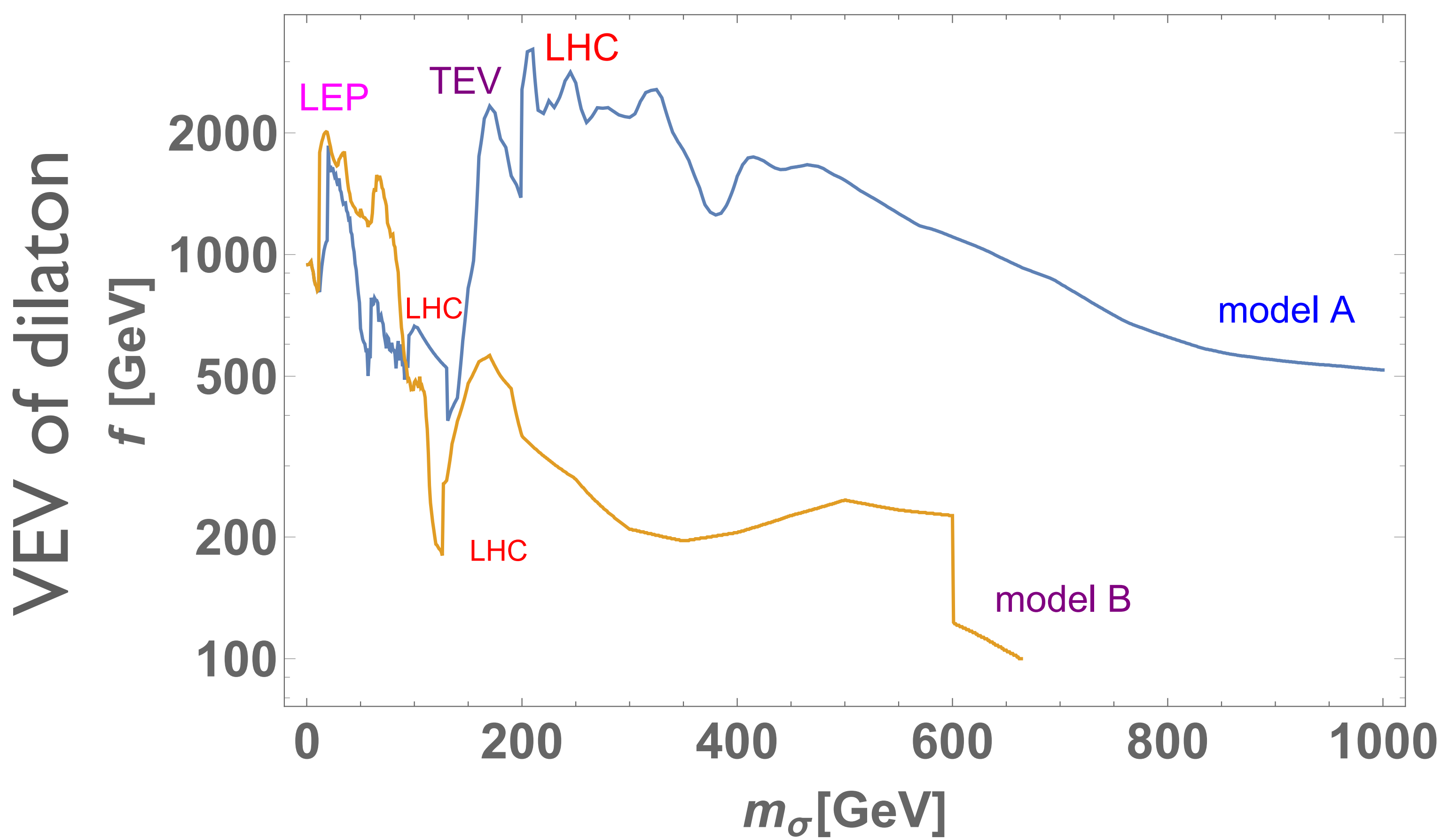
Axion dynamics during a supercooled EW phase transition can lead to baryogenesis

Servant, 1407.0030



requires a coupling between the Higgs and an additional light scalar (dilaton): Testable at the LHC!

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



[1410.1873]

Summary of this part

- SM+ 1 singlet: the most minimal and easiest way to get a strong 1st order EW phase transition, almost unconstrained by experimental data

- Dilaton-like potentials: a class of well-motivated and naturally strong 1st order phase transitions, with large supercooling

-Phase transition takes place in vacuum: maximal Gravity Wave signal (no loose of energy in reheating of the plasma)

-In ballpark of best eLISA sensitivity region

- Natural framework for cold EW baryogenesis mechanism

- Signatures at the LHC (light Higgs-like dilaton with suppressed couplings but accessible)

A first-order Electroweak Phase Transition in the Standard Model from Varying Yukawas

Baldes, Konstandin, Servant, 1604.04526

The new idea:

We show in a model-independent way how the nature of the EW phase transition is completely changed when the Standard Model Yukawas vary at the same time as the Higgs is acquiring its vacuum expectation value.

Origin of the fermion mass hierarchy?

fermion Yukawas $$y_{ij}\overline{f}^i_L \Phi^{(c)} f^j_R$$

$$\langle\Phi\rangle = v/\sqrt{2}$$

fermion masses $$m_f = y_f v/\sqrt{2}$$

There are three main mechanisms to describe fermion masses

$$m_f = y_f v/\sqrt{2}$$

1) Spontaneously broken abelian flavour symmetries as originally proposed by Froggatt and Nielsen

may be related by holography

2) Localisation of the profiles of the fermionic zero modes in extra dimensions

3) Partial fermion compositeness in composite Higgs models

The scale at which the flavour structure emerges is not known.

Usually assumed to be high but could be at the EW scale.

Origin of the fermion mass hierarchy?

Fermion Yukawas $$y_{ij}\overline{f}^i_L \Phi^{(c)} f^j_R$$

In Froggatt Nielsen constructions, the Yukawa couplings are controlled by the breaking parameter of a flavour symmetry. A scalar field "flavon" χ carrying a negative unit of the abelian charge develops a vacuum expectation value (VEV) and:

$$y_{ij} \sim (\langle\chi\rangle/M)^{-q_i+q_j+q_H}$$

flavor charges of the fermions

λ= $\langle\chi\rangle/M \sim 0.22$ $\Rightarrow$

$$\begin{aligned} Y_t &\sim 1, & Y_c &\sim \lambda^3, & Y_u &\sim \lambda^7, \\ Y_b &\sim \lambda^2, & Y_s &\sim \lambda^4, & Y_d &\sim \lambda^6, \\ s_{12} &\sim \lambda, & s_{23} &\sim \lambda^2, & s_{13} &\sim \lambda^3. \end{aligned}$$

The scale M is usually assumed close to the GUT scale

Emerging Flavour during Electroweak symmetry breaking

There are good motivations to consider that the flavour structure could emerge during electroweak symmetry breaking

For Example, if the Froggatt-Nielsen field dynamics is linked to the Higgs field

Extensive literature on models advocated to explain the fermion masses, however no study so far on the associated cosmology

On the other hand, in all flavour models, Yukawa couplings are controlled by the VEV of some scalar ``flavons" and it is natural to wonder about their cosmological dynamics.

Our working assumption: the flavon couples to the Higgs and therefore the flavon and the Higgs VEV dynamics are intertwined.

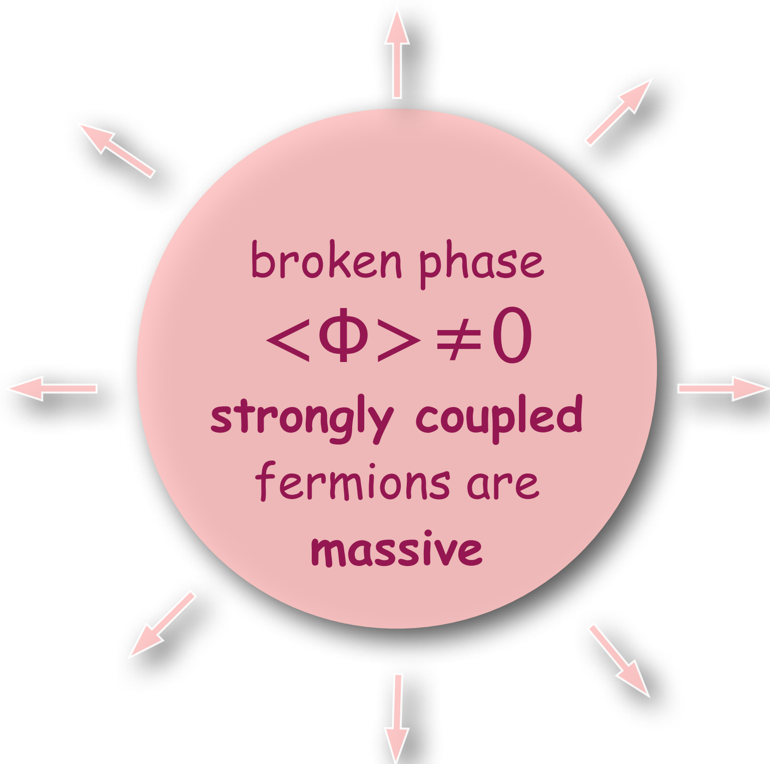
We do not need to specify the dynamics responsible for the evolution of the Yukawas to derive the nature of the EWPT.

The fact that the Yukawas of the SM were large during the EWPT is enough to completely change the nature of the EWPT, while relying only on the SM degrees of freedom.

Effect of fermionic masses on the EW Phase Transition

$$V_{\rm eff} \supset -g_* \pi^2 T^4/90$$

Regions in Higgs space in which species are massive correspond to a decrease in g_* and hence an increase in $V_{\rm eff}$. The effect of species coupled to the Higgs is therefore to delay and hence strengthen the phase transition.



symmetric phase

$<\Phi>=0$

massless fermions

It was noted that adding new strongly-coupled fermions with constant Yukawa couplings can help to strengthen the EW phase transition.

Carena, Megevand, Quiros, Wagner, hep-ph/0410352

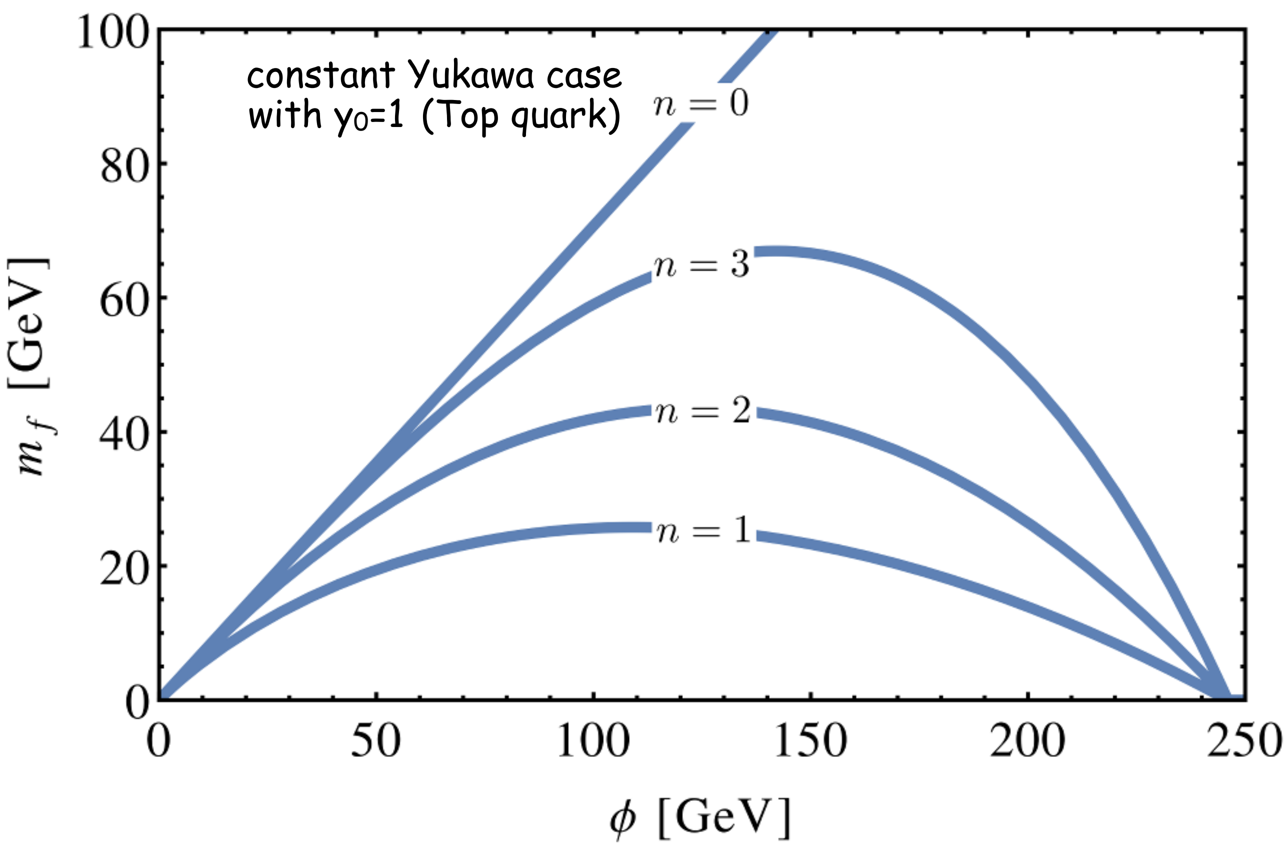
Although these do not create a thermal barrier on their own, they can lead to a decrease in g_* between the symmetric and broken phases and hence delay and strengthen the phase transition.

However, these models suffer from a vacuum instability near the EW scale due to the strong coupling of the new fermions: New bosons are also needed to cure this instability.

Mass of fermionic species for varying Yukawas

$$m_f = \frac{y(\phi)\phi}{\sqrt{2}}$$

$$\boxed{y(\phi) = \begin{cases} y_1\left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for} \quad \phi \le v, \\ y_0 & \text{for} \quad \phi \ge v. \end{cases}}$$



y_0: Yukawa value today

y_1: Yukawa value before the EW phase transition

High Temperature Effective Higgs Potential

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 piece	1-loop T=0 piece	1-loop T≠0 piece	Daisy resummation piece

1) Effects from the $T = 0$ one-loop potential:

$$V_1^0(\phi) = \sum_i \frac{g_i(-1)^F}{64\pi^2}\left\{m_i^4(\phi)\left(\mathrm{Log}\left[\frac{m_i^2(\phi)}{m_i^2(v)}\right] - \frac{3}{2}\right) + 2m_i^2(\phi)m_i^2(v)\right\}$$

A large fermionic mass significantly lowers V_1^0 between Φ=0 and Φ=v. This can lead to weaker - rather than stronger - phase transitions.

In addition, it can lead to the EW minimum no longer being the global minimum.

2) Barrier from the $T \neq 0$ one-loop potential:

$$V_1^T(\phi, T) \;=\; \sum_i \frac{g_i(-1)^F T^4}{2\pi^2} \times \;\int_0^\infty y^2 \mathrm{Log}\left(1 - (-1)^F e^{-\sqrt{y^2 + m_i^2(\phi)/T^2}}\right) \mathrm{d}y.$$

$$V_f^T(\phi, T) = -\frac{gT^4}{2\pi^2} J_f\left(\frac{m_f(\phi)^2}{T^2}\right)$$

High-T expansion:

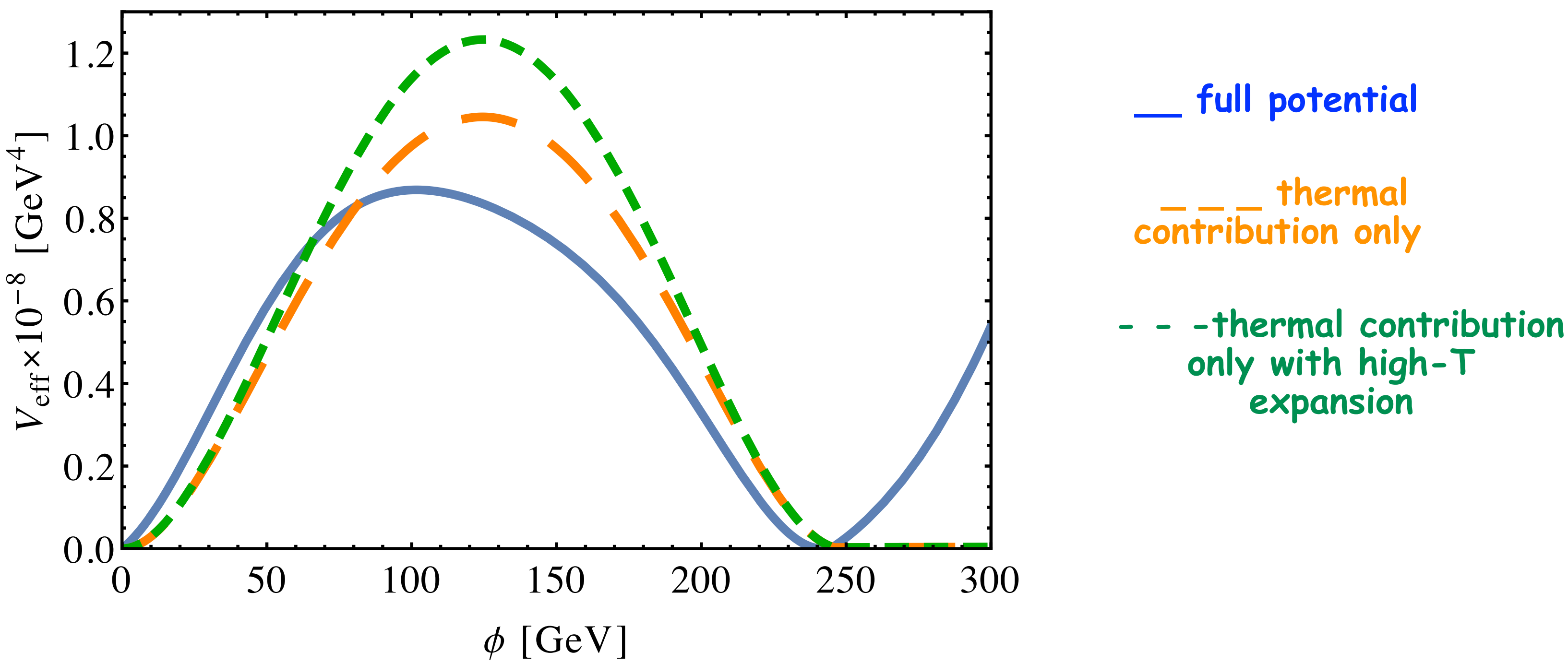
$$J_f(x^2) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24}x^2 - \frac{x^4}{32}\mathrm{Log}\left[\frac{x^2}{13.9}\right]$$

$$\delta V \equiv V_f^T(\phi, T) - V_f^T(0, T) \approx \frac{gT^2\phi^2[y(\phi)]^2}{96}$$

Fermionic fields create a barrier!

This leads to a cubic term in ϕ, e.g. for $y(\phi) = y_1(1 - \phi/v)$:

$$\delta V \approx \frac{g y_1^2 \phi^2 T^2}{96}\left(1 - 2\frac{\phi}{v} + \frac{\phi^2}{v^2}\right)$$



3) Effects from the Daisy correction:

come from resumming Matsubara zero-modes for the bosonic degrees of freedom

$$V_{\mathrm{Daisy}}(\phi,T)=\sum_i \frac{\overline{g}_i T}{12\pi}\left\{m_i^3(\phi)-\left[m_i^2(\phi)+\Pi_i(T)\right]^{3/2}\right\}$$

sum is over bosons

thermal mass

Consider the contribution from the Higgs:

$$V^{\phi}_{\mathrm{Daisy}}(\phi,T)=\frac{T}{12\pi}\left\{m_\phi^3(\phi)-\left[m_\phi^2(\phi)+\Pi_\phi(\phi,T)\right]^{3/2}\right\}$$

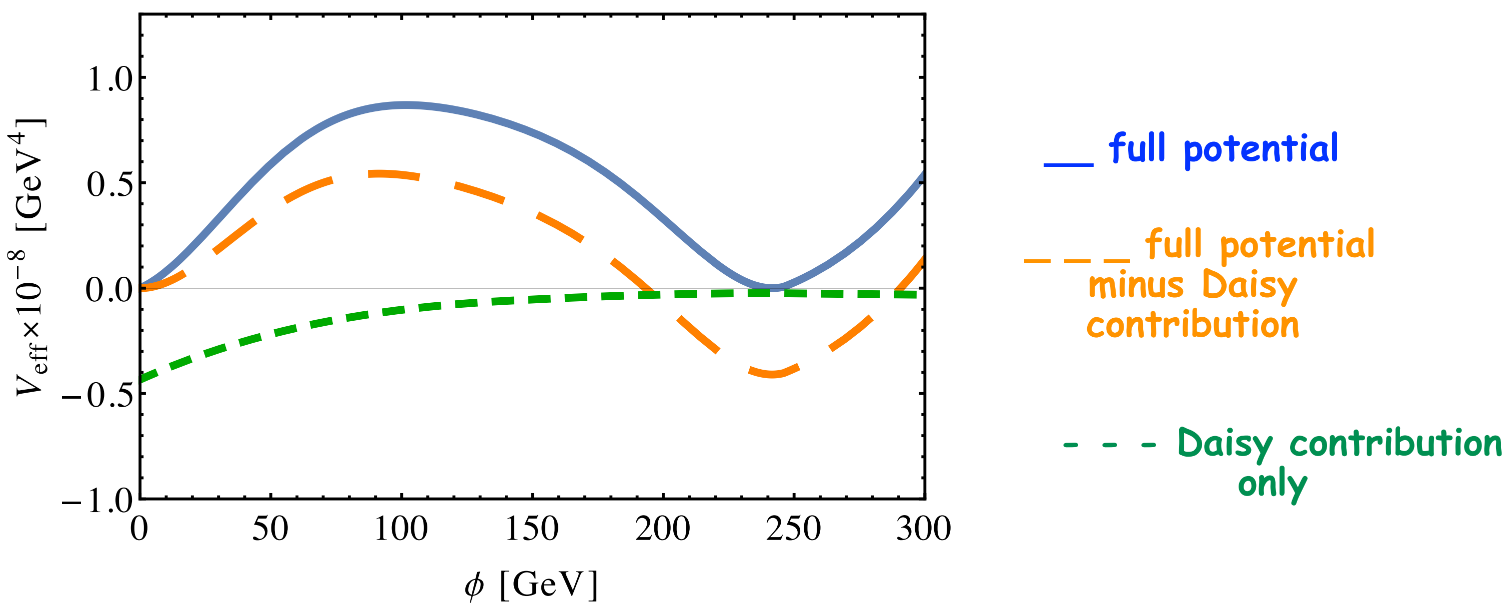
$$\Pi_\phi(\phi,T)=\left(\frac{3}{16}g_2^2+\frac{1}{16}g_Y^2+\frac{\lambda}{2}+\frac{y_t^2}{4}+\frac{gy(\phi)^2}{48}\right)T^2$$

The novelty is the dependence of the thermal mass on Φ, which comes from the Φ-dependent Yukawa couplings

3) Effects from the Daisy correction:

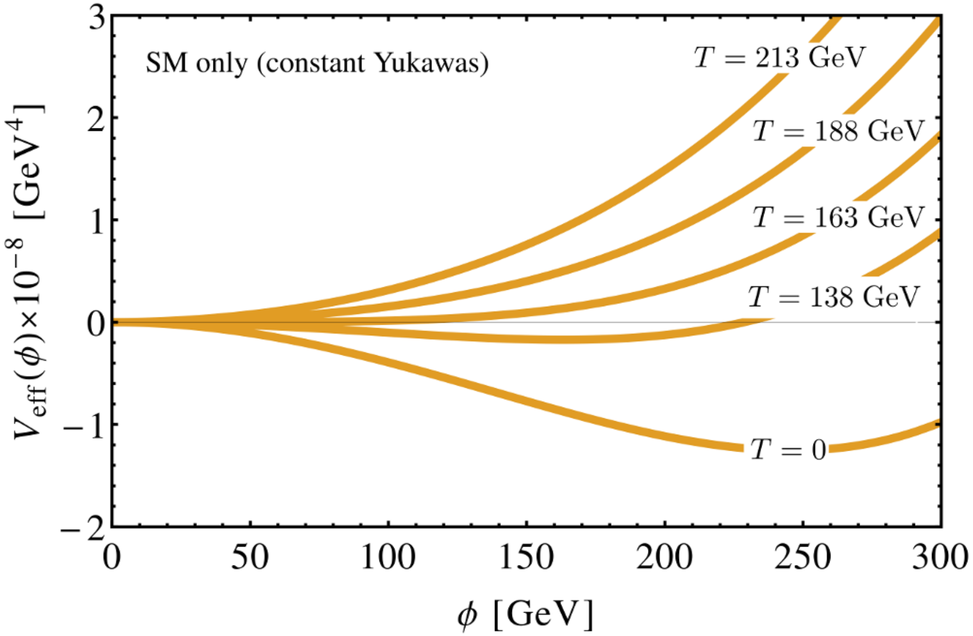
The effect is to lower the effective potential at Φ =0, with respect to the broken phase minimum.

By lowering the potential at Φ =0, the phase transition is delayed and strengthened.

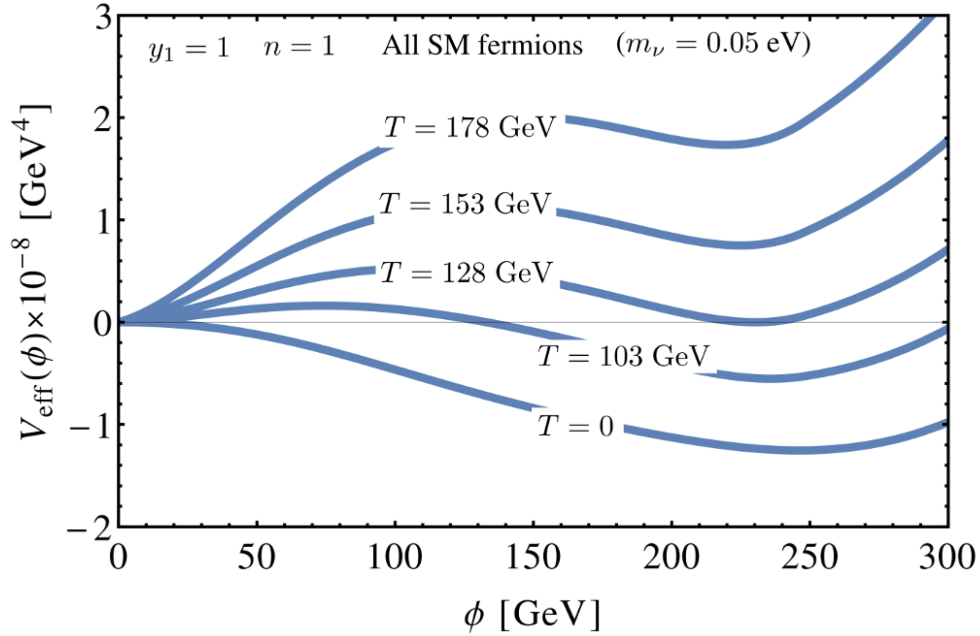


Full one-loop effective Higgs potential with Daisy Resummation

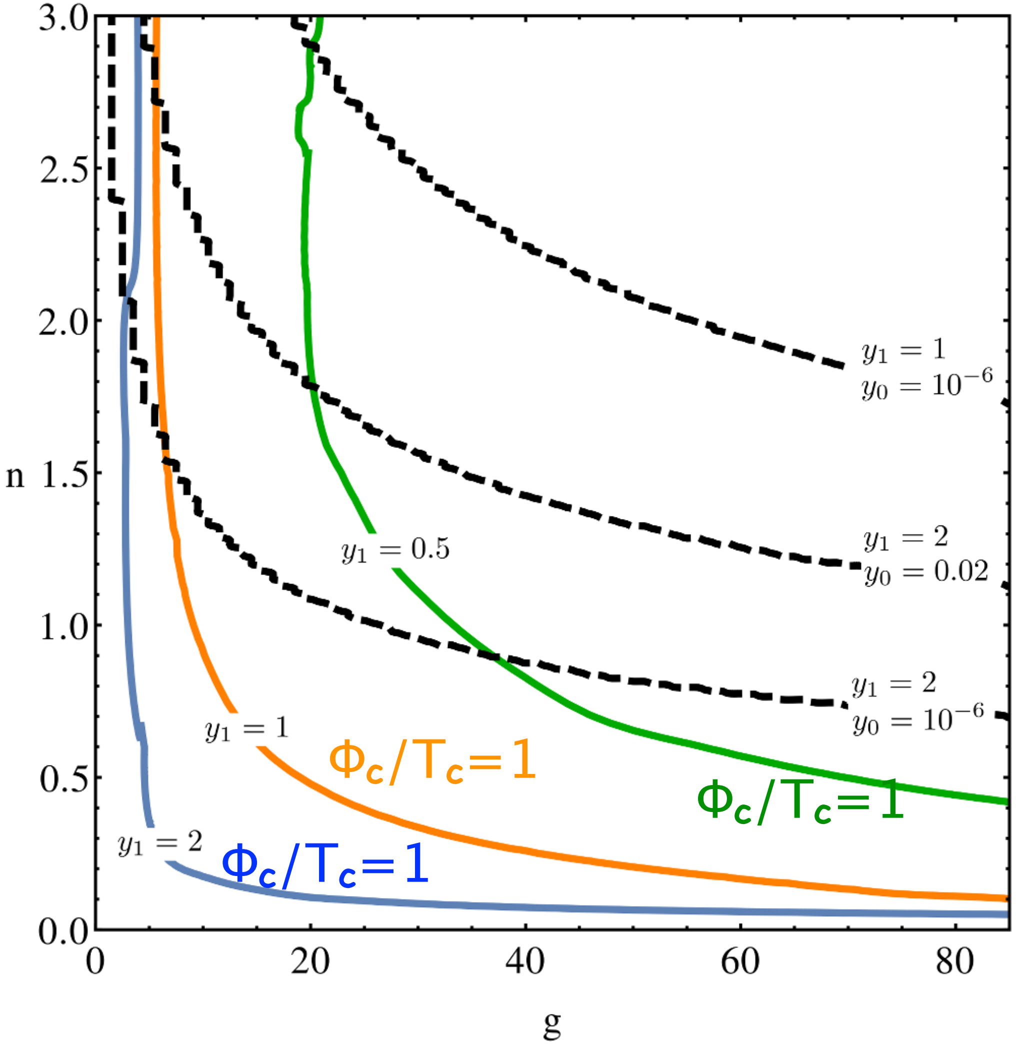
Standard Case (Constant Yukawas)



With varying Yukawas



Contours of $\Phi_c/T_c=1$ for different choices of y_1 and y_0, areas above these lines allow for EW baryogenesis.



Dashed lines: areas above these lines are disallowed (for the indicated choices of y_1 and y_0 due to the EW minimum not being the global one.

n characterizes how fast the Yukawa variation is taking place. Depending on the underlying model, the Higgs field variation will follow the flavon field variation at different speeds. Large n means the Yukawa coupling remains large for a greater range of phi away from zero. It strengthens the phase transition.

Summary

Variation of the Yukawas of SM fermions from O(1) to their present value during the EW phase transition generically leads to a very strong first-order EW phase transition,

This offers new routes for generating the baryon asymmetry at the electroweak scale, strongly tied to flavour models.

Second major implication:

the CKM matrix as the unique CP-violating source !

several works under completion with Baldes, Bruggisser, Konstandin, Servant, Von Harling

$$\begin{aligned}\Delta_{CP} &= v^{-12}\text{Im Det}\left[m_u m_u^\dagger, m_d m_d^\dagger\right] \\ &= J\, v^{-12} \prod_{i<j}(\tilde{m}_{u,i} - \tilde{m}_{u,j}^2) \prod_{i<j}(\tilde{m}_{d,i}^2 - \tilde{m}_{d,j}^2) \simeq 10^{-19},\end{aligned}$$

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

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

Berkooz, Nir, Volansky '04

Conclusion

EW baryogenesis: A beautiful framework for explaining the matter-antimatter of the universe relying on EW scale physics only

The second run of the LHC is going to be an interesting step in providing new probes of models leading to first-order EWPT, which would have dramatic implications for EW baryogenesis

We have shown how dynamical Yukawas during the EWPT change the nature of the EWPT due mainly to three effects on the Higgs effective potential.

The net result is a strong first-order phase transition in large areas of parameter space, while not being disallowed by creating a deeper minimum than the EW one.

The physics of varying Yukawas during the EWPT has important implications for electroweak baryogenesis with rich phenomenology. In addition to its effects on the nature of the EWPT, this has dramatic effects on CP violation.

We are working on identifying realistic models of Flavour emerging at the TeV scale and their experimental signatures

Conclusion continued

The possibility of time-dependent CP-violating sources allows to make EW baryogenesis compatible with EDM constraints and can be well-motivated theoretically. We provided 2 examples: strong CP from QCD axion, weak CP from dynamical CKM matrix