Higgs (and axion) implications for Baryogenesis

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RECERCA I ESTUDIS AVANÇATS

Matter Anti-matter asymmetry:

characterized in terms of the baryon to photon ratio

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

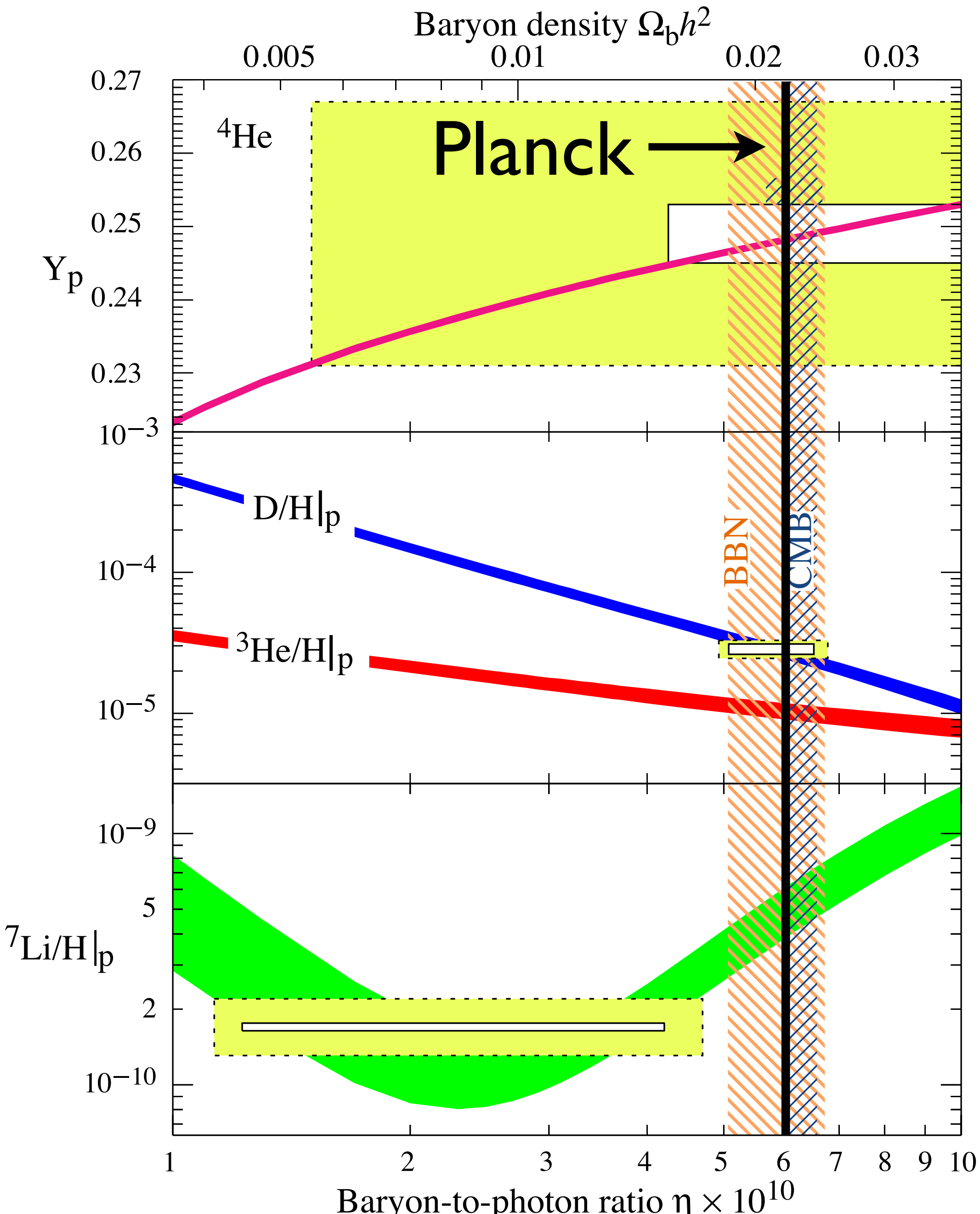
$$5.1 < \eta_{10} < 6.5 \ (95\% \ \mathrm{CL})$$

The great annihilation

10 000 000 001
Matter

10 000 000 000
Anti-matter

1
(us)



BAU from CMB is now more precise than BAU from BBN (D/H abundance)

[PDG 2012]

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

unconclusive attempts in cold EW baryogenesis

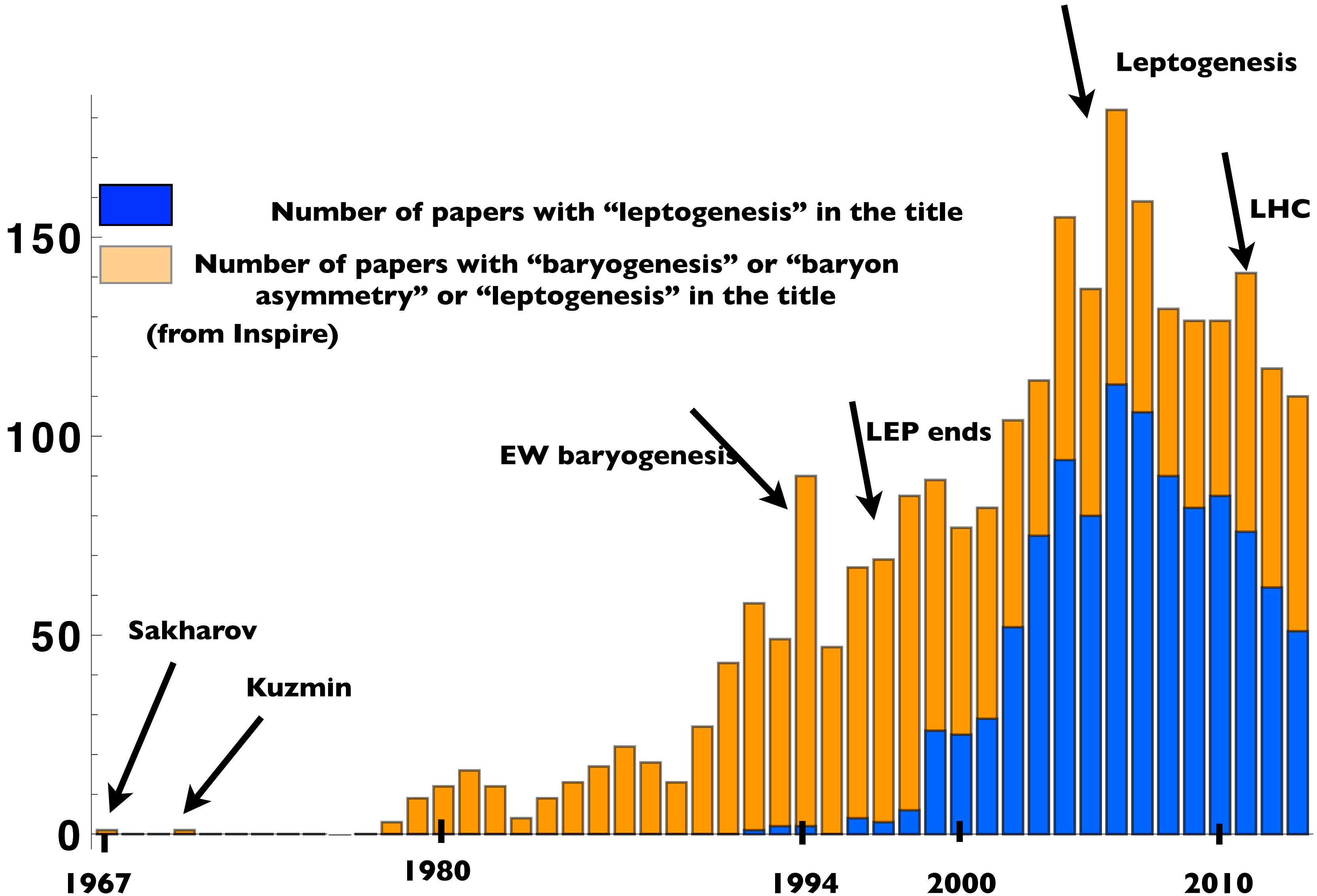
Tranberg, A. Hernandez, Konstandin, Schmidt '09
Brauner, Taanila,Tranberg,Vuorinen '12

Shaposhnikov,

Journal of Physics: Conference Series **171** (2009) 012005

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

History of baryogenesis papers



Two leading candidates for baryogenesis:

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

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

Models of Baryogenesis

T

GUT baryogenesis

B washout unless B-L ≠ 0

requires SO(10) → leptogenesis
requires too high reheat temperature to produce enough GUT particles

Thermal leptogenesis

hierarchy pb -> embed in susy-> gravitino pb (can be solved if M_gravitino>100 TeV and DM is neutralino or gravitino is stable)

Affleck-Dine (moduli decay)

Non-thermal leptogenesis (via oscillations)

Asymmetric dark matter-cogenesis

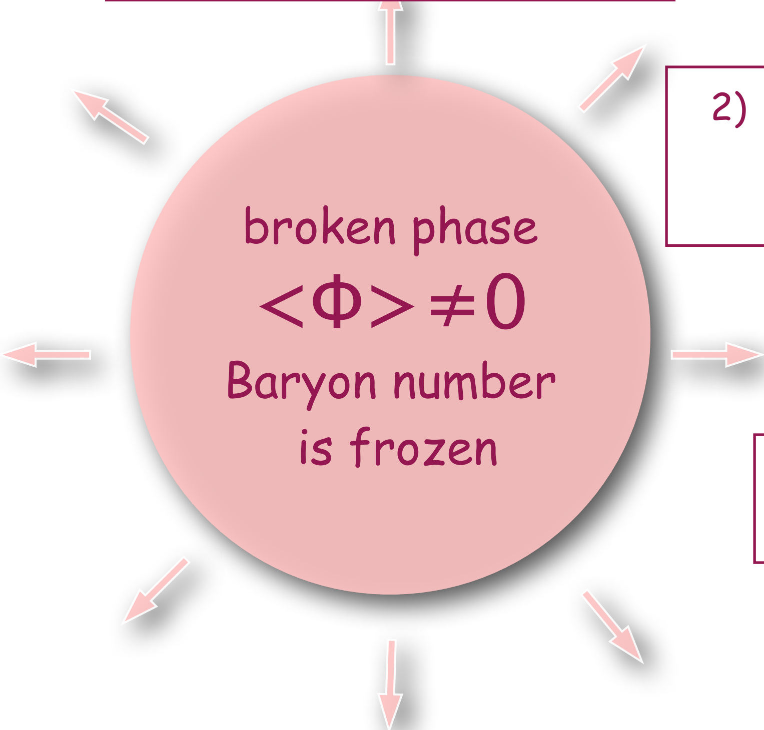
EW breaking, sphalerons freese-out

EW (non-local) baryogenesis

EW cold (local) baryogenesis

Baryon asymmetry and the EW scale

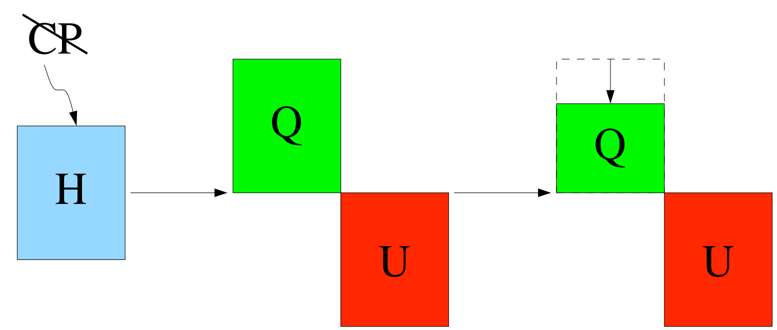
1) nucleation and expansion of bubbles of broken phase



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

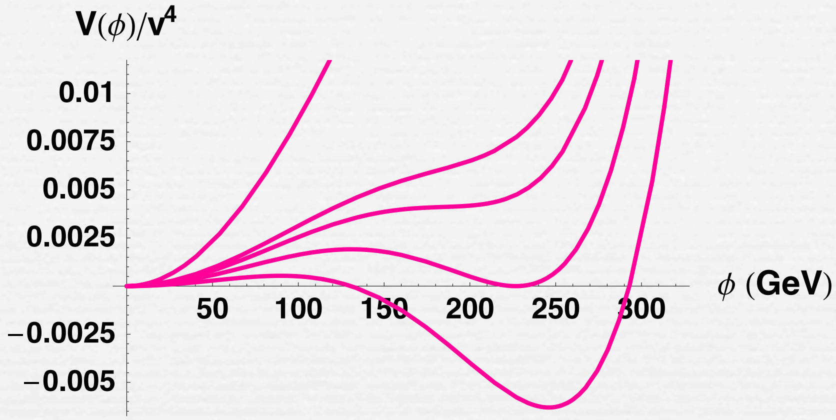
Chirality Flux in front of the wall

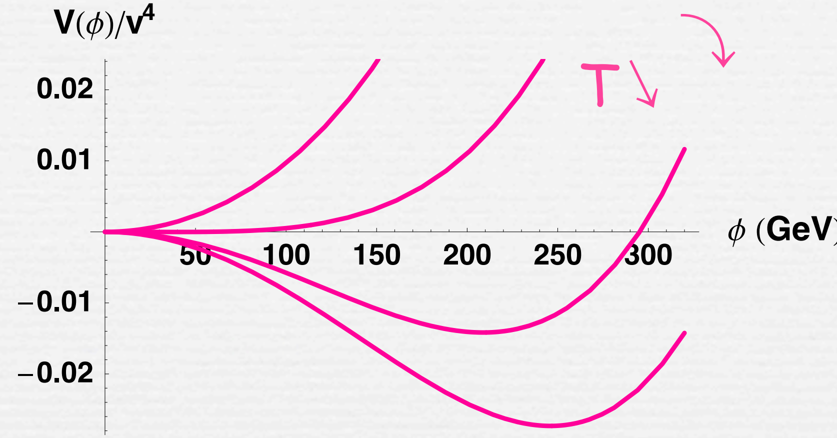
3) In symmetric phase, $<\Phi> = 0$, very active sphalerons convert chiral asymmetry into baryon asymmetry



Electroweak baryogenesis mechanism relies on a first-order phase transition

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

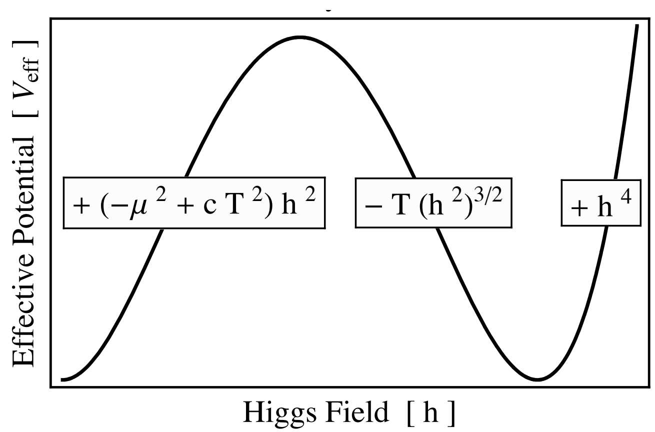
In the SM: $\sum_i \simeq \sum_{W,Z}$ → not enough

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

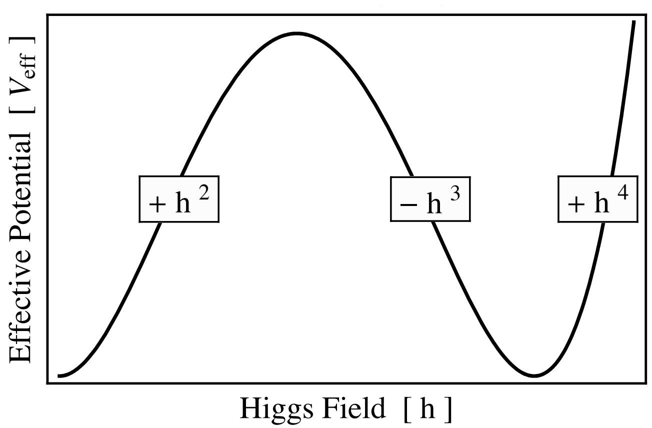
Three ways to obtain a strongly 1st order phase transition by inducing a barrier in the thermal effective potential



thermally driven

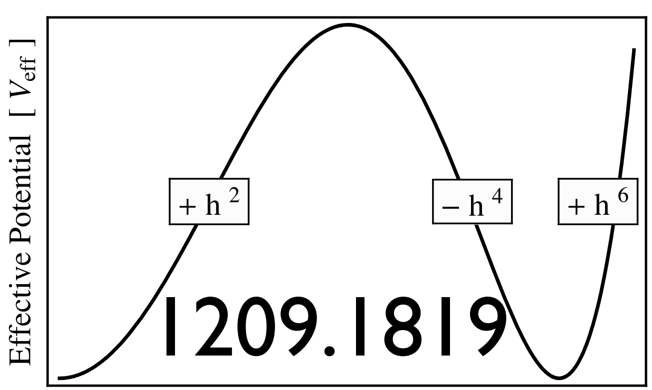
(thermal loop of bosonic modes)

(example:stop loop in MSSM)



tree-level driven

(competition between renormalizable operators)



tree-level driven

(competition between renormalizable and non-renormalizable operators)

Scenario where the 1st order phase transition is thermally driven

following [1401.1827]

most famous example: light stop scenario in MSSM

consider effect of new scalar coupled to the Higgs via

$$V \propto \kappa|\Phi|^2|H|^2 \ .$$

Its effect on the thermal Higgs effective potential is:

$$V_{\text{eff}}(\varphi;T) = V_0(\varphi) + V_T(\varphi;T) \approx \frac{1}{2}\left(-\mu^2 + \frac{g_\Phi \kappa T^2}{24}\right)\varphi^2 - \frac{g_\Phi \kappa^{3/2} T}{24\sqrt{2}\pi}\varphi^3 + \frac{\lambda}{4}\varphi^4.$$

as the mass of Φ in presence of background higgs field φ is:

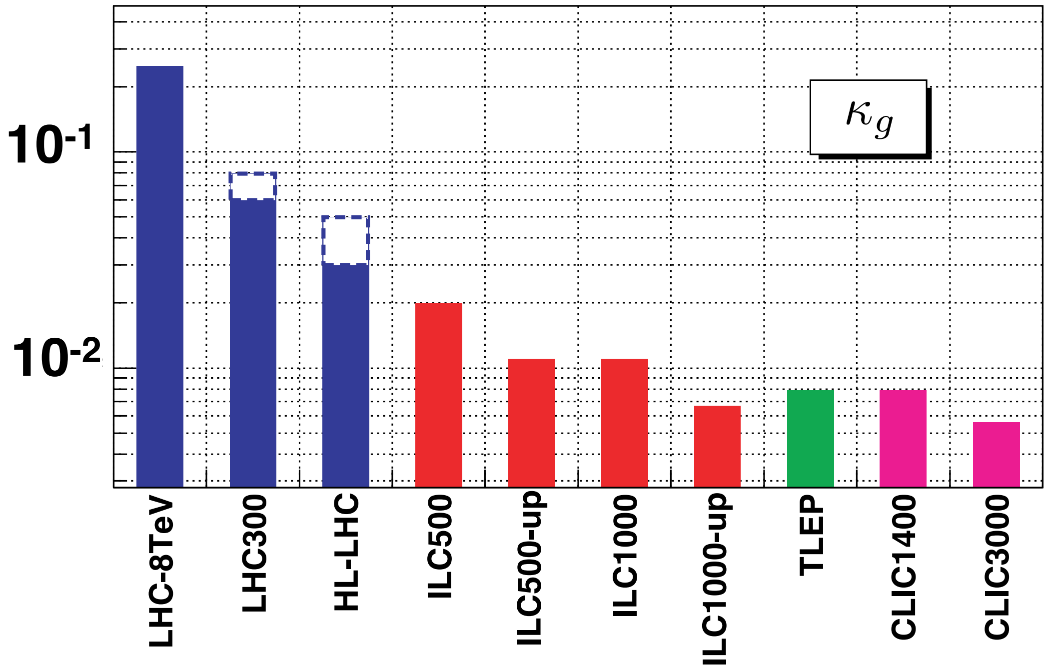
$$m_\Phi^2(\varphi) = m_0^2 + \frac{\kappa}{2}\varphi^2.$$

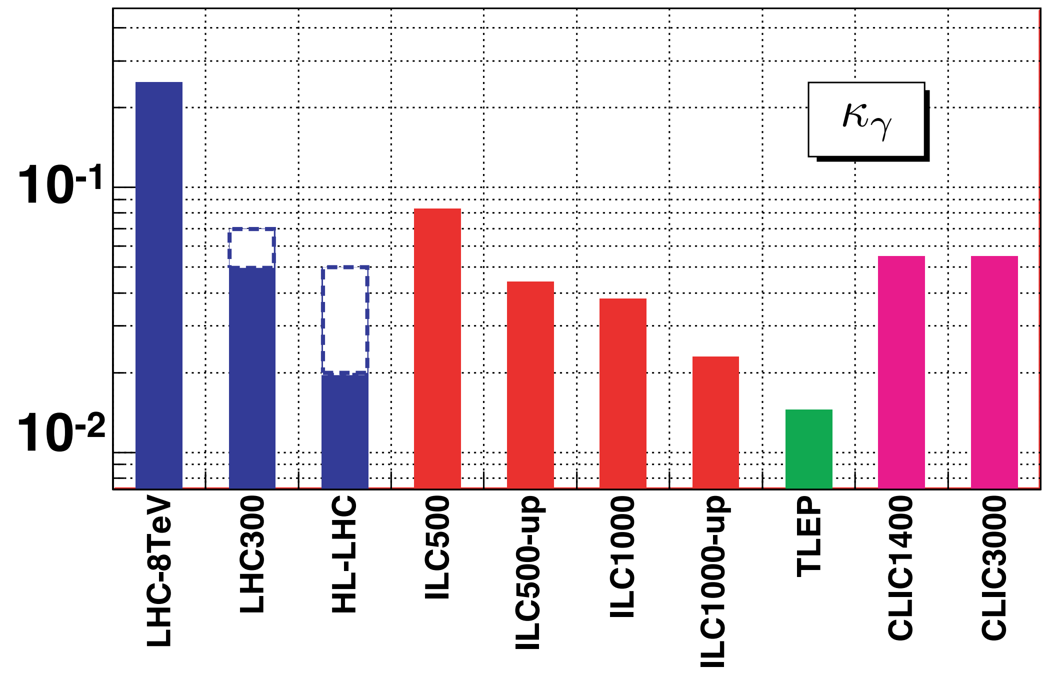
At the same time the Φ loop contributes
to the Higgs-gluon coupling

-> A strong 1st order PT leads to sizable deviations in Higgs production rate and decays in $\gamma\gamma$

-> typically excluded

Measurement precision on hgg and h$\gamma\gamma$ couplings





And if BSM scalar is neither colored nor electrically charged?

→ still induces a 1-loop contribution to Higgs wave function renormalization and affect e+e- -> hZ cross section

$$\delta_{hZ} = -\frac{g_\Phi \kappa^2 v^2}{24\pi^2 m_h^2}\left(1 + F(\tau_\Phi)\right)$$

1305.5251

expected deviation: ~0.6%

can be probed at upgraded ILC-500 and at TLEP

(similarly for colored and/or electrically charged BSM scalars)

→ still induces a deviation in the Higgs cubic self-coupling

expected deviation: ~10-20%

difficult to test with proposed facilities

Estimated per-experiment precision on Higgs triple self-coupling λ (1310.8361)

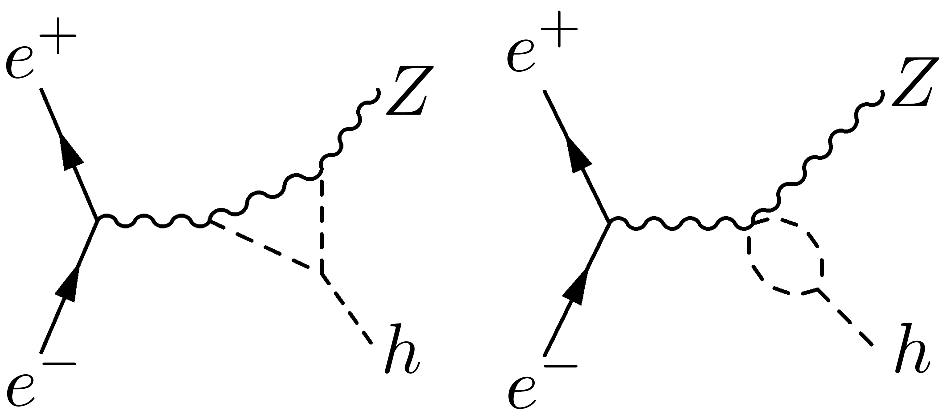
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

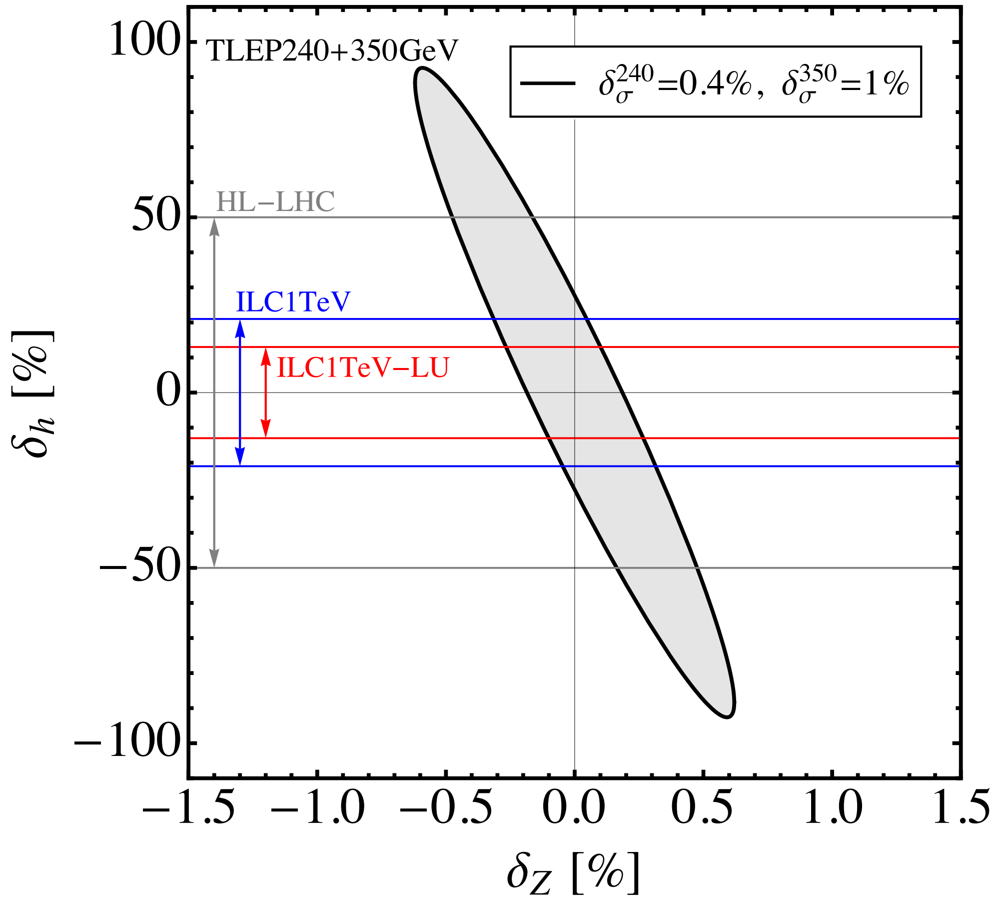
Estimated precision from combined facilities (1310.8361)

LHC	HL-LHC							
+ILC	+ILC-up	+(TLEP)			+ILC-up		+CLIC	
		+CLIC	+HE-LHC	+VLHC	+HE-LHC	+VLHC	+HE-LHC	+VLHC
21%	12.6%	15.2/9.8%	18.6%	7.9%	10.9%	6.8%	12.5/8.9%	7.2/6.2%

Indirect constraints on Higgs self-coupling at TLEP via its contribution to Higgsstrahlung

1312.3322





constrains deviations of order ~ 30%

This is all “standard” EW baryogenesis

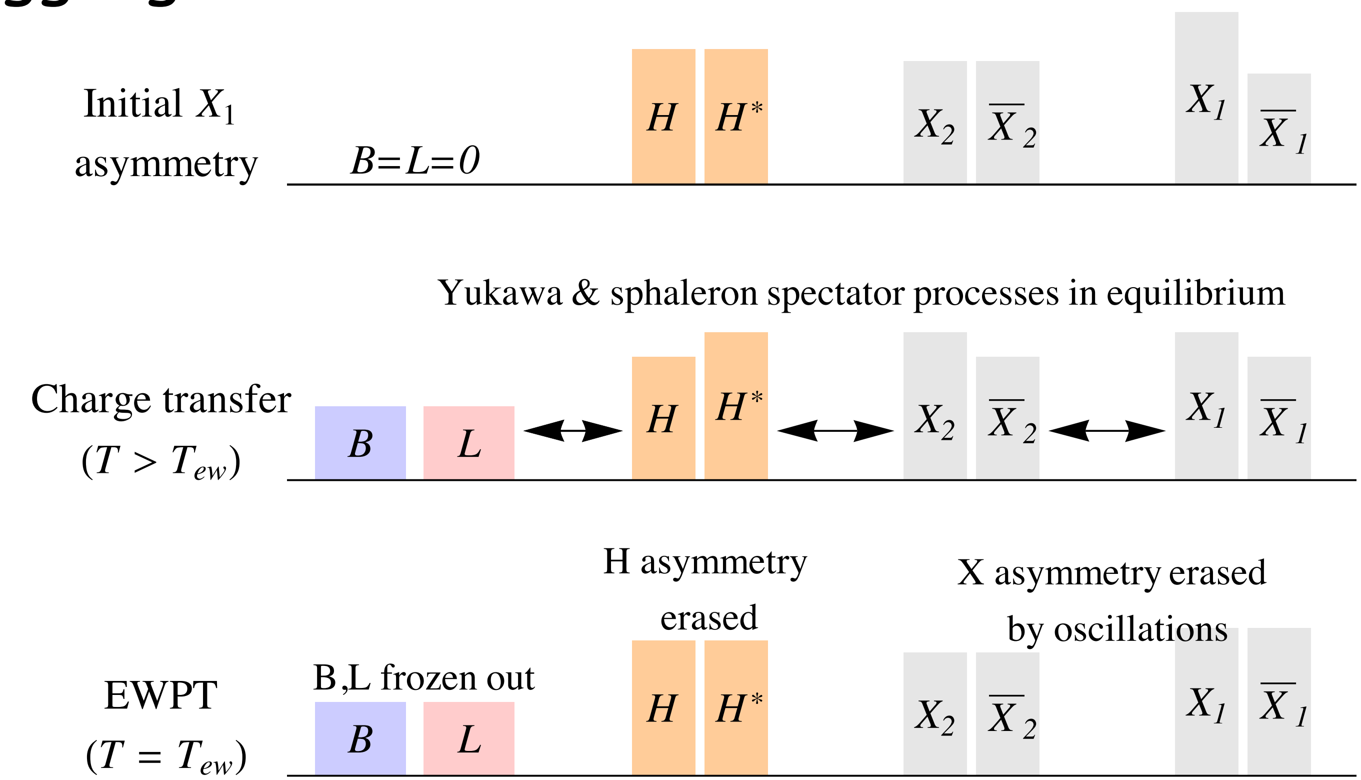
There is an interesting alternative mechanism for baryogenesis at the EW scale: the so-called “COLD” baryogenesis

other approach studied recently:
asymmetry in dark sector transmitted to visible sector

Baryogenesis from a primordial dark matter asymmetry

Servant & Tulin, '13

"Higgsogenesis"



DM is no longer asymmetric today

A theory of baryogenesis that does not require
B nor L violation beyond the SM but by having an asymmetry
trapped in spectator X_2 we bias sphalerons into generating B+L.

The Higgs is playing a central role in connecting the visible and dark asymmetries
see other higgsogenesis idea: Davidson et al. '13

Baryon number violation in the Standard Model

The B+L anomaly

The charge B+L is not conserved by quantum fluctuations of gauge fields while the orthogonal combination B-L remains a good symmetry of electroweak interactions.

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = -N_f \left(\frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu} - \frac{g'^2}{32\pi^2} f_{\mu\nu} \tilde{f}^{\mu\nu} \right)$$

The variation of the baryonic charge is given by $\Delta B = \int dt dx \partial_\mu j^\mu$

This integral is non-zero for certain gauge field configurations (instantons)

The topological charge of the instanton is defined by the Chern Simons number $N_{CS} = \int d^3x \ K^0$

where $\partial_\mu K^\mu = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$ $K^\mu = \frac{g^2}{32\pi^2} \epsilon^{\mu\nu\alpha\beta} (F^a_{\nu\alpha} A^a_\beta - \frac{g}{3} \epsilon_{abc} A^a_\nu A^b_\alpha A^c_\beta)$

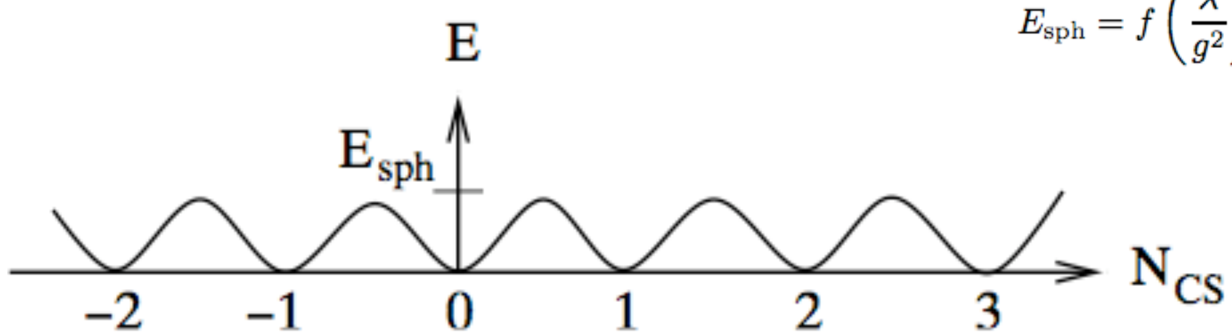
Baryon number violation in the Standard Model

due to chirality + topology

$$N_{CS}(t_1) - N_{CS}(t_0) = \int_{t_0}^{t_1} dt \int d^3x \, \partial_\mu K^\mu = \nu$$

$$\partial_\mu K^\mu = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$

$$E_{\rm sph} = f\left(\frac{\lambda}{g^2}\right)\frac{4\pi v}{g} \cong \frac{8\pi v}{g} = \frac{2M_W}{\alpha_W} f\left(\frac{\lambda}{g^2}\right)$$



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

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

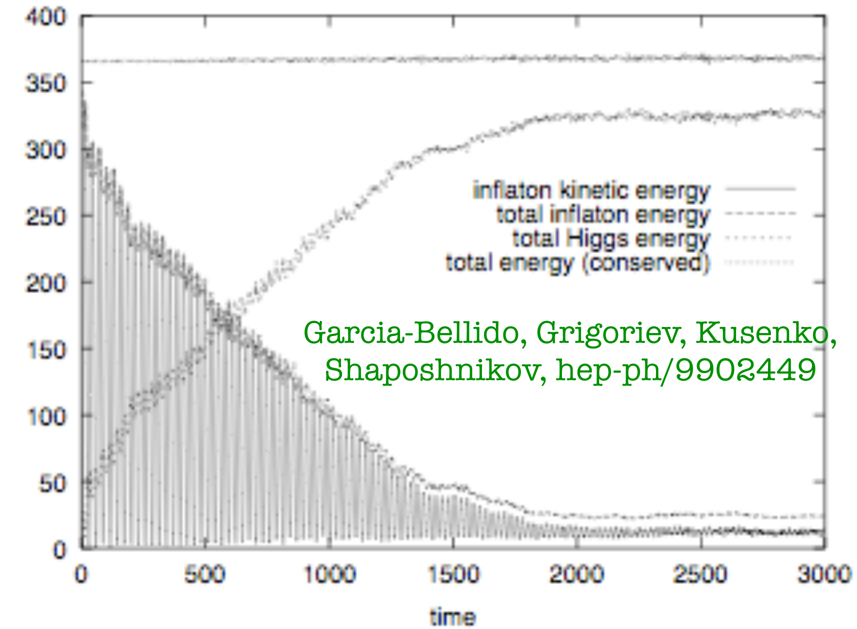
baryons are created by transitions between topologically distinct vacua of the $SU(2)_L$ gauge field

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



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.

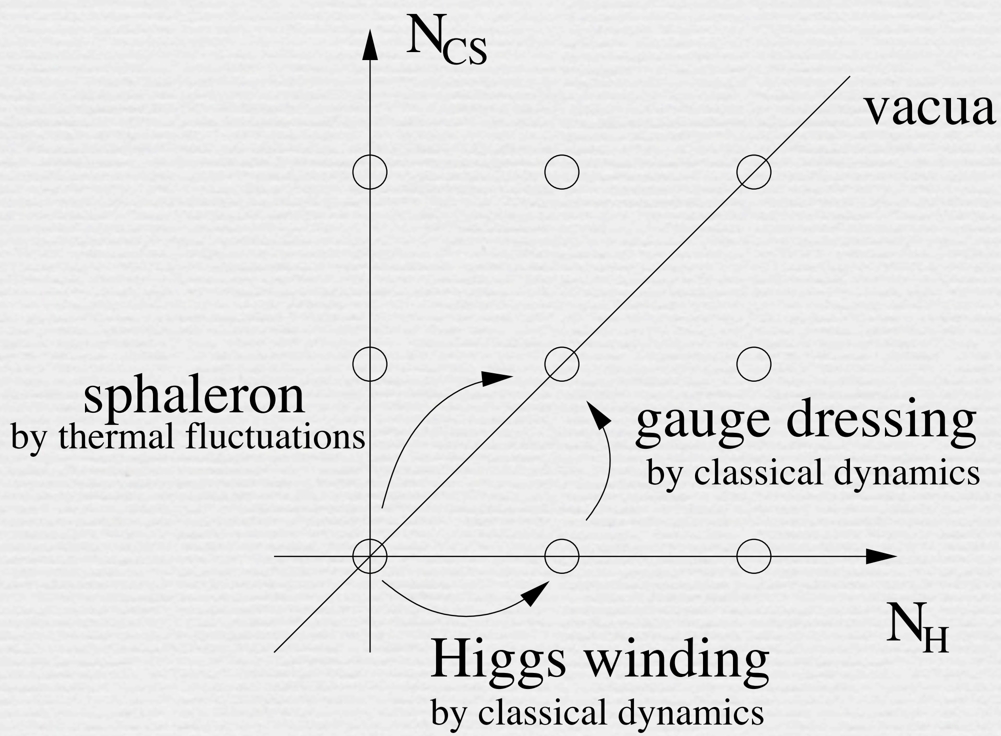
Cold Baryogenesis

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

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



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:

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

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

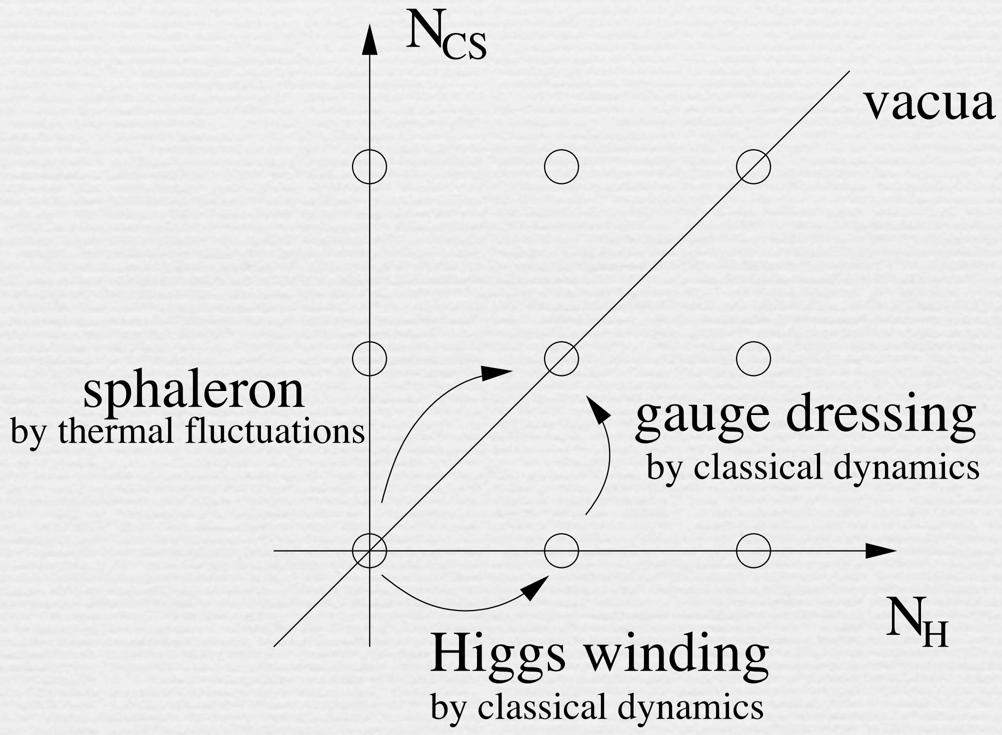
In vacuum: $N_H = N_{CS}$

Dynamics of textures $\delta N \equiv N_{CS} - N_H$

In vacuum: $\delta N = 0$

A texture is a configuration which has $\delta N \neq 0$. It is unstable and decays.

During the EWPT & preheating, configurations with $\Delta N_H \neq 0$ are produced. They relax to 0 by either changing N_H or N_{CS}.
In the latter case, there is anomalous fermion number production.



instead of using thermal fluctuations to go over the barrier and produce N_{CS}, use scalar field energy in winding configurations carrying N_H which then produce N_{CS} when decaying

The gauge fields relax to cancel the gradient energy in the Higgs field. This competes with the tendency of the Higgs field to unwind.

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.

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

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

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

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

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

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

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

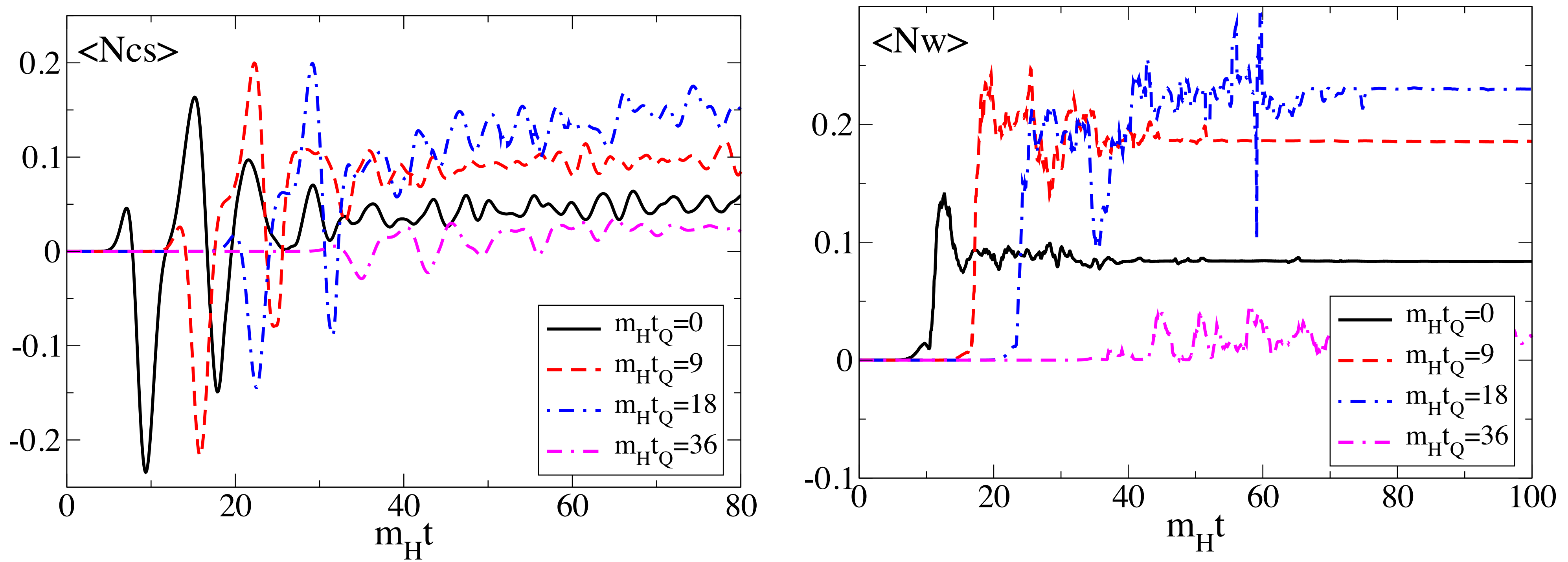
Cold baryogenesis has been simulated on the lattice where:

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

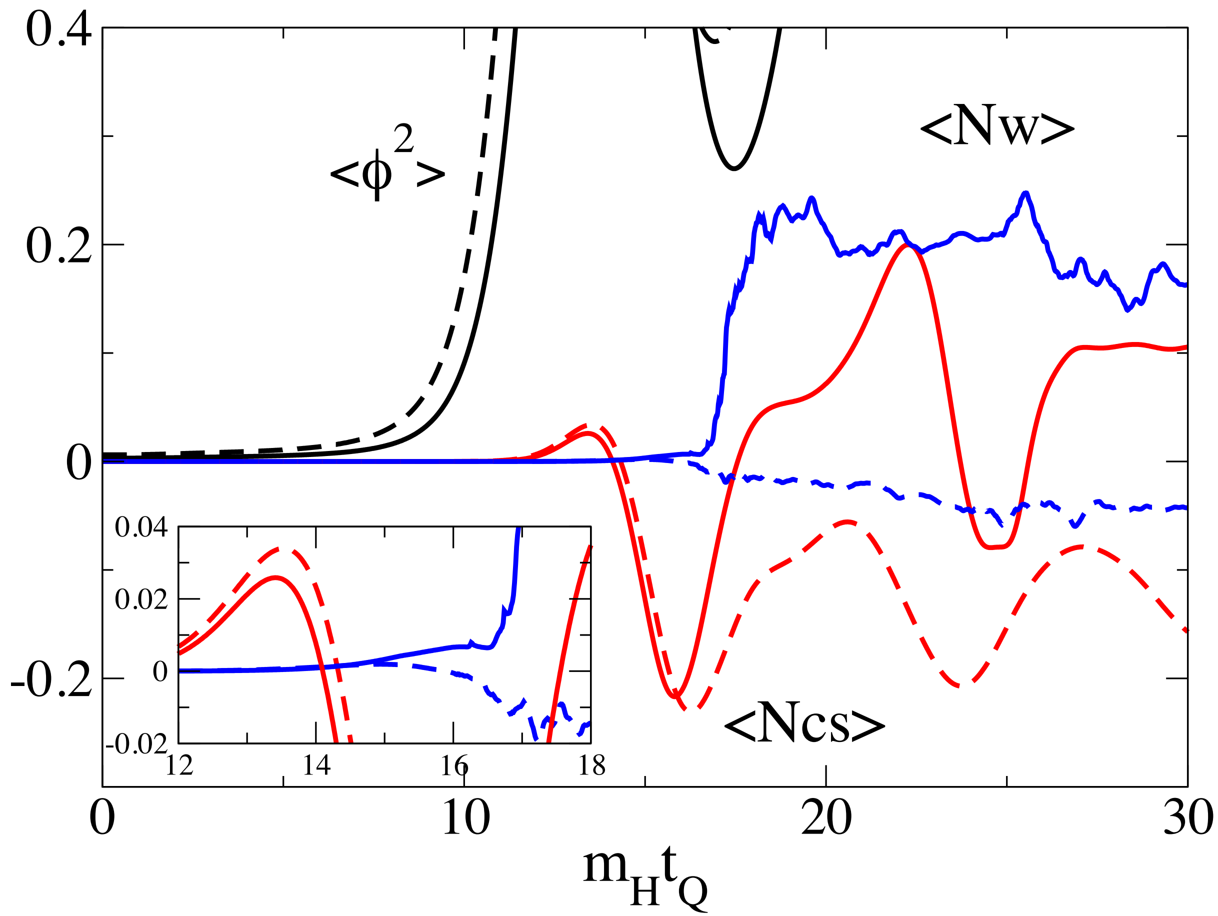
$$\mathcal{L}_{eff} = \frac{\alpha_W}{8\pi}\,\zeta(T)\mathrm{Tr}\,F\tilde{F}$$

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

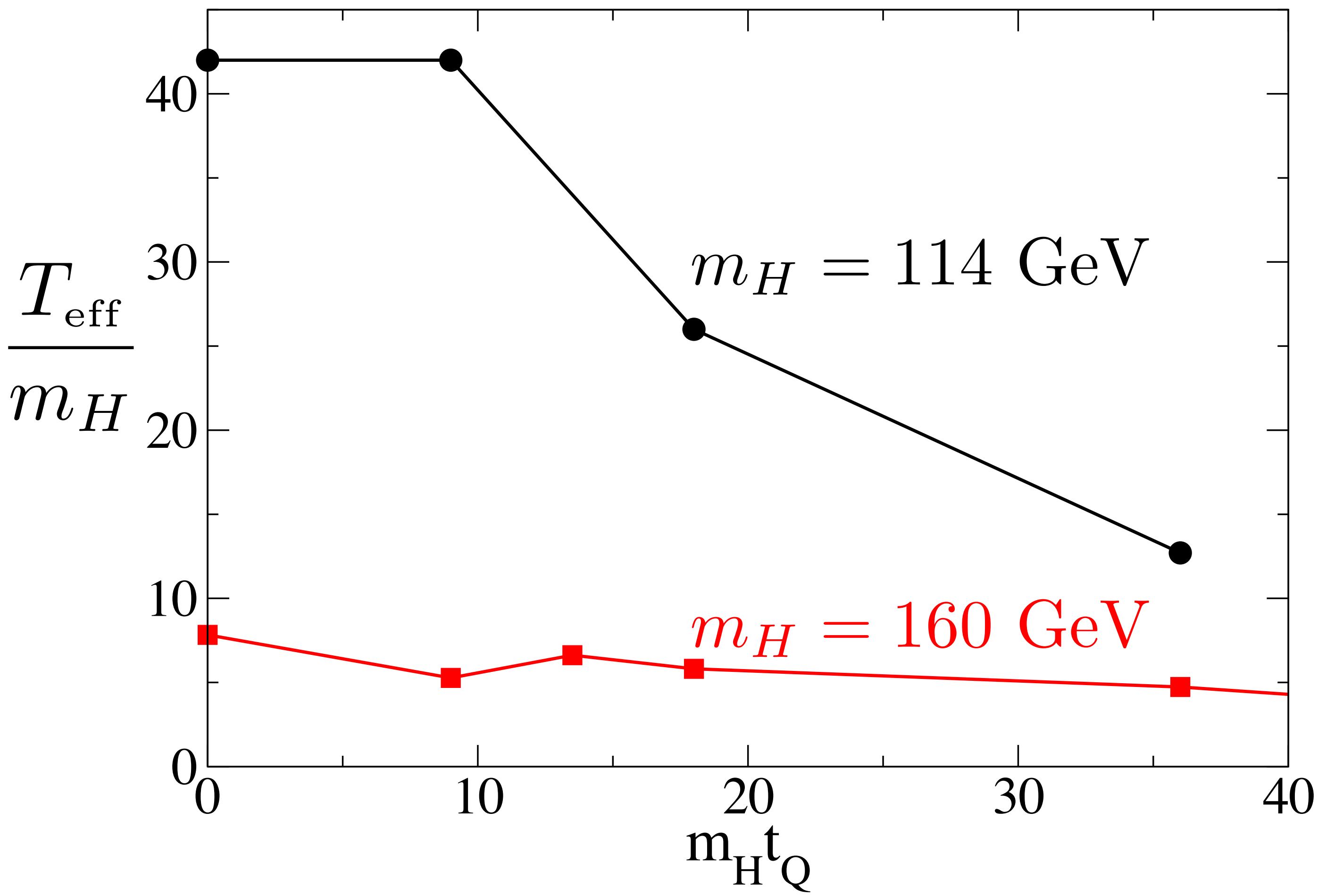
The latest electron EDM constraints lead to a bound of M>~ 65 TeV



Tranberg et al, hep-ph/0610096



Tranberg et al, hep-ph/0610096



Tranberg et al, 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

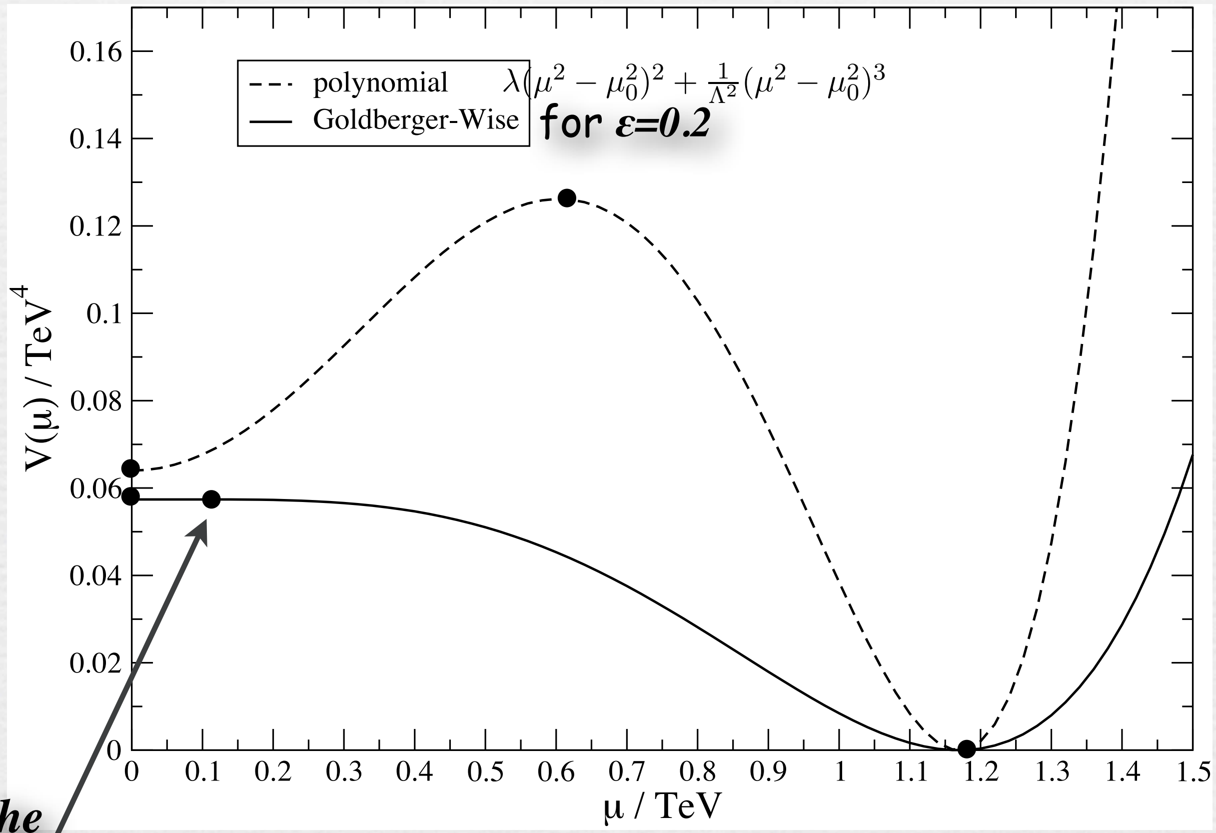
for $|\varepsilon| \ll 1$

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

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

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 $\sqrt{\mu_+\mu_-} \ll \mu_-$

Key point for the scenario to work:

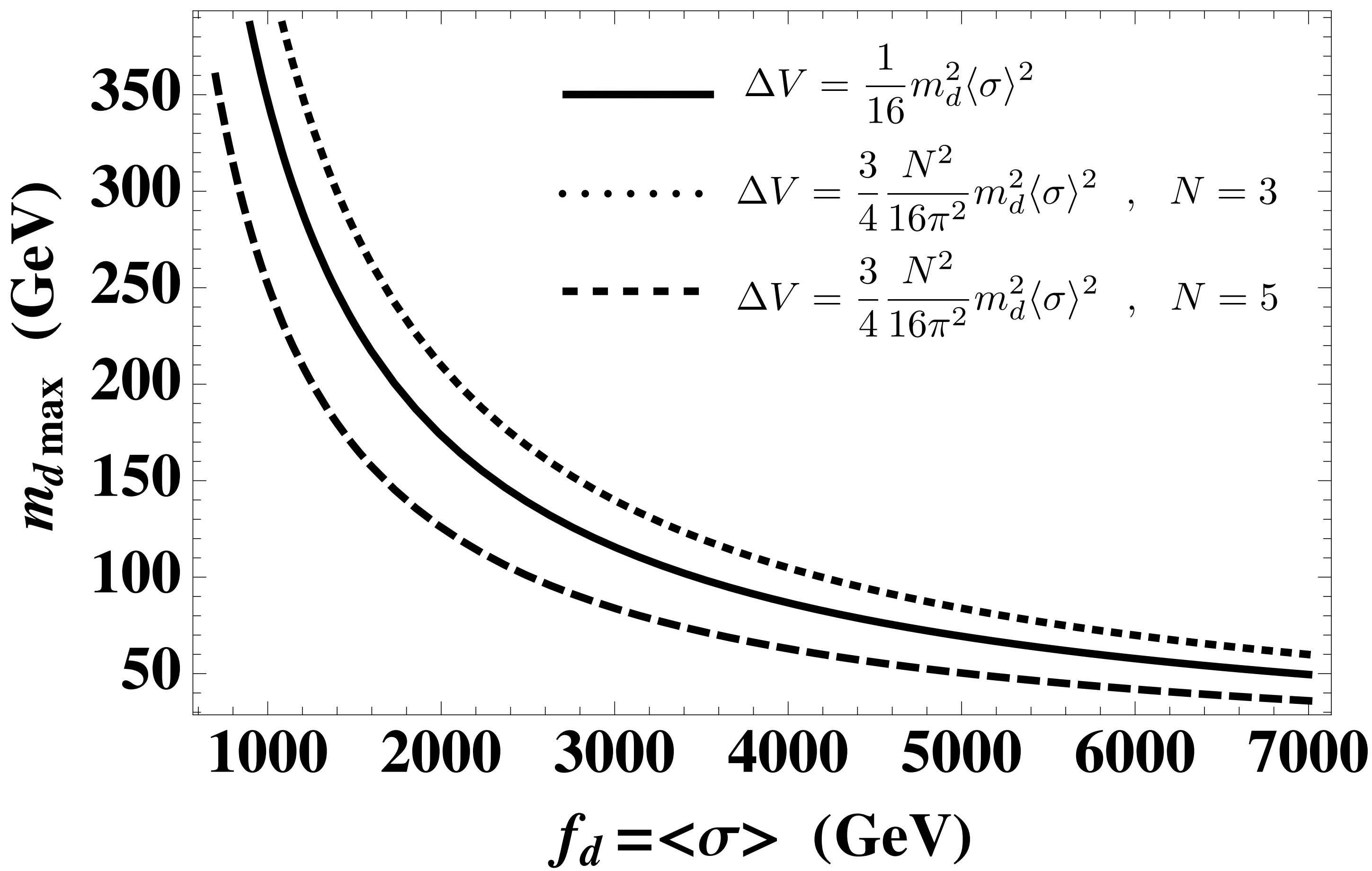
Reheat temperature below sphaleron freese-out temperature
to avoid washout

Bound on dilaton mass from reheating constraint

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

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

dilaton mass ~ O(100 GeV)



from 1407.0030

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

Operator relevant for baryogenesis:

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

EW field strength

time-varying function

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

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

$$\Rightarrow \quad \mathcal{L}_{eff} = \mu\ N_{CS}$$

$$\mu \equiv \partial_t\zeta$$

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

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

time-varying vev of the Higgs has been used successfully in cold baryogenesis studies

$$\frac{n_B}{s} \sim 10^{-5} \left(\frac{T_{eff}}{T_{reh}}\right)^3 \frac{v^2}{M^2}$$

M>65 TeV from electron electric dipole moment constraint

large enough asymmetry in the context of cold baryogenesis where $T_{eff} \gtrsim 5T_{reh}$

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:

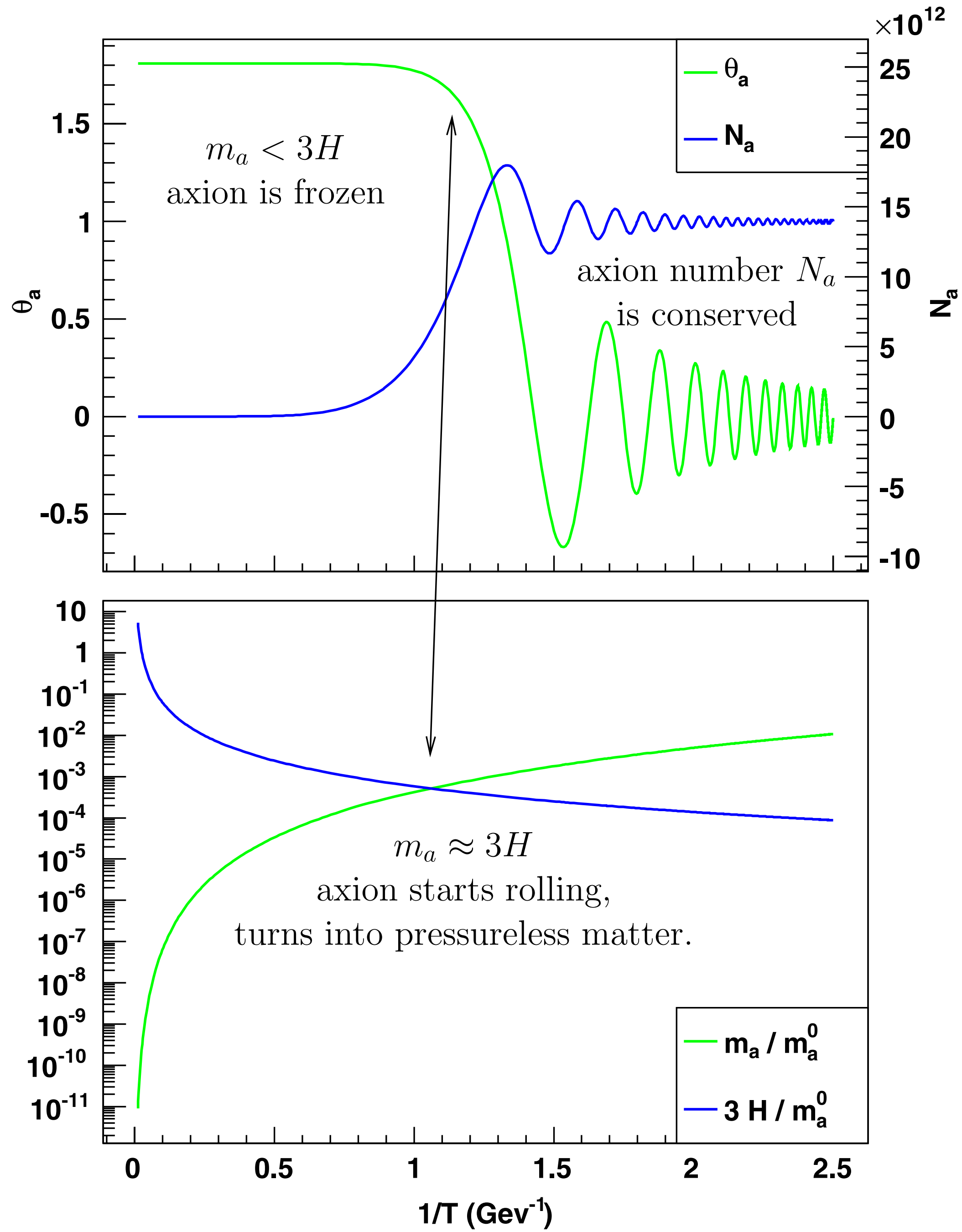
$$\bar{\Theta} \to \frac{a(x)}{f_a}$$

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

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:

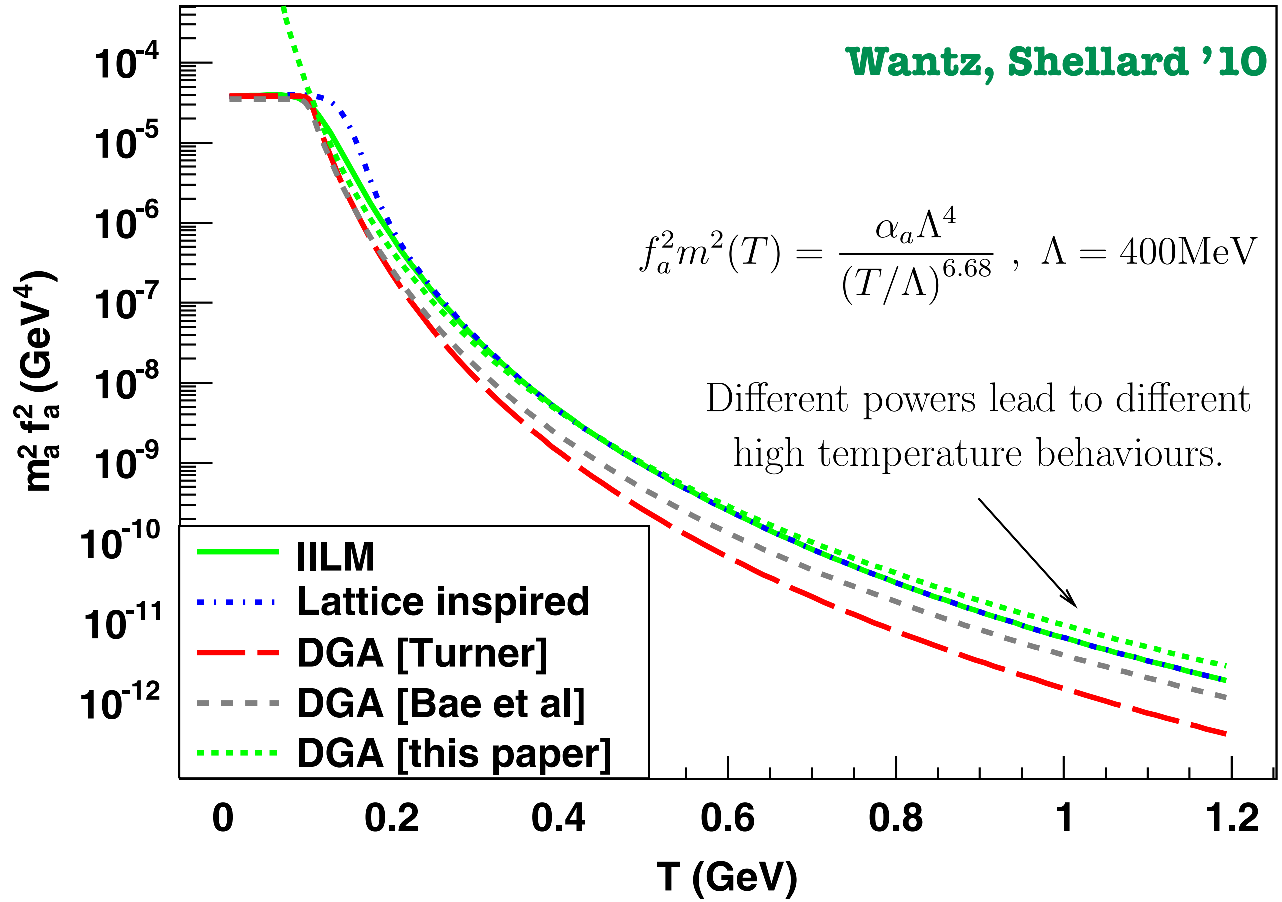
$$\mathcal{L}_{eff} = \frac{10}{F_\pi^2 m_{\eta'}^2} \sin\theta \; m_a^2(T) f_a^2 \quad \frac{\alpha_w}{8\pi} F\tilde{F}$$

$$\equiv \zeta(T)$$

time variation of axionic mass and field is source for baryogenesis

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

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

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

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

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

Kuzmin, Shaposhnikov, Tkachev ’92

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

I conjecture on the contrary that the axion can well explain 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 $\bar{\Theta}(T) \gtrsim 10^{-6}$

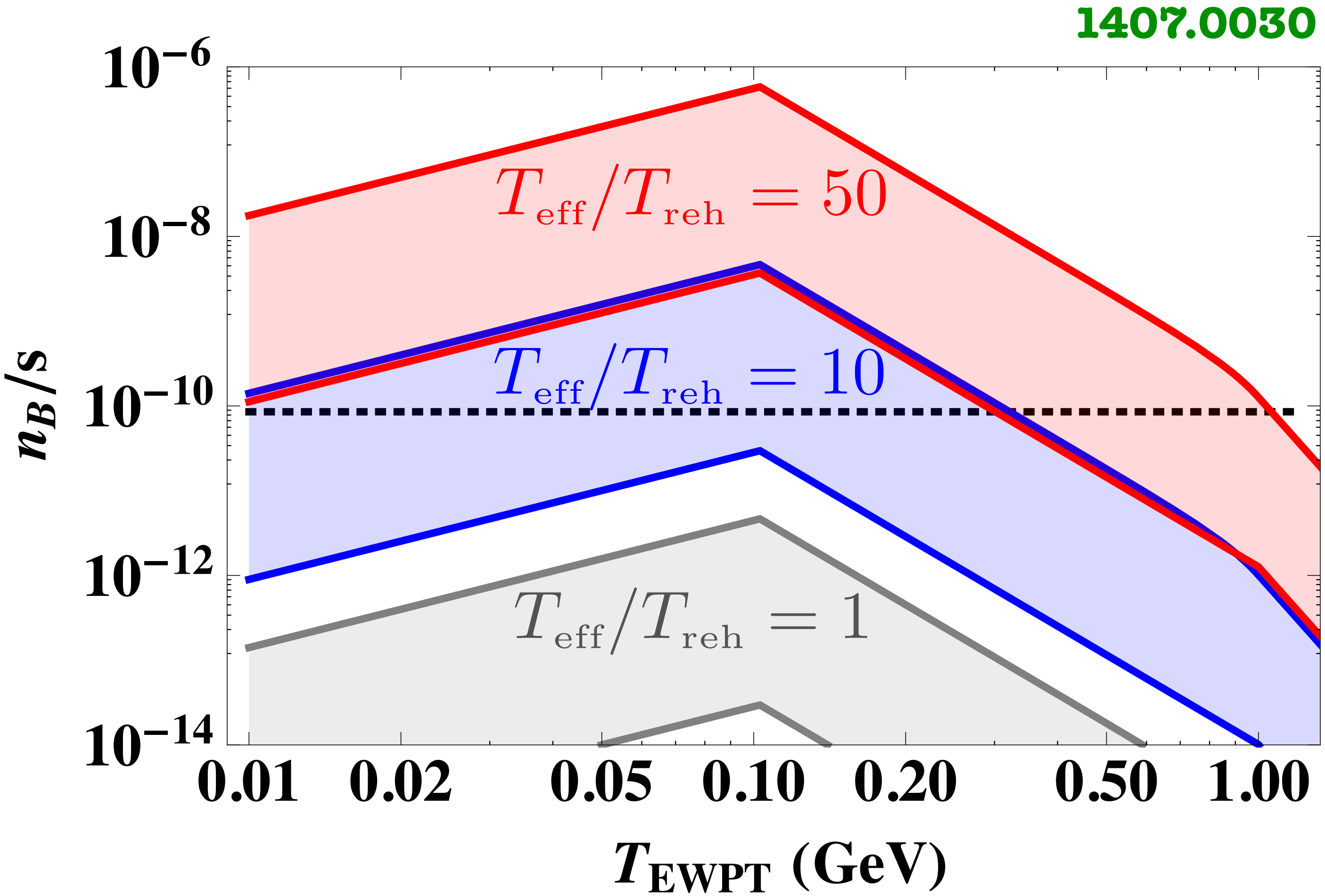
$$\frac{n_B}{s} \sim 10^{-8} \left(\frac{T_{eff}}{T_{reh}}\right)^3 \sin\bar{\Theta}\Big|_{EWPT}$$

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

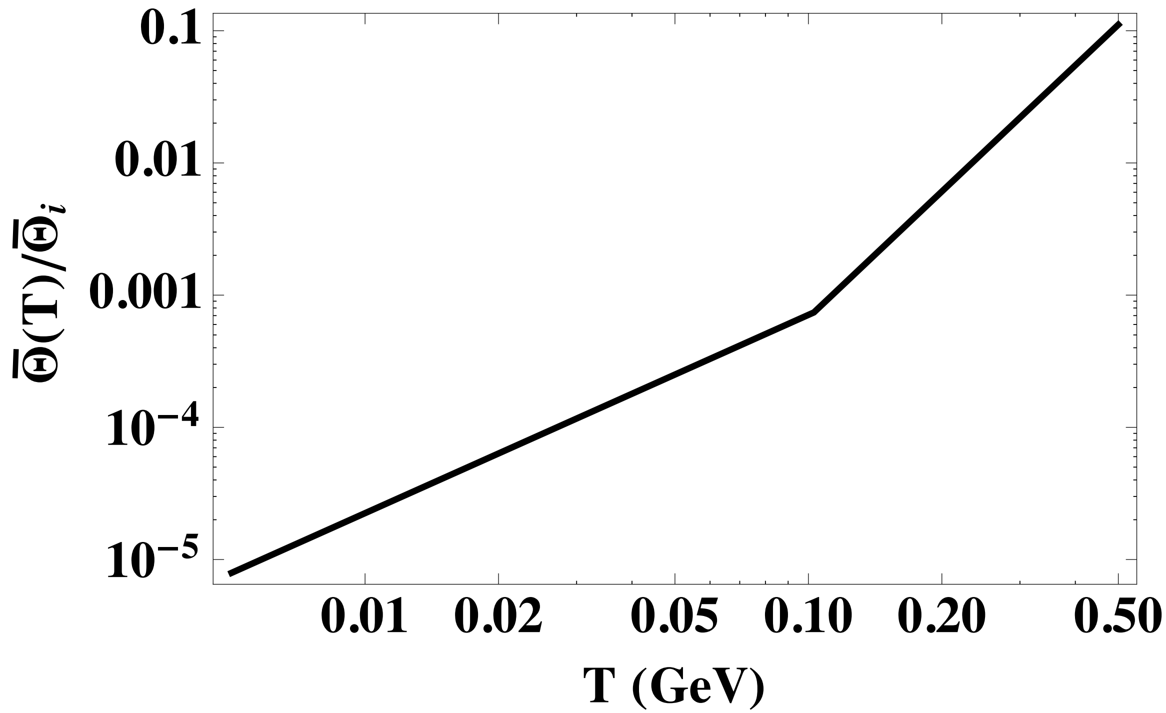
So even if $T_{EWPT} \lesssim \Lambda_{QCD}$ we can have $T_{eff} \gtrsim T_{reh} \sim m_H$

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

1407.0030


1407.0030
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
n_B/s
$T_{\rm eff}/T_{\rm reh} = 50$
$T_{\rm eff}/T_{\rm reh} = 10$
$T_{\rm eff}/T_{\rm reh} = 1$
0.01
0.02
0.05
0.10
0.20
0.50
1.00
$T_{\rm EWPT}$ (GeV)

Size of Theta versus temperature



EWPT should take place between T~ a few MeV and ~ 1 GeV to have sufficient CP violation for baryogenesis

Conclusion

Strong CP violation from the QCD axion can be responsible for the matter antimatter asymmetry of the universe in the context of cold baryogenesis

if the EW phase transition is delayed down to the QCD scale

These conditions can arise naturally in models with a light dilaton (e.g Goldberger-Wise radion stabilisation mechanism)

Peccei-Quinn scale predicted to be higher than usual to get the correct Dark Matter relic abundance

scenario testable at LHC : existence of a O(100) GeV Higgs-like dilaton