Baryogenesis from the Standard QCD axion

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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

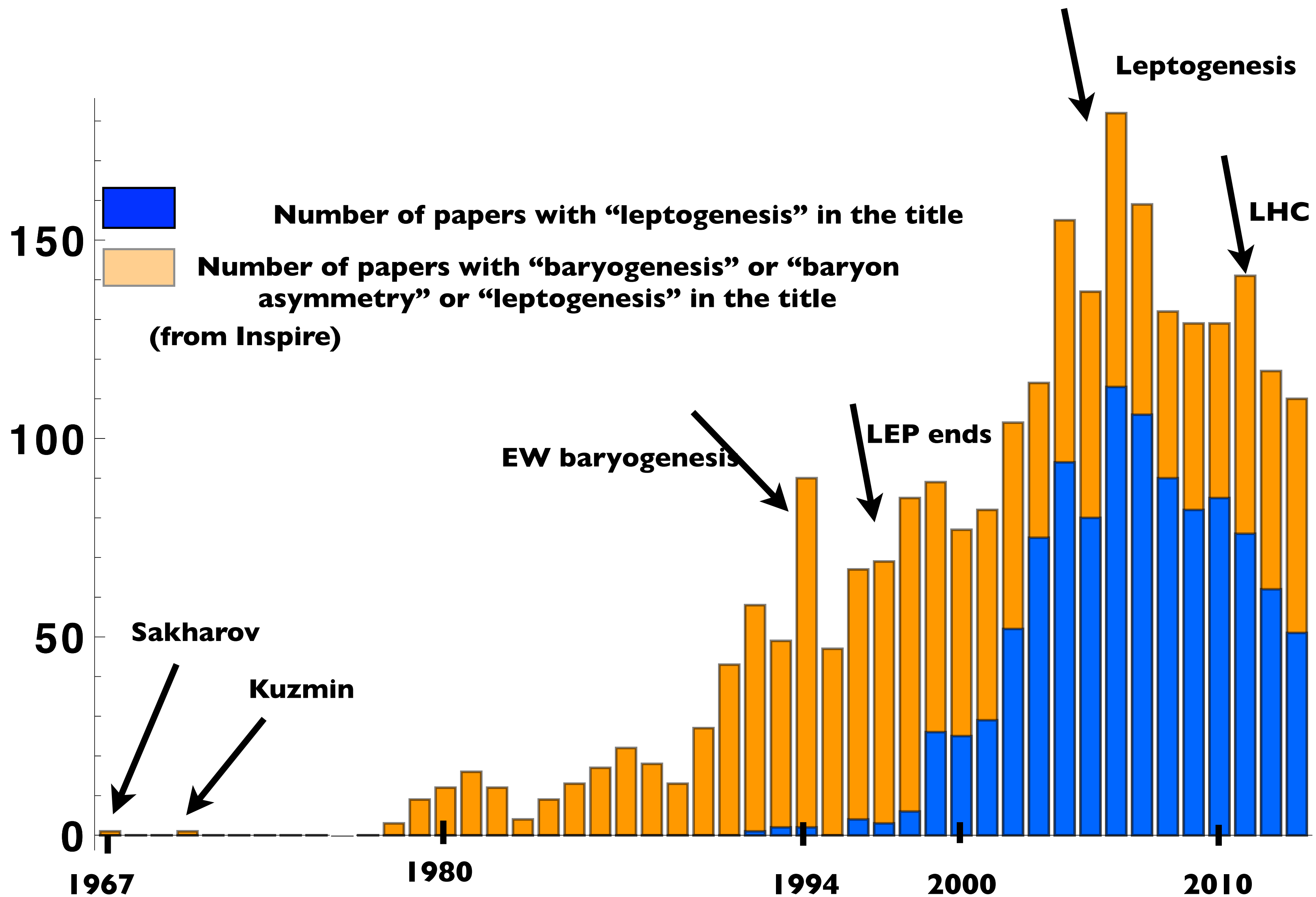
Shaposhnikov,

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.

Plethora of baryogenesis models taking place at all possible scales

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

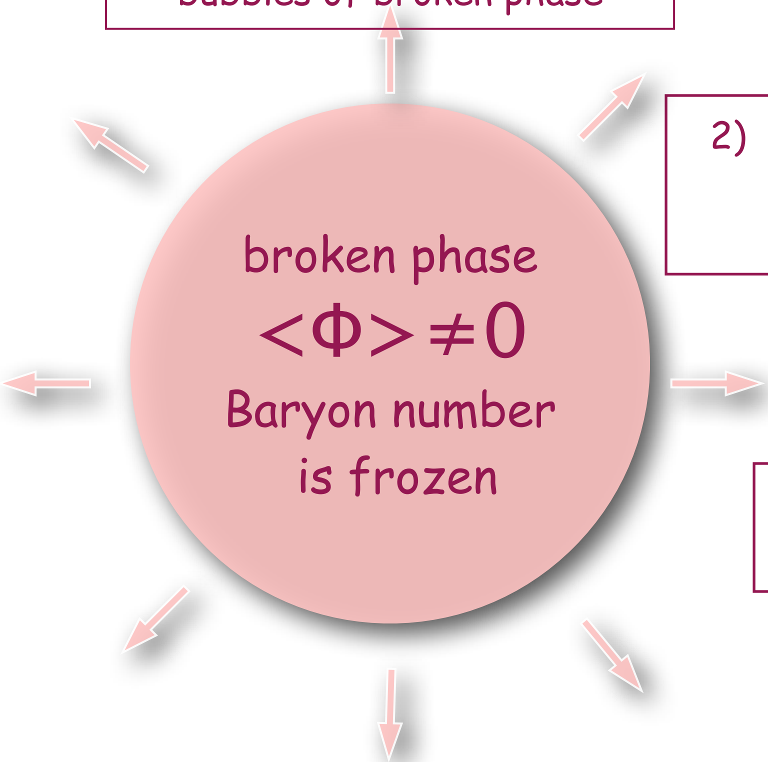
EW cold (local) baryogenesis

In these approaches baryogenesis is disconnected from the problem of dark matter generation.

No unified explanation for dark and visible matter densities.

Baryon asymmetry and the EW scale

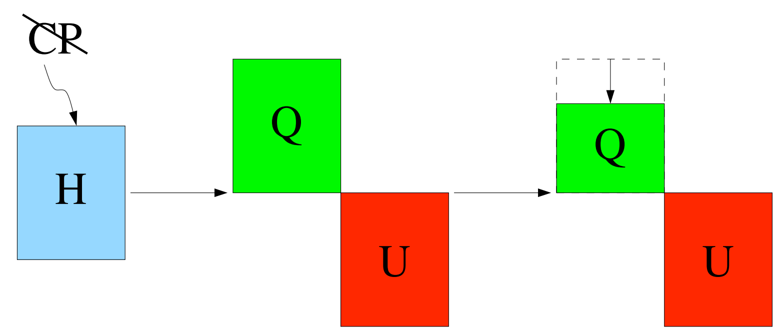
1) nucleation and expansion of bubbles of broken phase



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

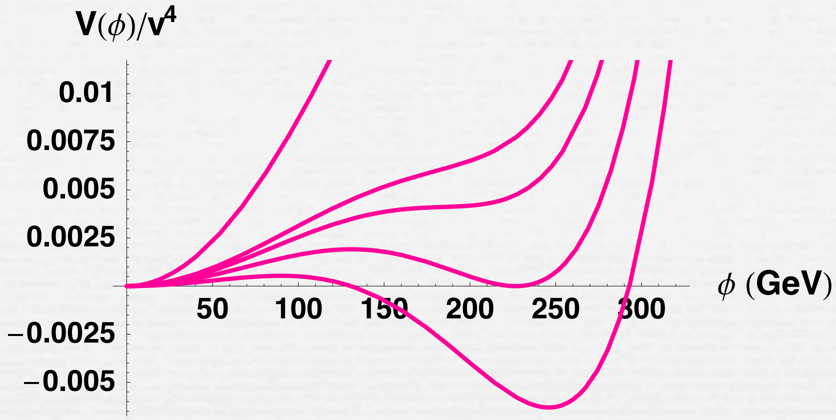
Chirality Flux in front of the wall

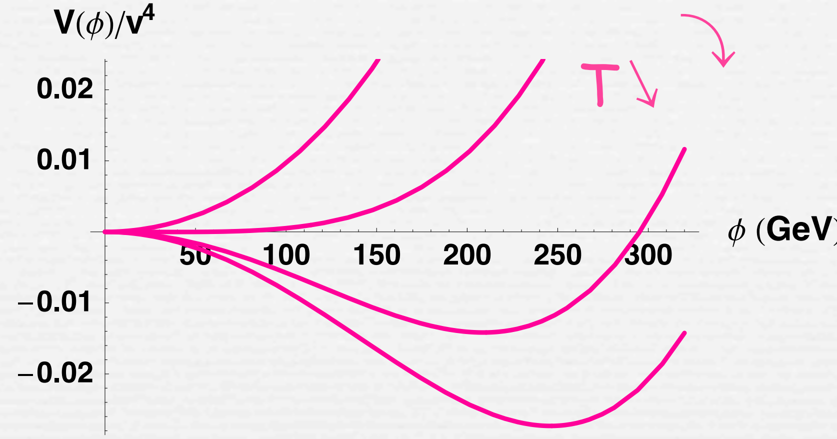
3) In symmetric phase, <Φ>=0, very active sphalerons convert chiral asymmetry into baryon asymmetry



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

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 mh>72 GeV, no 1st order phase transition

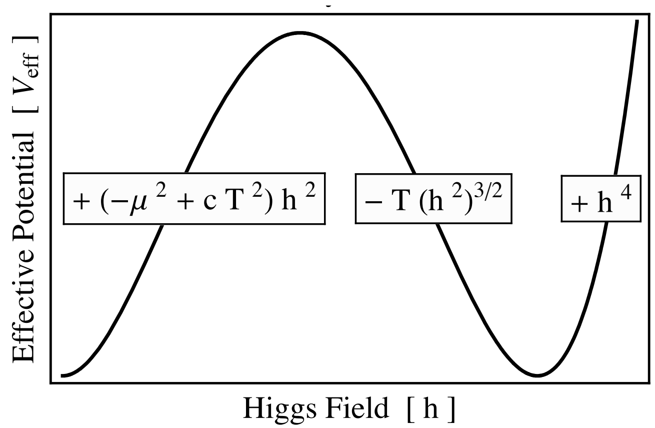
In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop

Detour on 1st order cosmological phase transitions

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

1)

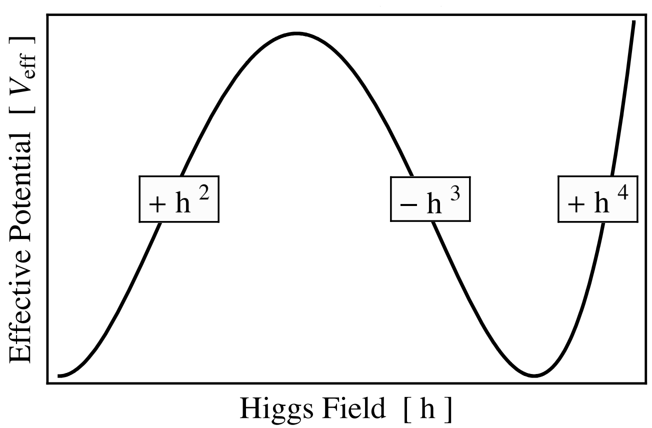


thermally driven

(thermal loop of bosonic modes)

(example:stop loop in MSSM)

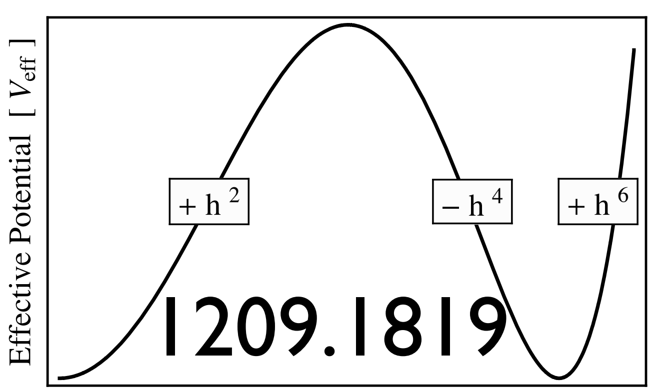
2)



tree-level driven

(competition between renormalizable operators)

3)



tree-level driven

(competition between renormalizable and non-renormalizable operators)

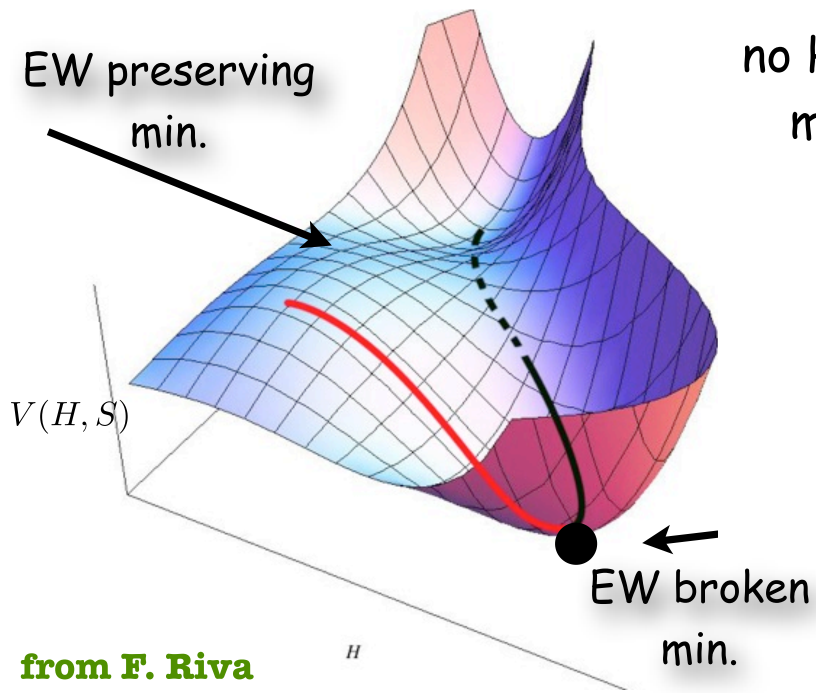
4) Two-stage EW phase transition (tree level)

example: the SM+ a real scalar singlet

1409.0005

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

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

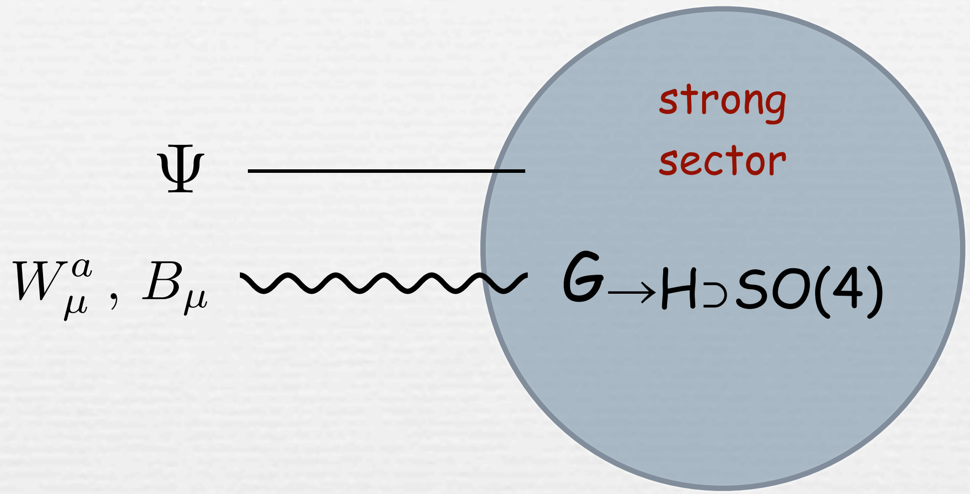


from F. Riva

-> Espinosa et al, 1107.5441

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.[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]

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

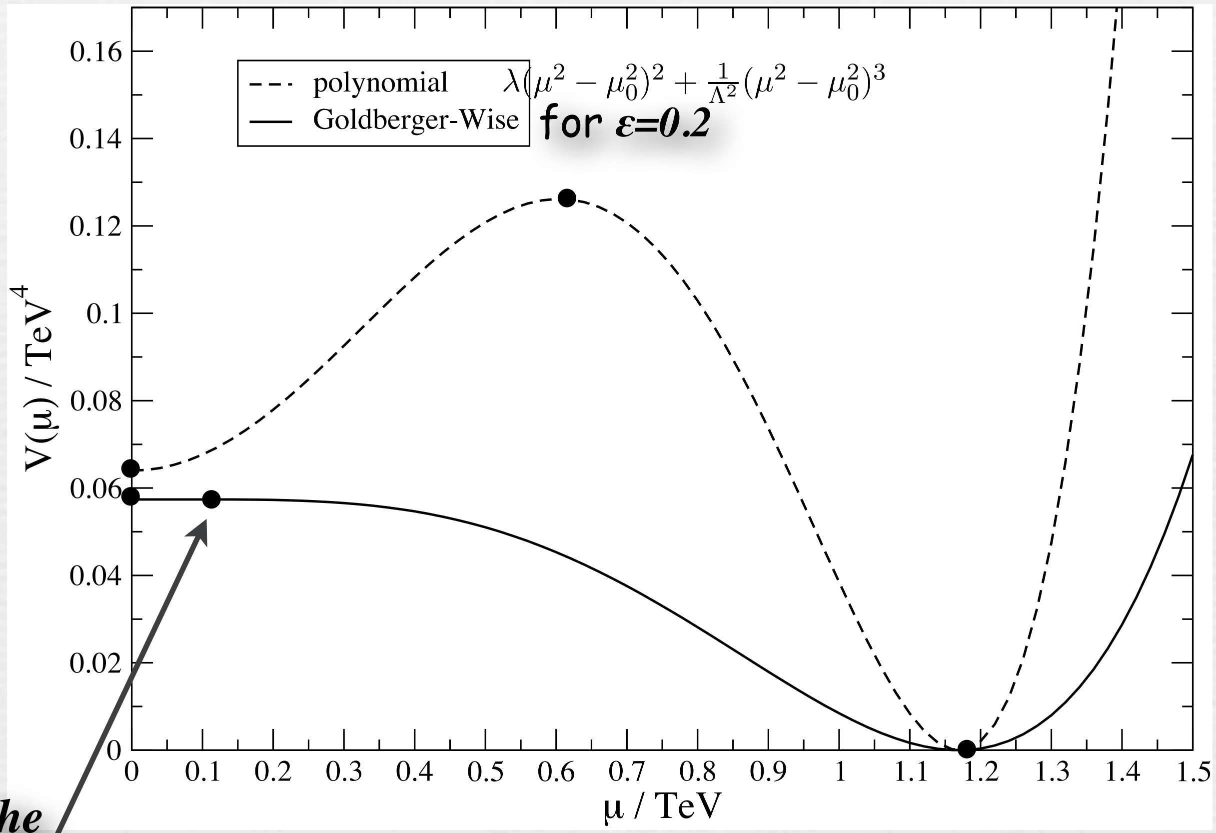
for $|\epsilon| \ll 1$

similar to Coleman-Weinberg mechanism where a slow Renormalization Group 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



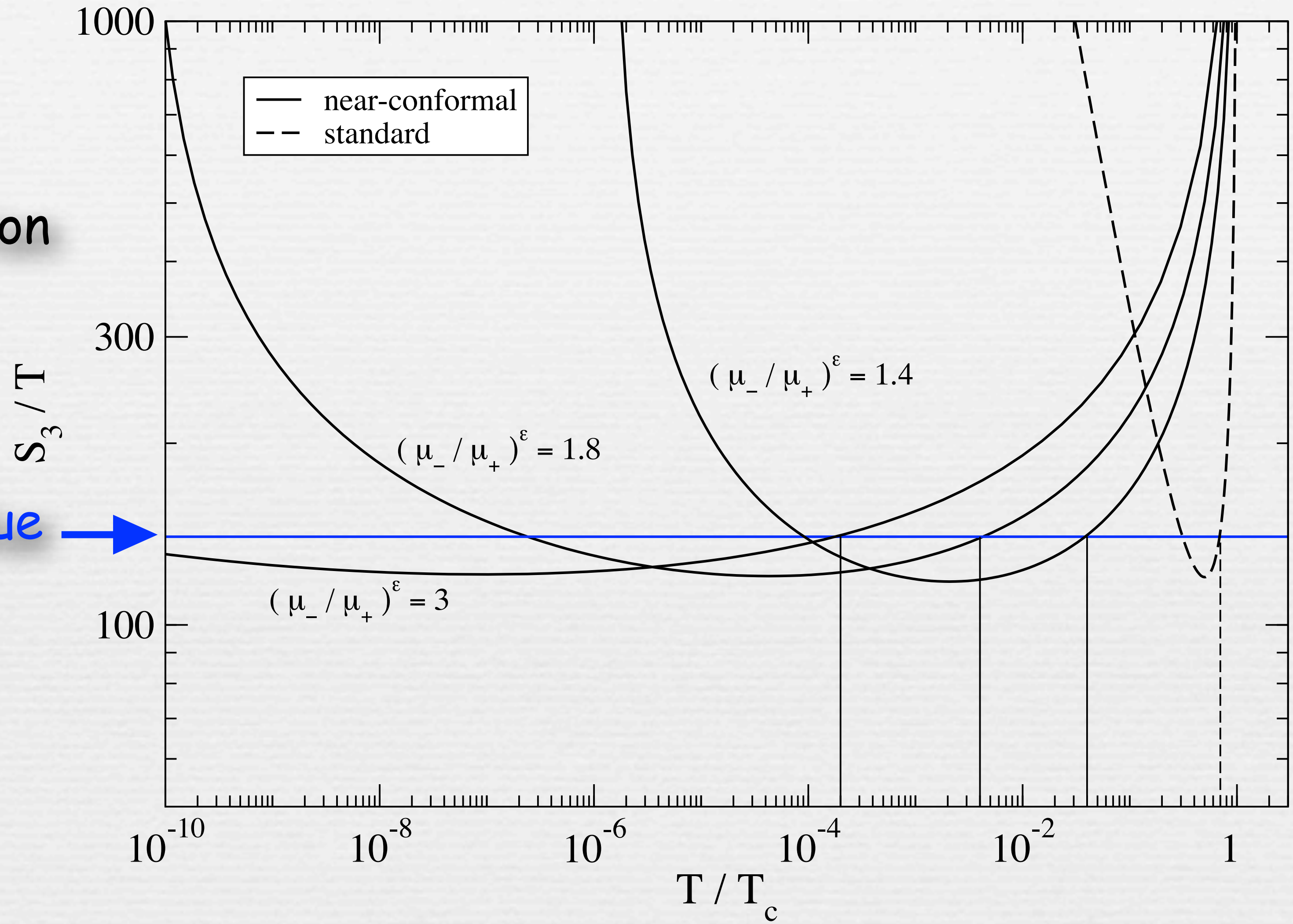
position of the maximum

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

Servant-Konstandin '11

bubble action

critical value



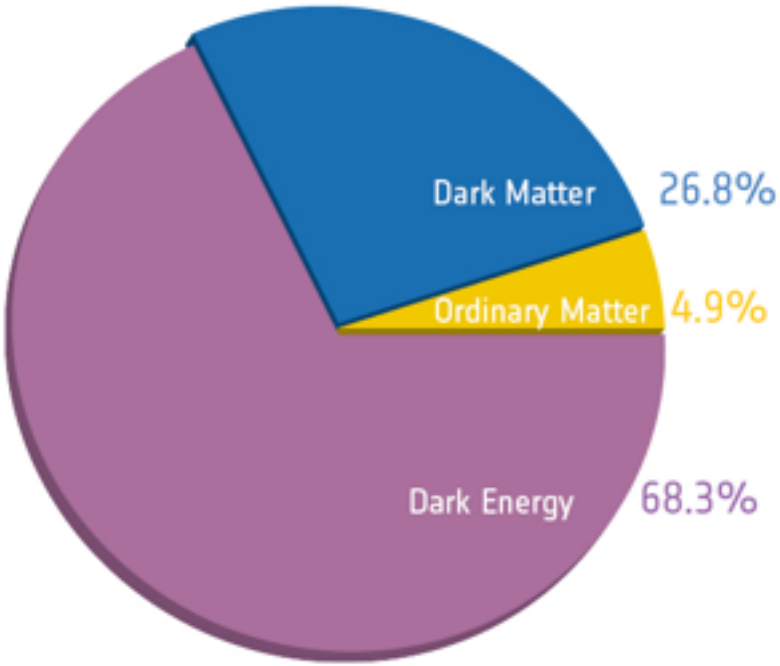
key point: value of the field at tunneling is much smaller than value at the minimum of the potential

nucleation temperature very small

keep this in mind,
will be relevant later in the talk.

Are the Dark Matter and baryon abundances related ?

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



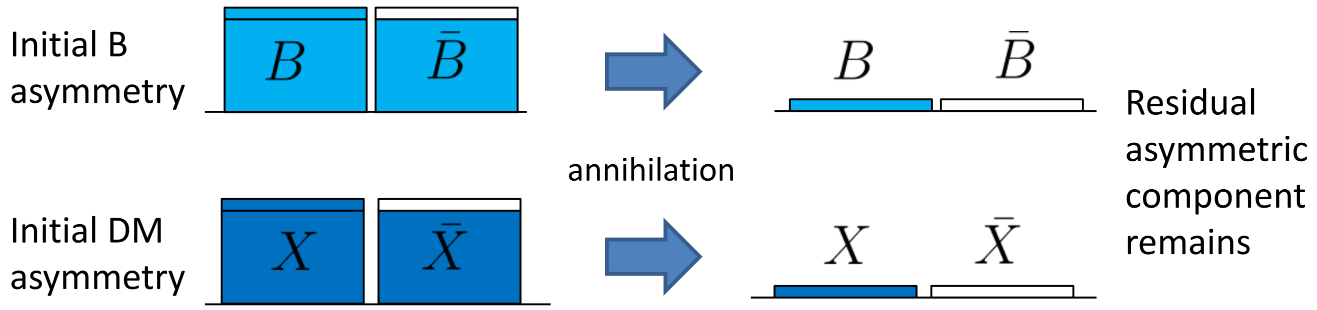
Atoms: 4.9 %

Photons: 0.0022 %

Neutrinos: 0.0016 %

Scenario I: Dark Matter is a WIMP

-> 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

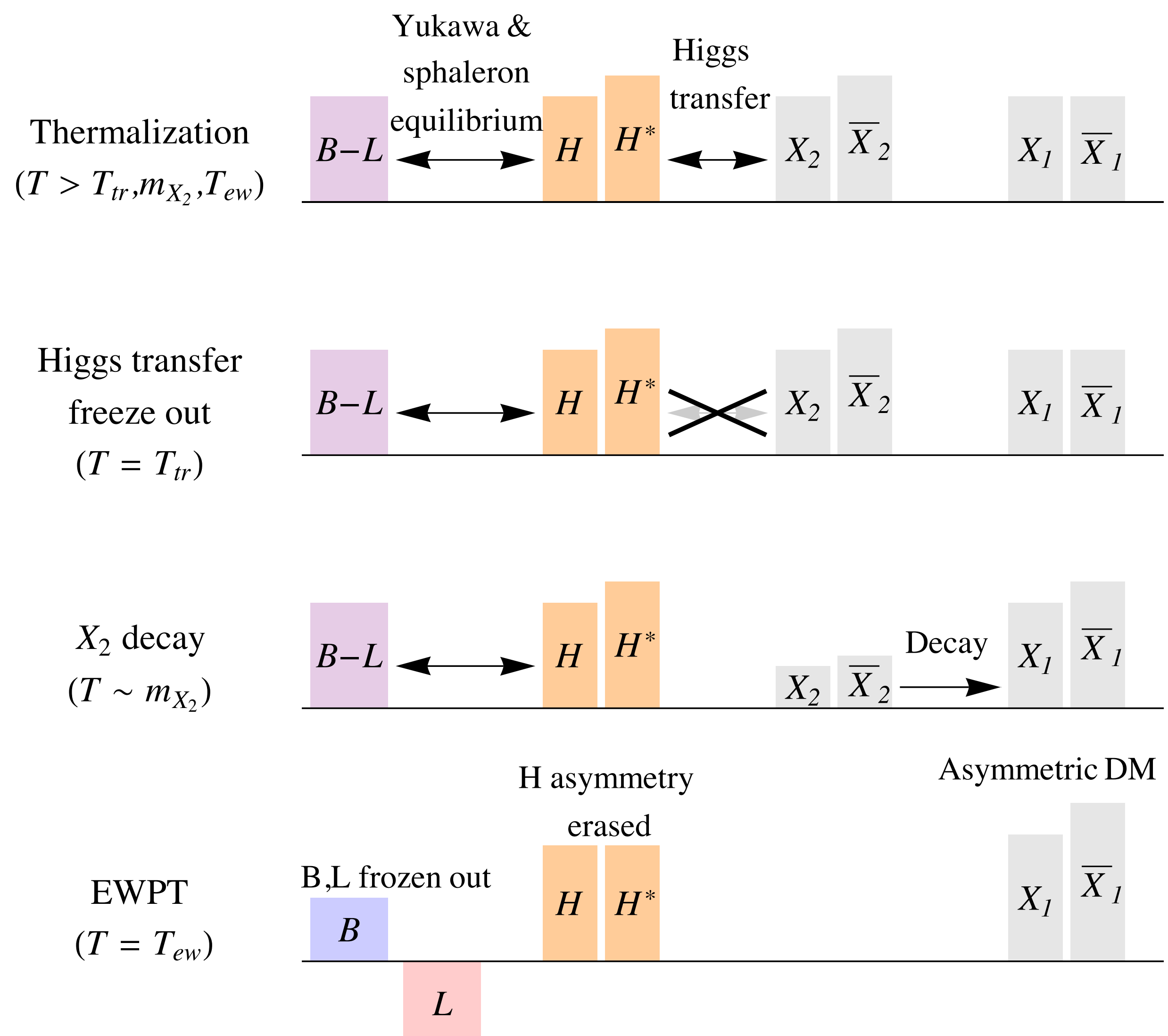
Just add to the Standard Model 2 vector-like fermions:
a singlet X_1 (Dark matter) and one EW doublet X_2 whose role is to transfer the asymmetries between the visible and dark sectors

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

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.

Scenario II:

Dark matter is the QCD axion

Can it play any role in baryogenesis?

Unique paper addressing this question so far was:

Kuzmin, Shaposhnikov, Tkachev '92

Baryogenesis from Strong CP violation

Servant'14, 1407.0030

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

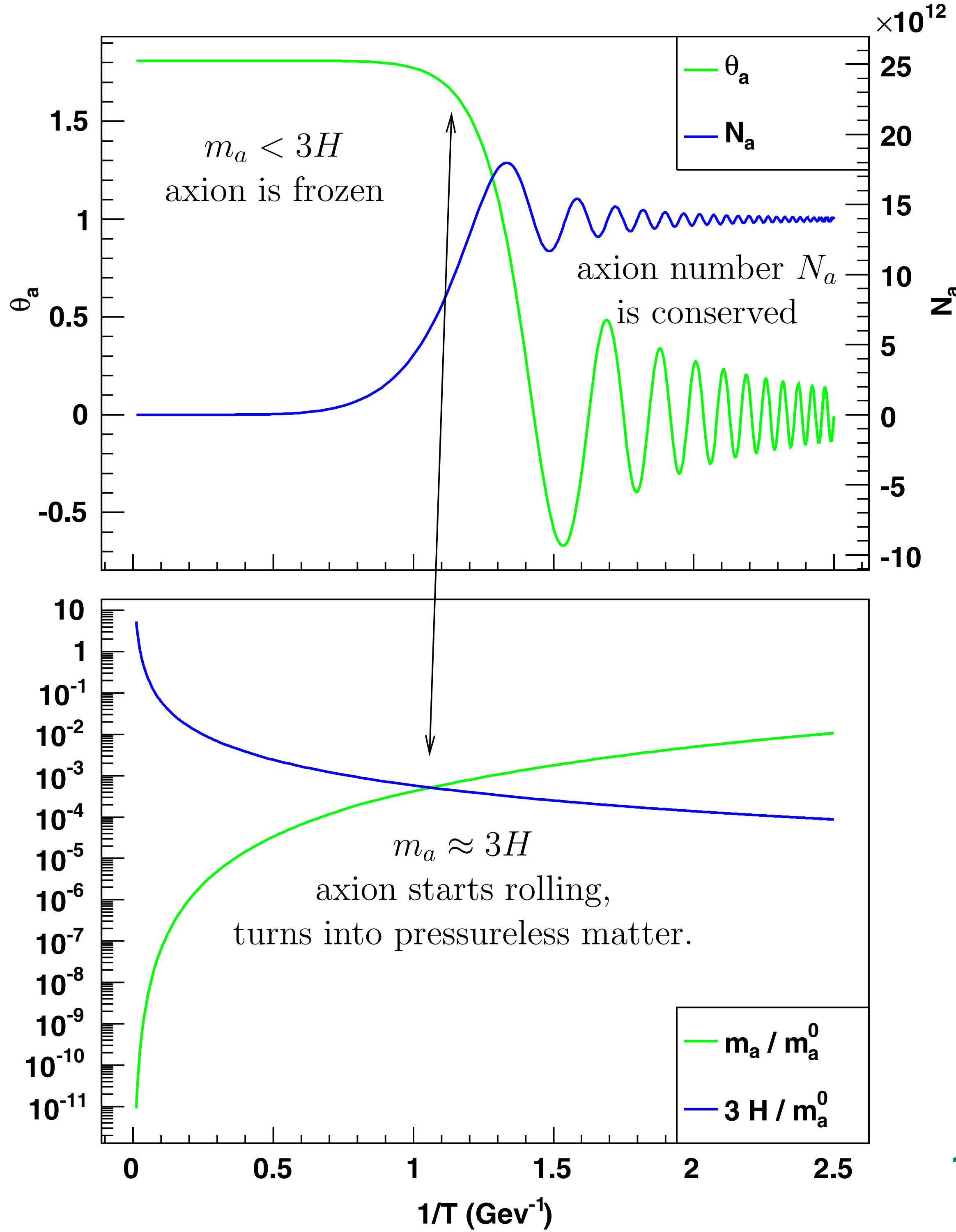
today $|\bar{\Theta}| < 10^{-11}$ as explained by Peccei-Quinn mechanism:

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



Wantz, Shellard '10

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

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

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

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

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

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 ~ $\frac{a(t)}{f_a} F\tilde{F}$

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.

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:

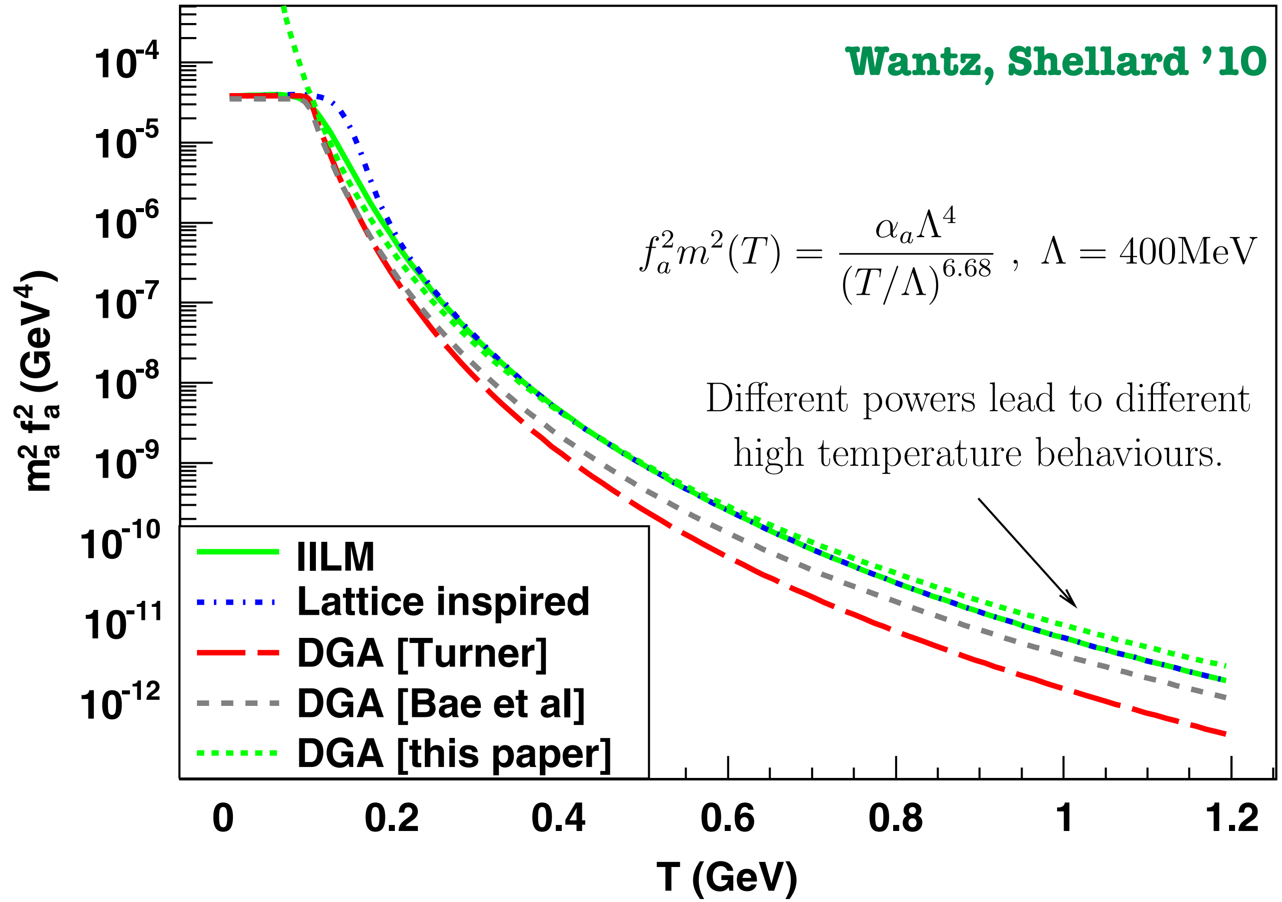
$$\mathcal{L}_{eff} = \frac{10}{F_\pi^2 m_{\eta'}^2} \sin\theta \; m_a^2(T) f_a^2 \; \frac{\alpha_w}{8\pi} F\tilde{F}$$

$$\equiv \zeta(T)$$

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

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

$\sim \bar{\Theta}(T_{eff})$

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

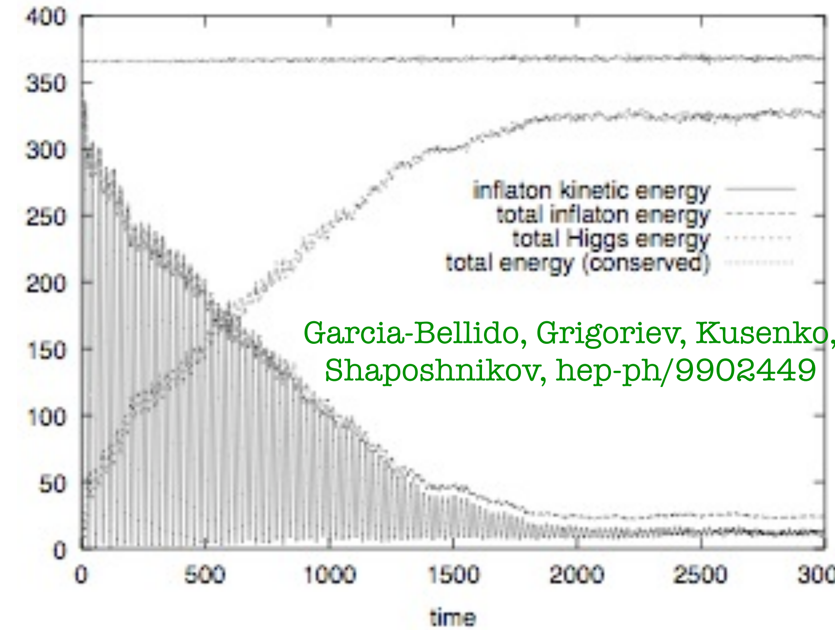
1407.0030

Cold baryogenesis 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

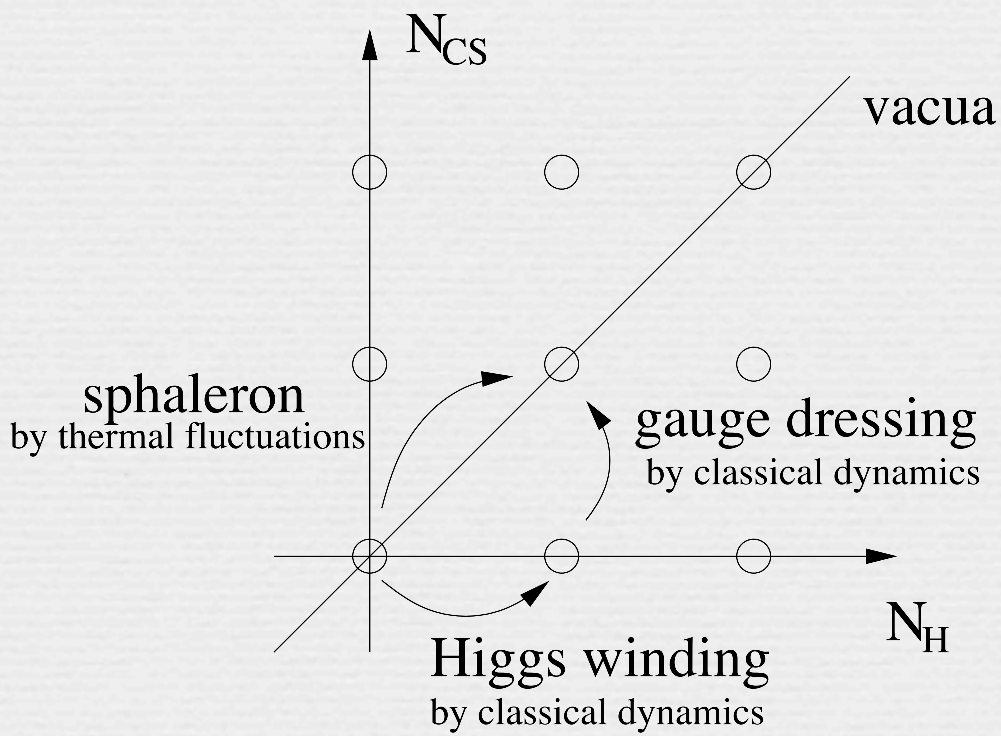
main idea:

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: $N_H = N_{CS}$

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 $T \sim 130$ 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

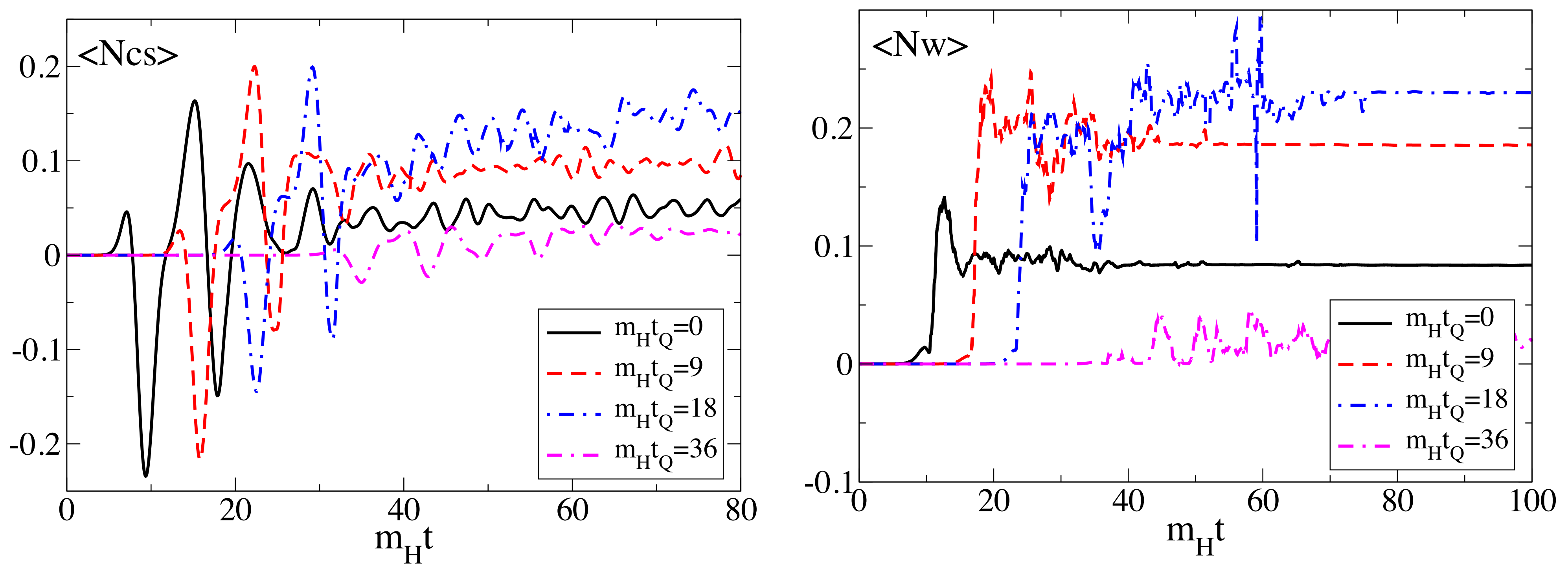
Cold baryogenesis has been simulated on the lattice where:

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

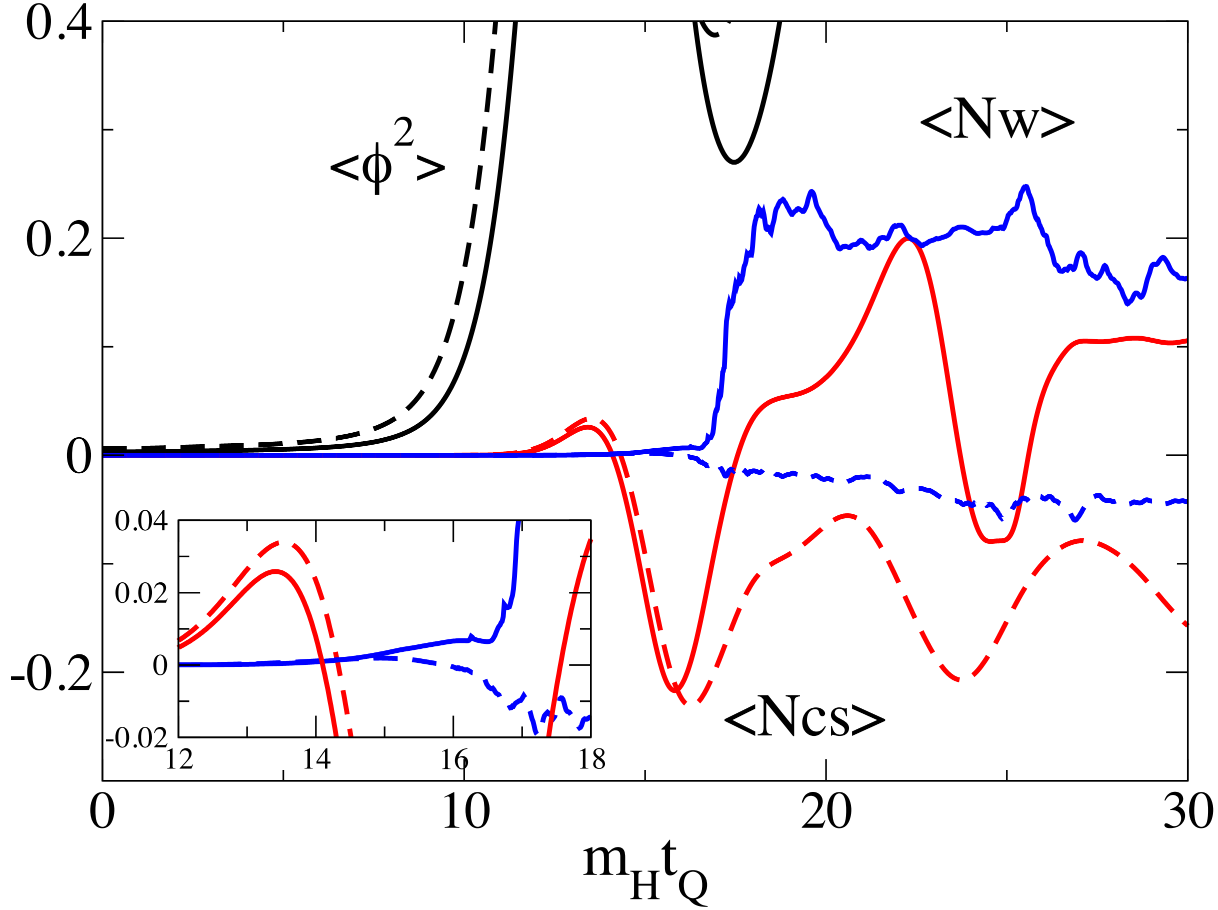
$$\mathcal{L}_{eff} = \frac{\alpha_W}{8\pi}\ \zeta(T)\mathrm{Tr}\ F\tilde{F}$$

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

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

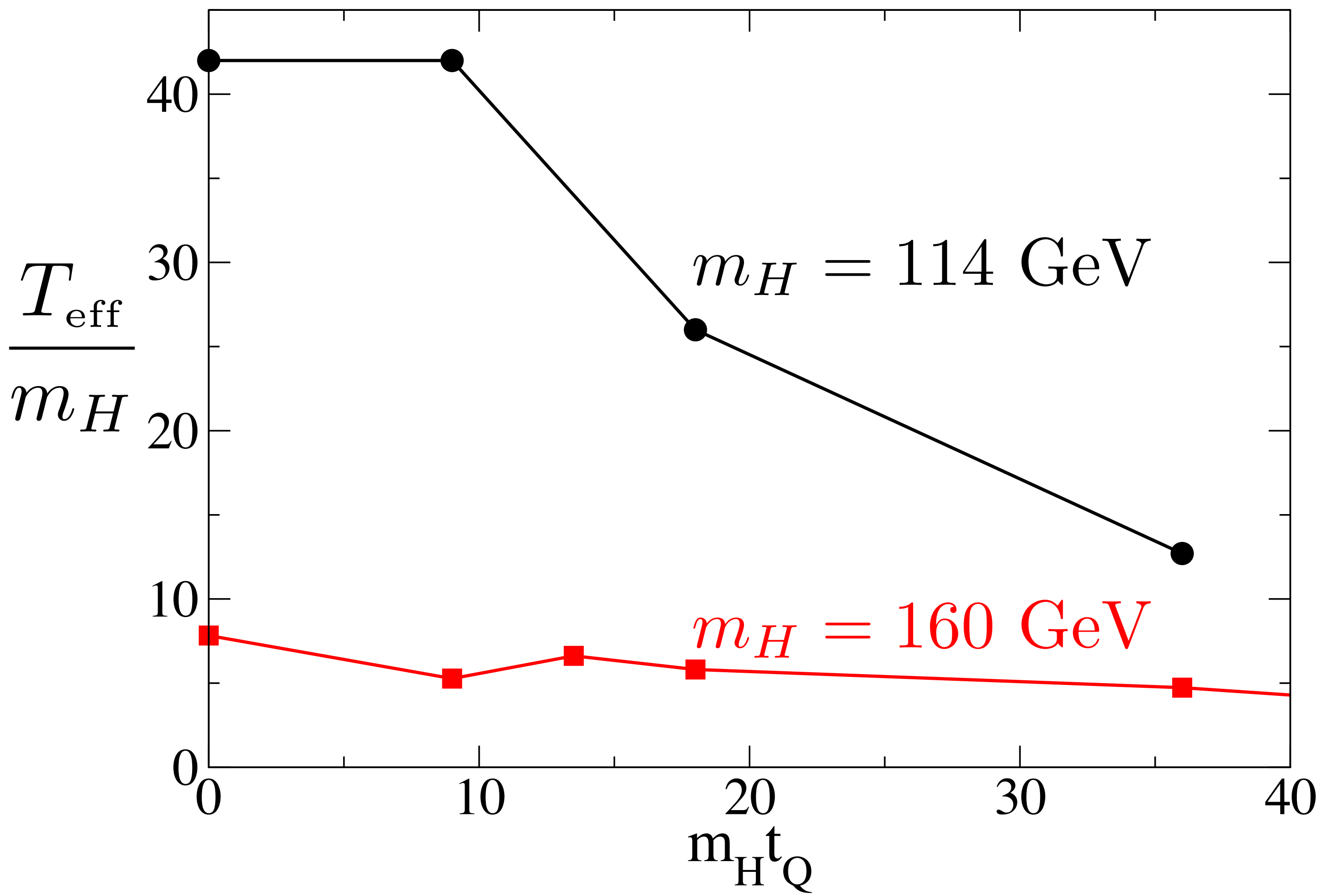


Tranberg, Smit, Hindmarsh, hep-ph/0610096



Tranberg, Smit, Hindmarsh, hep-ph/0610096

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)

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

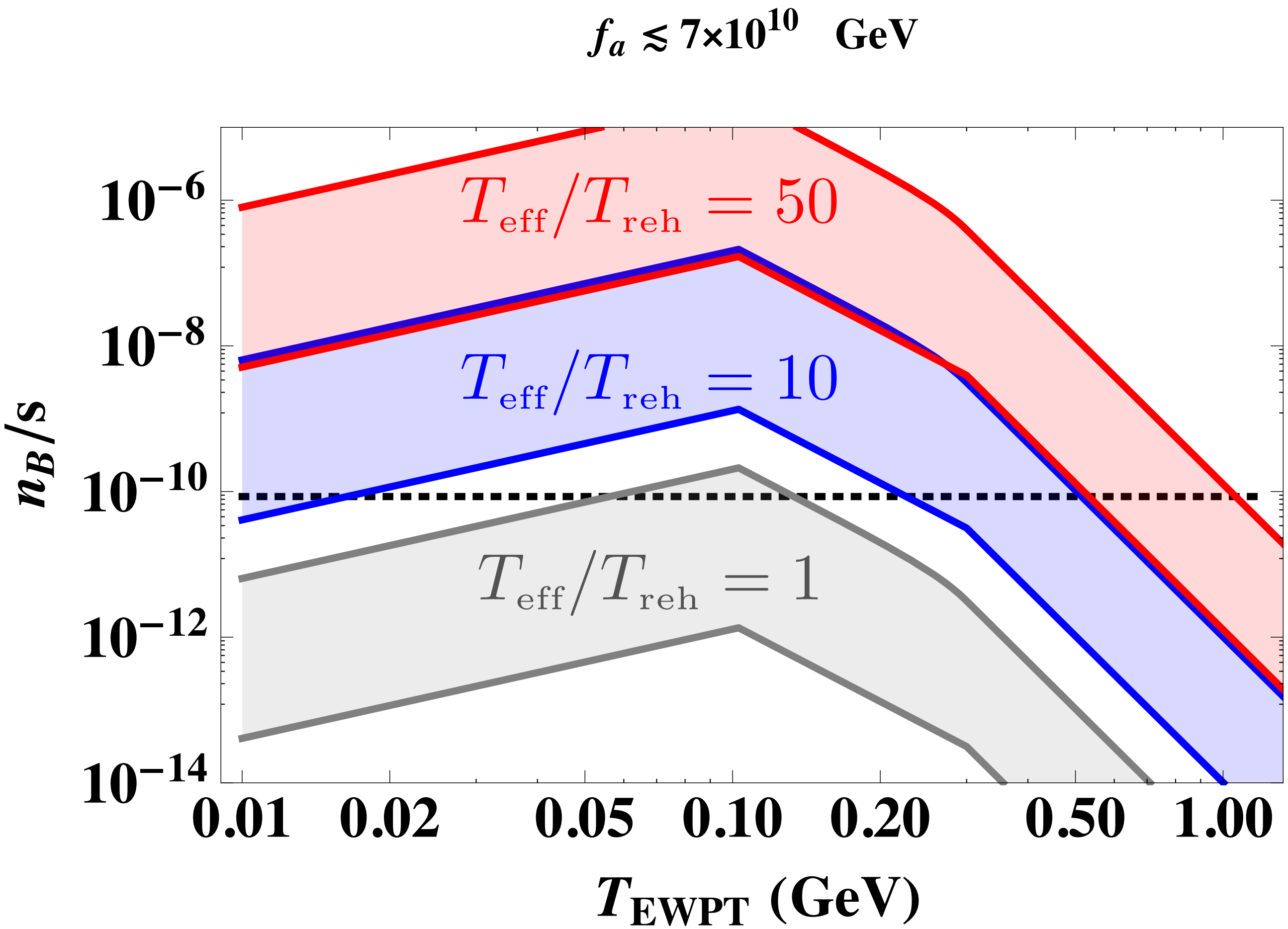
a scale invariant function modulated by a slow evolution through the σ^ϵ term

for $|\varepsilon| \ll 1$

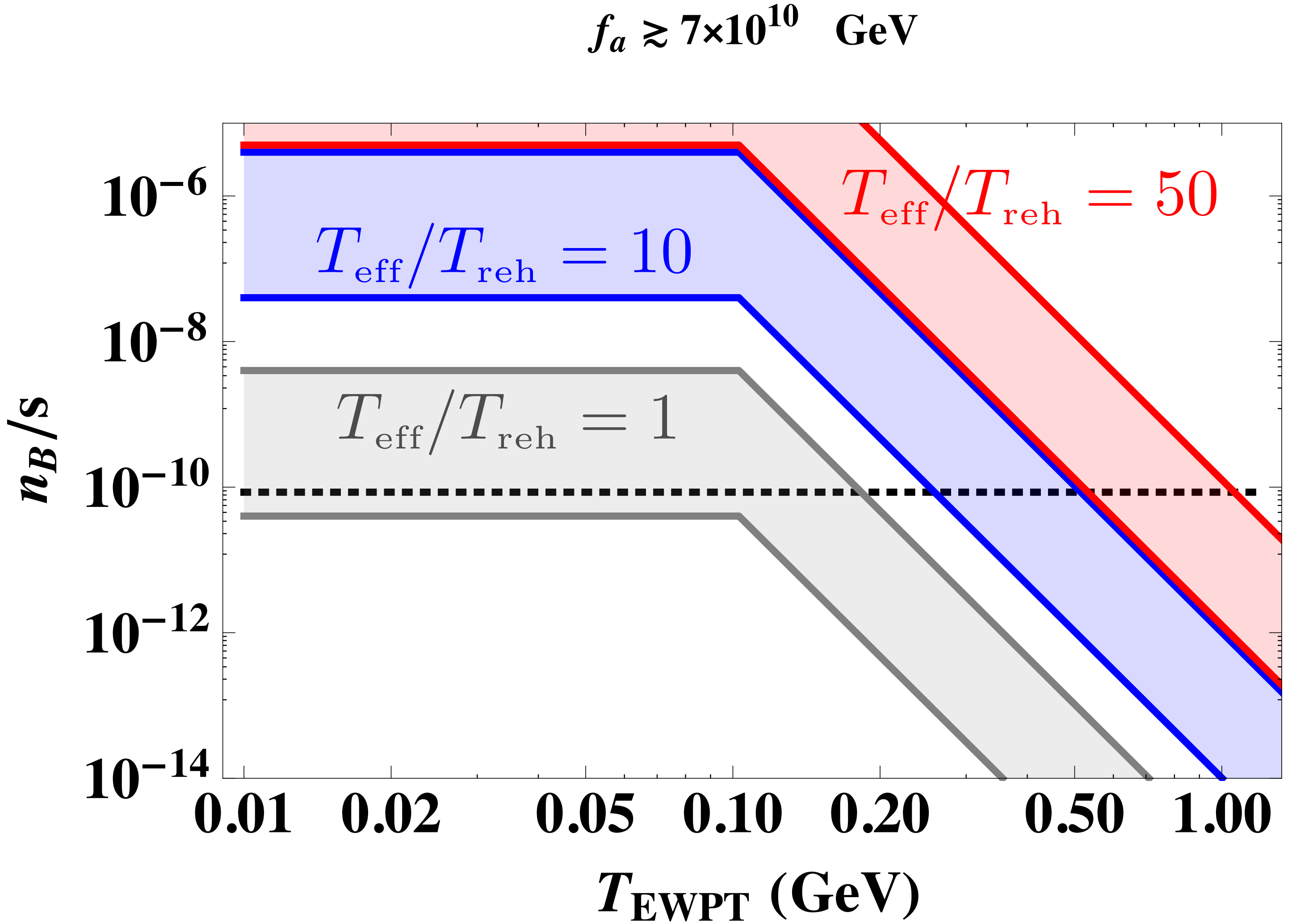
similar to Coleman-Weinberg mechanism where a slow RG evolution of potential parameters can generate widely separated scales

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

Servant, 1407.0030

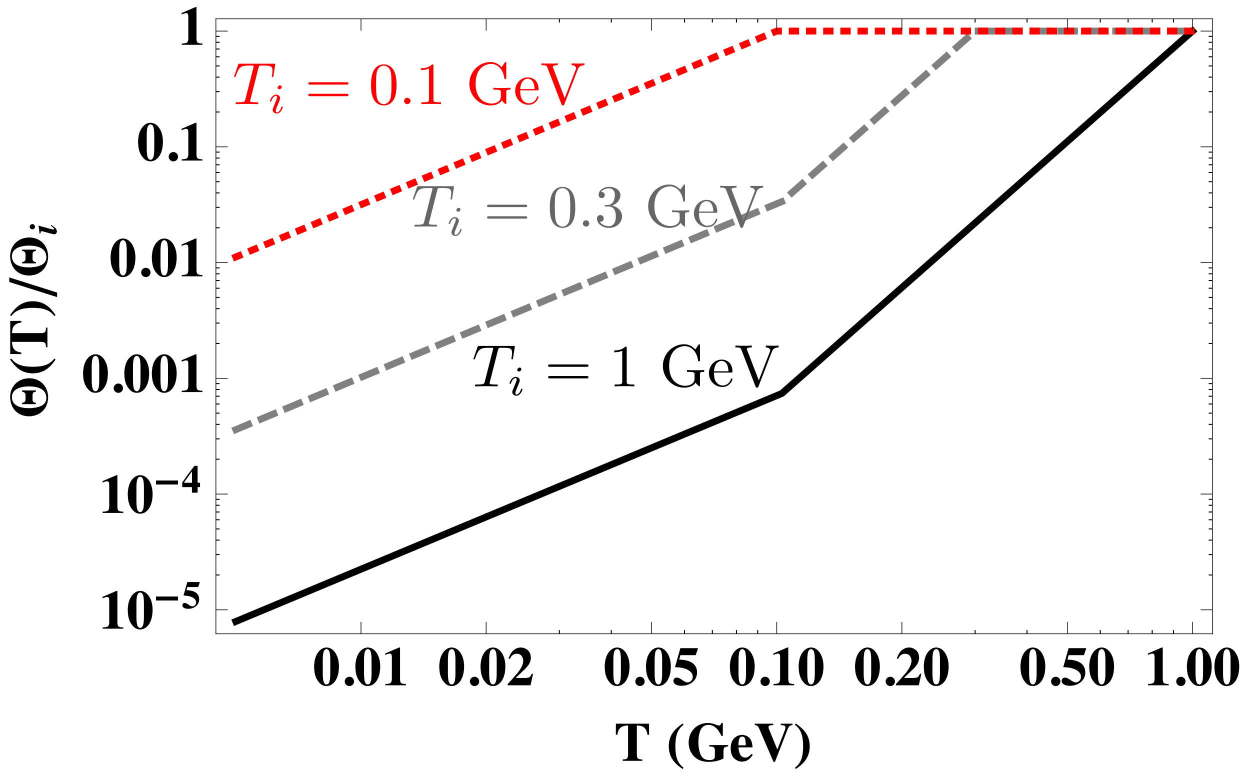


requires a coupling between the Higgs and an additional light scalar


$f_a \gtrsim 7\times10^{10}$ GeV
$T_{\rm eff}/T_{\rm reh} = 50$
$T_{\rm eff}/T_{\rm reh} = 10$
$T_{\rm eff}/T_{\rm reh} = 1$
n_B/s
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
0.01
0.02
0.05
0.10
0.20
0.50
1.00
$T_{\rm EWPT}$ (GeV)

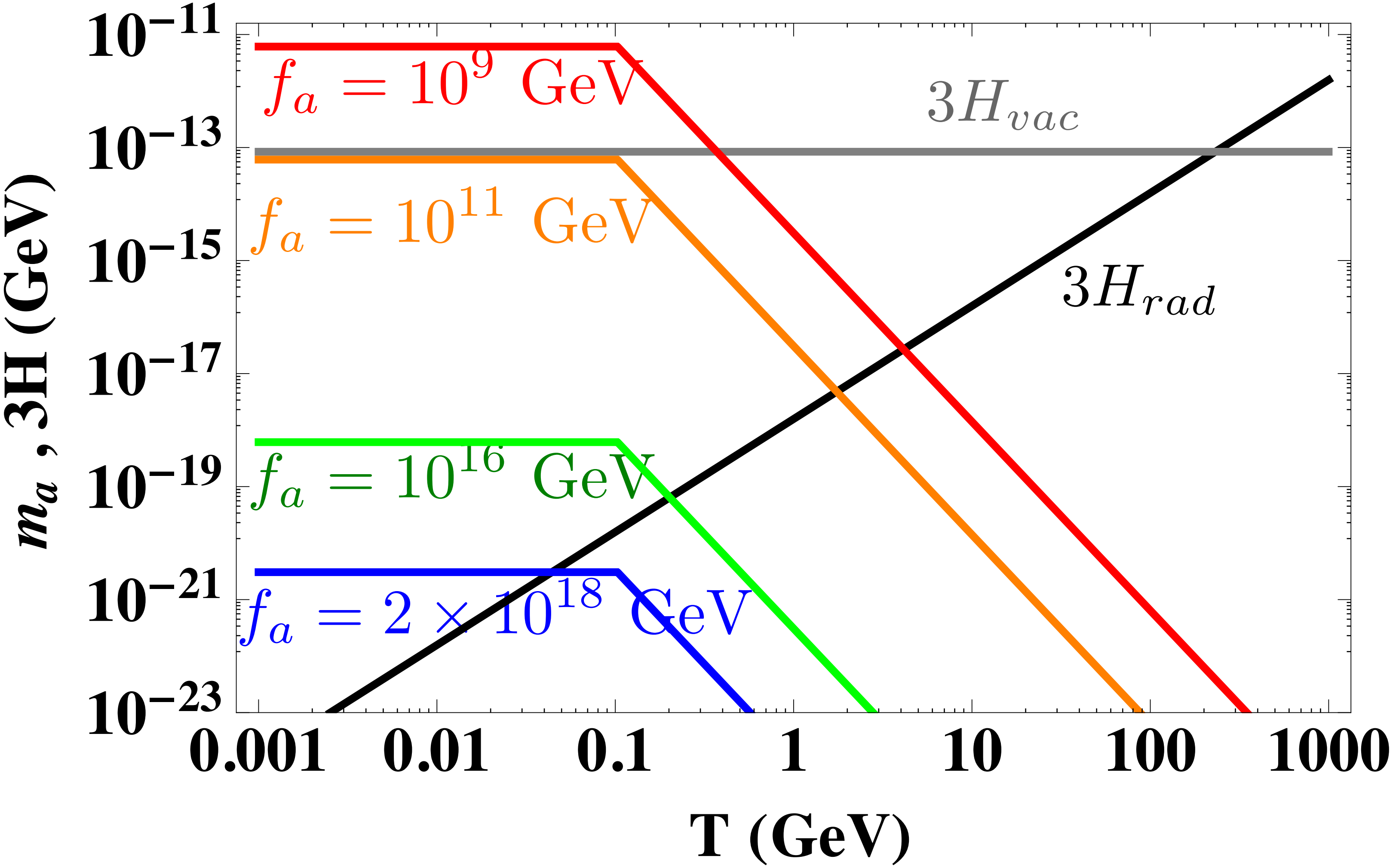
Size of Theta versus temperature

for different initial temperatures
at which oscillations start



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

Do axion oscillations start before or after the EW phase transition?



Key point for the scenario to work:

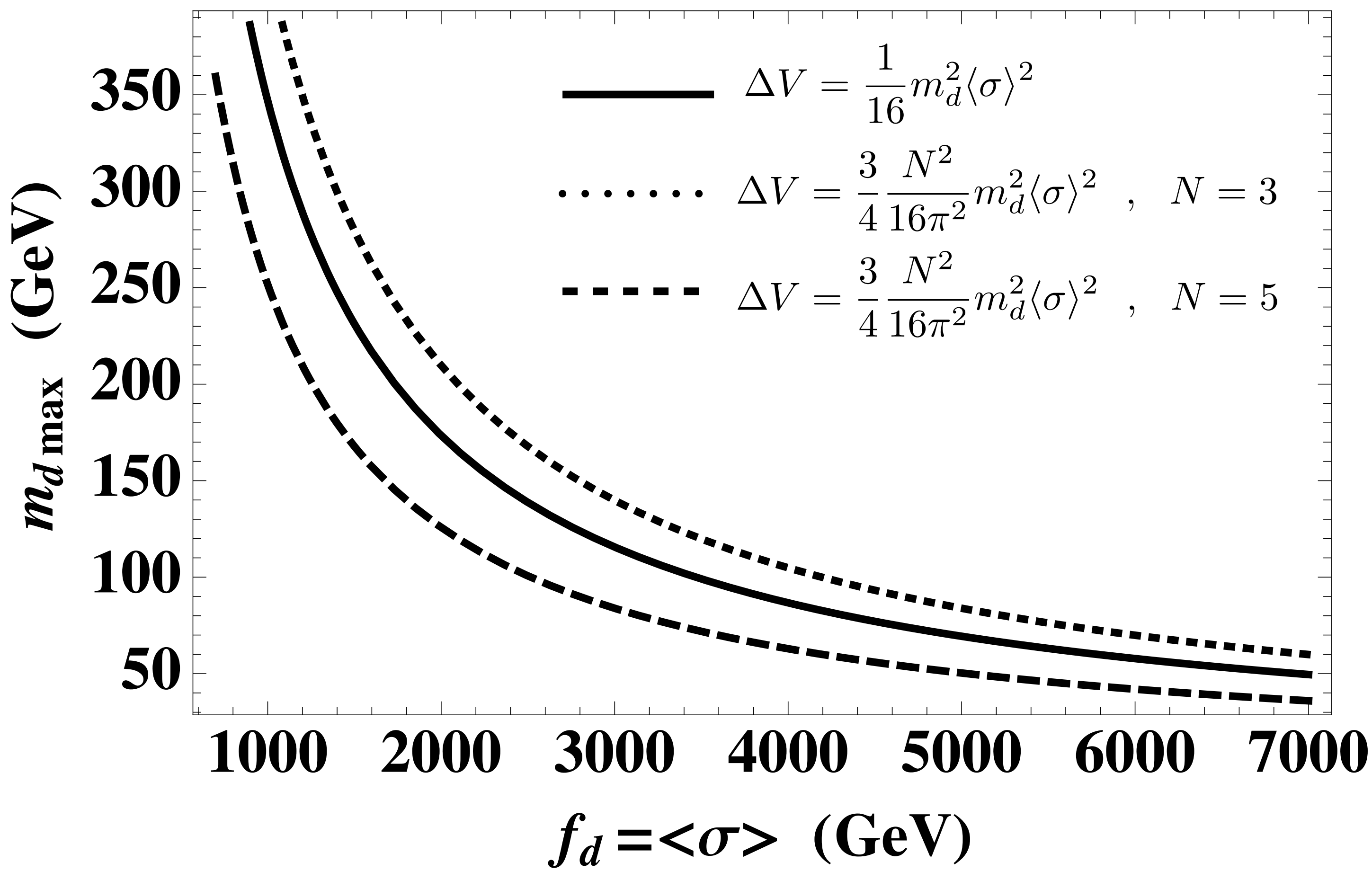
Reheat temperature below sphaleron freese-out temperature
to avoid washout

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

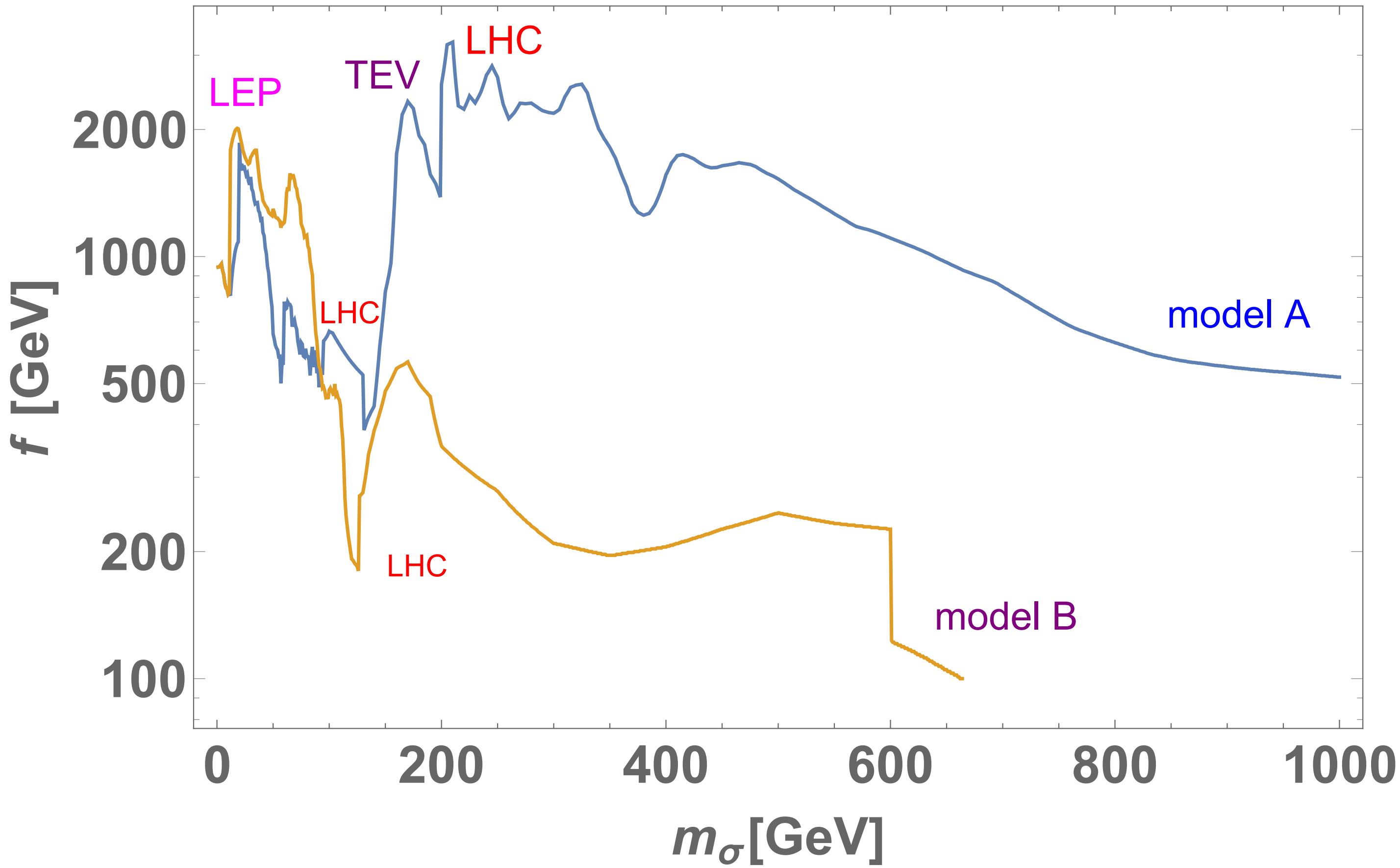
Coradeschi et al '13

Rattazzi Zaffaroni '01

cosmological consequences in

Servant-Konstandin '11

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



[1410.1873]

Summary

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)

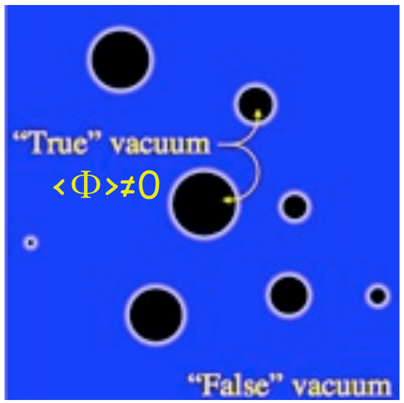
scenario testable at LHC : existence of a O(100) GeV Higgs-like dilaton

Usual DM predictions of QCD axions unaffected

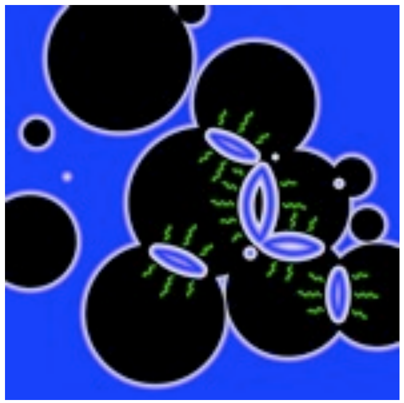
Smoking gun signature of a strongly first-order phase transition

Bubble nucleation

Bubble percolation



$\langle\Phi\rangle = 0$

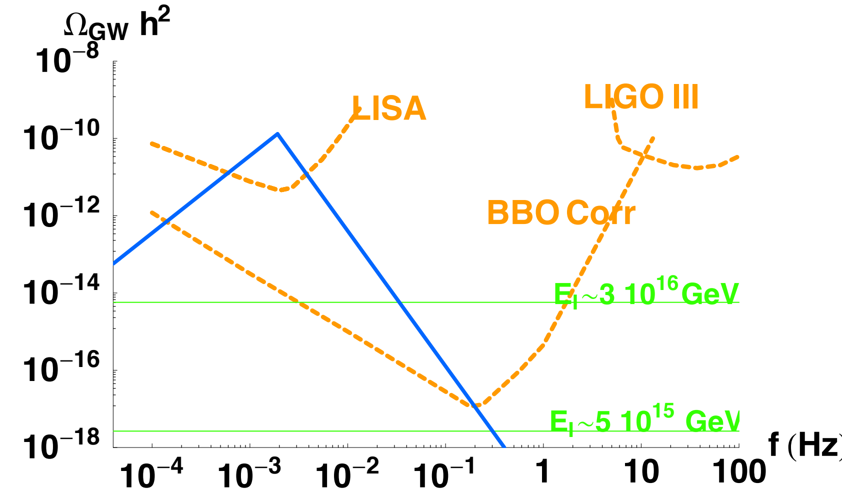


Fluid flows

turbulence

Magnetic fields

Stochastic background of gravitational radiation



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

characterizes amount of supercooling

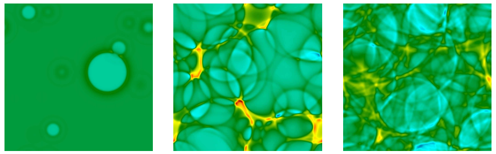
violent process if $v_b \sim O(1)$

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

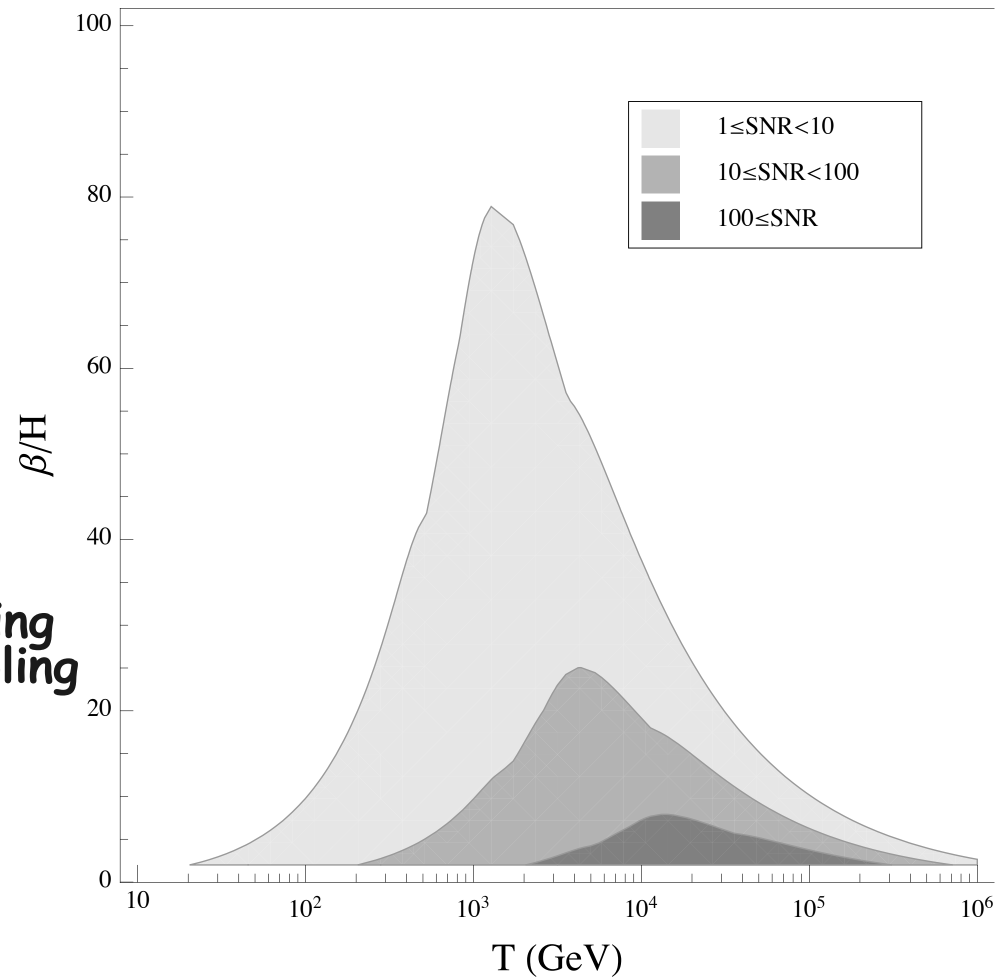
Grojean-Servant
hep-ph/0607107

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]

Conclusion

- 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)

Recent development on the Cosmology/axion/ Weak scale Connection

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.

No need for new degrees of freedom at the weak scale?