

# The Decline of Antimatter

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DESY/U.Hamburg

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# Matter Anti-matter asymmetry:

characterized in terms of the  
baryon to photon ratio

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

$$5.7 \leq \eta_{10} \leq 6.7 \text{ (95\%CL)}$$

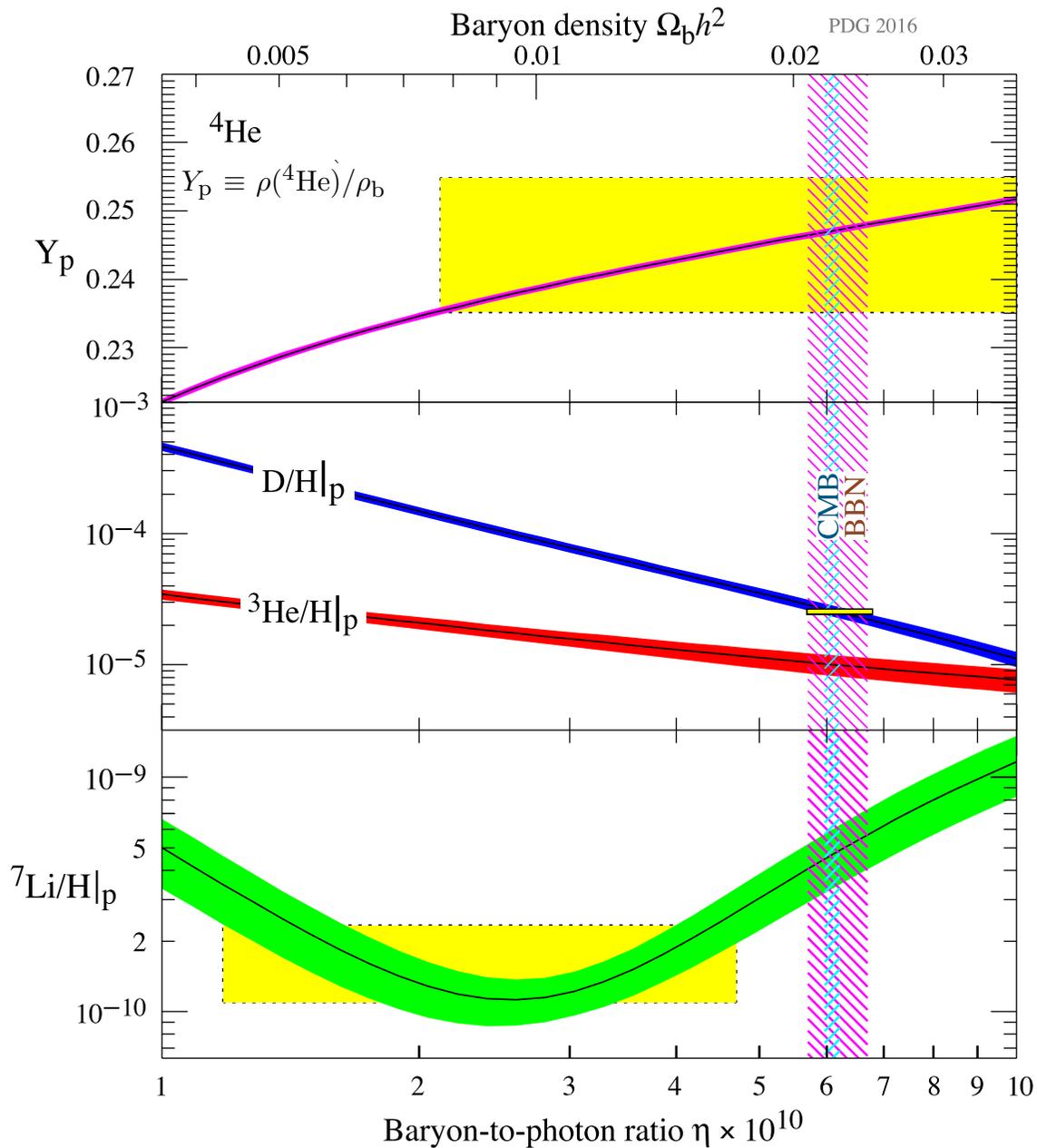
The great annihilation

10 000 000 001  
Matter

10 000 000 000  
Anti-matter

1  
(us)

$$\Omega_b = \rho_b / \rho_{\text{crit}} = 0.02207(27)h^{-2} = 0.0499(22)$$



The Baryon Asymmetry of the Universe (BAU) deduced from the Cosmic Microwave Background measurements is now more precise than the one deduced from Big Bang Nucleosynthesis ( $\text{D}/\text{H}$  abundance)

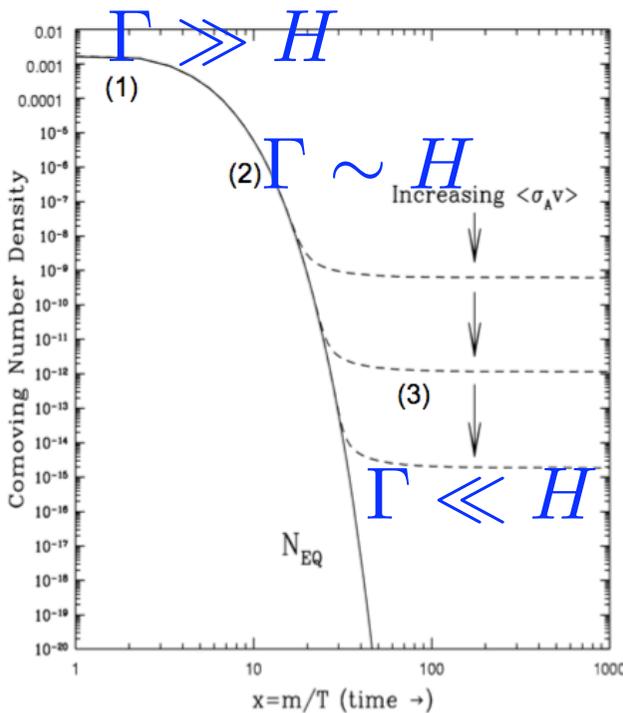
# Baryon asymmetry:

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

The great annihilation between nucleons & anti-nucleons



occurs when  $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T} / m_\pi^2 \sim H \sim \sqrt{g_*} T^2 / m_{Pl}$



corresponding to a freeze-out temperature  $T_F \sim 20$  MeV

In absence of an asymmetry:

$$\eta \approx 5 \times 10^{-19}$$

$10^9$  times smaller than observed,  
and there are no antibaryons  
 $\rightarrow$  need to invoke an initial asymmetry

# Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

2)  $C$  and  $CP$  violation

3) Loss of thermal equilibrium

we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass , so no asymmetry can develop

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$



# Baryon number violation in the Standard Model

It follows from the Electroweak anomaly

$$\partial_\mu j_B^\mu = N_F \frac{\alpha_W}{8\pi} \text{Tr} F \tilde{F}$$



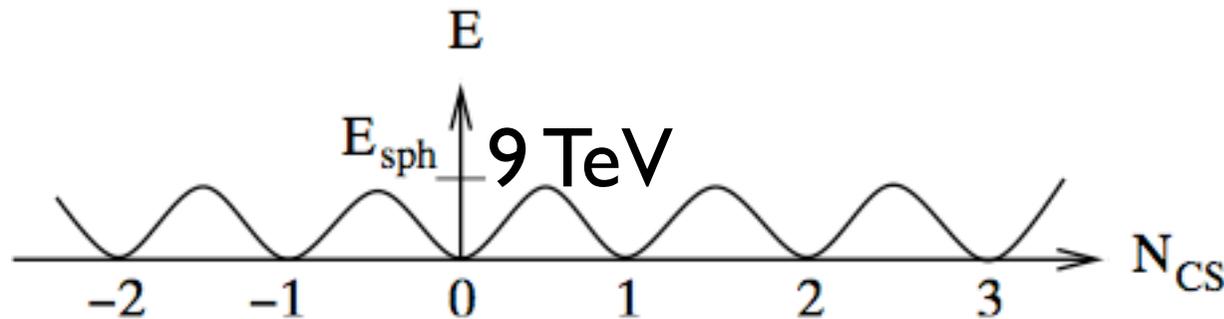
EW field strength

# Baryon number violation in the Standard Model

due to chirality + topology

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

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

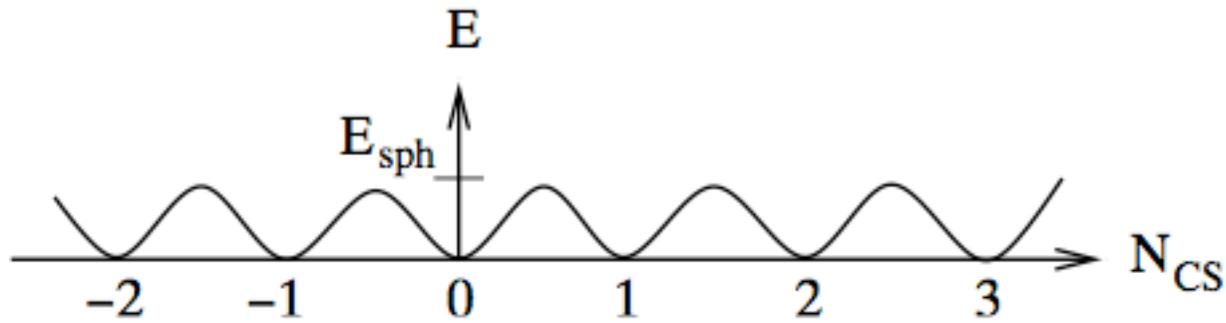


Energy of gauge field configuration as a function of Chern Simons number

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

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

⇒ Baryon number violation is totally suppressed in the SM at zero temperature but very efficient at high temperatures



Tunneling amplitude:  $\mathcal{A} \sim e^{-4\pi/\alpha_W} \sim 10^{-173}$

⇒ Baryon number violation is totally suppressed in  
the SM at zero temperature

# Rate of Baryon number violation in the Standard Model at finite temperature:

In the symmetric phase  $\Gamma \sim \alpha_W^4 T^4$

out-of-equilibrium condition:  $\alpha_W^4 T < T^2 / M_{\text{Pl}} \rightarrow T > 10^{12} \text{ GeV}$

In the broken phase  $\Gamma \sim v^4 e^{-c \langle \varphi \rangle / T}$

$$\text{(more precisely)} \frac{\Gamma}{V} = \text{const} \left( \frac{E_{\text{sph}}}{T} \right)^3 \left( \frac{m_W(T)}{T} \right)^4 T^4 e^{-E_{\text{sph}}/T}$$

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

out of equilibrium condition:  $\langle \varphi \rangle / T > 1$

$\eta$  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**

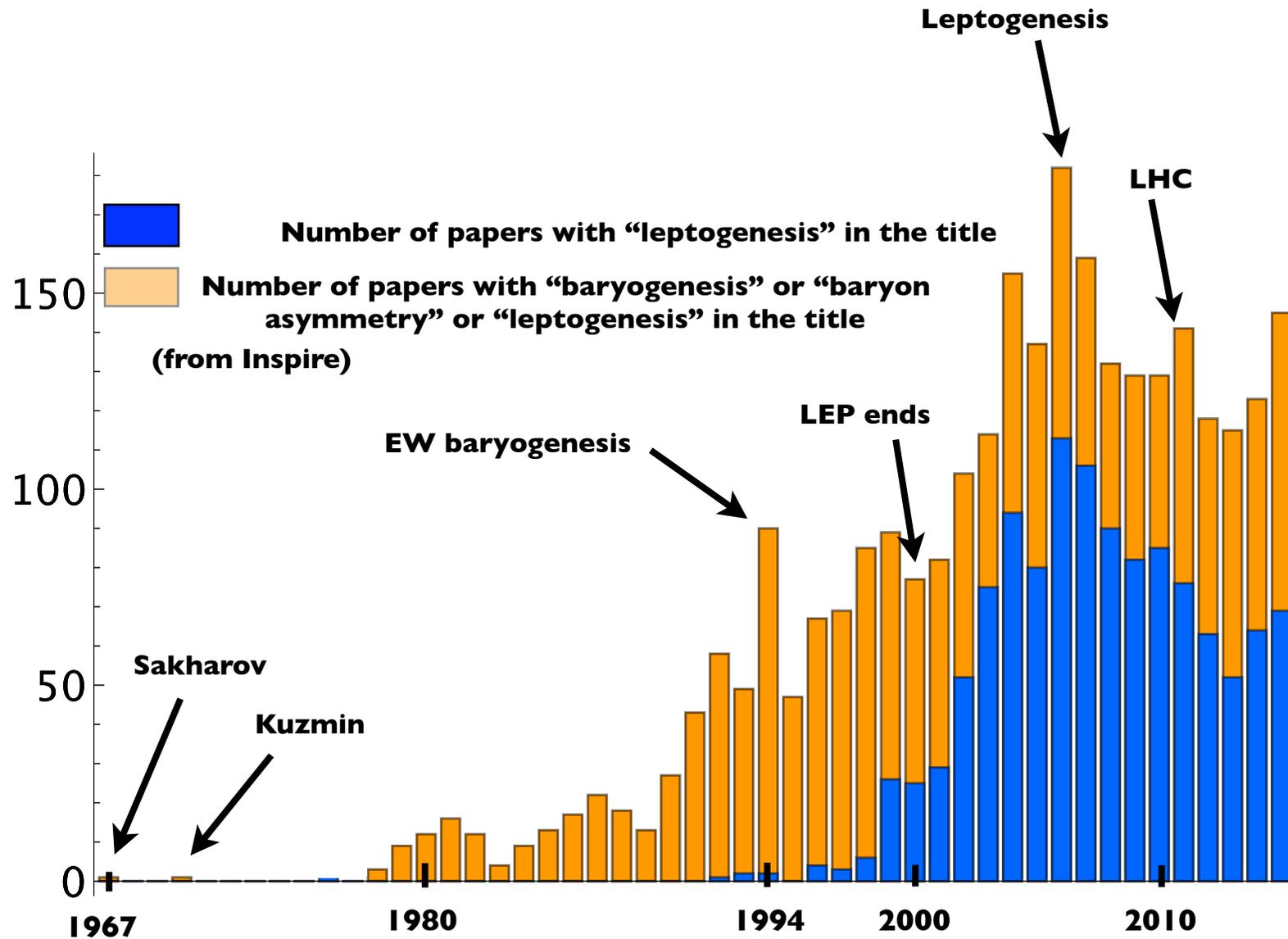
# Shaposhnikov,

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**

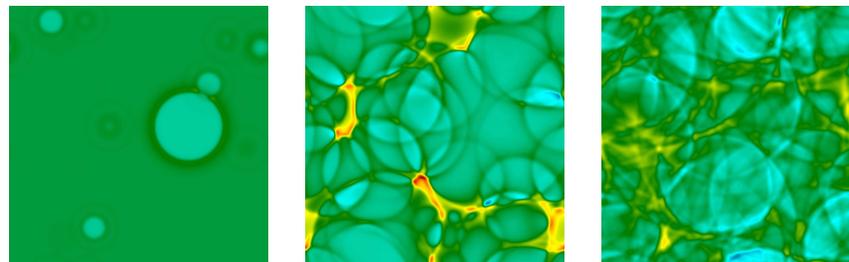
# History of baryogenesis papers



# 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  $B-L \neq 0$   
requires  $SO(10)$   
requires too high reheat  
temperature to produce  
enough GUT particles

→ leptogenesis

**Thermal leptogenesis**

hierarchy pb -> embed in susy ->  
gravitino pb (can be solved if  
 $M_{\text{gravitino}} > 100 \text{ TeV}$  and DM is  
neutralino or gravitino is stable)

**Affleck-Dine (moduli decay)**

**Non-thermal leptogenesis  
(via oscillations)**

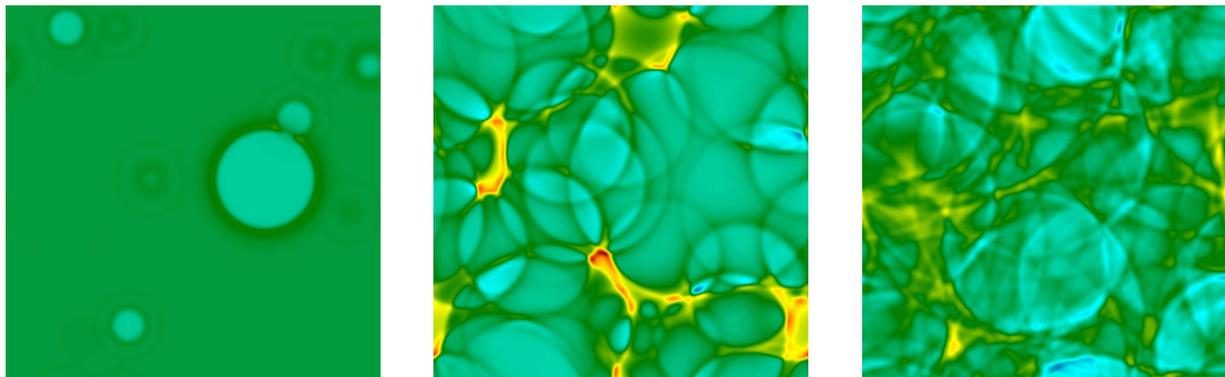
**Asymmetric dark matter-cogenesis**

**EW (non-local) baryogenesis**

**EW cold (local) baryogenesis**

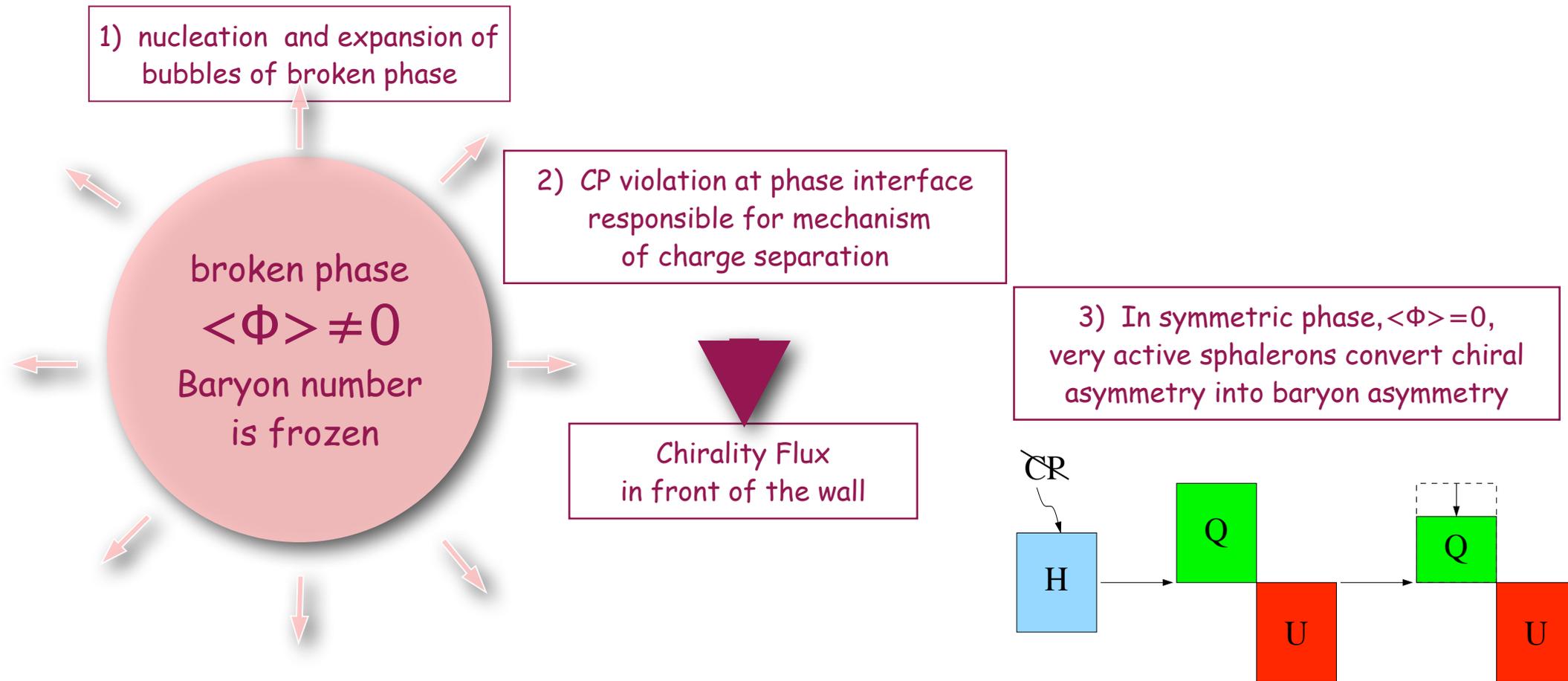
EW breaking,  
sphalerons  
freeze-out

# Baryogenesis at a first-order EW phase transition



# Baryon asymmetry and the EW scale

Cohen, Kaplan, Nelson'91

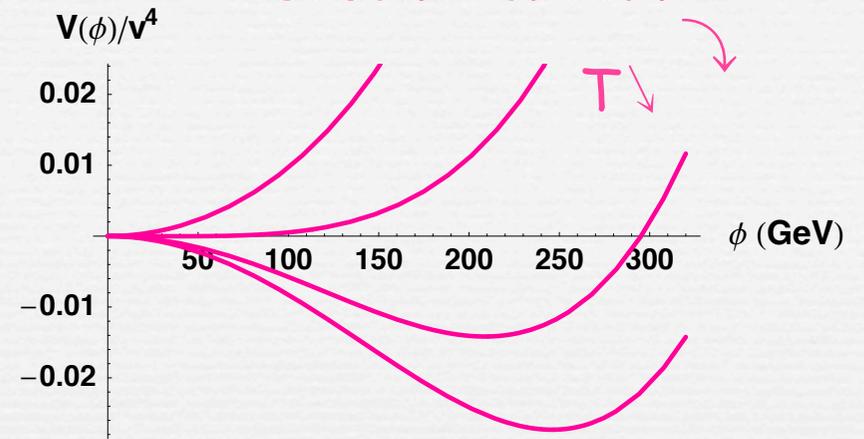
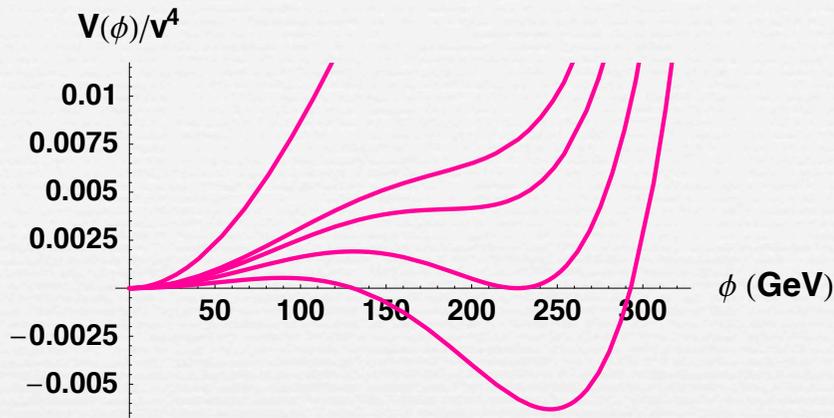


Electroweak baryogenesis mechanism relies on a first-order phase transition satisfying  $\frac{\langle \Phi(T_n) \rangle}{T_n} \gtrsim 1$

first-order

or

second-order?



In the SM, a 1st-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

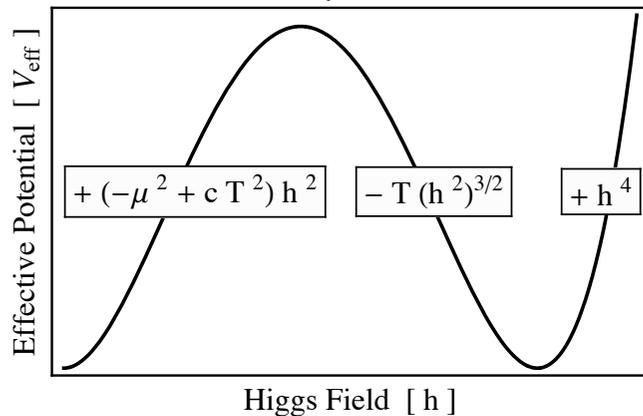
for  $M_H > 72$  GeV, no 1st order phase transition

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

Main effect due to the stop

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 !

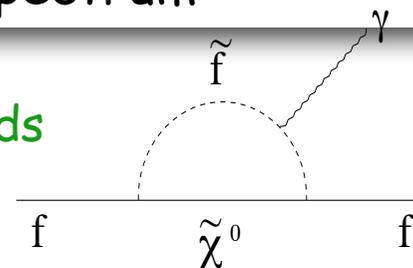
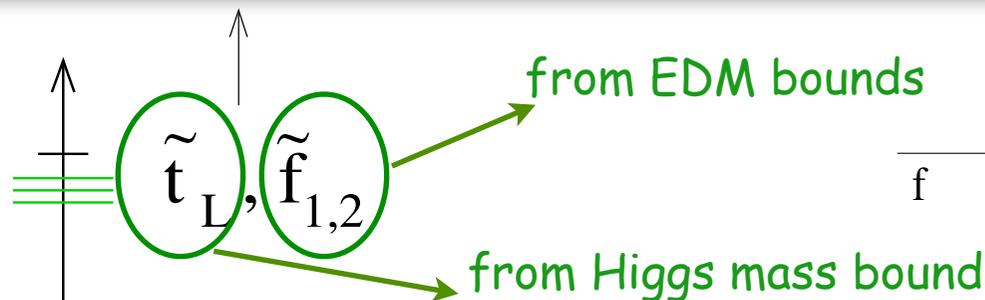
Katz, Perelstein '14

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

# The (former) EW baryogenesis window in the Minimal Supersymmetric Standard Model: A Stop-split supersymmetry spectrum

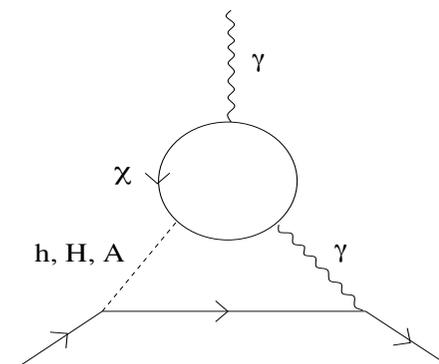
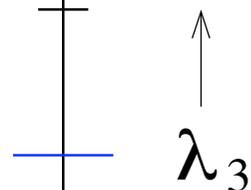
10 TeV



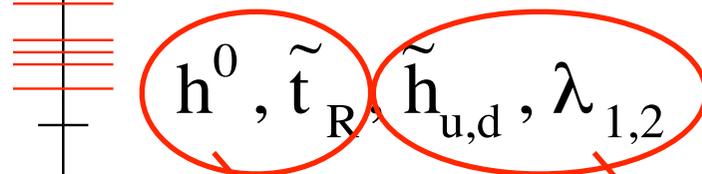
excluded by recent higgs measurements and stop searches

see 1207.6330

1 TeV



0.1 TeV



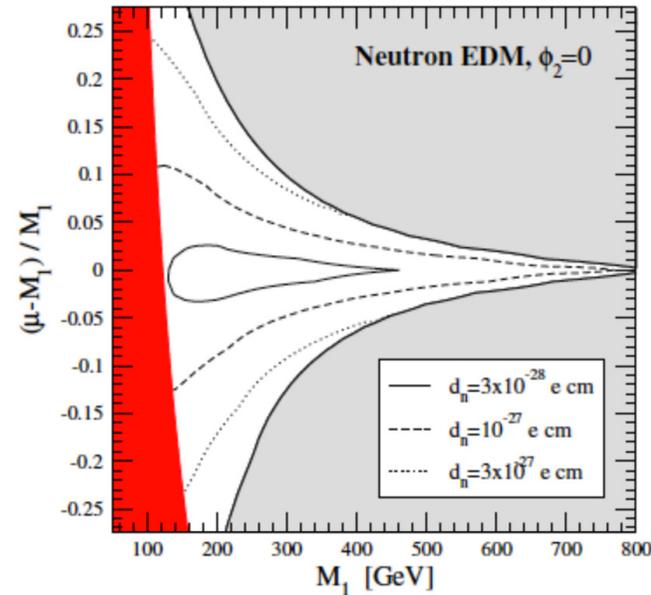
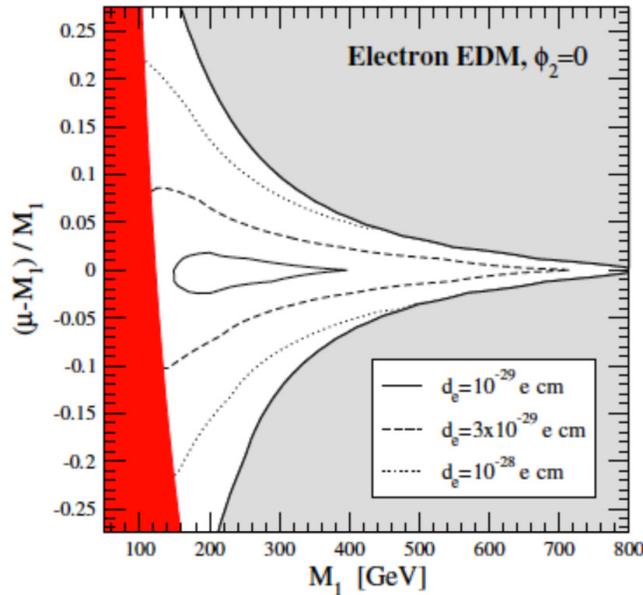
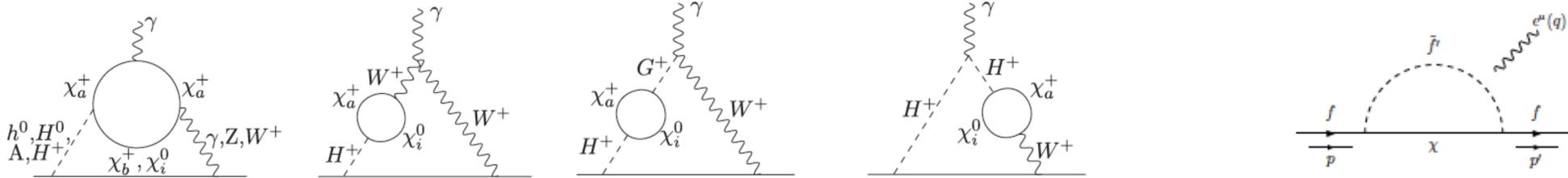
for strong 1st order phase transition

for sufficient CP violation  $\propto Im(\mu M_2)$

The light stop scenario: testable at the LHC

bounds get relaxed when adding singlets or in BSSM

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



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

versus

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

$$|d_e| < 8.7 \times 10^{-29} \text{ e cm} \quad @ 90\%CL$$

[1310.7534]

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

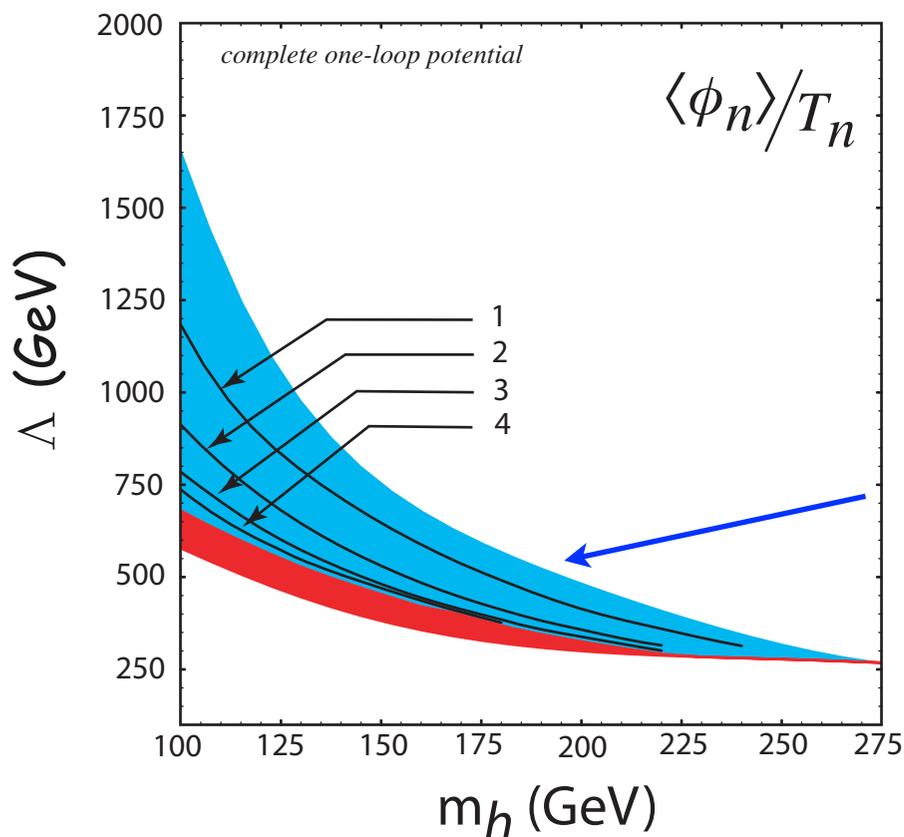
Easily seen in effective field theory approach:

Add a non-renormalizable  $\Phi^6$  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  $\Lambda \lesssim 1.3 \text{ TeV}$



region where EW phase transition is 1st order

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

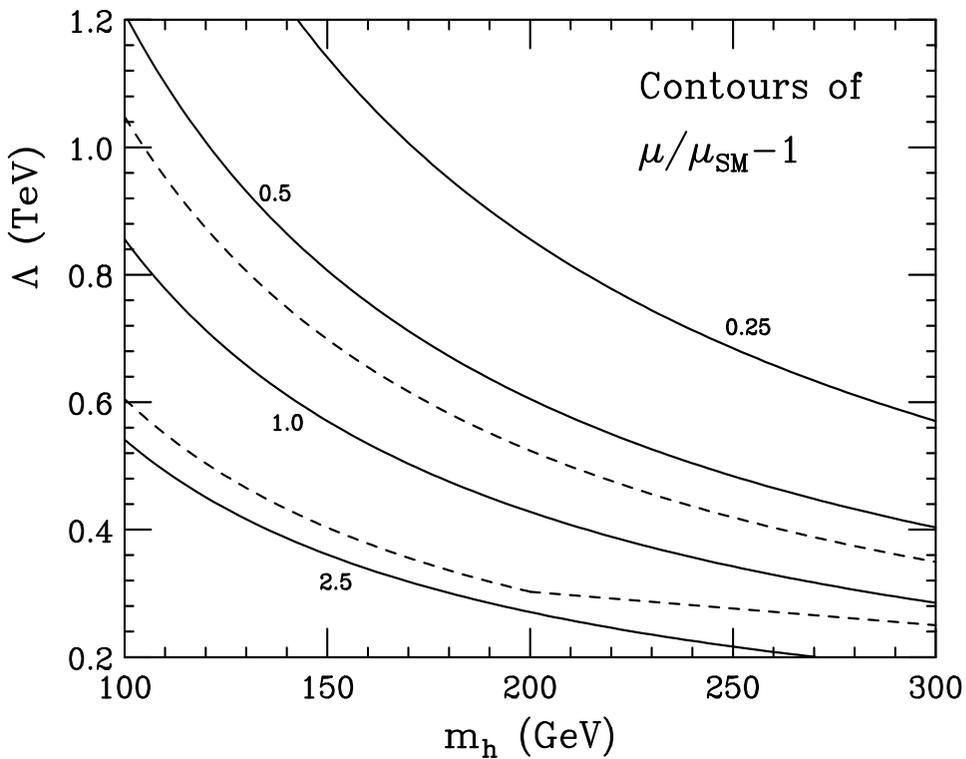
# but Typically large deviations to the Higgs self-couplings

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

where

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

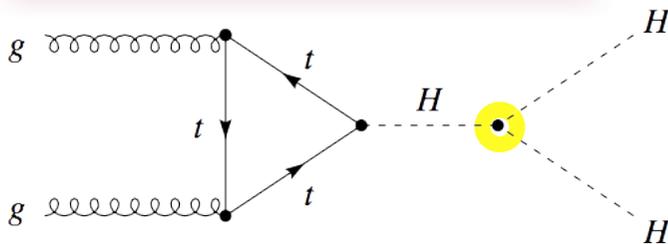
$$\eta = 3 \frac{m_H^2}{v_0^2} + 36 \frac{v_0^2}{\Lambda^2}$$



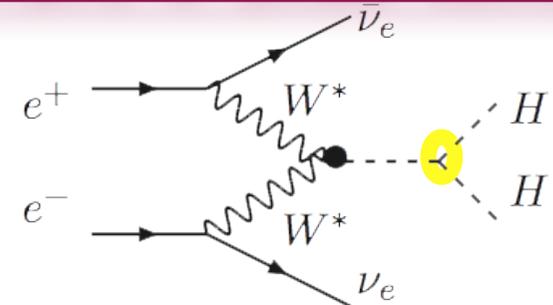
The dotted lines delimit the region for a strong 1st order phase transition

deviations between a factor 0.7 and 2

## at a Hadron Collider



## at an e<sup>+</sup> e<sup>-</sup> Linear Collider

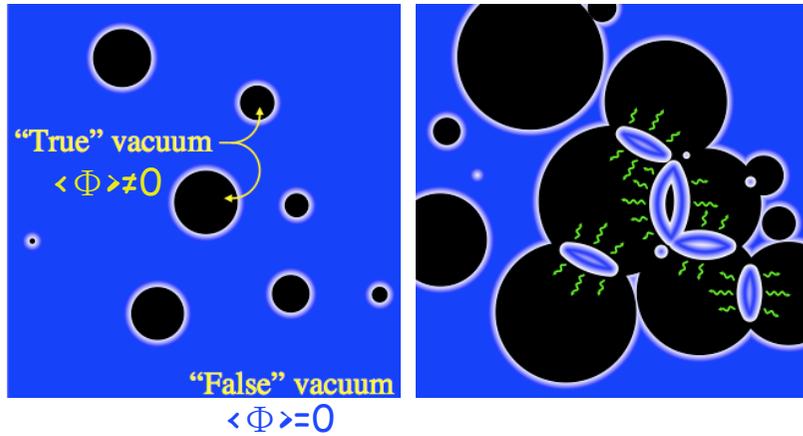


# Gravity wave signals from 1st order cosmological phase transitions

[eLISA Cosmology Working group, 1512.06239]

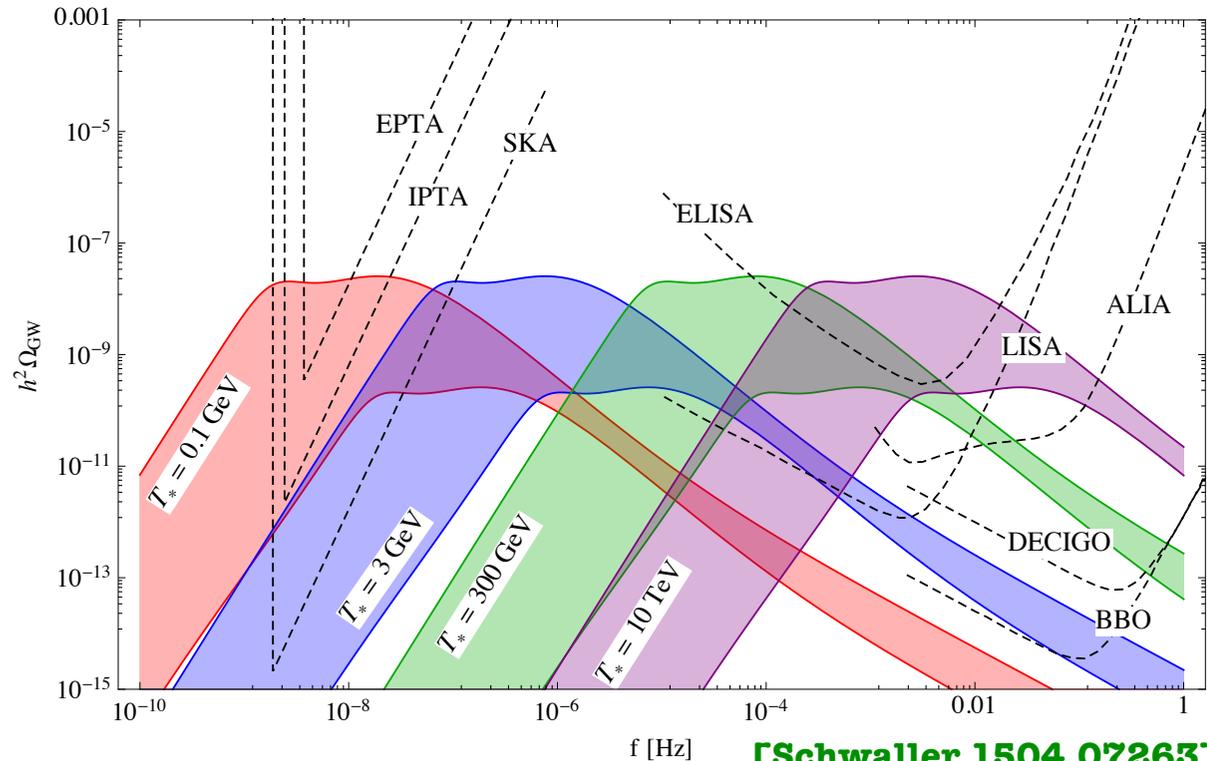
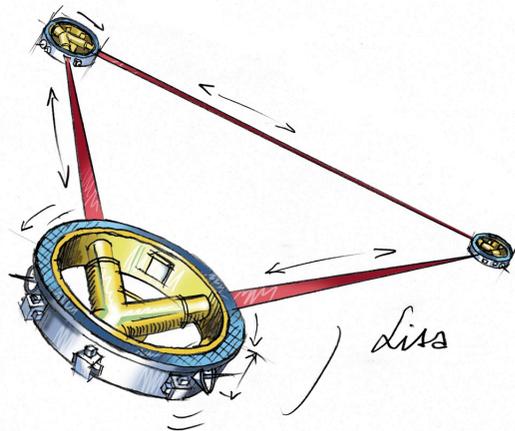
Bubble nucleation

Bubble percolation



Stochastic background of gravitational radiation

EW phase transition  
 -> mHz -> eLISA!



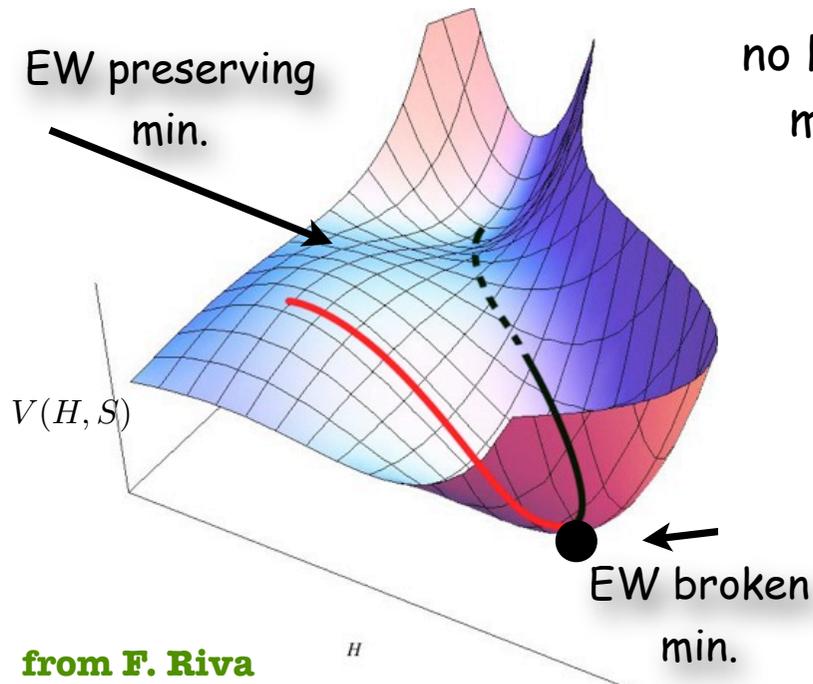
[Schwaller 1504.07263]

# 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:

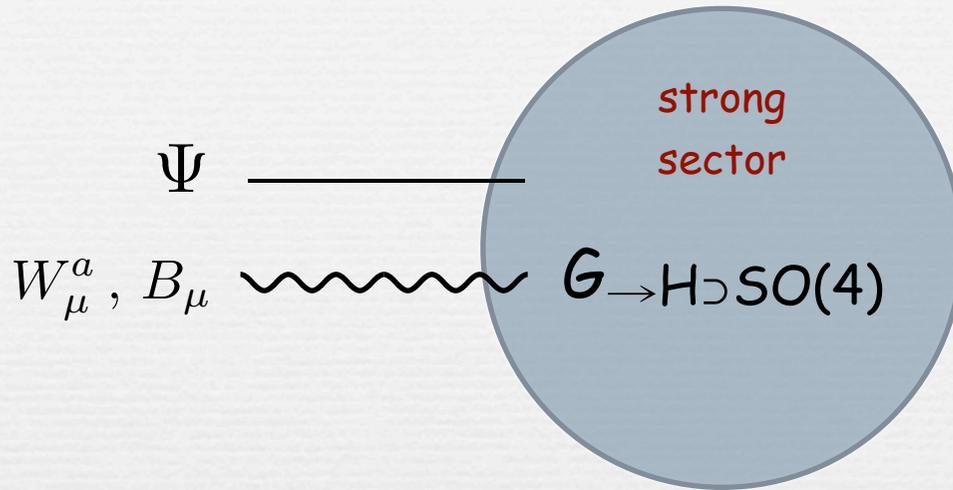
no Higgs- $S$  mixing  $\rightarrow$  no EW precision tests, tiny modifications of higgs couplings at colliders

**Poorly constrained**

$\rightarrow$  Espinosa et al, 1107.5441

Easy to motivate additional scalars, e.g:

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



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

custodial  $SO(4) \cong SU(2) \times SU(2)$

to avoid large corrections to the T parameter

$G$	$H$	$N_G$	NGBs rep. $[H] = \text{rep.}[SU(2) \times SU(2)]$
SO(5)	SO(4)	4	$4 = (\mathbf{2}, \mathbf{2})$ <b>-&gt; Agashe, Contino, Pomarol'05</b>
SO(6)	SO(5)	5	$5 = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	$SO(4) \times SO(2)$	8	$4_{+2} + \bar{4}_{-2} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$6 = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$G_2$	7	$7 = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$SO(5) \times SO(2)$	10	$10_0 = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[SO(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
Sp(6)	$Sp(4) \times SU(2)$	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
SU(5)	$SU(4) \times U(1)$	8	$4_{-5} + \bar{4}_{+5} = 2 \times (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	14	$14 = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$



Another easy way to get a strong 1st-order PT:  
dilaton-like potential naturally leads to supercooling

Konstantin Servant '11

not a polynomial

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

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  $\sigma^\epsilon$  term

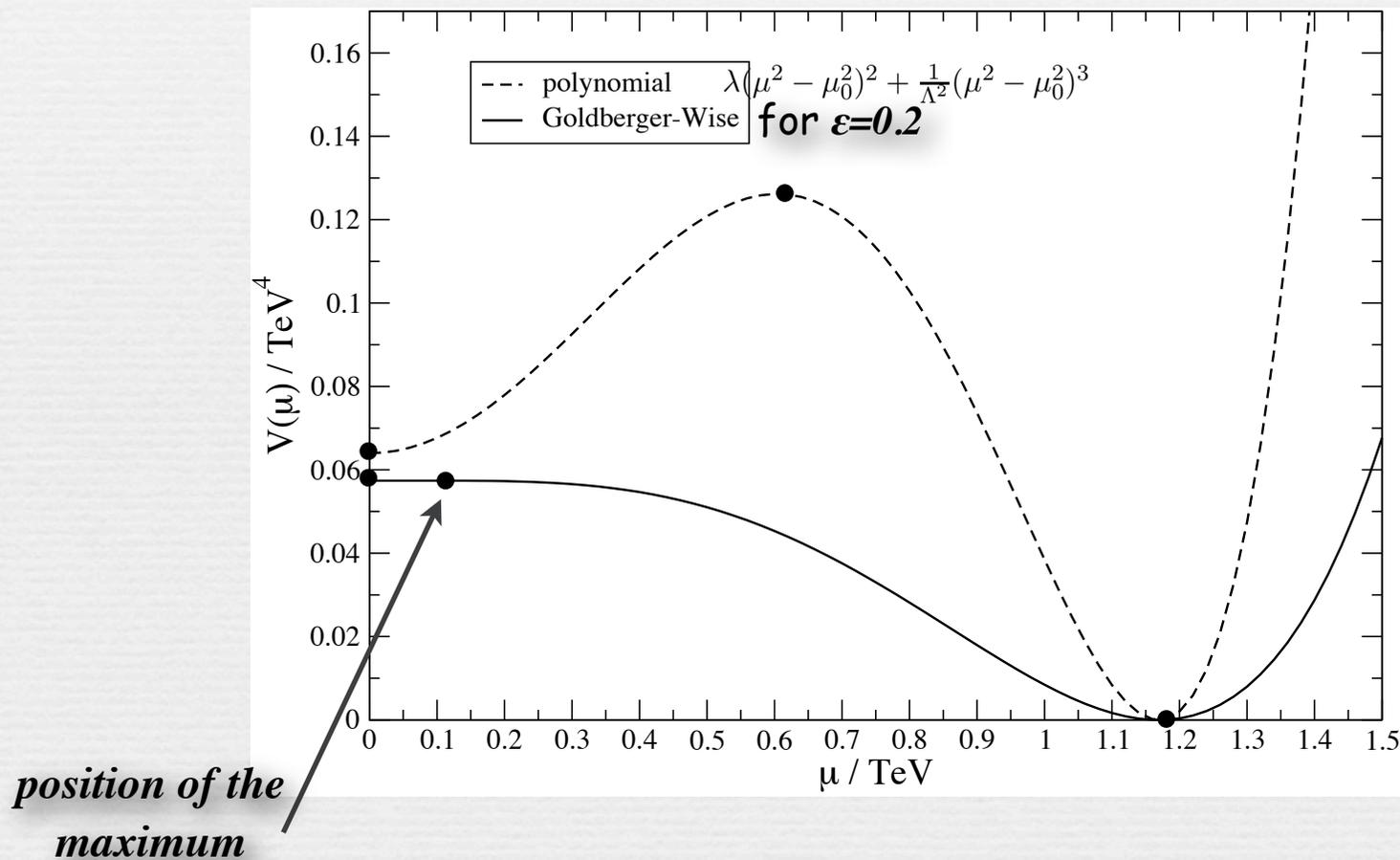
for  $|\epsilon| \ll 1$

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**

$$V(\mu) = \mu^4 P((\mu/\mu_0)^\epsilon). \quad \text{Konstandin Servant '11}$$

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



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

Application:

# Baryogenesis from Strong CP violation

1407.0030

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

today  $|\bar{\Theta}| < 10^{-11}$  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?

Application:

# Baryogenesis from the QCD axion

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

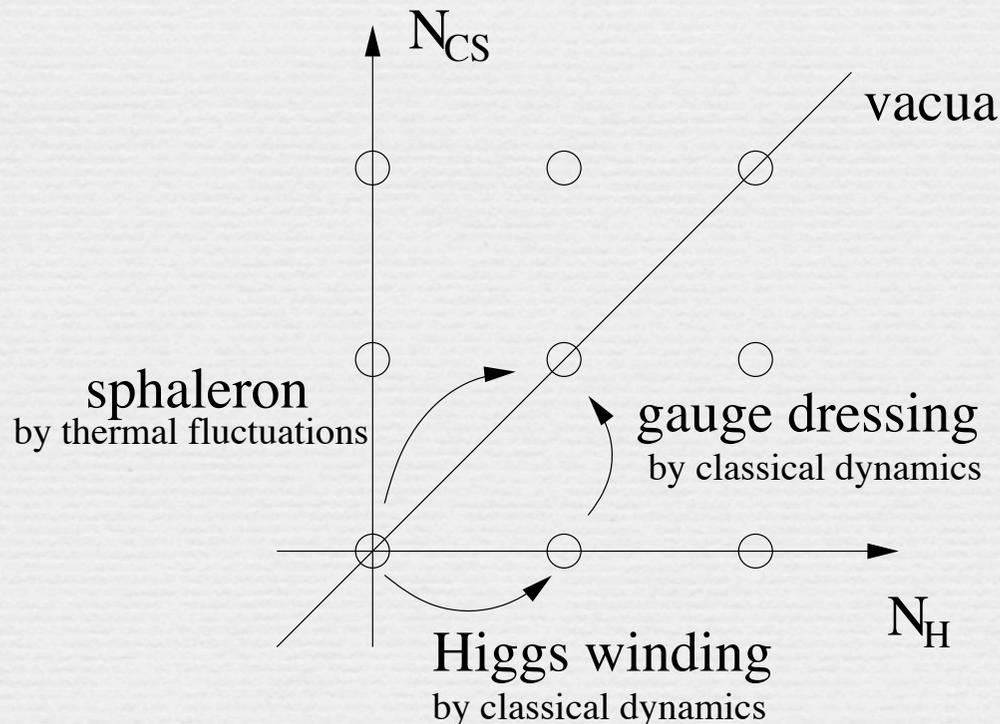
During quenched EWPT,  $SU(2)$  textures can be produced.  
They can lead to  $B$ -violation when they decay.

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:**

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

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

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

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

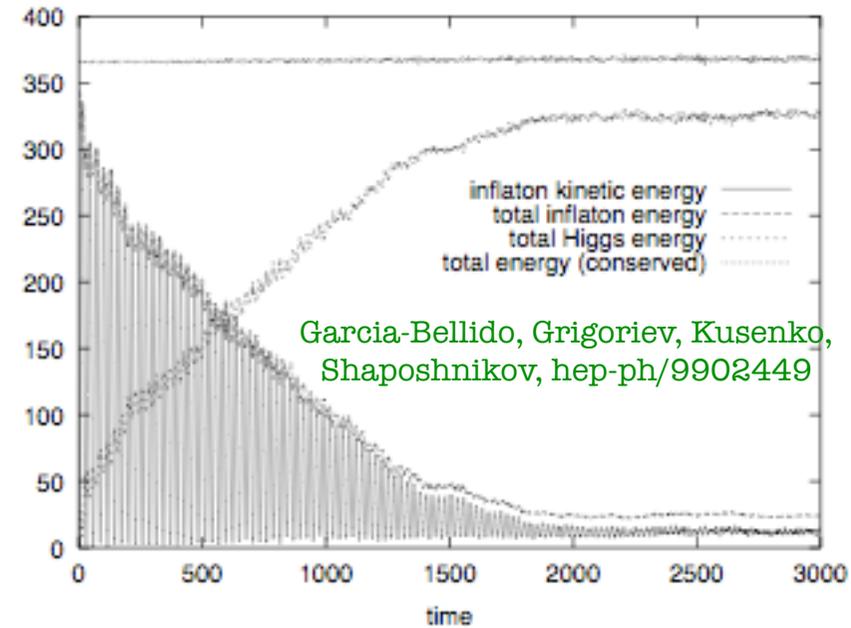
**In vacuum:  $N_H = N_{CS}$**

# 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

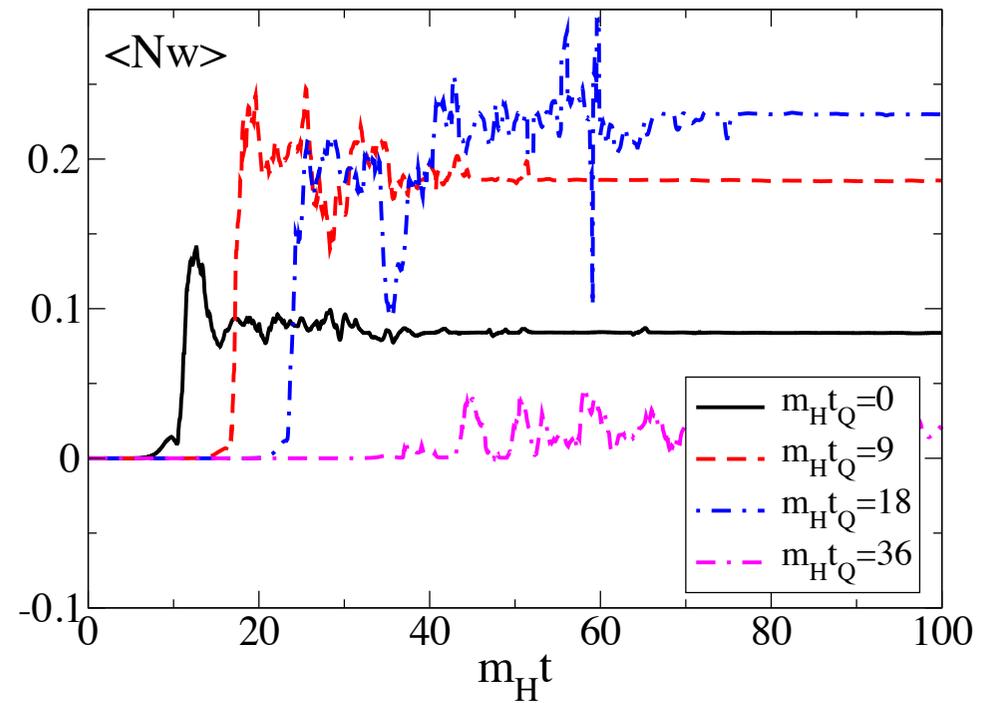
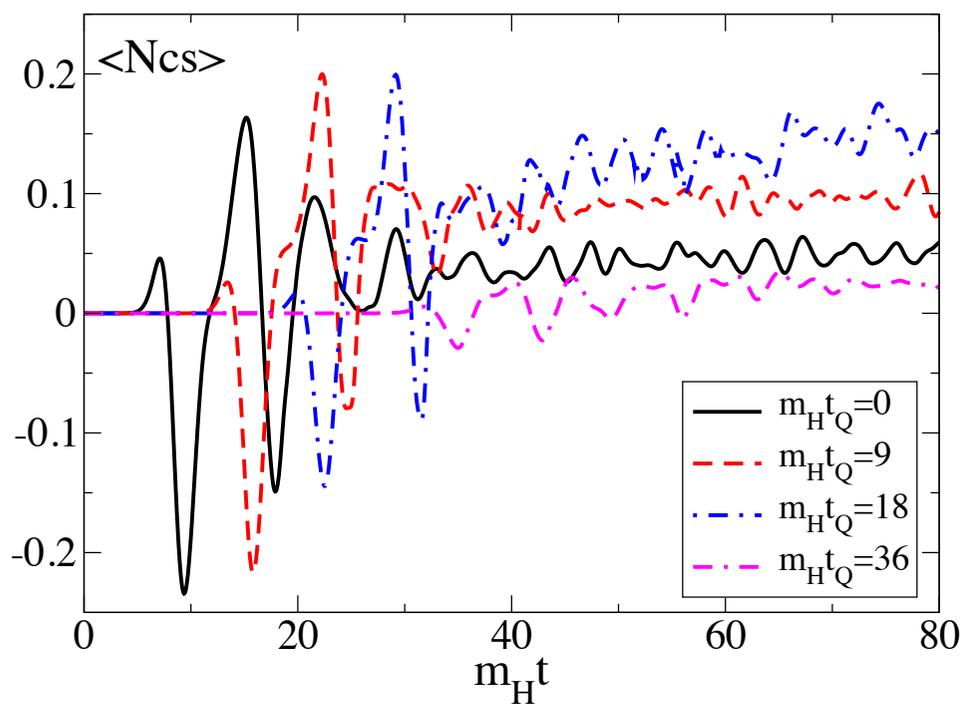


Higgs mass squared is not turning negative as a simple consequence of the cooling of the universe but because of its coupling to another field which is rolling down its potential. The Higgs is "forced" to acquire a vev by an extra field → Higgs quenching

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

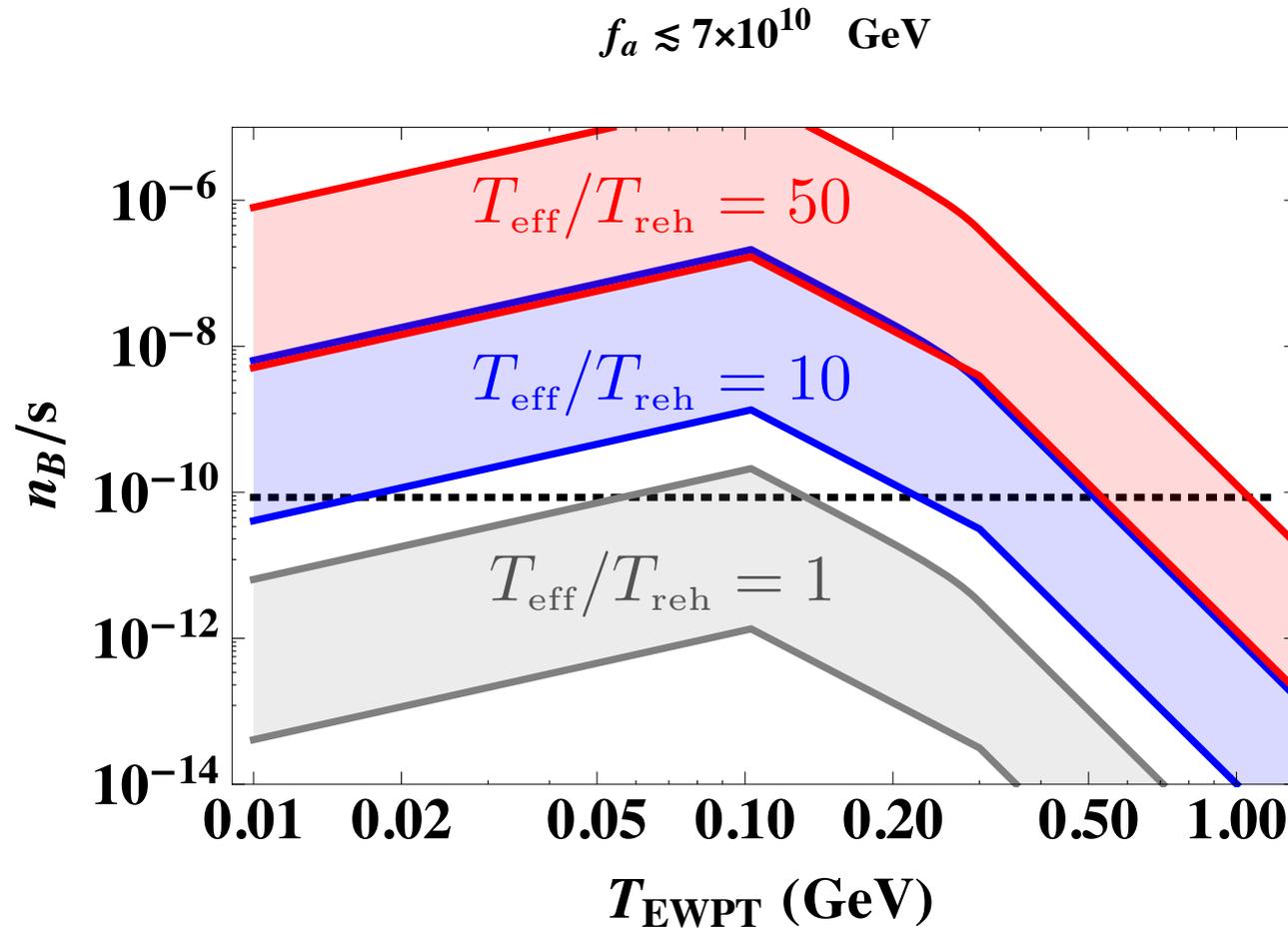
Cold baryogenesis has been simulated on the lattice



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

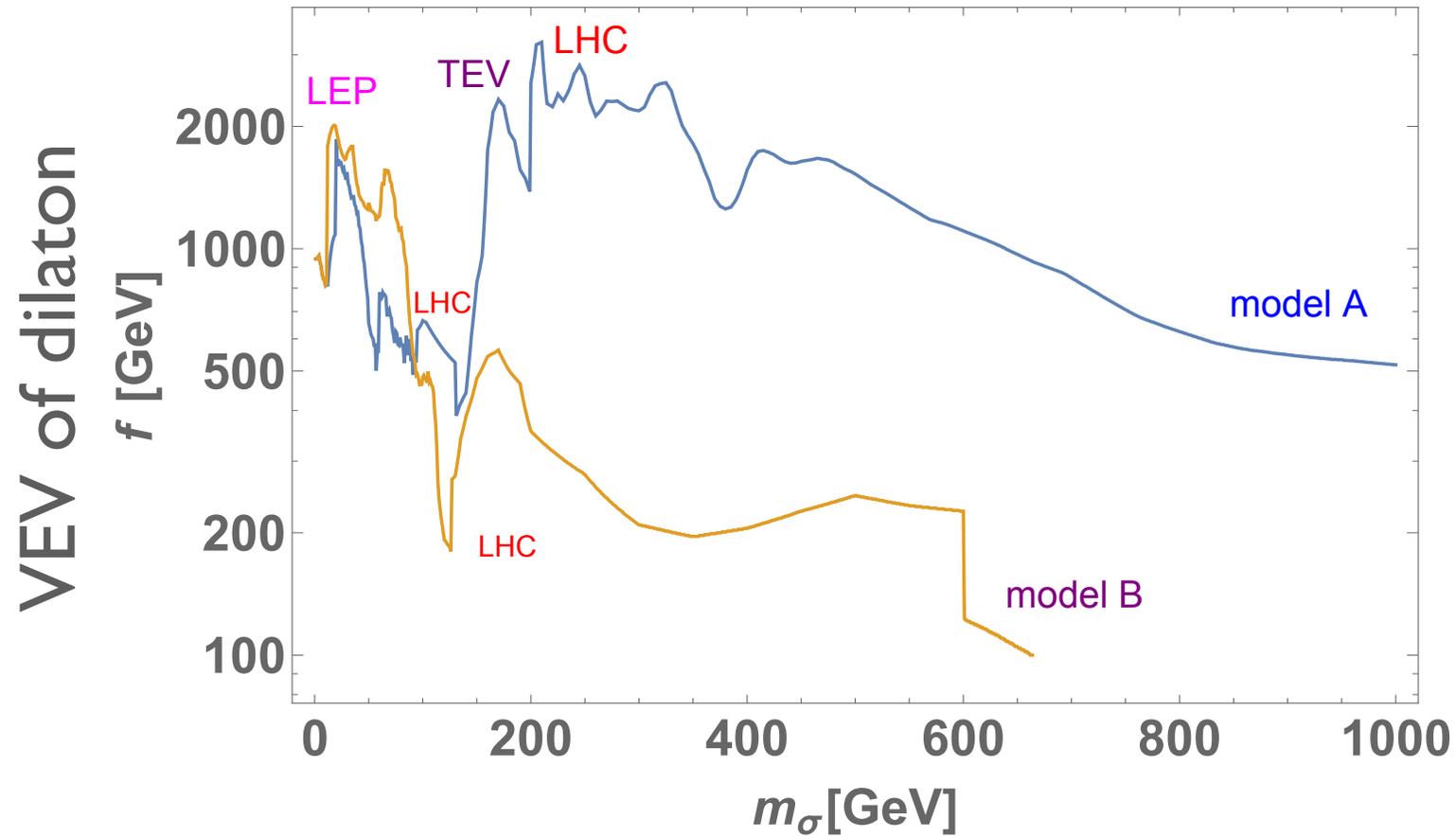
Axion dynamics during a supercooled EW phase transition can lead to baryogenesis

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 scalar:** 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 loss 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

$$y_{ij} \bar{f}_L^i \Phi^{(c)} f_R^j$$

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

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

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

3) Partial fermion compositeness in composite Higgs models

may be  
related by  
holography

**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

$$y_{ij} \bar{f}_L^i \Phi^{(c)} f_R^j$$

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

$$y_{ij} \sim \left( \langle \chi \rangle / M \right)^{-q_i + q_j + q_H} \quad \leftarrow \text{flavor charges of the fermions}$$

$$\lambda = \langle \chi \rangle / M \sim 0.22 \quad \longrightarrow \quad \begin{array}{lll} Y_t \sim 1, & Y_c \sim \lambda^3, & Y_u \sim \lambda^7, \\ Y_b \sim \lambda^2, & Y_s \sim \lambda^4, & Y_d \sim \lambda^6, \\ s_{12} \sim \lambda, & s_{23} \sim \lambda^2, & s_{13} \sim \lambda^3. \end{array}$$

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 “Flavon” 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.

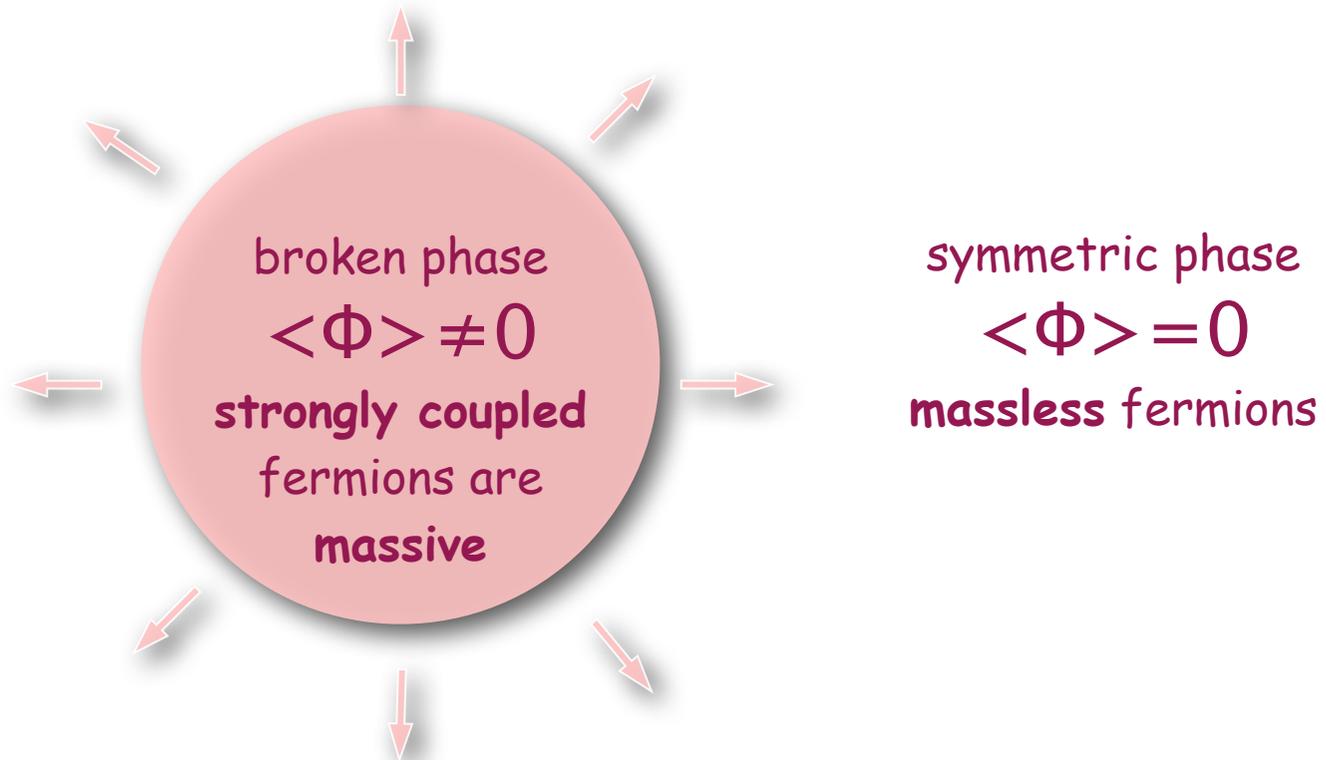
We do not need to specify the dynamics responsible for the evolution of the Yukawas to derive the nature of the EWPT.

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

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

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



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**

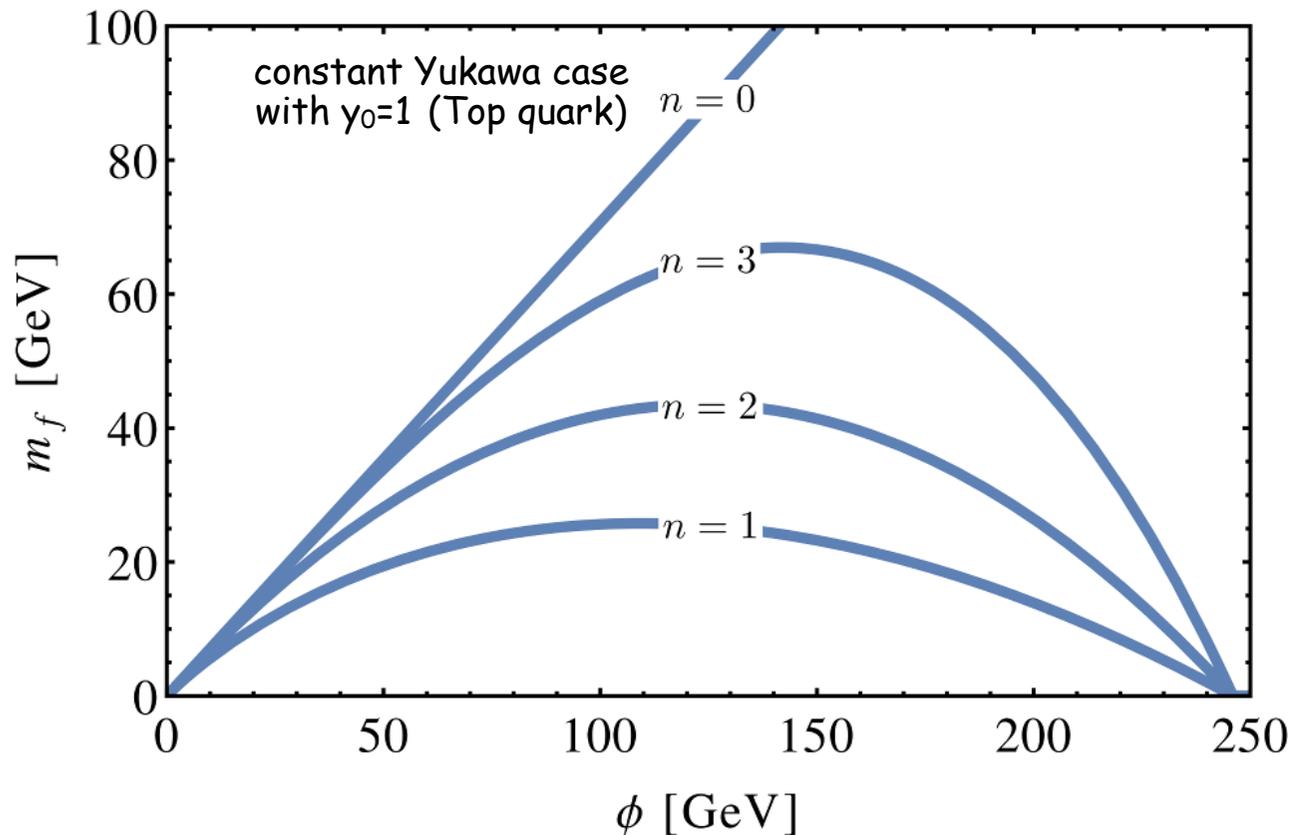
Although these do not create a thermal barrier on their own, they can lead to a decrease in  $g^*$  between the symmetric and broken phases and hence delay and strengthen the phase transition.

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

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

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



$y_0$ : Yukawa value today  
 $y_1$ : Yukawa value before the EW phase transition

# High Temperature Effective Higgs Potential

At one-loop:

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

tree  
level  
piece

l-loop  
T=0  
piece

l-loop  
T≠0  
piece

Daisy  
resummation  
piece

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

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

A large fermionic mass significantly lowers  $V_1^0$  between  $\Phi=0$  and  $\Phi=v$ . 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:

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

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

High-T expansion:

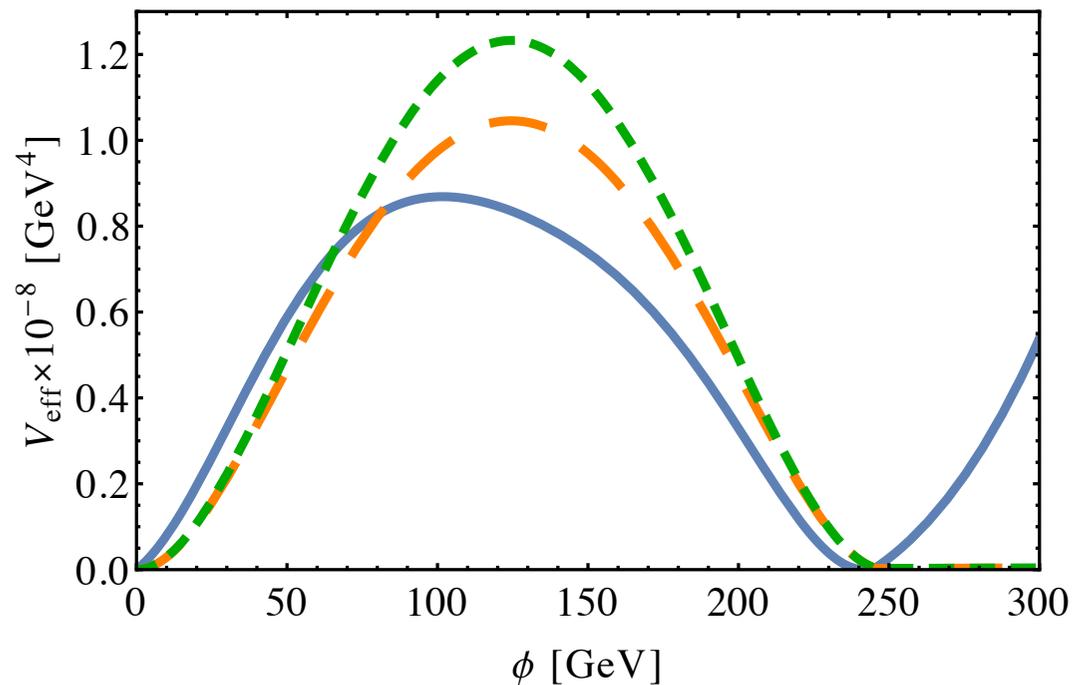
$$J_f(x^2) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24} x^2 - \frac{x^4}{32} \text{Log} \left[ \frac{x^2}{13.9} \right]$$

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

**Fermionic fields create a barrier!**

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

$$\delta V \approx \frac{gy_1^2\phi^2T^2}{96} \left( 1 - 2\frac{\phi}{v} + \frac{\phi^2}{v^2} \right)$$



— full potential

- - - thermal contribution only

- - - thermal contribution only with high-T expansion

### 3) Effects from the Daisy correction:

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

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

sum is over bosons

  
thermal mass

Consider the contribution from the Higgs:

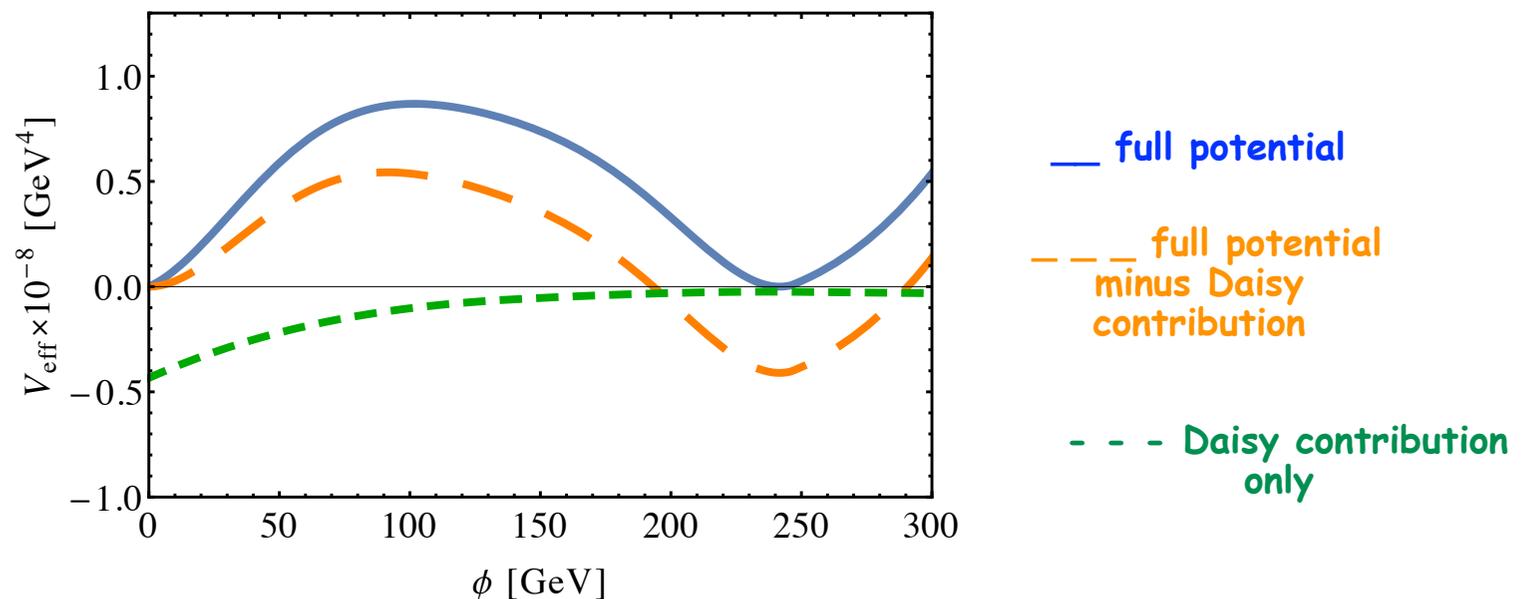
$$V_{\text{Daisy}}^\phi(\phi, T) = \frac{T}{12\pi} \left\{ m_\phi^3(\phi) - [m_\phi^2(\phi) + \Pi_\phi(\phi, T)]^{3/2} \right\}$$
$$\Pi_\phi(\phi, T) = \left( \frac{3}{16} g_2^2 + \frac{1}{16} g_Y^2 + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{gy(\phi)^2}{48} \right) T^2$$

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

### 3) Effects from the Daisy correction:

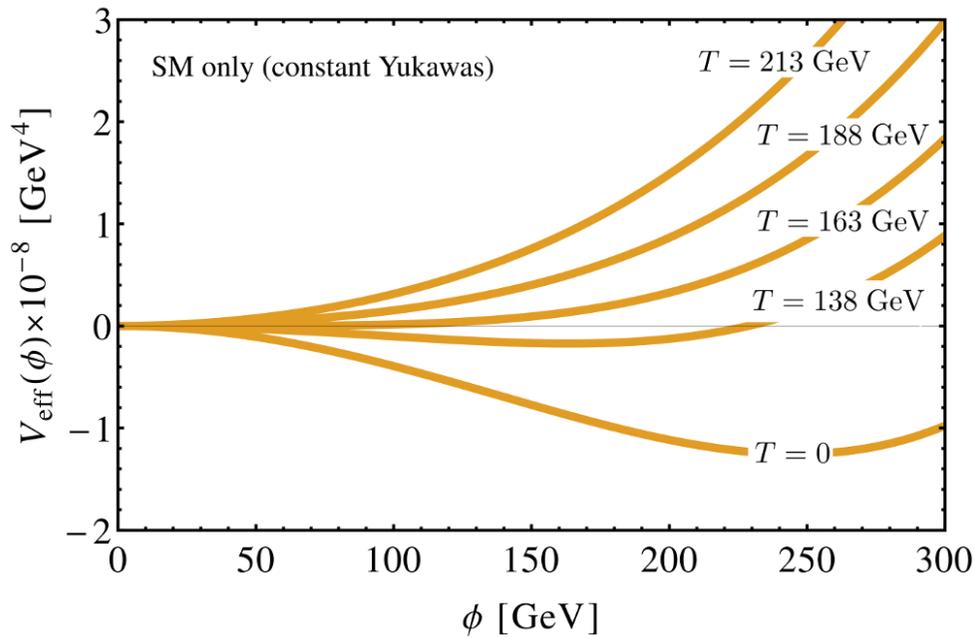
The effect is to lower the effective potential at  $\Phi = 0$ , with respect to the broken phase minimum.

By lowering the potential at  $\Phi = 0$ , the phase transition is delayed and strengthened.

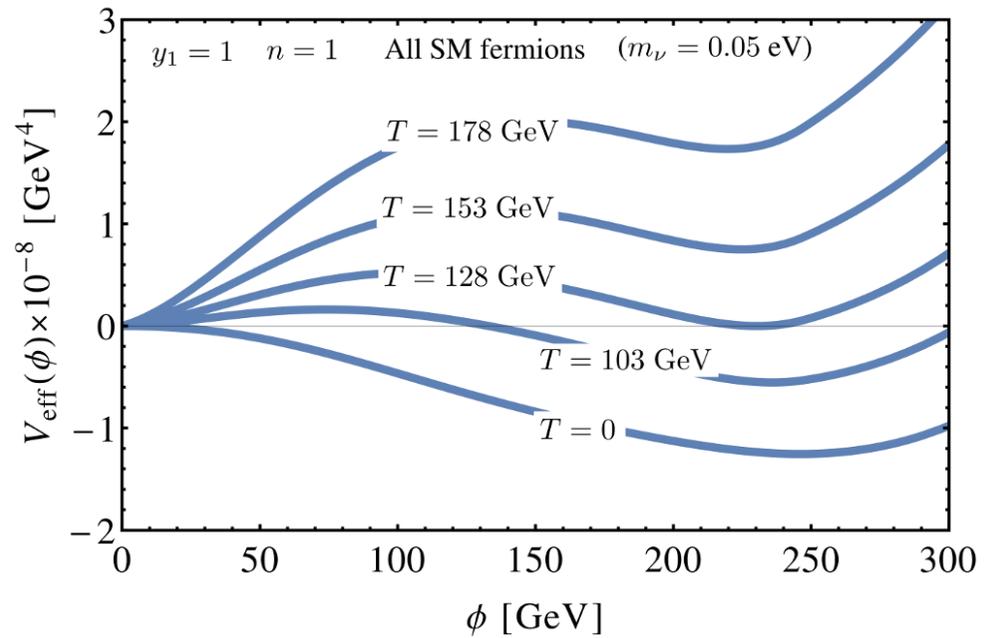


# Full one-loop effective Higgs potential with Daisy Resummation

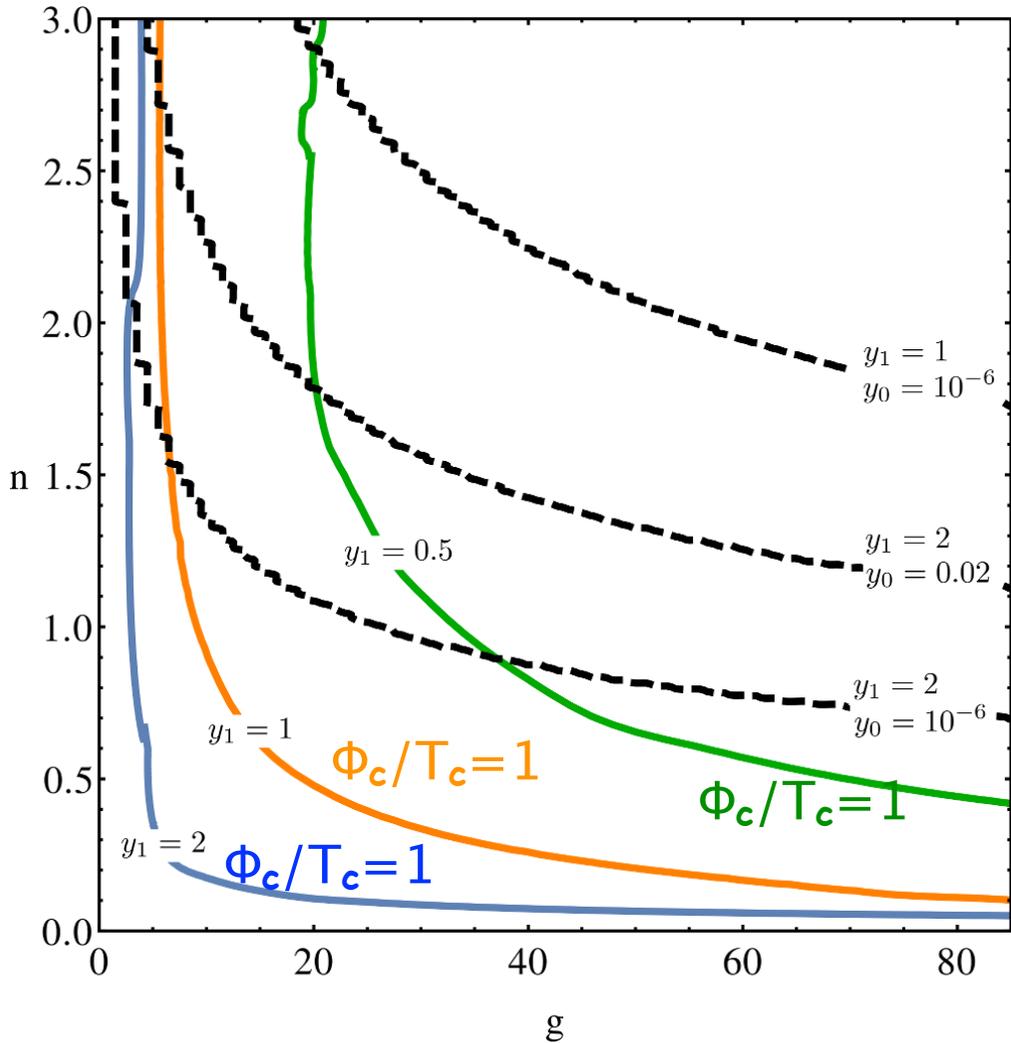
**Standard Case  
(Constant Yukawas)**



**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 !

**Bruggisser, Konstandin,  
Servant, to appear**

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

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

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 Electric Dipole Moment constraints and can be well-motivated theoretically. We provided 2 examples: strong  $CP$  from QCD axion, weak  $CP$  from dynamical CKM matrix