Baryogenesis from a Supercooled Phase Transition
in Randall-Sundrum Models

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Baryogenesis Confronts the Experiment
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Outline

The outline of this talk is [1]

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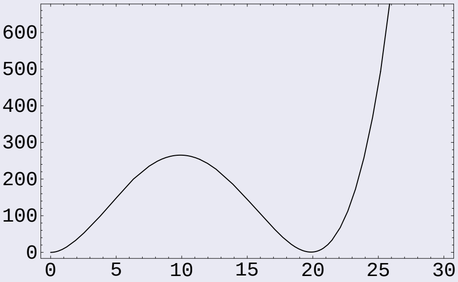
- Introduction
- Two phases of the RS model at finite temperature
- Adding the GW field
- Adding the Higgs field
- Supercooled phase transition
- Numerical results
- EWBG
- Conclusion

[1] Based on work done in collaboration with Germano Nardini and Andrea Wulzer, arXiv:0706.3388

Introduction

- In the Standard Model the Electroweak Phase Transition is extremely weak at the perturbative level [2]

At one-loop with $m_H = 125\,GeV$, $T \simeq 170\,GeV$ and $\langle\phi(T_c)\rangle/T_c \sim 0.12$



[2] It is so weak that it disappears (becomes a continuous cross-over) non-perturbatively

- This extreme weakness is one of the main obstacles the SM has to generate the baryon asymmetry (EWBG) [3], gravitational waves,...
- In fact imposing the non-erasure condition for baryon asymmetry generation a very strong upper limit on the Higgs mass $m_H \ll 114$ GeV was historically obtained.

Supercooling

- The situation would drastically change if for some reason the Higgs field were supercooled in the symmetric phase until sufficiently low temperatures

- Any extension of the Standard Model which strenghthen the EWPT should produce to some extent this effect

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- An interesting possibility appears in warped spaces with the Higgs localized in the IR brane
- The radion $\mu(x)$ VEV which fixes the distance between the UV and IR branes will play a major role in the phase transition
- At high temperatures ($\mu \sim 0$) the space is AdS and the IR brane is replaced by a black hole horizon

AdS/CFT correspondence

At high T IR brane does not exist $\Leftrightarrow$ Deconfined (phase) Higgs ($\phi = 0$)

- At temperature T_n ($\mu \neq 0$) the IR brane is nucleated from the horizon and the space is RS

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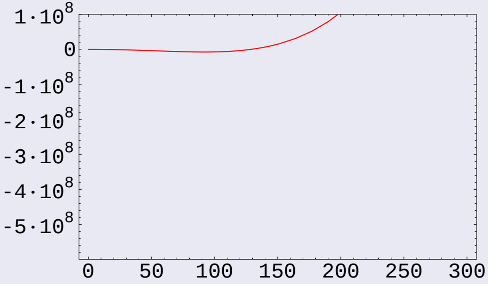
If supercooling is efficient $\langle\phi(T)\rangle \to v$ when $T \ll T_{EWPT}$ and easily $\langle\phi(T)\rangle/T \gg 1$

At one-loop with $m_H = 250\,GeV$, $T \simeq 305\,GeV$ and $\langle\phi(T)\rangle/T \sim 0.3$



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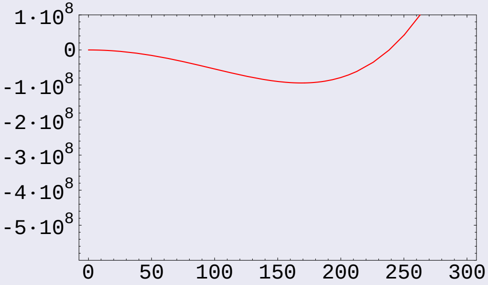
At one-loop with $m_H = 250 GeV$, $T \simeq 250 GeV$ and $\langle\phi(T)\rangle/T \sim 0.7$



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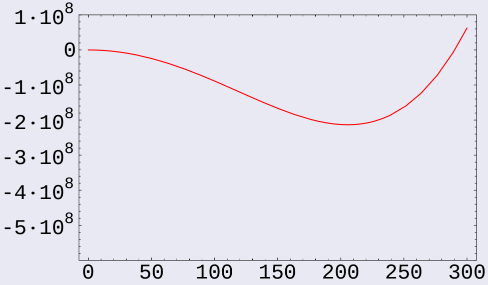
At one-loop with $m_H = 250\,GeV$, $T \simeq 200\,GeV$ and $\langle\phi(T)\rangle/T \sim 1$



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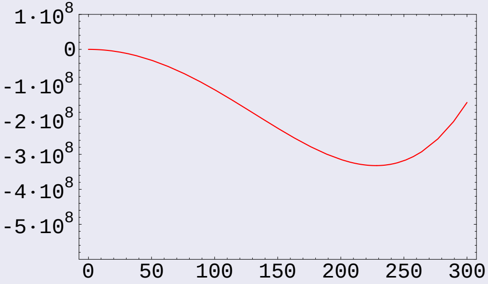
At one-loop with $m_H = 250 GeV$, $T \simeq 150 GeV$ and $\langle \phi(T) \rangle / T \sim 1.5$



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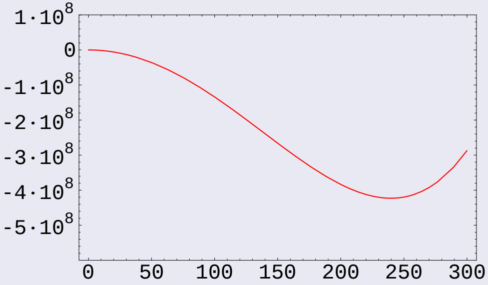
At one-loop with $m_H = 250\,GeV$, $T \simeq 100\,GeV$ and $\langle\phi(T)\rangle/T \sim 2.4$



The two phases

- We consider the Randall–Sundrum (RS) set–up *i.e.* $5D$ gravity with negative cosmological constant and two four-dimensional boundaries which are called UV and IR branes
- Holographically this corresponds to a $4D$ conformal field theory (CFT) coupled to gravity in which the conformal symmetry is also spontaneously broken
- The spontaneous breaking is an IR effect and its scale μ is associated to the position of the IR brane
- The presence of the UV brane, on the contrary, explicitely breaks the conformal symmetry as it couples the theory to gravity. This occurs at an UV scale $k = L^{-1}$, where L is the AdS radius, which also represents an UV cut–off for the CFT.

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- At finite temperature [4], the Euclidean $5D$ path integral has two stationary solutions at the classical level
- The first one is the Euclidean version of the standard RS geometry with compactified time

RS geometry

$$ds_{RS}^2 = \frac{L^2}{z^2}\left(\beta^2 d\tau^2 + V^{2/3} d\vec{\xi}^{\,2} + dz^2\right)$$

in the interval $[z_{UV} \equiv L = k^{-1}, z_{IR} \equiv \mu^{-1}]$

τ is a temporal variable with unit period and $\vec{\xi}$ span a square 3–torus of unitary volume

- Euclidean time is a circle of radius

Compactified time

$$\beta = 1/T$$

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interval $z \in [L,\, \beta_h/\pi]$ with $z_{BH} = \beta_h/\pi$ black-hole horizon

- Fixing the time peridicity at UV

$$\beta_h^2 = \frac{\beta^2}{2}\left[1 + \sqrt{1 + 4\pi^4(LT)^4}\right]$$

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- At finite temperature, one has two classical minima of the $5D$ action leading of course to completely different physical results
- From the $4D$ dual point of view, the RS and AdS-S minima correspond to two different phases, which we identify respectively, with the confining and deconfining phases of the gauge theory
- Depending on the temperature the physical minimum is the one with lowest $5D$ action or (equivalently) $4D$ free–energy
- As a general rule of AdS/CFT, the loop expansion on the gravity side corresponds to a large number of colors (large–N) expansion in the gauge theory. The squared coupling constant for $5D$ gravity is $1/(ML)^3$. The AdS/CFT relation

$$\frac{1}{N^2} = \frac{(ML)^{-3}}{16\pi^2},$$

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- For the confined (RS) phase

RS free-energy

$$F_{RS} = -24\,\frac{N^2}{16\pi^2}\,k^4$$

- For the deconfined (AdS-S) phase

AdS-S free-energy

$$F_{AdS-S} = \left[-24k^4 - 4\pi^4 T^4)\right]\frac{N^2}{16\pi^2}$$

- A problem: at any non–zero temperature $F_{AdS-S} < F_{RS}$ so that the RS space is metastable and no phase transition can ever occur from the AdS-S to the RS phase

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GW field

- In the RS phase the conformal symmetry is only spontaneously broken leading to a massless Goldstone boson, the radion with a flat potential
- An explicit breaking of conformal symmetry is required anyhow to avoid the presence of an exactly massless scalar. The so–called Goldberger–Wise (GW) mechanism [5] permits to stabilize the distance among the branes and give a mass (and a potential) to the radion by simply adding a $5D$ scalar field Φ

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GW action

$$S_{GW}^{E} = \int_{\mathcal{M}} \left[G^{MN}\partial_M\Phi\partial_N\Phi + m^2\,\Phi^2 \right] + \int_{\partial\mathcal{M}} \mathcal{L}_{\partial\mathcal{M}}(\Phi) + \int_{\partial\mathcal{M}_{IR}} k^4\delta T_1$$

- The parameters introduced by the GW potential are:
  - The explicit breaking of conformal invariance $\epsilon \simeq m^2L^2/4$ (both signs)
  - $\mathcal{L}_{\partial\mathcal{M}}$ fixes the GW field at the branes

$$\Phi(x, z_{IR,UV}) = k^{3/2} v_{1,0}$$

  - δT_1 is a correction to the IR brane tension
- Summary of the parameters

Parameters

$$N,\ \epsilon < 0,\ v_{0,1},\ \delta T_1$$

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There are conditions one has to impose on the GW parameters

- They have to provide a minimum of the GW potential μ_{TeV} and solve the hierarchy

Minimum of GW

$$\mu_{TeV} \simeq k(v_1/v_0)^{1/\epsilon} \sim TeV$$

- The GW field must provide a small back reaction on the RS metric
- Focussing on the negative ϵ case $(\delta T_1, v_1)$ traded for

$$\theta = \frac{4}{3}\frac{\pi^2|\delta T_1|}{N^2}, \qquad \nu = \frac{4}{3}\frac{\pi^2|\epsilon| v_1^2}{N^2}$$

Consistency and perturbativity conditions

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Higgs field

- We take (at least) the Higgs doublet $\bar{h}$, to be localized at the IR brane

Localized Higgs

$$S_{SM}^{E} = \int d^4x \left\{ \left(\frac{\mu}{\mu_{TeV}} \right)^2 |D_\mu h|^2 + \left(\frac{\mu}{\mu_{TeV}} \right)^4 V_0(h, v) \right\}$$

- The total potential obtained by adding up the GW and SM potentials

$$V_{RS}(\mu, \phi_c) = V_{GW}(\mu) + V_{SM}(\mu, \phi_c, T)$$
$$= V_{GW} \left[1 + \mathcal{O}(v^4/\mu_{TeV}^4) \right]$$

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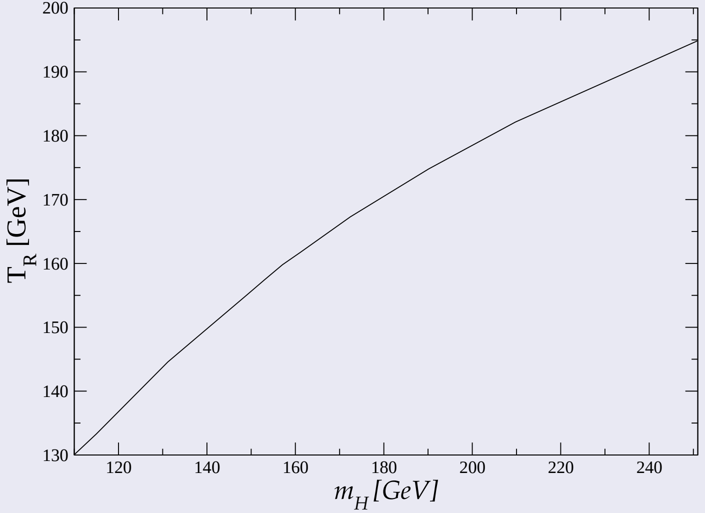
For earlier studies of the radion phase transition see [6]

The EW phase transition

At the typical radion nucleation temperatures T_n the SM potential is a little perturbation of the radion potential and should not alter much the corresponding Euclidean action that governs the radion phase transition. The radion potential then produces a supercooling of the system and the electroweak phase transition (EWPT) takes place at much lower temperatures than the typical SM ones and makes it to be much stronger. In the figure we show the required supercooling, i.e. the temperature at which $\langle \phi_c(T) \rangle / T = 1$, as a function of the Higgs mass

[6] P. Creminelli, A. Nicolis and R. Rattazzi, hep-th/0107141; L. Randall and G. Servant, hep-ph/0607158; J. Kaplan, P.C. Schuster and N. Toro, hep-ph/0609012

Plot of the temperature at which the SM potential is minimized at $\langle\phi_c(T)\rangle/T = 1$ as a function of the Higgs mass in GeV



The radion phase transition

- At high temperatures (early times) a deconfined (strongly–coupled) plasma fills the Universe
- As the Universe expands, it cools down and a confining phase transition can start when the free–energy of the deconfined phase equals the confined one. This happens at a critical temperature T_c

Critical temperature

$$T_c^4 = 3\sqrt{(\theta\nu - \nu^2)|\epsilon|}\left[\frac{1}{(1+\nu/2)^3} - \frac{2\Delta g^*}{45N^2}\right]^{-1}\left(\frac{\mu_{TeV}}{\pi}\right)^4$$

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- The rate of bubble nucleation for unit physical volume can be expressed as

$$\lambda(T) = A(T)\, e^{-S(T)}$$

- We can define the nucleation temperature as

Nucleation temperature

$$\lambda(T_n) \simeq \chi^4(T_n)$$

χ is the Hubble frecuency

- For the GW potential we will have that $T_n \ll T_c$
- Below the temperature

Inflation temperature

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- The phase transition produces a number of e-folds of inflation

$$N_e \sim \log \frac{T_i}{T_n}$$

- To have an idea of how fast the transition proceeds one can plot the probability that one point of space remains in the old (deconfined) phase at time t

$$p(T) = \exp\left[-\frac{4\pi}{3}\int_T^{T_i}\frac{dT_1}{T_1}\frac{\lambda(T_1)}{\chi^4}\left(1-\frac{T}{T_1}\right)^3\right]$$

- We will see the EWPT is then a strong first-order inflationary phase transition with a few e-folds of inflation
- The difference with respect to old inflation is that in the latter $\lambda(T) = \varepsilon_0\chi^4 = constant$ where $\epsilon_0 \sim 1$ ($\epsilon_0 \ll 1$) $\Rightarrow$ no inflation (no percolation)

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Tunneling condition

$$\varepsilon(T) = \lambda(T)/\chi^4 \sim 1$$

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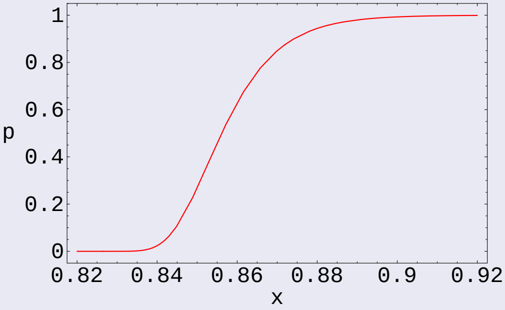
Plot of the probability as a function of T/T_n for $T_n = 10^{-3}\,T_i$



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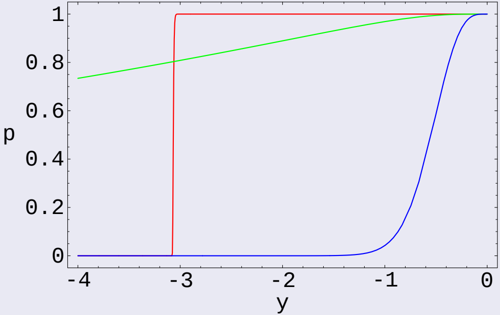
Comparison with $\epsilon_0 = 1$ (blue line) and $\epsilon_0 = .01$ (green line)



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Reheating temperature

$$\frac{\pi^2}{30} g^* T_R^4 = E_0$$

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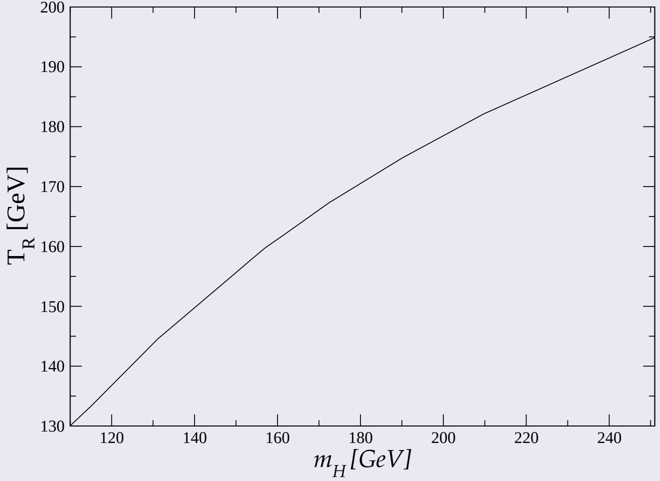
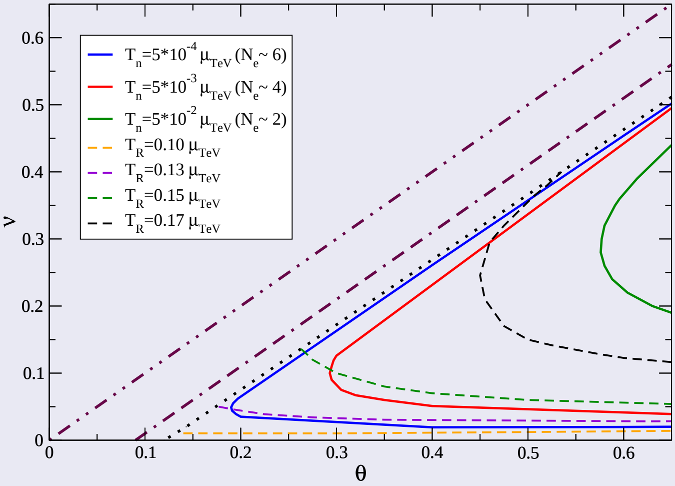
Maximum values of T_R as a function of the Higgs mass



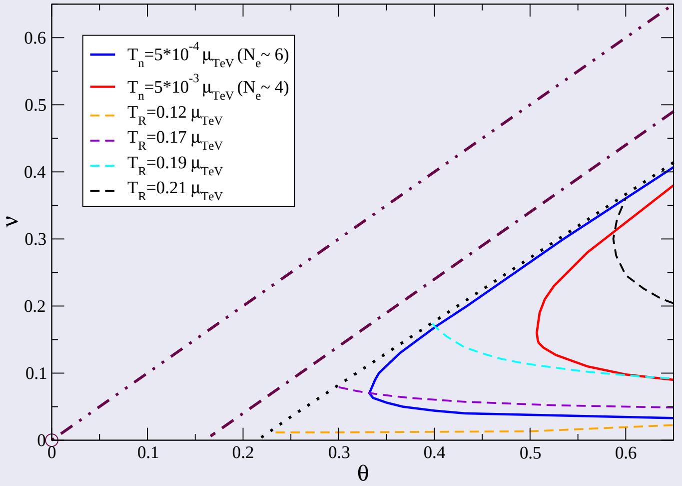
Numerical results

Plot of the allowed regions in the plane (θ, ν) for $N = 3$. We have fixed $\epsilon = -1/20$.



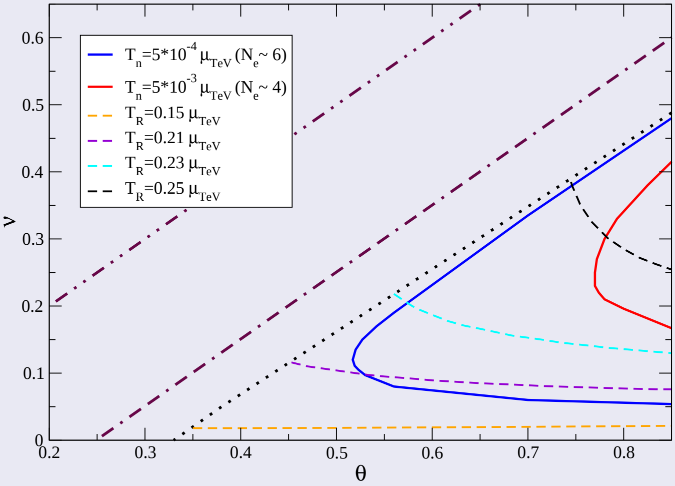
Numerical results

Plot of the allowed regions in the plane (θ, ν) for $N = 4$. We have fixed $\epsilon = -1/20$.



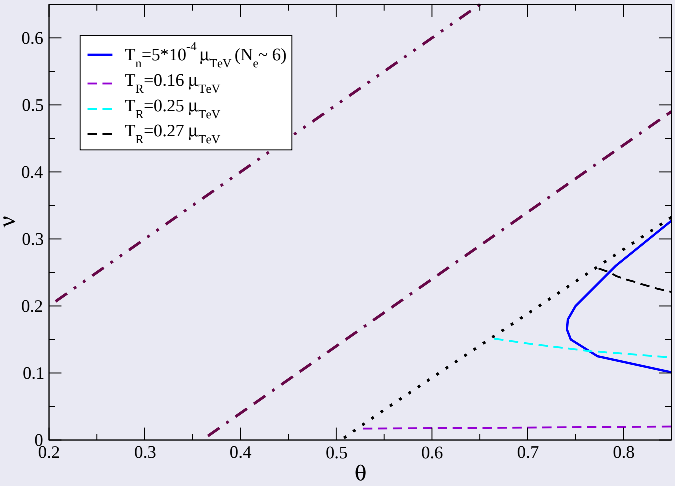
Numerical results

Plot of the allowed regions in the plane (θ, ν) for $N = 5$. We have fixed $\epsilon = -1/20$.



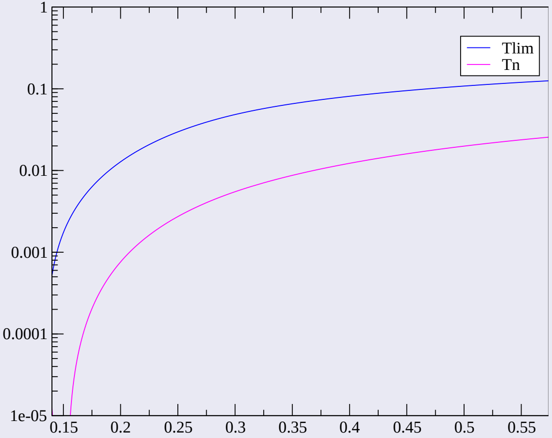
Numerical results

Plot of the allowed regions in the plane (θ, ν) for $N = 6$. We have fixed $\epsilon = -1/20$.



The nucleation temperatures are rather low generating some e-folds of inflation

Plot of T_n/μ_{TeV} (red) as a function of θ along the bisectrix of the allowed region in the plot of $N = 3$ figure.



EWBG

- Because the phase transition is strongly first order sphalerons are totally inactive inside the bubbles and the baryon asymmetry generated by some extra source of CP-violation (on top of the standard CKM phase) will not be erased in the broken phase.
- In the symmetric phase, outside the bubbles the rate of baryon number non-conserving processes has to be much larger than the expansion rate

Condition (i): sphalerons active in symmetric phase

$$V_B(T) = \frac{13}{2} N_f \frac{\Gamma_{sph}}{T^3} \gg \chi$$

$$\Updownarrow$$

$$\frac{T_n}{\mu_{TeV}} > 3 \times 10^{-12} N \left[(\theta\nu - \nu^2)|\epsilon| \right]^{1/4} \Leftrightarrow N_e < 26$$

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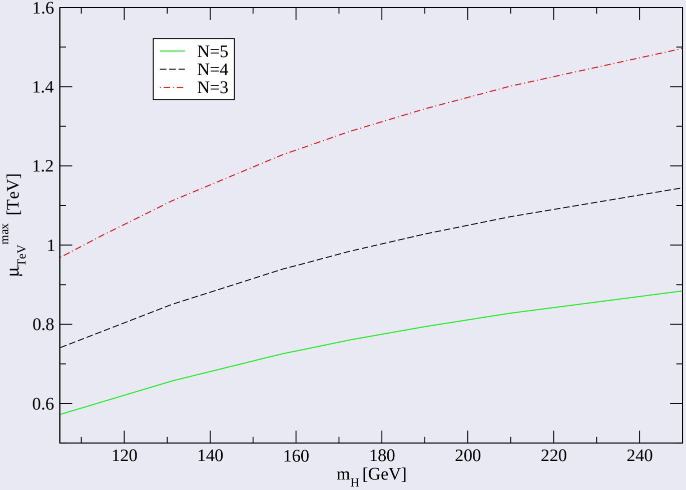
Condition (ii): upper bound on μ_{TeV} for different values of N as a function of the Higgs mass from the condition on T_R for $N_e < 6$



Conclusion

- The electroweak phase transition in the RS model triggered by the radion phase transition is a strong (supercooled) first order one
- As any supercooled phase transition it generates a number of e-folds of inflation
- Two conditions for non-erasure of the generated baryon asymmetry are easily fulfilled
  - $N_e < 26$
  - $T_R \ll T_{EW}$
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