Strong phase transitions and nearly conformal dynamics

Thomas Konstandin

in collaboration
with Geraldine Servant
1104.4791 & 1104.4793

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Motivation
\[ \alpha = \rho_{\text{vac}} / \rho_{\text{rad}}, \quad \beta \sim \tau^{-1}, \quad v_b, \quad T \]
In the Standard Model, the electroweak breaking proceeds by a *crossover* but the Higgs sector also suffers from a hierarchy problem:

The Higgs mass receives large corrections by quantum loops

\[ \Delta m_{Higgs}^2 = \Lambda_{\text{cut-off}}^2 \]

If the Planck scale is the cut-off of the theory, an Higgs mass of electroweak scales is unreasonable.
This indicates that there is some kind of new physics around the corner that did not appear in collider experiments yet.

In most extensions of the Standard Model, a first-order electroweak phase transition is possible or even generic.
Cosmology of warped extra dimensions
Warped extra dimensions provide one possible solution to the hierarchy problem

\[ \mathcal{L} \ni -M_5^3 \int d^5x \sqrt{g} \left[ R + \frac{12}{l^2} \right] \]

5D RS

UV

IR

\[ ds^2 = e^{-2r/l} dx^2 - dr^2 \]

\[ r_0 \sim 35 l \]

[Randall&Sundrum '99]
Warped extra dimensions provide one possible solution to the hierarchy problem

\[ L = -\frac{\sqrt{g}}{2} \int \! d^5x \, \sqrt{g} \left[ R + \frac{12}{l^2} \right] + \int \! d^5x \, \sqrt{g} \frac{1}{2} \left[ (\partial \phi)^2 + m^2 \phi^2 \right] \]

\[ \epsilon = (ml)^2/4 \sim 1/30 \]

5D RS

UV

IR

\[ ds^2 = e^{-2r/l} \, dx^2 - dr^2 \]

\[ r_0 \sim 35 \, l \]

\[ \phi \sim Ae^{-\epsilon r/l} + Be^{(4+\epsilon)r/l} \]

boundary conditions → stabilization

[Randall& Sundrum '99], [Goldberger&Wise '99]
Goldberger-Wise mechanism

Using the canonical normalization of the radion

$$\mu \propto l^{-1} e^{-r/l}$$

and appropriate boundary conditions for the bulk scalar leads to a nearly conformal radion potential

$$V(\mu) \sim \mu^4 \lambda((\mu l)^c)$$

This solves the hierarchy problem as long as

$$dV/d\mu = 0 \leftrightarrow \lambda((\mu l)^c) \sim 0$$

$$\leftrightarrow \mu_0 \sim l^{-1} O(1)^{1/\epsilon} \sim l^{-1} 10^{-16} \sim \text{TeV}$$
The resulting radion potential is quite peculiar.

In particular, there is a hierarchy between the maximum and the EW minimum.
In a thermal system a phase transition will connect the two stable phases of the system.

KK particles that are massive in the broken phase induce a difference in free energy between the two phases

\[ \Delta F = \frac{\pi^2}{90} \Delta g T^4 \]
Conformal Approximation

\[ V(\mu) = \lambda((\mu_r l)^\epsilon) \mu^4 \quad T \propto \mu_r (\lambda/g_*)^{1/4} \]

\[ S_3/T \propto \lambda^{-3/4}g_*^{1/4} \]

\[ \frac{\beta}{H} = T \frac{d}{dT} \frac{S_3}{T} \simeq \epsilon S_3/T \]
The semi-classical tunnel probability is given by the Euclidean action

\[ p \sim \frac{T^4}{H^4} e^{-S_3/T} \]

The tunnel action inherits the nearly conformal behavior of the scalar potential

\[ S_3/T \sim 4 \log T/H \sim 140 \]

\[ S_3/T \sim \text{polynomial}((T/T_c)^\epsilon) \]

large supercooling and extremely strong phase transitions generic

The nearly conformal potential evades the graceful exit problem of old inflation, but only \( \sim 15 \) efolds of inflation possible.

[Nardini, Wulzer, Quiros '07] [TK, Nardini, Quiros '10] [TK, Servant '11]
Gravitational waves

Sizable supercooling is the optimal condition for large gravitational wave production. [TK, Nardini, Quiros ’10]

\[ \alpha = \frac{\rho_{\text{vac}}}{\rho_{\text{rad}}} \gg 1 \]

\[ \tau^{-1} \gtrsim \text{a few } H \]

Even very large KK scales (~100 TeV) accessible
Several e-folds of inflation at the electroweak scale would have far-reaching implications for cosmology.

Pre-existing baryon asymmetries and dark matter abundances are heavily diluted. Particle production by bubble collisions.

Which baryogenesis mechanisms are possible during/after reheating depends on the radion mass and the Higgs potential.

<table>
<thead>
<tr>
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<th>$T_{reh} &gt; T_{EW}$</th>
<th>$T_{reh} &lt; T_{EW}$</th>
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<tbody>
<tr>
<td></td>
<td>EWPT $1^{st}$ order</td>
<td>$2^{nd}$ order crossover</td>
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<tr>
<td>cold EWBG</td>
<td>-</td>
<td>-</td>
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<td>non-local EWBG</td>
<td>if $\phi/T</td>
<td><em>{T</em>{reh}} &gt; 1$</td>
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<td>low-scale leptogenesis</td>
<td>+</td>
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<td>asymmetric dark matter</td>
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A surprisingly large GW signal from a phase transition at TeV scales is a hint for a nearly conformal sector and a possible solution of the hierarchy problem.

Sizable supercooling at electroweak scale has far-reaching implication for cosmology, in particular

- dark matter
- baryogenesis
- GW production
- particle production by bubble wall collisions

[Watkins & Widrow '92]
Cold electroweak baryogenesis
Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

\[ \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 10^{-10} \]

The main ingredients for viable baryogenesis are stated by the celebrated Sakharov conditions:

- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium

[Sakharov '69]
In the initial stages of tachyonic preheating, the Higgs and gauge fields evolve as classical fields in the Higgs potential.
Winding numbers

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

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

\[ \phi = \Omega \phi_0 \]

The difference of the two winding numbers is gauge invariant and at late times the system approaches the vacuum \( N_{CS} = N_H \).

A change in Chern-Simons number induces a change in baryon number according to the weak anomaly

\[ \Delta N_B = 3 \Delta N_{CS} \]

[van der Meulen, Sexty, Smit, Tranberg '06]
Decay vs. dressing

Consider the configuration with non-trivial winding

\[ \Omega = \exp(-i \chi(r) \overrightarrow{x} \cdot \overrightarrow{\sigma}/r), \quad \chi(r) = \pi \tanh(r/L) \]

Depending on the size L the winding will either decay or get the Higgs field gets dressed by gauge fields.

[Turok, Zadrozny '90]

bifurcation point (in $\sqrt{2}m_W$) as a function of the quartic Higgs coupling ($\lambda/g^2$)

\[ m_H < 200 \text{ GeV} \leftrightarrow L^{-1} < 20 \text{ GeV} \]

CPV will have an impact on the bifurcation point for winding / antiwinding.
Different behavior for winding and antiwinding \((p \neq q)\) requires CP violation, e.g.

\[ \mathcal{L} \ni \frac{1}{M^2} \phi^2 F_{\mu\nu} \tilde{F}^{\mu\nu} \]

that acts as a chemical potential for Chern-Simons number.
Simulations

The observed baryon asymmetry can be reproduced with

$$\mathcal{L} \ni \frac{1}{M^2} \phi^2 F_{\mu\nu} \tilde{F}^{\mu\nu}$$

while EDM constraints require

$$M > 14 \text{ TeV}$$
Cold electroweak weak baryogenesis is usually based on an era of low scale hybrid inflation with the Higgs as the waterfall field.

When the waterfall is triggered, the Universe is cold and all the energy resides as potential energy in the scalar sector.
Initial conditions

- low scale hybrid inflation
- preheating after first-order phase transition
  - sizable supercooling
  - relativistic (~vacuum) bubble walls

References:
[Hawking, Moss & Stewart '82]
[Watkins & Widrow '92]
[Giblin, Hui, Lim & Yang '10]
[TK & Servant '11]
Bubble Collisions

rather symmetric potential

rather asymmetric potential

[Giblin, Hui, Lim & Yang '10]
Bubble Collisions

rather symmetric potential

rather asymmetric potential

1+1 dim
The radion potential is prototypical for an asymmetric potential. The flatness of the potential even leads to some “slow roll” behavior.
Randomness

tachyonic preheating after hybrid inflation

preheating after supercooled first-order PT

simulations required
After the phase transition, all the energy resides in the scalar sector.

The scalar sector contains in this case $\text{Higgs} + \text{radion} \leftrightarrow \text{Higgs} + \text{inflaton}$

These are suitable conditions for cold electroweak baryogenesis

For viable baryogenesis one has to ensure that the electroweak symmetry is not restored after reheating (radion and Higgs masses)
Conclusions

Warped extra dimensions as solutions of the hierarchy problem lead to nearly conformal radion potentials and a strongly supercooled phase transition at the TeV scale.

Such a phase transition provides suitable conditions for cold electroweak baryogenesis.

The smoking gun signal for such a scenario are gravitational waves that peak at around $f \sim \text{mHz}$ but are stronger than from conventional (electroweak) phase transitions.
Comment on Holography

In AdS/CFT this phase transition is identified with the confining phase transition of the strongly coupled (almost CFT) gauge theory

[Arkani-Hamed, Porrati, Randall '00]
[Rattazzi, Zaffaroni, '01]

However, a large number of degrees of freedom imply a large tunnel action

\[ \Delta g \propto N^2 \]
\[ S_3/T \propto (M_5 l)^3 = N^2 / 16\pi^2 \]

that leads to a bound from meta-stability

[Creminelli, Nicolis, Rattazzi '01]
[Randall, Servant, '06]
[Hassanain, March-Russell, Schvellinger '07]
[Nardini, Quiros, Wulzer '09]
[TK, Nardini, Quiros '10]

\[ N < 3 \]  thermal / thin wall
\[ N < 13 \]  quantum / thick wall
throats
numerical
backreactions