From Boltzmann equations to steady wall velocities

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based on Work together with T.Konstandin and G.Nardini /arXiv:1407.3132

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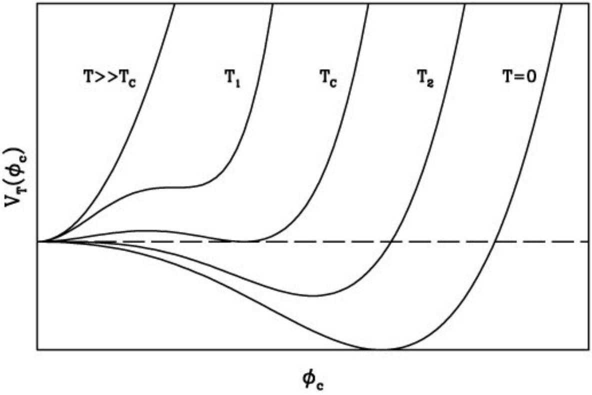
First-Order Phase Transitions

- Standard Example: Higgs-potential

$$V(\phi, T) = \frac{1}{2}D(T - T_0)^2\phi^2 - \frac{1}{3}E\phi^3 T + \frac{\lambda}{4}\phi^4 \qquad (1)$$



First-Order Phase Transitions in the Early Universe

- Interesting phenomenology. Possibility to generate relics (for example gravitational waves or baryons)
- Electroweak Phase Transition(EWPT) is a promising candidate for a strongly first-order phase transition(SFOPT), if there is new physics near the weak scale.
- Predictions for both rely on the dynamics of the expanding bubble walls (especially on the velocity)
- Problem: It is not possible to find general expressions for the dynamics

Outline

> First-Order phase transitions in the early Universe

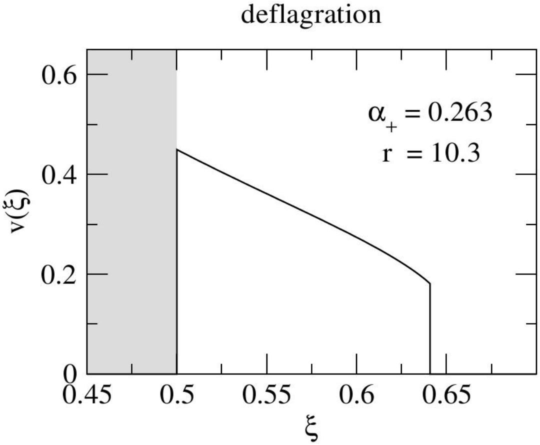
> **Bubble dynamics**

> Models

> Summary

Hydrodynamical picture

Fluid velocity during the Phase Transition



(Espinosa, Konstandin, No, Servant 2010)

Approach to obtain Bubble Dynamics

- Solve the Higgs EOM to find steady state solutions

$$\Box\phi + \frac{dV}{d\phi} + \sum_i \frac{dm^2}{d\phi} \int \frac{d^3 p}{(2\pi)^3 2E} \delta f = 0 \qquad (2)$$

- Microscopic Approach: Calculate friction on the Bubble Walls from scattering particles

  (Moore & Prokopec 1995)
  (John & Schmidt 2002)

- acceleration to final speed very fast and thus not relevant

- (starting point is the Schwinger-Keldysh formalism)

Calculation steps

- Gradient expansion of the Greens functions yields set equations
- Simplify this by assuming a perfect fluid

$$f(\vec{p},x) = \frac{1}{\exp[X] \pm 1} = \frac{1}{\exp[\beta(x)(u^{\mu}(x)p_{\mu} + \mu(x))] \pm 1} \qquad (3)$$

- linearize in the perturbations

$$\delta = \{\delta\mu_f, \delta T_f, \delta v_f, \delta\mu_b, \delta T_b, \delta v_b\} \qquad (4)$$

- fluid system is of the form

$$A(\delta'(x) + \delta'_{bg}(x)) + \frac{1}{\gamma}\Gamma(\delta(x) + \delta'_{bg}(x)) = F(x) \qquad (5)$$

Calculation steps (2)

- Fluid System:

$$A(\delta'(x) + \delta'_{bg}(x)) + \frac{1}{\gamma}\Gamma(\delta(x) + \delta'_{bg}(x)) = F(x) \tag{6}$$

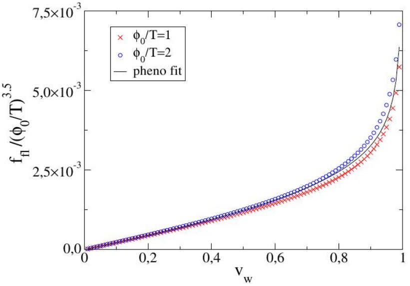
- One set of equations for every particle species (W-bosons, t-quarks)
- yields the fluctuations δf,which are needed to solve Higgs EOM with a 2-parameter wall shape Ansatz

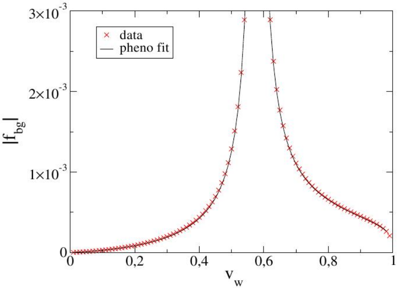
$$\phi(z) = \frac{\phi_0}{2}\left(\mathrm{Tanh}\,\frac{z}{L_w} + 1\right) \tag{7}$$

- Fixes wall velocity v_w and thickness L_w

resulting friction

- friction can be characterized by 3 different parameters ($\frac{\phi_0}{T}, v_w, L_w T$)
- Example: Bubble Wall velovity dependence of the friction





- intermediate regime has no stable solutions ($0.45 \lesssim v_w \lesssim 0.7$)

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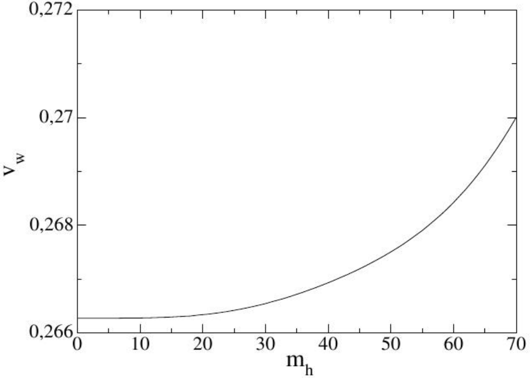
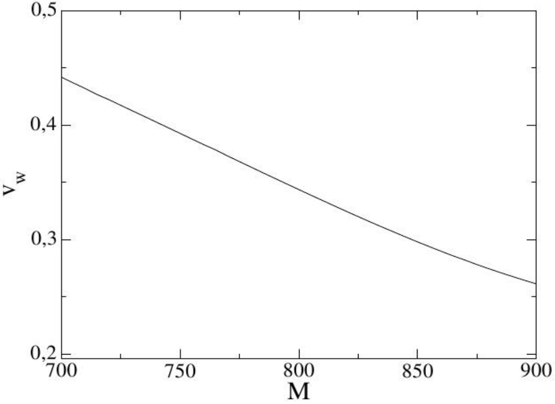
Standard Model with a light Higgs

- SM with a light Higgs (< 70 GeV) includes a FOPT
- Of course it is excluded, but an easy toy model
- allows to compare to previous work by M&P



Standard Model with a low cut-off

- SM +effective $\frac{1}{6M^2}\phi^6$-term
- intereseting collection of models, which are already being tested by LHC



Standard Model + scalar singlet

- introduce $\mathbb{Z}_2$-symmetric scalar singlet

$$V(\phi, s, T) = V_{SM}(\phi, T) - \frac{\mu(T)}{2} s^2 + \frac{\lambda_s}{4} s^4 + \frac{1}{2} \lambda_m s^2 \phi^2 \tag{8}$$

- in general often runaway walls *(Bödeker & Moore 2009)*

- for small potential differences it is possible to have all kinds of different solutions ($v_w \lesssim 0.45,\ v_w \gtrsim 0.7$)

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- > Models
- > **Summary**

Summary

- dynamics of first-order electroweak phase transitions in the early universe are unclear (velocity not well determined)
- microscopic approach: fluid system & friction calculation (relativistic)
- "model-independent" (EWPT with SM-plasma content) phenomenological fit for frictions
- application to some models: SM+light Higgs, SM+ϕ^6, SM+singlet