Thermal phase transitions in cosmology

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1. **Motivation**
2. **QCD thermodynamics**
3. **Electroweak phase transition**
4. **Higher scale phase transitions, and constraints on particle physics?**
5. **Conclusions**

Physics at microscopic energy scales of quantum mechanics leads to macroscopic cosmological remnants:

$\mathcal{O}$(eV) of atomic physics $\Rightarrow$ cosmic microwave background.

$\mathcal{O}$(MeV) of nuclear physics $\Rightarrow$ light element abundances.

What then about known energy scales of particle physics:

$\mathcal{O}$(GeV) of QCD $\Rightarrow$?

$\mathcal{O}$(TeV) of the electroweak theory $\Rightarrow$?

Large scale magnetic fields, baryon asymmetry, ...?

$\mathcal{O}(10^{15}$ GeV) of GUTs $\Rightarrow$ inflation, fluctuations in CMB?

It is not obvious that there are observable consequences!

1. Interactions strong $\Rightarrow$ difficult to deviate from equilibrium.

Need $\tau \sim \frac{1}{n\sigma v} \sim \frac{1}{\alpha^2 T} > t \sim \frac{m_{\rm Pl}}{T^2} \Rightarrow T > \alpha^2 m_{\rm Pl} \sim 10^{15}$ GeV.

But: theories may possess 1st order phase transitions, which allow for non-equilibrium even in strongly interacting systems!

2. Fluctuations (relevant for remnants such as magnetic fields) are produced only on very small length scales.

The QCD horizon today $\sim$ 1 ly, the EW horizon $\sim$ 1 AU.

But: non-linear magnetohydrodynamics may extend length scales more rapidly than comoving expansion.

3. The reheating temperature after inflation might not be as high as the phase transition temperature?

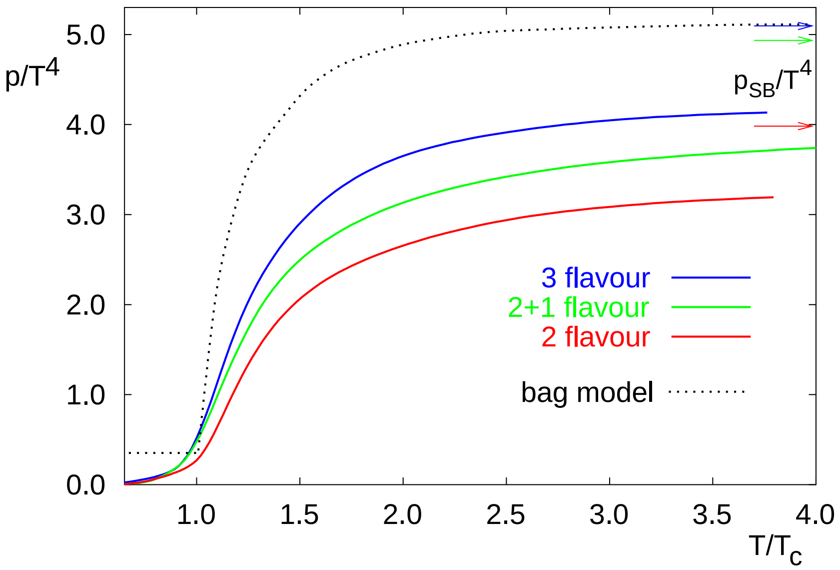
But: 1 GeV is reached momentarily even in terrestrial conditions, so Early Universe should be much hotter...

Concentrate here on the first issue, and not on the actual computation of cosmological remnants.

QCD thermodynamics

Naively degrees of freedom change considerably, suggesting a strong transition [(q,g,... $= 51.25) \to (\pi$,... $= 17.25)$].

However in practice particles are not free but very strongly interacting. Current status of lattice studies:



Karsch et al, hep-lat/0010027

$T_C \approx 170$ MeV

Existence of a singularity in the thermodynamic limit remains unresolved for physical quark masses, but if any, it is very weak.

But thermodynamics does differ from simple T^4 behaviour: e.g.

$$\frac{dT}{dt} = -\frac{\sqrt{24\pi}}{m_{\rm Pl}} \frac{\sqrt{e(T)}}{d\ln s(T)/dT} < \text{[ideal gas value]}.$$

Here $s = p'(T), e = T^2(p(T)/T)', T(\ln s(T))' = 1/v_s^2$. Universe cools slower, sound velocity dips slightly, etc.

EW transition

In SM resummed 1-loop gives 1st order transition with

$$\Delta\frac{v}{gT}=\frac{1}{8\pi}\frac{g^2}{\lambda}[1+\mathcal{O}(\frac{\lambda}{g^2})],\quad \frac{\lambda}{g^2}\approx\frac{1}{8}\frac{m_H^2}{m_W^2}+\mathcal{O}(\frac{g^2}{(4\pi)^2}\frac{m_{\text{top}}^4}{m_W^4}).$$

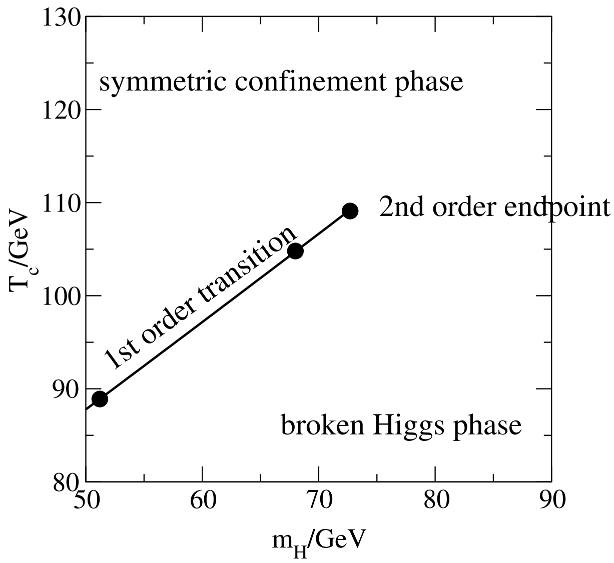
Transition strong enough for baryogenesis if $\Delta v/T \gtrsim 1.0$.

Baacke, Junker;
Kajantie et al;
G.D. Moore

2-loop effects seem to strengthen the transition — but with realistic m_{top}, not enough for any $m_H > m_{H,CW} \sim 10$ GeV.

Arnold, Espinosa;
Fodor, Hebecker;
Kajantie et al

Is perturbation theory reliable? The result of lattice simulations: the true transition is even weaker!



Rummukainen et al,
Gürtler et al,
Csikor et al

How to increase the strength?

Need light bosonic d.o.f.'s, with a strong coupling to Higgs.

Within MSSM there appears to be a unique way of doing this, utilising stop squarks.

Carena at al; Delepine et al;
de Carlos and Espinosa;
Cline and Kainulainen;
Losada; Laine; Bödeker et al;
Cline and Moore; ...

The stops come left- and right-handed, $\tilde{t}_L, \tilde{t}_R$. To have a small violation of the EW observable ρ, and a large m_H, the weakly interacting $\tilde{t}_L$ should be heavy:

$$\Delta\rho \propto \frac{m^2_{\text{top}}}{m^2_{\tilde{t}_L}}, \quad m_H^2 \sim m_Z^2 \cos^2 2\beta + \frac{3\alpha_W}{2\pi} \frac{m^4_{\text{top}}}{m_W^2} \ln \frac{m_{\tilde{t}_R} m_{\tilde{t}_L}}{m^2_{\text{top}}}.$$

On the contrary, $\tilde{t}_R$ can be "light": $m^2_{\tilde{t}_R} \sim m_U^2 + m^2_{\text{top}} < m^2_{\text{top}}$.

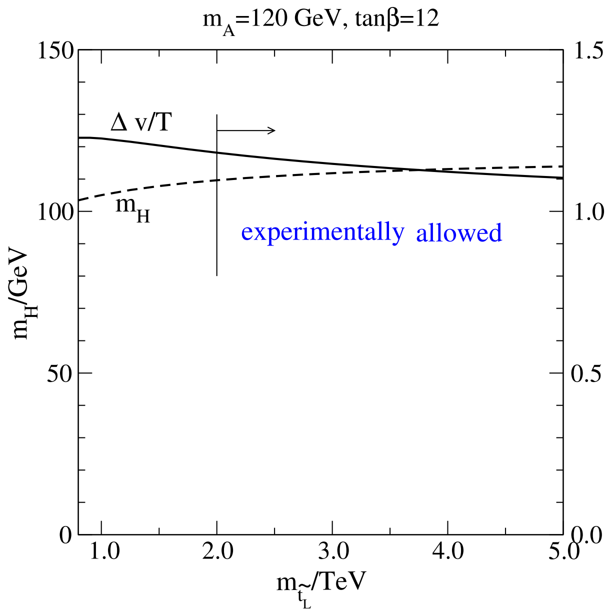
It should not be so light that the new direction gets broken, though, because then one never gets back to the EW minimum!

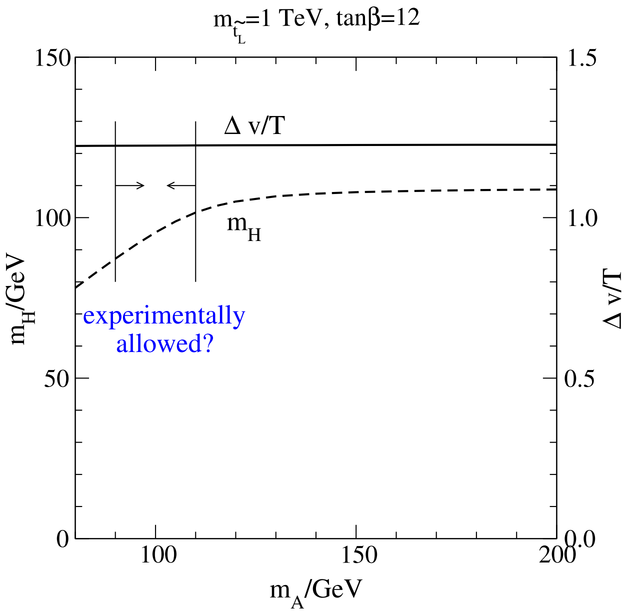
Cline, Moore and Servant

Other possibility: NMSSM with a gauge singlet scalar.

Pietroni;
Davies et al;
Huber, Schmidt

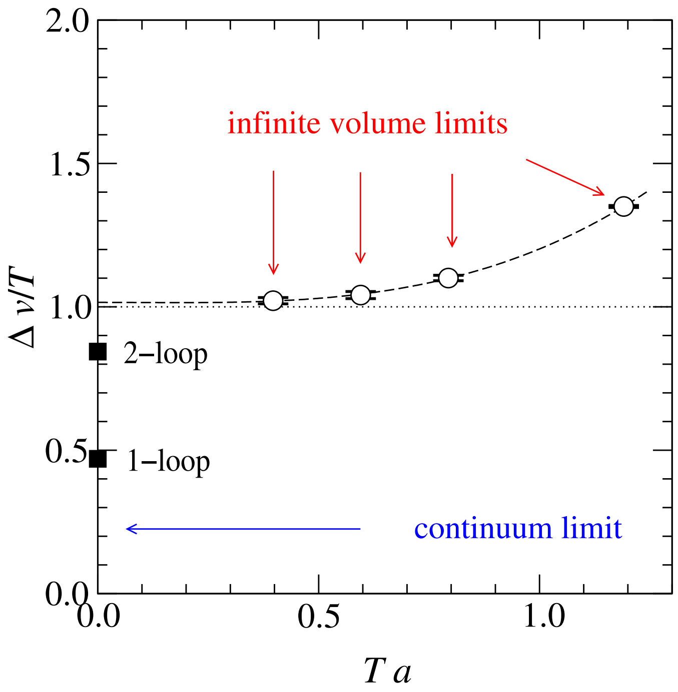
2-loop perturbation theory (for optimal $m_{\tilde{t}_R}$, "triple point"):





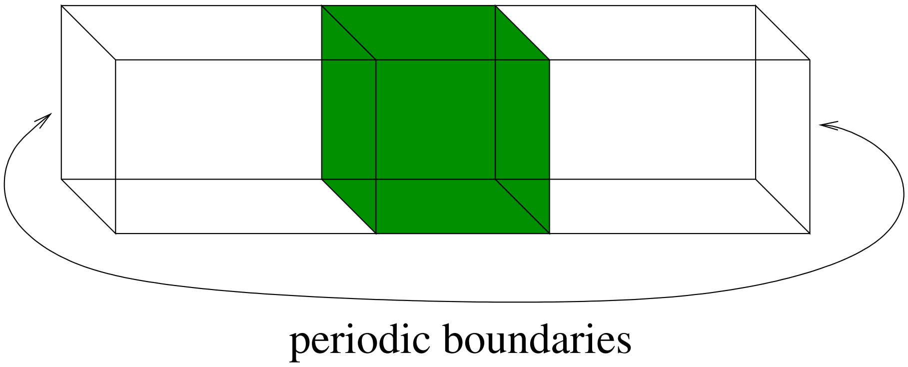
Can cope with $m_H \sim 115...120$ GeV if $m_Q \gtrsim$ a few TeV.
Or a small $m_A \lesssim 120$ GeV, relaxing constraints on m_H.

Check again perturbation theory with lattice simulations:

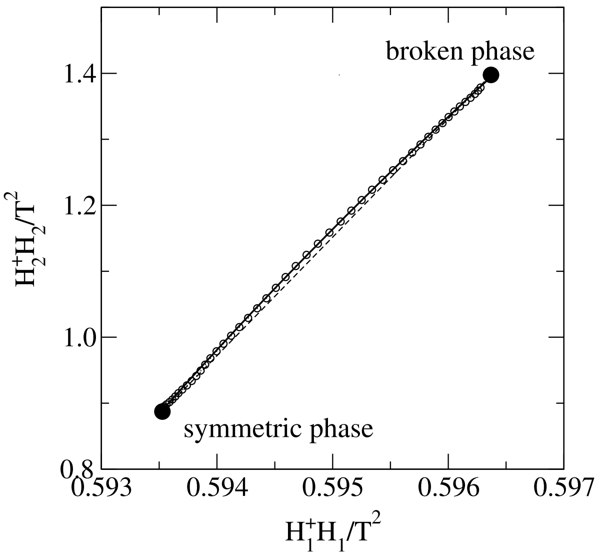


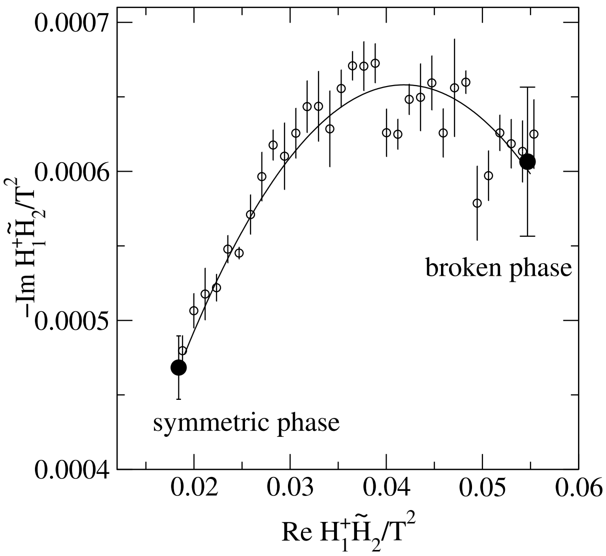
There are also interesting phenomena relating to the existence of two Higgs doublets $H_1, \tilde{H}_2$. Measure e.g. the gauge invariant CP-odd quantity $\langle \mathrm{Im}\, H_1^\dagger \tilde{H}_2(z) \rangle$.

Choose a geometry favouring the existence of planar walls:



Lattice results: (explicit CP violation included)





Such profiles could be inserted into semiclassical dispersion relations to find out about the difference in the behaviour of particles and anti-particles within the wall.

Thermal phase transitions at higher scales?

Suppose inflation and unification are not related, but inflation takes place early, while unification is at $\sim \mathcal{O}(\mathrm{TeV})$.

Dienes et al; ...

Then thermal phase transitions can place strong constraints on possible unification models. As a classic example, one may study whether topological defects would be produced.

For instance, the energy density $\delta\rho$ related to domain walls decays much slower than radiation. It would lead to $\delta\rho/\rho \gtrsim 10^{-5}$ at photon decoupling, if $\sigma \gtrsim (1 \text{ MeV})^3$. Thus any new theories leading to domain wall production are excluded!

Zeldovich, Kobzarev, Okun

An example: compact extra dimensions with only adjoint matter in the bulk generically lead to Z(N) domain walls.

Laine, Korthals Altes

Similarly, the winding of a brane around the extra dimension may lead to various types of cosmic strings & monopoles.

Dvali, Kogan, Shifman

Conclusions

QCD: Transition is very weak if any, but the system is strongly interacting, and thermodynamics deviates a lot from ideal gas.

Electroweak: In general there is no phase transition at all in electroweak theories with realistic Higgs masses, unless there is also another light scalar degree of freedom, which plays an essential role in phase transition dynamics.

Transition can be strong enough for baryogenesis in the MSSM if $m_H \sim 115$ GeV, and there is one very light and one very heavy stop. NMSSM with a gauge singlet has more freedom.

Higher scales: Overproduction of topological defects in phase transitions can place strong constraints on model building.

Non-thermal phase transitions, associated with low-scale inflation, offer more possibilities, but less predictive power...