Baryogenesis on electroweak scales

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Outline

Cosmology of warped extra dimensions

Cold electroweak baryogenesis

Goldberger-Wise mechanism

Warped extra dimensions provide one possible solution to the hierarchy problem

$$\mathcal{L} \ni -M_5^3 \int d^5x \sqrt{g} \left[R + \frac{12}{l^2} \right] + \int d^5x \sqrt{g} \frac{1}{2} \left[(\partial\phi)^2 + m^2\phi^2 \right]$$

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

5D RS

UV

$$ds^2 = e^{-2r/l} dx^2 - dr^2$$

$$r_0 \sim 35\, l$$

IR

$$\phi \sim A e^{-\epsilon r/l} + B e^{(4+\epsilon) r/l}$$

boundary conditions $\longrightarrow$ 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

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

This solves the hierarchy problem as long as

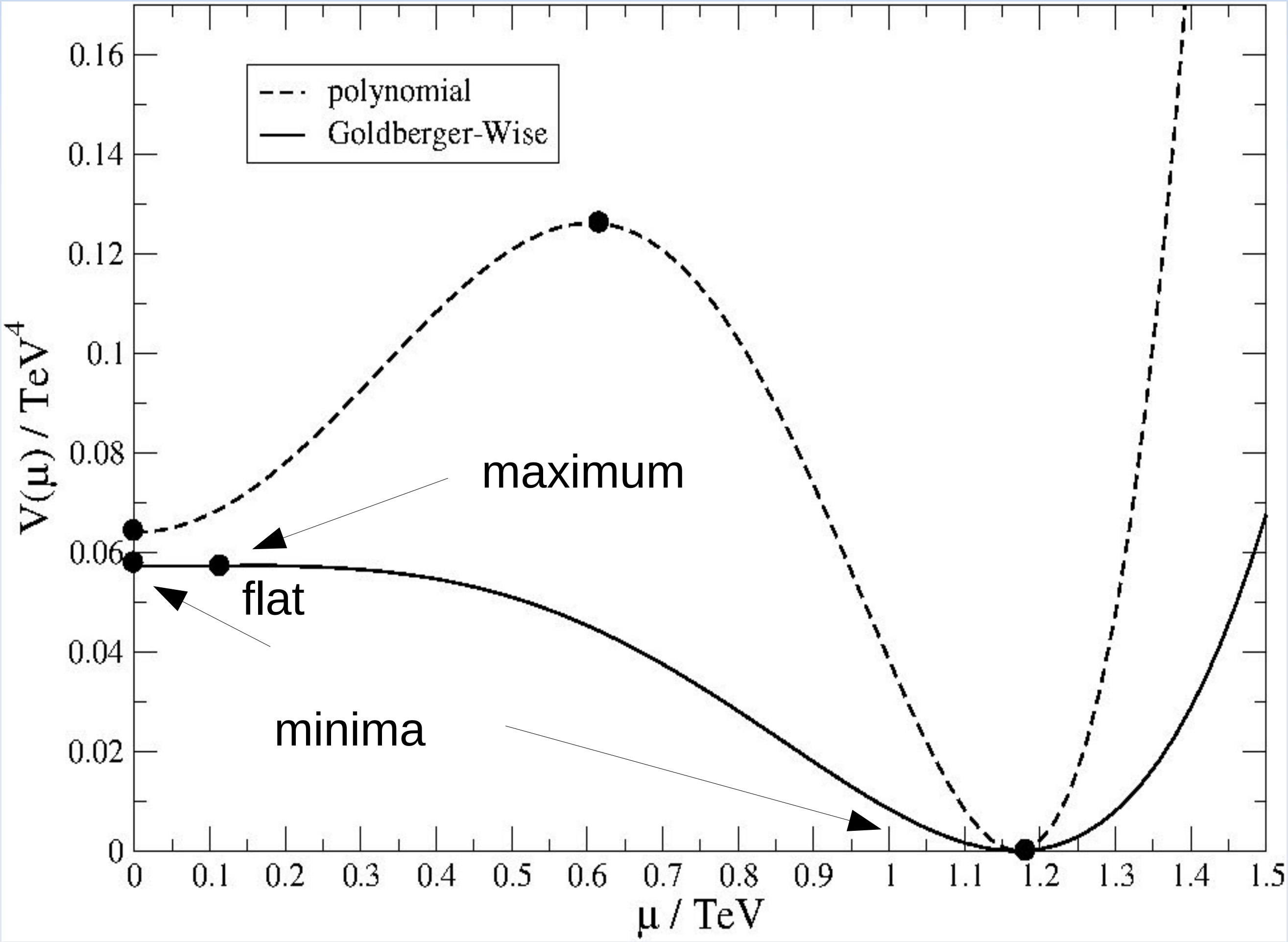
$$dV/d\mu = 0 \leftrightarrow \lambda((\mu l)^\epsilon) \simeq 0$$

$$\leftrightarrow \mu_0 \simeq l^{-1}\ O(1)^{1/\epsilon} \simeq l^{-1} 10^{-16} \simeq \mathrm{TeV}$$

Radion potential

The resulting radion potential is quite peculiar.

In particular, there is a hierarchy between the maximum and the EW minimum.

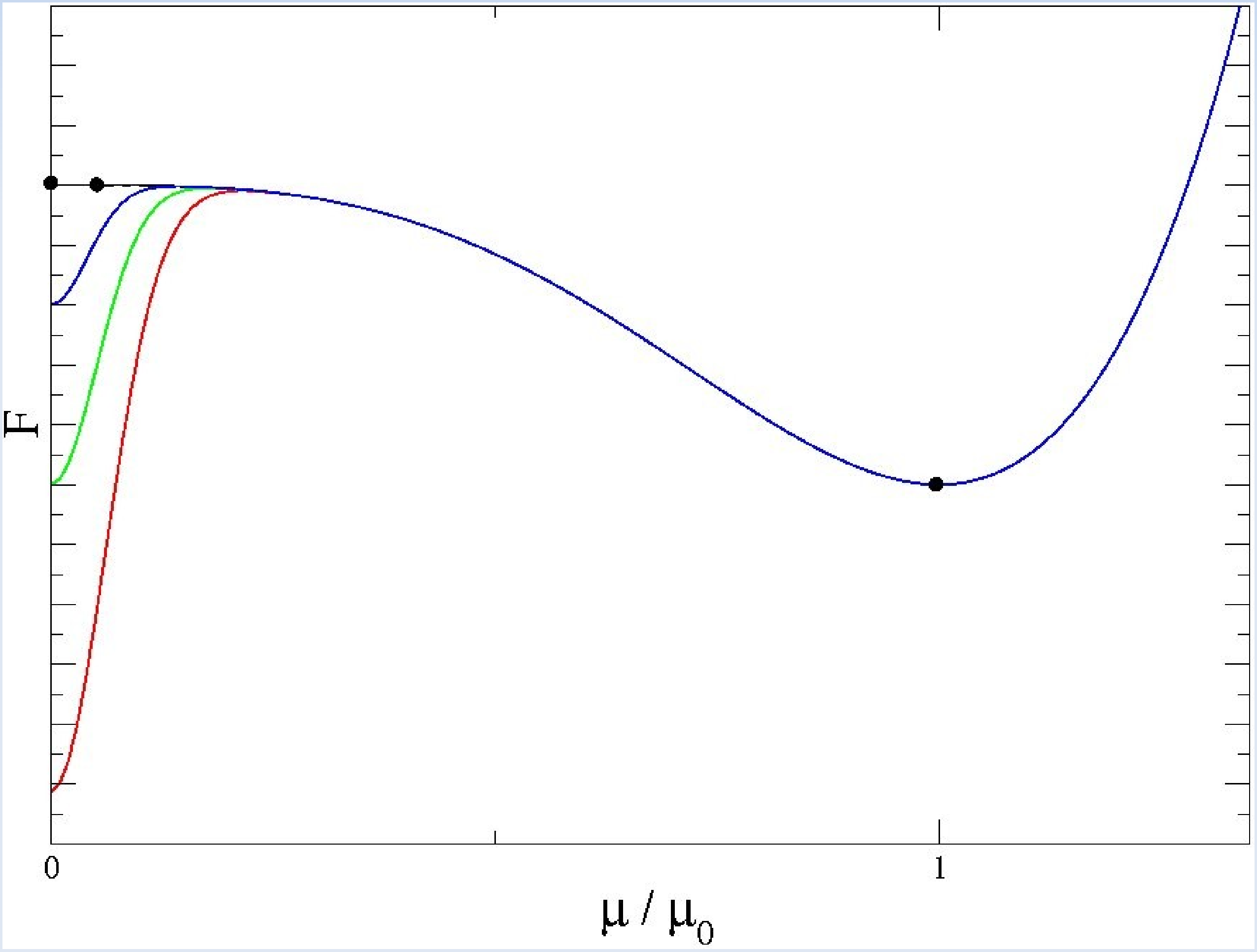


Free energy

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

$$\Delta F = \frac{\pi^2}{90}\,\Delta g\,T^4$$



Tunnel probability

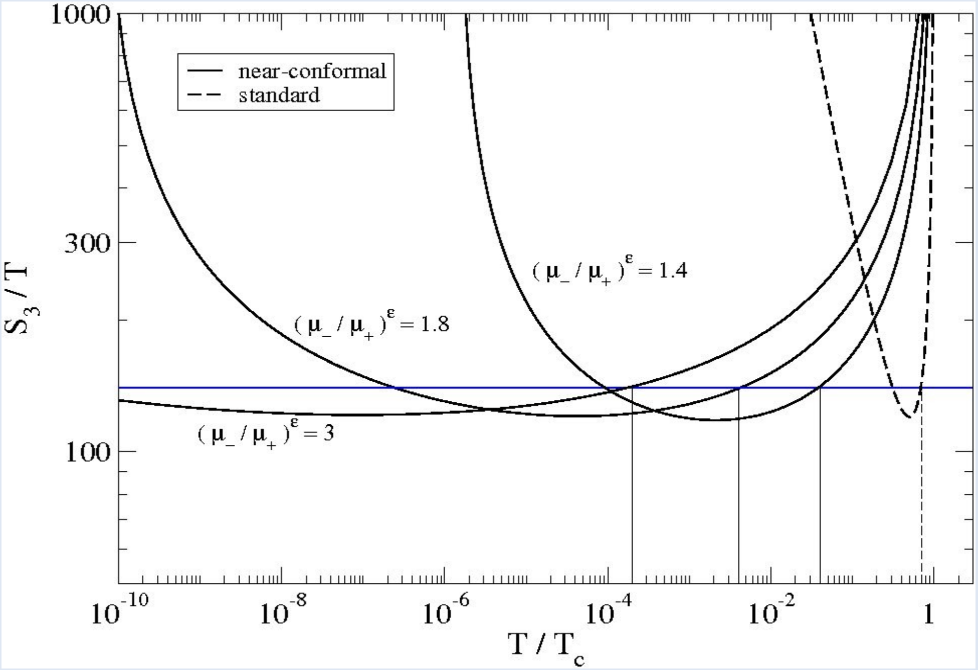
The semi-classical tunnel probability is given by the Euclidean action

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

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

$$S_3/T \sim 4 \log T/H \sim 140$$

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



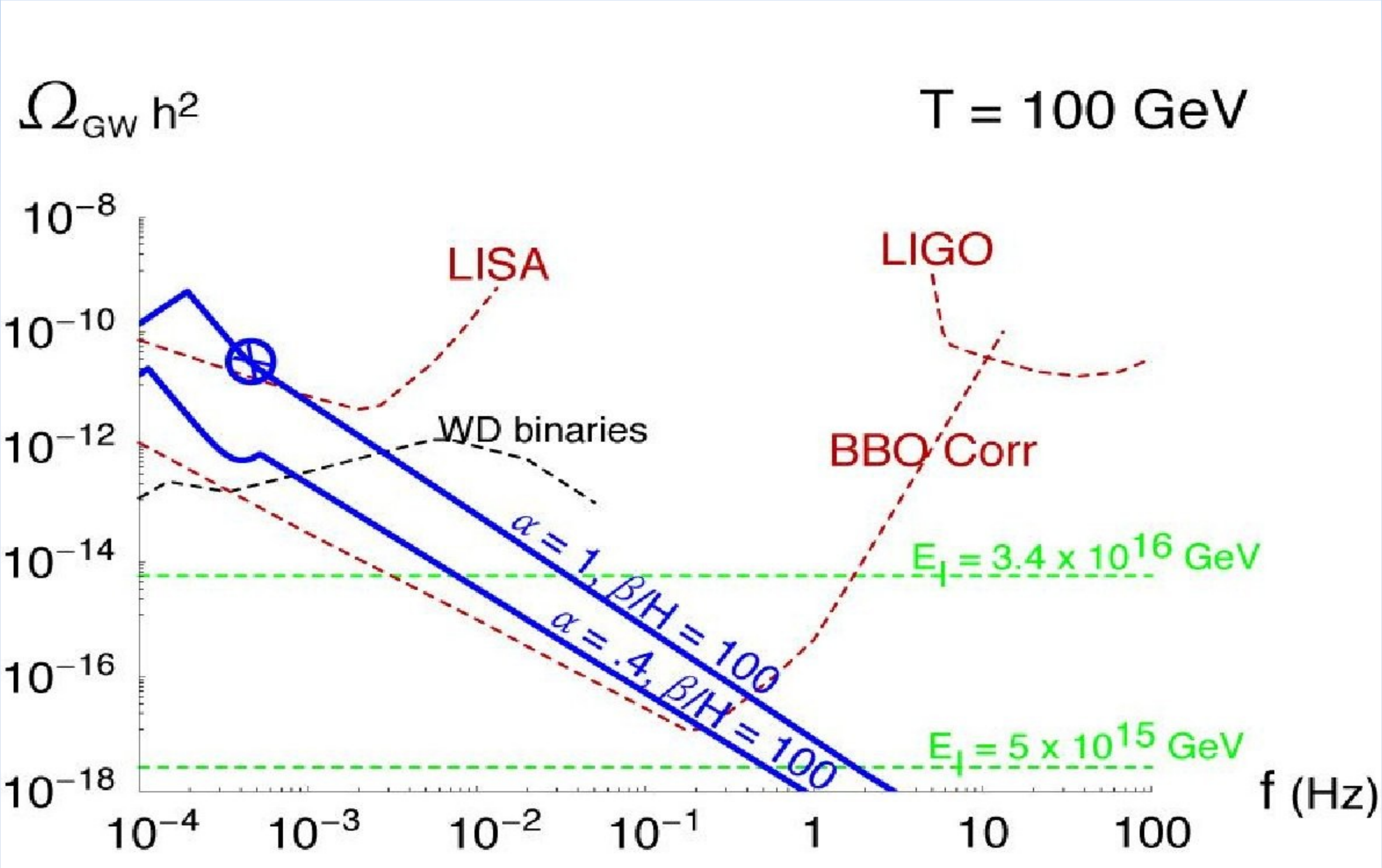
→ large supercooling and extremely strong phase transitions generic

The nearly conformal potential evades the graceful exit problem of old inflation, but only ~15 efolds of inflation possible.

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

Gravitational Waves

[Grojean, Servant '06] $\alpha = \rho_{vac}/\rho_{rad}, \quad \beta \sim \tau^{-1}, \quad v_b, \quad T$



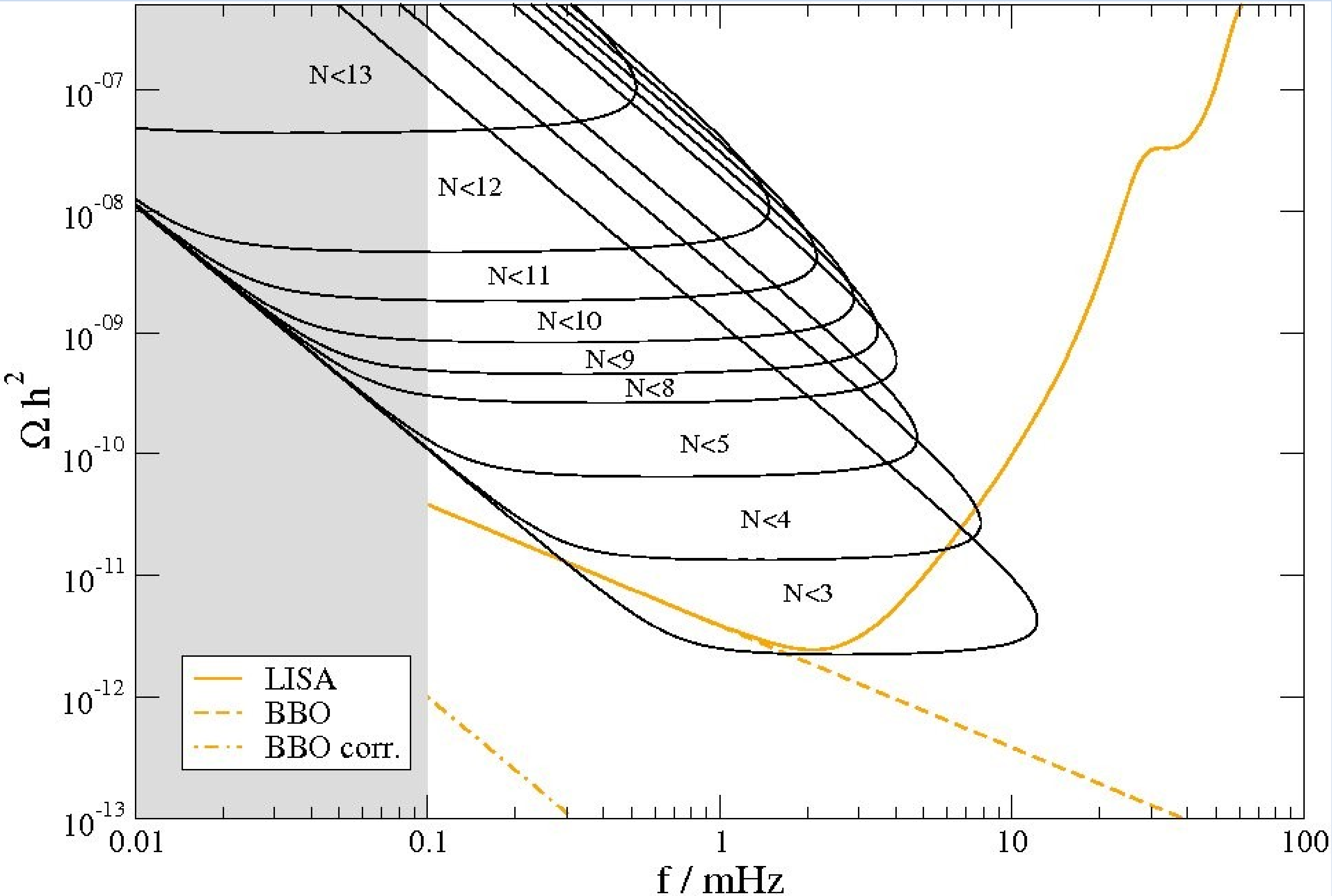
Gravitational waves

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

$$\alpha = \frac{\rho_{vac}}{\rho_{rad}} \gg 1$$

$$\tau^{-1} \gtrsim \mathrm{a\,few}\, H$$

Even very large KK scales (~100 TeV) accessible



Cosmology

Several efolds of inflation at the electroweak scale would have far-reaching implications for cosmology.

Pre-exisiting baryon asymmetries and dark matter abundances are heavily diluted.

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

	$T_{reh} > T_{EW}$		$T_{reh} < T_{EW}$	
	EWPT 1st order	2nd order crossover	$\left.\frac{\phi}{T}\right\|_{T_{reh}} > 1$	$\left.\frac{\phi}{T}\right\|_{T_{reh}} < 1$
cold EWBG	-	-	+	-
non-local EWBG	if $\phi/T\|_{T_{EW}} < 1$	-	-	-
low-scale leptogenesis	+	+	-	+
asymmetric dark matter	+	+	+	+

Summary I

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]*

Outline

Cosmology of warped extra dimensions

Cold electroweak baryogenesis

Baryogenesis

[Sakharov '69]

Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

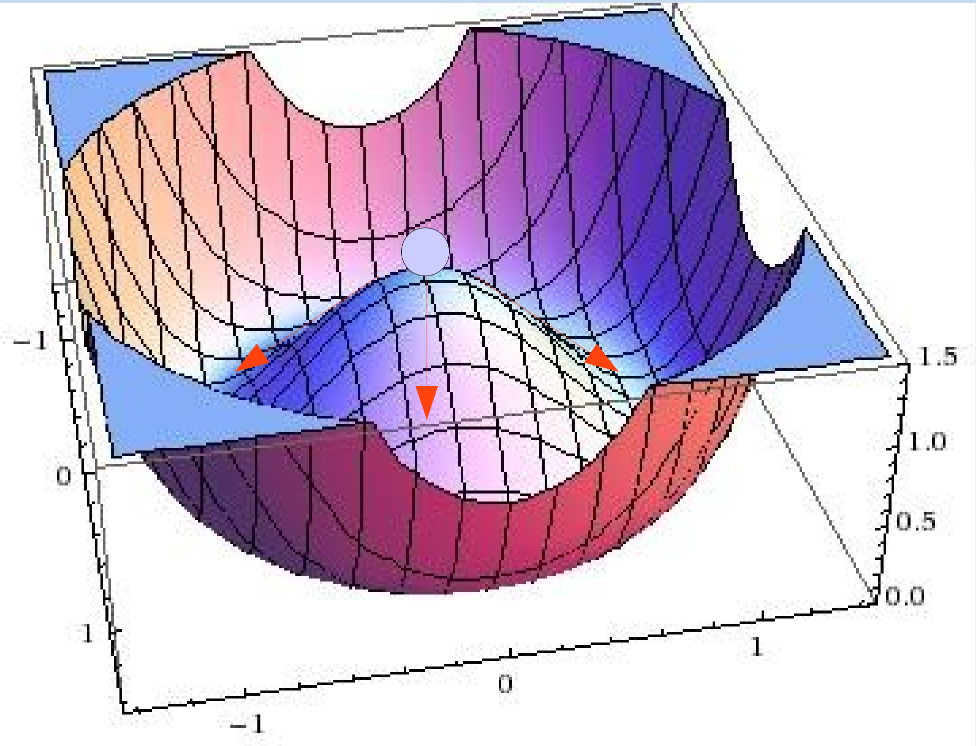
$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 10^{-10}$$

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

Tachyonic preheating

[Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov '99]
[Smit, Tranberg, '03]



In the initial stages of tachyonic preheating, the Higgs and gauge fields evolve as classical fields in the Higgs potential.

Winding numbers

$$N_{CS} = -\frac{1}{16\pi^2}\int dx^3\, \epsilon^{ijk}\mathrm{Tr}\left[A_i\left(F_{jk} + \frac{2i}{3}A_jA_k\right)\right]$$

$$N_H = \frac{1}{24\pi^2}\int dx^3\, \epsilon^{ijk}\mathrm{Tr}\left[\partial_i\Omega\Omega^{-1}\partial_j\Omega\Omega^{-1}\partial_j\Omega\Omega^{-1}\right]$$

$$\phi = \Omega\phi_0$$

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]

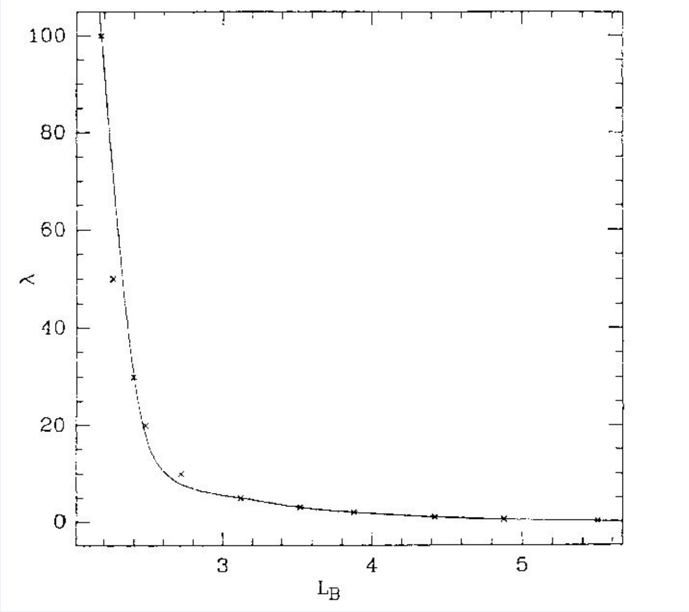
Decay vs. dressing

Consider the configuration with non-trivial winding

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

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

[Turok, Zadrozny '90]

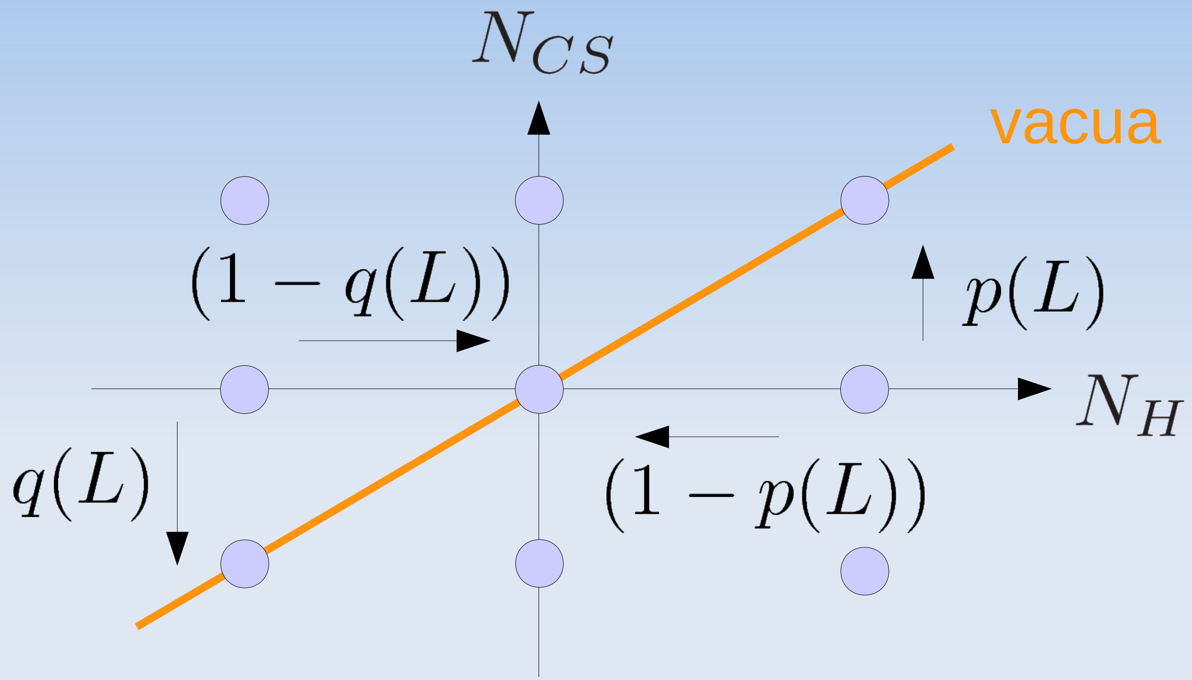


bifurcation point
(in $\sqrt{2}m_W$) as a function of the quartic Higgs coupling (λ/g^2)

$$m_H < 200\,\mathrm{GeV} \leftrightarrow L^{-1} < 20\,\mathrm{GeV}$$

CPV will have an impact on the bifurcation point for winding / antiwinding.

Winding numbers



Different behavior for winding and antiwinding $(p \neq q)$ requires CP violation, e.g.

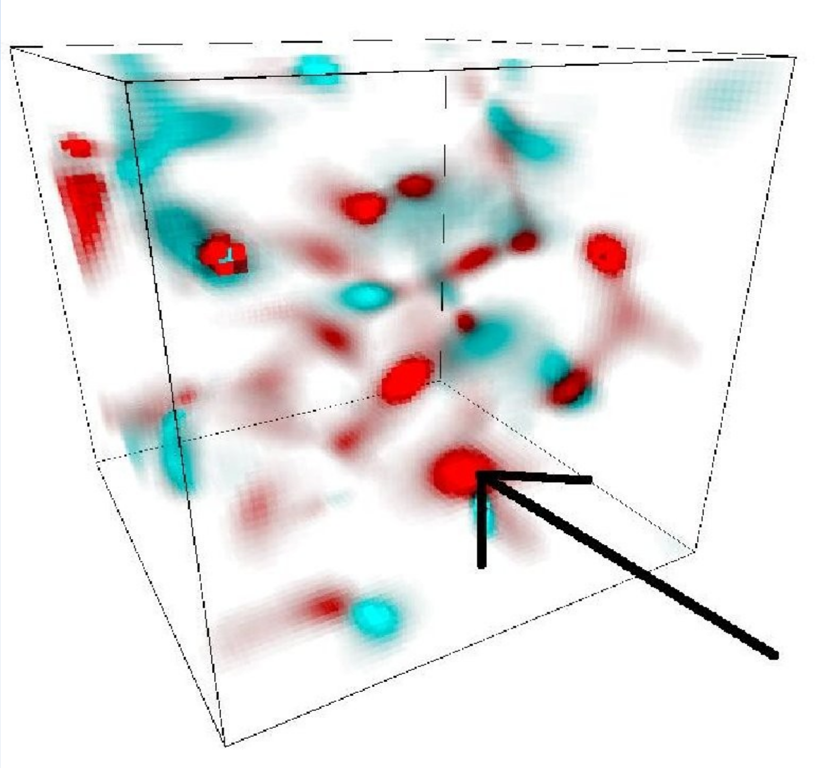
$$\mathcal{L} \ni \frac{1}{M^2}\phi^2 F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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

Simulations

[van der Meulen, Sexty, Smit, Tranberg '06]
[Garcia-Bellido, Garcia-Perez, Gonzlez-Arroyo '03]

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

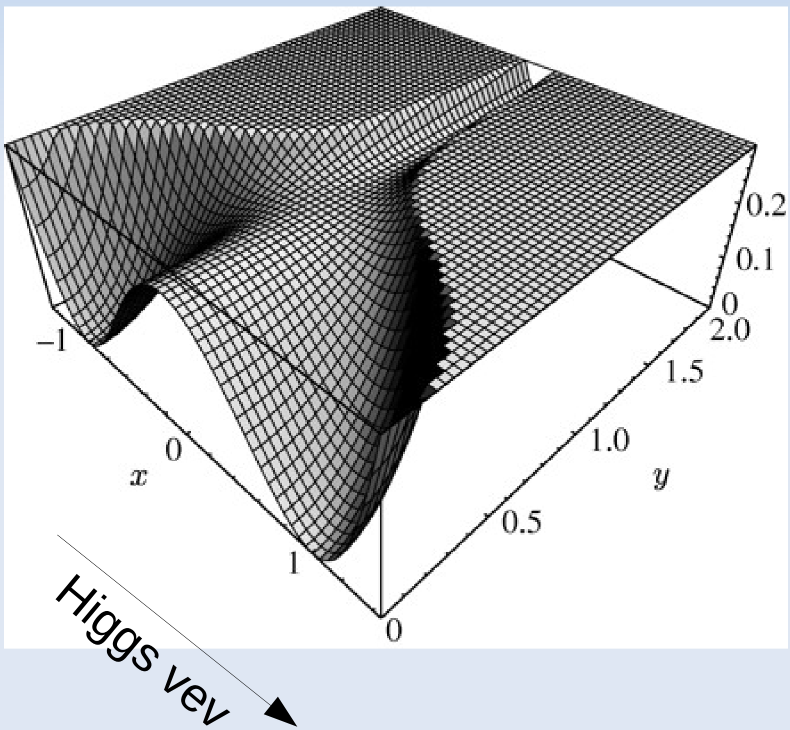


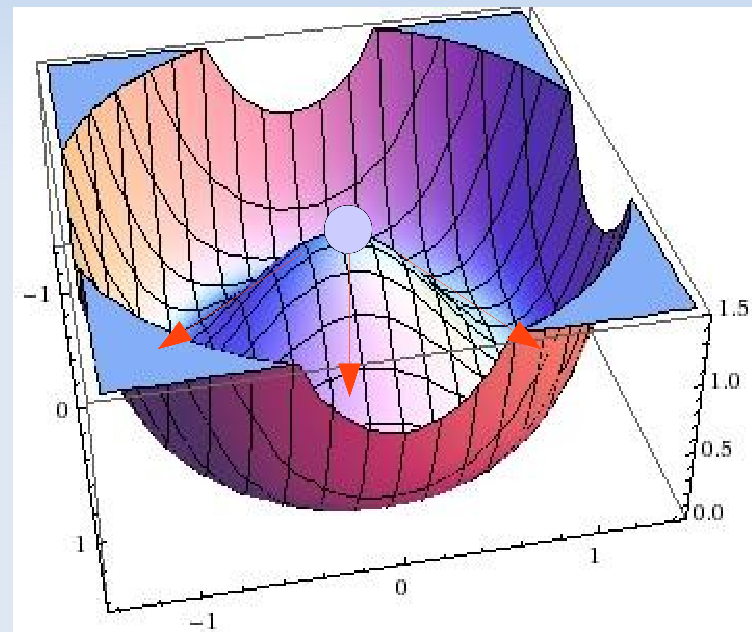
The observed baryon asymmetry can be reproduced with $M < 10^4 v$

while EDM constraints require $M > 14\,\mathrm{TeV}$

Initial conditions

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

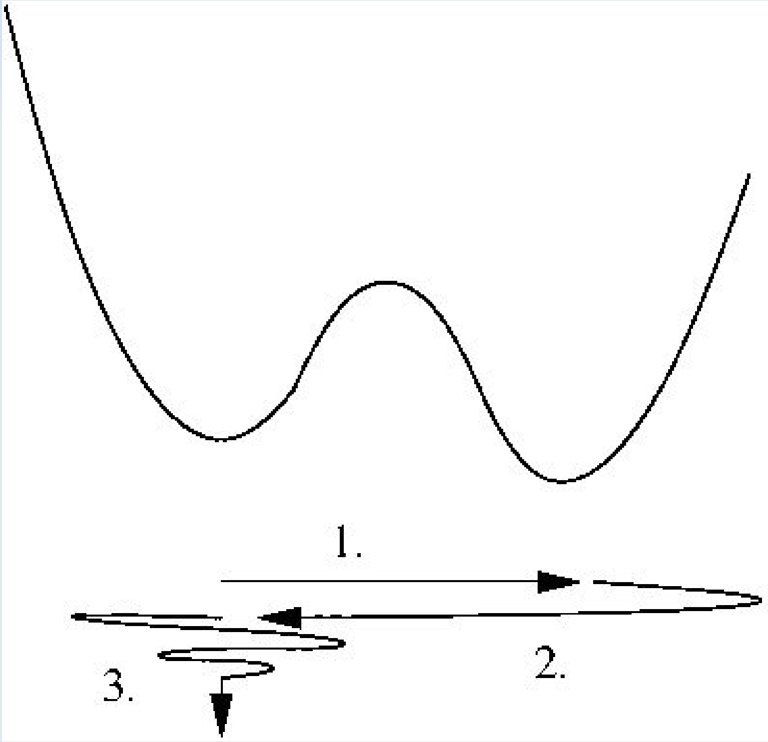
[Hawking, Moss & Stewart '82]
[Watkins & Widrow '92]
[Giblin, Hui, Lim & Yang '10]

- nearly conformal potential

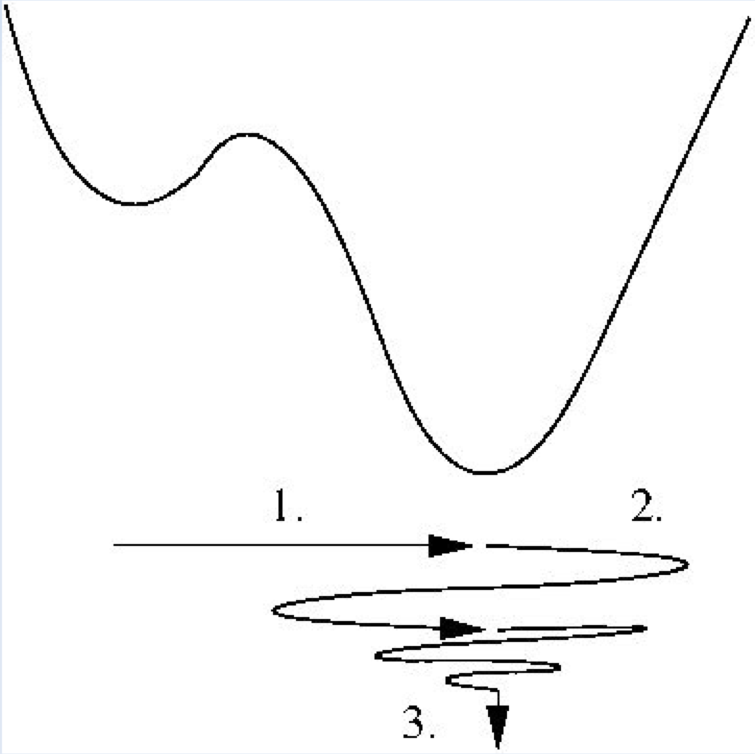
[TK & Servant '11]

Bubble Collisions

rather symmetric potential



rather asymmetric potential



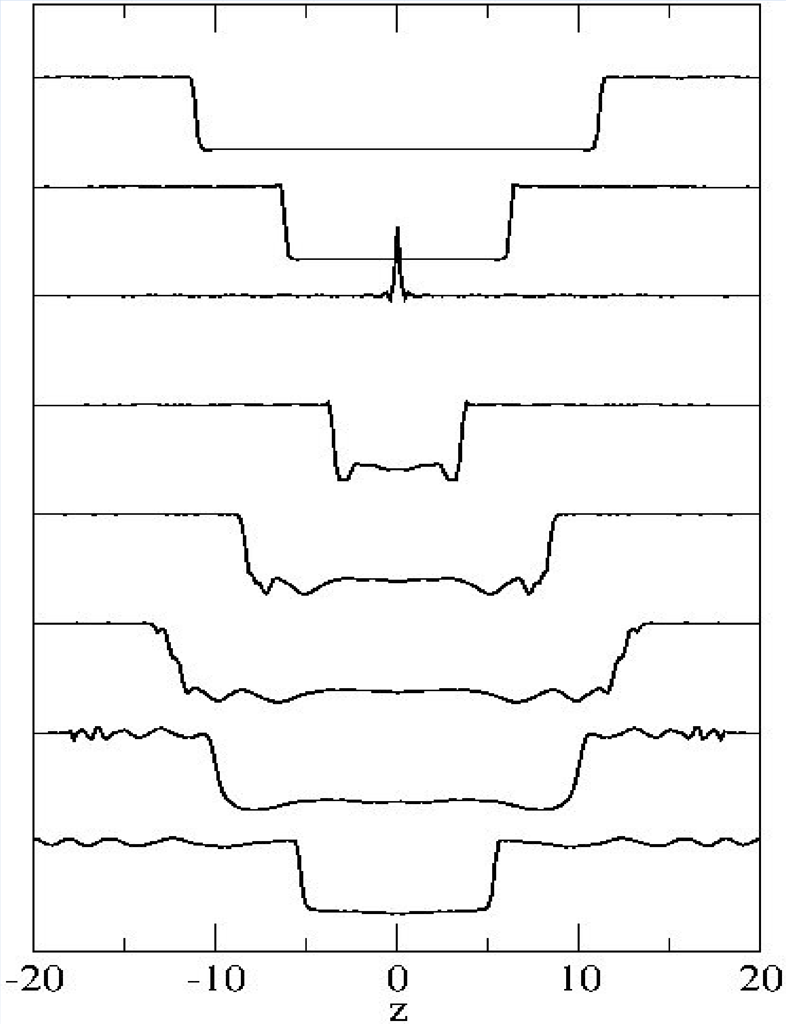
[Giblin, Hui, Lim & Yang '10]

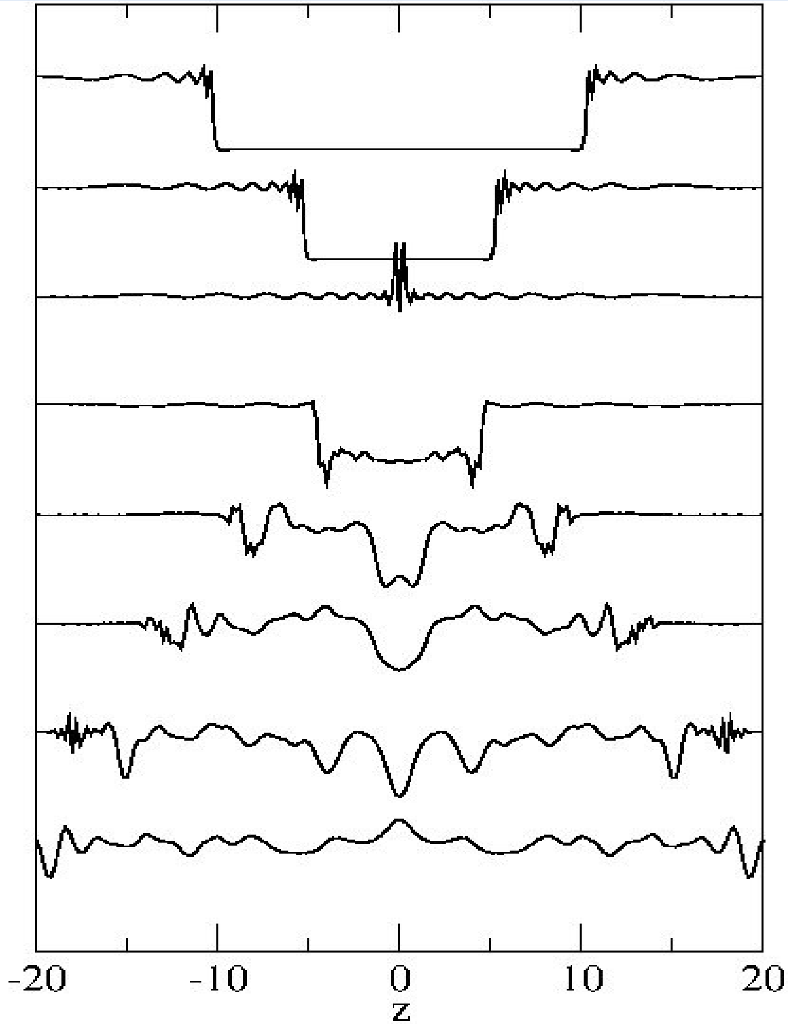
Bubble Collisions

rather symmetric potential

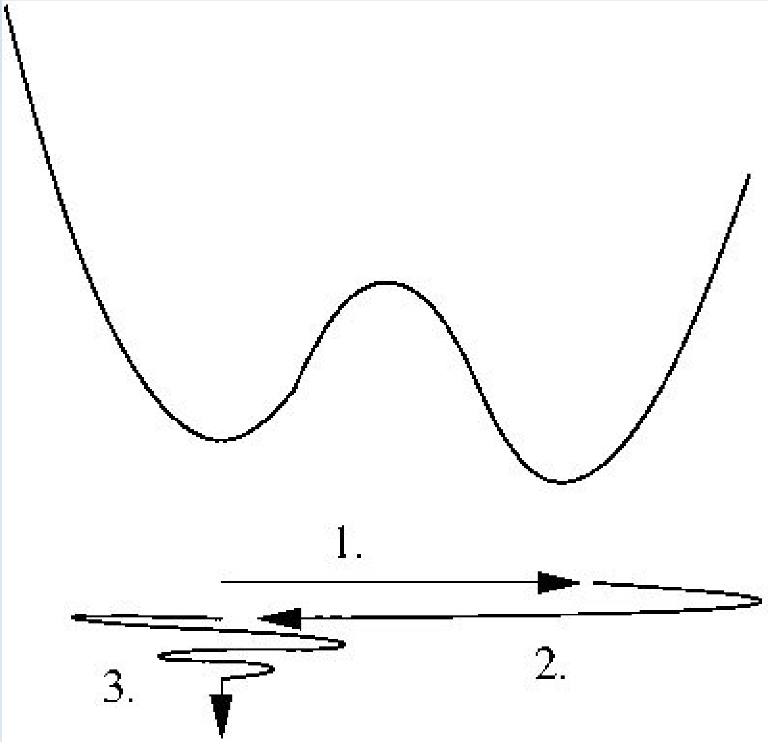
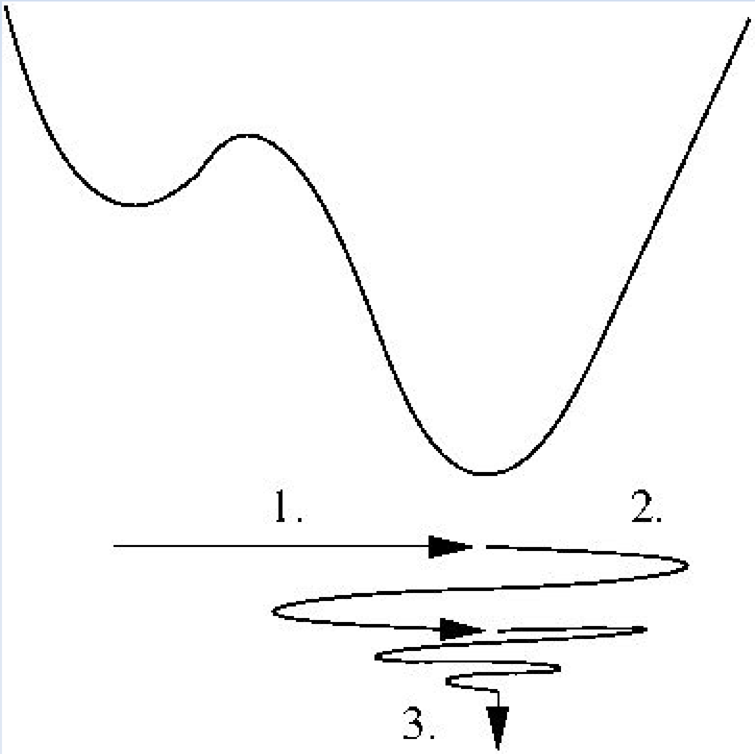
rather asymmetric potential

1+1 dim





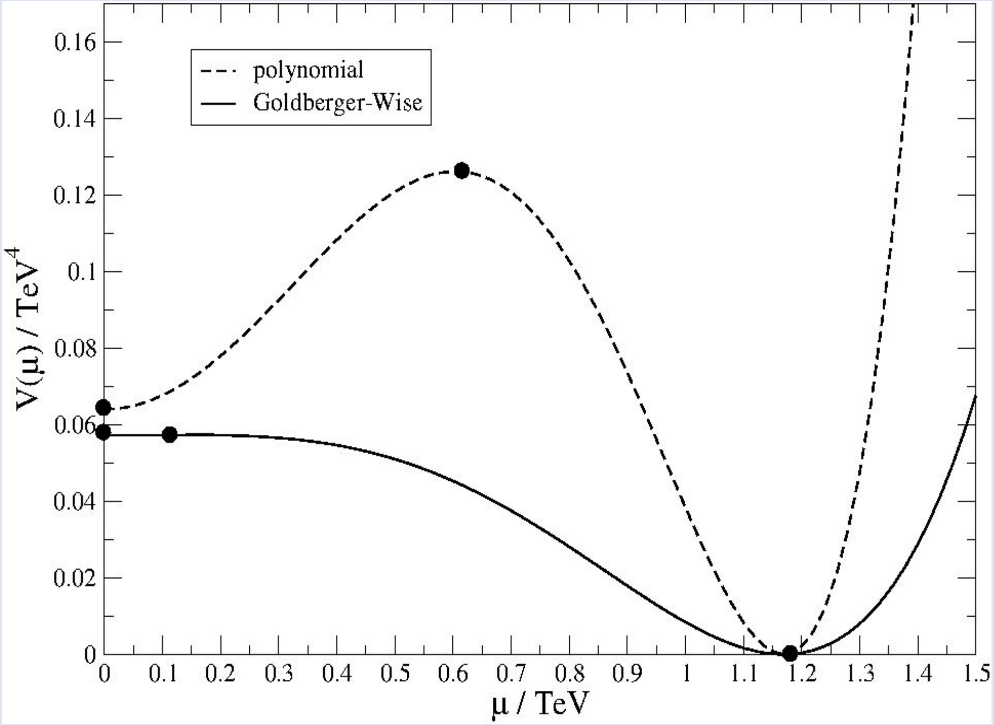
Bubble Collisions

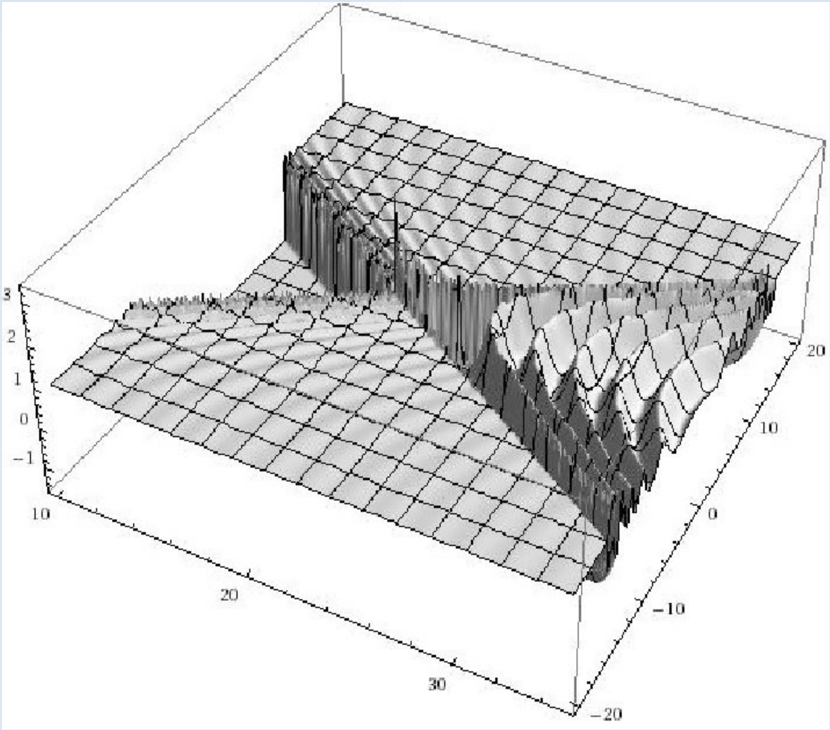
rather symmetric potential	rather asymmetric potential
	

Radion potential

The radion potential is prototypical for an asymmetric potential

The flatness of the potential even leads to some ”slow roll” behavior





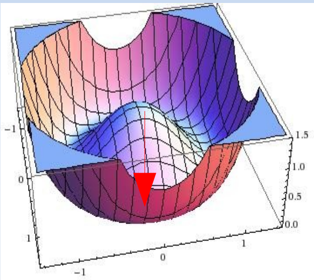
Summary II

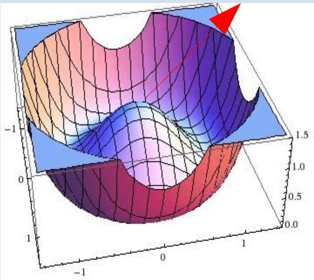
- After the phase transition, all the energy resides in the scalar sector.
- The scalar sector contains in this case

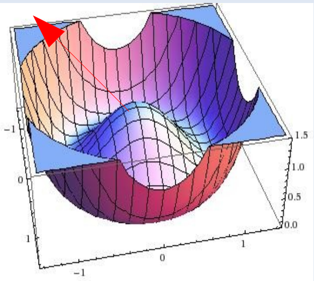
  Higgs+radion $\leftrightarrow$ Higgs+inflaton
- These are suitable conditions for cold electroweak baryogenesis
- For viable baryogenesis one has to ensure that the electroweak symmetry is not restored after reheating (radion and Higgs masses)

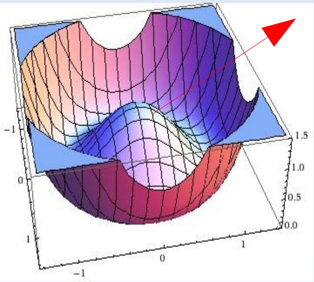
Randomness

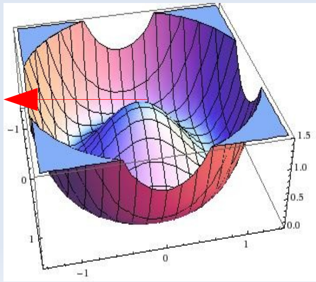
tachyonic preheating
after hybrid inflation



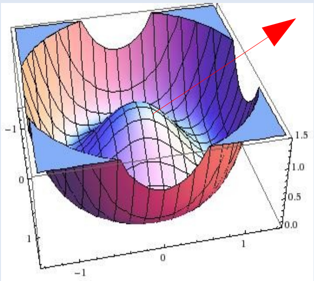


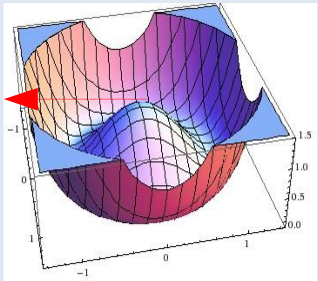






preheating after supercooled
first-order PT





simulations
required

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 singnal for such a scenario are gravitational waves that peak at around f ~ 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 (alsmost 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] $N < 3$ thermal / thin wall
[Randall, Servant, '06] quantum / thick wall
[Hassanain, March-Russell, Schvellinger '07] throats
[Nardini, Quiros, Wulzer '09] $N < 13$ numerical
[TK, Nardini, Quiros '10] backreactions