Natural cold baryogenesis from nearly conformal dynamics at the TeV scale

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references: Konstandin-Servant
1104.4791 & 1104.4793

Cold Baryogenesis I

An alternative to standard EW baryogenesis

1) Cold (the universe never reheats above the EW scale)

2) Local (B and CP violation occur together in space and time
i.e. the mechanism does not rely on charge transport)

3) In its present realization, does not rely on 1st order PT but on
inflationary phase instead

Cold Baryogenesis II

main idea:
During EWPT, SU(2) textures can be produced.
They can lead to B-violation when they decay.

Turok, Zadrozny '90
Lue, Rajagopal, Trodden, '96

However: large departure from equilibrium needed for

1) Sufficient production of winding number (possible via preheating)
2) Low reheat temperature to prevent washout afterwards

In practise: can only work for a "quenched" phase transition

Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, hep-ph/9902449

Krauss-Trodden, hep-ph/9902420

Cold Baryogenesis III

Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, hep-ph/9902449

Krauss-Trodden, hep-ph/9902420

- Inflation ends with reheating below the EW scale

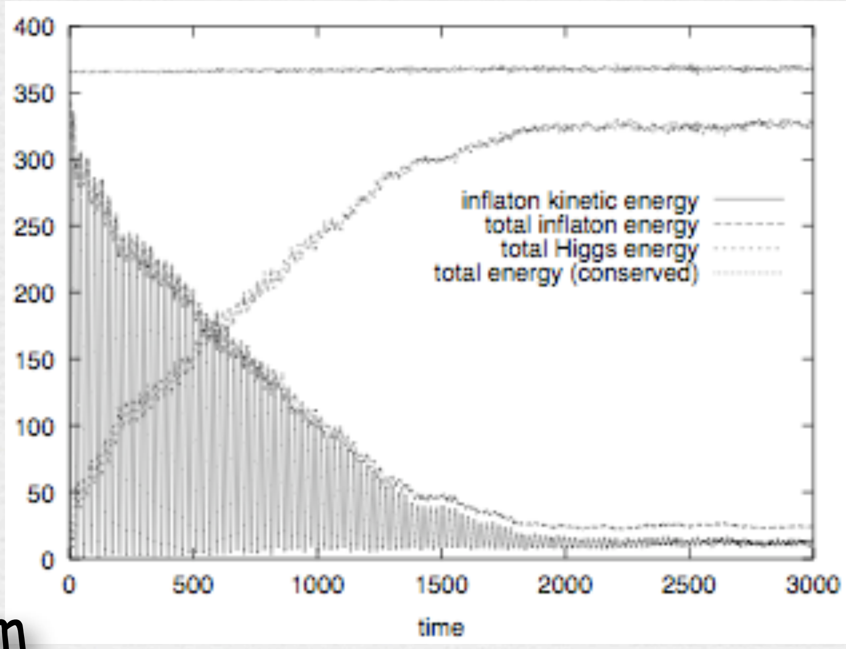
- Non-thermal production of sphalerons via preheating

  (inflaton oscillations induce large occupation numbers
  for long wavelength configurations of the Higgs)

Hybrid inflation potential:

$$V(\underset{\substack{\nwarrow \\ \text{inflaton}}}{\sigma}, \underset{\substack{\nwarrow \\ \text{Higgs}}}{\phi}) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{1}{2}\tilde{m}^2\sigma^2 + \frac{1}{2}g^2\sigma^2\phi^2$$

If $\frac{g^2\phi_0^2}{2m_\phi^2} > 10^3$ parametric resonance in EW fields



- Lack of naturalness remains a problem

We need to produce $$\Delta B = 3\Delta N_{CS}$$

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

key point: The dynamics of N_{CS} is linked to the dynamics of the Higgs field via the Higgs winding number N_H:

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

$$\frac{\rho}{\sqrt{2}}\Omega = (\epsilon\phi^*, \phi) = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix} \quad , \quad \rho^2 = 2(\phi_1^*\phi_1 + \phi_2^*\phi_2)$$

$$\delta N \equiv N_{CS} - N_H$$

In vacuum: $\delta N=0$

A texture is a configuration which has $\delta N \neq 0$. It is unstable and decays.
During the EWPT & preheating, configurations with $\Delta N_H \neq 0$ are produced. They relax to 0 by either changing N_H or N_{CS}.
In the latter case, there is anomalous fermion number production.

CP violation affects how textures unwind !

$\delta N<0$ configurations prefer to unwind by relaxing N_H while
$\delta N>0$ configurations prefer to unwind by relaxing N_{CS}

---> Baryogenesis

Common source of CP violation used in this context

$$\mathcal{O}_{CPV} = \frac{1}{M^2}\phi^\dagger\phi\tilde{F}F$$

acts as a chemical potential for the Chern Simons number

$$\int d^4x\,\frac{1}{M^2}\phi^\dagger\phi\,\tilde{F}F \leftrightarrow \int dt\,\mu_{cs}\,N_{cs},$$

$$\mu_{cs} \propto \frac{1}{M^2}\frac{d}{dt}\langle\phi^\dagger\phi\rangle$$

from simulations in the context of inverted hybrid inflation:

$$\boxed{\frac{n_B}{s} \propto 3\times 10^{-3}\,\frac{v^2}{M^2},}$$

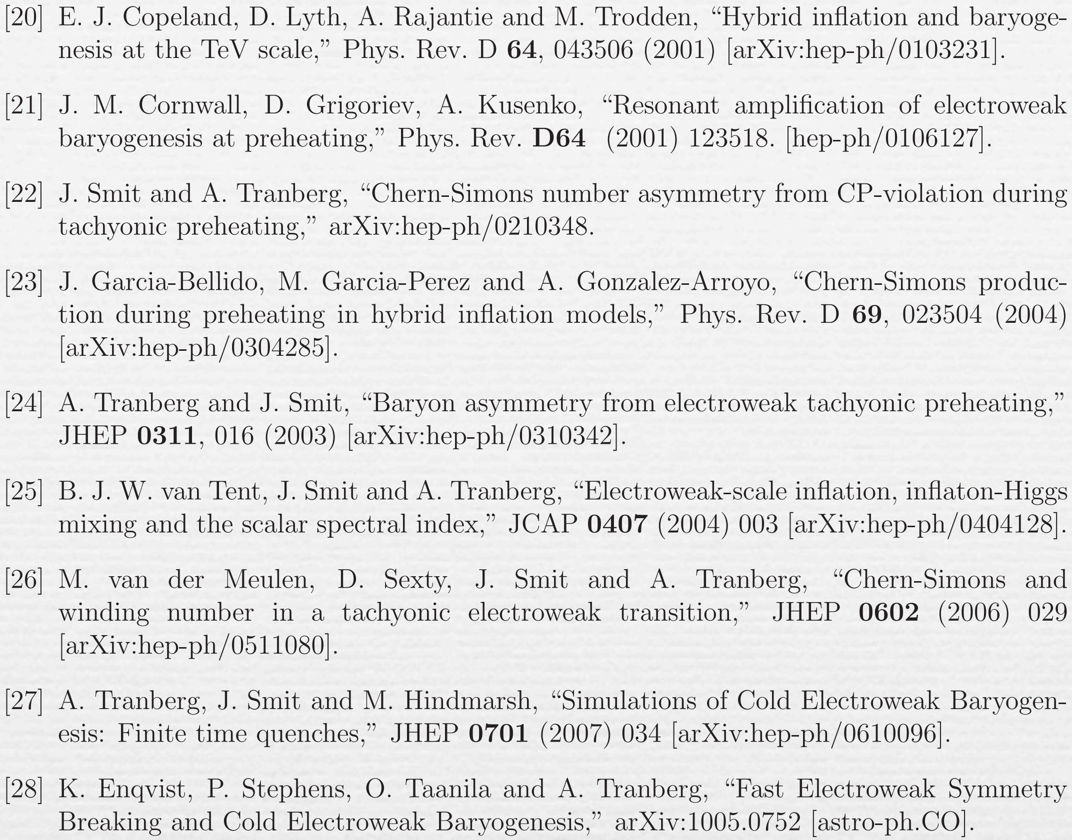
Tranberg, Smit, Hindmarsh
hep-ph/0610096

large enough provided that M ≲ 500 TeV

OK with EDM constraint if M ≳ 14 TeV

Literature on cold baryogenesis

15 papers following the
2 original articles:



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[22] J. Smit and A. Tranberg, "Chern-Simons number asymmetry from CP-violation during tachyonic preheating," arXiv:hep-ph/0210348.

[23] J. Garcia-Bellido, M. Garcia-Perez and A. Gonzalez-Arroyo, "Chern-Simons production during preheating in hybrid inflation models," Phys. Rev. D **69**, 023504 (2004) [arXiv:hep-ph/0304285].

[24] A. Tranberg and J. Smit, "Baryon asymmetry from electroweak tachyonic preheating," JHEP **0311**, 016 (2003) [arXiv:hep-ph/0310342].

[25] B. J. W. van Tent, J. Smit and A. Tranberg, "Electroweak-scale inflation, inflaton-Higgs mixing and the scalar spectral index," JCAP **0407** (2004) 003 [arXiv:hep-ph/0404128].

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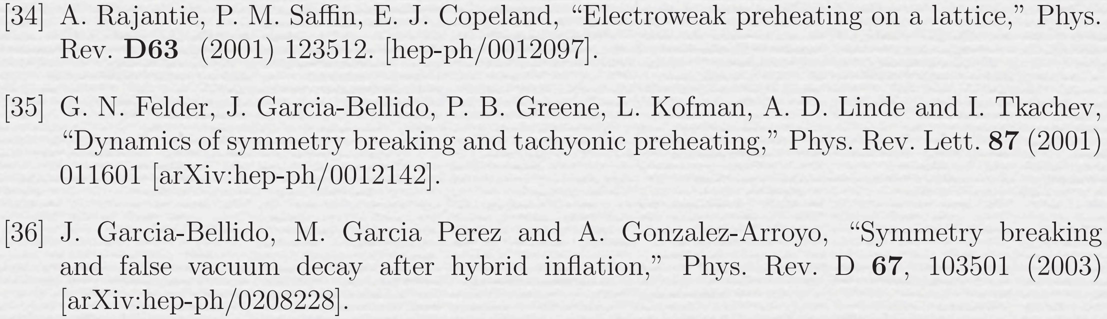

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[35] G. N. Felder, J. Garcia-Bellido, P. B. Greene, L. Kofman, A. D. Linde and I. Tkachev, "Dynamics of symmetry breaking and tachyonic preheating," Phys. Rev. Lett. **87** (2001) 011601 [arXiv:hep-ph/0012142].

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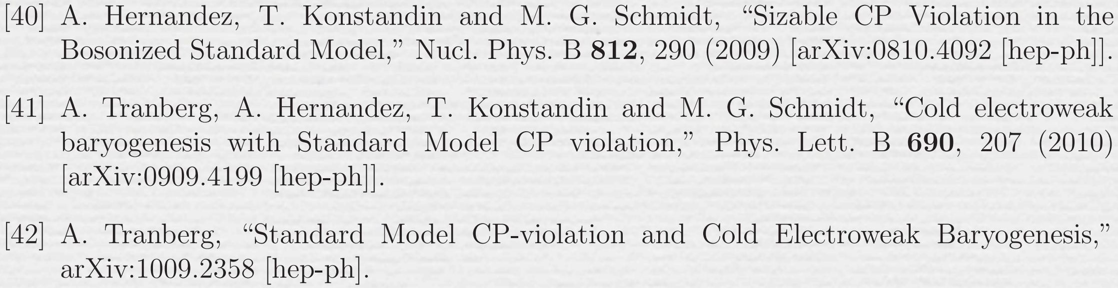

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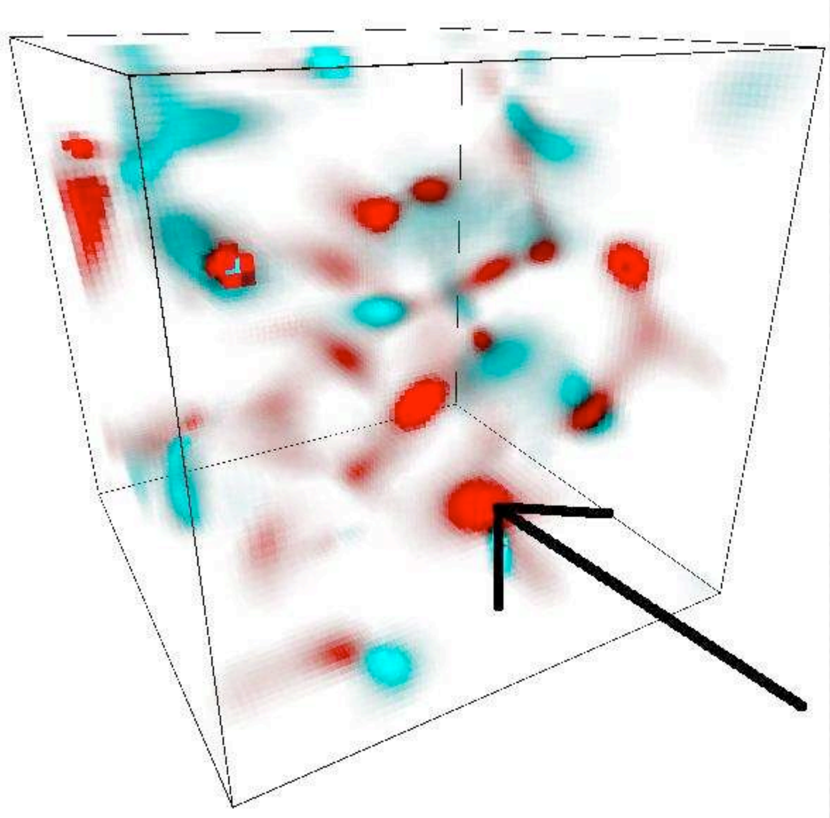
3D evolution of winding number density

van der Meulen, Sexty, Smit, Tranberg'05



Our motivation:

- make cold baryogenesis more natural
- and study it in the context of very strong first-order phase transitions

note:
only a few efolds of inflation are sufficient for cold baryogenesis to work

Our main points:

Konstandin Servant '11

1) Large winding configurations can be produced during a 1st order PT when bubbles collide in a cold universe, provided that the scalar potential is asymmetric or nearly conformal

2) This can lead to baryogenesis provided that the universe is sufficiently cold at nucleation and that the reheat temperature is below the sphaleron freese-out temperature

3) These conditions can arise naturally in models of nearly conformal dynamics at the TeV scale. A well-known explicit realization is the Goldberger-Wise radion stabilisation mechanism.

Reminder

Typically, an extended phase of inflation (at least several efolds) cannot be ended by a first-order phase transition.
Well-known graceful exit pb of eternal inflation

# of bubbles per horizon volume $\beta/H = T\frac{d}{dT}\frac{S_3}{T}\Big|_{T_n} \sim \frac{T_n}{\mu_0}\ \ \frac{S_3}{T}\Big|_{T_n}$

(μ_0 is the vev at the minimum)

$$S_3/T \approx \log\frac{T^4}{H^4}$$ ~ 140

$$N_{\rm efolds} \sim \log T_c/T_n \sim 10 \to T_n/T_c \sim 10^{-4}$$

β/H << 1 --> eternal inflation

Now consider a potential of the form

$$V(\mu) = \mu^4 P((\mu/\mu_0)^\epsilon).$$

Rattazzi, Zaffaroni '00

a scale invariant function modulated by a slow evolution through the μ^ϵ term

for $|\varepsilon| << 1$

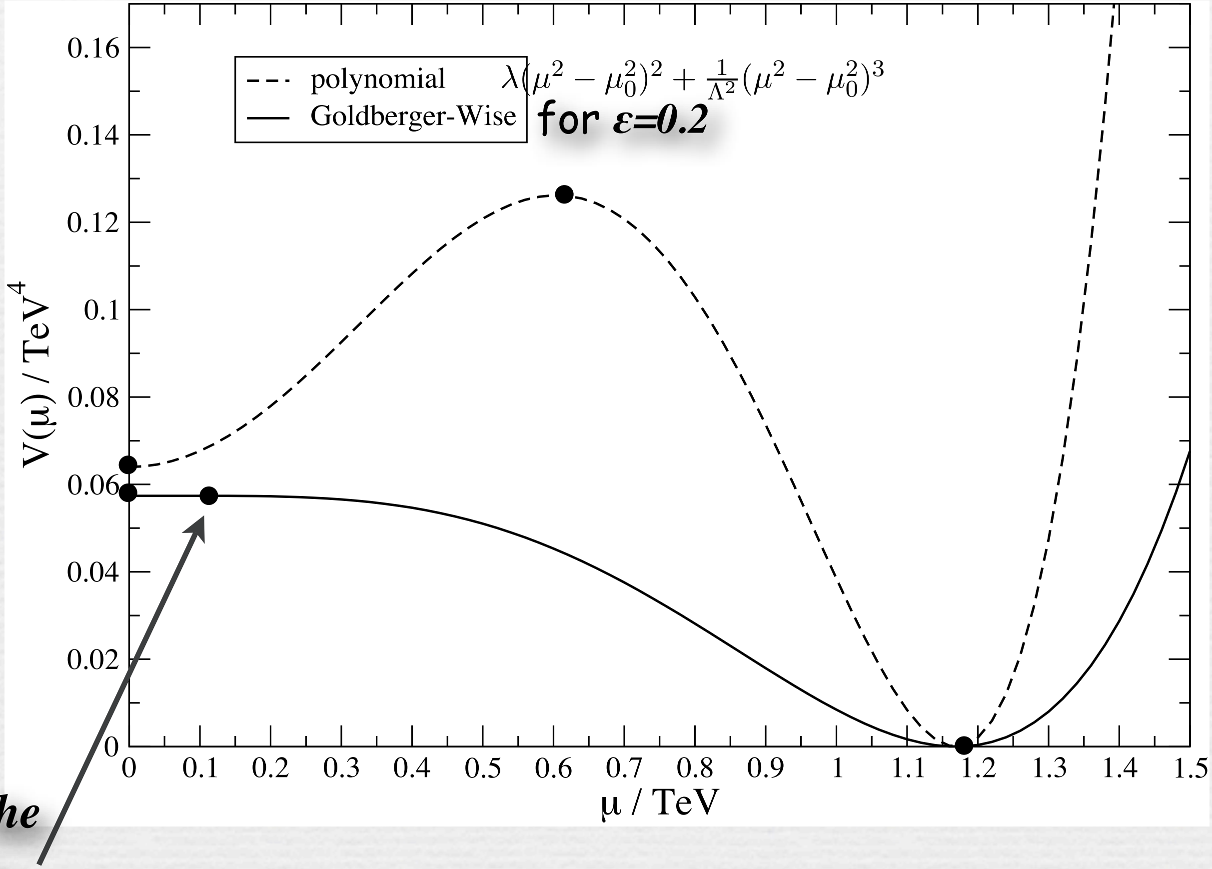
similar to Coleman-Weinberg mechanism where a slow RG evolution of potential parameters can generate widely separated scales

$$\beta/H = T \frac{d}{dT} \frac{S_3}{T}\bigg|_{T_n} \sim \epsilon \ \ \frac{S_3}{T}\bigg|_{T_n} \gtrsim 1.$$

possible to achieve several efolds of inflation and still complete the phase transition if ϵ~O(1/10)

$$V(\mu) = \mu^4 P((\mu/\mu_0)^\epsilon).$$

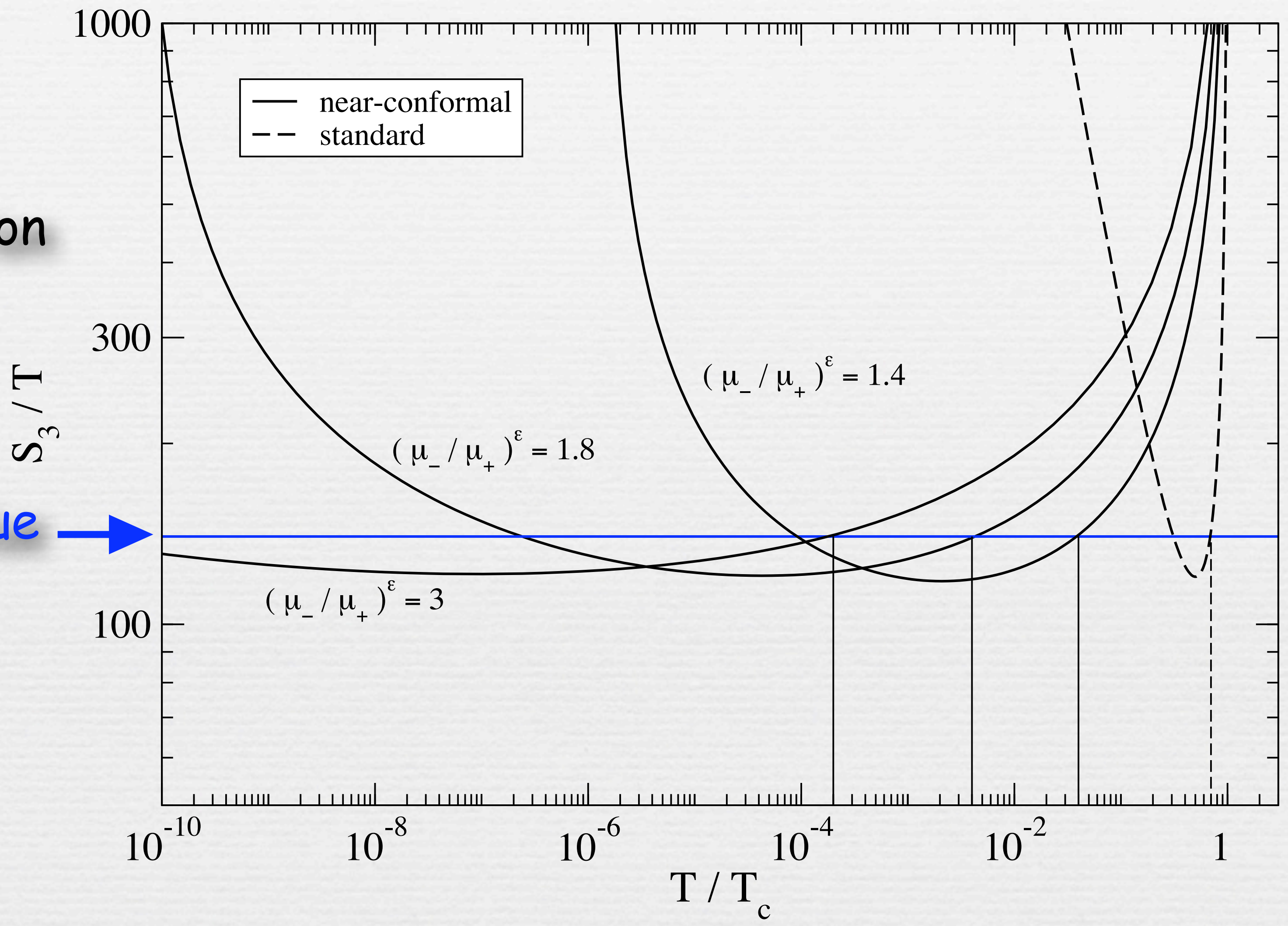
The position of the maximum μ_+ and of the minimum μ_- can be very far apart in contrast with standard polynomial potentials where they are of the same order



position of the maximum

The tunneling value μ_r can be as low as $\sqrt{\mu_+\mu_-} \ll \mu_-$

bubble action



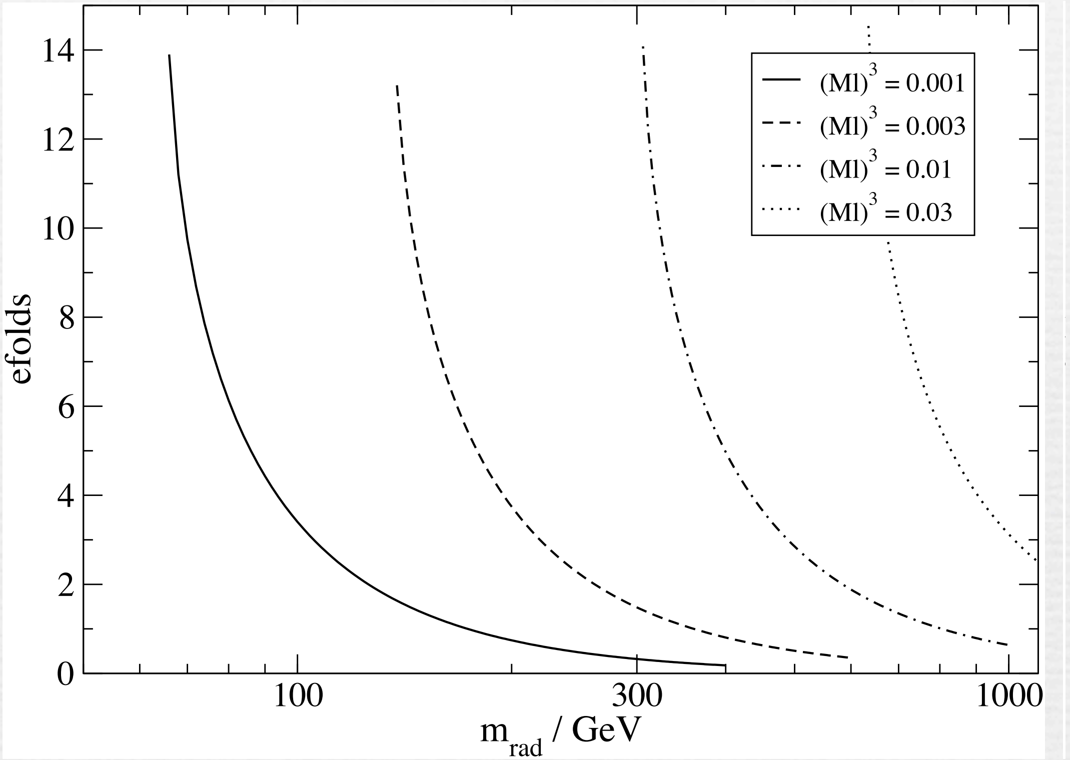
critical value

key point: value of the field at tunneling is much smaller than value at the minimum of the potential

nucleation temperature very small

Typical amount of supercooling (number of efolds)

$$N_{\rm efolds} \sim \log \frac{T_c}{T_n} \simeq \log \frac{\mu_-}{\mu_r} \,.$$



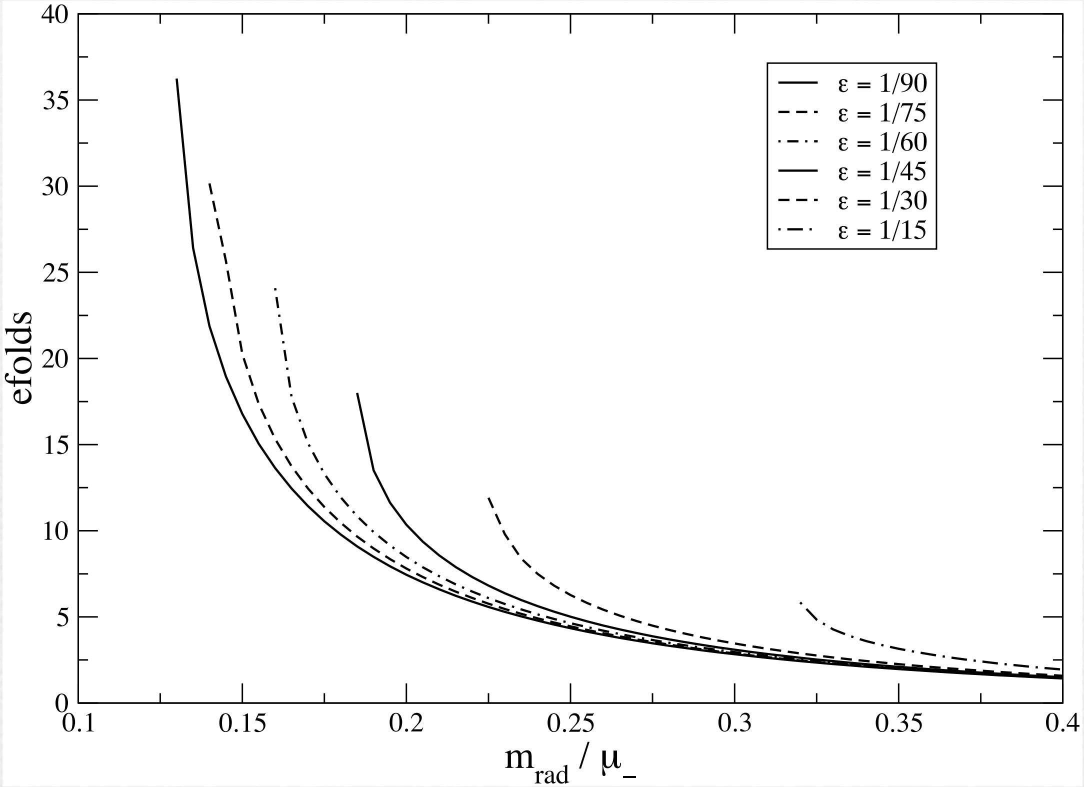
$$F_{\rm AdS-S} = -4\pi^4 (Ml)^3 T^4$$

$$(Ml)^3 = N^2/16\pi^2$$

In RS, the ratio μ_-/μ_+ is constrained by the EW/Planck scale hierarchy:

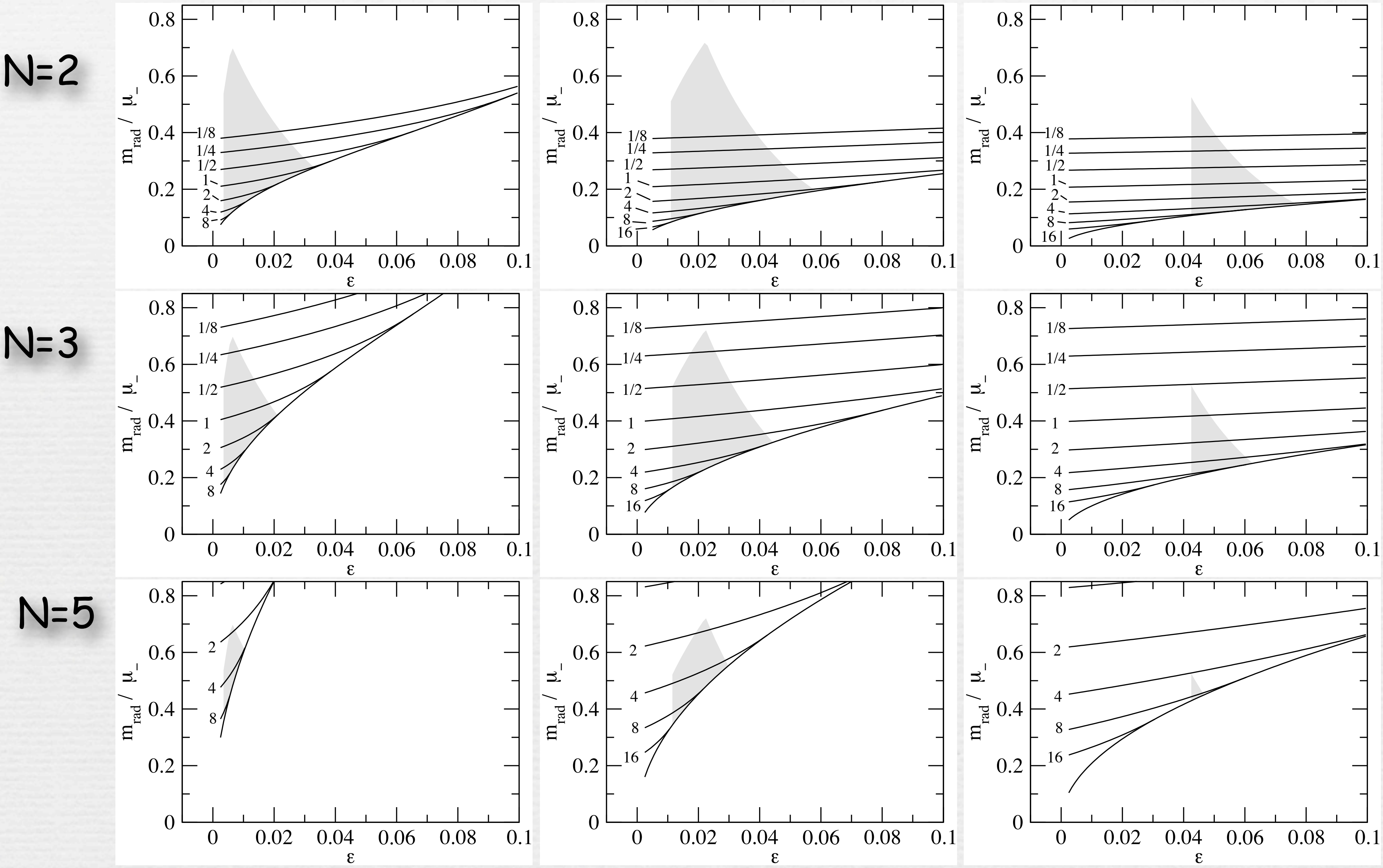
$\mu_-/\mu_+ < 10^{16}$ GeV thus $N_{\rm efolds} < 18$

Number of efolds when relaxing the constraint on the EW/Planck hierarchy:



Contours for number of efolds

(using Goldberger-Wise stabilization mechanism)



for earlier studies of this phase transition see

Cline, Firouzjahi'00
Creminelli, Nicolis, Rattazzi'01
Randall, Servant'06

Hassanain, March-Russell, Schwellinger'07
Nardini,Quiros,Wulzer'07
Konstandin,Nardini,Quiros'10

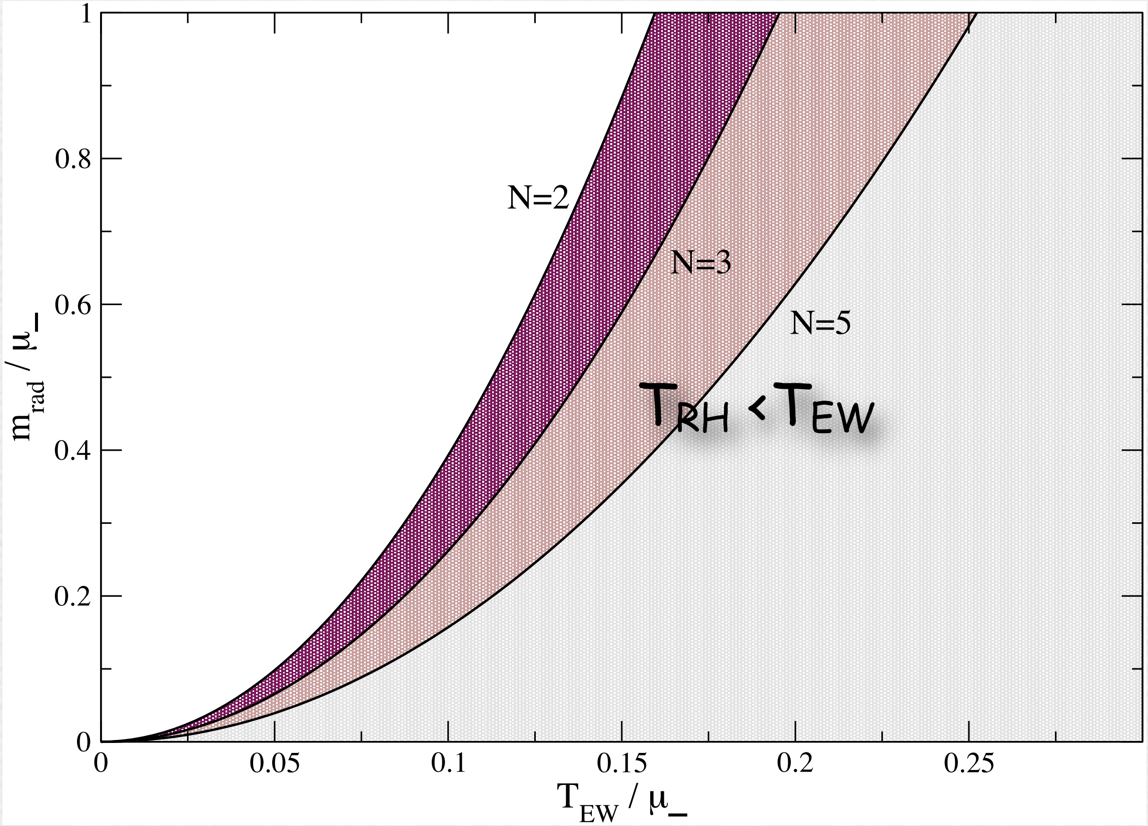
The full EW symmetry breaking sector has a potential of the form

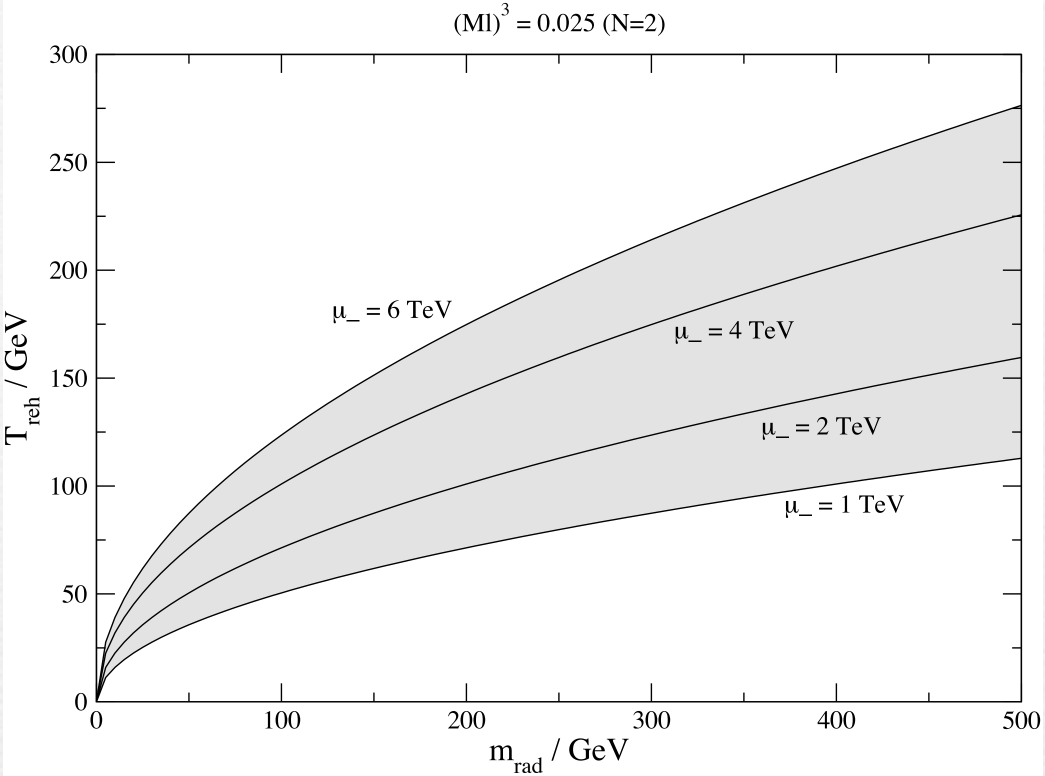
$$V(\mu,\phi) = \mu^4 \times \left(\ P((\mu/\mu_0)^\epsilon) + \mathcal{V}(\phi)/\mu_0^4\ \right)$$

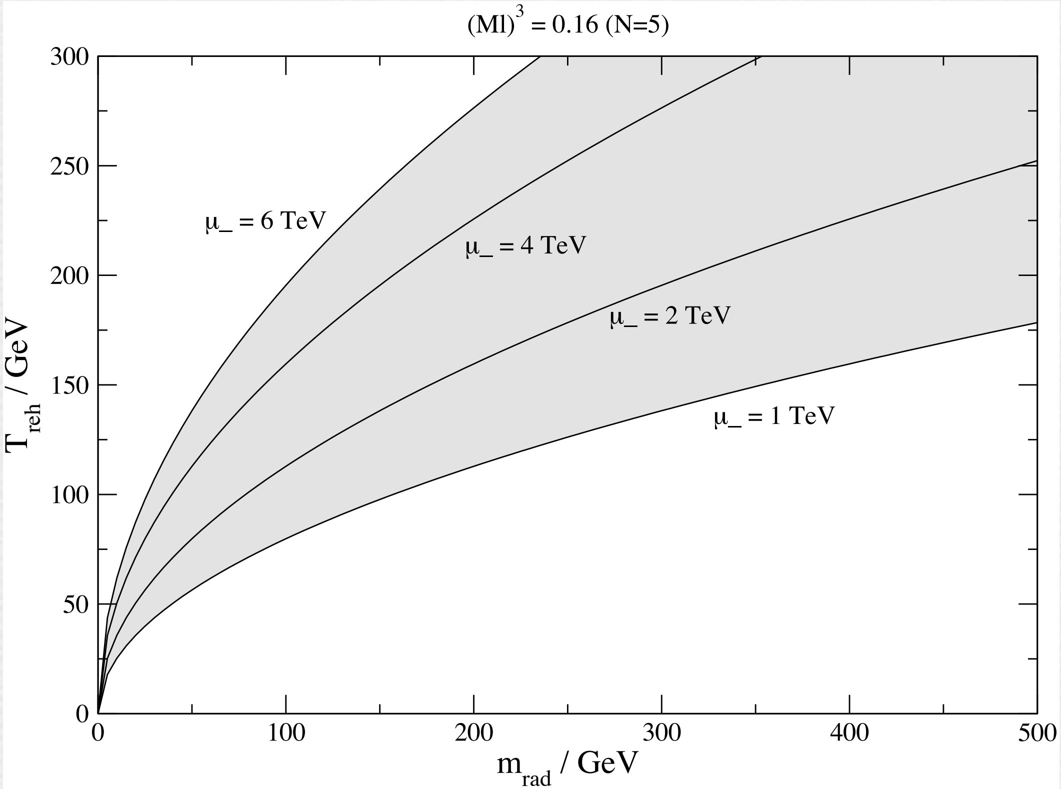
Reheat temperature

AT the TeV scale, expansion is negligible, reheat temperature estimated by

$$\Delta V = g^{*}\frac{\pi^2}{30}T_{\rm reh}^4$$




$(Ml)^3 = 0.025$ (N=2)
T_{reh} / GeV
m_{rad} / GeV
0
50
100
150
200
250
300
0
100
200
300
400
500
μ_ = 6 TeV
μ_ = 4 TeV
μ_ = 2 TeV
μ_ = 1 TeV


$(Ml)^3 = 0.16$ (N=5)
T_{reh} / GeV
m_{rad} / GeV
0
50
100
150
200
250
300
0
100
200
300
400
500
μ_ = 6 TeV
μ_ = 4 TeV
μ_ = 2 TeV
μ_ = 1 TeV

Viability of various baryogenesis mechanisms

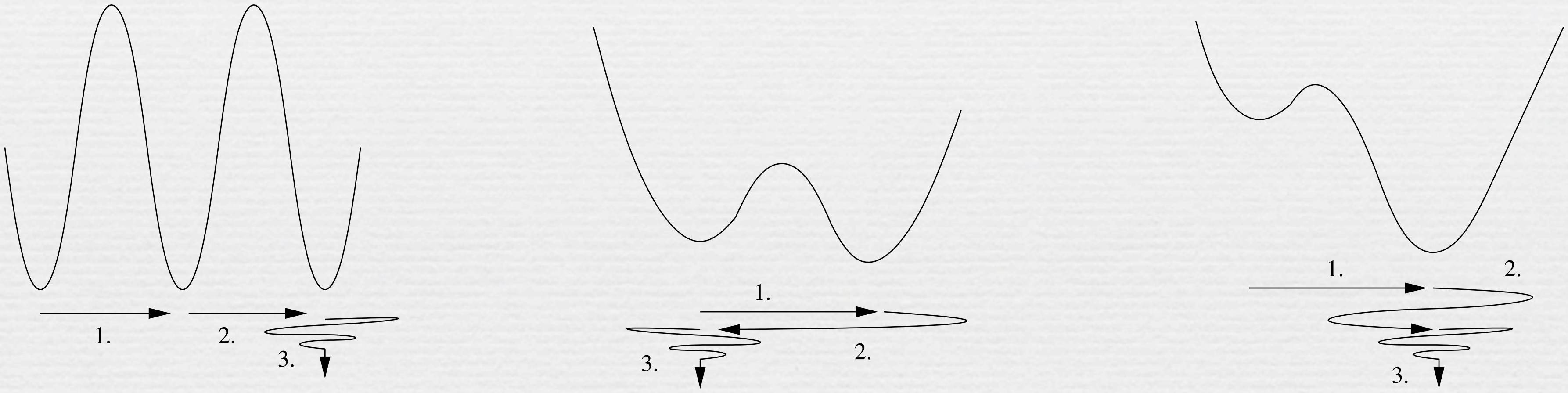
	$T_{\rm reh} > T_{\rm EW}$		$T_{\rm reh} < T_{\rm EW}$	
	EWPT is 1st-order	EWPT is crossover	$\frac{\phi}{T}\Big\vert_{T_{\rm reh}} > 1$	$\frac{\phi}{T}\Big\vert_{T_{\rm reh}} < 1$
cold EW baryogenesis	$-$	$-$	$+$	$-$
non-local EW baryogenesis	if $\phi/T\vert_{\rm EW} > 1$	$-$	$-$	$-$
low-scale lepto/baryogenesis from TeV particle decays	$+$	$+$	$-$	$+$
B-conserving baryogenesis from asymmetric dark matter	$+$	$+$	$+$	$+$

Reheating from bubble collisions

Watkins & Widrow ‘92

Kolb & Riotto ’96, Kolb, Riotto & Tkachev ‘97

strongly depends on the shape of the potential

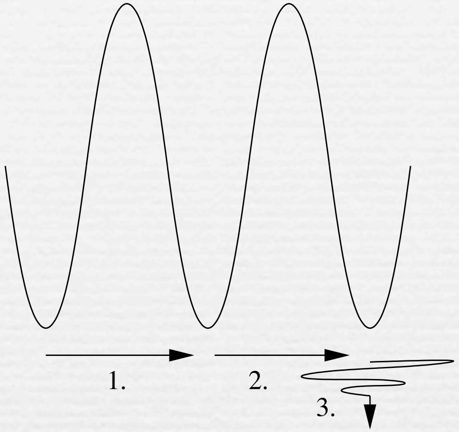


(a) (b) (c)

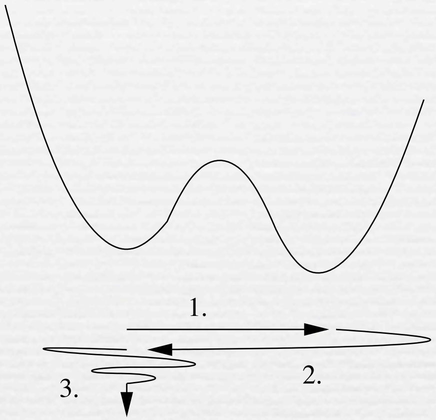
1. path of the scalar field in the expanding bubble wall
2. path during the collision
3. path in the collided region

Collision of planar bubble walls $v_w = 0.5$

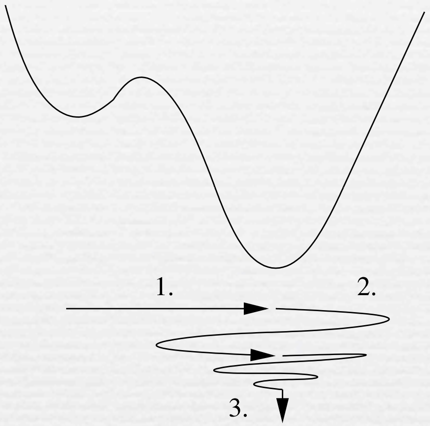
$$\partial_t^2\phi - \partial_z^2\phi = -\frac{dV}{d\phi},$$



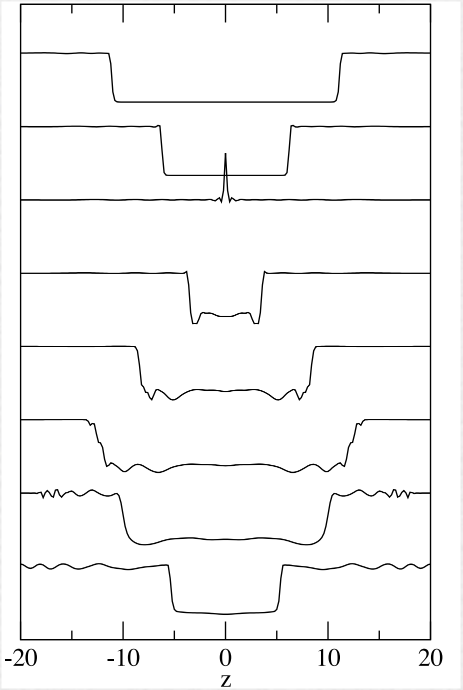
(a)

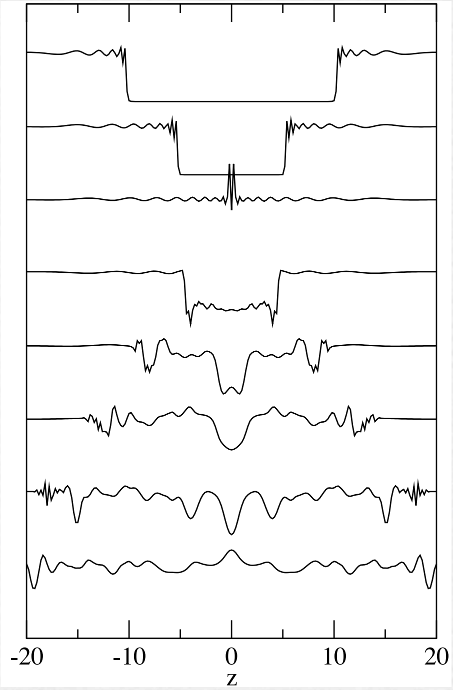


(b)



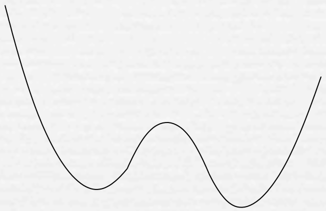
(c)

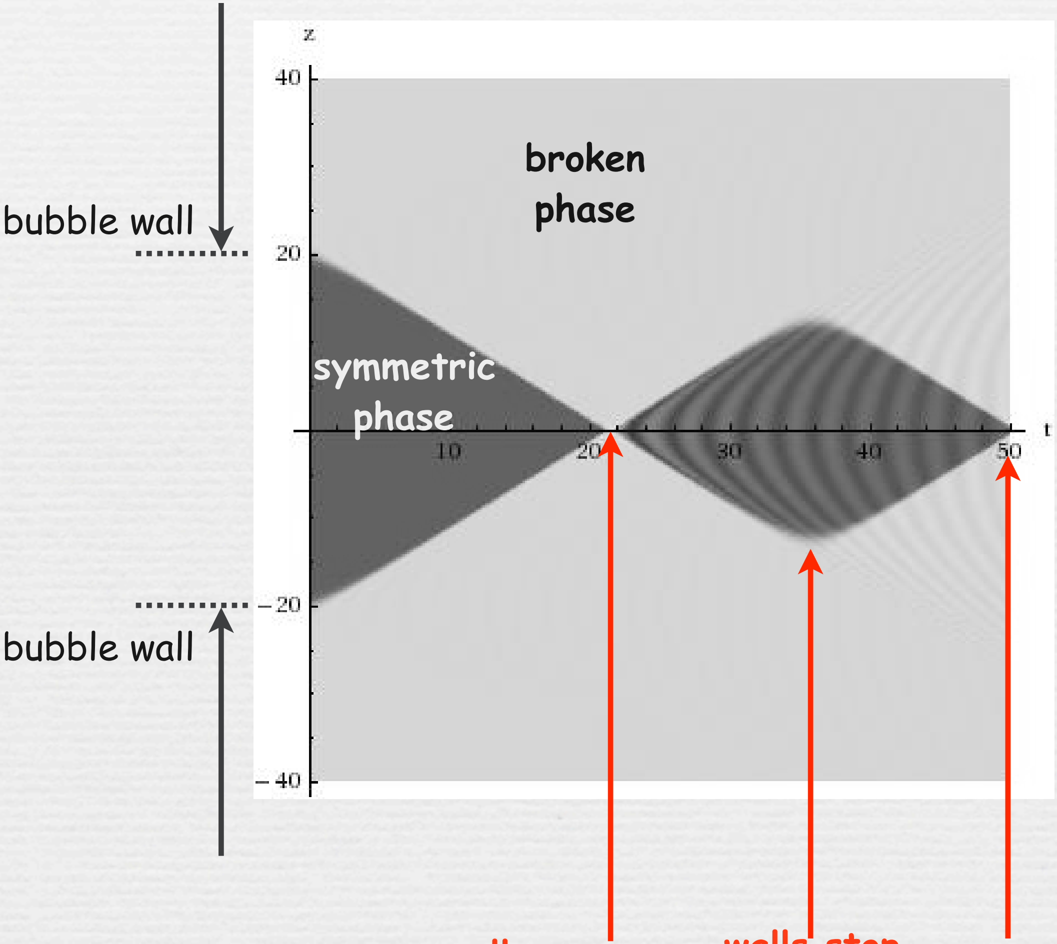




Collision of planar bubble walls $v_w = 0.5$

for a nearly symmetric potential:





bubble wall

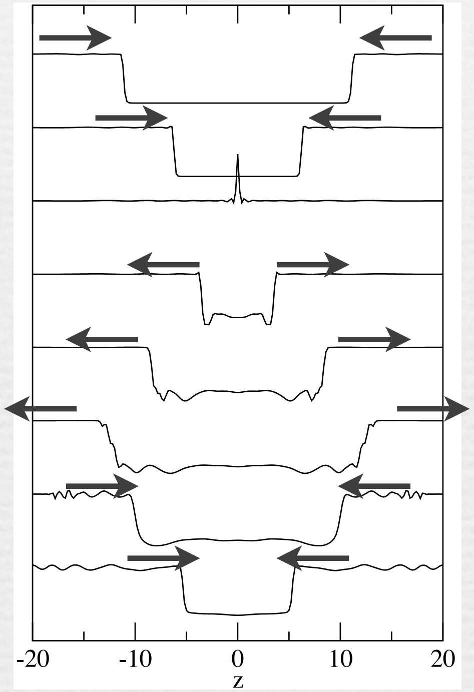
bubble wall

walls are reflected

walls stop expanding and symmetric phase collapses again

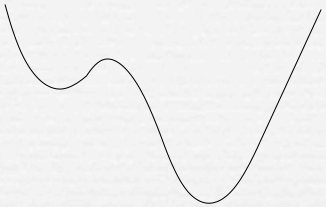
end of first collision

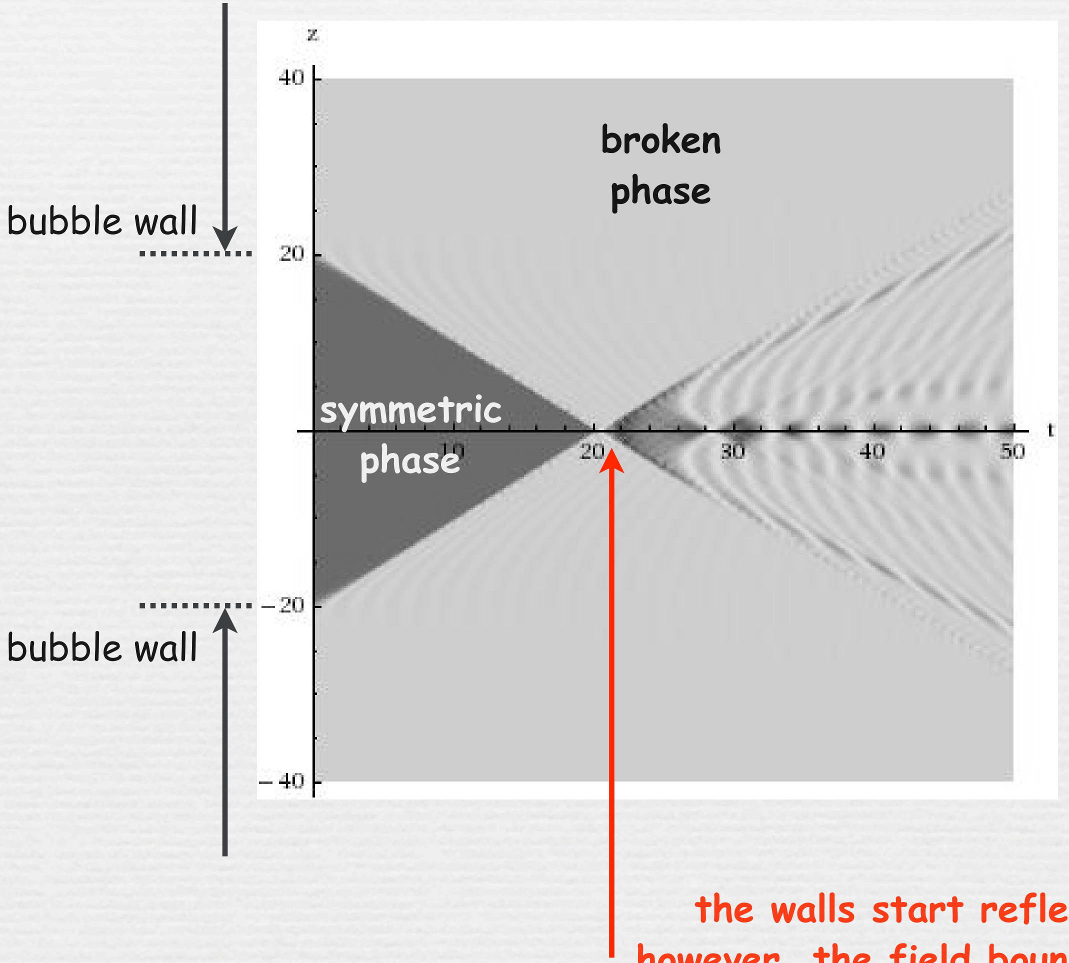
different slices of the collision:



Collision of planar bubble walls v_w =0.5

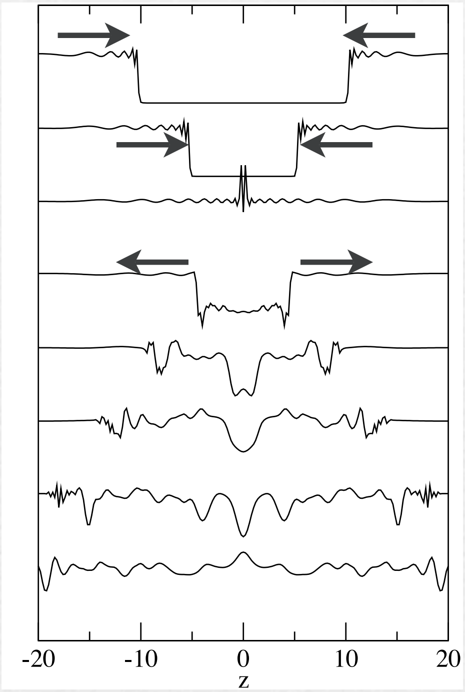
for an asymmetric potential:

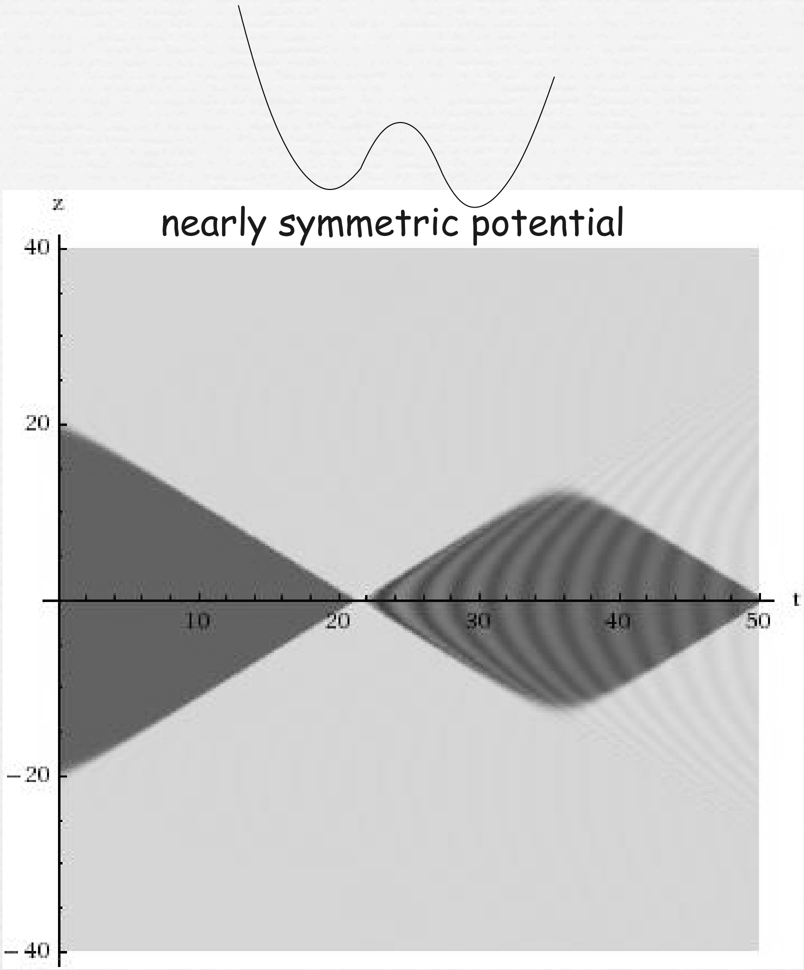


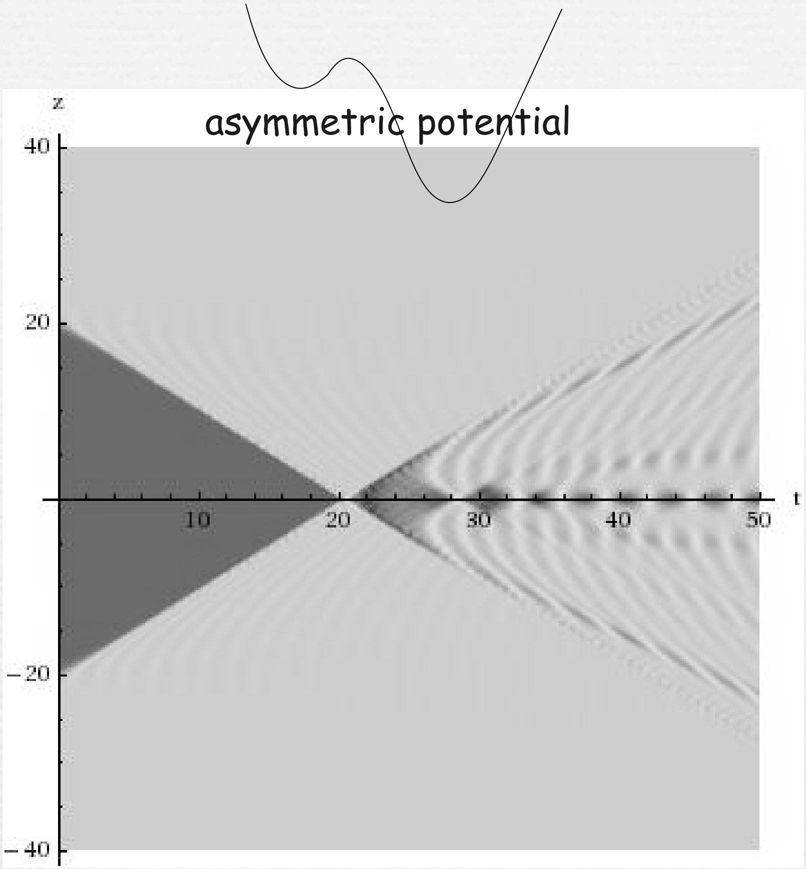


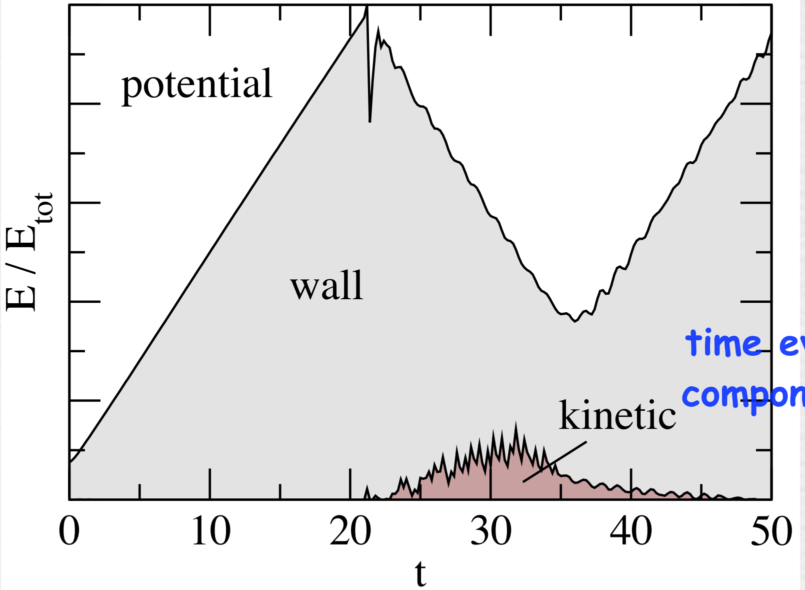
the walls start reflecting,
however, the field bounces close
to the broken phase minimum
and starts oscillating around it

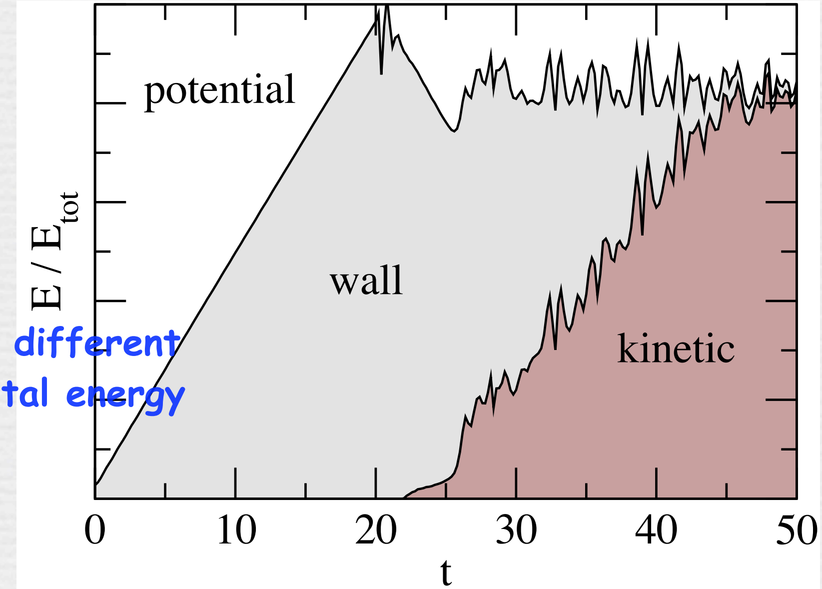
different slices of the collision:





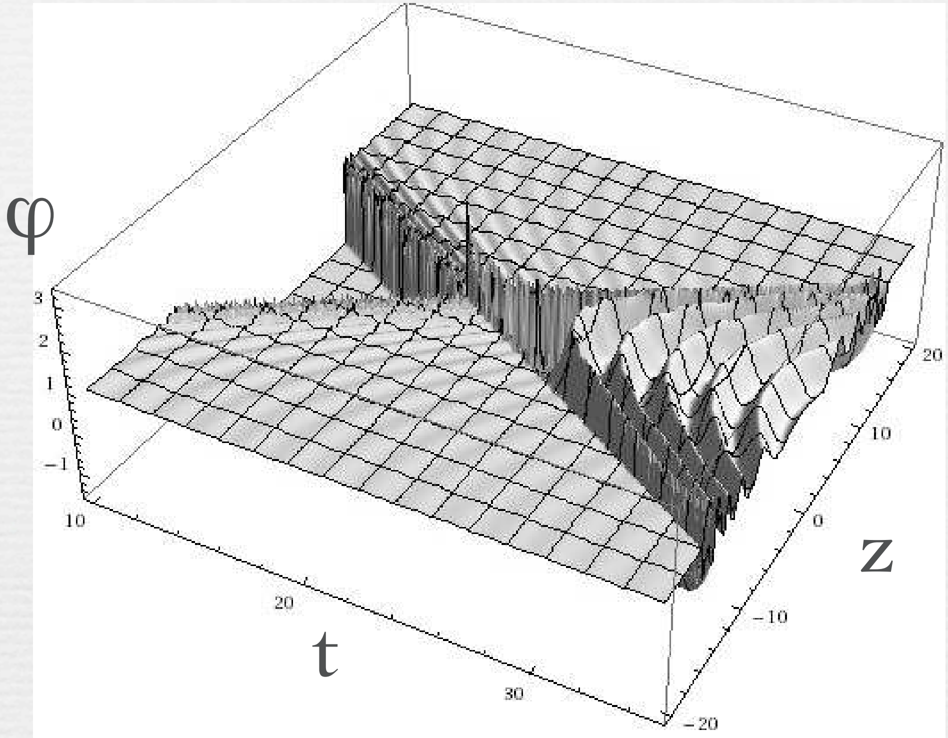






time evolution of the different components of the total energy

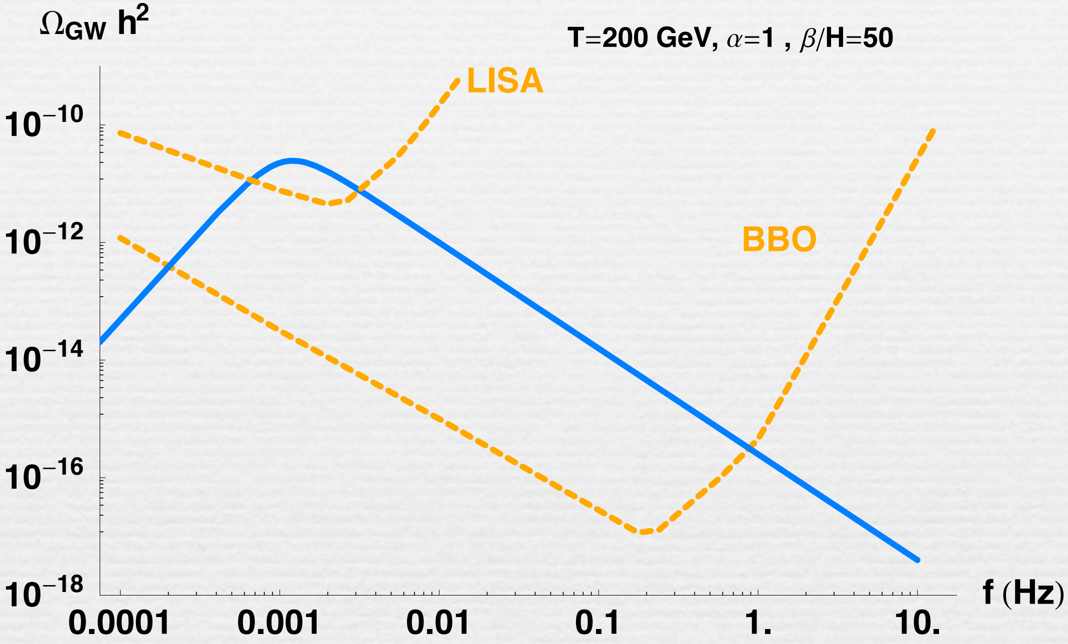
In 3D



Smoking gun signature

Randall-Servant'06

Konstandin,Nardini,Quiros'10

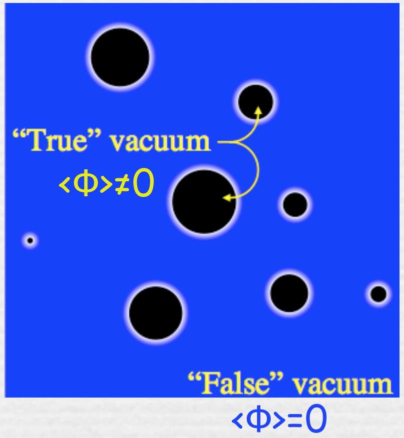


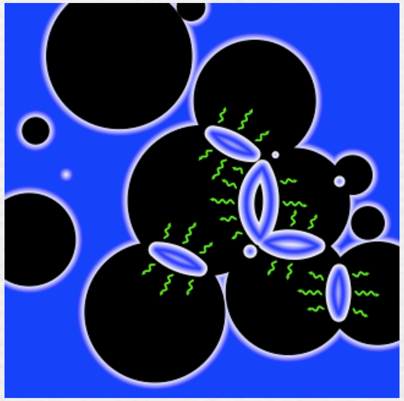
What we will hear about today

Chiara's talk

Bubble nucleation

Bubble percolation



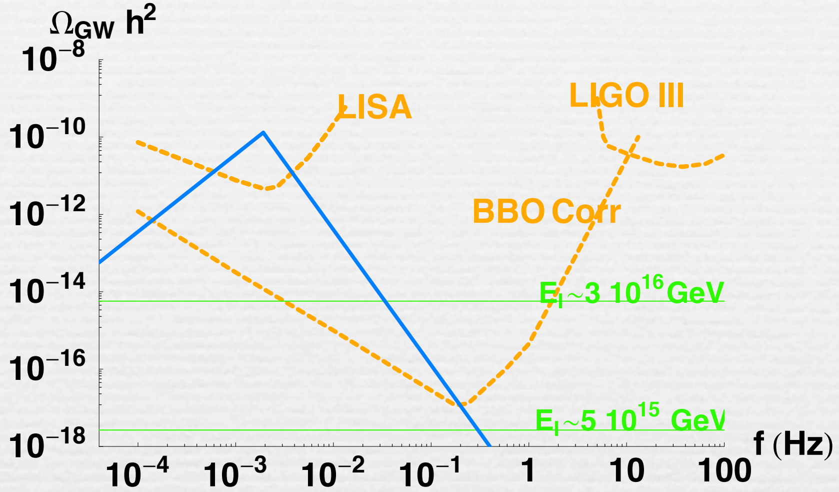


Fluid flows

turbulence

Magnetic fields

Stochastic background of gravitational radiation



$$\Omega_{GW} \sim \frac{1}{(\beta/H)^2}\kappa^2$$

fraction κ of vacuum energy density ϵ converted into kinetic energy

depends not only on α but
also on friction

$$\kappa = \frac{3}{\epsilon\xi_w^3}\int w(\xi)v^2\gamma^2\,\xi^2\,d\xi$$

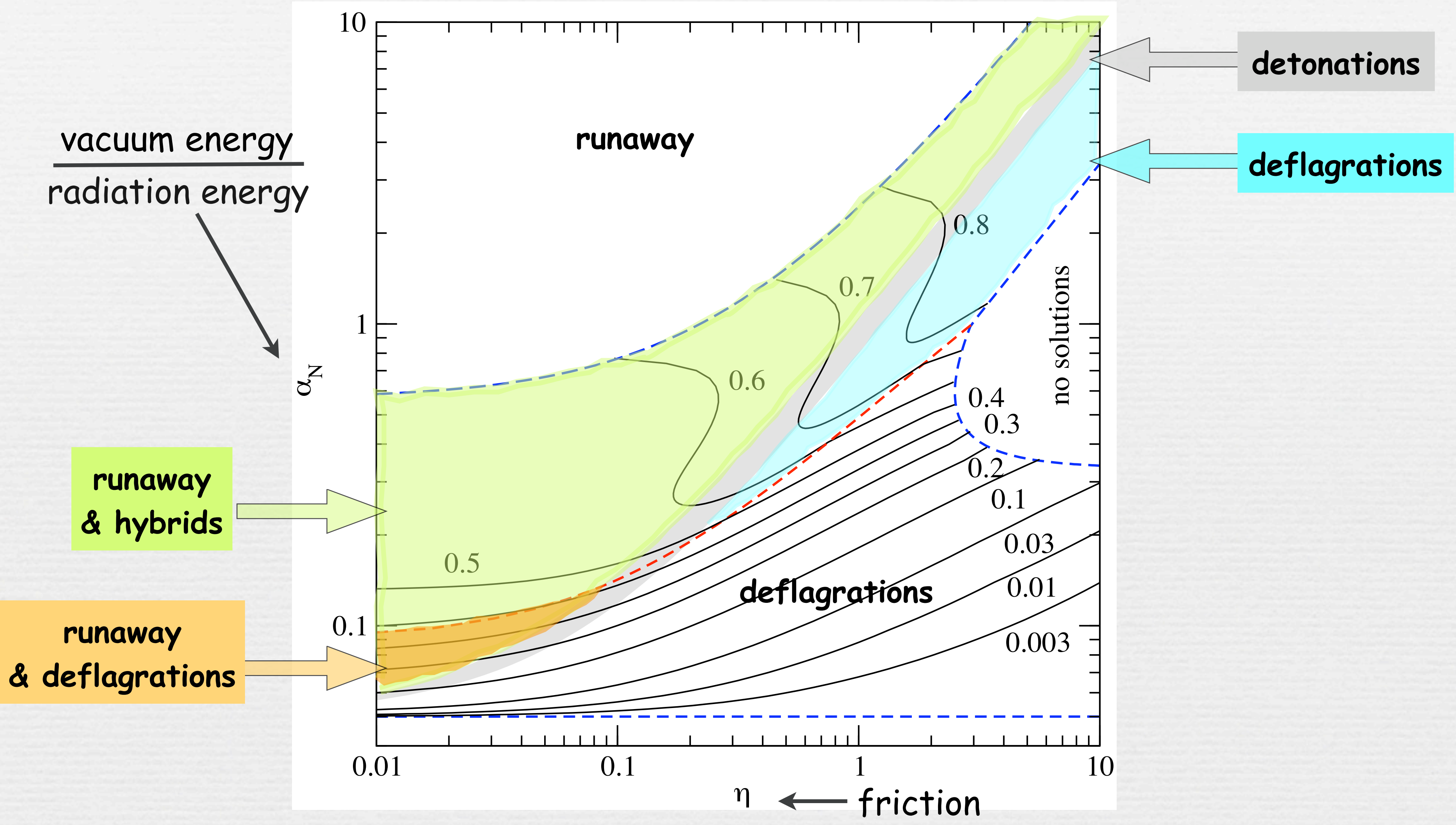
fluid velocity

wall velocity

$$\to \Omega_{GW} \sim v^4$$

Model-independent κ contours

Espinosa, Konstandin, No, Servant'10



$$\frac{\text{vacuum energy}}{\text{radiation energy}}$$

detonations

deflagrations

runaway
& hybrids

runaway
& deflagrations

η ← friction

$$\eta_{\mathrm{SM}} \sim 10^{-3}$$

$$\eta_{\mathrm{MSSM}} \sim 10^{-2}$$

$$v \sim 0.05 - 0.1$$

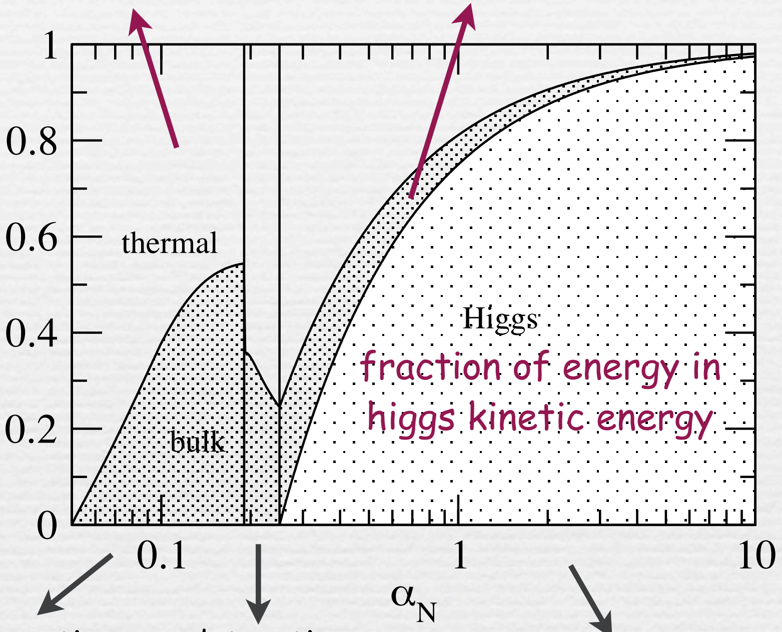
Energy budget of the phase transition

Espinosa, Konstandin, No, Servant'10

$\eta = 0.2$

fraction of energy in thermal radiation

fraction of energy in bulk fluid motion



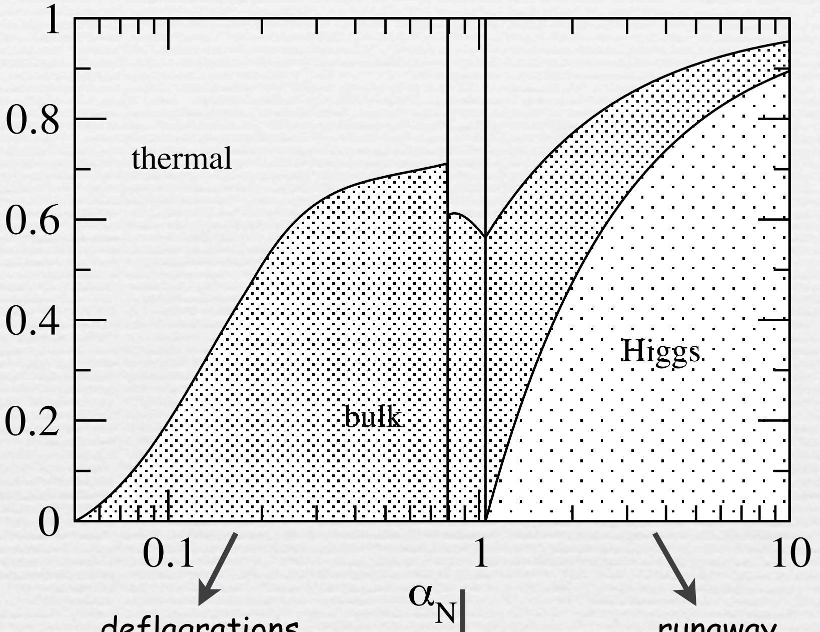
fraction of energy in higgs kinetic energy

deflagrations

detonations

runaway

$\eta = 1$



deflagrations

detonations

runaway

Determination of energy budget is important since gravity wave spectra from bubble collisions and turbulence are different

Large α, small η --> wall velocity too large for viable EW baryogenesis

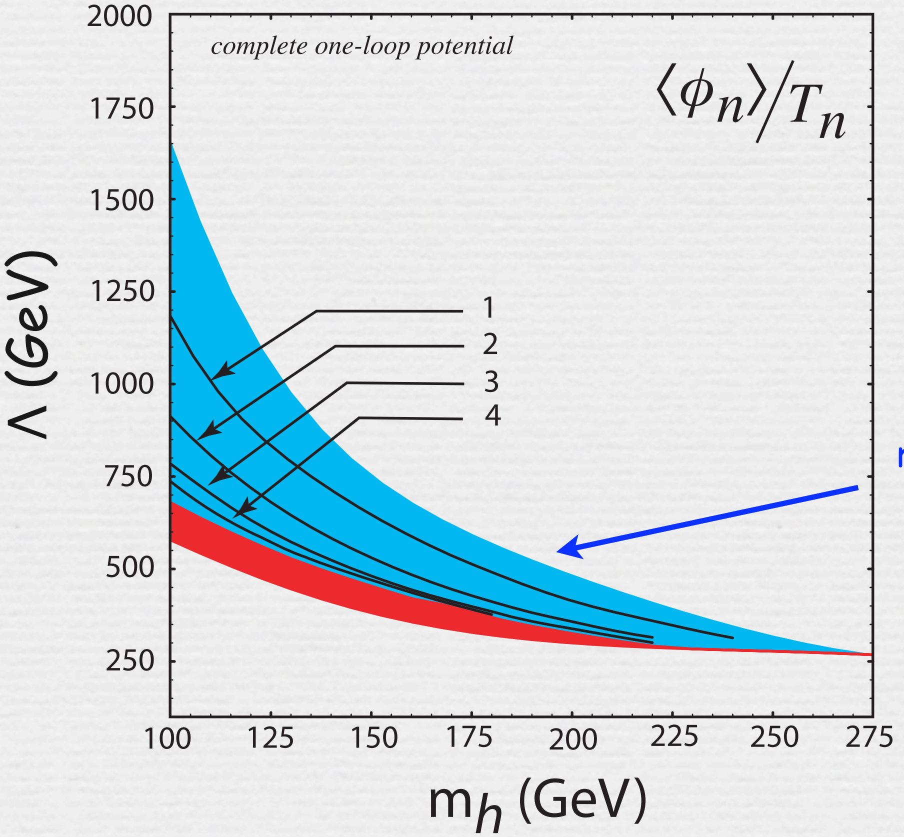
Effective field theory approach to the EW phase transition

add a non-renormalizable Φ^6 term to the SM Higgs potential and allow a negative quartic coupling

$$V(\Phi) = \mu_h^2 |\Phi|^2 - \lambda |\Phi|^4 + \frac{|\Phi|^6}{\Lambda^2}$$

"strength" of the transition does not rely on the one-loop thermally generated negative self cubic Higgs coupling

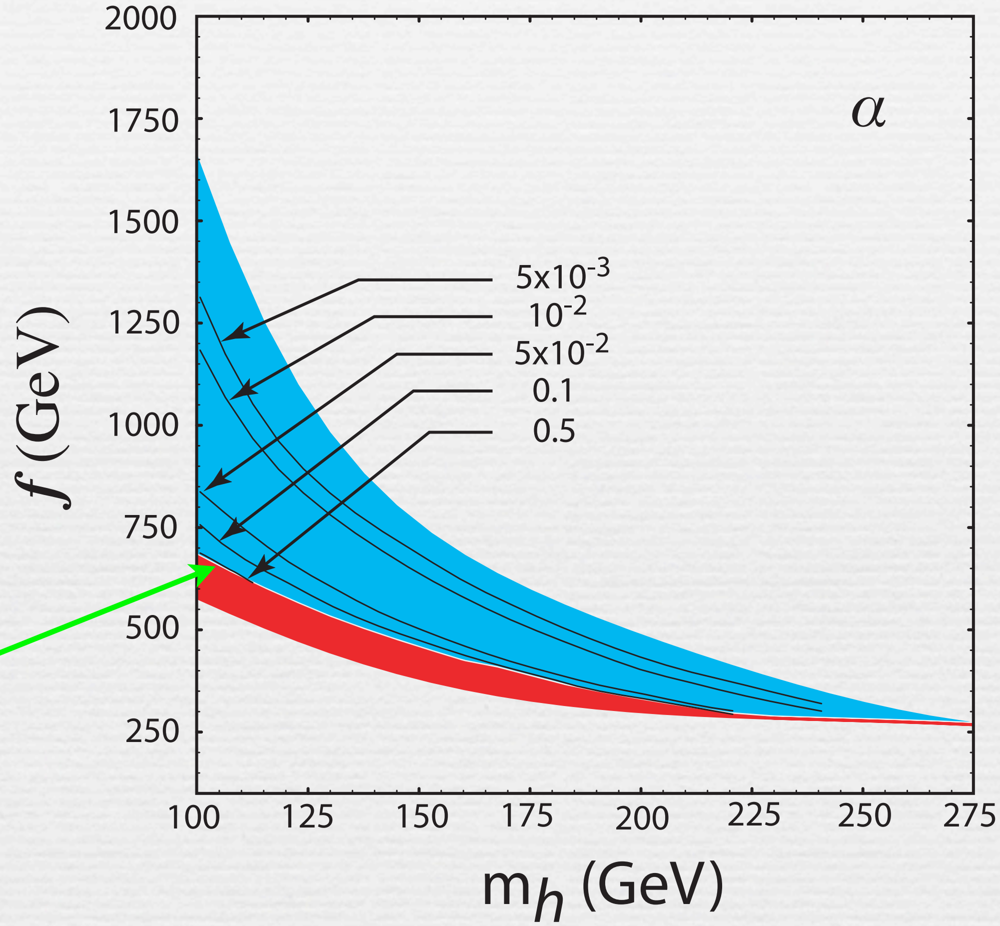
strong enough for EW baryogenesis if $\Lambda \lesssim 1.3$ TeV



region where EW phase transition is 1st order

Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

However, with typical polynomial potential,
getting a detectable signal of gravity waves is very fine-tuned



very tiny region
where α~0.5

different conclusion if near-conformal dynamics →

How likely is the possibility that we ever detect a GW signal from a 1st order phase transition?

(assuming a LISA-like interferometer is launched one day...)

High only if potential is of the form

$$V(\mu) = \mu^4 P((\mu/\mu_0)^\epsilon).$$

while it is easy to have a strong 1st order PT for baryogenesis, it is unlikely that any of the standard polynomial potentials lead to an observable signal of GW.

⇒ Detection of a GW stochastic background peaked in the milliHertz:

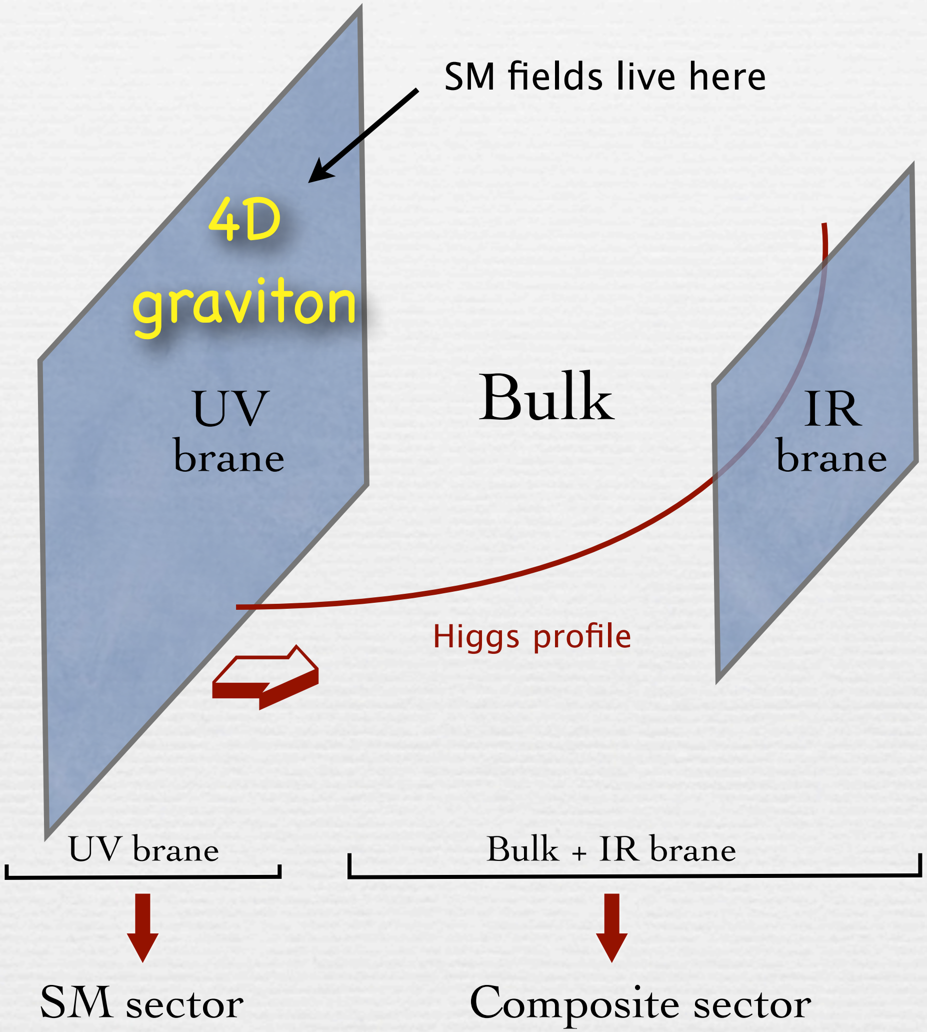
a signature of near conformal dynamics et the TeV scale

(or low scale preheating from hybrid inflation **Garcia-Bellido et al'07**)

Extra-Dimensional point of view

Warped Geometry

Space-time is a slice of AdS5



SM fields live here

4D graviton

UV brane

Bulk

IR brane

Higgs profile

UV brane

Bulk + IR brane

SM sector

Composite sector

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

Goldberger-Wise mechanism

Start with the bulk 5d theory $\mathcal{L} = \int dx^4 dz \sqrt{-g}[2M^3\mathcal{R} - \Lambda_5]$ $\Lambda_5 = -24M^3k^2$

The metric for RS1 is
$$ds^2 = (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2)$$
$$= e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$
where $k = L^{-1}$ is the AdS curvature
$$z = k^{-1}e^{ky}$$

and the orbifold extends from z=z₀=L (Planck brane) to z=z₁ (TeV brane)

Which mechanism naturally selects $z_1 \gg z_0$?

simply a bulk scalar field φ can do the job:

$$\int d^4x dz \left(\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2] + \delta(z - z_0)\sqrt{g_0}L_0(\phi(z)) + \delta(z - z_1)\sqrt{g_1}L_1(\phi(z))\right)$$

φ has a bulk profile satisfying the 5d Klein-Gordon equation

$$\phi = Az^{4+\epsilon} + Bz^{-\epsilon}$$
where
$$\epsilon = \sqrt{4 + m^2L^2} - 2 \approx m^2L^2/4$$

Plug this solution into
$$V_{eff} = \int_{z_0}^{z_1} dz\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2]$$

$$V_{\mathrm{GW}} = z_1^{-4}\left[(4+2\epsilon)\left(v_1 - v_0\left(\frac{z_0}{z_1}\right)^{\epsilon}\right)^2 - \epsilon v_1^2\right] + \mathcal{O}(z_0^4/z_1^8) = z_1^{-4}P(z_1^{-\epsilon})$$

$$z_1 \approx z_0\left(\frac{v_0}{v_1}\right)^{1/\epsilon}$$

~ scale invariant fn modulated by a slow evolution through the $z^{-\epsilon}$ term

similar to Coleman-Weinberg mechanism

AdS/CFT dictionnary

[Maldacena '97]
[Arkani-Hamed, Porrati, Randall '01]
[Rattazzi, Zaffaroni '01]

Warped extra dim (RSI) ↔ An almost CFT that very slowly runs but suddenly becomes strongly interacting at the TeV scale, spontaneously breaks the conformal invariance and confines, thus producing the Higgs

The hierarchy problem is solved due to the compositeness of the Higgs

KK modes localized on TeV brane ↔ bound state resonances

A gauge symmetry in the bulk ↔ A global symmetry of the CFT

$SU(2)_R$ will protect the rho parameter

[Agashe, Delgado, May, Sundrum '03]
[Csaki, Grojean, Pilo, Terning '03]

UV matter ↔ Fundamental particles coupled to the CFT

IR matter ↔ Composite particles of the CFT

RSI: A calculable model of technicolor

High-T Phase: AdS-S Black hole

$$ds^2 = \left(\frac{\rho^2}{L^2} - \frac{\rho_h^4/L^2}{\rho^2}\right) dt^2 + \frac{d\rho^2}{\frac{\rho^2}{L^2} - \frac{\rho_h^4/L^2}{\rho^2}} + \frac{\rho^2}{L^2}\sum_i dx_i^2$$

reduces to pure AdS metric for $\rho_h = 0$

$$T_h \equiv \frac{\rho_h}{\pi L^2}$$

$$\boxed{F_{\text{AdS-S}} = -2\pi^4 (ML)^3 T^4}$$

both local minima of free energy

by holography:
$(ML)^3 = N^2/16\pi^2$

Low-T Phase : RS1 geometry

Radion field determines spacing between branes

Require that radion is stabilized around TeV

$$\mu = e^{-k\pi r} M_{Pl}$$

$$F_{RS} = (4+2\epsilon)\mu^4 (v_1 - v_0(\mu/\mu_0)^\epsilon)^2$$
$$-\epsilon v_1^2 \mu^4 + \delta T_1 \mu^4 + \mathcal{O}(\mu^8/\mu_0^4)$$

$$\boxed{V_{min} \approx -\epsilon^{3/2} v_1^2 \mu_{\text{TeV}}^4}$$

Second brane emerges at T~TeV

i.e. radion starts at $\mu = 0$
and evolves to $\mu = \mu_{\text{TeV}}$

Key is stabilising mechanism

$$T_c = \left(\frac{-8V_{min}}{\pi^2 N^2}\right)^{1/4}$$

Below T_c , expect first-order phase transition

From 4D perspective , expect transition through bubble nucleation

From 5D perspective , spherical brane patches on horizon

LHC tests

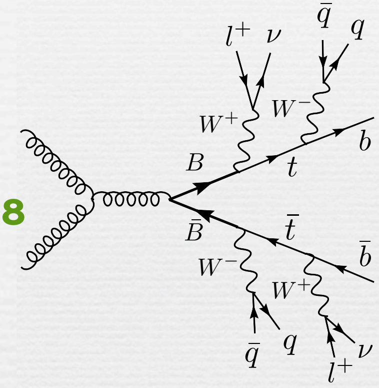
--Search for a light dilaton

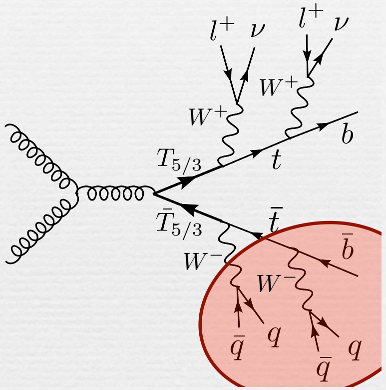
Goldberger et al'07 **Csaki et al'07**

$$\mathcal{L}_\chi = \frac{1}{2}\partial_\mu\bar{\chi}\partial^\mu\bar{\chi} - \frac{1}{2}m^2\bar{\chi}^2 + \frac{\lambda}{3!}\frac{m^2}{f}\bar{\chi}^3 + \frac{\bar{\chi}}{f}\sum_\psi m_\psi\bar{\psi}\psi + \left(\frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2}\right)\left[m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right]$$
$$+ \frac{\alpha_{EM}}{8\pi f}c_{EM}\bar{\chi}(F_{\mu\nu})^2 + \frac{\alpha_s}{8\pi f}c_G\bar{\chi}(G^a_{\mu\nu})^2$$

--Search for composite top partners if light enough

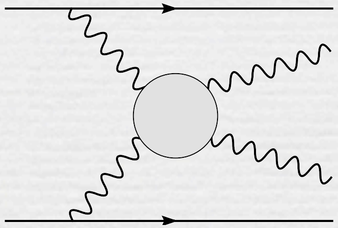
Contino-Servant'08

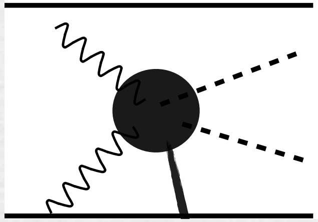




--Growth with energy of longitudinal gauge bosons scattering amplitudes & double higgs production

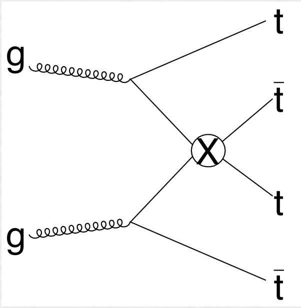
Contino et al'10





--Search for top compositeness in 4-top production

Pomarol-Serra'08
Gauthier-Servant' in prep.



--Modification of Higgs production and decay

Espinosa et al'10

--Multi Higgs framework ?

Gripaios et al'09

Summary

It will take some time at the LHC to determine whether EW symmetry breaking is purely SM-like or there are large deviations in the Higgs sector which could have led to a first-order PT, in particular, whether the origin of the EW scale is due to a new strong sector

We have studied cosmological consequences of this scenario by making the least possible reference to explicit models and used holography as a tool.

Nearly conformal dynamics can lead to a significant stage of supercooling (while typically any ordinary polynomial potential has to be fine-tuned to lead to several efolds of inflation ended by a 1st order PT or the latter never completes, i.e. eternal inflation pb)

cosmological features:

- A strongly first-order phase transition
- Reheating from bubble collisions
- A reheat temperature possibly below the sphaleron freeze-out temperature
- Efficient out-of-equilibrium heavy particle (or classical field configuration) production
- A smoking gun gravity wave stochastic background peaked in the millihertz range

--> revival of the few (3) papers in the nineties on heavy particle production from bubble collisions

--> motivating a new route for cold baryogenesis