2400-8

Workshop on Strongly Coupled Physics Beyond the Standard Model

25 - 27 January 2012

Cosmological aspects of strongly interacting EW symmetry breaking

Geraldine Servant
IPT CEA Saclay/CERN
SWITZERLAND

Cosmological aspects of strongly interacting Electroweak symmetry breaking

Géraldine SERVANT

CERN-Th

Which cosmological aspects?

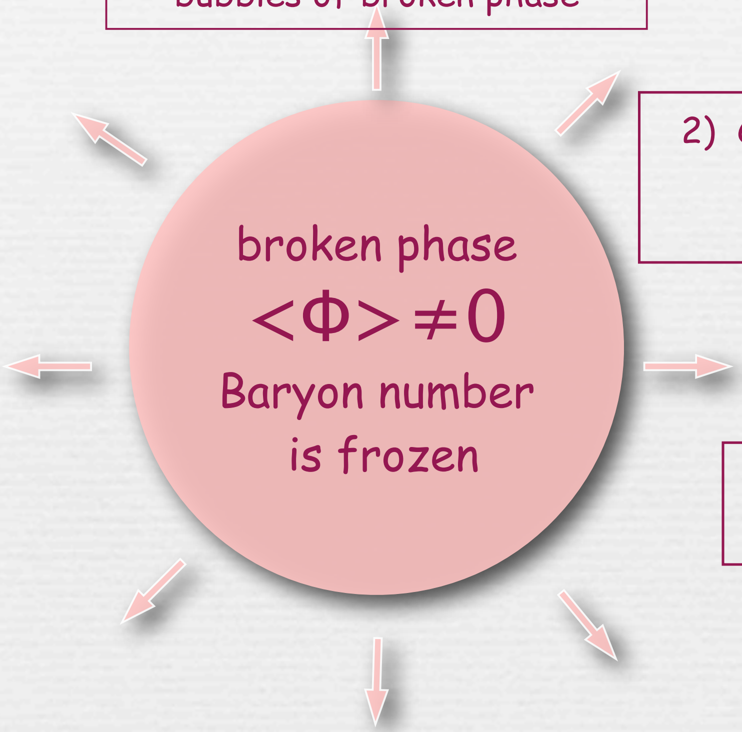
Those which can easily be connected with new EW scale physics

→ **baryogenesis**

→ **dark matter**

Baryon asymmetry and the EW scale

1) nucleation and expansion of
bubbles of broken phase

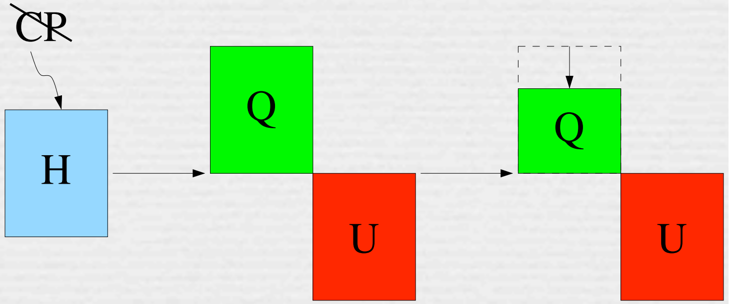


broken phase
$\langle \Phi \rangle \neq 0$
Baryon number
is frozen

2) CP violation at phase interface
responsible for mechanism
of charge separation

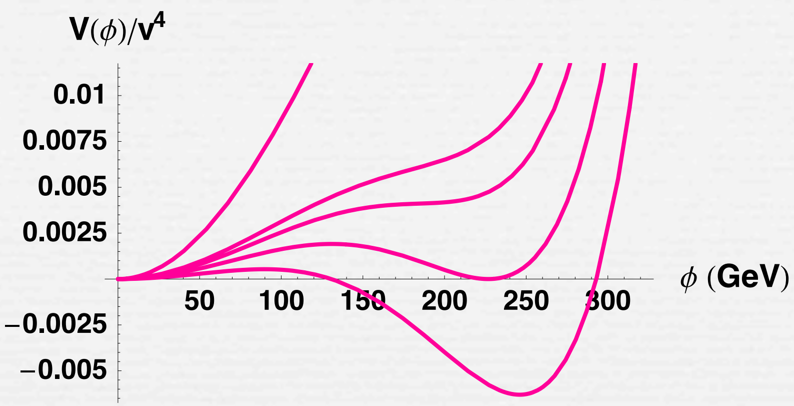
Chirality Flux
in front of the wall

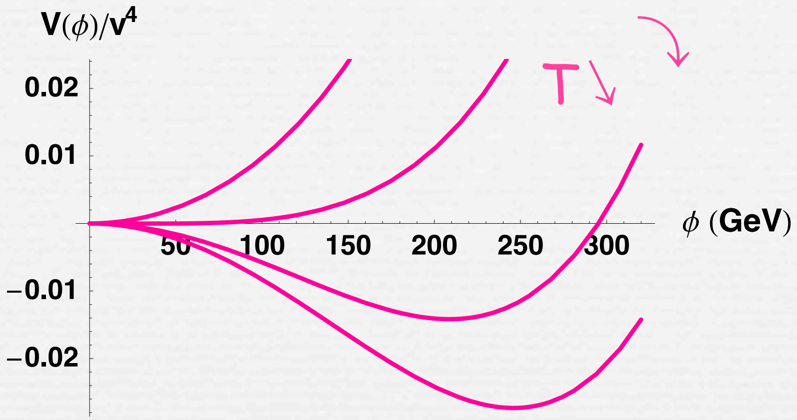
3) In symmetric phase, $\langle \Phi \rangle = 0$,
very active sphalerons convert chiral
asymmetry into baryon asymmetry



Electroweak baryogenesis mechanism relies on
a first-order EW phase transition

first-order or second-order?





In the SM, a 1rst-order phase transition can occur due to thermally generated cubic Higgs interactions:

$$V(\phi,T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - ET\phi^3$$

$$-ET\phi^3 \subset -\frac{T}{12\pi}\sum_i m_i^3(\phi)$$

Sum over all bosons which couple to the Higgs

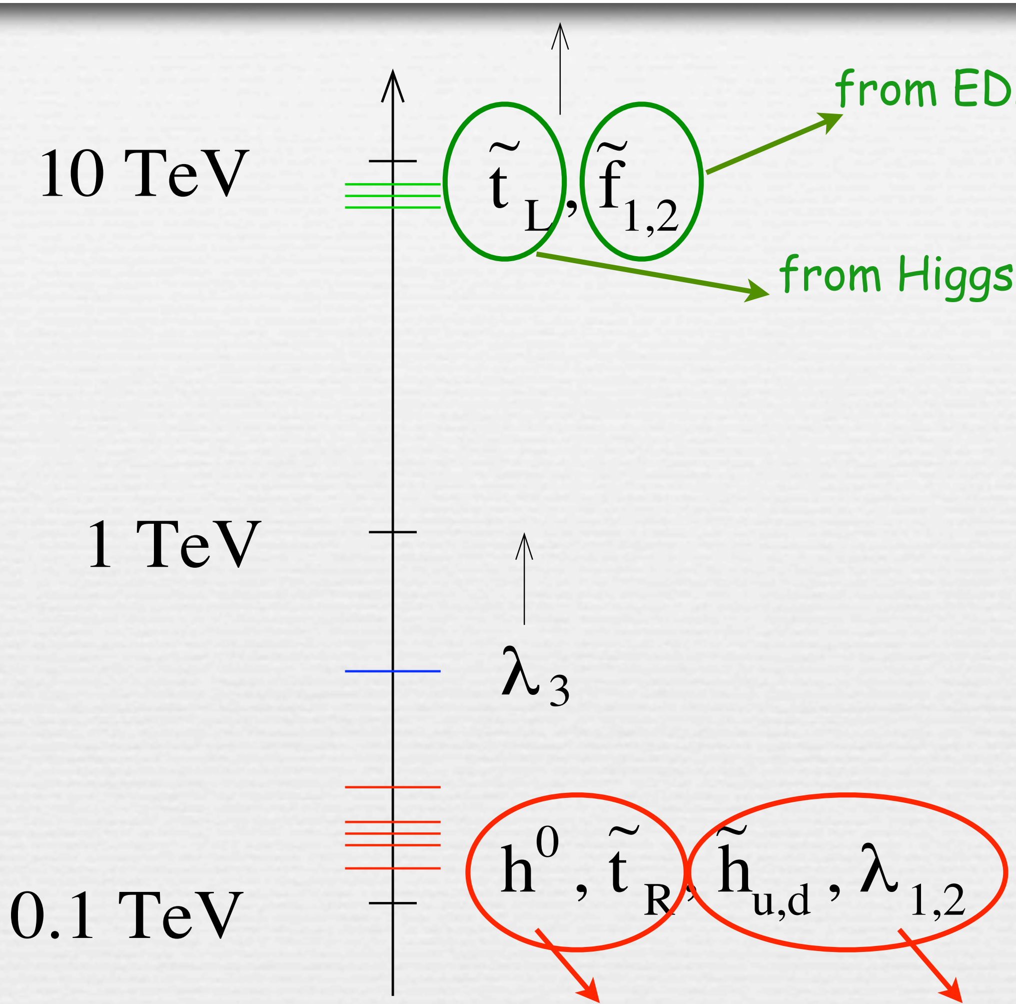
In the SM: $\sum_i \simeq \sum_{W,Z}$ → not enough

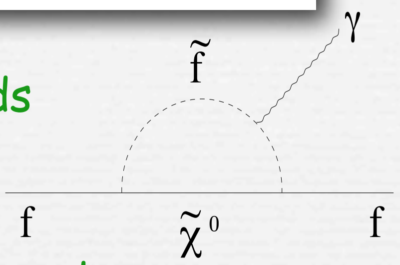
for mh>72 GeV, no 1st order phase transition

In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop

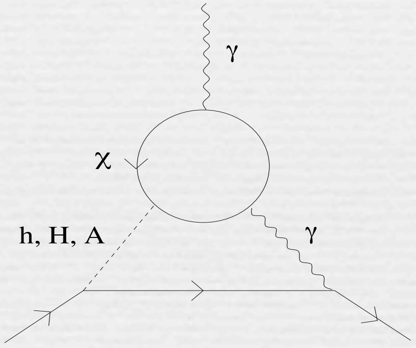
The (fine-tuned) MSSM EW baryogenesis window:
A Stop-split supersymmetry spectrum





from EDM bounds

from Higgs mass bound



for strong 1st order phase transition

for sufficient CP violation $\propto Im(\mu M_2)$

The light stop scenario: testable at the LHC, although challenging.

bounds get relaxed when adding singlets or in BSSM

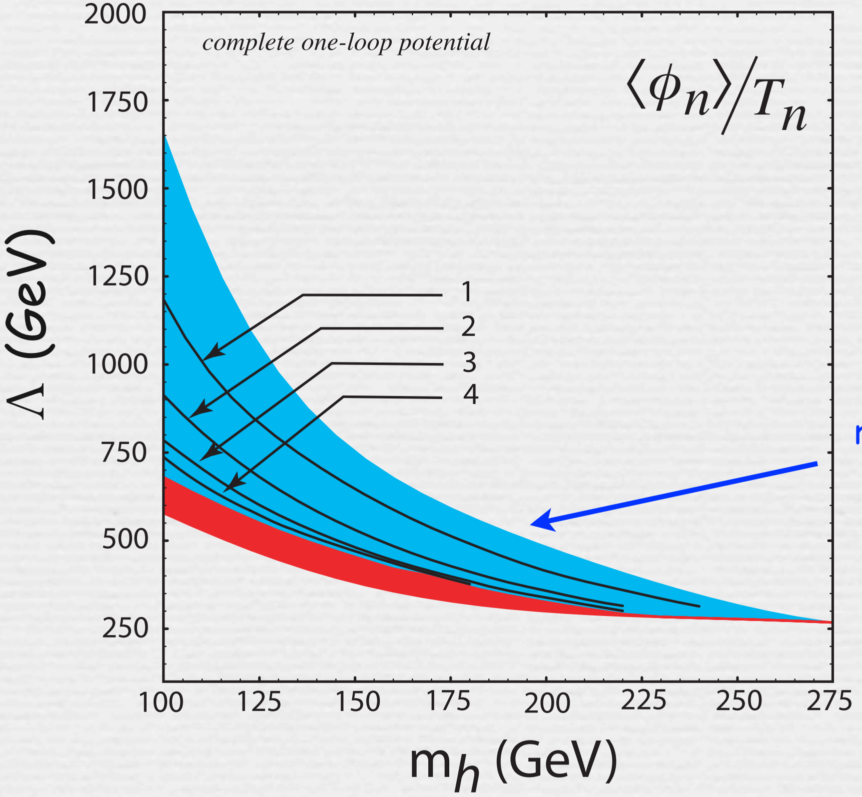
Effective field theory approach

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

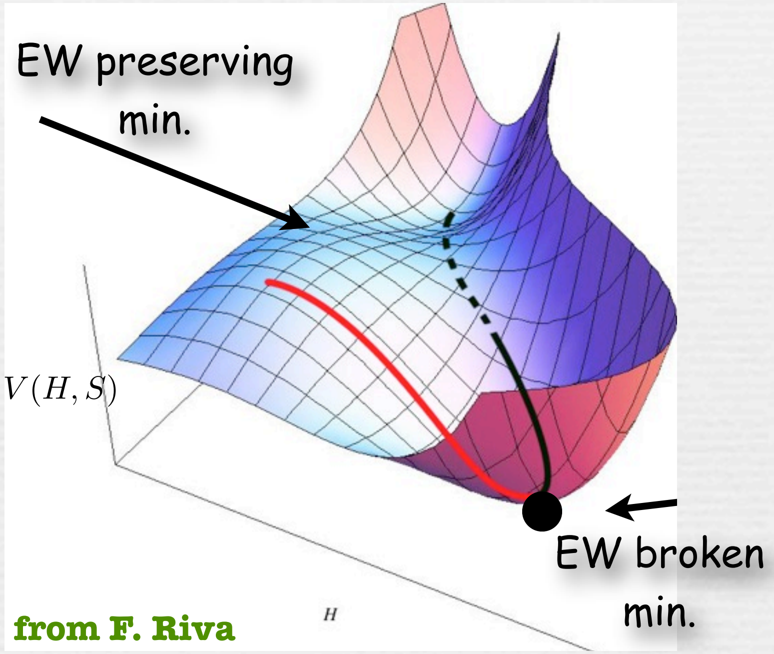


region where EW phase transition is 1st order

Grojean-Servant-Wells ’04
Delaunay-Grojean-Wells ’08

EW phase transition in the minimal extension of the Standard Model: the SM+ a real scalar singlet

$$V(H,S) = -\mu_H^2 H^2 + \lambda_H H^4 + \lambda_m H^2 S^2 - \mu_S^2 S^2 + \lambda_S S^4$$



from F. Riva

-> Espinosa et al, 1107.5441

EDM bounds (like for 2-Higgs Doublet Model)

Interestingly, well-motivated models naturally realize an extended Higgs sector:

models of Higgs compositeness

-> Gripaios et al, 0902.1483
-> Mrazek et al, 1105.5403
-> Espinosa et al, 1110.2876

Higgs scalars as pseudo-Nambu-Goldstone bosons of new dynamics above the weak scale

global symm. on u,d

strong int.

QCD: $SU(2)_L \times SU(2)_R \xrightarrow[SU(3)_c]{} SU(2)_V \supset U(1)_Q$

6 - 3 = 3 PNGB $\pi^{\pm}, \pi_0$

global symm. on techniquarks

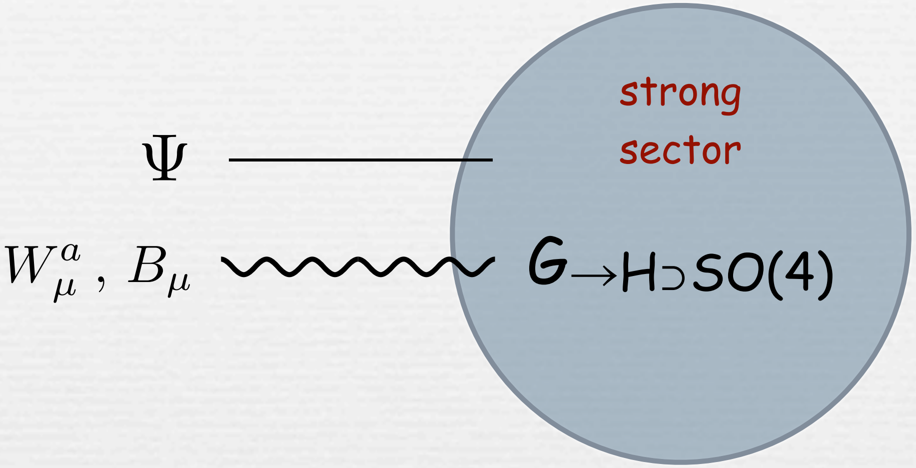
Composite Higgs: $SO(6) \times U(1)_x \xrightarrow[SU(N_c)]{} SO(5) \times U(1)_Y \supset SU(2) \times U(1)_Y$

16 - 11 = 5 PNGB H, S

SO(5)/SO(4) -> SM
SO(6)/SO(5) -> SM + S
SO(6)/SO(4) -> 2 HDM

associated LHC tests

New strong sector endowed with a global symmetry G spontaneously broken to H → delivers a set of Nambu Goldstone bosons



$$\mathcal{L}_{int} = A_\mu J^\mu + \bar{\Psi} O + h.c.$$

custodial SO(4)≅ SU(2)×SU(2)

to avoid large corrections to the T parameter

G	H	N_G	NGBs rep.$[H]$ = rep.[SU(2) × SU(2)]
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	G$_2$	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	[SO(3)]^3	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5} + \mathbf{\bar{4}_{+5}} = 2 \times (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

-> Agashe, Contino, Pomarol'05

[Mrazek et al, 1105.5403]

This is all “standard” EW baryogenesis

I am instead interested in an alternative mechanism of baryogenesis at the EW scale: so-called “COLD” baryogenesis and want to show that this could be natural in a generic class of models (RS inspired)

Cold Baryogenesis

An alternative to standard EW baryogenesis

1) Cold (the universe does not reheat 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 pre-2011 realization, does not rely on 1st order PT but on
inflationary phase instead

Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, hep-ph/9902449
Krauss-Trodden, hep-ph/9902420

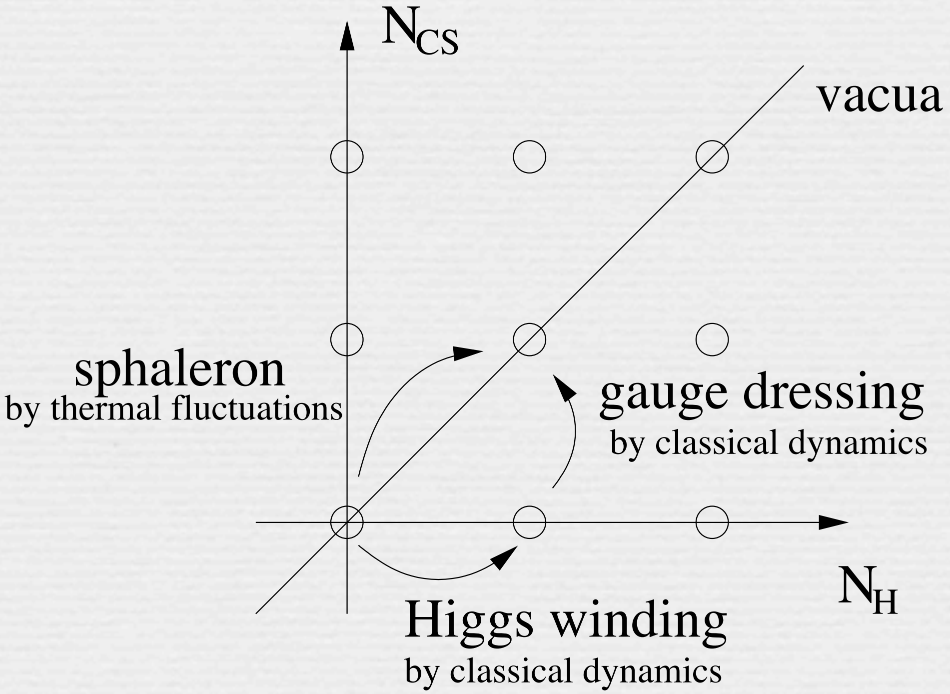
Cold Baryogenesis

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

$$\Delta B = 3\Delta N_{CS}$$



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:

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

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

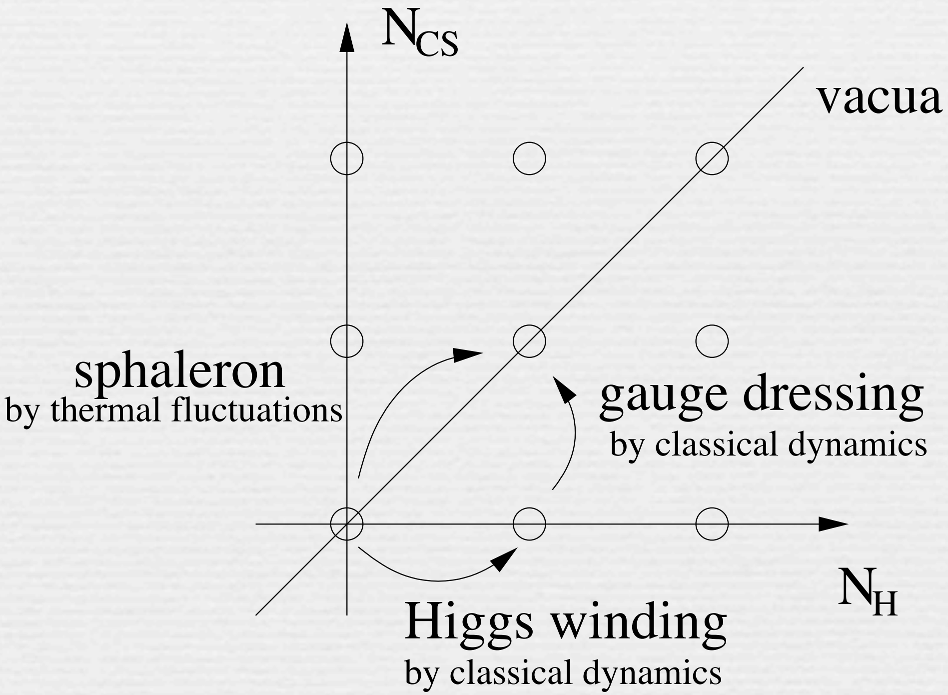
In vacuum: $N_H = N_{CS}$

Dynamics of textures $\delta N \equiv N_{CS} - N_H$

In vacuum: $\delta N=0$

A texture is a configuration which has $\delta N \neq 0$. It is unstable and decays.

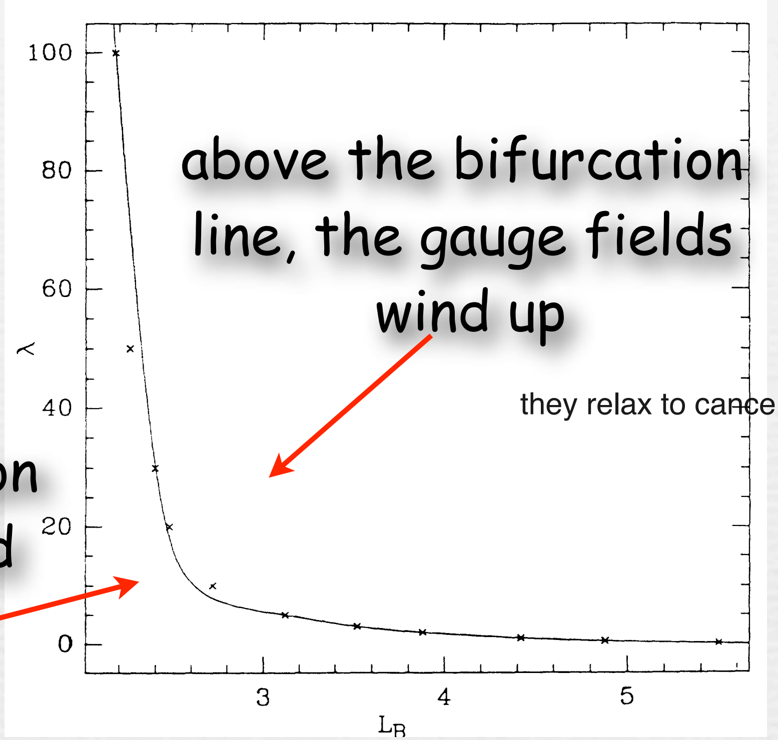
During the EWPT & preheating, configurations with $\Delta N_H \neq 0$ are produced. They relax to 0 by either changing N_H or N_{CS}. In the latter case, there is anomalous fermion number production.



instead of using thermal fluctuations to go over the barrier and produce N_{CS}, use scalar field energy in winding configurations carrying N_H which then produce N_{CS} when decaying

The gauge fields relax to cancel the gradient energy in the Higgs field. This competes with the tendency of the Higgs field to unwind.

Depending on the size L of a configuration of non-trivial winding, the winding will either decay or the higgs will get dressed by gauge fields.



above the bifurcation line, the gauge fields wind up

they relax to cancel the gradient energy in the Higgs field.

below the bifurcation line, the Higgs field unwinds

For small L (large gradient), there is not enough energy to carry the gauge fields over the sphaleron barrier.

CP violation affects how textures unwind !

CP violation has an impact on the bifurcation point and leads to different behaviors for winding/antiwinding.

---> 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 at the EW scale:

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

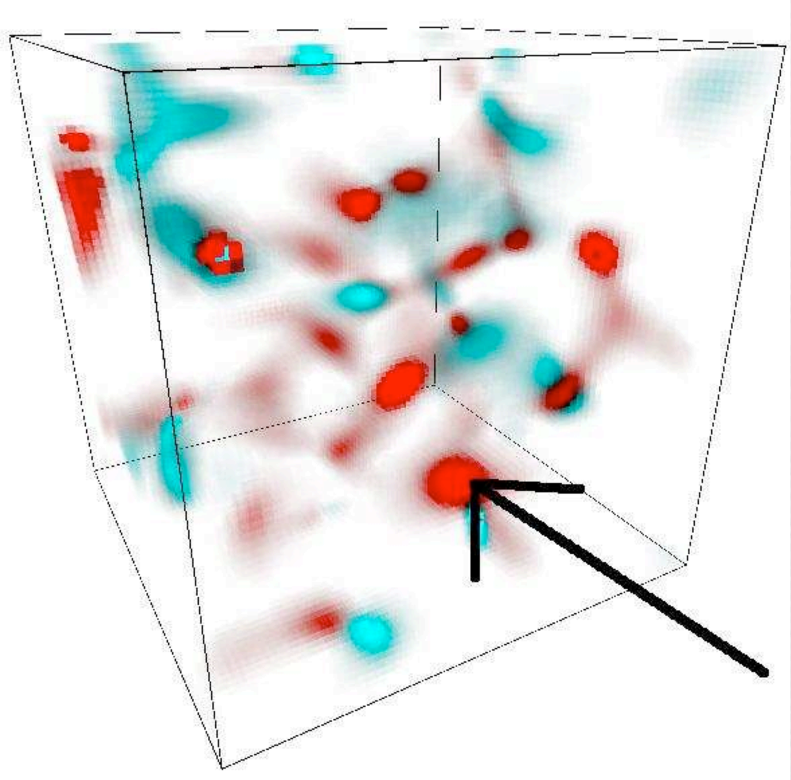
Tranberg, Smit, Hindmarsh
hep-ph/0610096

large enough provided that M ≲ 500 TeV

OK with EDM constraint if M ≳ 14 TeV

3D evolution of winding number density

van der Meulen, Sexty, Smit, Tranberg'05



Earlier proposal for Cold Baryogenesis

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

Krauss-Trodden, hep-ph/9902420 + 15 subsequent papers

- Inflation ends with reheating below the EW scale
- Non-thermal production of sphalerons via preheating

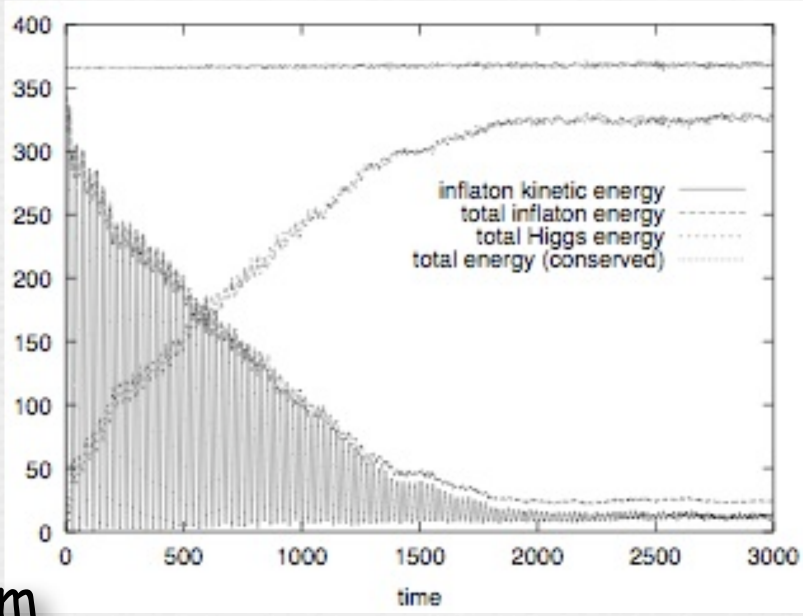
(inflaton oscillations induce large occupation numbers
for long wavelength configurations of the Higgs)

Hybrid inflation potential:

$$V(\sigma,\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{1}{2}\tilde{m}^2\sigma^2 + \frac{1}{2}g^2\sigma^2\phi^2$$

inflaton Higgs

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



- Lack of naturalness remains a problem

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.

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

$$\begin{aligned} ds^2 &= (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2) \\ &= e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \end{aligned}$$

where $k = L^{-1}$ is the AdS curvature

$z = k^{-1}e^{ky}$

and the orbifold extends from z=z$_0$=L (Planck brane) to z=z$_1$ (TeV brane)

Which mechanism naturally selects z$_1$ >> 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 $V_{eff} = \displaystyle\int_{z_0}^{z_1} dz\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2]$

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

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

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

similar to Coleman-Weinberg mechanism

Goldberger-Wise potential for the radion is of the form

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

e.g. Rattazzi, Zaffaroni '00

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

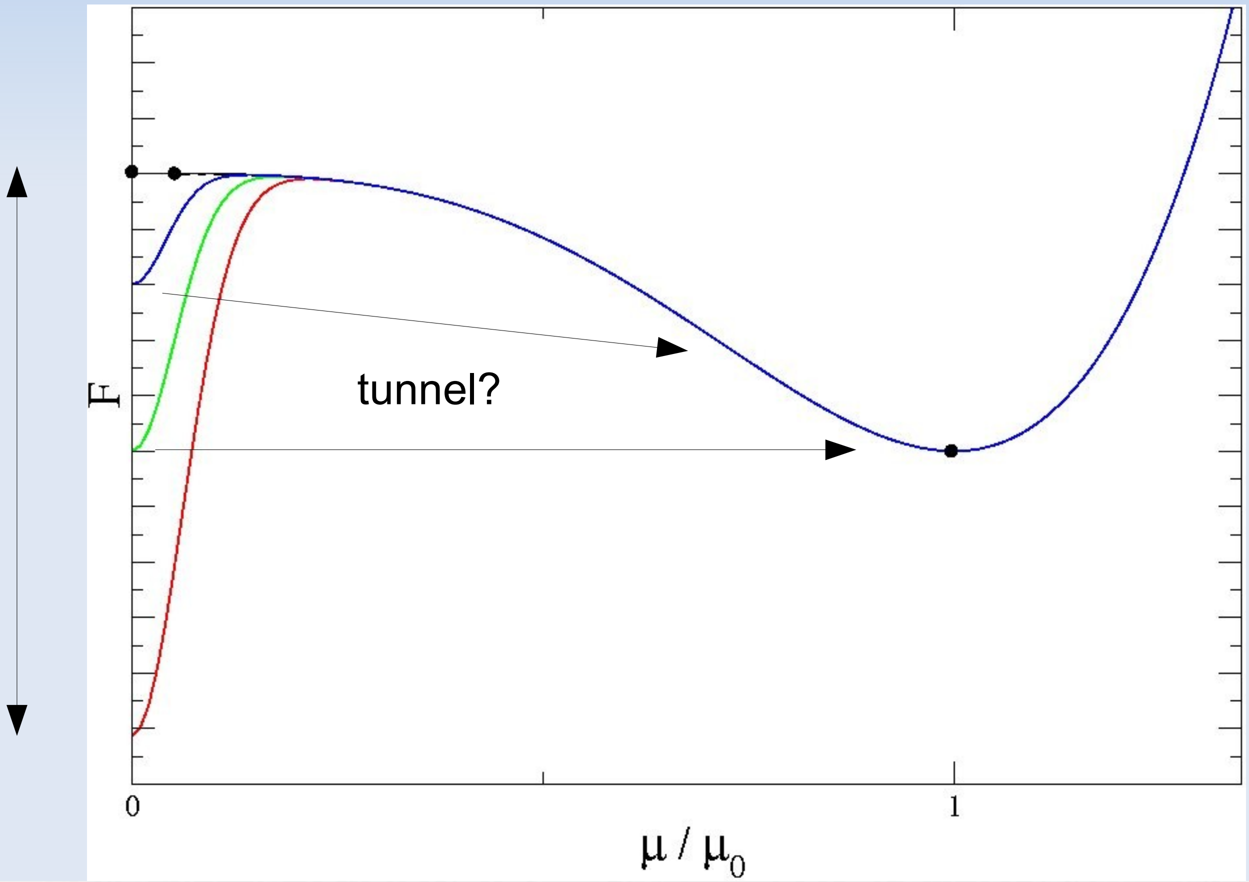
for $|\varepsilon|<<1$

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

Deconfining phase transition

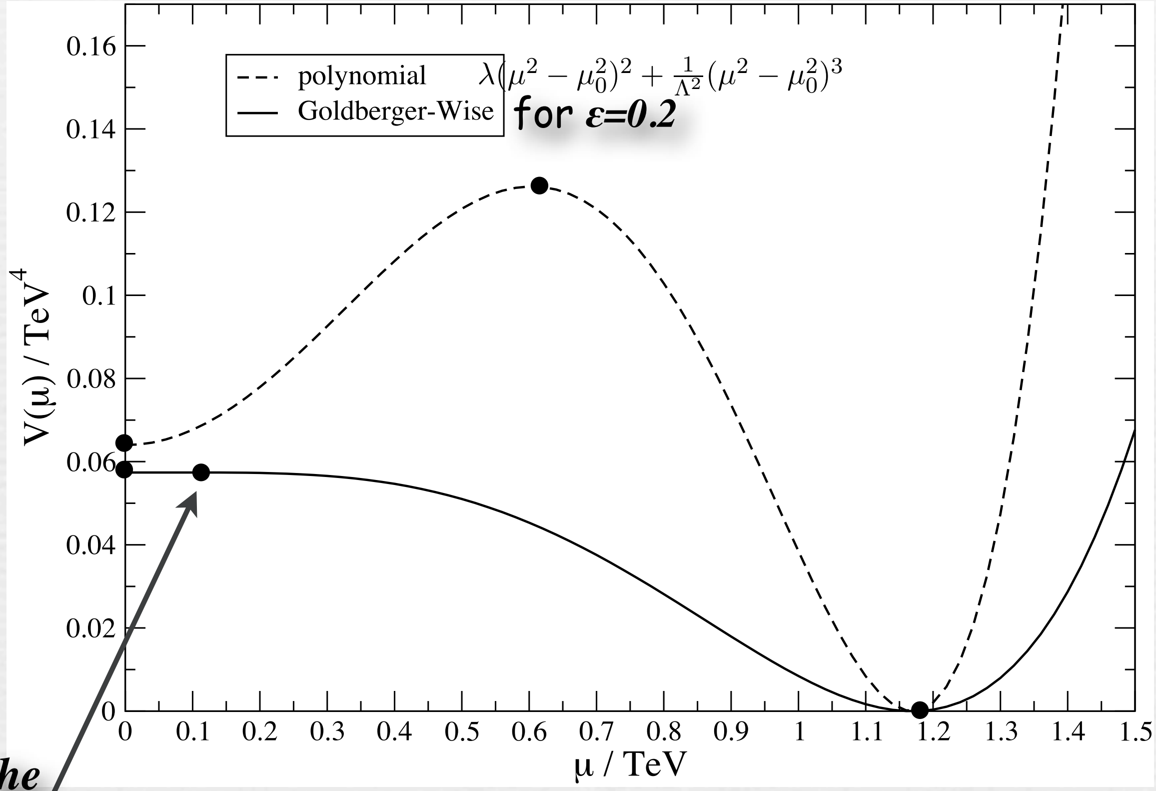
Quarks/gluons that are confined in the broken phase induce a difference in free energy between the two phases

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



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

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



$\lambda(\mu^2-\mu_0^2)^2+\frac{1}{\Lambda^2}(\mu^2-\mu_0^2)^3$

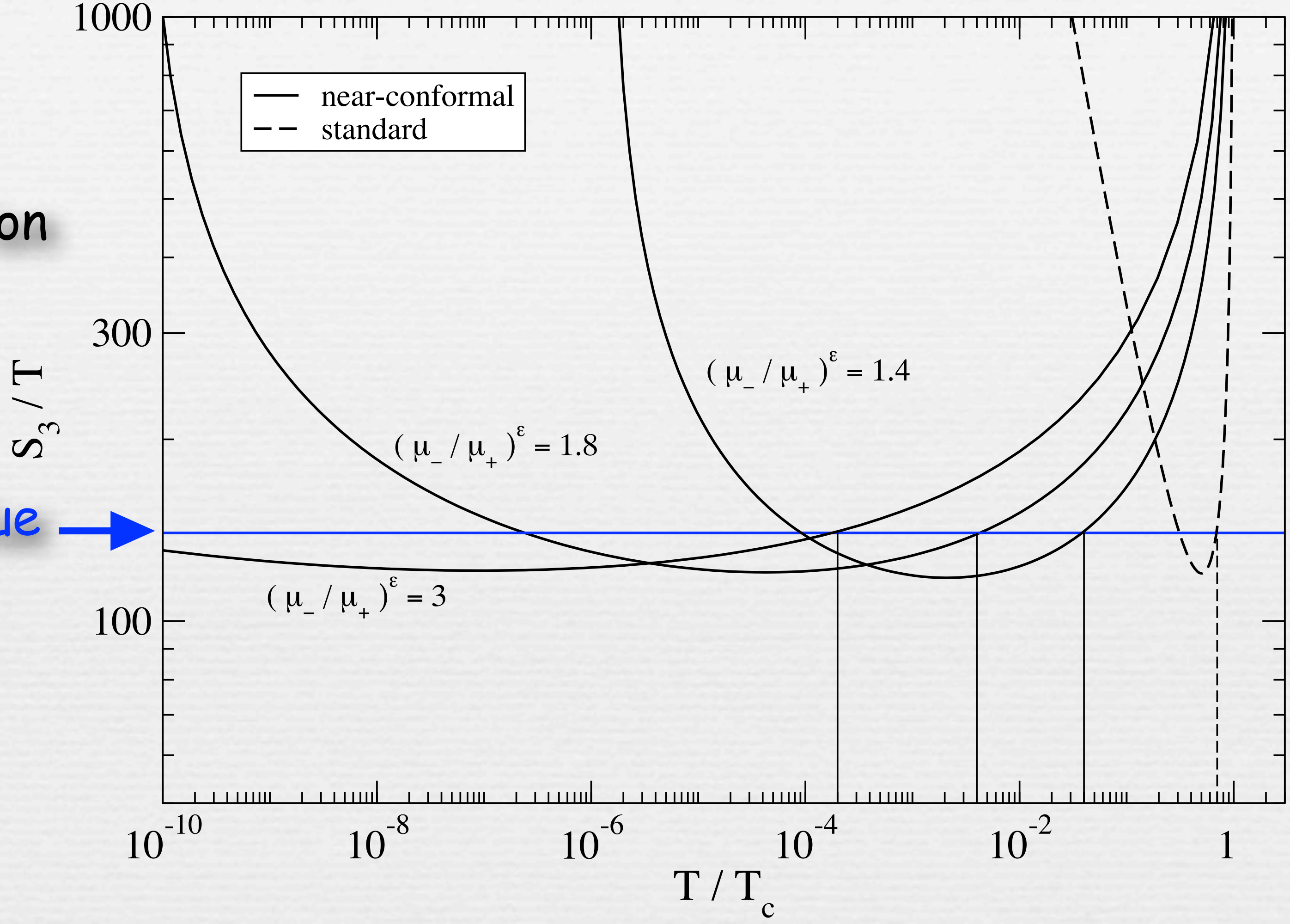
for *ε=0.2*

position of the maximum

The tunneling value ***μ***

Servant-Konstandin ‘11

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

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

--> nucleation temperature very small

--> significant supercooling

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

\# of bubbles per horizon volume

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

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

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

$$\beta/H = T\frac{d}{dT}\frac{S_3}{T}\bigg|_{T_n} \sim \frac{T_n}{\mu_0}\ \ \frac{S_3}{T}\bigg|_{T_n}$$

(where μ_0 is the vev at the minimum of the potential describing the phase transition)

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

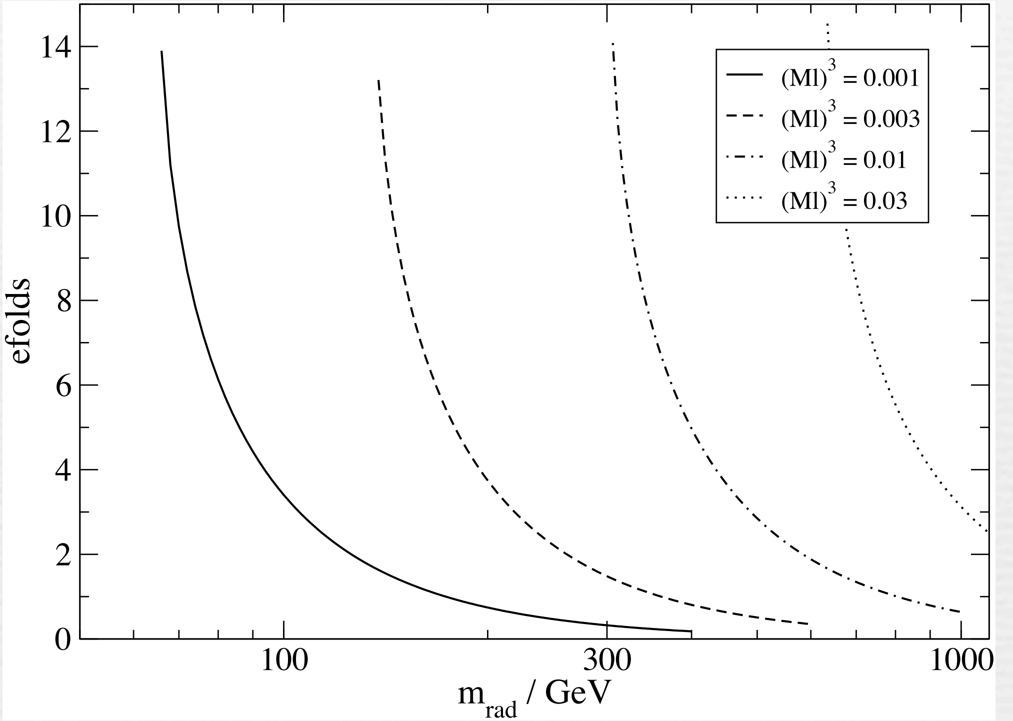
T_n : nucleation temperature
T_c : critical temperature

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

$\beta/H << 1$ --> eternal inflation

Typical amount of supercooling (number of efolds)

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



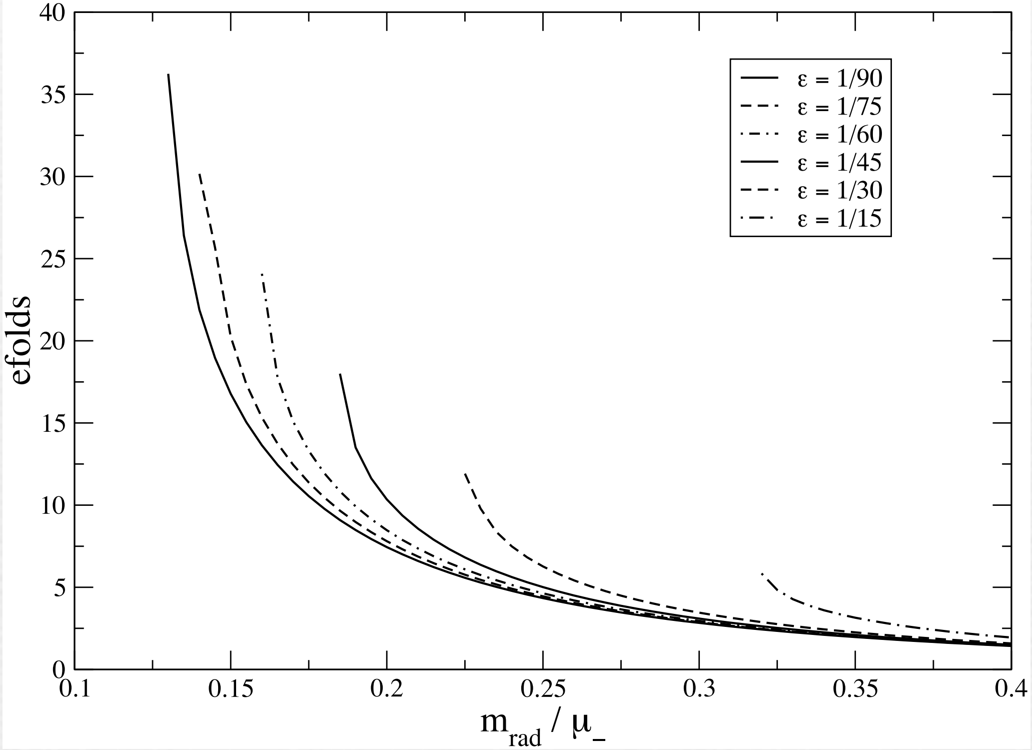
$$F_{\rm AdS-S} = -4\pi^4 (Ml)^3 T^4$$

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

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

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

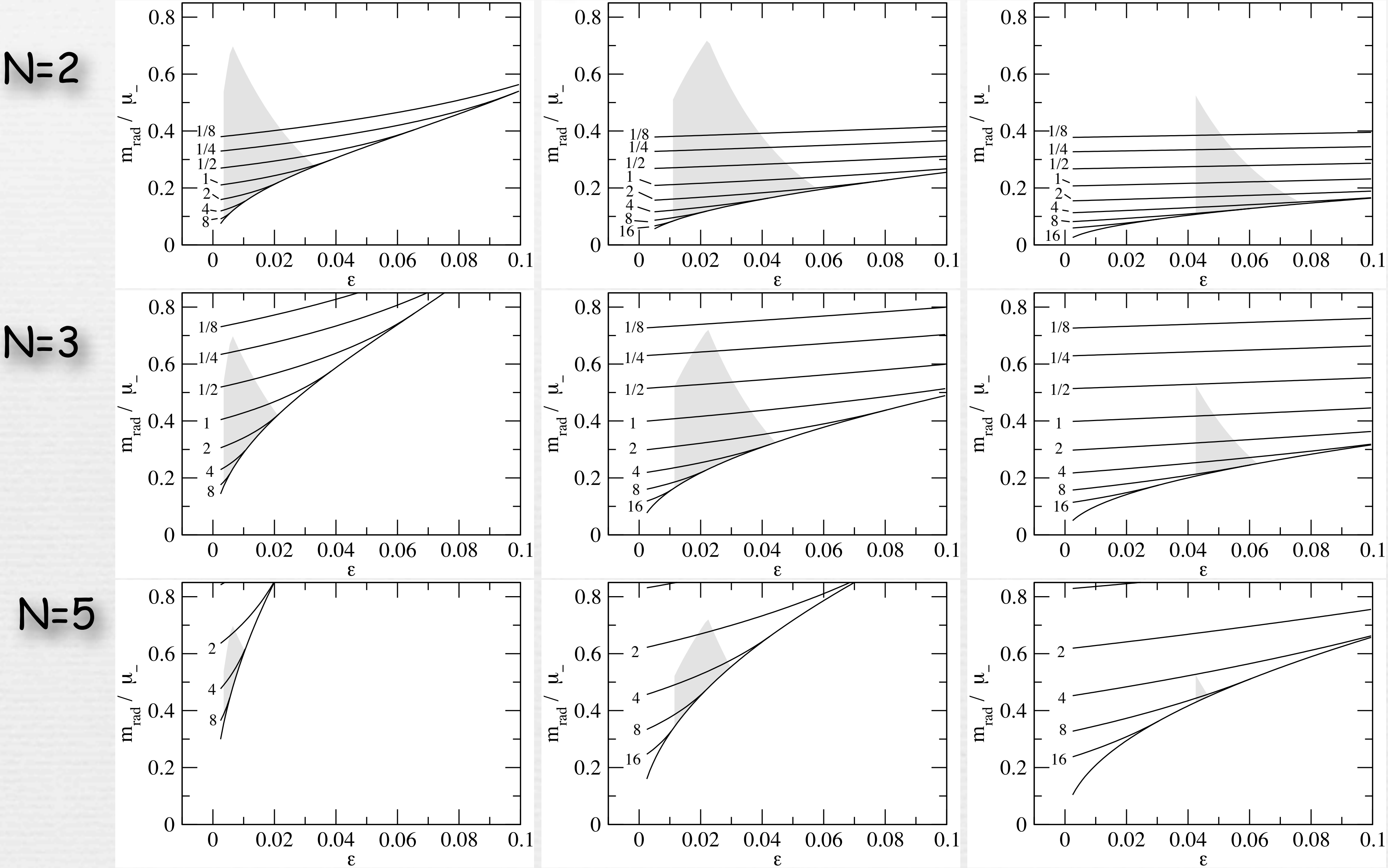
Number of efolds when relaxing the constraint on the EW/Planck hierarchy:



Contours for number of efolds

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

(using Goldberger-Wise stabilization mechanism)



for earlier studies of this phase transition see

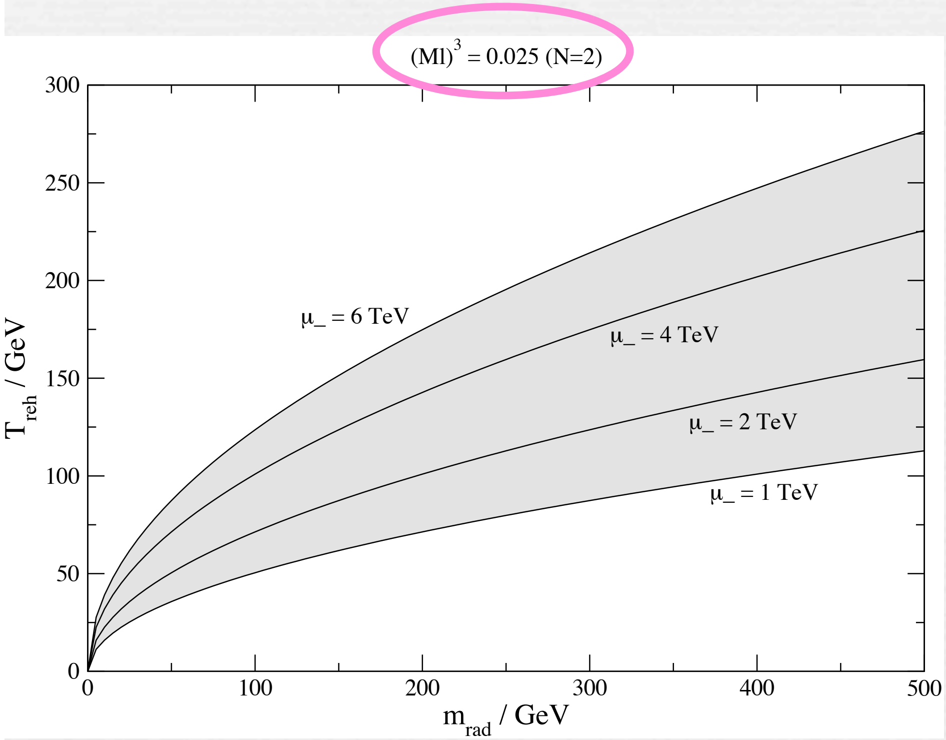
Cline, Firouzjahi'00
Creminelli, Nicolis, Rattazzi'01
Randall, Servant'06

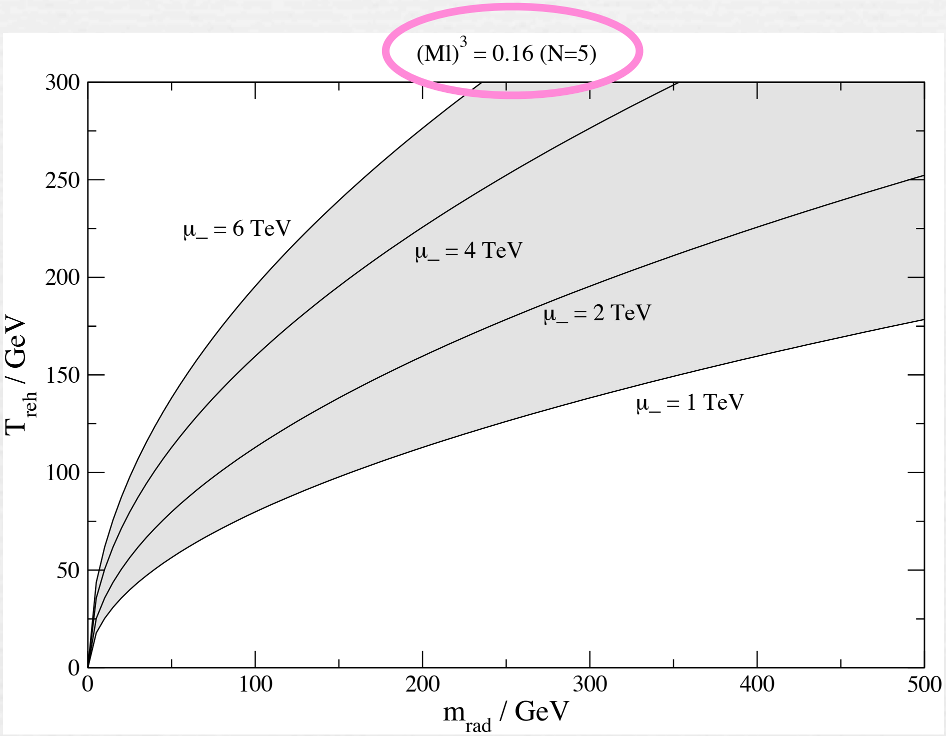
Hassanain, March-Russell, Schwellinger'07
Nardini,Quiros,Wulzer'07
Konstandin,Nardini,Quiros'10

Reheat temperature

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

$$\Delta V = g^* \frac{\pi^2}{30} T_{\rm reh}^4 \quad \Longrightarrow \quad \frac{T_{\rm reh}}{m_{\rm rad}} = \left(\frac{45}{2\pi^2 g_*}\right)^{1/4} \frac{\sqrt{N}}{2\sqrt{\pi}} \sqrt{\frac{\mu_-}{m_{\rm rad}}}$$





We can easily have $T_{\rm reheat} < T_{\rm sphaleron}$ ($T_{\rm sphaleron}$ depends on $M_{\rm H}$)

and $M_{KK} \approx 2.4\ \mu_-$

Viability of various baryogenesis mechanisms

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

Two mechanisms in which sphalerons are not involved

After having checked that the universe can be cold enough after reheating, we need to show that we can produce Higgs winding number by pumping energy from the radion sector

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

$$V(\mu,\phi) = \underset{\substack{\uparrow \\ \text{radion field}}}{\mu^4} \times \left(\, P((\mu/\mu_0)^\epsilon) + \mathcal{V}(\underset{\substack{\uparrow \\ \text{Higgs field}}}{\phi})/\mu_0^4 \,\right)$$

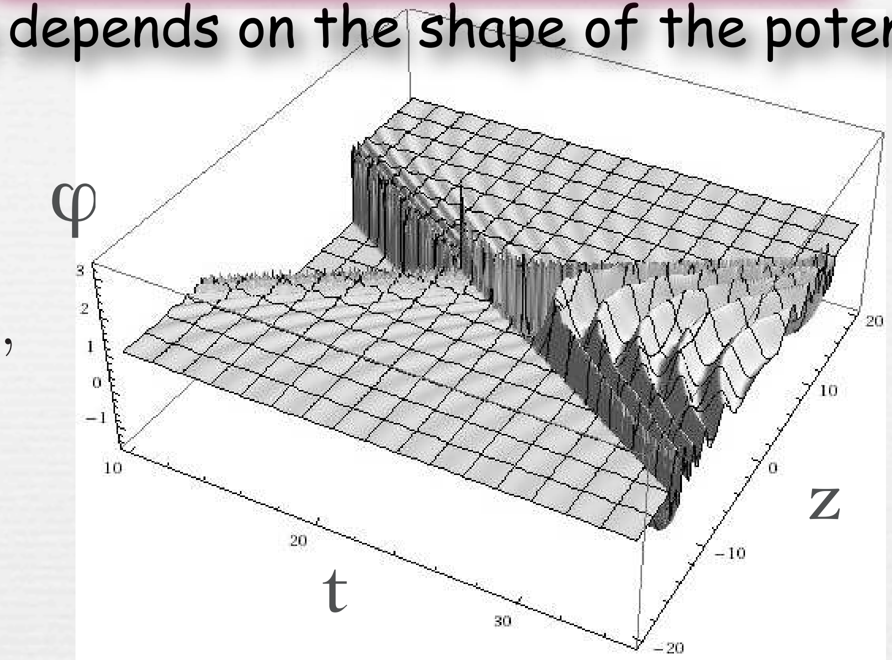
our pb: study the transfer of bubble wall kinetic energy into EW scale scalar configurations

Reheating from bubble collisions

Konstandin Servant '11

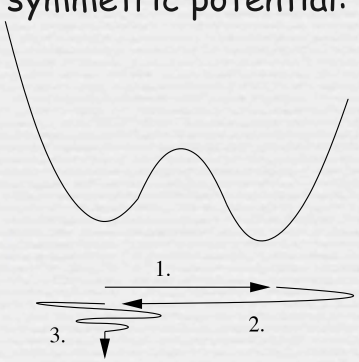
strongly depends on the shape of the potential

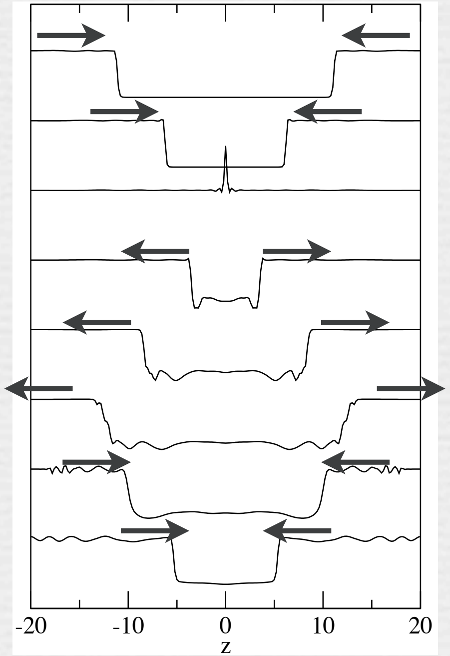
$$\partial_t^2\phi - \partial_z^2\phi = -\frac{dV}{d\phi},$$



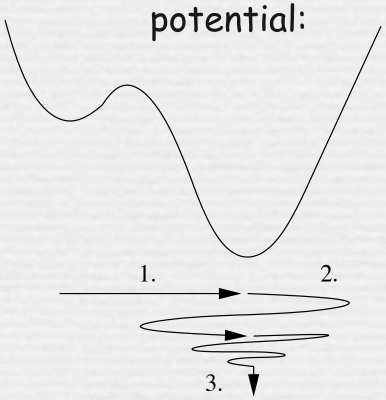
different slices of the collision:

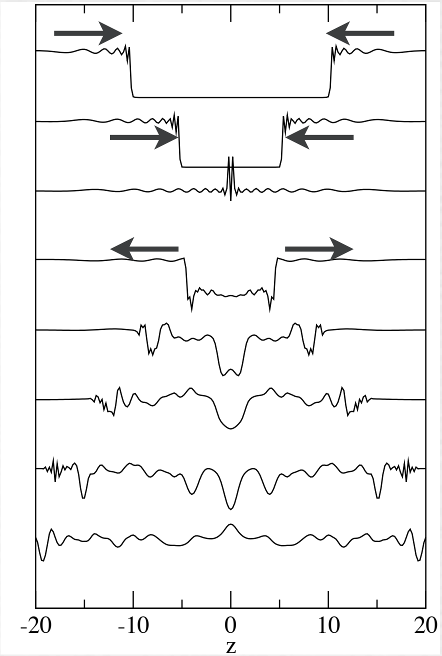
for a nearly symmetric potential:





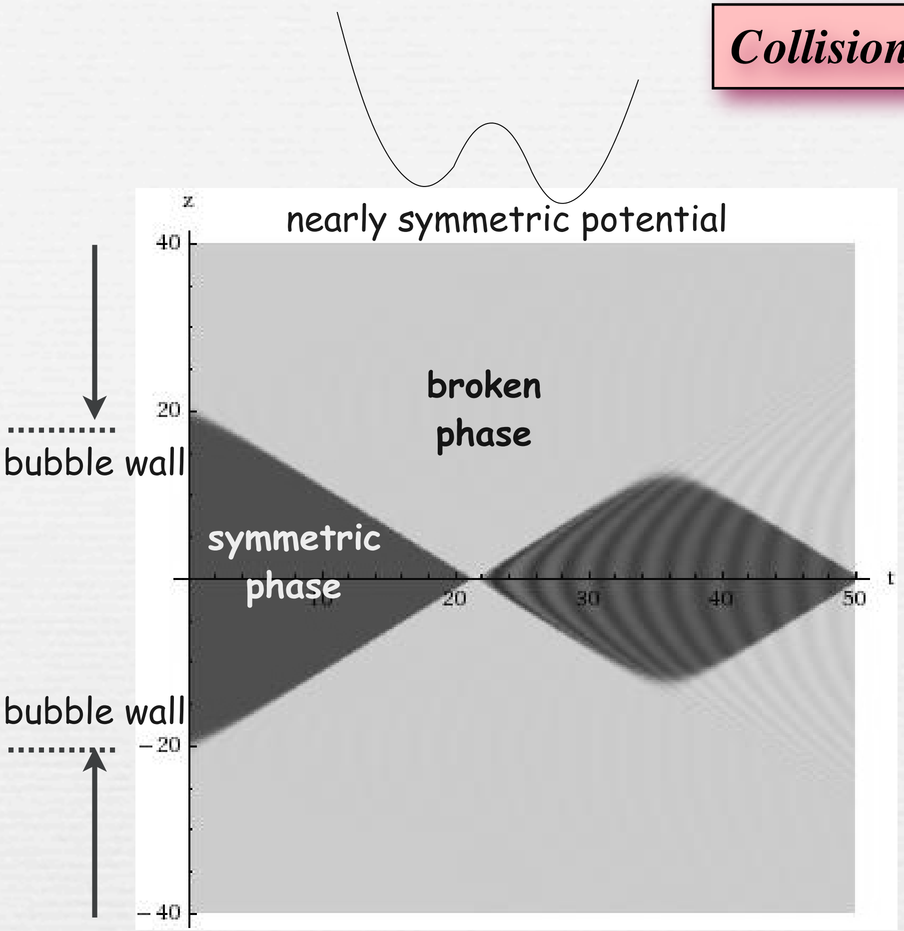
for an asymmetric potential:



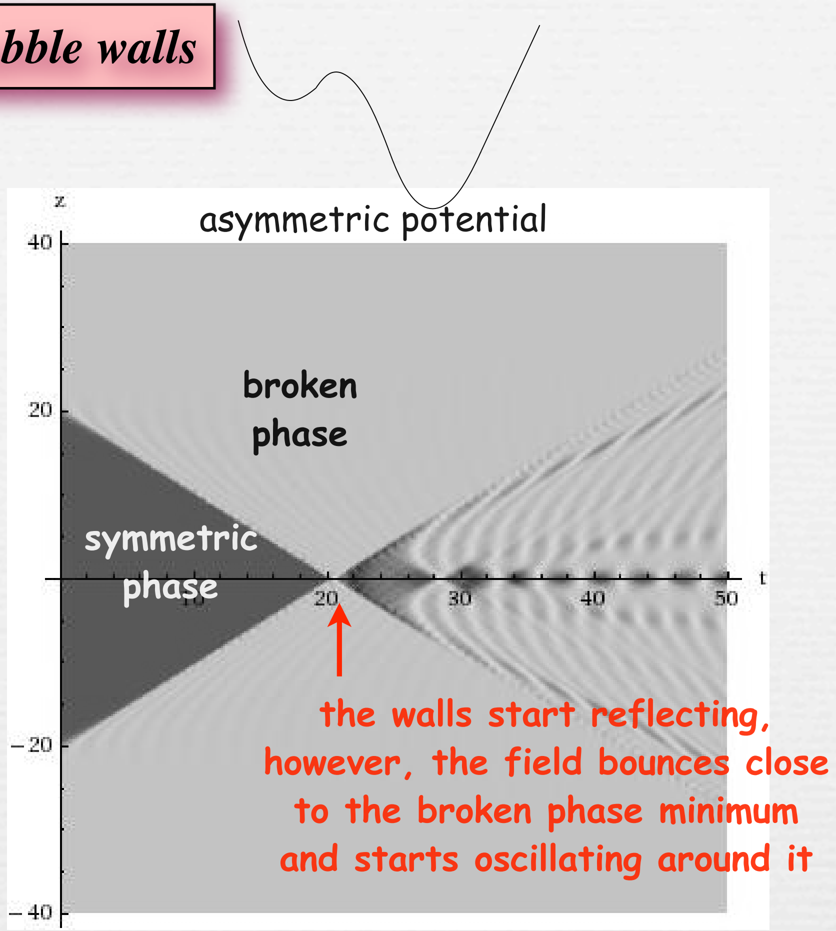


Collision of planar bubble walls

$v_W = 0.5$

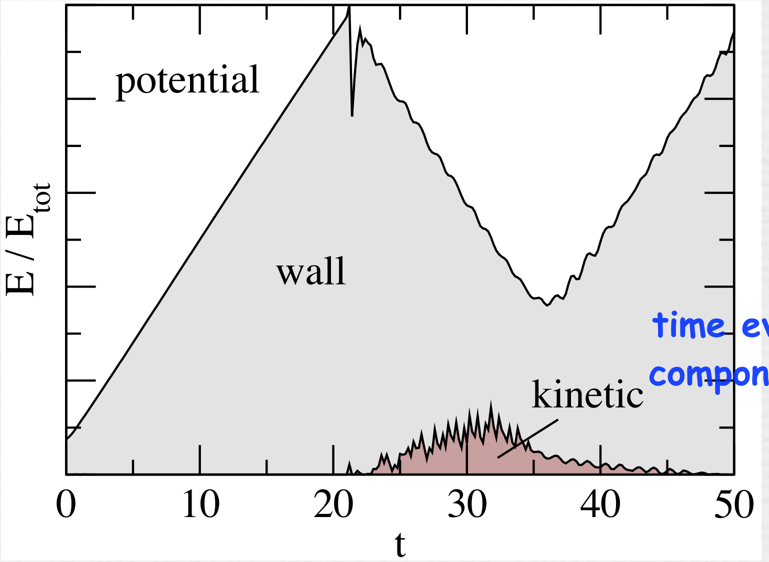


nearly symmetric potential

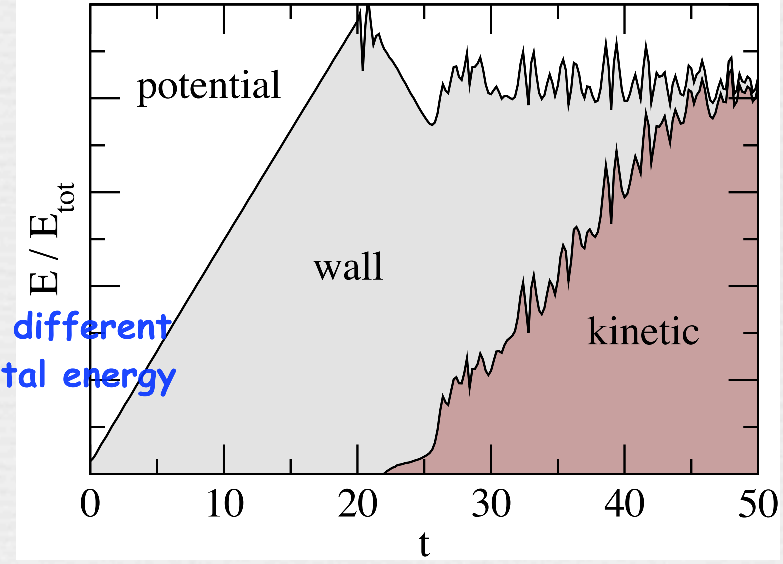


asymmetric potential

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



time evolution of the different components of the total energy



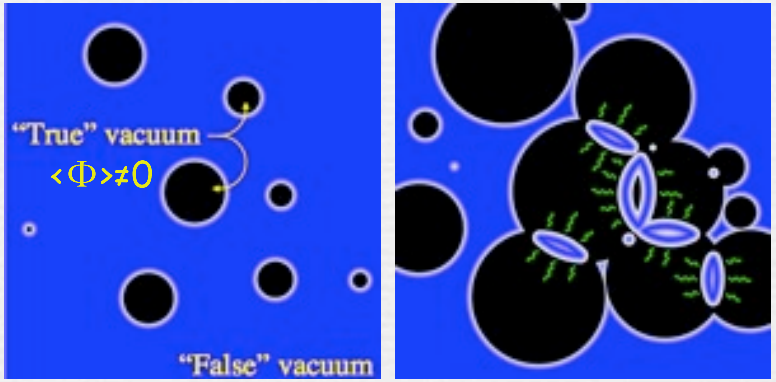
Smoking gun signature

Randall-Servant'06

Konstandin,Nardini,Quiros'10

Bubble nucleation

Bubble percolation



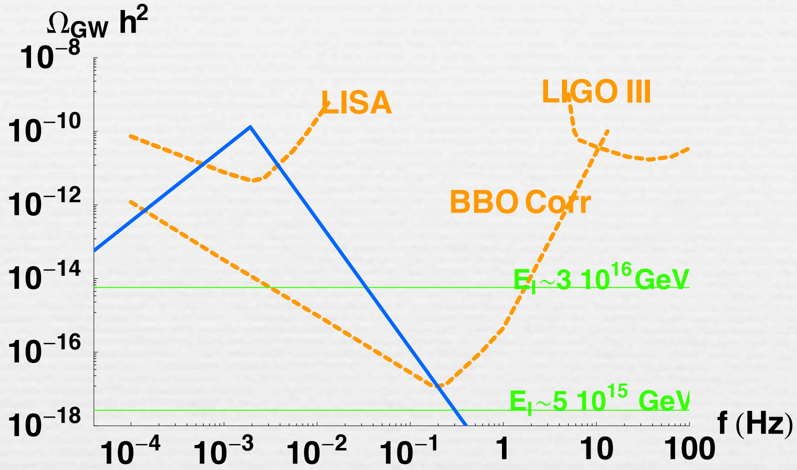
$<\Phi>=0$

Fluid flows

turbulence

Magnetic fields

Stochastic background of gravitational radiation



violent process if v_b ~O(1)

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

Detection of a GW stochastic background peaked in the milliHertz: a signature of near conformal dynamics et the TeV scale

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

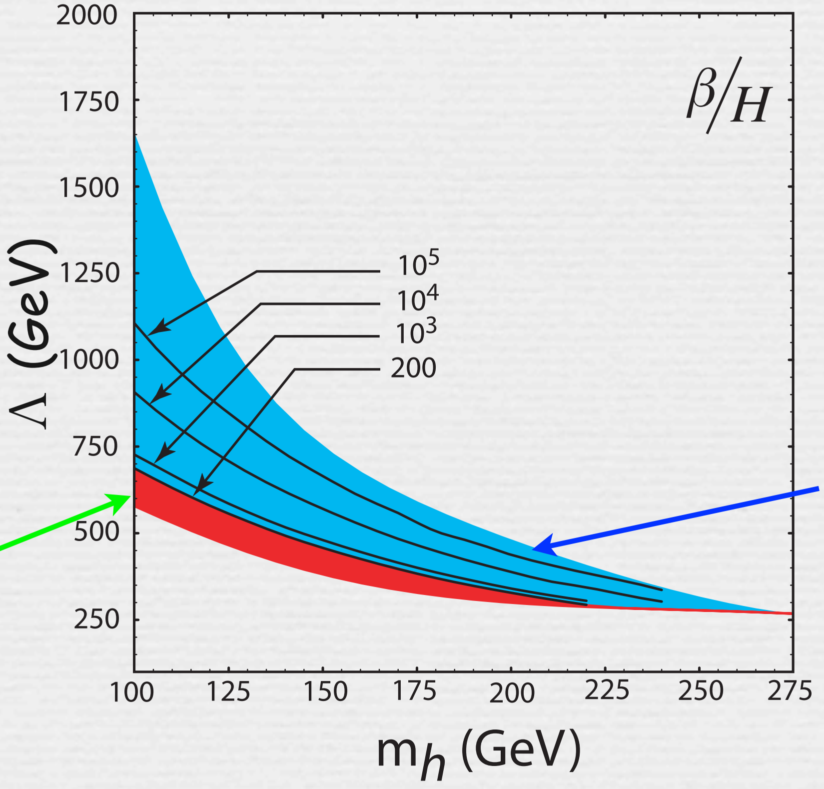
e.g: Effective field theory approach to the EW phase transition:

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

very tiny region
where β/H ≤
O(100)

Grojean-Servant-Wells ’04
Delaunay-Grojean-Wells ’08

Summary

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**
- **T_{reheat} possibly below the sphaleron freese-out temperature**

--> motivating a new route for cold baryogenesis

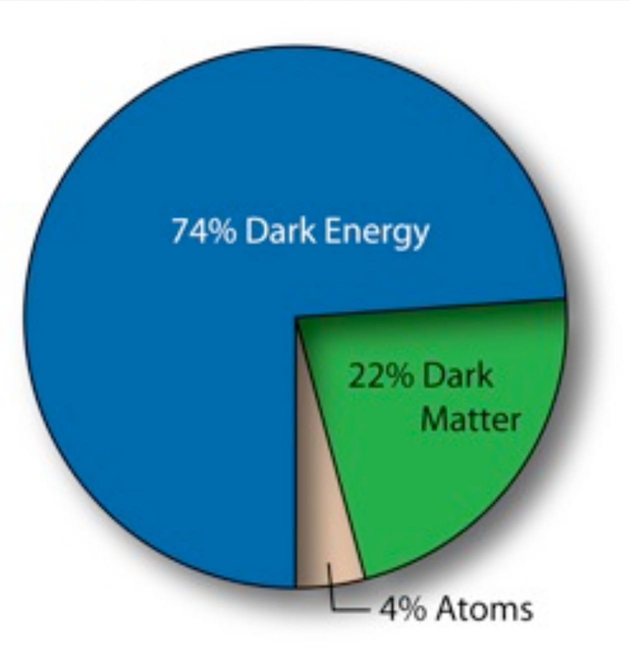
- **Efficient out-of-equilibrium production of heavy particles (or classical field configuration; any field with sizable coupling to the radion, i.e. composite states will be efficiently produced)**

--> Non-thermal DM production from bubble collisions

smoking gun signature:

--a gravity wave stochastic background peaked in the millihertz beyond the standard WIMP paradigm ...

Are the Dark Matter and baryon abundances related?



$\Omega_{DM} \approx 5\text{-}6\ \Omega_{baryons}$

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

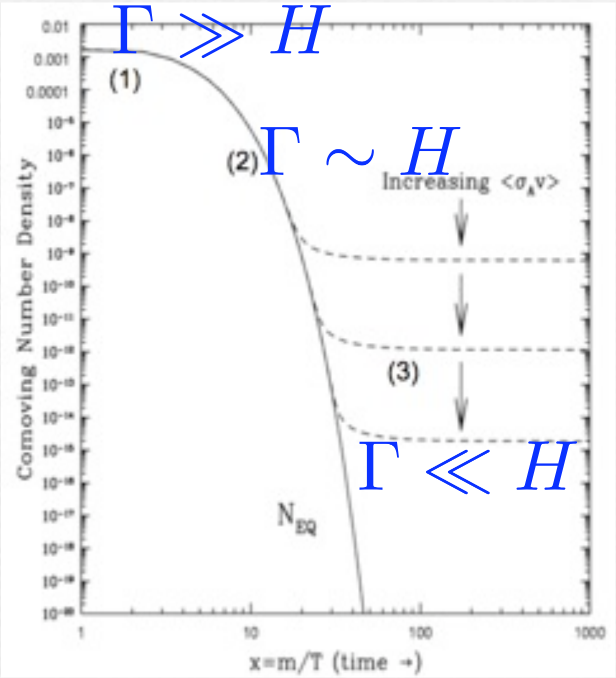
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \to \pi + \pi \to \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T}/m_\pi^2 \sim H \sim \sqrt{g_*}T^2/m_{Pl}$



corresponding to a freeze-out temperature T_F ~ 20 MeV

In absence of an asymmetry:

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

10 000 000 001
Matter

10 000 000 000
Anti-matter

1
(us)

Similarly, Dark Matter may be asymmetric

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

Does this indicate a common dynamics?

If $n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$

then $\displaystyle \frac{\Omega_{dm}}{\Omega_b} \sim \frac{(n_{dm} - \overline{n}_{dm})m_{dm}}{(n_b - \overline{n}_b)m_b} \sim C\frac{m_{dm}}{m_b}$

conservation of global charge: $Q_{\rm DM}(n_{\overline{\rm DM}} - n_{\rm DM}) = Q_b(n_b - n_{\overline{b}})$

if efficient annihilations: $\displaystyle \frac{\Omega_{dm}}{\Omega_b} \sim \frac{Q_b}{Q_{dm}} \frac{m_{dm}}{m_b} \longrightarrow$ typical expected mass ~ GeV

two possibilities:

1) asymmetries in baryons and in DM generated simultaneously

2) a pre-existing asymmetry (either in DM or in baryons) is transferred between the two sectors

Opening the window for Asymmetric Dark Matter with DM antiDM oscillations

Cirelli-Panci-Servant-Zaharijas '11

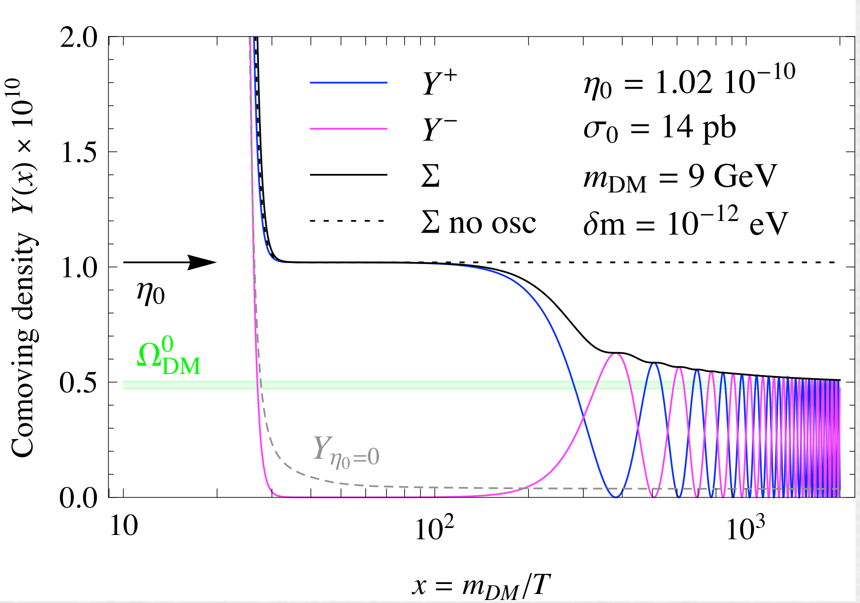
Assume a small DM-number violating Majorana mass term , e.g. $\delta m \sim \phi^\dagger \phi / M_{pl}$

It introduces a splitting between X and X^c
and leads to oscillations between DM and antiDM when δ m ~ H~T^2/M_{Pl}

i.e. at T~ <ϕ> at EW scale!

re-equilibration of the initial
asymmetry before freese-out

re-establishment of annihilations



Scaling of WIMP relic abundance

- **symmetric DM:**

$$\Omega_{\rm DM} \propto \frac{1}{\sigma_0}$$

no explicit dependence on $m_{\rm DM}$

- **Asymmetric DM:**

$$\Omega_{\rm DM} \propto \frac{m_{\rm DM} \times \eta_0}{1 + A(\delta m^2 M_{Pl}^6 \sigma_0^4 \eta_0^4)^{1/5}}$$

Cirelli-Panci-Servant-Zaharijas '11

$$\delta m \to 0$$

$$\Omega_{\rm DM} \propto m_{\rm DM} \times \eta_0$$

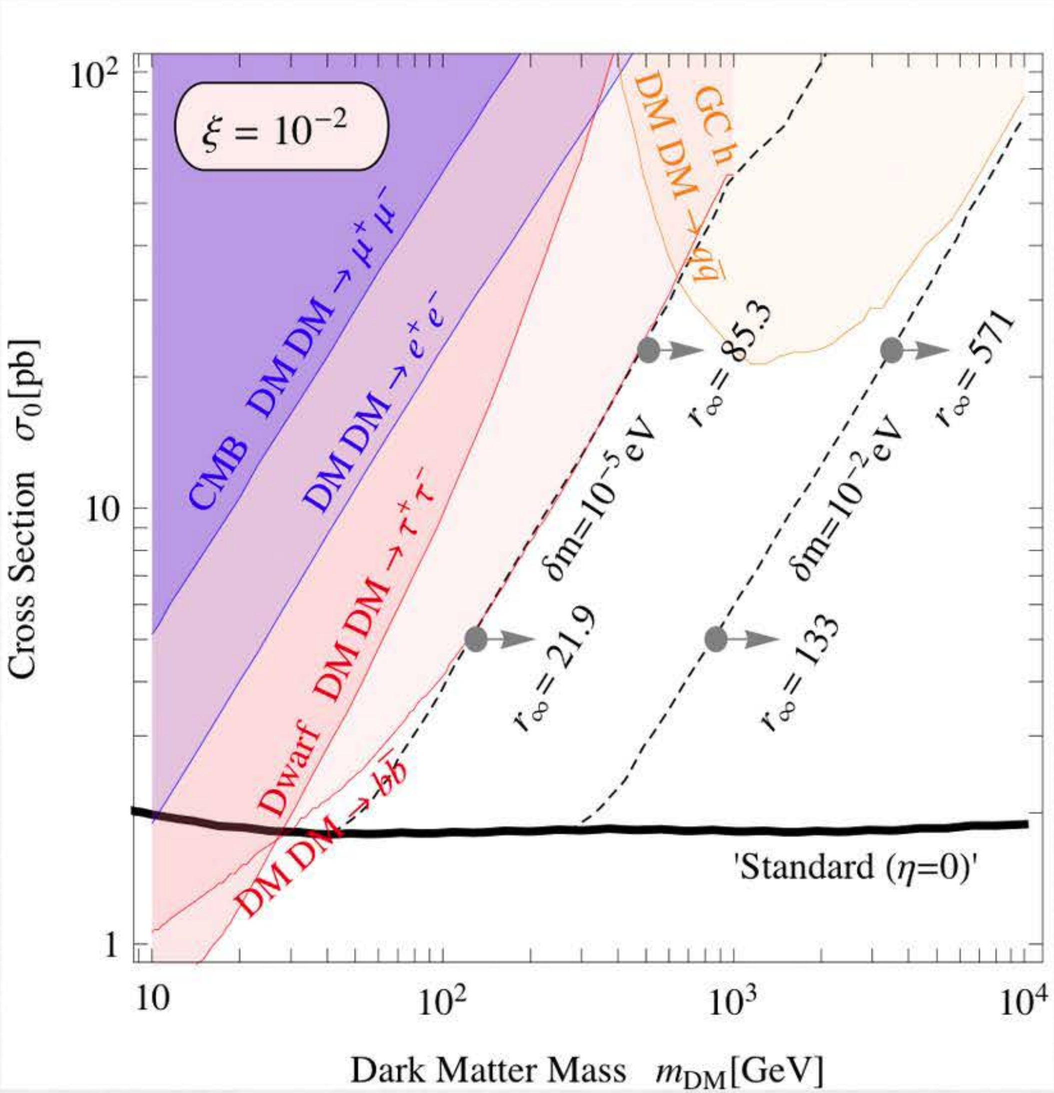
no dependence on σ_0

$$\delta m \gtrsim 1 \text{ eV}$$

$$\Omega_{\rm DM} \propto \frac{m_{\rm DM} \times \eta_0^{1/5}}{\delta m^{2/5} \sigma_0^{4/5}}$$

Explicit dependence on $m_{\rm DM}$

Opening the window for Asymmetric Dark Matter



Large masses naturally allowed !

Cirelli-Panci-Servant-Zaharijas '11

Conclusion

DM & Baryogenesis at the EW scale:

Interesting variants around the standard WIMP and EW baryogenesis scenarios

- Asymmetric TeV scale Dark Matter is an appealing possibility associated with an elegant unified explanation of dark and visible matter generation

  complementary constraints from direct, indirect and collider constraints.

both under testing !

- EW baryogenesis at a first-order EW phase transition

  still well alive

  + potentially new paradigm for cold baryogenesis if low reheat temperature