Cosmological probes of Electroweak symmetry breaking

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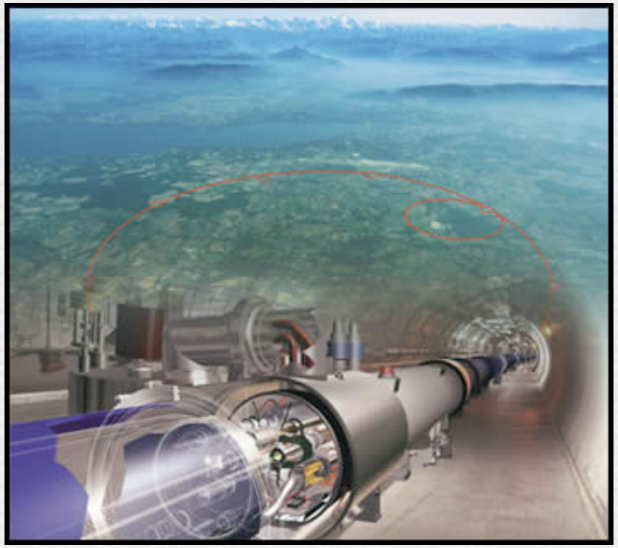
2010: First collisions at the LHC

Direct exploration of the TeV scale has started

main physics goal:

What is the mechanism of Electroweak Symmetry breaking ?



The Standard Model of Particle Physics

Forces **Matter** **Background**

$$\mathcal{L}_{\text{Standard Model}} = - F^{a}_{\mu\nu} F^{a\mu\nu} + \overbrace{(\lambda_{ij}\, \Psi_i \Psi_j\, h + h.c) + N_i M_{ij} N_j} + |D_\mu h|^2 - V(h)$$

gauge sector

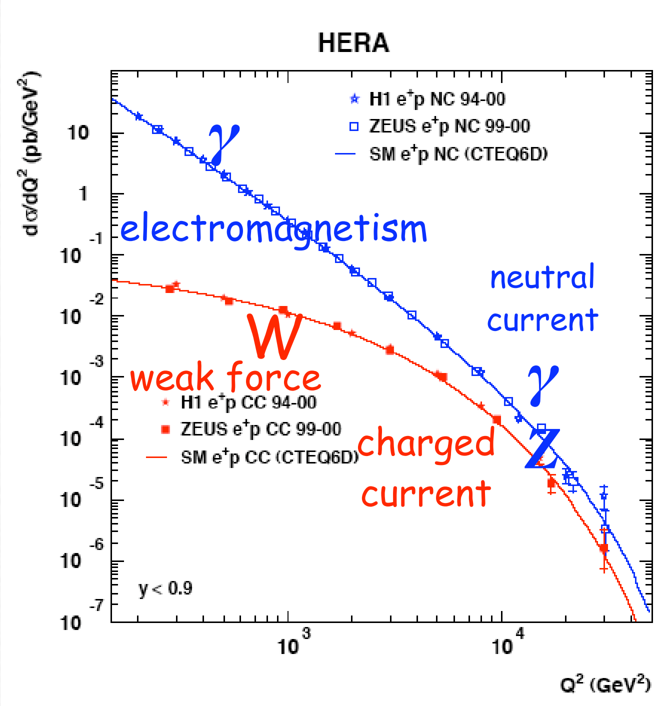
flavour sector

neutrino mass sector (if Majorana)

(spontaneous) electroweak symmetry breaking sector

$SU(3)_C \times SU(2)_L \times U(1)_Y$

- one century to develop it
- tested with impressive precision
- accounts for all data in experimental particle physics

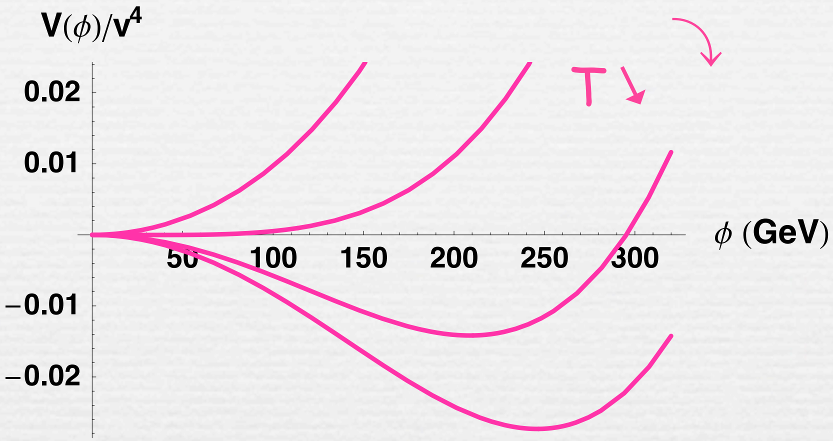


The Higgs is the only remaining unobserved piece

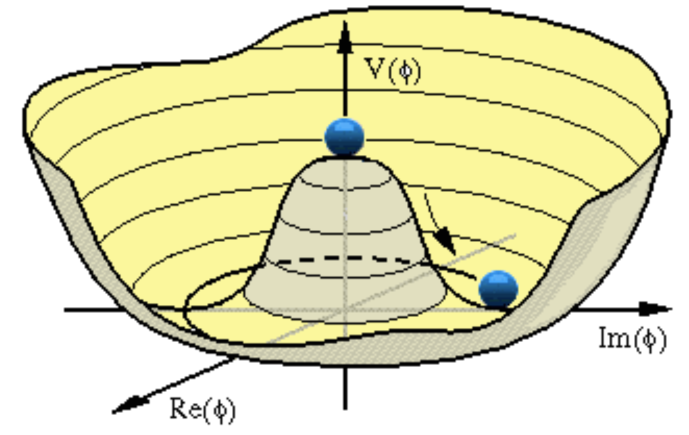
and a portal to new physics hidden sectors

Higgs Mechanism

EW symmetry breaking is described by the condensation of a scalar field



The Higgs selects a vacuum state by developing a non zero background value. When it does so, it gives mass to SM particles it couples to.

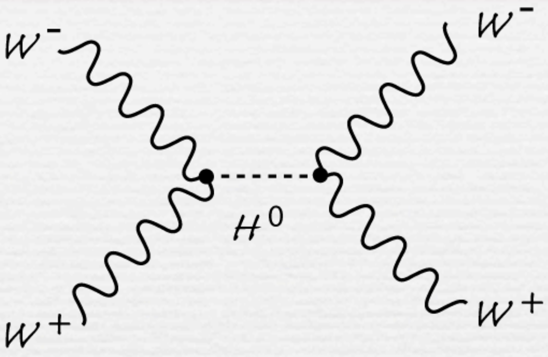


the puzzle:

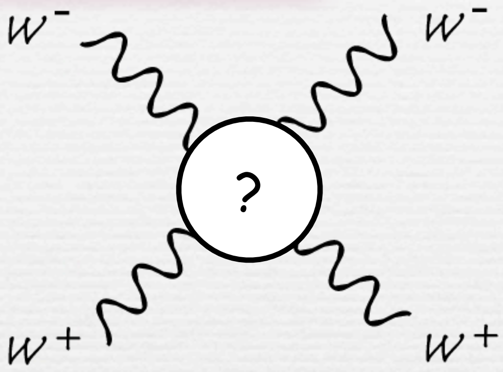
We do not know what makes the Higgs condensate.
We ARRANGE the Higgs potential so that the Higgs condensates but this is just a parametrization that we are unable to explain dynamically.

Electroweak symmetry breaking: 2 main questions

- ## What is unitarizing the $W_L W_L$ scattering amplitude?

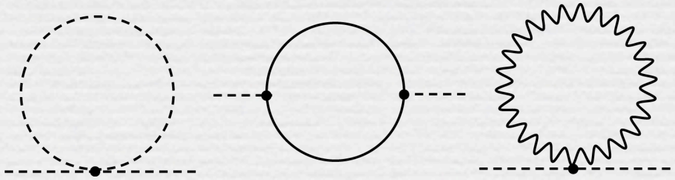


the Higgs or something else?



- ## What is cancelling the divergent diagrams?

(i.e what is keeping the Higgs light?)
: Hierarchy problem



$$\Rightarrow \delta M_H^2 \propto \Lambda^2$$

Λ , the maximum mass scale that the theory describes

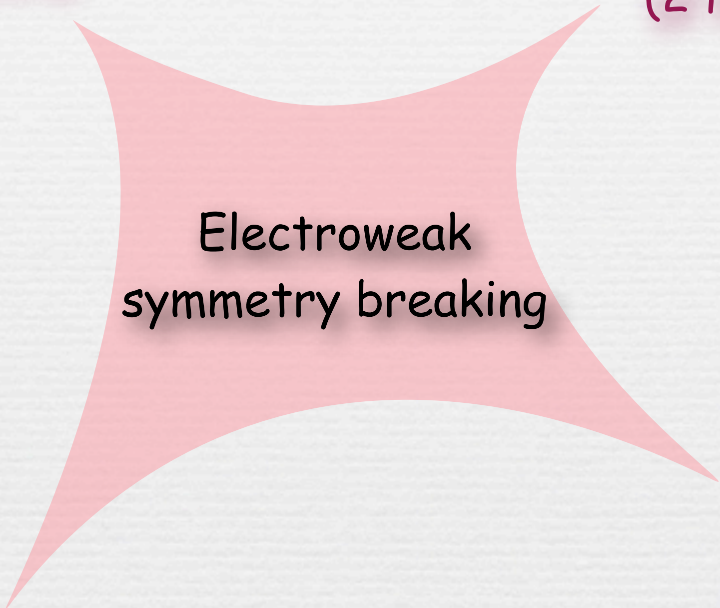
strong sensitivity on UV unknown physics

need new degrees of freedom & new symmetries to cancel the divergences

supersymmetry, gauge-Higgs unification, Higgs as a pseudo-goldstone boson...

→ theoretical need for new physics at the TeV scale

Which new physics?



Supersymmetric

Minimally extended
(2 Higgs doublets)

Electroweak
symmetry breaking

Higgsless,
technicolor-like,
5-dimensional

Composite, Higgs as
pseudo-goldstone
boson, $H=A_5$

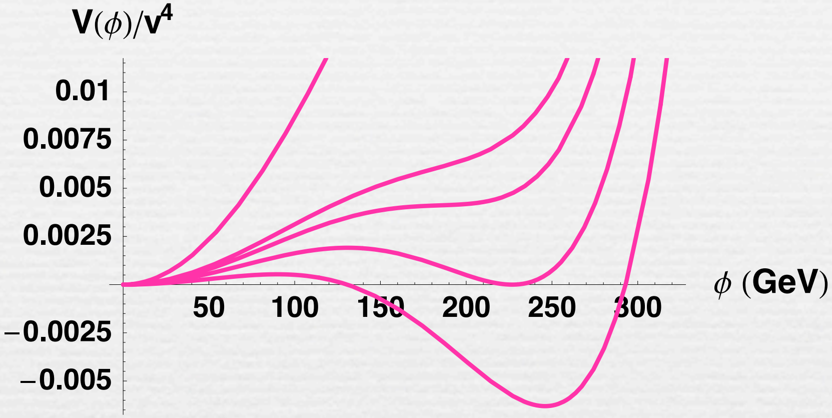
In all explicit examples, without unwarranted cancellations, new phenomena are required at a scale $\Lambda \sim [3-5] \times M_{Higgs}$

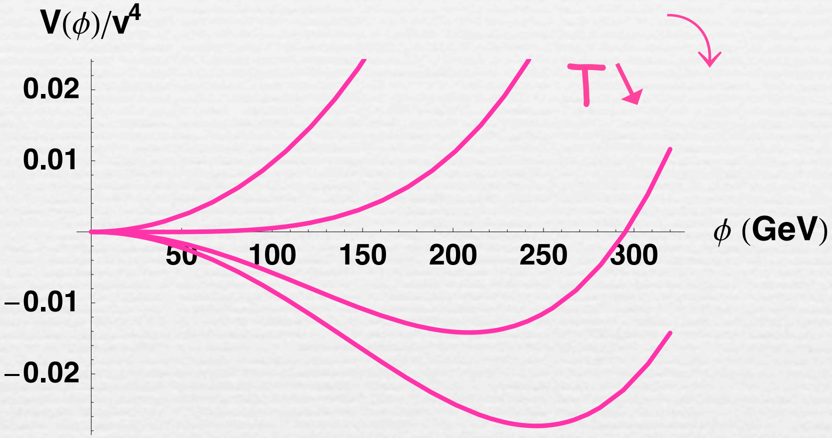
Which Higgs ?

- Composite Higgs ?
- Little Higgs ?
- Littlest Higgs ?
- Intermediate Higgs ?
- Slim Higgs ?
- Fat Higgs ?
- Gauge-Higgs ?
- Holographic Higgs ?
- Gaugephobic Higgs ?
- Higgsless ?
- UnHiggs ?
- Portal Higgs ?
- Simplest Higgs ?
- Private Higgs ?
- Lone Higgs ?
- Phantom Higgs ?

What is the nature of the electroweak phase transition ?

first-order or second-order?





LHC will provide insight as it will shed light on the Higgs sector

Question intensively studied within the Minimal Supersymmetric Standard Model (MSSM). However, not so beyond the MSSM (gauge-higgs unification in extra dimensions, composite Higgs, Little Higgs, Higgsless...)

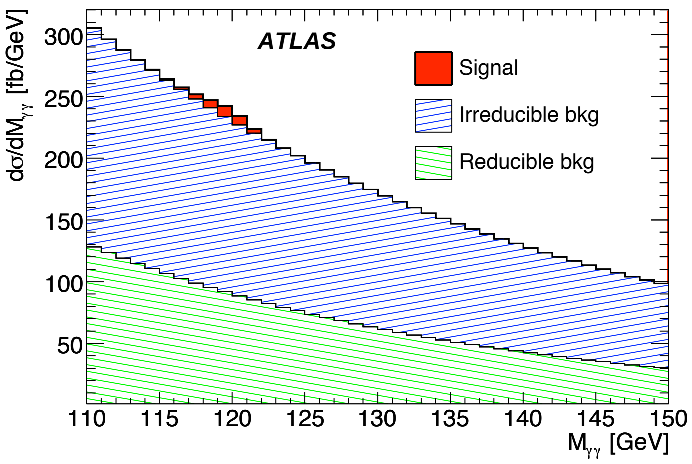
Why do we care?

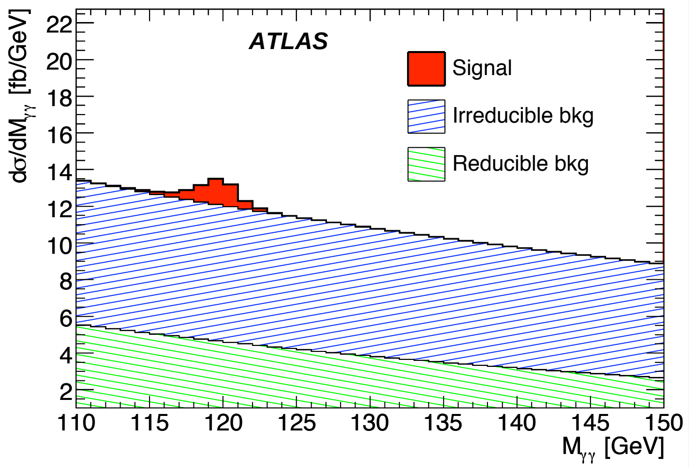
1) Nature and properties of the EW phase transition reflect information on the dynamics behind EW symmetry breaking (e.g weakly or strongly interacting).

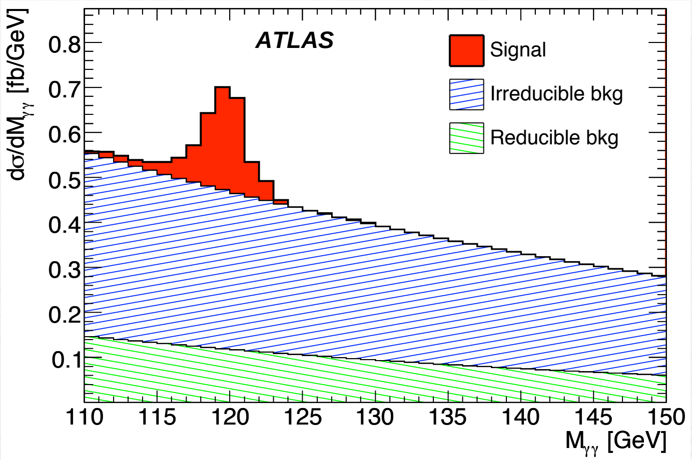
2) Crucial for reliable computations of electroweak baryogenesis

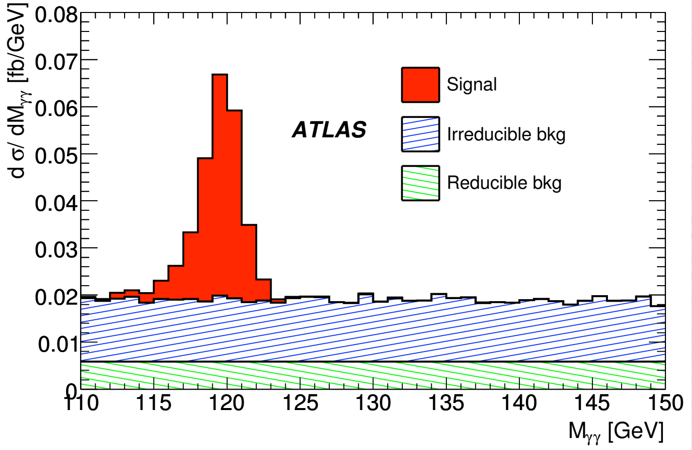
What questions the LHC experiments will try to answer :

- **Does a Higgs boson exist ?**









If yes :

- is there only one ?
- what are its mass, width, quantum numbers ?
- what are its couplings to itself and other particles
- Spin determination
- CP properties
- does it generate EW symmetry breaking and give mass to fermions too as in the Standard Model or is something else needed ?

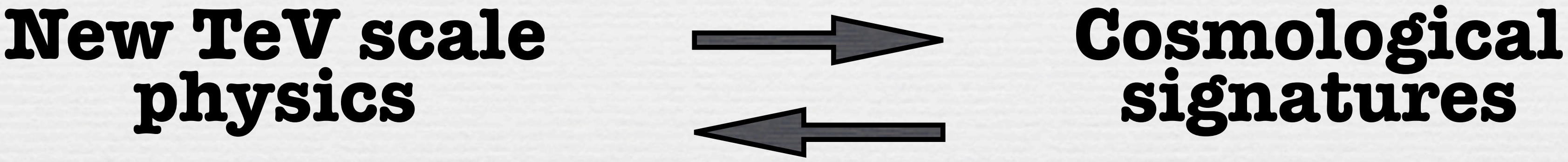
If not, be ready for

- very tough searches at the (S)LHC (VLVL scattering, ...) or
- more spectacular phenomena such as W', Z' (KK) resonances, technicolor, etc...

- **Searches for other new particles: Do they play any role in EW symmetry breaking?**

LHC will most likely not provide the final answer

Searching for complementary probes of the EW symmetry breaking mechanism in cosmological observables



New TeV scale physics

Cosmological signatures

mainly from
- dark matter
- baryogenesis (this talk)

(see also recent interest
in higgs inflation)

Imagine what our universe would look like if electroweak symmetry was not broken

- quarks and leptons would be massless

- mass of proton and neutron (the strong force confines quarks into hadrons) would be a little changed

- proton becomes heavier than neutron (due to its electrostatic self energy) ! no more stable

-> no hydrogen atom

-> very different primordial nucleosynthesis

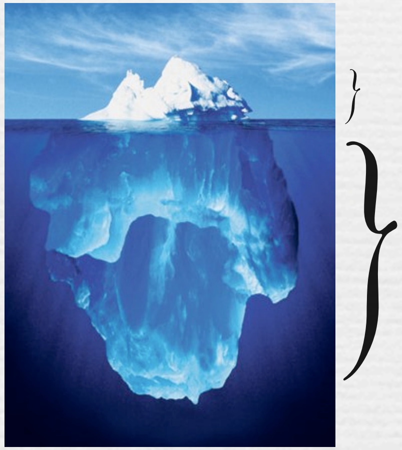
-> a profoundly different (and terribly boring) universe

2 major observations unexplained by the Standard Model

that may have something to do with new physics at the electroweak scale

- the Dark Matter of the Universe

Some invisible transparent matter (that does not interact with photons) which presence is deduced through its gravitational effects



15% baryonic matter (1% in stars, 14% in gas)

85% dark unknown matter

- the (quasi) absence of antimatter in the universe

baryon asymmetry: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-10}$

Matter Anti-matter asymmetry of the universe:

characterized in terms of the baryon to photon ratio

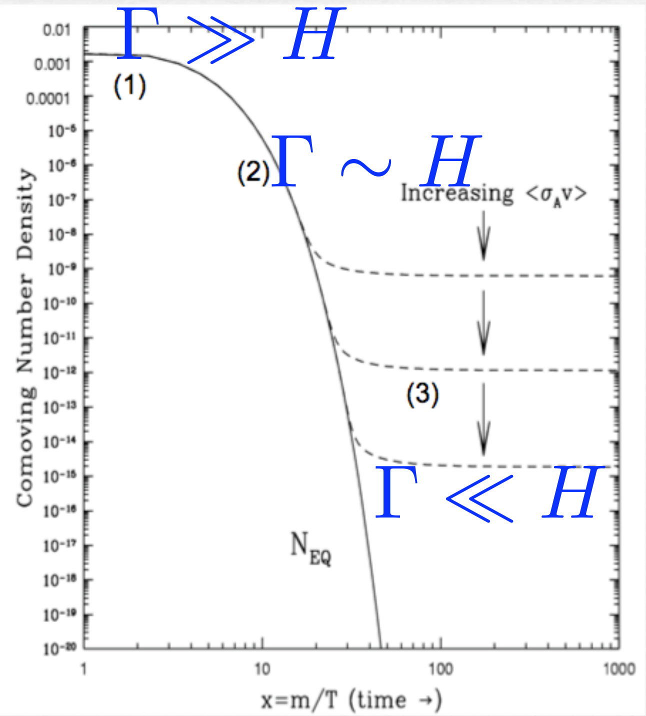
$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ 6. 10^{-10}

The great annihilation between nucleons & anti-nucleons

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

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)

Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

(we need a process which can turn antimatter into matter)

2) C (charge conjugation) and CP (charge conjugation ×Parity) violation

(we need to prefer matter over antimatter)

3) Loss of thermal equilibrium

In thermal equilibrium, any reaction which destroys baryon number will be exactly counterbalanced by the inverse reaction which creates it. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be erased by interactions

(we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass , so no asymmetry can develop)

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$

Why can't we achieve baryogenesis in the Standard Model?

B is violated

C and CP are violated

but which out-of-equilibrium condition?

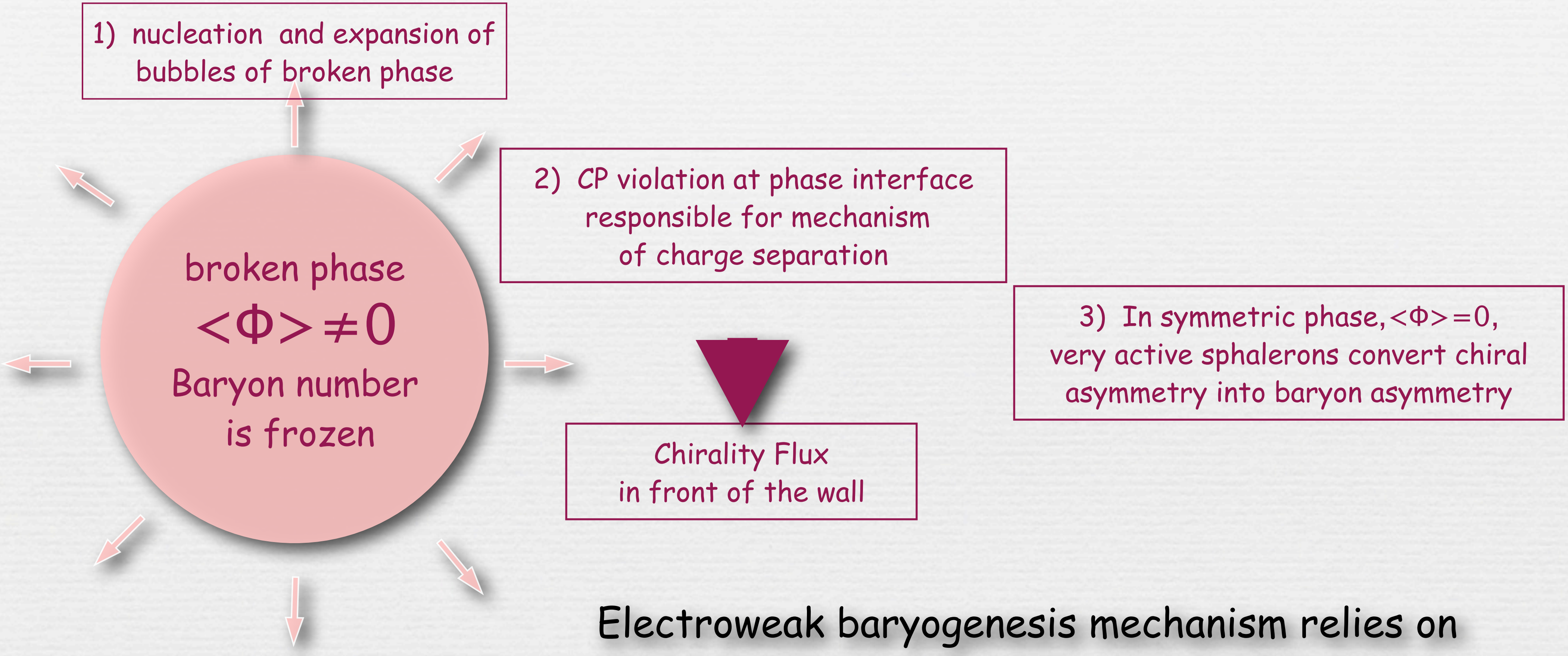
no heavy particle which could decay out-of-equilibrium

no strong first-order phase transition

Electroweak phase transition is a smooth cross over

Also, CP violation is too small (suppressed by the small quark masses, remember there is no CP violation if quark masses vanish)

Baryon asymmetry and the EW scale



1) nucleation and expansion of bubbles of broken phase

broken phase

$<\Phi>\neq 0$

Baryon number is frozen

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

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

Chirality Flux in front of the wall

Electroweak baryogenesis mechanism relies on a first-order phase transition

EW baryogenesis is natural ...

$$\left.\begin{aligned} n_{\rm B} &= \int_{-\infty}^{+\infty} \frac{dn_{\rm B}}{dt}\frac{dz}{v_z} \\ \frac{dn_{\rm B}}{dt} &\sim n_{\rm B}\frac{\Gamma_{sph}}{T^3} \end{aligned}\right\} \quad n_{\rm B} \propto \frac{\Gamma_{sph}}{T^3 v_z}\int_{-\infty}^{0} n_L\, dz$$

$$\Gamma_{sph} \sim 25\,\alpha_w^5 T^4 \sim \alpha_w^4 T^4 \Longrightarrow \frac{n_{\rm B}}{s} \sim \frac{\alpha_w^4}{g_*}\epsilon_{\rm CP} \sim 10^{-10}$$

$$\Longrightarrow \boxed{\epsilon_{\rm CP} \gtrsim 10^{-2}}$$

If CP violating effects are large at weak energies, we obtain the right amount of baryon asymmetry

-> However, strong bounds from EDMs

Rate of B violation in the EW broken phase

$$\Gamma = 2.8 \times 10^5 (\frac{\alpha_W}{4\pi})^4 \kappa C^{-7} \, T^4 \left(\frac{E_{sph}}{T}\right)^7 e^{-E_{sph}/T}$$

Arnold-McLerran'87
Khlebnikov-Shaposhnikov'88
Carson-McLerran'90
Carson-Li-McLerran-Wang'90

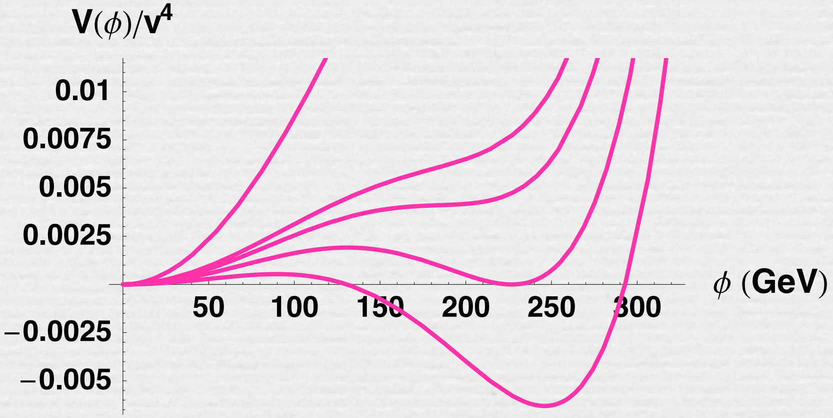
Out-of-equilibrium condition:

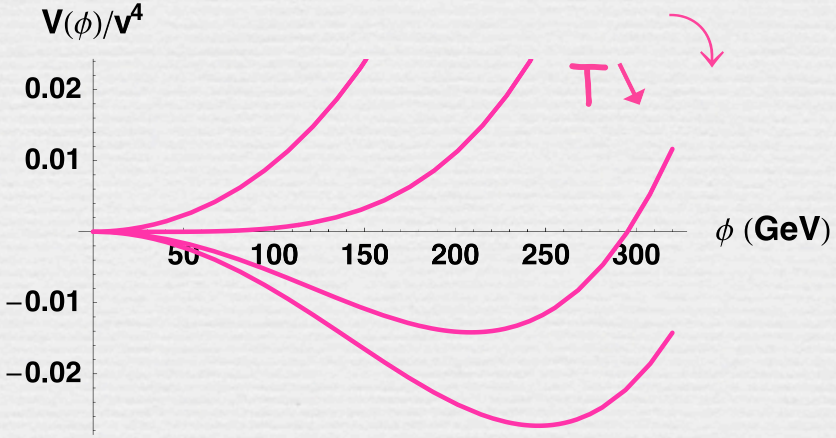
$$\boxed{\frac{\Gamma}{T^3} < H \sim \frac{\sqrt{\rho}}{m_{Pl}}} \quad \Rrightarrow \quad \left.\frac{\langle\phi\rangle}{T}\right|_{T_c} > 1$$

=`sphaleron bound '

What to expect for the EW phase transition

first-order or second-order?





Effective potential at finite temperature

$$V_{1-\text{loop}} = T\sum_i \pm \int \frac{d^3p}{(2\pi)^3} \ln\left(1 \mp e^{-\beta\sqrt{p^2+m_i^2(H)}}\right) \begin{cases}\text{bosons}\\ \text{fermions}\end{cases}$$

High-temperature expansion

$$\begin{aligned}V_{1-\text{loop}} &= \sum_{i\in B,F} \frac{m_i^2T^2}{48} \times \left\{\begin{array}{c} 2,\ \text{each real B} \\ 4,\ \text{each Dirac F}\end{array}\right\} \boxed{- \frac{m_i^3T}{12\pi}} \left\{\begin{array}{c} \cancel{1,\ \text{B}} \\ 0,\ \text{F}\end{array}\right\} \\ &+ \frac{m_i^4}{64\pi^2}\left(\ln\frac{m_i^2}{T^2} - c_i\right) \times \left\{\begin{array}{c} -1,\ \text{B} \\ +4,\ \text{Dirac F}\end{array}\right\} + O\left(\frac{m_i^5}{T}\right)\end{aligned}$$

$$c_i = \begin{cases} \frac{3}{2} + 2\ln 4\pi - 2\gamma_E \cong 5.408,\ \text{B} \\ c_B - 2\ln 4 \cong 2.635,\ \text{F}\end{cases}$$

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

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

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

Sum over all bosons which couple to the Higgs

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

mh<35 GeV would be needed to get Φ/T>1 and for mh >72 GeV, the phase transition is 2nd order

Strength of the transition in the SM:

$$\langle\phi(T_c)\rangle = \frac{2\ E\ T_c}{\lambda} \qquad \Rrightarrow \qquad \frac{\langle\phi(T_c)\rangle}{T_c} = \frac{2\ E\ v_0^2}{\lambda\ v_0^2} = \frac{4\ E\ v_0^2}{\boxed{m_h^2}}$$

$$v_0 \approx 246 \text{ GeV} \quad \text{and} \quad E = \frac{2}{3}\frac{2m_W^3 + m_Z^3}{4\pi v_0^3} \sim 6.3 \times 10^{-3}$$

$$\frac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1 \qquad \Longrightarrow \qquad m_h \lesssim 47 \text{ GeV}$$

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

Main effect due to the stop

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

in MSSM, 'stop' contribution:

$$m^2_{\tilde{t}_R}(h,T) \approx m^2_U + m_t(h)^2 + c_s T^2$$

we need $m^2_U < 0$

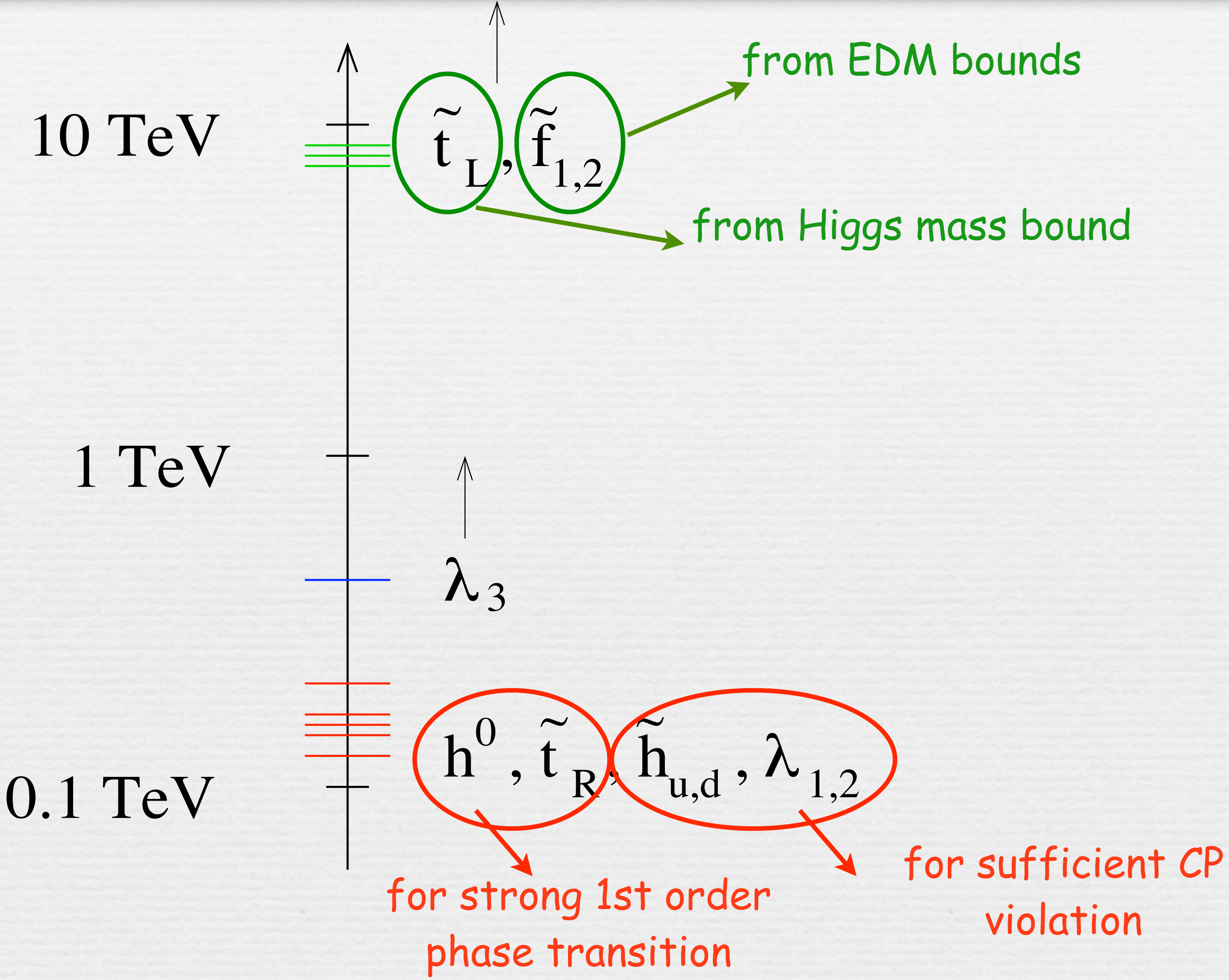
i.e. the 'stop' should be lighter than the top quark.

$$95\ \mathrm{GeV} \lesssim m_{\tilde{t}_R} \lesssim 125\ \mathrm{GeV}$$

the other stop must be very heavy to have $m_h > 114\ \mathrm{GeV}$

$$m_{\tilde{t}_L} \gtrsim 6\ \mathrm{TeV}$$

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

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

bounds get relaxed when adding singlets or in BSSM

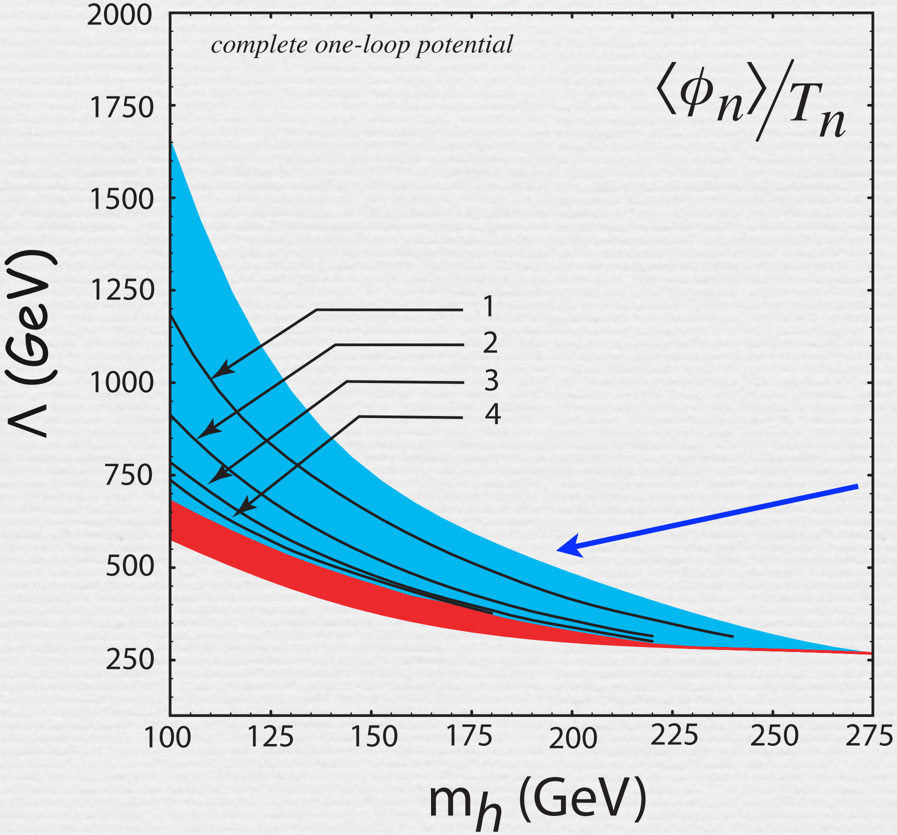
Effective field theory approach

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

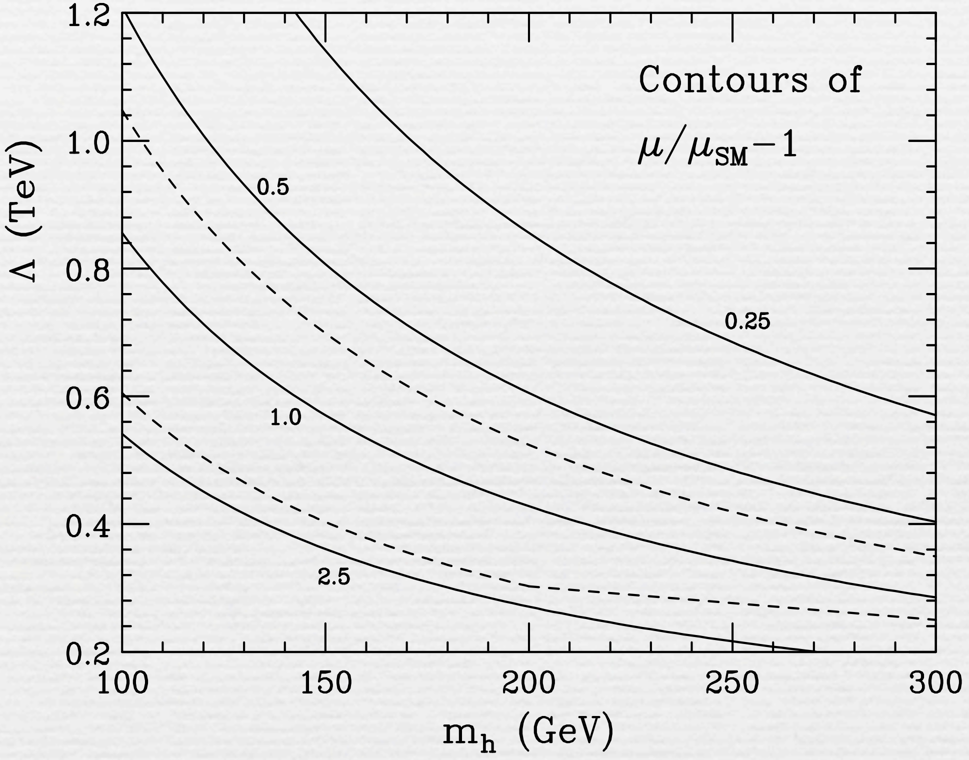
This scenario predicts large deviations to the Higgs self-couplings

$$\mathcal{L} = \frac{m_H^2}{2} H^2 + \frac{\mu}{3!} H^3 + \frac{\eta}{4!} H^4 + \ldots$$

where

$$\mu = 3 \frac{m_H^2}{v_0} + 6 \frac{v_0^3}{\Lambda^2}$$

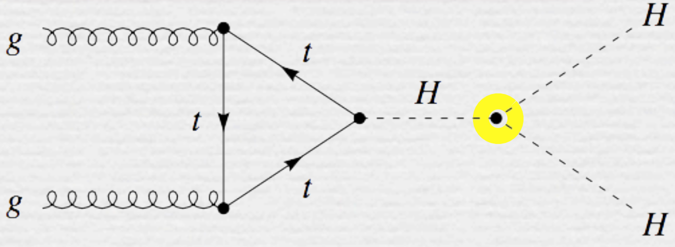
$$\eta = 3 \frac{m_H^2}{v_0^2} + 36 \frac{v_0^2}{\Lambda^2}$$



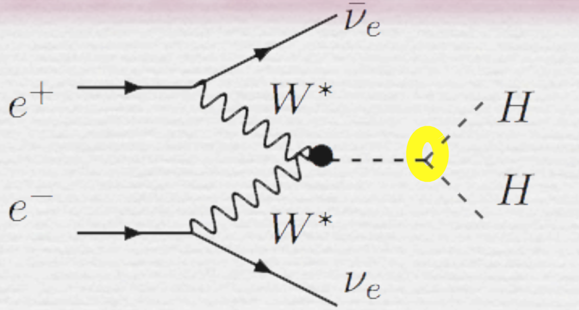
The dotted lines delimit
the region for a strong 1rst
order phase transition

deviations between a factor 0.7 and 2

at a Hadron Collider

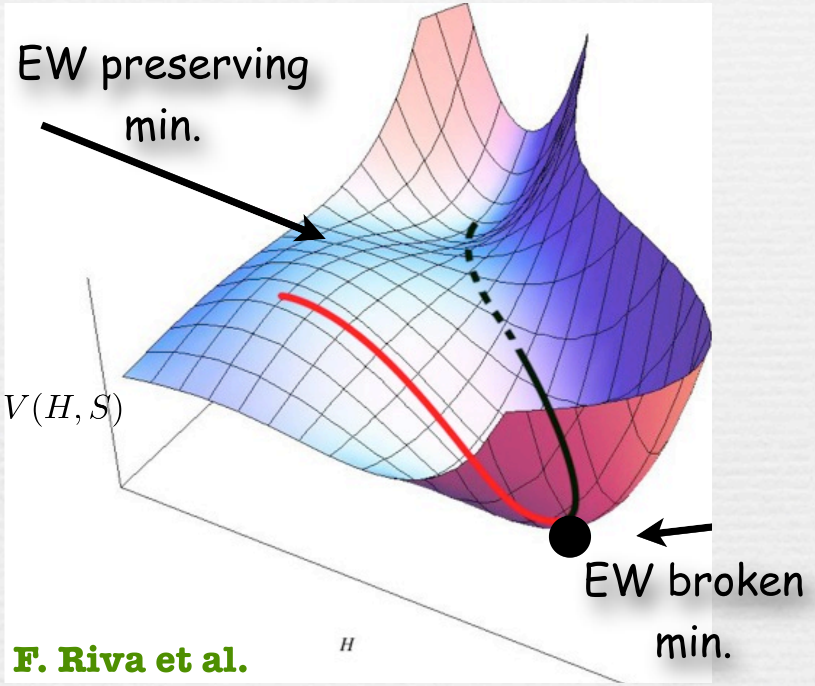


at an e$^+$ e$^-$ Linear Collider



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

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



F. Riva et al.

EDM bounds (like for 2-Higgs Doublet Model)

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

models of compositeness

-> Gripaios et al, 0902.1483

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

global symm. on u,d

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

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

global symm. on techniquarks

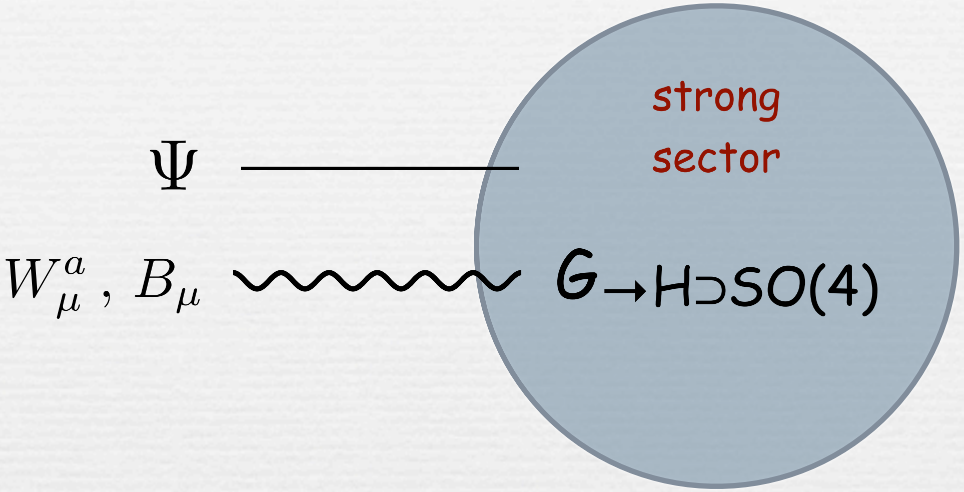
Composite Higgs: $SO(6) \times U(1)_x \xrightarrow[SU(N_c)]{} SO(5) \times U(1)_Y \supset SU(2) \times U(1)_Y$

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

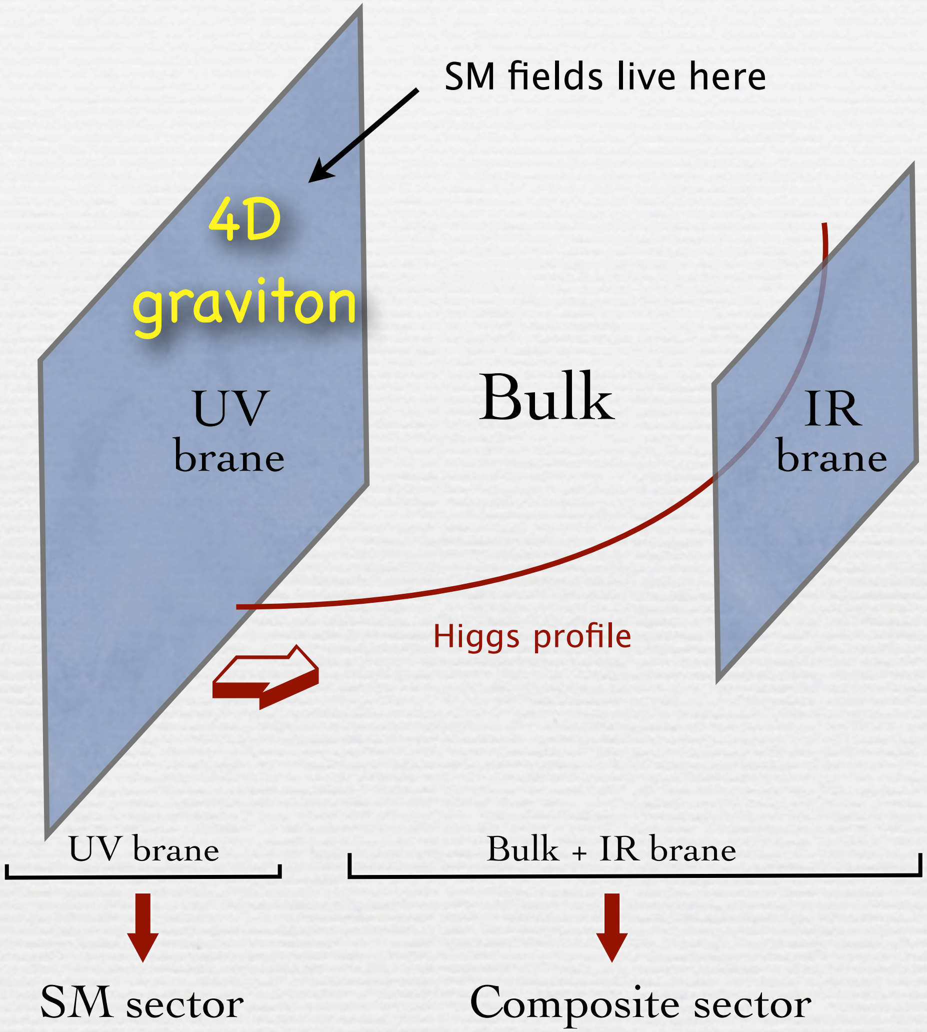
G	H	N_G	NGBs rep.$[H]$ = rep.[SU(2) × SU(2)]
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}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

Extra-Dimensional point of view: Warped Geometry

Space-time is a slice of AdS_5



SM fields live here

4D graviton

UV brane

Bulk

IR brane

Higgs profile

UV brane

Bulk + IR brane

SM sector

Composite sector

An almost CFT that becomes strongly interacting at the TeV scale & spontaneously breaks the conformal invariance

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

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

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=z_0=L (Planck brane) to z=z_1 (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 $V_{eff} = \int_{z_0}^{z_1} dz \sqrt{g}[-(\partial\phi)^2 - m^2\phi^2]$

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

→

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

~ 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

# of bubbles per horizon volume

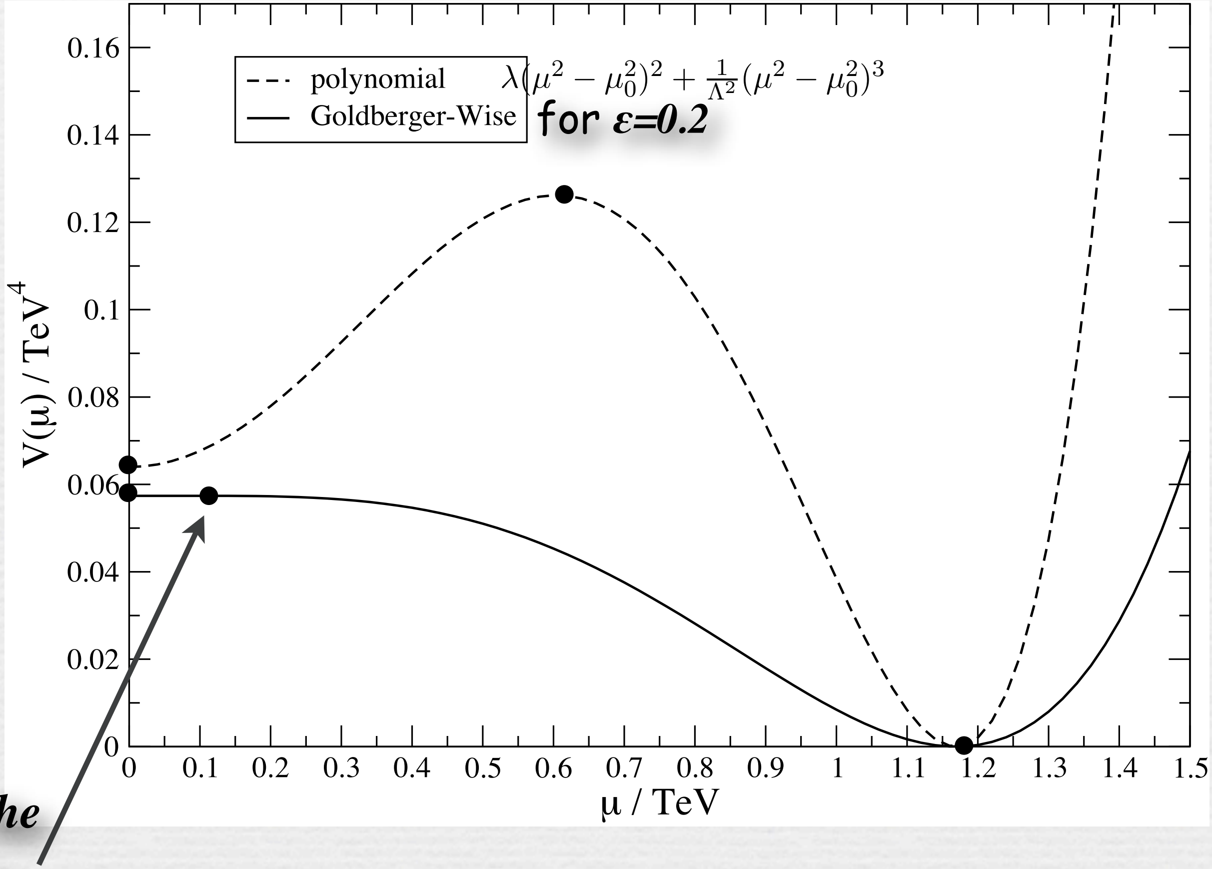
$$\beta/H = T \frac{d}{dT}\frac{S_3}{T}\bigg|_{T_n} \sim \epsilon \left.\frac{S_3}{T}\right|_{T_n} \gtrsim 1.$$

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

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



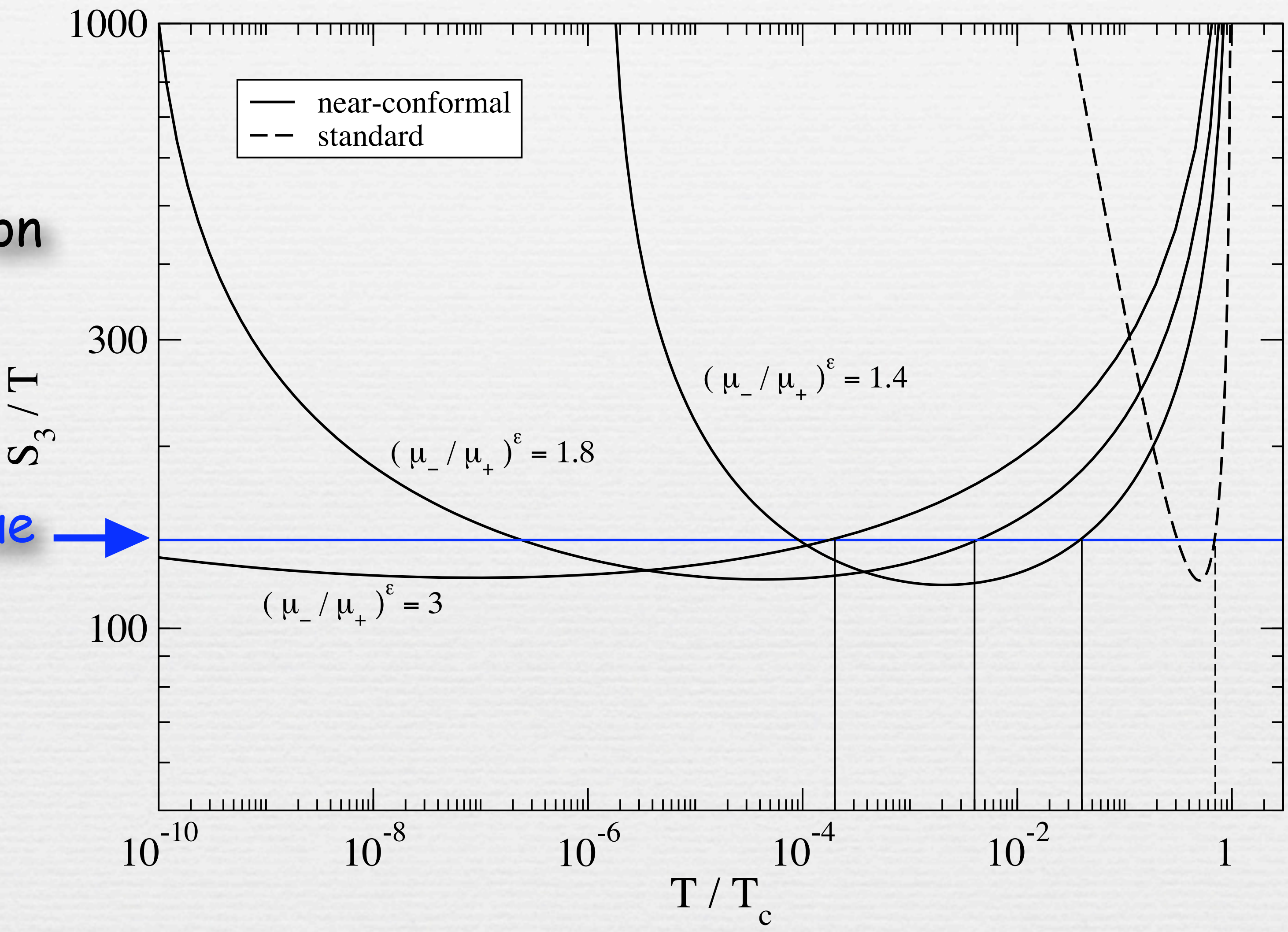
position of the maximum

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

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

Cosmological phase transition associated with radion stabilisation (appearance of TeV brane)

↔

strongly 1st order confining phase transition of SU(N) gauge theory (N>3)

Cosmology of the Randall-Sundrum model

At high T: AdS-Schwarzchild BH solution with event horizon shielding the TeV brane

At low T: usual RS solution with stabilized radion and TeV brane

Start with a black brane, nucleate “gaps” in the horizon which then grow until they take over the entire horizon.

[Creminelli, Nicolis, Rattazzi’01]

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

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

interesting cosmology

+ collider implications:

--Search for a light dilaton

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

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

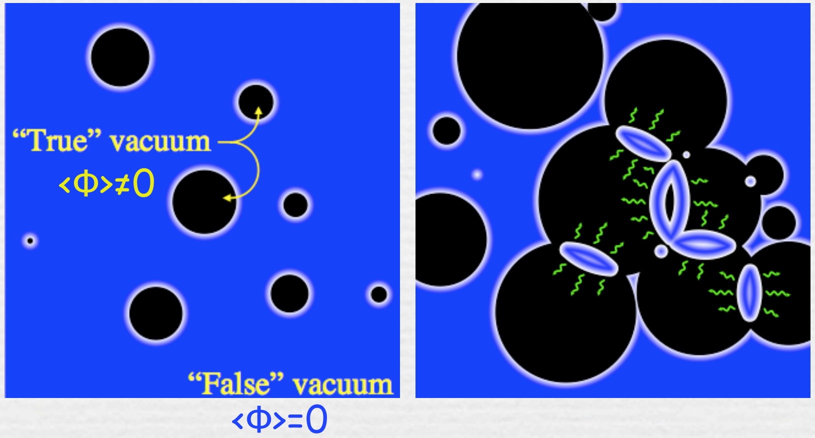
Smoking gun signature

Randall-Servant'06

Konstandin,Nardini,Quiros'10

Bubble nucleation

Bubble percolation

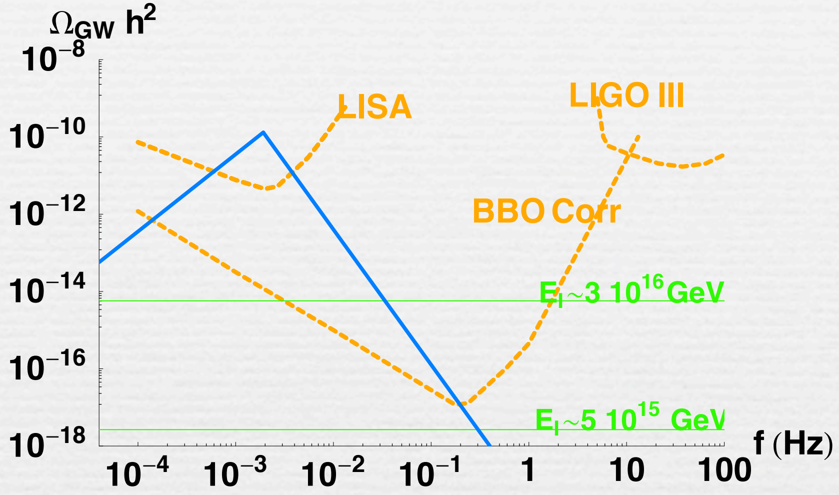


Fluid flows

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

Gravitational Waves: A way to probe astrophysics
... and high energy particle physics.

Gravitational Waves interact very weakly and are not absorbed

⇓ ⇓

direct probe of physical process of the very early universe

Small perturbations in FRW metric:

$$ds^2 = a^2(\eta)(d\eta^2 - (\delta_{ij} + 2h_{ij})dx^i dx^j) \qquad G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$\ddot{h}_{ij}(\mathbf{k},\eta) + \frac{2}{\eta}\dot{h}_{ij}(\mathbf{k},\eta) + k^2 h_{ij}(\mathbf{k},\eta) = 8\pi G a^2(\eta)\Pi_{ij}(\mathbf{k},\eta)$$

Source of GW:
anisotropic stress

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1^{st} order phase transitions...

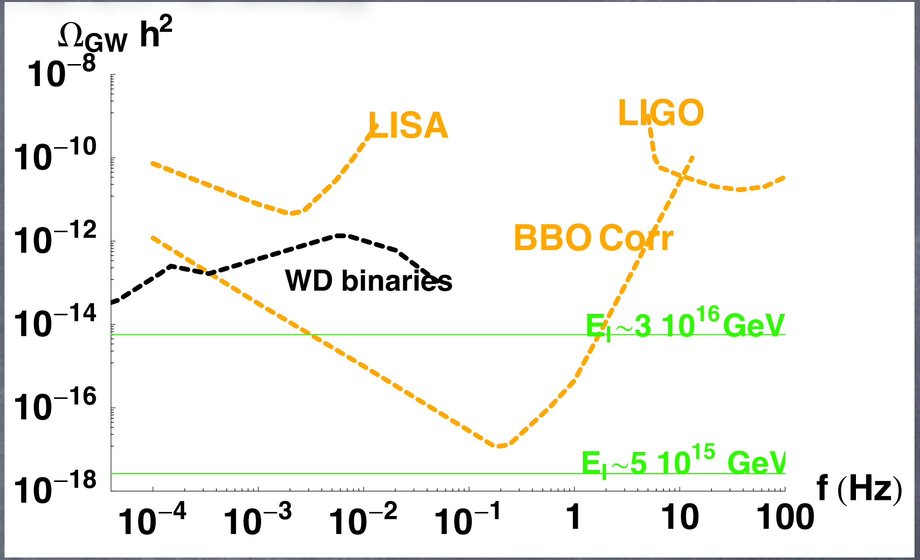
frequency observed today:

$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6 \times 10^{-3} \mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \mathrm{GeV}} \frac{f_*}{H_*}$$

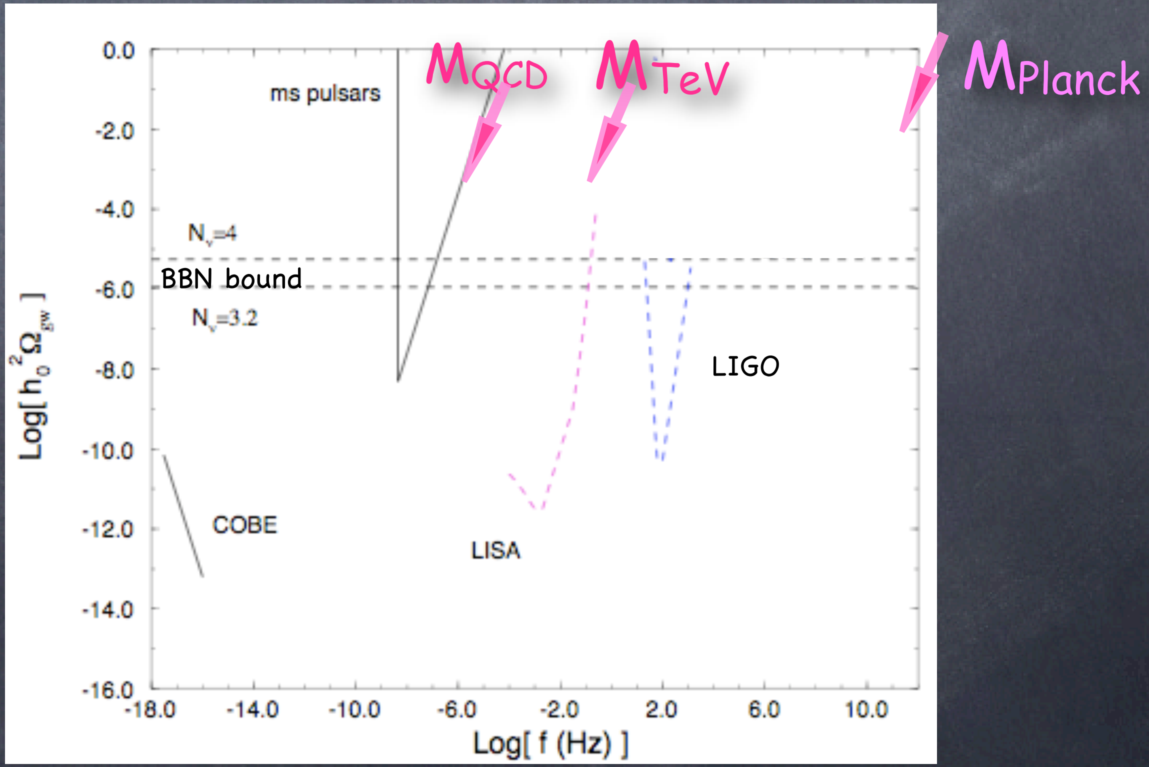
Beyond GW of astrophysical origin, another mission of GW astronomy will be to search for a stochastic background of gravitational waves of primordial origin (gravitational analog of the 2.7 K CMB)

Stochastic background:
isotropic, unpolarized, stationary

GW energy density: $$\Omega_G = \frac{\langle \dot{h}_{ij}\dot{h}^{ij}\rangle}{G\rho_c} = \int \frac{dk}{k}\,\frac{d\Omega_G(k)}{d\log(k)}$$



A huge range of frequencies

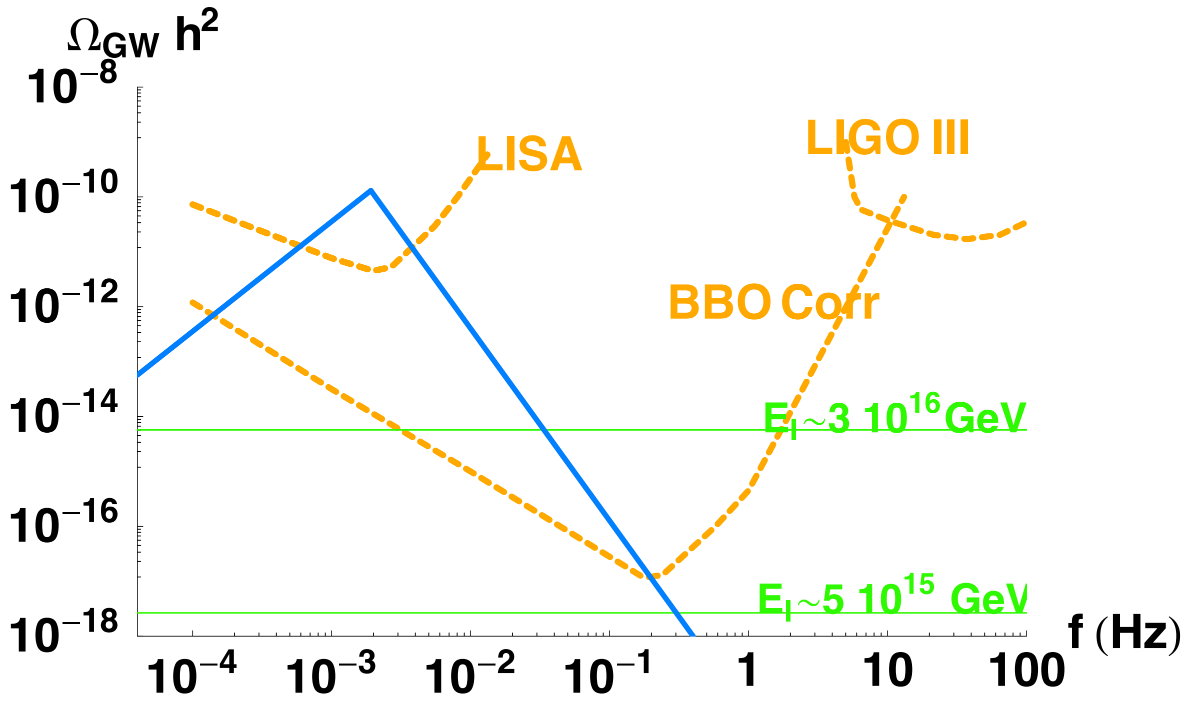


from Maggiore

Why should we be excited about mHZ freq.?

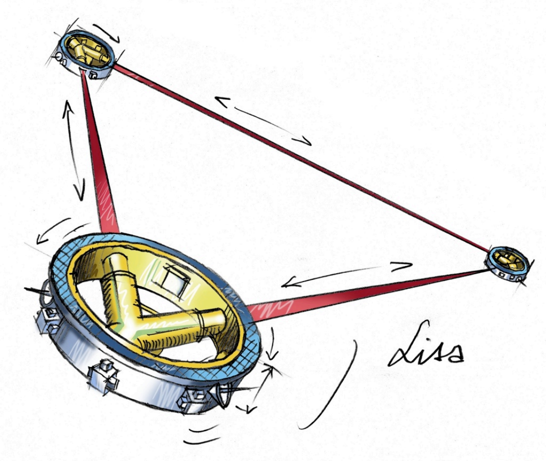
$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6 \times 10^{-3} \mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \mathrm{GeV}} \frac{f_*}{H_*}$$

LISA: Could be a new window on the Weak Scale



LISA band:

$10^{-4} - 10^{-2}$ Hz



complementary to collider informations

key quantities controlling the GW spectrum

$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 8\pi G a^2 T_{ij}^{(TT)}(k,t)$$

$$T_{ab}(\mathbf{x}) = (\rho + p)\frac{v_a(\mathbf{x})v_b(\mathbf{x})}{1 - v^2(\mathbf{x})}$$

Source of GW: anisotropic stress

β : (duration of the phase transition)$^{-1}$

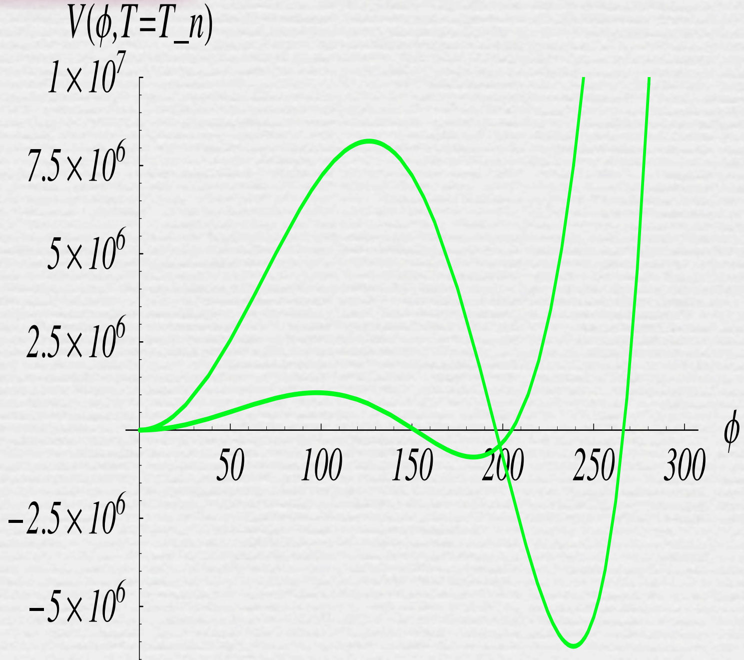
set by the tunneling probability $P \propto e^{\beta t} \propto \frac{T^4}{H^4} e^{-S_3/T} \sim 1$ ➔ $\frac{S_3}{T}$ ~ 140

and typically $\frac{\beta}{H} \sim \mathcal{O}(10^2 - 10^3)$

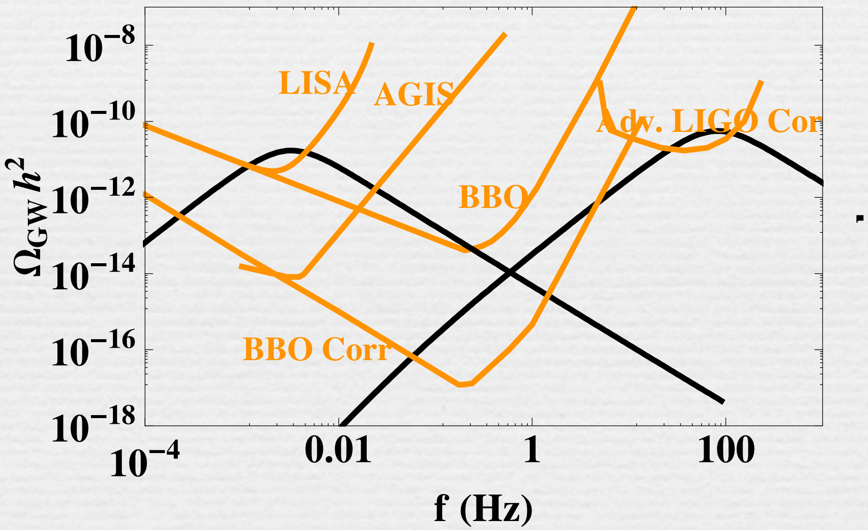
α : vacuum energy density/radiation energy density

α and β : entirely determined by the effective scalar potential at high temperature

$$\Omega_{GW_*} = \frac{H_*^2}{\beta^2} \frac{\rho_{kin}{}^2}{\rho_{tot}{}^2}$$

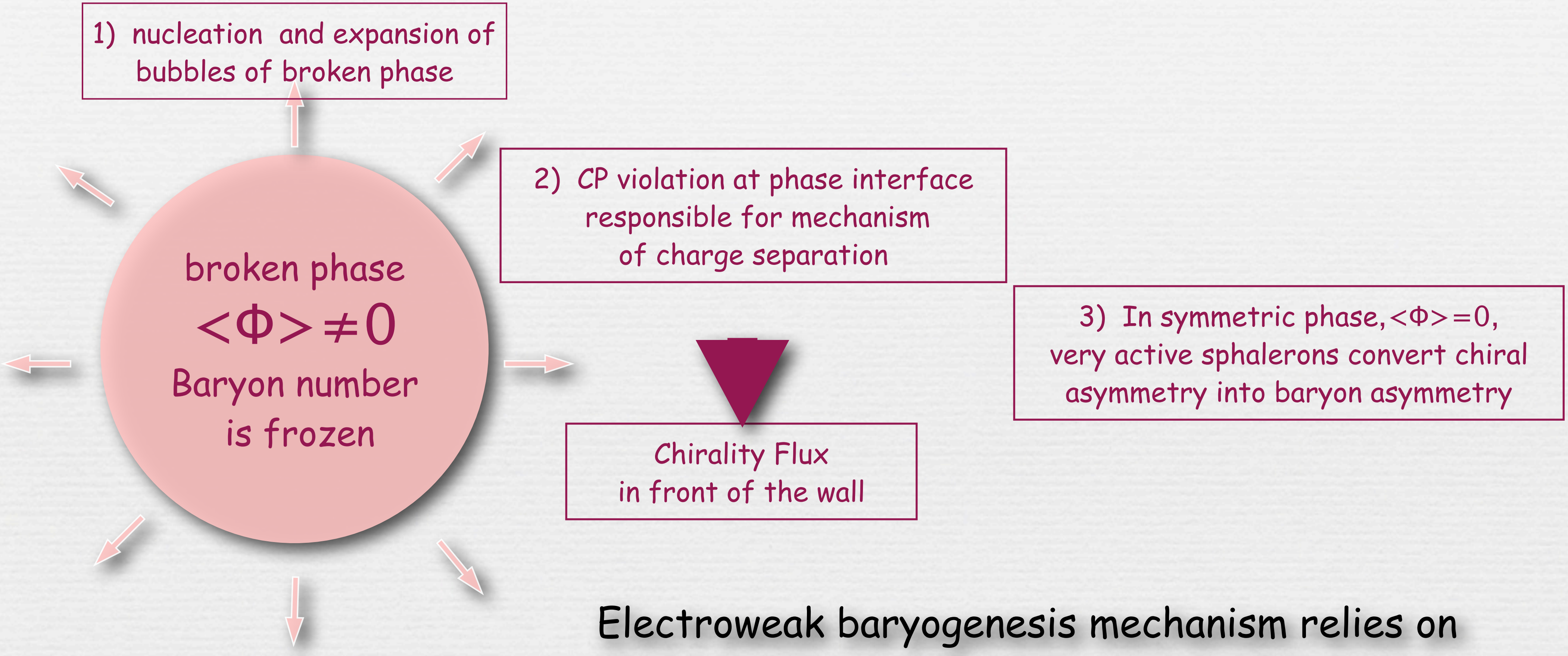


Discussion applies trivially to any other 1st order phase transition (only shift peak frequency, amplitude and shape of signal do not depend on the absolute energy scale of the transition)



Dynamics of bubble growth and energy budget

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 phase transition

wall velocity is a crucial quantity,
we need strong 1st order phase transition, however if too strong->
bubble expand too fast -> no time to build up the baryon asymmetry

1st order EW phase transition

higgs vaccuum energy is converted into :

- -kinetic energy of the higgs,
- -bulk motion
- - heating

$$\Omega_{GW} \sim \kappa^2(\alpha, v_b) \left(\frac{H}{\beta}\right)^2 \left(\frac{\alpha}{\alpha+1}\right)^2$$

fraction that goes into kinetic energy

$$\alpha = \frac{\epsilon}{\rho_{rad}}$$

$$\frac{\beta}{H} = \frac{1}{T}\frac{dS}{dT}$$

fraction κ of vacuum energy density ϵ converted into kinetic energy

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

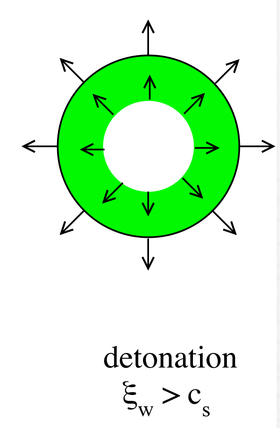
fluid velocity

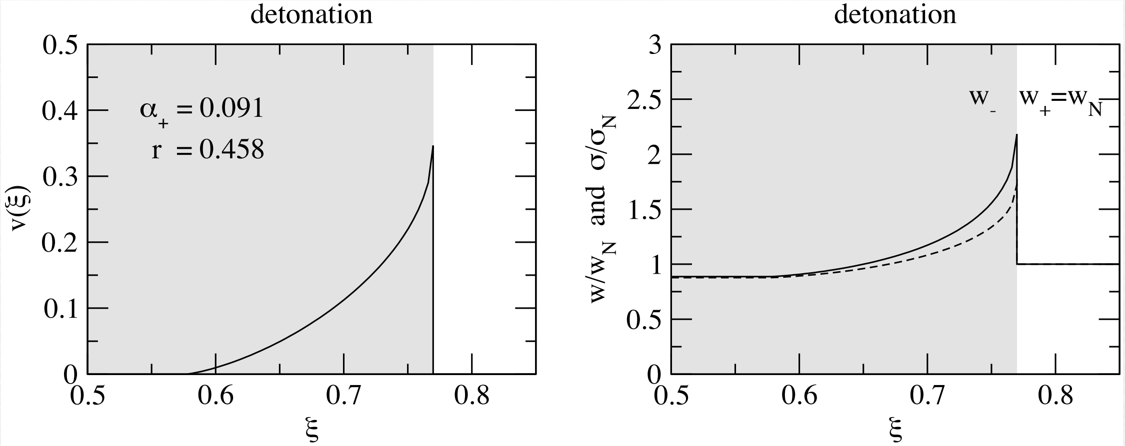
wall velocity

-> all boils down to calculating the fluid velocity profile in the vicinity of the bubble wall

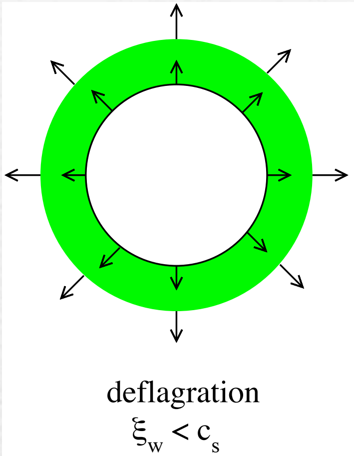
Depending on the boundary conditions at the bubble front, there are three possible solutions:

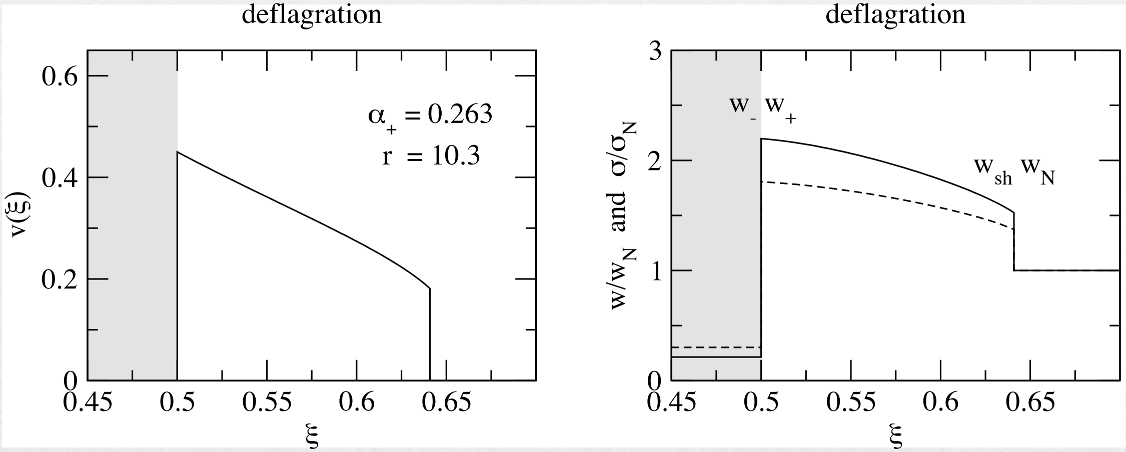
detonations -rarefaction wave



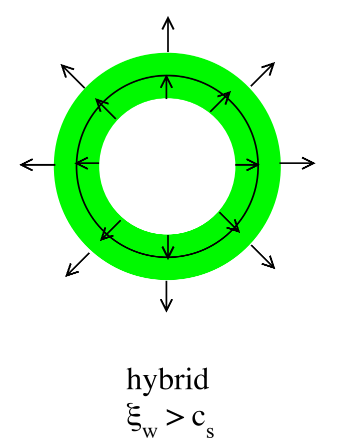


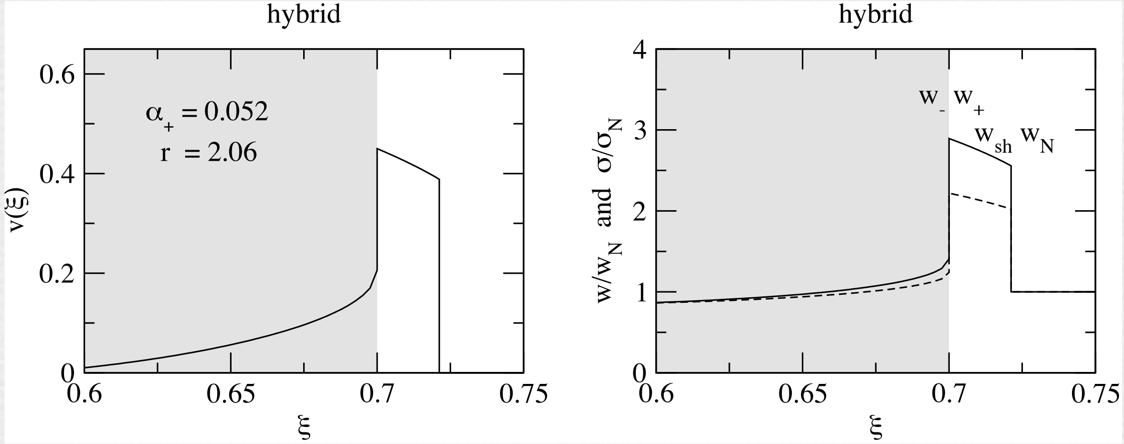
deflagrations -shock front





hybrids -both





Espinosa, Konstandin, No, Servant'10

The velocity of the bubble wall can be determined by solving:

$$\Box\phi + \frac{\partial \mathcal{F}}{\partial \phi} - \underbrace{T_N\ \overset{\text{friction coefficient}}{\swarrow}\!\!\tilde{\eta}\ u^\mu \partial_\mu \phi}_{= -\sum_i \frac{dm_i^2}{d\phi}\int \frac{d^3p}{(2\pi)^3 2E_i}\delta f_i(p)} = 0$$

the wall velocity grows until the friction force equilibrates and a steady state is reached

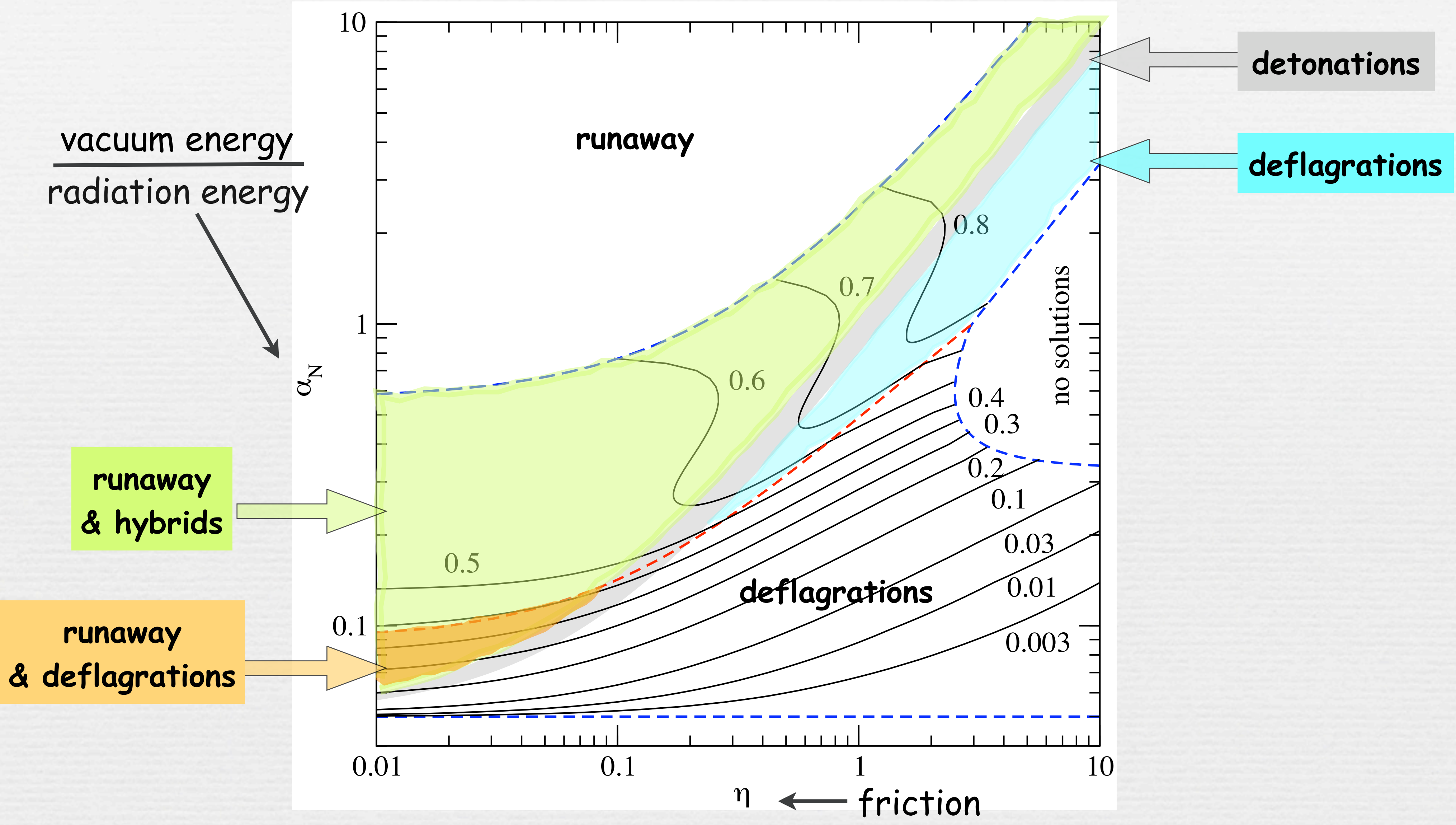
driving force: $$F_{dr} \equiv \int dz\, \partial_z\phi\, \frac{\partial \mathcal{F}}{\partial \phi}$$

$$F_{tot} = F_{dr} - F_{fr} = \Delta V_0 + \sum_i |N_i| \int dz \frac{dm_i^2}{dz} \int \frac{d^3p}{(2\pi)^3} \frac{f_i}{2E_i}$$

$\mathcal{F}_{tot} > 0$: runaway

[Bodecker-Moore '09]

Model-independent κ contours



Espinosa, Konstandin, No, Servant'10

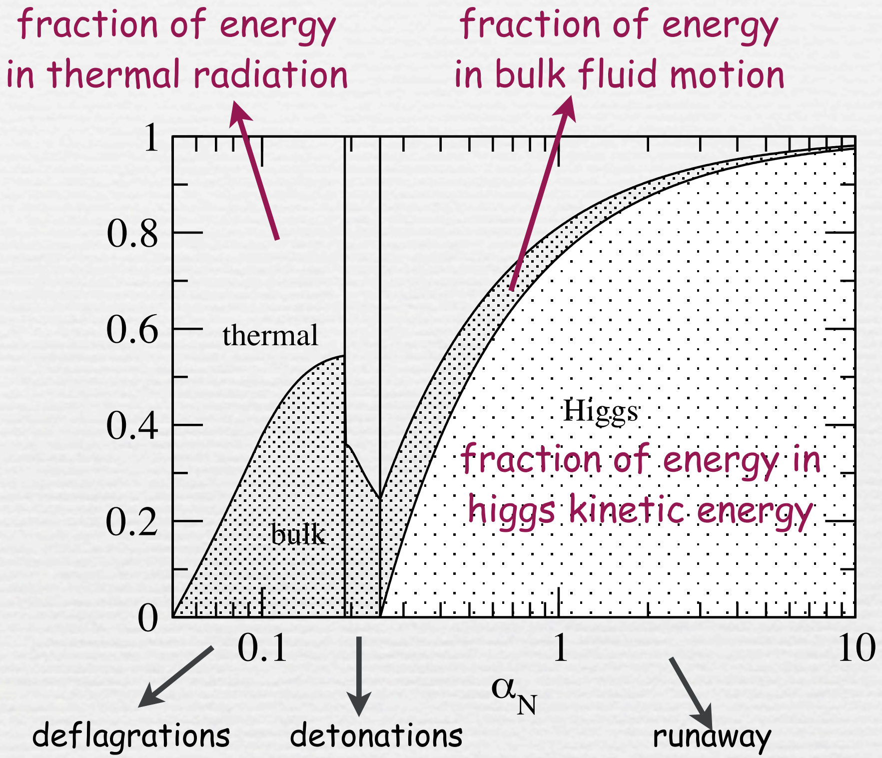
$$\eta_{\rm SM} \sim 10^{-3}$$

$$\eta_{\rm MSSM} \sim 10^{-2} \qquad v \sim 0.05 - 0.1$$

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

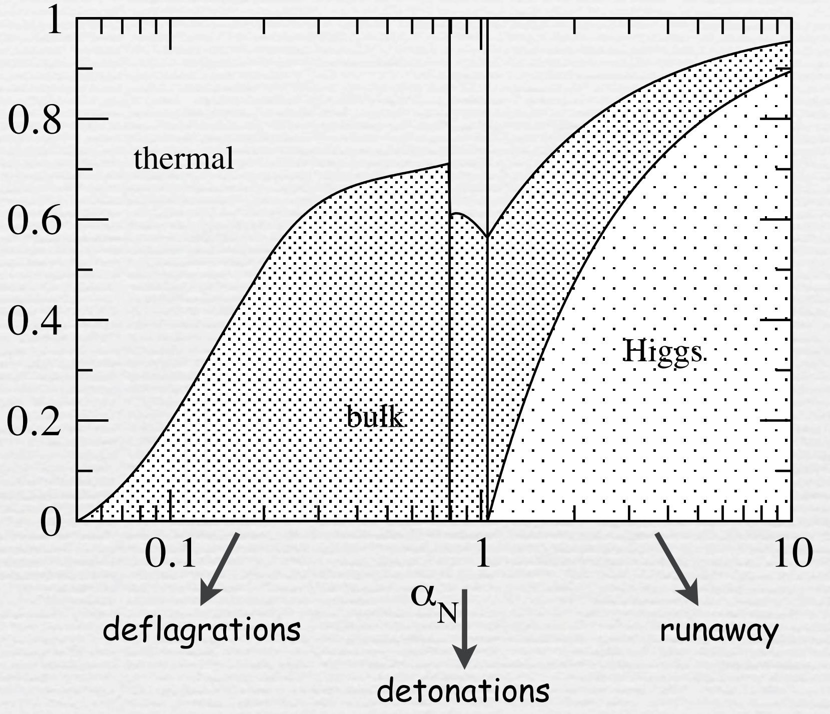
fraction of energy in higgs kinetic energy

deflagrations

detonations

runaway

$\eta = 1$



deflagrations

runaway

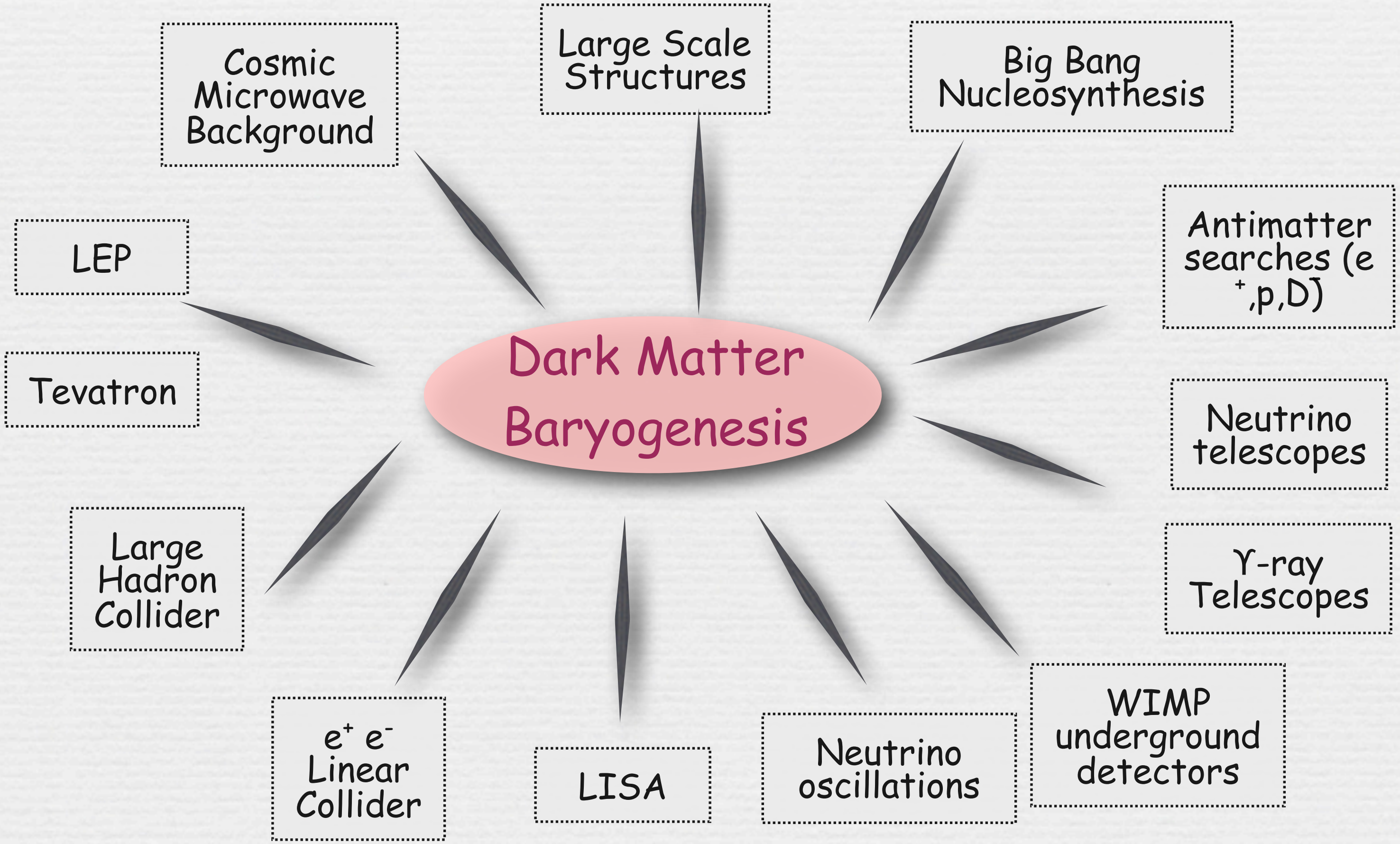
detonations

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

Summary

The nature of the EW phase transition is unknown & it will take time before we can 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

Cosmic connections of electroweak symmetry breaking: A multi-form and integrated approach



Cosmic Microwave Background

Large Scale Structures

Big Bang Nucleosynthesis

LEP

Antimatter searches (e^+,p,D)

Tevatron

Dark Matter
Baryogenesis

Neutrino telescopes

Large Hadron Collider

Υ-ray Telescopes

WIMP underground detectors

$e^+ e^-$ Linear Collider

LISA

Neutrino oscillations

Annexes

An alternative to standard EW baryogenesis

Cold 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)

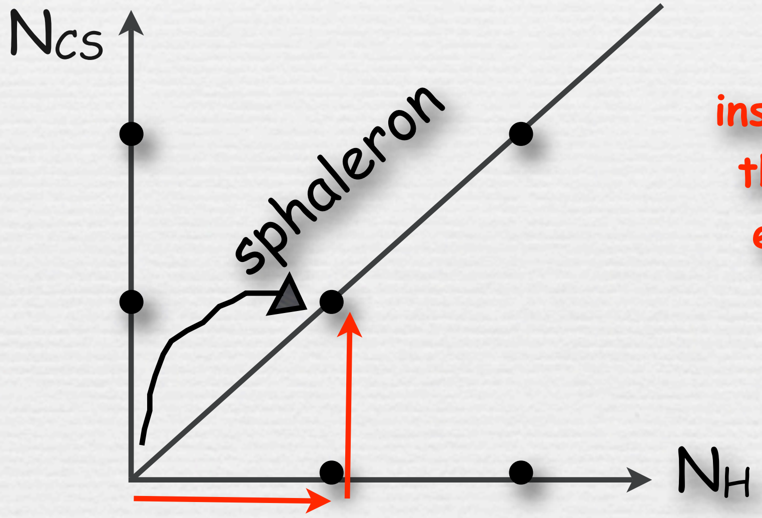
3) In its present realization, does not rely on 1st order PT but on
inflationary phase instead

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

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