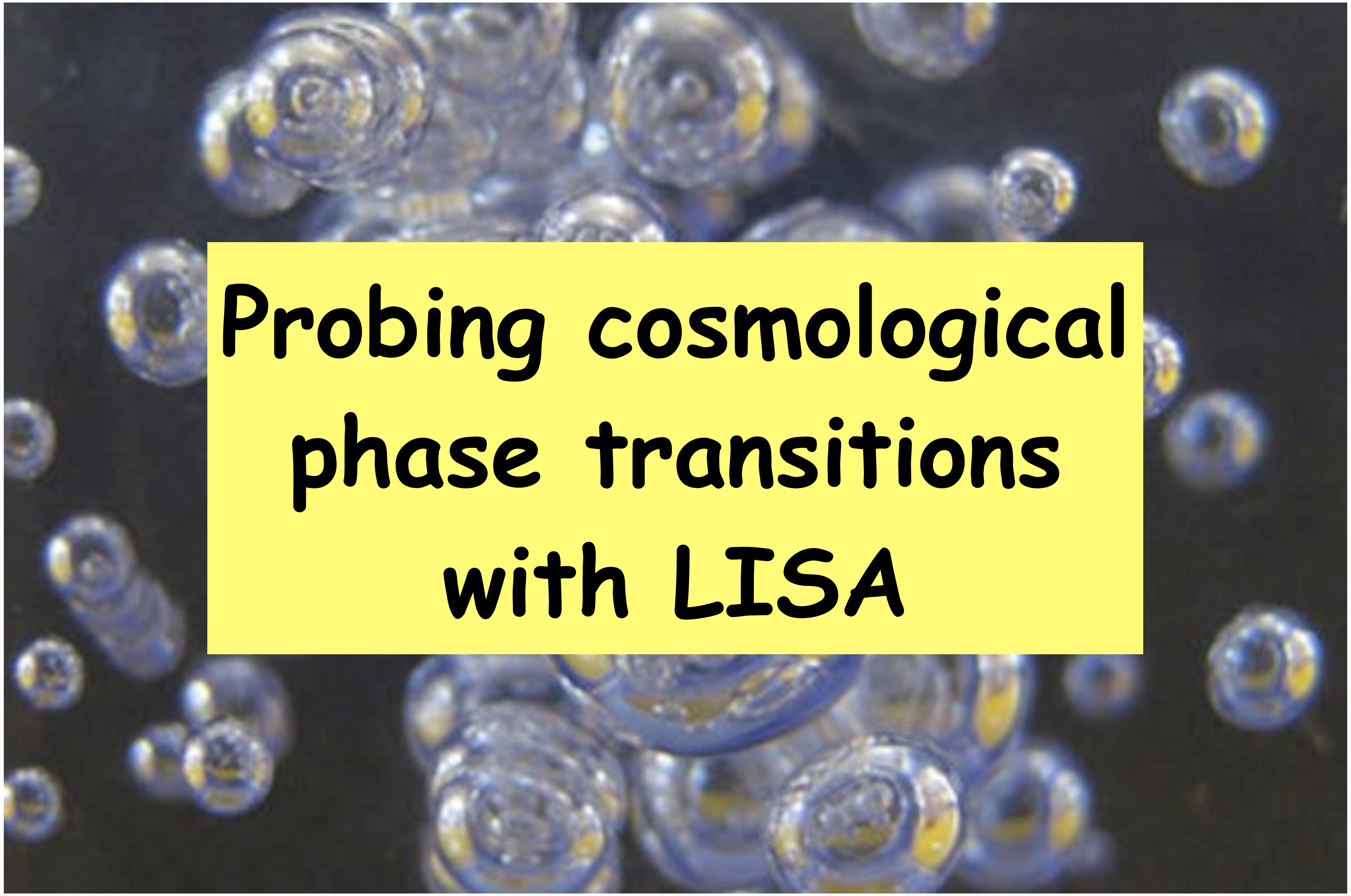


Probing cosmological phase transitions with LISA

Géraldine SERVANT

DESY/U.Hamburg

LISA Symposium

September 9 2016

HELMHOLTZ GEMEINSCHAFT

DESY

Universität Hamburg

See review:

arXiv:1512.06239

JCAP 1604 (2016) no.04, 001

Chiara Caprini, Mark Hindmarsh, Stephan Huber, Thomas Konstandin, Jonathan Kozaczuk, Germano Nardini, Jose Miguel No, Antoine Petiteau, Pedro Schwaller, Geraldine Servant, David J. Weir

as well as next talk by D. Weir on status of the art on the predictions for the GW spectrum

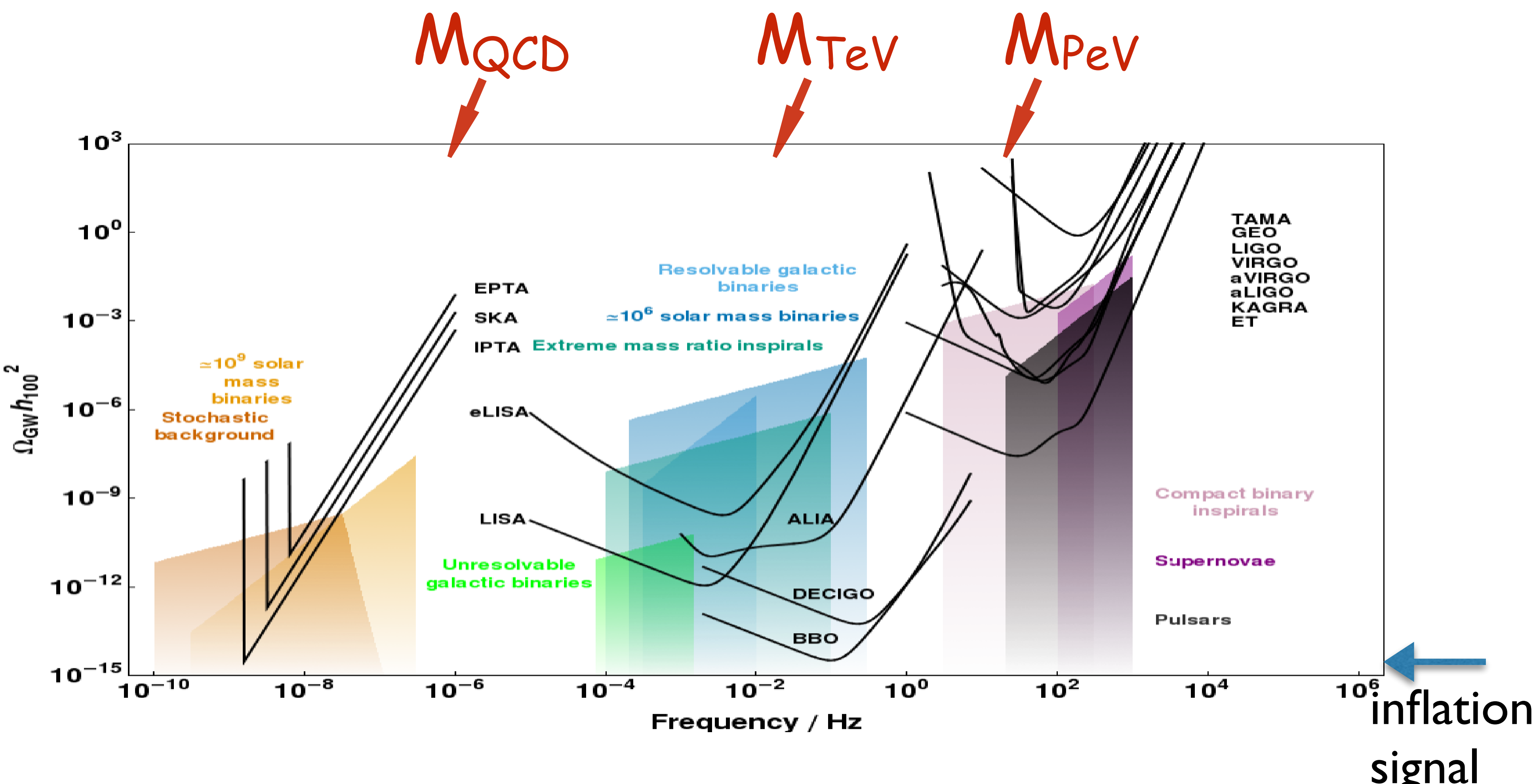
My talk is to insist on the physics motivations

GW Stochastic background: isotropic, unpolarized, stationary

GW energy density:

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

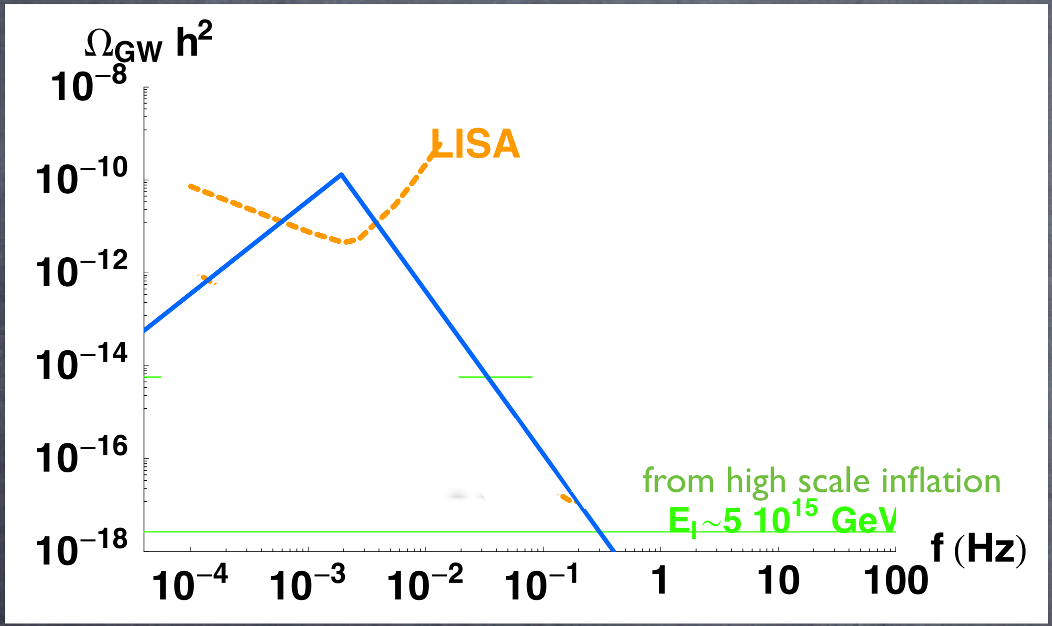
A huge range of frequencies

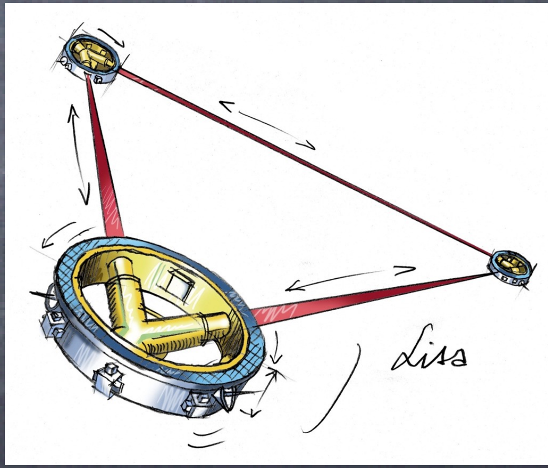


Why should we be excited about milliHZ frequency?

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

LISA: Could be a new window on the Weak Scale





complementary to collider informations

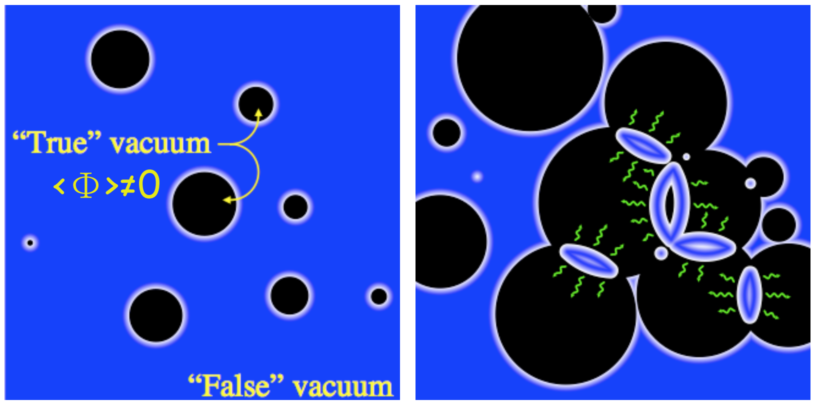
Which weak scale physics? $\Rightarrow$

transition

Stochastic background of gravitational radiation

Bubble nucleation

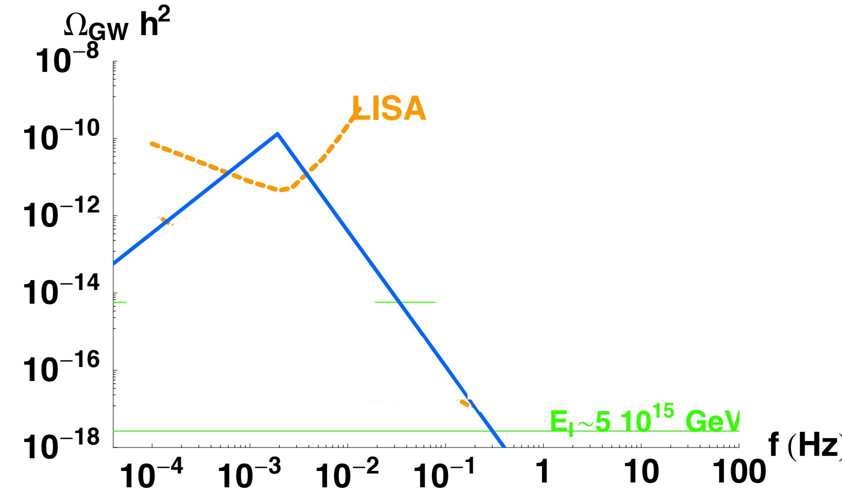
Bubble percolation



Fluid flows

turbulence

Magnetic fields



violent process if v

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

characterizes amount of supercooling

$$f_{\rm peak} \sim 10^{-2}\ {\rm mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ {\rm GeV}}\ \frac{\beta}{H_*}$$

Grojean-Servant hep-ph/0607107

- test of the dynamics of the phase transition
- relevant to models of EW baryogenesis
- reconstruction of the Higgs potential/study of new models of Electroweak symmetry breaking (little higgs, gauge-higgs,composite higgs,..)

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

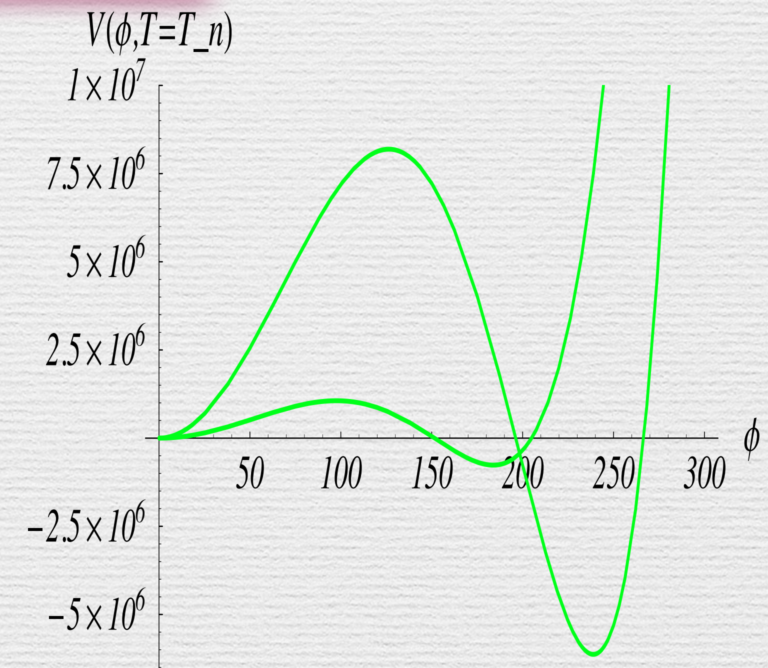
β : (duration of the phase transition)$^{-1}$

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

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

α : vacuum energy density/radiation energy density

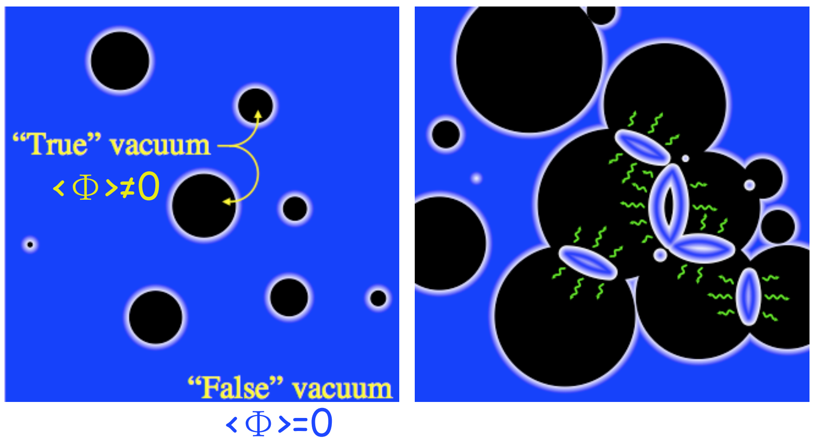
α and β : entirely determined by the effective scalar potential at high temperature



Gravity wave signals from 1st order cosmological phase transitions

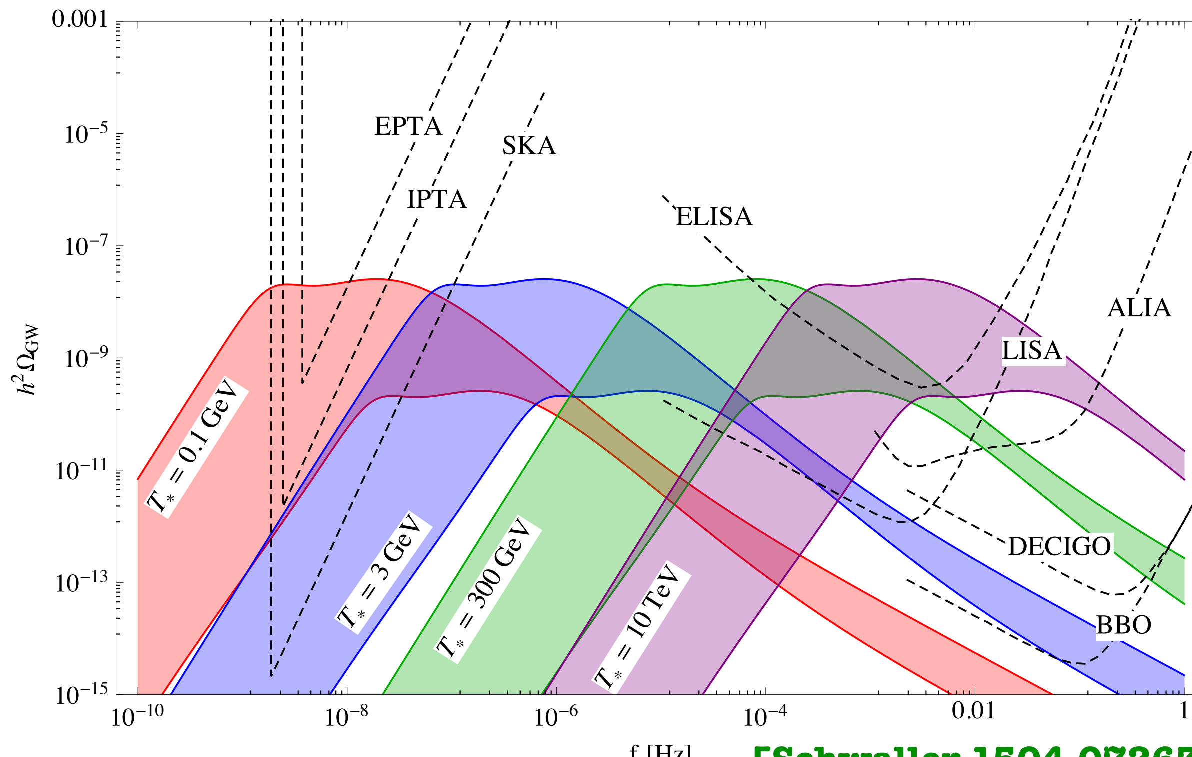
Bubble nucleation

Bubble percolation



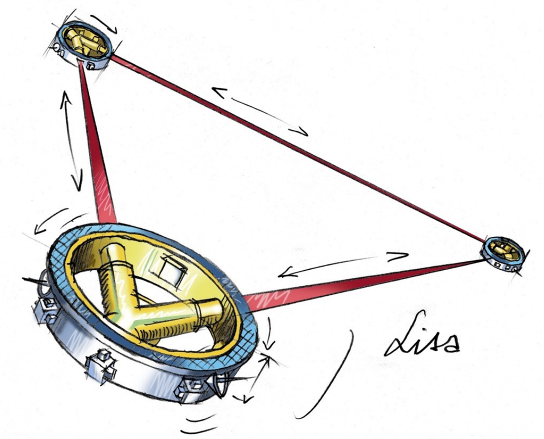
[eLISA Cosmology Working group, 1512.06239]

Stochastic background of gravitational radiation



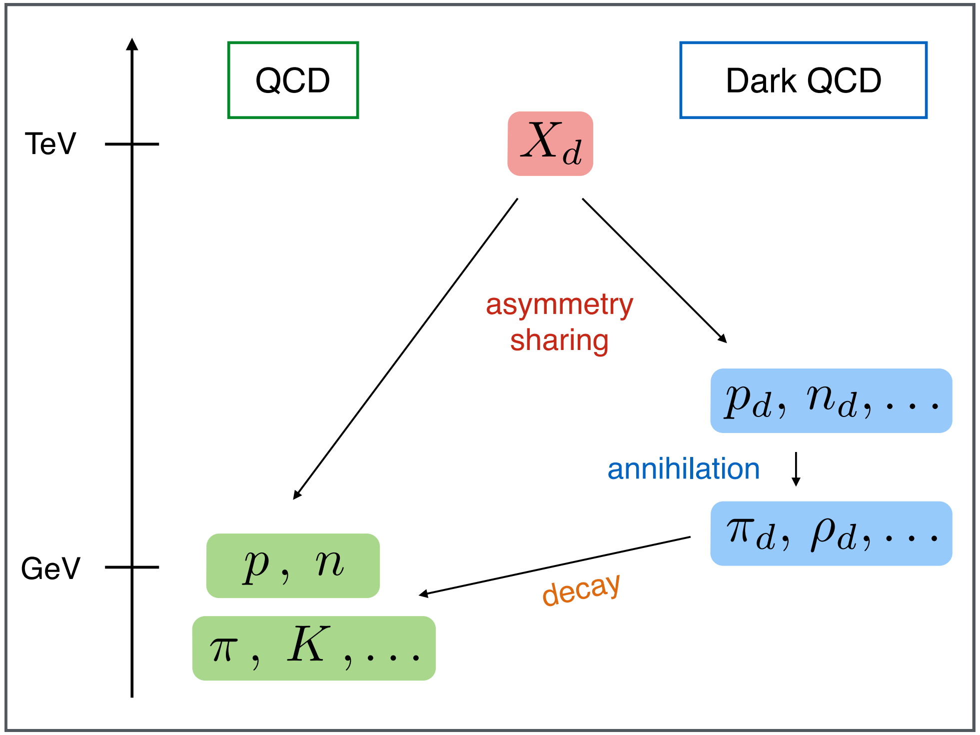
[Schwaller 1504.07263]

EW phase transition -> mHz -> eLISA!



e.g: from Dark QCD

Connecting Dark Matter and Baryogenesis



[Schwaller]

Estimate of the GW energy density at the emission time

$$\rho_{GW} \sim \dot{h}^2 / 16\pi G$$

$$\delta G_{\mu\nu} = 8\pi G T_{\mu\nu} \Rightarrow \beta^2 h \sim 8\pi G T \Rightarrow \dot{h} \sim 8\pi G T / \beta$$

where $T \sim \rho_{kin} \sim \rho_{rad} v^2$

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

$\rho_{kin}^2 \rightarrow \kappa^2 \alpha^2 v^4$

$$\Omega_{GW*} \propto \frac{H_*^2}{\beta^2} \frac{\kappa^2 \alpha^2 v^4}{(\alpha+1)^2}$$

κ : fraction of vacuum energy transformed into bulk fluid motions

3 parameters: α, β, v

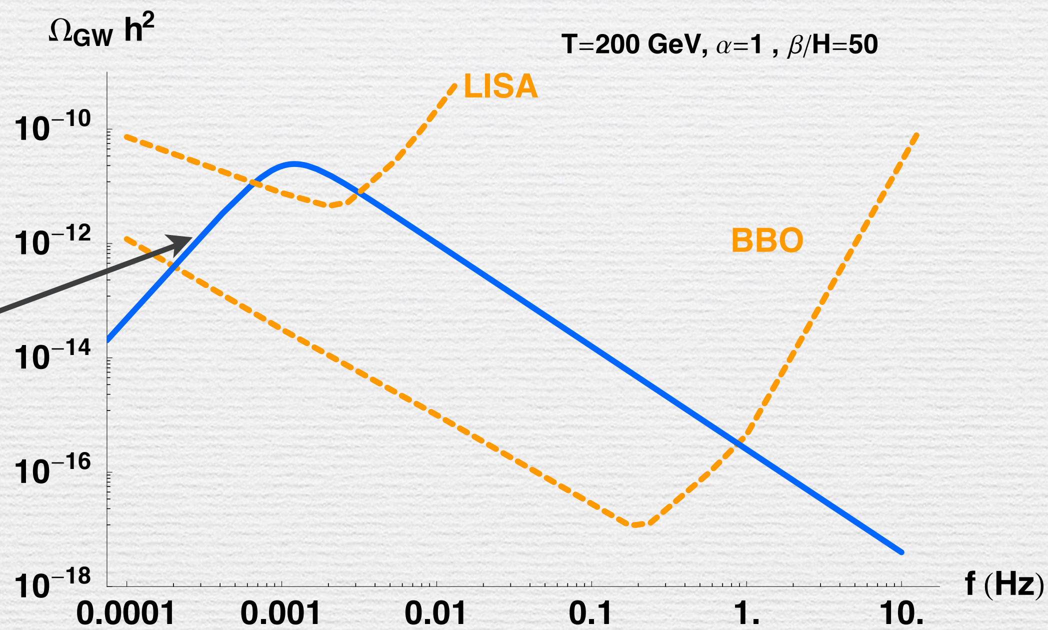
Fraction of the critical energy density in GW today

$$\Omega_{GW} = \frac{\rho_{GW}}{\rho_c} = \Omega_{GW*}\left(\frac{a_*}{a_0}\right)^4\left(\frac{H_*}{H_0}\right)^2 \simeq 1.67\times 10^{-5}h^{-2}\left(\frac{100}{g_*}\right)^{1/3}\Omega_{GW*}$$

has to be big ($\gtrsim 10^{-6}$) for detection

where we used: $\rho_{GW} = \rho_{GW*}\left(\frac{a_*}{a_0}\right)^4 \;,\;\; \rho_c = \rho_{c*}\frac{H_0^2}{H_*^2}$ and $H_0 = 2.1332\times h\times 10^{-42}\mathrm{GeV}$

Expected shape of the GW spectrum



large scale part of the GW spectrum

~ f^3

$$\frac{d\Omega_G}{d\ln k} = \frac{k^3|\dot{h}|^2}{G\rho_c}$$

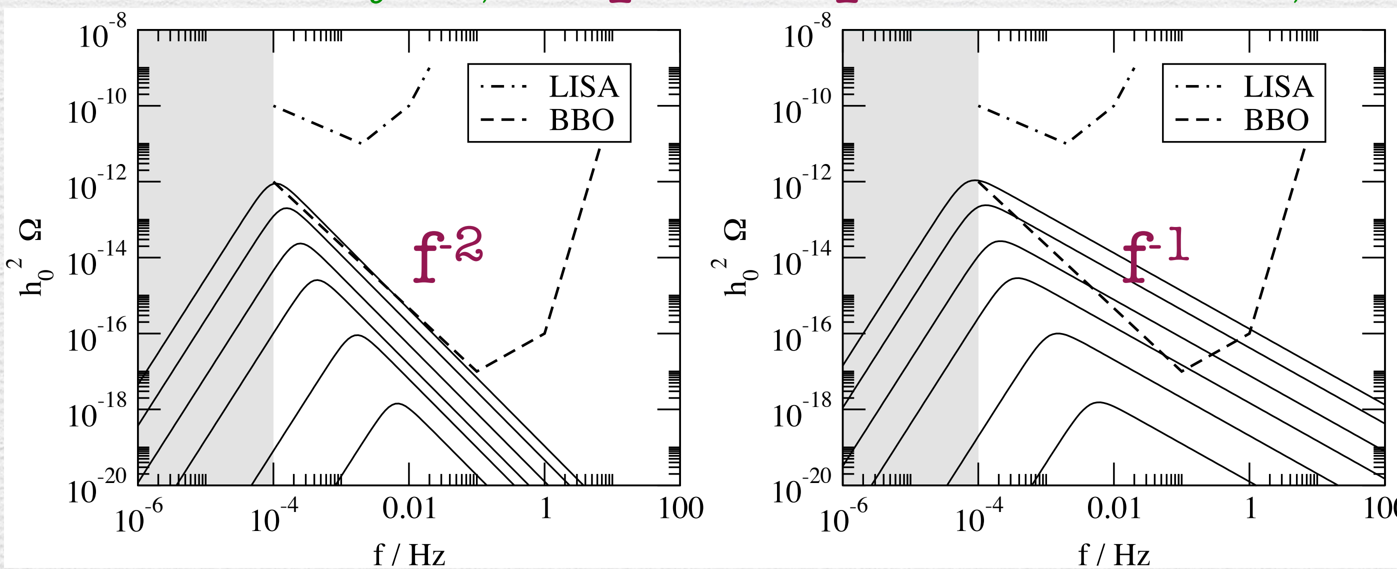
$$h_{ij}(\mathbf{k},\eta) = \int_{\eta_{\rm in}}^{\eta} d\tau \mathcal{G}(\tau,\eta)\Pi_{ij}(\mathbf{k},\tau)$$

white noise for the anisotropic stress -> k^3 for the energy density

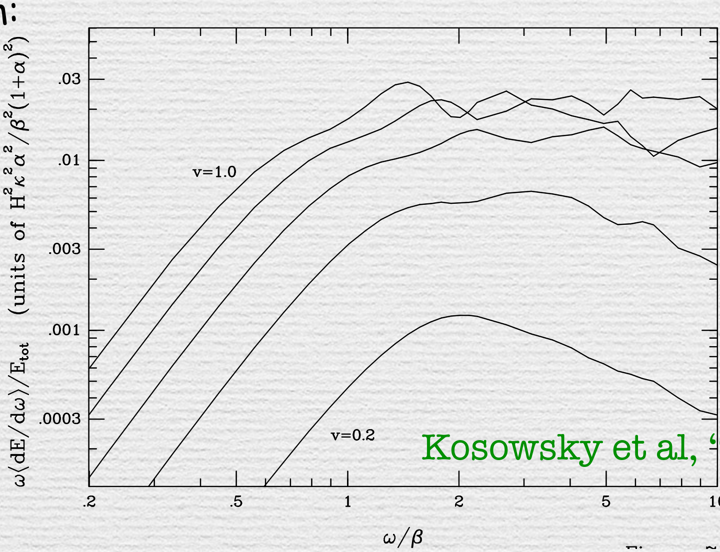
CAUSAL PROCESS: source is uncorrelated at scales larger than the peak scale

GW spectrum due to bubble collisions from numerical simulations: high frequency slope

Kosowsky et al, ’93 $f^{-2} \rightarrow f^{-1}$ Huber-Konstandin,’08



derived from:



Kosowsky et al, ‘93

and much progress in the last few years, see next talk

simulations with many bubbles and high accuracy too demanding in the 90ies

Bulk flow & hydrodynamics

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

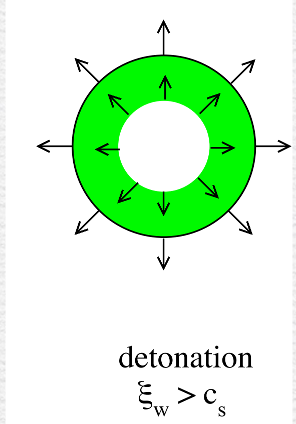
$$\kappa = \frac{3}{\epsilon \xi_w^3} \int w(\xi) v^2 \gamma^2 \, \xi^2 \, d\xi$$

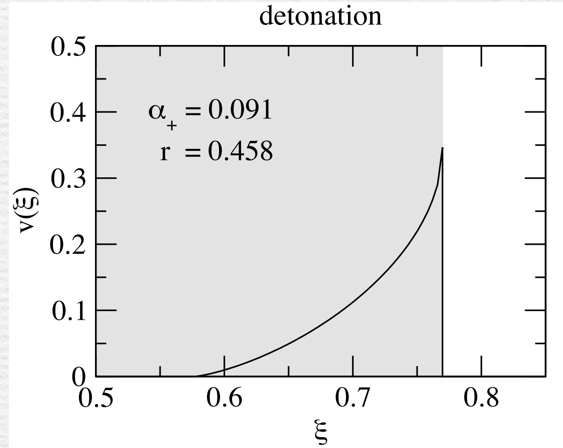
wall velocity (ξ_w); fluid velocity (v)

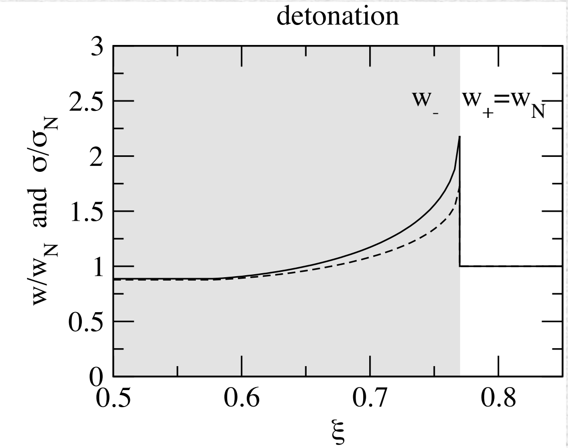
-> all boils down to calculating the fluid velocity profile in the vicinity of the bubble wall

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

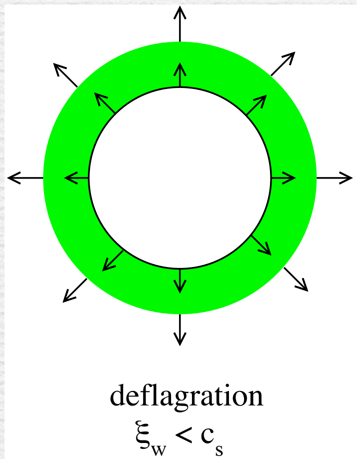
detonations -rarefaction wave

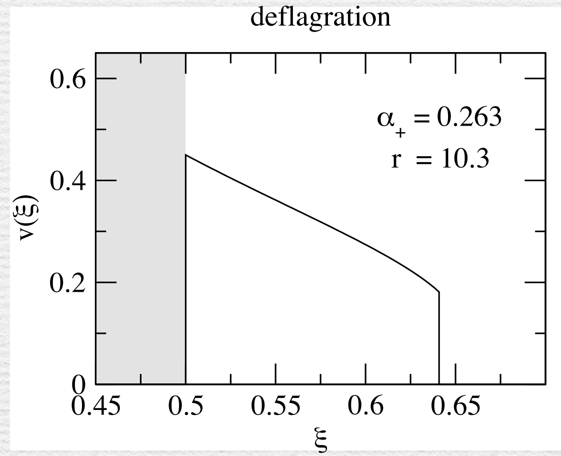


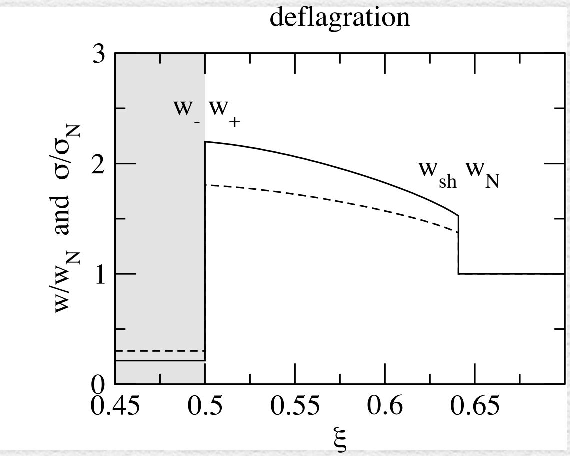




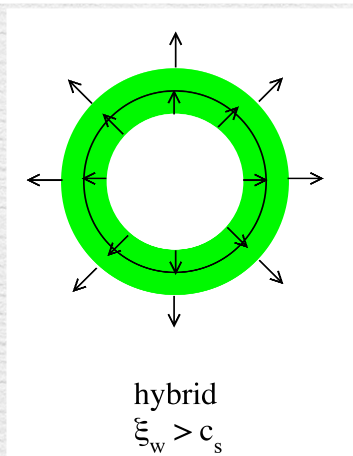
deflagrations -shock front

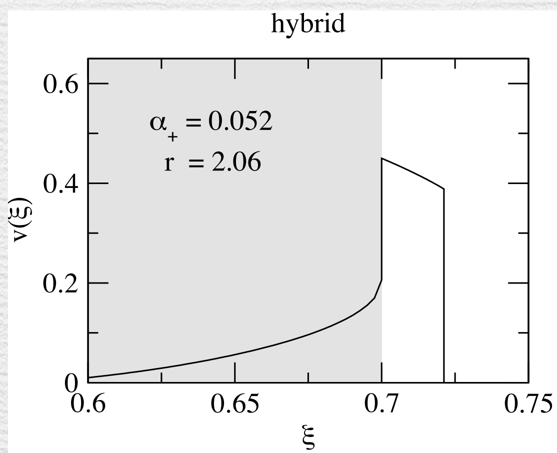


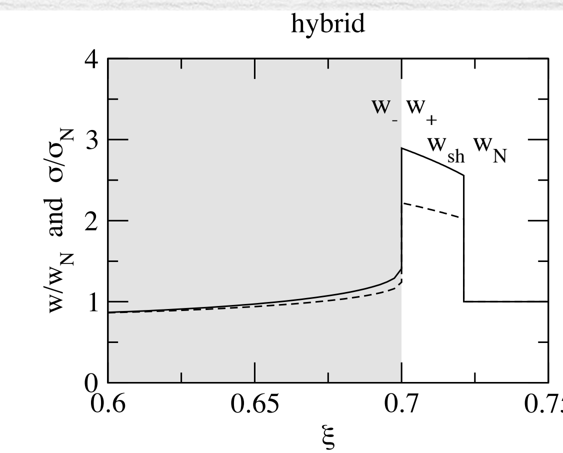




hybrids -both

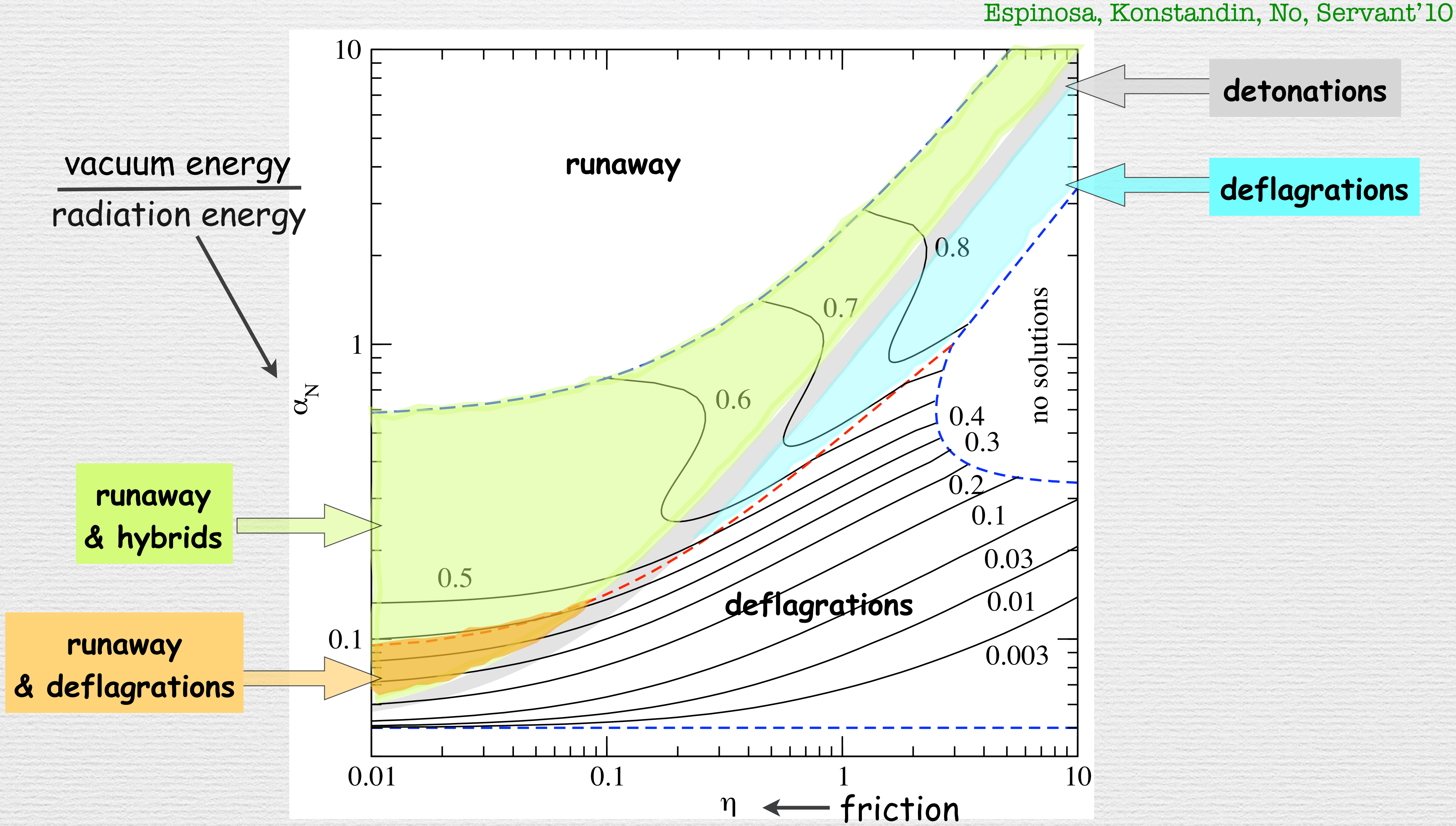






Espinosa, Konstandin, No, Servant'10

Model-independent κ contours



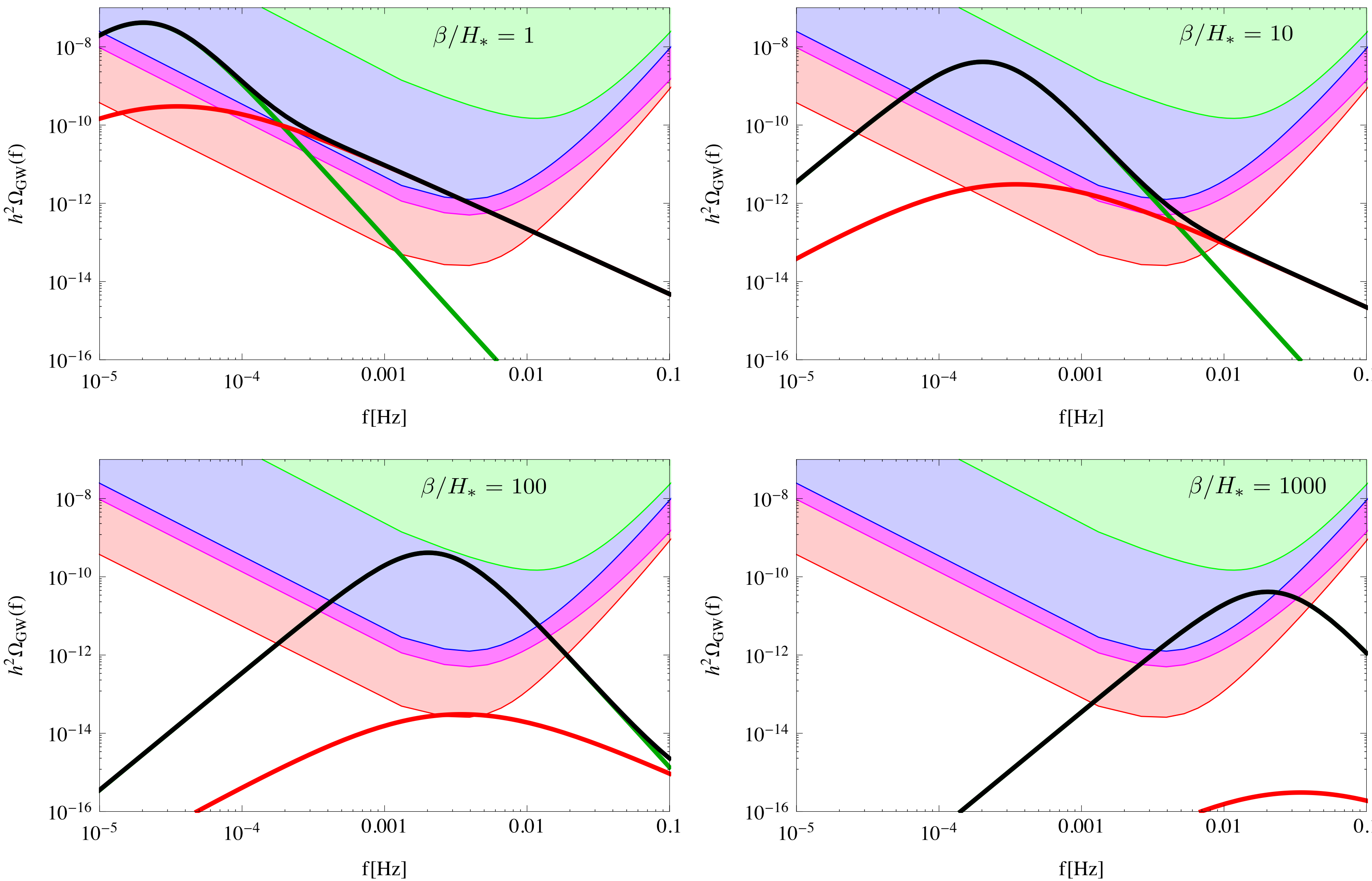
$$\eta_{\rm SM} \sim 10^{-3}$$

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

Examples of Spectra

[1512.06239]

$T_* = 100$ GeV, $\alpha = 0.5$, $v_w = 0.95$

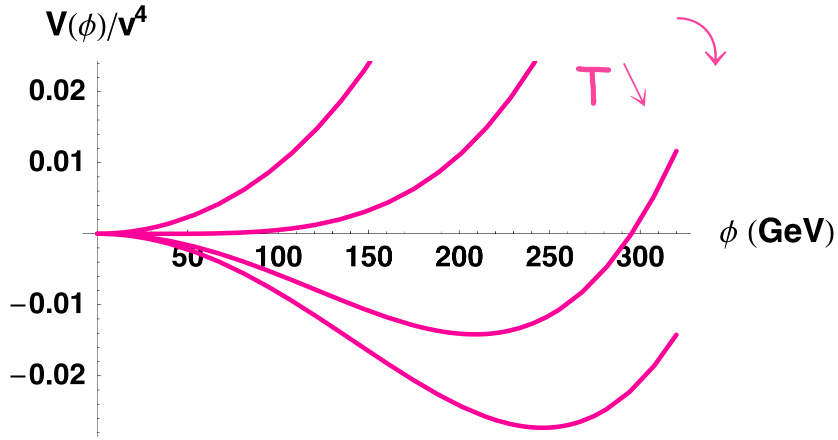


Predictions depend on the particle Physics Model

What is the nature of the Electroweak Phase Transition?

The Higgs Mechanism

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

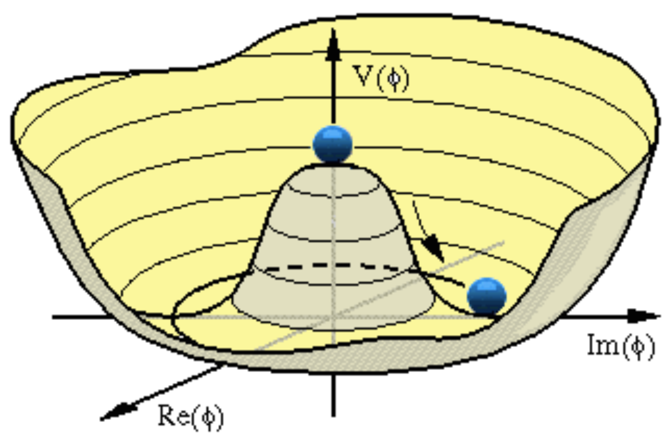


$$\Phi = \begin{bmatrix} \phi^+ \\ \frac{v + H + i\varphi_Z}{\sqrt{2}} \end{bmatrix}$$

Background value, Higgs medium

Higgs boson: excitation of the higgs medium

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.



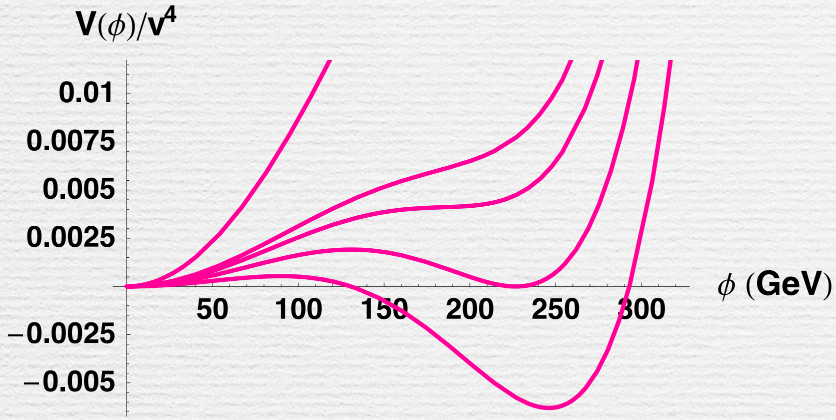
$$V(\Phi) = \frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}\Phi^\dagger\Phi$$

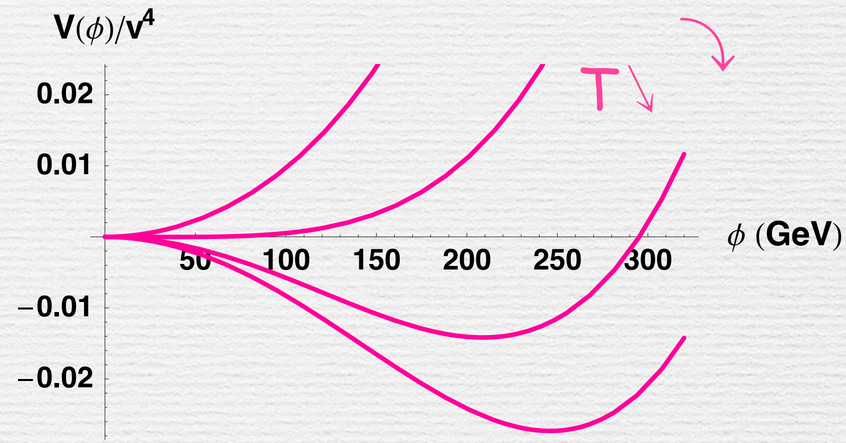
Why is μ^2 negative ?

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.

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

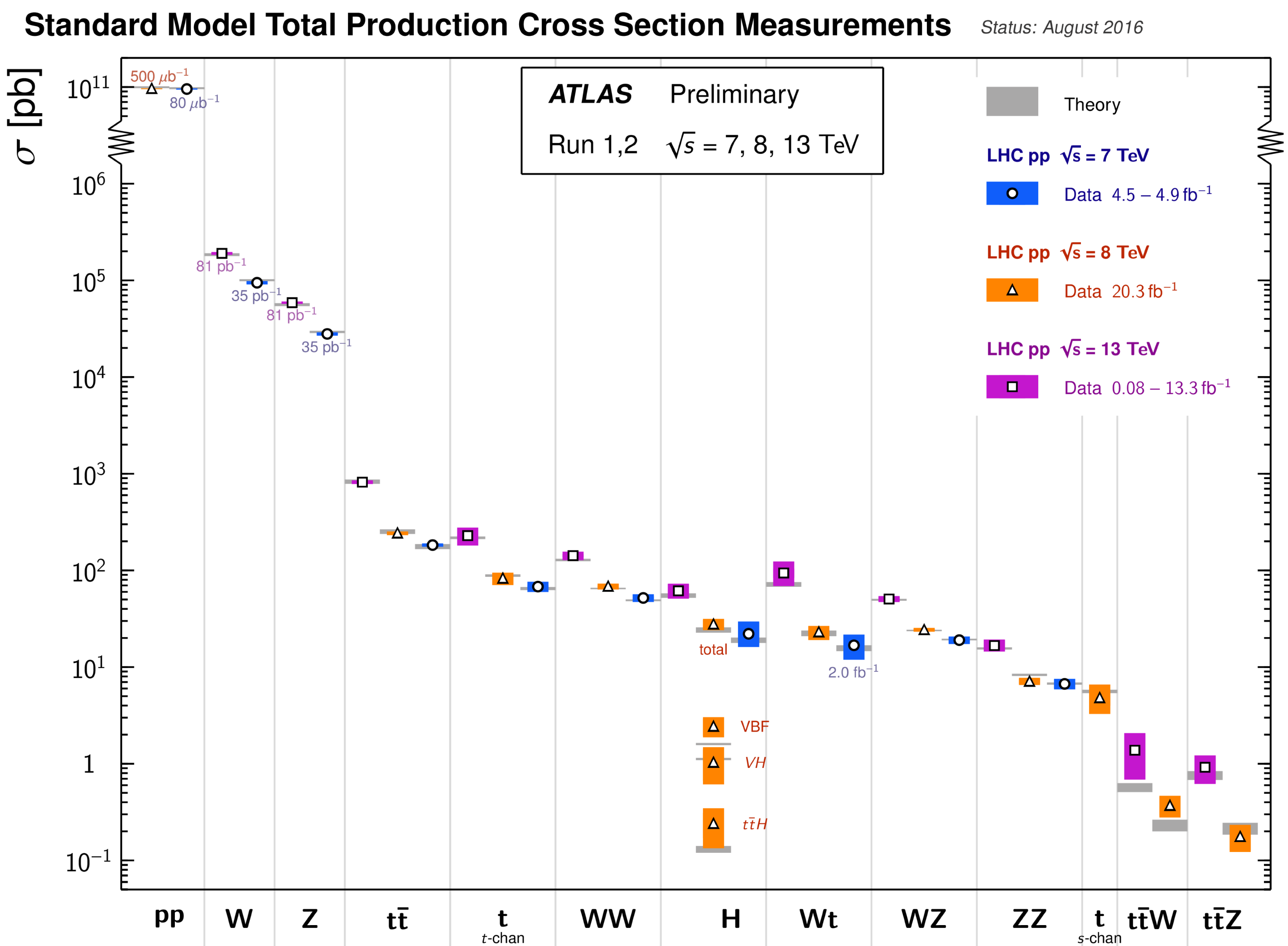
In the SM: $\sum_i \simeq \sum_{W,Z}$ → not enough

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

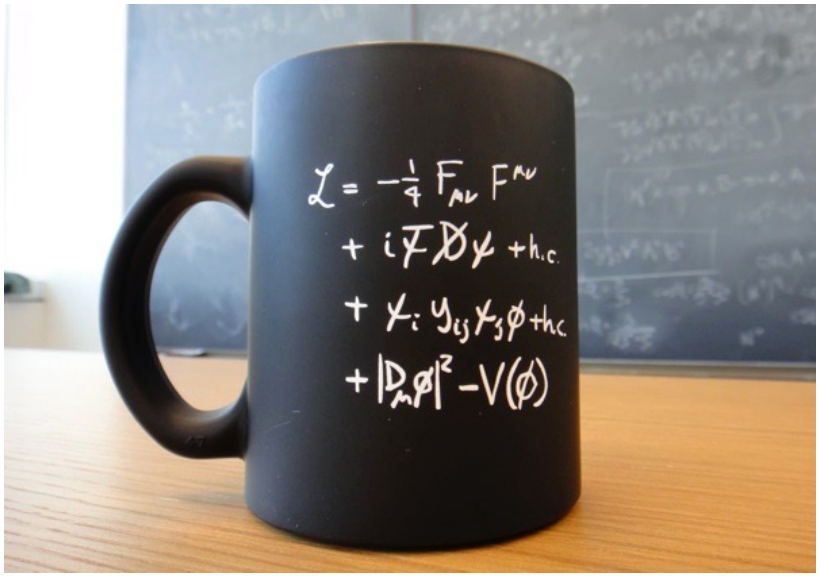
In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop

So far, everything amazingly consistent with the Standard Model



describes phenomena over many orders of magnitude!



But this equation fails to explain:

Baryon asymmetry of the universe

Dark Matter

Dark Energy

Inflation

Quantum Gravity

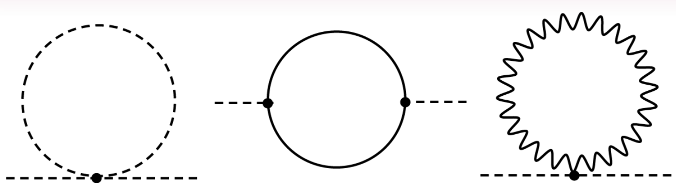
The hierarchy problem: What is keeping the Higgs boson light?

we need new degrees of freedom to cancel Λ^2 divergences
and ensure the stability of the weak scale

a problem that arises for any elementary SCALAR particle

does not arise for fermions (protected by chiral symmetry) or
gauge bosons (protected by the gauge symmetry)

What is cancelling the divergent diagrams?



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

A light Higgs calls for New Physics at the TeV scale

the "hierarchy problem": the main motivation for building the LHC

Matter Anti-matter asymmetry of the universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}$$

$$5.7 \le \eta_{10} \le 6.7 \ (95\%\mathrm{CL})$$

η remains unexplained within the Standard Model

double failure:

- lack of out-of-equilibrium condition

- so far, no baryogenesis mechanism that works with only SM CP violation (CKM phase)

proven for standard EW baryogenesis

Gavela, P. Hernandez, Orloff, Pene '94
Konstandin, Prokopec, Schmidt '04

attempts in cold EW baryogenesis

Tranberg, A. Hernandez, Konstandin, Schmidt '09
Brauner, Taanila,Tranberg,Vuorinen '12

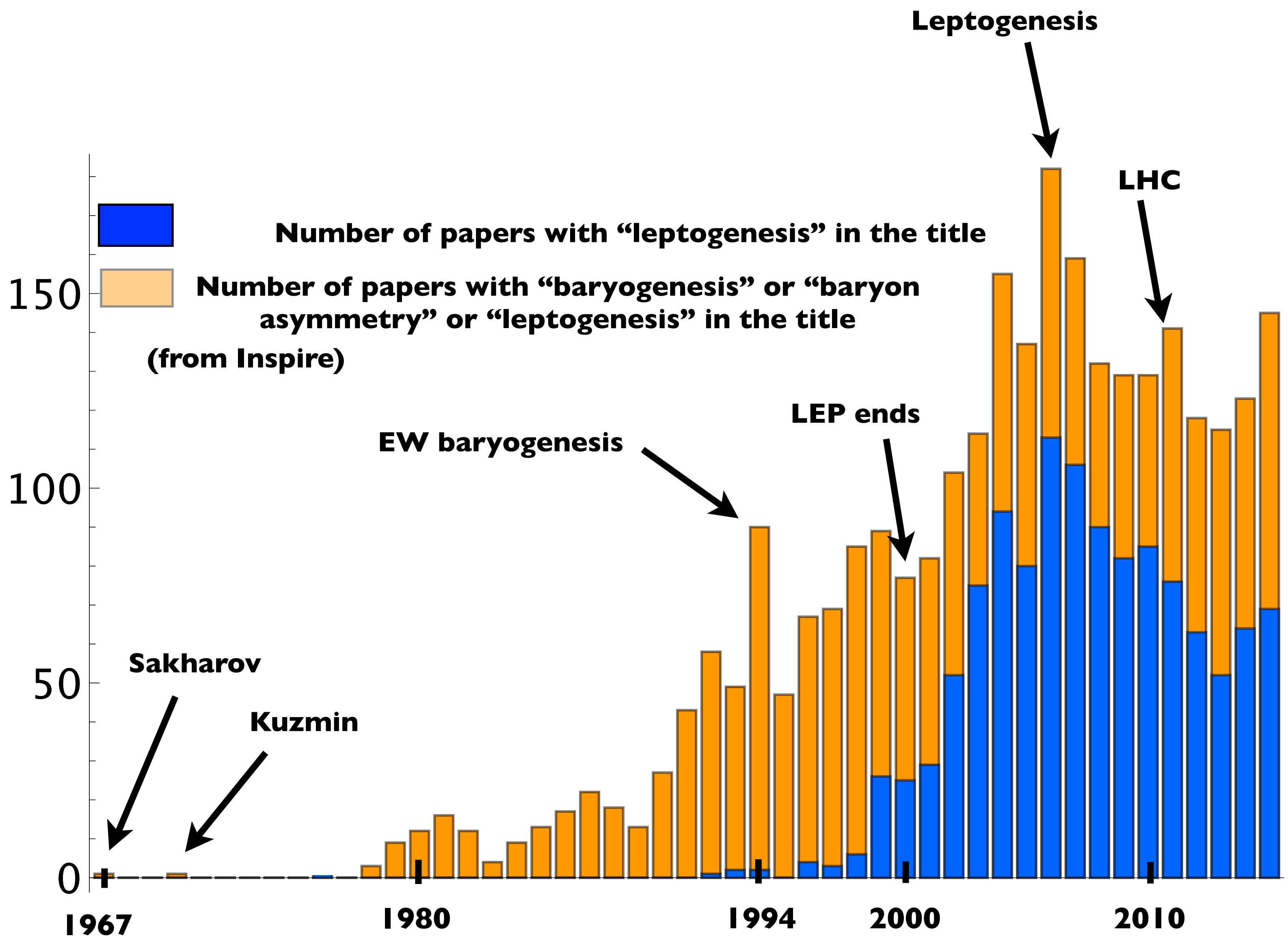
Shaposhnikov,

Journal of Physics: Conference Series **171** (2009) 012005

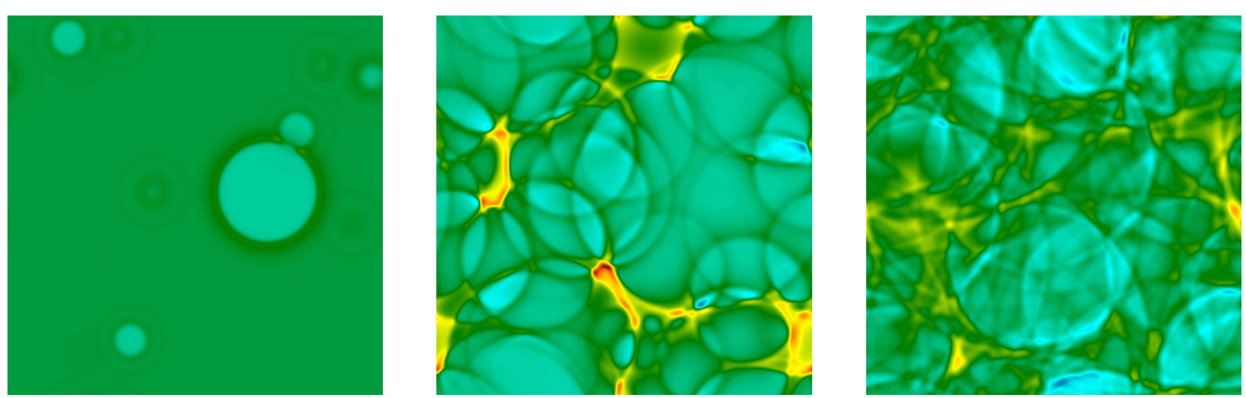
1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Plethora of baryogenesis models taking place at all possible scales

History of baryogenesis papers



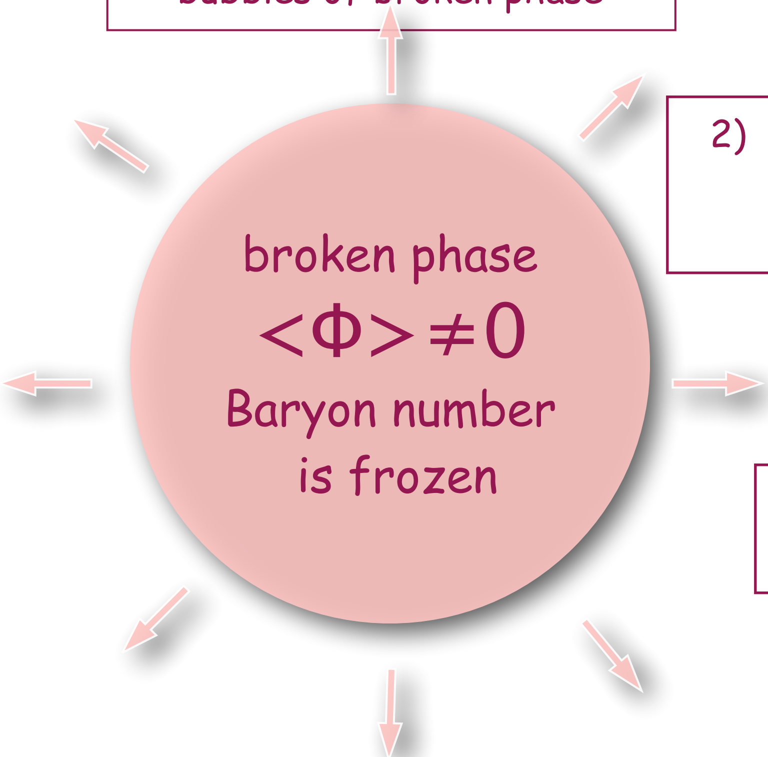
Baryogenesis at a first-order EW phase transition



Baryon asymmetry and the EW scale

Cohen, Kaplan, Nelson'91

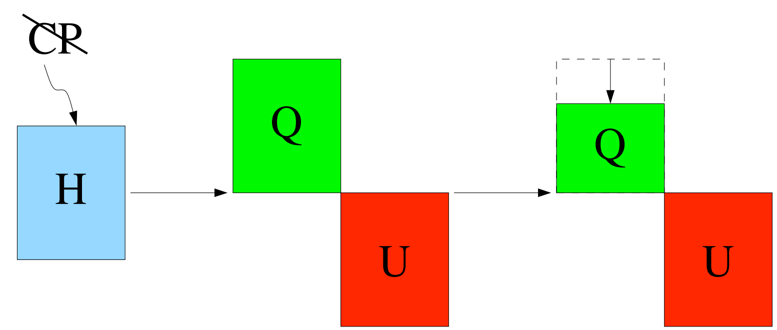
1) nucleation and expansion of bubbles of broken phase



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

Chirality Flux in front of the wall

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



Electroweak baryogenesis mechanism relies on a first-order phase transition satisfying $\frac{\langle \Phi(T_n) \rangle}{T_n} \gtrsim 1$

Matter Anti-matter asymmetry of the universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}$$

$$5.7 \leq \eta_{10} \leq 6.7 \ (95\%\mathrm{CL})$$

The Electroweak Baryogenesis Miracle:

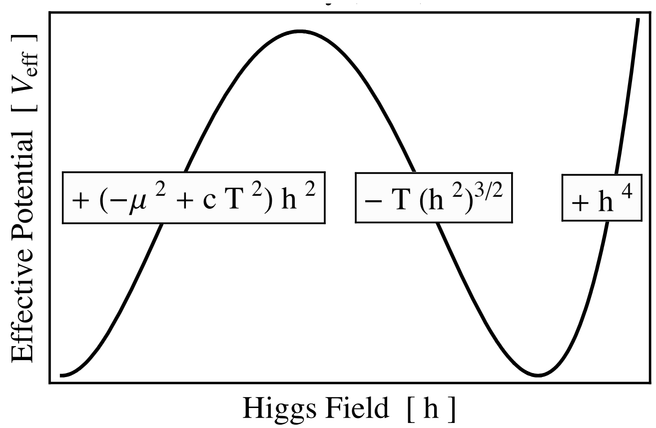
$$\eta_B = \frac{n_B}{s} = \frac{405\Gamma_{ws}}{4\pi^2 v_w g_* T} \int_0^\infty dz \ \mu_{B_L}(z) e^{-\nu z}, \qquad \nu = 45\Gamma_{ws}/(4v_w)$$

$$\Gamma_{ws} = 1.0 \times 10^{-6} T,$$

All parameters fixed by electroweak physics! If new CP violating source of order 1 then we get just the right baryon asymmetry!

The most common way to obtain a strongly 1st order phase transition by inducing a barrier in the effective potential is due to thermal loops of BOSONIC modes.

One adds new scalar coupled to the Higgs



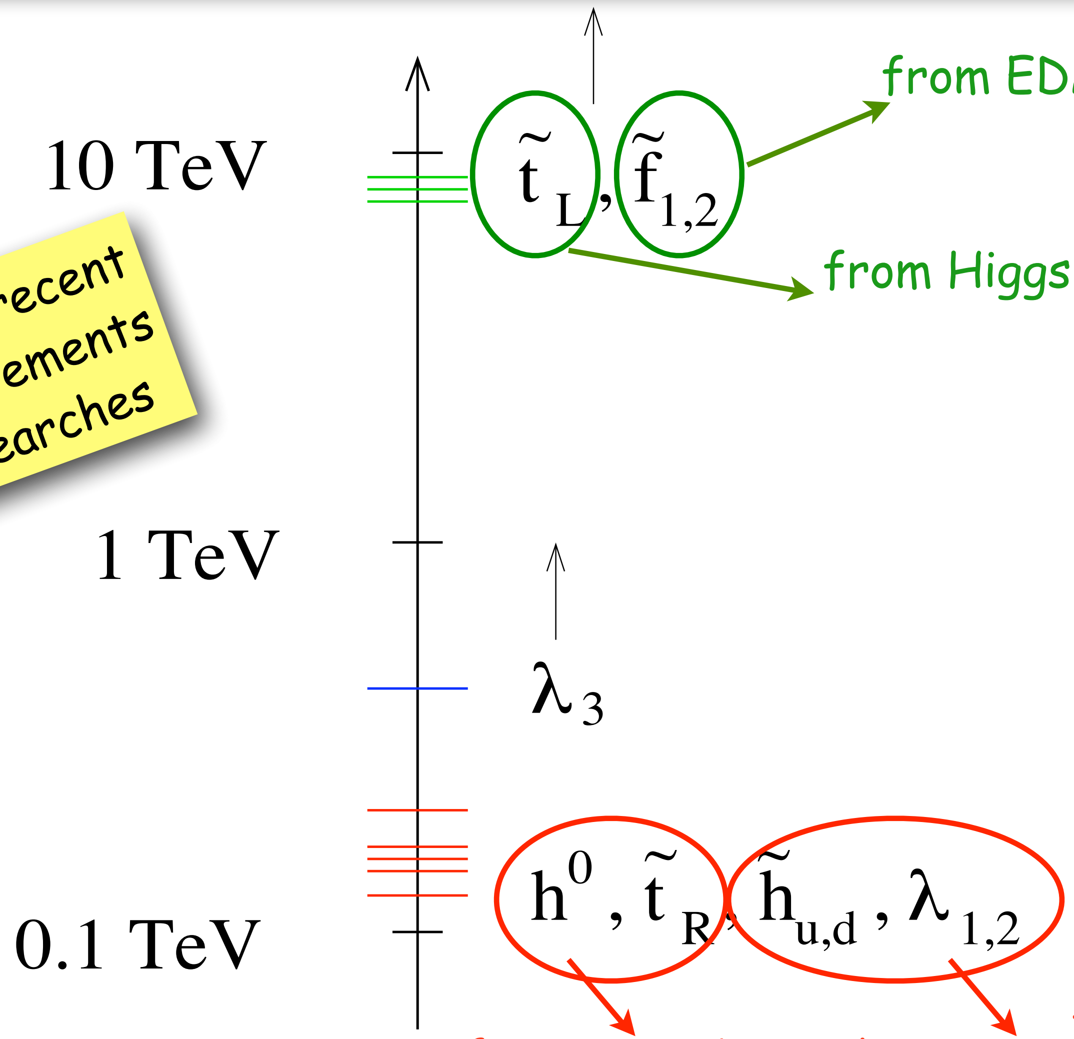
Very constrained by LHC !

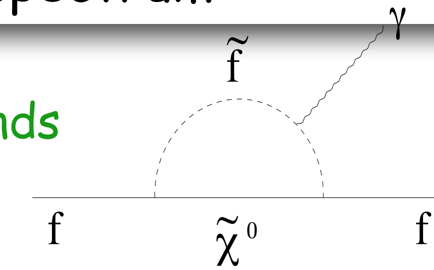
Katz, Perelstein '14

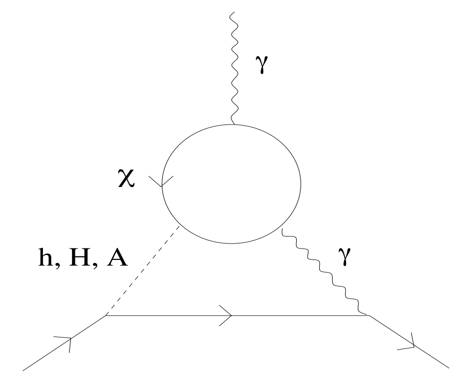
A strong 1st order PT leads to sizable deviations in hgg and $h\gamma\gamma$ couplings and therefore in Higgs production rate and decays in $\gamma\gamma$

e.g: Light stop scenario in Minimal Supersymmetric Standard Model

The (former) EW baryogenesis window in the Minimal Supersymmetric Standard Model: A Stop-split supersymmetry spectrum







excluded by recent higgs measurements and stop searches

see 1207.6330

The light stop scenario: testable at the LHC

bounds get relaxed when adding singlets or in BSSM

Higgs mass measurement does not constrain the nature of the EW phase transition

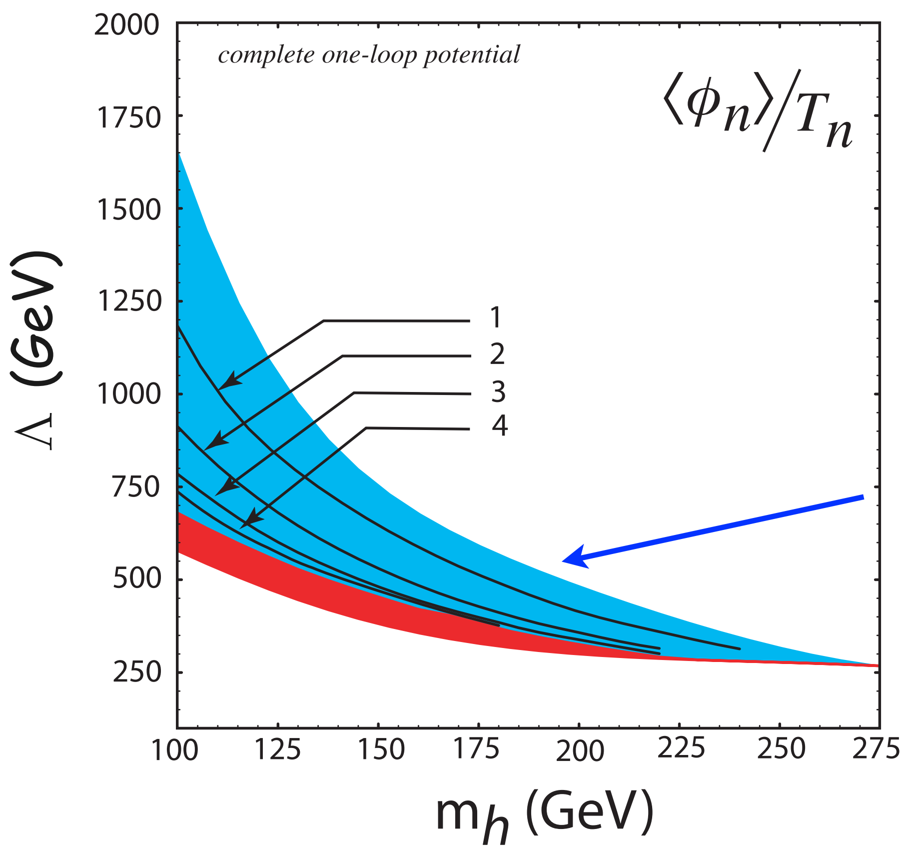
Easily seen in effective field theory approach:

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

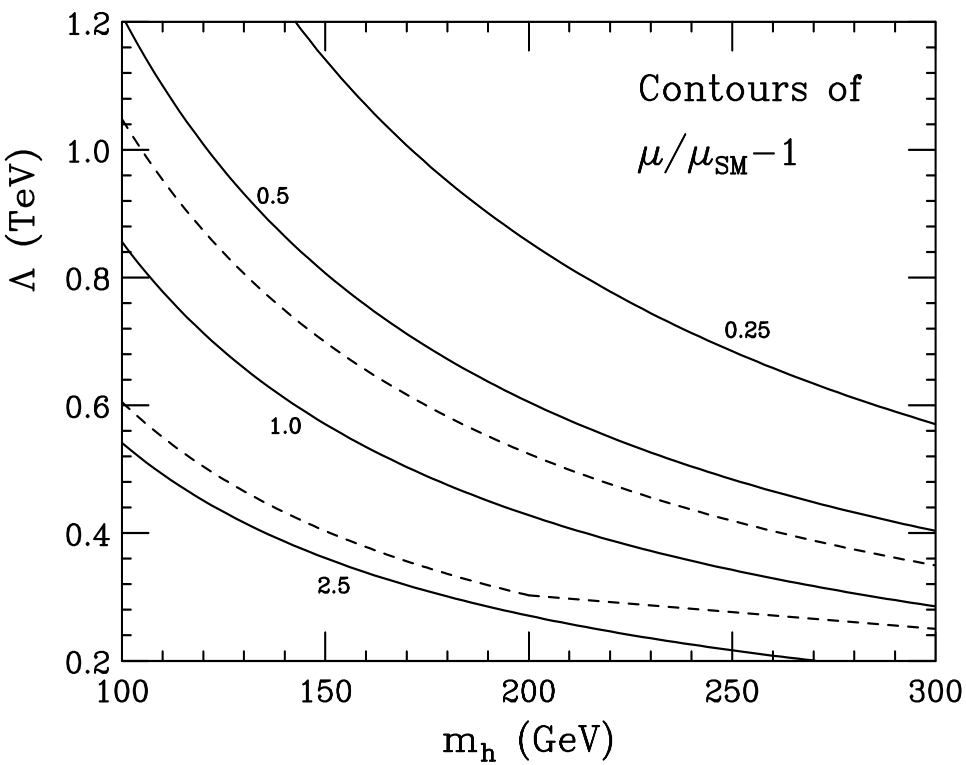
but Typically large deviations to the Higgs self-couplings

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

where

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

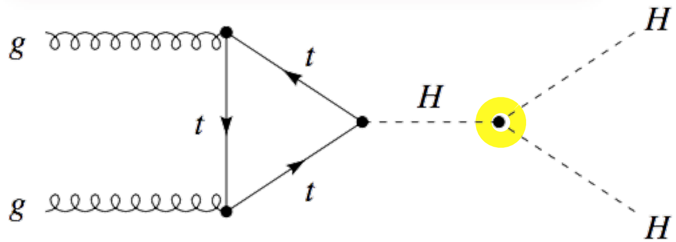
$$\eta = 3\frac{m_H^2}{v_0^2} + 36\,\frac{v_0^2}{\Lambda^2}$$



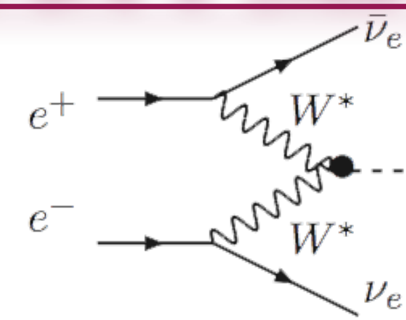
The dotted lines delimit the region for a strong 1rst order phase transition

deviations between a factor 0.7 and 2

at a Hadron Collider



at an e

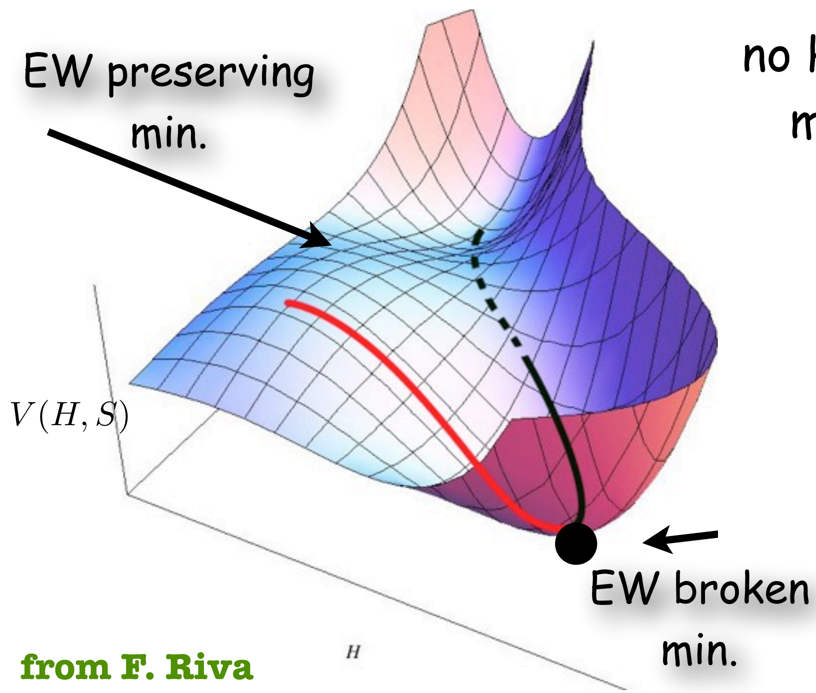


The easiest way: Two-stage EW phase transition

example: the SM+ a real scalar singlet

e.g 1409.0005

$$V_0 = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}\mu_S^2 S^2 + \lambda_{HS} |H|^2 S^2 + \frac{1}{4}\lambda_S S^4.$$



from F. Riva

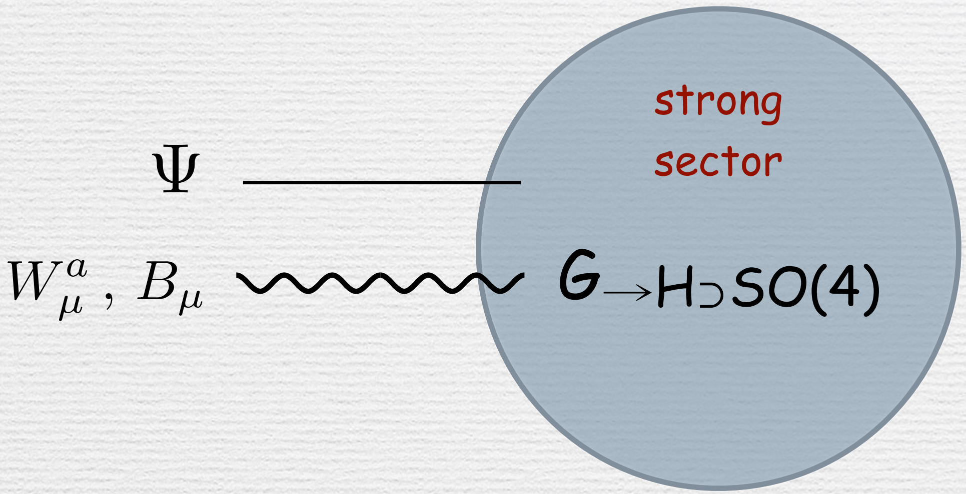
S has no VEV today:
no Higgs-S mixing-> no EW precision tests , tiny modifications of higgs couplings at colliders

Poorly constrained

-> Espinosa et al, 1107.5441

Easy to motivate additional scalars, e.g:

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



custodial SO(4)

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

to avoid large corrections to the T parameter

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times \mathrm{SU}(2)]$
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]

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

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

(global symm. on u,d)

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

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

(global symm. on techniquarks)

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

Another easy way to get a strong 1st-order PT:

dilaton-like potential naturally leads to supercooling

Konstandin Servant '11

not a polynomial ↘

$$V = V(\sigma) + \frac{\lambda}{4}(\phi^2 - c\sigma^2)^2 \qquad c = \frac{v^2}{\langle\sigma\rangle^2}$$

Higgs vev controlled by dilaton vev

(e.g. Randall-Sundrum scenario)

$$V(\sigma) = \sigma^4 \times f(\sigma^\epsilon)$$

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

for $|\varepsilon| << 1$

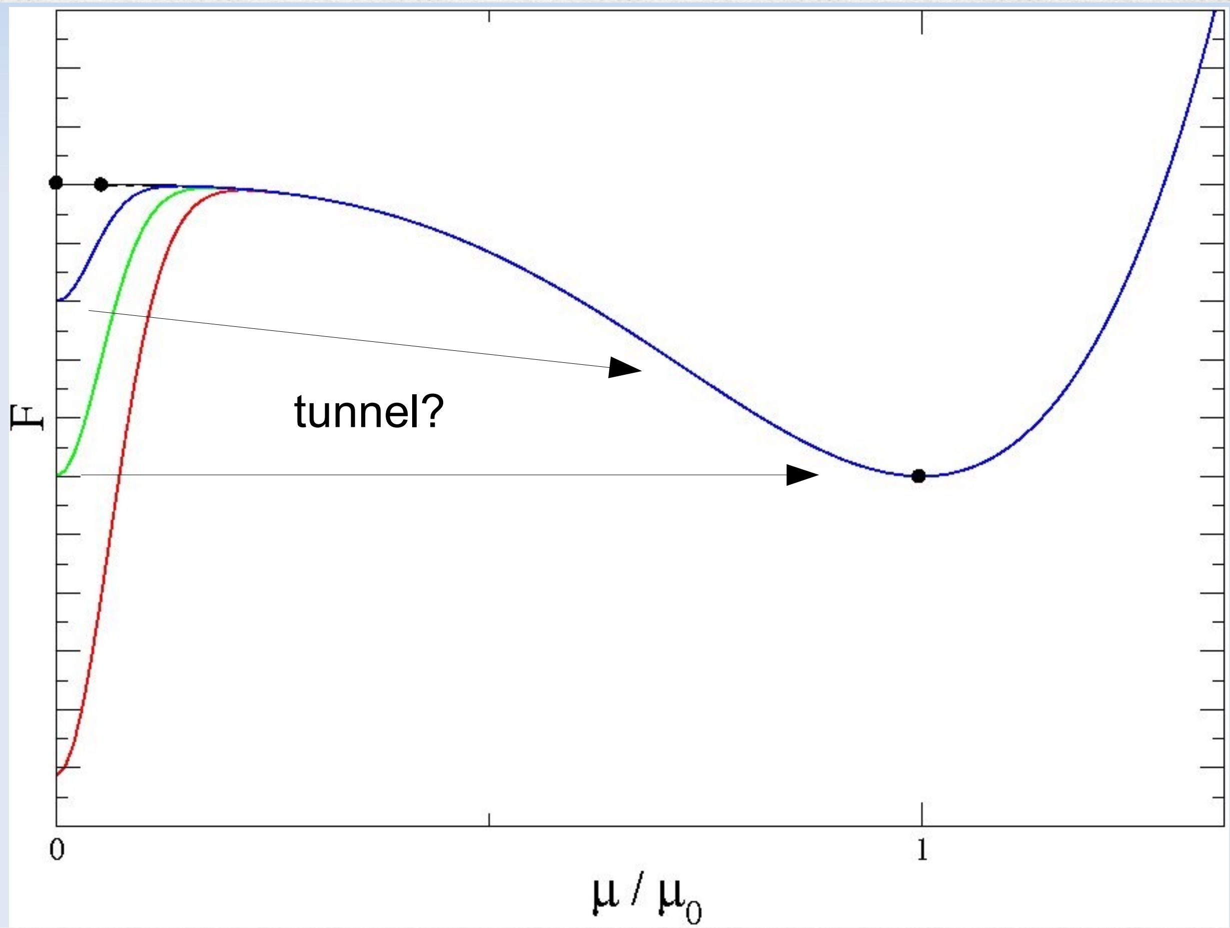
similar to Coleman-Weinberg mechanism where a slow Renormalization Group evolution of potential parameters can generate widely separated scales

Nucleation temperature can be parametrically much smaller than the weak scale

Deconfining phase transition

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

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



Creminelli, Nicolis, Rattazzi'01
Randall, Servant'06

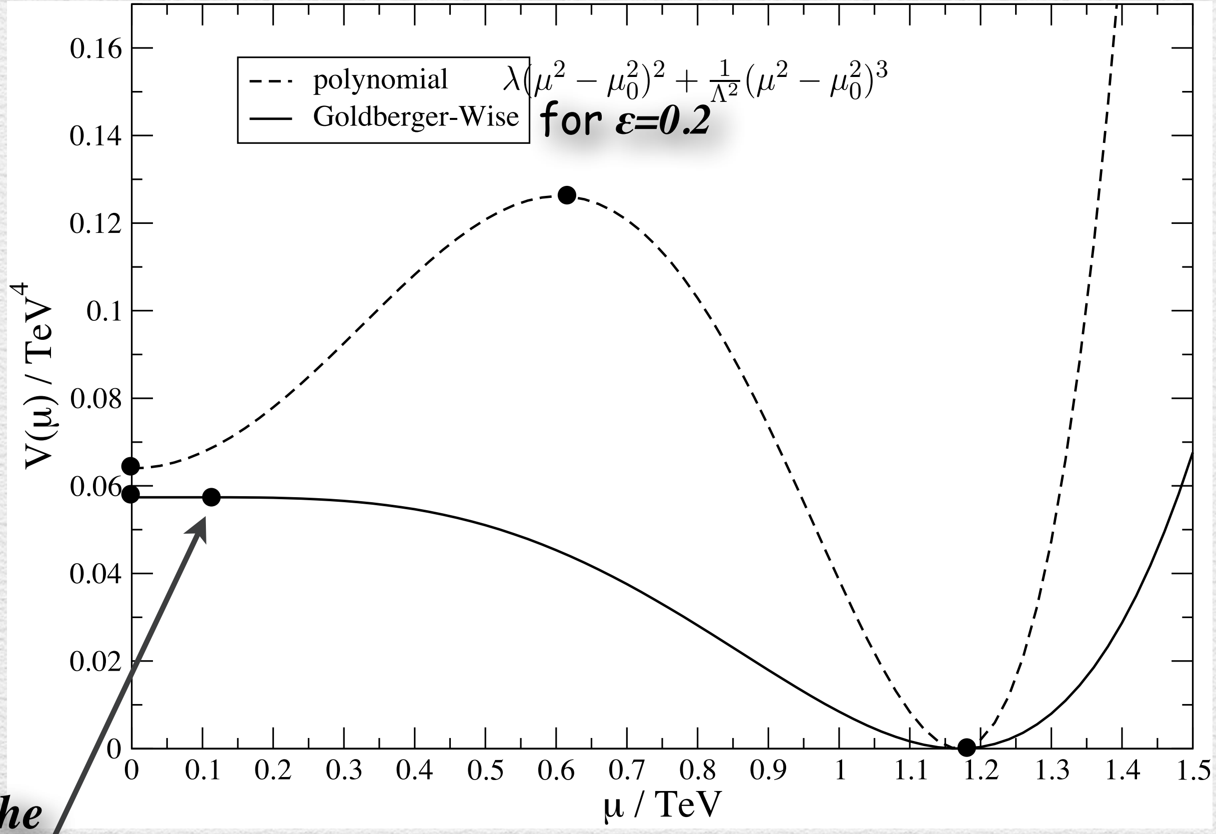
Hassanain, March-Russell, Schwellinger'07
Nardini,Quiros,Wulzer'07
Konstandin,Nardini,Quiros'10
Konstandin,Servant'1

sorry, notation switched from σ to μ

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

Konstandin Servant '11

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 $\sqrt{\mu_+\mu_-} \ll \mu_-$

Application:

Baryogenesis from Strong CP violation

1407.0030

$$\mathcal{L} = -\bar{\Theta}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}$$

today $|\bar{\Theta}| < 10^{-11}$ as explained by Peccei-Quinn mechanism:

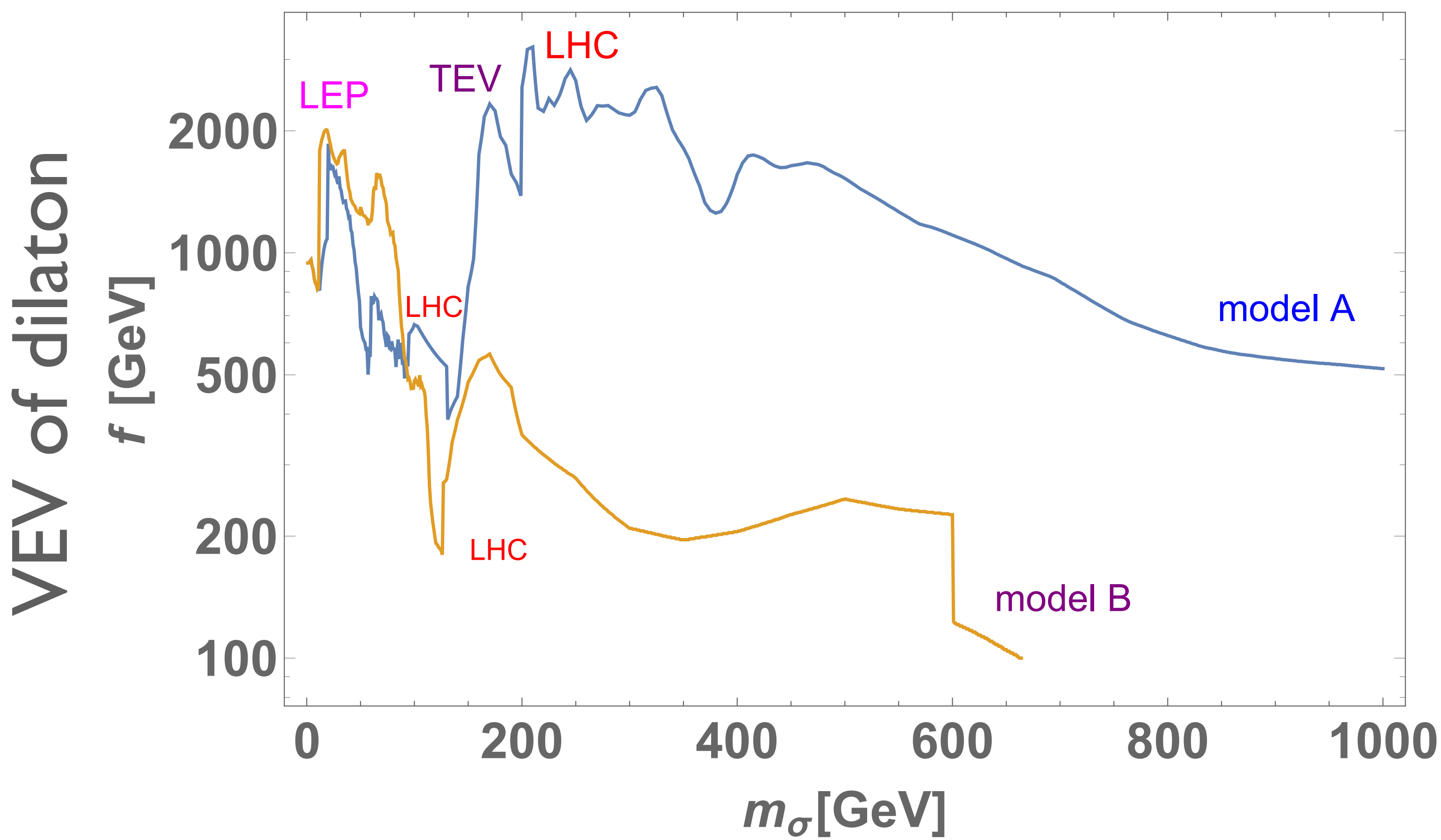
$\bar{\Theta} \rightarrow \frac{a(x)}{f_a}$ promoted to a dynamical field which relaxes to zero, to minimize the QCD vacuum energy.

in early universe, before the axion gets a mass around the QCD scale

$$|\bar{\Theta}| \sim 1$$

$\bar{\Theta}$ could have played any role during the EW phase transition.

LHC constraints on the scale of conformal symmetry breaking (dilaton)



[1410.1873]

Summary of this part

- SM+ 1 singlet scalar: the most minimal and easiest way to get a strong 1st order EW phase transition, almost unconstrained by experimental data

- Dilaton-like potentials: a class of well-motivated and naturally strong 1st order phase transitions, with large supercooling

-Phase transition takes place in vacuum: maximal Gravity Wave signal (no loose of energy in reheating of the plasma)

-In ballpark of best eLISA sensitivity region

- Natural framework for cold EW baryogenesis mechanism

- Signatures at the LHC (light Higgs-like dilaton with suppressed couplings but accessible)

Another recent development:

A first-order Electroweak Phase Transition in the Standard Model from Varying Yukawas

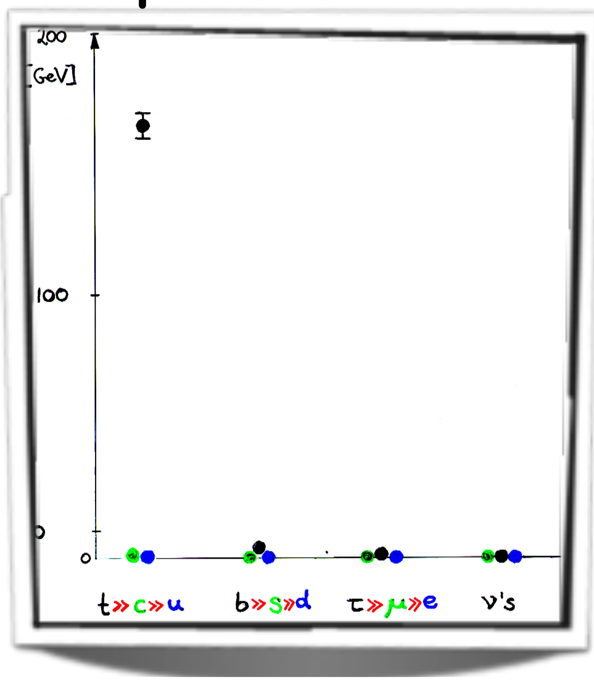
Baldes, Konstandin, Servant, 1604.04526

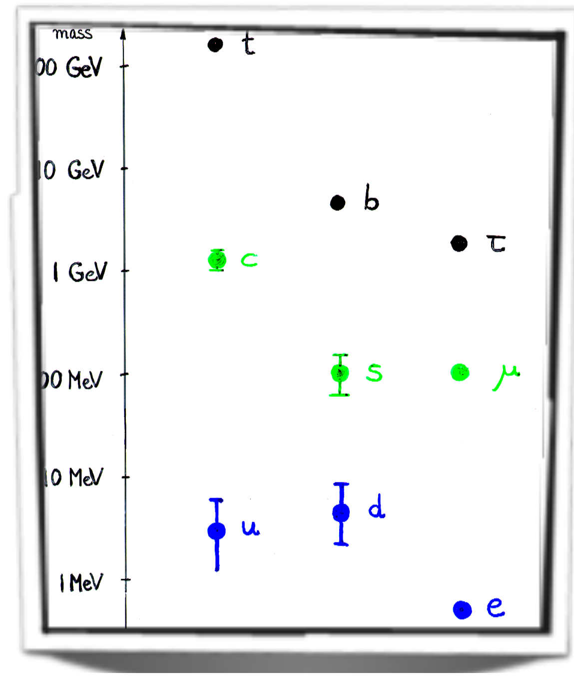
The new result:

The nature of the EW phase transition is completely changed when the Standard Model Yukawas vary at the same time as the Higgs is acquiring its vacuum expectation value.

Origin of the fermion mass hierarchy?

the mass spectrum of the fermions is intriguing





fermion Yukawas $y_{ij}\overline{f}^i_L \Phi^{(c)} f^j_R$

$$\langle\Phi\rangle = v/\sqrt{2}$$

fermion masses $m_f = y_f v/\sqrt{2}$

There are three main mechanisms to describe fermion masses

$$m_f = y_f v/\sqrt{2}$$

1) Spontaneously broken abelian flavour symmetries as originally proposed by Froggatt and Nielsen

may be related by holography {

2) Localisation of the profiles of the fermionic zero modes in extra dimensions

3) Partial fermion compositeness in composite Higgs models

The scale at which the flavour structure emerges is not known.

Usually assumed to be high but could be at the EW scale.

Emerging Flavour during Electroweak symmetry breaking

There are good motivations to consider that the flavour structure could emerge during electroweak symmetry breaking

For Example, if the "Flavon" field dynamics is linked to the Higgs field

Extensive literature on models advocated to explain the fermion masses, however no study so far on the associated cosmology

On the other hand, in all flavour models, Yukawa couplings are controlled by the VEV of some scalar ``flavons" and it is natural to wonder about their cosmological dynamics.

Our working assumption: the flavon couples to the Higgs and therefore the flavon and the Higgs VEV dynamics are intertwined.

High Temperature Effective Higgs Potential

2) Barrier from the $T \neq 0$ one-loop potential:

$$V_1^T(\phi, T) = \sum_i \frac{g_i(-1)^F T^4}{2\pi^2} \times \int_0^\infty y^2 \mathrm{Log}\left(1 - (-1)^F e^{-\sqrt{y^2 + m_i^2(\phi)/T^2}}\right) \mathrm{d}y.$$

$$V_f^T(\phi, T) = -\frac{gT^4}{2\pi^2} J_f\left(\frac{m_f(\phi)^2}{T^2}\right)$$

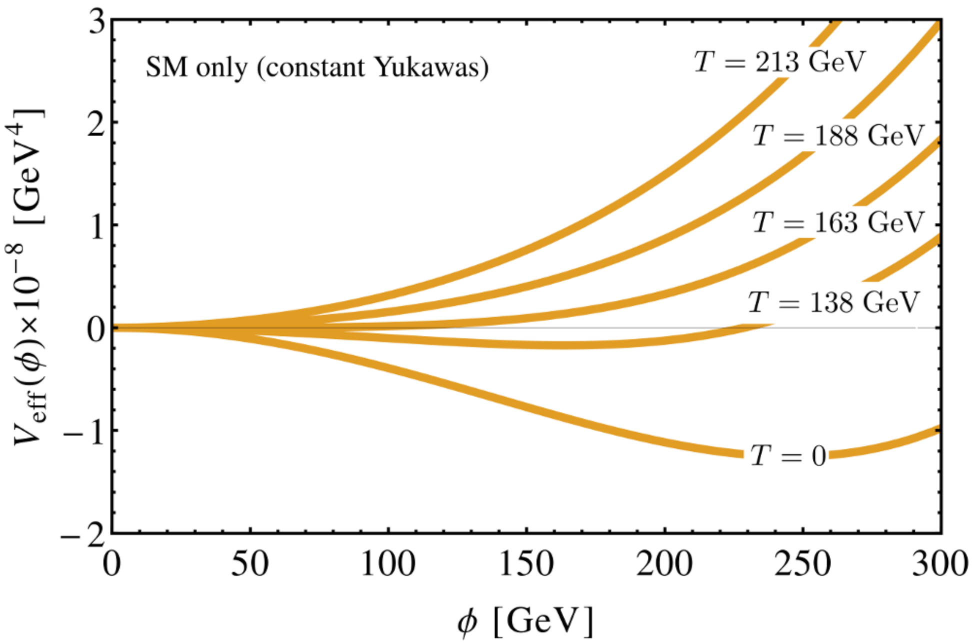
High-T expansion: $$J_f(x^2) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24}x^2 - \frac{x^4}{32}\mathrm{Log}\left[\frac{x^2}{13.9}\right]$$

$$\delta V \equiv V_f^T(\phi, T) - V_f^T(0, T) \approx \frac{gT^2\phi^2[y(\phi)]^2}{96}$$

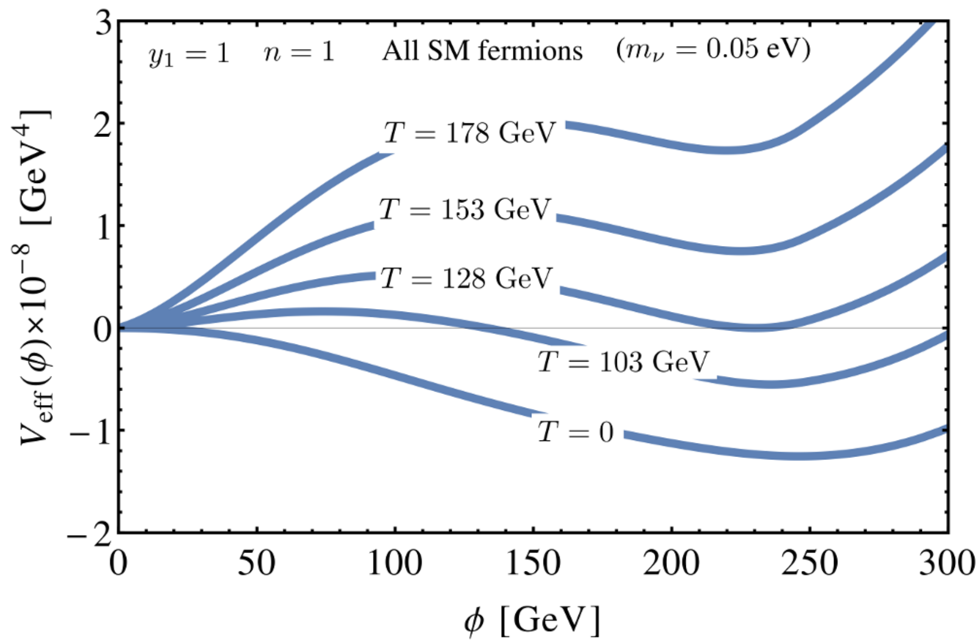
Fermionic fields create a barrier!

Full one-loop effective Higgs potential with Daisy Resummation

Standard Case (Constant Yukawas)



With varying Yukawas



Summary

Variation of the Yukawas of SM fermions from O(1) to their present value during the EW phase transition generically leads to a very strong first-order EW phase transition,

This offers new routes for generating the baryon asymmetry at the electroweak scale, strongly tied to flavour models.

Second major implication:

the CKM matrix as the unique CP-violating source !

Bruggisser, Konstandin, Servant, to appear

$$\begin{aligned}\Delta_{CP} &= v^{-12}\text{Im Det}\left[m_u m_u^\dagger, m_d m_d^\dagger\right] \\ &= J\, v^{-12} \prod_{i<j}(\tilde{m}_{u,i} - \tilde{m}_{u,j}^2) \prod_{i<j}(\tilde{m}_{d,i}^2 - \tilde{m}_{d,j}^2) \simeq 10^{-19},\end{aligned}$$

$$J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin(\delta) = (3.0 \pm 0.3) \times 10^{-5},$$

Large masses during EW phase transition
->no longer suppression of CKM CP violation

Berkooz, Nir, Volansky '04

Conclusion

Scalar fields are ubiquitous in physics beyond the Standard Model

The second run of the LHC will provide new probes of models leading to first-order EWPT, which would have dramatic implications for EW baryogenesis , A beautiful framework for explaining the matter-antimatter of the universe relying on EW scale physics only.

Will take time before we get a final answer.

LISA: Beautiful and complementary window on the TeV scale

See next talk for detection prospects

Many well-motivated models predict a strong first-order EW phase transition.

Most recent example in connection with flavour models :
Dynamical Yukawas during the Electroweak Phase Transition change the nature of the EW Phase Transition.