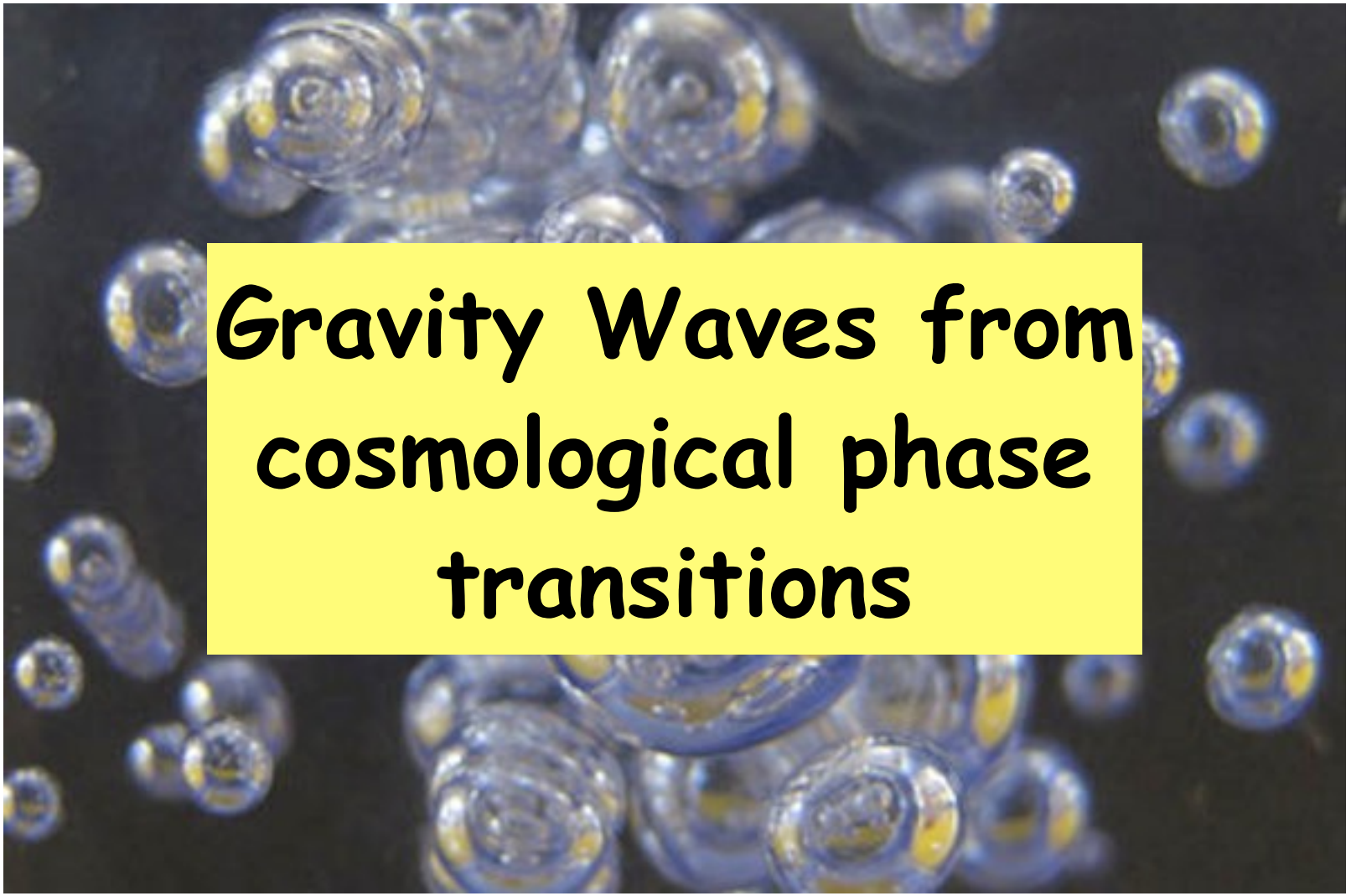


Gravity Waves from cosmological phase transitions

Géraldine SERVANT

DESY/U.Hamburg

DIS Workshop, BNL,
October 5 2016

HELMHOLTZ GEMEINSCHAFT

DESY

UHH Universität Hamburg

See review:

arXiv:1512.06239

JCAP 1604 (2016) no.04, 001

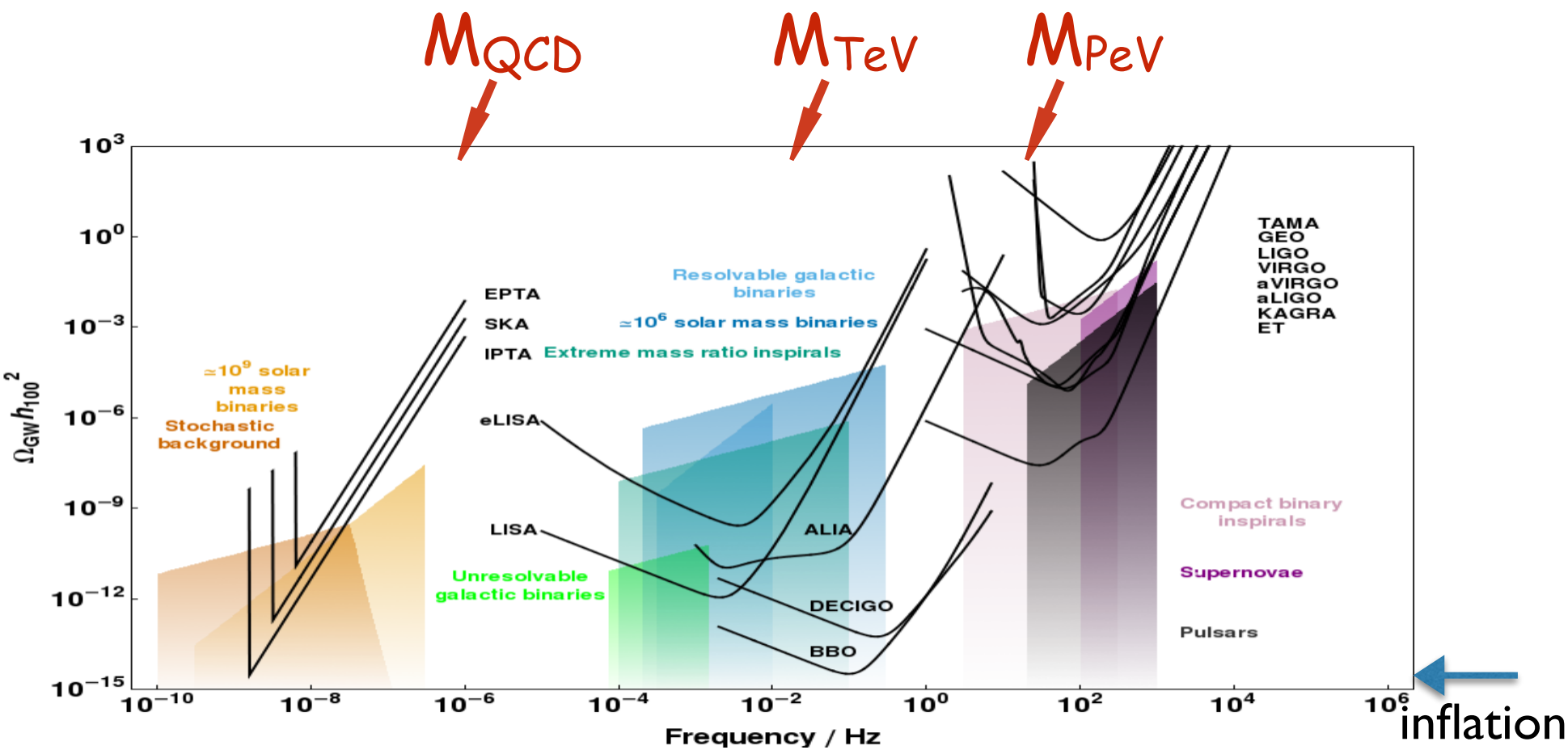
Chiara Caprini, Mark Hindmarsh, Stephan Huber, Thomas Konstandin, Jonathan Kozaczuk, Germano Nardini, Jose Miguel No, Antoine Petiteau, Pedro Schwaller, Geraldine Servant, David J. Weir

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

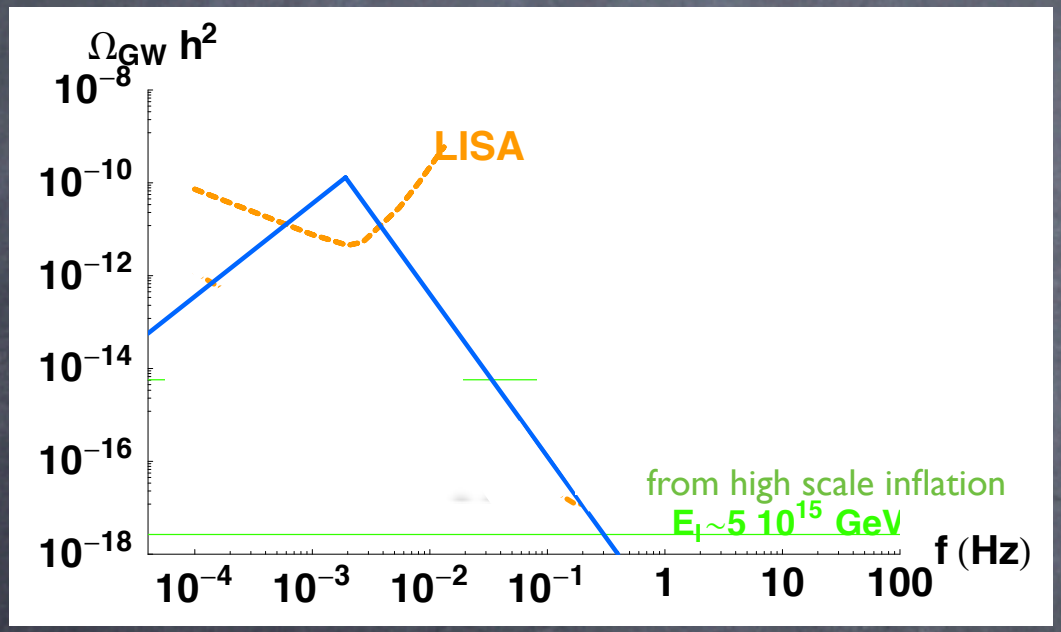


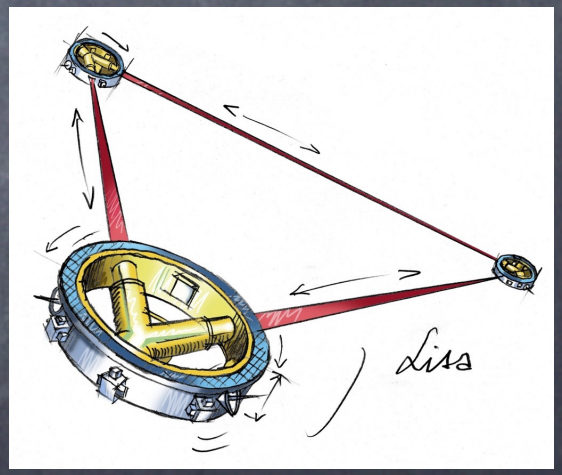
inflation signal

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



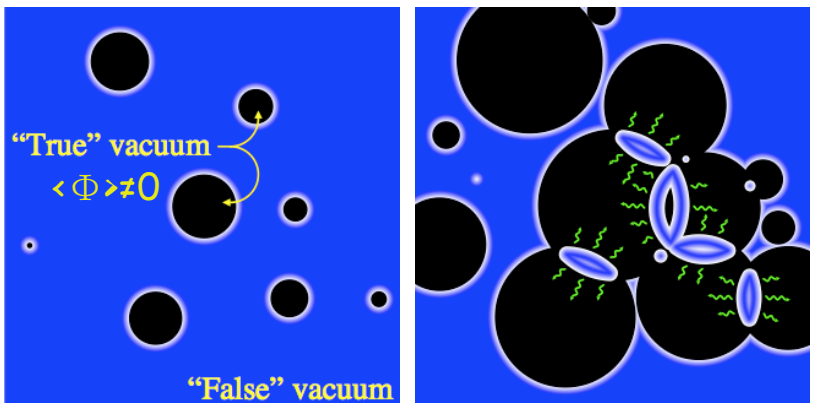


complementary to collider informations

Which weak scale physics? ⇒ transition

Bubble nucleation

Bubble percolation

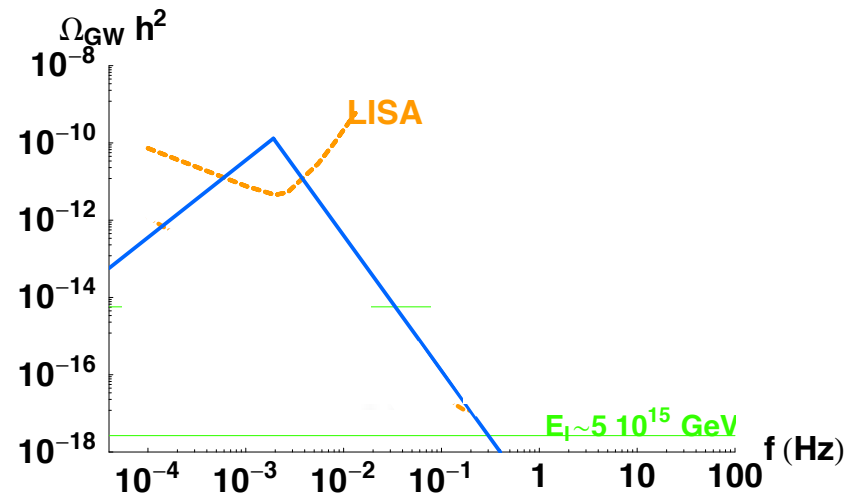


Fluid flows

turbulence

Magnetic fields

Stochastic background of gravitational radiation



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

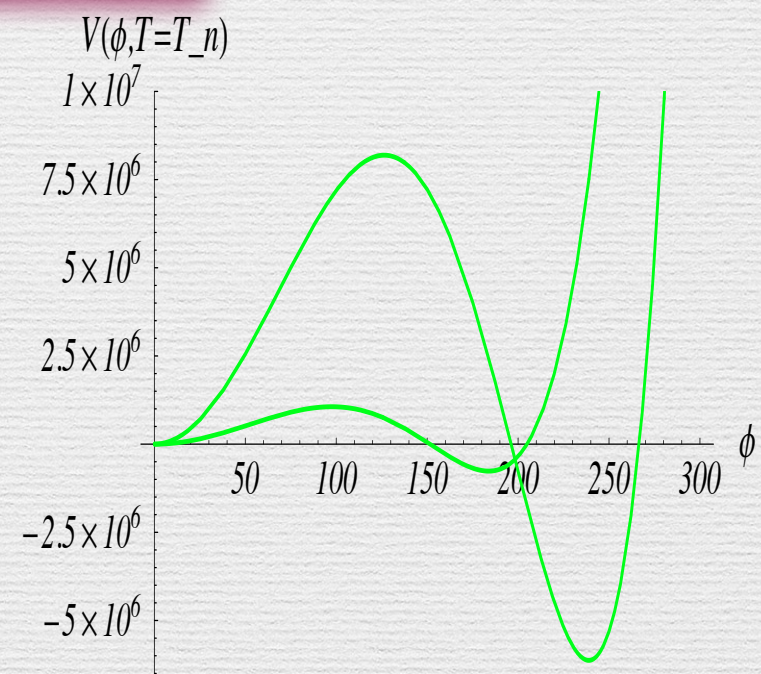
β : (duration of the phase transition)$^{-1}$

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

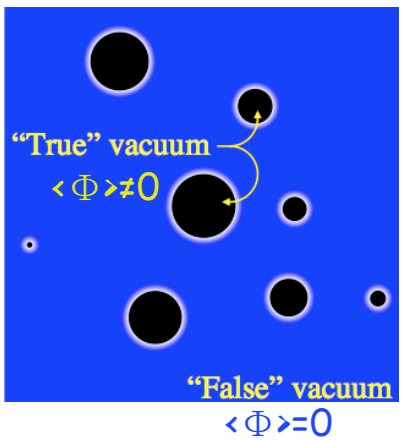
α and β : entirely determined by the effective scalar potential at high temperature

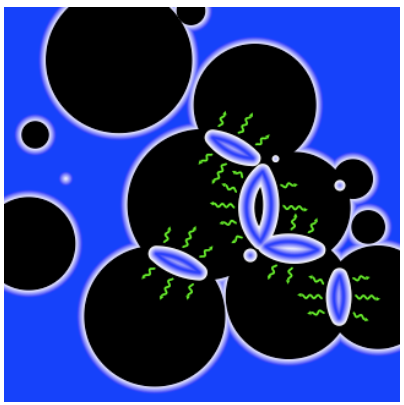


Gravity wave signals from 1st order cosmological phase transitions

Bubble nucleation

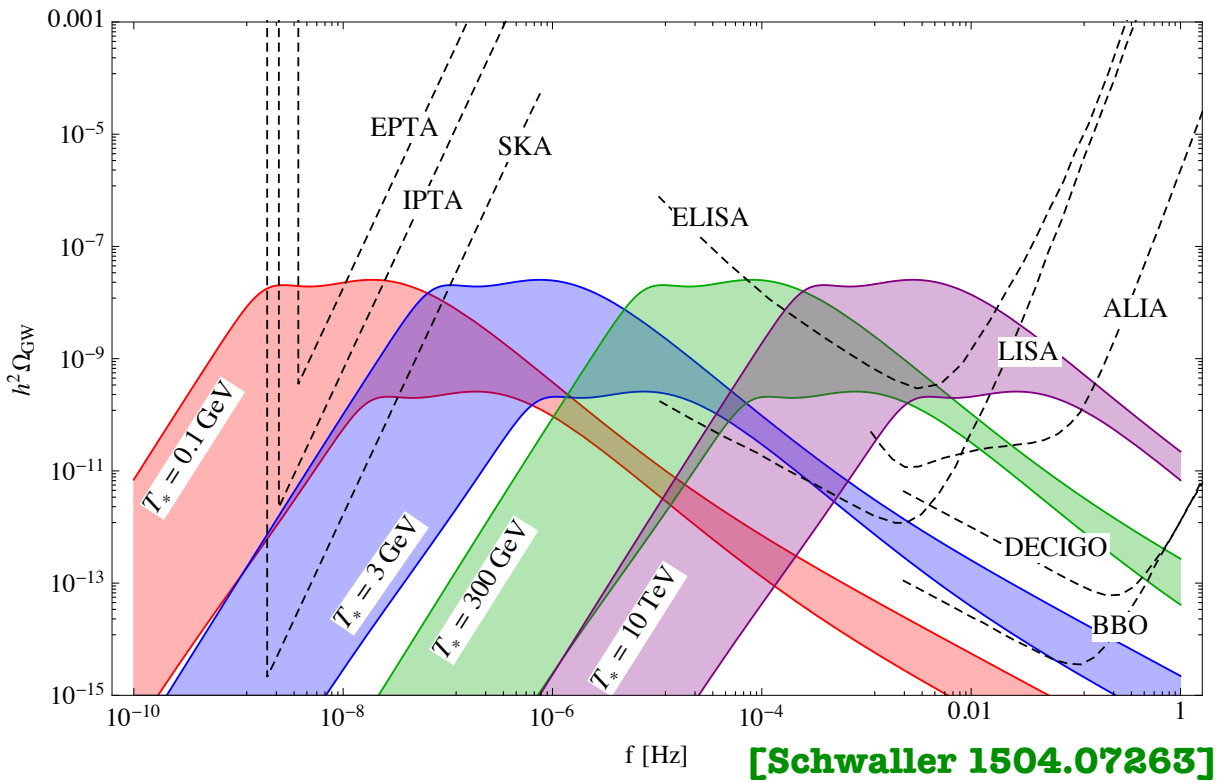
Bubble percolation





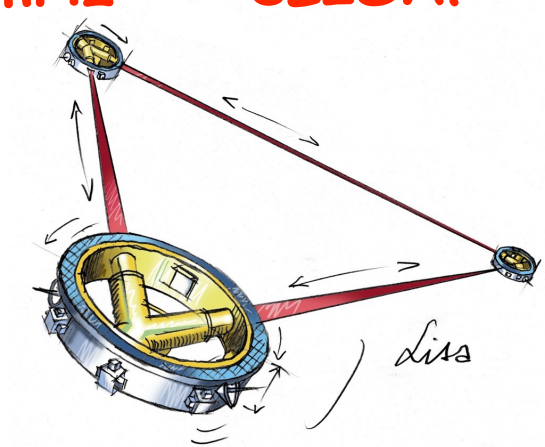
[eLISA Cosmology Working group, 1512.06239]

Stochastic background of gravitational radiation



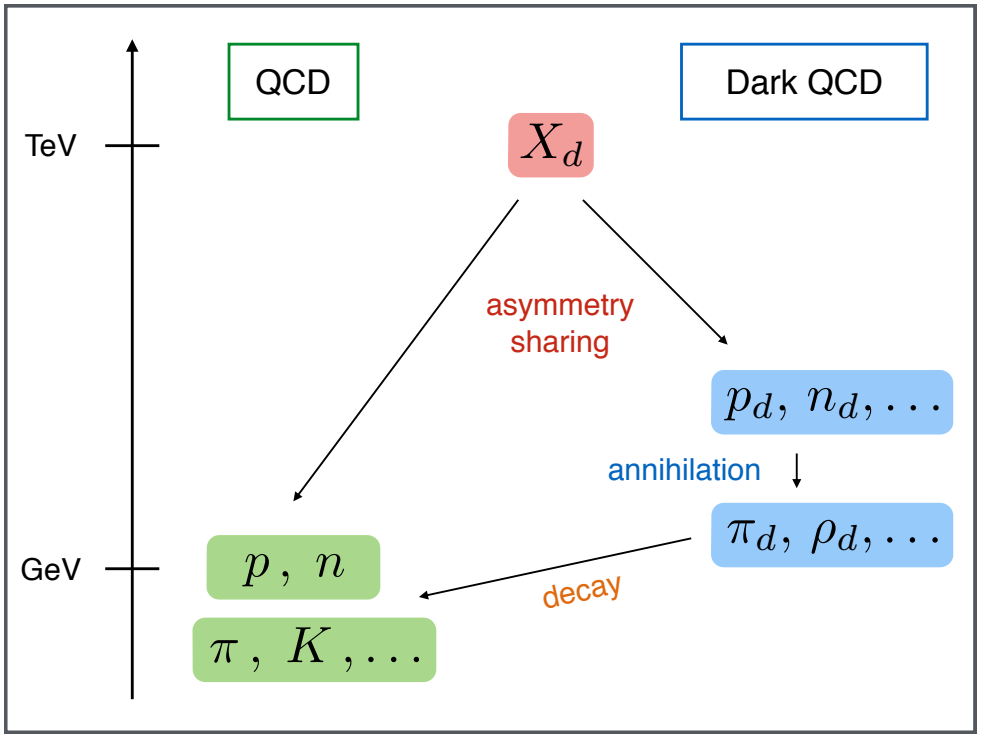
[Schwaller 1504.07263]

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

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

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

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

$$\Omega_{GW_*} = \frac{H_*^2}{\beta^2} \frac{\rho_{kin}^2}{\rho_{tot}^2} \qquad \rho_{kin}^2 \rightarrow \kappa^2 \alpha^2 v^4$$

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

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

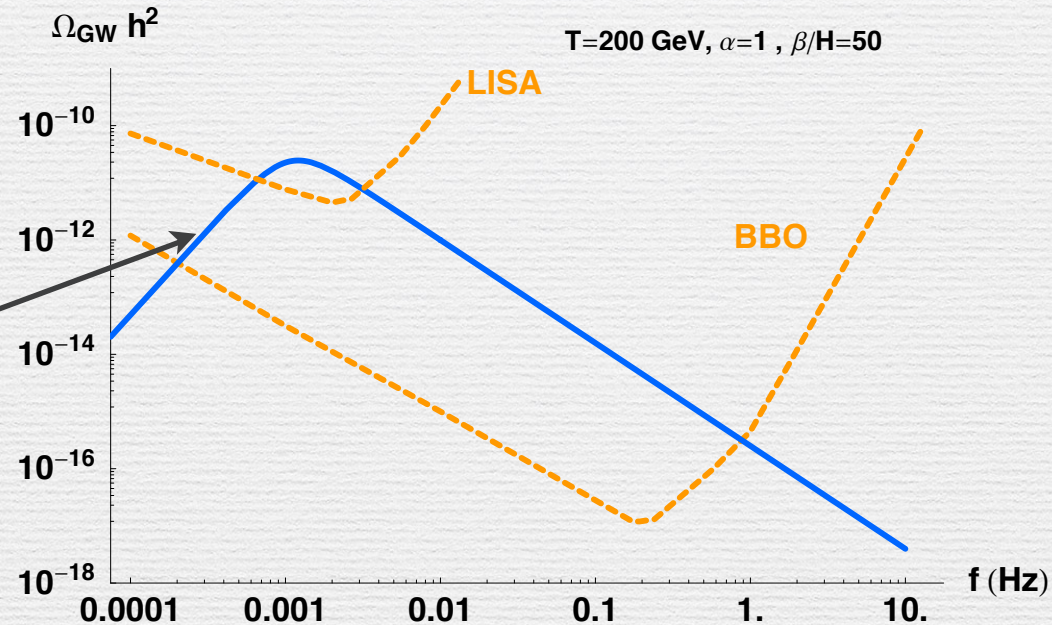
where we used:

$$\rho_{GW} = \rho_{GW*} \left(\frac{a_*}{a_0}\right)^4 \quad , \quad \rho_c = \rho_{c*} \frac{H_0^2}{H_*^2} \text{ and } H_0 = 2.1332 \times h \times 10^{-42} \text{GeV}$$

Expected shape of the GW spectrum

large scale part of the GW spectrum

~ f^3

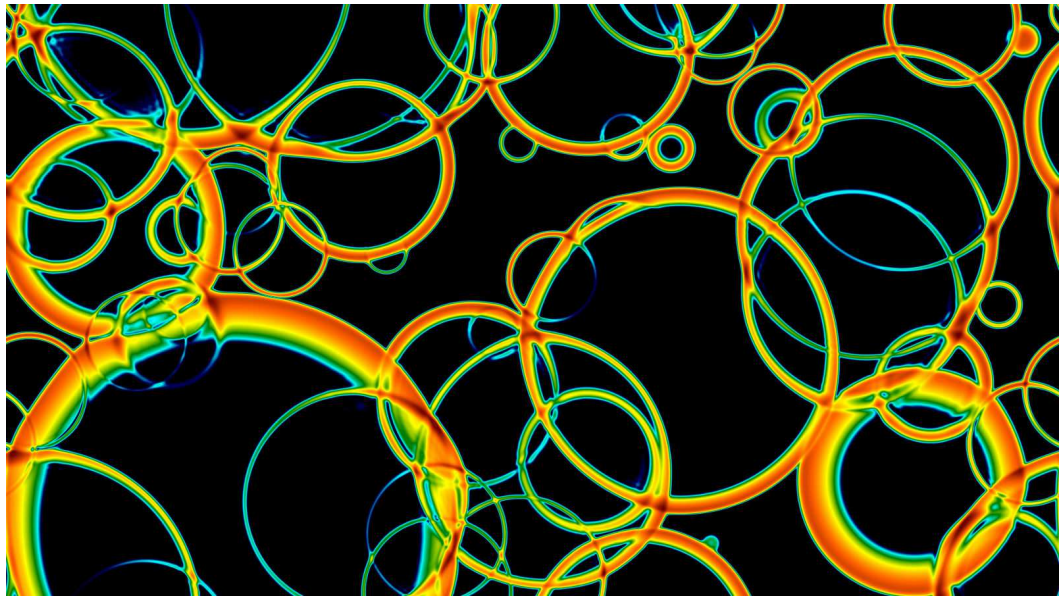


$$\frac{d\Omega_G}{d\ln k} = \frac{k^3|\dot{h}|^2}{G\rho_c}$$

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

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

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



[Credit:David Weir]

- Bubbles nucleate, most energy goes into plasma, then:
  1. $h^2\Omega_\phi$: Bubble walls and shocks collide – ‘envelope phase’
  2. $h^2\Omega_{\text{sw}}$: Sound waves set up after bubbles have collided, before expansion dilutes KE – ‘acoustic phase’
  3. $h^2\Omega_{\text{turb}}$: MHD turbulence – ‘turbulent phase’
- These sources then add together to give the observed GW power:

$$h^2\Omega_{\text{GW}} \approx h^2\Omega_\phi + h^2\Omega_{\text{sw}} + h^2\Omega_{\text{turb}}$$

- Each phase’s contribution depends on the nature of the phase transition.

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

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

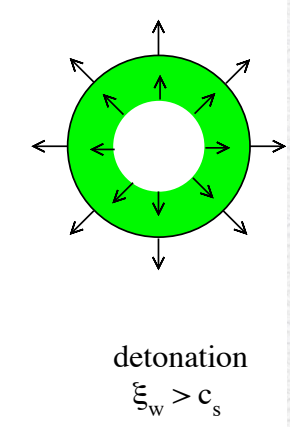
fluid velocity

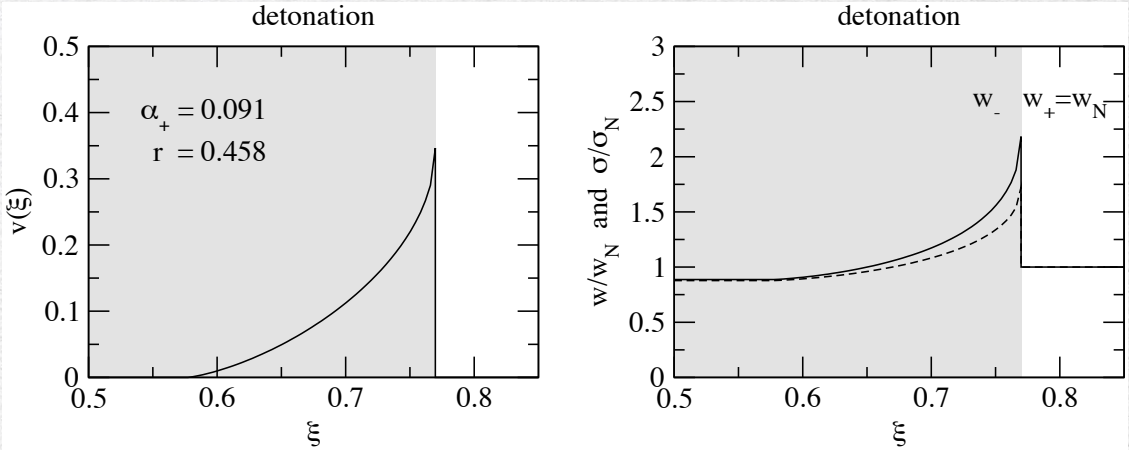
wall velocity

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

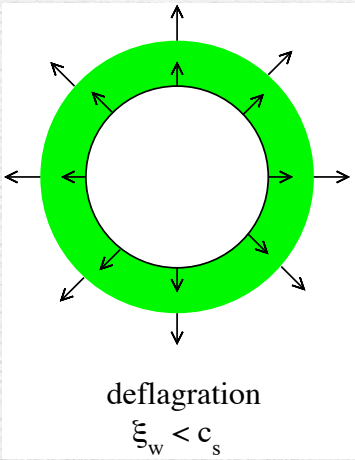
Depending on the boundary conditions at the bubble front, there are three possible solutions:

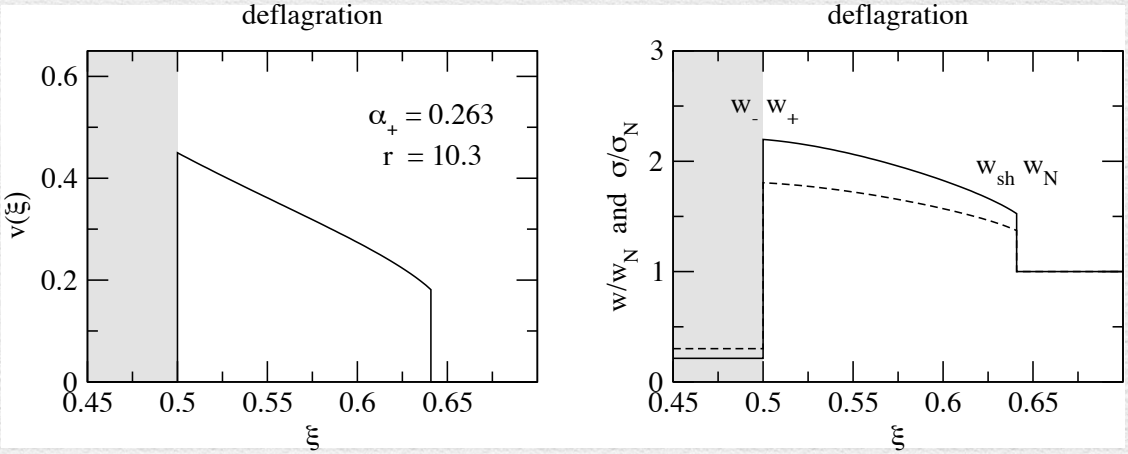
detonations -rarefaction wave



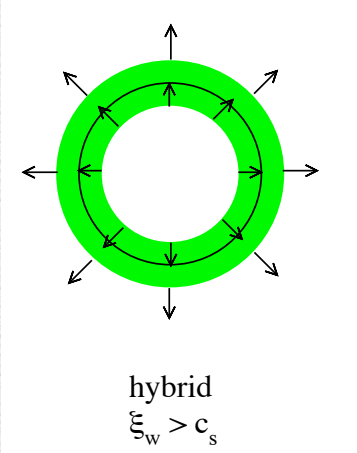


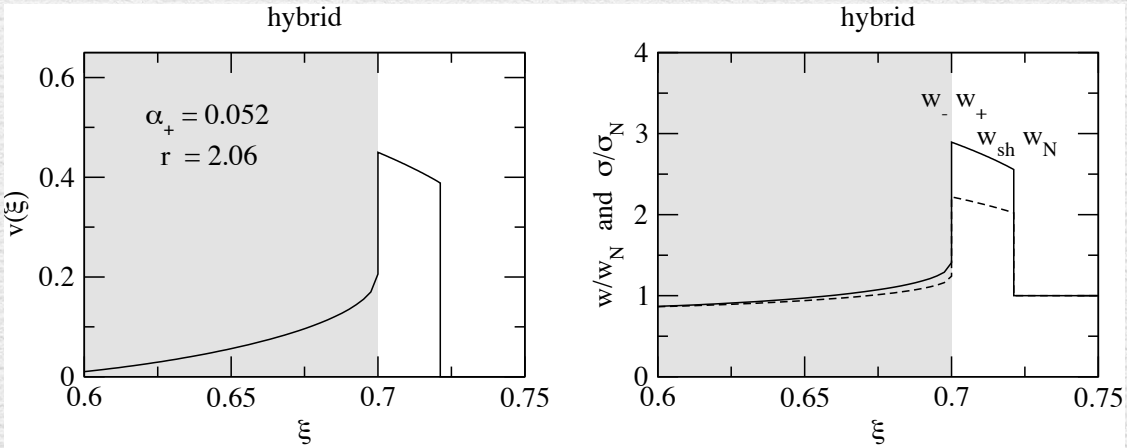
deflagrations -shock front





hybrids -both

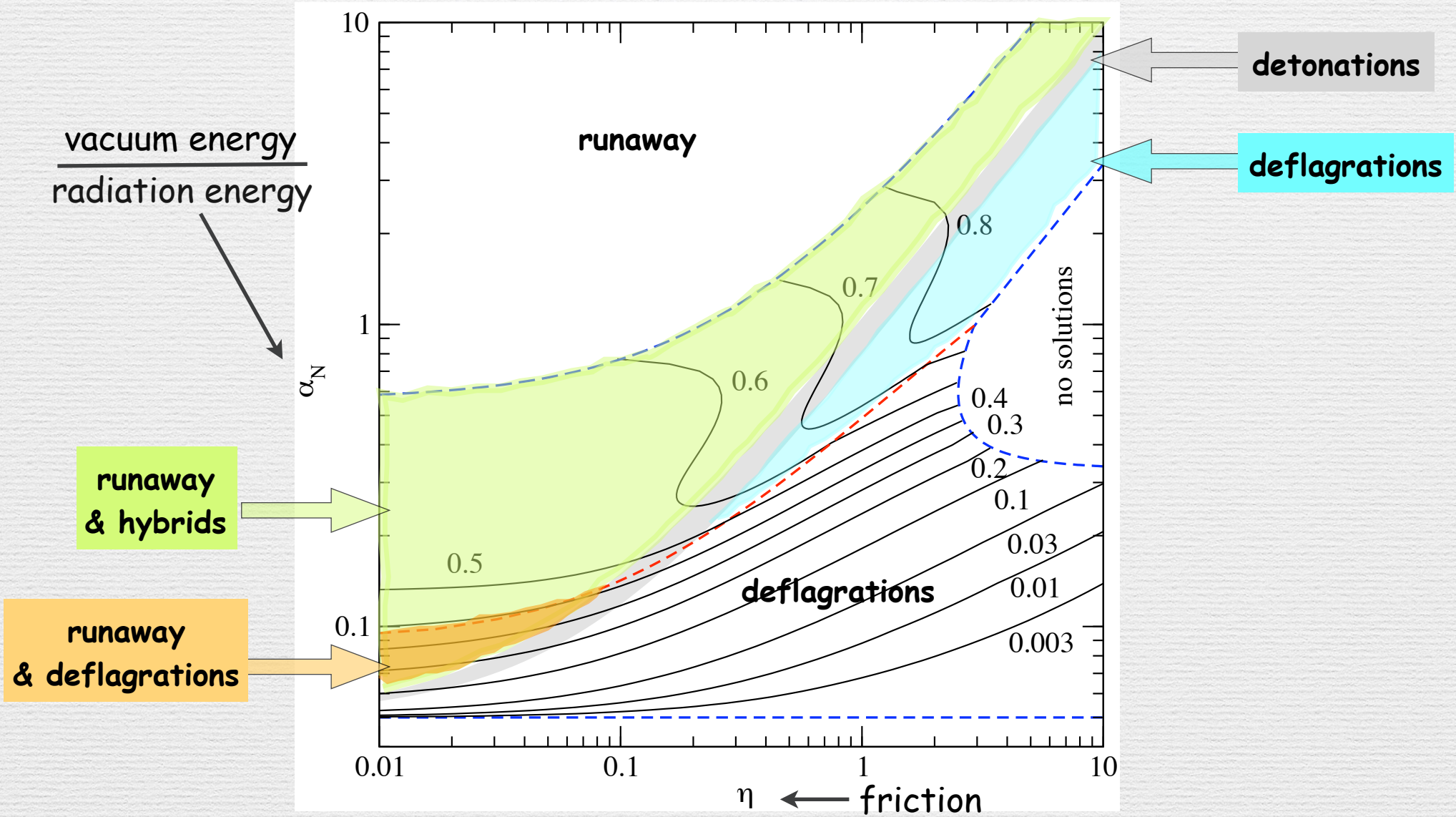




Espinosa, Konstandin, No, Servant'10

Model-independent κ contours

Espinosa, Konstandin, No, Servant'10

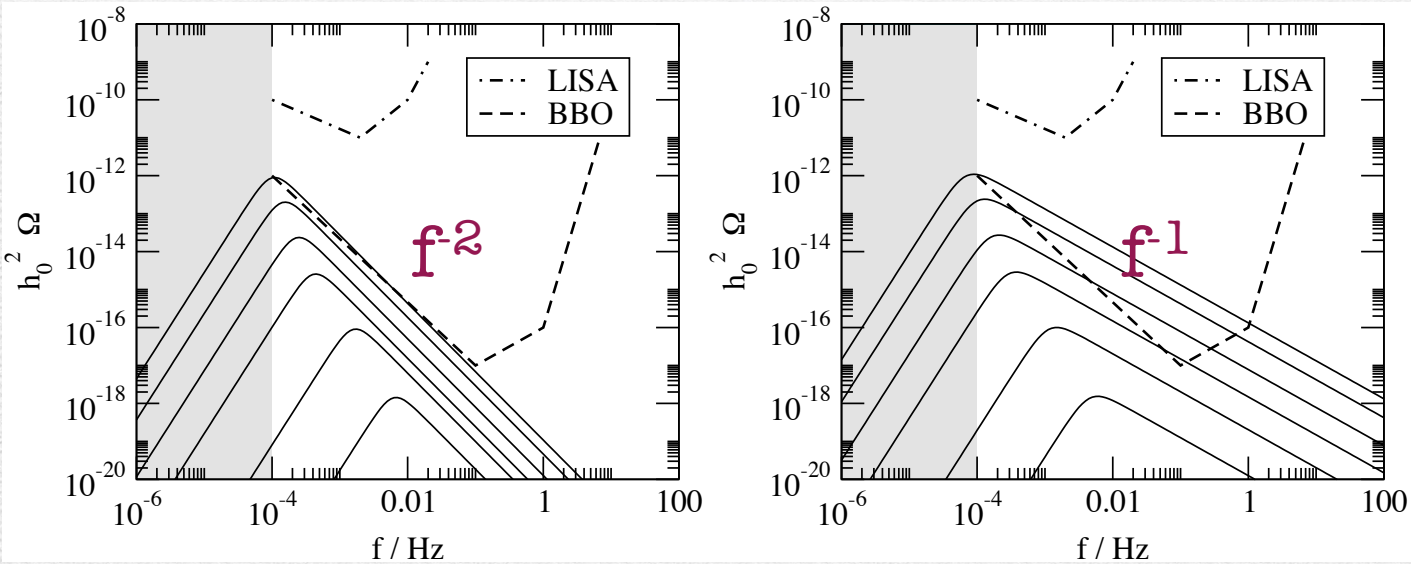


$$\eta_{\rm SM} \sim 10^{-3}$$

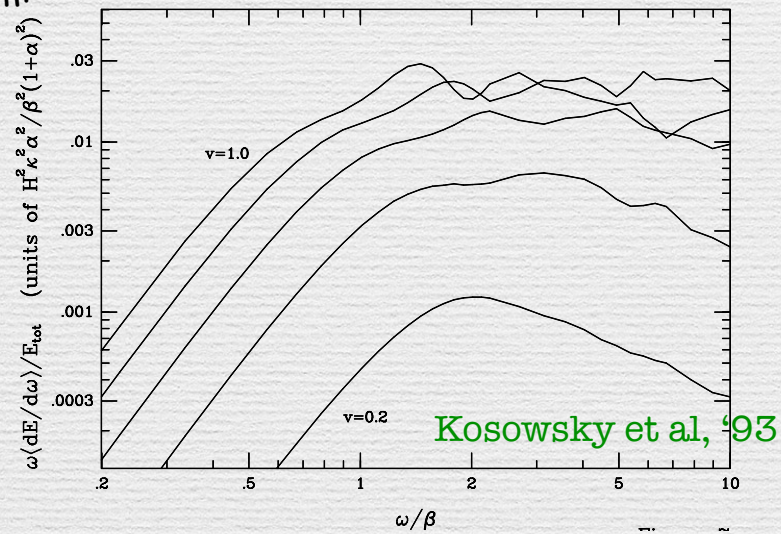
$$\eta_{\rm MSSM} \sim 10^{-2} \qquad v \sim 0.05 - 0.1$$

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

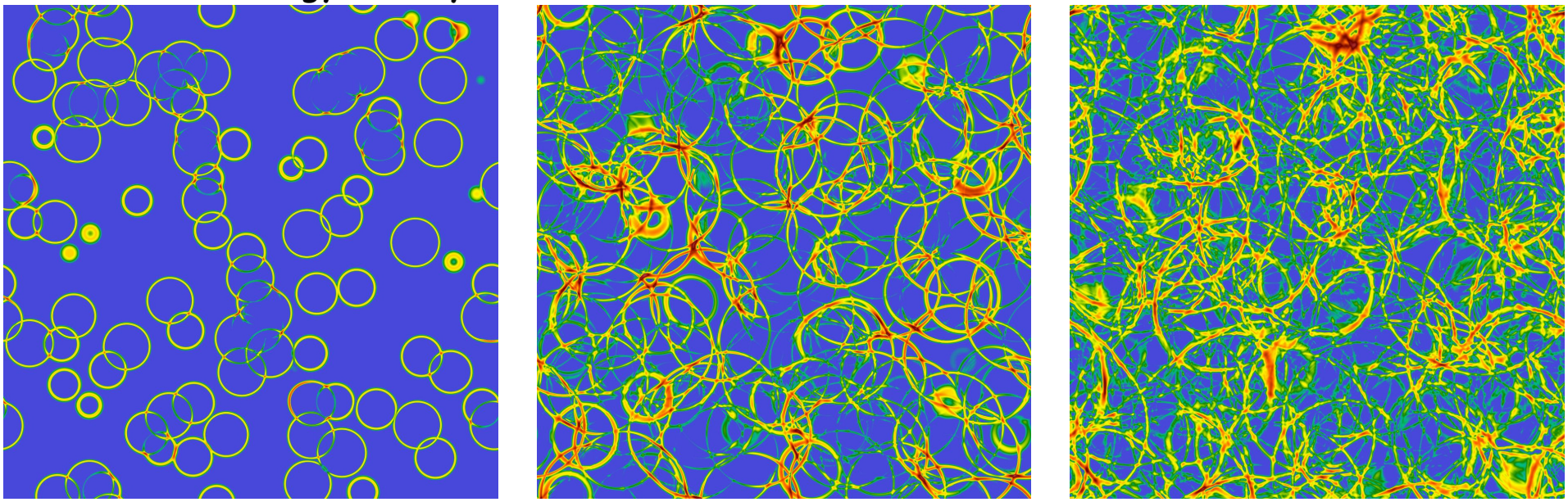
simulations with many bubbles and high accuracy too demanding in the 90ies

Recent developments from powerful simulations

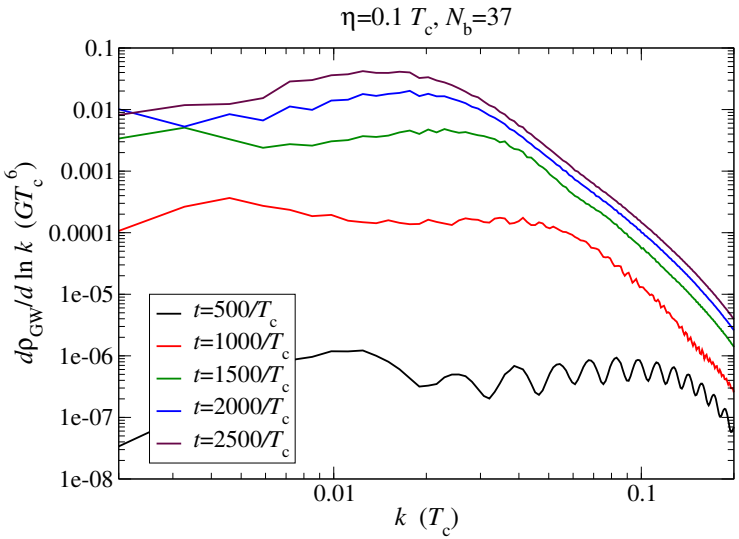
[Mark Hindmarsh, Stephan Huber, Kari Rummukainen, David Weir]

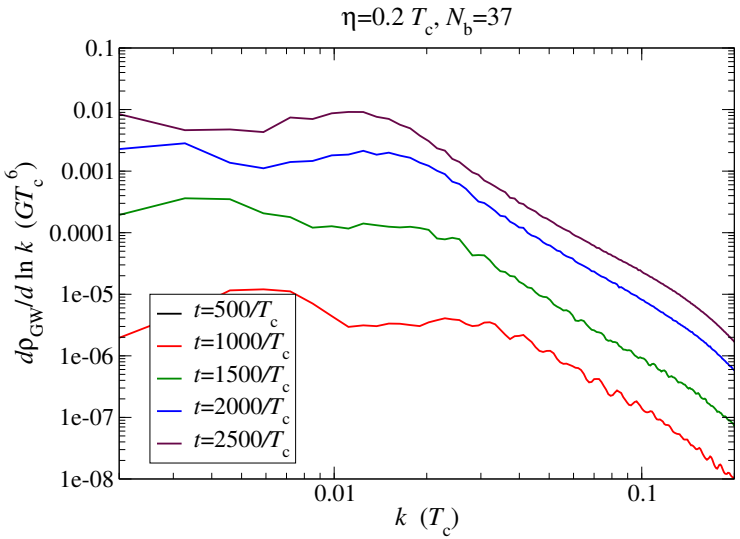
arXiv:1304.2433 arXiv:1511.04527 arXiv:1604.08429

Fluid kinetic energy density



detonation





deflagration

Examples of Spectra

[1512.06239]

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

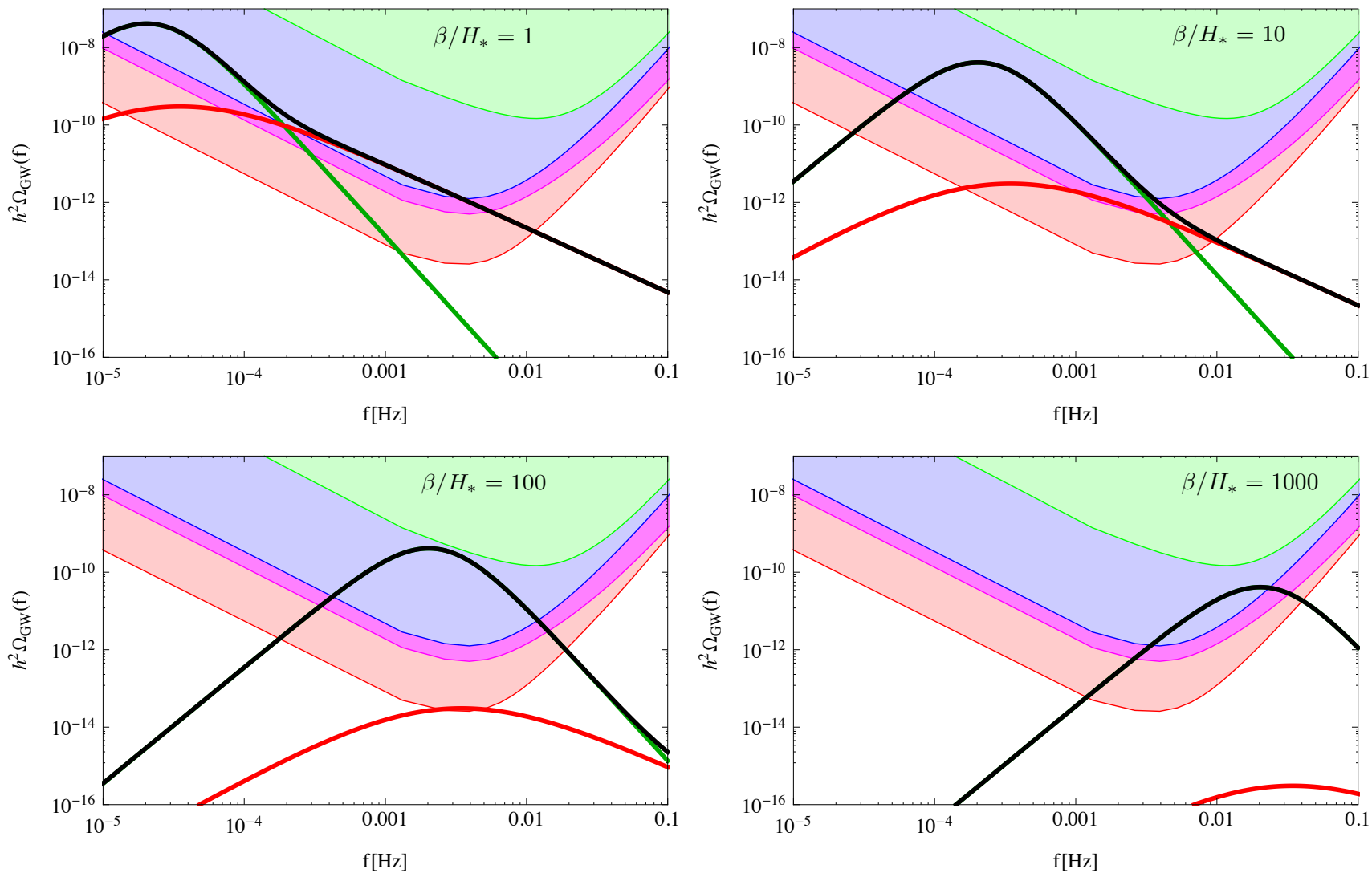
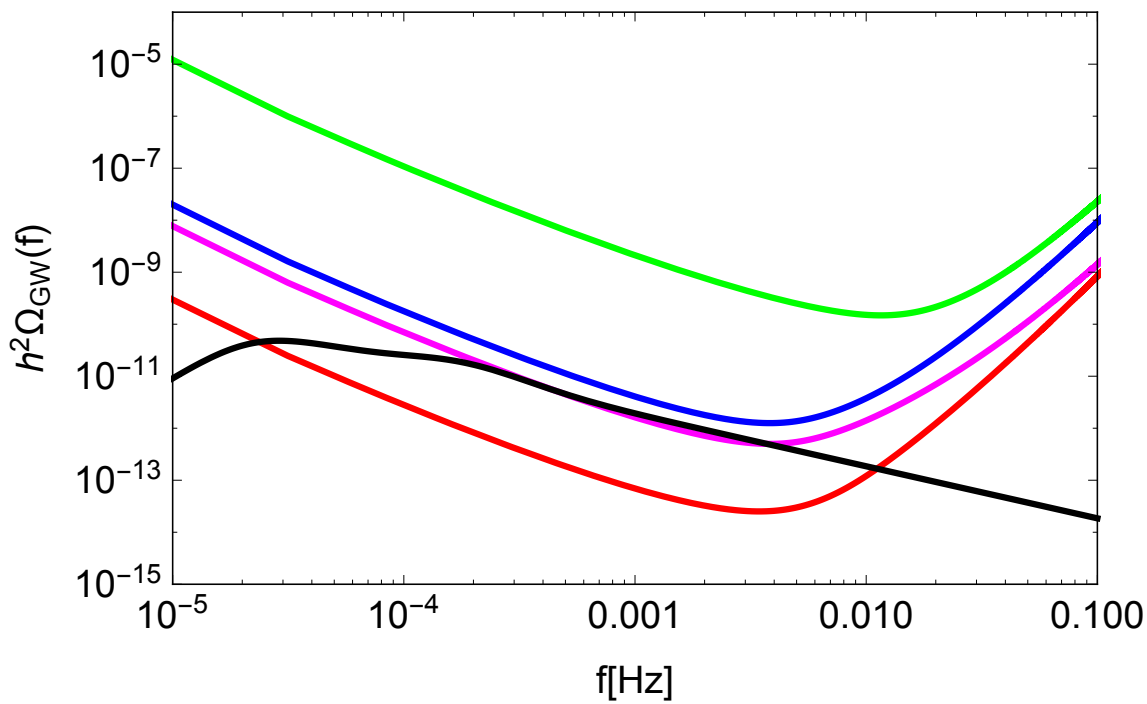
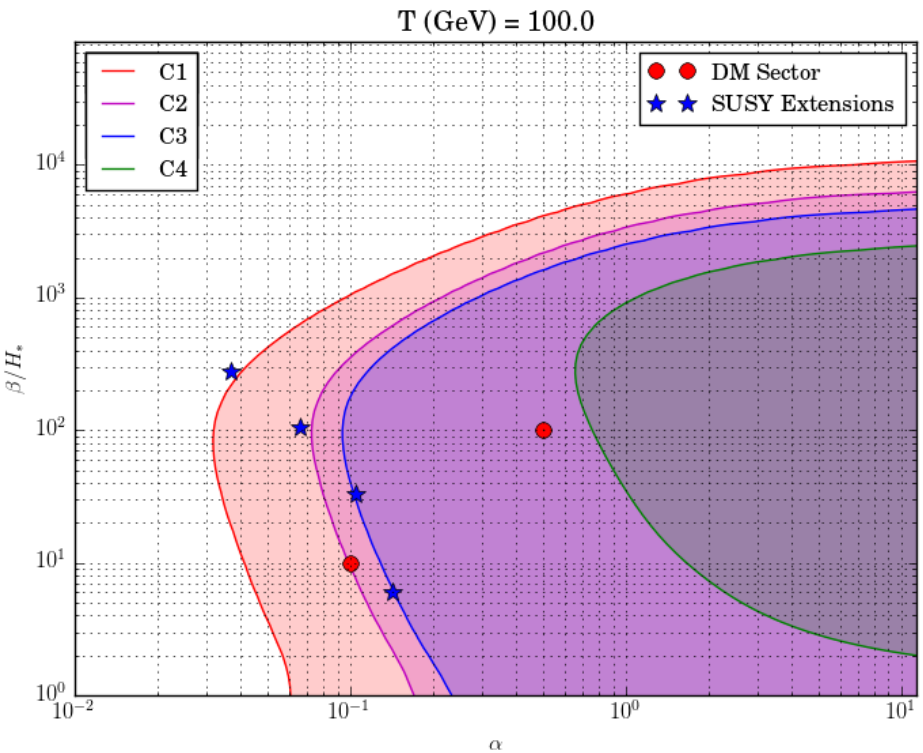


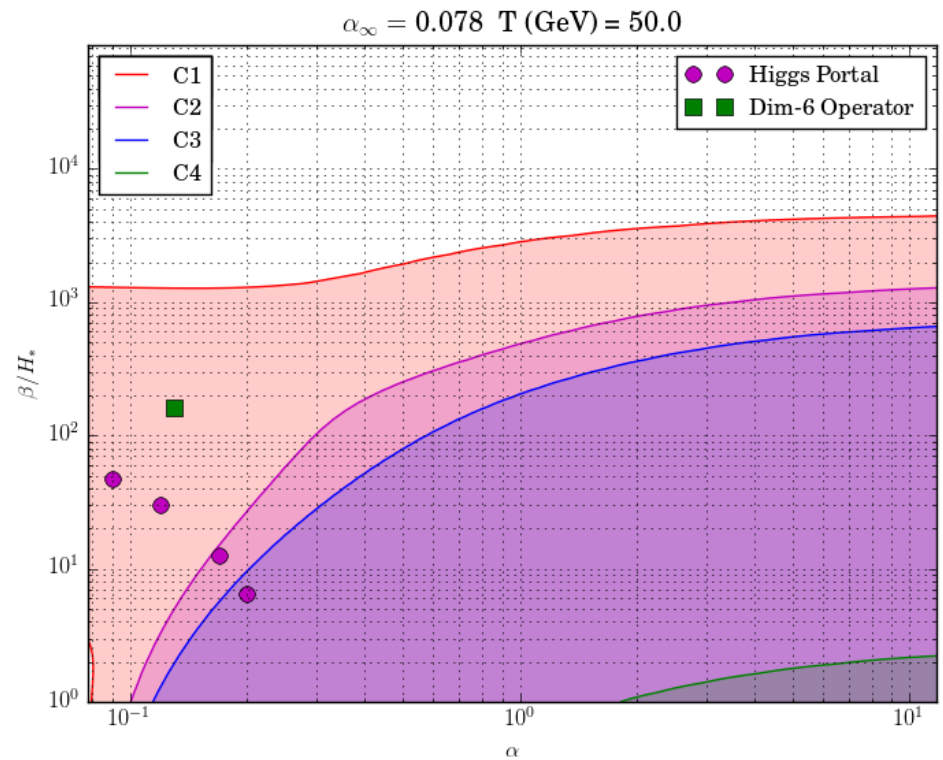
Table 1: Properties of the representative eLISA configurations chosen for this study. The corresponding sensitivity curves are shown in Figure 1. More details on these configurations and their sensitivity curves can be found in Ref. [3] and Ref. [31] respectively.

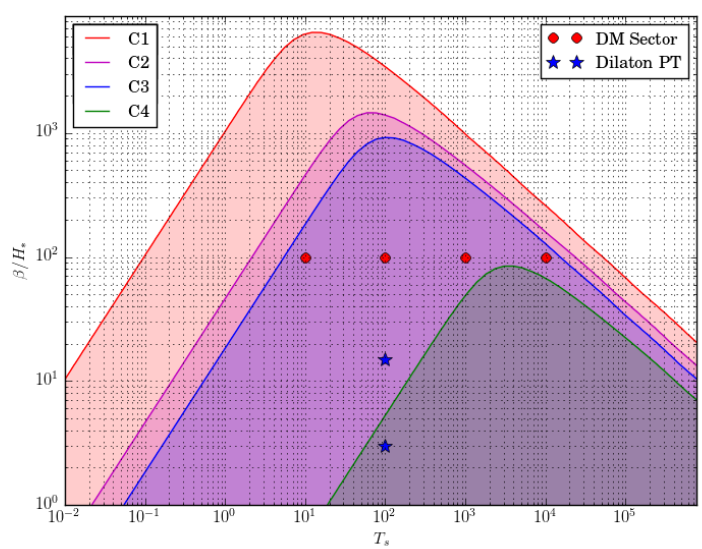
Name	C1	C2	C3	C4
Full name	N2A5M5L6	N2A1M5L6	N2A2M5L4	N1A1M2L4
# links	6	6	4	4
Arm length [km]	5M	1M	2M	1M
Duration [years]	5	5	5	2
Noise level	N2	N2	N2	N1



Detectable regions at eLISA for different types of PT





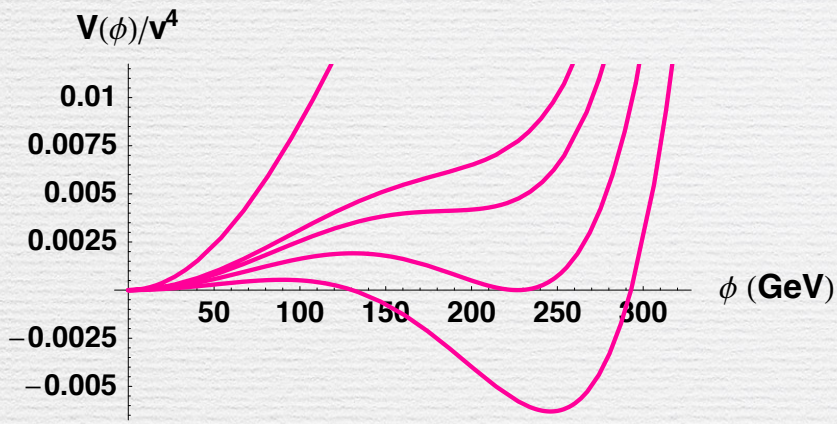


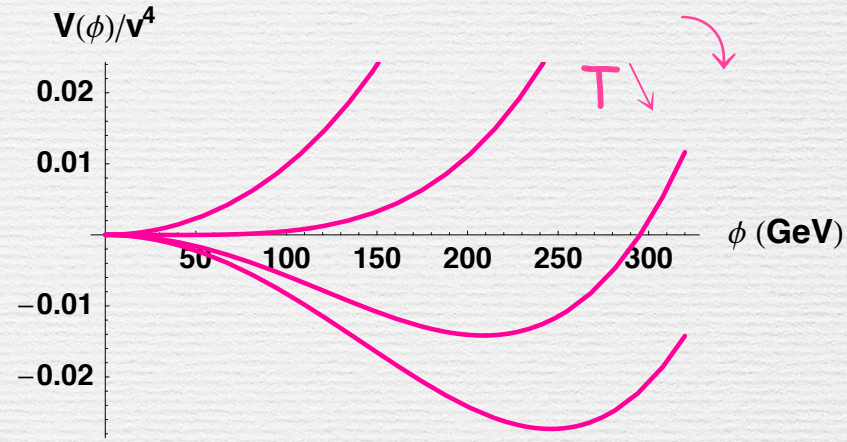
As $T_n \to 0$, $\alpha \to \infty$

Predictions depend on the particle Physics Model

What is the nature of the Electroweak Phase Transition?

first-order or cross over





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

Matter Anti-matter asymmetry of the universe

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

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

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

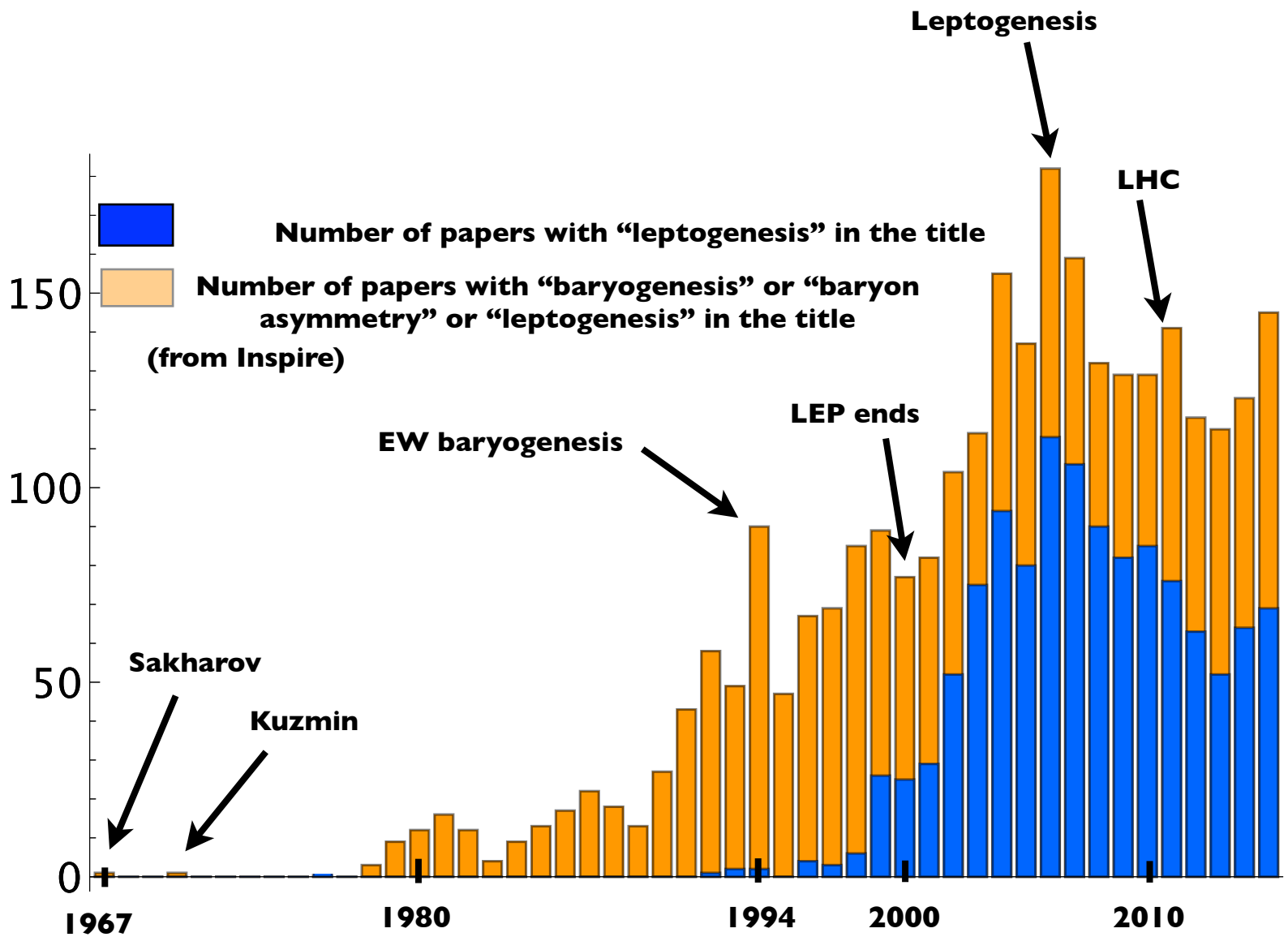
Shaposhnikov,

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

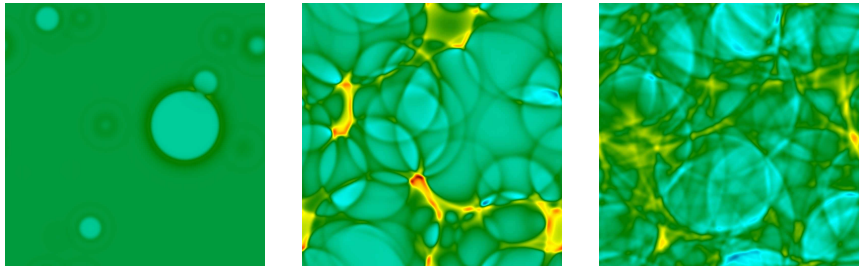
History of baryogenesis papers



Two leading candidates for baryogenesis:

--> Leptogenesis by out of equilibrium decays of RH neutrinos before the EW phase transition

--> Baryogenesis at a first-order EW phase transition



Models of Baryogenesis

T

GUT baryogenesis

B washout unless B-L ≠ 0

requires SO(10)
requires too high reheat temperature to produce enough GUT particles

→ leptogenesis

Thermal leptogenesis

hierarchy pb -> embed in susy-> gravitino pb (can be solved if M_gravitino>100 TeV and DM is neutralino or gravitino is stable)

Affleck-Dine (moduli decay)

Non-thermal leptogenesis (via oscillations)

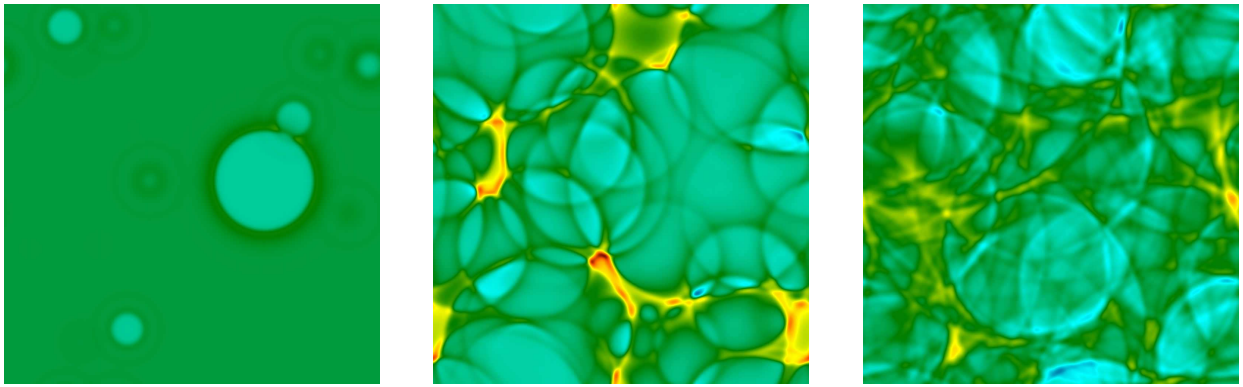
Asymmetric dark matter-cogenesis

EW breaking, sphalerons freese-out

EW (non-local) baryogenesis

EW cold (local) baryogenesis

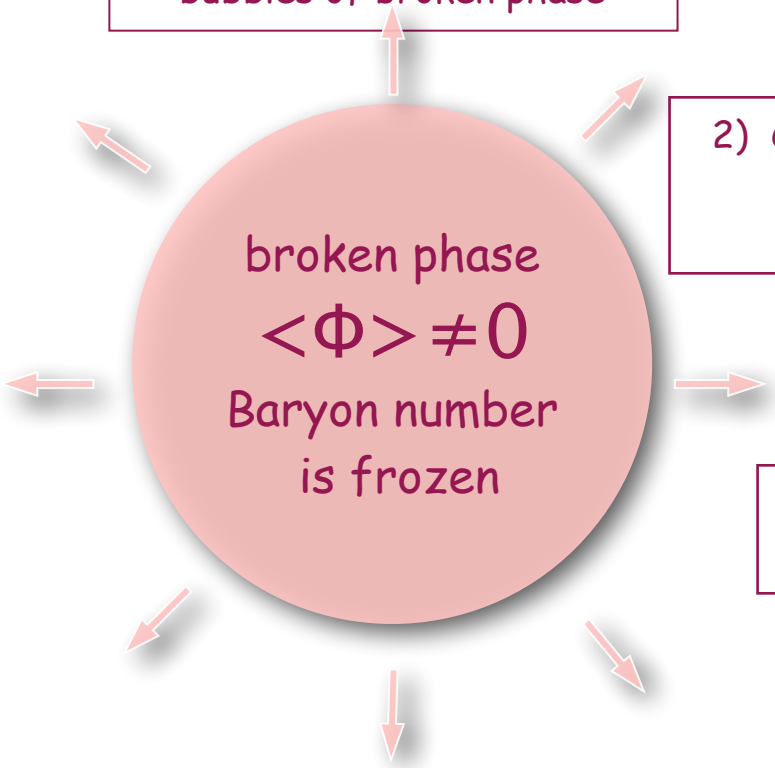
Baryogenesis at a first-order EW phase transition



Baryon asymmetry and the EW scale

Cohen, Kaplan, Nelson'91

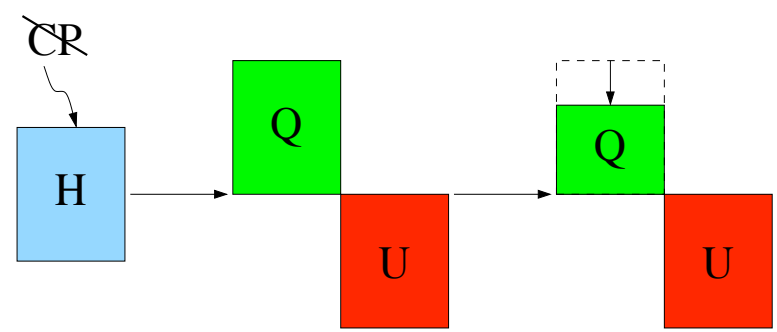
1) nucleation and expansion of bubbles of broken phase



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:

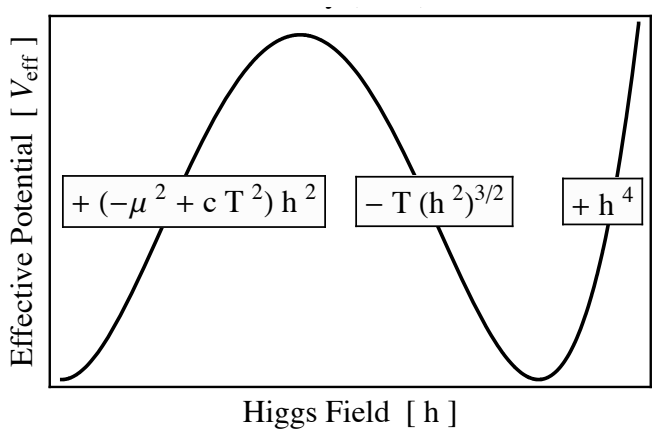
$$\eta_B = \frac{n_B}{s} = \frac{405\Gamma_{ws}}{4\pi^2 v_w g_* T} \int_0^\infty dz \ \mu_{B_L}(z) e^{-\nu z}, \qquad \nu = 45\Gamma_{ws}/(4v_w)$$

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

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



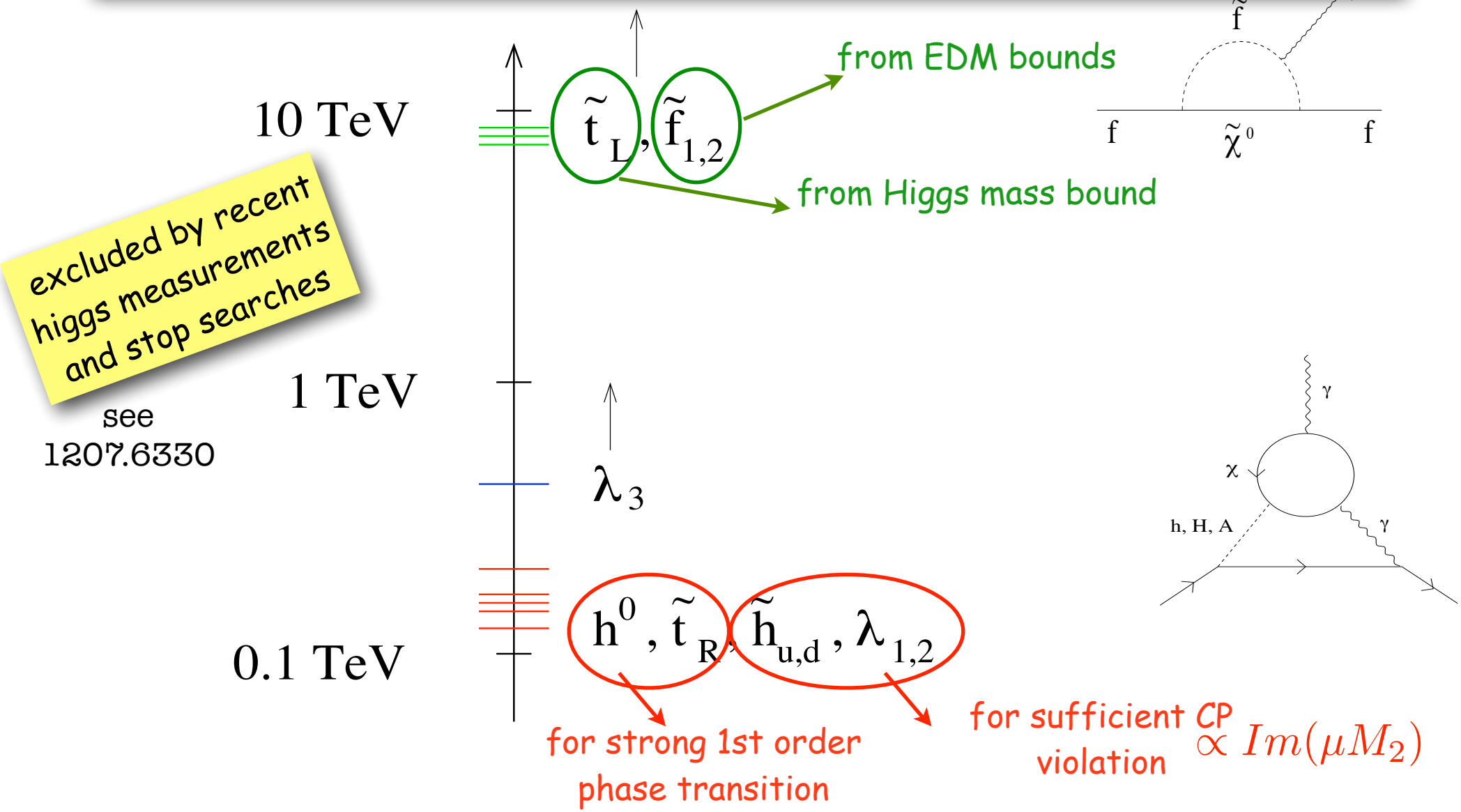
Very constrained by LHC !

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



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

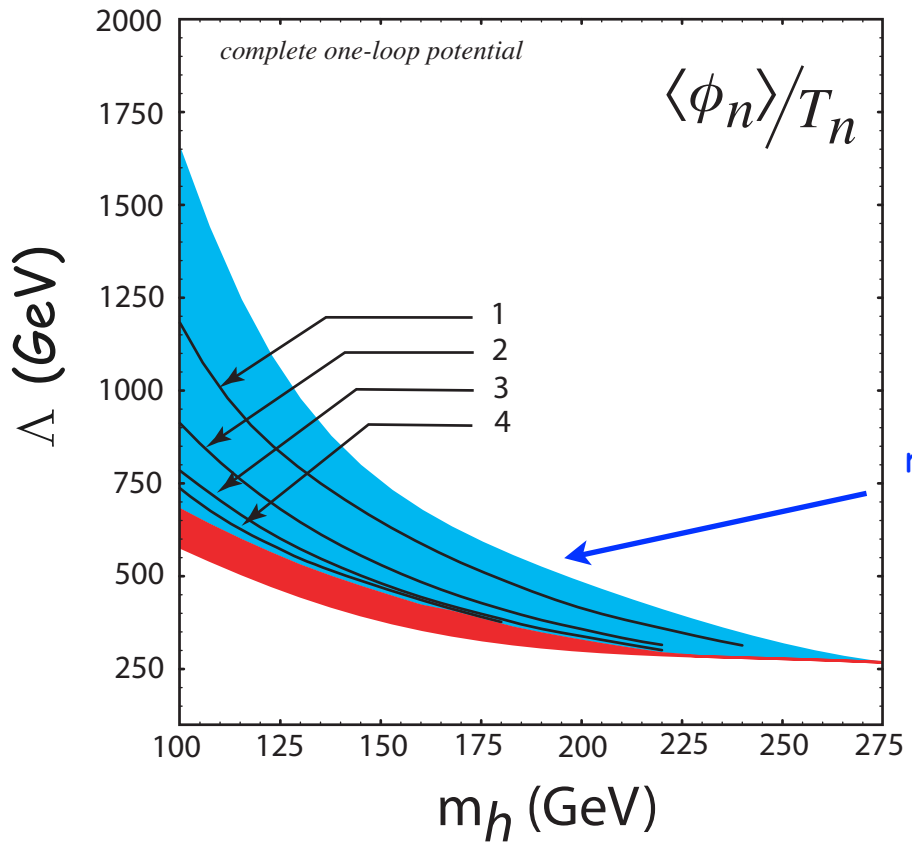
Easily seen in effective field theory approach:

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

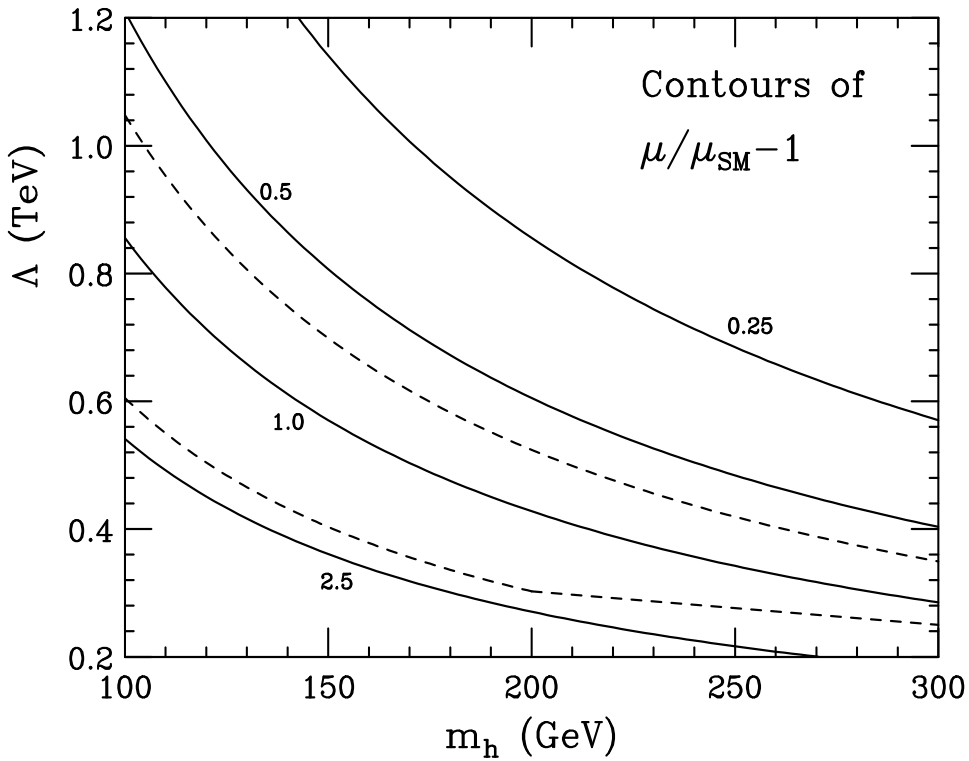
but Typically large deviations to the Higgs self-couplings

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

where

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

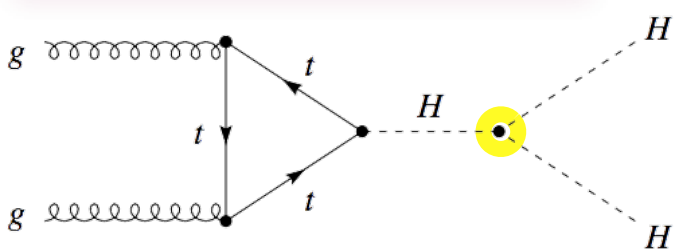
$$\eta = 3\frac{m_H^2}{v_0^2} + 36\,\frac{v_0^2}{\Lambda^2}$$



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



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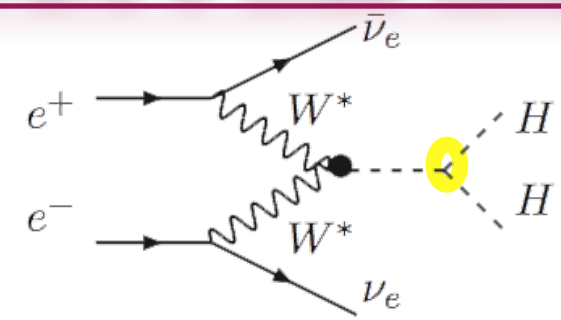
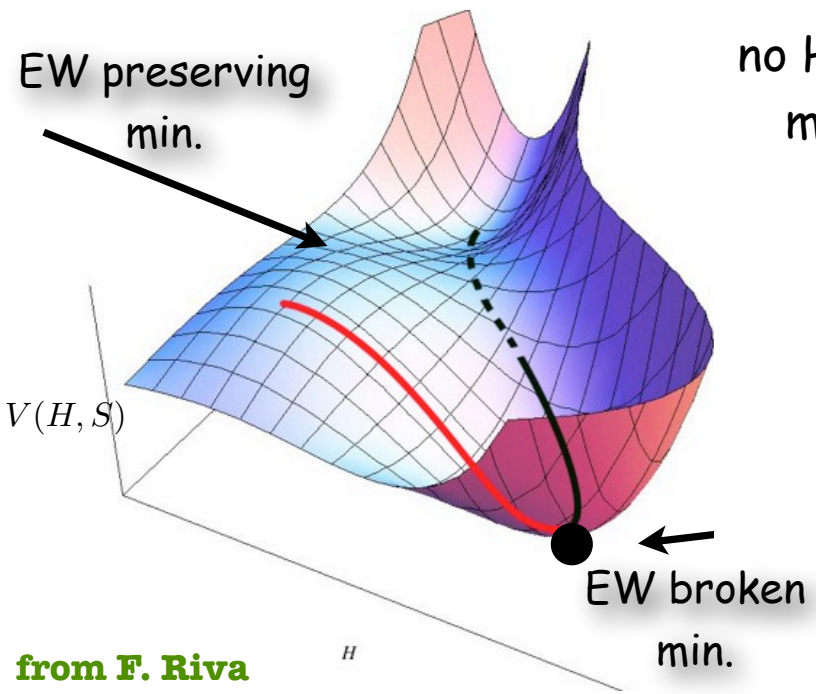


The easiest way: Two-stage EW phase transition

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

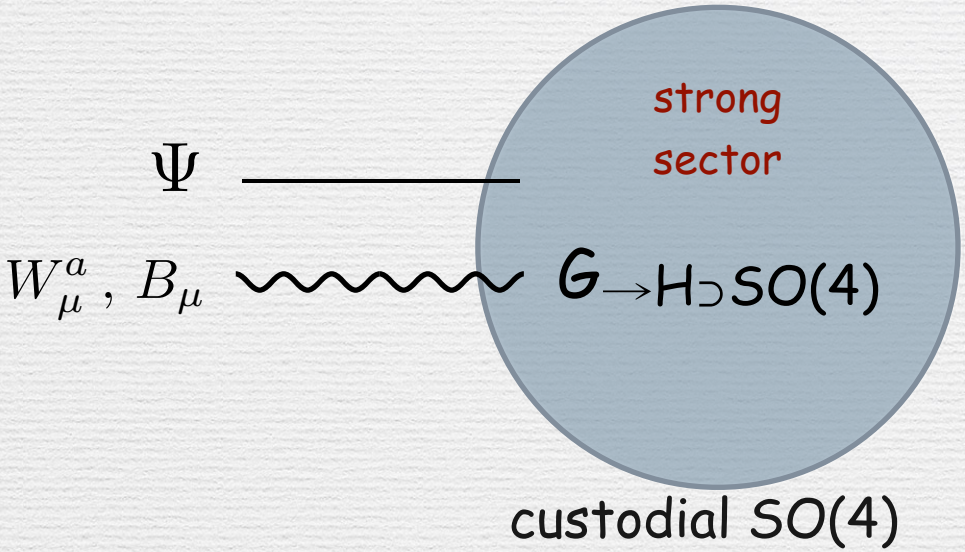
S has no VEV today:
no Higgs-S mixing-> no EW precision tests , tiny modifications of higgs couplings at colliders

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



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

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	$\mathbf{4}_{+\mathbf{2}} + \bar{\mathbf{4}}_{-\mathbf{2}} = 2\times(\mathbf{2},\mathbf{2})$
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	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2\times(\mathbf{2},\mathbf{2})$
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 $|\varepsilon| \ll 1$

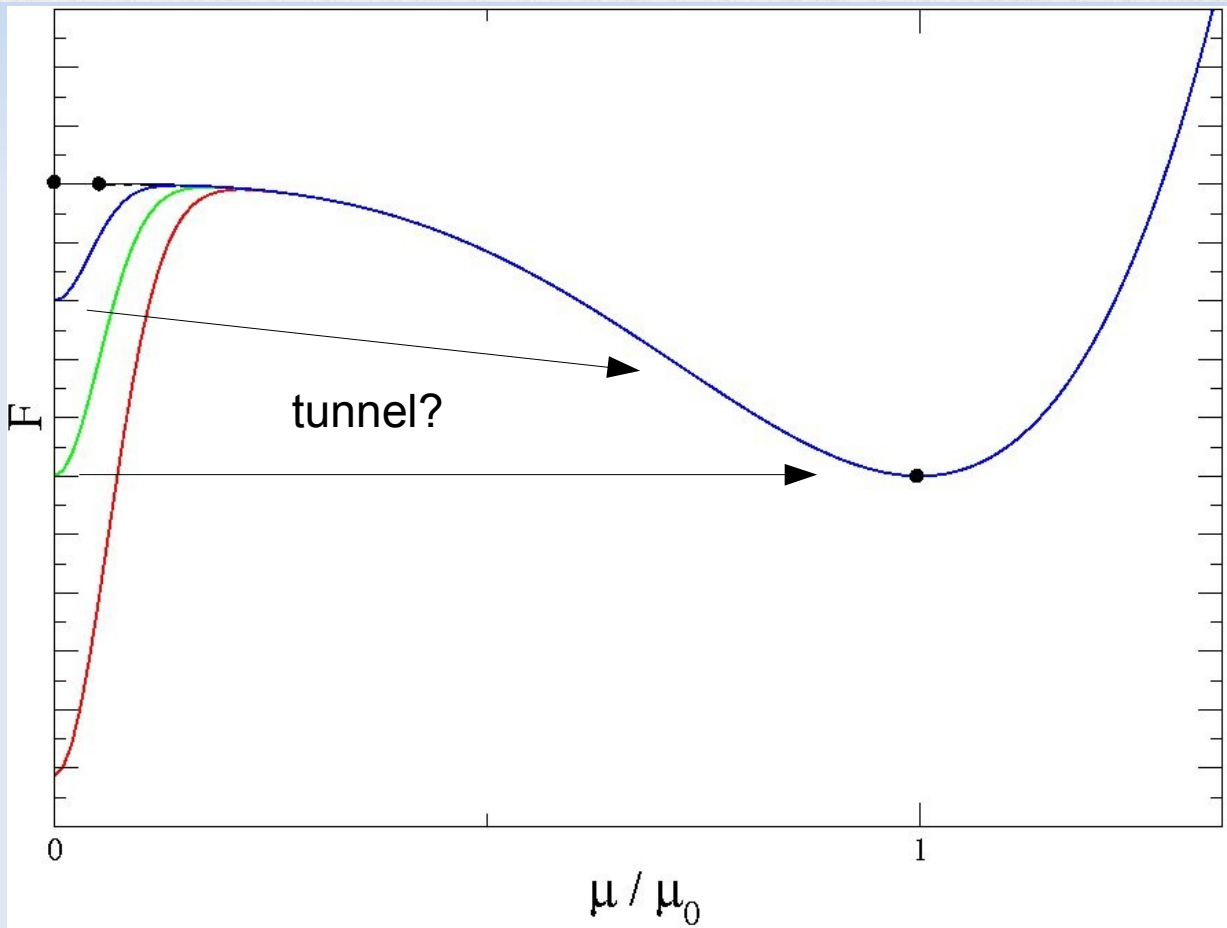
similar to Coleman-Weinberg mechanism where a slow Renormalization Group evolution of potential parameters can generate widely separated scales

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

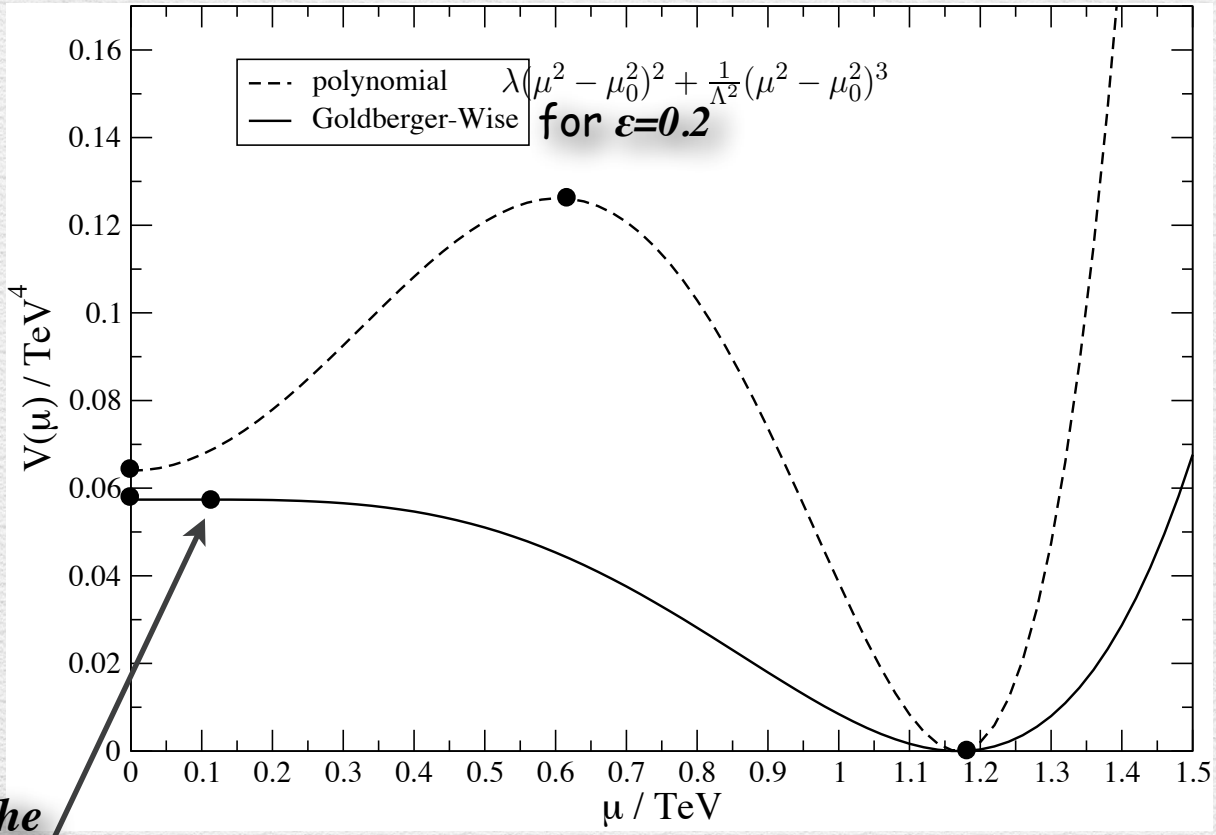
Hassanain, March-Russell, Schwellinger'07
Nardini,Quiros,Wulzer'07
Konstandin,Nardini,Quiros'10
Konstandin,Servant'1

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 and the QCD axion

A coupling of the type ~ $\frac{a(t)}{f_a} F\tilde{F}$ ← EW field strength

will induce from the motion of the axion field a chemical potential for baryon number given by $\frac{\partial_t a(t)}{f_a}$

This is non-zero only once the axion starts to oscillate after it gets a potential around the QCD phase transition.

Time variation of axion field can be CP violating source for baryogenesis if EW phase transition is supercooled

Servant, 1407.0030

→ **Cold Baryogenesis**

requires a coupling between the Higgs and an additional light scalar: testable @ LHC & compatible with usual QCD axion Dark matter predictions

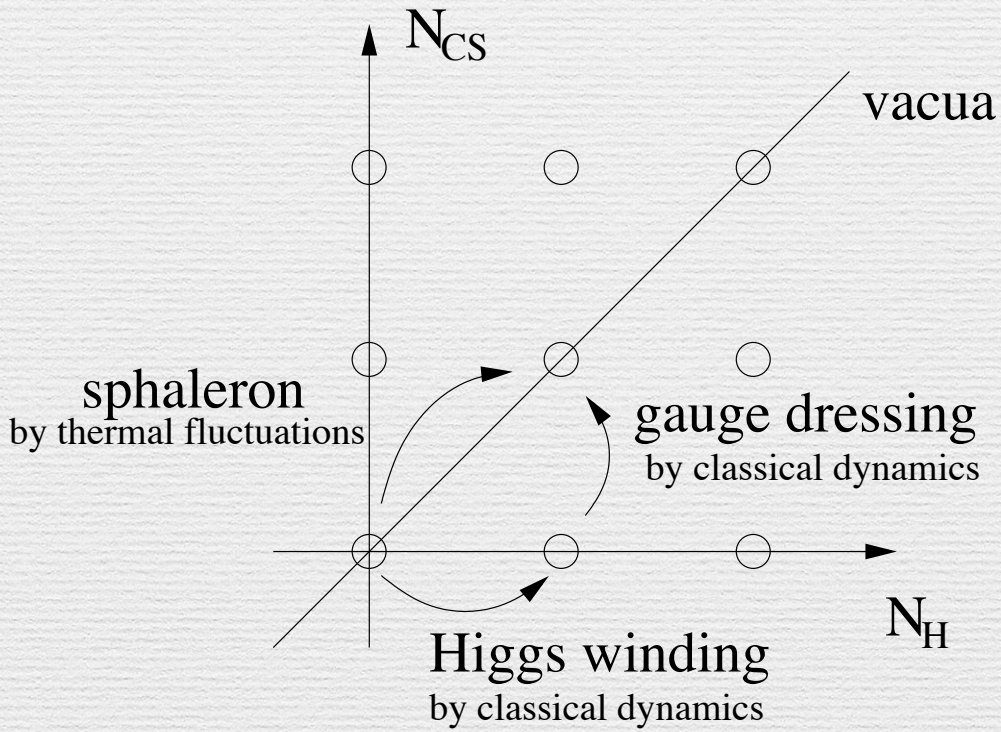
Cold Baryogenesis

main idea:

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

Turok, Zadrozny '90
Lue, Rajagopal, Trodden, '96
Garcia-Bellido, Grigoriev, Kusenko, Shaposhnikov, '99
Tranberg et al, '06

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



Requirements for cold baryogenesis

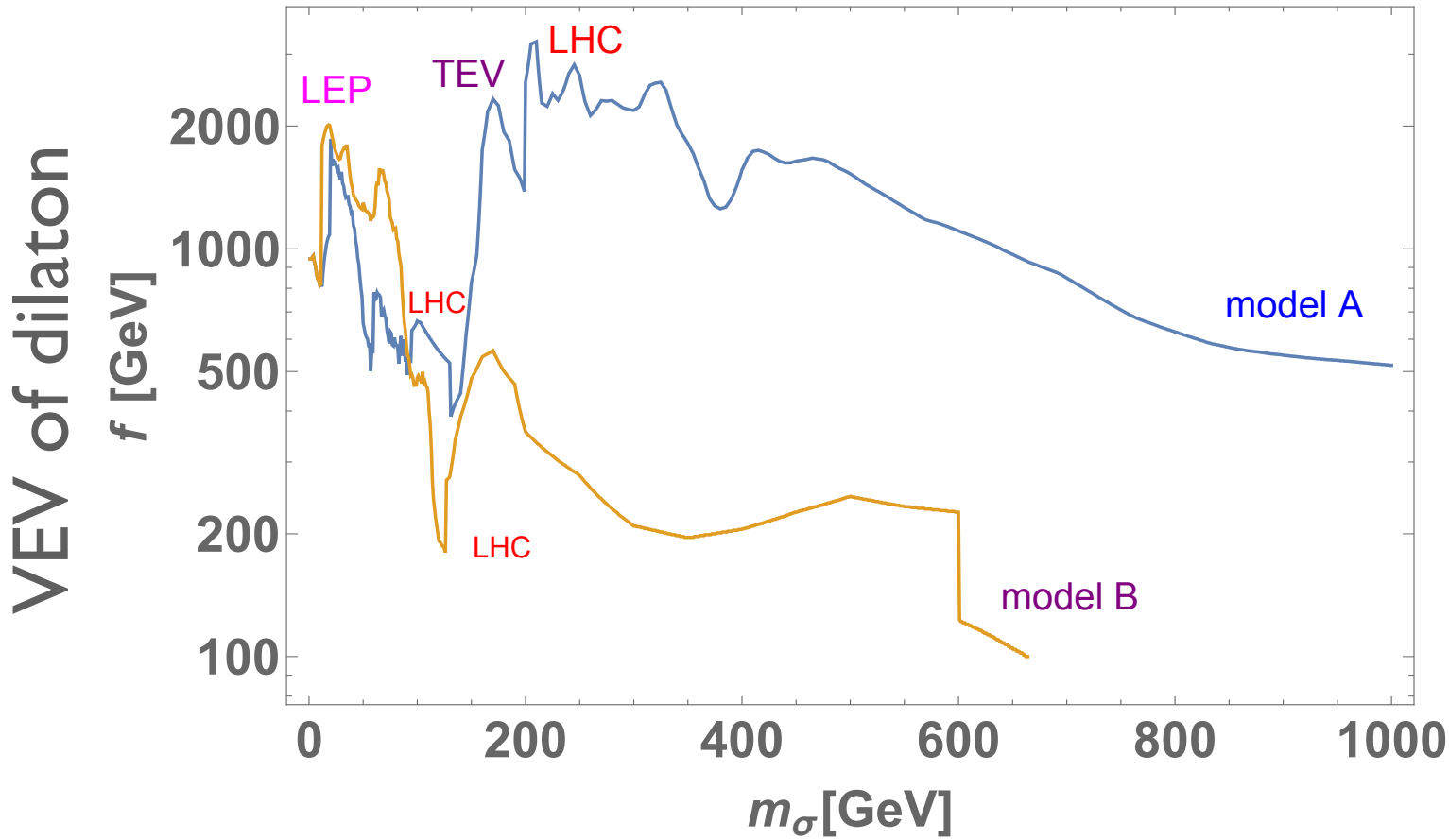
1) large Higgs quenching to produce Higgs winding number in the first place

2) unsuppressed CP violation at the time of quenching so that a net baryon number can be produced

3) a reheat temperature below the sphaleron freese-out temperature T ~ 130 GeV to avoid washout of B by sphalerons

can occur during supercooled EW phase transition, 1407.0030

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

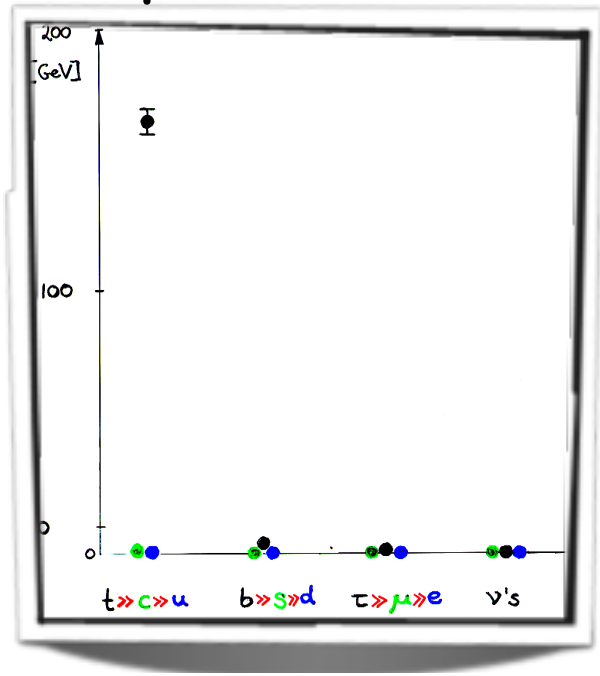
+1608.03254

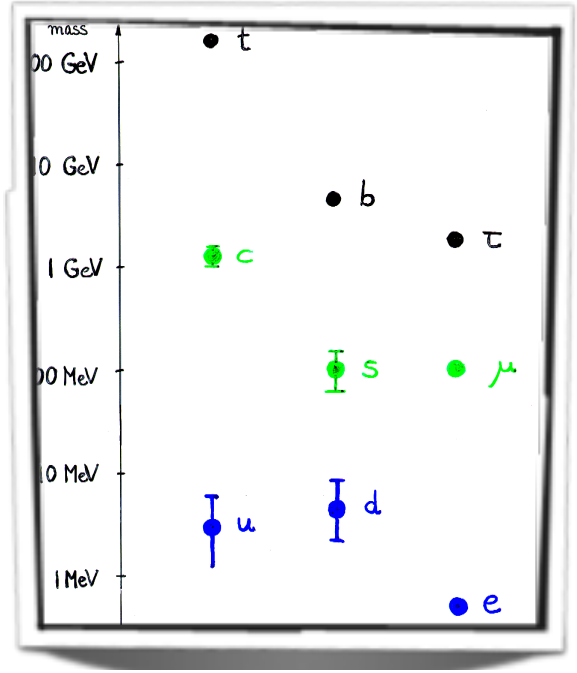
The new result:

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.

Origin of the fermion mass hierarchy?

Fermion Yukawas $$y_{ij}\overline{f}^{i}_{L}\Phi^{(c)}f^{j}_{R}$$

In Froggatt Nielsen constructions, the Yukawa couplings are controlled by the breaking parameter of a flavour symmetry. A scalar field "flavon" χ carrying a negative unit of the abelian charge develops a vacuum expectation value (VEV) and:

$$y_{ij} \sim (\langle\chi\rangle/M)^{-q_i+q_j+q_H}$$

flavor charges of the fermions

λ= $\langle\chi\rangle/M \sim 0.22$ ⟹

$$\begin{array}{lll} Y_t \sim 1, & Y_c \sim \lambda^3, & Y_u \sim \lambda^7, \\ Y_b \sim \lambda^2, & Y_s \sim \lambda^4, & Y_d \sim \lambda^6, \\ s_{12} \sim \lambda, & s_{23} \sim \lambda^2, & s_{13} \sim \lambda^3. \end{array}$$

The scale M is usually assumed close to the GUT scale

Emerging Flavour during Electroweak symmetry breaking

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

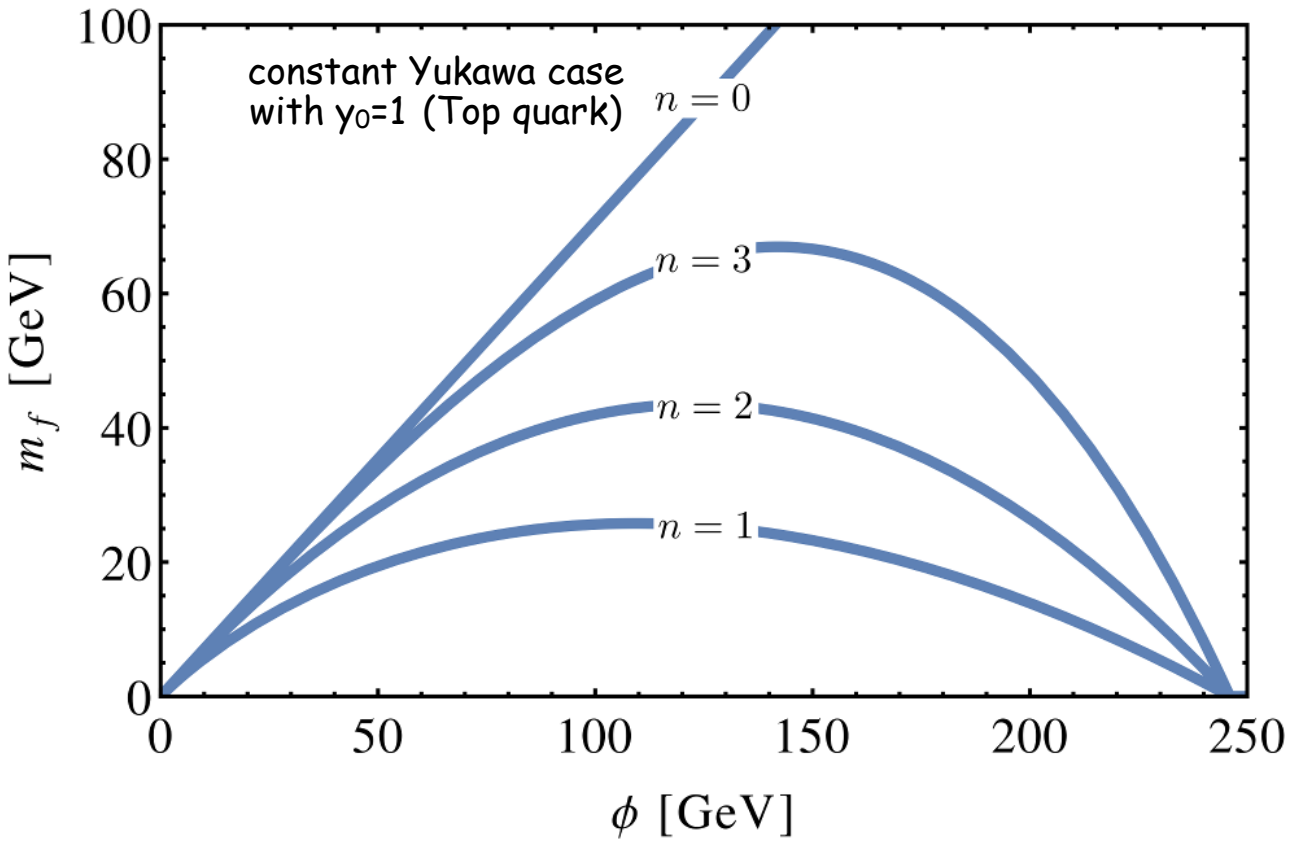
For Example, if the "Flavon" field dynamics is linked to the Higgs field

FLAVOUR COSMOLOGY

Mass of fermionic species for varying Yukawas

$$m_f = \frac{y(\phi)\phi}{\sqrt{2}}$$

$$y(\phi) = \begin{cases} y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for} \quad \phi \leq v, \\ y_0 & \text{for} \quad \phi \geq v. \end{cases}$$



y_0: Yukawa value today

y_1: Yukawa value before the EW phase transition

High Temperature Effective Higgs Potential

At one-loop:

$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T).$$

tree level piece	1-loop T=0 piece	1-loop T≠0 piece	Daisy resummation piece

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:

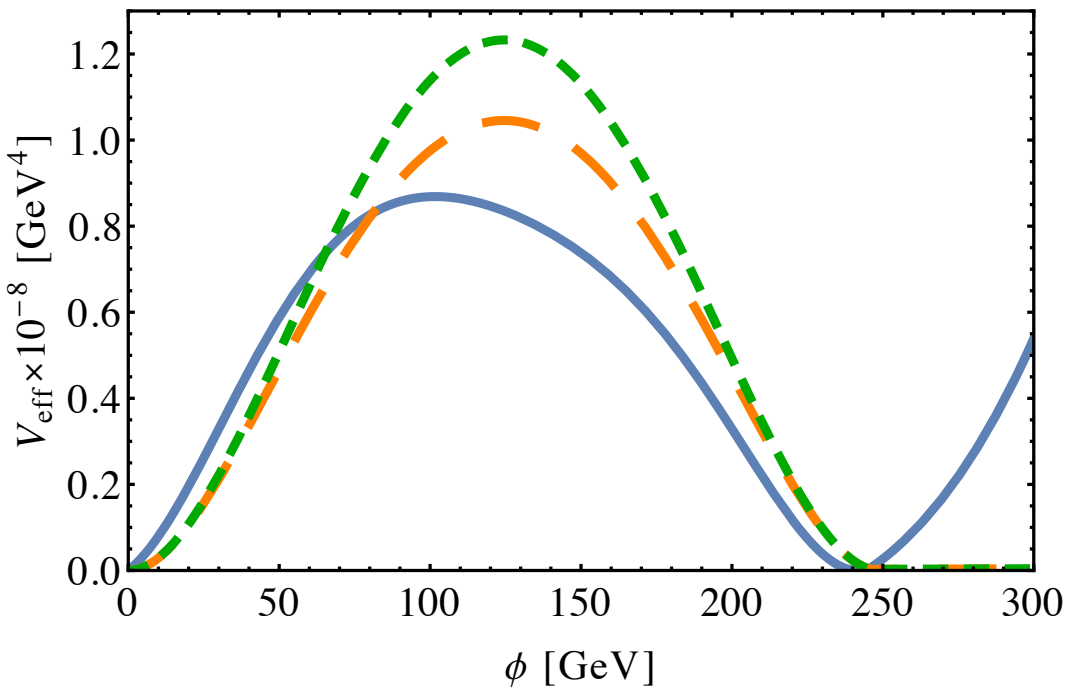
$$J_f(x^2) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24}x^2 - \frac{x^4}{32}\mathrm{Log}\left[\frac{x^2}{13.9}\right]$$

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

Fermionic fields create a barrier!

This leads to a cubic term in ϕ, e.g. for $y(\phi) = y_1(1 - \phi/v)$:

$$\delta V \approx \frac{g y_1^2 \phi^2 T^2}{96} \left(1 - 2\frac{\phi}{v} + \frac{\phi^2}{v^2}\right)$$



___ full potential

_ _ _ thermal contribution only

- - -thermal contribution only with high-T expansion

3) Effects from the Daisy correction:

come from resumming Matsubara zero-modes for the bosonic degrees of freedom

$$V_{\rm Daisy}(\phi,T) = \sum_i \frac{\bar{g}_i T}{12\pi}\left\{ m_i^3(\phi) - \left[m_i^2(\phi) + \Pi_i(T)\right]^{3/2}\right\}$$

sum is over bosons

thermal mass

Consider the contribution from the Higgs:

$$V^{\phi}_{\rm Daisy}(\phi,T) = \frac{T}{12\pi}\left\{ m_\phi^3(\phi) - \left[m_\phi^2(\phi) + \Pi_\phi(\phi,T)\right]^{3/2}\right\}$$

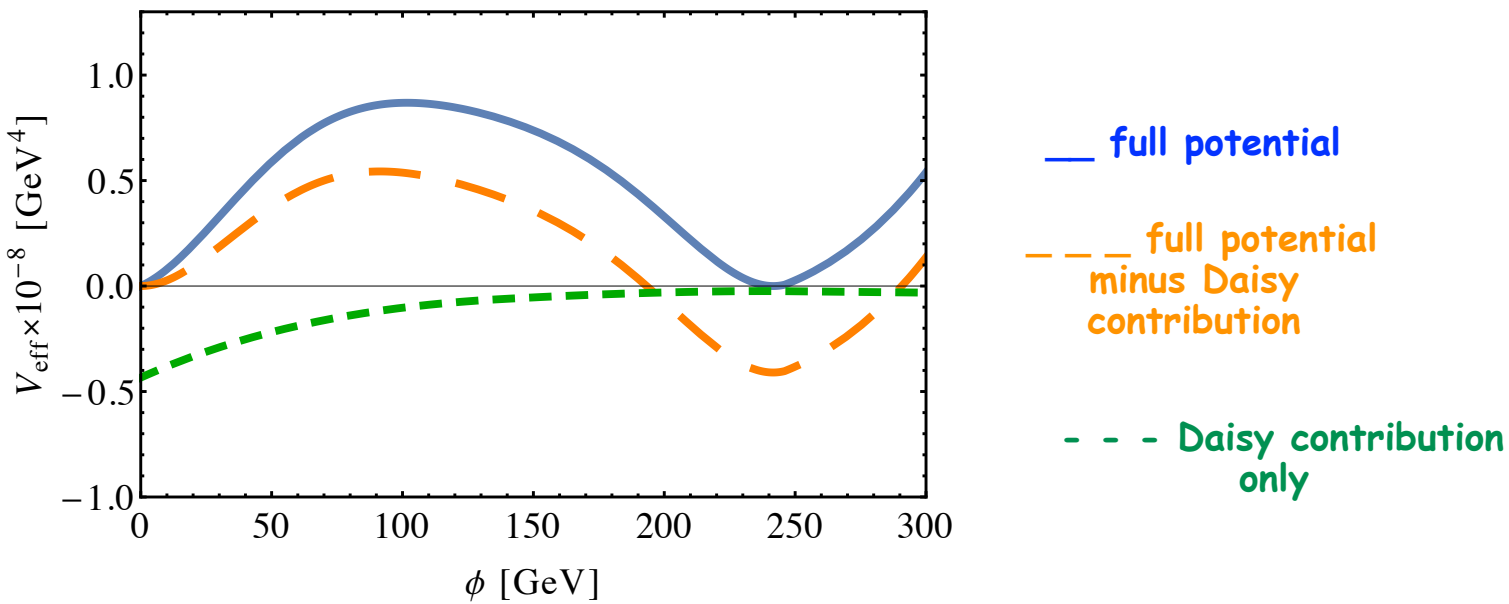
$$\Pi_\phi(\phi,T) = \left(\frac{3}{16}g_2^2 + \frac{1}{16}g_Y^2 + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{g y(\phi)^2}{48}\right) T^2$$

The novelty is the dependence of the thermal mass on Φ, which comes from the Φ-dependent Yukawa couplings

3) Effects from the Daisy correction:

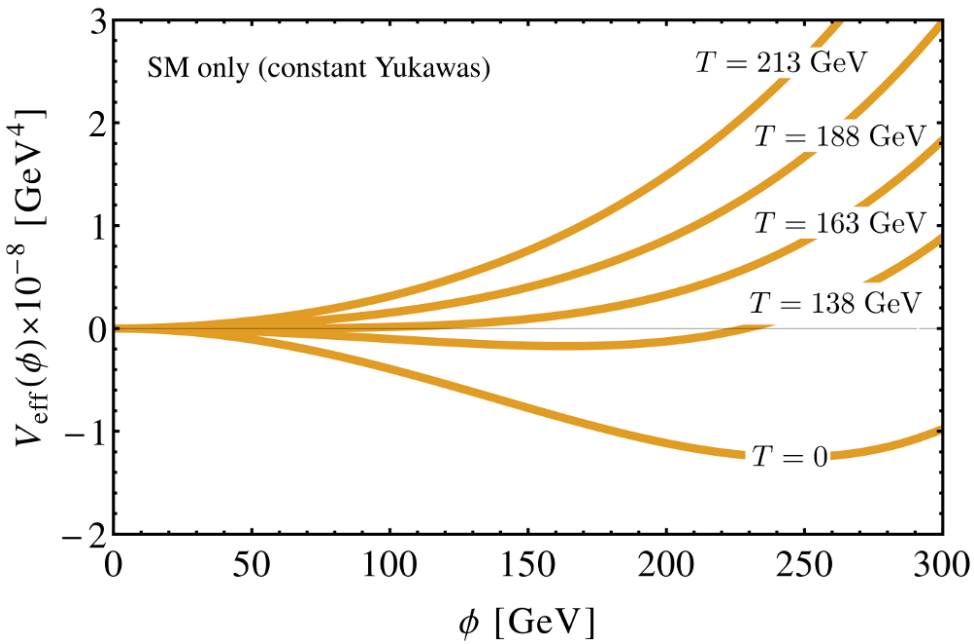
The effect is to lower the effective potential at Φ =0, with respect to the broken phase minimum.

By lowering the potential at Φ =0, the phase transition is delayed and strengthened.

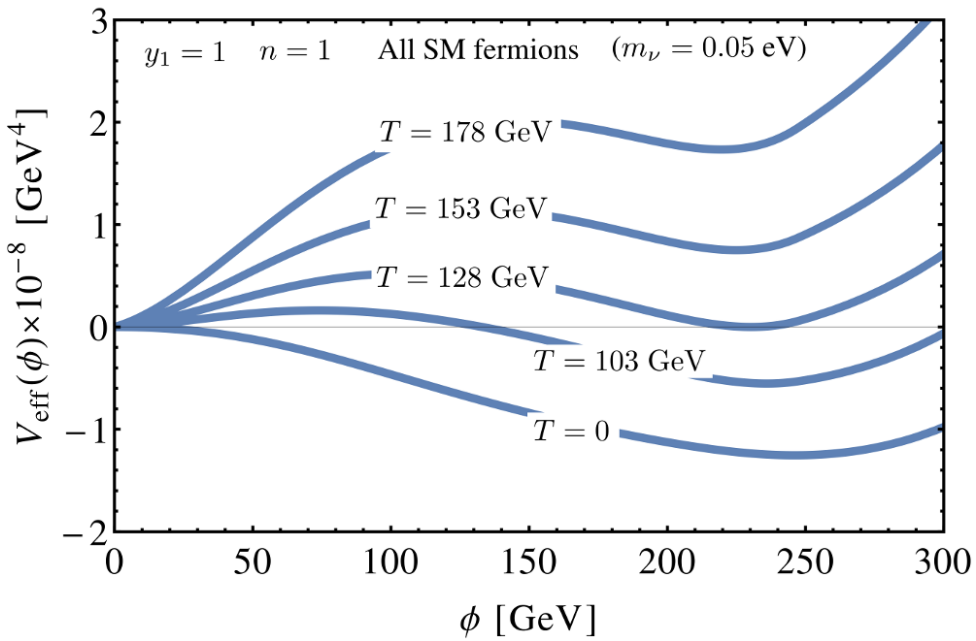


Full one-loop effective Higgs potential with Daisy Resummation

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

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

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

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

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

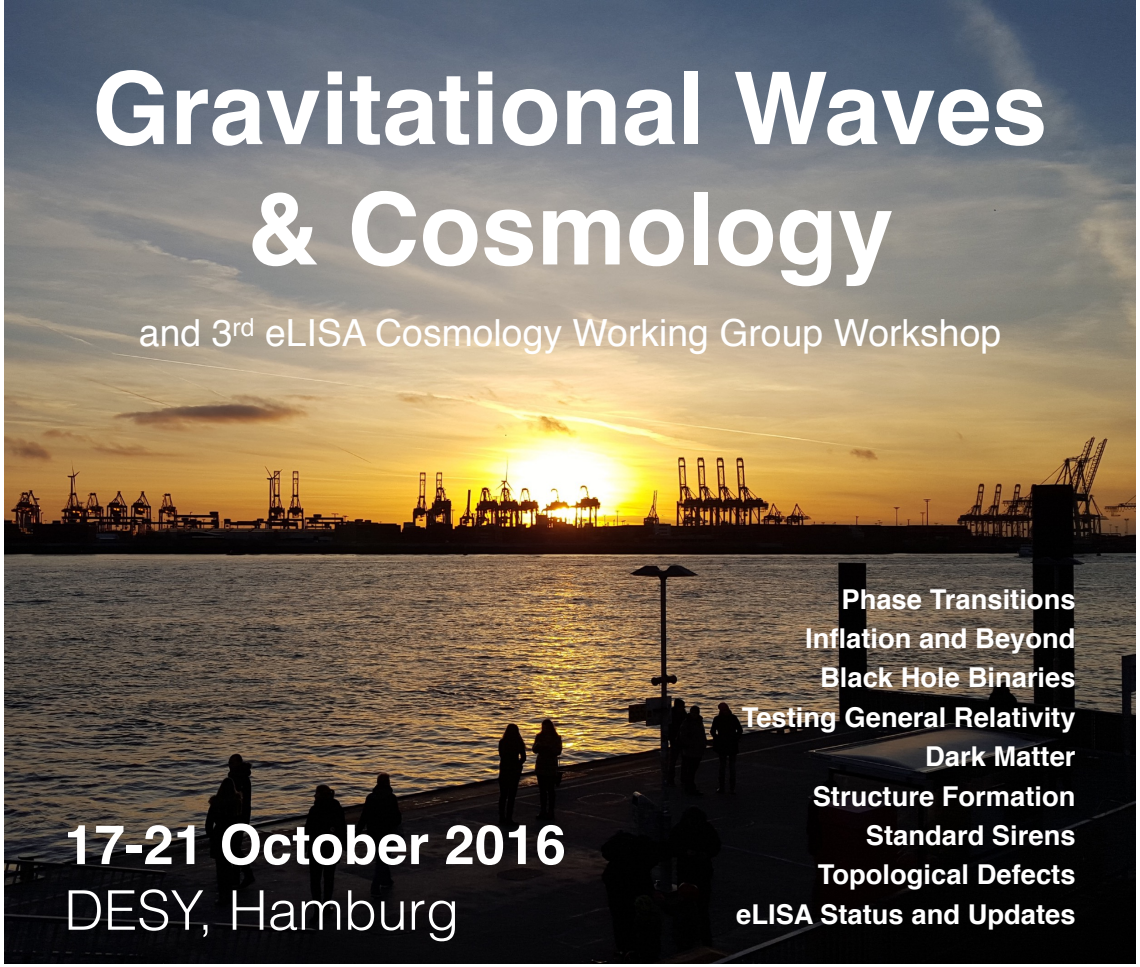
Most recent example in connection with flavour models :
Dynamical Yukawas during the Electroweak Phase Transition change the nature of the EW Phase Transition.

Conclusion continued

The possibility of time-dependent CP-violating sources allows to make EW baryogenesis compatible with Electric Dipole Moment constraints and can be well-motivated theoretically. We provided 2 examples: strong CP from QCD axion, weak CP from dynamical CKM matrix

Gravitational Waves & Cosmology

and 3rd eLISA Cosmology Working Group Workshop



Phase Transitions
Inflation and Beyond
Black Hole Binaries
Testing General Relativity
Dark Matter
Structure Formation
Standard Sirens
Topological Defects
eLISA Status and Updates

17-21 October 2016
DESY, Hamburg

Confirmed Speakers:

Bruce Allen (MPI Hannover)
Stanislav Babak (MPI Potsdam)
Enrico Barausse (IAP Paris)
Pierre Binetruy (U. Paris Diderot)
Luc Blanchet (IAP Paris)
Richard Brito (IST Lisbon)
Vitor Cardoso (IST Lisbon & CERN)
Nelson Christensen (U. Carleton)
Neil Cornish (Montana U.)
Valerie Domcke (APC Paris)
Sergei Dubovsky (UC Davis)
Gia Dvali (LMU Munich)
John Ellis (CERN & King's College)
Valeria Ferrari (U. Roma La Sapienza)
Raphael Flauger (U. Texas Austin)
Juan Garcia-Bellido (U. Madrid)
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Sotiris Sanidas (API Amsterdam)
Alberto Sesana (U. Birmingham)
Ignacy Sawicki (U. Geneva)
Atsushi Taruya (Kyoto U.)
Henry Tye (Cornell & Hong Kong U.)
Alfredo Urbano (CERN)
Michele Vallisneri (JPL Caltech)
David Weir (U. Stavanger)

Organisers:

Chiara Caprini (CEA Saclay)
Thomas Konstandin (DESY)
Germano Nardini (U. Bern)
Pedro Schwaller (DESY)
Géraldine Servant (DESY & UHH)

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Annexes

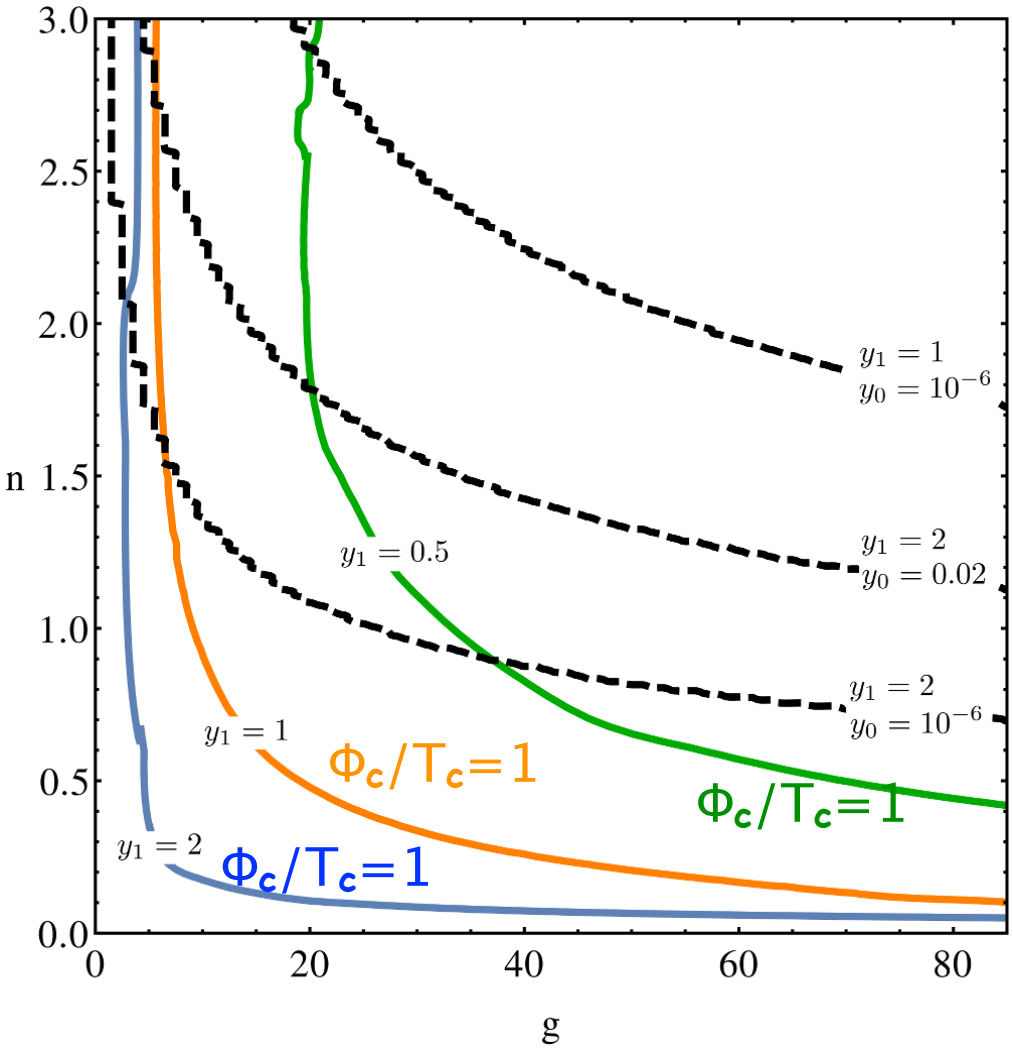
1) Effects from the $T = 0$ one-loop potential:

$$V_1^0(\phi) = \sum_i \frac{g_i (-1)^F}{64\pi^2} \left\{ m_i^4(\phi) \left(\mathrm{Log}\left[\frac{m_i^2(\phi)}{m_i^2(v)}\right] - \frac{3}{2} \right) + 2 m_i^2(\phi) m_i^2(v) \right\}$$

A large fermionic mass significantly lowers V_1^0 between Φ=0 and Φ=v. This can lead to weaker - rather than stronger - phase transitions.

In addition, it can lead to the EW minimum no longer being the global minimum.

Contours of $\Phi_c/T_c=1$ for different choices of y_1 and y_0, areas above these lines allow for EW baryogenesis.



Dashed lines: areas above these lines are disallowed (for the indicated choices of y_1 and y_0 due to the EW minimum not being the global one.

n characterizes how fast the Yukawa variation is taking place. Depending on the underlying model, the Higgs field variation will follow the flavon field variation at different speeds. Large n means the Yukawa coupling remains large for a greater range of phi away from zero. It strengthens the phase transition.

Baldes, Konstandin, Servant, 1604.04526