Electroweak baryogenesis after LHC8

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Moduli-induced baryogenesis [arXiv:1407.1827]

WIMPy baryogenesis [arXiv:1406.6105]

Baryogenesis by black holes [arXiv:1406.6215]

Inflatonic baryogenesis [arXiv:1405.1959]

Affleck-Dine baryogenesis [1404.3108]

....

Leptogenesis

Electroweak baryogenesis

The baryon asymmetry

$$\eta_B = \frac{n_B}{n_\gamma} = (6.047 \pm 0.074) \times 10^{-10}$$

[Planck 2013]

Good agreement between CMB and primordial nucleosynthesis

→ we understand the universe up to T~MeV

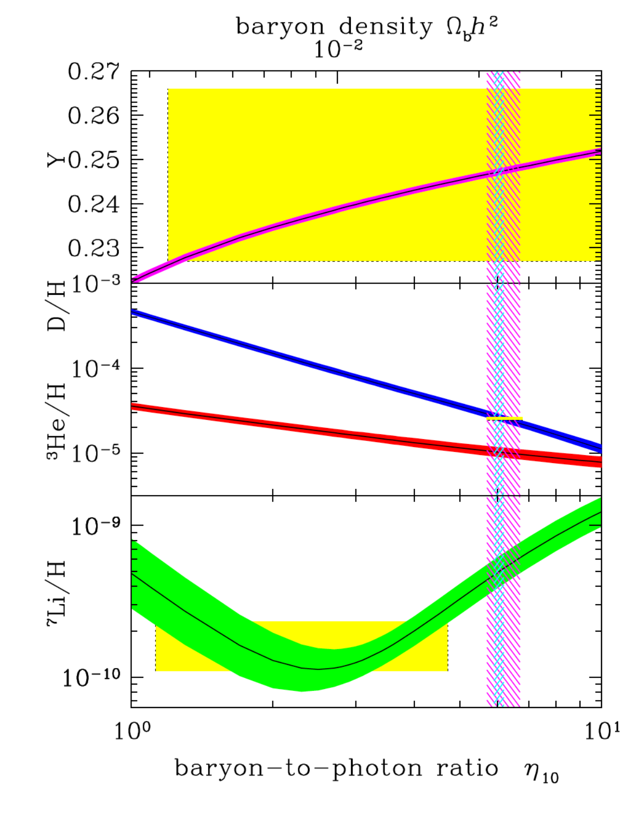
Can we repeat this success for the baryon asymmmetry?

Problem: only 1 observable

→ Need to be convinced by a specific model:

Theory?, Experiment? (belief??) …

T < TeV scale? → EWBG



[Particle Data Group]

Collider
Higgs properties
New particles

Model building

Gravitational
waves

Dark matter

First-order
electroweak
Phase transition

Cosmic
Magnetic
fields

CP violation
Electric dipole
moments

Computational tools
Transport
hydrodynamics

Baryon
asymmetry

Outline

- 2HDM (phase transition, baryogenesis)
- gravitational waves, fluid dynamics: Gravitational wave production is dominated by sound waves
- extended SUSY
- Summary & outlook

The 2HDM

The 2HDM

$$V(H_1, H_2) = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \mu_3^2 e^{i\phi} H_1^\dagger H_2 + \lambda_1|H_1|^4 + \ldots$$

→ 4 extra physical Higgs degrees of freedom: 2 neutral, 2 charged

→ CP violation, phase Φ (μ_3 breaks Z_2 symmetry softly)

→ there is a phase induced between the 2 Higgs vevs

$$v_1 = \langle H_1 \rangle, \qquad v_2 e^{i\theta} = \langle H_2 \rangle$$

early work:

Turok, Zadrozny ' 91

Davies, Froggatt, Jenkins, Moorhouse ' 94

Cline, Kainulainen, Vischer ' 95

Cline, Lemieux '96

simplified parameter choice:

1 light Higgs m_h → SM-like

3 degenerate heavy Higgses m_H → keeps EW corrections small

The phase transition

Evaluate 1-loop thermal potential:

loops of heavy Higgses generate a cubic term

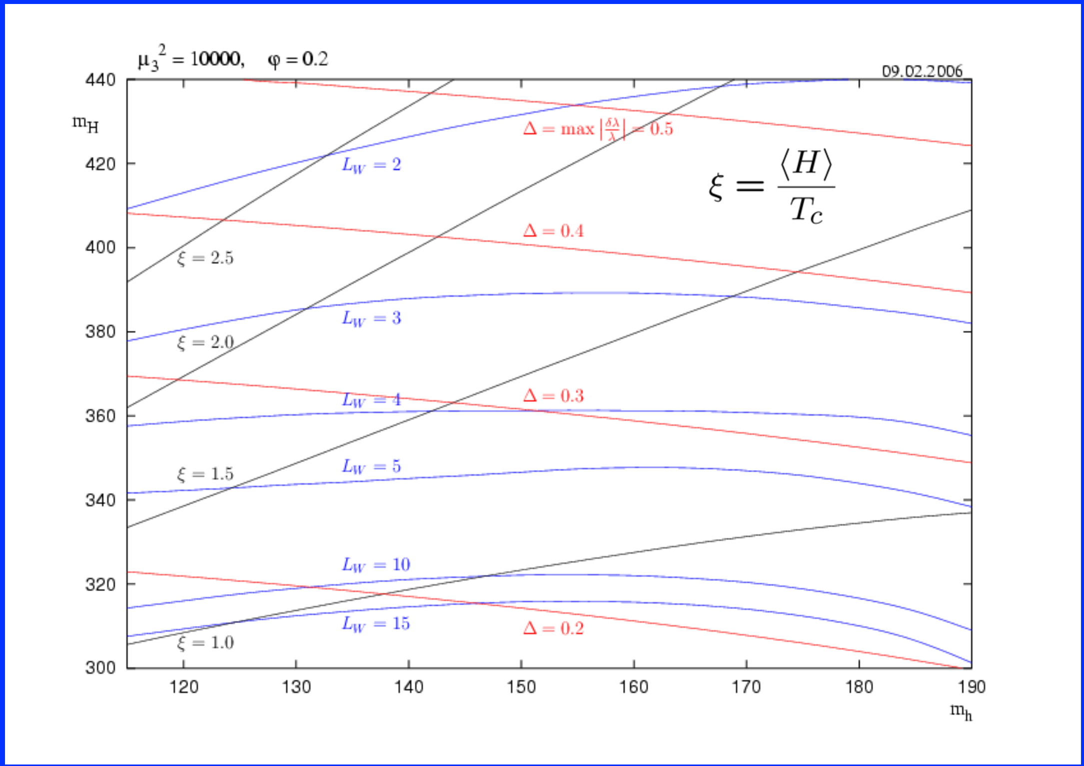
→ strong PT for

m_H>300 GeV

m_h up to 200 GeV

→ PT ~ independent of Φ

→ thin walls only for very strong PT (agrees with Cline, Lemieux ’96)



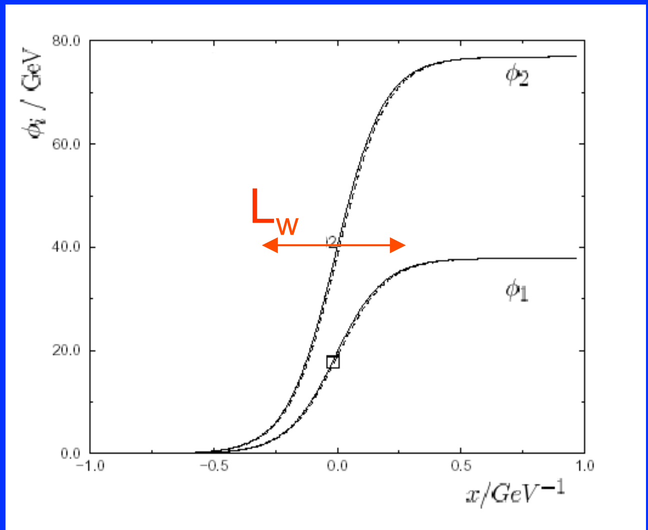
[Fromme, S.H., Senuich ’06]

missing: 2-loop analysis of the thermal potential; lattice; wall velocity

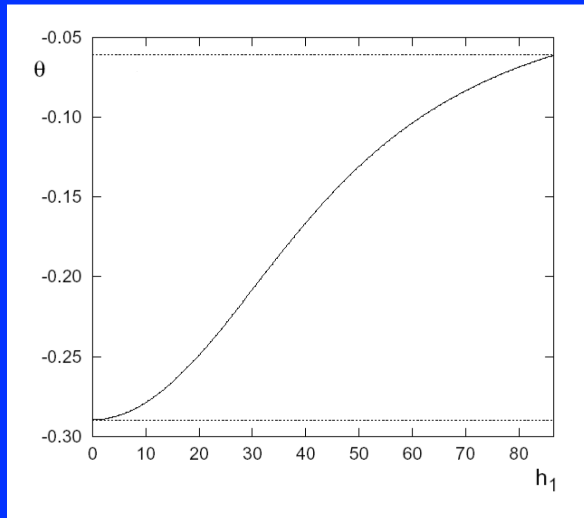
The bubble wall

Solve the field equations with the thermal potential → wall profile $\Phi_i(z)$

kink-shaped with wall thickness L_w



θ becomes dynamical



(numerical algorithm for multi-field profiles, T. Konstandin, S.H. ´06)

Transport

The interaction with the bubble wall induces a force on the particles, which is different for particles and antiparticles if CP is broken

$$(\partial_t + \dot{z}\partial_z + \dot{p}_z\partial_{p_z})f = \mathcal{C}[f]$$

Force: $\dot{p}_z = -\partial_z E(z, p_z)$

collision terms

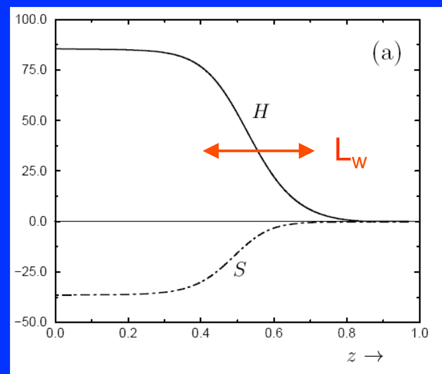
$$\begin{aligned} E_\pm &= E_0 \pm \Delta E_0 \\ &= \sqrt{p^2 + m^2} \pm \theta' \frac{m^2}{2(p^2+m^2)} \end{aligned}$$

Joyce, Prokopec, Turok ’95
Cline, Joyce, Kainulainen ’00
Kainulainen, Prokopec, Schmidt, Weinstock ‘02

Top mass phase varies along the wall (wall width L_w)

because the phase between the Higgs vevs changes:

$$M(z) = m(z)e^{i\theta(z)}$$



Charge transport equations:

$$
\begin{aligned}
3v_{\rm w}K_{1,t}\mu'_{t,2} + 3v_{\rm w}K_{2,t}(m_t^2)'\mu_{t,2} + 3u'_{t,2}& \\
-3\Gamma_y(\mu_{t,2}+\mu_{t^c,2}+\mu_{h,2}) - 6\Gamma_m(\mu_{t,2}+\mu_{t^c,2}) - 3\Gamma_W(\mu_{t,2}-\mu_{b,2})& \\
-3\Gamma_{ss}[(1+9K_{1,t})\mu_{t,2}+(1+9K_{1,b})\mu_{b,2}+(1-9K_{1,t})\mu_{t^c,2}] &= 0 \\
-3K_{4,t}\mu'_{t,2} + 3v_{\rm w}\tilde{K}_{5,t}u'_{t,2} + 3v_{\rm w}\tilde{K}_{6,t}(m_t^2)'u_{t,2} + 3\Gamma_t^{\rm tot}u_{t,2} &= S_t
\end{aligned}
$$

(8 TE's for velocities and chemical potentials)

$$S_t = -v_{\rm w}K_8(m_t^2\theta_t')' + v_{\rm w}K_9\theta_t' m_t^2(m_t^2)'$$

(CP violating source term)

$$\mu_{B_L} = \mu_{q_1,2} + \mu_{q_2,2} + \frac{1}{2}(\mu_{t,2}+\mu_{b,2})$$

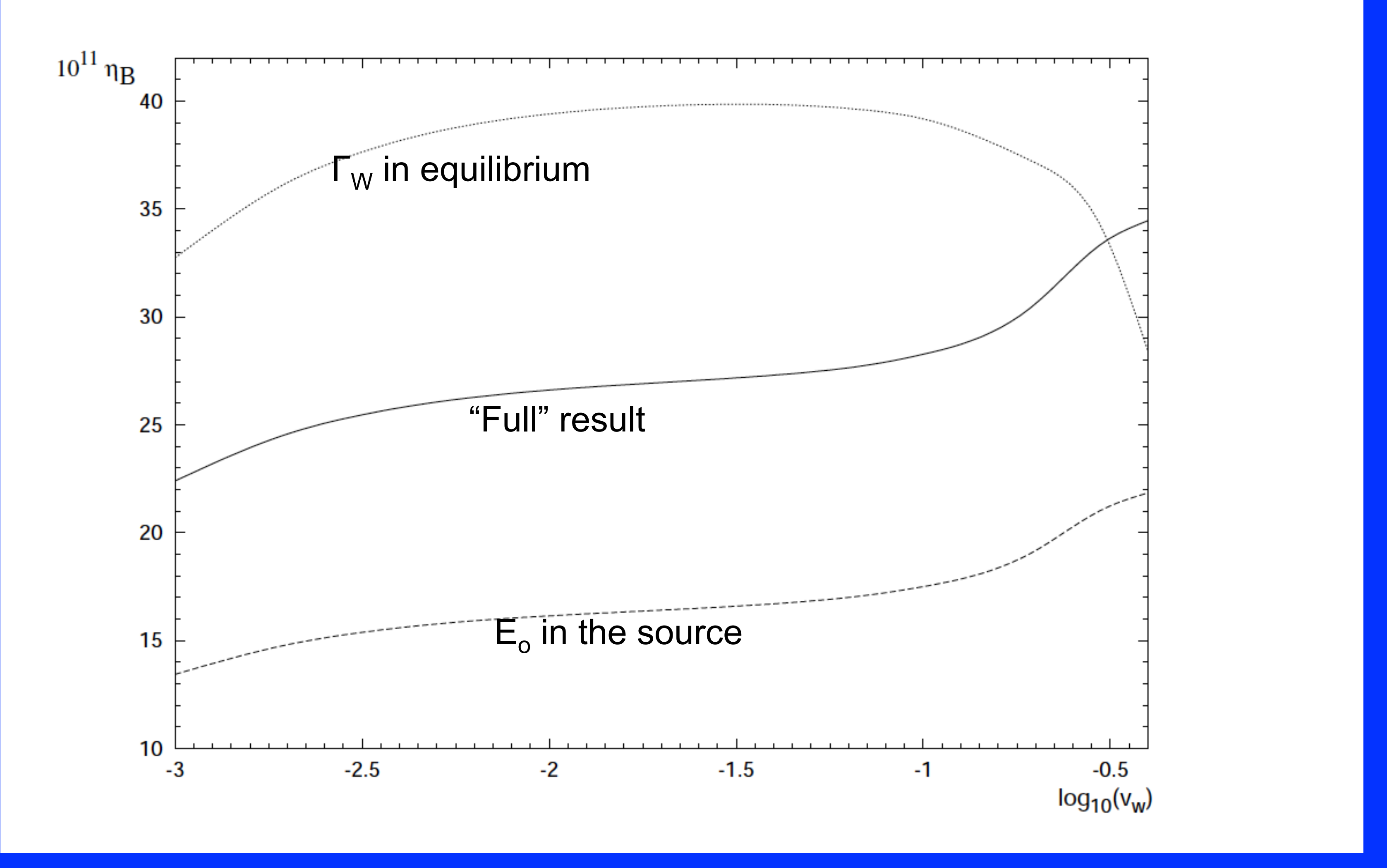
(left-handed quark chem. potential)

$$\eta_B = \frac{n_B}{s} = \frac{405\Gamma_{ws}}{4\pi^2 v_{\rm w} g_* T}\int_0^\infty dz\ \mu_{B_L}(z)e^{-\nu z}$$

(final baryon asymmetry)

Some rates badly known; additional sources from collisions?

Resulting baryon asymmetry: known to a factor few?



$m_h = 125$ $m_H = 350$ GeV, $\mu_3^2 = 10000$ GeV^2 and $\phi = 0.2$

The baryon asymmetry

The relative phase between the Higgs vevs, θ, changes along the bubble wall

→ phase of the top mass varies

$\theta_t = \theta/(1+\tan^2\beta)$

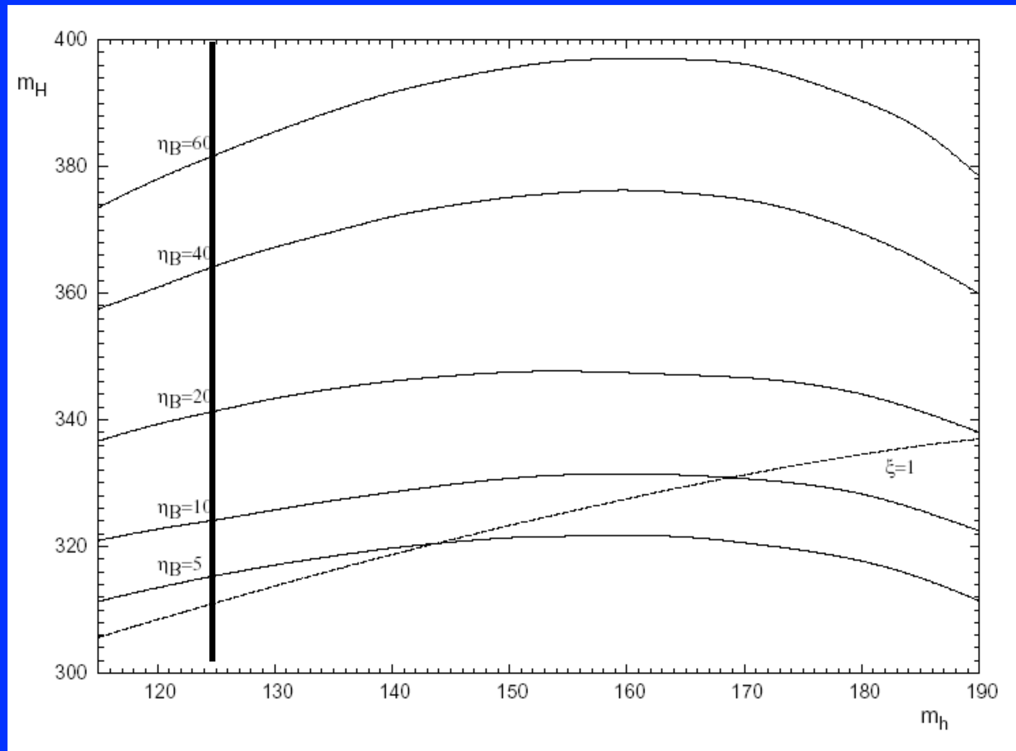
top transport generates a baryon asymmetry, but

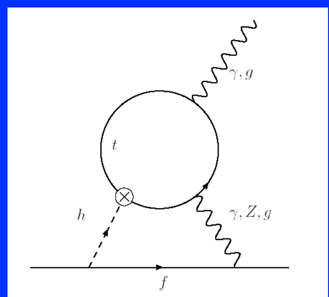
$\tan\beta < 10$ (?)

→ only one phase, so EDMs can be predicted: here

$d_n = 0.1\ 10^{-26} – 7\ 10^{-26}$ e cm

exp. bound: $d_n < 3.0\ 10^{-26}$ e cm





η_B in units of 10^{-11}, φ=0.2

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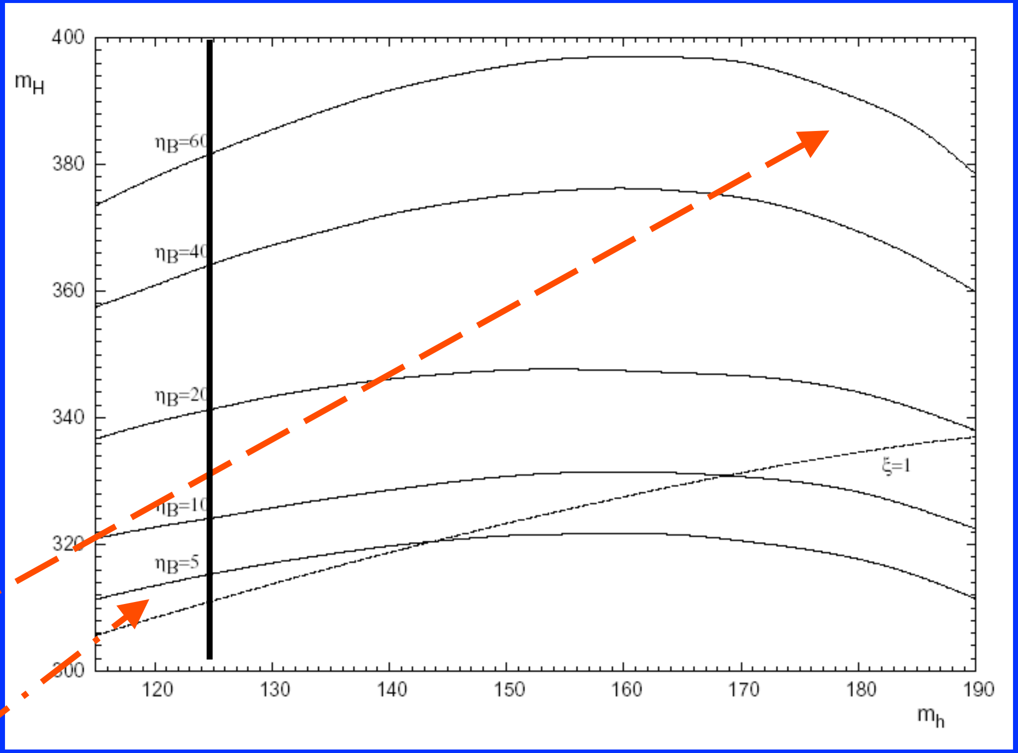
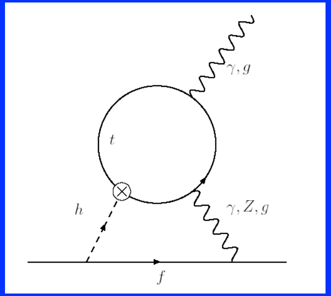




η_B in units of 10^{-11}, φ=0.2

New bound on electron EDM!

More general parameter scan

[Dorsch, S.H., No, 2013]

$$V_{tree}(\Phi_1,\Phi_2) = -\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{\mu^2}{2}\left(e^{i\phi}\Phi_1^\dagger\Phi_2 + H.c.\right) + \\ + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \\ + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right]$$

Type I or II, softly broken

No CP violation, i.e. Φ=0

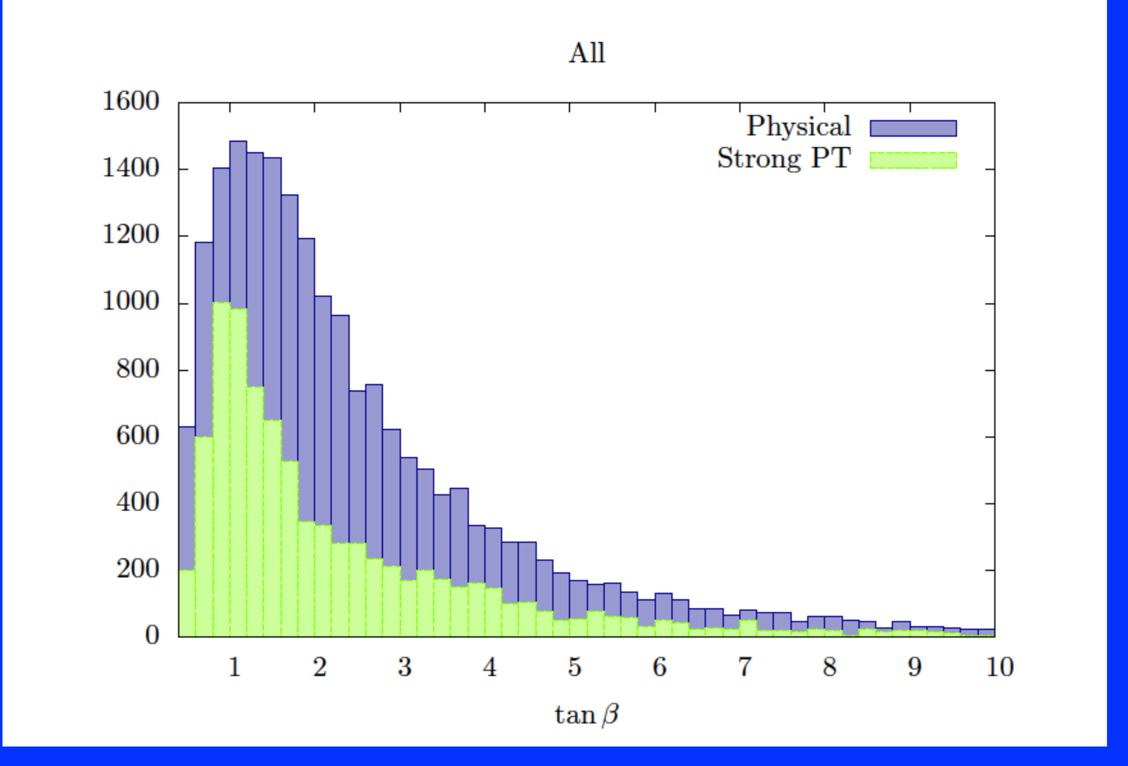
We analyze the thermal 1-loop potential

$$\begin{aligned} 0.4 \leq \; & \tan\beta \leq 10, \\ -\tfrac{\pi}{2} < \; & \alpha \leq \tfrac{\pi}{2}, \\ 0\text{ GeV} \leq \; & \mu \leq 1\text{ TeV}, \\ 100\text{ GeV} \leq \; & m_{A^0},\, m_{H^\pm} \leq 1\text{ TeV}, \\ 150\text{ GeV} \leq \; & m_{H^0} \leq 1\text{ TeV}. \end{aligned}$$

(parameter ranges, m_h=125 GeV)

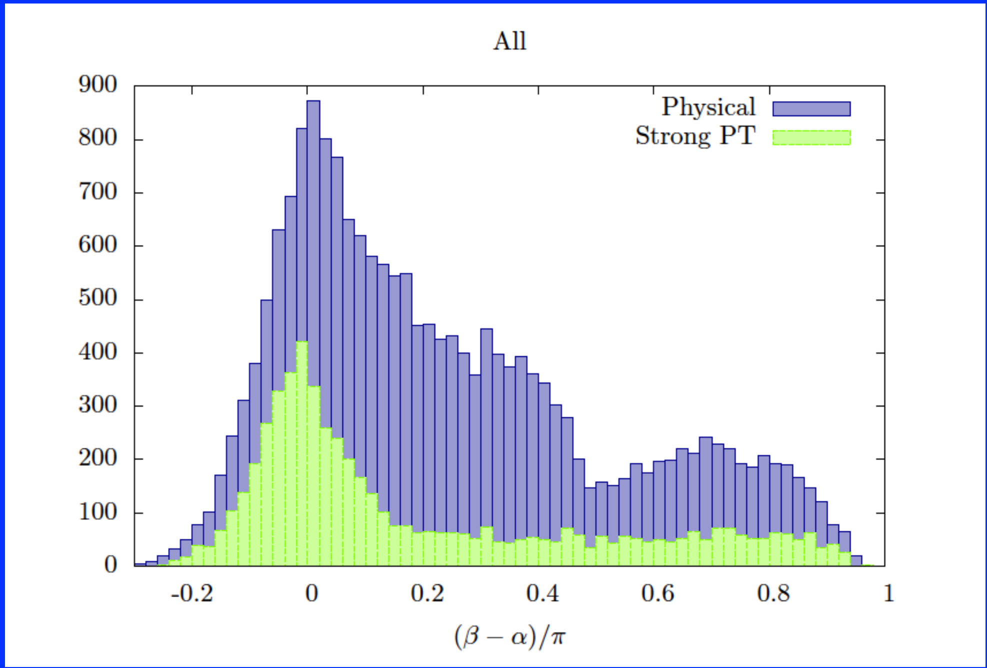
Constraints: rho-parameter

B→ s γ, B-Bbar mixing

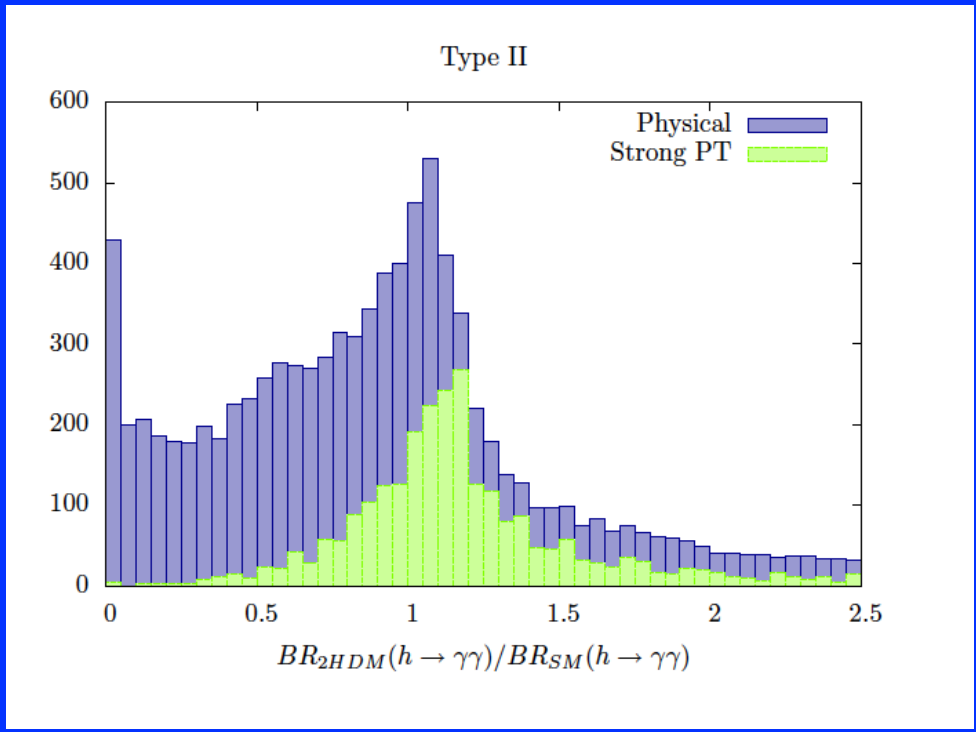


Preference for small tanβ

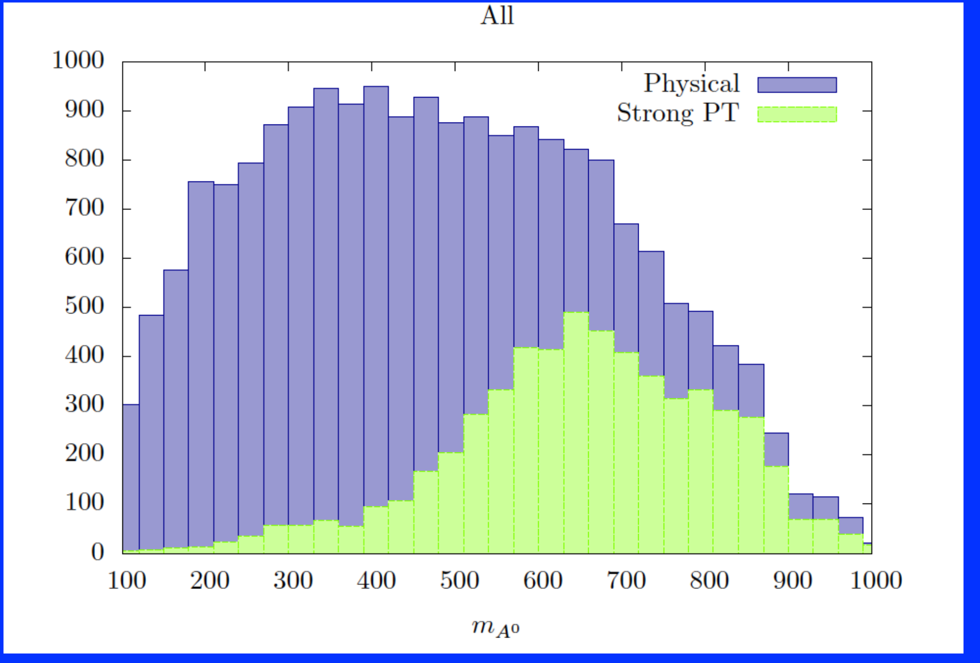
[Dorsch, S.H., No, 2013]



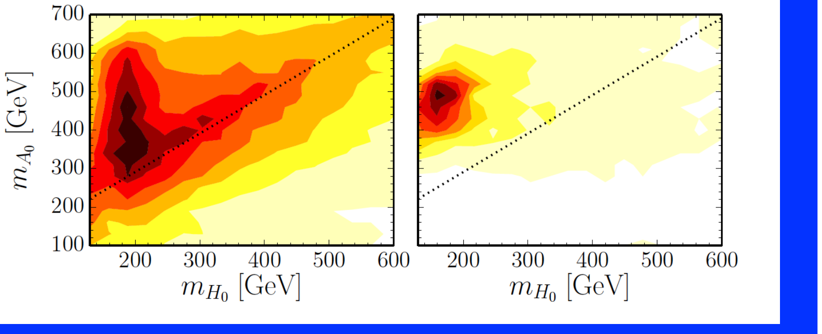
SM like Higgs?



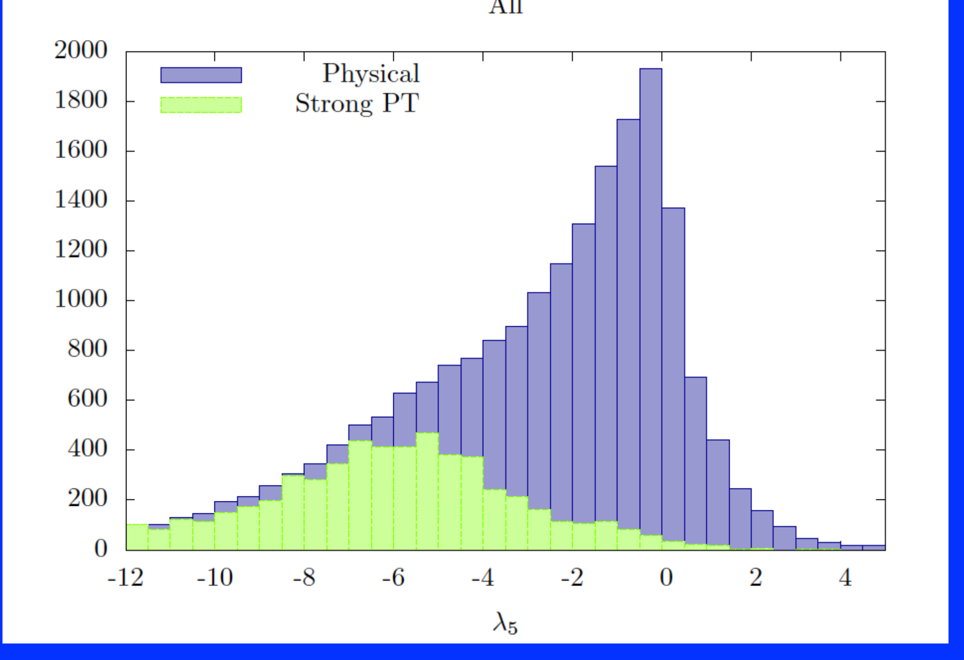
Di-photon channel



Preference for a heavy pseudoscalar



[Dorsch, S.H., Mimasu, No '14]



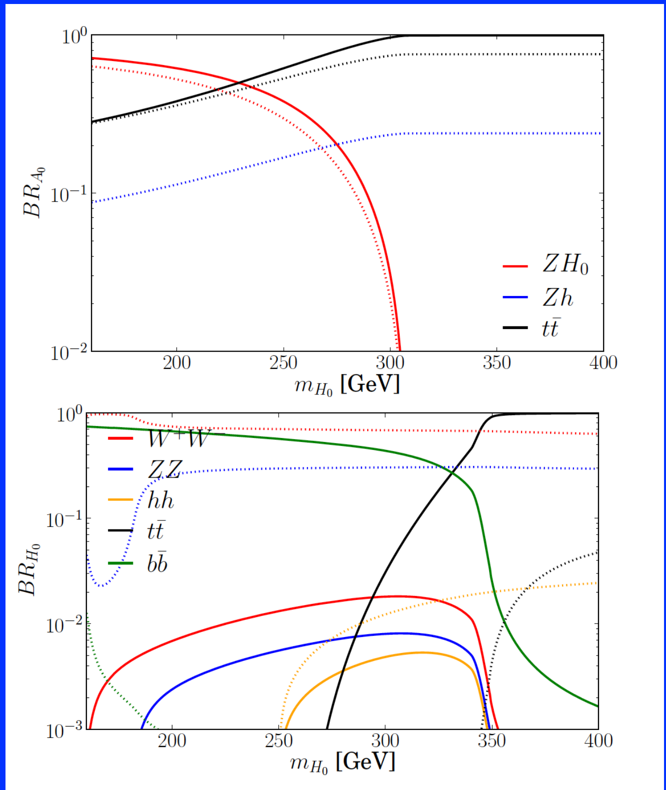
Preference for a large negative λ_5

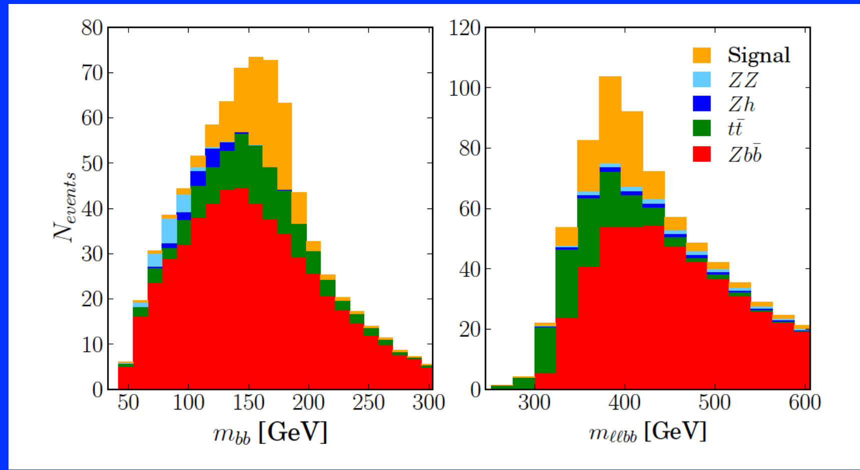
$$\frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + H.c.\right]$$

The strong phase transition at LHC

Search for $A_0 \to H_0 Z \to ll\ bb$

[Dorsch, S.H., Mimasu, No '14]





	Signal	$t\bar{t}$	$Z\,b\bar{b}$	ZZ	$Z\,h$
Event selection	14.6	1578	424	7.3	2.7
$80 < m_{\ell\ell} < 100$ GeV	13.1	240	388	6.6	2.5
$H_T^{\rm bb} > 150$ GeV $H_T^{\ell\ell{\rm bb}} > 280$ GeV	8.2	57	83	0.8	0.74
$\Delta R_{bb} < 2.5$, $\Delta R_{\ell\ell} < 1.6$	5.3	5.4	28.3	0.75	0.68
m_{bb}, $m_{\ell\ell bb}$ signal region	3.2	1.37	3.2	< 0.01	< 0.02

Discovery needs ~ 40 fb^{-1} (at 14 TeV)

($m^{\pm}$=400 GeV, m_{H_0}=180 GeV)

a strong phase transition in the 2HDM is very much consistent with a SM-like light Higgs

specific predictions for the mass spectrum and certain coupling constants

testable at LHC

Inert 2HDM:

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$$

doublet 2 does not get a vev

➔ Dark matter

CP violation from higher-dim. Operators

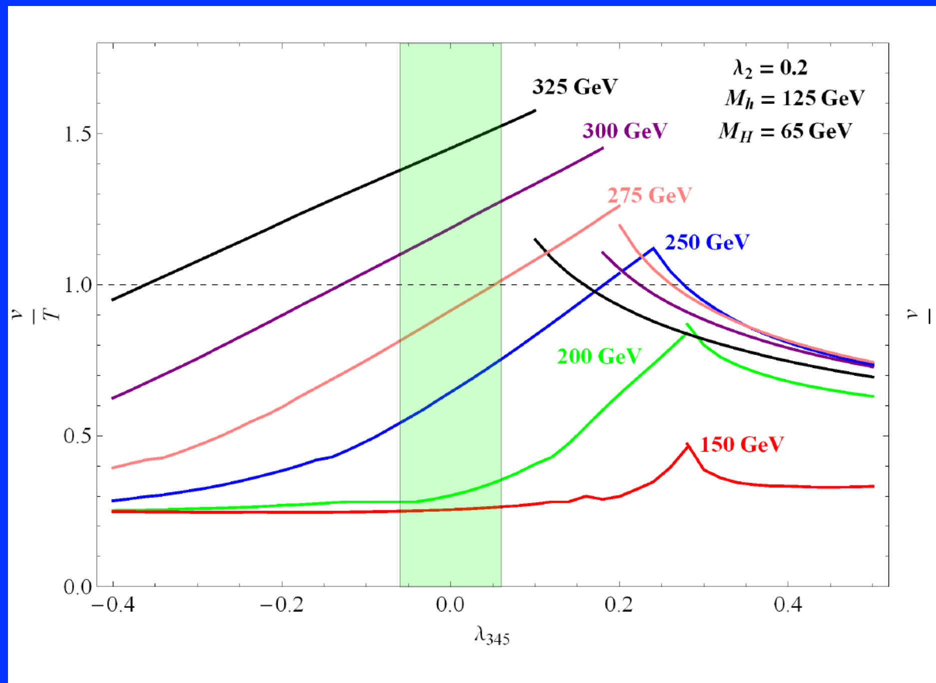
$$\mathbb{Z}_2: \quad \Phi_1 \to \Phi_1\,, \qquad \Phi_2 \to -\Phi_2\,,$$
$$\mathbb{Z}_2': \quad \Phi_1 \to -\Phi_1\,, \qquad \Phi_2 \to \Phi_2\,, \qquad f_R \to -f_R\,,$$

similar: Higgs + scalar singlet + fermion singlet dark matter

[Fairbairn, Hogan 2013]

NMSSM-like SUSY, e.g.

[Menon, Morrissey, Wagner '04]



[Gil, Chankowski, Krawczyk 2012]

Numerical Simulations

of a first-order phase transition
and gravitational waves
(with Hindmarsh, Rummukainen, Weir 2013)

Gravitational waves

sources of GW's: direct bubble collisions

turbulence

(magnetic fields)

sound waves

key parameters: available energy

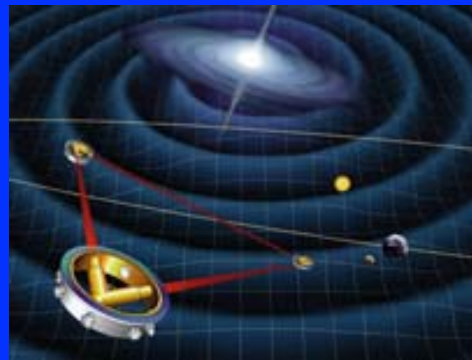
$$\alpha = \frac{\text{latent heat}}{\text{radiation energy}}$$

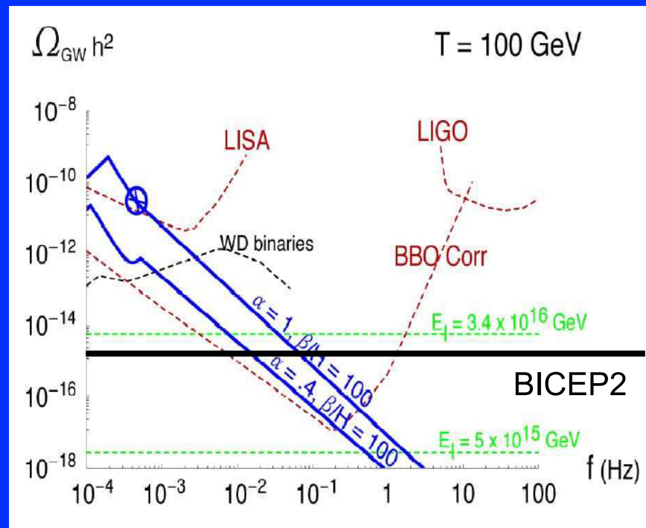
typical bubble radius

$$\langle R \rangle \propto v_b \, \tau \approx \frac{v_b}{\beta}.$$

v_b wall velocity

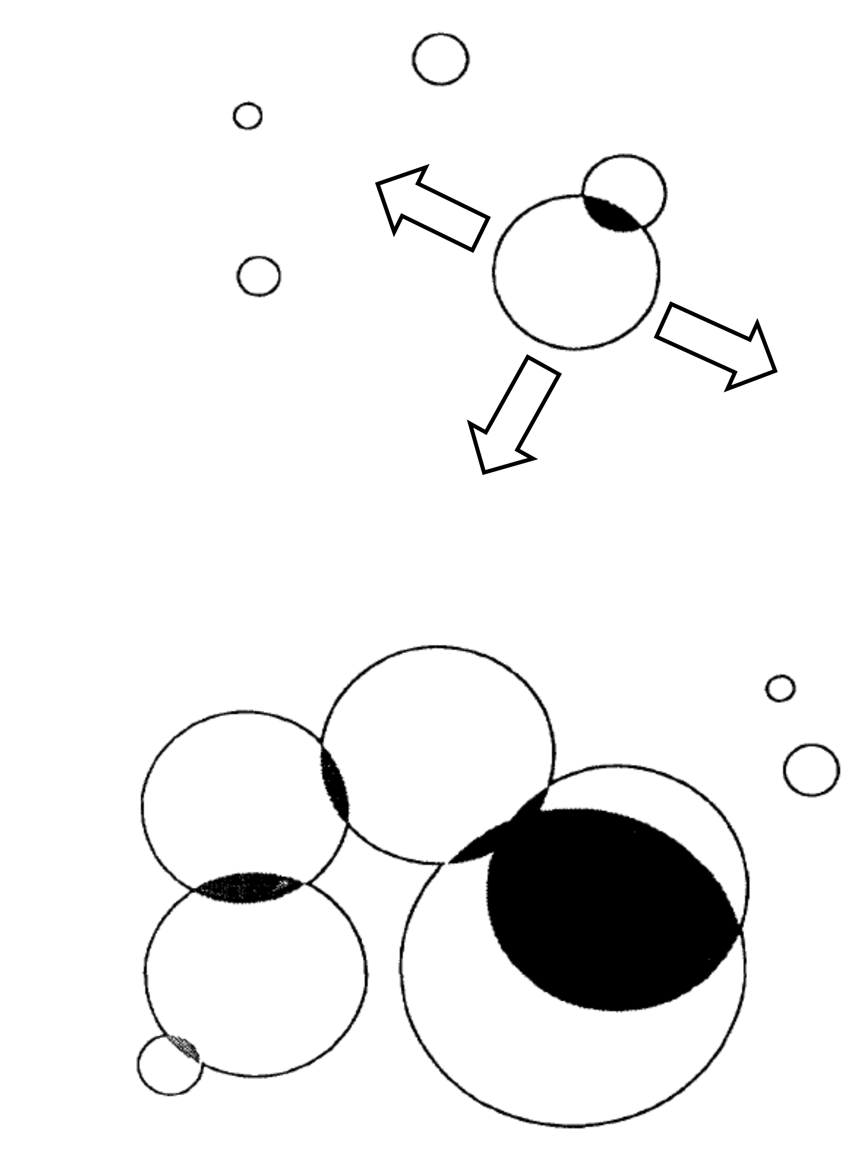
LISA / eLISA





Grojean, Servant '06

The envelope approximation: Kosowsky, Turner 1993



Energy momentum tensor of expanding bubbles modelled by expanding infinitely thin shells,

cutting out the overlap

→ very non-linear!

Tested by colliding two pure scalar bubbles

Recent scalar field theory simulation:

Child, Giblin 2012

What happens if the fluid is relevant?

Turbulence??

We performed the first 3d simulation of a scalar + relativistic fluid system:

$$V(\phi, T) = \frac{1}{2}\gamma(T^2 - T_0^2)\phi^2 - \frac{1}{3}\alpha T\phi^3 + \frac{1}{4}\lambda\phi^4.$$

(Thermal scalar potential)

$$-\ddot{\phi} + \nabla^2\phi - \frac{\partial V}{\partial \phi} = \eta W(\dot{\phi} + V^i\partial_i\phi)$$

(Scalar eqn. of motion)

$$\dot{E} + \partial_i(EV^i) + P[\dot{W} + \partial_i(WV^i)] - \frac{\partial V}{\partial \phi}W(\dot{\phi} + V^i\partial_i\phi) = \eta W^2(\dot{\phi} + V^i\partial_i\phi)^2. \quad (7)$$

(eqn. for the energy density)

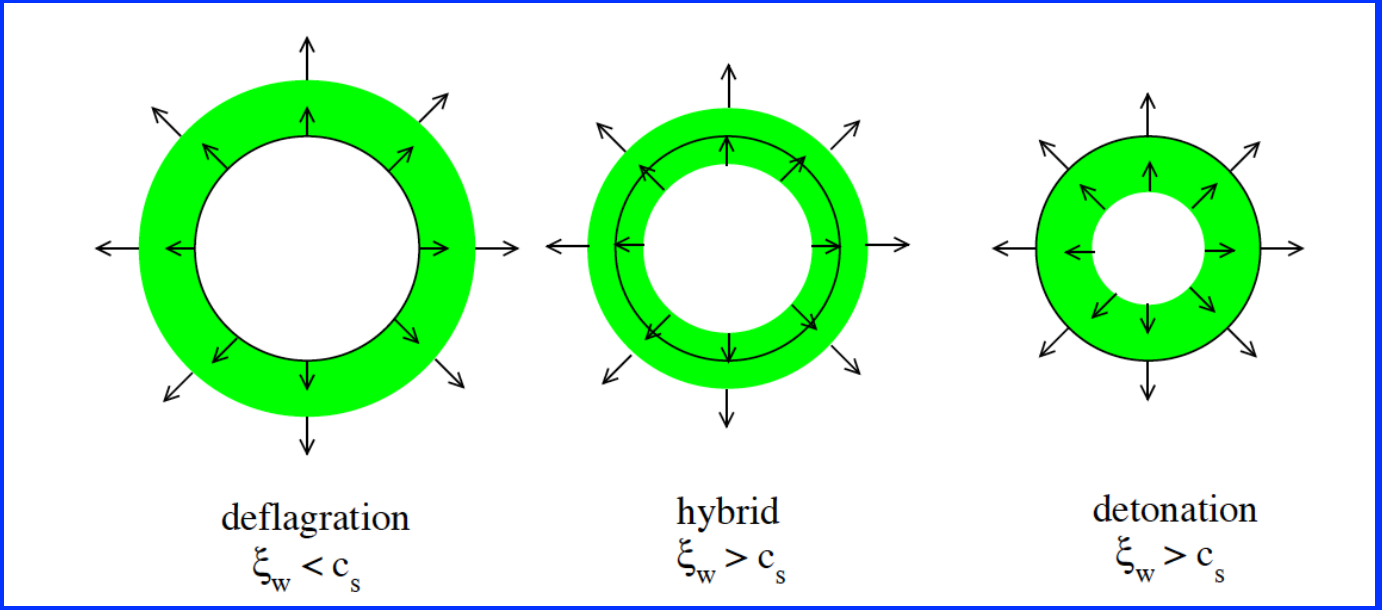
$$\dot{Z}_i + \partial_j(Z_iV^j) + \partial_i P + \frac{\partial V}{\partial \phi}\partial_i\phi = -\eta W(\dot{\phi} + V^j\partial_j\phi)\partial_i\phi.$$

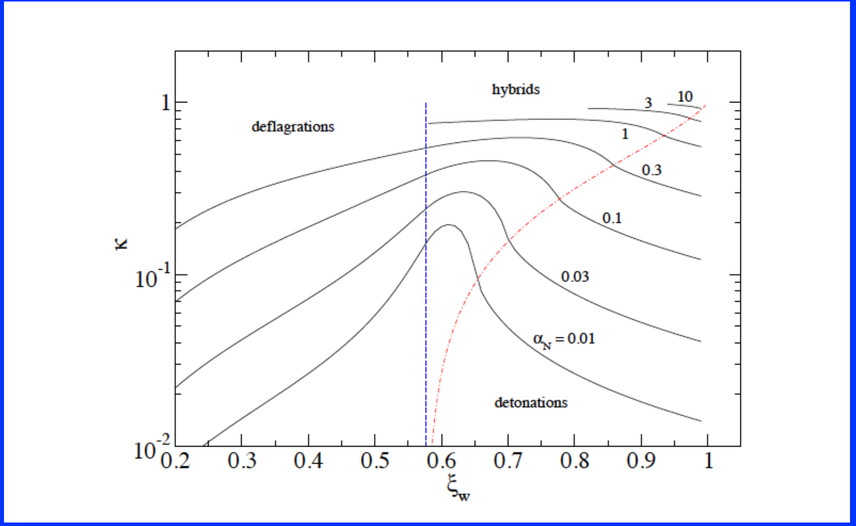
(eqn. for the momentum density)

$$\ddot{u}_{ij} - \nabla^2 u_{ij} = 16\pi G(\tau_{ij}^{\phi} + \tau_{ij}^{\mathrm{f}}),$$

(eqn. for the metric perturbations)

Types of single bubble solutions:



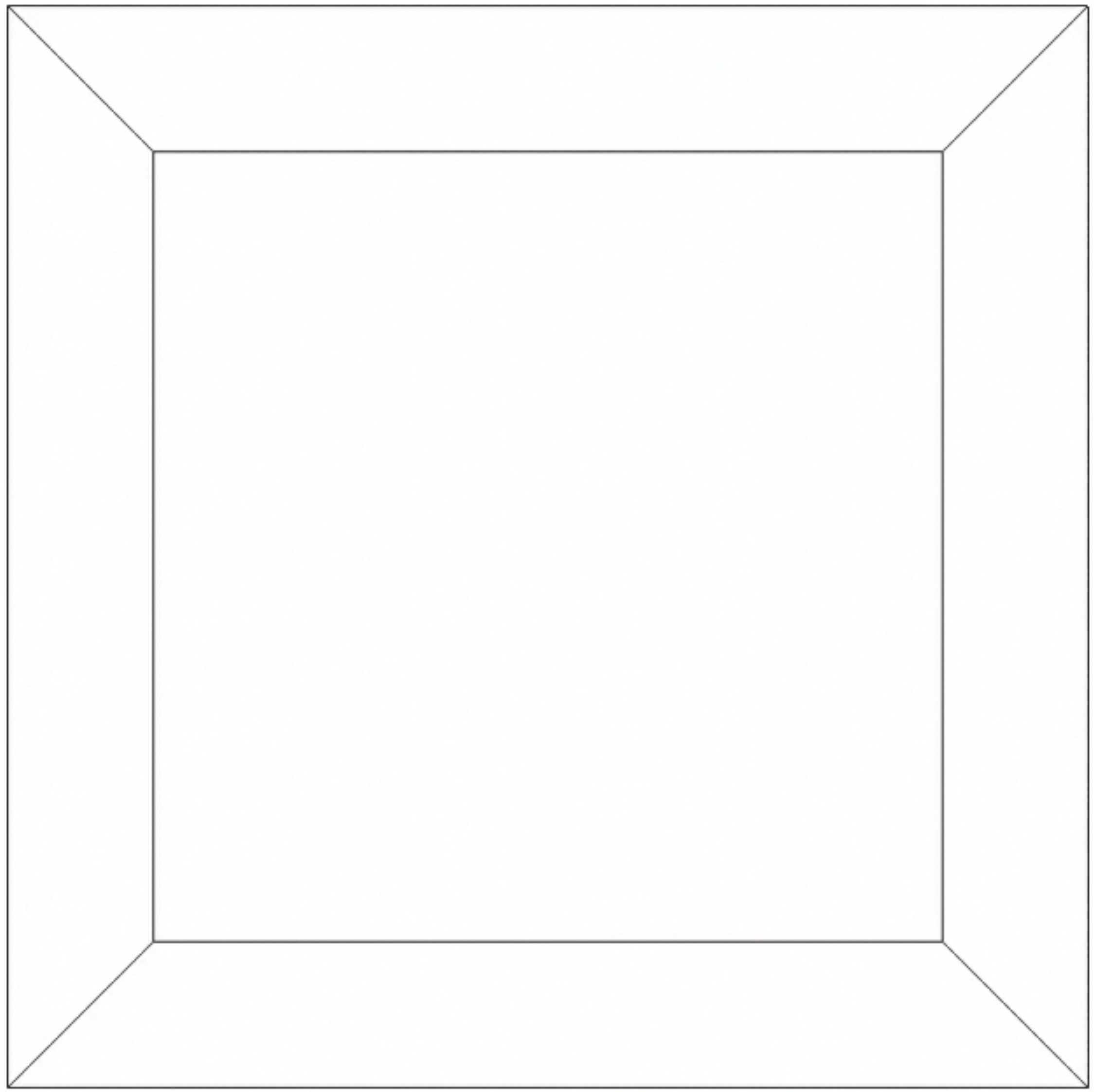


Espinosa, Konstandin, No, Servant '10

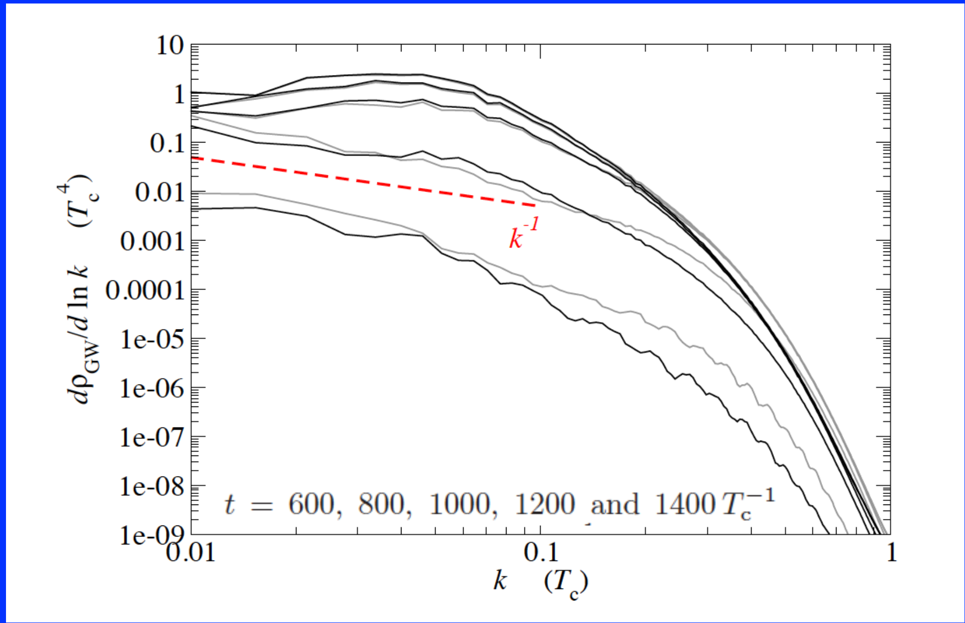
1024^3

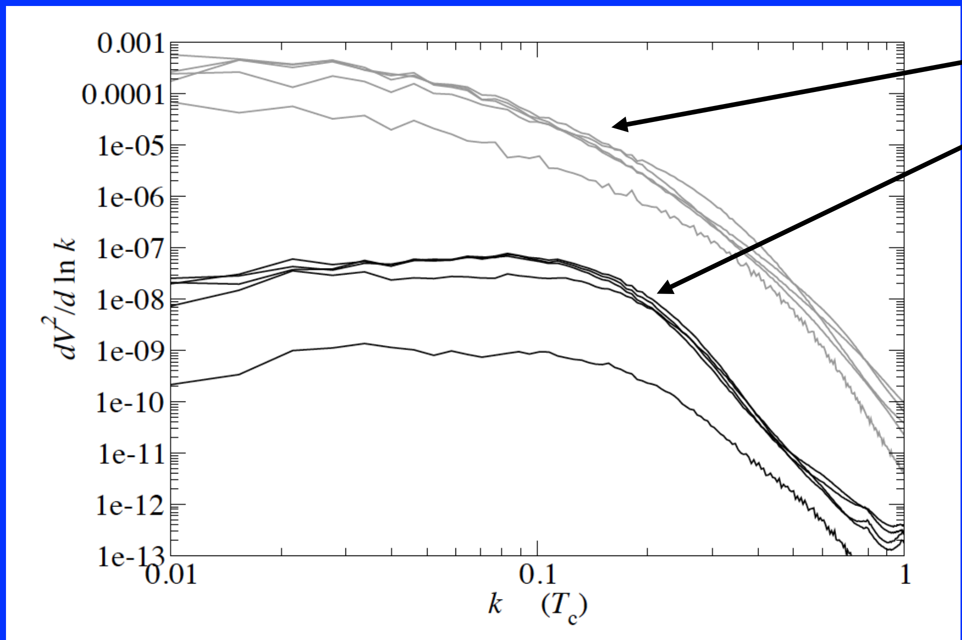
Lattice

Fluid energy



GW Spectrum





Transverse and longitudinal part of the fluid stress

Logitudinal part dominates
➔ Basically sound waves

Strength of the GW signal:

$$\Omega_{\rm GW} \simeq \frac{3\bar{\Pi}^2}{4\pi^2}(H_*\tau_{\rm s})(H_*R_*)(1+w)^2\overline{U}_{\rm f}^4,$$ simulation

$$\Omega_{\rm GW} \simeq \frac{0.11 v_{\rm w}^3}{0.42+v_{\rm w}^2}\left(\frac{H_*}{\beta}\right)^2 \frac{\kappa^2\alpha_T^2}{(\alpha_T+1)^2}$$ env. appr.

Enhancement by $\tau_{\rm s}/R_* v_{\rm w}$

What sets τ_s? Hubble time?

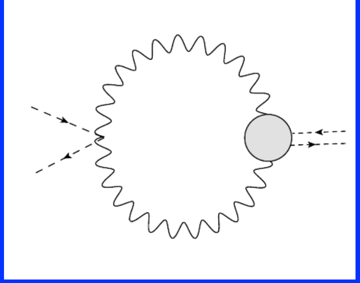
GW'Scale invariant Higgs

Higgs mass stabilized by conformal symmetry,

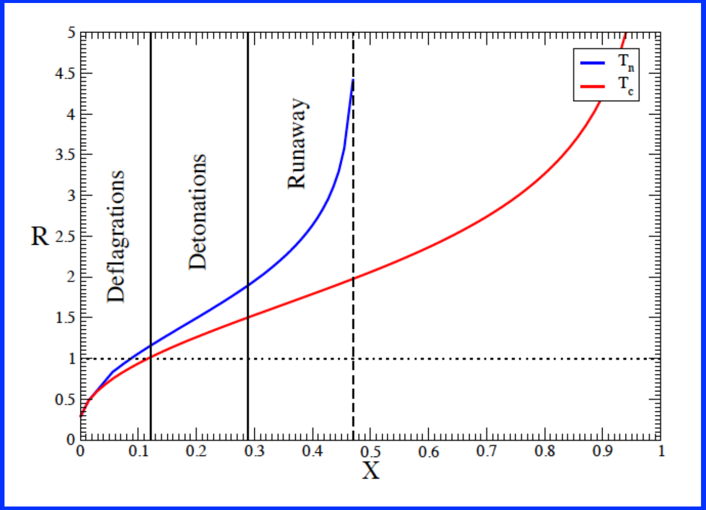
Broken in a hidden sector,

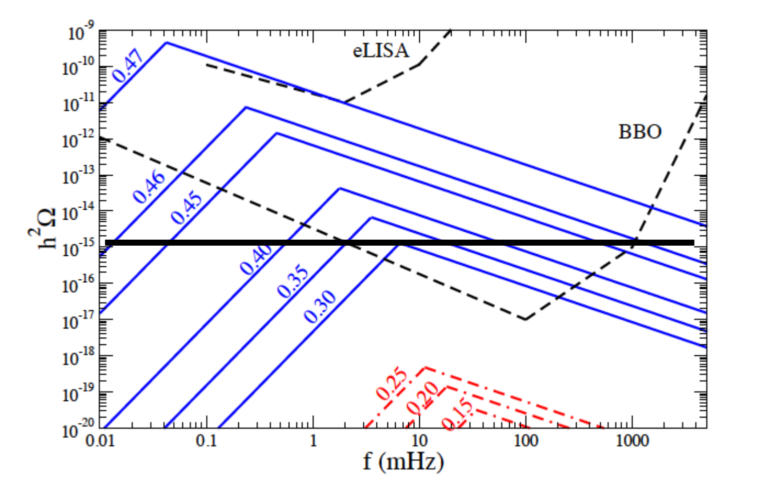
Transmitted to the SM by gauge mediation:

[Abel, Mariotti '13]



$$\delta V_{\rm eff} \equiv V_0 = -\frac{m_h^2}{4}\, h^2 \left(1 + X \log\left[\frac{h^2}{v^2}\right]\right) + \frac{\lambda}{4}\, h^4$$





MSSM + “singlets”

singlets models contain cubic (SHH) terms

at tree-level → stronger PT

New: problematic Higgs singlet mixing

also new sources of CP violation

problems: domain walls vs.

destabilization of the weak scale

which model to take?

Z_3 symmetry (NMSSM)

$Z_{5,7}$ R-symmetries (nMSSM)

extra U(1)’s (ESSM, …)

fat Higgs…

Pietroni ’92

Davies, Froggatt, Moorhouse ’96

S.H., Schmidt ’98

Bastero-Gil, Hugonie, King, Roy, Vespati ’00

Kang, Langacker, Li, Liu ’04

Menon, Morrissey, Wagner ’04

S.H., Konstandin, Prokopec, Schmidt ‘06

Balazs, Carena, Freitas, Wagner ‘07

(Profumo, Ramsey-Musolf, Shaughnessy ‘07)

Carena, Shah, Wagner ’11

Huang, Kang, Shu, Yang ’14

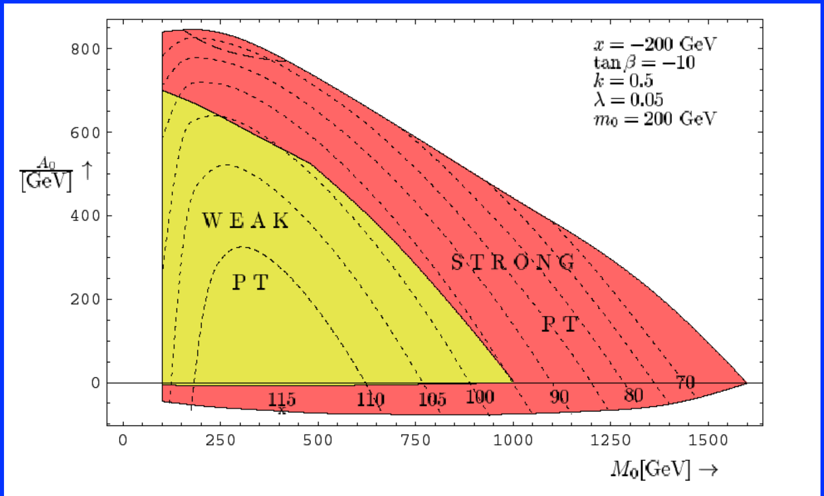
Kozaczuk, Profumo, Haskins, Wainwright ‘14

problem with 1-loop EDM‘s remains!

Strong phase transition

singlet model without discrete symmetries

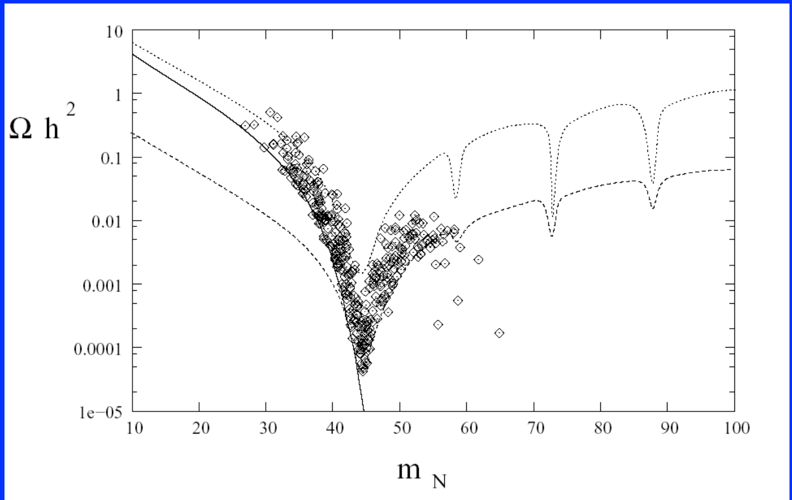
$$W = \lambda S H_1 H_2 + \frac{k}{3} S^3 + \mu H_1 H_2 + r S$$



S.H.,Schmidt '00

nMSSM

$$W_{nMSSM} = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + \frac{m_{12}^2}{\lambda} \hat{S}$$



Menon, Morrissey, Wagner ' 04

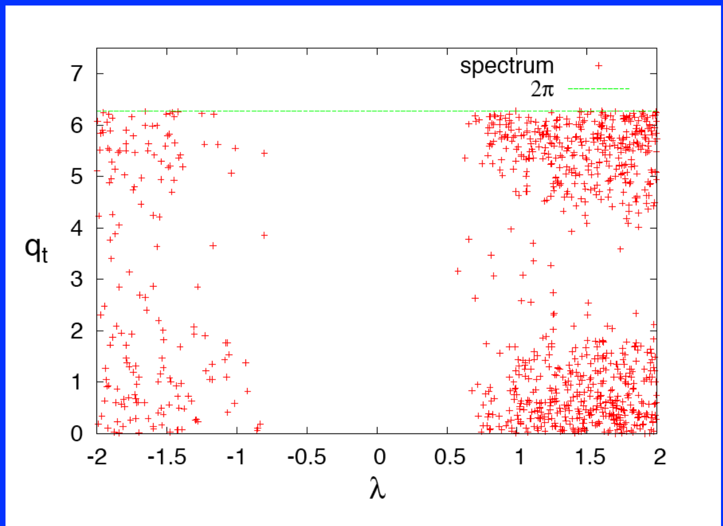
(S.H., Konstandin, Prokopec, Schmidt '06)

Baryogenesis in the nMSSM

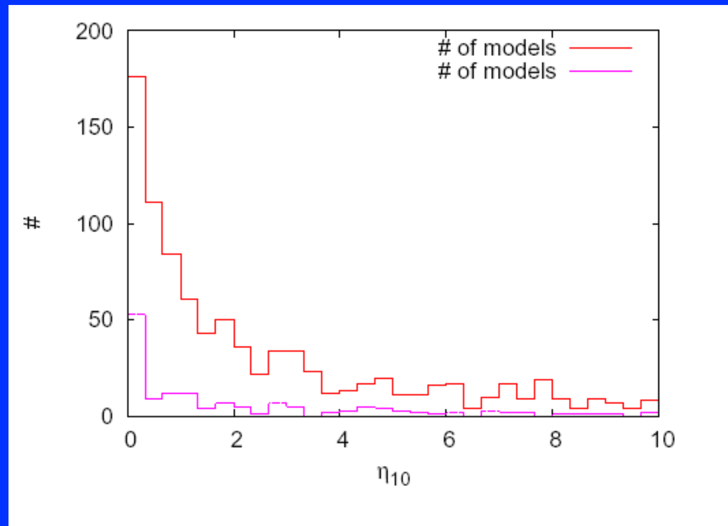
λ above Landau pole prefered:

(and tan β ~1)

CP violation in $t_S e^{iq} S$ (phase in μ parameter induced, not constant along the bubble wall)



EDM constraints with 1TeV sfermions (1. & 2. generation):



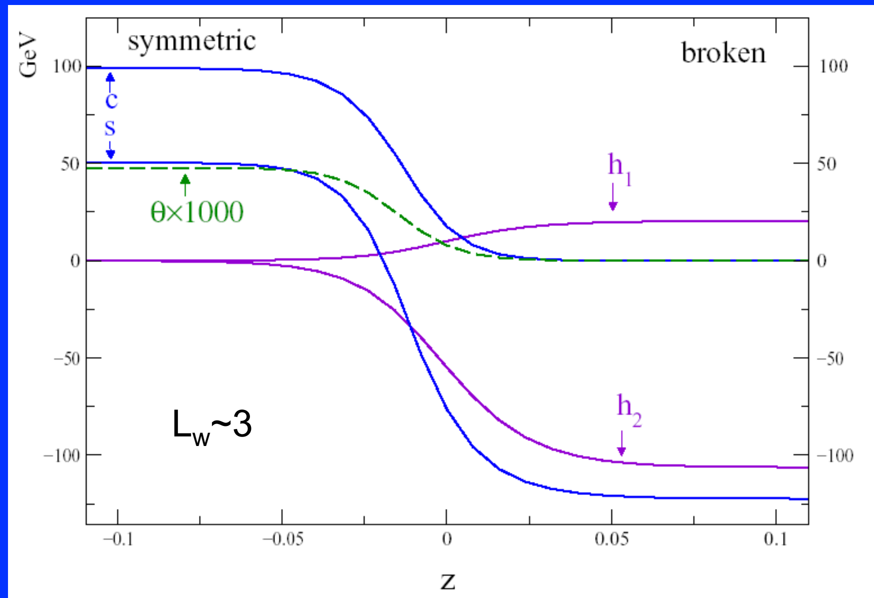
S.H., Konstandin, Prokopec, Schmidt '06

Transitional CP violation

in the general singlet model the broken minimum can be CP conserving, but the symmetric minimum violates CP

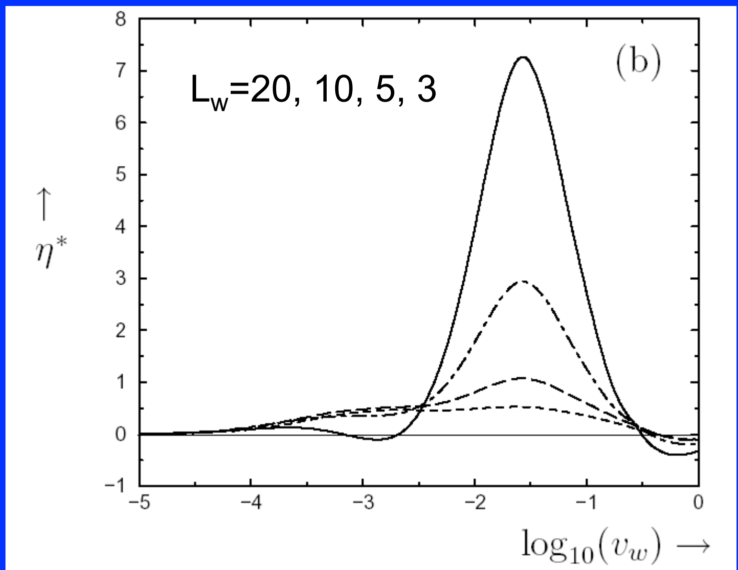
→ CP violating wall profile

CP conservation at T=0



x	$\tan\beta$	λ	k	M_0	A_0	m_0	A_λ	A_k	m_S^2
-150	-5	0.05	0.4	100	-100	200	−150	50	−2000

S.H., John, Laine, Schmidt '99

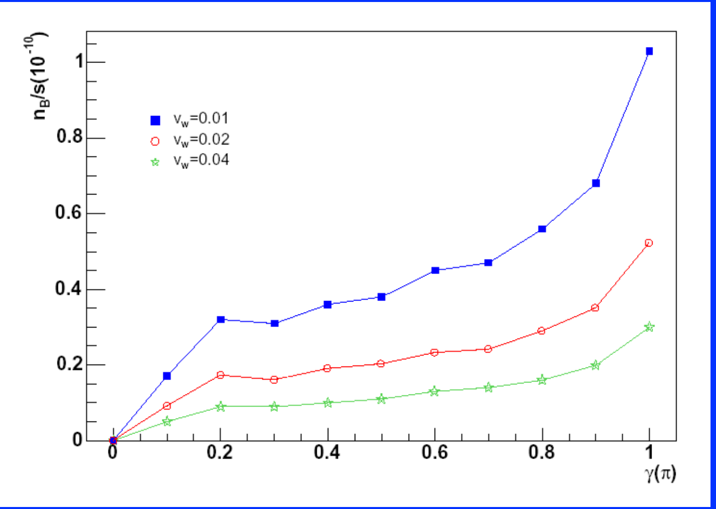


S.H., Schmidt '00

Extra U(1)´s

Kang, Langacker, Li, Liu ’04

$$W_H = hSH_dH_u + \lambda S_1S_2S_3$$



$$m^2_{S_1S_2} \equiv |m^2_{S_1S_2}|e^{i\gamma}$$

thin wall approximation used,
tau lepton contribution only

Ham, Oh ’07

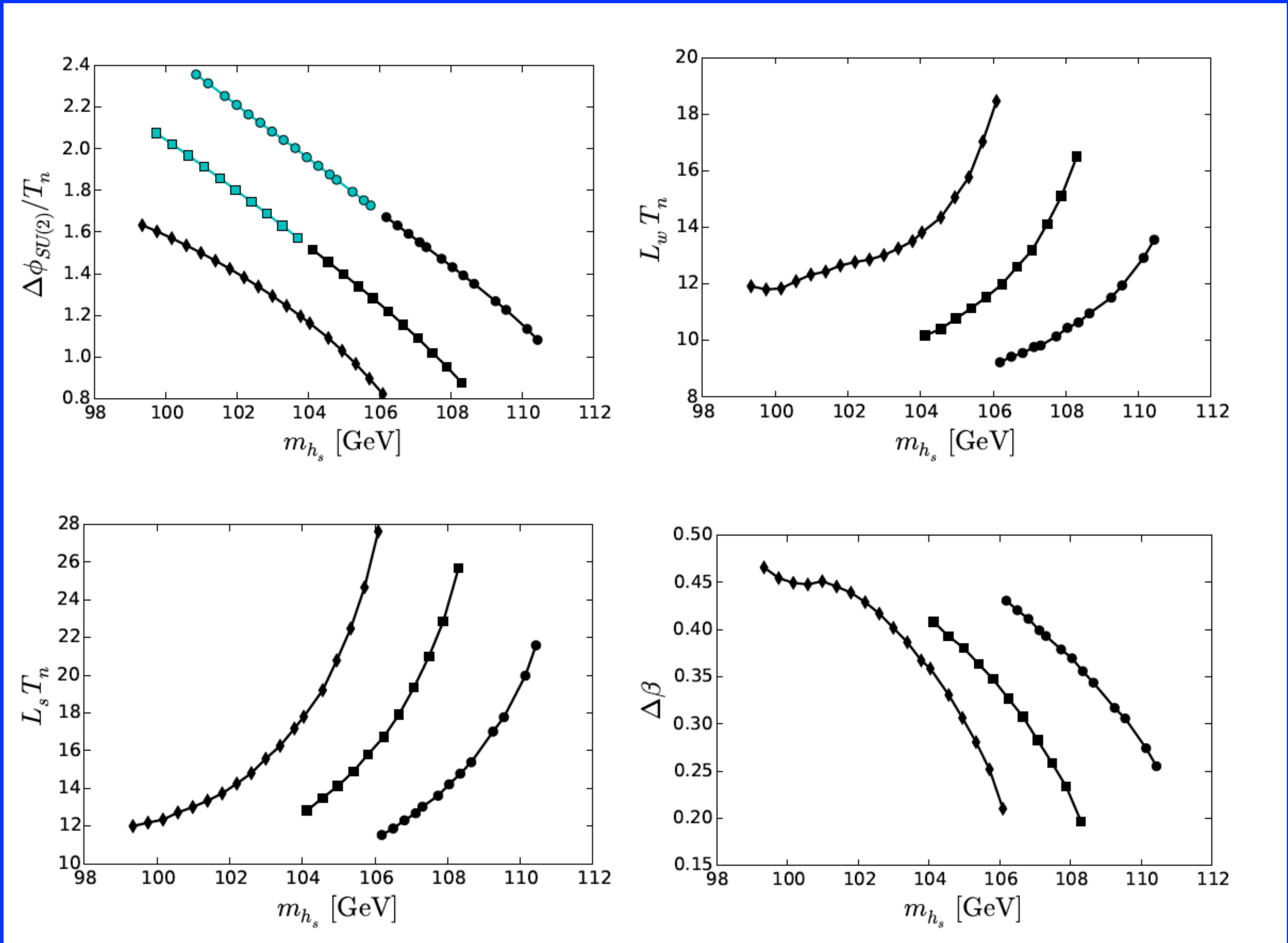
$$W \approx h_tQH_2t^c_R + \lambda NH_1^T\epsilon H_2$$

Strong phase transition possible

No computation of the BAU

Examples have large λ=0.7, 0.8

Z_3 NMSSM revisited: [Kozaczuk, Profumo, Haskins, Wainwright ’14]



Summary and outlook

► wealth of new constraints on a possible electroweak phase from measured Higgs properties

► strong phase transition in the 2HDM model is easy to realize and consistent with a SM-like light Higgs

► singlet extensions of the MSSM can easily accommodate baryogenesis: but there are interesting constraints from Higgs properties and EDMs

► first 3d numerical simulation of scalar + fluid

GW production by sound waves

no sign of turbulence

► Can one have baryogenesis and GW's at the same time?