Electroweak Baryogenesis before LHC run II

Stephan Huber, University of Sussex

NIKHEF, Amsterdam

February 2015

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]

Axino LSP baryogenesis [1412.5586]

....

Leptogenesis

Here: 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

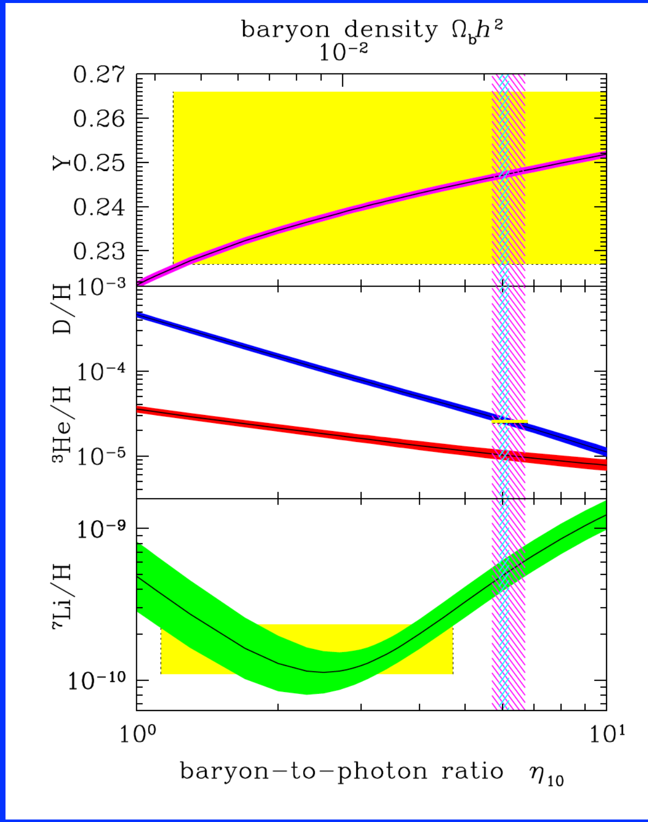
Can we repeat this success for the baryon asymmmetry?

Problem: only 1 observable

→ Need to be convinced by a specific model:

Theory?, Experiment? (inspiration??) …

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

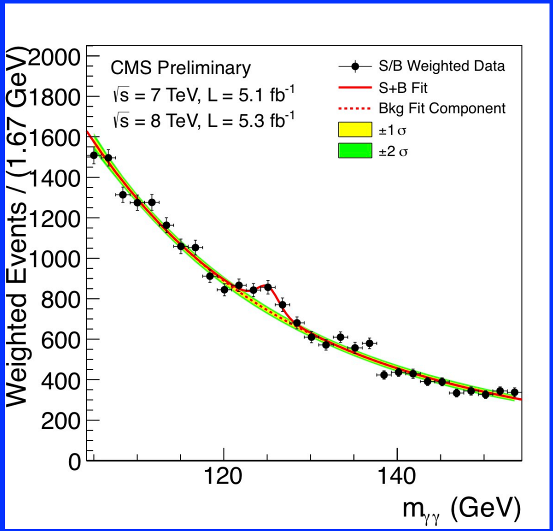
Electric dipole moments

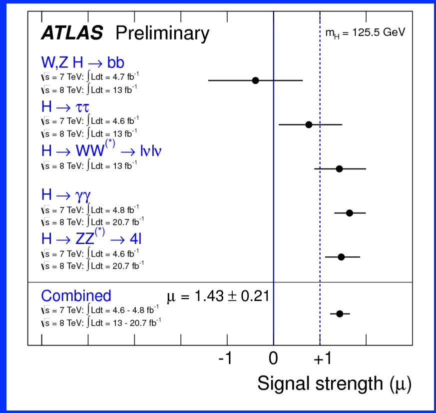
Computational tools

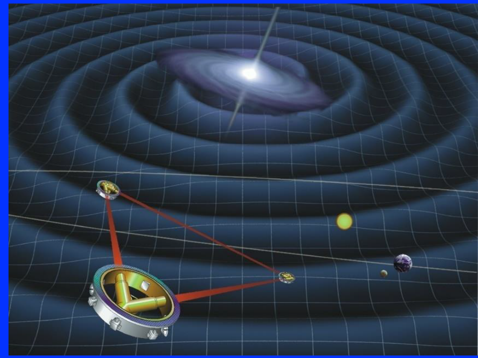
Transport

hydrodynamics

Baryon asymmetry







First-order electroweak Phase transition

eLISA 2034

eLISA cosmo working group meeting, CERN April 14-17 2015

New bound on electron EDM

Less progress for neutron EDM

Outline

- brief review (phase transition, baryogenesis)
- example 1: 2HDM: phase transition, baryogenesis, LHC
- gravitational waves, fluid dynamics: Gravitational wave production is dominated by sound waves
- example 2: scale breaking in hidden sector
- Summary & outlook

The basics

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

~~Baryon number~~

~~C~~

~~CP~~

~~Equilibrium~~

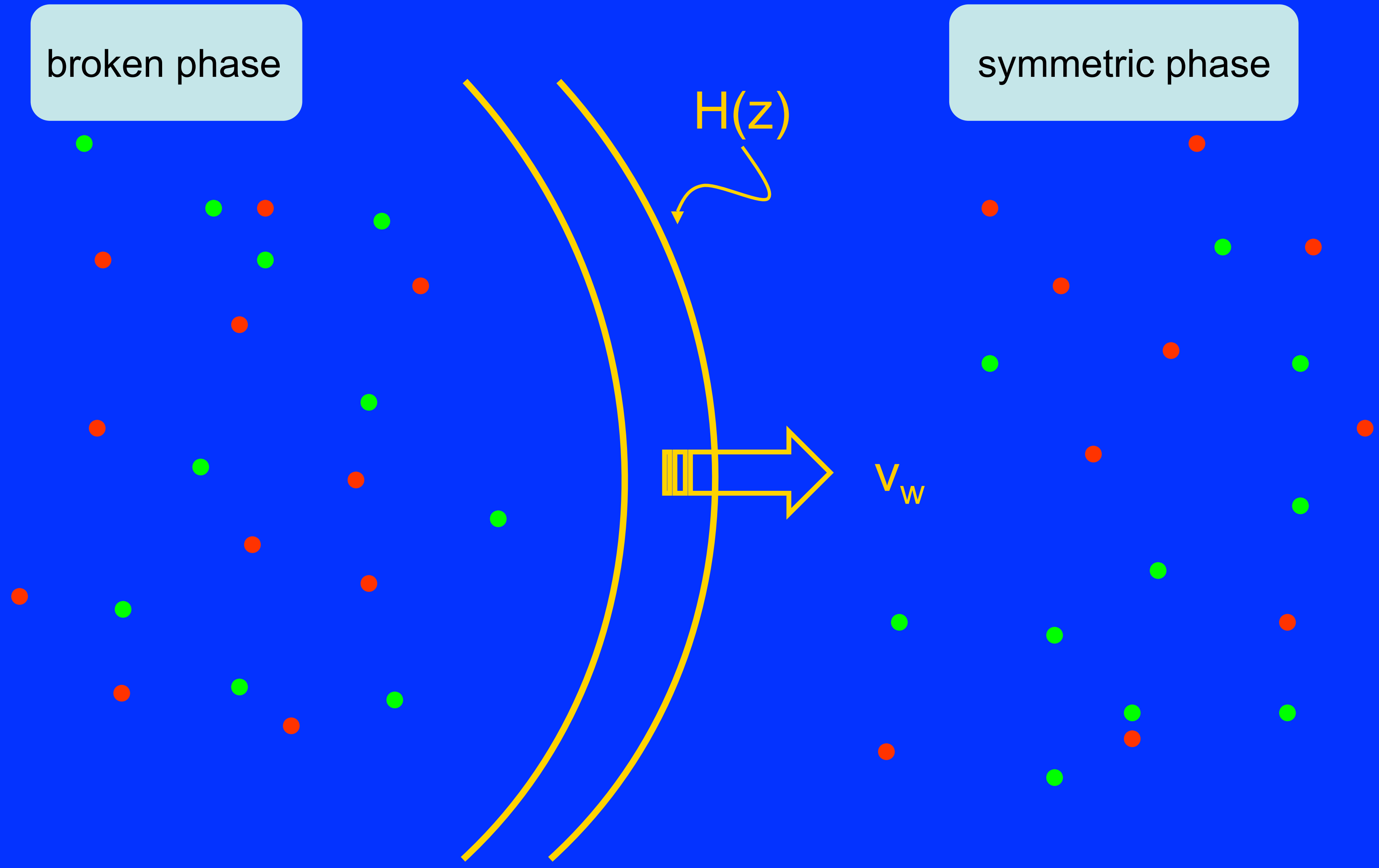
Sakharov ‘67

SM

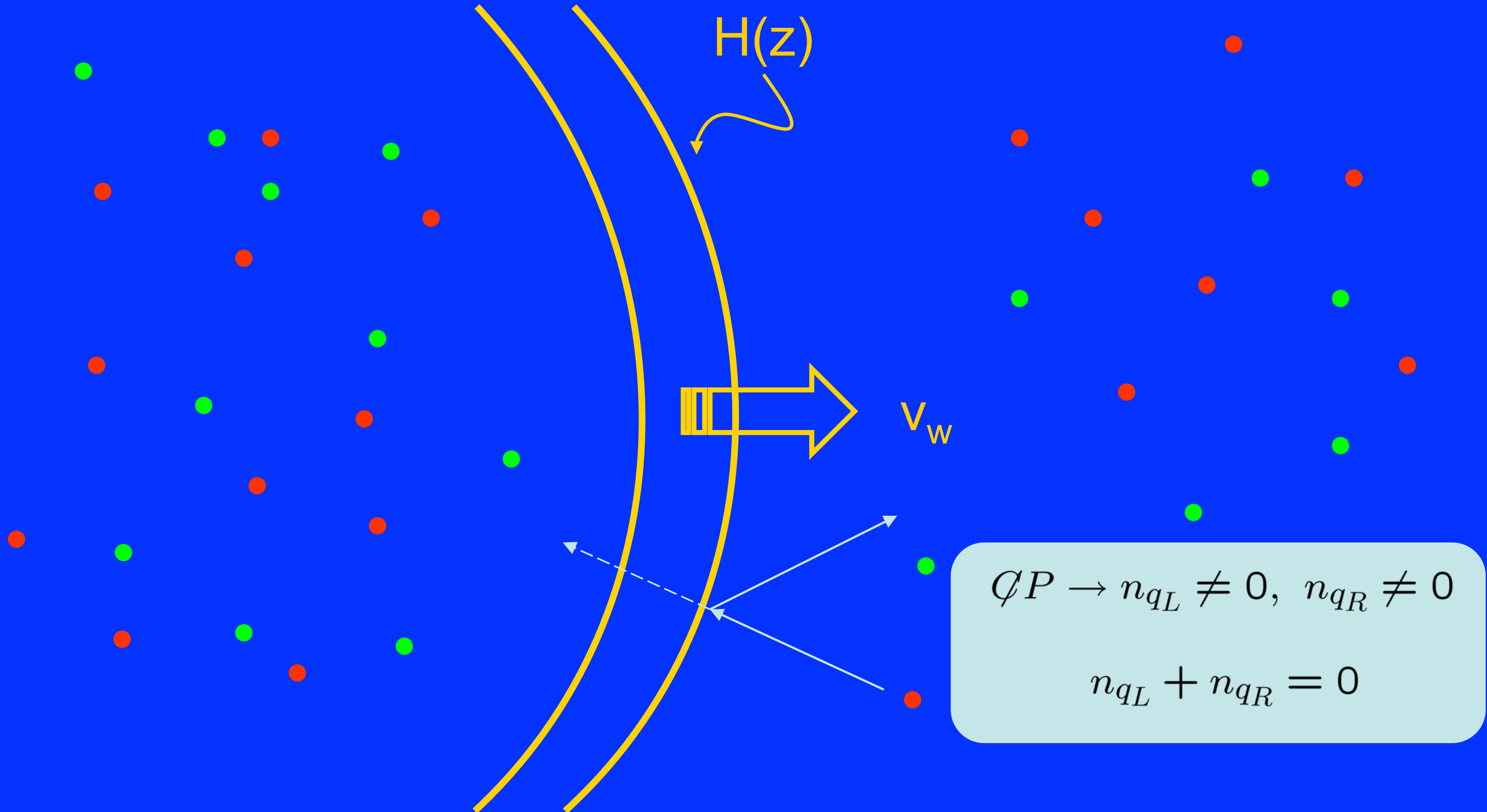
Sphalerons		+
Gauge interactions		+
Yukawa interactions		?
Electroweak phase transition		?

Kuzmin, Rubakov, Shaposhnikov ‘85

The mechanism



The mechanism



$$\not{C}P \rightarrow n_{q_L} \neq 0, \;\; n_{q_R} \neq 0$$

$$n_{q_L} + n_{q_R} = 0$$

The mechanism

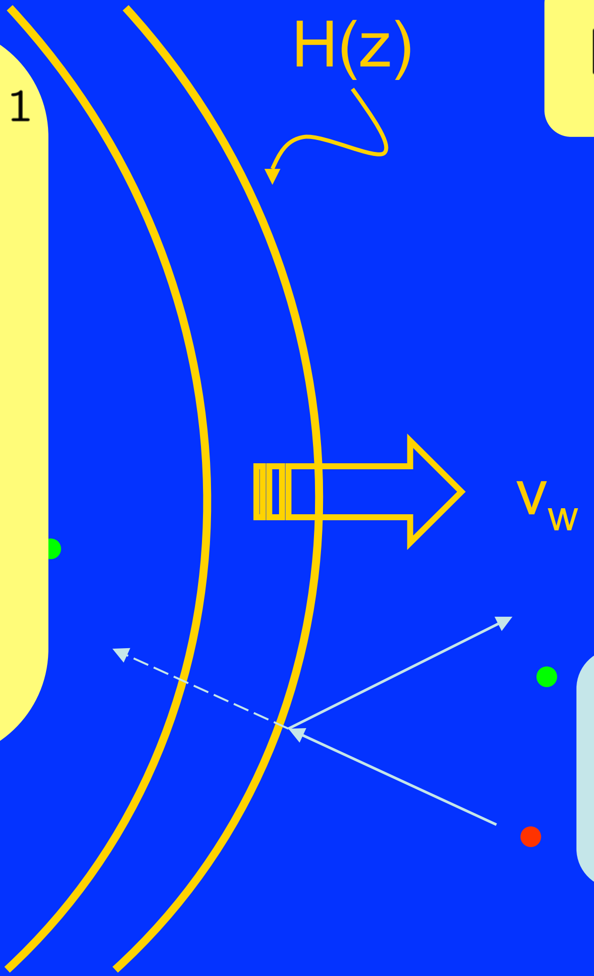
$\Gamma_{\text{sph}} \sim T_c^4 \exp(-\kappa v_c/T_c) \ll 1$

⇓

$$\frac{v_c}{T_c} > 1.0$$

⇕

“strong PT”



$\Gamma_{\text{sph}} \sim T_c^4 \longrightarrow \not{B}$

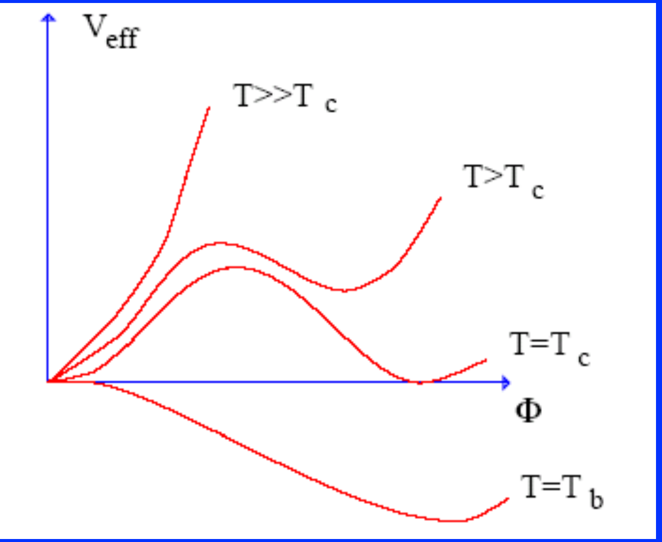
$\not{C}\not{P} \rightarrow n_{q_L} \neq 0,\ n_{q_R} \neq 0$

$n_{q_L} + n_{q_R} = 0$

The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$



- Bosons in the plasma:

SM: gauge bosons

strong PT: m_h<40 GeV (no top)

never (with realistic top mass)

Lattice: crossover for m_h>80 GeV → the SM fails: NEW PHYSICS!

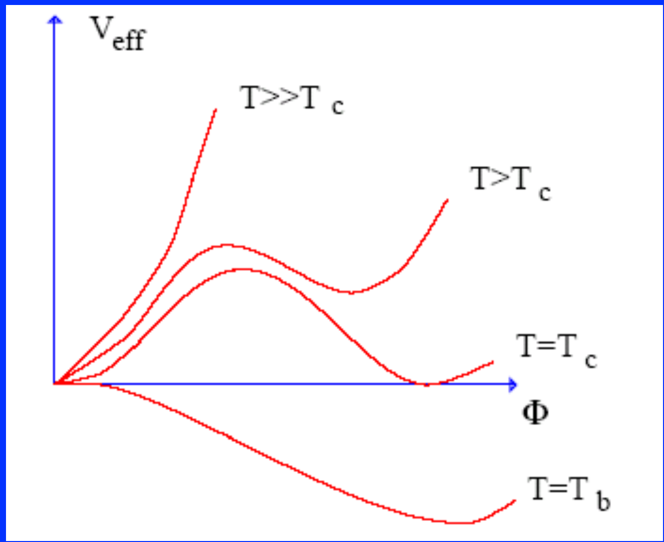
Kajantie, Laine, Rummukainen, Shaposhnikov 1996

Csikor, Fodor, Heitger 1998

The strength of the PT

Thermal potential:

$$V(H,T) = m^2(T)H^2 - E(T)H^3 + \lambda(T)H^4$$



- Bosons in the plasma:

  SM: gauge bosons

  SUSY: light stops [Laine, Nardini, Rummumainen '12]

  2HDM: heavy Higgses [Dorsch, SJH, No '13]

- tree-level: extra singlets: λSH^2, NMSSM, etc. [Kozaczuk et al.'14]
- replace H^4 by H^6 or introduce $H^2\log(H^2)$, etc. [Dorsch, SJH, No '14]

Transport and CP violation

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, many?

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

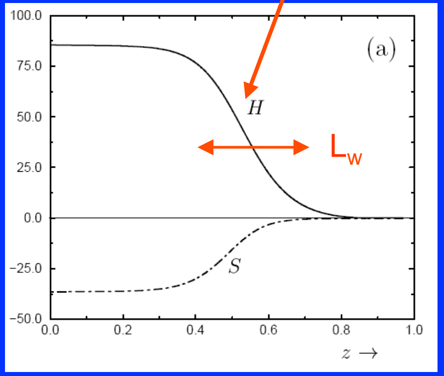
Joyce, Prokopec, Turok '95
Cline, Joyce, Kainulainen '00
Kainulainen, Prokopec, Schmidt, Weinstock '01-'04

„thick“

Phase in fermion mass can vary along the wall (wall width L_w)

e.g. because the phase between the Higgs vevs changes:

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



Classic: The MSSM

strong PT from stop loops

→ right-handed stop mass ~100 GeV

left-handed stop mass ~1000 TeV

CP violation from varying chargino mixing

resonant enhancement of η for M_2 ~ μ

chargino mass < ~300 GeV

large phases > 0.2 required

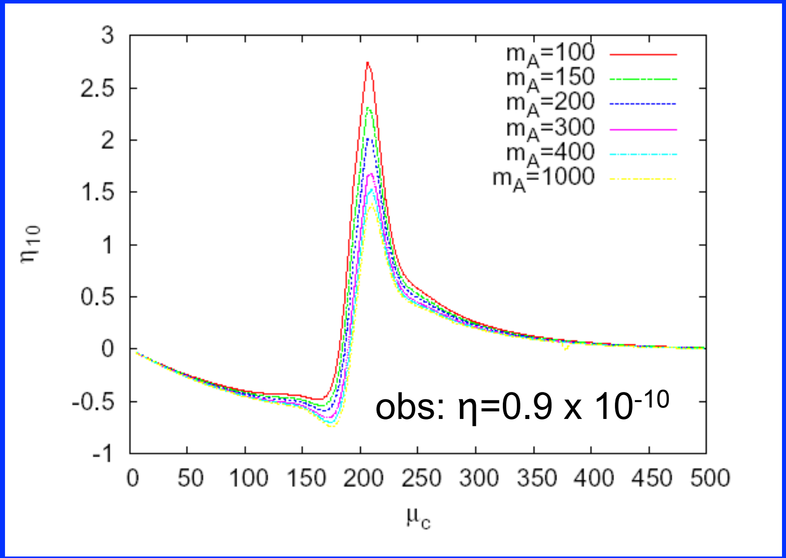
→ 1st and 2nd generation squarks

heavy to keep 1-loop EDMs small

→ "Split SUSY + light stop"

Konstandin, Prokopec, Schmidt, Seco '05

v_w=0.05, M_2=200 GeV, maximal phase



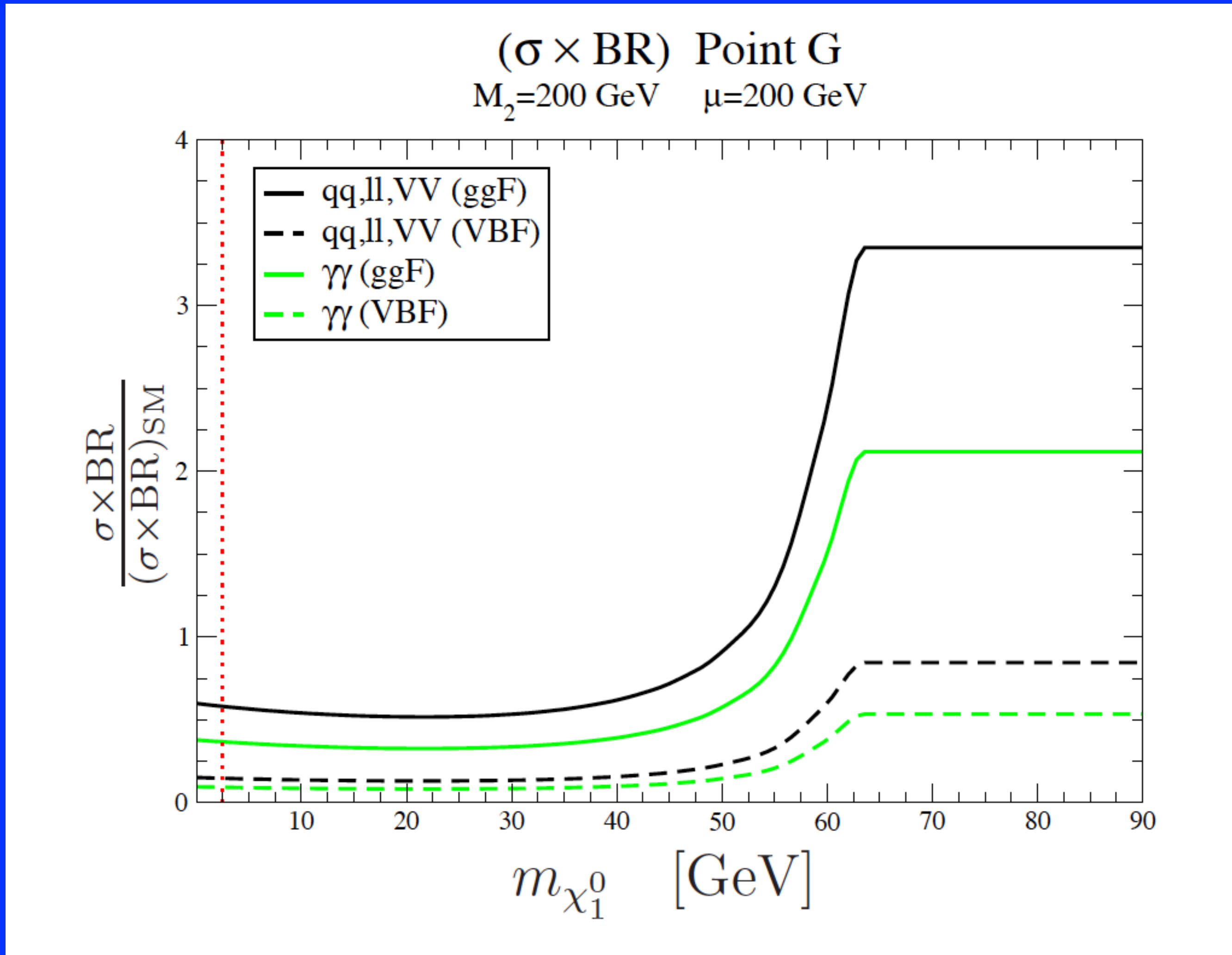
similar but somewhat more optimistic

results in Carena, Quiros, Seco, Wagner '02

Cirigliano, Profumo, Ramsey-Musolf '06

→ scenario is tightly constrained!

Possible test: modified Higgs branching ratios, e.g. into two photons:



[Carena, Nardini, Quiros,Wagner 2012]

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

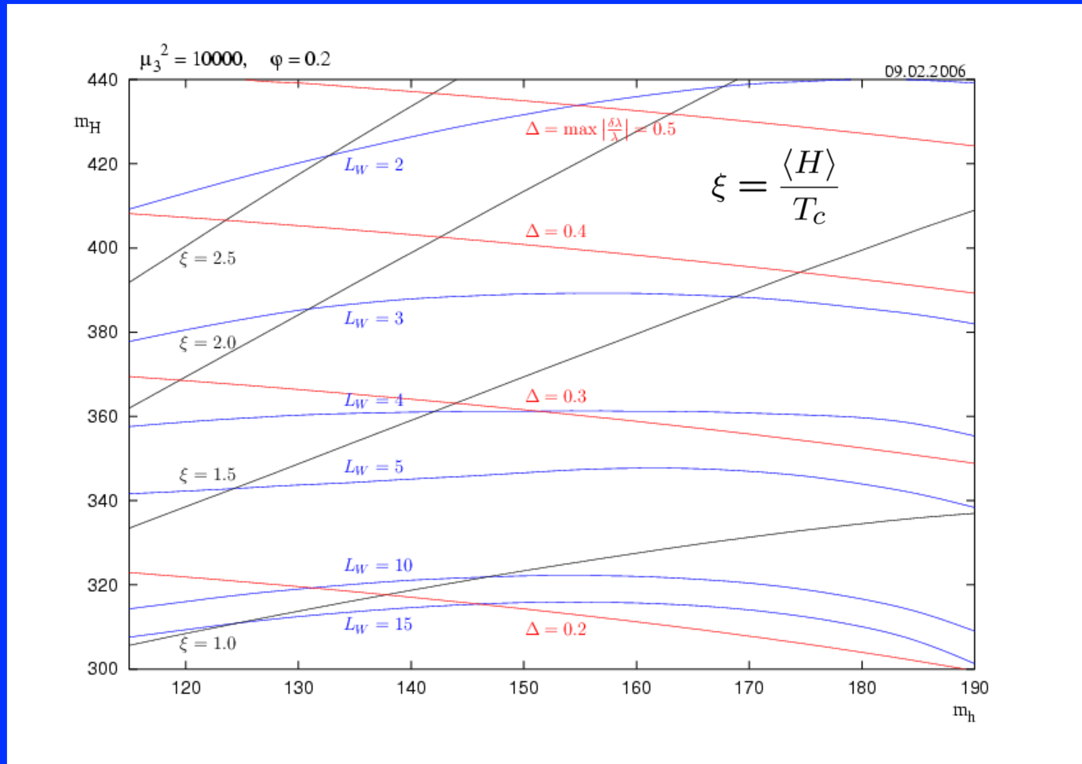
→ strong PT for

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]

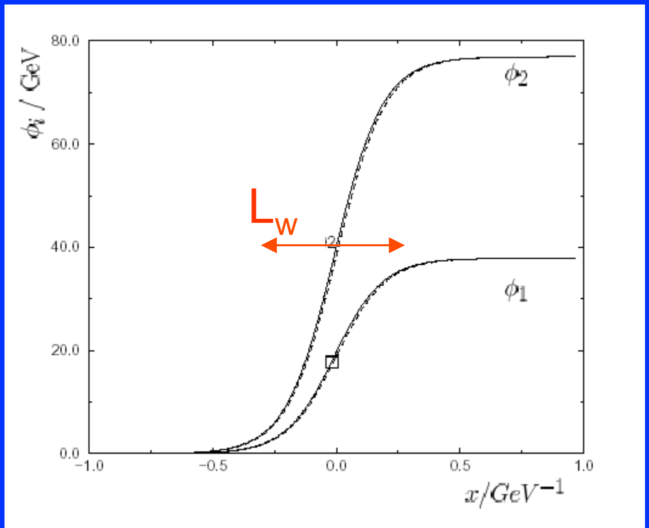
missing: 2-loop analysis of the thermal potential; lattice; wall velocity

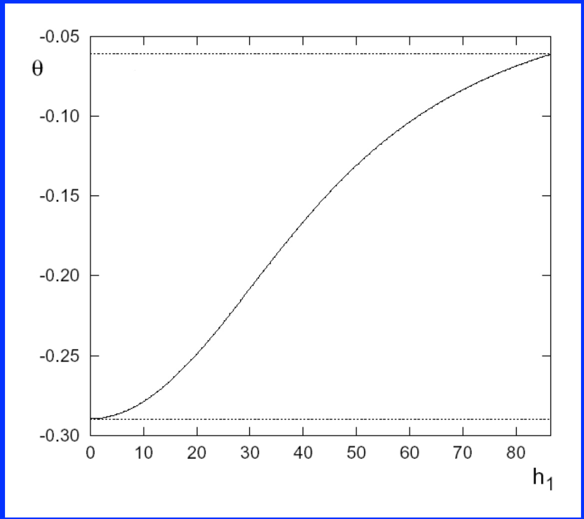
The bubble wall

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

kink-shaped with wall thickness L_w

θ becomes dynamical





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

The baryon asymmetry

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

→ phase of the top mass varies

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

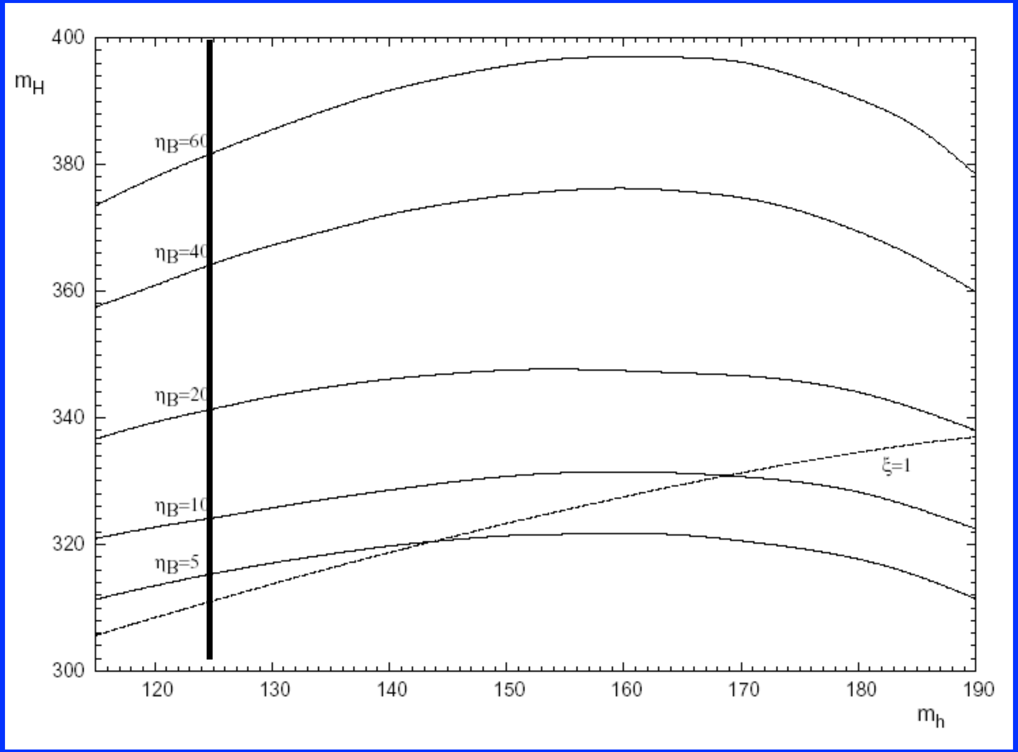
top transport generates a baryon asymmetry, but

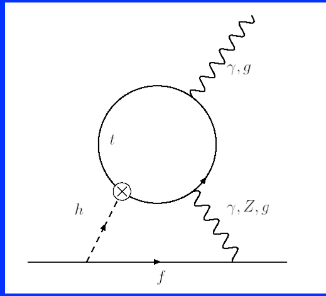
tanβ<10 (?)

→ 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

The baryon asymmetry

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

→ phase of the top mass varies

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

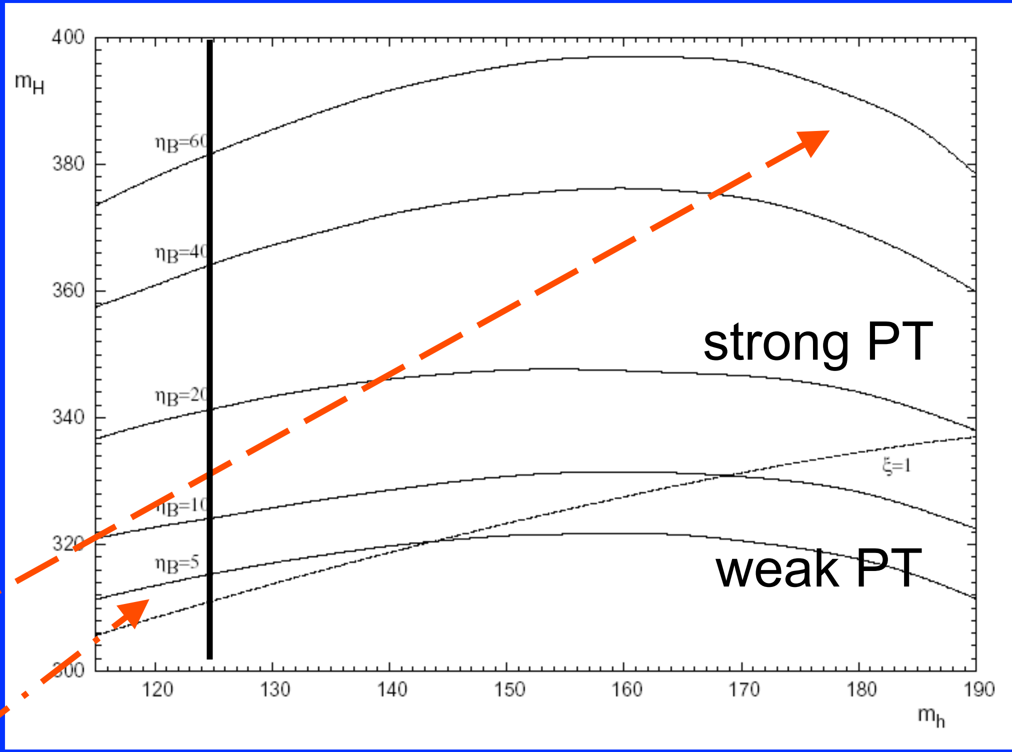
top transport generates a baryon asymmetry, but

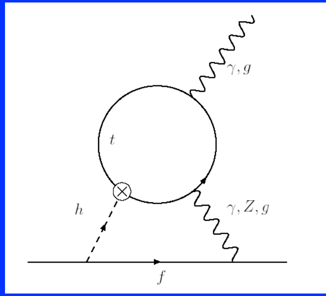
$\tan\beta < 10$ (?)

→ 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

In progress: update using the new bound on the 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

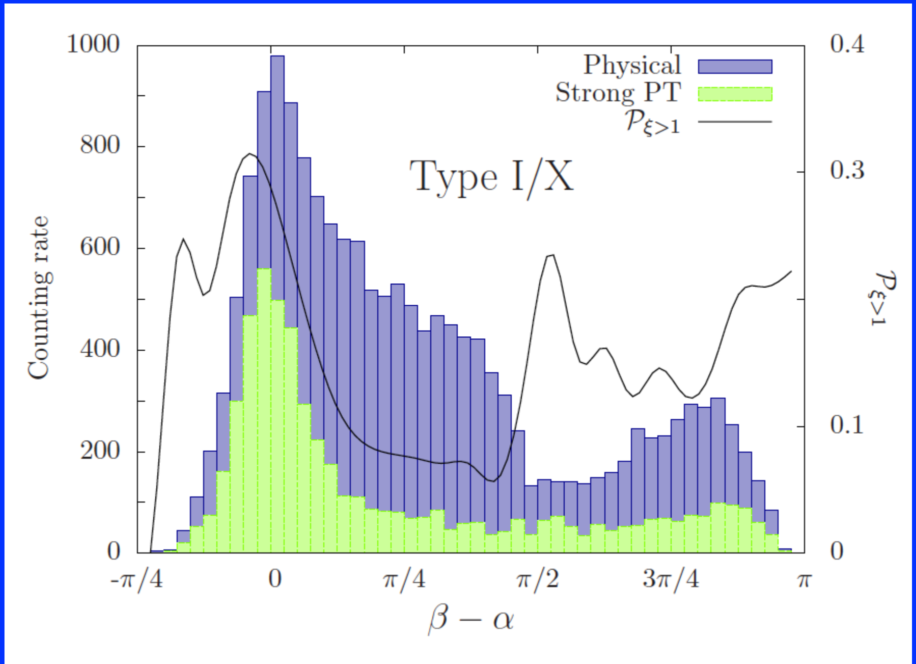
We analyze the thermal 1-loop potential

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

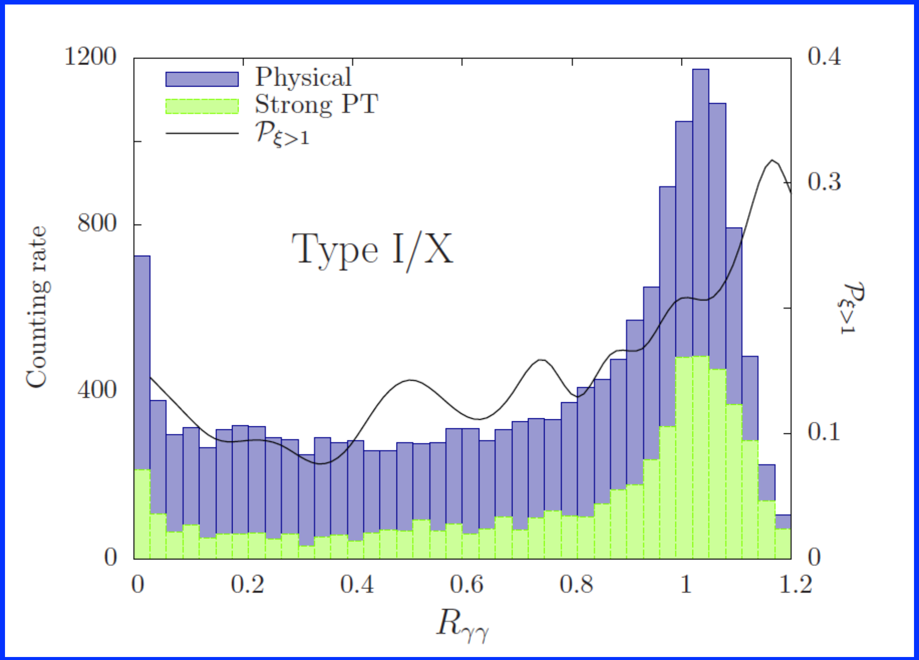
(parameter ranges, m_h=125 GeV)

Constraints: rho-parameter

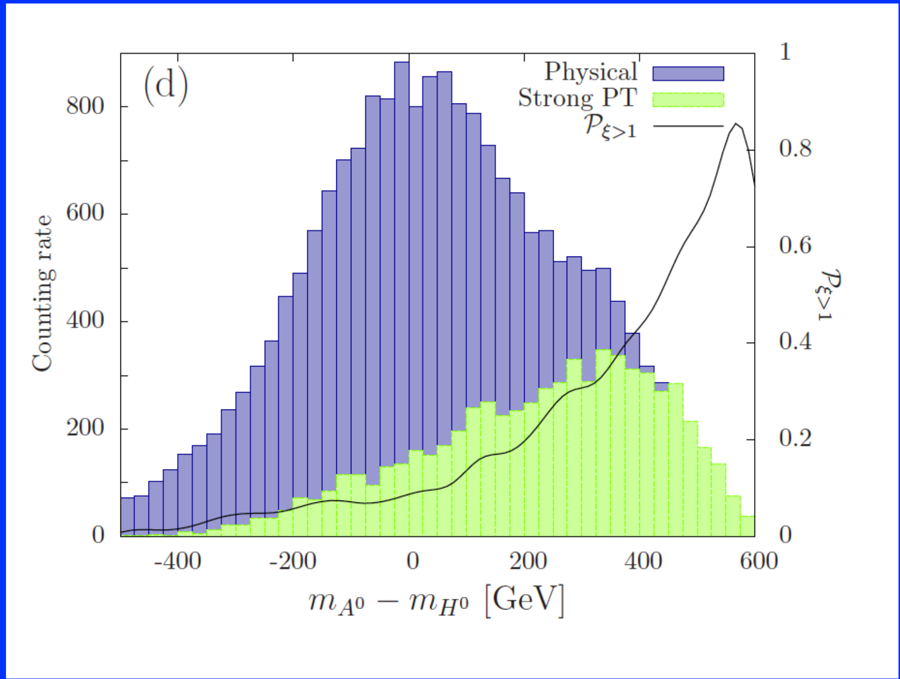
B→ s γ, B-Bbar mixing



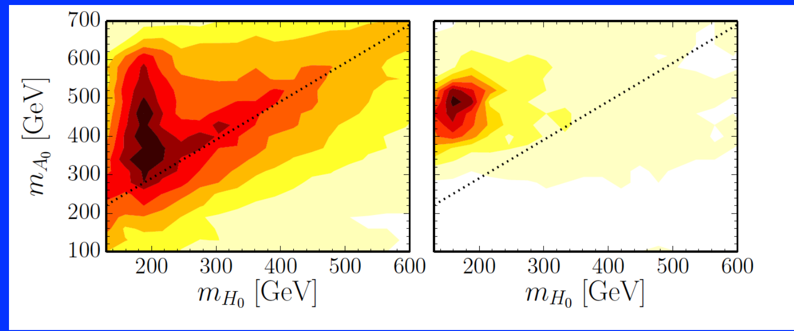
SM like
Higgs?



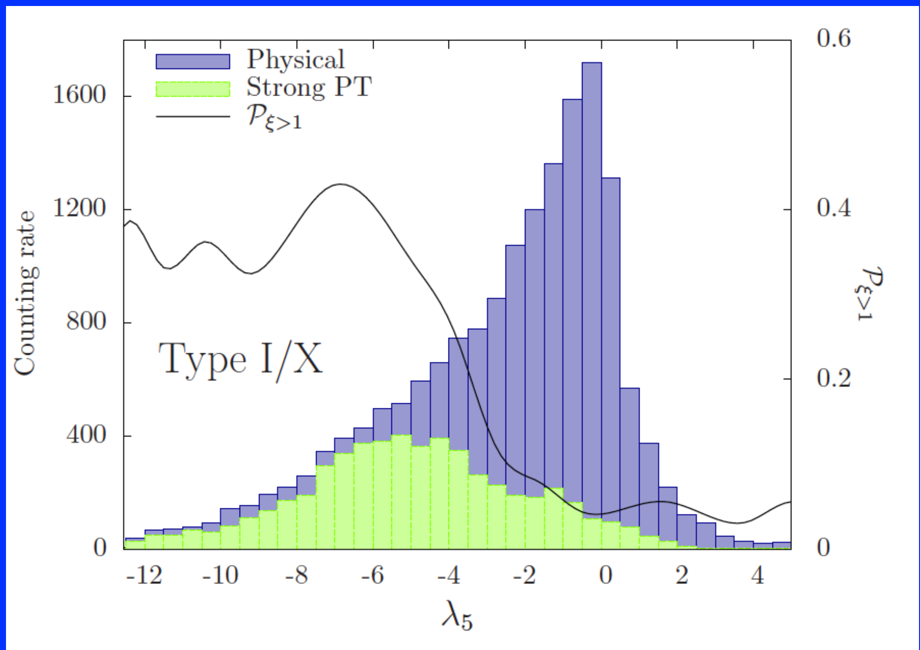
Di-photon channel



Preference for a heavy pseudoscalar



[Dorsch, S.H., Mimasu, No ‘14]



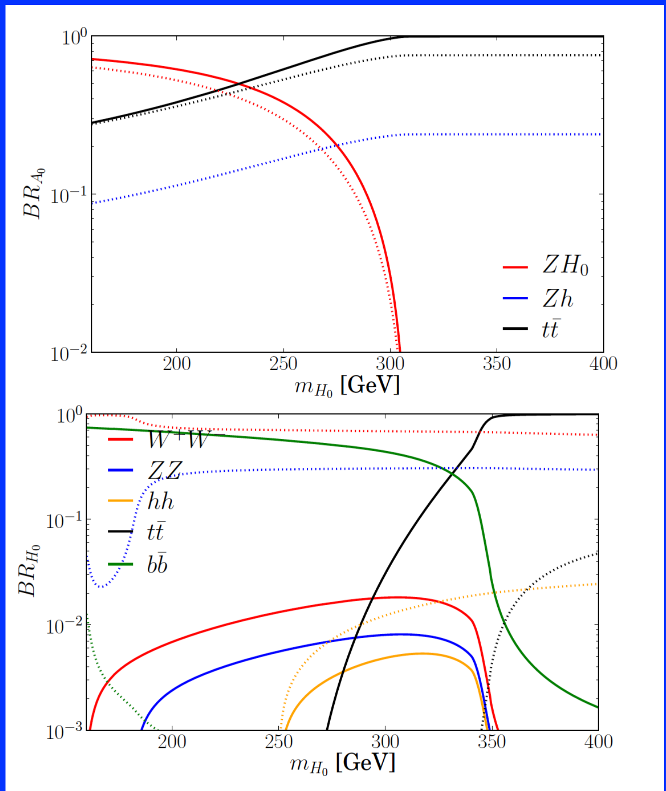
Preference for a large negative λ_5

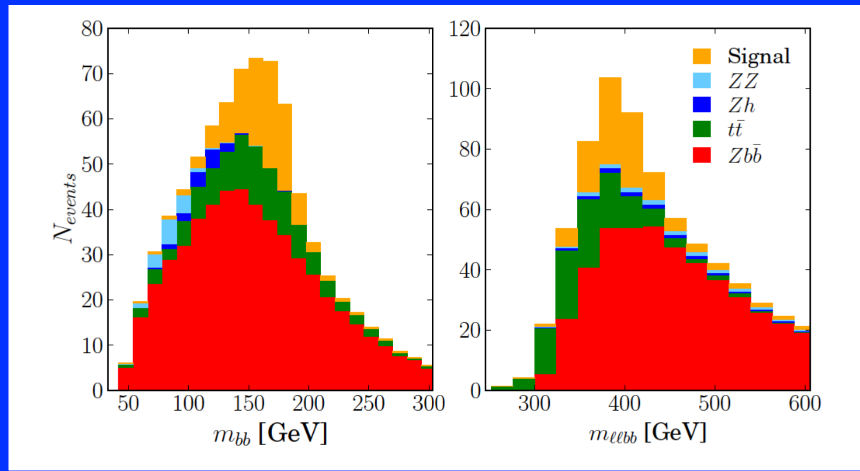
$$\frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right]$$

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

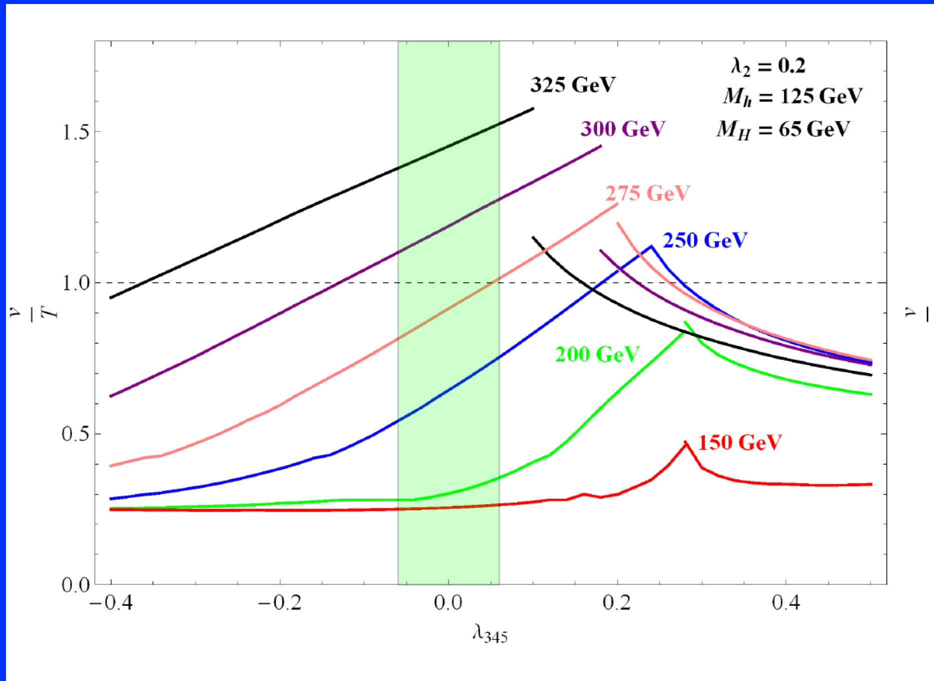
$$\mathbb{Z}_2: \quad \Phi_1 \to \Phi_1\,, \qquad \Phi_2 \to -\Phi_2\,,$$
$$\mathbb{Z}_2': \quad \Phi_1 \to -\Phi_1\,, \qquad \Phi_2 \to \Phi_2\,, \qquad f_R \to -f_R\,,$$

similar: Higgs + scalar singlet + fermion singlet dark matter

[Fairbairn, Hogan 2013]

NMSSM-like SUSY, e.g.

[Menon, Morrissey, Wagner ’04]



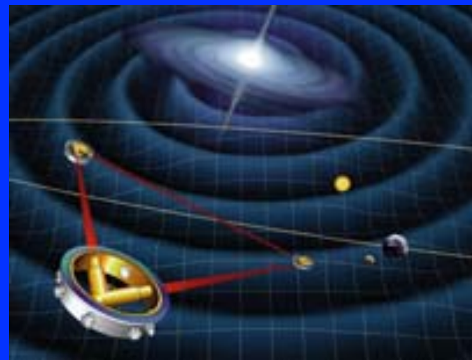
[Gil, Chankowski, Krawczyk 2012]

Numerical Simulations

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

Gravitational waves

LISA / eLISA



sources of GW's: direct bubble collisions

turbulence

(magnetic fields)

sound waves

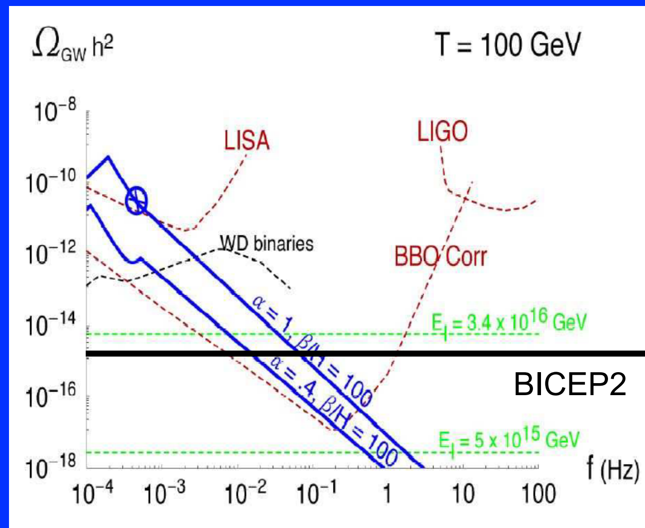
key parameters: available energy

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

typical bubble radius

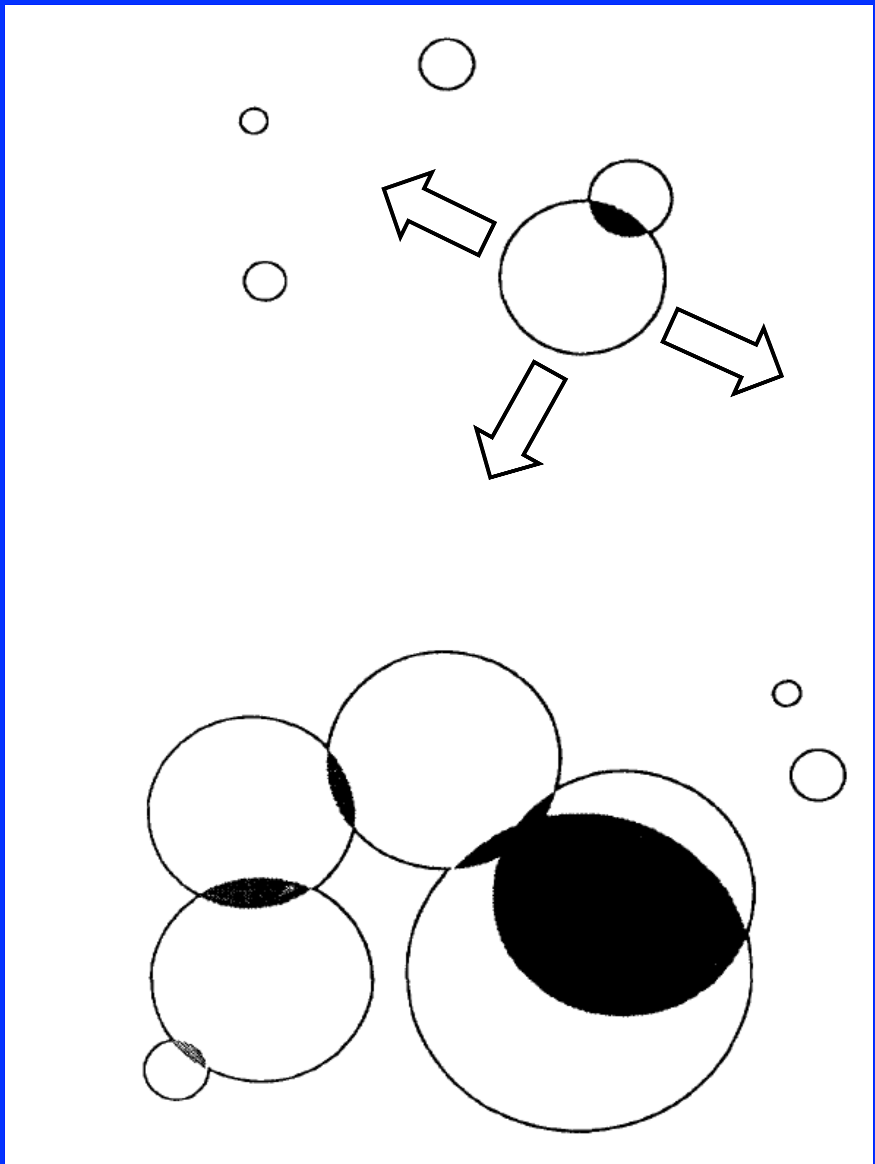
$$\langle R \rangle \propto v_b\,\tau \approx \frac{v_b}{\beta}.$$

v_b wall velocity



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)

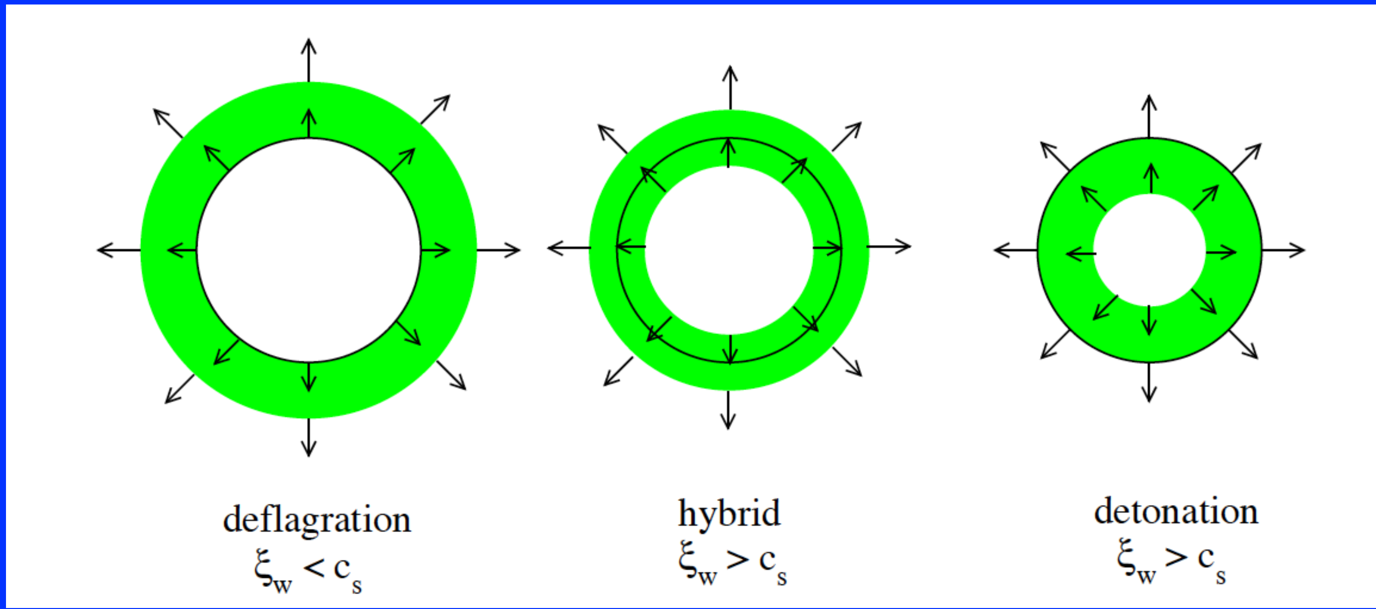
$$\dot{Z}_i + \partial_j(Z_iV^j) + \partial_iP + \frac{\partial V}{\partial \phi}\partial_i\phi = -\eta W(\dot{\phi} + V^j\partial_j\phi)\partial_i\phi.$$

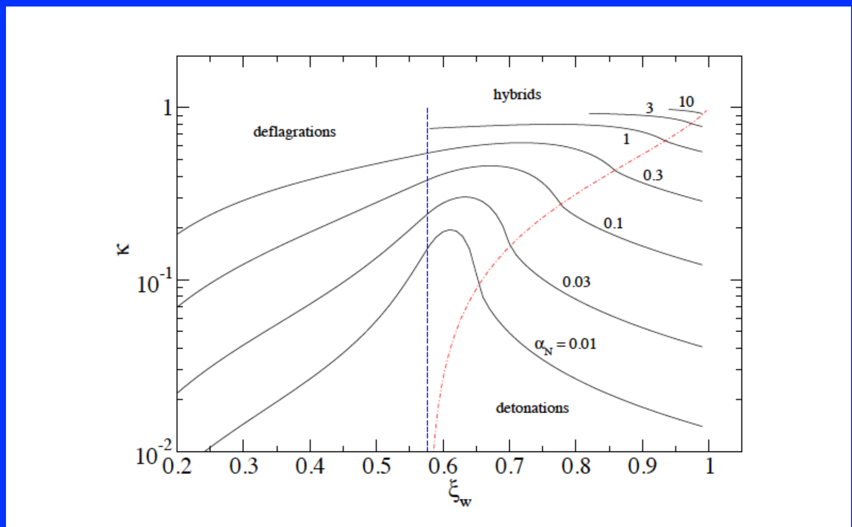
(eqn. for the momentum density)

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

(eqn. for the metric perturbations)

Types of single bubble solutions:



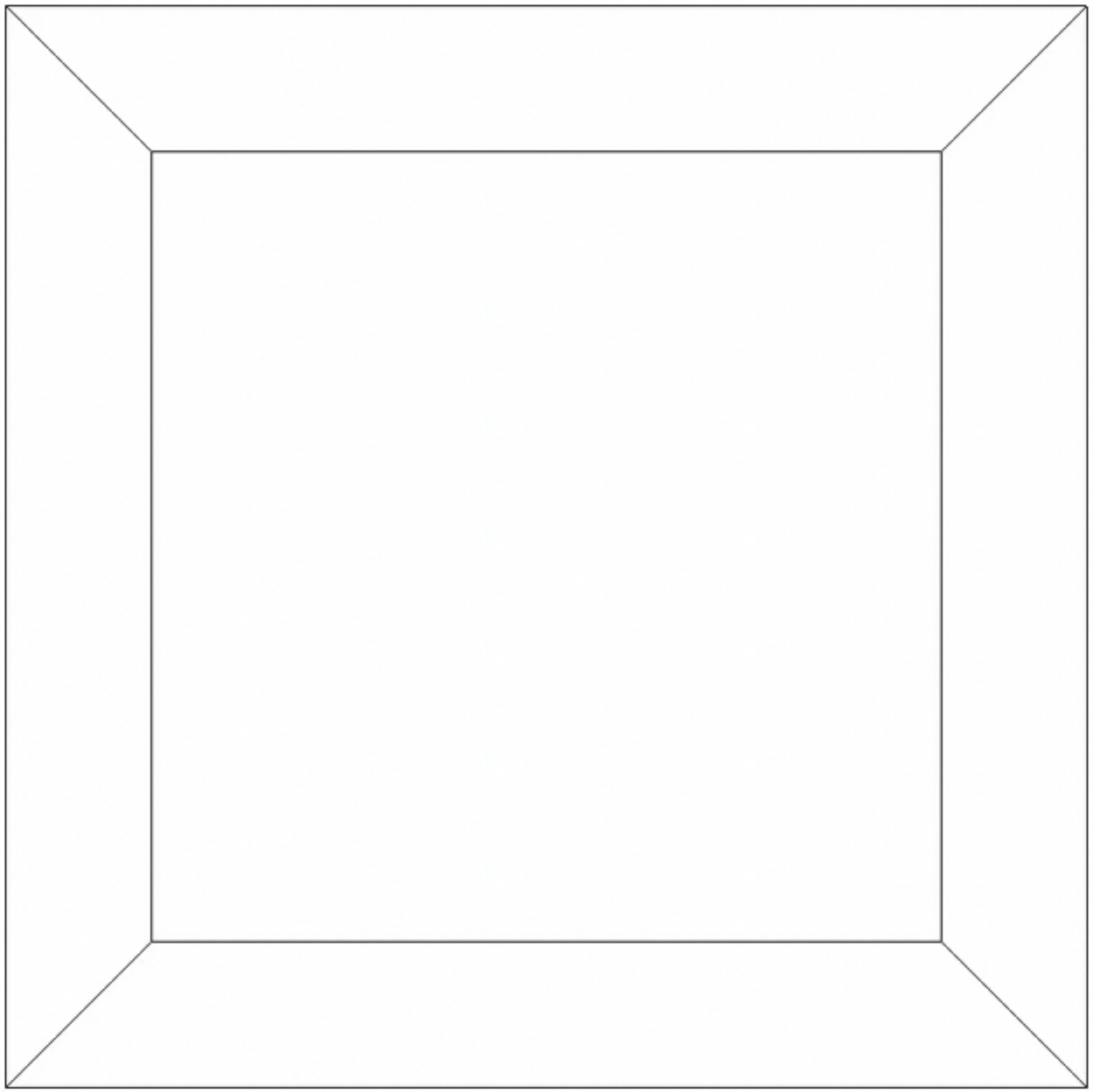


Espinosa, Konstandin, No, Servant ‘10

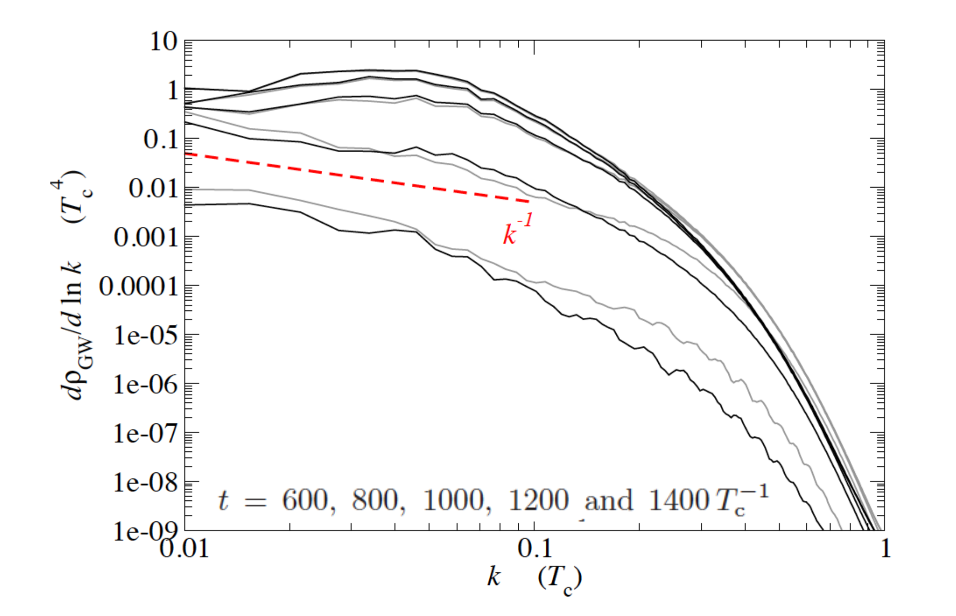
1024^3

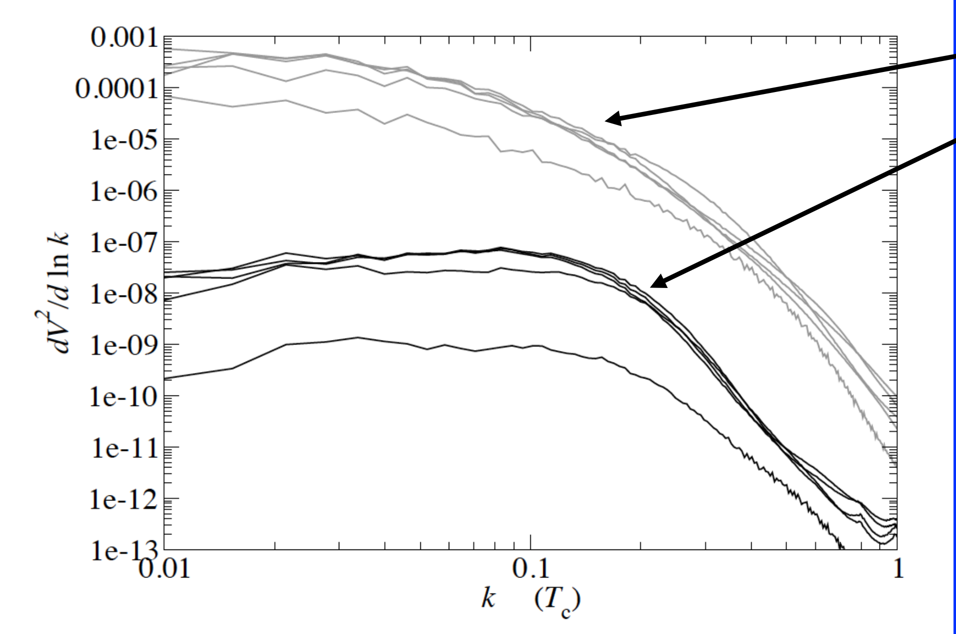
Lattice

Fluid energy



GW Spectrum





longitudinal and transverse 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?

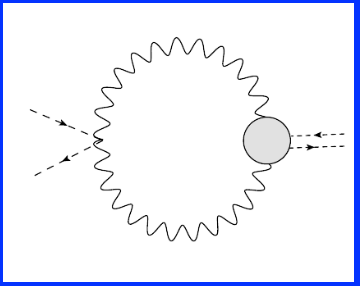
Scale invariant Higgs

Higgs mass stabilized by conformal symmetry,

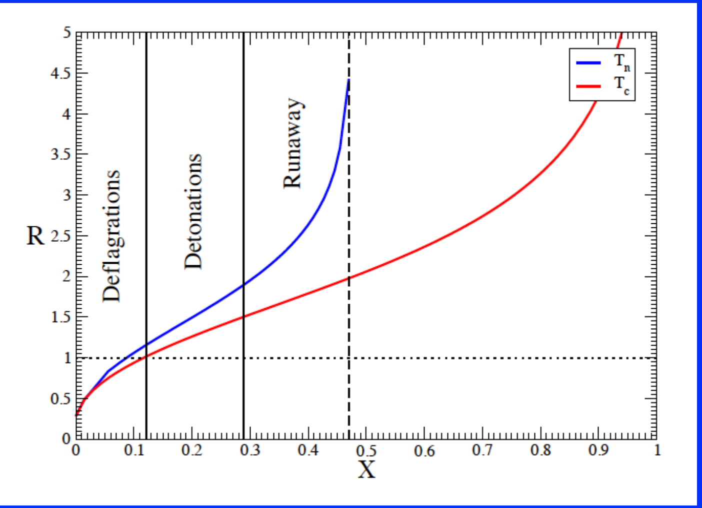
Broken in a hidden sector,

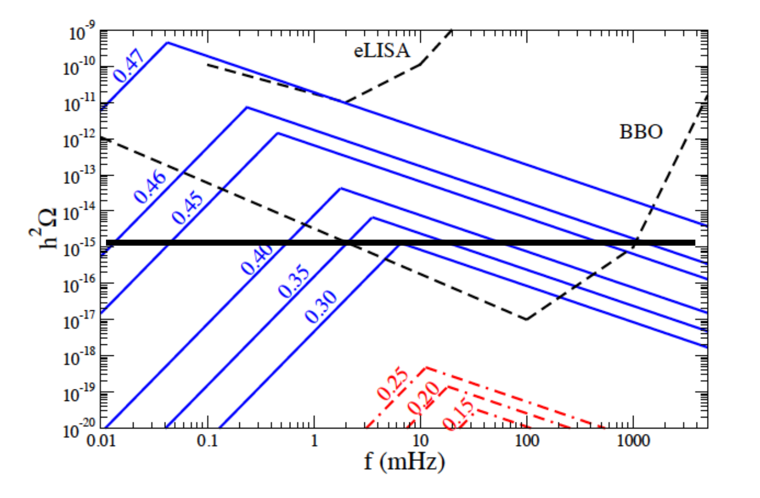
Transmitted to the SM by gauge mediation:

[Abel, Mariotti '13]



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





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

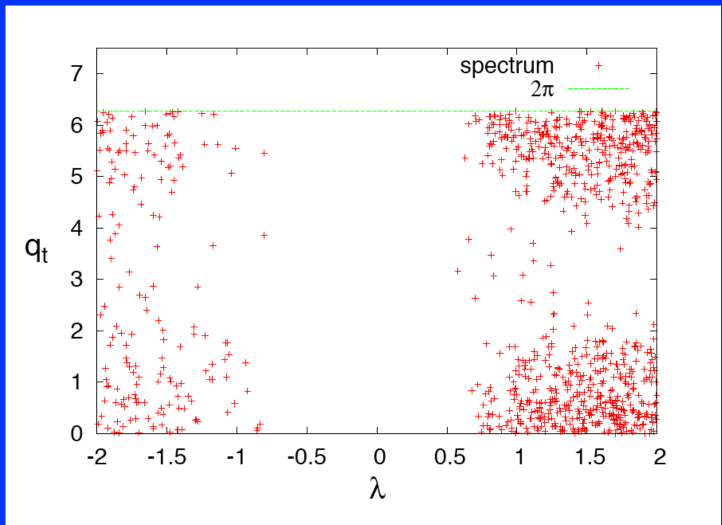
problem with 1-loop EDM's remains!

Baryogenesis in the nMSSM

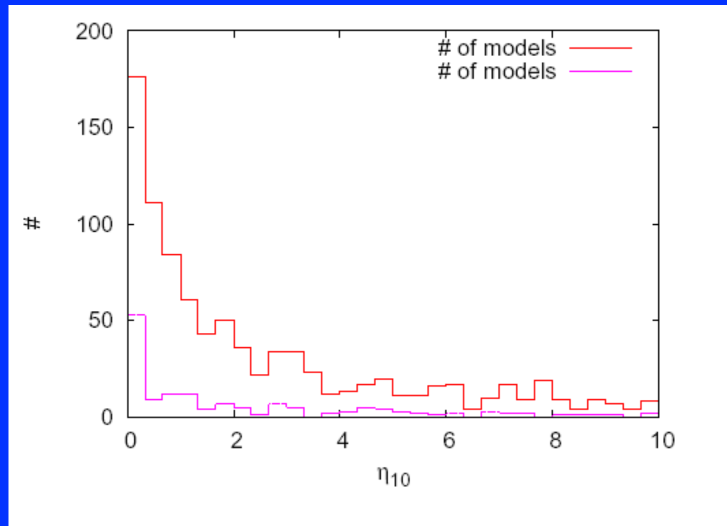
λ above Landau pole prefered:

(and tan β ~1)

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



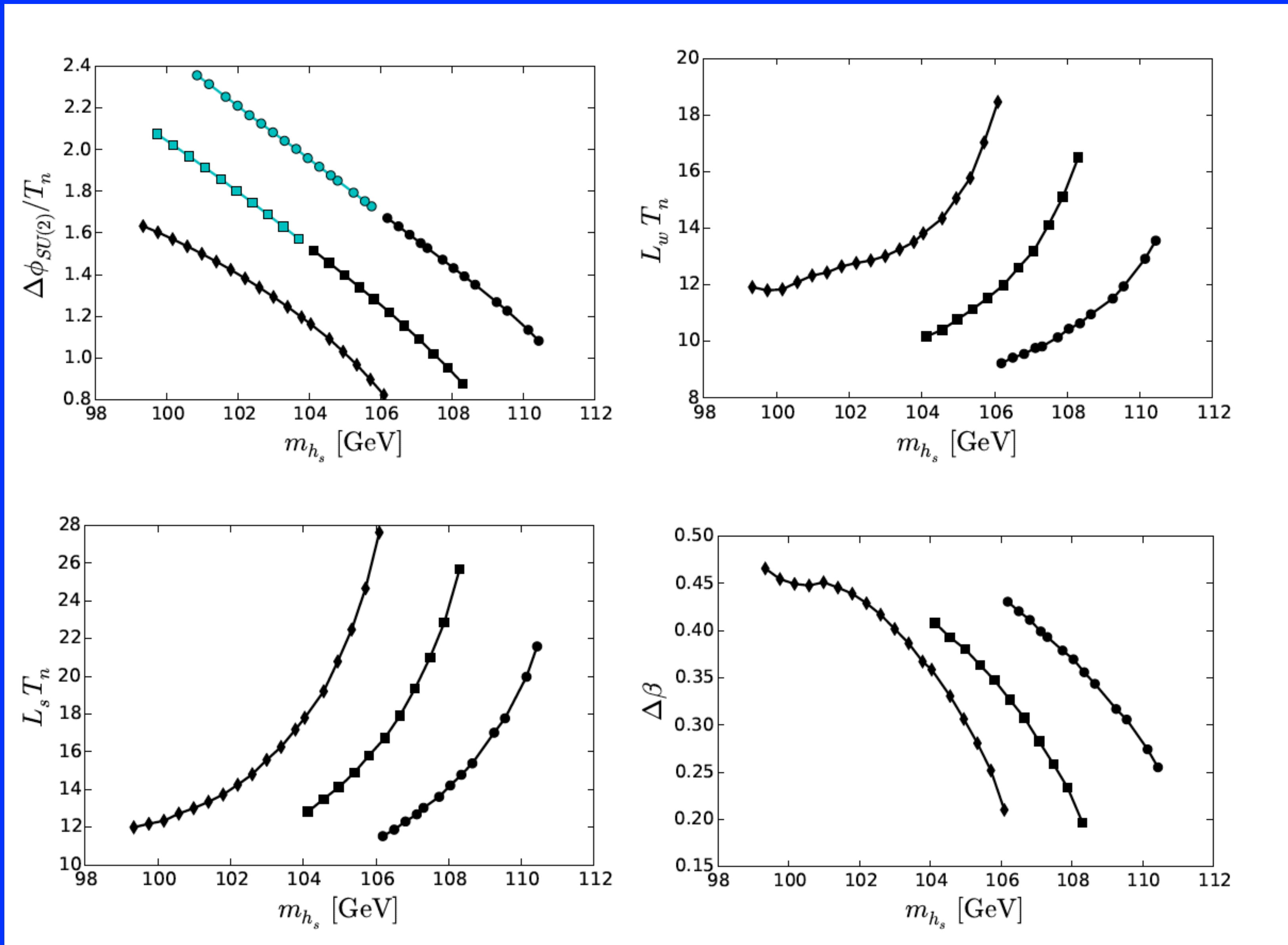
EDM constraints with 1TeV sfermions (1. & 2. generation):



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

Z_3 NMSSM revisited:

[Kozaczuk, Profumo, Haskins, Wainwright '14]



Summary

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

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

► new scalars at the LHC? EDMs?

► first 3d numerical simulation of scalar + fluid

GW production by sound waves

no sign of turbulence

► breaking of scale invariance in a hidden sector leads to a strong phase transition, giving a potentially observable gravitational wave spectrum