JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

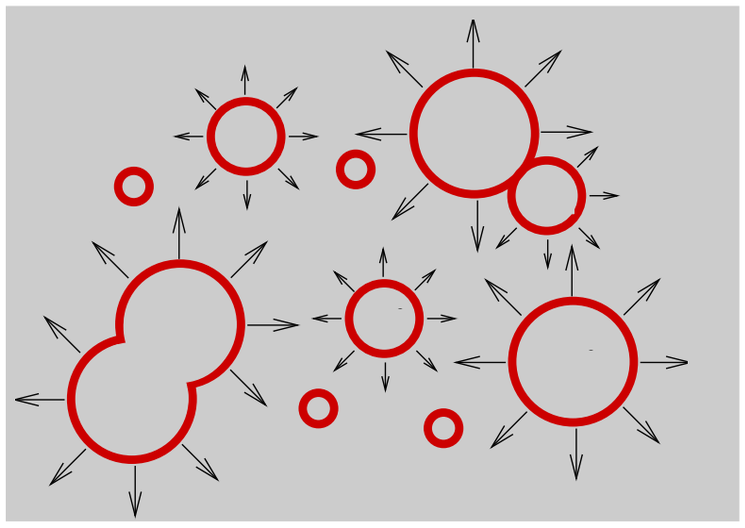
Baryogenesis and the EW Phase Transition:

some new developments and old connections

Kimmo Kainulainen,

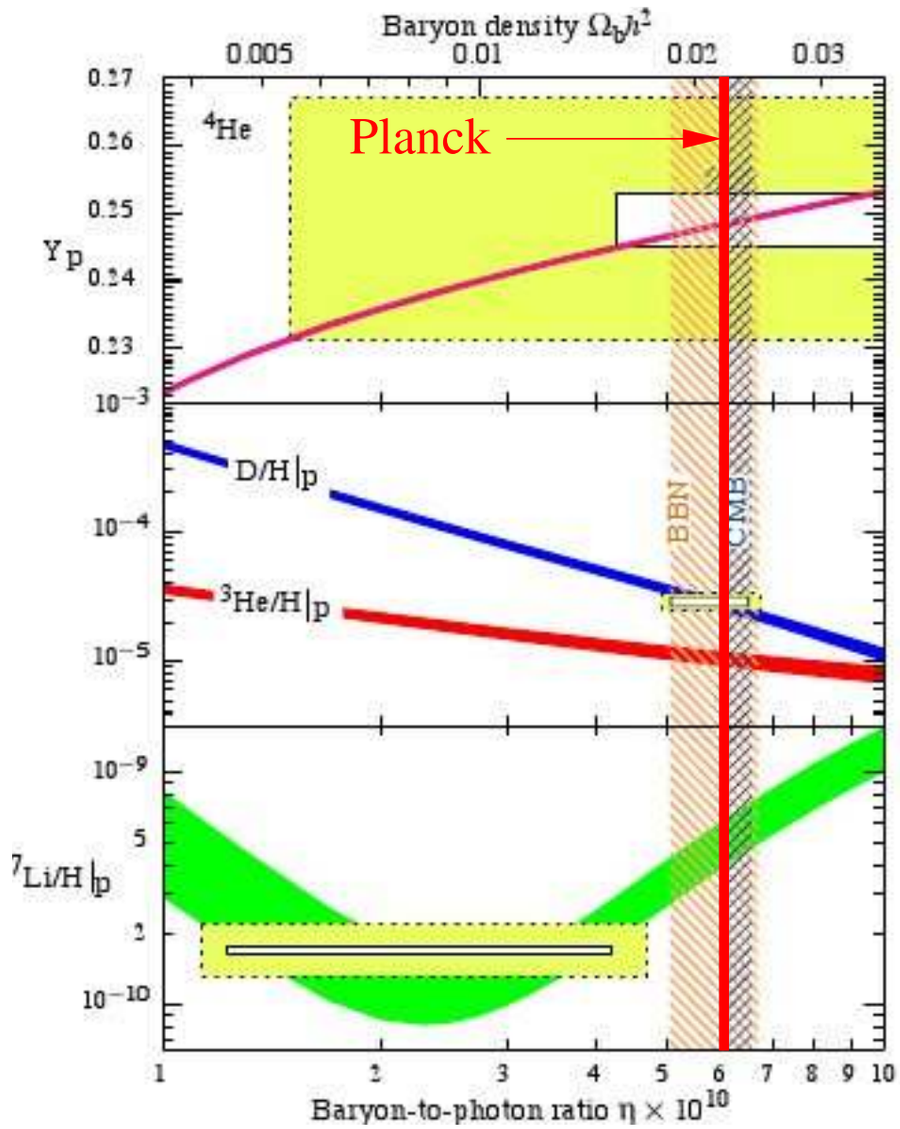
Progression on Old and New Themes in cosmology (PONT)

Avignon/14-18.4.2014



- SM does not explain BAU
- EWBG testable framework
- MSSM still OK ?
- 2HDM
- SSM, BAU + DM ?
- QTT and EWBG

Baryon asymmetry



$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

P.Ade et al, ArXiv:1303.5076
(Planck 2013 Cosmological Parameters)

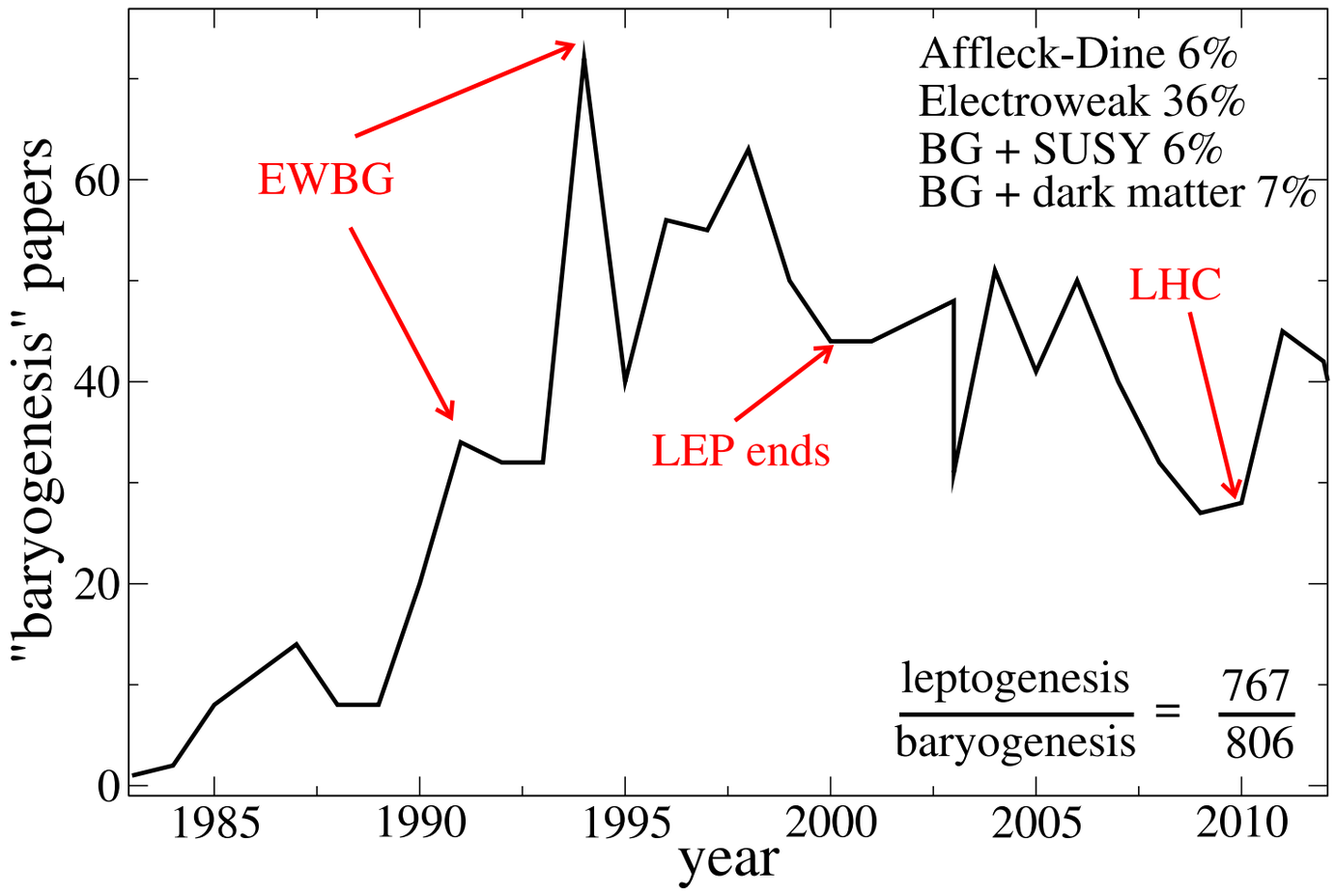
Because of **Inflation**,
now more certain than ever,
this cannot be initial condition.

BICEP2:

$$T_{\mathrm{BAU}} < 1.7 \times 10^{16} \left(\frac{r}{0.2}\right)^{1/4} \mathrm{GeV}$$

Fair amount of room to play...

EWBG



Thanks to Jim Cline, (Invisibles -13)

EWBG continues to be interesting because of its **testability**

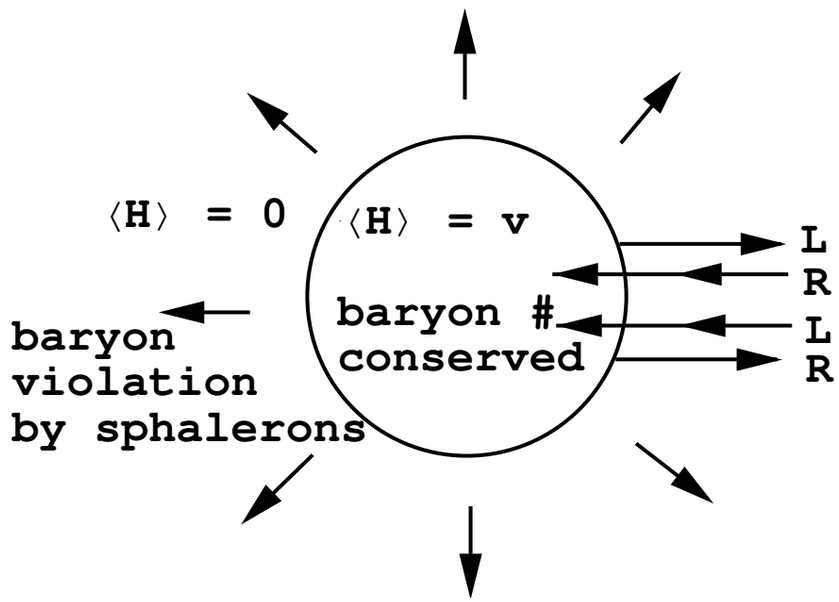
EWBG in a nutshell

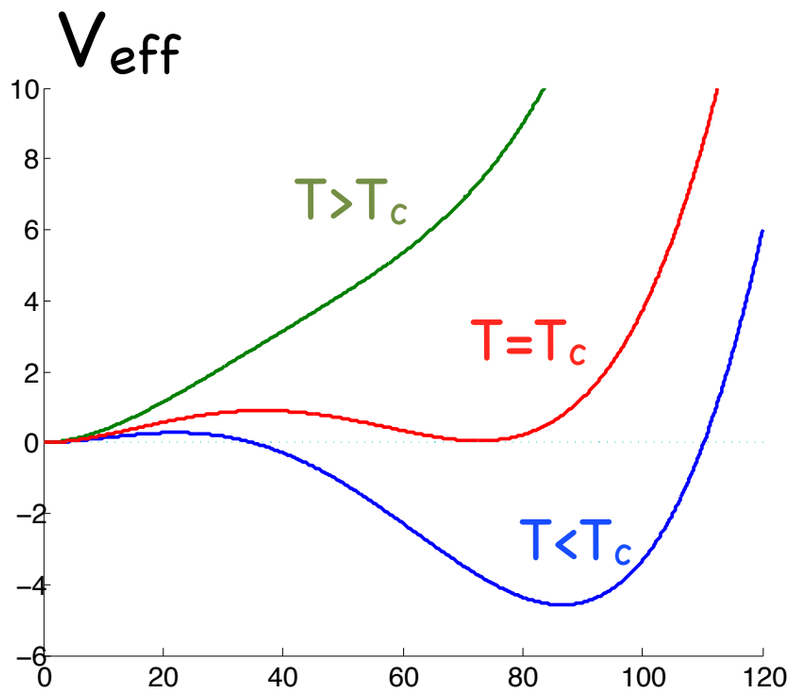
$$H \sim 10^{-14} T_{100}^2 \mathrm{GeV}$$
$$\Gamma \sim 10^{-5} T_{100} \mathrm{GeV}$$

1st order PT: at T_c ~100 GeV, bubbles of true vacuum, $\langle H \rangle \neq 0$, form and start expanding.

Particles interact with wall in a **CP** violating way

Baryon asymmetry forms inside the bubble





- Only **B**-violation by sphalerons is certainly present already in the SM.
- Strongly **1st order PT, not** present in SM;

$$V_{\mathrm{eff}} = \frac{1}{2}(-\mu^2 + cT^2)\phi^2 - T\delta\phi^3 + \frac{1}{4}\lambda_{\mathrm{eff}}\phi^4$$

Beyond SM: MSSM, NMSSM, 2HDM, NHDM, IHDM, SSM,...

EWBG, division of search tasks

To keep BA

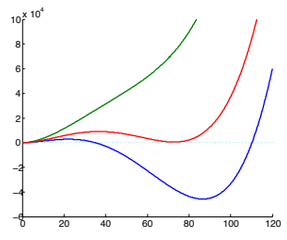
Sphaleron rate in the broken phase ... must be small

Kuzmin, Rubakov & Shapsohnkinov, Arnold & McLerran, ... Moore; Rummukainen etal;

- $V_{\rm eff}$ in Landau *gauge*

$$\frac{\phi_c}{T_c} < 1$$

H.H.Patel, M.J.Ramsey-Musolf, C.Wainwright, S.Profumo
JHEP 07 (2011) 029; PRD84 (2011) 023521; PRD86 (2012) 083537.
M.Garny and T.Konstandin, JHEP1207 (2012) 189, ...



- Dim. reduction to a 3D-Higgs-gauge theory simulated in Lattice

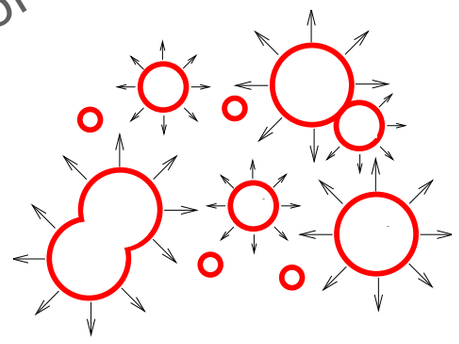
K.Kajantie, M.Laine, K.Rummukainen and M.E.Shaposhnikov,
NPB458 (1996) 90; NPB466 (1996) 189;
PRL77, 2887 (1996)....

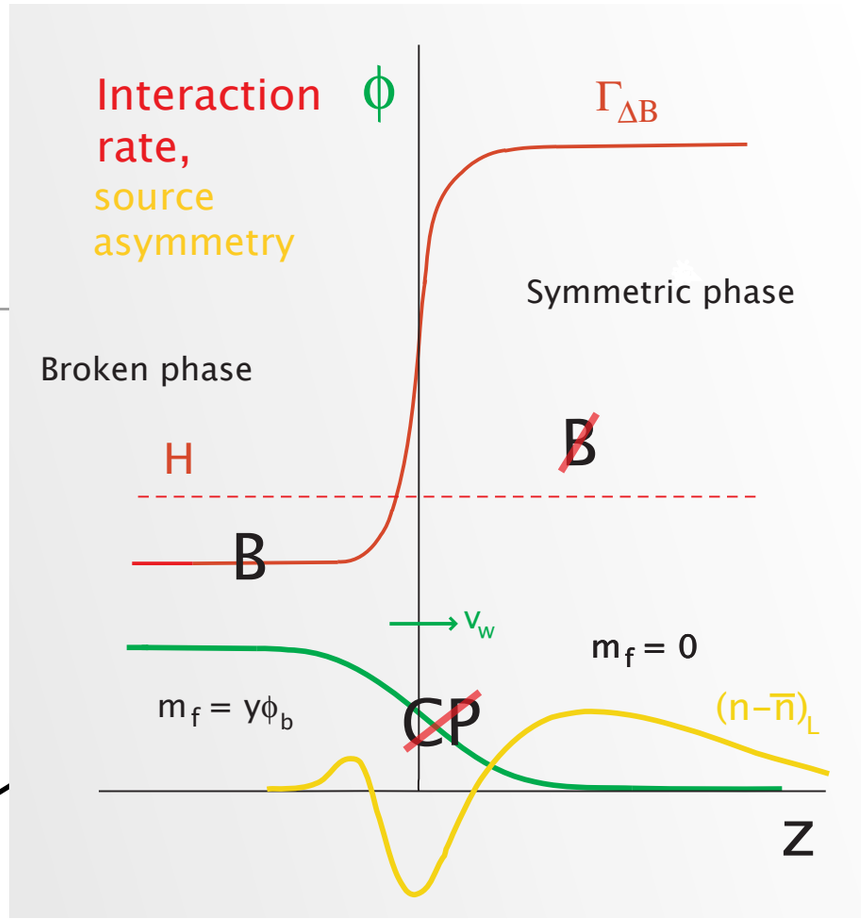
2-loop $V_{\rm eff}$ in LG ~OK

M.Laine, G.Nardini and
K.Rummukainen,
JCAP 1301 (2013) 011...

Equilibrium / Nonperturbative / Gauge issues

Out-of-equilibrium / quantum





CP-violating **source** in **transport eqs.**

- Thin wall: *quantum*
- Thick wall SC: **SC force** Joyce, Prokopec, Turok, Cline, KK, Schmidt, Weinstock, Konstandin, ...

Mass insertion
Riotto, Carena, Quiros, Wagner, ...

(CP-even) dynamics of the expanding wall

Parametrized by $v_{\rm w}$ and $\phi(z)$ Kajantie etal, Prokopec & Moore, John & Smith Espinosa, Konstandin, No & Servant (2010),...

Sphaleron rate in the unbroken phase

Ambjorn etal,... Moore; Rummukainen etal,..

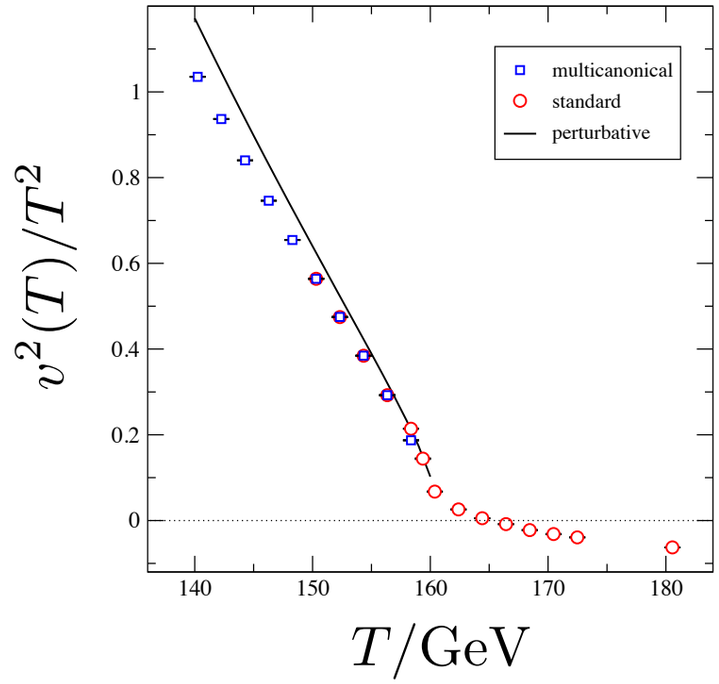
To make BA

EWBG in SM, Sphaleron rate

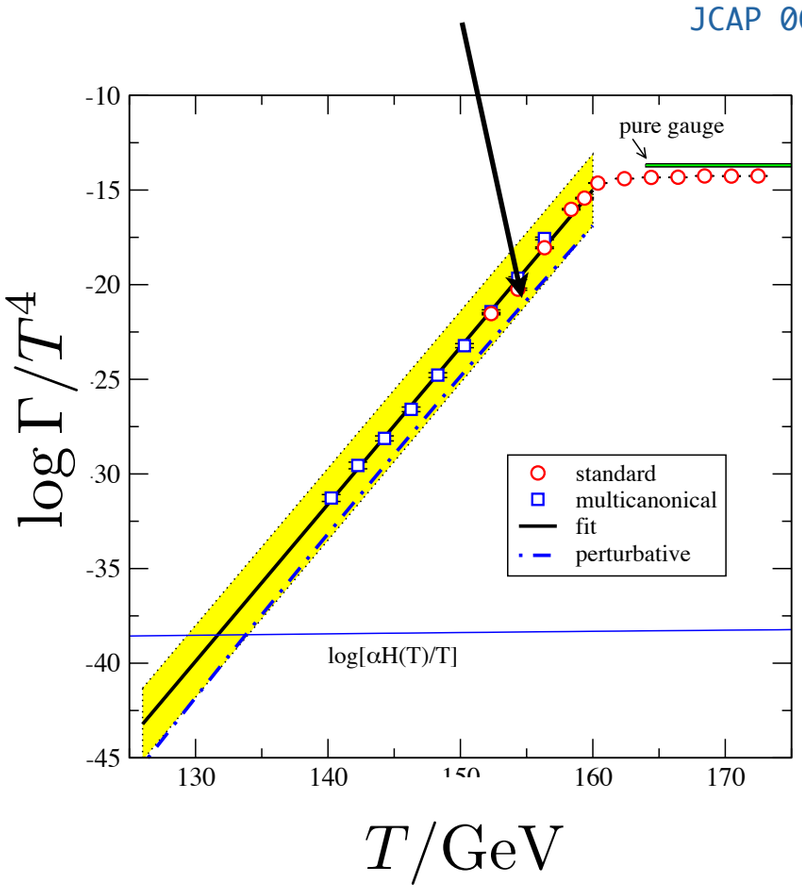
PT in SM, is a cross-over with

$T_c \approx 160$ GeV

K.Rummukainen, M.d'Onofrio and A.Tranberg, arXiv:1404.356



Perturbative result Y.Burnier, M.Laine & M.Shaposhnikov, JCAP 0602 (2006) 007



Sphaleron rate in SM

$$\Gamma_{\mathrm{Symm.}}/T^4 = (8.0 \pm 1.3) \times 10^{-7} \approx (18 \pm 3)\alpha_W^5$$

$$\log \frac{\Gamma_{\mathrm{Broken}}}{T^4} = (0.83 \pm 0.01)\frac{T}{\mathrm{GeV}} - (147.7 \pm 1.9)$$

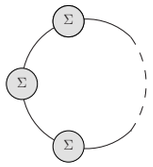
Sphalerons drop out of eq. in broken phase when

$\Gamma(T_*)/T_*^3 = \alpha H(T_*)$ eg: $T_* = (131.7 \pm 2.3)\,\mathrm{GeV}$

EWBG-models that can keep BAU / Loop corrections / MSSM

Most efforts have been put to increase the effective cubic coupling by loop corrections

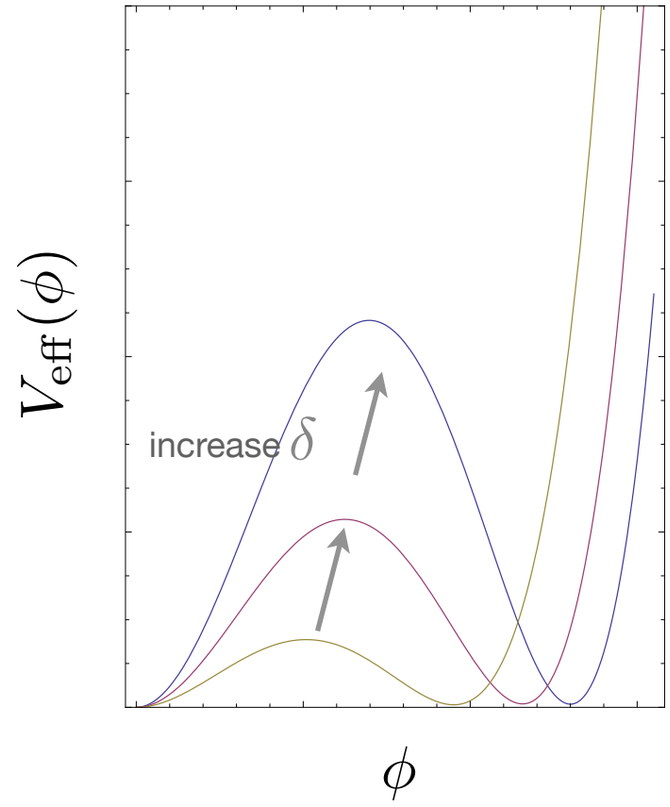
Need new light ($m_i < T$) bosonic fields strongly coupled to Higgs



$$\delta V_{\rm eff} = -\sum_i \frac{T m_i^3(\phi,T)}{12\pi} + \ldots$$

=> **L**ight **S**top **S**cenario in the MSSM and NMSSM

[Carena, Quiros, Wagner (1996),...]



However, also higgs mass mostly from

$$m_h^2 \sim y_t^2 \ \log \frac{m_{\tilde{t}_R}^2 m_{\tilde{t}_L}^2}{m_t^4}$$

Tension: light t_R => heavy t_L

=> **very** heavy t_L

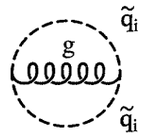
Early times early-**mid-90's**:

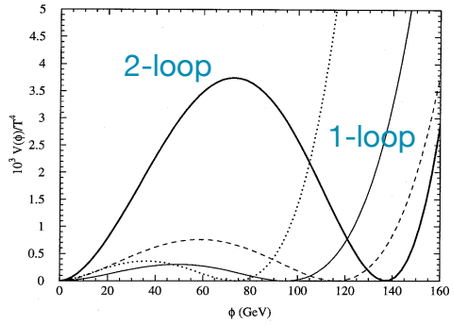
$V_{\text{1-loop}}$: Espinosa,Quiros,Zwirner, Carena, Wagner,...

1-loop DR: Laine,Cline,KK,Losada,...

J.R.Espinosa -96:
75% 2-loop enhancement on v/T

NPB475 (1996) 273.





MSSM, latest results

(Re)opening a BAU window in MSSM

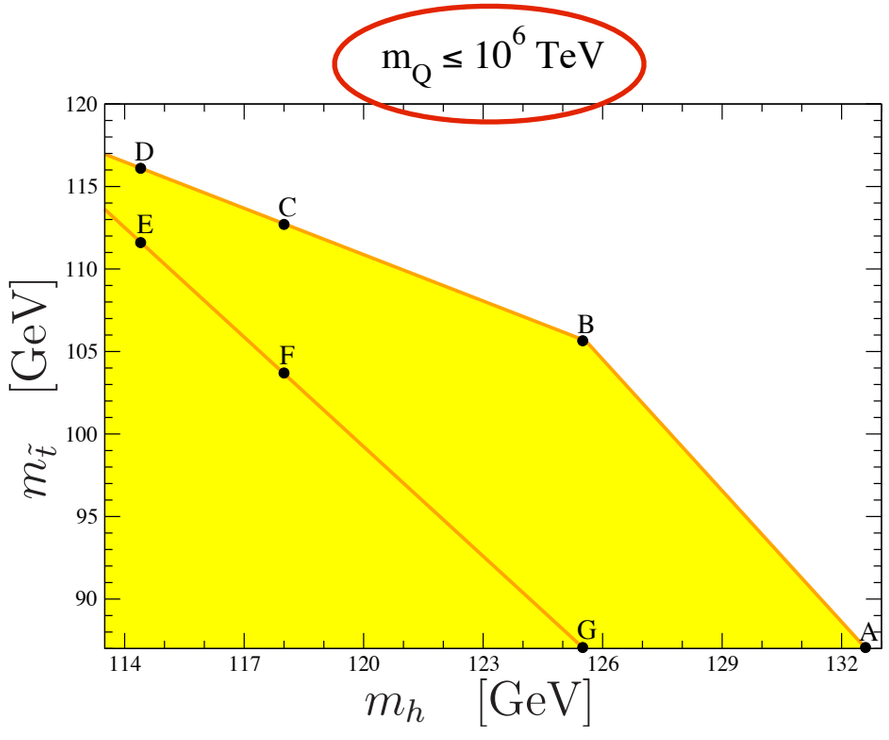
M.Carena, G.Nardini, M.Quiros & C.Wagner, NPB812 (2009) 243

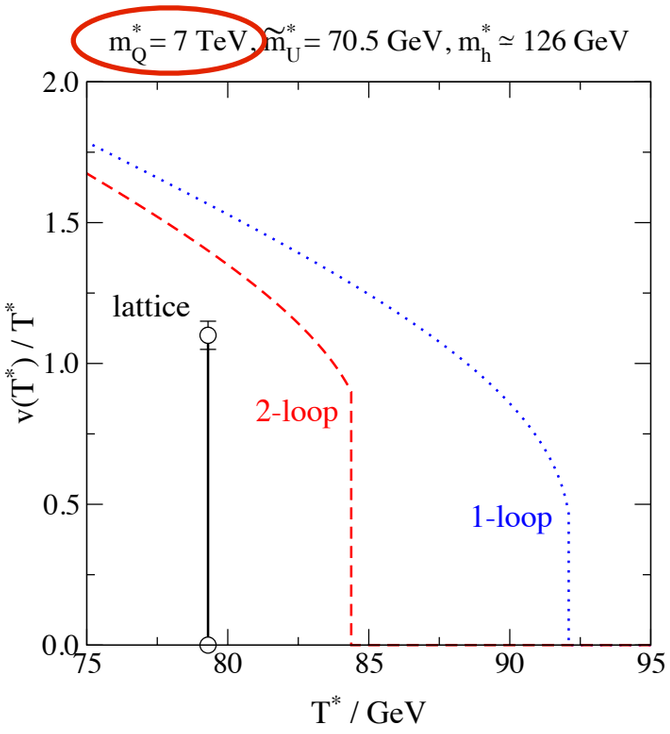
RGE-improved potential
Allowed models *metastable* against color breaking

$$m_h \leq 127\ \mathrm{GeV}, \quad m_{\tilde{t}_\mathrm{R}} \leq 120\ \mathrm{GeV}$$

LHC: Tension with light stop-enhanced gg-fusion decay of Higgs...
Balanced by an invisible DW to a light neutralino

M.Carena, G.Nardini, M.Quiros & C.Wagner, NPB812 (2009) 243





However, there is a recent lattice study:

Rummukainen Nardini and Laine ...

$$\left(\frac{v}{T_c}\right)_{\mathrm{latt}} = 1.117(5) \qquad \left(\frac{v}{T_c}\right)_{\mathrm{Landau}} = 0.9$$

$$\frac{L}{aT_c^4} \approx 0.012\left(\frac{110}{g_*}\right) < 0.015\left(\frac{\phi_N}{T_N}\right)^2$$

small v_w ok

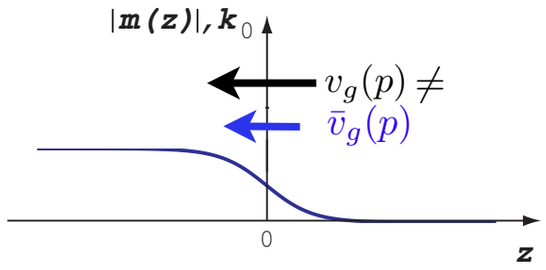
J.R.Espinosa, T.Konstandin, M.No and G.Servant, JCAP 1006 (2010) 028

MSSM EWBG appears to be still alive !

BAU generation, QM reflection or SC force

Thick wall limit: *SC force*

$\ell_w = 10 - 30\ T^{-1}$



$$(\partial_t + \mathbf{v}_g \cdot \partial_\mathbf{x} + \mathbf{F} \cdot \partial_\mathbf{p}) f_i = C[f_i, f_j, \ldots] \,.$$

$$v_g = \frac{p_0}{\omega}\left(1 + s_{\rm CP}\frac{s|m|^2\theta'}{2p_0^2\omega}\right)$$

$$F = -\frac{|m||m|'}{\omega} + s_{\rm CP}\frac{s(|m|^2\theta')'}{2\omega^2} \,.$$

CP-force

M.Joyce, T.Prokopec, N.Turok, PRD53 2958 (1996); PRL75 1695 (1995); PRD53 2930 (1996).
J.M.Cline, M.Joyce and KK PLB417 (1998) 79; JHEP 0007 (2000) 018
J.M.Cline and K.Kainulainen, PRL85 (2000) 5519.

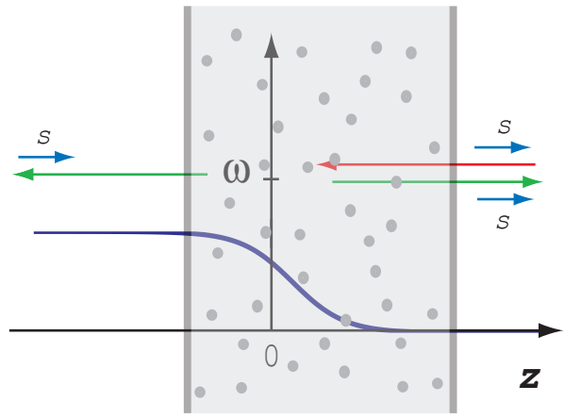
KK, T.Prokopec, M.G.Schmidt and S.Weinstock, JHEP 0106, 031 (2001); PRD66 (2002) 043502. T.Prokopec, M.G.Schmidt and S.Weinstock, Ann.Phys.314 208 (2004), Ann.Phys.314, 267 (2004).
T.Konstandin, T.Prokopec and M.G.Schmidt, NPB716 (2005) 373; NPB738 (2006) 1
V.Cirigliano, C.Lee, M.J.Ramsey-Musolf and S.Tulin, PRD81 (2010) 103503.

WKB

CTP

Thin wall limit: *quantum reflection*

$\ell_w =$ few T^{-1}



Collisionless case:

$$\left(i\,\partial\!\!\!/_u - m^\dagger P_L - m P_R\right)\psi(u) = 0\,.$$

Complex mass (matrix) => CP

Sufficient CP-violation in the MSM CKM-matrix?

G.R.Farrar and M.E.Shaposhnikov, PRL70, 2833 (1993); PRD (199...

NO

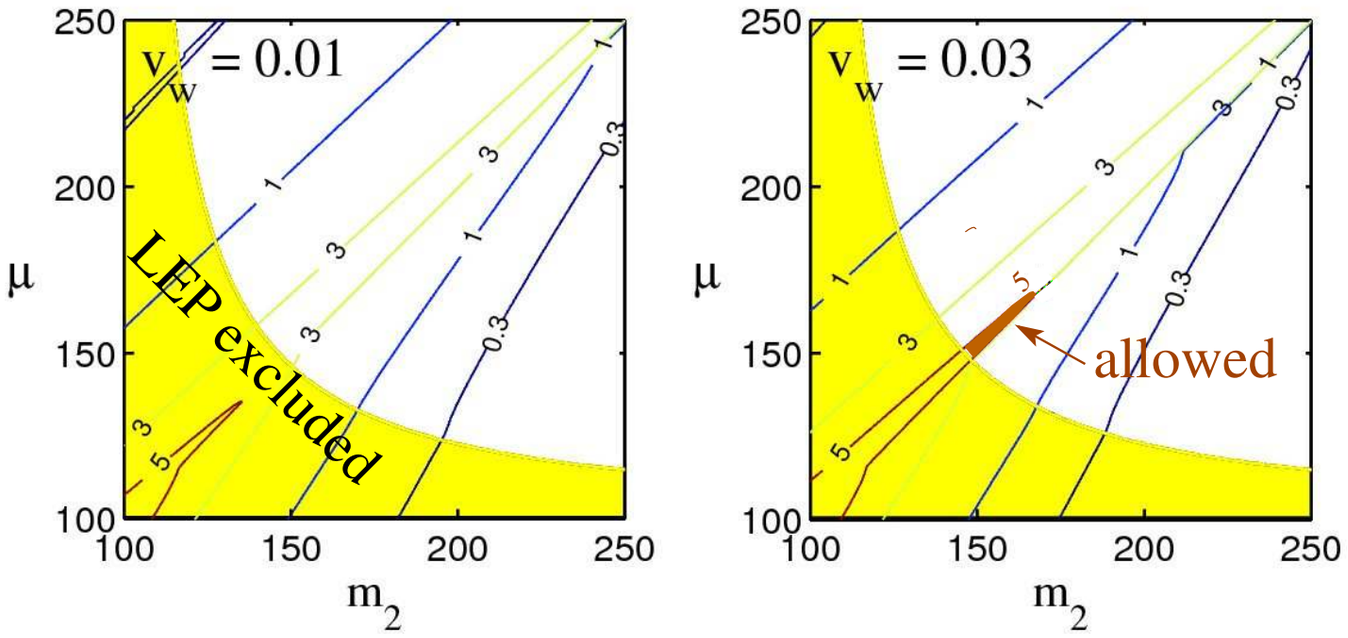
M.B.Gavela, P.Hernandez, J.Orloff and O.Pene, MPLA 9, 795 (1994)
Gavela, P. Hernandez, J. Orloff, O. Pene and C. Quimbay, NPB 430, 382 (1994) P.Huet and E.Sather, PRD51, 379 (1995).

But the QKE's used not sufficiently sophisticated

BAU generation, MSSM

Chargino transport

$$\mathcal{M}_{\chi^\pm} = \begin{pmatrix} M_2 & gh_2 \\ gh_1 & \mu \end{pmatrix}$$



J.M.Cline, M.Joyce and KK,
JHEP 0007 (2000) 018.

Similar results were found by

T.Konstandin, T.Prokopec, M.G.Schmidt,
and M.Seco, NPB738 (2006) 1.

which also used SC/CTP approach and included flavour mixing effects

However, there are differences in the literature:

paper	method	η/η_{obs}
[41] (2000)	mass insertion formalism; no Higgs resummation	~ 35
[42] (2002)	mass insertion formalism; including Higgs resummation	~ 10
[43] (2004)	mass insertion formalism; no Higgs resummation; more realistic diffusion network	~ 140
[24] (2005)	Kadanoff-Baym formalism; flavor oscillations; assumes the adiabatic regime	~ 3.5

T.Konstandin, arXiv:1302.6713 [hep-ph]

Neutralino transport:

Y.Li, S.Profumo, and M.Ramsey-Musolf,
PLB673 (2009) 95–100.

Stop transport:

J.Kozaczuk, S.Profumo, M.Ramsey-Musolf and CL.
Wainwrigh, PRD86 (2012) 096001

Does it work? Not fully settled.

2HDM, NHDM, IHDM,...

No sign of SUSY yet. What other possibilities for EWBG

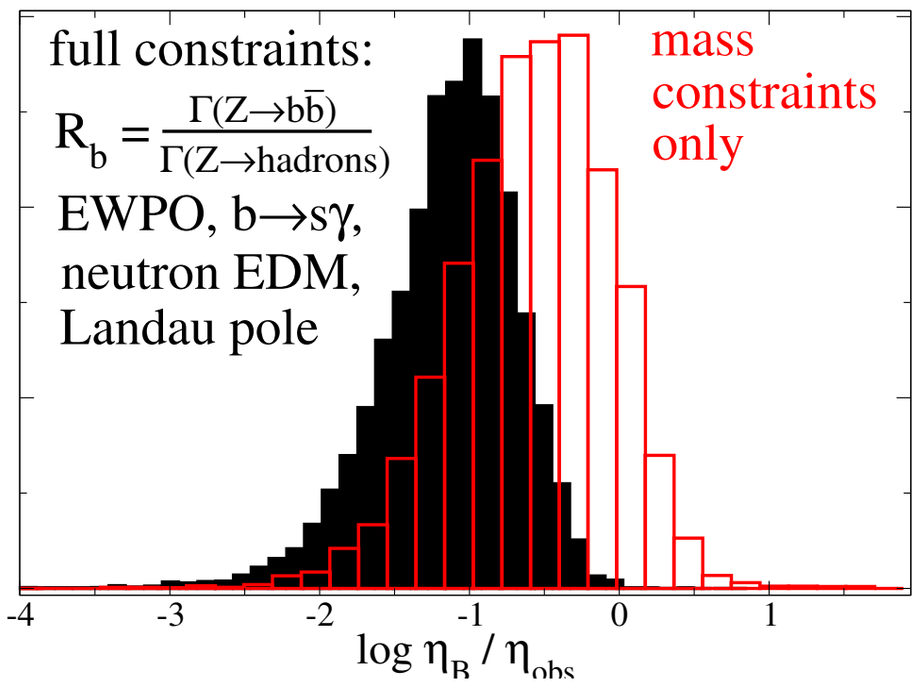
2HDM:

$$V = \frac{\lambda}{4}\left(H^{\dagger\,i}\,H_i - \frac{v^2}{2}\right)^2 + m_1^2\,(S^{\dagger i}\,S_i) + (m_2^2\,H^{\dagger\,i}S_i + \text{h.c.}),$$
$$+\lambda_1\,(H^{\dagger\,i}H_i)\,(S^{\dagger\,j}S_j), + \lambda_2\,(H^{\dagger i}\,H_j)\,(S^{\dagger j}\,S_i) + \left[\lambda_3 H^{\dagger i}\,H^{\dagger j}\,S_i\,S_j + \text{h.c.}\right],$$
$$+\left[\lambda_4 H^{\dagger i}\,S^{\dagger j}\,S_i\,S_j + \lambda_5 S^{\dagger i}\,H^{\dagger j}\,H_i\,H_j + \text{h.c.}\right] + \lambda_6 (S^{\dagger i}S_i)^2,$$
$$+\,y_t\bar{t}_L(H^{0*}\delta_{ti} + (\eta_U\delta ti + \eta'_U V^*_{tb}V_{bi}))S^{0*})q^i_R$$

Many new CP-violating phases

MFV for new Yukawa's to avoid **FCNC**
G.C.Branco, W.Grimus & L.Lavoura, PLB380 (1996) 119

Comprehensive MCMC of the PM-space finds both strong EWPT and BAU, but points are rare: **<1/10⁴**.
J.Cline, KK, M.Trott, JHEP 1111 (2011) 089



An even more detailed scan of different 2HDM's was carried out in: G.C.Dorsch, S.J.Huber & J.M.No, JHEP 1310 (2013) 029.

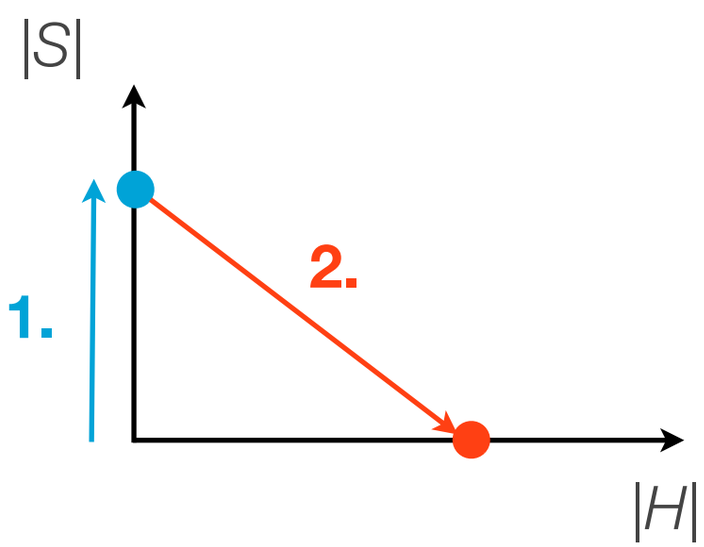
Singlet model can give a strong PT at tree level !

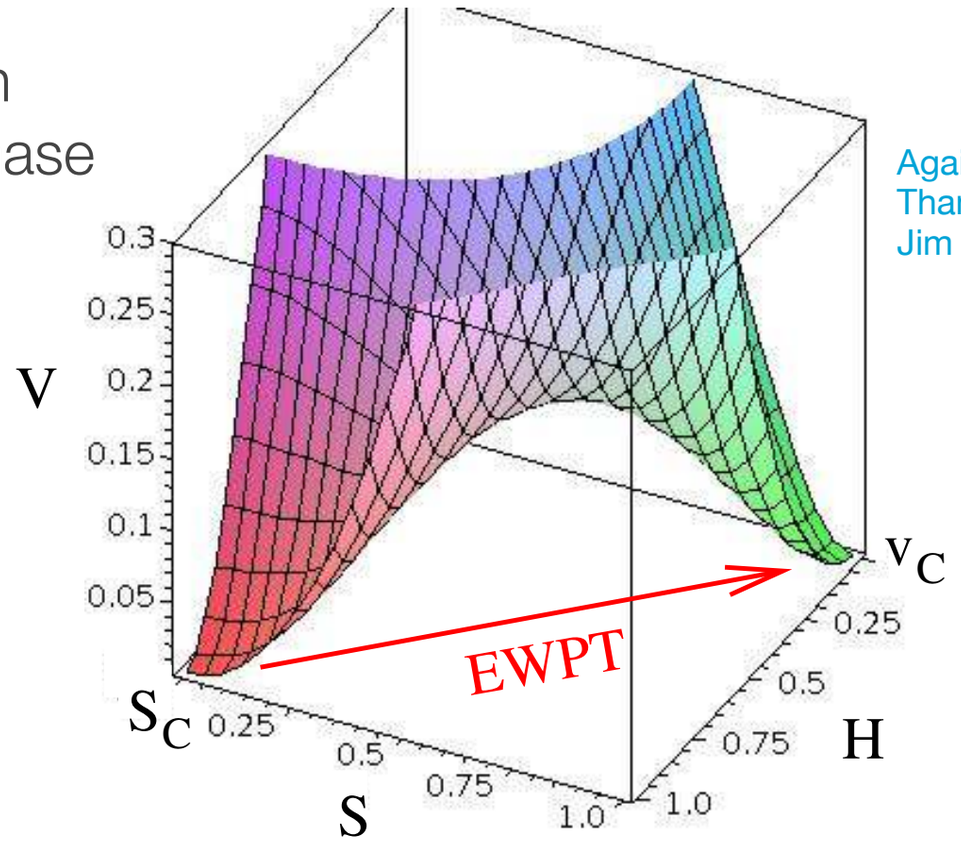
Consider

$$V = V_{\rm MSM} + \frac{1}{2}\mu_{\rm S}^2 S^2 + \frac{1}{2}\lambda_{sh} S^2 |H|^2 + \frac{1}{4}\lambda_s S^4 \qquad (\mu_{\rm S}^2 < 0)$$

If λ_{hs} is large enough, there is a barrier between $H = 0$ and $S = 0$ vacua at T = 0.

Transition can proceed in two steps, and model can give **a potential barrier at tree-level** → strong phase transition. J.R.Espinosa, T.Konstandin, F.Riva, NPB854 (2012) 592





Again Thanks to Jim Cline

Finite-T effects only lift the degeneracy of vacua. Strength of transition determined by tree-level V.

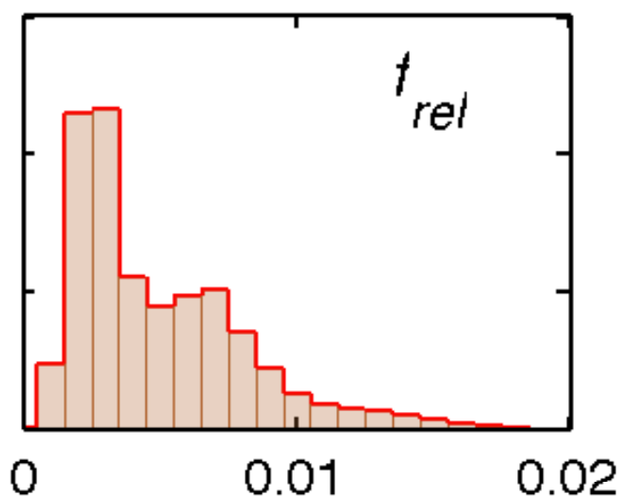
Singlet model: BAU *and* DM? Either - or, but not both

DM annihilation rate is proportional to same coupling that makes v/T large:

$$\langle v\sigma_{\rm DM}\rangle \sim \lambda_{sh}^2$$

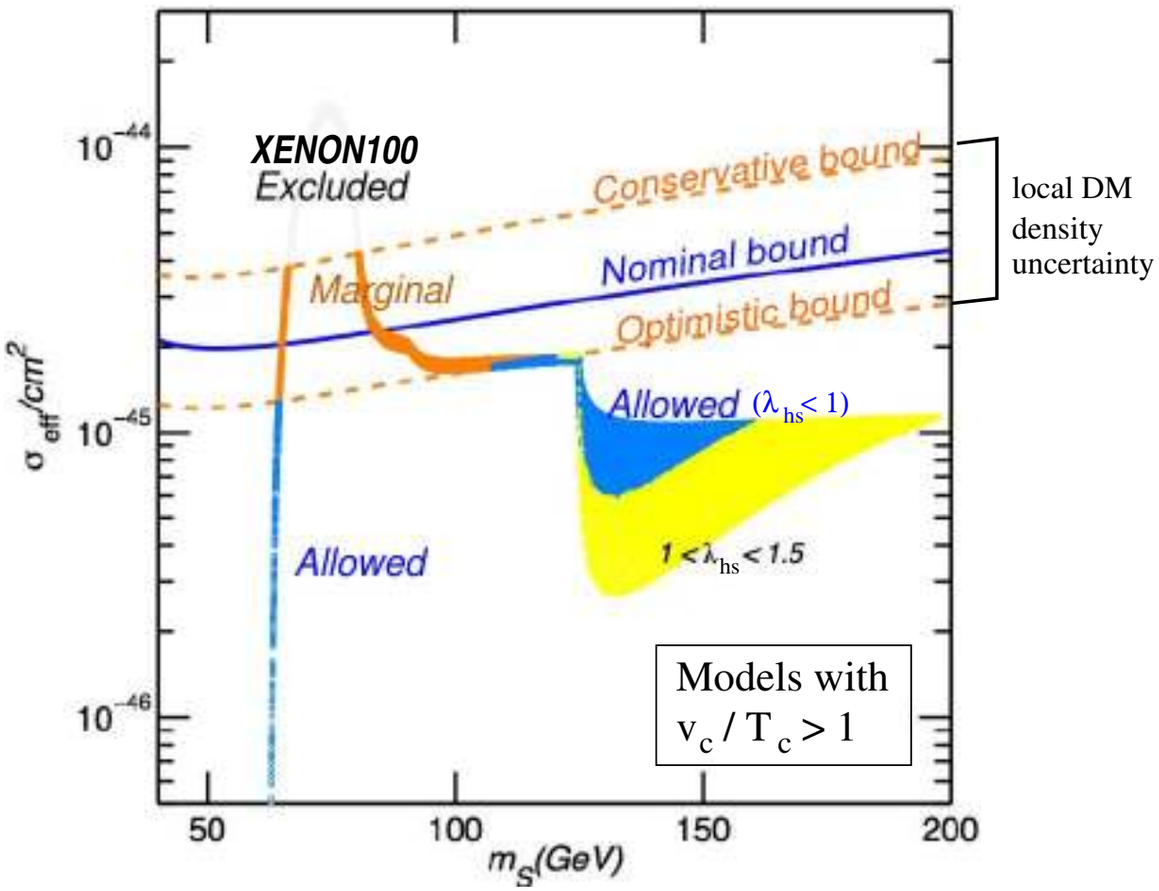
Large enough λ_{hs} gives subdominant DM

BAU acceptable *v/T >1* models



J.M. Cline, KK, JCAP 1301 (2013) 012

Subdominant DM would work as a **signal** for this BAU mechanism



Direct detection has all but excluded the **BAU-compatible** pm-space

Singlet model: only BAU

DM stability =>Z_2 symmetry: $\langle S \rangle_{T=0} = 0$

Source of CP violation eg Dim-6 operator

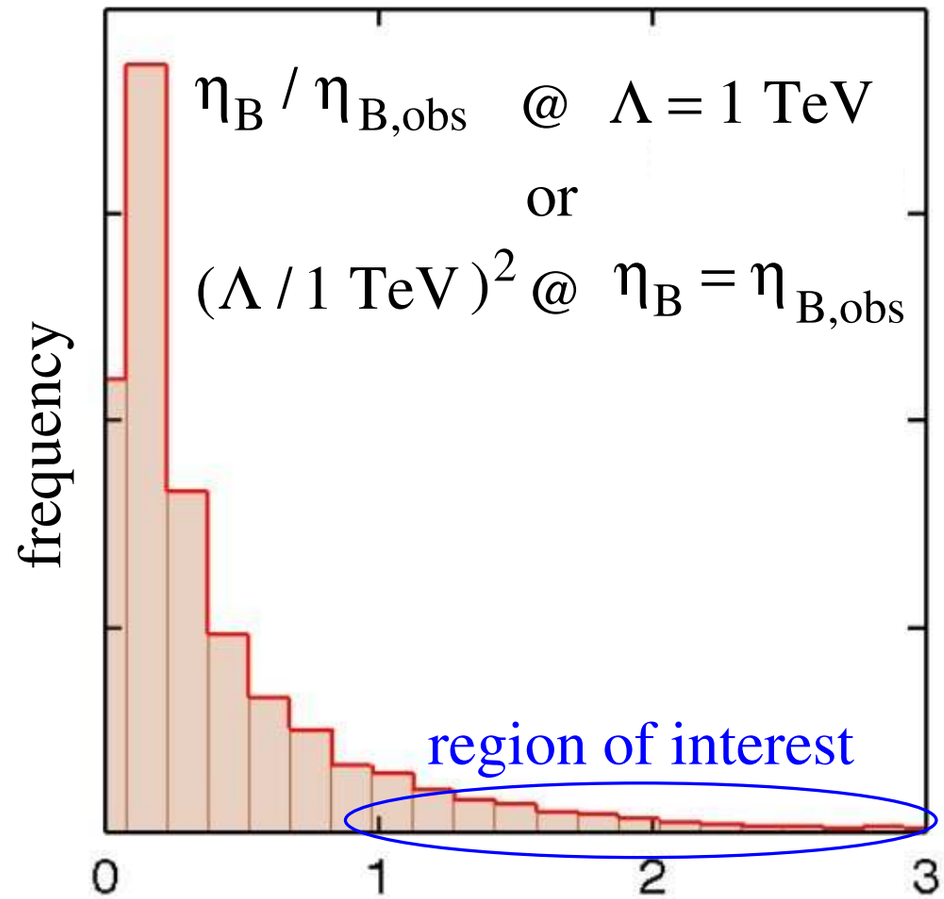
(If not DM could take Dim-5 as well) J.R.Espinosa, etal

$$y_t \bar{Q}_L H \left(1 + \frac{\eta}{\Lambda^2} S^2\right) t_R + \text{h.c.}$$

$$m_t(z) = \frac{y_t}{\sqrt{2}} h(z) \left(1 + i \frac{S^2(z)}{\Lambda^2}\right) \quad (\eta \equiv i)$$

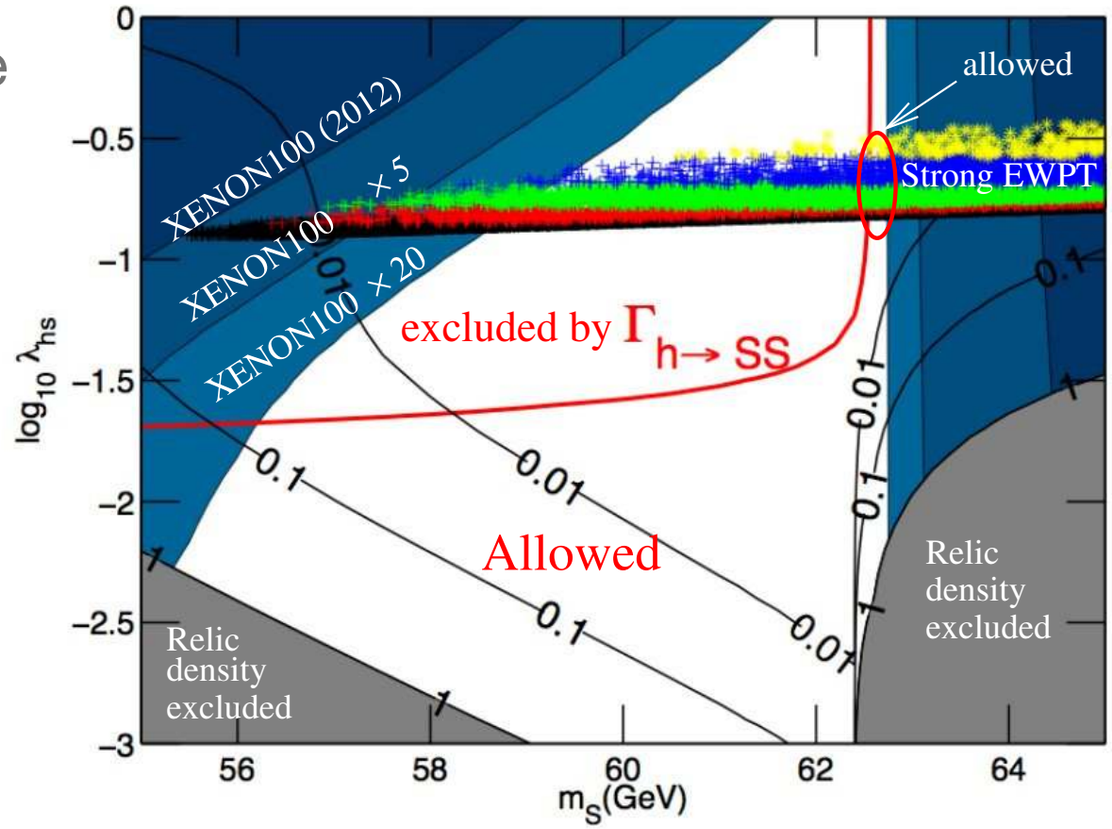
BAU from top source and transport

Large BAU much more frequent than in 2HDM



Singlet model, only Dark Matter

Abandoning BAU in one-singlet model one finds **pockets of DM-friendly parameters**



J.M.Cline, K.Kainulainen, P.Scott and C.Weniger, arXiv:1306.4710

Surely adding **two independent** singlets, one with a strong cross-coupling, and the other weak, the former could fix the transition and the other be DM. Interesting?

Or add new **independent doublets and singlets**...

A common model-building denominator would be welcome...

Quantum transport methods

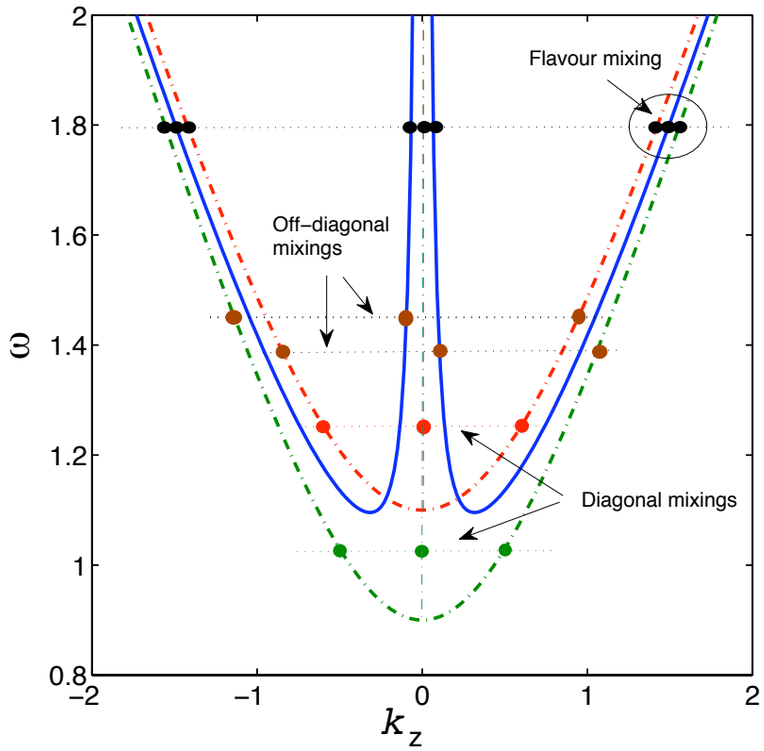
Singlet model would be more appealing if one could do without the new dim-5 or dim-6 operators for CP-violation.

Could the MSM CKM CP-phase be enough?
To make sure needs **more sophisticated methods.**

A suitable method (**cQPA**) in fact exists:

In planar symmetric problem, the **information about reflection coherence condenses to a set of new shell functions**
=> Extended **Boltzmann type eqns**.

M.Herranen, KK, P.M.Rahkila NPB810 (2009) 389



Tested already in **homogeneous problems**

M.Herranen, KK & P.M Rahkila,
JHEP 0809 (2008) 032; JHEP 0905 (2009) 119;
JHEP 1012 (2010) 072; JHEP 1202 (2012) 065
C.Fiedler, M.Herranen, KK & P.M Rahkila,
JHEP 1202 (2012) 080.

$$\partial_t \bar{\mathcal{S}}^<_{ij} = -i[H_{\rm eff}, \bar{\mathcal{S}}^<]_{ij} + \gamma^0 \langle \mathcal{C}_{ij} + \mathcal{C}^\dagger_{ij} \rangle \gamma^0$$

$$\bar{\mathcal{S}}^<_{ij} = \sum_{h\pm} P_h P_{i\pm} \gamma^0 \left(P_{j\pm} f^m_{ijh\pm} + P_{j\mp} f^c_{ijh\pm} \right)$$

Application to EWBG toy model ongoing: M.Herranen, KK, P.M.Rahkila, H.Jukkala

Conclusions

EWBG continues to be **interesting**, and boosted by LHC

MSSM EWBG still a possibility, albeit already somewhat **strange**

2HDM also possible, BAU fairly **restricted** in parameter space

S+SM:

strong 2-stage transition **at tree level**

BAU or DM possible, but not both, with only one singlet

Constant **evolution** on conceptual issues is being made