Electroweak Baryogenesis

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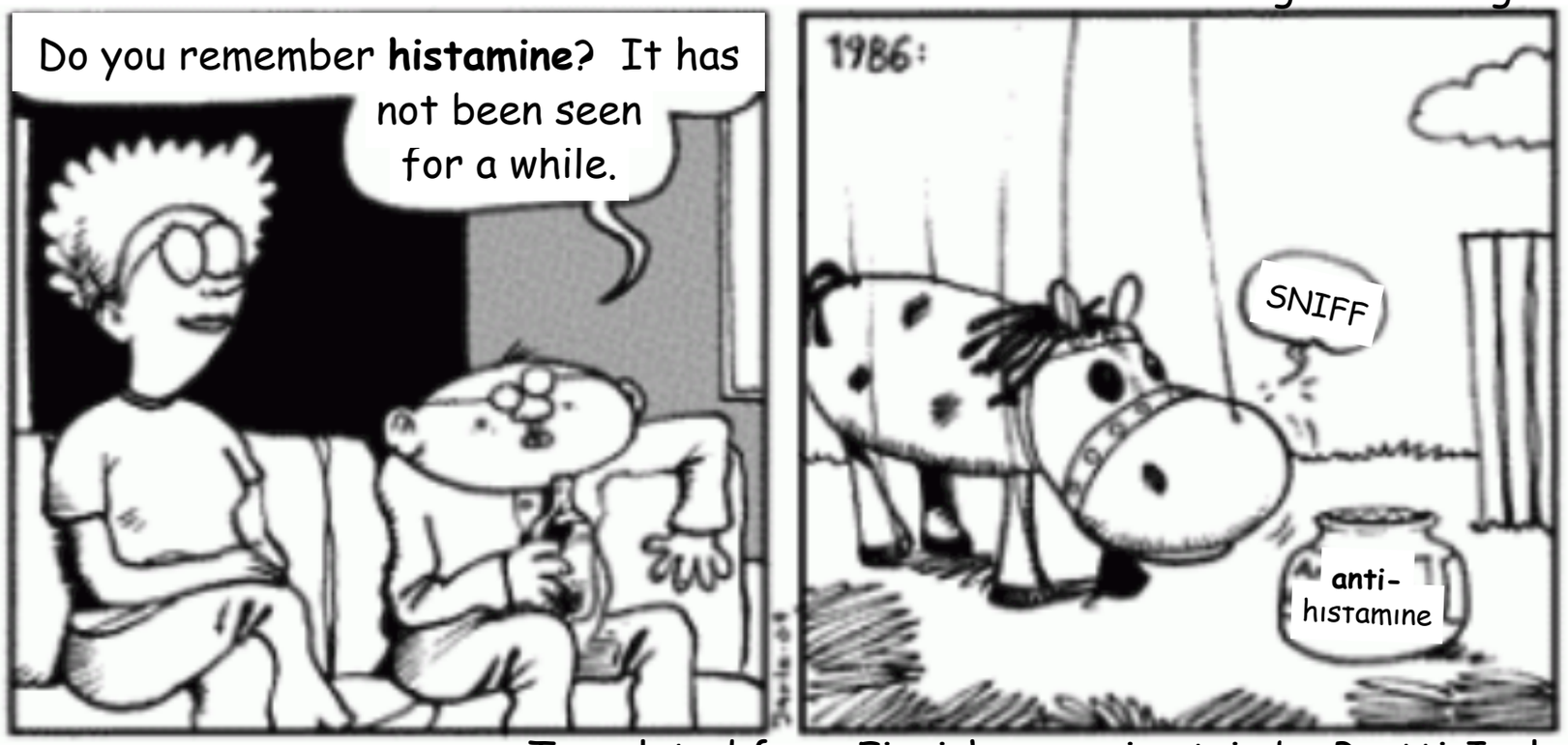
2015 The Spacetime Odyssey Continues

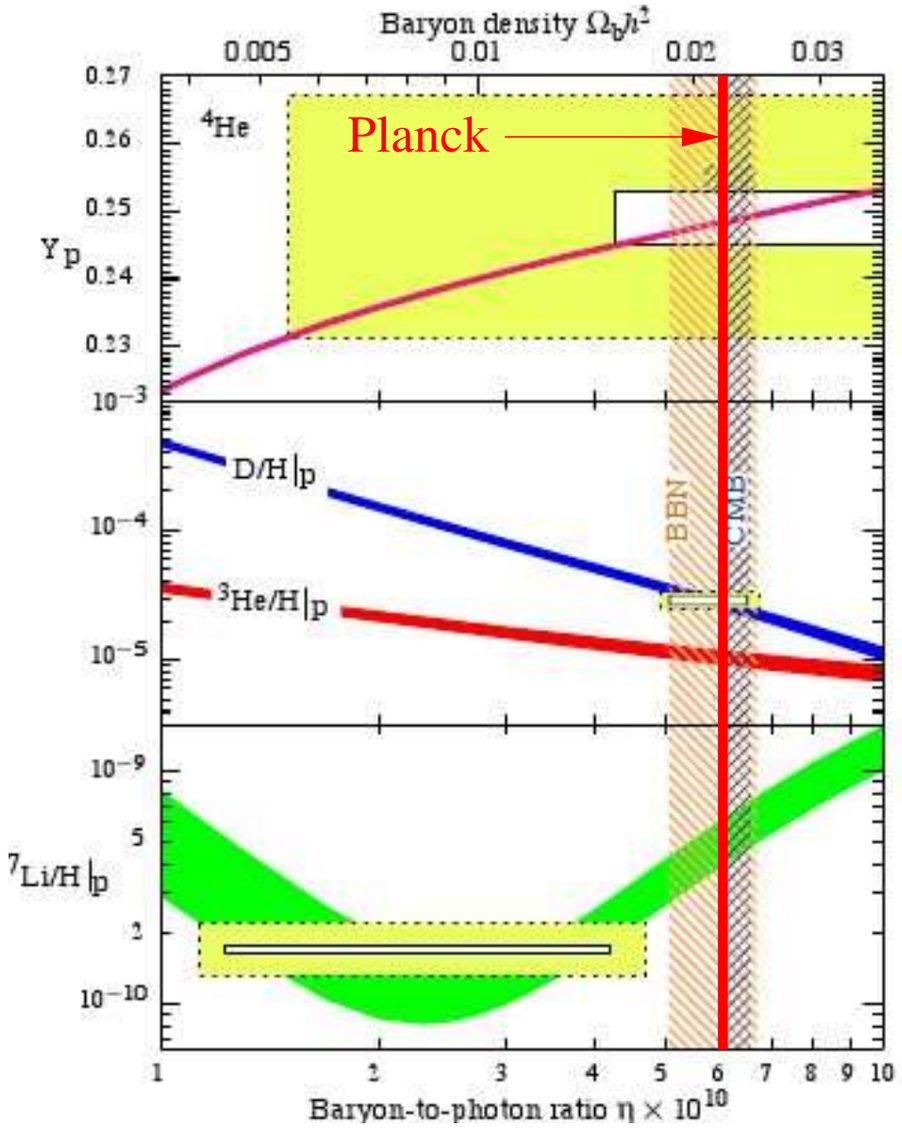
NORDITA, 6.5.2015

Favourite TV-horse gone missing...



Translated from Finnish, a comic strip by Pertti Jarla

Baryon asymmetry



$$\Omega_b h^2 = 0.02225 \pm 0.00016$$

P.Ade et al, ArXiv:1502.01589
(Planck 2015 Cosmological Parameters)

Because of **Inflation**,
this cannot be initial condition.

Tensors:

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

This leaves a fair amount of room to play:

$$100\,\text{GeV} < T_{\rm BAU} < 10^{16}\,\text{GeV}$$

Baryon asymmetry / mechanisms

Sakharov

- **Electroweak baryogenesis**
  - ~~MSM~~, ~~MSSM~~, NMSSM, 2HDM, SSM,...
- **Leptogenesis**
  - non-resonant
  - resonant
- **Warm, Cold, WIMPy, Dark, … Affleck-Dine mehanism, from GUT, neutrino oscillations, higher dimension operators, inflation, preheating, ….**

$T_{EWBG} \approx 100$GeV: works at the **lowest possible energy:** By far most **TESTABLE!**

EWBG in a nutshell

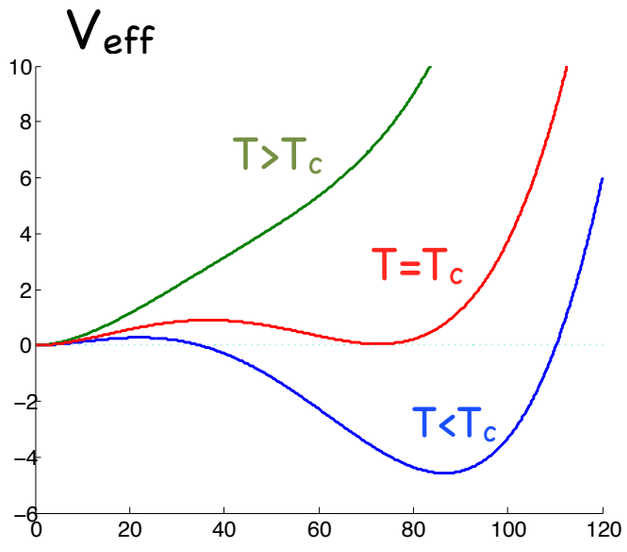
$$H \sim 10^{-14} T_{100}^2 \mathrm{GeV} \qquad \Gamma \sim 10^{-5} T_{100} \mathrm{GeV}$$

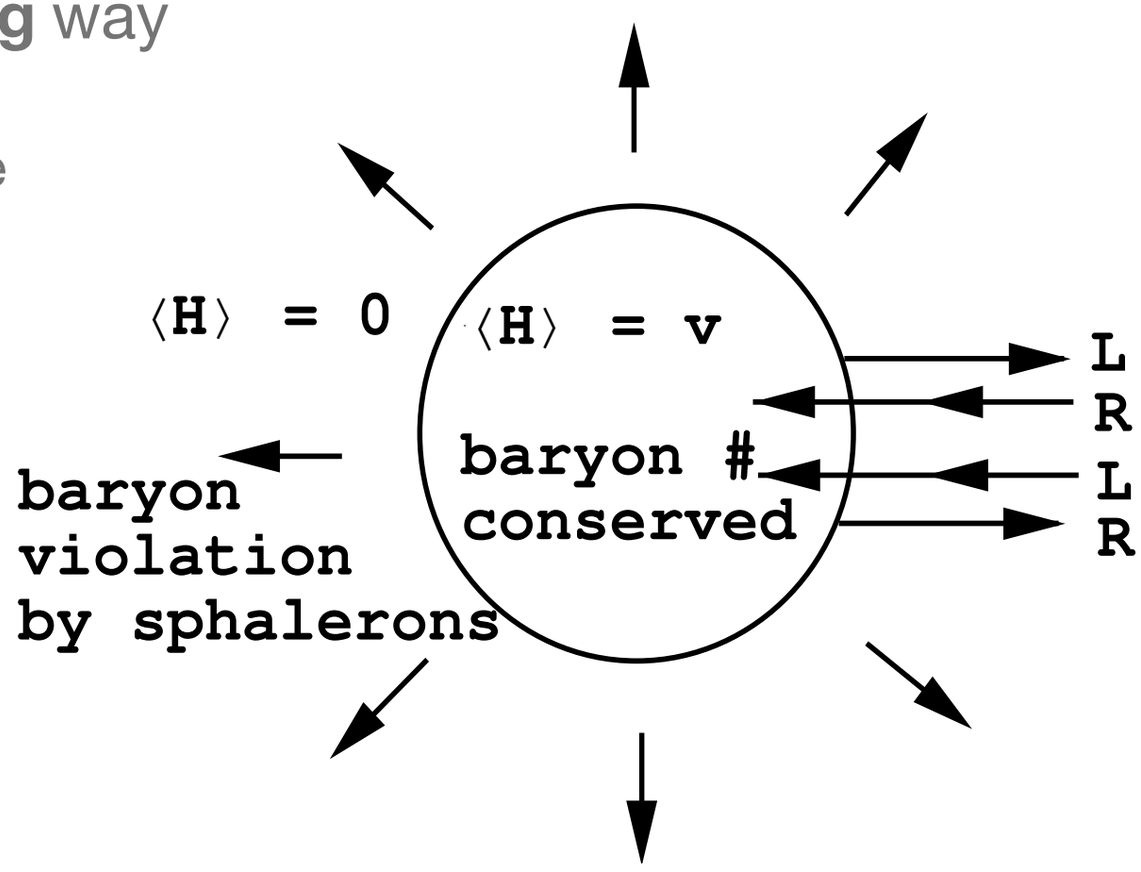
1st ~~order~~ PT

1st order PT at T_c **~100 GeV.**
bubbles of **true vacuum**, ⟨H⟩ ≠ 0, form and start expanding into the **false** symmetric **vacuum**.

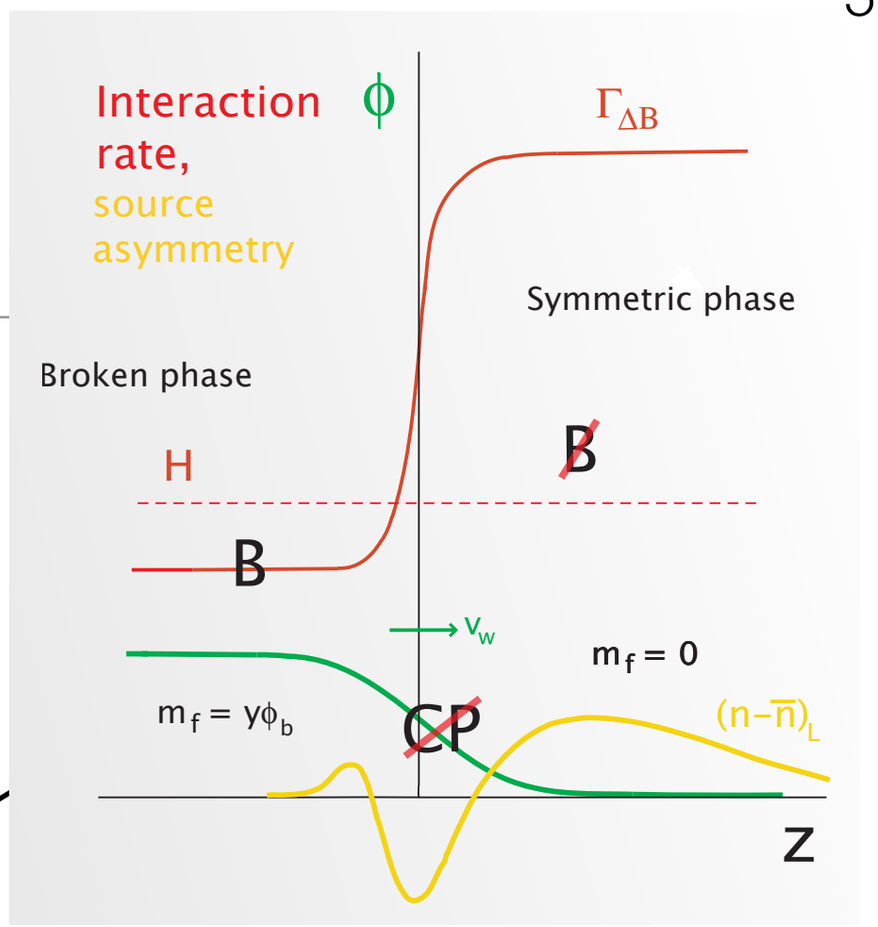
Particles interact with wall in **CP violating** way

Baryon asymmetry forms inside the bubble





EWBG, A SIGHTLY BIGGER NUTSHELL



To keep BA

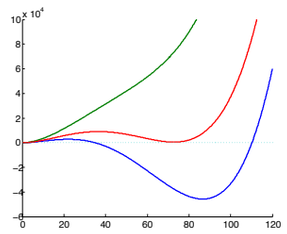
Sphaleron rate in the broken phase ... must be small

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

- From $V_{\rm eff}$ compute

$$\left(\frac{v(T_c)}{T_c}\right)_{\rm Landau} > 1$$

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, ...



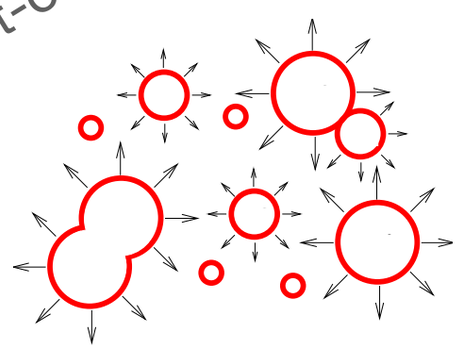
- Dim. reduction to a 3D-Higgs-gauge theory simulated in Lattice

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
Mostly out-of-equilibrium / quantum



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

- Thin wall: *quantum* (cQPA) Herranen, KK, Rahkila,…
- Thick wall SC: **SC force** Joyce, Prokopec, Turok, Cline, KK, Schmidt, Weinstock, Konstandin, ...

"vev-insertion"
Riotto, Carena, Quiros, Wagner, ...

(CP-even) dynamics of the expanding wall

Parametrized by v_w and $\phi(z)$ Kajantie etal, Prokopec & Moore, John & Smith Espinosa, Konstandin, No & Servant (2010),...

Sphaleron rate in the symmetric phase

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

To make BA

Short history of the EWBG

My most **sincere apologies** for the many, **many** people who did not get mentioned here despite their work of great importance !

B-violation in SM

't Hooft -76
Klinkhamer, Manton -84

1985

Kuzmin, Rubakov, **Shaposhnikov**, **fast B at high T in SM**

1987

Arnold, McLerran,..
Affleck-Langer, broken phase

$$\Gamma \sim Ae^{-E/T}$$

1990

Ambjørn, Krasniz, Shaposh… **1993 -1995**
first **Lattice** results (symm.ph)

$$\Gamma \sim \#\alpha^4 T$$

1995-1996

Rummukainen, Laine,
Moore, Bödeker,…
ChS-# diffusion in Lattice, HTL, Langevin eqs,..

$$\Gamma \sim \#\alpha^5 T$$

200n

Rummukainen, Moore,…
updates
Ramsey-Musolf,
Garny Konstandin,
gauge dep.
Rlotto,…
B-dependence,…

2014

Rummukainen, d'Onofrio,
Tranberg: definite results **SM-Lattice**

Transition strength

197n

Weinberg,Jackiw,Kiritsis,Linde,Niemi,Semenoff,…
FTFT, $V_{eff}(\phi,T)$

1992

Carrington: **$V_{eff}(\phi,T)_{SM}$**

1993 -

Arnold, O.Espinosa, Buchmuller
Fodor,… **EWPT industry using V_{eff}**

TOP

Kajantie, Rummukainen,
Laine, Shaposhnikov:
DR+Lattice => **SM dead**

1996 ~ 2000

LSS in MSSM,
Carena, Quiros, Wagner, J.R.Espinosa,… **(V_{eff})**
Cline, KK, Rummukainen, Laine, Losada…
DR+Lattice

2000-

MSSM / phenomenology
Carena, Quiros, Wagner, Nardini,..
Rummukainen, Laine, …
constraints on **LSS getting worse…**

2011

J.R.Espinosa, Gripaios, Konstandin, Riva:
strong 2-step trans. in SM+S

2012

HIGGS

Renewed interest on
NMSSM, 2HDM's, SM+S, portals,…

Baryon creation, QKE's

1990

Cohen, Kaplan, Nelson
spontaneous BG, …

1993-4

Farrar, Shaposhnikov,
Gavela, Hernandez,Orloff,Pene,..
Quantum Reflection

1994 -2002

M.Joyce, T.Prokopec, N.Turok,
Cline, KK, MJ,TP, Schmidt,Konstandin…
Semiclassical force BG
WKB / CTP $S_{\rm CP}(z)$

1996 -200n

Riotto, Carena, Quiros, Wagner,….
"vev-insertion method",
also from **CTP**
… Profumo,Ramsey-Musolf,Tulin,..

2003-

CTP mostly used to defelop **QKE's** for (resonant)
Leptogenesis
Pilaftisis etal,
Buchmuller etal, Garny etal,
Garbrecht etal, Herranen etal,

~2010-

(Morrissey, Ramsey-Musolf,…
Prokopec, Konstandin,…
Flavour mixing …)

~2009-

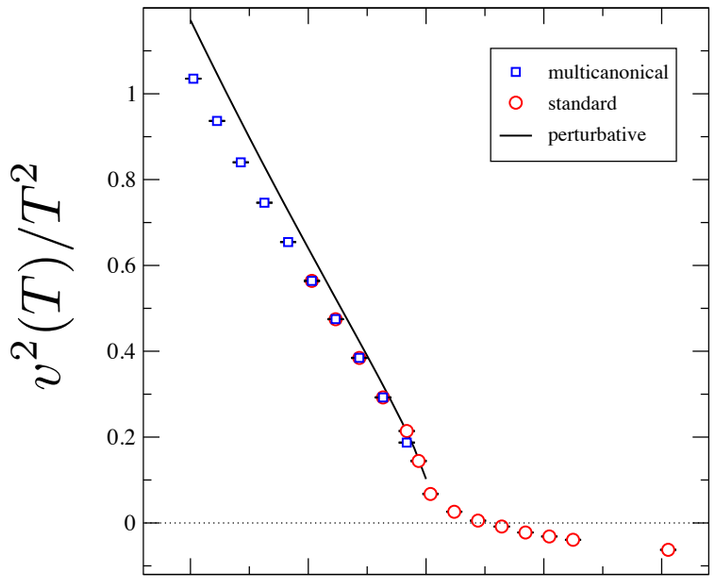
cQPA combines **SCBG** and **QR**, using **CTP**
Herranen, KK, Rahkila

EWPT and B-violation in the SM; latest results

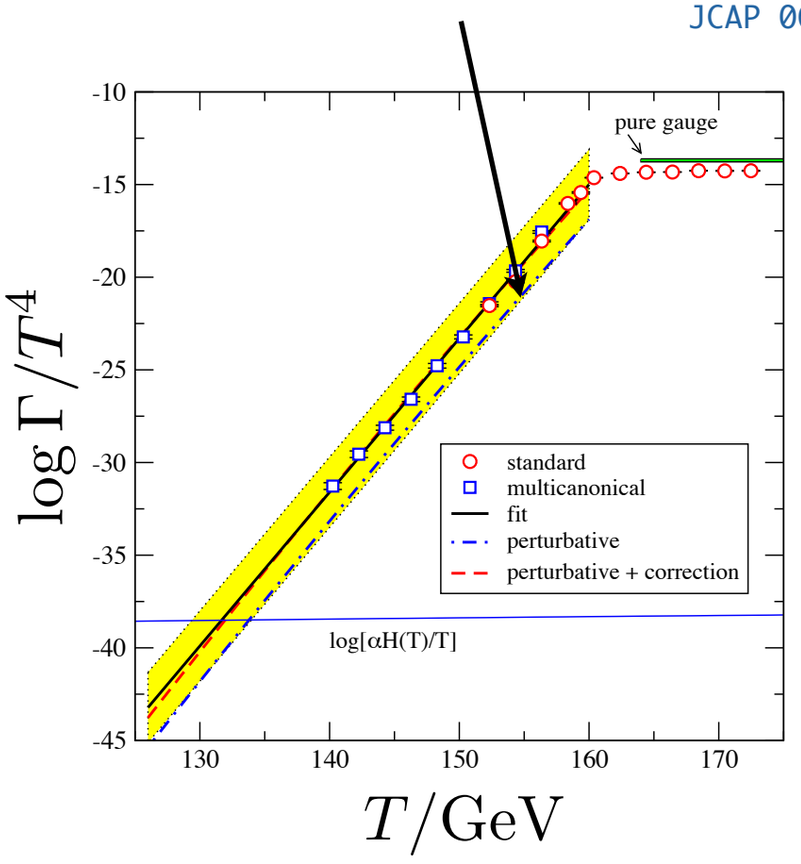
PT in SM, is a ***cross-over*** with

$T_c \approx 160$ GeV

K.Rummukainen, M.d'Onofrio and A.Tranberg, PRL113.141602



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



Sphaleron rate in SM

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

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

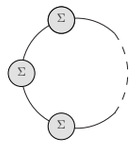
Sphalerons drop out of eq. in broken phase when

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

Models with a strong PT / Loop corrections / MSSM

Most effort has been put to increase the effective cubic coupling by **loop corrections**

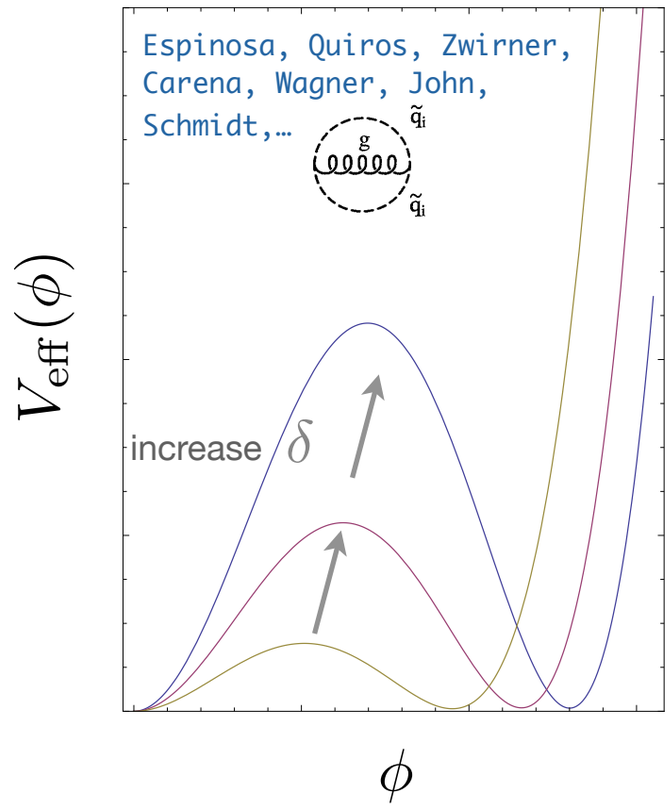
Need new light ($m_i < T$) bosonic fields strongly coupled to Higgs



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

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

[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 => **very** heavy t_L
eg. a very large SYSY breaking m_Q

ALSO, to keep m_{stop}(T) small need

Heavy gluino: $m_g > 500$ GeV

Small or negative m_R => $m_{stop} <\approx m_{top}$

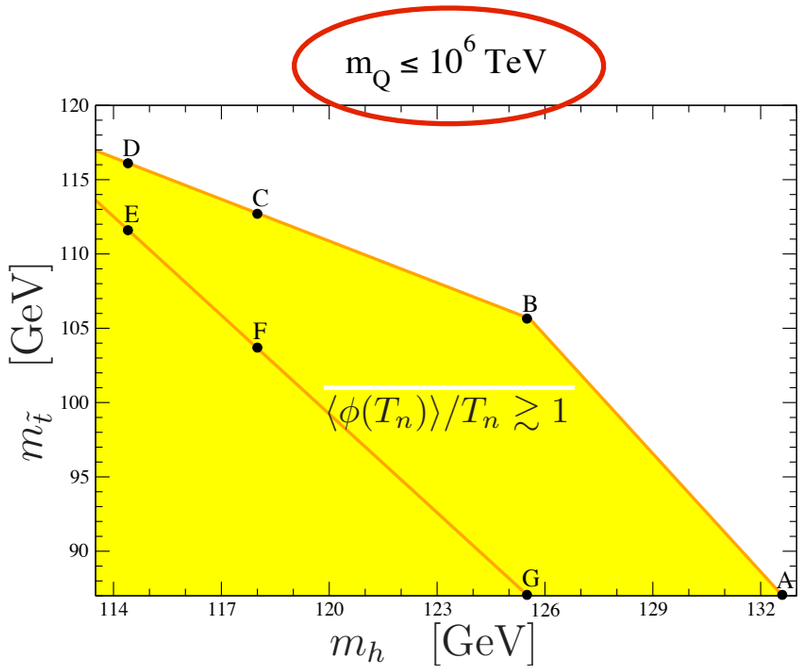
and danger of colour-breaking

etc (EDM's) … ==> Effective LSS / MSSM theory with only the light stop and a light neutralino.

MSSM-EWBG: *alive* (?) but perhaps *not so well*

RGE-improved low energy eff. th.
Allow *metastability* against color breaking…

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

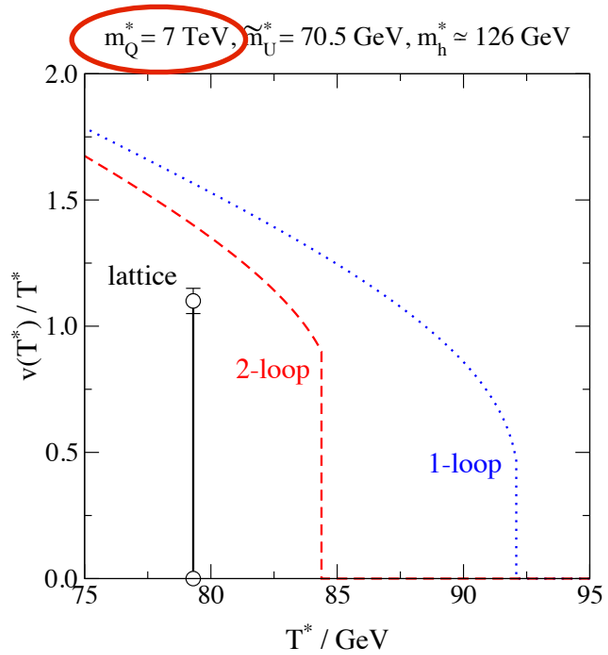


Carena, Nardini, Quiros & Wagner, 2009

LHC: **Stop mass bounds** generically **m > few x 100** GeV
Stop-enhanced H—>gg-fusion
One can get around these if there is
a light neutralino (bino) (*m* < 60 GeV)
M.Carena, G.Nardini, M.Quiros & C.Wagner, 2013

Lattice + DR: 3D-theory contains also light squarks

$$m_h \approx 126\ \text{GeV} \quad m_{\tilde{t}_r} < 155\ \text{GeV}$$



Laine, Nardini and Rummukainen. 2013

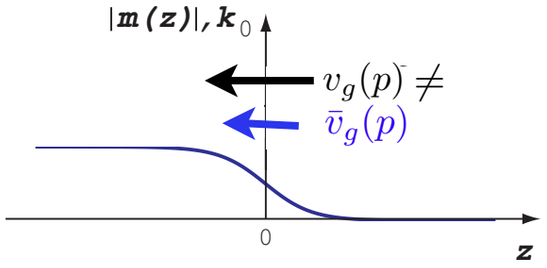
$$\left(\frac{v}{T_c}\right)_{\text{latt}} = 1.117(5) \qquad \left(\frac{v}{T_c}\right)_{\text{Landau}} = 0.9$$

GOOD NEWS TO BRING HOME WITH:
Transition typically much stronger than the (1-) loop caclulations of V_{eff} indicate.

BAU generation, QKE's / SC force - QM reflection

Thick wall: *SC force*

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



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

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

complex phase of m

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

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.

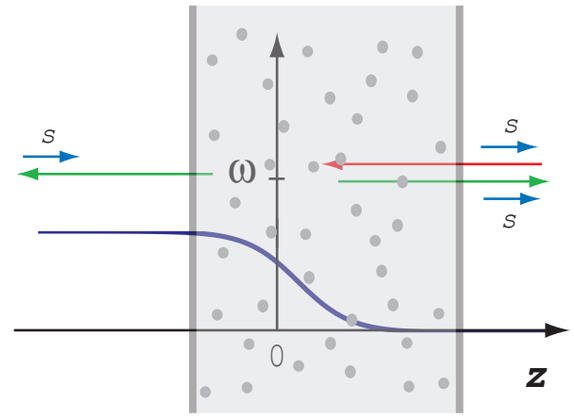
WKB

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.

CTP

Thin wall: *quantum reflection*

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



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, because of decoherence due to collisions

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 methods too rudimentary, need CTP/KB

QKE's, more advanced methods

Inclusion of quantum reflections into QKE's needs more sophisticated methods

A suitable method (**cQPA**) actually exists:

In planar symmetric problem, the **information about reflection coherence condenses to a set of new shell functions**

=> Extended **Boltzmann type eqs. with coherence**

Tested already in **homogeneous problems**

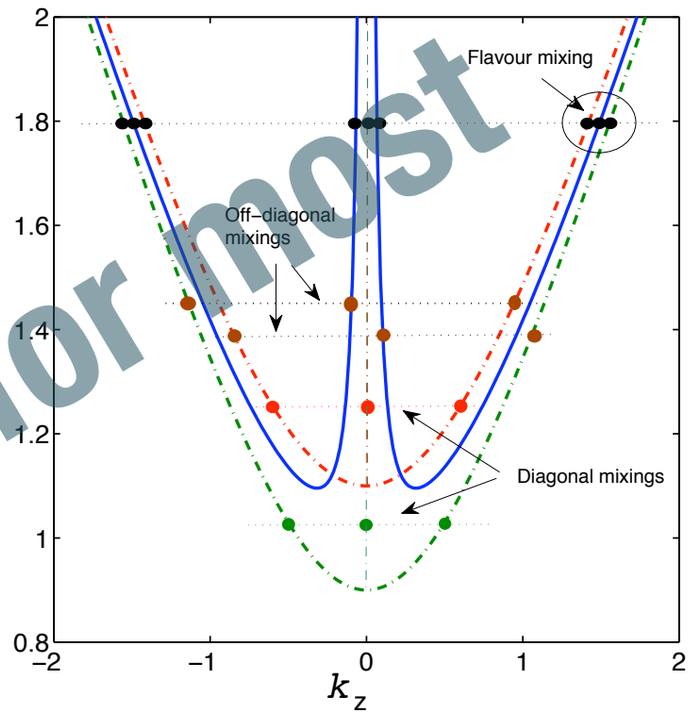
M.Herranen, KK & P.M Rahkila,
JHEP 0809 (2008) 032; JHEP 0905 (2009) 119;
JHEP 1012 (2010) 072; JHEP 1202 (2012) 065
C.Fiedler, M.Herranen, KK & P.M Rahkila,
JHEP 1202 (2012) 080.

Works also for **leptogenesis** M.Herranen, KK, P.M.Rahkila

Application to EWBG (toy model) ongoing:

M.Herranen, KK, P.M.Rahkila, H.Jukkala

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



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

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

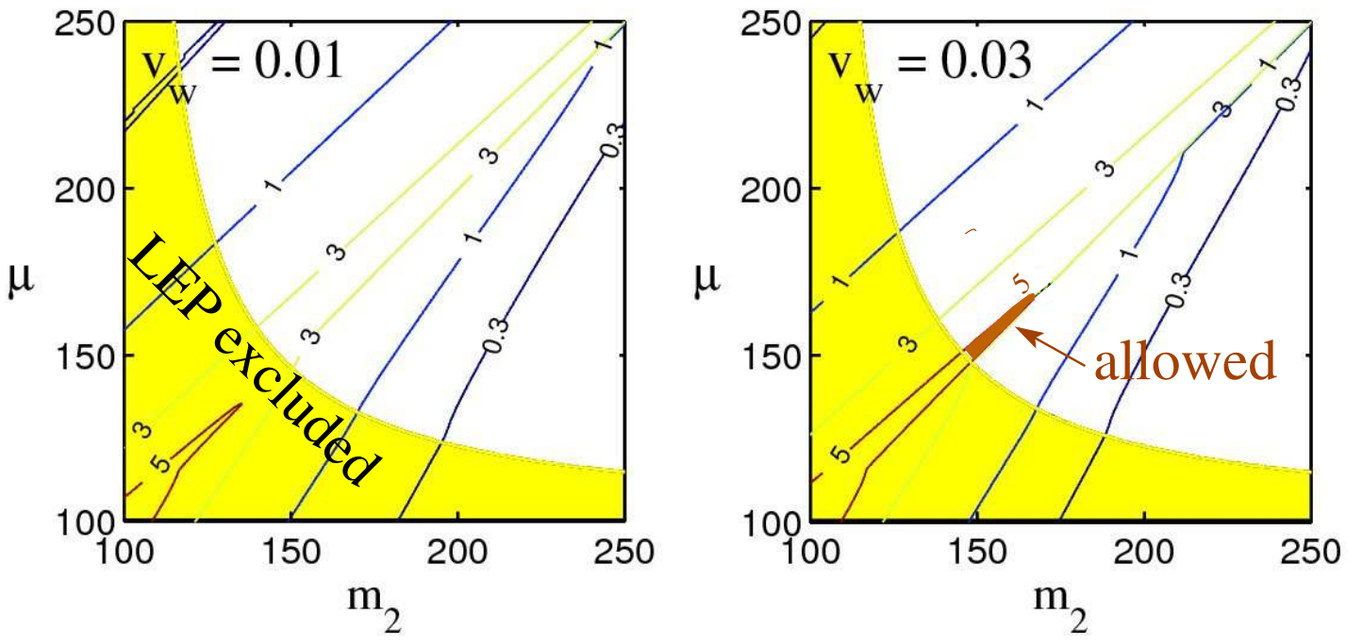
DREAM: A "CAMB" package for the EWBG analysis

BAU generation, MSSM / Thick wall - SC

Chargino transport

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

Enhancement when $m_2 \sim \mu$



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]

Adiabatic, flavour diagonal limit

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**

Stop transport (weak source [CJK])

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

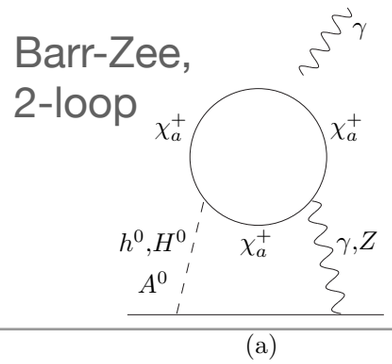
Neutralino transport (bino-driven) !!

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

MSSM / eEDM

Same phases that give BAU generate EDM's
(more generally supersymmetric CP problem)

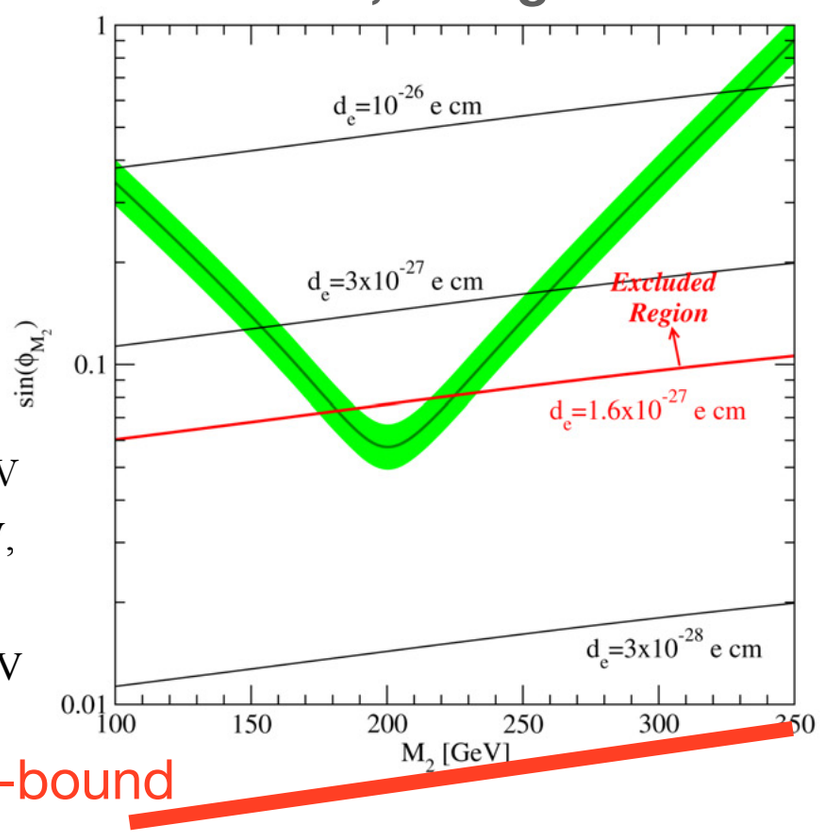
2013 ACME-bound on eEDM: $d_e < 8.9 \times 10^{-29}$
ACME collaboration, Science 343 (2014) 6168, 269-272



Bino driven EWBG (optimistic calculation) Li,Profumo,Ramsey-Musolf,PLB673 (2009)

EWBG-fridendly

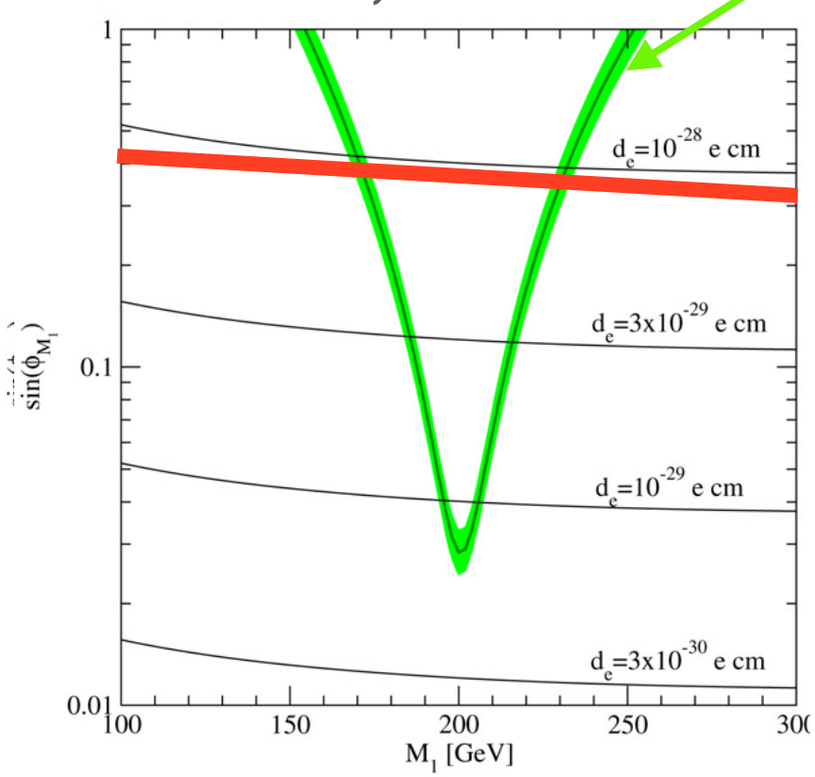
eEDM, charginos



$M_1 = 95$ GeV
$|\mu| = 200$GeV,
$\tan\beta = 10$,
$m_{A^0} = 300$GeV

ACME-bound

eEDM, neutralinos



ACME-bound

$M_2 = 190$GeV,
$|\mu| = 200$GeV,
$\tan\beta = 10$,
$m_{A^0} = 300$GeV

- **chargino transport** mechanism **excluded**
- **light** bino (< 60 GeV) appears *not ok*

Loopholes on loopholes? Finetuned cancellations

- between, CP-even and CP-odd higgses Bian,Liu,Shu,2014
- between, one and two-loop contributions Li, Wagner, 2015

EWBG in the MSSM ?

Is this not just fighting to keep a sinking ship afloat?

Leszek Roszkowski:
“SUSY cannot be disproved, only abandoned”

2HDM's

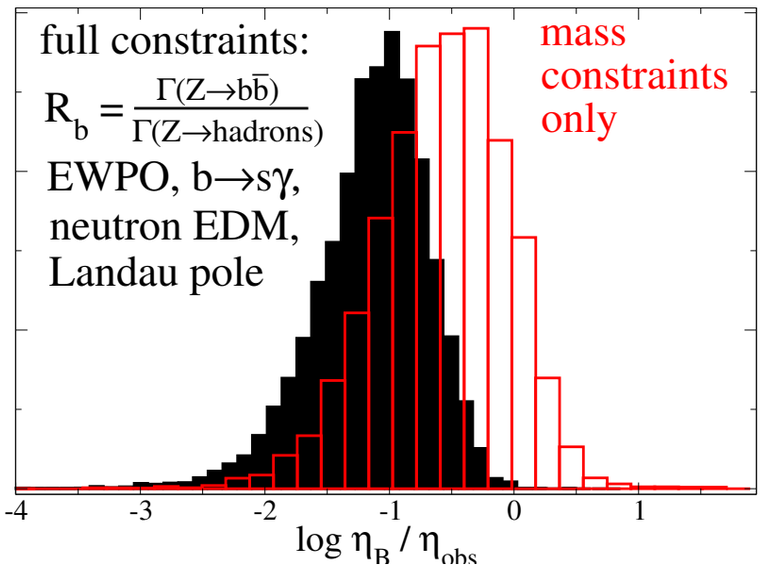
Many new CP-violating phases:

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

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

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

A more detailed scan of different types of 2HDM with similar results was carried out in:
G.C.Dorsch, S.J.Huber & J.M.No, JHEP 1310 (2013) 029.



Post-ACME analysis 2HDM + *vector like fermions* OK: Chao and Ramsey-Musolf: JHEP 1410 (2014) 180

Loophole with cancellations between, CP-even and CP-odd higgses works here as well. Bian,Liu,Shu,2014

SSM a strong PT at “tree level” !

Get easily models satisfying v/T > 1-limit with large enough a lambda.

eEDM and nEDM are not a problem.

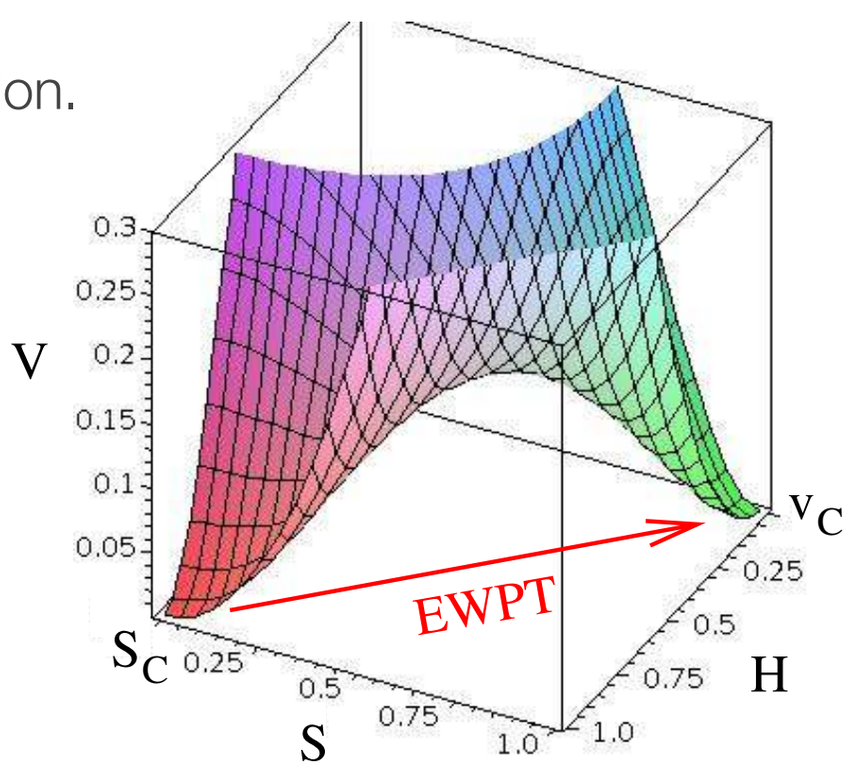
Take simply

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

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

Transition may proceed in two steps, and model can give **a potential barrier at tree-level at T_c** → strong phase transition.

J.R.Espinosa, T.Konstandin, F.Riva, NPB854 (2012) 592



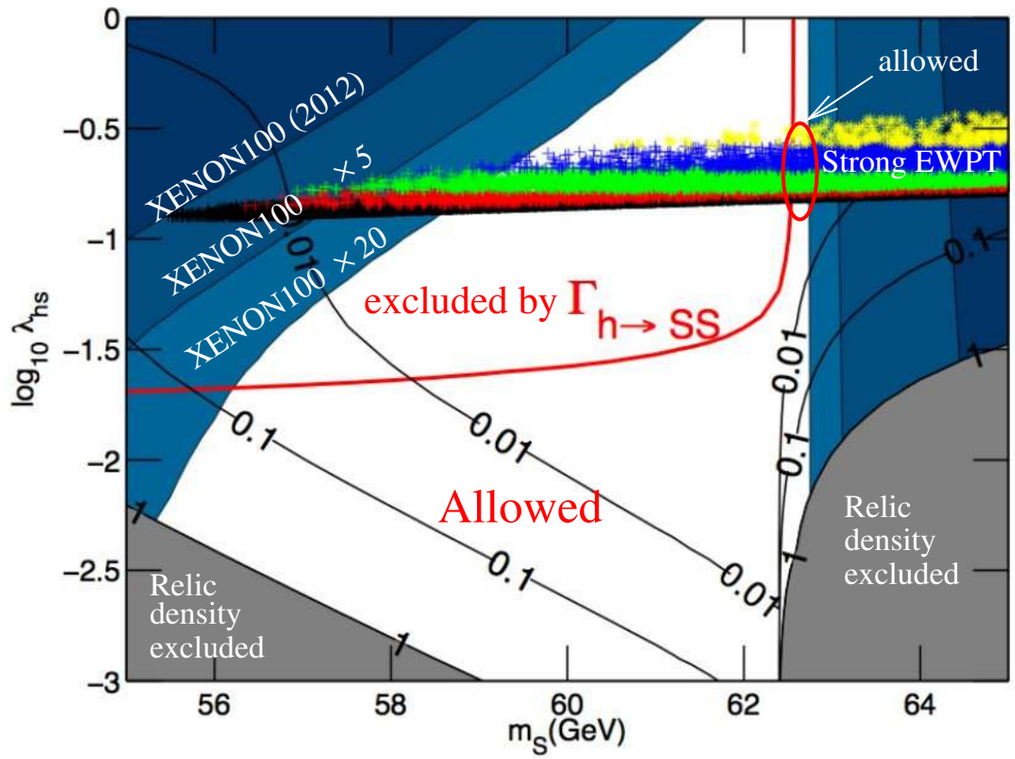
Finite-T effects only **lift the degeneracy of vacua. Strength of transition determined by tree-level V.**

SM+S with Z_2, BAU and DM

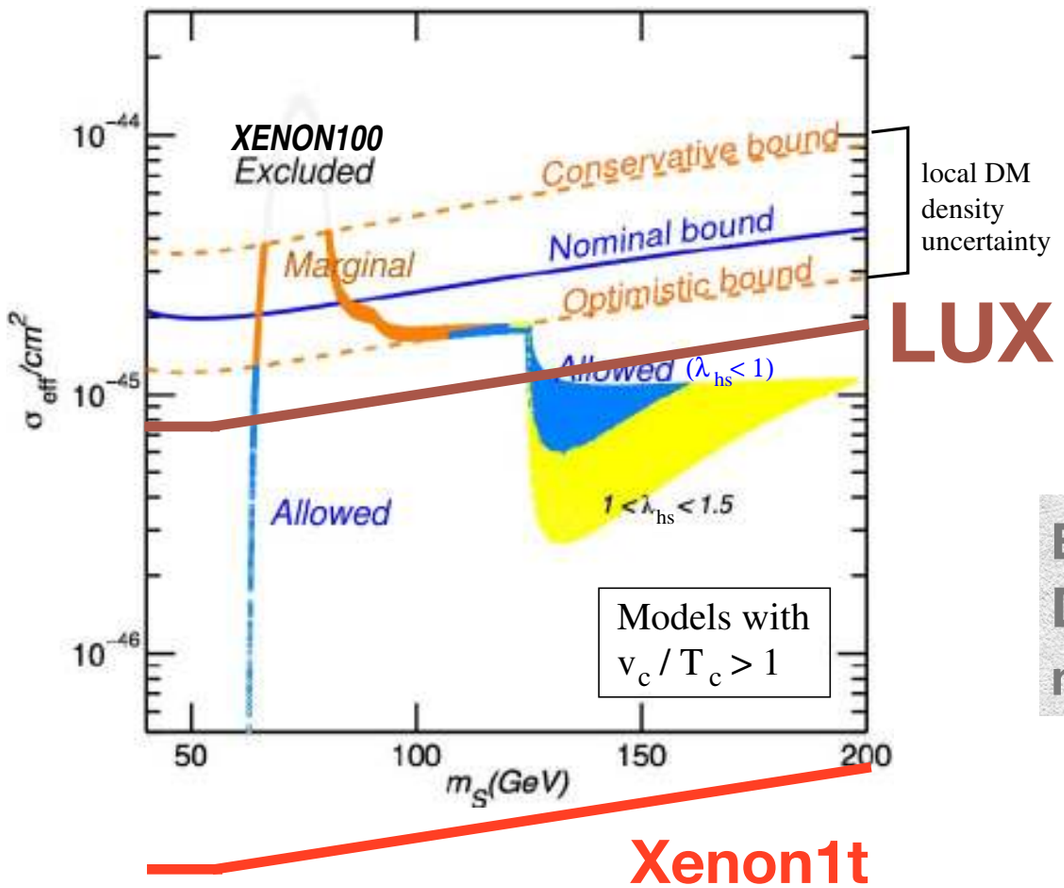
Strong PT: need a large λ_{sh}, yet

$$\Omega_{DM} \sim 1/v\sigma \sim 1/\lambda_{sh}^2$$

=> small Ω_{DM} . **Subleading DM**

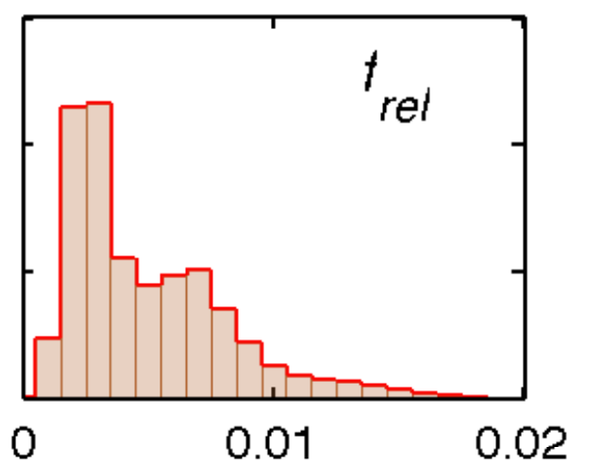


Cline,KK,Scott, Weniger, PRD 2013



Even subleading DM, BAU-capable models detectable

BAU acceptable *v/T >1* models



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

ETC: (IDM, NMSSM,...) TCDM

A model for **Dark Matter,** plausible **Naturalness** and a hint for a complete **Gauge Unification**

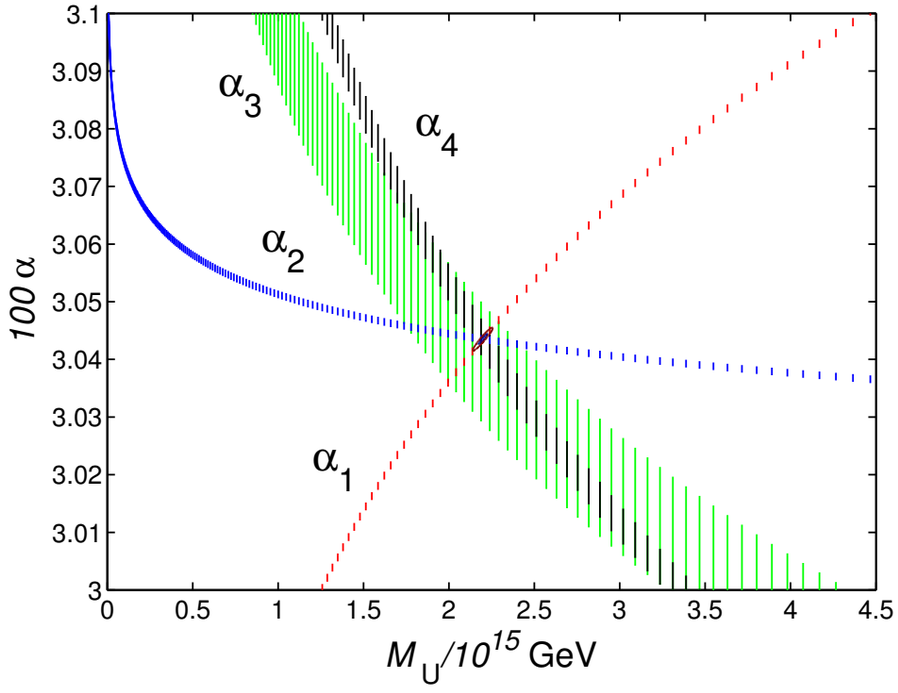
KK, Kimmo Tuominen and Jussi Virkajärvi

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(N_{TC})$	Z_2
L_L	1	2	-1/2	1	-1
E_R^c	1	1	1	1	-1
ω	1	adj	0	1	-1
β	1	1	0	1	-1
$\tilde{g}$	adj.	1	0	1	-1
Q_L	1	2	1/6	3	1
U_R^c	1	1	-2/3	3	1
D_R^c	1	1	1/3	3	1
η_1	1	1	0	3	-1
η_2	1	1	0	3	-1
$\tilde{G}$	1	1	0	adj.	-1

DM-sector

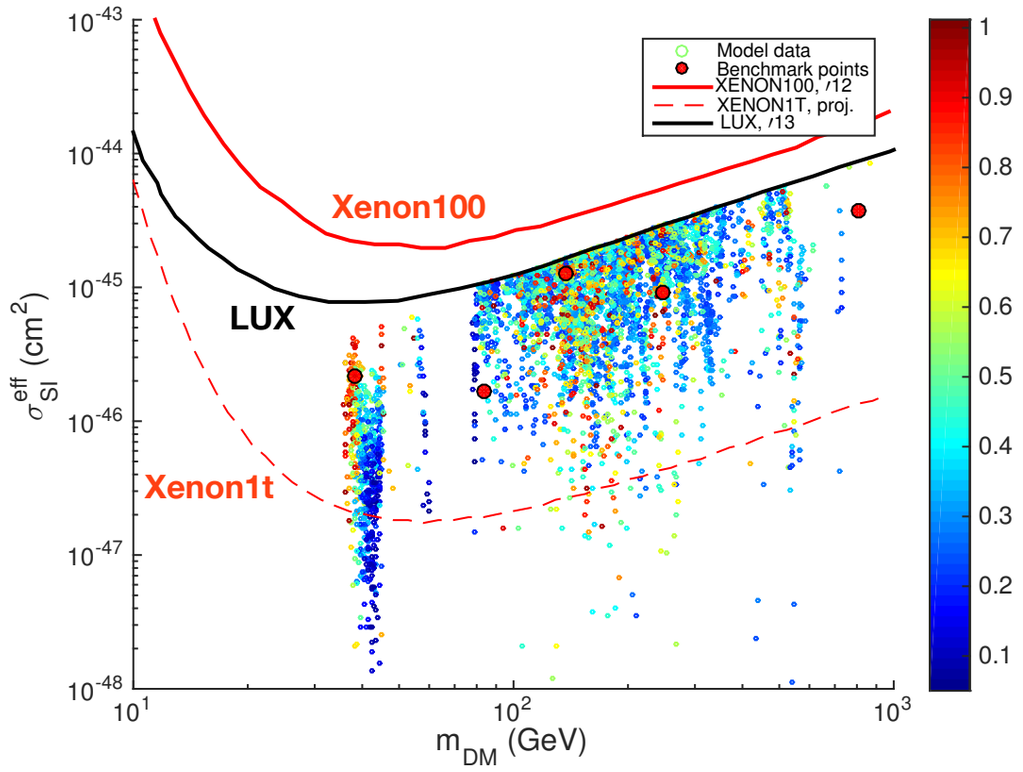
TC-sector

3 neutral Majorana fields + 2 charged Dirac fields



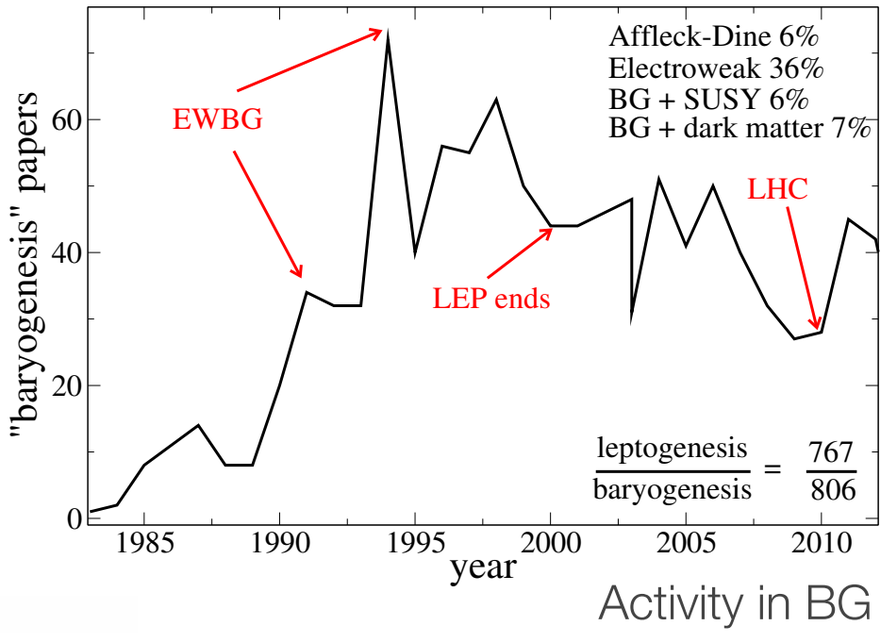
Particle spectrum and the unification consistency coupled to existence of a TeV TC-scale.

KK, Tuominen, Virkajärvi, arXiv:1504.07197



All pieces for EWBG are qualitatively in place.
(CP in DM-sector)
Calculation not done yet.

“Conclusions”



Activity in BG

EWBG continues to be interesting albeit ever more constrained by LHC and other lab data

Current action is in phenomenological model building

MSSM EWBG appears to be **all but dead / NMSSM** should be OK, btw

2HDM + exensions possible, though **restricted**

SSM:

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

Singlet effect is likely a part of a more complete working EWBG model.

QKE’s not fully understood (work in progress) Interesting but not pressing issue.