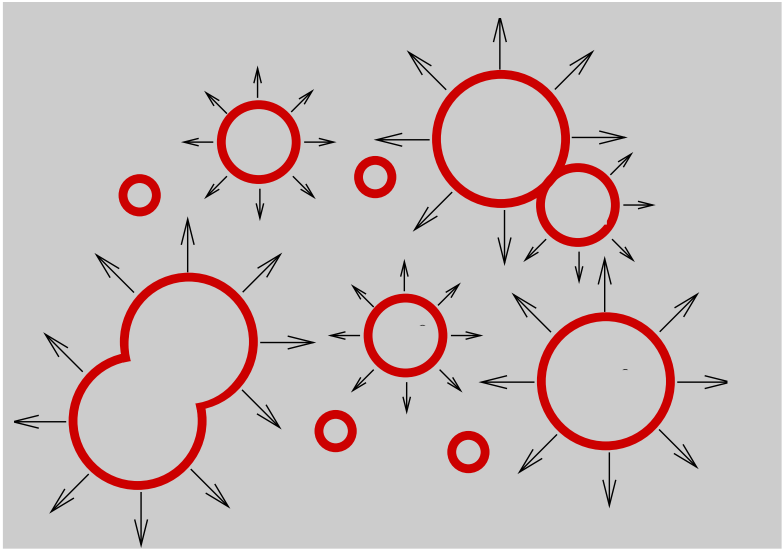
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Electroweak Baryogenesis

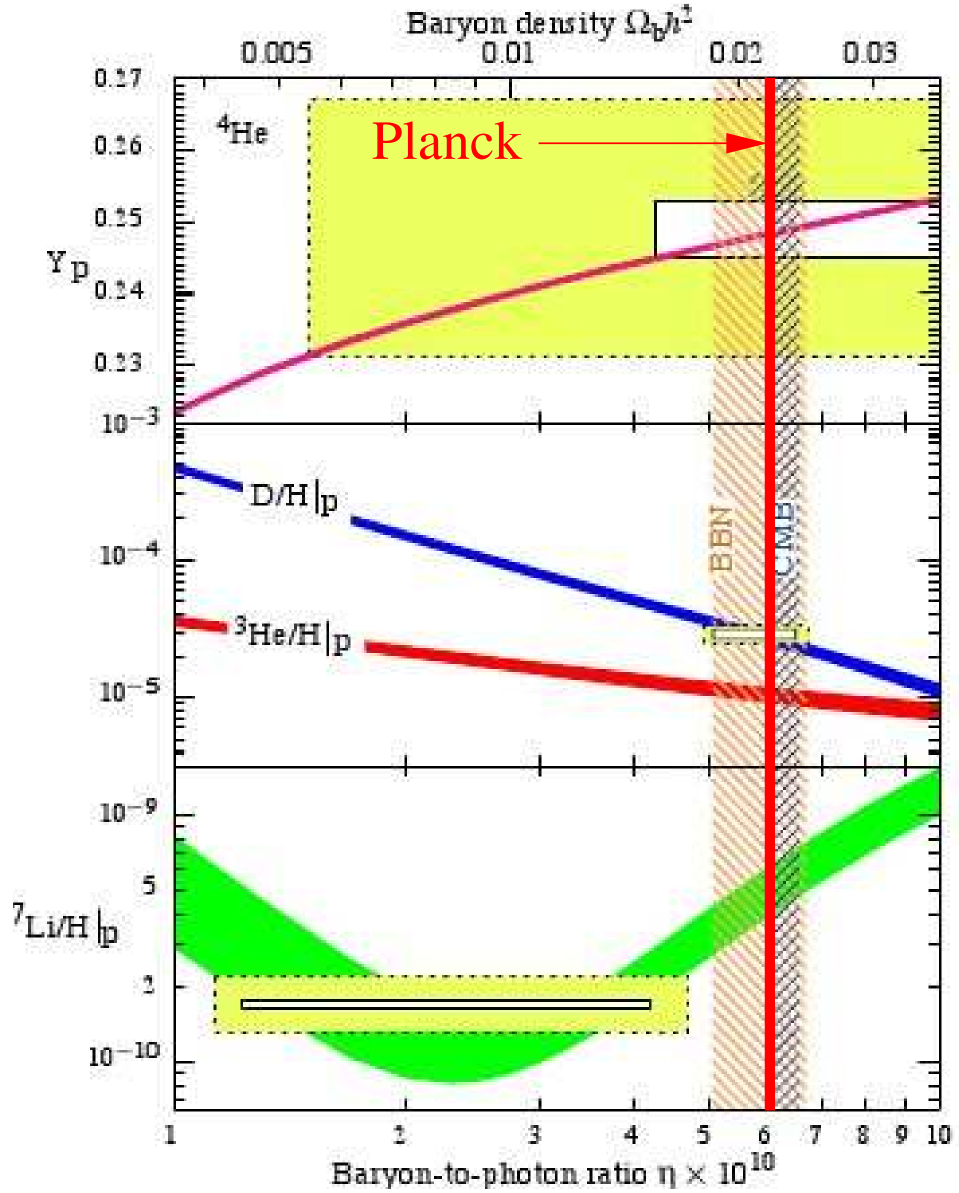
Kimmo Kainulainen,

Rencontres du Vietnam 2014, Physics at LHC and beyond,
16.8.2014



- **MSM** does not explain BAU
- **EWBG** testable framework
- MSM**:** not possible
- **MSSM:** very likely not possible
- Other extensions: **2HDM, SSM,..**

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**,
this cannot be initial condition.

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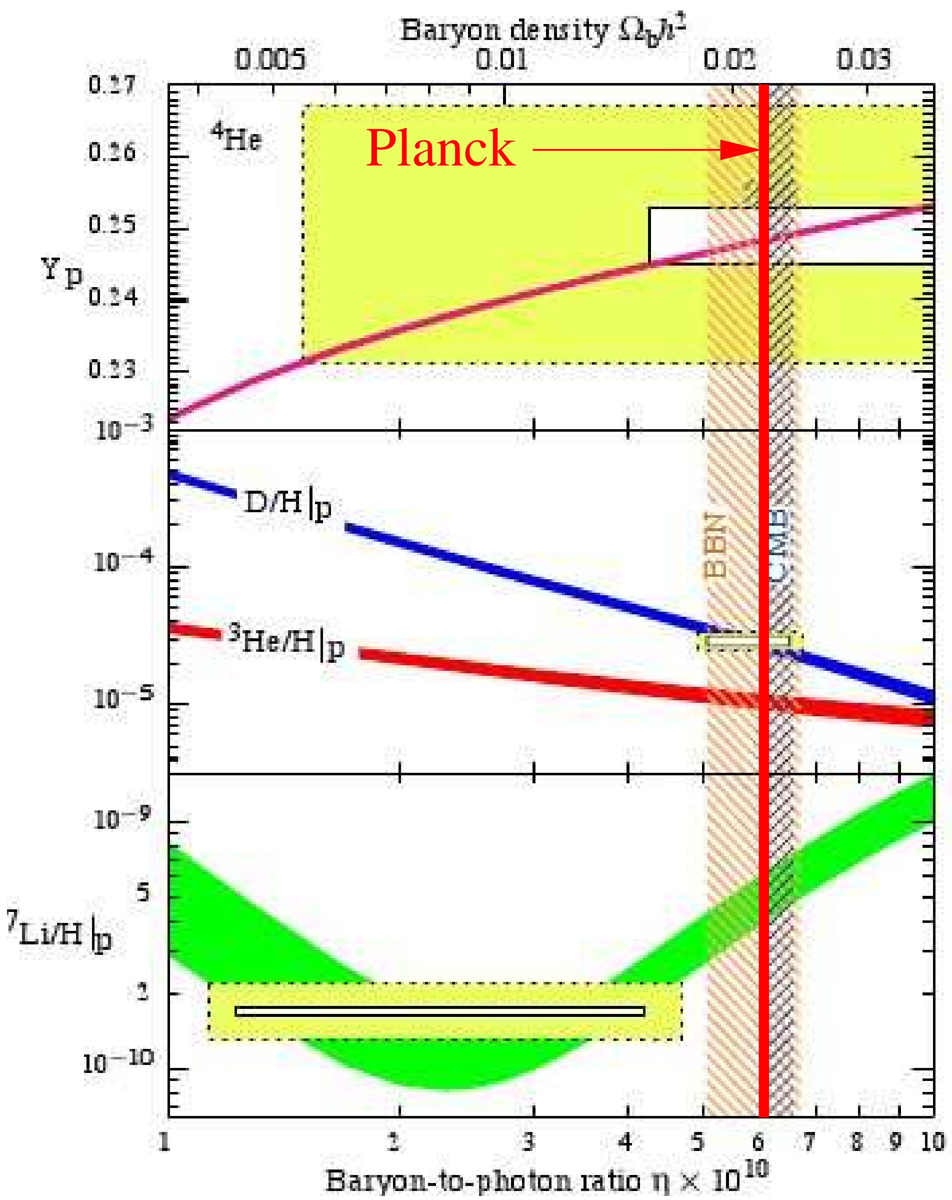

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BICEP2:

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

Fair amount of room to play.
EWBG == BG at EWPT,
at T ≈ 100 GeV, is the
lowest energy scale model

EWBG in a nutshell

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

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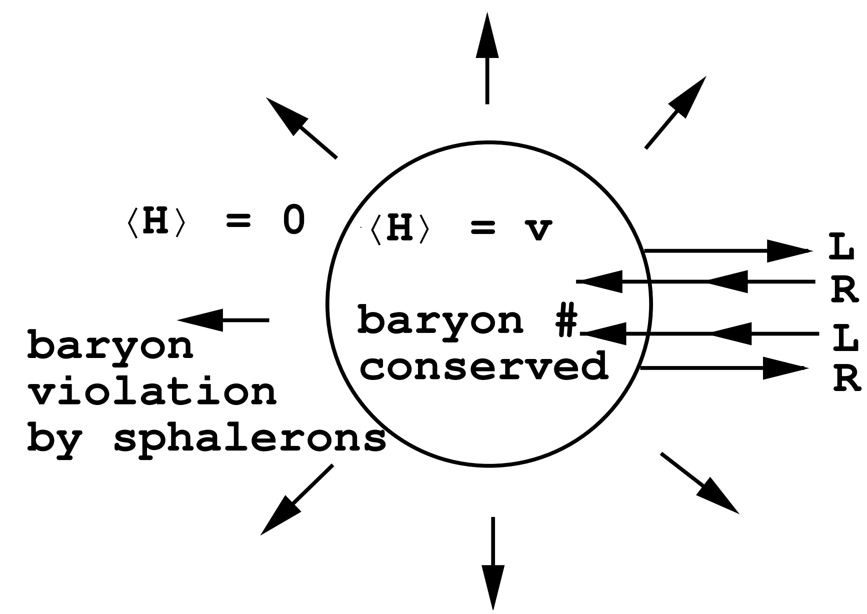
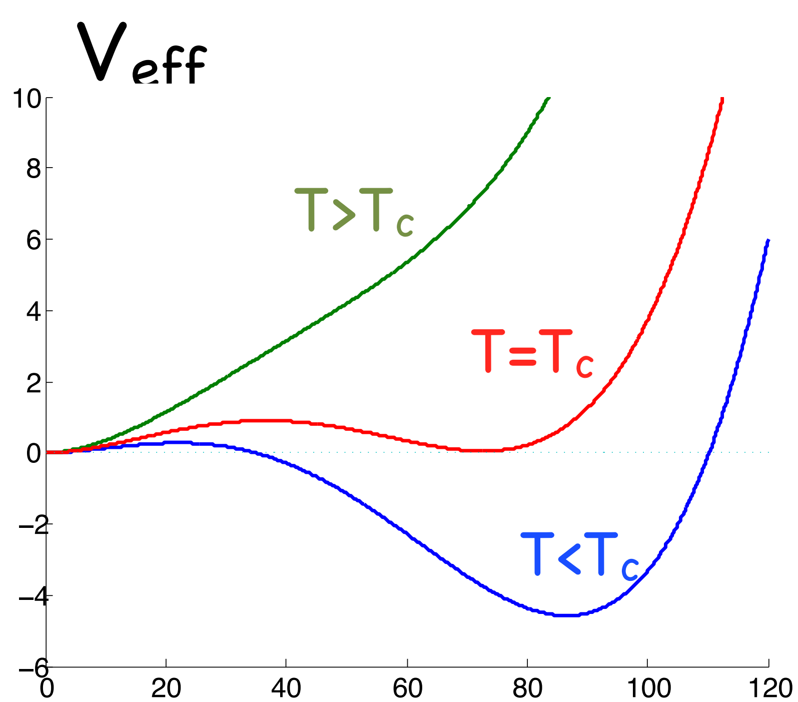
1st order PT: at T_c ~100 GeV, true vacuum bubbles, ⟨H⟩ ≠ 0, form and start expanding into the false symmetric vacuum.





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

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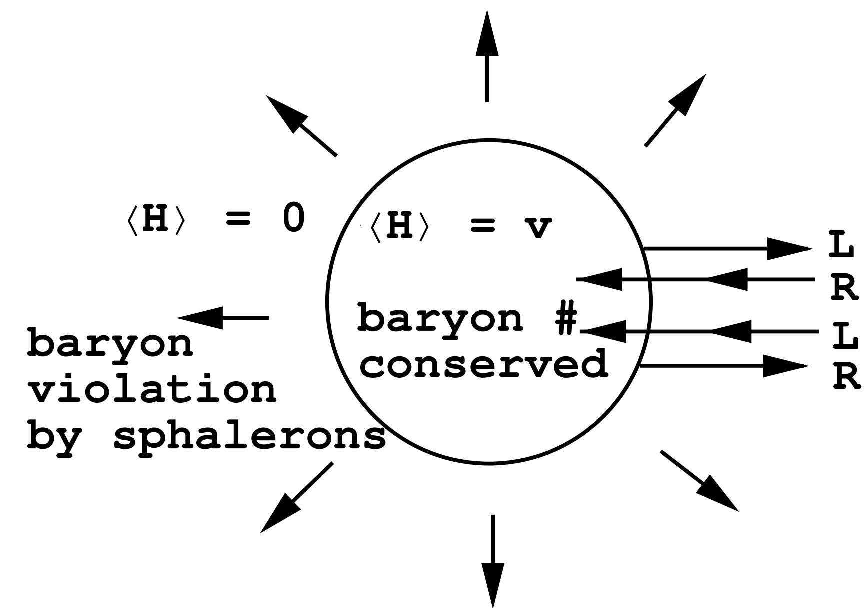
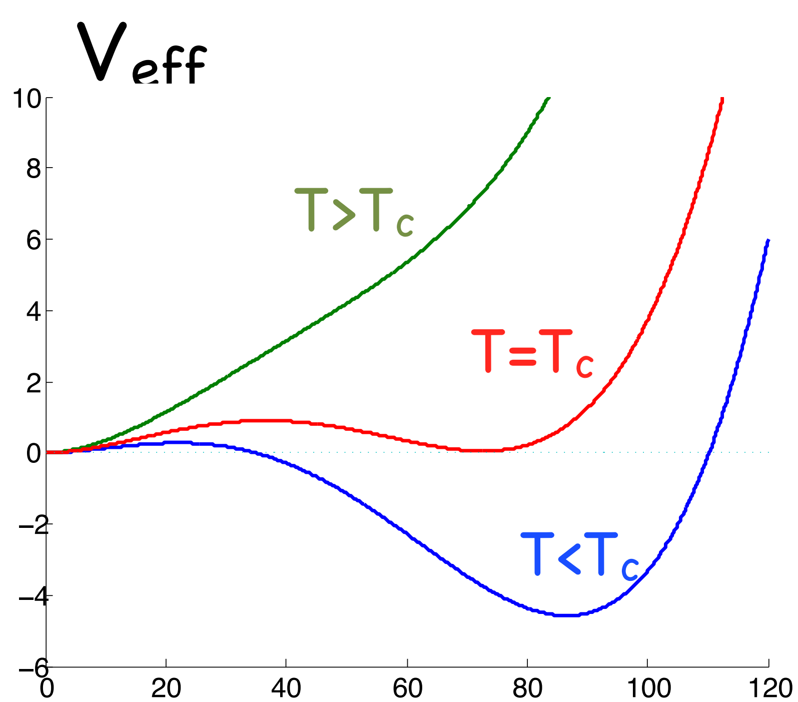
Particles interact with wall in **CP violating** way





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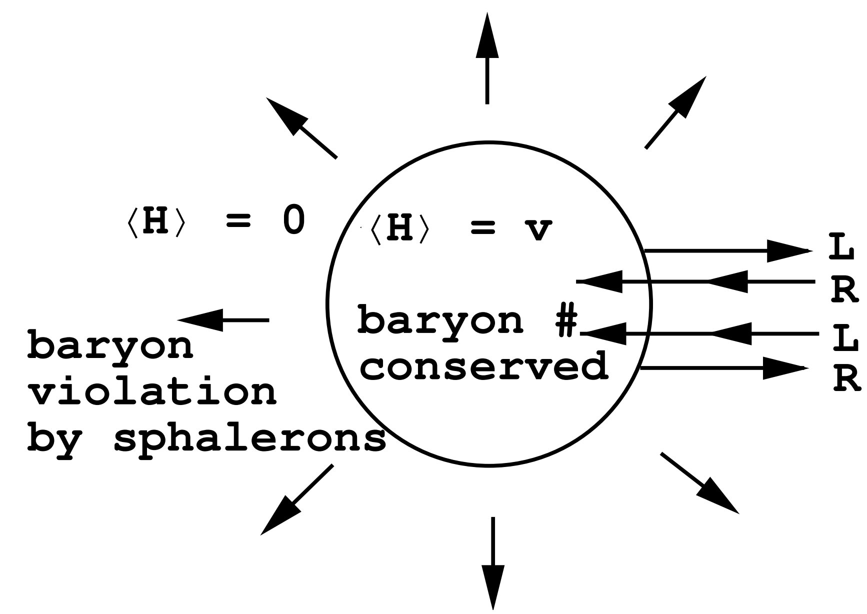

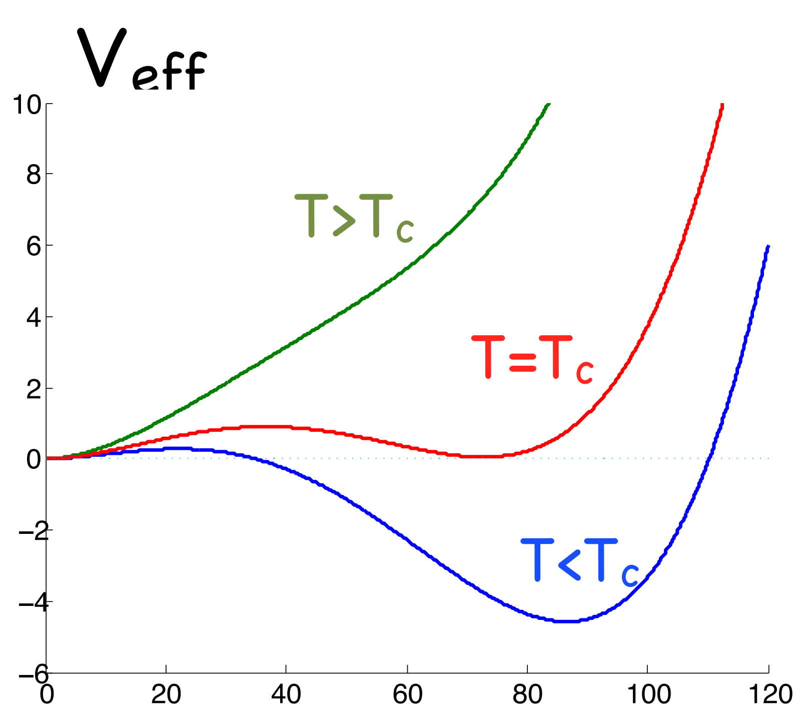

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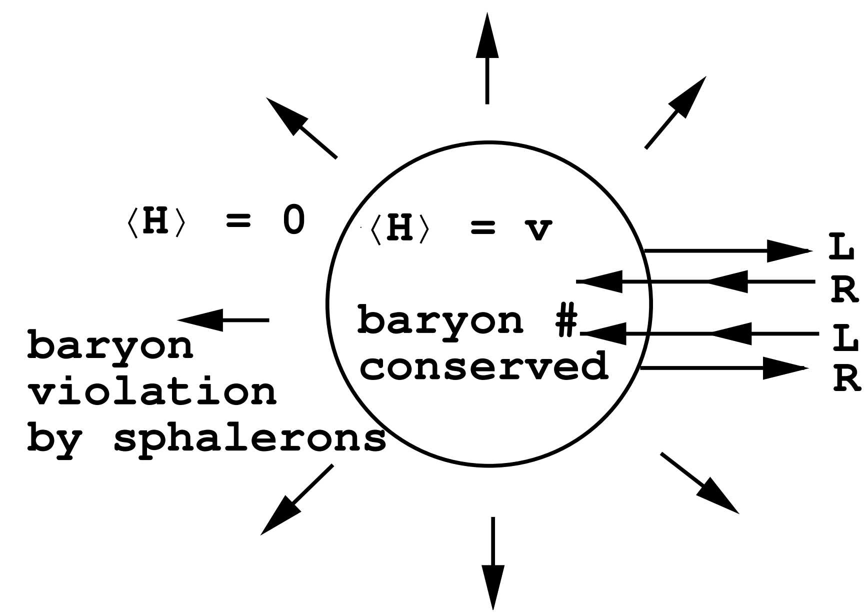

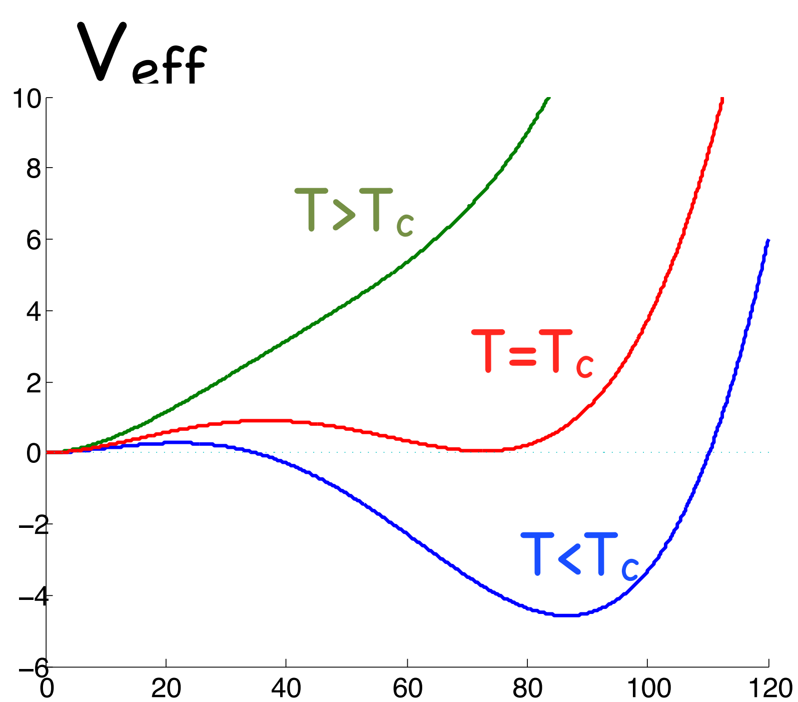

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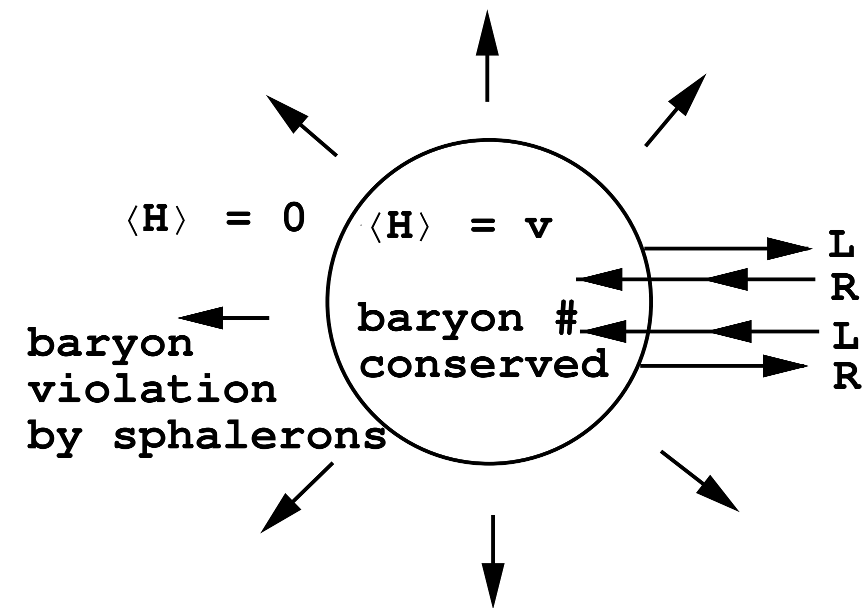

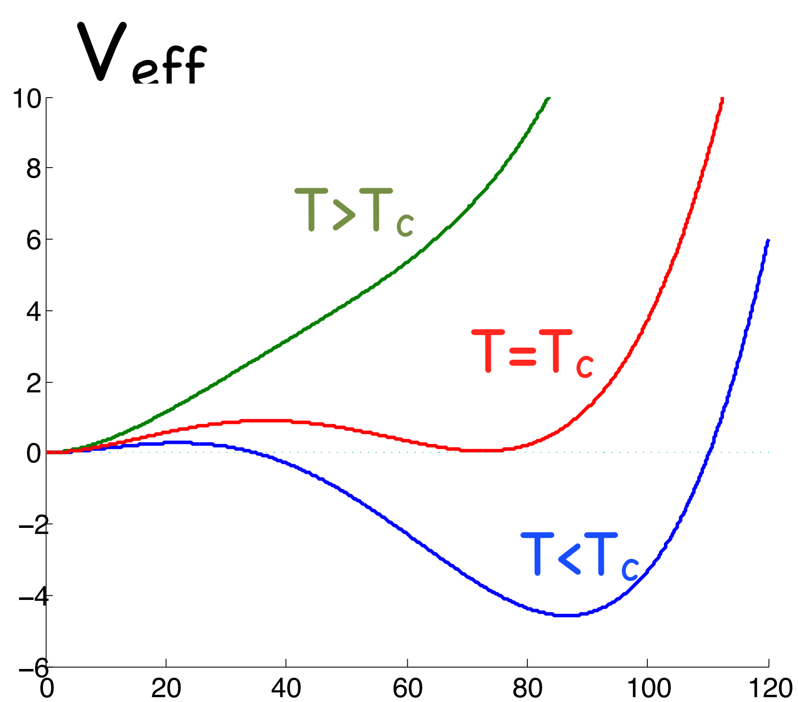

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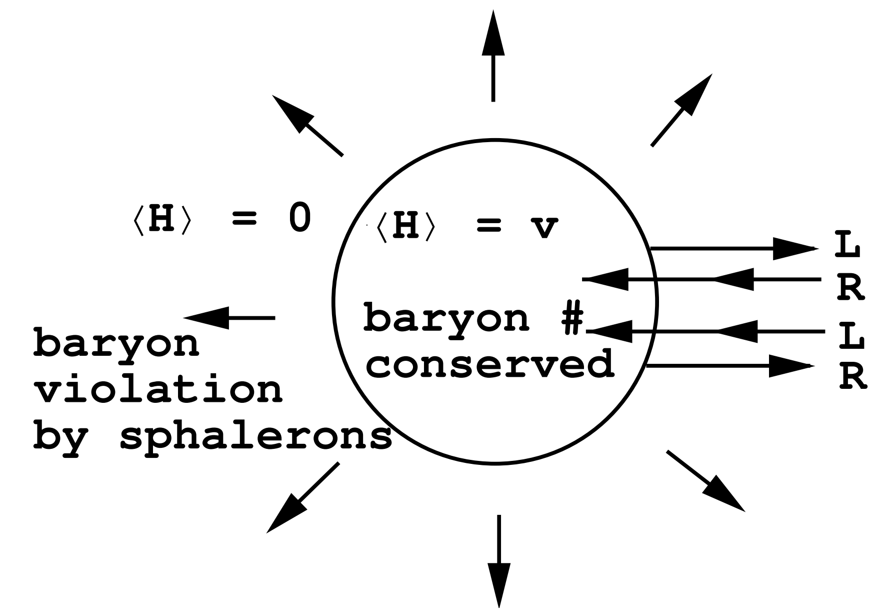

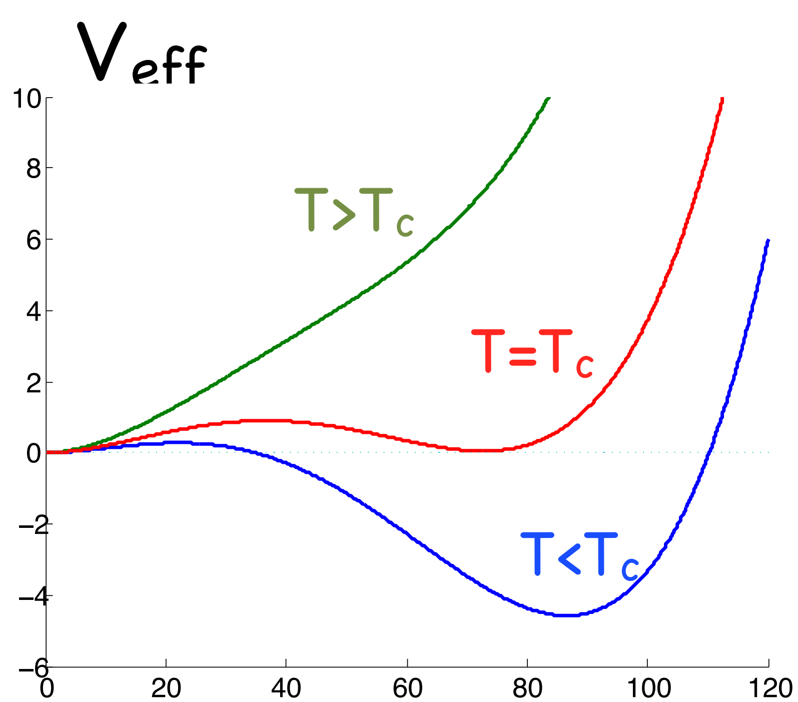

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IN MSM:

- Only **B-violation** (by sphalerons) is certainly present in the SM.
- ~~**CP**~~ **in CKM,** not sufficient
- **1st order PT,** <u>not</u> present in SM;

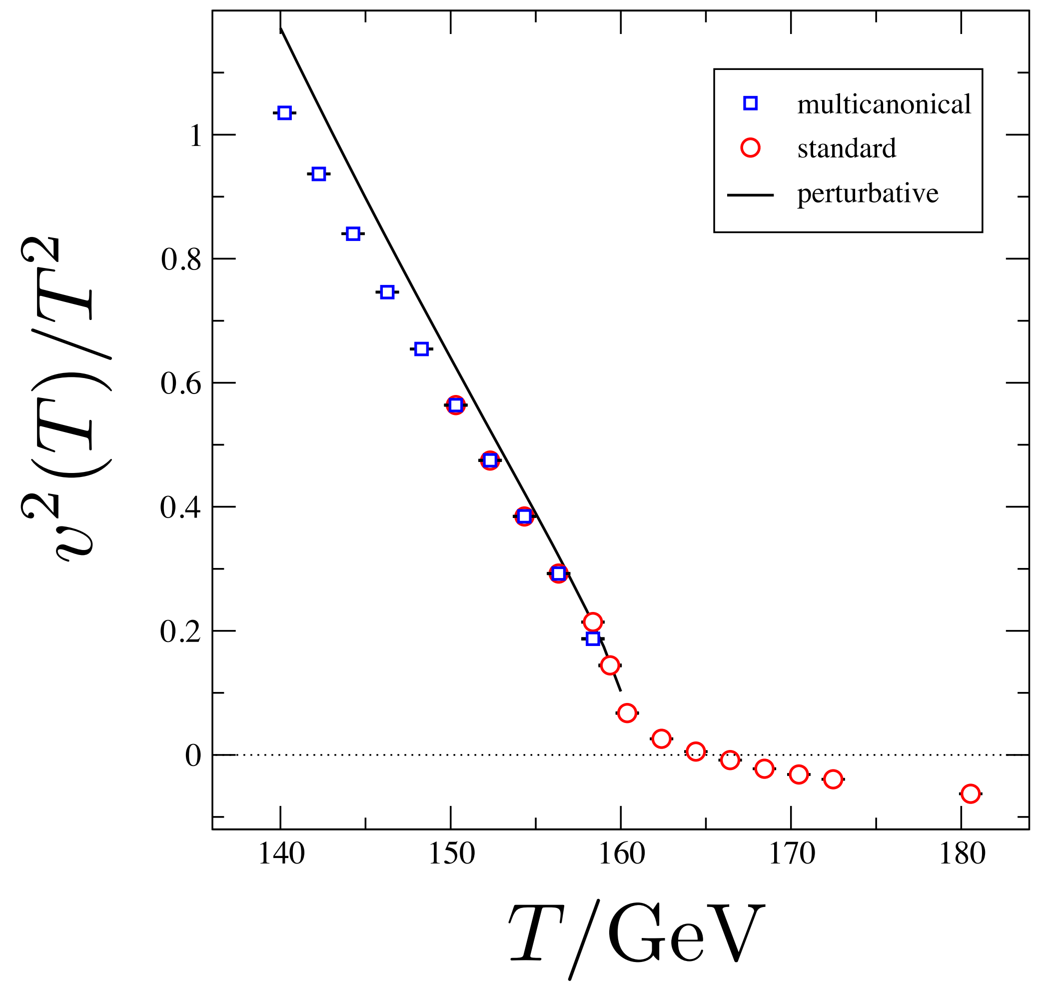
EWPT in SM, no jump in the order parameter

PT in SM, is a cross-over with

$T_c \approx 160$ GeV

M.d'Onofrio, K.Rummukainen, and A.Tranberg, arXiv:1404.3565

$$v^2(t) = \langle H^2 \rangle (T)$$



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

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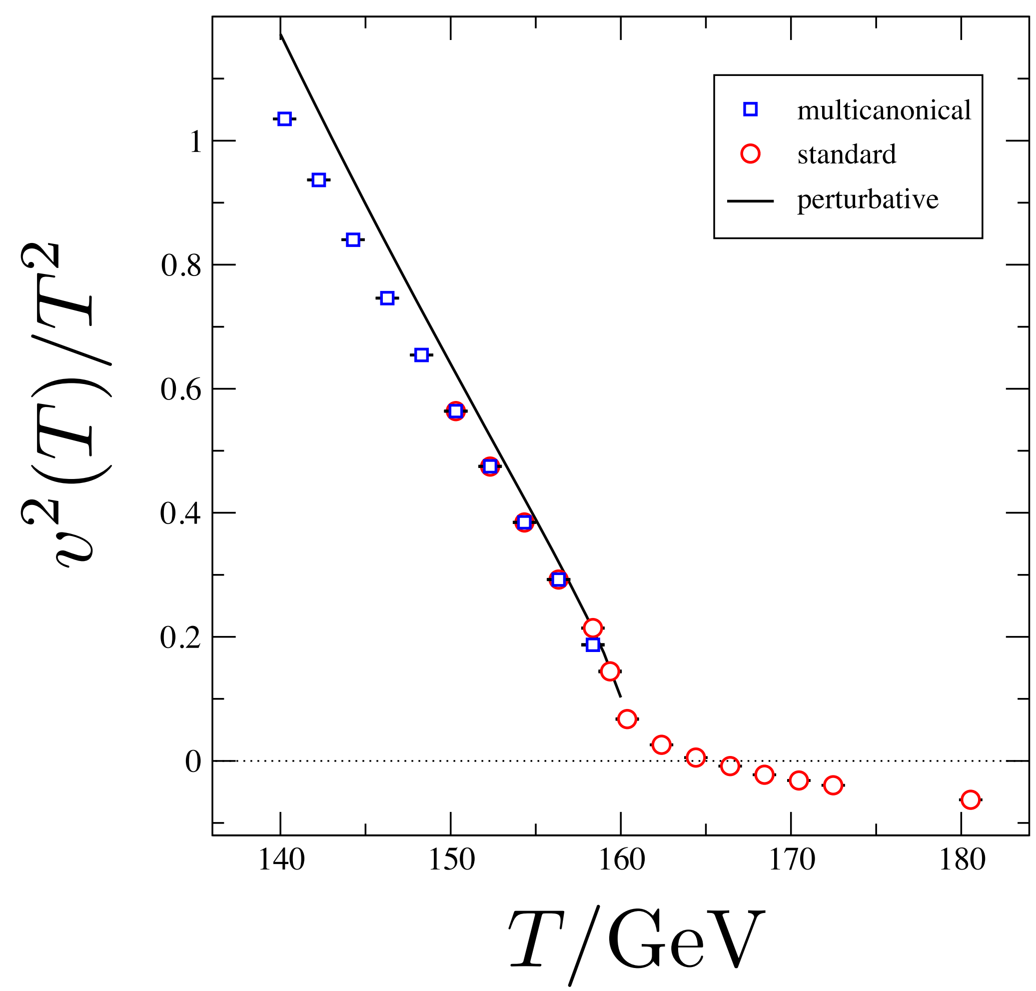

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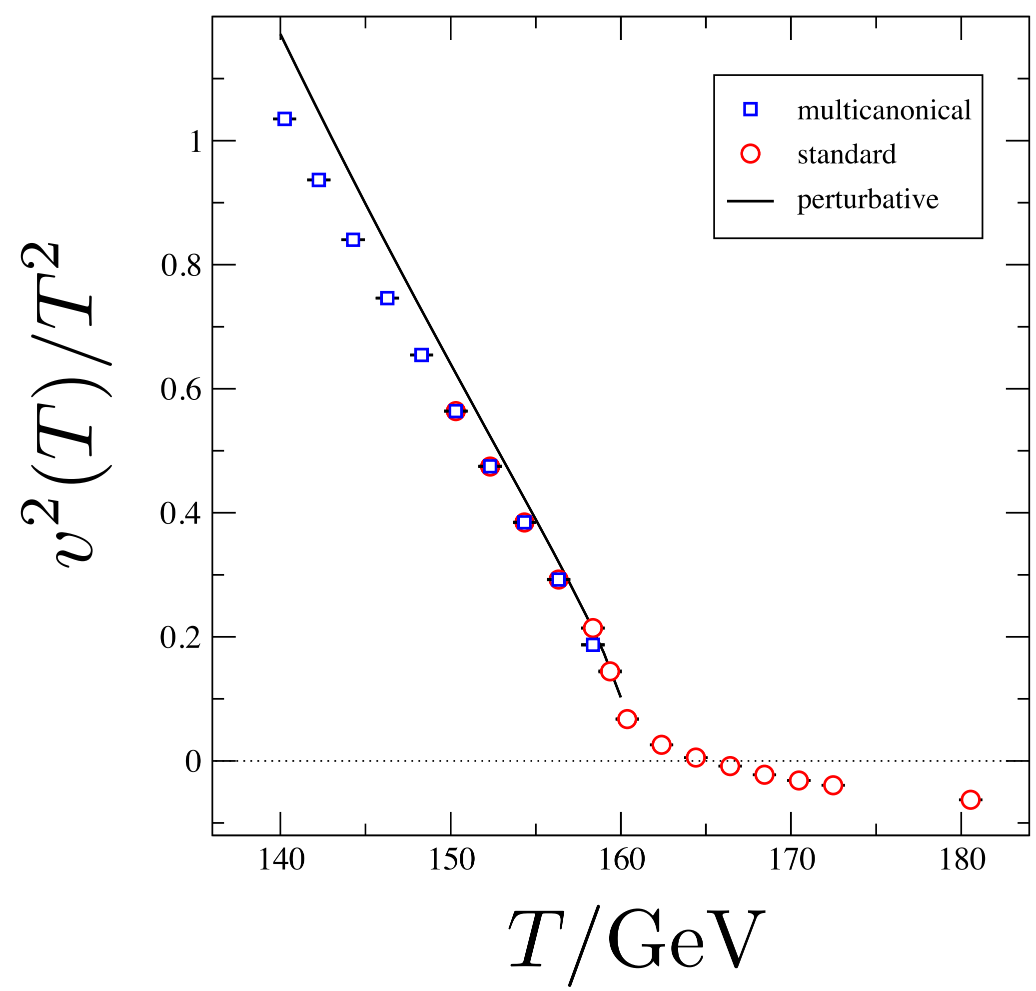

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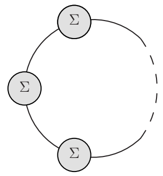
Beyond SM: **MSSM**, NMSSM, 2HDM, NHDM, IHDM, **SSM**,...

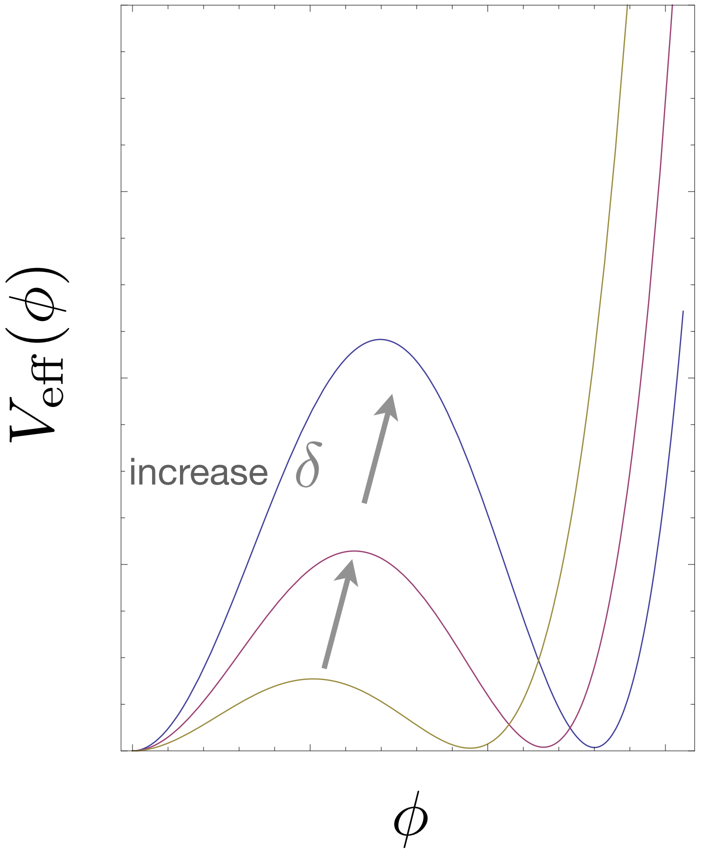
EWBG with new loop corrections, MSSM

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

Need new light bosonic fields strongly coupled to Higgs



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



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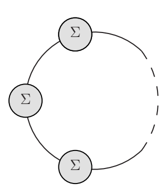

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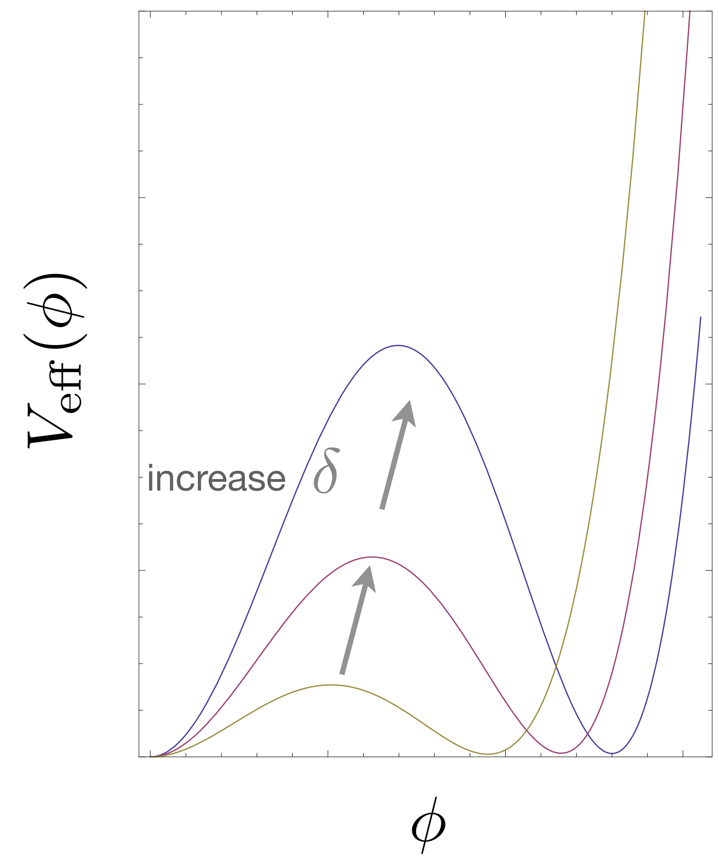

=> **L**ight **S**top **S**cenario in the MSSM and NMSSM

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

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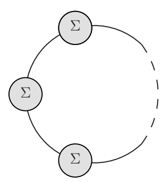

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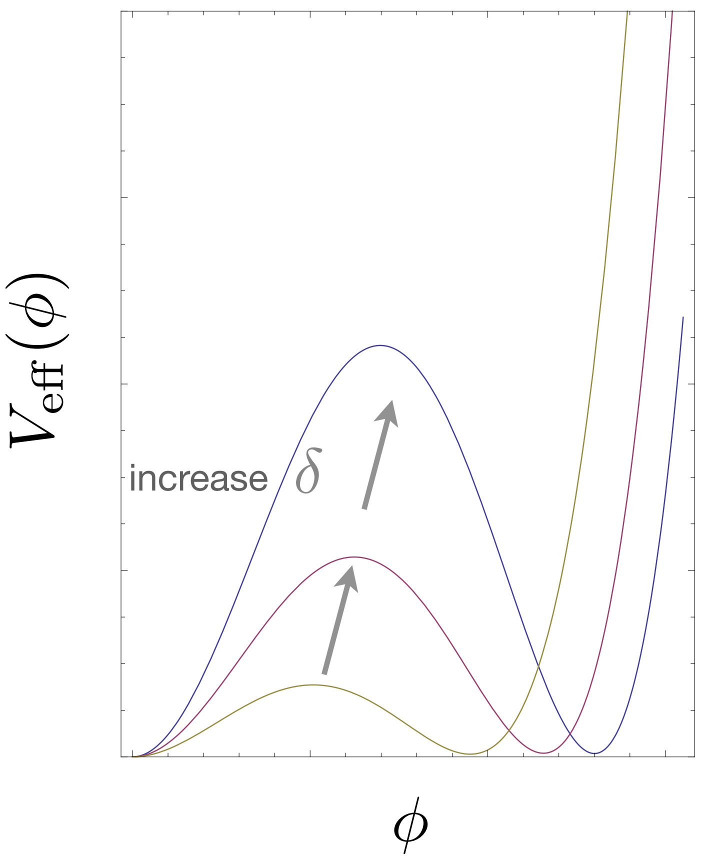

=> **Light Stop Scenario** in the MSSM and NMSSM

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However, also Higgs mass mostly from

$$m_h \sim C \log \frac{m_{\tilde{t}_L} m_{\tilde{t}_R}}{M_w^2}$$

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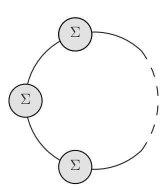

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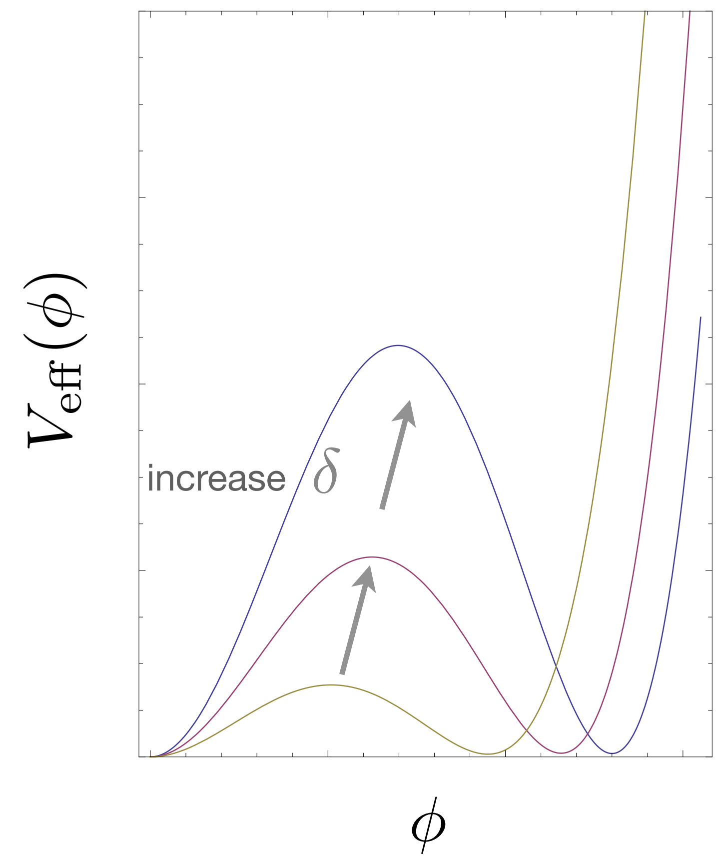

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Tension: light t_R => *very* heavy t_L

Need LARGE ~~SUSY~~ m_Q

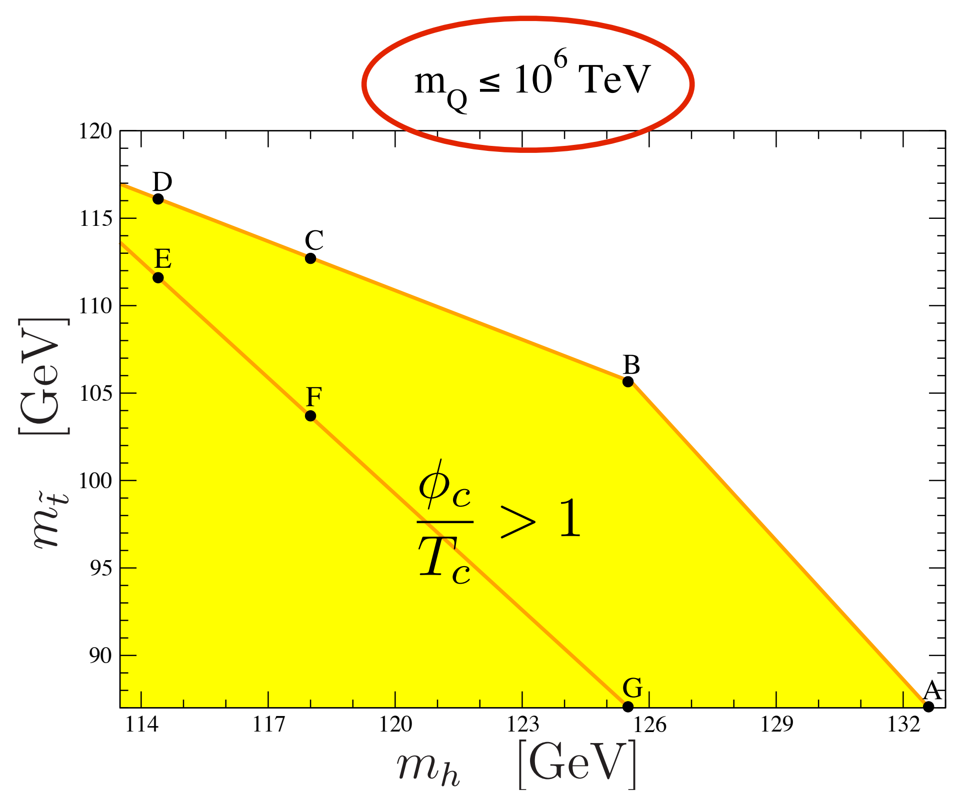
MSSM, latest results on PT strength

(Re)opening a BAU window in MSSM

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

RGE-improved potential: models
metastable against color breaking

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



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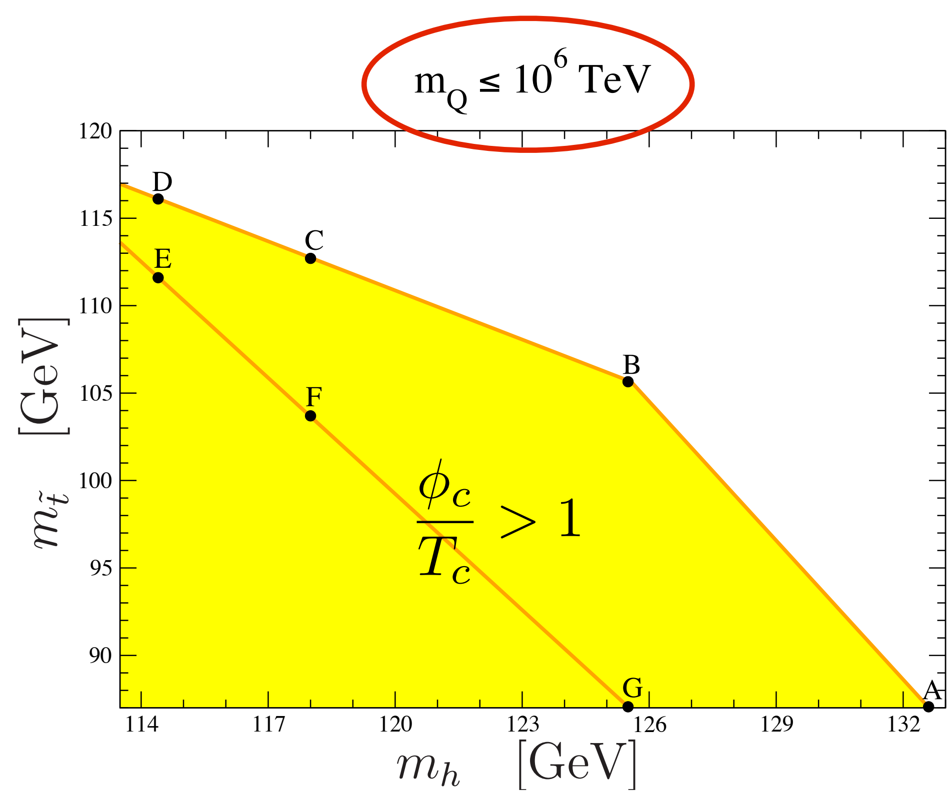

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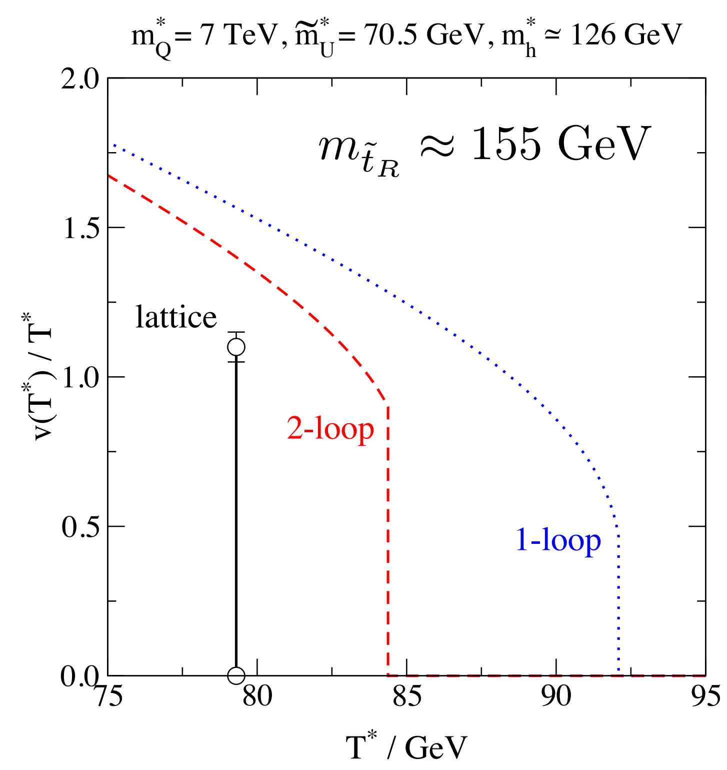

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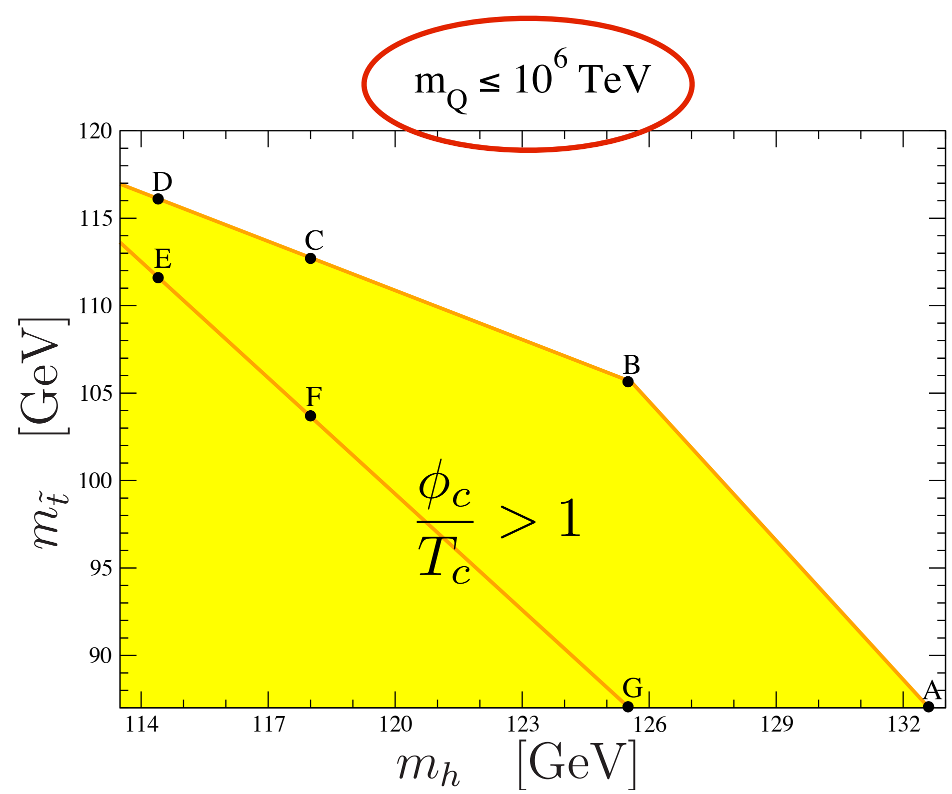

However, there is a recent **lattice** study:

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

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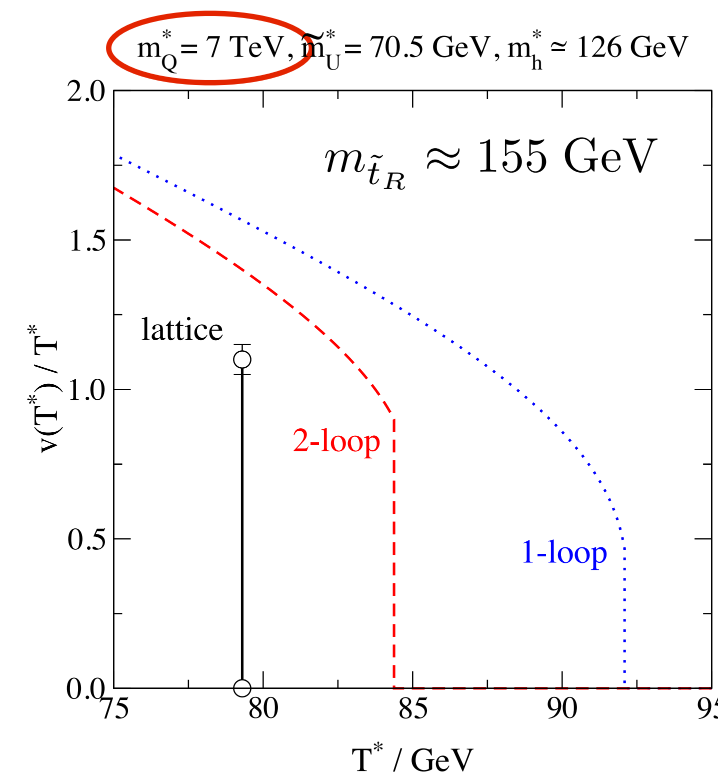

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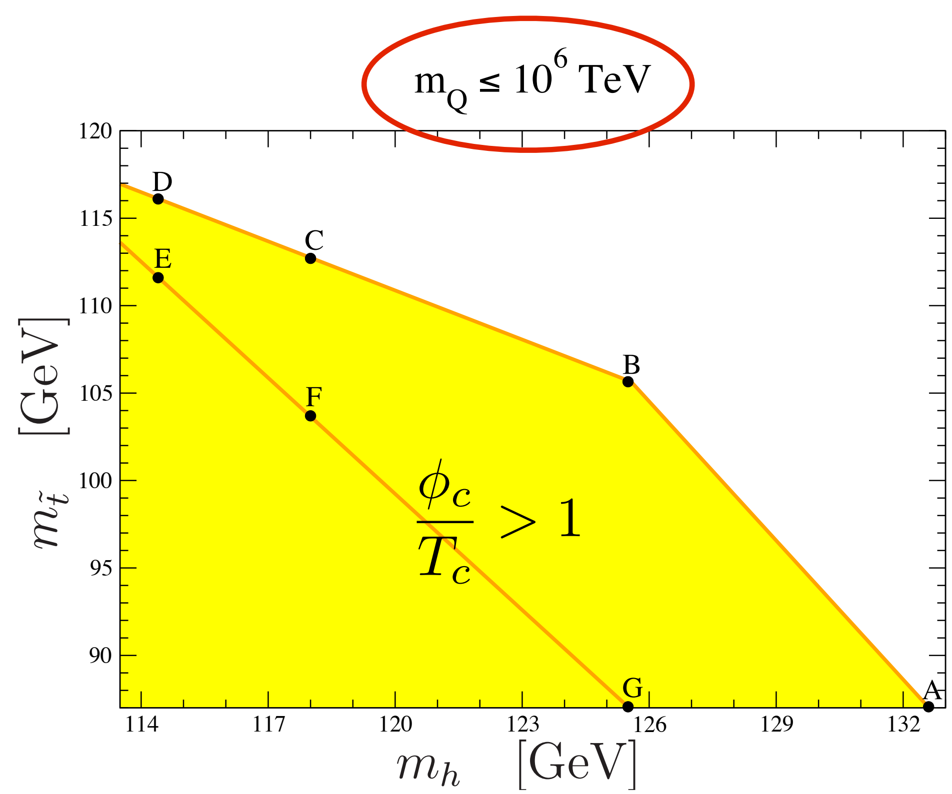

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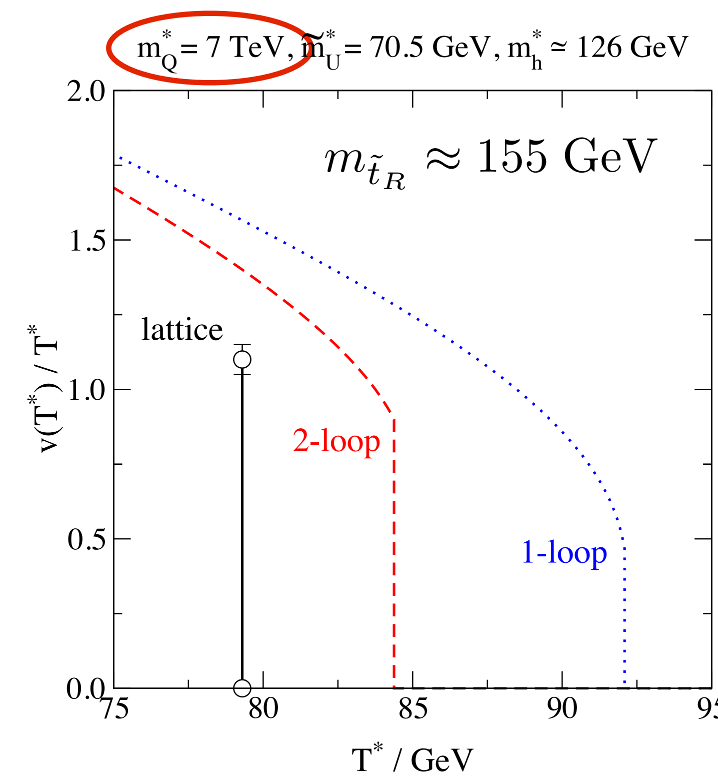

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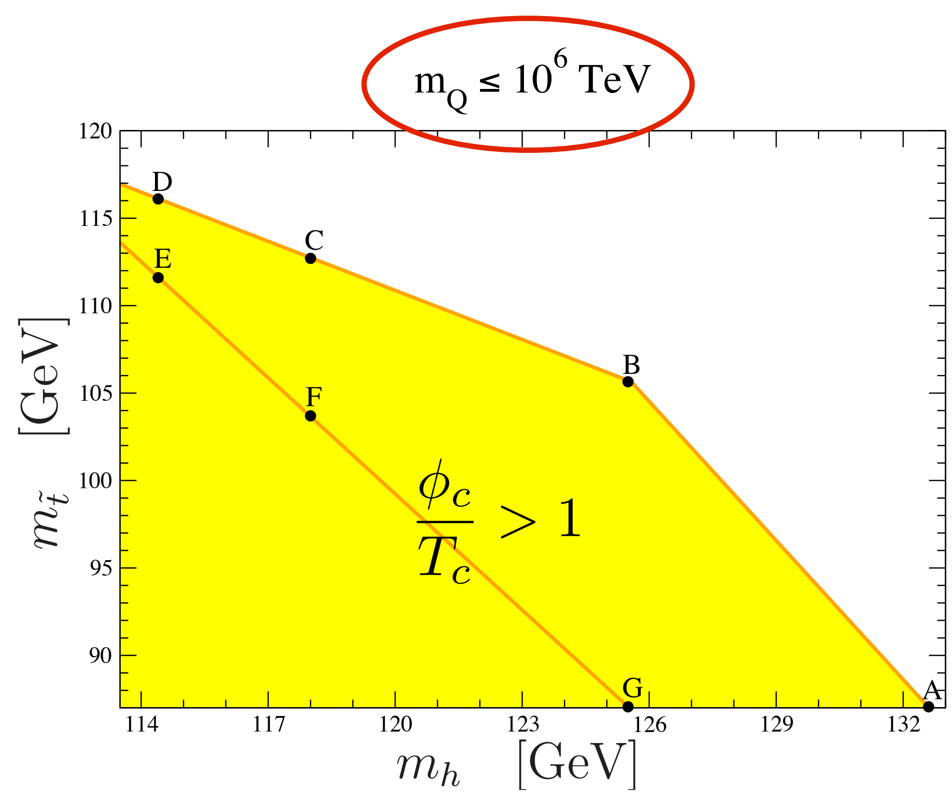

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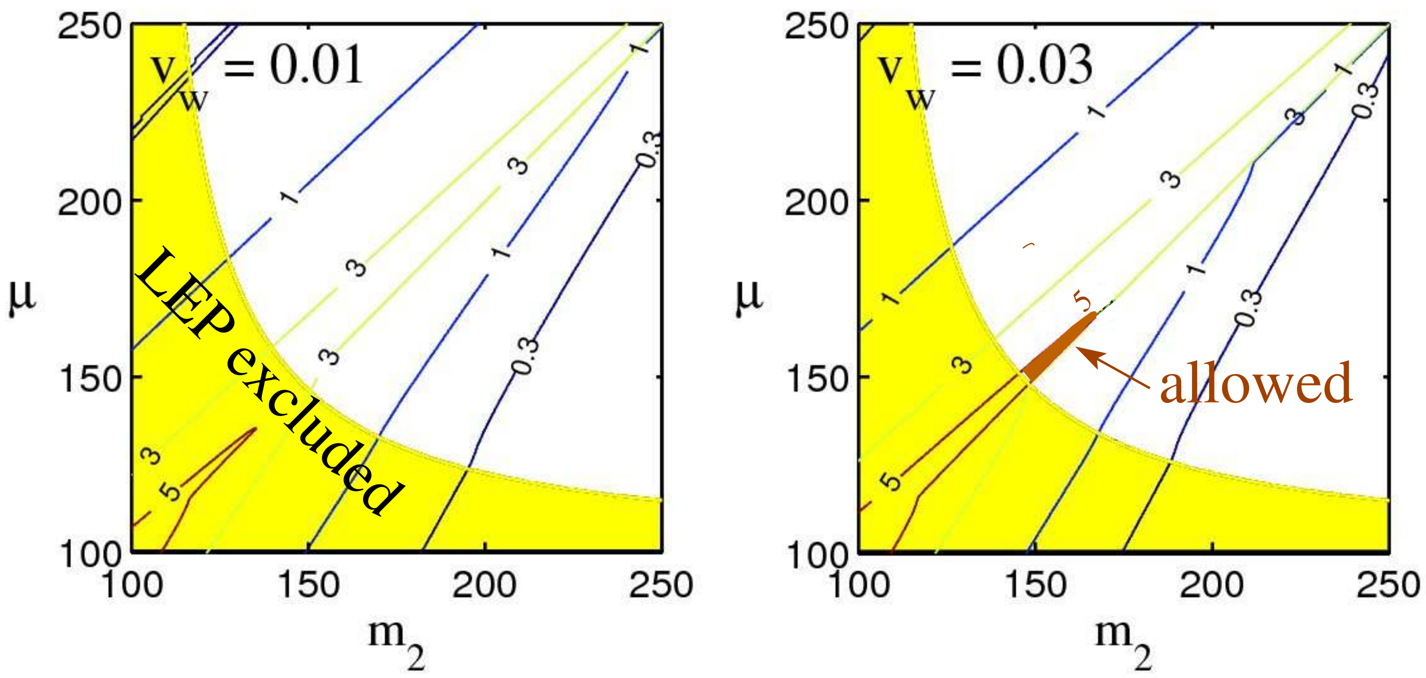
Still, looks awkward at best.
Probably, or not working.

MSSM BAU *generation*

Chargino transport $\mathcal{M}_{\chi\pm} = \begin{pmatrix} M_2 & gh_2 \\ gh_1 & \mu \end{pmatrix}$ **(maximal CP angles)**



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.

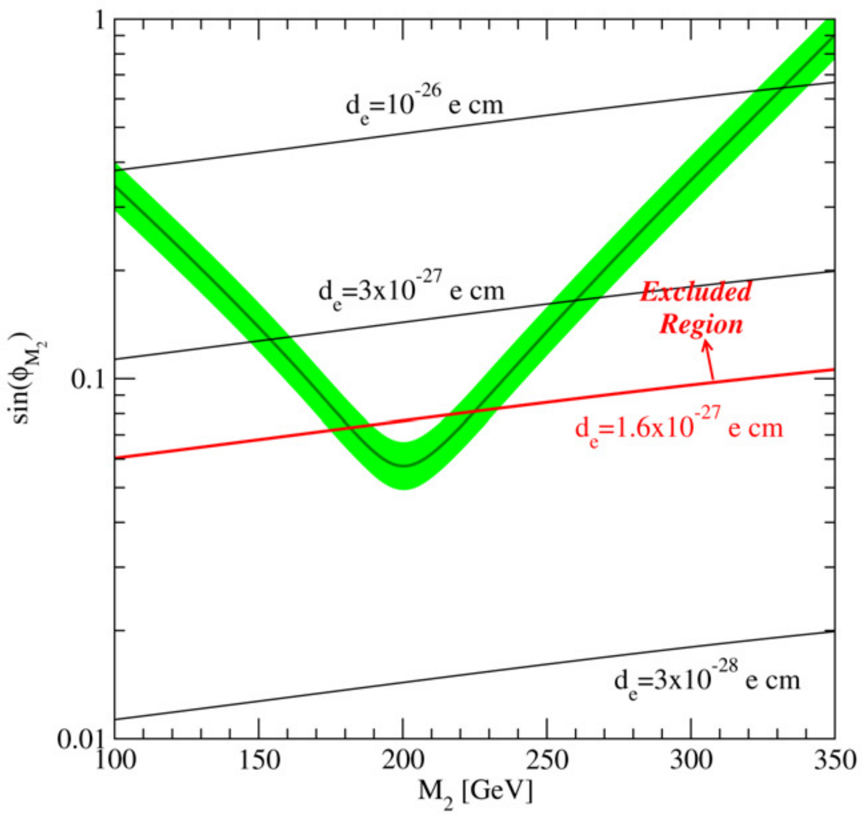
who also used SC method

- These results depend on *guesstimated* wall shape and wall speed
- **There are some discrepancies in results depending on the method (QTT-formalism) used.** (Some other methods promise larger asymmetries than SC.)

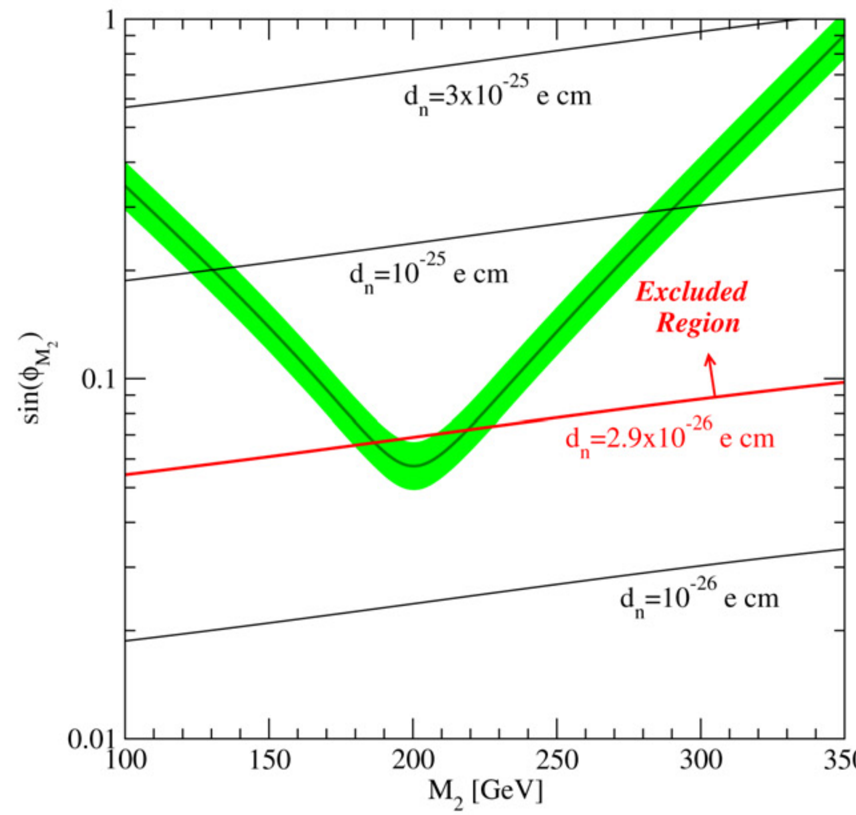
MSSM, EDM constraints, *charginos*

In any case**, chargino transport** mechanism is **clearly excluded by the electron EDM bound (2-loop EDMs):**

Electron EDM



Neutron EDM



Ref. point: $M_1 = 95\text{GeV}$
$|\mu| = 200\text{GeV},$
$\tan\beta = 10,$
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Y.Li, S.Profumo, and M.Ramsey-Musolf, PLB673 (2009) 95–100,

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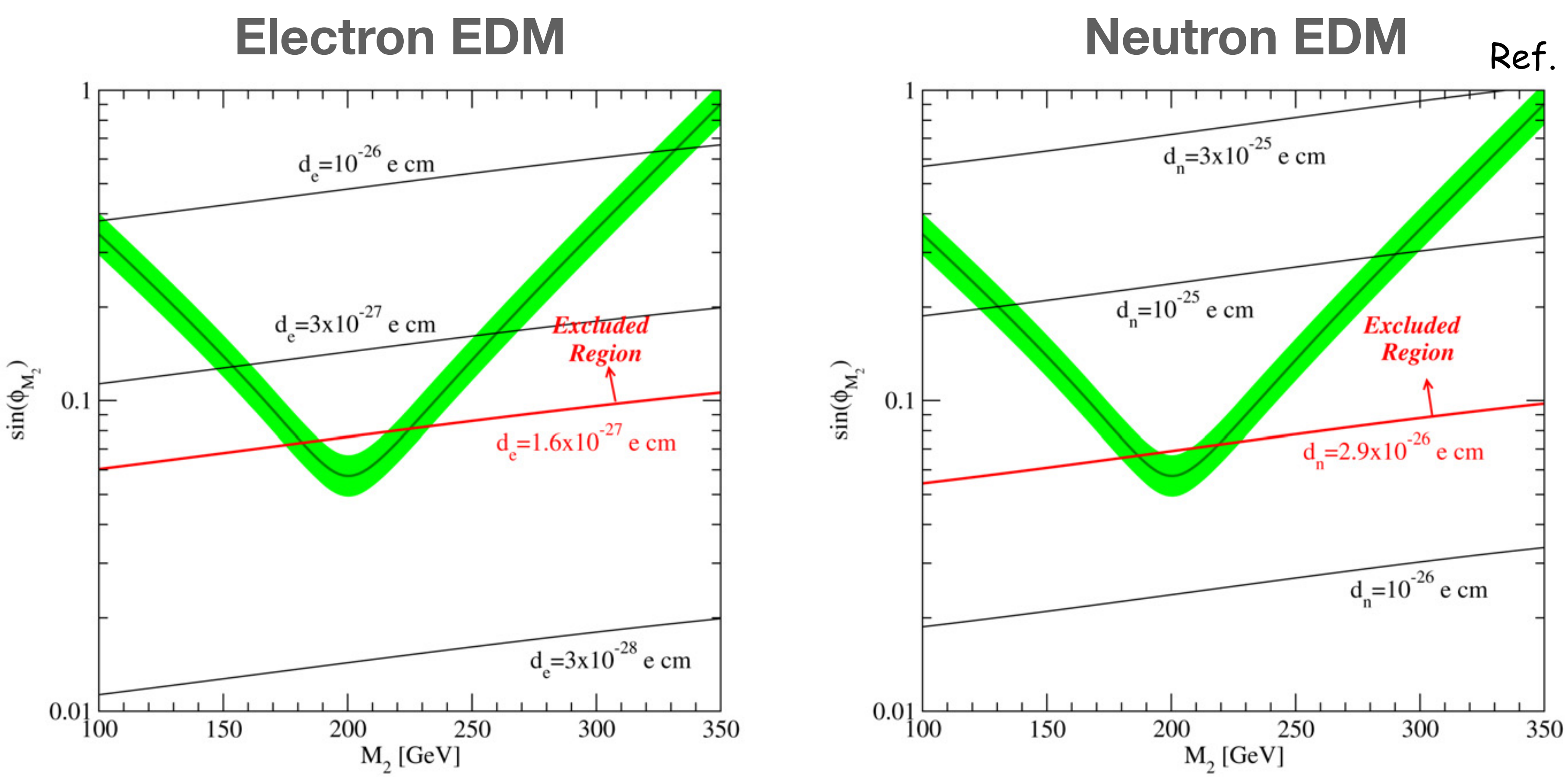

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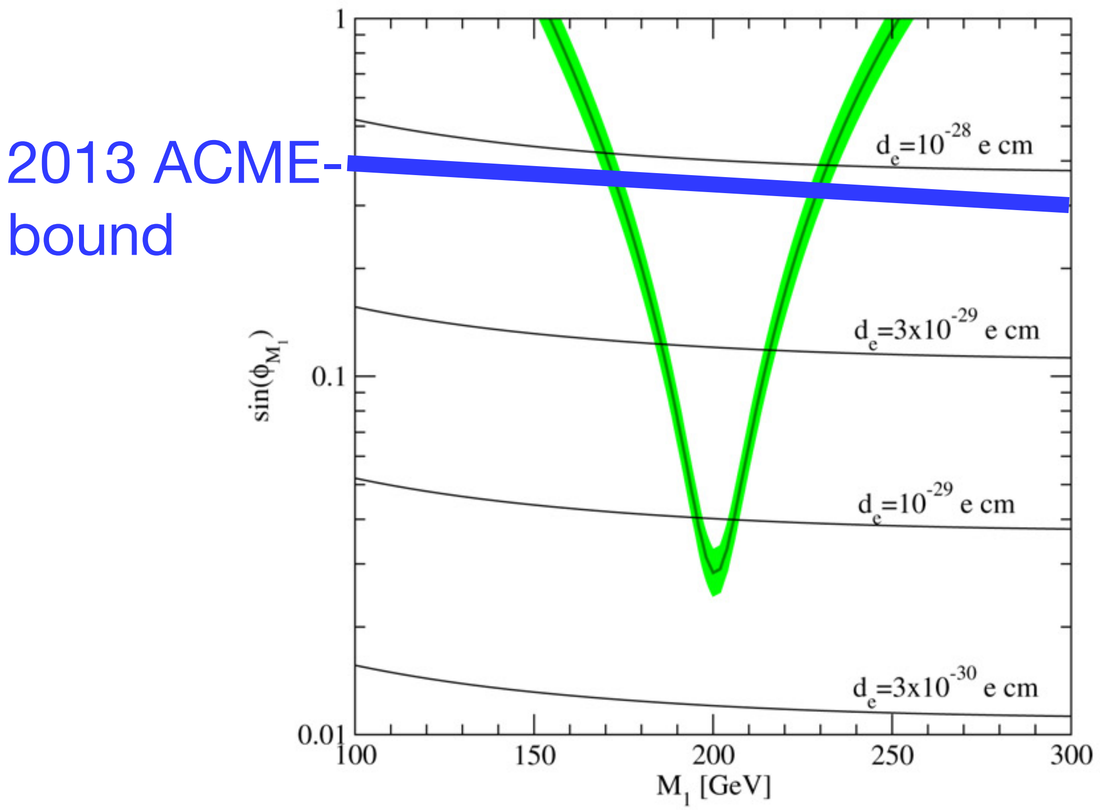
2013 ACME-bound: ***d_e* < 8.9 x 10^{-29}** => $\phi_{M_2} < 10^{-3}$

ACME collaboration, Science 343 (2014) 6168, 269-272

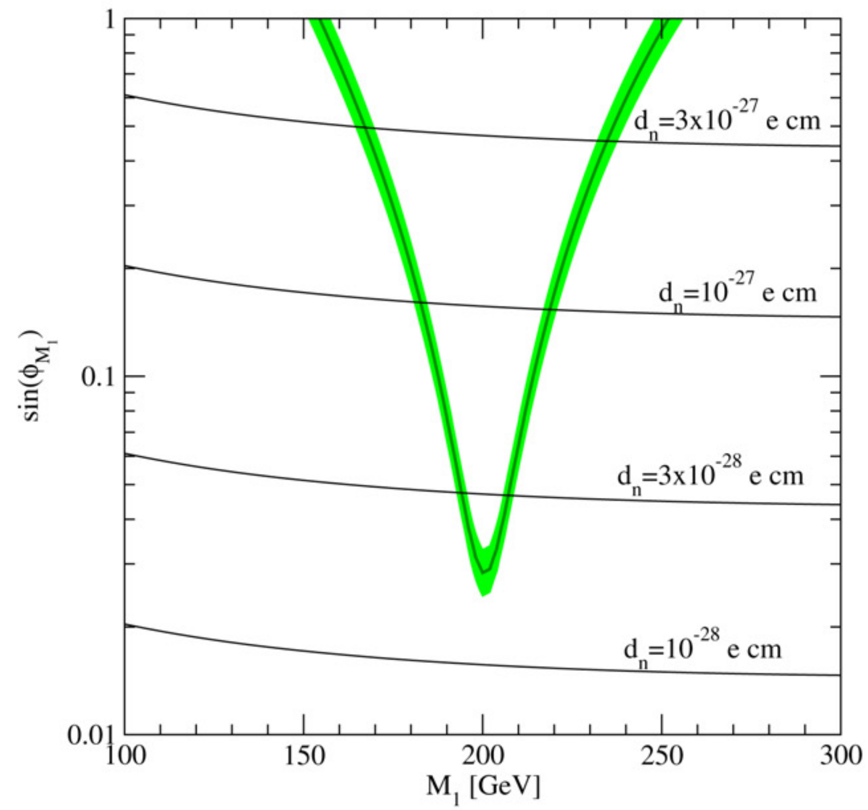
MSSM, EDM constraints, *neutralinos*

Neutralino transport fares better against EDM constraints:
but is already very constrained as well.

Electron EDM



Neutron EDM



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

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

- **Note 1:** transport calculation likely overly optimistic.
- **Note 2:** very light bino (<60GeV) is at least not obviously in the cards…

Other possibilities, 2HDM, NHDM, IHDM, ...

2HDM:

$$V = \frac{\lambda}{4}\left(H^{\dagger\, i}\, H_i - \frac{v^2}{2}\right)^2 + m_1^2\,(S^{\dagger i}\, S_i) + (m_2^2\, H^{\dagger\, i} S_i + \mathrm{h.c.}),$$

$$+\lambda_1\,(H^{\dagger\, i} H_i)\,(S^{\dagger\, j} S_j), +\lambda_2\,(H^{\dagger i}\, H_j)\,(S^{\dagger j}\, S_i) + \left[\lambda_3 H^{\dagger i}\, H^{\dagger j}\, S_i\, S_j + \mathrm{h.c.}\right],$$

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$$+\, y_t \bar{t}_L (H^{0*} \delta_{ti} + (\eta_U \delta ti + \eta_U' V_{tb}^* V_{bi}))S^{0*}) q_R^i$$

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Many new CP-violating phases

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

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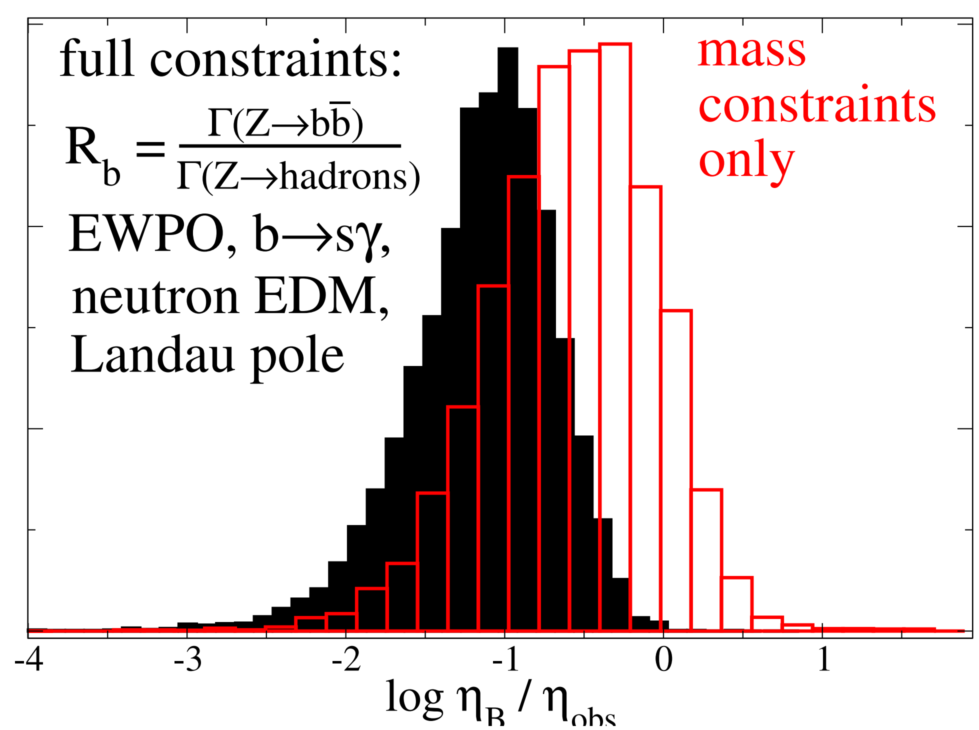
J.Cline, KK, M.Trott, JHEP 1111 (2011) 089



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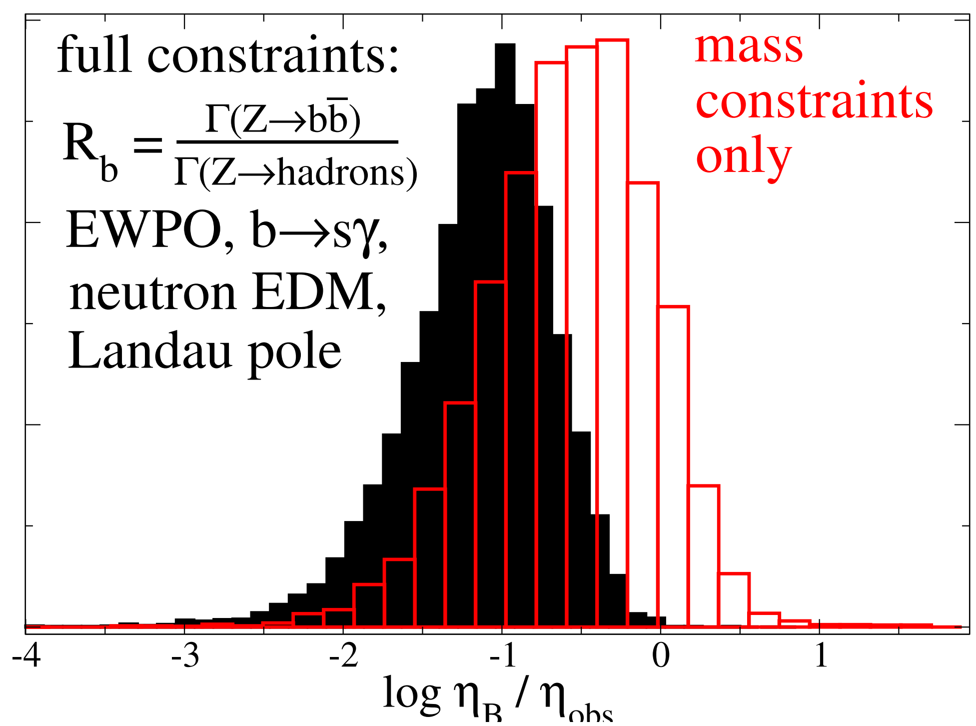

An even more detailed scan of different 2HDM's was carried out in: G.C.Dorsch, S.J.Huber & J.M.No, JHEP 1310 (2013) 029.

Singlet model can give a strong PT at tree level !

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

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**, 0 -> S -> H,
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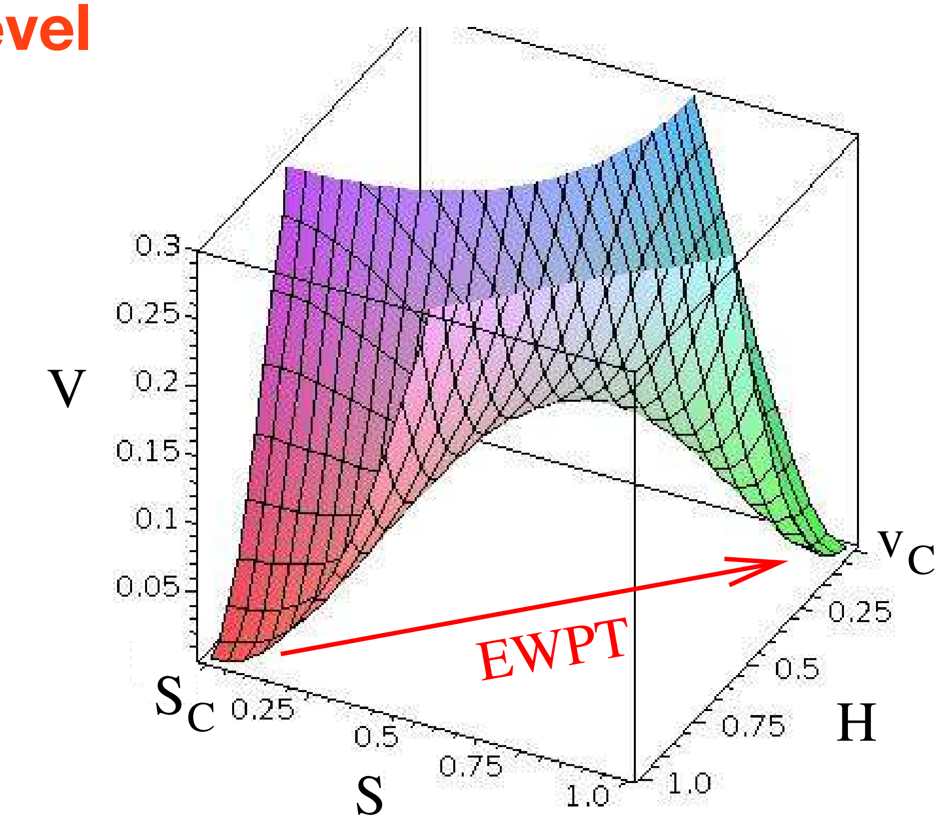
→ strong phase transition.

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



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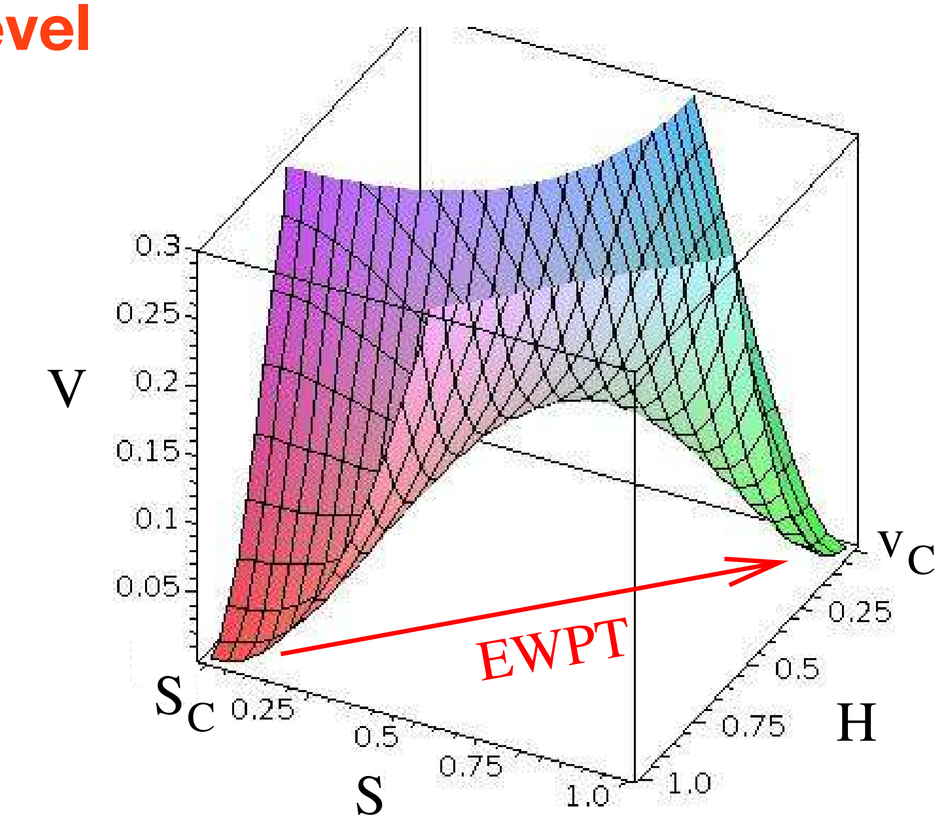

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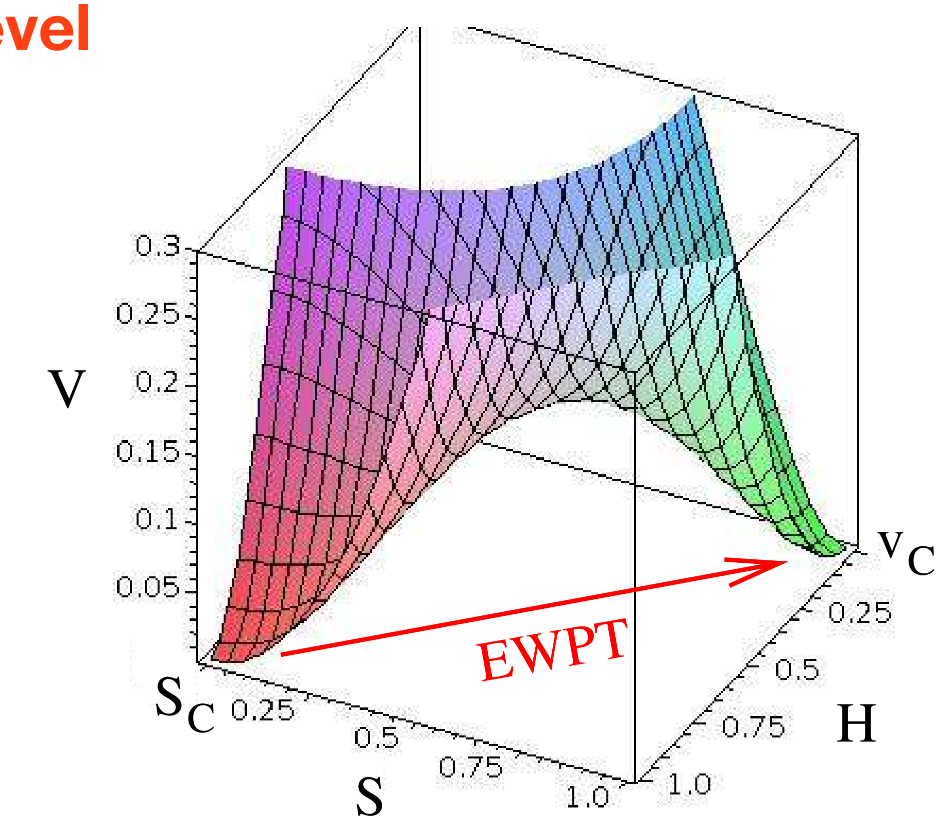

Get easily models satisfying v/T > 1-limit with large enough lambda.

Can induce BAU generation such that eEDM and nEDM are not a problem.

Thanks to Jim Cline

Singlet model: BAU *and* DM (in form of singlet S)?

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

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

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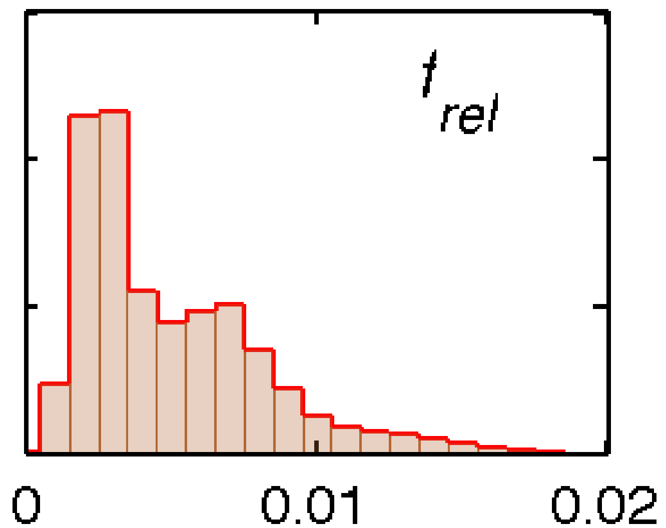

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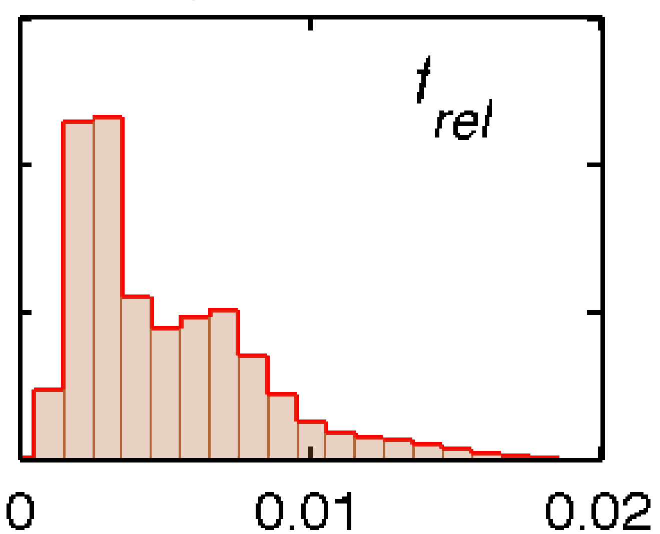

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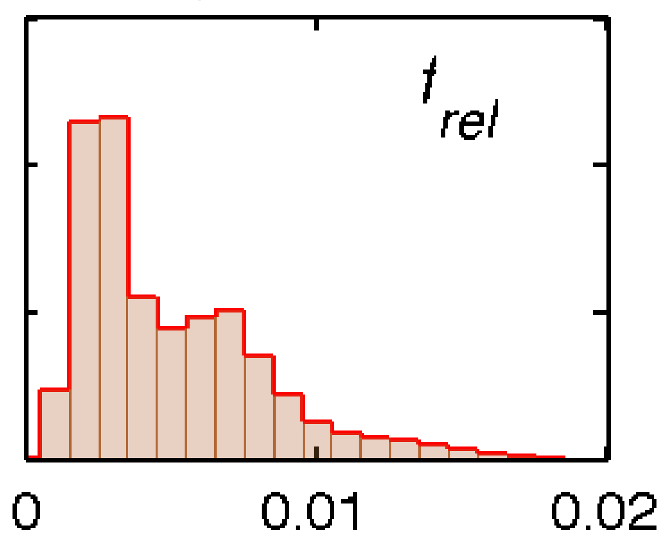

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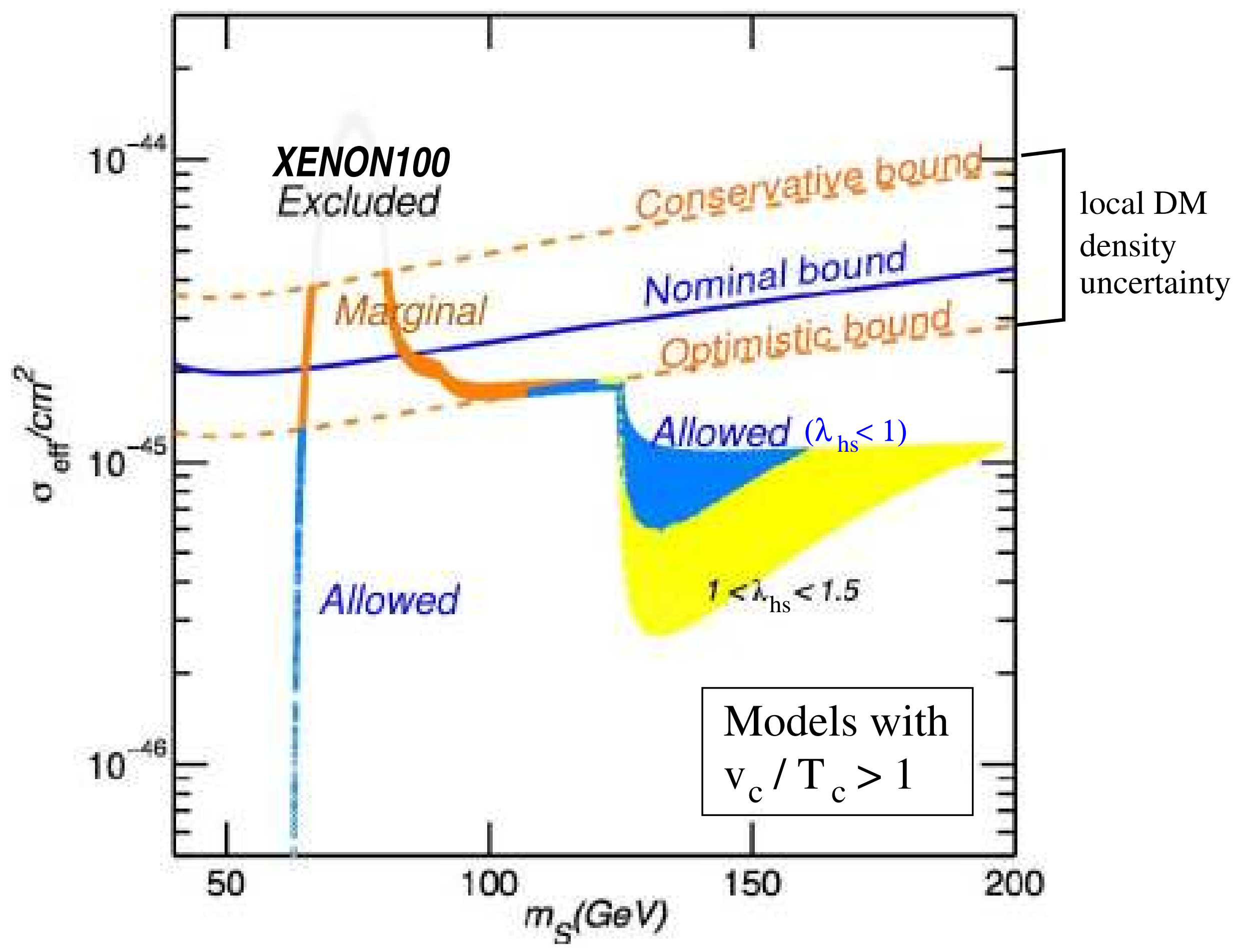

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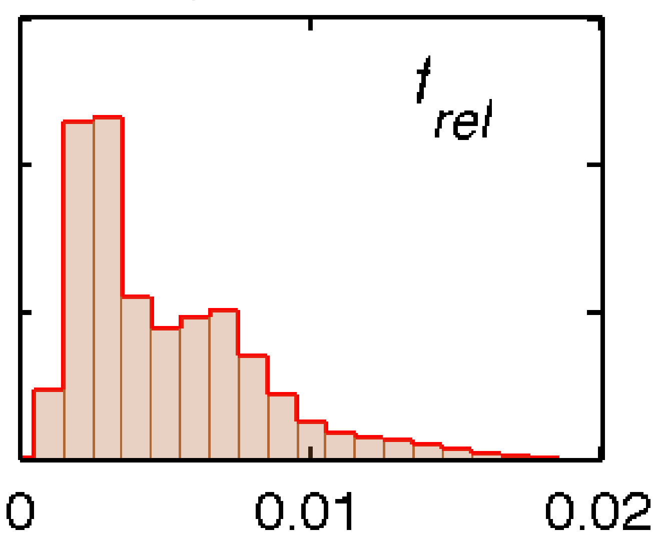

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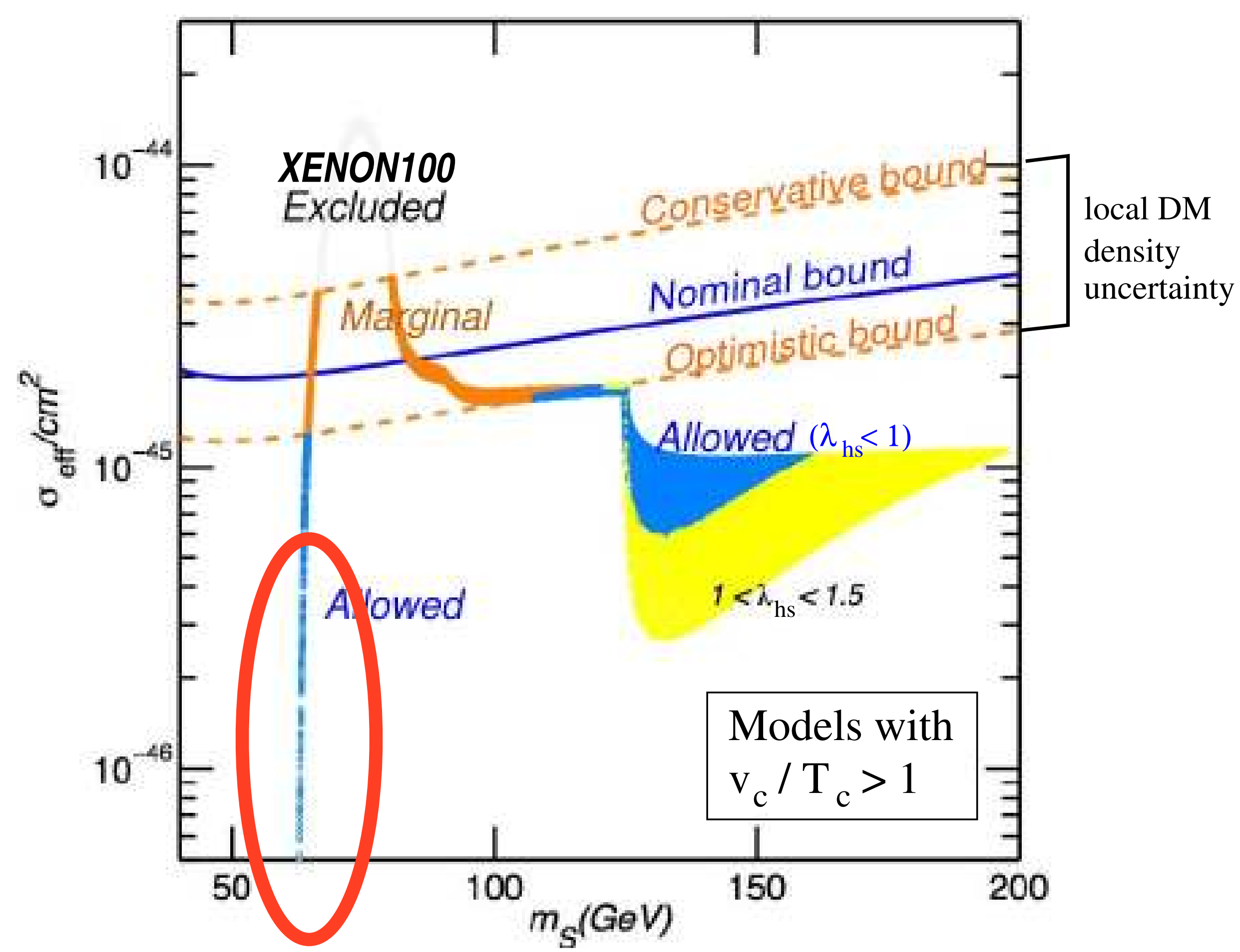

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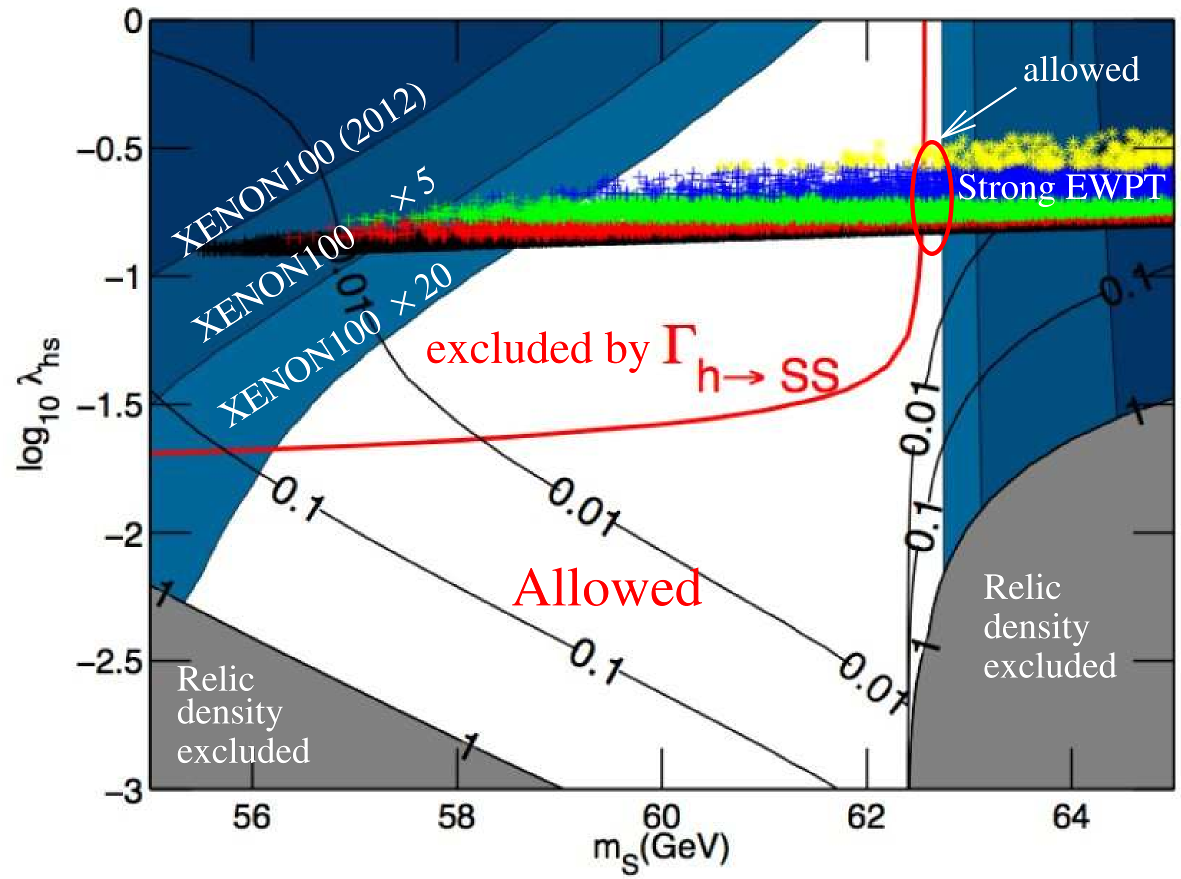
Blow-up of region $m_S < m_h/2$:

BAU-friendly models with subl. DM
Full (or subl.) **DM-models** without BAU



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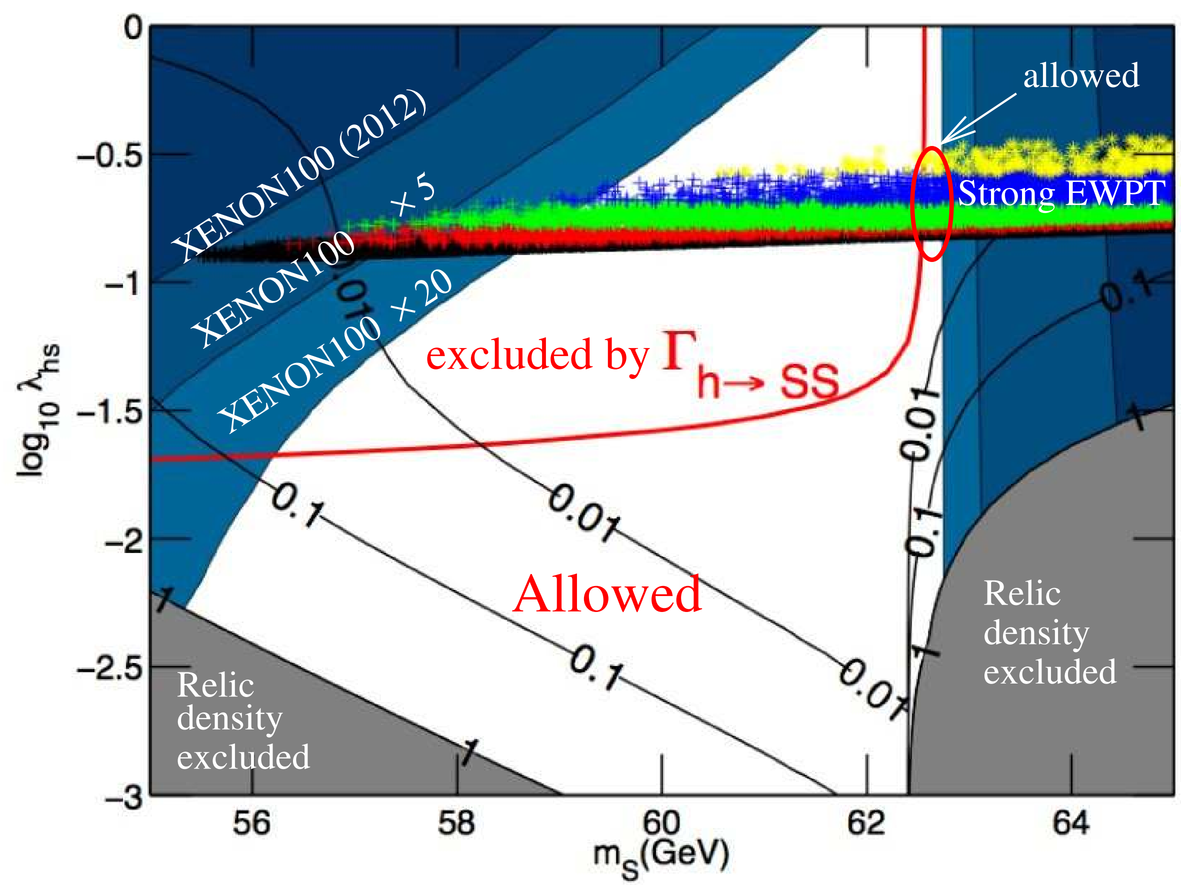

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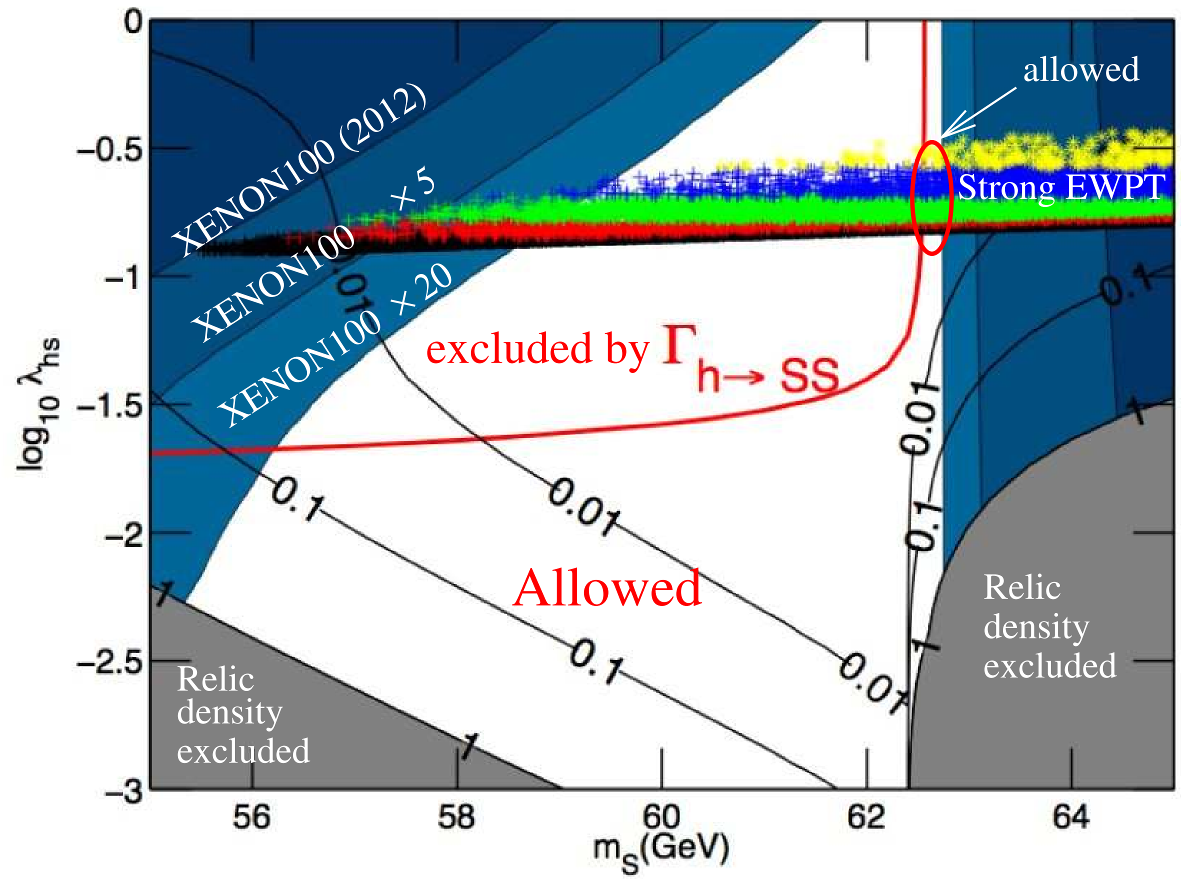
In a model with **two independent** singlets, one with a strong cross-coupling could fix BAU and the other with a weak one could be DM.



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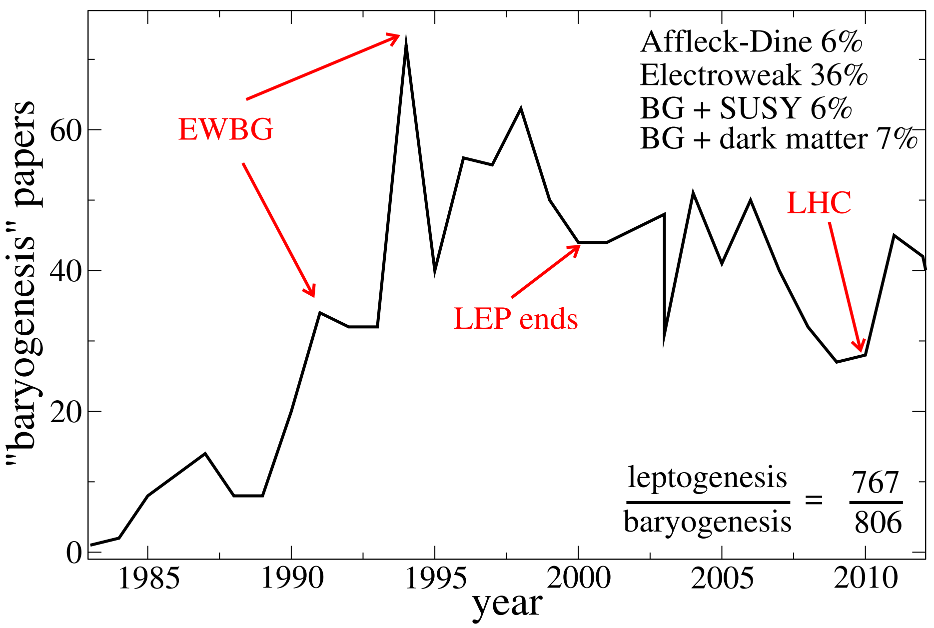
Or add new **independent doublets (with singlets…)** **… more complicated scalar sectors?**

Conclusions

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



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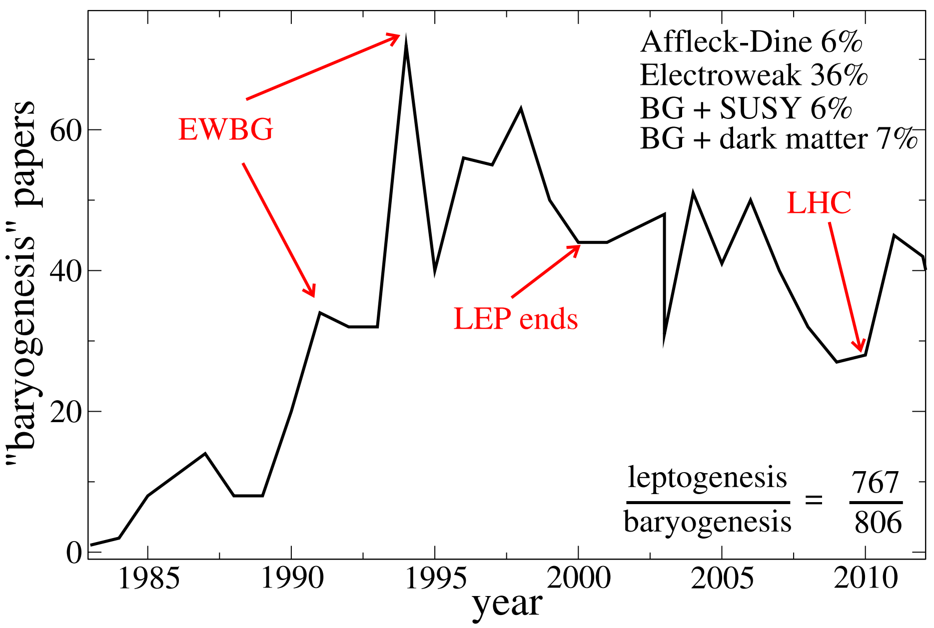

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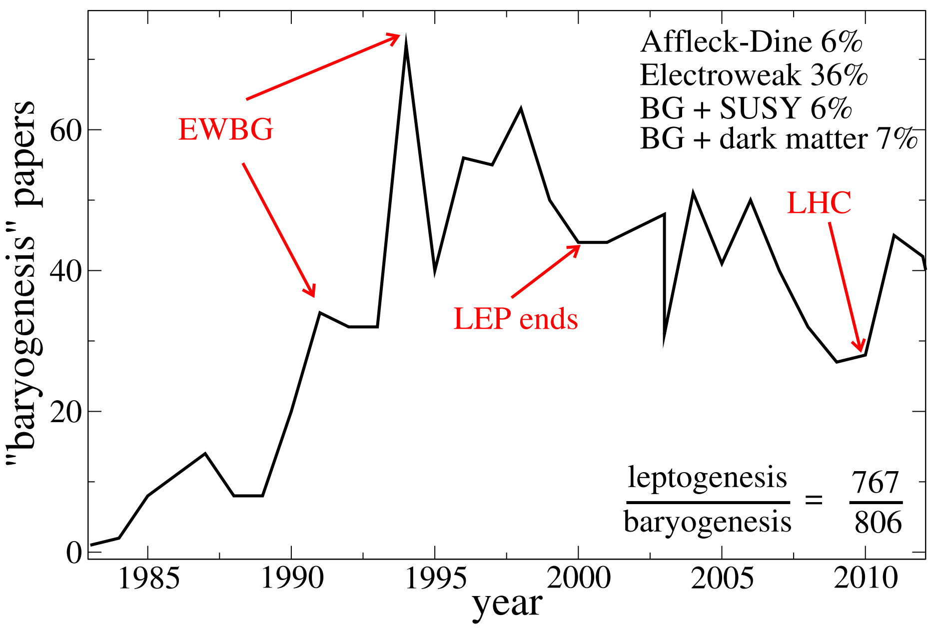

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Essentially all constraints come from *indirect* (loop) effects

MSSM EWBG appears to be all but **dead** (NMSSM,…)

2HDM possible, but also **restricted** in parameter space

SSM:

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

BAU <u>or</u> DM possible, but not both (with only one singlet)

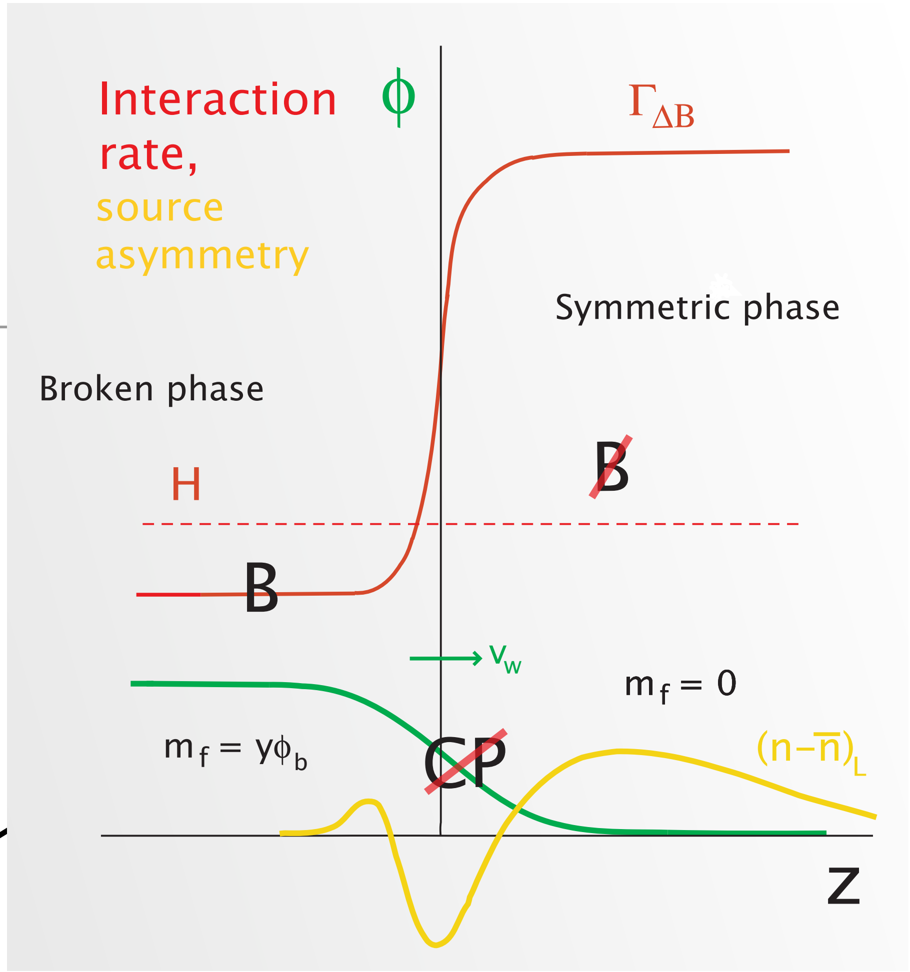
Singlet effect is likely a part of a more complete working EWBG model.

Supplementary slides…

EWBG, division of search tasks

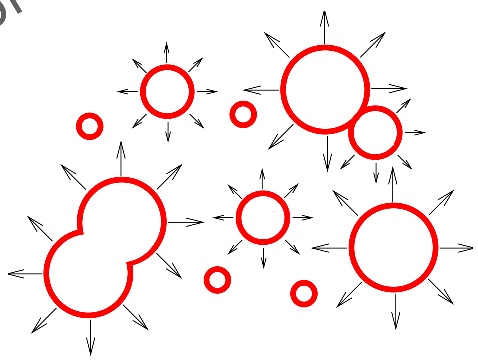
To keep BA

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



Equilibrium / Nonperturbative / Gauge issues

Out-of-equilibrium / quantum



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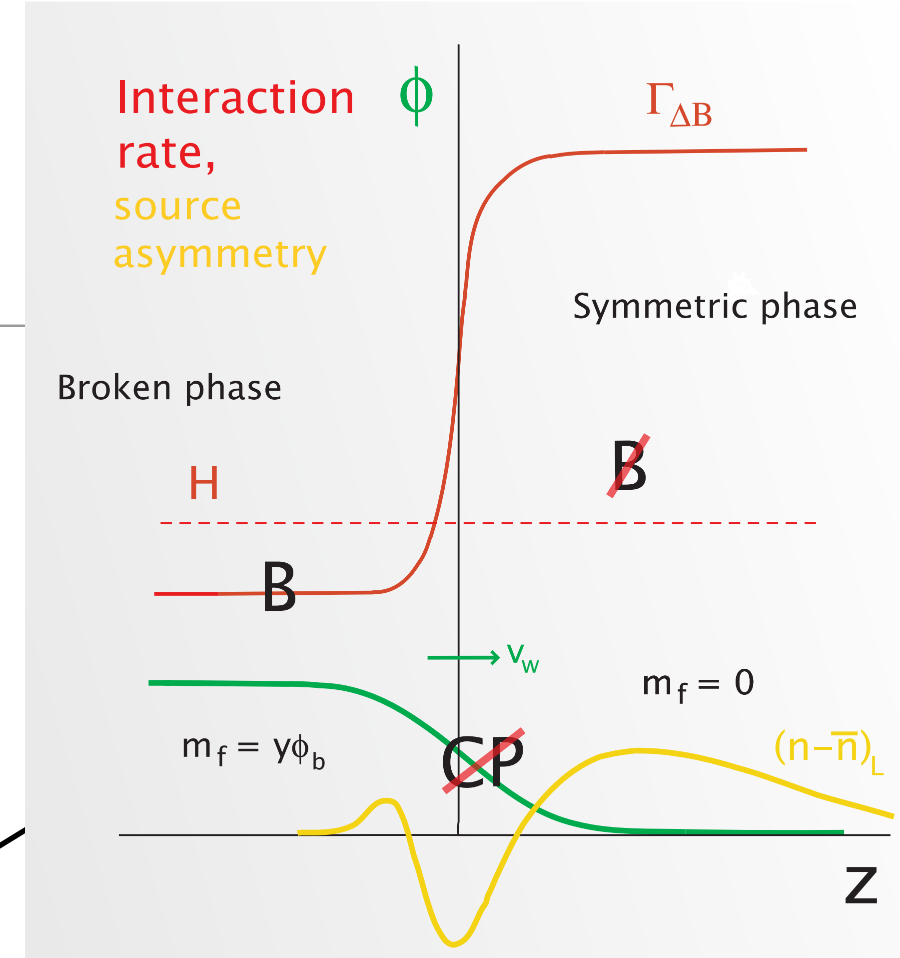

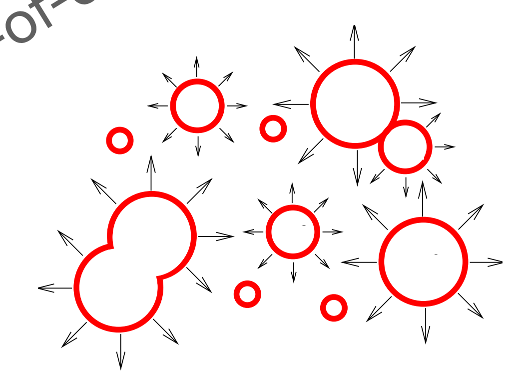

Sphaleron rate in the unbroken phase

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

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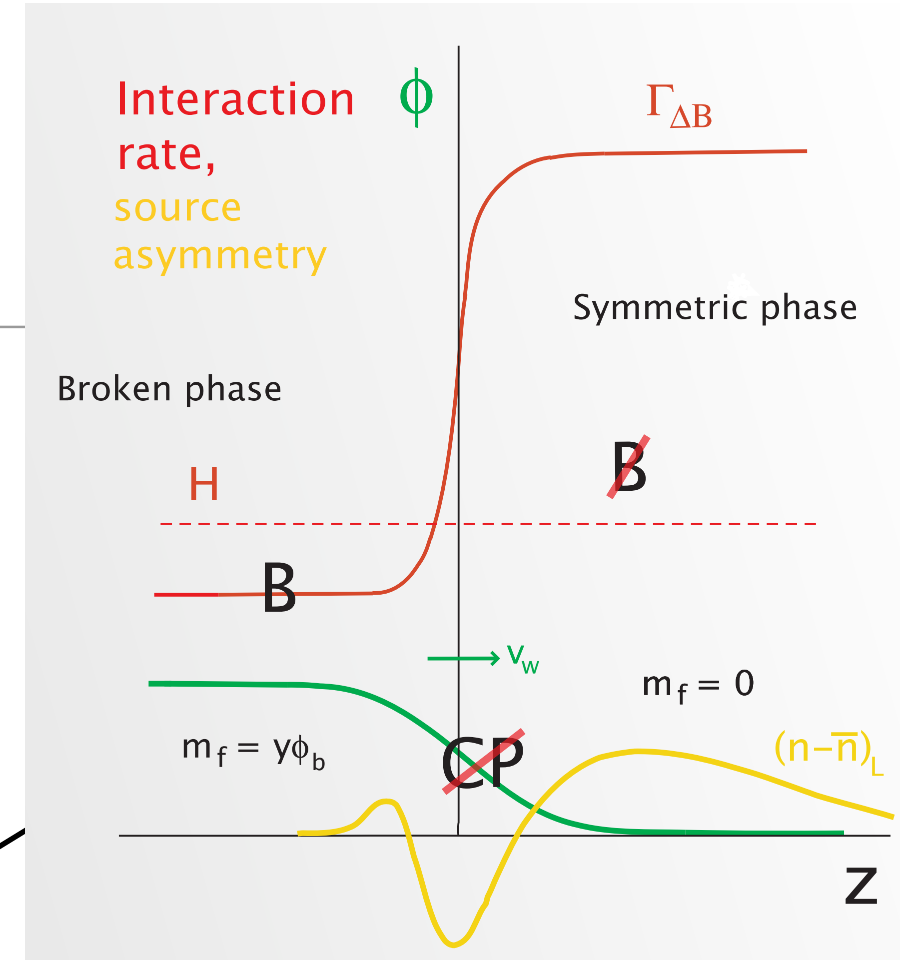

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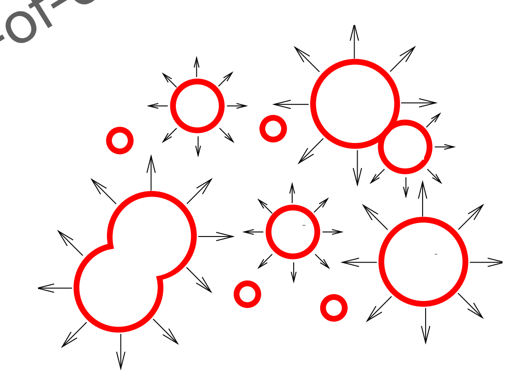

(CP-even) dynamics of the expanding wall

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

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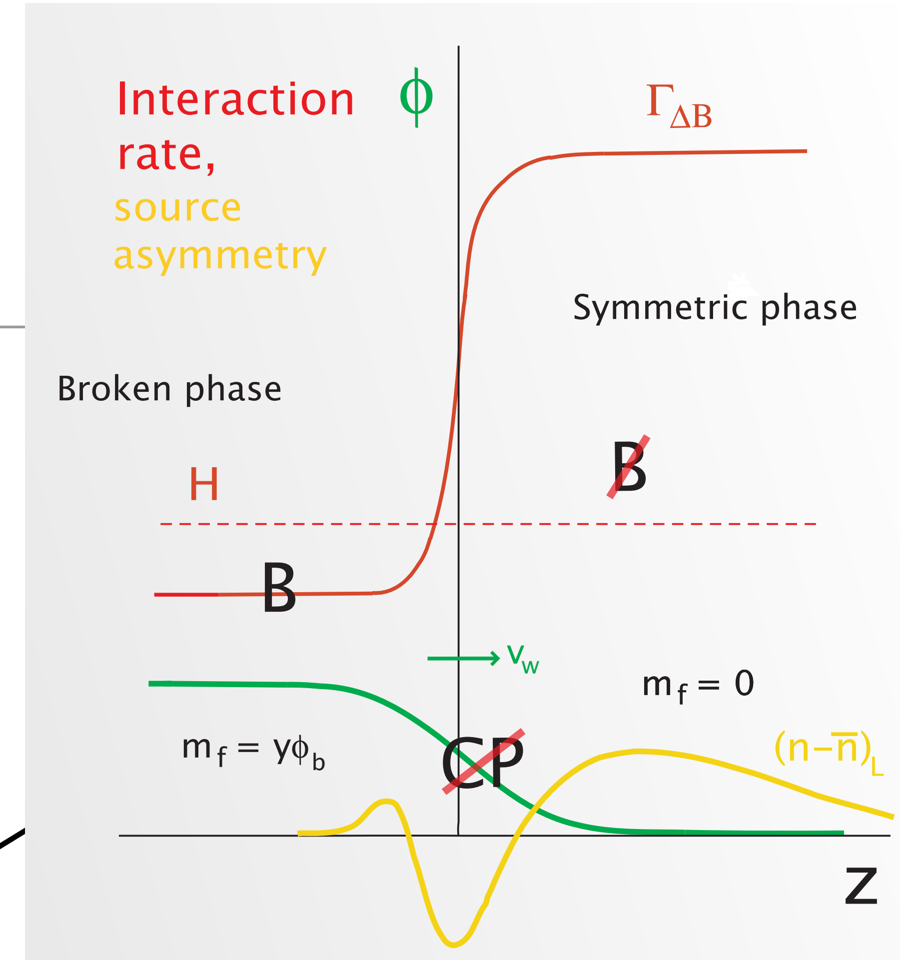

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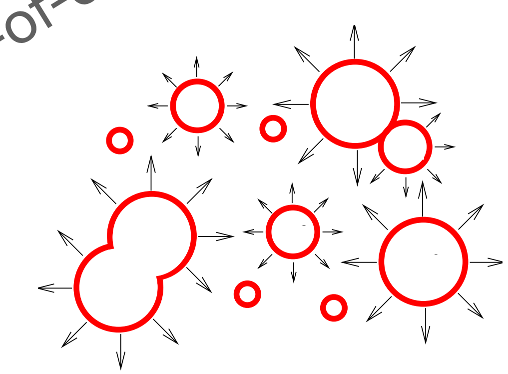

CP-violating **source** in **transport eqs.**

•Thin wall: *quantum*

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

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

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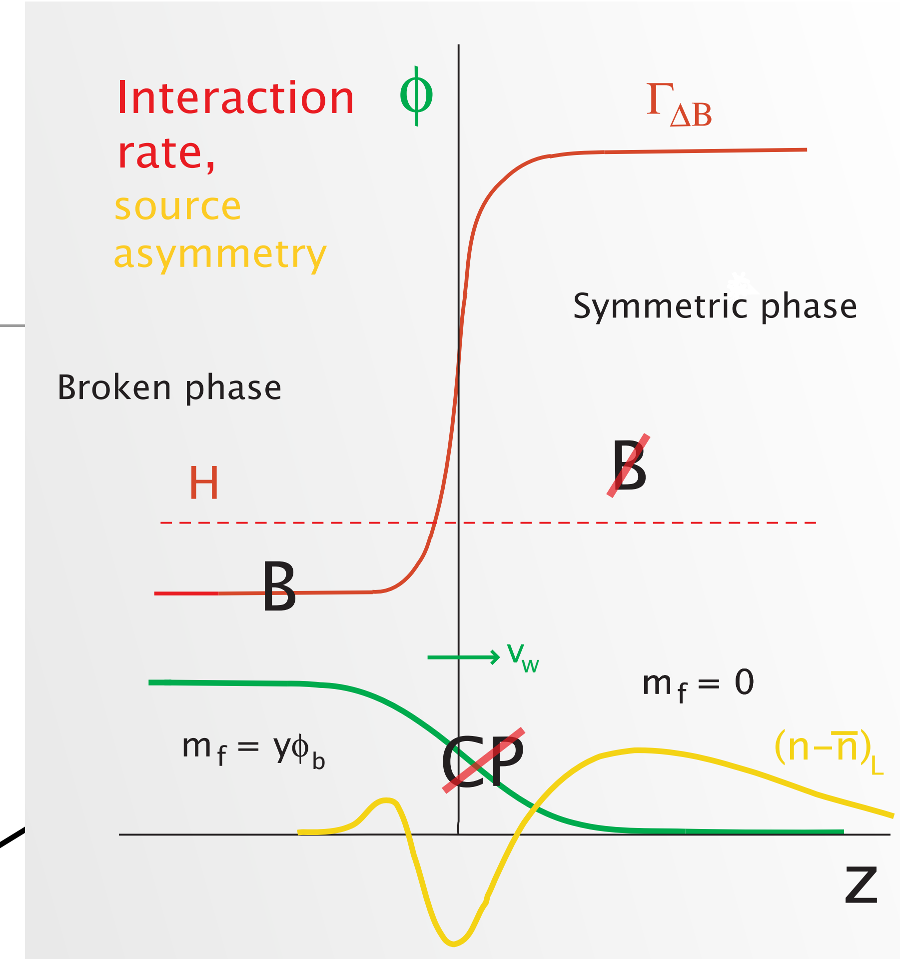

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Kuzmin, Rubakov & Shapsohnkinov, Arnold & McLerran, ... Moore; Rummukainen etal;

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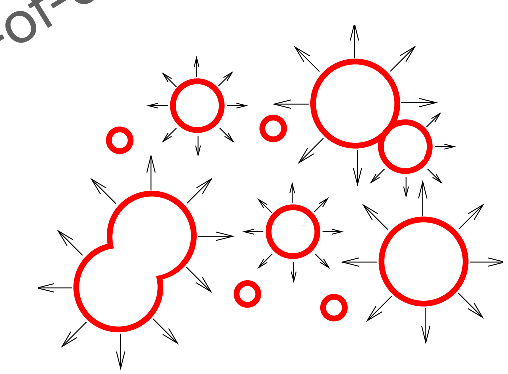

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Sphaleron rate in the broken phase ... must be small

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

•V_{eff} in Landau *gauge*

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, ...

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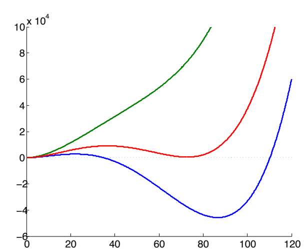

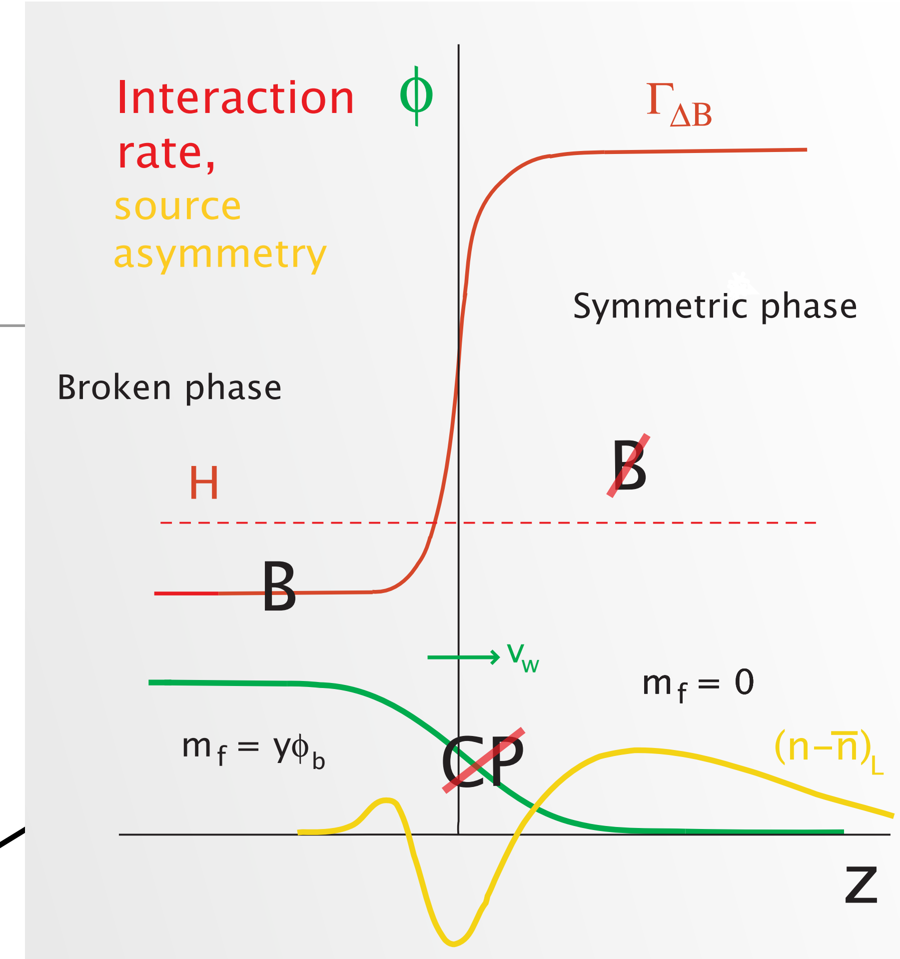

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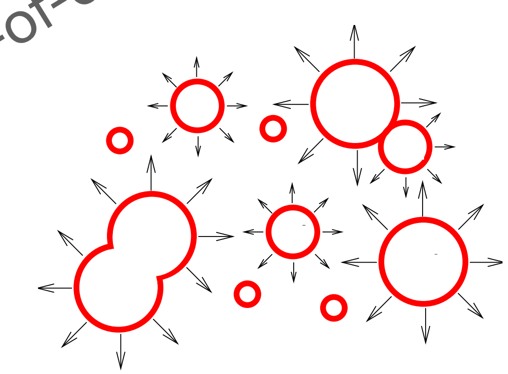
(CP-even) dynamics of the expanding wall

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



Sphaleron rate in the unbroken phase

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

To make BA

EWBG, division of search tasks

To keep BA

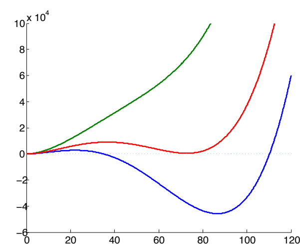
Sphaleron rate in the broken phase ... must be small

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

- V_{eff} in Landau *gauge*

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, ...

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



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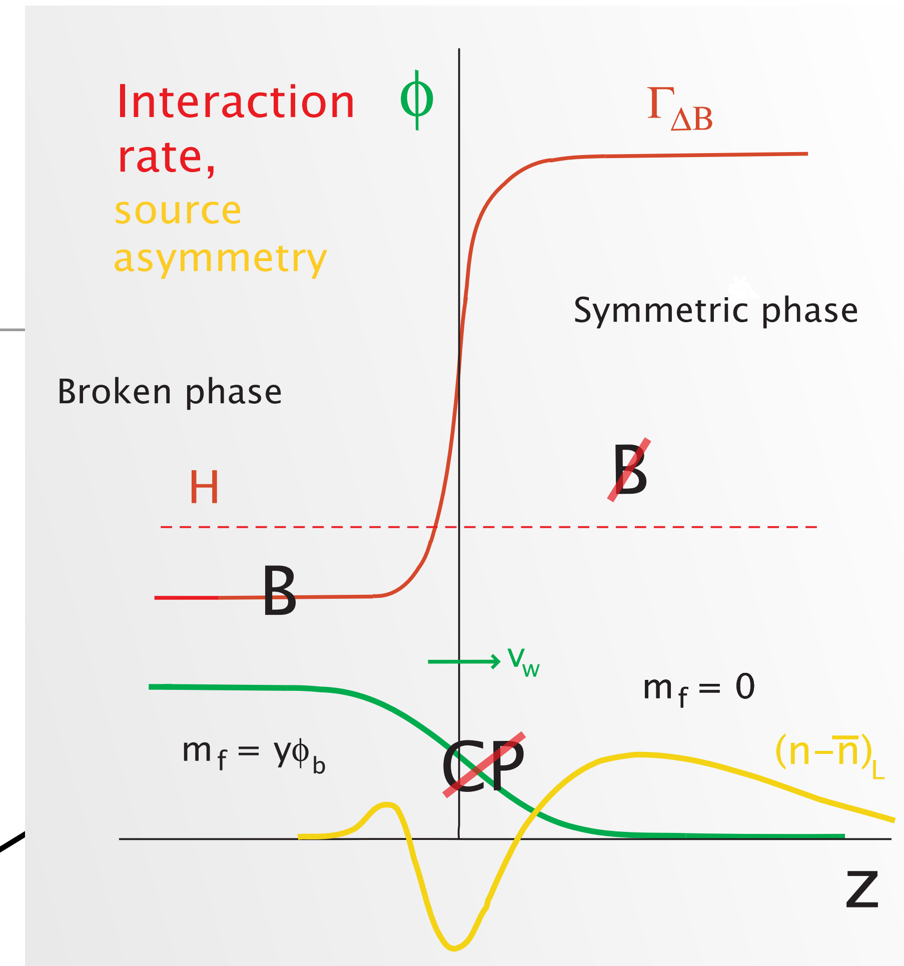
Equilibrium / Nonperturbative / Gauge issues

Out-of-equilibrium / quantum



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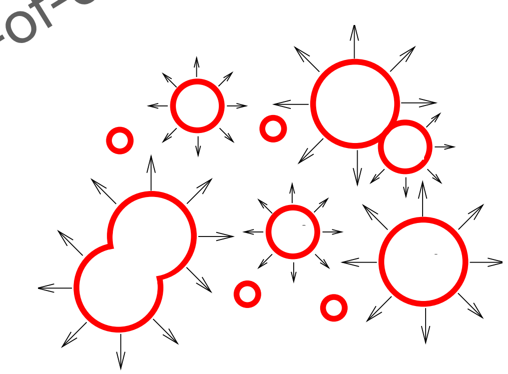

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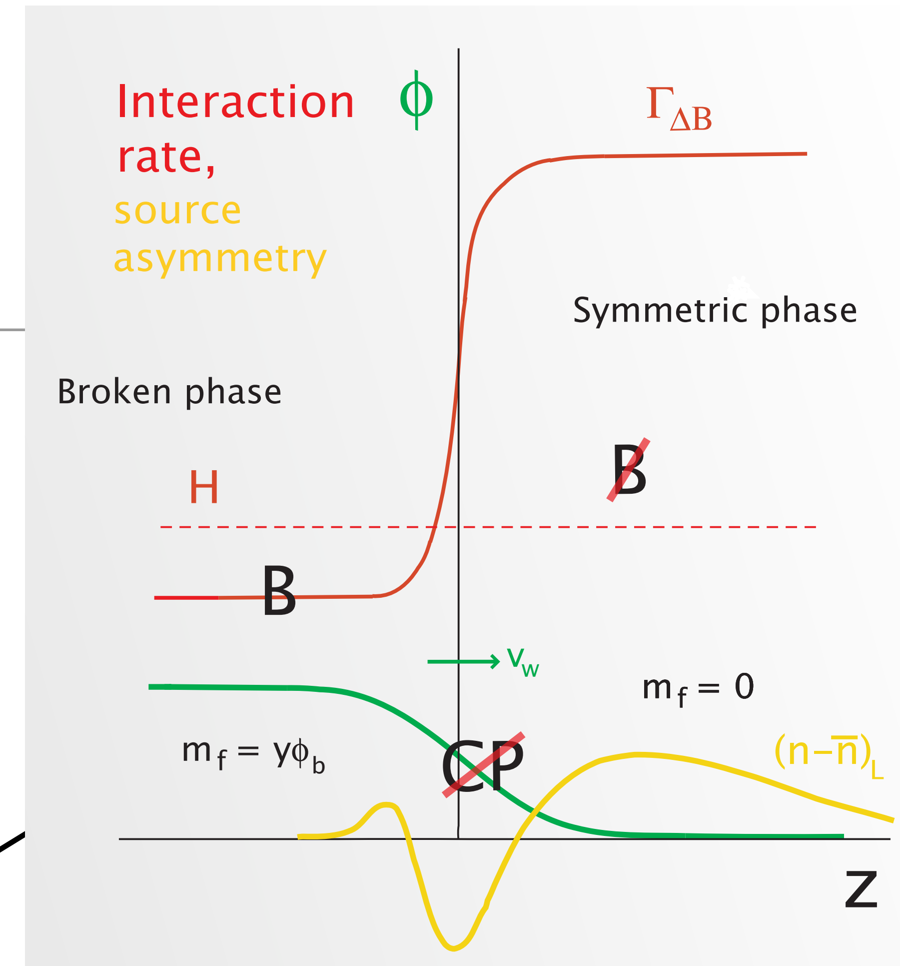

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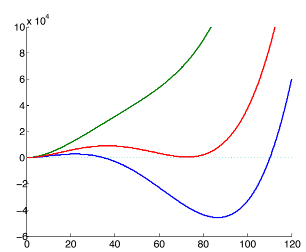

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2-loop $V_{\rm eff}$ in LG ~OK

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JCAP 1301 (2013) 011...

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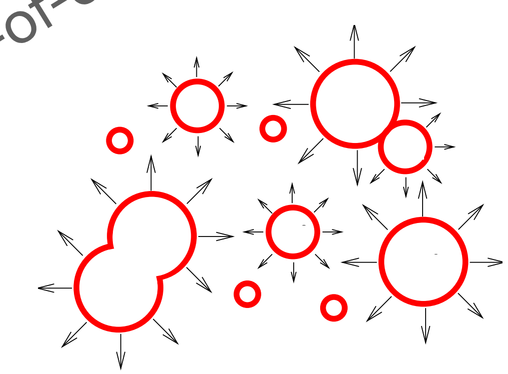

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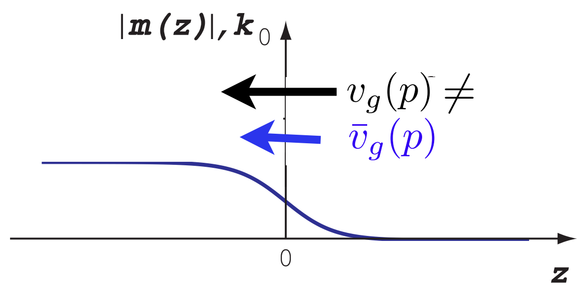
BAU generation, QM reflection or SC force

Thick wall limit: *SC force*

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



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

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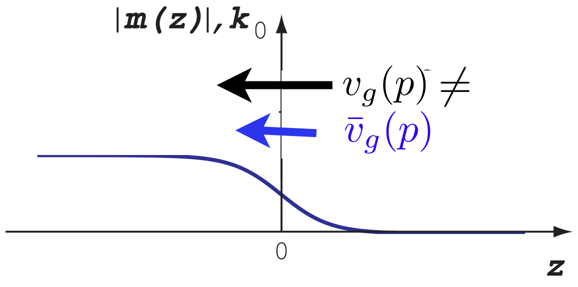

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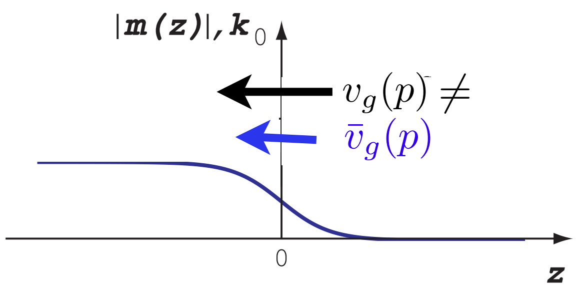

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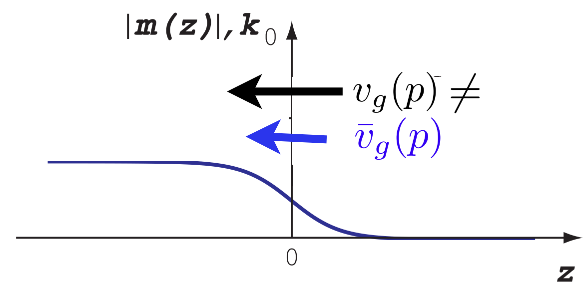

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CP-force

Thin wall limit: *quantum reflection*

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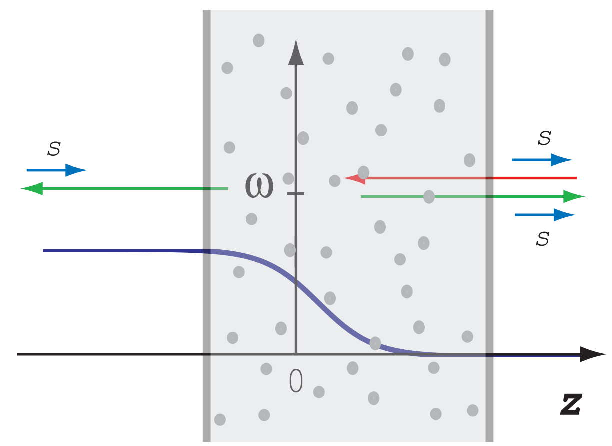

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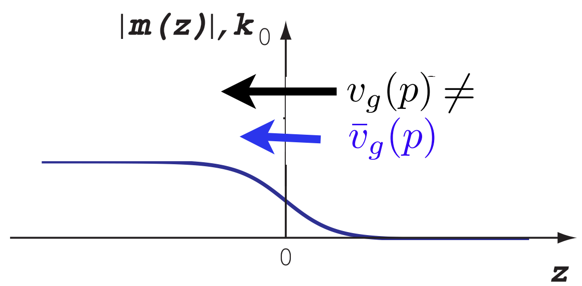

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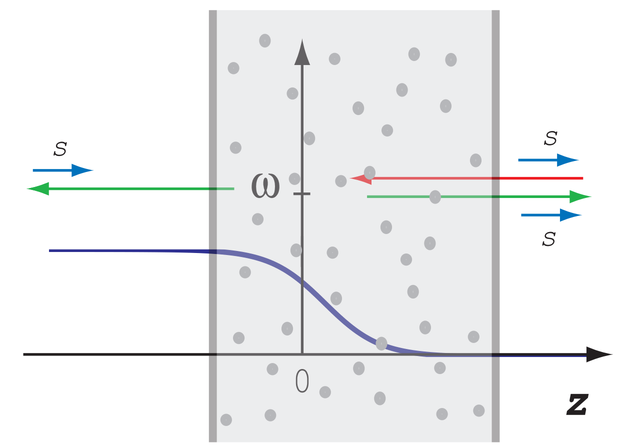

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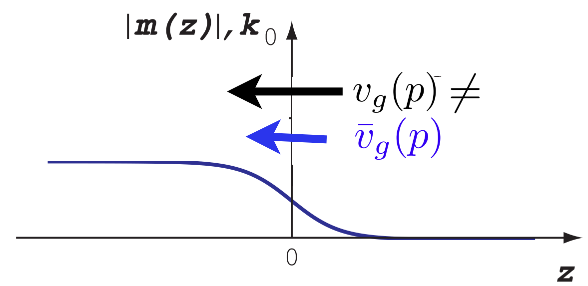

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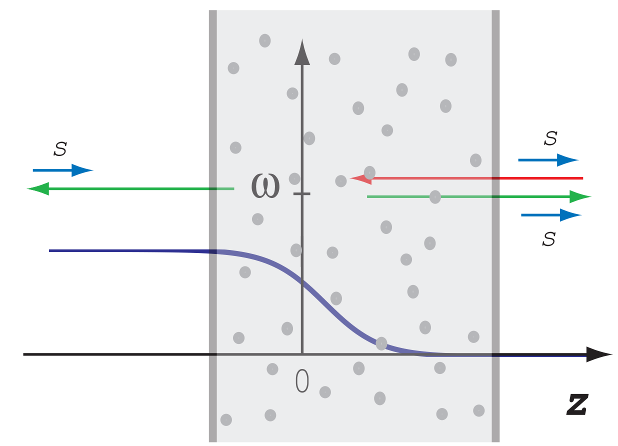

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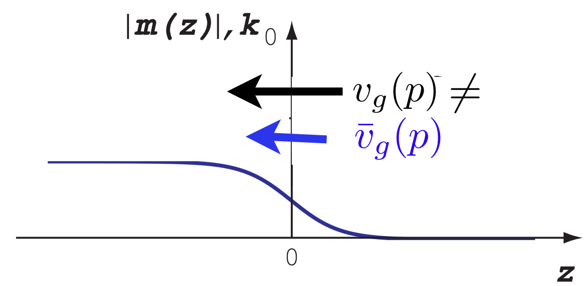

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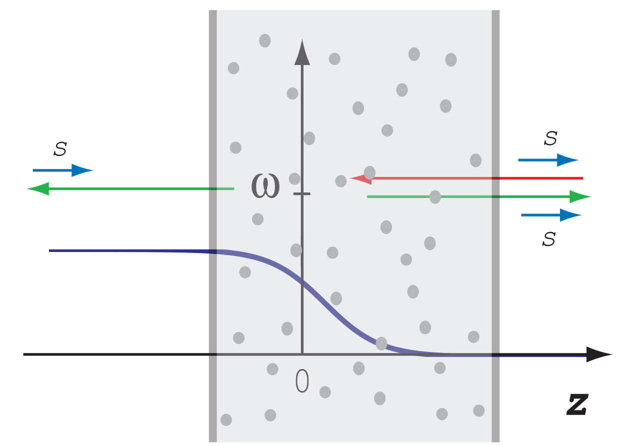

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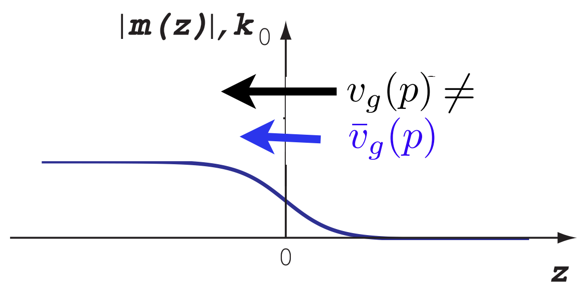

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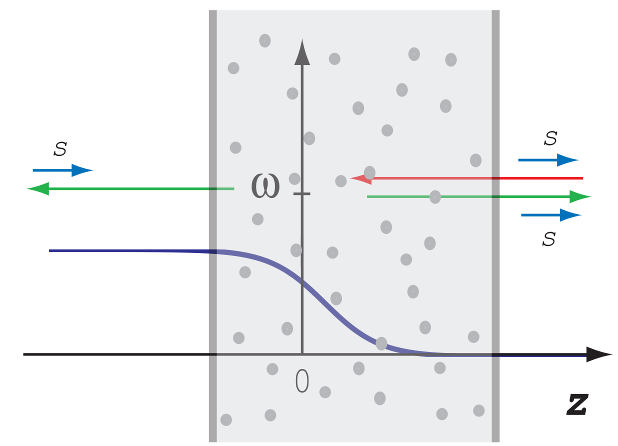

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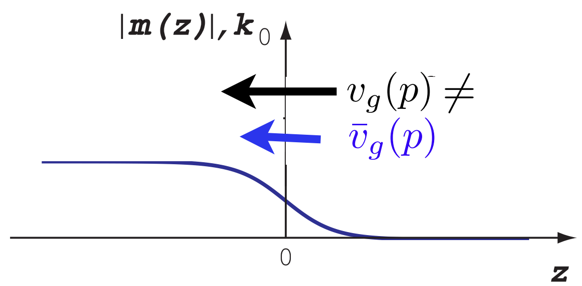

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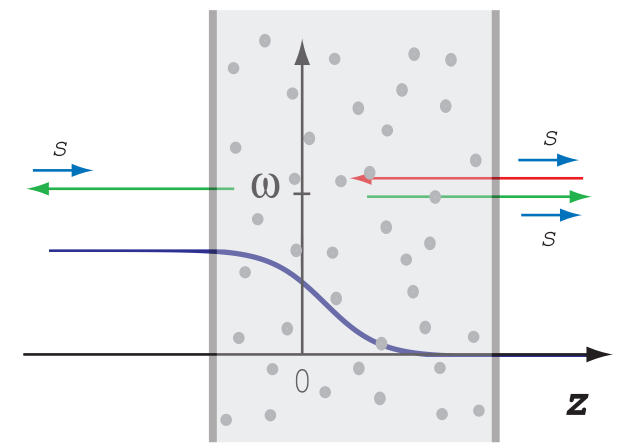

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Singlet model: BAU-generation

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 transport

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BAU from top transport

Large BAU much more frequent than in 2HDM

Singlet model: BAU-generation

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

Source of CP violation eg Dim-6 operator
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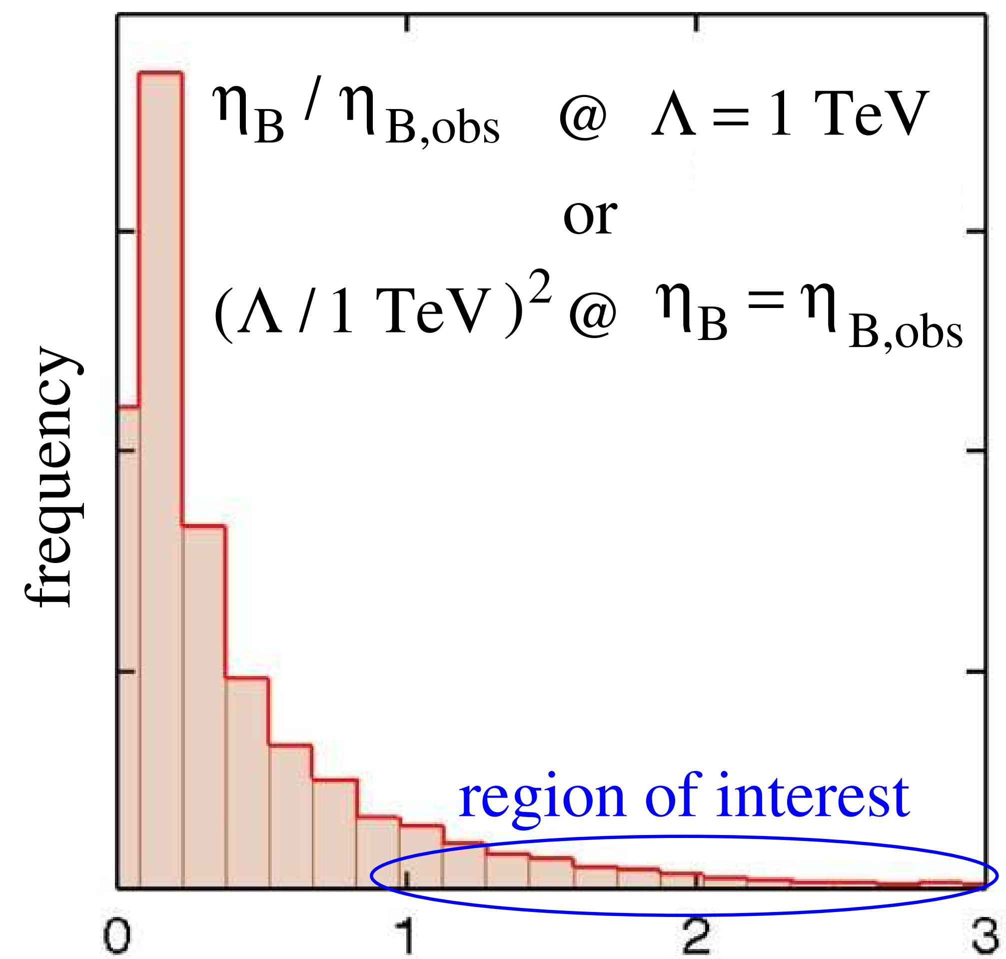

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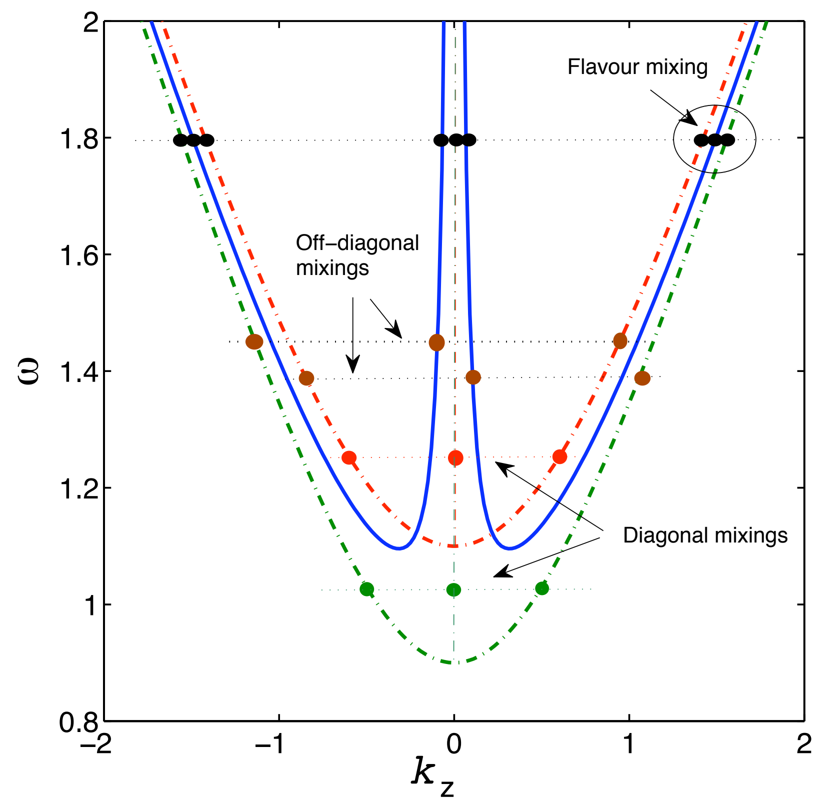
M.Herranen, KK, P.M.Rahkila NPB810 (2009) 389



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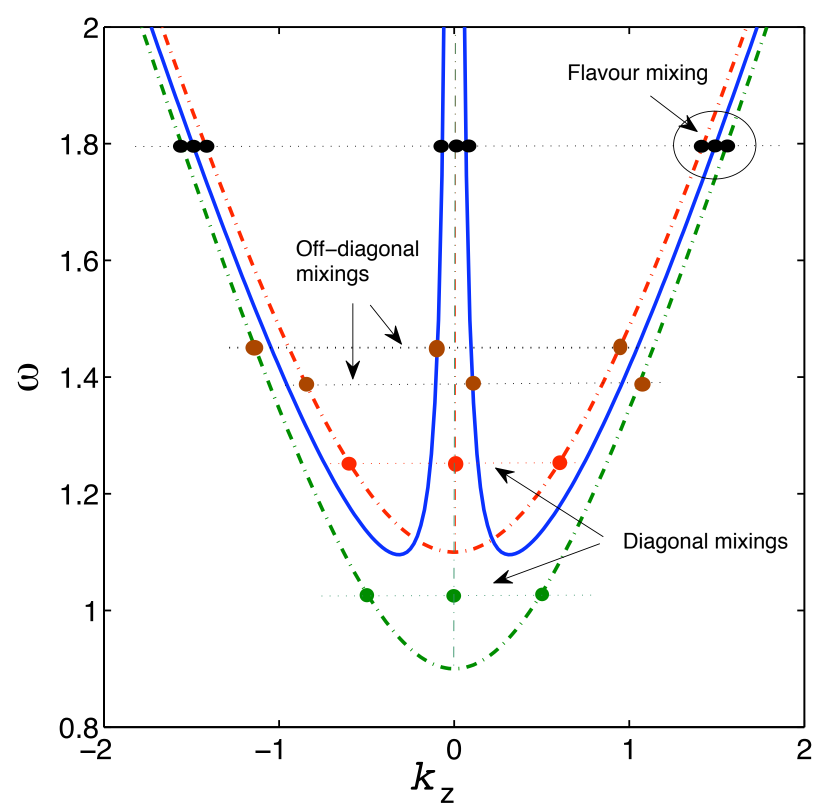

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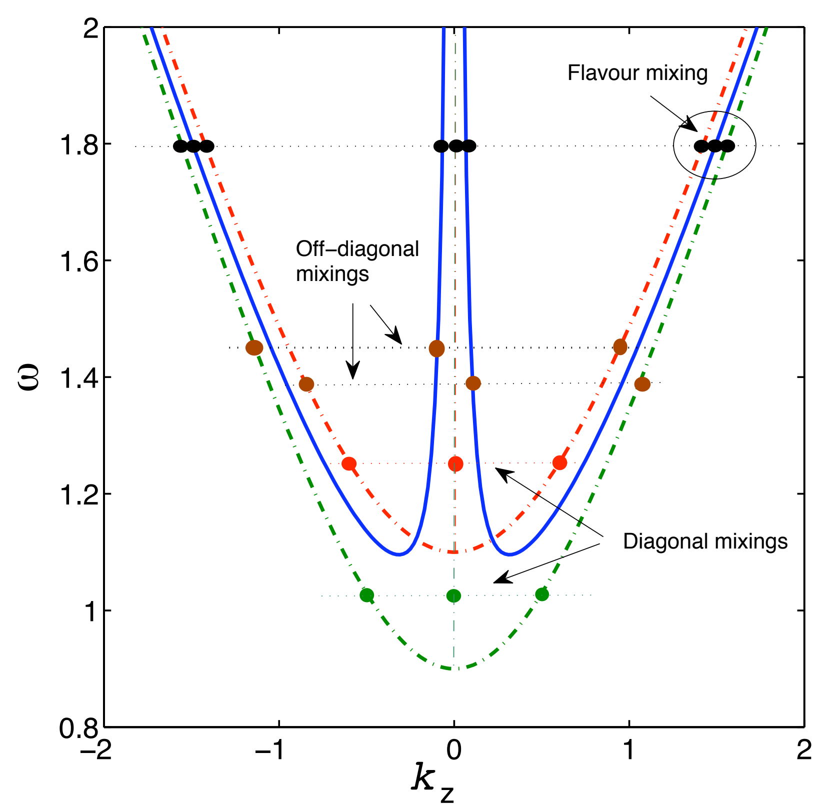

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Application to EWBG toy model ongoing: M.Herranen, KK, P.M.Rahkila, H.Jukkala