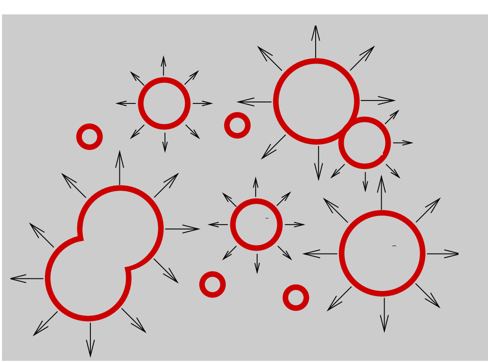
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Issues with Electroweak Baryogenesis

Kimmo Kainulainen,
The Big Bang and the little bangs - Nonequilibrium phenomena in cosmology and heavy-ion collisions
CERN/18.8.2016



with:
Tommi Alanne, Jim Cline, Pat Scott,
Mike Trott, Kimmo Tuominen,
Ville Vaskonen, Christoph Weniger, …

-SM almost UV-complete: follow simplicity
-DM and BG as guiding principles
-Singlet models, portals

EWBG:
-Transition strength
-CP-violation

2HD+S model

Paradigm I: UV-comple(x)(te) models

HIERARCHY PROBLEM

UNIFICATION

BARYOGENESIS

DARK MATTER

Paradigm I: UV-comple(x)(te) models

HIERARCHY PROBLEM
UNIFICATION

BARYOGENESIS
DARK MATTER

MSSM: HP/U/DM/~~EWBG~~

Leszek Roszkowski
(Nordita, June 2015):

[SUSY cannot be disproved, only abandoned]

Paradigm I: UV-comple(x)(te) models

HIERARCHY PROBLEM
UNIFICATION

BARYOGENESIS
DARK MATTER

MSSM: HP/U/DM/~~EWBG~~

MinimalWalkingTechniColor: HP/DM/U/EWBG?

K.K, K.Tuominen J.Virkajarvi,
- Phys.Rev. D82 (2010) 043511
- JCAP 1002 (2010) 029
- JCAP 1002 (2010) 029
- JCAP 1310 (2013) 036
- JCAP 1507 (2015) 034
- in progress (BG-part)

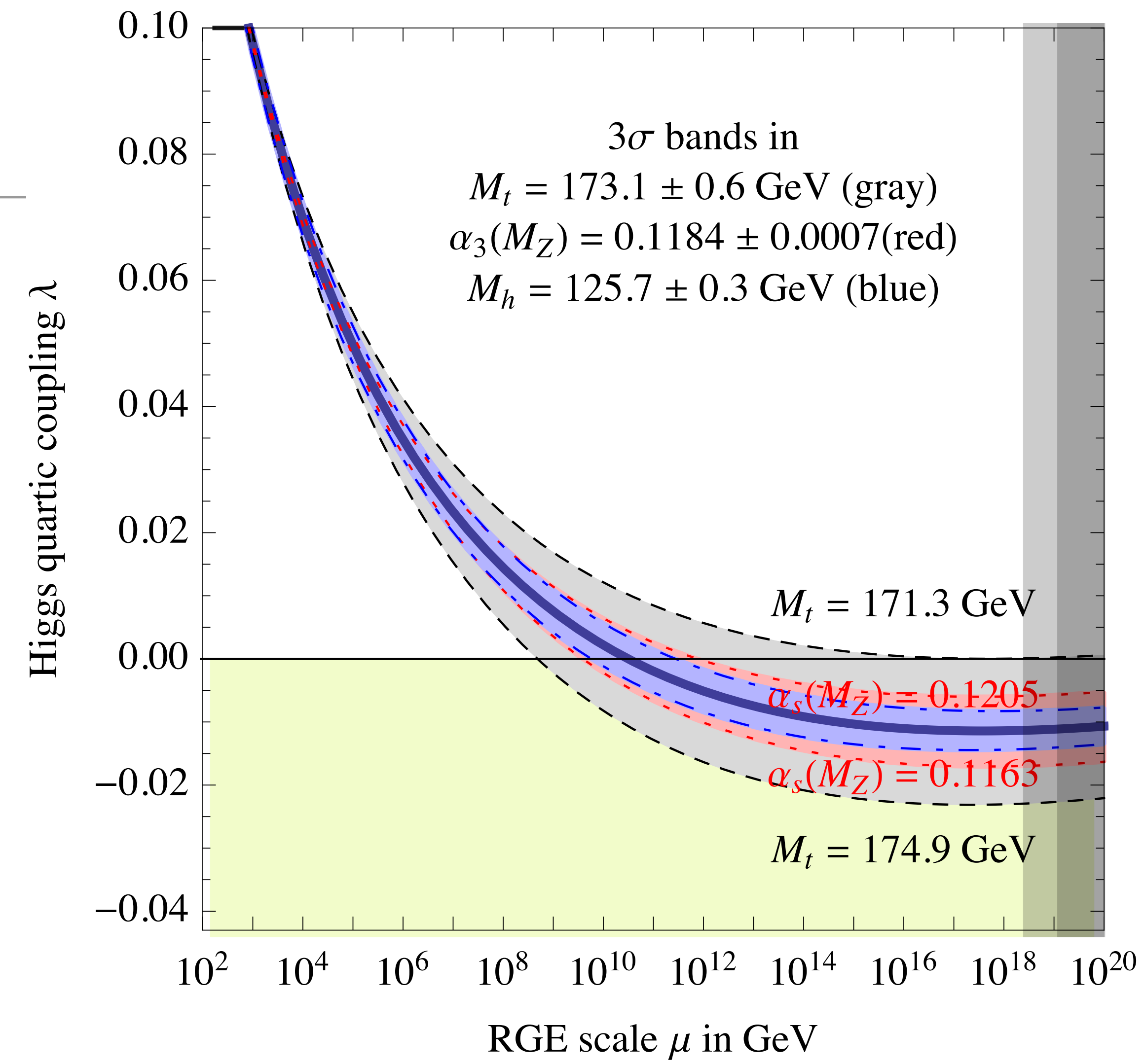
Leszek Roszkowski
(Nordita, June 2015):

[SUSY cannot be disproved, only abandoned]

Alternative: "Simplicity"

Could we have but (almost) SM all the way to the Planck scale?

Espinosa, Giudice, Riotto, JCAP 0805 (2008) 002
Degrassi etal, JHEP 1208 (2012) 098



Apparent running to negative coupling can be cured for example by a singlet S

$$\frac{1}{2}\lambda_{hs}|H|^2S^2 \Rightarrow \beta(\lambda) \rightarrow \beta(\lambda)_{\rm SM} + \frac{1}{2}\lambda_{hs}^2 \qquad (\lambda_{hs} \approx 0.7)$$

Other alternatives abound:

Chao etal, Phys.Rev. D86 (2012) 113017
Pyoungwon Ko, …

~~UNIFICATION~~ → **Asymptotic safety** ✓

problem of gauge Landau poles — with gravity corrections, or…

Robinson and Wilctzeck, PRL 96, 231601 (2006)
Wetterich and Shaposhnikov, Phys.Lett. B683 (2010)

~~HIERARCHY PROBLEM~~ → **No intermediate scales** ✓

behaviour of relevant operators

But remain the questions of DM and Baryon asymmetry

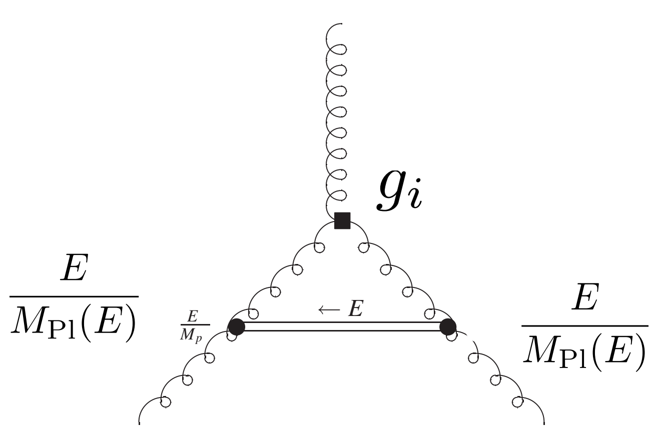
Asymptotic safety: <u>if OK, no need for unification</u>

Running couplings (incl. yukawas):

$$\mu \frac{\partial g_i}{\partial \mu} = \beta_{\mathrm{SM}}(g_i) + \beta_{\mathrm{grav}}(g_i)$$

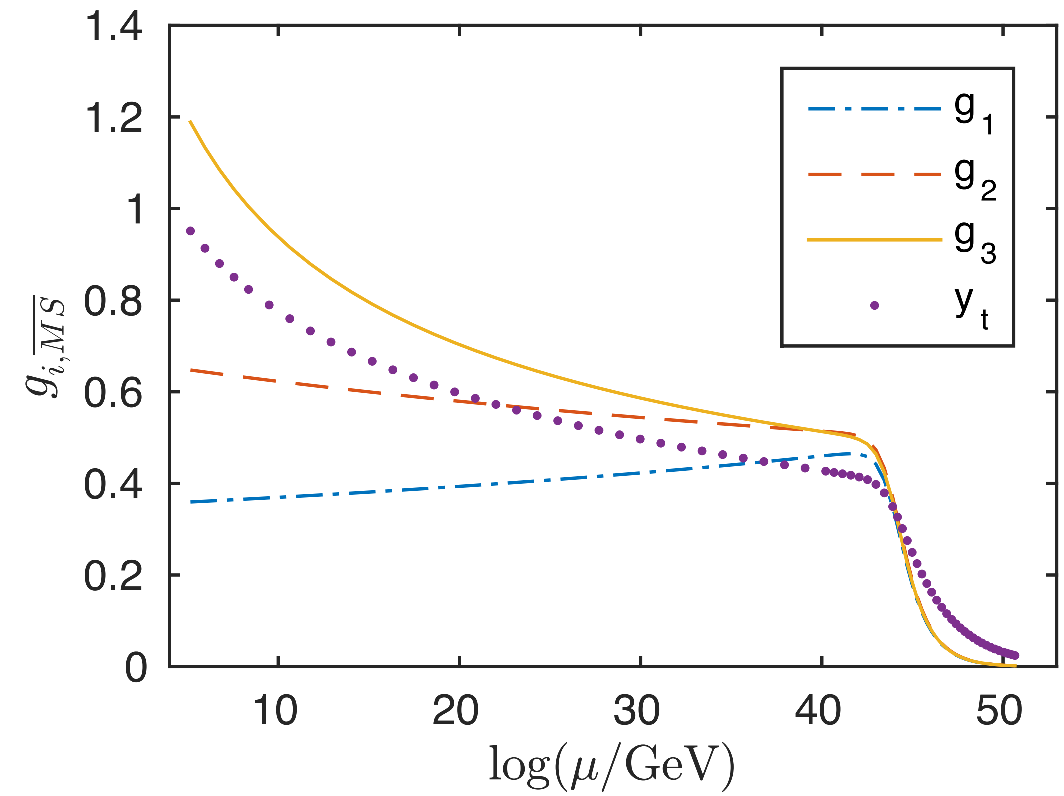
Where gravity correction is **parametrically**:

$$\beta(g_i)_{\mathrm{grav}} = \frac{a_i \mu^2}{M_{\mathrm{Pl}}^2 + \xi \mu^2} g_i$$



S.P. Robinson and F.Wilczek, PRL96 (2006) 231601

Laura Laulumaa,
MSc Thesis, JyU 2015.

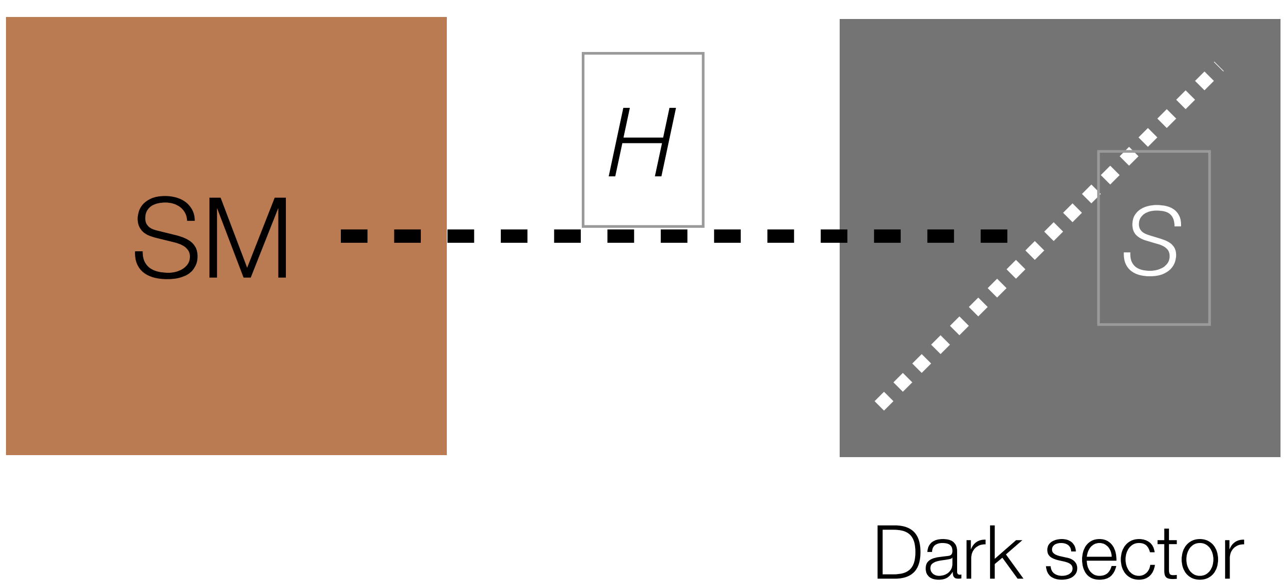


$$a_g \approx -1$$
$$a_{y_t} \approx -0.5$$
$$\xi \approx 0.024$$

Wetterich and Shaposhnikov,
Phys.Lett. B683 (2010) …

Portal models

Simple **Portal to** (complicated?) **DM sector**



J.M.Cline, KK,
JHEP 1111 (2011) 089
JCAP 1301 (2013) 012
Phys.Rev. D87 (2013)7,071701

J.M.Cline, KK, P.Scott, C.Weniger
PRD88 (2013) 055025

KK, K.Tuominen and V.Vaskonen
Phys.Rev. D93 (2016) 7 ,015016
T.Alanne, KK, K.Tuominen, V.Vaskonen
arXiv:1607.03303, JCAP, to appear

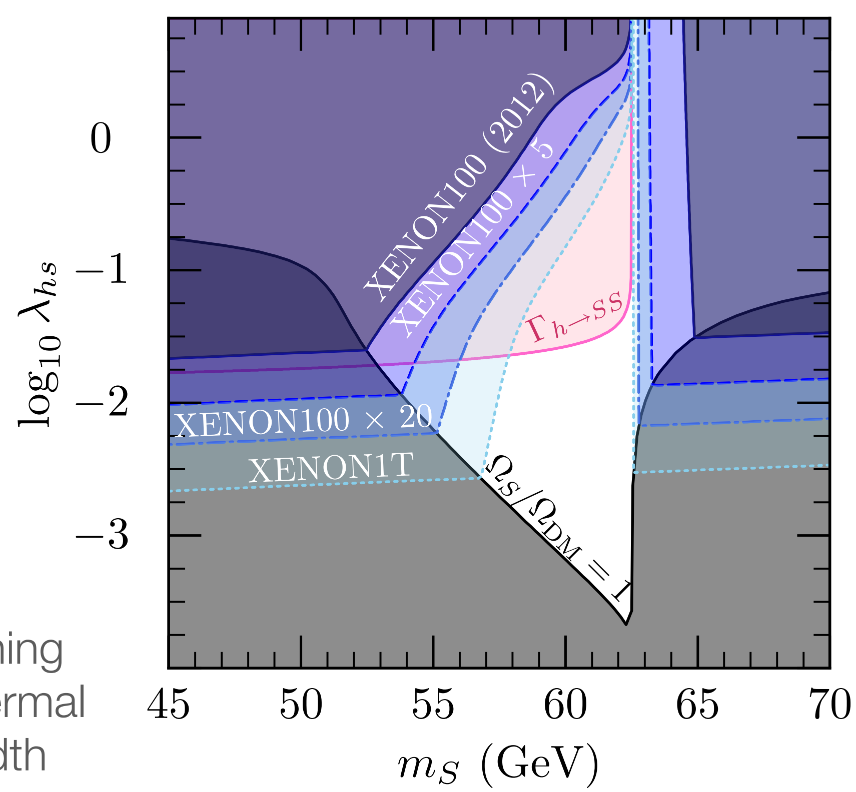
KK, S.Nurmi, T.Tenkanen,
K.Tuominen and V.Vaskonen
JCAP 1606 (2016) no.06, 022

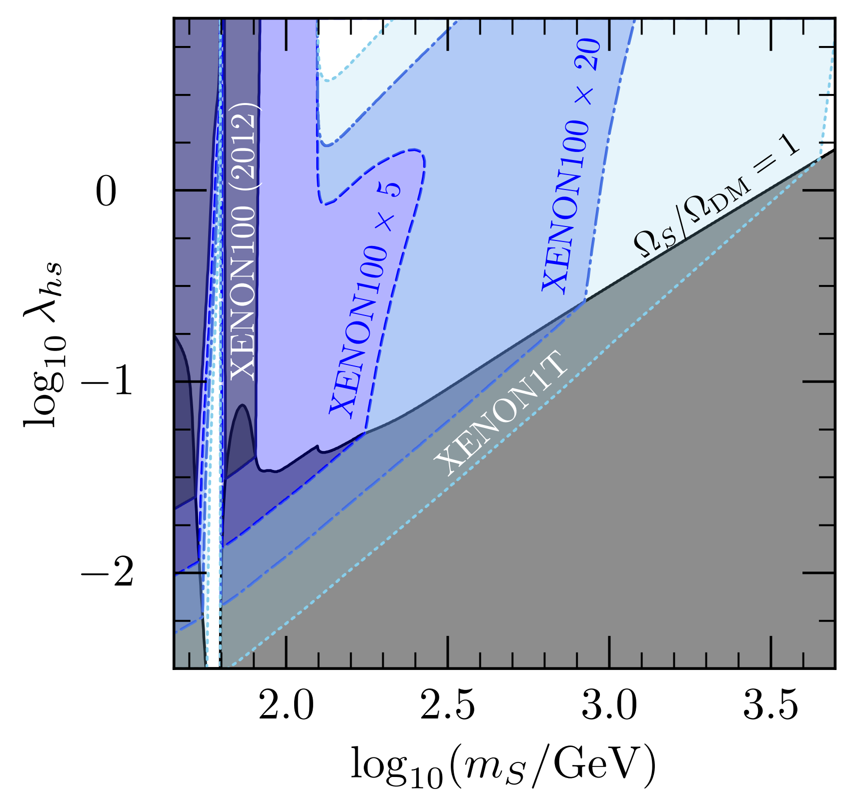
Motivation: DM

Given **Z_2-symmetry** singlet **can be DM:**

The model:

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





Xenon bounds account for the fact that $f_{\rm rel} \leq 1$.

J.M.Cline, KK, P.Scott, C.Weniger PRD88 (2013) 055025

Low-side opening reflects the thermal distribution width $\Delta\sqrt{s} \sim 0.1 m_S$

$$\Omega \sim \frac{1}{\langle v_{\rm Mol}\sigma\rangle} \sim \frac{1}{\lambda_{\rm hs}^2}$$

For $m_s > 100$ GeV there is a **potential instability** due to gravitational couplings (P. Ko's talk)

Motivation: Baryogenesis

Harder!

EWBG context:

* strength of the transition ✓
* CP-violation (enough B) ?

Leptogenesis

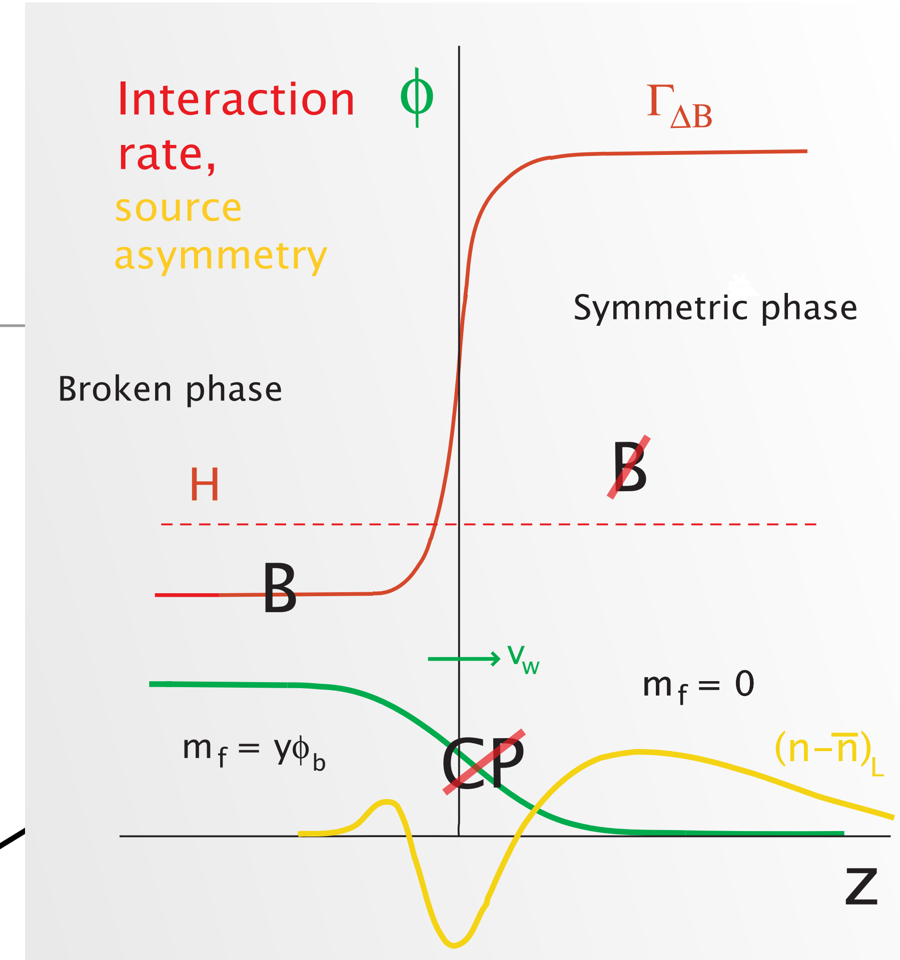
ARS

nuMSM

EWBG

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

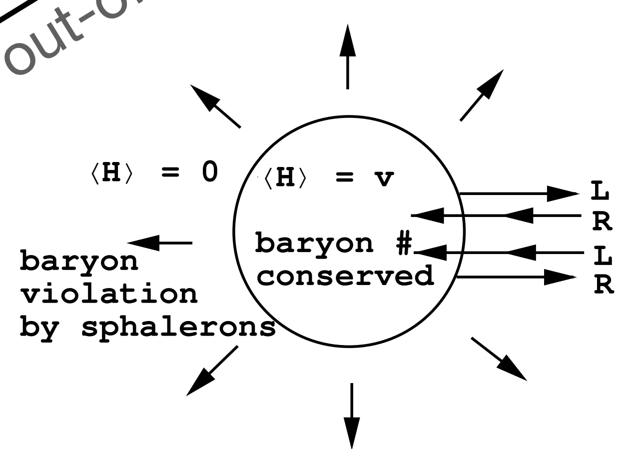
→ 



To keep BA

Equilibrium / Nonperturbative / Gauge issues

Mostly out-of-equilibrium / quantum



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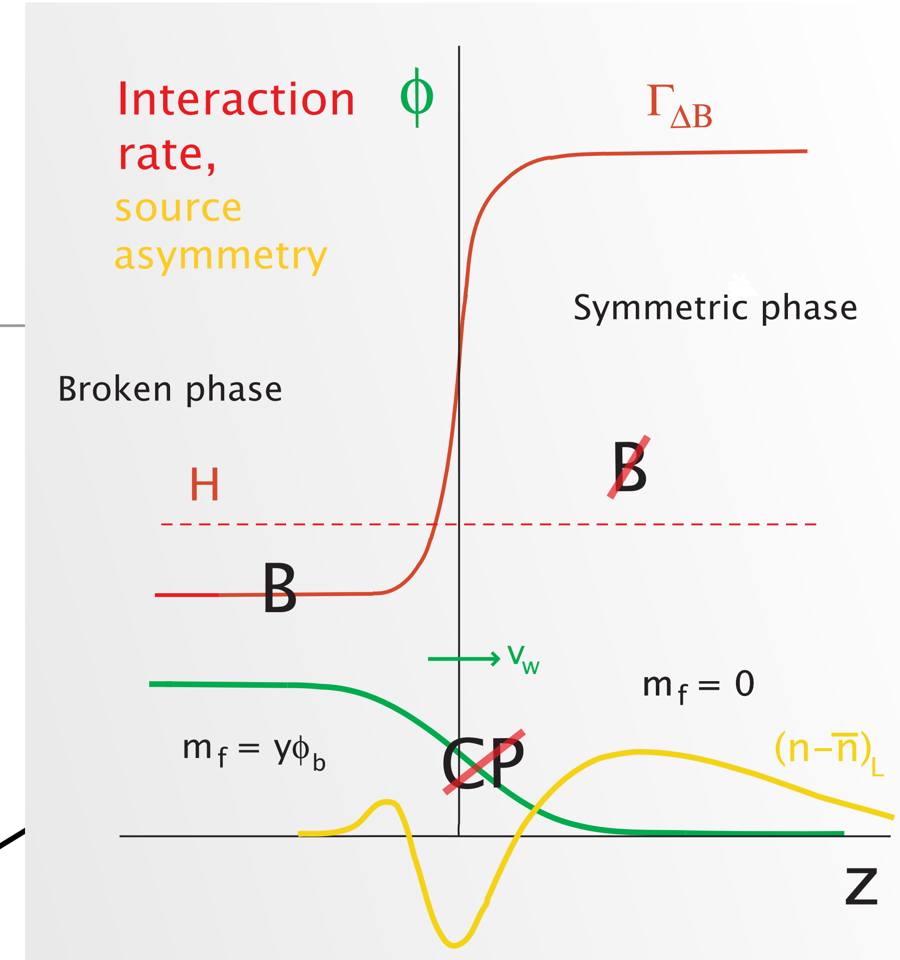

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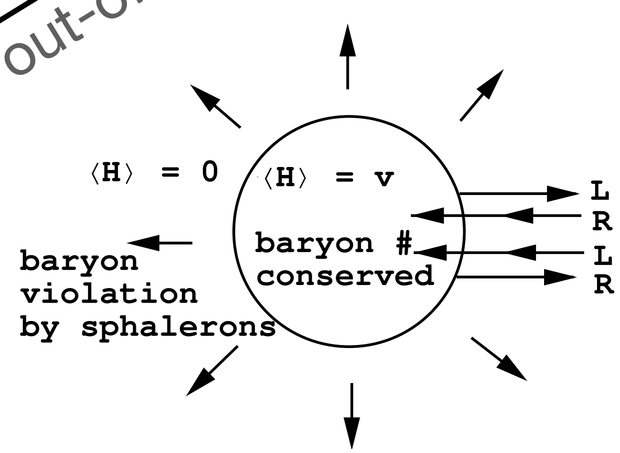

Sphaleron rate in the unbroken phase ✓

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

To make BA

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$$H \sim 10^{-14} T_{100}^2 \mathrm{GeV}$$
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To keep BA

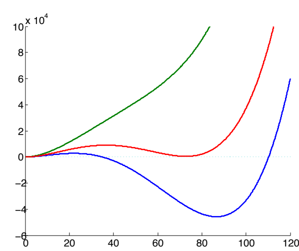
(Small) sphaleron rate in the broken phase

Kuzmin, Rubakov & Shapsohnkinov, Arnold & McLerran, Moore, Rummukainen…;

- V_{eff} in Landau *gauge*

$$\frac{\phi_n}{T_n} > 1$$

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_{eff} in LG ~OK

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

Equilibrium / Nonperturbative / Gauge issues

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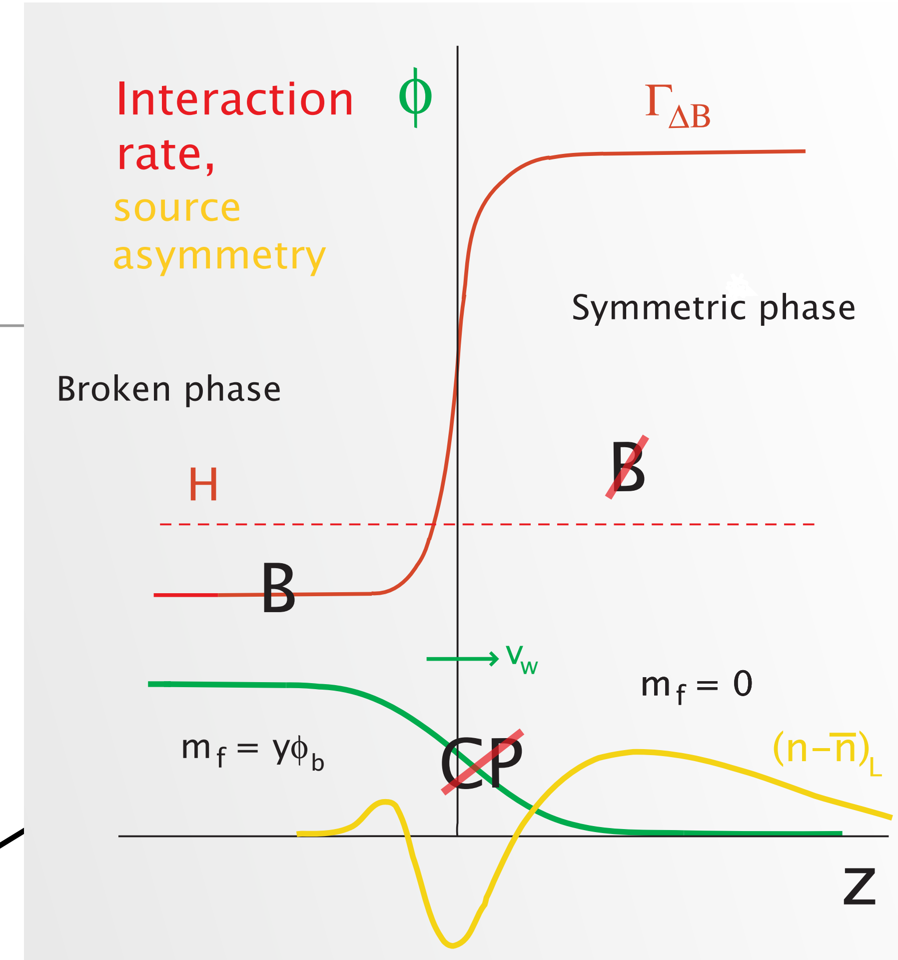

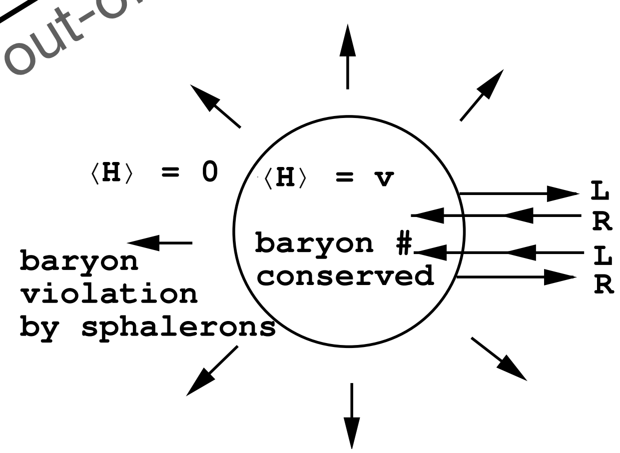

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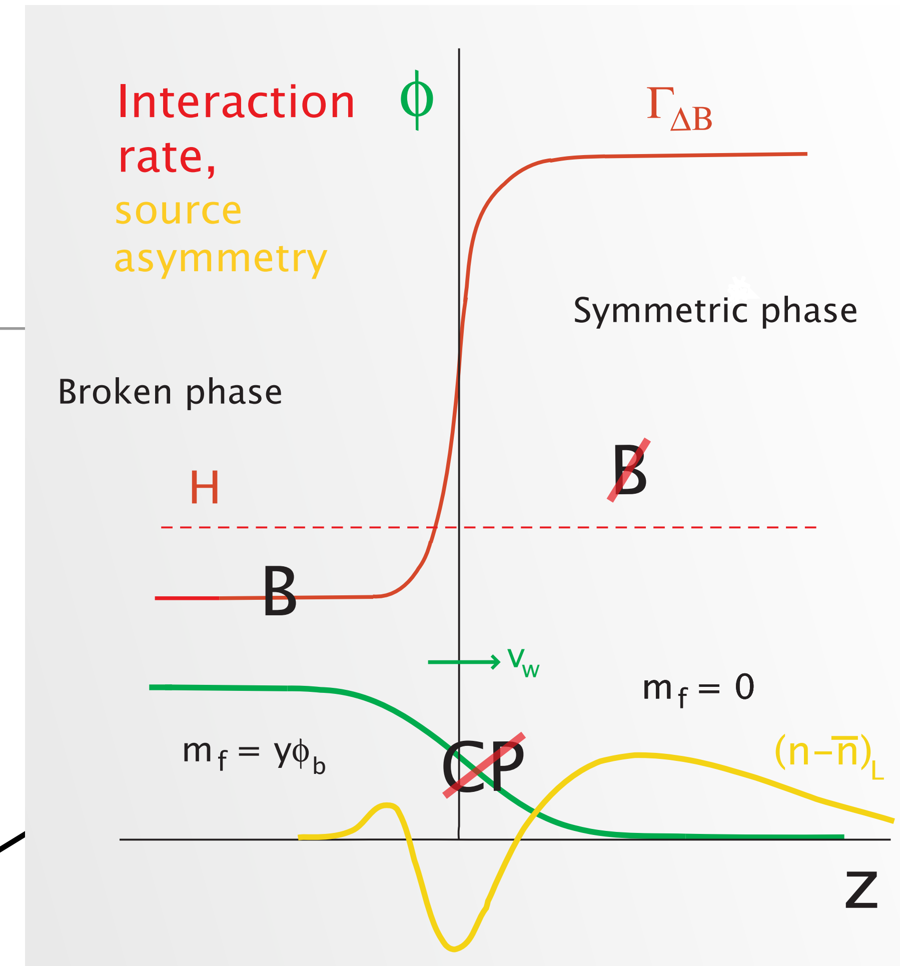
To make BA

EWBG

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



To keep BA

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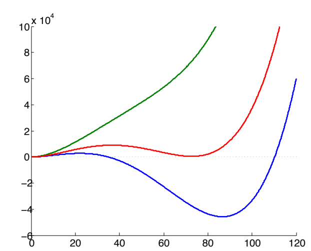

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M.Laine, G.Nardini and K.Rummukainen, JCAP 1301 (2013) 011...

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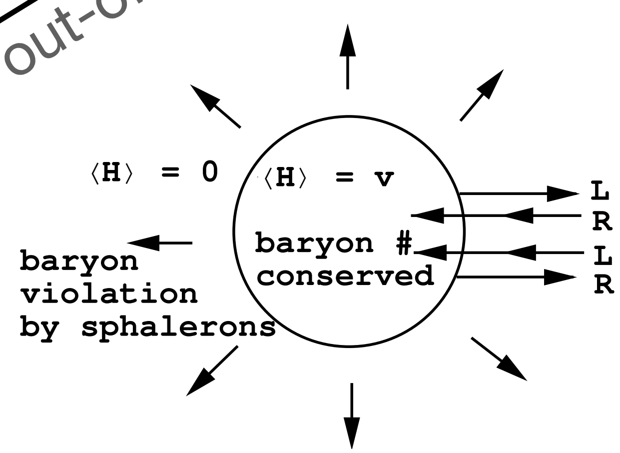

(CP-even) **dynamics of the expanding wall** ?

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,..

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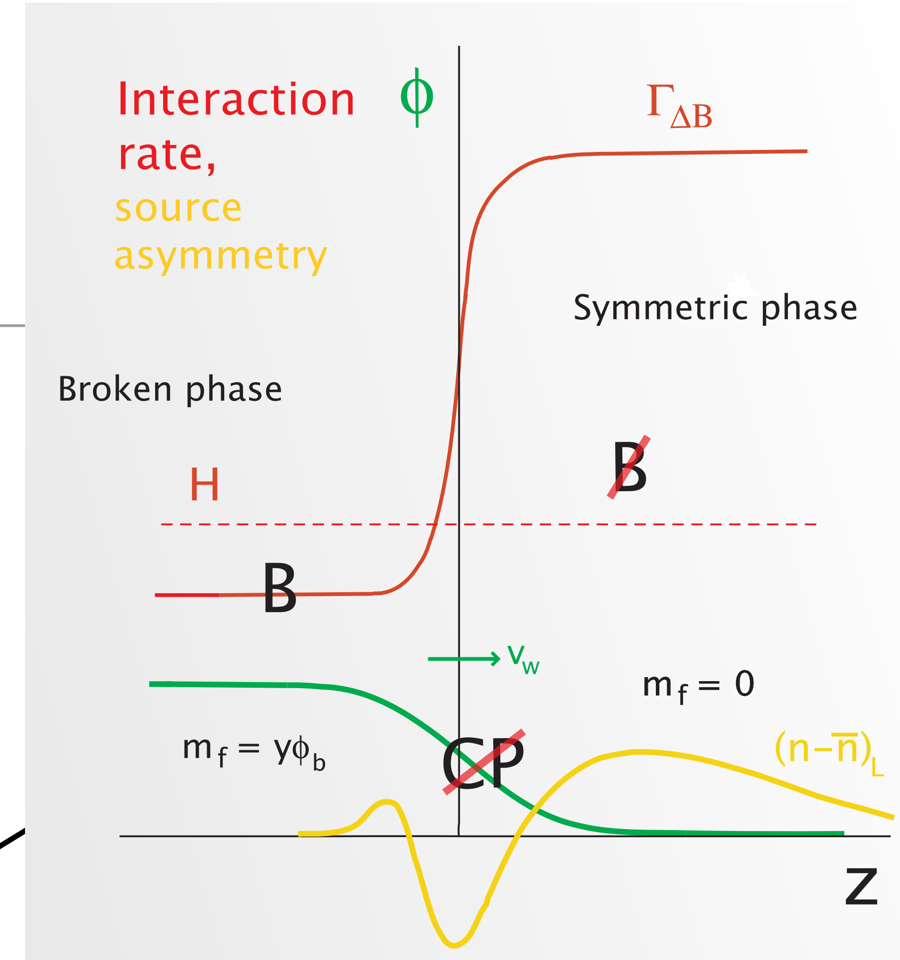

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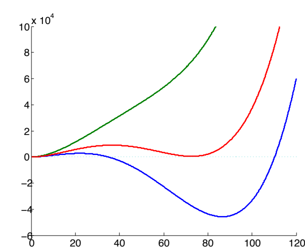

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JCAP 1301 (2013) 011...

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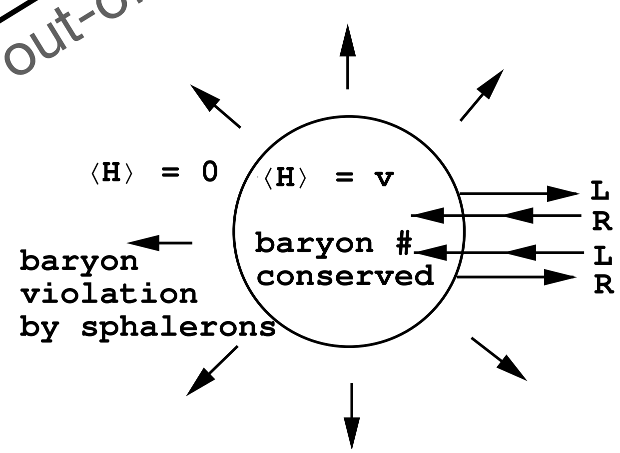
Mostly out-of-equilibrium / quantum



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_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,..

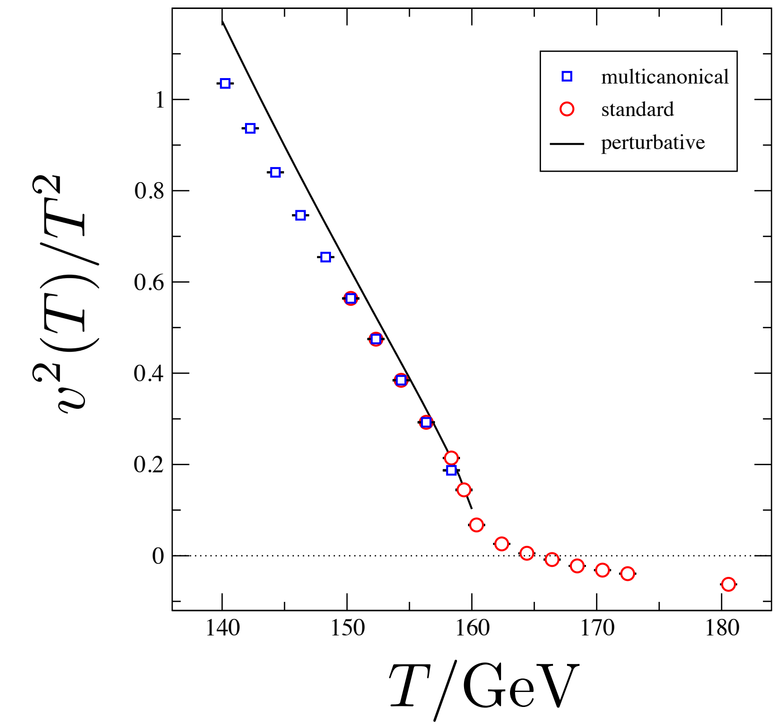
To make BA

SM, Transition strength / Sphaleron rate

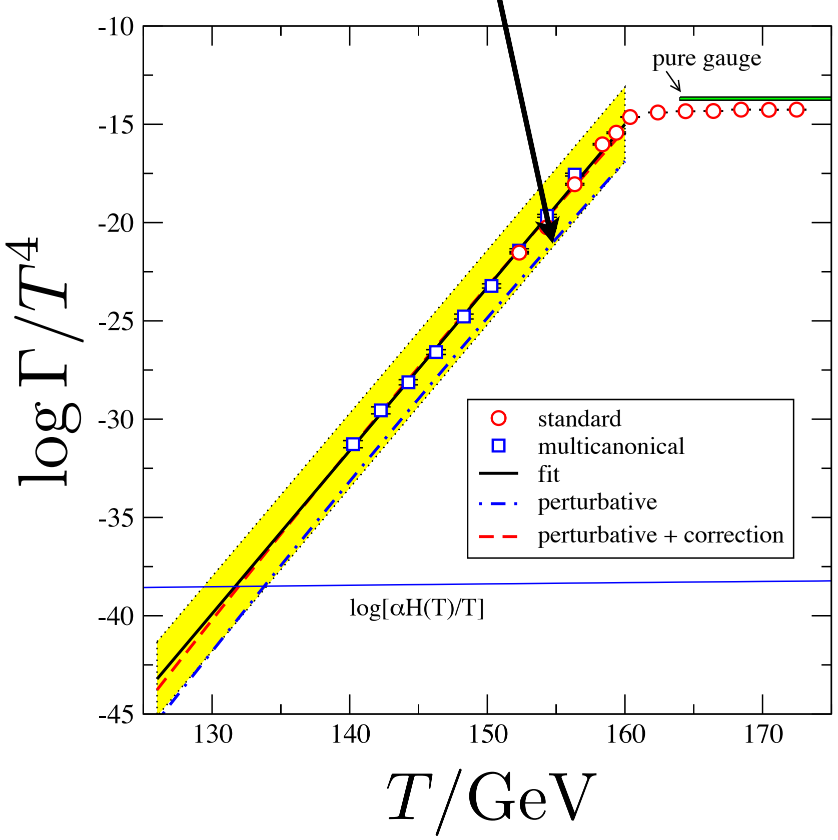
PT in SM, is a cross-over with

159.6 ± 0.1 ± 1.5 GeV

M.d'Onofrio, K.Rummukainen, A.Tranberg, Phys.Rev.Lett. 113 (2014) no.14, 141602



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



Sphaleron rate in SM

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

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

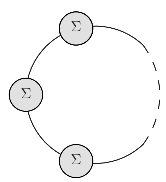
Sphalerons drop out of eq. in broken phase when

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

Transition strength, extensions / LSS

Traditionally: increase the strength by (effective cubic) **loop corrections**

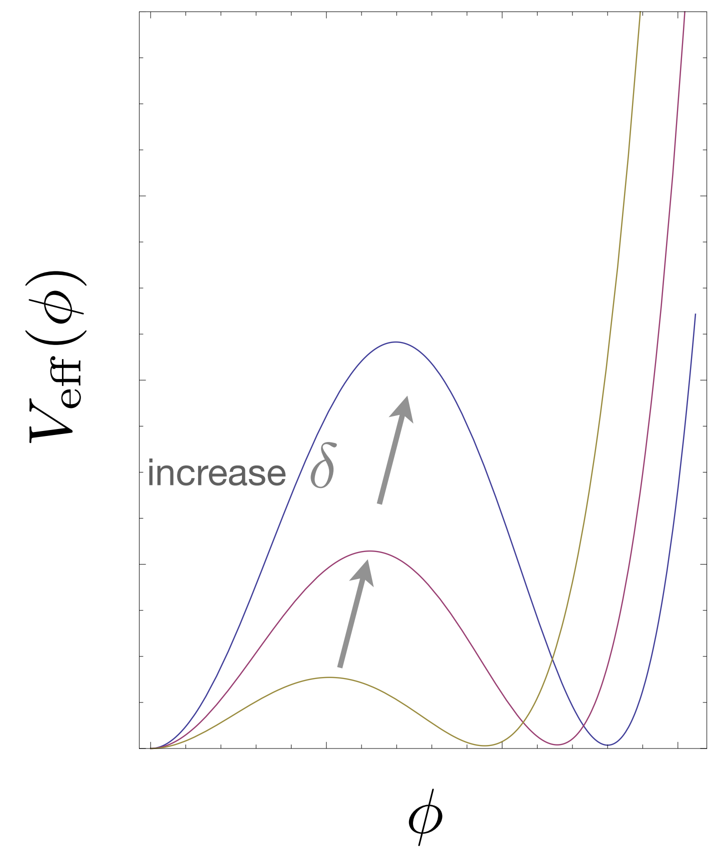
Need new light ($m_i < T$) bosonic fields strongly coupled to Higgs



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

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

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



However, also higgs mass mostly from

$$m_h^2 \sim y_t^2 \;\log \frac{m^2_{\tilde{t}_R}\, m^2_{\tilde{t}_L}}{m_t^4}$$

Tension: light t_R => **very heavy t_L**

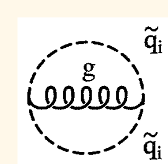
Early times early-**mid-90**'s:

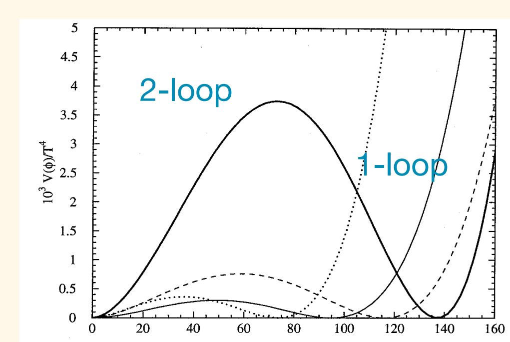
$V_{\text{1-loop}}$: Espinosa, Quiros, Zwirner, Carena, Wagner,...

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

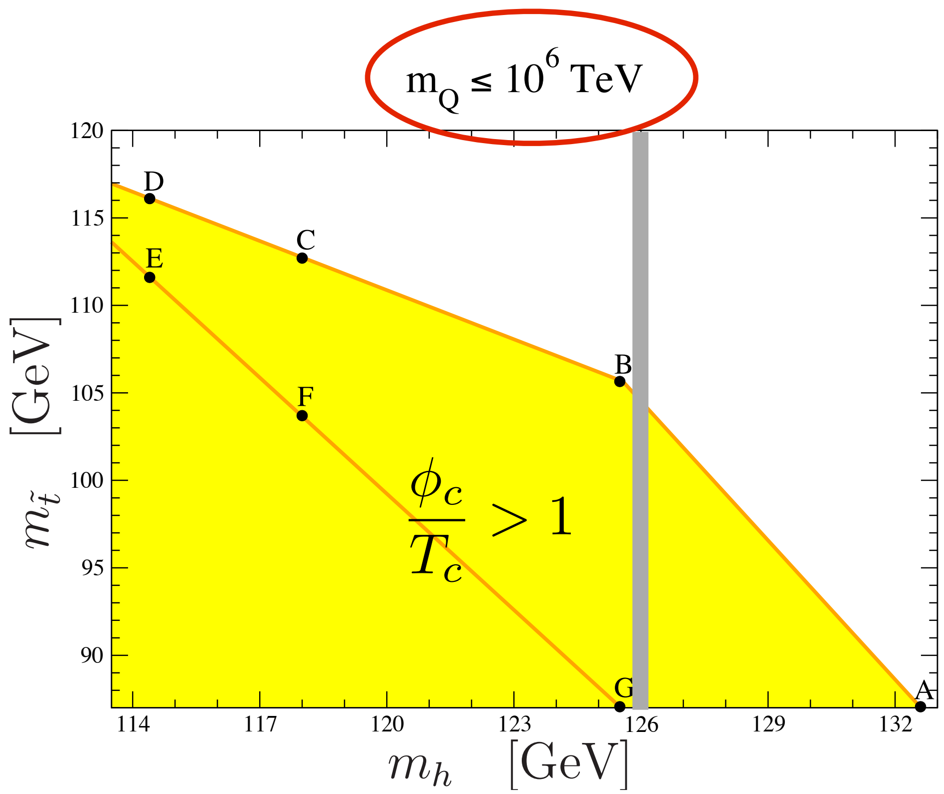
J.R.Espinosa -96:
75% 2-loop enhancement on v/T

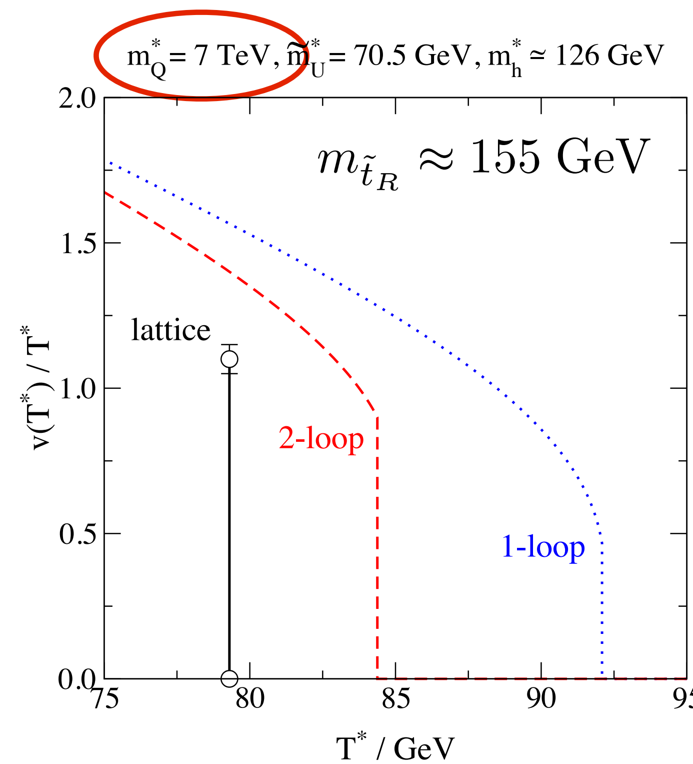
NPB475 (1996) 273.





Transition strength, MSSM-LSS





RGE-improved potential: models (*metastable* against color breaking)

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

Lattice is a bit more generous:

Rummukainen, Nardini and Laine ...

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

LHC:

Tension with light stop-enhanced gg-fusion Higgs production ... needs to be balanced by an invisible DW to light neutralinos (<60GeV) …

M.Carena, G.Nardini, M.Quiros & C.Wagner, NPB812 (2013)

But m_{stop} > 210-540 GeV
(depending on neutral higgsino mass)

Kobakihidze etal, Phys.Lett. B755 (2016) 76-81

Strong transition from a singlet

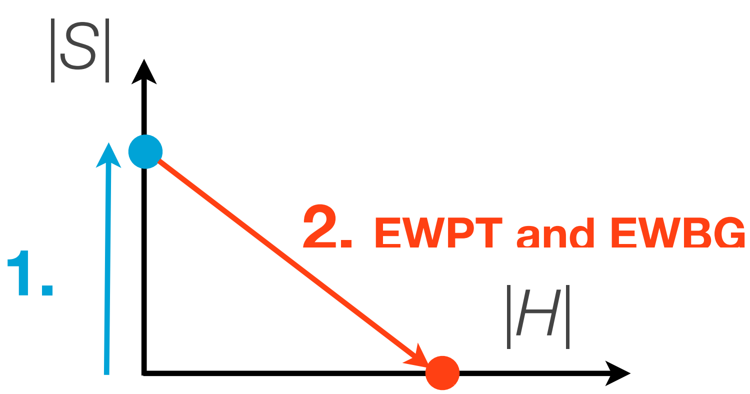
Anderson, Hall, PRD45, 2685 (1992)
Profumo, Ramsey-Musolf, Shaughnessy, JHEP 0708 (2007) 010

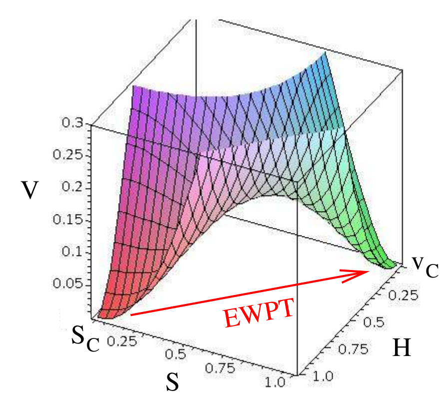
Use tree level barrier:

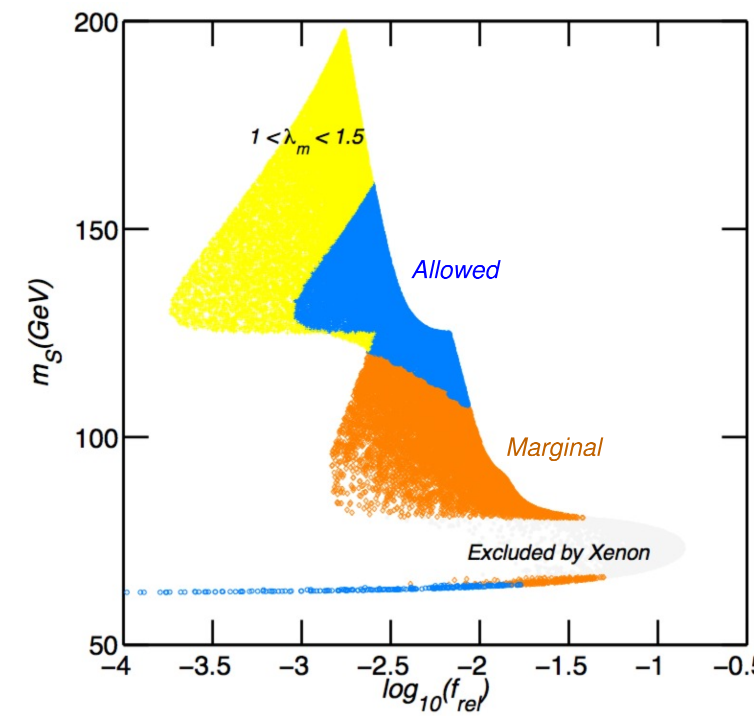
J.R.Espinosa, T.Konstandin, F.Riva, NPB854 (2012) 592

only the leading high-T

$$V = \frac{1}{2}\lambda_{hs}h^2s^2 - (\mu_s^2 - c_sT^2)s^2 - (\mu_h^2 - c_hT^2)h^2 + \ldots$$







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

Arrange c_s, c_h, μ_s and μ_h so that transition goes in *two steps* → large barrier at T_c → strong transition. This WORKS

- large barrier requires largish λ_{hs}
- 2-step mechanism needs small m_s

Variants of the scheme:

Inoue, Ovanesyan, Ramsey-Musolf, PRD93 (2016) 015013, etc…

Idea actually present in the MSSM ~color breaking

Laine, Rummukainen, Cline, Moore, Quiros …,

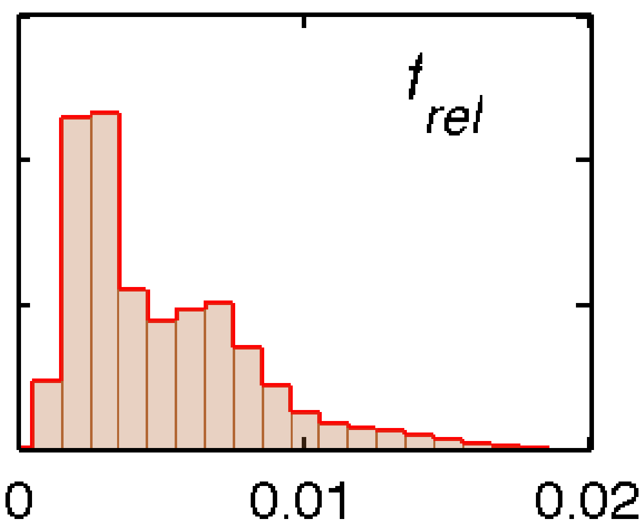
Strong transition *and* S-DM? (Not in simplest case)

However, **needs for a large v/T (large λ_{hs}) and a large Ω are in contrast:**

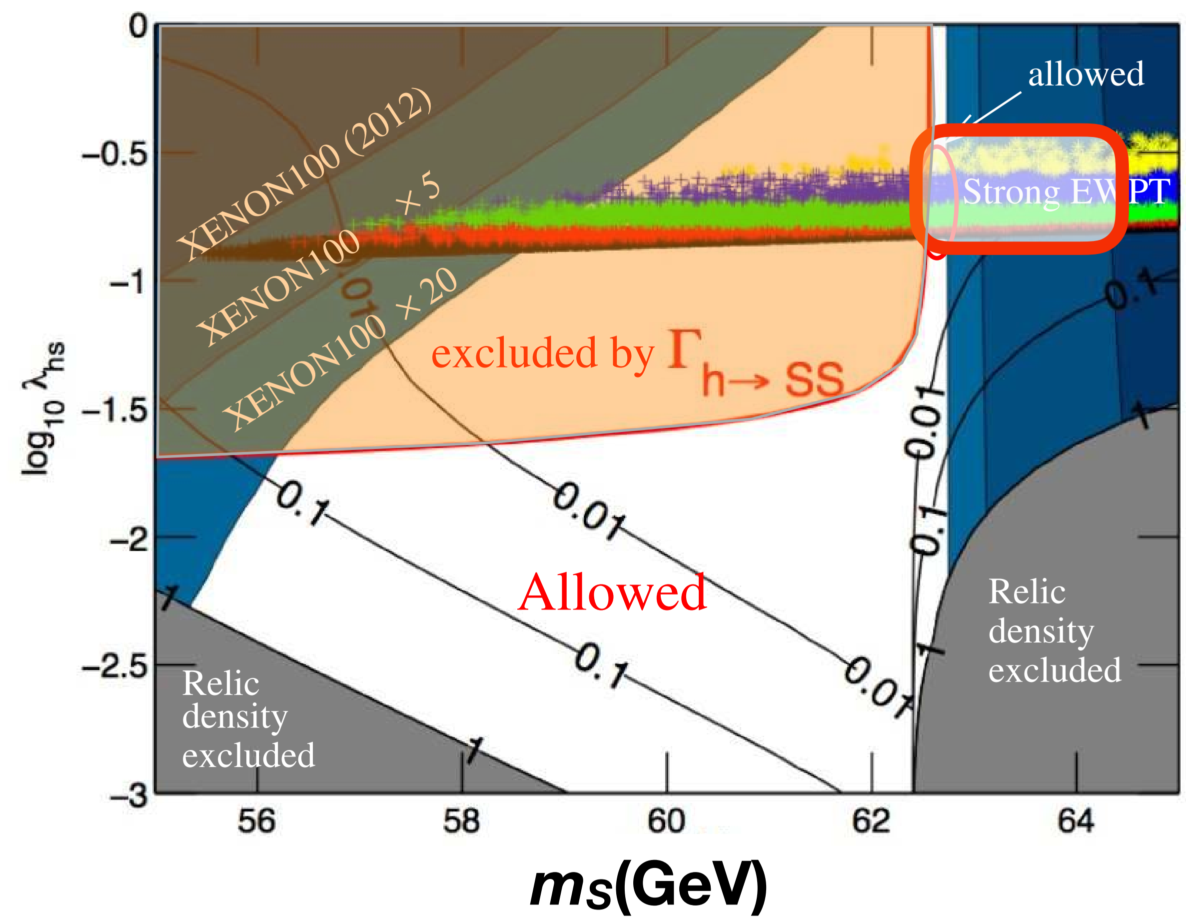
$$\Omega \sim \frac{1}{\langle v_{\rm Mol}\sigma\rangle} \sim \frac{1}{\lambda_{\rm hs}^2}$$

Large v/T implies a **subdominant DM**

BAU acceptable *v/T >1* models



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



J.M.Cline, KK, P.Scott and C.Weniger, PRD88 (2013) 055025

Obviously, with two singlets, with suitable λ_{hs}'s and masses, **both strong transition and DM** are bound to work!

Extend DS eg. with a DM-fermion

KK, K.Tuominen and V.Vaskonen, PRD93(2016) 7,015016

Electroweak baryogenesis:

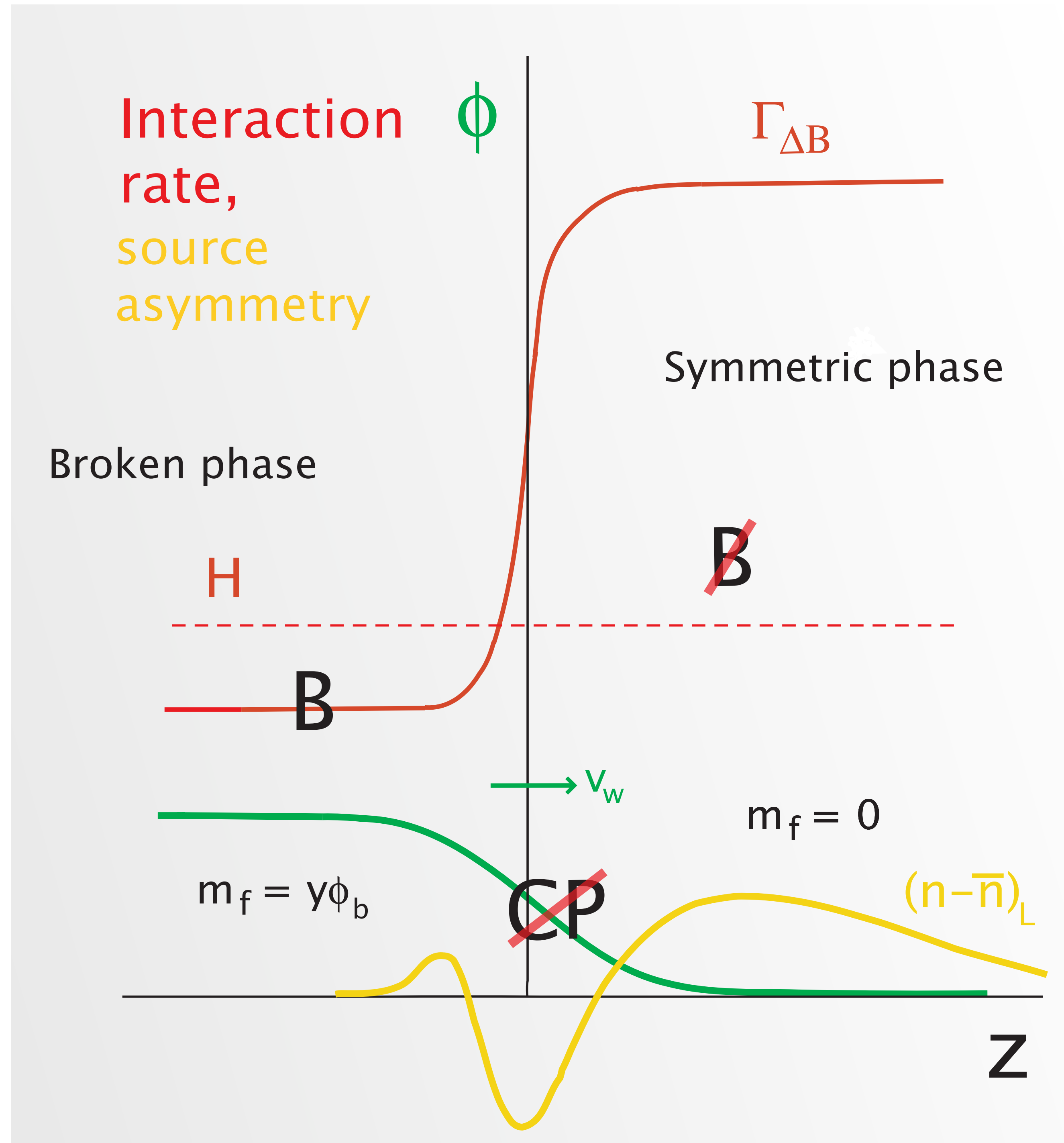
Need to compute:

$\xi_{q_L}(z) \sim$ nL(x)−n̄L(x)

to get

$$n_B = \frac{3\,\Gamma_{\rm sph}}{2\,v_w}\int_0^\infty dz\,\xi_{q_L}(z)e^{-k_B z}$$

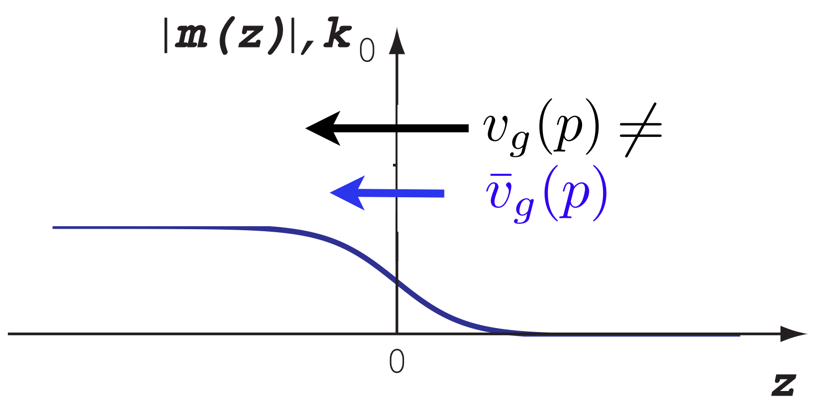
$$k_B \equiv \frac{3A}{2v_w}\frac{\Gamma_{\rm sph}}{T^3}$$



- Semiclassical, WKB-regime
- Quantum reflection

Needs **QKE's** for full treatment

WKB-regime: Semiclassical baryogenesis



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

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

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

CP -force

Stationary frame

$$(v_{gz}\partial_z + F_z\partial_{p_z}) f_i = \mathbf{C}_i[f]$$

Fluid ansaz

$$f_i(z, p_z, p) = \frac{1}{e^{\beta[\gamma_w(E_i + v_w p_z) - \mu_i]} \pm 1} + \delta f_i(z, p_z, p)$$

$$\int d^3p\ \delta f_i = 0$$

Integration with weights ***1*** and ***p/E***

=> Fluid equations for
μ and $u_i \equiv \langle (p_z/E_0)\delta f_i \rangle$

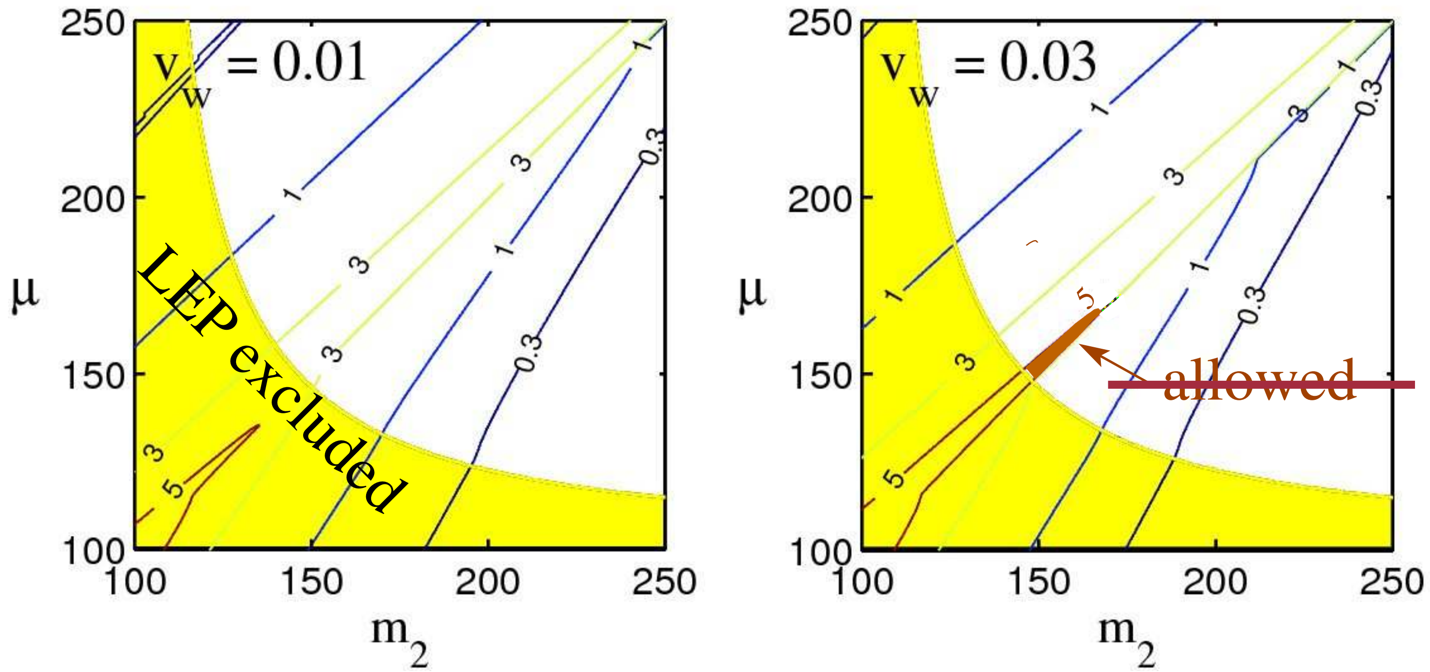
WKB J.M. Cline, M. Joyce and K. Kainulainen. PLB417 (1998) 79; JHEP 0007 (2000) 018
J.M. Cline and K. Kainulainen, PRL85 (2000) 5519.
M. Joyce, T. Prokopec and N. Turok, PRD53, 2958 (1996); PRL75, 1695 (1995); PRD53, 2930 (1996).

CTP K. Kainulainen, T. Prokopec, M.G. Schmidt and S. Weinstock, JHEP 0106, 031 (2001); PRD66 (2002) 043502.
T. Prokopec, M.G. Schmidt and S.Weinstock, Annals Phys. 314, 208 (2004), Annals Phys. 314, 267 (2004)

BAU generation, MSSM

Chargino transport

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



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Similar results were found by

T.Konstandin, T.Prokopec, M.G.Schmidt,
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which also used SC/CTP approach
and included flavour mixing effects

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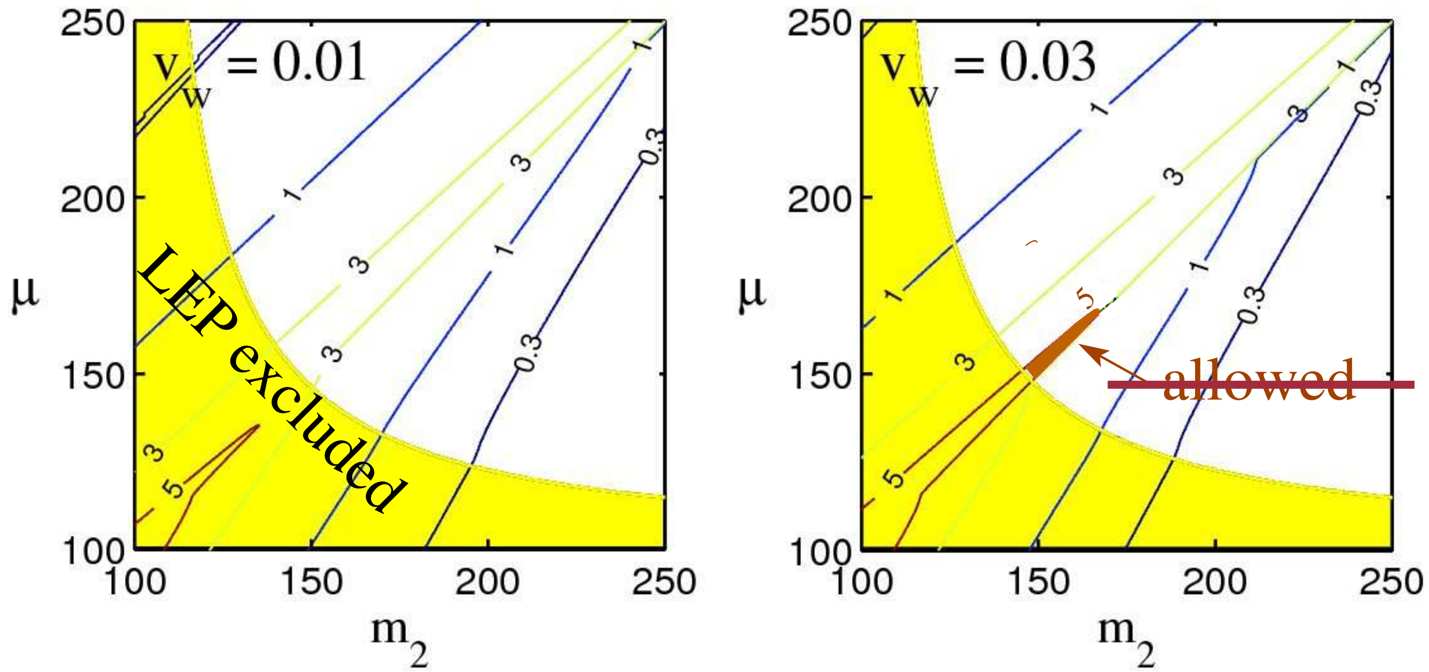

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However, there are differences (in the evaluation of the source) in the literature:

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]

Stop transport:

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

Neutralino transport:

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

Does it work? (Not likely)

Singlet model and BAU

BAU from top transport

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

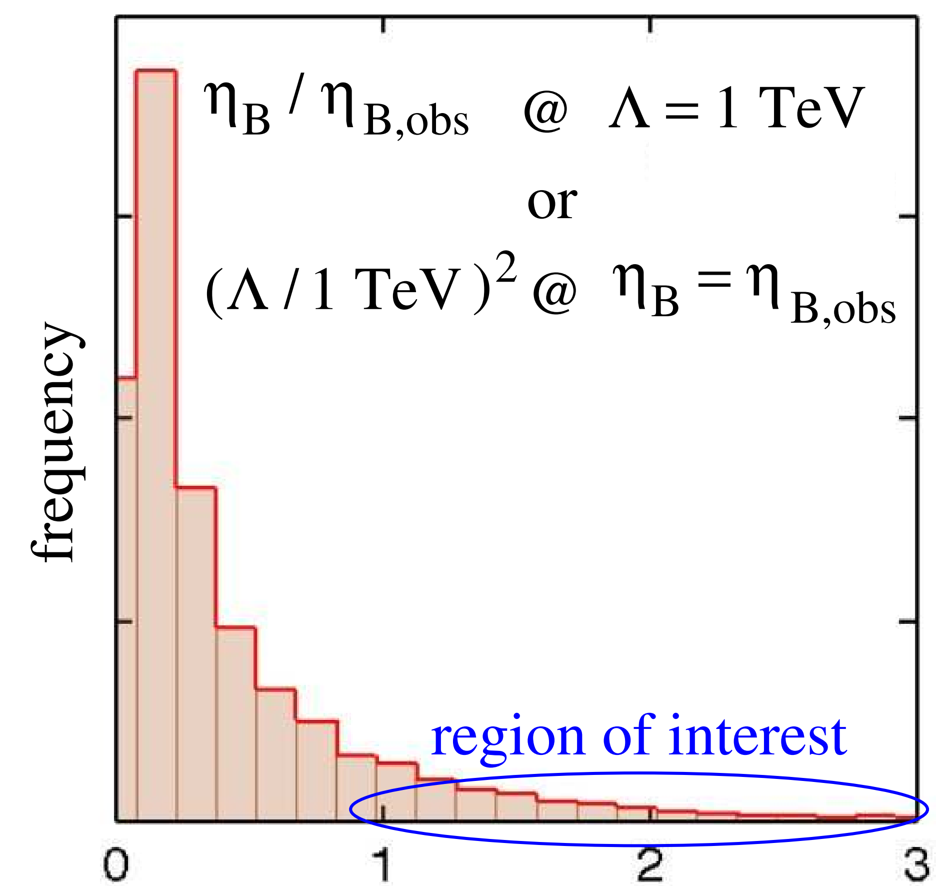
Source of CP violation Dim-6 operator
(If not DM could take Dim-5 as well) Espinosa, etal

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

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

2 singlets + CP-source: DM & BAU

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



Singlet model and BAU

BAU from top transport

However, there goes the UV-completion

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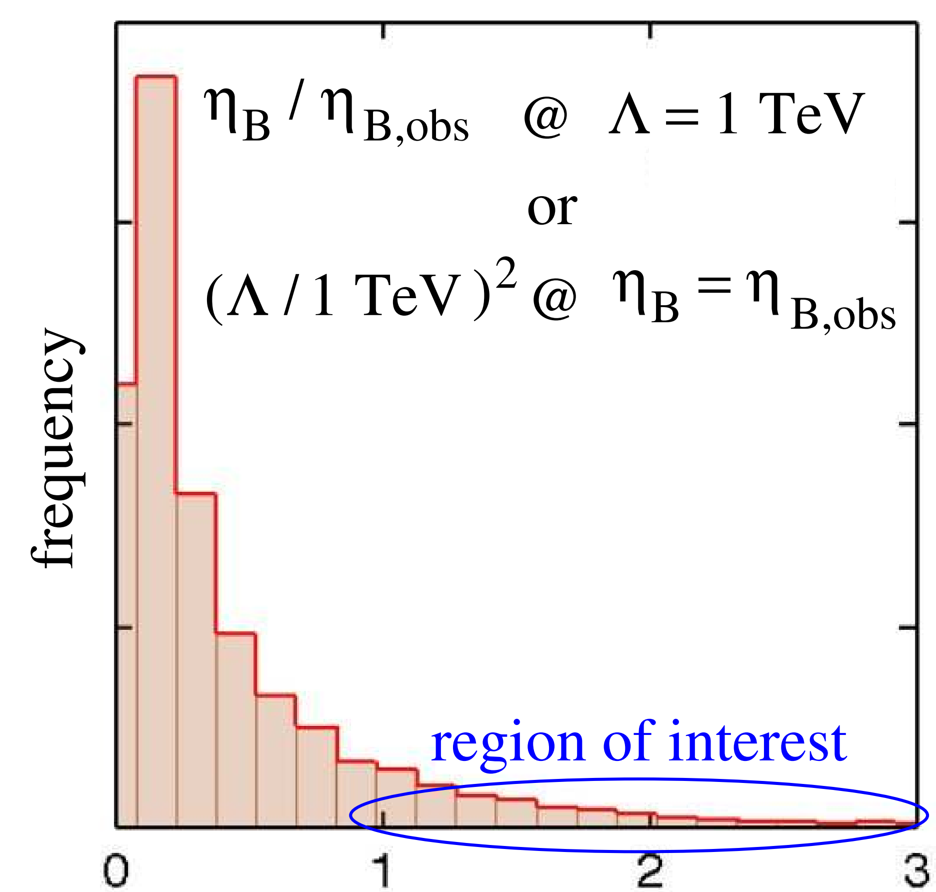
J.M. Cline, KK, JCAP 1301 (2013) 012



Pure 2HD models (at least renormalizable...)

Full GL(2,C)-reparametrization invariant potential

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

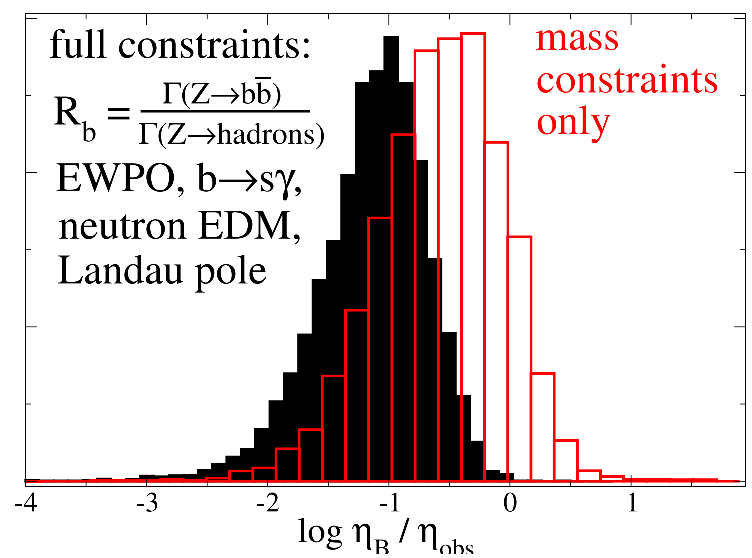
$$V = \frac{\lambda}{4}\left(H^{\dagger\, i} H_i - \frac{v^2}{2}\right)^2 + m_1^2\,(S^{\dagger i}\, S_i) + (m_2^2\, H^{\dagger\, i} S_i + \text{h.c.}),$$
$$+\lambda_1\,(H^{\dagger\, i} H_i)\,(S^{\dagger\, j} S_j), +\lambda_2\,(H^{\dagger i}\, H_j)\,(S^{\dagger j}\, S_i) + \left[\lambda_3 H^{\dagger i}\,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

MFV to avoid **FCNC**

G.C.Branco, W.Grimus & L.Lavoura, PLB380 (1996) 119

Strong EWPT and large BAU points were rare then: **<1/10⁴**.

Another scan of 2HDM's employing **Z_2-symmetries**:
Dorsch, Huber, No, JHEP 1310 (2013) 029



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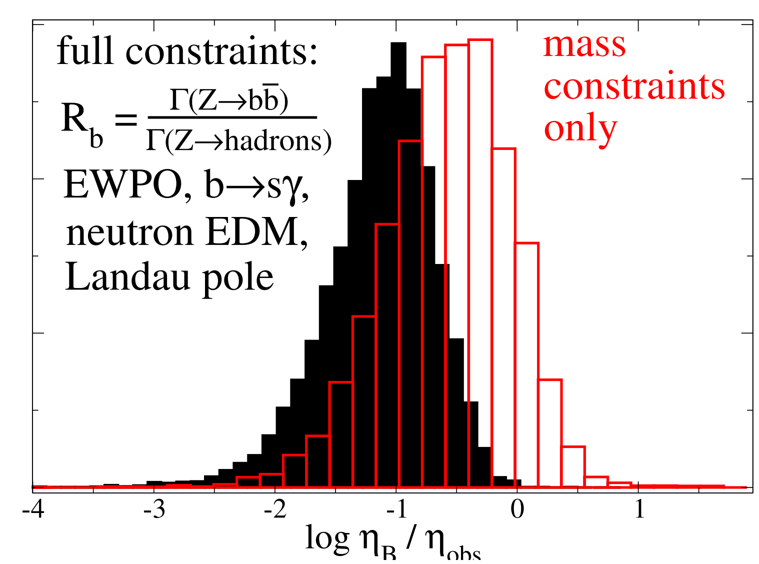

Strongest bounds always from EDM's, so ACME killed these models

Generic issue:

Strong transition > large $|\lambda_i\text{'s}|$
Large B > large phases

-> large EDM's

Need to add something to alleviate burden on 2HDM λ_i's

2HD+S model: ~~CP~~ from 2HDM - strength from S

Scalar sector:

$$\mathcal{L}_{\rm scalar} = Z^{ij}(D^\mu H_i)^\dagger D_\mu H_j + \frac{1}{2}(\partial_\mu S)^2 - V(H_1, H_2)_{\rm 2HDM}$$
$$-\Big[\ \tfrac{1}{4}\lambda_S S^4 + \tfrac{1}{2}\lambda_{S1}S^2|H_1|^2 + \tfrac{1}{2}\lambda_{S2}S^2|H_2|^2 + \Big(\tfrac{1}{2}\lambda_{S12}S^2 H_2^\dagger H_1 + \ \text{h.c.}\Big)\ \Big]$$

Fermions: Universal ($C_i^a \equiv C_i$) **Yukawa alignment** => No FCNC's

$$\mathcal{L}_{\rm Yukawa} = y_u C_u^i \bar{Q}_{\rm L}\tilde{H}_i u_{\rm R} + y_d C_d^i \bar{Q}_{\rm L} H_i d_{\rm R} + y_\ell C_\ell^i L_{\rm L} H_i e_{\rm R} + \text{h.c}$$

consistent with GL(2,C)-invariance

$$C_1^i \to 0$$
$$C_2^i \to 1$$

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consistent with GL(2,C)-invariance

$C_1^i \to 0$

$C_2^i \to 1$

Use GL(2,C)-invariance to construct all bounded potentials

$$Z^{ij}(D^\mu H_i)^\dagger D_\mu H_j \overset{\text{dilatations}}{\rightarrow} |D_\mu H_1|^2 + |D_\mu H_2|^2$$

Remaining SL(2,C)-invariant, bounded potential:

$$V = -\tfrac{1}{2}m_S^2 S^2 - \tfrac{1}{2}M_\mu^2 r^\mu + \tfrac{1}{4}r^\mu\lambda_{\mu\nu}r^\nu + \tfrac{1}{4}\lambda_{S\mu}r^\mu S^2 + \tfrac{1}{4}\lambda_S S^4$$

where (SO(1,3)$^+$-transformation)

$$\lambda_{\mu\nu} \equiv \Lambda_\mu{}^\alpha \lambda^D_{\alpha\beta}\Lambda^\beta{}_\nu \quad \text{and} \quad \lambda_S^\mu \equiv \Lambda^\mu{}_\nu(\lambda_S^D)^\nu$$
$$\lambda^D_{\alpha\beta} = \mathrm{diag}(\lambda^D_{00}, -\lambda^D_{11}, -\lambda^D_{22}, -\lambda^D_{33}), \quad \text{with} \quad \lambda^D_{00} > 0 \quad \text{and} \quad \lambda^D_{00} > \lambda^D_{ii}$$

I.P.Ivanov, PRD75 (2007) 035001)

Span LC$^+$

$$r^\mu \equiv \Phi^\dagger\sigma^\mu\Phi\,, \quad \text{where} \quad \sigma^\mu = (1,\sigma_i)$$
$$\Phi \equiv (H_1, H_2)^T$$

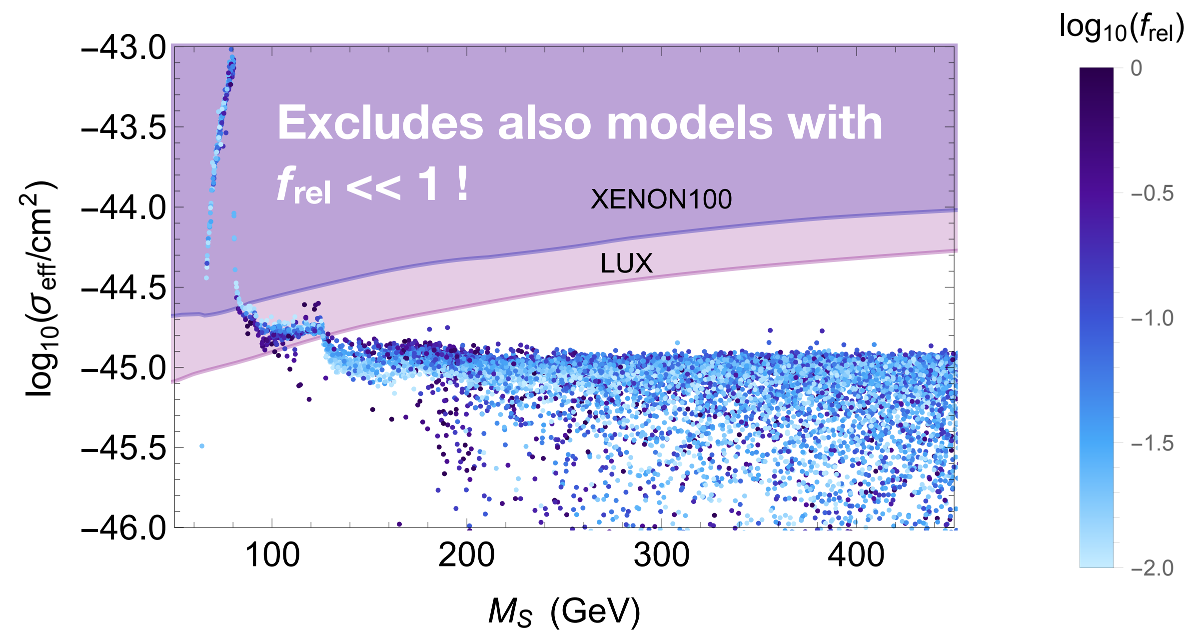
$$M_\mu^2 \equiv \left(m_1^2 + m_2^2,\, 2m_{12R}^2,\, -2m_{12I}^2,\, m_1^2 - m_2^2\right)\,,$$
$$\lambda_{S\mu} \equiv (\lambda_{S1}+\lambda_{S2},\, 2\lambda_{S12R},\, -2\lambda_{S12I},\, \lambda_{S1}-\lambda_{S2})$$

$$\lambda_{\mu\nu} \equiv \begin{pmatrix} \lambda_1+\lambda_2+\lambda_3 & \lambda_{6R}+\lambda_{7R} & -\lambda_{6I}+\lambda_{7I} & \lambda_1-\lambda_2 \\ \lambda_{6R}+\lambda_{7R} & \lambda_4+2\lambda_{5R} & -2\lambda_{5I} & \lambda_{6R}-\lambda_{7R} \\ -\lambda_{6I}+\lambda_{7I} & -2\lambda_{5I} & \lambda_4-2\lambda_{5R} & -\lambda_{6I}-\lambda_{7I} \\ \lambda_1-\lambda_2 & \lambda_{6R}-\lambda_{7R} & -\lambda_{6I}-\lambda_{7I} & \lambda_1+\lambda_2-\lambda_3 \end{pmatrix}$$

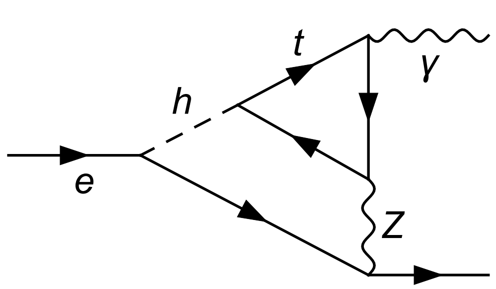
2HD+S model: CP from 2HDM - strength from S

Go through the usual excercices:

- Accelerator constraints
- EWP-data
- EDM's (electron, ACME)
- Perturbatiivity up to 1.5 TeV
- LUX-limits
- Strong transition (subleading DM)

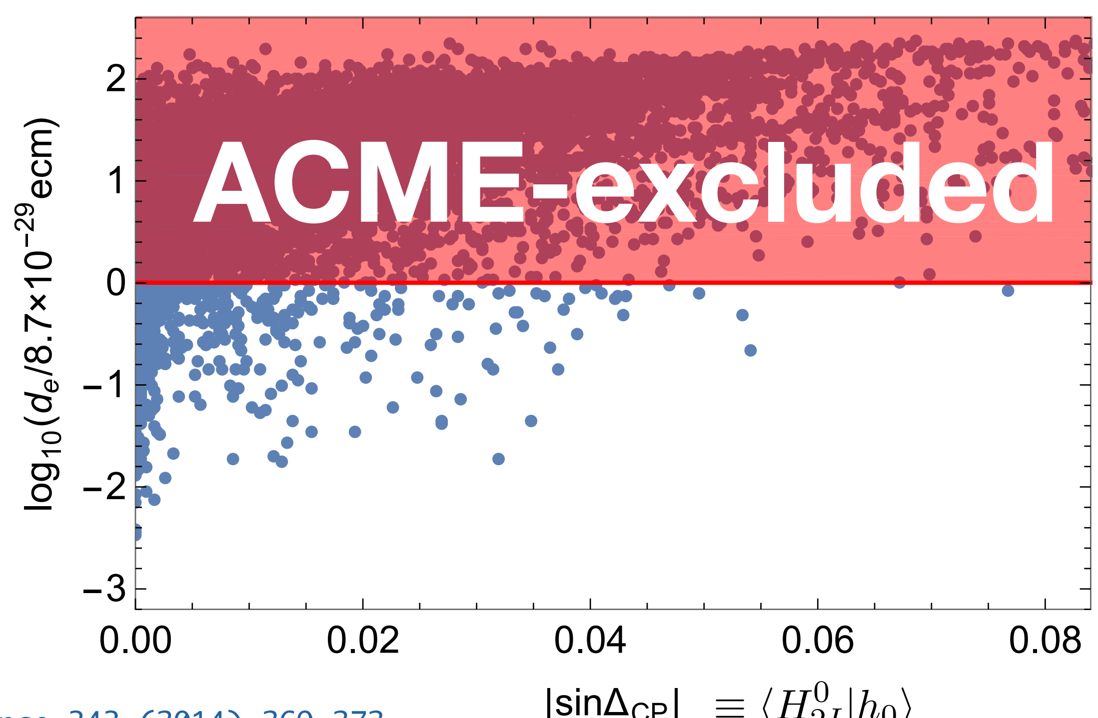


Only loop corrections: $$m_a^2(T) = -m_a^2 + c_a \frac{T^2}{12}$$



A diagram contributing to e-EDM:

$$d_e = d_t^{h\gamma\gamma} + d_t^{hZ\gamma} + d_{W^\pm}^{h\gamma\gamma} + d_{W^\pm}^{hZ\gamma} + d_{H^\pm}^{h\gamma\gamma} + d_{H^\pm}^{hZ\gamma} + d^{H^\pm W^\mp \gamma} < 8.7 \times 10^{-29} \text{ecm},$$



ACME Collaboration, Science 343 (2014) 269–272

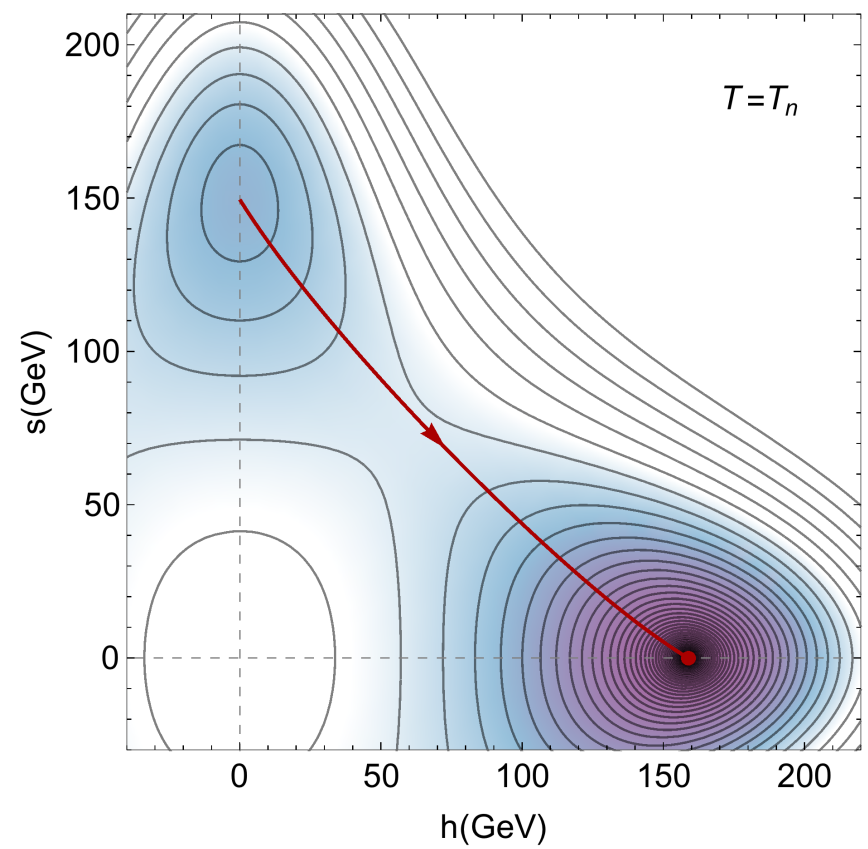
2HD+S model: EWBG source: top-transport

Minimize the Action (in Z=0-gauge) at $T=T_c$ => H_1, H_2, S and φ

$$S_1 = \int \mathrm{d}z \left(\sum_i \frac{1}{2}(\partial_z h_i)^2 + \frac{1}{2}(\partial_z S)^2 + \frac{1}{2}\frac{h_1^2 h_2^2}{h_1^2+h_2^2}(\partial_z \varphi)^2 + V(h_1,h_2,S,\varphi,T_c) \right)$$

relative phase between H_1 and H_2

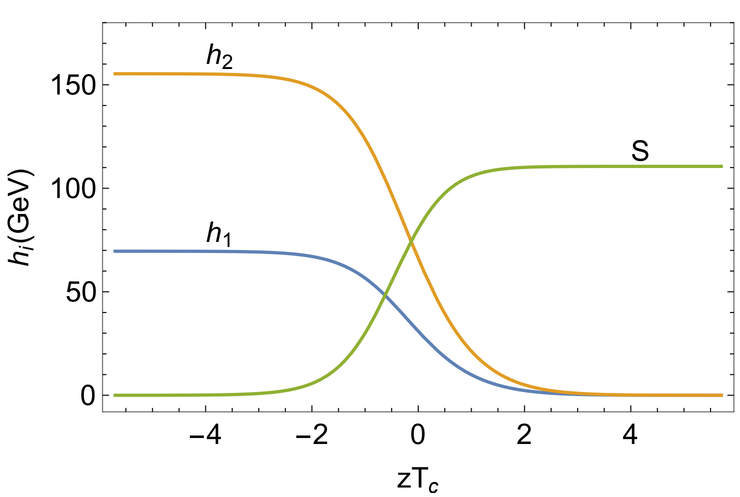
$$\partial_z \varphi_2 = -\frac{h_1^2}{h_1^2+h_2^2}\partial_z \varphi \quad \Rightarrow \quad m_t(z) = \frac{y_t}{\sqrt{2}} h_2(z) e^{i\varphi_2(z)}$$

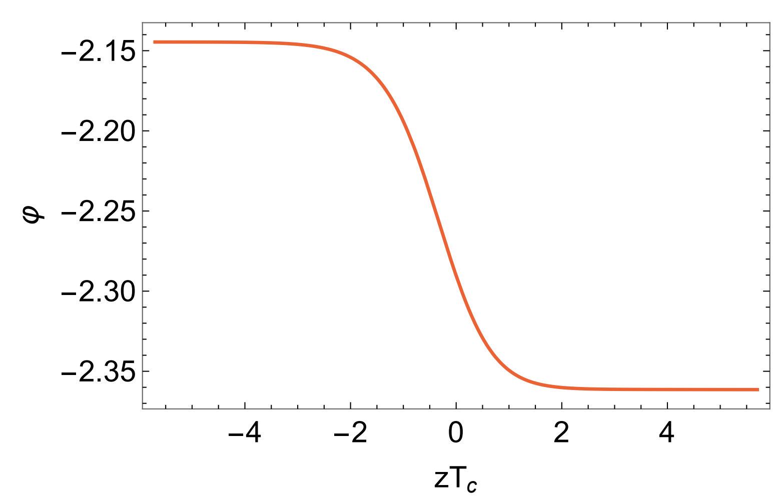


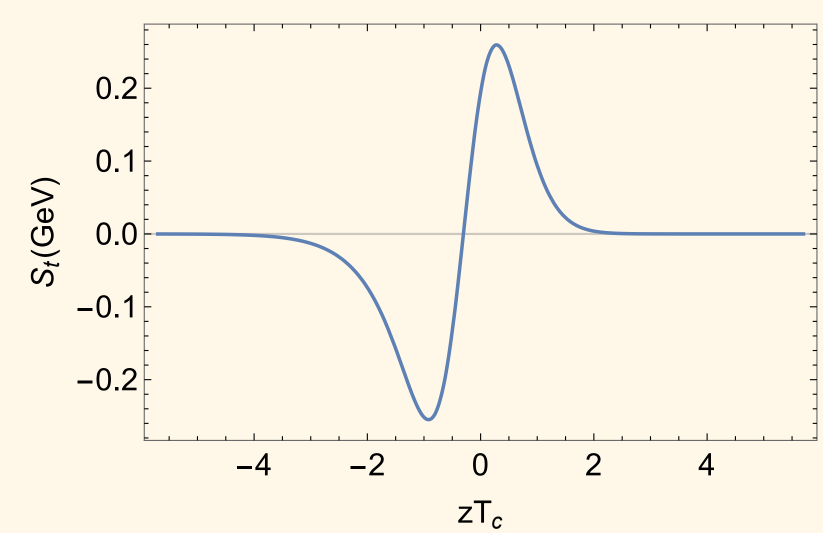
CP-violating SC-source ($x_t = m_t/T$):

wall velocity

$$S_t = \xi_w \left(K_{8,t}(x_t^2 \varphi_2')' - K_{9,t} x_t^2 x_t^{2\prime} \varphi_2' \right)$$





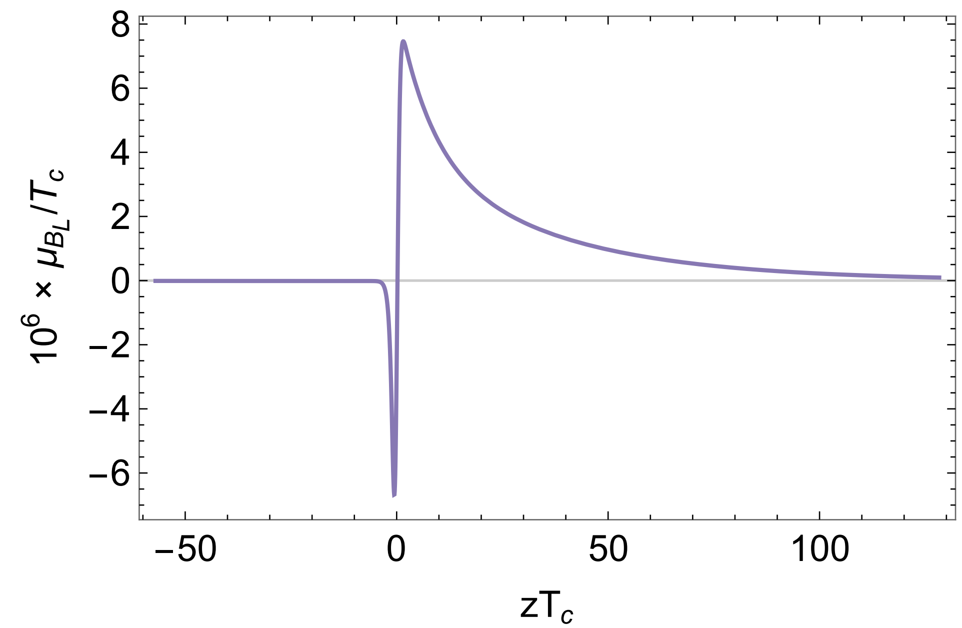


2HD+S model: Baryon asymmetry

Solve the diffusion equations:

$$\begin{aligned}\mu_{B_L} &= \mu_{q1,2} + \mu_{q2,2} + \frac{1}{2}(\mu_{t,2} + \mu_{b,2}) \\ &= \frac{1}{2}(1+4K_{1,t})\mu_{t,2} + \frac{1}{2}(1+4K_{1,b})\mu_{b,2} - 2K_{1,t}\mu_{t^c,2}\end{aligned}$$

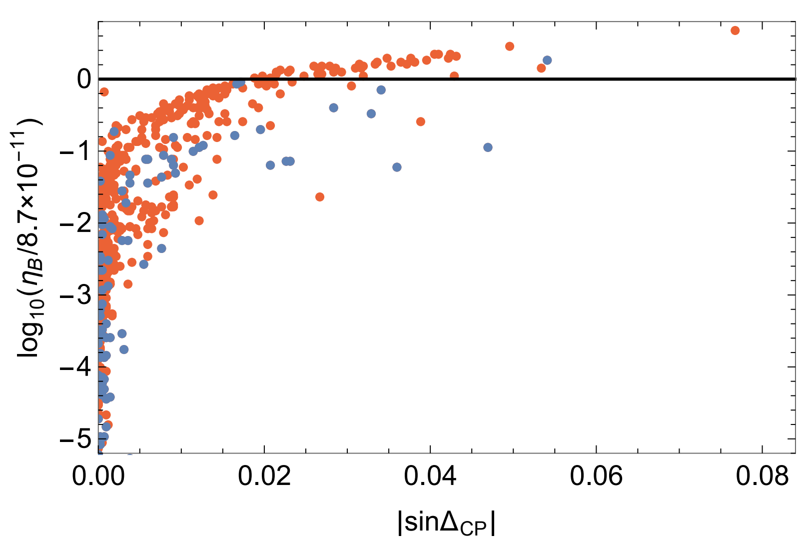
$$\eta_B = \frac{405}{4\pi^2 \xi_w g_* T_c}\int_0^\infty \mathrm{d}z\, \Gamma_{\rm sph}(z)\mu_{B_L}(z) e^{-45\Gamma_{\rm sph}(z)z/4\xi_w}$$

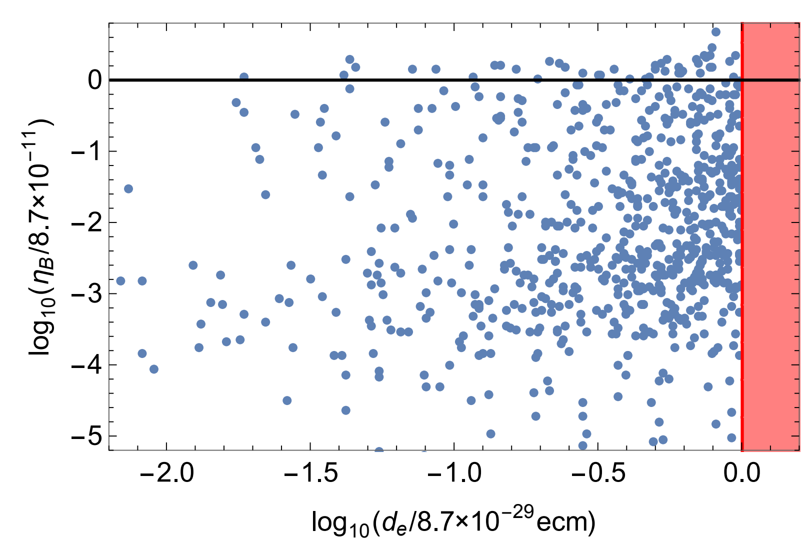


Models survive even with large η_B

Large η_B ~~correlates~~ with small d_e

Large η_B correlates with large ~~CP~~



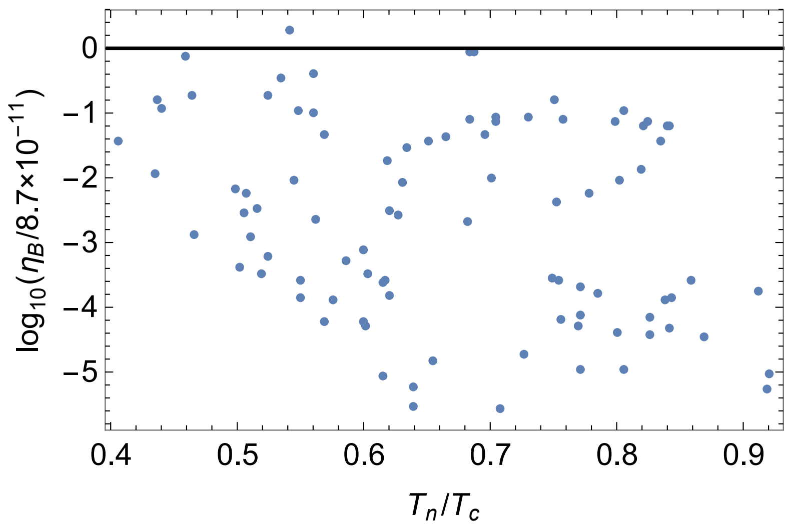


2HD+S model: Nucleation rate

Danger: unlike the cubic term the tree-level barrier does not disappear with decreasing T.

The bubble nucleation rate is:

$$\Gamma \sim T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left(-\frac{S_3(T)}{T}\right)$$



In thin wall limit:

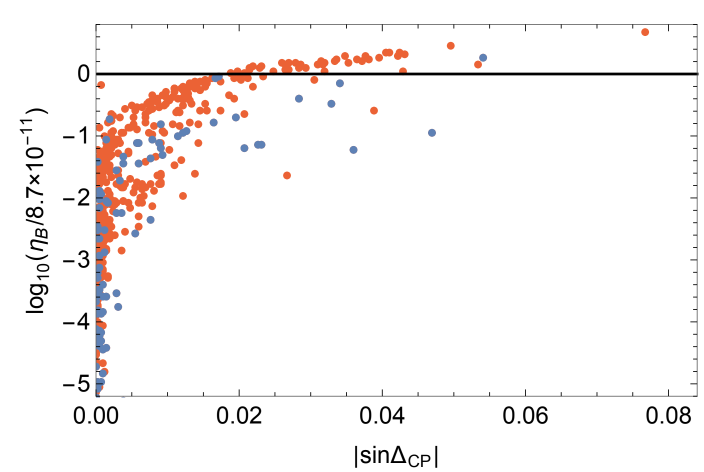
$$S_3(T) = \frac{16\pi}{3}\frac{\sigma^3}{\Delta V(T)^2} \qquad \sigma = \int d\phi \sqrt{2V}$$

Nucleation temperature ***($\Gamma = H(T_c)^4$)*****:**

$$\frac{S_3(T_n)}{T_n} = -\log\left(\frac{3}{4\pi}\left(\frac{H(T_n)}{T_n}\right)^4\left(\frac{2\pi T_n}{S_3(T_n)}\right)^{3/2}\right)$$

Problem:

- For most models, shown in red, **no T_n**
- Remaining ones are, or are in danger of being detonations



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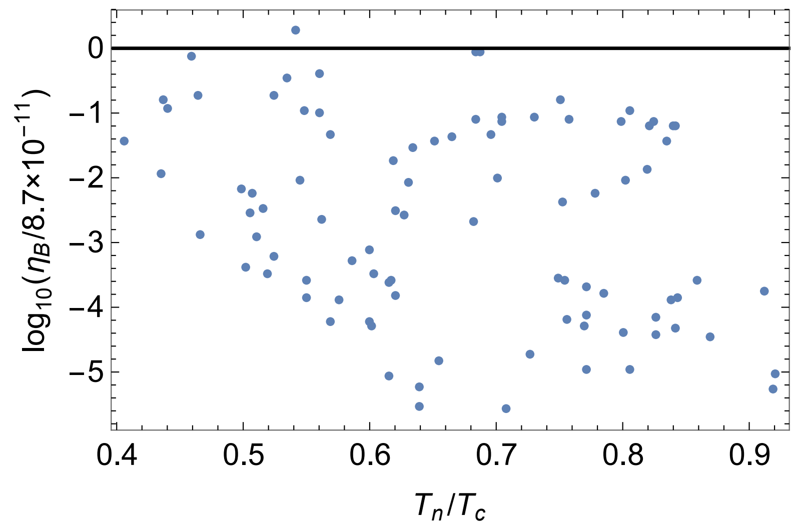

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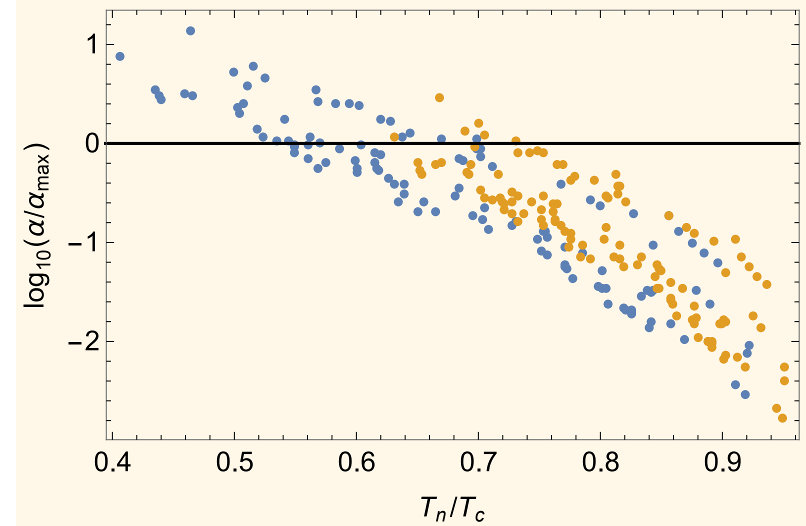

$$\alpha \equiv \frac{\Delta V(T_n)}{\rho(T_n)} < \frac{1}{3}(1-\xi_w)^{\frac{13}{10}} \equiv \alpha_{\max}$$

condition for deflagrations

Espinosa, Konstandin, No, Servant, JCAP 1006 (2010) 028;

Nucleation temperature $(\Gamma = H(T_c)^4)$**:**

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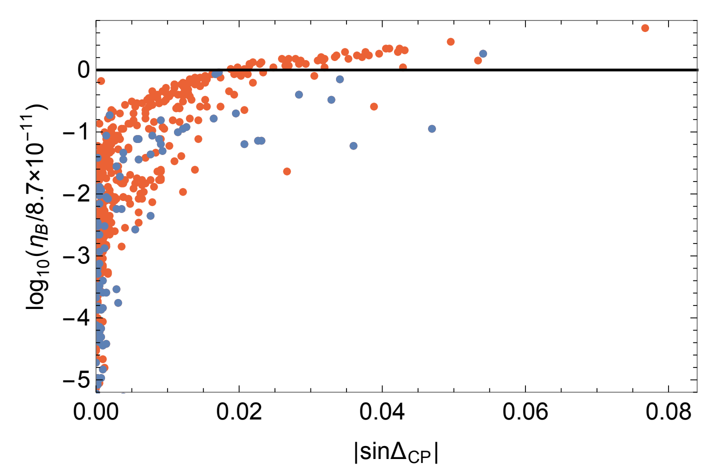


2HD+S model: fate of false vacuum, ameliorations

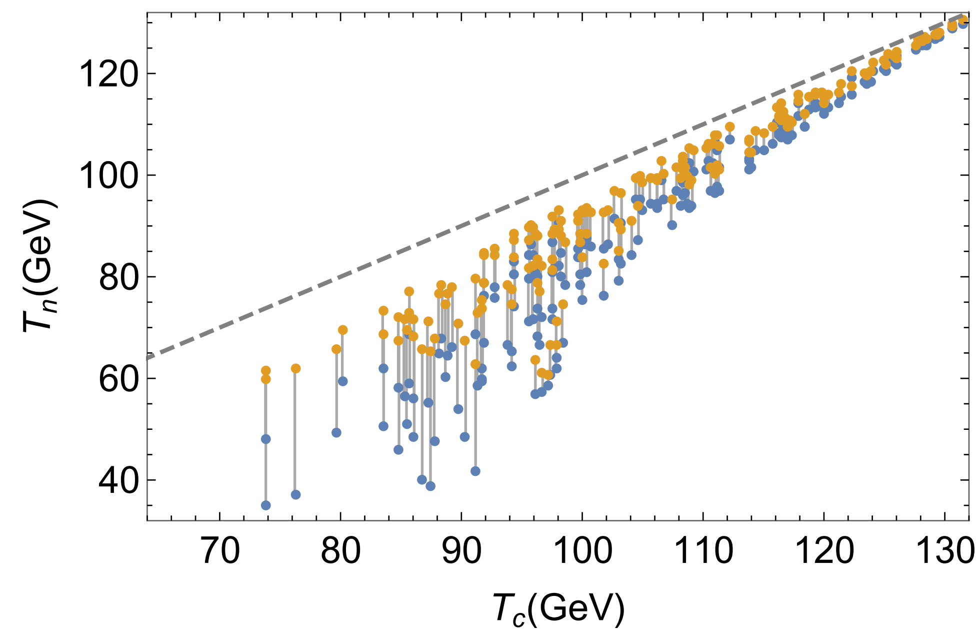
1. Thin wall limit underestimates decay rate,
but full solution of S_3 in 2HS+S-model hard

Solve exactly in SM + Singlet model

$$S_3(T) = 4\pi \int r^2 \mathrm{d}r \left(\frac{1}{2}\left(\frac{\mathrm{d}h}{\mathrm{d}r}\right)^2 + \frac{1}{2}\left(\frac{\mathrm{d}S}{\mathrm{d}r}\right)^2 + V_{\mathrm{SSM}}(h,S,T) \right)$$

Find: T_n systematically larger than in tw-case:

$$T_n = T_c + \kappa\,(T_c - T_n^{\mathrm{tw}}) \qquad \kappa \approx 0.7$$



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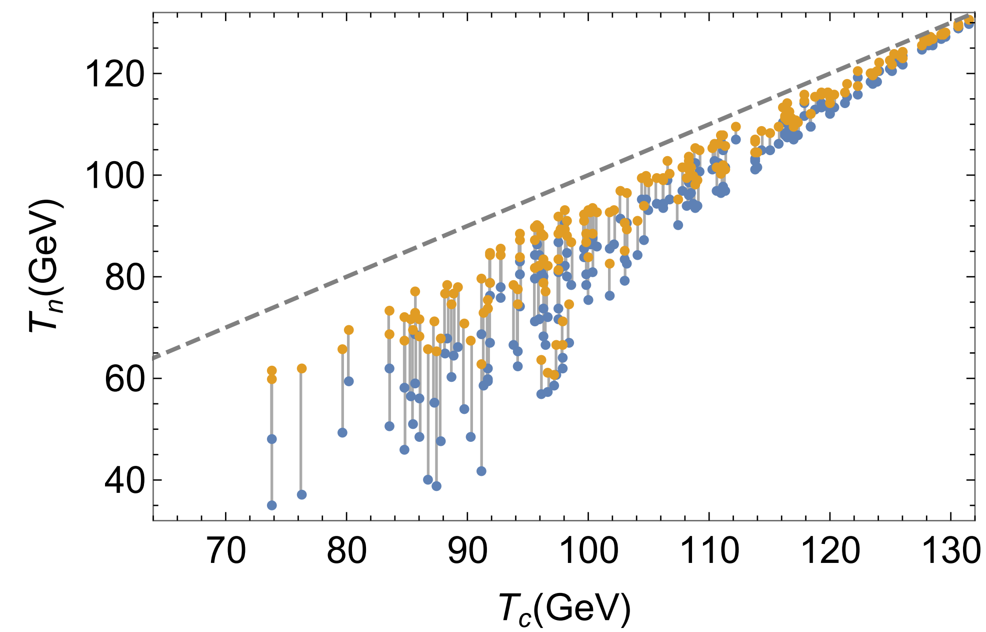


Solve exactly in SM + Singlet model

$$S_3(T) = 4\pi \int r^2 \mathrm{d}r \left(\frac{1}{2} \left(\frac{\mathrm{d}h}{\mathrm{d}r} \right)^2 + \frac{1}{2} \left(\frac{\mathrm{d}S}{\mathrm{d}r} \right)^2 + V_{\mathrm{SSM}}(h, S, T) \right)$$

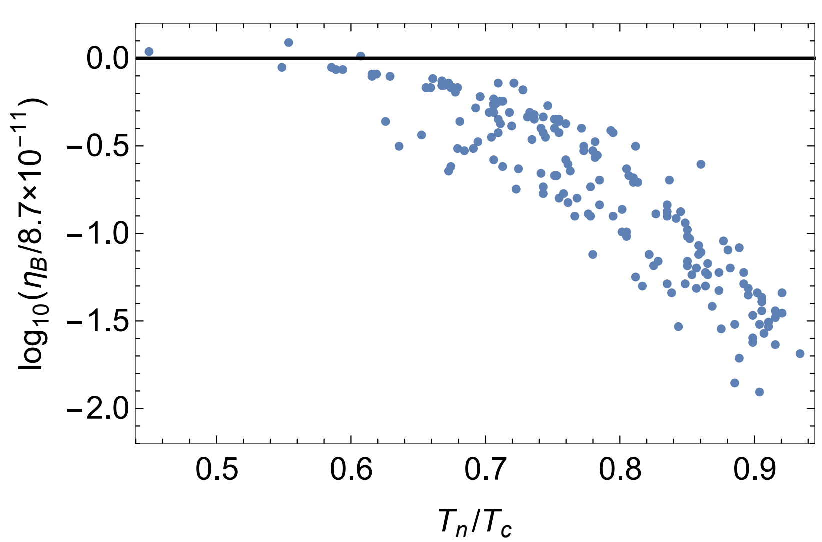
Find: T_n systematically larger than in tw-case:

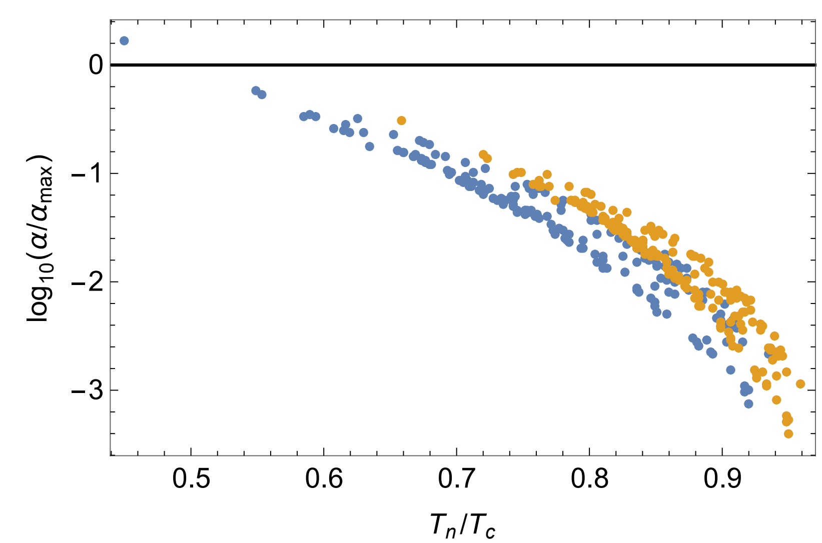
$$T_n = T_c + \kappa \left(T_c - T_n^{\mathrm{tw}} \right) \qquad \kappa \approx 0.7$$

2. Tune fore models with large T_c (> 80 GeV)

Find: situation less severe.

So, … ***maybe*.**





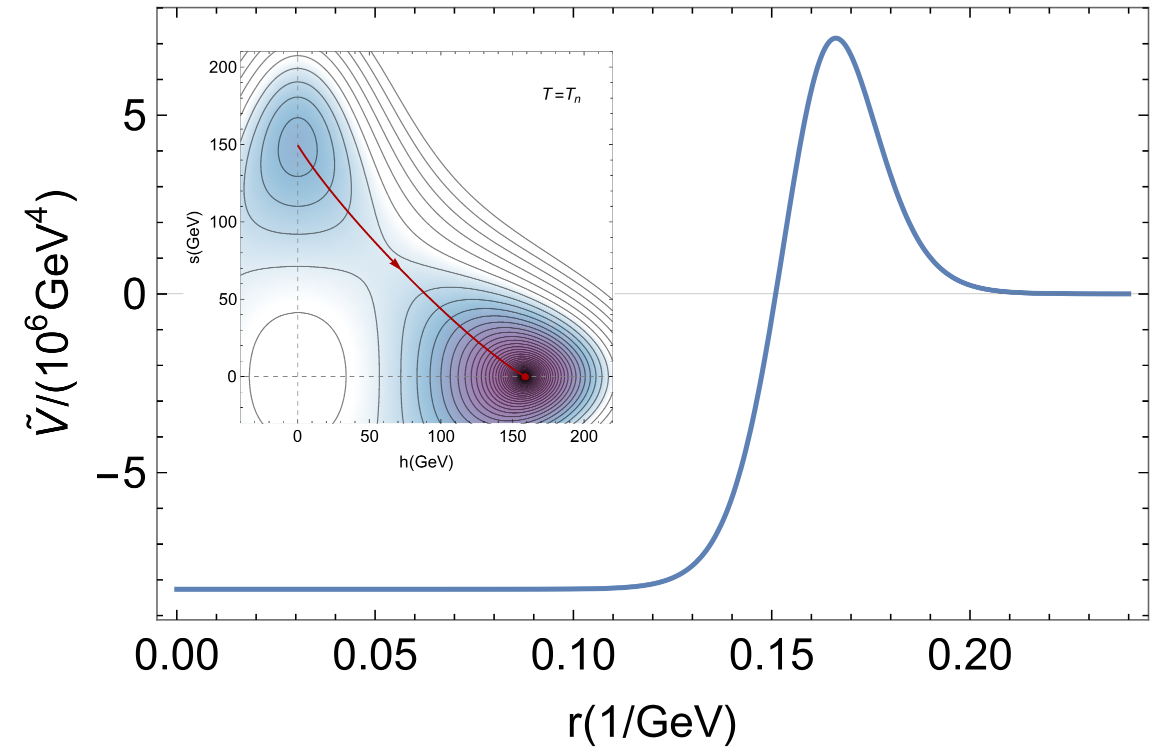
2HDM+S, summary

Generic issue: **2-step transition tends to be "too strong": *bubble nucleation* delayed: $T_n << T_c$.**

`also: Profumo etal, Phys.Rev. D91 (2015) no.3, 035018`

- 😟 Cannot trust B-calculation (that assumes $T=T_c$ bounce), but error presumably not very large (~O(2)).

- 😟 Cannot be sure if walls are deflagrations. Should be studied in detail (dynamical wall with friction). Hard.



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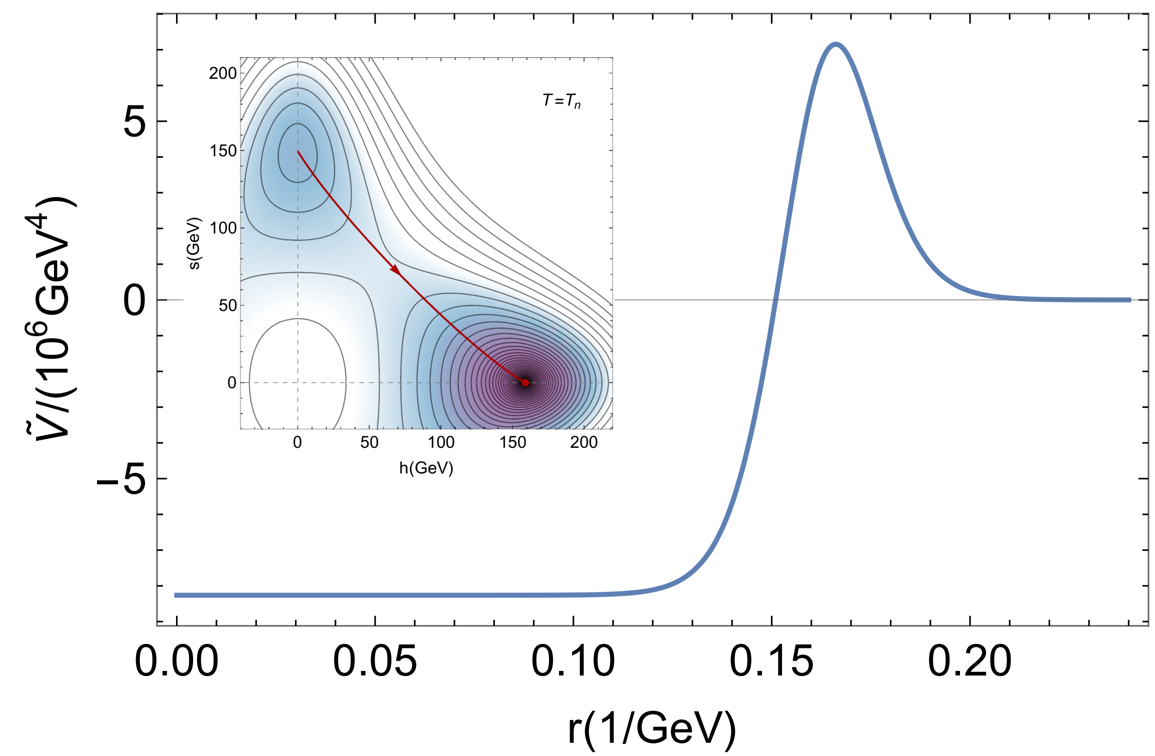

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Because of generic low energy Landau poles* 2HD-models no better than singlet model with Dim N>4 operators.**
- No UV-completion => solving BAU recreates need for BSM
- Problem is with the CP-violation

* Out of 10000 models in our final scan, ten survived to 10 TeV and none to 100 TeV.

**Unless embedded in an UV-complete setup, such as the NMSSM Demidov, Gorbunov, Kiripichnikov, arXiv:1608.01985v1

Conclusions

"Simple and yet complete" an interesting paradigm to follow

Unification and Hieararchy Problem not necessarily relevant

Some aspects are easily realized with help of singlets

DM
Strong EWPT

EWBG challenging due to need for new CP-violation

EWBG is *maybe* in 2HD+S model, but not UV-complete (NMSSM?)

Maybe some alternatives fit better into completenes scheme:

Leptogenesis (but beware of hierarchy problem)
Akhmedov-Rubakov-Smirnov mechanism
nuMSM