Electroweak Baryogenesis

Kimmo Kainulainen,

- 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.
**Baryon asymmetry**

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**BICEP2:**

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

Fair amount of room to play. **EWBG == BG at EWPT,** at \( T \approx 100 \text{ GeV}, \) is the **lowest energy scale model**
EWBG in a nutshell

\begin{align*}
H & \sim 10^{-14} T_{100}^2 \text{GeV} \\
\Gamma & \sim 10^{-5} T_{100} \text{GeV}
\end{align*}
EWBG in a nutshell

**1st order PT:** at $T_c \sim 100$ GeV, true vacuum bubbles, $\langle H \rangle \neq 0$, form and start expanding into the false symmetric vacuum.

\[
V_{\text{eff}} = \frac{1}{2}(-\mu^2 + cT^2)\phi^2 - T\delta\phi^3 + \frac{1}{4}\lambda_{\text{eff}}\phi^4
\]
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Particles interact with wall in CP violating way

$$V_{\text{eff}} = \frac{1}{2}(-\mu^2 + cT^2)\phi^2 - T\delta \phi^3 + \frac{1}{4}\lambda_{\text{eff}} \phi^4$$
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Baryon asymmetry forms inside the bubble

![Diagram of Veff](image)

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**IN MSM:**

- Only **B-violation** (by sphalerons) is certainly present in the SM.
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IN MSM:

- Only \textbf{B-violation} (by sphalerons) is certainly present in the SM.
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- 1st order PT, \textbf{not} 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
**EWPT in SM**, no jump in the order parameter

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Whereas for **EWBG** to work, we need a large jump in the order parameter (strong transition):

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

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

![Graph showing $v^2(T) = \langle H^2 \rangle (T)$]
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**Beyond SM:** MSSM, NMSSM, 2HDM, NHDM, IHDM, SSM,...
Most efforts have been put to increase the effective cubic coupling by loop corrections.

Need new light bosonic fields strongly coupled to Higgs:

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

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=> Light Stop Scenario in the MSSM and NMSSM

[Carena, Quiros, Wagner (1996), ...]
**EWBG with new loop corrections, MSSM**

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Need new **light bosonic** fields strongly coupled to Higgs

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\[ \Rightarrow \text{Light Stop Scenario} \quad \text{in the MSSM and NMSSM} \]

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

**However**, also Higgs mass mostly from

\[ m_h \sim C \log \frac{m_{i_L} m_{i_R}}{M_w^2} \]
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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

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

M. Carena, G. Nardini, M. Quiros & C. Wagner, NPB812 (2013) 243

\[ m_Q \leq 10^6 \text{ TeV} \]
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However, there is a recent lattice study:

Rummukainen Nardini and Laine ...

\[
\left( \frac{v}{T_c} \right)_{\text{latt}} = 1.117(5) \quad \left( \frac{v}{T_c} \right)_{\text{Landau}} = 0.9
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\[ m_{\tilde{t}} \approx 155 \text{ GeV} \]

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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)

- 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.)


Similar results were found by


who also used SC method
MSSM, EDM constraints, *charginos*

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

![Electron EDM](image1)

![Neutron EDM](image2)

Ref. point: \(M_1 = 95\text{GeV}\)

\[|\mu| = 200\text{GeV},\]

\[\tan\beta = 10,\]

\[m_{\tilde{\chi}^0} = 300\text{GeV}\]

Y.Li, S.Profumo, and M.Ramsey-Musolf, PLB673 (2009) 95–100,
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2013 ACME-bound: \( d_e < 8.9 \times 10^{-29} \) \( \Rightarrow \quad \phi_{M_2} < 10^{-3}\)

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.

2013 ACME-bound

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:

\[
V = \frac{\lambda}{4} \left( H^\dagger_i H_i - \frac{v^2}{2} \right)^2 + m^2_i (S^\dagger_i S_i) + (m^2_i H^\dagger_i S_i + \text{h.c.}),
\]

\[
+ \lambda_1 (H^\dagger_i H_i) (S^\dagger_j S_j), + \lambda_2 (H^\dagger_i H_j) (S^\dagger_j S_i) + \left[ \lambda_3 H^\dagger_i H^\dagger_j S_i S_j + \text{h.c.} \right],
\]

\[
+ \left[ \lambda_4 H^\dagger_i S^\dagger_j S_i S_j + \lambda_5 S^\dagger_i H^\dagger_j H_i H_j + \text{h.c.} \right] + \lambda_6 (S^\dagger_i S_i)^2,
\]

\[
+ y_t \bar{t}_L (H^0 \delta_i + (\eta_U \delta t + \eta_U' V^*_t V_{bi})) S^0_i q^i_R
\]
Other possibilities, 2HDM, NHDM, IHDM, ...

2HDM:

\[
V = \frac{\lambda}{4} \left( H^\dagger_i H_i - \frac{v^2}{2} \right)^2 + m_1^2 (S^\dagger_i S_i) + (m_2^2 H^\dagger_i S_i + \text{h.c.}),
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\]

\[
+ y_{tL} \left( H^{0*} \delta_{ti} + (\eta_U \delta_{ti} + \eta'_{U} V^{*}_{tb} V_{bi}) \right) S^{0*} q_R^i.
\]

Many new CP-violating phases
Other possibilities, 2HDM, NHDM, IHDM, ...

2HDM:

\[ V = \frac{\lambda}{4} \left( H_{i}^{\dagger} H_{i} - \frac{v^{2}}{2} \right)^{2} + m_{1}^{2} (S_{i}^{\dagger} S_{i}) + (m_{2}^{2} H_{i}^{\dagger} S_{i} + \text{h.c.}) , \]

\[ + \lambda_{1} (H_{i}^{\dagger} H_{i}) (S_{j}^{\dagger} S_{j}) , + \lambda_{2} (H_{i}^{\dagger} H_{j}) (S_{j}^{\dagger} S_{i}) + \left[ \lambda_{3} (H_{i}^{\dagger} H_{j}^{\dagger} S_{i} S_{j} + \text{h.c.}) , \right] , \]

\[ + \left[ \lambda_{4} H_{i}^{\dagger} S_{i}^{\dagger} S_{j} + \lambda_{5} S_{i}^{\dagger} H_{j}^{\dagger} H_{i} H_{j} + \text{h.c.} \right] + \lambda_{6} (S_{i}^{\dagger} S_{i})^{2} , \]

\[ + y_{t} t_{L} (H_{0}^{0*} \delta_{ti} + (\eta_{U} t_{i}^{*} + \eta_{U}^{t} b_{i} V_{bi})) S_{0}^{0*} q_{R}^{i} \]

Many new CP-violating phases

**MFV** for new Yukawa’s to avoid **FCNC**

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\[ V = \frac{\lambda}{4} \left( H_i^\dagger H_j - \frac{v^2}{2} \right)^2 + m_1^2 (S_i^\dagger S_i) + (m_2^2 H_i^\dagger S_i + h.c.), \]

\[ + \lambda_1 (H_i^\dagger H_j) (S_j^\dagger S_j) + \lambda_2 (H_i^\dagger H_j) (S_i^\dagger S_i) + \left[ \lambda_3 H_i^\dagger H_j S_i S_j + h.c. \right], \]

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\[ + y_t \tilde{t}_L (H_0^* \delta_{ti} + (\eta^L_{ti} \tilde{t}_i + \eta^R_{tb} V_{bi}) S_0^* q_R^i. \]

Many new CP-violating phases

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Comprehensive MCMC of the PM-space finds both strong EWPT and BAU, but points are rare: \(<1/10^4\).

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

![Histogram showing mass constraints and full constraints](image)
Other possibilities, 2HDM, NHDM, IHDM, ...

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

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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!

\[ V = V_{\text{MSM}} + \frac{1}{2} \mu_S^2 S^2 + \frac{1}{2} \lambda_{sh} S^2 |H|^2 + \frac{1}{4} \lambda_S S^4 \quad (\mu_S^2 < 0) \]

If \( \lambda_{hs} \) is large enough, there is a barrier between \( H = 0 \) and \( S = 0 \) vacua at \( T = 0 \).

Transition can proceed in **two steps**, \( 0 \rightarrow S \rightarrow H \), and model can give a potential barrier at **tree-level** → strong phase transition.

J.R.Espinosa, T.Konstandin, F.Riva, NPB854 (2012) 592
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Get easily models satisfying \( v/T > 1 \)-limit with large enough lambda.

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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:

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\langle \nu \sigma_{\text{DM}} \rangle \sim \lambda_{sh}^2
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Singlet model: BAU and DM (in form of singlet S)?

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

Large enough $\lambda_{hs}$ gives subdominant DM

BAU acceptable $\frac{v}{T} > 1$ models

Figure 4: Distributions of parameters satisfying the constraints $k_{uq8}$ and the nominal $k_{uq9}$ and $k_{vqt}$ and the nominal $k_{wqy}$. Top row shows input parameters, bottom two rows are derived. Dimensionful quantities are in GeV units and varied over the ranges $m_s = t$ to $v_0 / v_c = t$. Log $10$ $v_c / w_c \Rightarrow k_t$, $t_l$ produces models consistent with the constraint $k_{wqy}$ as well as with the sphaleron washout bound $k_{uq9}$ and the consistency requirement $k_{uq8}$ and the invisible Higgs decay width $k_{vqt}$ of previous sections. Distributions of various parameters in this set of models can be seen in figure $w$. One observes that the DM mass is typically in the range $8s_{tys}$ GeV for our choice $m < t$. Figure $u$ illustrates that higher masses are correlated with larger values of $m$. $v_c$ values fall in the range $tw_s$ GeV and as $T_c$ tends to be around $ts_s$ GeV, strong phase transitions are found with $v_c / T_c$ as high as $v$. $x$. The $w_c$ distribution peaks at $w_c \sim tys$ GeV with $w_c < xss$ GeV and the relic density fraction $f_{rel}$ tends to be $st$. $s$. $st$ We show the scatter plot of accepted models in $f_{rel}$ versus $m_S$ in figure $u$ and the same data in figure $x$ as $m_S$ versus $\cdot e \cdot f_{rel} \cdot SI$. $q$ The cross section $\cdot e$ indicates the reach of the future XENON experiments to rule out a given model or to verify the existence of its associated DM particle. All direct DM bounds inevitably suffer from uncertainties in the local Galactic abundance and velocity distribution of the DM. We estimate the effect of these uncertainties on the latest XENONtss constraint following ref $[8v]$, which shows that the constraint derived from standard assumptions about the local DM distribution could.
Singlet model: **BAU and DM** (in form of singlet $S$)?

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

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

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

**Figure 4**: Distributions of parameters satisfying the constraints $k_u < k_\text{q8}$ and the nominal DM direct detection bound $k_w$. Top row shows input parameters, bottom two rows are derived. Dimensionful quantities are in GeV units varied over the ranges $m = s_t$ to $v_0/v_c = t_s$. $\lambda_{hs}$ produces $uuxss$ models consistent with the constraint $k_w$ as well as with the sphaleron washout bound $k_\text{q9}$ and the consistency requirement $k_8$ and the invisible Higgs decay width $k_\nu$. Distributions of various parameters in this set of models can be seen in figure $wq$. One observes that the DM mass is typically in the range $8s_t y GeV$ for our choice $m < t$. Figure $u_8$ illustrates that higher masses are correlated with larger values of $m$. $v_c$ values fall in the range $tw_s GeV$ and as $T_c$ tends to be around $ts_s GeV$ strong phase transitions are found with $v_c/T_c$ as high as $v_x$. The $w_c$ distribution peaks at $w_c ^\ast y GeV$ with $w_c < xss GeV$ and the relic density fraction $f_{\text{rel}}$ tends to be $s$. $stq$ We show the scatter plot of accepted models in $f_{\text{rel}}$ versus $m_S$ in figure $u$ and the same data in figure $x$ as $m_S$ versus $\nu e f_{\text{rel}} e_{\text{SI}} q$ The cross section $\nu e$ indicates the reach of the future XENON experiments to rule out a given model or to verify the existence of its associated DM particle. All direct DM bounds inevitably suffer from uncertainties in the local Galactic abundance and velocity distribution of the DM. We estimate the effect of these uncertainties on the latest XENONts constraint following ref $[8v]$.o which shows that the constraint derived from standard assumptions about the local DM distribution could

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*J.M. Cline, KK, JCAP 1301 (2013) 012*
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Recent LUX bound has all but excluded the **BAU-compatible** pm-space

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Singlet model: BAU or DM, ... extensions?

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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J.M.Cline, K.Kainulainen, P.Scott and C.Weniger, arXiv:1306.4710
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LHC bound on $h \rightarrow SS$ kills a lot of the former

J.M. Cline, K. Kainulainen, P. Scott and C. Weniger, arXiv:1306.4710
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**LHC bound on $h \to SS$**
Kills a lot of the former

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.

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

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

EWBG continues to be interesting albeit ever more constrained by LHC and other lab data
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Essentially all constraints come from *indirect* (loop) effects
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EWBG continues to be interesting albeit ever more constrained by LHC and other lab data.

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 or DM possible, but not both (with only one singlet)

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

Graph showing the history of baryogenesis papers from 1985 to 2010.
Supplementary slides...
**EWBG**, division of search tasks

To keep BA

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

---

To make BA
**EWBG**, division of search tasks

To keep BA

\[
\frac{\phi_c}{T_c} > 1
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Equilibrium / Nonperturbative / Gauge issues

Out-of-equilibrium / quantum

Sphaleron rate in the unbroken phase

\[\text{Ambjorn et al., Moore; Rummukainen et al.,...}\]

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(\text{CP-even}) \text{ dynamics of the expanding wall}

\text{Parametrized} by $v_w$ and $\phi(z)$

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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, ...
- Riotto, Carena, Quiros, Wagner, ...

**Mass insertion**

- Kajantie et al., Prokopec & Moore, John & Smith Espinosa, Konstandin, No & Servant (2010), ...

**Espinosa, Konstandin, No & Servant (2010),**

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Kuzmin, Rubakov & Shaposhkin, Arnold & McLerran, ... Moore; Rummukainen et al;

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

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

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\[ V_{\text{eff}} \text{ in Landau gauge} \]

\[ \frac{\phi_c}{T_c} > 1 \]

H.H. Patel, M.J. Ramsey-Musolf, C. Wainwright, S. Profumo
M. Garny and T. Konstandin, JHEP1207 (2012) 189, ...

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

Parametrized by \( \nu_w \) and \( \phi(\tau) \)

Kajantie et al, Prokopec & Moore, John & Smith
Espinosa, Konstandin, No & Servant (2010), ...

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**Dynamics of the expanding wall**

Parametrized by $v_w$ and $\phi(z)$

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

**2-loop \( V_{\text{eff}} \) in LG**

\(~\text{OK}\)

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

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

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To make BA
BAU generation, QM reflection or SC force

Thick wall limit: SC force

\( \ell_{w} = 10 - 30 \, T^{-1} \)

\[
(\partial_t + v_g \cdot \partial_x + F \cdot \partial_p)f_i = C[f_i, f_j, \ldots].
\]

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

\[
F = -\frac{|m||m'|}{\omega} + s_{CP} \frac{s(|m|^2\theta')'}{2\omega^2}.
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\[\text{CP-force}\]
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KK, T. Prokopec, M.G. Schmidt and S. Weinstock, JHEP 0106, 031 (2001);
PRD66 (2002) 043502. T. Prokopec, M.G. Schmidt and S. Weinstock,

T. Konstandin, T. Prokopec and M.G. Schmidt, NPB716 (2005) 373; NPB738 (2006) 1

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\[ \ell_w = 10 - 30 T^{-1} \]

\[ |m(z)|, k_0 \]

\[ v_g(p) \neq \bar{v}_g(p) \]

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Thin wall limit: quantum reflection
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KK, T.Prokopec, M.G.Schmidt and S.Weinstein, JHEP 0106, 031 (2001);
PRD66 (2002) 043502. T.Prokopec, M.G.Schmidt and S.Weinstein,
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Thin wall limit: quantum reflection
\( \ell_w = \text{few} \, T^{-1} \)

Collisionless case:
\[
(i \delta_u - m^1 P_L - m P_R) \psi(u) = 0.
\]

Complex mass (matrix) \( \Rightarrow \) CP


KK, T. Prokopec, M.G. Schmidt and S. Weinstock, JHEP 0106, 031 (2001);
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Sufficient CP-violation in the MSM CKM-matrix?

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

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Thin wall limit: quantum reflection
\[ \ell_w = \text{few} \, T^{-1} \]

Collisionless case:
\[ \left( i \theta - m^T P_L - m P_R \right) \psi(u) = 0. \]

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Thin wall limit: quantum reflection
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Collisionless case:
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\left( i \frac{\partial}{\partial u} - m^+ P_L - m P_R \right) \psi(u) = 0.
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Sufficient CP-violation in the MSM CKM-matrix?
G.R.Farrar and M.E.Shaposhnikov, PRL70, 2833 (1993); PRD (199...)

NO

But the QKE’s used not sufficiently sophisticated

M.Joyce, T.Prokopec, N.Turok, PRD53 2958 (1996); PRL75 1695 (1995);

KK, T.Prokopec, M.G.Schmidt and S.Weinstock, JHEP 0106, 031 (2001);
PRD66 (2002) 043502. T.Prokopec, M.G.Schmidt and S.Weinstock,
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\begin{align*}
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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, et al

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

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

BAU from top transport
Singlet model: BAU-generation

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\]

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BAU from top transport

Large BAU much more frequent than in 2HDM
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\]

BAU from top transport

Large BAU much more frequent than in 2HDM

\[
\frac{\eta_B}{\eta_{B,\text{obs}}} \quad \text{or} \quad \left( \frac{\Lambda}{1 \text{ TeV}} \right)^2 \quad \eta_B = \eta_{B,\text{obs}}
\]
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.
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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.
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=> Extended **Boltzmann type eqns.**

Tested already in **homogeneous problems**

C.Fiedler, M.Herranen, KK & P.M.Rahkila, JHEP 1202 (2012) 080.

\[
\partial_t \bar{S}_{ij}^\leq = -i[H_{\text{eff}}, \bar{S}_{ij}^\leq] + \gamma^0 \langle C_{ij} + C_{ij}^\dagger \rangle \gamma^0
\]

\[
\bar{S}_{ij}^\leq = \sum_{h\pm} P_h P_{i\pm} \gamma^0 \left( P_{j\pm} f_{ijh\pm}^m + P_{j\mp} f_{ijh\mp}^c \right)
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M.Herranen, KK & P.M Rahkila,
JHEP 1012 (2010) 072; JHEP 1202 (2012) 065
C.Fiedler, M.Herranen, KK & P.M Rahkila,

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

\[
\partial_t \bar{S}_{ij}^{<} = -i[H_{\text{eff}}, S^{<}]_{ij} + \gamma^0 \langle C_{ij} + C_{ij}^\dagger \rangle \gamma^0
\]

\[
\bar{S}_{ij}^{<} = \sum_{h\pm} P_h P_{i\pm} \gamma^0 \left( P_{j\pm} f_{ijh\pm}^m + P_{j\pm} f_{ijh\pm}^c \right)
\]

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