# BARYOGENESIS AT THE ELECTROWEAK SCALE

Can we compute a number?

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Theory Seminar,
University of Oslo,
13/4-2016

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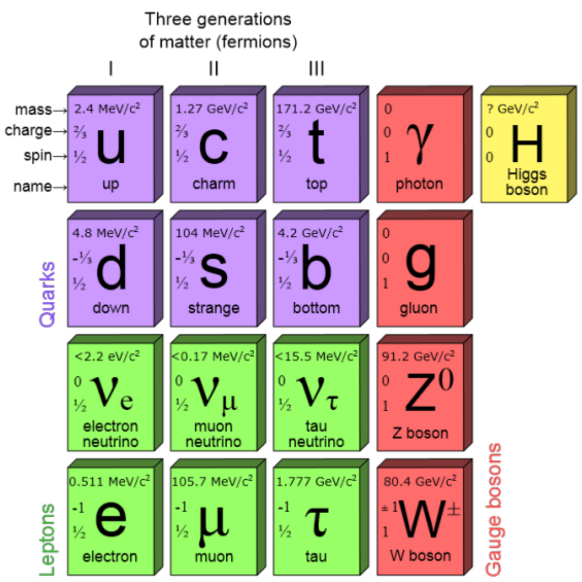
# Baryonic Matter Asymmetry

The Universe is composed of:

- Mostly Dark Energy (is the interpretation…)
- A lot of Dark Matter (we are pretty sure…)
- 5% ”Baryonic Matter” (we know for a fact…)




”Baryonic Matter” is currently composed of:

- Loads of CMB photons
- A bunch of neutrinos
- A few electrons and quarks, in a ratio:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.0 \pm 0.1) \times 10^{-10}$$

# Baryogenesis

**Free particles and anti-particles are completely equivalent.**

**Are fundamental interactions asymmetric, so that a symmetric initial state may produce an asymmetric final state?**

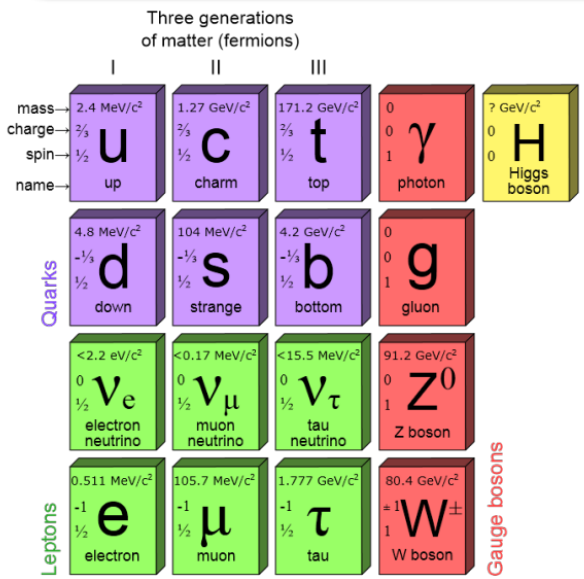
**Such a (sequence of) process(es) → Baryogenesis**

Process(es) must (together) break:

- Conservation of baryon and lepton number
- Symmetry under parity P (sometimes)
- Symmetry under charge conjugation C
- Symmetry under the combination CP
- Thermal equilibrium

# The Standard Model

**Easy peasy**:
- Electroweak interactions break C and P, conserve CP
- CKM matrix breaks CP (3 families of fermions)
- Baryon and lepton number violation from anomaly in electroweak sector
- Thermal equilibrium broken by Hubble expansion



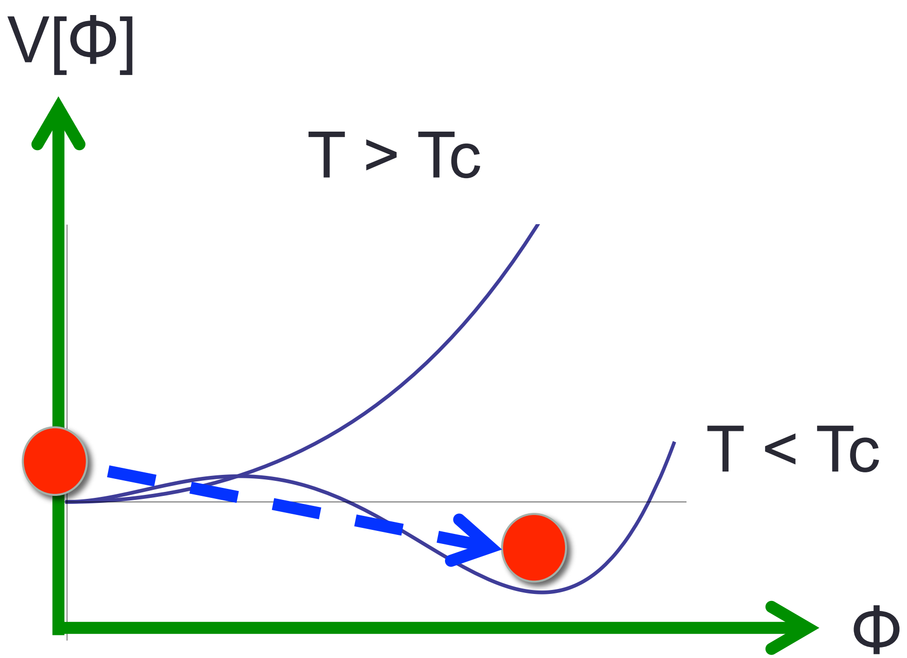

But:

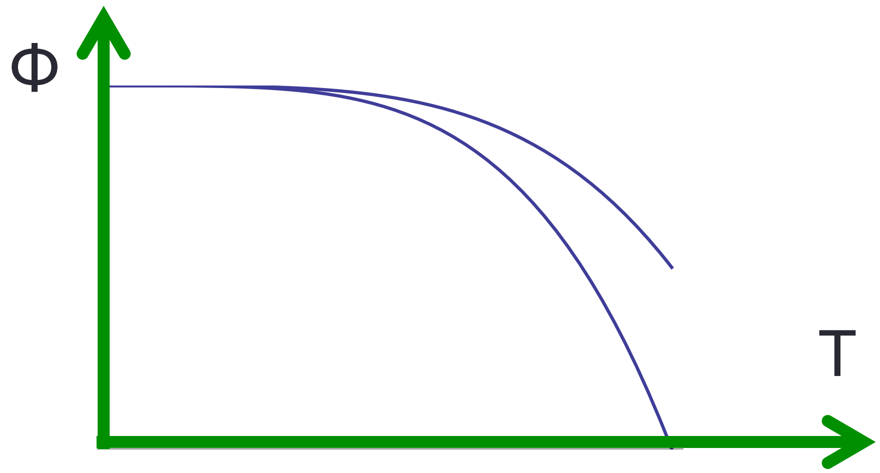
$$H \simeq \sqrt{\frac{(100\mathrm{GeV})^4}{3M_{\mathrm{pl}}^2}} \simeq 10^{-5}\mathrm{eV} \ll \Gamma_{\mathrm{EW}}$$

Thermal equilibrium throughout.

Electroweak symmetry breaking transition!

# Electroweak phase transition




First order: discontinuous Φ
Second order: continuous Φ
Crossover: smooth Φ

Somehow, Φ moved from 0 to 246 GeV as the Universe cooled down.

# Electroweak Baryon-number violation

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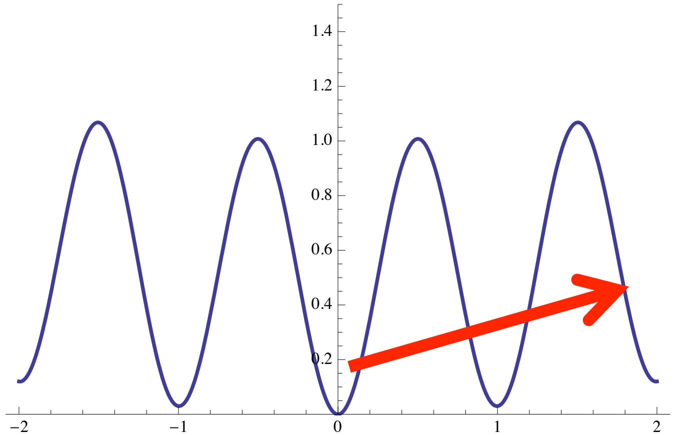
A fermion coupled chirally to an SU(2) gauge field experiences an anomalous current: 't Hooft ('85)

$$\partial_\mu j^\mu_L = \partial_\mu j^\mu_B = \frac{n_f}{16\pi^2}\mathrm{Tr}[F^{\mu\nu}\tilde{F}_{\mu\nu}], \qquad \partial_0 N_{\mathrm{cs}} = \int d^3x \frac{1}{16\pi^2}\mathrm{Tr}[F^{\mu\nu}\tilde{F}_{\mu\nu}]$$

$$B(t) - B(0) = L(t) - L(0) = n_f\left[N_{\mathrm{cs}}(t) - N_{\mathrm{cs}}(0)\right]$$

If the gauge field moves in such a way that Chern-Simons number changes, so does baryon number.

Is this possible? Yes, theory has infinite set of (semi-)degenerate vacua with integer Ncs.



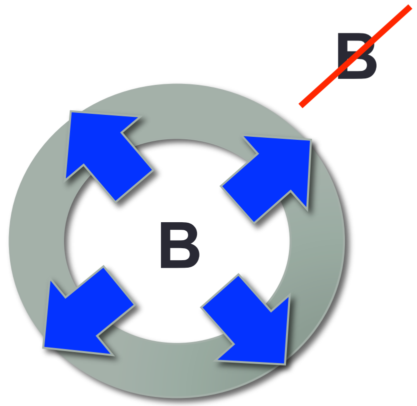
# Hot Electroweak Baryogenesis

Kuzmin, Rubakov, Shaposhnikov ('86)

**I**: Electroweak transition is 1.st order.
Nucleation, and expansion of bubbles of low-temperature vacuum inside high-temperature vacuum.

**II**: Bubble walls collide with plasma (fermions).
Higgs-fermion interaction breaks CP and produces net right/left-handed currents inside/outside bubbles.

**III**: Baryon number violating processes are active outside bubble, suppressed inside bubble. CP-asymmetry converted to B-asymmetry.




Complicated.
But could maybe work.

Processes separated in time and space:
Bubble-fermion interactions out of equilibrium and break CP.
C/P breaking + anomaly leads to baryon number violating processes → equilibrate "initial" state

# What to calculate?

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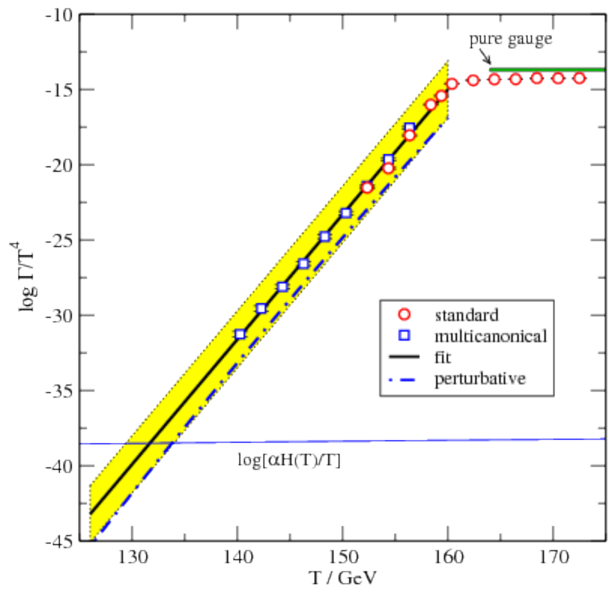
Phase diagram of SM:
Kajantie, Laine, Rummukainen, Shaposhnikov ('96)

Bubble nucleation rate:
Moore, Rummukainen (2000)
Moore, Rummukainen, AT (2001)

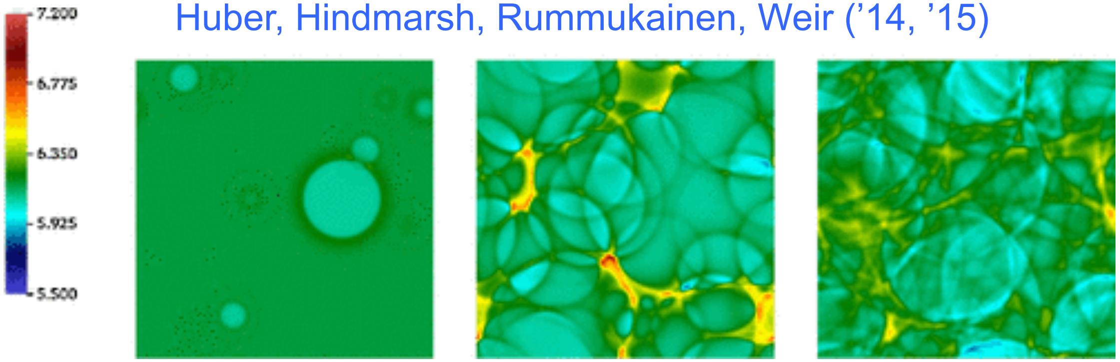
Bubble wall dynamics:
…
Huber, Hindmarsh, Rummukainen, Weir ('14, '15)

Bubble-fermion interactions:
Cohen, Kaplan, Nelson ('92, '93)
Schmidt, Kainulainen, Prokopec,
Joyce, Huber, … ('94…'0?)

Sphaleron rate:
Ambjørn, Krasnitz ('92)
Moore ('95-'98)
Moore, Rummukainen, Bödeker ('00)
D'Onofrio, Rummukainen, AT ('14)




Huber, Hindmarsh, Rummukainen, Weir ('14, '15)



# Three things went wrong

1: The Higgs mass > 80 GeV

→ electroweak phase transition is not first order.

Kajantie, Laine, Rummukainen, Shaposhnikov ('96)

→ No bubbles. Game over.

2: Effects of SM CP violation is "extremely small" at electroweak temperatures.

→ "Extremely small" asymmetry, we think.

Shaposhnikov, Farrar, Gavela, … ('87-)

3: Many people gave up trying to compute the asymmetry.

→ Because: What's the point?

→ And it's really hard, too.

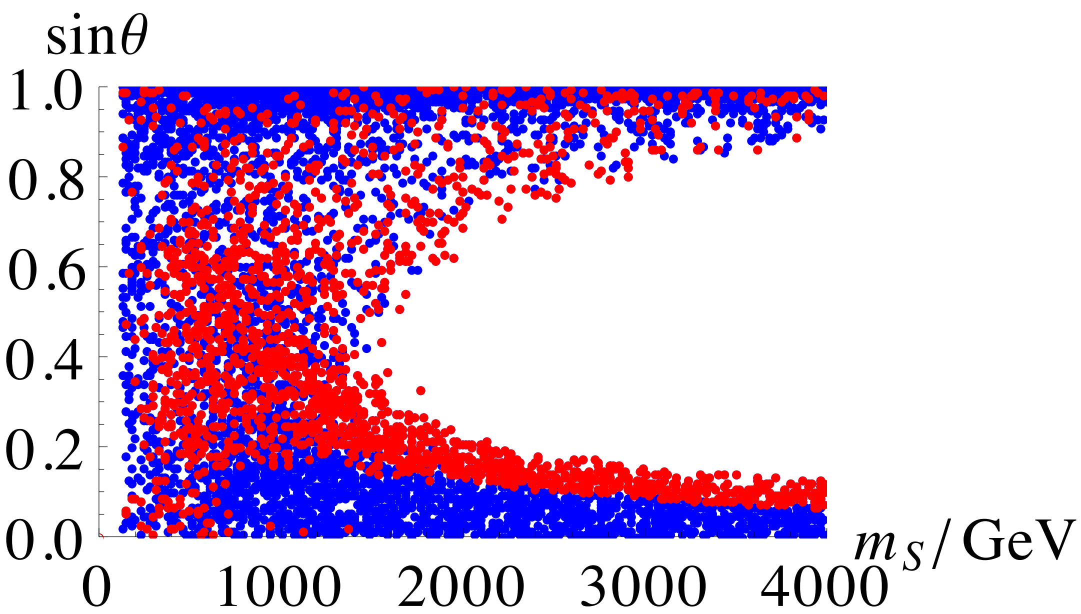
# Alternatives to SM 1.st order PT: I

The Standard Model is incomplete (inflation, Dark Matter, …)

Enlarged scalar sector provides strong 1.st order phase transtion

Example: SM + singlet.
5 parameters.
Project onto m_S, sin θ plane.

Experimentally accessible.




Damgaard, O'Connell, Haarr, AT ('15)

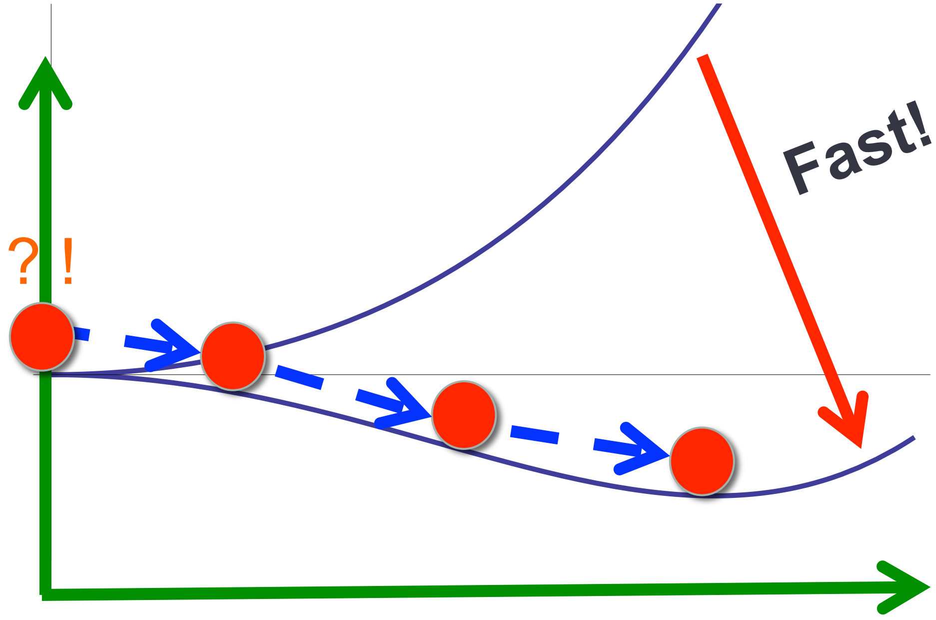
# Alternatives to SM 1.st order PT: II

Spinodal transition:
Field dynamics cannot keep up with potential quench.

Unstable IR modes
→ out of equilibrium

Does not work with temperature quench $H \simeq 10^{-5}\mathrm{eV}$

Need a second field to quench it:
- Hybrid low-scale inflation?
- Second field 1.st order jump?




**Cold Electroweak Baryogenesis**

Copeland, Lyth, Rajantie, Trodden ('01)
Smit, van Tent, AT ('04)
Enqvist, Stephens, Taanila, AT ('10)
Konstandin, Servant ('11)

Turok, Zadrozny ('90-'91), Krauss, Trodden ('99), Garcia-Bellido, Grigoriev, Kusenko, Shapohsnikov ('99)
Copeland, Lyth, Rajantie, Trodden ('01), Smit, AT ('03)

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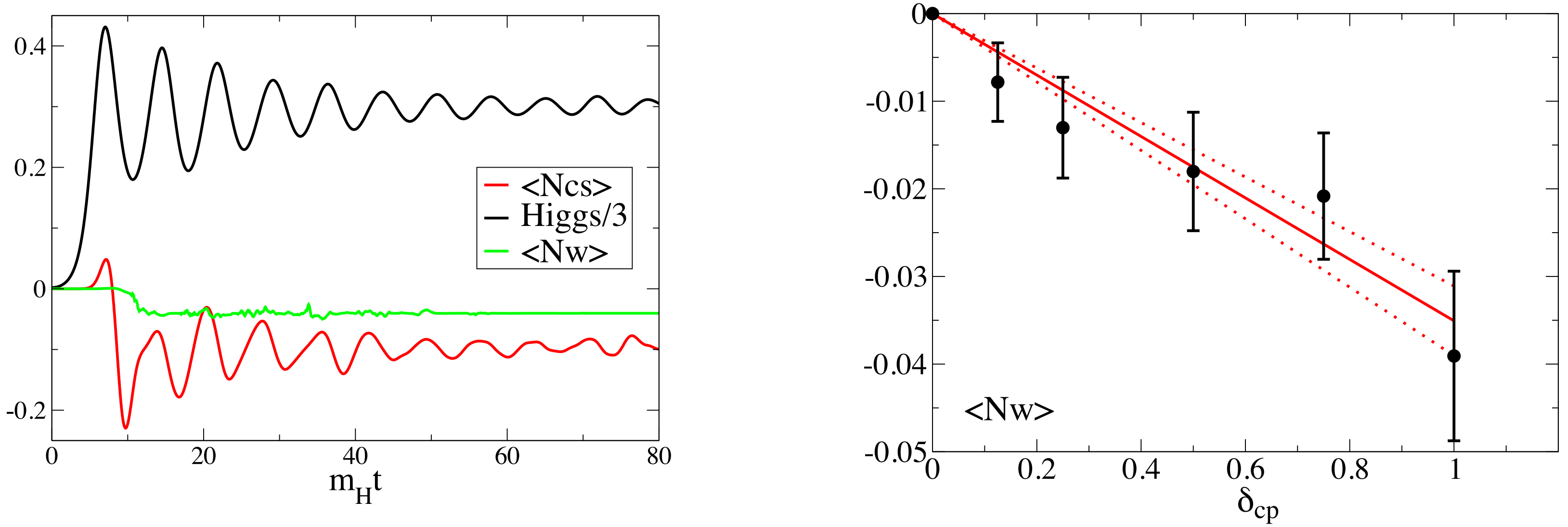
# Alternatives to SM CP-violation at EW temperature: I

Some other source of CP-violation:

$$\Delta S = \frac{3\delta_{\rm CP}}{16\pi^2 m_W^2}\phi^\dagger\phi {\rm Tr}[F^{\mu\nu}\tilde{F}_{\mu\nu}]$$




$\delta_{\rm CP} \simeq 1.5 \times 10^{-5}$ is a good number

Smit, AT ('06)

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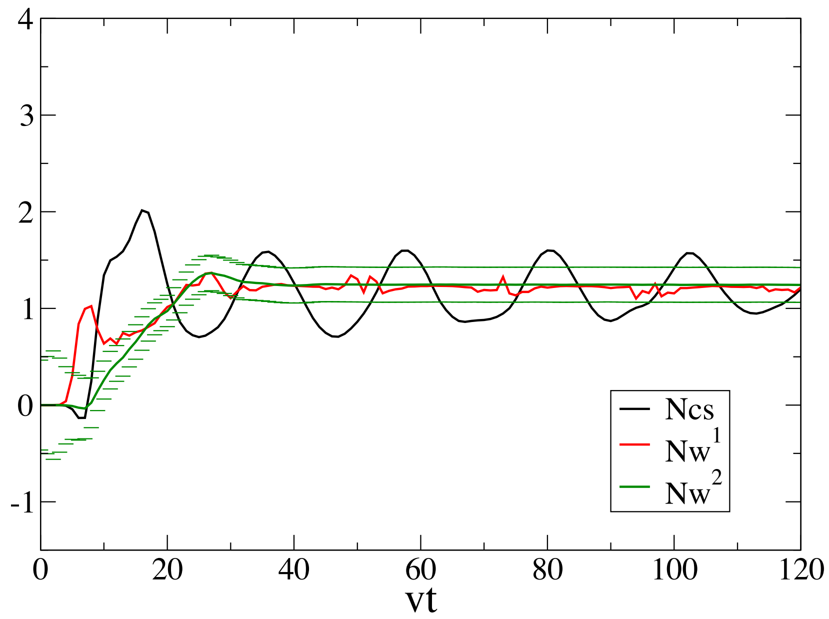
# Alternatives to SM CP-violation at EW temperature: II

Two Higgs doublets with C(P)-breaking potential, and C/P breaking:

$$\Delta S = \frac{3\delta_{C/P}}{16\pi^2 m_W^2} i(\phi_1^\dagger\phi_2 - \phi_2^\dagger\phi_1)\mathrm{Tr}[F^{\mu\nu}\tilde{F}_{\mu\nu}]$$




$$V(\phi_1,\phi_2) = -\frac{\mu_{11}^2}{2}\phi_1^\dagger\phi_1 - \frac{\mu_{22}^2}{2}\phi_2^\dagger\phi_2 - \frac{\mu_{12}^2}{2}\phi_1^\dagger\phi_2 - \frac{\mu_{12}^{2,*}}{2}\phi_2^\dagger\phi_1 + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_2^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \frac{\lambda_5^*}{2}(\phi_2^\dagger\phi_1)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_6^*(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + \lambda_7^*(\phi_2^\dagger\phi_2)(\phi_2^\dagger\phi_1).$$

$\delta_{C/P} \geq 3\times 10^{-4}$ is a good number

AT, Wu ('12-13)

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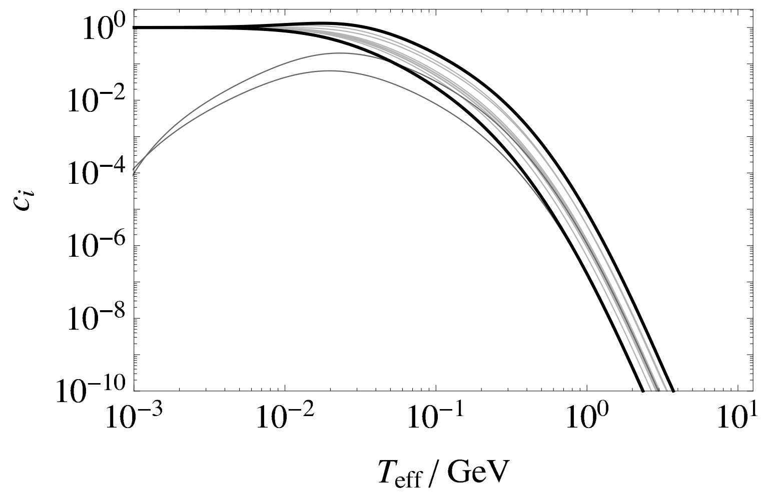
# Alternatives to SM CP-violation at EW temperature: III

SM CP-violation is extremely small at finite T, because, when integrating out the fermions, one would expect:

$$\delta_{\rm CP} \simeq 3\times 10^{-5}\frac{(m_b^2-m_d^2)(m_s^2-m_d^2)(m_b^2-m_s^2)(m_t^2-m_u^2)(m_c^2-m_u^2)(m_t^2-m_c^2)}{T^{12}} \simeq 10^{-19}$$

But doing the actual calculations:




$$\Delta S = \frac{3\delta_{\rm CP}}{16\pi^2 m_W^2}\phi^\dagger\phi {\rm Tr}[F^{\mu\nu}\tilde{F}_{\mu\nu}]$$

$\rightarrow$

$$\begin{aligned}
\mathcal{O}_0^+ &= -\frac{c_1}{3}(W^+)^2 W^-_{\mu\mu}W^-_{\nu\nu} + \frac{5c_2}{3}(W^+)^2 W^-_{\mu\nu}W^-_{\mu\nu} \\
&\quad -\frac{c_1}{3}(W^+)^2 W^-_{\mu\nu}W^-_{\nu\mu} + \frac{4c_3}{3}W^+_\mu W^+_\nu W^-_{\mu\alpha}W^-_{\alpha\nu} \\
&\quad -\frac{2c_1}{3}W^+_\mu W^+_\nu W^-_{\mu\alpha}W^-_{\nu\alpha} - 2c_4 W^+_\mu W^+_\nu W^-_{\alpha\mu}W^-_{\alpha\nu} \\
&\quad +\frac{4c_3}{3}W^+_\mu W^+_\nu W^-_{\mu\nu}W^-_{\alpha\alpha} - {\rm c.c.}, \qquad (10) \\
\mathcal{O}_1^+ &= \frac{8}{3}(Z_\mu+\varphi_\mu)\big[c_5(W^+)^2 W^-_\mu W^-_{\nu\nu} \\
&\quad -c_6(W^+)^2 W^-_\nu W^-_{\mu\nu} - c_6(W^+)^2 W^-_\nu W^-_{\nu\mu} \\
&\quad -c_3(W^+\cdot W^-)W^+_\mu W^-_{\nu\nu} \\
&\quad +c_7(W^+\cdot W^-)W^+_\nu W^-_{\mu\nu} + c_7 W^+_\mu W^+_\nu W^-_\alpha W^-_{\alpha\nu} \\
&\quad -c_{12}(W^+\cdot W^-)W^+_\nu W^-_{\nu\mu} - c_{12}W^+_\mu W^+_\nu W^-_\alpha W^-_{\nu\alpha} \\
&\quad +c_{13}W^-_\mu W^+_\nu W^+_\alpha W^-_{\nu\alpha}\big] - {\rm c.c.}, \qquad (11) \\
\mathcal{O}_2^+ &= 4(Z_\mu Z_\nu + \varphi_\mu\varphi_\nu) \\
&\quad \times\big[c_8(W^+)^2 W^-_\mu W^-_\nu - c_8(W^-)^2 W^+_\mu W^+_\nu\big] \\
&\quad -\frac{16}{3}(Z\cdot\varphi)\big[c_9(W^+\cdot W^-)^2 - 2c_6(W^+)^2(W^-)^2\big] \\
&\quad +\frac{4}{3}(Z_\mu\varphi_\nu + Z_\nu\varphi_\mu) \\
&\quad \times\big[c_{10}(W^+)^2 W^-_\mu W^-_\nu + c_{10}(W^-)^2 W^+_\mu W^+_\nu \\
&\quad -2c_{11}(W^+\cdot W^-)(W^+_\mu W^-_\nu + W^+_\nu W^-_\mu)\big], \qquad (12)
\end{aligned}$$

$T \leq 1$ GeV is a good temperature

Brauner, Taanila, AT, Vuorinen ('12)

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# Can we do the Two-Higgs model?

C and P violation explicitly broken maximally in gauge-fermion interactions. CP conserved. Integrating out fermions at one loop gives $\delta_{\mathrm{C/P}}$

Hard; but can we do better than integrating out at one-loop in equilibrium?

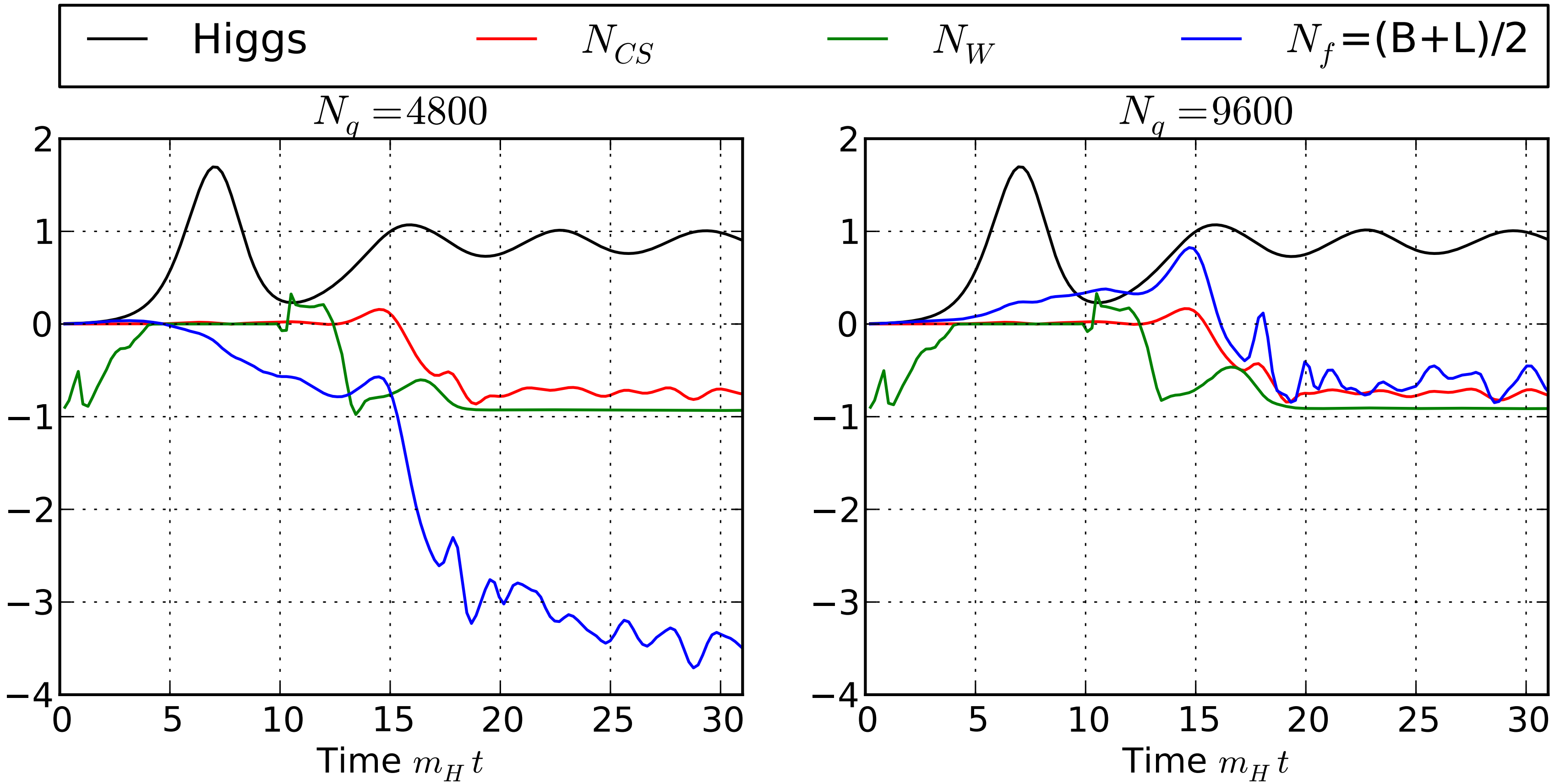
Put in the fermions dynamically in real-time!

Non-perturbative. Out-of-equilibrium. Quantum fermions. Classical bosonic fields. On the lattice. In the computer. Off we go.

Ensemble fermions: Replace quantum average by average over statistical realisations. Nq should be big enough for convergence.

Aarts, Smit ('98)
Borsanyi, Hindmarsh ('09)
Saffin, AT ('11, '12)

# …with fermions.




Mou, Saffin, AT ('13)

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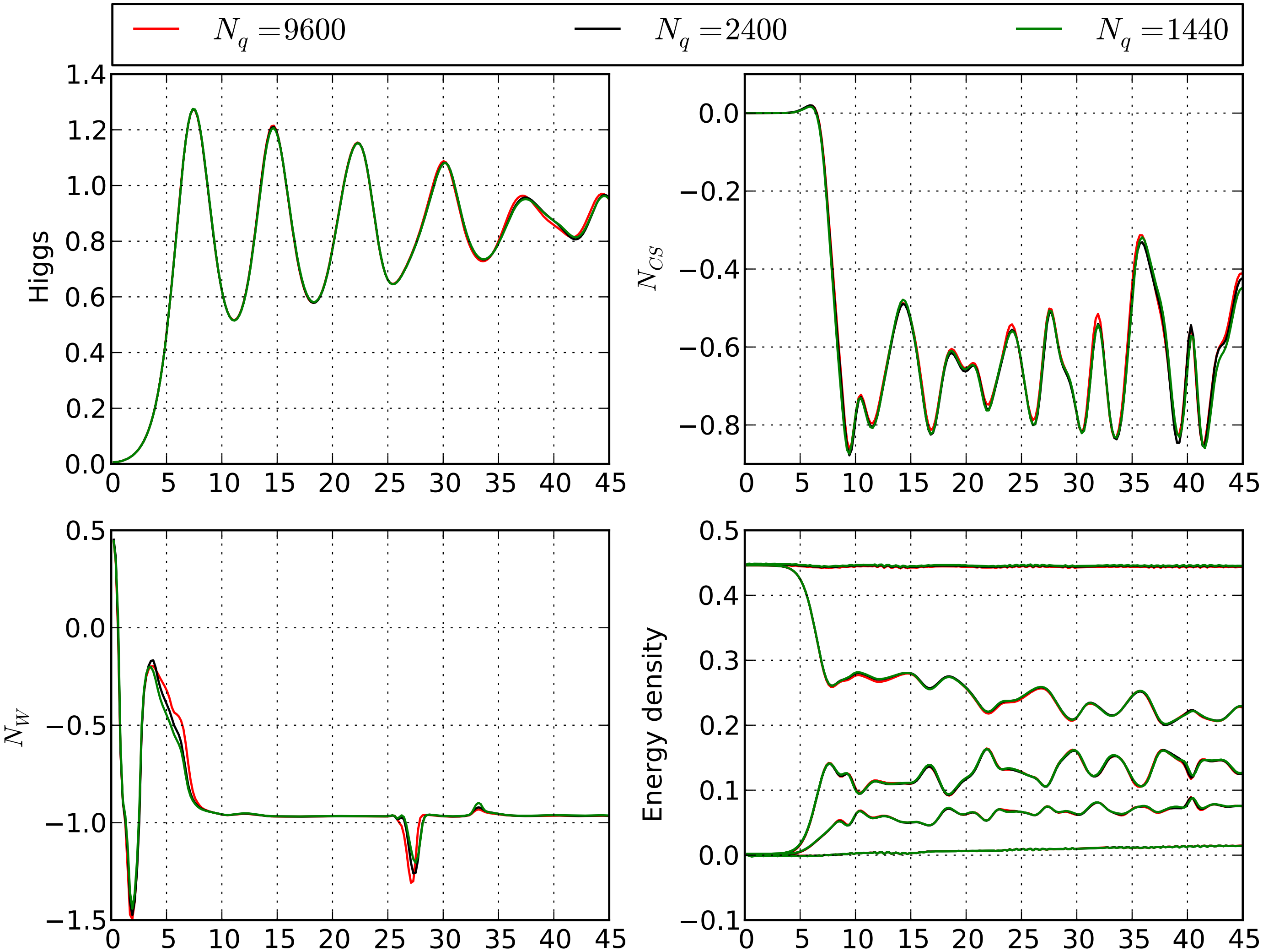
# …with fermions

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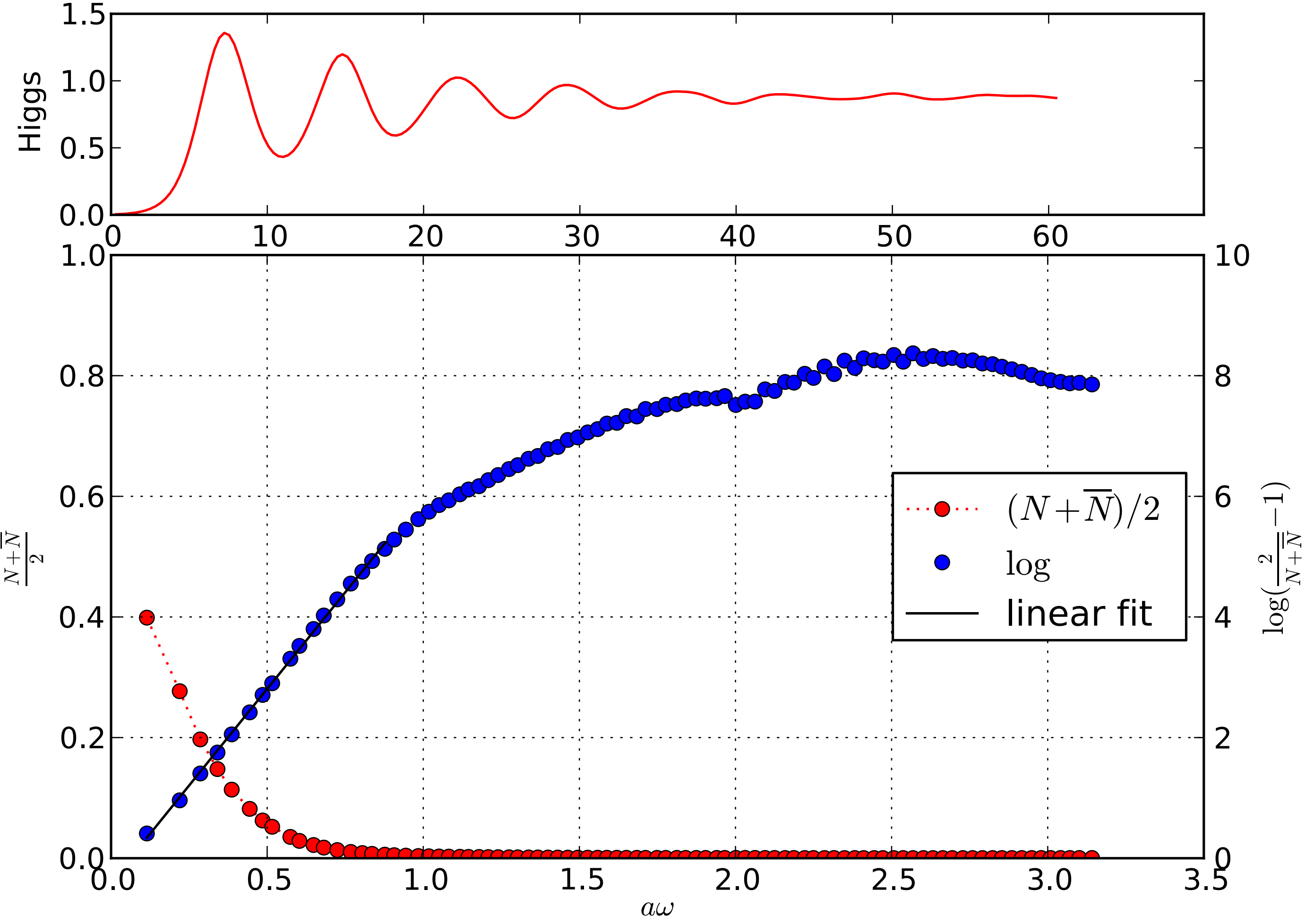
# …with fermions

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# …with fermions

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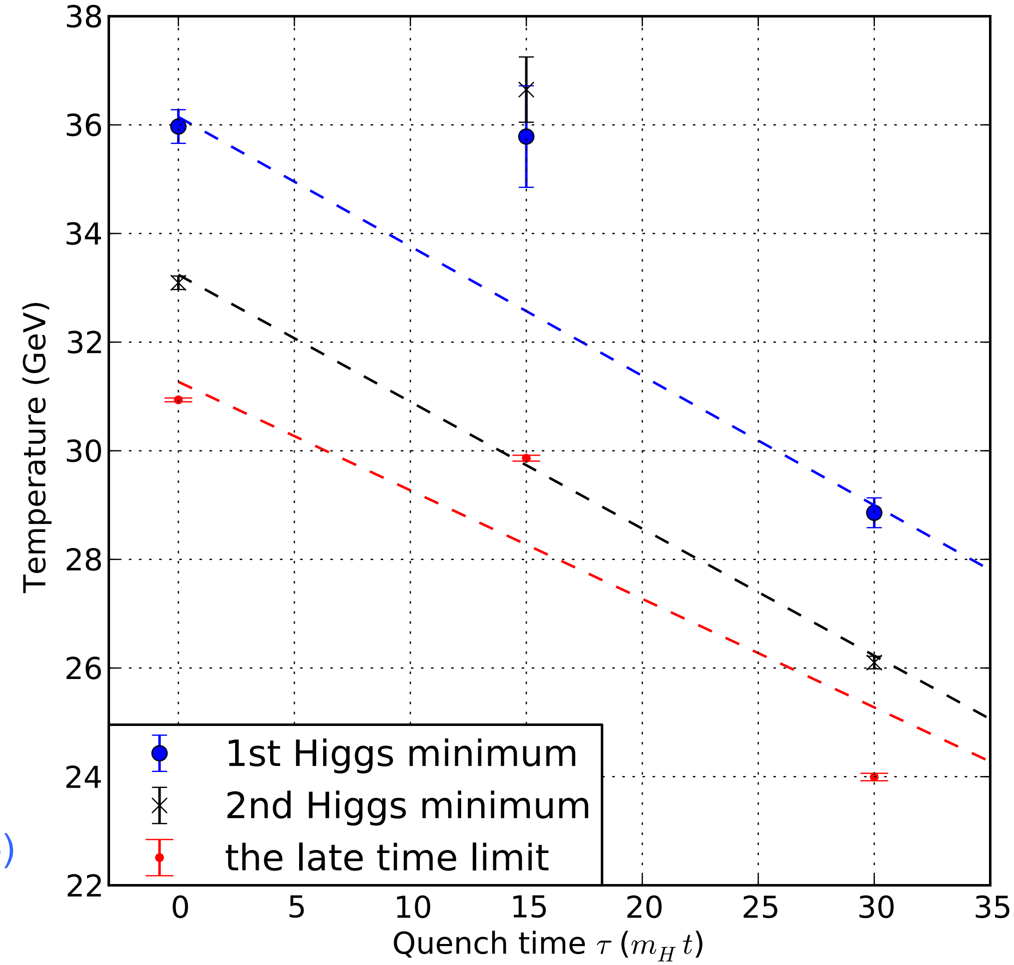
We can measure the temperature of the fermions as a function of the speed of the quench.

25 GeV is an optimistic number.

Does it even make sense to look for the asymmetry?

Mou, Saffin, AT ('13)



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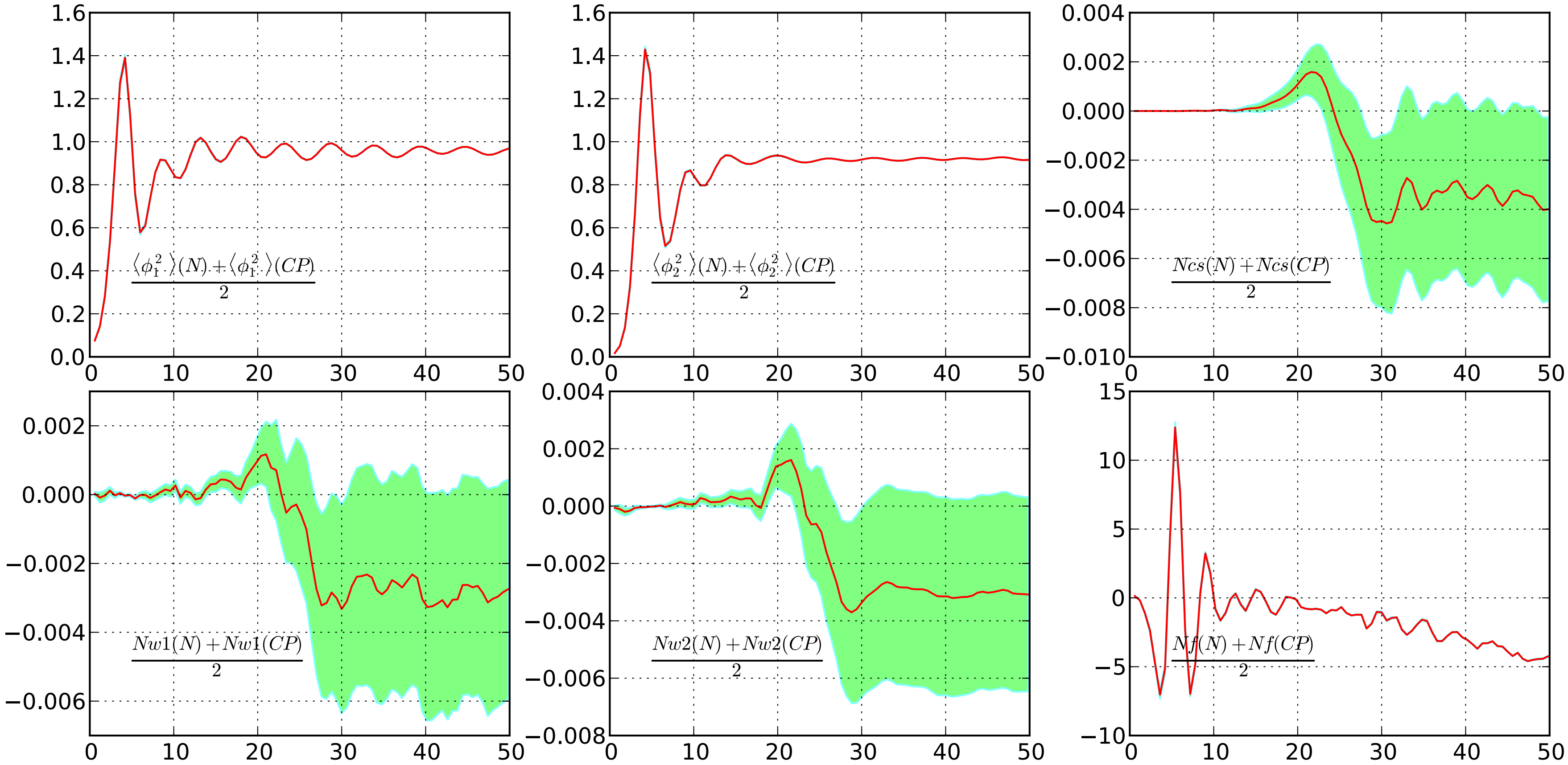
# Is there a number?




$\frac{n_B}{n_\gamma} = 3.5 \times 10^{-7}(1.0 \pm 1.0)$ is the number. $\delta_{C/P} = 0.03$ is another number.

Mou, Saffin, AT ('15)

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# Conclusions and To-do list

- We need to get going again with Hot and Cold EWBG.
- Extended scalar sectors give viable models of both kinds.
- Using effective bosonic theories, we can simulate Cold EWBG finding agreement with observations for certain values of $\delta_{\mathrm{CP}}, \quad \delta_{\mathrm{C/P}}$
- Not obvious that the operators considered are correct and/or dominant.
- Quantum fermions work and give an asymmetry. This is the first time a simulation has been done of baryogenesis from first principles all the way to the end!
- For optimised scalar potentials, 600 times observed asymmetry (maybe).
- Computer cost is extreme: 0.5 Mhours cpu-times. 9-dimensional parameter sweeps not an option.
- Quantum fermions also relevant for fermion-wall interactions in Hot EWBG (in progress…quite hard).

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Thank you
for your attention!