Baryogenesis

Relativistic quantum field theory, our understanding of fundamental interactions, implies the existence of antimatter*

we expect equal abundance of matter and antimatter in the early universe

we observe a negligible abundance of antimatter today

can we understand the abundance of matter?

can we compute η?

$$\eta = \frac{n_B}{n\gamma}$$

n_B : number density of baryons

$$n_B = n_H + 2n_D + 4n_{^4He} + \cdots = \frac{\#p + \#n}{\text{unit volume}}$$

n_γ : number density of photons

*) antiparticle = particle with the same mass and spin but with opposite charge(s)

energy density in baryons today given by η

$$\Omega_b = \frac{\rho_b}{\rho_c} \approx \frac{n_B m_p}{\rho_c} = \frac{\eta\, n_\gamma\, m_p}{3H_0^2/8\pi G} = \frac{7.4}{(h/0.7)^2} \times 10^7 \eta$$

$$H_0 = 100\, h\, \text{km s}^{-1}\text{Mpc}^{-1}, \quad n_\gamma = 0.24\, T^3$$

- η (Ω_b) influences the cosmological microwave background (CMB) anisotropy

- η is input in the theory of big-bang nucleosynthesis (BBN)

$$\begin{aligned} \eta &= (5.6 \pm 0.5) \times 10^{-10} \quad \text{BBN} \\ &= (6.0 \pm 0.6) \times 10^{-10} \quad \text{CMB} \end{aligned}$$

(From G. Steigman astro-ph/0202187)

Units:

$$\hbar = c = k = 1$$

[energy] = [mass] = [temperature] = [length]$^{-1}$
= [time]$^{-1}$

$$\begin{aligned}
1\,\mathrm{GeV} = 1000\,\mathrm{MeV} &= 1.6022 \times 10^{-3}\,\mathrm{erg} \\
&= 1.1605 \times 10^{13}\,\mathrm{K} \\
&= 1.7827 \times 10^{-24}\,\mathrm{g} \\
1\,\mathrm{GeV}^{-1} &= 1.9733 \times 10^{-14}\,\mathrm{cm} \\
&= 6.5822 \times 10^{-25}\,\mathrm{sec}
\end{aligned}$$

(reduced) Planck mass

$$m_{\mathrm{P}} \equiv (8\pi G)^{-1/2} = 0.244 \times 10^{-18}\,\mathrm{GeV}$$

Going back in time:

Before nucleosynthesis ($T \approx 1$ MeV)

$$n_B = n_p + n_n, \quad n_{\bar{p}} = n_{\bar{n}} \approx 0$$

Before the quark-hadron transition ($T \approx 170$ MeV)

$$n_B = \frac{1}{3}(n_q - n_{\bar{q}}) \quad \text{quark–antiquark asymmetry}$$

$$\frac{1}{3} n_{\bar{q}} \approx \frac{1}{3} n_q \approx n_\gamma = 0.24\, T^3, \quad T \gg 170\,\text{MeV}$$

For every 10^9 quarks there were about $10^9 - 1$ antiquarks

End of inflation: $n_q = n_{\bar{q}} = 0$, $\eta = 0$

can we predict η from particle theory?

Sakharov 1967:

- need violation of B conservation

- need violation of C and CP symmetry

- need conditions out of thermal equilibrium

(Extended) Standard Model ((E)SM)

SM fermions	quarks* (q)	u	c	t
		d	s	b
	leptons (ℓ)	ν_e	ν_μ	ν_τ
		e	μ	τ
bosons		W	Z	H
		γ	g	

masses (GeV):

$m_W = 81$, $m_Z = 93$, $m_H = 114 - 200$? Higgs
$m_\gamma = 0$, $m_g = 0$
$m_u \approx 3 \times 10^{-3}$, $m_c \approx 1.3$, $m_t \approx 175$
$m_d \approx 6 \times 10^{-3}$, $m_s \approx 0.1$, $m_b \approx 4.1$

$m_e = 0.51 \times 10^{-3}$, $m_\mu = 0.11$, $m_\tau = 1.7$

$\nu = (\nu_L, \nu_R)$, SM extended with ν_R to ESM to account for neutrino masses

$\nu \to \nu_L$ & N, $m_{\nu_L} \lesssim 10^{-9}$, $m_N \gg 10^3$? seesaw?

*) $qqq \to$ baryons: n, p, ...
$q\bar{q} \to$ mesons: π, K, ...

Phase transitions

$$H^2 = \frac{1}{3}\frac{\rho}{m_{\mathrm{P}}^2}$$

$\cdots$	10^{-9}	10^{-3}	10^{-1}	10^{2}	$\cdots$	T, $\rho^{1/4}$ (GeV)
$\cdots$	atoms	NS	QH	EW	$\cdots$	

electroweak (EW): W, Z, H, q, ℓ, ν get mass*
quark–hadron (QH): q & $g \to$ hadrons
nucleosynthesis (NS): p & $n \to$ nuclei

*) Before the EW transition there were effectively massless d.o.f. ϕ, $\bar{\phi}$, A, B, which metamorphose into H, W, Z and γ during the transition

Baryon number (B) and lepton number (L)

$n_B, \mathbf{j}_B$	baryon-, baryon-current-density
$n_L, \mathbf{j}_L$	lepton-, lepton-current-density

today:

$$\dot{n}_B + \nabla \cdot \mathbf{j}_B = 0, \quad B = \int d^3x\, n_B \quad \text{conserved*}$$
$$\dot{n}_L + \nabla \cdot \mathbf{j}_L = 0, \quad L = \int d^3x\, n_L \qquad ,,$$

before EW transition:

$B + L$ *not* conserved 'sphaleron transitions'

$B - L$ (*not*) conserved in (*E*)SM

$B - L$ may not be conserved in ESM due to 'Majorana interactions' with ν_R

B and L are conserved* after the electroweak transition

*) violation extremely small, $\propto$ exp$(-E_{\mathrm{sph}}/T)$ or $\propto$ exp$(-4\pi/\alpha_{\mathrm{W}}\}$
$E_{\mathrm{sph}} = O(10^4)$ GeV, sphaleron energy
$\alpha_{\mathrm{W}} \approx 1/30$, electroweak fine-structure constant

Discrete symmetries

C: particles $\leftrightarrow$ antiparticles

P: parity $\mathbf{x} \to -\mathbf{x}$

$$\begin{array}{cccc} B \stackrel{C}{\to} -B & \qquad & L \stackrel{C}{\to} -L \\ B \stackrel{CP}{\to} -B & \qquad & L \stackrel{CP}{\to} -L \end{array}$$

need C and CP violation to obtain non-zero B from $B = 0$

Sakharov ingredients are indeed present in (E)SM and early universe

many scenarios invented for baryogenesis: out-of-equilibrium decay, EW transition, ...

here we present:

- leptogenesis

- tachyonic EW preheating

Leptogenesis

Synopsis: $T > O(10^{10}\,\text{GeV}) \gg T_{\text{EW}}$; $n_B = 0$, $n_L = 0$. CP-violating decay of heavy neutrinos generates non-zero lepton number density $n_{L\,\text{i}}$. Subsequently $n_B + n_L$ gets washed-out by sphaleron transitions:

$$\begin{aligned} n_B &= \frac{n_B + n_L}{2} + \frac{n_B - n_L}{2} \to \frac{(n_B - n_L)_\text{i}}{2} = -\frac{n_{L\,\text{i}}}{2} \\ n_L &= \frac{n_B + n_L}{2} - \frac{n_B - n_L}{2} \to -\frac{(n_B - n_L)_\text{i}}{2} = \frac{n_{L\,\text{i}}}{2} \end{aligned}$$

At $T < T_{\text{EW}}$, B and L become separately conserved

Actors: N, ℓ, $\bar\ell$, ϕ, $\bar\phi$, ...
N : ESM heavy neutrinos, $m_N = O(10^{10}\,\text{GeV})$
ℓ & $\bar\ell$: SM leptons & antileptons, $m_\ell \to 0$
ϕ & $\bar\phi$: SM Higgs & antiHiggs d.o.f., $m_\phi \to 0$

Play:

$$\begin{aligned} N &\leftrightarrow \ell + \phi, & \Delta L &= \pm 1 \\ &\leftrightarrow \bar\ell + \bar\phi, & \Delta L &= \mp 1 \\ \ell + \phi &\leftrightarrow \bar\ell + \bar\phi, & \Delta L &= \mp 2 \\ \ell + \bar\ell &\leftrightarrow \phi + \bar\phi,\ q + \bar q, \ldots,\ \ldots & & \end{aligned}$$

Distribution functions

$$g f(\mathbf{p}, t) \frac{d^3p}{(2\pi)^3} \, d^3x = \text{number of particles in } d^3p \, d^3x$$

$g =$ d.o.f. per $\mathbf{p}$

$g_\ell = g_{\bar{\ell}} = 3 \times (1+2)$, $g_q = g_{\bar{q}} = 3 \times 3 \times (2+2)$, $g_\phi = g_{\bar{\phi}} = (1+1)$, $g_A = 3 \times 2$, $g_B = 2$, $g_g = 8 \times 2$, $g_N = 3 \times 2$

Equilibrium Fermi–Dirac (FD), Bose–Einstein (BE) and Boltzmann (B) distributions

$$\begin{aligned} f &= \frac{1}{e^{(E-\mu)/T} \pm 1} && \text{FD/BE} \\ &= e^{-(E-\mu)/T} && \text{B} \end{aligned}$$

where $E = \sqrt{\mathbf{p}^2 + m^2}$
In quasi-equilibrium, $T = T(t)$, $\mu = \mu(t)$

number density and energy density

$$\begin{aligned} n &= g \int \frac{d^3p}{(2\pi)^3} \, f \\ \rho &= g \int \frac{d^3p}{(2\pi)^3} \, f \, E \end{aligned}$$

number density for $T \gg m$ ($\mu = 0$)

$$\begin{aligned} n &= \frac{3}{4}\frac{\zeta(3)}{\pi^2}\, gT^3 \quad \text{FD} \\ &= \frac{\zeta(3)}{\pi^2}\, gT^3 \qquad \text{BE} \\ &= \frac{1}{\pi^2}\, gT^3 \qquad\quad \text{B} \end{aligned}$$

where $\zeta(3) = 1.20\cdots$

for $T \ll m$

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-(m-\mu)/T}$$

Asymmetry described by small chemical potential $\mu = -\bar{\mu}$ ($T \gg m$):

$$\begin{aligned} n - \bar{n} &= \frac{1}{6}\, gT^2\mu \qquad \text{FD} \\ &= \frac{1}{3}\, gT^2\mu \qquad \text{BE} \\ &= \frac{2}{\pi^2}\, gT^2\mu \qquad \text{B} \end{aligned}$$

Adiabatic expansion: entropy conserved (small chemical potentials)
in comoving volume a^3 (a : scale factor)
entropy density s

$$0 = \frac{d}{dt}(sa^3) = a^3(\dot{s} + 3\,\frac{\dot{a}}{a}\,s), \quad \dot{s} + 3Hs = 0$$

with $H = \dot{a}/a$ the Hubble rate

for $T \gg m$

$$\begin{aligned} s &= \frac{2\pi^2}{45}\, g_{*S} T^3 \\ g_{*S} &= \frac{7}{8}\sum_f g_f \left(\frac{T_f}{T}\right)^3 + \sum_b g_b \left(\frac{T_b}{T}\right)^3 \end{aligned}$$

For $T \gg 100$ GeV, $g_{*S} = 106.75$ in SM.

Today $g_{*S} = g_\gamma + (7/8)(4/11)(g_\nu + g_{\bar{\nu}}) = 3.91$,
$s = 1.80\, g_{*S}\, n_\gamma = 7.04\, n_\gamma$

Decoupling of a relative stable species (say N)

Simplified Boltzmann equation for two-particle processes $N + N \leftrightarrow \ell + \bar{\ell}, \ldots$

$$
\begin{aligned}
\dot{n}_N + 3Hn_N &= \langle \sigma_{NN}\, v\rangle \left(n_N^{\text{eq}\,2} - n_N^2\right) \\
\sigma_{NN} &: \text{ cross section} \\
v &: \text{ relative velocity} \\
\sigma_{NN}\, v\, f_\ell^{\text{eq}} f_{\bar{\ell}}^{\text{eq}} &: \text{ gain term} \\
f_\ell^{\text{eq}} f_{\bar{\ell}}^{\text{eq}} &\approx e^{-(E_\ell + E_{\bar{\ell}})/T} = e^{-(E_N + E_N)/T} \\
&\approx f_N^{\text{eq}} f_N^{\text{eq}} \to \langle \sigma_{NN}\, v\rangle\, n_N^{\text{eq}\,2} \\
-\sigma_{NN}\, v\, f_N f_N &\to \approx -\langle \sigma_{NN}\, v\rangle\, n_N^2 \qquad \text{loss term}
\end{aligned}
$$

used Boltzmann statistics; assumed kinetic equilibrium for N, $f_N = e^{-(E-\mu)/T}$

Useful quantity

$$
Y = \frac{n}{s}, \qquad \dot{Y}_N = -\langle \sigma\, v\rangle\, s \left(Y_N^2 - Y_N^{\text{eq}\,2}\right)
$$

Time scales: H vs $\langle \sigma v \rangle n$
radiation dominated universe ($a \propto t^{1/2}$)

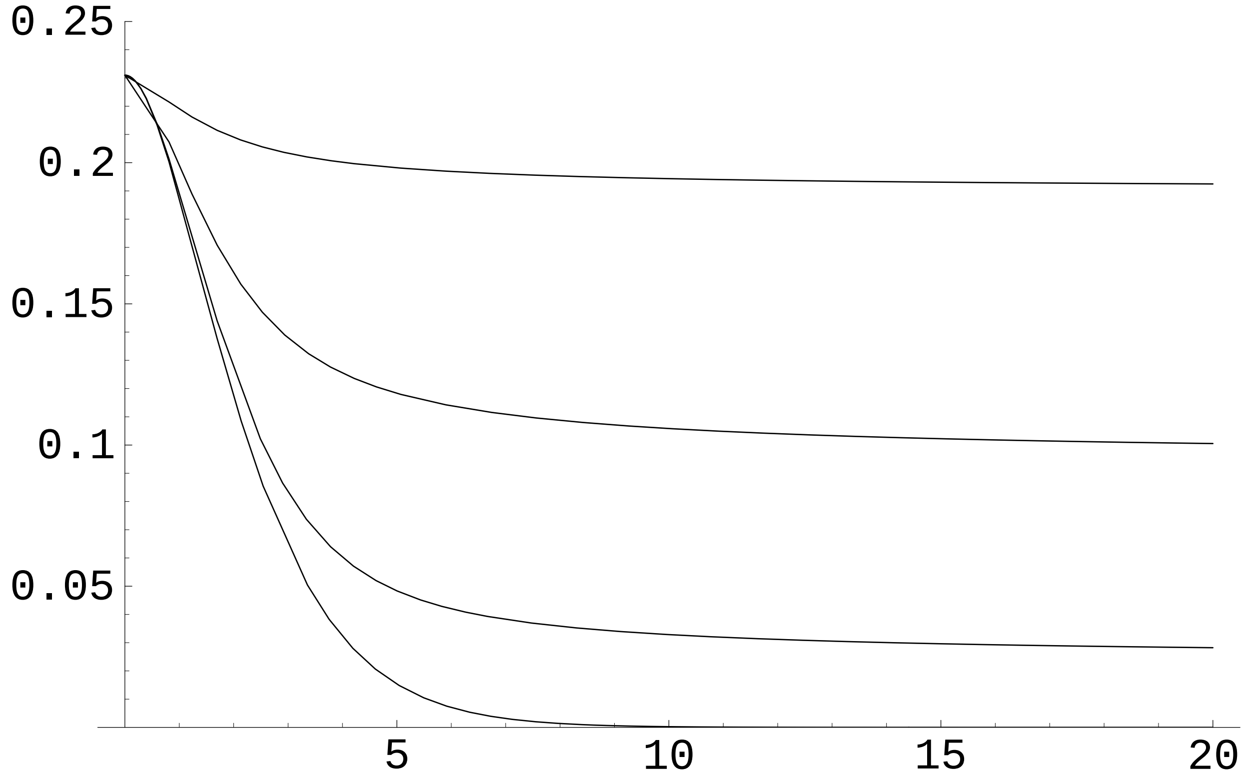
$$
\begin{aligned}
H &= \frac{\dot{a}}{a} = \frac{1}{2t} = \left(\frac{\rho}{3m_{\mathrm{P}}^2} \right)^{1/2} = 0.33\, g_* \frac{T^2}{m_{\mathrm{P}}} \\
z &= \frac{m_N}{T}, \quad t \propto z^2, \quad \frac{d}{dz} = \frac{z}{H(1)} \frac{d}{dt} \\
\frac{dY_N}{dz} &= -\frac{z \langle \sigma v \rangle s}{H(1)} \left(Y_N^2 - Y_N^{\mathrm{eq}\, 2} \right)
\end{aligned}
$$

Limiting behavior

$$
\begin{aligned}
Y_N^{\mathrm{eq}} &\approx 0.23 \frac{g_N}{g_{*S}}, \quad z \ll 1^* \\
&\approx 0.145 \frac{g_N}{g_* S} z^{3/2} e^{-z}, \quad z \gg 1 \\
\frac{z \langle \sigma v \rangle s}{H(1)} &\approx \text{const.}, \quad z \ll 1 \\
&\propto z^{-2}, \quad z \gg 1
\end{aligned}
$$

Y_N^{eq} falls exponentially fast; Y_N cannot keep up
$\Rightarrow N$ decouples

*) $0.23 \to 0.173$ for FD statistics



Behavior of $(g_{*S}/g_N)Y_N$ vs $z = m_N/T$, in case of relatively stable N. Top to bottom: increasing* two-particle annihilation rate $\sigma_{NN\to\ldots}$.
The bottom curve corresponds to $Y_N^{\rm eq}$.

*) The weak prevail!

Decoupling of a decaying N

Assume hierarchy in masses $m_{N_3} \gg m_{N_2} \gg m_{N_1}$

Simplified Boltzmann equation for $N \equiv N_1$:

$$\dot{n}_N + 3Hn_N = -\langle \Gamma_N \rangle \left(n_N - n_N^{\text{eq}} \right)$$

$$\Gamma_N \quad \propto \quad m_N/E_N \qquad \text{decay rate of } N$$

$$\langle \Gamma_N \rangle \quad = \quad \frac{1}{n_N} g_N \int \frac{d^3p}{(2\pi)^3} f_N \, \Gamma_N$$

$$H = 0,\, n_N^{\text{eq}} = 0 \Rightarrow n_N(t) = n_N(0)\, e^{-\Gamma_N t}$$

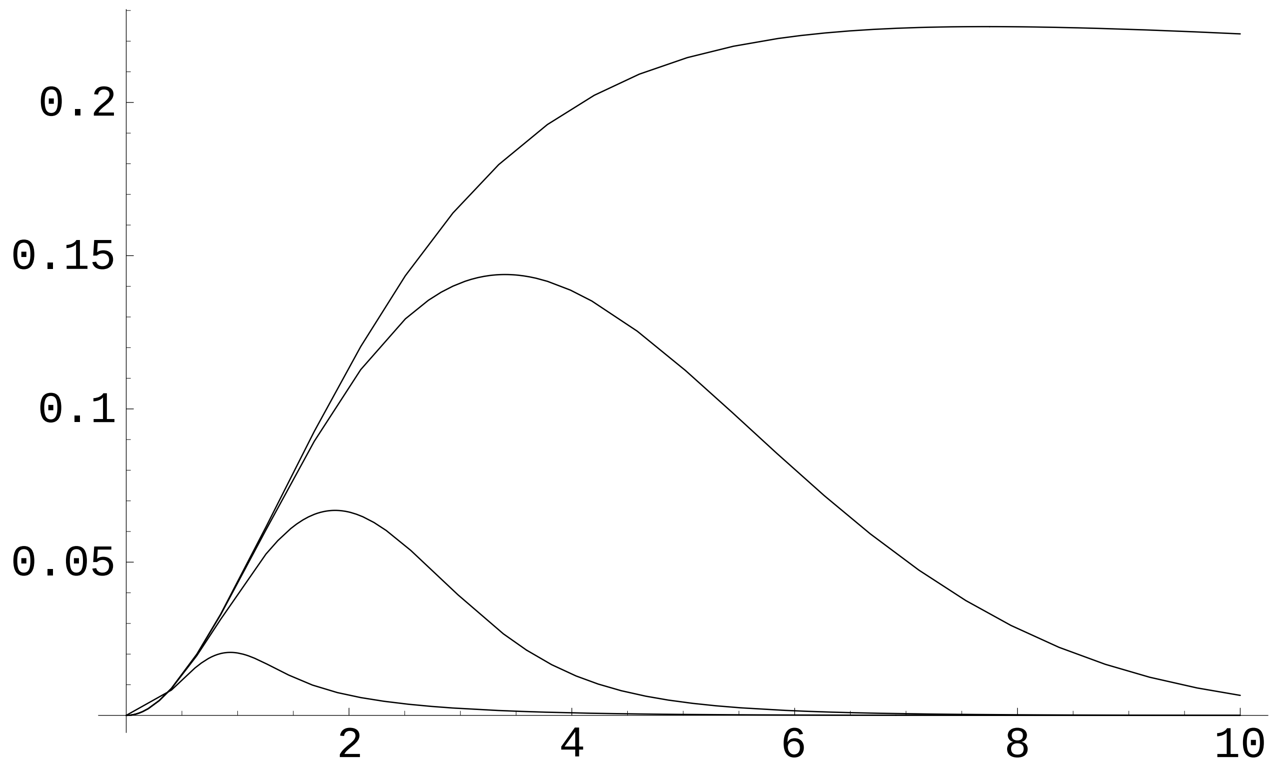
$$\begin{aligned} n_N^{\text{eq}} \quad &: \quad \text{inverse decay } \phi + \ell \to N,\, \bar{\phi} + \bar{\ell} \to N \\ f_N^{\text{eq}} \quad &\approx \quad e^{-E_N/T} = e^{-E_\ell/T}\, e^{-E_\phi/T} \approx f_\ell^{\text{eq}}\, f_\phi^{\text{eq}} \end{aligned}$$

in terms of $Y_N = n_N/s$ and $z = m_N/T$:

$$\frac{dY_N}{dz} \quad = \quad \frac{z \langle \Gamma_N \rangle}{H(1)} \left(Y_N - Y_N^{\text{eq}} \right)$$

$$\begin{aligned} \langle \Gamma_N \rangle \quad &\approx \quad z\, \Gamma_N(\infty)/2, \qquad z \ll 1 \\ &\approx \quad \Gamma_N(\infty), \qquad z \gg 1^* \end{aligned}$$

*) $\Gamma_N(\infty)$ is the decay rate at rest



Behavior of $(g_{*S}/g_N)\left(Y_N - Y_N^{\text{eq}}\right)$ vs $z = m_N/T$. Top to bottom: increasing $\Gamma_N(\infty)/H(1) = 0.01$, 0.1, 1, 10.

Y_N^{eq} falls exponentially fast; Y_N cannot keep up $\Rightarrow N$ decouples and decays freely, at later times with $\Gamma(\infty)$

The decay of N violates CP:

$$\epsilon = \frac{\Gamma(N \to \ell\phi) - \Gamma(N \to \bar{\ell}\bar{\phi})}{\Gamma(N \to \ell\phi) + \Gamma(N \to \bar{\ell}\bar{\phi})} < 0, \quad \text{CP asymmetry}$$

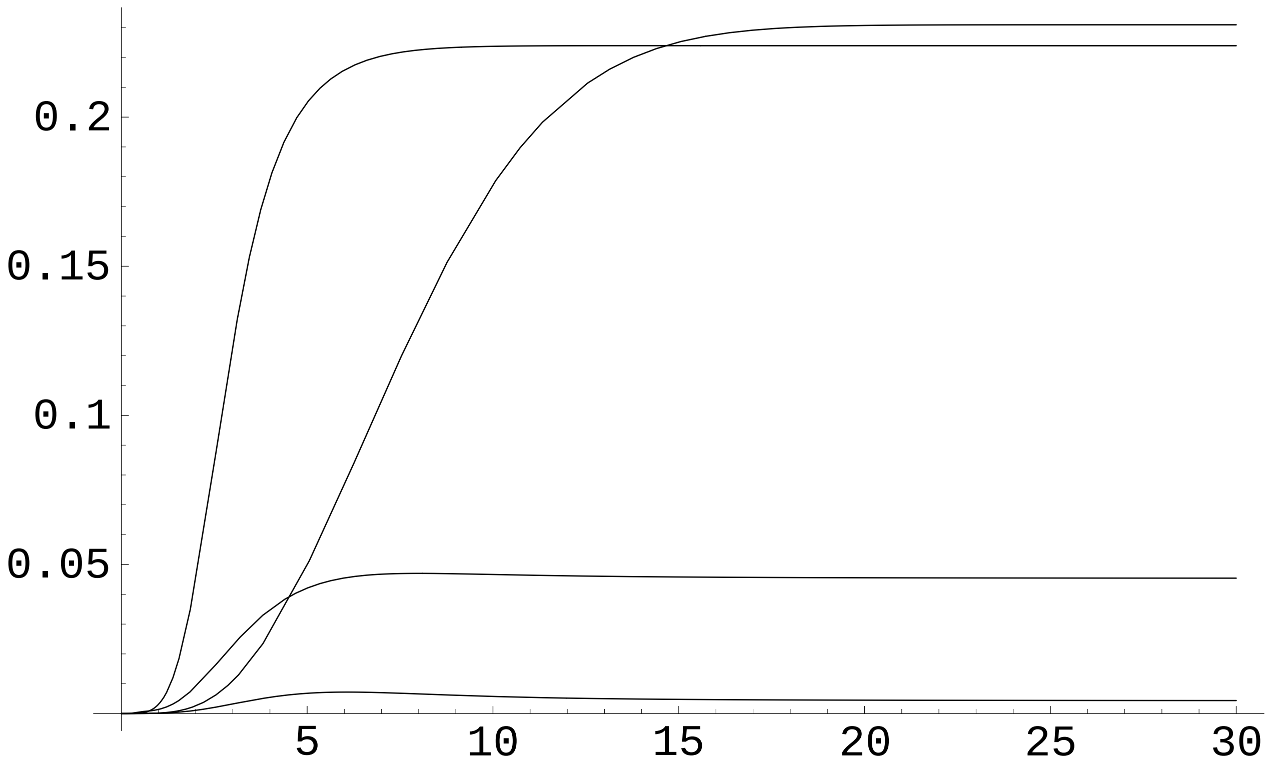
To first order in ϵ, $\mu_\ell = -\mu_{\bar{\ell}}$, $\mu_\phi = -\mu_{\bar{\phi}}$, equation for lepton asymmetry:

$$\begin{aligned} Y_L &= \frac{n_L}{s} \equiv \frac{n_\ell - n_{\bar{\ell}}}{s} \\ \frac{dY_L}{dz} &= \epsilon \frac{z\langle\Gamma_N\rangle}{H(1)} \left(Y_N - Y_N^{\text{eq}}\right) \\ &\quad - \frac{z\langle\Gamma_N\rangle}{H(1)} \left(\frac{5}{2}\frac{n_N^{\text{eq}}}{T^3} + 5\frac{\langle\sigma' v\rangle}{\langle\Gamma_N\rangle}\frac{n_\ell^{\text{eq}} n_\phi^{\text{eq}}}{T^3}\right) Y_L \end{aligned}$$

σ : cross section* for $\ell + \phi \leftrightarrow \bar{\ell} + \bar{\phi}$

the first term feeds the asymmetry, the second term damps the asymmetry
at late times the damping drops $\propto z^{-4}$ and Y_L becomes constant

*) σ' is the cross section with the intermediate-N contribution removed (this is already taken into account by the term $\propto (Y_N - Y_N^{\text{eq}})$)



Behavior of $(g_{*S}/\epsilon)Y_L$ vs $z = m_N/T$. Top to bottom: increasing $\Gamma_N(\infty)/H(1) = 0.04$, 1, 100, 1000. (The factor $z\left(\frac{5}{2}\frac{n_N^{\text{eq}}}{T^3} + 5\frac{\langle\sigma' v\rangle}{\langle\Gamma_N\rangle}\frac{n_\ell^{\text{eq}} n_\phi^{\text{eq}}}{T^3}\right)$ is modelled as $(1+z)^{-4}$.)

For small $\langle\Gamma_N\rangle/H(1)$, N decouples early, and

$$Y_L(\infty) \approx \epsilon\, Y_N^{\mathrm{eq}}(0) = 0.17\, \frac{g_N}{g_{*S}}\, \epsilon$$

In general, the final value of Y_L can be written as

$$Y_L(\infty) = c\, \frac{g_N}{g_{*S}}\, \epsilon$$

with $c < 0.17$ representing the effect of damping during decay

This gives for today, with $s = 7.04\, n_\gamma$, $g_N = 2$, and $Y_B = -Y_L/2$,

$$\frac{n_B}{n_\gamma} = -7.04\, g_N\, \frac{Y_L(\infty)}{2} = -\frac{7.04}{g_{*S}}\, c\, \epsilon$$

A close scrutiny, taking into account the measured properties of the neutrino masses, suggests that this a viable scenario for baryogenesis!

EW baryogenesis

Less pleasing aspects of leptogenesis:
- physics at very high energy scale $O(10^{10})$ GeV
- unknown parameters (including CP violation) involving heavy neutrinos

On the other hand:
- parameters in the quark sector of the SM have been measured, including CP violation
- CP violation in SM only possible with ≥ 3 generations, and *we observe* three generations!
- EW transition latest possibility for baryogenesis

SM baryogenesis during the EW transition?

- standard finite-temperature transition is too slow. The Hubble rate is very small at $T = T_{\text{EW}}$ ($H = O(10^{-14})$ GeV)

1st order? No, not for $m_H > 70$ GeV

"And now for something completely different":

Tachyonic EW preheating with CP bias

Assume inflation ends at a very low energy scale of order 100 GeV, resulting in a cold, empty universe

in the potential for the Higgs field ϕ,

$$V = \mu_{\text{eff}}^2\, \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$$

effective squared-mass changes sign*, e.g. caused by coupling to the inflaton field σ,

$$\begin{aligned} \mu_{\text{eff}}^2 &= \lambda_{\phi\sigma}\sigma^2 - \mu^2 > 0 \\ &\to -\mu^2 < 0, \qquad \sigma \to 0 \end{aligned}$$

instability, preheating

CP bias results in net baryon number

thermalization to $T \ll T_c$:
subsequent sphaleron transitions suppressed

*) usually assumed to be caused by falling T, here $T = 0$; name 'tachyonic' $\leftrightarrow$ $\mu_{\text{eff}}^2 < 0$

Dynamics dominated by Bose fields: SU(2) gauge field A and Higgs field ϕ
A_μ: vector potential*, $F_{\mu\nu}$: field strength of A_μ

lagrangian

$$
\begin{aligned}
-\mathcal{L} &= \frac{1}{2g^2}\,\mathrm{tr}\,F_{\mu\nu}F^{\mu\nu} + D_\mu\phi^\dagger D^\mu\phi \\
&\quad + \frac{\mu^4}{4\lambda} - \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \\
&\quad + \kappa\,\phi^\dagger\phi\,\frac{1}{2}\,\epsilon^{\mu\nu\rho\sigma}\mathrm{tr}\,F_{\mu\nu}F_{\rho\sigma}
\end{aligned}
$$

effective CP violation $\propto \kappa$, $[\kappa] = [\text{mass}]^{-2}$

a change in baryon number can be expressed in a change of Chern-Simons number $N_{\text{CS}}(A)$:

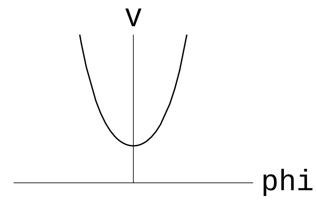
$$\Delta B = 3\,\Delta N_{\text{CS}}$$

Consider now $-\mu^2 \to \mu^2_{\text{eff}}$ in $\mathcal{L}$. Just after inflation the cold universe is in its ground state $A_\mu = \phi = 0$ (up to noise), corresponding to $\mu^2_{\text{eff}} > 0$

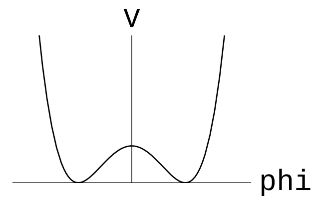
*) $\mu = 0, 1, 2, 3$, D_μ is a (gauge)covariant derivative

model EW transition by a quench:

$$\mu_{\text{eff}}^2 = +\mu^2, \qquad t > 0$$



$$= -\mu^2, \qquad t < 0$$



compute ΔN_{CS} as function of κ by numerical simulation

Simple analog model: abelian-Higgs model in 1+1 dimensions ($\mu = 0, 1$)

$$\begin{aligned} -\mathcal{L} &= \frac{1}{4e^2} F_{\mu\nu} F^{\mu\nu} + D_\mu \phi^* D^\mu \phi \\ &\quad + \frac{\mu^4}{4\lambda} - \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2 \\ &\quad + \kappa \frac{1}{2} \epsilon_{\mu\nu} F^{\mu\nu} \phi^* \phi \end{aligned}$$

Chern-Simons number

$$N_{\text{CS}}(t) = -\int_0^L dx\, A_1(x, t)$$

with L the "volume" of space (a circle)

Numerical results: abelian Higgs model

e.o.m in temporal gauge $A_0 = 0$

$$\begin{aligned}\ddot{\phi} &= D_1^2\phi + (\mu^2 - 2\lambda\phi^*\phi)\phi + \kappa\,\dot{A}_1\,\phi \\ \ddot{A}_1 &= e^2\,i(D_1\phi^*\phi - \phi^* D_1\phi) - e^2\kappa\,\partial_0(\phi^*\phi)\end{aligned}$$

Gauss constraint

$$-\partial_1\dot{A}_1 = e^2\,i(\dot{\phi}^*\phi - \phi^*\dot{\phi}) + e^2\kappa\,\partial_1(\phi^*\phi)$$

Chern-Simons number

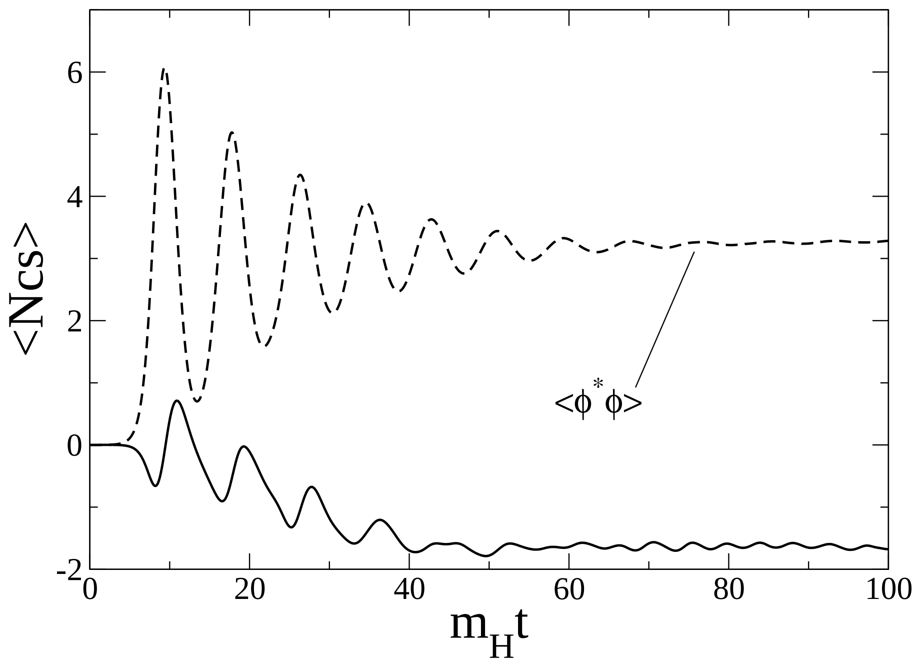
$$N_{\rm CS}(t) = -\frac{1}{2\pi}\int_0^L dx\,A_1(x,t)$$

$m_H^2 = 2\mu^2$, $m_W^2 = (e^2/2\lambda)\,m_H^2$

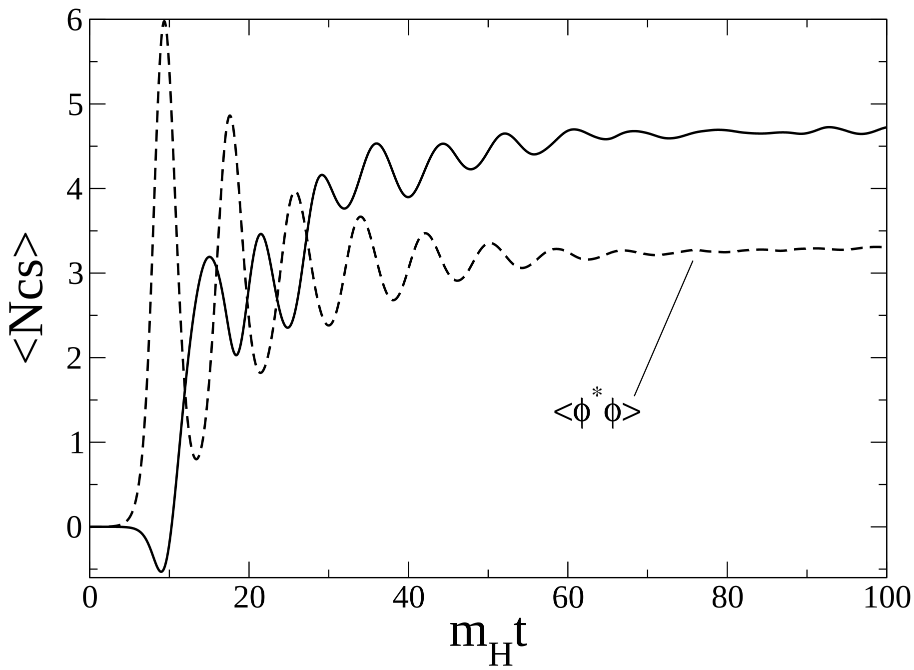
Space-time lattice: spatial spacing $am_H = 0.3$
volume typically $Lm_H = 512 \times 0.3 = 153.6$
coupling typically $\mu^2/\lambda = 4$, $\kappa \in [-0.05, 0.05]$.

generate initial configurations for ϕ and $\dot{\phi}$, with $A_1 = 0$ and $\dot{A}_1$ satisfying Gauss constraint
'measure' $N_{\rm CS}$

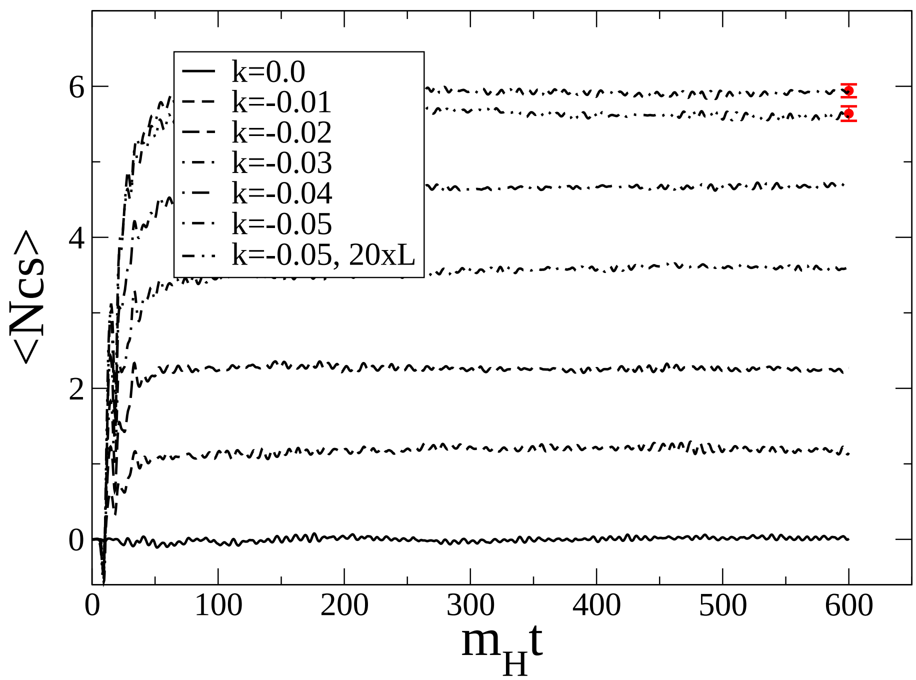
Examples of $\langle\phi^*\phi\rangle$ and $\langle N_{\mathsf{CS}}\rangle$ for $\kappa = -0.05$



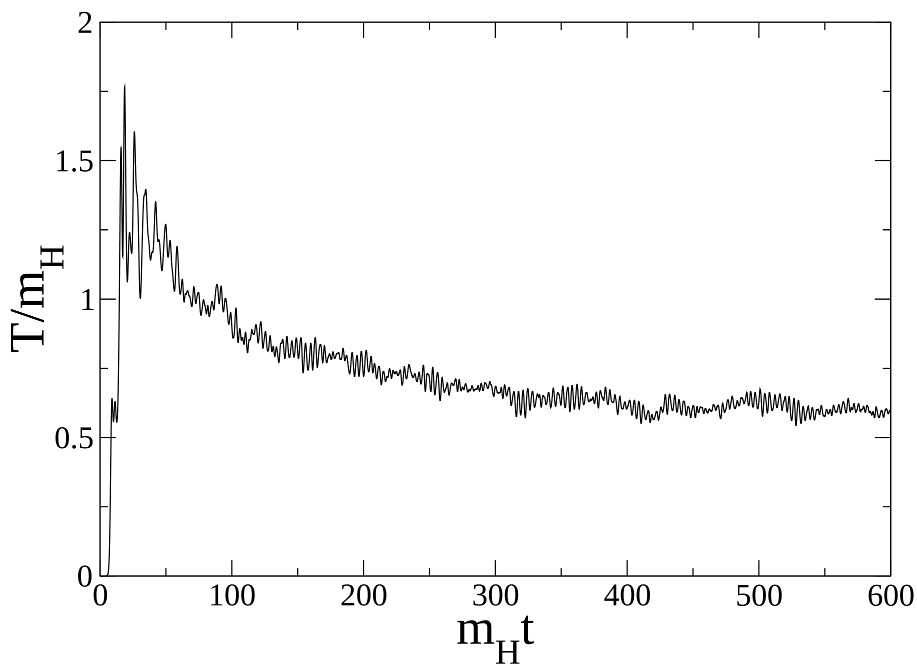
$m_H/m_W = 0.625$ (top) and 1.0625 (bottom)



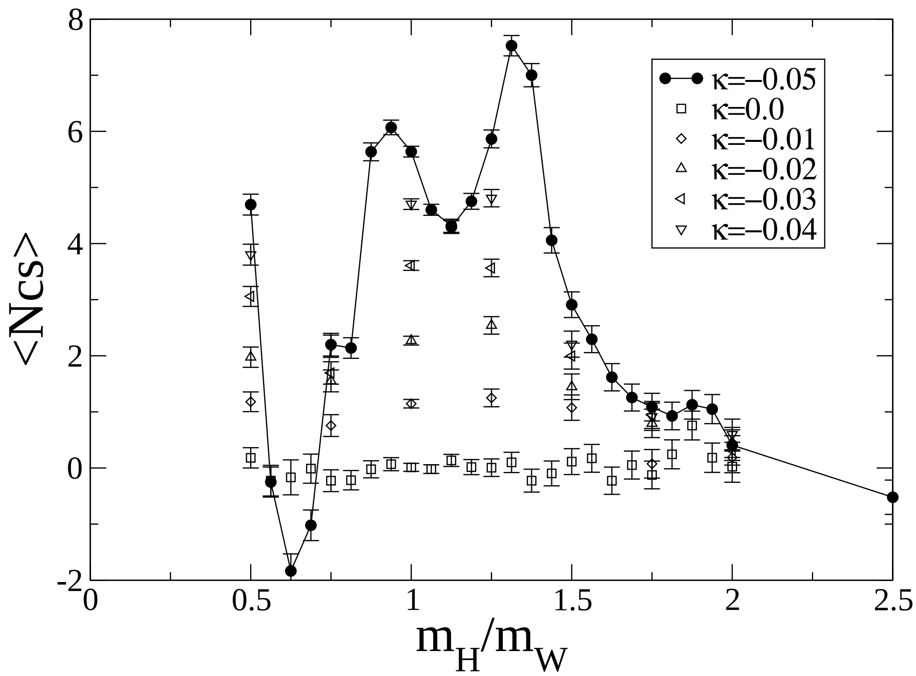
$\langle N_{\mathrm{CS}} \rangle$ & $\langle N_{\mathrm{CS}} \rangle/20$ in $20 \times L$



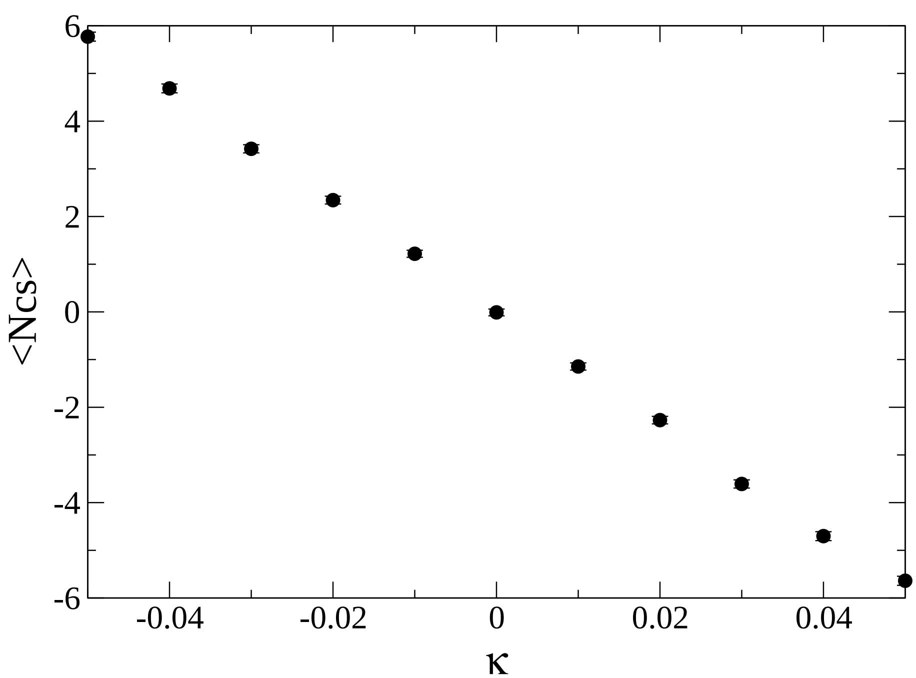
Effective temperature in long-wavelength modes



Dependence of final $\langle N_{\text{CS}} \rangle$ on m_H/m_W



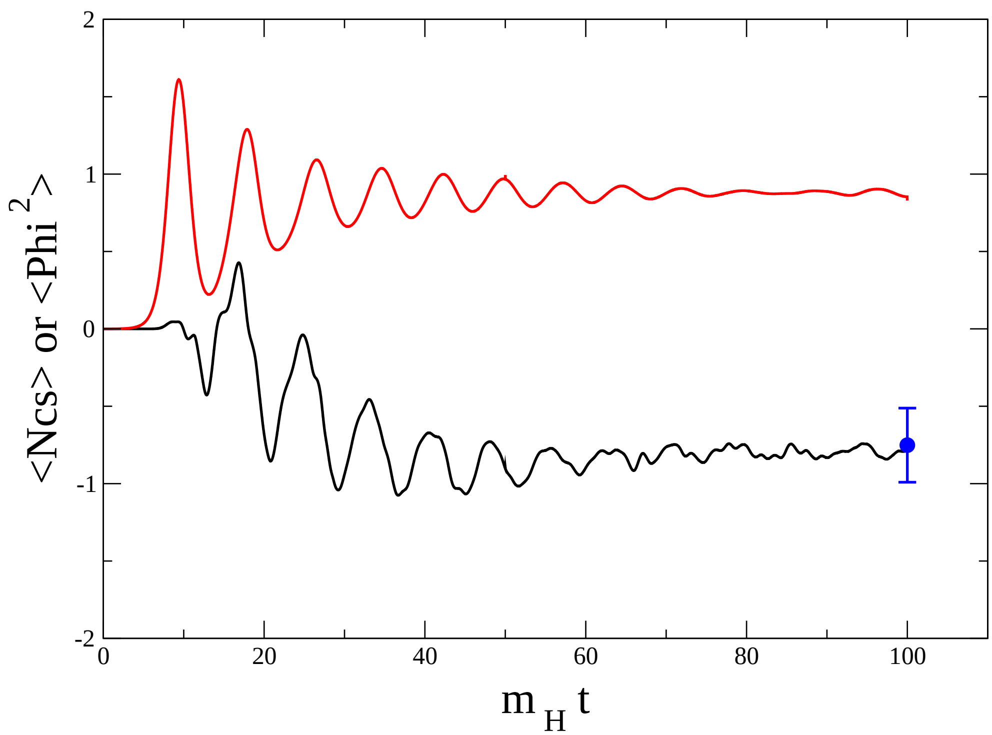
Dependence on κ



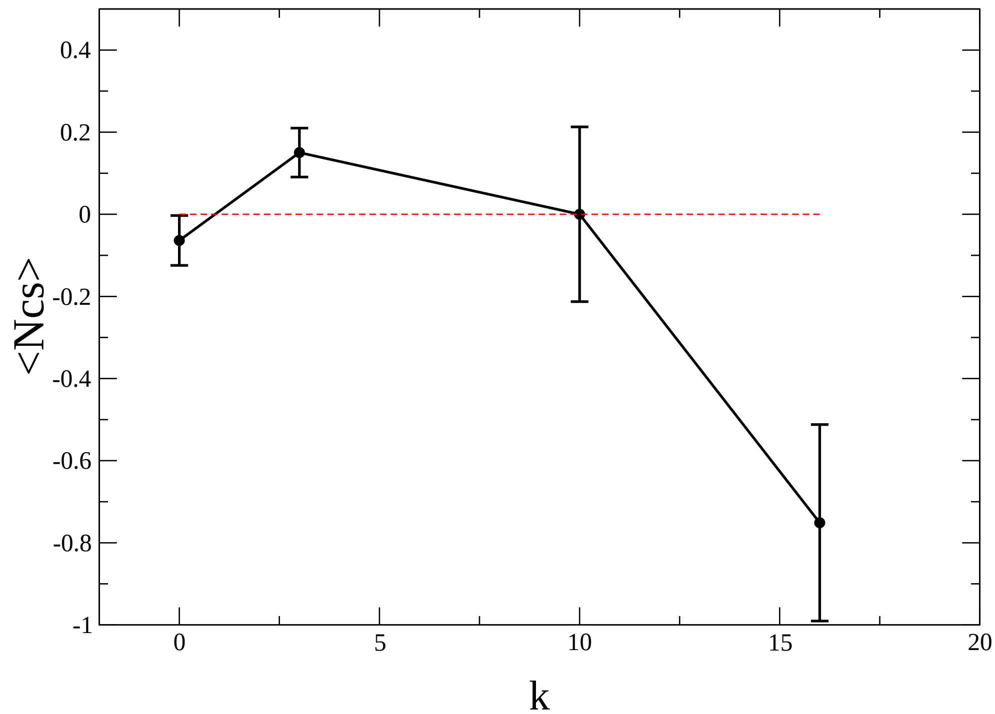
conclusion:
- κ dependence linear
- no sphaleron wash-out
- interesting dependence on m_H/m_W

Preliminary results for the SU(2) Higgs model

Space-time lattice, spatial spacing $am_H = 0.35$
Volume $(Lm_H)^3 = (60 \times 0.35)^3 = 21^3$
$m_H/m_W = 1$



$\langle N_{\mathrm{CS}}\rangle$ and $\langle \phi^\dagger \phi\rangle$ vs time, $\kappa\, m_W^2 = 1/\pi^2$



$\langle N_{\mathrm{CS}} \rangle$ versus κ looks strange ($k = 16\pi^2\, \kappa\, m_W^2$)

Preliminary results indicate substantial effect: assuming potential energy $\mu^4/4\lambda$ is converted to relativistic d.o.f. with $g_* = 80$ (photons, leptons, quarks, gluons), the $k = 1$ result gives

$$\frac{n_B}{n_\gamma} \approx 7 \times 10^{-3}\, \kappa\, m_W^2$$

How large is κ?

$\kappa = \delta_{\mathrm{CP}}/M^2$ represents approximately CP-violating effects of 'physics beyond the SM', at energy-scale M. $M = 10^3$ GeV $\Rightarrow$ δ_{CP} has to be $O(10^{-5})$, which appears reasonable

Within SM we have to replace the effective κ-interaction by the actual interactions of the (quantized) Fermi fields to the Bose fields. We hope to undertake this task (difficult, theoretically as well as numerically) in the near future

In conclusion ...

The problem of baryogenesis poses a great challenge for particle theory (beyond the SM?) and it brings together many parts of (astro)physics

Literature:

Kolb and Turner chapter 6 (see also ch. 5).

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C. Zwanenveld, afstudeerscriptie, UvA, 2002.

For tachyonic electroweak baryogenesis: A. Tranberg and J. Smit, hep-ph/0211243, hep-ph/0210349, hep-ph/0210348, and references therein.