Spontaneous Leptogenesis via Modulus Oscillations after Inflation

Kai Schmitz

Postdoc in the Particle and Astroparticle Physics Division at

Max Planck Institute for Nuclear Physics (MPIK), Heidelberg, Germany

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Based on *PRL **115**, 011302 (2015), arXiv:1412.2043 [hep-ph]*.

In collaboration with Alexander Kusenko (UCLA) and Tsutomu T. Yanagida (IPMU).

Teilchentee Seminar | ITP Heidelberg University | January 21, 2016

Standard baryogenesis à la Sakharov

Problem: Explain the baryon asymmetry of the Universe! (Not possible in the SM!)

$$\eta_B^0 \simeq \frac{n_b^0}{n_\gamma^0} \simeq 6 \times 10^{-10} \quad \Rightarrow \quad \text{Why} \quad \eta_b^0 \gg \eta_{\bar{b}}^0 \quad \text{and why} \quad \eta_b^0 \gg \eta_b^{\mathrm{eq}} \sim 10^{-18} \quad ?$$

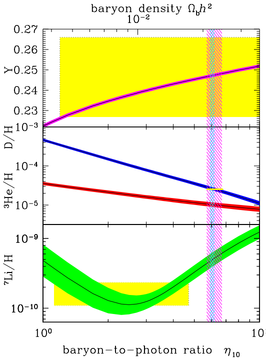
Conventionally: Dynamical mechanism satisfying the three Sakharov conditions: [Sakharov '67]

- *B* (or *L*) violation
- *C* and *CP* violation
- Out-of-equilibrium

Popular scenarios:

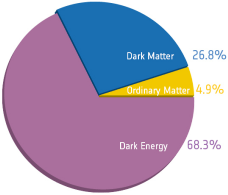
- EW baryogenesis
- Affleck-Dine mechanism
- Leptogenesis
- ...

Big bang nucleosynthesis



[PDG Review]

CMB fluctuations



[PLANCK Collaboration]

Baryogenesis in consequence of *CPT* violation (1)

However: All of these standard scenarios rely on the assumption of *CPT* invariance.

Alternatively: In an expanding universe at $T \neq 0$, CPT may be spontaneously broken.

- E.g., time-dependent evolution of some background scalar field after inflation.
- Baryogenesis even possible in thermal equilibrium or without $\not{CP}$. [Cohen & Kaplan '87]

$\rightarrow$ Paradigm of spontaneous baryogenesis!

Cohen & Kaplan: Time-dependent background provided, e.g., by pseudo-Nambu-Goldstone boson of a spontaneously *and* explicitly broken $U(1)$.

Baryogenesis in consequence of *CPT* violation (2)

Fully worked example in the context of the MSSM:

- Spontaneous baryogenesis along flat directions in the MSSM. [Chiba, Takahashi & Yamaguchi '04]

Recently, increased interest in consequence of the discovery of the SM Higgs:

- Leptogenesis during Higgs relaxation after the end of inflation. [Kusenko, Pearce & Yang '14]
- Several follow-up projects: Leptogenesis during Majoron relaxation [Ibe & Kaneta '15], leptogenesis via neutrino production during Higgs relaxation [Pearce, Peloso, Kusenko & Yang '15].

This talk: Generalization to leptogenesis during relaxation of an arbitrary modulus.

Main insights:

- LNV inherent to seesaw mechanism sufficient for *CPT*-violating leptogenesis.
- Constraints on properties of the modulus field $\rightarrow$ possible link to string theory.

See also recent papers on "spontaneous baryogenesis in the axiverse". [Takahashi et al. '15]

Outline

1. Model: Modulus relaxation as a novel opportunity for leptogenesis

2. Results: Efficiency of leptogenesis depending on axion parameters

3. Discussion: Comparison with other leptogenesis scenarios

4. Summary and outlook

Outline

$\cancel{CPT}$ from a time-dependent axion background

- Consider time-dependent axion-like field coupling to the electroweak gauge bosons.

$$\mathscr{L}_{\rm eff} \supset \frac{a}{f_a}\frac{g^2}{32\pi^2}\,\mathrm{Tr}\left[F_{\mu\nu}\widetilde{F}^{\mu\nu}\right] \quad \text{with} \quad \dot{a}(t) \neq 0 \quad \text{and} \quad F_{\mu\nu} = W_{\mu\nu}, B_{\mu\nu}\,.$$

Nonzero axion velocity $\dot{a}$ $\Rightarrow$ CP preserved. T and CPT spontaneously broken.

- Suppose the pseudoscalar a corresponds to the PNGB of a spontaneously broken global "Peccei-Quinn" symmetry that is anomalous under $SU(2)_L$ and/or $U(1)_Y$.
- Present in many models: model-independent / model-dependent axions in string theory, axion related to global symmetries in models of hidden strong dynamics, etc. [Witten '84; Witten '85; Choi & Kim '85; Svrcek & Witten '06]
- In string theory, one linear combination of axions might, for instance, couple to $F\tilde{F}$.

$$\frac{a}{f_a}\frac{g^2}{32\pi^2} \sim \frac{a}{M_{\rm Pl}} \quad \Rightarrow \quad f_a \sim 10^{15}\cdots 10^{16}\,\mathrm{GeV}$$

Note: Axion a represents dynamical version of electroweak vacuum angle $\theta_{\rm EW}$. [Patel & Pérez '14]

Axion-induced chemical potential (1)

What is the coupling $a F \tilde{F}$ good for? To see this, let us rewrite it in terms of $\dot{a} = \partial_t a(t)$.

Perform a quark phase rotation, i.e., a $U(1)_B$ transformation:

$$Q \to Q \exp\left(-i B \theta\right) , \quad Q = q, u, d , \quad \theta = \frac{1}{N_f} \frac{a}{f}$$

- Do not rotate leptons, since we assume $U(1)_L$ to be broken by $\mathscr{L} \supset \frac{1}{M} \ell H \ell H$.
- $\delta\mathscr{L}$ receives contributions from path integral measure & quark kinetic terms,

$$\delta\mathscr{L} = -N_f \, \theta \, \frac{g^2}{32\pi^2} F\tilde{F} + \frac{1}{3N_f} \frac{1}{f_a} \left(\partial_\mu a\right) J_Q^\mu$$

- Anomalous axion coupling rotated away! Because $\langle a \rangle \neq \mathrm{const.}$, still physical effects.
- If $\langle a \rangle = \mathrm{const.}$, vacuum angle θ_{EW} only physical if *B and L* were broken. [Patel & Pérez '14]

$aF\tilde{F}$ can be traded for a coupling of the axion to the quark number current J_Q^μ.

Axion-induced chemical potential (2)

Impose spatial homogeneity:

$$\frac{1}{3N_f}\frac{1}{f_a}\left(\partial_\mu a\right) J_Q^\mu \quad \rightarrow \quad \frac{1}{3N_f}\frac{1}{f_a}\dot{a}(t)\, J_Q^0 \quad \text{where} \quad J_Q^0 \equiv n_Q$$

$\dot{a}/f_a$ acts as an external chemical potential for the quark number: $\mu_q^{\text{ext}} = 1/(3N_f)\,\dot{a}/f_a$

To see this, notice that μ_q^{ext} induces a splitting between the quark / antiquark energy levels:

- Consider classical particle / antiparticle solutions of the free part of the Lagrangian:

$$q(p) = u(p)\, e^{-i p\cdot x} e^{-\mu_q^{\text{ext}} t}\,, \quad \bar{q}(p) = v(p)\, e^{i p\cdot x} e^{-\mu_q^{\text{ext}} t}$$

- Thus, shift in the energy dispersion relations of quarks and antiquarks:

$$E_q \rightarrow |\vec{p}| + \mu_q^{\text{ext}}\,, \quad E_{\bar{q}} \rightarrow |\vec{p}| - \mu_q^{\text{ext}}$$

- Modified quark phase space distribution functions in kinetic equilibrium:

$$f_q = \frac{1}{\exp\left[\left(|\vec{p}| + \mu_q^{\text{ext}} - \mu_q^{\text{bare}}\right)/T\right] + 1} \quad \Rightarrow \quad \mu_q^{\text{eff}} = \mu_q^{\text{bare}} - \mu_q^{\text{ext}}$$

Number densities in thermal equilibrium

Assume all SM gauge, Yukawa and sphaleron interactions to be in chemical equilibrium:

- Asymmetry in all fermion number densities with nonzero effective chemical potential:

$$n_{f,\bar{f}} = n_{f,\bar{f}}^0 \exp\left[\pm\mu_f^{\mathrm{eff}}/T\right] , \quad n_{f,\bar{f}}^0 \sim T^3 , \quad n_f - n_{\bar{f}} \sim \mu_f^{\mathrm{eff}}\, T^2$$

- Nonzero μ_q^{eff} induces, in particular, nonzero effective chemical potential for $B-L$:

$$\mu_{B-L}^{\mathrm{eff}} = N_f \left(2\mu_q^{\mathrm{eff}} + \mu_u^{\mathrm{eff}} + \mu_d^{\mathrm{eff}} - 2\mu_\ell^{\mathrm{eff}} - \mu_e^{\mathrm{eff}}\right) = -\frac{28}{33}\frac{\dot{a}(t)}{f_a} \simeq -\frac{\dot{a}(t)}{f_a}$$

- Nonvanishing $B-L$ asymmetry even in thermal equilibrium:

$$n_{B-L}^{\mathrm{eq}} \sim \mu_{B-L}^{\mathrm{eff}}\, T^2$$

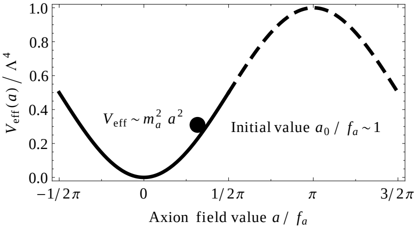
To use this result for leptogenesis, we have to answer two questions in the following:

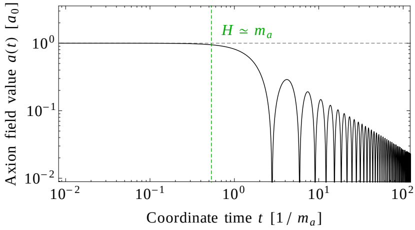
Q1: How do we set the axion field in motion, so that it evolves with $\dot{a} \neq 0$ for some time?

Q2: What force drives the actual number density n_{B-L} towards its equilibrium value n_{B-L}^{eq}?

A1: Axion relaxation after inflation

$$\ddot{a} + 3H\dot{a} = -\partial_a V_{\rm eff}(a)$$





Q1: How do we set the axion in motion, so that it evolves with $\dot{a} \neq 0$ for some time?

Time evolution of the axion background:

- $V_{\rm eff}$ from, e.g., coupling to strong dynamics in some hidden sector.
- Suppose strongly coupled $SU(N)$ anomalous under PQ symmetry,

$$V_{\rm eff} \sim m_a^2 a^2\,, \quad m_a = \Lambda^2/f_a$$

- Field value smoothed out during inflation over superhorizon scales.
- As long as $H \gtrsim m_a$, field value constant due to Hubble friction.
- Once $H \lesssim m_a$, oscillations around $a = 0$ with frequency $\omega = m_a$.

A1: Coherent oscillations around the minimum of the effective potential after inflation.

Constraints on parameter space

Upper bound on the inflationary Hubble rate:

- Baryon asymmetry will depend on the initial axion field value after inflation, a_0.
- Avoid large baryonic isocurvature perturbations due to axion quantum fluctuations:
  [Peebles '87; Enqvist & McDonald '99; Kawasaki et al. '14]

$$\frac{\delta a}{a_0} \lesssim 10^{-5}\,, \quad a_0 \sim f_a\,, \quad \delta a \simeq \frac{H_{\rm inf}}{2\pi} \quad \Rightarrow \quad H_{\rm inf} \lesssim 6 \times 10^{11}\,\mathrm{GeV}\left(\frac{f_a}{10^{15}\,\mathrm{GeV}}\right)$$

- Preference for small-field inflation. Testable in CMB polarization experiments.

Upper bounds on the axion mass and the inflaton decay rate:

- Require the axion to remain stabilized at its initial value until the end of inflation:

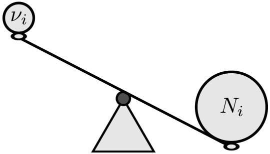
$$m_a \lesssim H_{\rm inf} \lesssim H_{\rm inf}^{\rm max}$$

- Prevent the inflaton from undergoing perturbative decay before the end of inflation:

$$\Gamma_\varphi \lesssim H_{\rm inf} \lesssim H_{\rm inf}^{\rm max}\,, \quad T_{\rm rh} \simeq 0.4\sqrt{\Gamma_\varphi M_{\rm Pl}}$$

Investigate remaining axion-inflaton parameter space spanned by f_a, m_a, and $T_{\rm rh}$.

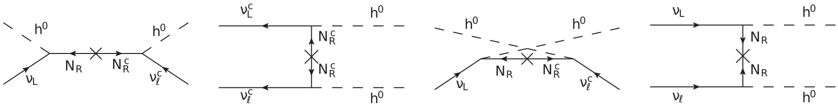
A2: Lepton number violation due to Majorana neutrinos



Q2: What drives the $B-L$ number density towards $n_{B-L}^{\rm eq}$?

- Extend the particle content of the SM by three generations of right-handed neutrinos, N_1, N_2, N_3.
- Small SM neutrino masses accounted for by the seesaw mechanism. [Yanagida '79; Gell-Mann, Ramond & Slansky '79]

Rapid $\Delta L = 2$ two-to-two scattering processes mediated by heavy Majorana neutrinos:



[Kusenko, Pearce & Yang '14]

- Assume for simplicity neutrino masses $M_i \sim \mathcal{O}\left(10^{-2} \cdots 10^0\right) \times \Lambda_{\rm GUT}$, so as to seperate our mechanism from contributions from ordinary thermal leptogenesis.
- Do not require any particular mass pattern nor any specific amount of CP violation in the heavy neutrino sector. The final asymmetry will be independent of these details.

Outline

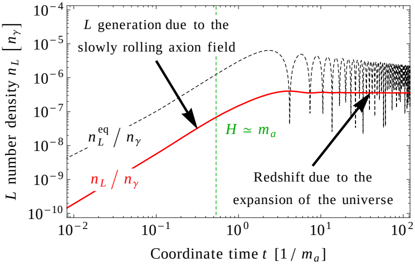
Computation of the final lepton asymmetry

Description based on Boltzmann equations:

[Giudice et al. '03; Buchmüller, Di Bari & Plümacher '04]

$$\dot{n}_{B-L} + 3\,H\,n_{B-L} \simeq 4\,n_\ell^{\rm eq}\,\sigma_{\rm eff}\left(n_{B-L}^{\rm eq} - n_{B-L}\right)$$

- n_{B-L} driven towards $n_{B-L}^{\rm eq} \propto \dot{a}/f_a\,T^2$.
- $\dot{a}$ acts as an adiabatic background.
- $\sigma_{\rm eff} \approx \frac{3}{32\pi\,v_{\rm ew}^4}\sum_i m_i^2 \simeq 10^{-31}\,{\rm GeV}^{-2}$.
- $\sum_i m_i^2 \lesssim (0.2\,{\rm eV})^2$ does not apply.



Equilibrium density actually never reached.

Require $\Delta L = 2$ scatterings to be in equilibrium before the onset of axion oscillations:

$$\Gamma_L \gtrsim H \gtrsim m_a\,, \quad \Gamma_L = 4\,n_\ell^{\rm eq}\,\sigma_{\rm eff}$$

- Typical temperature scale and axion mass scale in our leptogenesis scenario:

$$T \sim T_L = g_*^{1/2}\left(\pi\,\sigma_{\rm eff}\,M_{\rm Pl}\right)^{-1} \sim 10^{13}\,{\rm GeV}\,, \quad m_a \sim \sigma_{\rm eff}\,T_L^3 \sim 10^8\,{\rm GeV}\,.$$

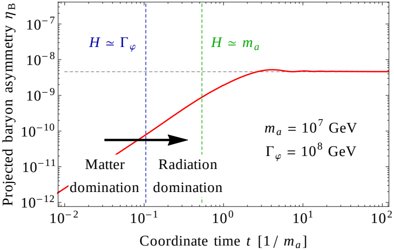
Anticipate: High-temperature alternative to thermal leptogenesis (where $T_{\rm rh} \gtrsim 10^9\,{\rm GeV}$).

Interplay between leptogenesis and reheating

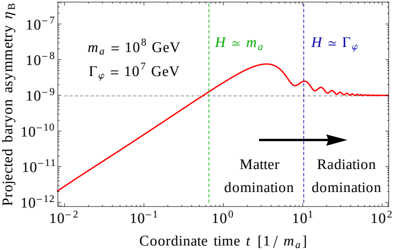
Lepton asymmetry converted to baryon asymmetry by electroweak sphaleron processes:

$$\eta_B^0 = c_{\mathrm{sph}} \frac{g_{*,s}^0}{g_*} \eta_{B-L} \simeq 0.013\, \eta_{B-L} \,.$$

$m_a \ll \Gamma_\varphi$



$m_a \gg \Gamma_\varphi$



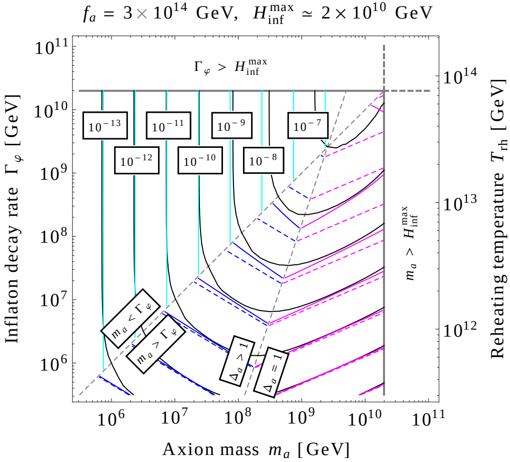
Oscillations after the end of reheating:

- Leptogenesis unaffected by reheating.
- Final asymmetry $\eta_B = \eta_B(m_a)$.

Oscillations before the end of reheating:

- Initial asymmetry diluted due to entropy production in inflaton decays.
- Final asymmetry $\eta_B = \eta_B(m_a, T_{\mathrm{rh}})$.

Baryon asymmetry as a function of m_a and $T_{\rm rh}$



Entropy production in the late-time decays of the axion:

- Axion decay rate:

$$\Gamma_a \simeq \frac{\alpha^2}{64\pi^3}\frac{m_a^3}{f_a^2}\,, \quad \alpha = \frac{g_2^2}{4\pi}$$

- Axion decay temperature:

$$T_{\rm dec} \simeq 10\,\mathrm{TeV}\left(\frac{m_a}{10^9\,\mathrm{GeV}}\right)^{\frac{3}{2}}\left(\frac{10^{15}\,\mathrm{GeV}}{f_a}\right)$$

- Dilution of the baryon asymmetry

$$\eta_B \rightarrow \frac{1}{\Delta_a}\eta_B\,, \quad \Delta_a = 1 \cdots \Delta_a \gg 1\,.$$

Parameter dependence of the final asymmetry different depending on
(1) the ratio m_a/Γ_φ as well as on (2) the impact of the late-time decays of the axion (Δ_a).

Viable parameter space

$4 \times 10^{10}\,\mathrm{GeV} \lesssim f_a \lesssim 4 \times 10^{15}\,\mathrm{GeV}$

- Smaller f_a: too large baryonic isocurvature perturbations.
- Larger f_a: too strong dilution due to late-time entropy production.

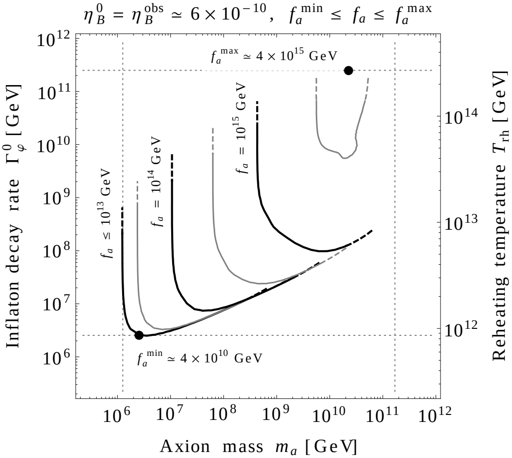
Viable parameter ranges:

$1 \times 10^{6}\,\mathrm{GeV} \lesssim m_a \lesssim 2 \times 10^{11}\,\mathrm{GeV}$

$3 \times 10^{6}\,\mathrm{GeV} \lesssim \Gamma_\varphi \lesssim 3 \times 10^{11}\,\mathrm{GeV}$

$9 \times 10^{11}\,\mathrm{GeV} \lesssim T_{\mathrm{rh}} \lesssim 3 \times 10^{14}\,\mathrm{GeV}$

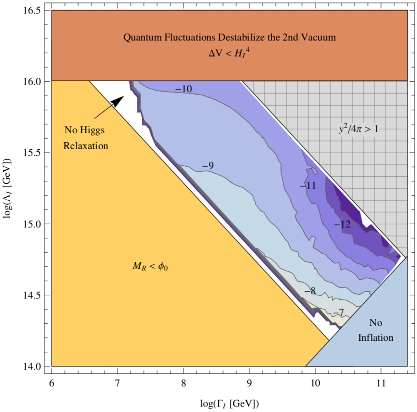
- Temperature significantly higher than for thermal leptogenesis.



Successful leptogenesis for parameter values as they appear in many axion models. Complementary to standard thermal leptogenesis, where $T_{\mathrm{rh}} \sim 10^{10}\,\mathrm{GeV}$ typically.

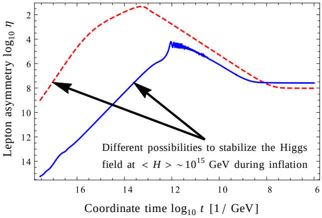
Outline

Axion-induced vs. Higgs-induced leptogenesis [Kusenko, Pearce & Yang '14]



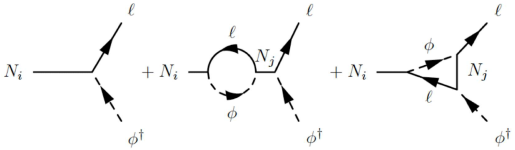
How about other scalars coupling to $F\tilde{F}$?

- One possibility: $a \to$ SM Higgs field.
- Require initial Higgs VEV of $\mathcal{O}\left(10^{15}\right)$ GeV after inflation.
- Potentially problematic because of EW vacuum stability as well as baryonic isocurvature perturbations.
- Stabilize Higgs VEV by means of higher-dimensional self-interactions or couplings to the inflaton field.



Viable and testable, but perhaps slightly fine-tuned alternative to our scenario!

Axion-induced vs. thermal leptogenesis [Fukugita & Yanagida '86]



Same, same, but different:

- Slightly larger particle content: heavy Majorana neutrinos + “axion“.
- Much higher T_{rh} required. $\rightarrow$ Constraints on, e.g., SUSY model building.
- Consistent with degenerate heavy neutrino masses close to the GUT scale.
- Independent of the amount of CP violation in the heavy neutrino sector.
- Upper bound on light neutrino masses, $\sum_i m_i^2 \lesssim (0.2\,\mathrm{eV})^2$, does not apply.

Very attractive alternative in case thermal leptogenesis begins to look less favorable!

Outline

Axion-induced spontaneous leptogenesis

Leptogenesis: a sailing trip in rough seas

[Janine Casse, Mauritian artist]

- Oscillating axion background $\leftrightarrow$ Surface of the sea, rising and falling as the tide comes in and goes out.
- Leptons / antileptons $\leftrightarrow$ Sailors that prefer to sail during high / low tide.
- $\Delta L = 2$ scatterings $\leftrightarrow$ Wind allowing the sailors to return to the shore.
- Final lepton asymmetry *fixed once the wind stops blowing and the sailors can no longer return to the shore.*

Next steps (some of which are work in progress):

- Better analytical understanding of the effect of washout during and after reheating.
- Assess whether the role of the axion field could also be played by the inflaton.
- Embedding into larger framework (possibly incl. supersymmetry, the QCD axion, etc.)

Exciting new direction in the field of leptogenesis. Stay tuned!

Thank you for your attention!