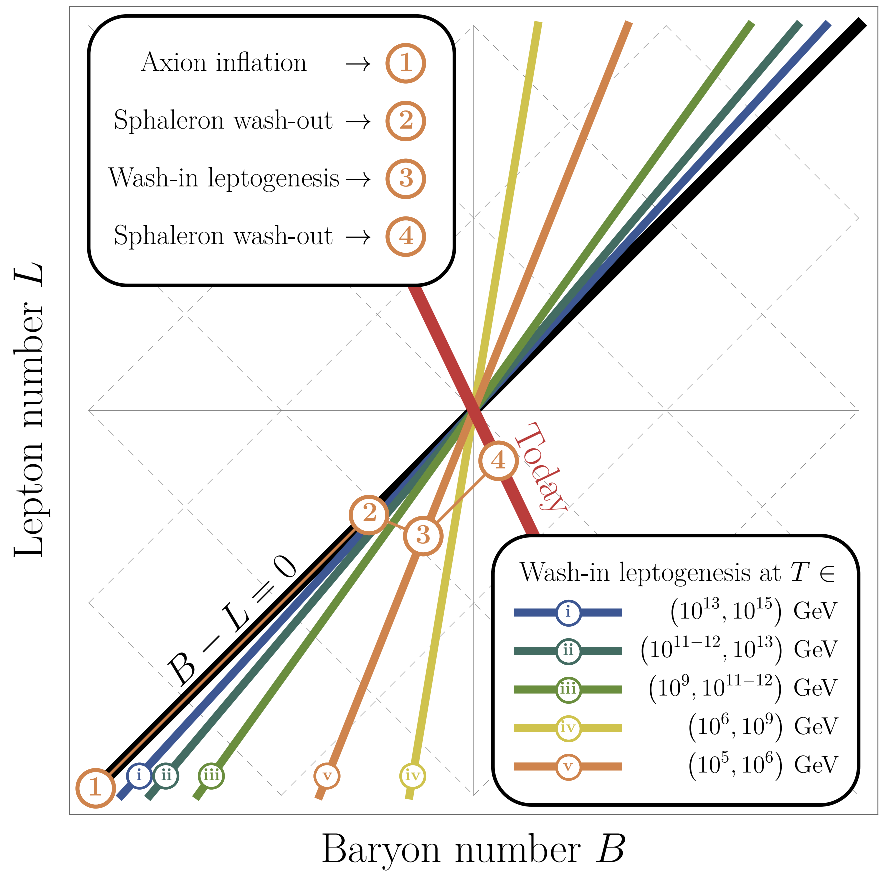
Wash-in leptogenesis



Valerie Domcke
CERN/EPFL

APEC Seminar @ IPMU,
02.12.2020

mainly based on arxiv:2011.09347
in collaboration with
Kohei Kamada, Kyohei Mukaida, Kai Schmitz, Masaki Yamada

introduction: baryogenesis

$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$

in the very early Universe

particles >> anti-particles

$$\frac{n_B}{n_\gamma} \sim 10^{-9}$$

Sakherov `67

Sakherov conditions:

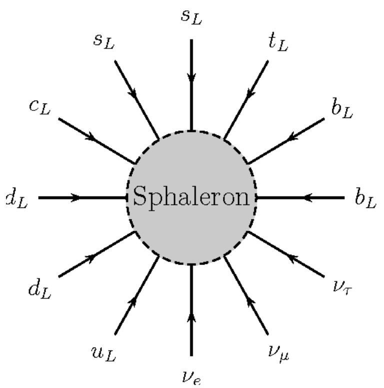
- B violation
- C and CP violation
- departure from thermal equilibrium

introduction: baryogenesis

GUT baryogenesis unification of forces Yoshimura `78, Dimopoulos, Susskind `78

$$X \xrightarrow[y_t]{\not{CP}} \mathrm{SM}$$

B + L asymmetry



But: non-perturbative sphaleron processes
wash out B+L asymmetry Kuzmin, Rubakov, Shaposhnikov `85

introduction: baryogenesis

GUT baryogenesis — unification of forces — Yoshimura `78, Dimopoulos, Susskind `78

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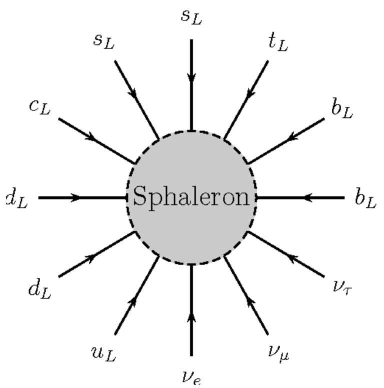

But: non-perturbative sphaleron processes wash out B+L asymmetry — Kuzmin, Rubakov, Shaposhnikov `85

Leptogenesis — neutrino masses — Fukugita, Yanagida `86

$$N_R \;\underset{y_N}{\overset{\not{CP}}{\longrightarrow}}\; \ell\phi\,,\bar{\ell}\bar{\phi}$$

B - L asymmetry

- N_R need to remain out of equilibrium (→ upper bound on y_N)
- sufficient CP violation requires $M_N > 10^9$ GeV

Davidson, Ibarra `02,
Buchmüller, Bari, Plümacher `02

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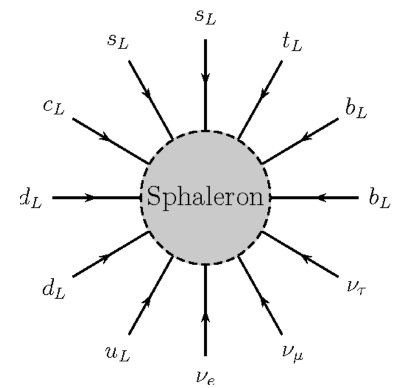
B + L asymmetry



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Davidson, Ibarra `02, Buchmüller, Bari, Plümacher `02

This talk: combine these two ideas

Outline

- SM interactions and conserved charges
- Wash-in leptogenesis
- initial conditions: GUT baryogenesis & axion inflation
- (spontaneous baryogenesis)

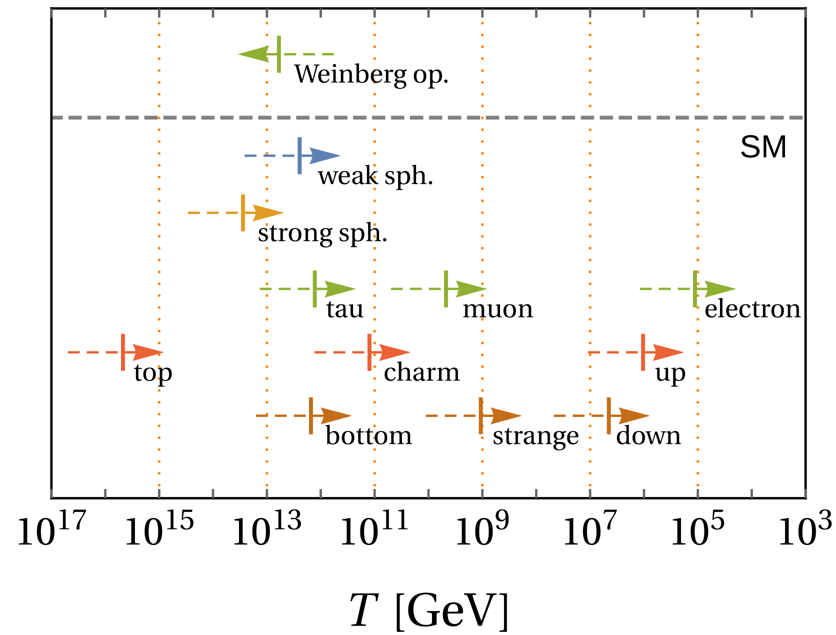
SM interactions and conserved charges

VD, Ema, Mukaida, Masaki `20

- exactely conserved charges: $B/3 - L_\alpha \, , \, Y$

  (lepton flavour, hypercharge)

- in the early Universe, SM interactions cannot keep up with expansion



→ additional approximately conserved charges:

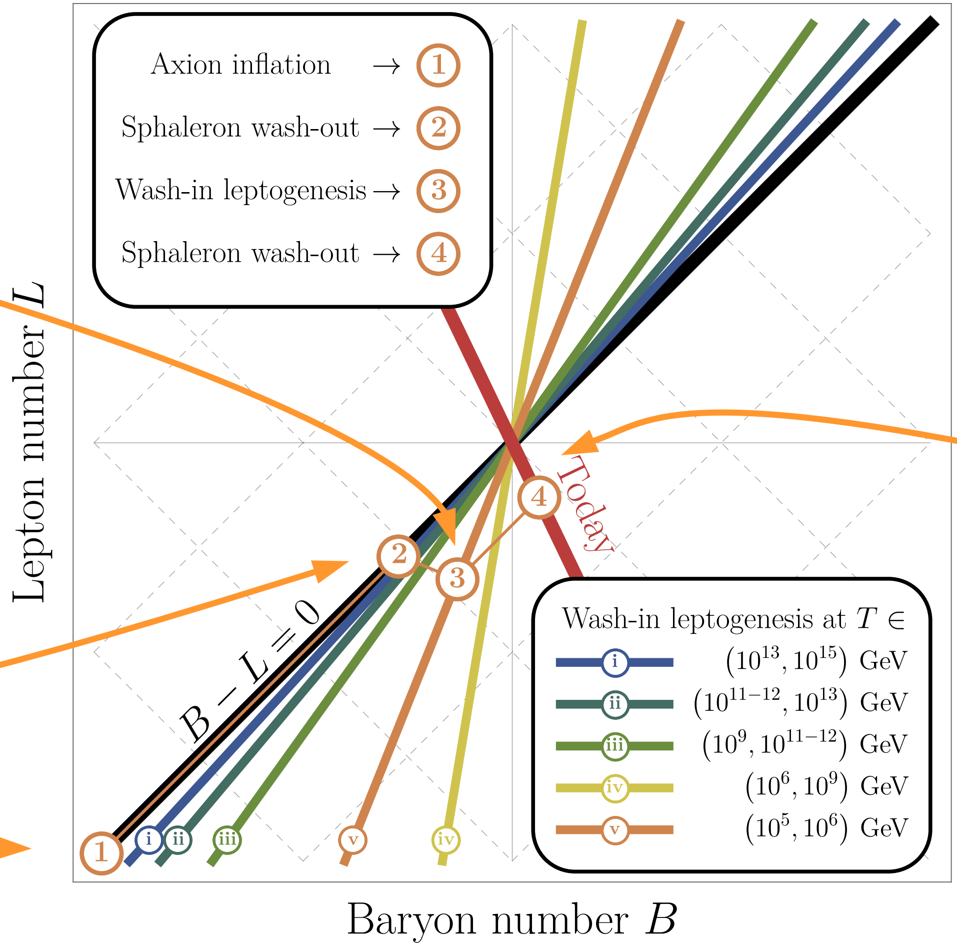
	T [GeV]	y_e	y_{ds}	y_d	y_s	y_{sb}	y_μ	y_c	y_τ	y_b	WS	SS	y_t
(v)	$(10^5, 10^6)$	q_e	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iv)	$(10^6, 10^9)$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iii)	$(10^9, 10^{11-12})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	✓	✓	✓	✓	✓	✓
(ii)	$(10^{11-12}, 10^{13})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	✓	✓
(i)	$(10^{13}, 10^{15})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	q_u	✓

conserved charges + # equilibrated interactions = # particle species = 16

wash-in leptogenesis

wash-in leptogenesis with $M_R \sim 10^{5...6}$ GeV (schematic) :

see also
Cambell et al `93, Cline et al `94,
Fukugita & Yanagida `02



equilibrium solutions depending on (fully) equilibrated interactions

3. include L-violating RHN interactions

4. RHN interactions decouple, sphalerons convert B & L

→ final baryon asymmetry

2. asymmetry washed out through SM interactions, erasure incomplete due to conserved charge q_e

L-violating „wash-out“ processes convert B+L to B-L → „wash-in“

1. initial condition with $B+L \neq 0$, $q_e \neq 0$

B-L asymmetry for strong washout

see also VD, Ema, Mukaida, Masaki `20

if the RHN is fully equilibriated, the B-L asymmetry (or any other charge) is obtained by solving an algebraic system of equations:(#)

$$q_{B-L}^{eq} = \sum_{C \neq \Delta_\alpha} x_C q_C \quad \text{with } C \text{ labelling conserved charges}\,, \qquad \frac{q_B}{s}\Big|_{\text{today}} = \frac{12}{37} \frac{q_{B-L}^{eq} + q_{B-L}^{th}}{s}$$

	T_{B-L} [GeV]	Index α	μ_e	$\mu_{2B_1-B_2-B_3}$	μ_{u-d}	μ_{d-s}	$\mu_{B_1-B_2}$	μ_μ	μ_{u-c}	μ_τ	μ_{d-b}	μ_B	μ_u	$\mu_{\Delta_\perp}$
(v)	$(10^5, 10^6)$	e, μ, τ	$-\frac{3}{10}$											
(iv)	$(10^6, 10^9)$	e, μ, τ	$-\frac{3}{17}$	0	$-\frac{7}{17}$									
(iii)	$(10^9, 10^{11-12})$	$\|_\tau, \tau$	$\frac{142-225P_\tau}{247}$	0	$-\frac{123}{247}$	$-\frac{82}{247}$	$\frac{123}{494}$	$\frac{142-225P_\tau}{247}$						$\frac{225}{247}$
(ii)	$(10^{11-12}, 10^{13})$	$\|$	$\frac{-23P+7}{30}$	$\frac{1}{5}$	$-\frac{3}{5}$	$-\frac{1}{6}$	$-\frac{3}{10}$	$\frac{-23P+7}{30}$	$\frac{3}{10}$	$\frac{-23P+7}{30}$	$-\frac{4}{15}$	$\frac{23}{90}$		$\frac{23}{30}$
(i)	$(10^{13}, 10^{15})$	$\|$	$\frac{-3P+1}{4}$	$\frac{1}{6}$	$-\frac{5}{6}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$\frac{-3P+1}{4}$	$\frac{1}{4}$	$\frac{-3P+1}{4}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{3}{4}$

toolkit to convert any set of primordial asymmetries to final baryon asymmetry using RHN

(#)
- SM interactions taken to be fully equilibrated or fully decoupled
- only one relevant RHN
- projection operators P, Pτ are model dependent and encode the flavour decomposition of primordial asymmetries with respect to RHN wash-out
- flavour coherence / decoherence taken into accoung

B-L asymmetry for mild washout

Solve Boltzmann equation for RHN:

$$-\left(\partial_t + 3H\right) q_{\Delta_\alpha} = \varepsilon_{1\alpha}\Gamma_1 \left(n_{N_1} - n_{N_1}^{\rm eq}\right) - \sum_\beta \gamma^{\rm w}_{\alpha\beta} \frac{\mu_{\ell_\beta} + \mu_\phi}{T}$$

$$q^{\rm win}_{\Delta_\alpha} = \sum_\beta \left(\delta_{\alpha\beta} - E_{\alpha\beta}\right) q^{\rm eq}_{\Delta_\beta} + \sum_\beta E_{\alpha\beta}\, q^{\rm ini}_{\Delta_\beta} \frac{s}{s^{\rm ini}}$$

$$E = \exp\left(-w\, K_1\, P\, C\right)$$

- $3\pi/4$ for MB statistics
- Γ_1/H decay parameter
- $\Gamma^w_{\alpha\beta} = P_{\alpha\beta}\Gamma_w$ flavour structure (RH)
- $\mu_{\ell_\alpha} + \mu_\phi = -C_{\alpha\beta}\,\mu_{\Delta_\beta}$ flavour coupling (LH)

- RHN as dynamical dof, with decays and inverse decays (vs Weinberg operator)
- including charged lepton flavour effects

reduces to equilibrium solution for $\Gamma_1 \gg H$

pros and cons of wash-in leptogenesis

depending on distribution of initial asymmetries

✔ works for $M_R \gtrsim 100\ \mathrm{TeV}$ (equilibration of electron Yukawa)

CP violation provided by initial conditions

✔ no CP violation in RHN sector required

✔ can be straightforwardly applied to various models generating primordial asymmetries

eg GUT baryogenesis

✘ not a complete model itself, requires non-trivial initial conditions

Outline

- SM interactions and conserved charges
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- (spontaneous baryogenesis)

GUT baryogenesis

see also Fukugita & Yanagida `02

eg SU(5) unification

$$H^c \to \bar{Q}_3\bar{Q}_3,\ t\tau,\ Q_3\ell_\tau,\ \bar{t}\bar{b} \qquad B - L = 0\,, \quad B + L \neq 0$$

→ wash-in leptogenesis works for $M_R \gtrsim 10^{11}\ \mathrm{GeV}$ (tau Yukawa equilibration)

projection operators

direction of N_1 washout: $N_1 \to \ell\phi$

$$h_\parallel \ell_\parallel = h_1^e\,\ell_e + h_1^\mu\,\ell_\mu + h_1^\tau\,\ell_\tau\,, \quad h_{\parallel_\tau}\ell_{\parallel_\tau} = h_1^e\,\ell_e + h_1^\mu\,\ell_\mu$$

$$h_\parallel^2 = |h_1^e|^2 + |h_1^\mu|^2 + |h_1^\tau|^2\,,$$
$$h_{\parallel_\tau}^2 = |h_1^e|^2 + |h_1^\mu|^2$$

initial asymmetries: $\bar{e} = c_e e + c_\mu \mu + c_\tau \tau\,, \quad \bar{e}_\tau = c_e^\tau e + c_\mu^\tau \mu$

projection operators: $P = \left|h_1^e c_e^* + h_1^\mu c_\mu^* + h_1^\tau c_\tau^*\right|^2 / |h_\parallel|^2\,, \quad P_\tau = \left|h_1^e c_e^{\tau *} + h_1^\mu c_\mu^{\tau *}\right|^2 / |h_{\parallel_\tau}|^2$

„axion“ inflation

slow-roll inflation → very flat scalar potential

reheating after inflation → coupling to the SM

↓

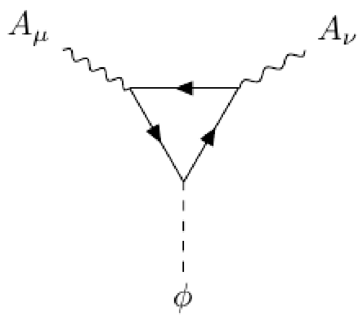
inflaton as Pseudo Goldstone Boson (PNGB, ALP) with shift-symmetric couplings:

$\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$

$(\partial_\mu \phi)\underbrace{\bar{\psi}\gamma^\mu\gamma^5\psi}_{J_5^\mu}$

related by chiral anomaly equation:

$$0 \neq \partial_\mu J_5^\mu = -\frac{1}{16\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$



„axion" inflation

- a minimal setup for SM + inflation:

axion with scalar potential

(hyper charge) U(1) gauge field

massless (SM) fermions

axion gauge field coupling

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_\alpha \bar\psi_\alpha(i\partial\cdot\gamma - gQA\cdot\gamma)\psi_\alpha + \frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde F^{\mu\nu}$$

SM chiral anomaly forces us to consider gauge fields and fermions simultaneously

after chiral fermion rotation:

$$(\partial_\mu\phi)\bar\psi\gamma^\mu\gamma^5\psi$$

shift-symmetric coupling to ϕ

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shift-symmetric coupling to ϕ

- axion – hypercharge coupling leads to exponential helical gauge field production (ignoring fermion backreaction for the moment):

$$\frac{d^2}{d\tau^2}A_\pm(\tau,k) + \left[k^2 \pm 2k\frac{\xi}{\tau}\right]A_\pm(\tau,k) = 0\,, \qquad \xi = \frac{\alpha\dot\phi}{2Hf_a}$$

fermion production in axion inflation

VD, Mukaida `18

helical gauge field production

- one gauge field helicity acquires tachyonic mass
- parallel E & B fields, constant & homogeneous on scales << H^{-1}

(chiral) fermion production

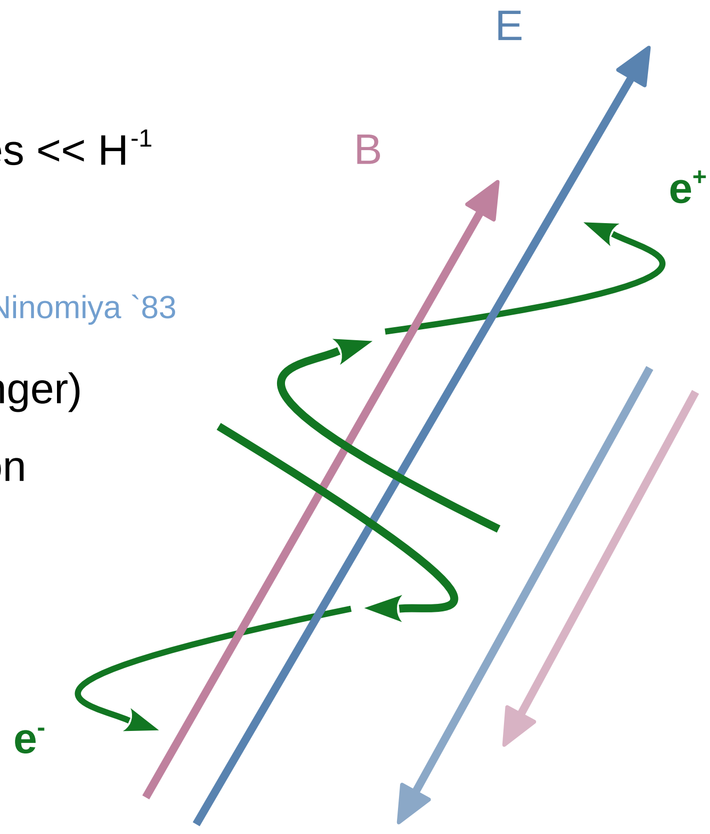
Nielsen, Ninomiya `83

- fermion production in constant E,B background (Schwinger)
- asymmetric production consistent with anomaly equation

backreaction on gauge field production

- fermions are accelerated in gauge field background
- induced current inhibits gauge field production

$$\Box A^\nu - \partial_\mu \left(\frac{\alpha \phi}{\pi f_a} \tilde{F}^{\mu\nu} \right) - g Q J^\nu_\psi = 0$$



dual production of helical gauge fields and chiral fermions

wash-in leptogenesis after axion inflation

VD, Mukaida `18; VD, von Harling, Morgante, Mukaida `19

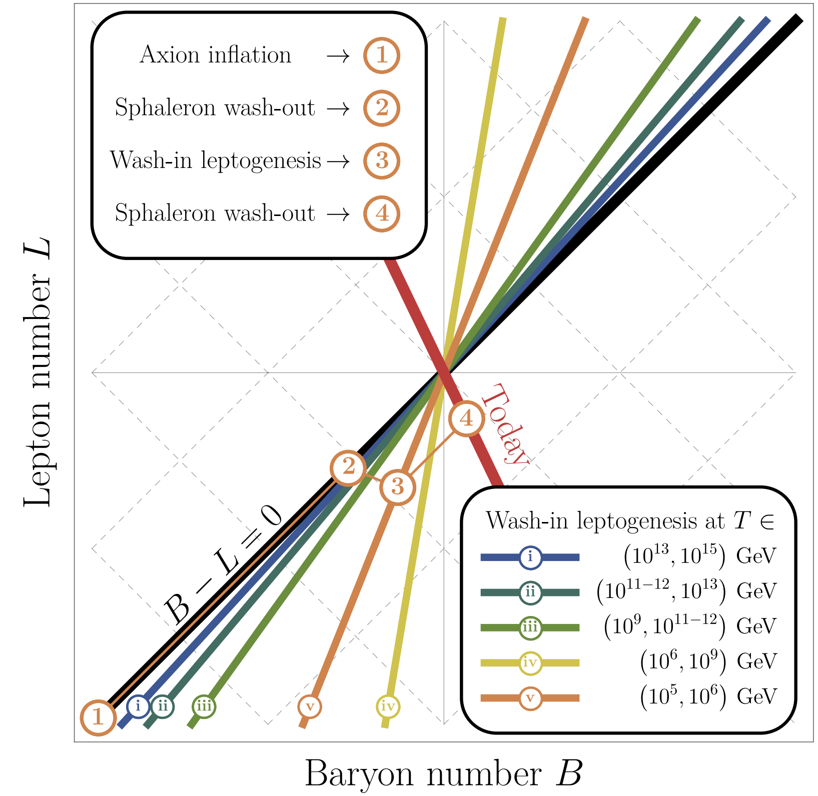
chemical potentials for all SM particles according to their hypercharge:

$$\frac{\mu_i}{T} = \pm 3 g_i (Q_i^Y)^2 \alpha_Y \frac{(\mathbf{A}_Y \cdot \mathbf{B}_Y)_{\rm rh}}{\pi T^3}$$

includes in particular RH electron

→ wash-in leptogenesis works for $M_R \gtrsim 100 \text{ TeV}$

→ $$\frac{\mu^{\rm win}_{B-L}}{T} = \frac{9}{10} \alpha_Y \frac{(\mathbf{A}_Y \cdot \mathbf{B}_\mathbf{Y})_{\rm rh}}{\pi T^3}$$



- additional contribution from baryogenesis from decaying helical hypermagneticfields possible, see VD, von Harling, Morgante, Mukaida `19
- here we assume μ_e/T to be small, avoiding anomalous violation through the chiral plasma instability

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spontaneous baryogenesis

wash-in leptogenesis
initial asymmetries
in conserved charges

→

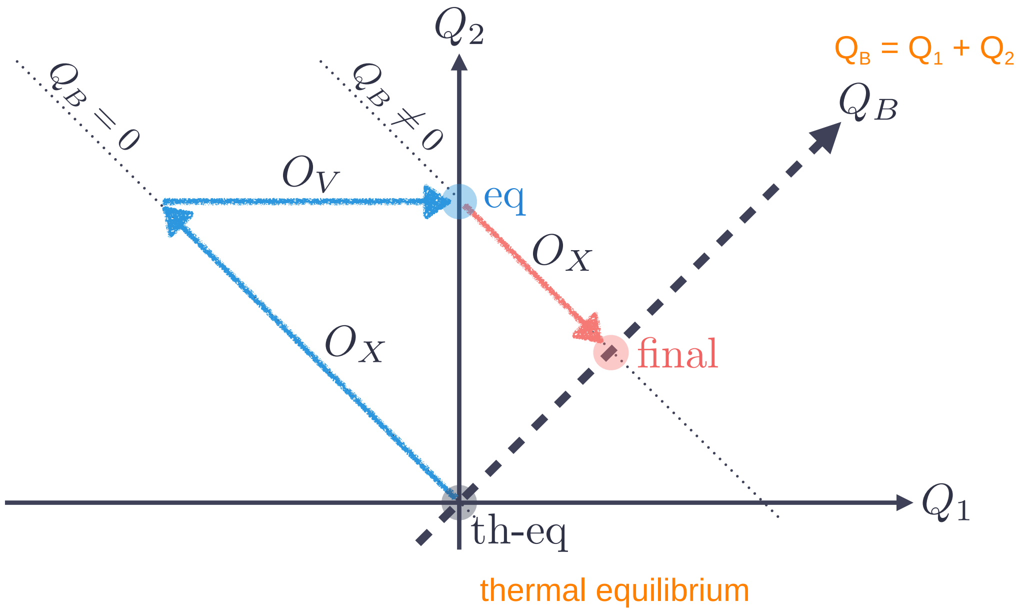
spontaneous baryogenesis
chemical potentials induced
by rolling axion field

Cohen, Kaplan `87,`88

- rolling of axion needs to happen when B,L violating processes are active (eg Weinberg operator, sphalerons)
- due to SM equilibration processes, no direct axion coupling to these processes needed, eg
  - ✔ any generic axion couplings
  - ✔ only axion-gluon coupling

    see also Co, Harigaya `19
- formalism inherently invariant under chiral fermion rotations

VD, Ema, Mukaida, Yamada `20



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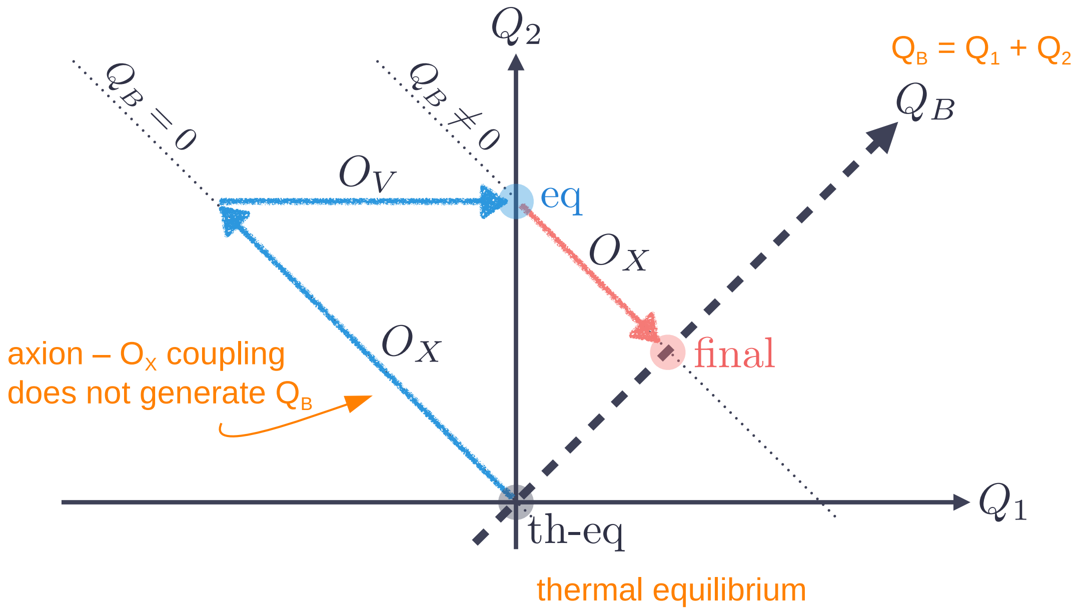

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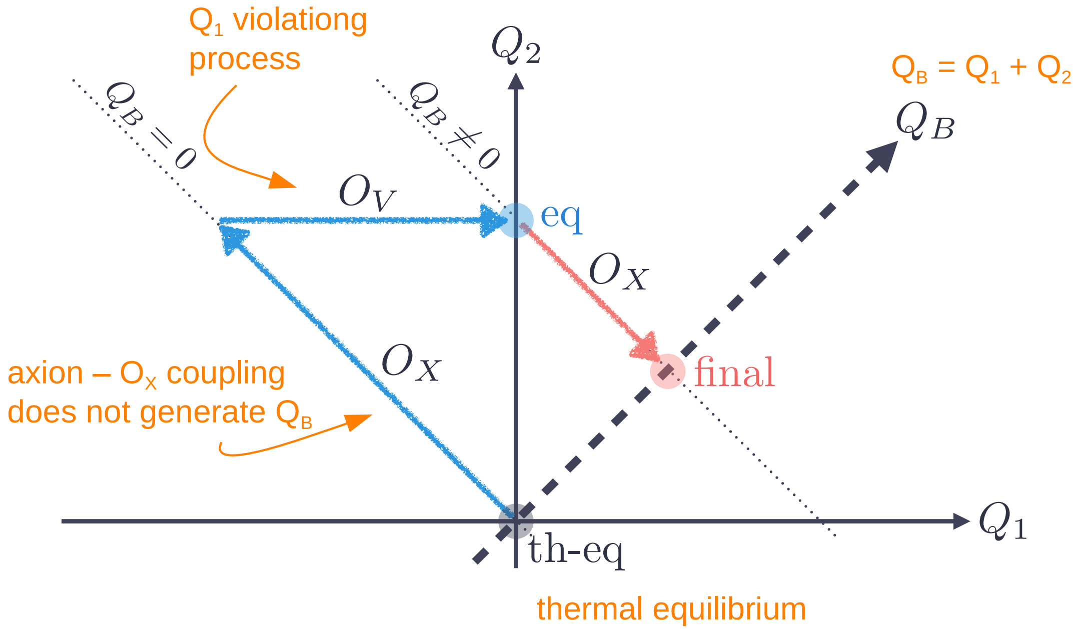

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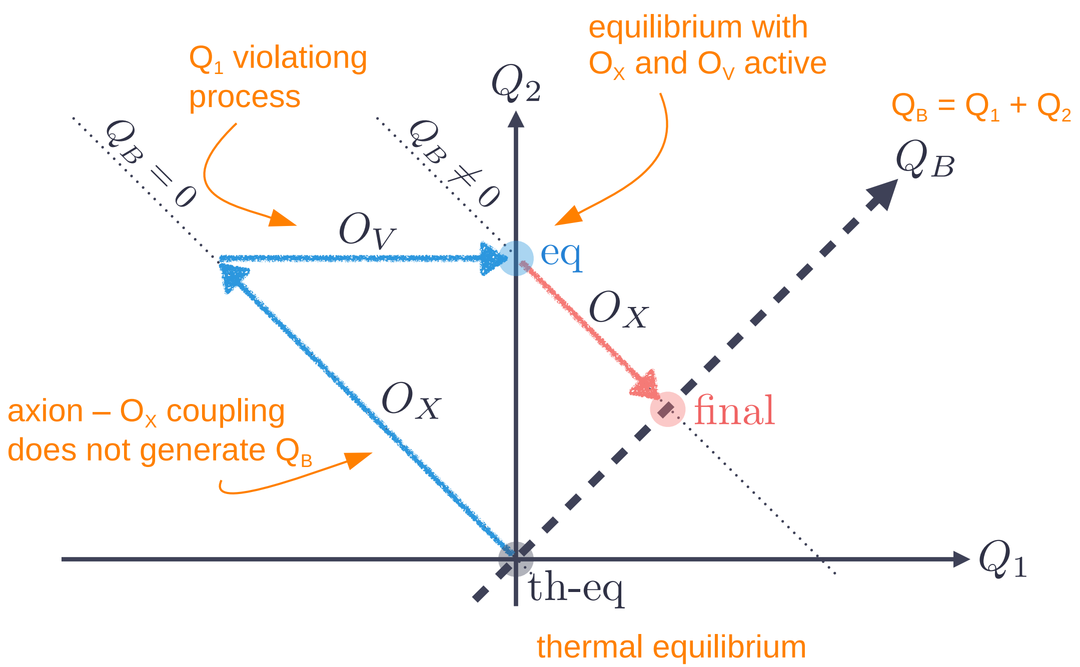

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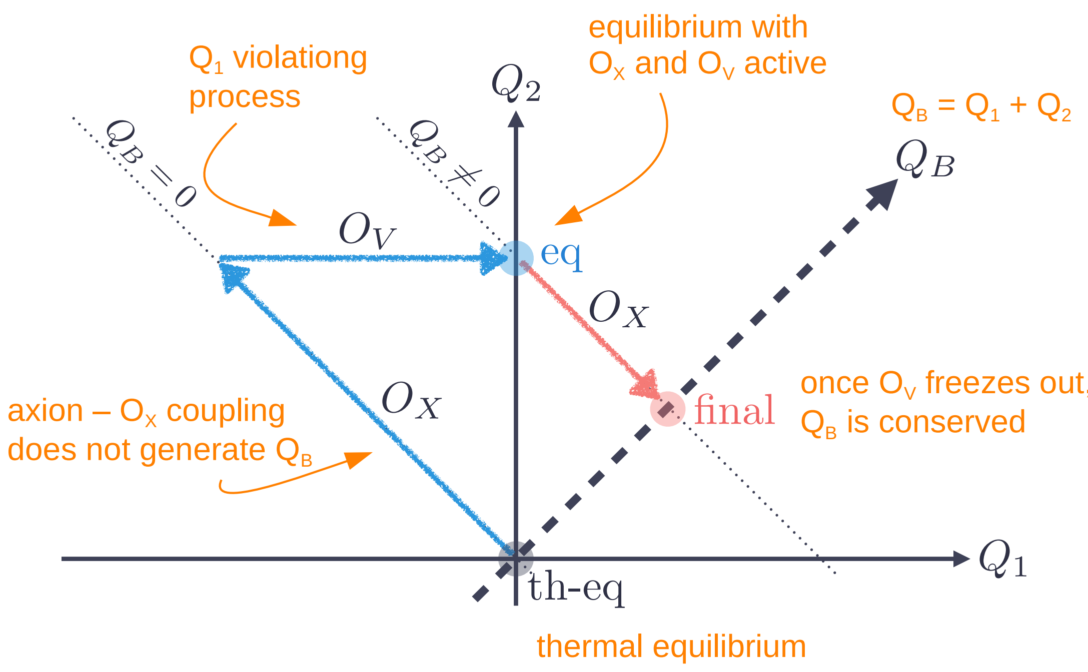

conclusions

- right-handed neutrinos are a minimal extension of the SM, elegantly explaining neutrino masses
- they may be responsible for the observed baryon asymmetry via standard thermal leptogenesis
- they also interfere with other baryogenesis mechanisms in a non-trivial way, rescuing eg GUT baryogenesis
- we provide an explicit toolkit to apply to a wide range of models and temperature regimes

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Questions ?