Wash-in leptogenesis

Valerie Domcke
CERN/EPFL

Nikhef colloquium,
12.03.2020

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:
(assuming CPT conservation)

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

introduction: baryogenesis

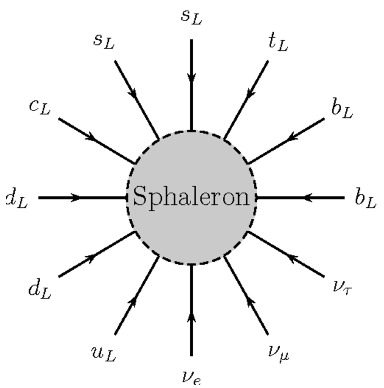
GUT baryogenesis

unification of forces

Yoshimura `78, Dimopoulos, Susskind `78

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

B + L asymmetry



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

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

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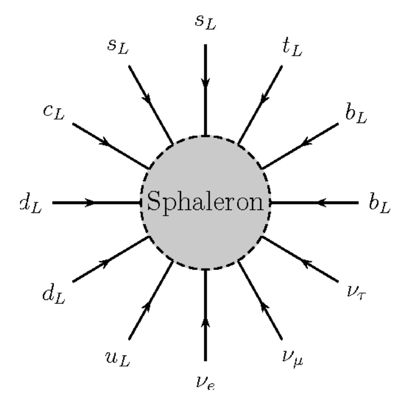

But: non-perturbative sphaleron processes
wash out B+L asymmetry Kuzmin, Rubakov, Shaposhnikov `85

Leptogenesis neutrino masses Fukugita, Yanagida `86

$$N_R \xrightarrow[y_N]{\not{CP}\ \ \not{L}} \ell\phi\,,\bar{\ell}\bar{\phi}$$

B - L asymmetry

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

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

introduction: baryogenesis

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

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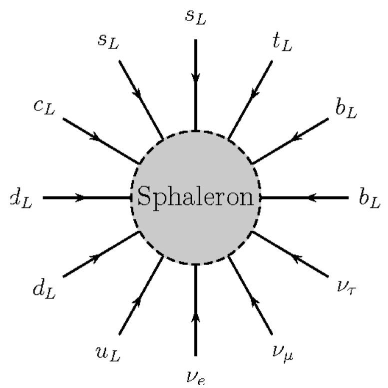

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Davidson, Ibarra `02, Buchmüller, Bari, Plümacher `02

This talk: combine these two ideas

Outline

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

thermal bath: equilibrium solutions

particle species

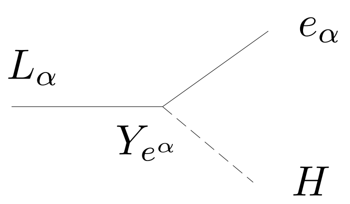
asymmetries described by chemical potentials $n_i - n_{\bar{i}} = \mu_i T^2/6$

in the SM: $i = \{e_\alpha, L_\alpha, u_\alpha, d_\alpha, Q_\alpha, H\}$

interactions

eg lepton Yukawa:

$\mu_{L_\alpha} - \mu_{e_\alpha} - \mu_H = 0$ iff $\Gamma_{Y_e^\alpha}/H \gg 1$



conserved quantities

particle species - # (linearly independent) interactions = # conserved charges

eg SM @ 1 TeV : 16 – 12 = 4 : $B/3 - L_\alpha \, , \, Y$

(lepton flavour, hypercharge)

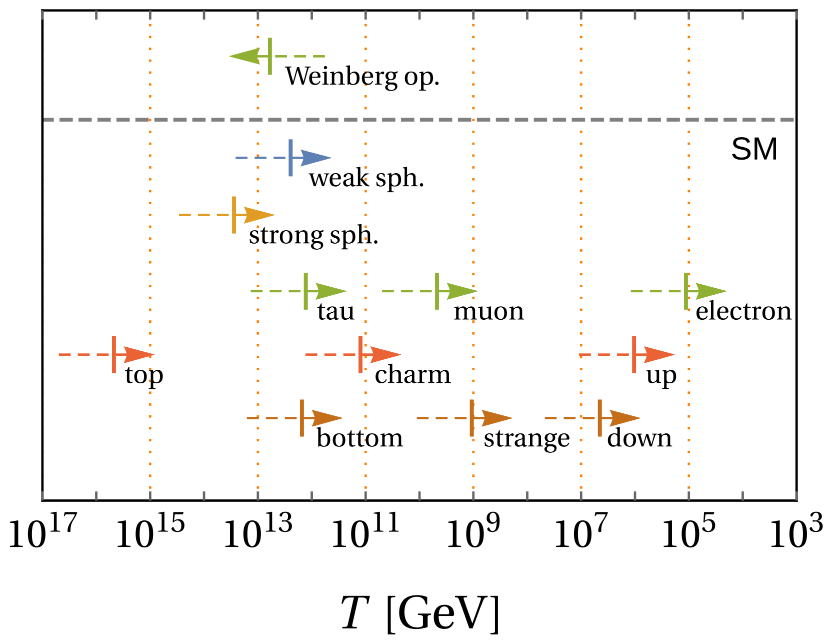
SM interactions and conserved charges

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

initial condition + SM + right-handed neutrinos $(M_N \gtrsim 100 \text{ TeV})$

$B + L \neq 0$ $\cancel{B + L}$ $\cancel{L}$

→ 'wash-in' leptogenesis $B - L \neq 0$

- RHN can thermalize
- M_N as low as ~ 100 TeV possible

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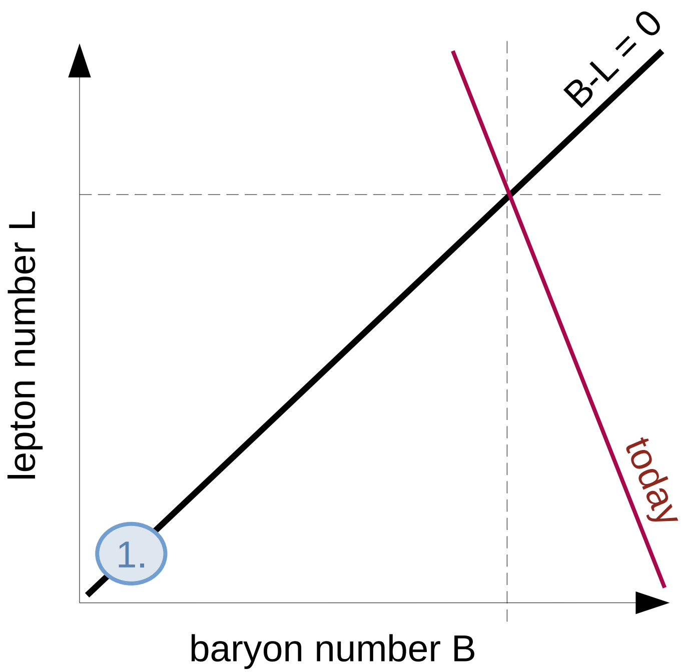

1. initial condition (see later)

VD, Ema, Mukaida, Yamada `20,
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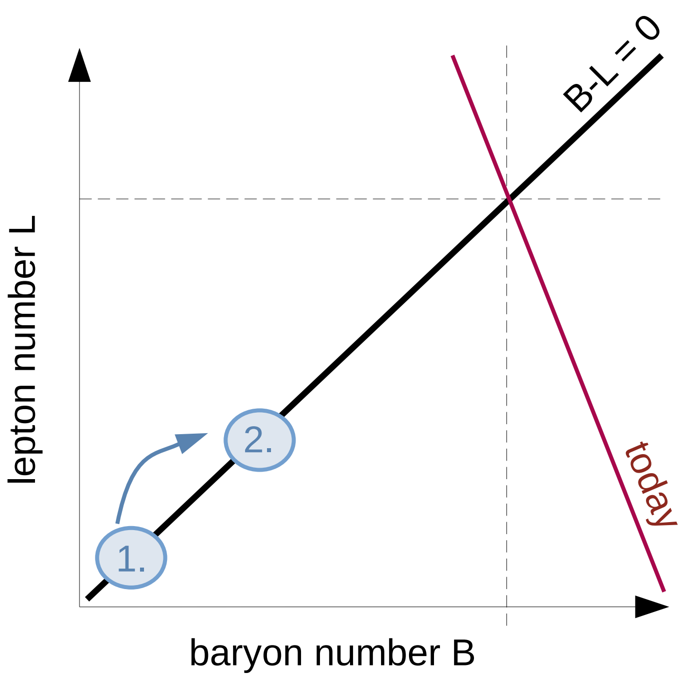

1. initial condition (see later)
2. equilbrium including SM interactions.

   B+L not fully erased due to $q_e \neq 0$

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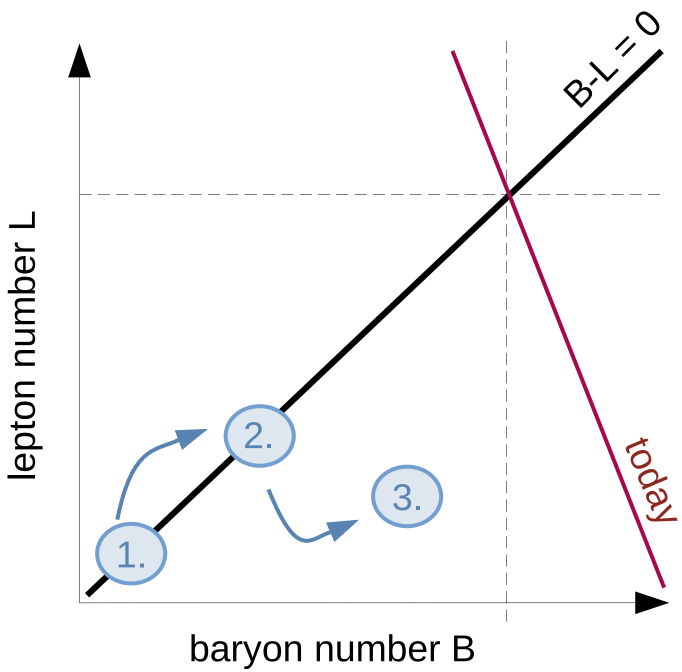

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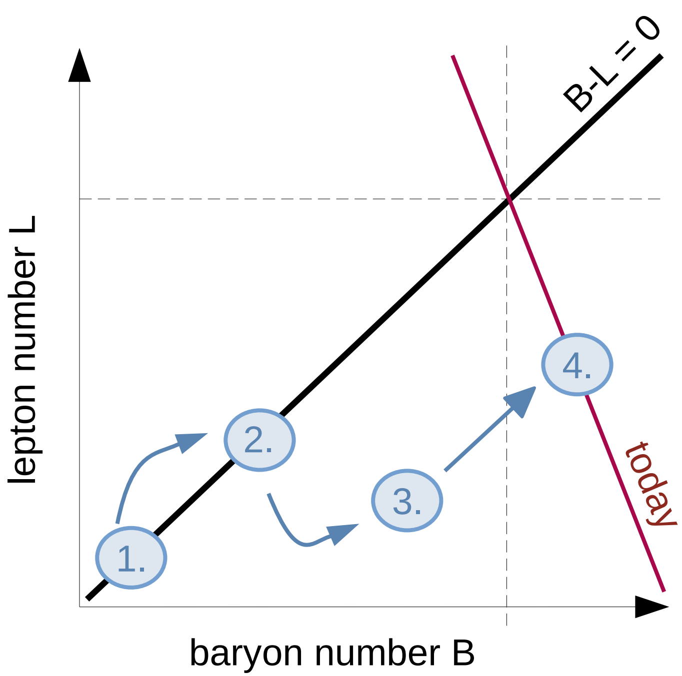

1. initial condition (see later)
2. equilbrium including SM interactions.

   B+L not fully erased due to $q_e \neq 0$
3. equilibrium including RH neutrino
4. RH neutrino and sphalerons decouple

VD, Ema, Mukaida, Yamada `20,
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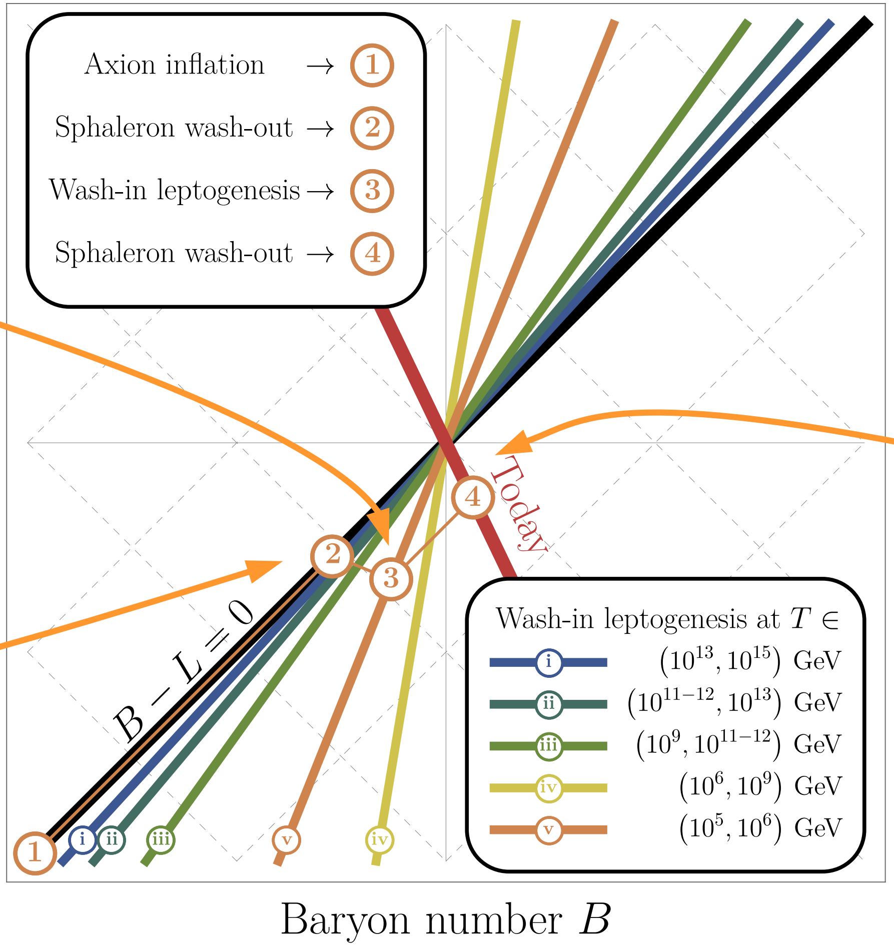
wash-in leptogenesis

wash-in leptogenesis with $M_R \sim 10^{5\ldots6}$ GeV (schematic) :

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

include L-violating RHN interactions

3.



equilibrium solutions depending on (fully) equilibrated interactions

4.

RHN interactions and sphalerons decoupled

→ final baryon asymmetry

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

2.

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)	$(10^9, 10^{11-12})$	$\parallel_\tau, \tau$	$\frac{142-225P_\tau}{247}$	0	$-\frac{123}{247}$	$-\frac{82}{247}$	$\frac{123}{494}$	$\frac{142-225P_\tau}{247}$						$\frac{225}{247}$
(ii)	$(10^{11-12}, 10^{13})$	$\parallel$	$\frac{-23P+7}{30}$	$\frac{1}{5}$	$-\frac{3}{5}$	$-\frac{1}{6}$	$-\frac{3}{10}$	$\frac{-23P+7}{30}$	$\frac{3}{10}$	$\frac{-23P+7}{30}$	$-\frac{4}{15}$	$\frac{23}{90}$		$\frac{23}{30}$
(i)	$(10^{13}, 10^{15})$	$\parallel$	$\frac{-3P+1}{4}$	$\frac{1}{6}$	$-\frac{5}{6}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$\frac{-3P+1}{4}$	$\frac{1}{4}$	$\frac{-3P+1}{4}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{3}$	$\frac{3}{4}$

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 account

B-L asymmetry for mild washout

Solve Boltzmann equations for RHN interactions:

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

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

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

- $3\pi/4$ 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

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

  depending on distribution of initial asymmetries

- ✔ no CP violation in RHN sector required

  CP violation provided by initial conditions

- ✔ can be straightforwardly applied to various models generating primordial asymmetries

  eg GUT baryogenesis

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

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- 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 $M_R \gtrsim 10^{11}$ GeV (tau Yukawa equilibration)

projection operators

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

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

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

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

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

a minimal setup for SM + inflation:

axion with scalar potential

(hyper charge) U(1) gauge field

massless (SM) fermions

axion gauge field coupling

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

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):

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

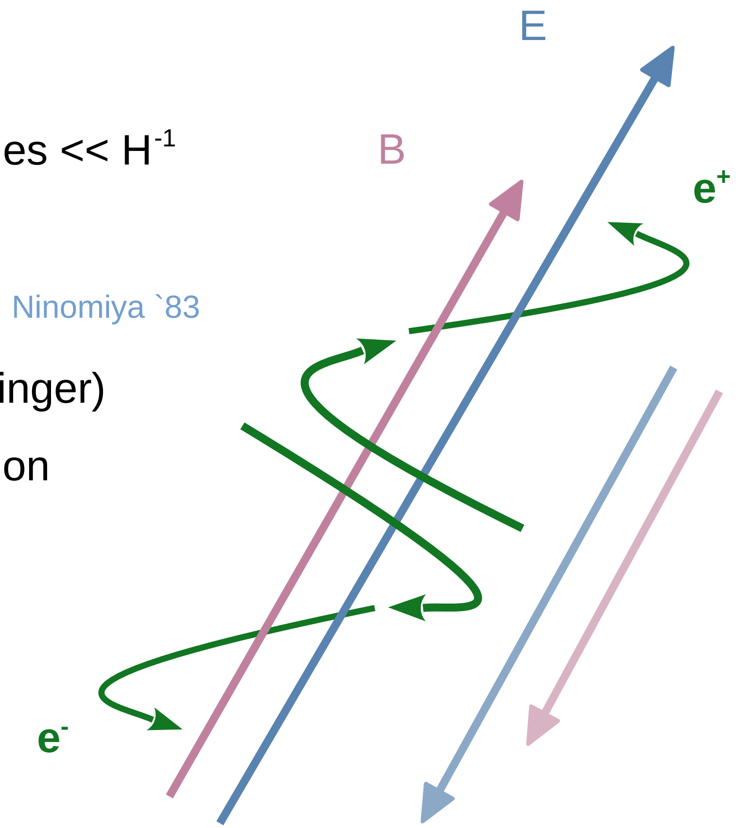
Turner, Widrow `88
Garretson, Field, Caroll `92

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

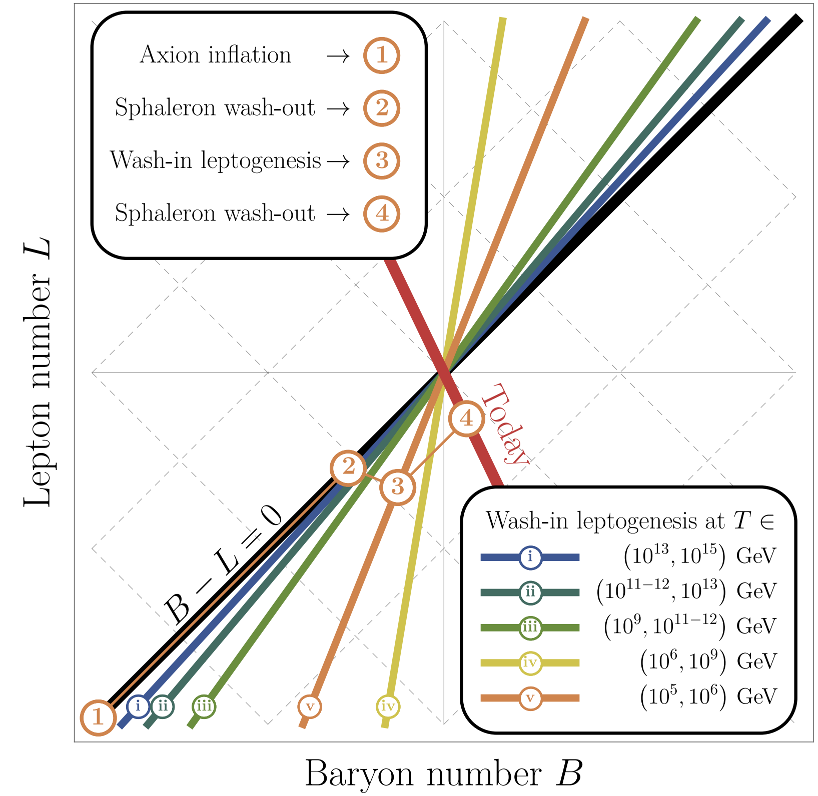
chemical potentials for all SM particles according to their hypercharge:

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

includes in particular RH electron

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

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



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

spontaneous baryogenesis

wash-in leptogenesis
initial asymmetries
in conserved charges

⟷

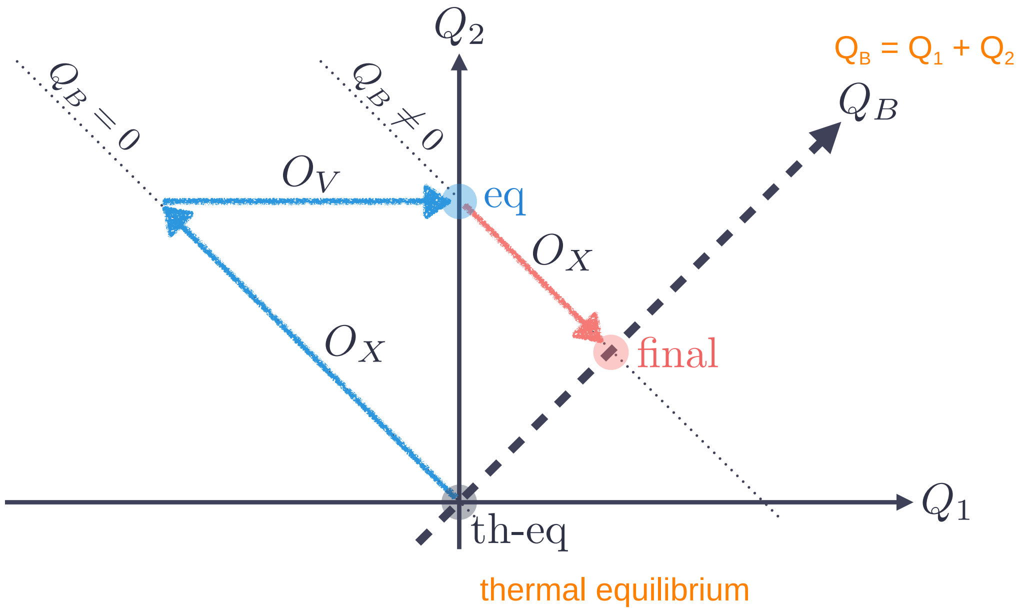
spontaneous baryogenesis
chemical potentials induced
by rolling axion field

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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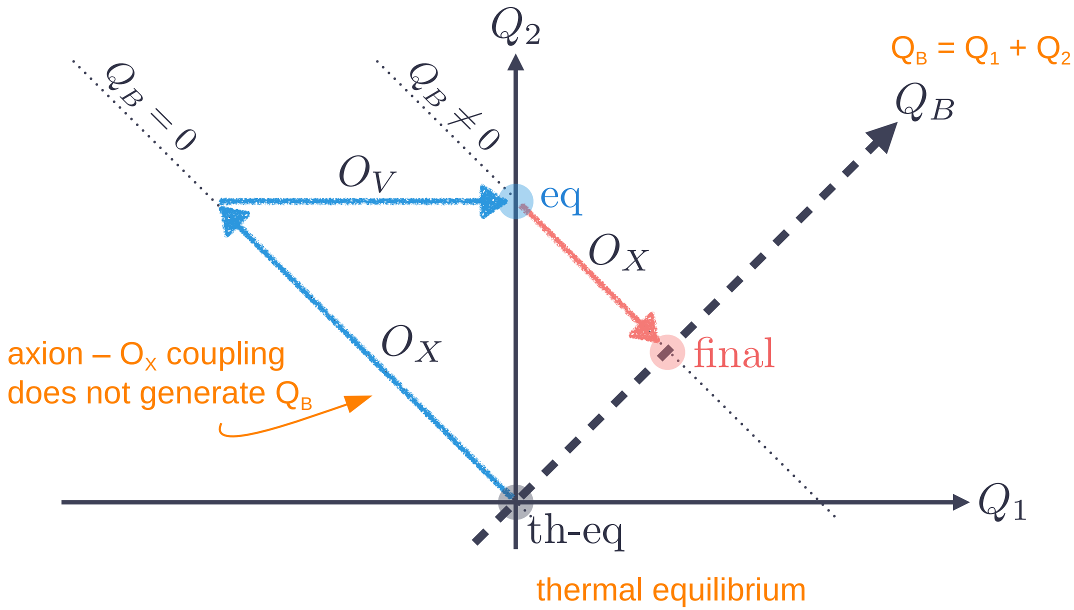

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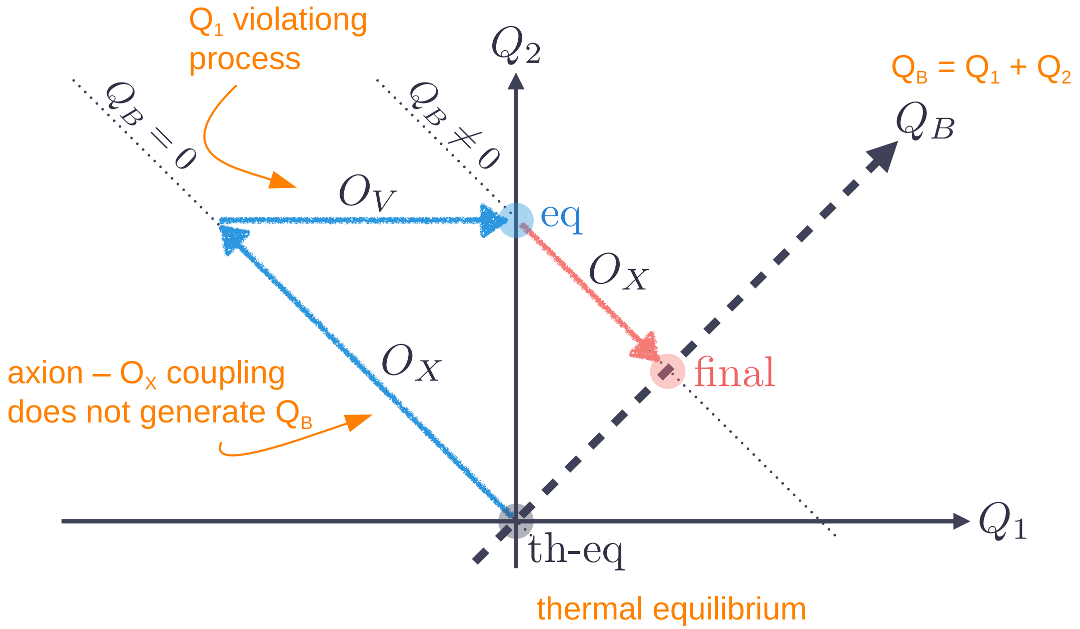

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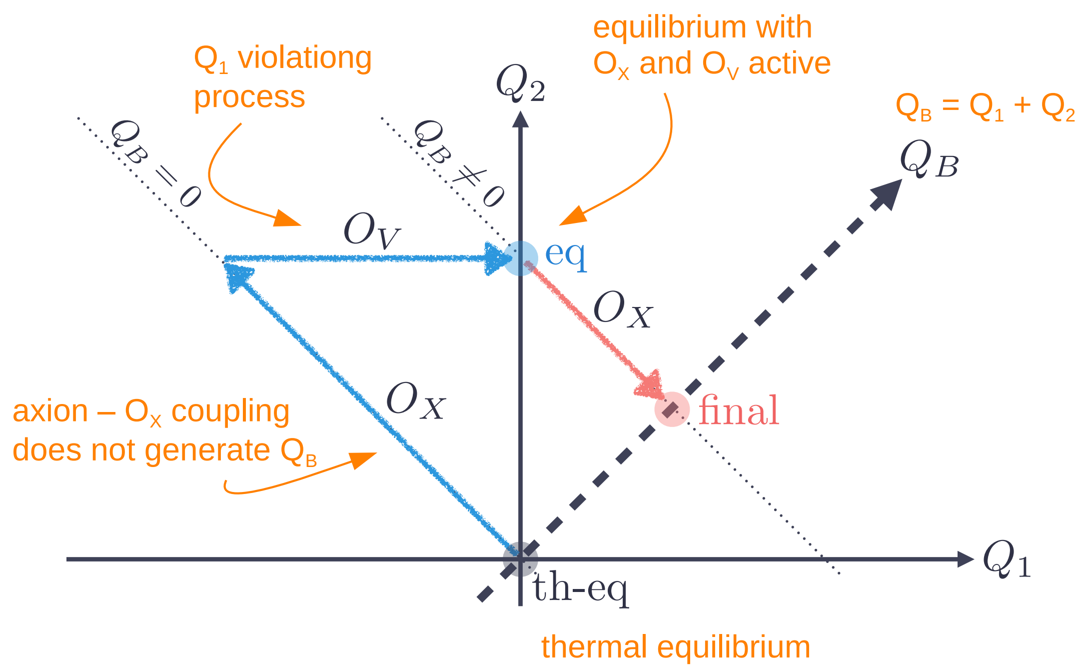

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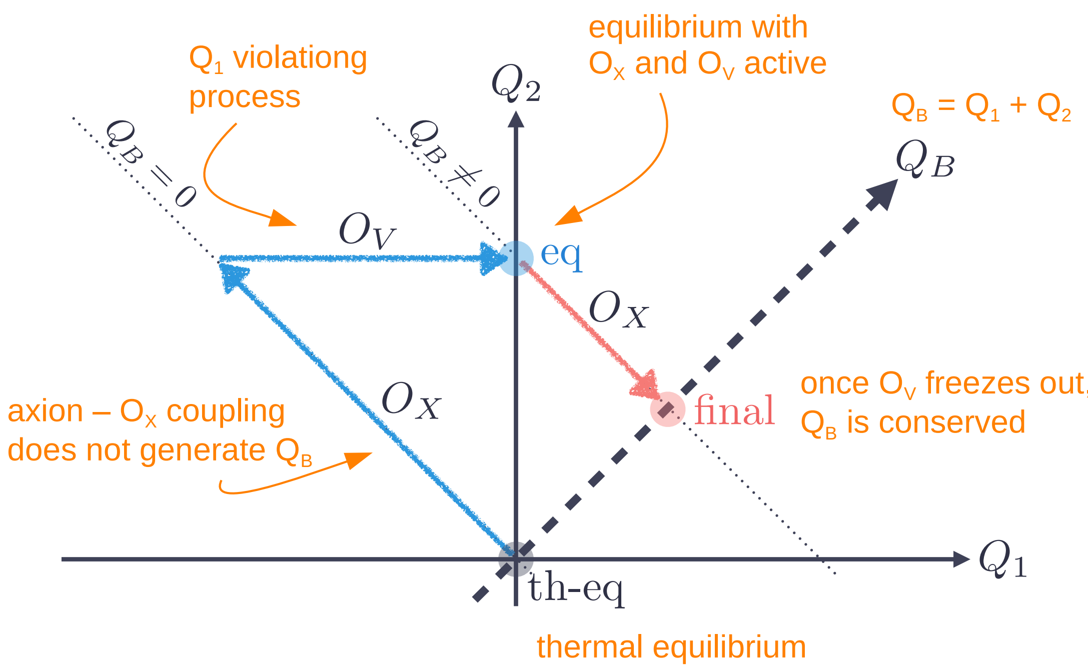

conclusions

- 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

Sustainable HEP

28-30 June 2021
CERN
Europe/Zurich timezone

Search...

- Overview
- Registration
- Participant List
- Videoconference Rooms

This virtual Zoom workshop aims at discussing the transition to a sustainable future in the field of high-energy physics (HEP), in particular, changes in our travel culture, based on some of the crucial lessons we learned during 2020: Online formats can be a viable alternative to traditional in-person meetings and enable broader participation and inclusion of previously underrepresented groups of researchers. At the same time, efficient communication and networking can be challenging in online formats. The workshop will therefore bring together various perspectives to develop a balanced and deliberate approach to our post-pandemic travel culture and its connection to the questions of climate action, sustainability, and social justice. The workshop will take place from 3 to 7 pm CEST on Monday through Wednesday. The program will consist of impulse talks, panel discussions, a best-practice examples session, and asynchronous flash talks accompanied by a discussion forum on Mattermost: mattermost.web.cern.ch/sustainable-hep (not open yet). All talks will be recorded and made available to the participants for the duration of the workshop, so as to allow for participation from all time zones.

Impulse talk: Monday, June 28th
Kenneth Hiltner (English and Environmental Studies, University of California, Santa Barbara)

Panel 1: Monday, June 28th
The Challenge for Institutions

- Susann Görlinger (ETH Zurich)
- Jan Louis (DESY, University of Hamburg)
- Rob Myers (Perimeter Institute)
- ...

Panel 2: Tuesday, June 29th
Social-Justice Dimension of Online Formats

- Clifford Johnson (University of Southern California)
- Prince Osei (African Institute for Mathematical Sciences, Quantum Leap Africa)
- Fernando Quevedos (University of Cambridge)
- Sumati Surya (Raman Research Institute)

Best-Practice Examples:

- Rachel Grange (ETH Zurich)
- Shaun Hotchkiss (University of Auckland)
- Rogerio Rosenfeld (ICTP São Paulo)
- Michael Spannowsky (University of Durham)
- ...

registration open @
https://indico.cern.ch/event/1004432/

Organizers:
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Valerie Domcke (CERN/EPFL)
Astrid Eichhorn (CP3 Origins)
Kai Schmitz (CERN)