



Baryon asymmetry from particle production during axion inflation

Collaborators: Valerie Domcke, Eduard Gorbar, Kohei Kamada, Kyohei Mukaida, Oleksandr Sobol, Stanislav Vilchinskii, and Masaki Yamada [[2011.09347](#), [2109.01651](#), [2111.04712](#), [2210.06412](#)]

Kai Schmitz

University of Münster, Germany

Bethe Forum “Axions”

University of Bonn | October 13, 2022

Part 1: Wash-in leptogenesis

Part 2: Axion inflation

Conclusions and outlook

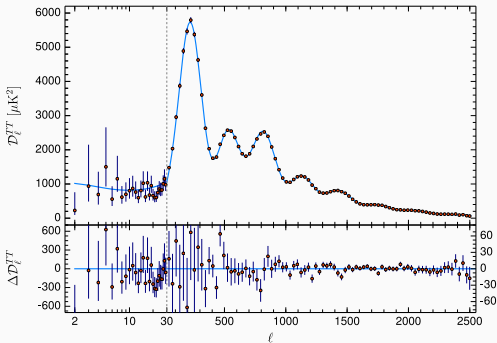
Part 1: Wash-in leptogenesis

Part 2: Axion inflation

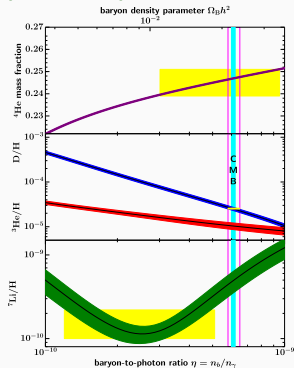
Conclusions and outlook

Baryon asymmetry of the Universe

[PLANCK Collaboration 2018]



[PDG Review 2021]

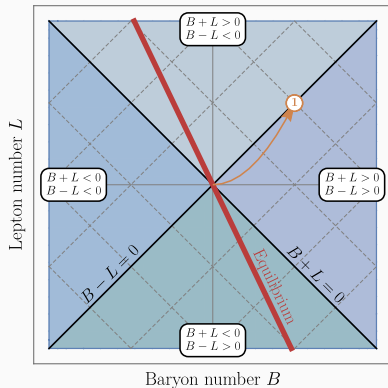


Cosmological concordance:

CMB and BBN point to baryon asymmetry $\eta_B = \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq \frac{n_b}{n_\gamma} \simeq 6.1 \times 10^{-10}$

- Cannot be explained within the Standard Model, evidence for new physics
- Sakharov (1967): B , C , CP violation, departure from thermal equilibrium

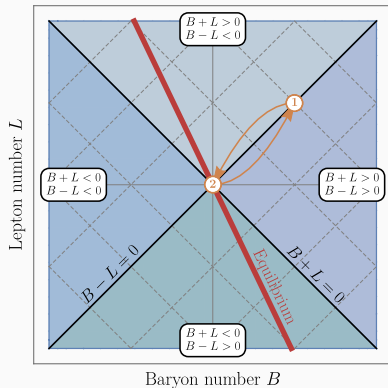
Baryogenesis and electroweak sphalerons



① $SU(5)$ GUT baryogenesis

[Yoshimura 1978] [Dimopoulos, Susskind 1978] [Toussaint, Treiman, Wilczek, Zee 1979] [Weinberg 1979] [Barr, Segre, Weldon 1979]

Baryogenesis and electroweak sphalerons

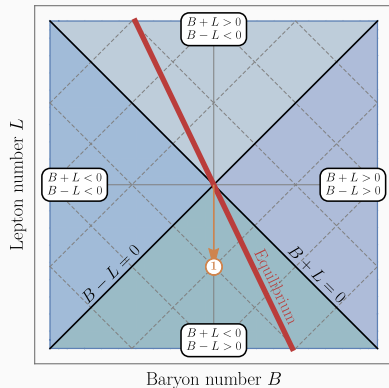
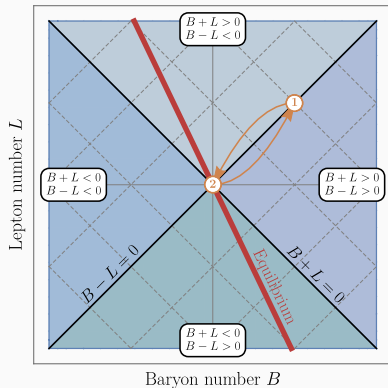


① $SU(5)$ GUT baryogenesis

② Sphaleron wash-out

[Yoshimura 1978] [Dimopoulos, Susskind 1978] [Toussaint, Treiman, Wilczek, Zee 1979] [Weinberg 1979] [Barr, Segre, Weldon 1979]
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Baryogenesis and electroweak sphalerons



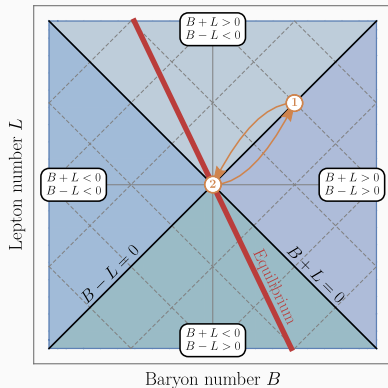
① $SU(5)$ GUT baryogenesis

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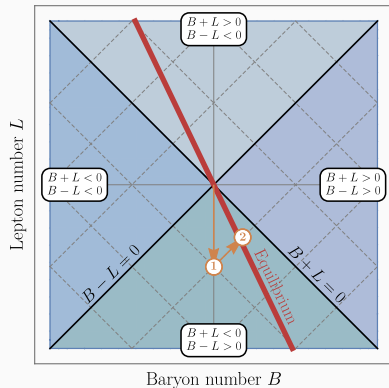
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Baryogenesis and electroweak sphalerons



① $SU(5)$ GUT baryogenesis

② Sphaleron wash-out



① Thermal leptogenesis

② Sphaleron conversion

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Chemical equilibrium in the electroweak phase

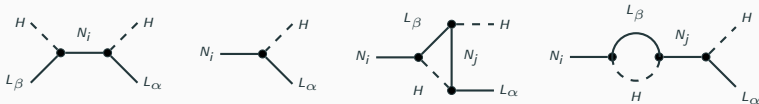
$$\begin{pmatrix} \mu_e \\ \mu_\mu \\ \mu_\tau \\ \mu_{\ell_e} \\ \mu_{\ell_\mu} \\ \mu_{\ell_\tau} \\ \mu_u \\ \mu_c \\ \mu_t \\ \mu_d \\ \mu_s \\ \mu_b \\ \mu_{Q_1} \\ \mu_{Q_2} \\ \mu_{Q_3} \\ \mu_\Phi \end{pmatrix} = \begin{pmatrix} -185/711 & 52/711 & 52/711 \\ 52/711 & -185/711 & 52/711 \\ 52/711 & 52/711 & -185/711 \\ -221/711 & 16/711 & 16/711 \\ 16/711 & -221/711 & 16/711 \\ 16/711 & 16/711 & -211/711 \\ -5/237 & -5/237 & -5/237 \\ -5/237 & -5/237 & -5/237 \\ -5/237 & -5/237 & -5/237 \\ 19/237 & 19/237 & 19/237 \\ 19/237 & 19/237 & 19/237 \\ 19/237 & 19/237 & 19/237 \\ 7/237 & 7/237 & 7/237 \\ 7/237 & 7/237 & 7/237 \\ 7/237 & 7/237 & 7/237 \\ -4/79 & -4/79 & -4/79 \end{pmatrix} \begin{pmatrix} \bar{\mu}_{\Delta_e} \\ \bar{\mu}_{\Delta_\mu} \\ \bar{\mu}_{\Delta_\tau} \end{pmatrix}$$

System of linear equations for 16 SM chemical potentials:

- 12 linearly independent interactions in thermal equilibrium
- 4 global charges: hypercharge Y , flavored $B - L$ charges $\Delta_\alpha = B/3 - L_\alpha$

Sphaleron conversion factor: $\bar{\mu}_B = \sum_i n_i^B g_i \mu_i = \frac{28}{79} (\bar{\mu}_{\Delta_e} + \bar{\mu}_{\Delta_\mu} + \bar{\mu}_{\Delta_\tau})$

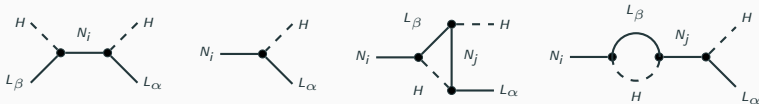
Flavor effects in leptogenesis



Boltzmann equation for leptogenesis via N_1 right-handed neutrino decays:

$$-(\partial_t + 3H) q_{\Delta_\alpha} = \varepsilon_{1\alpha} \Gamma_1 (n_{N_1} - n_{N_1}^{\text{eq}}) - \sum_{\beta} \gamma_{\alpha\beta}^{\text{w}} \frac{\mu_{\ell_\beta} + \mu_\Phi}{T}$$

Flavor effects in leptogenesis



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Flavor coupling because of spectator processes ($10^2 \text{ GeV} \ll T \ll 10^5 \text{ GeV}$):

$$\begin{pmatrix} \mu_{\ell_e} + \mu_\Phi \\ \mu_{\ell_\mu} + \mu_\Phi \\ \mu_{\ell_\tau} + \mu_\Phi \end{pmatrix} = - \begin{pmatrix} 257/711 & 20/711 & 20/711 \\ 20/711 & 257/711 & 20/711 \\ 20/711 & 20/711 & 257/711 \end{pmatrix} \begin{pmatrix} \bar{\mu}_{\Delta_e} \\ \bar{\mu}_{\Delta_\mu} \\ \bar{\mu}_{\Delta_\tau} \end{pmatrix}$$

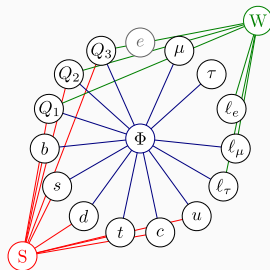
- Not enough CP violation, unless resonantly enhanced
- Efficient wash-out (detailed balance): $\mu_{\ell_\alpha} + \mu_\Phi = \mu_{N_1} = 0 \rightarrow \bar{\mu}_{\Delta_\alpha} = 0$

Higher temperatures

Electron Yukawa interaction not in equilibrium at
 $T \gtrsim 10^5 \text{ GeV} \rightarrow$ New chemical equilibrium:

$$\begin{pmatrix} \mu_{\ell_e} + \mu_\Phi \\ \mu_{\ell_\mu} + \mu_\Phi \\ \mu_{\ell_\tau} + \mu_\Phi \end{pmatrix} = - \begin{pmatrix} 6/13 & 0 & 0 \\ 0 & 41/111 & 4/111 \\ 0 & 4/111 & 41/111 \end{pmatrix} \begin{pmatrix} \bar{\mu}_{\Delta_e} \\ \bar{\mu}_{\Delta_\mu} \\ \bar{\mu}_{\Delta_\tau} \end{pmatrix}$$

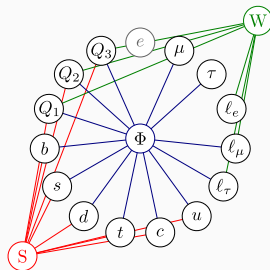
New flavor coupling matrix



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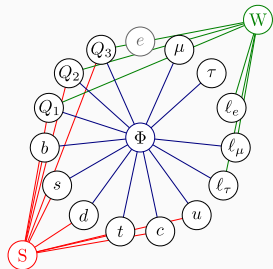


New flavor coupling matrix; new conserved global charge: RH electron number

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New flavor coupling matrix; new conserved global charge: RH electron number

Wash-in leptogenesis (spectator leptogenesis): [Domcke, Kamada, Mukaida, KS, Yamada 2020]

Suppose $\bar{\mu}_e \neq 0$ because of new dynamics at high energies (“electrogenesis”); then efficient right-handed-neutrino (RHN) interactions at $T \sim M_i$ result in

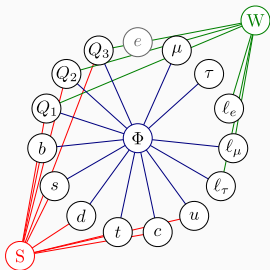
$$\mu_{\ell_\alpha} + \mu_\Phi = \mu_{N_1} = 0 \quad \rightarrow \quad \bar{\mu}_{\Delta_e} = -\frac{5}{6} \bar{\mu}_e, \quad \bar{\mu}_{\Delta_\mu} = \frac{4}{15} \bar{\mu}_e, \quad \bar{\mu}_{\Delta_\tau} = \frac{4}{15} \bar{\mu}_e$$

See also [Campbell, Davidson, Ellis, Olive 1992] [Cline, Kainulainen, Olive 1993, 1994] [Fukugita, Yanagida 2002] [Fong 2016]

Boltzmann equation

$$(\partial_t + 3H) \begin{pmatrix} q_{\Delta_e}^{\text{win}} \\ q_{\Delta_\mu}^{\text{win}} \\ q_{\Delta_\tau}^{\text{win}} \end{pmatrix} = \underline{\Gamma}^w \left[\begin{pmatrix} -5/13 \\ 4/37 \\ 4/37 \end{pmatrix} q_e - \begin{pmatrix} 6/13 & 0 & 0 \\ 0 & 41/111 & 4/111 \\ 0 & 4/111 & 41/111 \end{pmatrix} \begin{pmatrix} q_{\Delta_e}^{\text{win}} \\ q_{\Delta_\mu}^{\text{win}} \\ q_{\Delta_\tau}^{\text{win}} \end{pmatrix} \right]$$

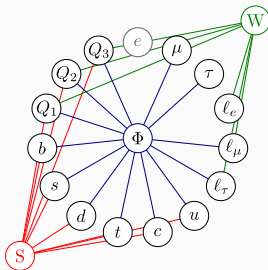
- Nontrivial chemical background results in new source term $\propto q_e$
- RHN interactions drive system towards new chemical attractor solution
- *Full* Boltzmann equation linear in $q_{\Delta_\alpha} \rightarrow q_{B-L}^{\text{tot}} = q_{B-L}^{\text{win}} + q_{B-L}^{\text{th}}$



Boltzmann equation

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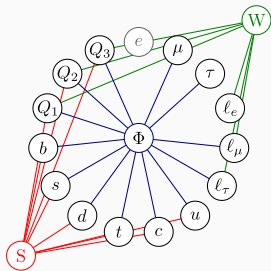
Characteristics of wash-in leptogenesis:

- Hierarchical RHN masses as low as 100 TeV
- RHNs are on-shell (decays, inverse decays)
- Independent of RHN CP violation
- Strong wash-out $\rightarrow$ strong wash-in

Generalization to even higher temperatures

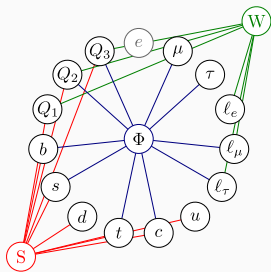
Temperature regimes, T [GeV]

$$[10^5, 10^6] \quad \bar{\mu}_{B-L} = -\frac{3}{10} \bar{\mu}_e$$



Generalization to even higher temperatures

Temperature regimes, T [GeV]

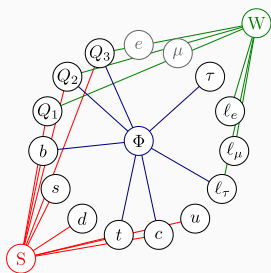


$$[10^5, 10^6] \quad \bar{\mu}_{B-L} = -\frac{3}{10} \bar{\mu}_e$$

$$[10^6, 10^9] \quad \bar{\mu}_{B-L} = -\frac{7}{17} \bar{\mu}_{u-d} - \frac{3}{17} \bar{\mu}_e$$

Generalization to even higher temperatures

Temperature regimes, T [GeV]



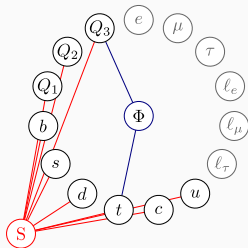
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$$[10^9, 10^{11 \dots 12}] \quad \bar{\mu}_{B-L} = \frac{123}{494} \bar{\mu}_{B_1-B_2} - \frac{82}{247} \bar{\mu}_{d-s} - \frac{123}{247} \bar{\mu}_{u-d} + \frac{142-225P_T}{247} (\bar{\mu}_e + \bar{\mu}_\mu) + \frac{225}{247} \bar{\mu}_{\Delta_\perp}$$

Generalization to even higher temperatures

Temperature regimes, T [GeV]



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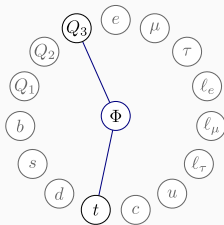
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$$[10^{11 \dots 12}, 10^{13}] \quad \bar{\mu}_{B-L} = \frac{23}{90} \bar{\mu}_B - \frac{4}{15} \bar{\mu}_{d-b} + \frac{3}{10} \bar{\mu}_{u-c} - \frac{3}{10} \bar{\mu}_{B_1-B_2} - \frac{1}{6} \bar{\mu}_{d-s} - \frac{3}{5} \bar{\mu}_{u-d} + \frac{1}{5} \bar{\mu}_{2B_1-B_2-B_3} + \frac{7-23P}{30} (\bar{\mu}_e + \bar{\mu}_\mu + \bar{\mu}_\tau) + \frac{23}{30} \bar{\mu}_{\Delta_\perp}$$

Generalization to even higher temperatures

Temperature regimes, T [GeV]



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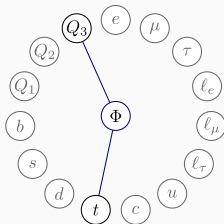
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$$\left[10^{13}, 10^{15}\right] \quad \bar{\mu}_{B-L} = \frac{1}{3} \bar{\mu}_u + \frac{1}{6} \bar{\mu}_B - \frac{1}{3} \bar{\mu}_{d-b} + \frac{1}{4} \bar{\mu}_{u-c} - \frac{1}{4} \bar{\mu}_{B_1-B_2} - \frac{1}{4} \bar{\mu}_{d-s} - \frac{5}{6} \bar{\mu}_{u-d} + \frac{1}{6} \bar{\mu}_{2B_1-B_2-B_3} + \frac{1-3P}{4} (\bar{\mu}_e + \bar{\mu}_\mu + \bar{\mu}_\tau) + \frac{3}{4} \bar{\mu}_{\Delta_\perp}$$

Generalization to even higher temperatures

Temperature regimes, T [GeV]



$$[10^5, 10^6] \quad \bar{\mu}_{B-L} = -\frac{3}{10} \bar{\mu}_e$$

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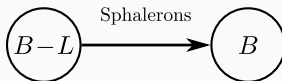
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Toolkit for baryogenesis via wash-in leptogenesis: [Domcke, Kamada, Mukaida, **KS**, Yamada 2020]

- Consistent treatment across ten orders of magnitude in temperature
- Charged-lepton flavor effects: P and P_τ factors quantify overlap between initial state in the UV and N_1 wash-in direction in $e-\mu-\tau$ flavor space

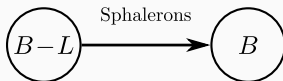
Opportunities for model building

If you believe in electroweak sphalerons (everyone does): $\eta_B = \mathcal{C}_{\text{sph}} \eta_{B-L}$
Baryogenesis via leptogenesis; do not generate B directly, start with $B - L$

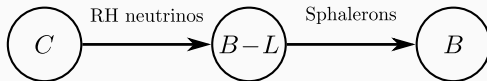


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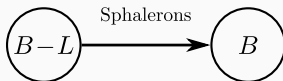


If you believe in right-handed neutrinos (many people do): $\eta_B = c_{\text{sph}} c_{\text{win}} \eta_C$
Baryogenesis via leptogenesis via chargegenesis; start with arbitrary charge C

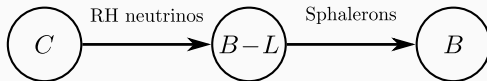


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If you believe in right-handed neutrinos (many people do): $\eta_B = c_{\text{sph}} c_{\text{win}} \eta_C$
Baryogenesis via leptogenesis via chargegenesis; start with arbitrary charge C



Examples of chargegenesis (that do not generate any $B-L$ charge):

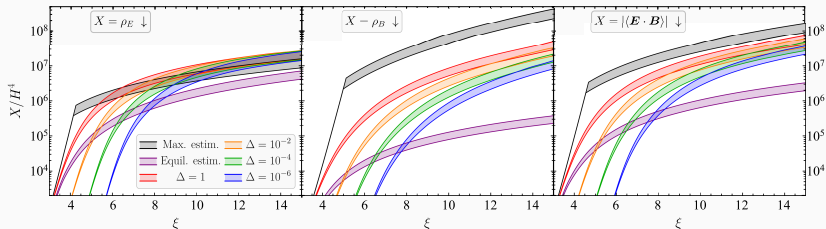
- Good old $SU(5)$ GUT baryogenesis
- Axion inflation coupled to the Standard Model hypercharge gauge field

Part 1: Wash-in leptogenesis

Part 2: Axion inflation

Conclusions and outlook

[Gorbar, KS, Sobol, Vilchinskii 2021]



Axion inflation coupled to the Standard Model hypercharge gauge field:

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset -\frac{\theta(\phi)}{4} Y_{\mu\nu} \tilde{Y}^{\mu\nu}, \quad \xi = \frac{\dot{\theta}(\phi)}{2H}, \quad \theta(\phi) = \frac{\beta\phi}{M_{\text{Pl}}}$$

- Tachyonic instability for states with either positive or negative helicity
- Primordial hypermagnetogenesis, maximally helical hypermagnetic field
- Novel gradient expansion formalism in terms of $\langle \mathbf{E} \cdot (\nabla \times)^n \mathbf{E} \rangle$, etc.

Infinite set of coupled differential equations

$$\dot{\mathcal{E}}^{(n)} + [(n+4)H + 2\sigma] \mathcal{E}^{(n)} - 2l'(\phi)\dot{\phi} \mathcal{G}^{(n)} + 2\mathcal{G}^{(n+1)} = [\dot{\mathcal{E}}^{(n)}]_b$$

$$\dot{\mathcal{G}}^{(n)} + [(n+4)H + \sigma] \mathcal{G}^{(n)} - \mathcal{E}^{(n+1)} + \mathcal{B}^{(n+1)} - l'(\phi)\dot{\phi} \mathcal{B}^{(n)} = [\dot{\mathcal{G}}^{(n)}]_b$$

$$\dot{\mathcal{B}}^{(n)} + (n+4)H \mathcal{B}^{(n)} - 2\mathcal{G}^{(n+1)} = [\dot{\mathcal{B}}^{(n)}]_b$$

for bilinear functions of the electric and magnetic fields involving n gradients

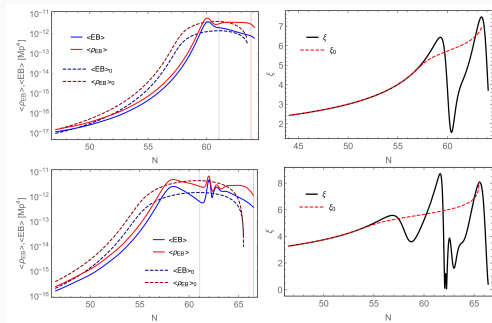
$$\mathcal{E}^{(n)} = \frac{\langle \mathbf{E} \cdot (\nabla \times)^n \mathbf{E} \rangle}{a^n}, \quad \mathcal{B}^{(n)} = \frac{\langle \mathbf{B} \cdot (\nabla \times)^n \mathbf{B} \rangle}{a^n}, \quad \mathcal{G}^{(n)} = -\frac{\langle \mathbf{E} \cdot (\nabla \times)^n \mathbf{B} \rangle}{a^n}$$

Alternative approaches

- Construct iterative self-consistent solution for discrete set of momenta
- Lattice simulations
- Qualitative arguments based on linear perturbation theory

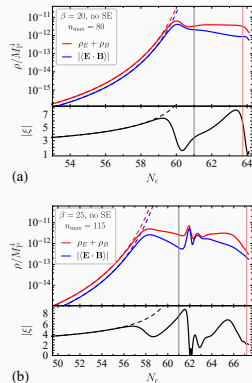
Good agreement with earlier results

Iterative self-consistent solution in k space



Note: Oscillatory behavior in the axion velocity

Gradient expansion

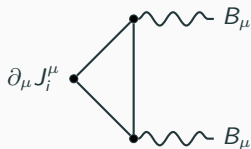


Hyperelectric field $\rightarrow$ Schwinger pair production, hyperelectric current:

$$g_Y \mathbf{J}_Y = \frac{41 g_Y^3}{72 \pi^2} \frac{E B}{a H} \coth \left(\pi \frac{B}{E} \right) \frac{\mathbf{E}}{E}$$

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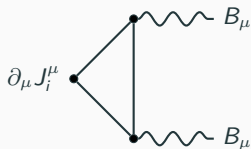


CP -odd contributions in agreement with the chiral anomaly of the SM fermion currents J_i^μ :

$$\partial_\mu J_i^\mu = -\varepsilon_i g_i Y_i^2 \frac{\alpha_Y}{4\pi} Y_{\mu\nu} \tilde{Y}^{\mu\nu} + \dots$$

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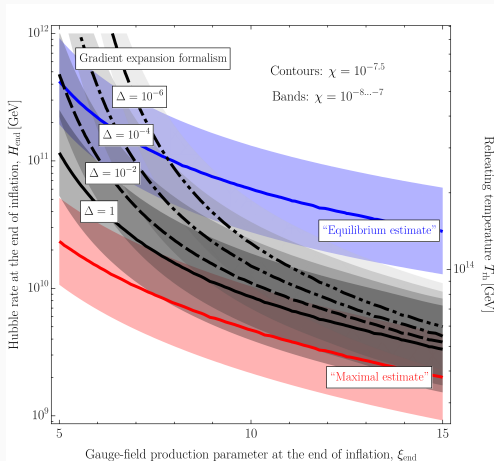
Global charges at the end of inflation:

$$\frac{\bar{\mu}_u}{T} = -8\chi, \quad \frac{\bar{\mu}_B}{T} = -9\chi, \quad \frac{\bar{\mu}_{u-d}}{T} = \frac{\bar{\mu}_{e,\mu,\tau}}{T} = -6\chi, \quad \chi = - \frac{\alpha_Y}{3\pi} \frac{\langle \mathbf{E} \cdot \mathbf{B} \rangle}{a^4 H T^3} \Big|_{\text{end}}$$

χ : dimensionless measure for the amount of CP violation during axion inflation

[Domcke Mukaida 2018] [Domcke, von Harling, Morgante, Mukaida 2019] [Domcke, Kamada, Mukaida, **KS**, Yamada (2022)]

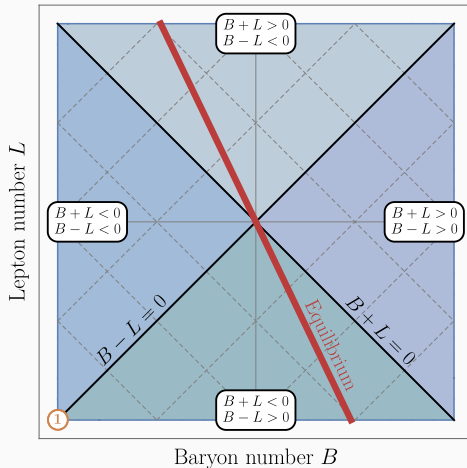
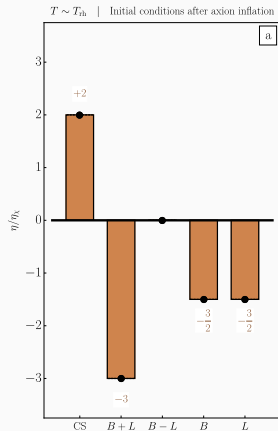
CP violation at the end of axion inflation



Final baryon asymmetry: $\eta_B \sim 0.02 \chi \rightarrow$ preferred χ values around $\chi \sim 10^{-7.5}$;
clearly achievable, despite remaining theory and model uncertainties

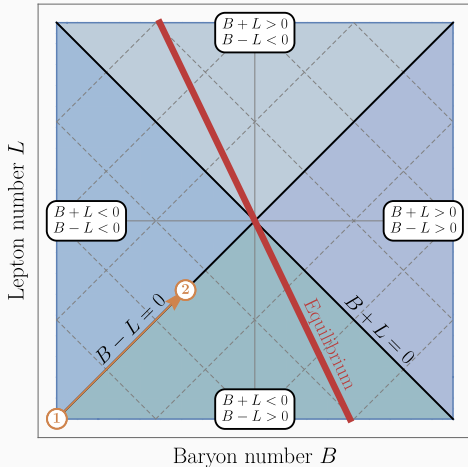
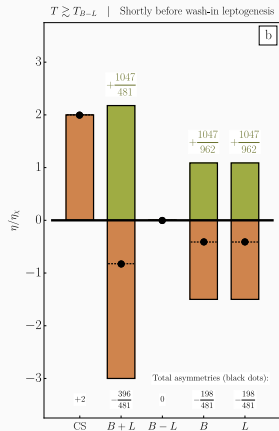
NB: $\Delta = e^{-\int d\tau \sigma}$ parametrizes model-dependent evolution of the conductivity

Wash-in leptogenesis after axion inflation



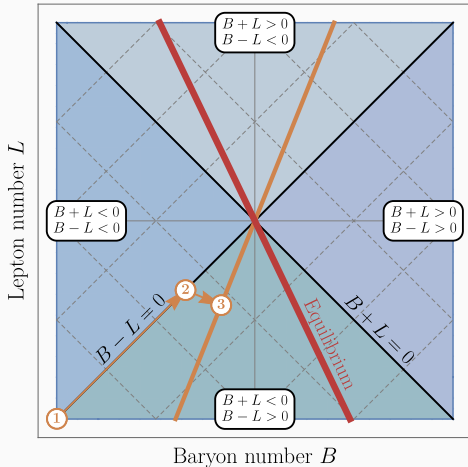
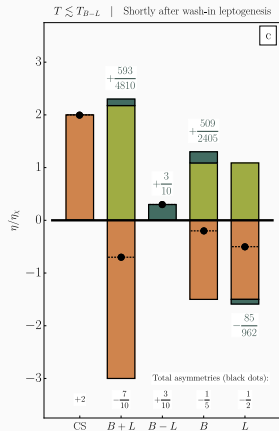
- 1 Axion inflation (chargegenesis)

Wash-in leptogenesis after axion inflation



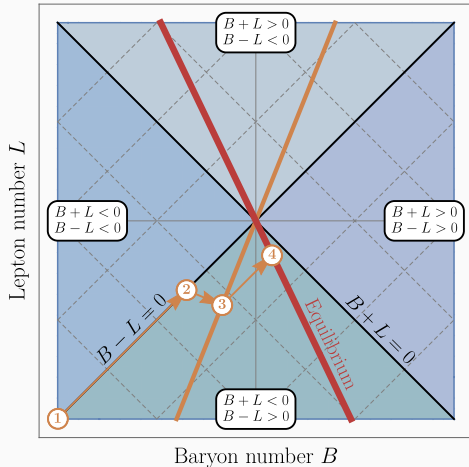
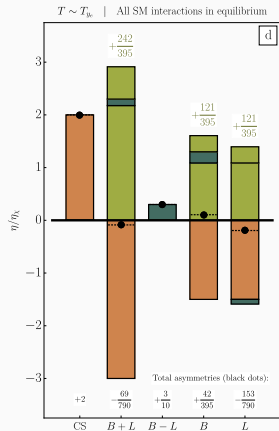
- ① Axion inflation (chargegenesis) ② Sphaleron wash-out

Wash-in leptogenesis after axion inflation



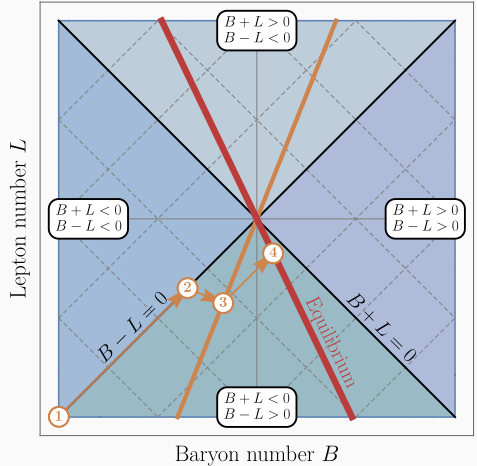
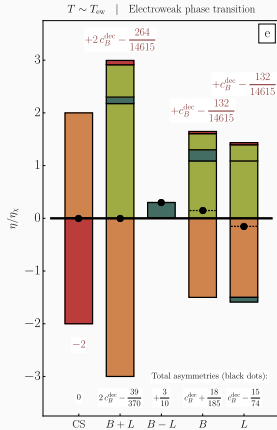
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- ③ Wash-in leptogenesis

Wash-in leptogenesis after axion inflation



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Wash-in leptogenesis after axion inflation



- ① Axion inflation (chargegenesis) ② Sphaleron wash-out
- ③ Wash-in leptogenesis ④ Sphaleron wash-out ⑤ Helicity decay

[Fujita, Kamada 2016] [Kamada, Long 2016] [Jiménez, Kamada, KS, Xu 2017] [Domcke, von Harling, Morgante, Mukaida 2019]

① Magnetic diffusion

- Washes out magnetic fields due to finite conductivity of the SM plasma
- Can be prevented if magnetic field can trigger turbulence evolution
- Require large initial magnetic Reynolds number

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- Large chiral chemical potential induces instability in the magnetic field
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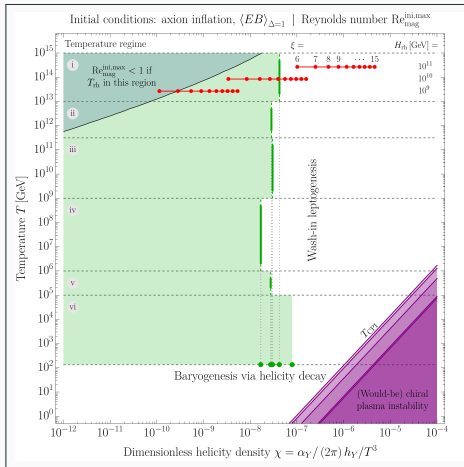
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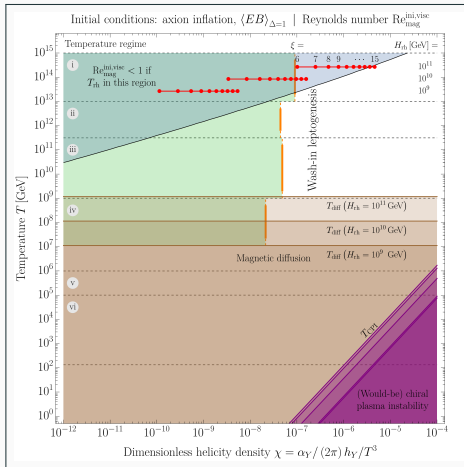
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Rough estimates of relevant temperature scales based on MHD approximation
Better understanding requires dedicated numerical MHD simulations.



- Assume equipartition of kinetic and magnetic energy densities
- Baryogenesis neither affected by magnetic diffusion nor the CPI

Viscous regime



- Assume small kinetic Reynolds number, plasma reaches viscous regime
- No baryogenesis from helicity decay because of magnetic diffusion

Conversion factors

T [GeV]	$(0, 10^5)$	$(10^5, 10^6)$	$(10^6, 10^9)$	$(10^9, 10^{11-12})$	$(10^{11-12}, 10^{13})$	$(10^{13}, 10^{15})$
Three-flavor regime						
c_{B-L}^{win}	0	$\frac{3}{10}$	$\frac{10}{17}$	$\frac{8}{9}$	$\frac{51}{88}$	$\frac{5}{18}$
c_B^{win}	0	$\frac{18}{185}$	$\frac{120}{629}$	$\frac{32}{111}$	$\frac{153}{814}$	$\frac{10}{111}$
$c_5^>$	0	$\frac{711}{481}$	$\frac{856}{537}$	$\frac{1765}{589}$	$\frac{1617}{368}$	$\frac{4841}{972}$
$c_5^<$	0	$\frac{11}{10}$	$\frac{61}{51}$	$\frac{67}{27}$	$\frac{1509}{352}$	$\frac{1204}{243}$
Two-flavor regime						
c_{B-L}^{win}	$\frac{64}{247} + \frac{225}{247} c_\perp^*$			$\frac{17}{37} + \frac{23}{37} c_\perp^*$	$\frac{2}{9} + \frac{3}{5} c_\perp^*$	
c_B^{win}	$\frac{768}{9139} + \frac{2700}{9139} c_\perp^*$			$\frac{204}{1369} + \frac{276}{1369} c_\perp^*$	$\frac{8}{111} + \frac{36}{185} c_\perp^*$	
$c_5^>$	$\frac{1765}{589} - \frac{188}{589} c_{\Delta_F+\mu}^* + \frac{88}{589} c_{\Delta_T}^*$			$\frac{1617}{368} - \frac{17}{92} c_{B-L}^*$	$\frac{4841}{972} - \frac{5}{54} c_{B-L}^*$	
$c_5^<$	$\frac{671}{247} - \frac{84}{247} c_\perp^*$			$\frac{2551}{592} - \frac{17}{148} c_\perp^*$	$\frac{1607}{324} - \frac{1}{18} c_\perp^*$	
One-flavor regime						
c_{B-L}^{win}					$\frac{17}{60} + \frac{23}{36} c_\perp^*$	$\frac{5}{36} + \frac{3}{4} c_\perp^*$
c_B^{win}					$\frac{17}{185} + \frac{46}{185} c_\perp^*$	$\frac{5}{111} + \frac{9}{37} c_\perp^*$
$c_5^>$					$\frac{1617}{368} - \frac{17}{92} c_{B-L}^*$	$\frac{4841}{972} - \frac{5}{54} c_{B-L}^*$
$c_5^<$					$\frac{521}{120} - \frac{17}{120} c_\perp^*$	$\frac{1073}{216} - \frac{5}{72} c_\perp^*$

Five temperature regimes; one, two, or three wash-in directions in flavor space

Part 1: Wash-in leptogenesis

Part 2: Axion inflation

Conclusions and outlook

Phenomenological consequences

- Helical hypermagnetic fields
- Enhanced scalar perturbations, primordial black holes
- Enhanced tensor perturbation, stochastic gravitational waves
- Hierarchical RHN masses as low as 100 TeV

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Next steps

- Better understanding of particle production during axion inflation
- Dedicated numerical MHD simulations using ICs set by axion inflation
- Density matrix formalism for wash-in leptogenesis

Stay tuned!

Thanks a lot for your attention