Flavor effects in baryon number freeze-out in the Standard Model, precisely

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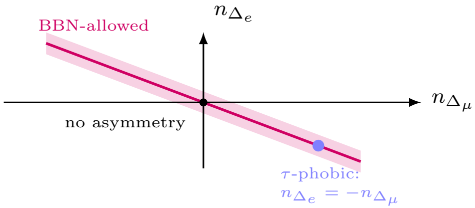
Why lepton flavor?

Sphalerons erase $B{+}L$ but conserve $n_{B\text{-}L}$ *and* each $\Delta_\alpha \equiv B/n_\mathrm{G} - L_\alpha$. The observed $n_b/n_\gamma = 6.1\times10^{-10}$ bounds the *total* asymmetry, $n_{B\text{-}L} \lesssim 10^{-9}$. But individual n_{Δ_α} compensating to $\sum_\alpha n_{\Delta_\alpha} \simeq 0$ can be large.

Baryogenesis depends on flavor structure of the sphaleron conversion,[1] needing $n_{\Delta_\tau}/s \sim 3\times10^{-5}$ (τ-philic) or $n_{\Delta_\mu}/s \sim 8\times10^{-3}$ (τ-phobic, at the BBN frontier).

the $n_{B\text{-}L} = 0$ plane: $\sum_\alpha n_{\Delta_\alpha} = 0$ at every point



[1] leptoflavorgenesis (LFG): Mukaida, Schmitz, Yamada, *Baryon Asymmetry of the Universe from Lepton Flavor Violation,* Phys. Rev. Lett. **129** (2022) 011803 [2111.03082]; BBN-allowed region sketched after Domcke, Escudero, Fernandez Navarro, Sandner, *Lepton flavor asymmetries: from the early Universe to BBN,* JHEP **06** (2025) 137 [2502.14960]

Sphalerons turn $B-L$ into baryon number

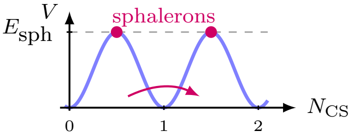
Baryogenesis and leptogenesis generate a $B-L$ asymmetry.[2] Electroweak sphalerons convert it into the observed baryon number,

$$n_B = C_{\text{sph}}\, n_{B\text{-}L}\,, \qquad n_{B\text{-}L} = \sum_\alpha n_{\Delta_\alpha}\,, \qquad \Delta_\alpha \equiv \frac{B}{n_{\text{G}}} - L_\alpha\,.$$

Obtain $\Delta B = \Delta L = n_{\text{G}} \Delta N_{\text{CS}}$ from the anomaly

$$\partial_\mu \mathcal{J}^\mu_{B,L} = \frac{n_{\text{G}}}{32\pi^2}\left[g_2^2 F\widetilde{F} - g_1^2 B\widetilde{B}\right], \qquad \partial_\mu \mathcal{J}^\mu_{B-L} = 0\,.$$

$B-L$ and flavored Δ_α are conserved;[3] also hypercharge and weak isospin, $\partial_\mu \mathcal{J}^\mu_Y = \partial_\mu \mathcal{J}^\mu_{T_3} = 0$. $B+L$ is washed out. These constraints fix all chemical potentials.



[2] Kuzmin, Rubakov, Shaposhnikov, *On anomalous electroweak baryon-number non-conservation in the early universe,* Phys. Lett. B **155** (1985) 36, Fukugita, Yanagida, *Baryogenesis Without Grand Unification,* Phys. Lett. B **174** (1986) 45

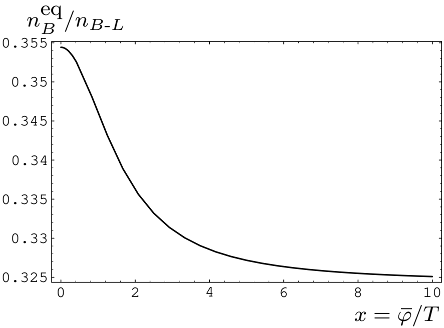
[3] Barni, Espinosa, *Globally Charged Vacuum Decay,* [2606.21653];/fix B violation from bubble collisions: talk by **N. Bhusal** on **Wed 12:00**

The textbook values and why they do not apply

In equilibrium, $n_{\rm G}\mu_B + \sum_\alpha \mu_{L_\alpha} = 0$ fixes $n_B^{\rm eq}$ in terms of $x = \bar\varphi/T$:[4]

$$\frac{n_B^{\rm eq,LO}(x)}{n_{B\text{-}L}} = \frac{4(77+27x^2)}{869+333x^2} \;\to\; \begin{cases} C_{\rm sph}^{\rm sym} = \frac{28}{79} \simeq 0.3544\,, & x\to 0 \\ C_{\rm sph}^{\rm bro} = \frac{12}{37} \simeq 0.3243\,, & x\to\infty \end{cases}$$

Both are equilibrium limits of *one* function, at $x=0$ and $x=\infty$.



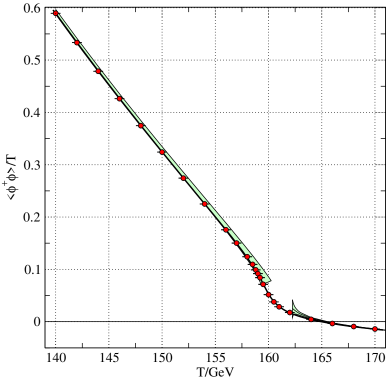
[4] Khlebnikov, Shaposhnikov, *Melting of the Higgs vacuum: Conserved numbers at high temperature,* Phys. Lett. B **387** (1996) 817 [hep-ph/9607386], Laine, Shaposhnikov, *A Remark on sphaleron erasure of baryon asymmetry,* Phys. Rev. D **61** (2000) 117302 [hep-ph/9911473]

. . . but freeze-out happens inside the crossover[5]

Condensate melts at $T_c \simeq 159.6$ GeV; freeze-out at $T_{fo} \simeq 133.5$ GeV.

At $x(T_{fo}) = \bar{\varphi}/T_{fo} = \mathcal{O}(1)$, $\Gamma_{ws}(T)$ has dropped by orders of magnitude.

Both C^{sym}_{sph} and C^{bro}_{sph} misestimate the baryon asymmetry by $\mathcal{O}(5\%)$.



[5] D'Onofrio, Rummukainen, *The Standard Model cross-over on the lattice*, Phys. Rev. D **93** (2015) 025003 [1508.07161]

What we improve

$\bar{\varphi}$	**Higgs VEV** $\bar{\varphi}(T)$	perturbative, no lattice fit
	Equilibrium input	$n_B^{\rm eq}$ at $\mathrm{N^2LO}$, with flavor
	Evolution equation	solved across the crossover

Together they give the surviving baryon number at freeze-out and the size of lepton-flavor effects.

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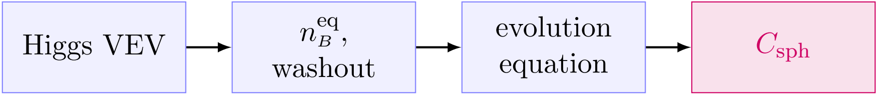


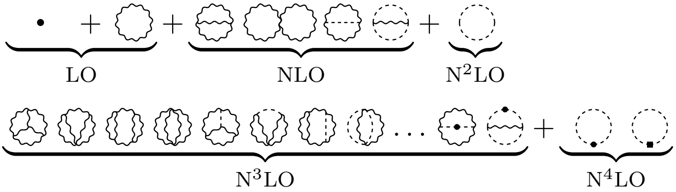
$\bar{\varphi}$ Higgs expectation value $\bar{\varphi}(T)$

Previously: empirical fits to the lattice $\langle \Phi^\dagger \Phi \rangle$ shown before.

Today: fully perturbative, from the high-T 3d EFT of the SM.[6]

Expand the effective potential and solve for the minimum, order by order,[7]

$-V_{\text{eff}}^{\text{bro}} =$



3d power counting $\lambda \sim g^3$; couplings RG-evolved from m_Z with 2-loop SM β-functions.

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[6] Kajantie, Laine, Rummukainen, Shaposhnikov, *Generic rules for high temperature dimensional reduction and their application to the standard model,* Nucl. Phys. B **458** (1996) 90 [hep-ph/9508379], Croon, Gould, Schicho, Tenkanen, White, *Theoretical uncertainties for cosmological first-order phase transitions,* JHEP **04** (2021) 055 [2009.10080]; EFT for thermal transitions: talk by **A. Dashko** on **Wed 15:00**

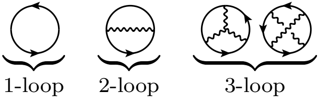
[7] three loops: Ekstedt, Schicho, Tenkanen, *Cosmological phase transitions at three loops: The final verdict on perturbation theory,* Phys. Rev. D **110** (2024) 096006 [2405.18349]

Equilibrium density and washout at N^2LO

Both follow from the grand canonical pressure, split by dimensional reduction into hard and soft parts,[8]

$$p(\mu, T, \bar{\varphi}) = p_{\text{hard}}(\mu, T) + p_{\text{soft}}(\mu, T, \bar{\varphi})$$

$$= \ldots\,, \qquad n_i = \frac{\partial p}{\partial \mu_i}\,.$$



At LO in the chemical potentials,

$$n_B^{\text{eq,LO}}(x) = \frac{4(77 + 27x^2)}{869 + 333x^2}\, n_{B\text{-}L}\,, \qquad \kappa^{\text{LO}}(x) = \frac{869 + 333x^2}{88 + 34x^2}\,.$$

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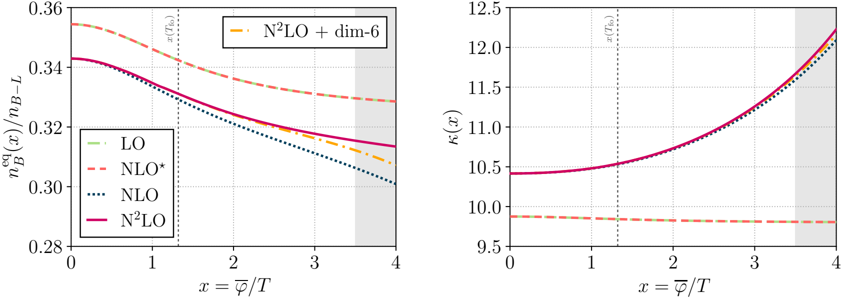
[8] Khlebnikov, Shaposhnikov, *Melting of the Higgs vacuum: Conserved numbers at high temperature,* Phys. Lett. B **387** (1996) 817 [hep-ph/9607386]; four-loop EoS: talk by **K. Seppänen** on **Mon 09:45**

Equilibrium density and washout at $\mathrm{N^2LO}$

$\mathrm{N^2LO}$ homework gives

- 2-loop hard 3d EFT matching $\mathcal{O}(g^2\mu^2)$, lepton Yukawas h_{e_α}
- 1-loop soft potential

g_s^2 shifts $n_B^{\rm eq}$ by $\mathcal{O}(10\%)$ at small x, h_t^2 dominates at large x, and $h_{e_\alpha}^2$ makes $n_B^{\rm eq}$ depend on the *individual* n_{Δ_α} (here use $n_{\Delta_\alpha} = \frac{1}{3} n_{B\text{-}L}$)



Evolution equation for n_B

Linear response in $\frac{\mu_i}{T} \ll 1$ relates anomaly to $B{+}L$ chemical potential,[8]

$$\frac{n_{\rm G}}{\mathcal{V}} \int_{\mathbf{x}} \langle \mathcal{O}_w \rangle = -n_{\rm G}^2 \, \Gamma_{\rm ws} \frac{\mu_{B+L}}{T} \,, \quad n_{\rm G}^2 \, \mu_{B+L} T^2 = \kappa(x) \big[n_B - n_B^{\rm eq}(x) \big] \,,$$

[8] following Domcke, Ema, Mukaida, Yamada, *Spontaneous Baryogenesis from Axions with Generic Couplings,* JHEP **08** (2020) 096 [2006.03148]

[9] Annala, Rummukainen, *Electroweak sphaleron in a magnetic field,* Phys. Rev. D **107** (2023) 073006 [2301.08626]

[10] Bödeker, Klose, *QCD corrections to the electroweak sphaleron rate,* JHEP **05** (2026) 024 [2510.20594]

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$$\Rightarrow \qquad \partial_t n_B + 3 H n_B = \mathcal{S}_B - \Gamma_B \big[n_B - n_B^{\rm eq} \big]\,, \quad \Gamma_B \equiv \kappa(x)\, \frac{\Gamma_{\rm ws}(T)}{T^3}\,.$$

Without helical hypermagnetic fields, $\mathcal{S}_B = 0$.
The sphaleron rate from the lattice[9]

$$\frac{\Gamma_{\rm ws}}{T^4} = \begin{cases} (6.23 \pm 0.05) \times 10^{-7}\,, & T \gtrsim T_{\rm c} \\ \exp\big[-(153.1 \pm 0.9) + (0.858 \pm 0.01) \frac{T}{\rm GeV}\big]\,, & T \lesssim T_{\rm c} \end{cases},$$

is raised 6% by QCD corrections to the weak-isospin conductivity.[10]

[8] following Domcke, Ema, Mukaida, Yamada, *Spontaneous Baryogenesis from Axions with Generic Couplings,* JHEP **08** (2020) 096 [2006.03148]

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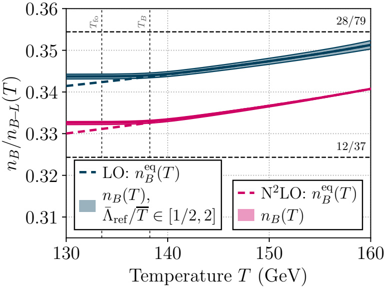
$B+L$ washout $\to$ surviving B

All $n_{B\text{-}L} \neq 0$ results take $n_{\Delta_\alpha} = \frac{1}{3} n_{B\text{-}L}$; then n_B follows $n_B^{\rm eq}$ until $\Gamma_B \sim H$ and freezes out at $T_{\rm fo} = 133.5 \pm 0.97$ GeV:



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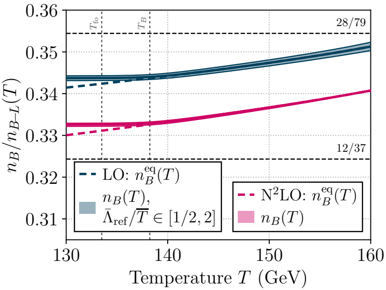
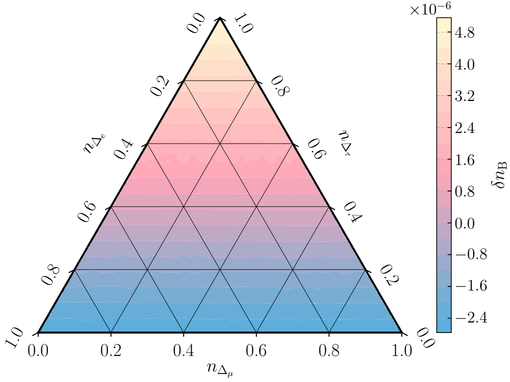


$$n_B/n_{B\text{-}L} = 0.33265$$

It lies between $\frac{28}{79}$ and $\frac{12}{37}$ at $\mathcal{O}(5\%)$ difference. It equals $C_{\rm sph}$ only without the flavor-diagonal terms. Scale variation dominates, so higher orders matter more than a better $\Gamma_{\rm ws}$.

Flavor effects at $n_{B\text{-}L} \neq 0$ are small

Scanning compositions at fixed $n_{B\text{-}L}$. The color shows *relative* shift $\delta n_B = (n_B - n_B^{\text{ref}})/n_B^{\text{ref}}$ away from central point $n_{\Delta_\alpha} = \frac{1}{3} n_{B\text{-}L}$: $\mathcal{O}(10^{-6})$.



For flavor effects at $n_{B\text{-}L} = 0$

the leading term vanishes and the $\mathcal{O}(h_{e_\alpha}^2)$ piece is the *entire* answer:

$$n_B^{\rm eq} = \frac{1034 + 2473x^2 + 792x^4}{(4\pi)^2(869 + 333x^2)} \sum_\alpha h_{e_\alpha}^2 \, n_{\Delta_\alpha} \, .$$

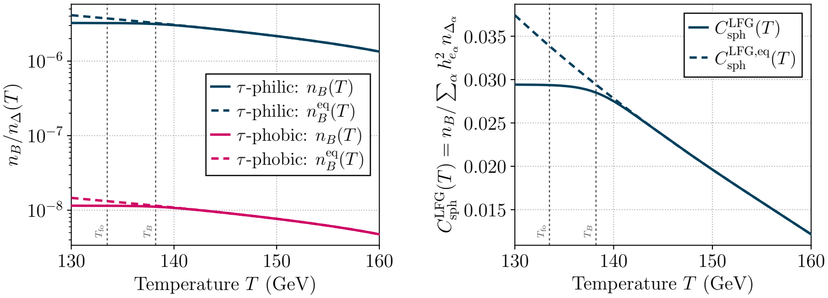
Since $\sum_\alpha n_{\Delta_\alpha} = 0$, it is the hierarchy of the h_{e_α}, not their smallness, that produces $n_B \neq 0$: degenerate Yukawas would give exactly zero.[11]

Two limiting flavor configurations for leptoflavorgenesis (LFG):

- τ-philic: $n_{\Delta_\tau} \neq 0$, $n_{\Delta_\tau} = -2n_{\Delta_{e,\mu}}$.
- τ-phobic: $n_{\Delta_e} = -n_{\Delta_\mu}$, $n_{\Delta_\tau} = 0$.

[11] Mukaida, Schmitz, Yamada, *Baryon Asymmetry of the Universe from Lepton Flavor Violation*, Phys. Rev. Lett. **129** (2022) 011803 [2111.03082]

τ-philic vs. τ-phobic



Dashed: N^{2}LO equilibrium $C_{\rm sph}^{\rm LFG,eq}$. Solid: solving transport equation.
Different conversion factor:

$$n_B = C_{\rm sph}^{\rm LFG} \sum_\alpha h_{e_\alpha}^2 n_{\Delta_\alpha}\,, \qquad \boxed{C_{\rm sph}^{\rm LFG} = 0.02942}\,.$$

τ-philic needs $n_\Delta/s \sim 3\times10^{-5}$.
τ-phobic is driven by h_μ^2 and needs $n_\Delta/s \sim 8\times10^{-3}$.

Conclusions

$n_B/n_{B\text{-}L} = 0.33265$ replaces $\frac{28}{79}$ and $\frac{12}{37}$, from

$\bar{\varphi}$	**Higgs VEV** $\bar{\varphi}(T)$	perturbative
	Equilibrium input	n_B^{eq}, κ at N^2LO with Yukawas
	Evolution equation	across the crossover

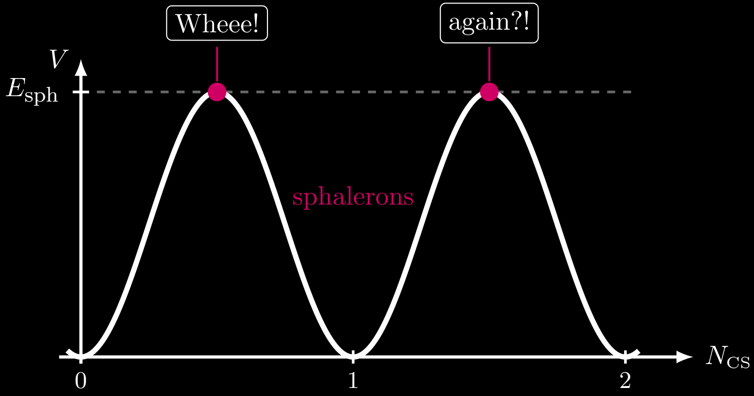
Flavor composition at fixed $n_{B\text{-}L}$ matters at $\mathcal{O}(10^{-6})$. Negligible for $n_{B\text{-}L} \neq 0$, but $n_{B\text{-}L} = 0$ still gives $n_B \neq 0$.

Next: switch on $\mathcal{S}_B \neq 0$ from hypermagnetic helicity.[12]

Ready to use in leptogenesis and baryogenesis calculations.

[12] Fujita, Kamada, *Large-scale magnetic fields can explain the baryon asymmetry of the Universe,* Phys. Rev. D **93** (2016) 083520 [1602.02109]

Kiitos



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Backup

Weak coupling expansion of equilibrium distribution

$$n_B^{\text{eq}}(x) = \left[\frac{4(77+27x^2)}{869+333x^2} + \frac{18}{\pi}\frac{\mathcal{S}(x)}{(869+333x^2)^2}\right] n_{B\text{-}L} + \frac{1034+2473x^2+792x^4}{(4\pi)^2(869+333x^2)} \sum_\alpha h_{e_\alpha}^2 n_{\Delta_\alpha}$$

$$- \frac{1}{(4\pi)^2}\frac{n_{B\text{-}L}}{(869+333x^2)^2}\left[\frac{4}{3}\big(126082+328295x^2+182277x^4+30456x^6\big)\sum_\alpha h_{e_\alpha}^2\right.$$

$$+ 9\big(3630+9823x^2+9405x^4+1944x^6\big)h_t^2$$

$$- 9\big(38599+27346x^2+5373x^4\big)g_1^2$$

$$- 27\big(5445+3542x^2+467x^4-72x^6\big)g_2^2 + 432\big(2904+2365x^2+441x^4\big)g_{\text{S}}^2$$

$$\left. + 144\big(242+792x^2+141x^4+18x^6\big)\lambda\right]$$

$\mathcal{S}(x)$: soft one-loop potential contribution.

Weak coupling expansion of washout coefficient

$$
\begin{aligned}
\kappa(x) = {} & \frac{869 + 333x^2}{2(44 + 17x^2)} + \frac{1}{8\pi}\frac{\mathcal{S}(x)}{(44 + 17x^2)^2} \\
& + \frac{1}{(4\pi)^2}\frac{1}{(44 + 17x^2)^2}\Bigg[\frac{2}{9}\big(77 + 27x^2\big)(418 + 1025x^2 + 360x^4\big)\sum_\alpha h_{e_\alpha}^2 \\
& \quad + \frac{1}{4}\big(61226 + 168432x^2 + 100935x^4 + 17496x^6\big)h_t^2 \\
& \quad + \frac{1}{8}\big(243936 + 185350x^2 + 35487x^4\big)g_1^2 \\
& \quad + \frac{1}{8}\big(385748 + 294690x^2 + 56145x^4 - 108x^6\big)g_2^2 \\
& \quad + 12\big(8833 + 6765x^2 + 1305x^4\big)g_\mathrm{s}^2 \\
& \quad - \big(242 + 792x^2 + 141x^4 + 18x^6\big)\lambda\Bigg]
\end{aligned}
$$

Both hold up to $\mathcal{O}(g_\mathrm{soft}^2, g^3)$.