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

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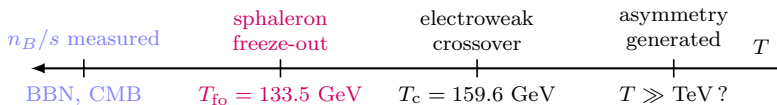
P. Schicho, C. Benso, D. Bödeker, K. Kamada, K. Mukaida, L. Sagunski, K. Schmitz, [2609.xxxxx].
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Something the Standard Model cannot produce

The Universe is made of matter, with essentially no antimatter left. What survived annihilation is **about one baryon per billion photons**,¹

$$\eta = \frac{n_B}{n_\gamma} \simeq 6.1 \times 10^{-10}, \quad \frac{n_B}{s} = (8.72 \pm 0.05) \times 10^{-11},$$

from Big Bang nucleosynthesis (BBN) and from the CMB.



¹ **Planck** Collaboration, Aghanim *et al.*, *Planck 2018 results. VI. Cosmological parameters*, *Astron. Astrophys.* **641** (2020) A6 [1807.06209]

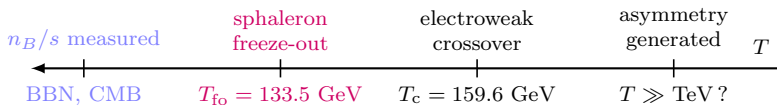
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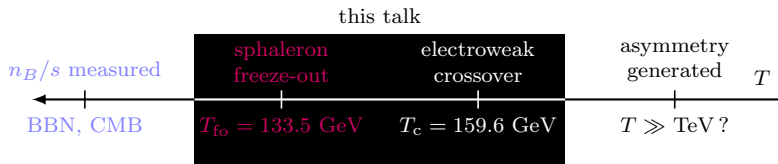
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Sphalerons turn $B-L$ into baryon number

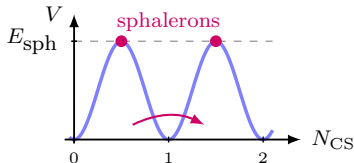
Baryogenesis and leptogenesis generate a $B-L$ asymmetry.² Electroweak sphalerons convert it into the observed baryon number,

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

Obtain $\Delta B = \Delta L = n_G \Delta N_{\text{CS}}$ from chiral anomaly

$$\partial_{\mu} \mathcal{J}_{B,L}^{\mu} = \frac{n_G}{32\pi^2} \left[g_2^2 F \tilde{F} - g_1^2 B \tilde{B} \right], \quad \partial_{\mu} \mathcal{J}_{B-L}^{\mu} = 0.$$

$B-L$ and flavored Δ_{α} are conserved;³ also hypercharge and weak isospin, $\partial_{\mu} \mathcal{J}_Y^{\mu} = \partial_{\mu} \mathcal{J}_{T_3}^{\mu} = 0$. $B+L$ is washed out.



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]; B violation: **W. Zhang, Thu 17:00**

The textbook values and why they do not apply

In equilibrium two values are quoted, as if for different eras,⁴

$$C_{\text{sph}}^{\text{sym}} = \frac{28}{79} \simeq 0.3544, \quad C_{\text{sph}}^{\text{bro}} = \frac{12}{37} \simeq 0.3243.$$

Should I use the **symmetric** or **broken** phase value?

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]

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Yes.



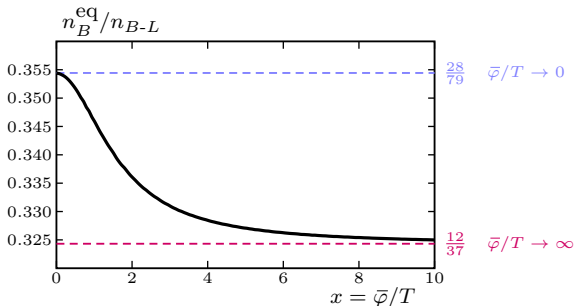
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They are two limits of *one function* of $x = \bar{\varphi}/T$.



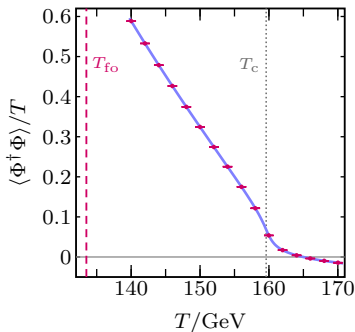
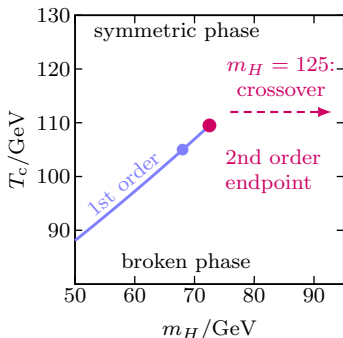
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...but freeze-out happens inside the crossover

At $m_H = 125$ GeV there is **no transition at all**.⁵

At $T_c = 159.6$ GeV, the condensate melts smoothly.

At $T_{fo} = 133.5$ GeV, $\bar{\varphi}/T \simeq 1.3$ is still finite but Γ_{ws} is tiny.



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At $T_{fo} = 133.5$ GeV, $\bar{\varphi}/T \simeq 1.3$ is still finite but Γ_{ws} is tiny.

Charged-lepton Yukawas h_{e_α} make the conversion flavor sensitive: one conversion factor is not enough,⁶

$$n_B = C_{\text{sph}} n_{B-L} + \mathcal{F}_{\text{sph}} \sum_{\alpha} h_{e_\alpha}^2 n_{\Delta_\alpha}.$$

A universe with **vanishing $B-L$** can still generate **B : leptoflavorgenesis**.

This talk determines both constants, C_{sph} and $\mathcal{F}_{\text{sph}}$.

⁵ Kajantie, Laine, Rummukainen, Shaposhnikov, *Is there a hot electroweak phase transition at $m_H \gtrsim m_W$?*, Phys. Rev. Lett. **77** (1996) 2887 [hep-ph/9605288]; lattice condensate: D'Onofrio, Rummukainen, *The Standard Model cross-over on the lattice*, Phys. Rev. D **93** (2015) 025003 [1508.07161]

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What we improve

 **Higgs VEV** $\bar{\varphi}(T)$ perturbative, no lattice fit

 **Equilibrium input** $C_{\text{sph}}^{\text{eq}}, \mathcal{F}_{\text{sph}}^{\text{eq}}, \kappa$ at N²LO

 **Evolution equation** solved across the crossover

Together they give the surviving baryon number at freeze-out: the flavor-blind C_{sph} and its flavored counterpart $\mathcal{F}_{\text{sph}}$.

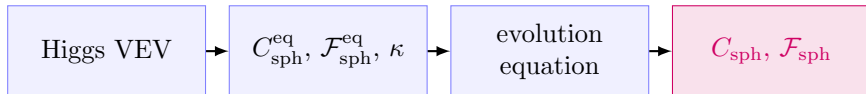
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$\bar{\varphi}$ Higgs expectation value

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

Today: fully perturbative $\bar{\varphi}(T)$ from the high- T 3d EFT of the SM.⁷

Expand effective potential and solve for the minimum, order by order,⁸

$$\begin{aligned} -V_{\text{eff}}^{\text{bro}} = & \underbrace{\bullet + \text{1-loop}}_{\text{LO}} + \underbrace{\text{2-loop} + \text{3-loop}}_{\text{NLO}} + \underbrace{\text{4-loop}}_{\text{N}^2\text{LO}} \\ & + \underbrace{\text{5-loop} + \text{6-loop} + \text{7-loop} + \text{8-loop} + \text{9-loop} + \text{10-loop} + \text{11-loop} + \text{12-loop}}_{\text{N}^3\text{LO}} + \underbrace{\text{13-loop} + \text{14-loop}}_{\text{N}^4\text{LO}} \end{aligned}$$

Couplings RG-evolved from m_Z with 2-loop SM β -functions.

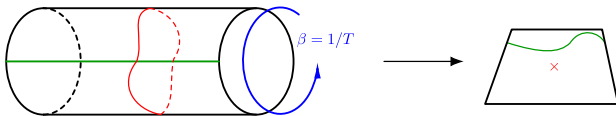
⁷ Kajantie, Laine, Rummukainen, Shaposhnikov, *Generic rules for high temperature dimensional reduction and their application to the standard model*, Nucl. Phys. B **458** (1996) 90 [hep-ph/9508379], Croon, Gould, Schicho, Tenkanen, White, *Theoretical uncertainties for cosmological first-order phase transitions*, JHEP **04** (2021) 055 [2009.10080]; EW transitions: **J. Cesca, Mon 17:00**; phase transitions: **J. van de Vis, Tue 11:00**

⁸three loops: Ekstedt, Schicho, Tenkanen, *Cosmological phase transitions at three loops: The final verdict on perturbation theory*, Phys. Rev. D **110** (2024) 096006 [2405.18349]

A robust EFT framework at high temperatures: 3d EFT⁹

Thermodynamics $\mathcal{Z} = \text{Tr} e^{-\beta \mathcal{H}}$ formulated in $\mathbb{R}^3 \times S^1_\beta$.

$$\underbrace{\int_{\mathbb{R}^3 \times S^1_\beta} \mathcal{L}}_{\text{bosons} + \text{fermions}} \rightarrow \underbrace{\int_{\mathbb{R}^3} \mathcal{L}_{\text{eff}}}_{\text{bosons only}} .$$



In 3d EFT, modified canonical mass dimensions render marginal operators relevant, $[A_0^a] = [g_{3,abc}] = 1/2$: **super-renormalizable** theory.

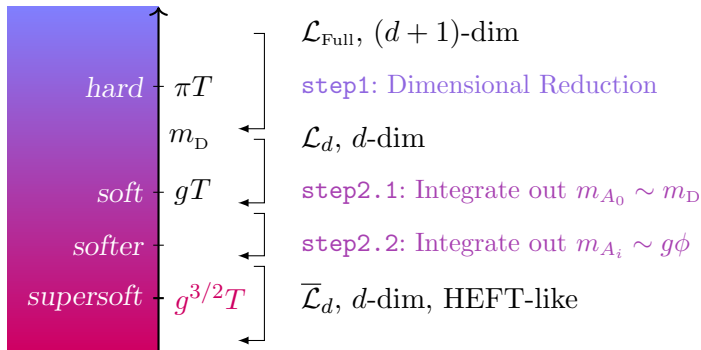
$$\int_{\mathbb{R}^3} \mathcal{L}_{\text{eff}} \supset \left[\frac{1}{2} \partial_i A_0^a \partial_i A_0^b - g_{3,abc} A_i^a A_0^b \partial_i A_0^c + \frac{m_{3,ab}^2}{2} A_0^a A_0^b \right] .$$

⁹ Braaten, Nieto, *Effective field theory approach to high temperature thermodynamics*, Phys. Rev. D **51** (1995) 6990 [hep-ph/9501375]

Dimensional Reduction (DR) for precision thermodynamics

of non-Abelian gauge theories as QCD and (EW) phase transition.¹⁰

Recently automated¹¹ two step procedure:



¹⁰ 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]

¹¹ Ekstedt, Schicho, Tenkanen, DRalgo: *A package for effective field theory approach for thermal phase transitions*, Comput. Phys. Commun. **288** (2023) 108725 [2205.08815]

Equilibrium density and washout at N²LO

Both follow from the **grand canonical pressure**, organized by dimensional reduction into hard and soft parts,¹²

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

$$= \underbrace{\text{1-loop}}_{\text{1-loop}} \quad \underbrace{\text{2-loop}}_{\text{2-loop}} \quad \underbrace{\text{3-loop}}_{\text{3-loop}} \dots, \quad n_i = \frac{\partial p}{\partial \mu_i}.$$

At **LO** in chemical potentials, the pressure is the **ideal gas** ($x \equiv \bar{\varphi}/T$):

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

$$\mathcal{F}_{\text{sph}}^{\text{eq,LO}}(x) = \mathbf{0}.$$

¹² Khlebnikov, Shaposhnikov, *Melting of the Higgs vacuum: Conserved numbers at high temperature*, Phys. Lett. B **387** (1996) 817 [hep-ph/9607386]; NLO*: Laine, Shaposhnikov, *A Remark on sphaleron erasure of baryon asymmetry*, Phys. Rev. D **61** (2000) 117302 [hep-ph/9911473]



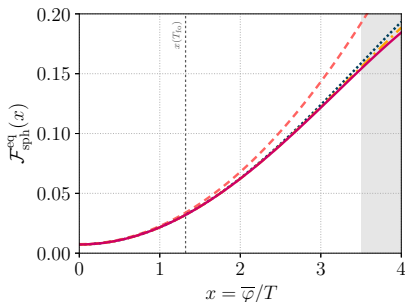
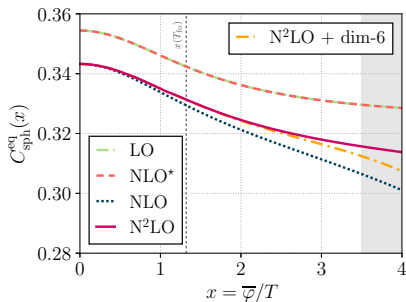
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N²LO “homework” gives (here use $n_{\Delta_\alpha} = \frac{1}{3}n_{B-L}$)

- ▷ 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^{eq} by $\mathcal{O}(10\%)$ at small x , h_t^2 dominates at large x .

Charged-lepton Yukawas $h_{e_\alpha}^2$ render n_B^{eq} dependent on *individual* n_{Δ_α} .



✍ Evolution equation for n_B

Linear response, $\frac{\mu_i}{T} \ll 1$, relates anomaly to $B+L$ chemical potential,¹²

$$\frac{n_G}{\mathcal{V}} \int_{\mathbf{x}} \langle F \tilde{F} \rangle \sim -n_G^2 \Gamma_{\text{ws}} \frac{\mu_{B+L}}{T}, \quad n_G^2 \mu_{B+L} T^2 = \kappa(x) [n_B - n_B^{\text{eq}}(x)],$$

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

¹² following Domcke, Ema, Mukaida, Yamada, *Spontaneous Baryogenesis from Axions with Generic Couplings*, JHEP **08** (2020) 096 [2006.03148]

¹³ Annala, Rummukainen, *Electroweak sphaleron in a magnetic field*, Phys. Rev. D **107** (2023) 073006 [2301.08626];
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Without helical hypermagnetic fields, $\mathcal{S}_B = 0$.

The **sphaleron rate** is fitted to the lattice:¹³

$$\frac{\Gamma_{\text{ws}}}{T^4} = \begin{cases} 6.23 \times 10^{-7}, & T \gtrsim T_c \text{ (symmetric)}, \\ \exp[-153.1 + 0.858 \frac{T}{\text{GeV}}], & T \lesssim T_c \text{ (broken)}. \end{cases}$$

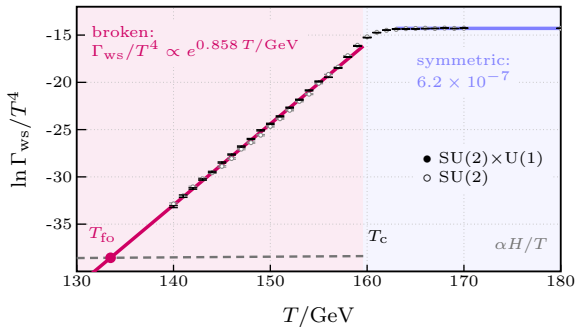
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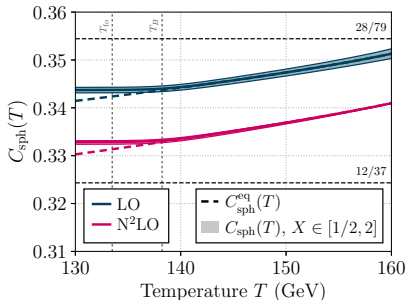
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$B+L$ washout $\rightarrow$ surviving B

All $n_{B-L} \neq 0$ results take $n_{\Delta_\alpha} = \frac{1}{3}n_{B-L}$.

Then n_B follows n_B^{eq} until $\Gamma_B \sim H$ and freezes out at T_{fo} :



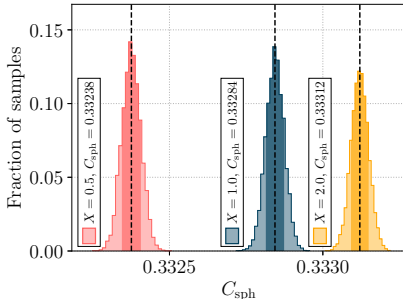
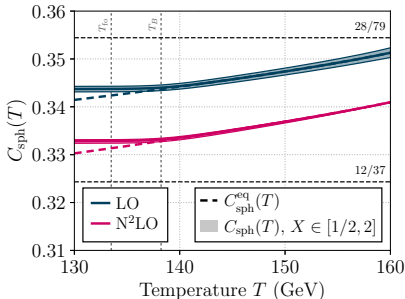
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$$C_{\text{sph}} = 0.3328(5)$$

Using $\bar{\Lambda} = X(2\pi T)$, higher orders matter more than a better Γ_{ws} .



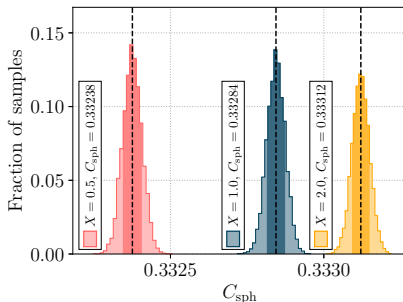
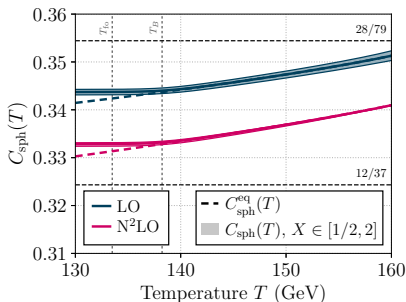
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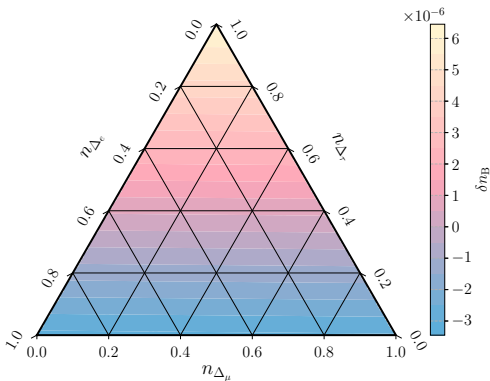
$$\frac{12}{37} < C_{\text{sph}} = 0.3328(5) < \frac{28}{79}$$

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

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



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

$C_{\text{sph}} n_{B-L}$ vanishes and only $n_B = \mathcal{F}_{\text{sph}} \sum_{\alpha} h_{e_{\alpha}}^2 n_{\Delta_{\alpha}}$ survives.

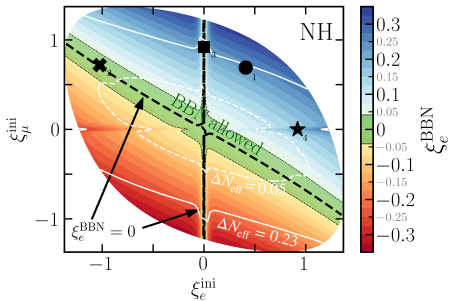
Hierarchy of charged-lepton Yukawas $h_{e_{\alpha}}$, generates $n_B \neq 0$.¹⁴

▷ τ -philic:

$$n_{\Delta_{\tau}} = -2n_{\Delta_{e,\mu}} \neq 0$$

▷ τ -phobic:

$$n_{\Delta_{\mu}} = -n_{\Delta_e}, n_{\Delta_{\tau}} = 0$$



axes: neutrino degeneracies $\xi_{\alpha} = \mu_{\alpha}/T$ before BBN,
at $\sum_{\alpha} n_{\Delta_{\alpha}} = 0$

¹⁴ Mukaida, Schmitz, Yamada, *Baryon Asymmetry of the Universe from Lepton Flavor Violation*, Phys. Rev. Lett. **129** (2022) 011803 [2111.03082]; BBN-allowed region: Domcke, Escudero, Fernandez Navarro, Sandner, *Lepton flavor asymmetries: from the early Universe to BBN*, JHEP **06** (2025) 137 [2502.14960]. NH/IH: normal/inverted mass ordering

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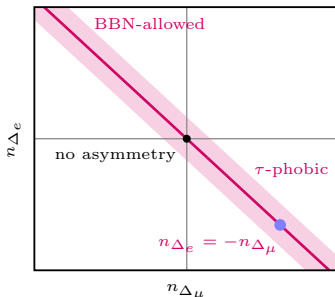
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the $n_{B-L} = 0$ plane: $\sum_{\alpha} n_{\Delta_{\alpha}} = 0$ at every point

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τ -philic vs. τ -phobic

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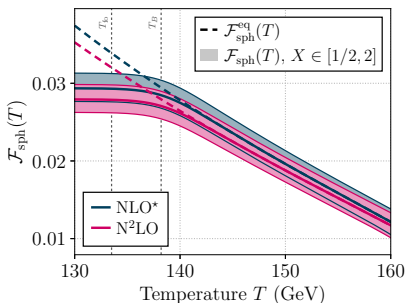
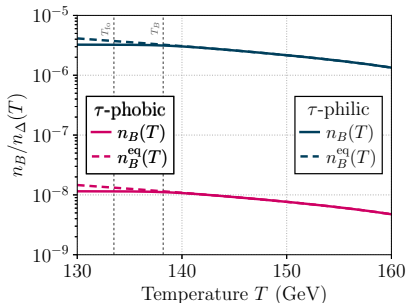
$$\mathcal{F}_{\text{sph}} = 0.0279(19).$$

Equilibrium at freeze-out gives $\mathcal{F}_{\text{sph}}^{\text{eq}} = 0.0320$: a **13%** effect.

τ -philic needs $n_{\Delta_{\tau}}/s \sim 3 \times 10^{-5}$.

τ -phobic is driven by h_{μ}^2 and needs $n_{\Delta_{\mu}}/s \sim 8 \times 10^{-3}$.

Dashed: N²LO equilibrium $\mathcal{F}_{\text{sph}}^{\text{eq}}$. **Solid:** solving the transport equation.



Some precision conclusions

$C_{\text{sph}} = 0.3328(5)$ replaces $\frac{28}{79}$ and $\frac{12}{37}$, and $\mathcal{F}_{\text{sph}} = 0.0279(19)$ is new:

 **Higgs VEV** $\bar{\varphi}(T)$ perturbative

 **Equilibrium input** $C_{\text{sph}}^{\text{eq}}, \mathcal{F}_{\text{sph}}^{\text{eq}}, \kappa$ at N²LO

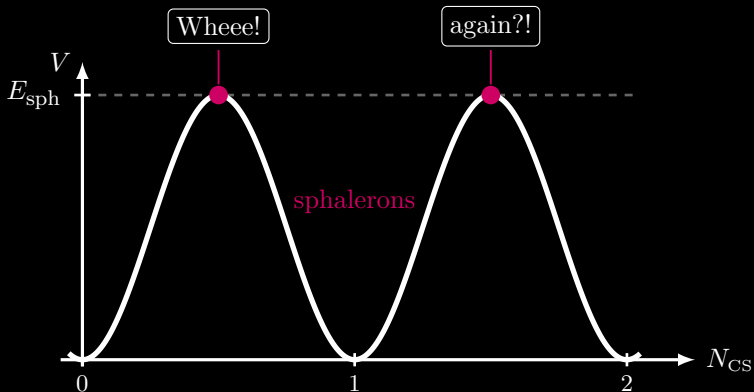
 **Evolution equation** across the crossover

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

Next: switch on $\mathcal{S}_B \neq 0$ from hypermagnetic helicity.¹⁵

Ready to use in leptogenesis and baryogenesis calculations.

¹⁵ Fujita, Kamada, *Large-scale magnetic fields can explain the baryon asymmetry of the Universe*, Phys. Rev. D **93** (2016) 083520 [1602.02109]



$$C_{\text{sph}} = 0.3328(5), \quad \mathcal{F}_{\text{sph}} = 0.0279(19)$$

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Backup

Weak coupling expansion of equilibrium distribution

$$\begin{aligned} C_{\text{sph}}^{\text{eq}}(x) = & \frac{4(77 + 27x^2)}{869 + 333x^2} + \frac{18}{\pi} \frac{\mathcal{S}(x)}{(869 + 333x^2)^2} \\ & - \frac{1}{(4\pi)^2} \frac{1}{(869 + 333x^2)^2} \left[\frac{4}{3} (126082 + 328295x^2 + 182277x^4 + 30456x^6) \sum_{\alpha} h_{e_{\alpha}}^2 \right. \\ & + 9(3630 + 9823x^2 + 9405x^4 + 1944x^6) h_t^2 \\ & - 9(38599 + 27346x^2 + 5373x^4) g_1^2 \\ & - 27(5445 + 3542x^2 + 467x^4 - 72x^6) g_2^2 + 432(2904 + 2365x^2 + 441x^4) g_S^2 \\ & + 144(242 + 792x^2 + 141x^4 + 18x^6) \lambda \\ & \left. - 288(242 + 66x^2 + 9x^4) \frac{\nu^2}{T^2} \right], \end{aligned}$$

$$\mathcal{F}_{\text{sph}}^{\text{eq}}(x) = \frac{1034 + 2473x^2 + 792x^4}{(4\pi)^2(869 + 333x^2)} + \mathcal{O}(h_{e_{\alpha}}^2).$$

$\mathcal{S}(x)$: soft one-loop potential contribution; ν^2 : Higgs mass parameter.

Weak coupling expansion of washout coefficient

$$\begin{aligned}\kappa(x) = & \frac{869 + 333x^2}{2(44 + 17x^2)} + \frac{1}{8\pi} \frac{\mathcal{S}(x)}{(44 + 17x^2)^2} \\ & + \frac{1}{(4\pi)^2} \frac{1}{(44 + 17x^2)^2} \left[\frac{2}{9} (77 + 27x^2)(418 + 1025x^2 + 360x^4) \sum_{\alpha} h_{e\alpha}^2 \right. \\ & + \frac{1}{4} (61226 + 168432x^2 + 100935x^4 + 17496x^6) h_t^2 \\ & + \frac{1}{8} (243936 + 185350x^2 + 35487x^4) g_1^2 \\ & + \frac{1}{8} (385748 + 294690x^2 + 56145x^4 - 108x^6) g_2^2 \\ & + 12(8833 + 6765x^2 + 1305x^4) g_S^2 \\ & - (242 + 792x^2 + 141x^4 + 18x^6) \lambda \\ & \left. + 2(242 + 66x^2 + 9x^4) \frac{\nu^2}{T^2} \right]\end{aligned}$$

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