Recent advances in Dirac Leptogenesis

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Phys.Rev.D 106 (2022) 11 and **JCAP 11 (2022) 042**

Kosmologietag Bielefeld 01.06.2023

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bctp

Baryon asymmetry and baryon-to-photon-ratio

Observation typically phrased in terms of

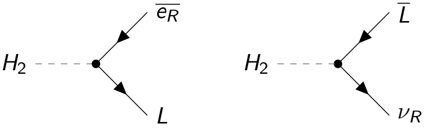
$$\eta \equiv \frac{n_B}{n_\gamma}\bigg|_{\text{today}} = \begin{cases} 5.93\times 10^{-10} \\ 6.12\times 10^{-10} \end{cases}, \Delta_B \equiv \frac{n_B - n_{\overline{B}}}{s} = \begin{cases} 8.47\times 10^{-11} & \text{BBN} \\ 8.74\times 10^{-11} & \text{CMB} \end{cases}$$

[Andrei Sakharov, 1966]

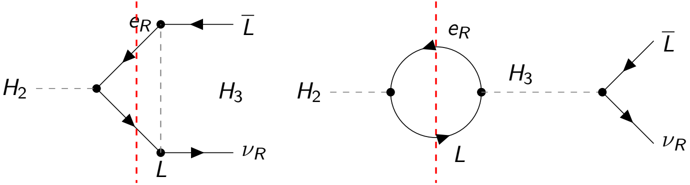
- B-L violation (for $B \neq 0$ from $B = 0$)
- $\not{C}$ and $\not{C}P$ (more particles than antiparticles)
- out of equilibrium $\rightarrow$ expansion of universe

Neutrino mass from SM Higgs: $\mathcal{L} \supset Y_\nu \, \overline{L}\tilde{H}\nu_R$ with $Y_\nu = \mathcal{O}(10^{-13})$

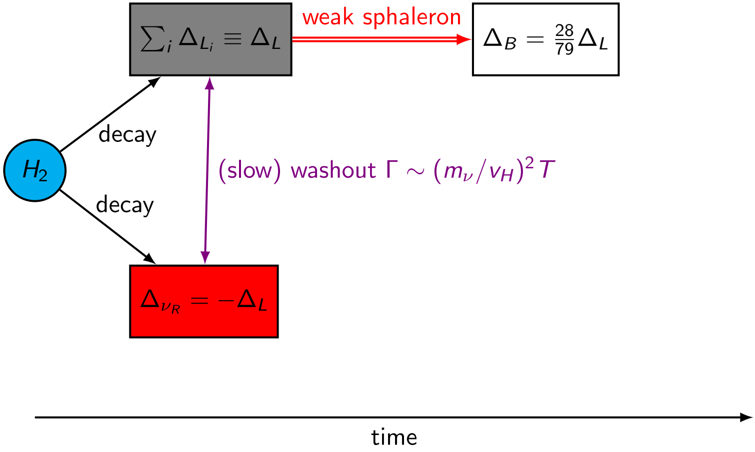
For $\not{C}\not{P}$ one needs **2 vertices**



as well as **two heavy Higgses** $H_2,\ H_3$



Dirac Leptogenesis (2) [Dick, Lindner, Ratz, Wright 1999]



$$\text{B-L} = (\text{B-L})_{\text{SM}} - L_{\nu_R} = 0$$

Dirac Leptogenesis (3) [Dick, Lindner, Ratz, Wright 1999]

- B+L from (B-L)$_{\text{SM}}$ with $c_{\text{sph.}} \simeq 0.3$

- $\not{C}\not{P}$ per decay: $\varepsilon \simeq \frac{\lambda^2}{16\pi}$ (for $\mu_2 < \mu_3$, **different** for $\mu_2 \simeq \mu_3$)

- out of equilibrium:

$$\left.\frac{\Gamma(H_2 \to L e_R,\ \overline{L}\nu_R)}{H(T)}\right|_{T=\mu_2} < 1 \quad \Rightarrow \quad \mu_2 > \frac{\lambda^2}{\sqrt{g_*}} M_{\text{Pl.}}$$

Works for: $\lambda \simeq 10^{-3}$ and $\mu_2 \simeq 10^{12}$ GeV

Type II Dirac Seesaw (1) [Berbig, 2022]

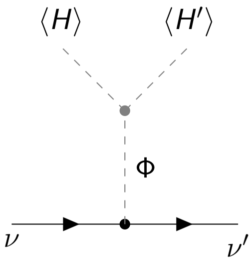
- $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)' \otimes \mathrm{U}(1)_X$

- P **to solve strong** $\not{C}\not{P}$
  [Barr, Chang, Senjanovic, 1991]

- $v' > 10^8$ GeV (collider)

- **Bi-Doublet** scalar

$$\Phi = \begin{pmatrix} \varphi_1^0 & \varphi_2^- \\ \varphi_1^- & \varphi_2^{--} \end{pmatrix} \sim (1, \mathbf{2}, \mathbf{2}, -1)$$



- $Y_\nu \; L\Phi^\dagger L'$ and $\kappa \; H\Phi^\dagger H'$

$$m_\nu \simeq 0.1\,\mathrm{eV} \cdot Y_\nu \cdot \left(\frac{|\kappa|}{1\,\mathrm{GeV}}\right) \cdot \left(\frac{v'}{10^9\,\mathrm{GeV}}\right) \cdot \left(\frac{5 \times 10^{10}\,\mathrm{GeV}}{\mu_\Phi}\right)^2$$

Type II Dirac Seesaw (2) [Berbig, 2022]

- EM charged colorful relics, DWs absent:

$$T_{\text{RH}} < m_{e'} \simeq 2 \times (10^3 - 10^6)\ \text{GeV}$$

- $\mu_\Phi \gg T_{\text{RH}}$ need **non-thermal** Dirac Leptogenesis during RH

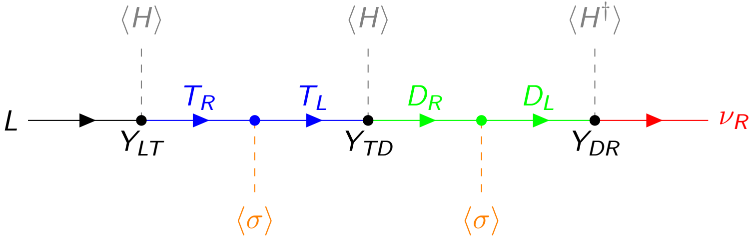
- **2 bidoublets** Φ, Φ_2 w. 2 decay modes $\Phi \to LL', HH'$

- $\varepsilon < \frac{r\sqrt{\text{BR}_l\ \text{BR}_H}}{8\pi}\frac{m_\nu\ \mu_\Phi}{v\ v'}$ suppressed by v/v'

- needs **resonant enhancement** [Bechinger, Seidl, 2009]

$$\varepsilon \sim \frac{\mu_\Phi^2}{\mu_{\Phi,2}^2 - \mu_\Phi^2 - \Gamma_{\text{tot.}}^2} \quad \text{with} \quad \frac{|\mu_{\Phi,2}^2 - \mu_\Phi^2|}{\mu_\Phi^2} \simeq 10^{-13}$$

Dimension 6 Dirac Seesaw in S.M.A.S.H.E.D.

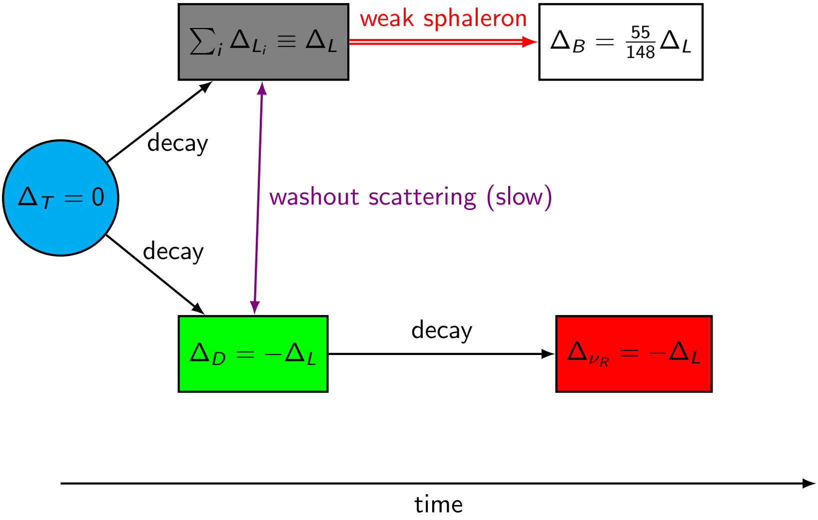


S.M.A.S.H.[1] needs $M_N < 10^9$ GeV, $T_{L,R} \sim (1,3,0)$, $D_{L,R} \sim (1,2,1/2)$

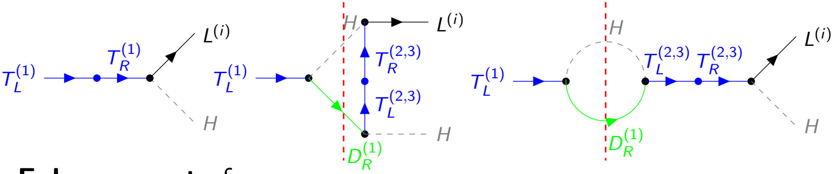
$$m_\nu \sim Y_{LT} Y_{TD} Y_{DR} \frac{v_H^3}{M_T M_D} \sim 0.1\,\mathrm{eV} \cdot \left(\frac{3\times 10^8\,\mathrm{GeV}}{M_T}\right) \cdot \left(\frac{3\times 10^8\,\mathrm{GeV}}{M_D}\right)$$

[1] [Ballesteros, Redondo, Ringwald, Tamarit, 2016]

Dirac Leptogenesis in S.M.A.S.H.E.D. [Berbig, 2022]



Non-resonant enhancement



- **Enhancement** of ε:
  - Type III Seesaw [Davidson, Ibarra, 2002]:
    $\varepsilon < 3 \times 10^{-9} \cdot \left(\frac{M_T}{10^8\,\text{GeV}}\right) \cdot \left(\frac{m_\nu}{0.1\,\text{eV}}\right) \quad \Rightarrow \quad M_T \gtrsim 1.5 \times 10^{10}\ \text{GeV}$

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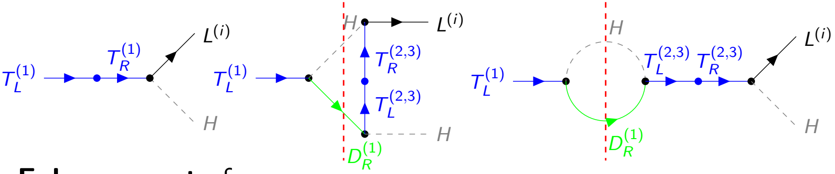

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  - S.M.A.S.H.E.D. [Berbig, 2022]:
    $\varepsilon < 3 \times 10^{-3} \cdot \left(\frac{M_T}{10^8\,\text{GeV}}\right) \cdot \left(\frac{m^{\text{eff.}}}{100\,\text{keV}}\right)$
  - $m_\nu = Y_{LT} Y_{TD} Y_{DR} v_H^3 / (M_T^{(2,3)} M_D^{(2,3)})$
  - $m^{\text{eff.}} = Y_{LT} Y_{TD} v_H^2 / M_T^{(2,3)}$ missing $\sim Y_{DR} v_H / M_D^{(2,3)}$ b.c. no ν_R

Enhancement of Efficiency κ

- κ: number of T decaying out of eq.
  - $\Gamma/H \ll 1$: **gauge annihil.** $\kappa \simeq M_T/10^{12}$ GeV $\simeq 10^{-4}$
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- larger κ for Dirac Lepto. [Berbig, 2022]
  - $LH \to N$ destroys Δ_L b.c. $\Delta_N = 0$
  - $LH, DH \to T$ transmits Δ_L, Δ_D into Δ_T
  - Δ_T decays back to Δ_L, Δ_D depending on BR
  - $\varepsilon < 3 \times 10^{-3}\sqrt{4B_L B_D}$
- inspired by scalar triplets (triplet **not self conjugate**, 2 decay modes) [Hambye, Raidal, Strumia, 2005]

Summary

- connection to m_ν
- **non-thermal** Dirac Leptogenesis
- resonant scalar Leptogenesis
- **non-resonant** enhancement
- larger efficiency

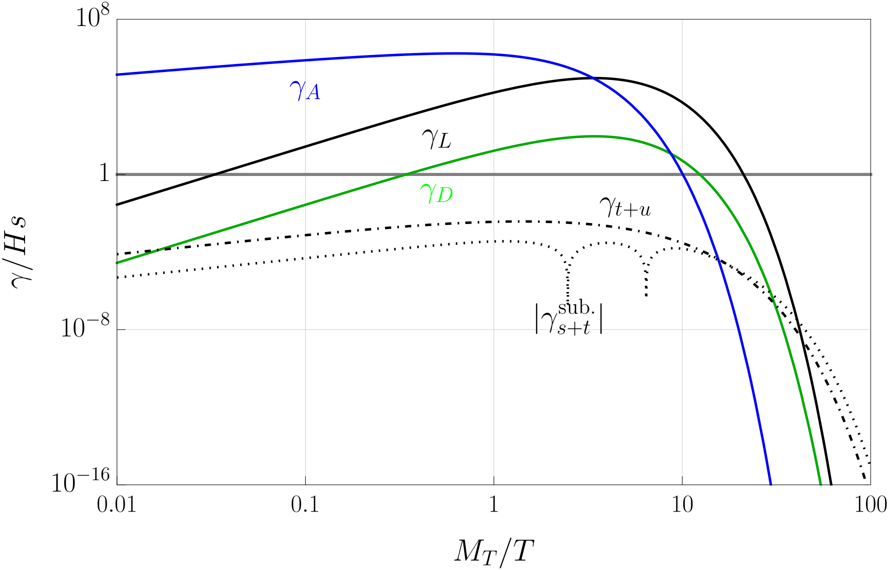
- **Dirac-Baryogenesis**
  $+$ proton decay
  [Heeck, Heisig, Thapa, 2023]
- Dirac-Lepto-**Axiogenesis**
  [Berbig, soon]

$\Rightarrow$ Dirac Leptogenesis is viable and many aspects are still unexplored!

Appendix

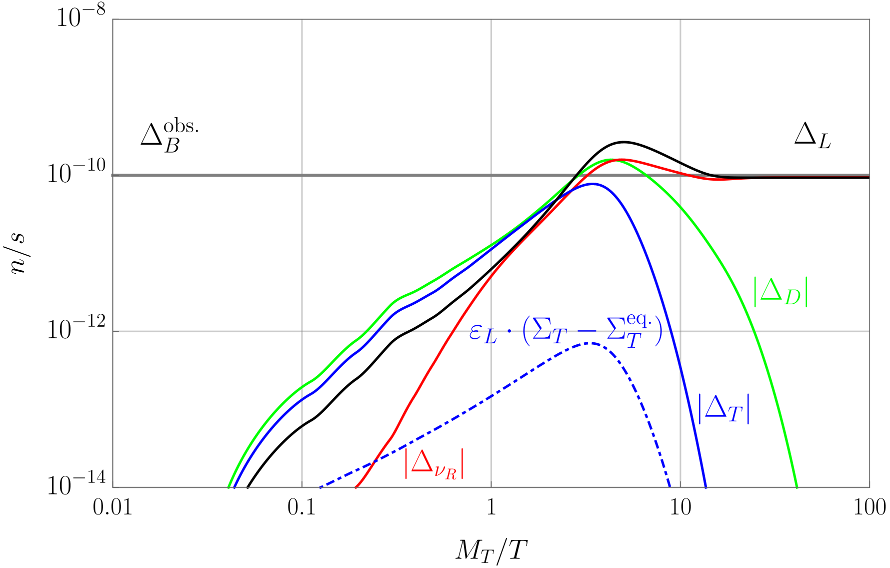
Here be dragons

Strong Washout regime (1)[2]



[2] $K = 10^5$, $B_L = 0.999$, $B_D = 10^{-3}$, $M_T = 3M_D = 10^8$ GeV

Strong Washout regime (2)[2]



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[2] $K = 10^5$, $B_L = 0.999$, $B_D = 10^{-3}$, $M_T = 3M_D = 10^8$ GeV, $\varepsilon_L^{\max} = 1.7 \times 10^{-3}$