Leptogenesis assisted by scalar decays

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Based on Jun-Yu Tong, Zhao-Huan Yu, Hong-Hao Zhang, arXiv:2406.13468

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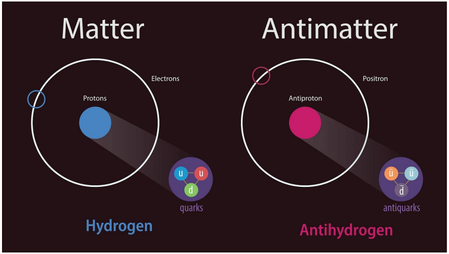
Matter-antimatter Asymmetry in the Universe

Although **matter** and **antimatter** are treated **symmetrically** in **particle physics** and **quantum field theory**, stars and galaxies in the celestial neighborhood are constituted **exclusively** by **baryonic matter**

The **baryon asymmetry** of the universe can be quantified by the **net baryon-to-photon number density** $\eta_B = \dfrac{n_B - n_{\bar{B}}}{n_\gamma} = (6.13 \pm 0.04) \times 10^{-10}$



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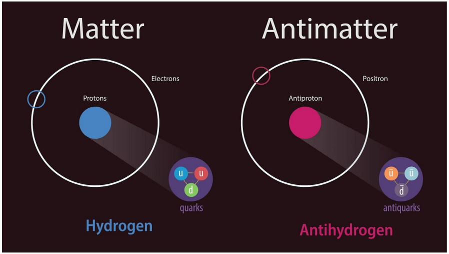
In order to generate such a baryon asymmetry, the related processes must satisfy **three Sakharov conditions** [Sakharov, Pisma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967)]

1. **Baryon number (B) violation**
2. C and CP **violations**
3. **Departure** from **thermal equilibrium**



Leptogenesis

🎈 **Leptogenesis** is a well-motivated mechanism to explain the **baryon asymmetry**

[Fukugita & Yanagida, PLB 174, 45–47 (1986)]

🪁 It introduces three generations of heavy **right-handed neutrinos** (**RHNs**), allowing **active neutrinos** to acquire **tiny masses** through the **type-I seesaw mechanism**

🎊 **Out-of-equilibrium RHN decays** lead to the **lepton asymmetry** (a **net L number**), which is converted into the **baryon asymmetry** via **electroweak sphaleron processes**

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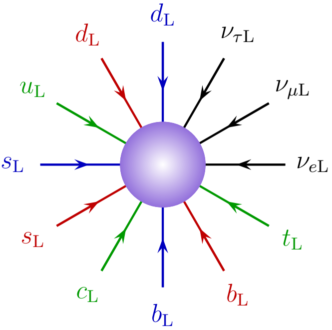
- Nonperturbative **sphaleron** processes at finite temperatures simultaneously **violate** the B and L numbers due to quantum anomalies, but keep the $B - L$ **numbers conserved**
- Once a **net $B - L$ number** is created, **sphaleron** processes will leave both the net B and L numbers **comparable** to the original $B - L$ number



Sphaleron

$\Delta B = \Delta L = \pm 3$

Type-I Seesaw Mechanism

🚙 Three **RHNs** $N_{i\mathrm{R}}$ $(i = 1, 2, 3)$ are introduced in the **standard leptogenesis**

$$\mathcal{L} \supset -h_{\nu,ij} \bar{L}_{i\mathrm{L}} \widetilde{H} N_{j\mathrm{R}} - \frac{1}{2} M_{N_i} \overline{N^{\mathrm{c}}_{i\mathrm{R}}} N_{i\mathrm{R}} + \mathrm{H.c.}$$

🚃 The **SM Higgs doublet** H develops a vacuum expectation value $v = 174$ GeV

🚖 **Yukawa couplings** $h_{\nu,ij}$ give **Dirac mass terms** for neutrinos after **electroweak symmetry breaking**, while M_{N_i} provide L-violating **Majorana mass terms**

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- The **mass terms** for the neutrinos are

$$\mathcal{L}_{\mathrm{mass}} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_{\mathrm{L}}} & \overline{N^{\mathrm{c}}_{\mathrm{R}}} \end{pmatrix} \begin{pmatrix} 0 & v h_\nu \\ v h_\nu^{\mathrm{T}} & M \end{pmatrix} \begin{pmatrix} \nu^{\mathrm{c}}_{\mathrm{L}} \\ N_{\mathrm{R}} \end{pmatrix}$$

- $M = \mathrm{diag}(M_{N_1}, M_{N_2}, M_{N_3})$ is the diagonal mass matrix for RHNs
- Through a block-diagonalization of the 6×6 mass matrix, the 3×3 mass matrix for the **active neutrinos** is given by $M_\nu \simeq -v^2 h_\nu M^{-1} h_\nu^{\mathrm{T}}$ for $M \gg v h_\nu$
- Thus, the **large RHN masses** give an origin to the **tiny masses** of the **active neutrinos** via the **type-I seesaw mechanism**

Casas-Ibarra parametrization

- **Flavor eigenstates** of the **RHNs** basically **coincide** with their **mass eigenstates**, and three **Majorana spinor fields** can be constructed by $N_i = N_{i\mathrm{R}}^{\mathrm{c}} + N_{i\mathrm{R}}$
- **Masses** of the **heavy Majorana neutrinos** N_i are approximately given by M_{N_i}
- The complex symmetric **mass matrix** M_ν for **active neutrinos** can be diagonalized by the unitary **Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix** U :

$$U^{\mathrm{T}} M_\nu U = M_\nu^{\mathrm{d}}, \quad \text{where } M_\nu^{\mathrm{d}} = \mathrm{diag}(m_1, m_2, m_3)$$

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- In the **Casas-Ibarra parametrization**, the **Yukawa coupling matrix** h_ν satisfies

$$h_\nu = \frac{i}{v} U^* \sqrt{M_\nu^{\mathrm{d}}} R^{\mathrm{T}} \sqrt{M}, \quad \text{where } R \text{ is a } 3\times 3 \text{ complex orthogonal matrix}$$

- Thus, **larger RHN mass matrix** M leads to **larger Yukawa couplings** h_ν
- **NuFIT global analysis** of **oscillation parameters** for the **normal mass hierarchy**:

θ_{12} (°)	θ_{23} (°)	θ_{13} (°)	δ_{CP} (°)	Δm_{21}^2 (10^{-5} eV^2)	Δm_{31}^2 (10^{-3} eV^2)
$33.44^{+0.77}_{-0.74}$	$49.2^{+1.0}_{-1.3}$	$8.57^{+0.13}_{-0.12}$	194^{+52}_{-25}	$7.42^{+0.21}_{-0.20}$	$2.515^{+0.028}_{-0.028}$

CP asymmetry

⛵ We assume $m_1 = 0$, leading to $m_2 = \sqrt{\Delta m_{21}^2}$ and $m_3 = \sqrt{\Delta m_{31}^2}$, so R is described by a **complex parameter** $z = z_\mathrm{r} + i z_\mathrm{i}$:

$$R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \\ 1 & 0 & 0 \end{pmatrix}$$

🚢 The CP **asymmetry** in $N_i \to \ell H / \bar{\ell}\bar{H}$ is

$$\varepsilon_i \equiv \frac{\Gamma(N_i \to \ell H) - \Gamma(N_i \to \bar{\ell}\bar{H})}{\Gamma(N_i \to \ell H) + \Gamma(N_i \to \bar{\ell}\bar{H})}$$

$$= \frac{1}{8\pi} \sum_{j \neq i} \left[f\left(\frac{M_{N_j}^2}{M_{N_i}^2} \right) - \frac{M_{N_i} M_{N_j}}{M_{N_j}^2 - M_{N_i}^2} \right] \frac{\mathrm{Im}\{[(h_\nu^\dagger h_\nu)_{ij}]^2\}}{(h_\nu^\dagger h_\nu)_{ii}}$$

🛶 Here $\ell = \ell_j^-, \nu_j$, $H = H^+, H^0$, and $f(x) = \sqrt{x}\left[1 - (1+x)\ln\frac{1+x}{x}\right]$

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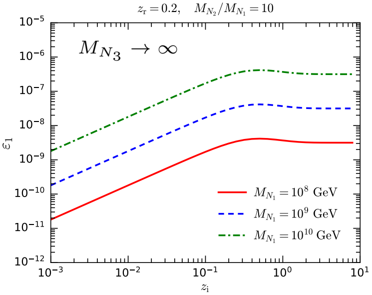

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- Basically, ε_i are **positively correlated** to $h_{\nu,ij}$ and hence M_{N_i}

- **Out-of-equilibrium** CP**-violating** N_i **decays** can generate a **lepton asymmetry**

Boltzmann Equations in the One-flavor Approximation

- For simplicity, we assume a **mass hierarchy** of $M_{N_1} \ll M_{N_2} \ll M_{N_3}$, and the **lepton asymmetry generated by** N_2 **and** N_3 will be **washed out** by $\ell H/\bar{\ell}\bar{H} \to N_1$
- The $B-L$ **numbers** yielded from N_1 are converted into the **baryon asymmetry** via **sphaleron**, resulting in $\eta_B \simeq 0.013 \dfrac{n_{B-L}}{n_\gamma}$

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- The $B-L$ **numbers** yielded from N_1 are converted into the **baryon asymmetry** via **sphaleron**, resulting in $\eta_B \simeq 0.013\, \dfrac{n_{B-L}}{n_\gamma}$
- Defining $Y_i = n_i/n_\gamma$ as the **ratio** of the **particle number density** to the **photon number density**, the **Boltzmann equations** with $N_1 \leftrightarrow \ell H/\bar{\ell}\bar{H}$ processes are

$$\frac{dY_{N_1}}{dx} = -\frac{x\langle\Gamma_{N_1}\rangle}{H(M_{N_1})}\left(Y_{N_1} - Y_{N_1}^{\rm eq}\right)$$

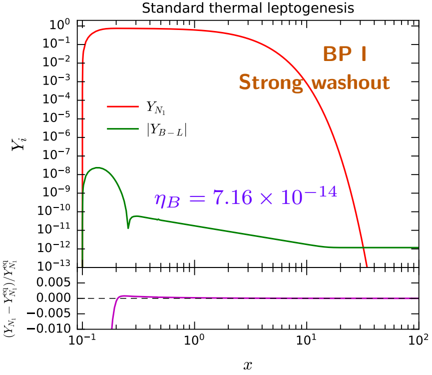
$$\frac{dY_{B-L}}{dx} = -\frac{x\varepsilon_1\langle\Gamma_{N_1}\rangle}{H(M_{N_1})}\left(Y_{N_1} - Y_{N_1}^{\rm eq}\right) - \frac{x\langle\Gamma_{N_1}\rangle Y_{N_1}^{\rm eq}}{2H(M_{N_1})Y_\ell^{\rm eq}}\, Y_{B-L}$$

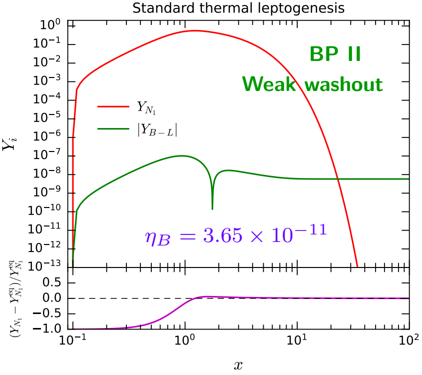
- $x = M_{N_1}/T$; $Y_i^{\rm eq}$ are **equilibrium** values; $H(M_{N_1})$ is Hubble rate at $T = M_{N_1}$
- The **lepton asymmetry** is generate by the CP **asymmetry** ε_1 and **departure** of the N_1 **particles** from **thermal equilibrium**; the **term proportional to** Y_{B-L} indicates the **washout** of the **generated lepton asymmetry** caused by the **inverse decays**

Partical Number Evolution

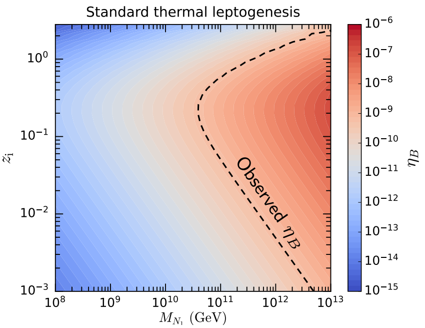
⚓ We assume that **after reheating**, **all SM particles** are in **thermal equilibrium**, while there are **no N_i particles** because their interactions are **too weak**

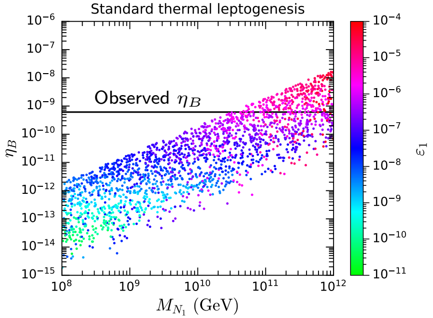
	M_{N_1} (GeV)	M_{N_2} (GeV)	z_r	z_i	ε_1	Γ_{N_1} (GeV)
BP I	10^{10}	10^{11}	0.2	3	3.17×10^{-7}	7.67×10^{5}
BP II	2×10^{9}	2×10^{10}	0.2	0.2	5.99×10^{-8}	66.04





Parameter Scans





- **Left panel**: **fixed parameters** are $M_{N_2} = 10 M_{N_1}$, $z_r = 0.2$
- **Larger** z_i gives not only **larger** ε_1, but also **larger** Γ_{N_1}, which **enhances washout**
- **Right panel**: **random scans** with 10^8 GeV $< M_{N_1} < 10^{12}$ GeV,

$$3 < M_{N_2}/M_{N_1} < 10^3,\ 10^{-3} < z_i < 3,\ \text{and}\ 0 < z_r < \pi/4$$

- η_B is **positively correlated** to both M_{N_1} and ε_1
- The **observed** η_B can be achieved for $M_{N_1} \gtrsim 3 \times 10^{10}$ GeV

Scale of Leptogenesis

🥀 In the **standard thermal leptogenesis**, the **generated lepton asymmetry** would be **strongly washed out** if $h_{\nu,ij}$ and M_{N_1} are **too large**

🏵️ Taking into account the **neutrino oscillation data**, $M_{N_1} \gtrsim 3 \times 10^{10}$ GeV is required to obtain the **correct** η_B

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- Such a **high mass scale** is **challenging** to be **further tested** by experiments
- In order to **lower down the RHN mass scale** and/or **circumvent** a **strong washout effect**, several solutions were proposed
  - **Resonant leptogenesis** [Pilaftsis & Underwood, hep-ph/0309342, NPB]
  - **Flavored leptogenesis** [Barbieri *et al.*, hep-ph/9911315, NPB]
  - Leptogenesis originating from **reheating** [Asaka, *et al.*, hep-ph/9906366, PLB]
  - RHN production from the **evaporation** of **primordial black holes** [Datta, *et al.*, 2012.14981, JCAP]
  - **Wash-in leptogenesis**: reprocess high-scale CP-violating interactions into the $B-L$ asymmetry by low-scale RHN interactions [Domcke, *et al.*, 2011.09347, PRL]

Scalar-assisted Leptogenesis

- Motivated by these efforts, we propose another approach to **decrease the RHN mass scale** by introducing a **scalar boson** ϕ **slowly decaying into** $N_1 N_1$

$$\mathcal{L} \supset -m_\phi^2 \phi^2 - \kappa H^\dagger H \phi - \lambda_{\phi H} H^\dagger H \phi^2 - \left(\frac{1}{2} y_i \overline{N_{i\mathrm{R}}^{\mathrm{c}}} N_{i\mathrm{R}} \phi + \mathrm{H.c.} \right)$$

- Assuming $2M_{N_1} < m_\phi < 2M_{N_2}$, only $\phi \to N_1 N_1$ and $\phi \to H\bar{H}$ are allowed

- The **out-of-equilibrium** ϕ **decays** can provide an additional source for N_1 **particles** and hence the **lepton asymmetry** when **washout** is **suppressed** at **low temperatures**

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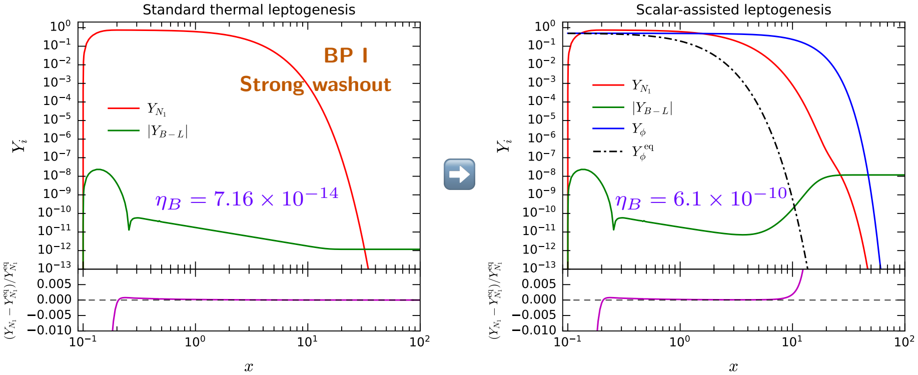
$$\frac{dY_\phi}{dx} = -\frac{x\langle \Gamma_{\phi\to N_1 N_1}\rangle}{H(M_{N_1})} \left[Y_\phi - \frac{Y_\phi^{\mathrm{eq}} Y_{N_1}^2}{(Y_{N_1}^{\mathrm{eq}})^2} \right] - \frac{x\langle \Gamma_{\phi\to H\bar{H}}\rangle}{H(M_{N_1})} (Y_\phi - Y_\phi^{\mathrm{eq}}) - \frac{x n_\gamma \langle \sigma_{\phi\phi\to H\bar{H}} v\rangle}{H(M_{N_1})} \left[Y_\phi^2 - (Y_\phi^{\mathrm{eq}})^2 \right]$$

$$\frac{dY_{N_1}}{dx} = -\frac{x\langle \Gamma_{N_1}\rangle}{H(M_{N_1})} (Y_{N_1} - Y_{N_1}^{\mathrm{eq}}) + \frac{x\langle \Gamma_{\phi\to N_1 N_1}\rangle}{H(M_{N_1})} \left[Y_\phi - \frac{Y_\phi^{\mathrm{eq}} Y_{N_1}^2}{(Y_{N_1}^{\mathrm{eq}})^2} \right]$$

$$\frac{dY_{B-L}}{dx} = -\frac{x\varepsilon_1 \langle \Gamma_{N_1}\rangle}{H(M_{N_1})} (Y_{N_1} - Y_{N_1}^{\mathrm{eq}}) - \frac{x\langle \Gamma_{N_1}\rangle Y_{N_1}^{\mathrm{eq}}}{2H(M_{N_1}) Y_\ell^{\mathrm{eq}}} Y_{B-L}$$

Strong Washout Scheme Assisted by Scalar decays

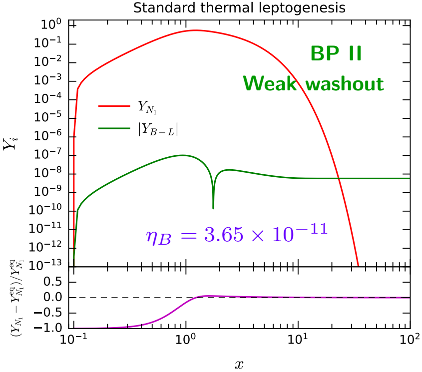
	M_{N_1} (GeV)	M_{N_2} (GeV)	z_r	z_i	m_ϕ	y_1	κ (GeV)	$\lambda_{\phi H}$
BP I	10^{10}	10^{11}	0.2	3	$2.5m_{N_1}$	1.11×10^{-4}	100	10^{-4}

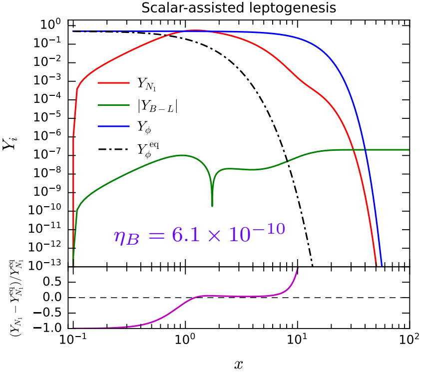


- ϕ **particles** become **out of thermal equilibrium** after $x\sim0.3$
- $\phi\to N_1N_1$ **decays** give rise to **nonthermal production** of N_1 **particles**

Weak Washout Scheme Assisted by Scalar decays

	M_{N_1} (GeV)	M_{N_2} (GeV)	$z_{\rm r}$	$z_{\rm i}$	m_ϕ	y_1	κ (GeV)	$\lambda_{\phi H}$
BP II	2×10^9	2×10^{10}	0.2	0.2	$2.5m_{N_1}$	4.6×10^{-5}	100	10^{-4}

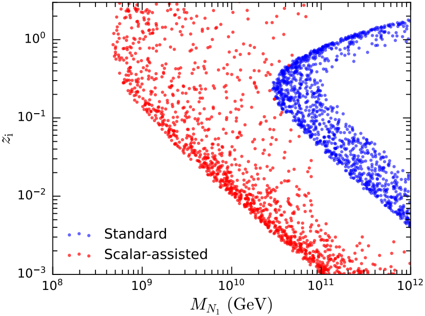


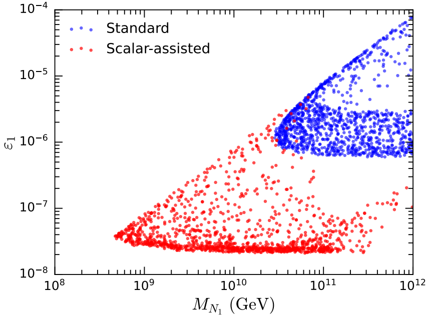


Selected Parameter Points with the Correct η_B

🐴 **Random scans** with 10^8 GeV $< M_{N_1} < 10^{12}$ GeV, $3 < M_{N_2}/M_{N_1} < 10^3$, $10^{-3} < z_{\rm i} < 3$, $0 < z_{\rm r} < \pi/4$, and $10^{-5} < y_1 < 10^{-3}$

🐷 $m_\phi = 2.5 m_{N_1}$, $\kappa = 100$ GeV, and $\lambda_{\phi H} = 10^{-4}$ are **fixed**





🐯 For obtaining the **correct** η_B in the **scalar-assisted case**, the **lowest viable** M_{N_1} is reduced from $\sim 3 \times 10^{10}$ GeV to $\sim 5 \times 10^8$ GeV

🦁 The **smallest viable** ε_1 decreases from $\sim 6 \times 10^{-7}$ to $\sim 2 \times 10^{-8}$

Summary and Outlook

1. We present a pragmatic approach to **lower down** the **RHN mass scale** in **leptogenesis** by introducing a **scalar**, whose **out-of-equilibrium decays into RHNs** provide an additional source for the **lepton asymmetry**
2. This mechanism works well at **low temperatures** when the **washout** of the generated lepton asymmetry is **suppressed**
3. Such a **scalar-assisted leptogenesis** can typically **decrease** the **viable RHN mass scale** by **two to four orders of magnitude**
4. The **origin of the scalar** could be linked to other interesting topics, such as the **origin of dark matter**, **grand unification**, **supersymmetry**, and so on

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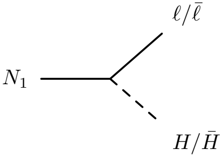
Thanks for your attention!

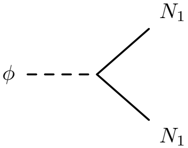
Decay Widths and Cross Sections

- Related **decay widths** and **annihilation cross sections**:

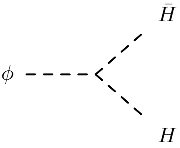
$$\Gamma_{N_1} = \Gamma(N_1 \to \ell H) + \Gamma(N_1 \to \bar{\ell}\bar{H}) \simeq \frac{1}{8\pi}(h_\nu^\dagger h_\nu)_{11} M_{N_1}$$



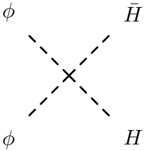
$$\Gamma(\phi \to N_1 N_1) = \frac{y_1^2 m_\phi}{16\pi}\left(1 - \frac{4M_{N_1}^2}{m_\phi^2}\right)^{3/2}$$



$$\Gamma(\phi \to H\bar{H}) \simeq \frac{\kappa^2}{8\pi m_\phi}$$

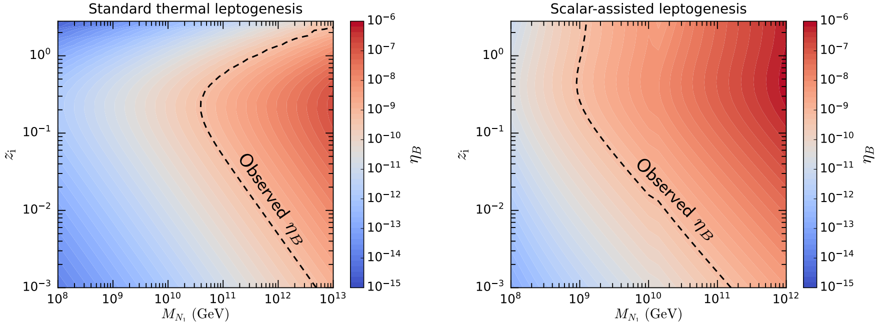


$$\sigma(\phi\phi \to H^0 \bar{H}^0) = \sigma(\phi\phi \to H^+ H^-) \simeq \frac{\lambda_{\phi H}^2}{4\pi s\sqrt{1 - 4m_\phi^2/s}}$$



- The **masses** of **light leptons** and **Higgs bosons** have been **neglected**

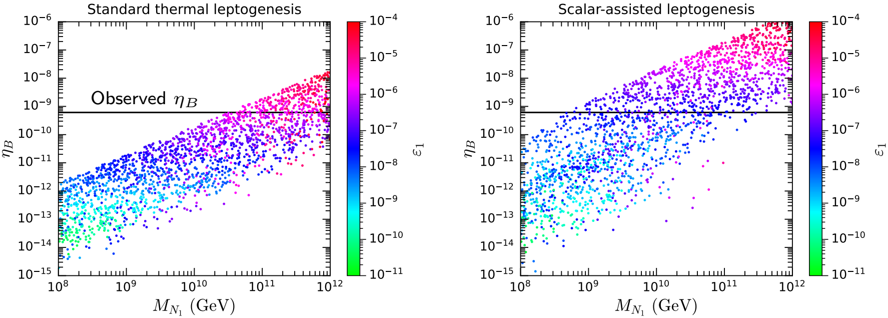
Standard vs. Scalar-assisted Leptogenesis



Fixed parameters: $M_{N_2} = 10 M_{N_1}$, $z_r = 0.2$, $m_\phi = 2.5 M_{N_1}$, $y_1 = 4.6 \times 10^{-5}$,

$\kappa = 100$ GeV, $\lambda_{\phi H} = 10^{-4}$

Standard vs. Scalar-assisted Leptogenesis



⚽ **Random scans** with 10^8 GeV $< M_{N_1} < 10^{12}$ GeV, $3 < M_{N_2}/M_{N_1} < 10^3$, $10^{-3} < z_{\rm i} < 3$, $0 < z_{\rm r} < \pi/4$, and $10^{-5} < y_1 < 10^{-3}$

🥅 $m_\phi = 2.5 m_{N_1}$, $\kappa = 100$ GeV, and $\lambda_{\phi H} = 10^{-4}$ are **fixed**