

The matter-antimatter question
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Leptogenesis
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Numerical results
oooo

Conclusion
oo

Graphical Leptogenesis

A new look at Leptogenesis

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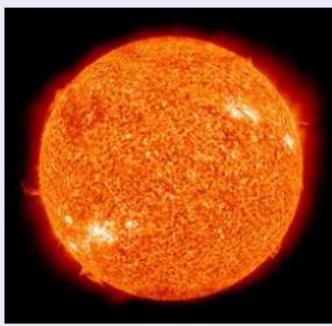
University of Victoria (Canada)

BUSSTEPP 2012

The matter-antimatter question



Planets?



Stars?



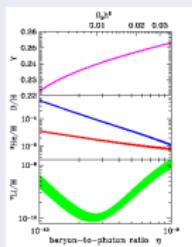
Galaxies?

Why can these objects form?

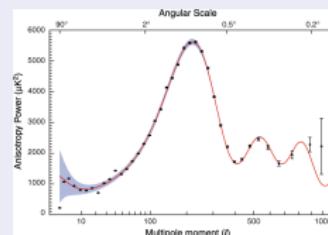
- Why is everything made out of matter?
- Where is antimatter?

Baryon Asymmetry of the Universe

Cosmological theories predictions



Nucleosynthesis



Power spectrum

Measurement of baryon asymmetry

$$\eta = \frac{n_B - \bar{n}_B}{n_\gamma} \sim 6 \cdot 10^{-10}$$

How can we explain the baryon asymmetry of the Universe?

Leptogenesis

Right-handed neutrino (RHN)

$$-\mathcal{L} = \lambda \overline{N_R} L \cdot H + M \overline{N_R^c} N_R + h.c$$

Sakharov's conditions to create an asymmetry

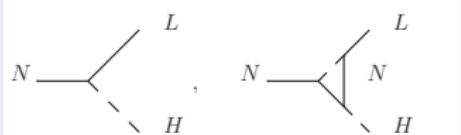
- ① Violation of lepton number: M
- ② Violation of C and CP symmetries: λ
- ③ Fall out of equilibrium:

$$K = \frac{\Gamma_N}{H(T=M)} = \frac{t(T=M)}{\tau_N}$$

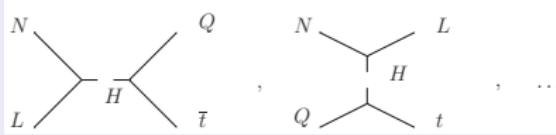
Work in progress

Higgs portal leptogenesis: connection to hidden sector

Generation of lepton asymmetry



Decays



2-to-2 scatterings

Boltzmann equations

$$Y'_N = -(D + S)(Y_N - Y_N^{eq})$$

$$Y'_{L-\bar{L}} = \epsilon D(Y_N - Y_N^{eq}) - W Y_{L-\bar{L}}$$

ϵ : CP-asymmetry

$\{D, S\}$: destroy RHN

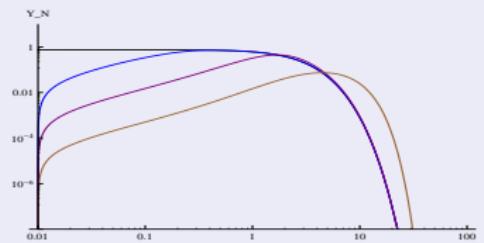
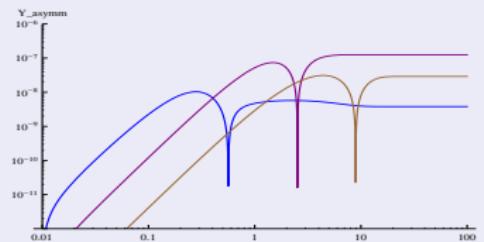
W : create RHN

Convert lepton asymmetry into baryon asymmetry

$$Y_{L-\bar{L}} = \frac{n_L - n_{\bar{L}}}{n_\gamma} \quad , \quad Y_{L-\bar{L}}^f \approx \frac{\eta}{2} \sim 3 \cdot 10^{-10}$$

Log-log plots

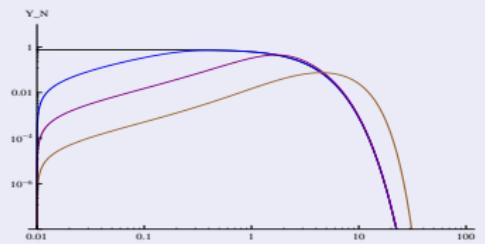
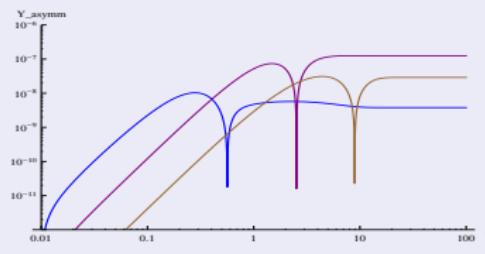
$\{Y_N, Y_{L-\bar{L}}\}$ function of $1/T$



✓ Dependence on T

Log-log plots

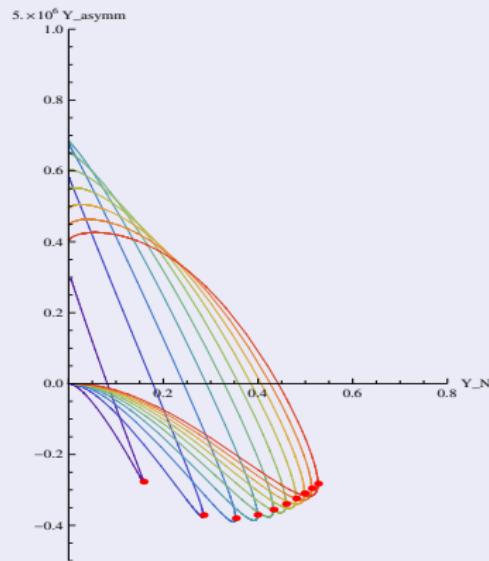
$\{Y_N, Y_{L-\bar{L}}\}$ function of $1/T$



✓ Dependence on T

Parametric plots

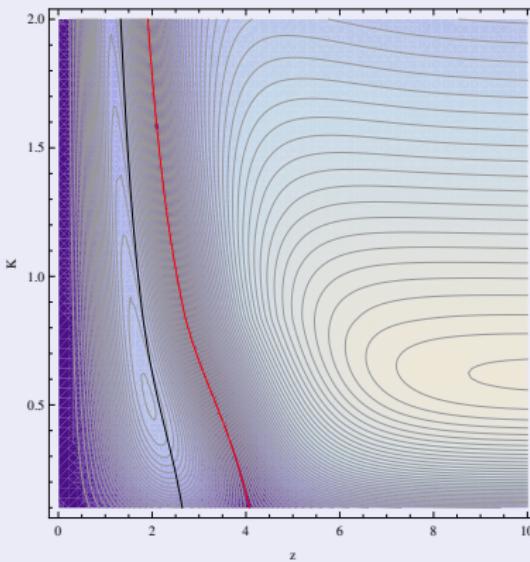
$Y_{L-\bar{L}}$ function of Y_N



✓ Inter dependence

Contour plots

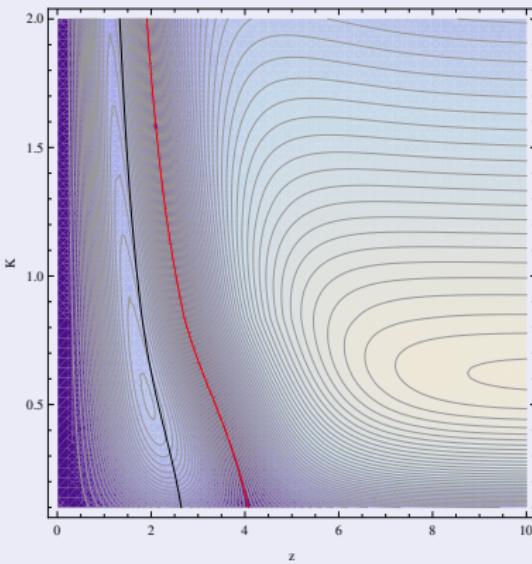
$Y_{L-\bar{L}}$ function of $\{1/T, K\}$



✓ Dependence on $\{T, K\}$

Contour plots

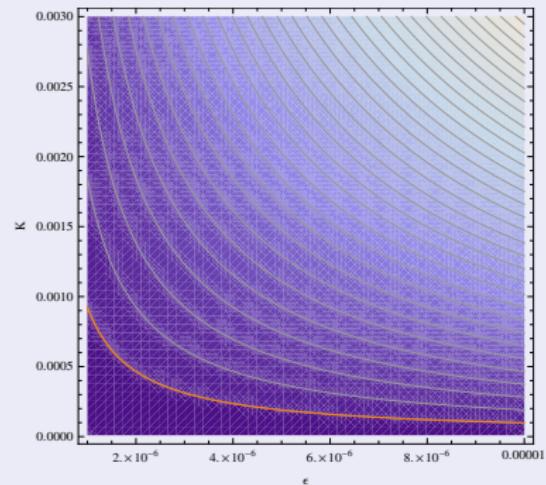
$Y_{L-\bar{L}}$ function of $\{1/T, K\}$



✓ Dependence on $\{T, K\}$

Parameter space

$Y_{L-\bar{L}}^f$ function of $\{\epsilon, K\}$



$$K^2 \epsilon \sim Y_{L-\bar{L}}^f$$

✓ Dependence on $\{\epsilon, K\}$

Take home message

Leptogenesis

Successfully and simply explains baryon asymmetry:

$$\eta \sim 6 \cdot 10^{-10}$$

New ways to look at leptogenesis



Log-log plots: Dependence on T ✓



Parametric plots: Dependence on Y_N ✓

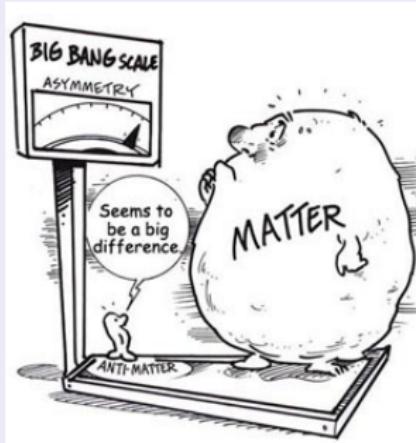


Contour plots: Dependence on $\{K, T\}$ ✓



Parameter space: Dependence on $\{K, \epsilon\}$ ✓

Thank you for your attention



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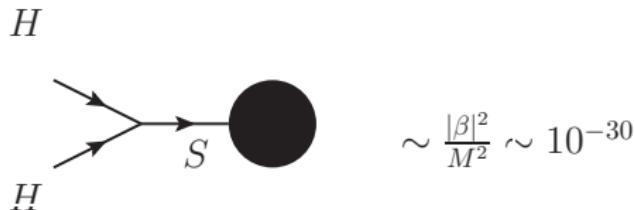
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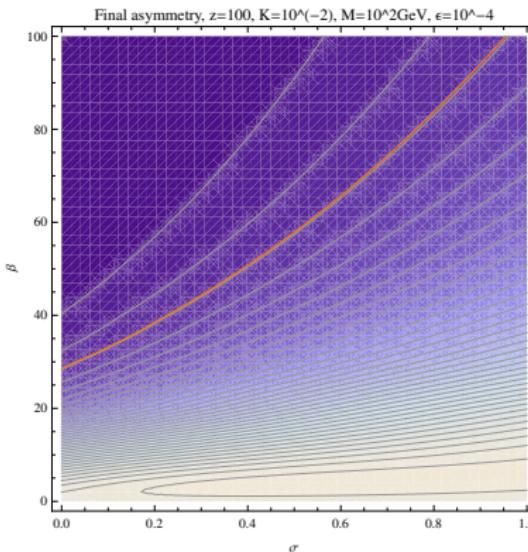
back up slides

$$\begin{aligned}-\mathcal{L}_{HPL} = & \lambda_{ij} \overline{N_{iR}} L_j \cdot H + M_{ij} \overline{N_{iR}^c} N_{jR} + h.c \\ & + \beta S H^\dagger H + \alpha_{ij} S \overline{N_{iR}^c} N_{jR} + h.c\end{aligned}$$

New interactions, but very suppressed



Parameter space



Large Coupling: $|\beta| \sim 10$

Small Neutrino mass: $M \sim 10^2\text{GeV}$ (Possibly impossible)

Scalar Mass: $m_S \sim 0.25M$

Large CP-asymmetry: $\epsilon = 10^{-4}$

Boltzmann equations, decays only

$$G = \frac{z}{n_\gamma^{eq} H(M=T)}, \quad D = \frac{G}{Y_N^{eq}} \gamma_D, \quad W_{ID} = \frac{Y_N^{eq}}{2Y_L^{eq}} D$$

$$\begin{aligned} Y'_N &= -D(Y_N - Y_N^{eq}) \\ Y'_{L-\bar{L}} &= \epsilon D(Y_N - Y_N^{eq}) - W_{ID} Y_{L-\bar{L}} \end{aligned}$$

Equivalently

$$\begin{aligned} Y'_N &= -DY_N + 2Y_L^{eq} W_{ID} \\ y'_{L-\bar{L}} &= DY_N - (2Y_L^{eq} + y_{L-\bar{L}}) W_{ID} \quad , \quad y_{L-\bar{L}} = \frac{Y_{L-\bar{L}}}{\epsilon} \end{aligned}$$

Decays: Lower $Y_N \Leftrightarrow$ Increase $Y_{L-\bar{L}}$,

Inverse decays: Increase $Y_N \Leftrightarrow$ Decrease $Y_{L-\bar{L}}$

Boltzmann equations, decays only

Exact solution

$$y_{L-\bar{L}}(z) = -Y_N(z) + \int_0^z \left(Y_N(z') W_{ID}(z') \exp \left\{ - \int_{z'}^z W_{ID}(z'') dz'' \right\} \right) dz'$$

Asymmetry turn over at $z = z_0$ such that

$$y'_{L-\bar{L}}(z_0) = 0 \quad \Rightarrow \quad y_{L-\bar{L}}(z_0) = -\frac{Y'_N(z_0)}{W_{ID}(z_0)} \neq 0$$

Two solutions:

$$z_0^- < z_{eq} \Leftrightarrow Y'_N(z_0) > 0$$

$$z_0^+ > z_{eq} \Leftrightarrow Y'_N(z_0) < 0$$

Neutrino abundance turn over

$$Y'_N(z_{eq}) = 0 \quad \Leftrightarrow \quad Y_N(z_{eq}) = Y_N^{eq}(z_{eq})$$

Only one solution such that

$$z_0^+ > z_{eq} > z_0^-$$

Physical constraints

CP-asymmetry

$$\epsilon = \frac{\text{Im}\{(\lambda^\dagger \lambda)_{21}^2\}}{(\lambda^\dagger \lambda)_{11}} f\left(\frac{M_2^2}{M_1^2}\right) \sim 0.1 \frac{\text{Im}\{(\lambda^\dagger \lambda)_{21}^2\}}{|\lambda_{11}|^2} \sim 10^{-6}$$

Out-of-equilibrium parameter

$$K = \frac{\Gamma_N}{H(T=M)} \sim \frac{|\lambda_{11}|^2}{80\pi} \frac{M_p}{M} \sim 10^{17} \frac{|\lambda_{11}|^2}{M} \sim 10^{-2}$$

Assumption on decay strength: $|\lambda_{11}|^2 = 10^{-4}$

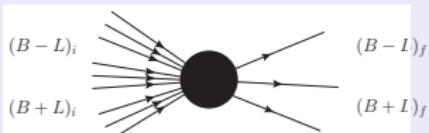
Parameter space constraint

$$K^2 \epsilon = k_0 \iff K^2 \epsilon \sim 10^{-10} \sim \frac{\eta}{2}$$

$\{K = 10^{-1}, \epsilon = 10^{-6}\}$ implies $M \sim 10^{15} \text{GeV}$, $\text{Im}\{(\lambda^\dagger \lambda)_{21}^2\} \sim 10^{-9}$

Step 2: generating a baryon asymmetry

Sphalerons convert lepton into baryon asymmetry



$$(B - L)_f = (B - L)_i$$

$$(B + L)_f \neq (B + L)_i$$

Most efficient above electroweak scale

$$T \ll m_W \quad : \quad \Gamma_{sph} \propto \exp\left(-\frac{m_W}{T}\right)$$

$$T \gg m_W \quad : \quad \Gamma_{sph} \propto T$$