# Lepton Flavor Violation

## III. Leptogenesis

$\mathrm{SSI}_{2010}$: Neutrinos – Nature's mysterious messengers

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# Plan of Lectures

1. The (extended) Standard Model flavor puzzle
2. The New Physics flavor puzzle
3. Leptogenesis
    - Baryogenesis
    - Leptogenesis, qualitatively
    - Leptogenesis, quantitatively
    - The future

# Baryogenesis

Sakharov, 1967

# The Baryon Asymmetry

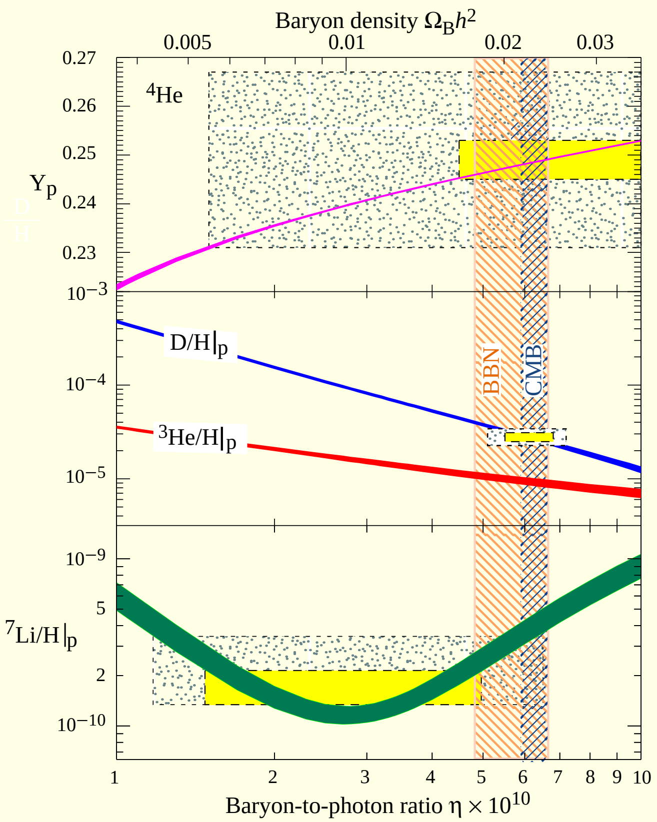
$$Y_B \equiv \frac{n_b - n_{\overline{b}}}{s} = (8.75 \pm 0.23) \times 10^{-11}$$

- $n_b/s \sim 10^{-10}$
- $n_{\overline{b}}/s \approx 0$

# Particle cosmology

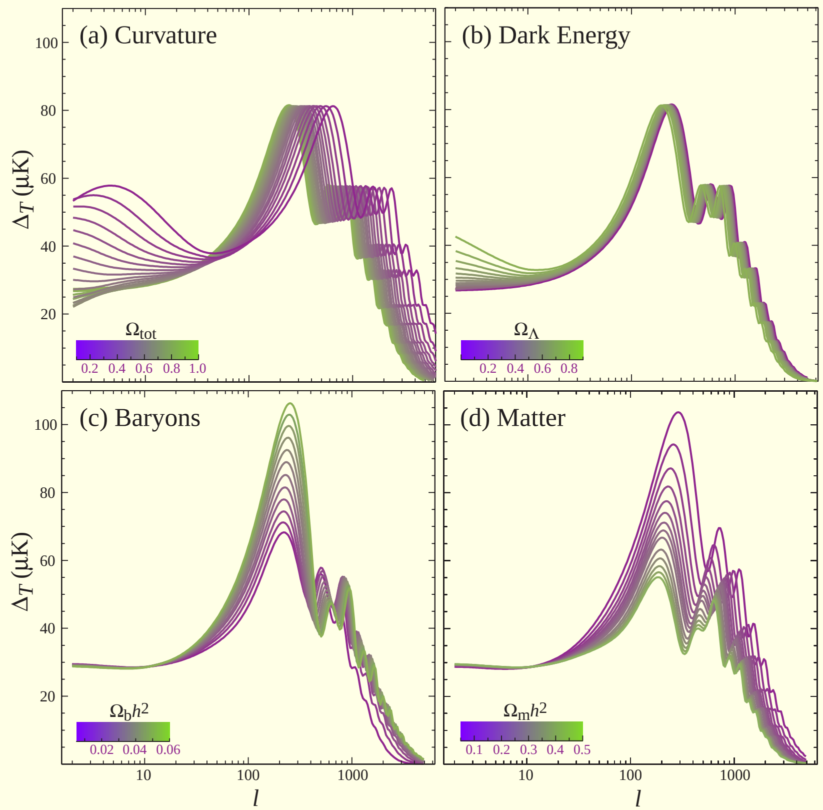
| | | | |
|---|---|---|---|
| LSS | $10^6$ years | gravitation | $+$ |
| CMB | $4 \times 10^5$ years | atomic physics | $++$ |
| Nucleosynthesis | $1 - 200$ seconds | nuclear physics | $++$ |
| Baryogenesis | $< 10^{-11}$ seconds | particle physics | $--$ |

# BBN + CMBR




Nucleosynthesis

$$\eta_{10} = 5.6 \pm 0.9$$




CMBR

$$\eta_{10} = 6.11 \pm 0.19$$

# Initial Conditions?

- Fine tuning:

For every 6,000,000 antiquarks – 6,000,001 quarks

- Inflation:

Any initial asymmetry would be erased

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- Fine tuning:

For every 6,000,000 antiquarks – 6,000,001 quarks

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Any initial asymmetry would be erased

$$\Downarrow$$

The baryon asymmetry was dynamically generated

$$\boxed{\text{BARYOGENESIS}}$$

# Sakharov Conditions

The baryon asymmetry can be dynamically generated ('baryogenesis') provided that

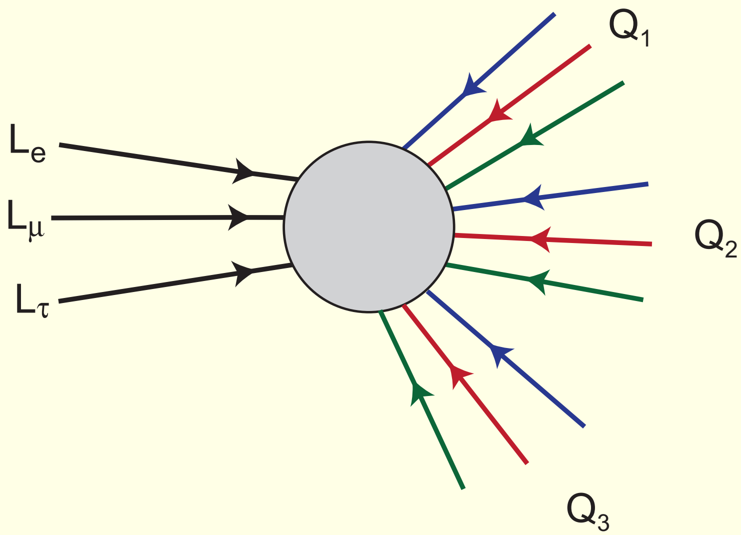
1. Baryon number is violated;
2. C and CP are violated;
3. Departure from thermal equilibrium.

# SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by $\delta_{\rm KM}$;
3. Departure from thermal equilibrium at the EWPT.

# SM $B + L$ violation




$$T = 0 \qquad \Gamma \propto e^{-8\pi^2/g^2}$$

$$T \gg T_{\mathrm{EWPT}} \qquad \Gamma \propto 250\alpha_w^5 T$$

$$\boxed{\Gamma > H \text{ for } T_{\mathrm{EWPT}} < T < 10^{12}\ \mathrm{GeV}}$$

# SM $CP$ violation

- CP violated within the SM only if

$$\begin{aligned} J_{CP} &\equiv (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\ &\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \\ &\times s_{12}s_{23}s_{13}c_{12}c_{23}c_{13}s_\delta \neq 0 \end{aligned}$$

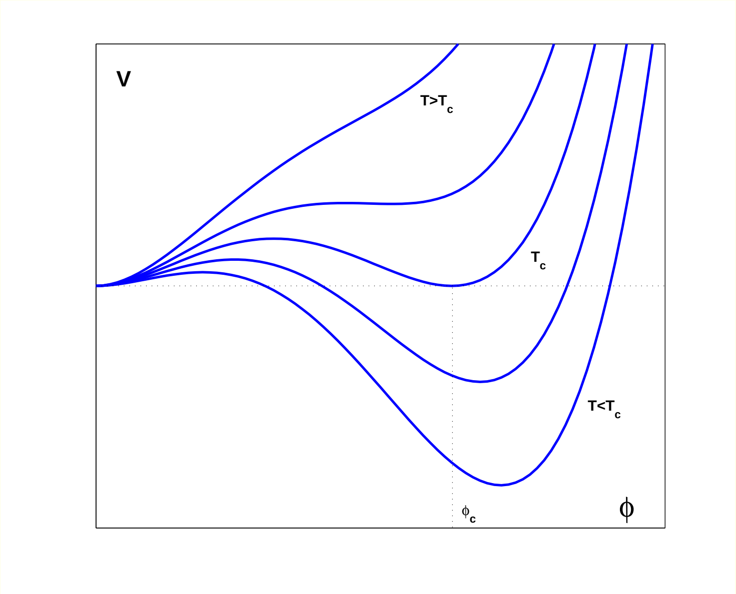
- The baryon asymmetry is therefore proportional to $J_{CP}$:

$$\frac{n_b}{n_\gamma} \propto \frac{J_{CP}}{T_c^{12}} \sim 10^{-20}$$

**The KM mechanism cannot produce large enough baryon asymmetry**

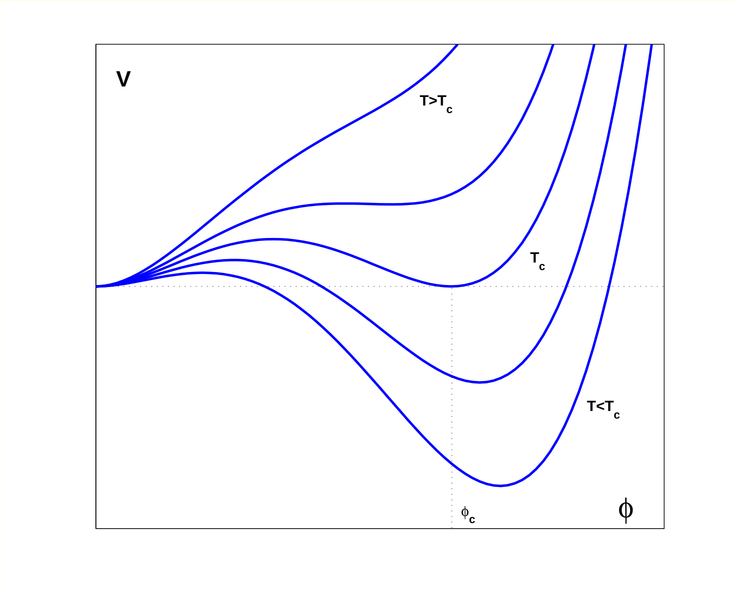
# SM EWPT

Need a strongly 1st-order PT

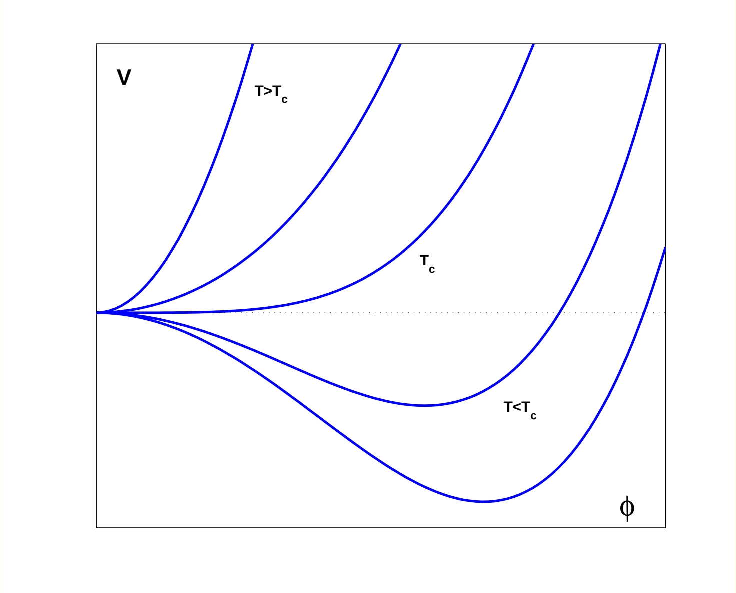


# SM EWPT

Need a strongly 1st-order PT




$m_H > 70$ GeV




- $\langle \phi \rangle : 0 \to v$ continuously and uniformly in space
- The $B + L$ violating processes switch off slowly
- The baryon asymmetry is erased

| The SM EWPT is not of the right kind |
|---|

# SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by $\delta_{\rm KM}$;
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# SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by $\delta_{\mathrm{KM}}$;
3. Departure from thermal equilibrium at the EWPT.

The SM fails on two aspects:

1. The Higgs sector does not give a strongly first order PT;
2. KM CP violation is too suppressed.

# Alternative Scenarios

Should have:

- New sources of CP violation
- Either a new departure from TE and $B - L$ violation
- Or a modification of the EWPT

MSSM baryogenesis is (still) viable:

- New scalars $\Longrightarrow$ first order PT is possible;
- At least two new phases $\Longrightarrow$ diagonal CP violation;
- Pushed to a corner of parameter space:
  $m_h < 120$ GeV, $m_{\tilde{t}_1} < m_t$ ($\Longrightarrow m_{\tilde{t}_2} > TeV$), $m_\chi < 250$ GeV.
- Testable at LHC

# Leptogenesis, qualitatively

Fukugita and Yanagida, 1986

# The Seesaw Mechanism

- Atmospheric + Solar Neutrinos $\Longrightarrow$ $\boxed{m_{\nu_3} \gtrsim 0.05\ eV}$

- In the SM: $m_\nu = 0$

- Add SM singlets $N$: $\mathcal{L}_N = Y\phi LN + MNN$
- Assume $M \gg \langle\phi\rangle$

$\Longrightarrow$ Neutrinos are massive but very light

- "The Seesaw Mechanism:" $\boxed{m_\nu \sim \frac{Y^2\langle\phi\rangle^2}{M}}$

($\Longrightarrow M/Y^2 \sim 10^{14}\ GeV$)

# The Seesaw ⇔ Leptogenesis Relation

$$\mathcal{L}_N = Y\phi LN + MNN$$

- Implications:

1. Lepton number is violated ($M$)
2. New sources of CP violation ($Y$)
3. If $\Gamma_{N_1} \lesssim H(T = M_{N_1})$ ($\Longrightarrow \tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} v^2}{M_1} \lesssim 10^{-3}\ eV$)
   $\Longrightarrow N_1$ decays out of equilibrium

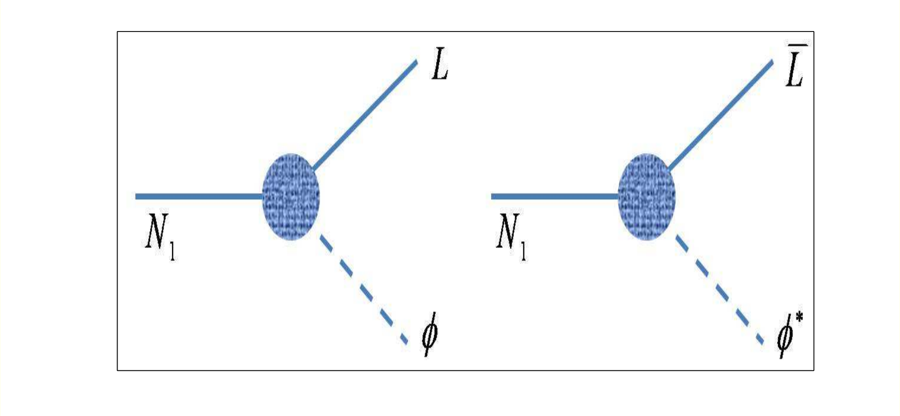
# Lepton number violation

$$\mathcal{L}_N = Y\phi LN + MNN$$

- Assign $L(N) = 0 \implies \begin{cases} M & LC \\ Y & LV \end{cases}$

- Assign $L(N) = -1 \implies \begin{cases} M & LV \\ Y & LC \end{cases}$

$\boxed{B - L \text{ violation is guaranteed}}$

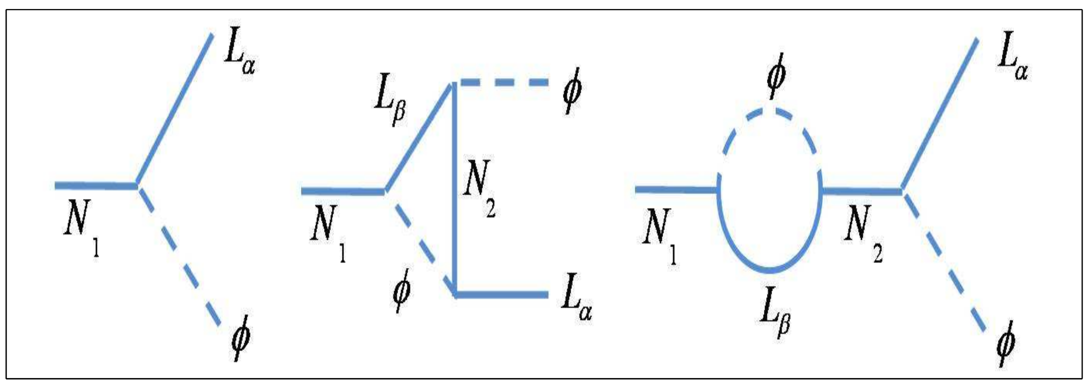


# CP violation

$$\mathcal{L}_N = Y\phi LN + MNN$$

- Choose $M$ diagonal and real
- Further changes of phases of $N$ are not allowed
- Changing the phases of $L$ –
  not enough to remove all phases from $Y$

$CP$ violation is very likely

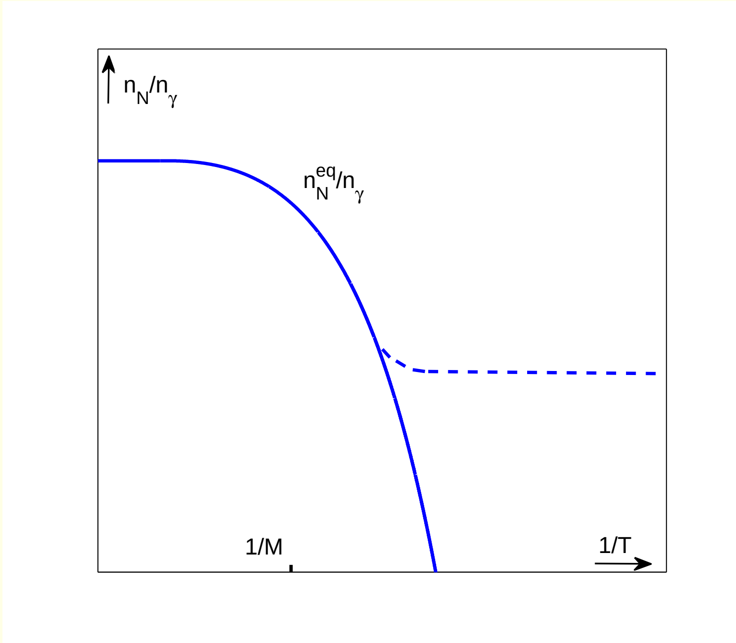


# Departure from thermal equilibrium

$$\mathcal{L}_N = Y\phi LN + MNN$$

- $N$ has only Yukawa interactions
- If small enough ($\Gamma < H(T = M)$), cannot keep $N$ in equilibrium

Decay out of equilibrium – if parameters are right



# The Seesaw ⇔ Leptogenesis Relation

$$\mathcal{L}_N = Y\phi L N + M N N$$

- Implications:

1. Lepton number (and B–L) violation – guaranteed
2. New sources of CP violation – very likely
3. Decay out of equilibrium – if parameters are right

# The Seesaw $\Leftrightarrow$ Leptogenesis Relation

$$\mathcal{L}_N = Y\phi L N + M N N$$

- Implications:

1. Lepton number (and B–L) violation – guaranteed
2. New sources of CP violation – very likely
3. Decay out of equilibrium – if parameters are right

$$\Downarrow$$

LEPTOGENESIS

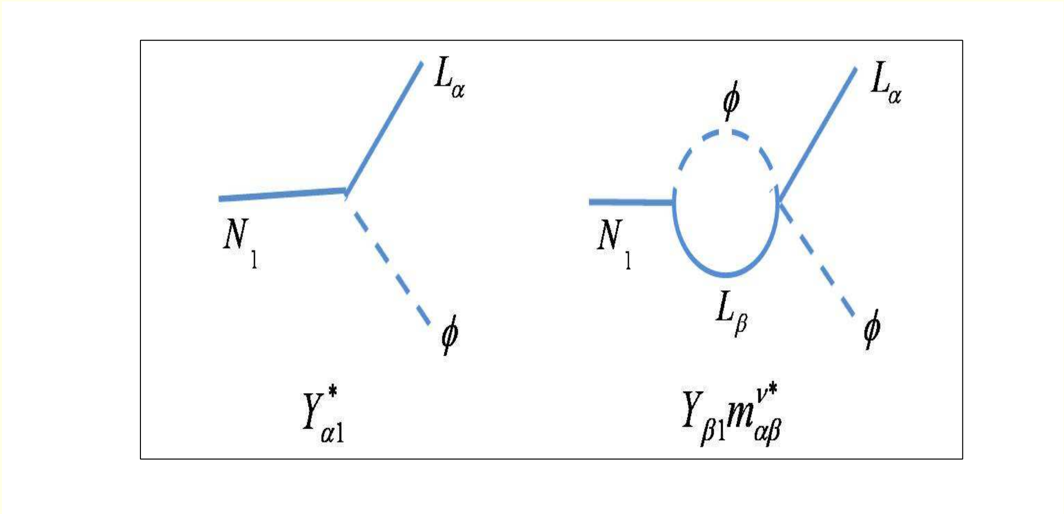
# Leptogenesis, quantitatively

# Putting it all together

$$\boxed{Y_B = 4 \times 10^{-3}\ \epsilon_{\rm CP}\ \eta_{\rm TE}\ C_{\rm BV}}$$

1. $\frac{n_N^{\rm eq}}{s} = \frac{135\zeta(3)}{4\pi^4 g_*} \sim 4 \times 10^{-3}$
2. $\epsilon_{\rm CP}$ – the price for CP violation
3. $\eta_{\rm TE}$ – the price for proximity to thermal equilibrium
4. $C_{\rm BV}$ – the price for baryon number violation

## $\epsilon_{\rm CP}$ – CP violation



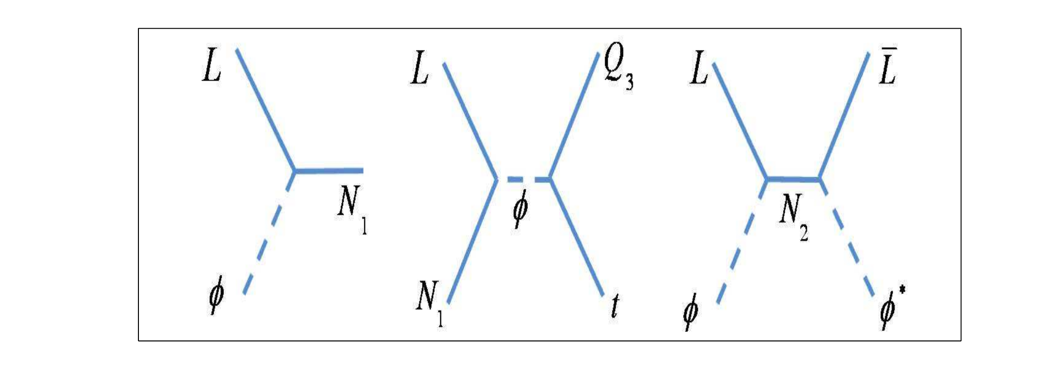

- $\epsilon \equiv \frac{\Gamma(N_1 \to L\phi) - \Gamma(N_1 \to \overline{L}\phi^\dagger)}{\Gamma(N_1 \to L\phi) + \Gamma(N_1 \to \overline{L}\phi^\dagger)}$
- Denominator $\propto \sum_\alpha Y^*_{\alpha 1} Y_{\alpha 1} = (Y^\dagger Y)_{11}$
- Numerator $\propto |\mathcal{M}_{\rm tree} + \mathcal{M}_{\rm loop}|^2 - |\overline{\mathcal{M}}_{\rm tree} + \overline{\mathcal{M}}_{\rm loop}|^2$
  $\Longrightarrow$ Numerator $\propto \mathcal{I}m \left( Y^*_{\alpha 1} Y^*_{\beta 1} m^\nu_{\alpha\beta} \right)$
- $\epsilon_{\rm CP} = \frac{3M_1}{16\pi v^2} \frac{\mathcal{I}m \sum_{\alpha,\beta} \left( Y^*_{\alpha 1} Y^*_{\beta 1} m^\nu_{\alpha\beta} \right)}{(Y^\dagger Y)_{11}} = \mathcal{O}\left( \frac{3Y^2}{16\pi} \right)$

# $\eta_{\rm TE}$ – departure from thermal equilibrium

- Roughly speaking, $N_1$ decays out of equilibrium if
  $\Gamma_D < H(T = M_1)$
- $\Gamma_D = \frac{(Y^\dagger Y)_{11} M_1}{8\pi}, \quad H(T = M_1) = 1.66 g_*^{1/2} \frac{M_1^2}{M_{\rm Pl}}$
- $\frac{8\pi v^2}{M_1^2}\Gamma_D < \frac{8\pi v^2}{M_1^2} H(T = M_1)$ equivalent to $\tilde{m}_1 < m_*$
  $\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} v^2}{M_1}, \quad m_* \equiv 8\pi 1.66 g_*^{1/2} \frac{v^2}{M_{\rm Pl}} \sim 10^{-3}$ eV
- $\tilde{m}_1 > m_1$
- Typically $\tilde{m}_1 \in (m_{\rm sol}, m_{\rm atm}) \sim 0.01 - 0.1$ eV $> m_*$

The $N_1$-decay is usually close to equilibrium

# $\eta_{\rm TE}$ – departure from thermal equilibrium




- Washout by inverse decays until $\Gamma_{ID} < H(T)$
- $\Gamma_{ID}(T < M_1) \sim \Gamma_D e^{-M_1/T}, \quad H \sim T^2/M_{\rm Pl}$
- $\Longrightarrow \Gamma_D e^{-M_1/T} \sim H$ at $T_f \sim M_1$
- Suppose ID wash-out $\epsilon_{\rm CP}$ completely until $\Gamma_{ID} = H$ and stop completely after that
- $\Longrightarrow \eta_{\rm TE} = \frac{n_N[T(\Gamma_{ID}=H)]}{n_N[T\gg M_1]} \sim e^{-M_1/T_f} \sim \frac{\Gamma_D}{H(T_f)} \sim \frac{m_*}{\tilde{m}_1}$
- $\eta_{\rm TE} \approx \frac{m_*}{\tilde{m}_1}$, expected to be $0.01 - 0.1$

# $C_{\mathrm{BV}}$ – Sphaleron interactions

- Fast interactions ($\Gamma \gg H$) $\Longrightarrow$ equilibrium
- The sum of chemical potentials over all particles entering an interaction = 0
- Example: Fast sphaleron interactions $\Longrightarrow$ $\sum_{i=1}^{3} \mu_{L_i} + 3\sum_{i=1}^{3} \mu_{Q_i} = 0$
- Chemical potential $\Leftrightarrow$ Particle asymmetry:
  $$n_i - n_{\bar{i}} = \begin{cases} (g_i/6)T^2\mu_i & \text{fermions} \\ (g_i/3)T^2\mu_i & \text{bosons} \end{cases}$$
- $\Longrightarrow C_{\mathrm{BV}} = \frac{Y_B}{Y_{B-L}} = \frac{28}{79}$

# Putting it all together

$$
\begin{aligned}
Y_B &= 4 \times 10^{-3}\ \epsilon_{\rm CP}\ \eta_{\rm TE}\ C_{\rm BV} \\
&\sim 10^{-3}\ \left(\frac{10^{-3}\ {\rm eV}}{\tilde{m}_1}\right)\ \epsilon_{\rm CP} \\
\epsilon_{\rm CP} &= \frac{3M_1}{16\pi v^2}\frac{\mathcal{I}m\sum_{\alpha,\beta}\left(Y^*_{\alpha 1}Y^*_{\beta 1}m^\nu_{\alpha\beta}\right)}{(Y^\dagger Y)_{11}}, \\
& \quad m^\nu_{\alpha\beta} = Y_{\alpha k}Y_{\beta k}M_k^{-1}, \\
\tilde{m}_1 &= \frac{(Y^\dagger Y)_{11}v^2}{M_1}
\end{aligned}
$$

# Implications

1. $m_{\rm sol} \lesssim \tilde{m}_1 \lesssim m_{\rm atm}$ – OPTIMAL:
    - Wash-out strong but not unacceptably strong
    - Leptogenesis independent of initial conditions
2. $Y_B \sim 10^{-10},\ \eta_{\rm TE} \sim 10^{-1} \Longrightarrow \epsilon_{\rm CP} \gtrsim 10^{-6}$ – EASY:
    - $\epsilon_{\rm CP} \sim \frac{3Y^2}{16\pi}$
3. $\frac{\mathcal{I}m(YYm)}{Y^\dagger Y} < m_{\rm max} \ \Longrightarrow\ \epsilon_{\rm CP} < \frac{3M_1 m_{\rm max}}{16\pi v^2}$
    - $M_1 \gtrsim 10^9\ {\rm GeV} \left(\frac{m_{\rm atm}}{m_{\rm max}}\right)\left(\frac{|\epsilon_{\rm CP}|}{10^{-7}}\right)$ – PROBLEM for SUSY?
4. No one-to-one relation between oscillation phases and leptogenesis phases
5. More HE (leptogenesis) parameters than LE (measurable) parameters

# Recent developments

Refinements:

- Thermal effects
- Spectator processes
- Flavor issues
- $N_{2,3}$ contributions

Variations:

- Soft leptogenesis
- Dirac leptogenesis
- Resonant leptogenesis

# Flavor Issues

- $N_1 \to \phi\ell_1$: Define $K_i = |\langle\ell_i|\ell_1\rangle|^2$ $(i = e, \mu, \tau)$
- $\epsilon_i \sim \epsilon K_i^0 + (K_i - \overline{K}_i)$
- For generic flavor structure $(K_i = \mathcal{O}(1), \neq 0, 1)$:
  $\eta_i \sim \eta K_i \quad \Longrightarrow \boxed{Y_{B-L} \propto \sum_{i=1}^{n_f} \eta_i\epsilon_i \sim n_f\ (\eta\epsilon)}$
  $n_f = 1_{T>10^{13}\ GeV},\ \ 2_{10^{11}<T<10^{13}\ GeV},\ \ 3_{T<10^{11}\ GeV}$
- For non-generic flavor structure $(K_i \ll 1, \neq 0)$:
  Large (order of magnitude) effects are possible
- Qualitatively new effects from $K_i \neq \overline{K}_i$
- $\boxed{M_1 \gtrsim 10^9\ GeV}$ but $\boxed{m_\nu \lesssim\ eV}$

Barbieri et al, NP B575 (2000) 61

Abada et al, JCAP 0604 (2006) 004; Nardi et al, JHEP 0601 (2006) 164

# The Future of Leptogenesis

# Direct Tests

Measuring $N_1$ interactions?

- $M_1 \gg E_{\text{experiments}}$
- $N_1$ = SM singlet
- If $M_1$ accessible – $Y$ probably tiny

Direct tests are very (very) unlikely

# Circumstantial Evidence

Sakharov conditions:

- Observation of $0\nu 2\beta \Longrightarrow$ Lepton number is violated
- Observation of $\Gamma(\nu_\mu \to \nu_e) \neq \Gamma(\overline{\nu_\mu} \to \overline{\nu_e}) \Longrightarrow$ CP is violated
- Impossible to probe the departure from thermal equilibrium

Observing LV and leptonic-CPV will make leptogenesis even more plausible

# The LHC will explore the unknown

| | |
|---|---|
| Energy | $0.6 \to 4$ TeV |
| Distance | $10^{-19} \to 10^{-20}$ m |
| “Time” | $10^{-11} \to 10^{-13}$ s |

# The LHC will explore the unknown

- What is the mechanism of electroweak symmetry breaking?
- What separates the electroweak scale from the Planck scale?
- What are the dark matter particles?
- What happened at the electroweak phase transition ($10^{-11}$ second after the big bang)?
- Was the baryon asymmetry generated by TeV scale physics?
  - If EWBG excluded – leptogenesis will become more attractive
  - If EWBG supported – leptogenesis will become less attractive

# Summary

- Two puzzles – $m_\nu \neq 0$ and $Y_B \gg Y_B^{\rm SM}$ – solved by the same natural extension of the SM
- Quantitatively, leptogenesis is plausible
- Leptogenesis may remain forever an attractive but unproven solution of the puzzle of the baryon asymmetry

Thanks to my leptogenesis collaborators:

Yuval Grossman, Tamar Kashti, YN, Esteban Roulet

**Phys. Rev. Lett. 91 (2003) 251801 [hep-ph/0307081]**

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Sacha Davidson, Enrico Nardi, YN

**Phys. Rep. 466 (2008) 105 [arXiv:0802.2962]**

Helen Quinn + YN

**'The Mystery of the Missing Antimatter' (PUP)**

Thanks to my EW baryogenesis collaborators:

Micha Berkooz, YN, Tomer Volansky

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**Phys. Rev. D78 (2008) 035005 [arxiv:0805.0097]**

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**JHEP 1005 (2010) 101 [arXiv:1003.2447]**

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