# Leptogenesis with Composite Neutrinos

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Based on arXiv:0811.0871
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Cornell University

Friday Lunch Talk

# The Outline Is Trivial...

- Leptogenesis
- Composite Neutrinos
- LG with Composite Neutrinos
- Conclusion

# Leptogenesis

# The Begining of The Story...

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}\Big|_0 = (8.66 \pm 0.35) \times 10^{-11}$$

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Can SM gives us a large enough asymmetry?

- No! The CPV is too small, and it is difficult to be out of equilibrium.

# The Begining of The Story...

$$Y_{\Delta B} = \frac{n_B - n_{\bar{B}}}{s}|_0 = (8.66 \pm 0.35) \times 10^{-11}$$

Need new physics to generate baryon asymmetry dynamically.

- e.g. GUT baryongenesis, EW baryogenesis, The Affleck-Dine mechanism, ..., Leptogenesis

# Sakharov's Conditions

Three ingredients are necessary to dynamically generate a baryon asymmetry:

- Baryon number violation
- C & CP violation
- Out of equilibrium dynamics

# Leptogenesis

**Idea**

Generate $Y_{\Delta B}$ by leptonic decays.

**Advantage**

Solve $Y_{\Delta B}$ & $m_{\nu_L}$ problems simultaneously.

**Leptonic decay** that gives **Lepton numer asymmetry**

**Sphaleron Effect**

**Lepton Number + Baryon Number**

# Receipe of The Day!

## Thermal LG, An easily making Baryon soup!

M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).

### Cook Time

$10^{-26}$ sec-$10^{-10}$ sec, about $10^{-10}$ sec, (after inflation)

### Oven Temperature

$10^{10}$ Gev-$10^{2}$ Gev

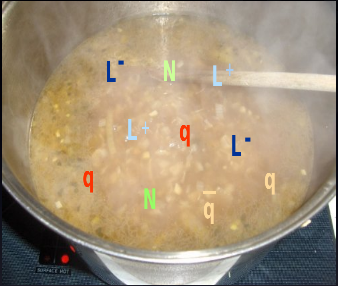
### Ingredients

- Maj-neutrinos, N, used for seesaw, $m_N \sim 10^{10}$ GeV.
- SM fields, $\gamma$, $L^{\pm}$, $H$, $q$, $\bar{q}$, ...
- Sphaleron Effect, from electroweak theory.

Seesaw Mechanism

$$MNN + Y_{ij}\bar{L}_i H^* N_j$$

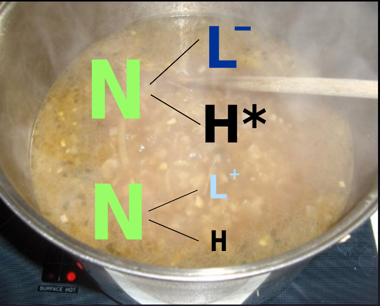
# Preparation



- $$\epsilon_L \equiv \frac{\Gamma(N \to LH^*) - \Gamma(N \to \bar{L}H)}{\Gamma(N \to LH^*) + \Gamma(N \to \bar{L}H)}$$
- $$\Gamma_N \sim |Y|^2 m_N < H|_{T=m_N} \sim 10^{-15} \frac{m_N^2}{TeV}$$
- $$m_\nu = \frac{|Y|^2 v^2}{m_N}$$

- Mix all the ingredients, including the sphaleron effect.
- After doing the inflation, cool down to $10^{10}$ GeV. At this time, $B = 0$, $L = 0$.

# N decay generates L-asymmetry



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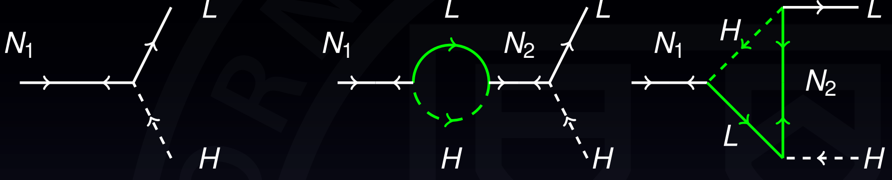
- When $T \sim m_N$, $N$ begins to decay.
- The CP phase in the Yukawa gives L-number access.

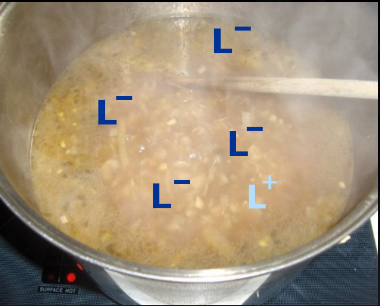
# A little more about N decay...



$$\begin{aligned} M_L &= M_t I_t + M_l I_l \\ M_L^* &= M_t^* I_t^* + M_l^* I_l^* \end{aligned} \qquad \begin{aligned} M_{\bar{L}} &= M_t I_t^* + M_l I_l^* \\ M_{\bar{L}}^* &= M_t^* I_t + M_l^* I_l \end{aligned}$$

$$\epsilon_L = \frac{|M_L|^2 - |M_{\bar{L}}|^2}{|M_L|^2 + |M_{\bar{L}}|^2} \sim \frac{Im(M_t M_l^*) Im(I_t I_l^*)}{|M_t I_t|^2} \sim |Y|^2$$

# N decay generates L-asymmetry



- $\epsilon_L \sim |Y|^2$
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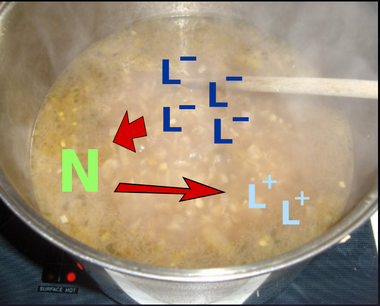
- The CP phase in the Yukawa gives L-number access.
  Now $L < 0$

# Washout effect!



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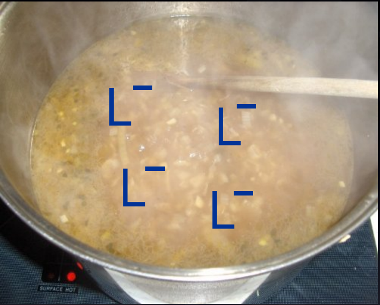
- The inverse decay, $2 \times 2$ scattering diminish the existing L-access.
- Need to make sure the RH neutrino is decoupled from the thermal bath. $\Gamma_N < H|_{T=m_N}$

# Ready for Baryongenesis!



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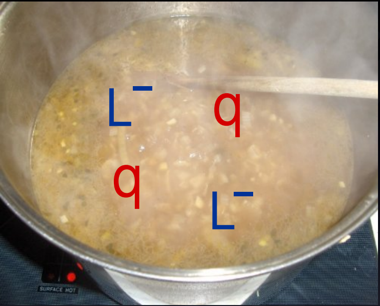
- Now we have $L < 0$, $B = 0$
- Sphaleron becomes useful!

# Sphaleron effect



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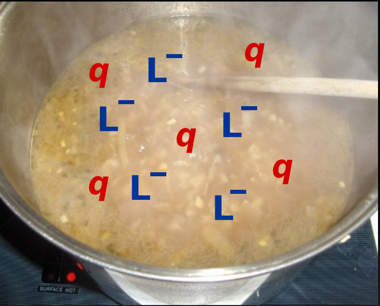
- The sphaleron effect only act on LH fields, conserves $B - L$ and damps $B + L$. This means $B_f - L_f = -L_i$, $B_f + L_f = 0$.
- In our soup, we can change $L$ & $B$ from $(L_i = -4, B_i = 0)$ to $(L_f = -2, B_f = 2)$

# After EWSB Ready to serve!!



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- We have both baryon & lepton access in the universe.
- With the mixing between heavy RH $N$, the LH neutrino has mass $m_\nu < 0.1 eV$.

# A short conclusion for the standard LG

The baryon asymmetry can be parametrized as

$$Y_{\Delta B} \sim \frac{1}{g^*} \times \epsilon_L \times \eta \times C \sim 10^{-10}$$

- $g^*$: relativistic degrees of freedom $O(10^2)$ in SM
- $\epsilon_L$: L-asymmetry, $O(10^{-7})$ when $\eta \sim O(1)$
- $\eta$: washout effect, $O(1)$ for out-of-equilibrium
- $C$: sphaleron effect, SM: $C = 12/37$, MSSM: $C = 10/31$

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Need to satisfy the constraints: two coefficients ($m_N$, $|Y|$), three constraints!

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# Dirac Leptogenesis

Can get LG even if $U(1)_L$ is conserved!

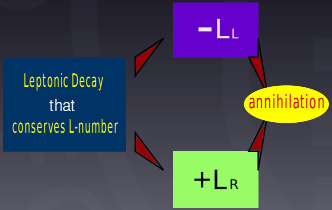
K. Dick, M. Lindner, M. Ratz and D. Wright, Phys. Rev. Lett. **84**, 4039 (2000).

**Idea**

leptonic decay + L conservation + L separation

**Advantage**

large $Y_{\Delta B}$, small $m_{\nu_L}$, no need of Majorana neutrinos



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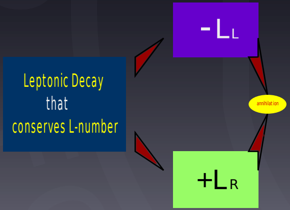

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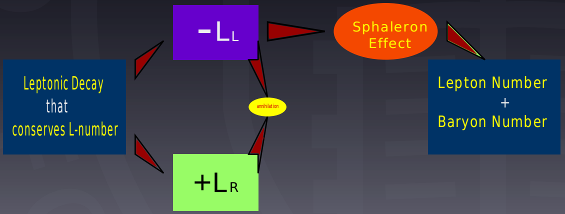


Leptonic Decay
that
conserves L-number

$-L_L$

$+L_R$

annihilation

Sphaleron
Effect

Lepton Number
+
Baryon Number

# A short conclusion for Dirac LG

Most of the constraints are the same:

$$Y_{\Delta B} \sim \frac{1}{g^*} \times \epsilon_L \times \eta \times C \sim 10^{-10}$$

- $\epsilon_L \sim |Y|^2$
- $\Gamma_N \sim |Y|^2 m_N < H|_{T=m_N} \sim 10^{-15} \frac{m_N^2}{TeV}$

Besides,

- New constraint for $m_\nu$.
- Equilibrating rate $R_{eq} < H(T)$ until EWSB.

# Composite Neutrinos

# Composite Neutrinos

Neutrinos are light because they are fat!

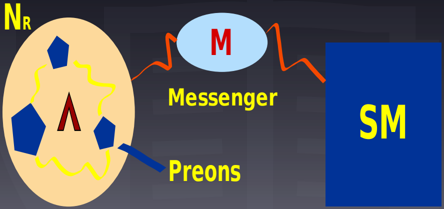
N. Arkani-Hamed and Y. Grossman,Phys. Lett. B **459**, 179 (1999).

**Idea**

$N_R$ are light composite fermions from a strong dynamics.

**Advantage**

The $\Lambda_{QCD}$ of the strong dynamics suppress $m_{\nu_L}$ naturally.



# Massless baryons?

G. 't Hooft's Cargese summer lectures (1979)

Usually,

- The baryons in SM have $m_{baryon} \sim \Lambda_{QCD}$ after confinement.
- The GSB's coming from the breaking of the global symmetry can remain massless, but this is not for fermions!

However,

- If the strong dynamics is chiral, and we have enough chiral symmetry left after SSB, the massless baryon can exit.

How to find the massless baryons in the confinement scale?

- Gauge symmetry + anomaly matching.

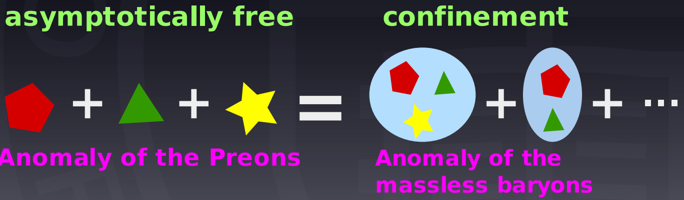
# Anomaly Matching

Anomaly will never die!

G. ’t Hooft’s Cargese summer lectures (1979)

## Idea

In strongly coupled theory with composite degrees of freedom, the anomalies of the constituents and the composites must match.



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However,

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How to identify the massless baryons in the confinement scale? (theory)

- By checking the anomaly & gauge symmetry, we can identify the correct massless baryons. i.e. massless composite fermions.

# The Composite Neutrinos!

S. Dimopoulos, S. Raby and L. Susskind, Nucl. Phys. B **173**, 208 (1980).

An SU$(n+4)$ gauge theory with

- 1 antisymmetric tensor $A$.
- $n$ antifundamentals $\psi_i$, $i = 1 \ldots n$.

can produce

- $\frac{n(n+1)}{2}$ massless composite "baryons" $B_{ij} = \psi_i A \psi_j = B_{ji}$.

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Can we use these massless baryons as the RH (or sterile) neutrinos?

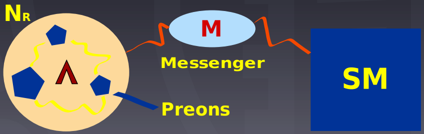
# The Composite Neutrinos!

## Yes, we can!

For the simplest case with $n = 2$, we have:

- $\frac{2(2+1)}{2} = 3\times$ RH neutrinos. $N_{ij} = \psi_i A \psi_j$
- the effective Yukawa coupling suppressed by the messenger mass M

$$\lambda^{ij,\alpha}\frac{(\psi_i A \psi_j) L_\alpha H^*}{M^3} = \lambda^{ij,\alpha}\left(\frac{\Lambda}{M}\right)^3 \hat{N}_{ij} L_\alpha H^*$$



# Two ways of getting $m_\nu$

Dirac neutrino mass:

- $(\frac{\Lambda}{M})^3 \hat{N} L H^*$
- $m_\nu = (\frac{\Lambda}{M})^3 v$ For $v = 10^2$GeV, $\frac{\Lambda}{M} = 10^{-4}$.

Majorana neutrino mass:

- $(\frac{\Lambda}{M})^3 \hat{N} L H^* + M(\frac{\Lambda}{M})^6 \hat{N}\hat{N}$
- $m_\nu = \frac{v^2}{M}$, $m_N = (\frac{\Lambda}{M})^6 M$

# UV complete the theory

Y. Grossman and Y. Tsai, JHEP **0812**, 016 (2008)

What are the fields give $\frac{(\psi A \psi) L H^*}{M^3}$ ?

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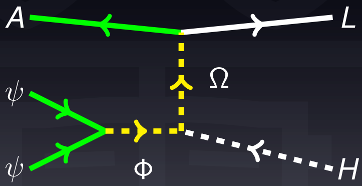

# The particle spectrum

| | $\mathrm{SU}(6)_C$ | $\mathrm{SU}(2)_L$ | $U(1)_Y$ | $Q$ | spin | $L$ | $Q_{ps}$ | $SU(2)_\psi$ |
|---|---|---|---|---|---|---|---|---|
| ${}_iL_L^\alpha$ | 1 | 2 | $-\frac{1}{2}$ | $0, -1$ | $\frac{1}{2}$ | 1 | 0 | 1 |
| ${}_iE_R$ | 1 | 1 | $-1$ | $-1$ | $\frac{1}{2}$ | $-1$ | 0 | 1 |
| $H^\alpha$ | 1 | 2 | $\frac{1}{2}$ | $1, 0$ | 0 | 0 | 0 | 1 |
| ${}_g\Omega^\alpha_{ab}$ | 15 | 2 | $-\frac{1}{2}$ | $0, -1$ | 0 | 0 | 2 | 1 |
| ${}_f\psi_a$ | $\bar{6}$ | 1 | 0 | 0 | $\frac{1}{2}$ | 0 | 1 | 2 |
| $A_{ab}$ | 15 | 1 | 0 | 0 | $\frac{1}{2}$ | $-1$ | 2 | 1 |
| $\Phi_{ab}$ | 15 | 1 | 0 | 0 | 0 | 0 | 2 | 1 |
| ${}_kN$ | 189 ; 1 | 1 | 0 | 0 | $\frac{1}{2}$ | break | 0 | 1 |

# What's next?

Now we have the UV completion of the theory, want to do LG with it...

- Can the decay of the new fields do the job?
- Do we have CP phase in the theory?
- Does the theory satisfy the experimental bound?

# Couplings

$Y^L_{gi} A \Omega^\dagger_g L_i + h.c.$

$\tilde{M}_g \tilde{H}^\dagger \Phi^\dagger \Omega_g + h.c.$

# CP phases

We have CP phases in the theory:

| Symbol | Number of parameters (R+I) | Number of Physical parameters (R+I) |
|---|---|---|
| $M^2_\Omega$ | 3+1 | 2+0 |
| $M^2_\Phi$ | 1+0 | 1+0 |
| $\tilde{M}$ | 2+2 | 2+0 |
| $Y^e$ | 9+9 | 3+0 |
| $Y^L$ | 6+6 | 6+3 |
| $Y^A$ | 1+1 | 1+0 |
| $M_N$ | 3+3 | 2+0 |
| $Y^N$ | 2+2 | 2+1 |
| $y^N$ | 6+6 | 6+6 |

# Experimental bound

$$\mu \longrightarrow e\gamma$$

Comparing to the experimental bound, $M_{\Omega}|Y^{L}| > 10\,TeV$.

# Experimental bound

## Big-Bang Nucleosynthesis (BBN)

- The composite $N_R$ give 3 more massless degrees of freedom.
- BBN and CMB data: $N_\nu \leq 3.3$ at 95% CL from E-density bound.
- To satisfy the E-density bound, need $T_{CN_R} \leq 0.5 T_{SM}$
- The early decoupling of $CN_R$ from thermal bath gives $T_{CN_R} \leq 0.47 T_{SM}$ Safe!

# A short conclusion for Composite Neutrinos

- The idea of $CN_R$ gives small Dirac $m_{\nu_L}$ naturally.
- We can also have Majorana mass term in the theory.
- The UV completion of the theory gives us the particle spectrum that:
  - gives CP phases & new decay channels that is necessary for LG.
  - satisfies the experimental bound.
  - has the preons $\psi$, $A$, $\phi$ & the messenger $\Omega$ that couples to the SM sector.

# Leptogenesis
# with
# Composite Neutrinos

# LG with Composite Neutrinos

Y. Grossman and Y. Tsai, JHEP **0812**, 016 (2008)

Now we have enough tools to begin the work!

- The idea of the standard LG (with Majo-neutrinos) & the Dirac LG (L-number conservation)
- The idea of the $CN_R$.
- The UV completion of the $CN_R$.

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Y. Grossman and Y. Tsai, JHEP **0812**, 016 (2008)

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- The idea of the $CN_R$.
- The UV completion of the $CN_R$.

Two LG possibilities!

# LG with C$N_R$ - The Standard LG

When the temperature $T$ that LG begins to happen satisfies

$$T \ll \Lambda$$

- Cannot see preons, there is only $N_R$.
- Gives the standard LG from $N_R \to H^* L$ decay.
- Have $m_N \sim 10^7$TeV, $\Lambda \sim 10^{12}$TeV, $M \sim 10^{14}$TeV.
- Still a high energy scale LG scenario.

**$N_R$** decay
that gives
Lepton numer
asymmetry

Sphaleron Effect

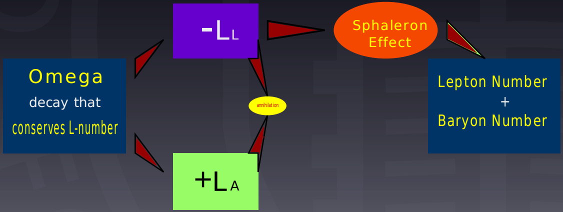
Lepton Number
+
Baryon Number

# LG with $CN_R$ - The Dirac LG

When the temperature $T$ that LG begins to happen satisfies

$$T \gg \Lambda$$

- No $N_R$, there are only preons.
- Gives the Dirac LG from the messenger decay $\Omega \rightarrow AL$.
- The annihilation between $A$ & $L$ is suppressed by $(T/M)^6$ and $\ll H$.
- Can have $m_\Omega$ as low as 10TeV.
- Can be a good candidate for low energy LG.



# Conclusion

Wake up!

- Leptogenesis is a plausible baryogenesis scenario which solves the $Y_{\Delta B}$ & small $m_\nu$ problems simultaneously.
- The Composite RH neutrinos gives small Dirac type $m_\nu$ suppressed by $(\Lambda/M)^3$
- The UV completion of the Composite Neutrino theory gives us interesting LG possibilities.