(Pseudo)-Dirac neutrinos and leptogenesis

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SAA, A Dedes and K Tamvakis, Phys Rev D 71 (2005) 033003; SAA and V Page, JHEP 0605:024,2006: hep-ph/0601149

Outline

1. Options for neutrino masses
2. Natural neutrino masses in supergravity
3. A model for small Dirac masses
4. Neutrinogenesis: the idea
5. Affleck-Dine: the idea
6. Affleck-Dine neutrinogenesis
7. The baryon number

Options for ν-mass?

General neutrino mass matrix (one flavour)

$$-L_{mass} = \frac{1}{2}\bar{\chi}_L^c M_\nu \chi_L + \frac{1}{2}\bar{\chi}_L M_\nu \chi_L$$

with

$$\chi = \begin{pmatrix} \nu \\ \nu^c \end{pmatrix} \; , \; \bar{\chi}^c = -(\bar{\nu}^c, \bar{\nu})$$

$$M_\nu = \begin{pmatrix} m_L & m_D \\ m_D^T & M_N \end{pmatrix}$$

Options for ν-mass?

a) Dirac

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix}$$

Two degenerate eigenvalues; $\pm m_D$. Maximal mixing $(\theta = \frac{\pi}{4})$ between active and sterile neutrino but no oscillations

Options for ν-mass?

b) Pseudo-Dirac

$$M_\nu = \begin{pmatrix} m_L \ll & m_D \\ m_D^T \gg & M_N \end{pmatrix}$$

Two eigenvalues; $m_D \pm (m_L + M_N)$. Maximal mixing $(\tan\theta = \frac{2m_D}{M_N + m_L})$ oscillations between active and sterile neutrino even with one generation.

Options for ν-mass?

c) See-Saw

$$M_\nu = \begin{pmatrix} m_L \ll & m_D \\ m_D^T \ll & M_N \end{pmatrix}$$

Sterile state ν^c is almost mass eigenstate.

Negligible mixing $(\tan\theta = \frac{2m_D}{M_N+m_L})$ and hence negligible active $\leftrightarrow$sterile.

Can Dirac neutrinos be natural ?

Consider supergravity: K, W where

e.g. $W \supset QH_uU^c + QH_dD^c$ and $K \supset \bar{\Phi}\Phi$ leads to $\partial\phi\partial\phi^*$.

Instead of $W \supset \lambda LH_uN^c$ assume

$$K \supset \frac{LH_uN^c}{M} + \frac{LH_d^*N^c}{M} + h.c.$$

Assume supersymmetry breaking is communicated by gravity with $m_{3/2} \sim 1$TeV. Then $\langle H_u \rangle \approx m_{top}$ and $M \approx M_P$ gives

$$m_\nu \approx \frac{m_{3/2}}{M}(\langle H_u \rangle + \langle H_d \rangle) \sim 10^{-4} eV$$

Close to measured value 0.05 eV!

Supergravity calculation

Most general K, W are ($s^i \equiv$hidden fields, $y^\alpha \equiv$visible "matter" fields)

$$
\begin{aligned}
W(s,y) &= W^{(h)}(s) + W^{(o)}(s,y) \\
K(s,s^*,y,y^*) &= K^{(h)}(s,s^*) + K^{(o)}(s,s^*,y,y^*)
\end{aligned}
$$

Supergravity calculation

Visible matter Lagrangian

$$L = iK_{\alpha\bar{\beta}}\,\bar{\chi}^{\bar{\beta}}\bar{\sigma}^{\mu}\partial_{\mu}\chi^{\alpha} - (m_{\alpha\beta}\chi^{\alpha}\chi^{\beta} + h.c.)$$

where the crucial terms are ...

$$\begin{aligned} 2m_{\alpha\beta} &= W^{(o)}_{\alpha\beta} - K^{\gamma\bar{\delta}}K^{(o)}_{\alpha\beta\bar{\delta}}W^{(o)}_{\gamma} - K^{i\bar{j}}K^{(o)}_{\alpha\beta\bar{j}}W^{(h)}_{i} \\ &\quad - K^{\gamma\bar{i}}K^{(o)}_{\alpha\beta\bar{i}}W^{(o)}_{\gamma} - K^{i\bar{\delta}}K^{(o)}_{\alpha\beta\bar{\delta}}W^{(h)}_{i} \\ &+ m_{3/2}(K^{(o)}_{\alpha\beta} - K^{\gamma\bar{\delta}}K^{(o)}_{\alpha\beta\bar{\delta}}K^{(o)}_{\gamma} - K^{i\bar{j}}K^{(o)}_{\alpha\beta\bar{j}}K^{(h)}_{i} \\ &\quad - K^{\gamma\bar{i}}K^{(o)}_{\alpha\beta\bar{i}}K^{(o)}_{\gamma} - K^{i\bar{\delta}}K^{(o)}_{\alpha\beta\bar{\delta}}K^{(h)}_{i}) \end{aligned}$$

Supergravity calculation

$$2m_{\alpha\beta} \supset K^{i\bar{j}} K^{(o)}_{\alpha\beta\bar{j}} W^{(h)}_i + m_{3/2} K^{(o)}_{\alpha\beta}$$

A model

How do we ensure that the Dirac mass terms are not in W?

Need a symmetry that treats K and W differently

-R-symmetry

Q	U^c	D^c	L	E^c	N^c	H_u	H_d
$2-r_d-r_h$	r_d+2r_h	r_d	$1+r_h$	$1-2r_h$	-1	$-r_h$	r_h

$$W \supset Y_U Q H_u U^c + Y_D Q H_d D^c + Y_E L H_d E^c$$

$$K \supset c_1(s,s^*)\, H_u H_d + c_2(s,s^*)\, L H_u N^c + c_3(s,s^*)\, L H_d^* N^c + h.c.$$

A model

find Dirac mass terms

$$m_\nu^D = v \sin\beta [\, m_{3/2}(c_2 - c_1 c_3) - F^s (c_2 + c_3 \cot\beta)_{,s}]$$

If $m_\nu^D = (0.04 - 0.05)$eV and $\langle c_{2,3} \rangle \simeq M^{-1}$ and $\langle (c_{2,3})_{,s} \rangle \simeq M^{-2}$

$$F^s \simeq \frac{m_\nu^D M^2}{v \sin\beta (1 + \cot\beta)} = (1.6 - 2.8) \times 10^{-13} M^2$$

If $F^s = \sqrt{3} m_{3/2} M_P$ then $100 < m_{3/2} < 10^4$GeV gives

$$4 \times 10^{16} GeV < M < 5 \times 10^{17} GeV$$

A model

Relaxing lepton number conservation also get Pseudo-Dirac neutrinos from

$$
\begin{aligned}
W &\supset Y_4 (L H_u)^2 \\
K &\supset c_4 W^{(h)} (N^c)^2
\end{aligned}
$$

Note that $m_s \sim F^s/M \sim 10$ TeV is high

Neutrinogenesis: the idea

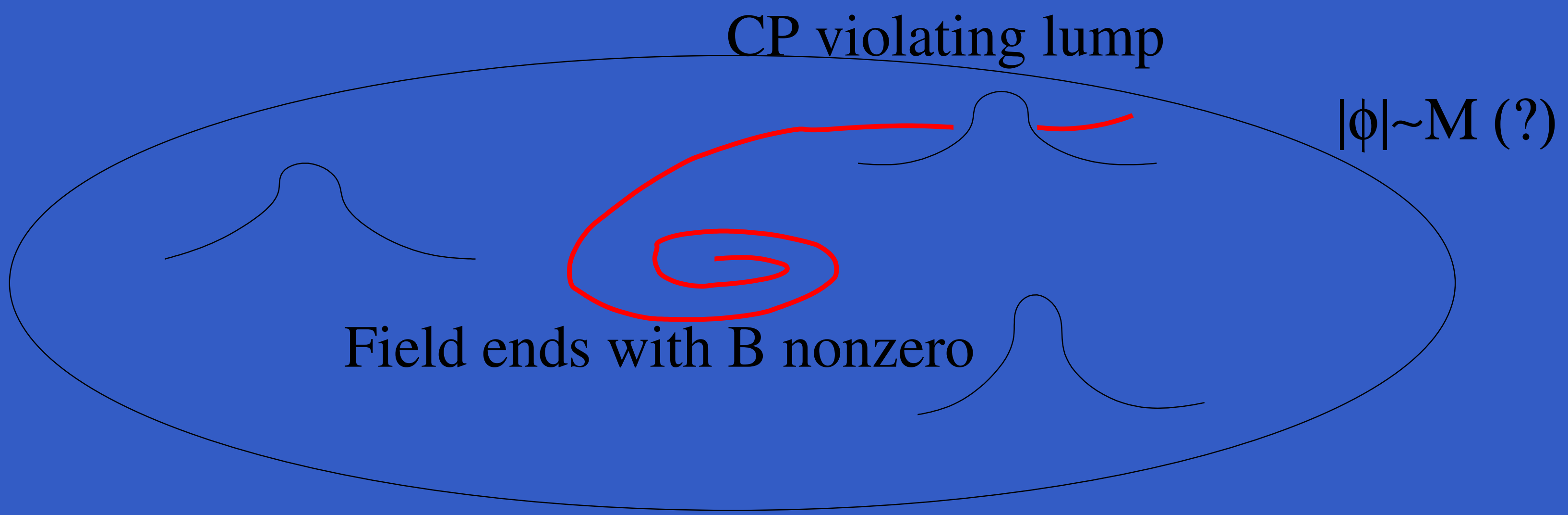
If both B and L conserved in K, W how can we get nett B?

Use sphalerons (Dick, Lindner, Ratz, Wright); e.g drift and decay of heavy ϕ

$$\phi \longrightarrow \nu_L + \bar{\nu}_R \longrightarrow -\alpha(B+L) + \nu_L + \bar{\nu}_R$$

- ν_R is inert because m_ν^D is small and holds lepton number
- sphalerons change $B+L$ but $B-L=0$
- CP violation in ϕ decays

Affleck Dine: the idea



Affleck Dine neutrinogenesis

Consider superpotential of effective global SUSY theory

$$W = Y_U Q H_u U^c + Y_D Q H_d D^c + Y_E L H_d E^c + Y_\nu L H_u N^c + \mu H_u H_d$$

$Y_\nu \approx 10^{-12}$ is an incredibly small coupling.

Affleck Dine neutrinogenesis

$D - flat$ directions correspond to scalars LH_u and N^c :

$$\begin{aligned} L &= \frac{1}{\sqrt{2}} \begin{pmatrix} \phi \\ 0 \end{pmatrix} \\ H_u &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \phi \end{pmatrix} \\ N^c &= \tilde{\bar{\nu}} \end{aligned}$$

Affleck Dine neutrinogenesis

Potential

$$V = V_{SB} + V_{Hubble} + V_F$$

$$\begin{aligned} V &= (m_\phi^2 - c_\phi H^2)|\phi|^2 + (m_\nu^2 - c_\nu H^2)|\bar{\tilde{\nu}}|^2 \\ &\quad + (Y_\nu(A + c_A H)\phi^2\bar{\tilde{\nu}} + h.c.) + \frac{|Y_\nu|^2}{4}|\phi^2|^2 + |Y_\nu|^2|\bar{\tilde{\nu}}\phi|^2 \end{aligned}$$

Affleck Dine neutrinogenesis

Minimum at

$$
\begin{aligned}
|\phi_{\rm min}| &\simeq \sqrt{\frac{c_\phi}{2}\frac{H}{|Y_\nu|}} \\
|\tilde{\bar{\nu}}| &\simeq \begin{cases} \frac{-c_\phi}{2c_\nu - c_\phi}\frac{|A|}{|Y_\nu|}, & c_A H \ll |A| \\ \frac{-c_\phi}{2c_\nu - c_\phi}\frac{H}{|Y_\nu|}, & c_A H \gg |A| \end{cases}
\end{aligned}
$$

Affleck Dine neutrinogenesis

Dynamics of $n_{LR} = n_L - n_R$

$$n_\nu = n_L + n_R$$

$$\begin{aligned} n_L &= \frac{i}{2}(\dot{\phi}^* \phi - \dot{\phi}\phi^*) \\ n_R &= -i(\dot{\bar{\tilde{\nu}}}^* \bar{\tilde{\nu}} - \dot{\bar{\tilde{\nu}}}\bar{\tilde{\nu}}^*) \end{aligned}$$

Need to solve eqns of motion, e.g.

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi^*} = 0$$

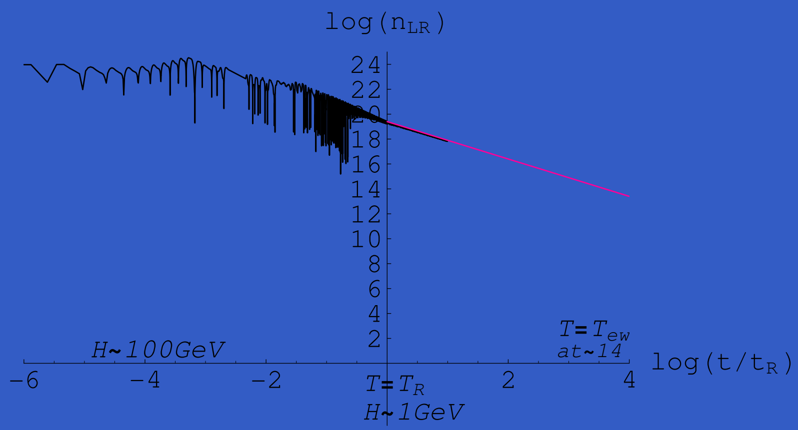
Affleck Dine neutrinogenesis

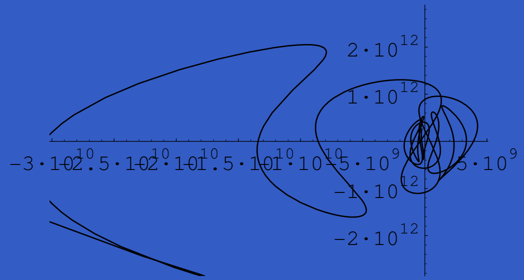
Gives

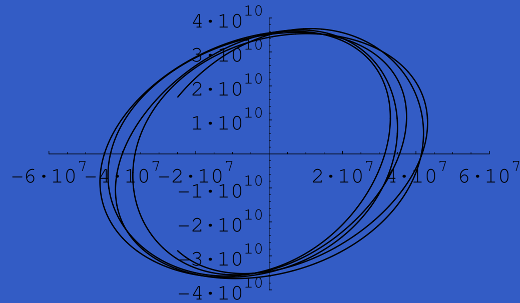
$$\begin{aligned} \dot{n}_\nu + 3Hn_\nu &= 0 \\ \dot{n}_{LR} + 3Hn_{LR} &= 4Im(Y_\nu A\phi^2\bar{\tilde{\nu}}) \end{aligned}$$

Affleck Dine neutrinogenesis

Thermal history







Affleck Dine neutrinogenesis

- $H \gg m_{3/2}$: inflaton oscillation $R \sim t^{2/3}$, matter dominated chaotic motion:

$$R^3 H^2 \phi^2 = const \Rightarrow n_{LR} \sim const$$

- $H(T_R) < H < m_{3/2}$: matter dominated cyclic motion:

$$R^3 m_\phi^2 \phi^2 = const \Rightarrow n_{LR} \sim t^{-1}$$

- $H < H(T_R)$: radiation dominated cyclic motion:

$$R^3 m_\phi^2 \phi^2 = const \Rightarrow n_{LR} \sim t^{-\frac{3}{2}}$$

Affleck Dine neutrinogenesis

Constraints:

- Gravitino bound: $T_R < 10^9$GeV. If $T_R = 10^9$GeV then $H(T_R) \sim T^2/M_P \sim 1$GeV.
- Decay of $\bar{\tilde{\nu}}$ oscillations after T_{ew}: $\tau_{decay} \sim 4\pi/(Y_\nu^2 m_{\tilde{\nu}})$ gives $T_{decay} \sim 100$MeV

Final baryon number

Until reheating

$$\frac{\rho_{n_{LR}}}{\rho_I} \sim \frac{m_{3/2}^2 |A/Y_\nu|^2}{m_{3/2}^2 M_P^2}$$

After reheating use $m_{\phi,\bar{\tilde{\nu}}} n_{LR} = \rho_{n_{LR}}$ scales like matter and entropy

$$\begin{aligned} \frac{n_{LR}}{s} &\approx \frac{|A/Y_\nu|^2}{M_P^2} \frac{T_R}{m_\phi} \\ &= 10^{-9} \left|\frac{A}{100GeV}\right|^2 \left|\frac{10^{-12}}{Y_\nu}\right|^2 \left|\frac{T_R}{1TeV}\right| \left|\frac{100GeV}{m_\phi}\right| \end{aligned}$$

Final baryon number

Finally when sphalerons are active

$$
\begin{aligned}
B &= L = \frac{8}{23} n_R \quad T > T_{ew} \\
B &= L = \frac{44}{137} n_R \quad T < T_{ew}
\end{aligned}
$$

Summary

- Supergravity provides attractive possibilities for (Pseudo)-Dirac neutrinos.
- $m_\nu \approx 0.05$eV consistent with $4 \times 10^{16} GeV < M < 5 \times 10^{17}$GeV
- Affleck-Dine works remarkably well with D-flat directions (LH_u and N^c). Find $n_B/s \sim 10^{-9}$ if $T_R \sim 1$TeV
- Baryon number related to DM $\rightarrow M_{\tilde{\nu}} \approx 1\, GeV$
- Pseudo-Dirac neutrinos can be accomodated.