OUTLINE

• NEUTRINOS & LEPTOGENESIS, BARYOGENESIS

• NEUTRINOS AND THE DARK SECTOR OF THE UNIVERSE

• COSMIC NEUTRINOS & VIOLATION OF FUNDAMENTAL SYMMETRIES
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Role of (heavy) Majorana Right-handed Neutrinos (νMSM)
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Neutrino Contributions to Dark Matter & Dark Energy (sterile, neutrino condensates, mass varying ν)
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CPT Violation in Early Universe & Baryon Asymmetry
Can we avoid Right-Handed $\nu$?
NEUTRINOS,
BARYOGENESIS &
LEPTOGENESIS
Generic Concepts

- **Leptogenesis**: physical *out of thermal equilibrium* processes in the (expanding) Early Universe that produce an asymmetry between leptons & antileptons

- **Baryogenesis**: The corresponding processes that produce an asymmetry between baryons and antibaryons

- **Ultimate question**: why *is the Universe made only of matter?*
Generic Concepts

- **Leptogenesis**: physical out of thermal equilibrium processes in the (expanding) Early Universe that produce an asymmetry between leptons & antileptons.

- **Baryogenesis**: The corresponding processes that produce an asymmetry between baryons and antibaryons.

- **Ultimate question**: why is the Universe made only of matter?
NEUTRINOS & LEPTOGENESIS

• Matter-Antimatter asymmetry in the Universe ➔ Violation of Baryon # (B), C & CP

• Tiny CP violation (O(10^{-3})) in Labs: e.g. $K^0 \overline{K}^0$

• But Universe consists only of matter

\[
\frac{n_B - \bar{n}_B}{n_B + \bar{n}_B} \sim \frac{n_B - \bar{n}_B}{s} = (8.4 - 8.9) \times 10^{-11},
\]

T > 1 GeV

Sakharov: Non-equilibrium physics of early Universe, B, C, CP violation

but not quantitatively in SM, still a mystery
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Assume CPT
Classical conservations of EW theory: $B, L_e, L_\mu, L_\tau$

$L_i$ Lepton #s
Classical conservations of EW theory: $B$, $L_e$, $L_\mu$, $L_\tau$

Quantum Anomalies:

$$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{n_f}{32\pi^2} \text{Tr} F_{\mu\nu} \tilde{F}_{\mu\nu} + U(1) \text{ part}$$

$L_i$ Lepton #s

Generation (flavour) #

SU(2)
Classical conservations of EW theory: $B, L_e, L_\mu, L_\tau$

Quantum Anomalies:

\[ \partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{n_f}{32\pi^2} \text{Tr} F_{\mu\nu} \tilde{F}_{\mu\nu} + U(1) \text{ part} \]

Allowed Processes (change of $B$ by multiples of 3)

\[ \text{bosons } \leftrightarrow \text{bosons } + 9q + 3l \]
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Allowed Processes (change of $B$ by multiples of 3)

bosons $\leftrightarrow$ bosons + $9q + 3l$ \(\rightarrow\) $L_i - B/3$ Conserved

(three quantities)
Classical conservations of EW theory: $B$, $L_e$, $L_\mu$, $L_\tau$

Quantum Anomalies:

$$\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{n_f}{32\pi^2} \text{Tr} F_{\mu\nu} \tilde{F}_{\mu\nu} + U(1) \text{ part}$$

Allowed Processes (change of $B$ by multiples of 3)

$$\text{bosons} \leftrightarrow \text{bosons} + 9q + 3l$$

$B/L_i = \text{B/3 Conserved (three quantities)}$

**BUT:**

OBSERVED NEUTRINO FLAVOUR OSCILLATIONS

$L-B$ conserved (one quantity)
$L=$total Lepton #
Classical conservations of EW theory: \( B, L_e, L_\mu, L_\tau \)

Quantum Anomalies:

\[
\partial_\mu J_\mu^B = \partial_\mu J_\mu^L = \frac{n_f}{32\pi^2} \text{Tr} F_{\mu\nu} \tilde{F}_{\mu\nu} + U(1) \text{ part}
\]

Allowed Processes (change of \( B \) by multiples of 3)

bosons \( \leftrightarrow \) bosons + 9q + 3l

\[ L_i - B/3 \text{ Conserved} \]

(three quantities)

**BUT:**

OBSERVED NEUTRINO FLAVOUR OSCILLATIONS

If neutrinos Majorana

\[ L-B \text{ conserved (one quantity)} \]

L=total Lepton #

L violated, No conserved numbers
OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

Rate of B violation in Early Universe

\[ \Gamma \sim \begin{cases} (\alpha_W T)^4 \left( \frac{M_{\text{sph}}}{T} \right)^7 \exp \left( -\frac{M_{\text{sph}}}{T} \right), & T \lesssim M_{\text{sph}}, \\ \alpha_W (\alpha_W T)^4 \log(1/\alpha_W), & T \gtrsim M_{\text{sph}}, \end{cases} \]

\[ \alpha_W = \text{SU}(2) \text{ fine structure } \text{``constant''} \]

Kuzmin, Rubakov, Shaposhnikov

Sphaleron Mass Scale
\((M_W/\alpha_W) = \text{height of energy Barrier separating SU}(2) \text{ vacua with different topologies}\)
Rate of B violation in Early Universe

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\end{cases} \]

Thermal Equilibrium (i.e. \( \Gamma > H \) (Hubble)) for B non conserv. occurs only for:

\[ T_{\text{sph}}(m_H) < T < (\alpha_W)^5 M_{\text{Pl}} \sim 10^{12} \text{ GeV} \]

\[ T_{\text{sph}}(m_H) \in [130, 190] \text{GeV} \]

\[ m_H \in [100, 300] \text{GeV} \]
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BAU could be produced this way only when sphaleron interactions freeze out, i.e.

\[ T \sim T_{\text{sph}} \]
OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

Rate of B violation in Early Universe

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BAU COULD BE PRODUCED @ \( T \simeq T_{\text{sph}} \)

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\[m_H \in [100, 300] \text{GeV}\]

Compute CP Violation Effects

Use CKM Matrix for \[T > T_{sph}\]

Kuzmin, Rubakov, Shaposhnikov
Within the Standard Model, lowest CP Violating structures

\[ d_{CP} = \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin\delta_{CP} \]
\[ \cdot (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \]
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Kobayashi-Maskawa CP Violating phase

Shaposhnikov

\[ D = \text{Im } \text{Tr} \left[ M_u^2 M_d^2 M_u M_d \right] \]

Jarlskog det

\[ \delta_{KM} \sim \frac{D}{T_{12}} \sim 10^{-20} \]
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This CP Violation Cannot be the Source of Baryon Asymmetry in The Universe

\[ T \sim T_{\text{sph}} \]

\[ T_{\text{sph}}(m_H) \in [130, 190] \text{GeV} \]
Role of Neutrinos?

• Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.)
• Massive $\nu$ are simplest extension of SM
• Right-handed supermassive $\nu$ may provide extensions of SM with:
  
  extra CP Violation and thus Origin of Universe’s matter-antimatter asymmetry due to neutrino masses, Dark Matter
SM Extension with N extra right-handed neutrinos

\[
L = L_{SM} + \bar{N}_I i \gamma^\mu \sigma_{\mu\nu} N_I - F_{\alpha I} \bar{L}_{\alpha} N_b \phi - \frac{M_{I}}{2} \bar{N}_c^I N_I + \text{h.c.}
\]

Paschos, Hill, Luty, Minkowski, Yanagida, Mohapatra, Senjanovic, de Gouvea…, Liao, Nelson, Buchmuller, Anisimov, di Bari…
Akhmedov, Rubakov, Smirnov, Davidson, Giudice, Notari, Raidal, Riotto, Strumia, Pilafitis, Underwood, Shaposhnikov … Hernandez, Giunti…
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\]

- Right-handed Massive **Majorana** neutrinos
- Leptons
SM Extension with N extra right-handed neutrinos

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Higgs scalar SU(2)
Dual:
\[ \tilde{\phi}_i = \epsilon_{ij} \phi_j^*. \]
SM Extension with N extra right-handed neutrinos

\[ \nu_{\text{MSM}} \]

\[ L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.} \]

Model with 2 or 3 singlet fermions works well in reproducing Baryon Asymmetry and is consistent with Experimental Data on neutrino oscillations.

Model with N=3 also works fine, and in fact it allows one of the Majorana fermions to almost decouple from the rest of the SM fields, thus providing candidates for light (kEV region of mass) sterile neutrino Dark Matter.
SM Extension with N extra right-handed neutrinos

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For Constraints
(compiled \( \nu \) oscillation data) and Yukawa couplings on (light) sterile neutrinos cf.: Matrix (N=2 or 3 )

\[ F = \tilde{K}_L f_d \tilde{K}_R^\dagger \]

Giunti, Hernandez talks
N=1 excluded by data

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Links with Inflation?
non minimal coupling of Higgs \( \phi \) with Curvature scalar \( R \)

\[ L_G = \ldots + \zeta \phi^+ \phi R \]

flat effective potential for large values of \( \phi \) (slow roll conditions)

Yukawa couplings
Matrix (N=2 or 3)

Experimental Data on neutrino oscillations

Shaposhnikov

This works well in reproducing Baryon Asymmetry

one of the Majorana fermions allows \textit{one} of the Majorana fermions from the rest of the SM fields, thus providing

sterile neutrino \textit{Dark Matter.}
SM Extension with N extra right-handed neutrinos

\[ \nu_{\text{MSM}} \]

Boyarski, Ruchayskiy, Shaposhnikov

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Yukawa couplings
Matrix (N=3)

$$F = \tilde{K}_L f_d \tilde{K}_R^\dagger$$

$$f_d = \text{diag}(f_1, f_2, f_3), \quad \tilde{K}_L = K_L P_\alpha, \quad \tilde{K}_R^\dagger = K_R^\dagger P_\beta$$

$$P_\alpha = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1), \quad P_\beta = \text{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$$

Majorana phases
SM Extension with N extra right-handed neutrinos

$\nu_{\text{MSM}}$

Boyariski, Ruchayskiy, Shaposhnikov

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Yukawa couplings

Matrix (N=3)

$$F = \tilde{K}_L f_d \tilde{K}_R^\dagger$$

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$$P_\alpha = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1), \quad P_\beta = \text{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$$

Mixing

$$K_L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{L23} & s_{L23} \\ 0 & -s_{L23} & c_{L23} \end{pmatrix} \begin{pmatrix} c_{L13} & 0 & s_{L13} e^{-i\delta_L} \\ 0 & 1 & 0 \\ -s_{L13} e^{i\delta_L} & 0 & c_{L13} \end{pmatrix} \begin{pmatrix} c_{L12} & s_{L12} & 0 \\ -s_{L12} & c_{L12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{Lij} = \cos(\theta_{Lij}) \text{ and } s_{Lij} = \sin(\theta_{Lij}).$$
$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$

Light Neutrino Masses through see saw

$m_\nu = -M_D \frac{1}{M_I} [M_D]^T$

$M_D = F_{\alpha I} \nu$

$\nu = \langle \phi \rangle \sim 175 \text{ GeV}$

$M_D \ll M_I$

Minkowski, Yanagida, Mohapatra, Senjanovic
**Thermal Properties**

\[ L = L_{SM} + \bar{N}_I i \gamma^\mu \partial_\mu N_I - F_\alpha I \bar{L}_\alpha N_I \phi - \frac{M_I}{2} \bar{N}_I^c N_I + h.c. \]

\[ |F|^2 \approx \frac{m_{atm}}{v^2} M_I \sim 2 \times 10^{-15} \frac{M_I}{\text{GeV}} \]

\[ |\Delta m^2_{atm}| \equiv m^2_{atm} = 2.40^{+0.12}_{-0.11} \times 10^{-3} \text{eV}^2 \]

*(Decay) processes in Early Universe*

\[ N_t \leftrightarrow \nu_t, \quad H \leftrightarrow N\nu \text{ or } N \leftrightarrow H\nu \]

Rate: \[ \frac{9 F^2 f_t^2 T}{(64 \pi^3)} \]

\( f_t = \text{top quark Yukawha coupling} \)

**Thermal equilibrium at temperatures**

\[ M_0 = \frac{M_P}{(1.66 \sqrt{g_{eff}})} \]

\[ \text{time} = \frac{M_0^2}{2T^2} \text{ (radiation era)} \]

\[ T_{eq} \approx \frac{9 f_t^2 m_{atm} M_0}{64 \pi^3 v^2} M_I \approx 5 M_I \]

(for \( T_{eq} > 100 \text{ GeV} \))
Thermal Properties

Two distinct physics cases: \( M_i > M_w \) & \( M_i < M_w \)
Thermal Properties

Two distinct physics cases: \( M_I > M_W \) & \( M_I < M_W \)

(i) \( M_I > M_W \) (electroweak scale)

Decay of Right-handed fermions

\[ T_{\text{decay}} \simeq \left( \frac{m_{\text{atm}}M_0}{24\pi v^2} \right)^{\frac{1}{3}} M_I \simeq 3M_I \]

Out of equilibrium for: \( T > T_{\text{eq}} \) or for \( T < T_{\text{decay}} \)

If \( T_{\text{eq}} > T_{\text{sph}} \)

Decays of Right-handed Majorana fermions occur for period of active Sphaleron processes

Thermal Leptogenesis

Fukugita, Yanagida,
Thermal Leptogenesis

Heavy Right-handed Majorana neutrinos enter equilibrium at $T = T_{eq}$.
Thermal Leptogenesis

Heavy Right-handed Majorana neutrinos enter equilibrium at $T = T_{\text{eq}}$

Independent of Initial Conditions @ $T >> T_{\text{eq}}$
Heavy Right-handed Majorana neutrinos enter equilibrium at $T = T_{eq} > T_{\text{decay}}$

Lepton number Violation

$N_I \rightarrow H\nu, \bar{H}\bar{\nu}$

Out of Equilibrium Decays

$T \simeq T_{\text{decay}} > T_{sph}$

Produce Lepton asymmetry

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov
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Produce Lepton asymmetry

Equilibrated electroweak $B+L$ violating sphaleron interactions

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov
Heavy Right-handed Majorana neutrinos enter \textit{equilibrium} at \( T = T_{eq} > T_{\text{decay}} \).

$\frac{N_I}{H} \rightarrow \text{Out of Equilibrium Decays}$

\[
L = \frac{2}{M} l_L l_L \phi \phi + \text{H.c.}
\]

where

\[
l_L = \begin{pmatrix}
\nu_e \\
e \\
\nu_\mu \\
\mu \\
\nu_\tau \\
\tau
\end{pmatrix}
\]

\textit{Equilibrated electroweak B+L violating sphaleron interactions}

\textit{Baryon asymmetry in the Universe (BAU)}

\textit{Independent of Initial Conditions @ $T >> T_{eq}$}

\textit{Thermal Leptogenesis}
Heavy Right-handed Majorana neutrinos enter equilibrium at $T = T_{eq} > T_{\text{decay}}$

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Produce Lepton asymmetry

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Independent of Initial Conditions

Observed Baryon Asymmetry In the Universe (BAU)

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov
**Thermal Leptogenesis**

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Produce Lepton asymmetry

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Independent of Initial Conditions

Observed Baryon Asymmetry In the Universe (BAU)

Estimate BAU by solving Boltzmann equations for Heavy Neutrino Abundances

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov

Pilafsis, Buchmuller, di Bari et al.
Predicted BAU in such models is found to be of order:

\[ \frac{n_B}{n_\gamma} = \Delta \sim \frac{1}{g_{\text{eff}}} \delta_{CP} \cdot S_{\text{macro}} S_{\text{sph}}, \]

\[ \delta_{CP} = \frac{\Gamma(N \rightarrow H\nu) - \Gamma(N \rightarrow \bar{H}\bar{\nu})}{\Gamma_{\text{tot}}} \]

Pilaftsis, Shaposhnikov…

Majorana fermion
Kinematics

Sphaleron effects L -> B

\[ S_{\text{macro}} S_{\text{sph}} \sim \mathcal{O} \left( \frac{1}{10} \right) \]
Predicted BAU in such models is found to be of order:

\[ Pilaftsis, Shaposhnikov... \]

Non mass degenerate Majorana neutrinos

\[ |M_I - M_J| \sim M_K \]
\[ \frac{n_B}{s} \sim 10^{-3} F^2 \sim 10^{-10} \]

\[ F^2 \sim 10^{-7} \]

reproduced observed BAU

\[ \frac{n_B}{n_\gamma} = \Delta \sim \frac{1}{g_{\text{eff}}} \delta_{CP} \cdot S_{\text{macro}} S_{\text{sph}}, \]

\[ \delta_{CP} = \frac{\Gamma(N \rightarrow H\nu) - \Gamma(N \rightarrow \bar{H}\bar{\nu})}{\Gamma_{\text{tot}}} \]
\[ S_{\text{macro}} S_{\text{sph}} \sim \mathcal{O} \left( \frac{1}{10} \right) \]
Predicted BAU in such models is found to be of order:

Non mass degenerate Majorana neutrinos

\[
\frac{n_B}{s} \sim 10^{-3} F^2 \sim 10^{-10}
\]

\[
F^2 \sim 10^{-7}
\]

\[m_\nu = -M_D^T \frac{1}{M_I} [M_D]^T\]

\[M_D = F_{\alpha I} \nu\]

\[\nu = \langle \phi \rangle = 174 \text{ GeV}\]

\[M_N \sim 10^{11} \text{ GeV}\]
Predicted BAU in such models is found to be of order:

Non mass degenerate Majorana neutrinos

\[ \frac{n_B}{s} \sim 10^{-3} F^2 \approx 10^{-10} \]

\[ F^2 \sim 10^{-7} \]

reproduced observed BAU

\[ m_\nu = -M_D \frac{1}{M_I} [M_D]^T \]

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Non mass degenerate Majorana neutrinos

Stability of Higgs mass against higher loops in danger!

reproduced observed BAU

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\[ m_{\nu} = -M_D \frac{1}{M_I} [M_D]^T \]
\[ M_D = F_{\alpha I} \nu \]
\[ \nu = \langle \phi \rangle = 174 \text{ GeV} \]

Non mass degenerate Majorana neutrinos

Stability of Higgs mass against higher loops in danger!

e.g. one loop

\[ F^2 M_I^2 / (4\pi) \sim 10^{14} \text{ GeV}^2 \]

reproduced observed BAU

\[ M_N \sim 10^{11} \text{ GeV} \]
POSSIBLE RESOLUTION: DEGENERATE RIGHT-HANDED NEUTRINOS

If, say: $N_2, N_3$ degenerate in mass

enhanced CP violation
contribution from mixing
(cf. neutral kaons)

but much smaller Yukawa
 couplings $F$ allowed

BAU estimated in this case:

\[
\frac{n_B}{s} \sim 10^{-3} f^2 \frac{M_2 \Gamma_{\text{tot}}}{(M_2 - M_3)^2 + \Gamma_{\text{tot}}^2}
\]

\[
|M_2 - M_3| \sim \Gamma_{\text{tot}}
\]

\[
\frac{|M_2 - M_3|}{M_2} \sim f^2 \sim \frac{m_\nu M_W}{v^2} \sim 10^{-13}
\]

$M_I \sim M_W$
POSSIBLE RESOLUTION: DEGENERATE RIGHT-HANDED NEUTRINOS

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\]

\[M_I \sim M_W\]

\[|M_2 - M_3| \sim \Gamma_{\text{tot}}\]

NB: For \( M_I < 10^7 \) GeV

no Problem for Higgs mass stability
A restricted Case: \( N_1 \) only out of equilibrium decay
\( N_{2,3} \) in thermal equilibrium

**Resonant \( \tau \) Leptogenesis**

*One lepton number (\( \tau \)) resonantly produced by out-of-equilibrium decays*

\[
-L_{Y,M} = \frac{1}{2} (\bar{\nu}_i R)^c (M_S)_{ij} \nu_j R + \hat{h}^l_{ii} \bar{L}_i \Phi l_{iR} + h^\nu_{ij} \bar{L}_i \Phi \nu_{jR} + \text{H.c.,}
\]

\[
h^\nu_R = \begin{pmatrix}
\varepsilon_e & ae^{-i\pi/4} & ae^{i\pi/4} \\
\varepsilon_\mu & be^{-i\pi/4} & be^{i\pi/4} \\
\varepsilon_\tau & ce^{-i\pi/4} & ce^{i\pi/4}
\end{pmatrix}.
\]
A restricted Case: $N_1$ only out of equilibrium decay
$N_{2,3}$ in thermal equilibrium

Resonant $\tau$ Leptogenesis

One lepton number ($\tau$) resonantly produced by out-of-equilibrium decays

\[ -\mathcal{L}_{Y,M} = \frac{1}{2} (\bar{\nu}_{iR})^c (M_S)_{ij} \nu_{jR} + \hat{h}_{ii} \bar{\nu}_i \Phi l_{iR} \\
+ h^{\nu_R}_{ij} \bar{L}_i \Phi \nu_{jR} + \text{H.c.}, \]

\[ h^{\nu_R} = \begin{pmatrix} \varepsilon_e & ae^{-i\pi/4} & ae^{i\pi/4} \\ \varepsilon_\mu & be^{-i\pi/4} & be^{i\pi/4} \\ \varepsilon_\tau & ce^{-i\pi/4} & ce^{i\pi/4} \end{pmatrix}. \]
A restricted Case: $N_1$ only out of equilibrium decay. $N_{2,3}$ in thermal equilibrium.

Avoid $L_\tau$ excess $\rightarrow$ $N_{2,3}$ decay rates suppressed.

$$-\mathcal{L}_{Y,M} = \frac{1}{2} (\bar{\nu}_R^c)(M_S)_{ij} \nu_{jR} + h^l_{ii} \bar{L}_i \Phi l_{iR}$$

$$+ h_{ij}^{\nu_R} \bar{L}_i \Phi \nu_{jR} + \text{H.c.},$$

$$h^{\nu_R} = \begin{pmatrix}
\epsilon_e & ae^{-i\pi/4} & ae^{i\pi/4} \\
\epsilon_\mu & be^{-i\pi/4} & be^{i\pi/4} \\
\epsilon_\tau & ce^{-i\pi/4} & ce^{i\pi/4}
\end{pmatrix}.$$
A restricted Case: $N_1$ only out of equilibrium decay $N_{2,3}$ in thermal equilibrium

Avoid $\Lambda_\tau$ excess $\Rightarrow$ $N_{2,3}$ decay rates suppressed

Predicted BAU

$$\eta_B \sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\Gamma(N_1 \rightarrow L_\tau \Phi)}{\Gamma(N_{2,3} \rightarrow L_\tau \Phi)}$$

$$\sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\varepsilon_\tau^2}{c^2}$$

$$\frac{\Gamma_{N_1}}{H(z = 1)} \approx 10$$

Resonant $\tau$ Leptogenesis

$$-\mathcal{L}_{Y,M} = \frac{1}{2} (\tilde{\nu}_{iR})^c (M_S)_{ij} \nu_{jR} + h_{ii}^l \tilde{L}_i \Phi \Phi_{iR} + \text{H.c.}$$

$$h_{ij}^\nu \tilde{L}_i \tilde{\Phi} \nu_{jR} + \text{H.c.},$$

$$h_{ij}^\nu = \begin{pmatrix} \varepsilon_e & ae^{-i\pi/4} & ae^{i\pi/4} \\ \varepsilon_\mu & be^{-i\pi/4} & be^{i\pi/4} \\ \varepsilon_\tau & ce^{-i\pi/4} & ce^{i\pi/4} \end{pmatrix}.$$
A restricted Case: $N_1$ only out of equilibrium decay 
$N_{2,3}$ in thermal equilibrium

Avoid $L_\tau$ excess \[\Rightarrow\] $N_{2,3}$ decay rates suppressed

Predicted BAU

\[\eta_B \sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\Gamma(N_1 \rightarrow L_\tau \Phi)}{\Gamma(N_{2,3} \rightarrow L_\tau \Phi)} \]
\[\sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\epsilon_\tau^2}{c^2} \]
\[\Gamma_{N_1}/H(z = 1) \approx 10 \]

Resonant $\tau$ Leptogenesis

\[-\mathcal{L}_{Y,M} = \frac{1}{2} (\bar{\nu}_{iR})^c (M_S)_{ij} \nu_{jR} + \hat{h}_{ii}^L \bar{L}_i \Phi l_{iR} \]
\[+ h_{ij}^\nu \bar{L}_i \Phi \nu_{jR} + \text{H.c.,} \]

\[h_{ij}^\nu = \begin{pmatrix} \epsilon_e & ae^{-i\pi/4} & ae^{i\pi/4} \\ \epsilon_\mu & be^{-i\pi/4} & be^{i\pi/4} \\ \epsilon_\tau & ce^{-i\pi/4} & ce^{i\pi/4} \end{pmatrix} .\]
A restricted Case: $N_1$ only out of equilibrium decay $N_{2,3}$ in thermal equilibrium

Avoid $L_\tau$ excess $\Rightarrow$ $N_{2,3}$ decay rates suppressed

Predicted BAU

\[
\eta_B \sim -10^{-2} \frac{\delta^\tau_{N_1}}{K_{N_1}} \frac{\Gamma(N_1 \rightarrow L_\tau \Phi)}{\Gamma(N_{2,3} \rightarrow L_\tau \Phi)} \approx 10
\]

$|\delta^\tau_{N_1}| \sim 10^{-5}$ and $\varepsilon_\tau/c \sim 10^{-2}$

Resonant $\tau$ Leptogenesis

Pilaftsis
A restricted Case: $N_1$ only out of equilibrium decay
$N_{2,3}$ in thermal equilibrium

Avoid $L_\tau$ excess $\Rightarrow$ $N_{2,3}$ decay rates suppressed

Predicted BAU

$$\eta_B \sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\Gamma(N_1 \rightarrow L_\tau \Phi)}{\Gamma(N_{2,3} \rightarrow L_\tau \Phi)}$$

$$\sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \epsilon_{\tau}^2 \frac{c^2}{c^2}$$

$$|\delta_{N_1}^\tau| \sim 10^{-5} \text{ and } \epsilon_{\tau}/c \sim 10^{-2}$$

Estimate agrees with:

Boltzmann eq calculated neutrino $N_1$ abundance
A restricted Case: $N_1$ only out of equilibrium decay, $N_{2,3}$ in thermal equilibrium

Avoid $L_\tau$ excess $\implies$ $N_{2,3}$ decay rates suppressed

Predicted BAU

$$\eta_B \sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\Gamma(N_1 \rightarrow L_\tau \Phi)}{\Gamma(N_{2,3} \rightarrow L_\tau \Phi)}$$

$$\sim -10^{-2} \frac{\delta_{N_1}^\tau}{K_{N_1}} \frac{\varepsilon_{\tau}^2}{c^2}$$

$$\bar{\Gamma}_{N_1}/H(z = 1)$$

$z = m_{N_1}/T$

$$|\delta_{N_1}^\tau| \sim 10^{-5} \text{ and } \varepsilon_{\tau}/c \sim 10^{-2}$$

Resonant $\tau$ Leptogenesis

Pilaftsis Underwood

Leptogenesis possible for low-mass $N_i$: $M_N = O(M_W \text{ - TeV})$
A restricted Case: $N_1$ only out of equilibrium decay
$N_{2,3}$ in thermal equilibrium

Predicted BAU

$M_N = O(M_W - \text{TeV})$

Resonant $\tau$ Leptogenesis

Pilaftsis
Underwood

$\mu \rightarrow e \gamma$

$B(\mu \rightarrow e \gamma) \approx 6 \times 10^{-4} (a^2 b^2 v^4)/m_N^4$

$a, b \sim 3 \times 10^{-3}$

future sensitivity to $10^{-13}$

MEG experiment:

$\mu^+ \rightarrow e^+ + \gamma$

$B(\mu^+ \rightarrow e^+ + \gamma) \leq 2.4 \times 10^{-12}$

1107.5547

$B(\mu^+ \rightarrow e^+ + \gamma) \leq 2.4 \times 10^{-12}$
A restricted Case: $N_1$ only out of equilibrium decay $N_{2,3}$ in thermal equilibrium

Predicted BAU

$$M_N = O(M_W - \text{TeV})$$

$$B(\mu \rightarrow e\gamma) \approx 6 \times 10^{-4} (a^2 b^2 v^4)/m_N^4$$

$$a, b \sim 3 \times 10^{-3}$$

$$B_{\text{exp}}(\mu \rightarrow e\gamma) \leq 1.2 \times 10^{-11}$$

Future sensitivity to $10^{-13}$

Resonant $\tau$ Leptogenesis

Pilaftsis
Underwood

Effects at $e^+e^-$ linear collider? Study production of electroweak scale $N_{2,3}$ via their decays to $e, \mu$ (not $\tau$)
Boltzmann equations are classical phase space equations, time evolution of phase space distribution functions \( f(p,x,t) \):

\[
\frac{d}{dt} n + 3Hn = C[f],
\]

\[
\int d^3p f(p,x,t) = n
\]

*But*: Collision terms \( C[f] \) on the r.h.s. are quantum effects involving loop corrected cross sections (particularly in Leptogenesis).

Buchmuller, Di Bari, Plumacher (2002)
Can calculate directly Heavy $\nu$ abundances by using non-equilibrium field theory Schwinger-Keldysh formalism & Kadanoff-Baym (KB) equations, based on Green’s functions, not on densities

Result: Conventional Boltzmann eqs. for Lepton asymmetry give pretty good agreement with quantum field theory treatments when SM gauge interactions are taken into account

Anisimov, Bucmueller, Drewes, Mendizabal arXiv:1012582
Can calculate directly Heavy ν abundances by using non-equilibrium field theory Schwinger-Keldysh formalism & Kadanoff-Baym (KB) equations, based on Green’s functions, not on densities

Result: Conventional Boltzmann eqs. for Lepton asymmetry give pretty good agreement with quantum field theory treatments when SM gauge interactions are taken into account
Two distinct physics cases: $M_i > M_w$ & $M_i < M_w$
Thermal Properties

Two distinct physics cases: $M_i > M_W$ & $M_i < M_W$

(i) $M_i < M_W$  (electroweak scale), e.g. $M_i = O(1) \text{ GeV}$

Keep light neutrino masses in right order, Yukawa couplings must be:

$$F_{\alpha I} \sim \frac{\sqrt{m_{\text{atm}} M_i}}{v} \sim 4 \times 10^{-8}.$$

Baryogenesis through coherent oscillations right-handed singlet fermions

Akhmedov, Rubakov, Smirnov
Heavy Majorana fermions $N_i$ thermalize only for $T < M_W$

Out of Equilibrium decays of $N_i$ for $T > M_W$

BAU depends in this case on initial conditions

But at the end of inflation we may reasonably assume that the $N_i$ populations are washed out, hence set their end-of-inflation concentrations to zero value

Majorana masses small compared to Sphaleron freeze-out $T$

Total Lepton number conserved

Assume Mass generacy $N_{2,3}$ enhanced CP violation

Coherent Oscillations between these singlet fermions

Lepton number of active left-handed $\nu$ transferred to Baryons due to equilibrated sphaleron processes
BAU ESTIMATES

Assume *Mass degeneracy* $N_{2,3}$, hence enhanced CP violation

*Coherent Oscillations* between these singlet fermions

$$\omega \sim \frac{|M_2^2 - M_3^2|}{E_I} \sim \frac{M_2 \Delta M(T)}{T}$$

$$E_I \sim T$$

$$\Delta M(T) \ll M_2 \approx M_3$$

$N_2 - N_3$ MASS DIFF.
Assume *Mass degeneracy* $N_{2,3}$, hence enhanced CP violation *Coherent Oscillations* between these singlet fermions.

\[ \omega \sim \frac{|M_2^2 - M_3^2|}{E_I} \sim \frac{M_2 \Delta M(T)}{T} \]

\[ E_I \sim T \]
\[ \Delta M(T) \ll M_2 \approx M_3 \]

**BAU ESTIMATES**

FOR CP VIOLATION TO OCCUR MUST HAVE: Oscillation rate $> \text{Hubble rate} \ H(T)$

**Baryogenesis occurs @:**

\[ T_B \sim \left( M_I \Delta M(T) M_0 \right)^{1/3} \]

eg $O(100) \ \text{GeV}$

Quite effective Mechanism: Maximal Baryon asymmetry

\[ \Delta \equiv \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \approx 1 \]

for $T_B = T_{\text{sph}} = T_{\text{eq}}$

**Assumption:** Interactions with plasma of SM particles do not destroy quantum mechanical coherence of oscillations
Assume **Mass degeneracy** $N_{2,3}$, hence enhanced CP violation **Coherent Oscillations** between these singlet fermions.

\[
\omega \sim \frac{|M_2^2 - M_3^2|}{E_I} \sim \frac{M_2 \Delta M(T)}{T}
\]

\[
E_I \sim T \\
\Delta M(T) \ll M_2 \approx M_3
\]

**BAU ESTIMATES**

For CP violation to occur must have: Oscillation rate $>\ $Hubble rate $H(T)$

**Baryogenesis occurs @:**

\[
T_B \sim \left( M_I \Delta M(T) M_0 \right)^{1/3}
\]

\[
\frac{n_B}{s} \approx 1.7 \cdot 10^{-10} \delta_{CP} \left( \frac{10^{-5}}{\Delta M(T)/M_2} \right)^{2/3} \left( \frac{M_2}{10 \text{ GeV}} \right)^{5/3}
\]

\[
\delta_{CP} = 4 s_{R23} c_{R23} \left[ s_{L12} s_{L13} c_{L13} (c_{L23}^4 + s_{L23}^4) c_{L13}^2 - s_{L13}^2 \right] \cdot \sin(\delta_L + \alpha_2)
\]

\[
+ c_{L12} c_{L13}^3 s_{L23} c_{L23} (c_{L23}^2 - s_{L23}^2) \cdot \sin \alpha_2
\]

eg $O(100)$ GeV
BAU ESTIMATES

Assume *Mass degeneracy* $N_{2,3}$, hence enhanced CP violation

*Coherent Oscillations* between these singlet fermions

\[ \omega \sim \frac{|M_2^2 - M_3^2|}{E_I} \sim \frac{M_2 \Delta M(T)}{T} \]

\[ E_I \sim T \]

\[ \Delta M(T) \ll M_2 \approx M_3 \]

FOR CP VIOLATION TO OCCUR MUST HAVE: Oscillation rate $> Hubble$ rate $H(T)$

**Baryogenesis occurs @:**

\[ T_B \sim \left( M_1 \Delta M(T) M_0 \right)^{1/3} \]

\[ \frac{n_B}{s} \approx 1.7 \cdot 10^{-10} \delta_{CP} \left( \frac{10^{-5}}{\Delta M(T)/M_2} \right)^{2/3} \left( \frac{M_2}{10 \text{ GeV}} \right)^{5/3} \]

\[
\text{Mass } N_2 (N_3) / \text{(Mass } N_1) = O(10^5)
\]

*N₁ Lightest Sterile nutrino is a natural DARK MATTER candidate*
NEUTRINOS & THE DARK SECTOR OF THE UNIVERSE
Current Energy Budget of the Cosmos

Observations from:

- Supernovae Ia
- CMB
- Baryon Acoustic Oscillations
- Galaxy Surveys
- Structure Formation data
- Strong & Weak lensing

Active $\nu$
TYPES OF DARK MATTER

• **HOT DARK MATTER (HDM):** form of dark matter which consists of particles that travel with ultrarelativistic velocities: e.g. neutrinos

• **COLD DARK MATTER (CDM):** form of dark matter consisting of slowly moving particles, hence cold,
  - e.g. WIMPS (stable supersymmetric particles (neutralinos etc.) or MACHOS.

• **WARM DARK MATTER (WDM):** form of dark matter with properties between those of HDM and CDM, sterile neutrinos, light gravitinos-partner of gravitons in supergravity theories….)
PHYSICS: WMAP and Dark Matter

WMAP results so far:

- Disfavor strongly hot dark matter (neutrinos), $\Omega_\nu h^2 < 0.0076$ ($< m_\nu > e < 0.23$ eV).

- Warm Dark Matter (gravitino) disfavoured by evidence for re-ionization at redshift $z \sim 20$.

- Cold Dark Matter (CDM) remains: axions, supersymmetric dark matter (lightest SUSY particle (LSP)), superheavy (masses $\sim 10^{14\pm 5}$ GeV)

WMAP results: $\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$ (matter), $\Omega_b h^2 = 0.0224 \pm 0.0009$ (baryons), hence, assuming CDM is the difference, $\Omega_{CDM} h^2 = 0.1126^{+0.0161}_{-0.0181}$, (2$\sigma$ level).
**WMAP excludes WARM Dark Matter**

Numerical simulations for structure formation in Cold Dark Matter (CDM) (top) and Warm Dark Matter (WDM) (middle) with mass $m_X = 10$ KeV at $z = 20$. **Bottom:** Dark halos with mass $> 10^5 M_\odot$ for CDM (left) and for WDM (right).

**IMPORTANT COMMENTS:**

Such structure formation arguments can only place a lower bound on mass of the WDM candidate: $m_X > 10$ KeV.

Above results exclude Light Gravitino Models ($m_X < 0.5 KeV$) of Particle Physics as DM candidates.  
**NB!** WDM with $m_X \geq 100$ KeV becomes indistinguishable from Cold Dark Matter, as far as structure formation is concerned.
Contribution of neutrinos to energy density of Universe: \( \Omega_\nu h^2 = \frac{\sum_i m_i}{94.0 \text{ eV}} \) (sum over light neutrino species (decouple while still relativistic)).

WMAP and other experiments (the Lyman \( \alpha \) data etc) \( \Omega_\nu h^2 < 0.0076 \Rightarrow < m_\nu >_e < 0.23 \text{ eV} \):

Excludes HOT DM.

NB: WMAP still consistent with Majorana neutrinos, and also marginally with \( \beta\beta \)-decay (Heidelberg-Moscow Coll.).
Contribution of neutrinos to energy density of Universe: \( \Omega_\nu h^2 = \frac{\sum_i m_i}{94.0 \text{ eV}} \)

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<table>
<thead>
<tr>
<th>Model</th>
<th>Observables</th>
<th>$\Sigma m_\nu$ (eV) 95% Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega CDM + \Delta N_{\text{rel}} + m_\nu$</td>
<td>CMB+HO+SN+BAO</td>
<td>$\leq 1.5$</td>
</tr>
<tr>
<td>$\omega CDM + \Delta N_{\text{rel}} + m_\nu$</td>
<td>CMB+HO+SN+LSSPS</td>
<td>$\leq 0.76$</td>
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<td>$\Lambda CDM + m_\nu$</td>
<td>CMB+H0+SN+BAO</td>
<td>$\leq 0.61$</td>
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<tr>
<td>$\Lambda CDM + m_\nu$</td>
<td>CMB+H0+SN+LSSPS</td>
<td>$\leq 0.36$</td>
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<tr>
<td>$\Lambda CDM + m_\nu$</td>
<td>CMB (+SN)</td>
<td>$\leq 1.2$</td>
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<td>$\Lambda CDM + m_\nu$</td>
<td>CMB+BAO</td>
<td>$\leq 0.75$</td>
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<td>CMB+LSSPS</td>
<td>$\leq 0.55$</td>
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<tr>
<td>$\Lambda CDM + m_\nu$</td>
<td>CMB+H0</td>
<td>$\leq 0.45$</td>
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## COMBINE COSMO-DATA & OSCILLATIONS

<table>
<thead>
<tr>
<th>Model</th>
<th>Observables</th>
<th>$m_{\nu_e}$ (eV)</th>
<th>$m_{ee}$ (eV)</th>
<th>$\Sigma m_\nu$ (eV)</th>
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</thead>
<tbody>
<tr>
<td>$\omega$CDM + $\Delta N_{rel} + m_\nu$</td>
<td>CMB+HO+SN+BAO</td>
<td>N [0.0047 – 0.51]</td>
<td>I [0.047 – 0.51]</td>
<td>N [0.00 – 0.51]</td>
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<tr>
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<td>N [0.0047 – 0.27]</td>
<td>I [0.047 – 0.27]</td>
<td>N [0.00 – 0.25]</td>
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<td>$\Lambda$CDM + $m_\nu$</td>
<td>CMB+H0+SN+BAO</td>
<td>N [0.0047 – 0.20]</td>
<td>I [0.048 – 0.21]</td>
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<td>CMB+H0+SN+LSSSP</td>
<td>N [0.0047 – 0.12]</td>
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<td>N [0.00 – 0.12]</td>
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<tr>
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<td>CMB (+SN)</td>
<td>N [0.0047 – 0.40]</td>
<td>I [0.047 – 0.40]</td>
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<td>I [0.047 – 0.16]</td>
<td>N [0.00 – 0.14]</td>
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</tbody>
</table>

Gonzalez-Garcia, Maltoni, Slavado, 1008.3795
Contribution of neutrinos to energy density of Universe: $\Omega_\nu h^2 = \frac{\sum_i m_i}{94.0 \text{ eV}}$ (sum over light neutrino species (decouple while still relativistic)).

WMAP and other experiments (the Lyman $\alpha$ data etc) $\Omega_\nu h^2 < 0.0076 \Rightarrow < m_\nu > < 0.23 \text{ eV}$:

Excludes HOT DM.

Model dependence...

NB: WMAP still consistent with Majorana neutrinos, and also marginally with $\beta\beta$-decay (Heidelberg-Moscow Coll.).
**Caution:**
FRW- Comology & local Lorentz invariance **assumed**.
If Lorentz violated (TeVeS) ν of 2 eV mass could have \( \Omega_\nu \sim 0.15 \) to reproduce CMB spectrum (Dodelson-Liguori 2006)

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**BUT…TeVeS excluded by Gravitational Lensing Data (Sakellariadou, Yusaf, NEM)**

Contribution of neutrinos to energy density of Universe: 
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Light Sterile Neutrinos (mass > KeV) may provide good dark Matter Candidates

To be DM: life time > age of Universe

Davidson, Widrow, Shi, Fuller, Dolgov, Hansen, Abazajian, Patel, Tucker …
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Sterile neutrinos and DARK MATTER

Lightest of singlet fermions $N_1$ plays that role

Coupling with SM matter: superweak

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$\theta_1 \lesssim 1.8 \times 10^{-5} \left(\frac{\text{keV}}{M_1}\right)^5$
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Boyarski, Ruchayskiy, Shaposhnikov…

**vMSM**

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\[ \theta_1^2 \lesssim 1.8 \times 10^{-5} \left( \frac{\text{keV}}{M_1} \right)^5, \]

Contributions to mass matrix of active neutrinos

$$\delta m_\nu \sim \theta_1^2 M_1$$
Light Sterile Neutrinos (mass > KeV) may provide good dark Matter Candidates

Boyarski, Ruchayskiy, Shaposhnikov…

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vMSM

Boyarski, Ruchayskiy, Shaposhnikov...

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$M_1 \geq 2KeV \Rightarrow$

mass contribution smaller than solar mass diff experimental error

Contributions to mass matrix of active neutrinos

$\delta m_{\nu} \sim \theta_1^2 M_1$

$\theta_1^2 \lesssim 1.8 \times 10^{-5} \left( \frac{\text{keV}}{M_1} \right)^5$
More than one sterile neutrino needed to reproduce Observed oscillations

\( \nu_{MSM} \)

Boyarski, Ruchayskiy, Shaposhnikov...

Constraints on two heavy degenerate singlet neutrinos

\( N_1 \) DM production estimation in Early Universe must take into account its interactions with \( N_{2,3} \) heavy neutrinos

X-ray constraints \( \tau > 10^{-24} \text{ s} \)

BBN \( \tau < 0.1 \text{ s} \)
More than one sterile neutrino needed to reproduce Observed oscillations

Decaying $N_1$ produces narrow spectral line in spectra of DM dominated astrophysical objects

$vMSM$

Constraints on two heavy degenerate singlet neutrinos

$N_1$ DM production estimation in Early Universe must take into account its interactions with $N_{2,3}$ heavy neutrinos
More than one sterile neutrino needed to reproduce Observed oscillations

$\nu_{\text{MSM}}$

Boyarski, Ruchayskiy, Shaposhnikov…

Constraints on two heavy degenerate singlet neutrinos

$N_1$ DM production estimation in Early Universe must take into account its interactions with $N_{2,3}$ heavy neutrinos
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS

$\Omega_{N_1} > \Omega_{DM}$

$\sin^2(2\theta_1)$ vs $M_1$ (keV)

X-ray constraints

BBN limit: $L_6^{BBN} = 2500$

$\Omega_{N_1} < \Omega_{DM}$
MASS HIERARCHY ($N_1 << N_{2,3}$) AMONG STERILE NEUTRINOS

PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?
MASS HIERARCHY \((N_1 \ll N_{2,3})\) AMONG STERILE NEUTRINOS

PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

(I) **FLAVOUR SYMMETRIES**:

\[ M_1 = 0 \text{ if symmetry unbroken,} \]

Breaking of global Lepton symmetry generate singlet fermion mass hierarchy

\[ M_2 \approx M_3 \gg \text{GeV} \]

\[ M_2 \gg \text{GeV} \]

\[ L_e - L_\mu - L_\tau \]

\[ L_e \gg L_\mu \gg L_\tau \]

\[ M_1 \sim \text{keV} \]

\[ M_1 = 0 \]

Shaposhnikov Lindner, Merle, Niro

e.g. GUT models

Mohapatra, Senjanovic, Ross…
BRANE WORLD RANDALL-SUNDRUM MODELS: Exponential Mass Suppression

MASS HIERARCHY \((N_1 \ll N_{2,3})\) AMONG STERILE NEUTRINOS

PHENOMENOLOGICAL...

MICROSCOPIC EXPLANATIONS?

(II) Kushenko, Takahashi, Yanagida

Shadow world

Our Brane world

\[ M_1 \sim \frac{2m_i}{e^2m_i^2 - 1} \]

\[ M_2 \sim 10^{11} \text{GeV} \]

\[ M_3 > M_2 \]

\[ M_1 \sim \text{keV} \]
One fermion acquires mass via Higgs mechanism, others via higher order multiple see-saw

\[ L_{\text{leptons}} = -Y_{e}^{ij} e_{iR} H L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{k_{i}+f_{j}} + \text{h.c.} - Y_{D}^{ij} N_{iR} \tilde{H} L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{g_{i}+f_{j}} + \text{h.c.} \]

\[ -\frac{1}{2} N_{iR} \tilde{M}_{R}^{ij} (N_{jR})^{C} \left( \frac{\Theta}{\Lambda} \right)^{g_{i}+g_{j}} + \text{h.c.} - \frac{1}{2} Y_{L}^{ij} (L_{iL})^{C} (i\sigma_{2}\Delta) L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{f_{i}+f_{j}} + \text{h.c.} \]
FROGATT – NIelsen mechanism: One fermion acquires mass via Higgs mechanism, others via higher order multiple see-saw

\[ \mathcal{L}_{\text{leptons}} = -Y_{e}^{ij} \overline{e_{iR}} H L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{k_{i}+f_{j}} + \text{h.c.} - Y_{D}^{ij} \overline{N_{iR}} \tilde{H} L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{g_{i}+f_{j}} + \text{h.c.} \]

\[-\frac{1}{2} \overline{N_{iR}} \tilde{M}_{R} \left( N_{jR} \right) \left( \frac{\Theta}{\Lambda} \right)^{g_{i}+g_{j}} + \text{h.c.} - \frac{1}{2} Y_{L}^{ij} \overline{(L_{iL})^{C}} (i\sigma_{2}\Delta) L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{f_{i}+f_{j}} + \text{h.c.} \]

``Flavon'' field \[ \langle \Theta \rangle \]

\[ \lambda = \frac{\langle \Theta \rangle}{\Lambda} \] being a small quantity of the order of the Cabibbo angle: \[ \lambda \approx 0.22 \]
MASS HIERARCHY \( (N_1 << N_{2,3}) \) AMONG STERILE NEUTRINOS

PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

(III) FROGATT – NIELSEN MECHANISM:

One fermion acquires mass via
Higgs mechanism, others via
higher order multiple see-saw

\[
L_{\text{leptons}} = -Y^{ij}_{e} e^{iR} H L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{k_i+f_j} + \text{h.c.} - Y^{ij}_{D} \bar{N}_{iR} \tilde{H} L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{g_i+f_j} + \text{h.c.} - \frac{1}{2} \bar{N}_{iR} \tilde{M}^{ij}_R (N_{jR})^C \left( \frac{\Theta}{\Lambda} \right)^{g_i+g_j} + \text{h.c.} - \frac{1}{2} Y^{ij}_{L} (L_{iL})^C (i\sigma_2\Delta) L_{jL} \left( \frac{\Theta}{\Lambda} \right)^{f_i+f_j} + \text{h.c.}
\]
MASS HIERARCHY (N₁ << N₂,₃) AMONG STERILE NEUTRINOS

PHENOMENOLOGICAL…

**MICROSCOPIC EXPLANATIONS?**

(III) FROGATT – NIELSEN MECHANISM:
One fermion acquires mass via Higgs mechanism, others via higher order multiple see-saw

MASS MATRICES

Charged lepton

\[
M_e = v \begin{pmatrix}
Y_{e11} \lambda^{k_1+f_1} & Y_{e12} \lambda^{k_1+f_2} & Y_{e13} \lambda^{k_1+f_3} \\
Y_{e21} \lambda^{k_2+f_1} & Y_{e22} \lambda^{k_2+f_2} & Y_{e23} \lambda^{k_2+f_3} \\
Y_{e31} \lambda^{k_3+f_1} & Y_{e32} \lambda^{k_3+f_2} & Y_{e33} \lambda^{k_3+f_3}
\end{pmatrix}
\]

Dirac neutrino

\[
m_D = v \begin{pmatrix}
Y_{D11} \lambda^{g_1+f_1} & Y_{D12} \lambda^{g_1+f_2} & Y_{D13} \lambda^{g_1+f_3} \\
Y_{D21} \lambda^{g_2+f_1} & Y_{D22} \lambda^{g_2+f_2} & Y_{D23} \lambda^{g_2+f_3} \\
Y_{D31} \lambda^{g_3+f_1} & Y_{D32} \lambda^{g_3+f_2} & Y_{D33} \lambda^{g_3+f_3}
\end{pmatrix}
\]

Merle Niro
Barry, Rodejohann, Zhang
MASS HIERARCHY \((N_1 \ll N_{2,3})\) AMONG STERILE NEUTRINOS

PHENOMENOLOGICAL…

**MICROSCOPIC EXPLANATIONS?**

(III) **FROGATT – NIELSEN MECHANISM**:  
*One fermion acquires mass via Higgs mechanism, others via higher order multiple see-saw*

**MASS MATRICES**

<table>
<thead>
<tr>
<th>Field</th>
<th>(L_{iL})</th>
<th>(e_{iR})</th>
<th>(N_{iR})</th>
<th>(H)</th>
<th>(\Delta)</th>
<th>(\Theta)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>U(1)(_FN)</td>
<td>(f_i)</td>
<td>(k_i)</td>
<td>(g_i)</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

\[ M_R = \begin{pmatrix} M_{11} & M_{12} & M_{13} \\ M_{22} & M_{22} & M_{23} \\ M_{33} & M_{33} & M_{33} \end{pmatrix} \]

\[ m_\nu = -m_D^T M_R^{-1} m_D = \begin{pmatrix} a_1 \lambda |f_1|^2 & b_1 \lambda |f_1+f_2|^2 & c_1 \lambda |f_1+f_3|^2 \\ d_1 \lambda |f_2|^2 & e_1 \lambda |f_2+f_3|^2 & f_1 \lambda |f_3|^2 \end{pmatrix} \]

Right-handed Neutrino sector then via see-saw
MASS HIERARCHY \((N_1 \ll N_{2,3})\) AMONG STERILE NEUTRINOS

Phenomenological… Microscopic Explanations?

FROGATT-NIELSEN MECHANISM:

One fermion acquires mass via Higgs mechanism, others via higher order multiple see-saw.

\[ \lambda = 0.22 \]

\[
M_R = \begin{pmatrix}
M^{11}_{R} & \cdots & M^{12}_{R} \\
\vdots & \ddots & \vdots \\
M^{13}_{R} & \cdots & M^{13}_{R}
\end{pmatrix}
\]

\[
m^I_\nu = -m^T_D M^{-1}_R m_D = \begin{pmatrix}
a_1 \lambda |^{2f_1|} & b_1 \lambda |^{f_1+f_2|} & c_1 \lambda |^{f_1+f_3|} \\
\vdots & \ddots & \vdots \\
\vdots & \ddots & \ddots \\
\end{pmatrix}
\]

Right-handed Neutrino sector

then via see-saw
(III) FROGATT – NIELSEN MECHANISM:

One fermion acquires mass via Higgs mechanism, others via higher order multiple see-saw.

BUT... presently
Lack of High Energy (UV) COMPLETION
Curious Coincidence: order of Cosmological Constant today not far from that provided by observed light neutrino mass differences

\[ \Lambda \sim \left( \Delta m^2 \right)^2 \frac{M_P^4}{M_P^4} \]

\[ \Delta m^2 \sim 10^{-3} \text{ eV}^2 \]

Is there a link?
Formation of fermion condensates dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) four-fermion interactions of sterile Majorana neutrino in the early Universe

Kapusta, Antusch, Kersten, Lindner, Ratz, Barenboim, Bhatt, Desai, Ma, Rajasekaran, U. Sarkar NEM,
Formation of fermion condensates dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) four-fermion interactions of light sterile Majorana neutrino in the early Universe

\[ H_I = -\mathcal{C} (\bar{\nu}_M \nu_M) (\bar{\nu}_M \nu_M) \]

\[ \nu_M = \lambda \nu_R + \nu^c_L \]

One light (O(10^{-3}) eV) sterile Majorana neutrino forms the condensate

\[ M_\nu = \begin{pmatrix} m_1 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 \\ 0 & 0 & m_3 & M \\ \end{pmatrix} \]
Consider Models of (effective) four-fermion interactions of light sterile Majorana neutrino in the early Universe as in Nambu-Jona-Lasinio model.

One light ($O(10^{-3})$ eV) sterile Majorana neutrino forms the condensate.

Dirac light masses of $O(0.1)$ eV.
Consider Models of (effective) four-fermion interactions of light sterile Majorana neutrino in the early Universe

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\[ M_\nu = \begin{pmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & 0 & m_3 \\ 0 & 0 & m_3 & M \end{pmatrix} \]

pseudo Dirac light neutrino

Model consistent with solar neutrino data
Formation of fermion **condensates** dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) four-fermion interactions of *light* sterile Majorana neutrino in the early Universe

\[
H_I = -\mathcal{C} \, (\overline{\nu}_M \, \nu_M) \, (\overline{\nu}_M \, \nu_M) 
\]

\[
\nu_M = \lambda \nu_R + \nu^c_L, 
\]

One light sterile Majorana neutrino forms condensate

\[
\left< \chi_a \, \overline{\chi}_b \right> = \epsilon_{ab} \, D 
\]

\[
H_{1}^{MF} = -2 \, \mathcal{C} \left[ \lambda^* \, \overline{\chi}_a \, \chi_b \, D + \lambda^2 \, \overline{\chi}_a \, \overline{\chi}_b \, D^* \right] \, \epsilon_{ab}. 
\]

Coherence length, Gap Equation in FRW backgrounds **Dark Energy** contribution
Formation of fermion **condensates** dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) four-fermion interactions of *light sterile* Majorana neutrino in the early Universe

\[ H_I = -\mathcal{C} \left( \bar{\nu}_M \nu_M \right) \left( \bar{\nu}_M \nu_M \right) \]

\[ \nu_M = \frac{1}{M \sqrt{2}} \]

\[ \nu_M = \frac{1}{M \sqrt{2}} \]

\[ \langle \chi_a \bar{\chi}_b \rangle = \epsilon_{ab} D \]

Better UV behaviour than flat space e.g. in de Sitter space time absorb UV infinities in Hubble H, and Planck scale \( M_P \)

*Candelas, Reine (1975)*

Kapusta, Antusch, Kersten, Lindner, Ratz, Barenboim, Bhatt, Desai, Ma, Rajasekaran, U. Sarkar

NEM,

e.g. through heavy scalar exchange

\[ c = \frac{f^2}{m_s^2} \]

\[ \chi_a \bar{\chi}_b \]

\[ D^* \]

\[ \epsilon_{ab} \]

Coherence length,

Gap Equation in

FRW backgrounds

*Dark Energy* contribution
Formation of fermion condensates dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) attractive four-fermion interactions in the early Universe, including (right-handed) light neutrinos e.g. through heavy BSM $U(1)$ exchange in string/membrane-inspired models assuming neutrinos are ``charged'' under these extra $U(1)$

\[
S_G = \frac{1}{\kappa} \int d^4 x \det(e) \left( \Lambda - \frac{1}{2} e^\mu_a e_\nu^b \hat{R}_{\mu \nu}^{ab}(e) + \sum_j \frac{i\kappa}{2} e^\mu_a [\bar{\psi}_j \gamma^a \hat{D}_\mu \psi_j - \hat{D}_\mu \bar{\psi}_j \gamma^a \psi_j] + \kappa^2 \left( \frac{3}{16} - \eta G \right) [\bar{\psi}_i \psi_j] (\bar{\psi}_j \psi_i) - [\bar{\psi}_i \gamma_5 \psi_j] (\bar{\psi}_j \gamma_5 \psi_i) \right) + \\
\frac{1}{2} \kappa^2 \left( \frac{3}{16} + \eta G \right) \left[ (\bar{\psi}_i \gamma^\mu_\nu \psi_j) (\bar{\psi}_j \gamma^\mu_\nu \psi_i) + (\bar{\psi}_i \gamma_5 \gamma^\mu_\nu \psi_j) (\bar{\psi}_j \gamma_5 \gamma^\mu_\nu \psi_i) \right],
\]

(Fierz)
Consider Models of (effective) attractive four-fermion interactions in the early Universe, including (right-handed) light neutrinos.

Formation of fermion condensates dynamically in Early Universe as in Nambu-Jona-Lasinio model.

\[
S_G = \frac{1}{\kappa} \int d^4x \det(e) \left( \Lambda - \frac{1}{2} e^\mu_a e^\nu_b \tilde{R}^{ab}_{\mu\nu}(e) + \sum_j \frac{i\kappa}{2} e^\mu_a [\bar{\psi}_j \gamma^a \hat{D}_\mu \psi_j - \hat{D}_\mu \psi_j \gamma^a \psi_j] + \kappa^2 \left( \frac{3}{16} - \eta \xi \right) \left( \bar{\psi}_i \psi_j \right) \left( \bar{\psi}_j \psi_i \right) - \left( \bar{\psi}_i \gamma_5 \psi_j \right) \left( \bar{\psi}_j \gamma_5 \psi_i \right) \right) + \frac{1}{2} \kappa^2 \left( \frac{3}{16} + \eta \xi \right) \left[ \left( \bar{\psi}_i \gamma^\mu \psi_j \right) \left( \bar{\psi}_j \gamma^\mu \psi_i \right) + \left( \bar{\psi}_i \gamma_5 \gamma^\mu \psi_j \right) \left( \bar{\psi}_j \gamma_5 \gamma^\mu \psi_i \right) \right],
\]  

(Fierz)

e.g. through heavy BSM $U(1)$ exchange in string/membrane-inspired models assuming neutrinos are ``charged'' under these extra $U(1)$
COSMIC NEUTRINO CONDENSATES & DARK ENERGY

Formation of fermion **condensates** dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) **attractive** four-fermion interactions in the early Universe, *including* (right-handed) light neutrinos

\[ S_G = \frac{1}{\kappa} \int d^4x \det(e) \left( \Lambda - \frac{1}{2} e^\mu_a e^\nu_b \hat{R}_{\mu\nu}^{ab}(e) + \sum_j \frac{i\kappa}{2} e^\mu_a [\overline{\psi}_j \gamma^a \hat{D}_\mu \psi_j - \overline{\hat{D}_\mu \psi}_j \gamma^a \psi_j] + \kappa^2 \left( \frac{3}{16} + \eta G \right) \left[ (\overline{\psi}_i \psi_j)(\overline{\psi}_j \psi_i) - (\overline{\psi}_i \gamma_5 \psi_j)(\overline{\psi}_j \gamma_5 \psi_i) \right] + \frac{1}{2} \kappa^2 \left( \frac{3}{16} + \eta G \right) \left[ (\overline{\psi}_i \gamma^\mu \psi_j)(\overline{\psi}_j \gamma^\mu \psi_i) + (\overline{\psi}_i \gamma_5 \gamma^\mu \psi_j)(\overline{\psi}_j \gamma_5 \gamma^\mu \psi_i) \right] \right) , \]

(Fierz)

Repulsive contributions due to gravitational torsion induced by fermions

\[ + \frac{3\kappa^2}{16} (\overline{\psi}_i \gamma_\mu \gamma_5 \psi_i)^2 \]
Formation of fermion **condensates** dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) **attractive** four-fermion interactions in the early Universe, **including** (right-handed) light neutrinos

\[
S_G = \frac{1}{\kappa} \int d^4x \det(e) \left( \Lambda - \frac{1}{2} \epsilon^\mu_a \epsilon^\nu_b \hat{R}_{\mu\nu}^{ab}(e) + \sum_j \frac{i\kappa}{2} \epsilon^\mu_a [\bar{\psi}_j \gamma^a \hat{D}_\mu \psi_j - \hat{D}_\mu \psi_j \gamma^a \psi_j] + \right.
\]

\[
\kappa^2 \left( \frac{3}{16} - \eta G \right) \left[ (\bar{\psi}_i \psi_j) (\bar{\psi}_j \psi_i) - (\bar{\psi}_i \gamma_5 \psi_j) (\bar{\psi}_j \gamma_5 \psi_i) \right] + \\
\left. + \frac{1}{2} \kappa^2 \left( \frac{3}{16} + \eta G \right) \left[ (\bar{\psi}_i \gamma^\mu \psi_j) (\bar{\psi}_j \gamma^\mu \psi_i) + (\bar{\psi}_i \gamma_5 \gamma^\mu \psi_j) (\bar{\psi}_j \gamma_5 \gamma^\mu \psi_i) \right] \right),
\]

(Fierz)

Formation of scalar (spin -0) condensates lead to contributions to **Dark Energy** but also mixing Dark Energy- **Dark matter** *(through studies of equation of state)*

---

**NEM**

---

**e.g.** through heavy BSM **U(1) exchange** in string/membrane-inspired models assuming neutrinos are "charged" under these **extra U(1)**
Formation of fermion **condensates** dynamically in Early Universe as in Nambu-Jona-Lasinio model

Consider Models of (effective) attractive four-fermion interactions in the early Universe, *including* (right-handed) light neutrinos

\[
S_G = \frac{1}{\kappa} \int d^4x \det(e) \left( \Lambda - \frac{1}{2} e^\mu_a e^\nu_b \hat{R}^{ab}_{\mu\nu}(e) + \sum_j \frac{ik}{2} e^\mu_a [\bar{\psi}_j \gamma^a \hat{D}_\mu \psi_j - \hat{\nabla}_\mu \bar{\psi}_j \gamma^a \psi_j] + 
\right.
\]

\[
\kappa^2 \left( \frac{3}{16} - \eta G \right) [(\bar{\psi}_i \psi_j) (\bar{\psi}_j \psi_i) - (\bar{\psi}_i \gamma_5 \psi_j) (\bar{\psi}_j \gamma_5 \psi_i)] + 
\]

\[
+ \frac{1}{2} \kappa^2 \left( \frac{3}{16} + \eta G \right) \left( (\bar{\psi}_i \gamma^\mu \psi_j) (\bar{\psi}_j \gamma^\mu \psi_i) + (\bar{\psi}_i \gamma_5 \gamma^\mu \psi_j) (\bar{\psi}_j \gamma_5 \gamma^\mu \psi_i) \right),
\]

Interesting Possibility, worthy of further astrophysical tests

OF COURSE, *not* the whole of DM

Growth of Structure in the Universe studies
Mass *Varying* neutrinos & the Dark Sector

Couple Scalar cosmic fields with potential $U(\varphi, T)$ and massless fermions $\psi$ through Yukawa couplings

$$ S = S^E_B + S^E_D |_{m=0} + g \int_0^\beta d\tau \int a^3 d^3 x \varphi \bar{\psi} \psi $$

$$ S^E_B = \int_0^\beta d\tau \int a(t)^3 d^3 x \left[ \frac{1}{2} (\partial_\tau \varphi)^2 + \frac{1}{2a^2} (\nabla \varphi)^2 + U(\varphi) \right] $$

Fermion mass:

$$ m = g \phi_c $$
Mass *Varying* neutrinos & the Dark Sector

Couple Scalar cosmic fields with potential $U(\varphi, T)$ and massless fermions $\psi$ through Yukawa couplings

\[
S = S^E_B + S^E_D|_{m=0} + g \int_0^\beta d\tau \int a^3 d^3 x \, \varphi \bar{\psi} \psi
\]

\[
S^E_B = \int_0^\beta d\tau \int a(t)^3 d^3 x \left[ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2a^2}(\nabla \varphi)^2 + U(\varphi) \right]
\]

Fermion mass: $m = g \phi_c$ Minimum of action
Mass \textit{Varying} neutrinos & the Dark Sector

Couple Scalar cosmic fields with potential $U(\varphi, T)$ and massless fermions $\psi$ through Yukawa couplings

\[
S = S_B^E + S_D^E \bigg|_{m=0} + g \int_0^\beta d\tau \int a^3 d^3 x \varphi \overline{\psi} \psi
\]

\[
S_B^E = \int_0^\beta d\tau \int a(t)^3 d^3 x \left[ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2a^2}(\nabla \varphi)^2 + U(\varphi) \right]
\]

Fermion mass:

\[
m = g \phi_c
\]

Thermodynamic potential density

\[
\Omega(\phi_c) = U(\phi_c) + \Omega_D(\phi_c)
\]

\[
Z_D \equiv \text{Tr} e^{-\beta(\hat{H} - \mu \hat{\phi})} = \int \mathcal{D}\overline{\psi} \mathcal{D}\psi e^{-S_D^E}
\]

\[
\Omega_D \equiv -\frac{1}{\beta a^3 V} \log Z_D
\]
Mass *Varying* neutrinos & the Dark Sector

Couple Scalar cosmic fields with potential $U(\varphi, T)$ and massless fermions $\psi$ through Yukawa couplings

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S_B^E = \int_0^\beta d\tau \int a(t)^3 d^3 x \left[ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2a^2}(\nabla \varphi)^2 + U(\varphi) \right]
\]

Fermion mass:

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m = g \phi_c
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Thermodynamic potential density

\[
\Omega(\phi_c) = U(\phi_c) + \Omega_D(\phi_c)
\]

\[
Z_D \equiv \text{Tr} e^{-\beta(\hat{H} - \mu \hat{Q})} = \int D\bar{\psi} D\psi e^{-S_D^E}
\]

\[
\Omega_D \equiv -\frac{1}{\beta a^3 V} \log Z_D
\]

*comoving volume*
Mass *Varying* neutrinos & the Dark Sector

Couple Scalar cosmic fields with potential $U(\varphi, T)$ and massless fermions $\psi$ through Yukawa couplings

$$
S = S_B^E + S_D^E \big|_{m=0} + g \int_0^\beta d\tau \int a^3 d^3 x \varphi \bar{\psi} \psi \\
S_B^E = \int_0^\beta d\tau \int a(t)^3 d^3 x \left[ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2a^2}(\nabla \varphi)^2 + U(\varphi) \right]
$$

Fermion mass:

$$
m = g \phi_c
$$

$$
\Omega(\phi_c) = U(\phi_c) + \Omega_D(\phi_c)
$$

$$
\frac{\partial \Omega(\varphi)}{\partial \varphi} \bigg|_{\varphi=\phi_c} = 0
$$

$$
\frac{\partial^2 \Omega(\varphi)}{\partial \varphi^2} \bigg|_{\varphi=\phi_c} > 0
$$

$$
\phi_c = \langle \varphi \rangle
$$

Thermodynamic potential density

$$
\mathcal{Z}_D \equiv \text{Tr} e^{-\beta(\hat{H} - \mu \hat{Q})} = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi e^{-S_D^E}
$$

$$
\Omega_D \equiv -\frac{1}{\beta a^3 V} \log \mathcal{Z}_D
$$

T dependent!
Mass *Varying* neutrinos & the Dark Sector

Couple Scalar cosmic fields with potential $U(\varphi, T)$ and massless fermions $\psi$ through Yukawa couplings

\[
S = S^E_B + S^E_D \bigg|_{m=0} + g \int_0^\beta d\tau \int a^3 d^3 x \, \varphi \bar{\psi} \psi
\]

\[
S^E_B = \int_0^\beta d\tau \int a(t)^3 d^3 x \left[ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2a^2}(\nabla \varphi)^2 + U(\varphi) \right]
\]

Fermion mass:

\[
m = g \phi_c
\]

Thermodynamic potential density

\[
\Omega(\phi_c) = U(\phi_c) + \Omega_D(\phi_c)
\]

\[
Z_D \equiv \text{Tr} \, e^{-\beta(\hat{H} - \mu \hat{Q})} = \int D\bar{\psi} D\psi e^{-S^E_D}
\]

\[
\Omega_D = -\frac{1}{\beta a^3 V} \log Z_D
\]

\[
\phi_c = \langle \varphi \rangle
\]

T dependent!
COSMIC NEUTRINO CONDENSATES & DARK ENERGY

OTHER INTERESTING TOPICS

Mass Varying neutrinos & the Dark Sector

Couple Scalar cosmic fields with potential $U(\varphi, T)$ and massless fermions $\psi$ through Yukawa couplings

$$\begin{align*}
S &= S_B^E + S_D^E |_{m=0} + g \int_0^\beta d\tau \int a^3 d^3 x \ varphi \bar{\psi} \psi \\
S_B^E &= \int_0^\beta d\tau \int a(t)^3 d^3 x \left[ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2a^2}(\nabla \varphi)^2 + U(\varphi) \right]
\end{align*}$$

Fermion mass:

$$m = g \phi_c$$

$$\phi_c = \langle \varphi \rangle$$

$$\rho_s \equiv \frac{\langle \hat{N} \rangle}{V} = \frac{\partial \Omega_D}{\partial m} = \rho_0 + \frac{m}{\pi^2} \int_0^\infty \frac{k^2 dk}{\varepsilon(k)} \left[ n_F(\varepsilon_-) + n_F(\varepsilon_+) \right]$$

$$\hat{N} = \int d^3 x \bar{\psi} \psi$$
COSMIC NEUTRINO CONDENSATES & DARK ENERGY

OTHER INTERESTING TOPICS

Mass *Varying* neutrinos & the Dark Sector

Nelson, Fardon, Weiner Chitov, August, Natarajan, Kahniashvili

\[
U'(\phi_c) + g \rho_s = 0
\]

\[
U(\varphi) = \frac{M^{\alpha+4}}{\varphi^\alpha}
\]

\[\alpha > 0.\]

Fermion mass:

\[
m = g \phi_c
\]

High T phase:

\[
\frac{m}{M} \approx (\sqrt{6\alpha \frac{M}{T}})^{\frac{2}{\alpha+2}} \propto T^{-\frac{2}{\alpha+2}}
\]

*Fermionic* contribution to thermodynamic potential *dominant*

Scalar mass

\[
m_\phi \approx \sqrt{\frac{\alpha + 1}{6}} T
\]
COSMIC NEUTRINO CONDENSATES & DARK ENERGY

OTHER INTERESTING TOPICS

Mass **Varying** neutrinos & the Dark Sector

Nelson, Fardon, Weiner Chitov, August, Natarajan, Kahniashvili

**Equation of state:**

\[ U'(\phi_c) + g \rho_s = 0 \]

\[ U(\varphi) = \frac{M^{\alpha+4}}{\varphi^\alpha}, \quad \alpha > 0. \]

Towards \( w = -1 \) for low \( T \) (Cosmo. Const. like)

\[ \Delta = M/T \]
Mass Varying neutrinos & the Dark Sector

Neutrino Dark Energy evolution vs Dark Matter $\Omega_M$

$$M = 2.39 \times 10^{-3} \text{ eV} \ (\alpha = 0.01)$$
Mass **Variying** neutrinos & the Dark Sector

\[ M = 2.39 \cdot 10^{-3} \text{ eV} \quad (\alpha = 0.01) \]

Equation of state of entire Universe including radiation contributions:

\[ P_{\text{tot}} = w_{\text{tot}} \rho_{\text{tot}} \]

\[ P_{\text{tot}} = P_\gamma + P_{\varphi \nu} \]

\[ P_\gamma = \frac{1}{3} \rho_\gamma \]

Towards \( w = -1 \) for low \( z \) (Cosmo. Const. like)
COSMIC NEUTRINO CONDENSATES & DARK ENERGY

OTHER INTERESTING TOPICS

Mass *Varying* neutrinos & the Dark Sector

Chitov, August, Natarajan, Kahniashvili

Neutrino mass evolution

\[ U(\varphi) = \frac{M^{\alpha+4}}{\varphi^\alpha} \]

\[ M = 2.39 \cdot 10^{-3} \text{ eV} \quad (\alpha = 0.01) \]

Graph showing the evolution of neutrino mass with temperature.
COSMIC NEUTRINO CONDENSATES & DARK ENERGY

OTHER INTERESTING TOPICS

Mass *Varying* neutrinos & the Dark Sector

Nelson, Fardon, Weiner Chitov, August, Natarajan, Kahniashvili

Acceptable Cosmology & Neutrino phenomenology
COSMIC NEUTRINOS & VIOLATION OF FUNDAMENTAL SYMMETRIES
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

**CPT Invariance Theorem:**
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell revisited by: Greenberg, Chaichian, Dolgov, Novikov…
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

CPT Invariance Theorem:
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
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(ii)-(iv) Independent reasons for violation

Schwinger, Pauli, Luders, Jost, Bell
revisited by: Greenberg, Chaichian, Dolgov, Novikov…
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

**CPT Invariance Theorem:**
(i) Flat space-times  
(ii) Lorentz invariance  
(iii) Locality  
(iv) Unitarity

Kostelecky, Mewes, Diaz ....  
Standard Model Extension (SME)  
PHENOMENOLOGICAL  
3-LV parameter (texture) model for neutrinooscillations fitting also LSND, MINOS

(ii)-(iv) Independent reasons for violation
CPT Violation in the Early Universe

GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

CPT Invariance Theorem:
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Barenboim, Borissov, Lykken
PHENOMENOLOGICAL models with non-local mass parameters

(ii)-(iv) Independent reasons for violation

\[ S = \int d^4x \bar{\psi}(x)i\partial\psi(x) + \frac{im}{\pi} \int d^3x \int dt dt' \bar{\psi}(t, x) \frac{1}{t - t'} \psi(t', x). \]
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

CPT Invariance Theorem:
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

(ii)-(iv) Independent reasons for violation

e.g. QUANTUM SPACE-TIME FOAM AT PLANCK SCALES
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

CPT Invariance Theorem:
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Hawking, Ellis, Hagelin, Nanopoulos Srednicki, Banks, Peskin Strominger, …Lopez, NEM

(ii)-(iv) Independent reasons for violation

QUANTUM GRAVITY INDUCED DECOHERENCE EVOLUTION OF PURE QM STATES TO MIXED AT LOW ENERGIES

LOW ENERGY CPT OPERATOR NOT WELL DEFINED

Wald (79), Bernabeu, NEM, Papavassiliou,…
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

Assume CPT Violation.
e.g. due to *Quantum Gravity* fluctuations, *strong* in the Early Universe
GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

Assume CPT Violation.
e.g. due to Quantum Gravity fluctuations, strong in the Early Universe

ONE POSSIBILITY:
particle-antiparticle mass differences

\[ m \neq \bar{m} \]
Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

\[
f(E, \mu) = \frac{1}{\exp[(E - \mu)/T] \pm 1}
\]

\[
\delta n \equiv n - \bar{n} = gdf \int \frac{d^3p}{(2\pi)^3} \left[ f(E, \mu) - f(\bar{E}, \bar{\mu}) \right]
\]

\[
E = \sqrt{p^2 + m^2}, \quad \bar{E} = \sqrt{p^2 + \bar{m}^2}
\]

\[
m \neq \bar{m}
\]

\[
\delta m = m - \bar{m}
\]

Dolgov, Zeldovich, Dolgov (2009)

Assume dominant contributions to Baryon asymmetry from quarks-antiquarks

\[
m(T) \sim gT
\]

High-T quark mass >> Lepton mass
Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

\[ f(E, \mu) = \frac{1}{\exp[(E - \mu)/T] \pm 1} \]

\[ \delta n \equiv n - \bar{n} = g_d f \int \frac{d^3p}{(2\pi)^3} \left[ f(E, \mu) - f(\bar{E}, \bar{\mu}) \right] \]

\[ E = \sqrt{p^2 + m^2}, \quad \bar{E} = \sqrt{p^2 + \bar{m}^2} \]

Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

\[ \beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left( 18m_u \delta m_u + 15m_d \delta m_d \right) / T^2 \]

\[ n_\gamma = 0.24T^3 \quad \text{photon equilibrium density at temperature } T \]

\[ m \neq \bar{m} \]

\[ \delta m = m - \bar{m} \]
\[ \beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left(18m_u \delta m_u + 15m_d \delta m_d\right) / T^2 \]

\[ n_\gamma = 0.24T^3 \]

Current bound for protons

\[ \delta m_p < 2 \cdot 10^{-9} \text{ GeV} \]

Reasonable to take:

\[ \delta m_q \sim \delta m_p \]

**NB:** To reproduce the observed

\[ \beta^{(T=0)} = 6 \cdot 10^{-10} \]

need

\[ \delta m_q(T = 100 \text{ GeV}) \sim 10^{-5} - 10^{-6} \text{ GeV} \gg \delta m_p \]
\[ \beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} (18m_u\delta m_u + 15m_d\delta m_d) / T^2 \]

\[ n_\gamma = 0.24T^3 \]

Current bound for protons \( \delta m_p < 2 \cdot 10^{-9} \text{ GeV} \)

Reasonable to take: \( \delta m_q \sim \delta m_p \)

**NB:** To reproduce the observed

\[ \beta^{(T=0)} = 6 \cdot 10^{-10} \text{ need} \]

\[ \delta m_q(T = 100 \text{ GeV}) \sim 10^{-5} - 10^{-6} \text{ GeV} \gg \delta m_p \]

CPT Violating quark-antiquark Mass difference alone CANNOT REPRODUCE observed BAU
But… CPT Violating neutrino-antineutrino Mass difference alone MAY REPRODUCE observed BAU

\[ m_i = \tan \beta_i \bar{m}_i \]

\[ i = 1, 2, 3 \quad \text{Light } \nu \text{ species} \]

\[ n_B = n_\nu - n_{\bar{\nu}} \lesssim \frac{\mu_\nu T^2}{6} \]

\[ \frac{n_B}{s} \sim \frac{\mu_\nu}{T} \sim 10^{-11} \]

@ 100 GeV
BUT CPT VIOLATION NOT NECESSARILY IMPLIES $\delta m = m - \overline{m}$

Quantum-Gravity as "environment"

Decoherence "Environmental" couplings difference between particle and antiparticle create lepton asymmetry in Early Universe

$$\rho = \text{Tr} |\Psi\rangle\langle\Psi|$$

neutrino density matrix evolution

$N = \text{flavour} \#$

$$\frac{\partial \rho_{ij}}{\partial t} = \sum_{ij} h_{ij} \rho_{ij} + \sum_{\nu} \mathcal{L}_{\mu\nu} \rho_{\mu},$$

$\mu, \nu = 0, \ldots N^2 - 1, \quad i, j = 1, \ldots N^2 - 1$
BUT CPT VIOLATION NOT NECESSARILY IMPLIES

\( \delta m = m - \overline{m} \)

Quantum-Gravity as ``environment''

Decoherence ``Environmental'' couplings difference between particle and antiparticle create lepton asymmetry in Early Universe

\[
\rho = \text{Tr} |\Psi\rangle \langle \Psi| \\
\text{neutrino density matrix evolution}
\]

\( N = \text{flavour } \# \)

\[
\frac{\partial \rho_{\mu}}{\partial t} = \sum_{ij} h_{ij} \rho_{ij\mu} + \sum_{\nu} L_{\mu\nu} \rho_{\mu} ,
\]

\( \mu, \nu = 0, \ldots N^2 - 1, \quad i, j = 1, \ldots N^2 - 1 \)

\( i[\rho, H] \)  

QM part
Quantum-Gravity as "environment"

Decoherence "Environmental" couplings
difference between particle and antiparticle
create lepton asymmetry in Early Universe

\[
\delta m = m - \bar{m}
\]

Barenboim, NEM (04)

\[
\rho = \text{Tr} |\Psi\rangle \langle \Psi| 
\]

neutrino density matrix evolution
N = flavour #

``Environment'' (Lindblad part)
e.g. due to Quantum Gravity, different between ν – anti-ν
Complete positivity
Entropy increase
Energy conservation (average)
HIGH-ENERGY (ASTRO)PHYSICS CONSTRAINTS ON DECOHERENCE & CPT VIOLATION IN (ANTI)NEUTRINO SECTOR

• **DECOHERENCE:** DAMPING OF OSCILLATORY TERMS IN OSCILLATION PROBABILITIES

\[
\langle P_{\alpha\beta} \rangle = \delta_{\alpha\beta} - \sum_{a=1}^{n} \sum_{b=1, a<b}^{n} \text{Re} \left( U_{\alpha}^* U_{\beta a} U_{\alpha b} U_{\beta}^* \right) \left( 1 - \cos(2\ell \Delta m_{ab}^2 e^{-q_1 L - q_2 L^2}) \right)
\]

\[- \sum_{a=1}^{n} \sum_{b=1, a<b}^{n} \text{Im} \left( U_{\alpha}^* U_{\beta a} U_{\alpha b} U_{\beta}^* \right) \sin(2\ell \Delta m_{ab}^2) e^{-q_1 L - q_2 L^2} \]

with \( \ell \equiv \frac{L}{4E} \)

\[
q_1 = \gamma L n b \left( \frac{E}{\text{GeV}} \right)^n
\]

e.g. Benatti, Floreanini, Lisi, Marrone, Montanino… Hooper, Morgan, Winstanley Barenboim, NEM, Meregaglia, Rubbia, Sarkar, Sakharov…
**DECOHERENCE:** Damping of oscillatory terms in oscillation probabilities

\[
\langle P_{\alpha\beta} \rangle = \delta_{\alpha\beta} - \\
2 \sum_{a=1}^{n} \sum_{b=1, a < b}^{n} \text{Re} \left( U_{\alpha a}^* U_{\beta a} U_{\alpha b} U_{\beta b}^* \right) \left( 1 - \cos(2\ell \Delta m^2_{ab}) e^{-q_1 L - q_2 L^2} \right) \\
- 2 \sum_{a=1}^{n} \sum_{b=1, a < b}^{n} \text{Im} \left( U_{\alpha a}^* U_{\beta a} U_{\alpha b} U_{\beta b}^* \right) \sin(2\ell \Delta m^2_{ab}) e^{-q_1 L - q_2 L^2}
\]

with \( \ell \equiv \frac{L}{4E} \) and

\[
q_1 = \gamma_{Ln b} \left( \frac{E}{\text{GeV}} \right)^n
\]

- \( \gamma_{Ln b} < 0.67 \times 10^{-24} \text{ GeV} \), \( n = 0 \)
- \( \gamma_{Ln b} < 0.47 \times 10^{-20} \text{ GeV} \), \( n = 2 \)
- \( \gamma_{Ln b} < 0.78 \times 10^{-26} \text{ GeV} \), \( n = -1 \)

Stringent constraints on \( q_1(E) \) in neutrino sector from current neutrino data + ICE CUBE — no observed damping

**Not clear** situation in antineutrinos, e.g. LSND, MINOS antineutrino oscillation anomalies
**BUT CPT VIOLATION NOT NECESSARILY IMPLIES**

\[ \delta m = m - \bar{m} \]

Barenboim, NEM (04)

**Quantum-Gravity as "environment"

Decoherence "Environmental" couplings
difference between particle and antiparticle
create lepton asymmetry in Early Universe

\[ \rho = \text{Tr} |\Psi\rangle\langle\Psi| \]

neutrino density matrix evolution
N = flavour #

Simple model (phenomenological): neutrino sector \( \gamma_i = 0 \)

antineutrinos:

\[ [\mathcal{L}_{\mu\nu}] = \text{Diag} (0, -\bar{\gamma}_1, -\bar{\gamma}_2, -\bar{\gamma}_3 - \bar{\gamma}_4, -\bar{\gamma}_5, -\bar{\gamma}_6, -\bar{\gamma}_7, -\bar{\gamma}_8) \]

\( \bar{\gamma}_i = \bar{\gamma}_{i+1} \) for \( i = 1, 4, 6, 7 \) and \( \bar{\gamma}_1 = \bar{\gamma}_4, \bar{\gamma}_3 = \bar{\gamma}_8 \)
BUT CPT VIOLATION NOT NECESSARILY IMPLIES $\delta m = m - \overline{m}$

Quantum-Gravity as ``environment’’

Decoherence ``Environmental’’ couplings
difference between particle and antiparticle
create lepton asymmetry in Early Universe

Simple model (phenomenological): neutrino sector $\gamma_i = 0$

antineutrinos: $\overline{\gamma}_i = \overline{\gamma}_{i+1}$ for $i = 1, 4, 6, 7$ and $\overline{\gamma}_1 = \overline{\gamma}_4$, $\overline{\gamma}_3 = \overline{\gamma}_8$

$\overline{\gamma}_1 = \overline{\gamma}_2 = \overline{\gamma}_4 = \overline{\gamma}_5 = 2 \cdot 10^{-18} \cdot E$

and

$\overline{\gamma}_3 = \overline{\gamma}_6 = \overline{\gamma}_7 = \overline{\gamma}_8 = 1 \cdot 10^{-24} / E$

$\Delta m^2_{12} = \Delta m^2_{12} = 7 \cdot 10^{-5} \text{ eV}^2$,

$\Delta m^2_{23} = \Delta m^2_{23} = 2.5 \cdot 10^{-3} \text{ eV}^2$,

$\theta_{23} = \theta_{23} = \pi/4$, $\theta_{12} = \theta_{12} = .45$,

$\theta_{13} = \theta_{13} = .05$,

masses & mixings are the same
BUT CPT VIOLATION NOT NECESSARILY IMPLIES \[ \delta m = m - \overline{m} \]

Quantum-Gravity as "environment"

Decoherence "Environmental" couplings
difference between particle and antiparticle
create lepton asymmetry in Early Universe

Simple model (phenomenological): neutrino sector \( \gamma_i = 0 \)

antineutrinos:
\[ \bar{\gamma}_i = \bar{\gamma}_{i+1} \text{ for } i = 1, 4, 6, 7 \text{ and } \bar{\gamma}_1 = \bar{\gamma}_4 , \bar{\gamma}_3 = \bar{\gamma}_8 \]

\[ \begin{array}{c}
\bar{\gamma}_1 = \bar{\gamma}_2 = \bar{\gamma}_4 = \bar{\gamma}_5 = 2 \cdot 10^{-18} \cdot E \\
\text{and} \\
\bar{\gamma}_3 = \bar{\gamma}_6 = \bar{\gamma}_7 = \bar{\gamma}_8 = 1 \cdot 10^{-24} / E
\end{array} \]

Amusing: choice to best fit LSND anomaly in antineutrino sector with rest of neutrino data…
BUT CPT VIOLATION NOT NECESSARILY IMPLIES \( \delta m = m - \bar{m} \)

Quantum-Gravity as "environment"

Decoherence "Environmental" couplings difference between particle and antiparticle create lepton asymmetry in Early Universe

Simple model (phenomenological): neutrino sector \( \gamma_i = 0 \)

antineutrinos: \( \bar{\gamma}_i = \bar{\gamma}_{i+1} \) for \( i = 1, 4, 6, 7 \) and \( \bar{\gamma}_1 = \bar{\gamma}_4, \bar{\gamma}_3 = \bar{\gamma}_8 \)

\[
\begin{align*}
\bar{\gamma}_1 &= \bar{\gamma}_2 = \bar{\gamma}_4 = 2 \cdot 10^{-18} \cdot E \\
\text{and} \\
\bar{\gamma}_3 &= \bar{\gamma}_6 = \bar{\gamma}_7 = 1 \cdot 10^{-24}/E
\end{align*}
\]

Amusing: Can also produce acceptable BAU!
BUT CPT VIOLATION NOT NECESSARILY IMPLIES $\delta m = m - \overline{m}$

Quantum-Gravity as "environment"

Decoherence "Environmental" couplings difference between particle and antiparticle create lepton asymmetry in Early Universe

Simple model (phenomenological): neutrino sector $\gamma_i = 0$

antineutrinos: $\overline{\gamma}_i = \overline{\gamma}_{i+1}$ for $i = 1, 4, 6, 7$ and $\overline{\gamma}_1 = \overline{\gamma}_4$, $\overline{\gamma}_3 = \overline{\gamma}_8$

$\overline{\gamma}_1 = \overline{\gamma}_2 = \overline{\gamma}_4 = \overline{\gamma}_5 = 2 \cdot 10^{-18} \cdot E$

and $\overline{\gamma}_3 = \overline{\gamma}_6 = \overline{\gamma}_7 = \overline{\gamma}_8 = 1 \cdot 10^{-24} / E$

$\frac{\langle \nu \rangle - \langle \overline{\nu} \rangle}{\langle \nu \rangle + \langle \overline{\nu} \rangle} \simeq \hat{\gamma}_1 \simeq 10^{-6}$

$\hat{\gamma}_1 = 10^{-18} \cdot E / \sqrt{\Delta m^2}$

Neutrino-antineutrino asymmetry
BUT CPT VIOLATION NOT NECESSARILY IMPLIES \( \delta m = m - \bar{m} \)

Quantum-Gravity as ``environment''

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\[
\mathcal{A} = \frac{\langle \nu \rangle - \langle \bar{\nu} \rangle}{\langle \nu \rangle + \langle \bar{\nu} \rangle} \simeq \hat{\gamma}_1 \simeq 10^{-6}
\]

\[
\hat{\gamma}_1 = \frac{T}{M_P} \cdot \frac{E}{\sqrt{\Delta m^2}}
\]

Lepton number is communicated to Baryon Sector by means of \( B+L \) violating sphaleron processes

\[
B = \frac{n_\nu - n_{\bar{\nu}}}{g} \sim \frac{A n_\nu}{g s n_\gamma}
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BUT CPT VIOLATION NOT NECESSARILY IMPLIES

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Lepton number is communicated to Baryon Sector by means of B+L violating sphaleron processes. Due to CPTV: Sakharov conditions on out-of-equilibrium processes and CPV can be avoided.
BUT CPT VIOLATION NOT NECESSARILY IMPLIES $\delta m = m - \bar{m}$

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Of course Model lacks Microscopic Understanding at present
BUT CPT VIOLATION NOT NECESSARILY IMPLIES \( \delta m = m - \overline{m} \)

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\[
B = \frac{n_\nu - \overline{n}_\nu}{g} \sim \frac{A n_\nu}{g \star n_\gamma}
\]

Of course Model lacks Microscopic Understanding at present but is worthy of pursuing....
OTHER EFFECTS OF CPT/UNITARITY VIOLATION –
FAILURE OF DETAILED BALANCED IN A SINGLE CHANNEL

Boltzman Eqs. for phase-space particle, anti-particle distributions

\[
\frac{df_j}{dt} = I_j^{(coll)}
\]

\[
I_j^{(coll)} = -\frac{1}{2E_j} \sum_f \int d\tau_j^{(in)} d\tau^{(fin)} (2\pi)^4 \delta^4 \left( \sum p_{in} - \sum p_{fin} \right) \left[ |A_{if}|^2 F_{if} - |A_{fi}|^2 F_{fi} \right]
\]

\[
F_{if} = \prod_i f_i \prod_f (1 \pm f_f)
\]

CPT Violation

\[
|A_{fi}|^2 = |A_{if}|^2 (1 + \Delta_{if})
\]

Unitarity violation if in a single channel
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CPT Violation

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Estimate this way matter-antimatter asymmetry in Universe. Lack of Microscopic Theory hampers detailed computations.
IS THIS CPTV ROUTE WORTH FOLLOWING? ....

Construct Microscopic Quantum Gravity models with strong CPT Violation in Early Universe (dominant in (anti)neutrino sector?), but weak today… Fit with all data… Estimate in this way matter-antimatter asymmetry in Universe.
• Neutrinos (Sterile) may explain matter-antimatter origin in the Universe
• May also provide interesting Dark matter Candidates
• Neutrino condensates may contribute to dark energy
• Mass Varying $\nu$

• If CPT is assumed Violated in Early Universe, active neutrinos may generate matter-antimatter asymmetry
• Interesting Physics for the Early Universe to be investigated
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QUESTION:

Which fundamental symmetries do (anti) neutrinos respect & why?