Neutrinos and the Universe

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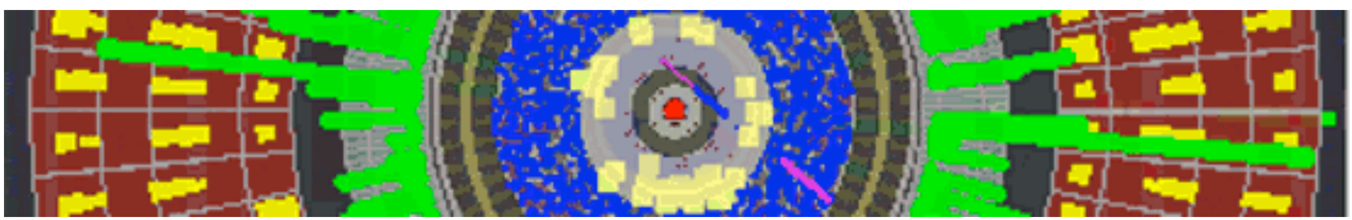

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BIRMINGHAM HIGH ENERGY PHYSICS GROUP

Seminar, February 20 2013

OUTLINE

Neutrinos & Baryon Asymmetry in Universe

Neutrinos & the Dark Sector of Universe:

CPT Violation in the Early Universe & Neutrinos

Conclusions - Outlook

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Role of (heavy) Majorana
Right-handed Neutrinos
In Leptogenesis/Baryogenesis

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anomalous generation of neutrino mass
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CPT Violation in Early Universe
Geometries & particle/antiparticle
asymmetries already
in thermal equilibrium

Conclusions - Outlook

PART I
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?***

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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

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$

T > 1 GeV

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

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Assume CPT

ELECTROWEAK THEORY & FERMION # NON-CONSERVATION

Classical conservations of EW theory: B, L_e , L_μ , L_τ

Quantum Anomalies in Standard Model (SM):

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

Allowed Processes (change of B by multiples of 3)

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

→ L_i – B/3 Conserved

(three quantities)

BUT:
OBSERVED NEUTRINO FLAVOUR OSCILLATIONS

→ L-B conserved (one quantity)
L=total Lepton #

If neutrinos Majorana → **L violated, No conserved numbers**

OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

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

Kuzmin, Rubakov, Shaposhnikov

Rate of B violation in Early Universe

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

α_W = SU(2) fine structure ``constant''

Sphaleron Mass Scale (M_W/α_W) = height of energy Barrier separating SU(2) vacua with different topologies

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

$$T_{\rm sph}(m_H) < T < (\alpha_W)^5 M_{Pl} \sim 10^{12}\ {\rm GeV}$$

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

$$m_H \in [100, 300]\,{\rm GeV}$$

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BAU could be produced this way only when sphaleron interactions freeze out, i.e.

$$T \simeq T_{\rm sph}$$

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BAU COULD BE PRODUCED @ $T \simeq T_{\rm sph}$ ← **Compute CP Violation Effects**

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Compute CP Violation Effects

$$T_{\rm sph}(m_H) \in [130, 190]\,\mathrm{GeV}$$

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Use CKM Matrix for $T > T_{sph}$

Within the Standard Model, lowest CP Violating structures

$$d_{CP} = \sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin\delta_{CP} \cdot (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

Cabbibo-Kobayashi-Maskawa CP Violating phase

Shaposhnikov

$$D = \mathrm{Im}\ \mathrm{Tr}\left[\mathcal{M}_u^2 \mathcal{M}_d^2 \mathcal{M}_u \mathcal{M}_d\right]$$

$$\delta_{KM}^{CP} \sim \frac{D}{T^{12}} \sim 10^{-20}$$

$$<< \frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4 - 8.9) \times 10^{-11}$$

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This CP Violation Cannot be the Source of Baryon Asymmetry in The Universe

Role of Neutrinos?

- Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.)

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- Massive ν are **simplest** extension of SM

- Right-handed massive ν may provide extensions of SM with:

  extra CP Violation and thus Origin of Universe's matter-antimatter asymmetry due to neutrino masses, **Dark Matter**

BASICS: TYPES OF NEUTRINO MASS TERMS

THE MOST GENERAL, LORENTZ-INVARIANT NEUTRINO MASS TERM

$$\mathcal{L}^{\mathrm{D+M}} = -\frac{1}{2}\,\bar{\nu}_L\, M_L^{\mathrm{M}}(\nu_L)^c - \bar{\nu}_L\, M^{\mathrm{D}}\,\nu_R - \frac{1}{2}\,\overline{(\nu_R)^c}\, M_R^{\mathrm{M}}\nu_R + \mathrm{h.c.}$$

$$\nu_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \qquad \nu_R = \begin{pmatrix} \nu_{eR} \\ \nu_{\mu R} \\ \nu_{\tau R} \end{pmatrix}$$

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MIXING

$$\nu_{lL}(x) = \sum_{i=1} U_{li}\;\nu_{iL}(x) \quad (l = e, \mu, \tau)$$

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DIRAC

CONSERVE TOTAL LEPTON (L) NUMBER

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$$(\nu_{lL})^c = C\,\bar{\nu}_{lL}^T$$

$$(\nu_{lR})^c = C\,\bar{\nu}_{lR}^T$$

***C* = Charge Conjugation**

VIOLATE LEPTON (L) NUMBER

MAJORANA LEFT-HANDED

MAJORANA RIGHT-HANDED

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MAJORANA FIELDS ARE MASS EIGENSTATES
PARTICLE=ANTIPARTICLE

$$\nu^M = U^\dagger \nu_L + (U^\dagger \nu_L)^c = \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad m = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

$$(\nu^M(x))^c = \nu^M(x)$$

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X

$$(\nu_{lR})^c = C\,\bar{\nu}_{lR}^T$$

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DIRAC

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(L) NUMBER

**MAJORANA
RIGHT-HANDED**

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FOR SEESAW : NO LEFT-HANDED MAJORANA

SM Extension with N extra right-handed neutrinos

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

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

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Right-handed Massive **Majorana** neutrinos

Leptons

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Higgs scalar SU(2) Dual: $\tilde{\phi}_i = \epsilon_{ij}\phi_j^*.$

SM Extension with N extra right-handed neutrinos

νMSM

Boyarski, Ruchayskiy, Shaposhnikov

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Yukawa couplings
Matrix (N=2 or 3)

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

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Majorana masses to (2 or 3) active neutrinos via ***seesaw***

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NB: Upon Symmetry Breaking
<Φ> = v ≠ 0 → Dirac mass term

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Minkowski,Yanagida, Mohapatra, Senjanovic Sechter, Valle …

Light Neutrino Masses through see saw

$$m_\nu = -M^D \frac{1}{M_I}[M^D]^T \,.$$

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

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

$$M_D \ll M_I$$

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From Constraints (compiled ν oscillation data) on (light) sterile neutrinos:
Giunti, Hernandez ...
N=1 *excluded by data*

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Majorana masses to (2 or 3) active neutrinos via seesaw

Yukawa couplings Matrix (N=2 or 3)

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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.***

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Yukawa couplings Matrix (N=3)

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

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

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

Majorana phases

Mixing

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

$$c_{Lij} = \cos(\theta_{Lij}) \text{ and } s_{Lij} = \sin(\theta_{Lij}).$$

Thermal Properties

Shaposhnikov…

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$$|F|^2 \approx \frac{m_{\rm atm} M_I}{v^2} \sim 2\times 10^{-15}\frac{M_I}{\rm GeV}$$

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

(Decay) processes in Early Universe

$$Nt \leftrightarrow \nu t,\ H \leftrightarrow N\nu \text{ or } N \leftrightarrow H\nu$$

Rate: $9F^2 f_t^2 T/(64\pi^3)$

Akhmedov, Rubakov, Smirnov

f_t = top quark Yukawa coupling

Thermal equilibrium at temperatures

$$T_{\rm eq} \simeq \frac{9 f_t^2 m_{\rm atm} M_0}{64\pi^3 v^2} M_I \simeq 5 M_I$$

$M_0 = M_P/(1.66\sqrt{g_{eff}})$

time $= M_0^2/2T^2$ (radiation era)

(for T_{eq} > 100 GeV)

Thermal Properties

Two distinct physics cases
(M_W = electroweak scale = O(100) GeV):

(i) $M_I > M_W$

(ii) $M_I < M_W$

Thermal Properties

Shaposhnikov…

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

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

Decay of Right-handed fermions

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

Out of equilibrium for: $T > T_{\rm eq}$ or for $T < T_{\rm decay}$

If $T_{\rm eq} > T_{\rm sph}$

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

$T_{\rm decay} > T_{\rm sph}$

Thermal Leptogenesis

Fukugita, Yanagida,

Thermal Leptogenesis

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

Thermal Leptogenesis

Independent of Initial Conditions @ T >> T_{eq}

Heavy Right-handed Majorana neutrinos enter ***equilibrium at T = T_{eq}***

Thermal Leptogenesis

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

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

enhanced CP V. **Lepton number Violation**

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

Out of Equilibrium Decays

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

Produce Lepton asymmetry

Fukugita, Yanagida,

Kuzmin, Rubakov, Shaposhinkov

Thermal Leptogenesis

Independent of Initial Conditions
@ T >> T_{eq}

Heavy Right-handed Majorana neutrinos enter ***equilibrium at T = T_{eq} > T_{decay}***

enhanced CP V. **Lepton number Violation**

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Produce Lepton asymm

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

where

$$l_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

Equilibrated electroweak B, L violating sphaleron interactions (B-L conserv)

Observed Baryon Asymmetry In the Universe (BAU)

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Fukugita, Yanagida,

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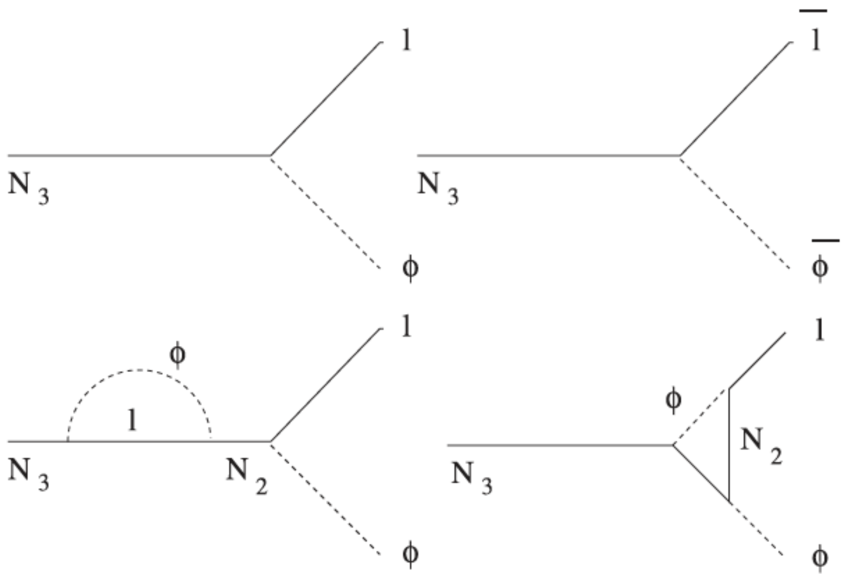
Estimate BAU by solving Boltzmann equations for Heavy Neutrino Abundances

Pilafsis, Riotto… Buchmuller, di Bari *et al.*

Predicted BAU in such models is found to be of order:

Pilaftsis, Shaposhnikov…



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

$$\delta_{CP} = \frac{\Gamma(N \to H\nu) - \Gamma(N \to \bar{H}\bar{\nu})}{\Gamma_{\rm tot}}$$

Majorana
fermion
Kinematics

Sphaleron
effects L -> B

$$S_{\rm macro} S_{\rm sph} \sim \mathcal{O}\left(\frac{1}{10}\right)$$

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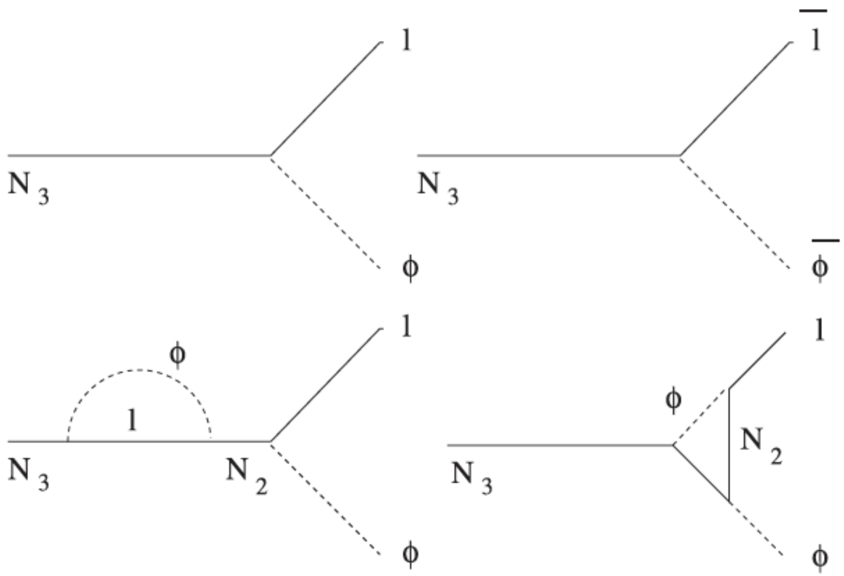

Non mass degenerate Majorana neutrinos

$$|M_I - M_J| \sim M_K$$

$$\frac{n_B}{s} \sim 10^{-3} F^2 \simeq 10^{-10}$$

$$F^2 \sim 10^{-7}$$

reproduced observed BAU

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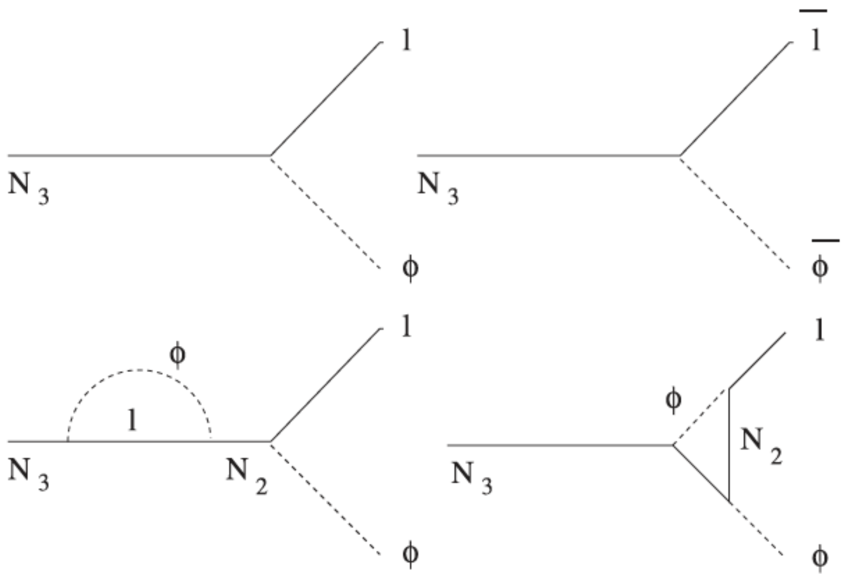

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reproduced observed BAU

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

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

$$v = \langle \phi \rangle = 174 \text{ GeV}$$

$$M_N \sim 10^{11} \text{ GeV}$$

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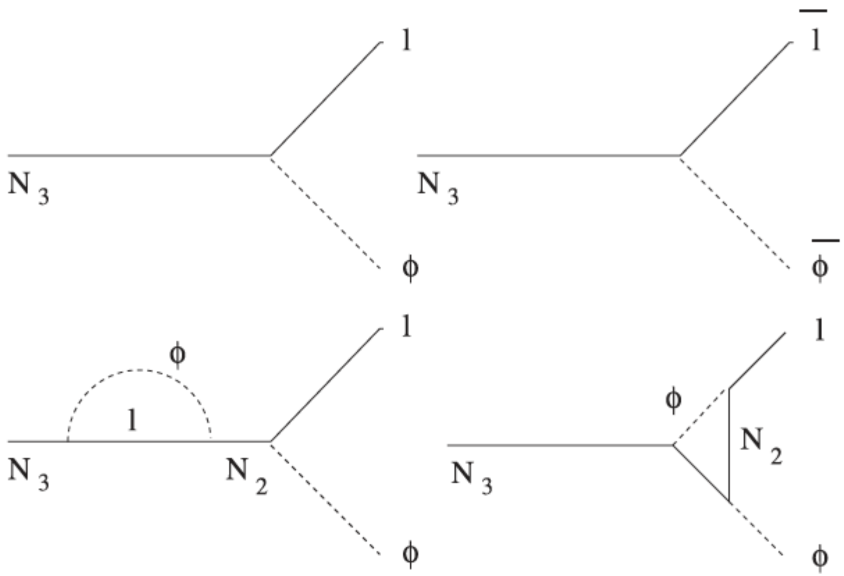

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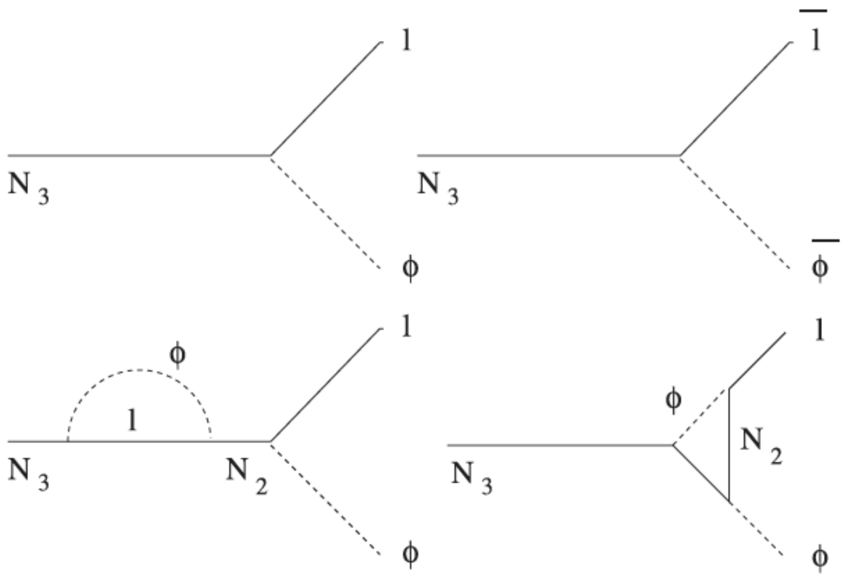

Non mass degenerate Majorana neutrinos

Stability of Higgs mass against higher loops in danger !

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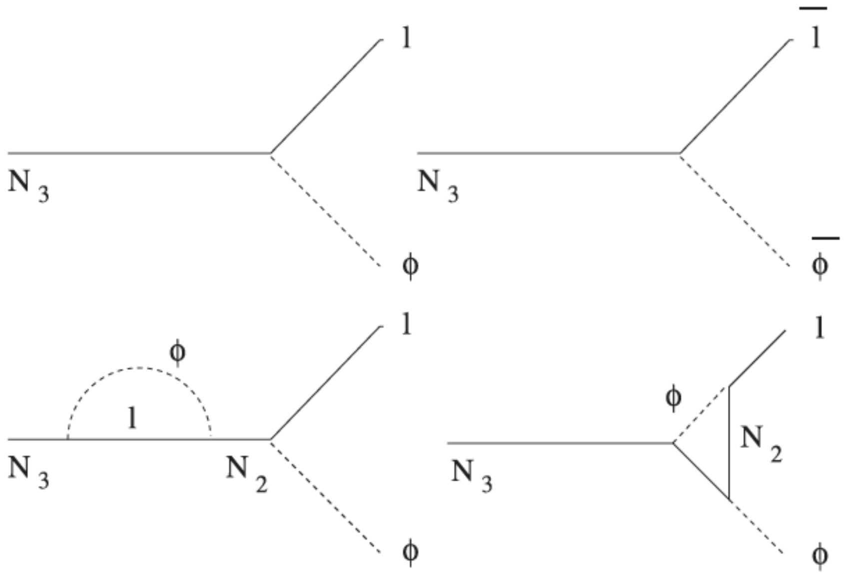


Non mass degenerate Majorana neutrinos

Stability of Higgs mass against higher loops in danger !

e.g. one loop

$$F^2 M_I^2/(4\pi) \sim 10^{14}\mathrm{GeV}^2$$

reproduced observed BAU

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

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

$$v = \langle \phi \rangle = 174 \text{ GeV}$$

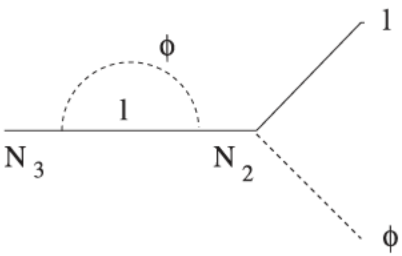
$$M_N \sim 10^{11} \text{ GeV}.$$

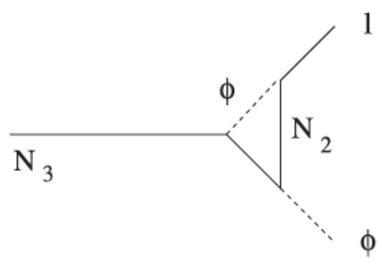
POSSIBLE RESOLUTION: DEGENERATE RIGHT-HANDED NEUTRINOS

Pilaftsis
Shaposhnikov

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:

$$\frac{n_B}{s} \sim 10^{-3} f^2 \frac{M_2 \Gamma_{\rm tot}}{(M_2 - M_3)^2 + \Gamma^2_{\rm tot}}$$

$$|M_2 - M_3| \sim \Gamma_{\rm tot}$$

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

$$M_I \sim M_W$$

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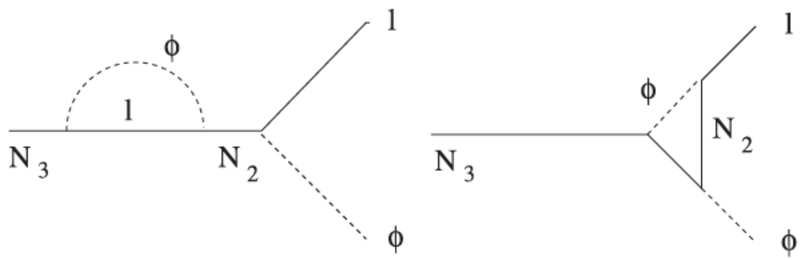

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$$M_I \sim M_W$$

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 τ Leptogenesis

One lepton number (τ) resonantly produced by out-of-equilibrium decays

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

$$h^{\nu_R} = \begin{pmatrix} \varepsilon_e & a e^{-i\pi/4} & a e^{i\pi/4} \\ \varepsilon_\mu & b e^{-i\pi/4} & b e^{i\pi/4} \\ \varepsilon_\tau & c e^{-i\pi/4} & c e^{i\pi/4} \end{pmatrix}.$$

Pilaftsis

De Simone, Riotto

Resonant τ Leptogenesis

Pilaftsis

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

Avoid L_τ excess ➤ $N_{2,3}$ decay rates suppressed

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Pilaftsis

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Avoid L_τ excess ➔ $N_{2,3}$ decay rates suppressed

Predicted BAU

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

$$\eta_B \sim -10^{-2}\frac{\delta^\tau_{N_1}}{K_{N_1}}\frac{\Gamma(N_1 \to L_\tau \Phi)}{\Gamma(N_{2,3} \to L_\tau \Phi)} \sim -10^{-2}\frac{\delta^\tau_{N_1}}{K_{N_1}}\frac{\varepsilon_\tau^2}{c^2}$$

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⬇

$\bar{\Gamma}_{N_1}/H(z=1)$ ≈10

$z = m_{N_1}/T$

Pilaftsis

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$N_{2,3}$ in thermal equilibrium

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$\bar{\Gamma}_{N_1}/H(z=1) \approx 10$ ✔

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$$z = m_{N_1}/T$$

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

agreement with observed BAU

Resonant τ Leptogenesis

Pilaftsis

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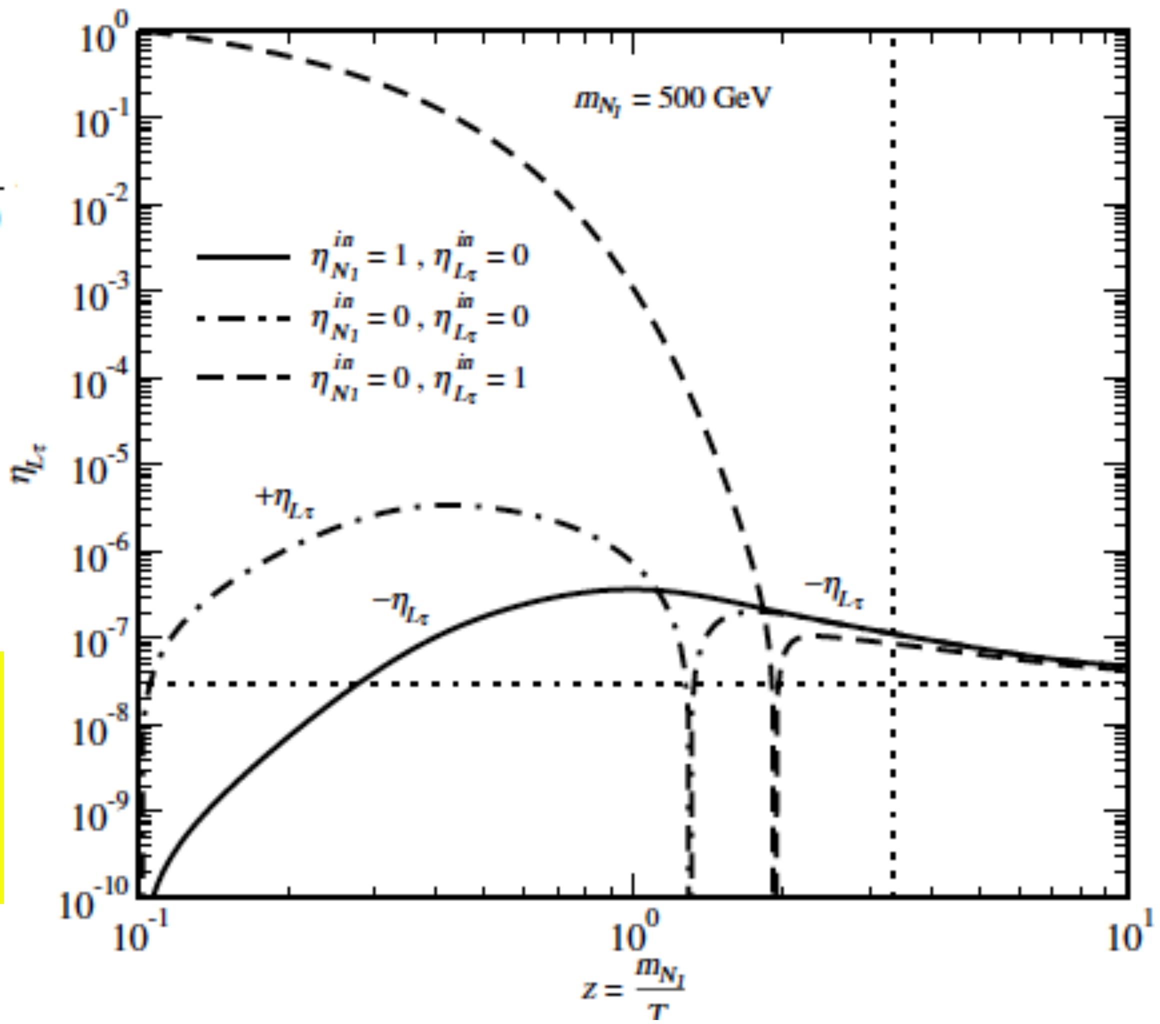

Estimate agrees with:

Boltzmann eq calculated neutrino N_1 abundance

Resonant τ Leptogenesis

Pilaftsis
Underwood

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$N_{2,3}$ in thermal equilibrium

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agreement with observed BAU

Leptogenesis possible for low-mass N_l : $M_N = O(M_W$ - TeV)

Resonant τ Leptogenesis

Pilaftsis
Underwood

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

Predicted BAU

M_N = O(M_W - TeV) $\mu \rightarrow e\gamma$

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

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

$$B^{\exp}(\mu \rightarrow e\gamma) \lesssim 1.2 \times 10^{-11}$$

future sensitivity to 10^{-13}

MEG experiment: $\mu^+ \rightarrow e^+ + \gamma$

1107.5547 $B(\mu^+ \rightarrow e^+ + \gamma) \leq 2.4 \times 10^{-12}$

Resonant τ Leptogenesis

A restricted Case : N_1 only *out of equilibrium* decay
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Pilaftsis
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Effects at e^+e^- linear collider? Study production of electroweak scale $N_{2,3}$ via their decays to e, μ (not τ)

Thermal Properties

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

Thermal Properties

Ashaka, Shaposhnikov…

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

(ii) $M_I < M_W$ (electroweak scale), *e.g.* M_I = O(1) GeV

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

$$F_{\alpha I} \sim \frac{\sqrt{m_{\rm atm} M_I}}{v} \sim 4 \times 10^{-8}$$

Baryogenesis through coherent oscillations right-handed singlet fermions

Akhmedov, Rubakov, Smirnov

$$F_{\alpha I} \sim \frac{\sqrt{m_{\rm atm} M_I}}{v} \sim 4 \times 10^{-8}$$

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 compated to Sphaleron freeze-out T

Total Lepton number conserved

Assume Mass generacy $N_{2,3}$ enhanced CP violation
Coherent Oscillations between these singlet fermions ,

Total Lepton zero but unevenly distributed between active & sterile v

Lepton number of active left-handed v 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.

BAU ESTIMATES

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

Baryogenesis occurs @: $T_B \sim \left(M_I \Delta M(T) M_0\right)^{1/3}$ eg O(100) GeV

$$\frac{n_B}{s} \simeq 1.7 \cdot 10^{-10}\, \delta_{CP} \left(\frac{10^{-5}}{\Delta M(T)/M_2}\right)^{\frac{2}{3}} \left(\frac{M_2}{10\ \ \mathrm{GeV}}\right)^{\frac{5}{3}}$$

$$\delta_{CP} = 4 s_{R23} c_{R23} \Big[s_{L12} s_{L13} c_{L13} \left((c_{L23}^4 + s_{L23}^4) c_{L13}^2 - s_{L13}^2 \right) \cdot \sin(\delta_L + \alpha_2) + c_{L12} c_{L13}^3 s_{L23} c_{L23} \left(c_{L23}^2 - s_{L23}^2 \right) \cdot \sin \alpha_2 \Big] .$$

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Quite effective Mechanism: Maximal Baryon asymmetry $\Delta \equiv \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 1$

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

Assumption: Interactions with plasma of SM particles
do not destroy quantum mechanical coherence of oscillations

BAU ESTIMATES

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Coherent Oscillations between these singlet fermions

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Mass N_2 (N_3) / (Mass N_1) = O(10^5)

N_1 Lightest Sterile nutrino is a natural DARK MATTER candidate

PART II

NEUTRINOS
&
THE DARK SECTOR OF THE UNIVERSE

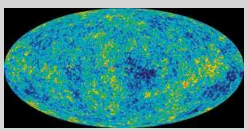
NEUTRINOS & THE DARK SECTOR OF THE UNIVERSE

Current Energy Budget of the Cosmos

Observations from:

Supernovae Ia

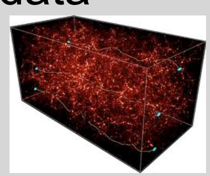
CMB



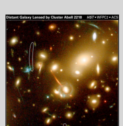
Baryon Acoustic Oscillations

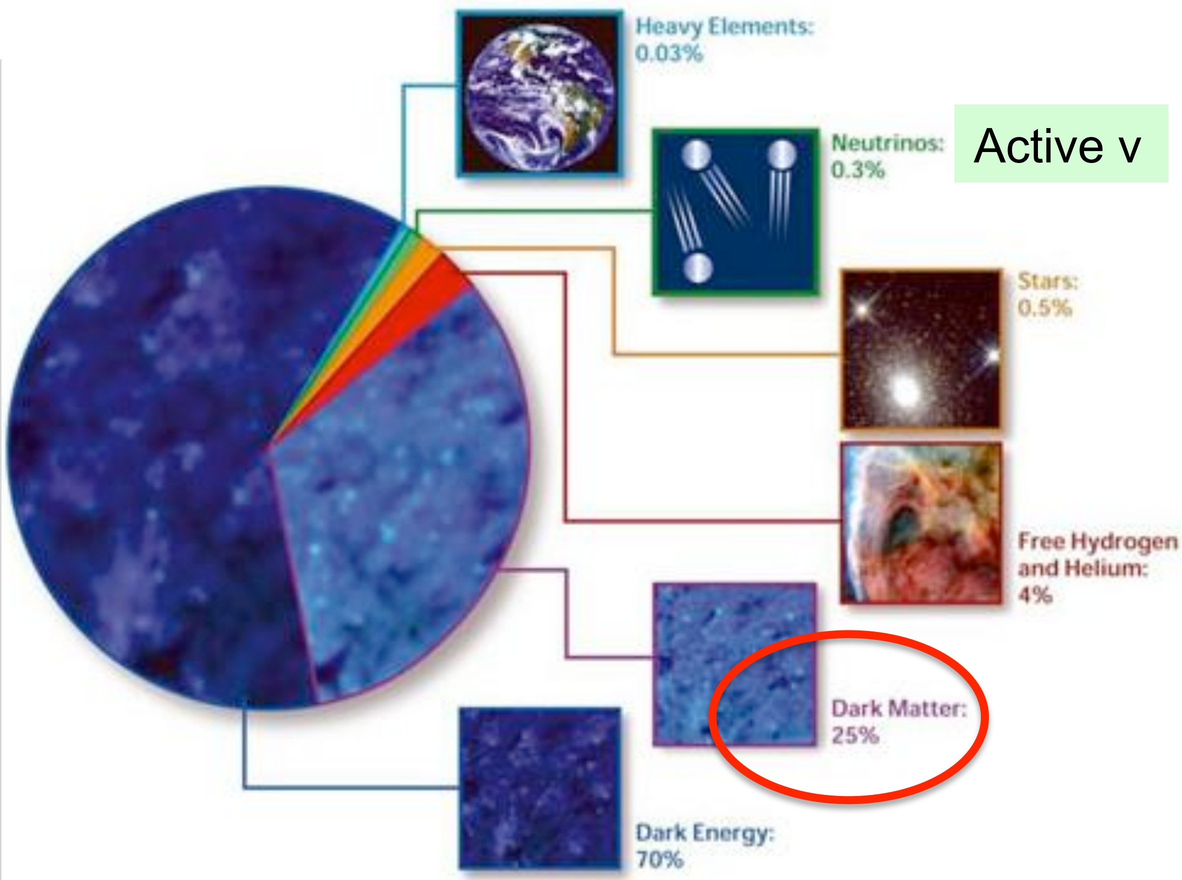
Galaxy Surveys

Structure Formation data



Strong & Weak lensing





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…)

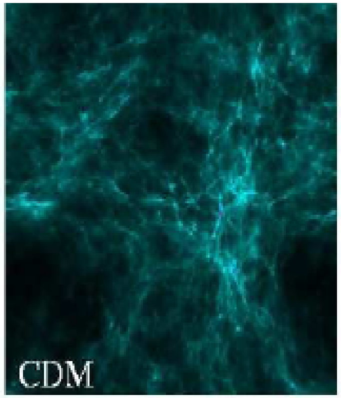
PHYSICS: WMAP and Dark Matter

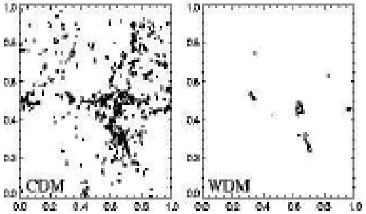
WMAP results so far:

- 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





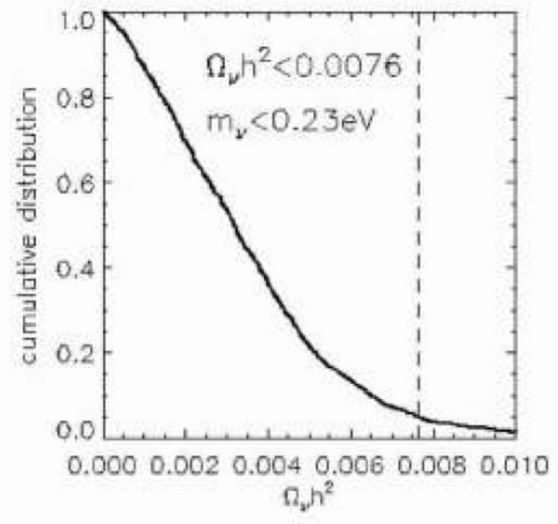
Numerical simulations for structure formation in Cold Dark Matter (CDM) (top) and Warm Dark Matter (WDM) (middle) with mass $m_X = 10$ KeV at $z = 20$. Bottom: Dark halos with mass $> 10^5 M_\odot$ for CDM (left) and for WDM (right).

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.

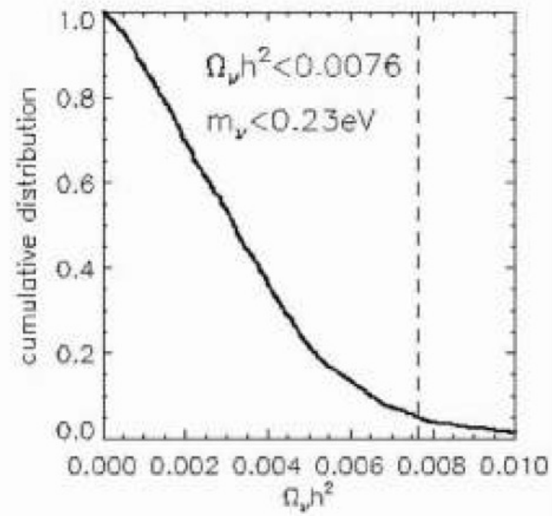
WMAP excludes HOT Dark Matter



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 α data etc) $\Omega_\nu h^2 < 0.0076 \Rightarrow < m_\nu >_e < 0.23$ eV :
Excludes HOT DM.

NB: WMAP still consistent with Majorana neutrinos, and also marginally with $\beta\beta$-decay (Heidelberg-Moscow Coll.).

WMAP excludes HOT Dark Matter



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Gonzalez-Garcia, Maltoni , Slavado, 1008.3795

UNCERTAINTY IN COSMOLOGICAL DATA DUE TO VARIETY OF SOURCES & MEASUREMENTS

Model	Observables	Σm_ν (eV) 95% Bound
$o\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+HO+SN+BAO	≤ 1.5
$o\omega\text{CDM} + \Delta N_{\text{rel}} + m_\nu$	CMB+HO+SN+LSSPS	≤ 0.76
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+BAO	≤ 0.61
$\Lambda\text{CDM} + m_\nu$	CMB+H0+SN+LSSPS	≤ 0.36
$\Lambda\text{CDM} + m_\nu$	CMB (+SN)	≤ 1.2
$\Lambda\text{CDM} + m_\nu$	CMB+BAO	≤ 0.75
$\Lambda\text{CDM} + m_\nu$	CMB+LSSPS	≤ 0.55
$\Lambda\text{CDM} + m_\nu$	CMB+H0	≤ 0.45

COMBINE COSMO-DATA & OSCILLATIONS

Gonzalez-Garcia, Maltoni , Slavado, 1008.3795

		Cosmo+Oscillations 95% Ranges		
Model	Observables	m_{ν_e} (eV)	m_{ee} (eV)	Σm_ν (eV)
$o\omega$CDM $+\Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+BAO	N [0.0047 – 0.51] I [0.047 – 0.51]	N [0.00 – 0.51] I [0.014 – 0.51]	N [0.056 – 1.5] I [0.098 – 1.5]
$o\omega$CDM $+\Delta N_{\rm rel} + m_\nu$	CMB+HO+SN+LSSPS	N [0.0047 – 0.27] I [0.047 – 0.27]	N [0.00 – 0.25] I [0.014 – 0.25]	N [0.056 – 0.75] I [0.098 – 0.76]
ΛCDM $+ m_\nu$	CMB+H0+SN+BAO	N [0.0047 – 0.20] I [0.048 – 0.21]	N [0.00 – 0.20] I [0.014 – 0.21]	N [0.056 – 0.61] I [0.097 – 0.61]
ΛCDM $+ m_\nu$	CMB+H0+SN+LSSSP	N [0.0047 – 0.12] I [0.047 – 0.12]	N [0.00 – 0.12] I [0.014 – 0.12]	N [0.056 – 0.36] I [0.098 – 0.36]
ΛCDM $+ m_\nu$	CMB (+SN)	N [0.0047 – 0.40] I [0.047 – 0.40]	N [0.00 – 0.40] I [0.014 – 0.41]	N [0.056 – 1.2] I [0.098 – 1.2]
ΛCDM $+ m_\nu$	CMB+BAO	N [0.0052 – 0.25] I [0.047 – 0.25]	N [0.00 – 0.25] I [0.014 – 0.25]	N [0.056 – 0.75] I [0.099 – 0.75]
ΛCDM $+ m_\nu$	CMB+LSSPS	N [0.0047 – 0.18] I [0.048 – 0.19]	N [0.00 – 0.18] I [0.014 – 0.19]	N [0.056 – 0.55] I [0.099 – 0.55]
ΛCDM $+ m_\nu$	CMB+H0	N [0.0047 – 0.14] I [0.047 – 0.16]	N [0.00 – 0.14] I [0.014 – 0.16]	N [0.056 – 0.44] I [0.097 – 0.45]

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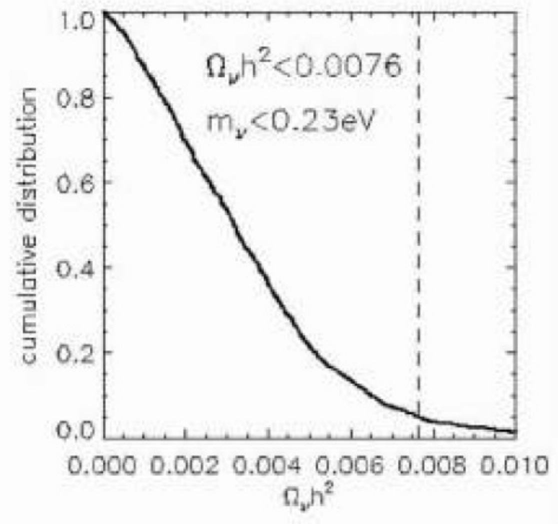

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Model dependence…

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WMAP excludes HOT Dark Matter

Caution:
FRW- Comology &
local Lorentz
invariance **assumed.**
If Lorentz violated (TeVeS)
ν of 2 eV mass could have
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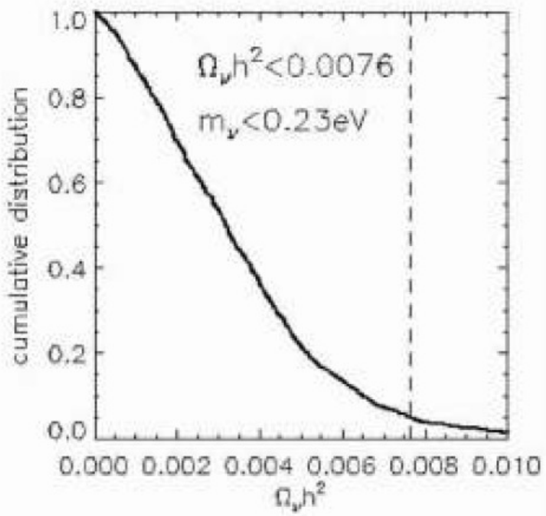
(Dodelson-Liguori 2006)



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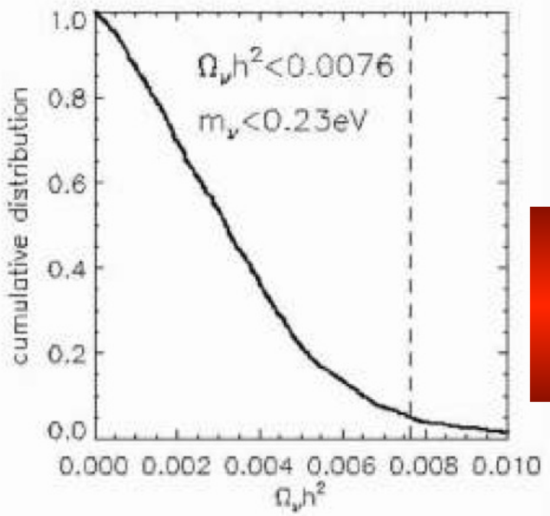

BUT…TeVeS excluded by Gravitational Lensing Data (Sakellariadou,Yusaf, NEM)

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Sterile neutrinos and DARK MATTER

Light Sterile Neutrinos (mass > keV) may provide good dark Matter Candidates

Davidson, Widrow, Shi, Fuller, Dolgov, Hansen, Abazajian, Patel, Tucker …

To be DM : life time > age of Universe

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νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

Lightest of singlet fermions N_1 plays thar role

Coupling with SM matter: superweak

$$\theta_1 G_F = \sum_{\alpha=e,\mu,\tau} \frac{v^2 |F_{\alpha I}|^2}{M_1^2}$$

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$$\theta_1^2 \lesssim 1.8\times10^{-5}\left(\frac{\text{keV}}{M_1}\right)^5,$$

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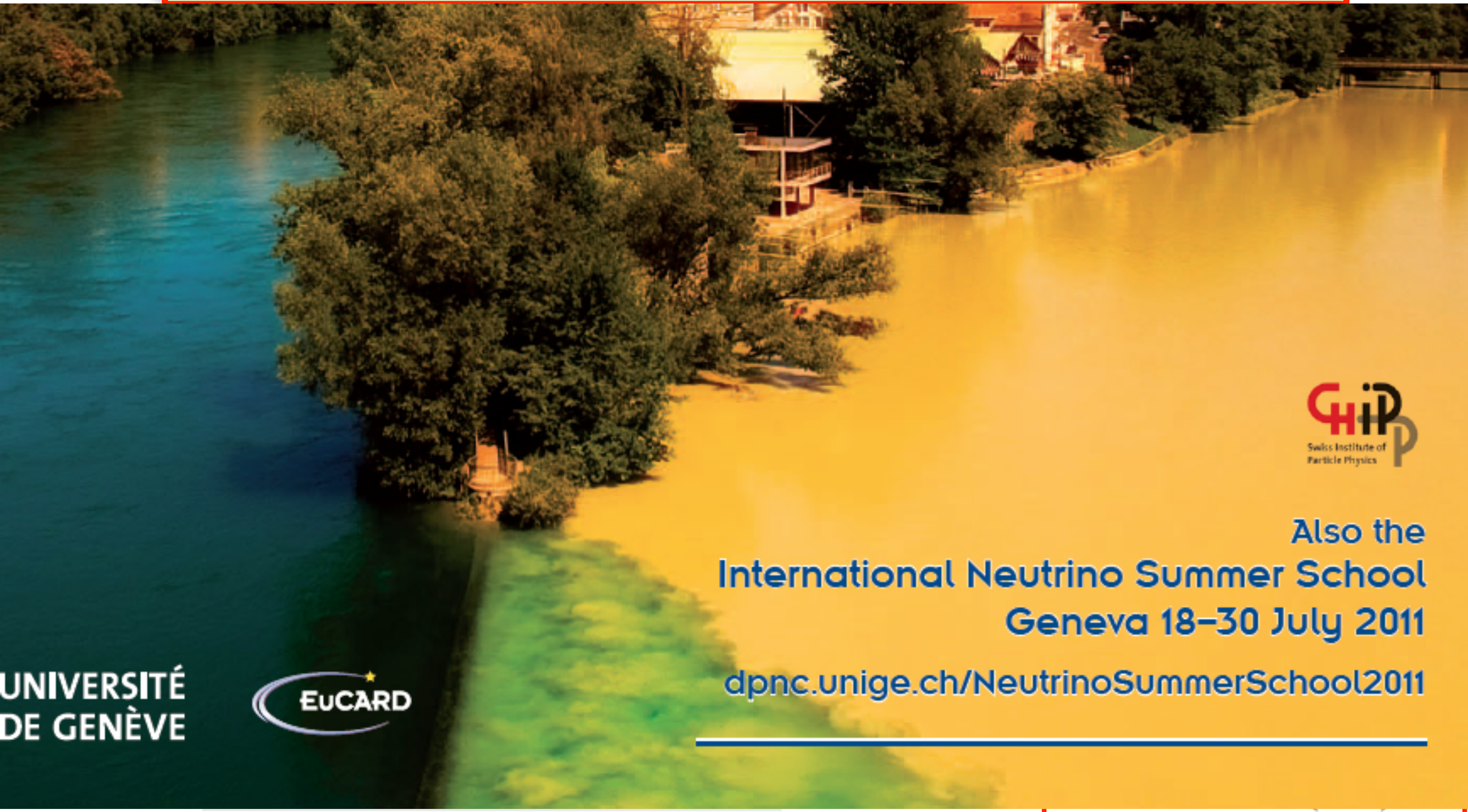

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mass contribution smaller than solar mass diff experimental error

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νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

$$\Delta m^2_{\rm sol} = 7.65^{+0.23}_{-0.20} \times 10^{-5}\,{\rm eV}^2$$

$$\Delta m^2_{\rm atm} = 2.40^{+0.12}_{-0.11} \times 10^{-3}\,{\rm eV}^2$$

$$M_1 \geq \ 2\ {\rm keV} \Rightarrow$$

mass contribution smaller than solar mass diff experimental error

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

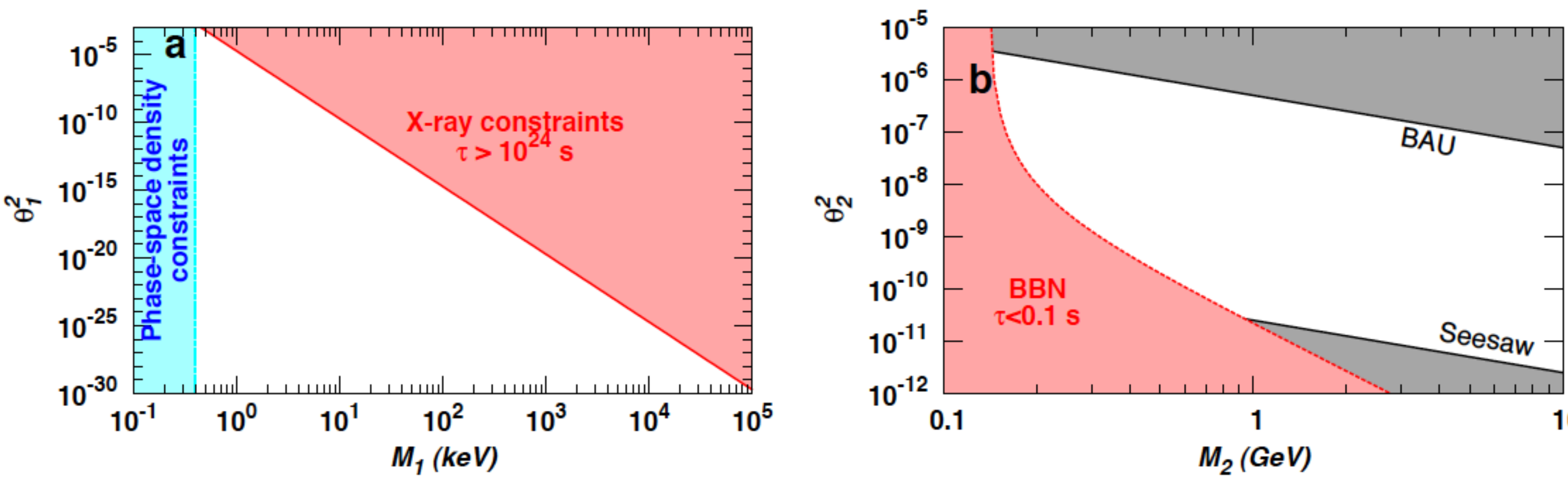
$$\delta m_\nu \sim \theta_1^2 M_1$$

Contributions to mass matrix of active neutrinos

More than one sterile neutrino needed to reproduce Observed oscillations

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…



Constraints on two heavy degenerate singlet neutrinos

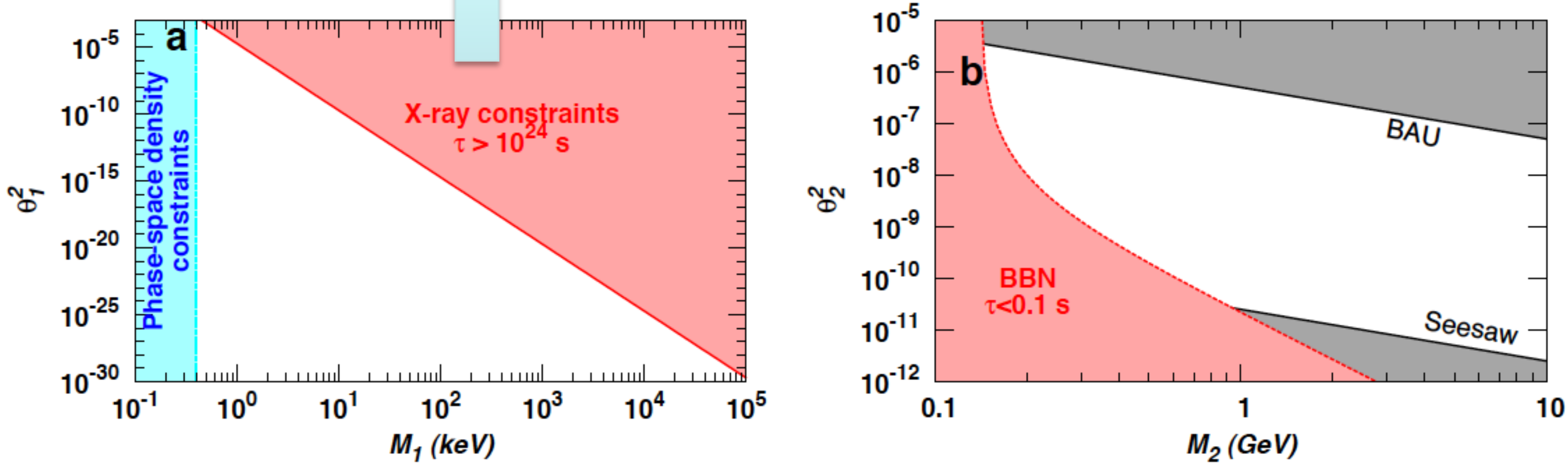
N_1 DM production estimation in Early Universe must take into account its interactions with $N_{2,3}$ heavy neutrinos

More than one sterile neutrino needed to reproduce Observed oscillations

νMSM

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

Boyarski, Ruchayskiy, Shaposhnikov…



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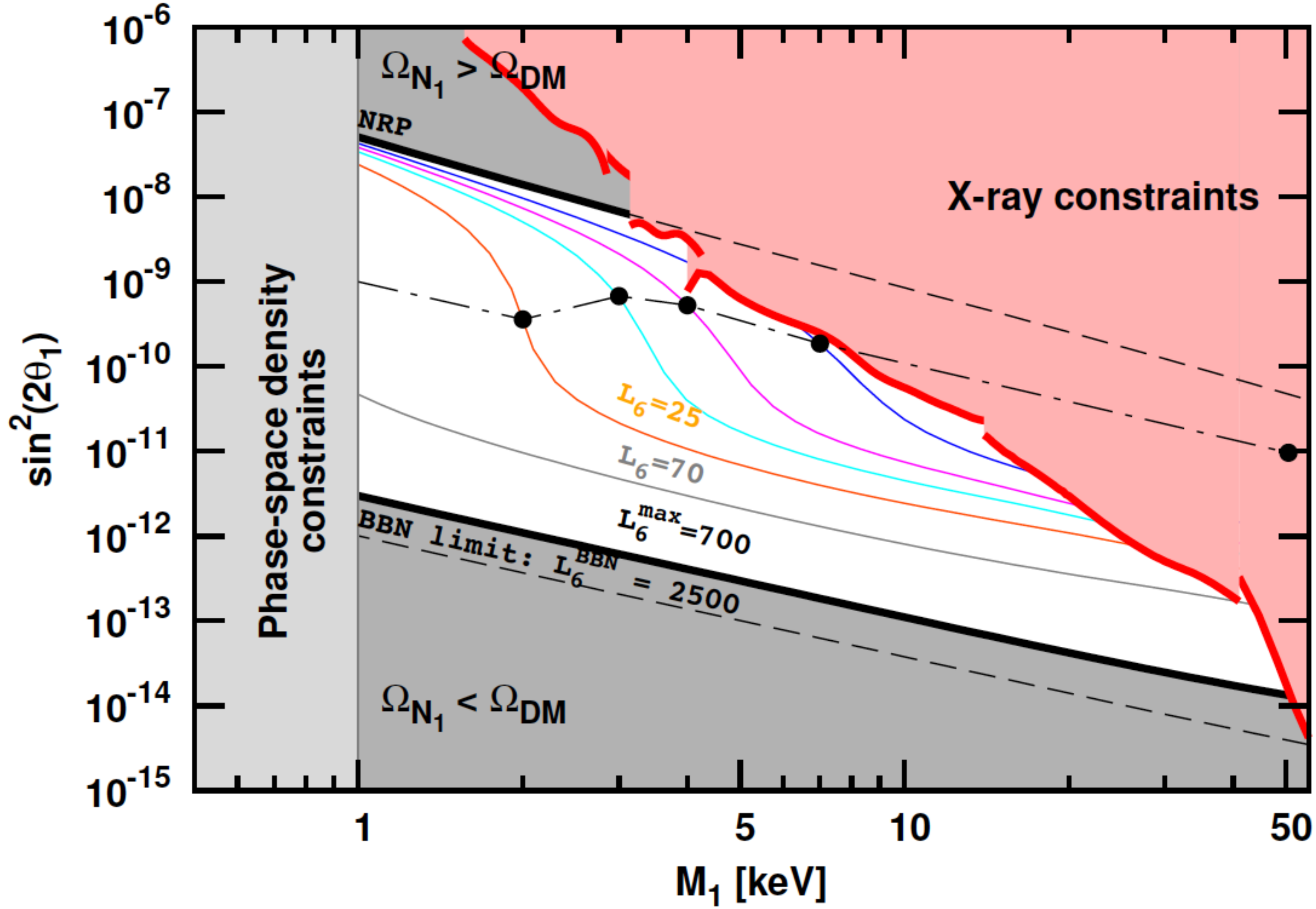
Boyarski, Ruchayskiy, Shaposhnikov…

MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS



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

PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

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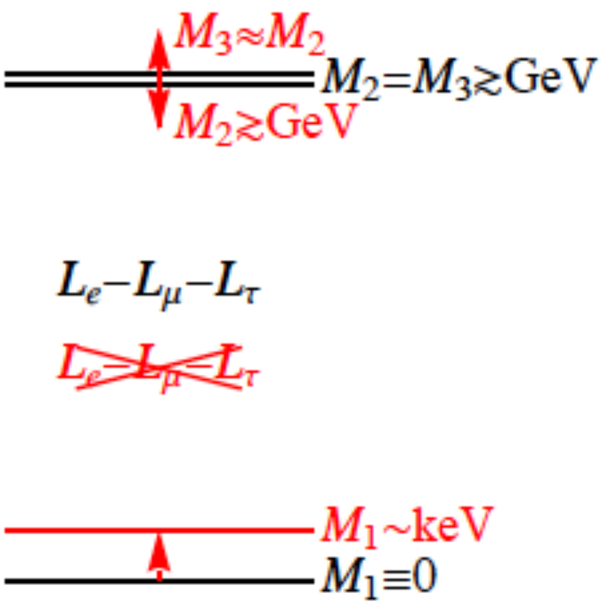
MICROSCOPIC EXPLANATIONS?

(I) ***FLAVOUR SYMMETRIES :*** $M_1 = 0$ if symmetry unbroken,
Breaking of global
Lepton symmetry generate
singlet fermion mass hierarchy



Shaposhnikov
Lindner, Merle, Niro

e.g. GUT models

Mohapatra, Senjanovic, Ross…

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

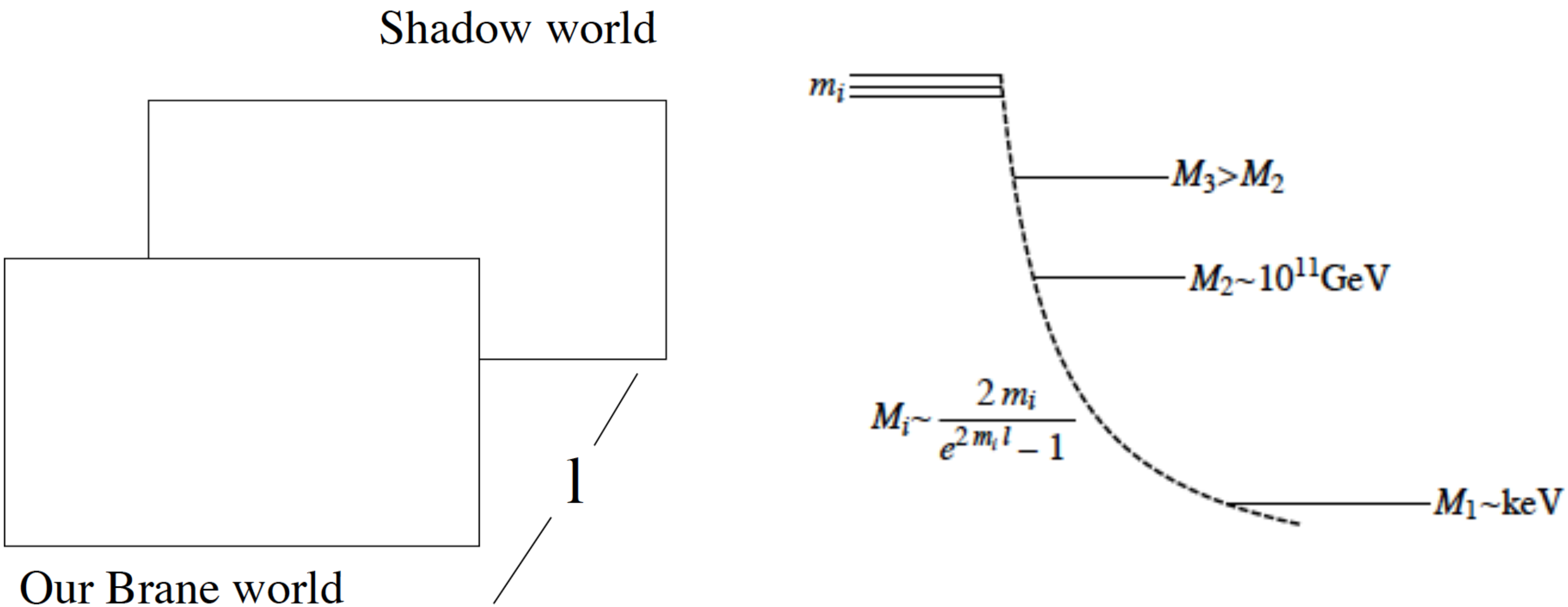
PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

(II) BRANE WORLD RANDALL-SUNDRUM MODELS:

Exponential Mass Suppression

Kushenko, Takahashi,Yanagida



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PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

Merle Niro
Barry, Rodejohann, Zhang

(III) FROGATT – NIELSEN MECHANISM :

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

$$\mathcal{L}_{\rm leptons} = -Y_e^{ij}\,\overline{e_{iR}}\,H\,L_{jL}\left(\frac{\Theta}{\Lambda}\right)^{k_i+f_j} + h.c. - Y_D^{ij}\,\overline{N_{iR}}\,\tilde{H}\,L_{jL}\left(\frac{\Theta}{\Lambda}\right)^{g_i+f_j} + h.c.$$

$$-\frac{1}{2}\,\overline{N_{iR}}\,\tilde{M}_R^{ij}\,(N_{jR})^C\left(\frac{\Theta}{\Lambda}\right)^{g_i+g_j} + h.c. - \frac{1}{2}Y_L^{ij}\,\overline{(L_{iL})^C}\,(i\sigma_2\Delta)\,L_{jL}\left(\frac{\Theta}{\Lambda}\right)^{f_i+f_j} + h.c.$$

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``*Flavon*'' field $\langle\Theta\rangle$

$\lambda = \frac{\langle\Theta\rangle}{\Lambda}$ being a small quantity of the order of the Cabibbo angle: $\lambda \simeq 0.22$

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Field	L_{iL}	$\overline{e_{iR}}$	$\overline{N_{iR}}$	H	Δ	Θ
$SU(2)_L$	$\underline{\mathbf{2}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$
$U(1)_{FN}$	f_i	k_i	g_i	0	0	-1

MASS MATRICES

Charged lepton

$$M_e = v \begin{pmatrix} Y_e^{11}\,\lambda^{|k_1+f_1|} & Y_e^{12}\,\lambda^{|k_1+f_2|} & Y_e^{13}\,\lambda^{|k_1+f_3|} \\ Y_e^{21}\,\lambda^{|k_2+f_1|} & Y_e^{22}\,\lambda^{|k_2+f_2|} & Y_e^{23}\,\lambda^{|k_2+f_3|} \\ Y_e^{31}\,\lambda^{|k_3+f_1|} & Y_e^{32}\,\lambda^{|k_3+f_2|} & Y_e^{33}\,\lambda^{|k_3+f_3|} \end{pmatrix}$$

Dirac neutrino

$$m_D = v \begin{pmatrix} Y_D^{11}\,\lambda^{|g_1+f_1|} & Y_D^{12}\,\lambda^{|g_1+f_2|} & Y_D^{13}\,\lambda^{|g_1+f_3|} \\ Y_D^{21}\,\lambda^{|g_2+f_1|} & Y_D^{22}\,\lambda^{|g_2+f_2|} & Y_D^{23}\,\lambda^{|g_2+f_3|} \\ Y_D^{31}\,\lambda^{|g_3+f_1|} & Y_D^{32}\,\lambda^{|g_3+f_2|} & Y_D^{33}\,\lambda^{|g_3+f_3|} \end{pmatrix}$$

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MASS MATRICES

Right-handed Neutrino sector

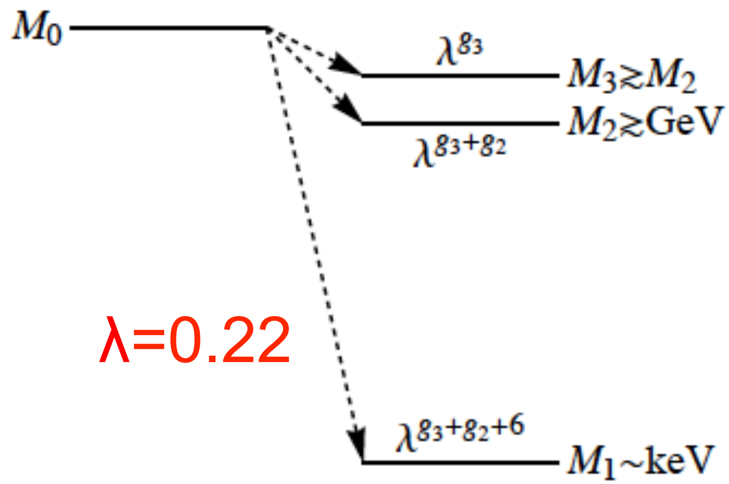
$$M_R = \begin{pmatrix} \tilde{M}_R^{11}\,\lambda^{|2g_1|} & \tilde{M}_R^{12}\,\lambda^{|g_1+g_2|} & \tilde{M}_R^{13}\,\lambda^{|g_1+g_3|} \\ \bullet & \tilde{M}_R^{22}\,\lambda^{|2g_2|} & \tilde{M}_R^{23}\,\lambda^{|g_2+g_3|} \\ \bullet & \bullet & \tilde{M}_R^{33}\,\lambda^{|2g_3|} \end{pmatrix}$$

then via see-saw

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

MASS HIERARCHY ($N_1 << N_{2,3}$) AMON

M_R	Eigenvalues
$\begin{pmatrix} A\,\lambda^6 & A\,\lambda^3 & A\,\lambda^3 \\ A\,\lambda^3 & A & B \\ A\,\lambda^3 & B & A \end{pmatrix}$	$M_1 = \mathcal{O}(\lambda^6) \simeq \mathcal{O}(\text{keV})$ $M_2 = A - B \simeq \mathcal{O}(\text{GeV})$ $M_3 = A + B \simeq \mathcal{O}(\text{GeV})$
$\begin{pmatrix} A\,\lambda^6 & A\,\lambda^3 & A\,\lambda^3 \\ A\,\lambda^3 & B & C \\ A\,\lambda^3 & C & B \end{pmatrix}$	$M_1 = \mathcal{O}(\lambda^6) \simeq \mathcal{O}(\text{keV})$ $M_2 = B - C \simeq \mathcal{O}(\text{GeV})$ $M_3 = B + C \simeq \mathcal{O}(\text{GeV})$
$\begin{pmatrix} A\,\lambda^6 & B\,\lambda^3 & B\,\lambda^3 \\ B\,\lambda^3 & C & D \\ B\,\lambda^3 & D & C \end{pmatrix}$	$M_1 = \mathcal{O}(\lambda^6) \simeq \mathcal{O}(\text{keV})$ $M_2 = C - D \simeq \mathcal{O}(\text{GeV})$ $M_3 = C + D \simeq \mathcal{O}(\text{GeV})$



Field	L_{iL}	$\overline{e_{iR}}$	$\overline{N_{iR}}$	H	Δ	Θ
$SU(2)_L$	$\underline{\mathbf{2}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$
$U(1)_{FN}$	f_i	k_i	g_i	0	0	-1

Right-handed Neutrino sector

$$M_R = \begin{pmatrix} \tilde{M}_R^{11}\,\lambda^{|2g_1|} & \tilde{M}_R^{12}\,\lambda^{|g_1+g_2|} & \tilde{M}_R^{13}\,\lambda^{|g_1+g_3|} \\ \bullet & \tilde{M}_R^{22}\,\lambda^{|2g_2|} & \tilde{M}_R^{23}\,\lambda^{|g_2+g_3|} \\ \bullet & \bullet & \tilde{M}_R^{33}\,\lambda^{|2g_3|} \end{pmatrix}$$

then via see-saw

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

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

PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

Merle Niro
Barry, Rodejohann, Zhang

(III) FROGATT – NIELSEN MECHANISM :

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

Field	L_{iL}	$\overline{e_{iR}}$	$\overline{N_{iR}}$	H	Δ	Θ
$SU(2)_L$	$\underline{\mathbf{2}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{3}}$	$\underline{\mathbf{1}}$
				0	0	-1

$|g_1+g_3|$

$|g_2+g_3|$

$|2g_3|$

BUT… presently Lack of High Energy (UV) COMPLETION

(IV) BEYOND SEE-SAW ? UV complete models?

Mavromatos, Pilaftsis
arXiv: 1209.6387
(PRD 86, 124038 (2012))

ANOMALOUS GENERATION OF RIGHT-HANDED MAJORANA NEUTRINO MASSES THROUGH TORSIONFUL QUANTUM GRAVITY

- Field Theories with (Kalb-Ramond) torsion & axion fields : *String inspired models, loop quantum gravity effective field theories …*

UV complete models

- Majorana Neutrino Masses from (three-loop) ***anomalous*** terms with axion-neutrino couplings

Microscopic UV complete underlying theory of quantum gravity :

STRINGS

Massless Gravitational multiplet of (closed) strings: **spin 0 scalar (dilaton)**
spin 2 traceless symmetric rank 2 tensor (graviton)
spin 1 antisymmetric rank 2 tensor

KALB-RAMOND FIELD $B_{\mu\nu} = -B_{\nu\mu}$

Effective field theories (low energy scale E << M_s) `` gauge" invariant

$$B_{\mu\nu} \to B_{\mu\nu} + \partial_{[\mu}\theta(x)_{\nu]}$$

Depend only on field strength : $H_{\mu\nu\rho} = \partial_{[\mu}B_{\nu\rho]}$

Bianchi identity :

$$\partial_{[\sigma}H_{\mu\nu\rho]} = 0 \to d \star \mathbf{H} = 0$$

Anomaly (gravitational vs gauge) **cancellation** in strings require redefinition of H so that Bianchi identity now is extended to :

$$\mathbf{H} = \mathbf{d}\ \mathbf{B} + \frac{\alpha'}{8\kappa}\Big(\Omega_L - \Omega_V\Big)$$

$$\kappa^2 = 8\pi G_N = \frac{8\pi}{M_P^2}$$

Lorentz (L) & Gauge (V) Chern-Simons three forms

EXTENDED BIANCHI IDENTITY

$$\mathbf{d}\ \mathbf{H} = \frac{\alpha'}{8\kappa}\mathrm{Tr}\Big(\mathbf{R}\wedge\mathbf{R} - \mathbf{F}\wedge\mathbf{F}\Big)$$

ROLE OF H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT CAN BE EXPRESSED IN TERMS OF ***A GENERALIZED CURVATURE*** RIEMANN TENSOR WHERE THE CHRISTOFFEL CONNECTION INCLUDES ***TORSION*** PROVIDED BY **H-FIELD**

4-DIM PART

$$S^{(4)} = \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}H^{\mu\nu\rho}\Big)$$
$$= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R} - \frac{1}{3}\kappa^2 H_{\mu\nu\rho}H^{\mu\nu\rho}\Big)$$

$$\overline{\Gamma}^{\mu}_{\nu\rho} = \Gamma^{\mu}_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^{\mu}_{\nu\rho} \neq \overline{\Gamma}^{\mu}_{\rho\nu}$$

IN 4-DIM DEFINE DUAL OF H AS $\mathbf{Y} = {}^\star\mathbf{H}$

$$Y_\sigma = -3\sqrt{2}\partial_\sigma b = \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

Pseudoscalar
(Kalb-Ramond (KR) axion)

IN 4-DIM DEFINE DUAL OF H AS $\mathbf{Y} = {}^{\star}\mathbf{H}$

$$Y_\sigma = -3\sqrt{2}\partial_\sigma b = \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

REWRITE EXTENDED BIANCHI IDENTITY AS

$$\nabla_\sigma Y^\sigma = \frac{\alpha'}{32\kappa}\sqrt{-g}\,\epsilon_{\mu\nu\lambda\sigma}\left(R_{ad}{}^{\mu\nu}R^{\lambda\sigma ad} - F^{\mu\nu}F^{\lambda\sigma}\right)$$

HENCE EFFECTIVE ACTION

$$S^{(4)} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2\kappa^2}R - \frac{1}{2}\partial_\mu b(x)\,\partial^\mu b(x) + \frac{\alpha'\sqrt{2}}{192\kappa}b(x)\,\epsilon_{\mu\nu\rho\lambda}\left(R_{ad}{}^{\mu\nu}R^{\rho\lambda ad} - F^{\mu\nu}F^{\rho\lambda}\right)\Big]$$

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$b R\tilde{R}$ coupling

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cf. axion-electromagentic field coupling

$$a(x)F_{\mu\nu}\tilde{F}^{\mu\nu} = a(x)\vec{E}\cdot\vec{B}$$

$- F^{\mu\nu}F^{\lambda\sigma}\Big)$

${}^{\mu}b(x)\big)$

$$+\frac{\alpha'\sqrt{2}}{192\kappa}b(x)\,\epsilon_{\mu\nu\rho\lambda}\Big(R_{ad}{}^{\mu\nu}R^{\rho\lambda ad} - F^{\mu\nu}F^{\rho\lambda}\Big)\Big]$$

$bR\tilde{R}$ coupling

NB: Torsion Couples to fermions via gravitational covariant derivative → integrating out torsion in path integral results in extra **fermion-fermion-axial current interactions**

$$\int Db \, \exp\left[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^{\star}\mathrm{d}b - \frac{1}{f_b} bG(\mathbf{A},\omega) + \frac{1}{2f_b^2}\mathbf{J}^5\wedge\mathbf{J}^5\right]$$

$$J^5_\mu = \overline{\psi}\,\gamma_\mu\,\gamma_5\,\psi$$

$$f_b = (3\kappa^2/8)^{-1/2} = \frac{M_P}{\sqrt{3\pi}}$$

$$\nabla_\mu J^{5\mu} = \frac{e^2}{8\pi^2} F^{\mu\nu}\widetilde{F}_{\mu\nu} - \frac{1}{192\pi^2} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} \equiv G(\mathbf{A},\omega)\,.$$

Quantum anomaly (1-loop) equation

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$$J^5_\mu = \overline{\psi}\, \gamma_\mu \ldots \qquad \ldots \frac{M_P}{\sqrt{3\pi}}$$

$$\nabla_\mu J^{5\mu} = \ldots \rho\sigma$$

$$\equiv \ldots$$

above effective action generic… in loop quantum gravity *etc* → b-field implements constraint of Bianchi identity (conservation of quantum torsion ``charge'')

…p) equation

Mavromatos, Pilaftsis arXiv: 1209.6387

ANOMALOUS MAJORANA NEUTRINO MASS TERMS from QUANTUM TORSION

SHIFT SYMMETRY b(x) → b(x) + c

$c\, R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma}$ and $c\, F^{\mu\nu}\widetilde{F}_{\mu\nu}$. total derivatives

OUR SCENARIO ***Break*** such ***shift symmetry*** by coupling first b(x) to another pseudoscalar field such as QCD axion a(x) (or e.g. other string axions)

$$
\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} + \frac{1}{2f_b^2} J^5_\mu J^{5\mu} + \gamma(\partial_\mu b)\,(\partial^\mu a) + \frac{1}{2}(\partial_\mu a)^2 - y_a i a\left(\overline{\psi}_R^{\ C}\psi_R - \overline{\psi}_R\psi_R^{\ C}\right)\Big]\,,
$$

Mavromatos, Pilaftsis arXiv: 1209.6387

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Yukawa

neutrino fields

Field redefinition

$$b(x) \to b'(x) \equiv b(x) + \gamma a(x)$$

so, effective action becomes

$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b')^2 + \frac{1}{2}\left(1-\gamma^2\right)(\partial_\mu a)^2 + \frac{1}{2f_b^2}J^5_\mu J^{5\mu} + \frac{b'(x) - \gamma a(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} - y_a i a\left(\overline{\psi}_R^C\psi_R - \overline{\psi}_R\psi_R^C\right)\Big] \,.$$

must have $|\gamma| < 1$ *otherwise axion field a(x) appears as a ghost* → *canonically normalised kinetic terms*

$$\mathcal{S}_a = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu a)^2 - \frac{\gamma a(x)}{192\pi^2 f_b\sqrt{1-\gamma^2}} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} - \frac{i y_a}{\sqrt{1-\gamma^2}}\, a\left(\overline{\psi}_R^C\psi_R - \overline{\psi}_R\psi_R^C\right) + \frac{1}{2f_b^2}J^5_\mu J^{5\mu}\Big] \,.$$

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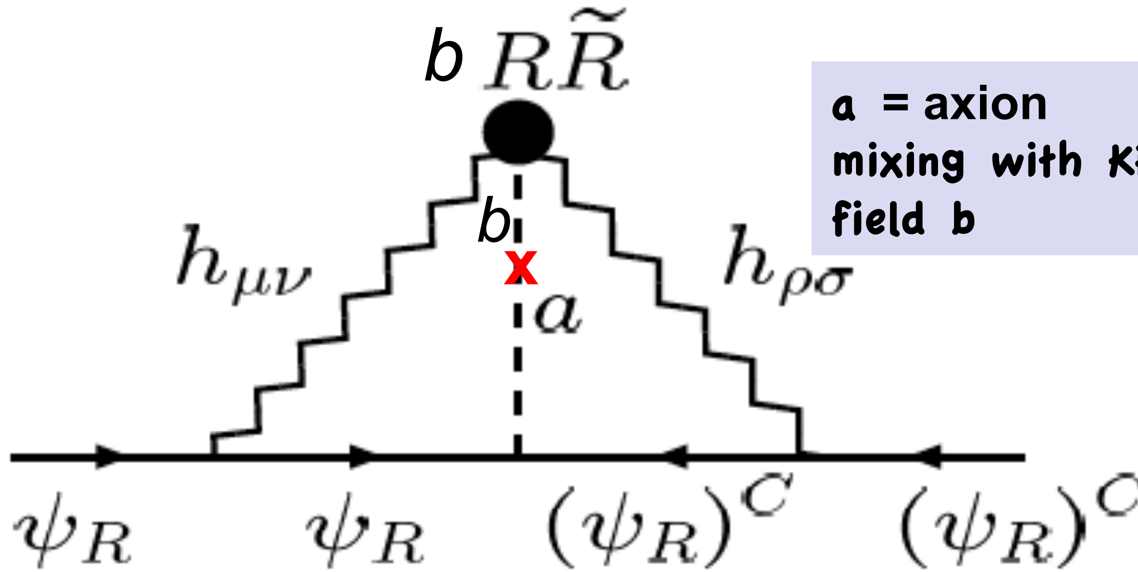
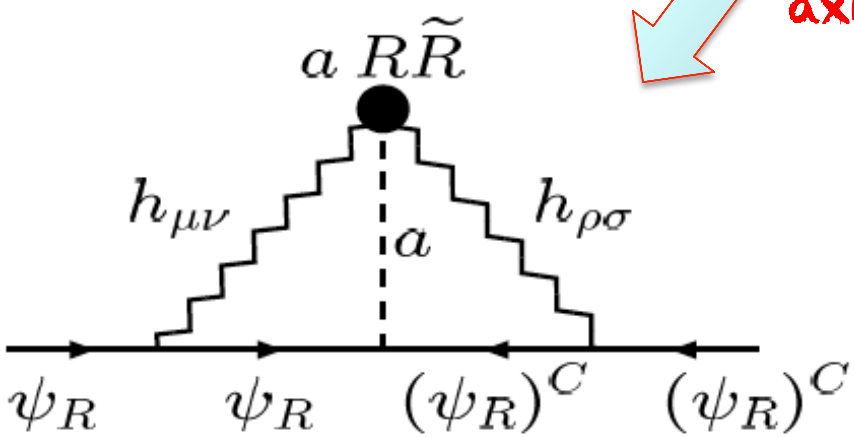
CHIRALITY CHANGE

NEM, Pilaftsis arXiv: 1209.6387

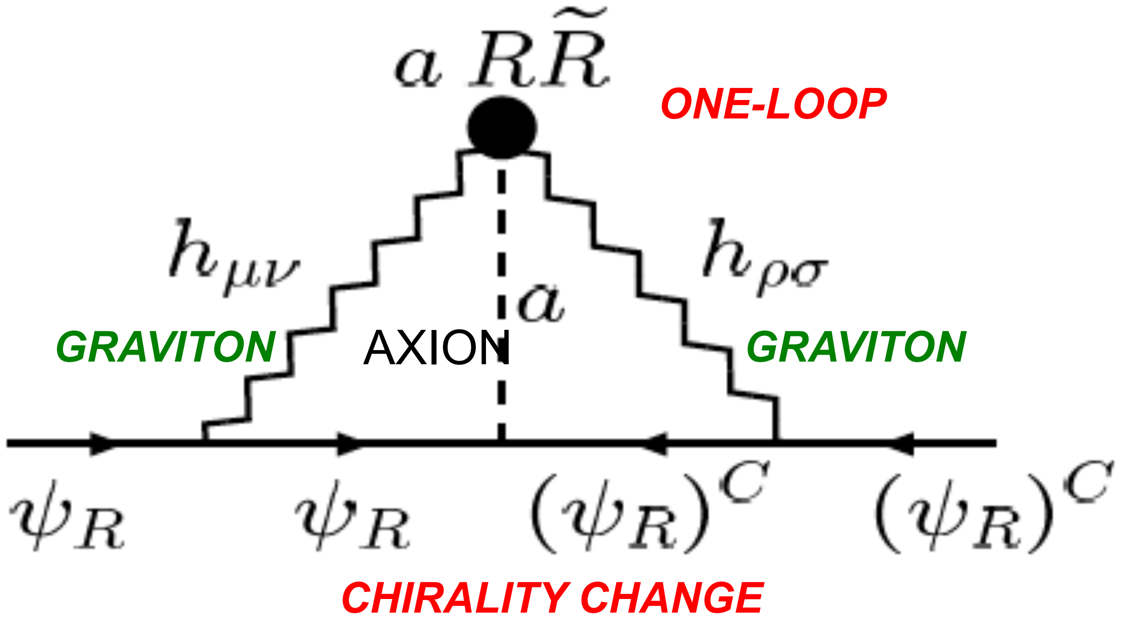


a = axion mixing with KR field b

axion field redefinition



THREE-LOOP ANOMALOUS FERMION MASS TERMS



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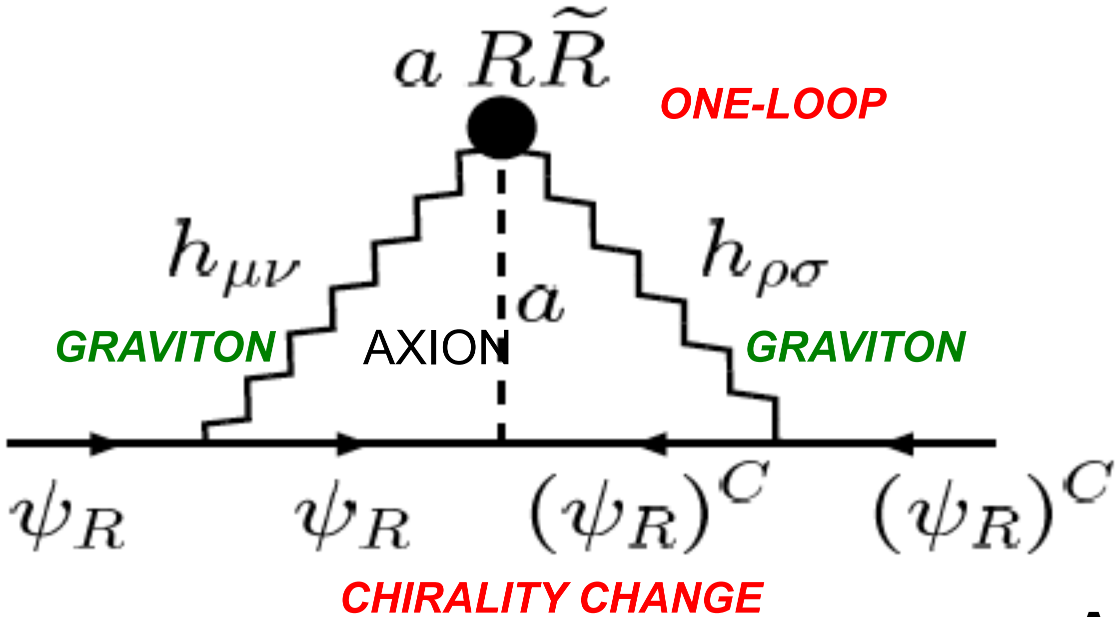

Λ = UV cutoff

$$M_R \sim \frac{1}{(16\pi^2)^2}\,\frac{y_a\,\gamma\,\kappa^4\Lambda^6}{192\pi^2 f_b(1-\gamma^2)} = \frac{\sqrt{3}\,y_a\,\gamma\,\kappa^5\Lambda^6}{49152\sqrt{8}\,\pi^4(1-\gamma^2)}$$

SOME NUMBERS

$\Lambda = 10^{17}$ GeV

$\gamma = 0.1$

M_R is at the TeV

for $y_a = 10^{-3}$

$\Lambda = 10^{16}$ GeV

$M_R \sim 16$ keV,

$y_a = \gamma = 10^{-3}$

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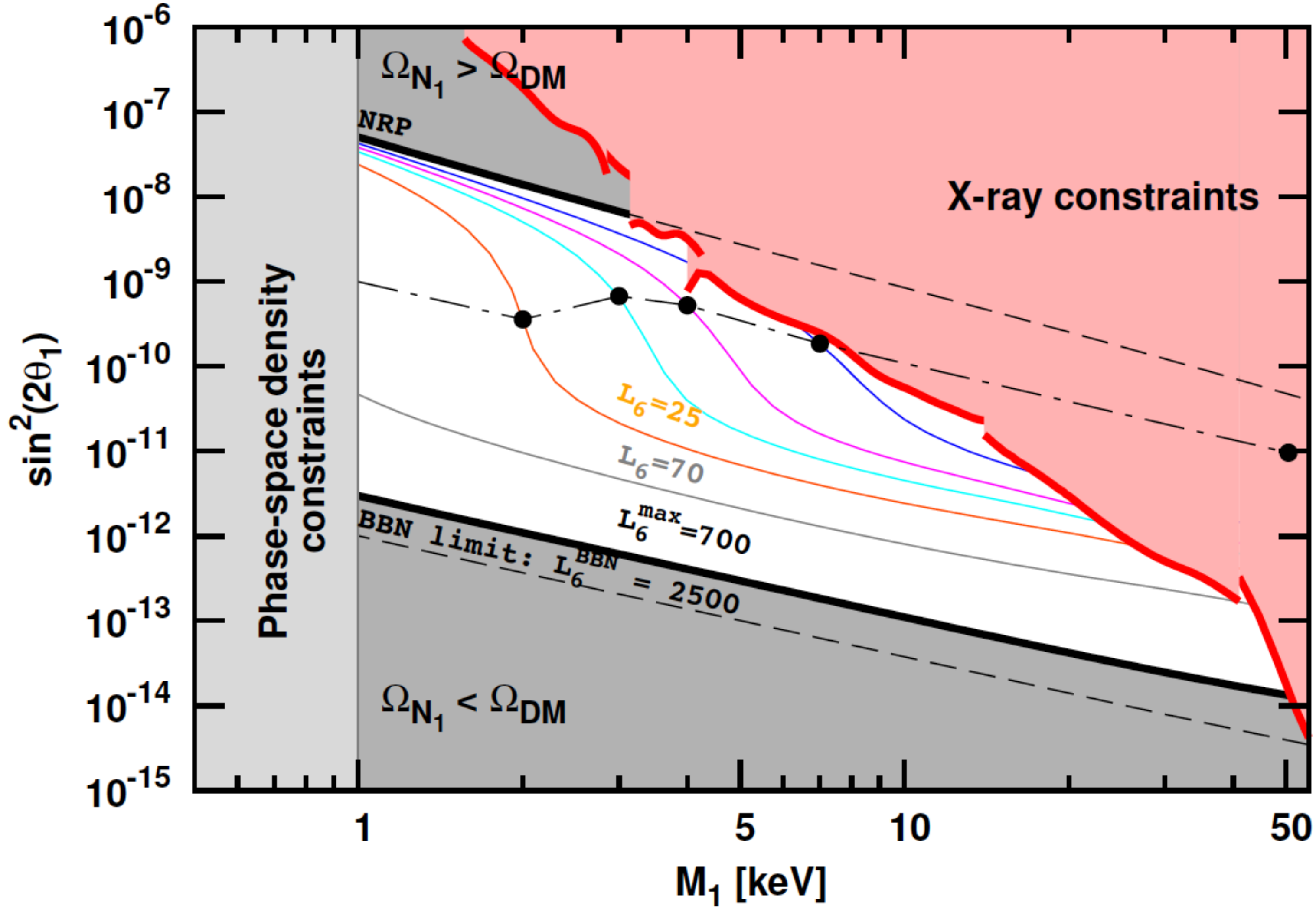
INTERESTING WARM DARK MATTER REGIME

Appropriate Hierarchy for the other two massive Right-handed neutrinos for Leptogenesis-Baryogenesis & Dark matter cosntraints can be arranged by choosing Yukawa couplings

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

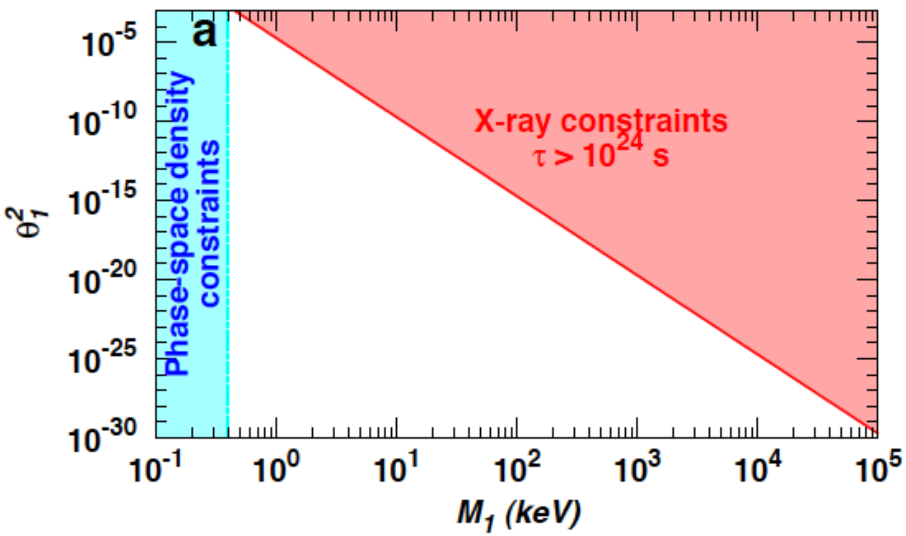
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS

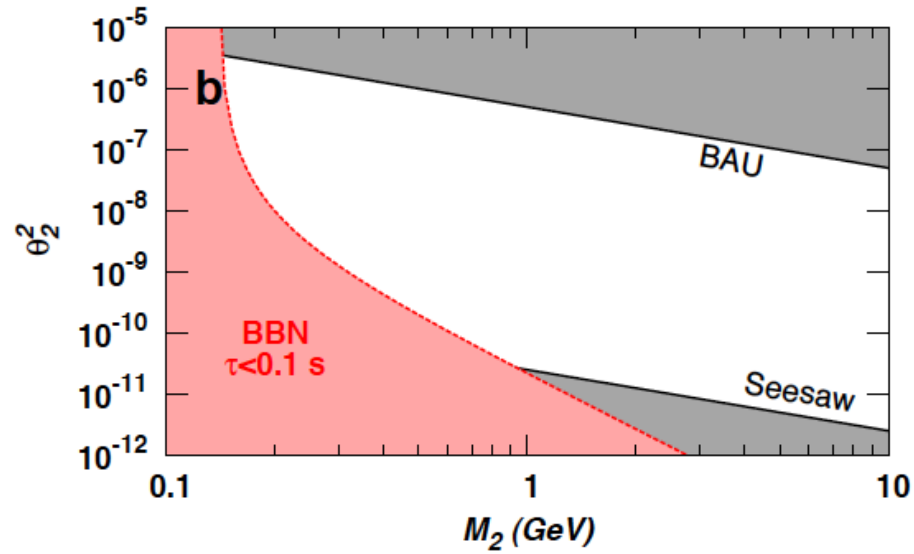


More than one sterile neutrino needed to reproduce Observed oscillations

νMSM

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

FINITENESS OF THE MASS

MULTI-AXION SCENARIOS (e.g. string axiverse)

$$\mathcal{S}_a^{\rm kin} = \int d^4x \sqrt{-g} \left[\frac{1}{2} \sum_{i=1}^{n} \left((\partial_\mu a_i)^2 - M_i^2 \right) + \gamma (\partial_\mu b)(\partial^\mu a_1) - \frac{1}{2} \sum_{i=1}^{n-1} \delta M_{i,i+1}^2 \, a_i a_{i+1} \right] ;$$

$$\delta M_{i,i+1}^2 \; < \; M_i M_{i+1}$$

positive mass spectrum
for all axions

simplifying all mixing equals

$$M_R \sim \frac{\sqrt{3}\, y_a \, \gamma \, \kappa^5 \Lambda^{6-2n} (\delta M_a^2)^n}{49152\sqrt{8}\, \pi^4 (1-\gamma^2)} \qquad n \leq 3$$

$$M_R \sim \frac{\sqrt{3}\, y_a \, \gamma \, \kappa^5 (\delta M_a^2)^3}{49152\sqrt{8}\, \pi^4 (1-\gamma^2)} \, \frac{(\delta M_a^2)^{n-3}}{(M_a^2)^{n-3}} \quad n > 3$$

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M_R: UV finite for n=3 @ 2-loop independent of axion mass

In this gravitationally-induced right-handed neutrino mass scenario the ordinary (active) neutrinos are supposed to acquire their Majorana masses via standard Yukawa couplings & see-saw type mechanisms

$$y_e \overline{\nu_e}_R \left(i\tau_2\, \phi^\star \right)^\dagger \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \text{h.c.} + \text{other flavours}$$

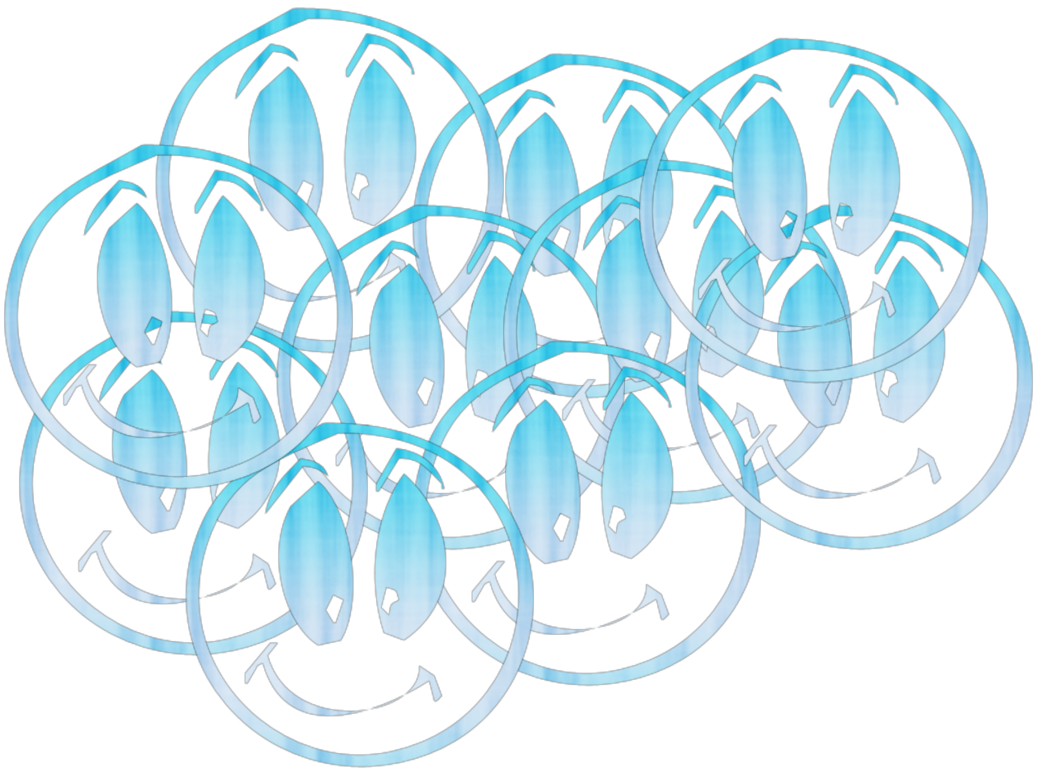
More thoughts and detailed analyses required...

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

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

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

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



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

e.g. through heavy scalar exchange $\mathcal{C} = \frac{f^2}{m_S^2}$

$$H_I = -\mathcal{C}\, (\overline{\nu_M}\, \nu_M)\, (\overline{\nu_M}\, \nu_M)$$

$$\nu_M = \lambda \nu_R + \nu^c{}_L$$

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

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

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Dirac light masses of O(0.1) eV

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

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

pseudo Dirac light neutrino

Model consistent with solar neutrino data

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

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

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

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

$$H_I = -C\,(\overline{\nu_M}\,\nu_M)\,(\overline{\nu_M}\,\nu_M)$$

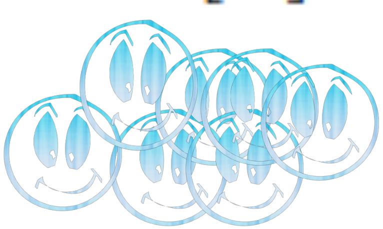
e.g. through heavy scalar exchange $C = \frac{f^2}{m_S^2}$

$$\nu_M = \lambda \nu_R + \nu^c{}_L$$

One light sterile Majorana neutrino forms condensate

$$\nu_M = \begin{bmatrix} \chi \\ \lambda \overline{\chi} \end{bmatrix}$$

$$H_1^{MF} = -2\,C\left[\lambda^{*2}\,\overline{\chi}_a^{\dagger}\,\chi_b\,D + \lambda^2\,\chi_a^{\dagger}\,\overline{\chi}_b\,D^*\right]\epsilon_{ab}\,.$$



$$\langle \chi_a\,\overline{\chi}_b^{\dagger}\rangle = \epsilon_{ab}\,D$$

→ Coherence length,
Gap Equation in FRW backgrounds
Dark Energy contribution

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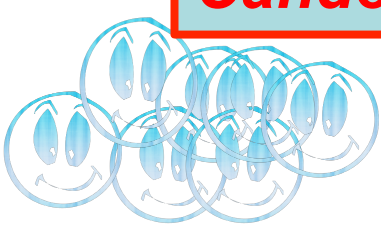
$\nu_M =$ … …trino forms condensate

$\nu_M =$ … $+ \lambda^2\, \chi_a^\dagger\, \overline{\chi}_b\, D^*\big]\, \epsilon_{ab}\,.$

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)



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…oherence length, Gap Equation in FRW backgrounds ***Dark Energy*** contribution

PART III
CPT VIOLATION IN THE EARLY UNIVERSE & NEUTRINOS

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

Schwinger, Pauli, Luders, Jost, Bell revisited by: Greenberg, Chaichian, Dolgov, Novikov…

(ii)-(iv) Independent reasons for violation

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e.g. due to ***Quantum Gravity*** fluctuations,
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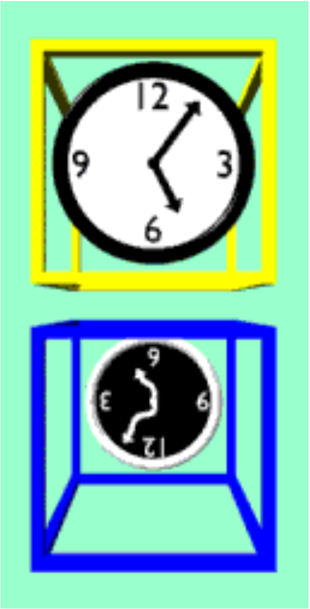

physics.indiana.edu

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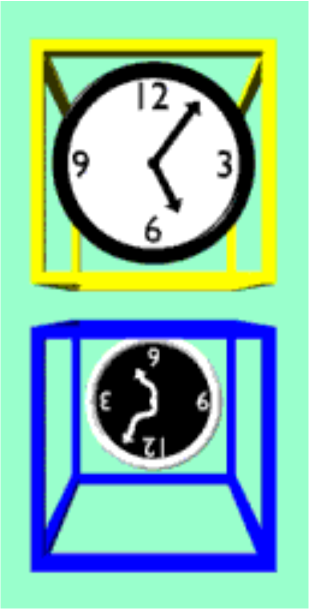

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ONE POSSIBILITY:

particle-antiparticle mass differences

$$m \neq \overline{m}$$

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

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

$$m \neq \overline{m}$$

$$\delta m = m - \overline{m}$$

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

$$E = \sqrt{p^2 + m^2},\ \bar{E} = \sqrt{p^2 + \bar{m}^2}$$

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?

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Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

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

Dolgov, Zeldovich
Dolgov (2009)

$n_\gamma = 0.24 T^3$ photon equilibrium density at temperature T

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

$$n_\gamma = 0.24 T^3$$

Dolgov (2009)

Current bound for proton-anti proton mass diff.

$$\delta m_p < 7 \cdot 10^{-10} \text{ GeV}$$

ASACUSA Coll. (2011)

Reasonable to take: $\delta m_q \sim \delta m_p$ → ***Too small $\beta^{T=0}$***

NB: To reproduce the observed $\beta^{(T=0)} = 6 \cdot 10^{-10}$ need

$$\delta m_q(T = 100 \text{ GeV}) \sim 10^{-5} - 10^{-6} \text{ GeV} >> \delta m_p$$

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CPT Violating quark-antiquark Mass difference alone CANNOT REPRODUCE observed BAU

GRAVITATIONALLY-INDUCED CPT VIOLATION

GRAVITATIONAL BACKGROUNDS GENERATING **CPT VIOLATING EFFECTS** IN THE EARLY UNIVERSE:

PARTICLE-ANTIPARTICLE DIFFERENCES IN DISPERSION RELATIONS →

Differences in populations

→ freeze out → Baryogenesis or

→ Leptogenesis → Baryogenesis

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Gravitational Baryogenesis

Davoudiasl, Kitano, Kribs, Murayama, Steinhardt

Quantum Gravity (or something else (e.g. SUGRA)) may lead at low-energies (below Plnack scale or a scale M_*) to a term in the effective Lagrangian (in curved back space-time backgrounds):

$$\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu\mathcal{R})J^\mu$$

Current *e.g.* baryon-number J_μ^B current (non-conserved in Standard Model due to anomalies)

Generation (flavour) #

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

SU(2)

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Term Violates CP but is CPT conserving *in vacuo*
It ***Violates* CPT** in the background space-time of a
expanding FRW Universe

$$\dot{\mathcal{R}} = -(1-3w)\frac{\dot{\rho}}{M_P^2} = \sqrt{3}\,(1-3w)(1+w)\frac{\rho^{3/2}}{M_P^3}$$

Energy differences between particle vs antipartic $\pm\dot{\mathcal{R}}/M_*^2$ ***Dynamical CPTV***

LIKE A CHEMICAL POTENTIAL FOR FERMIONS

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Energy differences between particle vs antipartic $\pm\dot{\mathcal{R}}/M_*^2$; ***Dynamical CPTV***

Baryon Asymmetry $\frac{n_B}{s} \approx \frac{\dot{\mathcal{R}}}{M_*^2 T}\Big|_{T_D}$

Calculate for various w in some scenarios

@ $T < T_D$, T_D = Decoupling T

GRAVITATIONAL BACKGROUNDS GENERATING **CPT VIOLATING EFFECTS** IN THE EARLY UNIVERSE:

PARTICLE-ANTIPARTICLE DIFFERENCES IN DISPERSION RELATIONS →

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REVIEW VARIOUS SCENARIOS

GRAVITATIONAL BACKGROUNDS GENERATING **CPT VIOLATING EFFECTS** IN THE EARLY UNIVERSE:

PARTICLE-ANTIPARTICLE DIFFERENCES IN DISPERSION RELATIONS →

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B-L conserving GUT
or
Sphaleron

REVIEW VARIOUS SCENARIOS

NB: (

Standard Thermal Leptogenesis

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

Heavy Right-handed Majorana neutrinos enter ***equilibrium at $T = T_{eq} > T_{decay}$***

Lepton number Violation

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

enhanced CP V

Out of Equilibrium Decays

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

Produce Lepton asymmetry

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

where

$$l_L = \begin{bmatrix} \nu_e \\ e \end{bmatrix}_L, \begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}_L, \begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix}_L$$

Equilibrated electroweak B+L violating sphaleron interactions

Independent of Initial Conditions

Observed Baryon Asymmetry In the Universe (BAU)

Estimate BAU by solving Boltzmann equations for Heavy Neutrino Abundances

CPT Violating Thermal Leptogenesis

Early Universe
$T > 10^{15}$ GeV

CPT Violation

already in thermal equilibrium

No need for **enhanced CPV** from Heavy Right-handed Majorana neutrinos?

Produce Lepton asymmetry

$$L = \frac{2}{M} l_L l_L \phi\phi + \mathrm{H.c.}$$

where

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Equilibrated electroweak B+L violating sphaleron interactions

Independent of Initial Conditions

Observed Baryon Asymmetry In the Universe (BAU)

Estimate BAU by fixing CPTV background parameters
In some models this may imply fine tuning ….

NB:)

2. CPTV Effects of different Space-Time-Curvature/Spin couplings between neutrinos/antineutrinos

B. Mukhopadhyay, U. Debnath, N. Dadhich, M. Sinha
Lambiase, Mohanty

Curvature Coupling to **fermion spin** may lead to different dispersion relations between neutrinos and antineutrinos (assumed ***dominant*** in the Early eras) in **non-spherically symmetric** geometries in the Early Universe.

Dirac Lagrangian

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a\psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \frac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\gamma\mu} e_c^\gamma e_a^\mu\right).$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\alpha\mu} e_c^\alpha e_a^\mu\right)$$

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

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for the Majorana neutrinos, above $\mathcal{L}_I$ turns out explicitly as

$$\mathcal{L}_I = \psi_L^\dagger \gamma^a \psi_L B_a, \qquad \mathcal{L}_I = -\psi_L^{c\,\dagger} \gamma^a \psi_L^c B_a$$

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For homogeneous and isotropic **Friedman-Robertson-Walker** geometries the resulting B^μ ***vanish***

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

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$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\alpha\mu} e_c^\alpha e_a^\mu\right)$$

Can be constant in a given local frame in Early Universe **axisymmetric (Bianchi) cosmologies** or **near rotating Black holes**

DISPERSION RELATIONS OF NEUTRINOS ARE *DIFFERENT* FROM THOSE OF ANTINEUTRINOS IN *SUCH* GEOMETRIES

$(p_a \pm B_a)^2 = m^2$, ± refers to chiral fields (here neutrino/antineutrino)

CPTV Dispersion relations

$$E = \sqrt{(\vec{p} - \vec{B})^2 + m^2} + B_0 \ , \quad \bar{E} = \sqrt{(\vec{p} + \vec{B})^2 + m^2} - B_0$$

but (bare) masses are equal between particle/anti-particle sectors

NOT the Effective fermion/antifermion masses (*p=0*) $m^{\rm eff}_{F\pm} = m \pm B^0$

Abundances of neutrinos in Early Universe, then, ***different*** from those of antineutrinos if $\mathbf{B_0}$ is ***non-trivial***.

Abundances of neutrinos in Early Universe *different* from those of antineutrinos if $B_0 \neq 0$

$$\Delta n = \frac{g}{(2\pi)^3} \int d^3\mathrm{p} \left[\frac{1}{1+\exp(E_\nu/T)} - \frac{1}{1+\exp(E_{\bar{\nu}}/T)} \right]$$

$$\Delta n = \frac{g}{(2\pi)^2} T^3 \int_0^\infty \int_0^\pi \left[\frac{1}{1+e^u\, e^{B_0/T}} - \frac{1}{1+e^u\, e^{-B_0/T}} \right] u^2\, d\theta\, du$$

$$u = |\vec{p}|/T$$

$$\Delta n_\nu \equiv n_\nu - n_{\bar{\nu}} \sim g^\star\, T^3 \left(\frac{B_0}{T} \right)$$

with $g^\star$ the number of degrees of freedom for the (relativistic) neutrino.

Case I: BARYOGENESIS VIA GUT LEPTOGENESIS

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star T^3 \left(\frac{B_0}{T}\right)$$

@ T = T_d (decoupling Temp. of Lepton number (L) Violating processes) there is a ***constant ratio*** of net neutrino/antineutrino asymmetry (ΔL) to entropy density (~T^3)

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d}$$

for $T_d \sim 10^{15}$ GeV and $B_0 \sim 10^5$ GeV

$\Delta L \sim 10^{-10}$, in agreement with observations (***Leptogenesis***)

Communicated to Baryon sector, and thus generates BAU either via a B-L conserving symmetry as in GUT models or via B + L conserving sphaleron processe → ***BARYOGENESIS***

Case II : Black-Hole induced neutrino-antineutrino population difference

$$\Delta n = \frac{g}{(2\pi)^3}\int_{R_i}^{R_f} dV \int d^3|\vec{p}| \left[\frac{1}{1+exp(E_\nu/T)} - \frac{1}{1+exp(E_{\bar{\nu}}/T)}\right]$$

Consider Kerr black holes for which $\vec{B}\,.\,\vec{p} \ll B_0\, p^0$ and show that

$$\Delta n = \frac{g}{(2\pi)^2} T^3 \int_{R_i}^{R_f}\int_0^{\infty}\int_0^{\pi} \left[\frac{1}{1+e^u\, e^{B_0/T}} - \frac{1}{1+e^u\, e^{-B_0/T}}\right] u^2\, d\theta\, du\, dV$$

$$u = |\vec{p}|/T$$

Then, if $B^0 << T$

$$\Delta n \sim g\,T^3 \left(\frac{\overline{B_0}}{T}\right)$$

averaged over the spatial volume V

$$\Delta n \sim g T^3 \left(\frac{\overline{B_0}}{T} \right)$$

REMARKS

Asymmetry depends on the sign of ***B^0***

PRIMORDIAL BLACK HOLES WITH MASSES M_{BH} < 10^{15} gm have evaporated today, only BH with masses $M_{BH} > 10^{15}$ gm may survive today

Hawking temperature $T = \frac{\hbar}{8\pi k_B M} \sim 10^{-7} K \left(\frac{M_\odot}{M} \right)$

$T \sim 10^{11}$ K $\sim 1.6 \times 10^{-5}$ erg, $\overline{B_0} \sim 1.6 \times 10^{-6}$ erg, then $\Delta n \sim 10^{-16}$.

To reproduce observed Baryon asymmetry Δn = O(10^{-10}) we need 10^6 BH with the same sign of B^0 → ***fine tuning …..***

3. Fermions in Gravity with TORSION

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \tfrac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu} e^\gamma_c e^\mu_a\right).$$

If torsion then $\Gamma_{\mu\nu} \neq \Gamma_{\nu\mu}$ ***antisymmetric*** part is the contorsion tensor, contributes to

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

$$e^\mu{}_a e^\nu{}_b \eta^{a\,b} = g^{\mu\nu}$$

vielbeins (tetrads) independent from spin connection $\omega_\mu{}^{ab}$ now ….

ROLE OF Kalb-Ramond H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT CAN BE EXPRESSED IN TERMS OF ***A GENERALIZED CURVATURE*** RIEMANN TENSOR WHERE THE CHRISTOFFEL CONNECTION INCLUDES **H-FIELD *TORSION***

4-DIM PART

$$S^{(4)} = \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big)$$
$$= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R} - \frac{1}{3}\kappa^2 H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big)$$

$$\overline{\Gamma}^{\mu}_{\nu\rho} = \Gamma^{\mu}_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^{\mu}_{\nu\rho} \neq \overline{\Gamma}^{\mu}_{\rho\nu}$$

IN 4-DIM DEFINE DUAL OF H AS :

$$-3\sqrt{2}\partial_\sigma b = \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

***b(x)* = Pseudoscalar (Kalb-Ramond (KR) axion)**

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu\overline{\mathcal{D}}_\mu\psi - (\overline{\mathcal{D}}_\mu\overline{\psi})\gamma^\mu\psi\Big)$$

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

$$\overline{\mathcal{D}}_\mu = \overline{\nabla}_\mu - ieA_\mu \qquad \overline{\omega}_{ab\mu} = \omega_{ab\mu} + K_{ab\mu}$$

gauge field — contorsion

$$K_{abc} = \frac{1}{2}\Big(T_{cab} - T_{abc} - T_{bca}\Big)$$

$$\downarrow$$

$$H_{cab}$$

Non-trivial contributions to B^μ ←

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^\mu_a\right)$$

$$\overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}} H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu \overline{\mathcal{D}}_\mu \psi - (\overline{\mathcal{D}}_\mu \overline{\psi})\gamma^\mu \psi\Big)$$

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$$H_{cab}$$

Non-trivial contributions to B^μ

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\alpha\mu} e_c^\alpha e_a^\mu\right)$$

Constant *H* ?

$$\overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}} H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

Exact (conformal Field Theories on World-sheet) Solutions from String theory

Antoniadis, Bachas, Ellis, Nanopoulos

Cosmological Solutions, non-trivial time-dependent dilatons, axions

In Einstein frame *E* (Scalar curvature term in gravitational effective action has canonical normalisation):

$$ds^2 = g^E_{\mu\nu}(x)dx^\mu dx^\nu = dt^2 - a(t)^2\delta_{ij}dx^i dx^j$$

$$a(t) = t$$

$$\Phi = -\ln a(t) + \phi_0$$

$$H_{\mu\nu\rho} = e^{2\Phi}\epsilon_{\mu\nu\rho\sigma}\partial^\sigma b(x) \qquad b(x) = \sqrt{2}e^{-\phi_0}\sqrt{Q^2}\frac{M_s}{\sqrt{n}}t$$

Central charge of uderlying world-sheet conformal field theory $n \in Z^+$

$$c = 4 - 12Q^2 - \frac{6}{n+2} + c_I$$

``internal" dims central charge

Kac-Moody algebra level

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H-torsion & CPTV

NEM & Sarben Sarkar, arXiv:1211.0968

Covariant Torsion tensor

$$\overline{\Gamma}^{\lambda}_{\ \mu\nu} = \Gamma^{\lambda}_{\ \mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}_{\ \mu\nu} + T^{\lambda}_{\ \mu\nu}$$

$$T_{ijk} \sim \epsilon_{ijk}\dot{b} = \epsilon_{ijk}\sqrt{2Q^2}e^{-\phi_0}\frac{M_s}{\sqrt{n}}$$

Constant

constant B^0

$$B^0 \sim \sqrt{2Q^2}e^{-\phi_0}\frac{M_s}{\sqrt{n}}\ \mathrm{GeV} > 0.$$

Lepton Asymmetry as in previous cases , *e.g.* for neutrinos

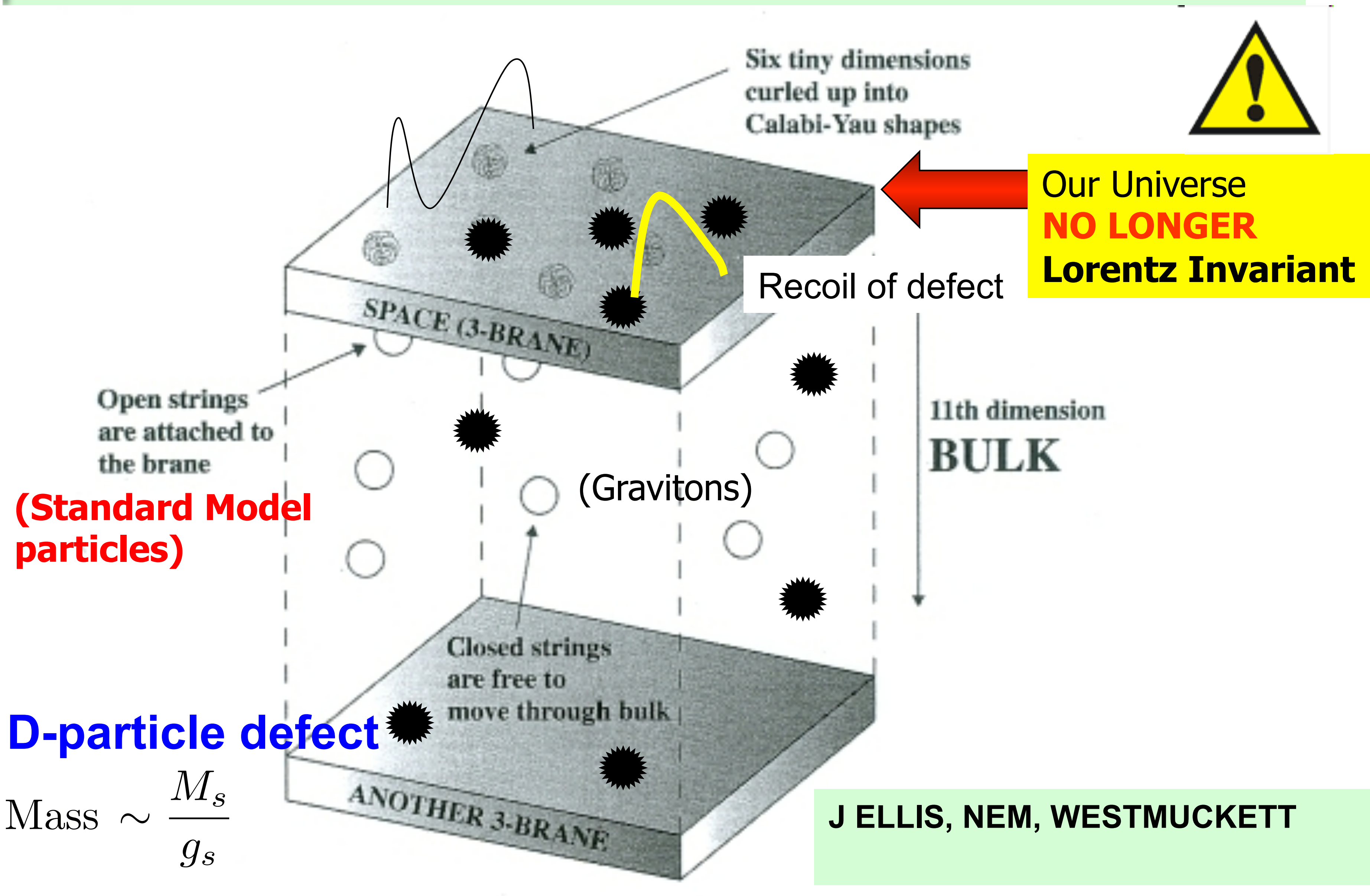
$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d}$$

Requires $B^0 \sim 10^5\ \mathrm{GeV}$ @ T_d

4. STRINGY SPACE-TIME D(efect)-FOAM & CPTV

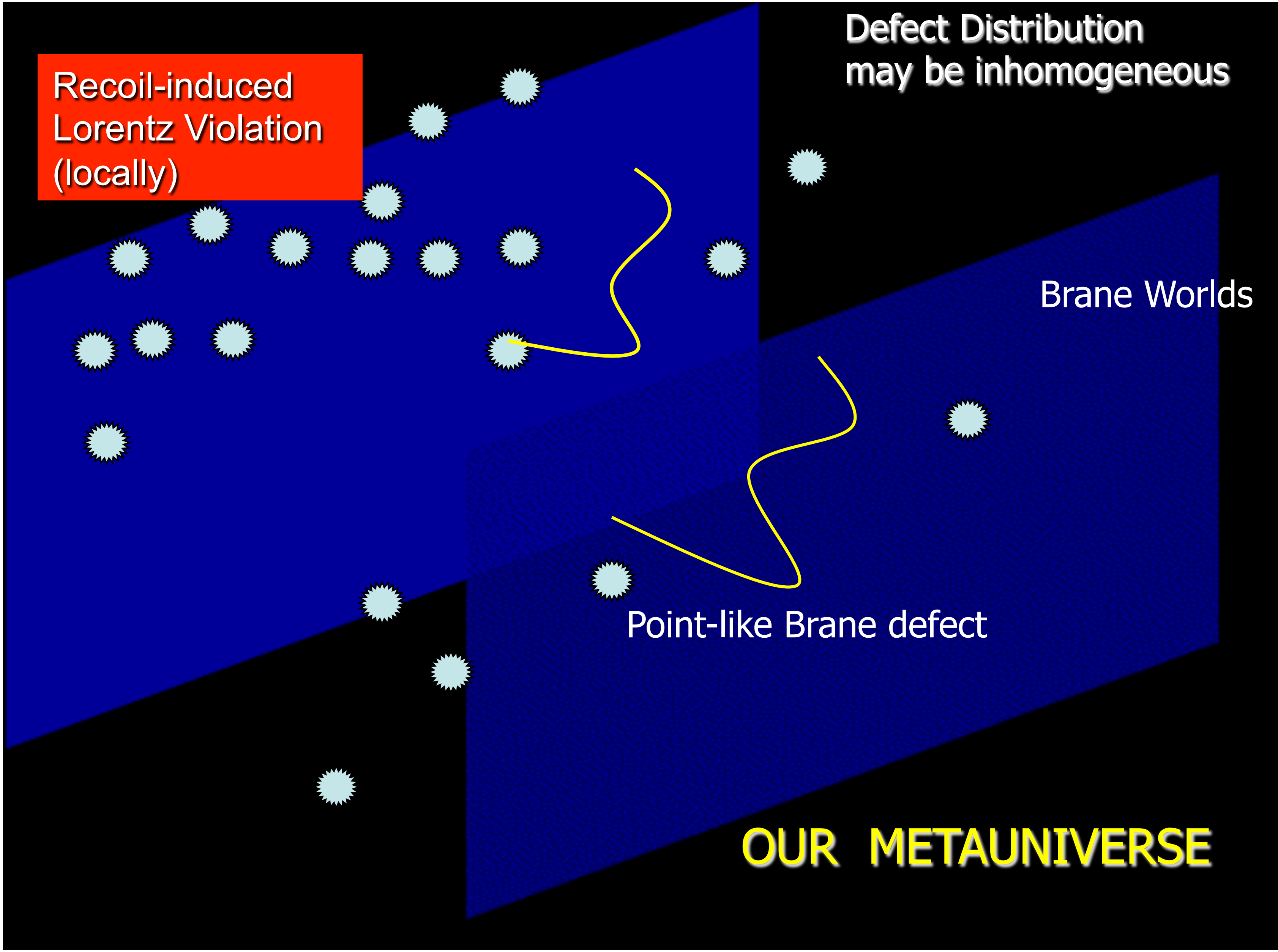
NEM & Sarben Sarkar, arXiv:1211.0968

BRANE-WORLDS with D-PARTICLE (POINT-LIKE BRANE) DEFECTS



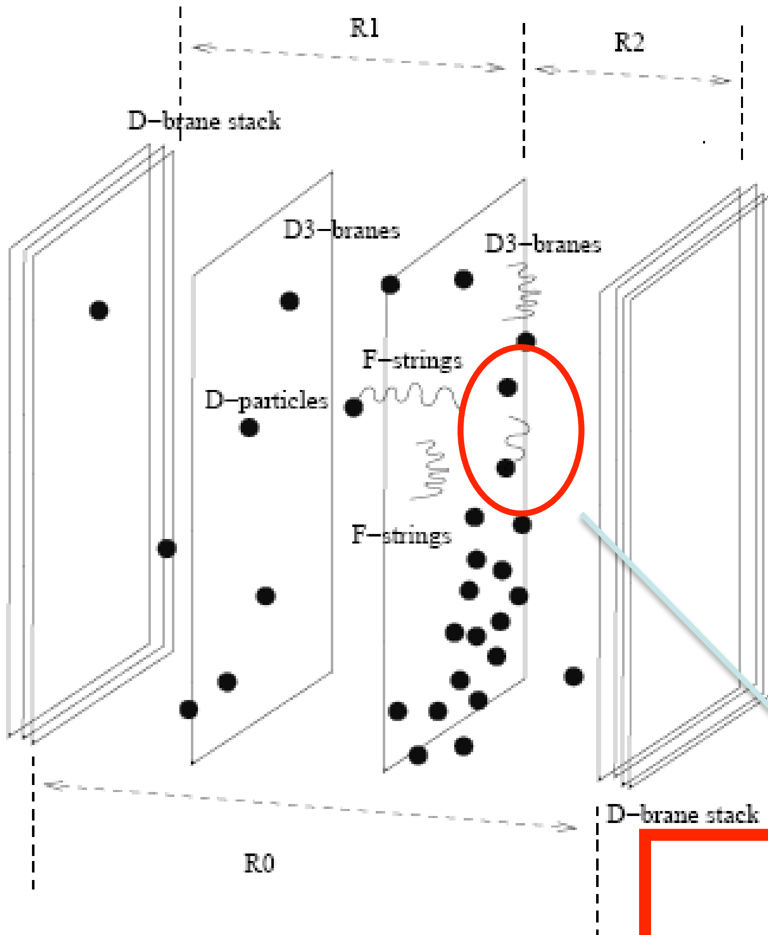
$$\text{Mass} \sim \frac{M_s}{g_s}$$

J ELLIS, NEM, WESTMUCKETT



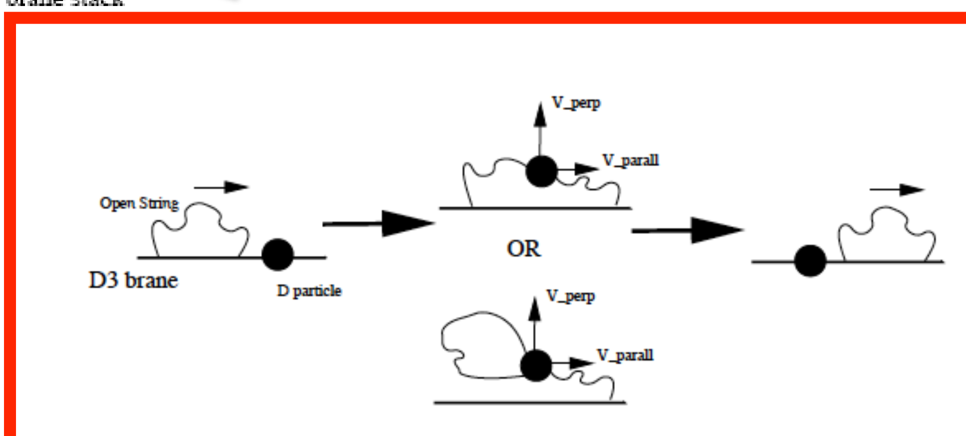
Colliding Brane world model of Space-Time with point-like space-time defects

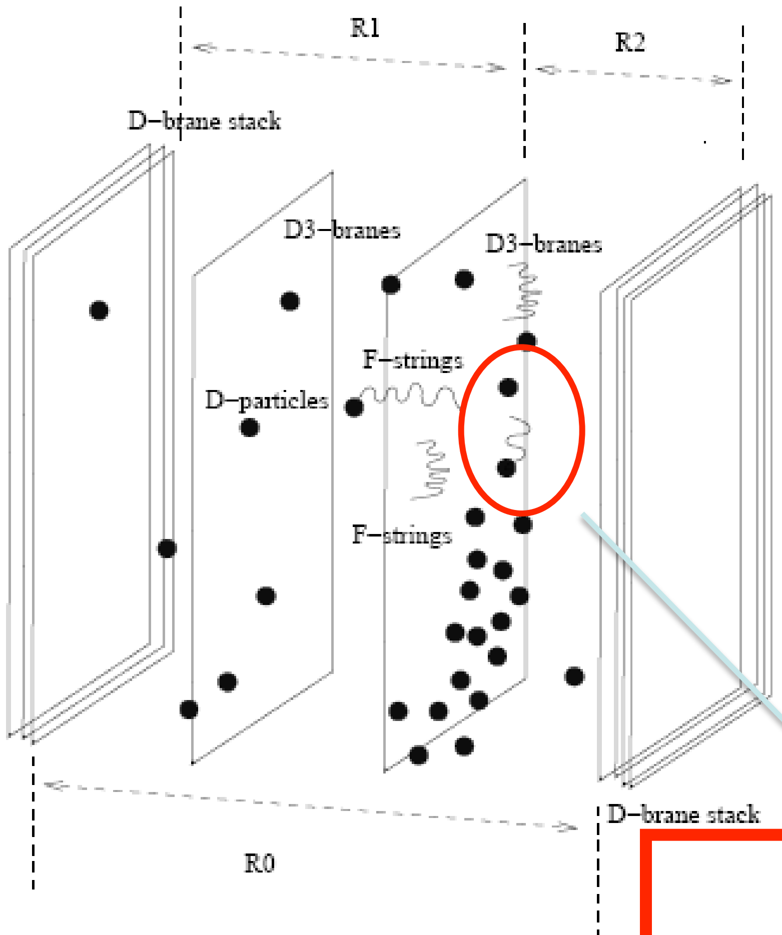
Matter/D-foam Interactions



String ***Splitting*** &
(``momentary'')
Capture by the defects

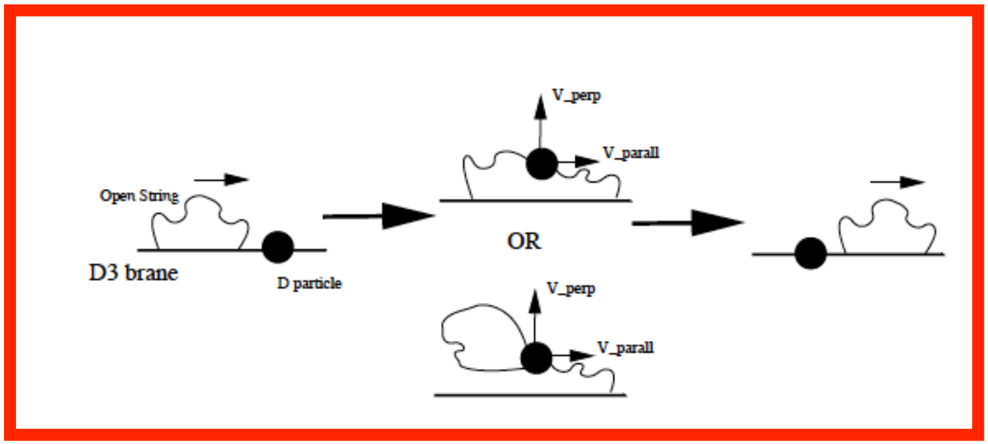
INTEMEDIATE STRING
CREATION/EXCHANGE
PURELY ***NON-LOCAL*** EFFECT



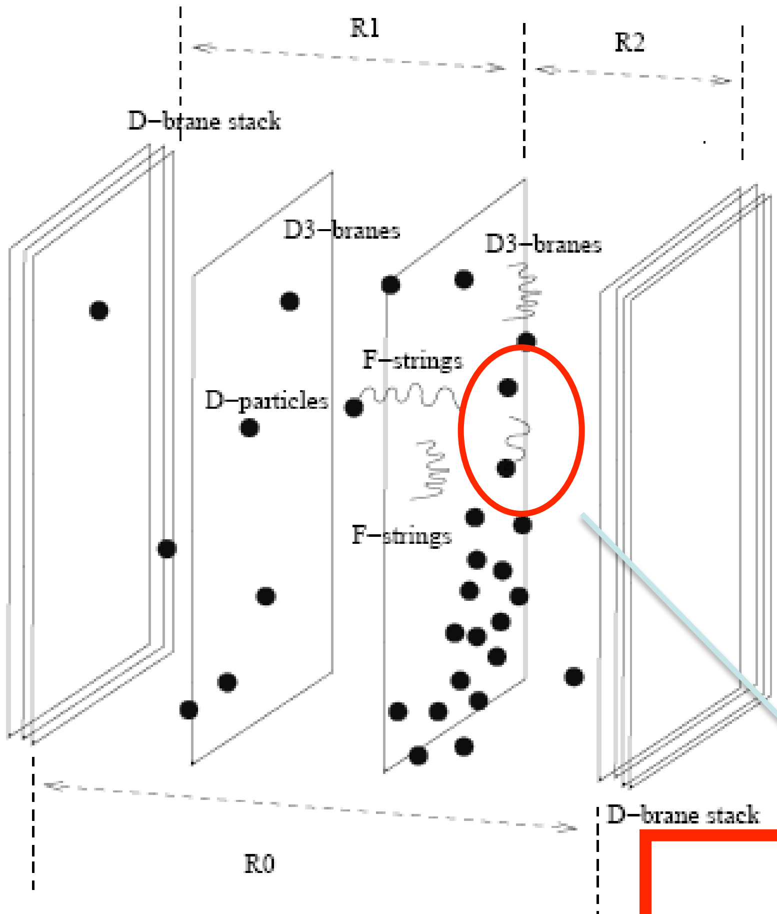


CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

ONLY ELECTRICALLY NEUTRAL EXCITATIONS (e.g. Photons, Neutrinos) INTERACT VIA CAPTURE DOMINANTLY WITH FOAM



ELLIS, NEM, SAKHAROV, NANOPOULOS



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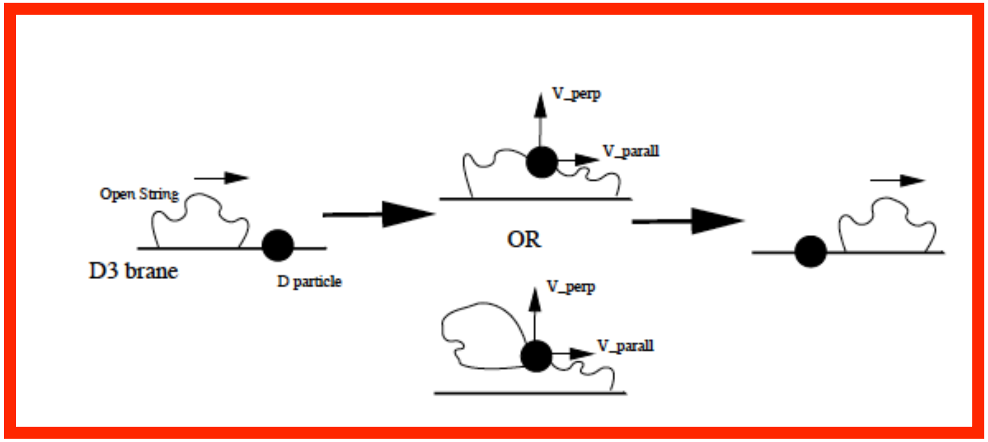
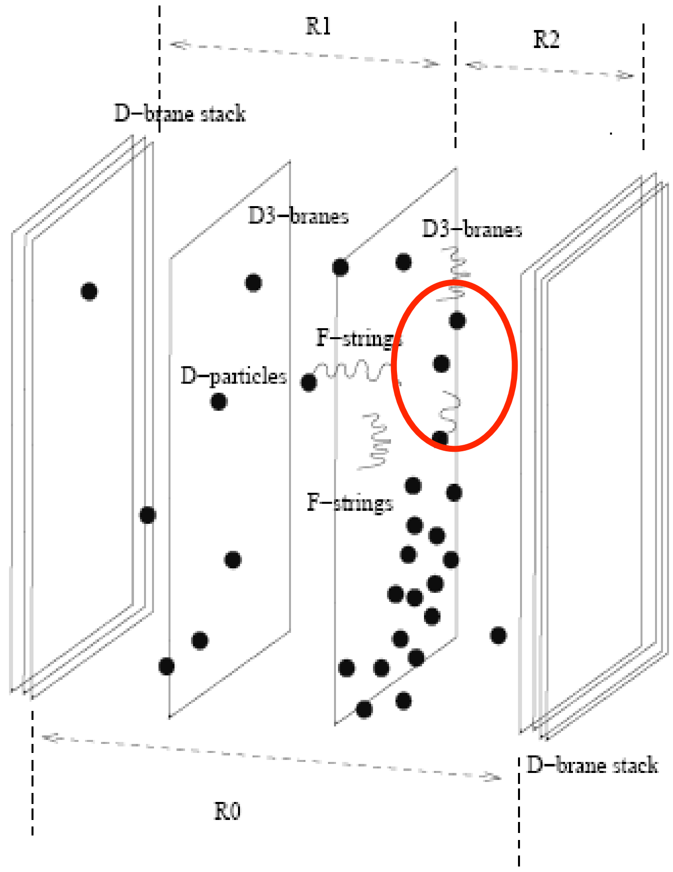


Time Delays due to Intermediate String Creation & Oscillations – ***Subluminal Vacuum Refractive Index***

J ELLIS, NEM, NANOPOULOS



***Local Lorentz Violation* due to direction of Defect recoil velocities**

***Induced metric* depends on momenta as well as coordinates (Finsler type) : e.g. u || X_1**

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h_{01} = g_s \frac{\Delta k_i}{M_s} \equiv u_1$$

Explicit local breaking of SO(3,1) down to SO(2,1) rotation and boosts in transverse directions

``Frame Dragging by recoiling D-particle"

Space time Foam situations –
Average over both populations of defects & quantum fluctuations

Isotropic & (in)homogeneous foam

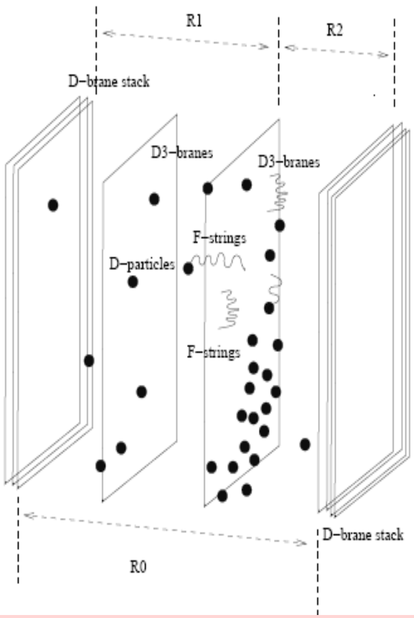
for a brane observer:

$$\langle u_i \rangle \equiv \frac{g_s}{M_s} \langle \Delta k_i \rangle = 0$$

$$\frac{g_s^2}{M_s^2} \langle \Delta k_i \Delta k_j \rangle = \sigma^2 \delta_{ij}$$

Lorentz Invariance on Average

Violated in flcts



c.f. Stochastic Foam, through coherent graviton states

leading to light cone fluctuations

Ford (95)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$\langle h_{\mu\nu} \rangle = 0$$

$$\langle h_{\mu\nu} h_{\rho\sigma} \rangle \neq 0$$

D-foam Induced CPTV for Neutrinos

$$\ll E_\nu \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2$$

$$\ll E_{\overline{\nu}} \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) + \frac{1}{2}\frac{M_s}{g_s}\,\sigma^2$$

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cf. **``Frame Dragging"**
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$\pm B_0$

One can thus generate a Lepton asymmetry and, then through B-L conserving processes in the Early Universe a Baryon asymmetry.

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constant > 0
if $\sigma^2 \approx$ const
in an era

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Correct Sign for Matter dominance over Antimatter due to Energetics
no Fine Tuning

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$$\Delta n = \frac{g}{(2\pi)^3}\int d^3\mathbf{p}\left[\frac{1}{1+\exp(E_\nu/T)} - \frac{1}{1+\exp(E_{\overline{\nu}}/T)}\right]$$

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star T^3\left(\frac{B_0}{T}\right)$$

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d}$$

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One can thus generate a Lepton asymmetry and through B+L conserving processes in the Early Universe a Baryon asymmetry.

The correct value (observed) for BAU is reproduced for, *e.g.* GUTs

$$\boxed{\frac{1}{2}\frac{M_s}{g_s}\sigma^2 \sim 10^5\,\mathrm{GeV}}$$

for D-foam at $T_d \sim 10^{15}$ GeV

implying that in these scenarios, for $\sigma^2 < 1$, one must have $M_s/g_s > 200$ TeV

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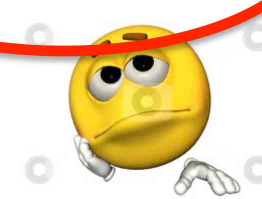
PHENOMENOLOGY OF EARLY UNIVERSE NEEDS TO BE CHECKED FOR COMPATIBILITY…. IN PROGRESS



IS THIS CPTV ROUTE WORTH FOLLOWING? ….

CPT Violation

Construct Microscopic Quantum Gravity models with strong CPT Violation in Early Universe, but maybe weak today… Fit with all available data… Estimate in this way matter-antimatter asymmetry in Universe.

CONCLUSIONS-OUTLOOK

- ***Neutrinos (Sterile) may explain matter-antimatter origin in the Universe***
- **May also provide interesting Dark matter Candidates**
- ***Neutrino condensates may contribute to dark energy***

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THANK YOU !

SPARES

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MASS-VARYING NEUTRINOS & COSMOLOGY

OTHER INTERESTING TOPICS

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

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

Couple Scalar cosmic fields with potential U(φ, T) and massless fermions ψ through Yukawa couplings

$$\mathcal{S} = S_B^E + S_D^E\big|_{m=0} + g\int_0^\beta d\tau \int a^3 d^3x\ \varphi\bar{\psi}\psi$$

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Fermion mass: $m = g\phi_c$

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Thermodynamic potential density

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

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

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

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comoving volume

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

T dependent !

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$$U'(\phi_c) + g\rho_s = 0$$

$\phi_c = \langle\varphi\rangle$

$$\rho_s \equiv \frac{\langle\hat{N}\rangle}{V} = \frac{\partial\Omega_D}{\partial m} = \rho_0 + \frac{m}{\pi^2}\int_0^\infty \frac{k^2 dk}{\varepsilon(k)}\left[n_F(\varepsilon_-) + n_F(\varepsilon_+)\right] \qquad \hat{N} = \int d^3x\bar{\psi}\psi$$

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

Fermion mass: $m = g\phi_c$

$$\alpha > 0.$$

High T phase:

$$\frac{m}{M} \approx \left(\sqrt{6\alpha}\frac{M}{T}\right)^{\frac{2}{\alpha+2}} \propto T^{-\frac{2}{\alpha+2}}$$

Fermionic contribution to thermodynamic potential **dominant**

Scalar mass $m_\phi \approx \sqrt{\frac{\alpha+1}{6}}T$

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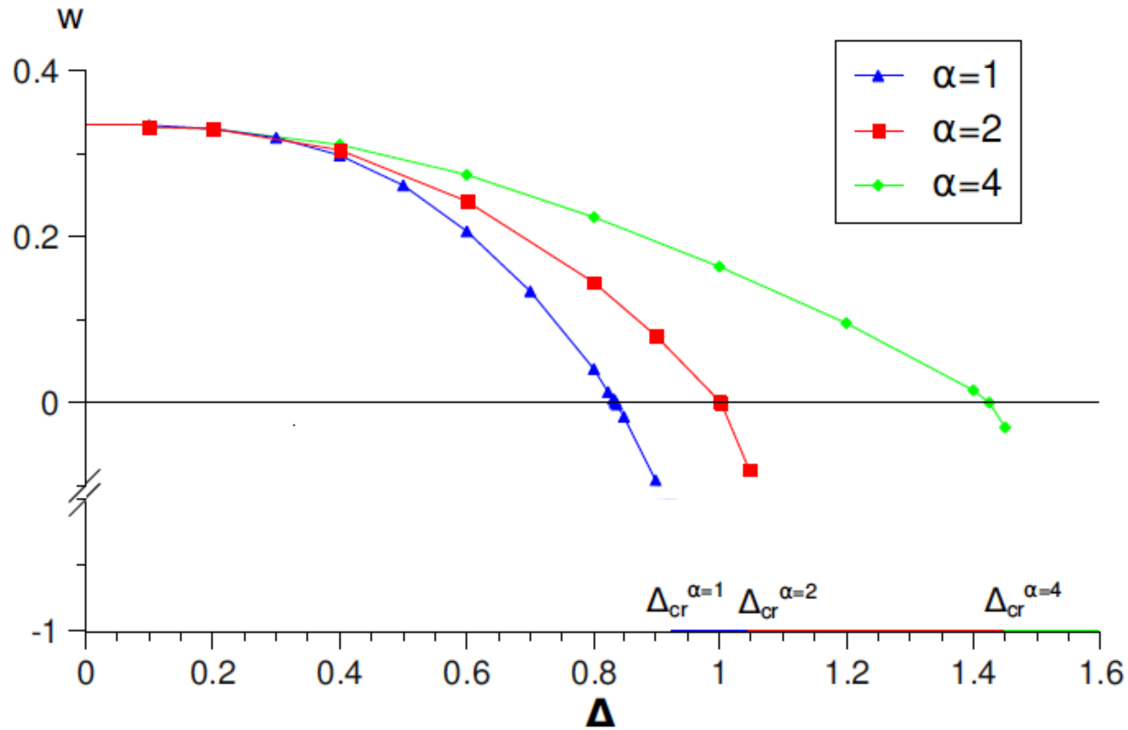
$$U'(\phi_c) + g\rho_s = 0$$

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

Equation of state:

Δ=M/T

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



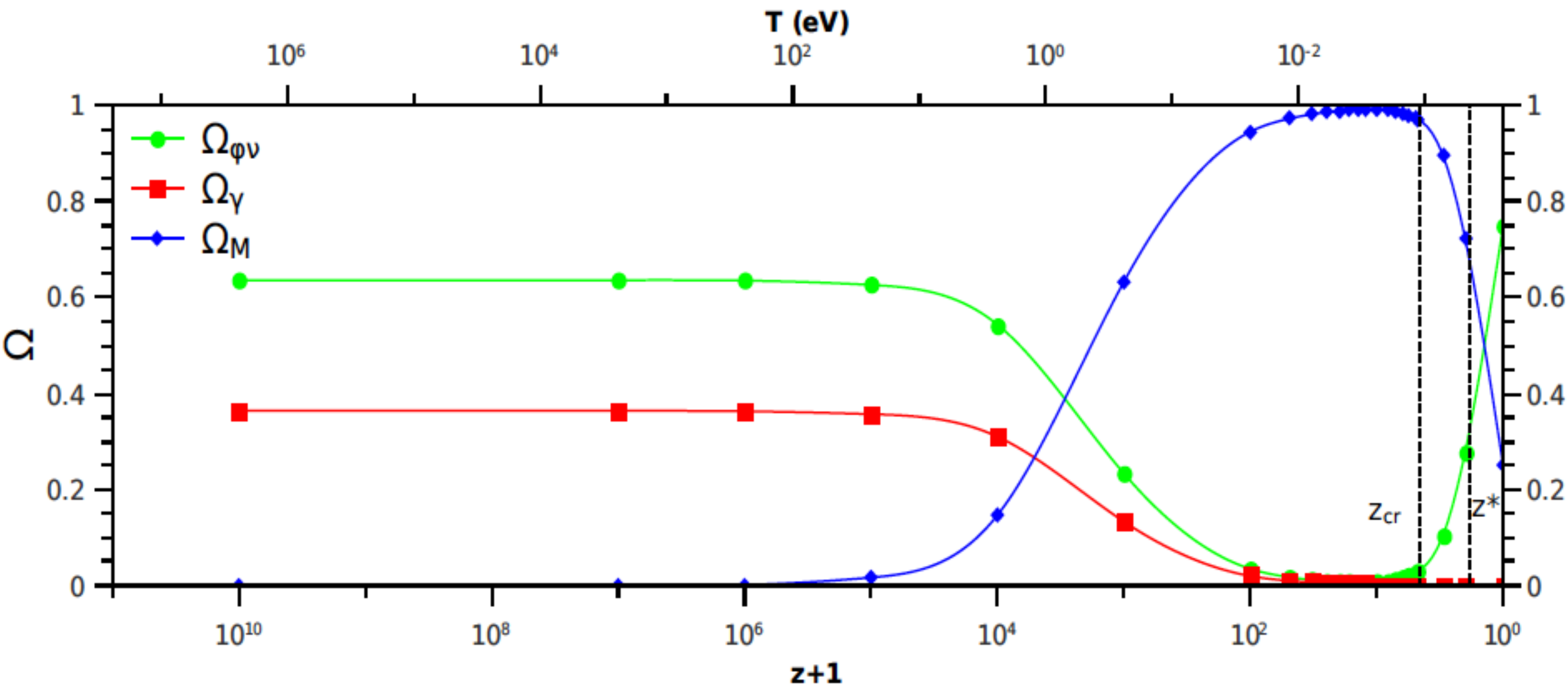
MASS-VARYING NEUTRINOS & COSMOLOGY

OTHER INTERESTING TOPICS

Chitov, August, Natarajan, Kahniashvili

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

Neutrino Dark Energy evolution vs Dark Matter Ω_M $M = 2.39 \cdot 10^{-3}$ eV ($\alpha = 0.01$)



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

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

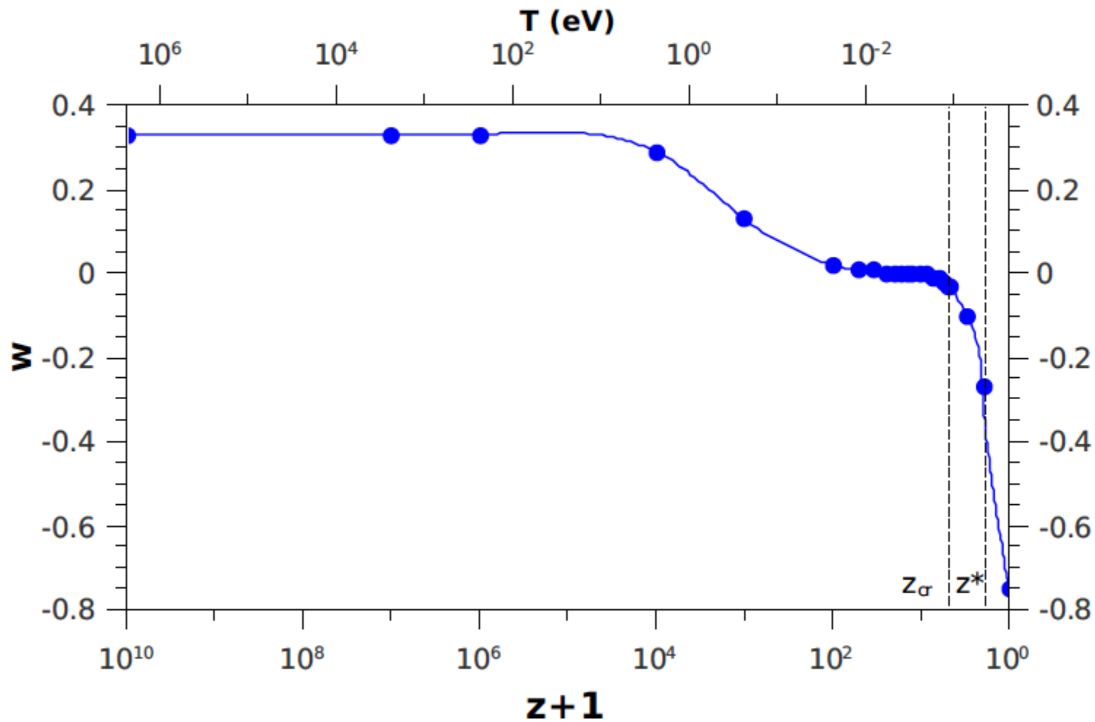
$$U(\varphi) = \frac{M^{\alpha+4}}{\varphi^{\alpha}} \quad \alpha > 0.$$

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)

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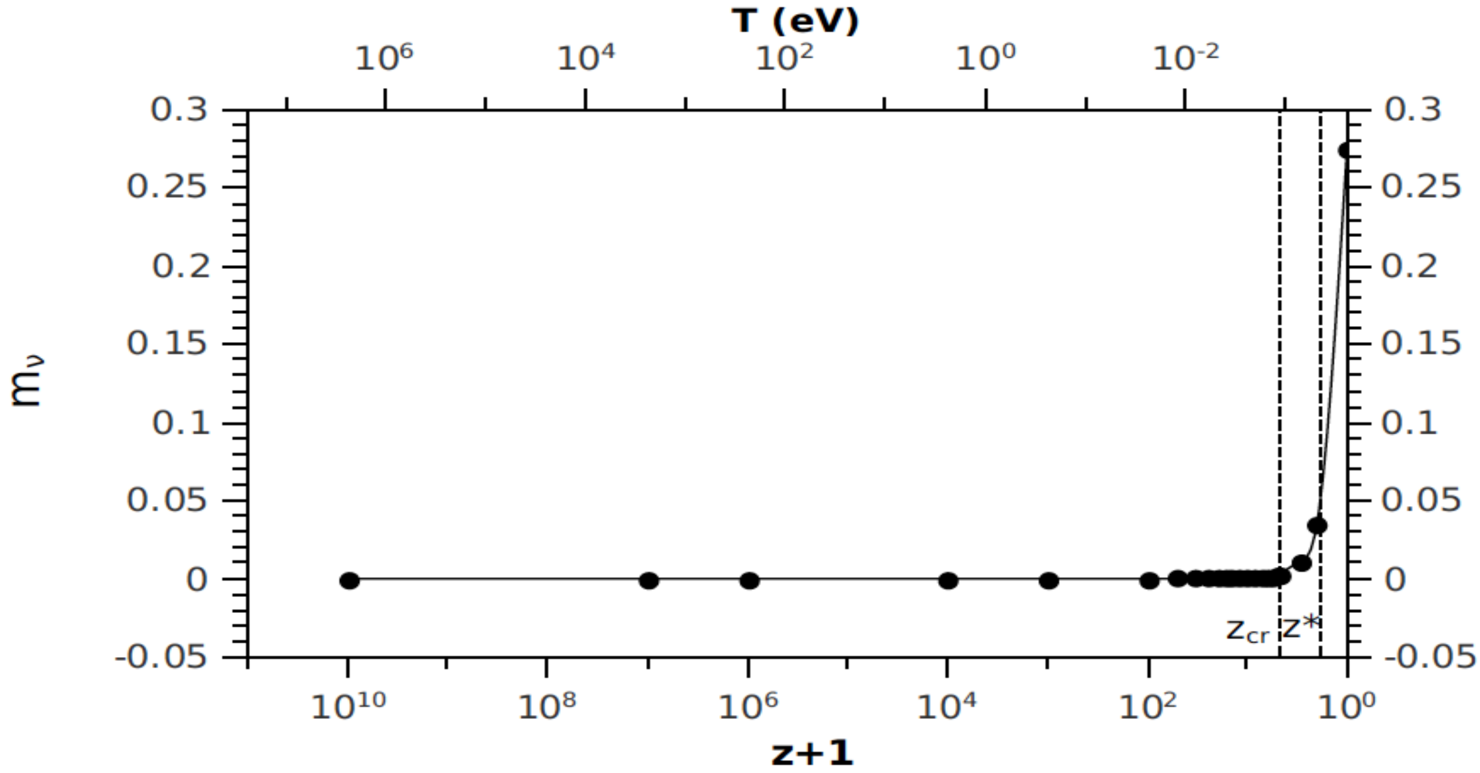
Mass ***Varying*** neutrinos & the Dark Sector

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

Neutrino mass evolution

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



MASS-VARYING NEUTRINOS & COSMOLOGY

OTHER INTERESTING TOPICS

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

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

Acceptable Cosmology
&
Neutrino phenomenology

Effective (Anti)Neutrino CPTV D-foam Mass

No mixing $\nu - \overline{\nu}$

$$m_\nu^{\rm eff} = m_\nu(1 + \frac{1}{2}\sigma^2(T)) - \frac{M_s}{g_s}\sigma^2(T) \simeq m_\nu - \frac{M_s}{g_s}\sigma^2(T)$$

$$m_{\overline{\nu}}^{\rm eff} = m_\nu(1 + \frac{1}{2}\sigma^2(T)) + \frac{M_s}{g_s}\sigma^2(T) \simeq m_\nu + \frac{M_s}{g_s}\sigma^2(T)$$

$$\frac{1}{2}\frac{M_s}{g_s}\sigma^2 \sim 10^5\,{\rm GeV}$$ @ $T_d \sim 10^{15}$ GeV

to generate BAU

Bounds from WMAP Cosmology (z < 1000)

$$\sum_{i=1}^{3} m_\nu^{\rm eff} < 0.69\,{\rm eV}$$

$$\sigma^2(T) \sim \Delta^2(T) g_s^2 \frac{\overline{p}^2}{M_s^2} \sim \frac{g_s^2}{M_s^2}\beta_0(1+z)^3$$

Dust type D-particles

$$\sum m_\nu - 3\frac{g_s}{M_s}\beta_0 < 10^{-3}\,{\rm eV}$$

is a safe not strong bound on foam flcts σ^2 today (within current exp errors)

CPTV → neutrino/antineutrino mixing & oscillations

M Sinha & B. Mukhopadhyay
arXiv: 0704.2593

$$\mathcal{L} = det(e)\,\bar{\Psi}\left(\frac{i}{2}\gamma^a \overleftrightarrow{\partial}_a - m + \gamma^a\gamma^5 B_a\right)\Psi$$

$$B^d = \epsilon^{abcd}\omega_{bca}$$

$$E_\nu = \sqrt{(\vec{p} - \vec{B})^2 + m^2} + B_0,$$

$$E_{\nu^c} = \sqrt{(\vec{p} + \vec{B})^2 + m^2} - B_0$$

Assume Majorana neutrino in Weyl rep (Lepton number violation unavoidable)

$$\Psi = \begin{pmatrix} \psi_L^c \\ \psi_L \end{pmatrix} \qquad \mathcal{D}_\mu \equiv (\partial_0, \partial_i + \gamma^5 B_i).$$

Majorana mass term violates L number

$$(-g)^{-1/2}\mathcal{L} = \begin{pmatrix} \psi^{c\dagger} & \psi^\dagger \end{pmatrix} \frac{i}{2}\gamma^0\gamma^\mu \overleftrightarrow{\mathcal{D}}_\mu \begin{pmatrix} \psi^c \\ \psi \end{pmatrix} - \begin{pmatrix} \psi^{c\dagger} & \psi^\dagger \end{pmatrix} \begin{pmatrix} -B_0 & -m \\ -m & B_0 \end{pmatrix} \begin{pmatrix} \psi^c \\ \psi \end{pmatrix}$$

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Lead to neutrino/antineutrino mixing & oscillations

$$(-g)^{-1/2} \mathcal{L} = \begin{pmatrix} \psi^{c\dagger} & \psi^\dagger \end{pmatrix} \frac{i}{2} \gamma^0 \gamma^\mu \overleftrightarrow{\mathcal{D}}_\mu \begin{pmatrix} \psi^c \\ \psi \end{pmatrix} - \begin{pmatrix} \psi^{c\dagger} & \psi^\dagger \end{pmatrix} \begin{pmatrix} -B_0 & -m \\ -m & B_0 \end{pmatrix} \begin{pmatrix} \psi^c \\ \psi \end{pmatrix}$$

mass eigenstates ν_1 and ν_2 as

$$|\nu_1\rangle = \frac{1}{N}\left\{\left(B_0 + \sqrt{B_0^2 + m^2}\right)|\psi^c\rangle + m\,|\psi\rangle\right\}$$
$$|\nu_2\rangle = \frac{1}{N}\left\{-m\,|\psi^c\rangle + \left(B_0 + \sqrt{B_0^2 + m^2}\right)|\psi\rangle\right\}.$$

$$m_{1,2} = \mp\sqrt{B_0^2 + m^2}.$$

$$|\nu_1\rangle = \cos\theta\,|\psi^c\rangle + \sin\theta\,|\psi\rangle$$
$$|\nu_2\rangle = -\sin\theta\,|\psi^c\rangle + \cos\theta\,|\psi\rangle$$

NB: neutrino CPTV mass shifts

neutrino/antineutrino mixing

$$\tan\theta = \frac{m}{B_0 + \sqrt{B_0^2 + m^2}}.$$

$$|\psi^c\rangle = \cos\theta\,|\nu_1\rangle - \sin\theta\,|\nu_2\rangle$$
$$|\psi\rangle = \sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle.$$

oscillations

$$\mathcal{P}(t) = \sin^2 2\theta\,\sin^2\delta(t)$$
$$= \frac{m^2}{B_0^2 + m^2}\sin^2\{(B_0 - |\vec{B}|)t\}$$

$$\delta(t) = \frac{|E_\nu - E_{\nu^c}|t}{2},$$

mass eigenstates ν_1 and ν_2 as

$$|\nu_1\rangle = \frac{1}{N}\left\{\left(B_0 + \sqrt{B_0^2 + m^2}\right)|\psi^c\rangle + m|\psi\rangle\right\}$$
$$|\nu_2\rangle = \frac{1}{N}\left\{-m|\psi^c\rangle + \left(B_0 + \sqrt{B_0^2 + m^2}\right)|\psi\rangle\right\}.$$

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oscillations

$$\mathcal{P}(t) = \sin^2 2\theta\,\sin^2\delta(t) = \frac{m^2}{B_0^2 + m^2}\sin^2\{(B_0 - |\vec{B}|)t\}$$

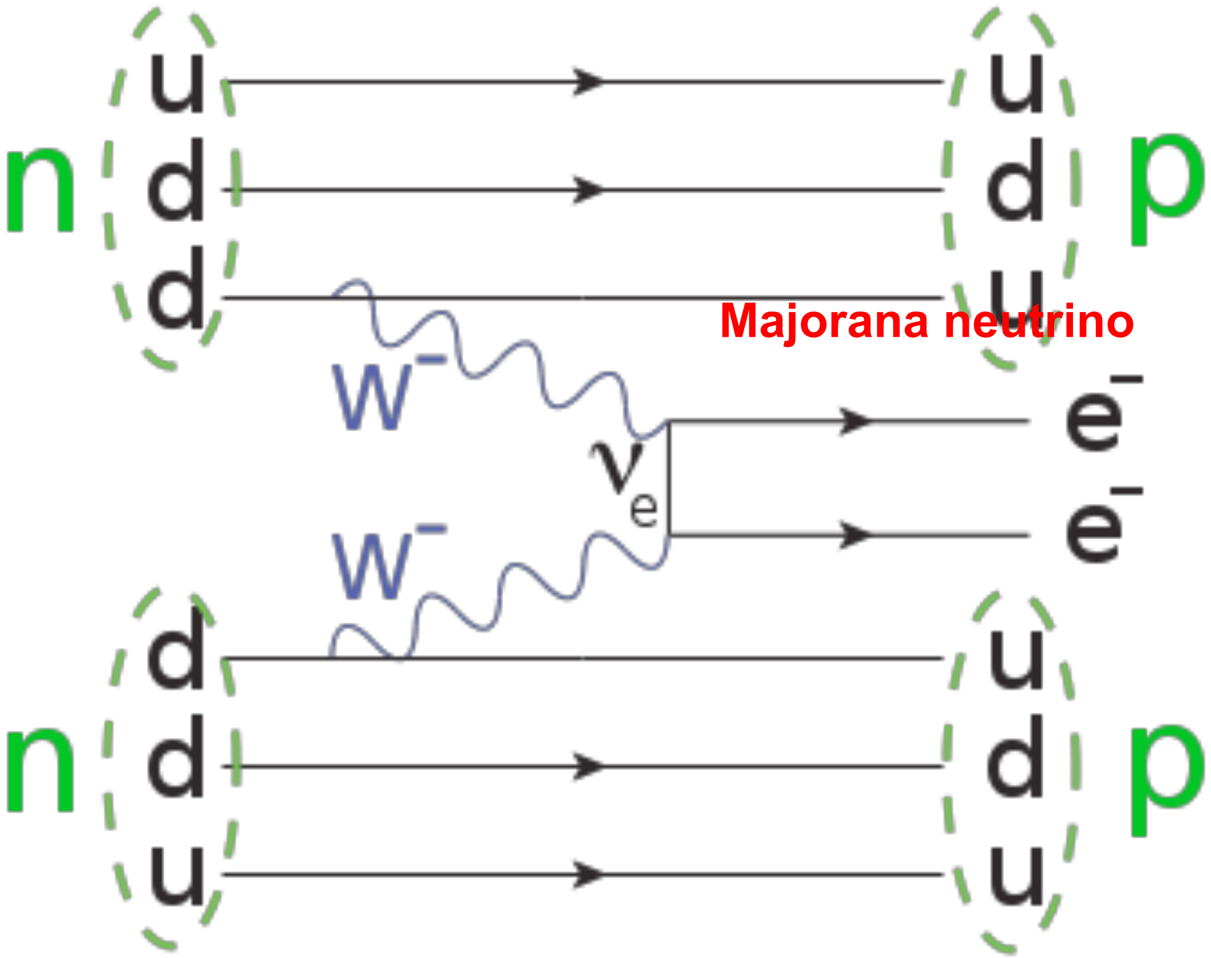
$$\delta(t) = \frac{|E_\nu - E_{\nu^c}|t}{2},$$

oscilaltion lengt

$$\lambda = \frac{\pi}{B_0 - |\vec{B}|}.$$

Modifications in Neutrinoless 2Beta decay rate in 2 flavour mixing
(due to CPTV modified effective mass)

M Sinha & B. Mukhopadhyay
arXiv: 0704.2593



ignore neutrino/antineutrino mixing here:

Amplitude $A \propto \sqrt{B_0^2 + m_e^2}.$

CPTV Effects of different Space-Time-Curvature/Spin couplings between ν, $\bar{\nu}$ in Bianchi Cosmologies

B. Mukhopadhyay, U. Debnath, N. Dadhich, M. Sinha
Lambiase, Mohanty

Assumption: Neutrinos non clustering properties, dominant species in early Universe

$$ds^2 = -dt^2 + S(t)^2\, dx^2 + R(t)^2\, [dy^2 + f(y)^2\, dz^2] - S(t)^2\, h(y)\, [2dx - h(y)\, dz]\, dz$$

Bianchi II, VIII and IX models, respectively $f(y)$ and $h(y)$ are given as

$$f(y) = \{y, \sinh y, \sin y\}, \qquad h(y) = \{-y^2/2, -\cosh y, \cos y\}.$$

$$B^0 = \frac{S[-f^2R^2(hf'R + Sh') + h^2S^2(hf'R + Sh') + 2fhRS(Rf' - hh'S)]}{f^4R^4 + f^2h^2R^2S^2}$$

$$B^2 = \frac{h[-f^2R^2 + 2fRS + h^2S^2][RS' - R'S]}{f^3R^4 + fh^2R^2S^2}.$$

$B^3 = B^1 = 0$

Neutrino/antineutrino asymmetry around black holes

B. Mukhopadhyay, astro-ph/0505460

Consider the metric of a Kerr **(rotating)** black hole

$$ds^2 = \eta_{ij}\, dx^i\, dx^j - \left[\frac{2\alpha}{\rho}\, s_i\, v_j + \alpha^2\, v_i\, v_j\right] dx^i\, dx^j$$

$$\alpha = \frac{\sqrt{2Mr}}{\rho}, \qquad \rho^2 = r^2 + \frac{a^2 z^2}{r^2} \qquad v_i = \left(1,\ \frac{ay}{a^2+r^2},\ \frac{-ax}{a^2+r^2},\ 0\right)$$

$$s_i = \left(0,\ \frac{rx}{\sqrt{r^2+a^2}},\ \frac{ry}{\sqrt{r^2+a^2}},\ \frac{z\sqrt{r^2+a^2}}{r}\right)$$

and we have $r^4 - r^2\,(x^2+y^2+z^2-a^2) - a^2 z^2 = 0$

Modified Neutrino dispersion relations due to locally induced metric

$$p^\mu p^\nu g_{\mu\nu} = -m^2 \Rightarrow \qquad E = \vec{p}\cdot\vec{u} \pm \sqrt{p^2 + m^2 + (\vec{p}\cdot\vec{u})^2}$$

Interpret (Dirac hole theory) negative energies as corresponding to anti-particles ←→ Fermions, exclusion principle

$$\ll E \gg = \ll \vec{p}\cdot\vec{u} \gg \pm \ll \sqrt{p^2 + m^2 + (\vec{p}\cdot\vec{u})^2} \gg$$

$$\ll E \gg \simeq \pm\sqrt{p^2 + m^2}\left(1 + \frac{1}{2}\sigma^2\right), \qquad p \gg m$$

Momentum-Energy conservation during ν scattering with D-particles

$$\ll \vec{p}_1 + \vec{p}_2 \gg = \frac{M_s}{g_s} \ll \vec{u} \gg = 0$$

$$\ll E_1 \gg = \ll E_2 \gg + \frac{1}{2}\frac{M_s}{g_s} \ll u^2 \gg \qquad \Rightarrow$$

$$\ll E_2 \gg = \pm\sqrt{p^2 + m^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

NEM, Sarkar, Tarantino
Phys.Rev. D84 (2011) 044050