Neutrinos & the Universe

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OUTLINE

- NEUTRINOS & LEPTOGENESIS, BARYOGENESIS
- NEUTRINOS AND THE DARK SECTOR OF THE UNIVERSE
- COSMIC NEUTRINOS & VIOLATION OF FUNDAMENTAL SYMMETRIES

OUTLINE

- **NEUTRINOS & LEPTOGENESIS, BARYOGENESIS**

Role of (heavy) Majorana Right-handed Neutrinos (νMSM)

- **NEUTRINOS AND THE DARK SECTOR OF THE UNIVERSE**

- **COSMIC NEUTRINOS & VIOLATION OF FUNDAMENTAL SYMMETRIES**

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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 ν?

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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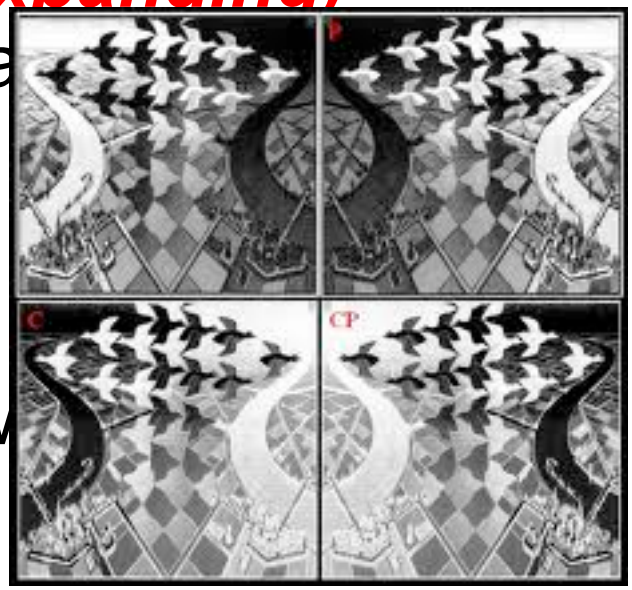

escher

- ***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**

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Assume CPT

ELECTROWEAK THEORY & FERMION # NON-CONSERVATION

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

L_i Lepton #s

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Quantum Anomalies:

Generation (flavour) #

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

SU(2)

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(three quantities)

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OBSERVED NEUTRINO FLAVOUR OSCILLATIONS

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

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If neutrinos Majorana

→ **L violated, No conserved numbers**

OBSERVED CP VIOLATION UNLIKELY TO EXPLAIN BARYON ASYMMETRY IN THE UNIVERSE

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

Within the Standard Model, lowest CP Violating structures

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

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Kobayashi-Maskawa CP Violating phase

Shaposhnikov

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

Jarlskog det

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

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

Role of Neutrinos?

- Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.)
- Massive ν are **simplest** extension of SM
- Right-handed supermassive 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**

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: $\tilde{\phi}_i = \epsilon_{ij}\phi_j^*$.

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νMSM

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Yukawa couplings Matrix (N=2 or 3)

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

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

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Links with Inflation? non minimal coupling of Higgs φ with Curvature scalar R

$$L_G = \ldots + \zeta\, \varphi^+ \varphi\, R$$

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

Shaposhnikov

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Boyarski, Ruchayskiy, Shaposhnikov

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

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

Majorana phases

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Majorana phases

Mixing

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

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

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Light Neutrino Masses through see saw

Minkowski, Yanagida, Mohapatra, Senjanovic

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

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

$$v = \langle \phi \rangle \sim 175 \text{ GeV} \qquad M_D \ll M_I$$

Thermal Properties

Shaposhnikov…

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

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

(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

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

Thermal equilibrium at temperatures

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

$$\text{time} = M_0^2/2T^2 \text{ (radiation era)}$$

(for T_{eq} > 100 GeV)

Thermal Properties

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

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(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 $T = T_{eq}$***

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

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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

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Fukugita, Yanagida,

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Lepton number
Viola

$N_I \to H$

Out of Equilibrium Decays

$T_{\rm sph}$

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

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
B+L violatin
interactions

ita, Yanagida,

in, Rubakov,
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Observed Baryon Asymmetry In the Universe (BAU)

Thermal Leptogenesis

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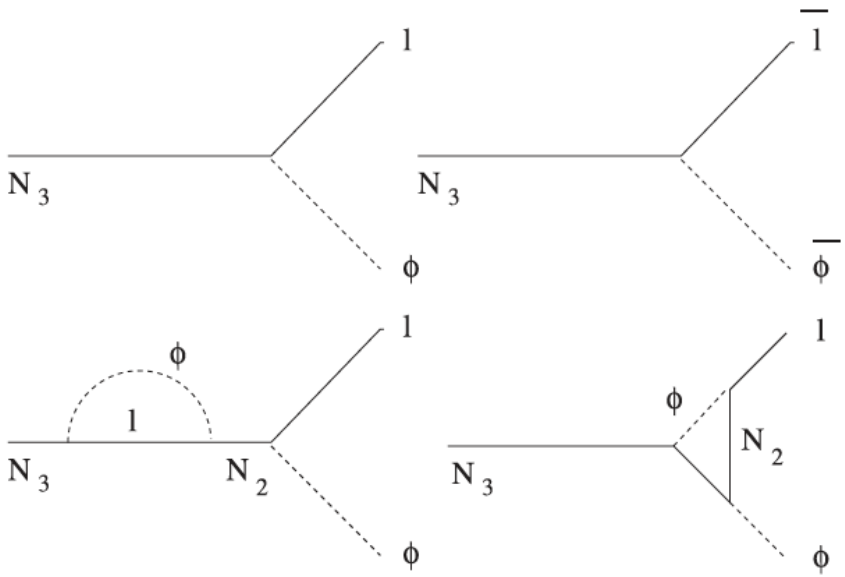
Estimate BAU by solving Boltzmann equations for Heavy Neutrino Abundances

Pilafsis, Buchmuller, di Bari *et al.*

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

Pilaftsis, Shaposhnikov…



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

Majorana fermion Kinematics

Sphaleron effects L -> B

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

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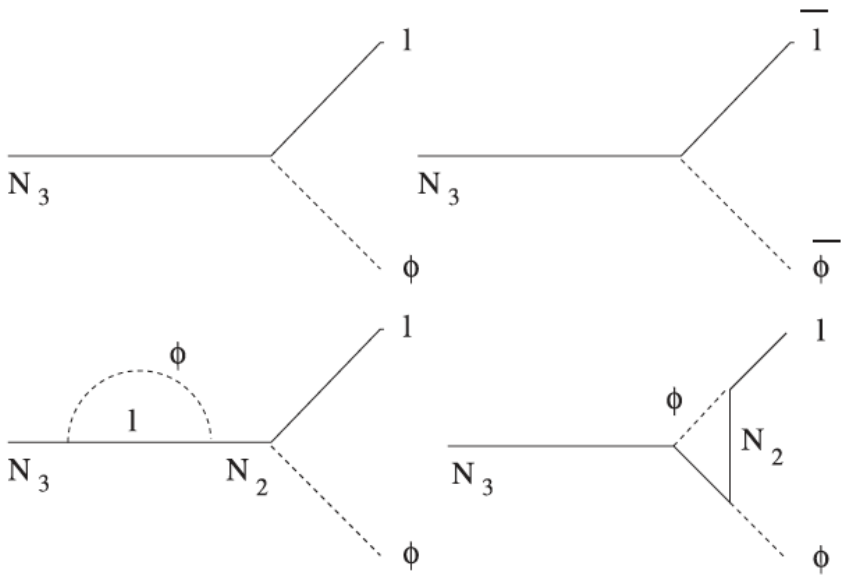

Non mass degenerate Majorana neutrinos

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

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

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

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

reproduced observed BAU

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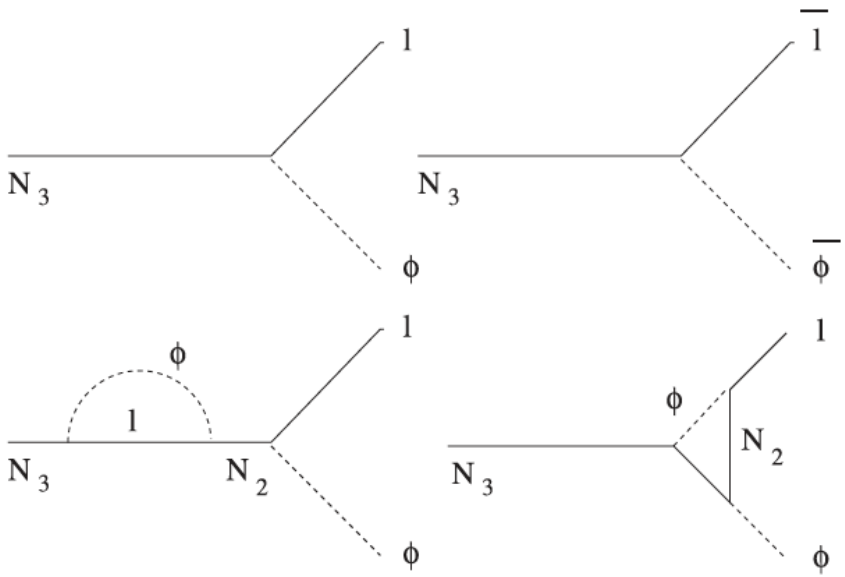

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$$M_D = F_{\alpha I} v$$

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

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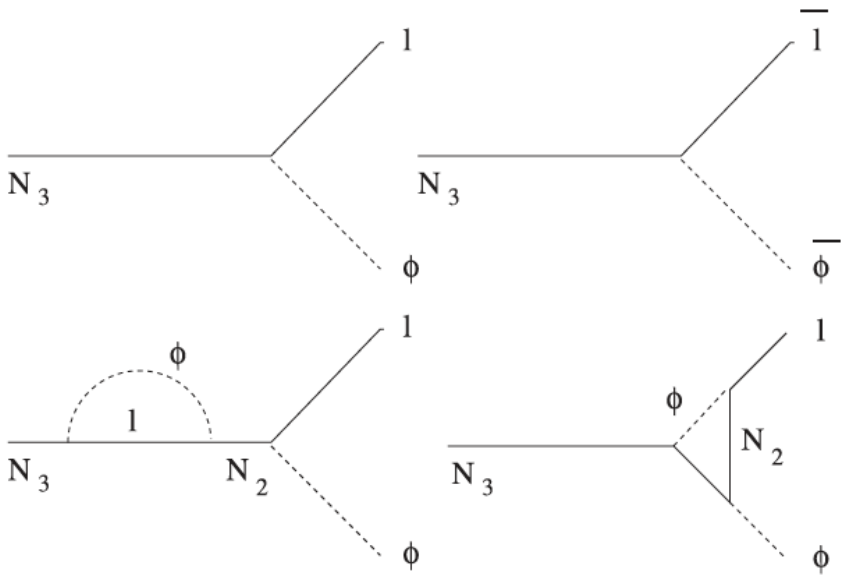

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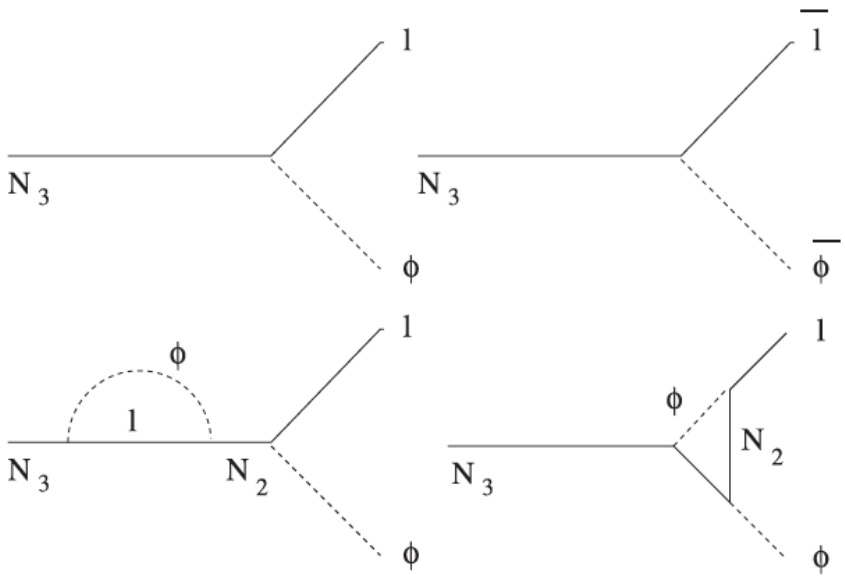

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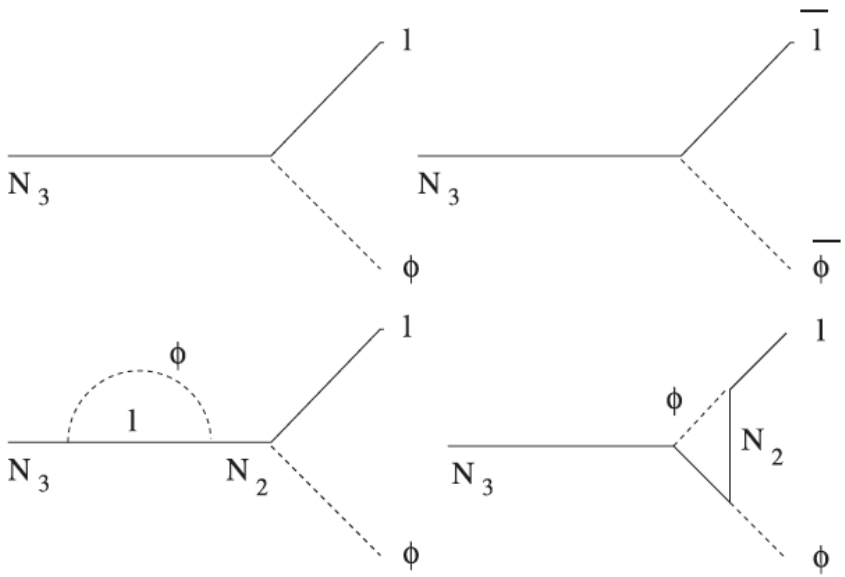

Non mass degenerate Majorana neutrinos

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

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POSSIBLE RESOLUTION: DEGENERATE RIGHT-HANDED NEUTRINOS

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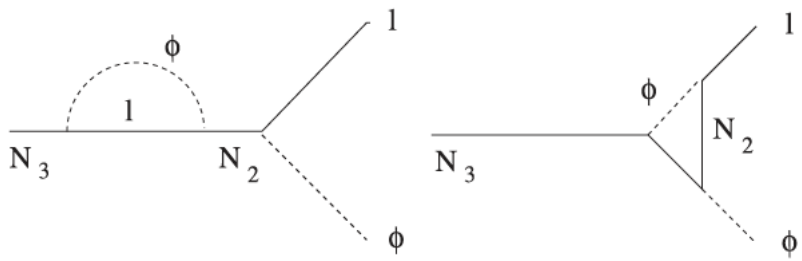
Shaposhnikov

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:

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

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

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

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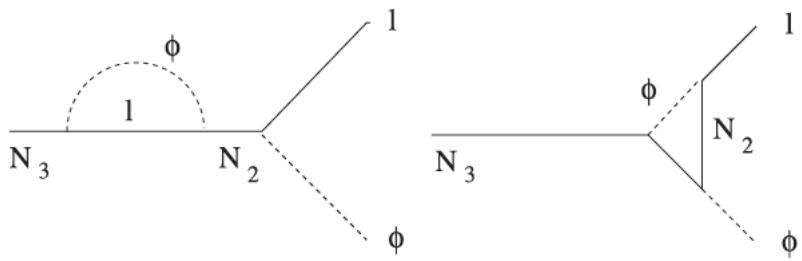

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NB: For $M_I < 10^7$ GeV

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

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

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Pilaftsis

De Simone, Riotto

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Predicted BAU

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

$$\sim -10^{-2} \frac{\delta^\tau_{N_1}}{K_{N_1}} \frac{\varepsilon^2_\tau}{c^2}$$

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

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agreement with observed BAU

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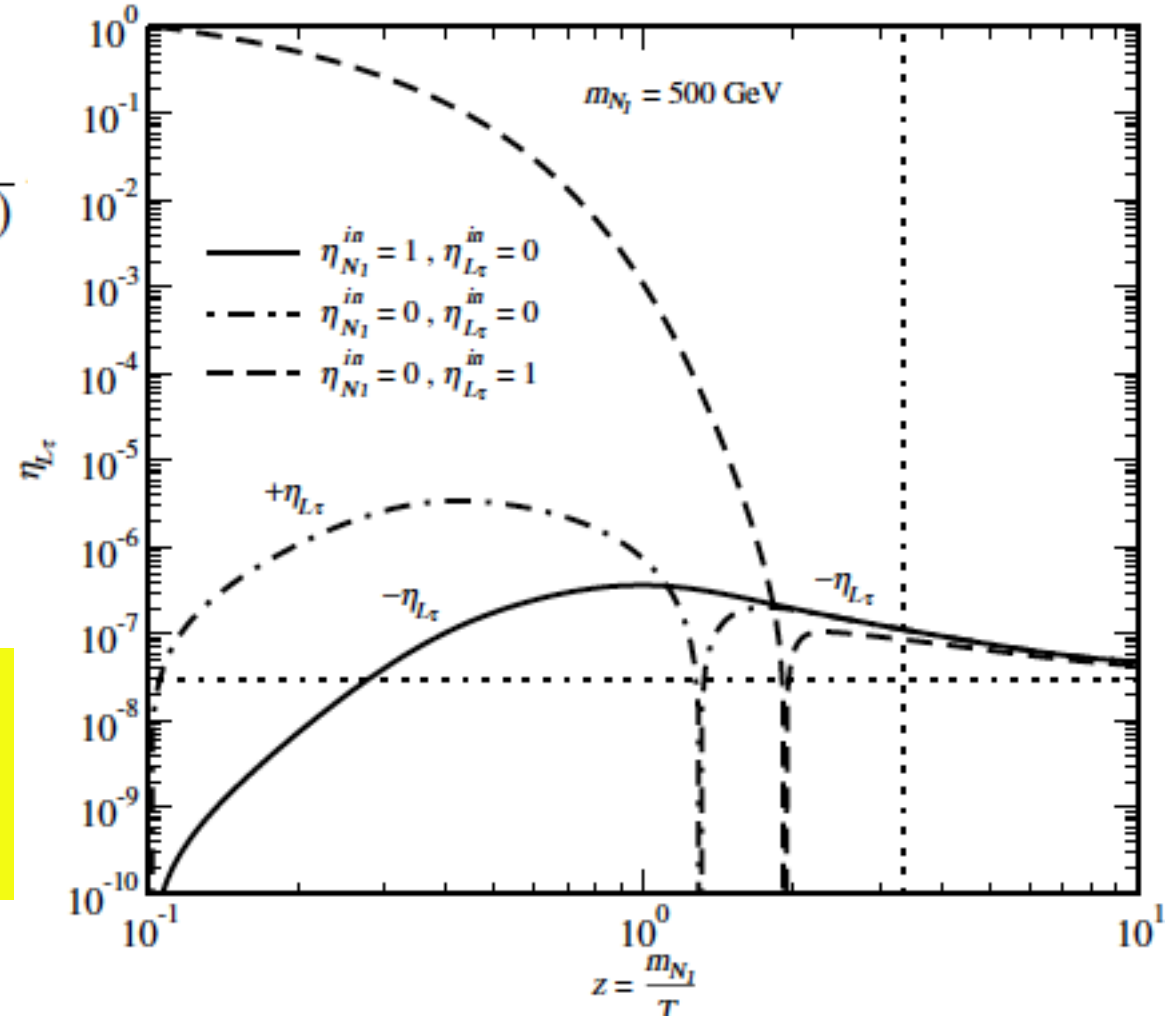

Estimate agrees with:

Boltzmann eq calculated neutrino N_1 abundance

Resonant τ Leptogenesis

Pilaftsis
Underwood

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

Resonant τ Leptogenesis

Pilaftsis
Underwood

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

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

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

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

future sensitivity to 10^{-13}

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

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

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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)

NB: Quantum Effects in Boltzmann

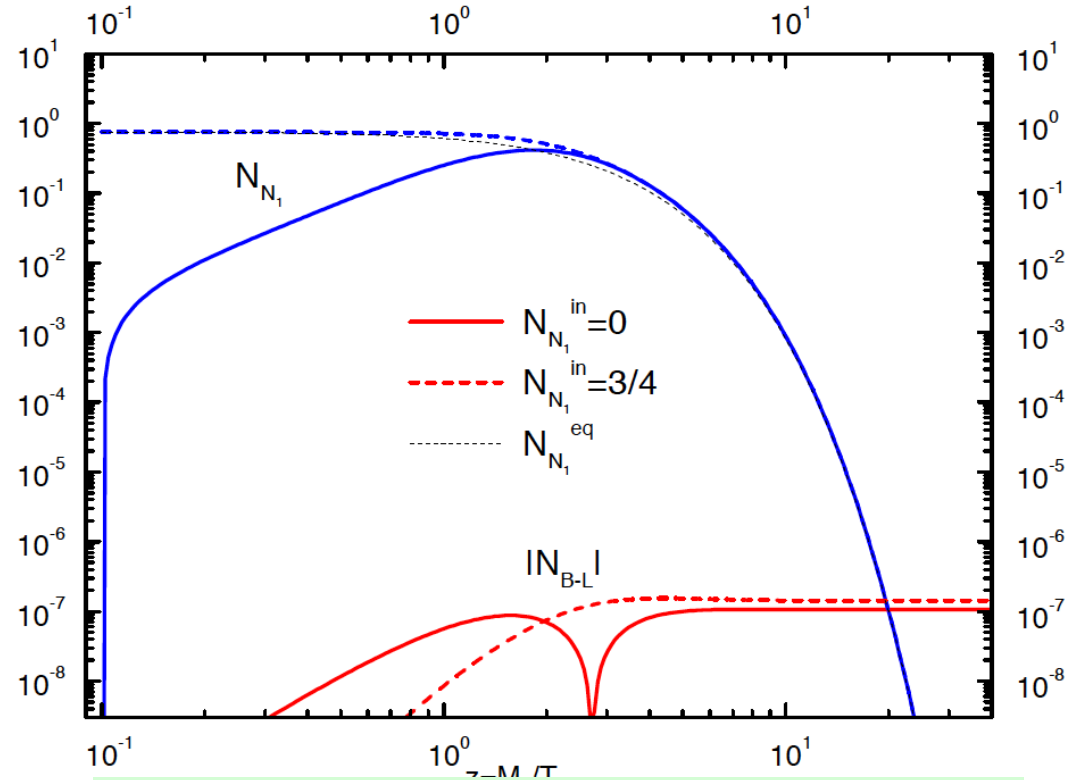
Quantum Boltzmann (QB)
De Simone, Riotto (2007)

Boltzmann eqs. are classical phase space equations, time evolution of phase space distribution functions f(p,x.t)

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

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

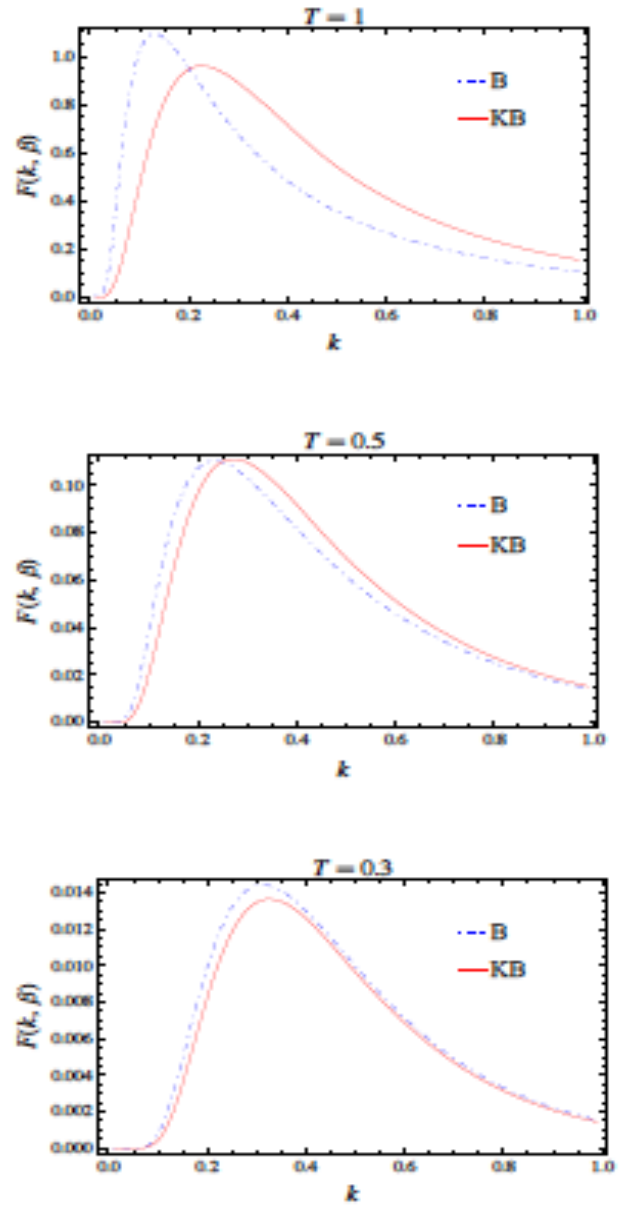
But : Collision terms C[f] on r.h.s. are quantum effects involving loop corrected cross sections (particularly in Leptogenesis)



Buchmuller, Di Bari, Plumacher (2002)

NB: Non-Equilibrium Quantum Field Theory Effects in Boltzmann: Beyond Quantum Boltzmann

Lepton Asymmetry



Can calculate directly Heavy ν abundances by using non-equlibrium 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

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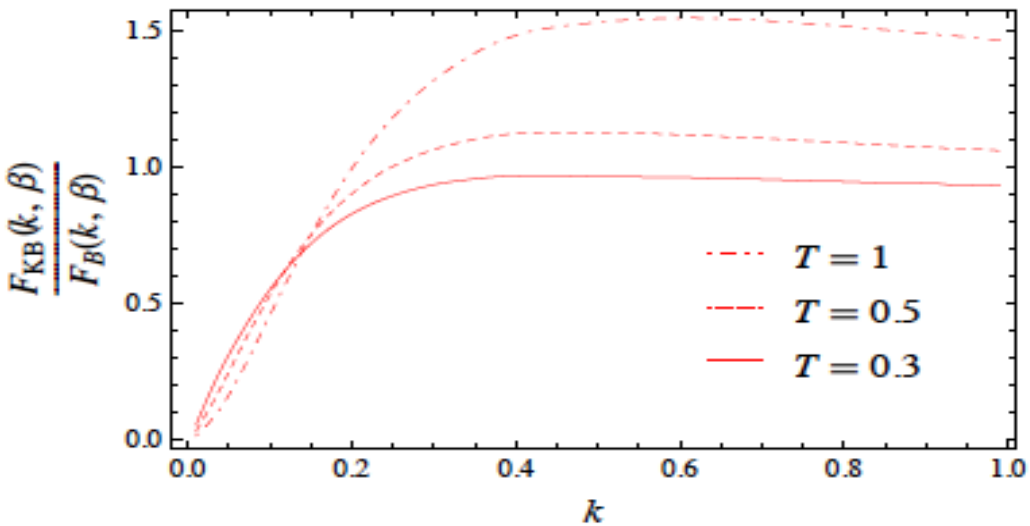

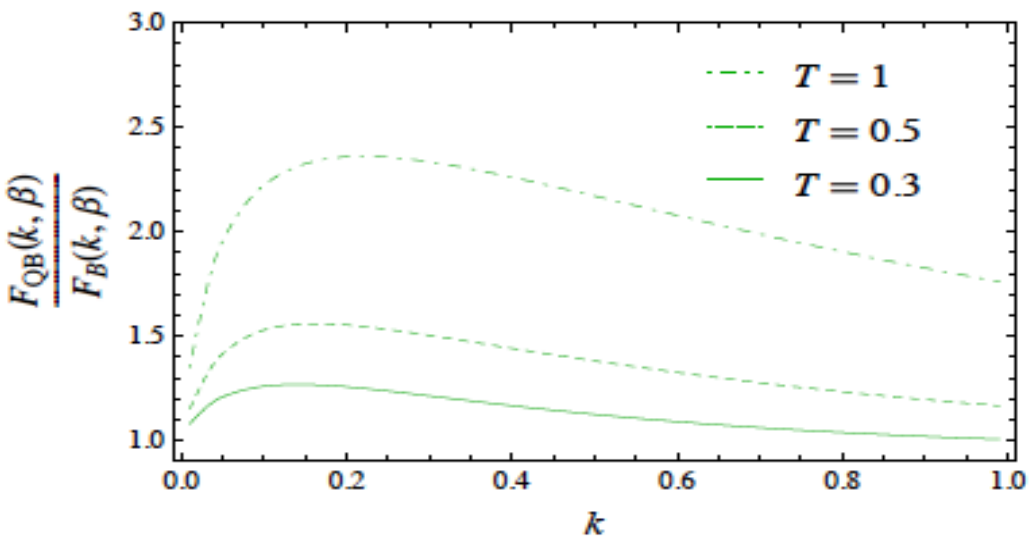

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Thermal Properties

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

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 ν

Lepton number of active left-handed ν 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

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

$$E_I \sim T$$

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

$N_2 - N_3$ MASS DIFF.

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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

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

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

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

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

N_1 Lightest Sterile nutrino is a natural DARK MATTER candidate

NEUTRINOS & THE DARK SECTOR OF THE UNIVERSE

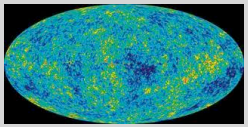
NEUTRINOS & THE DARK SECTOR OF THE UNIVERSE

Current Energy Budget of the Cosmos

Observations from:

Supernovae Ia

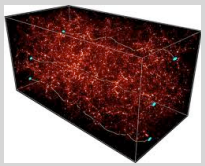
CMB



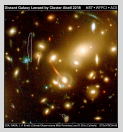
Baryon Acoustic Oscillations

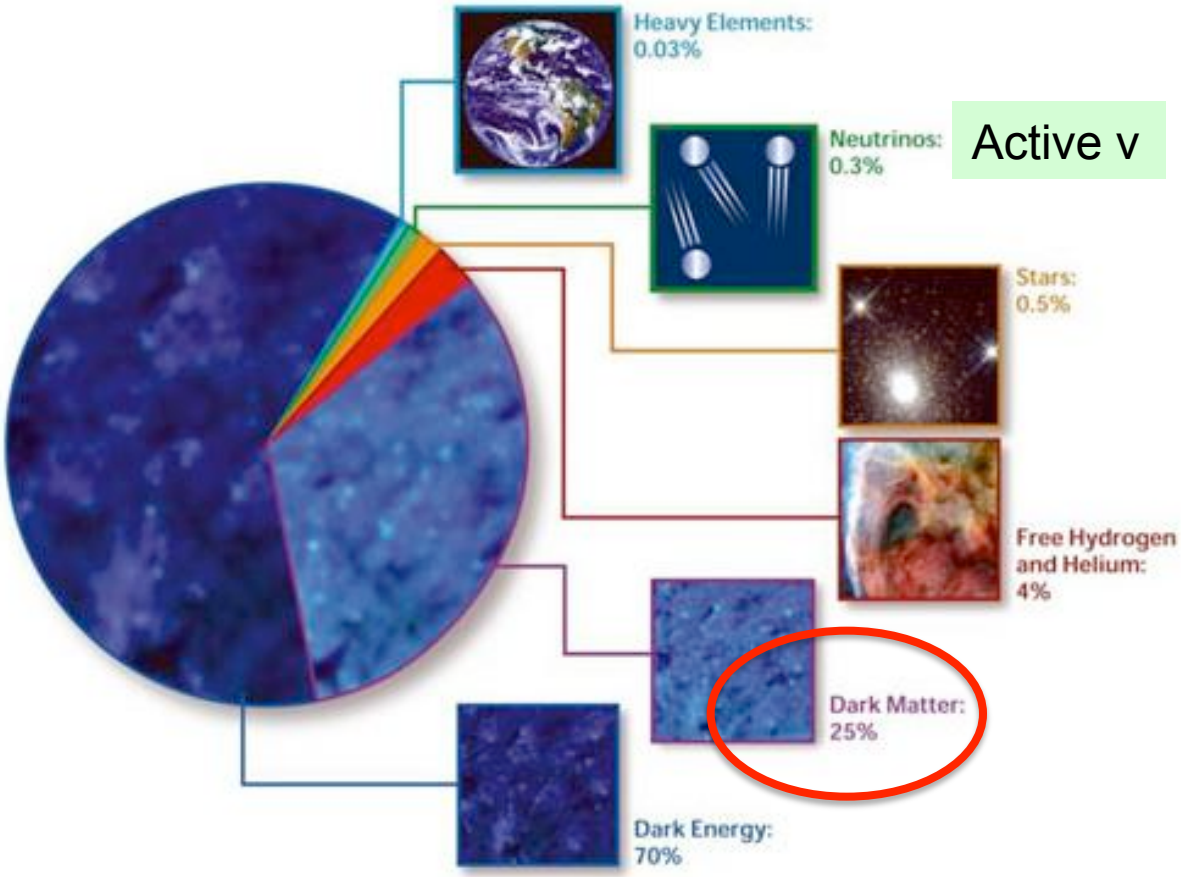
Galaxy Surveys

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…)

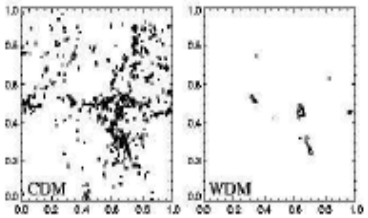
PHYSICS: WMAP and Dark Matter

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 $\sim 10^{14\pm5}$ 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).

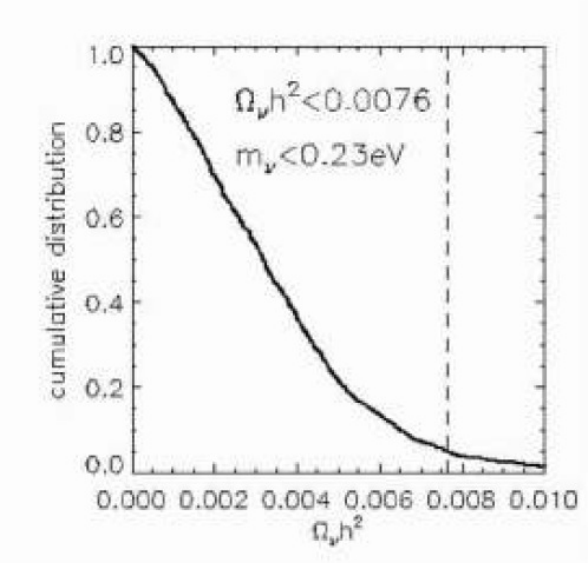
IMPORTANT COMMENTS:

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

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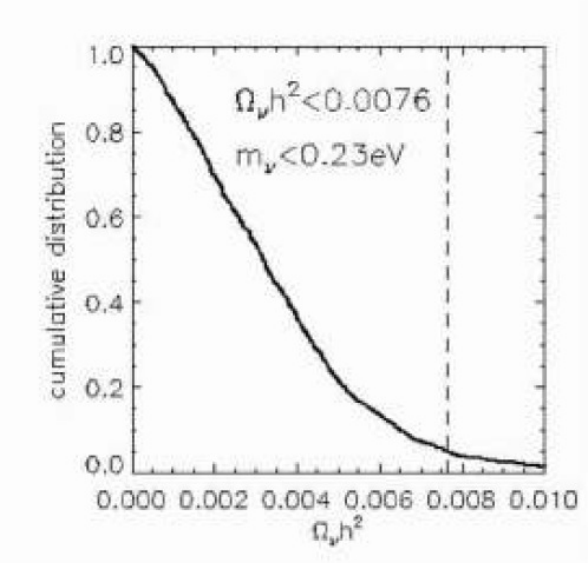

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Gonzalez-Garcia, Maltoni , Slavado, 1008.3795

UNCERTAINTY IN COSMOLOGICAL DATA DUE TO VARIETY OF SOURCES & MEASUREMENTS

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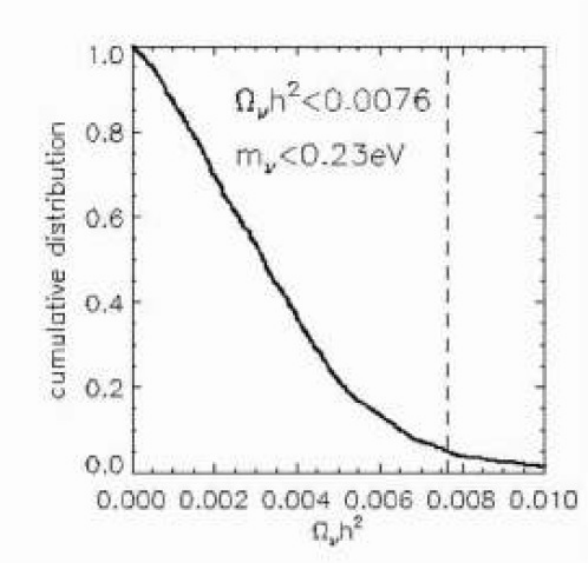

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Model dependence…

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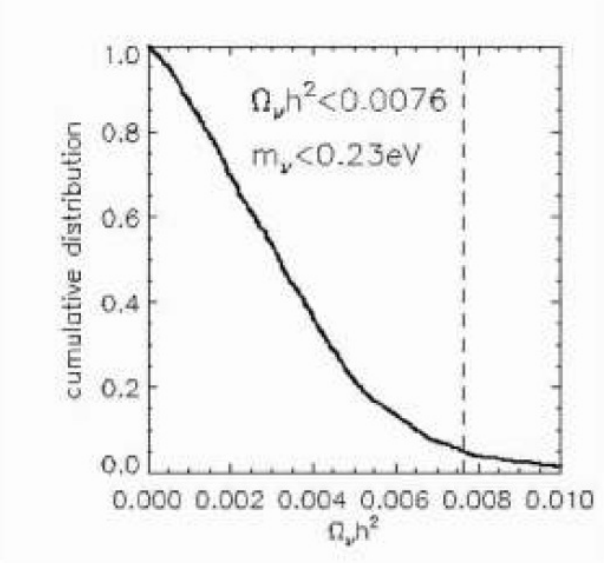
Caution:
FRW- Comology &
local Lorentz
invariance **assumed.**
If Lorentz violated (TeVeS)
ν of 2 eV mass could have
$\Omega_\nu \sim 0.15$ to reproduce
CMB spectrum
(Dodelson-Liguori 2006)



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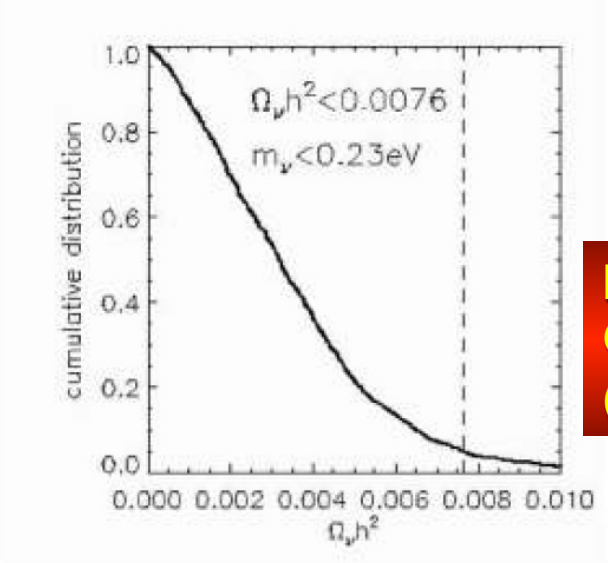

BUT…TeVeS excluded by
Gravitational Lensing Data
(Sakellariadou,Yusaf, NEM)

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Sterile neutrinos and DARK MATTER

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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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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Contributions to mass matrix of active neutrinos

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

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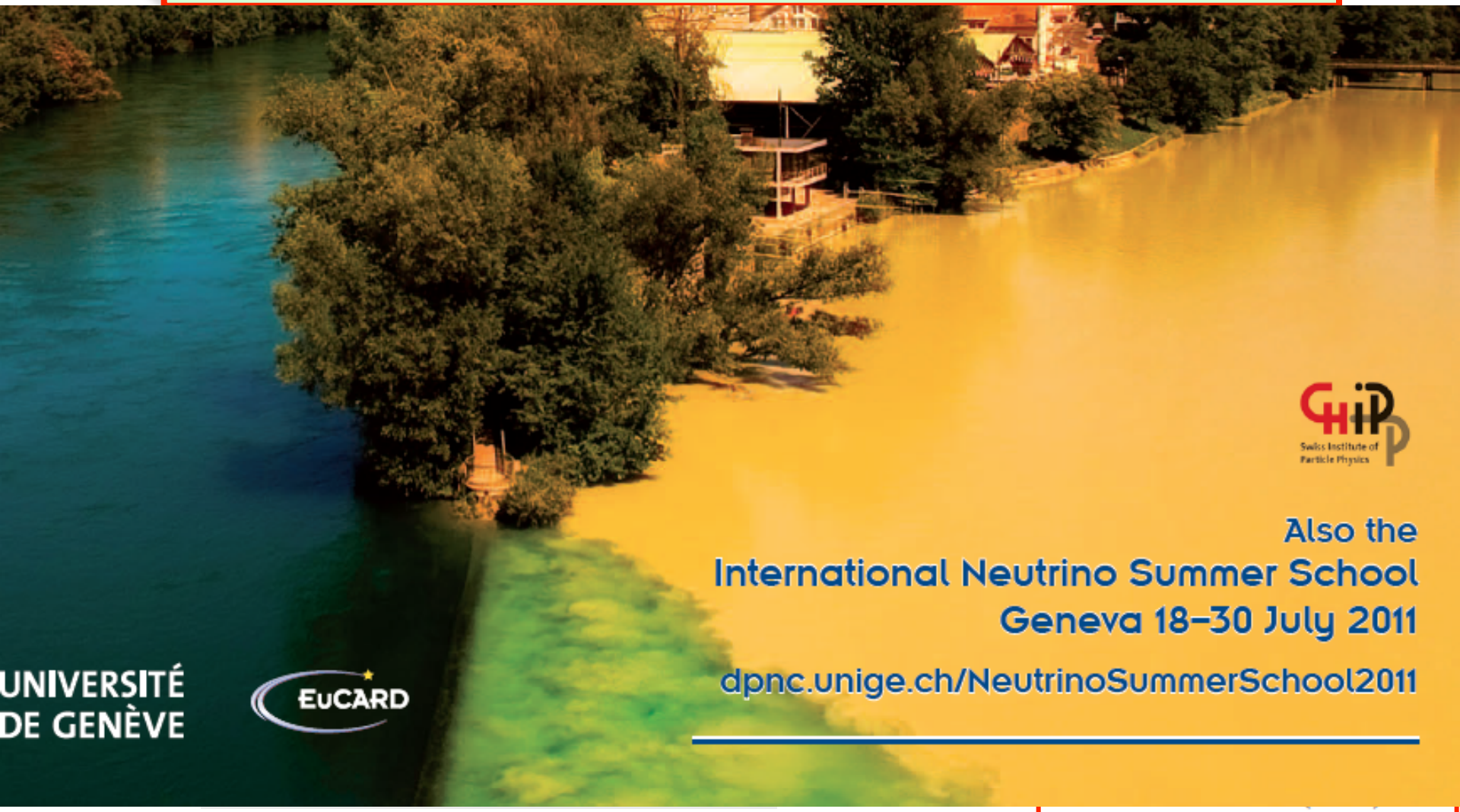

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$$M_1 \geq 2KeV \Rightarrow$$

mass contribution smaller than solar mass diff experimental error

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Contributions to mass matrix of active neutrinos

More than one sterile neutrino needed to reproduce Observed oscillations

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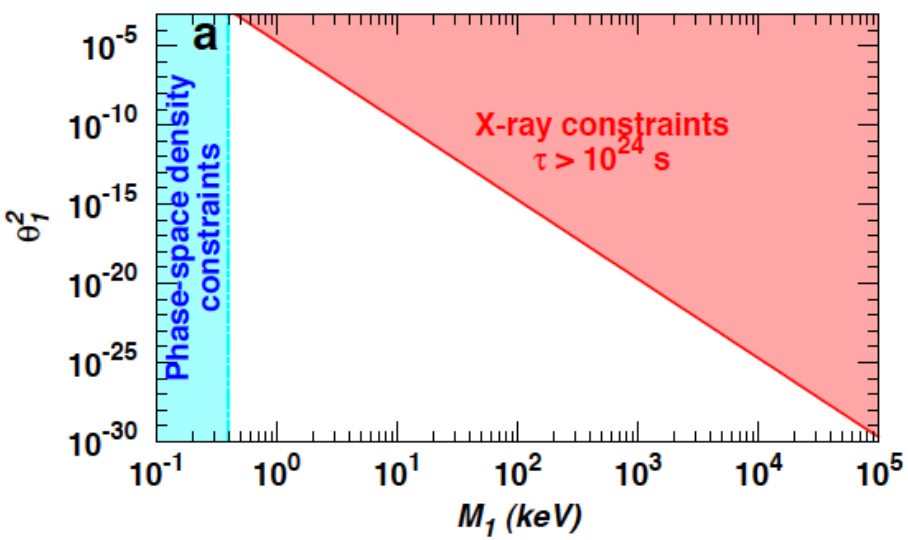
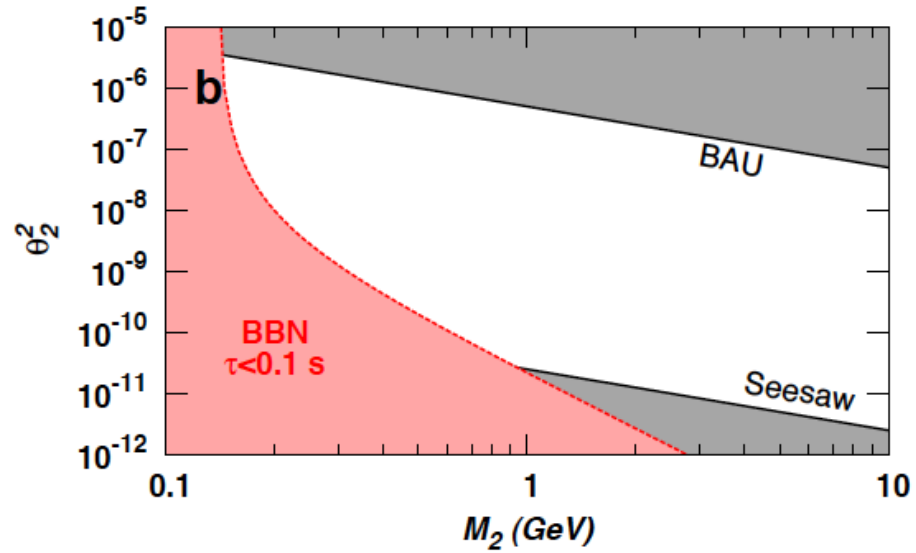




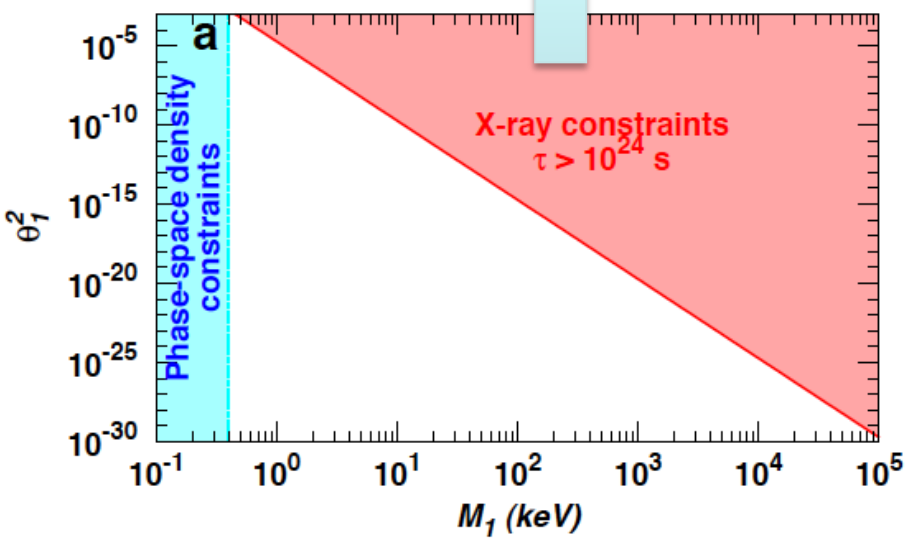
Constraints on two heavy degenerate singlet neutrinos

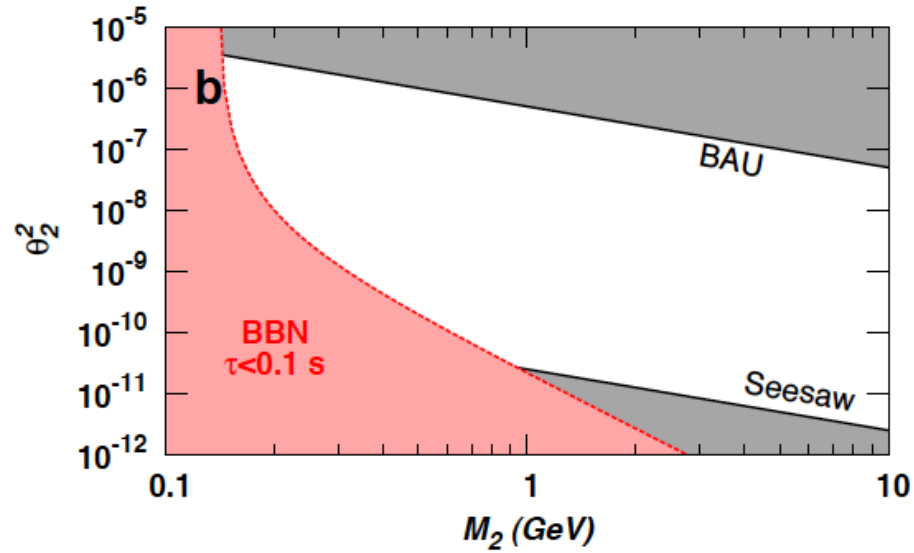
N_1 DM production estimation in Early Universe must take into account its interactions with $N_{2,3}$ heavy neutrinos

More than one sterile neutrino needed to reproduce Observed oscillations

vMSM

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





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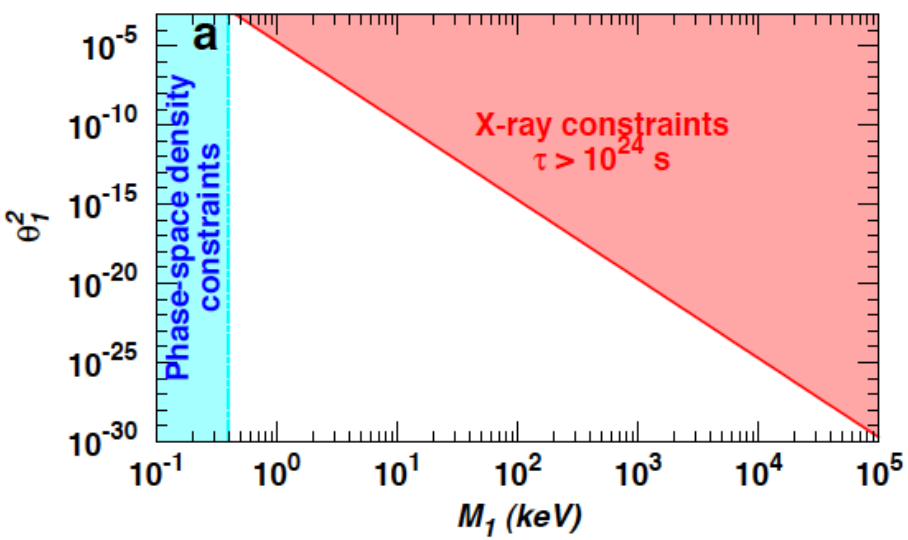

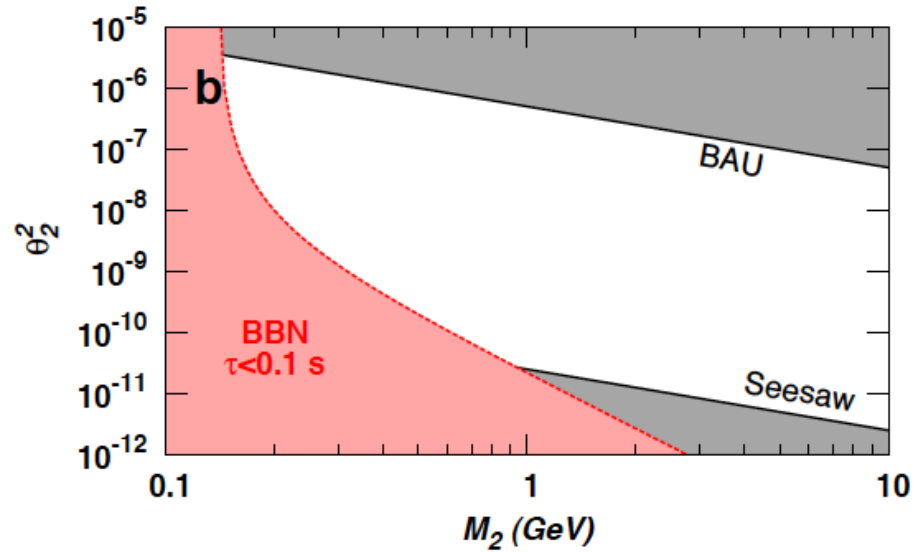

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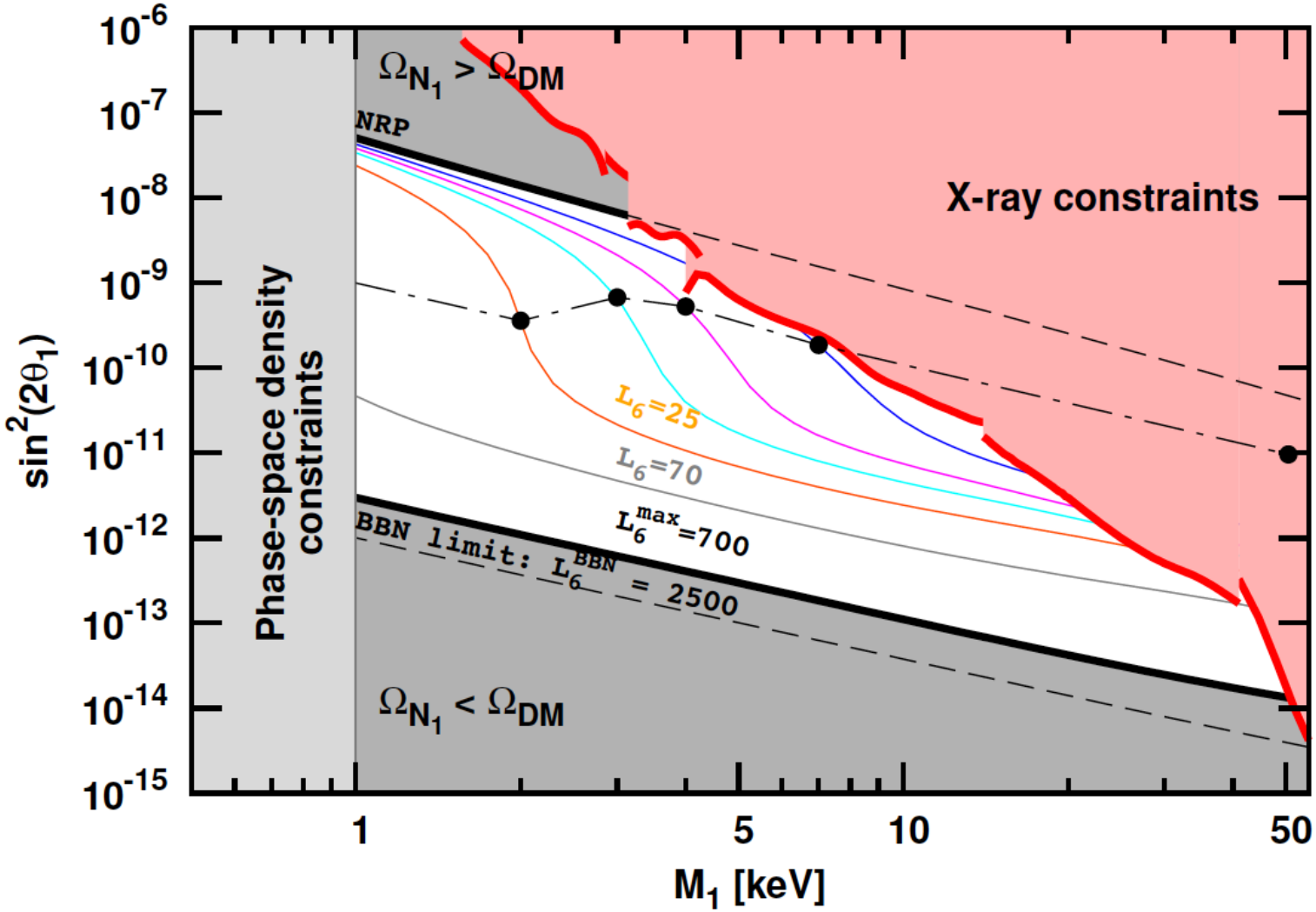
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS



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

PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

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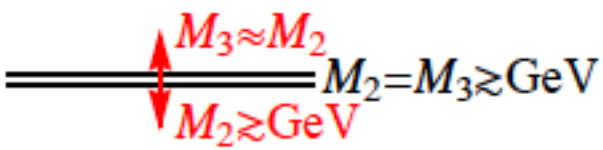
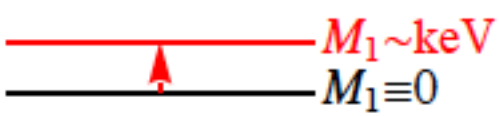
(I) ***FLAVOUR SYMMETRIES :*** $M_1 = 0$ if symmetry unbroken,
Breaking of global
Lepton symmetry generate
singlet fermion mass hierarchy



$L_e - L_\mu - L_\tau$

$\cancel{L_e = L_\mu = L_\tau}$

Shaposhnikov
Lindner, Merle, Niro



e.g. GUT models

Mohapatra, Senjanovic, Ross…

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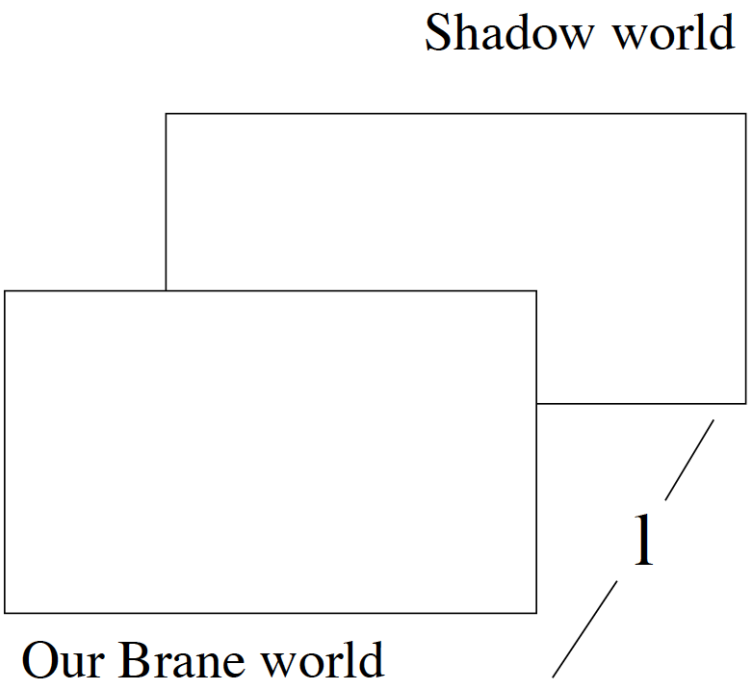
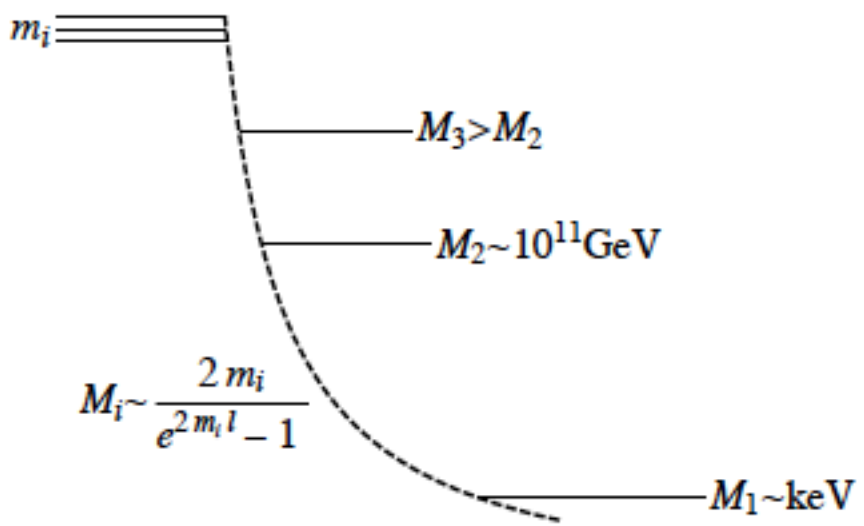
(II) BRANE WORLD RANDALL-SUNDRUM MODELS:
Exponential Mass Suppression

Kushenko, Takahashi, Yanagida





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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

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

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

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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: $\lambda \simeq 0.22$

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

PHENOMENOLOGICAL…

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(III) FROGATT – NIELSEN MECHANISM :

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

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

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

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

PHENOMENOLOGICAL…

MICROSCOPIC EXPLANATIONS?

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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

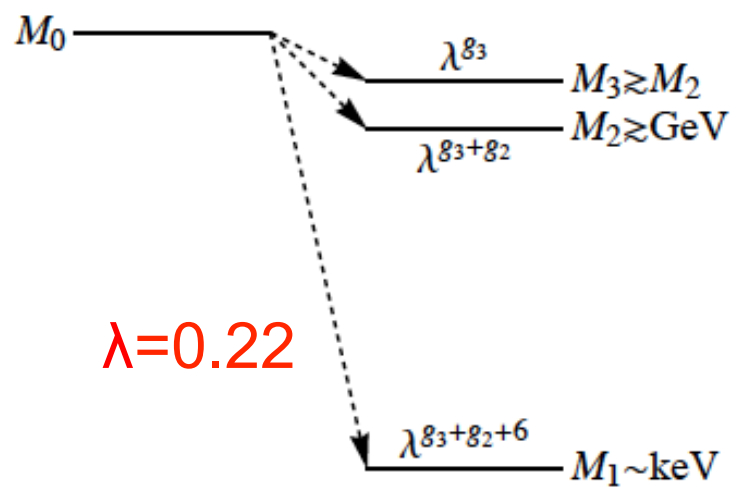
$$M_R = \begin{pmatrix} \tilde{M}_R^{11}\,\lambda^{|2g_1|} & \tilde{M}_R^{12}\,\lambda^{|g_1+g_2|} & \tilde{M}_R^{13}\,\lambda^{|g_1+g_3|} \\ \bullet & \tilde{M}_R^{22}\,\lambda^{|2g_2|} & \tilde{M}_R^{23}\,\lambda^{|g_2+g_3|} \\ \bullet & \bullet & \tilde{M}_R^{33}\,\lambda^{|2g_3|} \end{pmatrix}$$

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



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				0	0	-1

$$|g_1+g_3| \quad |g_2+g_3| \quad |2g_3|$$

MA

F

th

BUT… presently Lack of High Energy (UV) COMPLETION

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

Curious Coincidence : ***order of Cosmological Constant today not far from that provided by observed light neutrino mass differences***

$$\Lambda \sim \frac{(\Delta m^2)^2}{M_P^4} M_P^4$$

$$\Delta m^2 \sim 10^{-3}\,\mathrm{eV}^2$$

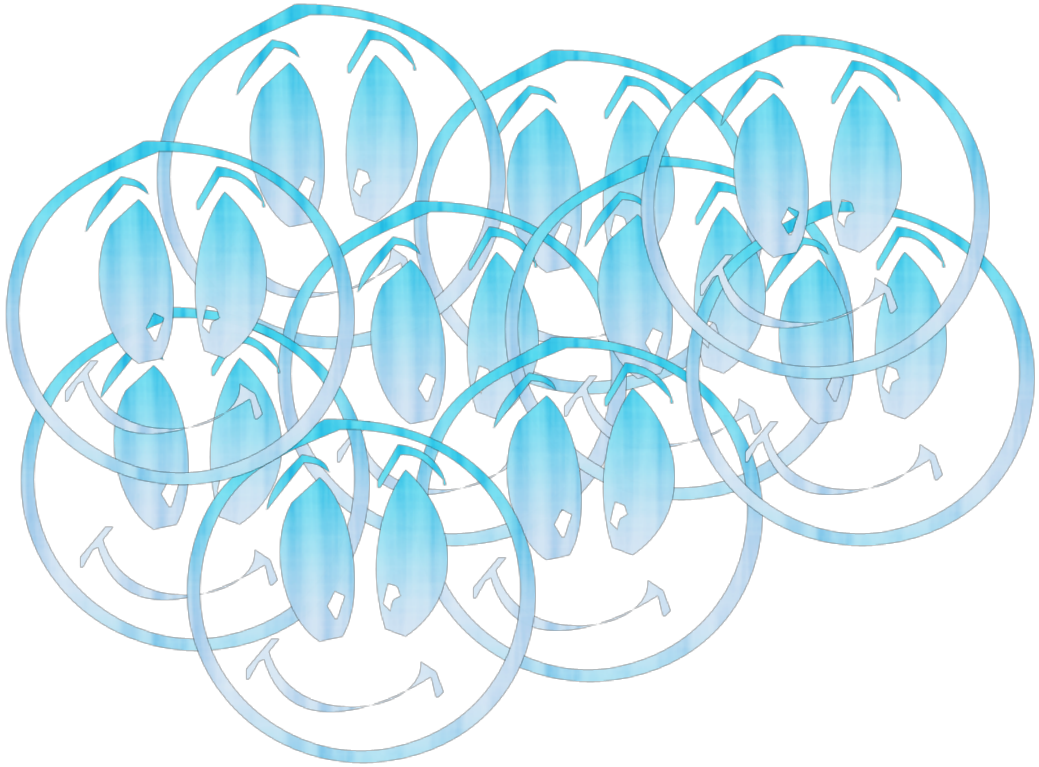
Is there a link?

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 sterile Majorana neutrino in the early Universe



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

e.g. through heavy scalar exchange

$$\mathcal{C} = \frac{f^2}{m_S^2}$$

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

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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pseudo Dirac light neutrino

Model consistent with solar neutrino data

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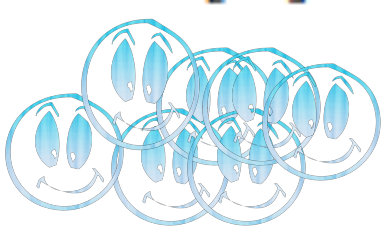
$$\mathcal{C} = \frac{f^2}{m_S^2}$$

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

One light sterile Majorana neutrino forms condensate

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

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



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

Coherence length,
Gap Equation in
FRW backgrounds
Dark Energy contribution

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e.g. through heavy scalar exchange

$$H_I = -\mathcal{C}\,(\overline{\nu_M}\,\nu_M)\,(\overline{\nu_M}\,\nu_M) \qquad \mathcal{C} = \frac{f^2}{m_S^2}$$

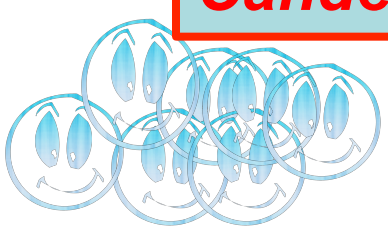
$\nu_M =$ **trino forms condensate**

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

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)

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



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

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

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

NEM

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)***

$$S_{\rm G} = \frac{1}{\kappa}\int d^4x \det(e)\Bigg(\Lambda - \frac{1}{2}e^{\mu}_{a}e^{\nu}_{b}\widehat{R}_{\mu\nu}^{\;\;ab}(e) + \sum_{\jmath}\frac{i\kappa}{2}e^{\mu}_{a}[\overline{\psi_\jmath}\gamma^a\widehat{\mathcal{D}}_\mu\psi_\jmath - \overline{\widehat{\mathcal{D}}_\mu\psi_\jmath}\gamma^a\psi_\jmath] +$$

$$\kappa^2(\frac{3}{16} - \eta\mathcal{G})[(\overline{\psi_\imath}\psi_\jmath)(\overline{\psi_\jmath}\psi_\imath) - (\overline{\psi_\imath}\gamma_5\psi_\jmath)(\overline{\psi_\jmath}\gamma_5\psi_\imath)] +$$

$$+\frac{1}{2}\kappa^2(\frac{3}{16} + \eta\mathcal{G})\,[(\overline{\psi_\imath}\gamma^\mu\psi_\jmath)(\overline{\psi_\jmath}\gamma^\mu\psi_\imath) + (\overline{\psi_\imath}\gamma_5\gamma^\mu\psi_\jmath)(\overline{\psi_\jmath}\gamma_5\gamma^\mu\psi_\imath)]\Bigg)\ ,$$

(Fierz)

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(Fierz)

Repulsive contributions due to gravitational torsion induced by fermions

$$+\frac{3\kappa^2}{16}\left(\overline{\psi}_i\gamma_\mu\gamma_5\psi_i\right)^2$$

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(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***)

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Interesting Possibility, worthy of further astrophysical tests

OF COURSE, ***not*** the whole of DM

Growth of Structure in the Universe studies

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

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

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

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

Fermion mass: $m = g\phi_c$

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Thermodynamic potential density

Fermion mass: $m = g\phi_c$

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

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

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

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comoving volume

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OTHER INTERESTING TOPICS

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

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

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

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

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

Thermodynamic potential density

Fermion mass: $m = g\phi_c$

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

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

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

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

T dependent !

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

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

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

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Fermion mass: $m = g\phi_c$

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

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

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

$$\hat{N} = \int d^3x\bar{\psi}\psi$$

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

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

$$\alpha > 0.$$

Fermion mass: $m = g\phi_c$

High T phase:

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

Fermionic contribution to thermodynamic potential **dominant**

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

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

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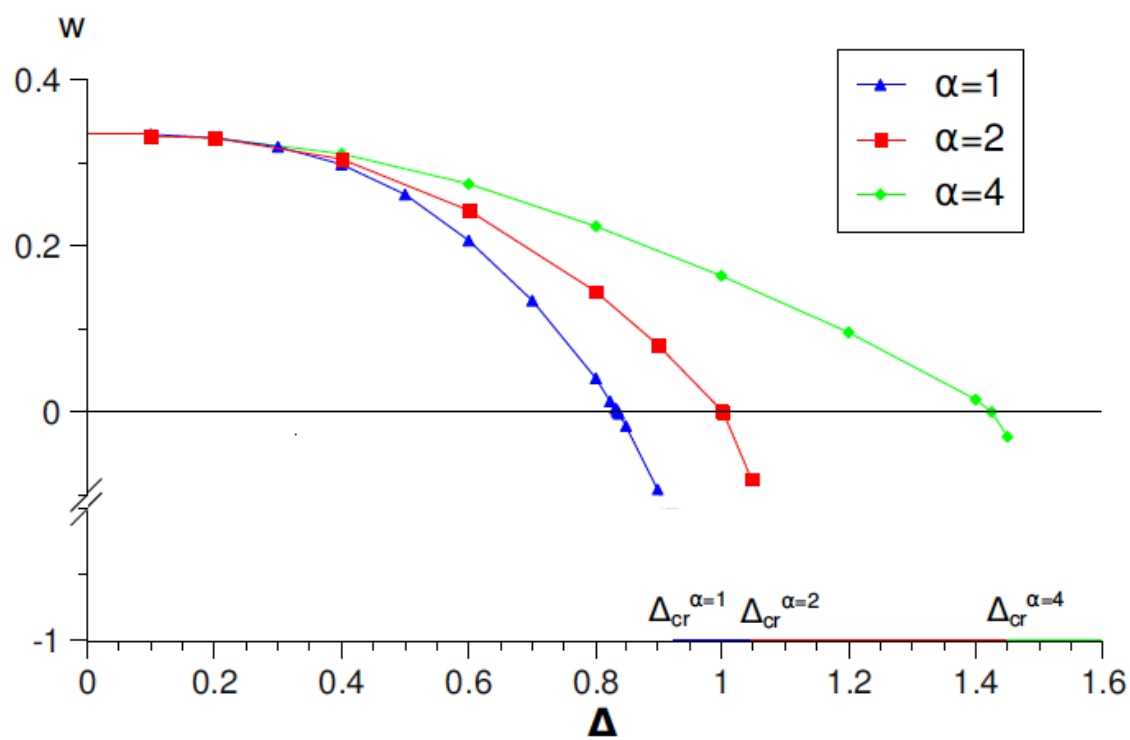
Equation of state:

Δ=M/T



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

COSMIC NEUTRINO CONDENSATES & DARK ENERGY

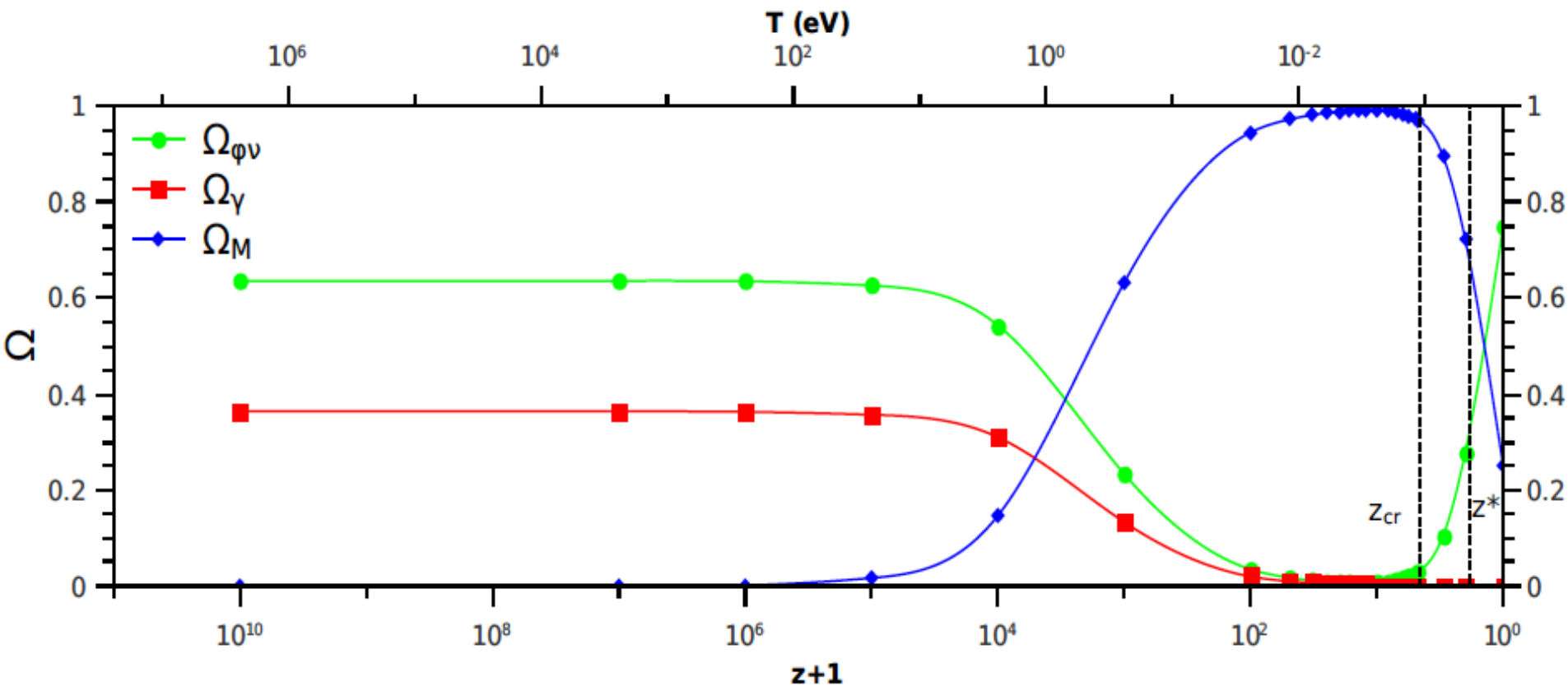
OTHER INTERESTING TOPICS

Chitov, August, Natarajan, Kahniashvili

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

Neutrino Dark Energy evolution vs Dark Matter Ω_M

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



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

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

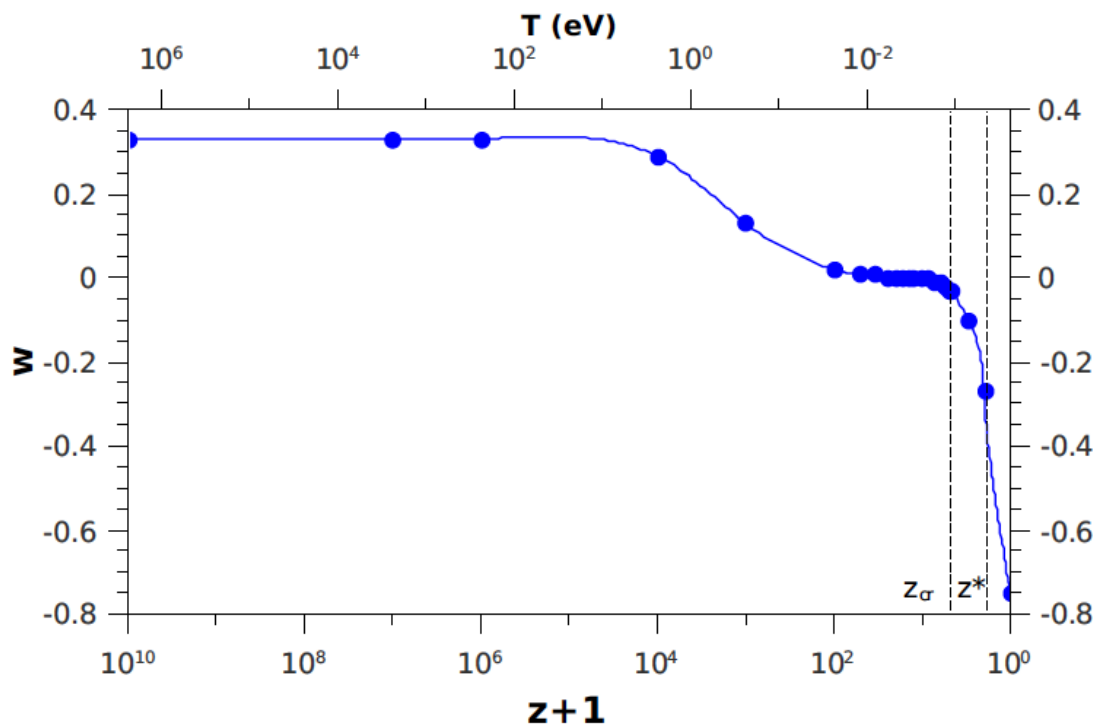
$$U(\varphi) = \frac{M^{\alpha+4}}{\varphi^{\alpha}} \qquad \alpha > 0.$$

Equation of state of entire Universe including radiation contributions:

$$P_{\mathrm{tot}} = w_{\mathrm{tot}} \rho_{\mathrm{tot}}$$

$$P_{\mathrm{tot}} = P_{\gamma} + P_{\varphi\nu}$$

$$P_{\gamma} = \frac{1}{3}\rho_{\gamma}$$



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

Neutrino mass evolution

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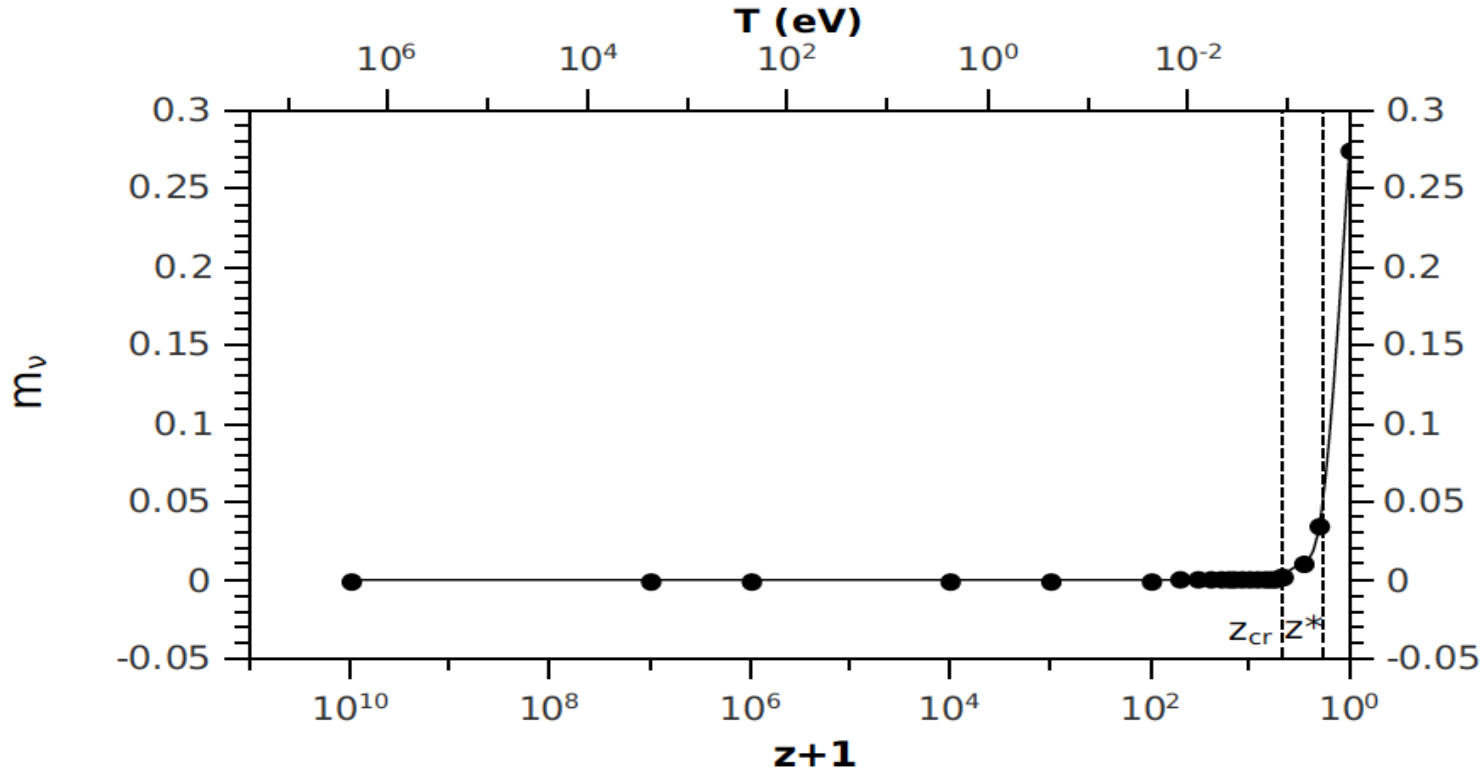

OTHER INTERESTING TOPICS

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Acceptable Cosmology
&
Neutrino phenomenology

COSMIC NEUTRINOS & VIOLATION OF FUNDAMENTAL SYMMETRIES

CPT VIOLATION IN THE EARLY UNIVERSE

GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile 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…

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(ii)-(iv) Independent reasons for violation

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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

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

(ii)-(iv) Independent reasons for violation

$$\mathbf{S} = \int d^4x\, \bar{\psi}(x) i\partial\!\!\!/ \psi(x) + \frac{im}{\pi} \int d^3x \int dt dt'\, \bar{\psi}(t, \mathbf{x}) \frac{1}{t - t'} \psi(t', \mathbf{x}).$$

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(ii)-(iv) Independent reasons for violation

e.g. ***QUANTUM SPACE-TIME FOAM AT PLANCK SCALES***

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

CPT Invariance Theorem :

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(ii) Lorentz invariance
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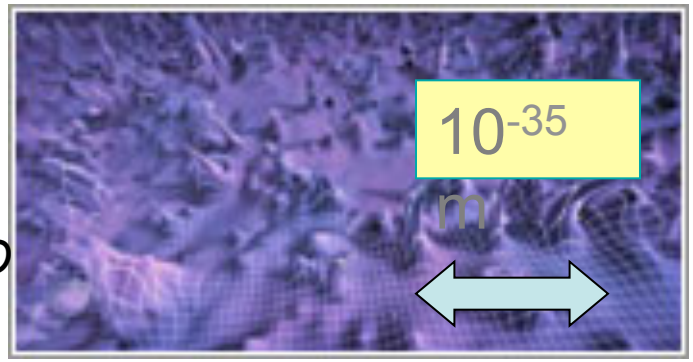
(iv) Unitarity

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



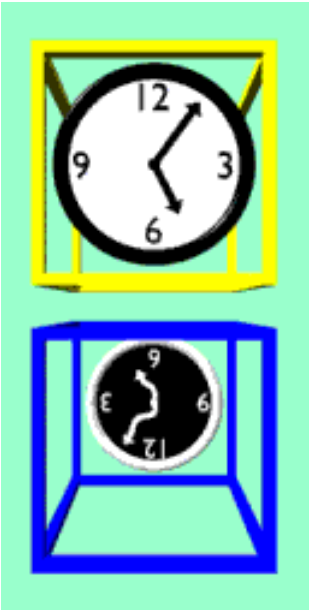
*LOW ENERGY **CPT** OPERATOR **NOT** WELL DEFINED*

Wald (79), Bernabeu, NEM, Papavassiliou,…

CPT VIOLATION 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



physics.indiana.edu

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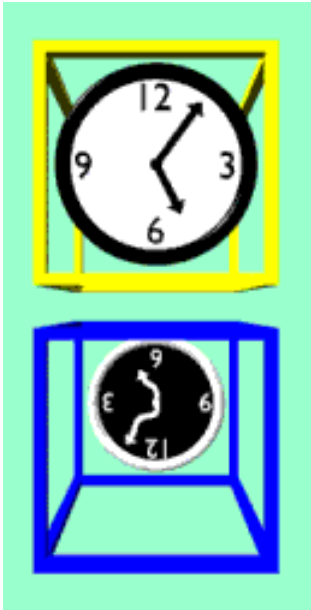

ONE POSSIBILITY:

particle-antiparticle mass differences

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

physics.indiana.edu

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

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Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

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

Dolgov, Zeldovich
Dolgov (2009)

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

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

Dolgov (2009)

Current bound for protons

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

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

But…CPT Violating neutrino-antineutrino Mass difference alone MAY REPRODUCE observed BAU

$$m_i = \tan\beta_i \overline{m}_i$$

$i = 1, 2, 3$ Light ν species

Barenboim, Borissov, Lykken, Smirnov (01) PHENOMENOLOGICAL MODELS

$$n_B = n_\nu - n_{\bar{\nu}} \simeq \frac{\mu_\nu T^2}{6}$$

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

@ 100 GeV ✔

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

Barenboim, NEM (04)

Quantum-Gravity as ``environment"

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

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

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

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

neutrino density matrix evolution
N = flavour ♯

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$$i[\rho, H]$$

QM part

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``Environment" (Lindblad part)
e.g. due to Quantum Grtavity, 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

e.g. **Benatti, Floreanini, Lisi, Marrone, Montanino… Hooper, Morgan,Winstanley Barenboim, NEM, Meregaglia, Rubbia, Sarkar, Sakharov…**

$$\langle P_{\alpha\beta}\rangle = \delta_{\alpha\beta} -$$

$$2\sum_{a=1}^{n}\sum_{b=1,a<b}^{n} \mathrm{Re}\left(U^*_{\alpha a}U_{\beta a}U_{\alpha b}U^*_{\beta b}\right)\left(1-\cos(2\ell\Delta m^2_{ab})e^{-q_1 L - q_2 L^2}\right)$$

$$-2\sum_{a=1}^{n}\sum_{b=1,a<b}^{n} \mathrm{Im}\left(U^*_{\alpha a}U_{\beta a}U_{\alpha b}U^*_{\beta b}\right)\sin(2\ell\Delta m^2_{ab})e^{-q_1 L - q_2 L^2}$$

with $\ell \equiv \dfrac{L}{4E}$ $\quad$ $q_1 = \gamma_{\mathrm{Lnb}}\left(\dfrac{E}{\mathrm{GeV}}\right)^n$

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with $\ell \equiv \frac{L}{4E}$

$$q_1 = \gamma_{\mathrm{Lnb}}\left(\frac{E}{\mathrm{GeV}}\right)^n$$

$$\gamma_{\mathrm{Lnb}} < 0.67\times 10^{-24}\ \mathrm{GeV}\ ,\quad n=0$$

$$\gamma_{\mathrm{Lnb}} < 0.47\times 10^{-20}\ \mathrm{GeV}\ ,\quad n=2$$

$$\gamma_{\mathrm{Lnb}} < 0.78\times 10^{-26}\ \mathrm{GeV}\ ,\quad n=-1$$

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

Barenboim, NEM (04)

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

neutrino density matrix evolution
N = flavour ♯

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

antineutrinos:

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

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

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$$\overline{\gamma_1} = \overline{\gamma_2} = \overline{\gamma_4} = \overline{\gamma_5} = 2 \cdot 10^{-18} \cdot E$$

and

$$\overline{\gamma_3} = \overline{\gamma_6} = \overline{\gamma_7} = \overline{\gamma_8} = 1 \cdot 10^{-24}/E$$

$$\Delta m_{12}^2 = \Delta \overline{m_{12}}^2 = 7 \cdot 10^{-5}\ \mathrm{eV}^2,$$
$$\Delta m_{23}^2 = \Delta \overline{m_{23}}^2 = 2.5 \cdot 10^{-3}\ \mathrm{eV}^2,$$
$$\theta_{23} = \overline{\theta_{23}} = \pi/4,\ \theta_{12} = \overline{\theta_{12}} = .45,$$
$$\theta_{13} = \overline{\theta_{13}} = .05,$$

masses & mixings are the same

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and

$$\overline{\gamma_3} = \overline{\gamma_6} = \overline{\gamma_7} \quad = \quad \overline{\gamma_8} = 1 \cdot 10^{-24}/E$$

Amusing: choice to best fit LSND anomaly in antineutrtino sector with rest of neutrino data…

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and

$$\overline{\gamma_3} = \overline{\gamma_6} = \overline{\gamma_7} \quad = \quad \overline{\gamma_8} = 1 \cdot 10^{-24}/E$$

Amusing: Can also produce acceptable ***BAU*** !

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

Barenboim, NEM (04)

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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 $\bar{\gamma}_1 = \bar{\gamma}_4$, $\bar{\gamma}_3 = \bar{\gamma}_8$

$$\overline{\gamma_1} = \overline{\gamma_2} = \overline{\gamma_4} = \overline{\gamma_5} = 2 \cdot 10^{-18} \cdot E$$

and

$$\overline{\gamma_3} = \overline{\gamma_6} = \overline{\gamma_7} = \overline{\gamma_8} = 1 \cdot 10^{-24}/E$$

$$\frac{\langle \nu \rangle - \langle \overline{\nu} \rangle}{\langle \nu \rangle + \langle \overline{\nu} \rangle} \simeq \widehat{\gamma_1} \simeq 10^{-6}$$

$$\widehat{\gamma_1} = 10^{-18} \cdot E/\sqrt{\Delta m^2}.$$

Neutrino-antineutrino asymmetry

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

Barenboim, NEM (04)

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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

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

Dolgov

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

$$F_{if} = \Pi_i f_i \Pi_f (1 \pm f_f)$$

CPT Violation →

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

Unitarity violation if in a single channel

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Unitarity violation if in a single channel

Estimate this way matter-antimatter asymmetry in Universe.
Lack of Microscopic Theory hampers detailed computations

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

CPT Violation

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.

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***
- ***Mass Varying ν***
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- **Interesting Physics for the Early Universe to be investigated**

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QUESTION:

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

SPARES