Introduction of Non-Standard Physics in Neutrinos

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東京大学宇宙線研究所

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Neutrinos
Windows to New Physics

Neutrino Oscillations provided

- Neutrino Masses
- Neutrino Flavor Mixings

New Symmetry

Connecting Physical Phenomena

Leptogenesis, Lepton Flavor Violation

Sterile Neutrino
Mass Varying Neutrino
CPT Violation ……

Alternative Solutions to Neutrino Oscillations

Neutrino Decays

Decoherence

However, data disfavor non-standard interaction.

Neutrino Decays

$$\mathcal{L} = g_\alpha \overline{\nu}^c_\beta \nu_\alpha J$$

J : Massless Scalar Majoron

$\nu_\alpha \to \overline{\nu}_\beta + J$ (massless scalar)

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta e^{-\alpha L/E} + 2\sin^2\theta\cos^2\theta e^{-\alpha L/2E}\cos\frac{\Delta m^2 L}{2E}$$

where $\alpha = \dfrac{m_2}{\tau_2}$

Decoherence Effect

量子状態間の干渉の消失

Neutrino system to be copled to an environment

Instead of Schrödinger Equations, we are forced to use
Liouville Equation for neutrino density matrix ρ

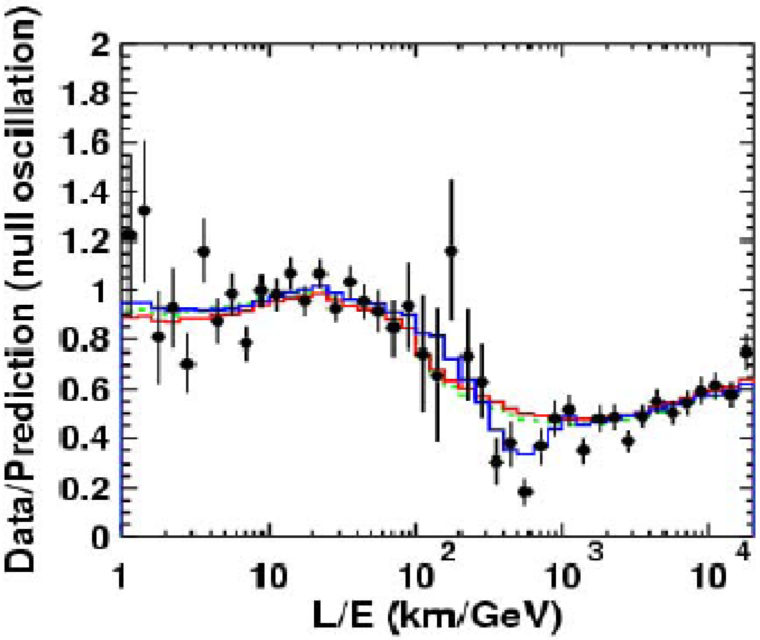
$$\dot{\rho} = -i[H_m, \rho] - \mathcal{D}[\rho]$$

Decoherence Term

$$P_{\mu\tau} = \frac{1}{2}\sin^2 2\theta \left(1 - e^{-d^2 L}\cos\frac{\Delta m^2 L}{2E}\right)$$

In $\Delta m^2=0$ limit, the pure neutrino decoherence formula is obtained.
In $d=0$ limit, the neutrino oscillation formula is obtained.

Tests for neutrino decay & decoherence



Best fit parameters

Δm^2=2.3x10^{-3},$\sin^2 2\theta$=1.00

χ^2_{min}=83.9/83 d.o.f

($\sin^2 2\theta$=1.03, χ^2_{min}=83.4/83 d.o.f)

2.0x10^{-3} < Δm^2 < 2.8x10^{-3} eV^2

0.93 < $\sin^2 2\theta$ at 90% C.L.

— **Oscillation**	χ^2_{osc} =	83.9/83 d.o.f	SK-I
— **Decay**	χ^2_{dcy} =	107.1/83 d.o.f, $\Delta\chi^2$ = 23.2(**4.8**σ)	3.4σ
— **Decoherence**	χ^2_{dec} =	112.5/83 d.o.f, $\Delta\chi^2$ = 27.6(**5.3**σ)	3.8σ

Nevertheless,
Non-Standard Interaction may be comparable oscillation effect.

Broken of Neutral Current Universality

Flavor Changing Interactions

NuTeV Anomaly

Sterile Neutrinos

CPT Violations

Mass Varying Neutrinos

Broken of Neutral Current Universality

hep-ph/0603268 M.Honda, N. Okamura and T. Takeuchi

$Z\nu_\ell\nu_\ell$ coupling: Charm and Charm II

$$g^{\nu_e} = 0.528 \pm 0.085$$

$$g^{\nu_\mu} = 0.502 \pm 0.017$$

$$g^{\nu_e}/g^{\nu_\mu} = 1.05^{+0.15}_{-0.18} = 0.87 \sim 1.20$$

Contraint by Z invisible width measured LEP and SLD

$$(g^{\nu_e})^2 + (g^{\nu_\mu})^2 + (g^{\nu_\tau})^2$$

Effective Hamiltonian for Neutrino Oscillation in Matter

$$i\frac{d}{dt}|\nu\rangle = H|\nu\rangle$$

$$H = U\frac{1}{2E}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger + \begin{bmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} b_e & 0 & 0 \\ 0 & b_\mu & 0 \\ 0 & 0 & b_\tau \end{bmatrix}$$

U is MNS matrix in vacuum:

$a = \sqrt{2}G_F N_e$:

W exchange interaction with e:

$b = -\frac{1}{\sqrt{2}}G_F N_n$: if $b_e = b_\mu = b_\tau = b$

Z exchange interaction with n

b does not contribute to neutrino oscillations.

However,

if $b_e \neq b_\mu \neq b_\tau$, b_i matix cannot be ignored.

Non-Standard Interactions

hep-ph/0606013 N.Kitazawa, H. Sugiyama and O.Yasuda

Four Ferimi Interactions

$$\mathcal{L}_{\text{eff}}^{\text{NSI}} = -2\sqrt{2}\epsilon_{\alpha\beta}^{fP} G_F (\overline{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\overline{f}\gamma^\mu P f)$$

$$f = e, u, d, \qquad P = P_L, P_R$$

Effective Hamiltonian for Neutrino Oscillation in Matter

$$\begin{aligned} H &= U\frac{1}{2E}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix}U^\dagger + \begin{bmatrix} a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} b_{ee} & b_{e\mu} & b_{e\tau} \\ b^*_{e\mu} & b_{\mu\mu} & b_{\mu\tau} \\ b^*_{e\tau} & b^*_{\mu\tau} & b_{\tau\tau} \end{bmatrix} \\ &= U\frac{1}{2E}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix}U^\dagger + a\begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix} \end{aligned}$$

$$a = \sqrt{2}G_F N_e:$$

$$\epsilon_{\alpha\beta} \simeq \sum_P \left(\epsilon^{eP}_{\alpha\beta} + 3\epsilon^{uP}_{\alpha\beta} + 3\epsilon^{dP}_{\alpha\beta}\right); \quad P = L, R$$

$\varepsilon_{\alpha\,\beta}$ have bounds at present:

S. Davidson, C. Pena-Garay, N. Rius, A. Santamaria, JHEP 0303 (2003) 011

Present Bounds

$$\begin{bmatrix} -4 < \epsilon_{ee} < 2.6 & |\epsilon_{e\mu}| < 3.8 \times 10^{-4} & |\epsilon_{e\tau}| < 1.9 \\ & -0.05 < \epsilon_{\mu\mu} < 0.08 & |\epsilon_{\mu\tau}| < 0.25 \\ & & |\epsilon_{\tau\tau}| < 18.6 \end{bmatrix}$$

Effect of $\epsilon_{\alpha\beta}$: 2 family $(e,\ \mu)$ case:

$$\tan 2\theta_M = \frac{\frac{\Delta m^2}{2E}\sin 2\theta + 2a\epsilon_{e\mu}}{\frac{\Delta m^2}{2E}\cos 2\theta - a(1+\epsilon_{ee}-\epsilon_{\mu\mu})}$$

$$\left(\frac{\Delta m_M^2 L}{4E}\right)^2 = \left(\frac{\Delta m^2 L}{4E}\cos 2\theta - \frac{aL}{2}(1+\epsilon_{ee}-\epsilon_{\mu\mu})\right)^2 + \left(\frac{\Delta m^2 L}{4E}\sin 2\theta + aL\epsilon_{e\mu}\right)^2$$

Posibility to find the large effect of the non-standard interactions in LBL oscillation experiments.

NuTeV Anomaly

$$\frac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)}, \quad \frac{\sigma(\overline{\nu}_\mu N \to \overline{\nu}_\mu X)}{\sigma(\overline{\nu} N \to \mu^+ X)}$$

are smaller than expected by SM

$$g_L^2 = 0.30005 \pm 0.00137 \quad g_L^2(SM) = 0.3042$$
$$g_R^2 = 0.03076 \pm 0.00110 \quad g_R^2(SM) = 0.0301$$

Differ from the NuTeV result by 3 σ in g_L^2

heavy gauge singlet

$$\nu = \nu_{light} \cos\theta + \nu_{heavy} \sin\theta, \quad \theta \simeq 0.05$$

$Z\nu\nu$ is supressed by $\cos^2\theta$, $W\ell\nu$ is by $\cos\theta$.

T. Takeuchi, W. Loinaz, hep-ph/0410201
W. Loinaz, N. Okamura, T. Takeuchi, L.C.R. Wijewardhana, PRD67 (2003) 073012

CPT Violation

Phenomenological Motivation comes from LSND result.
If CPT is broken in the neutrino sector, one expects differences

$$\nu_\mu \to \nu_e \ , \quad \overline{\nu}_\mu \to \overline{\nu}_e$$

$$\Delta m^2 \neq \Delta \overline{m}^2$$

However, Gonzales-Garcia, Maltoni and Schwetz showed
a global fit of all data except that of LSND is
in agreement with the CPT conserving solution:

$$\Delta m^2 = \Delta \overline{m}^2$$

The situation is changed if Decoherence effect is taken.

G. Barenboim, N. Mavromatos, JHEP 0501 (2005) 034

Dynamical Realization of Neutrino CPT Violation

Derivative coupling of the dark energy scalar

$$\mathcal{L}_{eff} \sim \partial_\mu \phi \; \bar{l}_L \gamma^\mu l_L \;\; \Rightarrow \;\; \dot{\phi} l^\dagger l = \dot{\phi} n_L$$

$\dot{\phi} \neq 0$ violates CPT invariance because translation invariance is broken in the spacetime.

Dark Energy Scalar : Quintessence, Acceleron

However, the laboratory experimental limit on CPT Violation in electrons is so stringent.

Interesting idea: Derivative coupling to ν_{Ri}

$$\mathcal{L}_{eff} \sim \frac{f_{ij}}{\Lambda} \partial_\mu \phi \; \overline{\nu}_{Ri} \gamma^\mu \nu_{Rj}$$

P-H. Gu, X-J. Bi and X. Zhang, hep-ph/0511027

Sterile Neutrinos

Sterile Neutrino Mass and Active-Sterile neutrino mixing

substantial impact of induced 3×3mass matrix

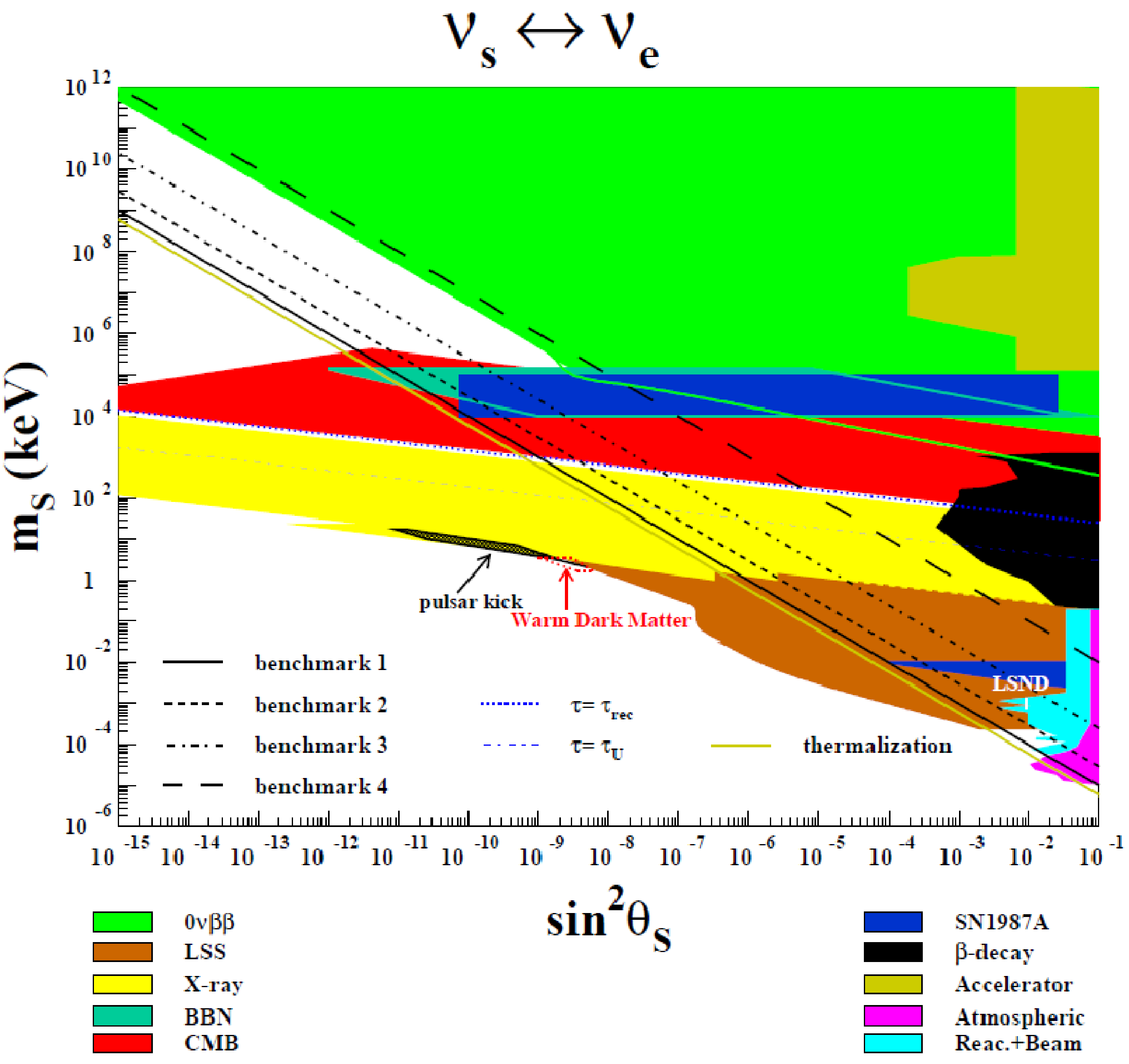
$$m_S \sim (0.1 - 0.3)\ \text{eV and } \sin^2\theta_{as} \sim 10^{-3} - 10^{-2}$$

$$m_S \geq 300\ \text{MeV and } \sin^2\theta_{aS} \leq 10^{-9}$$

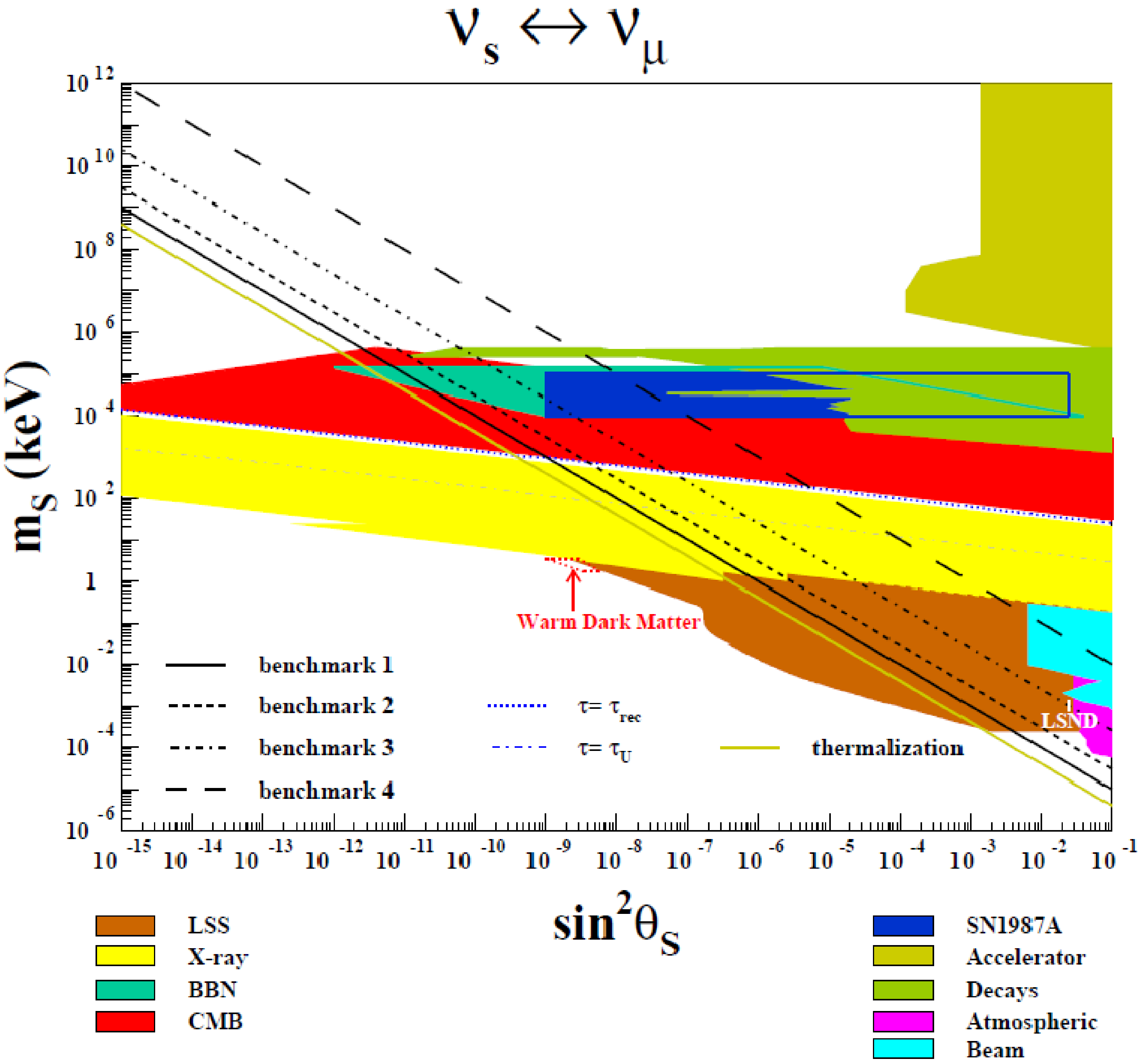
Three Benchmarks

$$\sin^2\theta_{aS}\ m_s = 10^{-3},\ 3\times 10^{-3},\ (2-3)\times 10^{-2}\ \text{eV}$$

A. Yu. Smirnov, R.Z. Funchal, hep-ph/0603009



$\nu_s \leftrightarrow \nu_e$
m_S (keV)
$\sin^2\theta_S$
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
pulsar kick
Warm Dark Matter
LSND
benchmark 1
benchmark 2
benchmark 3
benchmark 4
$\tau = \tau_{rec}$
$\tau = \tau_U$
thermalization
0νββ
LSS
X-ray
BBN
CMB
SN1987A
β-decay
Accelerator
Atmospheric
Reac.+Beam



$\nu_s \leftrightarrow \nu_\mu$
m_S (keV)
$\sin^2\theta_S$
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
10^{-15}
10^{-14}
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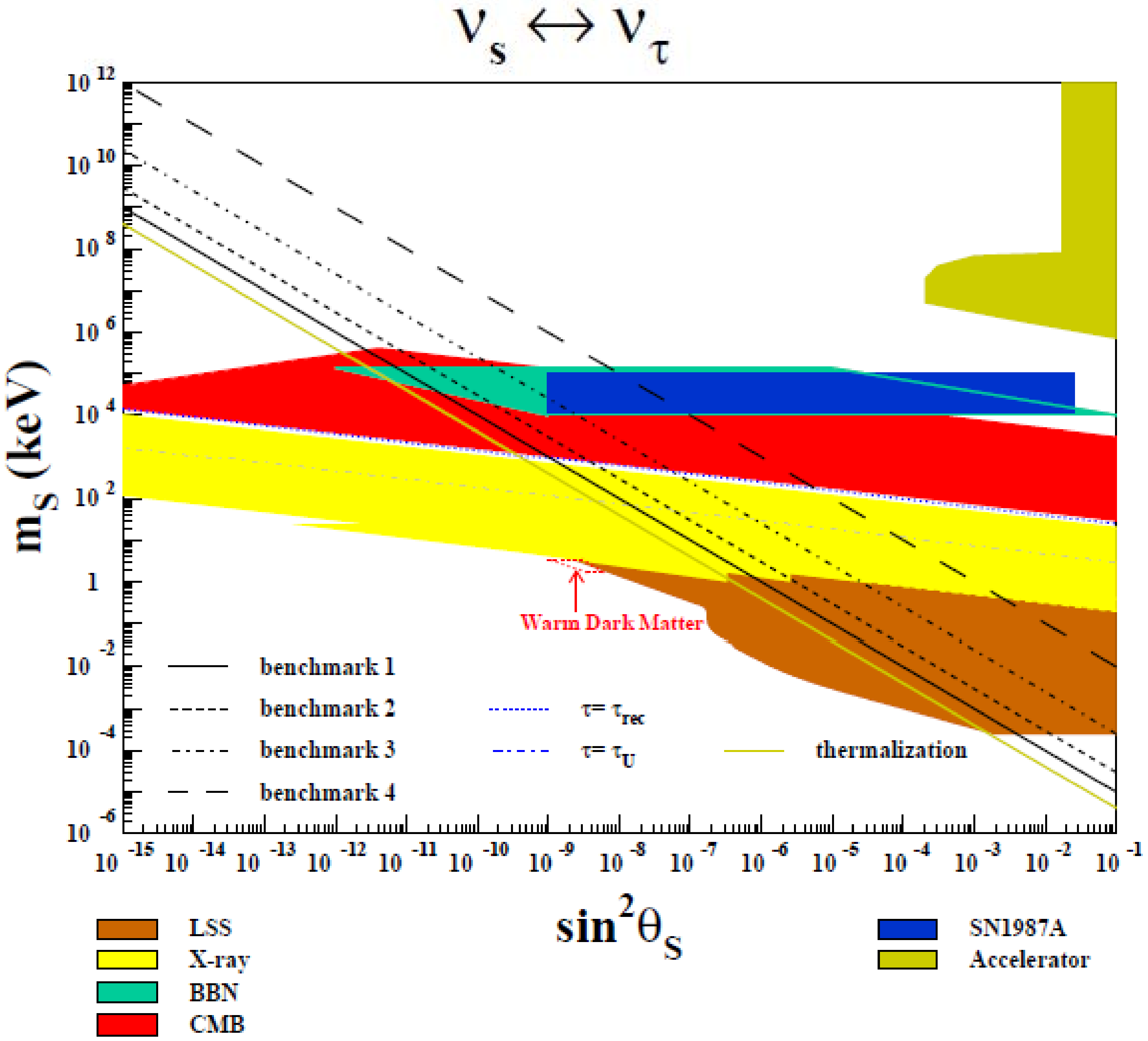

$\nu_s \leftrightarrow \nu_\tau$
m_S (keV)
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10^{-2}
10^{-4}
10^{-6}
$\sin^2\theta_S$
10^{-15}
10^{-14}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
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$\tau = \tau_{rec}$
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SN1987A
Accelerator

Mass Varying Neutrinos

R.Fardon, A.E.Nelson, N.Weiner, Astropart.Phys.10(2004)005
P.Gu, X-L.Wang and X-Min.Zhang, PRD68(2003)087301

Motivations

Very little is known about the cosmological behavior of neutrinos and the neutrino energy density.

The energy scale of the dark energy is close to the neutrino mass scale:

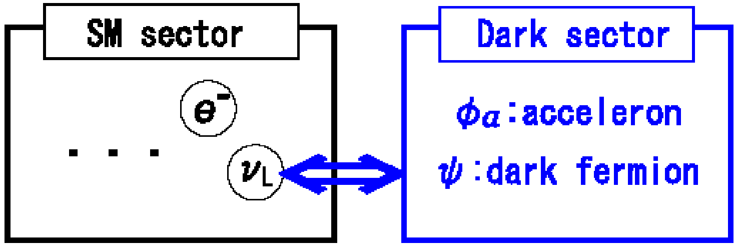
$$\Delta m_{sol}^2 \sim 8.0 \times 10^{-5} \mathrm{eV}^2 \ \text{[KamLAND,SNO]}$$
$$\Delta m_{atm}^2 \sim 2.5 \times 10^{-3} \mathrm{eV}^2 \ \text{[K2K,SK]}$$
$$7 \times 10^{-4} < \Omega_\nu < 0.02$$

$$\Lambda_{DE} \sim (2 \times 10^{-3} \mathrm{eV})^4$$

MaVaNs Scenario

Assumption 1: m_ν is the function of φ_a (Acceleron).

$$\mathcal{L}_Y = \lambda\phi_a\psi\psi + \bar{\nu}_L m_D \psi \quad \Rightarrow \quad m_\nu = -\frac{m_D m_D^T}{\lambda\phi_a}$$



SM sector

e^-

. . .

ν_L

Dark sector

ϕ_a :acceleron

ψ :dark fermion

Assumption 2: ρ_{DE} has two components.

$$\rho_{DE} = \rho_\nu + V(\phi_a(m_\nu))$$

Stationarity of ρ_{DE} leads to the varying neutrino mass.

$$\frac{\partial \rho_{DE}}{\partial m_\nu} = \overset{n_\nu}{\frac{\partial \rho_\nu}{\partial m_\nu}} + \frac{\partial V(\phi_a(m_\nu))}{\partial m_\nu} = 0$$

Non-rela neutrinos

$\rho_\nu = m_\nu n_\nu$

Neutrino Oscillations as a Probe of Dark Energy

D.B. Kaplan, A.E. Nelson, N. Weiner, PRL 93(2004) 091801

Solar mass-varying neutrino oscillation
V.Barger, P. Huber, D. Marfatis, PRL 95(2005) 211802
Mass varing neutrinos in the sun
M. Cirelli, M.C. Gonzalez-Garcia, C. Pena-Garay, NPB719(2005) 219
Confronting mass-varing neutrinos with MiniBooNE
V. Barger, D. Marfatia, K. Whisnant, PRD73 (2006) 013005
Testing mass-varing neutrinos with reactor experiments
T. Schwetz, W. Winter, PL B633(2006) 557
Effects of environment dependence of neutrino mass versus solar and reactor neutrino data
M.C. Gonzalez-Garcia, P.C. Hondara, R.Z. Funchal, PRD73(2006)033008

Dark Energy in non-relativistic neutrino background

$$V_{dark}(\phi_a) = n_\nu m_\nu(\phi_a) + V_0(\phi_a)$$

In the presence of matter, we have new effective potential for ϕ:

$$V = \lambda \frac{\rho_B \phi}{M_{planck}} + V_{dark}(\phi)$$

$$V_{dark}(\phi) = V(\phi_0) + V'(\phi_0)\phi + \frac{1}{2} V''(\phi_0)\phi^2 + \ldots$$

$$V(\phi_0) = \text{dark energy}, \; V'(\phi_0) = 0, \; V''(\phi_0) = m_\phi^2$$

$$\frac{\partial V}{\partial \phi} = 0 \Rightarrow \phi = -\frac{\lambda \; \rho_B}{m_\phi^2 \; M_{\text{planck}}}; \qquad \lambda_\nu = \left. \frac{\partial m_\nu}{\partial \phi} \right|_{\phi_0}$$

$$m_\nu(\phi) = m_\nu(\phi_0) + \frac{\partial m_\nu}{\partial \phi}\phi + \ldots = m_\nu(\phi_0) + \lambda_\nu \phi + \ldots$$

$$\Delta m_\nu \equiv m_\nu(\phi_0) - m_\nu(\phi) = -\lambda_\nu \phi = \frac{\lambda \; \lambda_\nu \; \rho_B}{m_a^2 M_{planck}} \quad = 1\text{eV}$$

$$\lambda = 10^{-2}, \; \lambda_\nu = 10^{-1}, \; \rho_B = 3g/cm^3, \; m_a = 10^{-6} \text{ eV}$$

Challenge to observe
the non-stanadrd physics
in future Neutrino
Oscillation Experiments !