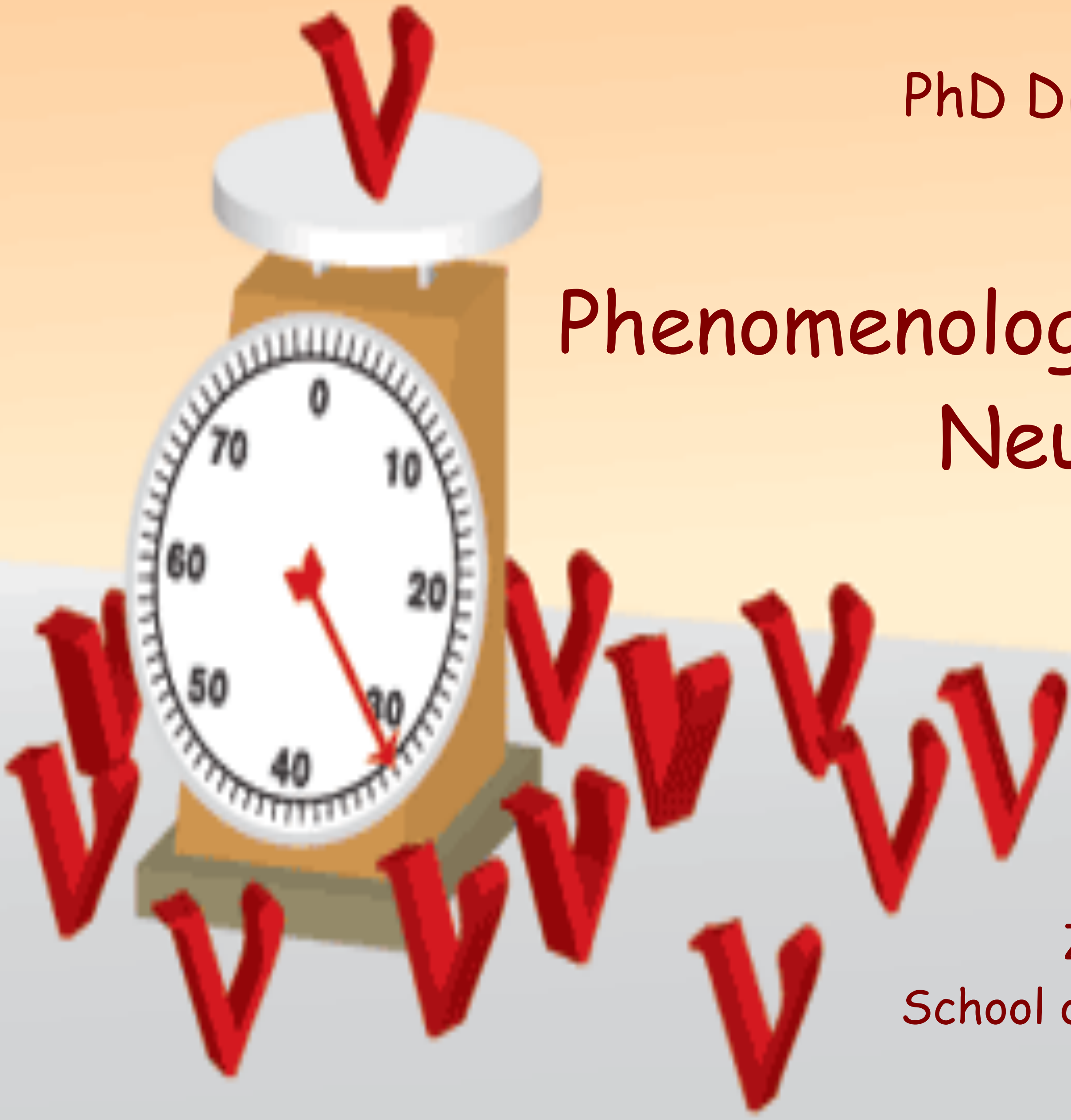
PhD Dissertation

Phenomenology of the Sterile Neutrinos



Zahra Khajeh Tabrizi
School of particles and accelerators
IPM

16 July 2015

Secret Interactions of Sterile Neutrinos and MeV-scale gauge boson

O. Peres and Z. Tabrizi

arXiv:1507.06486

Motivation

- ✓ Neutrino oscillation experiments show evidence for light sterile neutrinos with mass ~ 1 eV.

- ✓ These sterile neutrinos are disfavored by cosmology due to the Big Bang Nucleosynthesis (BBN):

$$\Sigma m_\nu = 0.23 \text{ eV, } 68\% \text{ C.L.}$$

$$\Delta N_{eff} = 0.45, \; 68\% \text{ C.L.}$$

Planck, 2015

Motivation

✓ One solution is assuming the sterile neutrinos are strongly interacting with a new light gauge boson with mass ∼MeV.

Dasgupta and Kopp, 2014
Hannestad, Hansen and Tram, 2014

$$G_X \equiv \frac{g_X^2}{M_X^2}$$

✓ This gives a significant matter potential to the sterile neutrinos; and therefore, suppresses the active-sterile mixing in the early universe.

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{(\cos 2\theta_0 + \frac{2E}{\Delta m^2} V_{\text{eff}})^2 + \sin^2 2\theta_0} \quad \& \quad |V_{\text{eff}}| \gg \left|\frac{\Delta m^2}{2E}\right|$$

"Secret Interaction" of sterile neutrinos

The sterile neutrinos can have Neutral Current matter potential:

$$V_s(r) = -\frac{\sqrt{2}}{2} G_X N_e(r) \equiv \alpha V_{NC}(r)$$
$$V_{NC}(r) = -\frac{\sqrt{2}}{2} G_F N_e(r)$$

&

$$\alpha = \frac{G_X}{G_F}$$

N_e ↓ electron number density

G_F ↓ Fermi constant

For $\alpha \to 0$ we recover the usual (3+1) model.

To solve the tension with cosmology, α must be between 10^3-10^4!!!

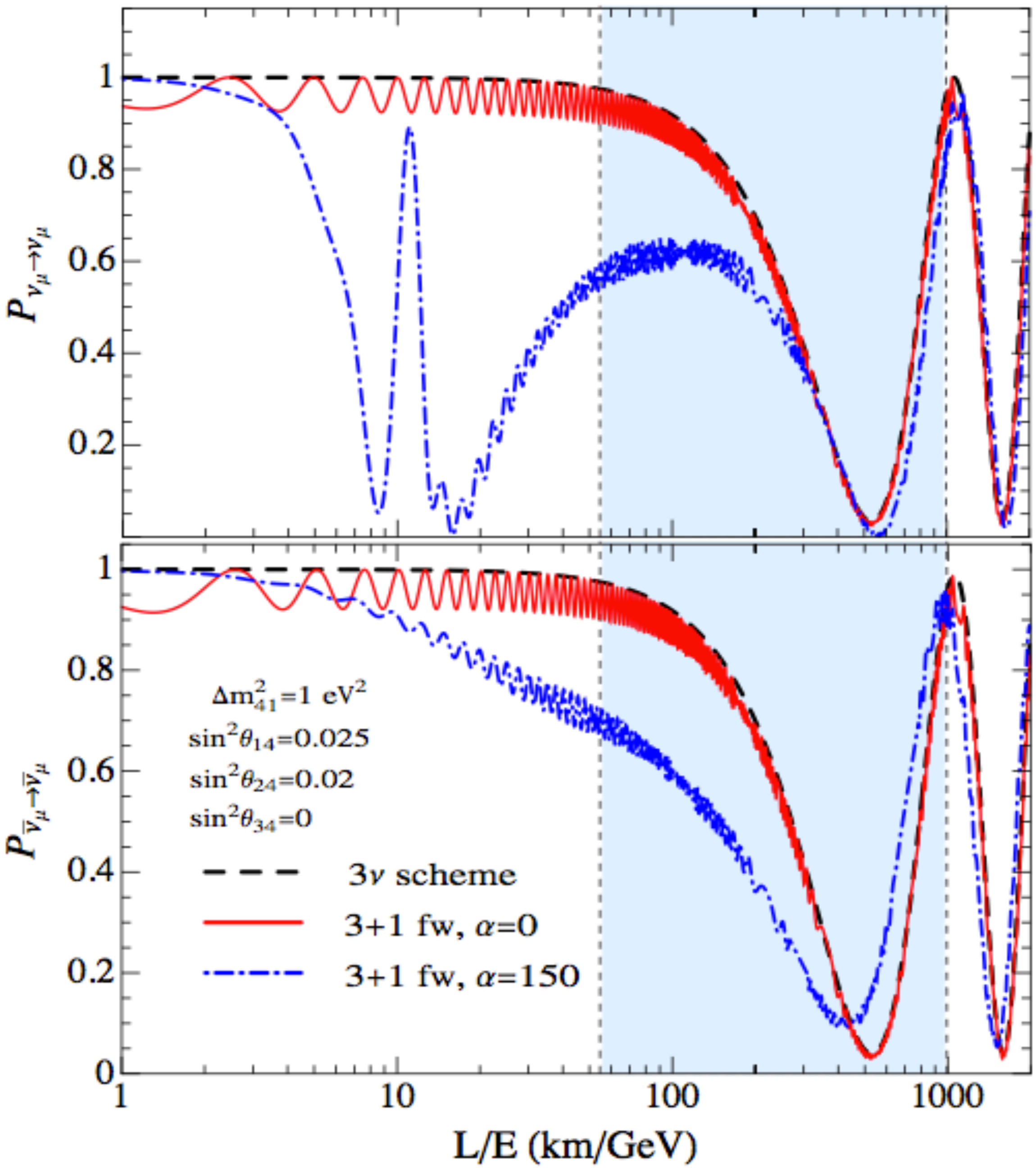
To find the evolution of neutrinos in the SI model, we need to solve the following equation:

$$i\frac{d}{dr}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \left[\frac{1}{2E_\nu}U^{(4)}M^2U^{(4)^\dagger} + V^{\mathrm{SI}}(r)\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix}$$

$$M^2 = \mathrm{diag}\left(0, \Delta\mathrm{m}^2_{21}, \Delta\mathrm{m}^2_{31}, \Delta\mathrm{m}^2_{41}\right) \qquad V^{\mathrm{SI}}(r) = \sqrt{2}G_F N_e(r)\mathrm{diag}\left(1, 0, 0, \frac{1-\alpha}{2}\right)$$

The same evolution equation applies to anti-neutrinos with the replacement $V^{SI}(r) \rightarrow -V^{SI}(r)$.

The probability in the SI model



- ✓ The 3-neutrino parameters are fixed to their best fit values.
- ✓ The usual (3+1) model only adds a very fast oscillation on the top of the oscillation induced by Δm^2_{31}.
- ✓ The $\alpha \neq 0$ case changes the oscillation probability drastically.
- ✓ The resonance induced by the SI model appears in the ν_μ survival probability, due to the negative sign of α in the potential.

The analysis

We analyze the collected muon and anti-muon neutrino beam data in the MINOS experiment.

The expected number of events in each energy bin:

$$N_i^{\mathrm{osc}}(\theta_{23}, \theta_{24}, \Delta m_{31}^2, \Delta m_{41}^2; \alpha)$$
$$= N_i^{\mathrm{no-osc}} \times \langle P_{\mathrm{sur}}(\theta_{23}, \theta_{24}, \Delta m_{31}^2, \Delta m_{41}^2; \alpha) \rangle_i$$

The free parameters are α, $\Delta m^2{}_{31}$, $\Delta m^2{}_{41}$, θ_{23} and θ_{24}.

$$\chi^2(a, b, \theta_{23}, \theta_{24}, \Delta m_{31}^2, \Delta m_{41}^2; \alpha)$$
$$= \sum_i \frac{\left[(1+a)N_i^{\mathrm{osc}} + (1+b)N_i^b - N_i^{\mathrm{obs}}\right]^2}{(\sigma_i{}^{\mathrm{obs}})^2} + \frac{a^2}{\sigma_a^2} + \frac{b^2}{\sigma_b^2}$$

$\alpha \sim 0\text{-}1000$

$\Delta m^2{}_{31} \sim (10^{-3}\text{-}10^{-1})\ \mathrm{eV}^2$

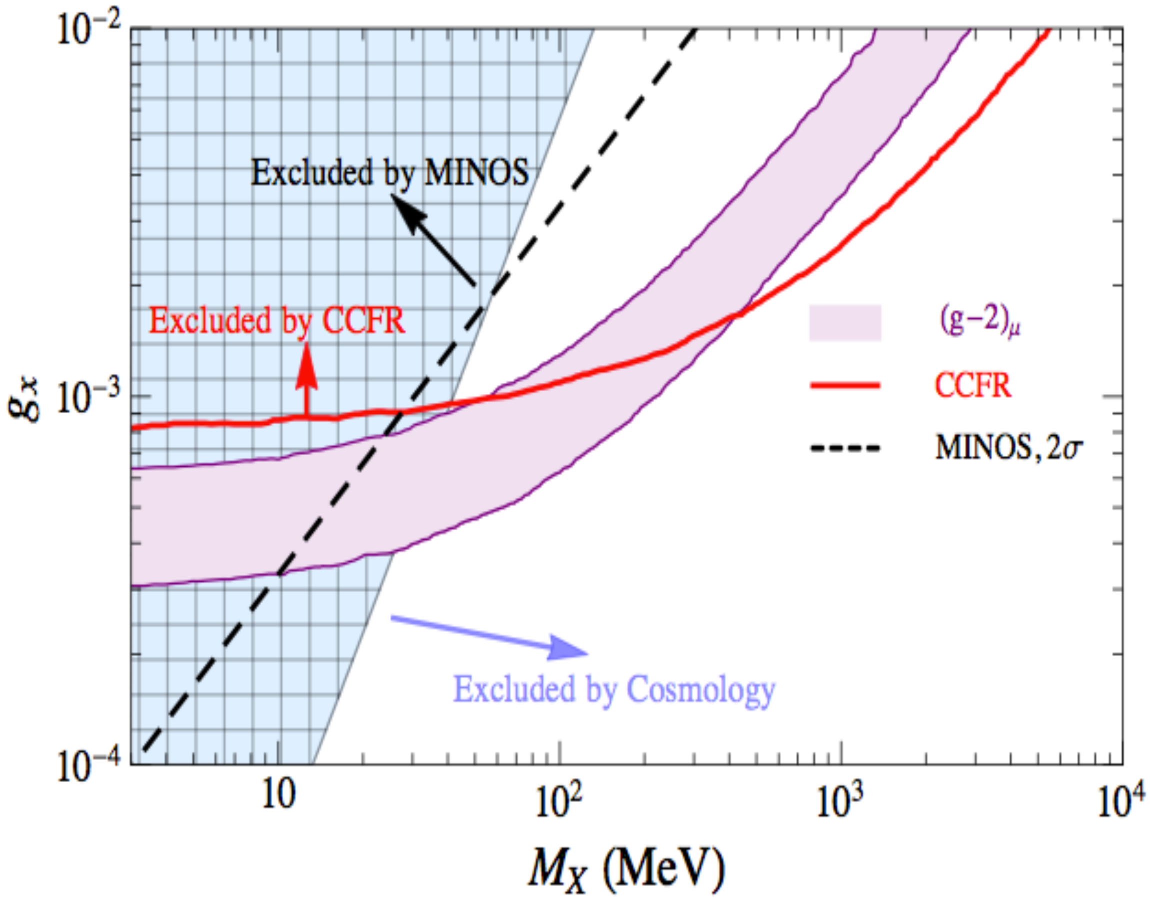
$\Delta m^2{}_{41} \sim (0.5\text{-}5)\ \mathrm{eV}^2$

Results

We find that values above α=92.4 are excluded at 2σ C.L., which means it is "unlikely" the sterile neutrinos can have very huge field strength with the new gauge boson.

$$\alpha = 19.95$$
$$\sin^2\theta_{23} = 0.67$$
$$\Delta m^2_{31} = 2.43 \times 10^{-3}\ \mathrm{eV}^2$$
$$\sin^2\theta_{24} = 0.029$$
$$\Delta m^2_{41} = 4.35\ \mathrm{eV}^2$$

Results



- ✓ For $4\times10^{-4} \lesssim g_X \lesssim 8\times10^{-4}$, which is allowed by $(g-2)_\mu$ constraint, MINOS excludes $M_X \lesssim 10$–24 MeV with 2σ C.L..
- ✓ There is only a very tiny region in the $(M_X - g_X)$ plane which is allowed by all the experimental bounds and cosmology.

Conclusions

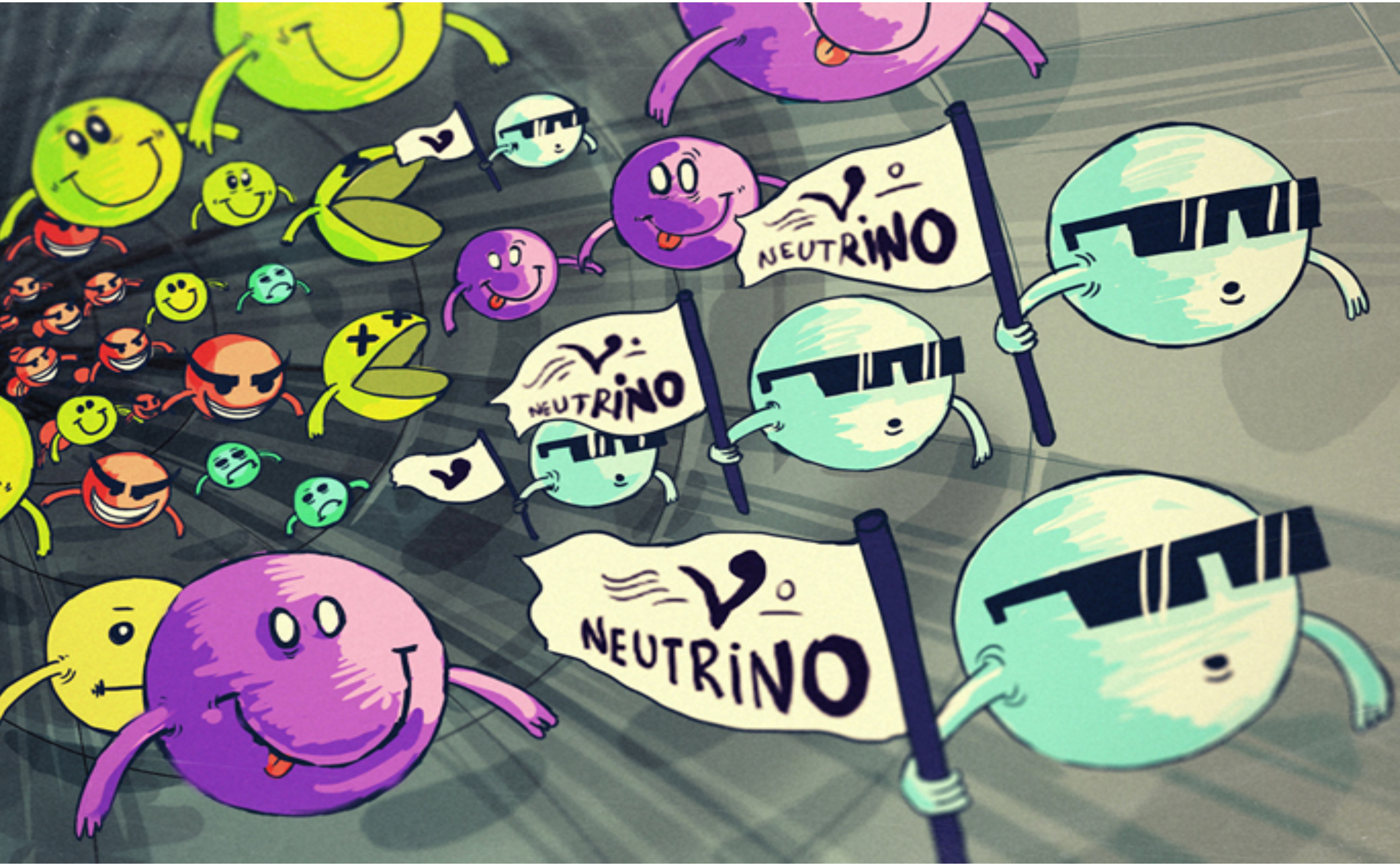
We studied the secret interaction of the sterile neutrinos using the beam data of the MINOS experiment.

We showed that values above α=92.4 are excluded using the data of the MINOS experiment, where α is the ratio of the neutral current matter potential of the sterile state and the active neutrinos.

Conclusions

We used the MINOS neutrino experiment to constrain the mass of the light gauge boson through the SI model. We found that for $4\times10^{-4} \lesssim g_X \lesssim 8\times10^{-4}$, which is allowed by $(g-2)_\mu$ constraint, MINOS excludes $M_X \lesssim 10$–24 MeV with 2σ C.L..

We showed that there is only a tiny region in the M_x–g_x region which is allowed with all experiments and cosmology, that favors the "MeV" gauge bosons.

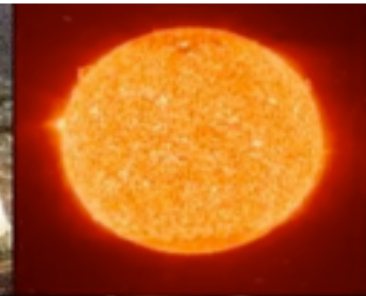


Thanks for your attention

Back up slides

Neutrinos are everywhere!

Nuclear Reactors

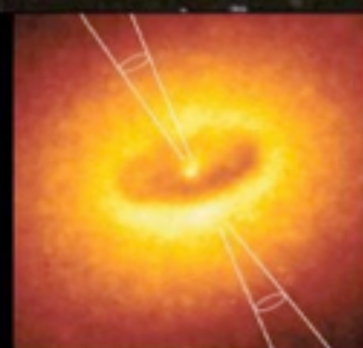


SUN

Accelerators

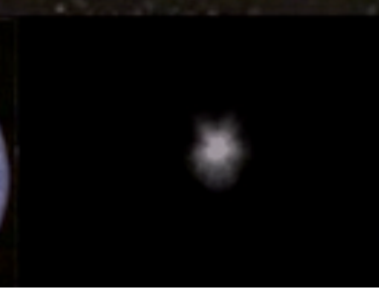
Supernova (Stellar Collapse)

Atmospheric (Cosmic Rays)



Astrophysical Accelerators

Earth's Crust/Mantle

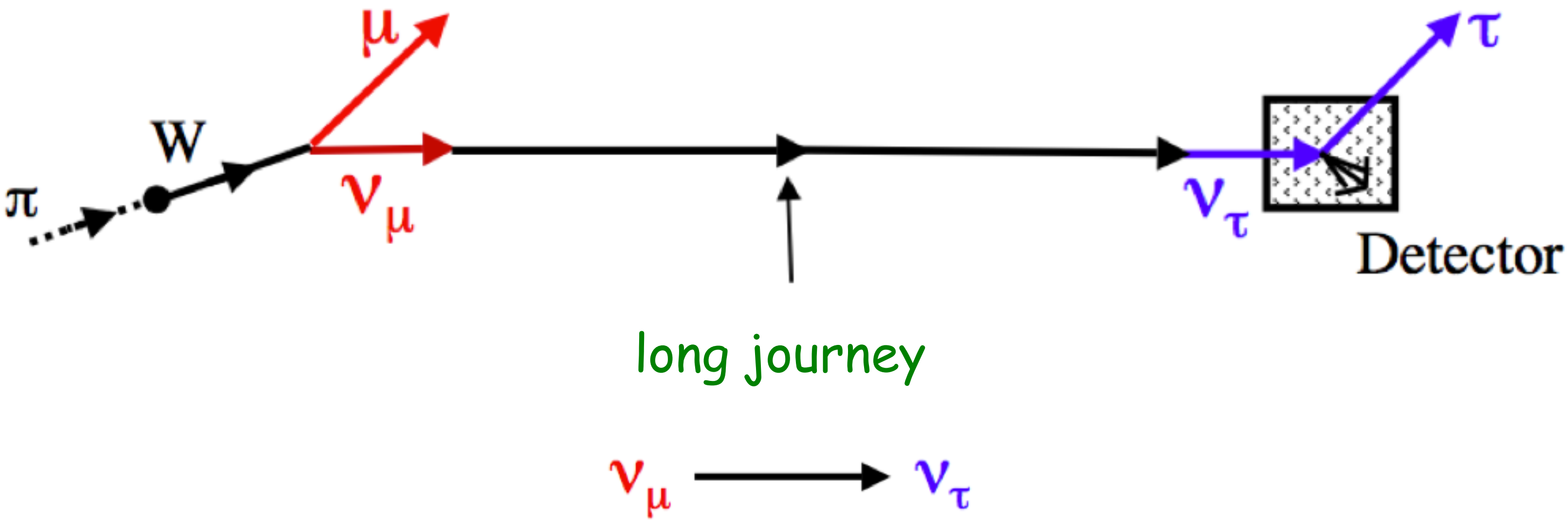


Big Bang ($330\ \nu/cm^3$)

The oscillation is described by the "PMNS" matrix!

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \overline{\ell^i_L} \gamma^\mu \boxed{U_{PMNS}} \nu_j W^+_\mu + h.c.$$

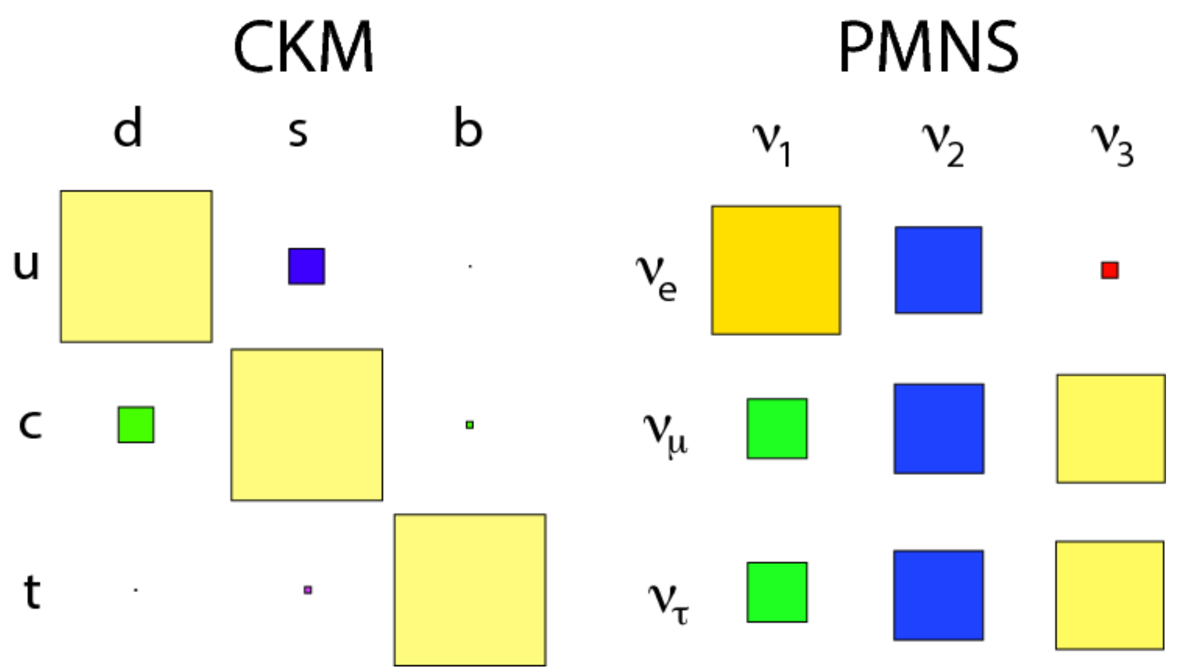
If neutrinos have mass, and leptons mix, we can have neutrino oscillation:



Neutrino experiments performed in the last 2 decades have proved that such flavor changes actually occur!

PMNS VS CKM

$$U_{CKM} = \begin{pmatrix} 0.974 & 0.225 & 0.0035 \\ 0.225 & 0.973 & 0.041 \\ 0.0086 & 0.040 & 0.999 \end{pmatrix} \qquad U_{PMNS} = \begin{pmatrix} 0.779 & 0.510 & 0.122 \\ 0.183 & 0.385 & 0.613 \\ 0.200 & 0.408 & 0.589 \end{pmatrix}$$



Neutrino Oscillation in Vacuum

Survival probability

$$P_{\nu_\alpha \to \nu_\alpha}(L) = 1 \quad - \quad 4 \sum_{i>j} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right)$$

oscillation phase

$$\frac{\Delta m_{ij}^2 L}{4E} = 1.27 \left(\frac{\Delta m_{ij}^2}{\mathrm{eV}^2} \right) \left(\frac{L}{\mathrm{km}} \right) \left(\frac{\mathrm{GeV}}{E} \right)$$

No information on the mass scale

The case of 2 neutrinos

1 mixing angle
No CP phase

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

1 Mass squared difference

$$\Delta m^2_{12} \equiv \Delta m^2$$

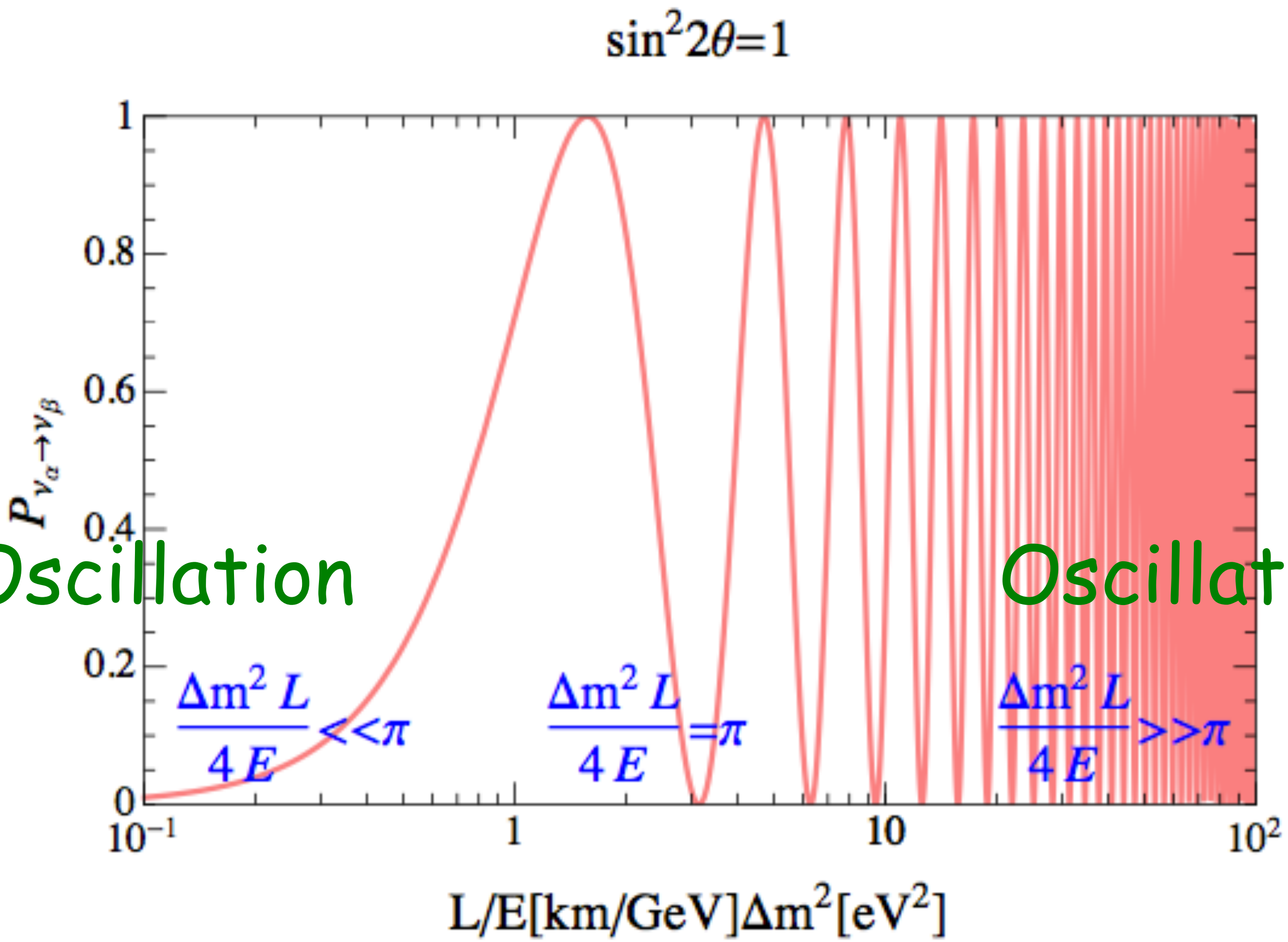
Transition Probability

$$P_{\nu_\alpha \to \nu_\beta}\Big|_{\alpha \neq \beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

survival Probability

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - P_{\nu_\alpha \to \nu_\beta}\Big|_{\alpha \neq \beta}$$

The case of 2 neutrinos



Small Oscillation

Oscillates Rapidly

Sensitivity of Experiment

Neutrino oscillation in matter

Charged Current and Neutral Current Potential

$$V_{CC}(r) = \sqrt{2}G_f N_e(r),$$
$$V_{NC}(r) = -\frac{\sqrt{2}}{2}G_f N_n(r),$$

Potential matrix

$$V(r) = \begin{pmatrix} V_{CC}(r) + V_{NC}(r) & 0 & 0 \\ 0 & V_{NC}(r) & 0 \\ 0 & 0 & V_{NC}(r) \end{pmatrix}$$

MSW effect

$$\Delta m_M^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - A_{\mathrm{CC}}\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$A_{\mathrm{CC}} = 2E_\nu V_{\mathrm{CC}}$$

Mikhaev, Smirnov and Wolfenstein, 1985

Resonance condition

$$A_{\mathrm{CC}}^R = \Delta m^2 \cos 2\theta$$

ν_e ($\bar{\nu}_e$) disappearance experiments

Baseline: L<100 m

The survival probability:

$$P^{3+1}_{\nu_e(\bar{\nu}_e)\to\nu_e(\bar{\nu}_e)} = 1 - 4|U^{(4)}_{e4}|^2(1-|U^{(4)}_{e4}|^2)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$
$$= 1 - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right),$$

ν_μ ($\bar{\nu}_\mu$) disappearance experiments

Baseline: L~a few hundred-a few thousand km

The survival probability:

$$P^{3+1}_{\nu_\mu(\bar{\nu}_\mu)\to\nu_\mu(\bar{\nu}_\mu)} = 1 - 4|U^{(4)}_{\mu 4}|^2(1 - |U^{(4)}_{\mu 4}|^2)\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) appearance experiments

The transition probability:

$$P^{3+1}_{\nu_\mu(\bar{\nu}_\mu)\rightarrow\nu_e(\bar{\nu}_e)} = 4|U^{(4)}_{\mu 4}|^2|U^{(4)}_{e4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Global analysis on sterile neutinos

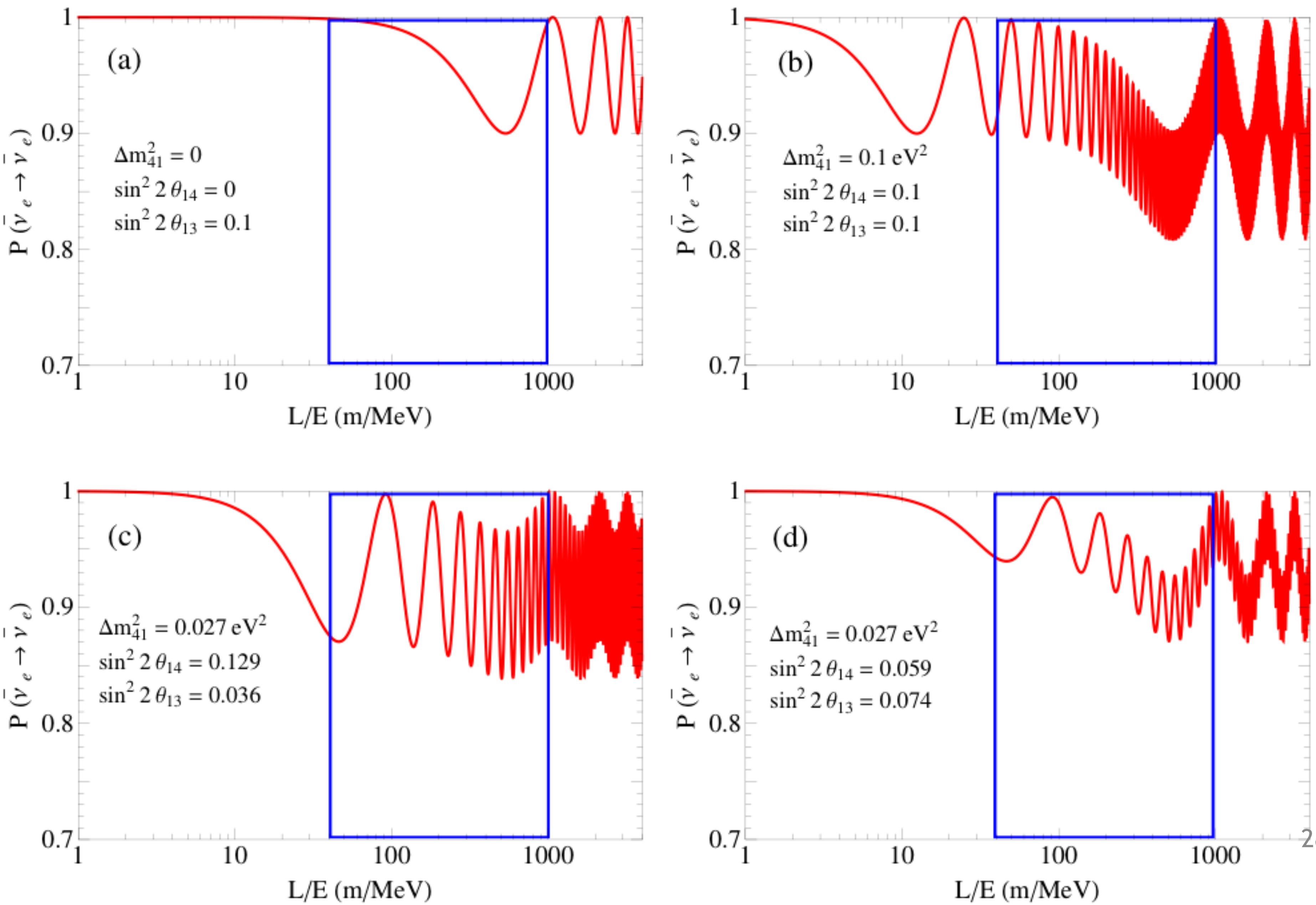
Kopp, Machado, Maltoni and Schwetz, 2013

$$\begin{aligned} \Delta m_{41}^2 &= 0.93\ \mathrm{eV}^2, \\ |U_{e4}^{(4)}| &= 0.15, \\ |U_{\mu 4}^{(4)}| &= 0.17, \\ |U_{\tau 4}^{(4)}|^2 &\leq 0.2; \end{aligned}$$

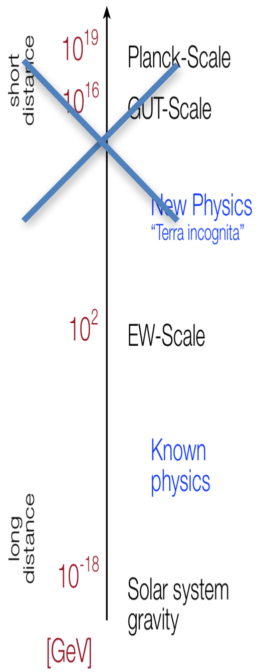
$$\begin{aligned} \sin^2\theta_{14} &= 0.022, \\ \sin^2\theta_{24} &\simeq 0.029, \\ \sin^2\theta_{34} &\leq 0.19. \end{aligned}$$

Probing light sterile neutrinos in medium baseline reactor experiments

Survival probability in $(3+1)_{light}$ model



Probing Large Extra Dimensions With IceCube



LED: One solution to the hierarchy problem

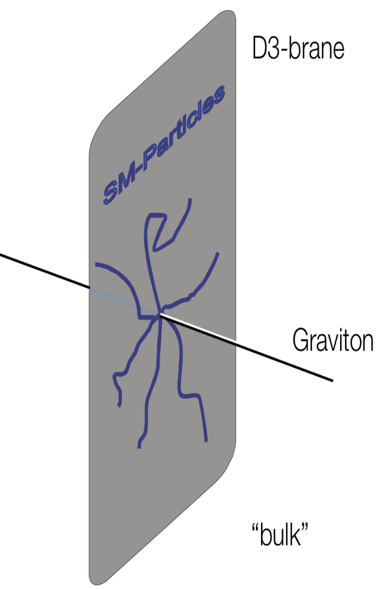
Idea: Graviton propagates in the extra dimension

$$4D \rightarrow (4+n)D$$
$$\Lambda_{Pl} \rightarrow M \sim m_{ew}$$

- ✓ "n" compactified extra space dimensions with size R.
- ✓ Gravity in all "3+n" space dimensions
- ✓ SM interactions and all matter particles (including ▢▢$_L$) have to be confined to our 4-dimensional world.

$$M^2_{Pl} = V_n M_f^{2+n}$$

$$V_n = (2\pi)^n R^n$$

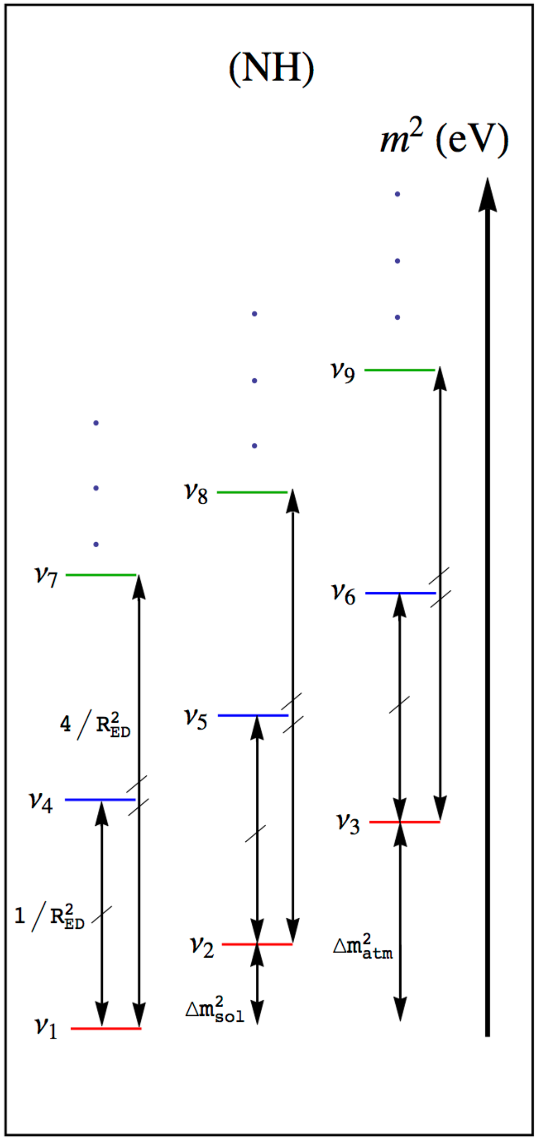


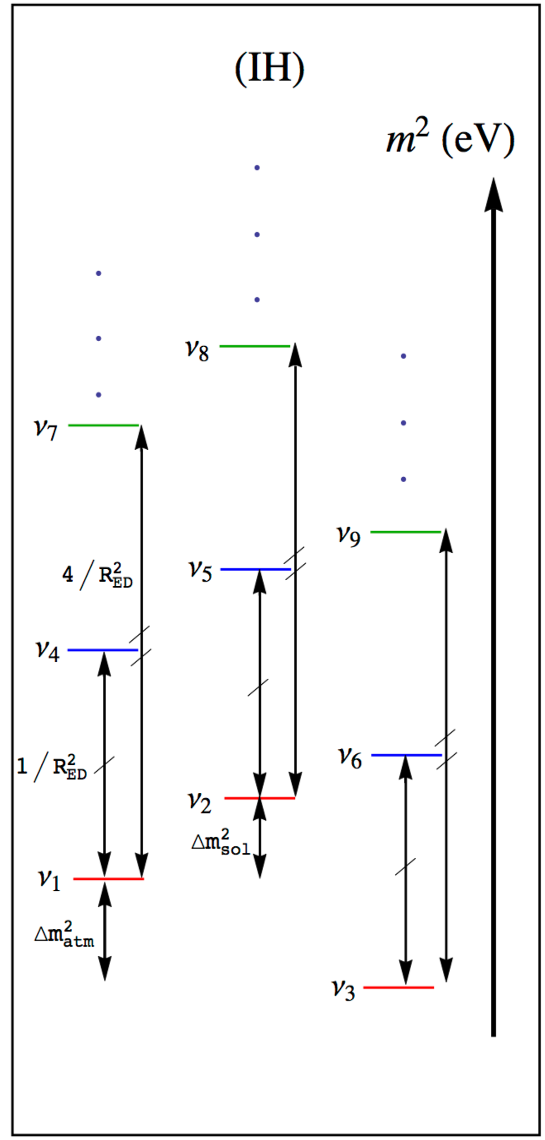
$$n \geq 2$$

- ✓ At least 2 extra dimensions are needed:

The mass terms:

$$m^D_{\alpha\beta}(\bar{\nu}^{\alpha(0)}_R \nu^\beta_L + \sqrt{2}\sum_{n=1}^{\infty} \bar{\nu}^{\alpha(n)}_R \nu^\beta_L) + \sum_{n=1}^{\infty} \frac{n}{R_{\rm ED}} \bar{\nu}^{\alpha(n)}_R \nu^{\alpha(n)}_L + \text{h.c.}$$





Smallness of neutrino masse

λ_{ij}: Yukawa couplings

V_D: The volume of the LED

v: vacuum expectation value

M_F: Fundamental Planck constant

M_{Pl}: observed Planck constant

$$m_{ij}^D = \frac{\lambda_{ij} v}{\sqrt{V_D}} = h_{ij} \frac{M_F}{M_{\rm Pl}} v$$

$$[\lambda_{ij}]_M = -\frac{D}{2}$$

$$h_{ij} = \lambda_{ij} M_F^{D/2}$$

$$h_{ij} \sim \mathcal{O}(1).$$

$$\frac{M_F}{M_{\rm pl}} \simeq 10^{-16} \frac{M_F}{1 \text{ TeV}}$$

$$
i\frac{d}{dr}\begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \\ \nu_{1L}^{(1)} \\ \nu_{2L}^{(1)} \\ \nu_{3L}^{(1)} \\ \nu_{1L}^{(2)} \\ \nu_{2L}^{(2)} \\ \nu_{3L}^{(2)} \\ \vdots \\ \nu_{1L}^{(N)} \\ \nu_{2L}^{(N)} \\ \nu_{3L}^{(N)} \end{pmatrix} = \frac{1}{2ER_{\mathrm{ED}}^2}\begin{pmatrix}
\eta_1 + V_{11} & V_{12} & V_{13} & \xi_1 & 0 & 0 & 2\xi_1 & 0 & 0 & \cdots & N\xi_1 & 0 & 0 \\
V_{21} & \eta_2 + V_{22} & V_{23} & 0 & \xi_2 & 0 & 0 & 2\xi_2 & 0 & \cdots & 0 & N\xi_2 & 0 \\
V_{31} & V_{32} & \eta_3 + V_{33} & 0 & 0 & \xi_3 & 0 & 0 & 2\xi_3 & \cdots & 0 & 0 & N\xi_3 \\
\xi_1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & \xi_2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & 0 & \xi_3 & 0 & 0 & 1 & 0 & 0 & 0 & \cdots & 0 & 0 & 0 \\
2\xi_1 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 0 & \cdots & 0 & 0 & 0 \\
0 & 2\xi_2 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & \cdots & 0 & 0 & 0 \\
0 & 0 & 2\xi_3 & 0 & 0 & 0 & 0 & 0 & 4 & \cdots & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
N\xi_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & N^2 & 0 & 0 \\
0 & N\xi_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & N^2 & 0 \\
0 & 0 & N\xi_3 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & 0 & 0 & N^2
\end{pmatrix}
\times \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \\ \nu_{1L}^{(1)} \\ \nu_{2L}^{(1)} \\ \nu_{3L}^{(1)} \\ \nu_{1L}^{(2)} \\ \nu_{2L}^{(2)} \\ \nu_{3L}^{(2)} \\ \vdots \\ \nu_{1L}^{(N)} \\ \nu_{2L}^{(N)} \\ \nu_{3L}^{(N)} \end{pmatrix}_{N\to\infty}
$$

$$
\eta_i = (N + \tfrac{1}{2})\xi_i^2
$$

$$
\xi_i = \sqrt{2} m_i R_{\mathrm{ED}}
$$

$$
V_{ij} = 2ER_{\mathrm{ED}}^2 X_{ij}
$$

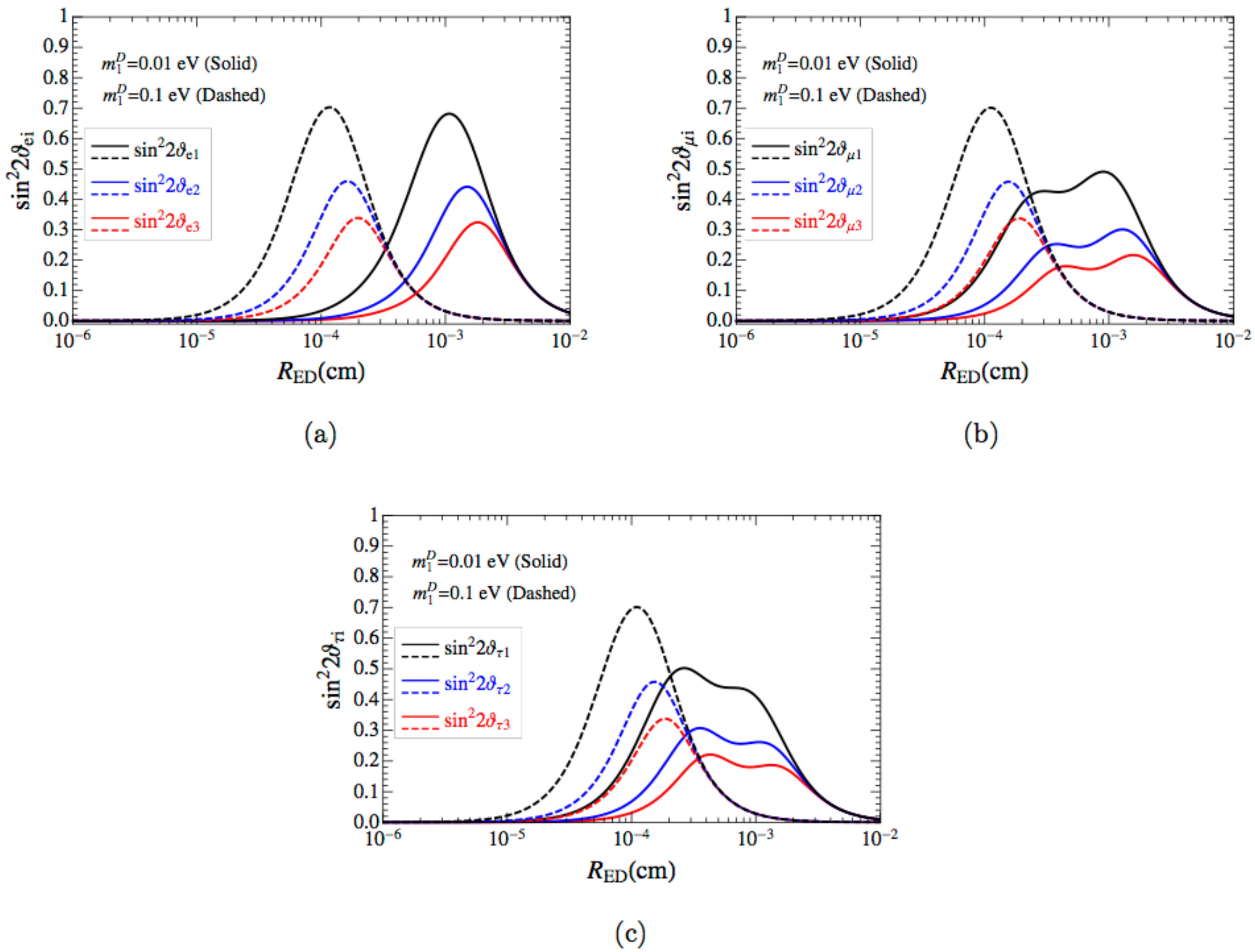
$$
X_{kj} = \textstyle\sum_\alpha U_{\alpha k}^* U_{\alpha j} V_\alpha
$$

$$
V_\alpha = \delta_{e\alpha} V_{\mathrm{CC}} + V_{\mathrm{NC}} = \sqrt{2} G_F \left(\delta_{e\alpha} N_e - \frac{N_n}{2}\right)
$$

Effective Mixing Angles

In the two-flavor system of "□$_a$ - □$_s^{(p)}$"

$$\sin\vartheta_{\alpha p} = \left[\sum_{i=1}^{3} \left|U_{\alpha i} S_i^{0p}\right|^2\right]^{1/2}$$

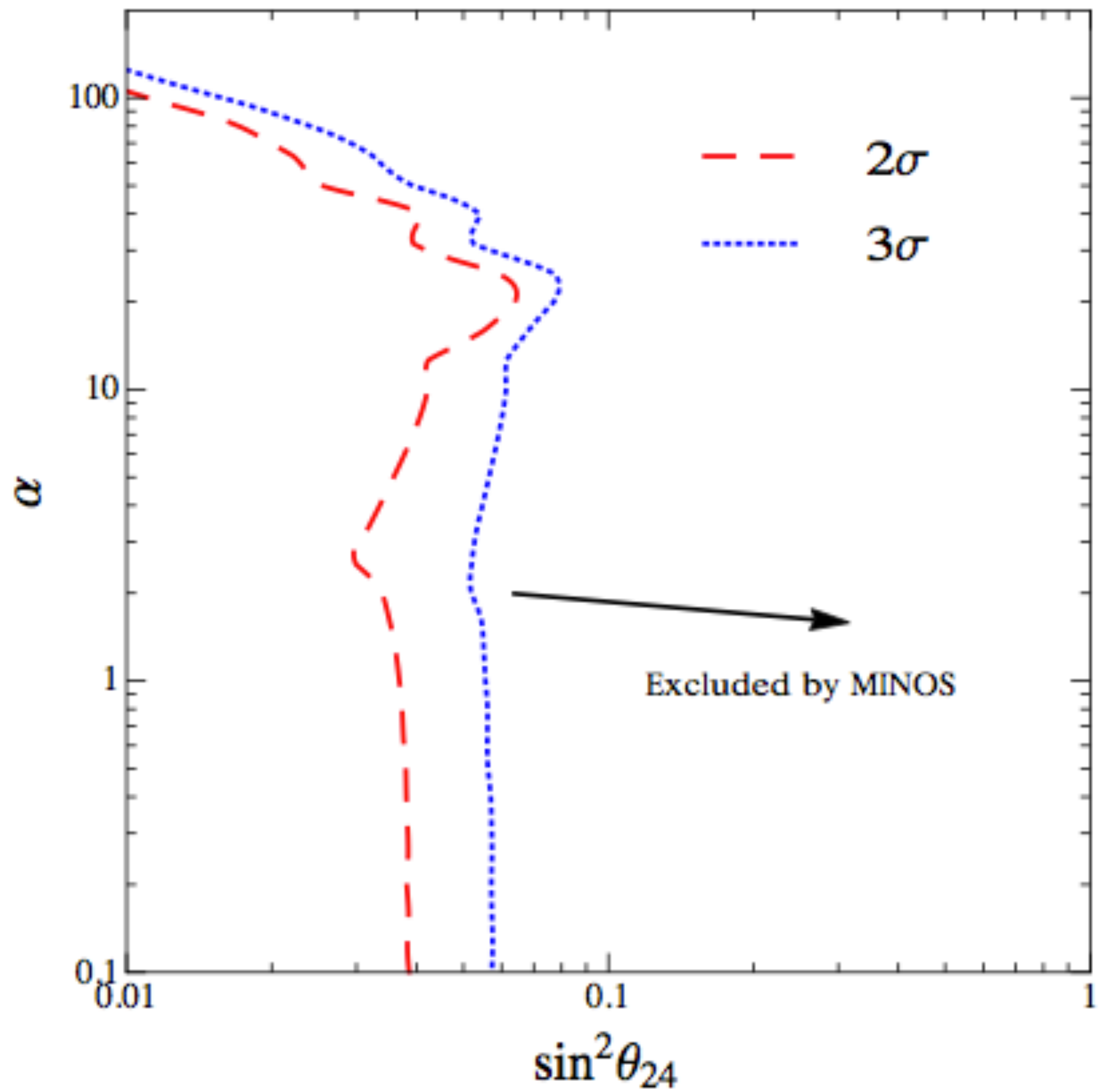


The effective area

The neutrino effective area A^{ν}_{eff} is defined as the equivalent area of the detector for which the probability of the neutrino detection would be 100%. In principle, the concept of the neutrino effective area is used to describe the response of the detector to the flavor, energy and zenith angle distribution of neutrinos.

"MeV" gauge boson and Secret Interaction of Sterile Neutrinos

Results



- ✓ For $\alpha \lesssim 25$, the sensitivity of MINOS to the SI model is almost independent of the value of α.

- ✓ For $\alpha \gtrsim 25$, we have: $\alpha \propto \sin^2\theta_{24}^{-0.85}$. This means that the MINOS experiment is sensitive to the larger values of α for the smaller values of $\sin^2\theta_{24}$.

On the Viability of Minimal Neutrinophilic 2HD Models

We determine the mass eigenstates defining the following rotations:

$$\begin{pmatrix} \phi_1^- \\ \phi_2^- \end{pmatrix} = - \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^- \\ H^- \end{pmatrix}$$

$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = - \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} G^0 \\ A \end{pmatrix}$$

$$\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = - \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix};$$

Where

$$c_{\alpha(\beta)} \equiv \cos \alpha(\beta) \;\&\; s_{\alpha(\beta)} \equiv \sin \alpha(\beta)$$

The physical masses in terms of the couplings are:

$$m_H^2 = M^2 \sin^2(\alpha - \beta) + \left(\lambda_1 \cos^2\alpha \cos^2\beta + \lambda_2 \sin^2\alpha \sin^2\beta + \frac{\lambda_{345}}{2} \sin 2\alpha \sin 2\beta\right) v^2,$$

$$m_h^2 = M^2 \cos^2(\alpha - \beta) + \left(\lambda_1 \sin^2\alpha \cos^2\beta + \lambda_2 \cos^2\alpha \sin^2\beta - \frac{\lambda_{345}}{2} \sin 2\alpha \sin 2\beta\right) v^2,$$

$$m_A^2 = M^2 - \lambda_5 v^2,$$

$$m_{H^\pm}^2 = M^2 - \frac{\lambda_{45}}{2} v^2.$$

where $$M^2 \equiv \frac{m_{12}^2}{\sin\beta\cos\beta}$$

The couplings in terms of the physical masses:

$$\lambda_1 = \frac{1}{v^2}\left(-\tan^2\beta M^2 + \frac{\sin^2\alpha}{\cos^2\beta}m_h^2 + \frac{\cos^2\alpha}{\cos^2\beta}m_H^2\right),$$

$$\lambda_2 = \frac{1}{v^2}\left(-\cot^2\beta M^2 + \frac{\cos^2\alpha}{\sin^2\beta}m_h^2 + \frac{\sin^2\alpha}{\sin^2\beta}m_H^2\right),$$

$$\lambda_3 = \frac{1}{v^2}\left(-M^2 + 2m_{H^\pm}^2 + \frac{\sin(2\alpha)}{\sin(2\beta)}(m_H^2 - m_h^2)\right),$$

$$\lambda_4 = \frac{1}{v^2}\left(M^2 + m_A^2 - 2m_{H^\pm}^2\right)$$

$$\lambda_5 = \frac{1}{v^2}\left(M^2 - m_A^2\right),$$

where $$M^2 \equiv \frac{m_{12}^2}{\sin\beta\cos\beta}$$

Theoretical constraints

✓ Stability at tree level:

$$\lambda_{1,2} > 0, \qquad \lambda_3 > -(\lambda_1\lambda_2)^{1/2} \qquad \text{and} \qquad \lambda_3 + \lambda_4 - |\lambda_5| > -(\lambda_1\lambda_2)^{1/2}.$$

✓ Stationary conditions:

$$\frac{\lambda_1}{2}v_1^3 + \frac{\lambda_{345}}{2}v_1v_2^2 + m_{11}^2v_1 - m_{12}^2v_2 = 0,$$
$$\frac{\lambda_2}{2}v_2^3 + \frac{\lambda_{345}}{2}v_2v_1^2 + m_{22}^2v_2 - m_{12}^2v_1 = 0,$$

& $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5.$

✓ To have tre $|a_\pm|, |b_\pm|, |c_\pm|, |f_\pm|, |e_{1,2}|, |f_1|, |p_1| < 8\pi$ ty:

✓
$$a_\pm = \frac{3}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2 + (2\lambda_3+\lambda_4)^2},$$
$$b_\pm = \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2},$$
$$c_\pm = \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2},$$
$$f_+ = \lambda_3 + 2\lambda_4 + 3\lambda_5,$$

$$f_- = \lambda_3 + \lambda_5,$$
$$e_1 = \lambda_3 + 2\lambda_4 - 3\lambda_5,$$
$$e_2 = \lambda_3 - \lambda_5,$$
$$f_1 = \lambda_3 + \lambda_4,$$
$$p_1 = \lambda_3 - \lambda_4.$$

SUMMARY

SUMMARY

The main goal of this thesis was studying the phenomenology of the sterile neutrinos.

We first studied the light sterile neutrinos with $\Delta m^2_{41} \sim (10^{-3}-10^{-1})$ eV^2, using the data of the medium baseline reactor experiments.

We reproduced the results of these experiments in the 3ν framework. Then we performed the 3+1 analysis, first for the Double Chooz experiment and then combining Double Chooz, RENO and Daya Bay.

SUMMARY

We found that for the case of the Double Chooz experiment, the best-fit value of θ_{13} angle is significantly different than the reported value in the experiment, and $\theta_{13}=0$ is allowed in less than 1σ C.L.. We also showed that the $(3+1)_{light}$ model isfavored at 2.2σ C.L..

After combining the results of Double Chooz with the rate information of RENO and Daya Bay, we found that the $(3+1)_{light}$ model was favored at 1.2σ C.L.. The value of θ13 angle also became close to the reported value in the 3ν framework and so the robustness of the determination of θ13 was claimed.

SUMMARY

In the second work we studied models with Large Extra Dimensions (LED). We studied the phenomenological consequences of this picture for the high energy atmospheric neutrinos.

We calculated the probabilities in the LED model in the presence of the matter effects of the earth.

We also found an equivalence between the LED model and a (3 + n) scenario consisting of 3 active and n extra sterile neutrino states.

SUMMARY

We used the high energy atmospheric data of the IceCube experiment to perform an analysis on the LED model. We obtained the limits on the LED parameters.

In the third work we studied the secret interaction (SI) of the sterile neutrinos which is proposed to solve the tension between the sterile hypothesis and cosmology.

We studied the probability in the SI model and showed that this model model can change the oscillation probability of neutrinos drastically.

SUMMARY

Using the data of the MINOS experiment, we showed that values above [illegible]=92.4 are excluded at 2σ C.L., which means it is unlikely the sterile neutrinos can have very huge field strength with the new gauge boson.

We also constrained the mass of the light gauge boson using the MINOS neutrino experiments. We showed that for

$$4\times10^{-4} \lesssim g_X \lesssim 8\times10^{-4},$$

$M_X \lesssim 10 - 24$ MeV is excluded with 2σ C.L..

SUMMARY

In addition to the phenomenology of the sterile neutrinos, in this thesis we studied the smallness of neutrino masses using neutrinophilic 2HDMs, in which the vev of the first Higgs doublet is responsible for the masses of the particles in the SM, while the second Higgs doublet is the sole responsible for the masses of neutrinos through its small vev.

We introduced 2 specific symmetries to prevent the neutrinos to couple to the first Higgs Doublet: the model with Z_2 symmetry and the model with a softly broken U(1) symmetry.

SUMMARY

We found that if there is no additional particle content, the model with Z_2 symmetry will be in severe tension with the electroweak precision tests due to a very light h scalar. Therefore, the neutrinophilic 2HDM with a spontaneously broken Z_2 symmetry is strongly disfavored by data.

The analysis of the model with global U(1) symmetry reveals a region of the parameter space which is allowed by all bounds considered, however this parameter space is considerably constrained by current data. Particularly, the mass of the new charged scalar has to be similar to the mass of the new neutral scalars.