

Flavor Ratios of Extragalactical Neutrinos and
Neutrino Shortcuts in Extra Dimensions
[arXiv:1410.0408]

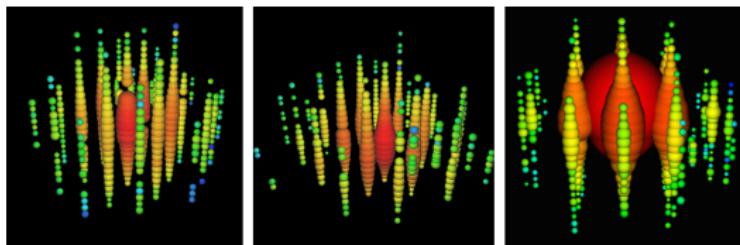
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E. Aeikens, H. Päs, S. Pakvasa, **Philipp Sicking**

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- 3 Adiabatic Limit
- 4 Resulting Constraints
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High Energy Neutrinos at IceCube

36 neutrino events detected by IceCube in the high energy region 30 TeV up to 2 PeV



Ernie: 1.0 Pev

Bert: 1.1 Pev

Big Bird: 2.0 Pev



Astrophysical Neutrino Oscillation

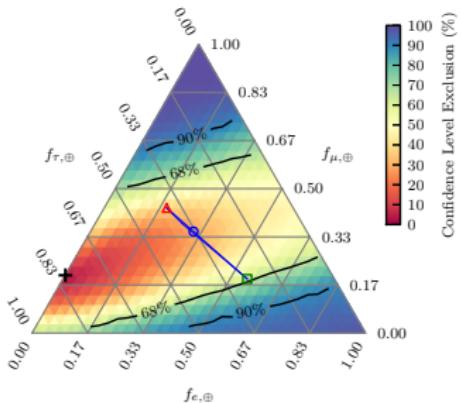
- atmospheric origin ruled out at more than 5.7σ [IceCube, 2014]
- usual neutrino oscillation averaged out

$$P_{\alpha\beta} = P_{\nu_\alpha \rightarrow \nu_\beta}(t) = \delta_{\alpha\beta} - 4 \sum_{k>j} (U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*) \sin^2 \left(\frac{\delta m_{kj}^2 L}{4E} \right)$$
$$\rightarrow \sum_j |U_{\alpha k}|^2 |U_{\beta k}|^2 \quad \text{for} \quad L \gg \frac{\delta m^2}{E}$$

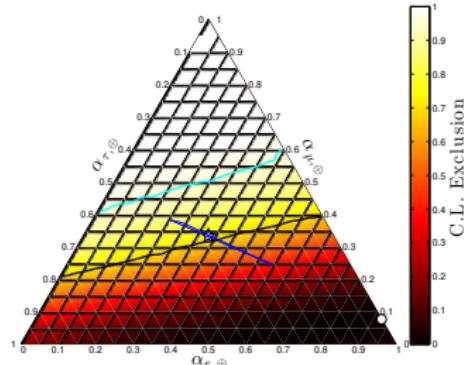
- lead to canonical Flavor ratio of (1:1:1) in case of initial pion source

Flavor Composition ($\Phi_e : \Phi_\mu : \Phi_\tau$)

Deviation from canonical (1:1:1) ratio?!



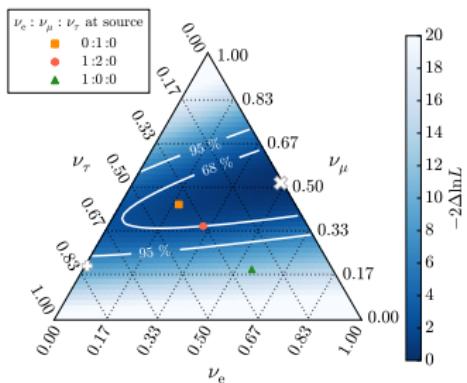
[IceCube, 2015]
35 TeV - 1.9 PeV, Best Fit: (0:0.2:0.8)



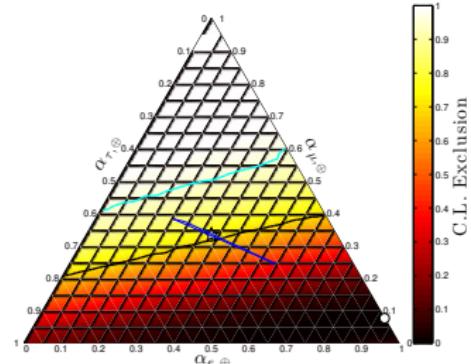
[Palomares-Ruiz, Vincent, Mena, 2015]
28 TeV - 3 PeV, Best Fit: (0.92:0.08:0)

Flavor Composition ($\Phi_e : \Phi_\mu : \Phi_\tau$)

Deviation from canonical (1:1:1) ratio?!



[IceCube, 2015]
25 TeV - 2.8 PeV, Best Fit: (0.49:0.51:0)



[Palomares-Ruiz, Vincent, Mena, 2015]
28 TeV - 3 PeV, Best Fit: (0.92:0.08:0)

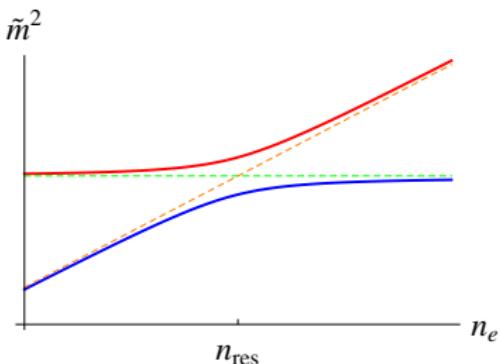
Possible Explanation

- Results still compatible with expected canonical ratio!
- Wait for higher statistic to either confirm canonical ratio, or open the door to new physics
- no Glashow events at 6.3 PeV?
(resonant production of $\bar{\nu}_e e \rightarrow W$)
- several new physics models proposed
- idea in this talk: modification due to altered dispersion relation
→ shortcuts in extradimensions

How to change the expected flavor ratio?

Famous Example: MSW Effect [Wolfenstein, 1978], [Barger, Whisnant, Pakvasa, 1980], [Mikheyev, Smirnov, 1986]

- solves solar neutrino-problem
- $\bar{\nu}_e$ can interact via charged current with e^-
- slowly decreasing electron-density \rightarrow varying effective masses for the neutrinos
- $\bar{\nu}_e$ is produced in high density-region \rightarrow
 $\bar{\nu}_e \approx \nu_1$
- adiabatic conversion \rightarrow probability of measuring $\bar{\nu}_e$ is strongly reduced



How to change the expected flavor ratio?

Varying effective Potential necessary for MSW-like conversion

Problem: No Standard-Model Mechanism for neutrinos in the interstellar spacetime

- No matter, especially no huge matter density differences
- Electromagnetic fields: neutrinos uncharged
- gravity: not flavor specific

⇒ Idea: **Spacetime** itself causes a conversion into a **sterile** neutrino

NOTE: Several new interactions of the sterile neutrino possible

⇒ see this model as a proof of concept

Effect on Flavor Ratios

- Conversion of mass eigenstates into undetectable sterile states
- Coupling ν_2 and ν_3 to two sterile states, leads to ν_1 as the only detectable neutrino state
- Effect has to happen only at high energies
 - ⇒ Expected flavor ratio will be 4 : 1 : 1 (in case of only ν_1 remaining)

Model

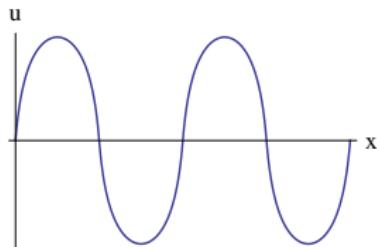
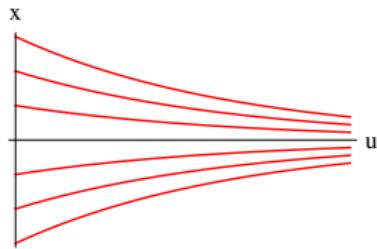
- for simplification 1 active + 1 sterile neutrino with mixing angle θ
- Assumption: Asymmetrically warped space time:

$$ds^2 = dt^2 - e^{-2k|u|} dx^2 - du^2$$

- leads to geodesic for sterile neutrino [Hollenberg, Micu, Päs, 2009]

$$u(x) = \pm \frac{1}{2k} \ln[1 + k^2 x(l - x)]$$

- two free parameter: warp factor k , periodic length l



New Mixing

- shortcut-parameter [Päs, Pakvasa, Weiler, 2005]:

$$\epsilon = 1 - e^{-k|u|} = 1 - \frac{1}{\sqrt{1 + k^2 x(l-x)}}$$

- new effective Hamiltonian:

$$H = \frac{\delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} \epsilon E & 0 \\ 0 & 0 \end{pmatrix}$$

- New effective Mixing-Angle:

$$\cos 2\tilde{\theta} = \frac{\cos 2\theta - 2E^2 \left(1 - \frac{1}{\sqrt{1+k^2 x(l-x)}} \right)}{\sqrt{\left(\frac{2E^2}{\delta m^2} \left(1 - \frac{1}{\sqrt{1+k^2 x(l-x)}} \right) - \cos 2\theta \right)^2 + \sin^2(2\theta)}}$$

Adiabatic Limit

- MSW-like effect occurs only when potential changes slowly enough
- condition for adiabatic behaviour: $\tau_{\text{system}} \ll \tau_{\text{interaction}}$ leads to

$$\gamma_{\text{res}} = \frac{4E^3}{(\delta m^2)^2 \sin^2(2\theta)} \left. \frac{d\epsilon}{dx} \right|_{\text{res}} \ll 1$$

- approximative condition for geometric parameters $k^2 l$:

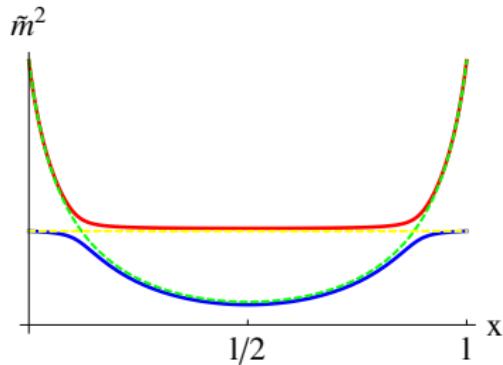
$$\frac{2E^3}{(\delta m^2)^2 \sin^2(2\theta)} k^2 l \ll 1$$

Effective Masses

$$\tilde{m}_i^2 = -\frac{A}{2} \pm \frac{\delta m^2}{2} \sqrt{\left(\frac{A}{\delta m^2} - \cos 2\theta\right)^2 + \sin^2(2\theta)}$$

with $A=2E^2 \left(1 - \frac{1}{\sqrt{1+k^2x(I-x)}}\right)$

- produced active neutrino travels as lighter neutrino which converges to sterile neutrino at $x = \frac{1}{2}$ and back to active neutrino



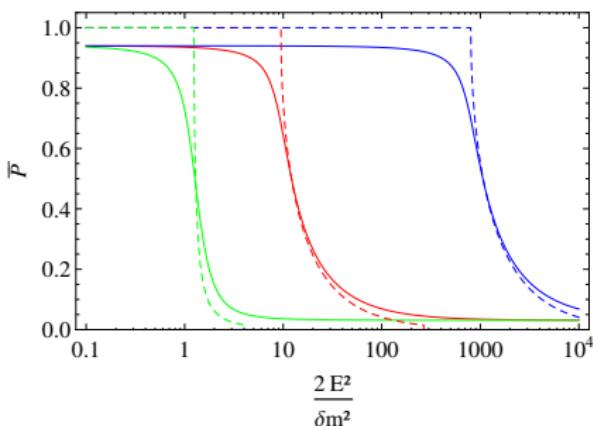
Transition Probability

$$P_{\nu_a \rightarrow \nu_a}(x) = \cos^2 \theta \cdot \cos^2 \tilde{\theta} + \sin^2 \theta \cdot \sin^2 \tilde{\theta}$$

$$P_{\nu_a \rightarrow \nu_s}(x) = \sin^2 \theta \cdot \cos^2 \tilde{\theta} + \cos^2 \theta \cdot \sin^2 \tilde{\theta}$$

- averaging over cosmic sources $\hat{=}$ averaging over periodic length

$$\bar{P} = \frac{1}{I} \int_0^I P_{\nu_a \rightarrow \nu_a}(x) dx$$

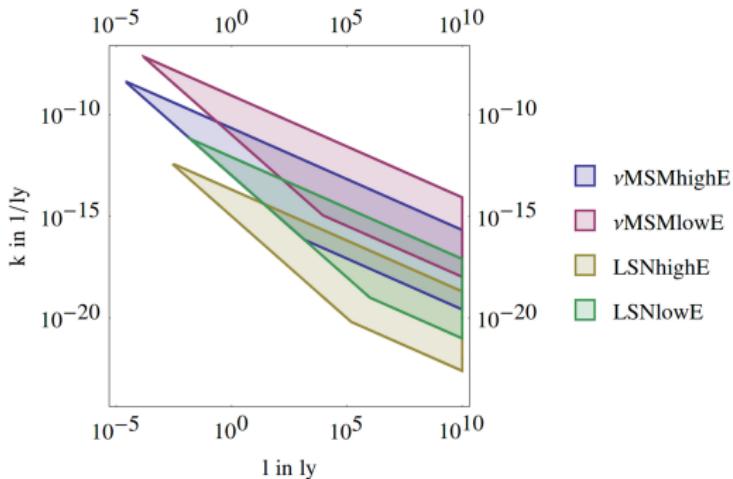


Constraints for geometric parameters

- adiabatic condition \rightarrow small $k^2 l$
- substantial decrease of ν_μ and ν_τ flux: $\bar{P} < 0.25 \rightarrow$ big $k l$
- solar neutrinos should not be affected \rightarrow position of resonance occur at distances higher than earth-sun
- two different models of sterile neutrinos: ν MSM [Asaka, Laine, Shaposhnikov, 2007] and light sterile neutrino (LSN) [Kopp, Machado, Maltoni, Schwetz, 2013]

Constraints for geometric parameters

Model	δm^2	$\sin^2(2\theta)$	E	kl	$k^2 l/eV$
LSN	$(1\text{eV})^2$	0.12	30 TeV	$\gtrsim 10^{-13}$	$\ll 2.2 \cdot 10^{-42}$
LSN	$(1\text{eV})^2$	0.12	1.2 PeV	$\gtrsim 10^{-15}$	$\ll 3.5 \cdot 10^{-47}$
ν MSM	$(1\text{ keV})^2$	10^{-7}	30 TeV	$\gtrsim 10^{-11}$	$\ll 5.5 \cdot 10^{-29}$
ν MSM	$(1\text{ keV})^2$	10^{-7}	1.2 PeV	$\gtrsim 10^{-13}$	$\ll 3.5 \cdot 10^{-32}$



Modification due to constant Potential

- introducing the resonance energy

$$E_{Res} = \sqrt{\frac{\delta m^2 \cos 2\theta}{2\epsilon}}$$

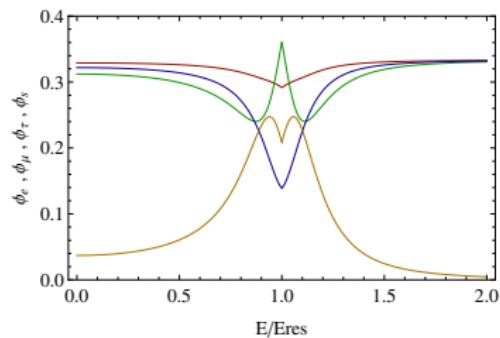
- new effective mixing angle

$$\sin^2 2\tilde{\theta} = \frac{\sin^2 2\theta}{\sin^2 2\theta + \cos^2 2\theta \left[1 - \left(\frac{E}{E_{Res}} \right)^2 \right]^2},$$

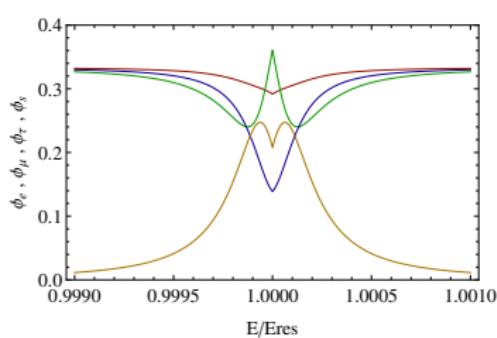
- leading again to energy depending (but baseline independent) flavor ratios

$$\Phi_\alpha(E) = \sum_\beta P_{\alpha\beta}(E) \Phi_\beta^{init} \neq \Phi_\alpha^0$$

Φ_e , Φ_μ , Φ_τ , Φ_s

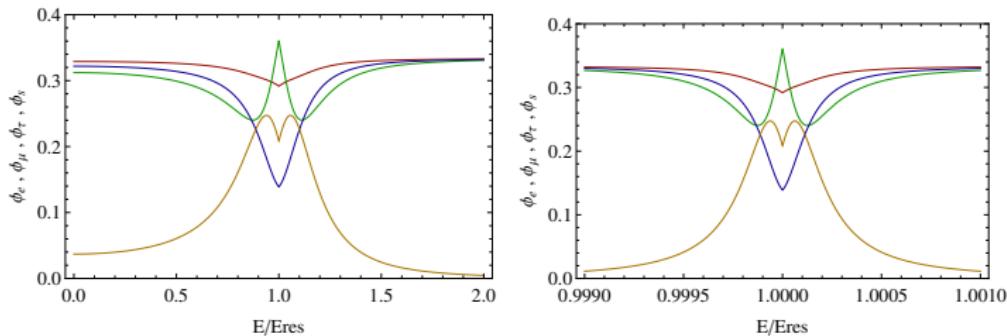


LSN
 $(\delta m^2 \simeq 1 \text{ eV}^2, \quad \sin^2(2\theta) \simeq 0.12)$



ν MSM
 $(\delta m^2 \simeq 1(\text{keV})^2, \quad \sin^2(2\theta) \simeq 10^{-7})$

$\Phi_e, \Phi_\mu, \Phi_\tau, \Phi_s$



$$\frac{\delta E(\text{FWHM})}{E_{\text{Res}}} \simeq 2\theta$$

$$\frac{\delta E(\text{FWHM})}{E_{\text{Res}}} \simeq 35\%$$

$$\frac{\delta E(\text{FWHM})}{E_{\text{Res}}} \simeq 3 \cdot 10^{-2}\%$$

Flavor Ratios at Resonance

source	Φ_{β}^0	mixing	$\Phi_{\beta}(\theta^{\alpha 4})$	R	S	T	G
Pion	1:2:0:0	none ($\theta^{\alpha 4} = 0$)	1:1:1:0	1/2	1	1/3	1/9
		$\nu_e - \nu_4$	4:11:11:6	11/19	8/11	11/30	4/45
		$\nu_\mu - \nu_4$	5:5:5:3	1/2	1	1/3	1/9
		$(\nu_e, \nu_\mu) - \nu_4$	32:41:41:30	41/73	32/41	41/114	16/171
		$(\nu_\mu, \nu_\tau) - \nu_4$	21:26:10:15	26/31	21/10	26/57	7/57
Damped Muon	0:1:0:0	none ($\theta^{\alpha 4} = 0$)	4:7:7:0	7/11	4/7	7/18	2/27
		$\nu_e - \nu_4$	4:9:9:2	9/13	4/9	9/22	2/33
		$\nu_\mu - \nu_4$	1:2:2:1	2/3	1/2	2/5	1/15
		$(\nu_e, \nu_\mu) - \nu_4$	16:115:115:42	115/131	16/115	115/246	8/369
		$(\nu_\mu, \nu_\tau) - \nu_4$	7:16:4:9	16/11	7/4	16/27	7/81
Neutron Beam	1:0:0:0	none ($\theta^{\alpha 4} = 0$)	5:2:2:0	2/7	5/2	2/9	5/27
		$\nu_e - \nu_4$	2:1:1:2	1/3	2	1/4	1/2
		$\nu_\mu - \nu_4$	3:1:1:1	1/4	3	1/5	3/5
		$(\nu_e, \nu_\mu) - \nu_4$	10:1:1:6	1/11	10	1/12	5/12
		$(\nu_\mu, \nu_\tau) - \nu_4$	35:14:14:9	2/7	5/2	2/9	5/9

Conclusion & Outlook

- measurement of high energy flavor ratios can be a probe for non-standard neutrino properties
- new effective potentials due to new sterile neutrino physics
- provide non standard energy dependence
- adiabatic conversion in asymmetric warped space time could explain a ratio of 4:1:1
- constant effective potential needs “large” mixing angle to provide visible effect
- further experimental results needed

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⇒ Look at exotic phenomenology,
the time has come

Backup

Model	δm^2	$\sin^2(2\theta)$	E	kl	$k^2 l/\text{eV}$	$\frac{\delta m^2 \cos 2\theta}{E^2}$
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LSN	$(1\text{eV})^2$	0.12	1.2 PeV	$\gtrsim 10^{-15}$	$\ll 3.5 \cdot 10^{-47}$	$6.5 \cdot 10^{-31}$
ν MSM	$(1 \text{ keV})^2$	10^{-7}	30 TeV	$\gtrsim 10^{-11}$	$\ll 5.5 \cdot 10^{-29}$	$1.1 \cdot 10^{-21}$
ν MSM	$(1 \text{ keV})^2$	10^{-7}	1.2 PeV	$\gtrsim 10^{-13}$	$\ll 3.5 \cdot 10^{-32}$	$6.9 \cdot 10^{-25}$

Backup

$$10^6 \text{ly} = 5 \cdot 10^{25} \frac{1}{\text{eV}} > x_{res} > 8 \cdot 10^{17} \frac{1}{\text{eV}} = 1.6 \cdot 10^{-5} \text{ly} \quad (1)$$

leads to

$$\frac{1}{64} 10^{-17} \frac{1}{\text{eV}} \frac{\delta m^2 \cos 2\theta}{2E^2} > k^2 I > \frac{1}{40} 10^{-25} \frac{1}{\text{eV}} \frac{\delta m^2 \cos 2\theta}{2E^2} \quad (2)$$

Backup

- Shortcut through extra dimension → time shift $\delta t \rightarrow$ difference in the action

$$\Delta S \sim \mathbf{H} \delta t \Rightarrow \Delta \mathbf{H}_{\text{eff}} = \mathbf{H} \frac{\delta t}{T} \sim \epsilon E$$

- shortcut-parameter [Päs, Pakvasa, Weiler, 2005]: $\epsilon = 1 - \eta(u)$
- new effective Hamiltonian:

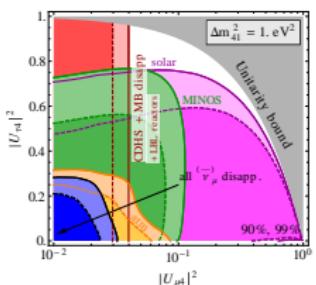
$$\mathbf{H} = \frac{\delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} \epsilon E & 0 \\ 0 & 0 \end{pmatrix}$$

- New effective Mixing-Angle:

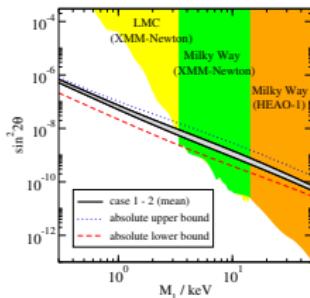
$$\cos 2\tilde{\theta} = \frac{\cos 2\theta - \frac{2E^2}{\delta m^2} \epsilon}{\sqrt{\left(\frac{2E^2}{\delta m^2} \epsilon - \cos 2\theta\right)^2 + \sin^2(2\theta)}}$$

Backup

[Kopp et al., 2013]



[Asaka, et al., 2007]



Light Sterile Neutrino (LSN)

- motivated by LSND, MiniBoone and Gallium anomalies
- $\delta m^2 \simeq 1 \text{ eV}^2$
- $\sin^2(2\theta) \simeq 0.12, \quad (\sin^2(\theta) \simeq 0.03)$

Neutrino Minimal Standard Model (ν MSM)

- sterile neutrino as warm dark matter
- $\delta m^2 \simeq 1(\text{keV})^2$
- $\sin^2(2\theta) \simeq 10^{-7}, \quad (\sin^2(\theta) \simeq 10^{-8})$

Backup

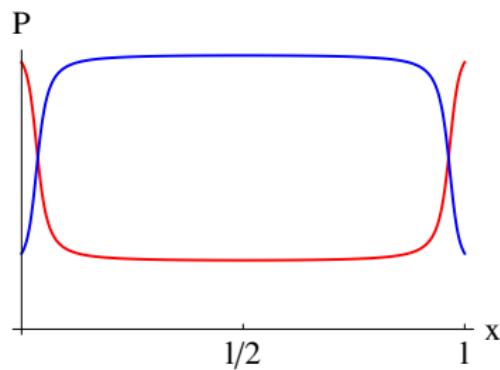


Figure : Appearance- and disappearance-probability

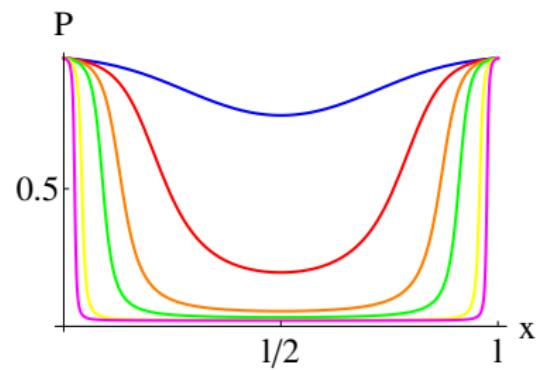


Figure : Appearance-probability for different energies

Backup

Effective masses

$$\tilde{m}_l^2 = -\frac{A}{2} \pm \frac{\delta m^2}{2} \sqrt{\left(\frac{A}{\delta m^2} - \cos 2\theta\right)^2 + \sin^2(2\theta)}$$

with $A=2E^2 \left(1 - \frac{1}{\sqrt{1+k^2x(l-x)}}\right)$