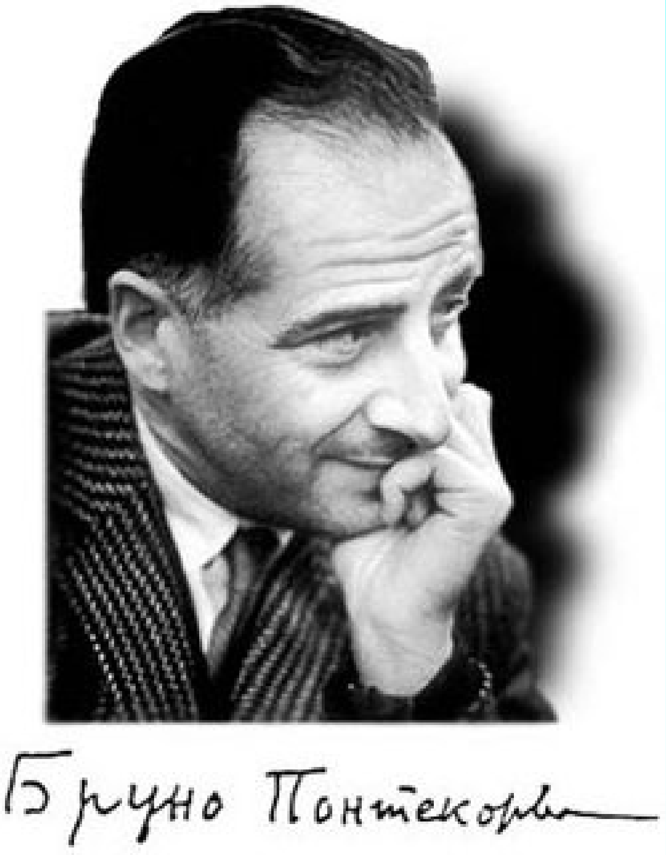
Sterile neutrinos: searches & implications

A. Yu. Smirnov

International Centre for Theoretical Physics, Trieste, Italy

Planck 2011, May29, Lisbon

Sterile neutrino ν_s



Бруно Понтекорво

Sov. Phys. JETP 26 984 (1968)

in the context of idea of
neutrino–antineutrino oscillations

Light

No weak interactions:
- singlets of the SM symmetry group

RH - components
of neutrinos

Couple with usual neutrinos
via (Dirak) mass terms

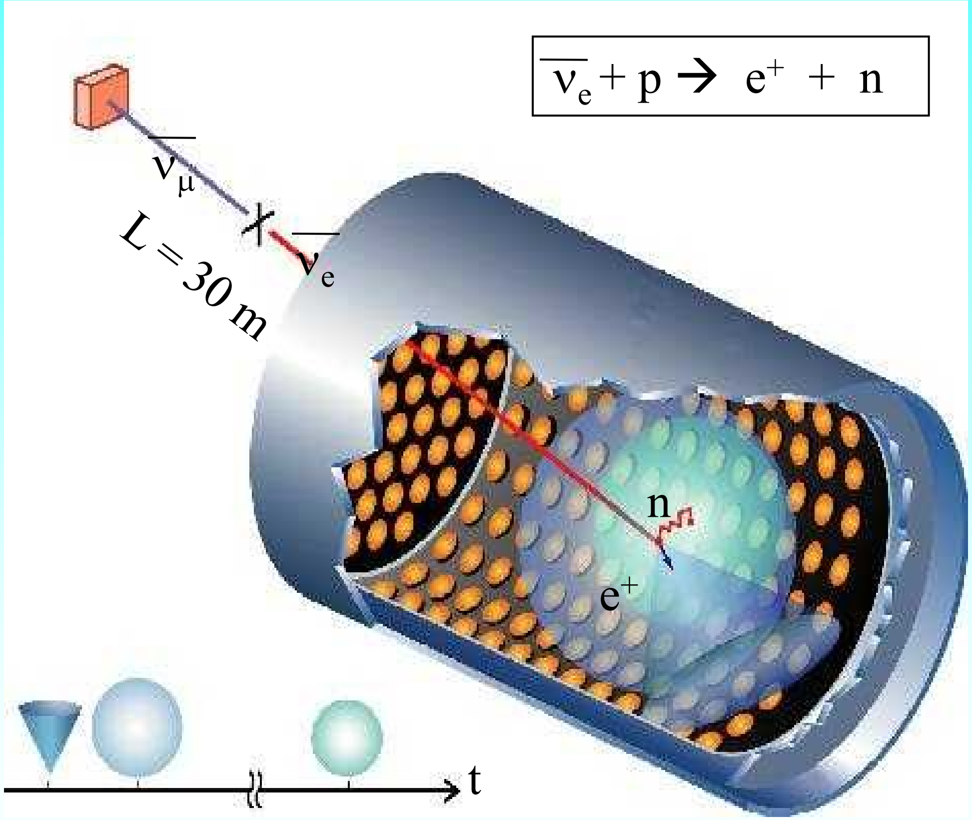
Mix with active neutrinos

may have Majorana
mass terms
maximal mixing?

LSND is back?

Large Scintillator
Neutrino Detector

Los Alamos Meson Physics Facility



$\overline{\nu}_e + p \rightarrow e^+ + n$

$$\begin{aligned} p \;&\text{-->} \\ &\pi^+ \;\text{-->}\; \boxed{\mu^+} + \nu_\mu \\ &\qquad\qquad \text{-->}\; e^+ + \nu_e + \boxed{\overline{\nu}_\mu} \end{aligned}$$

decay at rest

$\overline{\nu}_\mu$ --> $\overline{\nu}_e$

$P = (2.64 \pm 0.67 \pm 0.45)\, 10^{-3}$

Oscillations?
$\Delta m^2 > 0.2$ eV^2

3.8σ excess

Cherenkov cone + scintillations

200 t mineral
oil scintillator

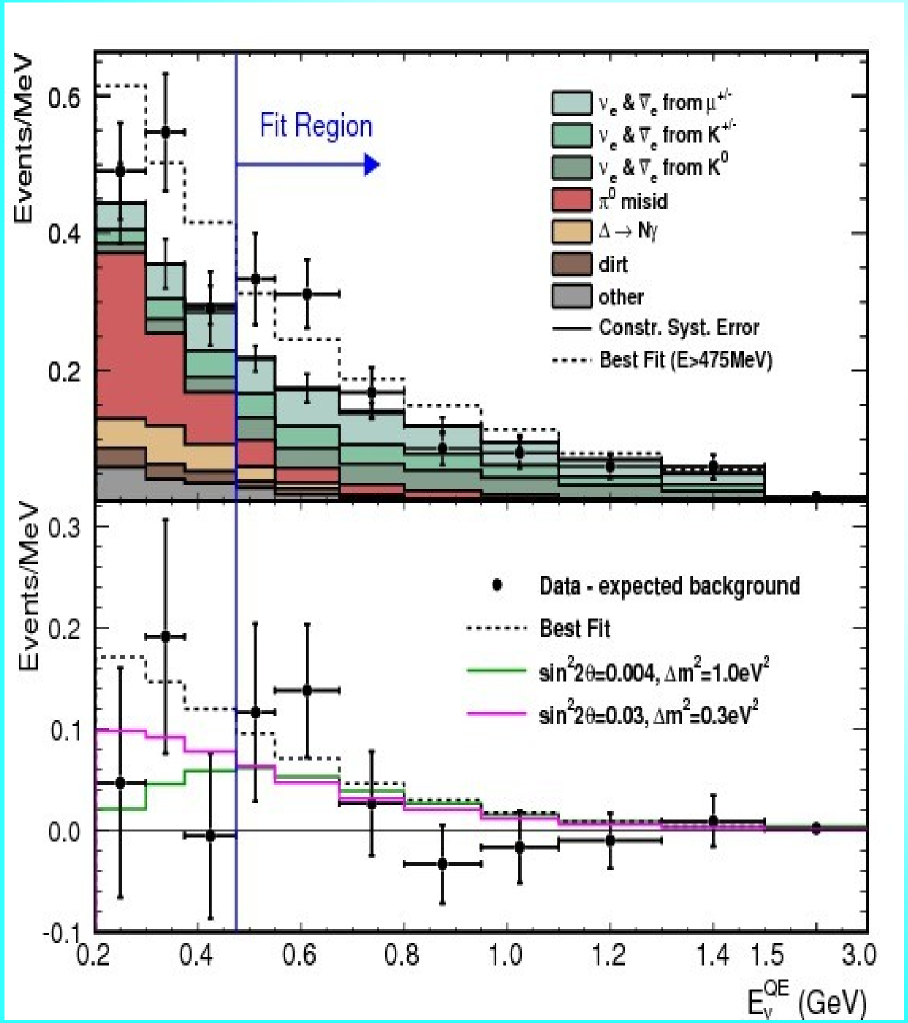
Sterile neutrinos as
solution of all the problems

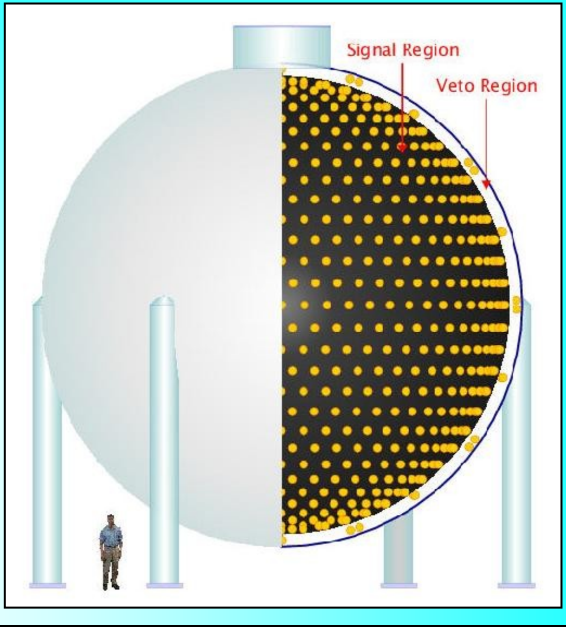
Plan:

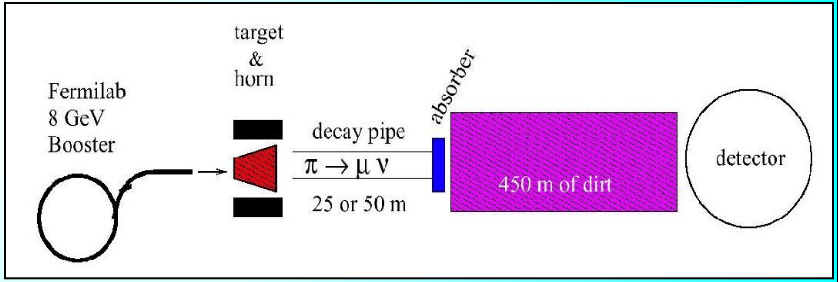
1. New evidences?
2. The Sun: sterile shining
3. Searching for sterile in ice

New evidences?

MiniBooNE: anti-nu







L = 541 m, $\langle E_\nu \rangle$ ~ 800 MeV
12 m diameter tank
450 t (mineral oil) 1280 PMT

Reactor neutrino anomaly

Increase of the Mean flux by 3%

Revised value of cross-section

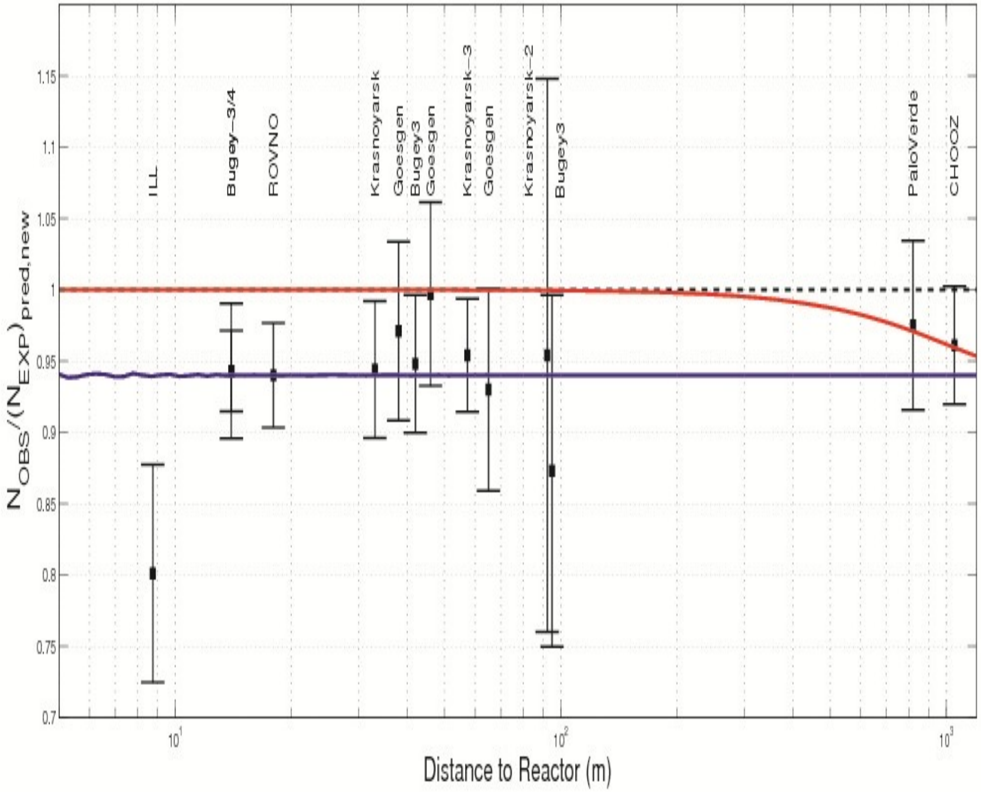
G.Mention et al, arXiv: 1101.2755

R_{react} = 0.937 +/- 0.027

2.14 σ

$\Delta m^2 > 1.5$ eV^2

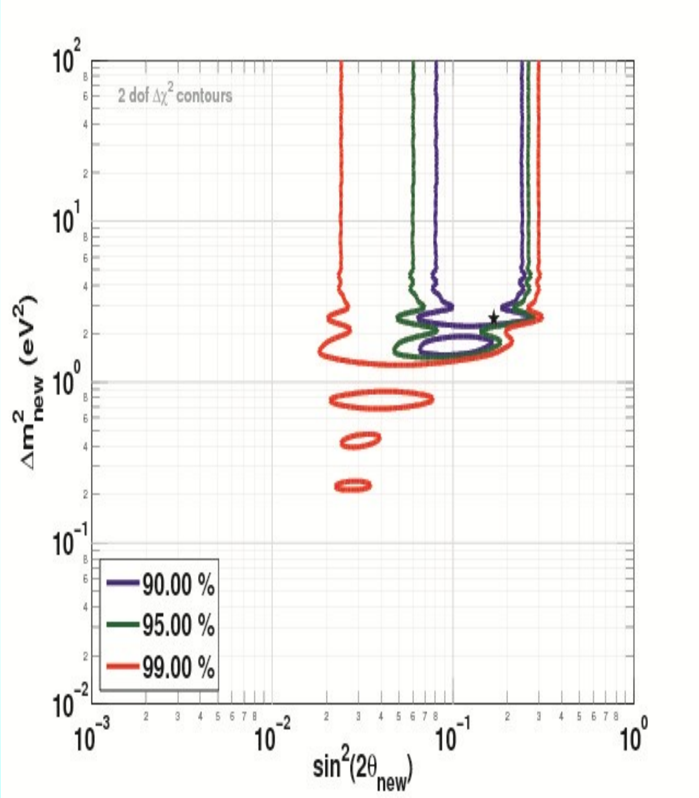
$\sin^2 2\theta = 0.17$ +/- 0.1



Gallium anomaly

Calibration

Source + reactor



Gallex/GNO ^{51}Cr
SAGE ^{51} Cr, ^{37}Ar

R_{Ga} = 0.87 +/- 0.05

$\sin^2 2\theta$ = 0.24

Δm^2 = 2.15 eV^2

C Giunti, M. Laveder

G.Mention et al,
arXiv: 1101.2755

Consistency

Controversial and not convincing

With reactor anomaly global fit of data in terms of nu-sterile becomes better

Limit on U_{e4} becomes weaker

$|U_{e4}|^2 : 0.02 \rightarrow 0.04$

Smaller values of $U_{\mu4}$ are allowed to explain LSND/MiniBooNE – less tension with SBL experiment bounds

$|U_{\mu4}|^2 : 0.04 \rightarrow 0.02$

Global fit

3 + 2 scheme

ν_4	ν_5
$\Delta m_{41}^2 = 0.47\ eV^2$	$\Delta m_{51}^2 = 0.87\ eV^2$
$U_{e4} = 0.128$	$U_{e5} = 0.138$
$U_{\mu4} = 0.165$	$U_{\mu5} = 0.148$

J Kopp, M. Maltoni, T.Schwetz
1103.4570 [hep-ph]

Extra radiation in the Universe

Effective number of neutrino species

$N_{eff} = 4.34^{+0.86}_{-0.88}$ (68 % CL)

- WMAP-7
- Barion Acoustic Oscillations
- Hubble constant

E. Komatsu et al
arXiv: 1001.4538 [astro-ph.CO]

N_{eff} = 5.3 +/- 1.3 (68% CL)

- WMAP–7
- Atacama Cosmology Telescope

J. Dunkley et al
arXiv:1009.0866 [astro-ph.CO]

ΔN_{eff} = (0.02 – 2.2) (68% CL)

J. Hamann et al
PRL 105 (2010)181301

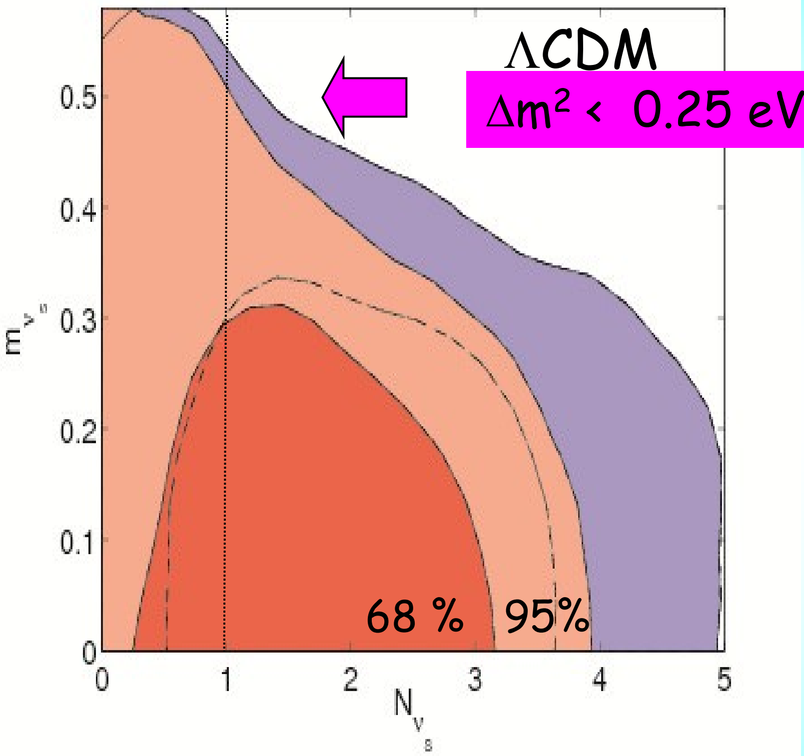
BBN

$N_{eff} = 3.68^{+0.80}_{-0.70}$ (68 % CL)

Y. I. Izotov and T X Thuan
Astrophys J 710 (2010) L67

Cosmological bounds

E Giusarma et al 1102.4774 [astro-ph]



ΛCDM

$\Delta m^2 < 0.25\ eV^2$

run 1 (blue)
- WMAP
- SDSS (red galaxy clustering)
- Hubble (prior on H_0)

+ BBN

run 2 (red)
- Supernova Ia Union Compilation 2 (in add)

J R Kristiansen, O Elgaroy 1104.0704 [astro-ph]

Inverse approach:

wCDM + $2\nu_S$

1). $w < -1$

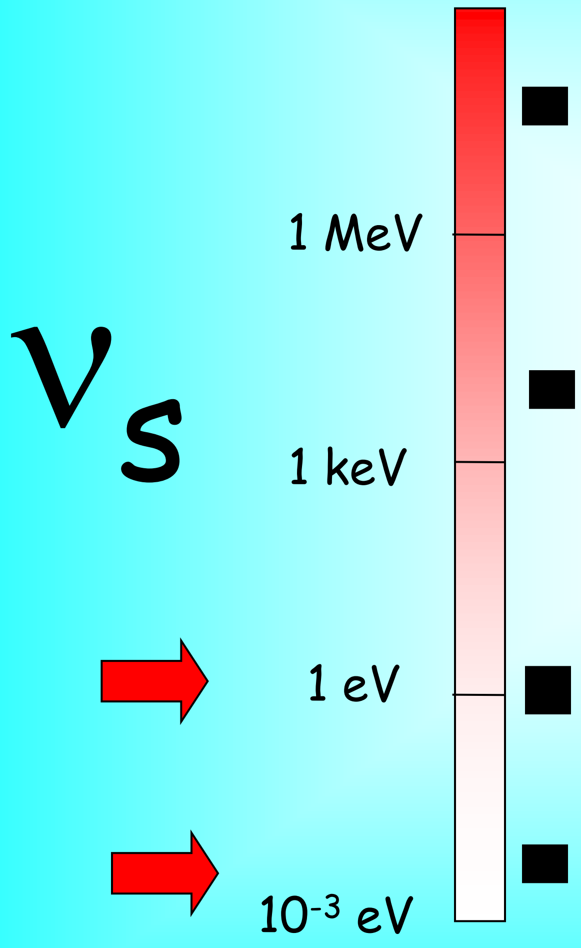
ruling out Λ

2). Age of the Universe
12.58 +/- 0.26 Gyr

too young?

The oldest globular clusters
13.4 +/- 0.8 +/- 0.6 Gyr

Mass scales



40 - 70 MeV	- LSND, MiniBooNE
~ 10 keV	- Warm Dark matter - Pulsar kick
0.5 - 2 eV	- LSND, MiniBooNE - Reactor anomaly - Calibration experiments - Extra radiation
(2 – 4) 10^{-3} eV	- Solar neutrinos - Extra radiation in the Universe

Mixing

Mass matrix

$$\begin{array}{c|ccc|c}
\nu_e & m_{ee} & m_{e\mu} & m_{e\tau} & m_{eS} \\
\nu_\mu & \ldots & m_{\mu\mu} & m_{\mu\tau} & m_{\mu S} \\
\nu_\tau & \ldots & \ldots & m_{\tau\tau} & m_{\tau S} \\
\hline
\nu_S & \ldots & \ldots & \ldots & m_{SS}
\end{array}$$

For $m_{SS} \sim 1$ eV $\tan\theta_{jS} = m_{jS}/m_{SS} \sim 0.2$ - is not small

produces large corrections to the active neutrino mass matrix

$\delta m_{ij} \sim -\tan\theta_{iS}\tan\theta_{jS}\, m_{SS} \sim 0.04\, m_{SS}$ $m_{SS} \gg m_{ab}, m_{aS}$

In general can not be considered as small perturbation!

Effect can be small if

Active neutrino spectrum
is quasi degenerate
$m_{SS} \sim m_{ab}$

m_{eS} $m_{\mu S}$ $m_{\tau S}$ have
certain symmetry

*J. Barry,
W. Rodejohann,
He Zhang
arXiv: 1105.3911*

Applications

$$\boxed{m_\nu = m_a + \delta m}$$

Original active mass
matrix e.g. from see-saw

Induced mass matrix
due to mixing with nu sterile

δm can change structure (symmetries) of the original mass matrix completely (not a perturbation)

produce dominant $\mu\tau$ - block
with small determinant

Enhance lepton mixing

Generate TBM mixing

Be origin of difference of

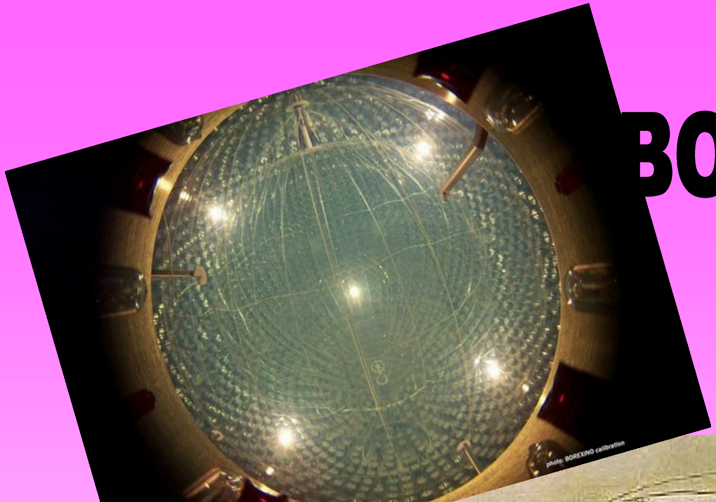
U_{PMNS} and V_{CKM}

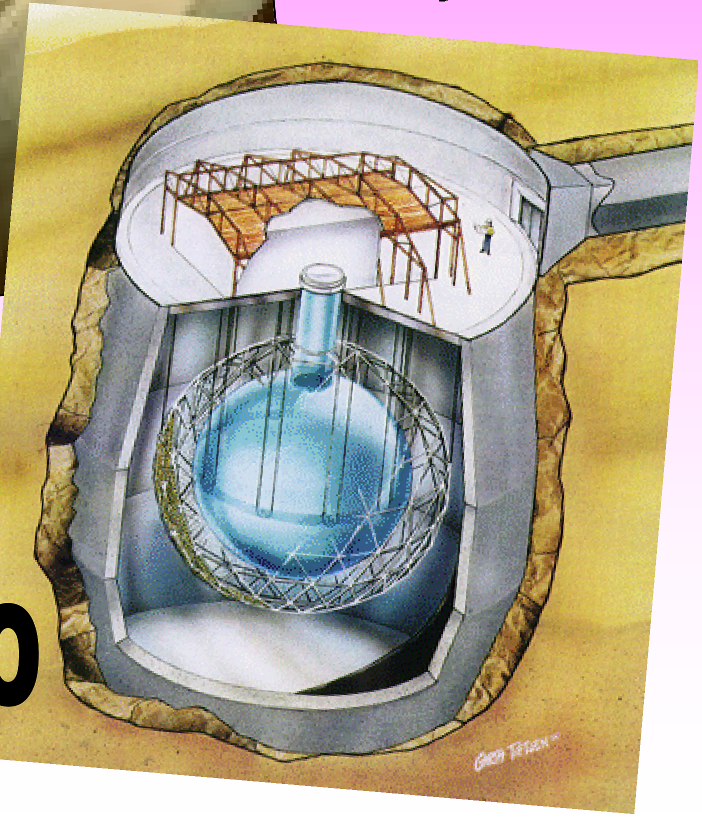
The Sun:
shining in sterile

P. C. de Holanda, A. Yu. S. 1012.5627 [hep-ph]

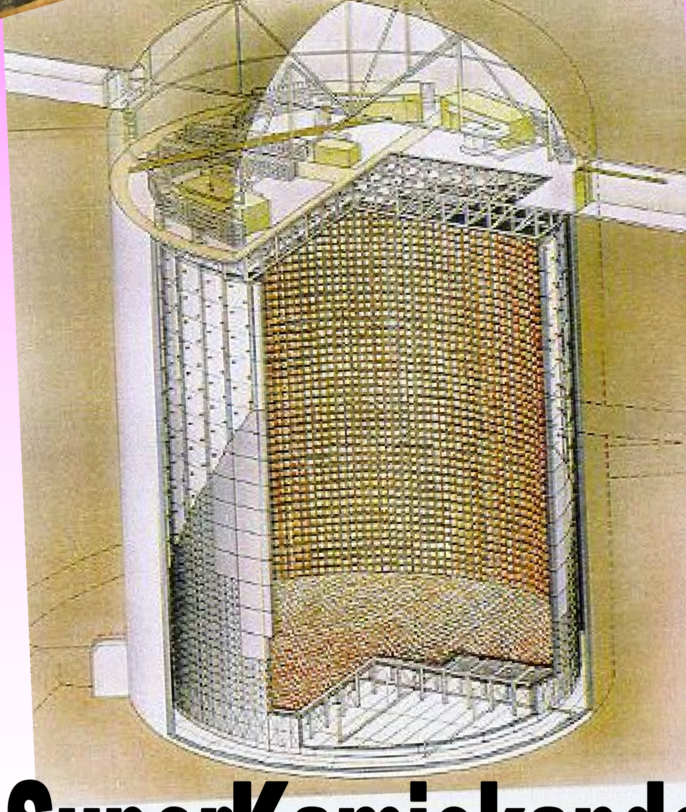
Homestake

BOREXINO





SNO



SuperKamiokande

Problem?

- $Q_{Ar}^{exp} < Q_{Ar}^{LMA}$

  2.55 +/- 0.25 SNU   > 3.1 SNU

- No turn up of the spectrum in SK

P. de Holanda, A.S.
Phys. Rev. D69 (2004)
113002 hep-ph 0307266

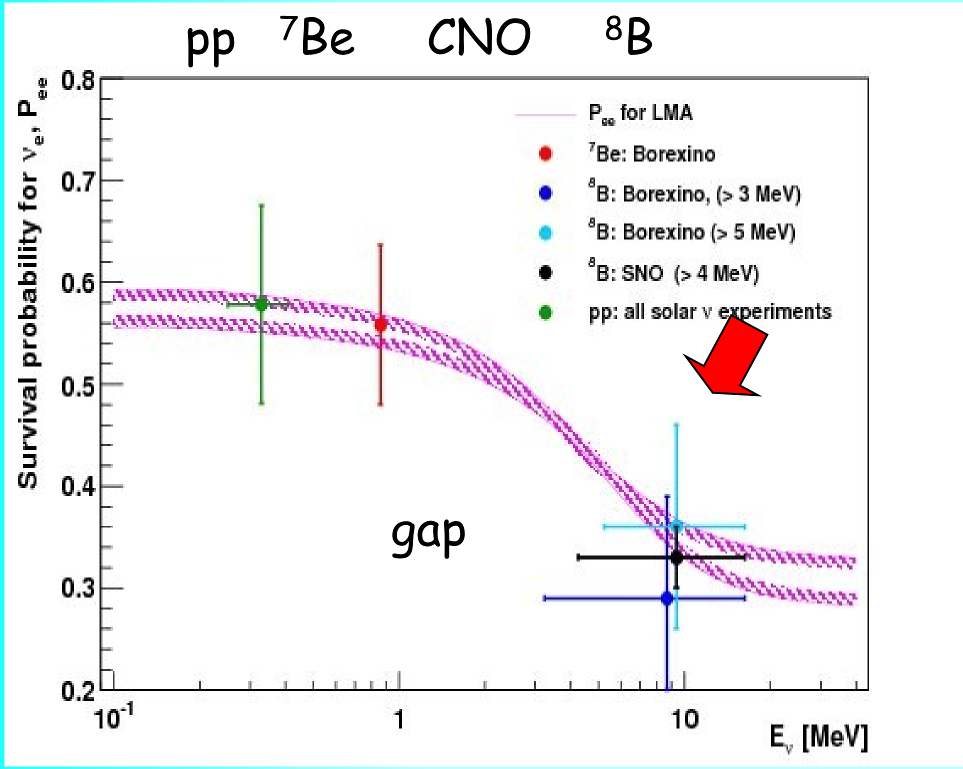
Light sterile neutrino $R_{\Delta} = \Delta m_{01}^2 / \Delta m_{21}^2 \ll 1$

$\alpha \ll 1$ - mixing angle of sterile- active neutrinos

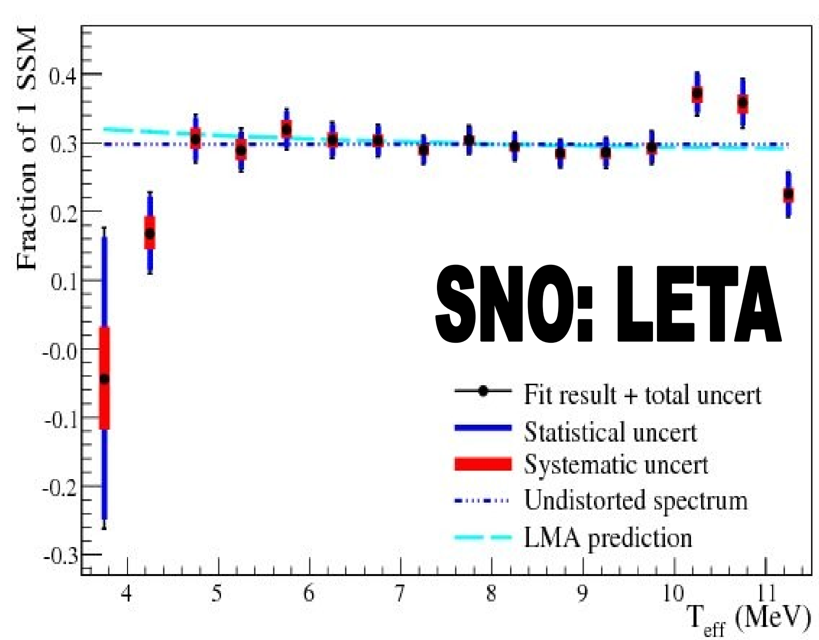
→ dip in survival probability

Motivation for the low energy solar neutrino experiments BOREXINO, KamLAND …

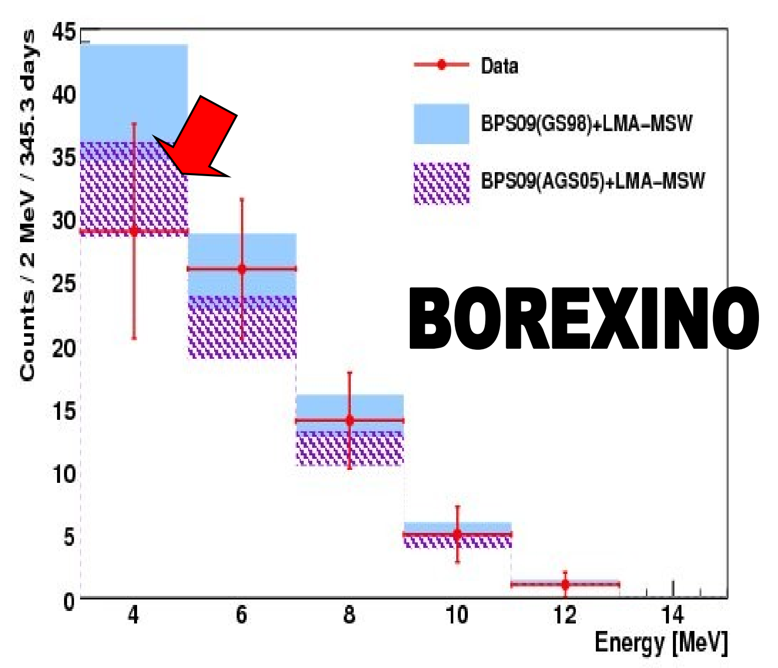
Up-turn?



ν_e - survival probability from solar neutrino data vs LMA-MSW solution

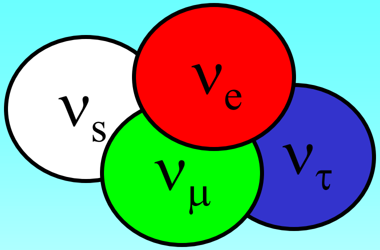


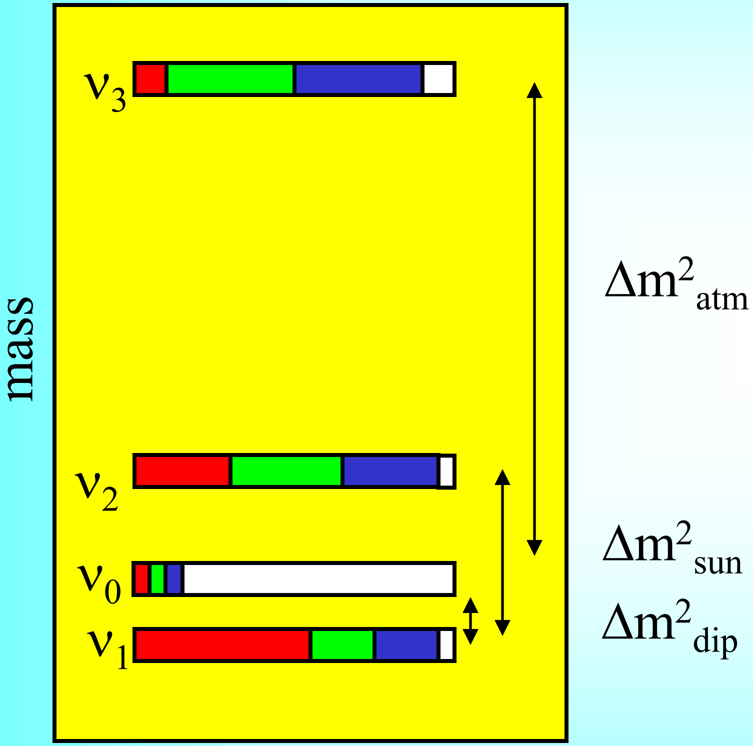
SNO: LETA



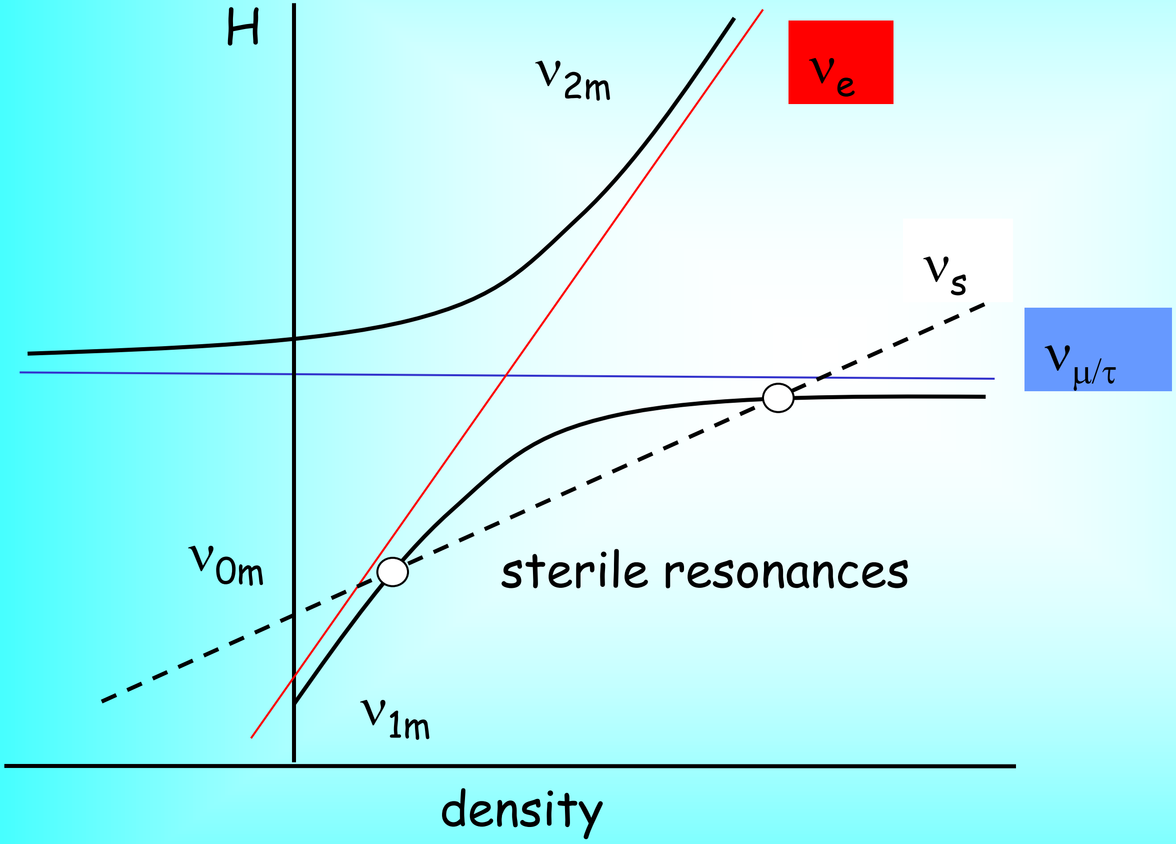
BOREXINO

(3 + 1) scheme


ν_s
ν_e
ν_μ
ν_τ


mass
ν_3
ν_2
ν_0
ν_1
Δm^2_{atm}
Δm^2_{sun}
Δm^2_{dip}

Level crossing



$\Delta m_{01}^2 > (0.2 - 2)\ 10^{-5}\ eV^2$

$\sin^2 2\alpha = 10^{-4} - 10^{-3}$

non-adiabatic
level crossing

Mixing scheme and transitions

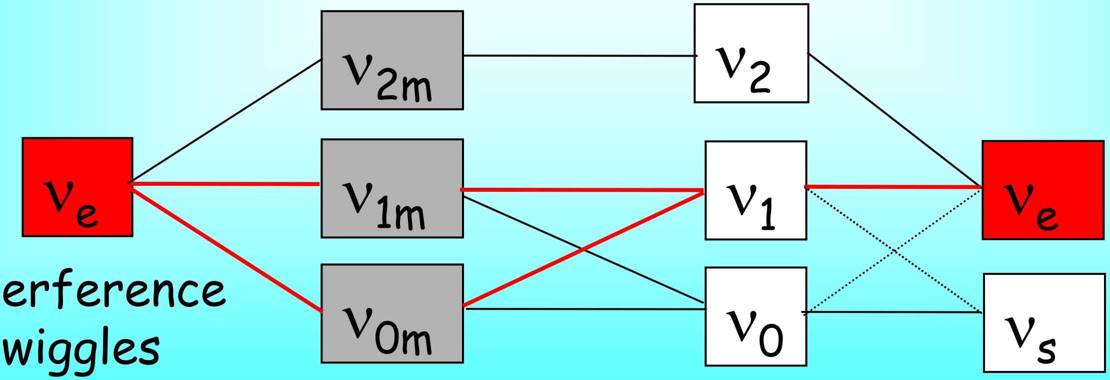
$$\begin{pmatrix} \nu_s \\ \nu_e \\ \nu_a \end{pmatrix} \qquad U = U_\theta \; U_\alpha \qquad \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \end{pmatrix}$$

U_θ - rotation in 12-plane on θ_{12}

U_α - rotation in 01- plane on α

ν_s mixes in ν_0 and ν_1

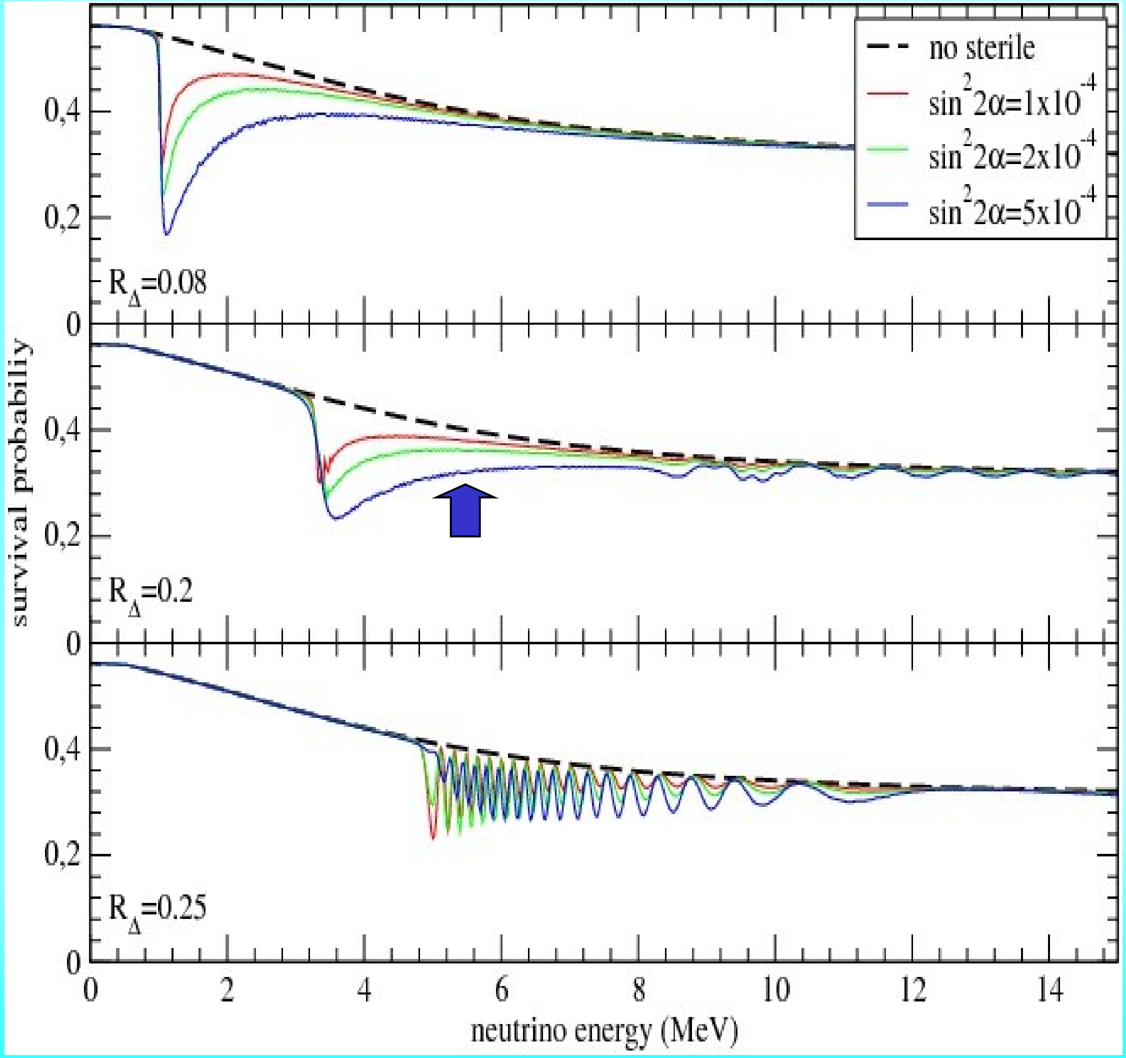
Scheme of transitions



interference
→ wiggles

$$P(\nu_e \rightarrow \nu_e) \sim |U_{e1}^m A_{11} + U_{e0}^m A_{01}|^2 \, |U_{e1}|^2 + |U_{e2}^m|^2 |U_{e2}|^2$$

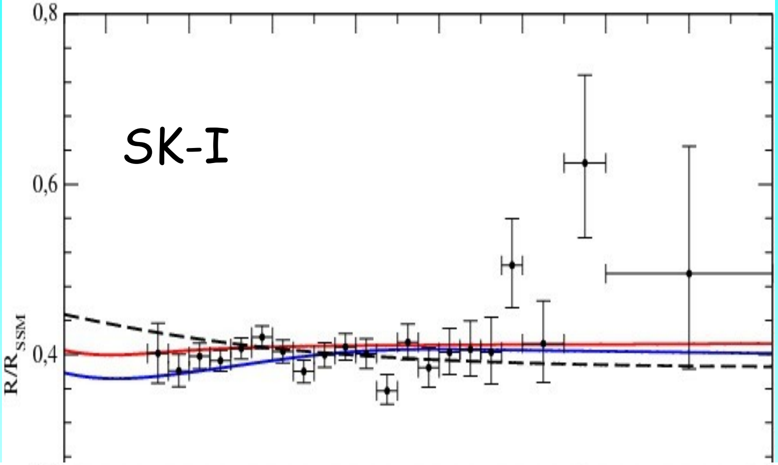
Survival probability



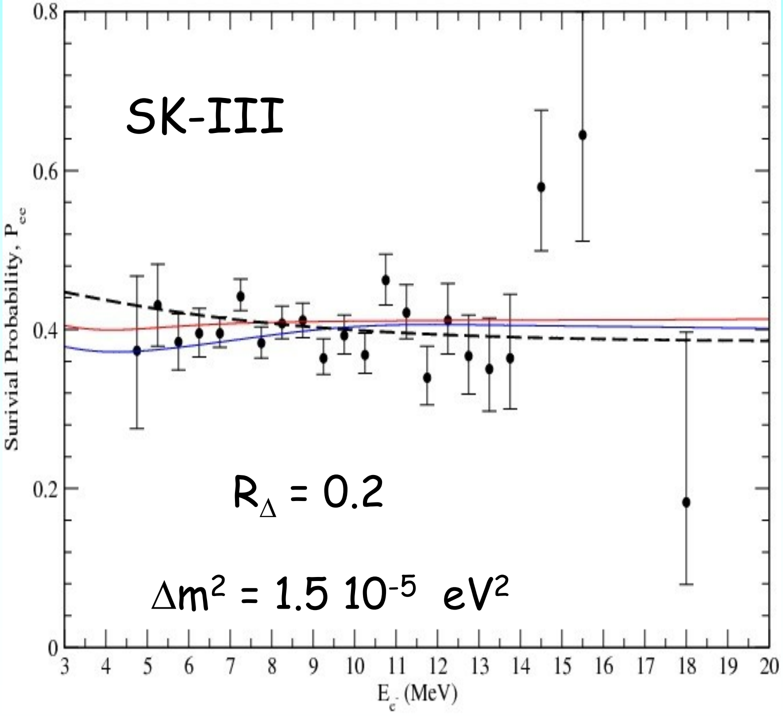
- dip
- wiggles

Spectra

$\sin^2 2\alpha = 10^{-3}$ (red), $5\ 10^{-3}$ (blue)



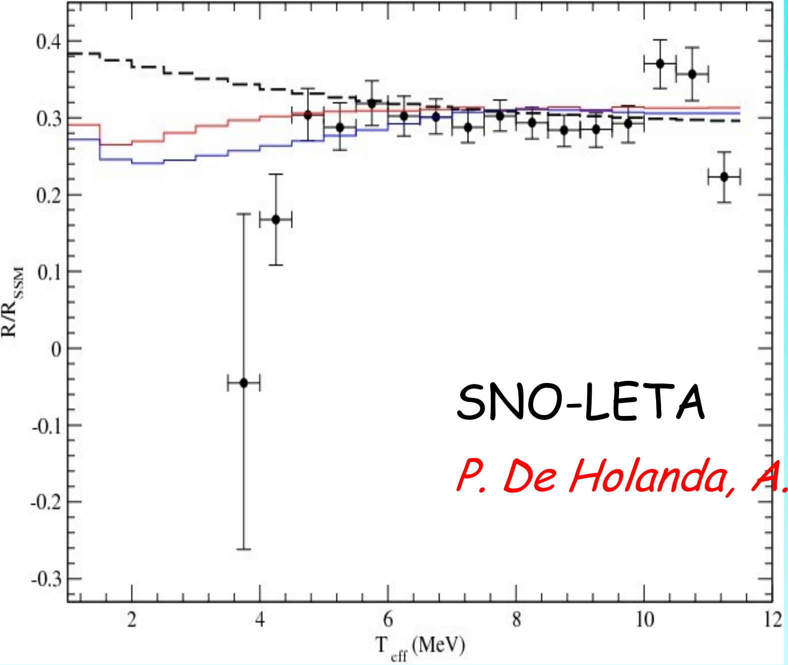
SK-I



SK-III

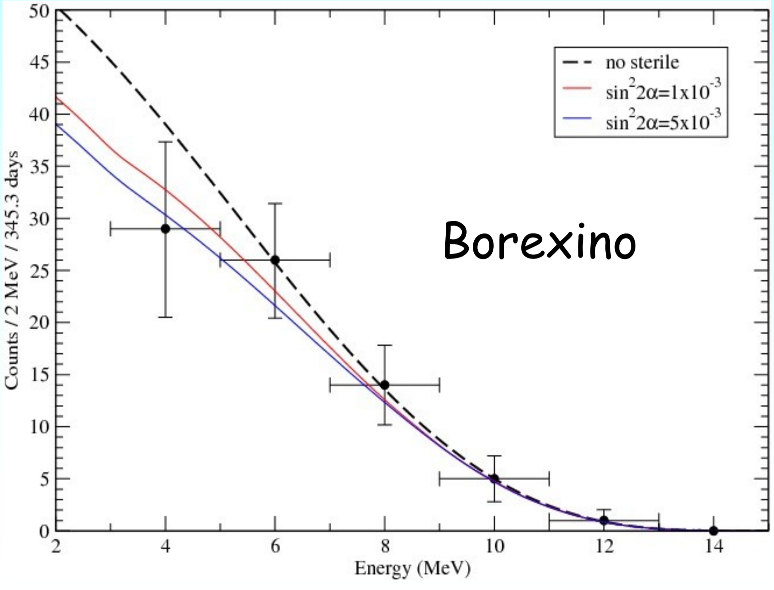
$R_\Delta = 0.2$

$\Delta m^2 = 1.5\ 10^{-5}\ \text{eV}^2$



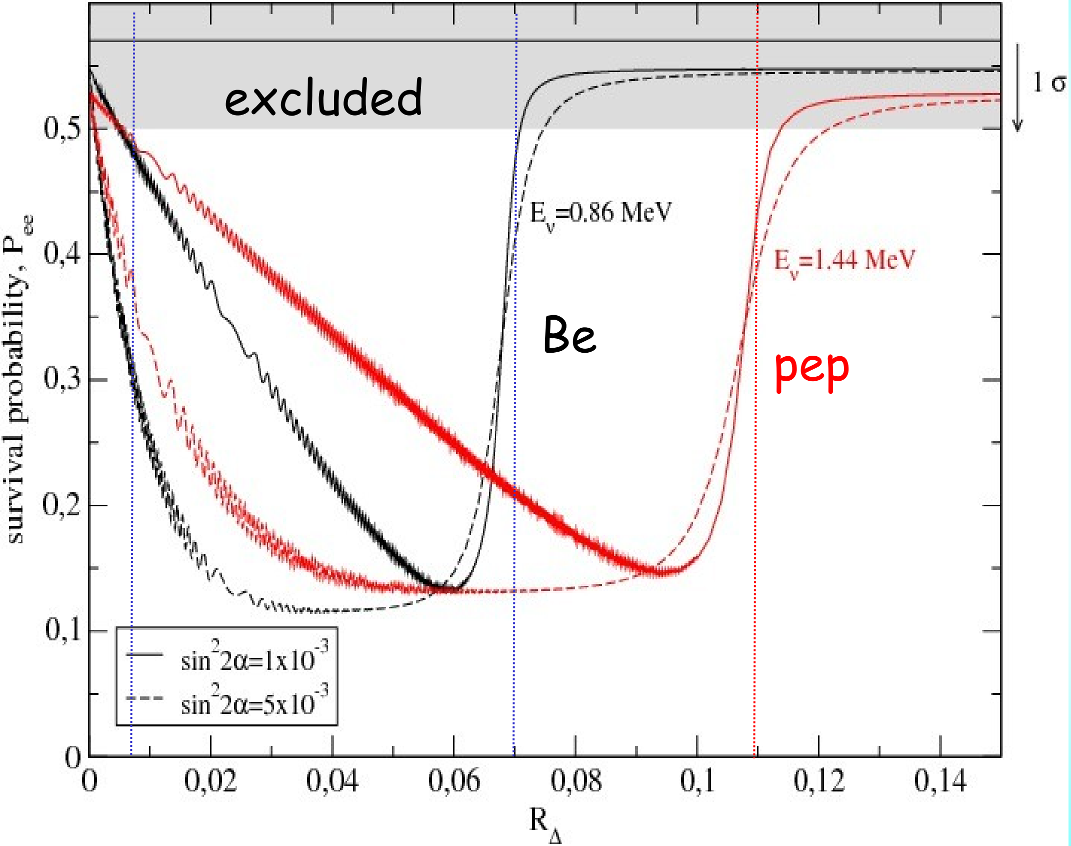
SNO-LETA

P. De Holanda, A.S.



Borexino

BOREXINO: Be line



pep-suppressed

data

excluded

$R_\Delta = 0.007 \ - 0.07$

$\Delta m_{01}^2 > 0.5\ 10^{-5}\ eV^2$

Predictions for pep-neutrinos

$R_\Delta = 0.07 \ - 0.115$

P(pep) = 0.2 – 0.3

P(Be) = 0.55

$R_\Delta > 0.12$

P(pep) = 0.53

Fit of spectra

χ^2 fit of spectra with sterile neutrino dip:
SK-I, SK-III, SNO-LETA, SNO-NC, Borexino

Best fit values: $\Delta m_{01}^2 \sim 1.5\ 10^{-5}\ \mathrm{eV}^2$ $\sin^2 2\alpha \sim 10^{-3}$ $\Delta\chi^2 = 7.5$

Interval with
$\Delta\chi^2 > 6$

$\Delta m_{01}^2 = (1 - 2)\ 10^{-5}\ \mathrm{eV}^2$ $\sin^2 2\alpha \sim (0.5 - 1)\ 10^{-3}$

➡ $m_0 > 0.003$ eV

Alternative: mixing with level ν_{2m}

$R_\Delta = \Delta m_{01}^2 / \Delta m_{21}^2 = 1.1$ $\sin^2 2\alpha \sim (0.5 - 1)\ 10^{-3}$

Implications

$m_0 \sim 0.003$ eV

$$\boxed{m_0 = \frac{M^2}{M_{Planck}}}$$

$M \sim 2 - 3$ TeV

mixing

$\sin^2 2\alpha \sim 10^{-3}$

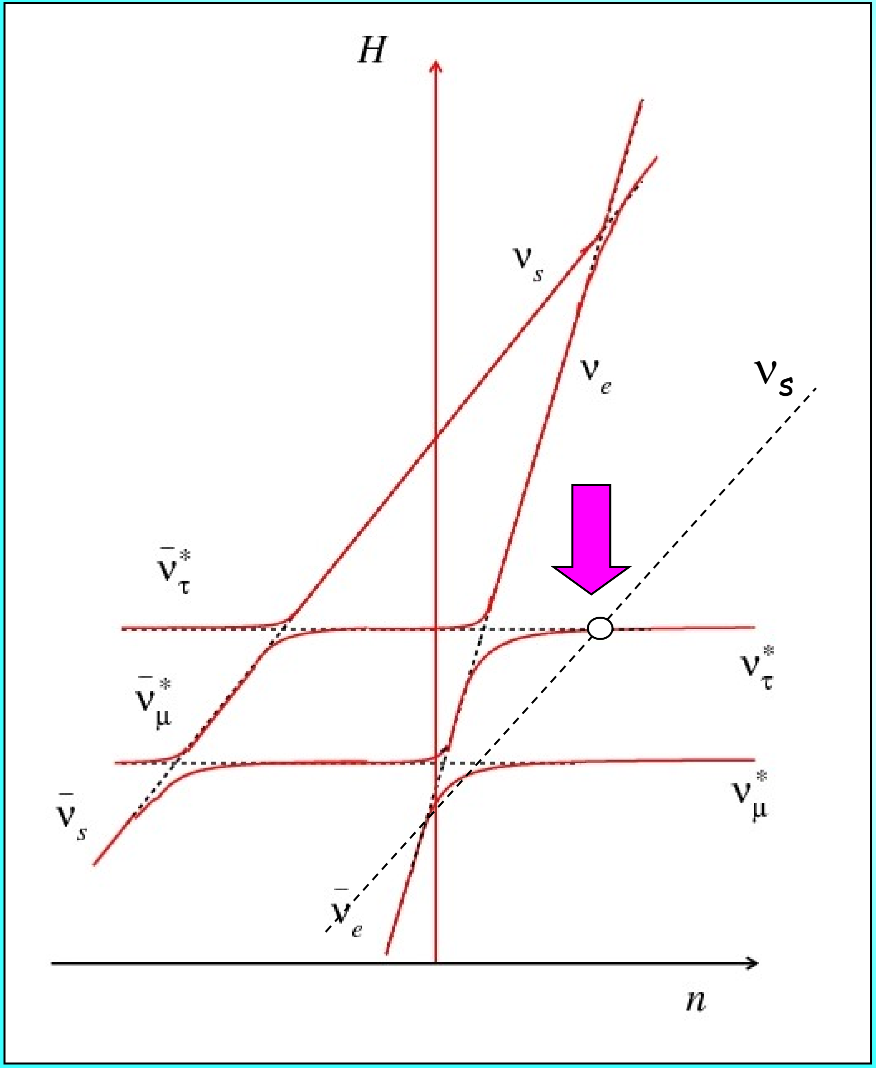
$$\alpha \sim \frac{h\, v_{EW}}{M}$$

$h = 0.1$

$\sin^2 2\beta \sim 10^{-1}$

$$\beta \sim \frac{v_{EW}}{M}$$

Level crossing scheme



P. De Holanda, A.S.

Mixing with the third active state

Extra radiation in the Universe

Production of sterile in the Early universe

Mixing of ν_s in ν_3

$\nu_3 = \cos\beta\ \nu_\tau{}' + \sin\beta\ \nu_s$

where $\nu_\tau{}' = \cos\theta_{23}\ \nu_\tau + \sin\theta_{23}\ \nu_\mu$

$\Delta m_{30}{}^2 \sim 2.5\ 10^{-3}\ \mathrm{eV}^2$

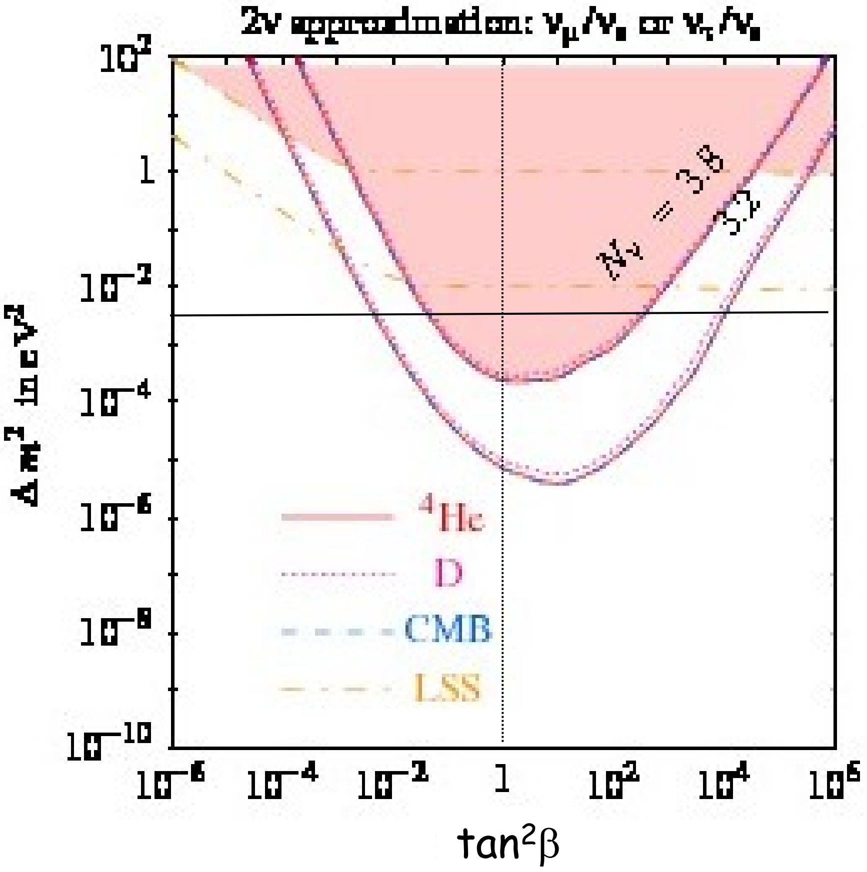
Atmospheric neutrinos:

$\sin^2\beta < 0.2 - 0.3\ (90\%)$

MINOS:

$\sin^2\beta < 0.23\ (90\%)$

M Cirelli G Marandella A Strumia F Vissani



Other consequences

Atmospheric neutrinos

$\nu_\tau' - \nu_s$ resonance $E_R \sim 12$ GeV

$\nu_\mu \rightarrow \nu_s$ resonance peak 10 – 15 GeV

IceCube Deep Core

Supernova neutrinos

Additional suppression of ν_e flux

Searching for sterile in Ice

S Razzaque and A. S.
arXiv:1104.1390 [hep-ph]

Test

H Nunokawa O L G Peres
R Zukanovich-Funchal
Phys. Lett B562 (2003) 279

ν_μ - ν_s oscillations with $\Delta m^2 \sim 1$ eV^2 are enhanced
in matter of the Earth in energy range 0.5 – few TeV

This distorts the energy spectrum and zenith angle distribution of the atmospheric muon neutrinos, also modifies μ/e ratio

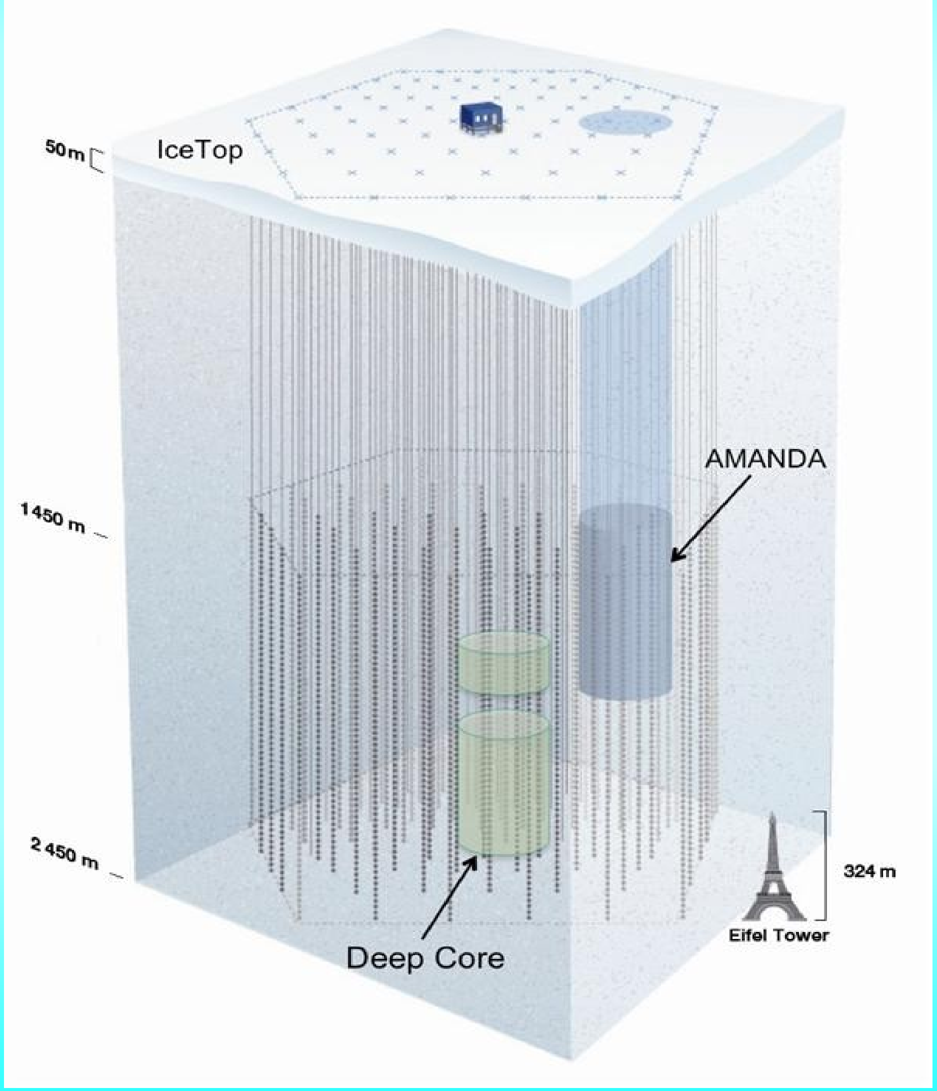
S Choubey JHEP 0712 (2007) 014

Can be tested by IceCube

First data from IceCube

- Check theoretical considerations, generalize …
- perform analysis of the data

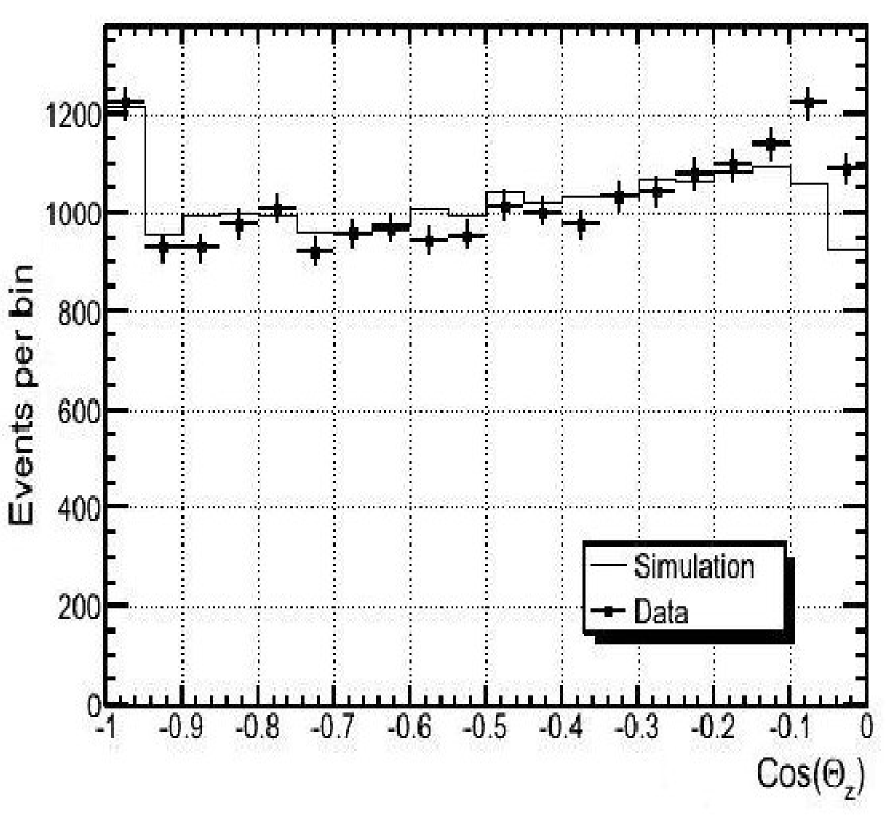
IceCube

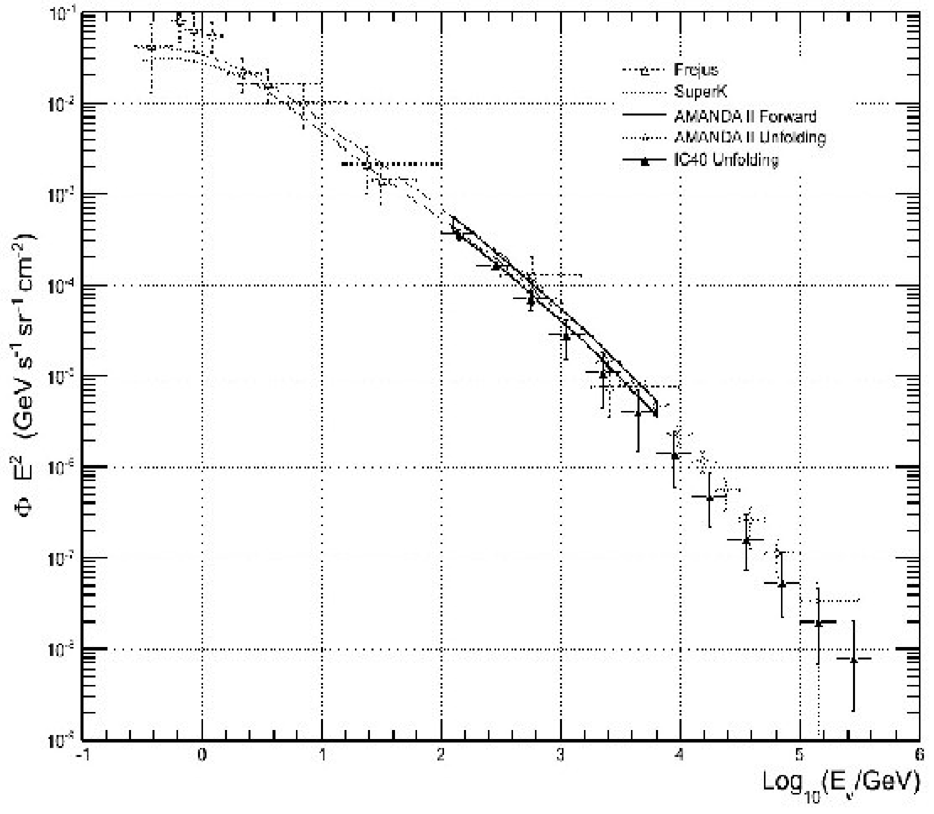


IceCube results

R. Abbasi et al, arXiv:1010.3980 [astro-ph.CO]

Zenith angle distribution

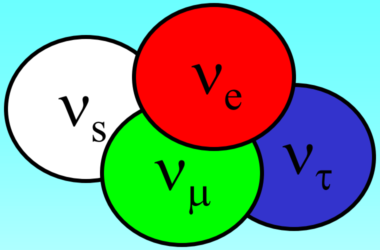


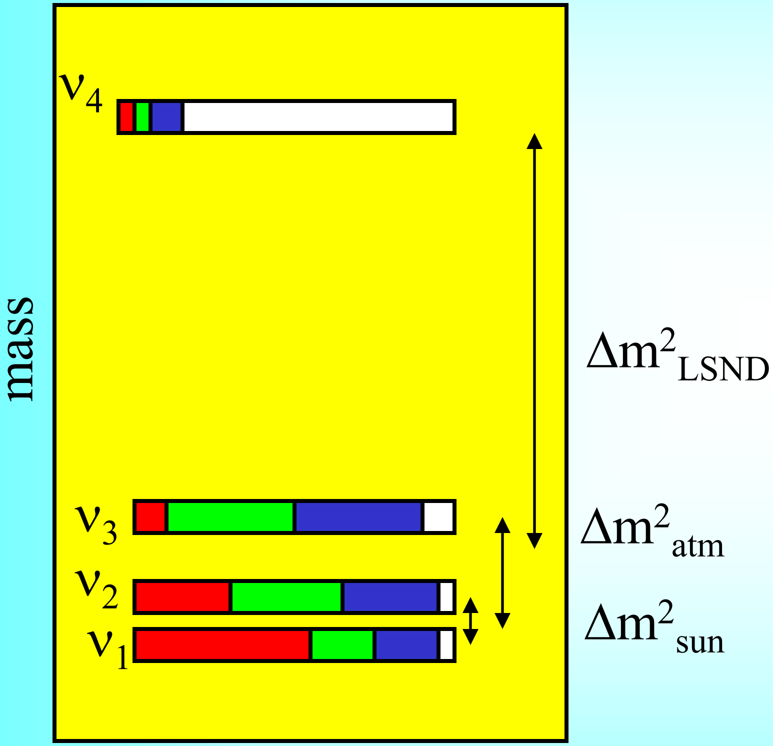


Unfolded neutrino spectrum

April 2008 – May 2009
40 strings
100 GeV – 400 TeV
18 000 up-going muons

(3 + 1) scheme





LSND/MiniBooNE: vacuum oscillations

$$P \sim 4|U_{e4}|^2|U_{\mu4}|^2$$

Restricted by short baseline experiments CHOOZ, CDHS, NOMAD

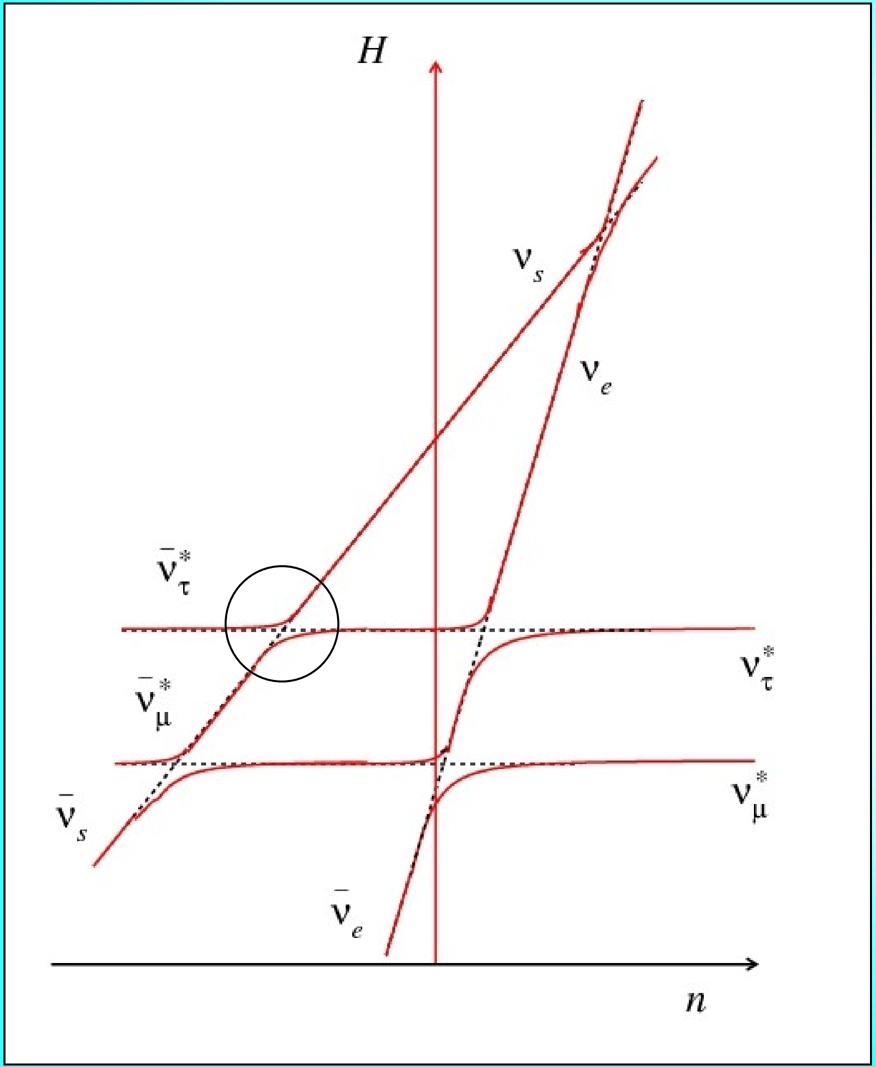
With new reactor data:

$\Delta m_{41}^2 = 1.78\ \mathrm{eV}^2$

$U_{e4} = 0.15$

$U_{\mu4} = 0.23$

Level crossing scheme



- Normal mass hierarchy in the flavor block; m_0 ~ 1 eV
- Three new level crossings
- $|U_{e4}|^2 \quad |U_{\mu4}|^2$ are large enough, so that evel crossings are adiabatic
- $V_e - V_s = \sqrt{2}\, G_F\, (n_e - n_n/2)$

ν_s - mass mixing scheme

$$\begin{matrix}\nu_s\\ \nu_\tau\\ \nu_\mu\end{matrix} \qquad U_f = U_{23}\, U_\alpha \qquad \begin{matrix}\nu_0\\ \nu_3\\ \nu_2\end{matrix}$$

ν_s mixes in the mass states ν_3 and ν_0

$$\boxed{\begin{aligned}\nu_0 &= -\sin\alpha\, \tilde{\nu}_3 + \cos\alpha\, \nu_s\\ \nu_3 &= \cos\alpha\, \tilde{\nu}_3 + \sin\alpha\, \nu_s\\ \nu_2 &= \tilde{\nu}_2\end{aligned}}$$

where

$$\tilde{\nu}_3 = \cos\theta_{23}\, \nu_\tau + \sin\theta_{23}\, \nu_\mu$$

$$\tilde{\nu}_2 = \cos\theta_{23}\, \nu_\mu - \sin\theta_{23}\, \nu_\tau$$

ν_s mixes with $\tilde{\nu}_3$

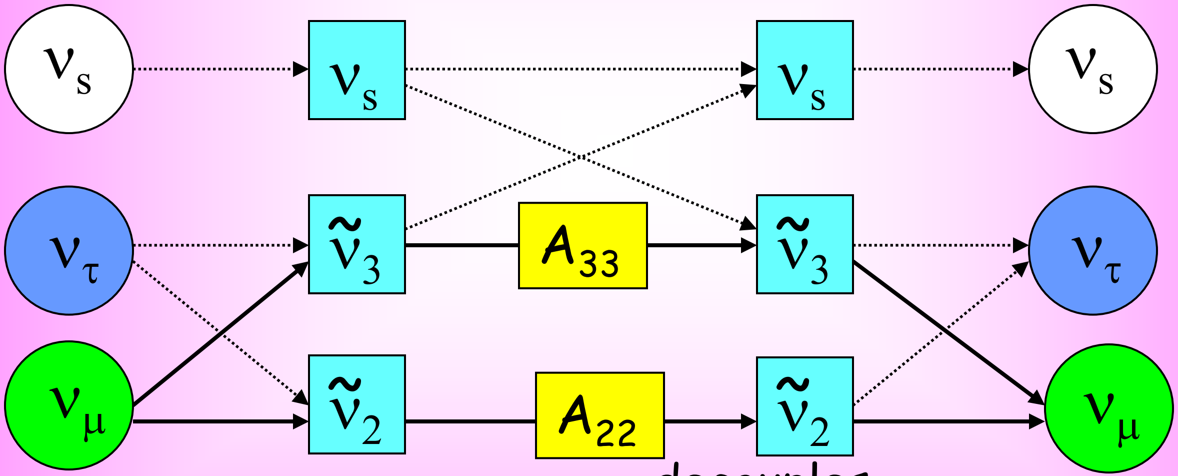
Propagation basis: $\nu_s, \tilde{\nu}_3, \tilde{\nu}_2$

Evolution is reduced to 2ν-problem exactly

Evolution

Propagation basis

$$\boxed{\nu_f = U_{23}\,\tilde{\nu}}$$



decouples

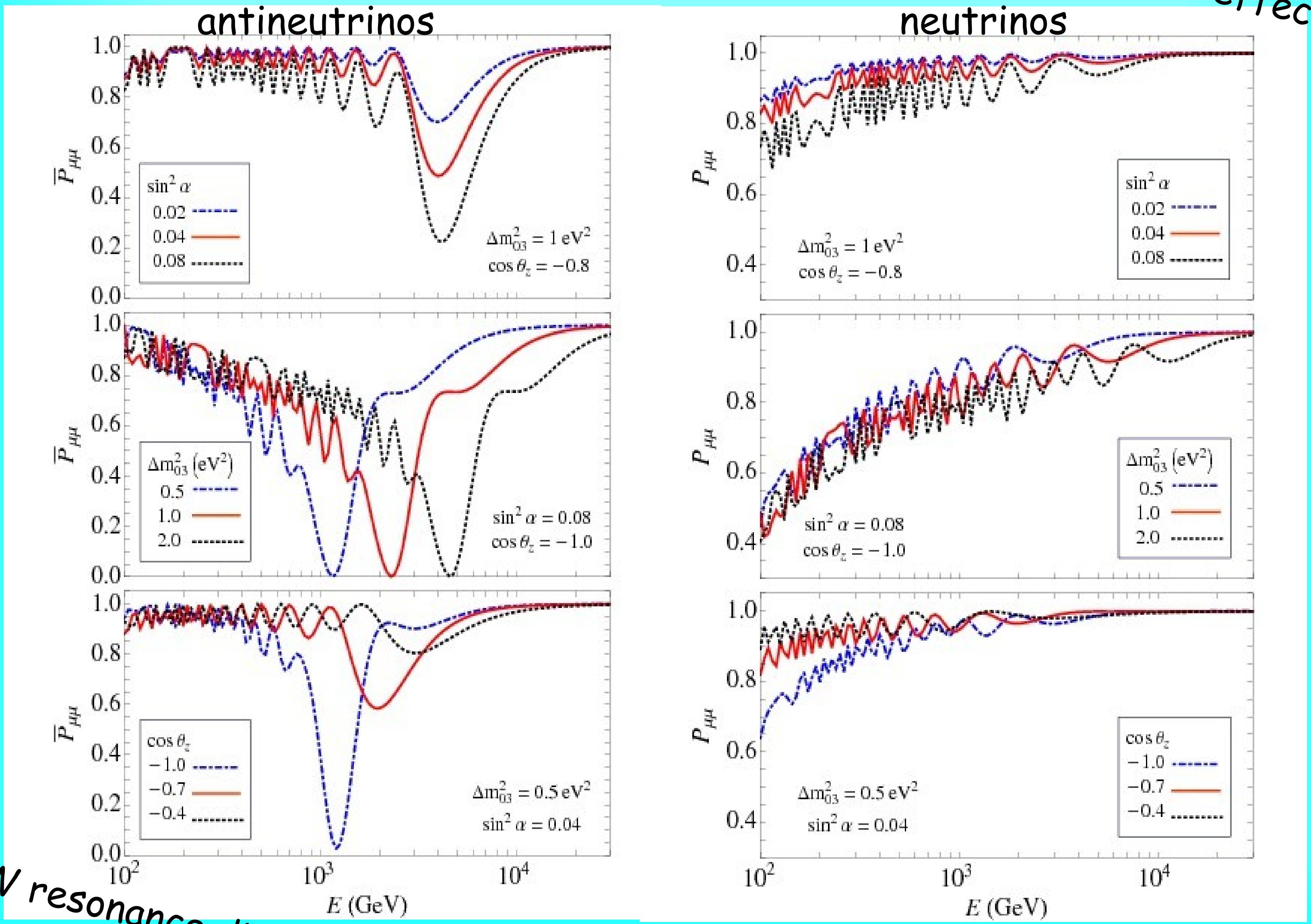
projection propagation projection

S

$$P(\nu_\mu \to \nu_\mu) = |\cos^2\theta_{23} A_{22} + \sin^2\theta_{23} A_{33}|^2$$

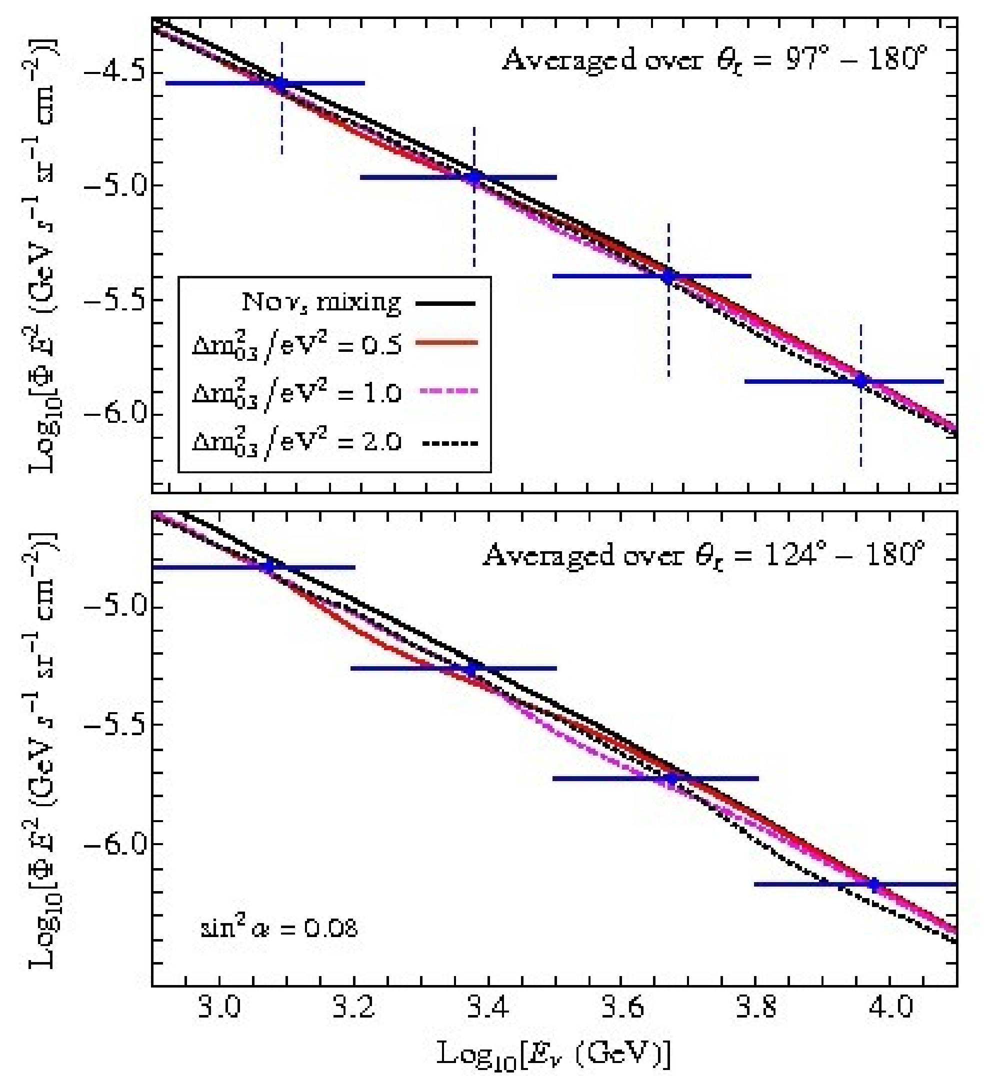
Survival probability

Effect of phase shift for the $\nu_\mu - \nu_\tau$ oscillations due to matter effects



MSW resonance dip

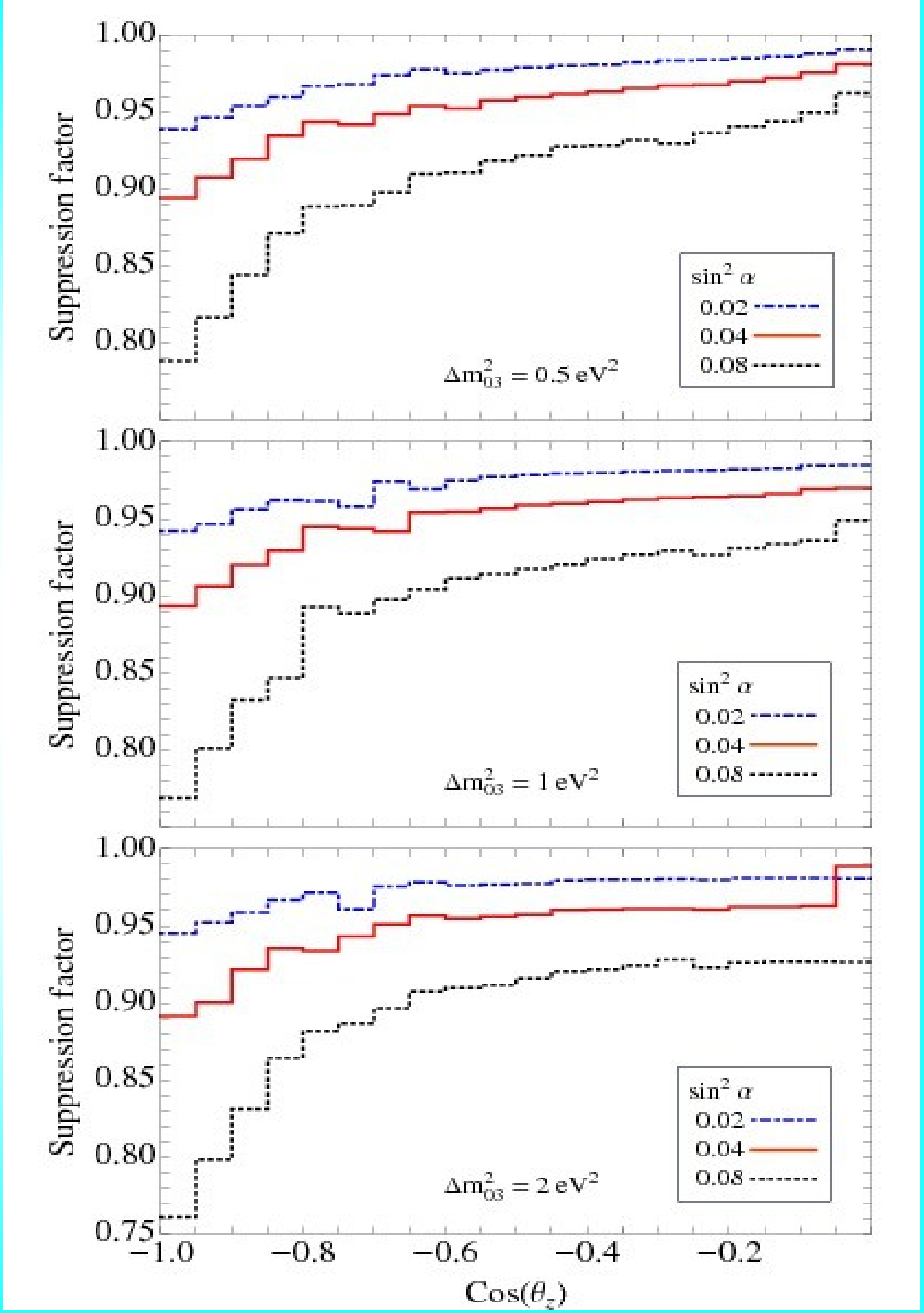
Energy spectra



Suppression factor

$S = N(\text{osc.})/N(\text{no osc.})$

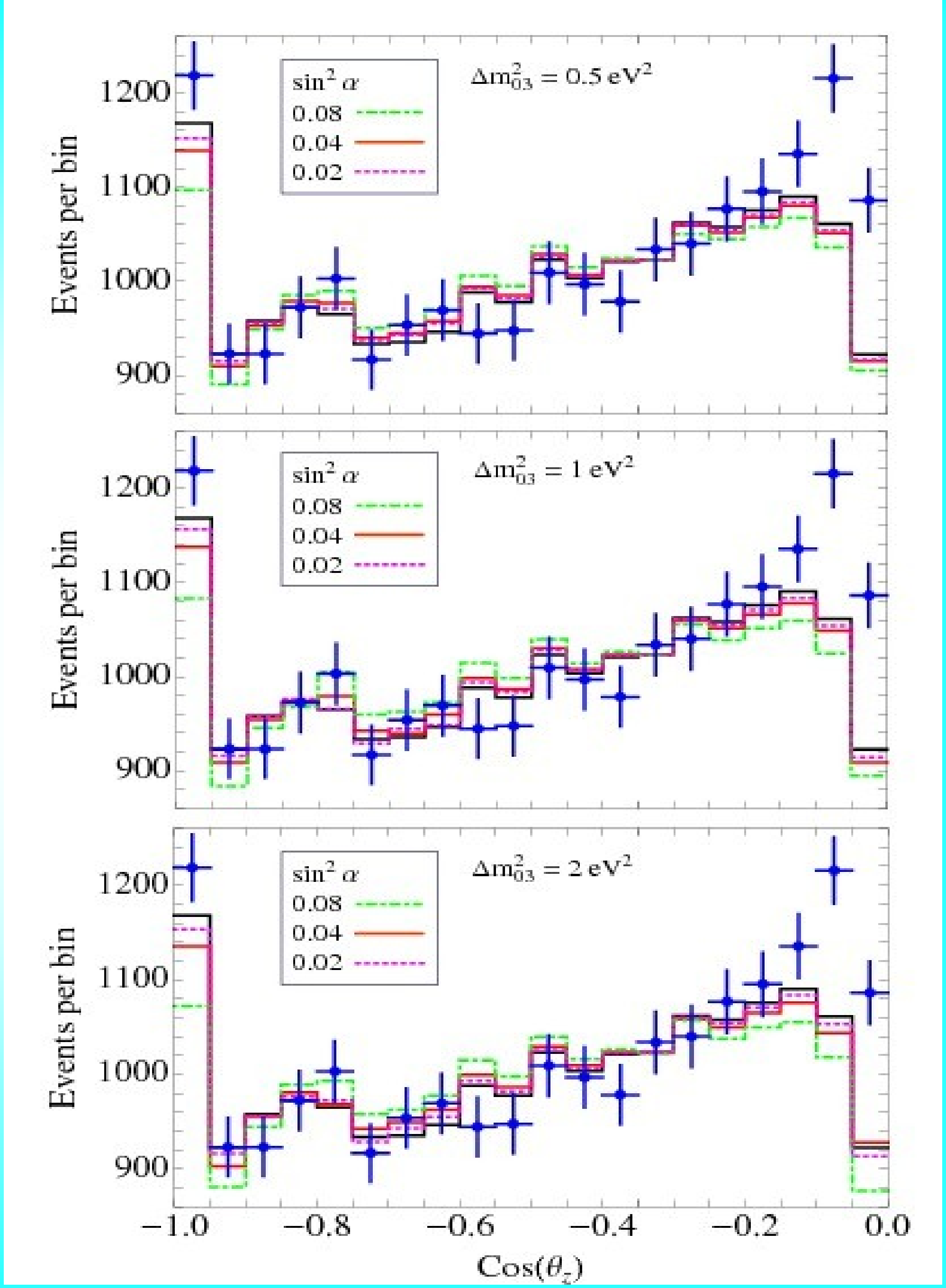
$E_{th} = 0.1$ TeV



Zenith angle distribution

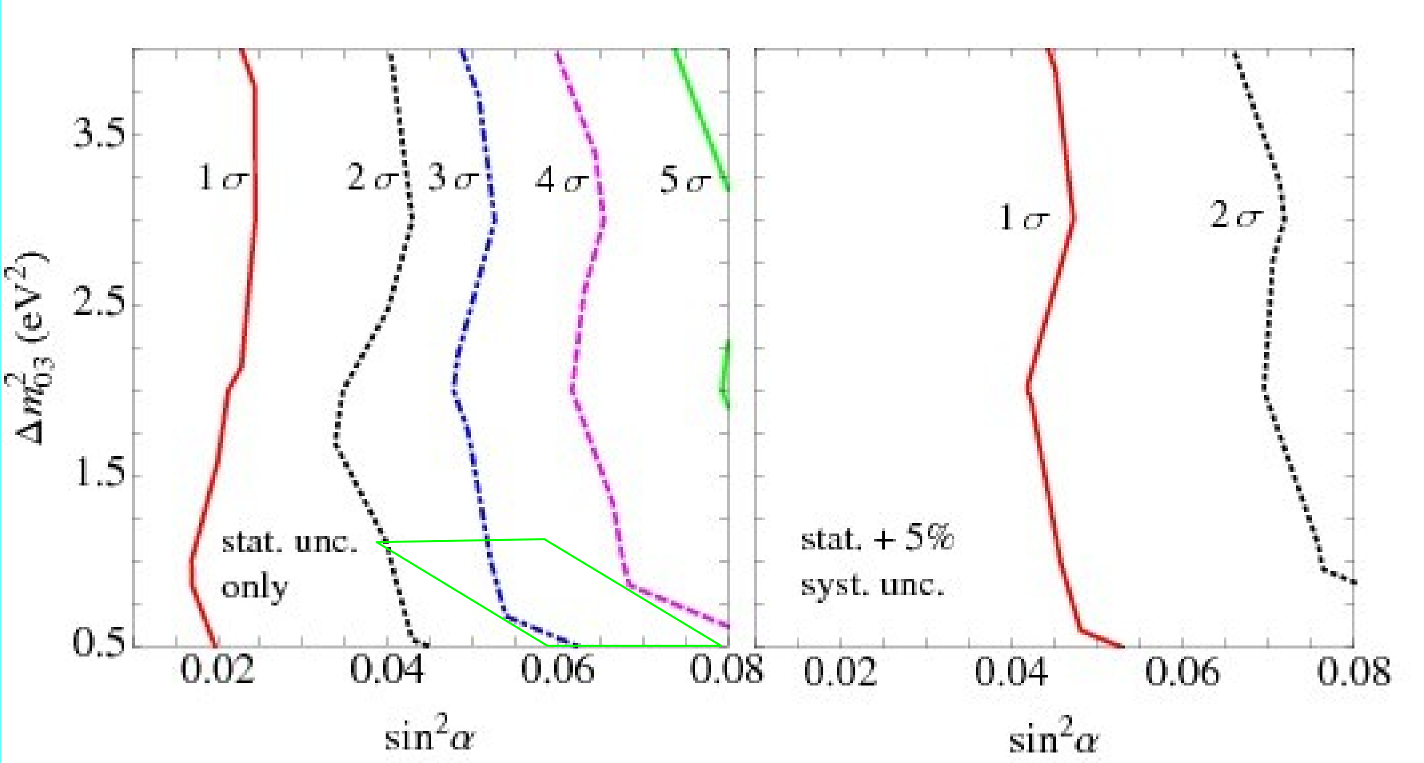
ν_S - mass mixing case

Free normalization and tilt factor



Bounds on mixing

Illustrative fit
in the simplest
mixing scheme



LSND: **$\sin^2\alpha > 0.04$**

+ 5% uncorrelated
systematic errors

Statistical errors +
free normalization + tilt

$\nu_s - \nu_\mu$ - mixing

$$\begin{pmatrix} \nu_s \\ \nu_\tau \\ \nu_\mu \end{pmatrix} \qquad U_f = U_\beta U_{23} \qquad \begin{pmatrix} \nu_0 \\ \nu_3 \\ \nu_2 \end{pmatrix}$$

ν_s mixes with ν_μ

$$\nu_0 = - \sin\beta\, \nu_\mu + \cos\beta\, \nu_s$$

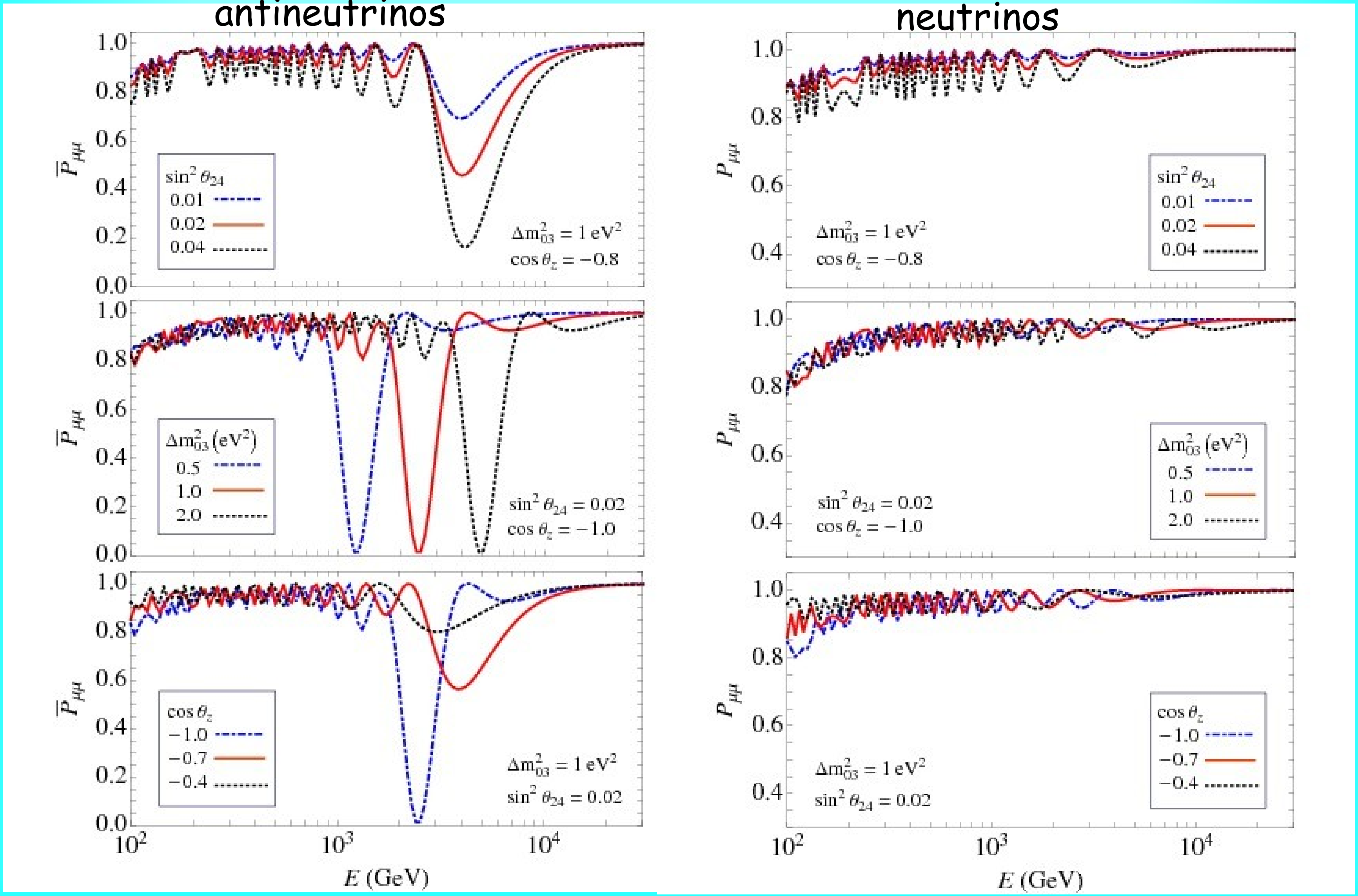
$$\nu_3 = - \cos\beta \sin\theta_{23}\, \nu_\mu + \cos \theta_{23}\, \nu_\tau - \sin\beta \sin\theta_{23}\, \nu_s$$

$$\nu_2 = - \sin\beta \cos\theta_{23}\, \nu_\mu + \sin \theta_{23}\, \nu_\tau - \cos\beta \cos\theta_{23}\, \nu_s$$

Propagation basis = flavor basis

Evolution is not reduced to the 2ν - evolution exactly

Probabilities



antineutrinos

neutrinos

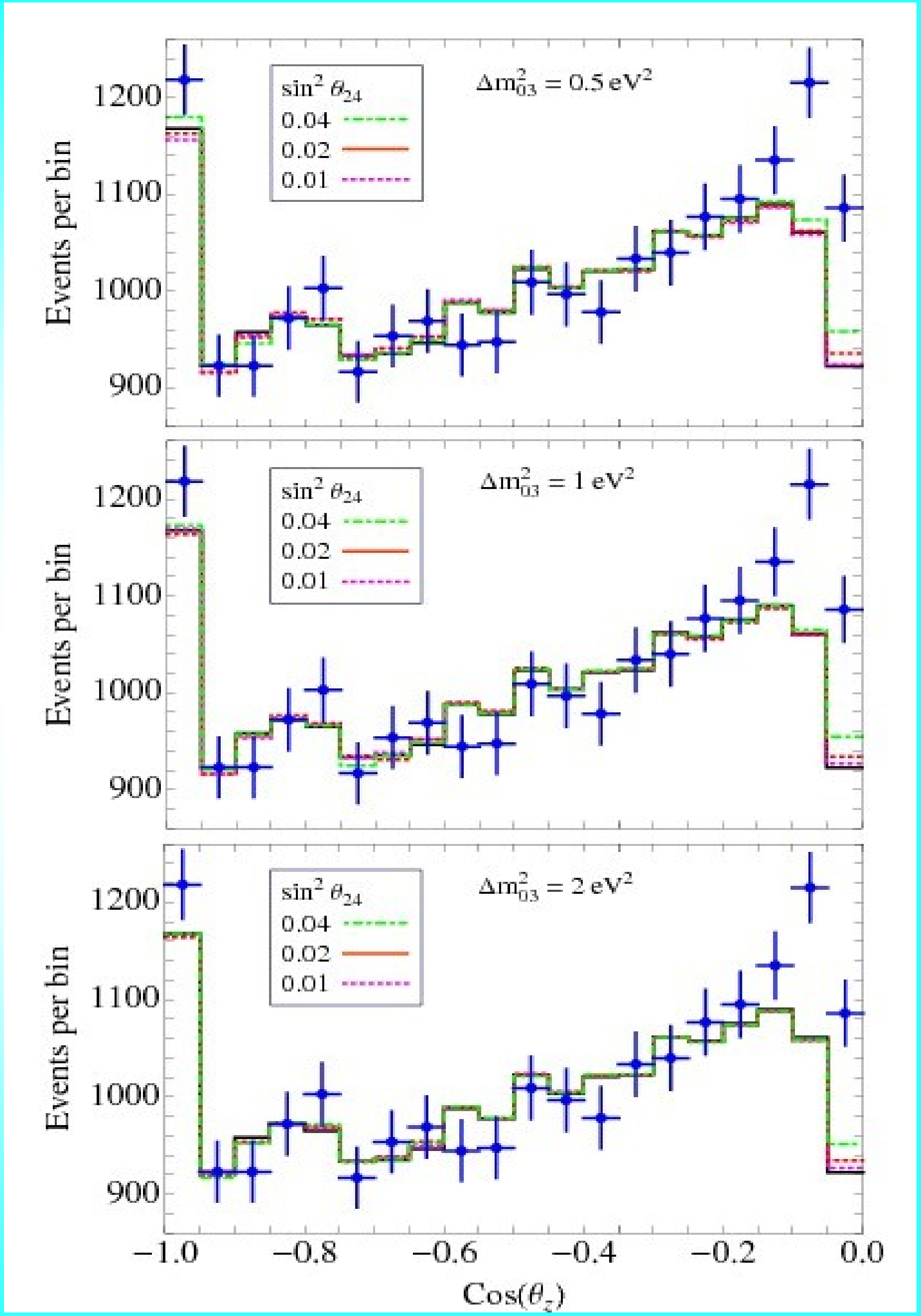
Zenith angle distribution

ν_S - ν_μ mixing

Free normalization
and tilt factor

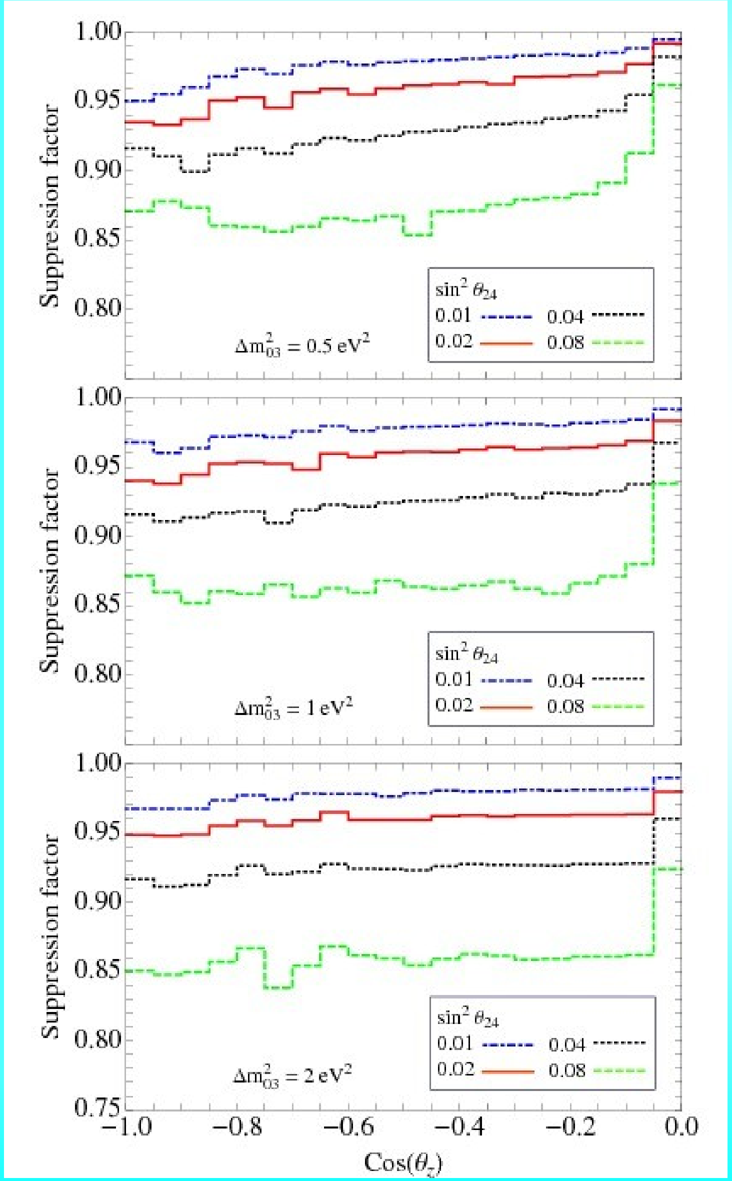
Fit with sterile is even better

E_{th} = 0.1 TeV

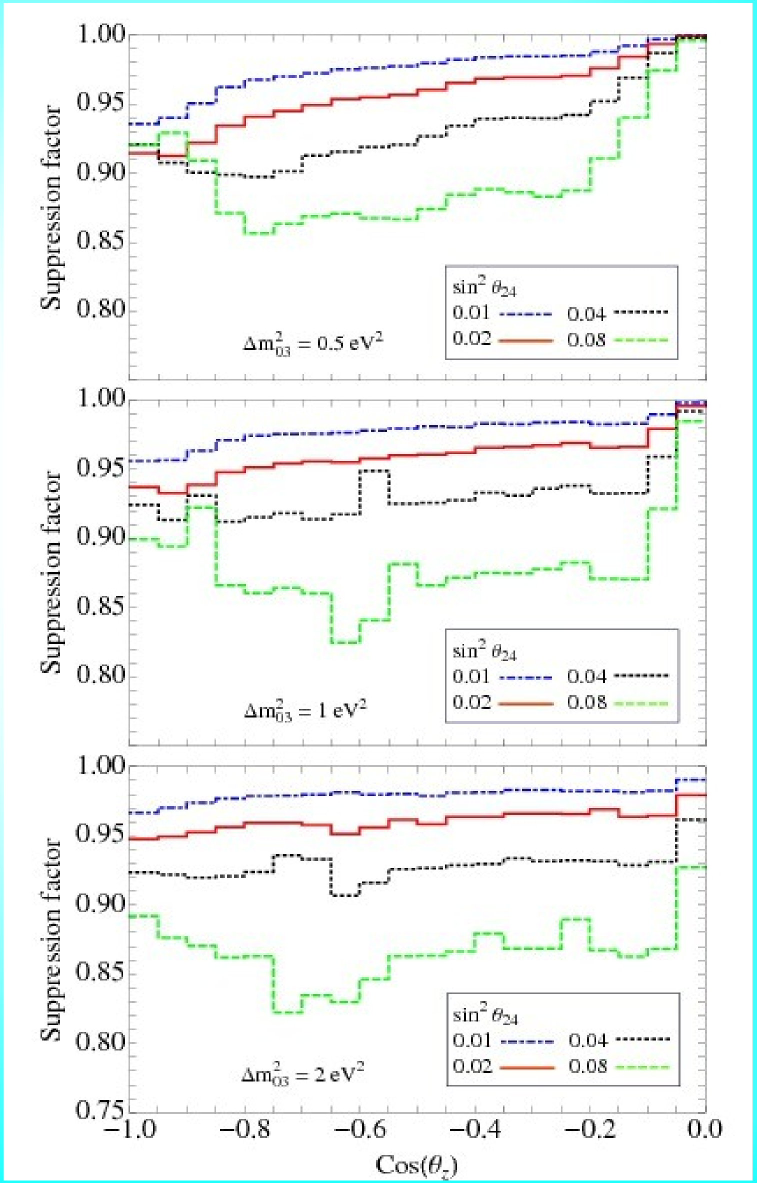


Suppression factors

E_{th} = 0.1 TeV



E_{th} = 1 TeV



Summary

New evidences/hints of existence of sterile: MiniBooNE, reactors, Gallium calibration, solar, additional radiation in the Universe

Convincing? Consistent? Controversial?

Light sterile neutrino mixed in ν_1 or/and ν_2 with

$\Delta m_{01}^2 \sim 1.5\ 10^{-5}\ eV^2$

$\sin^2 2\alpha \sim 10^{-3}$

leads to the dip in the spectrum which explains an absence of the up turn of the spectrum, reduces prediction for the Ar production rate

Being mixed in ν_3 with $\sin^2\beta \sim 0.2$ sterile can be generated in the Early Universe $\Delta N_{eff} \sim 1$, thus explaining additional radiation

IceCube has high sensitivity to sterile mixing with

$\Delta m_{01}^2 \sim 1$ eV^2

$\sin^2 \alpha > 0.01$

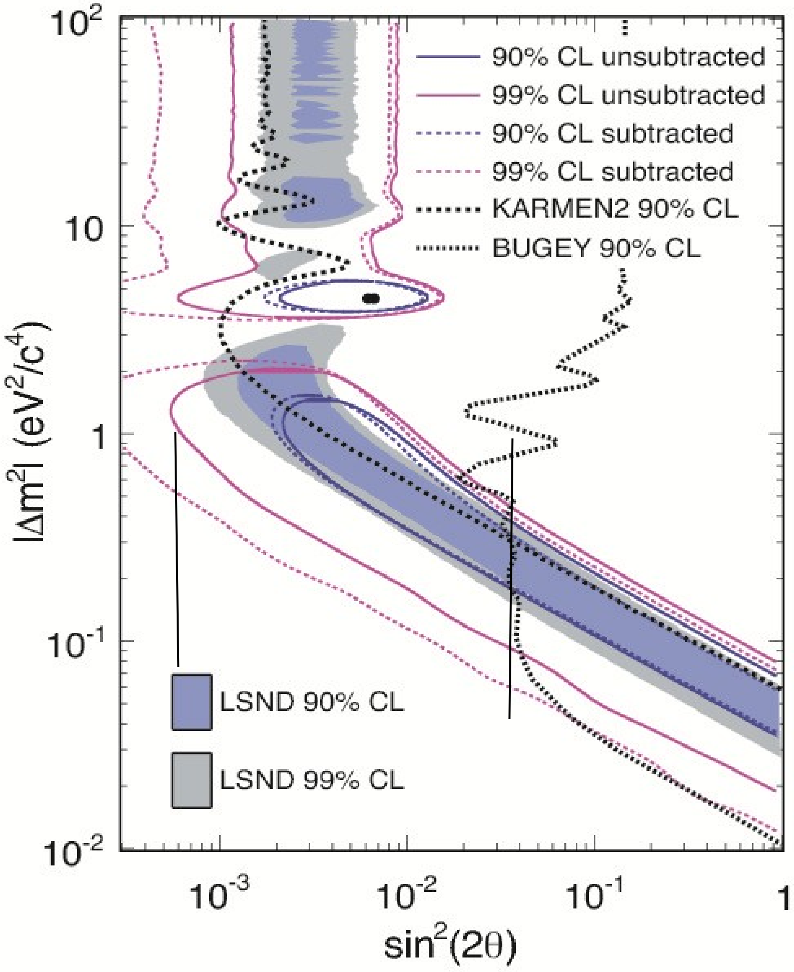
Depending on values of parameters, $U_{\mu 4}$, $U_{\tau 4}$, Δm_{42}^2 large variety of zenith angle distribution can be obtained.

With present data only part of the parameter space relevant for LSND/MiniBooNE can be excluded and in some ranges the fit can be even improved.

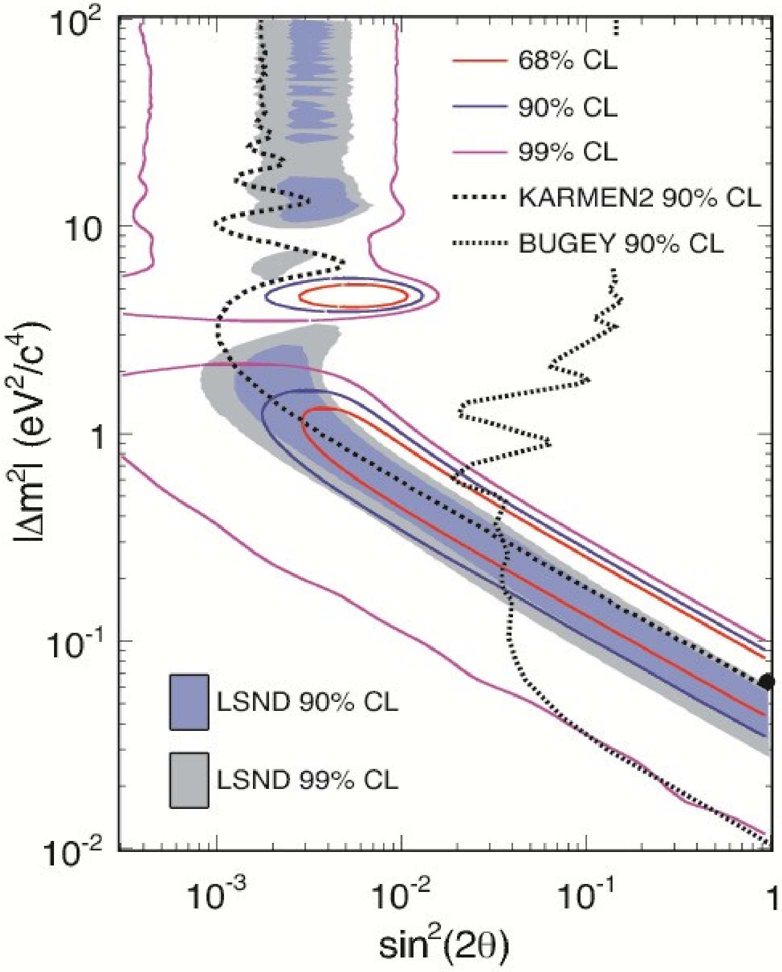
Future high statistics studies of the zenith angle distributions in different energy regions (with different energy thresholds) can provide sensitive search of sterile in whole parameter space and discriminate different mixing scenarios.

MINOS bound

E = 200 MeV



E = 475 MeV



Dependence on mixing scheme

In general,
the Hamiltonian

$$H = \Delta_0 V_0 \times V_0^T + \Delta_2 V_2 \times V_2^T$$

$V_i^T = (U_{Si} , U_{\tau i} , U_{\mu i})$, $\Delta_i = \Delta m_{i3}^2 / 2E$ $(i = 0, 2)$

In the lowest
order at high
energies

$$H \sim \Delta_0 V_0 \times V_0^T \qquad V_0^T = (U_{S0} , U_{\tau 0} , U_{\mu 0})$$

$$P(\nu_\mu \rightarrow \nu_\mu) \sim | \sin^2\theta' A_{33}(\alpha) + \cos^2\theta' |^2$$

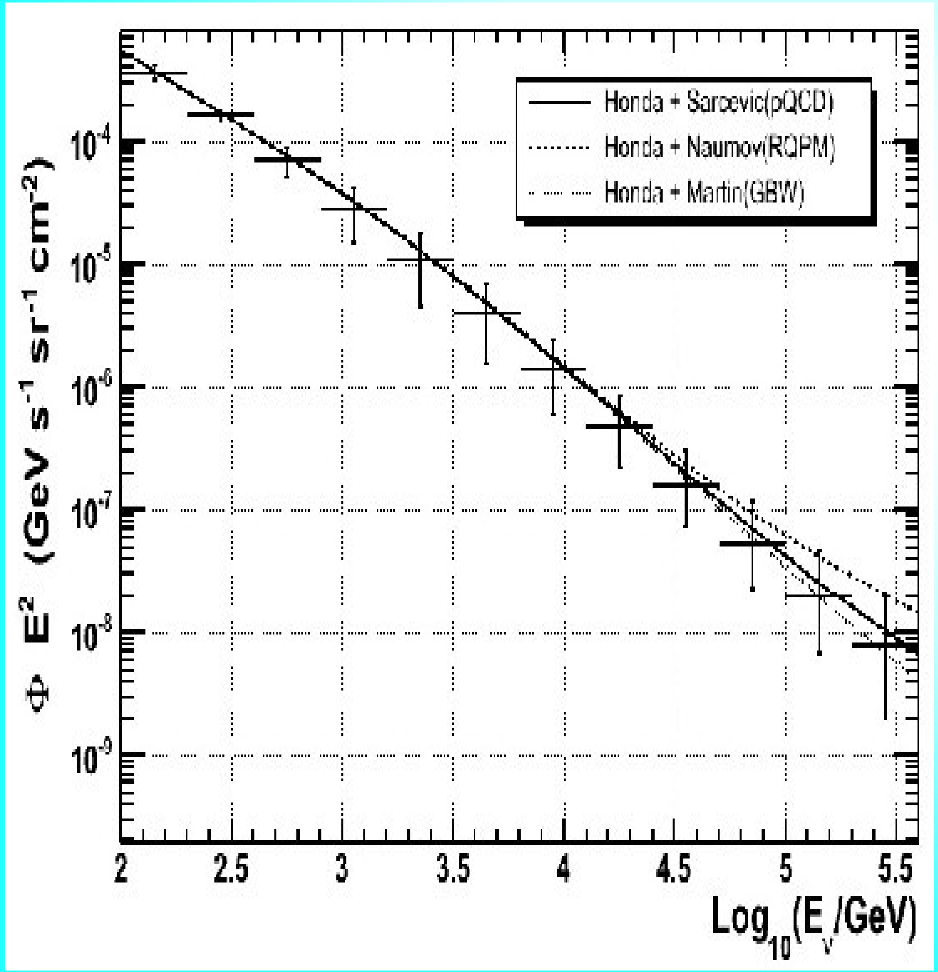
$\tan\theta' = - U_{\mu 0} / U_{\tau 0}$

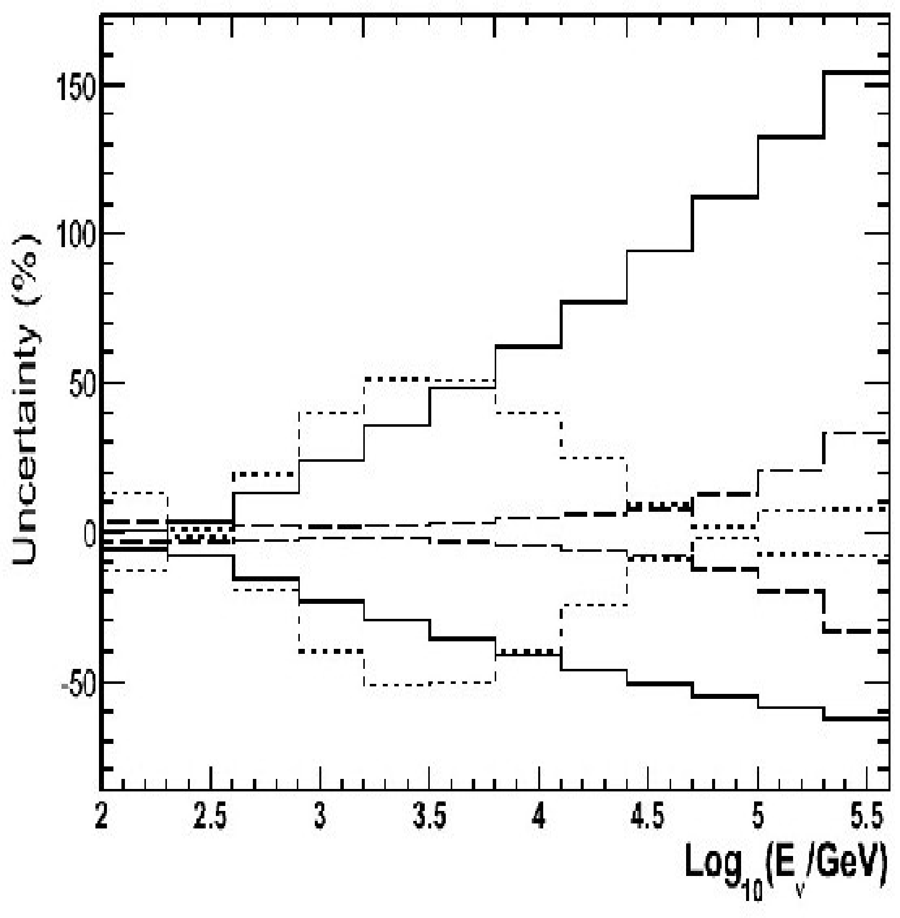
$\sin^2\alpha = |U_{\mu 0}|^2 + | U_{\tau 0}|^2$

$|U_{\mu 0}|^2 \sim 0.02 - 0.04$ $\Delta m_{03}^2 = 1\ \mathrm{eV}^2$ LSND/MiniBooNE

$|U_{\tau 0}|^2 < 0.5$ MINOS, Atmospheric neutrinos

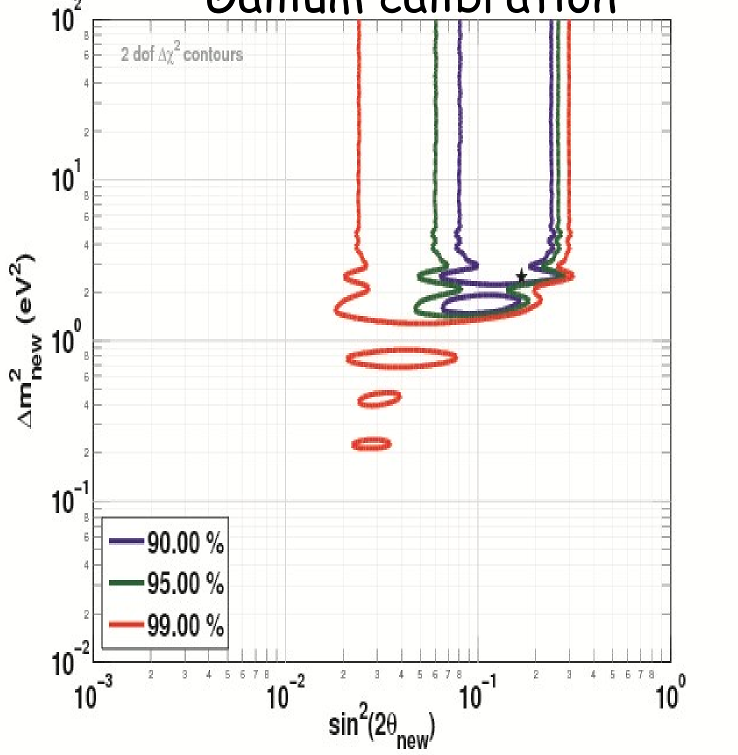
Fluxes


Honda + Sarcevic(pQCD)
Honda + Naumov(RQPM)
Honda + Martin(GBW)
$\Phi\ E^2$ (GeV s^{-1} sr^{-1} cm^{-2})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
2
2.5
3
3.5
4
4.5
5
5.5
$Log_{10}(E_\nu/GeV)$

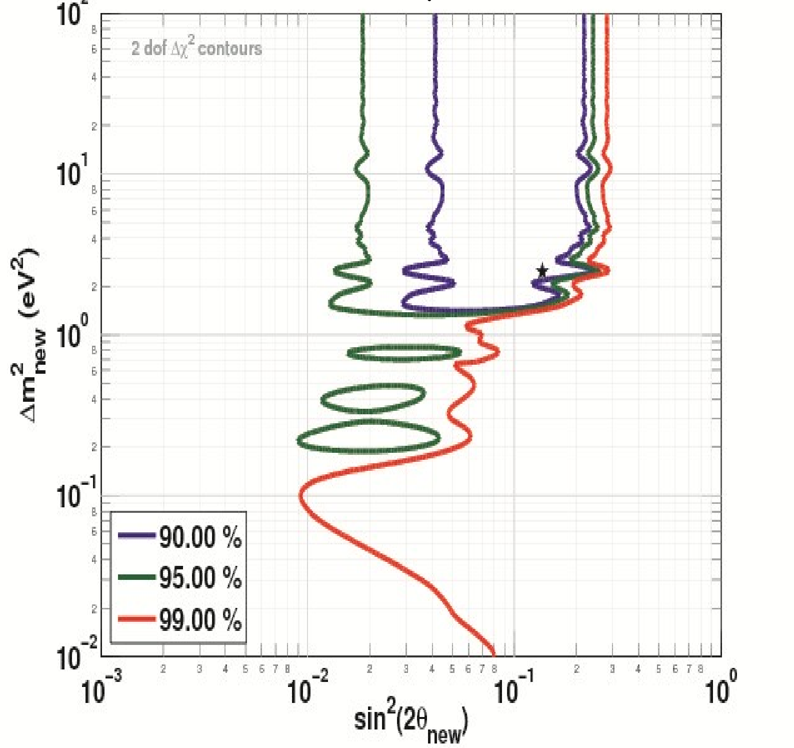

Uncertainty (%)
150
100
50
0
-50
2
2.5
3
3.5
4
4.5
5
5.5
$Log_{10}(E_\nu/GeV)$

Gallium anomaly

Gallium calibration



Reactor, miniboone



Calibration

Gallex/GNO ^{51}Cr
SAGE ^{51}Cr, ^{37}Ar

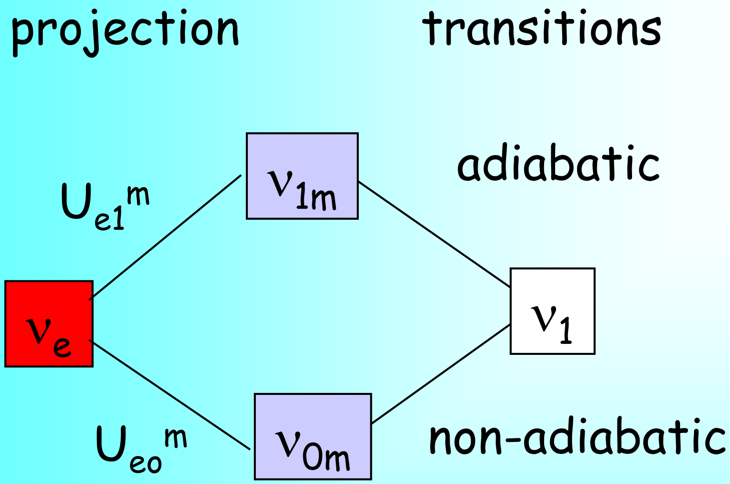
G.Mention et al,
arXiv: 1101.2755

R_{Ga} = 0.87 +/- 0.05

C Giunti, M. Laveder

Wiggles

Interference of two amplitudes of transition



projection

transitions

U_{e1}^m

ν_e

ν_{1m}

adiabatic

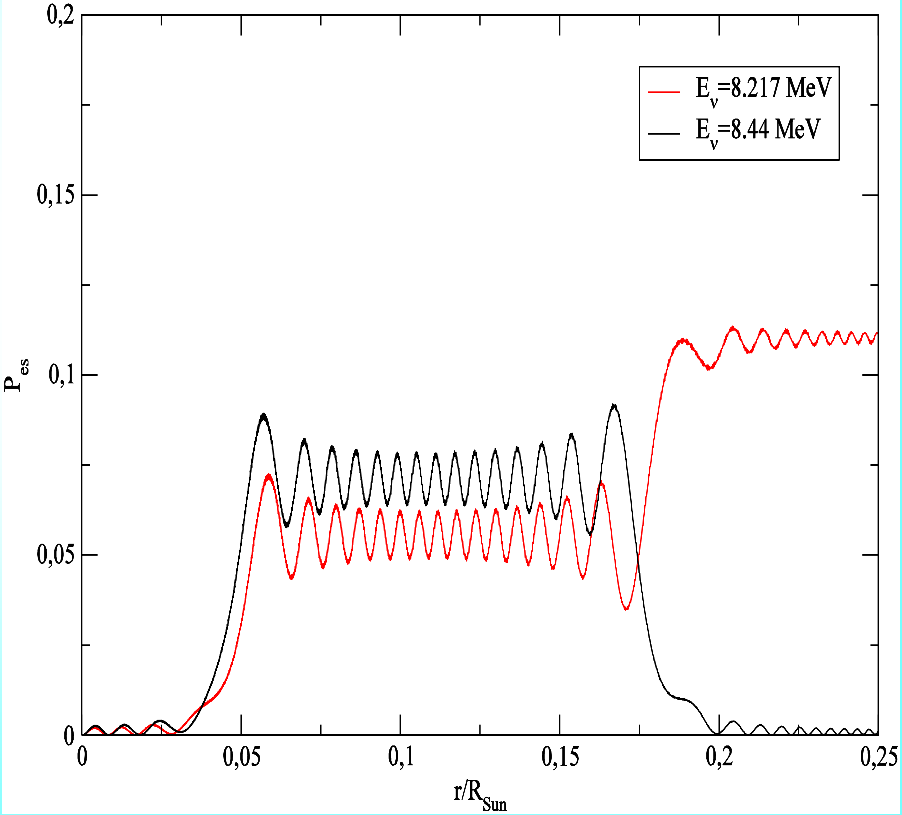
ν_1

U_{eo}^m

ν_{0m}

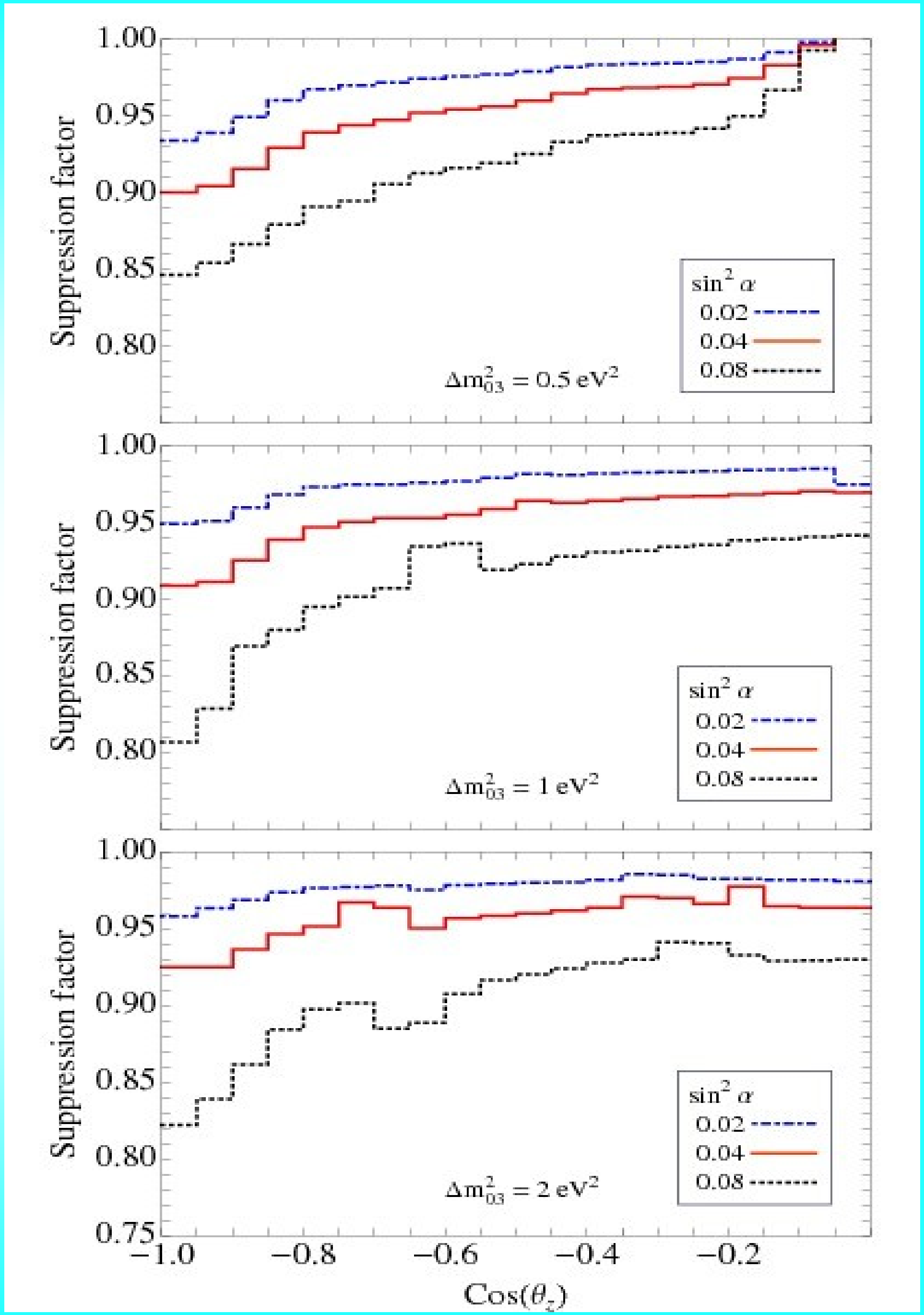
non-adiabatic

Evolution between two sterile resonances



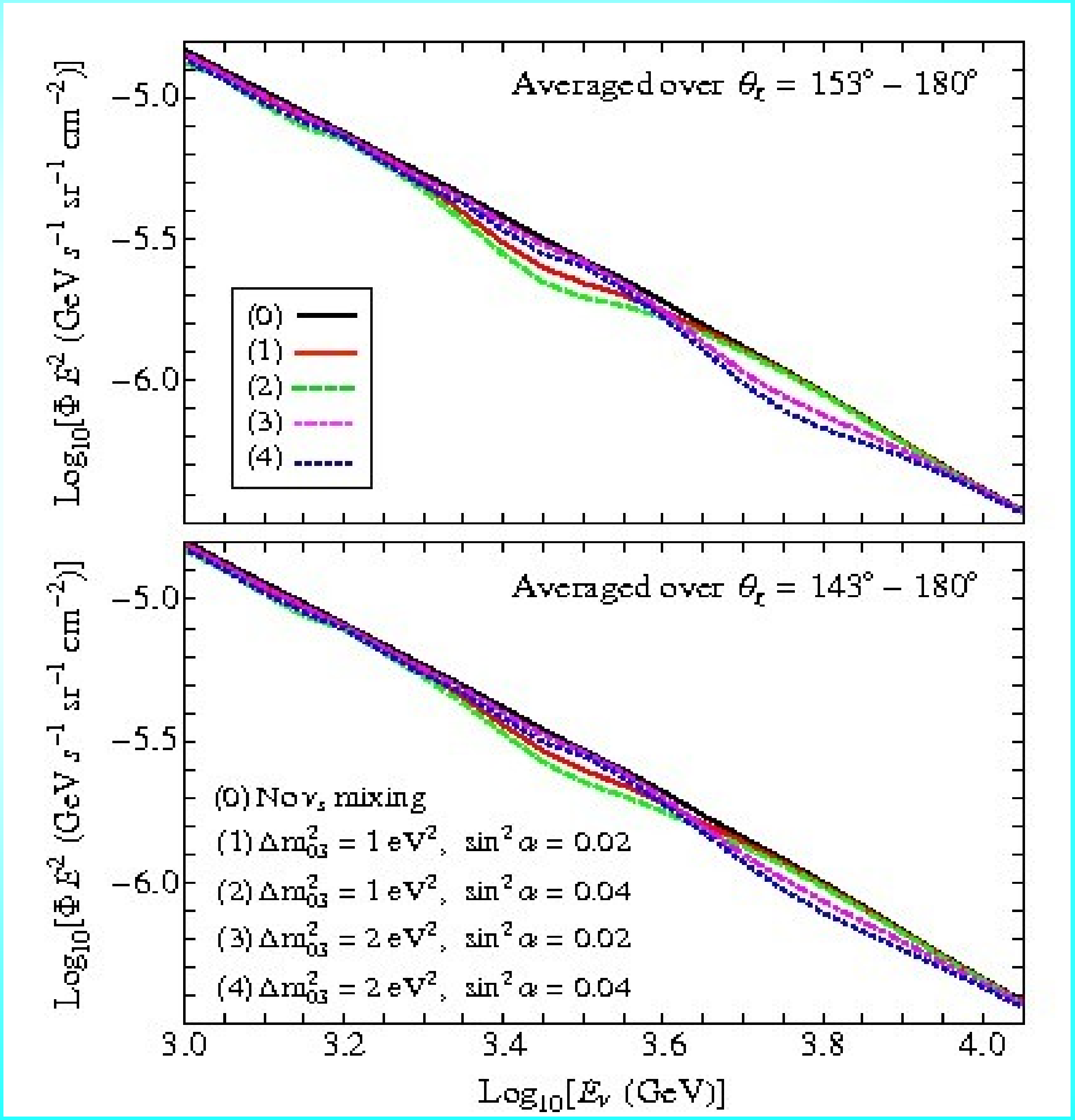
Suppression factor

E_{th} = 1 TeV



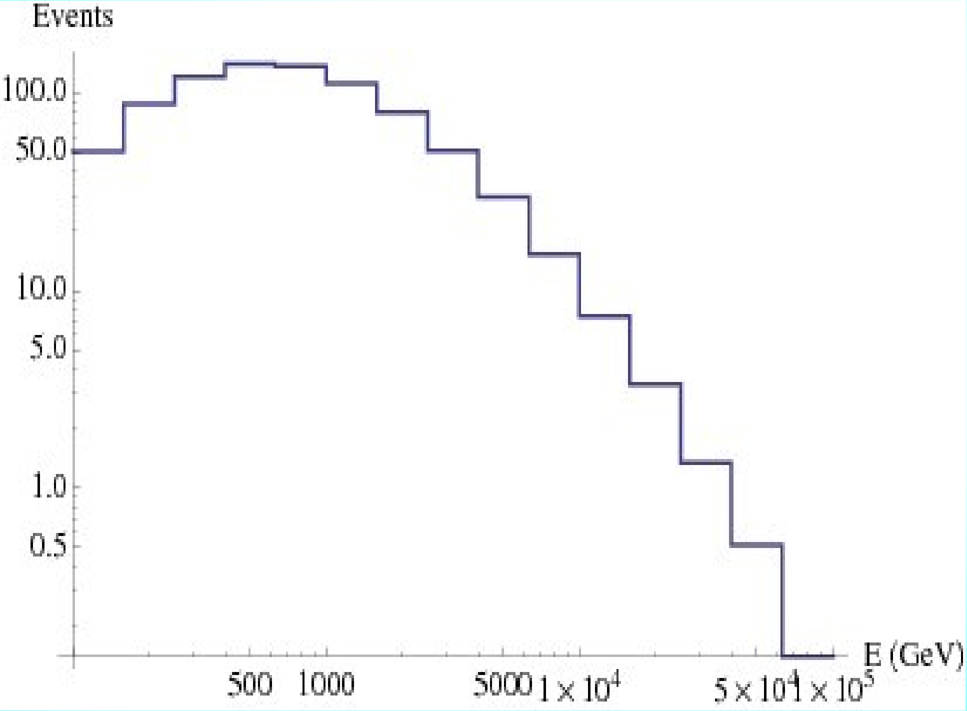
Energy spectra

Narrowing the zenith angle interval – enhances Effect→ 40 %



Number of events

$E\,F_\mu\,A_{eff}$



Flux of muon neutrinos:

$$F_\mu = F_\mu^0\,P_{\mu\mu} + F_e^0\,P_{e\mu} + $$

$$+ F_\mu^0\,P_{\mu\tau}(kE)\,B_\mu$$

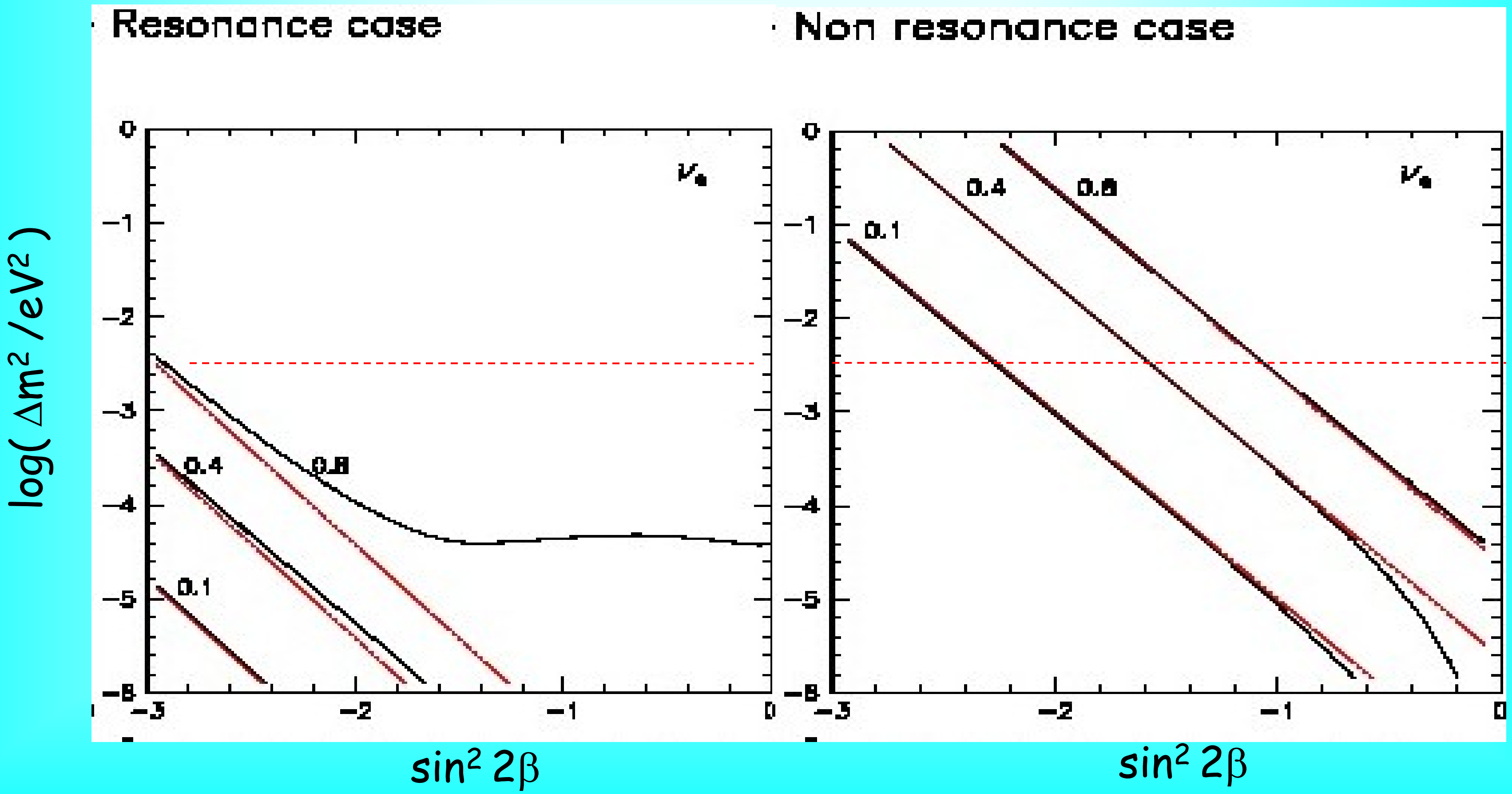
$$\sim F_\mu^0\,P_{\mu\mu}$$

Production of sterile in the Early universe

$\Delta N_{eff} = 0.8 - 1$

can be generated

A D Dolgov, F L Villante



Probabilities for different mixing schemes

$$\sin^2\beta = \begin{cases} 0.5 & \nu_S \text{ - mass mixing} \\ 1.0 & \nu_S - \nu_\mu \text{ -mixing} \end{cases}$$

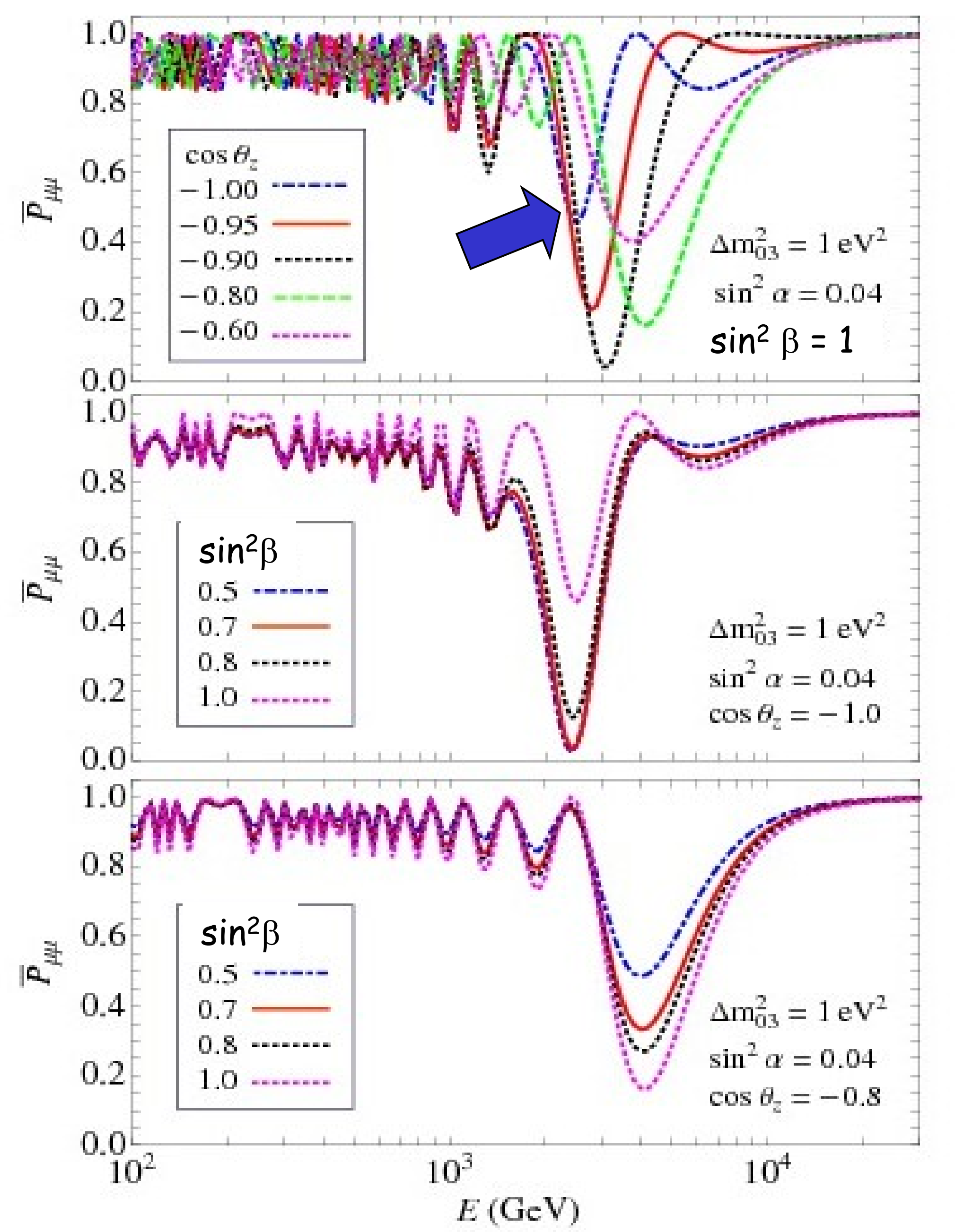
no strong suppression in vertical bin

With increase of $|U_{\tau 0}|^2$

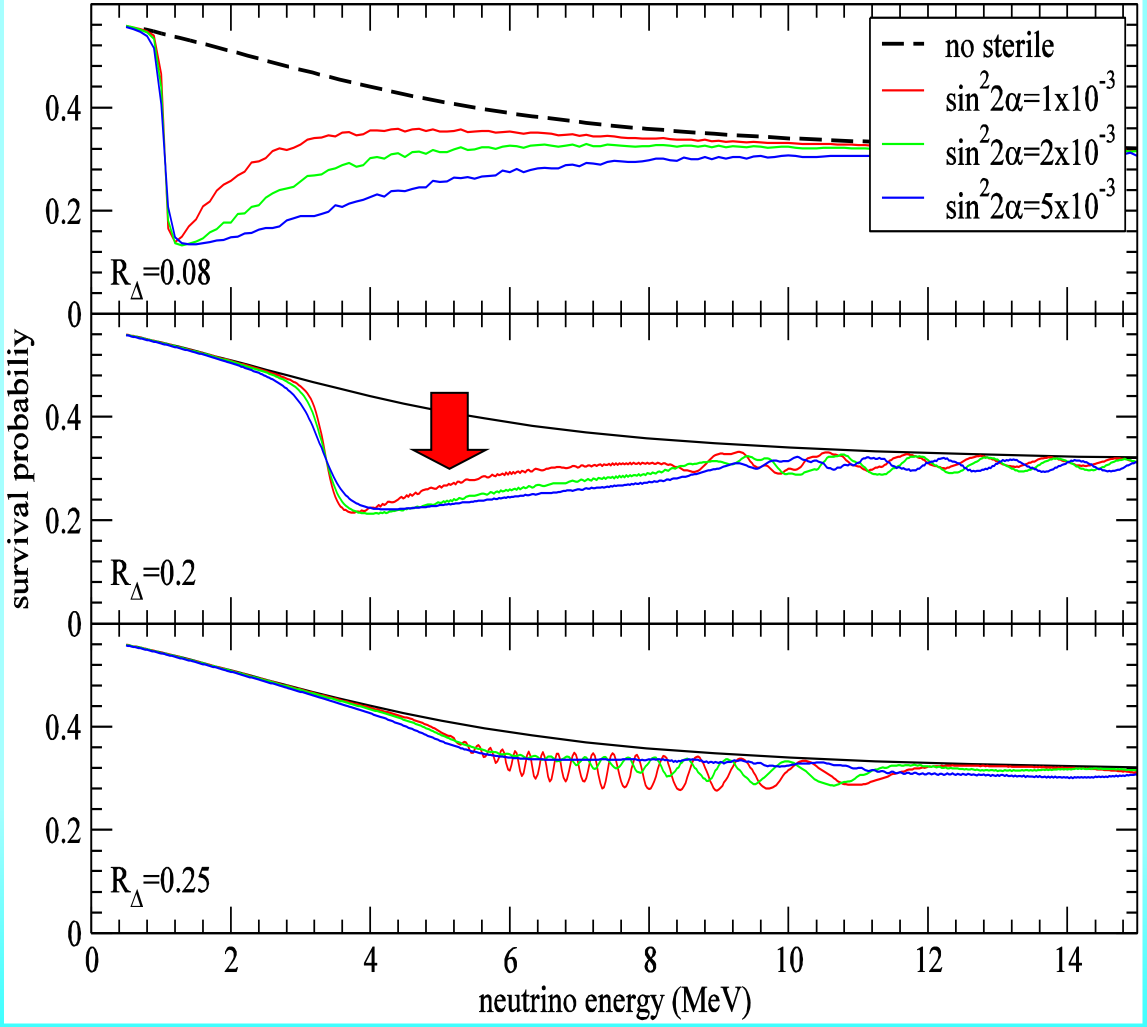
$\sin^2\beta$ decreases

$\sin^2\alpha$ increases, resonance disappears

distortion of the E and θ_Z distributions becomes weaker



Survival probability

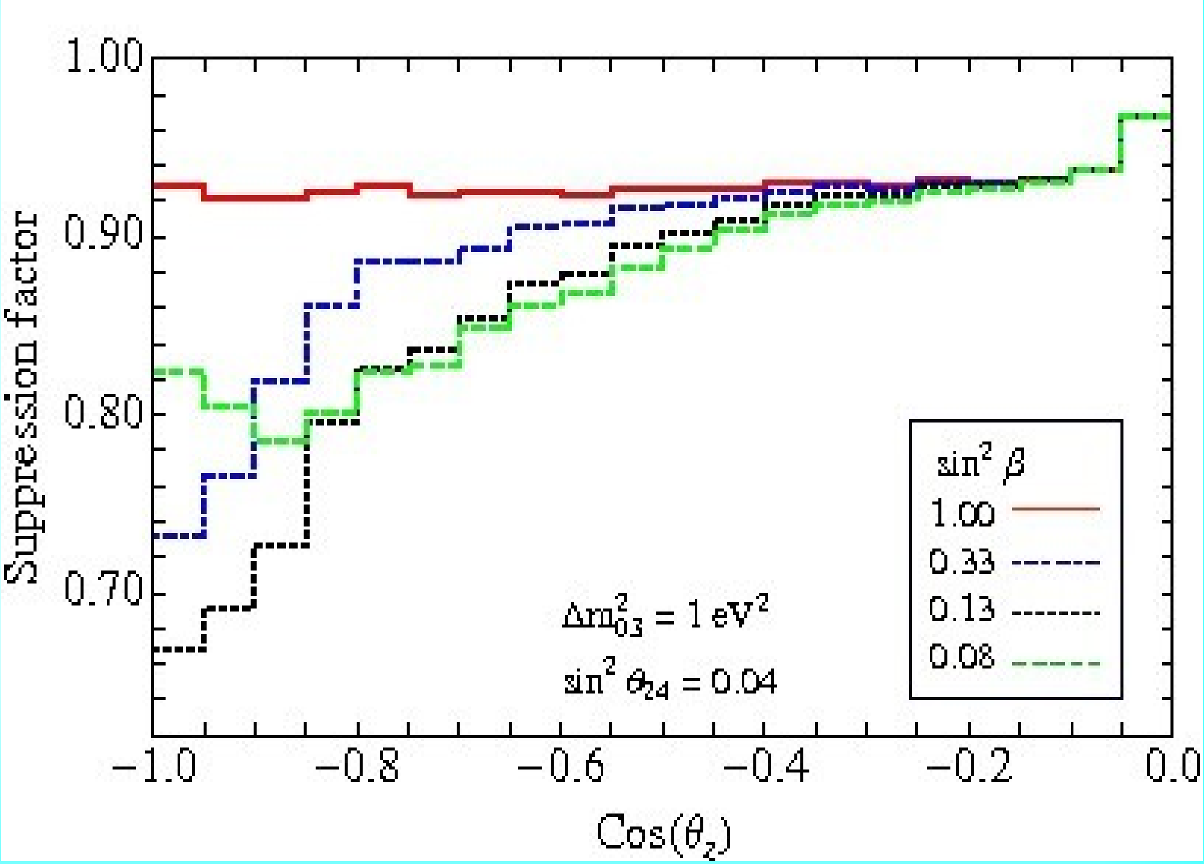


Zenith angle distributions

For different mixing schemes

Varying $|U_{\tau 0}|^2$

$$\sin^2\beta = \frac{s_{24}^2}{s_{24}^2 + s_{34}^2}$$



Probabilities