Hunting for Sterile neutrinos

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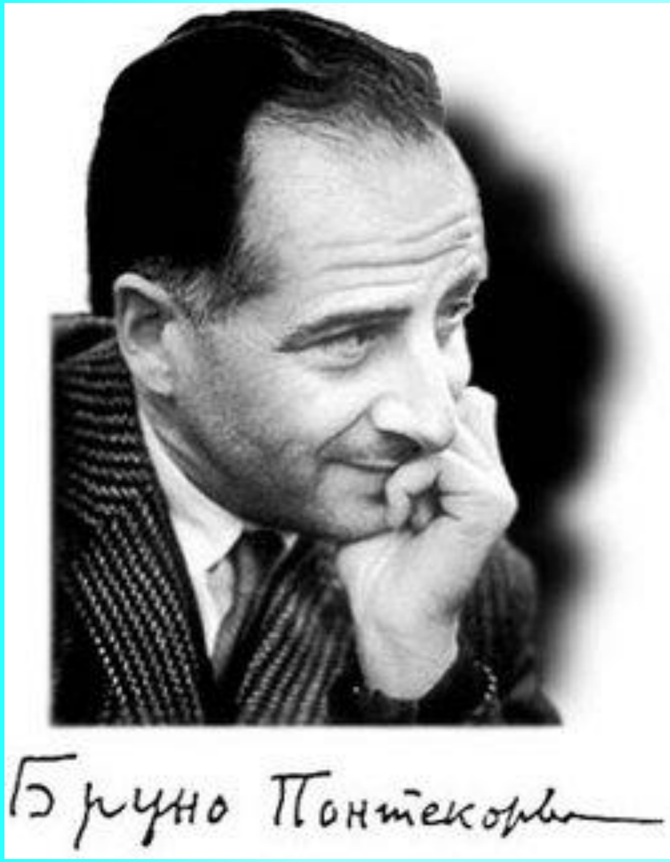
Kyoto, November 24, 2011,

Sterile neutrino ν_s



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?

Plan:

1. Motivations, status
2. The Sun: shining in sterile
3. Searching for sterile in ice

1. Motivations & Status

Mass scales

ν_s

Scale	Mass range	Phenomenology
	40 - 70 MeV	- LSND, MiniBooNE
1 MeV		
	1 - 10 keV	- Warm Dark matter - Pulsar kick
1 keV		
1 eV	0.5 - 2 eV	- LSND, MiniBooNE - Reactor anomaly - Ga-calibration experiments - Extra radiation
10^{-3} eV	$(2 - 4)\ 10^{-3}$ eV	- Solar neutrinos - Extra radiation in the Universe

rich phenomenology

Sterile neutrinos as a solution to all neutrino problems

Juha Peltoniemi: hep-ph/9506228

- Neutrino – antineutrino oscillations
- 17 kev neutrinos
- Dark energy and mass varying neutrinos
- solar, atmospheric neutrinos
- OPERA

Sterile neutrinos (effectively) propagate faster than light in 4D, ``short-cut'' in extra dimensions

H Pas, S Pakvasa, T Weiler hep-ph/0504096

Problem

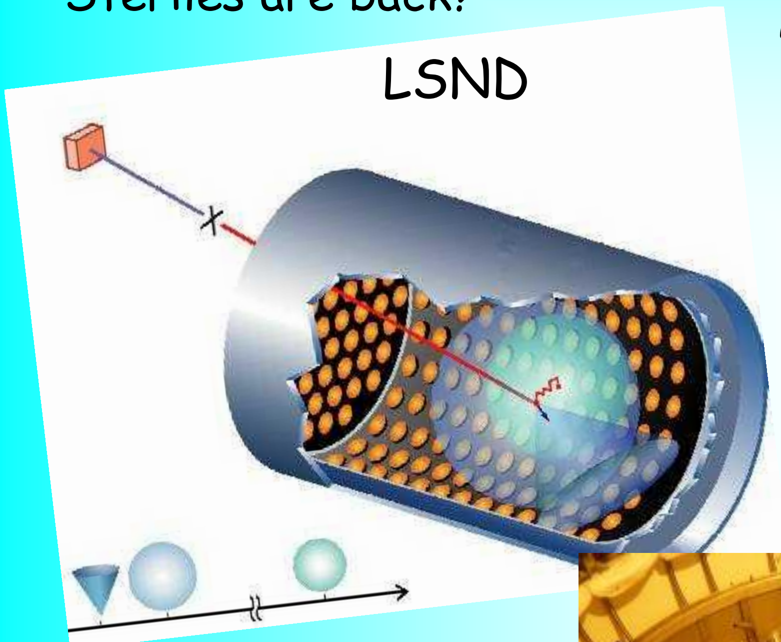
Only small part of neutrino flux (state) propagates faster than light or/and whole the ν_μ signal is strongly suppressed

contradicts OPERA result (especially the latest one with 3 ns neutrino bunches)

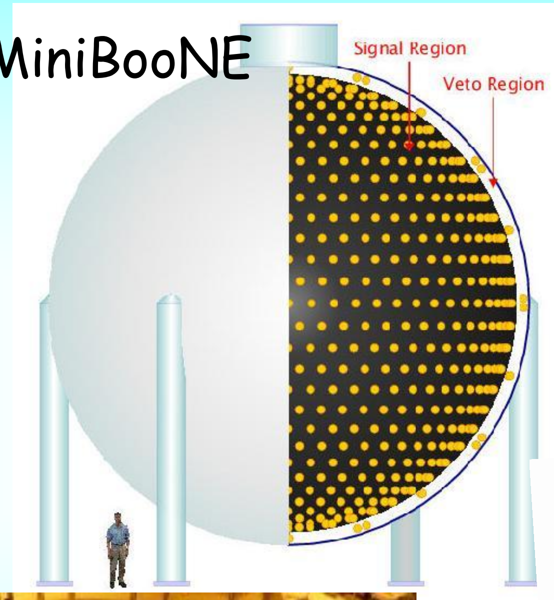
New evidences?

Steriles are back?

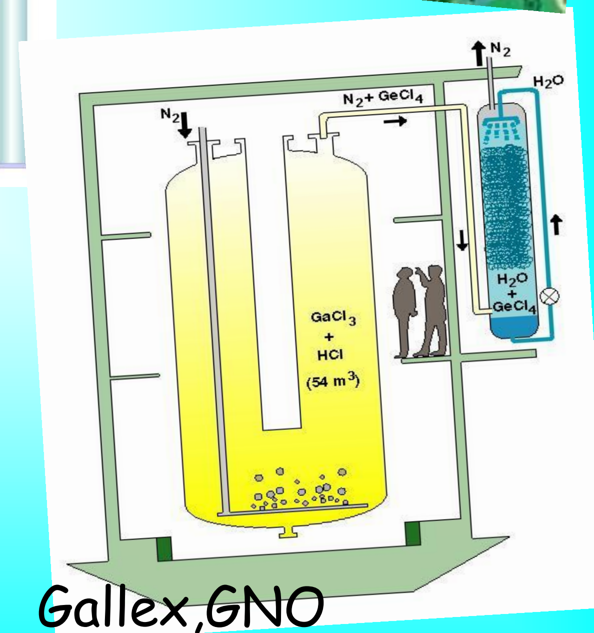
LSND

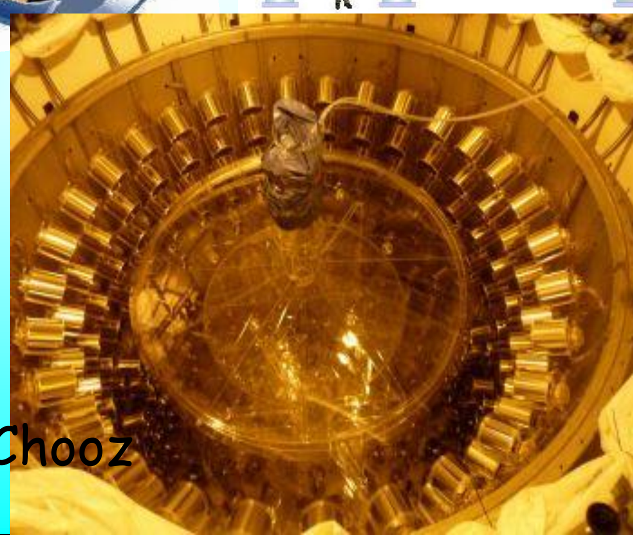


MiniBooNE



SAGE





Double-Chooz

Gallex,GNO

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]

$\Delta N_{eff} = (0.02 – 2.2)$ (68% CL)

J. Hamann et al PRL 105 (2010)181301

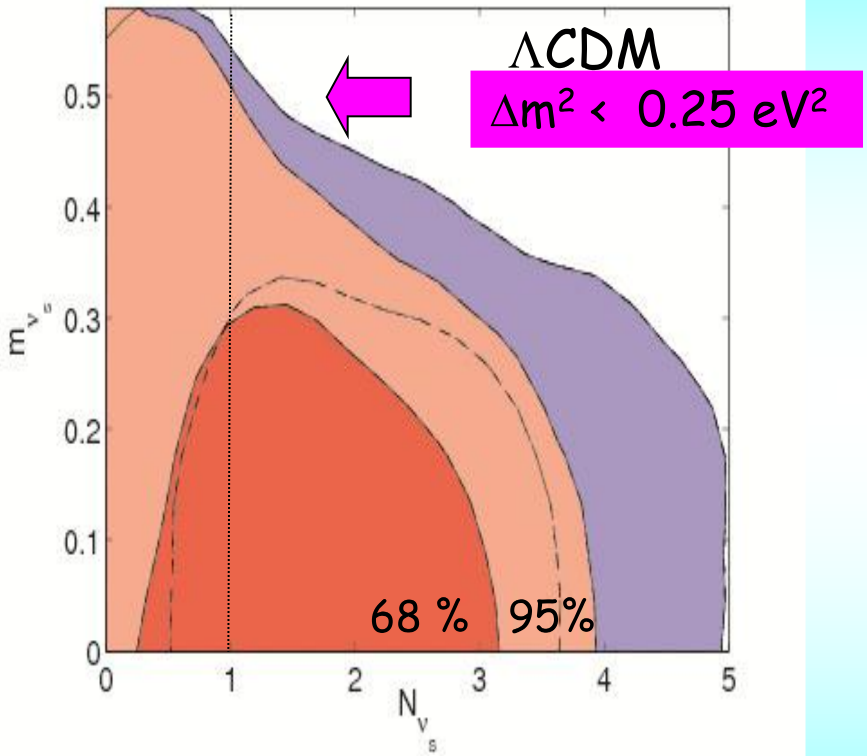
BBN

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

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

Cosmological bounds

E Giusarma et al 1102.4774 [astro-ph]



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

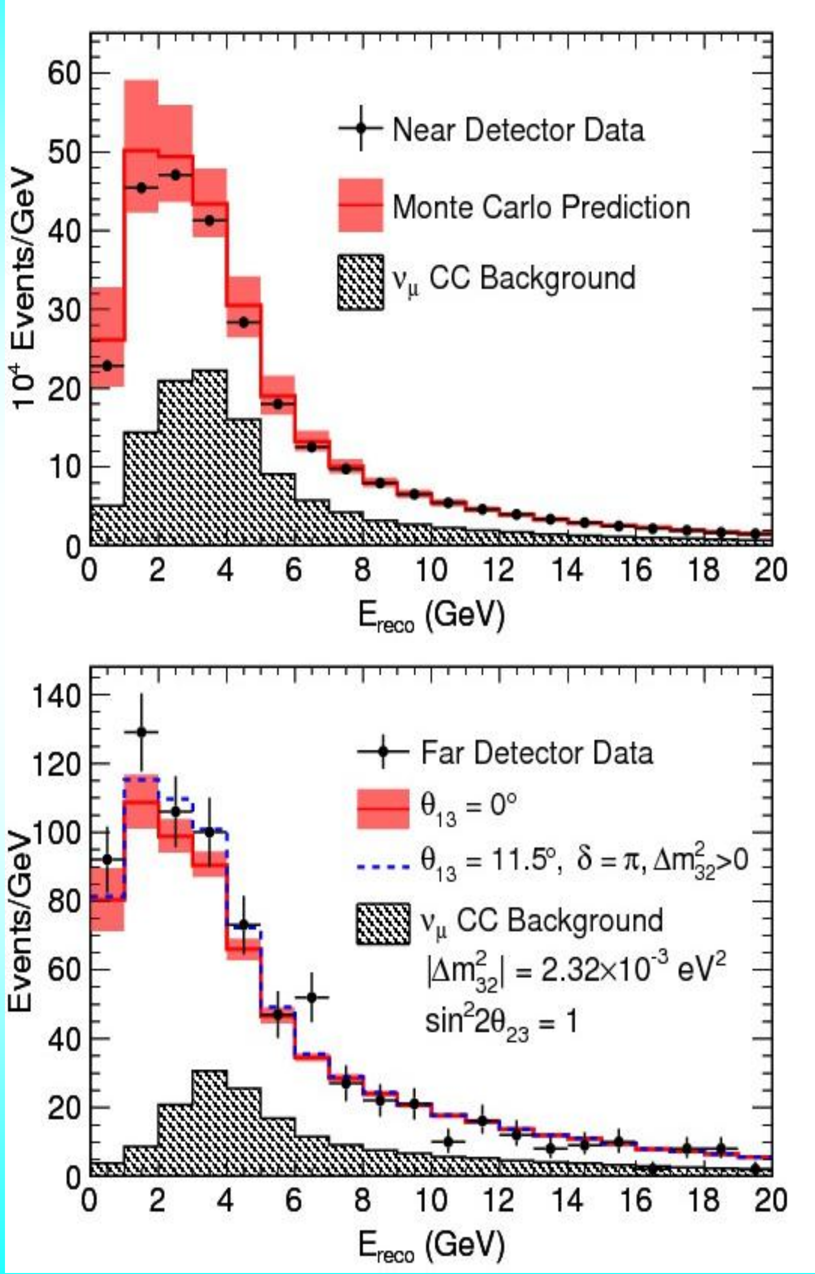
too young?

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

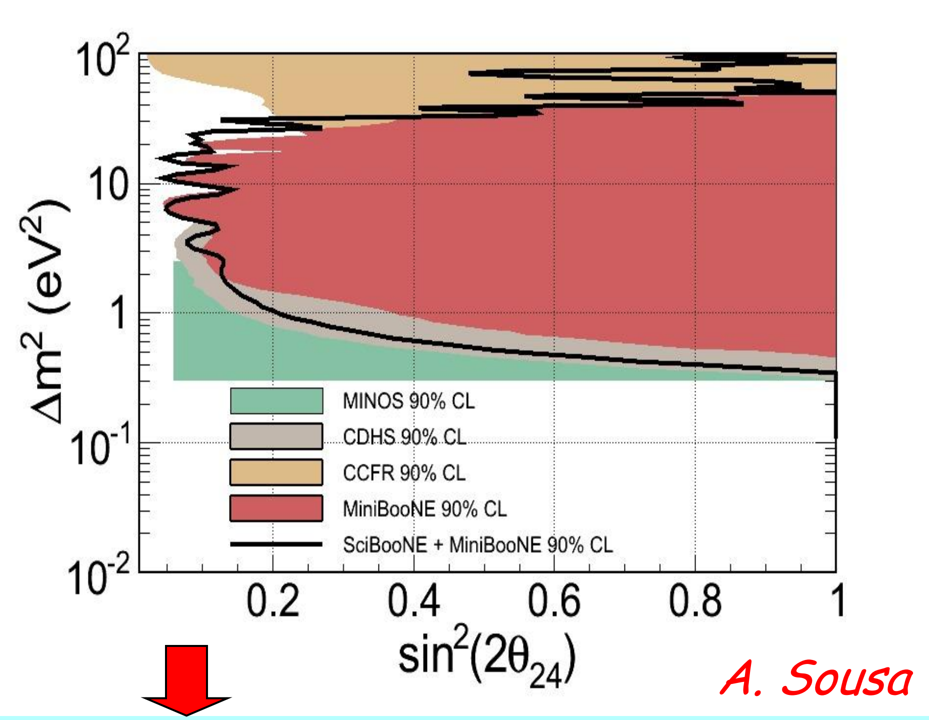
MINOS:

Searches for sterile

Accelerator neutrinos



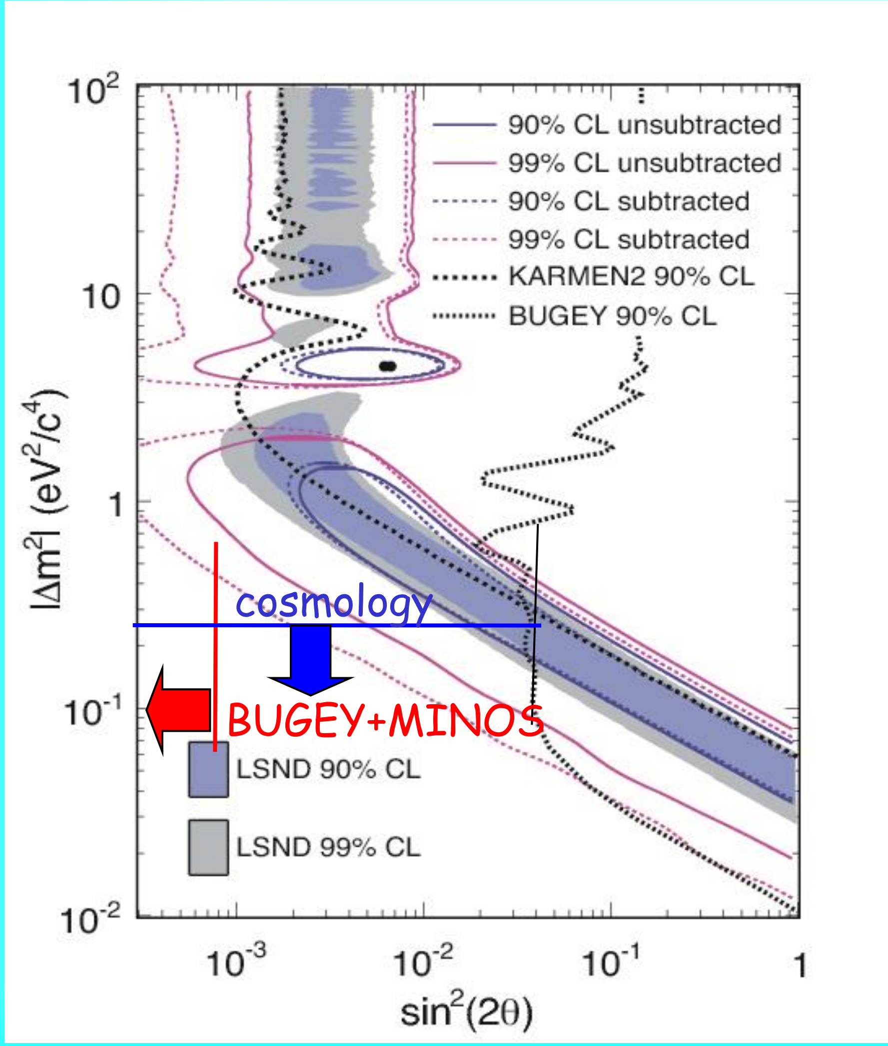
MINOS bound



$|U_{\mu 4}|^2 < 0.015$ (90% CL)

MINOS bound

ν_μ - ν_s mixing



In assumption of
no-oscillations in ND

$|U_{\mu 4}|^2 < 0.015$ (90% CL) $\theta_{13} = 0$

$|U_{\mu 4}|^2 < 0.019$ (90% CL) $\theta_{13} = 11.5^o$

LSND/MiniBooNE require:

$|U_{\mu 4}|^2 > 0.025$ $\Delta m_{41}^2 < 0.5\ eV^2$

or modification of Cosmology:

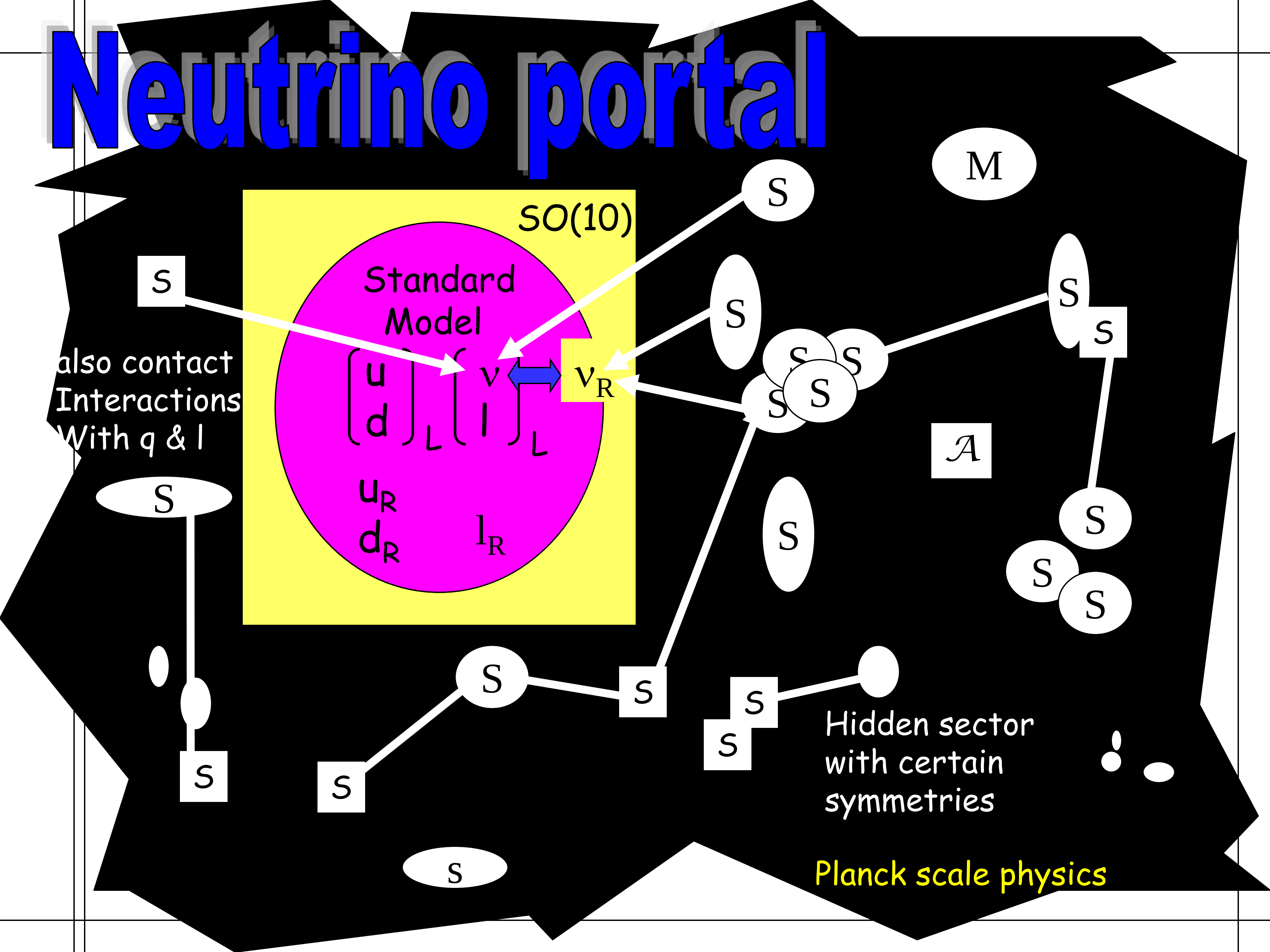
$\Delta N = 1.23$ (massless)

$\omega = -1.11$

chemical potential for ν_e

J Hamann et al 1108.4136

Neutrino portal



Theoretical implications

Mass matrix

ν_e	m_{ee}	$m_{e\mu}$	$m_{e\tau}$	m_{eS}
ν_μ	...	$m_{\mu\mu}$	$m_{\mu\tau}$	$m_{\mu S}$
ν_τ	...	...	$m_{\tau\tau}$	$m_{\tau S}$
ν_S	...	...	...	m_{SS}

For m_{SS} ~ 1 eV $\tan\theta_{jS} = m_{jS}/m_{SS}$ ~ 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

$$m_\nu = m_a + \delta m$$

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

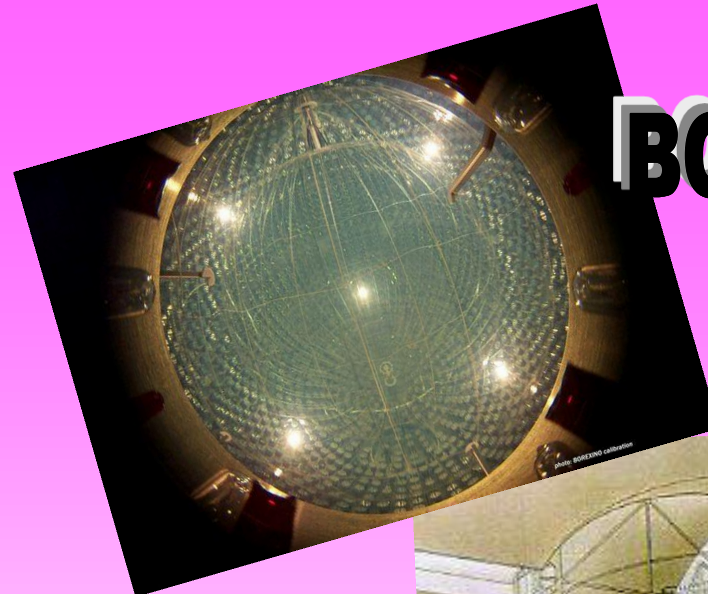
Be origin of difference of U_{PMNS} and V_{CKM}

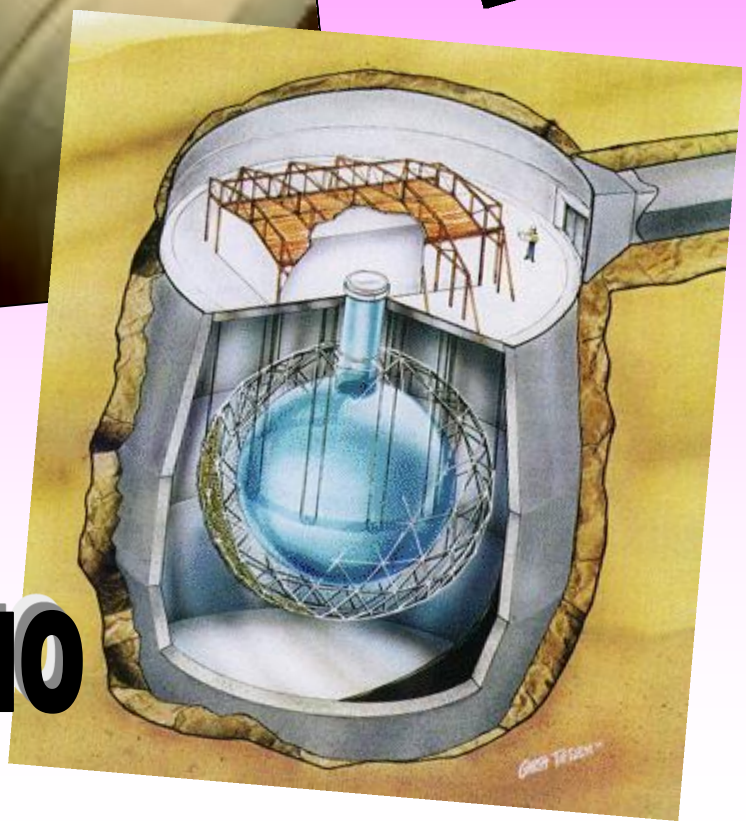
2. The Sun: shining in sterile

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

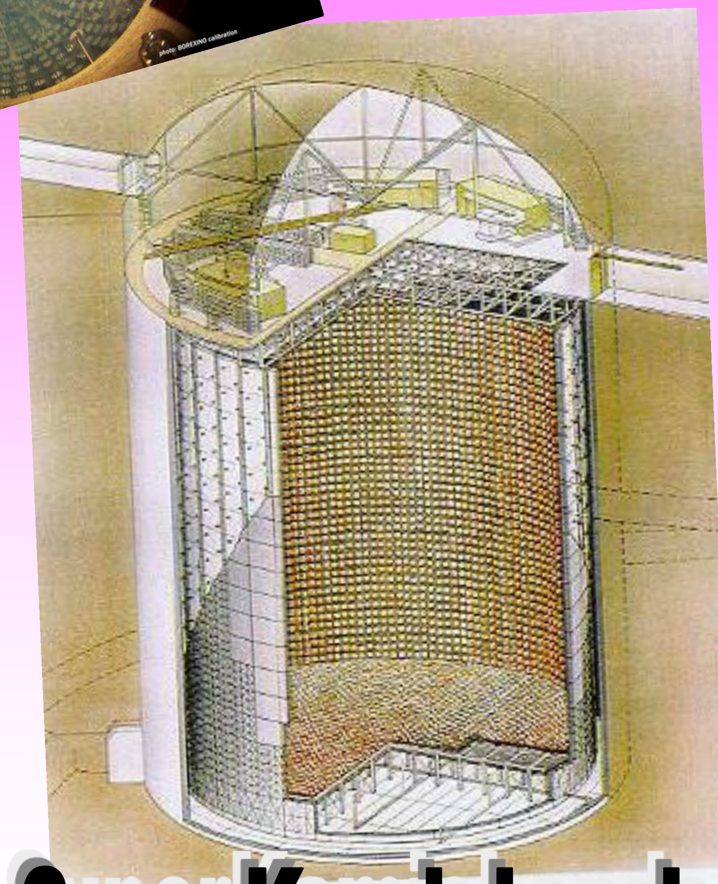
Homestake

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

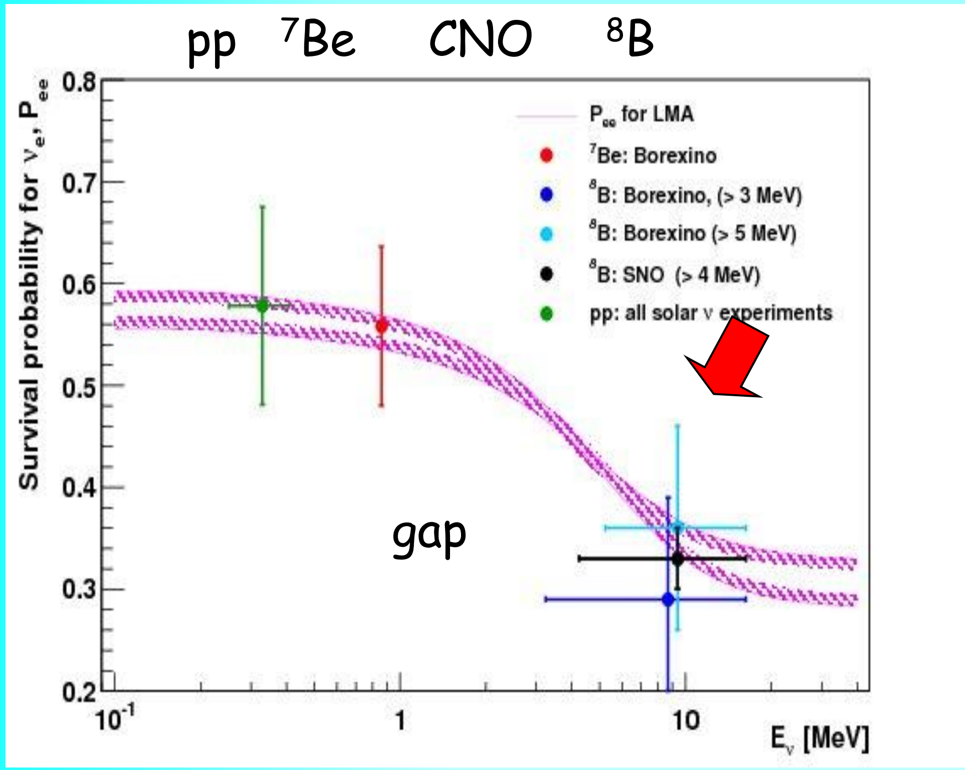
Light sterile neutrino $R_\Delta = \Delta m_{01}^2 / \Delta m_{21}^2 \ll 1$

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

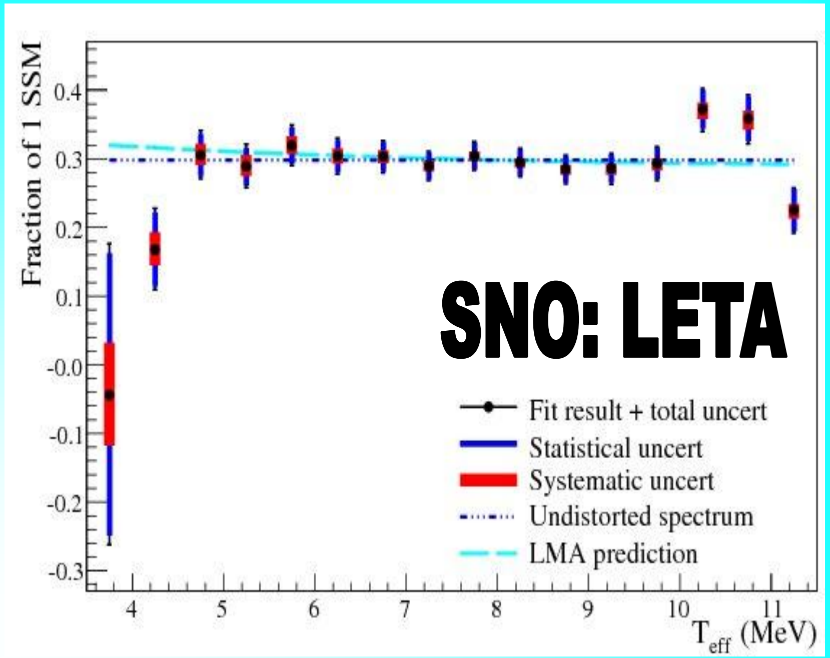
→ dip in survival probability

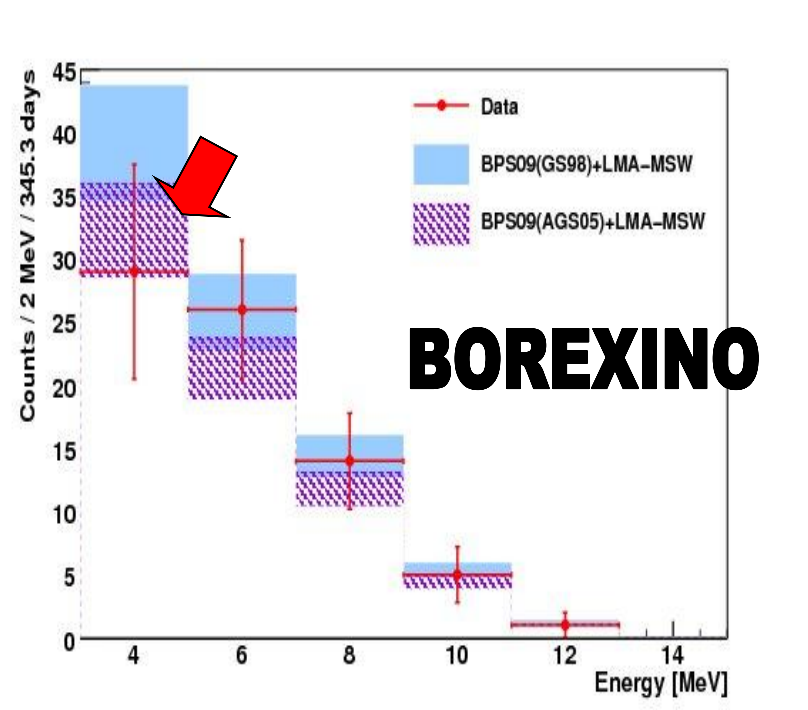
Motivation for the low energy solar neutrino experiments BOREXINO, KamLAND ...

Up-turn?



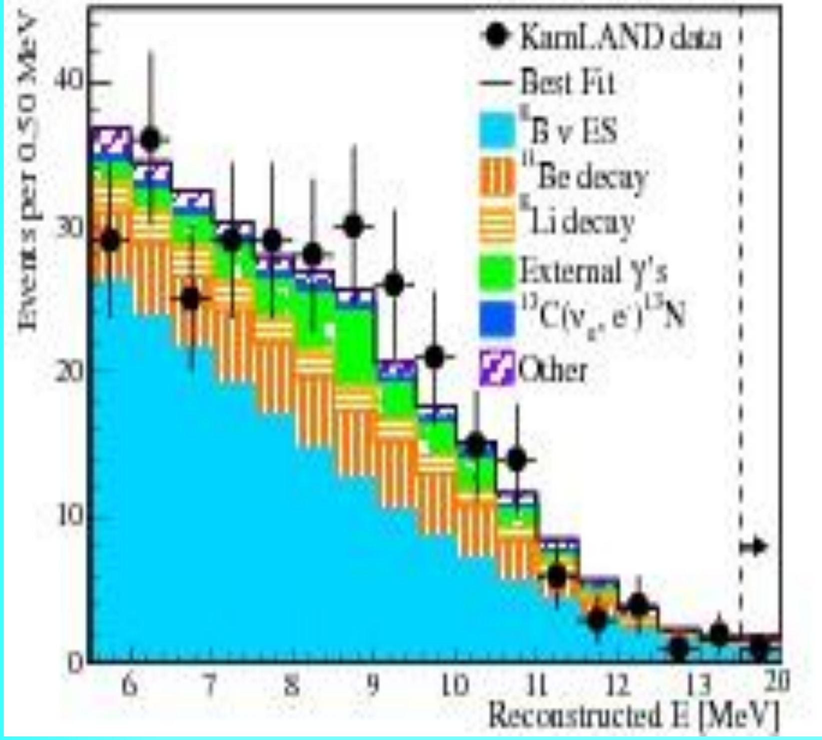
ν_e - survival probability from solar neutrino data vs LMA-MSW solution

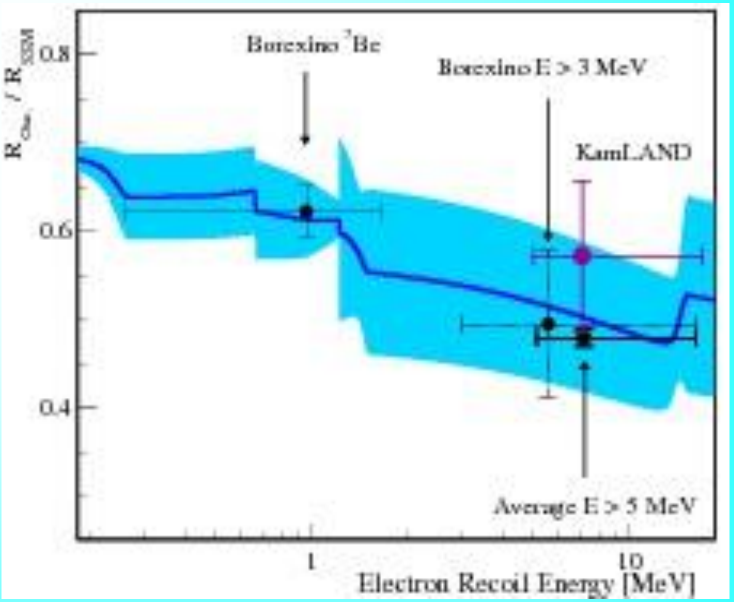




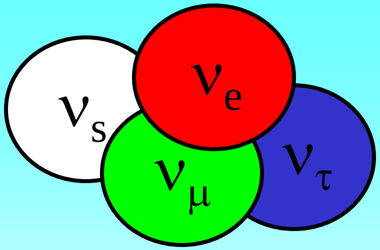
KamLAND solar

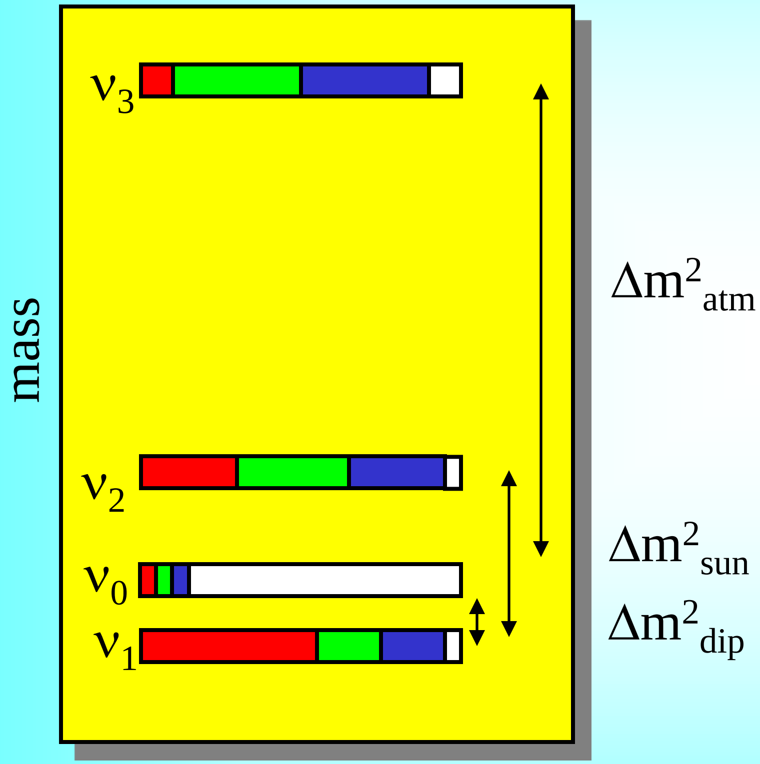
S. Abe, at al., [The KamLAND collaboration] 1106.0861 [hep-ex]





(3 + 1) scheme





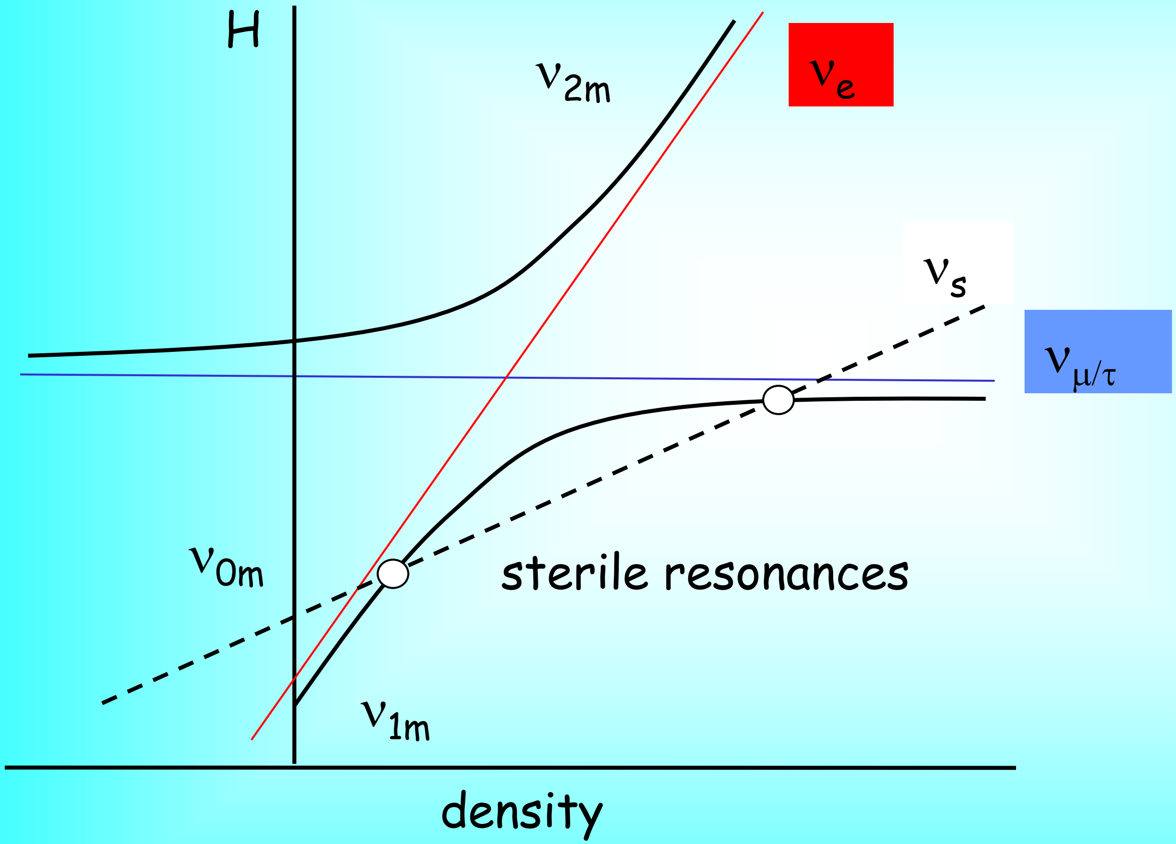
Very light sterile neutrino

Motivated by

- solar neutrino data

- additional radiation in the Universe if mixed in ν_3
- no problem with LSS (bound on neutrino mass)

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

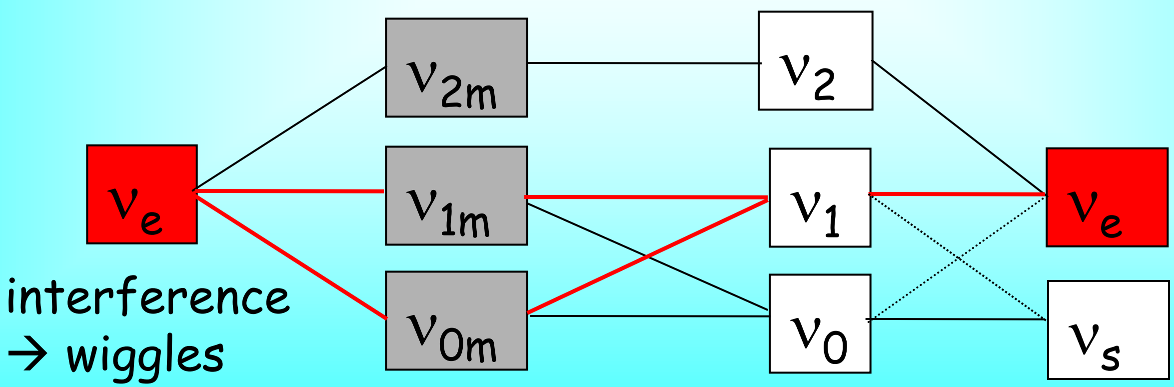
$$\begin{pmatrix} \nu_s \\ \nu_e \\ \nu_a \end{pmatrix} \qquad U = U_\theta \; U_\alpha \qquad \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \end{pmatrix}$$

U_θ - rotation in 12-plane on θ_{12}

U_α - rotation in 01- plane on α

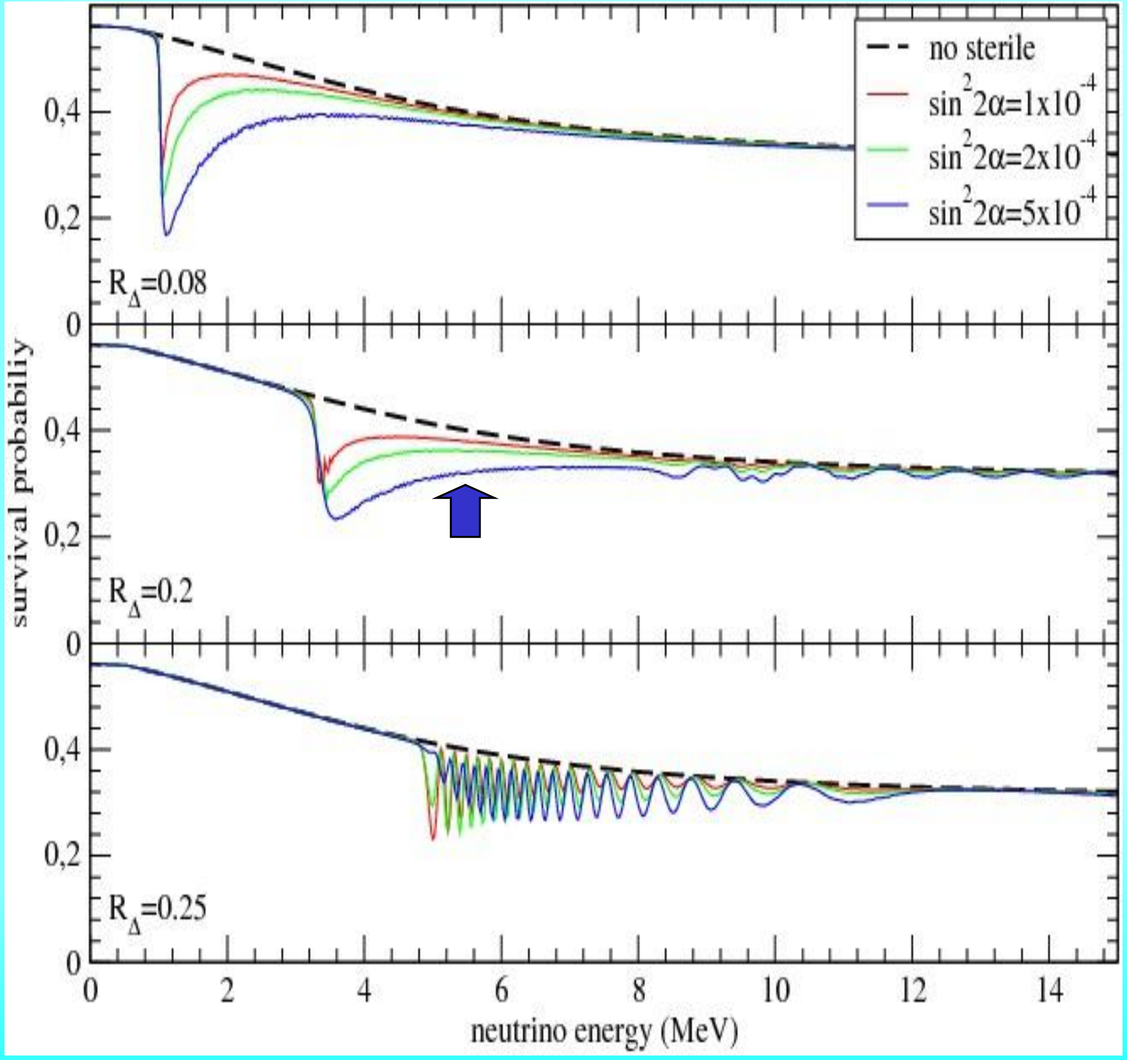
ν_s mixes in ν_0 and ν_1

Scheme of transitions



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

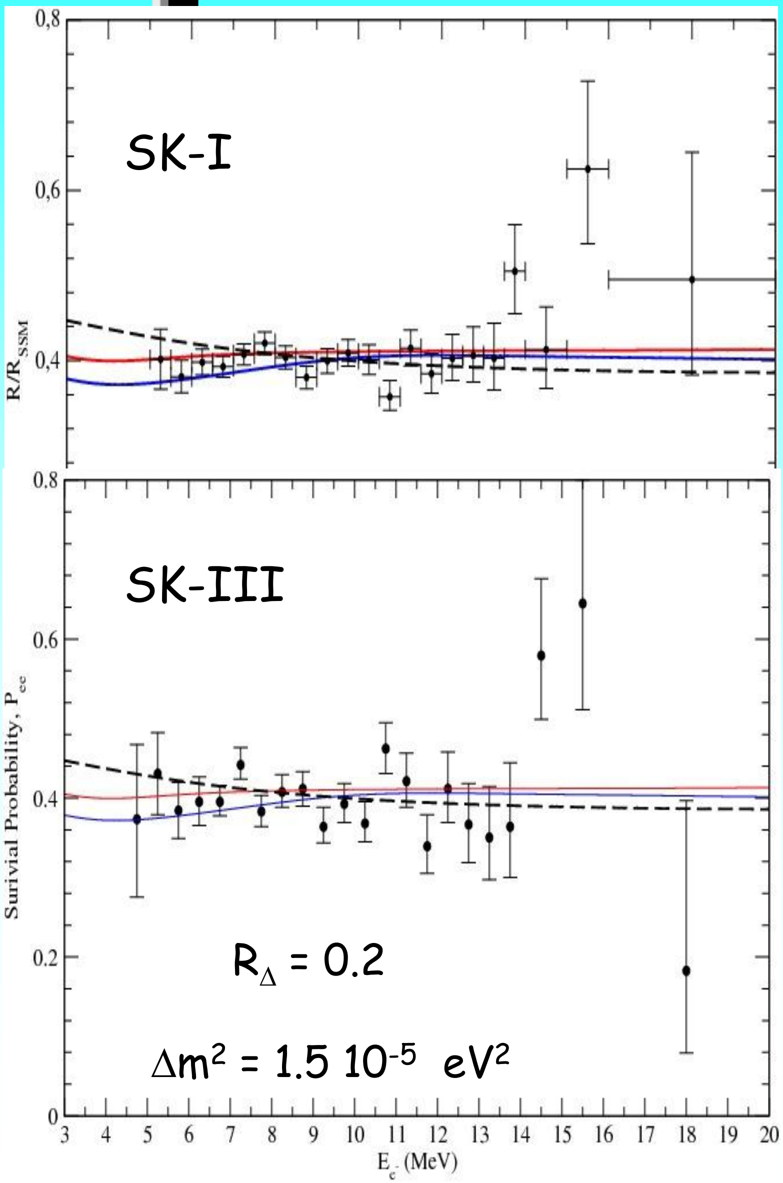
Survival probability

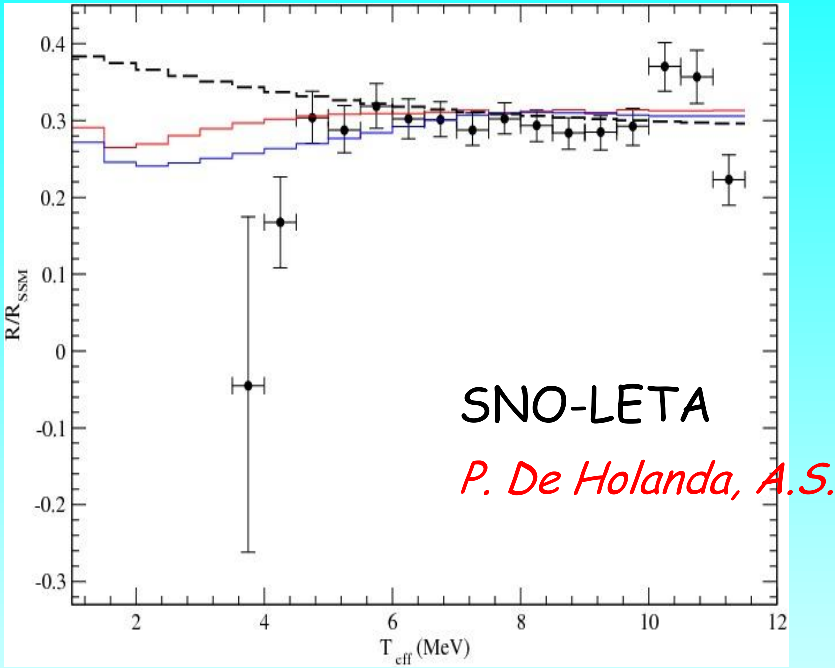


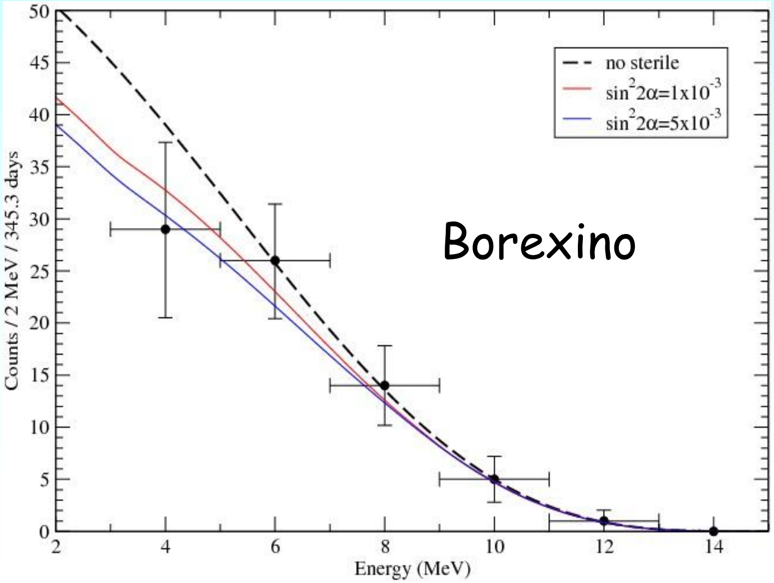
- dip
- wiggles

Spectra

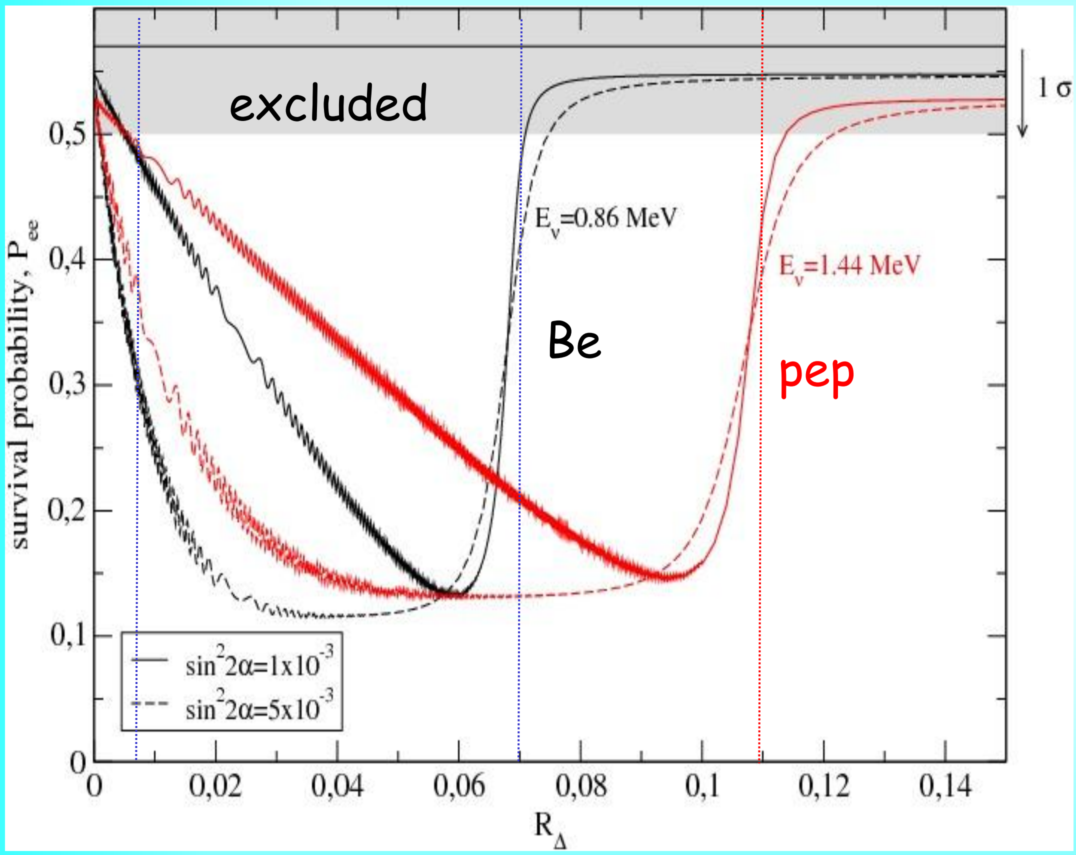
$\sin^2 2\alpha = 10^{-3}$ (red), $5\ 10^{-3}$ (blue)







BOREXINO: Be and pep-lines



data

Be excluded

R_Δ = 0.007 - 0.07

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

BOREXINO:

pep- flux is consistent with the LMA suppression

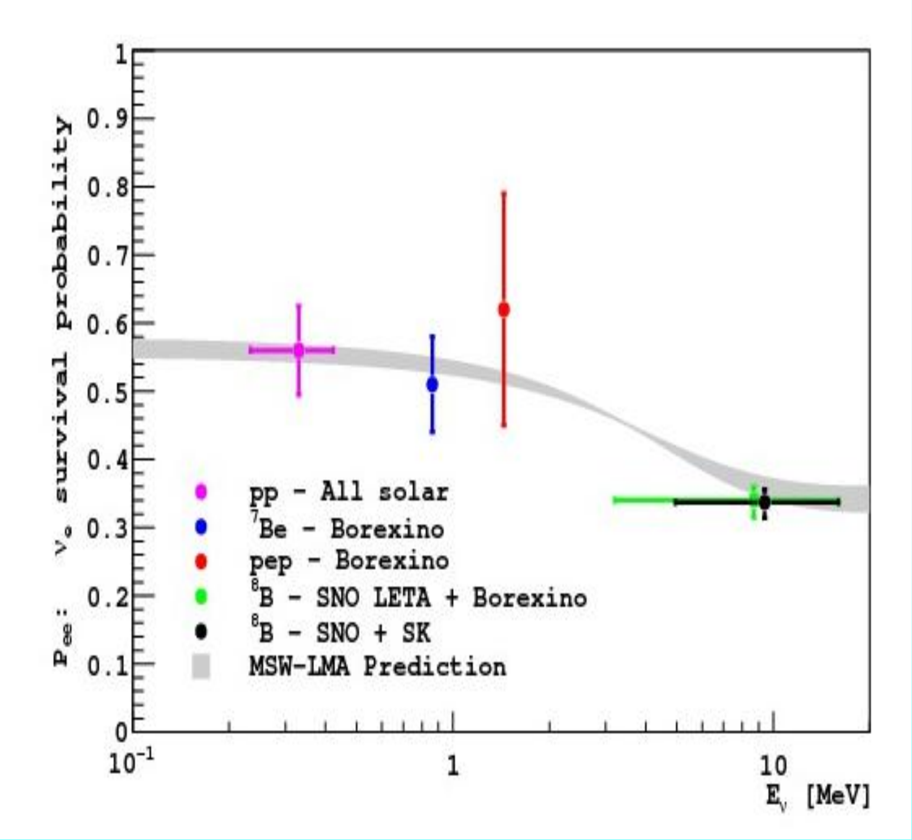
P(pep) = 0.53

$R_\Delta > 0.12$

$\Delta m_{01}^2 > 0.9\ 10^{-5}\ eV^2$

pep-neutrinos

BOREXINO Collaboration,
ArXiv: 1110.3230



Fit of spectra

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

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

Interval with $\Delta\chi^2 > 6$ $\Delta m_{01}^2 = (1 - 2)\ 10^{-5}\ eV^2$ $\sin^2 2\alpha \sim (0.5 - 1)\ 10^{-3}$

⇒ $m_0 > 0.003$ 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

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

$M \sim$ 2 - 3 TeV

mixing

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

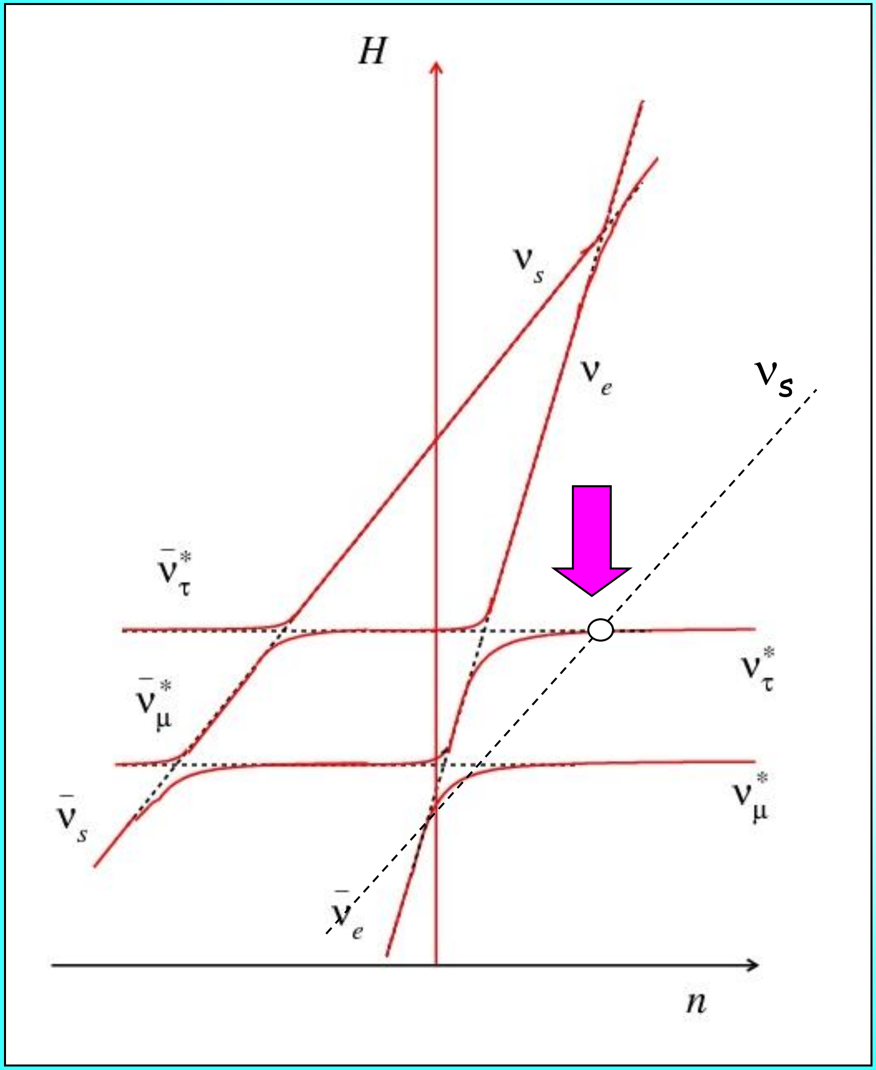
$$\alpha \sim \frac{h\, v_{EW}}{M}$$

$h = 0.1$

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

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

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

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

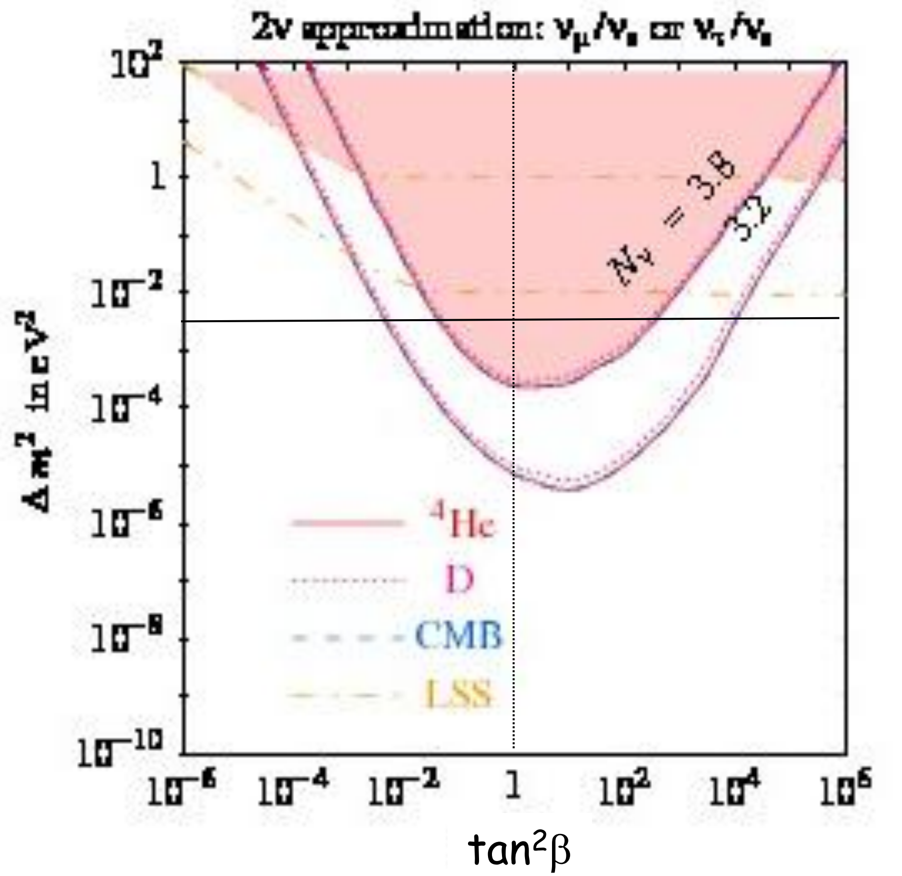
Atmospheric neutrinos:

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

MINOS:

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

M Cirelli G Marandella A Strumia F Vissani



Atmospheric neutrinos

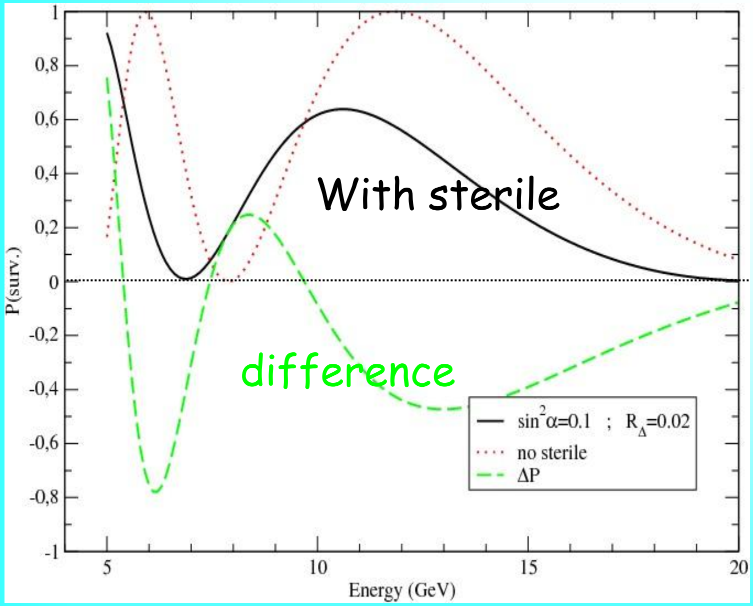
$\nu_\tau' - \nu_s$ resonance $E_R \sim 12$ GeV

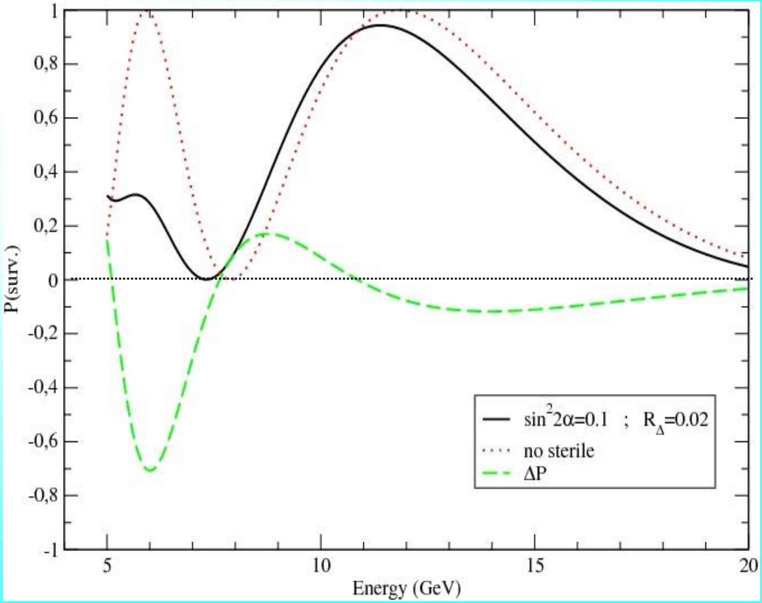
$\nu_\mu \rightarrow \nu_s$ resonance peak 10 – 15 GeV

Interplay of $\nu_\mu \rightarrow \nu_s$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations

Phase shift and decrease of amplitude of oscillations:

P. De Holanda, A. S.





IceCube Deep Core

~ 20 % suppression of rate of events in the muon energy bins 5 – 15 GeV

3. Searching for sterile in Ice

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

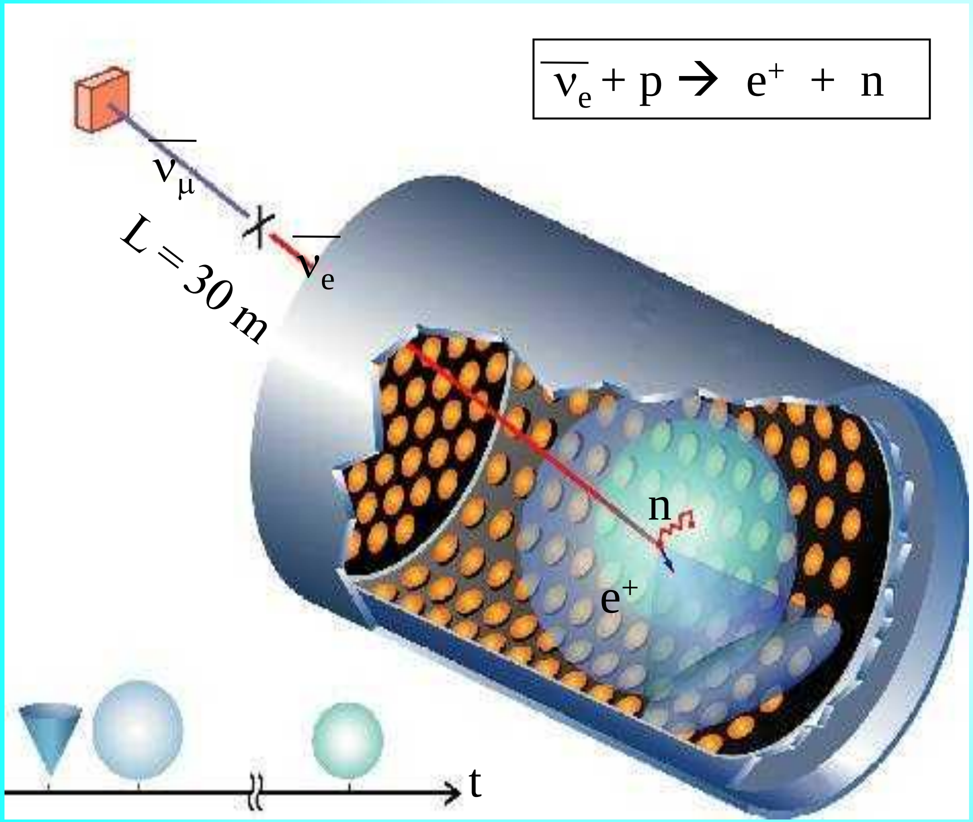
LSND is back?

Large Scintillator
Neutrino Detector

$p \rightarrow$
$\pi^+ \rightarrow \mu^+ + \nu_\mu$
$\rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

decay at rest

Los Alamos Meson Physics Facility



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$P = (2.64 +/- 0.67 +/- 0.45)\ 10^{-3}$

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

3.8σ excess
- now less?

Cherenkov cone + scintillations

200 t mineral
oil scintillator

Confirmation?

MiniBooNE

Now an excess is observed both in neutrino and antineutrino channels

In both channels an excess exists both at small (below 475 MeV) and at high energies

L/E consistency with LSND

An excess smoothly increases with decrease of energy starting from ~800 MeV

It seems this is the same effect and there is no justification to split data

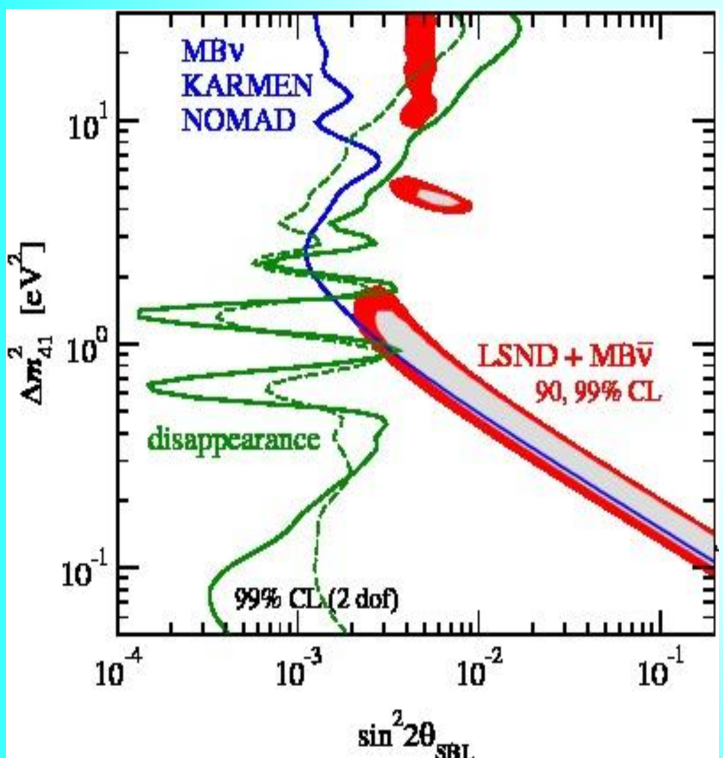
Neutrino and antineutrino data are consistent

No need to introduce second sterile
Not possible to explain by oscillations?

Large uncertainties in neutrino cross-sections
Energy determination?

Cosmology-MINOS

3+1 fit



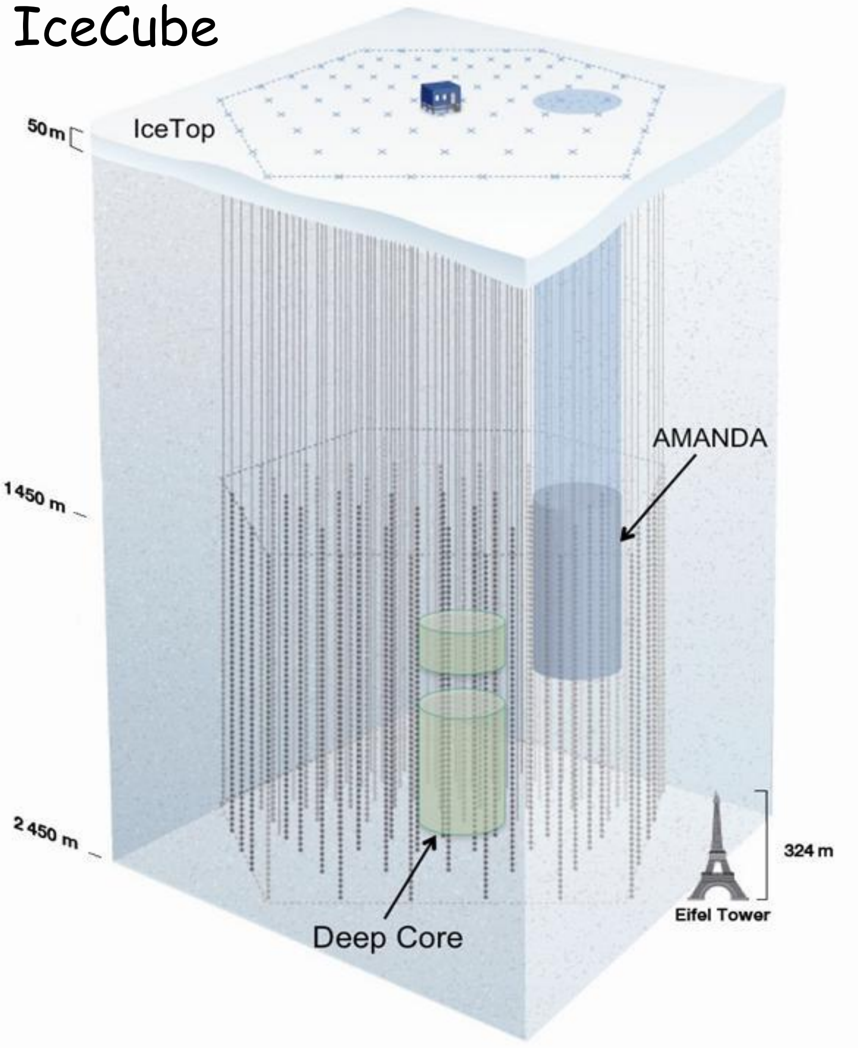
In spite of this….

New experiments:
- Reactors (NUCIFER, SCRAAM)
- MegaCurie strength sources
- Accelerator SBL experiments
  OscSNS BooNE
  MicroBooNE (LArTPC),
  CERN-PS

C Giunti, M Laveder
1107.1452 [hep-ph]

Looking for sterile in ice

IceCube



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

Can be tested by IceCube

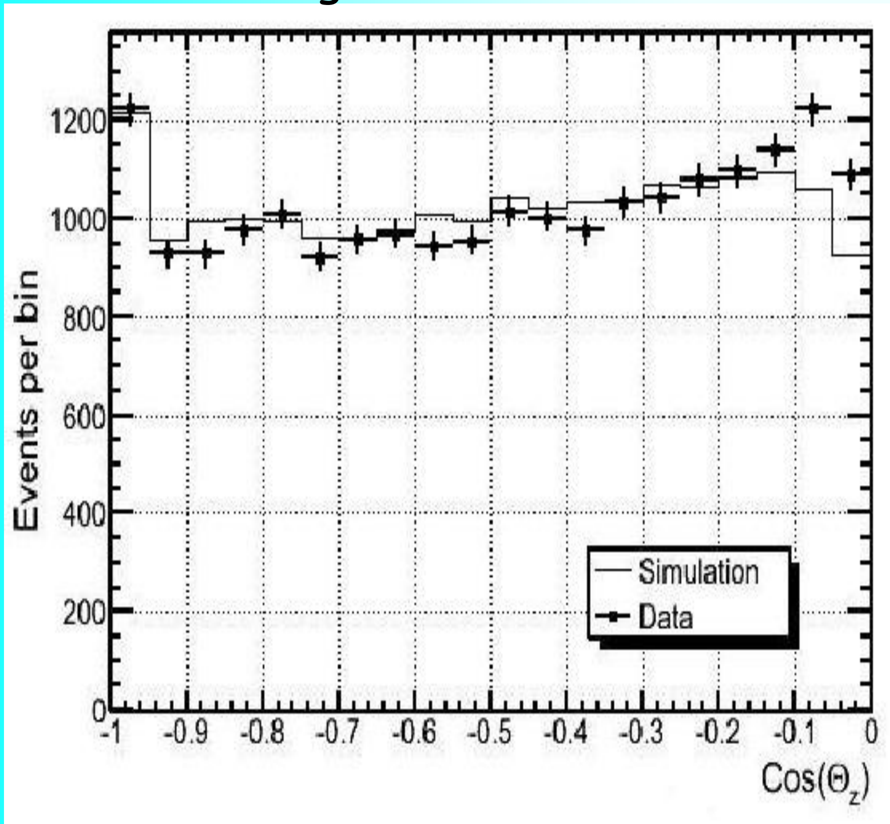
S Choubey JHEP 0712 (2007) 014

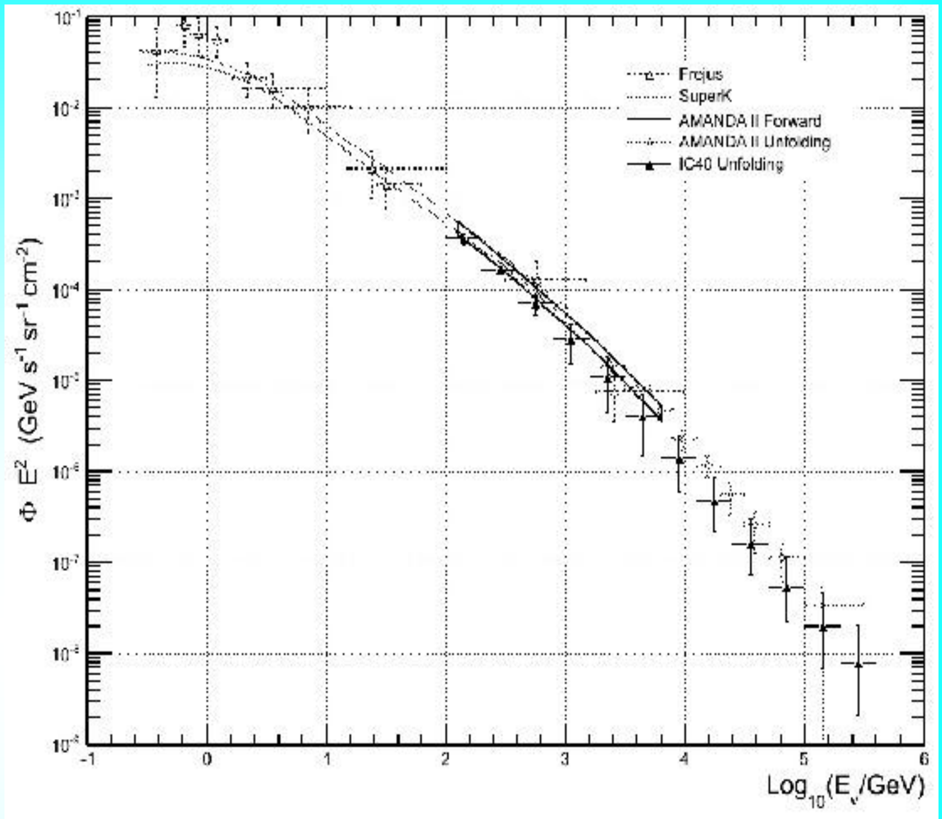
S Razzaque and AYS , 1104.1390, [hep-ph]

IceCube results

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

Zenith angle distribution

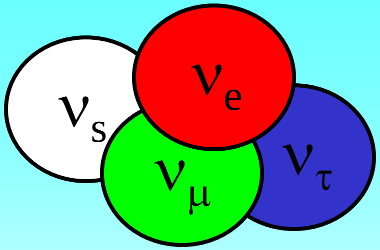


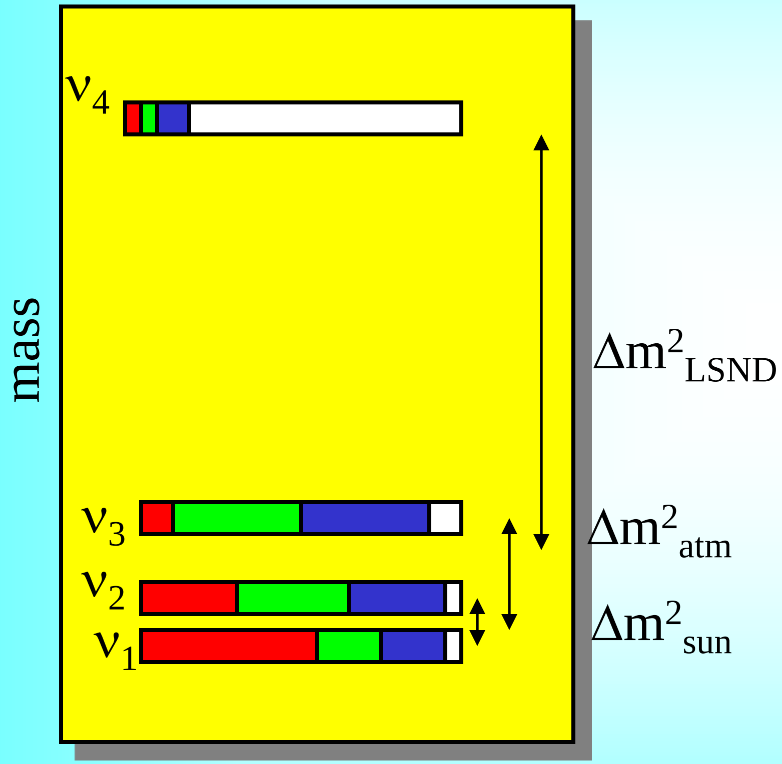


Unfolded neutrino spectrum

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

(3 + 1) scheme





LSND/MiniBooNE: vacuum oscillations

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

Restricted by short baseline experiments CHOOZ, CDHS, NOMAD

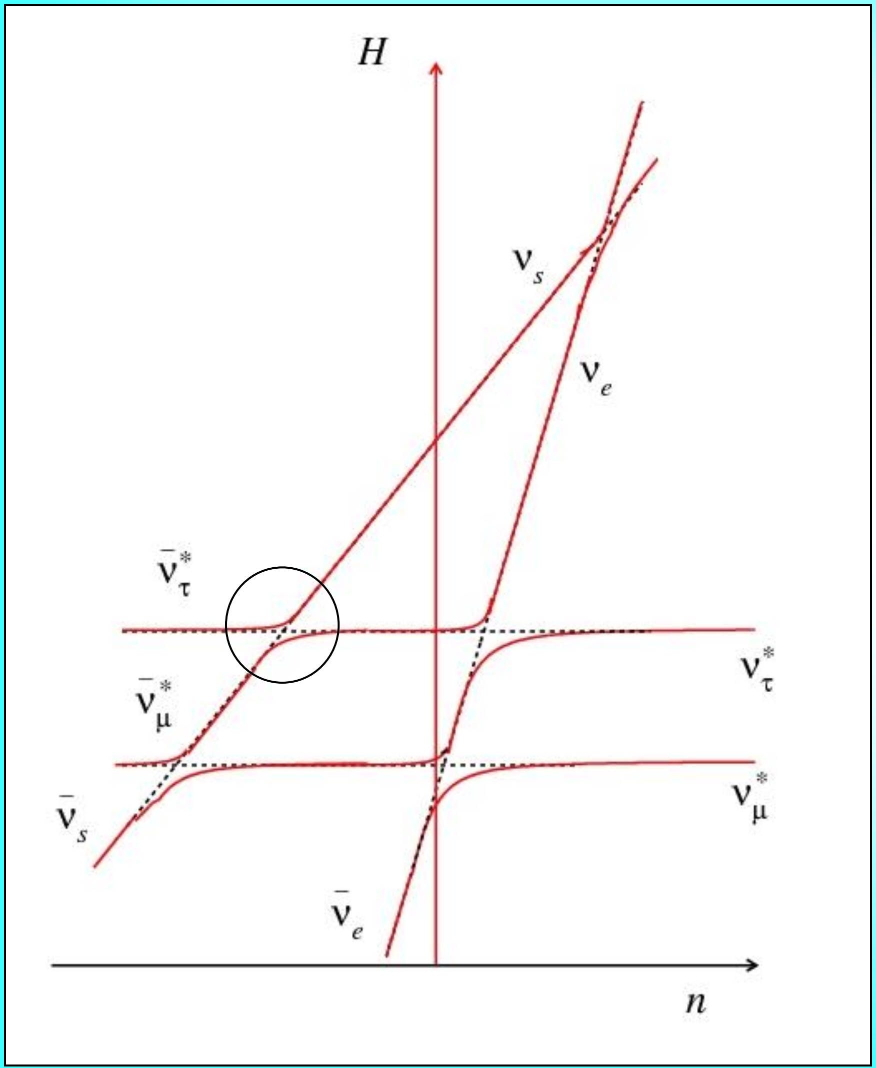
With new reactor data:

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

$U_{e4} = 0.15$

$U_{\mu 4} = 0.23$

Level crossing scheme



- Normal mass hierarchy in the flavor block; $m_0 \sim 1$ eV
- Three new level crossings
- $|U_{e4}|^2$ $|U_{\mu 4}|^2$ 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

$s_{24}^2 = s_{34}^2$

$U_f = U_{23} U_\alpha$

ν_s		ν_0
ν_τ		ν_3
ν_μ		ν_2

ν_s mixes in the mass states ν_3 and ν_0

$$\nu_0 = -\sin\alpha\,\tilde{\nu}_3 + \cos\alpha\,\nu_s$$
$$\nu_3 = \cos\alpha\,\tilde{\nu}_3 + \sin\alpha\,\nu_s$$
$$\nu_2 = \tilde{\nu}_2$$

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 $\tilde{\nu}_3$

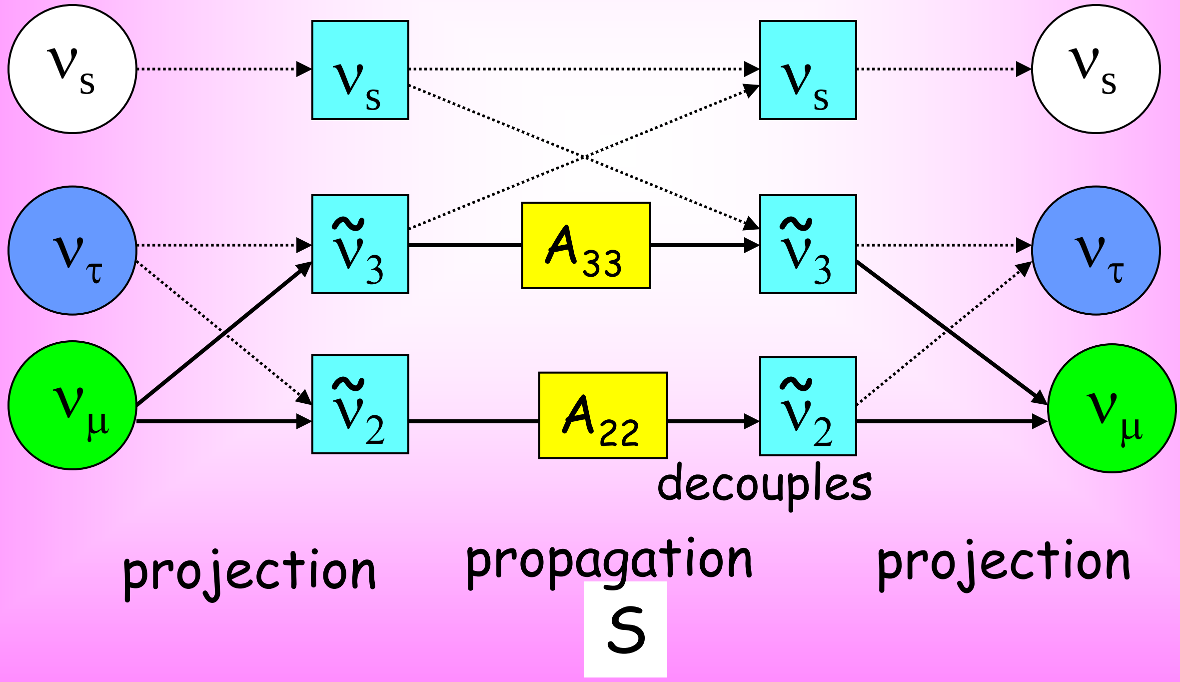
Propagation basis: $\nu_s, \tilde{\nu}_3, \tilde{\nu}_2$

Evolution is reduced to 2ν-problem exactly

Evolution

Propagation basis

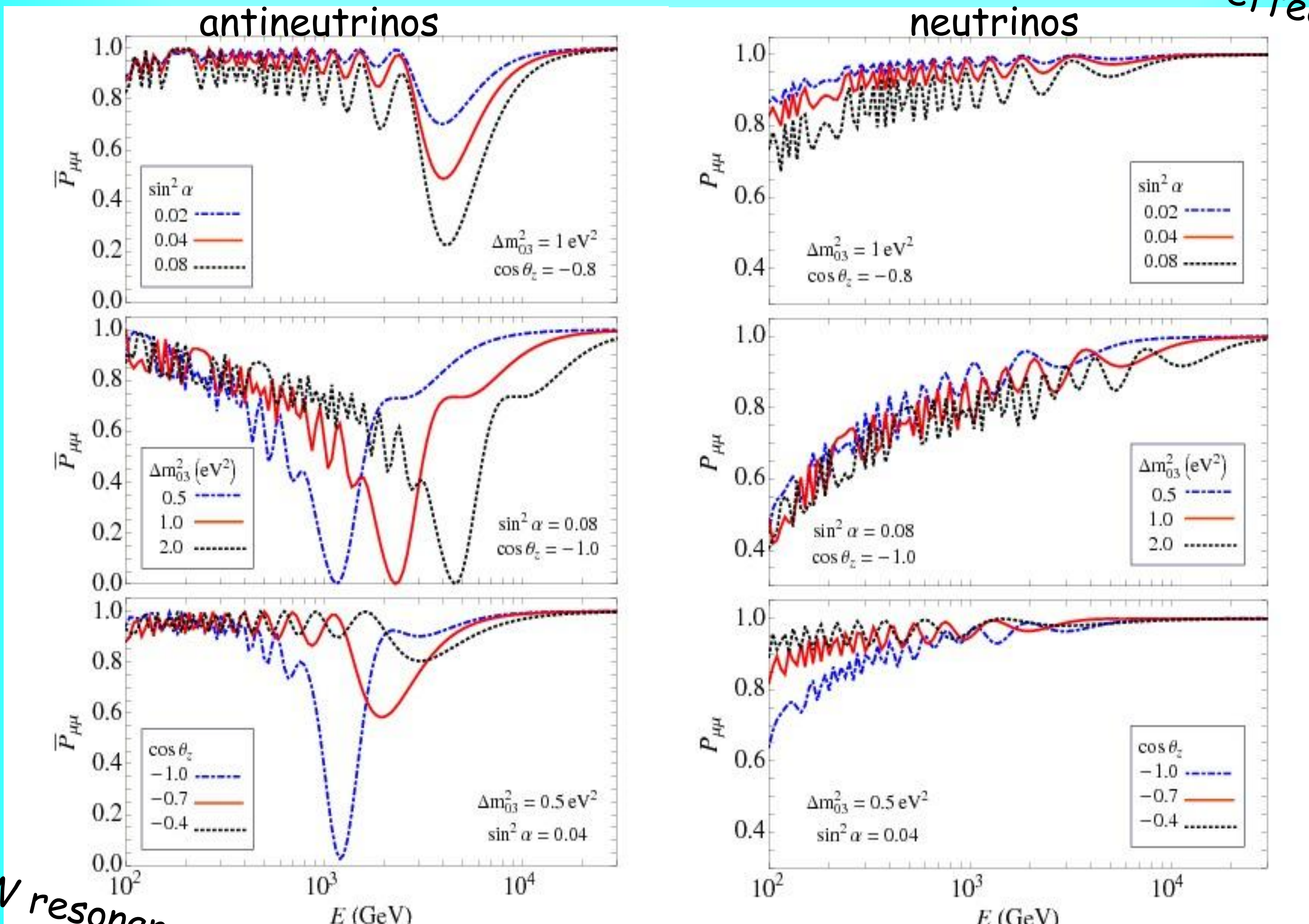
$$\nu_f = U_{23}\,\tilde{\nu}$$



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

Survival probability

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

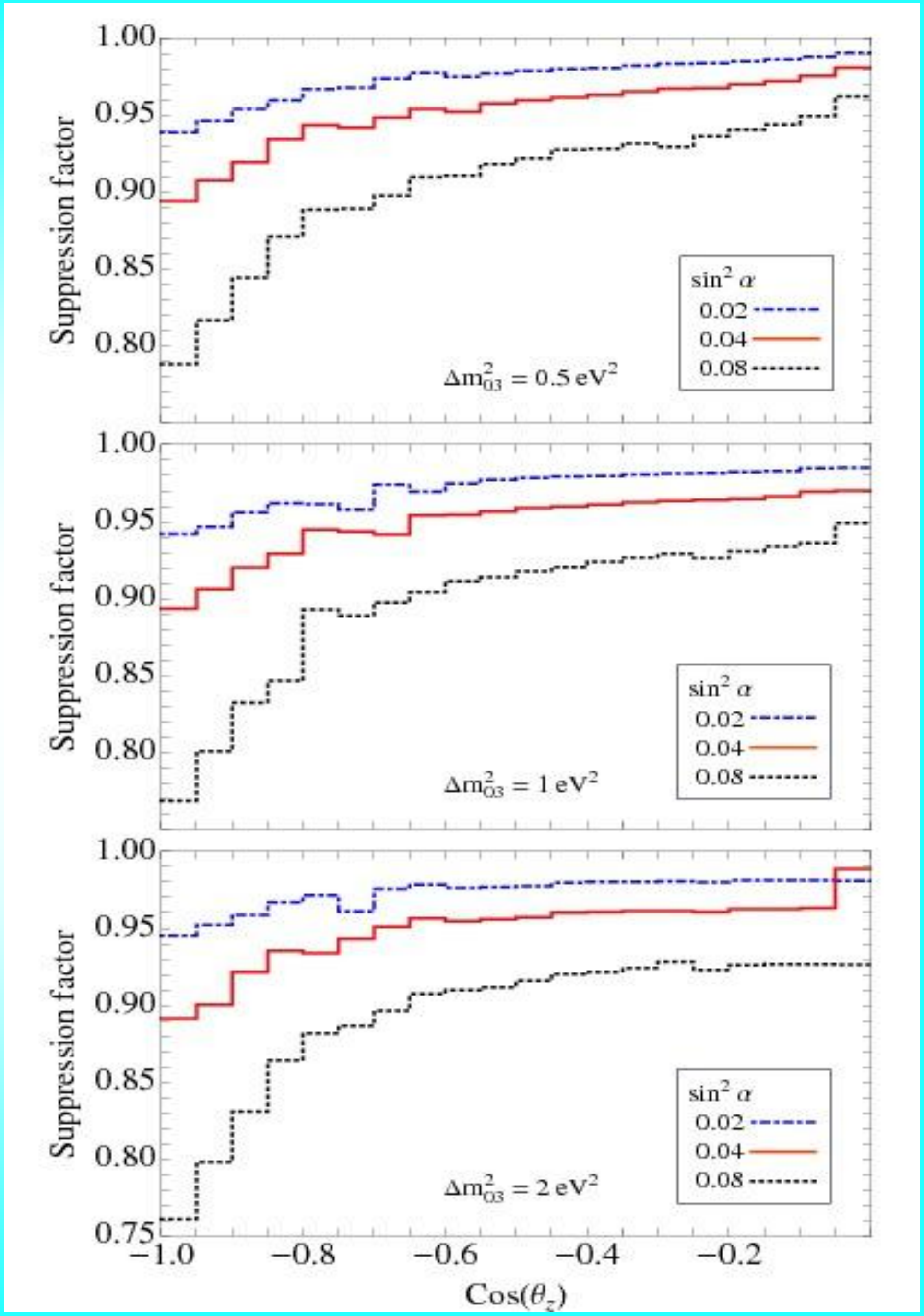


MSW resonance dip

Suppression factor

$S = N(osc.)/N(no\ osc.)$

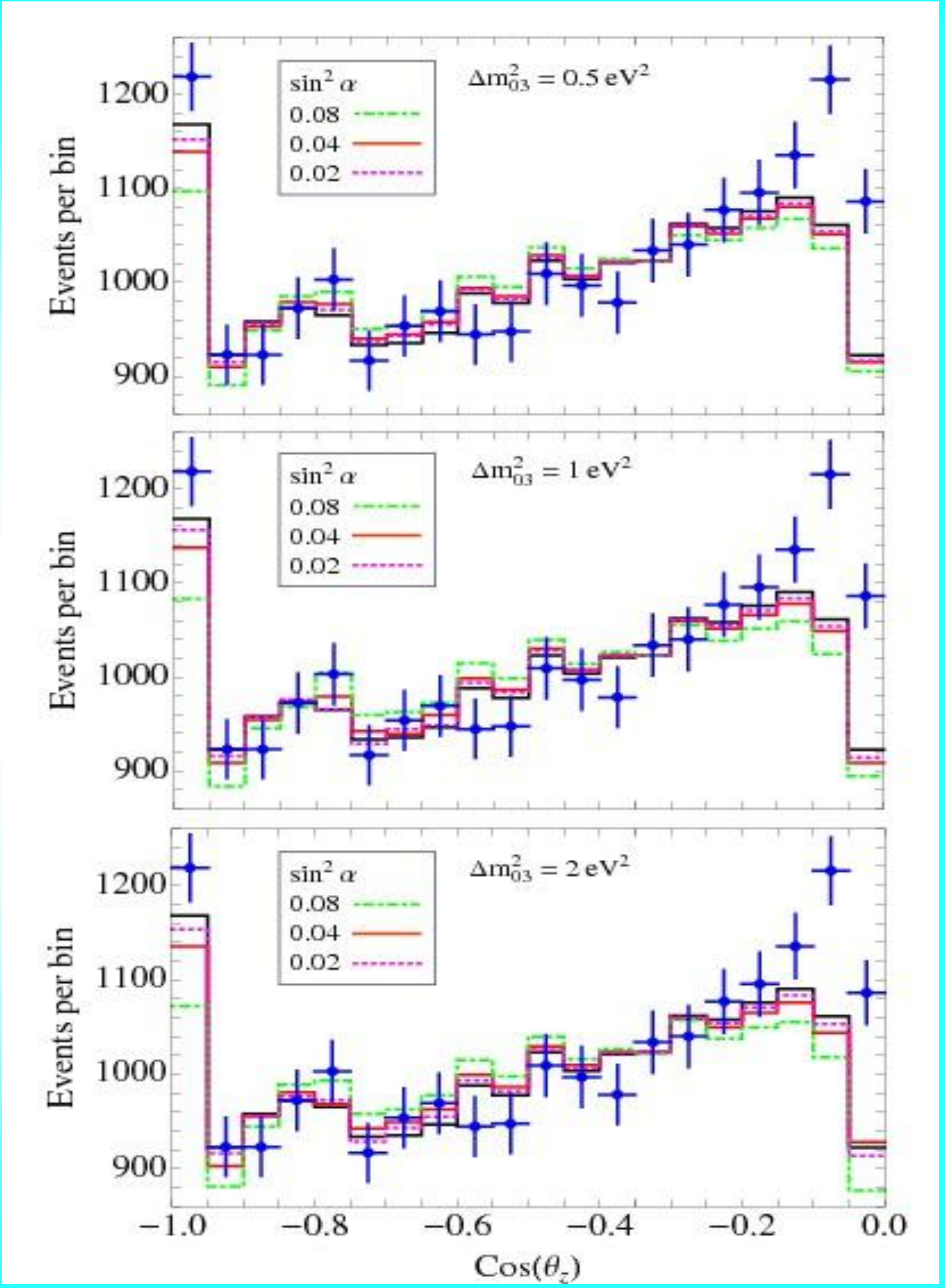
$E_{th} = 0.1$ TeV



Zenith angle distribution

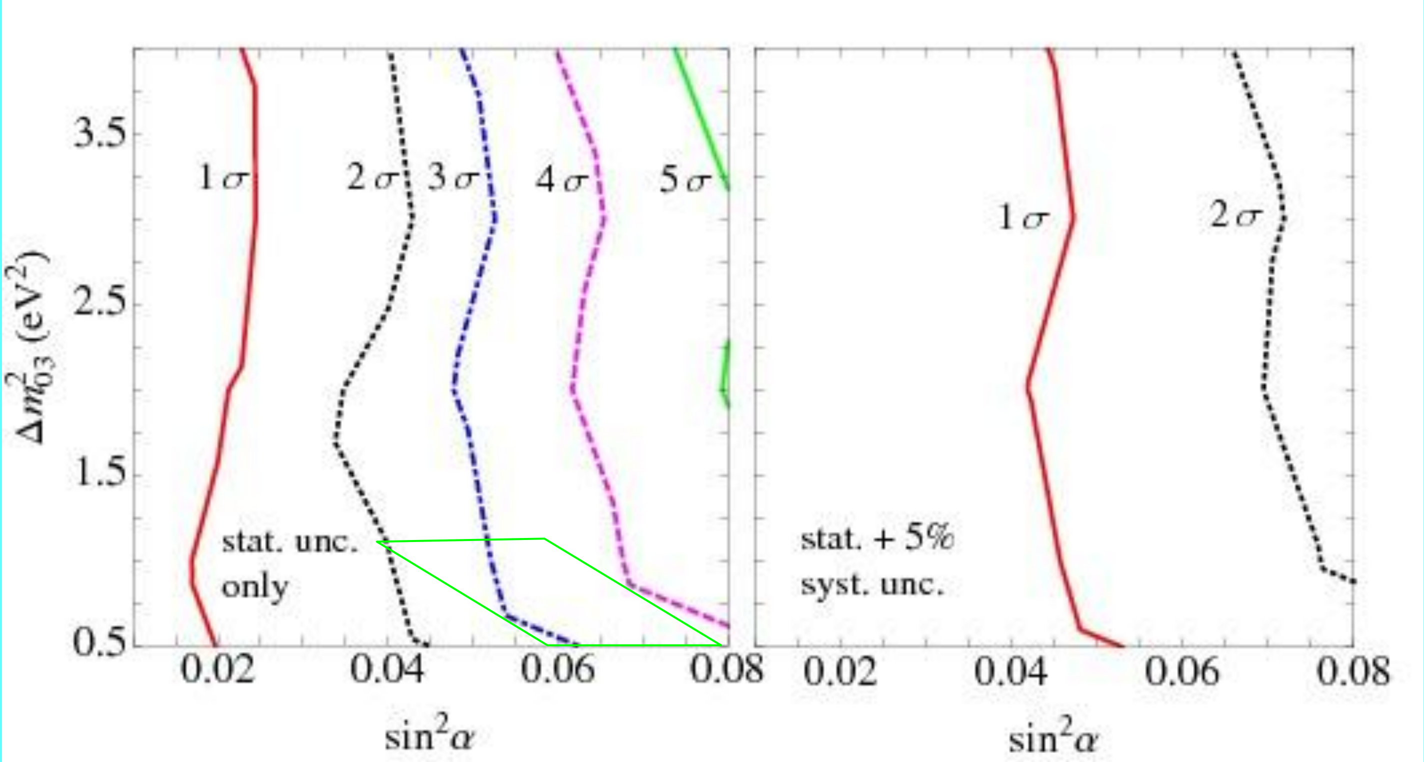
ν_S - mass mixing case

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

$s_{34}^2 = 0$

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

ν_s mixes with ν_μ

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

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

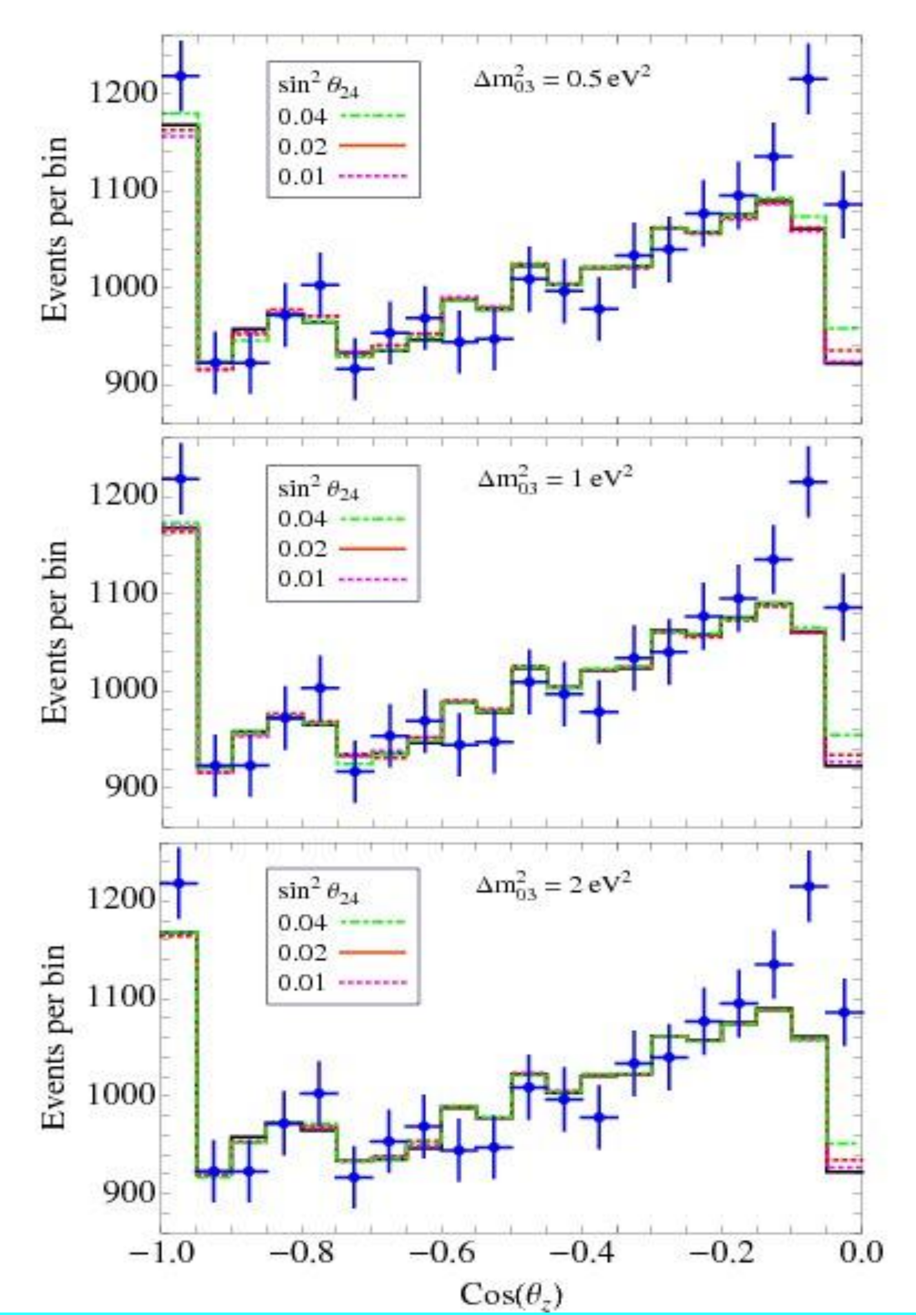
$$\nu_2 = - \sin\beta \cos\theta_{23}\, \nu_\mu + \sin \theta_{23}\, \nu_\tau - \cos\beta \cos\theta_{23}\, \nu_s$$

Propagation basis = flavor basis

Evolution is not reduced to the 2ν - evolution exactly

Zenith angle distribution

ν_S - ν_μ mixing



Free normalization
and tilt factor

Fit with sterile is even better

E_{th} = 0.1 TeV

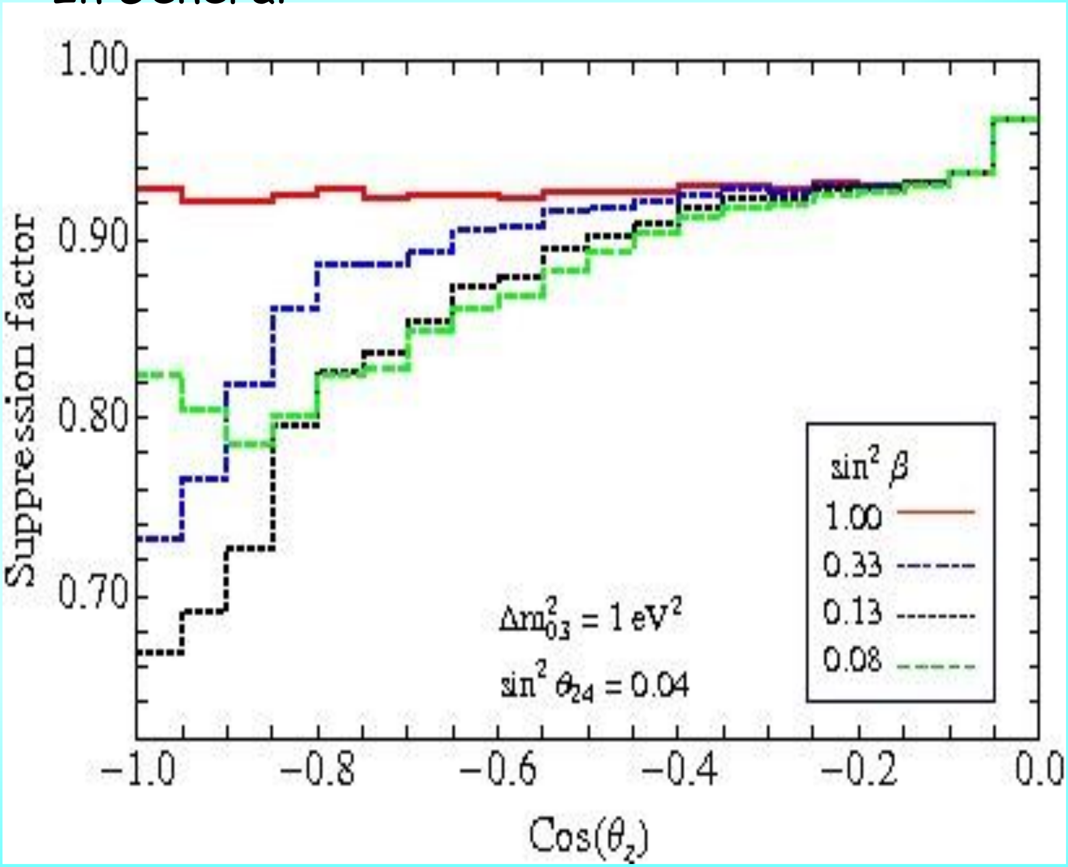
Zenith angle distributions

In General

For different mixing schemes

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

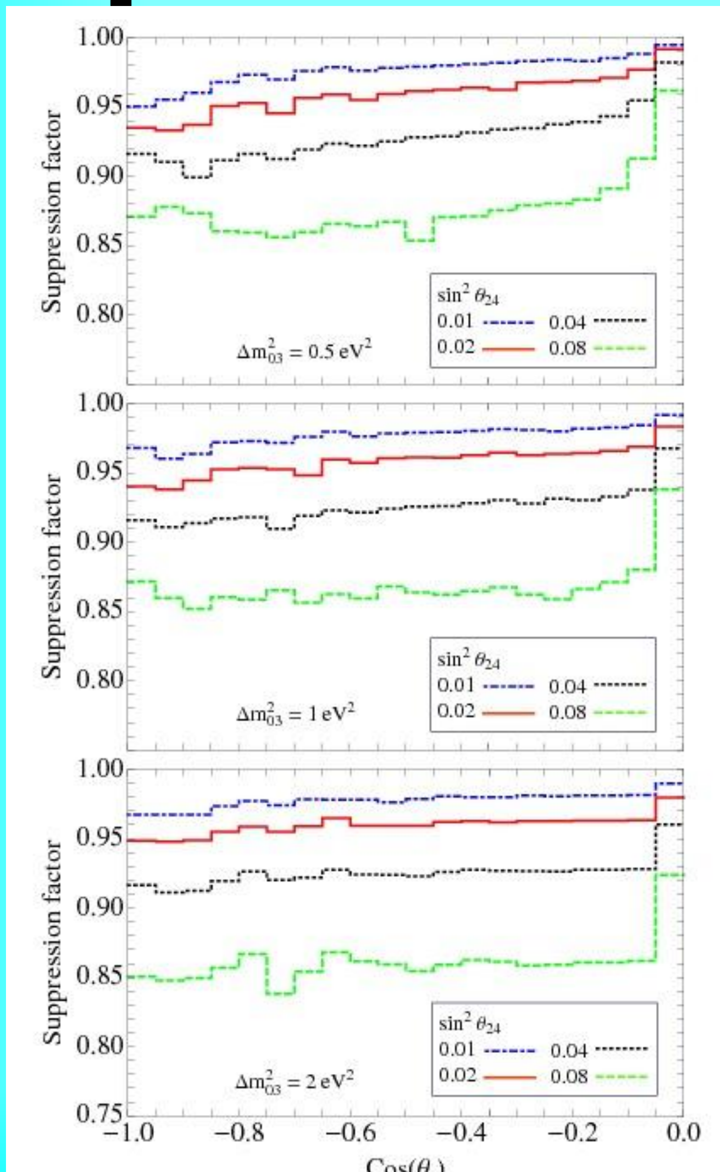
$$\sin^2\beta = \frac{s_{24}^2}{s_{24}^2 + s_{34}^2}$$



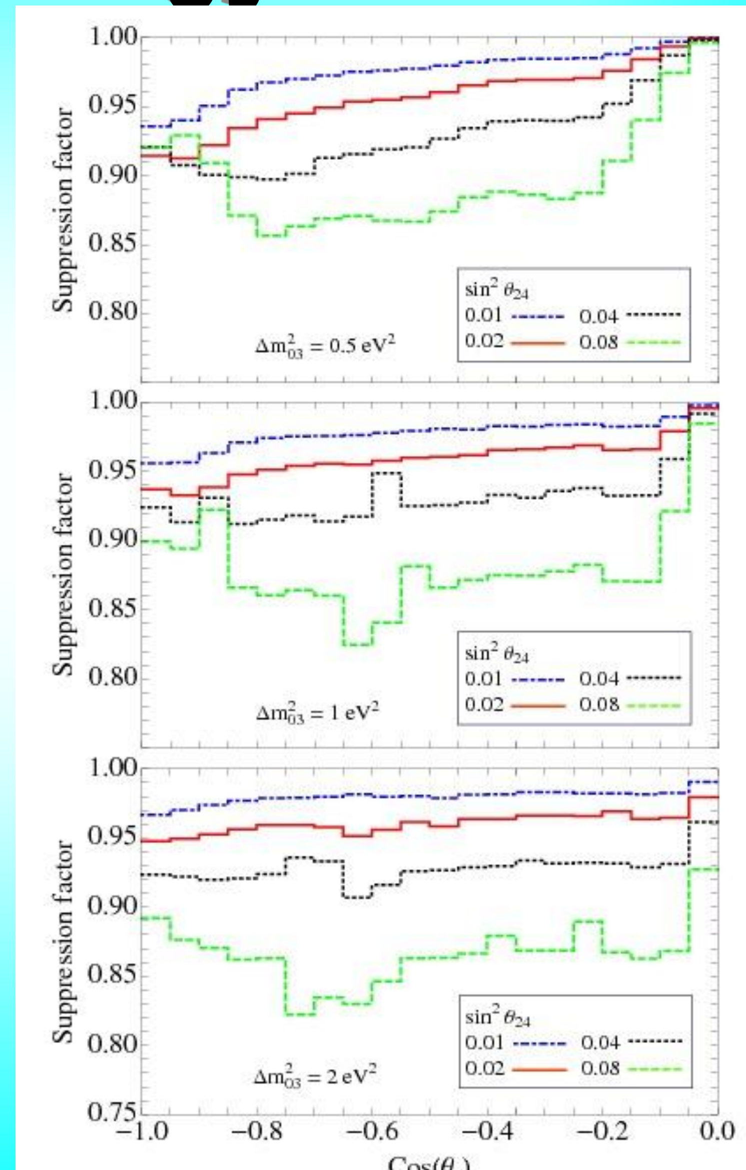
Zenith angle distribution depends on admixture of ν_τ in 4th mass state

Dependence on energy threshold

E_{th} = 0.1 TeV



E_{th} = 1 TeV

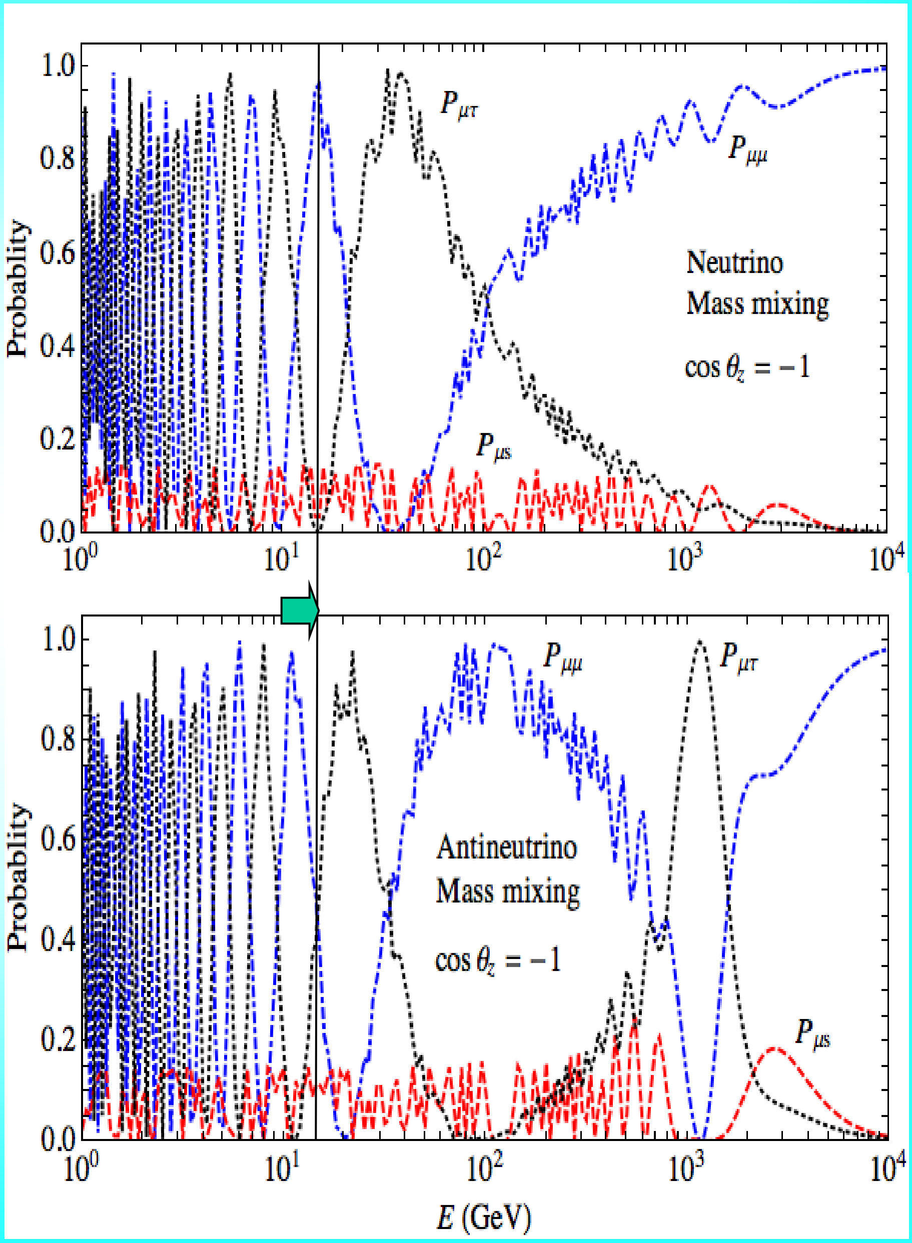


DeepCore IC can help?

S. Razzaque, A.S.

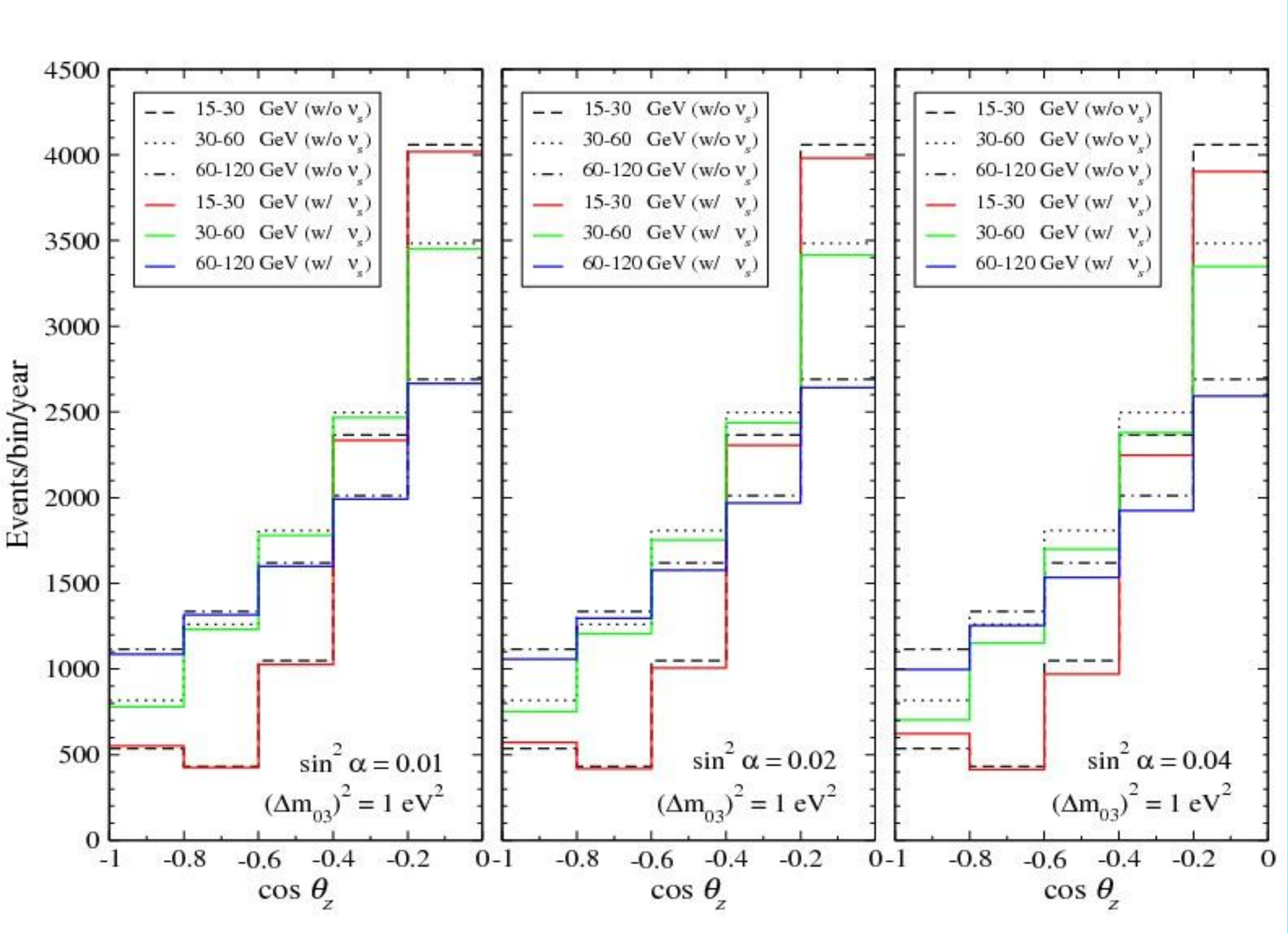
at low energies

Shift of phase quantifies effect of sterile neutrino



Number of events

IceCube DeepCore



S Razzaque
A.S.

Zenith angle distribution of events in different energy ranges

Summary

Hunting steriles continues:
- Rich phenomenology
- Must for further advance in theory

meV scale 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 eV scale: Convincing? Consistent? Controversial?

IceCube has high sensitivity to sterile mixing with

$\sin^2 \alpha > 0.01$

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

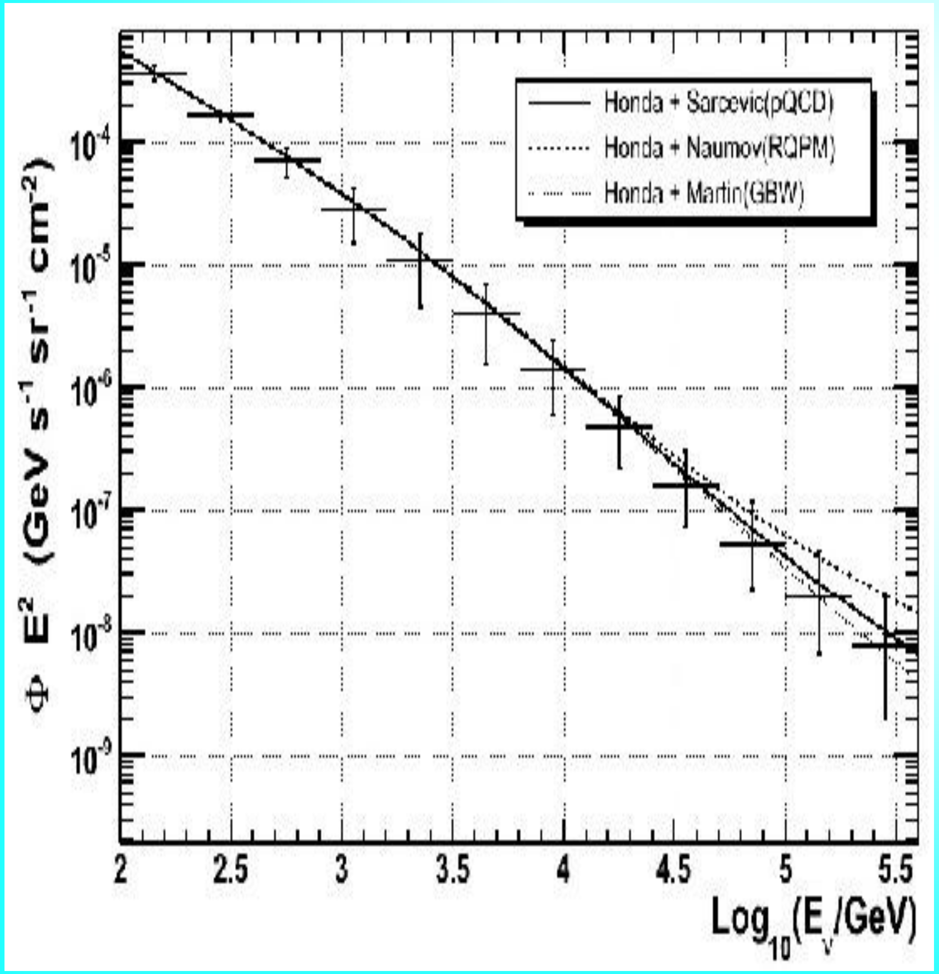
With present data only part of the parameter space relevant for LSND/MiniBooNE can be excluded and in some ranges the fit can be even improved.

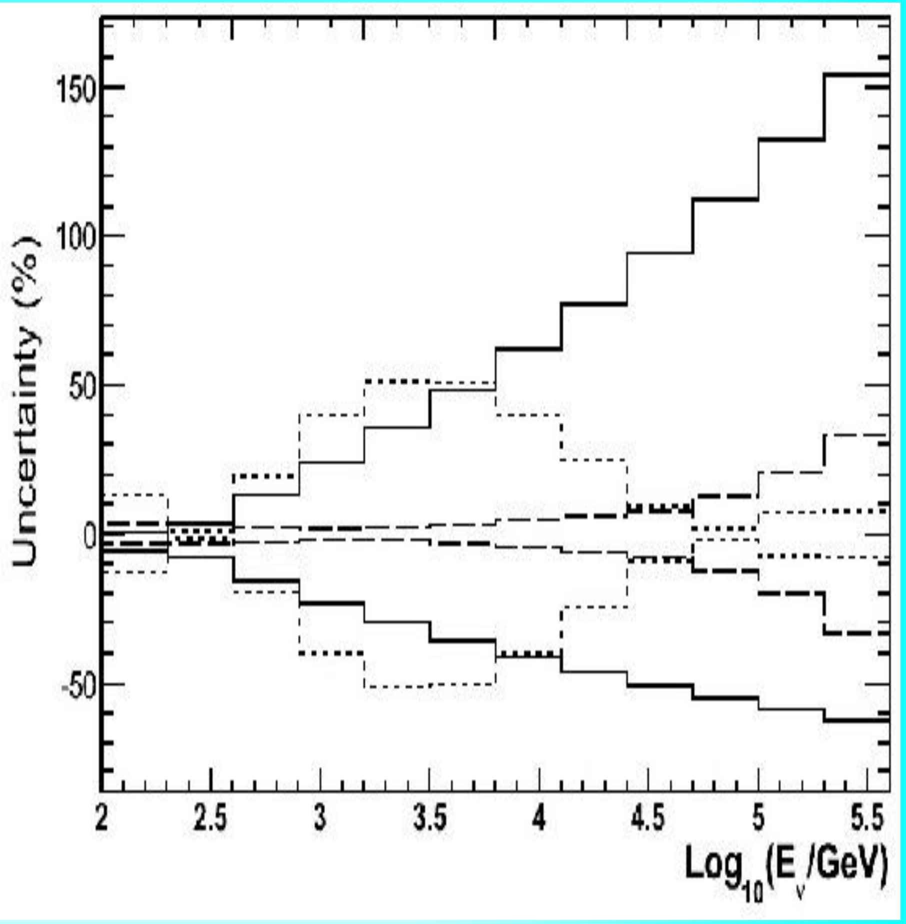
Future high statistics studies of the zenith angle distributions in different energy regions (with different energy thresholds) can provide sensitive search of sterile in whole parameter space and discriminate different mixing scenarios.

DeepCore
IceCube can help

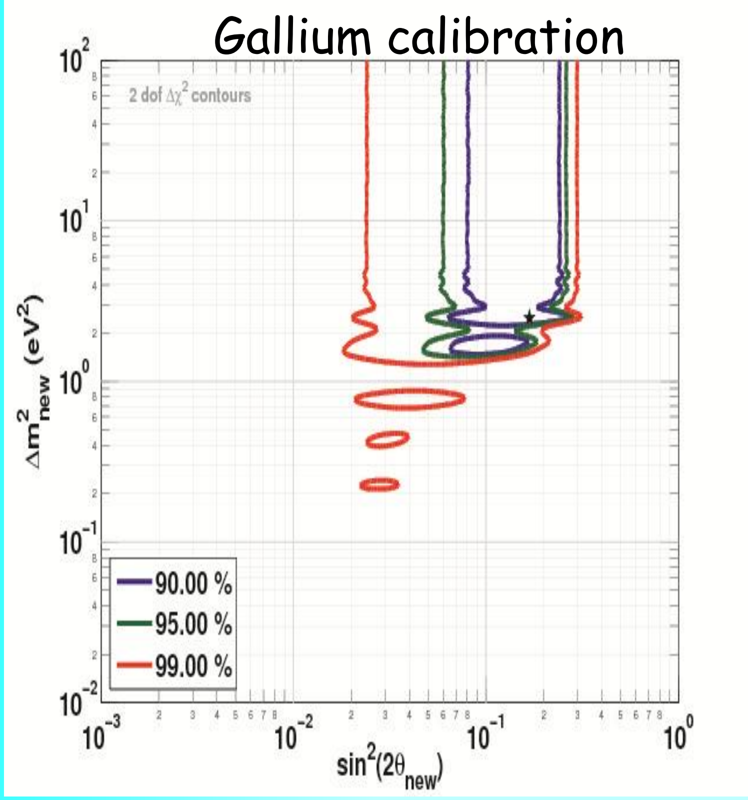
Cosmology: eV + meV steriles ?

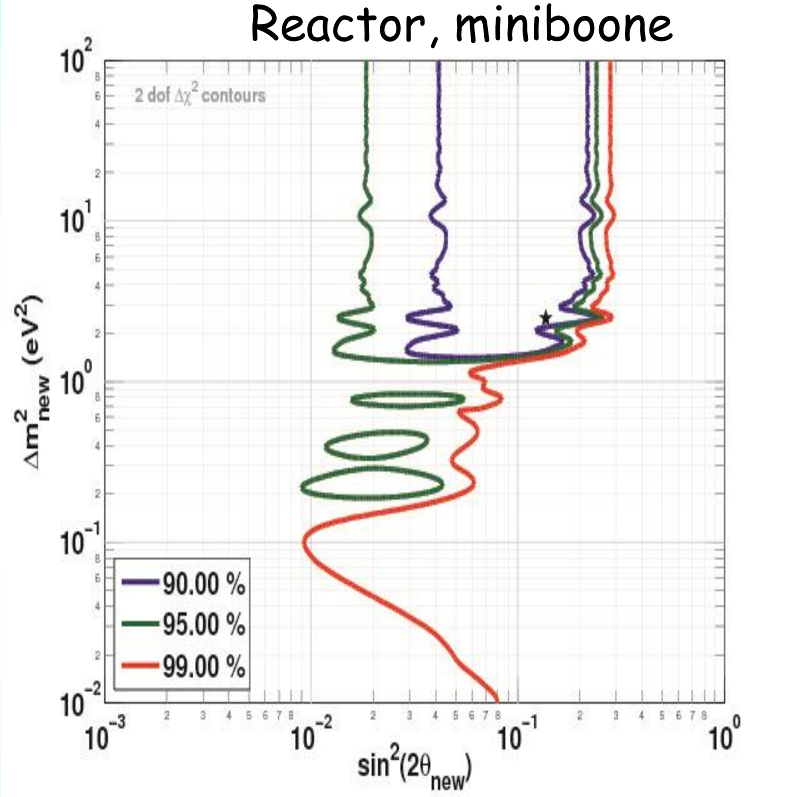
Fluxes


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





Calibration

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

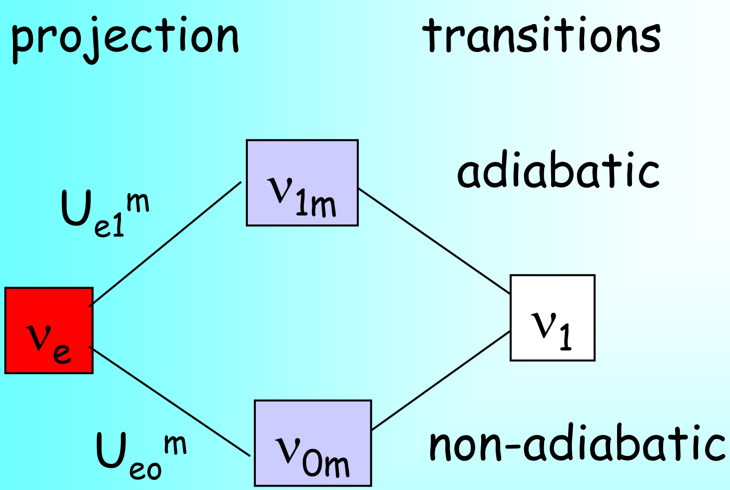
G.Mention et al, arXiv: 1101.2755

R_{Ga} = 0.87 +/- 0.05

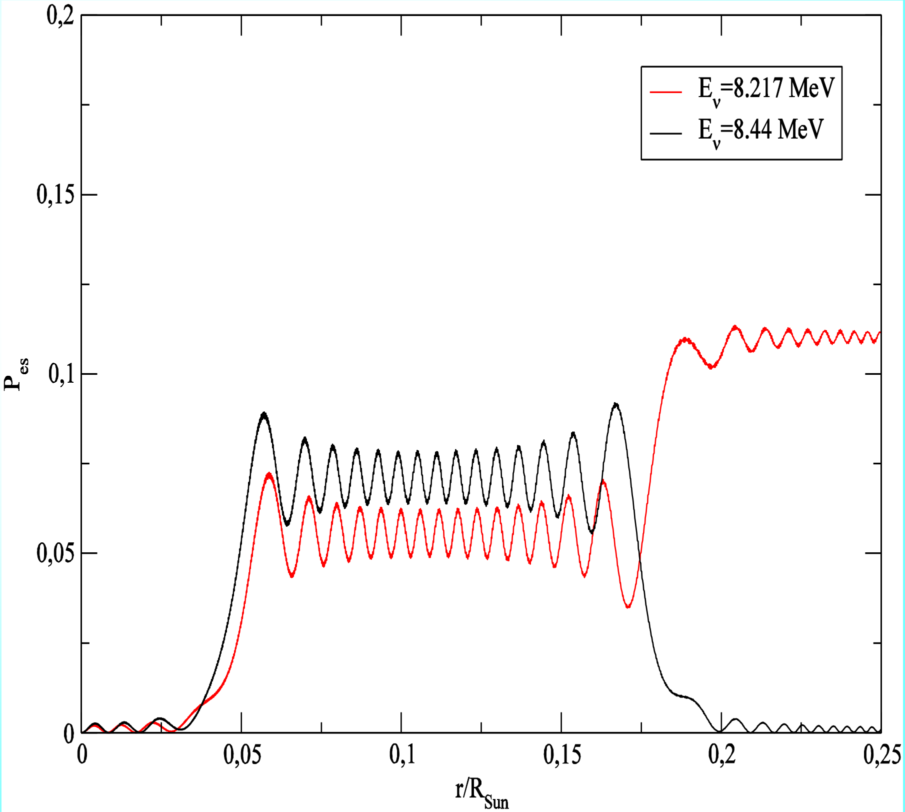
C Giunti, M. Laveder

Wiggles

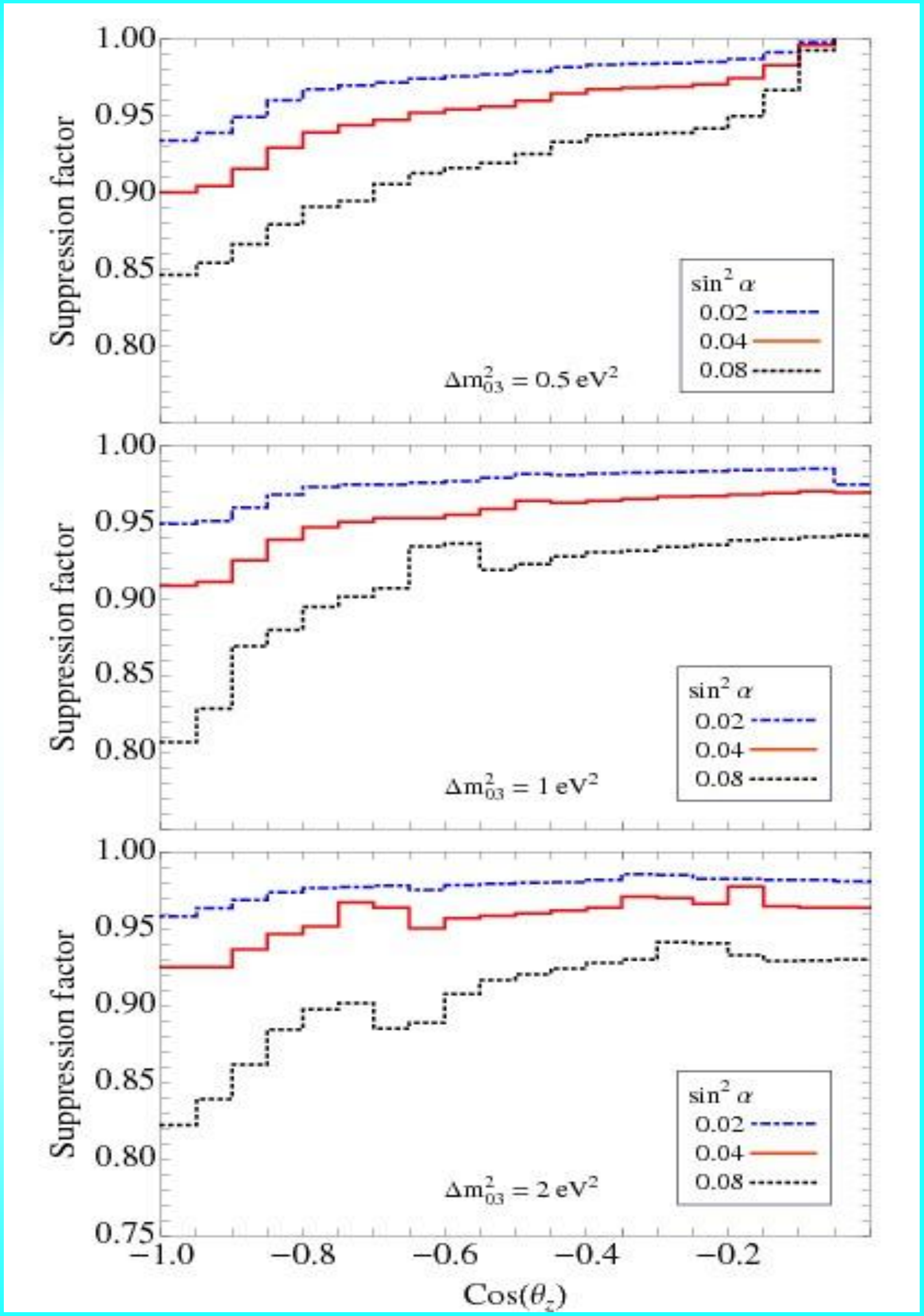
Interference of two amplitudes of transition



Evolution between two sterile resonances



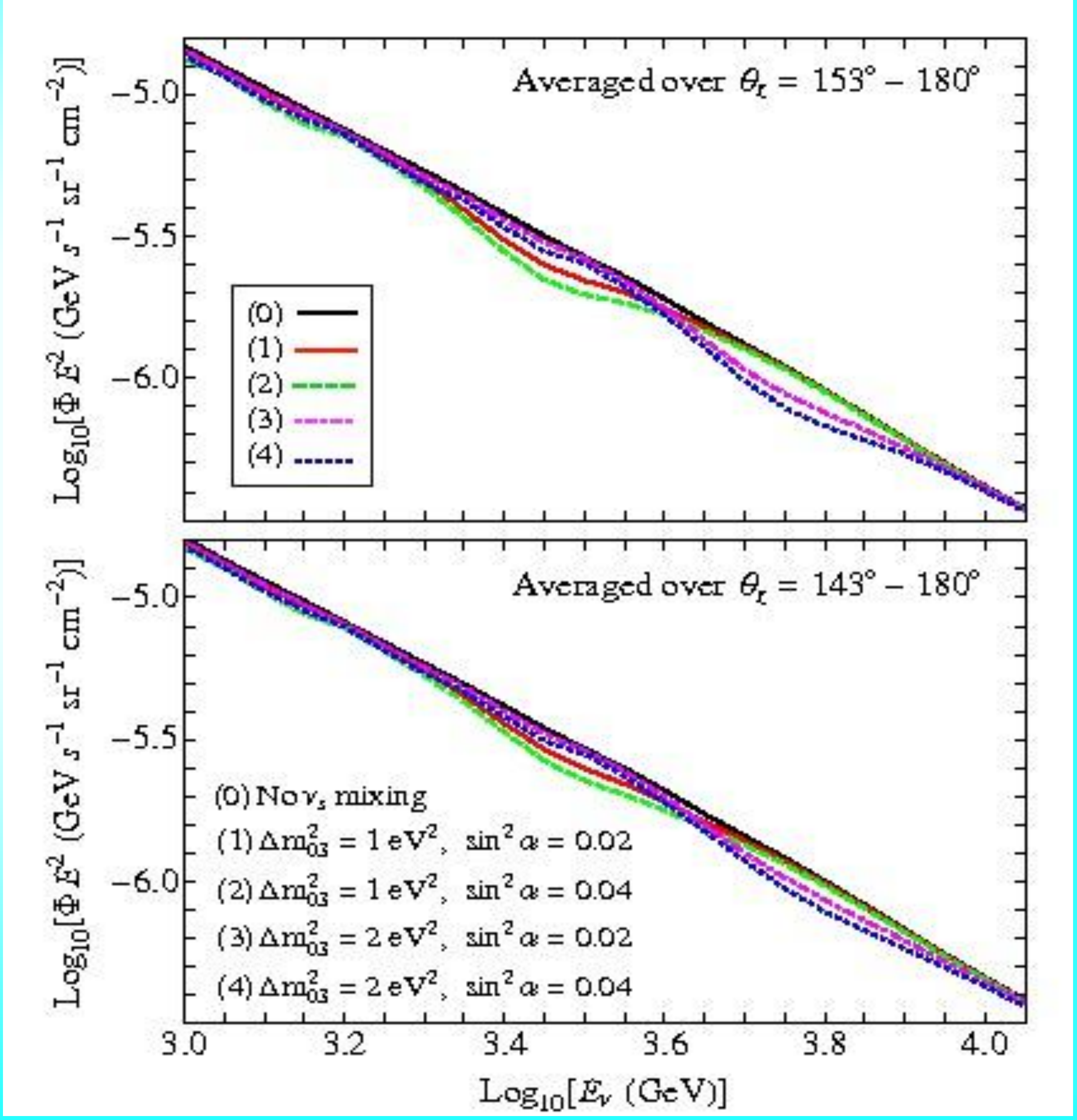
Suppression factor



E_{th} = 1 TeV

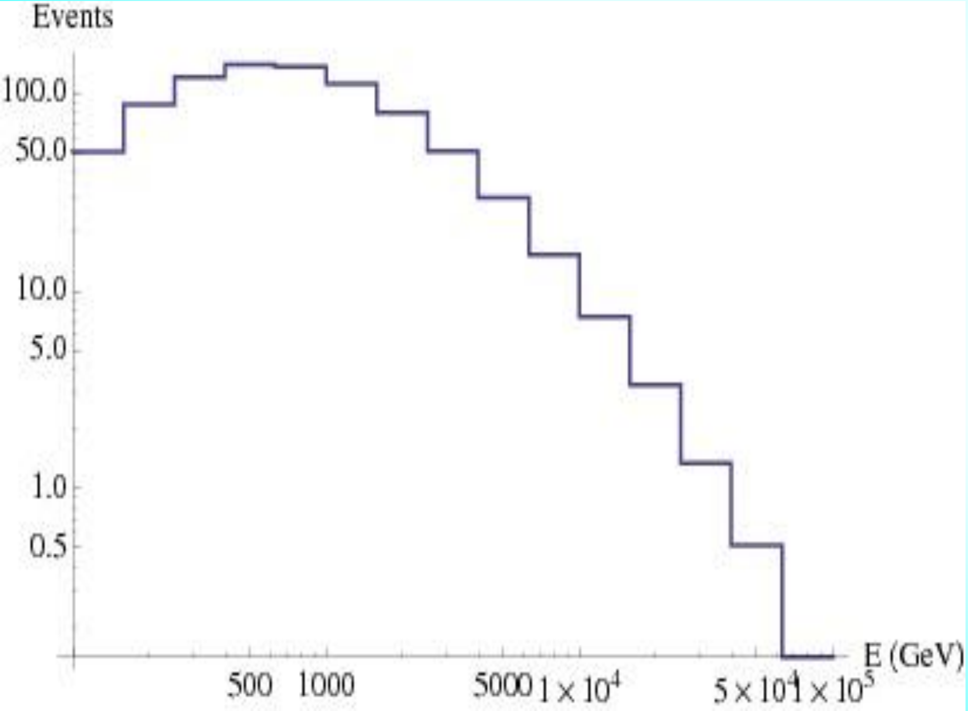
Energy spectra

Narrowing the zenith angle interval – enhances Effect→ 40 %



Number of events

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



Flux of muon neutrinos:

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

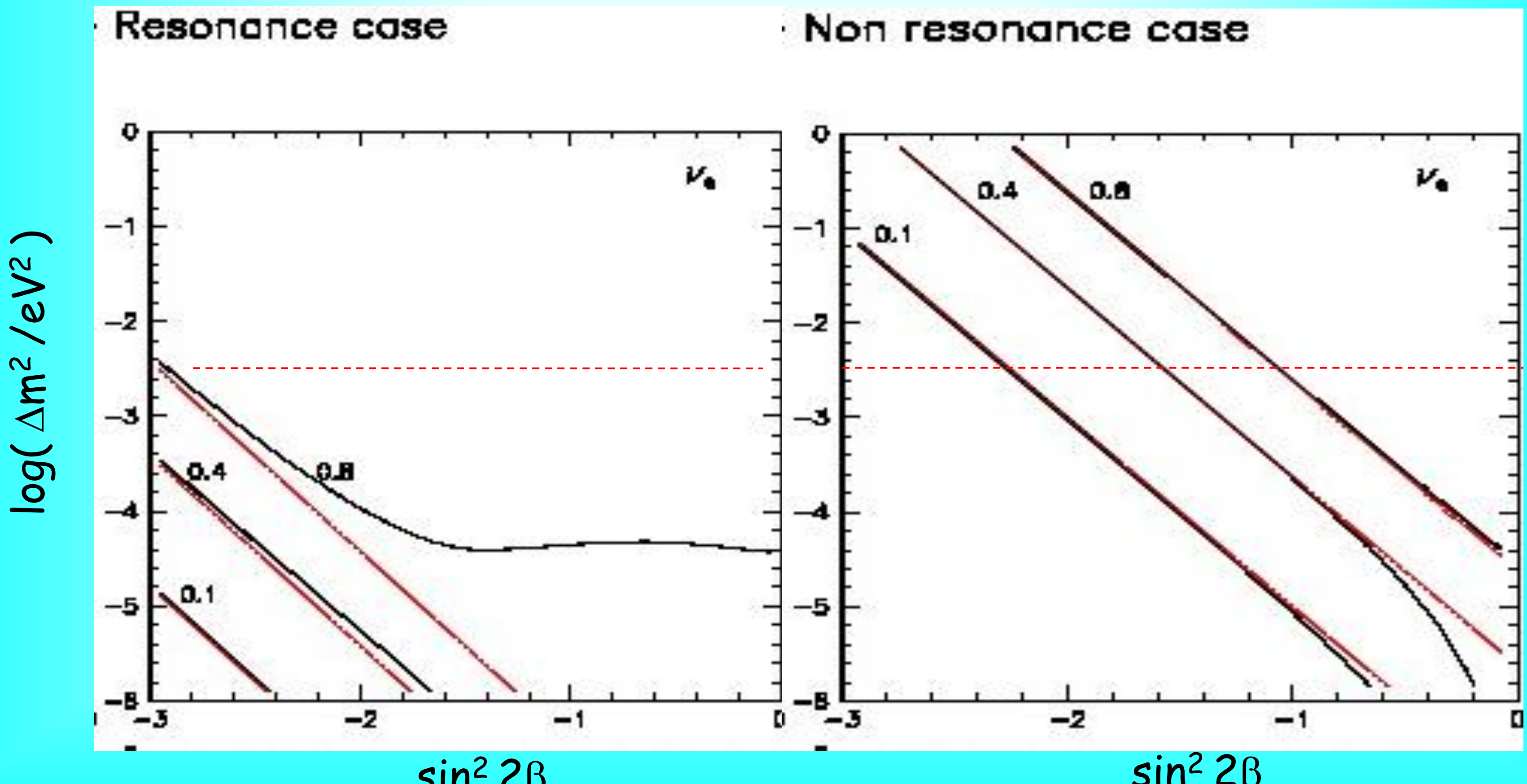
$$\sim F_\mu^0 P_{\mu\mu}$$

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

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

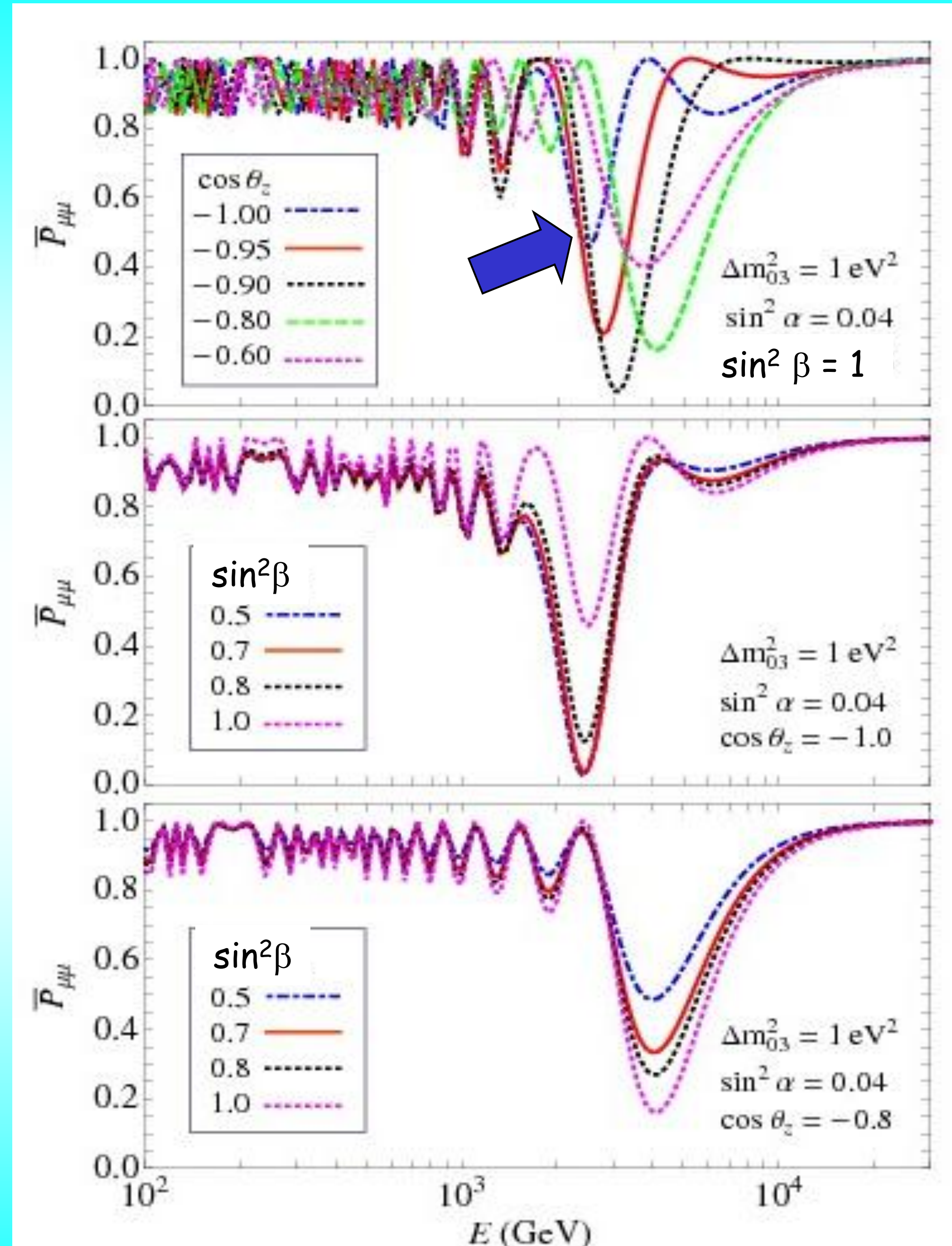
no strong suppression in vertical bin

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

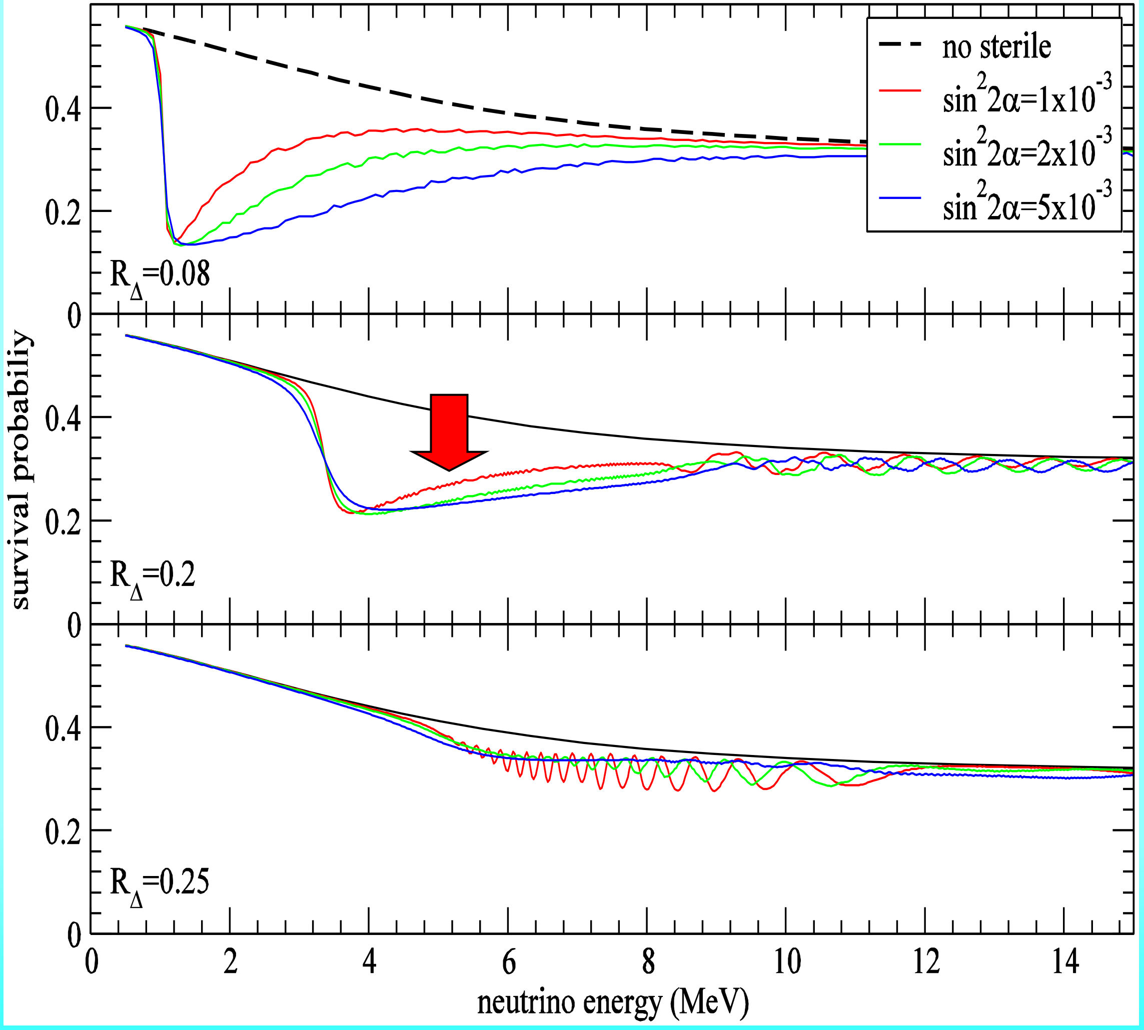
$\sin^2\beta$ decreases

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

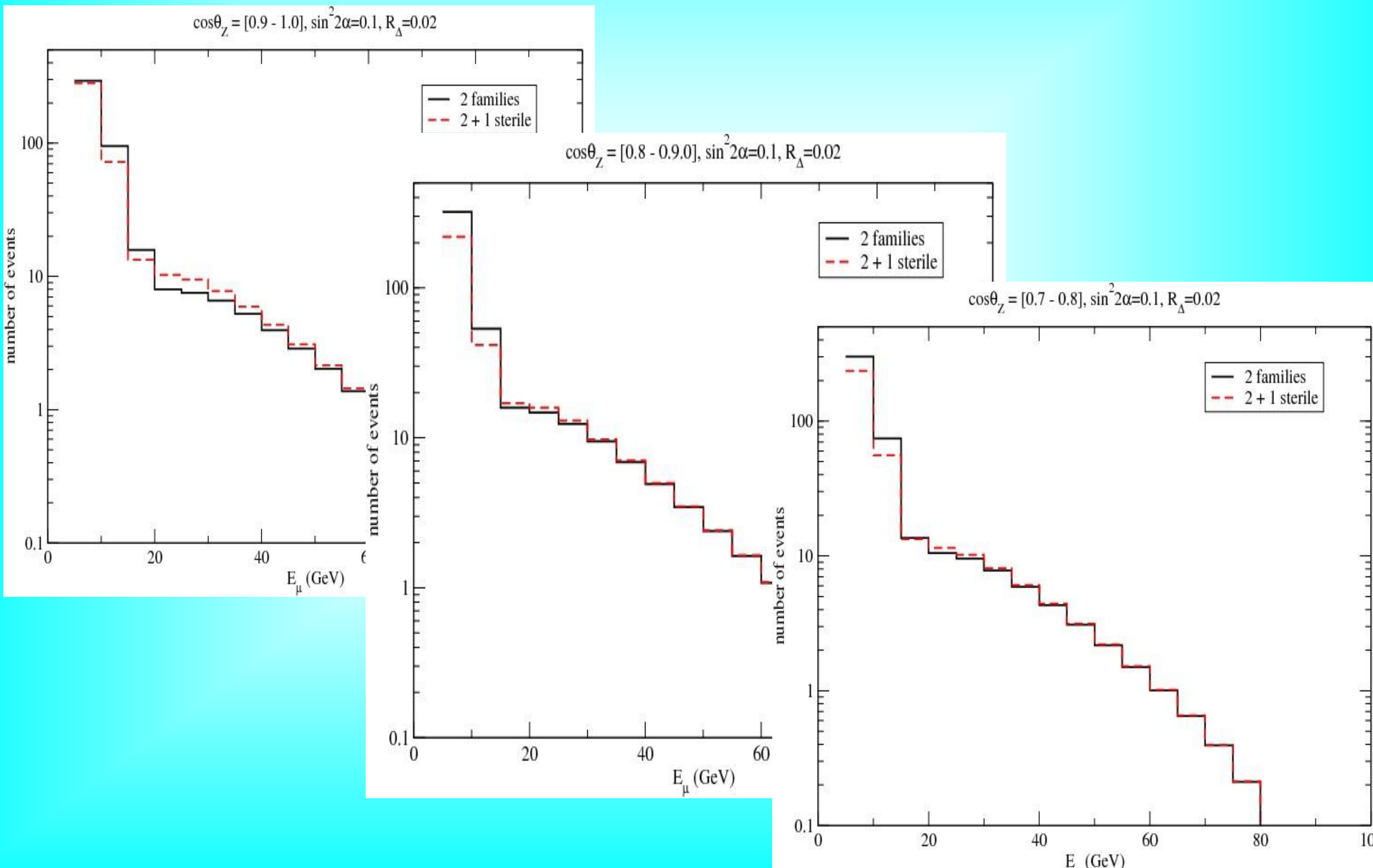
distortion of the E and θ_Z distributions becomes weaker



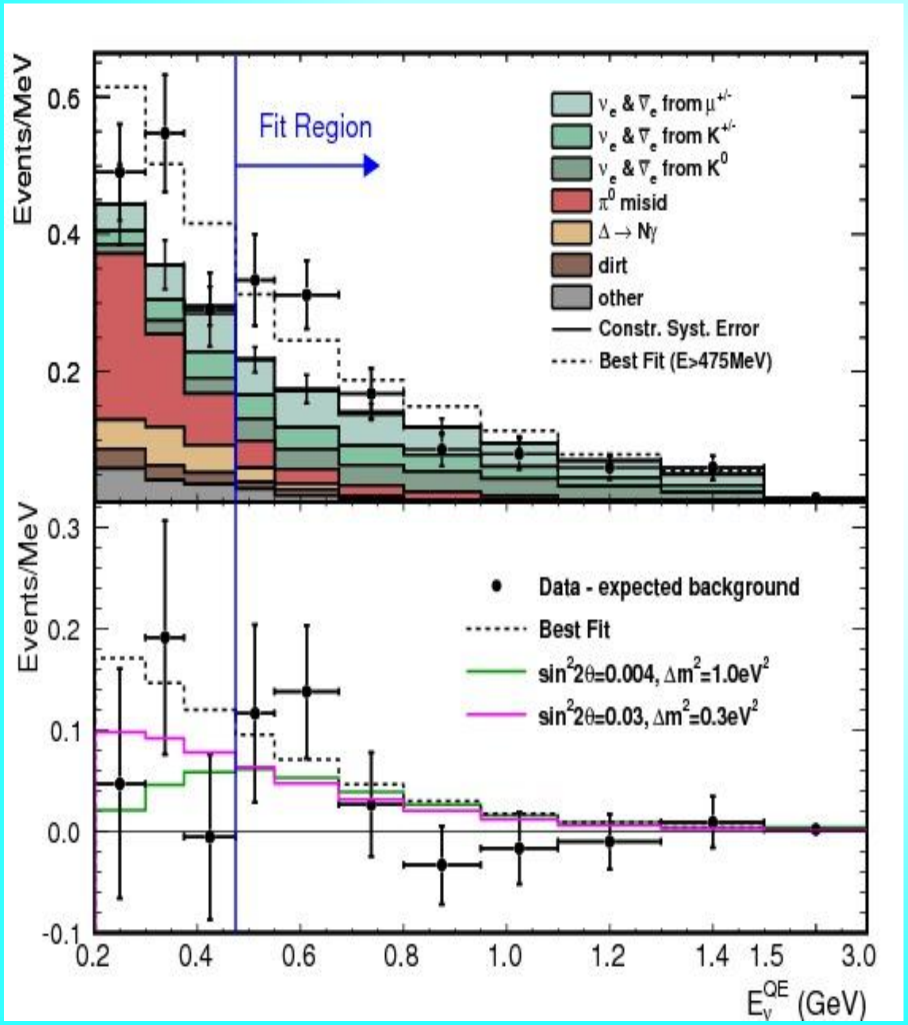
Survival probability

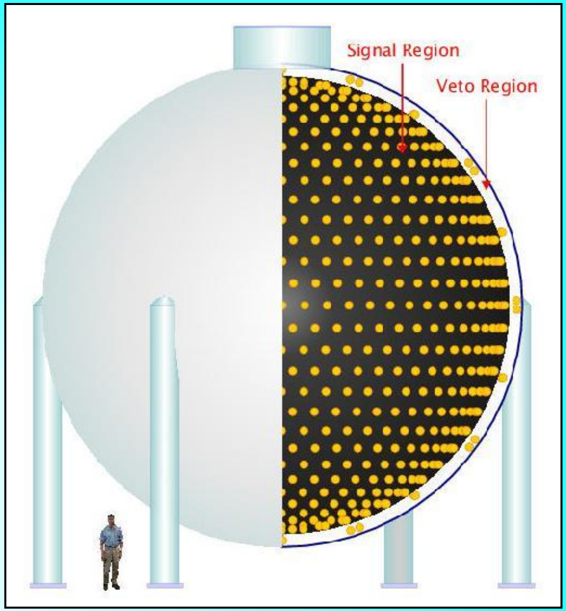


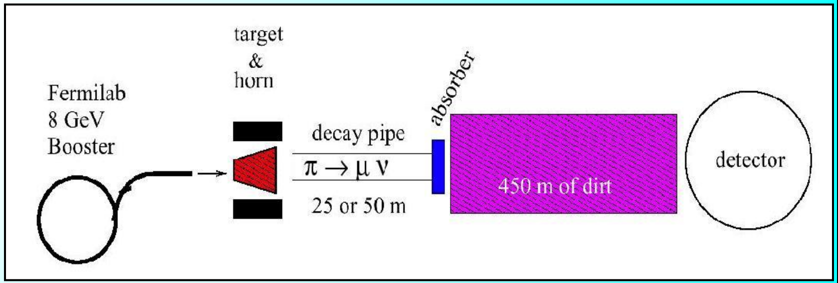
Rate of events



MiniBooNE: anti-nu



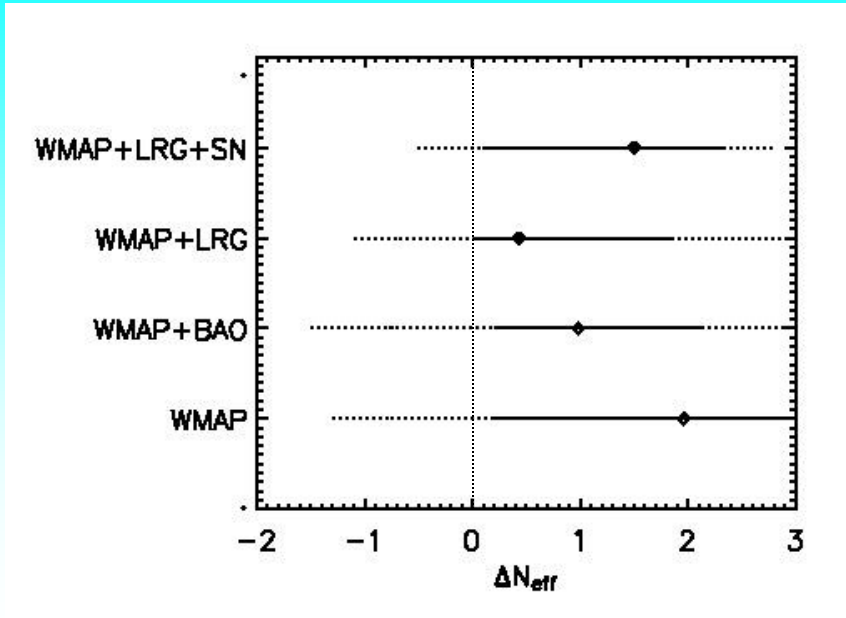


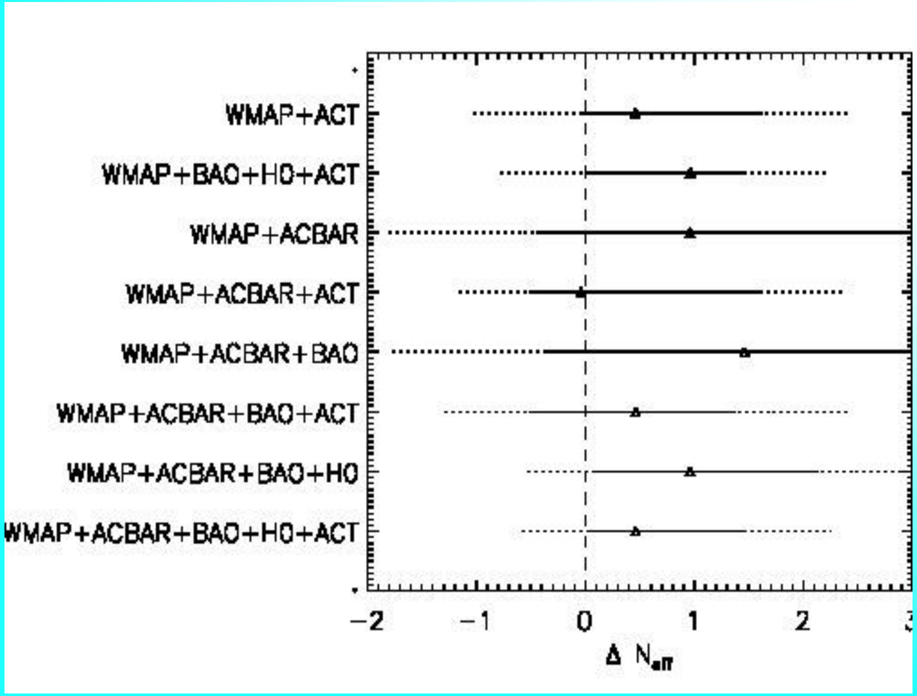


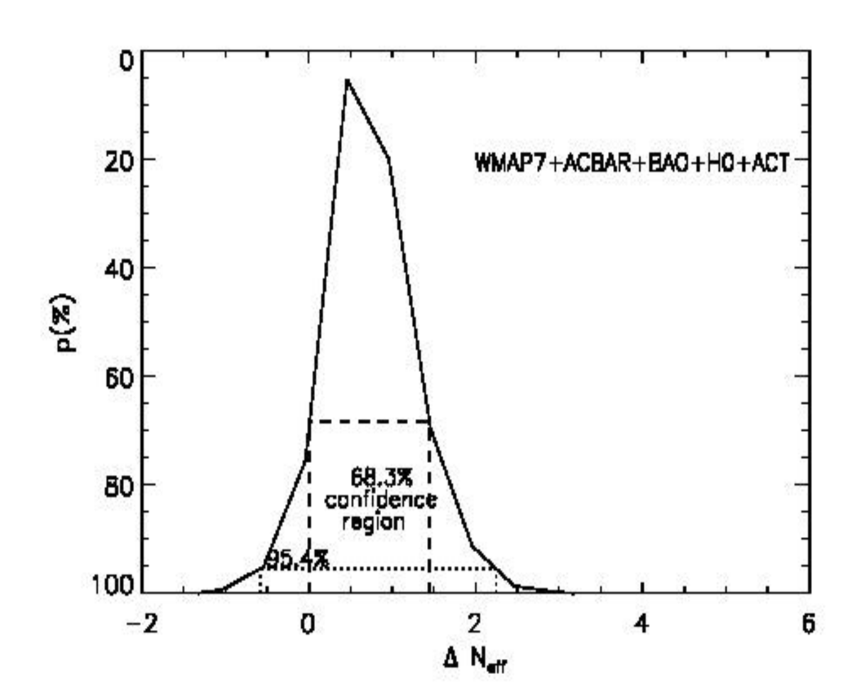
L = 541 m, $\langle E_\nu \rangle$ ~ 800 MeV
12 m diameter tank
450 t (mineral oil) 1280 PMT

N_eff

Alma X Conzalelez-Morales, et al
1106.5052 [astro-ph,CO]







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 → 0.04

Smaller values of $U_{\mu 4}$ are allowed to explain LSND/MiniBooNE – less tension with SBL experiment bounds

$|U_{\mu 4}|^2$: 0.04 → 0.02

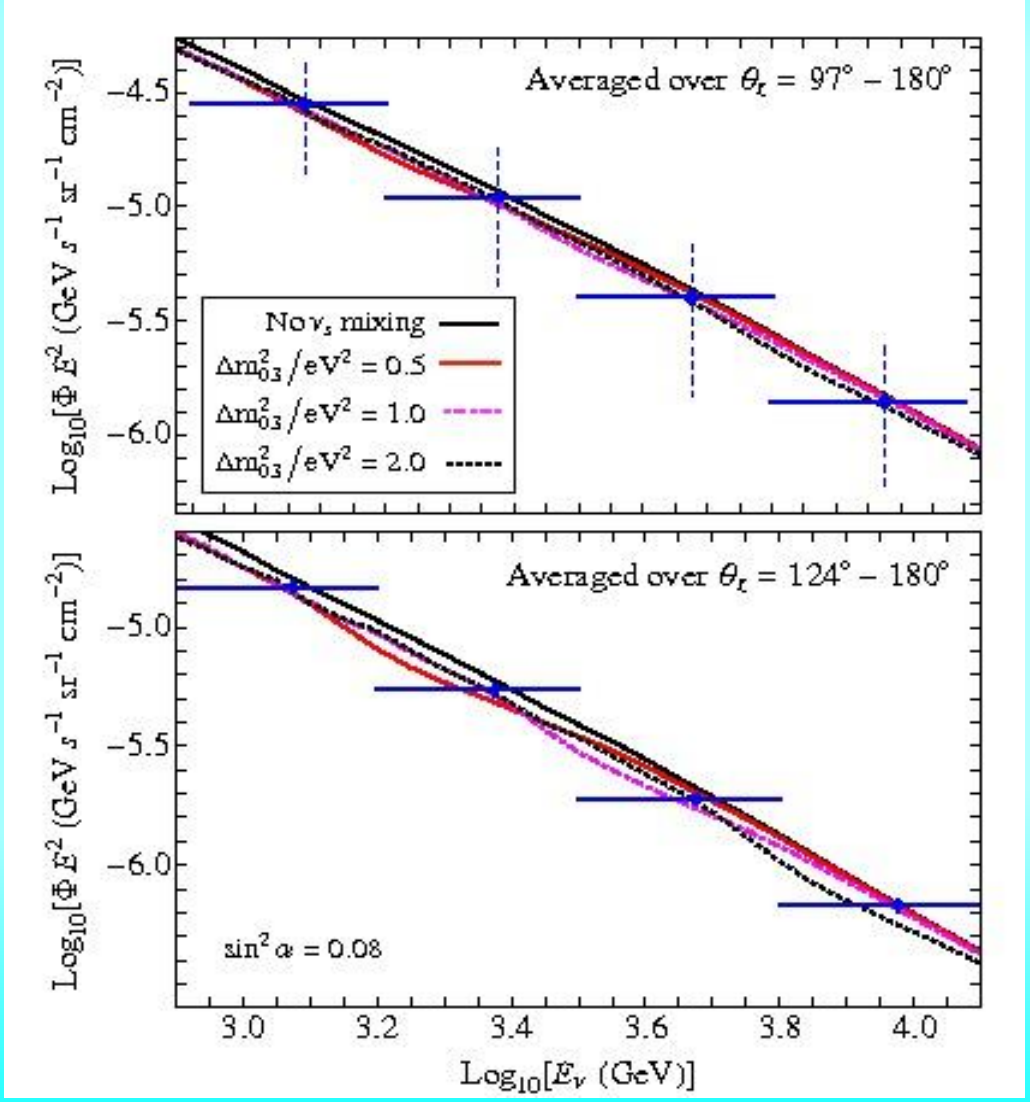
Global fit

3 + 2 scheme

ν_4	ν_5
$\Delta m_{41}^2 = 0.47\ eV^2$	$\Delta m_{51}^2 = 0.87\ eV^2$
$U_{e4} = 0.128$	$U_{e5} = 0.138$
$U_{\mu 4} = 0.165$	$U_{\mu 5} = 0.148$

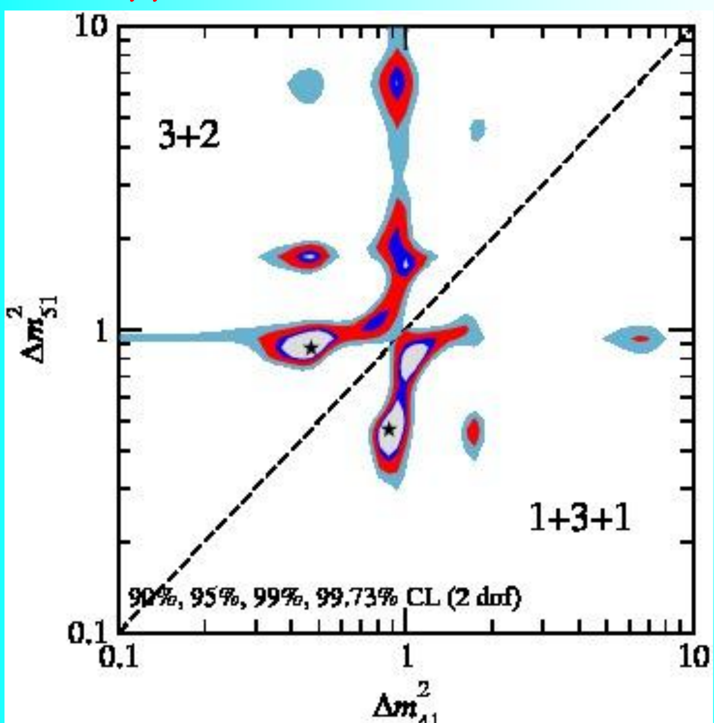
J Kopp, M. Maltoni, T.Schwetz
1103.4570 [hep-ph]

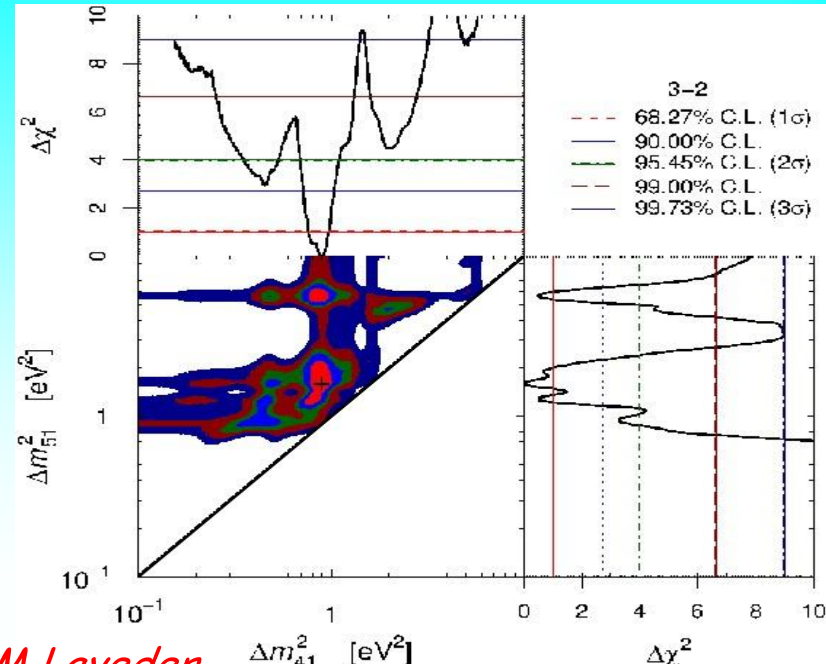
Energy spectra



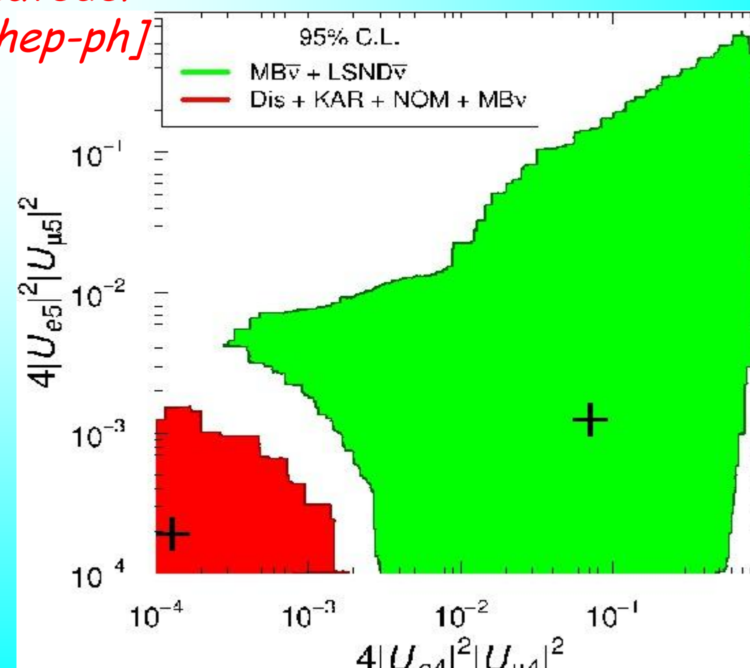
3+2 fit and consistency

J. Kopp, M Maltoni, T. Schwetz





C Giunti, M Laveder
1107.1452 [hep-ph]



Reactor neutrino anomaly

Increase of the Mean flux by 3%

Revised value of cross-section

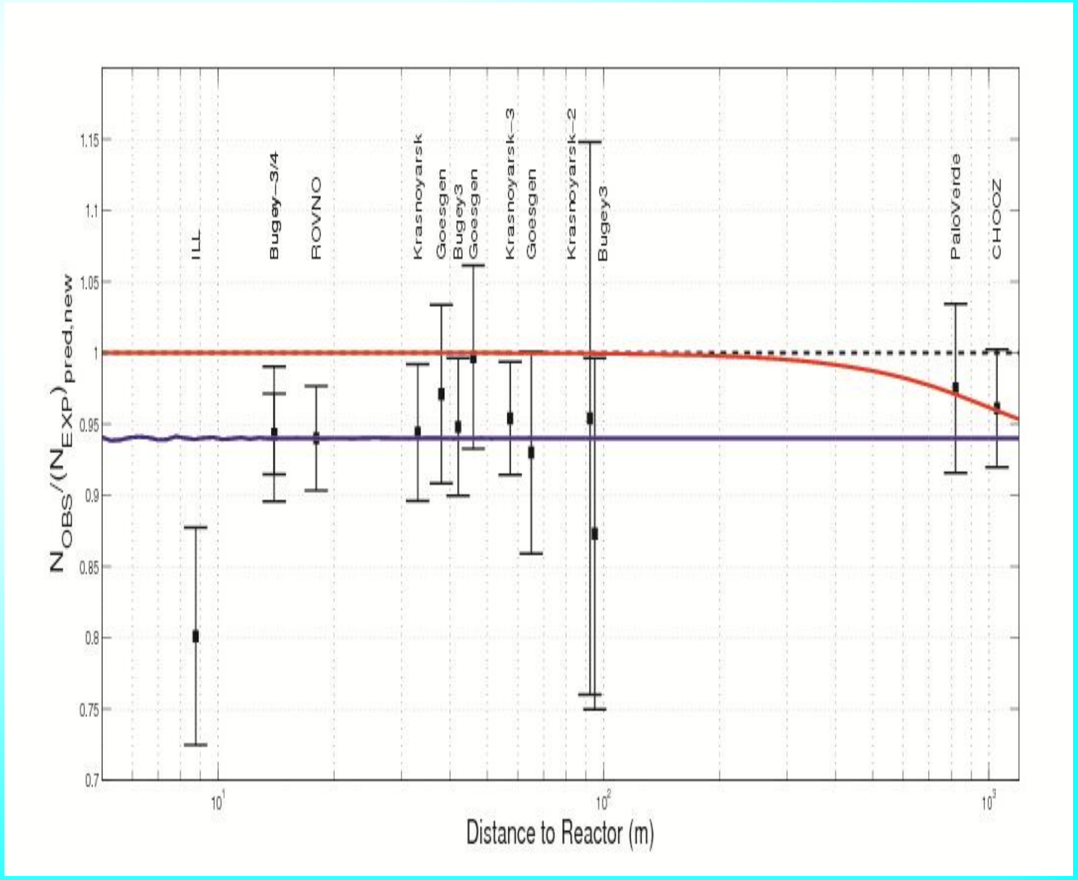
G.Mention et al, arXiv: 1101.2755

R_{react} = 0.937 +/- 0.027

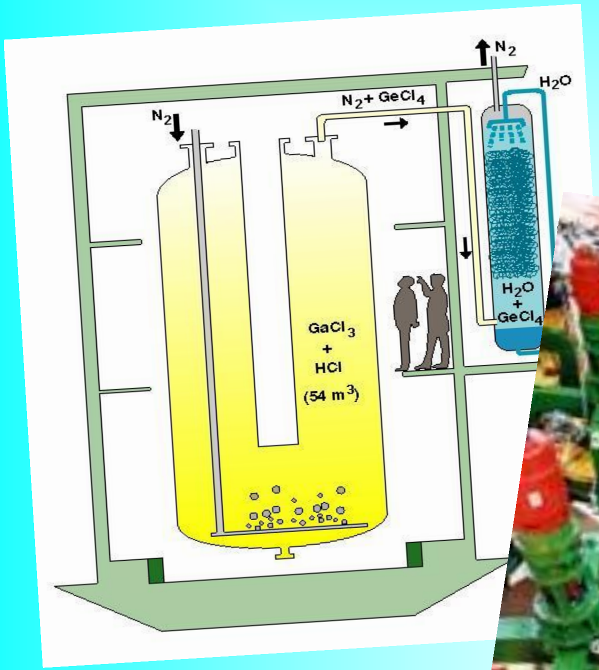
2.14 σ

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

$\sin^2 2\theta = 0.17 \pm 0.1$

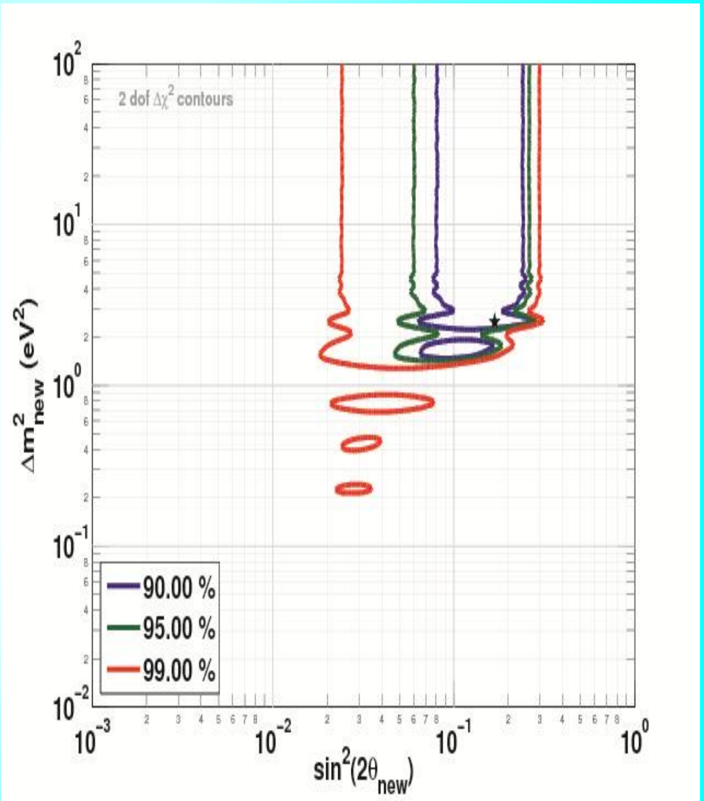


Gallium anomaly



Calibration

Source + reactor



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

$R_{Ga} = 0.87 +/- 0.05$

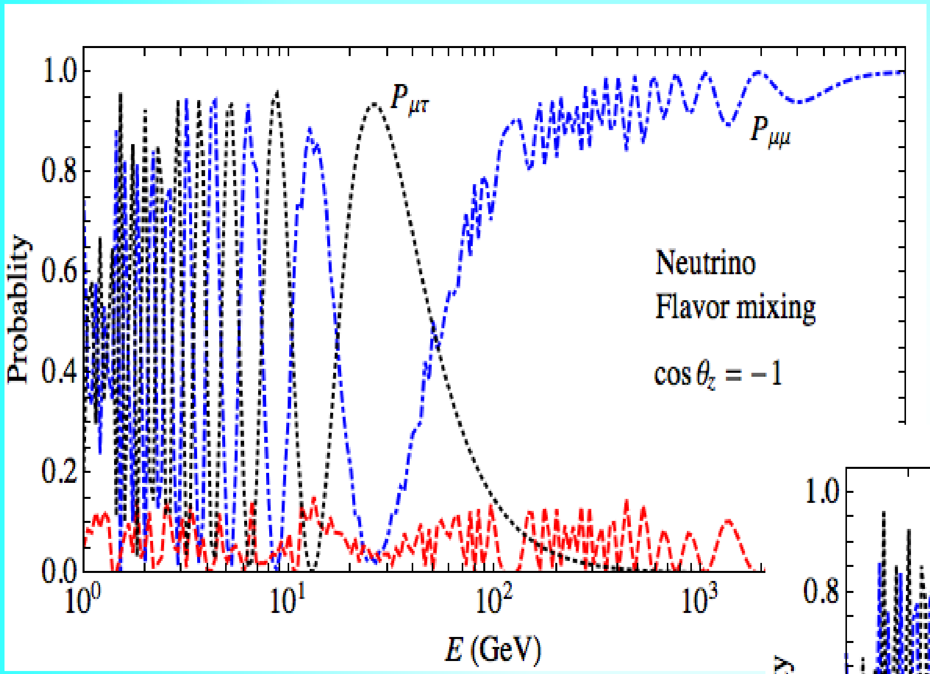
$\sin^2 2\theta = 0.24$

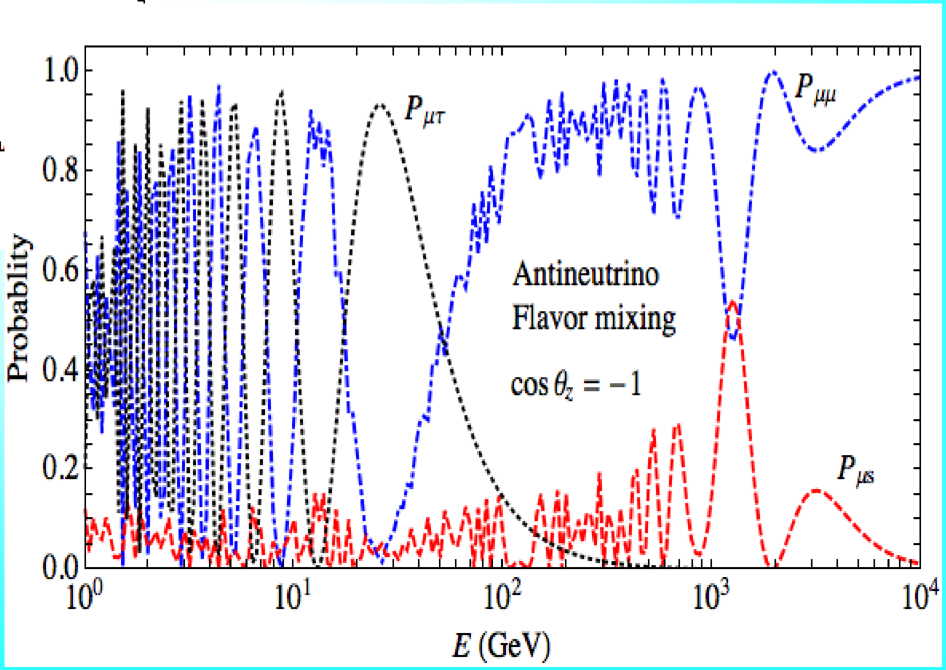
$\Delta m^2 = 2.15 \ eV^2$

C Giunti, M. Laveder

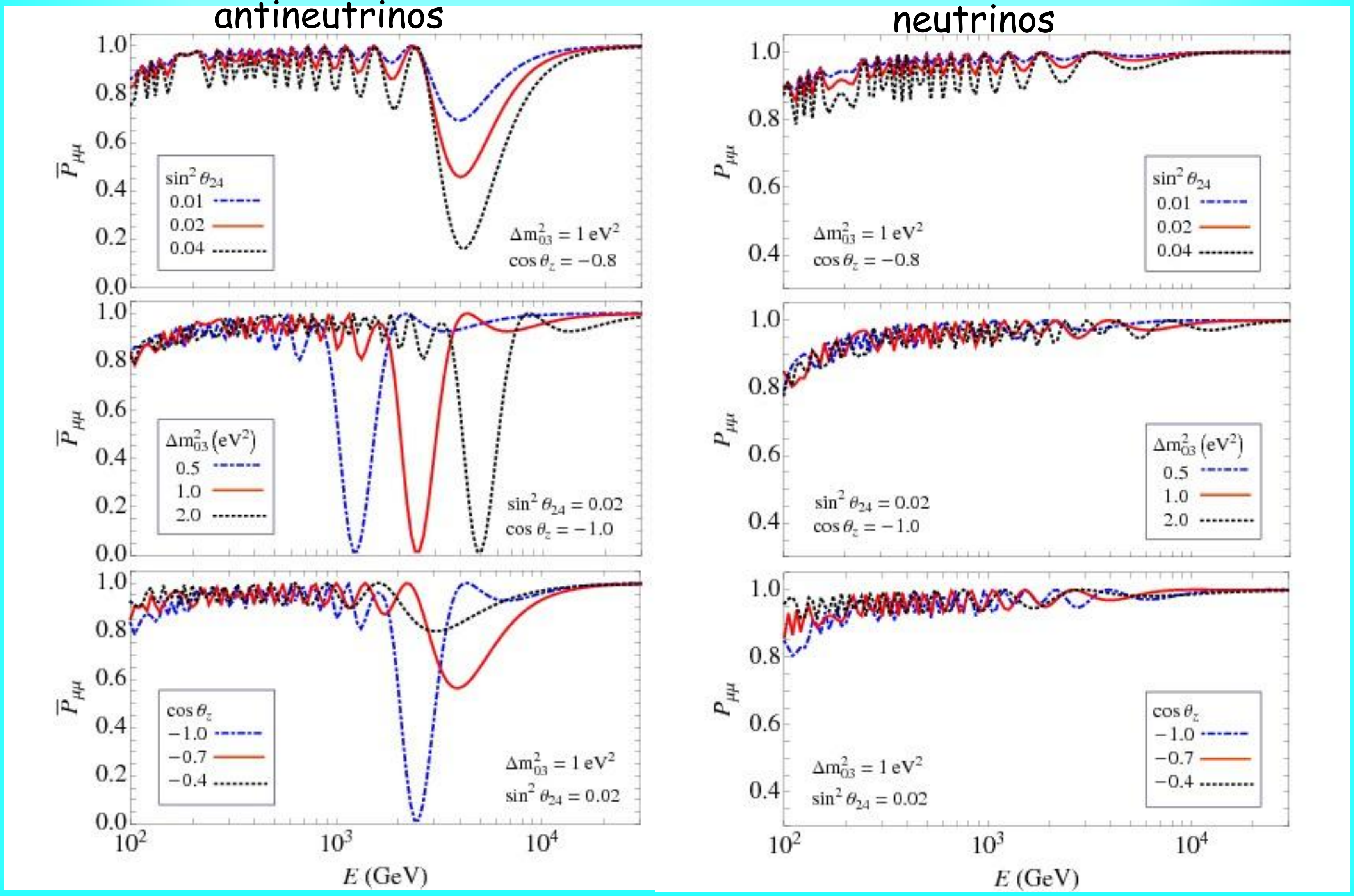
G.Mention et al, arXiv: 1101.2755

Probabilities





Probabilities



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

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

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

$\tan\theta' = - U_{\mu 0} / U_{\tau 0}$
$\sin^2\alpha = |U_{\mu 0}|^2 + | U_{\tau 0}|^2$

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

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

Probabilities