Status of the theory of Neutrino mass & mixing

A. Yu. Smirnov

International Centre for Theoretical Physics, Trieste, Italy

July 21, 2011,
The international school Daniel Chalonge

Status

the theory of neutrino mass & mixing does not exist yet

We even don't know

- nature of neutrino mass:
  Dirac vs. Majorana,
  soft vs. hard;
- absolute mass scale;
- number of neutrinos

Neutrinos & Dark Matter

indirect connection

Mechanism of neutrino mass generation

Z_2

Light active neutrinos

new particles

HDM

right handed neutrinos

Direct connection

Mixing pattern

play the role of DM

New neutrino states

Flavor symmetries

ensure stability of DM particles

Hot,warm DM

Content

I. Neutrino mass & mixing:
what do we really know

II. To the theory of neutrino mass & mixing

III. Sterile neutrinos and DM

I. Neutrino mass & mixing: what do we know

Solar neutrinos

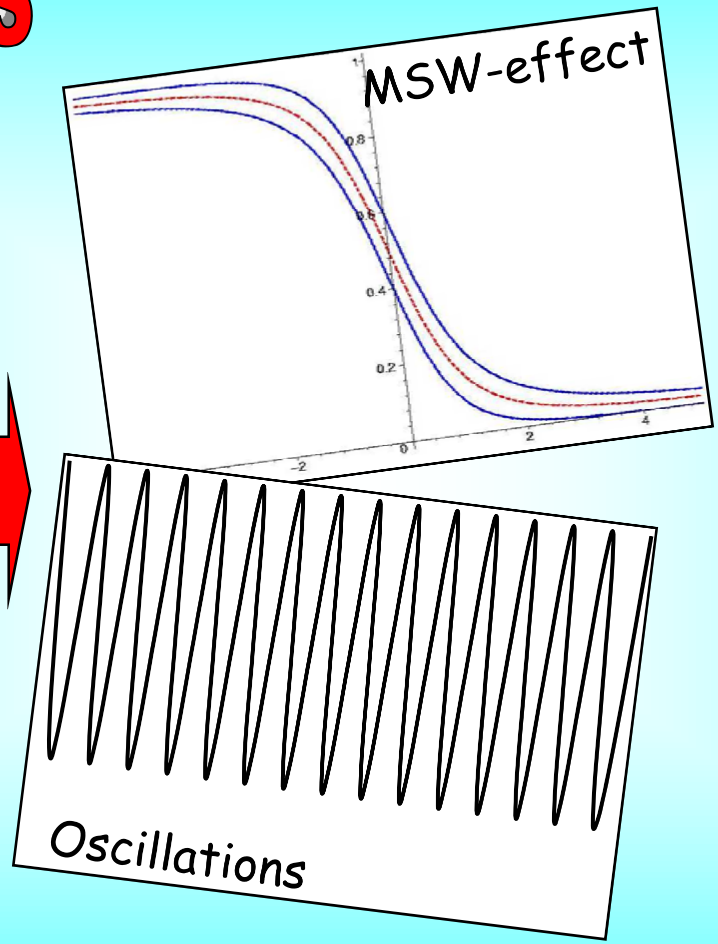
KamLAND

Atmospheric neutrinos

MINOS

K2K

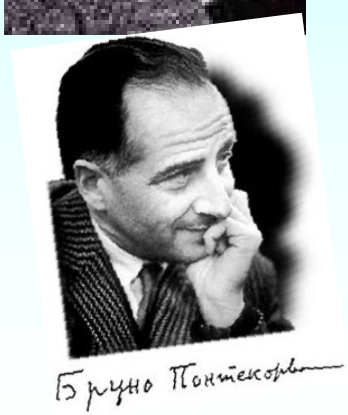
T2K



Δm^2

θ

Absolute mass scale



MINOS, atmospheric neutrinos

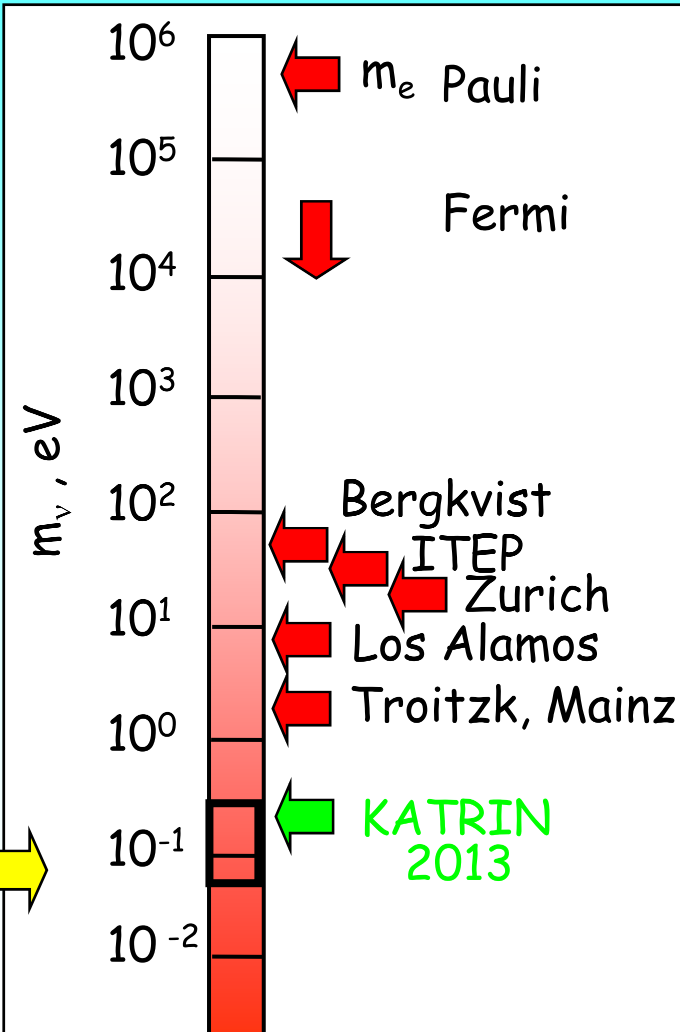
$$m > \sqrt{\Delta m_{31}^2} > 0.045 \text{ eV}$$

COSMOLOGY: bound on the sum of neutrino masses

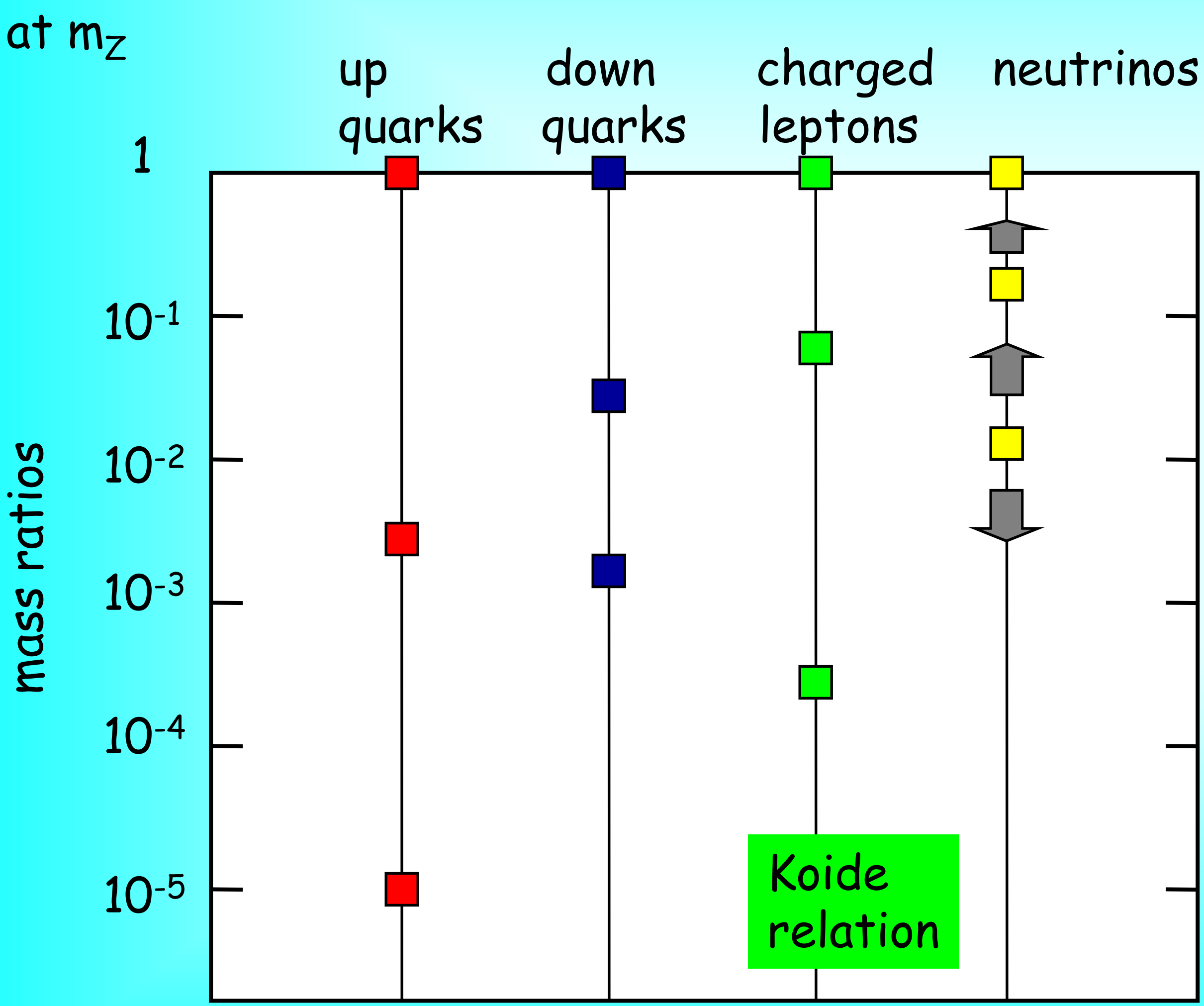
$$m < \Sigma/3 < 0.2 - 0.3 \text{ eV}$$

The heaviest neutrino has mass is in the range (0.045 - 0.30) eV

Kinematical measurements



Mass hierarchies



Solar, KamLAND

$$\frac{m_2}{m_3} \gtrsim \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{32}^2}}$$

~ 0.18

Neutrinos have the weakest mass hierarchy (if any) among fermions

Related to the large lepton mixing?

$m_u m_t = m_c^2$

$\sin\theta_C \sim \sqrt{m_d/m_s}$ Gatto-Sartori-Tonin relation

Neutrino mixing

Flavor neutrino states:

ν_e ν_μ ν_τ

e μ τ

- correspond to certain charged leptons
- interact in pairs
- flavor –characteristic of interaction

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

$\pi \rightarrow \mu + \nu_\mu$

Mass eigenstates

ν_1 ν_2 ν_3

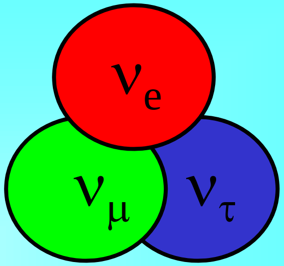
m_1 m_2 m_3

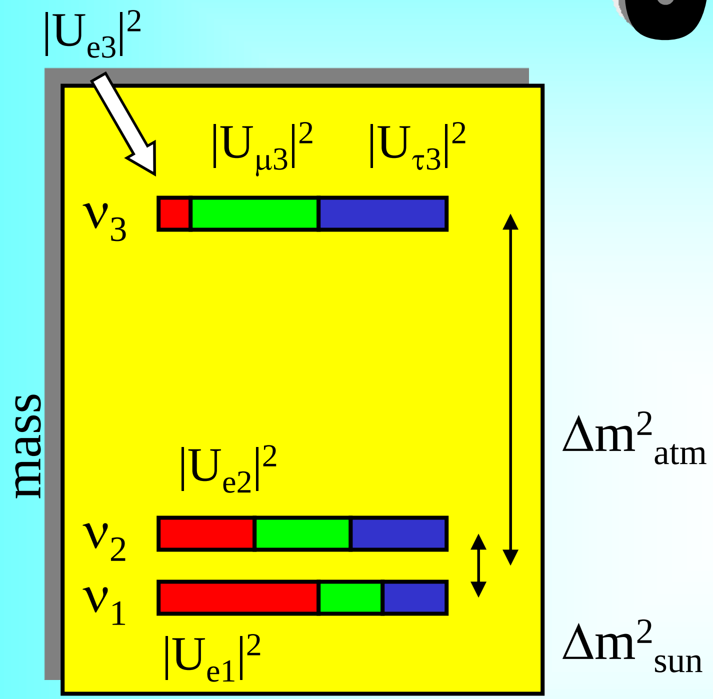
Mixing

Flavor states $\neq$ Mass eigenstates

$\nu_f = U_{PMNS}\, \nu_{mass}$

Mixing angles





Normal mass hierarchy

$$\Delta m^2_{atm} = \Delta m^2_{32} = m^2_3 - m^2_2$$

$$\Delta m^2_{sun} = \Delta m^2_{21} = m^2_2 - m^2_1$$

Mixing parameters, parameterization

$$\tan^2\theta_{12} = |U_{e2}|^2 \; / \; |U_{e1}|^2$$

$$\sin^2\theta_{13} = |U_{e3}|^2$$

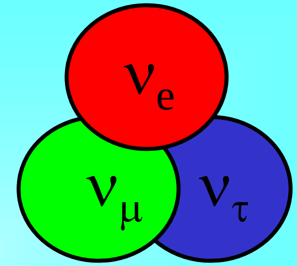
$$\tan^2\theta_{23} = |U_{\mu 3}|^2 \; / \; |U_{\tau 3}|^2$$

Rotation in 3D space

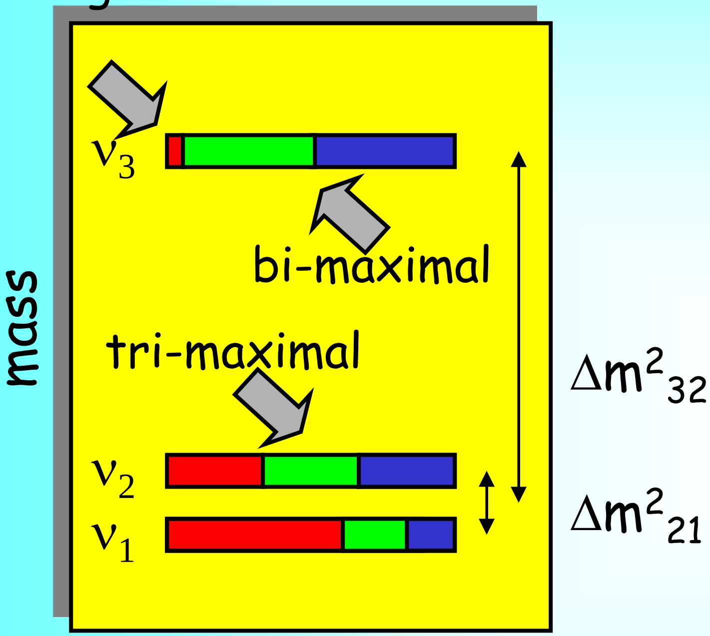
$$\nu_f = U_{PMNS} \, \nu_{mass}$$

$$U_{PMNS} = U_{23} \; I_\delta \, U_{13} \, I_{-\delta} \, U_{12}$$

Mixing

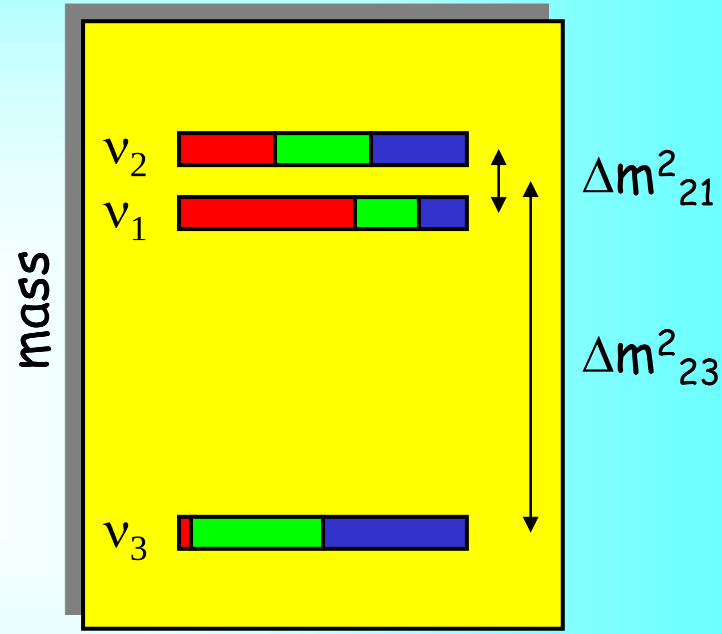


non zero
1-3 mixing



Normal mass hierarchy

?



Inverted mass hierarchy

Symmetry?

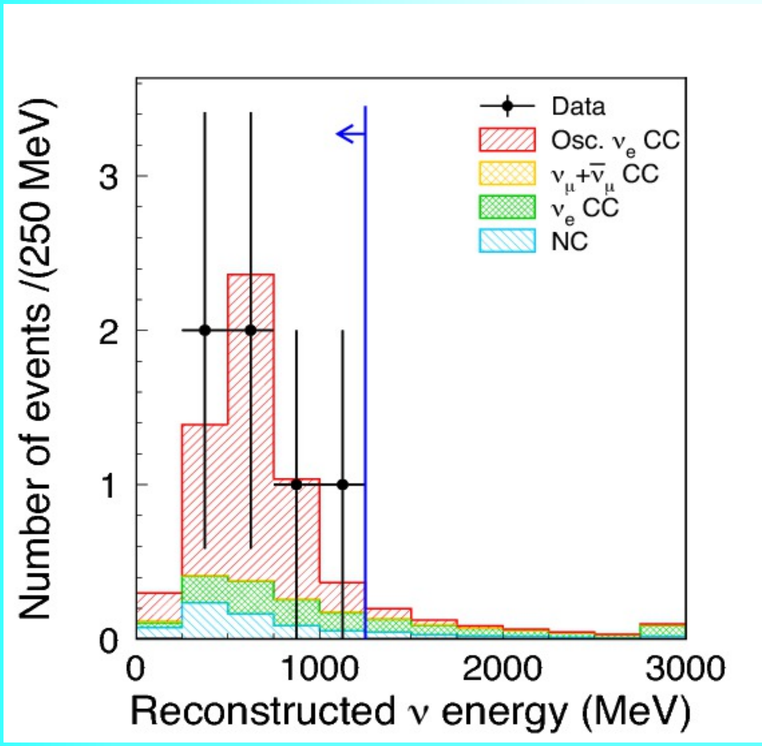
Tri-bimaximal mixing
if 1-3 mixing is zero

Accidental?

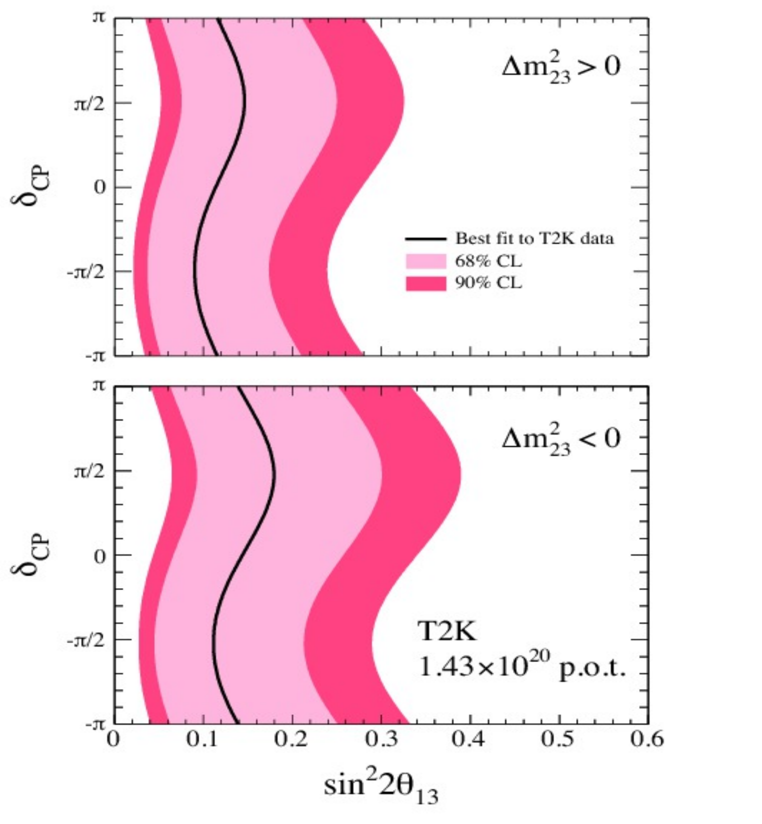
Deviations?

T2K: 1-3 mixing

K Abe, et al [The T2K Collaboration] 1106.2822 [hep-ex]



for maximal 2-3 mixing



Background = 1.5+/-0.3

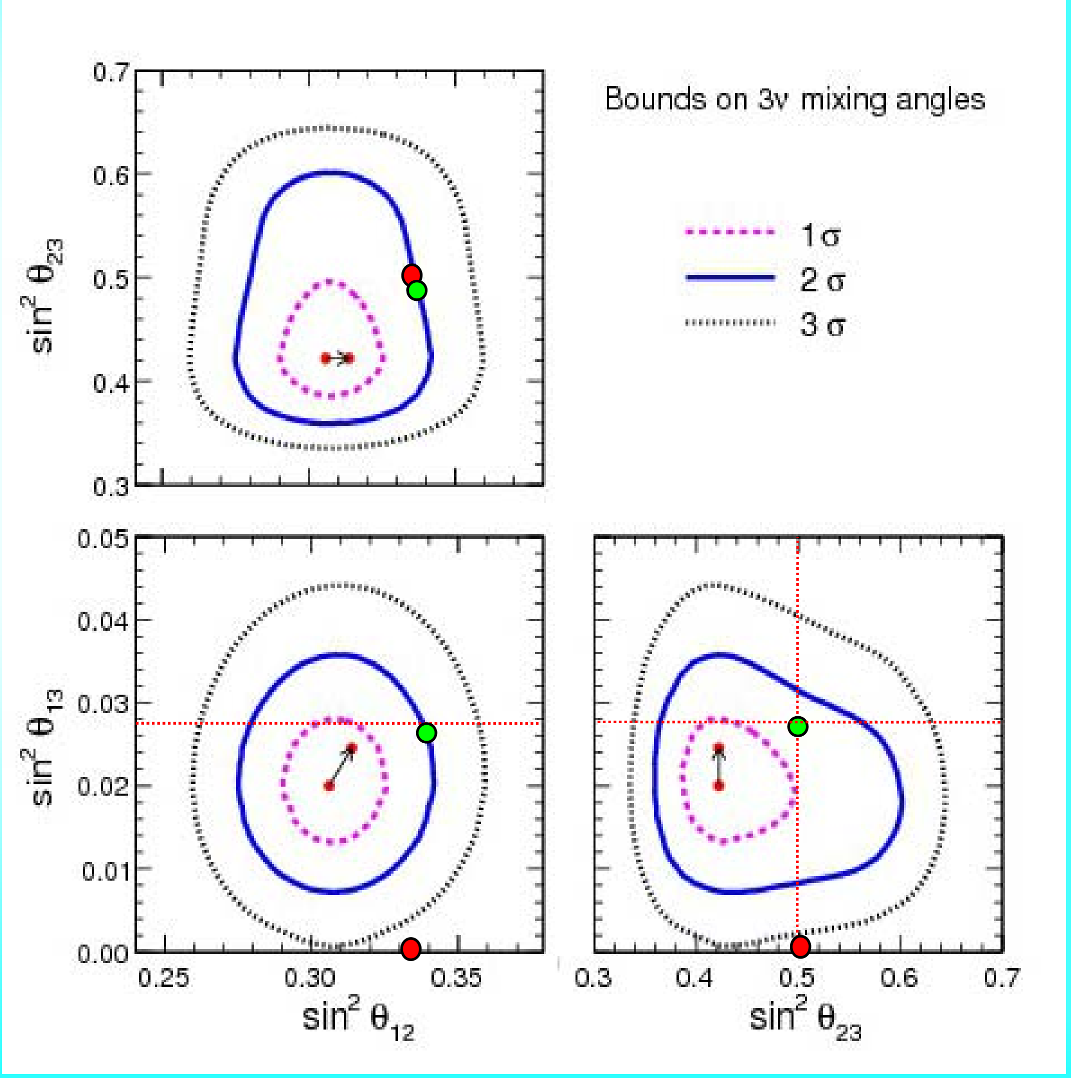
$\sin^2 2\theta_{13} \sim 0.11$

Global fit

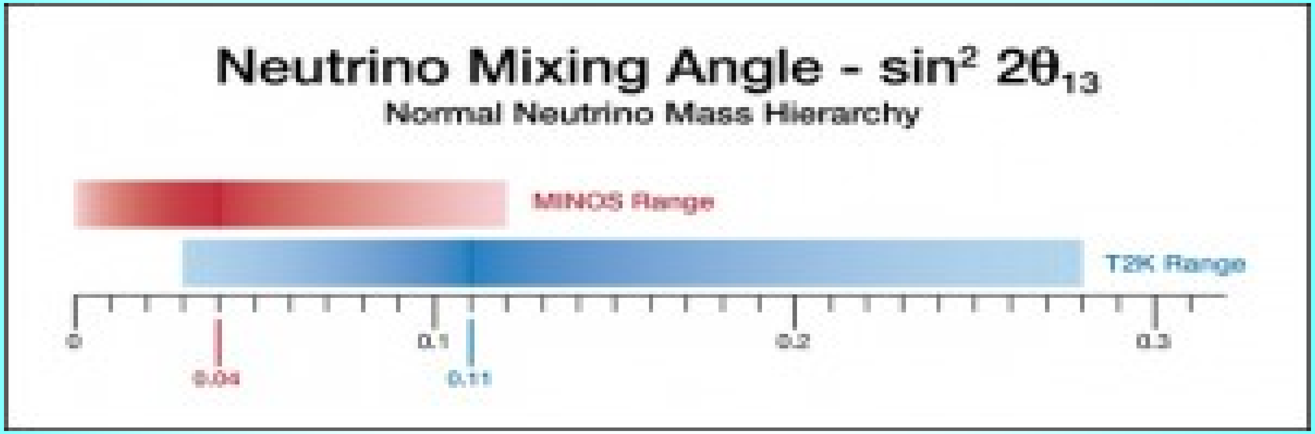
G.L Fogli et al., 1106.6028 [hep-ph]

- TBM
- QLC

New reactor fluxes
- shift by arrows



Implications



Strongly broken TBM?

Typical for flavor models of TBM: $\sin\theta_{13} \sim \sin^2\theta_C$

Quark-lepton complementarity:

$\sin^2\theta_{13} \sim 2\sin^2\theta_C$

No special symmetry in the leptonic sector

II. To the theory of neutrino mass & mixing

"Standard" neutrino scenario

1. There are only 3 types of light neutrinos

2. Interactions are described by
   the Standard (electroweak) model

3. Masses and mixing have pure vacuum origin;
   they are generated at the EW and probably
   higher mass scales

= ``Hard" masses

- High scale see-saw
- no special symmetries
- no connection to DM

Smallness of m_ν

New large mass scale

See-saw mechanism

Extra dimensions

Overlap mechanism

different localization

New symmetries

Forbid the usual Dirac mass terms

Radiative generation

High dimension operators

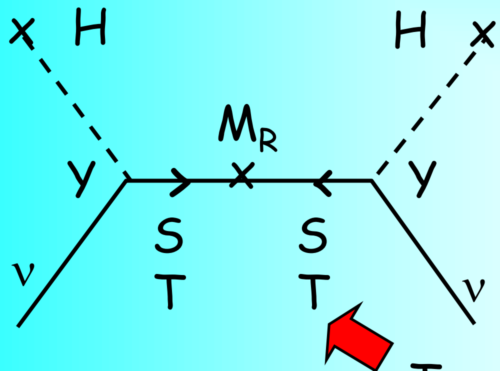
``Chiral mismatch"

Properties of RH neutrino components

See-saw

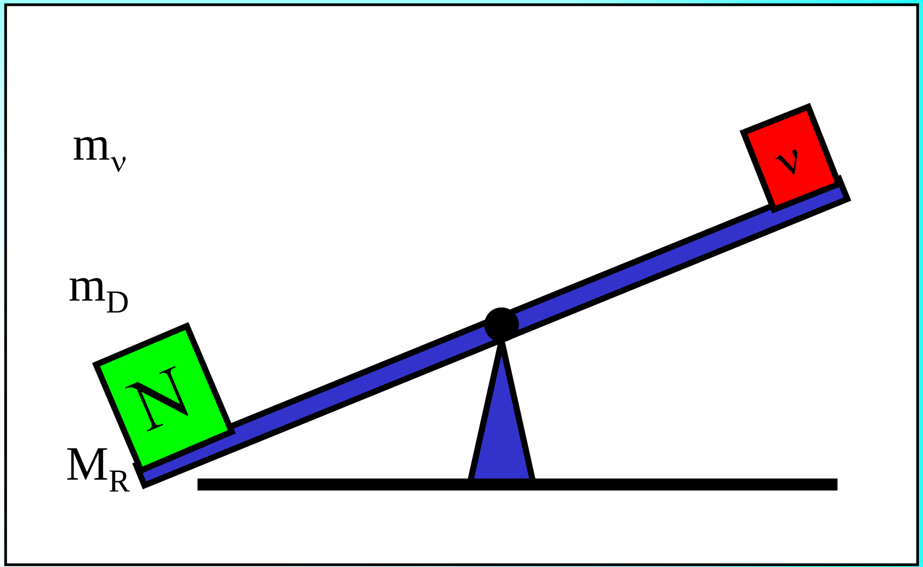
P. Minkowski
T. Yanagida
M. Gell-Mann, P. Ramond, R. Slansky
S. L. Glashow
R.N. Mohapatra, G. Senjanovic

Type 1

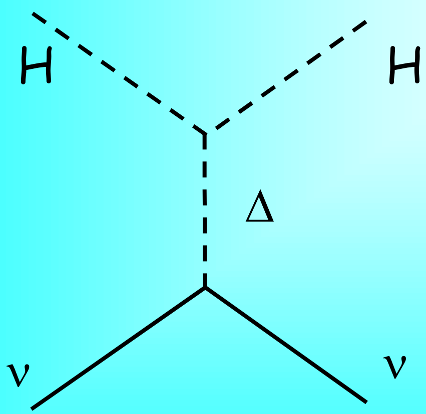


$m_D = Y\langle H\rangle$

Type 3 (triplet)



Type 2



- $$\begin{array}{c|cc} & \nu & N \\ \hline \nu & 0 & m_D \\ N & m_D^T & M_R \end{array}$$

- If $M_R \gg m_D$

$$m_n = -\ m_D^T\, M_R^{-1}\, m_D$$

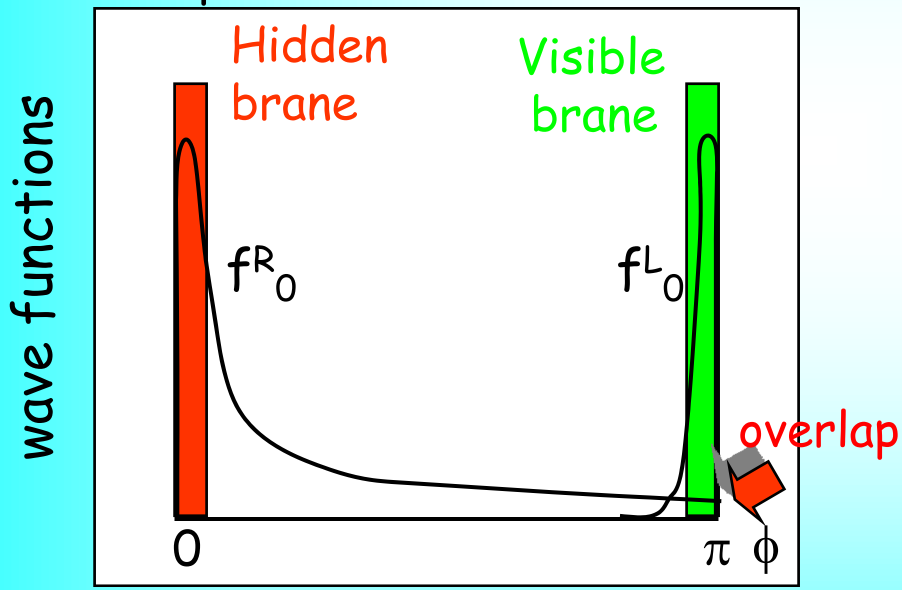
Overlap in extra dimensions

Right handed components are localized differently in extra dimensions

small Dirac masses due to overlap suppression:

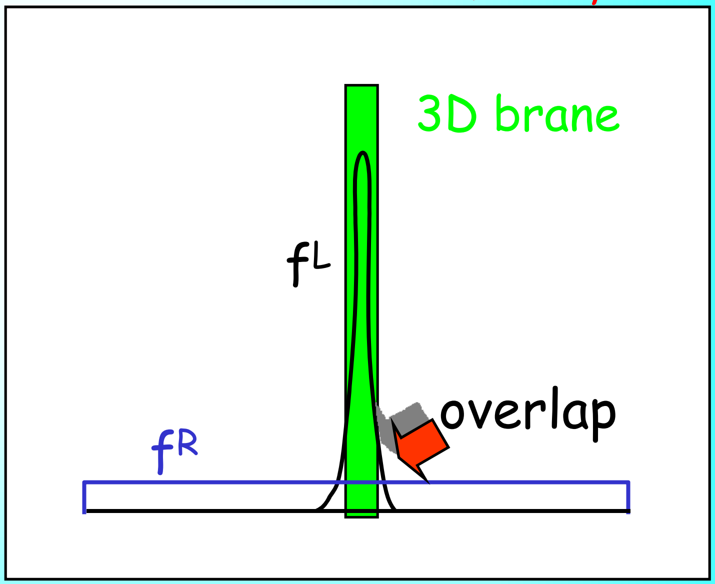
Warped extra D

Grossman Neubert



Flat extra D

Arkani-Hamed, Dvali, Dimopoulos



$$m\,\varepsilon\,\overline{f^L}\,f^R + h.\,c.$$

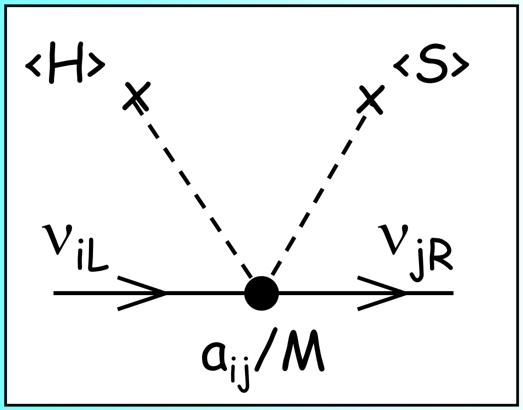
amount of overlap in extra D

Small effective couplings

renormalizable coupling is suppressed by symmetry

effective coupling produced by non-renormalizable operators:

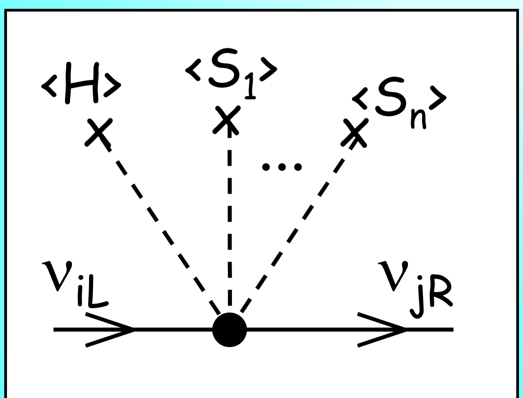
$$a_{ij}\, l_{iL} \nu_{iL}\, H \frac{S}{M}$$



$$h_{ij} = a_{ij} \frac{\langle S \rangle}{M}$$

For $a_{ij} \sim O(1)$

$$\frac{\langle S \rangle}{M} \sim 10^{-13}$$



in general

SUSY / GUT scales?

$m_{3/2}/M_{Planck}$

Mixing pattern

Tri-bimaximal mixing

Quark-Lepton complementarity

Quark-lepton universality

Assuming that it is not accidental and there is certain fundamental physics behind

Based on observation: lepton mixing = maximal mixing - quark mixing

The same principle as in quark sector

Large mixing is related to smallness of neutrino mass and weak mass hierarchy of neutrinos

<u>With different implications</u>

Tri-bimaximal mixing

L. Wolfenstein

P. F. Harrison
D. H. Perkins
W. G. Scott

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

- maximal 2-3 mixing
- zero 1-3 mixing, no CP-violation

- $\sin^2\theta_{12} = 1/3$

ν_3 is bi-maximally mixed

ν_2 is tri-maximally mixed

$U_{tbm} = U_{23}(\pi/4)\, U_{12}$

Mixing follows from diagonalization of mass matrices

Mass matrix in flavor basis:

$$m_{TBM} = \begin{pmatrix} a & b & b \\ \ldots & c & d \\ \ldots & \ldots & c \end{pmatrix}$$

Mass relations

$m_{e\mu} = m_{e\tau}$

$m_{\mu\mu} = m_{\tau\tau}$

$m_{ee} + m_{e\mu} = m_{\mu\mu} + m_{\mu\tau}$

Symmetry

TBM-symmetry

Invariance: $V_i^T m_{TBM} V_i = m_{TBM}$

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ \dots & -1 & 2 \\ .. & \dots & -1 \end{pmatrix} \qquad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

The mass matrix
of the charged leptons
is diagonal due to symmetry

$$T = \begin{pmatrix} 1 & 0 & 0 \\ \dots & \omega^2 & 0 \\ \dots & \dots & \omega \end{pmatrix} \qquad \omega = \exp(-2i\pi/3)$$

$$T^+ (m_e^+ m_e) T = m_e^+ m_e$$

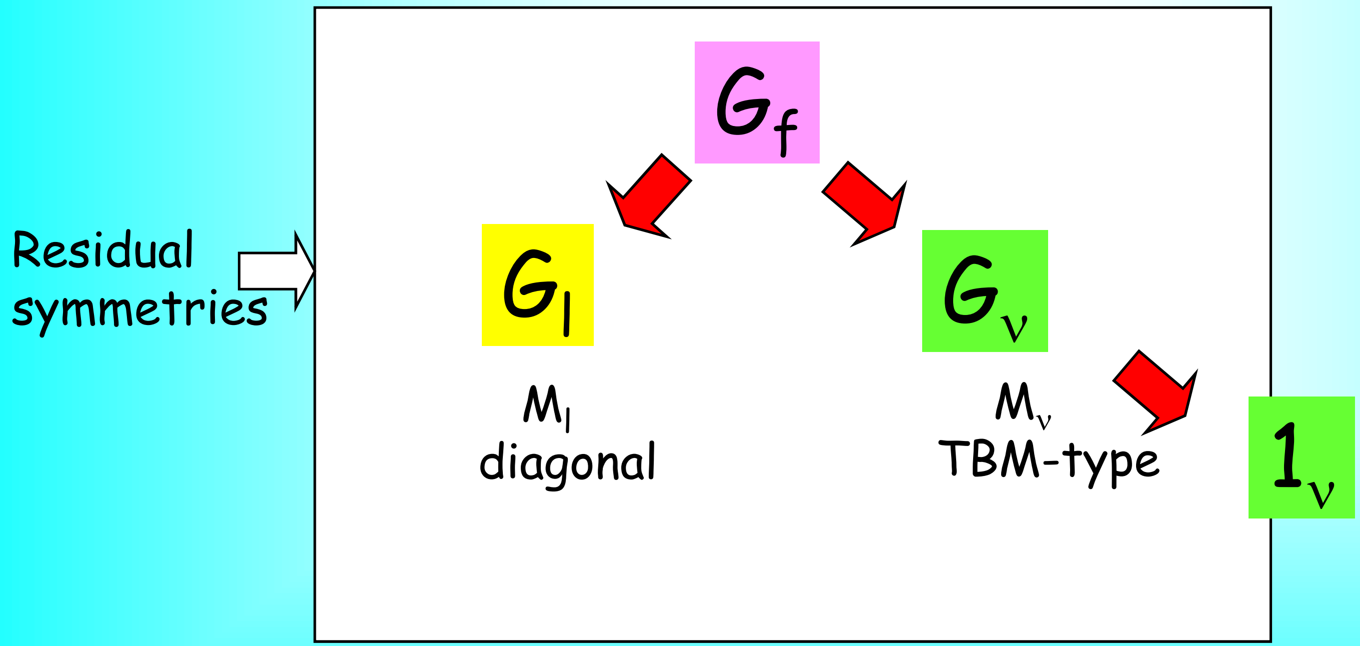
S, T, U – elements of S_4

Symmery breaking

No exact flavor symmetry

Mixing appears as a result of different ways of the flavor symmetry breaking in neutrino and charged lepton sectors

Symmetry is not broken completely; residual symmetries in the neutrino and charged lepton sectors are different



In turn, this split originates from different flavor assignments of the RH components of N^c and l^c and different higgs multiplets

Flavons and Flavored higgses

Flavons

Singlet of gauge
symmetry group

Separation of the EW symmetry
and flavor symmetry breakings

$$\frac{1}{\Lambda^{n-1}} L\, e^c\, H\, f^n$$

Λ - above GUT scale?

→ difficult to test

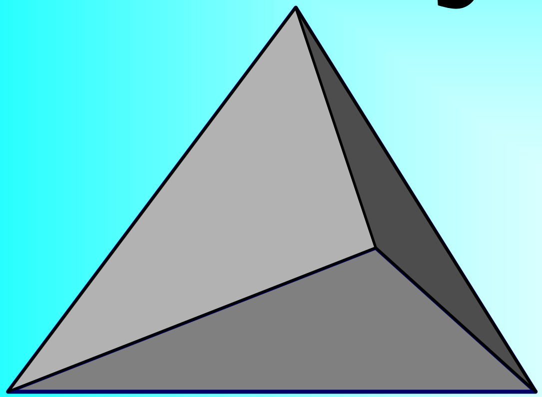
Flavored higgses

Many Higgs doublets
- tests at LHC

Strongly restricted:
- FCNC
- anomalous magnetic moment of muon

A_4 symmetry

E. Ma
G Branco, H P Nilles



A_4 Symmetry group of even permutations of 4 elements

Symmetry of tetrahedron

Generators: S, T

Presentation of the group: $S^2 = 1$ $T^3 = 1$ $(ST)^3 = 1$

no U = $A_{\mu\tau}$

Irreducible representations: $\underline{3}$, $\underline{1}$, $\underline{1}'$, $\underline{1}''$

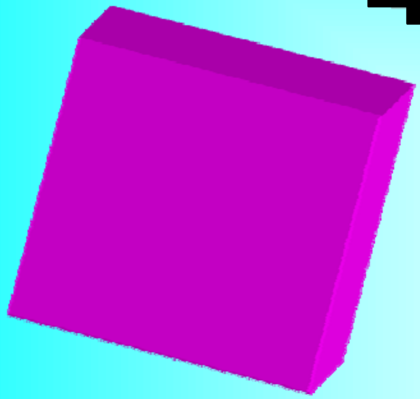
Products and invariants

$\underline{3} \times \underline{3} = \underline{3} + \underline{3} + \underline{1} + \underline{1}' + \underline{1}''$

$\underline{1}' \times \underline{1}'' \sim \underline{1}$

S_4-symmetry

S Pakvasa



Order 24, permutation of 4 elements

Generators: S, T, U

Presentation: $T^3 = 1$, $S^2 = 1$, $(ST)^3 = 1$ $U^2 = 1$

or

$A^3 = B^4 = (BA^2)^2 = 1$

Irreducible representations:

$1,\ 1',\ 2,\ 3,\ 3'$

Products and invariants

$3 \times 3 = 3' \times 3' = 1 + 2 + 3 + 3'$

$3 \times 3' = 1' + 2 + 3 + 3'$

$1' \times 1' = 1$

New flavor structure

$2 \times 3 = 2 \times 3' = 3 + 3'$

$2 \times 2 = 1 + 1' + 2$

$1' \times 2 = 2$

Is TBM accidental?

Numerology without underlying framework

Interplay of various independent contributions

1. Experiment: deviations from TBM mixing

RGE-effects

Symmetry mass relations can be broken maximally

2. No simple and convincing model for TBM

- Complicated structure, large number of assumptions and new parameters
- Follows from certain correlation of unrelated sectors

3. Often: no connection between masses and mixing
additional symmetries are introduced

4. Inclusion of quarks: further complication.
GUT – additional requirements

Quark-Lepton Complementarity

Based on relations:

A.S.
M. Raidal
H. Minakata

$$\theta^l_{12} + \theta^q_{12} \sim \pi/4$$

$$\theta^l_{23} + \theta^q_{23} \sim \pi/4$$

qualitatively:

- 2-3 leptonic mixing is close to maximal because 2-3 quark mixing is small
- 1-2 leptonic mixing deviates from maximal substantially because 1-2 quark mixing is relatively large

Possible implications

``Lepton mixing = bi-maximal mixing – quark mixing"

Quark-lepton symmetry

Unification or
family symmetry

Existence of structure
which produces
bi-maximal mixing

See-saw?
Properties of
the RH neutrinos

Bi-maximal mixing

$U_{bm} = U_{23}^m U_{12}^m$

Two maximal rotations

F. Vissani

V. Barger et al

$$U_{bm} = \begin{pmatrix} \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \sqrt{\frac{1}{2}} \\ \frac{1}{2} & -\frac{1}{2} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

- maximal 2-3 mixing
- zero 1-3 mixing
- maximal 1-2 mixing
- no CP-violation

In seesaw: structure of Majorana mass matrix of RH neutrinos

In the lowest approximation:

$V_{quarks} = I, \quad V_{leptons} = V_{bm}$

$m_1 = m_2 = 0$

Corrections generate
- mass splitting
- CKM and
- deviation from bi-maximal

Deviation

Complementarity or Cabibbo ``haze''

Deviations from BM due to high order corrections *P. Ramond*

Altarelli et al

Complementarity:
implies quark-lepton
symmetry or GUT,
or horizontal symmetry

Weak complementarity or
Cabibbo haze

Corrections from high order
flavon interactions which generate
simultaneously Cabibbo mixing and
deviation from BM,
GUT is not necessary

or

$$\sin\theta_C = \sqrt{\frac{m_\mu}{m_\tau}}$$

→

$\sin\theta_C = 0.22$
as ``quantum'' of
flavor physics

Neutrino and unification

Correspondence:

u_r , u_b , u_j <-> ν
d_r , d_b , d_j <-> e

Symmetry:

Leptons as 4th color Pati-Salam

Unification:

Form multiplet of the extended gauge group, in particular, 16-plet of SO(10)

Can it be accidental?

GUT

Unification of
- quarks & leptons
- couplings

SO(10) GUT + ...

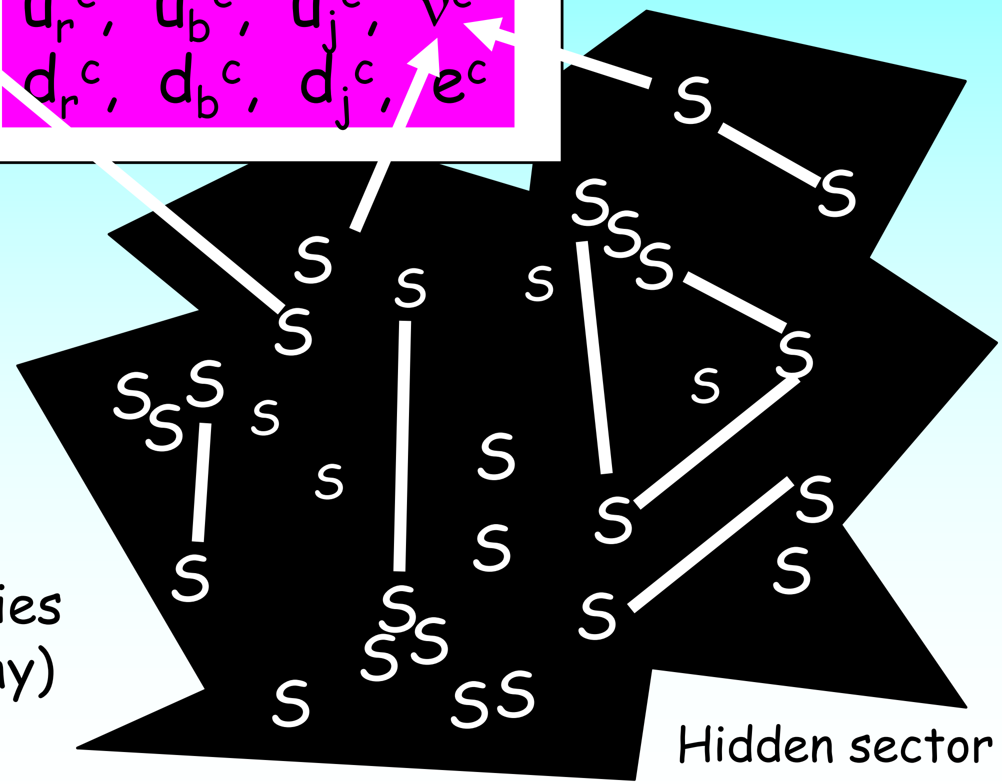
Hagedorn
Schmidt
AS

Something is missed?

RH-neutrino

16

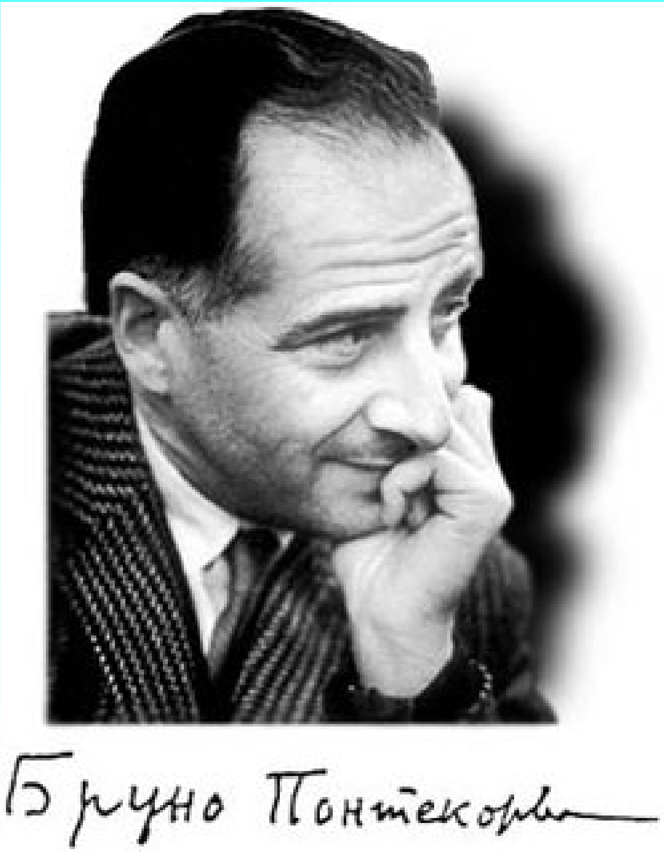
u_r , u_b , u_j , ν	u_r^c, u_b^c, u_j^c, ν^c
d_r , d_b , d_j , e	d_r^c, d_b^c, d_j^c, e^c



- Decrease effective scale
- Enhance mixing
- Produce zero order mixing
- Screen Dirac mass hierarchies
- Produce randomness (anarchy)
- Seesaw symmetries

III. Sterile neutrinos

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

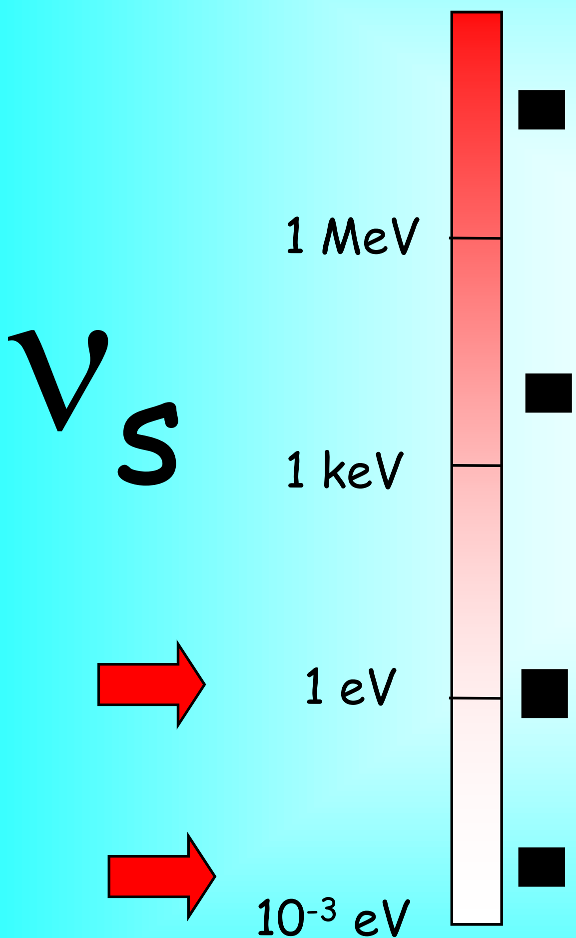
RH - components
of neutrinos

Couple with usual neutrinos
via (Dirak) mass terms

Mix with active neutrinos

may have Majorana
mass terms
maximal mixing?

Mass scales



40 - 70 MeV
- LSND, MiniBooNE

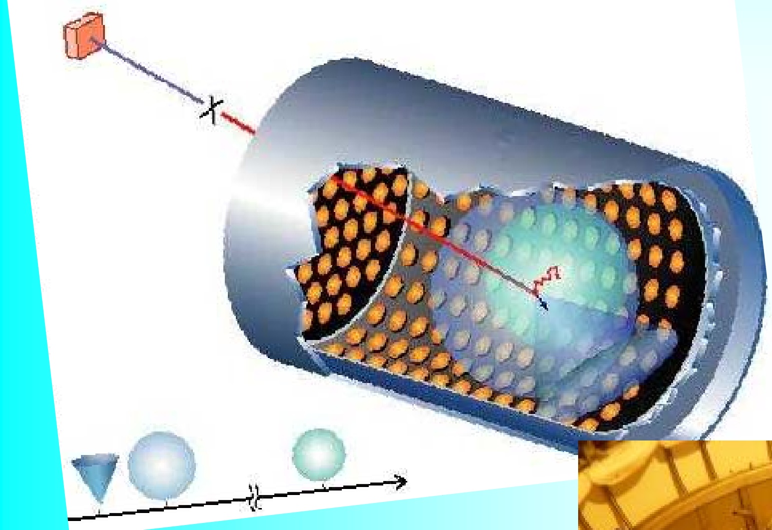
~ 10 keV
- Warm Dark matter
- Pulsar kick

0.5 - 2 eV
- LSND, MiniBooNE
- Reactor anomaly
- Calibration experiments
- Extra radiation

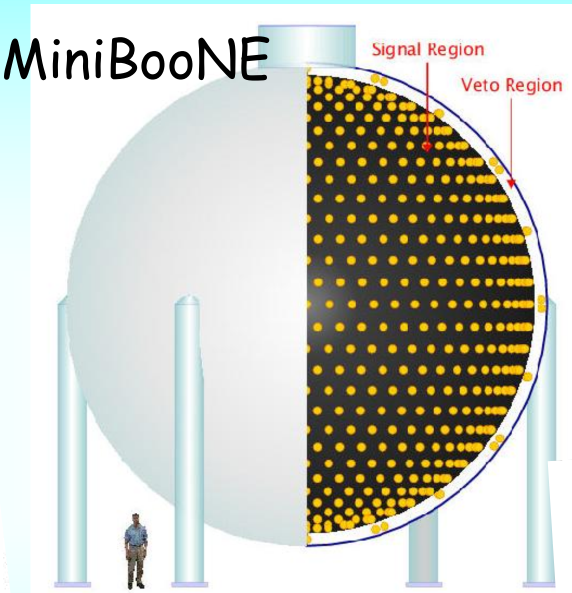
(2 – 4) 10^{-3} eV
- Solar neutrinos
- Extra radiation in the Universe

New evidences?

LSND

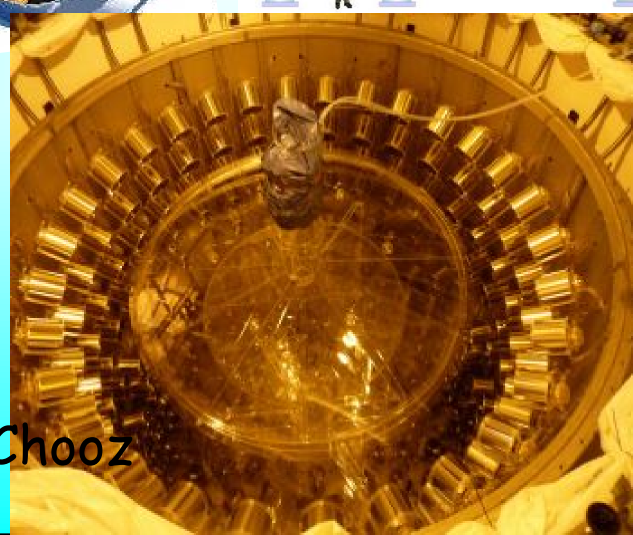


MiniBooNE

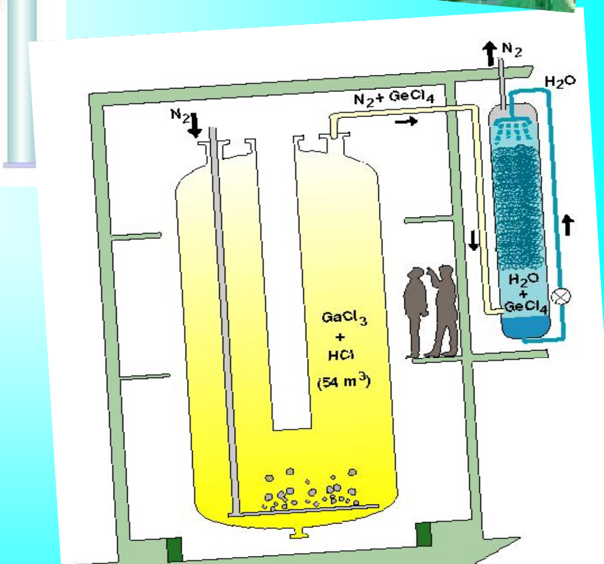


SAGE

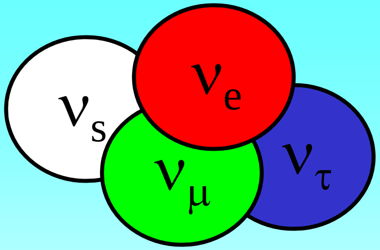
Double-Chooz

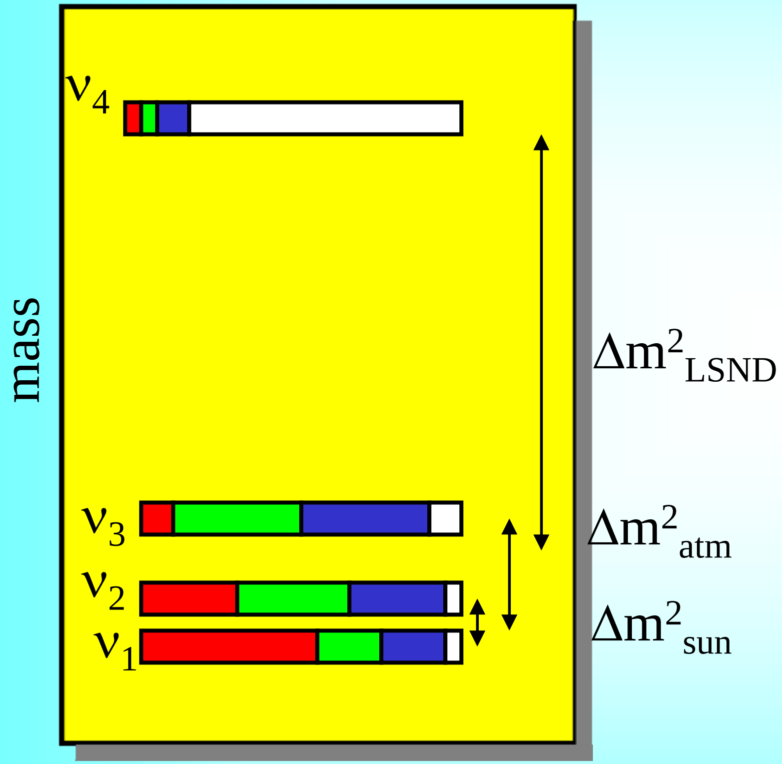


Gallex,GNO



(3 + 1) scheme





LSND/MiniBooNE: vacuum oscillations

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

restricted by short baseline exp.
BUGEY, CHOOZ, CDHS, NOMAD

For reactor and source experiments

$P \sim 4|U_{e4}|^2(1 - |U_{e4}|^2)$

With new reactor data:

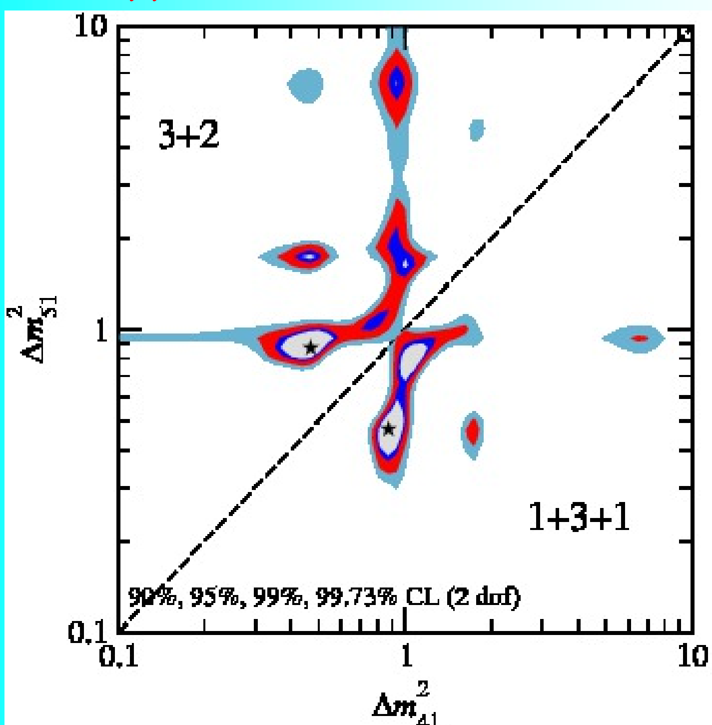
$\Delta m_{41}{}^2$ = 1.78 eV^2 (0.89 eV^2)

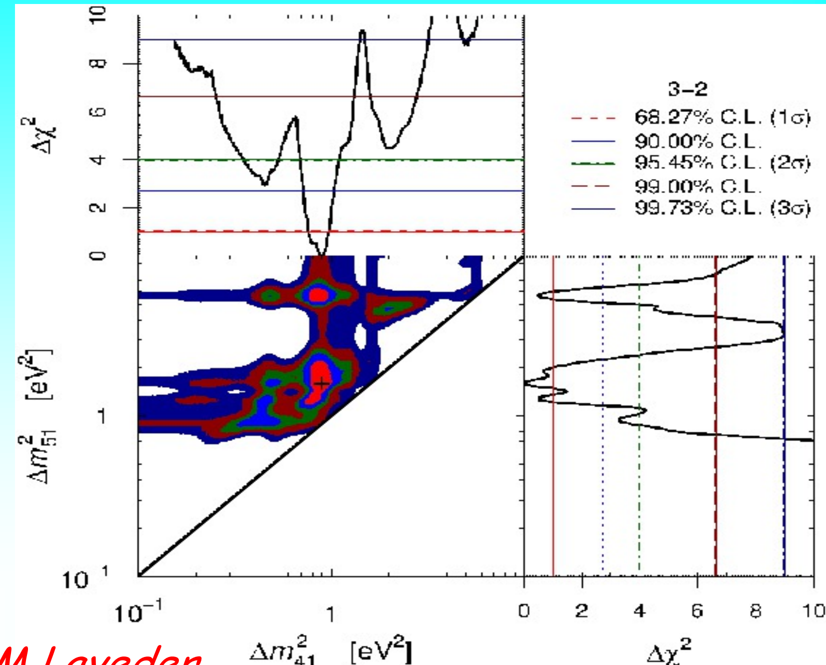
U_{e4} = 0.15 $U_{\mu 4}$ = 0.23

- additional radiation in the universe
- bound from LSS?

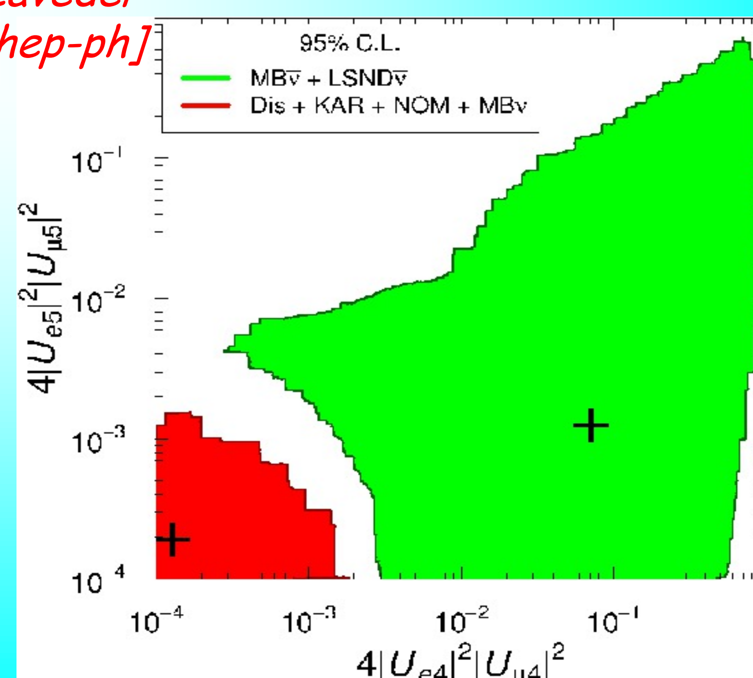
3+2 fit and consistency

J. Kopp, M Maltoni, T. Schwetz



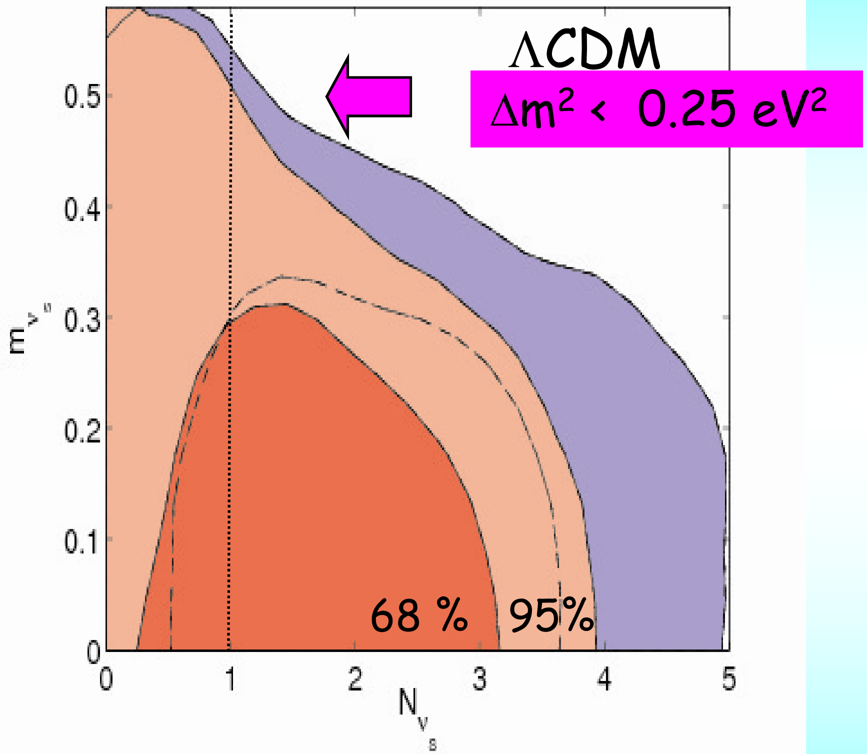


C Giunti, M Laveder
1107.1452 [hep-ph]



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

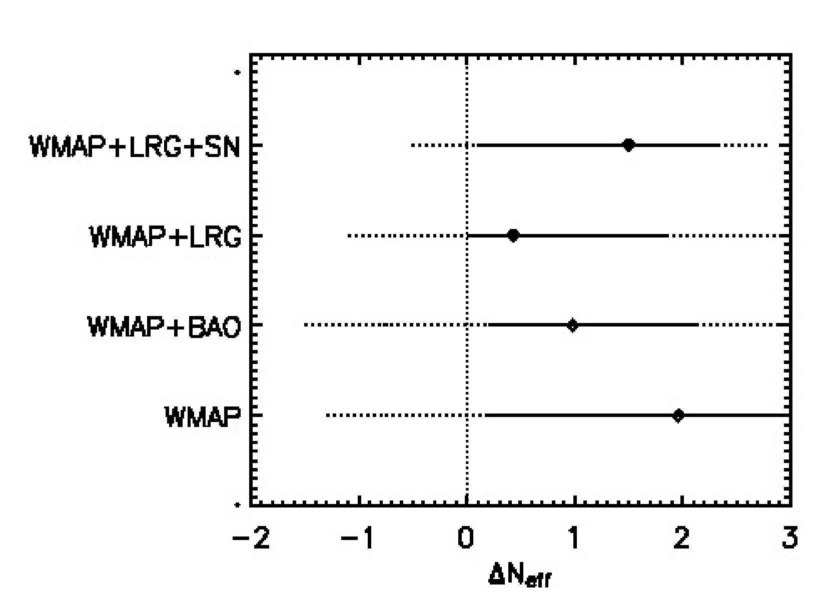
2). Age of the Universe
12.58 +/- 0.26 Gyr

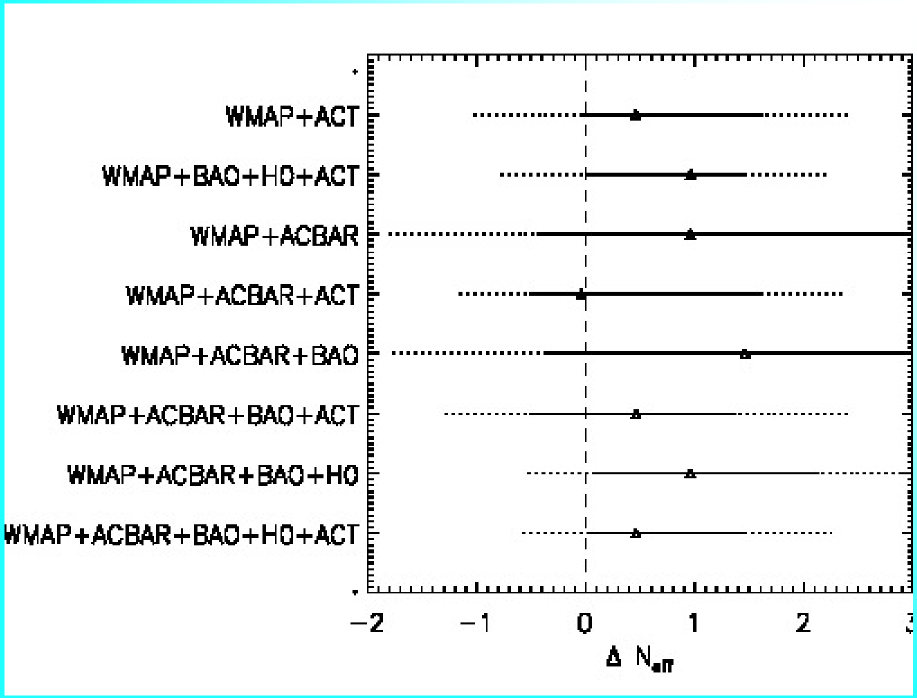
too young?

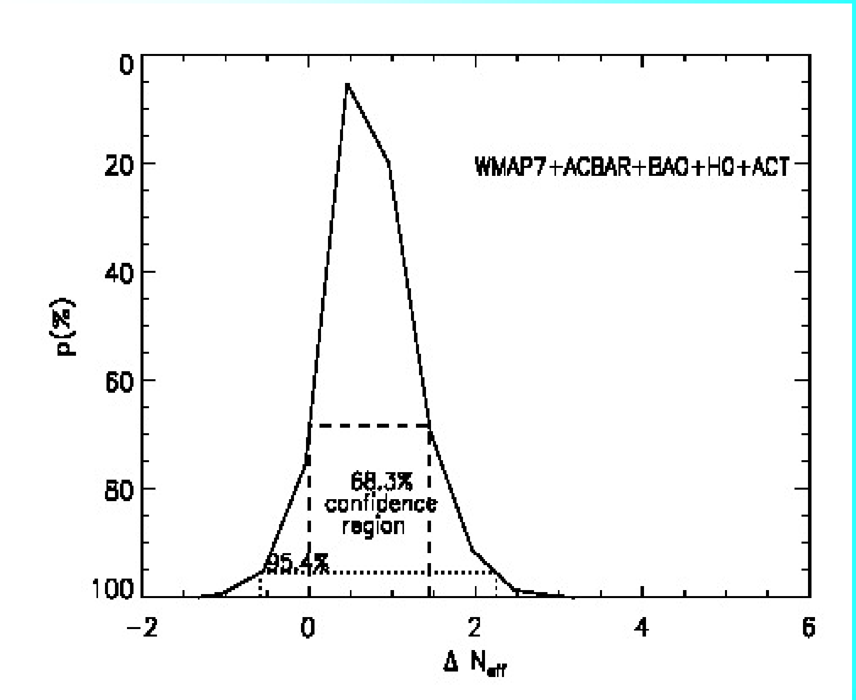
The oldest globular clusters
13.4 +/- 0.8 +/- 0.6 Gyr

N_eff

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



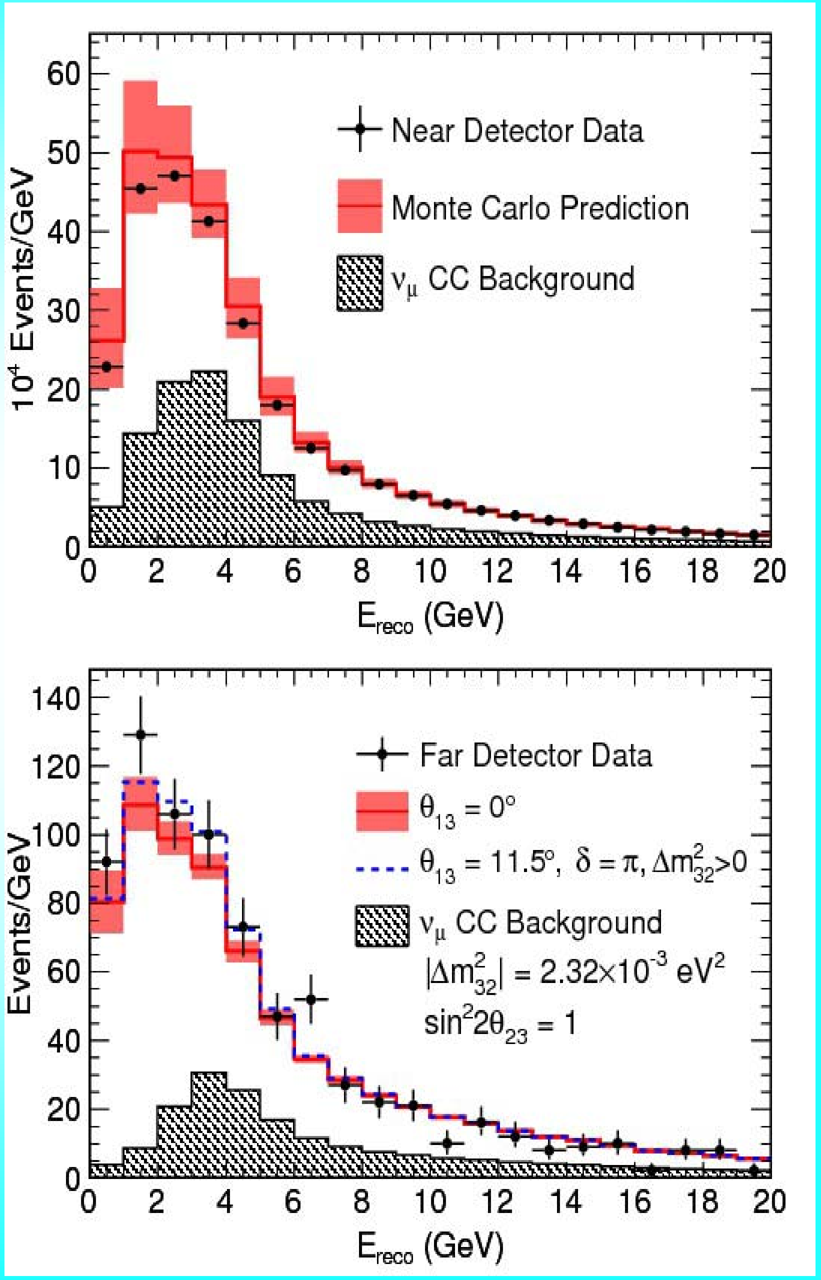




MINOS:

Searches for sterile

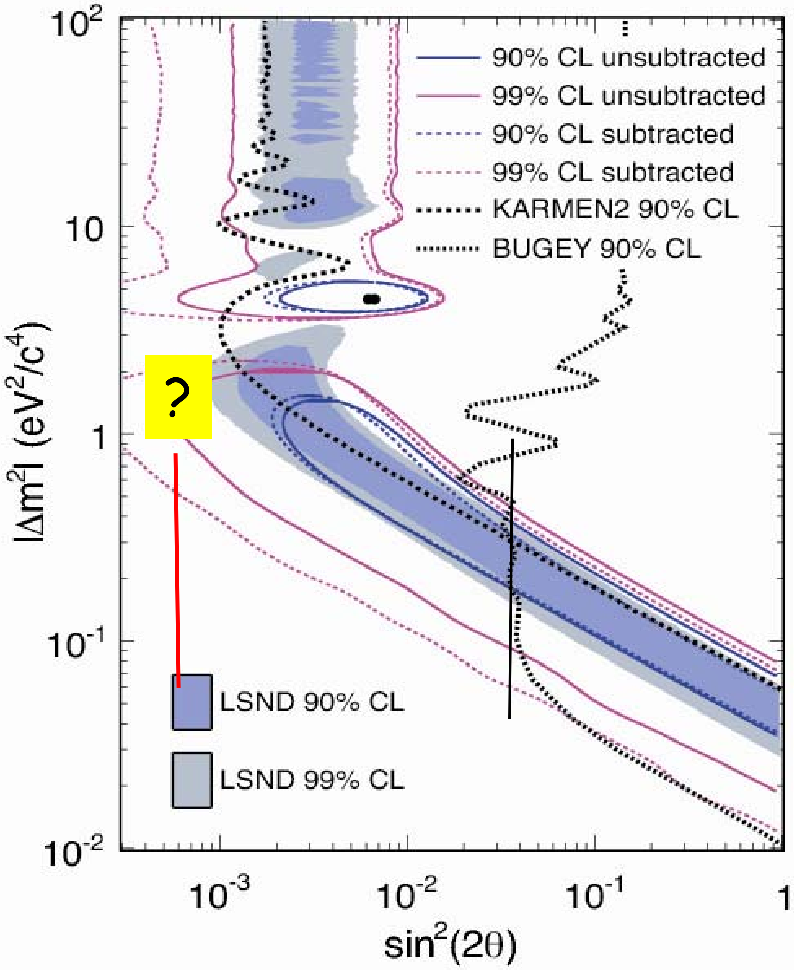
Accelerator neutrinos



MINOS bound

ν_μ - ν_s mixing

E = 200 MeV



In assumption of
no-oscillations in the 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:

$|U_{\mu 4}|^2 > 0.025$

$\Delta m_{41}^2 < 0.5$ eV^2

Mixing

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

produces large corrections to the active neutrino mass matrix

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

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)

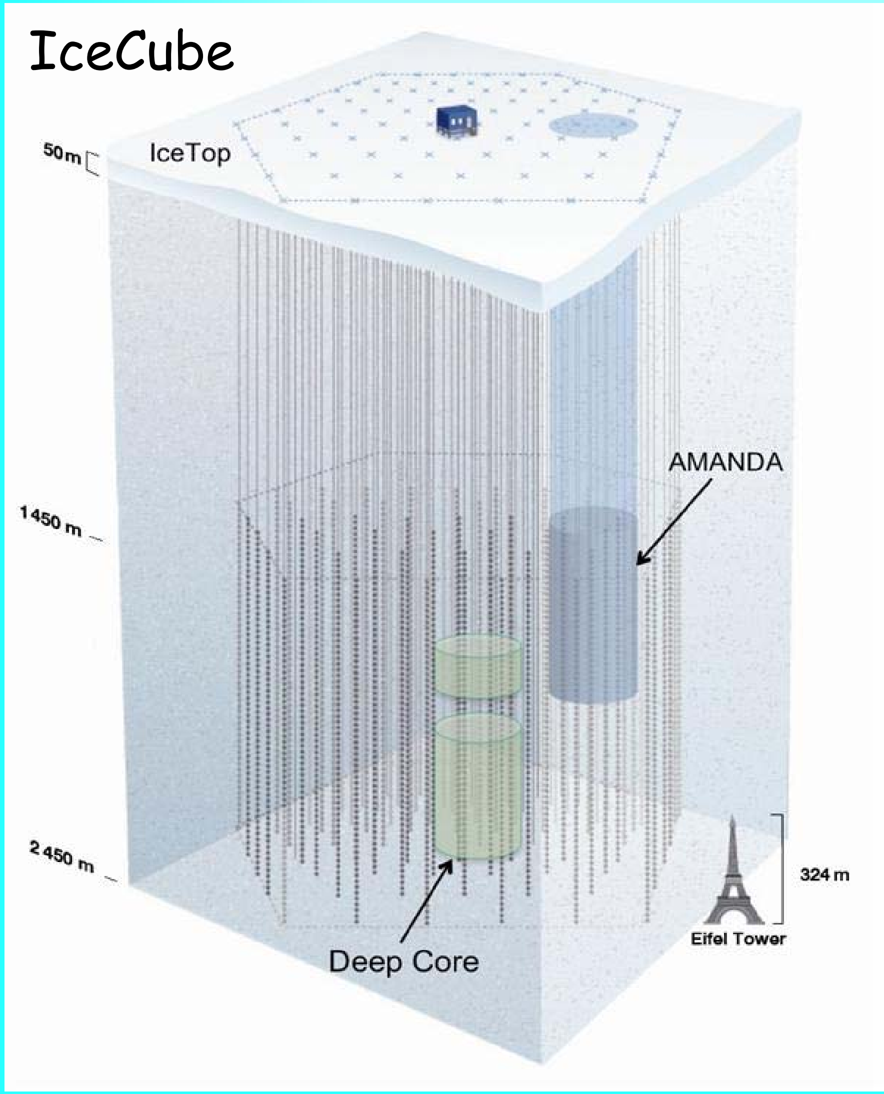
produce dominant $\mu\tau$ - block with small determinant

Enhance lepton mixing

Generate TBM mixing

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

Looking for sterile in ice



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

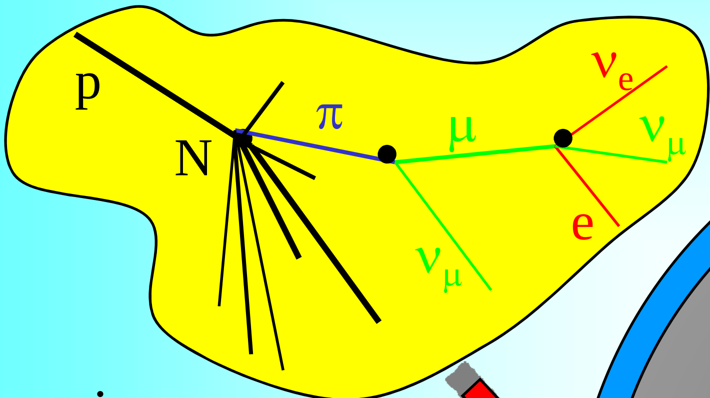
S Choubey HEP 0712 (2007) 014

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

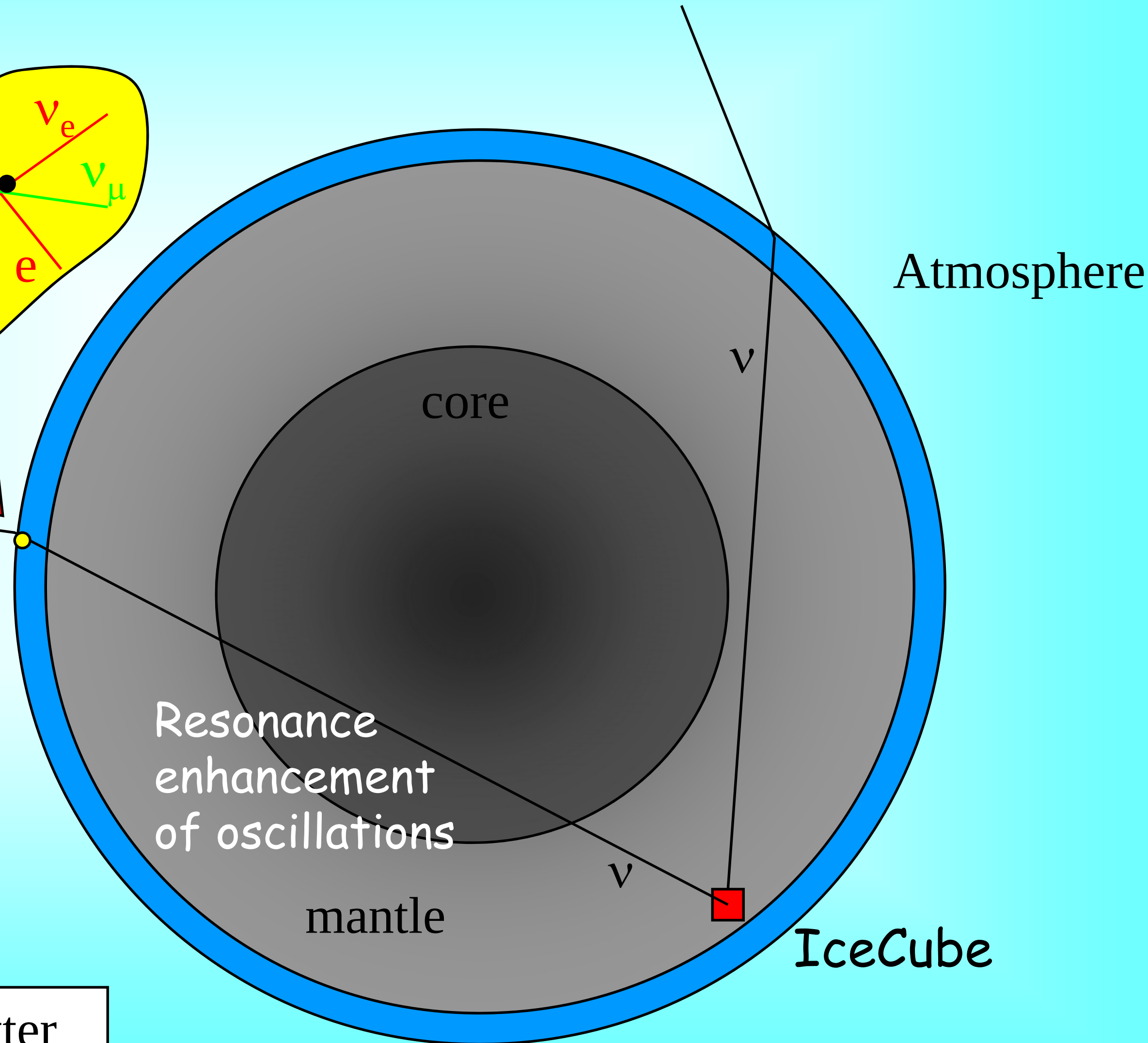
This distorts the energy spectrum and zenith angle distribution of the atmospheric muon neutrinos

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

Atmospheric neutrinos



Cosmic rays



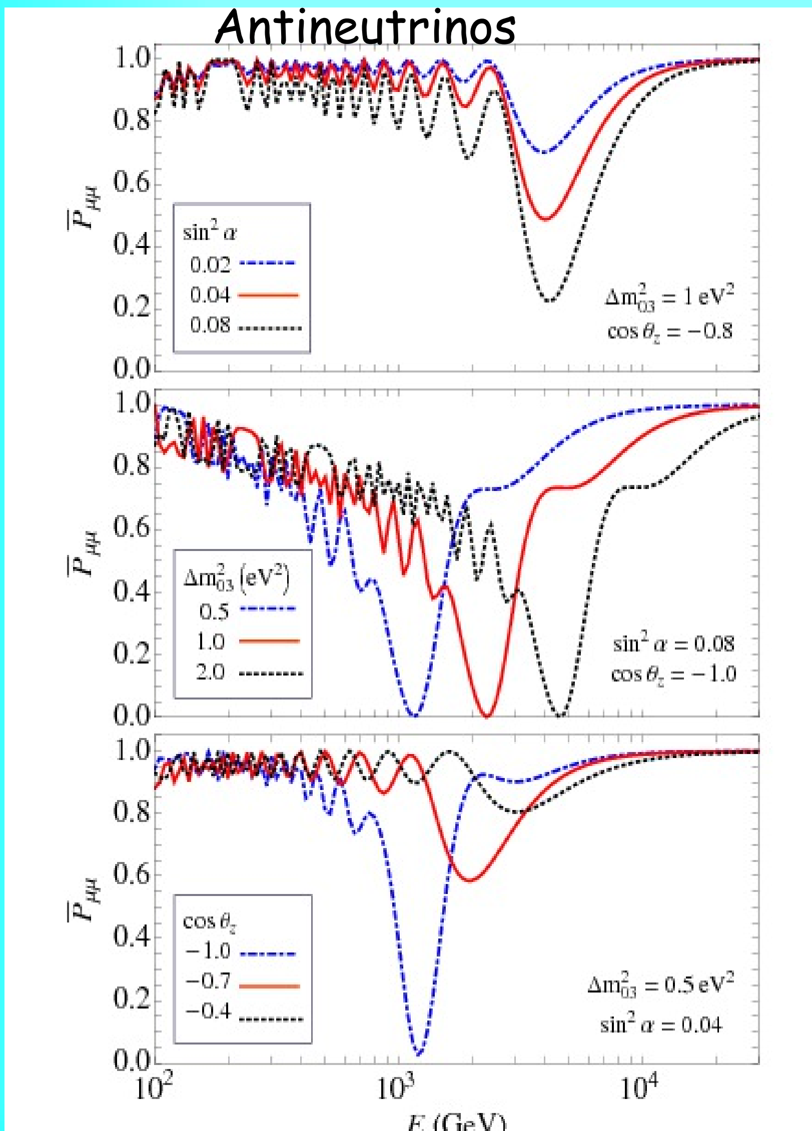
At high energies:

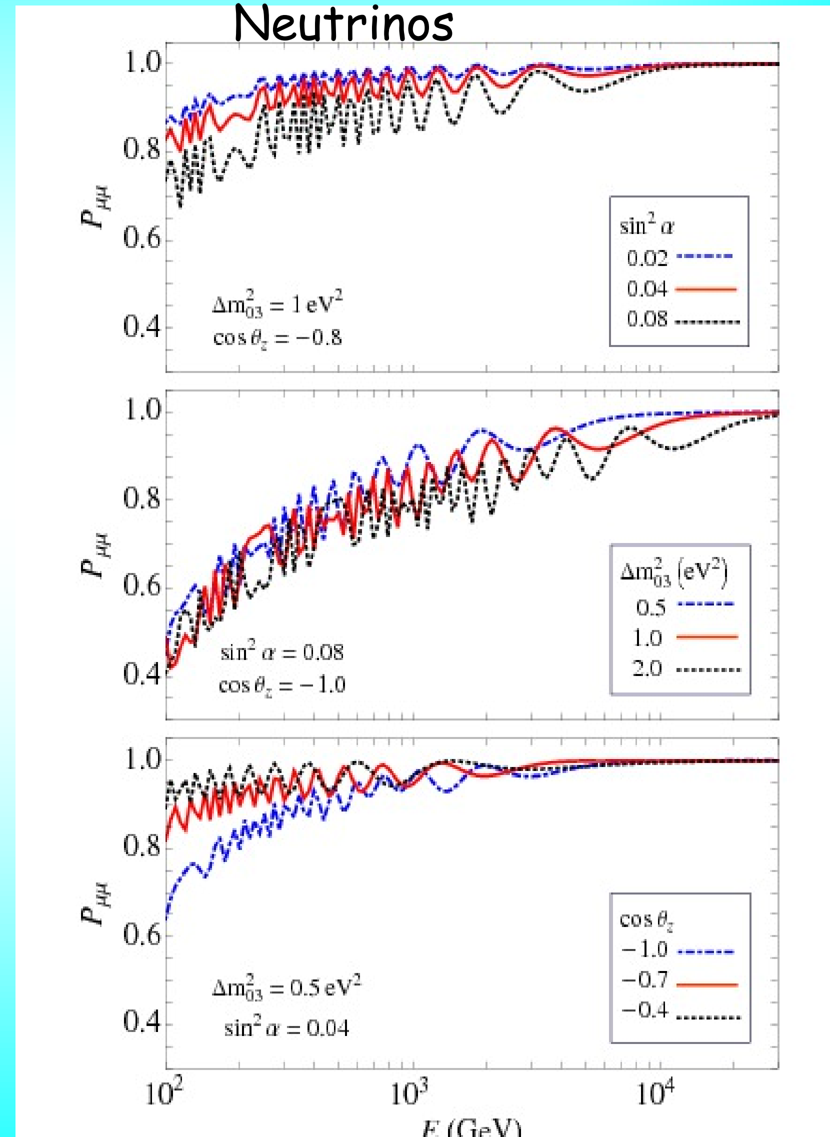
$r = F_\mu / F_e > 4$

$\nu_\mu - \nu_\tau - \nu_s$

$\nu_\mu - \nu_S$ oscillations in matter

Survival probability



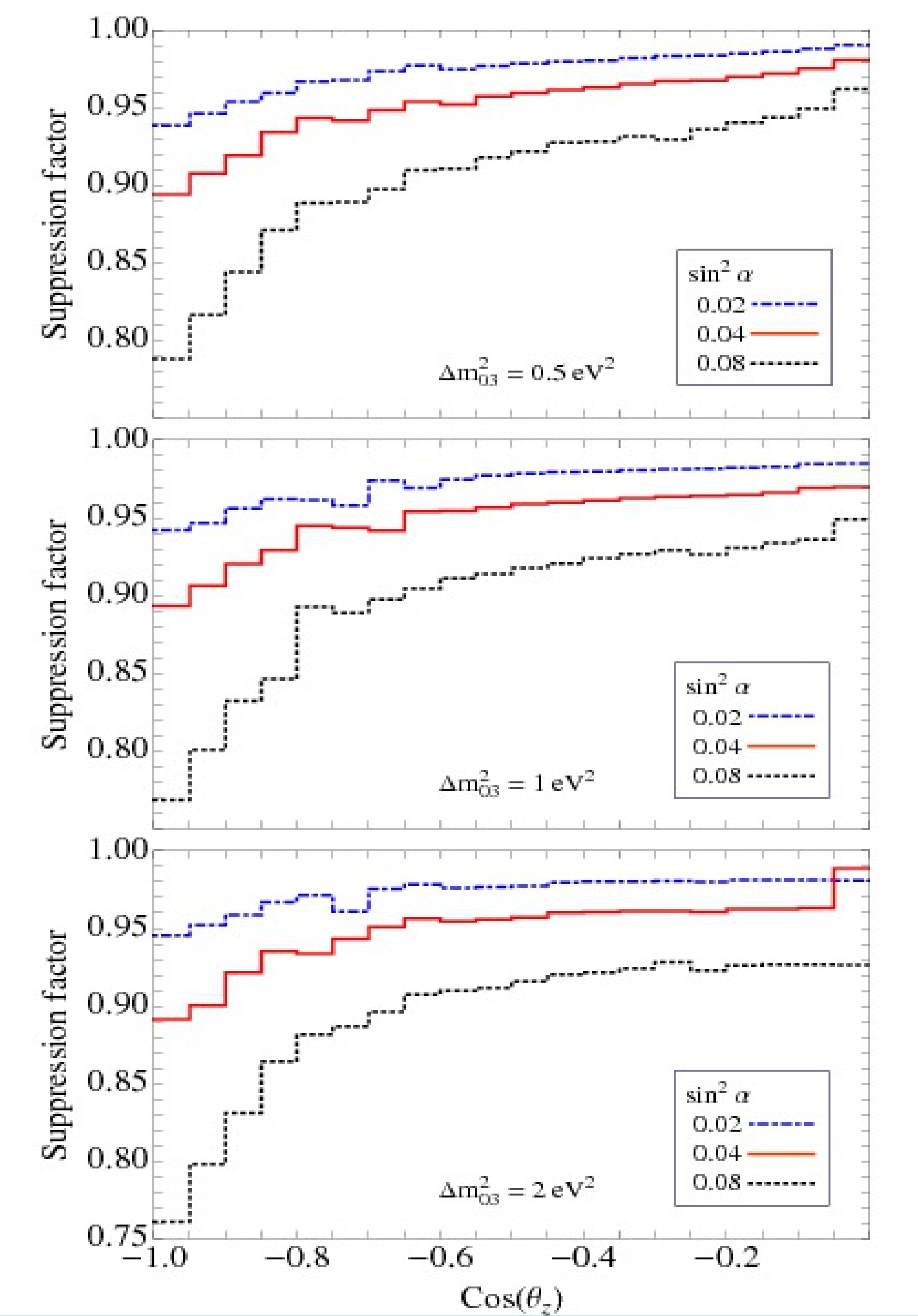


MSW resonance dip

Suppression factor

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

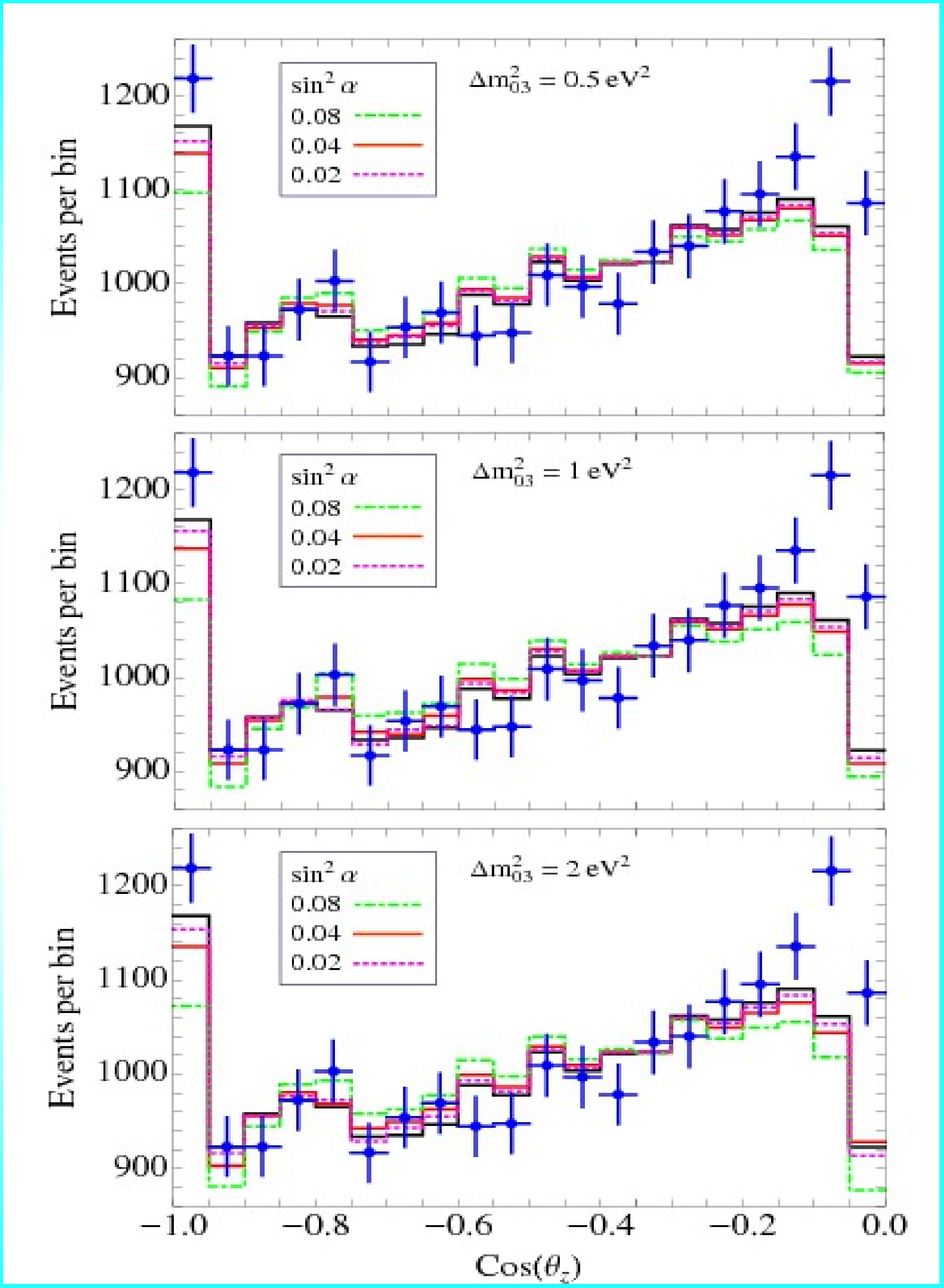
E_{th} = 0.1 TeV



Zenith angle distribution

ν_S - mass mixing case

Free normalization and tilt factor



Shining in sterile

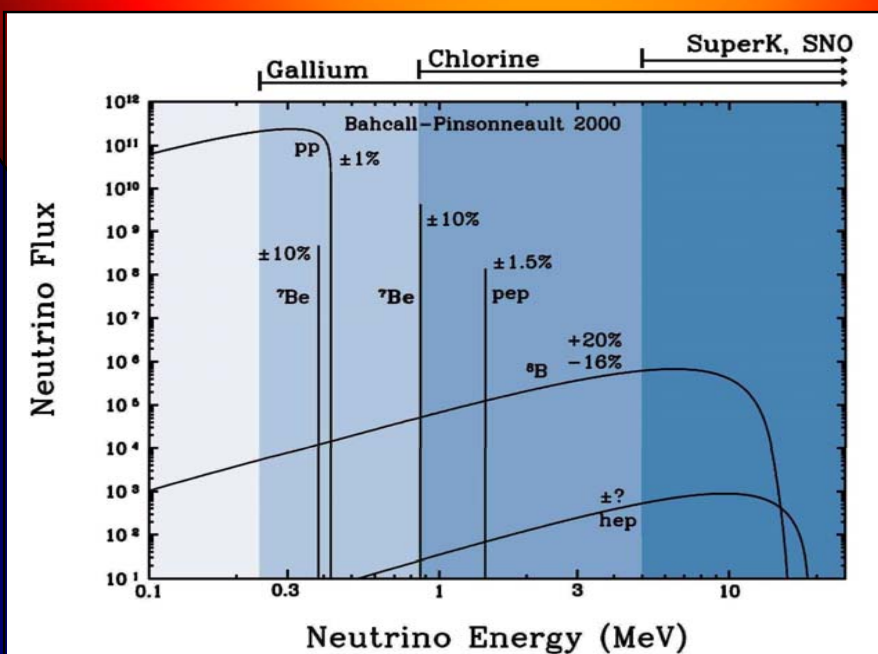
$4p + 2e^- \rightarrow {}^4He + 2\nu_e + 26.73$ MeV

P. De Holanda A.S.
1012.5627 [hep-ph]
PR D83 113011 (2011)

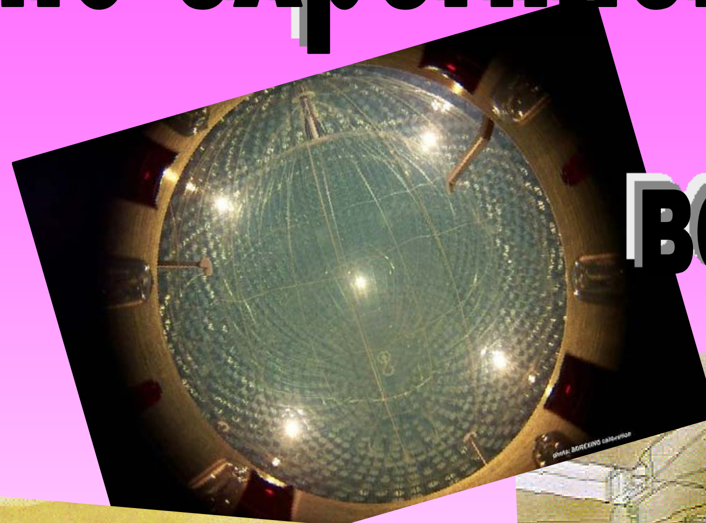
Adiabatic conversion

ν

Oscillations in matter of the Earth

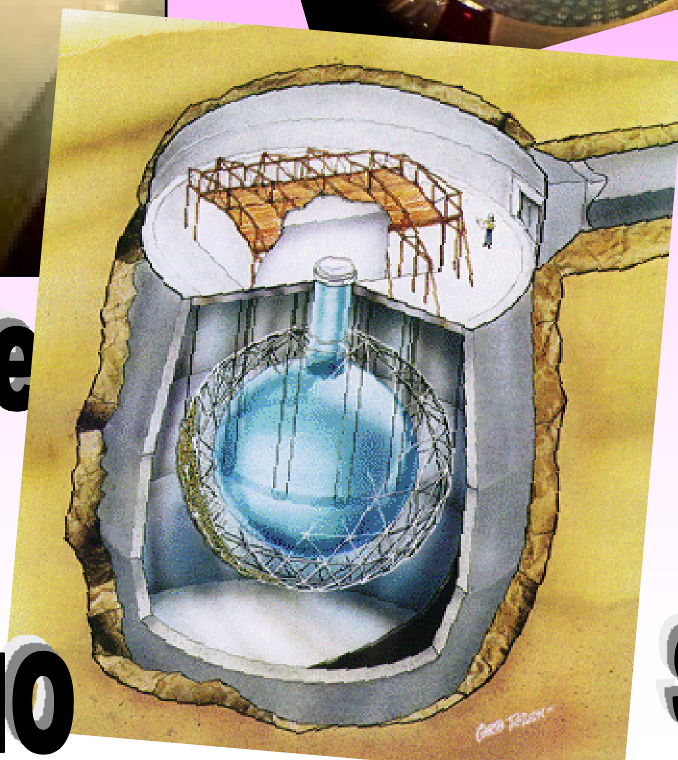


Solar neutrino experiments

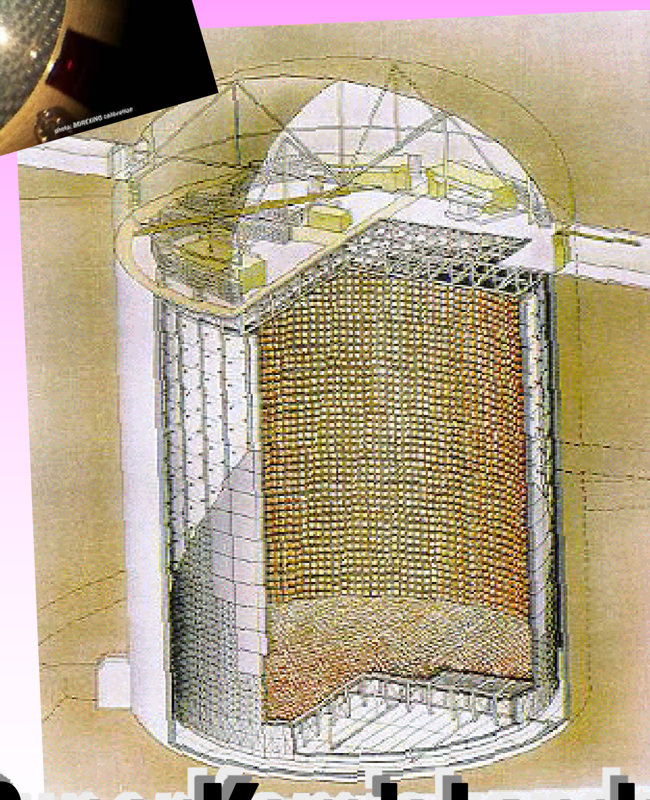


BOREXINO

Homestake

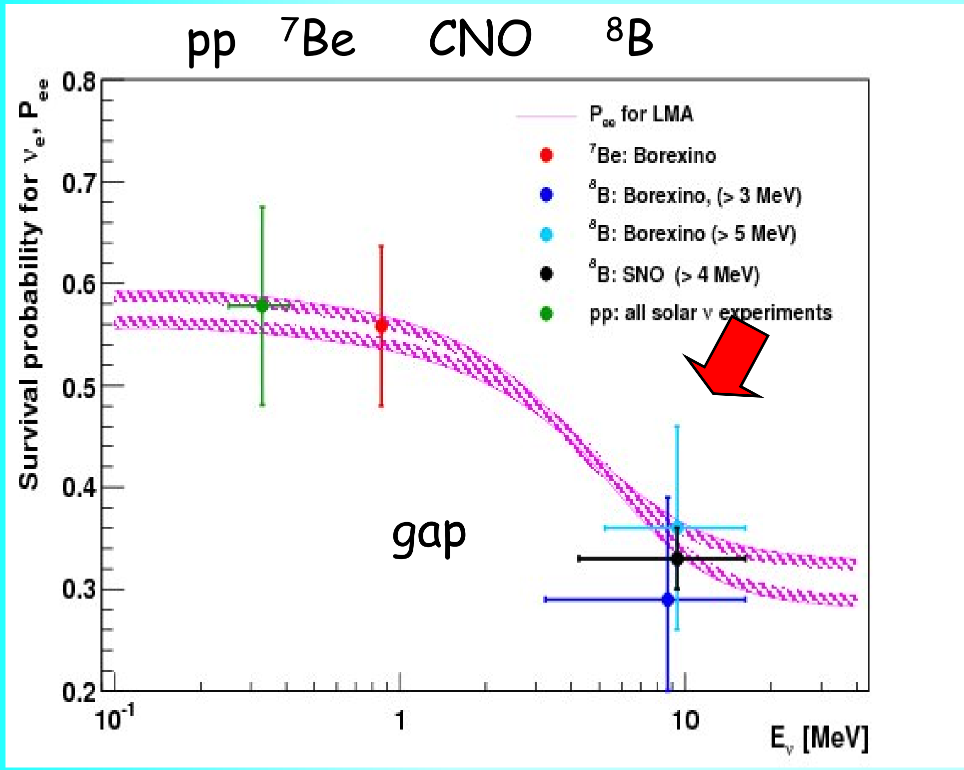


SNO

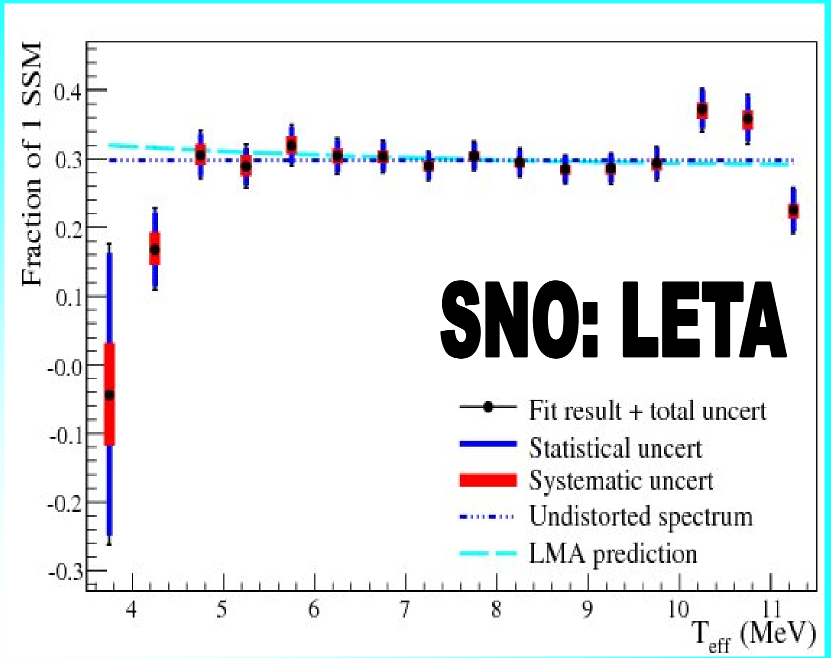


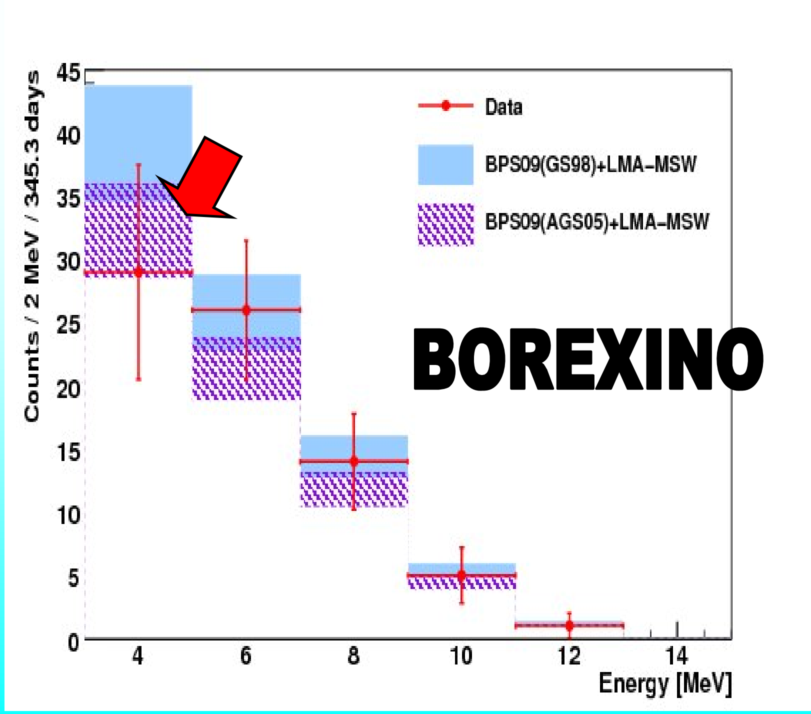
SuperKamiokande

Up-turn?

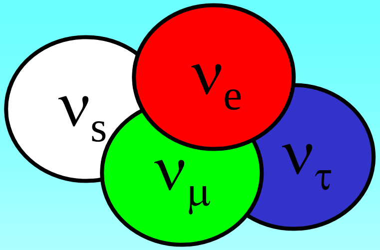


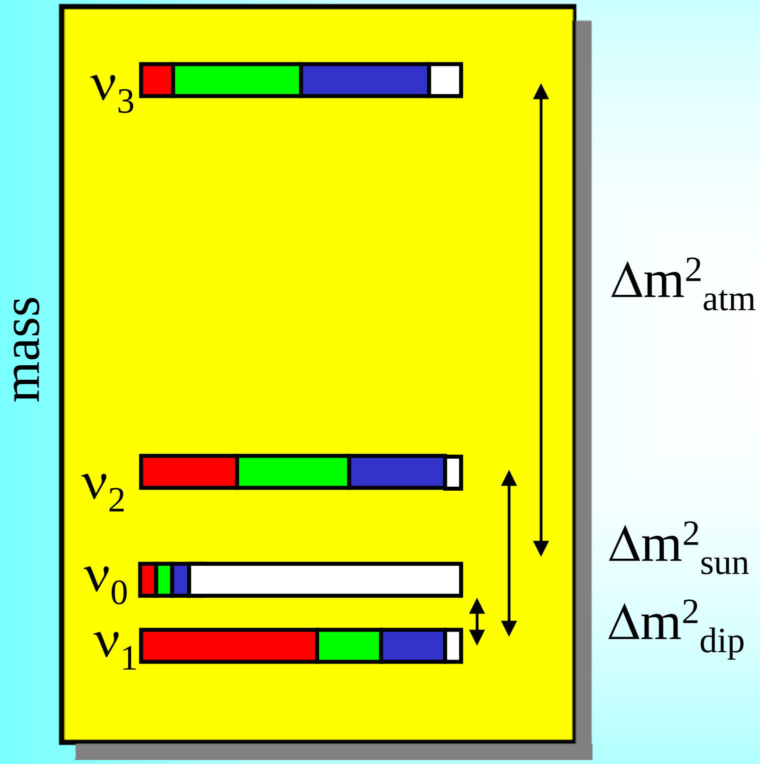
ν_e - survival probability from solar neutrino data vs LMA-MSW solution





(3 + 1) scheme

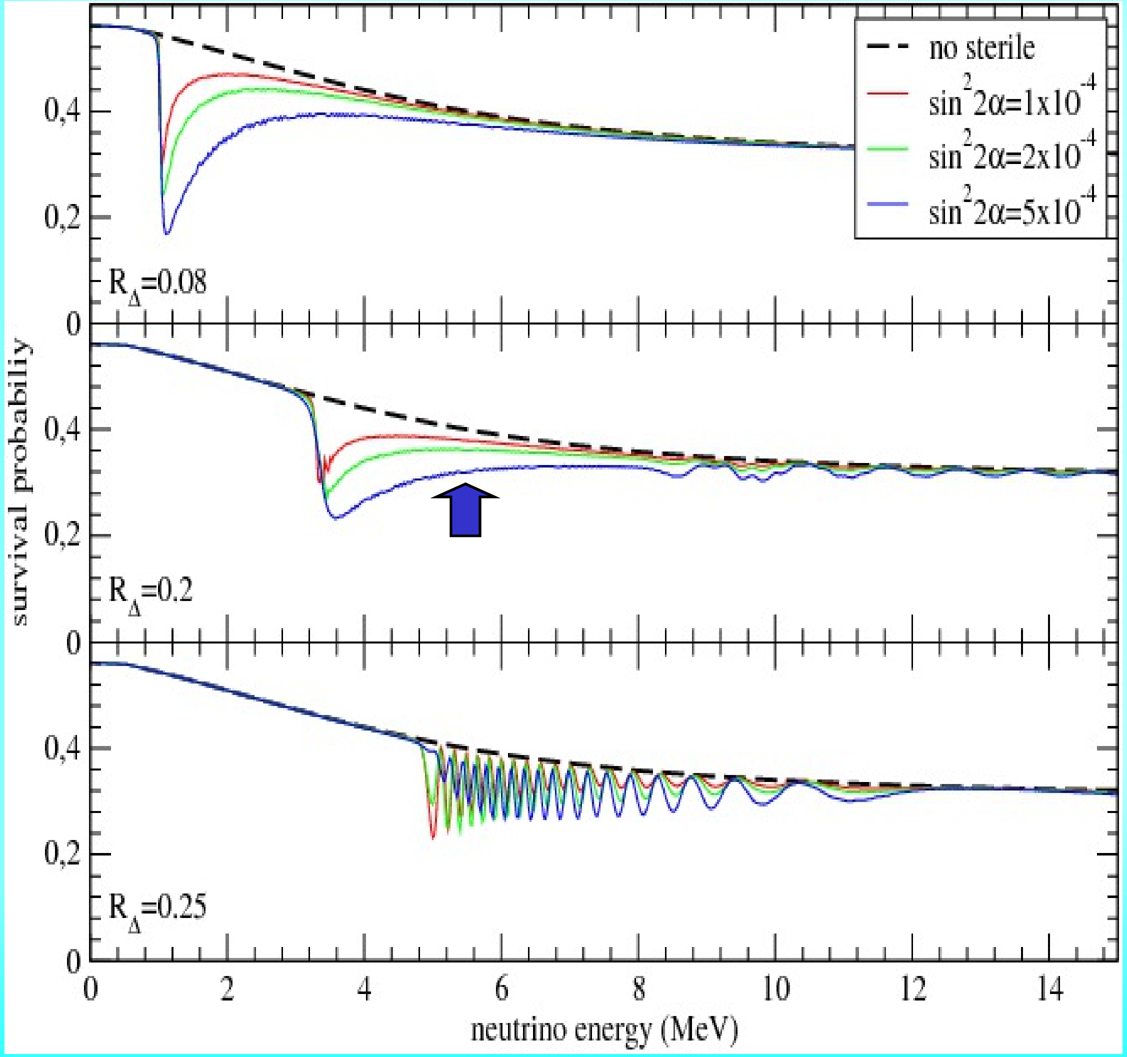




Very light sterile neutrino

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

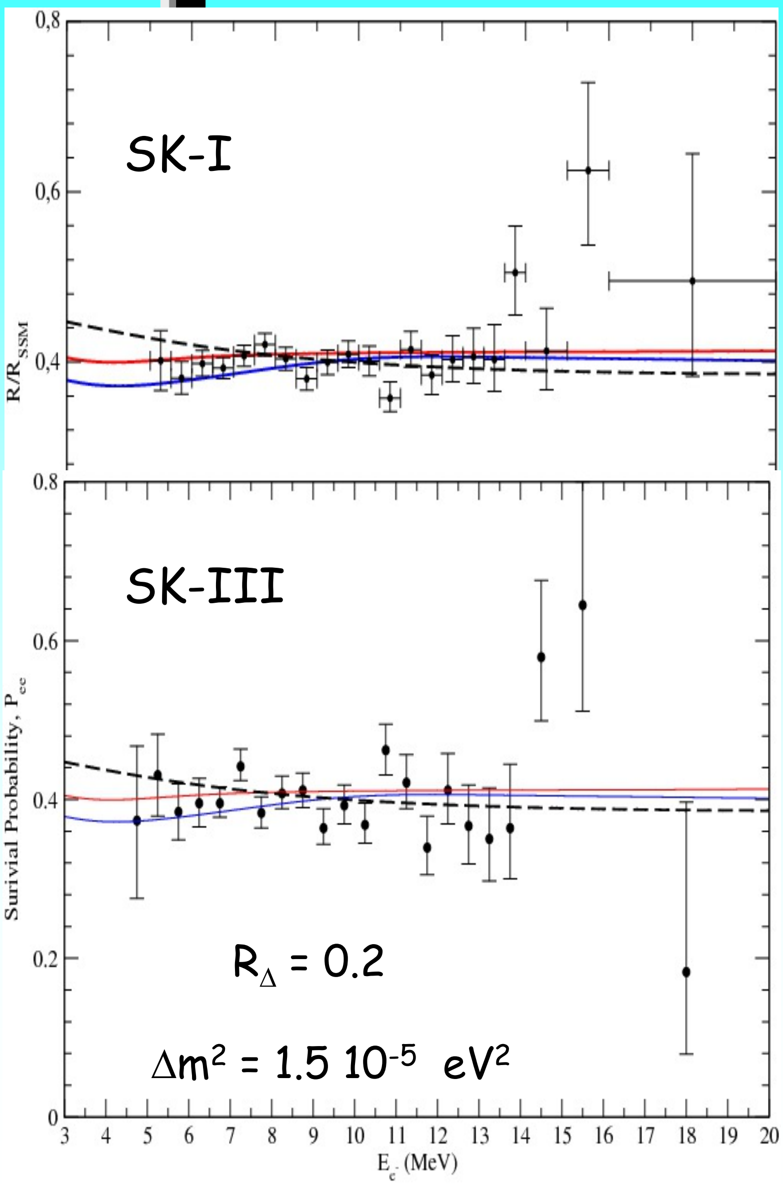
Survival probability

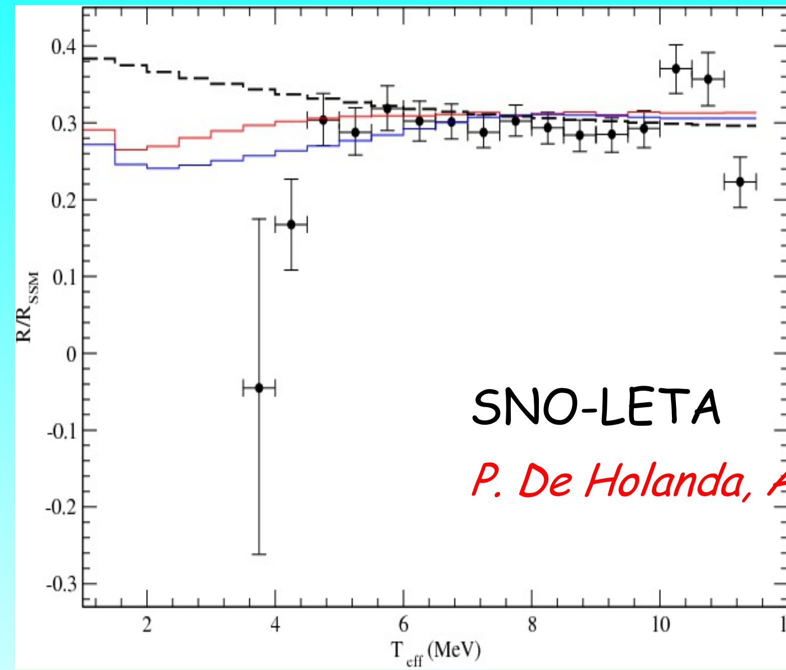


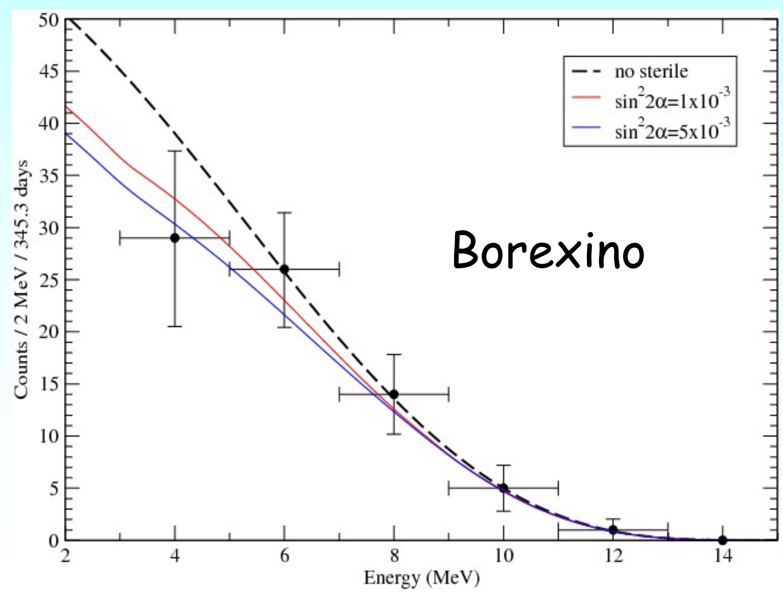
- dip
- wiggles

Up-turns

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

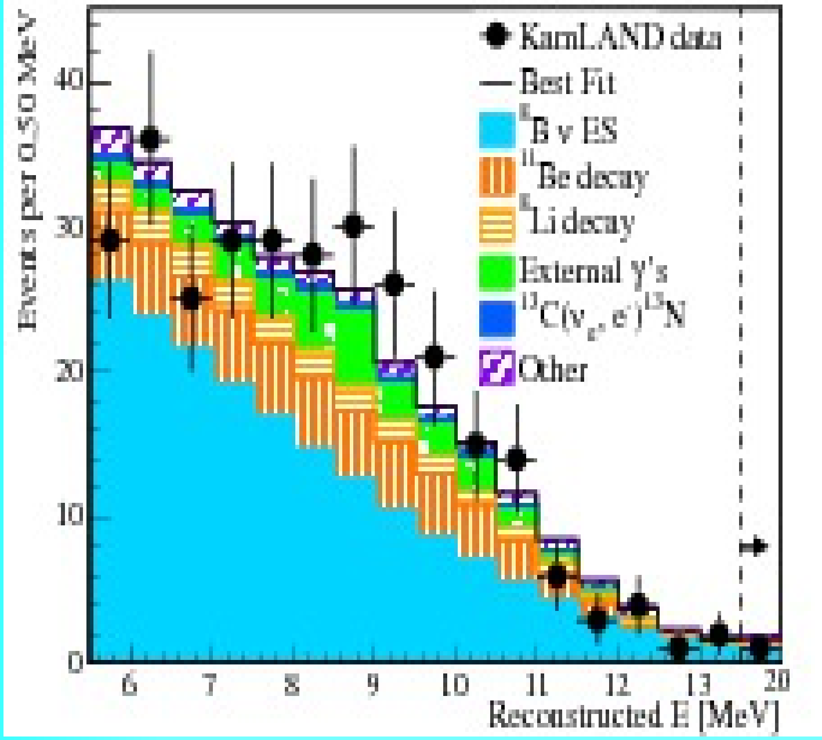


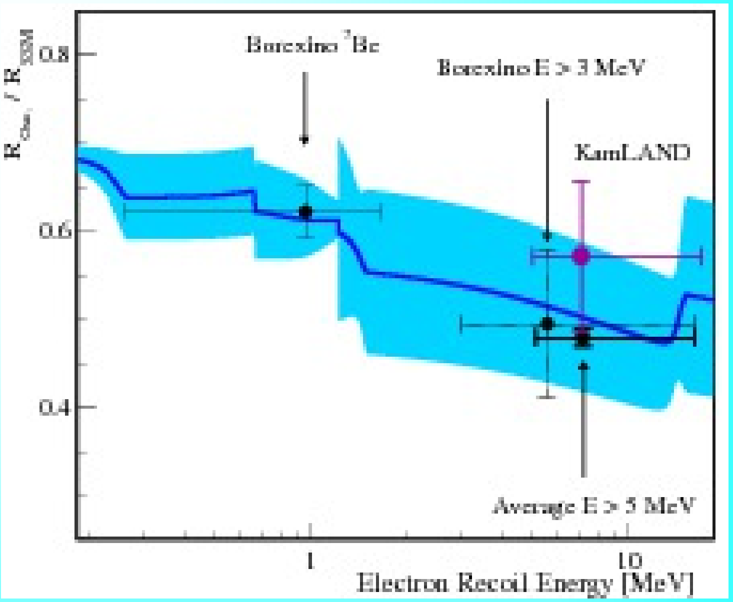




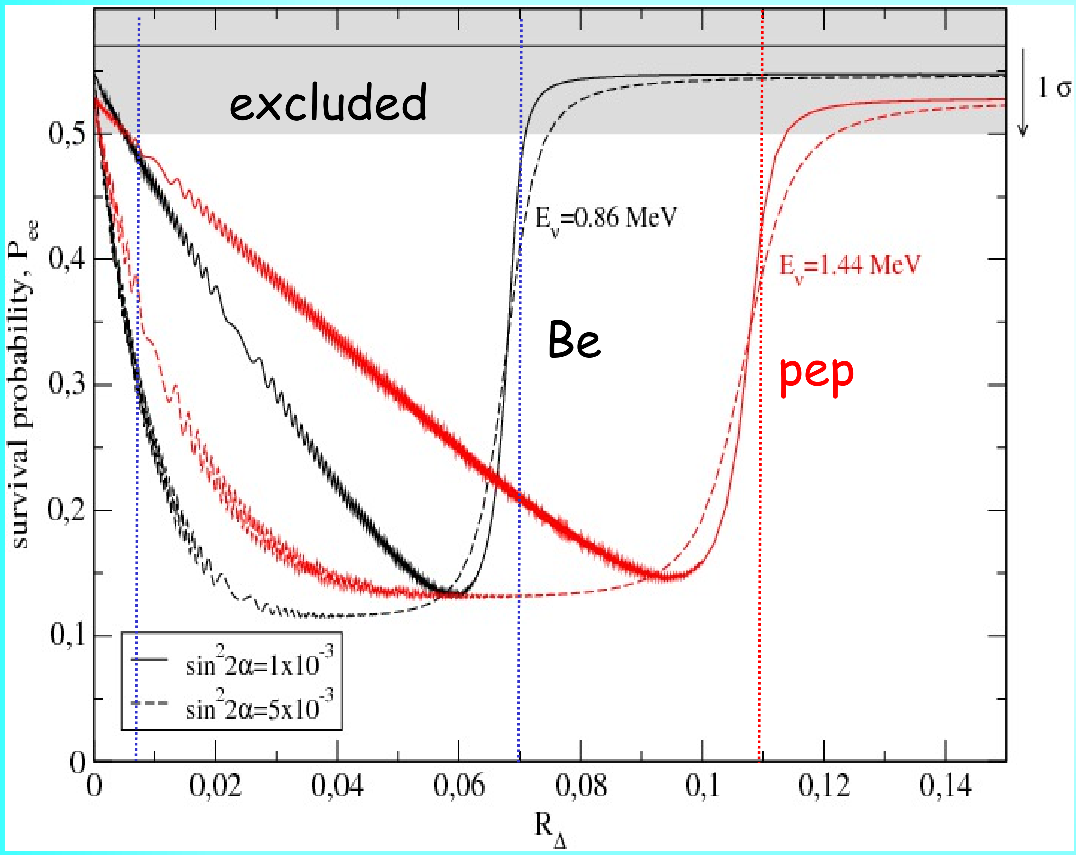
KamLAND solar

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





BOREXINO: Be line



pep-suppressed

data

excluded

R_Δ = 0.007 - 0.07

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

Predictions for pep-neutrinos

R_Δ = 0.07 - 0.115

P(pep) = 0.2 – 0.3

P(Be) = 0.55

$R_\Delta > 0.12$

P(pep) = 0.53

Extra radiation in the Universe

Mixing of ν_s in ν_3

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

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

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

Atmospheric neutrinos:

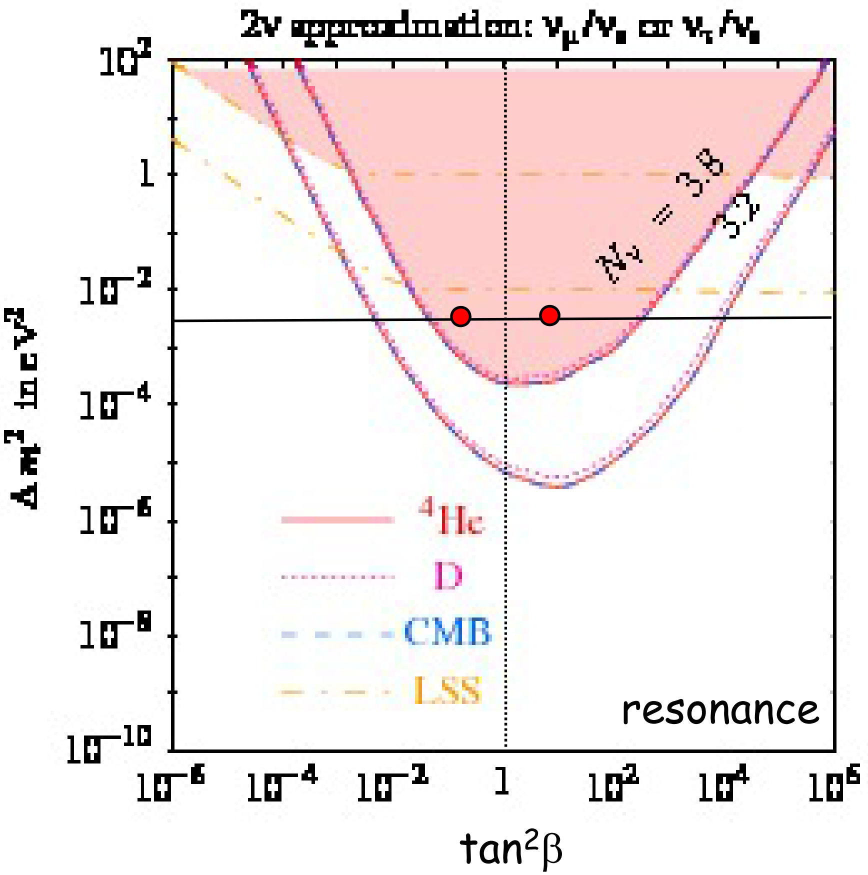
$\sin^2\beta < 0.2 - 0.3$ (90%)

MINOS:

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

Production of steriles in the Early universe

M Cirelli G Marandella A Strumia F Vissani



Implications; consequences

Theory:

$m_0 \sim 0.003$ eV $\Rightarrow$ $m_0 = \frac{M^2}{M_{Planck}}$ $M \sim 2 - 3$ TeV

mixing

$\sin^2 2\alpha \sim 10^{-3}$ $\alpha \sim \frac{h\, v_{EW}}{M}$ $h = 0.1$

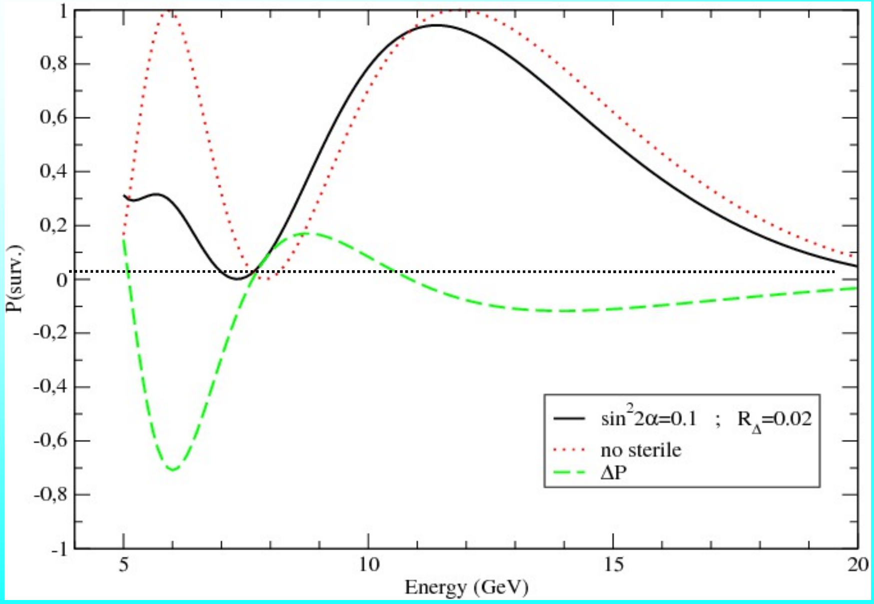
$\sin^2 2\beta \sim 10^{-1}$ $\beta \sim \frac{v_{EW}}{M}$

Phenomenology:

SN

Atmospheric

IceCube DeepCore



Conclusions

Understanding neutrino mass and mixing is on cross-roads:
Discrete symmetries? TBM accidental? QLC? Quark-lepton unification?
Preferable: GUT + seesaw + fermion singlets (hidden sector)
with some symmetries?

Relation to CDM, WDM?

New (still controversial) evidences of new neutrino states
= sterile neutrinos. Implications for Cosmology:
additional radiation in the Universe in epoch of decoupling
and additional HDM.

Tests: with Solar and atmospheric neutrinos
IceCube, deep-core IceCube

Additional slides

Mass and nothing more?

Standard Model + Mass and Mixing

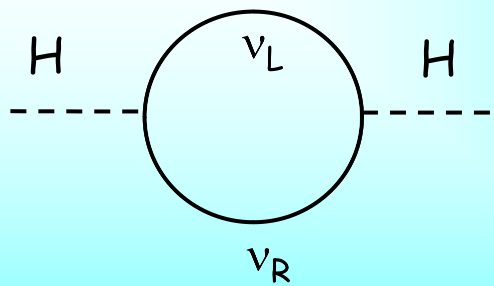
Neutrino interactions

generated by $\frac{1}{\Lambda}$ L L H H *S. Weinberg*

No other manifestations of new physics

Λ ~ 10^{14} GeV << M_{Pl}

New physics below Planck scale



~ Λ^2

SUSY ?

If ν_R exists: M_R ~ Λ

Dirac mass

- small Yukawa coupling
- additional doublet with small VEV

DM?

Comments:

Data show both order, regularities and some degree of randomness

Different pieces of data testify for different underlying physics

No simple relation between masses and mixing parameters which could testify for certain simple scenario

No simple explanation is expected?

BM - symmetry

BM mass relations

$m_{e\mu} = m_{e\tau}$

$m_{\mu\mu} = m_{\tau\tau}$

$m_{ee} = m_{\mu\mu} + m_{\mu\tau}$

Invariance:

$V_i^T m_{BM} V_i = m_{BM}$

$$S_{BM} = \begin{pmatrix} 0 & -\sqrt{\frac{1}{2}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{2}} & \frac{1}{2} & -\frac{1}{2} \\ -\sqrt{\frac{1}{2}} & -\frac{1}{2} & \frac{1}{2} \end{pmatrix} \qquad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

The mass matrix of the charged leptons is diagonal due to symmetry with respect to transformations:

$T = \mathrm{diag}(-1, -i, i)$

T, S_{BM} generators of S_4

Consistency

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
Δm_{41}^2 = 0.47 eV^2	Δm_{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]

ν_s - mass mixing scheme

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

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 $\tilde{\nu}_3$

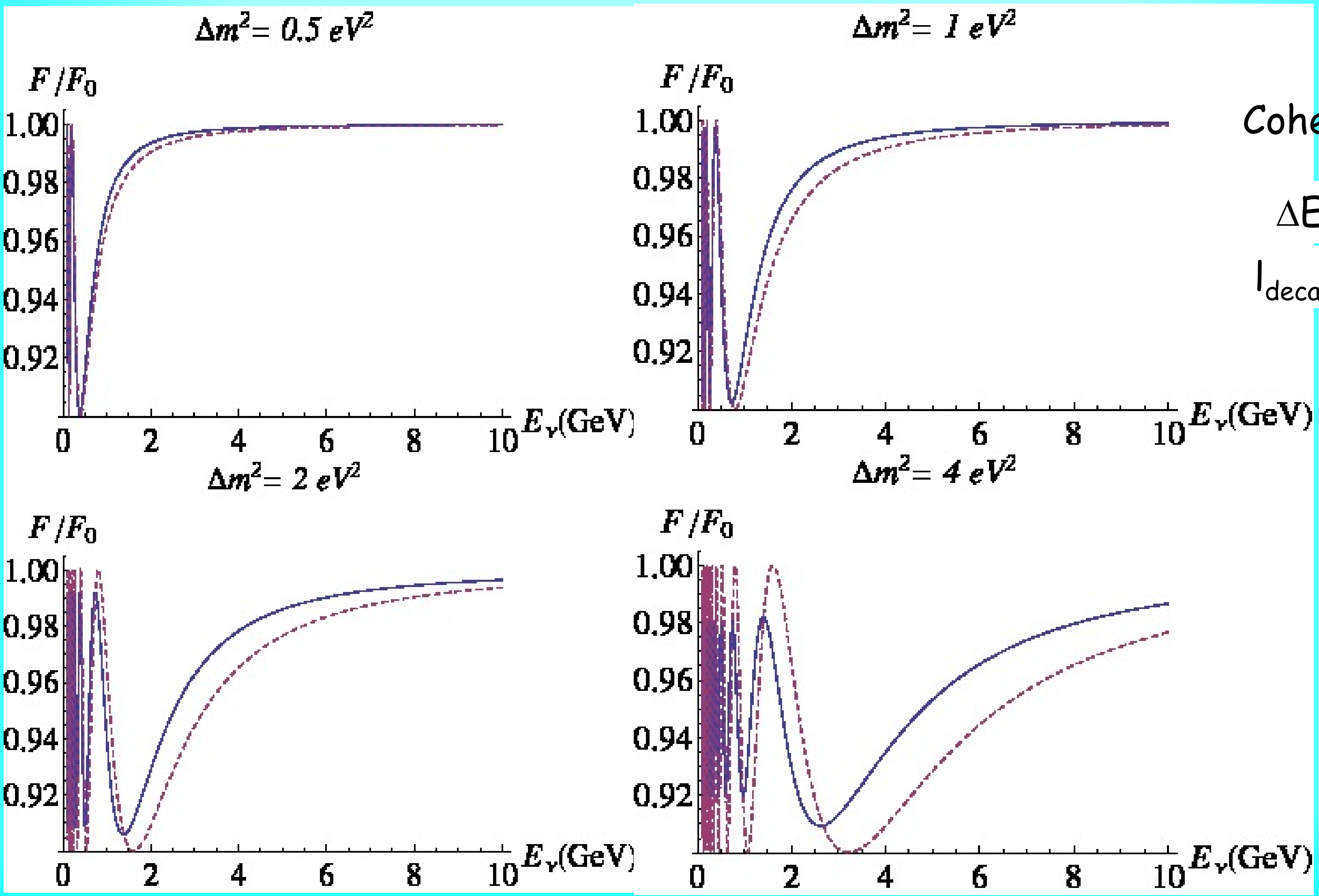
Propagation basis: $\nu_s, \tilde{\nu}_3, \tilde{\nu}_2$

Evolution is reduced to 2ν-problem exactly

Probabilities

D. Henandez A.S.

$P(\nu_\mu \rightarrow \nu_\mu)$



Coherence:

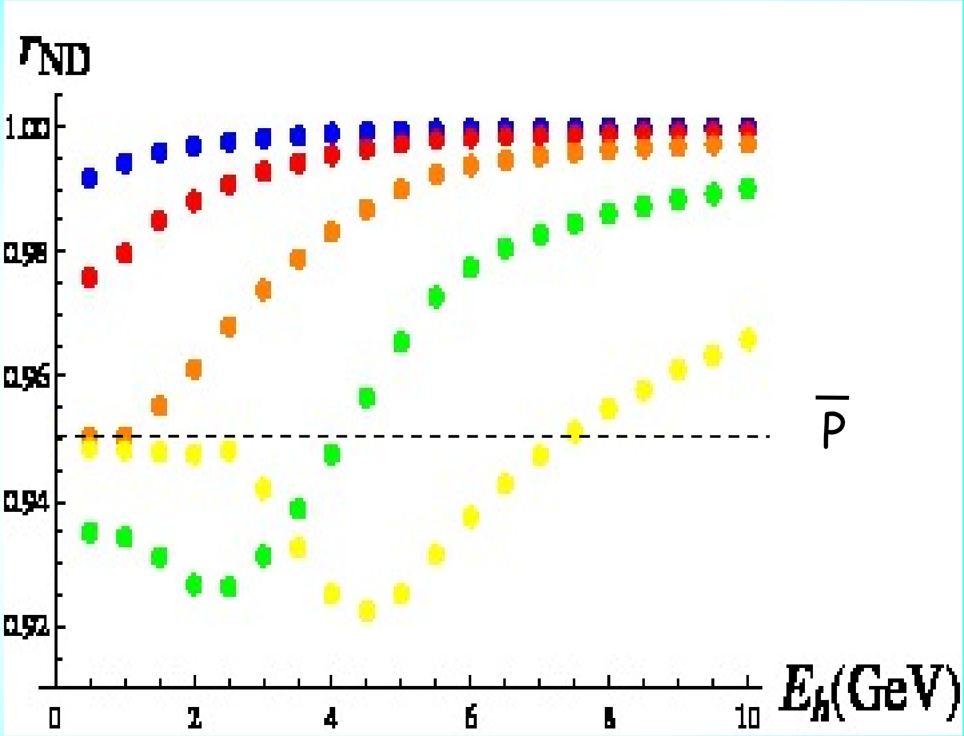
$\Delta E \sim \Gamma$

$l_{decay} \sim l_\nu$

Oscillation effects

Near Detector $r_{NC} = \frac{n_{NC}}{n_{NC}^0}$

Far Detector: $\frac{\overline{P}}{r_{NC}}$

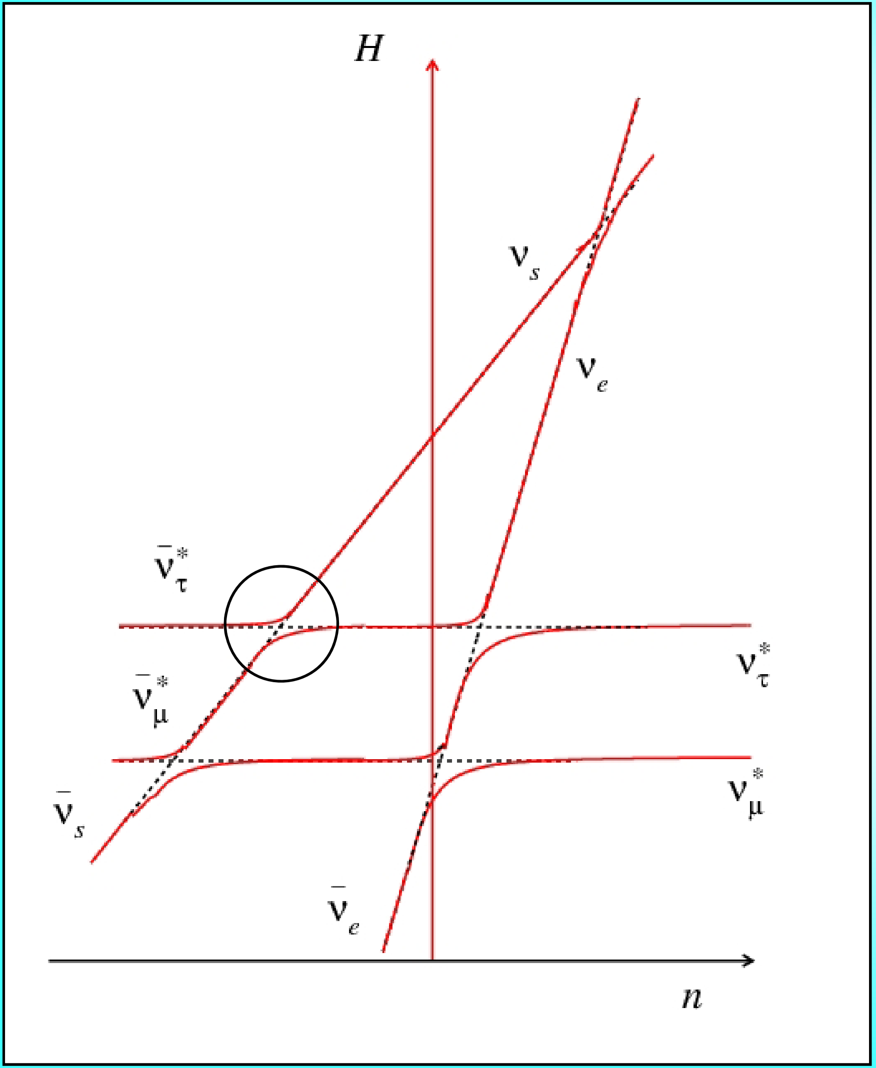


Light neutrinos
Dark matter
and Standard model of the Universe

Neutrino as dark energy
Hot dark matter and structure formation
Extra radiation in the Universe

Aspects related to the main topic of the school
In connection to dark matter.

Level crossing scheme



- Normal mass hierarchy in the flavor block; $m_0 \sim 1$ eV
- Three new level crossings
- $|U_{e4}|^2 \quad |U_{\mu 4}|^2$ are large enough, so that evel crossings are adiabatic
- $V_e - V_s = \sqrt{2}\, G_F\, (n_e - n_n/2)$

Evolution

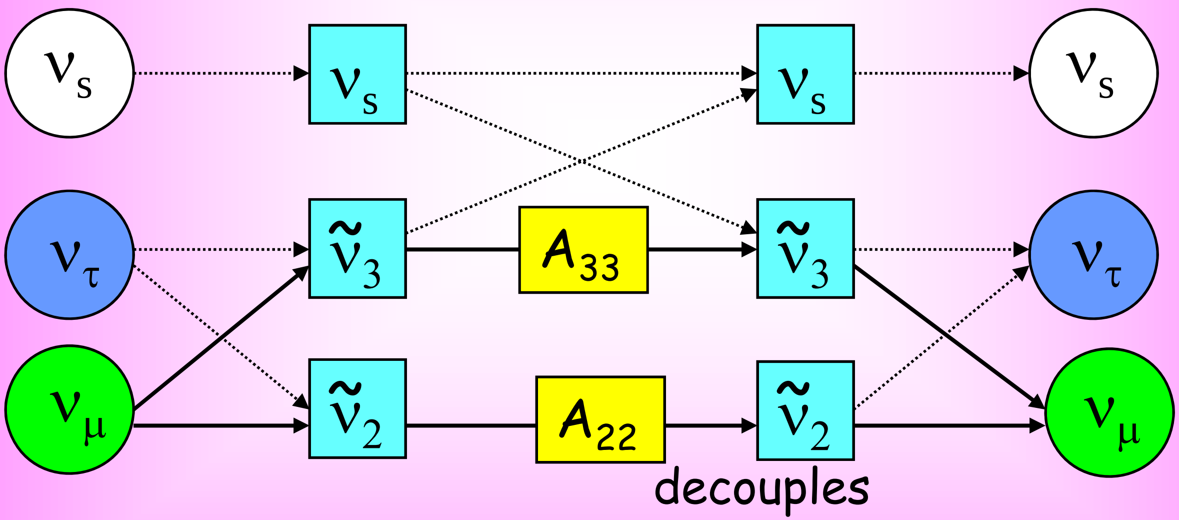
ν_s mass mixing scheme:

$U_f = U_{23}\, U_\alpha$

ν_s mixes in the mass states ν_3 and ν_0

Propagation basis

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

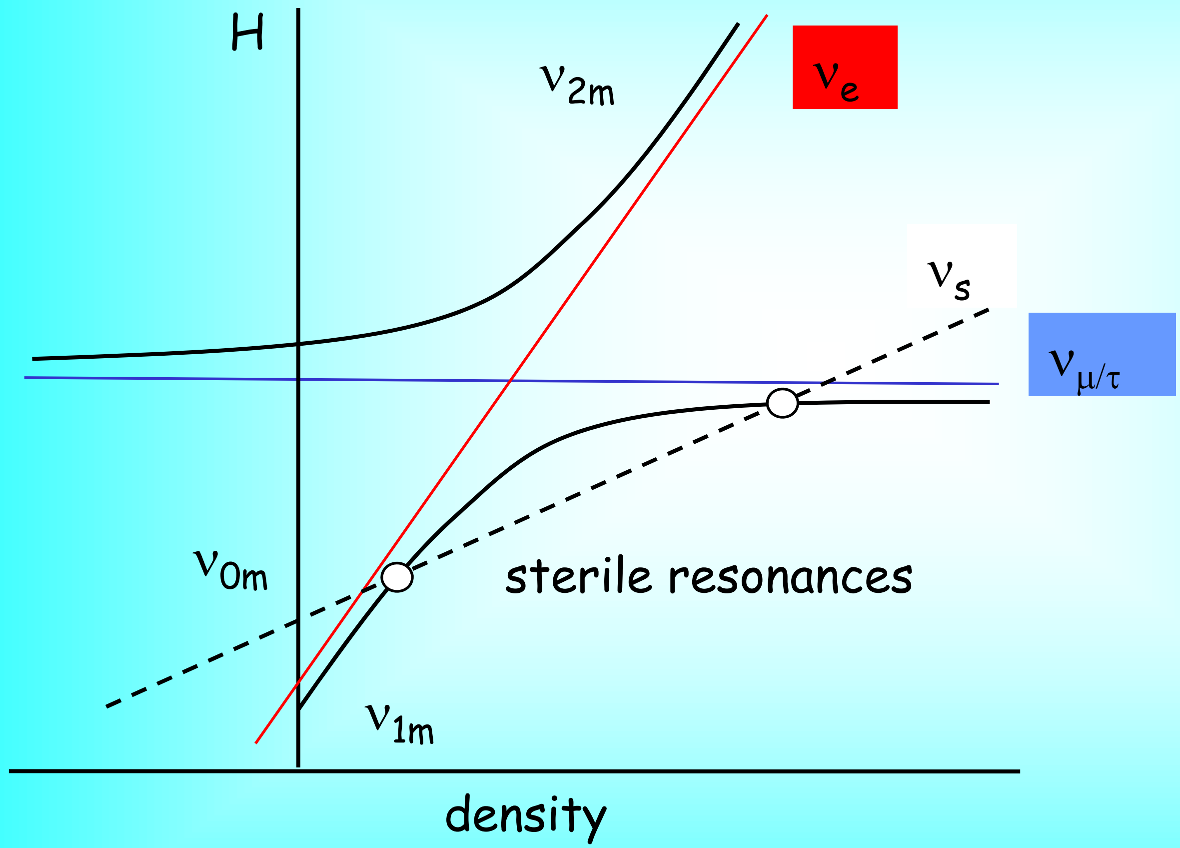


projection propagation projection

S

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

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

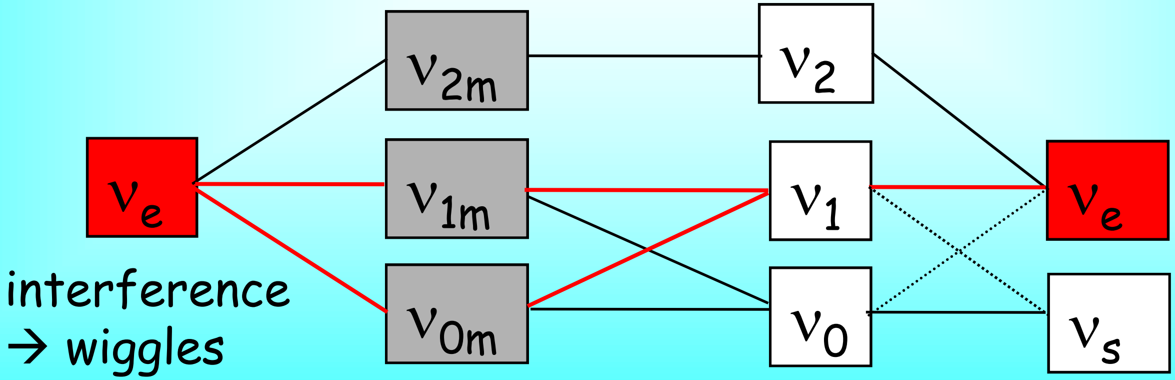
$$\begin{pmatrix} \nu_s \\ \nu_e \\ \nu_a \end{pmatrix} \qquad U = U_\theta \; U_\alpha \qquad \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \end{pmatrix}$$

U_θ - rotation in 12-plane on θ_{12}

U_α - rotation in 01- plane on α

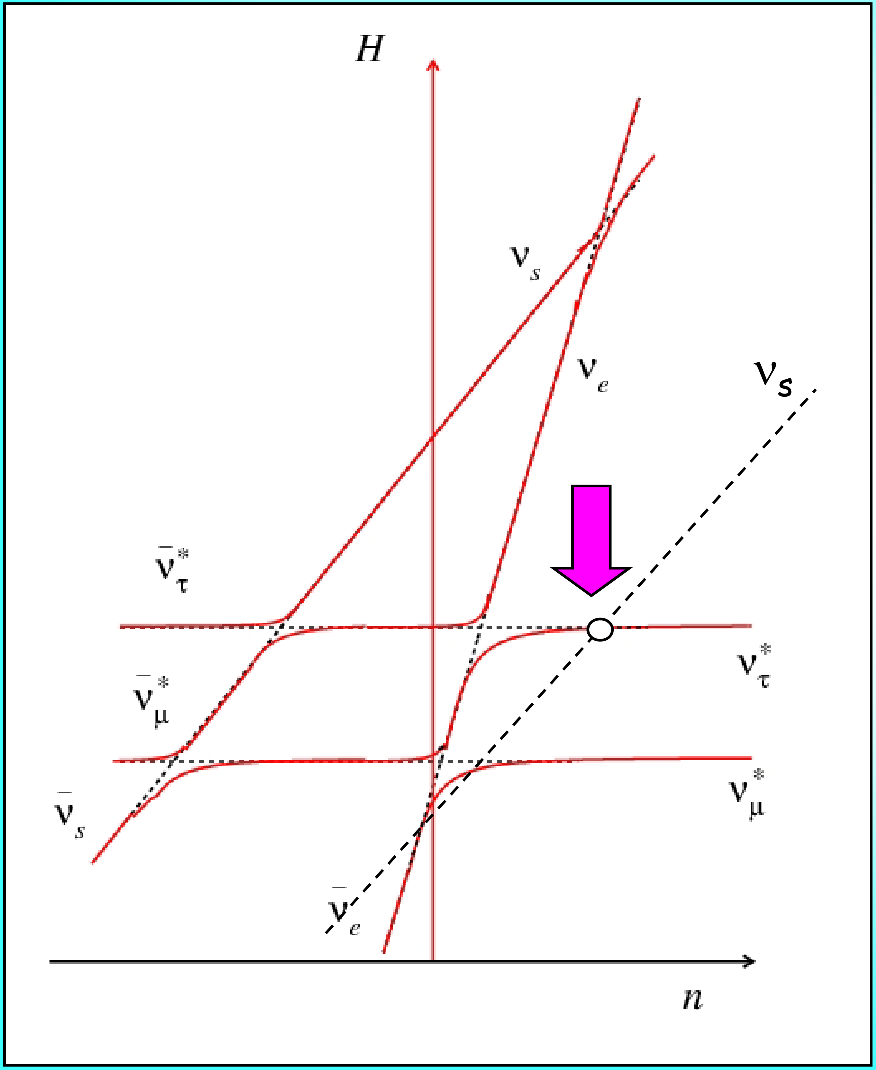
ν_s mixes in ν_0 and ν_1

Scheme of transitions



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

Level crossing scheme



P. De Holanda, A.S.

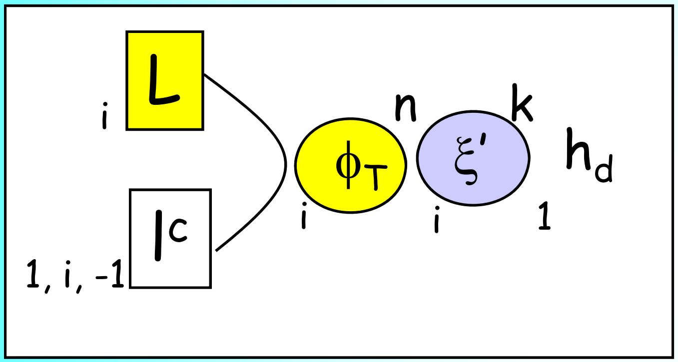
Mixing with the third active state

An A_4 model

G. Altarelli
D. Meloni

Yukawa sectors

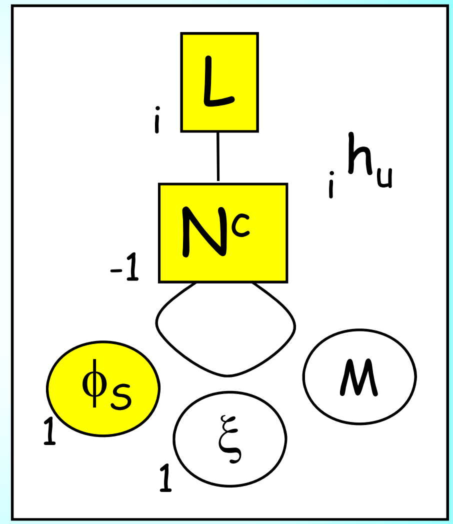
Charged lepton



$$<\phi_T> = v_S\ (0, 1, 0)$$

n = 1, … k = 0, …

Neutrinos



$$<\phi_S> = v_S\ (1, 1, 1)$$

A_4	Z_4
3	1
1	i
1′	-1
1″	-i

1, i, -1, -i at multiplets

Particular selection of representations

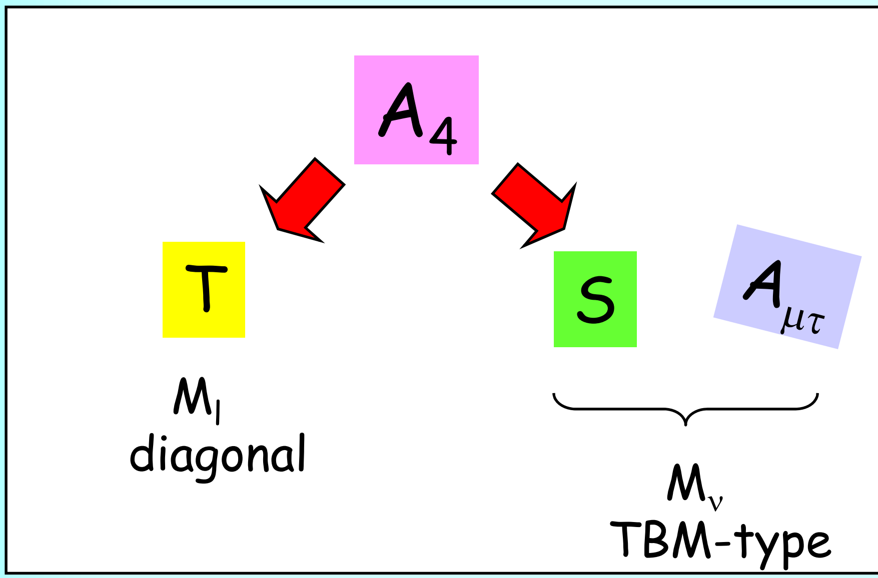
Flavon sector

				$U(1)_R$
ϕ_T	ϕ_S	ξ	ξ'	0
ϕ_T^0 (-1)	ϕ_S^0 (1)	ξ^0 (1)		2

2 Driving fields → Vacuum alignment

GUT-scale or higher?

A_4 symmery breaking

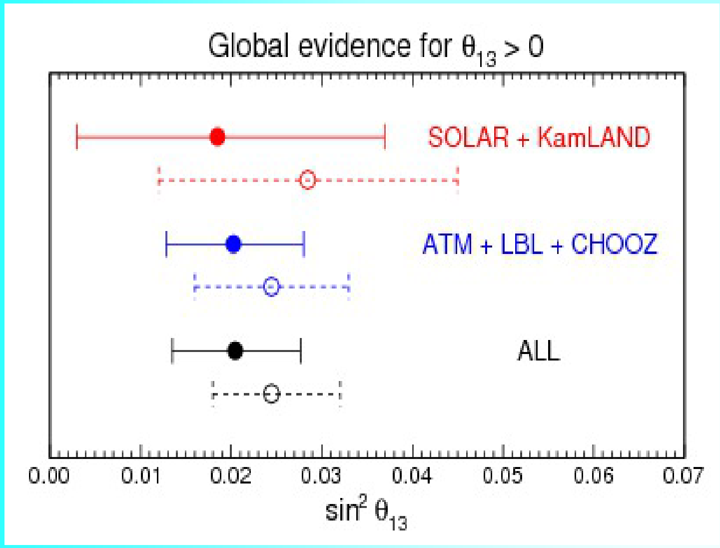


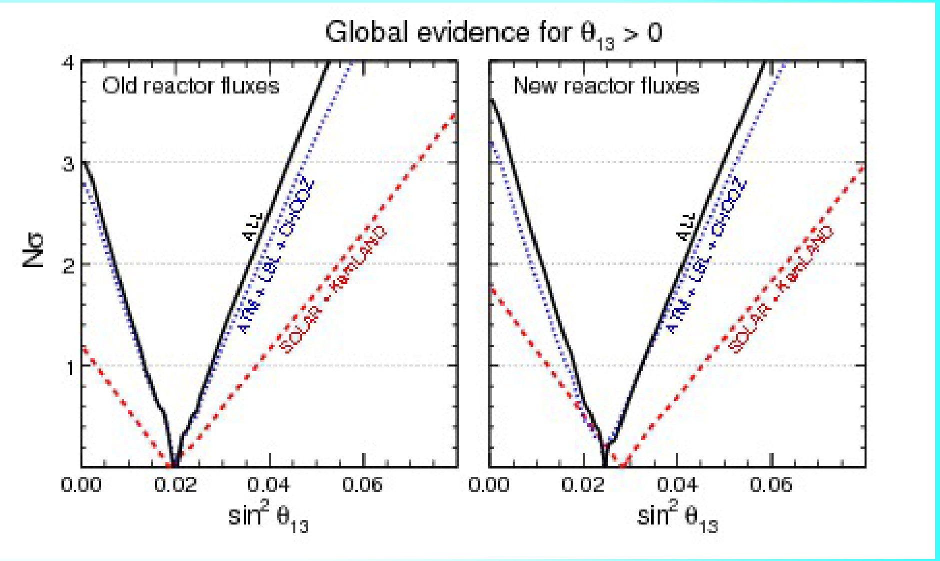
``accidental'' symmetry due to particular selection of flavon representations and configuration of VEV's

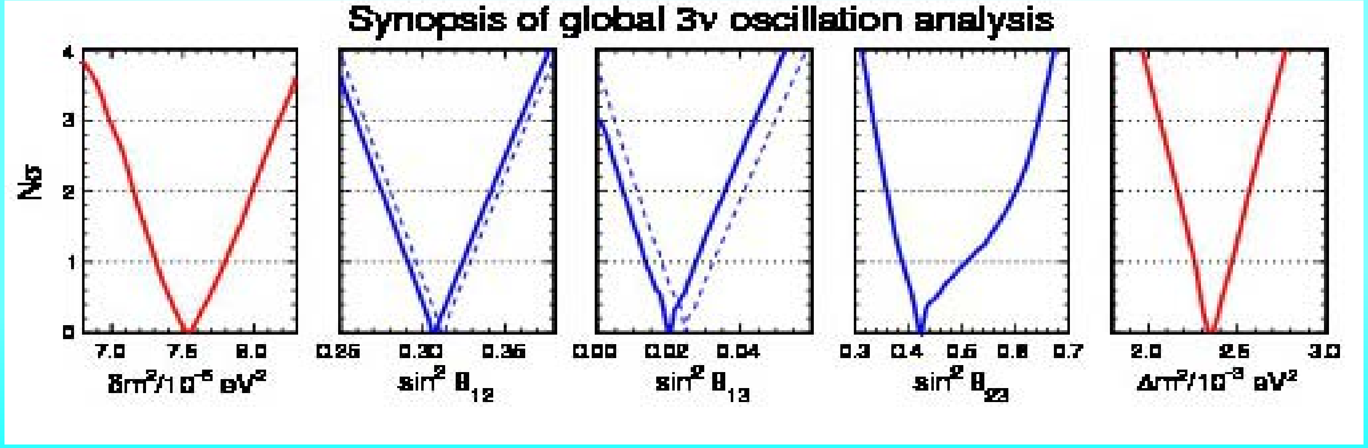
In turn, this split originates from different flavor assignments of the RH components of N^c and l^c and different higgs multiplets

Additional slides

1-3 mixing: global fit







Neutrinos & Dark Matter

Direct connection

Light neutrinos

Hot DM

Influence
LSS formation

Clumping
Form
structures

At least two
of them are
non-relativistic

As probe,
of DM

appear in annihilation
or decay of DM
particles

Search for DM
signal with neutrino
detectors

New
neutrino
states

Hot,warm DM

Huge impact of small angle

U_{e3}

theoretical implications

symmetry

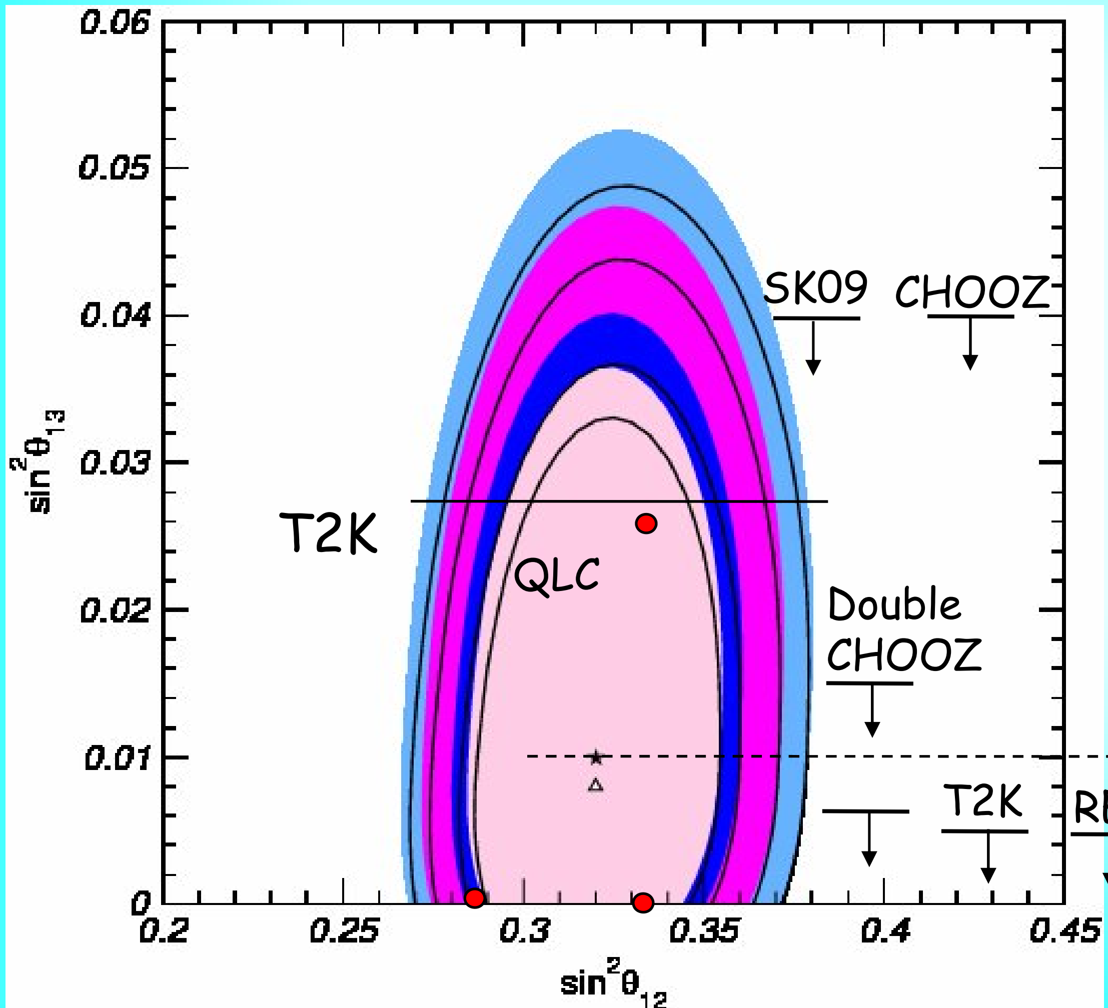
atmospheric neutrinos

dominant factor for SN neutrinos

door to determination of CP-violation

mass hierarchy

12 - and 13 - mixings



Global fit of oscillation data

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado

with 90% CL bounds from different experiments in assumption that true value $\sin^2\theta_{13} = 0$

90, 95, 99, 3σ CL contours

Evidence?

RH neutrino components have large Majorana mass

$$m_\nu = - m_D^T \frac{1}{M_R} m_D$$

$$M_R \sim \begin{cases} M_{GUT} & \text{in the presence of mixing} \\ \dfrac{M_{GUT}^2}{M_{Pl}} & \end{cases}$$

$m_D(\nu) \sim m_D(q, l)$

$M_{GUT} \sim 10^{16}$ GeV

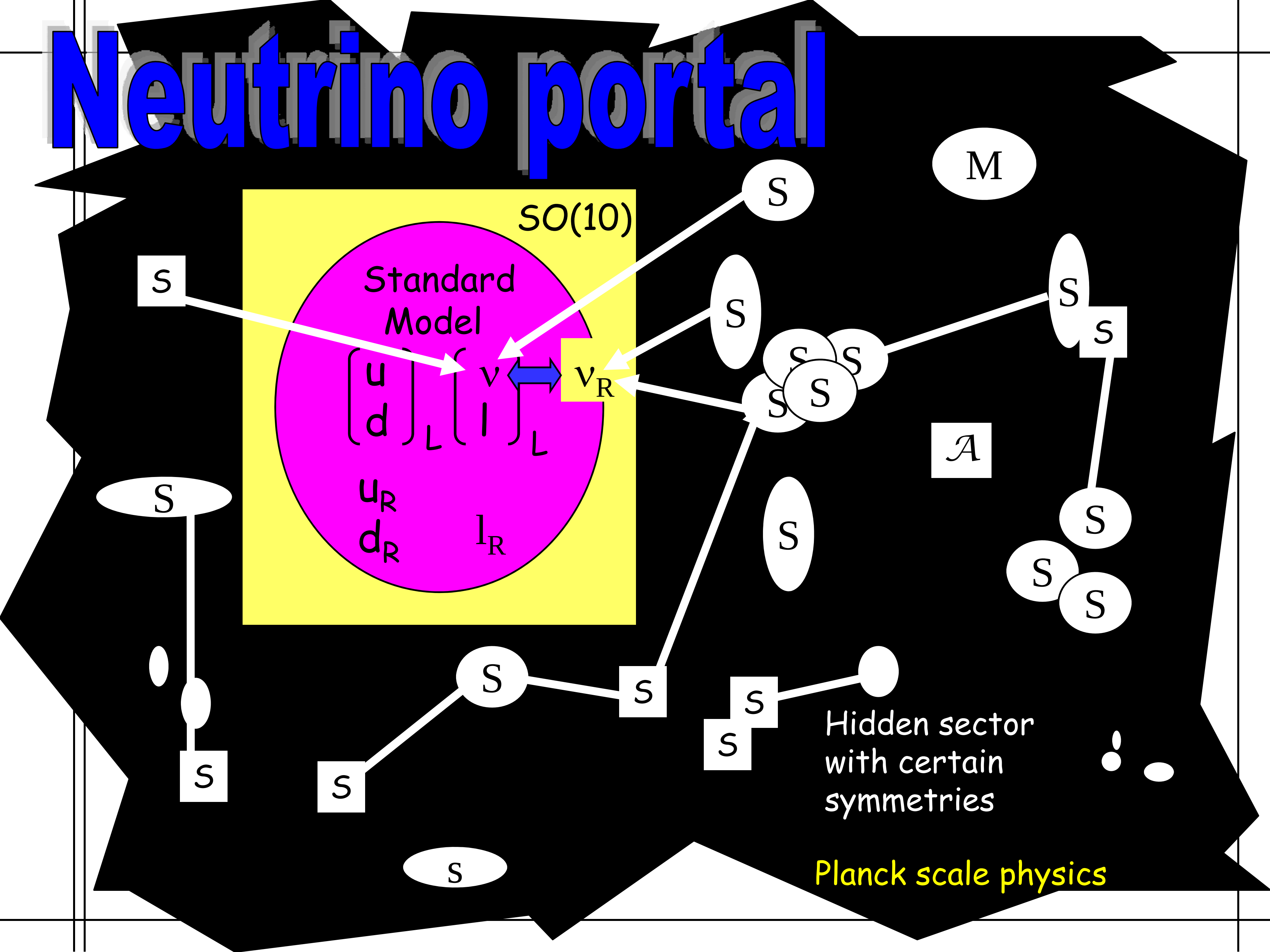
Neutrino mass as an evidence of Grand Unification ?

Leptogenesis:
the CP-violating out of equilibrium decay

$N \to l + H$

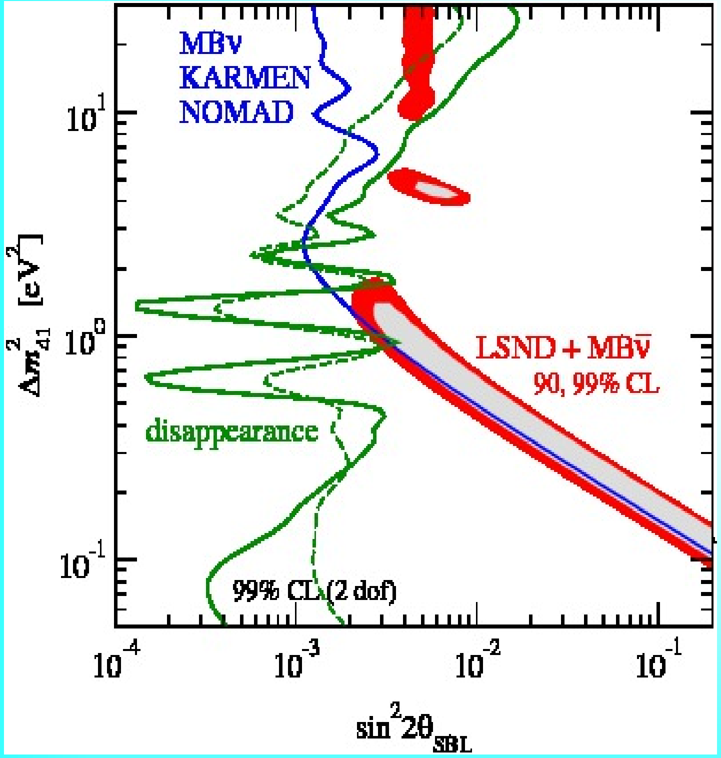
→ lepton asymmetry
→ baryon asymmetry of the Universe

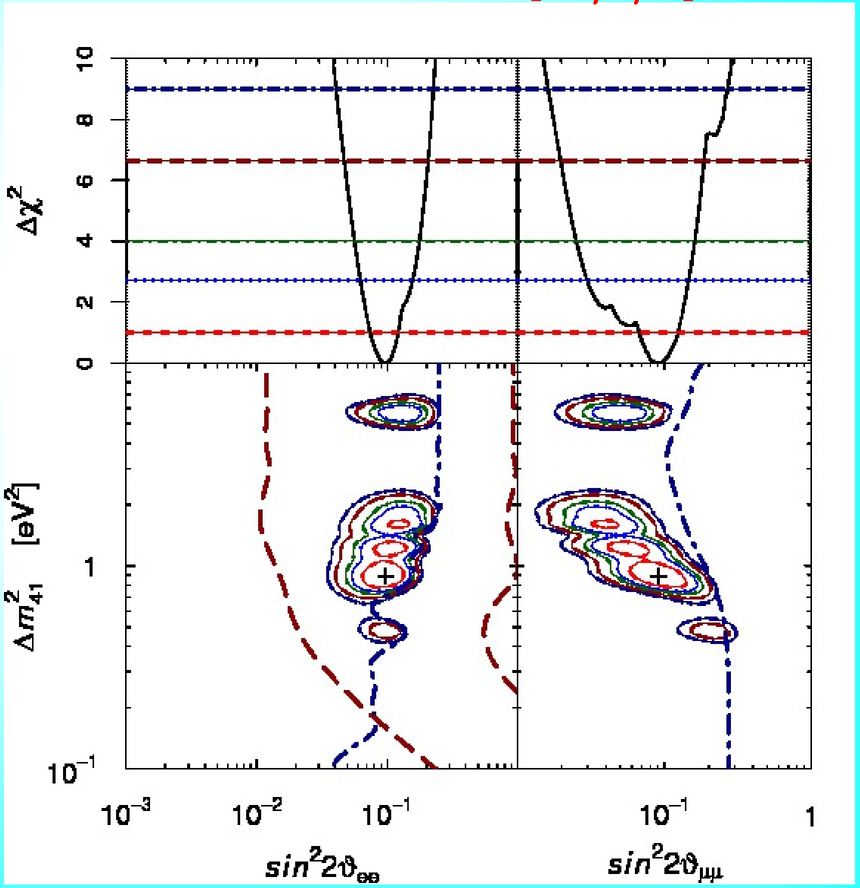
Neutrino portal



3+1 fit

C Giunti, M Laveder
1107.1452 [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]

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

J. Hamann et al PRL 105 (2010)181301

No evidence of $\Delta N_{eff} > 0$

A X Gonzalez-Morales, et al 1106.5052 [astro-ph. CO]

BBN

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

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

But $\Delta N_{eff} < 1$ (95% CL)

G. Mangano , P. D. Serpico, 1103.1261