Remarks

A. Yu. Smirnov

A. Yu. Smirnov

without conclusions

Content:

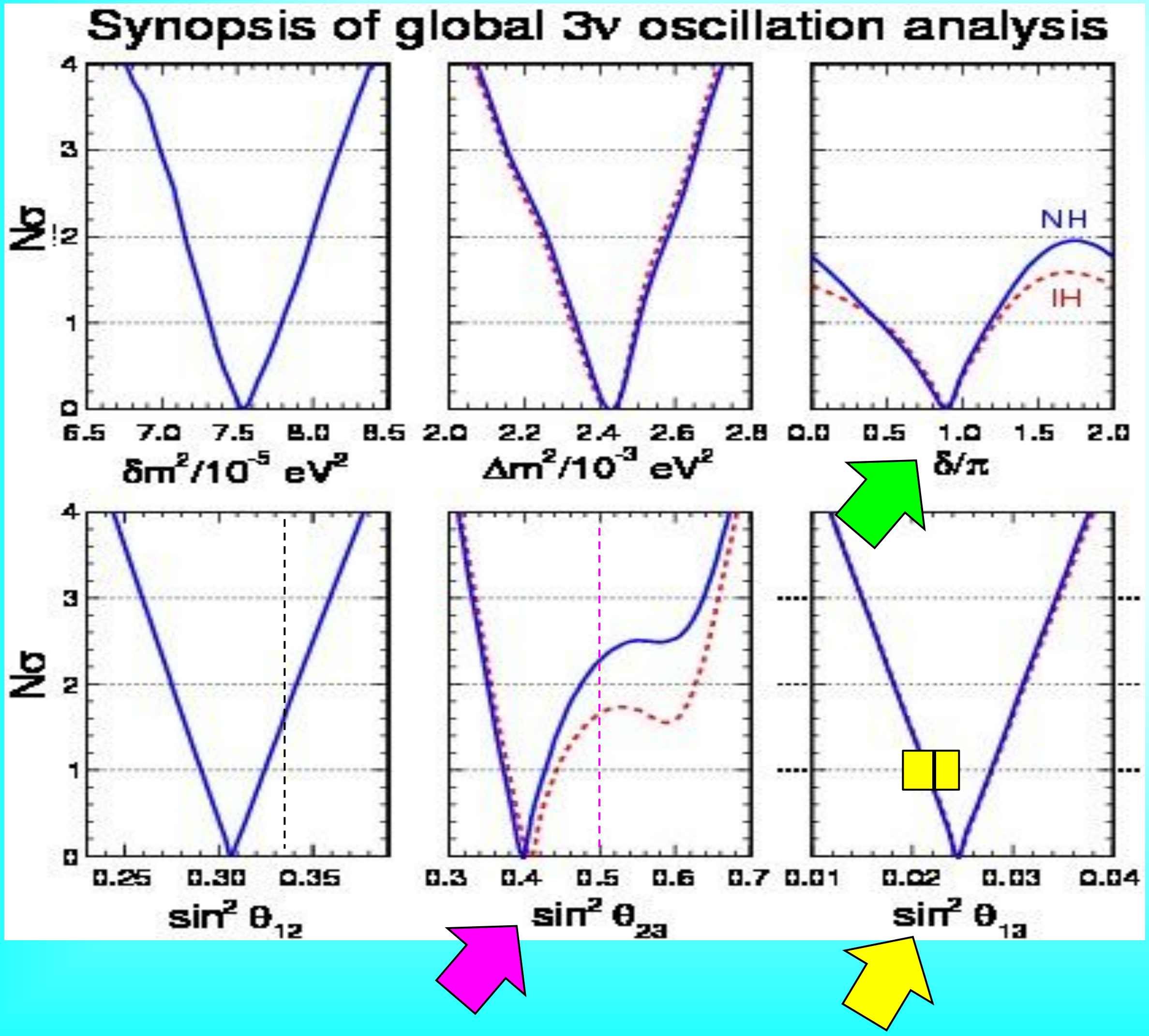
1. From special to normal
2. Back to the Sun
3. Physics with HAND’s

From ~~special~~ exceptional to normal

Synopsis

before
nu2012

G. L. Fogli


Synopsis of global 3ν oscillation analysis

Serious implications for theory

Non-zero, relatively Large 1-3 mixing

Substantial deviation of the 2-3 mixing from maximal

$\delta_{CP} \sim \pi$

DB new

Robust ?

Deviation of 2-3 mixing from maximal

$d_{23} = \frac{1}{2} - \sin^2\theta_{23}$

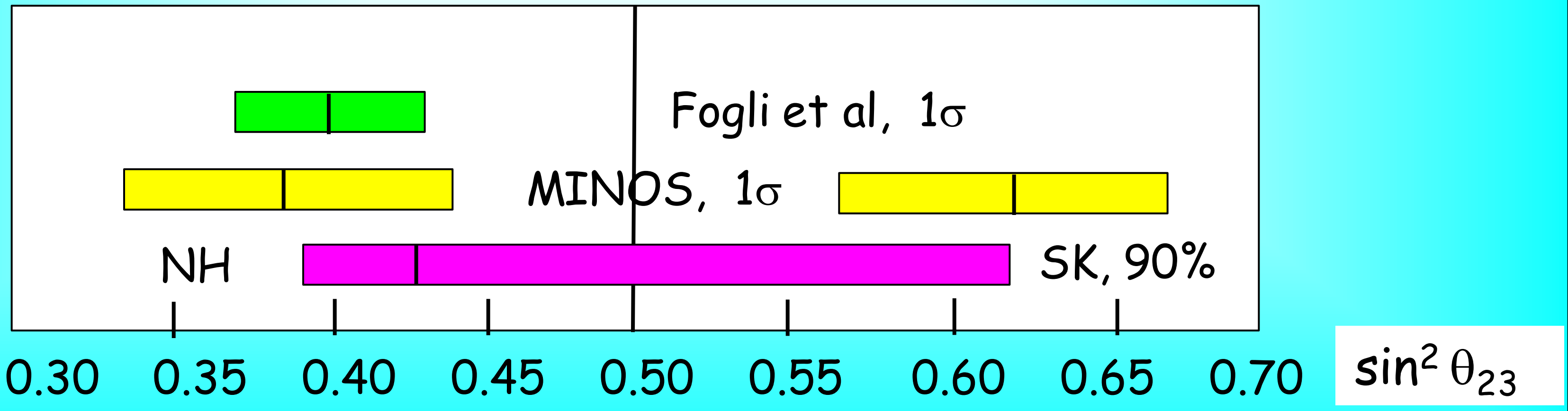
the key to (probe) understand the underlying physics

$\nu_\mu - \nu_\tau$ symmetry violation

Connection to 1-3 mixing

Quark -Lepton Complementarity

$\theta_{23} \sim \pi/2 - V_{cb}$



Measuring the deviation

Atmospheric neutrinos

ν_e - oscillation effects

$$\frac{F_e}{F_e^0} - 1 = P_{e2}\,(r\,c_{23}^2 - 1)$$

sub-GeV range

$$= P_{e3}\,(r s_{23}^2 - r)$$

multi-GeV range

$r = F_\mu^0/F_e^0 \sim 2$

``screening factor"

The e-like event excess – ar low energies and deficit at higher energies - signature of deviation of the 2-3 mixing from maximal (first quatrant)

T2K

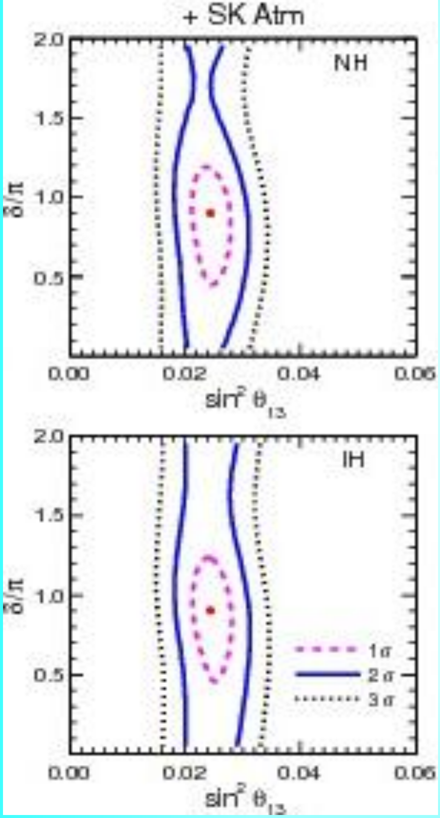
MINOS

$P_{\mu e} \sim \sin^2\theta_{13} \sin^2\theta_{23}$ - appearance

$P_{\mu\mu} \sim \sin^2 2\theta_{23}$ - disappearance

PINGU

CP-phase: measurements and predictions



G. L. Fogli

First glimpses?

T. Yanagida δ_{CP} ~ $\pi/2$ +/- 0.02

Third way

Neutrino-antineutrino asymmery

Dependence of probabilities on energy in wide range

Reconstruction of unitarity triangle

Key measurement: amplitudes of the ν_μ - ν_μ oscillations due to solar and atmospheric mass splittings

Do we have predictions for the phase in quark sector?
Why do we think that we can predict leptonic mixing?
Again because of neutrinos are special ? Symmetries?

Implications for theory

$\sin^2\theta_{13} \sim 0.025$ The same 1-3 mixing with completely different implications

$\sin^2\theta_{13} =$

$O(1)\,\frac{\Delta m_{21}^2}{\Delta m_{32}^2}$ ``Naturalness'' of mass matrix

$\sim \frac{1}{2}\sin^2\theta_C$ Quark Lepton Complementarity

$\sim \frac{1}{2}\cos^2 2\theta_{23}$ $\nu_\mu - \nu_\tau$ - symmetry violation

> 0.025 Mixing anarchy *A. De Gouvea, H .Murayama*

$\theta_{13} + \theta_{12} = \theta_{23} \sim \pi/4$ Self-complementarity

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

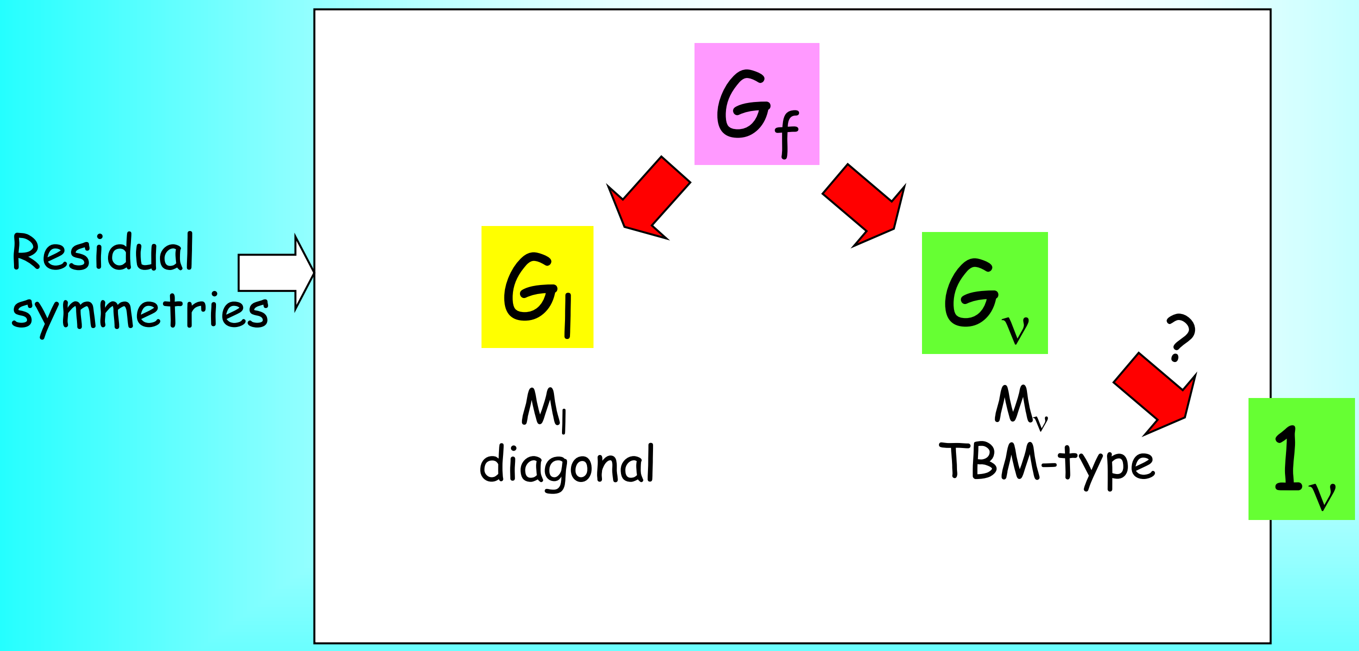
With different implications

Still something special?

Symmetry in sector responsible for smallness of neutrino mass?
RH neutrinos?

Symmetry without TBM

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



G_f

Residual symmetries

G_l

M_l
diagonal

G_ν

M_ν
TBM-type

?

1_ν

A_4 T_7 S_4 T'

Flavons

Flavored higgses

the splitting originates from different flavor assignments of the RH components of N^c and l^c and different higgs multiplets

Relations between mixing parameters

If G is von Dyck group D(2, m, p)

For column of the mixing matrix:

$$|U_{\beta i}|^2 = |U_{\gamma i}|^2$$

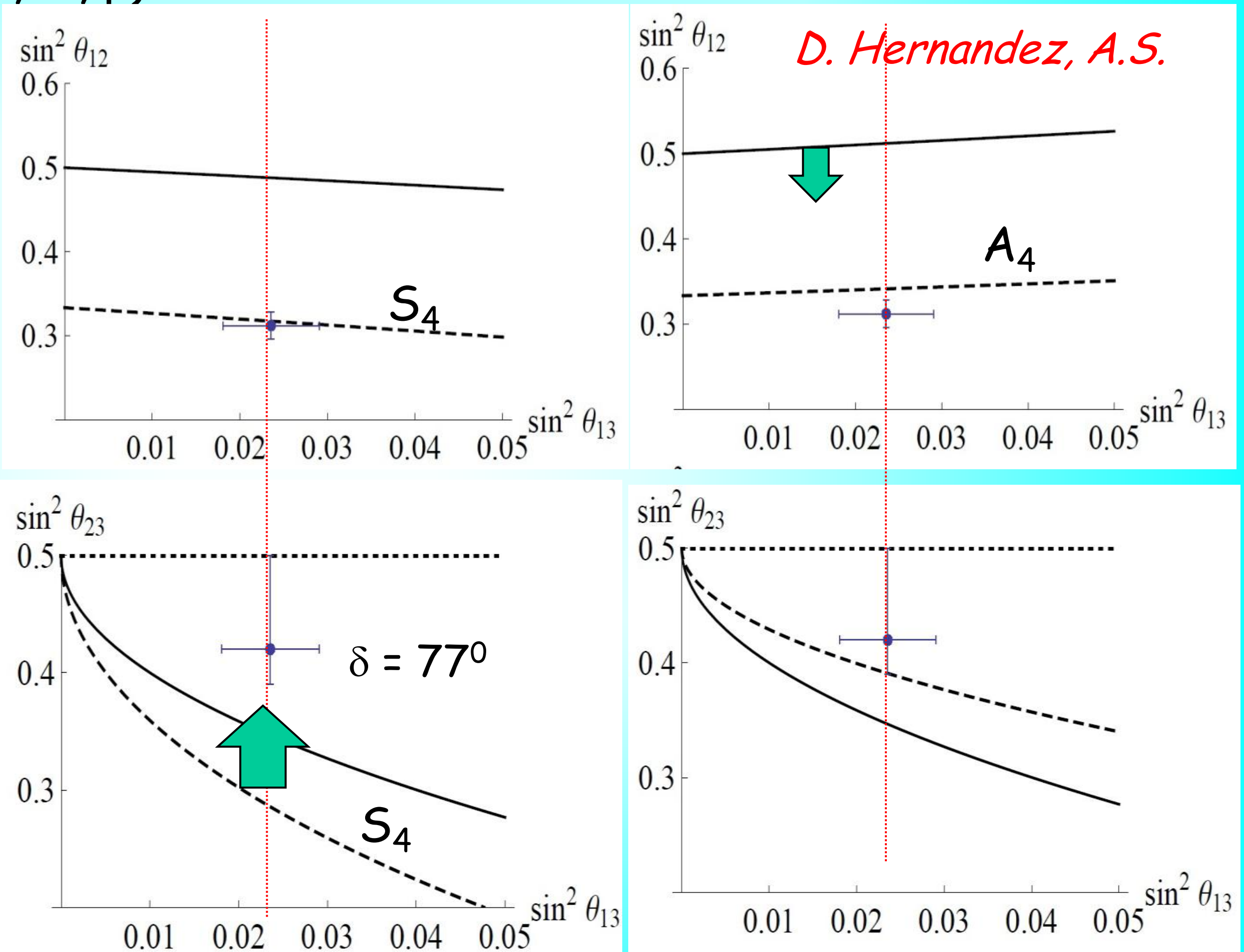
$$|U_{\alpha i}|^2 = \frac{1 - a}{4 \sin^2 (\pi k/m)}$$

A is determined from condition

$$\lambda^3 + a\,\lambda^2 - a^*\,\lambda - 1 = 0$$

$$\lambda_i^p = 1$$

k, m, p integers which determine symmetry group



D. Hernandez, A.S.

Also S. F. Ge, D. A. Dicus, W. W. Repko, PRL 108 (2012) 041801

Realizations: QLC

$$\theta_{13} \sim \frac{1}{\sqrt{2}}\theta_c$$

$$\sin^2\theta_{13} \sim \frac{1}{2}\sin^2\theta_c$$

First obtained in the context of Quark-Lepton Complementarity

H. Minakata, A Y S

Follows from permutation of matrices

$$U_{12}(\theta_c)\, U_{23}(\pi/2)$$

From charged leptons

Maximal from neutrinos

Permutation - to reduce the lepton mixing matrix to the standard form

Again neutrinos are special!

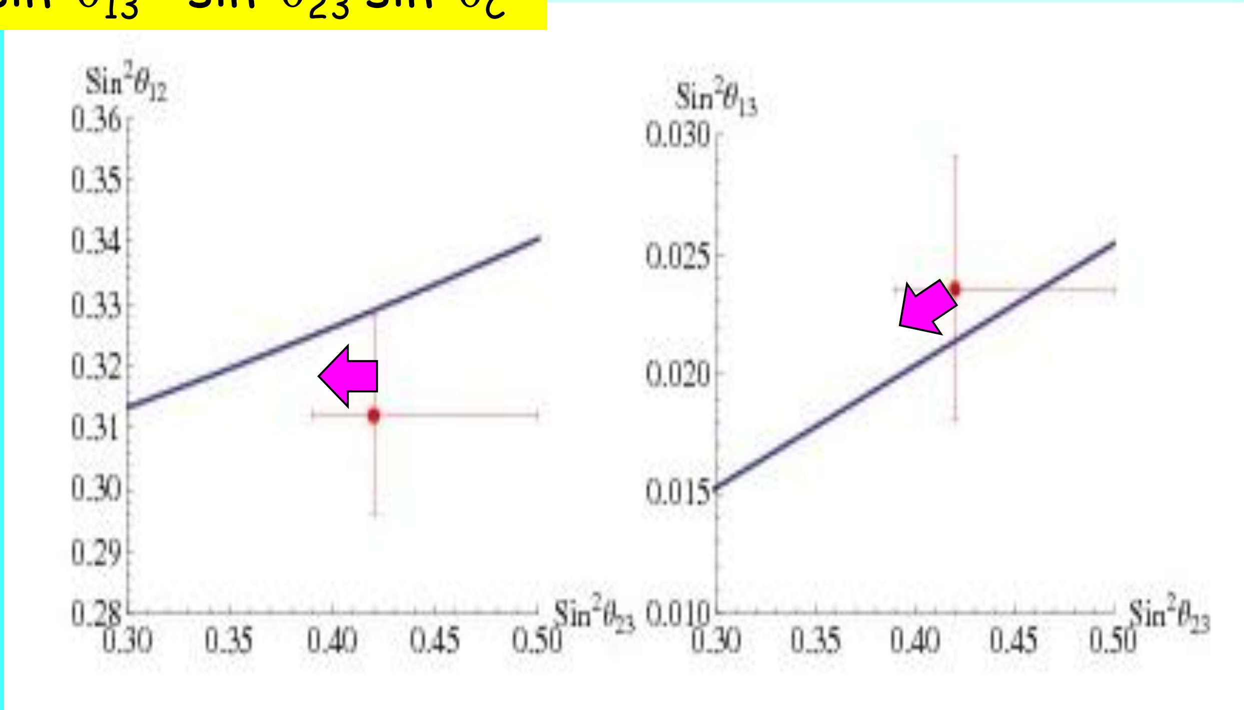
Related to smallness of mass

See-saw,
symmetry of RH neutrino sector

QLC: generalization

$\sin^2\theta_{13} \sim \sin^2\theta_{23} \sin^2\theta_C$

D. Hernandez, A.S.



Improves also predictions for 1-2 mixing

Bi-maximal mixing?

RGE effect

$\sin^2\theta_{13} \sim \sin^2\theta_{23} \sin^2\theta_C$

QLC or Cabibbo "haze"

P. Ramond

Deviations from BM due to high order corrections

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

Weak complementarity or
Cabibbo haze

Altarelli et al

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

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

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

Self-complementarity relations

Xinyi Zhang Bo-Qian Ma, arXiv:1202.4258

Quark-lepton universality?

Similar Ansatz for
structure of mass matrices

M Fukugita T. Yanagida

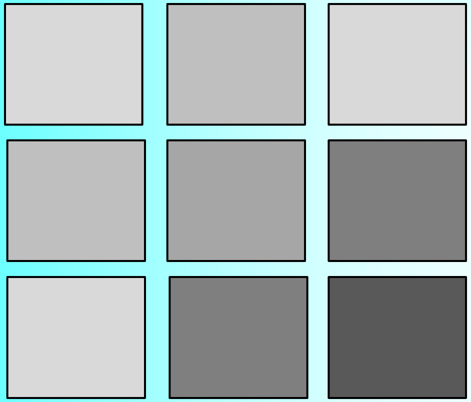
Relations between
masses and mixing

Fritsch Anzatz
similar to quark sector
3 RH neutrinos with equal
masses →
Normal mass hierarhy,
Right value of 13 mixing

Flavor ordering

Flavor alignment

Values of elements gradually decrease from $m_{\tau\tau}$ to m_{ee}



corrections wash out sharp difference of elements of the dominant $\mu\tau$-block and the subdominant e-line

This can originate from power dependence of elements on large expansion parameter $\lambda \sim 0.7 - 0.8$.
Another complementarity: $\lambda = 1 - \theta_C$

Froggatt-Nielsen?

Masses and mixing

$$\sin^2\theta_{13} \sim \frac{\Delta m_{21}^2}{\Delta m_{32}^2}$$

1. Two mass scales in the mass matrix

$\sqrt{\Delta m_{21}^2}$ $\sqrt{\Delta m_{31}^2}$

Assumptions

2. Two large mixing angles

3. Normal mass hierarchy

4. No fine tuning - no equalities of matrix elements

$$\sin\theta_{13} \sim \sqrt{\Delta m_{21}^2 / \Delta m_{31}^2} = 0.17 - 0.20$$

Implications:
- no particular (for leptons) flavor symmetries,
- normal mass hierarchy

Old does not mean wrong

After many speculations back to good old picture?

High scale seesaw

GUT

???

Something is
still missed

Flavor physics at
very high scales
above GUT?

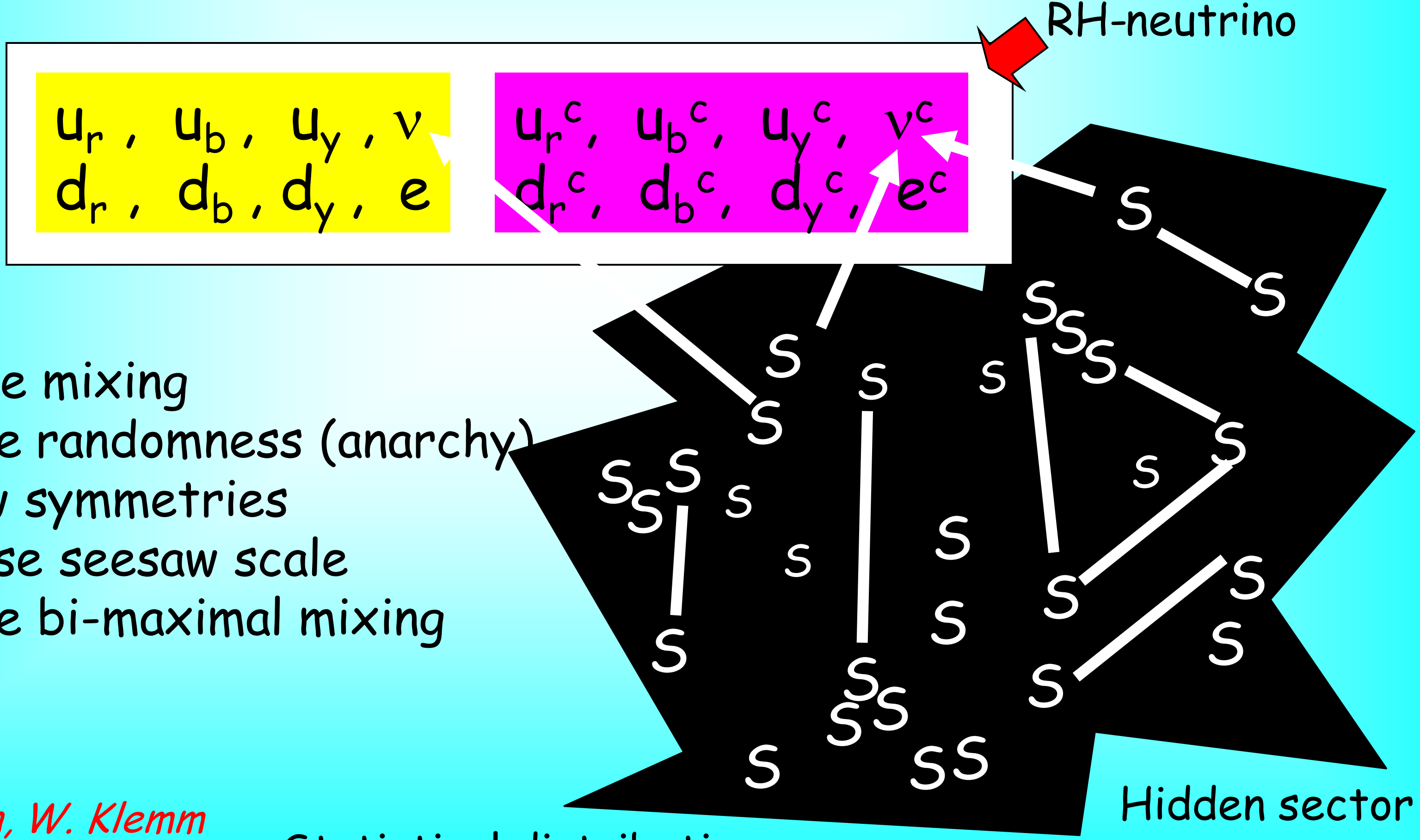
The same mechanism which explains
smallness of neutrino mass is responsible
for large lepton mixing

Seesaw enhancement of mixing
No particular symmetry?

Difference of quark and lepton mixings
is related to smallness of neutrino mass

Hidden sector at GUT,
Planck scales

SO(10) GUT + ...



16

u_r , u_b , u_y , ν
d_r , d_b , d_y , e

$u_r^c, u_b^c, u_y^c, \nu^c$
d_r^c, d_b^c, d_y^c, e^c

RH-neutrino

Hidden sector

- Enhance mixing
- Produce randomness (anarchy)
- Seesaw symmetries
- Increase seesaw scale
- produce bi-maximal mixing

Statistical distribution ...

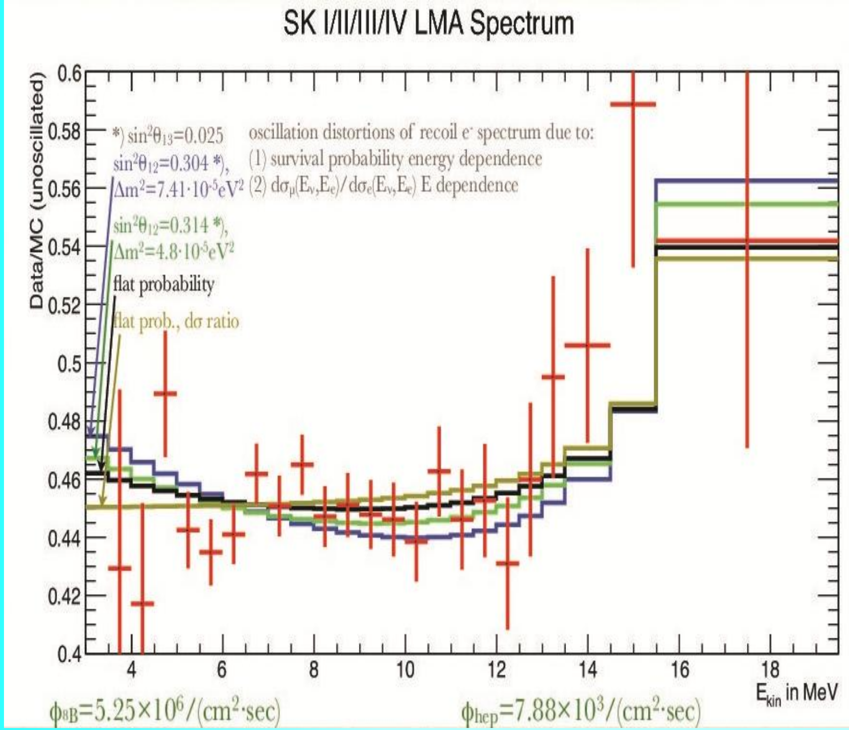
B. Feldstein, W. Klemm
arXiv: 1111.6690

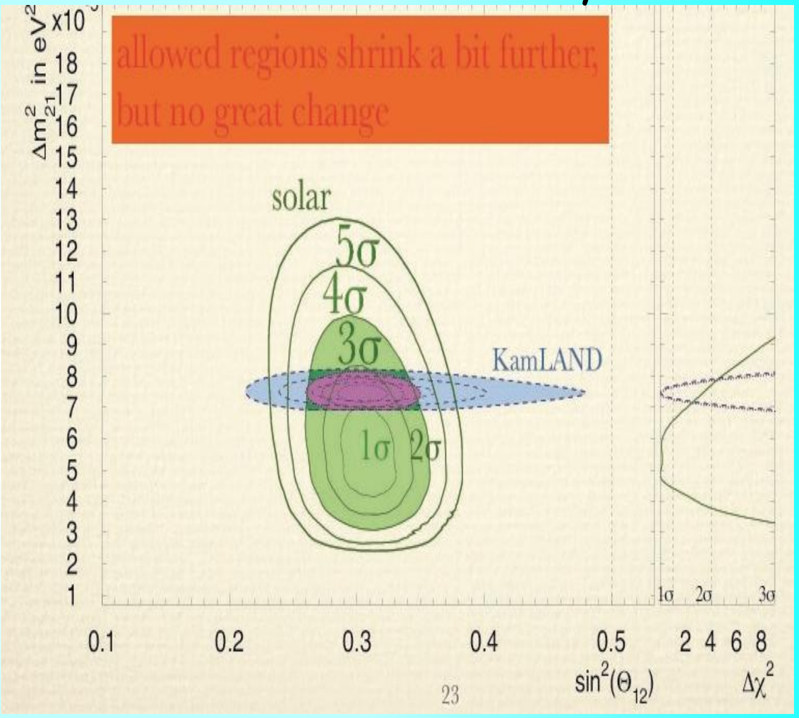
Back to the Sun

Solar neutrinos: two features

SuperKamiokande

M. Smy



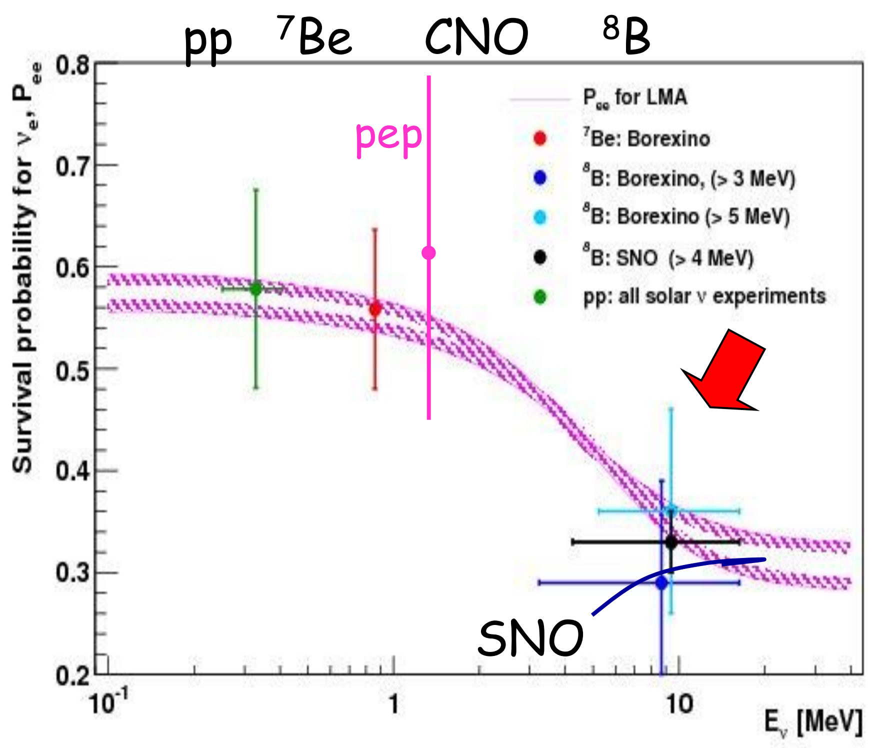


No distortion of the energy spectrum at low energies : the upturn is disfavored at (1.1 – 1.9) σ level

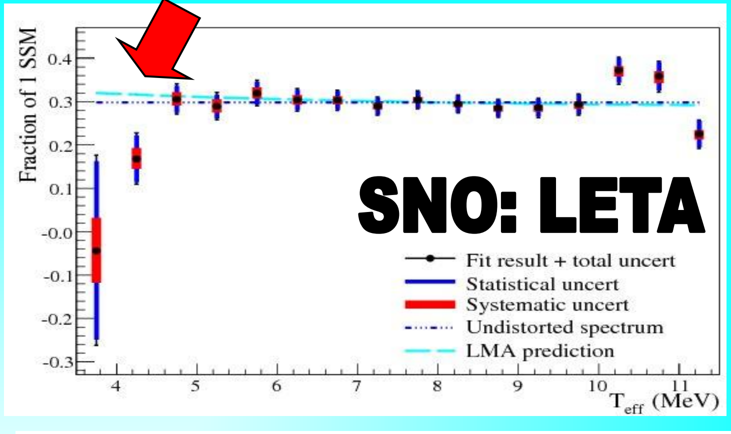
Increasing tension between Δm^2_{21} measured by KamLAND and in solar neutrinos 1.3σ level

This is how new physics may show up

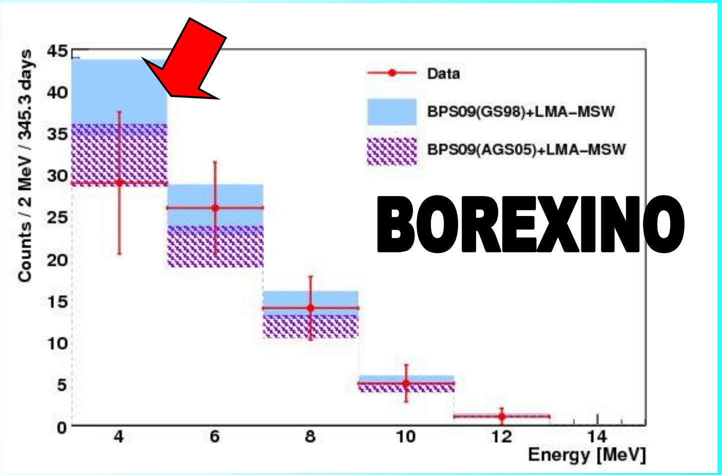
Up-turn?



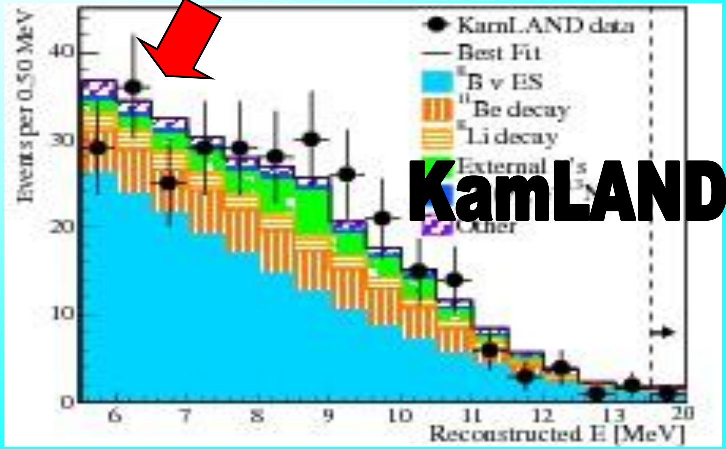
ν_e - survival probability from solar neutrino data vs LMA-MSW solution



SNO: LETA



BOREXINO

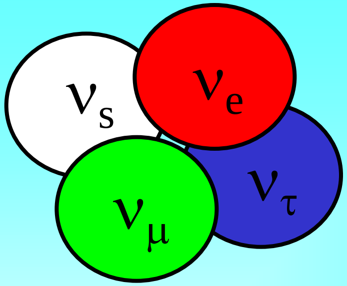


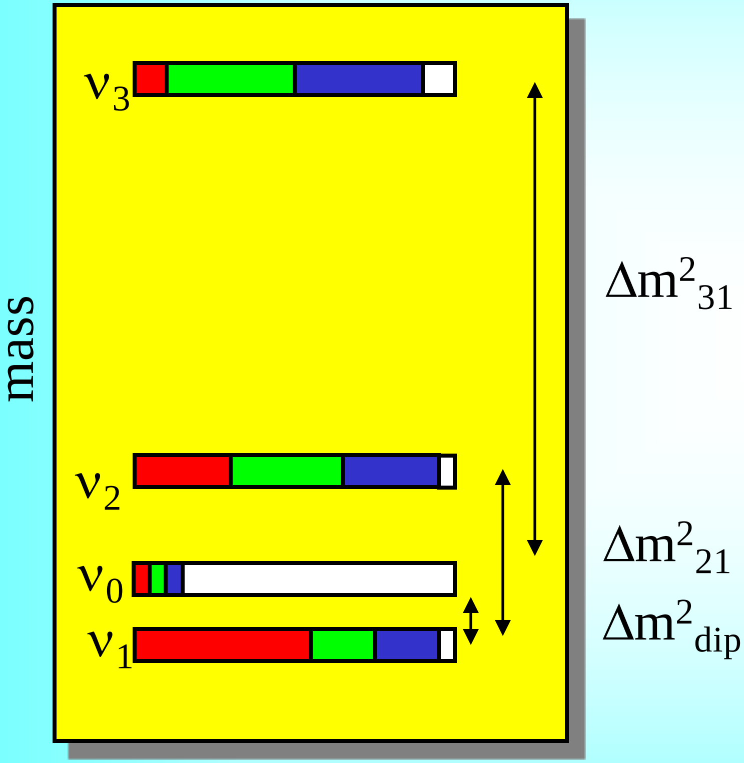
KamLAND

HOMESTAKE
low rate

SNO+

Very light sterile





Very light sterile neutrino

$m_0 \sim 0.003$ eV DE scale?

$\frac{M^2}{M_{Planck}}$ $M \sim$ 2 - 3 TeV

- solar neutrino data

- additional radiation in the Universe if mixed in ν_3

no problem with LSS (bound on neutrino mass)

can be tested in atmospheric neutrinos with DC IceCube

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

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

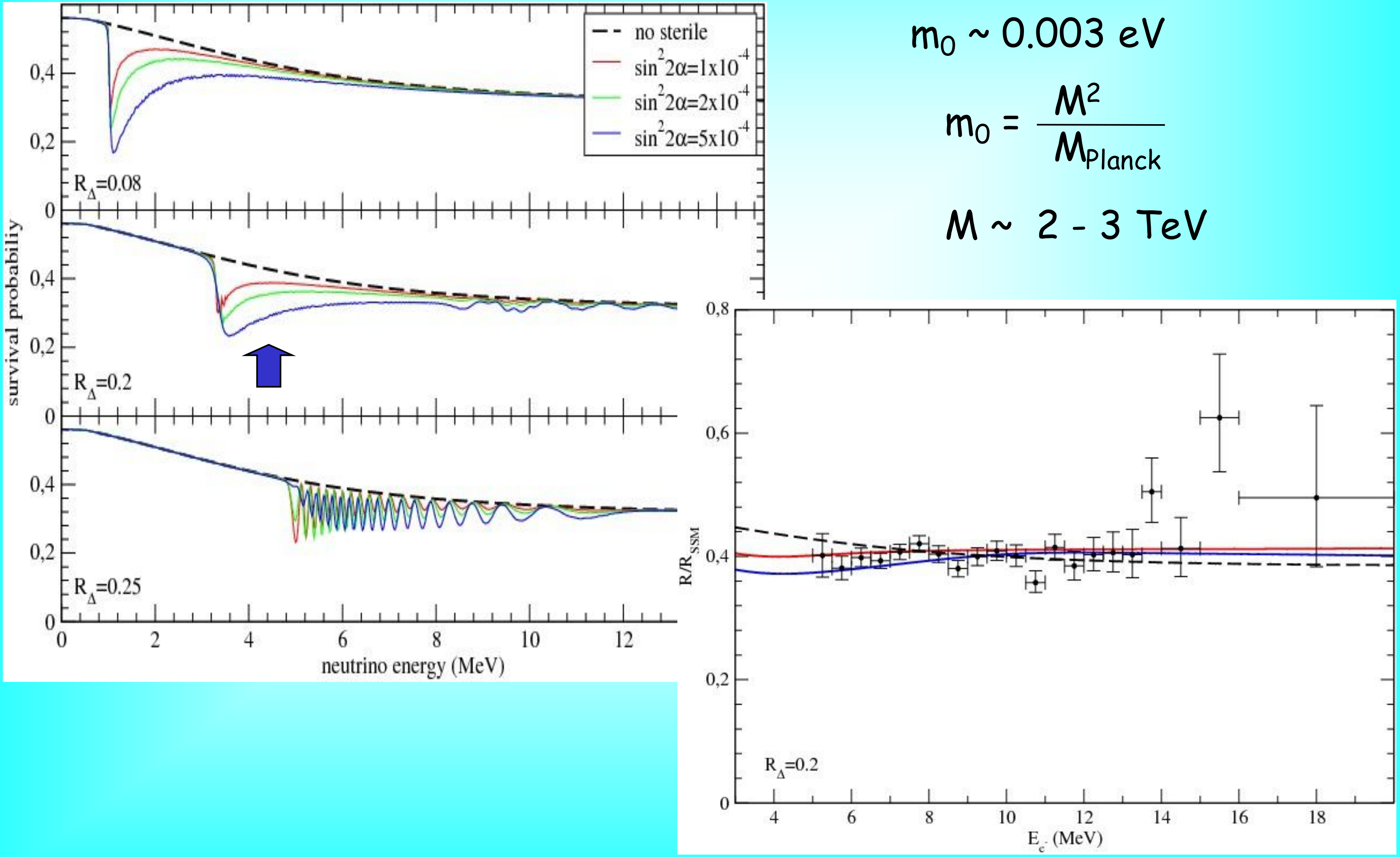
Survival probability

P. de Holanda,
AYS

$m_0 \sim 0.003$ eV

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

$M \sim$ 2 - 3 TeV



Day and Night

Accumulating data at SK SK I - IV

Day-Night effect: at 2.3 σ – level in agreement with the LMA MSW solution

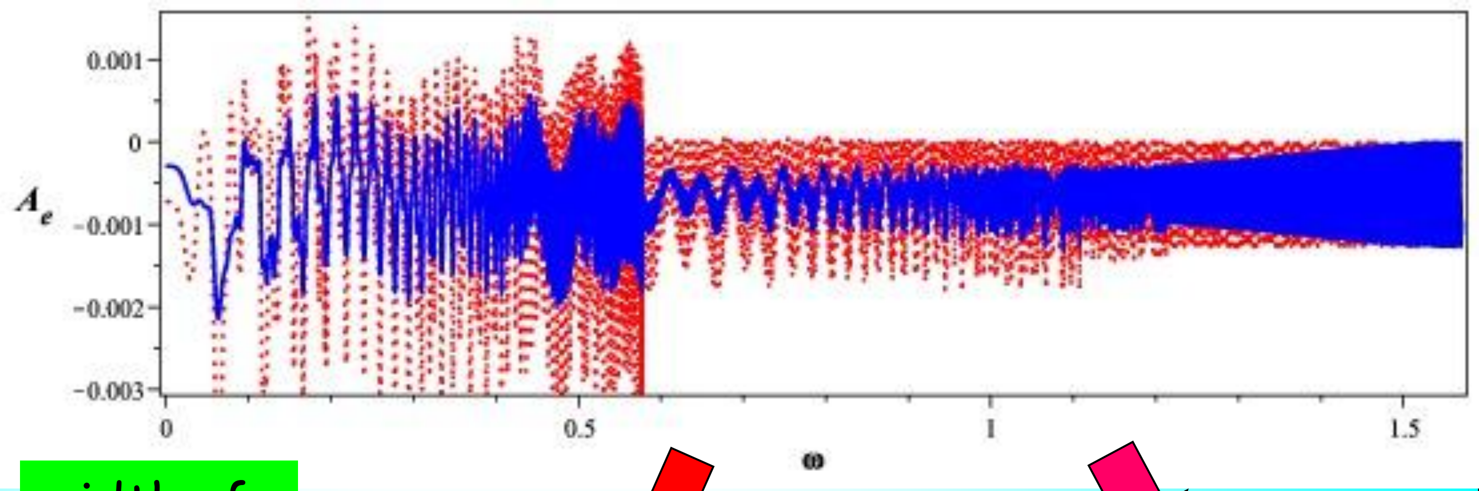
Provides overall test of the solution

New precision level - new possibilities: HyperKamiokande, LENA, MICA

LENA and Earth matter effect

Be neutrino line

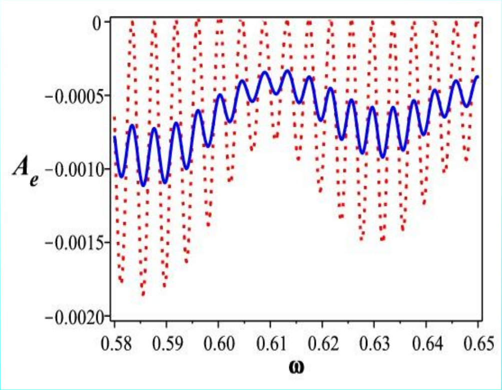
A Ioanissian, AYS

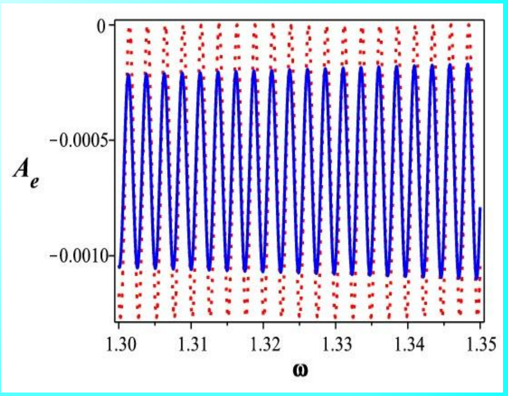


Period of oscillations in energy scale

~

width of Beryllium nu line





Width of the Be nu line → central temperature of the Sun

Precise measurements of Δm_{21}^2

Tomography of the Earth with resolution 20 km

Physics with HAND'S

Huge
Atmospheric
Neutrinos
Detectors

or race for hierarchy

Race for hierarchy

Matter effect on 1-3 mixing

Precise measurements of Δm^2 at reactors

Cosmology Σm

Atmospheric neutrinos

LBL experiments

Supernova neutrinos

Double beta decay m_{ee}

PINGU

INO

NH ←→ IH
nu ←→ antinu

NOvA
Neutrino beam
Fermilab-PINGU(W. Winter)

Earth matter effect
Energy spectrs

Sterile neutrinos may help?

Atmospheric neutrinos

Oscillation physics with Huge
atmospheric neutrino detectors

P. Coyle

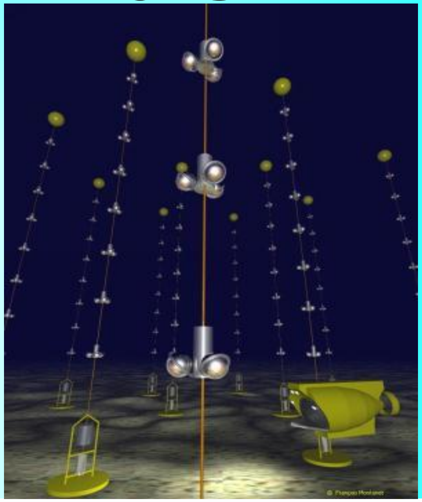
ANTARES — Oscillations 2.7σ

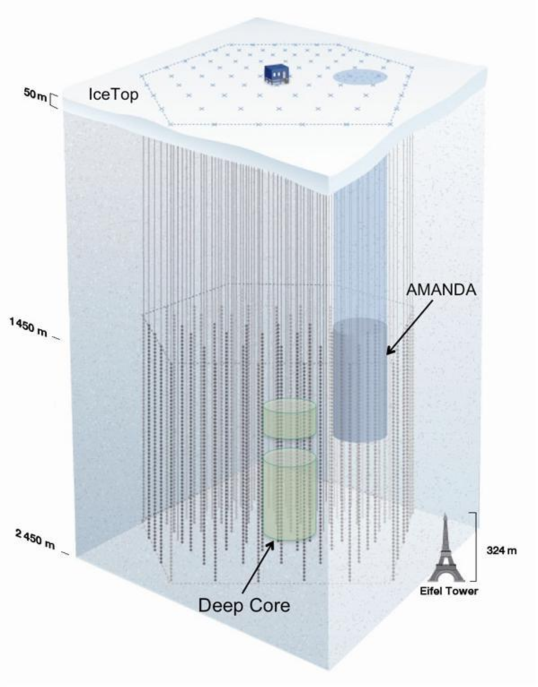
G. Sullivan

DeepCore — Oscillations at high energies 10 – 100 GeV in agreement with low energy data

Ice Cube — no oscillation effect at E > 100 GeV

Bounds on non-standard interaction,
Lorentz violation etc





PINGU Geometry

Precision IceCube Next Generation Upgrade

Denser array

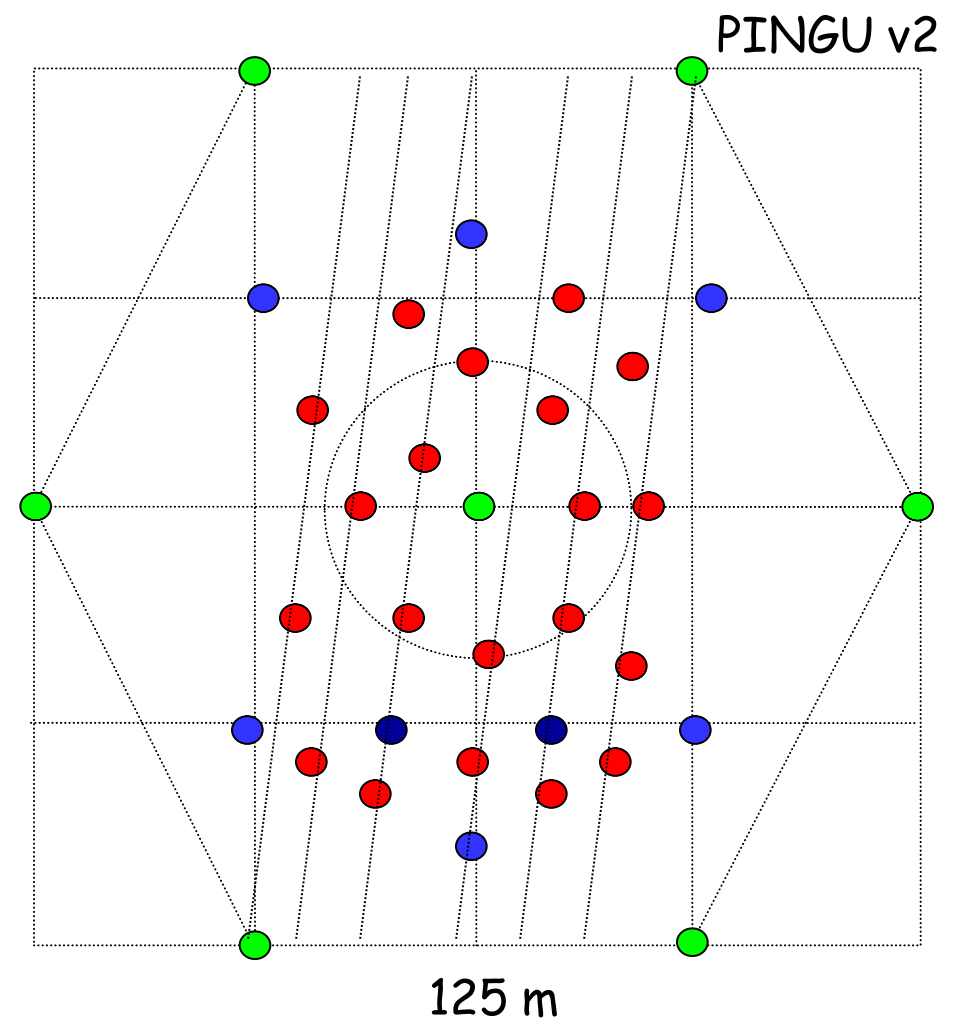
20 new strings (~60 DOMs each)
in 30 MTon DeepCore volume

⇩

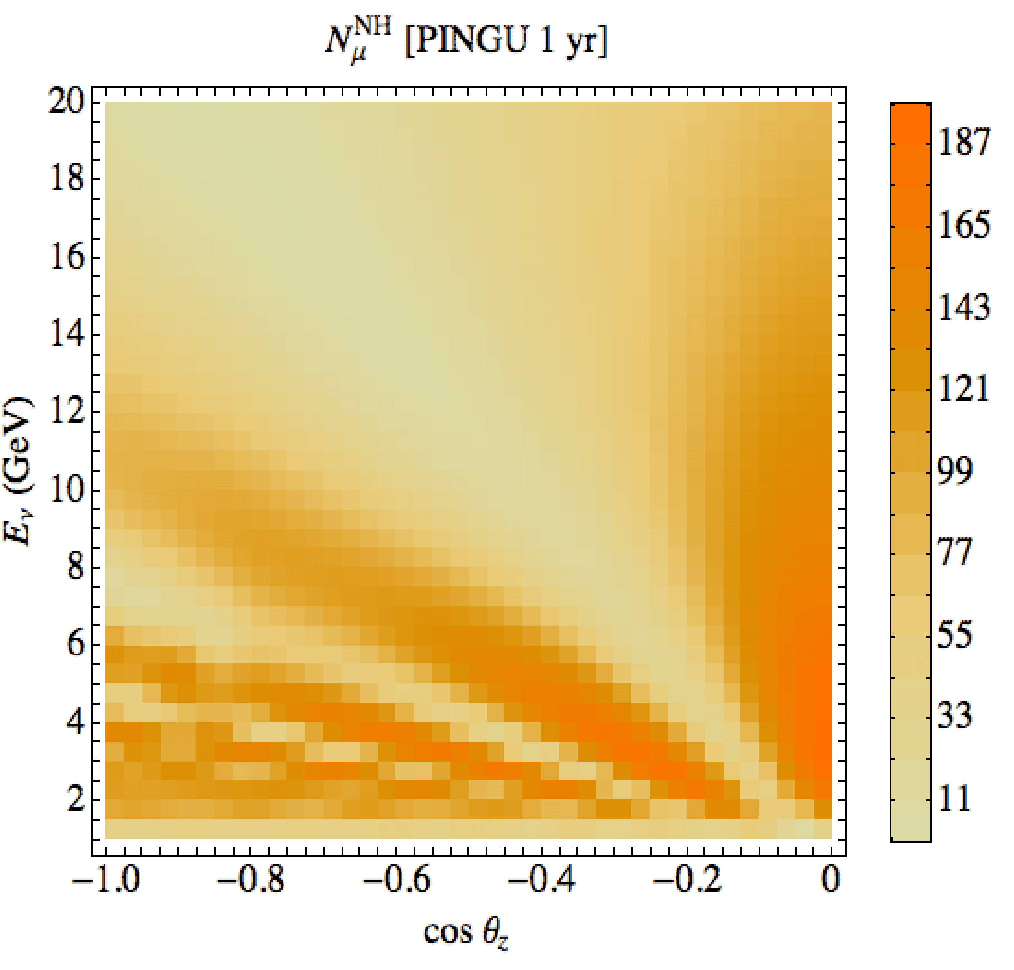
Few GeV threshold in inner
10 Mton volume

Energy resolution ~ 3 GeV

- 🟢 Existing IceCube strings
- 🔵 Existing DeepCore strings
- 🔴 New PINGU-I strings



Muon neutrino events



High statistics can cure other problems

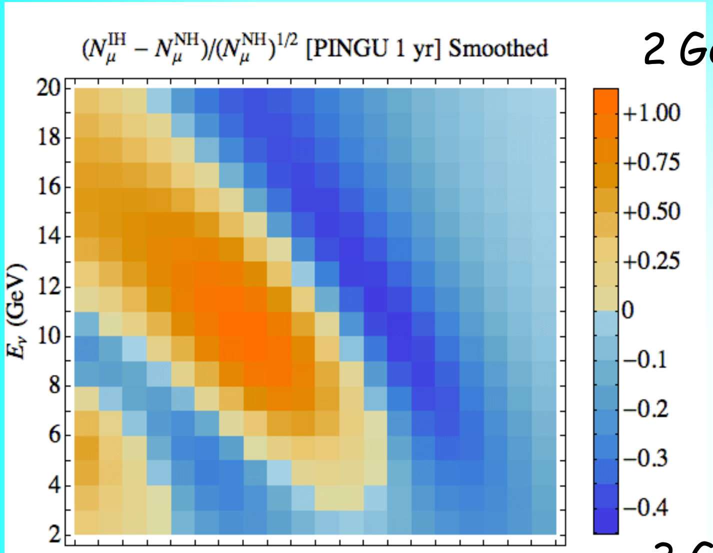
PINGU and mass hierarchy

E. Akhmedov, S. Razzaque, A. Y. Smirnov
arXiv: 1205.7071

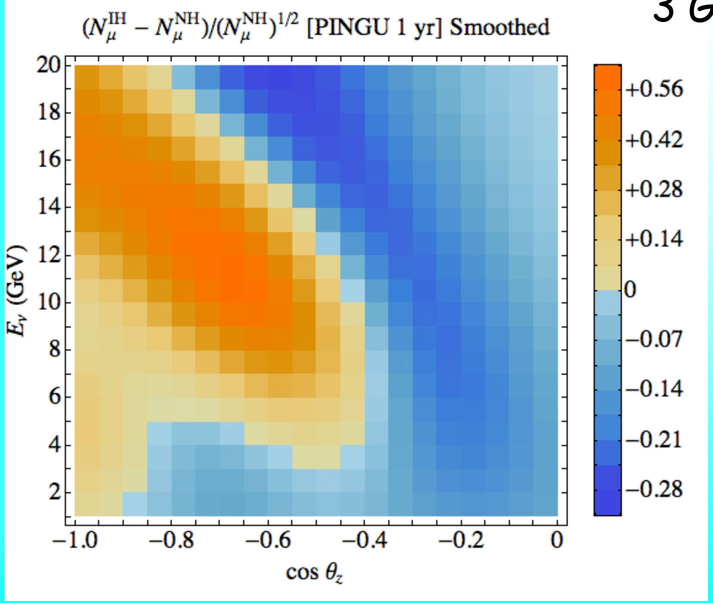
Smearing with Gaussian reconstruction functions characterized by (half) widths

$(\sigma_E\ ,\ \sigma_\theta)$

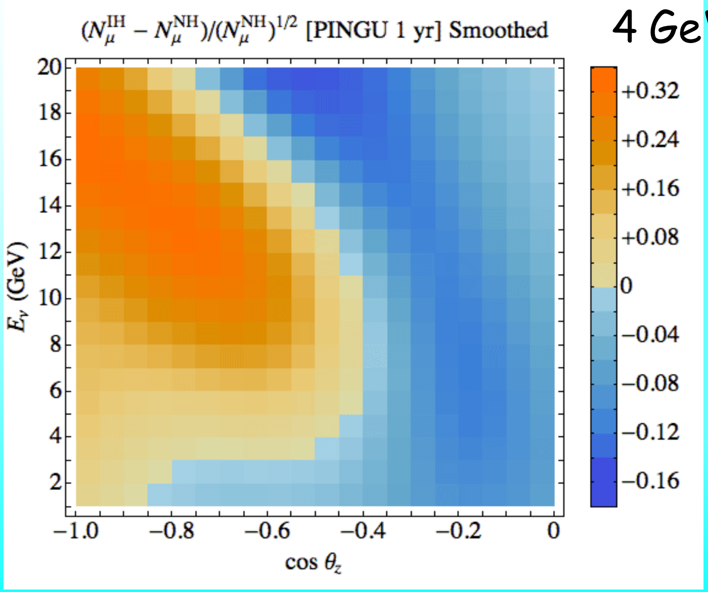
2 GeV, 11.25^0



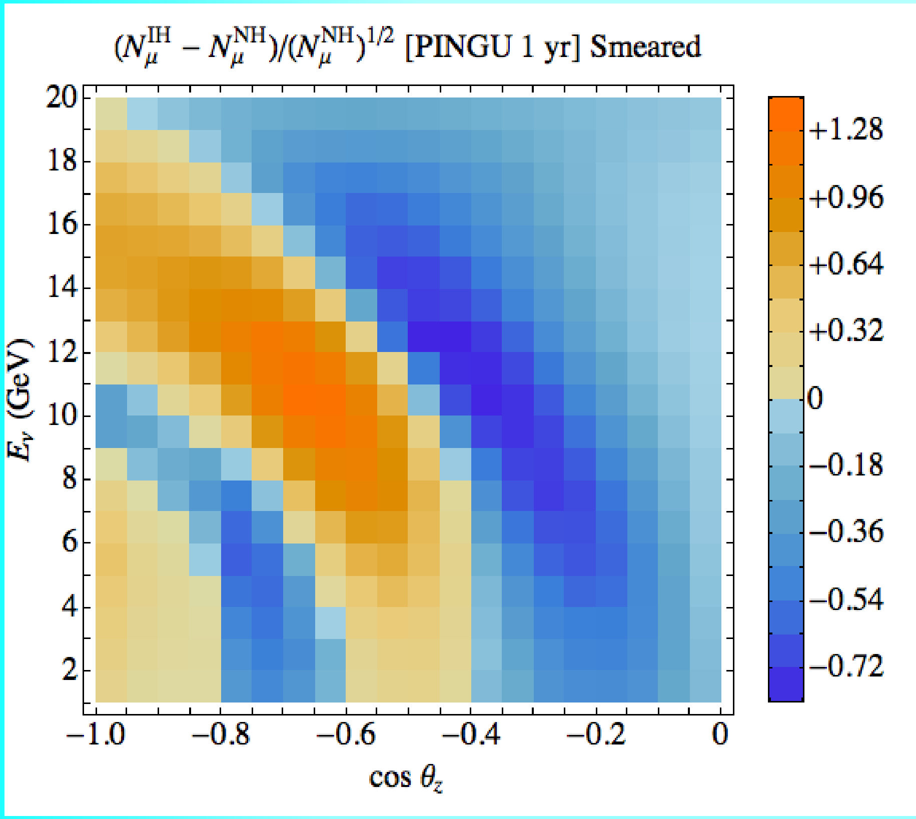
3 GeV, 15^0



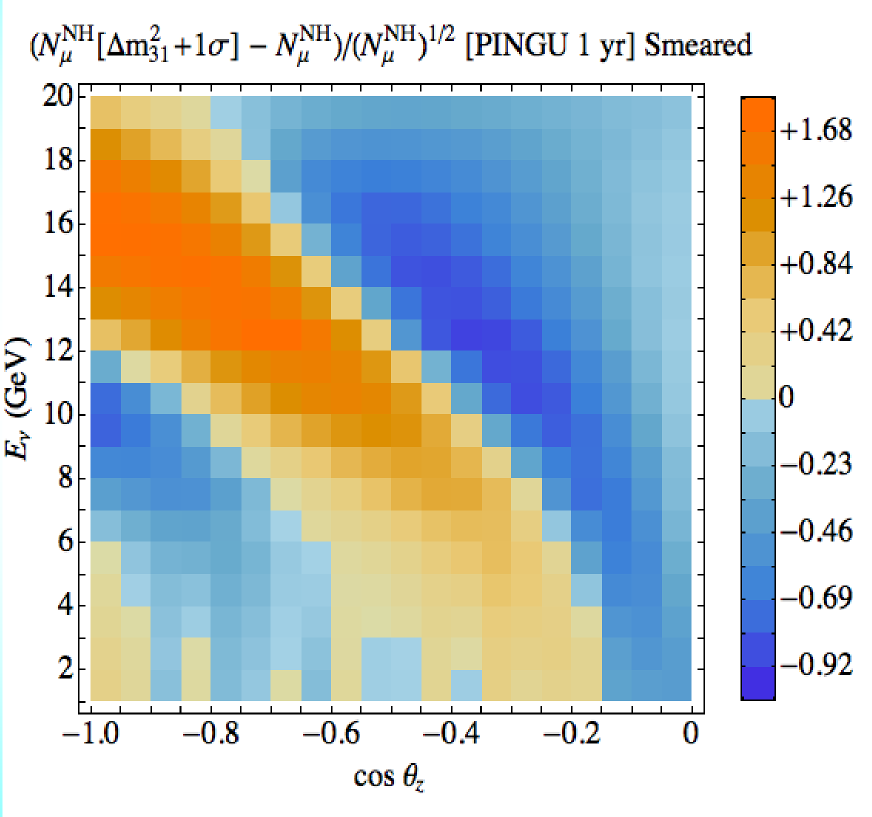
4 GeV, 22.5^0



Hierarchy with PINGU



$(N_\mu^{\mathrm{IH}} - N_\mu^{\mathrm{NH}})/(N_\mu^{\mathrm{NH}})^{1/2}$ [PINGU 1 yr] Smeared



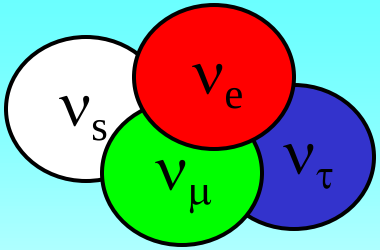
$(N_\mu^{\mathrm{NH}}[\Delta m^2_{31}+1\sigma] - N_\mu^{\mathrm{NH}})/(N_\mu^{\mathrm{NH}})^{1/2}$ [PINGU 1 yr] Smeared

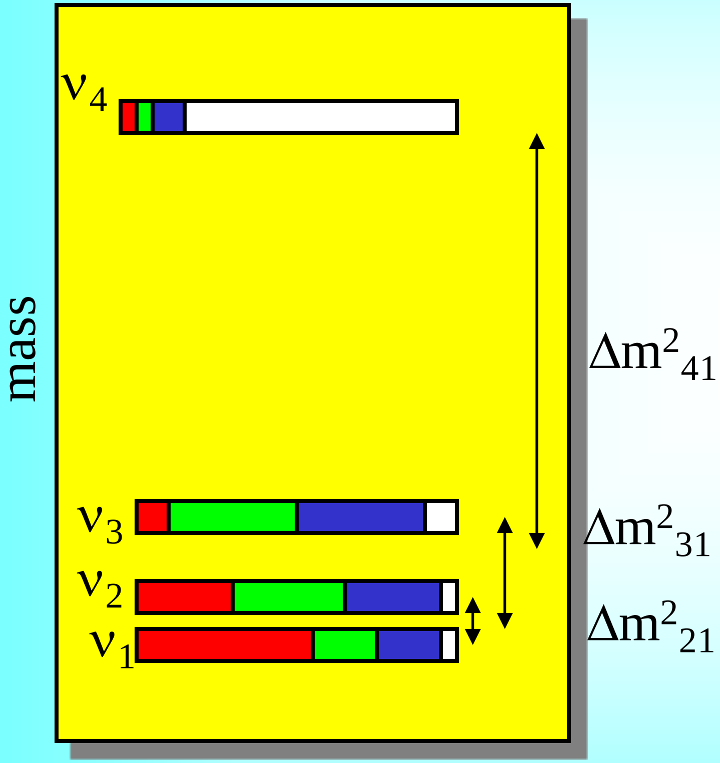
$\sigma_E = 0.2E$

$\sigma_\theta \sim 1/E^{0.5}$

Degeneracy

(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:

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

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

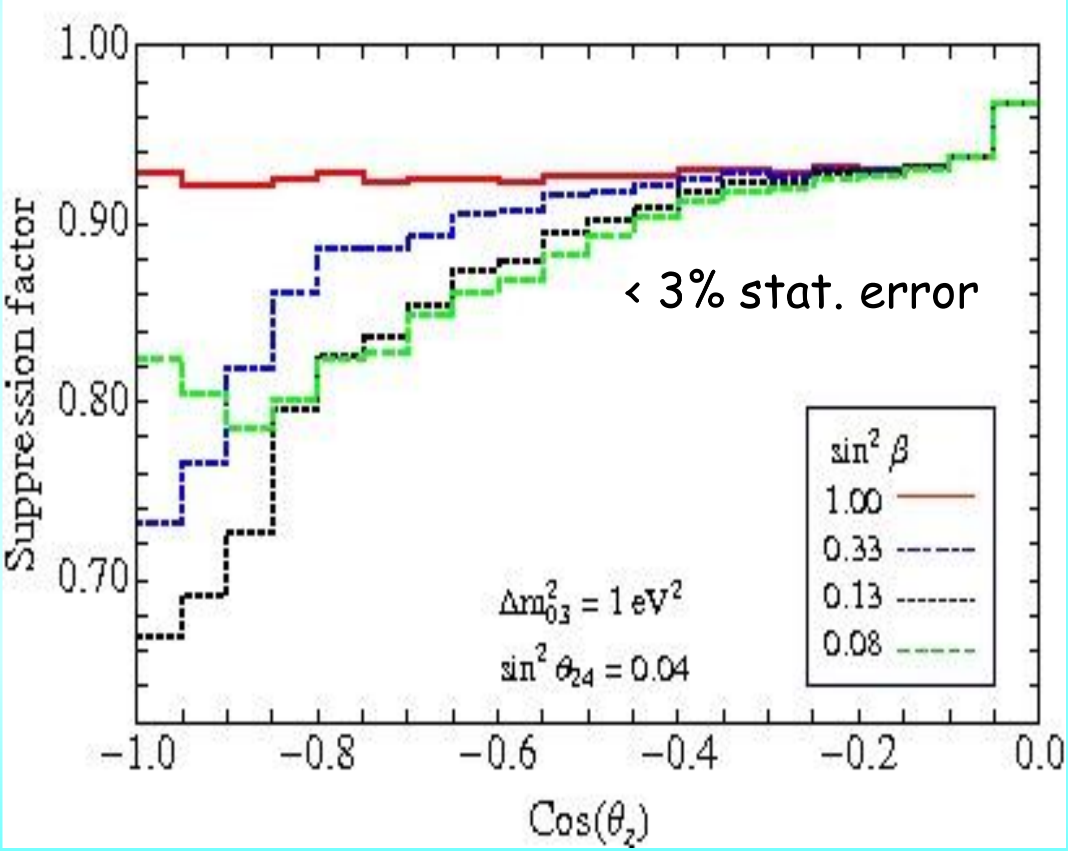
- additional radiation in the universe
- bound from LSS?

Zenith angle distributions

For different mixing schemes

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

In general



< 3% stat. error

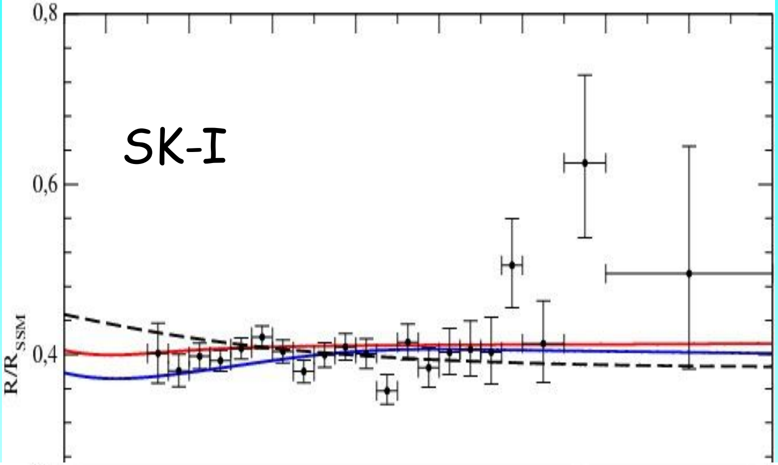
Zenith angle distribution depends on admixture of ν_τ in 4th mass state without conclusions

but

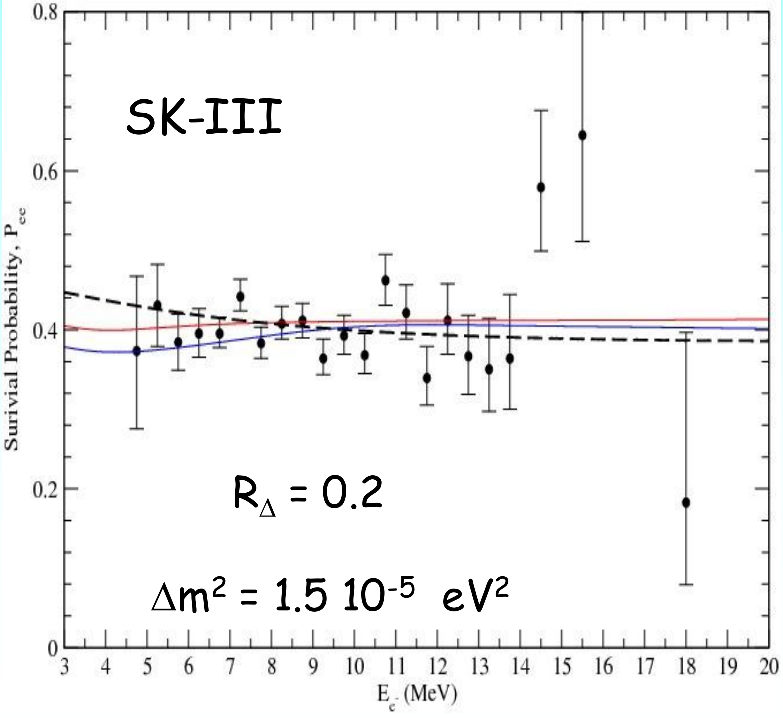
with many thanks to you!

Up-turns

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



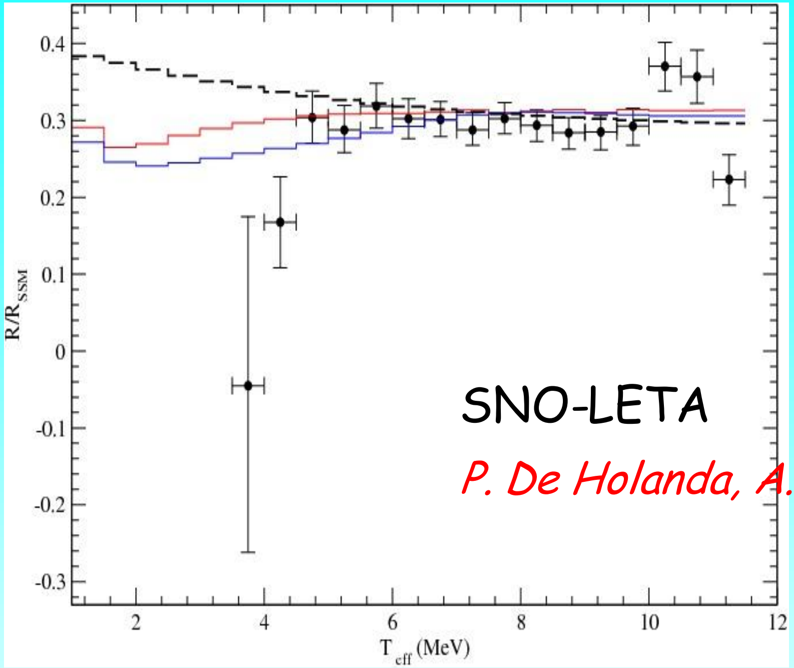
SK-I



SK-III

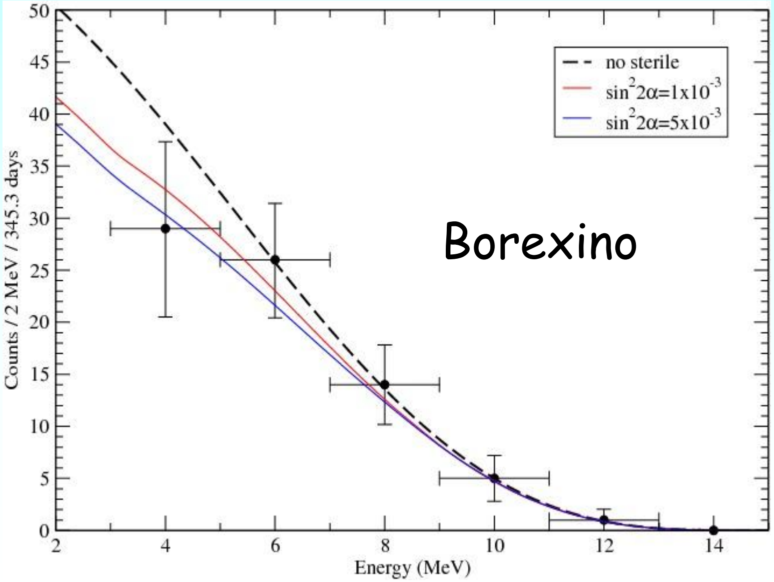
$R_\Delta = 0.2$

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



SNO-LETA

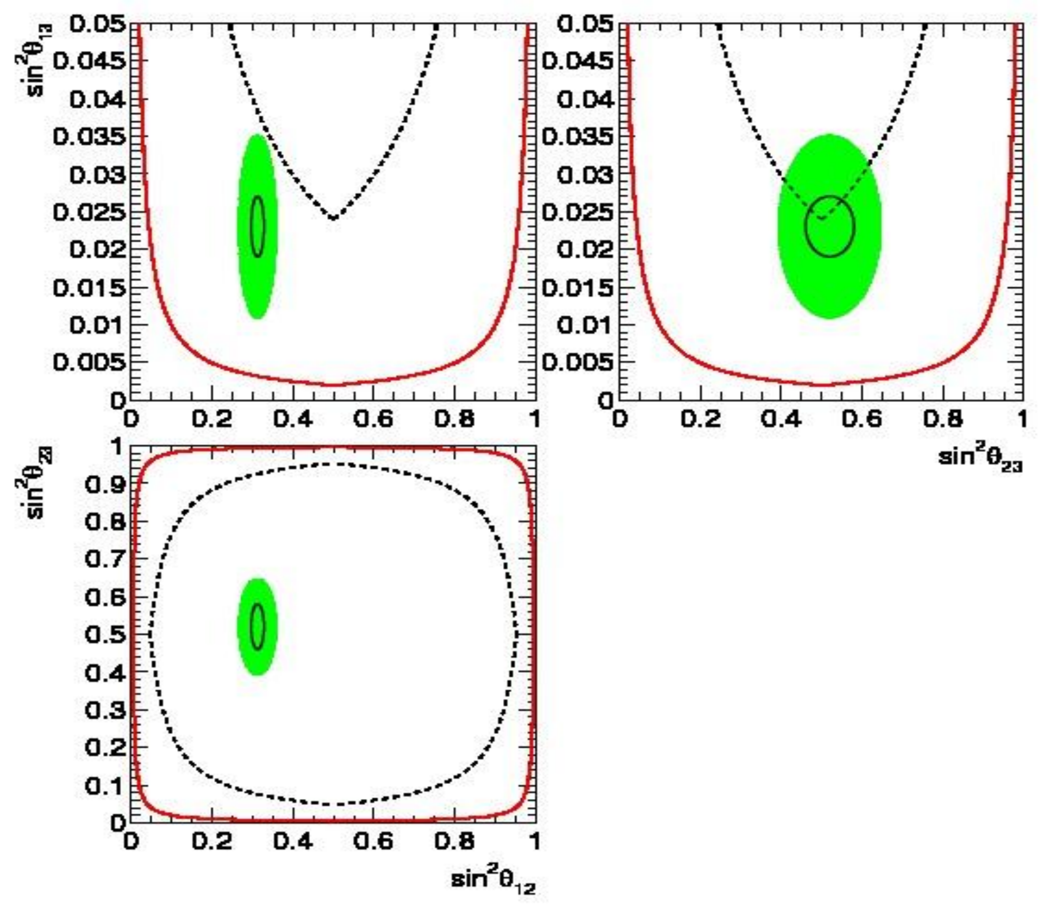
P. De Holanda, A.S.



Borexino

Anarchy

De Gouvea,
Murayama



Global view

from global fits

Standard 3 neutrino framework

with salient probably features

smallness of mass

related

Peculiar (?) pattern of mixing

strongly differs from quark mixing

- Mass hierarchy (ordering)
- Deviation of 2-3 mixing from maximal
- CP violation
- Majorana nature
- Absolute scale

Usual ``hard" masses

Generated at the electroweak and higher mass scales

challenge:

Sterile neutrinos

Not a small perturbation of the standard framework

Tri-bimaximal mixing

L. Wolfenstein

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

$$U_{tbm} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0.15 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

0.6
0.8

- 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

Should be broken

Mass matrix in flavor basis:

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

Mass relations

Symmetry

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

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

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

SN neutrinos and large 1-3 mixing

Level crossing
in the H-resonance
is highly adiabatic

Strong suppression of
the neutronization peak:

NH

$\nu_e \rightarrow \nu_3$

Permutations of flavor spectra
which depend on mass hierarchy

Earth matter effects

Normal mass hierarchy:
in the antineutrino channel only

Inverted mass hierarchy:
in the neutrino channel only

If the earth matter effect is
observed for antineutrinos
NH is established!

Shock wave effect

Adiabaticity is broken in shock front
if the relative width of the front:

$\Delta R/R < 10^{-4} \rightarrow 10$ km

if larger – no shock wave effect:
probe of the width of front

Complication?

Collective effects

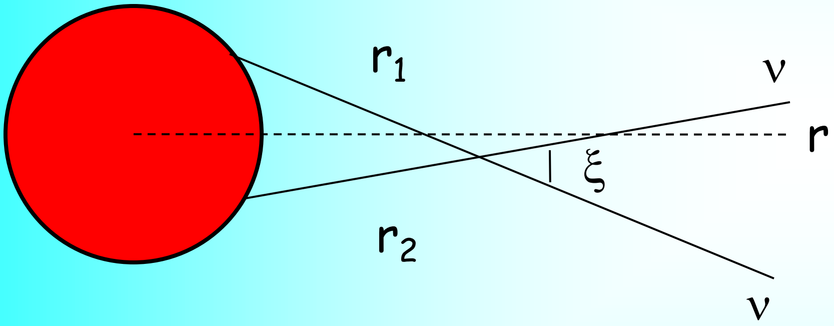
neutrinosphere

$R = 20 - 50$ km

usual matter potential: $\lambda = V = \sqrt{2}\, G_F\, n_e$

neutrino potential:

$\mu = \sqrt{2}\, G_F\, (1 - \cos\xi)\, n_\nu$



$n_\nu \sim 1/r^2$

$\xi \sim 1/r$ for large r

Multiple spectral splits -swaps

Multi-angle effect: $r_2 < r_1$ $\phi_2 < \phi_1$

Different phases from
different directions
due to usual matter potential

$n_\nu \sim 10^{33}$ cm^{-3}

$n_e \sim 10^{35}$ cm^{-3}

→ $\lambda >> \mu$

decoherence

QLC predictions

H. Minakata, A.S.

Leptons

$U_\nu = U_{bm}$ seesaw

$U_l = U_{CKM}$

q-l symmetry

$U_{PMNS} = U_l^+ U_\nu = U_{CKM}^+ U_{bm}$

Quarks

$V_u = I$

$V_d = V_{CKM}$

$V_{quarks} = V_u^+ V_d = V_{CKM}$

1-3 mixing is generated by permutation of U_{12} and U_{23}

$\sin\theta_{13} = \sin\theta_{23} \sin\theta_C \sim 0.16$

$\sin\theta_{12} = \sin(\pi/4 - \theta_C) + 0.5\sin\theta_C (\sqrt{2} - 1 - V_{cb}\cos\delta)$ $\Rightarrow$ $\sin^2\theta_{12} = 0.3345$

RGE -> can reduce

M. Schmidt, A.S.

$D_{23} = 0.5 \sin^2\theta_C + \cos^2\theta_C V_{cb} \cos\delta = 0.02 +/- 0.04$

Symmetry and mixing

D. Hernandez, A.S.

$D(2,3,3) = A_4$
$D(2,3,4) = S_4$
$D(2,3,5) = A_5$

If G is von Dyck group $D(2, m, p)$

the mixing matrix should satisfy condition

$$(S_i\, U_{PMNS}^{+} T\, U_{PMNS})^p = I \qquad i = 1, 2, 3$$

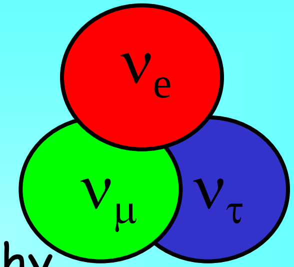
S_i is the symmetry transformation of the neutrino mass matrix in mass basis

$S_1 = \mathrm{diag}\,(1, -1, -1)$ $S_2 = \mathrm{diag}\,(-1, 1, -1)$ $S_i^2 = I$

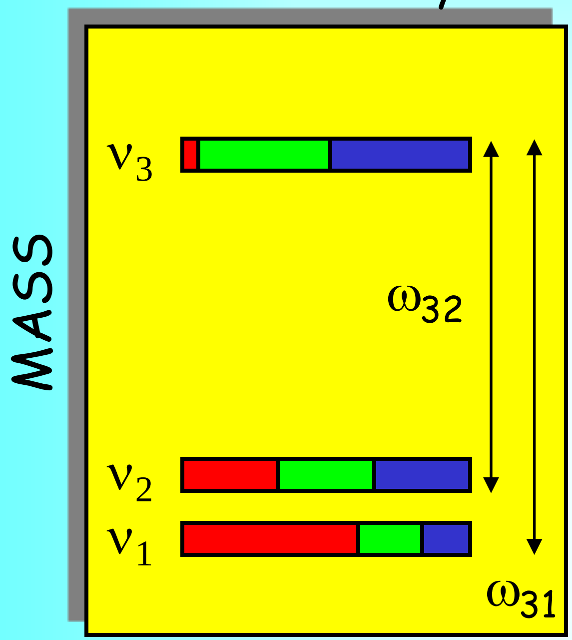
T is the symmetry transformation of the charged lepton mass matrix in mass basis

$T = \mathrm{diag}\,(e^{i\phi_1}, e^{i\phi_2}, e^{i\phi_3})$ $\phi_i = 2\pi k_i / m$ $T^m = I$

Mass hierarchy (ordering)



Normal hierarchy



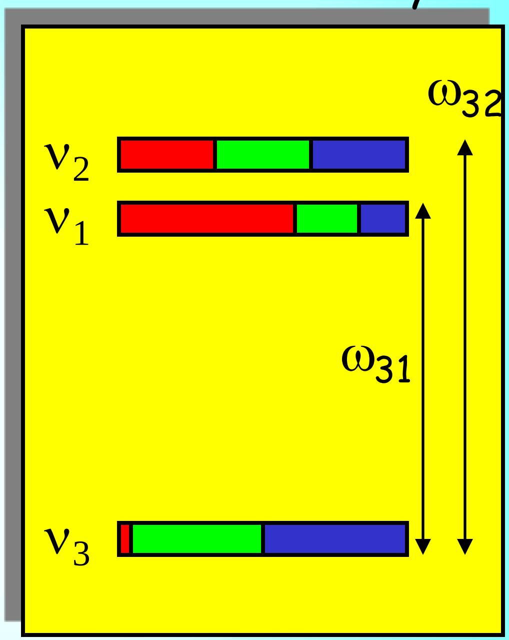
Cosmology

$\beta\beta$-decay

$\omega_{ij} = \Delta m^2_{ij}/2E$

Mass states can
be marked by
ν_e - admixtures

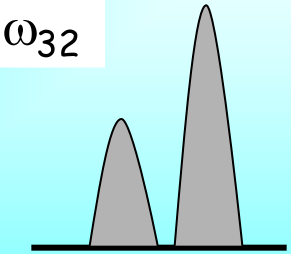
Inverted hierarchy



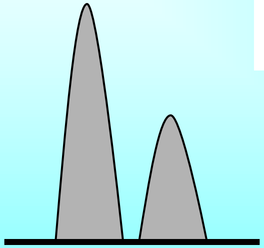
$\omega_{31} > \omega_{32}$

Oscillations

$D_{31} \sim 2D_{32}$



Fourier
analysis



ω

$\omega_{31} < \omega_{32}$

S. Petcov
M. Piai

Matter
effect

makes the e-flavor heavier ⇨
changes two spectra differently