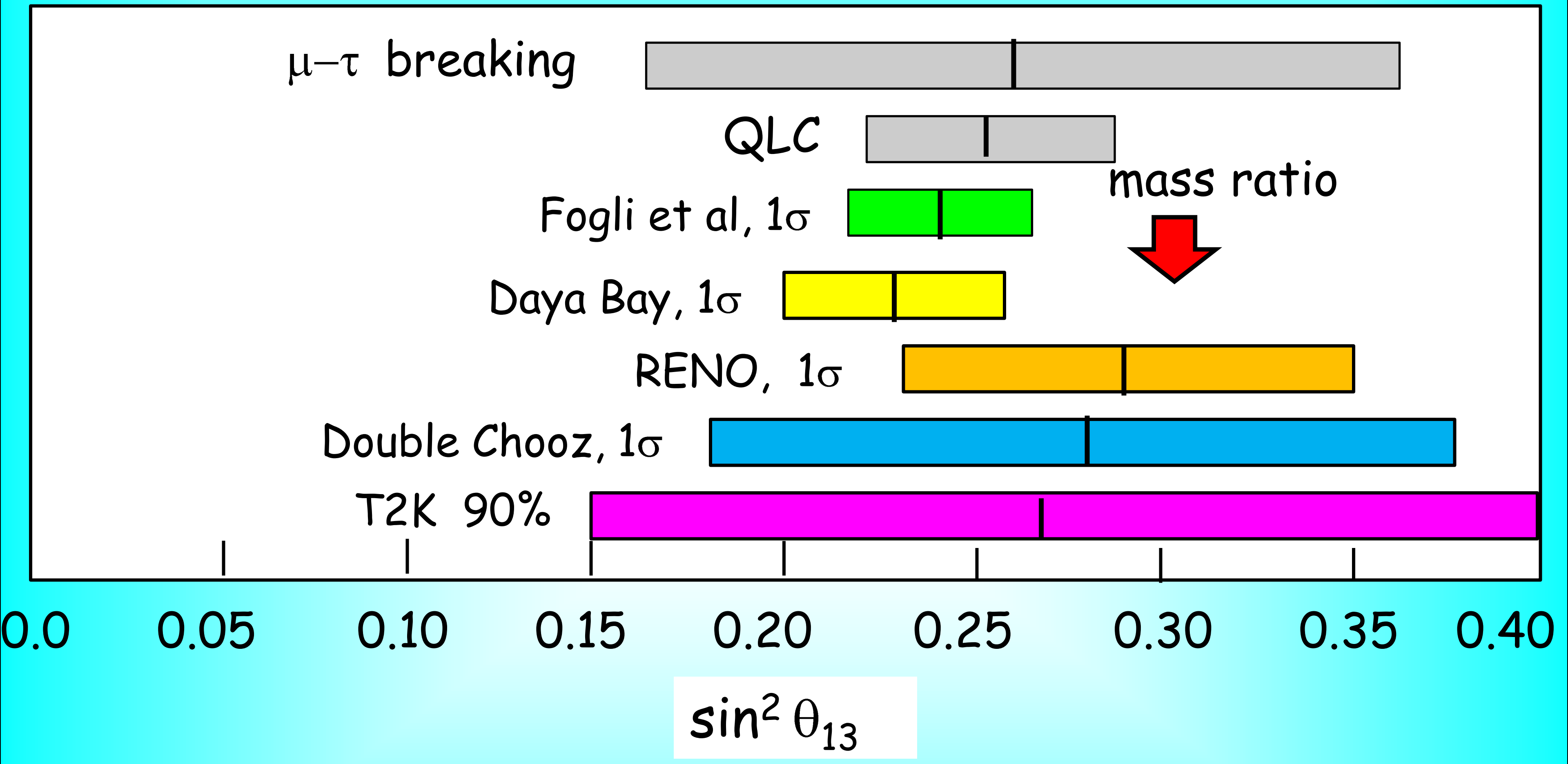
"BENE-2012"
BEHIND NEUTRINO MASS

Workshop on theoretical aspects of neutrino masses and mixing

ICTP, Trieste, Italy
September 17 – 23, 2012

1-3 and 2-3

Ongoing progress



Direct measurements of 13 mixing

Deviation of 2-3 mixing from maximal

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

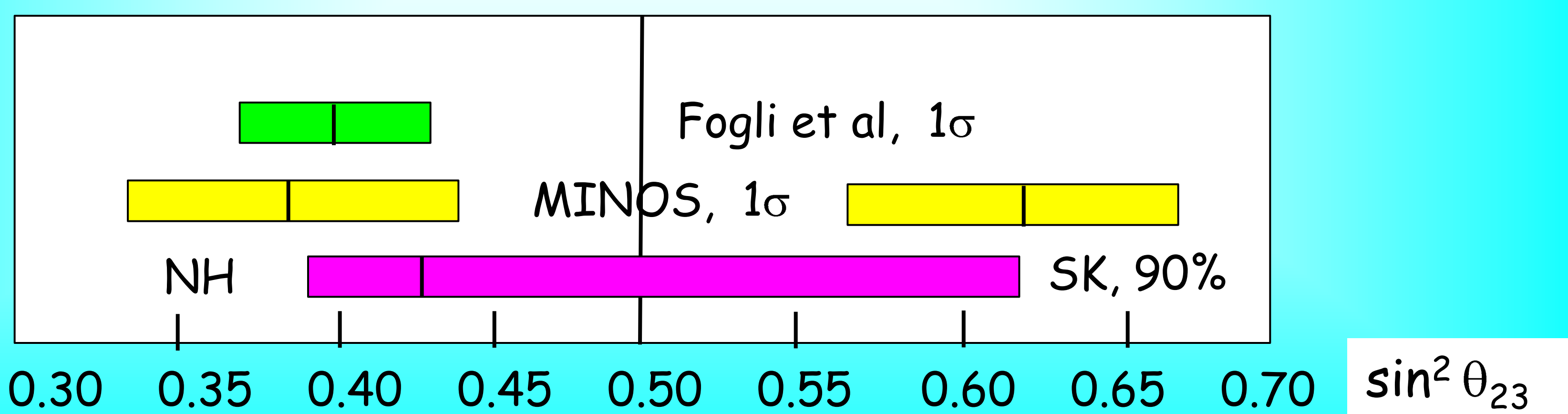
the key to (probe) understand the underlying physics

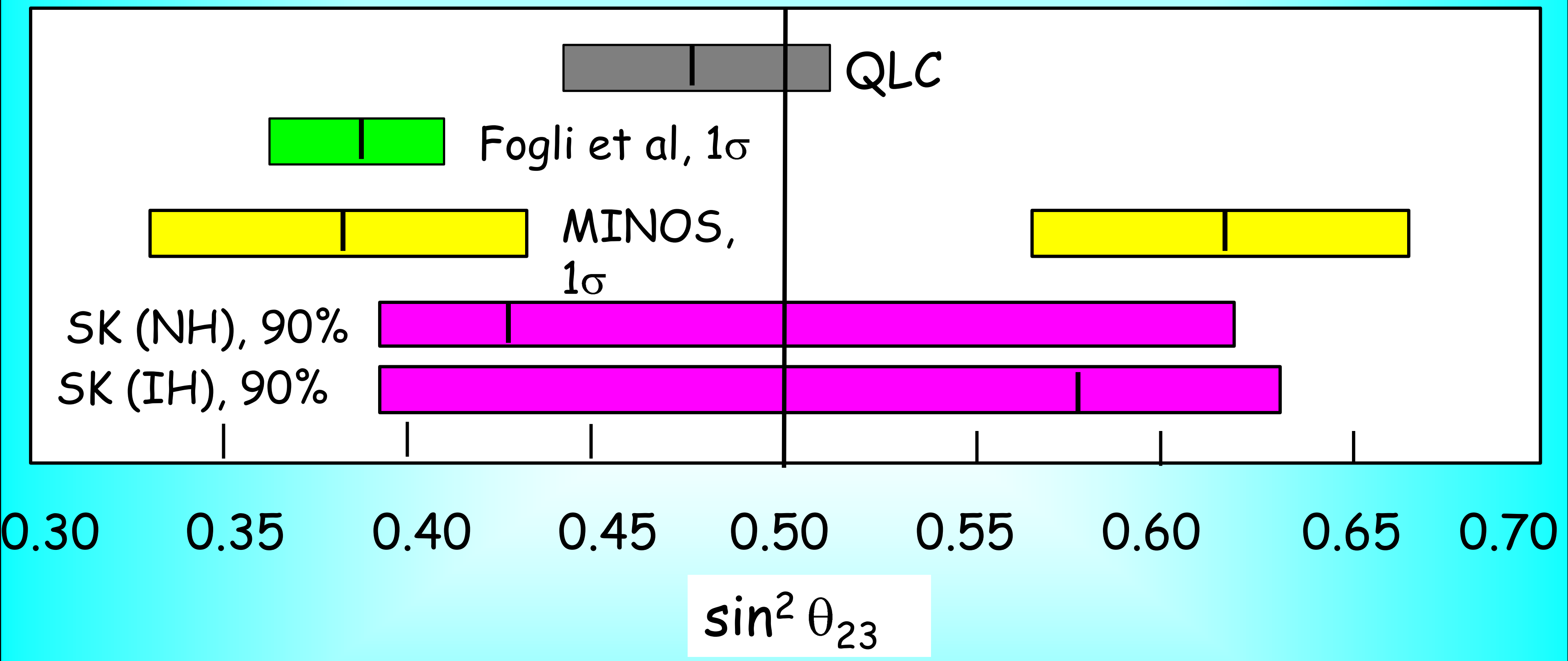
$\nu_\mu - \nu_\tau$ symmetry violation

Connection to 1-3 mixing

Quark -Lepton Complementarity

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




QLC
Fogli et al, 1σ
MINOS, 1σ
SK (NH), 90%
SK (IH), 90%
0.30
0.35
0.40
0.45
0.50
0.55
0.60
0.65
0.70
sin² θ23

Implications of 1-3 mixing for theory

$\sin^2\theta_{13} \sim 0.022$

$$\sin^2\theta_{13} = \begin{cases} O(1)\ \dfrac{\Delta m_{21}^2}{\Delta m_{32}^2} & \text{``Naturalness'' of mass matrix} \\ \sim \frac{1}{2}\sin^2\theta_C & \text{Quark Lepton Complementarity} \\ \sim \frac{1}{2}\cos^2 2\theta_{23} & \nu_\mu - \nu_\tau \text{ - symmetry violation} \\ \theta_{13} + \theta_{12} \sim \pi/4 & \text{Self-complementarity} \end{cases}$$

Mixing anarchy

The same 1-3 mixing with completely different implications

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

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

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

Again neutrinos are special!

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

Related to smallness of mass

See-saw, symmetry of RH neutrino sector

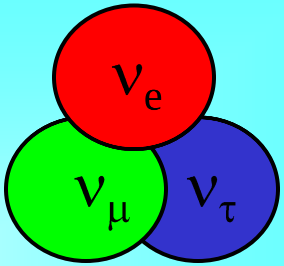
Realizations: QLC

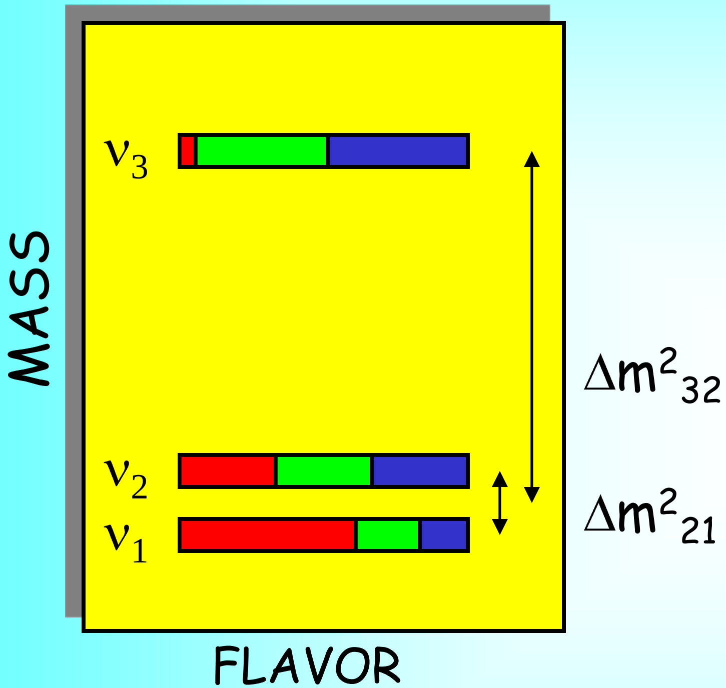
Race for hierarchy and CP

$\Delta m^2_{31} \rightarrow - \Delta m^2_{31}$

Resonance in the antineutrino channel> $V \rightarrow -V$

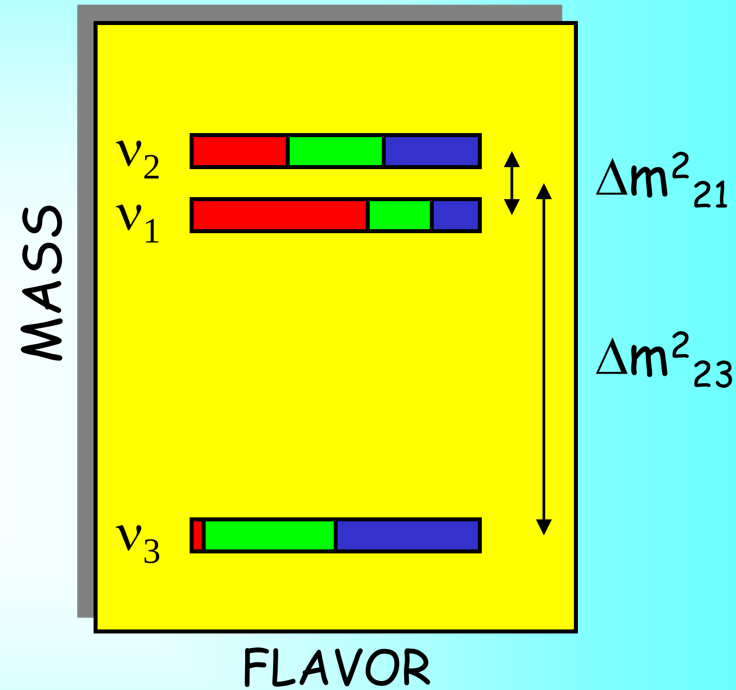
Mixing & masses





Normal mass hierarchy

?



Inverted mass hierarchy

Two large mixings

$\Delta m^2_{32} = 2.3 \times 10^{-3}$ eV^2

$\Delta m^2_{21} = 8 \times 10^{-5}$ eV^2

PINGU Geometry

Precision IceCube Next Generation Upgrade

Denser array

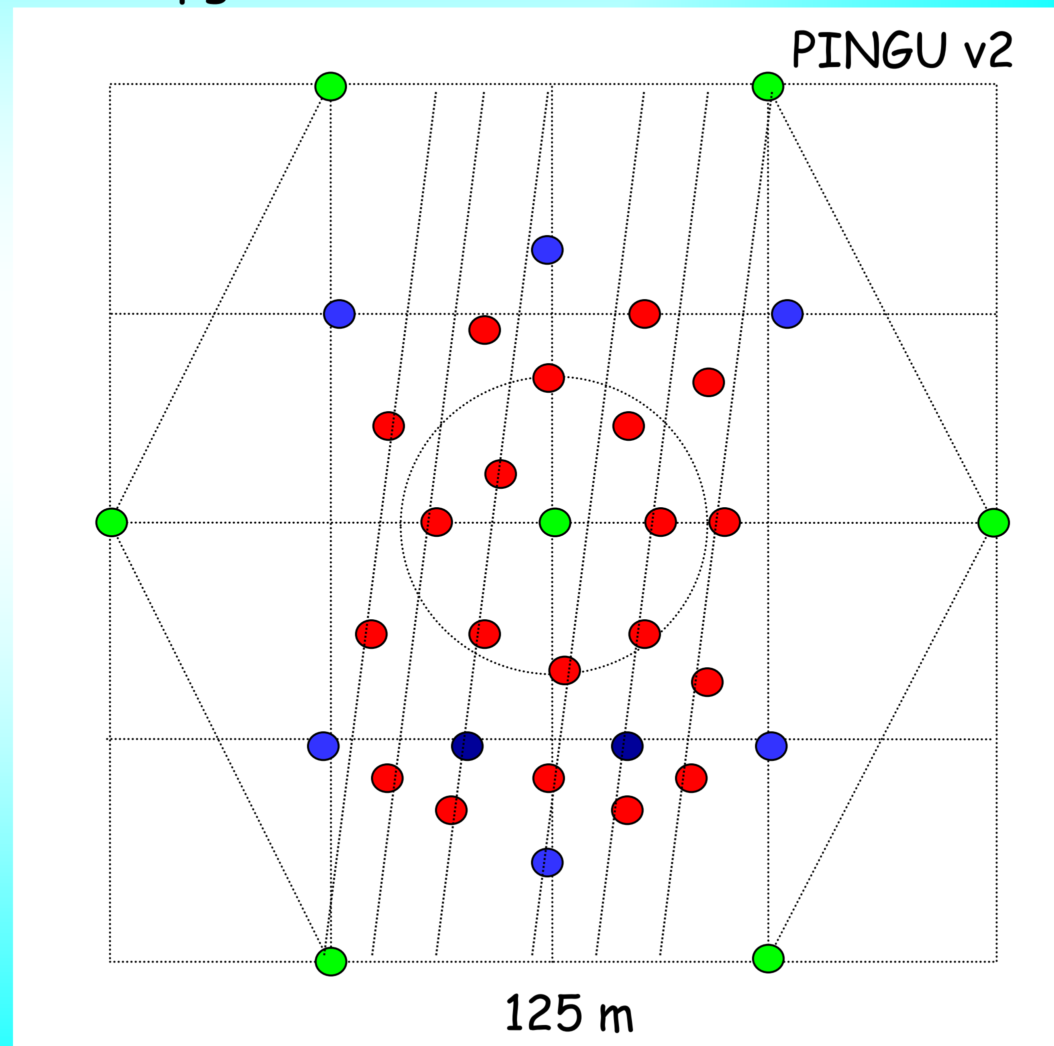
20 new strings (~60 DOMs each)
in 30 MTon DeepCore volume

⇩

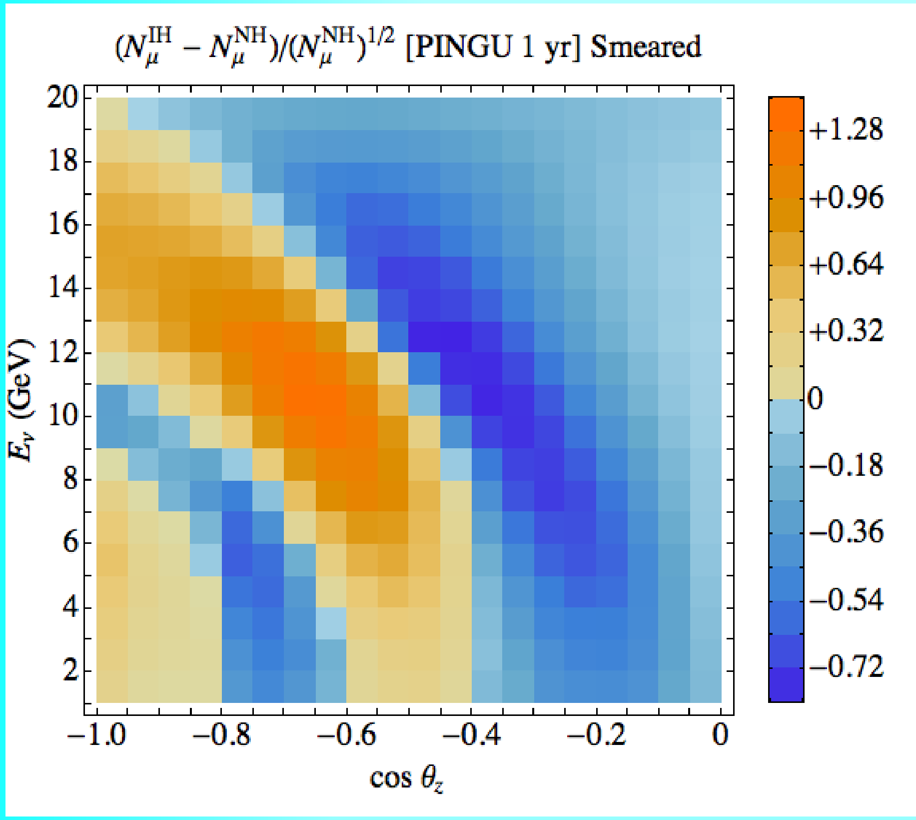
Few GeV threshold in inner
10 Mton volume

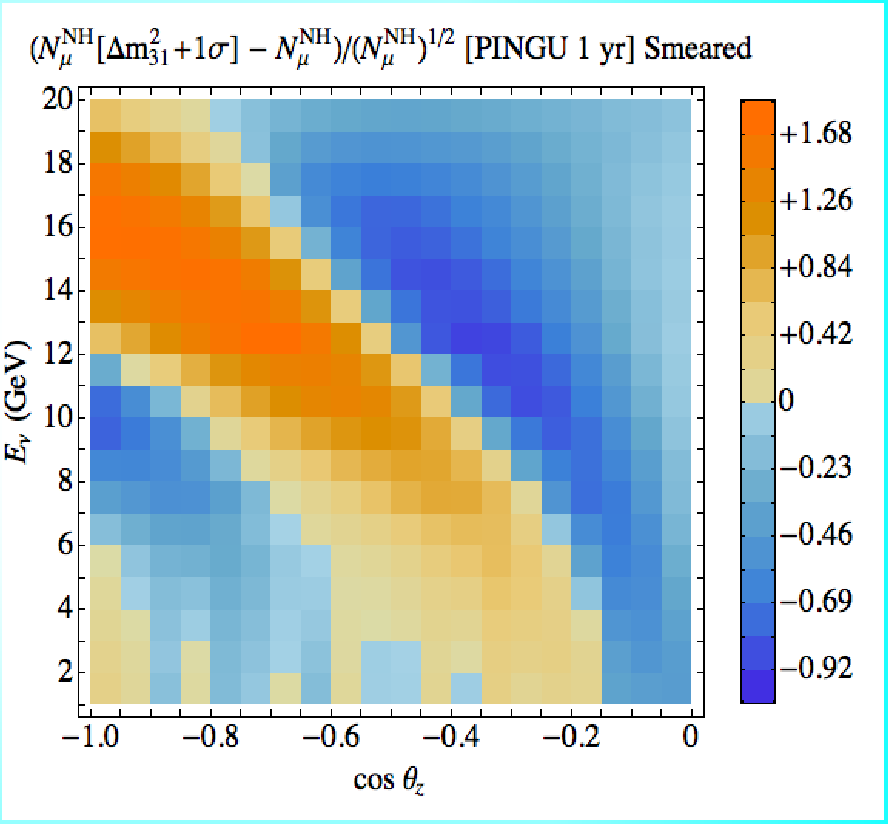
Energy resolution ~ 3 GeV

- Existing IceCube strings
- Existing DeepCore strings
- New PINGU-I strings



Hierarchy with PINGU



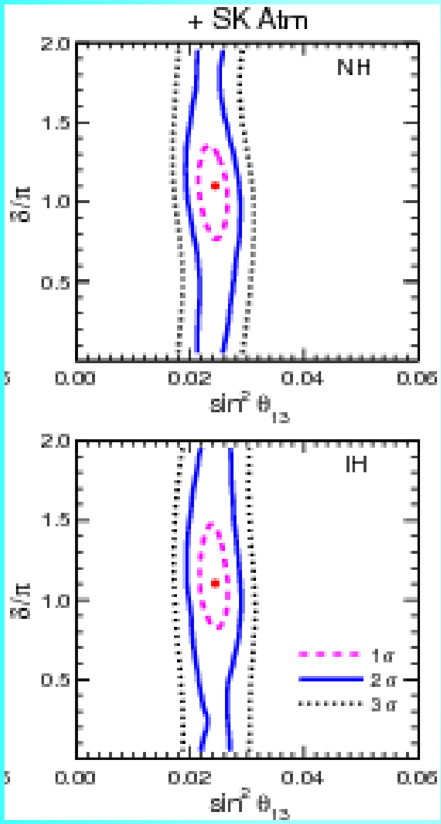


$\sigma_E = 0.2E$

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

Degeneracy

CP-phase: measurements and predictions



G. L. Fogli

First glimpses?

T. Yanagida $\delta_{CP} \sim \pi/2$ +/- 0.02

Third way

Neutrino-antineutrino asymmery

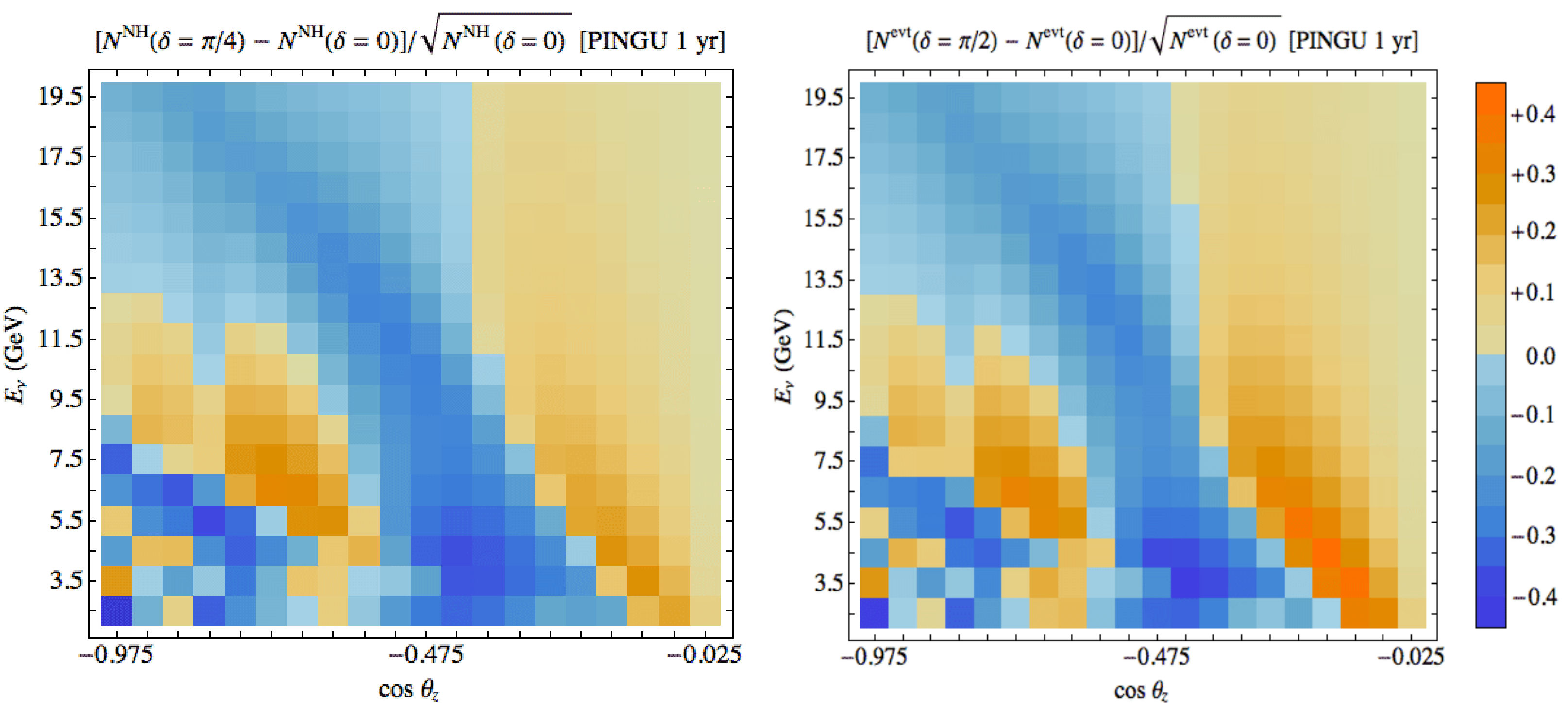
Dependence of probabilities on energy in wide range

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?

CP asymmetry



From Special to Normal
Symmetry or no symmetry?

Tri-bimaximal mixing

L. Wolfenstein

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

In the first approximation

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

0.15

0.62

0.78

ν_3 is bi-maximally mixed

ν_2 is tri-maximally mixed

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

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

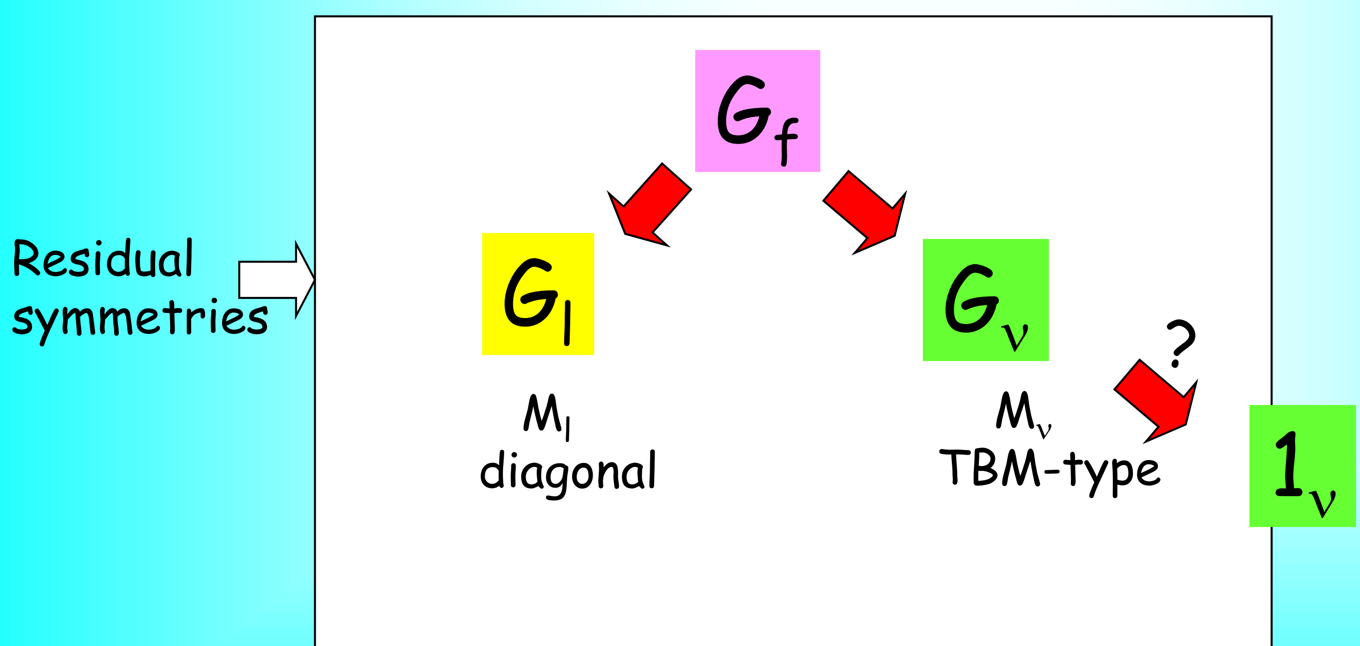
- $\sin^2\theta_{12} = 1/3$

Uncertainty related to sign of 2-3 mixing:
$\theta_{23} = \pi/4 \rightarrow -\pi/4$

Symmetry from mixing matrix

Symmetry without TBM

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



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

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 θ_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

Relations between
masses and mixing

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

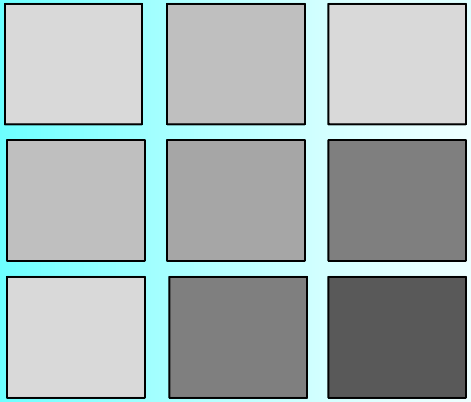
The same coupling
strength between
generations

$$\sin\theta_{13} \sim \tfrac{1}{2} \sin\theta_{12} \sin\theta_{23}$$

Flavor ordering in
mass matrix

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?

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 quarks and leptons is related to smallness of neutrino mass

Hidden sector at GUT, Planck scales

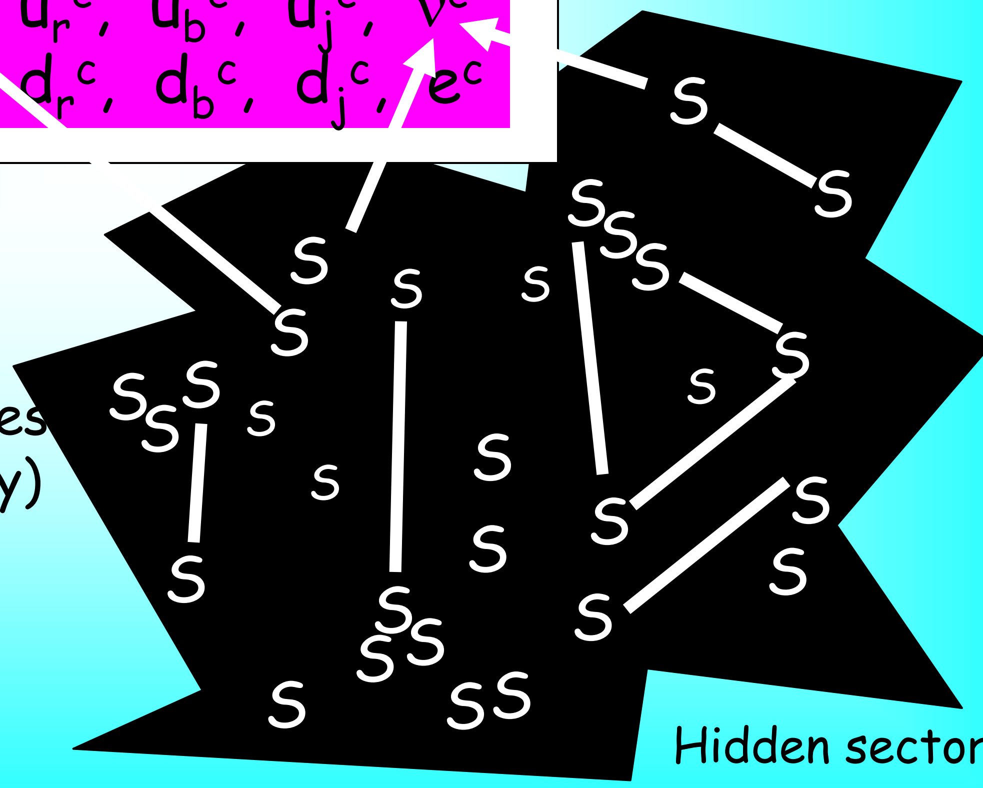
QLC: certain symmetries at High scales → bi-maximal mixing;
Double seesaw?

SO(10) GUT + ...

RH-neutrino

16 $\begin{array}{cccc} u_r, & u_b, & u_j, & \nu \\ d_r, & d_b, & d_j, & e \end{array}$ $\begin{array}{cccc} u_r^c, & u_b^c, & u_j^c, & \nu^c \\ d_r^c, & d_b^c, & d_j^c, & e^c \end{array}$

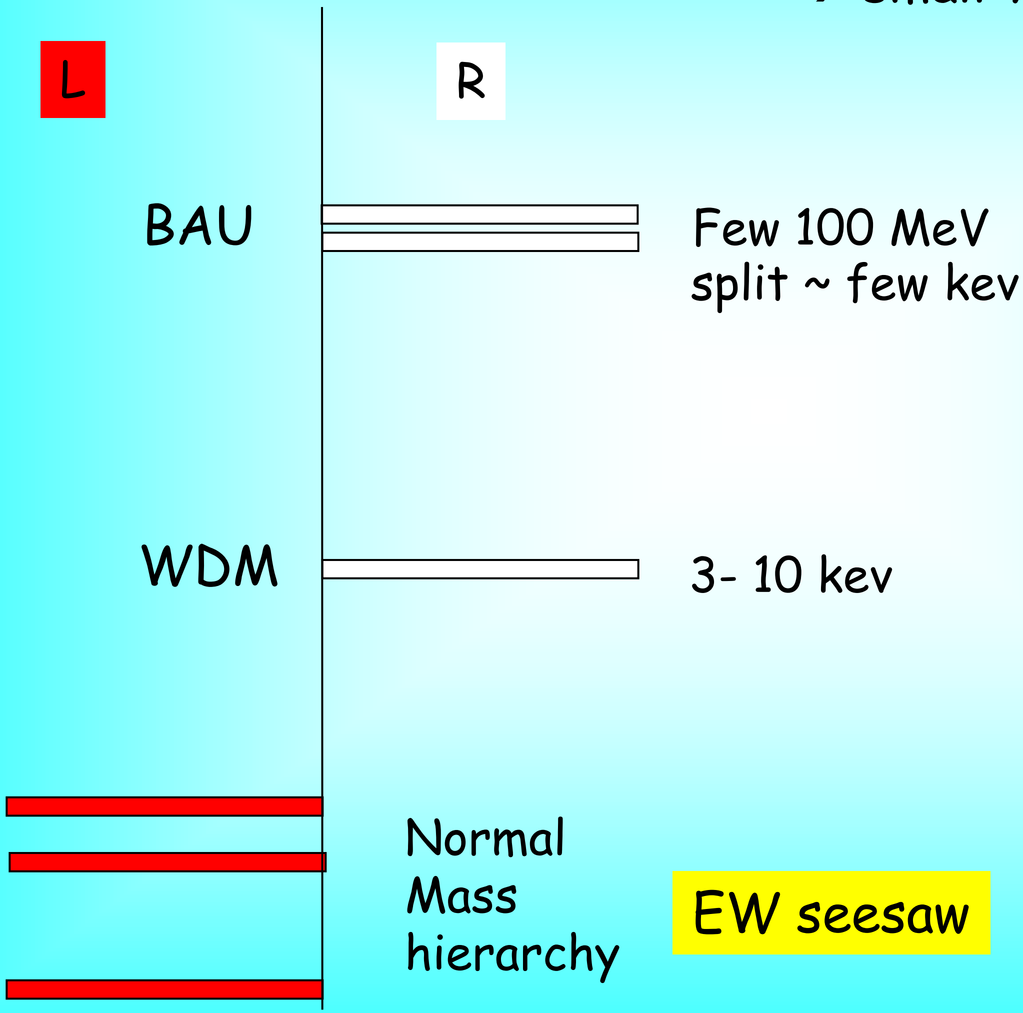
- Enhance mixing
- Produce zero order mixing
- Screen Dirac mass hierarchies
- Produce randomness (anarchy)
- Seesaw symmetries
- Increase seesaw scale



ν MSM

M. Shaposhnikov et al

Everything below EW scale
→ small Yukawa couplings



- generate light mass of neutrinos
- generate via oscillations lepton asymmetry in the Universe
- can beproduced in B-decays (BR ~ 10^{-10})

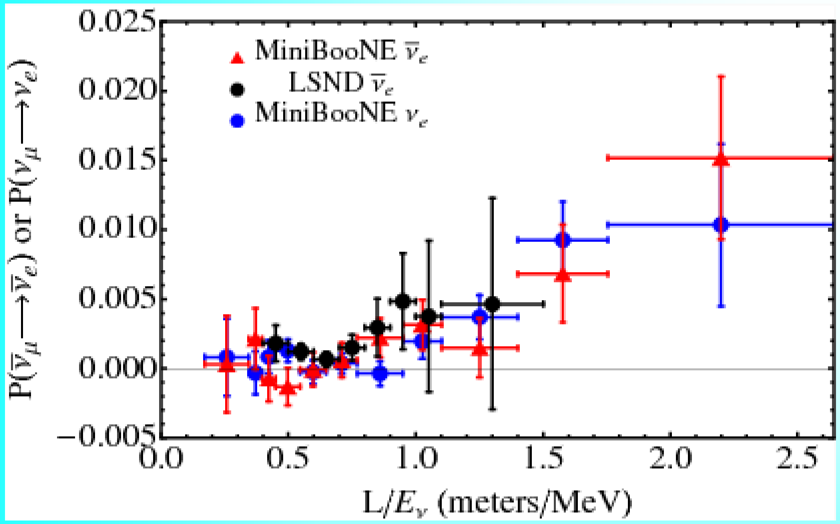
- warm dark matter
- radiative decays → X-rays

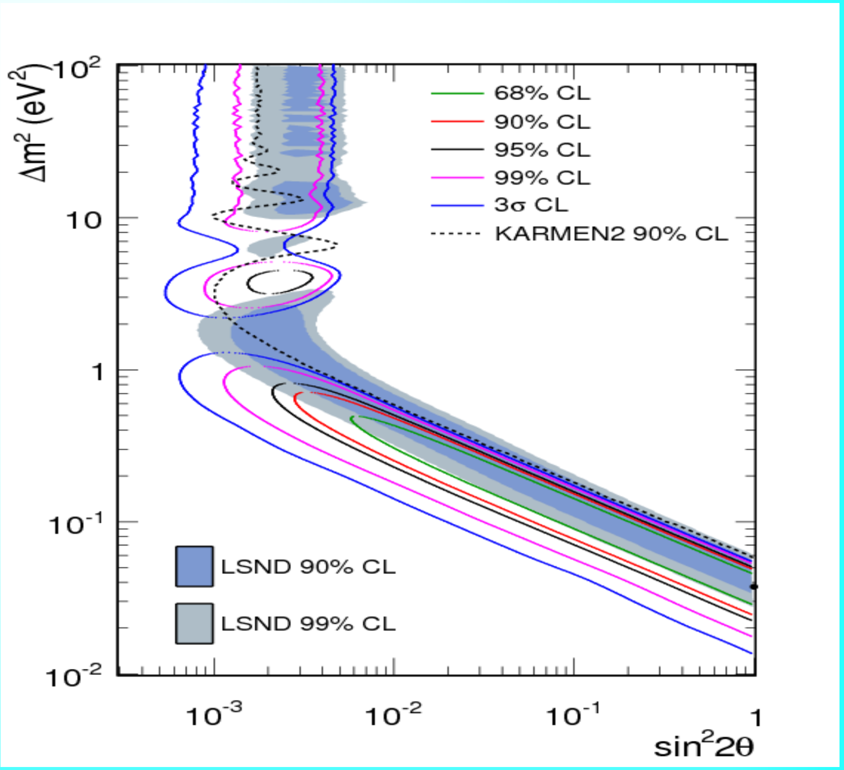
EW seesaw

Phenomenology of sterile neutrinos

Sterile challenge

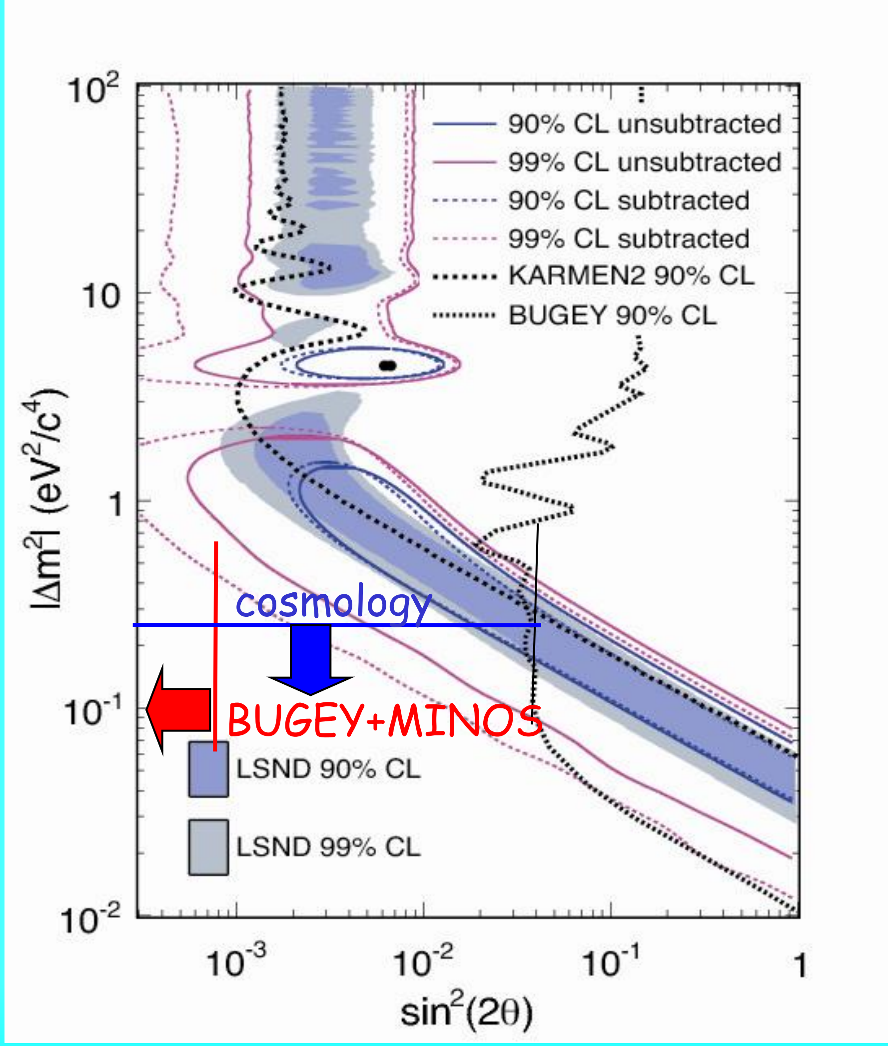
LSND and MiniBooNE





MINOS and Cosmology

ν_μ - ν_s mixing



In assumption of no-oscillations in ND

$|U_{\mu 4}|^2 < 0.019$ (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:

ΔN = 1.23 (add massless)

ω = - 1.11

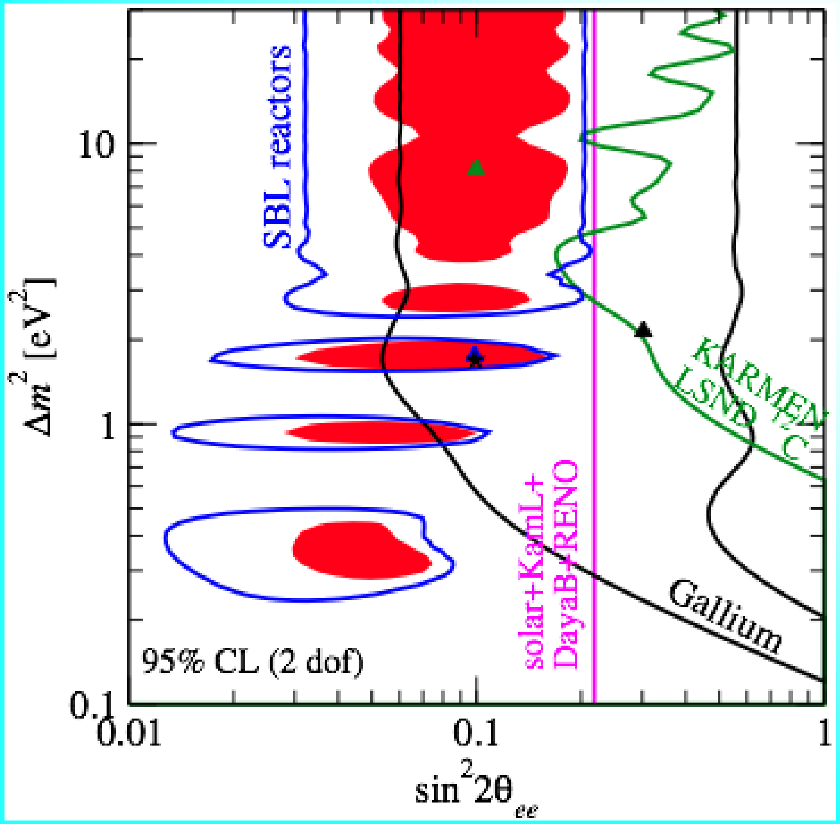
BBN: chemical potential for ν_e

J Hamann et al 1108.4136

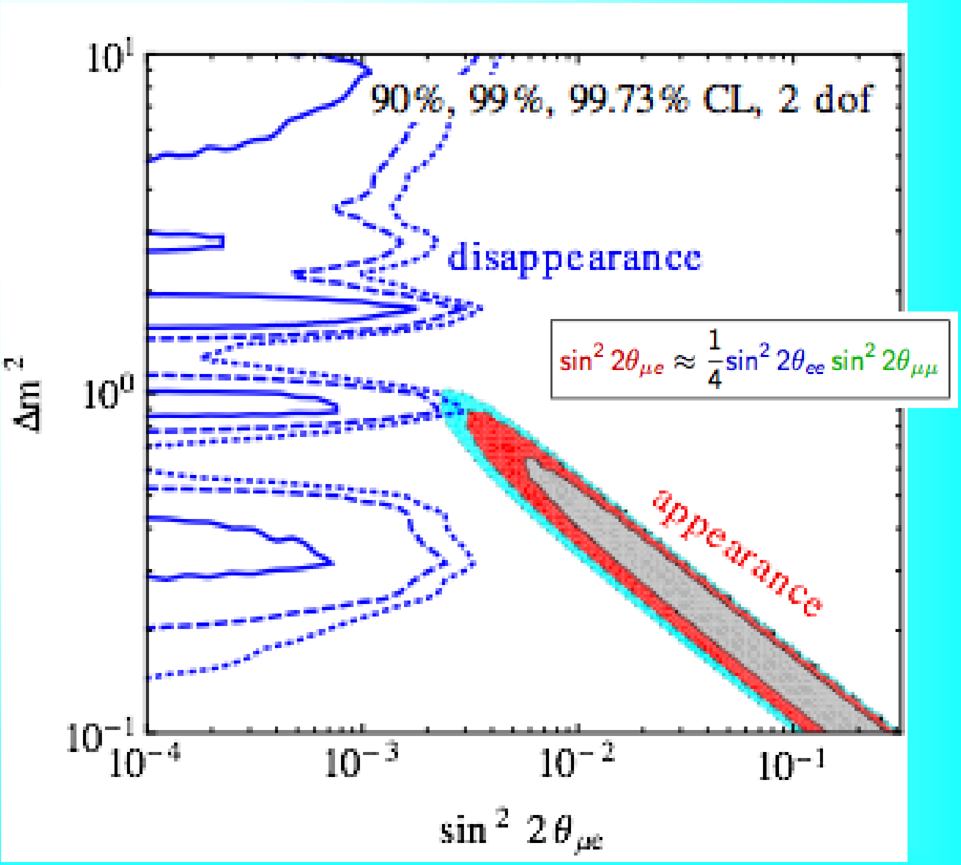
Appearance and disappearance

T. Schwetz

Hints from ν_e disappearance (reactor and gallium anomalies)



Strong tension between disappearance data and $\nu_\mu \rightarrow \nu_e$ LSND-MiniB signals (non-observation of ν_μ disappearance)



Not a small perturbation

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

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)

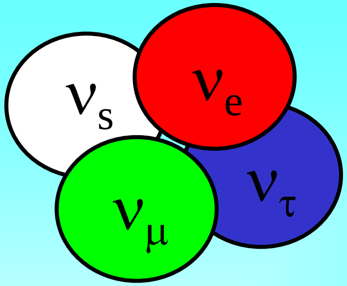
produce dominant $\mu\tau$ - block with small determinant

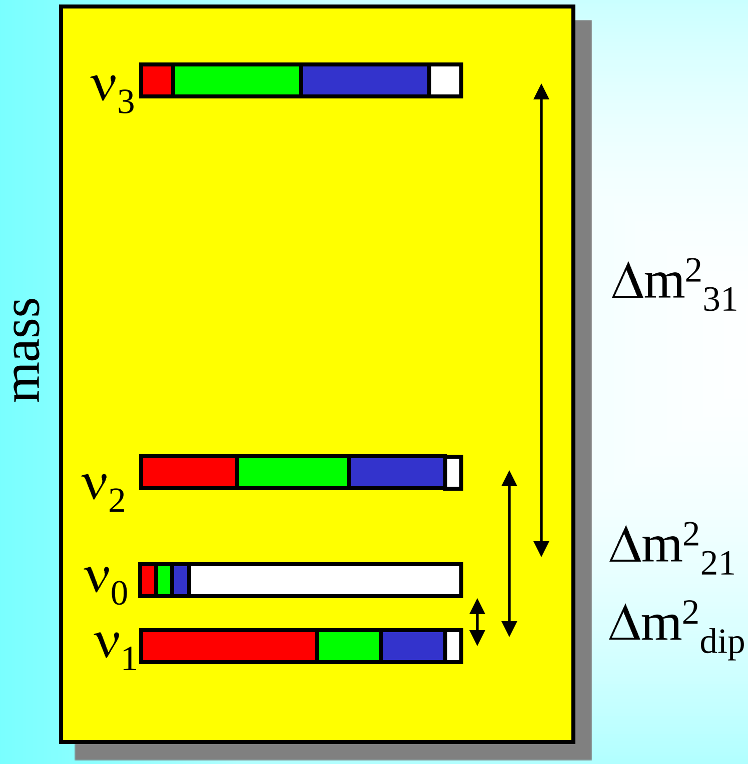
Enhance lepton mixing

Generate TBM mixing

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

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

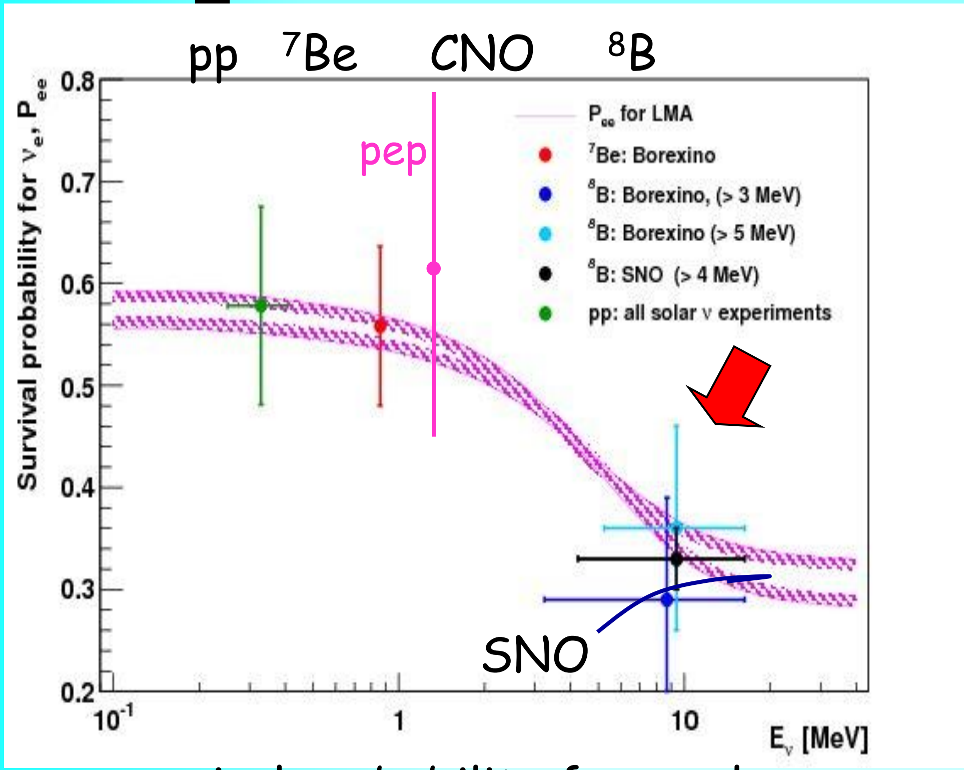
no problem with LSS (bound on neutrino mass)

can be tested in atmospheric neutrinos with DC IceCube

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

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

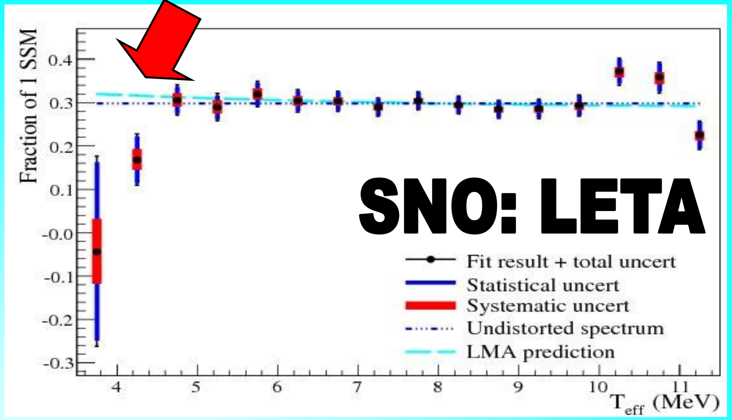
Up-turn?

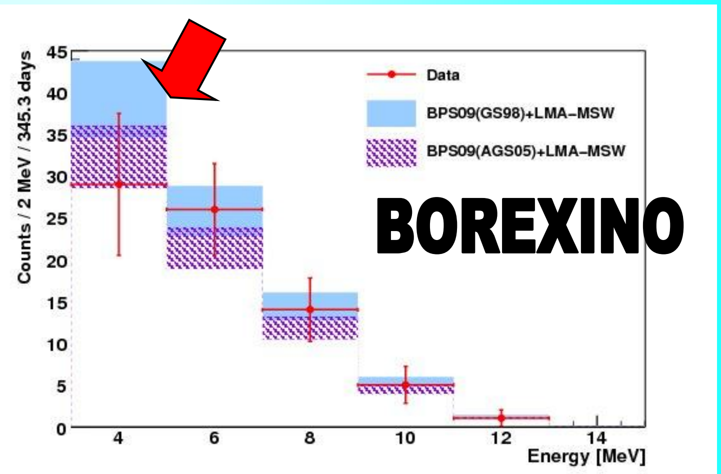


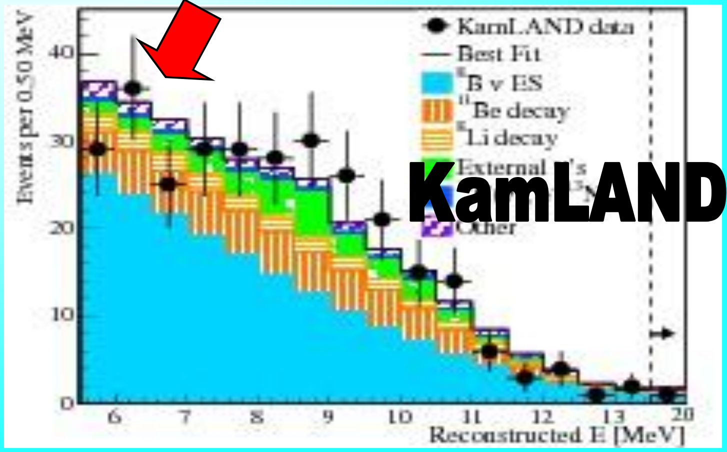
ν_e - survival probability from solar neutrino data vs LMA-MSW solution

HOMESTAKE
low rate

SNO+



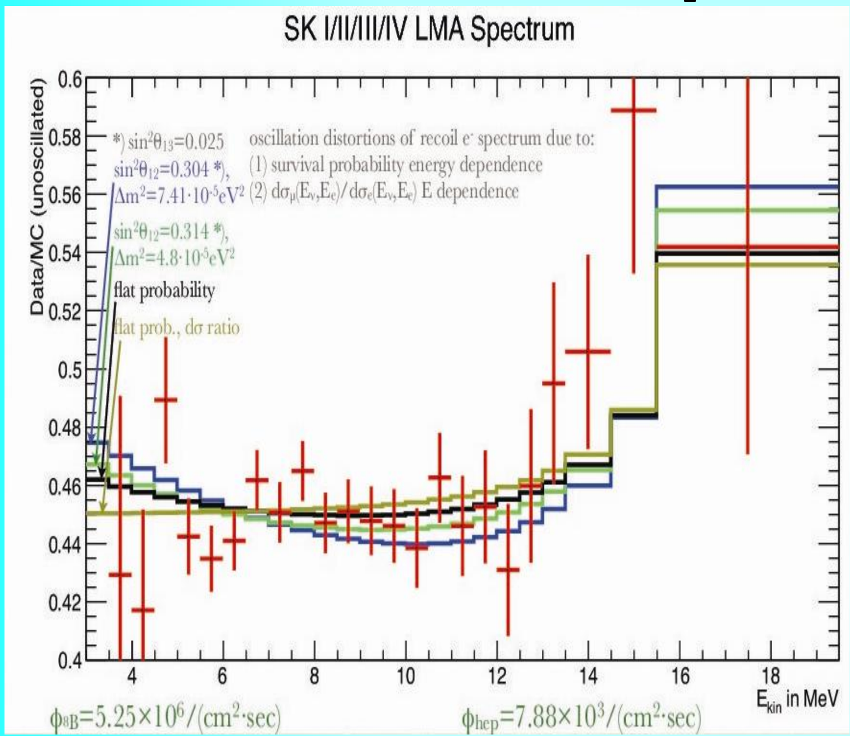


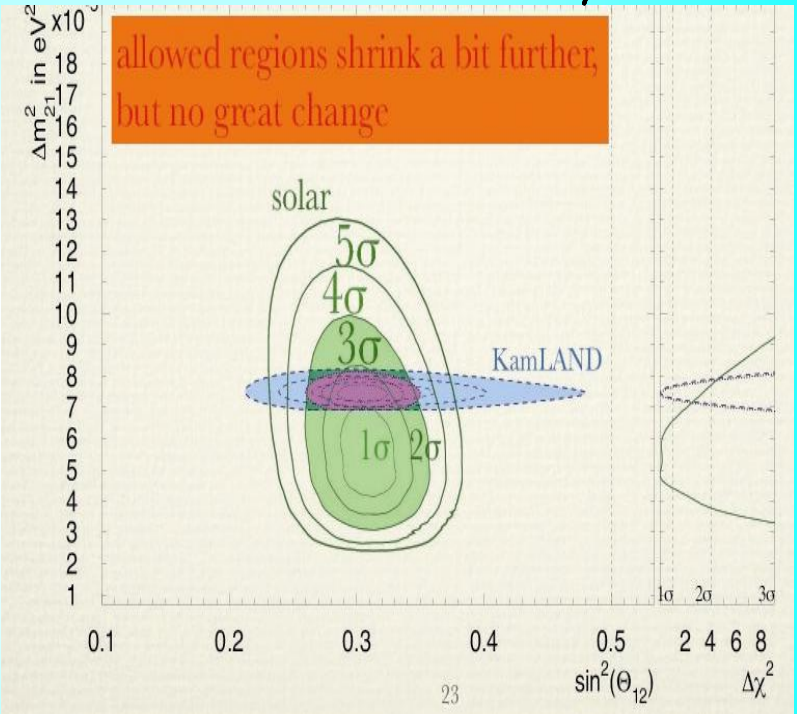


Solar neutrinos: two features

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

Neutrinos and the dark Universe

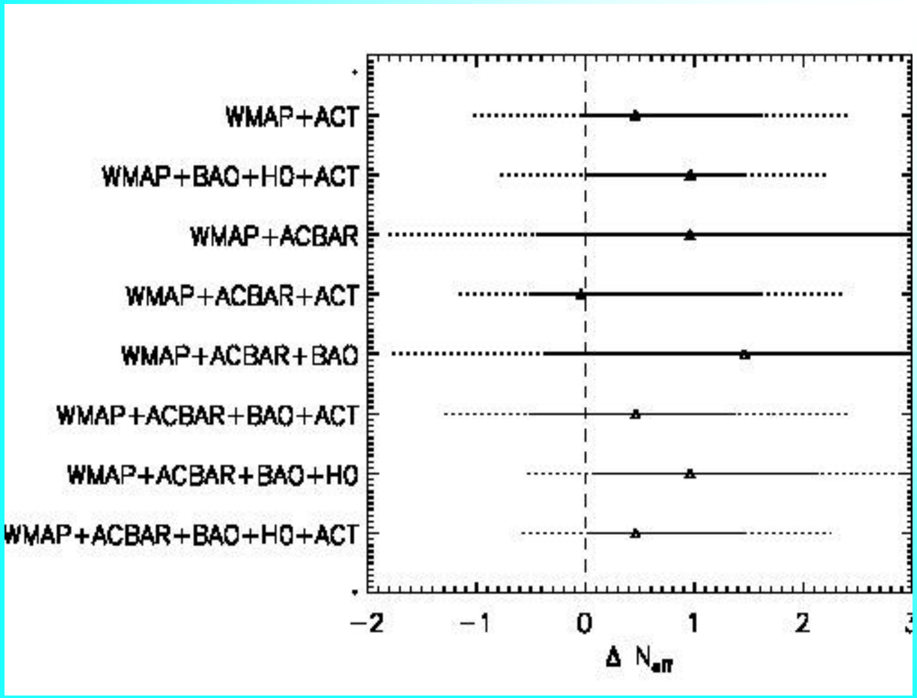
Dark radiation in the Universe

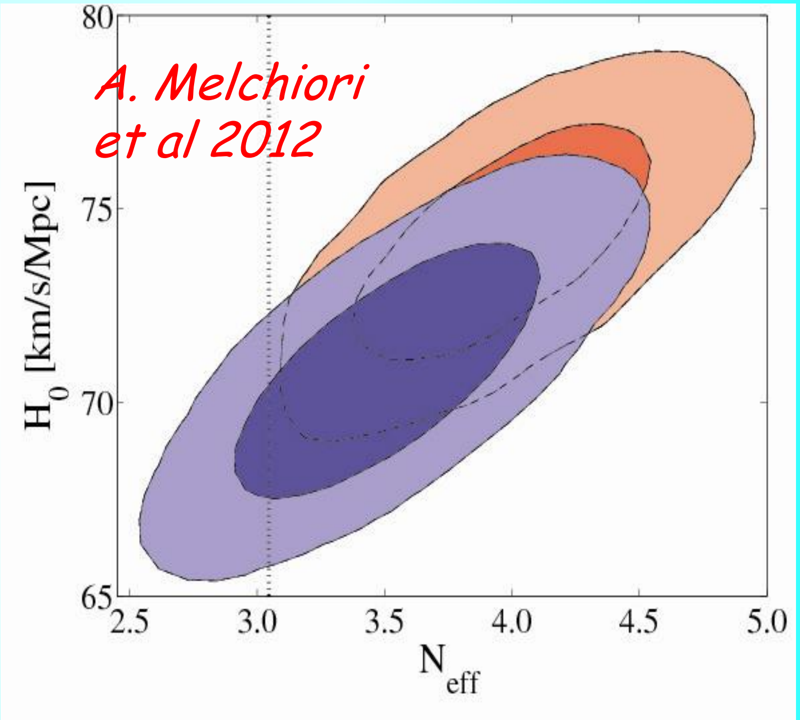
L. Verde

BBN:

N_ν = 3.0 +/-0.5

Pettini and Cooke 2012





Neutrinos & Dark Sector

of the Universe

indirect
connection

Mechanism of
neutrino mass
generation

Z_2

Light active
neutrinos

HDM

new particles

right handed
neutrinos

Direct
connection

Mixing pattern

play the role of DM

New
neutrino
states

Flavor symmetries

ensure stability
of DM particles

Neutrinos
and gravitino
as DM

Warm DM

Dark
Energy

W. Buchmueller

Everything from one

Conclusion

Challenges

1-3 mixing

Discovery of relatively large 1-3 mixing – important implications for theory, phenomenology and experiment. Strong impact on further developments.

Next

Mass hierarchy: with NOvA, atmospheric neutrinos ICAL INO, DeepCore IC, PINGU-I, supernova neutrinos

Measurements of the deviation of 23 mixing from maximal, CP- phase, absolute mass scale

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

NH ←→ IH
nu ←→ antinu

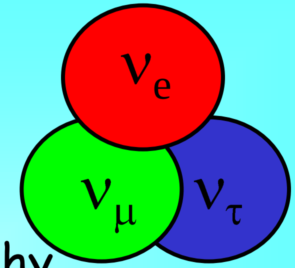
INO

NOvA
Neutrino beam
Fermilab-PINGU(W. Winter)

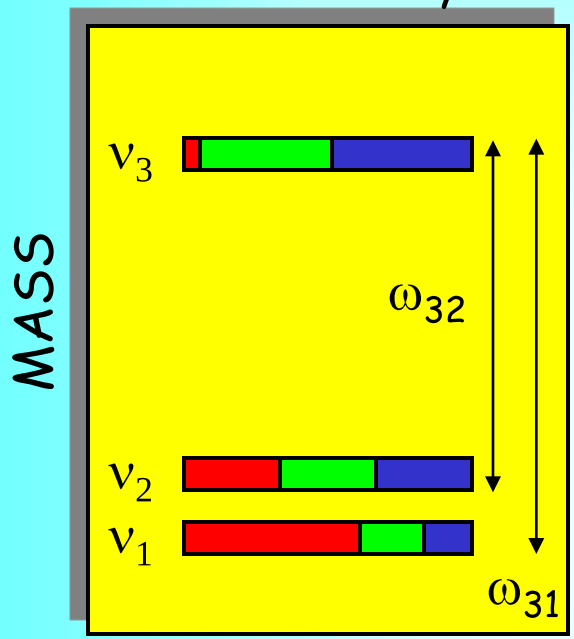
Earth matter effect
Energy spectrs

Sterile neutrinos may help?

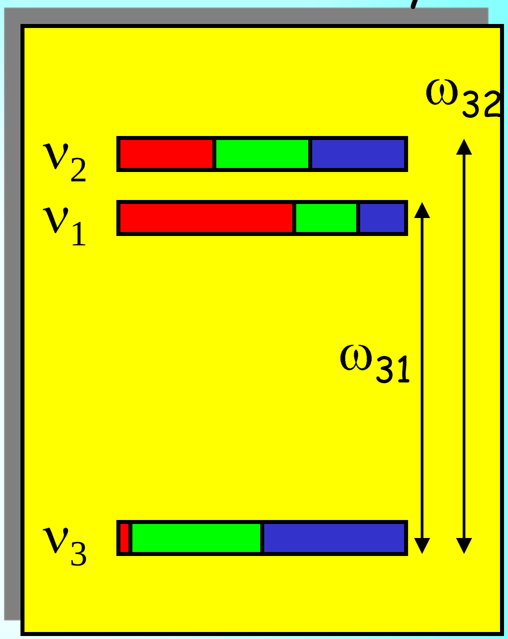
Mass hierarchy (ordering)



Normal hierarchy



Inverted hierarchy



Cosmology

$\beta\beta$-decay

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

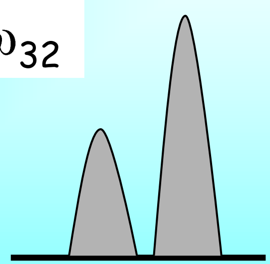
Mass states can be marked by ν_e - admixtures

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

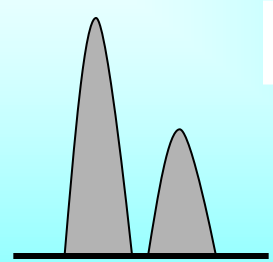
$\omega_{31} < \omega_{32}$

Oscillations

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



Fourier analysis



ω

S. Petcov
M. Piai

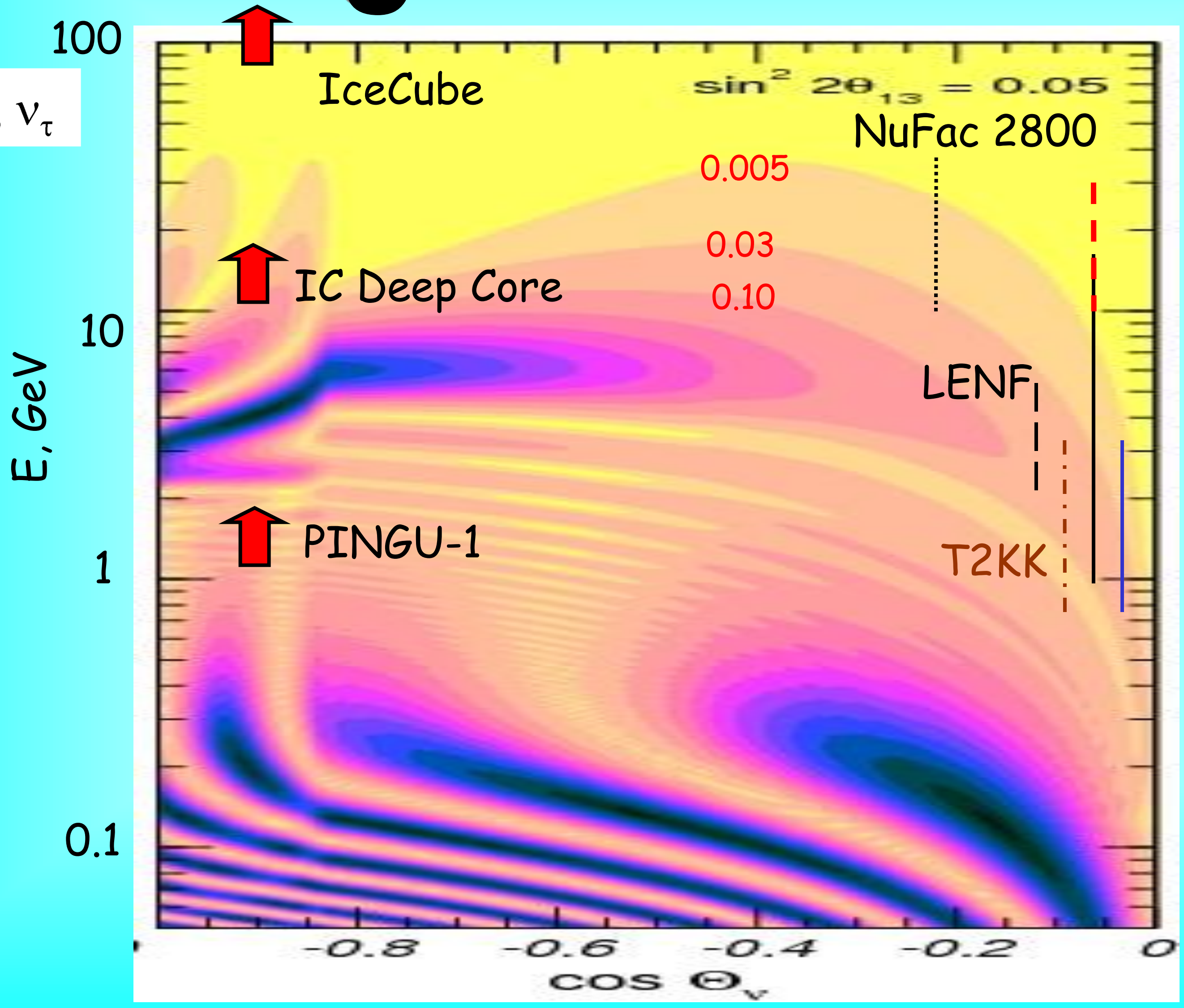
Matter effect

makes the e-flavor heavier ⇒ changes two spectra differently

Oscillograms

contours of constant oscillation probability in energy- nadir (or zenith) angle plane

$\nu_e \rightarrow \nu_\mu , \nu_\tau$



CNGS

MINOS

NOvA

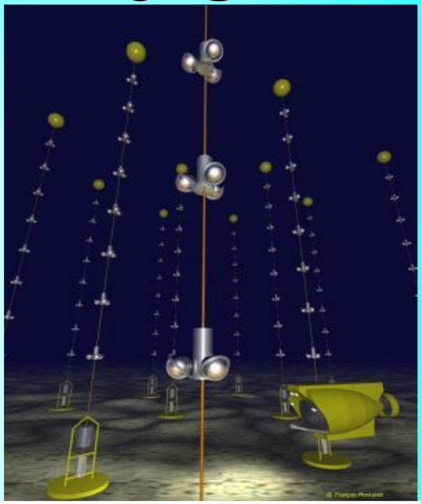
T2K HyperK

OK for CP

Atmospheric neutrinos

Oscillation physics with Huge
atmospheric neutrino detectors

P. Coyle

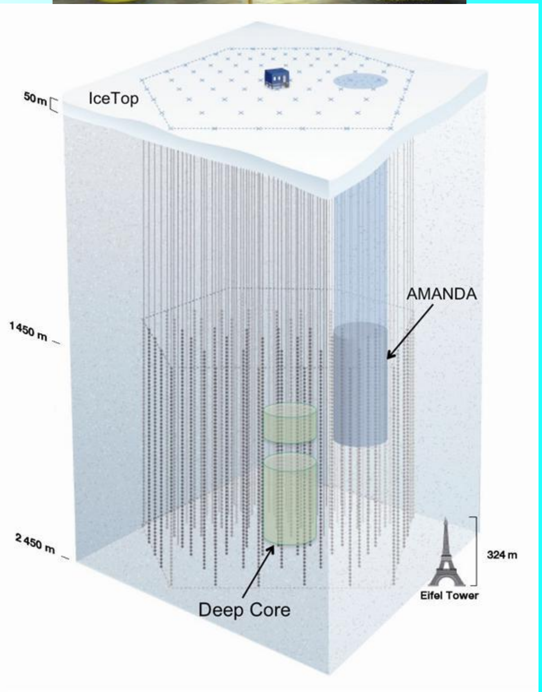


ANTARES — Oscillations 2.7σ

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

Summary

All three mixing angles are measured

Determination of 1-3 mixing (which turns out to be not very small)
→ strong impact on phenomenology , theory and future experimental programs

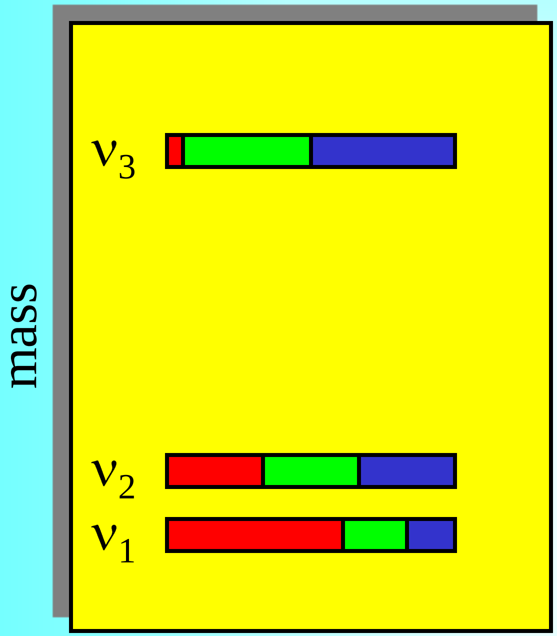
Indications of significant deviation of the 2-3 mixing from maximal
→ important implications for theory

Next step: determination of neutrino mass hierarchy and CP-violating phase

Studies of atmospheric neutrinos with huge (multi-megaton scale detectors) can play crucial role

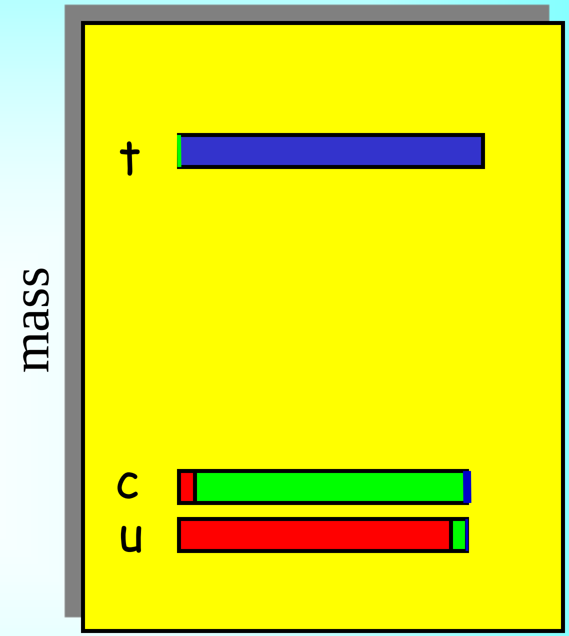
Establishing the absolute neutrino mass scale, and Majorana nature → among main goals

Leptons versus quarks



Leptons

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



Quarks

$U_d = U_{CKM}^{+}\, U$

$U = (u, c, t)$

combination of down-quarks produced with a given up quark

Huge impact of small angle

theoretical implications

symmetry

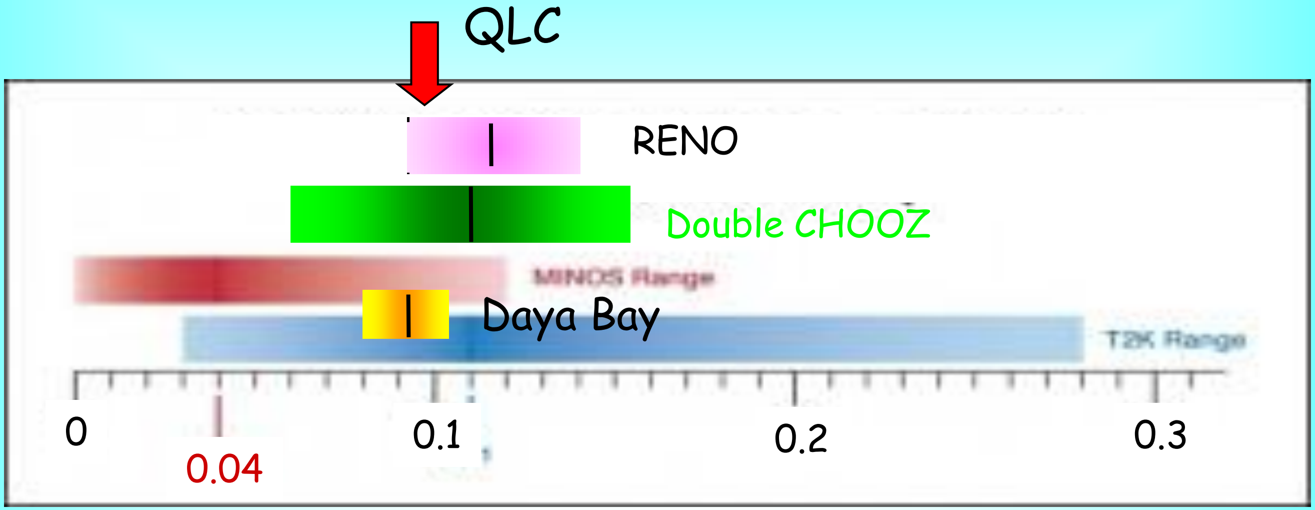
atmospheric neutrinos

U_{e3}

dominant factor
for SN neutrinos

door to determination of
CP-violation
mass hierarchy

Direct measurements of 13 mixing



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

Daya Bay: 0.092 +/- 0.012

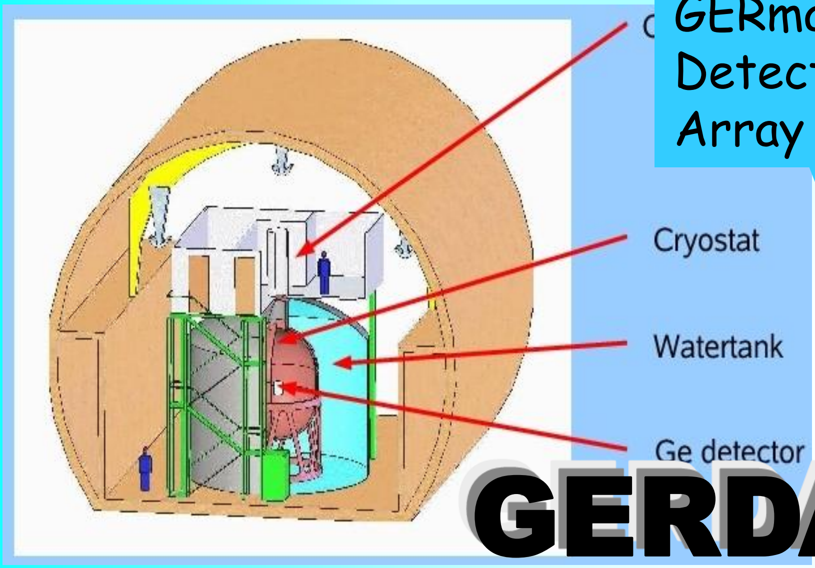
RENO: 0.116 +/- 0.024

> 7σ from 0

Important: Daya Bay, RENO and T2K
(different energies, setups..) give the same value of the angle

New experiments

GERmanium Detector Array in LAr

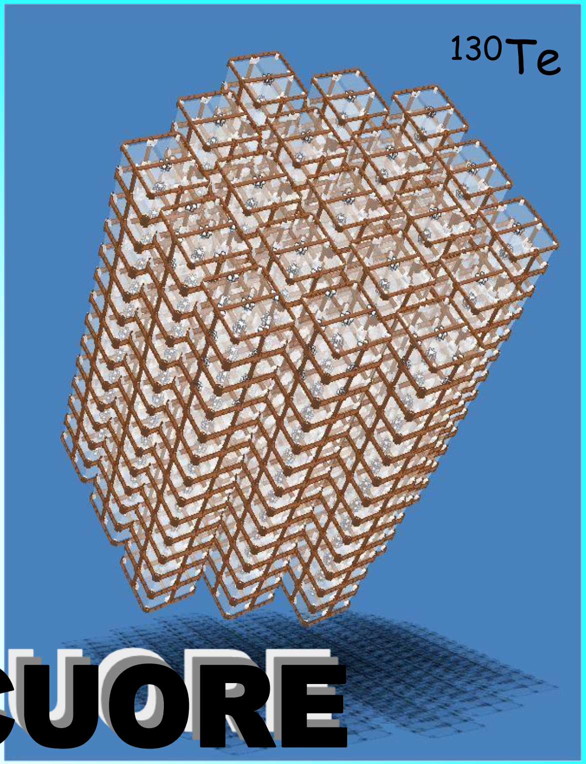


GERDA

Phase I: 15 kg y: 0.3 – 0.9 eV

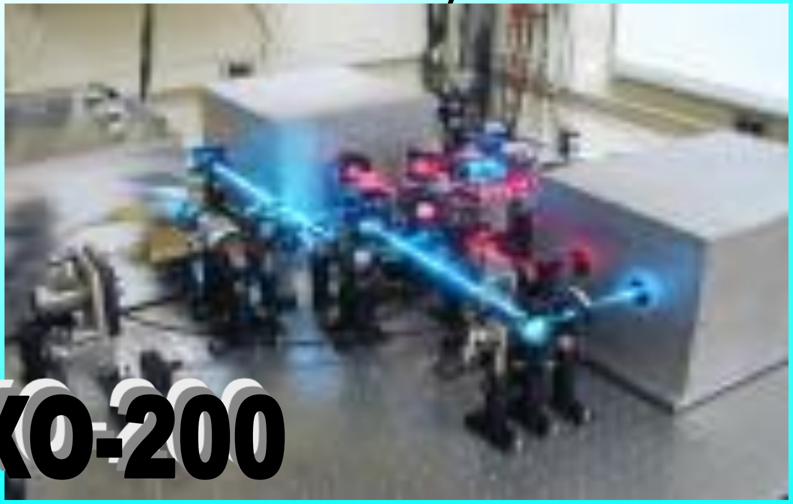
Phase II: 37.5 kg y: 0.09 – 0.29 eV

Phase III: 1 ton 0.01 eV



CUORE

Cryogenic Underground Observatory for Rare Events

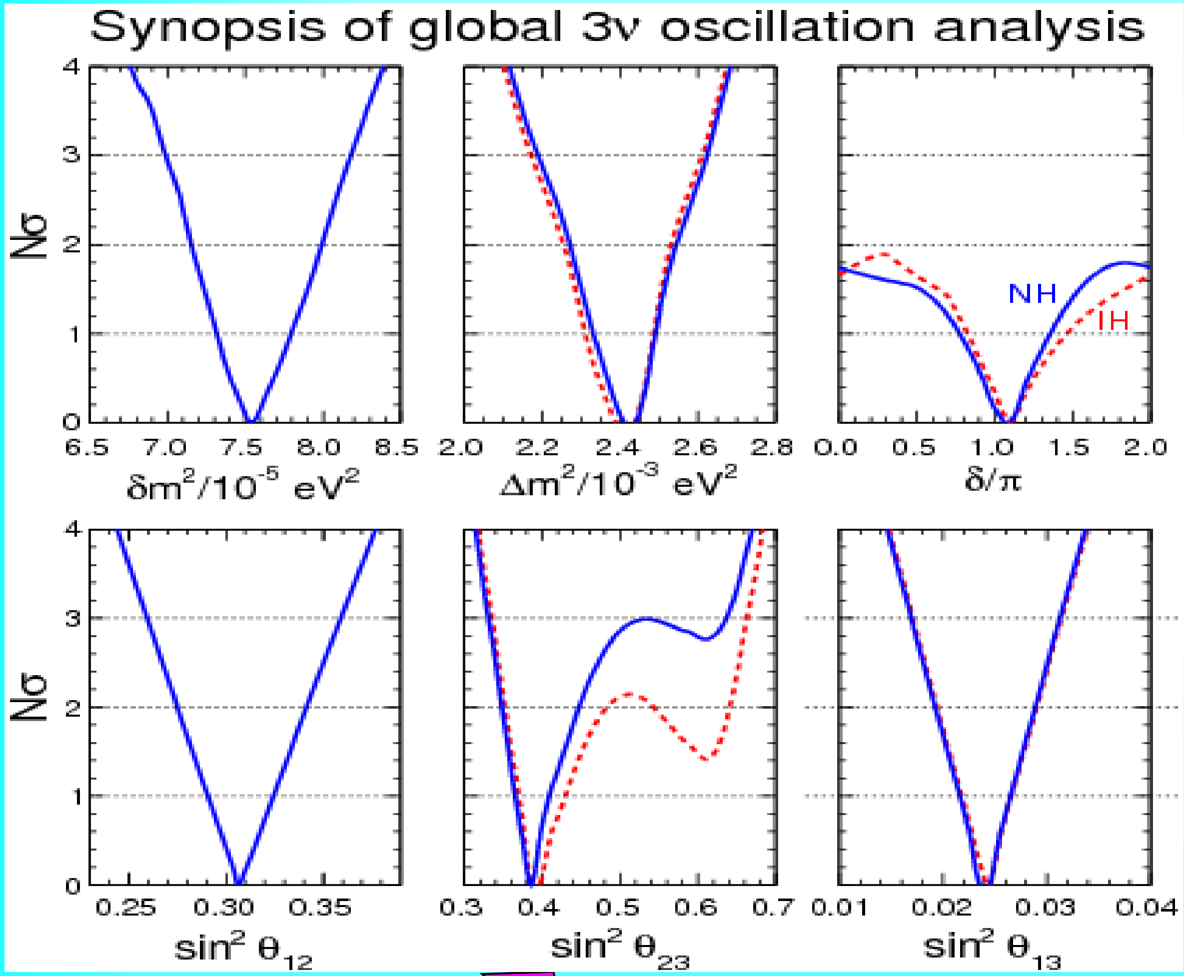


EXO-200

Xe- Observatory

Synopsis

G. L. Fogli



Serious implications for theory

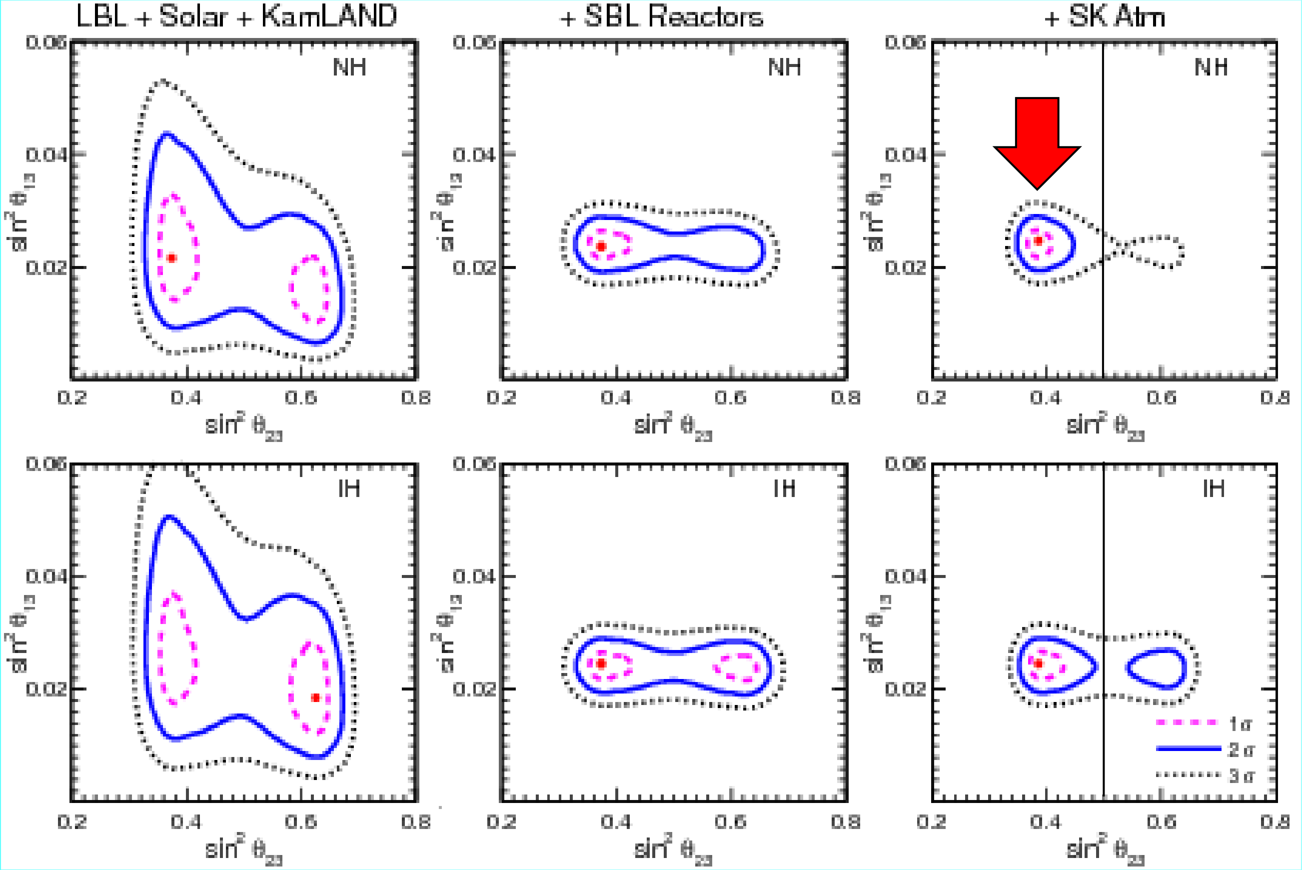
Non-zero, relatively Large 1-3 mixing

Substantial deviation of the 2-3 mixing from maximal

$\delta_{CP} \sim \pi$

Robust ?

2-3 deviation and quadrant



Global fit of oscillation data

Mass-mixing relation

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

E. Akhmedov,
G. Branco et al 2002

M Frigerio E. Ma, 2006

W. Rodejohann et al,
arXiv 1201.4936

Assumptions

1. Two mass scales in the mass matrix

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

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

Mu-tau symmetry breaking

$\sin^2\theta_{13} \sim \frac{1}{2}\cos^2 2\theta_{23}$

1. ν_μ - ν_τ – symmetry of m_ν

- maximal 2-3 mixing
- zero 1-3 mixing

2. breaking of ν_μ - ν_τ symmetry by corrections to matrix elements:

$$|m_{e\mu} - m_{e\tau}| \sim |m_{\mu\mu} - m_{\tau\tau}| = \delta m$$

3. Normal mass hierarchy

$$\sin\theta_{13} \sim \frac{\delta m}{\sqrt{2} m_3}$$

$$D = \frac{1}{2} - \sin^2\theta_{23} \sim \frac{\delta m}{2 m_3}$$

D - deviation from maximal 23 mixing

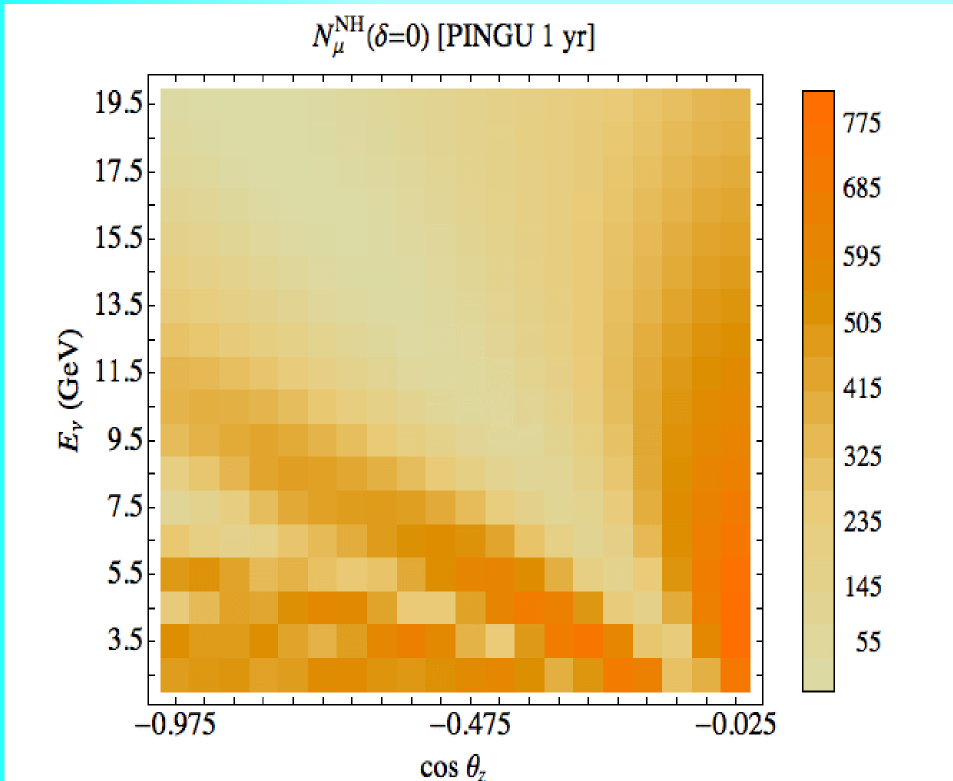
$\delta m \sim m_2$

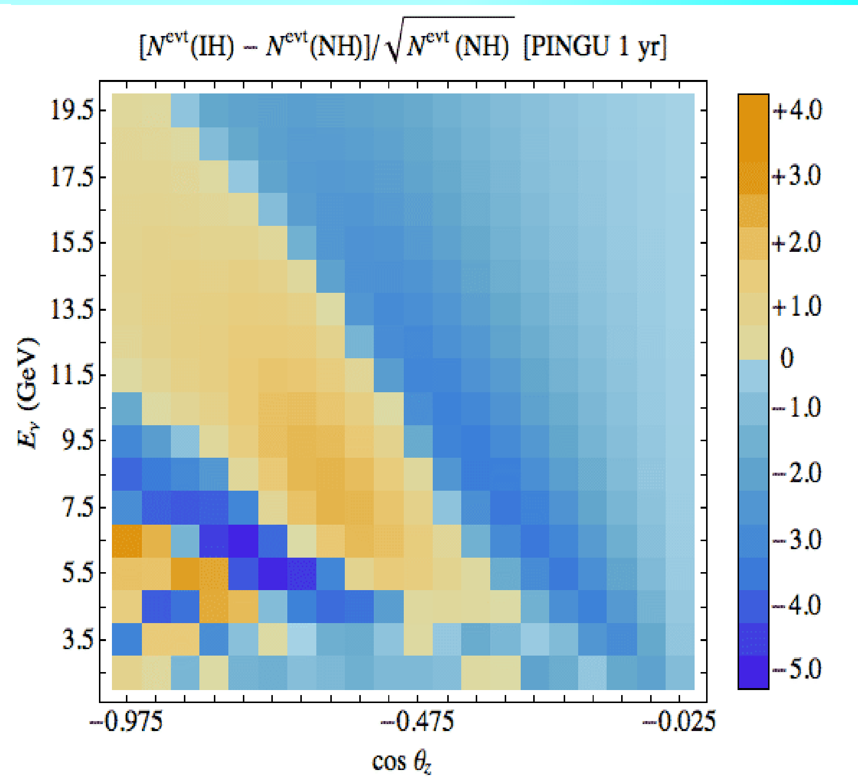
also: the ν_μ - ν_τ symmetry is broken by charged leptons

PINGU: Tracking events

E. Kh Akhmedov,
S Razzaque,
A. Y. S.

Asymmetry, statistical significance





Quick estimation of significance

$S_{tot} \sim s\, n^{1/2}$

Effective average significance in individual bin

Number of bins in resolution domains

Systematics reduces significance by factor 2

Many RH neutrinos

B. Feldstein, W. Klemm
arXiv: 1111.6690

Origins: KK states of extra dimensions

Statistical distribution of Yukawa couplings y

$$\boxed{\rho(y) \sim \frac{1}{y^{1+\delta}}}$$

$y = 10^{-6} - 1$

reasonable fit
for charged leptons

$M = 10^{14} - 10^{16}$ GeV

Linear scale

Seesaw type I

Random simulations, random phases

Anarchical spectrum

Realizations

Mass matrix in the flavor basis $\begin{pmatrix} \lambda & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$

$\lambda \ll 1$
(matrix elements are defined up to coefficients ~ O(1))

If there is no fine tuning of 12 and 13 elements

$$\sin\theta_{13} = \frac{\tan 2\theta_{12}}{2\tan\theta_{23}} \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{31}^2} \cos 2\theta_{12}}$$ ~ 0.2

E. Akhmedov, G. Branco et al 2002

$$\sin\theta_{13} = \tfrac{1}{2} \sin 2\theta_{12} \cot\theta_{23} \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{31}^2}}$$

$m_{e\mu} = 0$

W. Rodejohann et al, arXiv 1201.4936

$$\sin\theta_{13} = \tfrac{1}{2} \sin 2\theta_{12} \tan\theta_{23} \sqrt{\frac{\Delta m_{21}^2}{\Delta m_{31}^2}}$$

$m_{e\tau} = 0$

QLC predictions

H. Minakata, A.S.

Leptons

$U_\nu = U_{bm}$ seesaw

$U_l = U_{CKM}$ q-l symmetry

Quarks

$V_u = I$

$V_d = V_{CKM}$

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

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

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

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

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

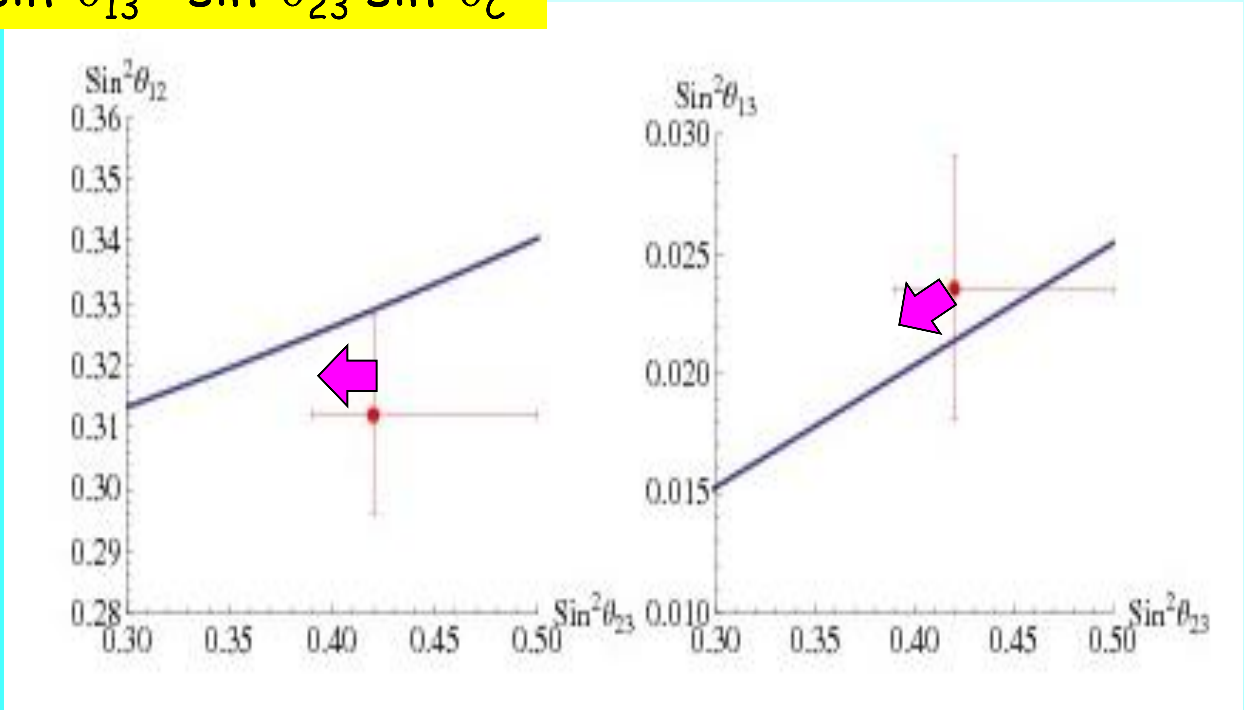
RGE -> can reduce

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

M. Schmidt, A.S.

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

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

Relations between mixing parameters

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

For column of the mixing matrix:

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

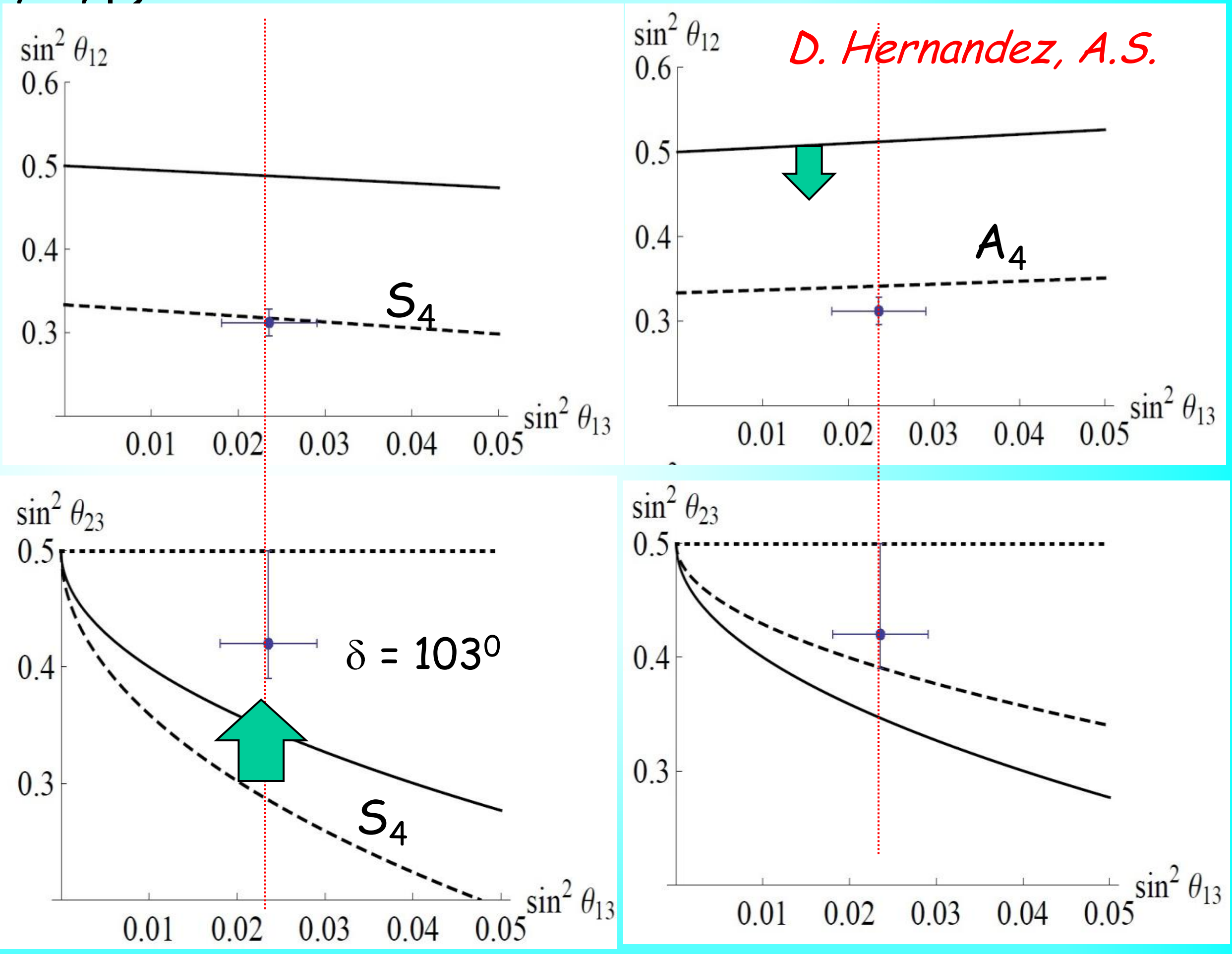
$$|U_{\alpha i}|^2 = \frac{1 - a}{4 \sin^2 (\pi k/m)}$$

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



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

Self-complementarity

Based on relation $\theta_{13} + \theta_{12} \sim \pi/4$

H. J. He, X. J. Xu

1203.2908 [hep-ph]

Bi-maximal mixing

Octahedral group

Geometric violation of residual symmetry in the charged lepton sector (additional rotation from charged leptons)

$\theta_{13} \sim \varepsilon$

$\theta_{12} \sim \pi/4 - \varepsilon$

Grand unification?

RH neutrino components have large Majorana mass

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

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

$M_{GUT} \sim 10^{16}$ GeV - possible scale of unification of EM, strong and weak interactions

Neutrino mass as an evidence of Grand Unification ?

Leptogenesis: the CP-violating out of equilibrium decay

$N \rightarrow l + H$

→ lepton asymmetry
→ baryon asymmetry of the Universe

Phenomenology

Solar neutrinos

Accelerator experiments

Supernova neutrinos

ν_s

Atmospheric neutrinos

Double beta decay

Cosmology

Reactor experiments

Beta decay

DM searches

Theoretical implications

Mass matrix

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

$m_{SS} >> m_{ab}\, ,\, m_{aS}$

For $m_{SS} \sim 1$ eV $\tan\theta_{jS} = m_{jS}/m_{SS} \sim 0.2$

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

In general can not be considered as small perturbation!

Effect on mixing is 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

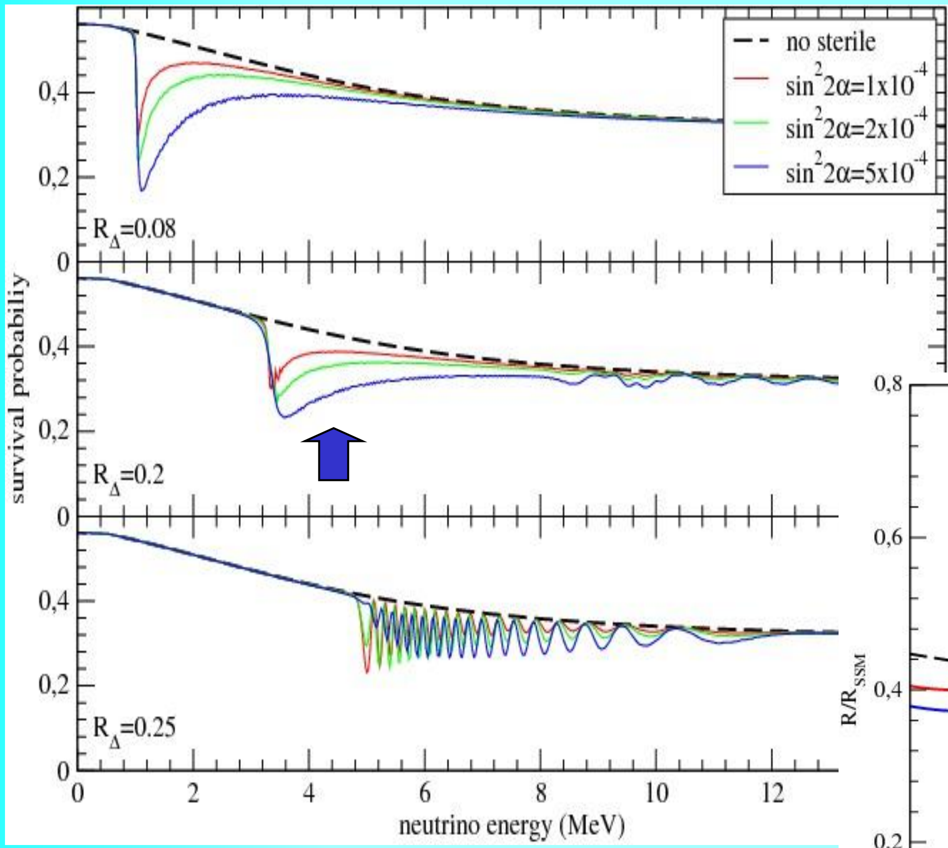
Survival probability

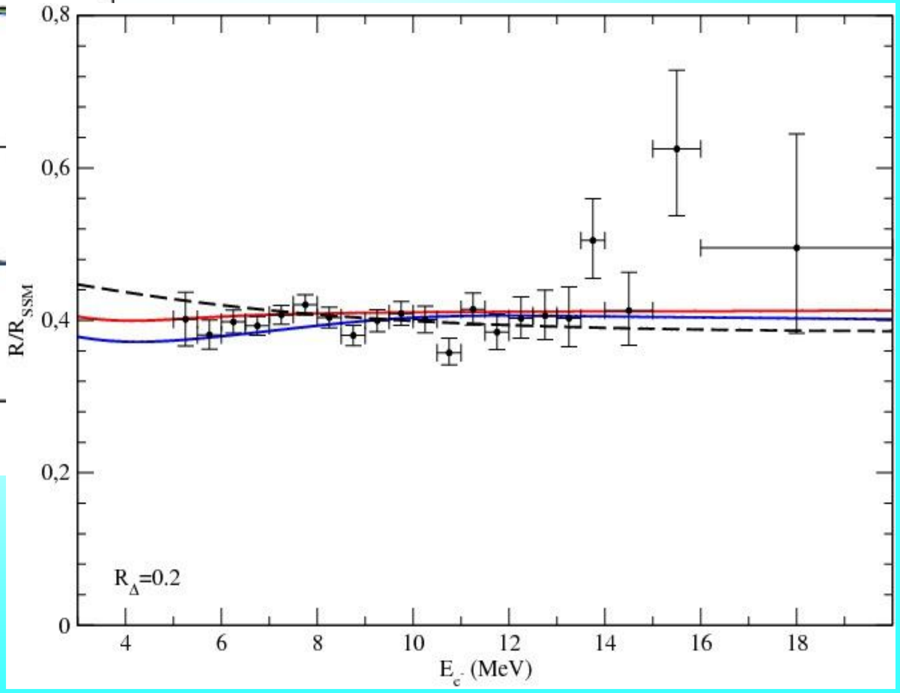
P. de Holanda, AYS

$m_0 \sim 0.003$ eV

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

$M \sim 2 - 3$ TeV





Implications

$m_0 \sim 0.003$ eV

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

$M \sim 2 - 3$ TeV

mixing

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

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

$h = 0.1$

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

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