Neutrino Masses and Mixing: New Symmetry of Nature?

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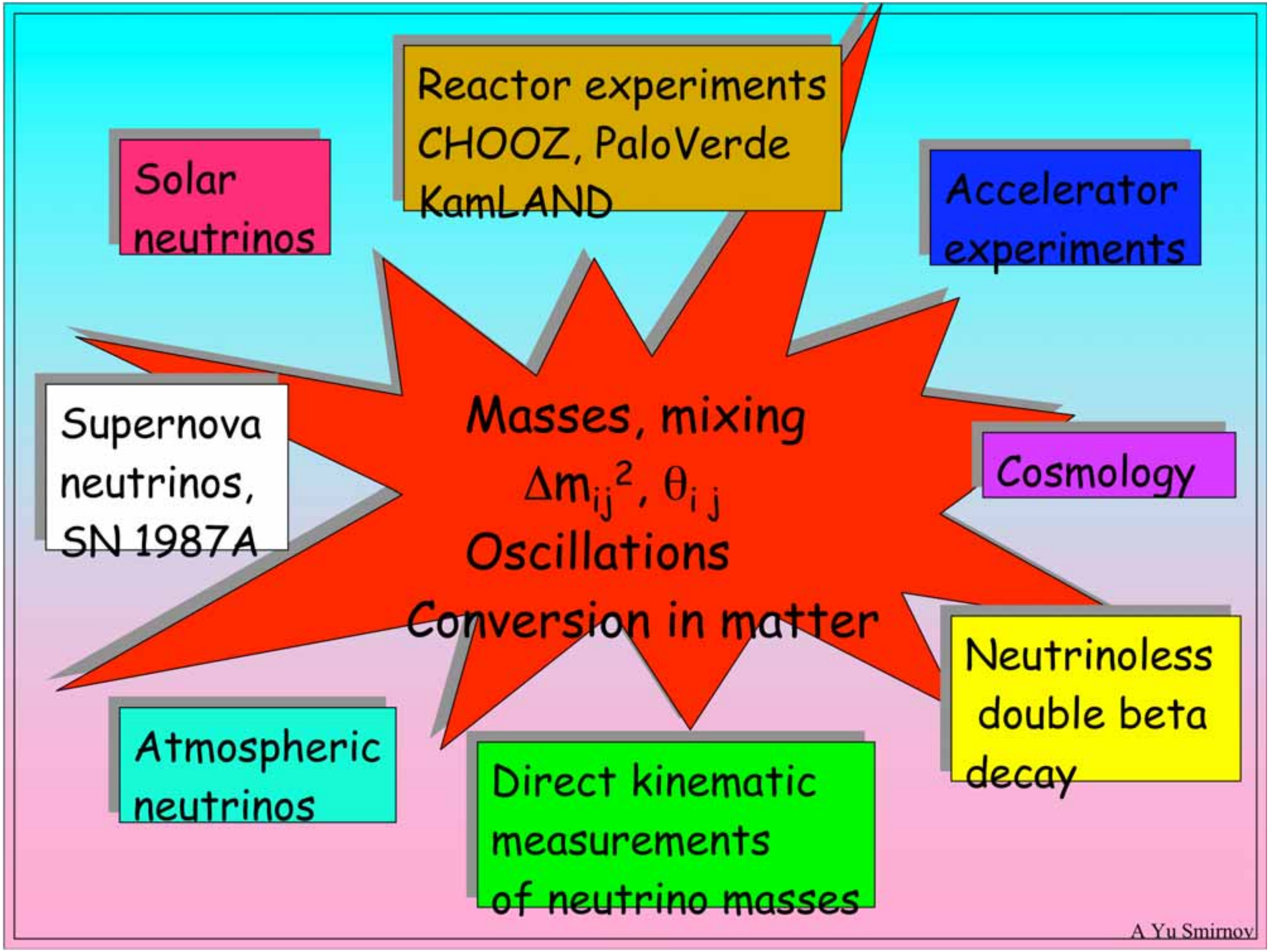
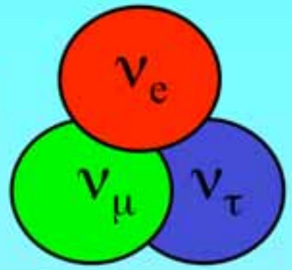
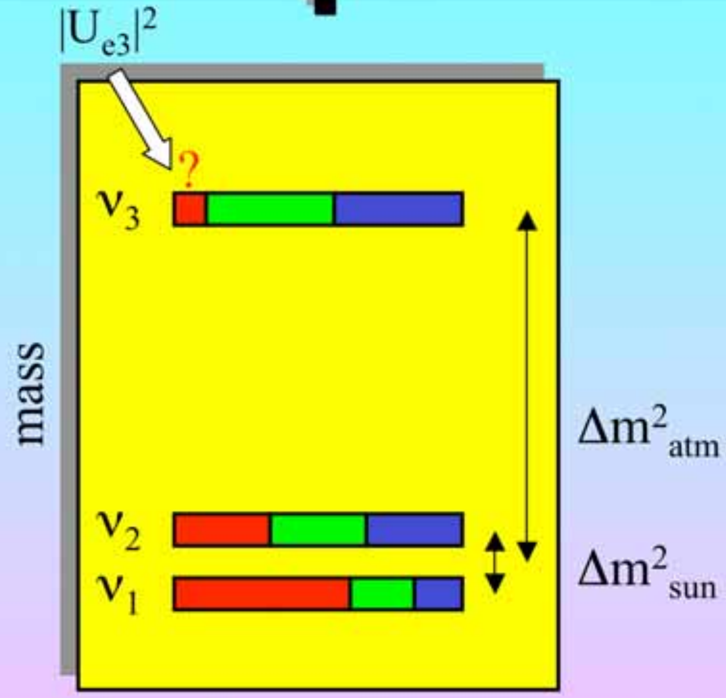
- Summary of results
  Pattern of lepton mixings: New theoretical puzzle?
- Towards the underlying physics: New symmetry of Nature?
- Symmetry case
- ``No symmetry" framework

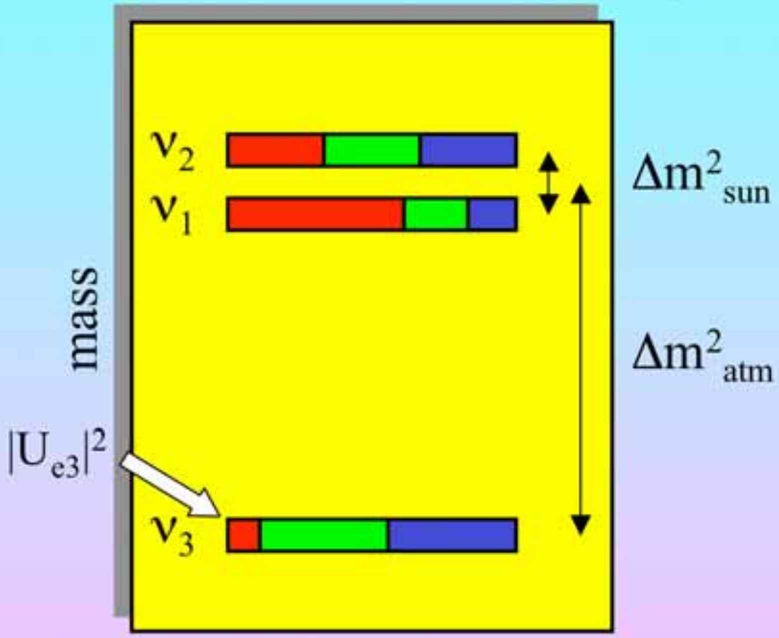

Reactor experiments
CHOOZ, PaloVerde
KamLAND
Solar neutrinos
Accelerator experiments
Supernova neutrinos, SN 1987A
Masses, mixing
Δm_{ij}^2, θ_{ij}
Oscillations
Conversion in matter
Cosmology
Neutrinoless double beta decay
Atmospheric neutrinos
Direct kinematic measurements of neutrino masses
A Yu Smirnov

Mass spectrum and mixing





Normal mass hierarchy
(ordering)



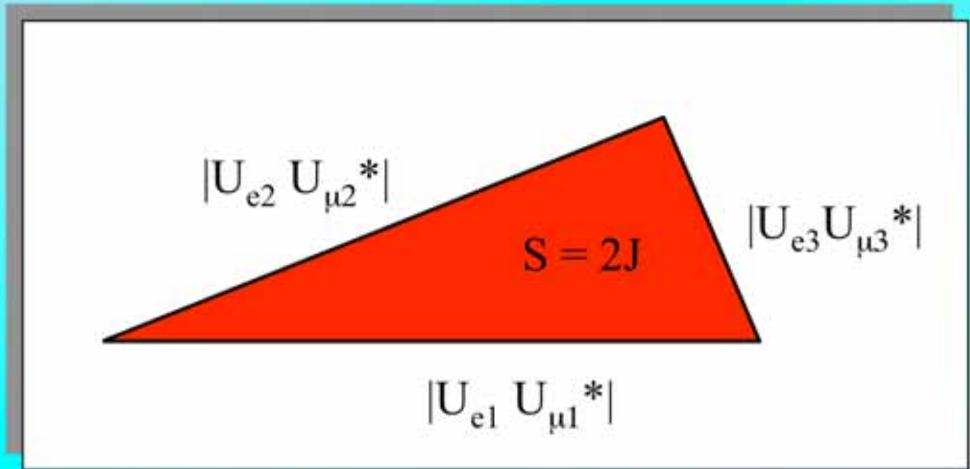
Inverted mass hierarchy
(ordering)

- Type of mass spectrum: with Hierarchy, Ordering, Degeneracy
  - ➡ absolute mass scale
- Type of the mass hierarchy: Normal, Inverted
- $U_{e3} = ?$

Leptonic Unitarity Triangle

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.78 - 0.88 & 0.47 - 0.62 & 0.0 - 0.23 \\ 0.18 - 0.55 & 0.40 - 0.73 & 0.57 - 0.82 \\ 0.19 - 0.55 & 0.41 - 0.75 & 0.55 - 0.82 \end{pmatrix}$$

Global fit of the oscillation data 3σ M.C. Gonzalez-Garcia ,



- $|U_{e3}| = 0.16$
- nearly best fit values of other angles

Y. Farsan, A.S.

Can we reconstruct the triangle?
Can we use it to determine the CP-violating phase?

$$J = s_{12}\, c_{12}\, s_{13}\, c_{13}^2\, s_{23}\, c_{23} \sin\delta$$

Problem: coherence (we deal with coherent states and not mass eigenstates of neutrinos)

Main features

- Heaviest mass: $m_h > \sqrt{\Delta m_{23}^2} > 0.04\ \mathrm{eV}$ ⇒ $\boxed{m_h \sim (0.04 - 0.4)\ \mathrm{eV}}$

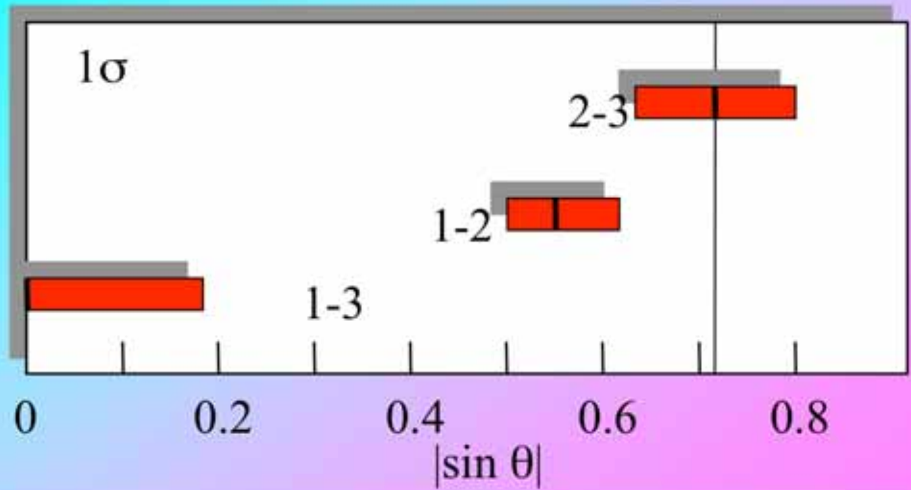
- Hierarchy of mass squared differences: $\boxed{|\Delta m_{12}^2 / \Delta m_{23}^2| = 0.01 - 0.15}$

- No strong hierarchy of masses: $|m_2/m_3| > \sqrt{|\Delta m_{12}^2 / \Delta m_{23}^2|} = 0.18^{+0.22}_{-0.08}$

- Bi-large or large-maximal mixing between neighboring families (1- 2), (2- 3):

  $\boxed{\theta_{12} + \theta_C = \theta_{23} \sim 45^o}$

- bi-maximal + corrections?



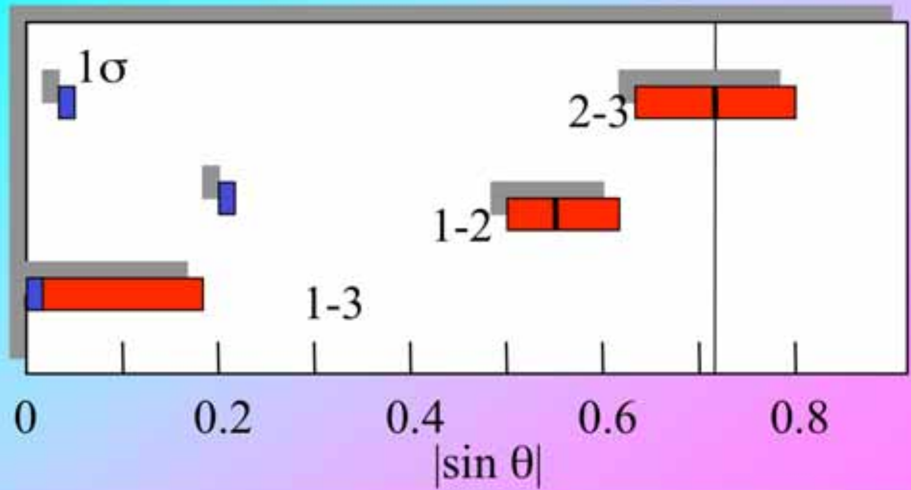
Quarks and Leptons

Mixing	Quarks	Leptons
1-2, θ_{12}	13°	32°
2-3, θ_{23}	2.3°	45°
1-3, θ_{13}	~ 0.5°	<13°

$$\theta_{12} + \theta_C = \theta_{23} \sim 45^o$$

Hierarchy of mass:

- Neutrinos $|m_2/m_3| > 0.18$
- Charged leptons $|m_\mu/m_\tau| = 0.06$
- Down quarks $|m_s/m_b| \sim 0.02 - 0.03$
- Up-quarks $|m_c/m_t| \sim 0.005$



Cabibbo-solar mixing relation

- Solar mixing = maximal - Cabibbo $\theta_{sun} = \pi/4 - \theta_C$ $\tan 2\theta_{sun} = \text{ctg}\, 2\theta_C$

S.Petcov, A.S. 1994

- Solar data + KamLAND $\theta_{Sun} = 32.3^0 \ +/- \ 2.4^0$
- Cabibbo angle at m_Z $\theta_C = 12.8^0 \ +/- \ 0.15^0$

1σ

$\theta_{Sun} + \theta_C = 45.1^0 \ +/- \ 2.4^0$

$\tan^2\theta_{sun} = 0.40 \ +/- \ 0.08$

$\tan^2(\pi/4 - \theta_C) = 0.40$

$$\theta_{sun} + \theta_C = \pi/4$$

H.Minakata, A.S.

Accidental equality

?

Quark-Lepton symmetry

Grand Unification

Bi-maximal mixing

"Neutrino scenario"

In the symmetry basis

Leptons

Quarks

- $V_\nu = R_{23}^{max} R_{12}^{max}$

Seesaw?

$V_u = I$

- $V_l = V_{CKM}$

q-l symmetry

$V_d = V_{CKM}$

$V_{leptons} = V_d^+ V_\nu = V_{CKM}^+ R_{23}^{max} R_{12}^{max}$

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

Predictions:

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

$\tan^2\theta_{sun} = 0.495$

$\sin\theta_{13} = \sin\theta_{atm}\sin\theta_C = 0.16$

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

H. Minakata, A.S.

Charged Lepton scenario

Leptons

Quarks

M. Raidal

- $V_\nu = V_{CKM}^+$ — q-l symmetry — $V_u = V_{CKM}^+$
- $V_l = R_{12}^{max} R_{23}^{max}$ — $V_d = I$

``Lopsided''

$V_{leptons} = R_{23}^{max+} R_{12}^{max+} V_{CKM}^+$

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

- Predictions:

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$\sin\theta_{sun} \sim \sin(\pi/4 - \theta_C)$

$\sin^2\theta_{13} = -\sin\theta_{sun} V_{cb} = 0.03$

$D_{23} = \cos\theta_{sun} V_{cb} \cos\delta < 0.03$

Hybrid scenario

H. Minakata, A.S.

Leptons | **Quarks**

- Seesaw? $\boxed{V_\nu = R_{12}^{max}}$ | $\boxed{V_u = I}$
- $\boxed{V_l = V_{CKM} R_{23}^{max\,+}}$ | **q-l symmetry** | $\boxed{V_d = V_{CKM}}$

$$\boxed{V_{leptons} = V_d^{+} V_\nu = R_{23}^{max} V_{CKM}^{+} R_{12}^{max}}$$

$$\boxed{V_{quark} = V_u^{+} V_d = V_{CKM}}$$

- Predictions:

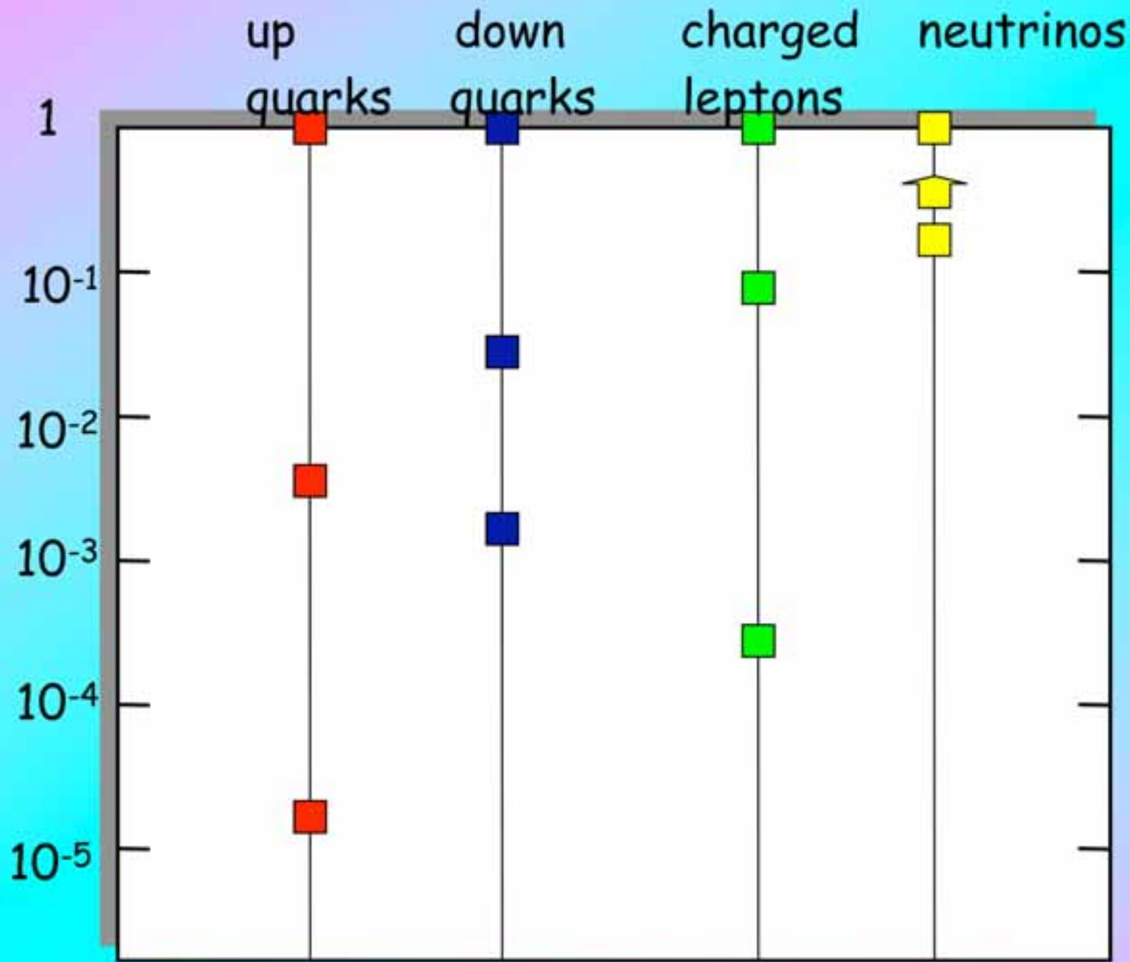
$$\boxed{\sin\theta_{sun} \sim \sin(\pi/4 - \theta_C)}$$

$$\boxed{\sin\theta_{13} \sim V_{ub} \sim 0.003}$$

Single maximal mixing

The hope was...

that neutrinos sill shed some light on the fermion mass problem in general



$m_u\, m_t = m_c^2$

$V_{us}\, V_{cb} \sim V_{ub}$

Mass-mixing relation?

Toward the underlying physics

- Neutrino masses and mixing - important message which we can not understand yet
- In which terms, at which level theory (principles) should be formulated?

Observables

masses mixing angles are fundamental parameters which show certain symmetry

Schemes with bi-maximal mixing, or broken bi-maximal mixing; Tri-bimaximal mixing

Mass matrices

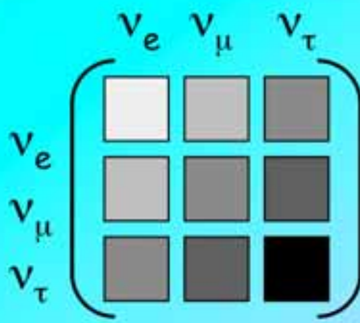
their properties, symmetries at certain energy scale

observables are outcome, can be to some extend accidental numbers which do not reflect the underlying symmetry

No regularities - ``anarchy"

- Smallness of neutrino masses and pattern of lepton mixing are related? → **See-saw**

Mixing and Mass Matrix



Mixing:

Mass matrix for the flavor states

$\nu_f = (\nu_e, \nu_\mu, \nu_\tau)^T$, m_f is not diagonal

(Majorana)

Diagonalization:

$\boxed{\nu_f = U_\nu \nu_{mass}}$ $\nu_{mass} = (\nu_1, \nu_2, \nu_3)^T$

$\boxed{m_f = U_\nu^T m_{diag} U_\nu^*}$ $m_{diag} = \mathrm{diag}(m_1, m_2, m_3)$

Charged leptons

In general (symmetry) basis the mass matrix of the charged leptons is also non-diagonal

$\boxed{l_{S\,L} = U_{lL}\, l_{mass\,L}}$ $l = (e, \mu, \tau)^T$

Lepton mixing matrix

$\boxed{U_{P\text{-}MNS} = U_{lL}^+ U_\nu}$

Lepton mixing --> the mismatch of rotations of the neutrinos and the charge leptons which diagonalize the corresponding

Seesaw

Smallness of neutrino masses

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

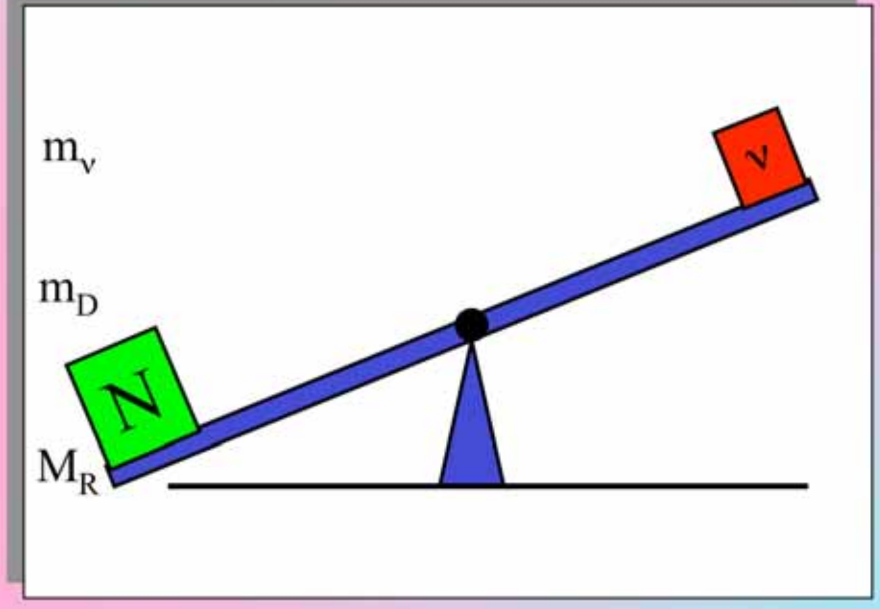
- $\boxed{N^T Y\, L\, H + \frac{1}{2} N^T M_R N + \text{h.c.}}$

$L = (\nu,\ l)^T \qquad N = (\nu_R)^c$

$\Rightarrow \begin{array}{c} \nu \\ N \end{array} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \quad m_D = Y\langle H\rangle$

If $M_R >> m_D$

$\Rightarrow \boxed{m_\nu = -\, m_D^T M_R^{-1} m_D}$



- Zero charges
  -> can have Majorana mass
- Right handed components: singlets of the SM symmetry group
  -> mass is unprotected by symmetry can be large -- at the scale of lepton number violation

Neutrality
$Q_{EM} = 0$,
$Q_c = 0$

$\Rightarrow$

Smallness of neutrino mass

New Symmetry of Nature?

What can testify ?

Maximal or close to maximal 2-3 mixing

Degenerate or partially degenerate spectrum

Very small 1 -3 mixing

$|0.5 - \sin^2\theta_{23}| \ll \sin^2\theta_{23}$

$\Delta m \ll m$

$\theta_{13} \ll \theta_{12} \times \theta_{23}$

2ν data fit:
Best fit value:
$\sin^2 2\theta_{23} = 1.0$

$\sin^2 2\theta_{23} > 0.91$, 90% CL

$m_1 = m_2 = m_3$

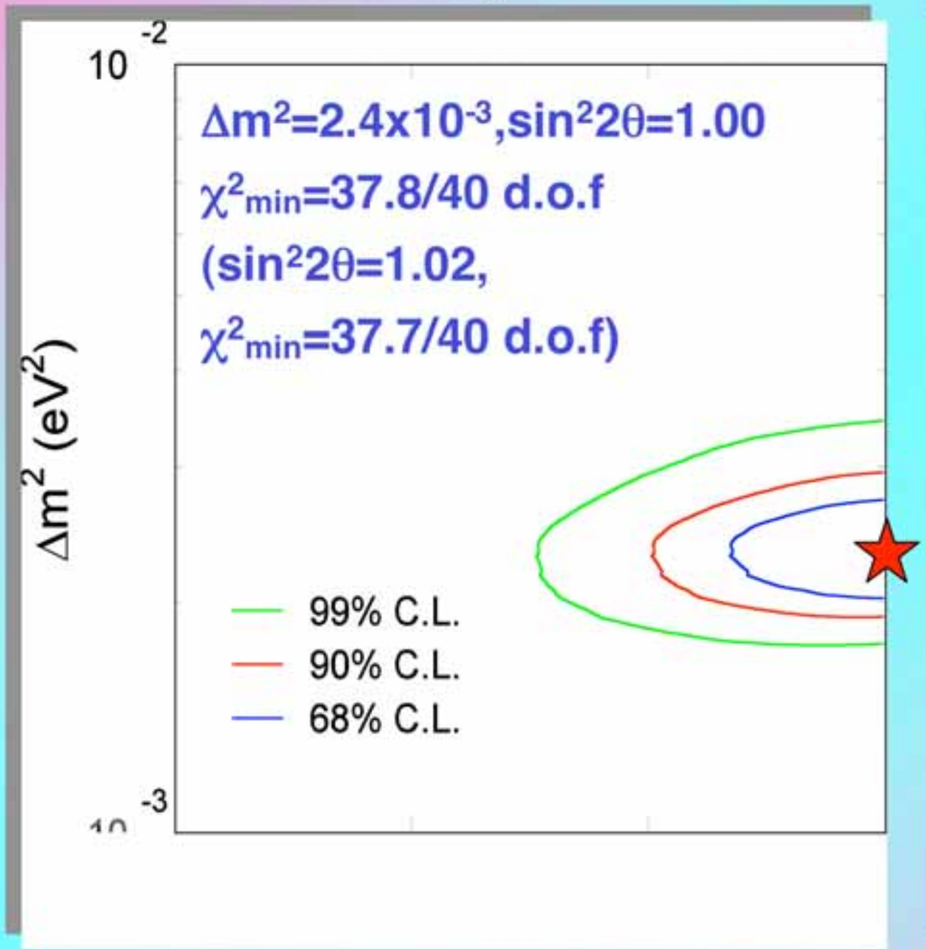
$m_3 = m_2 \ll m_1$
(inverted hierarchy) ?

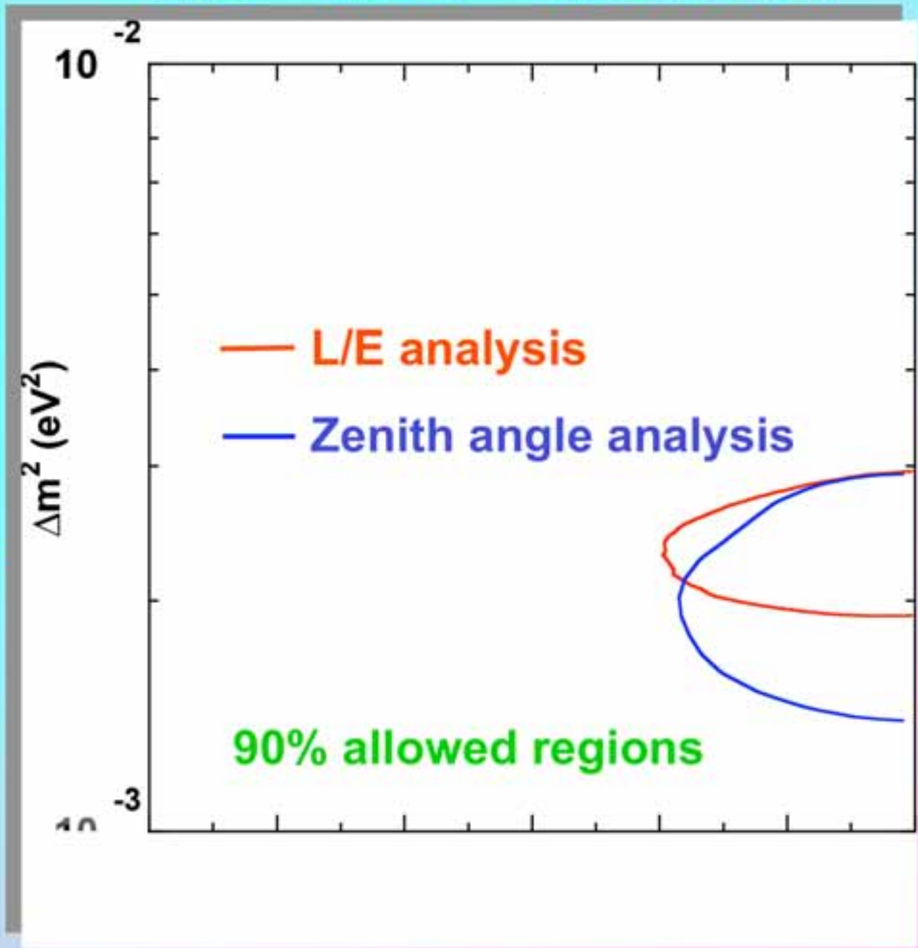
Oscillation parameters

SuperKamiokande

$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2
$0.90 < \sin^2 2\theta$ at 90% C.L.

Preliminary





Degenerate spectrum

$\Delta m/m_0 \sim \Delta m_{atm}^2/2m_0^2$ ⇒ Degenerate: $m_0 >$ (0.08 - 0.10) eV

- Large or maximal mixing ⇔ Mass degeneracy

- Cosmology: $m_0 = 0.20$ +/- 10 eV

  Large scale structure analysis including X-ray galaxy clusters
  S.W Allen, R.W. Schmidt, S. L. Bridle

- Heidelberg-Moscow result
  77.7 kg y
  4.2σ effect

  $m_i > m_{ee}$ at least for one mass eigenstate

  m_{ee} = (0.29 - 0. 60) eV (3σ)

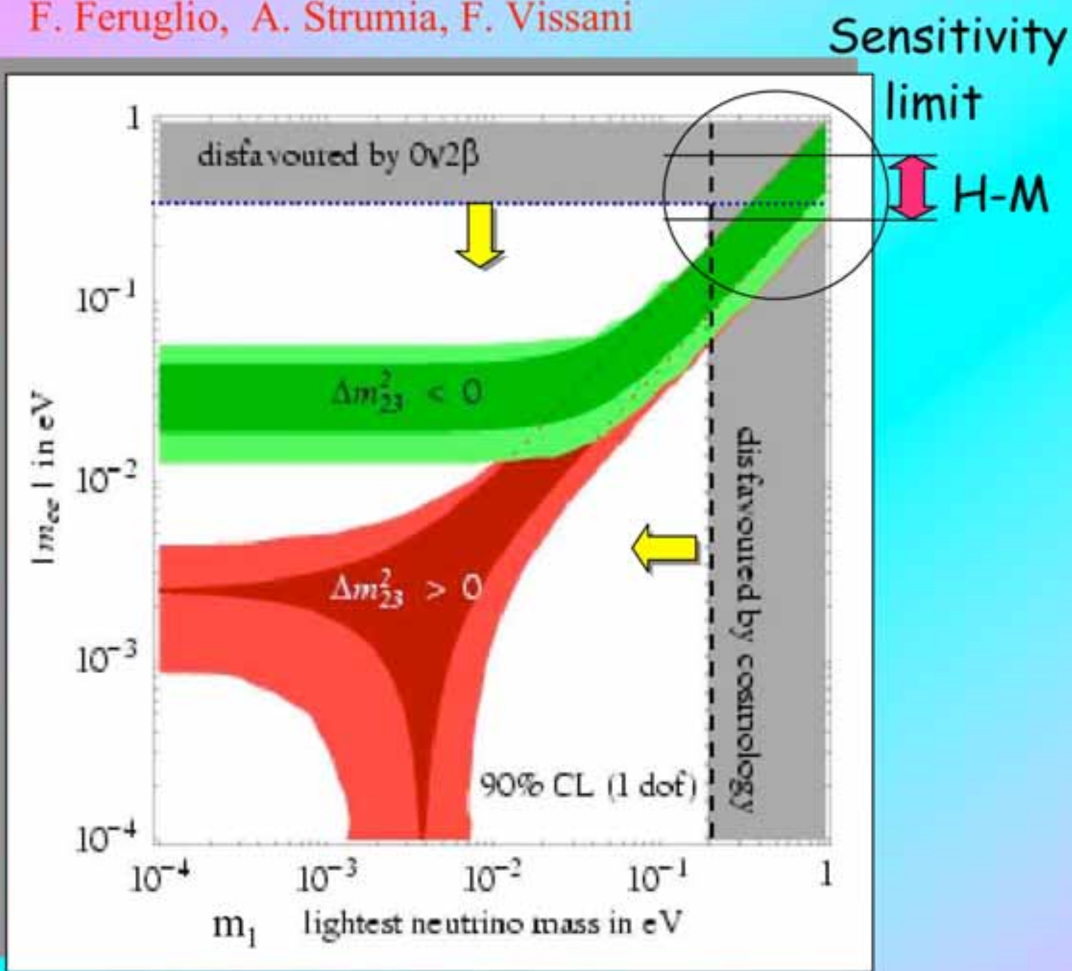
  m_{ee}(b.f.) = 0.44 eV

  H. Klapdor-Kleingrothaus, et al.

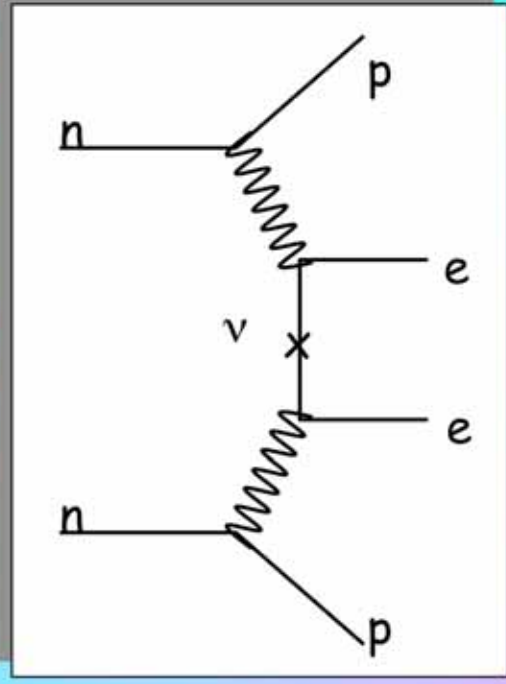
Absolute scale of mass

F. Feruglio, A. Strumia, F. Vissani

Neutrinoless double beta decay



Kinematic searches, cosmology



$m_{ee} = \Sigma_k U_{ek}{}^2 m_k e^{i\phi(\kappa)}$

Both cosmology and double beta decay have similar sensitivities

Large mixing and Degeneracy

Degeneracy parameter: $\delta_{23} = \Delta m/m = \Delta m^2/2m^2$

Deviation from maximal mixing: $D_{23} = 0.5 - \sin^2\theta_{23}$

Degeneracy vs. deviation.

examples

1). $\begin{pmatrix} 0 & 1 \\ 1 & \varepsilon \end{pmatrix} \Rightarrow D_{23} = \delta_{23}$

2). $\begin{pmatrix} 1 & \varepsilon \\ \varepsilon & 1 \end{pmatrix} \Rightarrow D_{23} = 0,\ \delta_{23} = 2\varepsilon$ maximal mixing, arbitrary mass split

3). $\begin{pmatrix} \varepsilon & 1 \\ 1 & -\varepsilon \end{pmatrix} \Rightarrow D_{23} = \varepsilon/2,\ \delta_{23} = 0$ arbitrary mixing zero mass split

For $m = 0.25$ eV: $\delta_{23} = 0.03$, $D_{23} \sim 0.1$ will exclude the possibility 1).

Simple relation is absent due to presence of
- third neutrino
- Majorana phases

$\Rightarrow$ Smaller δ_{21} is associated to larger D_{21}

U_e3 - expectations

- Naively $\sin\theta_{13} \sim \sin\theta_{12} \times \sin\theta_{23}$

  $\sim$ 0.3 - 0.5

  excluded which implies dominant structures or/and degeneracy in the mass matrix

- A bit seriously solar sector $\Leftrightarrow$ $\sin\theta_{13}$ $\Leftrightarrow$ Atmospheric sector

  Mass scales: $\sqrt{\Delta m_{sun}{}^2}$ $\sqrt{\Delta m_{atm}{}^2}$

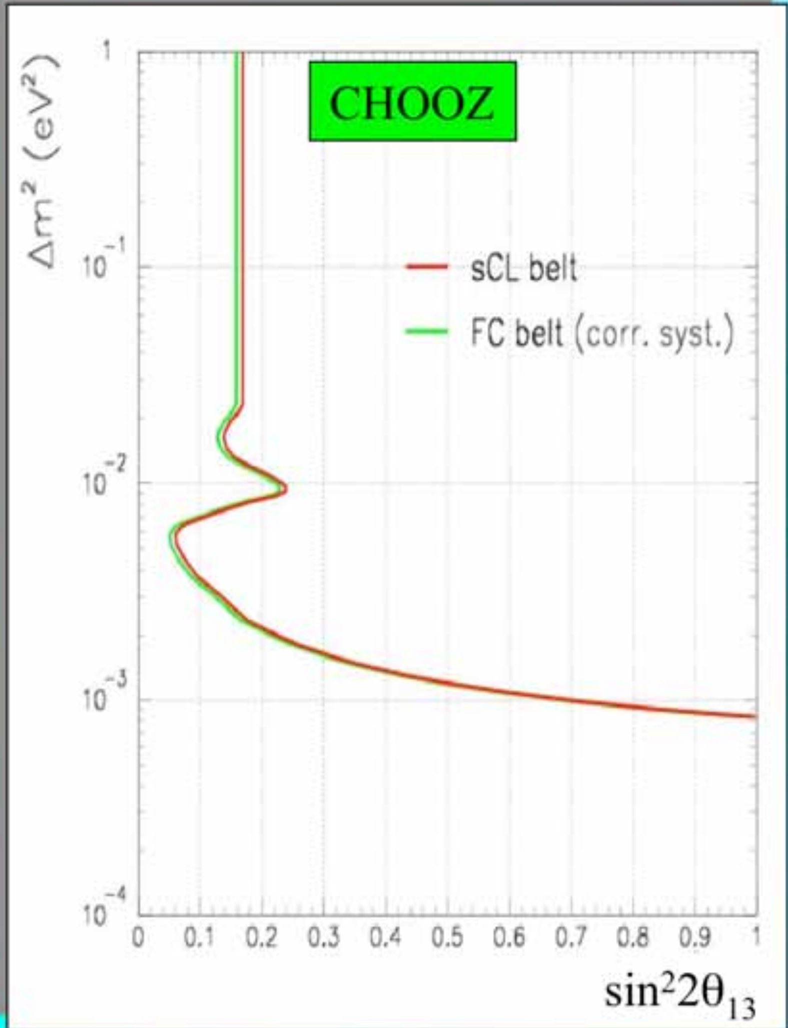
  $\Rightarrow$ $\sin\theta_{13} \sim \sqrt{\Delta m_{sun}{}^2 / \Delta m_{atm}{}^2}$ ~ 0.15 - 0.20

  With comparable contribution from the charge leptons

  If there is no cancellation: $\sin^2\theta_{13} \sim 0.01 - 0.05$

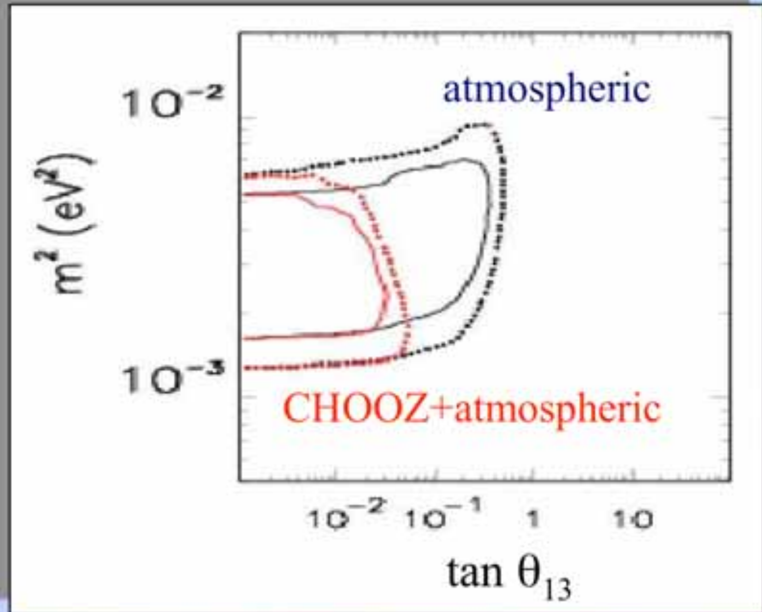
U_e3

$$U_{e3} = \sin\theta_{13}\, e^{-i\delta}$$
$$= \langle \nu_e \,|\, \nu_3 \rangle$$



Has important implications for phenomenology and theory:

- supernova neutrinos: can lead to O(1) effect;
- atmospheric neutrinos (resonance enhancement, parametric effects);
- allows to establish mass hierarchy;
- LBL experiments;
- CP-violations requires U_{e3} = 0;
- key test of models of large



Relations?

Degeneracy of mass spectrum

Deviation of 2-3 mixing from maximal

1-3 mixing

?

Symmetry which leads to maximal 2-3 mixing e.g. Permutations, Z_2 can give $\sin \theta_{13} = 0$

Violation of the symmetry

$D_{23} \neq 0$
$\sin \theta_{13} \neq 0$

Two extreme cases

Quasi-degenerate spectrum

- New symmetry $SO(3)$, A_4, Z_2, ...
- Quark -lepton symmetry?

S Barshay,
M. Fukugita,
T. Yanagida
...

Hierarchical Spectrum

- No particular symmetry
- Deviation from maximal mixing
- Quark-lepton analogy/symmetry

Symmetry case

In the flavor basis: $\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix}$

$$\boxed{m_\nu = m_0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} + \delta m} \qquad \delta m \ll m_0$$

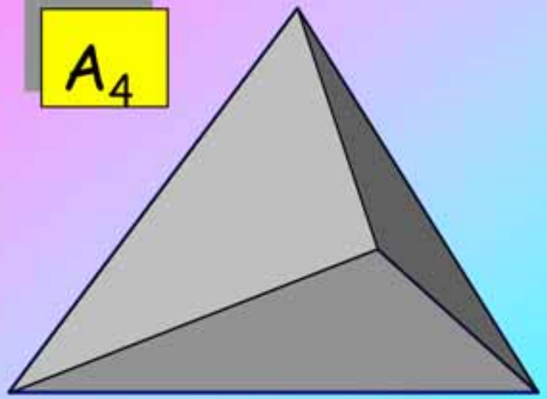
Features:

- Degenerate spectrum: $m_1 = m_2 = - m_3$
- Maximal or near maximal 2-3 mixing
- Opposite CP parities of ν_2 and ν_3
  ν_2 and ν_3 form pseudo-Dirac pair
- Neutrinoless double beta decay: $m_{ee} \sim m_0$
- Most of the oscillation parameters are not imprinted in to the dominant structure: all Δm^2 as well as 1-2 and 1-3 mixings are determined by δm.
- δm is due to the radiative corrections?

Symmetry

E. Ma,
G. Rajasekaran
K.S. Babu,
J. Valle

A_4



Symmetry group of even permutations of 4 elements

Symmetry of tetrahedron: (4 faces, 4 vertices)

→ Plato's fire

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

- Transformations under A_4 $(\nu_i\,,\ e_i) \sim \underline{3}$ $(u_i\,,\ d_i) \sim \underline{3}$ $(i = 1, 2, 3)$ $H_{1,2} \sim \underline{1}$

  $u_1^c, d_1^c, e_1^c \sim \underline{1}$ $u_2^c, d_2^c, e_2^c \sim \underline{1'}$ $u_3^c, d_3^c, e_3^c \sim \underline{1''}$

- New heavy quarks leptons and Higgs are introduced $U_i,\ U_i^c, D_i,\ D_i^c, E_i,\ E_i^c, N_i^c\ , \chi_i \sim \underline{3}$

- Explicit asymmetry of charged fermions and neutrino sector:

  no ν_i^c and N_i → Leads to different mixing of quarks and leptons

Model: quarks and leptons

- Problem to include leptons and quarks in unique model
  Symmetry between leptons and quarks is explicitly broken

- Neutral and charge lepton sectors are different:

Extra symmetries required (e.g. Z_3)

H_1: e_i — E_i^c ----- E_i — e_1^c, $<\chi_i>$, M_E

A_4 is broken

H_2: ν_i — N_i^c, M_N

$i = 1, 2, 3$

Majorana mass

- Seesaw
- Mixing - from the charged leptons in the symmetry basis

Mixing of quarks: $U_L^+ U_L = I$

Mixing of leptons: $U_L^T U_L = M_0$

$$U_L = \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix}$$

$$\omega = \exp(-2i\pi/3)$$

- Oscillation parameters are determined by δm
  - an additional theory independent on A_4 required
- Masses and mixing angles are unrelated

Symmetry approach

Realization requires introduction of

- New leptons and quarks;
- Extended non-trivial Higgs sector to break symmetry;
- Additional symmetries to suppress unwanted interactions of new particles

Often - difficult to embed into Grand Unified schemes

➡ Profound implications or Misleading approach ???

Do we really see a symmetry?

1). The only serious indication is nearly maximal 2-3 mixing:

$\sin^2 2\theta_{23} > 0.91, \quad 90\ \%\ CL$

2). $\sin^2 2\theta_{23}$ is a ``bad'' parameter from theoretical point of view

$\sin^2\theta_{23}$ is better, but for this parameter:

$\sin^2\theta_{23} = \quad (0.35 - 0.65) \quad 90\ \%\ CL$ ⇨

Relative deviation from maximal mixing (1/2) can be large

$\Delta\sin^2\theta_{23} / \sin^2\theta_{23} \sim \quad 0.7$

3). The atmospheric neutrino results may provide some hint that the mixing is not maximal

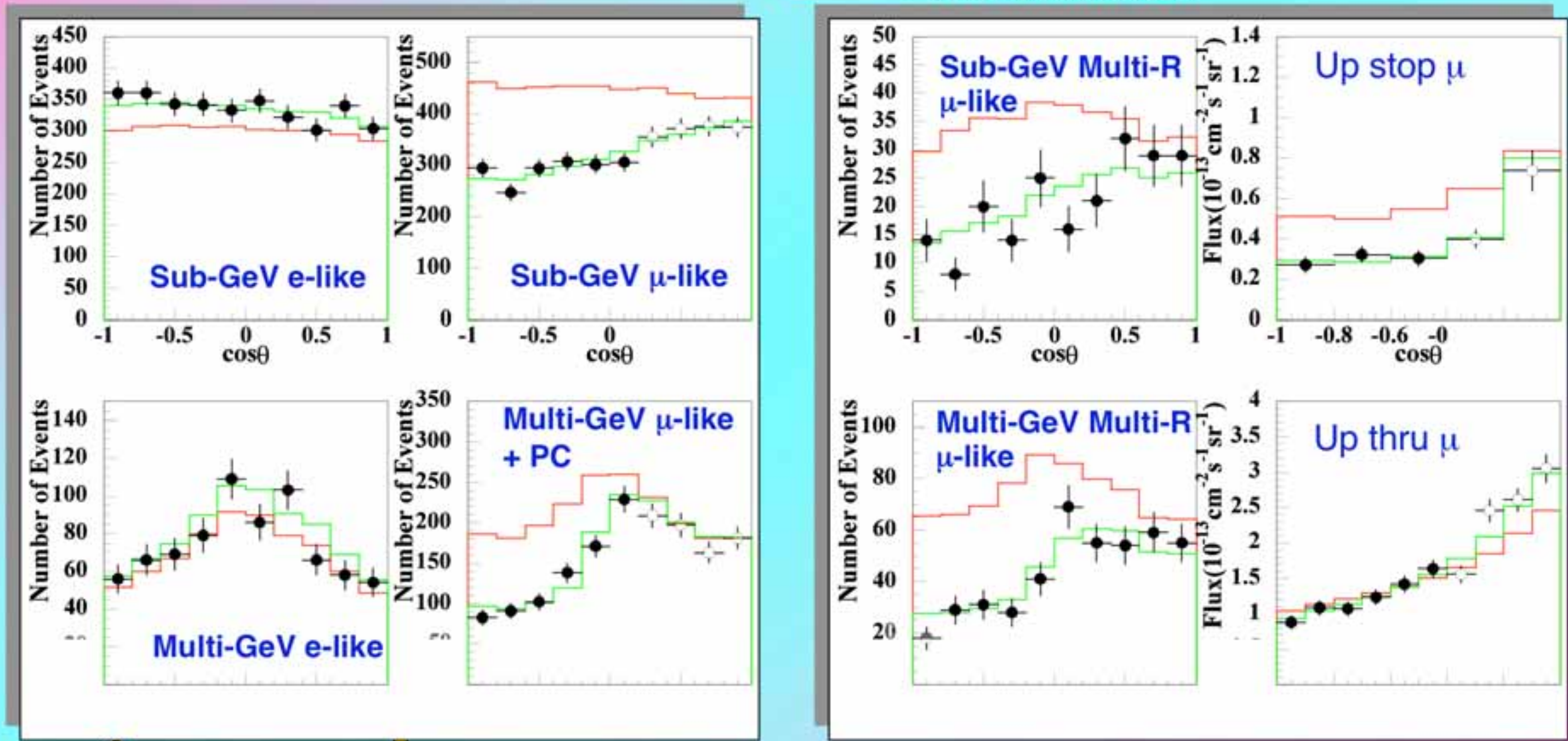
Excess of the e-like events (?)

Three neutrino analysis of data is needed

Zenith angle distributions

$\nu_\mu \leftrightarrow \nu_\tau$

Best fit
$\sin^2 2\theta = 1.0$, $\Delta m^2 = 2.0\times10^{-3}$ eV^2
Null oscillation



~13000km ~500km ~15km

SuperKamiokande

LMA oscillations of atmospheric neutrinos

Excess of the e-like events in sub-GeV

$$\frac{F_e}{F_e^0} - 1 = P_2 (r\, c_{23}^2 - 1)$$

``screening factor"

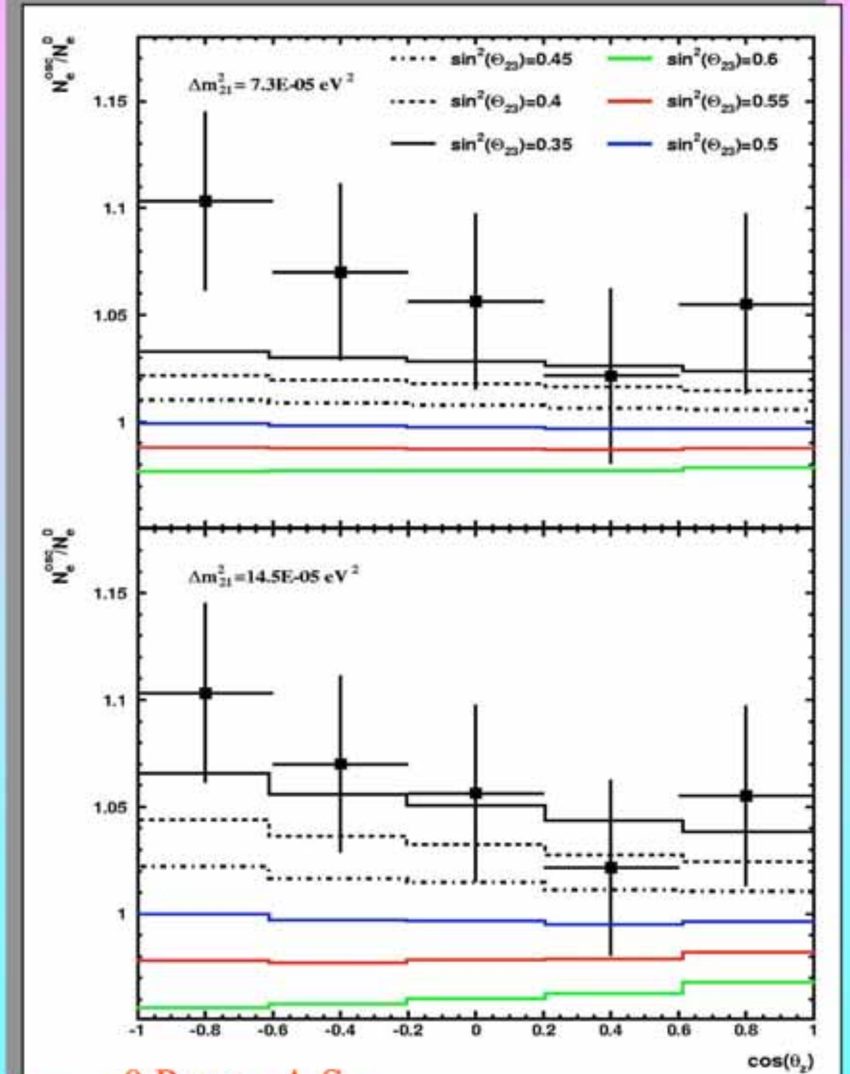
$P_2 = P(\Delta m^2_{12}, \theta_{12})$ is the 2ν transition probability

In the sub-GeV sample $r = F_\mu^0 / F_e^0 \sim 2$

➡ The excess is zero for maximal 23- mixing

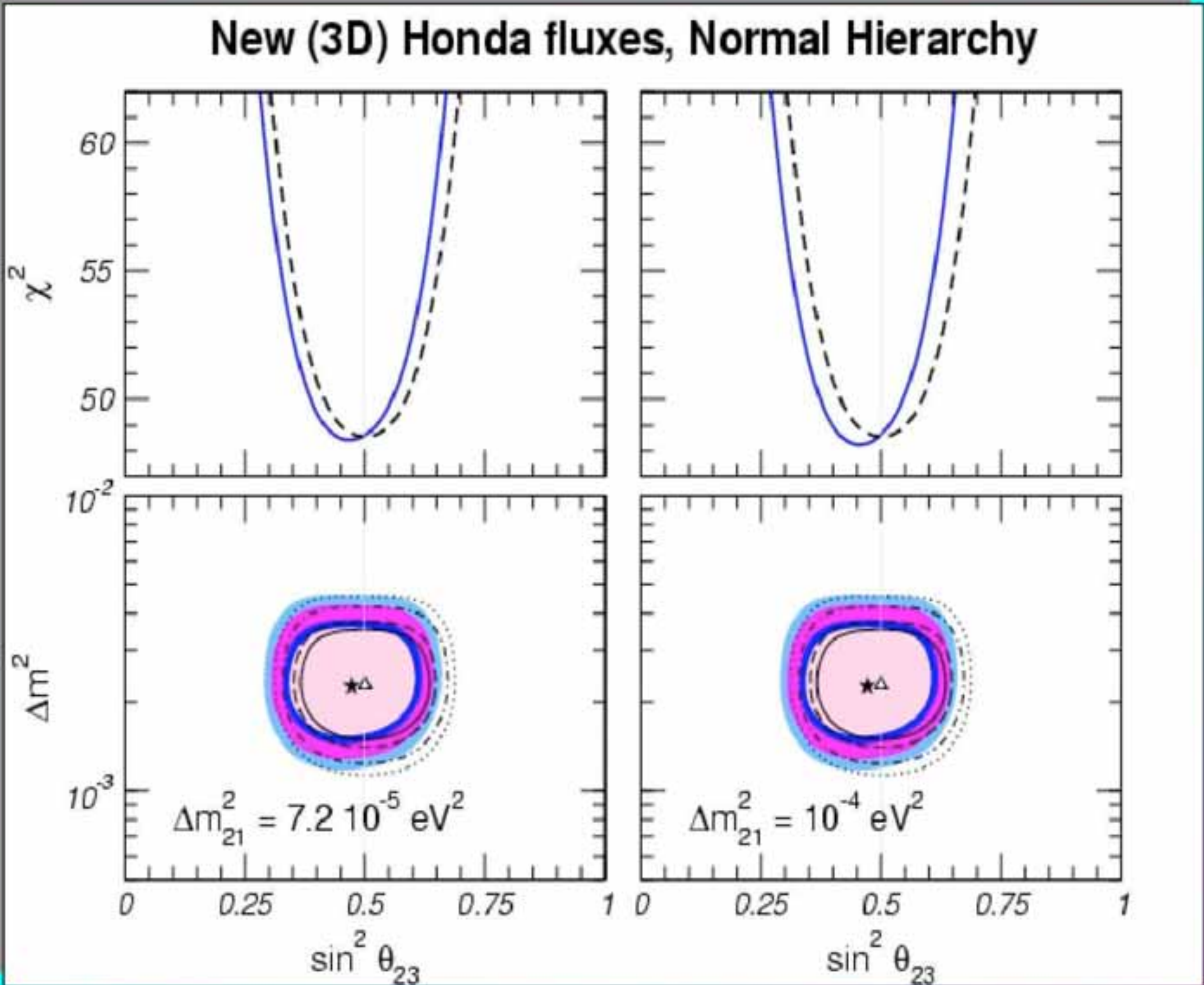
Searches of the excess can be used to restrict deviation of the 2-3 mixing from maximal

Zenith angle dependences of the e-like events



0.Peres, A.S.

Deviation of 2-3 mixing from maximal



$\Delta m^2 = 0$

$\Delta m^2 \neq 0$

$\sin^2\theta_{23} = 0.45 - 0.47$

M. C. Gonzalez-Garcia
M. Maltoni, A.S.

"No-symmetry" framework

I. Dorsner, A. S.
hep-ph/0403305

2-3 mixing differs from maximal one

No special symmetry for neutrinos or leptons

Approximate quark-lepton symmetry (analogy, correspondence)

Family structure, weak interfamily connections
no large mixing in the original mass matrices

All quark and lepton mass matrices have similar structure with ``flavor alignment"

$\theta_{ij} \sim \sqrt{m_i/m_j}$

$\theta_{atm} = 36 - 38^0$

Seesaw mechanism of neutrino mass generation

Large lepton mixing is the artifact of seesaw

Singular matrices and Q-L symmetry

Allows to explain difference in mass hierarchies and mixings of quarks and leptons by small perturbations of the universal structure

Singular mass matrices Det M = 0

strongly different mass hierarchies

Due to small perturbations of the singular structure

enhancement of lepton mixing

Strong hierarchy of masses of the RH neutrinos

$\Rightarrow$ Seesaw enhancement of lepton mixing

seesaw: $m \sim 1/M$

Quark-Lepton symmetry

- Quarks-Lepton symmetry is realized in terms of the mass matrices (matrices of the Yukawa couplings).
- For the Dirac mass matrices of all quarks and leptons:

$$\boxed{Y_U \sim Y_D \sim Y_{\nu D} \sim Y_L \sim Y_0}$$

(implies large $\tan\beta$)

Specifically: $\boxed{Y_f = Y_0 + \Delta Y_f}$ $\boxed{(Y_0)_{ij} \gg (\Delta Y_f)_{ij}}$ $f = u, d, L, D, M$

- Y_0 is ``unstable": det $(Y_0) = 0$ (as well as determinants of sub-matrices)

⇒ small perturbations produce significant change of masses and and mixings

Assume:

$$Y_0 = \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda \\ \lambda^2 & \lambda & 1 \end{pmatrix}$$

$\lambda \sim 0.2 - 0.3$

Other forms are possible

Perturbations

- $Y^f = Y_0 + \Delta Y^f$ $\quad (\Delta Y^f)_{ij} \ll (Y_0)_{ij}$ $\quad f = u, d, L, D, M$
- $(\Delta Y^f)_{ij} = (Y_0)_{ij}\, \varepsilon^f_{ij}$ $\quad \varepsilon^f_{ij} < \lambda$

Perturbation of a given element is proportional to the element itself

$$Y^f = \begin{pmatrix} (1+\varepsilon^f_{11})\lambda^4 & (1+\varepsilon^f_{12})\lambda^3 & (1+\varepsilon^f_{13})\lambda^2 \\ (1+\varepsilon^f_{21})\lambda^3 & (1+\varepsilon^f_{22})\lambda^2 & (1+\varepsilon^f_{23})\lambda \\ (1+\varepsilon^f_{31})\lambda^2 & (1+\varepsilon^f_{32})\lambda & 1 \end{pmatrix}$$

the structure of mass matrix is not changed

- Observables (masses and mixings) appear as small perturbations of the dominant structure given by Y_0.
- Theory is reduced to theory of ε^f_{ij} , though some qualitative features follow from general form of matrices

Singular matrices:

- ``Democratic" matrices:

$$Y_0 = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

E. Akhmedov, G. C. Branco,
F. R. Joaquim J. Silva-Marcos, 2000
R. Dermisek, 2003

H. Fritzsch,
M. Fukugita, T. Yanagida

- After diagonalization all these singular matrices are reduced to

$$Y_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

One can ``work" immediately in this basis.

- Key point is how perturbations are introduced

This can lead to different predictions and
different implications to theory

See-saw

Enhances (by factor ~ 2) the mixing which comes from diagonalization of the neutrino mass matrix

Leads to smallness of neutrino masses

Changes the relative sign of ``rotations'' which diagonalize mass matrices of the charge leptons and neutrinos

For the RH neutrino mass matrix we take for simplicity the same form

$M_R \sim Y_0$

Flipping the sign of rotation

quark mixing:

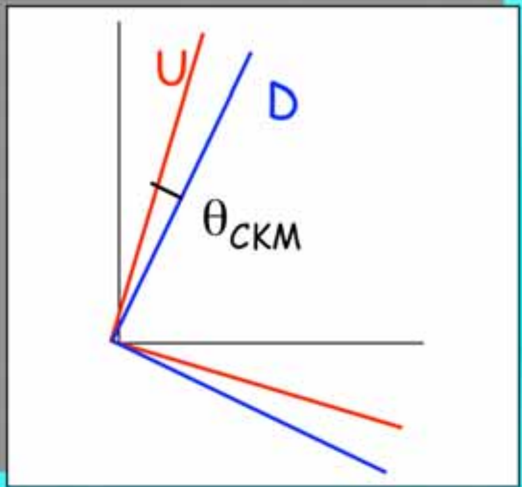
$V_{CKM} = U(up)^{+} U(down)$

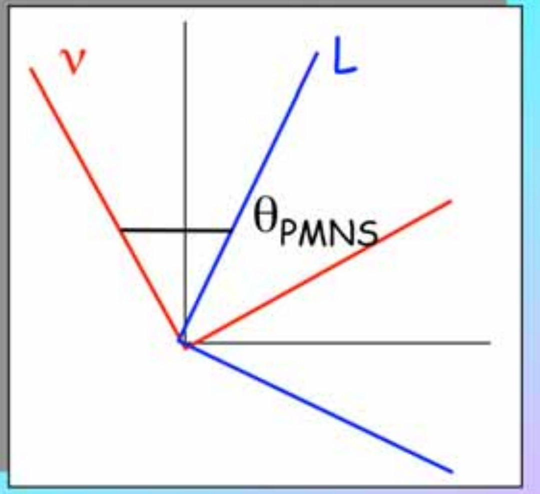
lepton mixing:

$V_{P\text{-}MNS} = U(l)^{+} U(\nu)$

For quarks the up and down rotations cancel each other leading to small mixing whereas for leptons they sum up producing large mixing

S. Barshay





It is the see-saw leads to flip of the sign of rotation which diagonalizes the neutrino mass matrix

changes the sign of the 23-elements

leads to m(22) > m(33)

Enhances 22 and 23 elements

Expansion parameter

λ is determined by the weakest mass hierarchy of leptons (muon and tau) and by inequality of masses of the s-quark and the muon (one would expect $m_\mu = m_s$ in the case of exact q-l symmetry)

$m_s/m_b = k_q \lambda^3$

$m_\mu / m_\tau = k_L \lambda^3$

$k_f \lambda \sim \varepsilon_{22} - 2\varepsilon_{23}$

These mass ratios can be reproduces if

$\lambda > 0.25$

Quark mixing and masses

Quark and charged lepton mass ratios

$m_1 / m_2 = \lambda^2 \varepsilon$

$m_2 / m_3 = \lambda^2 r(\varepsilon)$

$m_1 / m_3 = \lambda^4 \varepsilon$

ε are combinations of ε_{ij} in the mass matrices

$r(\varepsilon) \sim O(1)$ is the ratio of combinations of ε_{ij}

Quark mixing:

$V_{us} = \lambda\, r(\varepsilon)$

$V_{cb} = \lambda\, \varepsilon$

$V_{ub} = \lambda^2 \varepsilon$

Reproduces correct hierarchy of mixings

$V_{ub} / V_{cb} = \lambda$

$V_{cb} / V_{us} = \varepsilon$

Neutrino masses and lepton mixing

- $\tan 2\theta_{23} = 2\lambda \left[(1 + \varepsilon^D_{23}) + A_{seesaw} \right]$

Where the seesaw term

$$A_{seesaw} = \frac{(\varepsilon^D_{23} - \varepsilon^M_{23})(\varepsilon^D_{22} - 2\varepsilon^D_{23} - \varepsilon^D_{23}{}^2)}{\varepsilon^M_{22} - 2\varepsilon^M_{23} - 2\varepsilon^D_{23}\varepsilon^M_{23} + \varepsilon^D_{23}{}^2 + \lambda^2 \varepsilon}$$

- Seesaw enhancement: $\varepsilon^M_{22} = 2\varepsilon^M_{23} + \varepsilon^2$ ⇒ small det M_R ⇒ $M_2 / M_3 = \lambda^2 \varepsilon^2$

- $\sin\theta_{12} = r(\varepsilon)$ $\quad U_{u3} \sim \lambda^2$

ε are combinations of ε_{ij} in the mass matrices

- $m_1/m_3 = \lambda^4 \varepsilon$ $\quad m_2/m_3 = \lambda^2 \varepsilon$ $\quad m_3 \sim \sqrt{\Delta m_{atm}^2}$

- $m_{ee} \sim \sin^2\theta_{12} \sqrt{\Delta m_{sol}^2} \sim (2 - 3)\, 10^{-3}$ eV

$r(\varepsilon) \sim O(1)$ is the ratio of combinations of ε_{ij}

An example

$\lambda \sim 0.26$

- $$\varepsilon^{l}_{ij} = \begin{pmatrix} 0 & -0.171 & -0.036 \\ \dots & 0.254 & -0.268 \\ \dots & \dots & 0 \end{pmatrix} \qquad \varepsilon^{D}_{ij} = \begin{pmatrix} 0 & 0.233 & 0 \\ \dots & 0.104 & 0.042 \\ \dots & \dots & 0 \end{pmatrix}$$

  $$\varepsilon^{M}_{ij} = \begin{pmatrix} 0 & 0.0065 & 0 \\ \dots & 0.0010 & 0.0050 \\ \dots & \dots & 0 \end{pmatrix}$$

  For quarks $|\varepsilon_{ij}|$ are smaller than 15%

- $m_1 = 0.0017$ eV
- $m_{ee} = 0.001 - 0.005$ eV
- $|\sin^2\theta_{13}| = 0.005$

  Generically $|\sin\theta_{13}| \sim (1-3)\lambda^2$

- Masses of the RH neutrinos:

  $M_1 = 1.2\ 10^{10}$ GeV
  $M_2 = 5.8\ 10^{10}$ GeV
  $M_3 = 8.8\ 10^{14}$ GeV

  Strong hierarchy: seesaw enhancement of 23-mixing

Origin of mass matrices

Froggatt- Nielsen: U(1) family symmetry

$$(Y^f)_{ij} = a_{ij}\, \lambda^{\,q(i) + q(j)}$$

$$\lambda = \langle\sigma\rangle / M_F$$

$\lambda = \langle\sigma\rangle / M_F$

$q(i)$ is the U(1) charge of i-family

$a_{ij} = O(1)$,

$\langle\sigma\rangle$ is the F-N scalar field which violates U(1) symmetry

M_F is the mass scale at which F-N operators are produced:

$$a_{ij} f_i\, f_j\, H \left(\frac{\sigma}{M_F}\right)^{q(i) + q(j)}$$

For the simplest prescription $q(1) = 2$, $q(2) = 1$, $q(3) = 0$, $q(\sigma) = -1$
the required structure is reproduced

Implications

No special symmetry for neutrinos of
for lepton sector

Y_0 can be reproduced with U(1) family symmetry
and charges q, q + 1, q + 2 charges,
if unut charge is associated with
one degree of ε (a la Froggatt-Nielsen)

Violation of the symmetry appears
at the level ε^2 - ε^3 ~ (1 - 3) 10^{-2}

If the flavor symmetry is at GU scale its
violation can come e.g. from the string scale

Conclusions

One of the main results is an amazing pattern of the lepton mixing which differs strongly from the quark mixing

The key question to the underlying physics is if there is a new (different from quark) symmetry behind neutrino mass spectrum and mixing
- maximal (near) maximal 2-3 mixing
- degenerate spectrum
- probably, small 1-3 mixing

Cabibbo-solar mixing relation?

New symmetry of Nature, which is realized (manifest itself) in the properties of neutrinos or lepton sector.

?

Nothing special: weakly broken quark-lepton symmetry; family structure, small interfamily mixing. Large lepton mixing - artifact of the seesaw mechanism

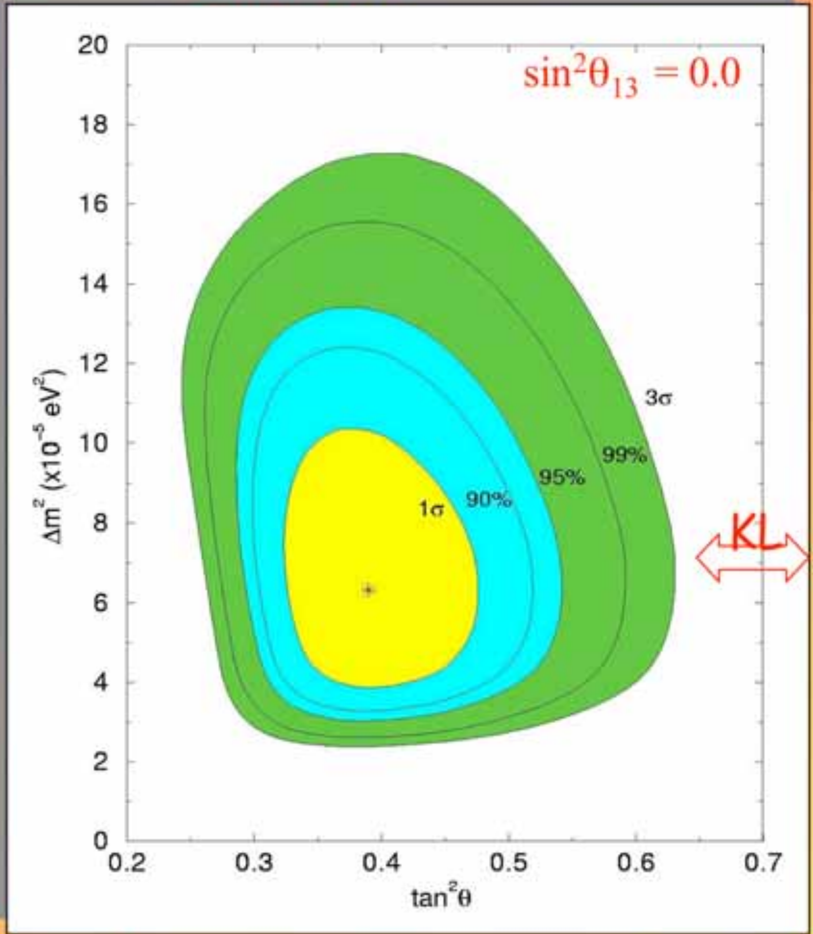
Neutrinos can shed some light on the fermion mass problem in general.
Hint: flavor alignment, $\varepsilon \sim 0.25$, ``unstable" mass matrices, U(1)

Priorities

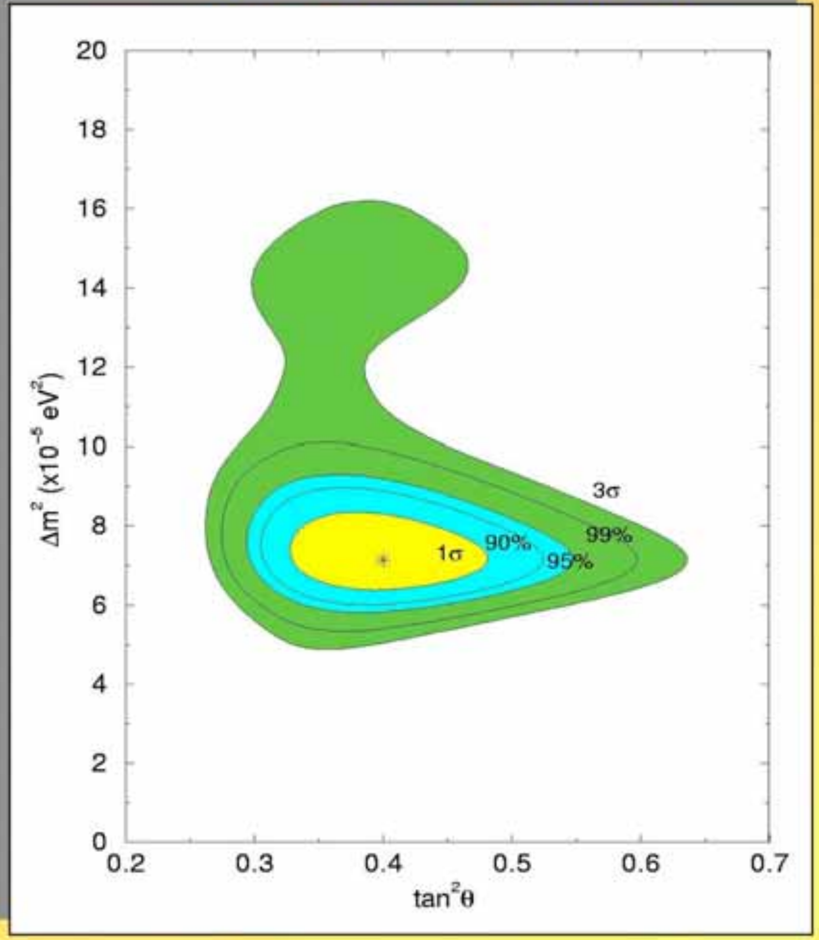
After SNO salt results

P. de Holanda, A.S.

solar data



solar data + KamLAND



$\Delta m^2 = 6.3\ 10^{-5}\ eV^2$
$\tan^2\theta = 0.39$

$\Delta m^2 = 7.1\ 10^{-5} eV^2$
$\tan^2\theta = 0.40$

Flavors, Masses, Mixing

Flavor states:

ν_e ν_μ ν_τ

Eigenstates of the CC weak interactions

ν_s Sterile neutrinos ?
no weak interactions

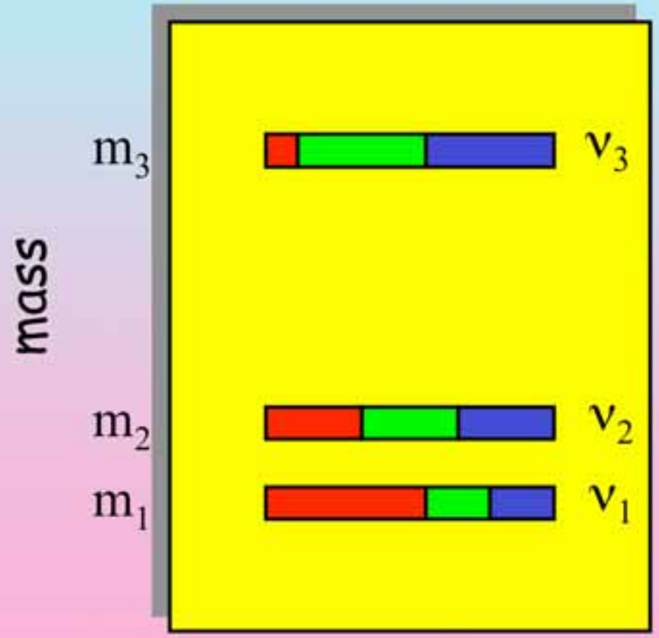
Mass eigenstates:

ν_1 ν_2 ν_3

m_1 m_2 m_3

Mixing:

Flavor states $\neq$ Mass eigenstate



Neutrino mass and flavor spectrum

A Yu Smirnov

Mixing and Flavor states

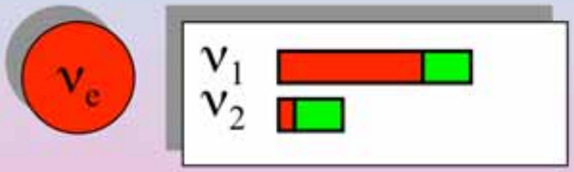
$\nu_2 = \sin\theta\, \nu_e + \cos\theta\, \nu_\mu$

$\nu_1 = \cos\theta\, \nu_e - \sin\theta\, \nu_\mu$

vacuum mixing angle

$\boxed{\nu_e = \cos\theta\, \nu_1 + \sin\theta\, \nu_2}$

coherent mixture of mass eigenstates



wave packets

$$\Delta\phi = \frac{\Delta m^2}{2E}\, l$$

$\boxed{\Delta m^2 = m_2^2 - m_1^2}$

Interference of the parts of wave packets with the same flavor depends on the phase difference $\Delta\phi$ between ν_1 and ν_2