Neutrinos:
"... annus mirabilis"

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- 2002- 2003 achievements and essentials
- Pattern of mixings: New theoretical puzzle?
- Symmetry or no symmetry?
- Degenerate or hierarchical?
- Priorities

"... annus mirabilis"

- December 4, 2002 K2K: ``Indication of neutrino oscillations in a 250 km ..."
- December 6, 2002 ``First Results from KamLAND: Evidence for Reactor ..."
- December 10, 2002 Ceremony of the Nobel Prize award: ``for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

  Raymond Davis Jr. Masatoshi Koshiba

- February 11, 2003 WMAP: First year Wilkinson microwave anisotropy probe observations: determination of cosmological parameters
- September 3, 2003 ``Precise measurement of the solar neutrino Day/Night and seasonal variations in Super-Kamiokande-1"
- September 7, 2003 SNO salt phase results: ``Measurements of the Total..."
- October 27, 2003 Sloan Digital Sky Survey: ``Cosmological parameters..."
- December ??, 2003 ...?

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Confirmation of the LMA MSW solution of the solar neutrino problem,

Determination of Δm_{12}^2, θ_{12}

Key step in the reconstruction of the neutrino mass spectrum

Possibility to measure the CP violation in lepton sector

Conversion of neutrinos from SN 1987A

KamLAND

SNO WMAP

SDSS

Birth of neutrino geophysics

Strong bound on the leptonic asymmetry of the Universe

A possibility of cancellation in the neutrinoless $\beta\beta$-decay

LMA oscillations of the atmospheric electron neutrinos

New cosmological bounds on neutrino mass

New puzzle for theory

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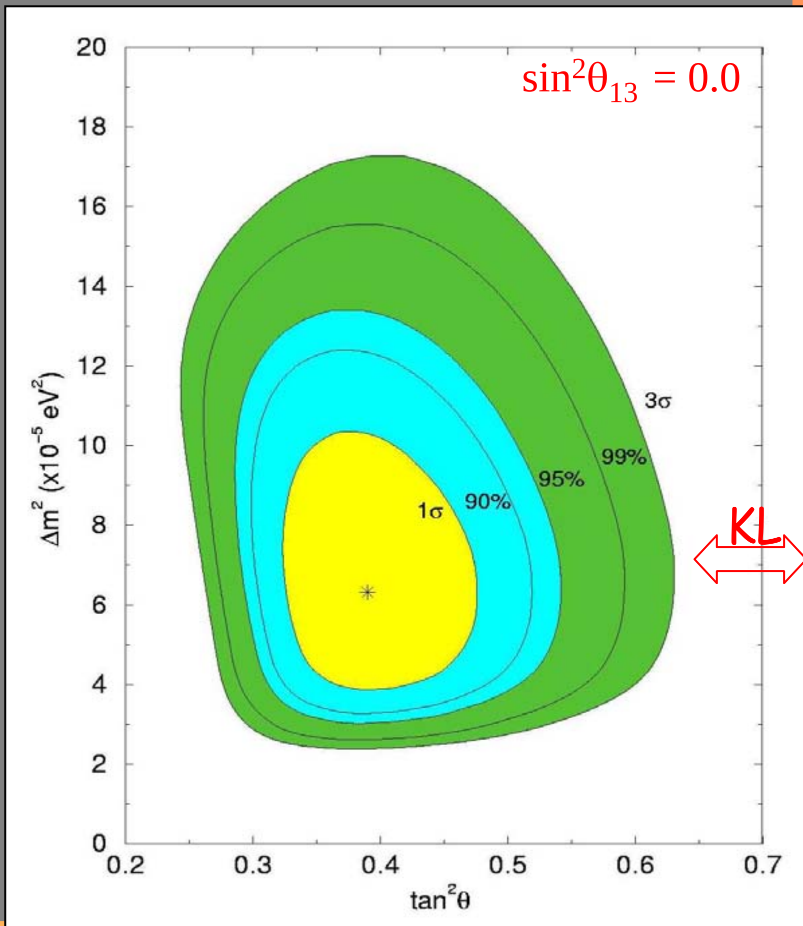
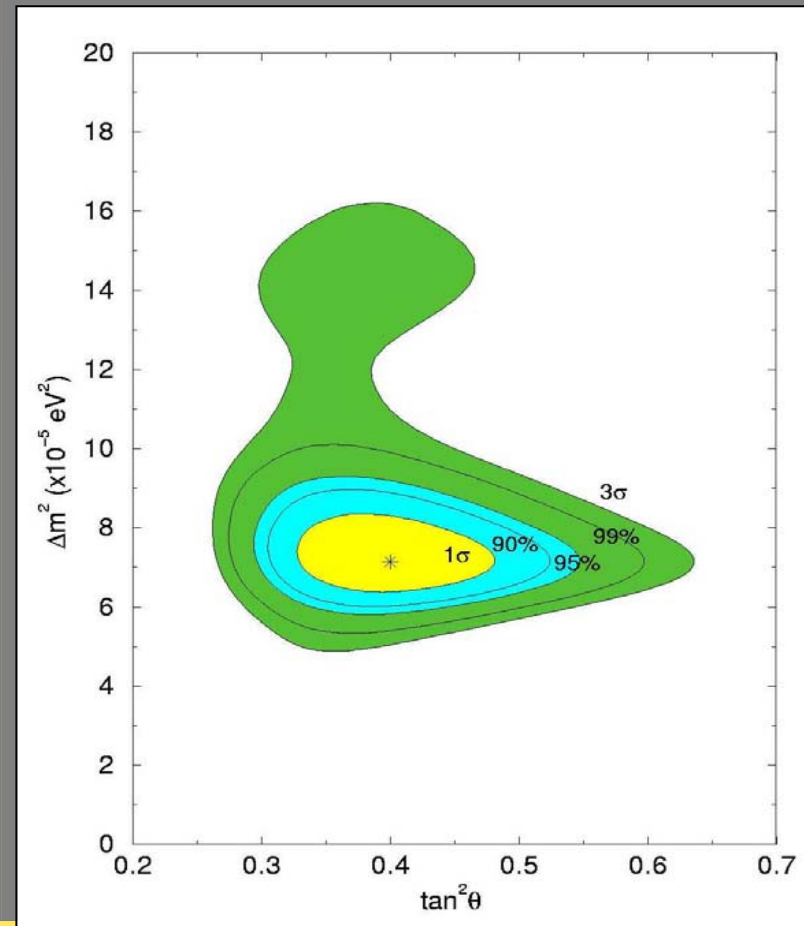
After SNO salt results

P. de Holanda, A.S.

solar data



solar data + KamLAND



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

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

Remarks

- h-LMA region ($\Delta m^2 > 10^{-4}$ eV^2) is strongly disfavored (accepted at 3σ)

- Stronger upper bounds on 1-2 mixing:

$$\tan^2\theta < \begin{cases} 0.48 & 1\sigma \\ 0.54 & 2\sigma \\ 0.63 & 3\sigma \end{cases}$$

Significant deviation from maximal mixing:

$$1/2 - \sin^2\theta \sim \sin^2\theta$$

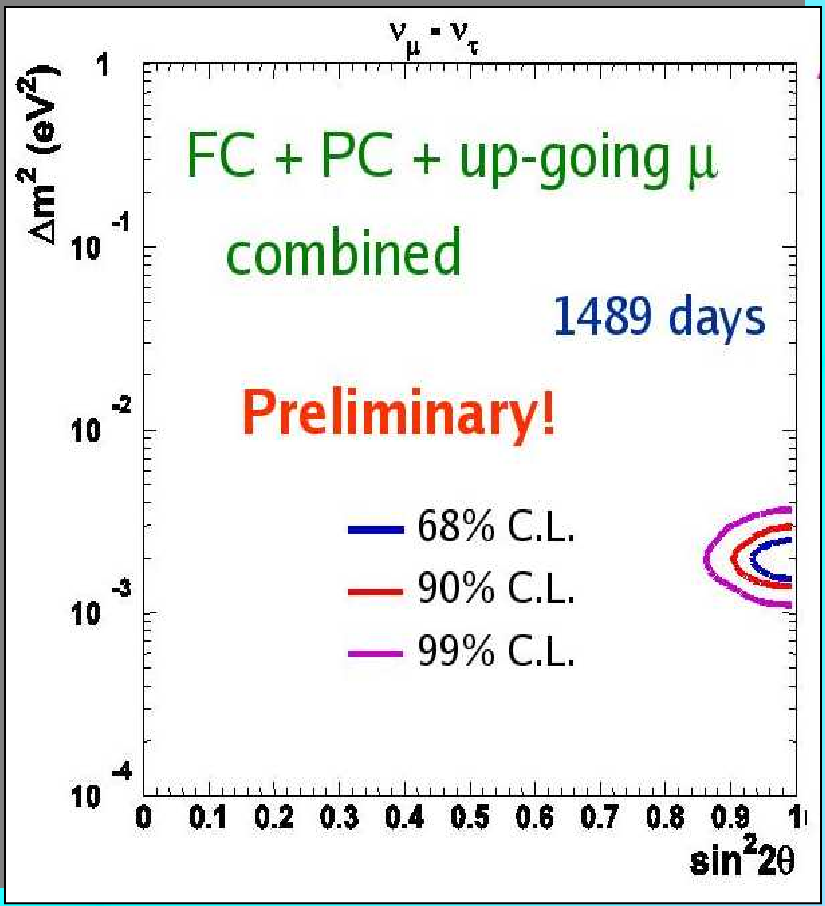
Physical picture of the effect is determined

Next KamLAND data release: stability of results, still some shift in Δm^2 is not excluded...

- Low Homestake rate?
- Absence of the upturn of the spectrum?

Atmospheric Neutrinos

SuperKamiokande:



$\Delta m_{32}^2 = (1.3 - 3.0)\ 10^{-3}\ \mathrm{eV}^2$
$\sin^2 2\theta_{23} > 0.9$

(90 % C.L.)

Best fit point:

$\Delta m_{32}^2 = 2.0\ \ 10^{-3}\ \mathrm{eV}^2$
$\sin^2 2\theta_{23} = 1.0$

Confirmed by
MACRO, SOUDAN, K2K

Combined analysis of CHOOZ, atmospheric (SK) and solar data:

$\sin^2 \theta_{13} < 0.067\ \ (3\sigma)$

G.L. Fogli et al, hep-ph/p0308055

LMA oscillations of atmospheric neutrinos

Excess of the e-like events in sub-GeV

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

``screening factor"

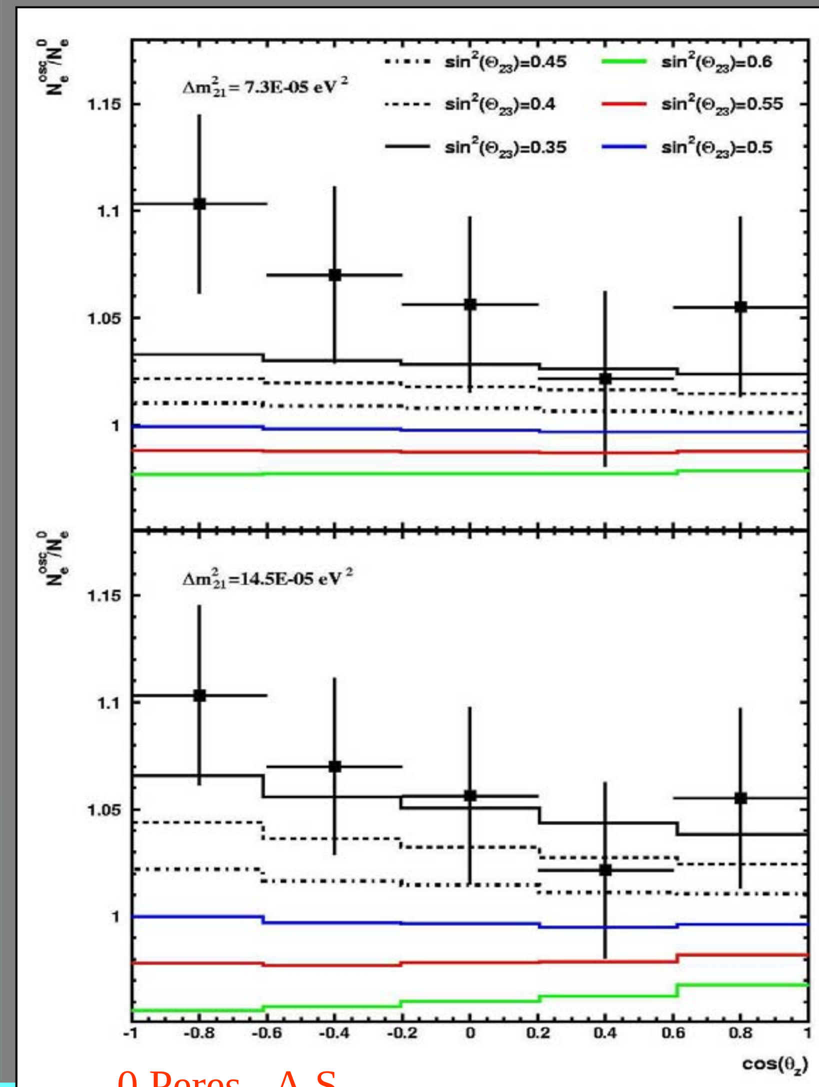
$P_2 = P(\Delta m^2_{12}, \theta_{12})$ is the 2ν transition probability

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

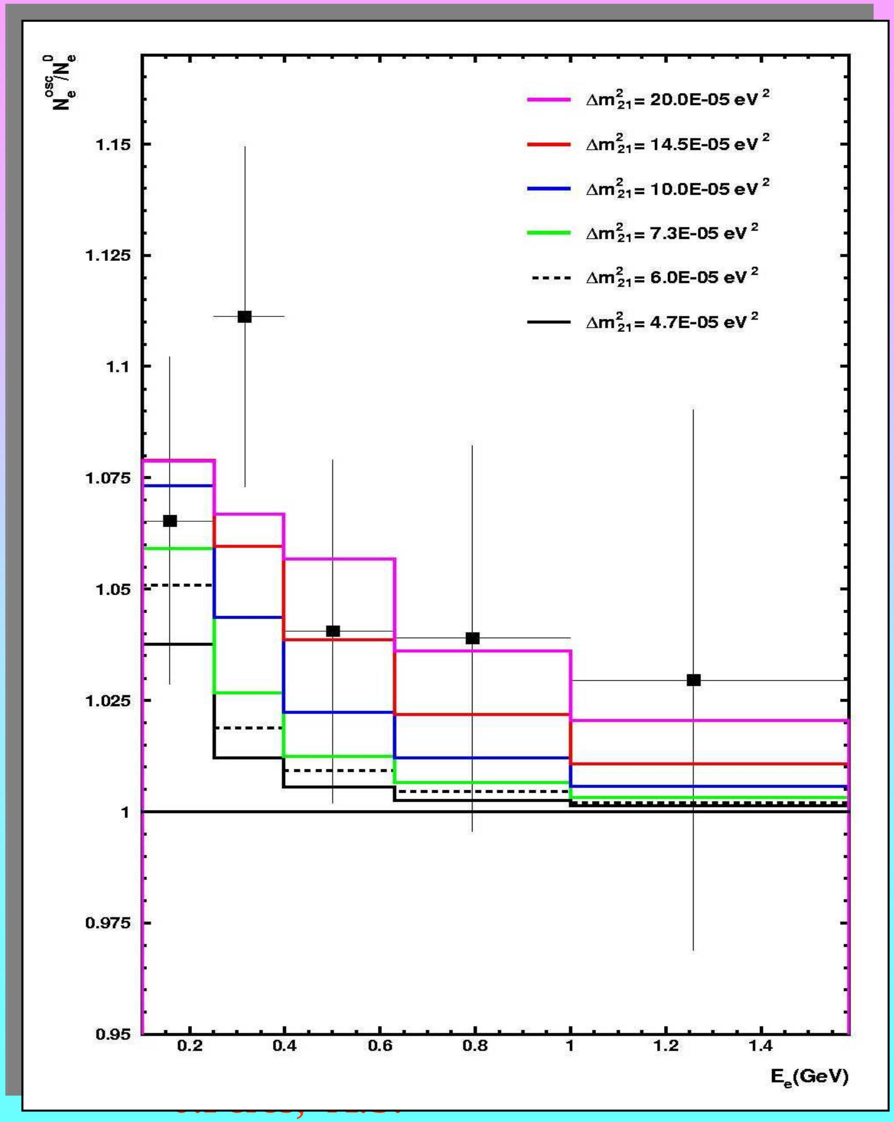


0.Peres, A.S.

LMA oscillations of atmospheric neutrinos

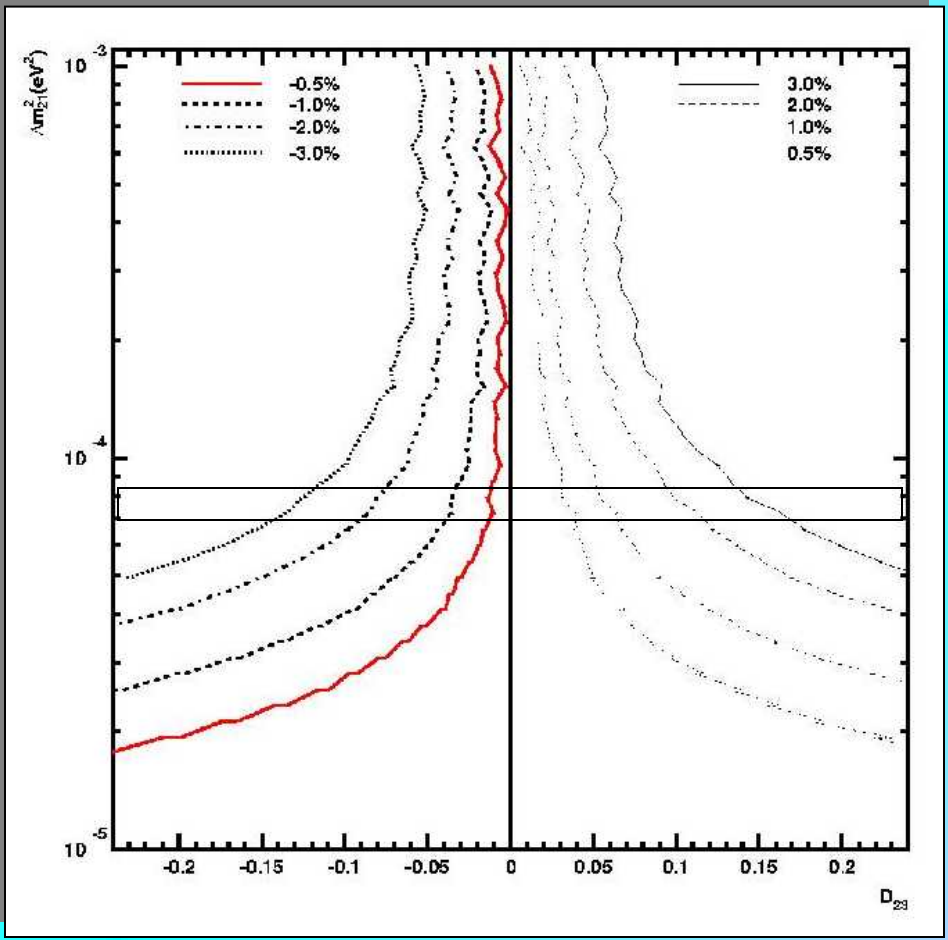
Excess of the e-like events for different energy intervals

Energy dependences of the e-like events



Measuring 2-3 mixing

O. Peres & A.S.



$D_{23} = 0.5 - \sin^2\theta_{23}$

Contours of constant excess of the e-like events in %

KamLAND: 10% accuracy in measurements of Δm^2

Ambiguity related to $\sin\theta_{13}$

$\sin^2 2\theta = 0.91 \Rightarrow \sin^2\theta = 0.35$

important theoretical implications

Still significant deviation of the 2-3 mixing from maximal is possible

Conversion of neutrinos from SN1987A

- After KamLAND: one must take into account conversion effects of supernova neutrinos

- $$F(\bar{\nu}_e) = F^0(\bar{\nu}_e) + p\,\Delta F^0$$

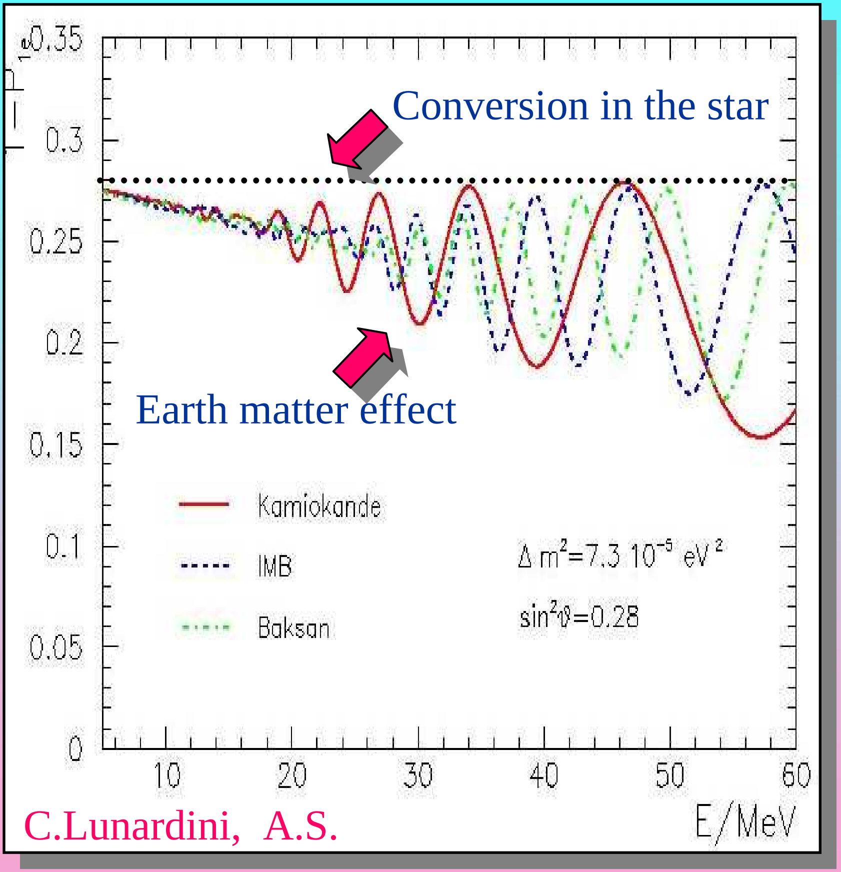
  p is the permutation factor

  $$\Delta F^0 = F^0(\bar{\nu}_\mu) - F^0(\bar{\nu}_e)$$

- p depends on distance traveled by neutrinos inside the earth to a given detector:

$$d = \begin{cases} 4363\ \text{km} & \text{Kamioka} \\ 8535\ \text{km} & \text{IMB} \\ 10449\ \text{km} & \text{Baksan} \end{cases}$$

p



C.Lunardini, A.S.

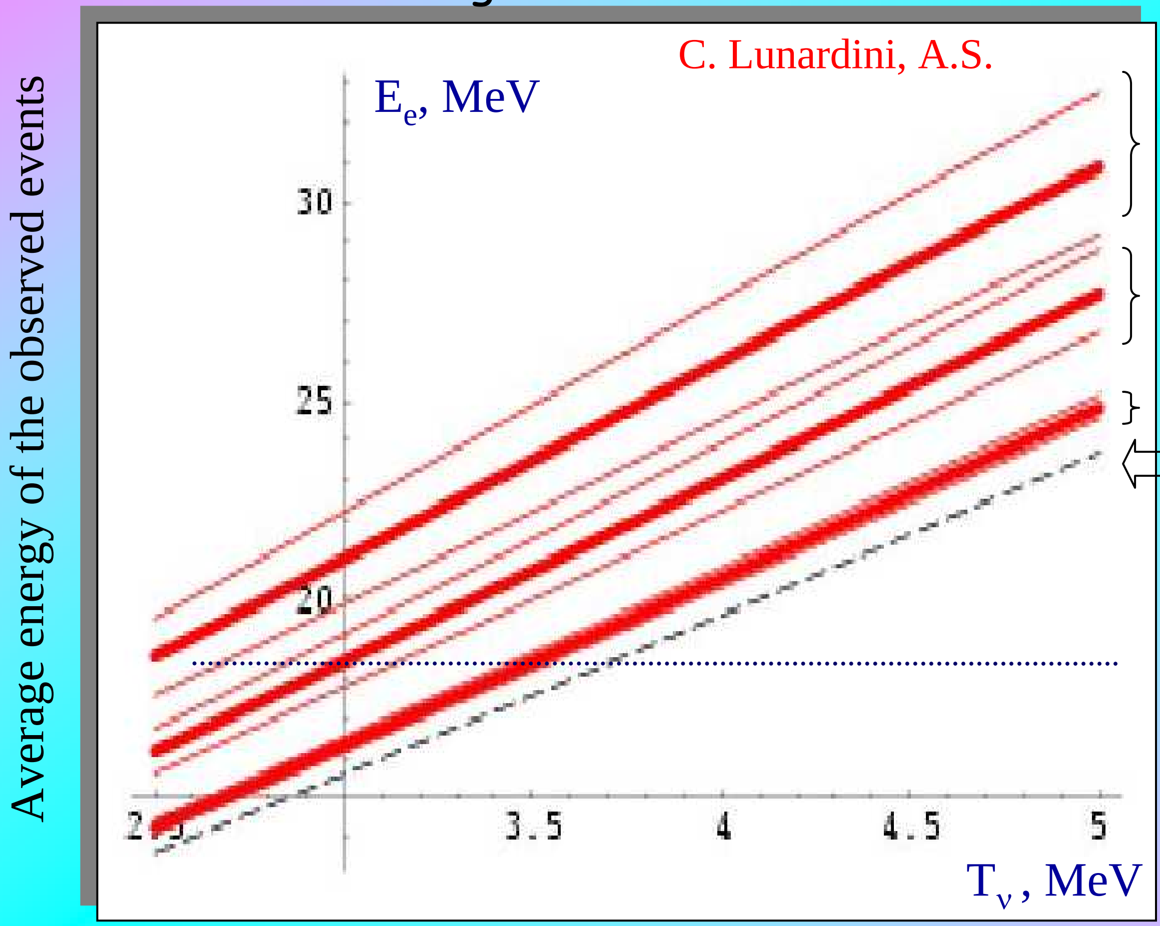
- The earth matter effect can partially explain the difference of Kamiokande and IMB: spectra of events

- Normal hierarchy is preferable

  H. Minakata, H. Nunokawa,
  J Bahcall, D Spergel, A.S.

Neutrinos from SN1987A

Possible effect of the SN neutrino conversion on the Kamiokande signal



(Average energy of the neutrino spectrum)/3.15

$\frac{E(\nu_x)}{E(\nu_e)}$

2.0

1.6

1.2

no osc.

$\frac{L(\nu_x)}{L(\nu_e)}$

thick lines:
1.0

thin lines:
1.50 (upper)
0.67 (lower)

Effect of conversion on the extracted temperature:

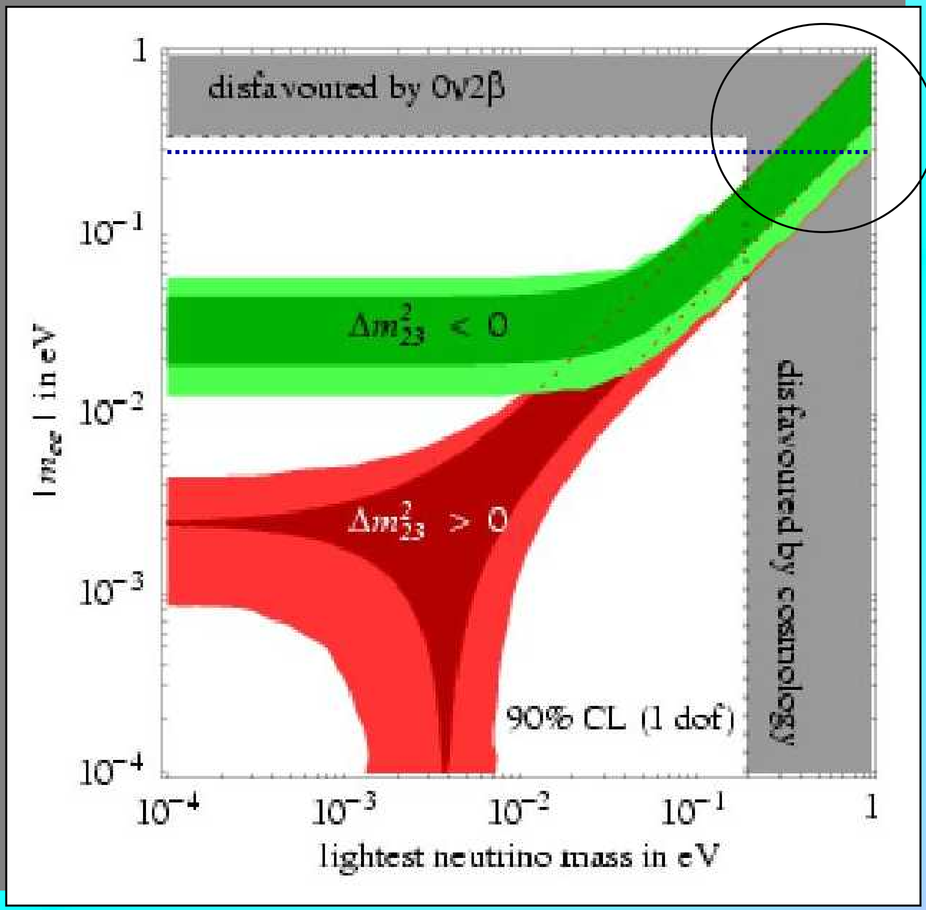
T_ν = 3.7 –> 2.5 MeV

up to 30 - 40% decrease

Absolute scale of mass

F. Feruglio, A. Strumia, F. Vissani

Neutrinoless double beta decay



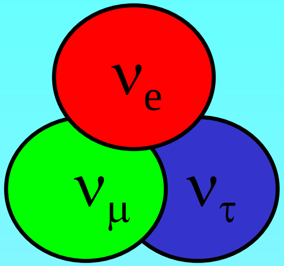
Kinematic searches, cosmology

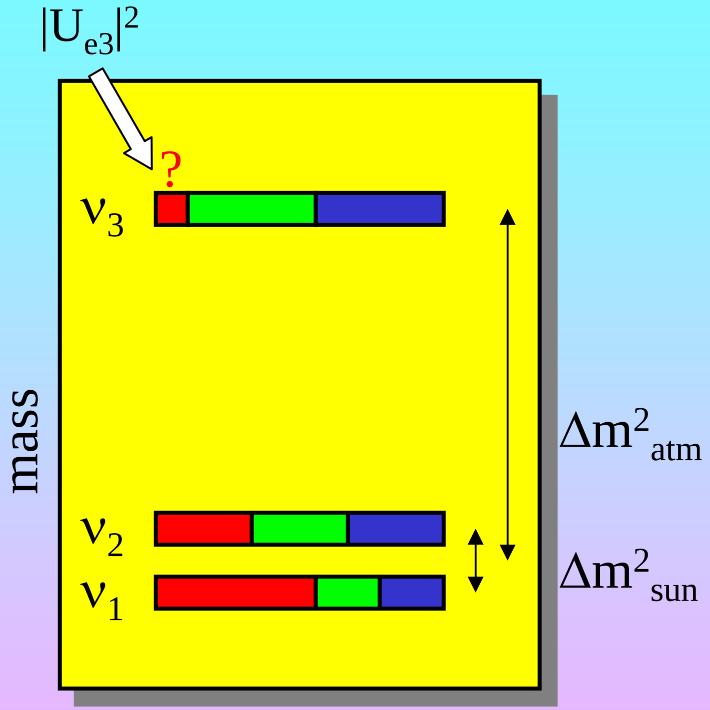
Present sensitivity limit

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

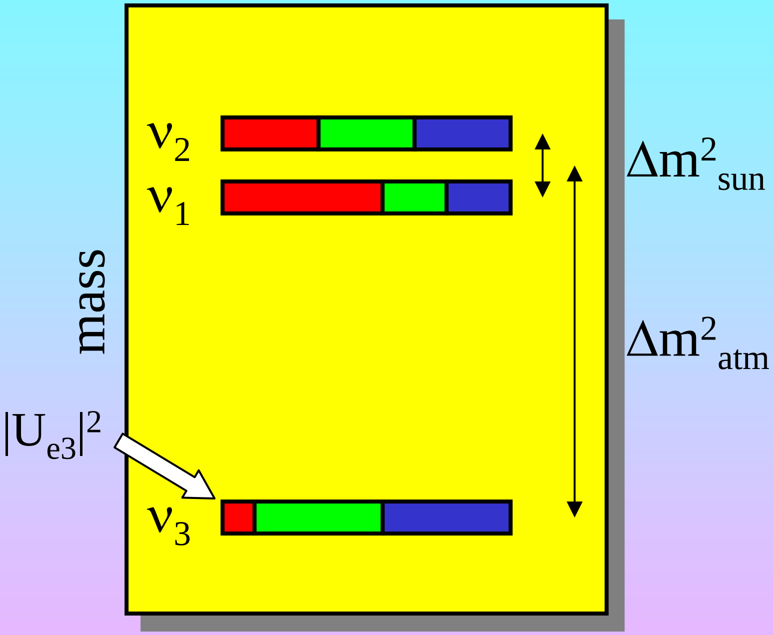
Both cosmology and double beta decay have similar sensitivities

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} = ?

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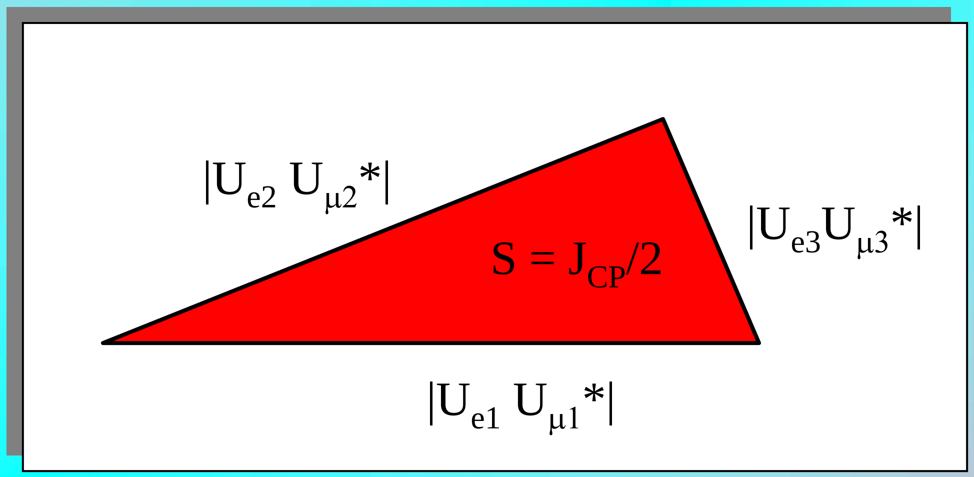
Leptonic Unitarity Triangle

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.79 - 0.86 & 0.50 - 0.61 & 0.0 - 0.16 \\ 0.24 - 0.52 & 0.44 - 0.69 & 0.63 - 0.79 \\ 0.26 - 0.52 & 0.47 - 0.71 & 0.60 - 0.77 \end{pmatrix}$$

Global fit of the oscillation data 1σ

M.C. Gonzalez-Garcia , C. Pena-Garay



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

Can we reconstruct the triangle?
Can we use it to determine the CP-violating phase? Y. Farsan, A.S.

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

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Main features

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

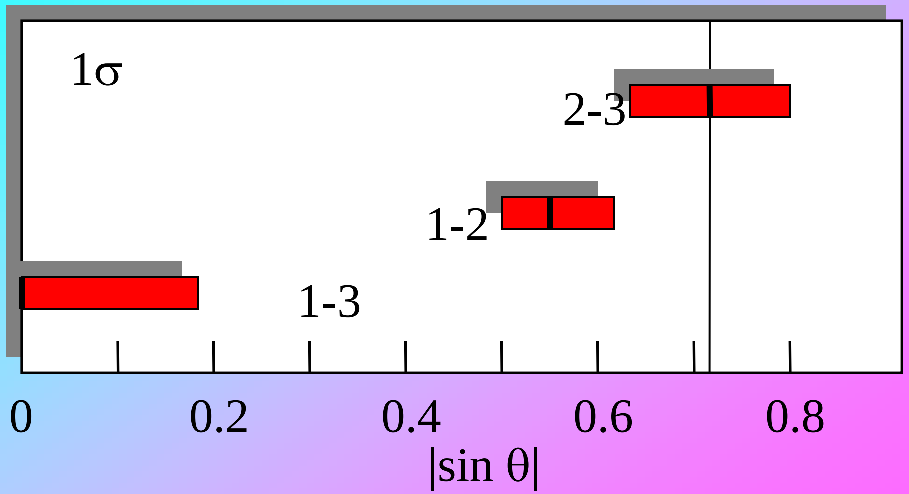
- Hierarchy of mass squared differences: $\boxed{|\Delta m_{12}^2 / \Delta m_{23}^2| = 0.01 - 0.15}$

- 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?



Mass Matrix

Another perspective

Flavor basis
(charged lepton
mass matrix
is diagonal)

Majorana
particles

$$m = U^* \, m^{diag} \, U^+$$

$$m^{diag} = \mathrm{diag}\,(m_1 e^{-2i\rho},\ m_2,\ m_3 e^{-2i\sigma})$$

$$U = U(\theta_{ij}, \delta)$$

$$m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}$$

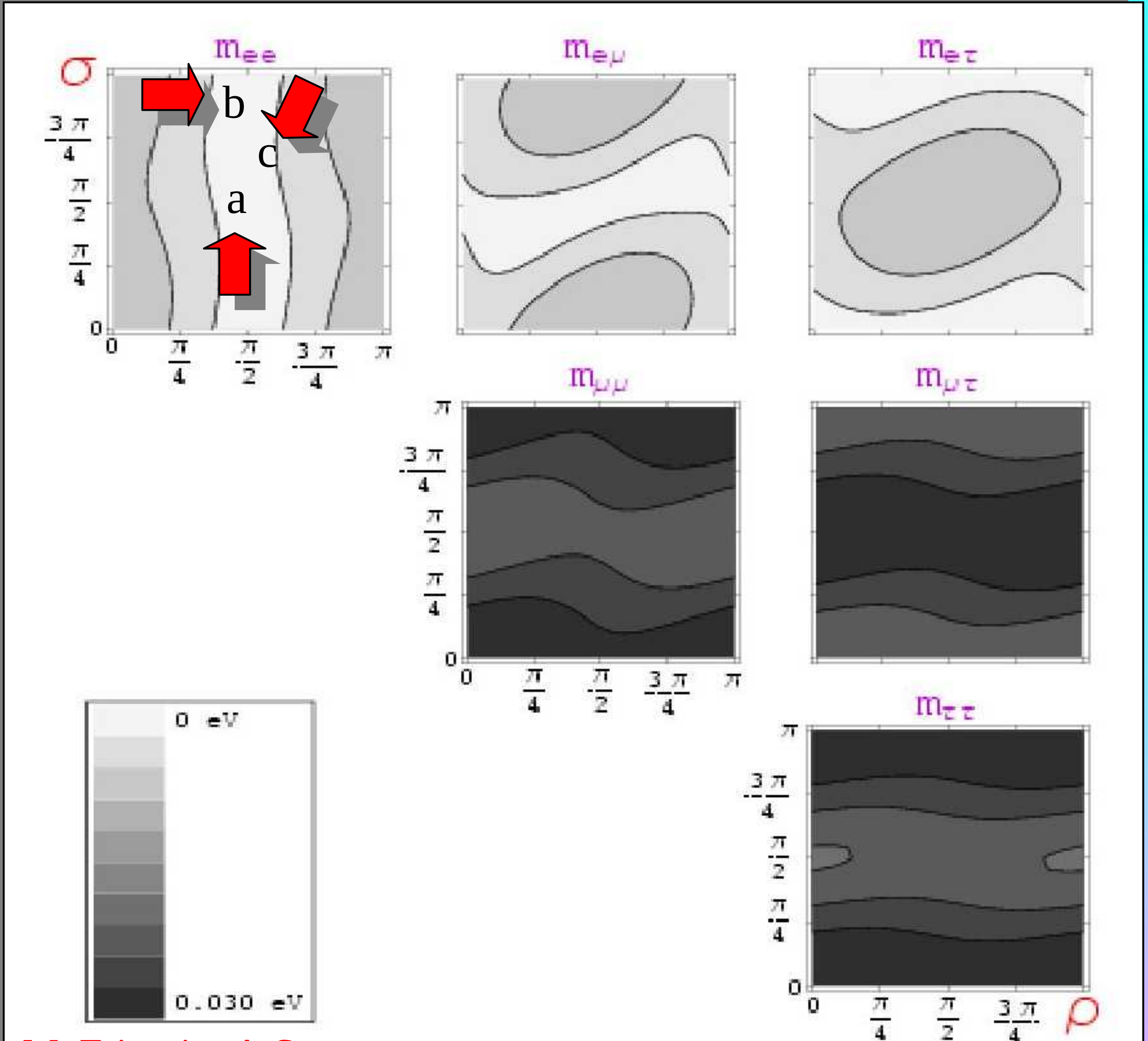
$$m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$$

ρ and σ are the Majorana phases

Advantages:
- unifies information contained in masses and mixing
- elements are physical parameters
- small renormalization group effects in SM and MSSM
  structure does not change at GU scale

Disadvantage: the flavor basis may not coincide with the symmetry basis

Normal hierarchy



M. Frigerio, A.S.

$m_3/m_2 = 5$

$m_1 = 0.006$ eV

$\sin^2 2\theta_{23} = 1$

$\sin\theta_{13} = 0.1 \quad \delta = 0$

a). $\begin{pmatrix} 0 & 0 & \lambda \\ 0 & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$

b). $\begin{pmatrix} 0 & \lambda & 0 \\ \lambda & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$

c). $\begin{pmatrix} \lambda^2 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$

$\lambda \sim 0.2$

$\begin{pmatrix} q^4 & q^3 & q^2 \\ q^3 & q^2 & q \\ q^2 & q & 1 \end{pmatrix}$

$q \sim 0.7$

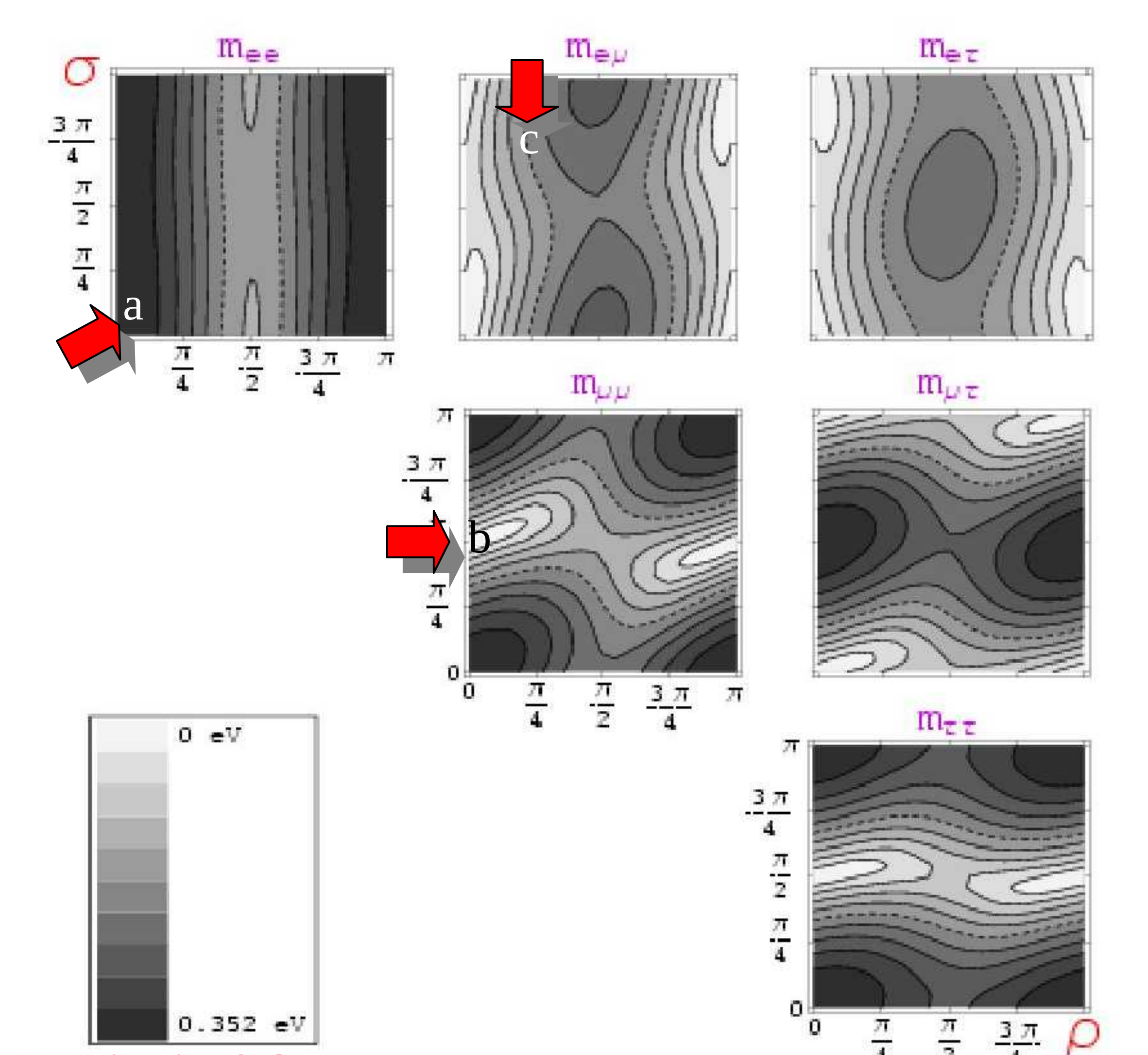
Quasi-degeneracy

$m_3 / m_2 = 1.01$

$m_1 = 0.35$ eV

$\sin^2 2\theta_{23} = 1$

$\sin\theta_{13} = 0.1 \quad \delta = 0$



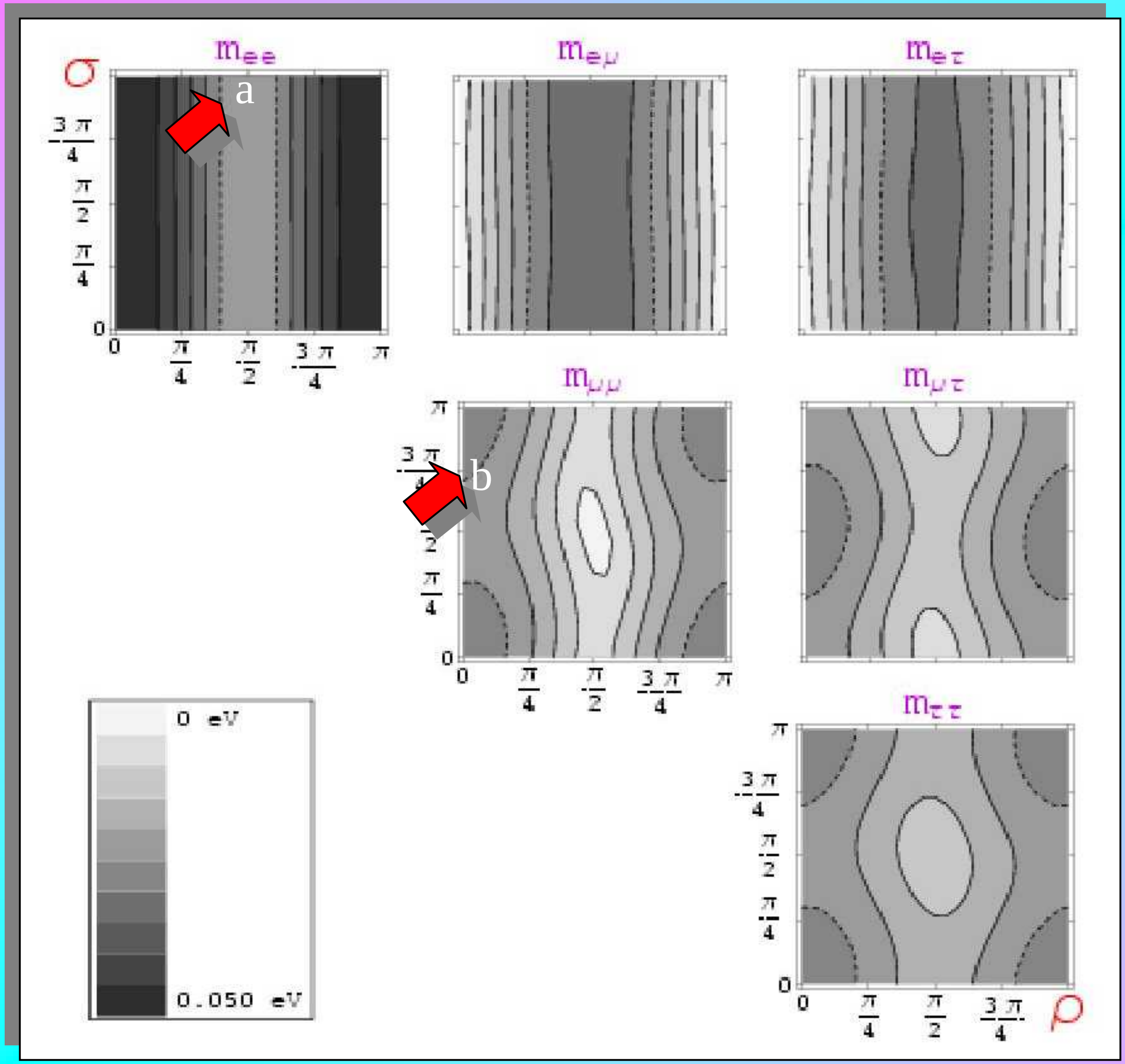
M. Frigerio, A.S

a). $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$

b). $\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$

c). $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$

Inverted hierarchy



$m_3 / m_2 = 0.1$

$m_3 = 0.005$ eV

$\sin^2 2\theta_{23} = 1$

$\sin\theta_{13} = 0.1 \quad \delta = 0$

a). $\begin{pmatrix} 0.7 & 1 & 1 \\ 1 & 0.1 & 0.1 \\ 1 & 0.1 & 0.1 \end{pmatrix}$

b). $\begin{pmatrix} 1 & < 0.1 & < 0.1 \\ < 0.1 & 0.5 & 0.5 \\ < 0.1 & 0.5 & 0.5 \end{pmatrix}$

Observations

Variety of different structures is still possible, depending strongly on unknown m_1, type of mass hierarchy/ordering, Majorana phases ρ and σ.

Generically the hierarchy of elements is not strong: within 1 order of magnitude. Although, matrices with one or two zeros are possible.

Typically, the hierarchical structures appear for ρ and σ near 0, $\pi/2$, π

Structures (in the flavor basis):
- with dominant blocks
- democratic structures,
- with flavor alignment,
- non-hierarchical structures with all elements of the same order
- with flavor disordering (anarchy)

The structures can be parameterized in terms of power of small parameter λ = 0.2 - 0.3 consistent with Cabibbo mixing

Achieved results

Clear program of further phenomenological and experimental studies

- Absolute mass scale, m_1
- 1 - 3 mixing
- Type of mass hierarchy ordering
- Deviation of 2-3 mixing from maximal
- Majorana phases
- MNSP CP-violating phase
- Searches for new neutrino states

New theoretical puzzle which may lead to fundamental discoveries?

- Pattern of the lepton mixing
- Mass spectrum?

What is behind the observed structure of the neutrino masses and mixings?

Symmetry ?

New theoretical problem?

The hope was that neutrinos will reveal something simple which will shed a light on physics of high energy scales and fermion masses in general

Plausible scenario was

See-saw mechanism

Quark-lepton symmetry

m_D(neutrino) ~ m(quark)

Simple structure of M_R

- mass matrix of RH neutrinos
  $M_R \sim I$ or $M_R \sim$ m(quarks)

⇒

- Hierarchical mass spectrum
- Small lepton mixing

If this would be confirmed ...

Instead

Amazing pattern of the lepton mixing is found:

- Maximal or near maximal 2-3 mixing
- Large 1- 2 mixing with significant deviation from maximal maximal mixing; the deviation is not a small parameter

- Type of spectrum is not yet clear; hierarchy, if exists, is weaker than that for quarks and charge leptons

Quark-lepton symmetry?

Still can be realized at some level?

See-saw mechanism?

No clear indication from pattern of mixing

Simple structure of the mass matrix of RH neutrinos?

Two extreme spectra

Quasi-degeneracy

- Symmetry SO(3), A_4 ...

- Strongest deviation from the quark masses/mixing pattern

  Inclusion of charged leptons, quarks ?

- Δm_{12}^2 and Δm_{23}^2 have no substantial imprint in the mass matrix: appear as small perturbations of the structure determined by the mixing and the Majorana phases

Hierarchy

- No particular symmetry

- Mixings are determined by the condition of naturality

$$\boxed{\tan\theta_{ij} \sim \sqrt{\frac{m_i}{m_j}}}$$

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

2-3 mixing:

$$\theta_{23} \sim \sqrt{\frac{m_2}{m_3}} + \sqrt{\frac{m_\mu}{m_\tau}} \sim 38^o$$

Deviation from maximal mixing

- Parameters are well imprinted into the structure of mass matrix
  Majorana phases are unimportant

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

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

3). $\begin{pmatrix} \varepsilon & 1 \\ 1 & -\varepsilon \end{pmatrix}$ ⇒ $D_{23} = \varepsilon/2$, $\delta_{23} = 0$ 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

⇒ Smaller δ_{21} is associated to larger D_{21}

No simple structures?

Neutrino mass matrix can get relevant contributions from new physics at all possible scales, M_a, from the EW to Planck scale.

S. Weinberg

$$\Sigma_a \frac{\lambda_{a,ij}}{M_a} (l_i H)^T (l_j H)$$

$$m_{ij} = \Sigma_a \frac{\lambda_{a,ij} \langle H \rangle^2}{M_a}$$

l_i - leptons,
H - Higgs, $\lambda_{a,ij} < 1$,
$i, j = e, \mu, \tau$

For $M = M_{Pl}$ and $\lambda_{ij} \sim 1$: $m_{ij} \sim 10^{-5}$ eV

relevant for sub-leading structures of the mass matrix and phenomenology

Barbieri Ellis, Akhmedov
Berezhiani Senjanovic

Existence of new (sterile) neutrinos

- Heavy sterile neutrinos, M > 1 kev, can contribute to the sum modifying substantially mixing of the active neutrinos, and mass splitting
- Light sterile neutrinos can modify low energy phenomenology and therefore determination of the neutrino parameters

To understand neutrino masses /mixing we need to restrict/control possible effects of sterile neutrinos

Conclusions

Enormous progress in determination of the neutrino masses and mixings, reconstruction of the mass spectrum, studies of properties of mass matrix.

Achieved results allow to formulated clear program of further experimental and phenomenological studies.

Amazing pattern of the lepton mixing probably composes new theoretical puzzle which may lead to new fundamental results

New symmetries ?

From this theoretical perspective
the most important measurements are
- determination of the absolute mass scale, test of degenerate scenario
- establishing Majorana nature of neutrinos
- searches for deviation of 2-3 mixing from the maximal one
- 1-3 mixing