Neutrino Physics: Open Theoretical Questions

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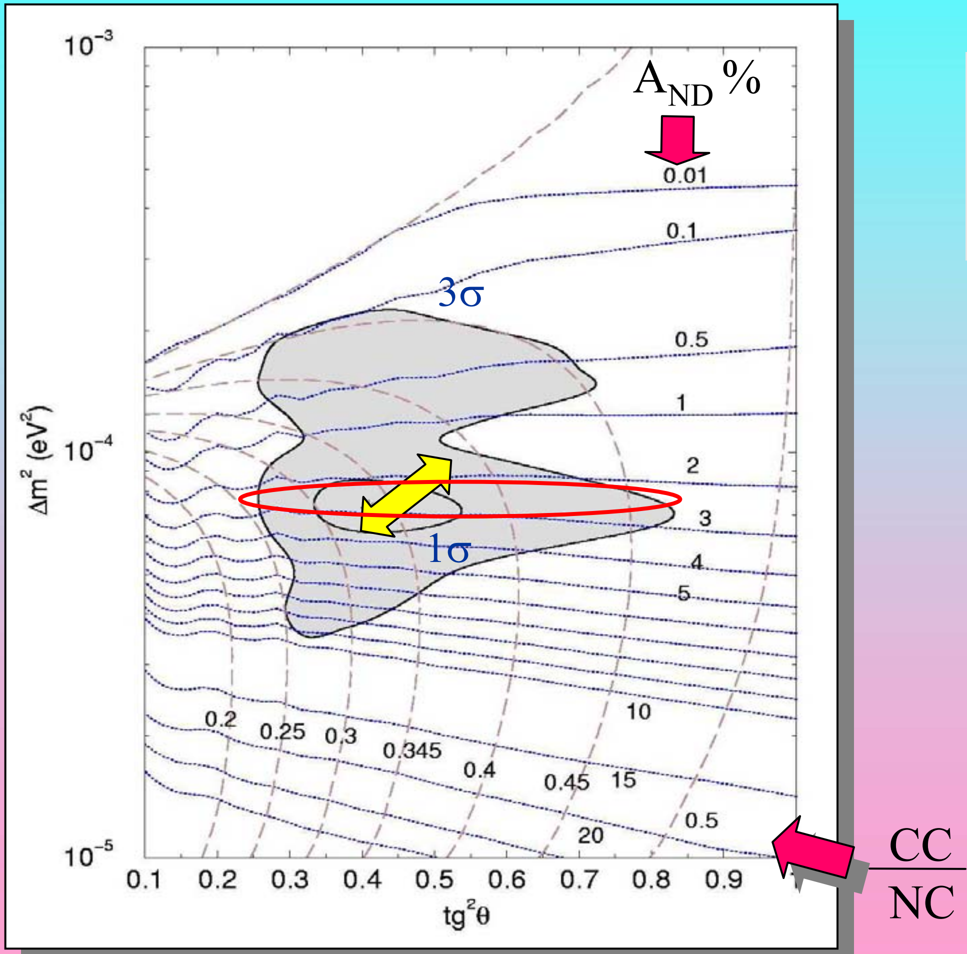
- What we have learned?
- Open theoretical questions
- Bottom-up
- How we might go...

1. What we have learned?

Neutrino masses and lepton mixing:
Summary

Solar Neutrinos

P.de Holanda, A.S.



Lines of constant CC/NC ratio and Day-Night asymmetry at SNO

Best fit point:

$\Delta m_{12}^2 = 7 \; 10^{-5}$ eV^2
$\tan^2\theta_{12} = 0.4$
$\sin^2\theta_{13} \sim 0$

LM MSW

Any problem?

- ~ 2 higher Ar-production rate than Homestake result
- Absence of the upturn of the spectrum

Survival probability

Light sterile neutrino

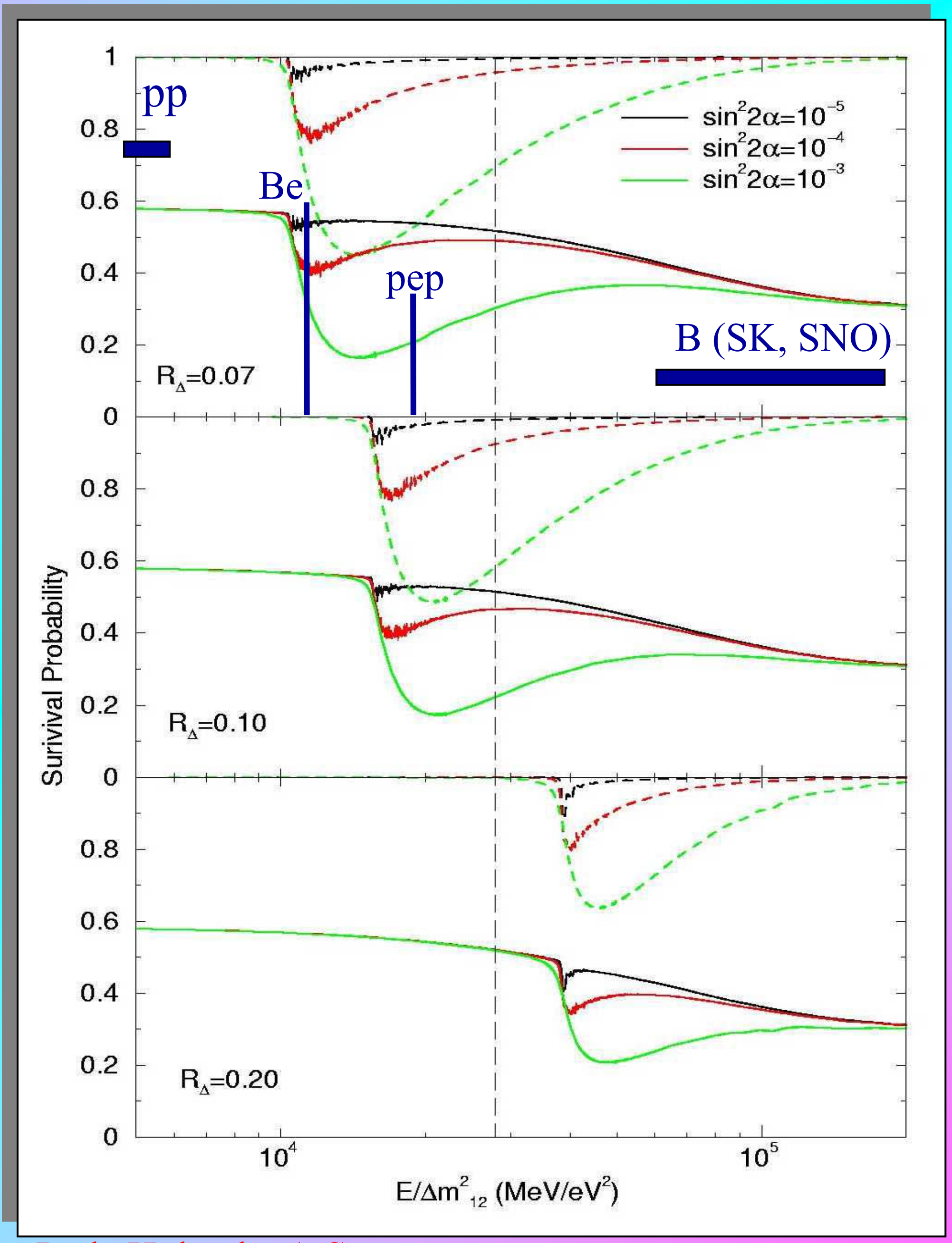
$R_\Delta = \Delta m_{01}^2 / \Delta m_{21}^2$

α - mixing angle of sterile neutrino

Dip in the survival probability:

- reduces the Ar-production rate
- suppresses the upturn of spectrum

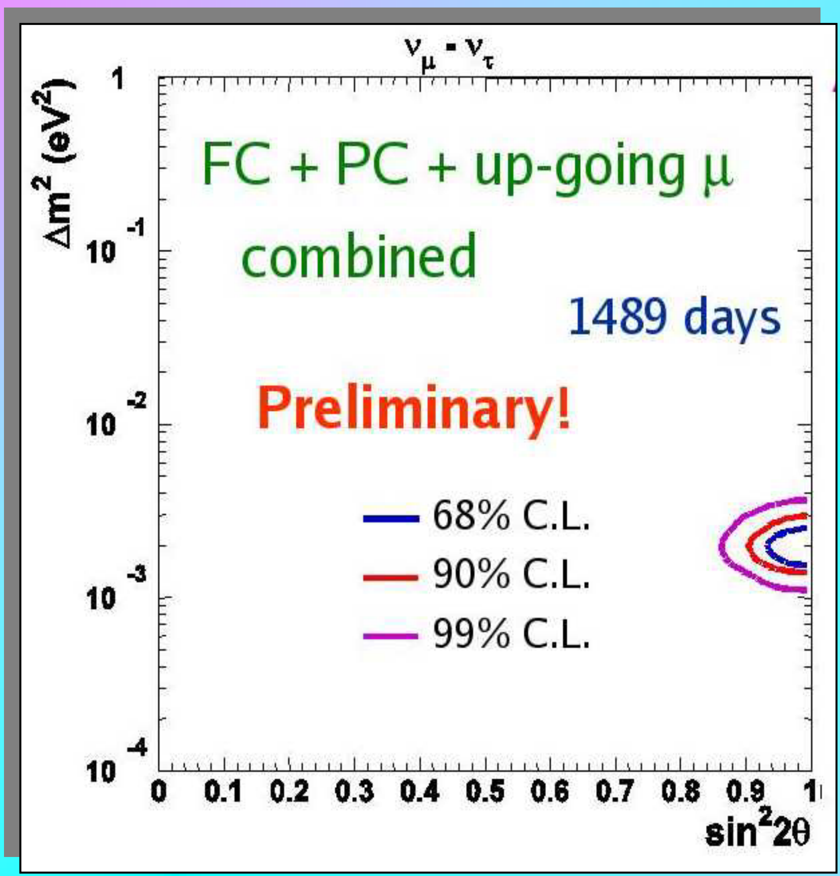
Motivation for the low energy solar neutrino experiments
BOREXINO, KamLAND
MOON, LENS ...



P. de Holanda, A.S.

Atmospheric Neutrinos

SuperKamiokande:



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

(90 % C.L.)

Confirmed by
MACRO,
SOUDAN
K2K

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

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

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

Best fit point: $\sin^2 2\theta_{23} = 1.0$
$\Delta m_{32}^2 = 2.0\ \ 10^{-3}\ eV^2$

LMA oscillations of atmospheric neutrinos

Excess of the e-like events in sub-GeV

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

``screening factor"

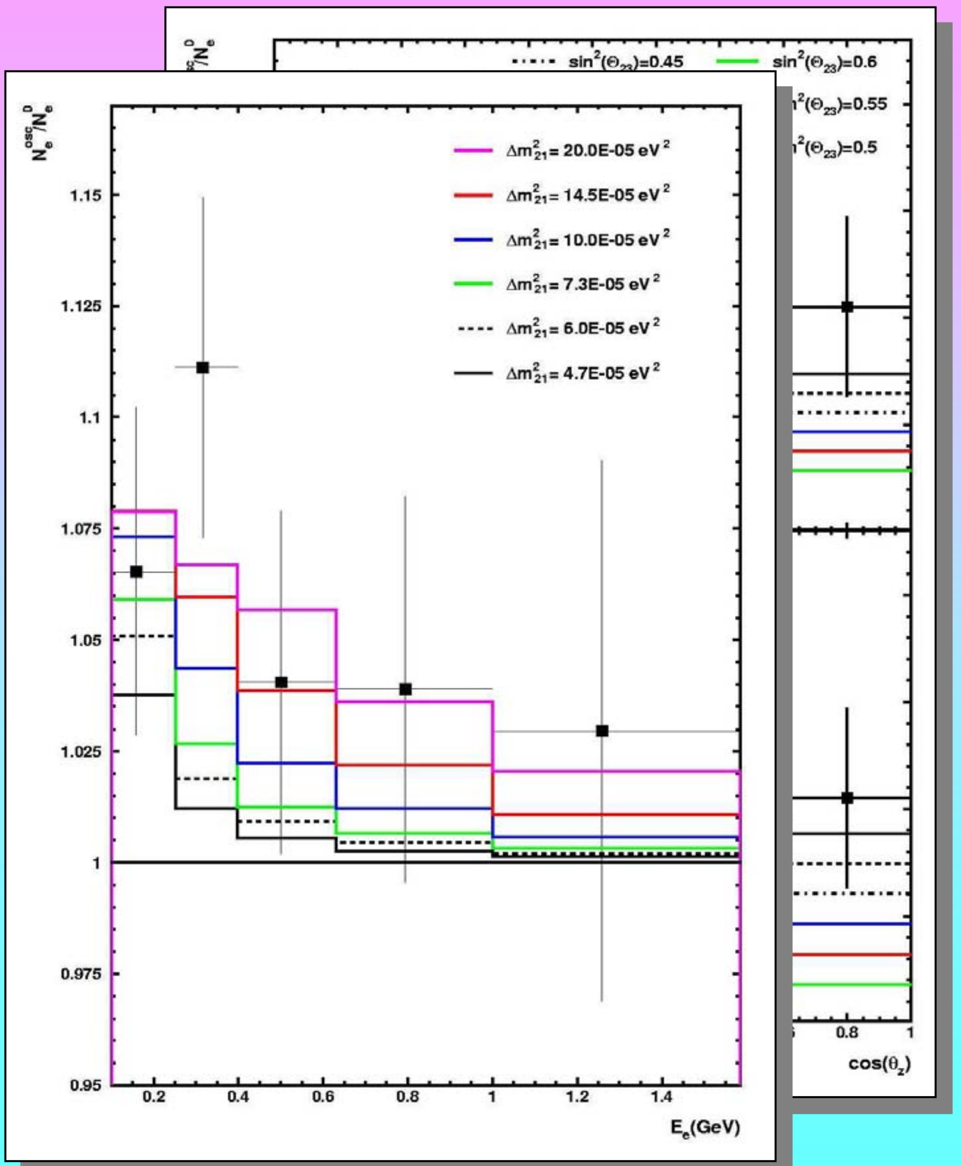
$P_2 = P(\Delta m^2_{12}, \theta_{12})$ is the 2ν transition probability

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 and energy dependences of the e-like events



Conversion of neutrinos from SN1987A

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

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

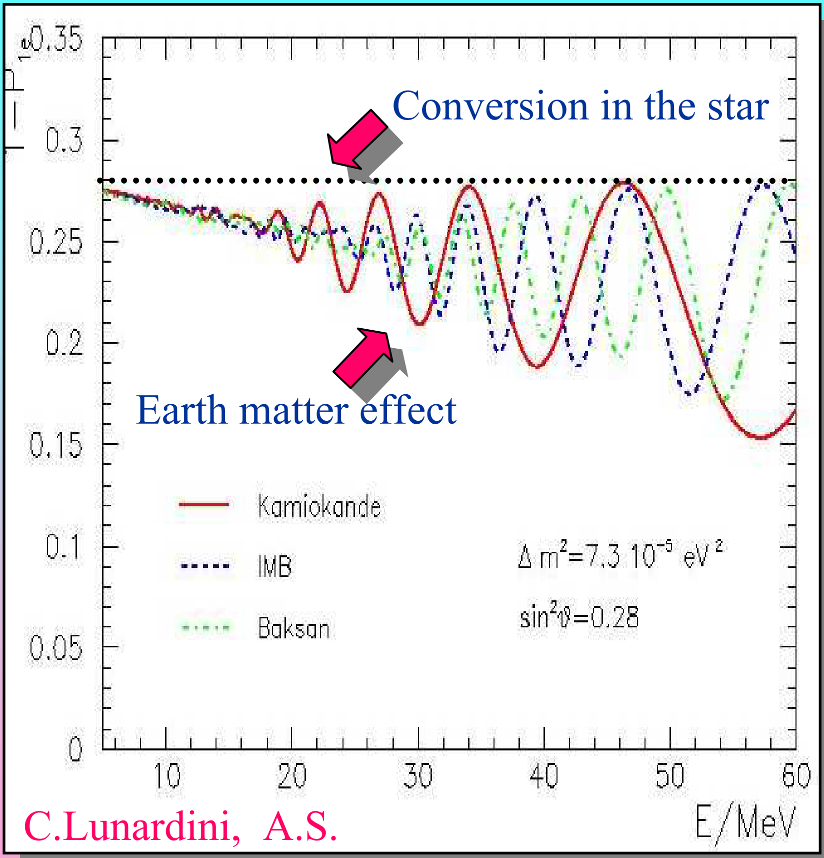
  p is the permutation factor

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

- 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

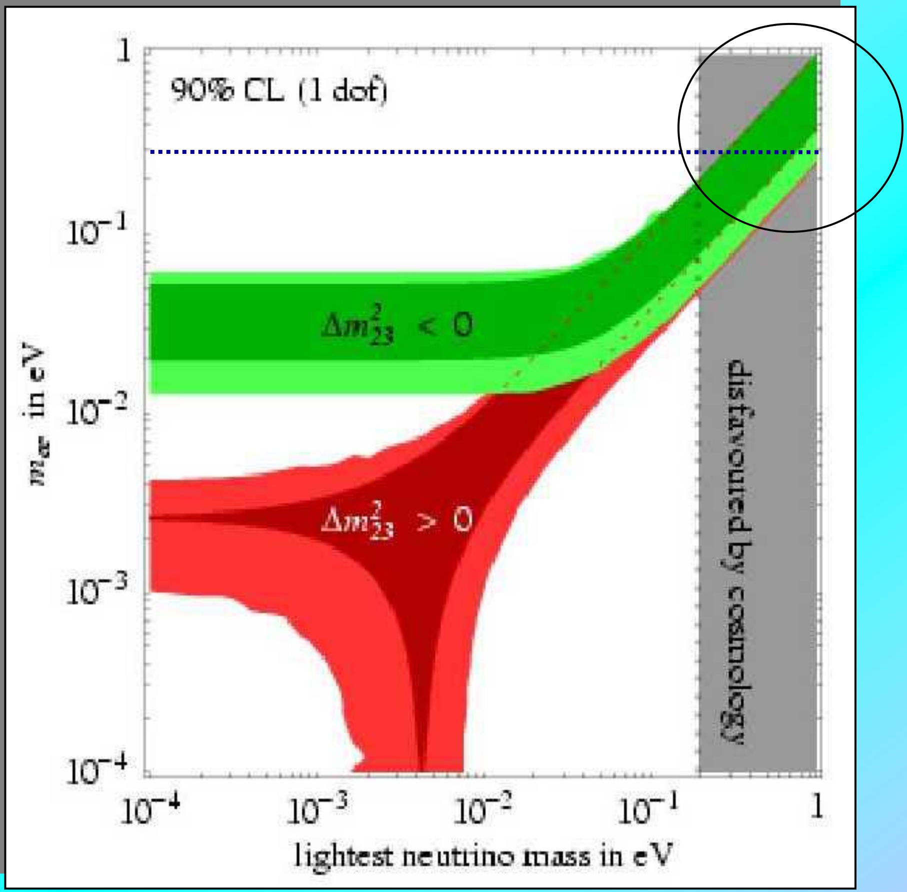
- Normal hierarchy is preferable

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

Absolute scale of mass

F. Feruglio, A. Strumia, F. Vissani

Neutrinoless double beta decay



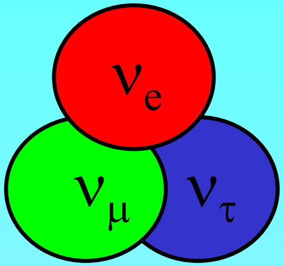
Kinematic searches, cosmology

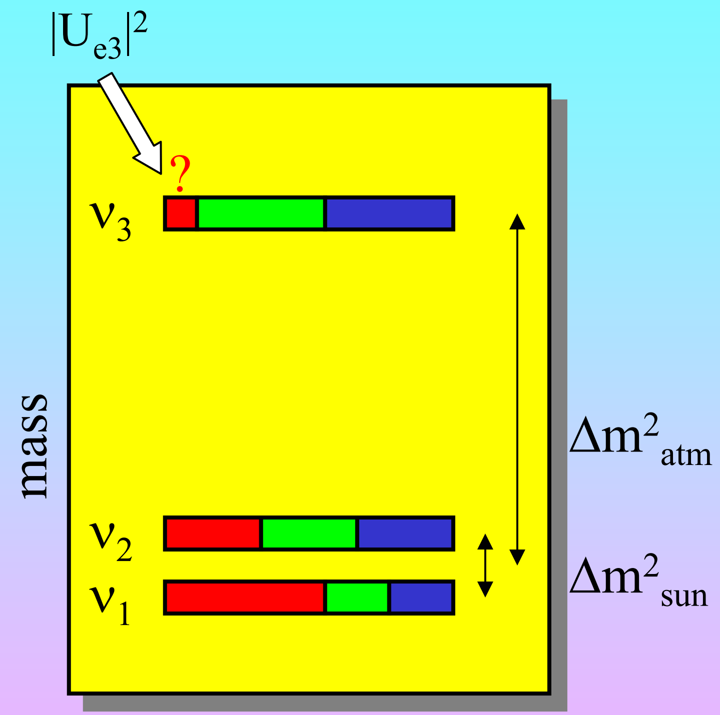
Sensitivity limit

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

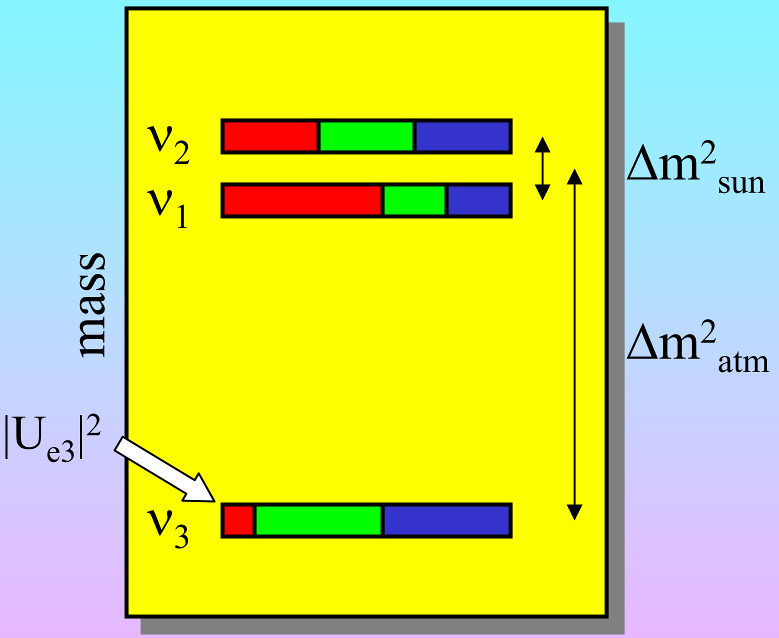
Both cosmology and
double beta decay
have similar sensitivities

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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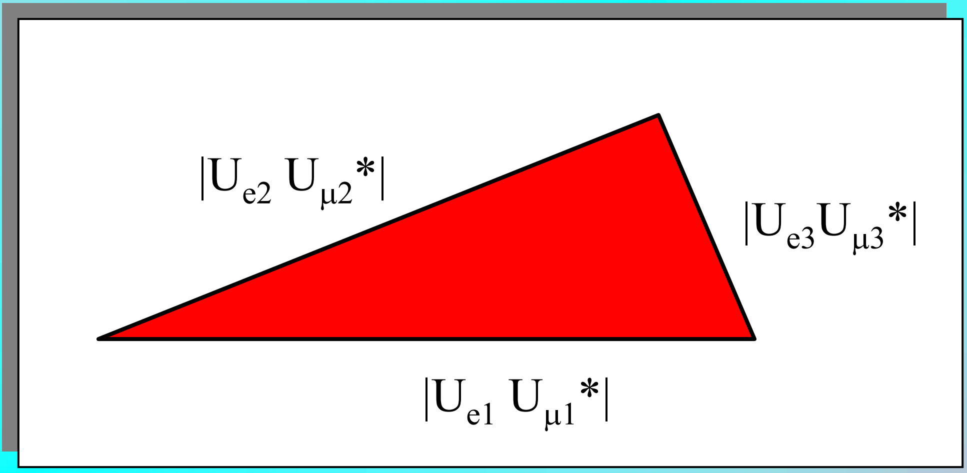
Leptonic Unitarity Triangle

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

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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LSND

Ultimate oscillation
anomaly?

CPT-violation

After KamLAND:
G. Barenboim,
L. Borissov, J. Lykken

Non-standard Interactions

K.Babu, S Pakvasa

Disfavored by a new analysis of KARMEN collaboration

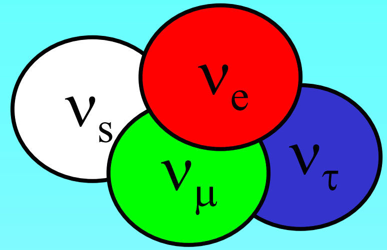
Sterile neutrino (3 + 1)-scheme (3 + 2) ?

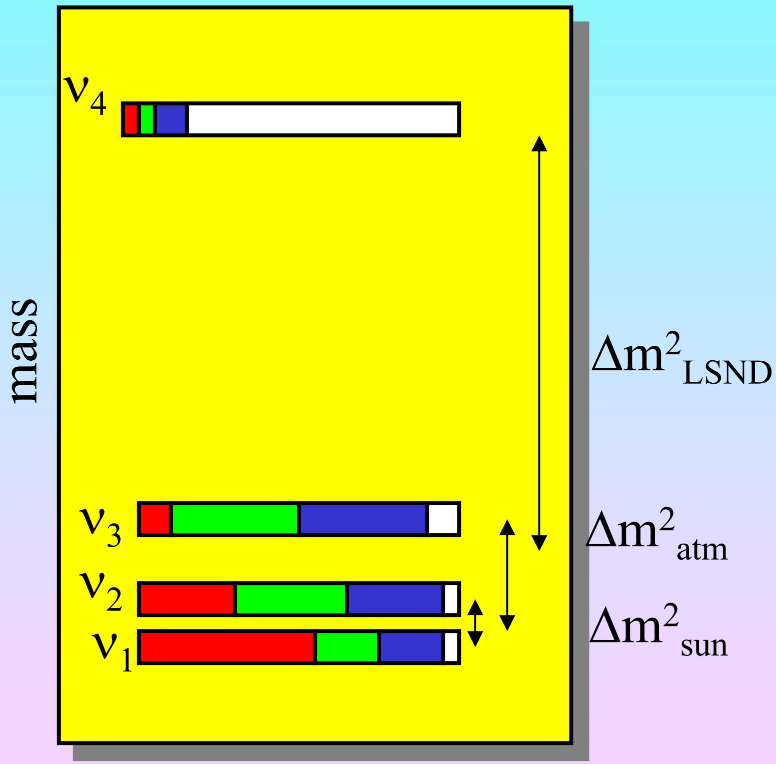
O. Peres, A.S.
M. Sorel, J. Conrad, M. Shaevitz

Disfavored by atmospheric neutrino data, no compatibility of LSND and all-but LSND data below 3σ-level

M.C. Gonzalez-Garcia,
M. Maltoni, T. Schwetz

(3 + 1)





The problem is

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

Restricted by short baseline experiments CHOOZ, CDHS, NOMAD

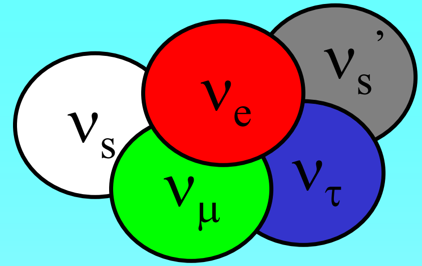
2 - 3σ below the observed probability

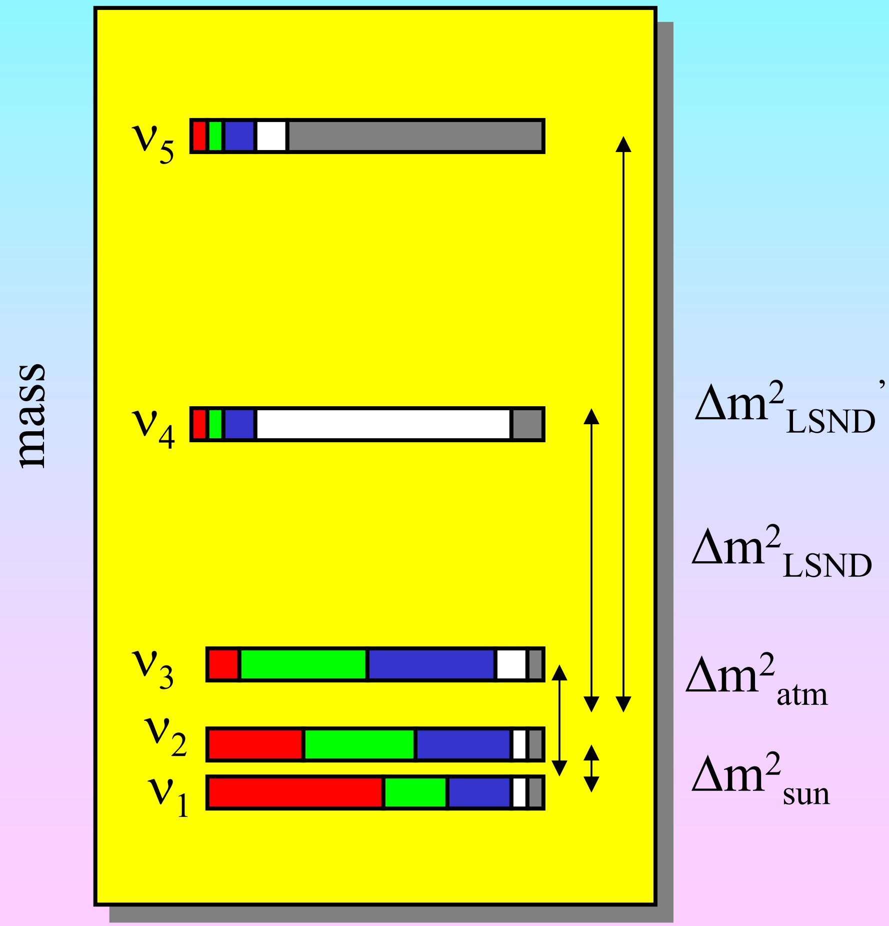
Generic possibility of interest even independently of the LSND result

Generation of large mixing of active neutrinos due to small mixing with sterile state

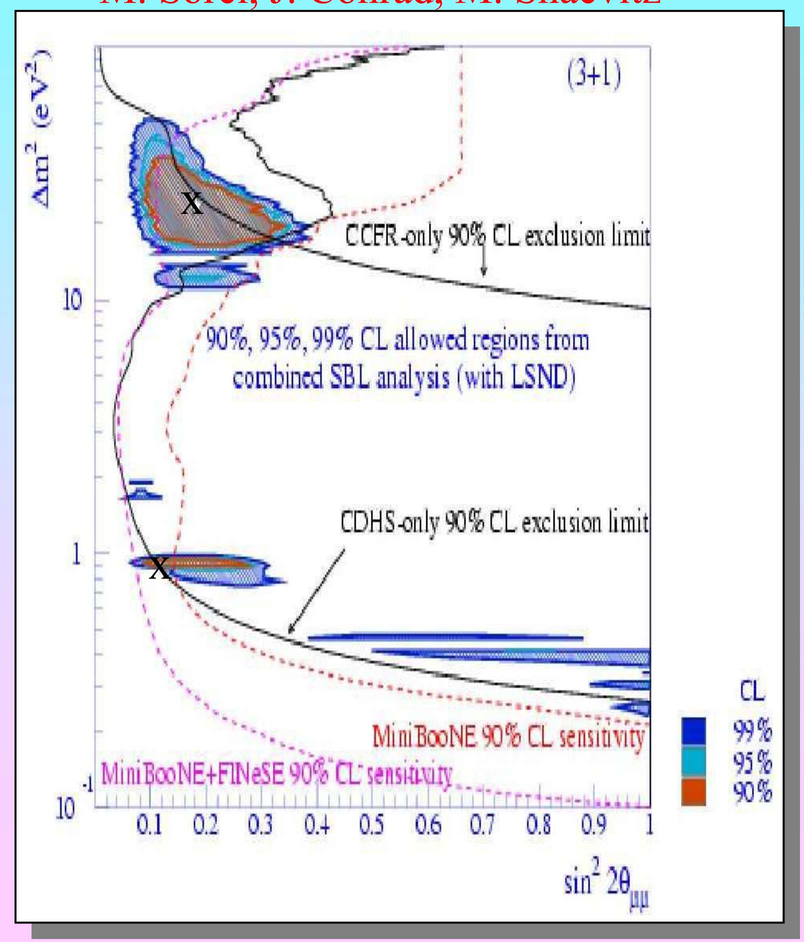
Produces uncertainty in interpretation of results

3 + 2 scheme





M. Sorel, J. Conrad, M. Shaevitz



FINeSE

Main features

- Smallness of masses:

$m_\nu < (1 - 2)$ eV $\qquad m_\nu << m_l,\ m_q$

$m_\nu > \sqrt{\Delta m_{23}^2} > 0.04$ eV (at least for one mass)

- Hierarchy of mass squared differences:

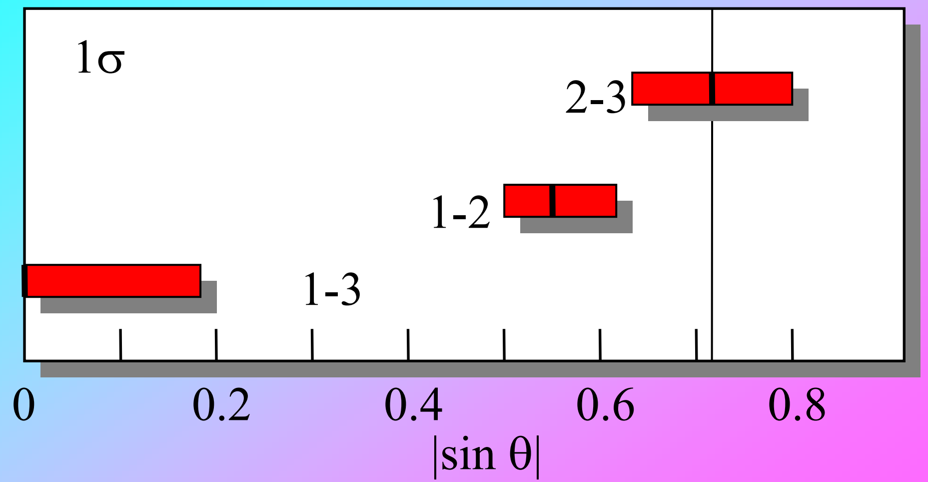
$|\Delta m_{12}^2 / \Delta m_{23}^2| = 0.01 - 0.15$

- No strong hierarchy of masses:

$|m_2/m_3| > |\Delta m_{12}^2 / \Delta m_{23}^2| = 0.18^{+0.22}_{-0.08}$

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

- Small mixing between remote families (1- 3):



...and unknown

Several key elements are unknown yet which leads to variety of possible interpretations

Absolute mass scale, m_1
type of spectrum

- hierarchical
- partially degenerate
- quasi degenerate

CP-violating phases, especially Majorana phases

$\sin\theta_{13}$

test of mechanisms of the lepton mixing enhancement

Type of mass hierarchy ordering of states (sign of $\Delta m_{13}^2 = m_1^2 - m_3^2$)

- normal
- inverted

Deviation of 2-3 and 1-2 mixings from maximal

Existence of new neutrino states

Phenomenological and experimental problems

2. Open theoretical questions

What does all this mean?

(results on neutrino masses and mixing)

Old...

What is the origin of neutrino mass?

- we do not know yet the origin of quark and charged lepton masses where information is more complete
- for neutrinos the problem can be even more complex
- the hope is that neutrinos can shed some light on whole problem of fermion masses

Why neutrino masses are small?

- small in comparison with charged leptons and quarks masses
- what are relations with other mass scales in nature? e.g., dark energy scale?

and New:

How the observed pattern of the lepton mixing is generated?

- two large mixings and one small (zero)?
- one maximal mixing?
- what are relations between mixing angles?

Why the lepton mixing is large?
Why it is so different from quark mixing?

- may be correct question is why the quark mixing is so small?
  In quark sector the smallness of mixing can be related to strong mass hierarchy

Do neutrinos show certain flavor or horizontal symmetry?

- if so, is this symmetry consistent with quark masses and mixing?
- ad hoc introduced symmetries for neutrinos only do not look appealing

Are results on neutrino masses and mixing consistent with

- quark-lepton symmetry?
- Grand Unification?

If new light (sterile) neutrino(s) exist

- what is their nature?
- why they are light?

Experimental and phenomenological problem

What are implications of the neutrino results for

- GUT
- SUSY
- Extra Dimensions?
- Strings

vice versa

What these theories can tell us about neutrinos?

3. Bottom-Up

Bottom -Up and Top-Down

Theory of neutrino mass and mixing

Identify symmetry and underlying dynamics

Identify symmetry scale and symmetry basis
Renormalization group effects

Reconstruct the neutrino mass matrix in the flavor basis

Experimental results on

$\Delta m_{ij}^2 \quad \theta_{ij} \quad m_{ee}$

Mass matrix unifies information contained in masses and mixing

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

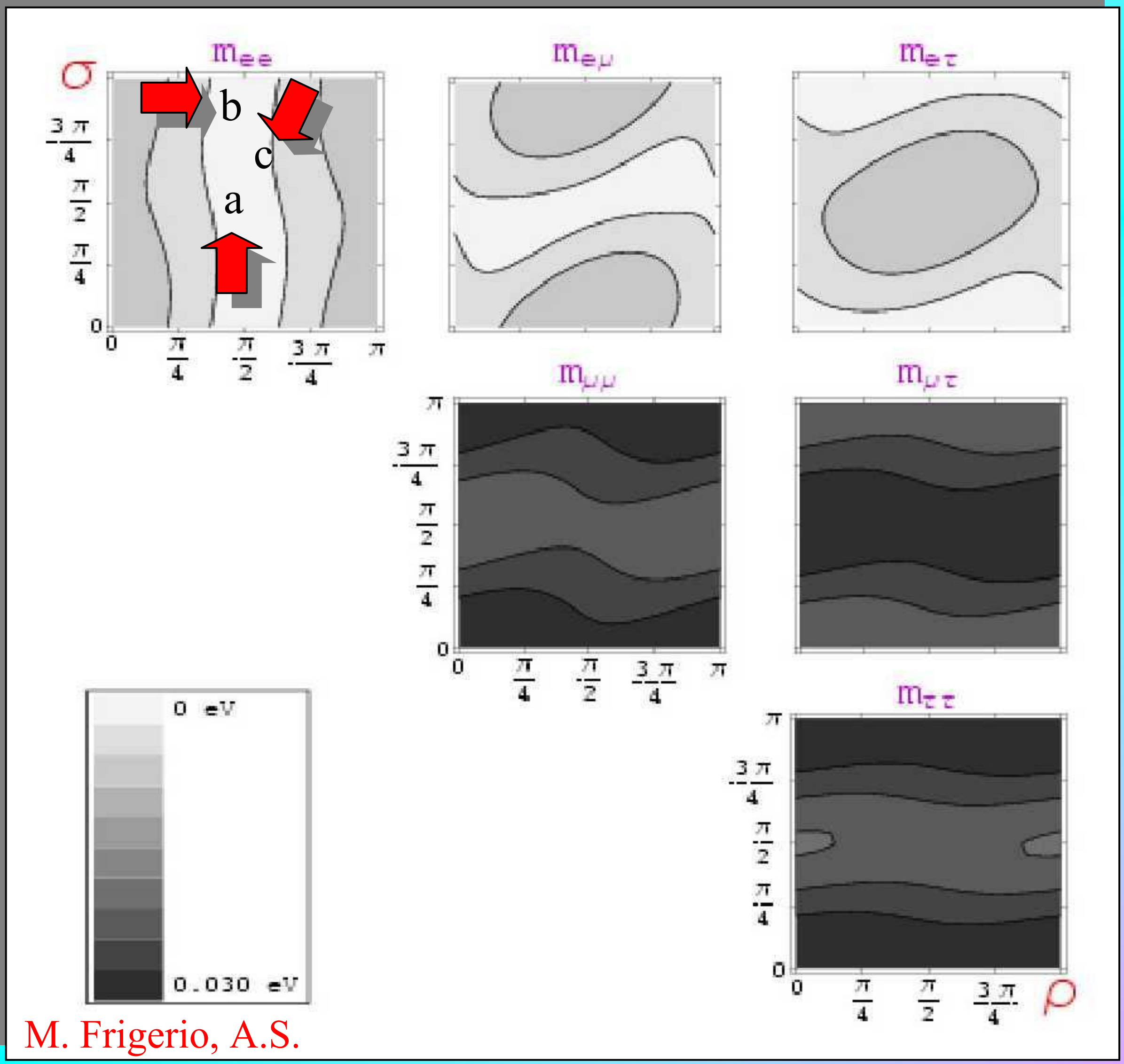
$$m^{diag} = diag(m_1 e^{-2i\rho}, m_2, m_3 e^{-2i\sigma})$$

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

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

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

Normal hierarchy



$m_3 / m_2 = 5$

$m_1 = 0.006$ 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). $\begin{pmatrix} 0 & \lambda & 0 \\ \lambda & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$

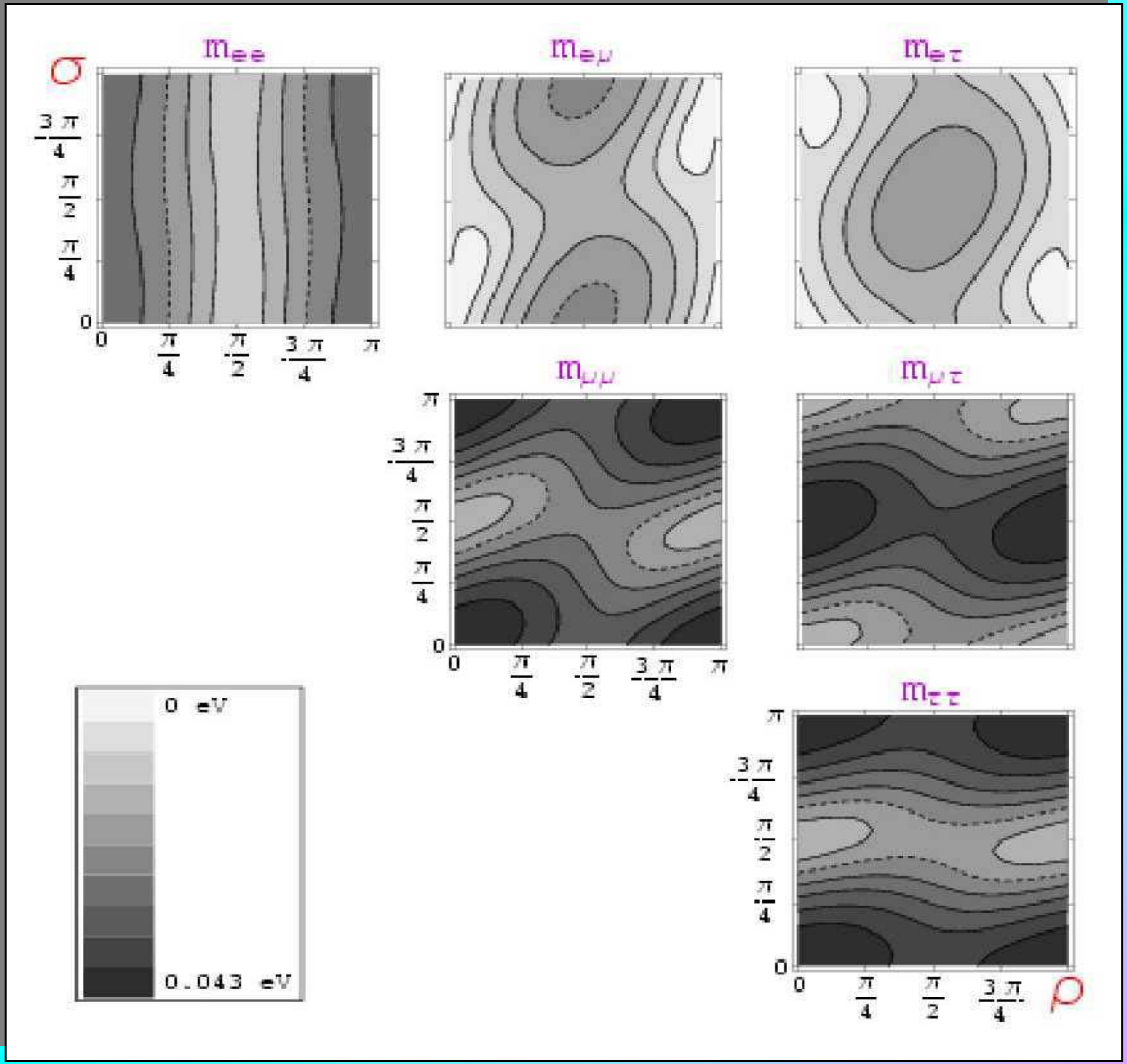
c). $\begin{pmatrix} \lambda^2 & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix}$

$\lambda \sim 0.2$

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

$q \sim 0.7$

Normal ordering



$m_3 / m_2 = 2$

$m_1 = 0.027$ eV

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

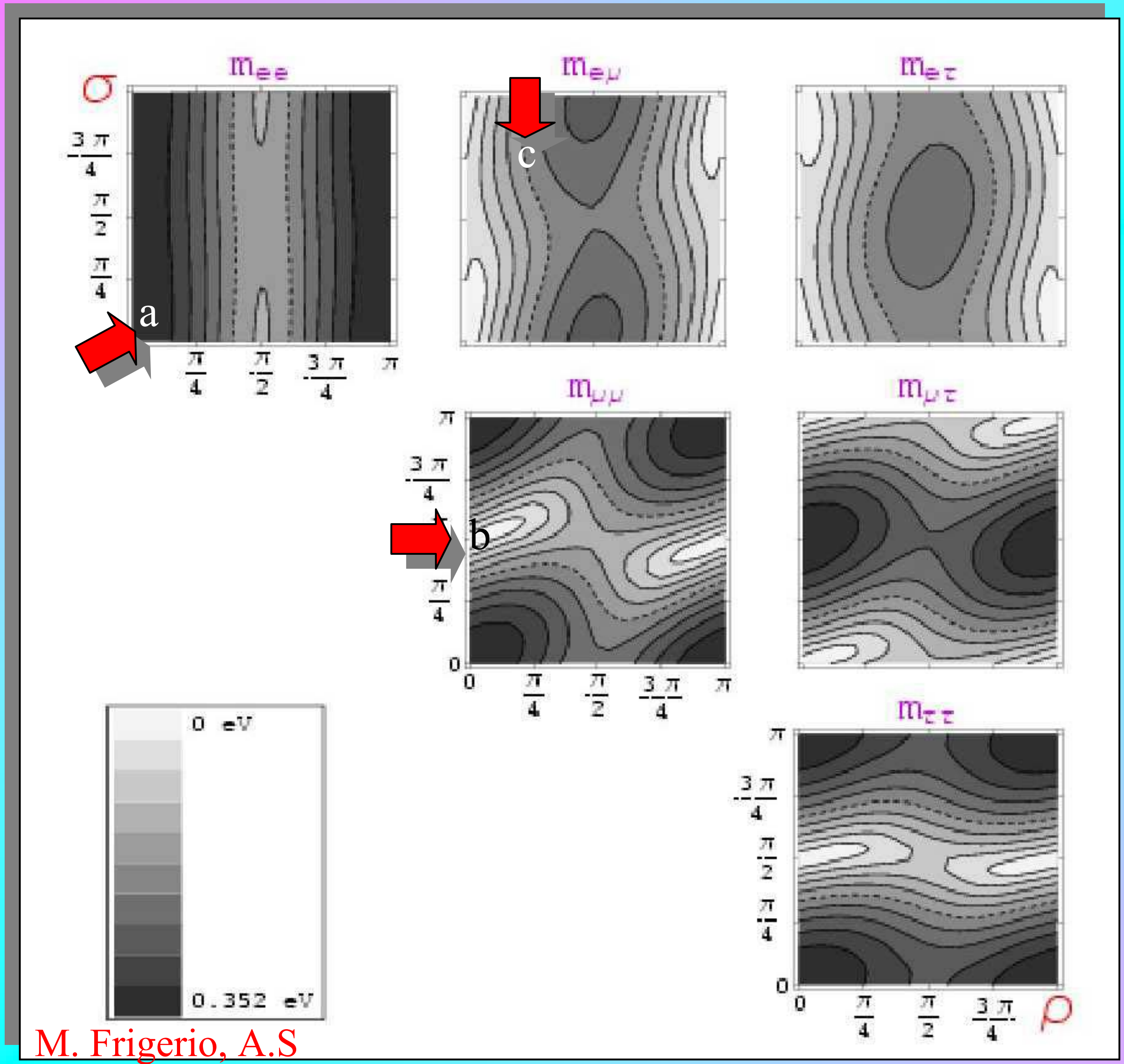
$\sin\theta_{13} = 0.1 \quad \delta = 0$

Flavor alignment

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

$q \sim 0.7$

Quasi-degeneracy



$m_3 / m_2 = 1.01$

$m_1 = 0.35$ eV

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

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

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

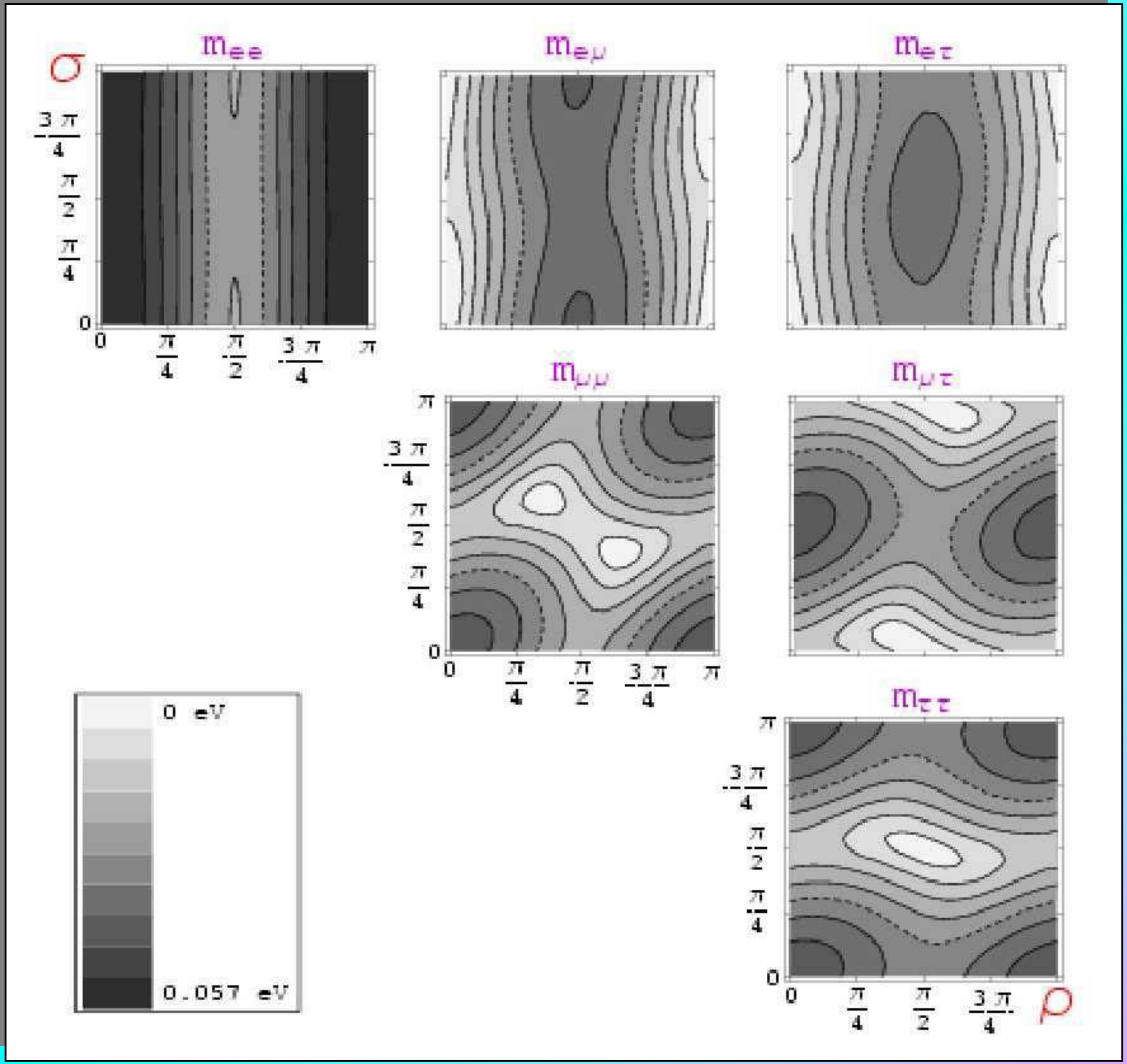
Inverted ordering

$m_3 / m_2 = 0.5$

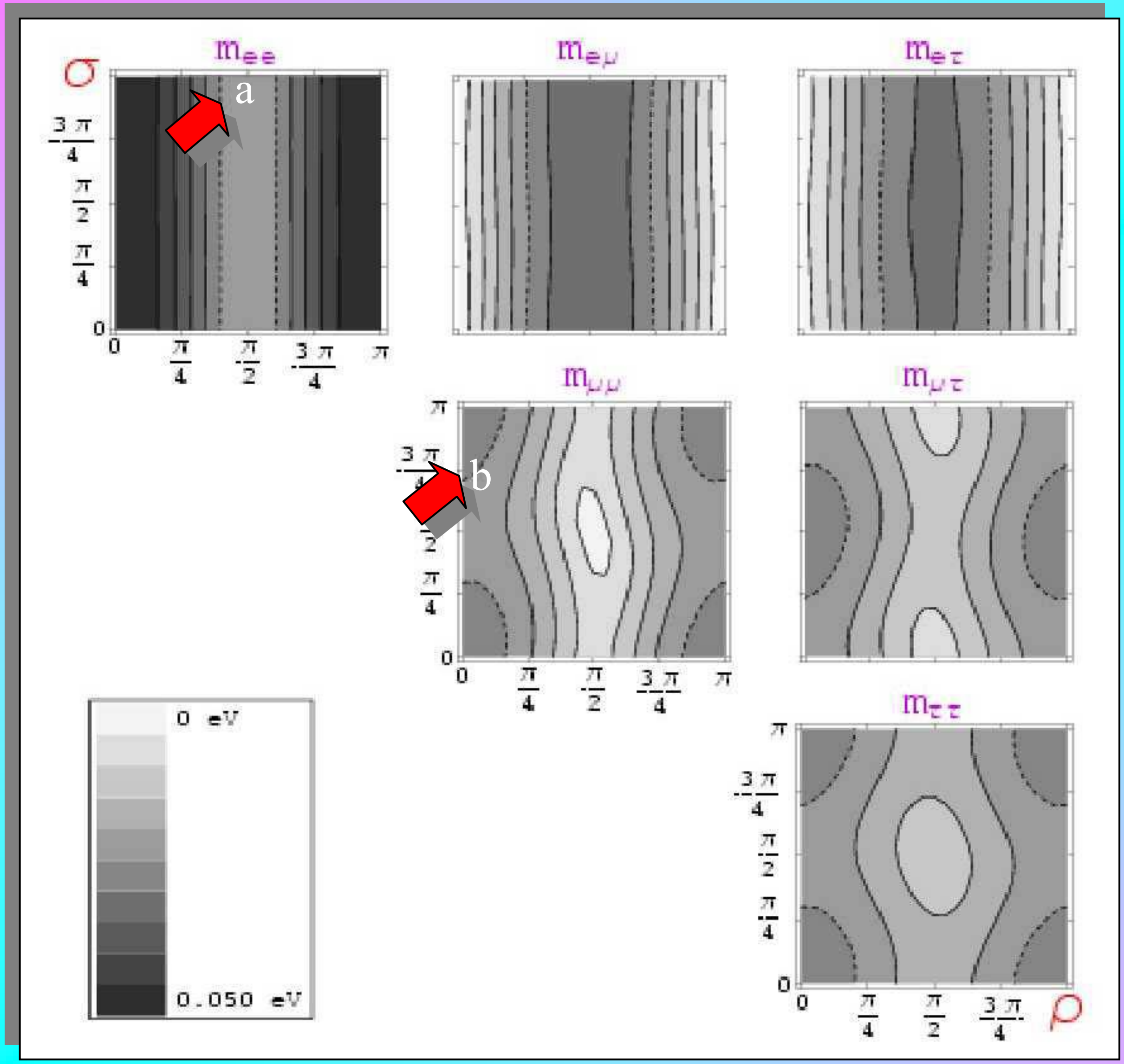
$m_3 = 0.029$ eV

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

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



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

1). Large variety of different structures is still possible, depending strongly on unknown m_1, type of mass hierarchy, Majorana phases ρ and σ, weaker dependence is on $\sin\theta_{13}$ and δ.

L.Hall,
H. Murayama,
A.de Gouvea,
F.Vissani,
G. Altarelli,
F. Feruglio,
J.R. Espinosa

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

3). Structures (in the flavor basis):

- with dominant diagonal elements (~ I), or dominant $\mu\tau$-block,
- with dominant e-row elements, (ee-, $\mu\tau$- , $\tau\mu$-) elements, etc.
- democratic structures,
- with flavor alignment,
- non-hierarchical structures with all elements of the same order
- with flavor disordering,
- with zeros and various equalities of matrix elements.

Anarchy?

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

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

Neutrino mass and horizontal symmetry

Do neutrino results on masses and mixing or
the neutrino mass matrix show some symmetry?

Is the neutrino mass matrix consistent with symmetries suggested for quarks?

$L_e - L_\mu - L_\tau$

Discrete symmetries
A_4 S_3 Z_4 D_4

Treat quarks and leptons differently

U(1)

in the Froggatt-Nielsen context
can describe mass matrices both quarks and leptons.
U(1) charges: discrete free parameters,
also coefficients ~O(1) in front of

SU(2)

SU(3)

Complicated higgs sector to break symmetry too restrictive...

4. How we might go ...

Neutrality and mass

Minimal number of new concepts

Minimalistic approach:

Relate features of the neutrino masses and mixing with already known difference of neutrino and quarks and charged leptons.

Neutrality
$Q_\gamma = 0$
$Q_c = 0$

possibility to be a Majorana particle (Majorana mass term)

Can mix with singlets of the SM symmetry group

Can propagate in extra dimensions

Can have large Majorana masses $M_R \gg V_{EW}$

Properties of mass spectrum and mixing

Right handed components, if exists, are singlet of SU(3) x SU(2) xU(1)

Unprotected by this symmetry

Is this enough?

q - l, $SU(2)_L xU(2)_R xU(1)_{B-L}$

Seesaw

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

- $\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \Rightarrow$ $m_\nu = - m_D^T M_R^{-1} m_D$ (type I)

  $m_D = Y\, v_{EW}$ $\quad M_R = f_S \langle S \rangle = f_S\, v_R$

- If the SU(2) triplet, Δ_L, exists with interaction $f_\Delta\, l^T l\, \Delta_L$ + h.c., then $f_\Delta\, l^T l\, \Delta_L$ + h.c.

  $m_\nu = m_L - m_D^T M_R^{-1} m_D$ (type II)

- If Δ_L is heavy, induced VEV due to the interaction with doublet $\langle \Delta_L \rangle = \langle H \rangle^2 / M$

- In SO(10): Δ_L and S are in the same 126, $f_\Delta = f_S = f$

$$m_\nu = f \lambda \frac{v_{EW}^2}{v_R} - m_D^T f^{-1} m_D = \frac{v_{EW}^2}{v_R} (f \lambda - Y^T f^{-1} Y)$$

Flavor structure of two contributions correlates

Variations on the theme

The number of the RH neutrinos can differ from 3

Less than 3 ...
3x2-seesaw
(two RH neutrinos)

limit when one of ν_R is very heavy $M \sim M_{Pl}$
motivated by horizontal $SU(2)_H$

- one massless neutrino
- less number of parameters

More than 3 ...
Double seesaw

Beyond SM: many heavy singlets
…string theory

R.N. Mohapatra
J. Valle

Three additional singlets S
which couple with RH neutrinos

$$\Rightarrow \begin{pmatrix} 0 & m_D & \\ m_D & 0 & M \\ 0 & M & \mu \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}$$

$$m_\nu = - m_D^T M_D^{-1T} \mu M_D^{-1} m_D$$

$\mu << M_D$ allows to lower the scales

$\mu >> M$

$\mu \sim M_{GU}, M \sim M_{Pl}$ explains intermediate scale

Grand Unification and neutrino Mixing

- GUT provide large scale comparable to the scale of RH neutrino masses
- One can argue that GUT (+ seesaw) can naturally lead to large lepton mixing, or inversely, that large lepton mixing testifies for GUT

1. Suppose that all quarks and
l
i
((

2. Suppose that all yukawa couplings

3. If Dirac masses are generated by
a unique higgs multiplet, (10 of SO(10)),
the
down
have
will b

As a result,
-
-

4. In contrast to other fermions RH
n
i
g

5. Since those (Majorana type) Yukawa couplings are also of generic form they produce M with large mixing which leads then to large lepton mixing

Need to be slightly corrected

Problem:

- Strong hierarchy of the quark and charged lepton masses

In this scenario $m_D = \mathrm{diag}(m_u, m_c, m_t)$

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

Then for generic M_R the seesaw of the type I produces strongly hierarchical matrix with small mixing

Possible solutions:

Type II seesaw: no dependence on m_D

Special structure of M_R which compensate strong hierarchy in m_D

Substantial difference of Dirac matrices of quarks and leptons $m_D(q) \neq m_D(l)$

Seesaw enhancement of mixing

Can the same mechanism (seesaw) which explains
a smallness of neutrino mass also explain large lepton mixing?
Large lepton mixing is an artifact of seesaw?

A.S.
M. Tanimoto
M.Bando,
T.Kugo
P. Ramond

Quark-lepton symmetry
$m_D \sim m_{up}$, $m_l \sim m_d$,
small mixing in Dirac sector

Special structure of M_R → Large lepton mixing

Two possibilities:

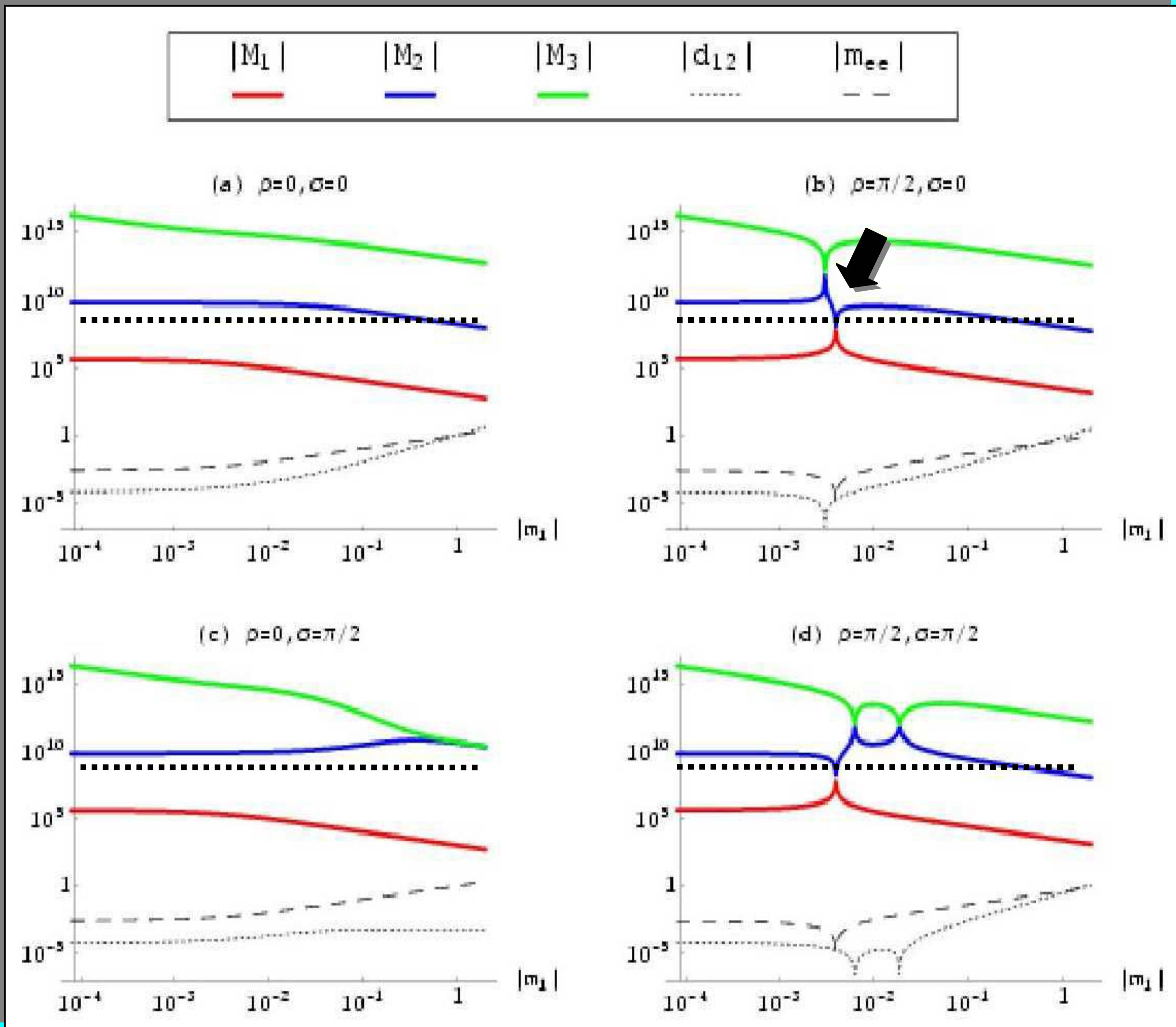
Strong (``quadratic") hierarchy of the right handed neutrino masses:

$$M_{iR} \sim (m_{i\,up})^2$$

Strong interfamily connection (pseudo Dirac structures)

$$M_R = \begin{pmatrix} a & 0 & 0 \\ 0 & 0 & b \\ 0 & b & 0 \end{pmatrix}$$

Masses of RH neutrinos



Leptogenesis gives strong restrictions

In the hierarchical case the lower bound on the lightest mass

$M_1 > 4\ 10^8$ GeV

W. Buchmuller
P. di Bari M. Plumacher,
S. Davidson, A. Ibarra

Only in particular cases with strong degeneracy: $M_1 = M_2$ required asymmetry can be produced

E. Kh. Akhmedov,
M.Frigerio, A.S.

Large mixing and type II Seesaw

- Structure of the mass matrix generated by the type II (triplet) seesaw can be related to quark and lepton masses

K. Babu, R. Mohapatra, Matsuda,
B.Bajc, G. Senjanovic, F.Vissani
R. Mohapatra, Goh, Ng

126 of SO(10)

generates neutrino masses m_L

gives contribution to quark and lepton masses (Georgi-Jarlskog relation)

$m_L \sim Y_{126}$

$m_b - m_\tau \sim Y_{126}$ (subtraction of 10 -contribution)

Large 2-3 mixing needs b - τ unification

b - τ unification: element $(Y_{126})_{33} \sim (Y_{126})_{23} \ll 1$
--> large 2-3 lepton mixing

- Successful leptogenesis is possible with participation of the scalar triplet

T. Hambye, G. Senjanovic

Single RH neutrino dominance

S. F. King,
R. Barbieri, Creminelli,
A. Romanino,
G. Altarelli, F.Feruglio,
I. Masina

- Large mixing from the Dirac neutrino mass matrix

$$m_D = m \begin{pmatrix} * & * & \varepsilon \\ * & * & 1 \\ * & * & 1 \end{pmatrix} \qquad M_R^{-1} = M \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(* \ll \varepsilon)$$

Seesaw gives:

$$m_\nu = \begin{pmatrix} \varepsilon^2 & \varepsilon & \varepsilon \\ \varepsilon & 1 & 1 \\ \varepsilon & 1 & 1 \end{pmatrix}$$

- In another version it may coincide with seesaw enhancement: Single RH neutrino dominance is realized when other RH neutrinos are heavy = strong hierarchy

"Lopsided" Models

K. Babu, S.M. Barr,
C.H. Albright,
J.Sato, T. Yanagida,
N. Igres, S. Lavignac,
P.Ramond

- Large mixing follows from charged lepton mass matrix
- Non-symmetric mass matrices
- No contradiction with GUT:
  in SU(5): LH components of leptons are unified
  with RH components of quarks: 5 = (d^c, d^c, d^c, l, ν)

- $m_D = m_{\underline{u}} \begin{pmatrix} \eta & 0 & 0 \\ 0 & 0 & \varepsilon \\ 0 & -\varepsilon & 1 \end{pmatrix}$ $m_l = m_d \begin{pmatrix} 0 & \delta & d' \\ \delta & 0 & \sigma + \varepsilon \\ \delta' & -\varepsilon & 1 \end{pmatrix}$ ↕ μ τ Single lopsided

$\eta << \delta,\ \delta' << \varepsilon$ $\sigma \sim 1$

- Also possible in SO(10) if it is broken via SU(5)
- Double lopsided (for both large mixings) K. Babu, S. Barr
- Hybrid possibilities: large 2-3 mixing from charged lepton mass matrix
  large 1-2 mixing from neutrino mass matrices

Radiative enhancement of mixing

- Mixing is small at the Unification scale (similar to quark mixing) running to low energies ➡ enhancement of mixing.

K. Babu, C.N. Leung, J. Pantaleone, P. Chankowski, M. Pluciniek, J. Ellis, S. Lola, J. Casas, M.Lindner. …..

Requirement: **Large mixing** ⟷ **Quasi-degenerate spectrum**

e.g.

$$\frac{d\,\sin\theta_{23}}{dt} \sim (\sin\theta_{12}\, U_{\tau 1}\, D_{31} - \cos\theta_{12}\, U_{\tau 2}\, D_{32})$$

$t = 1/8\pi^2 \log q/M \qquad D_{ij} = (m_i + m_j)/(m_i - m_j)$

Enhancement when neutrinos become more degenerate

- Requires fine tuning of the initial mass splitting and radiative corrections

- In MSSM both 1-2 and 2-3 mixings can be enhanced. In SM ?

- If masses from Kahler potential: large mixing infrared fixed point

J.A.Casas, J.R. Espinosa, I. Navarro

- Generation of small elements ratiatively: Δm_{12}^2, $\sin\theta_{13}$

S. Petcov, A.S. A. Joshipura, M. Lindner

How to test Seesaw?

How to test existence of the heavy Majorana RH neutrinos?

Leptogenesis

M. Fukugita, T. Yanagida

For hierarchical RH neutrino spectrum gives bound on

- Mass of the lightest RH neutrino M_{1R}
- Effective parameter $\tilde{m}_1$ which determines the washout effect

Probe of $(Y Y^{+})_{ij}$

W. Buchmuller
P. di Bari
M. Plumacher

$M_{1R} > 4\ 10^8$ GeV ⇒ $m_\nu < 0.1$ eV excluding degenerate spectrum (?)

for type II seesaw: still possible

G.Senjanovic
T. Hambye

Renormalization effects of RH neutrinos

Renormalization effects between the scale M_{iR} and GUT

e.g., on m_b - m_τ mass relation

F. Vissani, A.S.,
H. Murayama, R. Rattazzi
A. Brignole

SUSY Seesaw

- Superpotential $W_{lep} = e^{c\,T} Y_e\, l\, H_1 + \nu^{c\,T} Y\, l\, H_2 + \frac{1}{2} \nu^{cT} M_R\, \nu^c$

- Structures relevant for seesaw (Y, M_R) — Imprinted into — structure of SUSY (slepton) sector

- Assumptions: 1). Universal soft masses (m_0^2, A_0) at high scale M_X 2). No new particles apart from those in MSSM

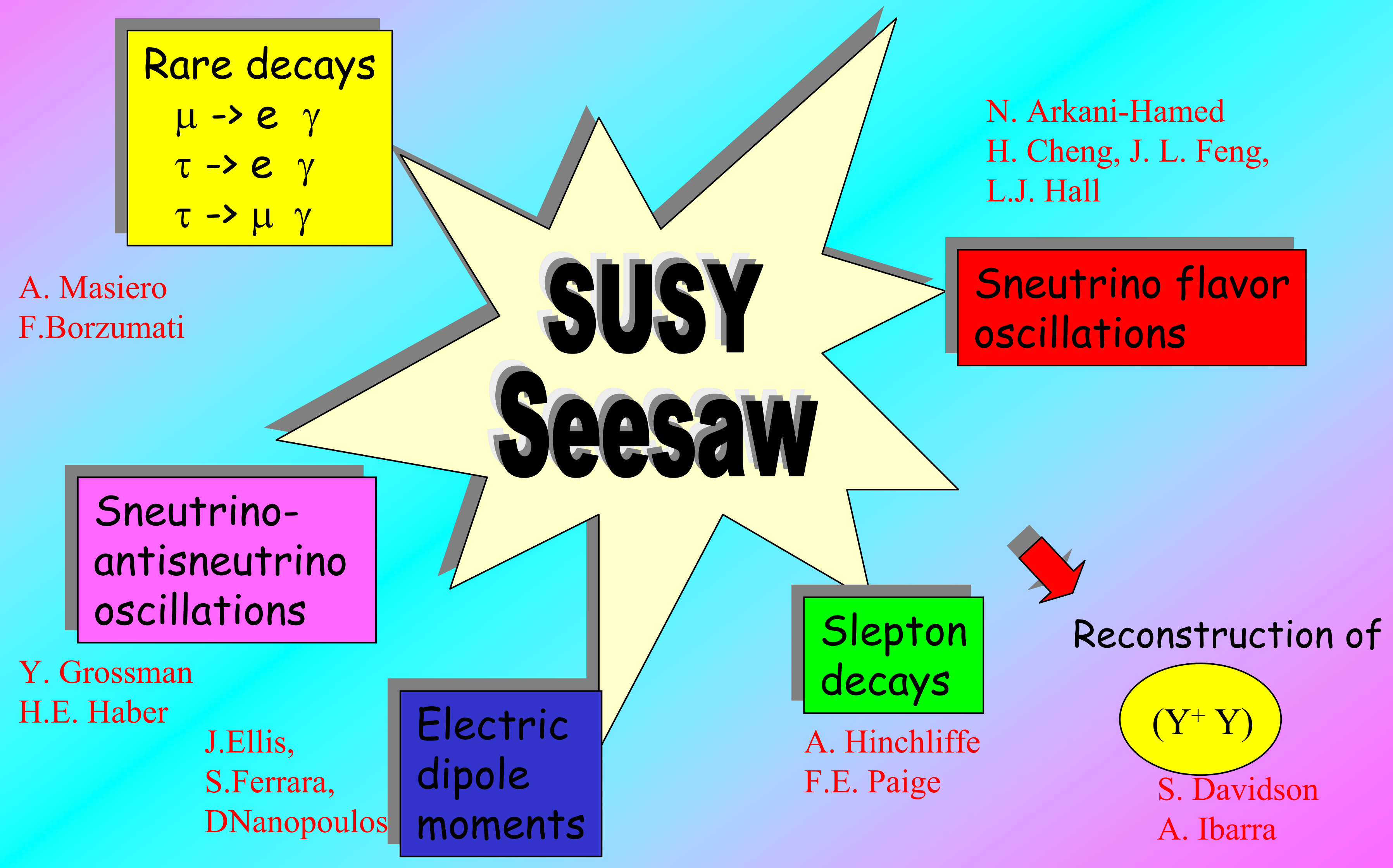
- Contribution to the low energy left handed slepton mass matrices:

$$(m_S^2)_{ab} = m_a^2\, \delta_{ab} - \frac{1}{8\pi^2}(3\, m_0^2 + A_0^2)\, (Y^+)_{ai}\, (Y)_{ib} \log(M_X / M_{iR})$$

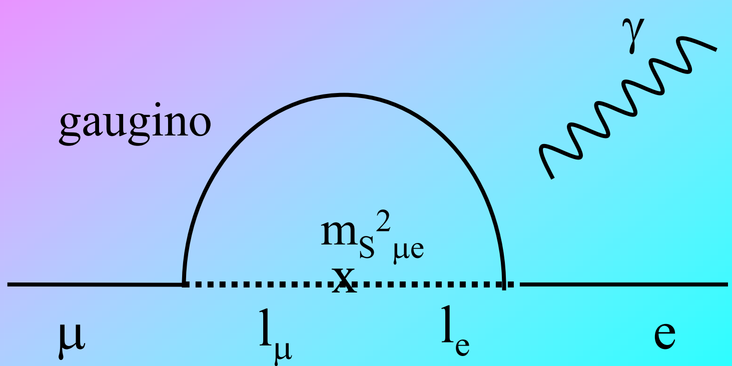
⇧ diagonal part

A.Masiero, F.Borzumatti, L.J. Hall, V.A.Kostelecky, S. Raby, F. Gabbiani, E Gabrielli, L. Silvestrini

Testing SUSY seesaw



Rare decays



$$B(\mu \to \gamma \; e) = \frac{\alpha^3 \; |(m_S{}^2)_{\mu e}|^2 \; \tan^2\beta}{G_F{}^2 \, m_s{}^8}$$

$m_s = m_s(m_0\,,\, m_{1/2})$
effective SUSY
mass parameter

$$(m_S{}^2)_{\mu e} = \frac{1}{8\pi^2}(3\,m_0{}^2 + A_0{}^2)\,(Y^+)_{\mu i}\,(Y)_{ie}\,\log(M_X/M_{iR})$$

A.Masiero,
F.Borzumatti
F. Gabbiani,
E Gabrielli,
L. Silvestrini

- If large lepton mixing originates from the Dirac matrix (lopsided models, versions of SRHN dominance) $(Y)_{\mu i}$, $(Y)_{ie}$ are large

$$B(\mu \to \gamma \; e) \sim 10^{-11} - 10^{-12}$$

At the level of present bound

Beyond
leading log:
S. Petcov,
S.Profumo,
Y. Takanishi,
C.E. Yaguna

Other mechanisms

Radiative mechanims

Zee (one loop, generalized)
Zee-Babu (two loops)
Trilinear R- violating couplings

Bi-linear R-parity violation

Extra Dimensions

Large extra D (ADD)
Warped extra D (RS)
Infinite extra D (Dvali-Poratti)
...

Dynamical symmetry breaking
Technicolor

Little Higgs

Can accommodate
neutrino masses
produce some interesting
features

Deconstruction

Conclusions

Enormous progress in determination of the neutrino masses and mixings, studies of properties of mass matrix. Still large freedom in possible structures exists which leads to very different interpretations.

Main open question: what is behind obtained results? Preference? Probably seesaw, and probably associated with Grand Unification. Although other mechanisms are not excluded and can give important or sub-leading contributions.

How to check our ideas about neutrinos? Future experiments will perform precision measurements of neutrino parameters. Apart from that we will need results from non-neutrino experiments:

- from astrophysics and cosmology
- from searches for proton decay and rare decays
- from future high energy colliders.