Origins of Neutrino Mass

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Gif 2011, School on Neutrinos

Grand unification?

RH neutrino components have large Majorana mass

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

$$M_R \sim \begin{cases} M_{GUT} \\ \dfrac{M_{GUT}^2}{M_{Pl}} \end{cases}$$

in the presence of mixing

$M_{GUT} \sim 10^{16}$ 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

$N \to l + H$

→ lepton asymmetry
→ baryon asymmetry of the Universe

GUT's

generically

Give relations between masses of leptons and quarks

$m_b = m_\tau$

In general: ``sum rules"

Provide with all the ingredients necessary for seesaw mechanism

- RH neutrino components
- Large mass scale
- Lepton number violation

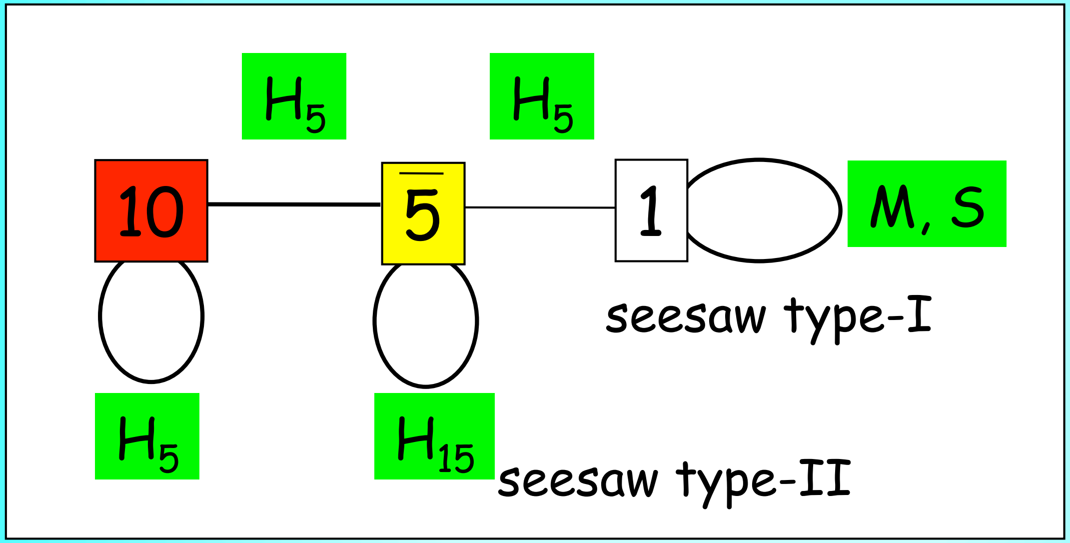
b - τ unification ⇔ large 2-3 leptonic mixing

Some flavor features can be generated

But - no real explanation of the flavor structure

SU(5) GUT

Fermion masses



Notice: q-l unification may not imply q-l correspondence and symmetry

No RH neutrinos or $M_R \sim M_{Pl}$

Hierarchy of Yukawa couplings is related to dimension of representation:

K. Babu

$Y_{10} \sim \varepsilon^2$ strong hierarchy of the up-quark masses

$Y_5 \sim \varepsilon$

$Y_1 \sim 1$ weak hierarchy, large neutrino mixing

SO(10) GUT

16-spinorial representation which can accommodate all known fermionic components including RH neutrinos

RH-neutrino

16	u_r , u_b , u_j , ν d_r , d_b , d_j , e	u_r^c, u_b^c, u_j^c, ν^c d_r^c, d_b^c, d_j^c, e^c

- charge quantization
- correct quantum numbers for all components

Gauge coupling unification → SUSY without intermediate scales

Proton decay? → Non-SUSY – with intermediate scale

RH neutrino mass: $16\ 16\ \overline{126}_H$

$\frac{1}{M}\ 16\ 16\ 16_H\ 16_H$

Mass and nothing more?

Standard Model + Mass and Mixing

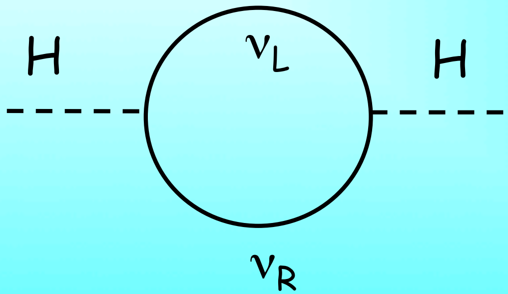
Neutrino interactions

generated by $\frac{1}{\Lambda} L L H H$ *S. Weinberg*

No other manifestations of new physics

$\Lambda \sim 10^{14}$ GeV << M_{Pl}

New physics below Planck scale



$\sim \Lambda^2$

SUSY ?

If ν_R exists: $M_R \sim \Lambda$

Dirac mass

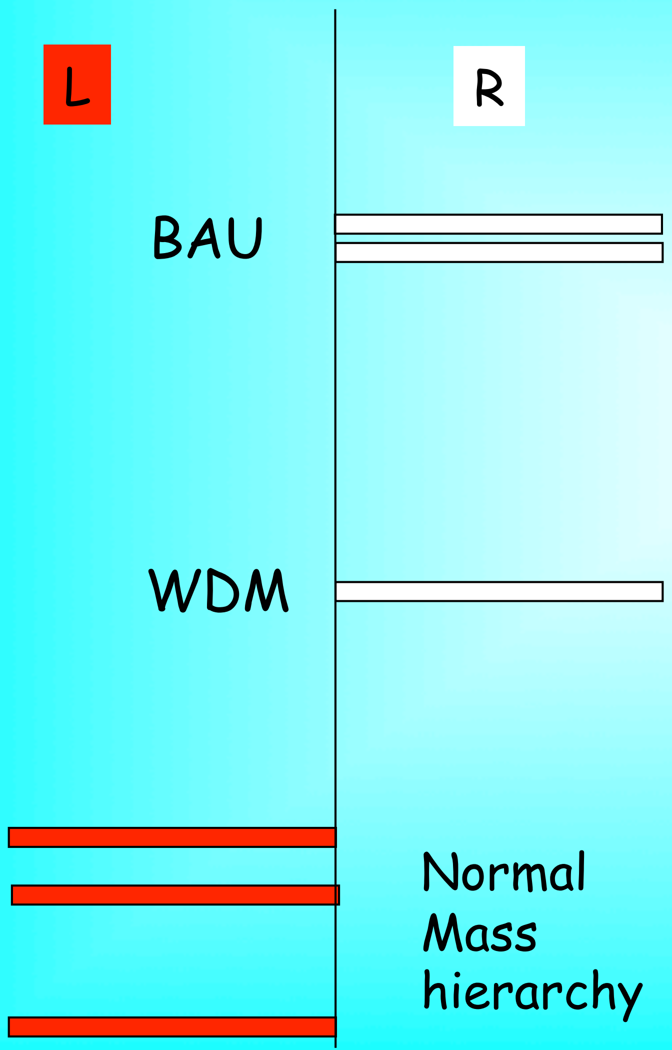
- small Yukawa coupling
- additional doublet with small VEV

DM?

ν MSM

M. Shaposhnikov et al

Everything below EW scale
→ small Yukawa couplings



Few 100 MeV
split ~ few kev

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

3- 10 kev

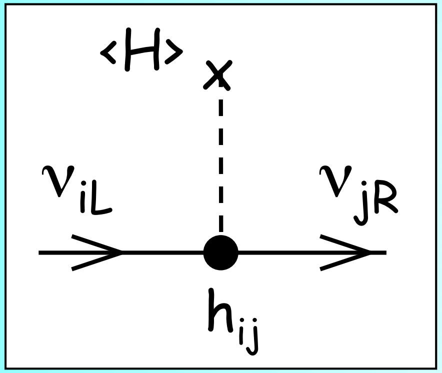
- warm dark matter
- radiative decays → X-rays

Normal
Mass
hierarchy

EW seesaw

Phenomenology of sterile neutrinos

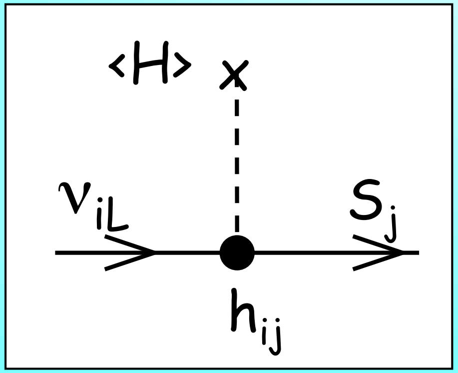
Small Yukawa couplings



$h_{ij} \sim 10^{-13}$

Unnatural
untestable
can be excluded
if $\beta\beta_{0\nu}$-decay is
discovered

Dirac mass term is formed by LH neutrino and new singlet
which may have some particular symmetry properties or
come from the hidden sector of theory



Usual Dirac term is suppressed
by seesaw or multi-singlet couplings

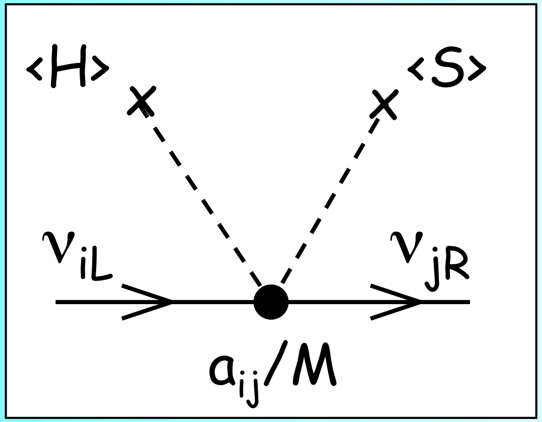
Suppressed by
symmetry or seesaw

Small effective couplings

renormalizable coupling is suppressed by symmetry

effective coupling produced by non-renormalizable operators:

$$a_{ij}\, l_{iL} \nu_{iL}\, H \frac{S}{M}$$



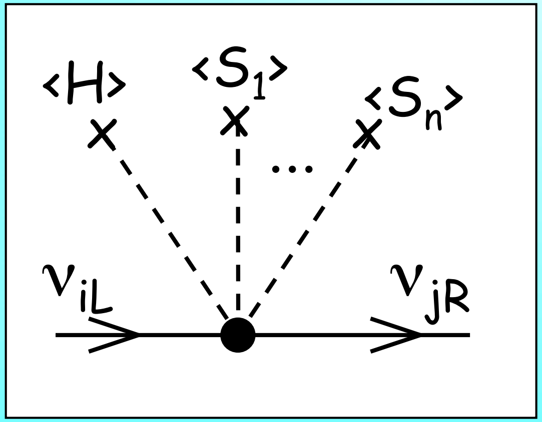
$$h_{ij} = a_{ij} \frac{\langle S\rangle}{M}$$

For $a_{ij} \sim O(1)$

$$\frac{\langle S\rangle}{M} \sim 10^{-13}$$

SUSY / GUT scales?

$m_{3/2}/M_{Planck}$



in general

Zee-mechanism

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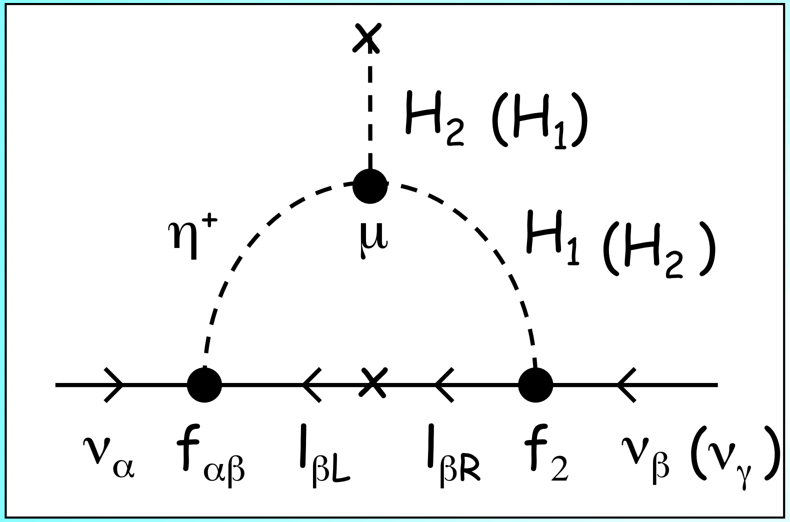
No RH neutrinos

new bosons: singlet η^+, doublet H_2



$$\boxed{\begin{aligned} m_\nu = A\,[&(f\,m^2 + m^2 f^T) - \\ - \; &v\,(\cos\beta)^{-1}\,(\,f\,m\,f_2 + f_2{}^T m\;f^T)\,] \end{aligned}}$$

$$A = \sin 2\theta_Z \;\ln(M_2/M_1)/\,(8\pi^2\, v \tan\beta)$$

$$m = (m_e\,,\, m_\mu,\, m_\tau)$$

X-G He

P. Frampton, M. C. Oh

T. Yoshikawa

If only H_1 couples with leptons

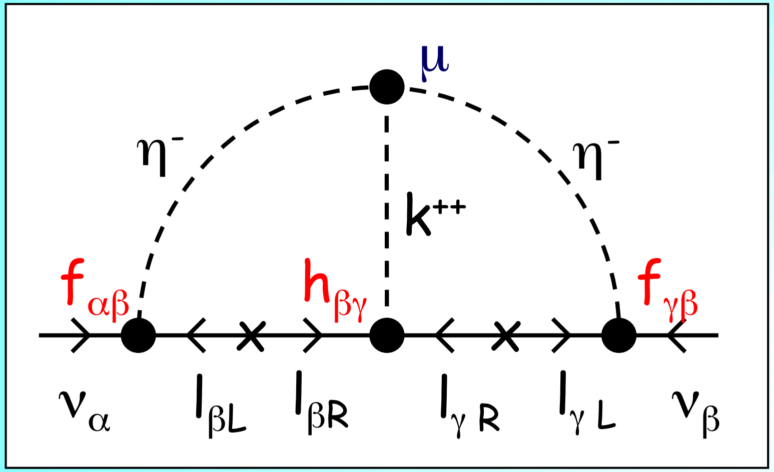
$$\begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ & 0 & m_{\mu\tau} \\ & & 0 \end{pmatrix}$$

Can not reconcile
two large mixings
one small mixing and
hierarchy of Δm^2

- inverse hierarchy of $f_{\alpha\beta}$
- $f_{\alpha\beta} < 10^{-4}$

Zee-Babu mechanism

x



K.S. Babu,
C. Macesanu

No RH neutrinos
new scalar singlets η^- and k^{++}

$$\boxed{m_\nu \sim 8\,\mu\, f\, m_l\, h\, m_l\, f\, I}$$

m_l = diag (m_e, m_μ, m_τ)

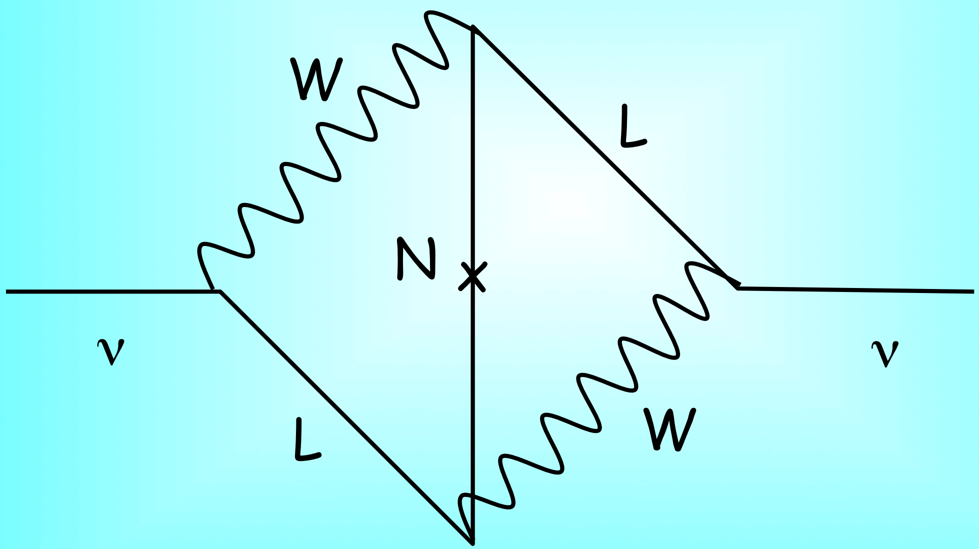
f and h are matrices of the couplings in the flavor basis

Features:
- the lightest neutrino mass is zero
- neutrino data require inverted hierarchy of couplings h
- f, h ~ 0.1

Testable:
- new charged bosons
- decays $\mu \to \gamma\ e$, $\tau \to 3\mu$ within reach of the forthcoming experiments

Two loop mechanism

K S Babu, E Ma



If usual neutrinos mix with heavy Majorana lepton N

4th generation of fermions → main contribution

Extra dimensions

New mechanism of generation
of small Dirac masses: overlap suppression

$$\boxed{\text{Mass term:} \quad m\, \overline{f^L}\, f^R \; + \; h.\,c.}$$

If left and right components are localized differently in extra dimensions → suppression:

Related to the fact that the right-handed components of neutrinos have no SM interactions

$$\boxed{m\, \varepsilon\, \overline{f^L}\, f^R \; + \; h.\,c.}$$

amount of overlap in extra D

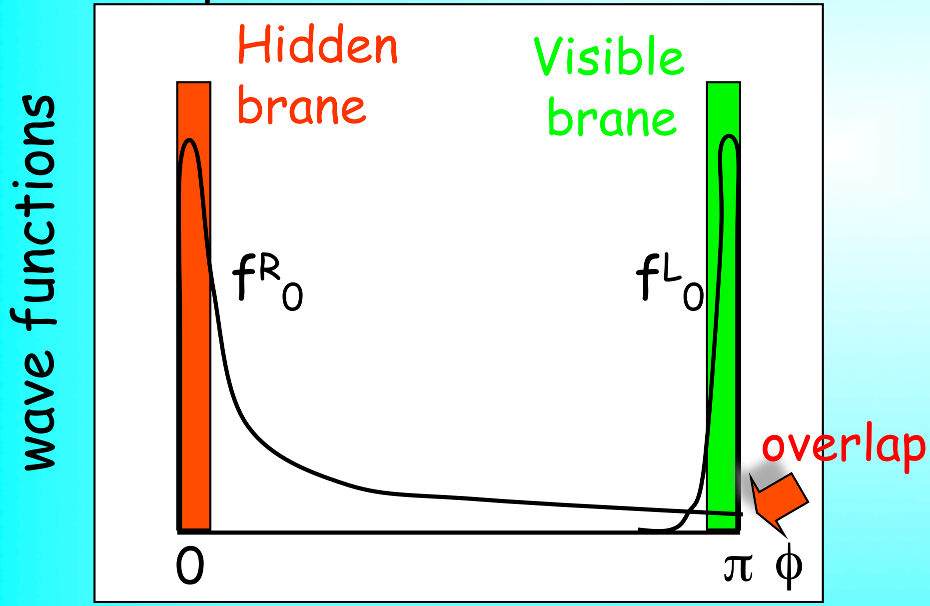
As in strings

Overlap in extra dimensions

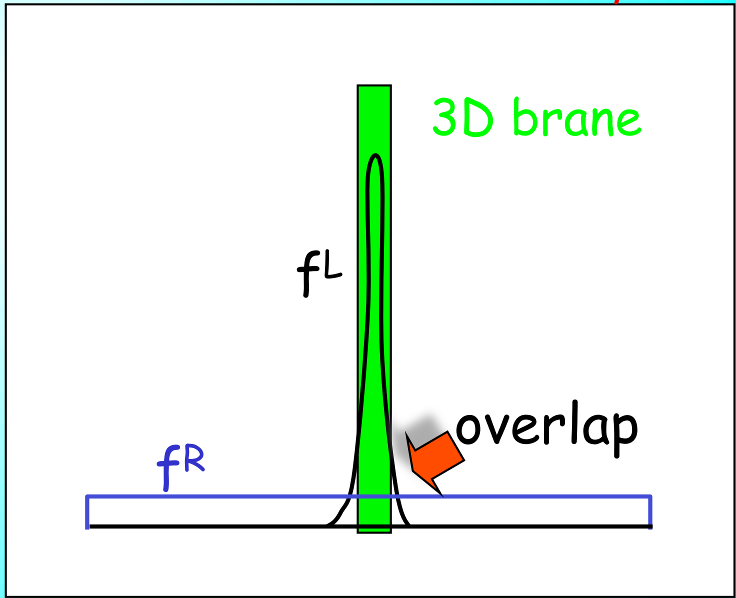
Right handed components are localized differently in extra dimensions

small Dirac masses due to overlap suppression:

Warped extra D *Grossman Neubert*



Flat extra D *Arkani-Hamed, Dvali, Dimopoulos*



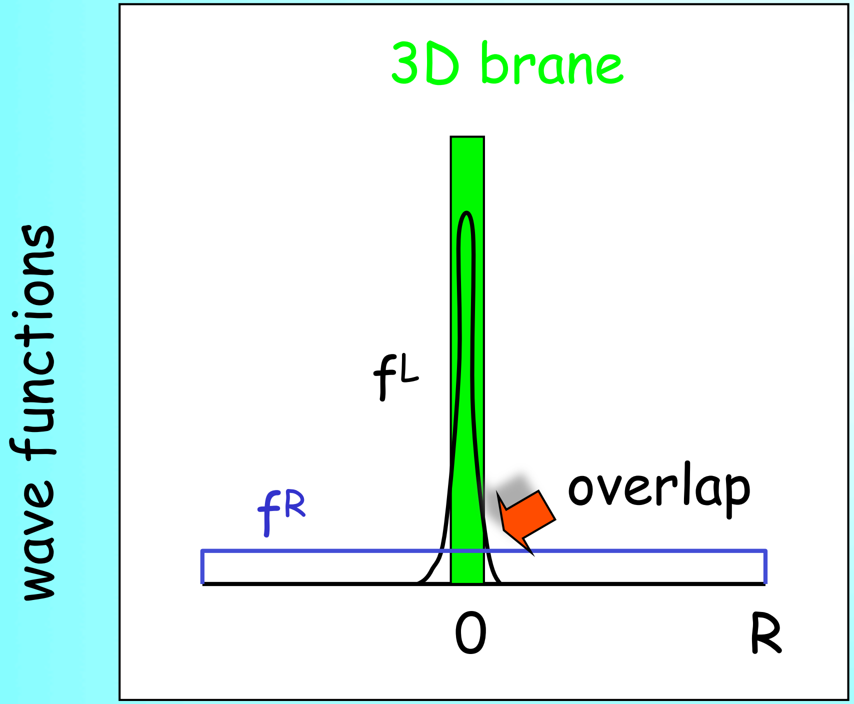
$$m\,\varepsilon\,\overline{f^L}\,f^R + \text{h. c.}$$

amount of overlap in extra D

...in large flat extra D

Arkani-Hamed, Dvali, Dimopoulos

Large extra D + 3D brane



RH neutrinos propagate in the bulk

From WF normalization: $f^R \sim 1/\sqrt{R}$

Width of the brane: $d = 1/M$

M ~ 10 - 100 TeV is the fundamental scale

Overlap of the wave functions:

$d\, f^R \sim 1/\sqrt{MR}$

for δ extra D: $1/\sqrt{M^\delta V_\delta}$

$$m_D = \lambda\, v_{EW} \left(\frac{1}{M^\delta V_\delta} \right)^{\frac{1}{2}} = \lambda\, v_{EW}\, M/M_{Pl}$$

Supersymmetry

Genuine SUSY mechanisms/features

New mass scales

SUSY breaking scale, $m_{3/2}$

μ – mass term for 2 higgses

$$\boxed{m_\nu \sim \mu\, v_{EW}\, M_{GUT}^{-1}}$$

New interactions

New phenomenology

New particles

Neutralinos: (higgsinos, wino, bino)

Neutral fermions with Majorana masses

Neutrinos are not unique:

→ can mix with neutralinos if R-parity is broken

→ new mechanism of neutrino mass generation

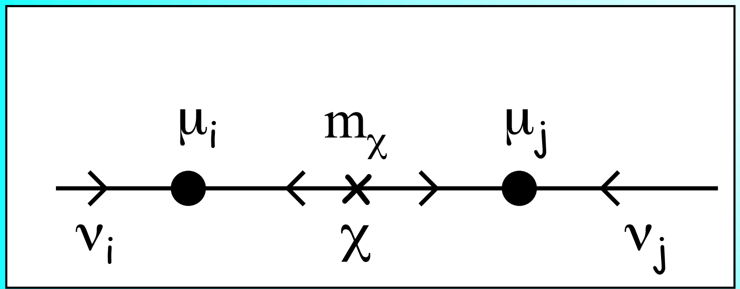
R-parity violating SUSY

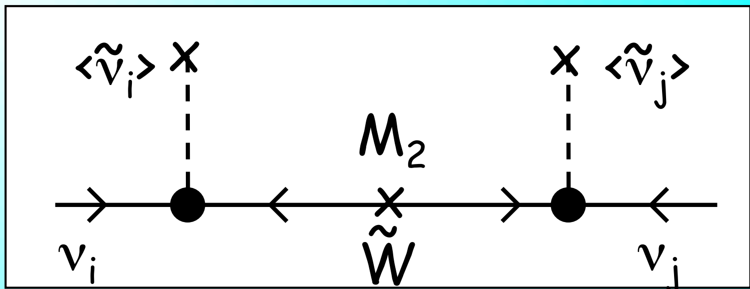
×

Superpotential: Z_3 - baryon triality (Ibanez, Ross)

$$W = -\mu_\alpha L_\alpha H_U - 1/2\, \lambda_{\alpha\beta\, m} L_\alpha L_\beta e_m + \lambda'_{\alpha nm} L_\alpha Q_n d_m - h_{nm} H_U Q_n u_m$$

Bi-linear (Hall-Suzuki) $\alpha = 0, 1, 2, 3$, $m = 1,2,3$ $L_0 = H_D$





in the basis $\langle\tilde{\nu}_m\rangle = 0$

in the basis $\mu_m = 0$

$\frac{h_b^2}{16\pi^2}$

Neutrino mass

$m_{ij} = X\, \mu_i\, \mu_j$, $X \sim \cos^2\beta / m_\chi$

$m_{ij} = A\, \langle\nu_i\rangle \langle\nu_j\rangle$

EW seesaw

Only one neutrino acquires mass, mixing is determined by μ_i/μ_j

III. Neutrino mixing and flavor symmetries

on crossroads...

Mixing pattern

Tri-bimaximal mixing

Quark-Lepton complementarity

Quark-lepton universality

Assuming that it is not accidental and there is certain fundamental physics behind

Based on observation: lepton mixing = maximal mixing - quark mixing

The same principle as in quark sector

Large mixing is related to smallness of neutrino mass and weak mass hierarchy of neutrinos

<u>With different implications</u>

Tri-bimaximal mixing

L. Wolfenstein

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

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

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:
$\theta_{23} = \pi/4 \; \lozenge - \pi/4$

Symmetry from mixing matrix

The TBM- mass matrix

Mixing from diagonalization of mass matrix

$$m_{TBM} = U_{TBM}\, m^{diag}\, U_{TBM}^{T}$$

$$m^{diag} = \mathrm{diag}\,(|m_1|,\ |m_2|e^{i2\phi 2},\ \ |m_3|e^{\,i2\phi 3}\ )$$

$$m_{TBM} = \begin{pmatrix} a & b & b \\ \dots & \tfrac{1}{2}(a+b+c) & \tfrac{1}{2}(a+b-c) \\ \dots & \dots & \tfrac{1}{2}(a+b+c) \end{pmatrix}$$

$a = (2m_1 + m_2)/3$ $\qquad$ $b = (m_2 - m_1)/3$ $\qquad$ $c = m_3$

The matrix has S_2 permutation symmetry $\quad \nu_\mu$ <-> ν_τ

TBM-symmetry

TBM mass relations

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

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

Three angles → three conditions

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

Key point is that relations are simple and mass matrix has certain symmetry

or $\Sigma_\alpha m_{e\alpha} = \Sigma_\beta m_{\mu\beta}$

Invariance: $V_i^T m_{TBM} V_i = m_{TBM}$

$$S = \begin{pmatrix} -1 & 2 & 2 \\ \dots & -1 & 2 \\ .. & \dots & -1 \end{pmatrix} \qquad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

The mass matrix of the charged leptons is diagonal due to symmetry

$$T = \begin{pmatrix} 1 & 0 & 0 \\ \dots & \omega^2 & 0 \\ \dots & \dots & \omega \end{pmatrix}$$

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

$T^+ (m_e^+ m_e) T = m_e^+ m_e$

S, T, U –elements of S_4

furthermore

$$m_{TBM} = \frac{m_1}{6}\begin{pmatrix} 4 & -2 & -2 \\ -2 & 1 & 1 \\ -2 & 1 & 1 \end{pmatrix} + \frac{m_2}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} + \frac{m_3}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix}$$

Three singular matrices

If m_1 is small

$$m_{TBM} \sim A \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} (1, 1, 1) + B \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} (0, 1, -1)$$

This indicates on

- see-saw, D = 5 operatots
- universal coupling (which can be obtained two product of triplets)
- VEV's of scalar triplet: (1, 1, 1) and (0, 1, -1) which can be obtained easily in SUSY version

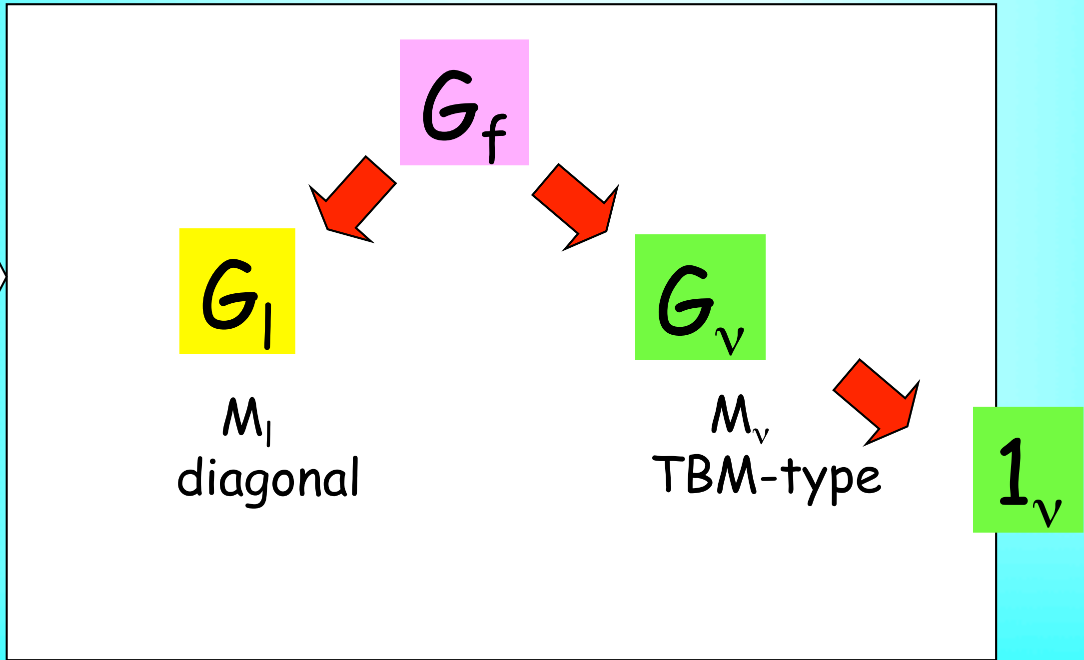
Symmery breaking

No exact flavor symmetry

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

Symmetry is not broken completely; residual symmetries in the neutrino and charged lepton sectors are different

Residual symmetries



In turn, this split originates from different flavor assignments of the RH components of N^c and l^c and different higgs multiplets

Flavons and Flavored higgses

Flavons

Singlet of gauge symmetry group

Separation of the EW symmetry and flavor symmetry breakings

$$\boxed{\frac{1}{\Lambda^{n-1}} L\, e^c H f^n}$$

Λ - above GUT scale?

→ difficult to test

Flavored higgses

Many Higgs doublets
- tests at LHC

Strongly restricted:
- FCNC
- anomalous magnetic moment of muon

Small groups

with irreducible representations 3

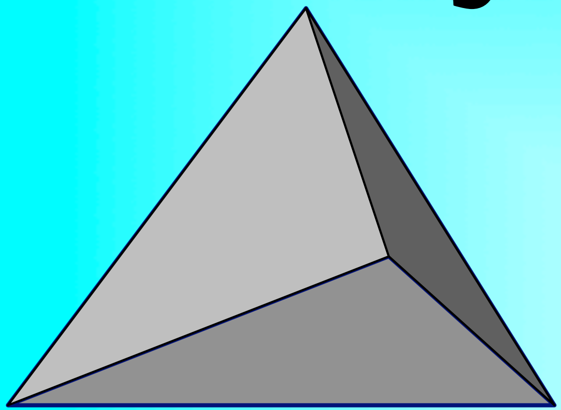
Group	Order	Representations
A_4	12	1, 1′ 1″ 3
S_4	24	1 1′ 2 3 3′
T′	24	1 1′ 1″ 2 2′ 2″ 3
T_7	21	1 1′ 1″ 3 3*
Δ(27)	27	1_1 - 1_9 3 3′

...

A_4 symmetry

E. Ma

G Branco, H P Nilles



A_4 Symmetry group of even permutations of 4 elements

Symmetry of tetrahedron

Generators: S, T

Presentation of the group: $S^2 = 1 \qquad T^3 = 1 \qquad (ST)^3 = 1$

no $U = A_{\mu\tau}$

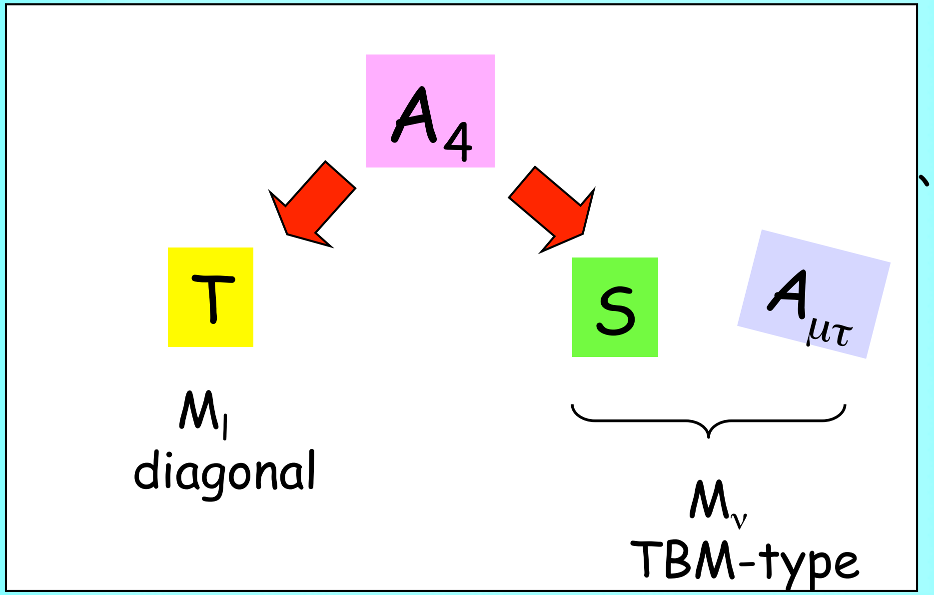
Irreducible representations: $\underline{3}$, $\underline{1}$, $\underline{1}'$, $\underline{1}''$

Products and invariants

$$\underline{3} \times \underline{3} = \underline{3} + \underline{3} + \underline{1} + \underline{1}' + \underline{1}''$$

$$\underline{1}' \times \underline{1}'' \sim \underline{1}$$

A_4 symmery breaking



``accidental'' symmetry due to particular selection of flavon representations and configuration of VEV's

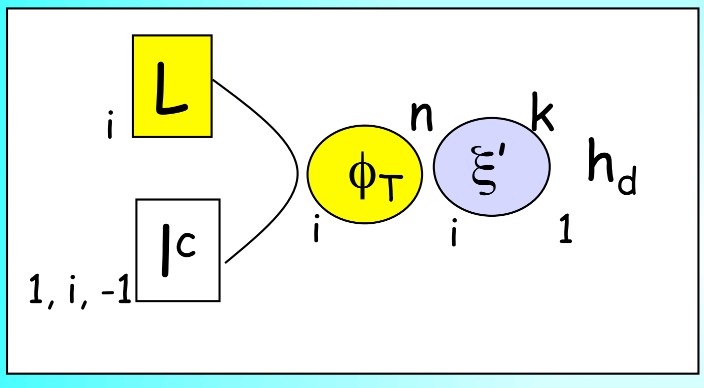
In turn, this split originates from different flavor assignments of the RH components of N^c and l^c and different higgs multiplets

An A_4 model

G. Altarelli
D. Meloni

Yukawa sectors

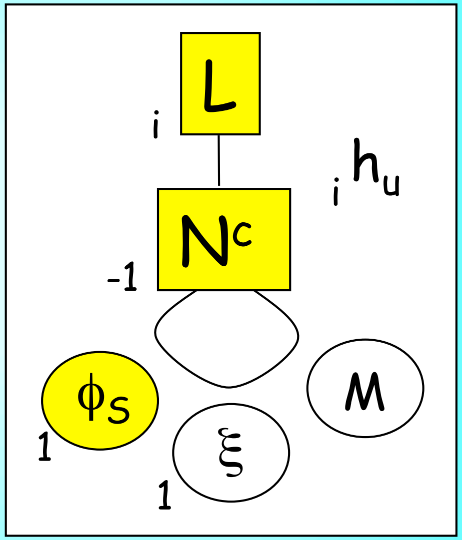
Charged lepton



$< \phi_T > = v_S \, (0, 1, 0)$

$n = 1, \ldots \qquad k = 0, \ldots$

Neutrinos



$< \phi_S > = v_S \, (1, 1, 1)$

A_4	Z_4
3	1
	i
1	-1
1′	-i
1″	

at multiplets

Flavon sector

				$U(1)_R$
ϕ_T	ϕ_S	ξ	ξ'	0
-1 ϕ_T^0	1 ϕ_S^0	1 ξ^0		2

Particular selection of representations

Driving fields → Vacuum alignment

GUT-scale or higher?

Generic problem

$$m = F(Y, v)$$

Mechanism of mass generation

Yukawa couplings

VEV's

- different contributions
- high order corrections

VEV alignment

follow from independent sectors

Yukawa sector

Scalar potential

TBM

All these components should be correlated

``Natural" – consequence of symmetry?

tune by additional symmetries

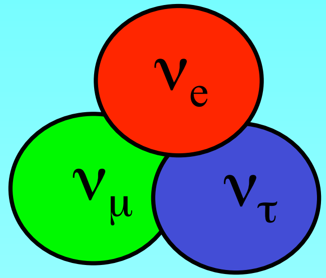
one step constructions do not work

From leptons to quarks

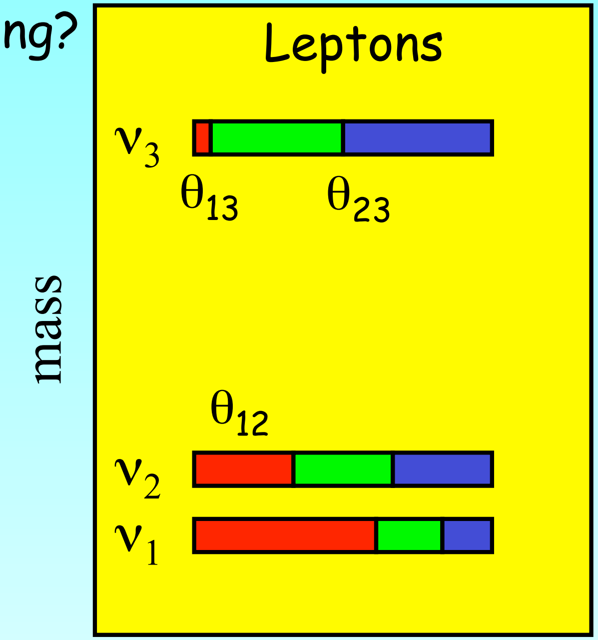
Discrete flavor symmetries have not been mentioned
in the talk by A Weiler

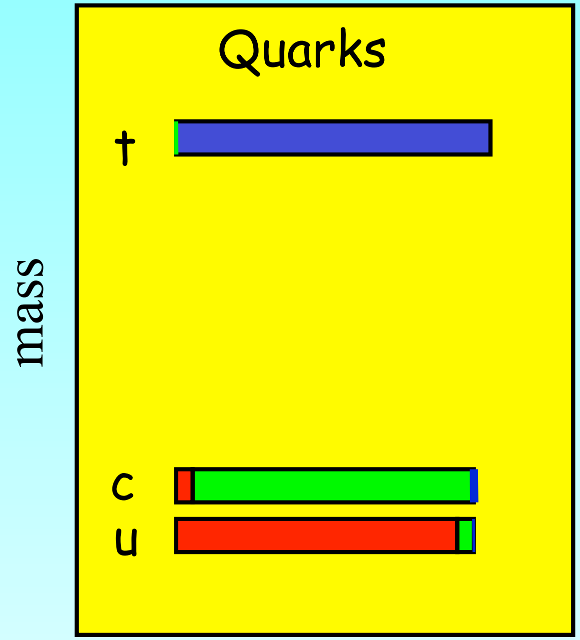
Do quarks need the leptonic discrete symmetries?

Mass & Mixing



zero 1-3
mixing?





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

$q_d \;=\; U_{CKM}^{+}\, q_u$

$q_{\underline{u}} = (u, c, t)$

Extending symmetries

the same 3,1 representations

$V_{CKM} = I$ $U_{PMNS} = U_{tbm}$

As the lowest order

Corrections from high order operators

different representations

2 + 1 structure
→ different groups

T' - symmetry

Order 24, double covering A_4 or binary tetrahedron group

Generators: S, T, R

Presentation: $T = 1$, $S^2 = R$, $(ST)^3 = 1$ $\quad R^2 = 1$ $\qquad R = \begin{cases} 1 & \text{odd} \\ -1 & \text{even} \end{cases}$ dimension of representation

Irreducible representations: $1,\ 1',\ 1'',\quad 2,\ 2',\ 2'',\quad 3$

complex conjugate

Products and invariants

$3 \times 3 = 1 + 1' + 1'' + 3 + 3$

$1' \times 1'' = 1$

as in A_4

$2^a \times 3 = 2 + 2' + 2''$

$2 \times 2 = 1 + 3$

$1 \times 2 = 2$

(with ``conservation'' of primes)

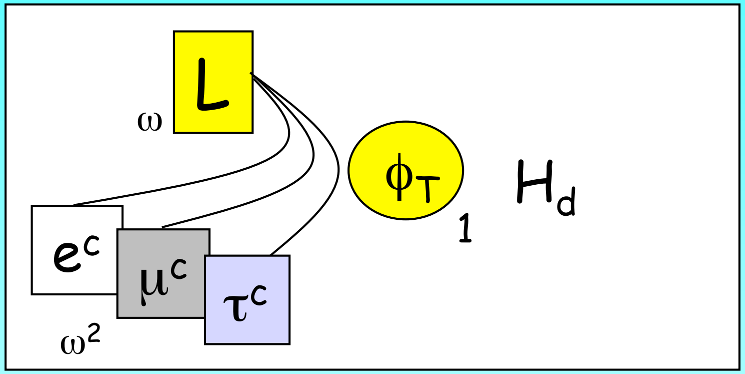
New flavor structure

T' - symmetry model

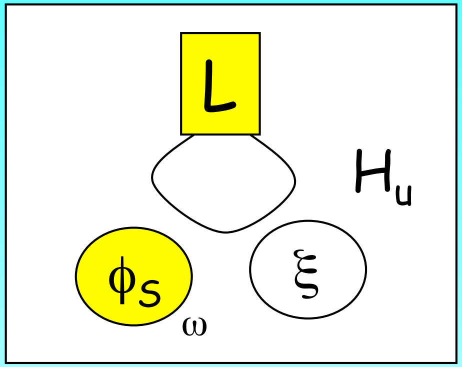
F. Feruglio,
C. Hagedorn
Yin Lin
L. Merlo

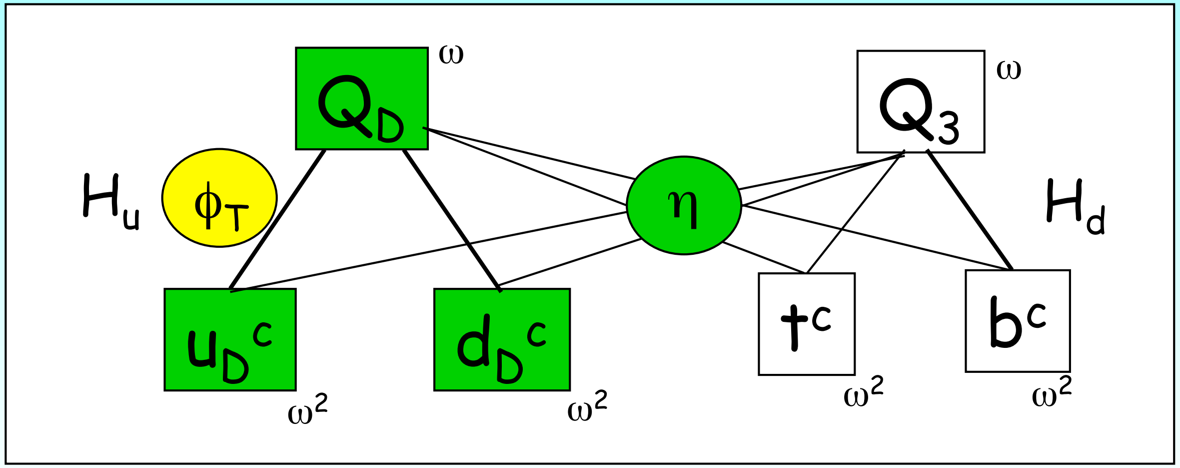
$T' \times Z_3 \times U(1)_{FN}$

Charged lepton



Neutrinos





T'	Z_3
3	1
2	ω
2'	ω^2
2''	
1	
1'	
1''	

at multiplets

Vacuum alignment

$< \phi_S > = v_S\,(1,\ 1,\ 1)$

$< \phi_T > = v_T\,(1, 0, 0)$

$< \eta > = v\,(1, 0)$

$<\xi> = u \qquad <\xi''> = <\bar{\xi}> = 0$

x

Is TBM accidental?

Numerology without underlying framework

Interplay of various independent contributions

1. Experiment: deviations from TBM mixing

RGE-effects

Symmetry mass relations can be broken maximally

2. No simple and convincing model for TBM

- Complicated structure, large number of assumptions and new parameters
- Follows from certain correlation of unrelated sectors

3. Often: no connection between masses and mixing additional symmetries are introduced

4. Inclusion of quarks: further complication. GUT – additional requirements

QLC and QL- symmetries

QLC relations

$\theta^{l}_{12} + \kappa\, \theta^{q}_{12} \sim \pi/4$ $\theta^{l}_{23} + \theta^{q}_{23} \sim \pi/4$

A.S.
M. Raidal
H. Minakata

$\kappa = 2^{-1/2}$ or 1

qualitatively:

- 2-3 leptonic mixing is close to maximal because 2-3 quark mixing is small
- 1-2 leptonic mixing deviates from maximal substantially because 1-2 quark mixing is relatively large

Possible implications

``Lepton mixing = bi-maximal mixing – quark mixing"

Quark-lepton symmetry

Unification or family symmetry

Existence of structure which produces bi-maximal mixing

See-saw? Properties of the RH neutrinos

Bi-maximal mixing

$U_{bm} = U_{23}^m U_{12}^m$

Two maximal rotations

F. Vissani

V. Barger et al

$$U_{bm} = \begin{pmatrix} \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \sqrt{\frac{1}{2}} \\ \frac{1}{2} & -\frac{1}{2} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

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

In seesaw: structure of Majorana mass matrix of RH neutrinos

In the lowest approximation:

$V_{quarks} = I, \quad V_{leptons} = V_{bm}$

$m_1 = m_2 = 0$

Deviation

Corrections generate
- mass splitting
- CKM and
- deviation from bi-maximal

QLC predictions

Leptons

$V_\nu = V_{bm}$ ← Seesaw?

$V_l = V_{CKM}$

q-l symmetry

Quarks

$V_u = I$

$V_d = V_{CKM}$

$V_{PMNS} = V_l^+ V_\nu = V_{CKM}^+ V_{bm}$

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

Predictions:

$\sin\theta_{13} = \sin\theta_{23} \sin\theta_C = 0.16$ ⇒ large !

H. Minakata, A.S.

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

RGE -> can reduce

M. Schmidt, A.S.

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

BM - symmetry

BM mass relations

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

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

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

Invariance: $V_i^T m_{BM} V_i = m_{BM}$

$$S_{BM} = \begin{pmatrix} 0 & -\sqrt{\frac{1}{2}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{2}} & \frac{1}{2} & -\frac{1}{2} \\ -\sqrt{\frac{1}{2}} & -\frac{1}{2} & \frac{1}{2} \end{pmatrix} \qquad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

The mass matrix of the charged leptons is diagonal due to symmetry with respect to transformations:

$T = \mathrm{diag}\,(-1, -i, i)$ $\qquad$ T, S_{BM} generators of S_4

S_4-symmetry

Order 24, permutation of 4 elements

Generators: S, T, U

Presentation: $T^3 = 1$, $S^2 = 1$, $(ST)^3 = 1$ $U^2 = 1$

or

$A^3 = B^4 = (BA^2)^2 = 1$

Irreducible representations:

1 , 1′ , 2, 3, 3′

Products and invariants

$3 \times 3 = 3' \times 3' = 1 + 2 + 3 + 3'$

$3 \times 3' = 1' + 2 + 3 + 3'$

$1' \times 1' = 1$

$2 \times 3 = 2 \times 3' = 3 + 3'$

New flavor structure

$2 \times 2 = 1 + 1' + 2$

$1' \times 2 = 2$

Model for BM-mixing

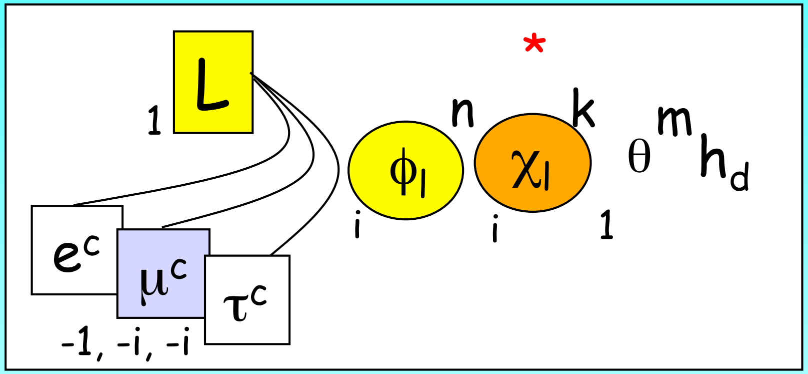
G. Altarelli
F. Feruglio,
L. Merlo

×

S_4 *	Z_4
3	1
3′	i
2	-1
1	-i
1′	

at multiplets

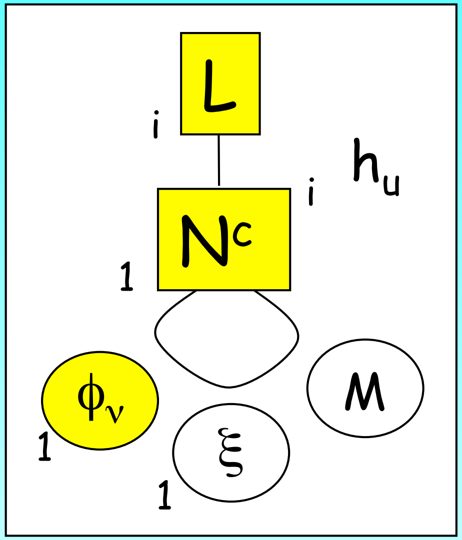
Charged lepton



$<\phi_l> = v_l\ (0, 1, 0)$

$<\chi_l> = v_l\ (0, 0, 1)$

Neutrinos



$<\phi_\nu> = v_\nu\ (0, 1, -1)$ *

No doublet representations

Flavon sector

					U(1)$_R$
i ϕ_l	i χ_l		ϕ_ν	ξ	0
	-1 χ_l^0	-1 ψ_l^0	1 ϕ_ν^0	ξ^0	2 Driving fields

Froggatt-Nielsen sector

	e^c, μ^c, τ^c	θ
U(1)$_{FN}$	2, 1, 0	-1

Complementarity or Cabibbo "haze "

Deviations from BM due to high order corrections *P. Ramond*

Altarelli et al

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

Weak complementarity or
Cabibbo haze

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

or

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

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

Golden ratio

Observation: $\cot\theta_{12} = \phi$ $\tan 2\theta_{12} = 2$

$\phi = \frac{1}{2}(1+\sqrt{5})$ is golden ratio

Appears from diagonalization of the neutrino mass matrix
$$\begin{pmatrix} 0 & m & 0 \\ m & m & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Invariant under $Z_2 \times Z_2$

$$R = \frac{1}{\sqrt{5}}\begin{pmatrix} -1 & 2 & 0 \\ 2 & 1 & 0 \\ 0 & 0 & \sqrt{5} \end{pmatrix} \qquad R' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

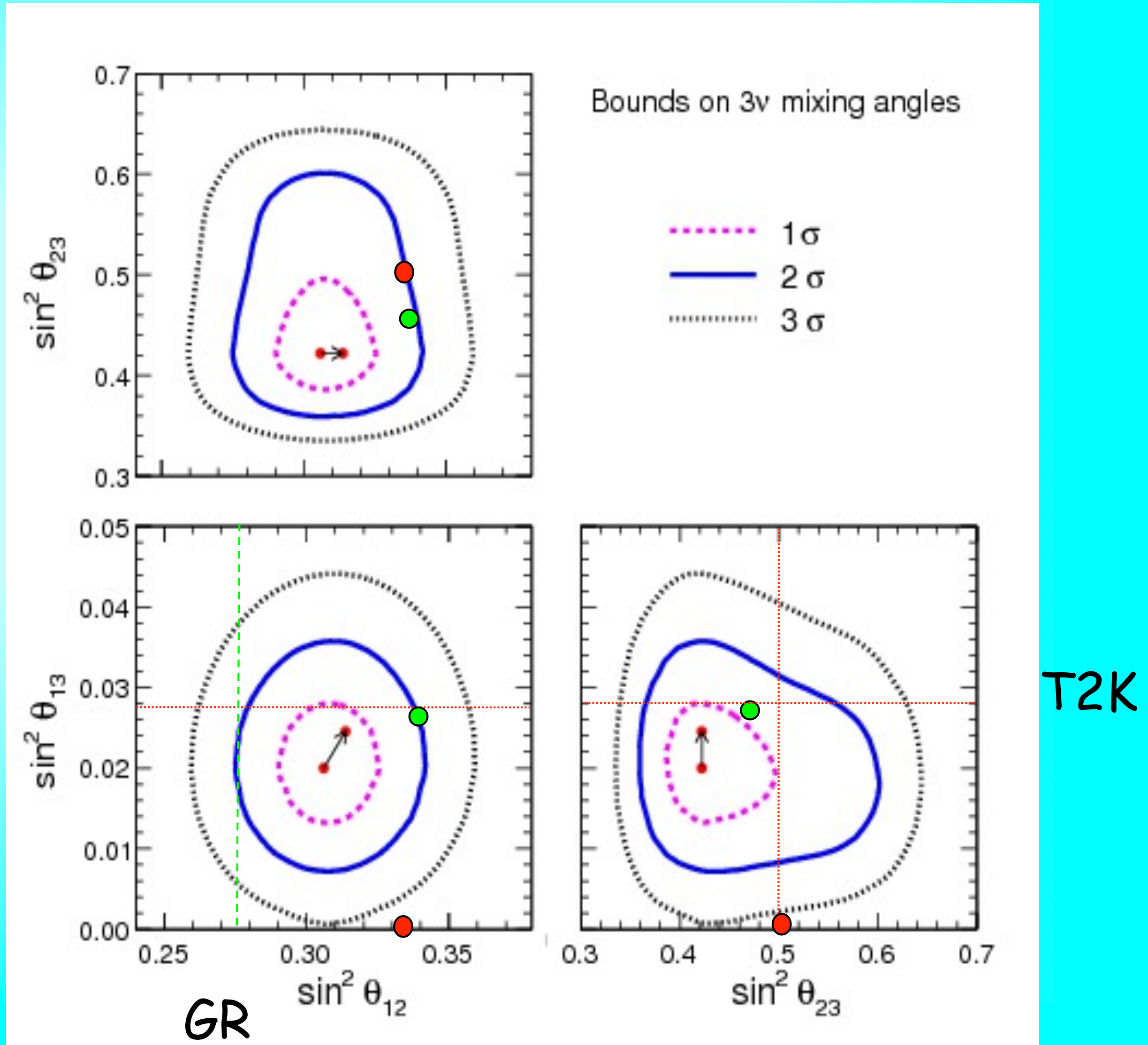
A_5 symmetry

Global fit

G.L Fogli et al., 1106.6028 [hep-ph]

- TBM
- QLC

New reactor fluxes
- shift by arrows



Neutrino and unification

Correspondence:

u_r , u_b , u_j <-> ν
d_r , d_b , d_j <-> e

Symmetry:

Leptons as 4^{th} color   Pati-Salam

Unification:

Form multiplet of the extended gauge group, in particular, 16-plet of SO(10)

Can it be accidental?

GUT

Unification of
- quarks & leptons
- couplings

SO(10) GUT + ...

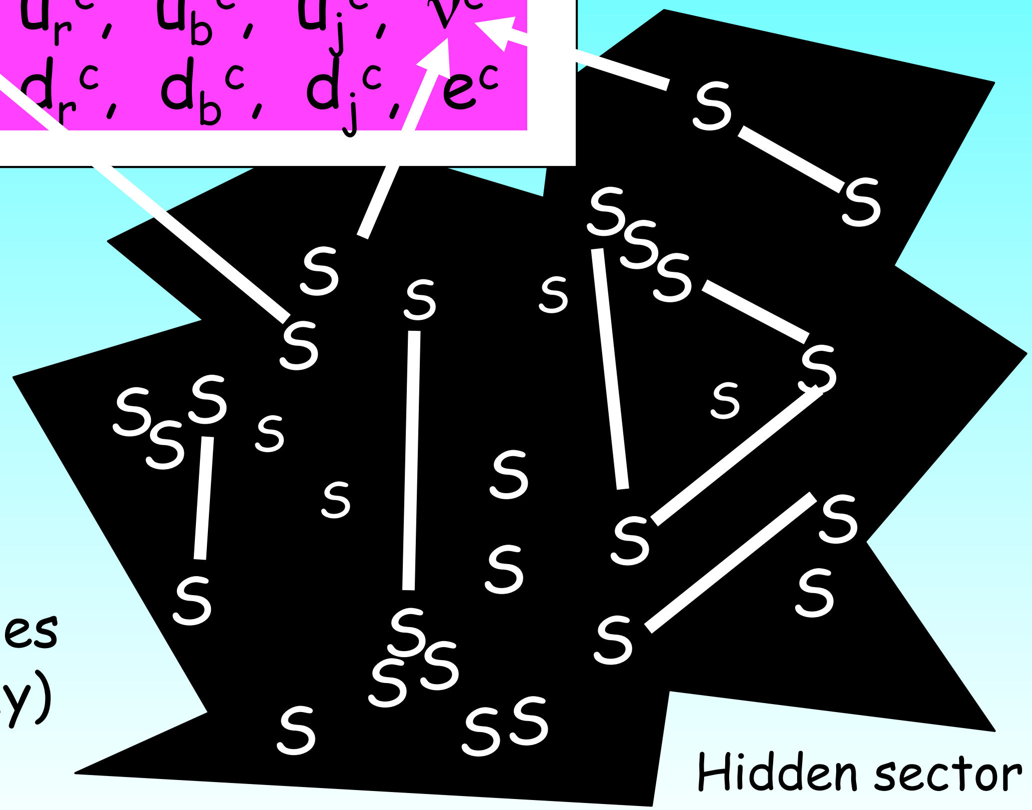
Hagedorn
Schmidt
AS

Something is missed?

RH-neutrino

16

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



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

SO(10) x G_f

More challenging

$SO(10) \times G_{flavor}$ + ...

New elements should be added

C Hagedorn
M. Schmidt
A.S.

- Singlet fermions
- 16_H
- flavons
- T_7

Screening of the
Dirac structures
Leptons from quarks

B. Dutta ,
Y Mimura
R. Mohapatra

- 126 $\overline{126}$
- pair vector-like: 16 $\overline{16}$ matter fields
- 10'
- Flavons
- $S_4 \times Z_n$

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

Implications for theory

T2K: $\sin^2\theta_{13} = 0.028$

$$\sin^2\theta_{13} = \begin{cases} O(1)\ \dfrac{\Delta m_{21}^2}{\Delta m_{32}^2} \\ \frac{1}{2}\sin^2\theta_C \\ A\cos^2 2\theta_{23} \end{cases}$$

Naturalness of mass matrix, two large mixings (absence of fine tuning), normal mass hierarchy

QLC (GUT + BM mixing) → Quark-lepton unification + Horizontal symmetry

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

Normal mass hierarchy is preferrable

➡ Violation of TBM with certain flavor hierarchy of the breaking parameters

Accidental?

Minimal SO(10) predictions

Fermion masses (Yukawa couplings) due to 10_H and $\overline{126}_H$

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

$$W = Y_{10}\, 16\, 16\, 10_H + Y_{126}\, 16\, 16\, \overline{126}_H$$

Mass matrices

$$M_u = Y_{10}\, v_u^{10} + Y_{126}\, v_u^{126}$$

$$M_d = Y_{10}\, v_d^{10} + Y_{126}\, v_d^{126}$$

$$M_l = Y_{10}\, v_d^{10} - 3Y_{126}\, v_d^{126}$$

$$M_\nu = Y_{126}\, k$$

assumption: Seesaw II gives main contribution

$$\boxed{M_\nu = a\,(M_l - M_d)}$$

``sum rule"

S. Bertolini, et al

For second and third generation

$$\tan 2\theta_{23} \sim \frac{2\sin\theta_{23}^q}{2\sin^2\theta_{23}^q - (m_b - m_\tau)/m_b}$$

Large 2-3 mixing needs b - τ unification

$$\sin\theta_{13} \sim 0.16$$

$\sin\theta_{13} \sim O(1) \sin\theta_c$

From fit of the quark mases and mixing

U_e3 - expectations

Notice that $\sin\theta_{13} < \sin\theta_{12} \times \sin\theta_{23}$ ~ 0.3 - 0.5

solar sector ⟷ $\sin\theta_{13}$ ⟷ Atmospheric sector

Mass scales: $\sqrt{\Delta m_{21}^2}$ $\sqrt{\Delta m_{31}^2}$

$$\sin\theta_{13} \sim \sqrt{\Delta m_{21}^2 / \Delta m_{31}^2}$$ ~ 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 - expectations

×

- Being small $\sin\theta_{13}$ is generated by small perturbations of the dominant structure of mass matrix responsible for the ``atmospheric" mass/mixing

$$\begin{pmatrix} \lambda & \lambda & \lambda \\ \lambda & 1 & 1 \\ \lambda & 1 & 1 \end{pmatrix} \qquad \lambda \ll 1$$

(matrix elements are defined up to coefficients ~ O(1))

If there is no fine tuning of 12 and 13 elements

$$\boxed{\sin\theta_{13} = \frac{\tan 2\theta_{sun}}{2\tan\theta_{atm}}\sqrt{\frac{\Delta m_{sun}^2}{\Delta m_{atm}^2}\cos 2\theta_{sun}}} \quad \sim 0.2$$

Akhmedov et al

IV. New neutrino states

Active neutrinos

Sterile neutrinos

Sterile neutrino ν_s

Sov. Phys. JETP 26 984 (1968)

in the context of idea of
neutrino–antineutrino oscillations

Light

No weak interactions:
- singlets of the SM symmetry group

RH - components of neutrinos

Couple with usual neutrinos via (Dirak) mass terms

Mix with active neutrinos

may have Majorana mass terms
maximal mixing?

Mass scales

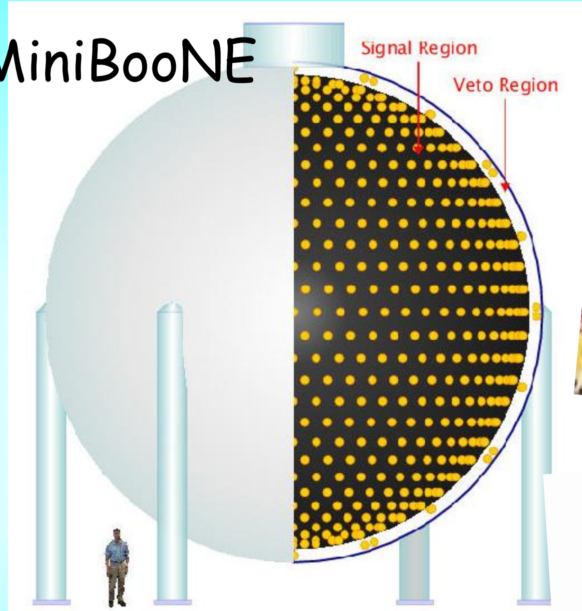
ν_s

Scale	Mass	Motivation
	40 - 70 MeV	- LSND, MiniBooNE
1 MeV		
	~ 10 keV	- Warm Dark matter - Pulsar kick
1 keV		
1 eV	0.5 - 2 eV	- LSND, MiniBooNE - Reactor anomaly - Calibration experiments - Extra radiation
10^{-3} eV	(2 – 4) 10^{-3} eV	- Solar neutrinos - Extra radiation in the Universe

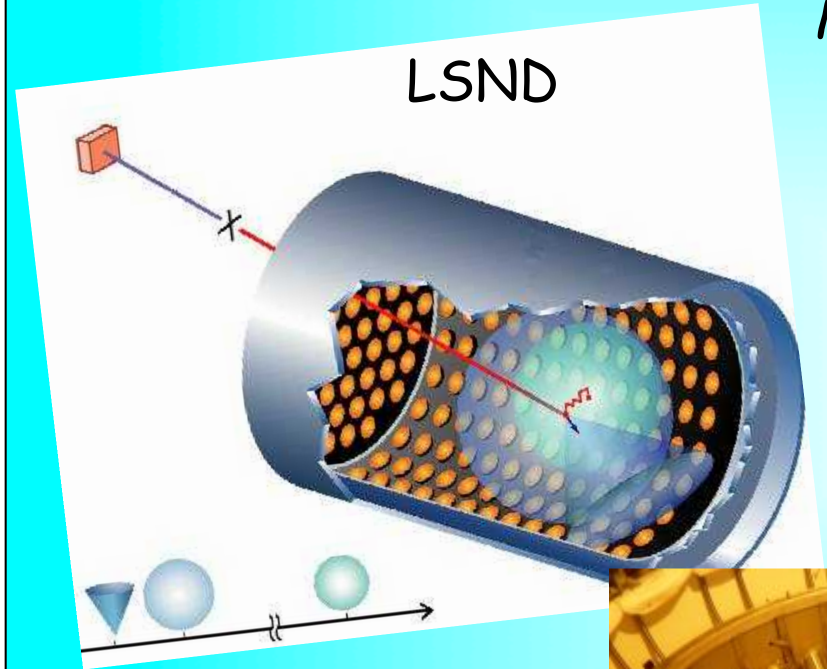
New evidences?

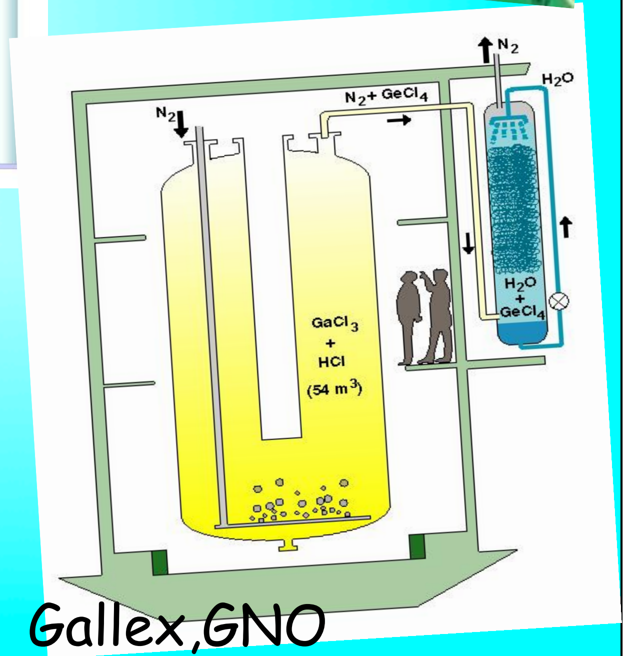
SAGE

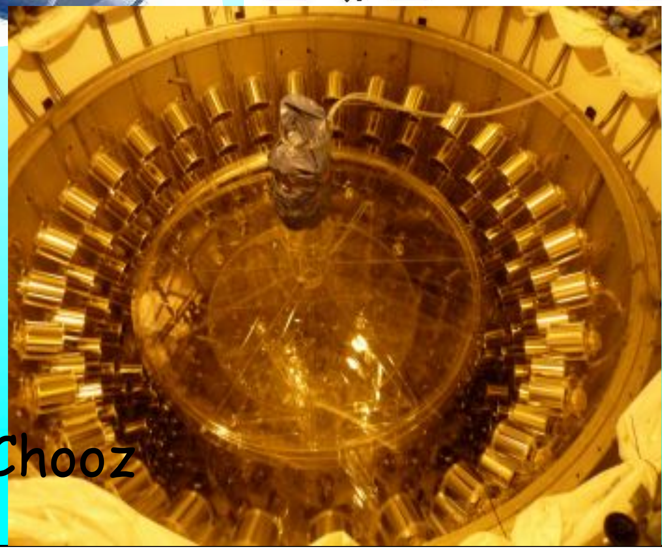
MiniBooNE



LSND



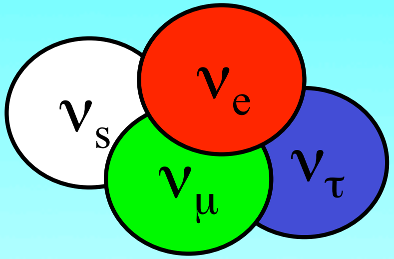


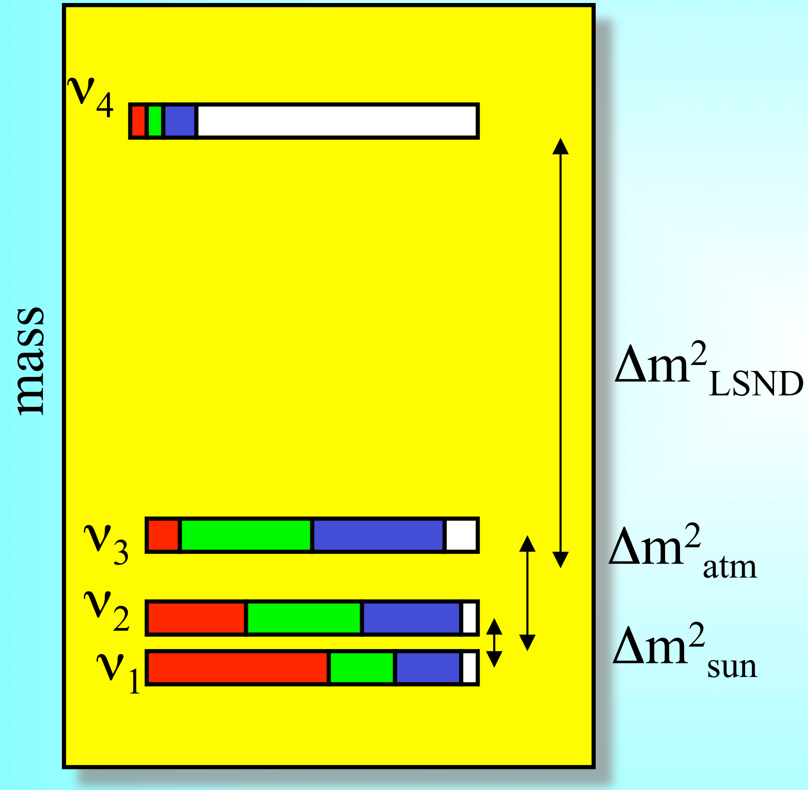


Double-Chooz

Gallex,GNO

(3 + 1) scheme





LSND/MiniBooNE: vacuum oscillations

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

restricted by short baseline exp.
BUGEY, CHOOZ, CDHS, NOMAD

For reactor and source experiments

$$P \sim 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

With new reactor data:

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

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

- additional radiation in the universe
- bound from LSS?

Mixing

Mass matrix

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

For $m_{SS} \sim 1$ eV $\quad \tan\theta_{jS} = m_{jS}/m_{SS} \sim 0.2$ - is not small

produces large corrections to the active neutrino mass matrix

$\delta m_{ij} \sim - \tan\theta_{iS}\tan\theta_{jS}\, m_{SS} \sim 0.04\, m_{SS}$ $\qquad m_{SS} >> m_{ab}, m_{aS}$

In general can not be considered as small perturbation!

Effect can be 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

Applications

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

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

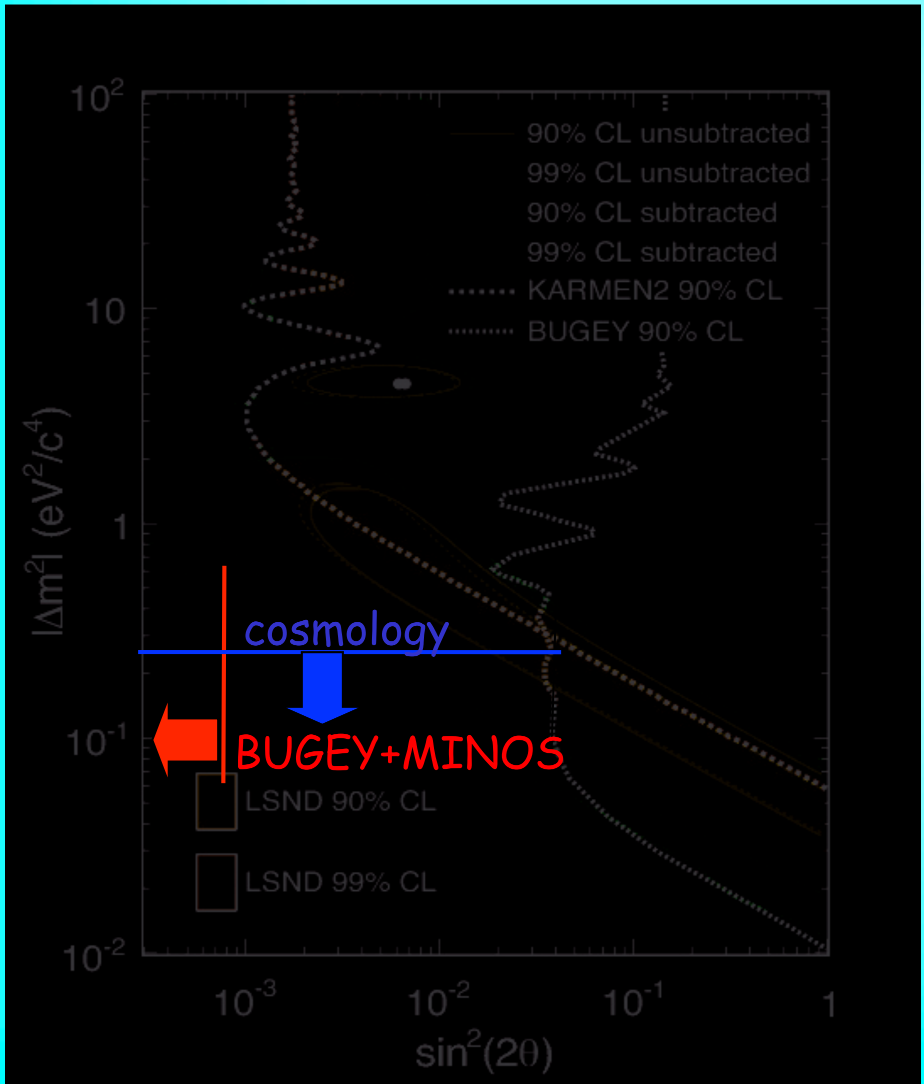
Enhance lepton mixing

Generate TBM mixing

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

MINOS bound

$\nu_\mu - \nu_s$ mixing



In assumption of
no-oscillations in ND

$|U_{\mu 4}|^2 < 0.015$ (90% CL) $\theta_{13} = 0$

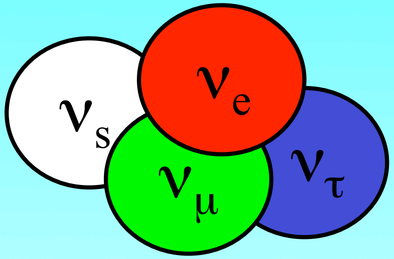
$|U_{\mu 4}|^2 < 0.019$ (90% CL) $\theta_{13} = 11.5°$

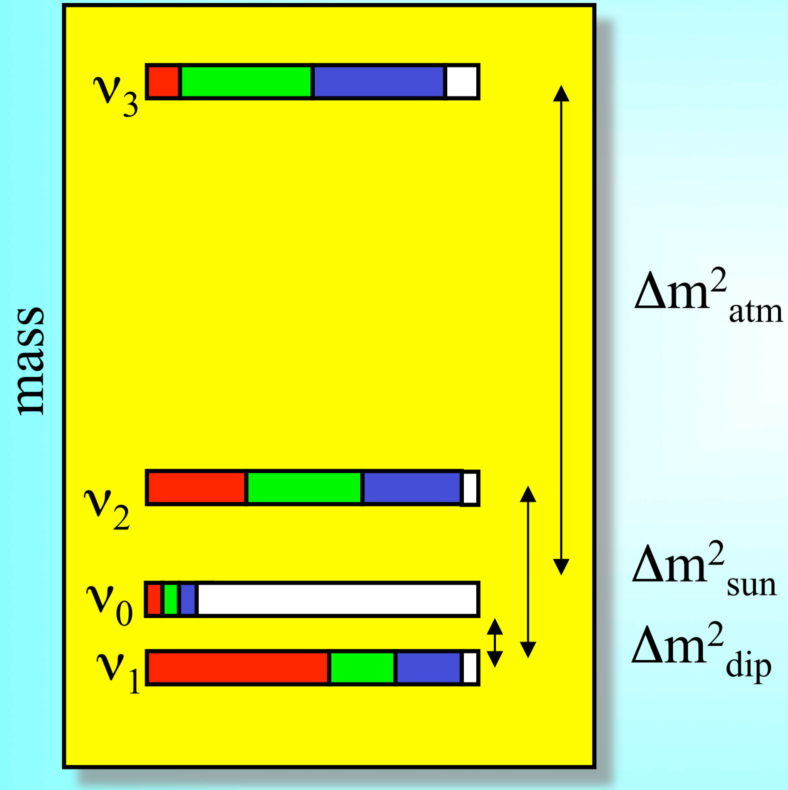
LSND/MiniBooNE:

$|U_{\mu 4}|^2 > 0.025$

$\Delta m_{41}^2 < 0.5$ eV^2

(3 + 1) scheme





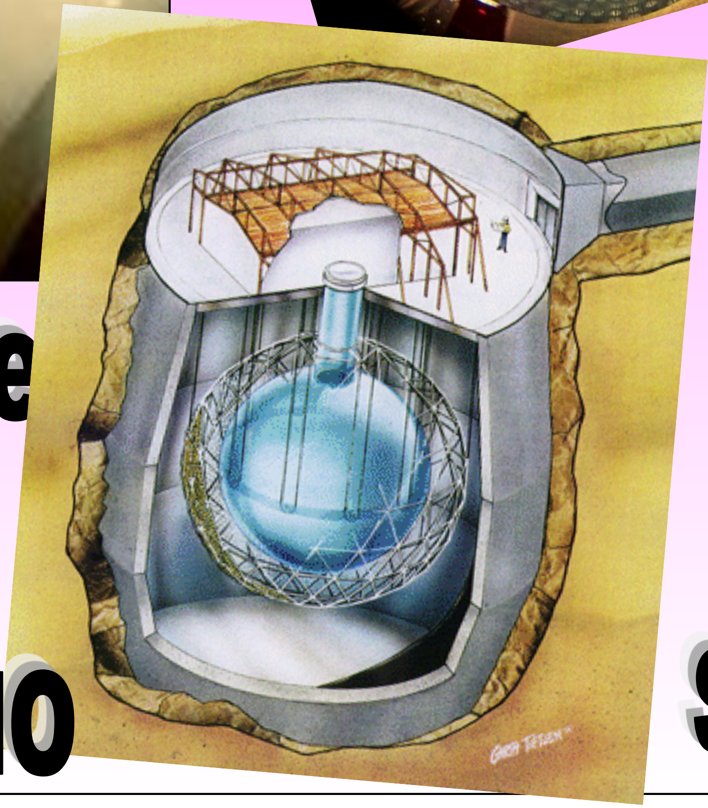
Very light sterile neutrino

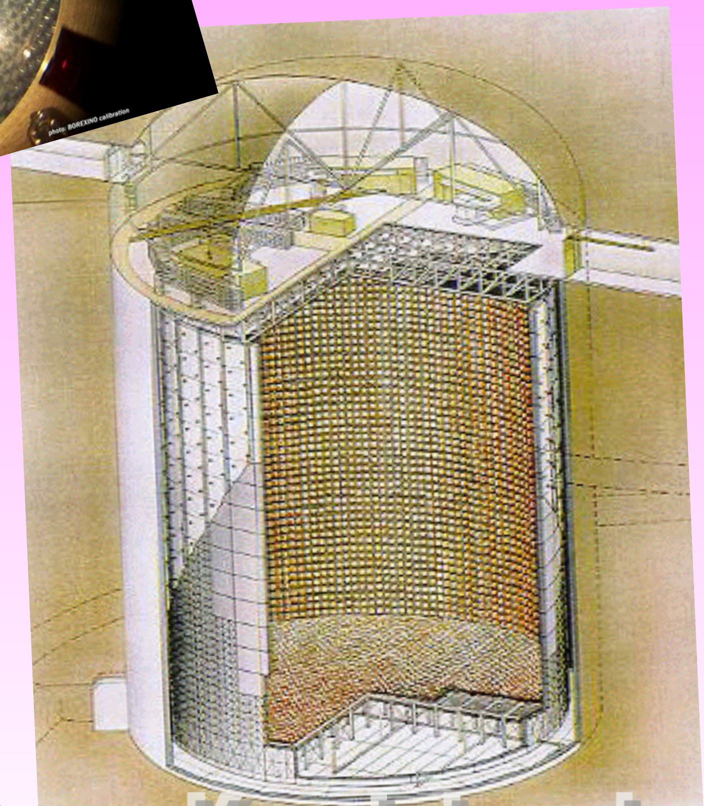
- additional radiation in the Universe
- no problem with LSS (bound on neutrino mass)

Solar neutrino experiments

BOREXINO

Homestake





SNO

SuperKamiokande

Implications; consequences

Theory:

$m_0 \sim 0.003$ eV $\Rightarrow$ $\boxed{m_0 = \frac{M^2}{M_{Planck}}}$ $M \sim 2 - 3$ TeV

mixing

$\sin^2 2\alpha \sim 10^{-3}$ $\alpha \sim \frac{h\, v_{EW}}{M}$ $h = 0.1$

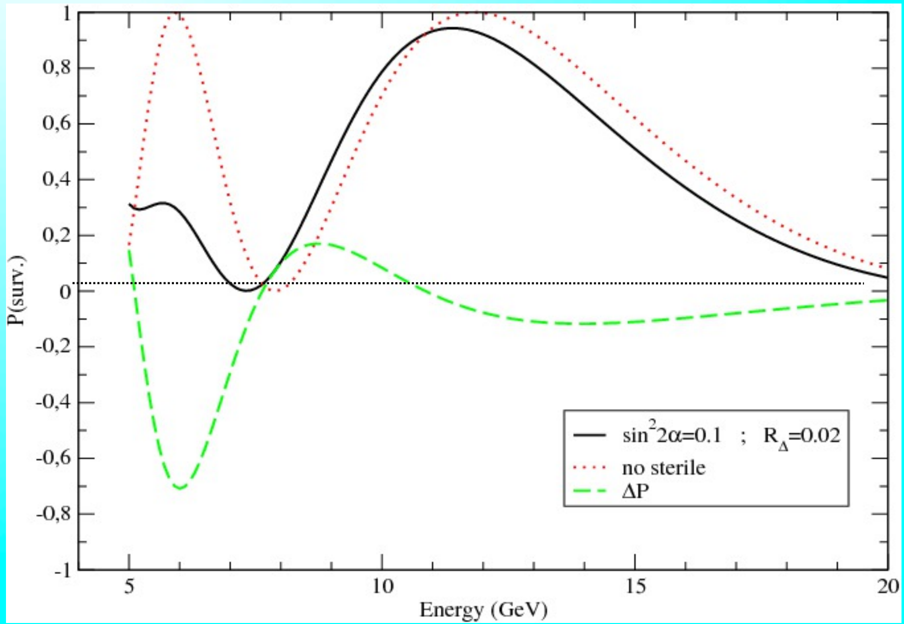
$\sin^2 2\beta \sim 10^{-1}$ $\beta \sim \frac{v_{EW}}{M}$

Phenomenology:

SN

Atmospheric

IceCube DeepCore



Conclusions

Plausible scenario: High mass scale seesaw (Type I) probably related to Grand Unification or/and Planck scale, additional very heavy neutral fermions can be involved

Minimality in principles: the same mechanism
- suppresses usual Dirac mass,
- gives finite mass of neutrino,
- enhances mixing

New (still controversial) evidences of new neutrino states = sterile neutrinos.

Flavor symmetry: may be not in their present realizations
- UHE physics (GUT?)
- broken and ``poluted" by RGE and other effects
- originates from in hidden sector?

TBM - accidental?
Quark-lepton complementarity better chance?

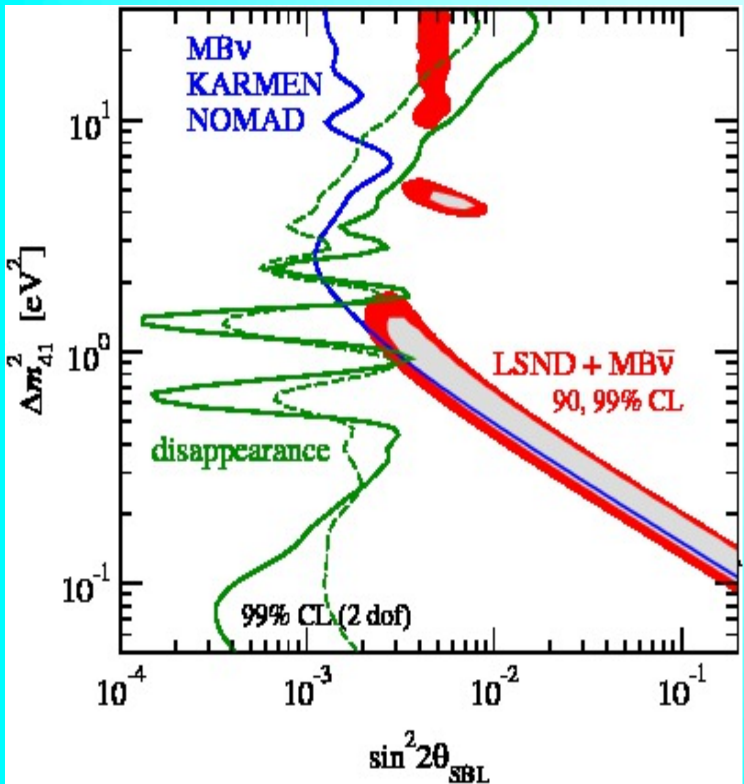
Tests of the picture:
- proton decay
- No extra D,
- SUSY?

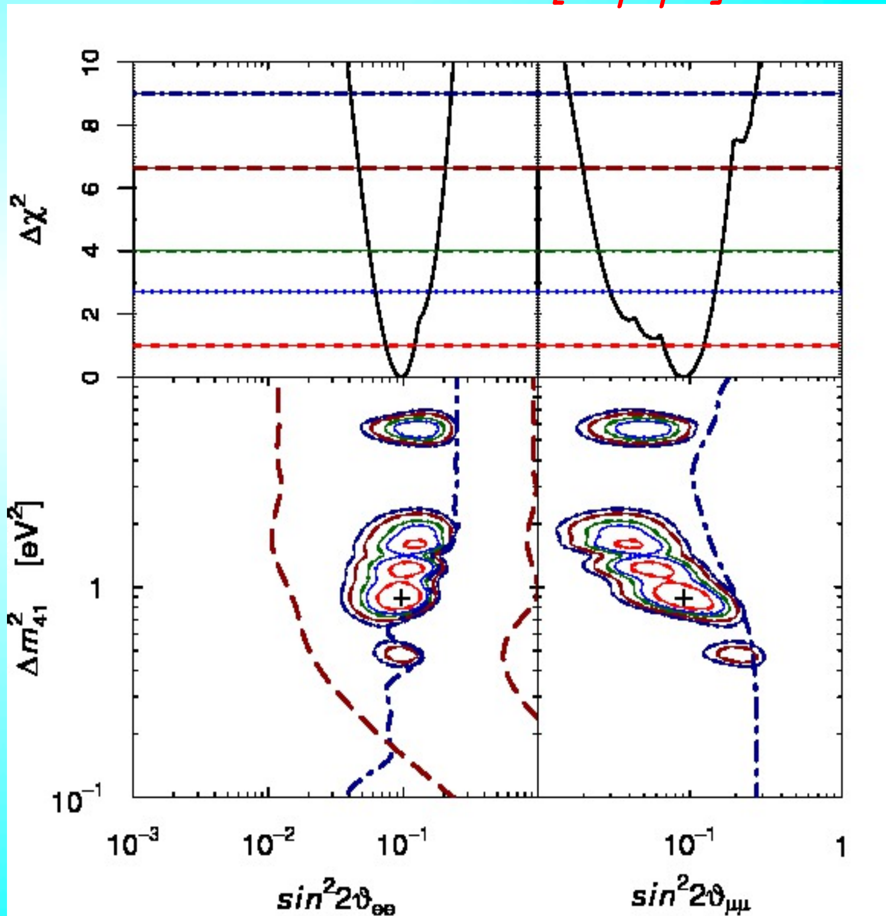
Tests of picture contra:
- Can be strongly affected by possible discoveries at LHC
- Low scale seesaw (lepton number violation)...
- Violation of fundamental symmetries
- discoveries of sterile...

Additional slides

3+1 fit

C Giunti, M Laveder
1107.1452 [hep-ph]





Connections

Rare LNV decays MEG, etc

B-physics

Leptogenesis

Proton Decays

Neutrino Mass

LHC HE accelerator experiments

Leptonic EDM

Cosmology

Further studies of neutrinos may reveal some new features

Real or accidental?

Tri-bimaximal mixing

Q-L-complementarity

Very small 1-3 mixing

Maximal 2-3 mixing

Koide relation

Real:
immediate ``one step"

Accidental: interplay of different independent factors / contributions

Discovery of degenerate neutrino mass spectrum would be convincing evidence of existence of symmetry

KATRIN

Heidelberg-Moscow

Degenerate spectrum and TBM are not related ?

Possible scenario

Disappointing scenario

High scale seesaw

GUT

Flavor physics at very high scales
above GUT?

Difference of quarks and leptons
is related to smallness of neutrino mass

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

Hidden sector at GUT,
Planck scales

SUSY-?
Hierarchy problem?

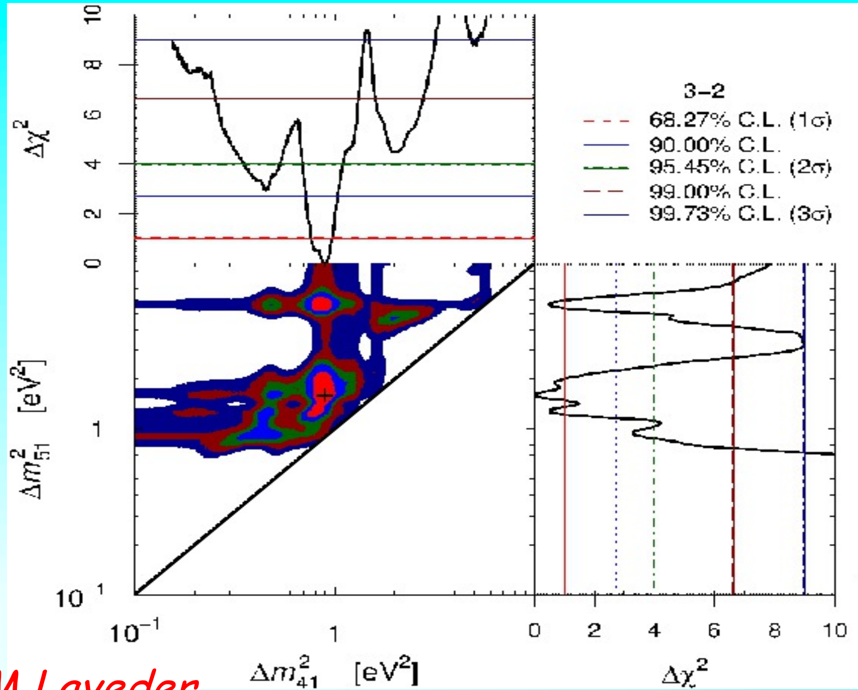
Negligible unitarity violation

Negligible NSI

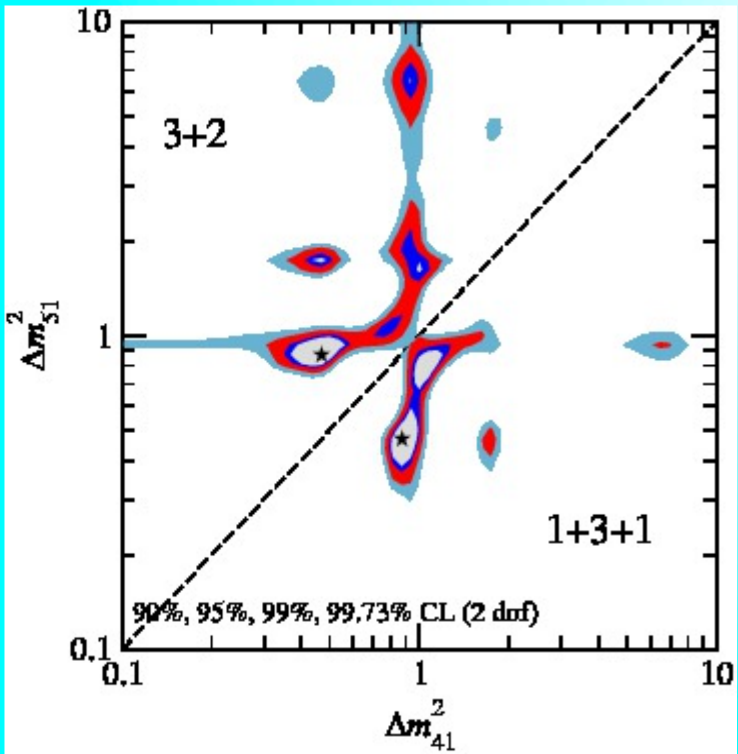
Seesaw enhancement of mixing
No particular symmetry?

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

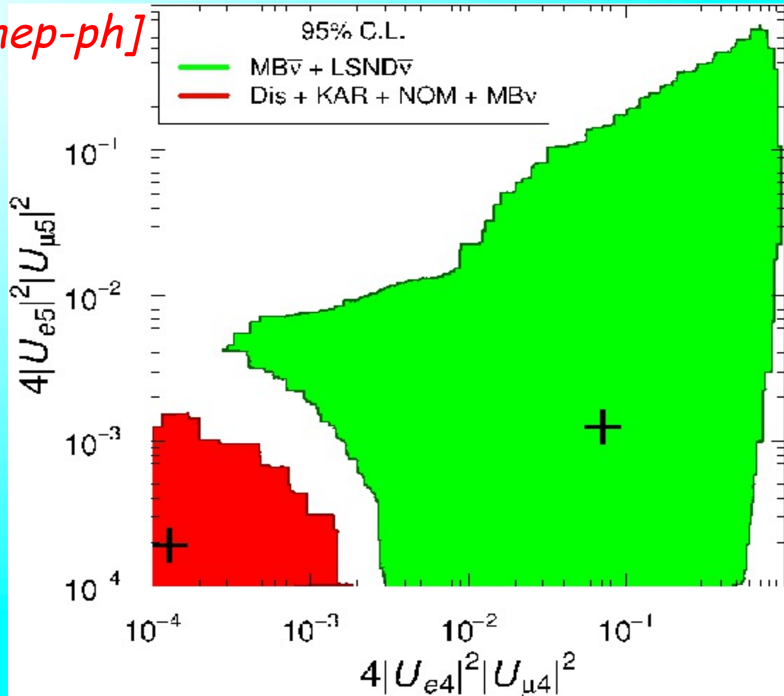
3+2 fit and consistency



J. Kopp, M Maltoni, T. Schwetz



C Giunti, M Laveder
1107.1452 [hep-ph]



Consistency

With reactor anomaly global fit of data in terms of nu-sterile becomes better

Limit on U_{e4} becomes weaker

$|U_{e4}|^2 : 0.02 \rightarrow 0.04$

Smaller values of $U_{\mu 4}$ are allowed to explain LSND/MiniBooNE – less tension with SBL experiment bounds

$|U_{\mu 4}|^2 : 0.04 \rightarrow 0.02$

Global fit

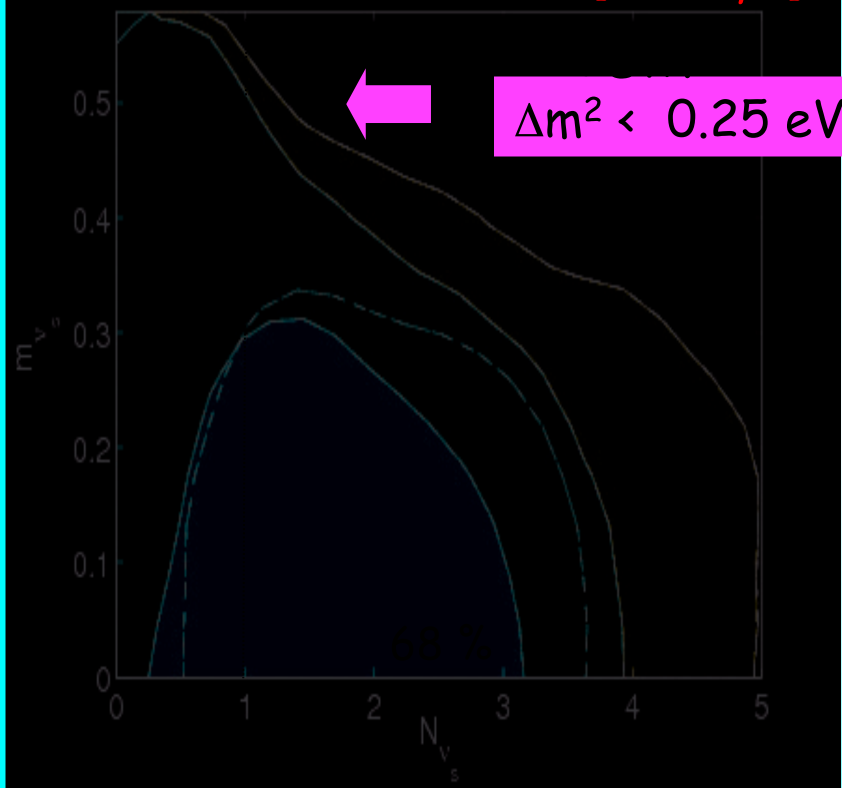
3 + 2 scheme

ν_4	ν_5
$\Delta m_{41}^2 = 0.47\ eV^2$	$\Delta m_{51}^2 = 0.87\ eV^2$
$U_{e4} = 0.128$	$U_{e5} = 0.138$
$U_{\mu 4} = 0.165$	$U_{\mu 5} = 0.148$

J Kopp, M. Maltoni, T.Schwetz
1103.4570 [hep-ph]

Cosmological bounds

E Giusarma et al 1102.4774 [astro-ph]



$\Delta m^2 <$ 0.25 eV^2

J R Kristiansen, O Elgaroy
1104.0704 [astro-ph]

Inverse approach:

wCDM + $2\nu_S$

1). $w < -1$

ruling out Λ

2). Age of the Universe
12.58 +/- 0.26 Gyr

too young?

The oldest globular clusters
13.4 +/- 0.8 +/- 0.6 Gyr

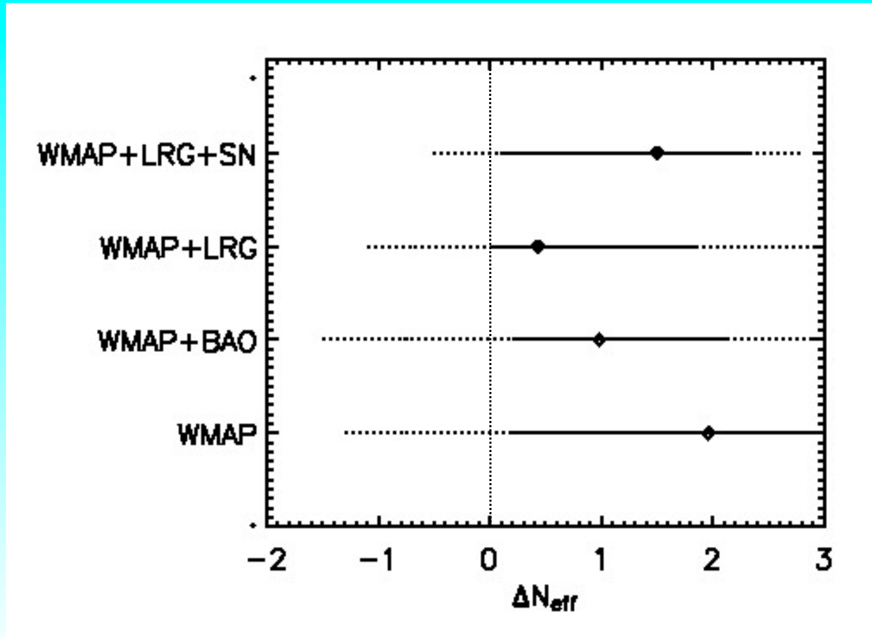
run 1 (blue)
- WMAP
- SDSS (red galaxy clustering)
- Hubble (prior on H_0)

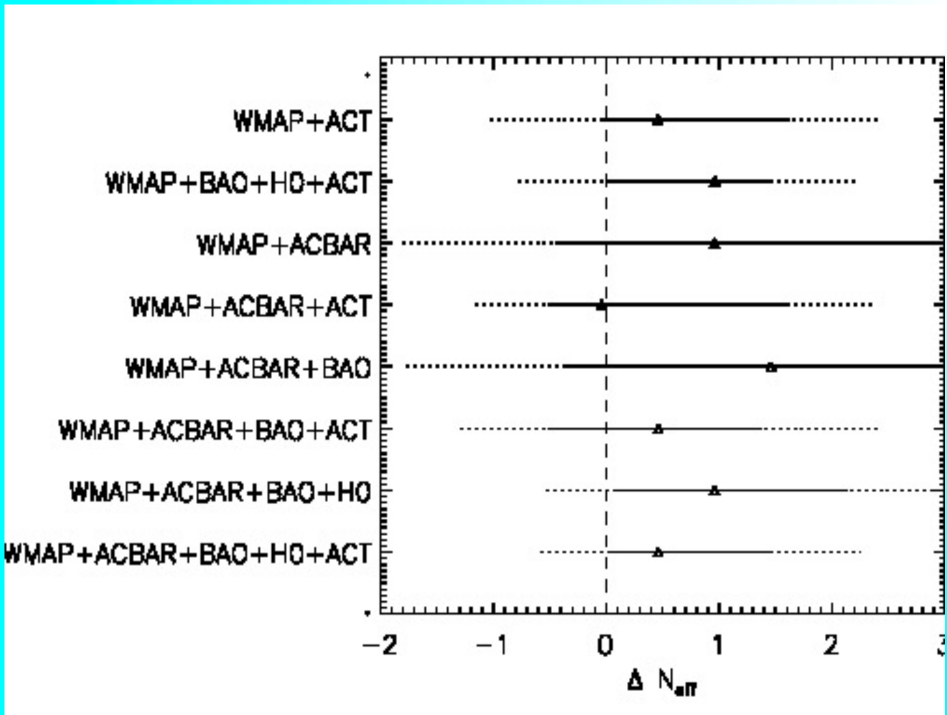
+ BBN

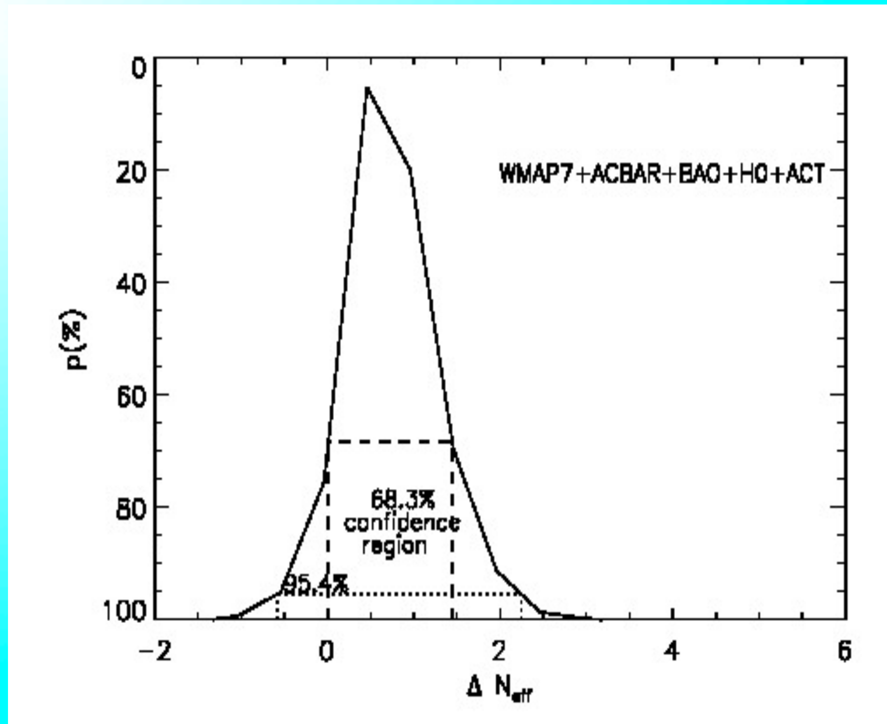
run 2 (red)
- Supernova Ia Union Compilation 2 (in add)

N_eff

Alma X Conzalelez-Morales, et al
1106.5052 [astro-ph,CO]

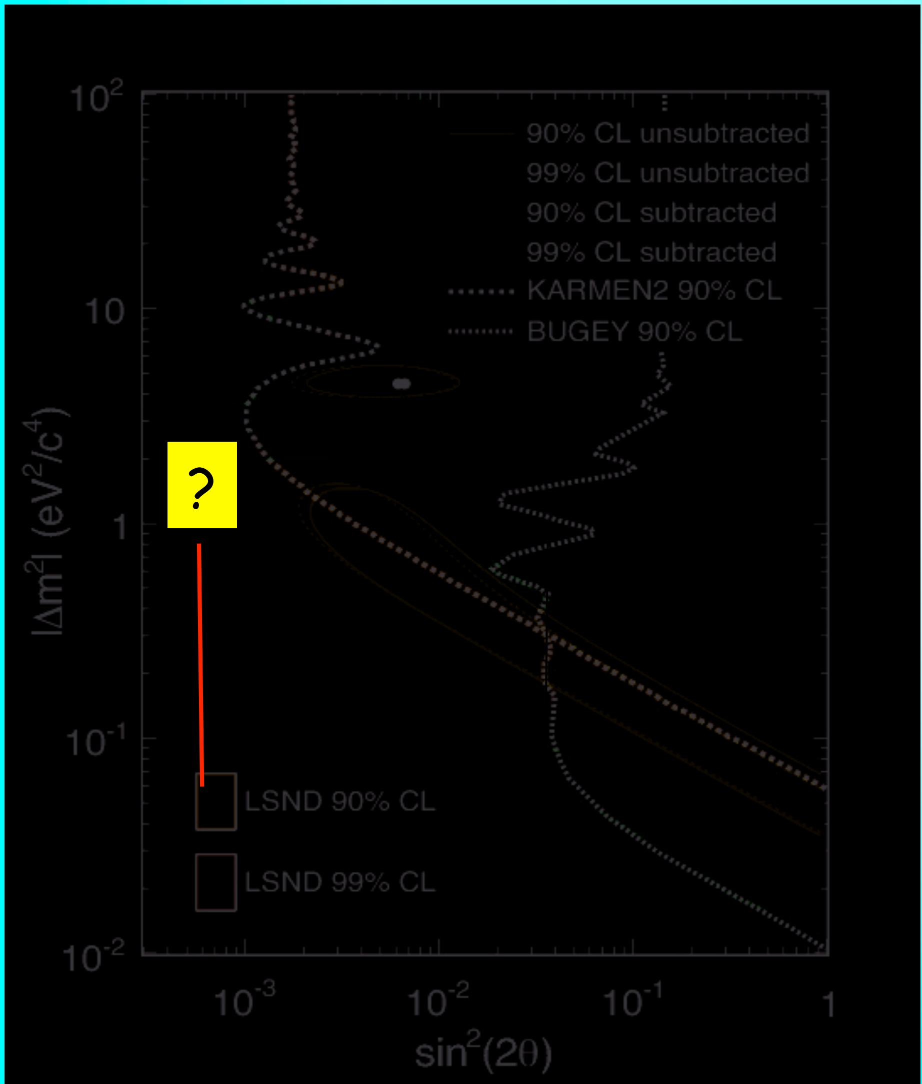






MINOS bound

$\nu_\mu - \nu_s$ mixing



In assumption of
no-oscillations in the ND

$|U_{\mu 4}|^2 < 0.015$ (90% CL)

$\theta_{13} = 0$

$|U_{\mu 4}|^2 < 0.019$ (90% CL)

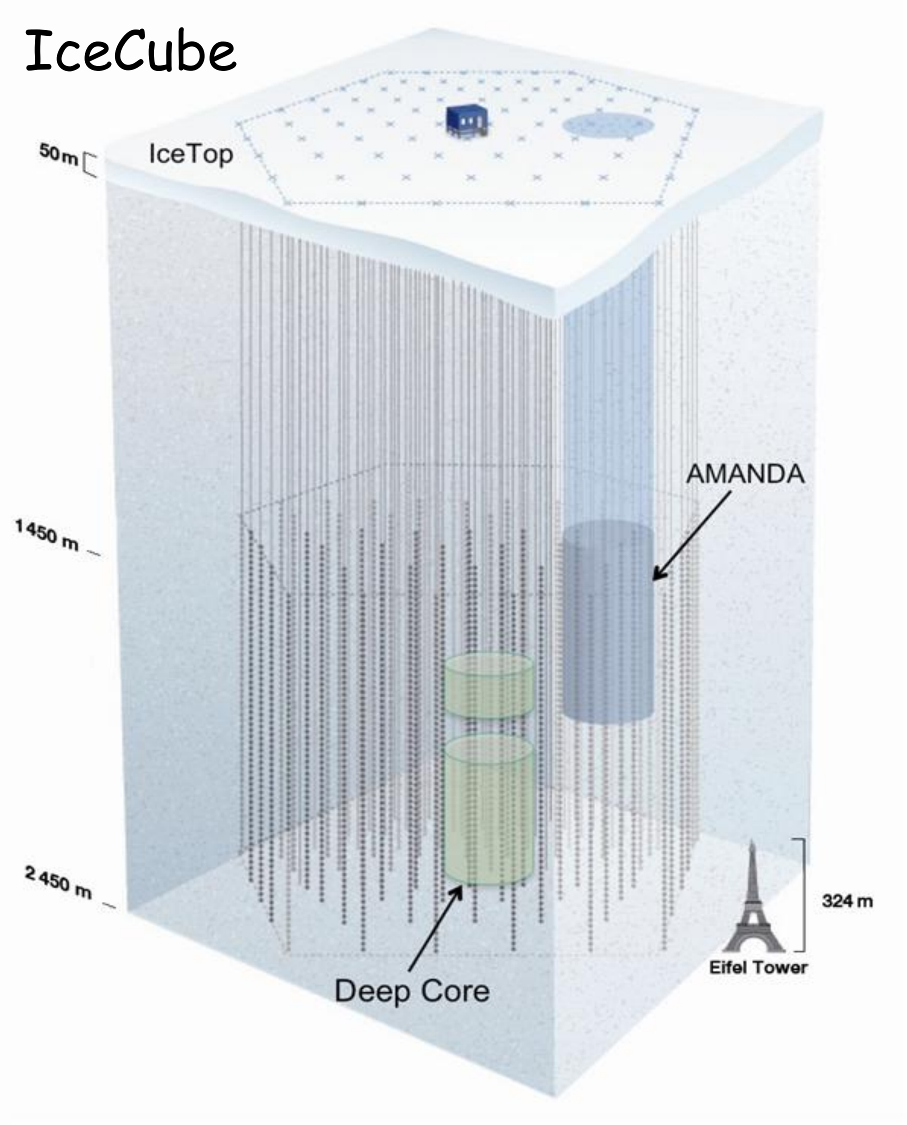
$\theta_{13} = 11.5^o$

LSND/MiniBooNE:

$|U_{\mu 4}|^2 > 0.025$

$\Delta m_{41}^2 < 0.5\ eV^2$

Looking for sterile in ice



H Nunokawa O L G Peres
R Zukanovich-Funchal
Phys. Lett B562 (2003) 279

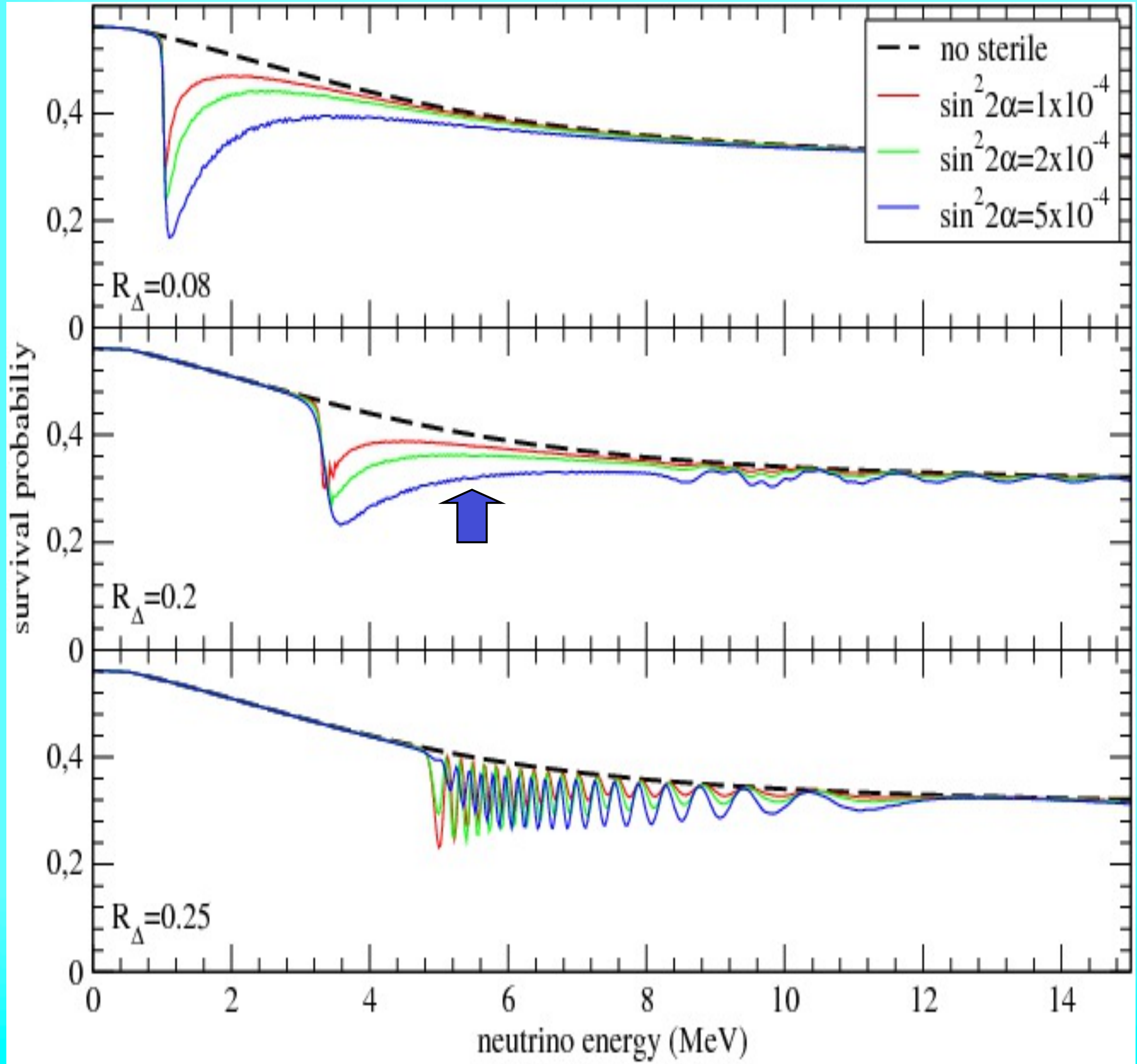
S Choubey HEP 0712 (2007) 014

ν_μ - ν_s oscillations with $\Delta m^2 \sim 1$ eV^2 are enhanced in matter of the Earth in energy range 0.5 – few TeV

This distorts the energy spectrum and zenith angle distribution of the atmospheric muon neutrinos

S Razzaque and AYS ,
1104.1390, [hep-ph]

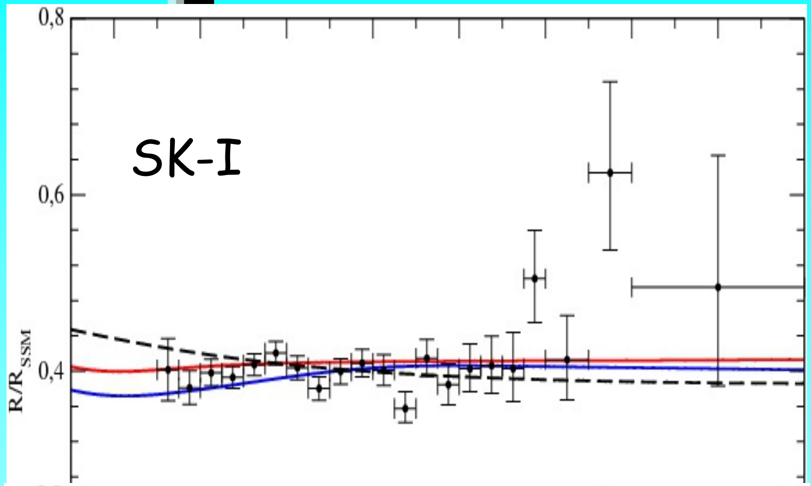
Survival probability

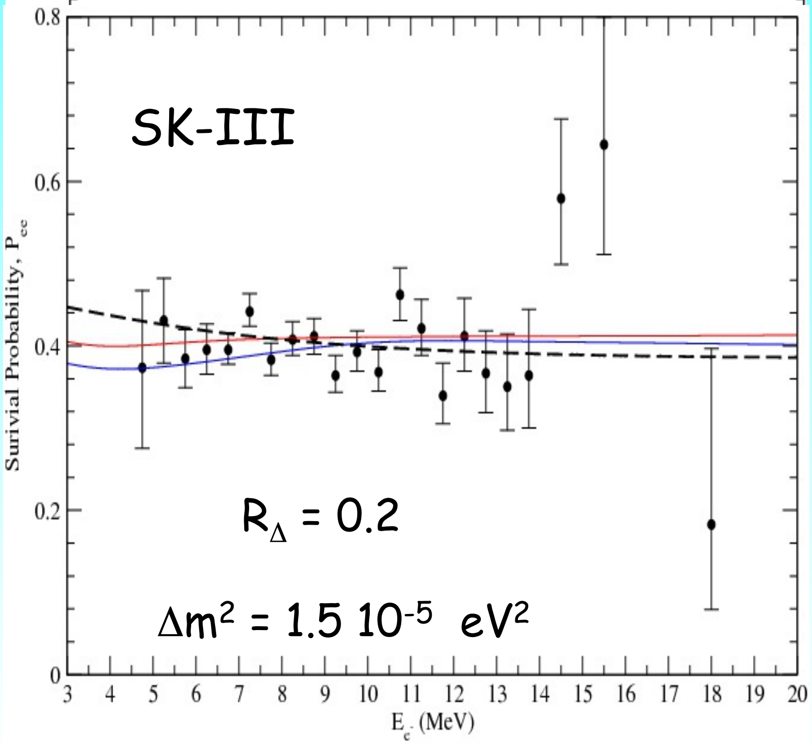


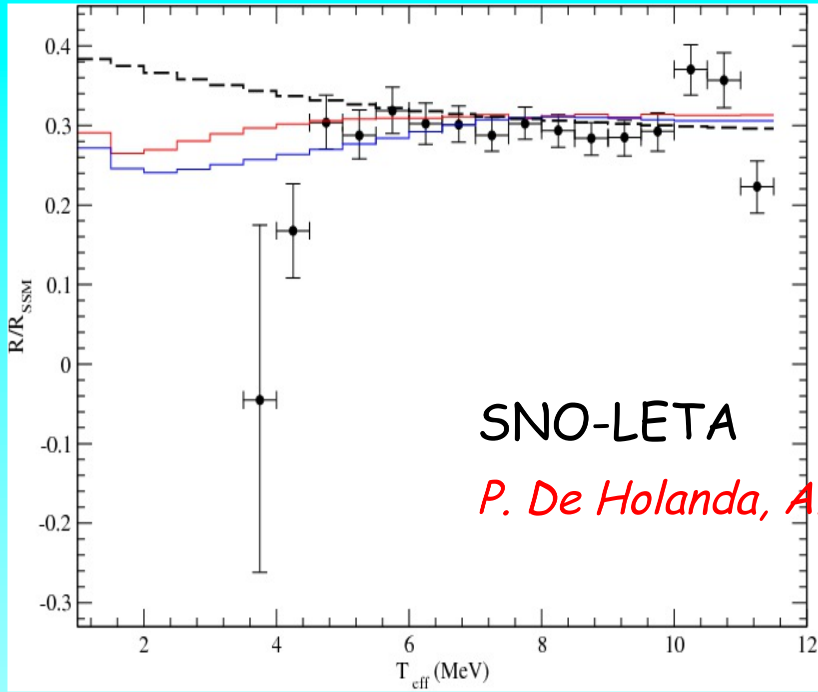
- dip
- wiggles

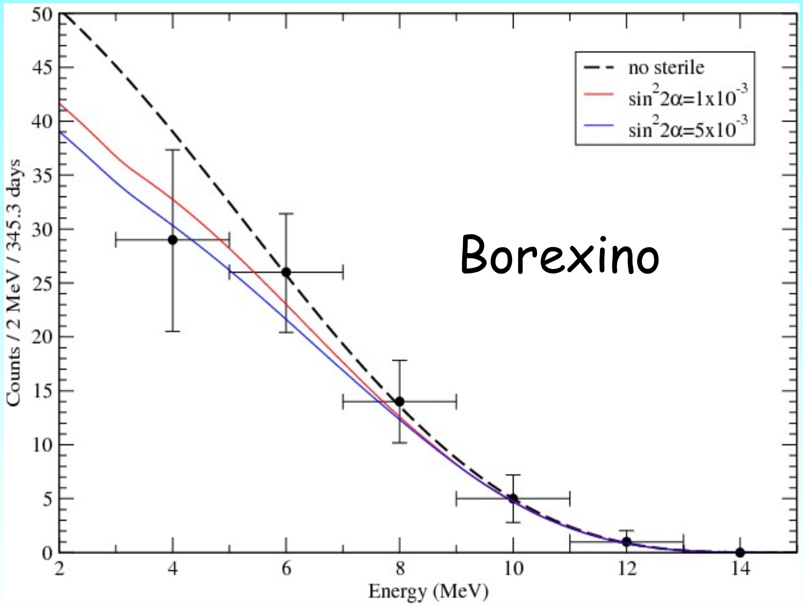
Up-turns

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



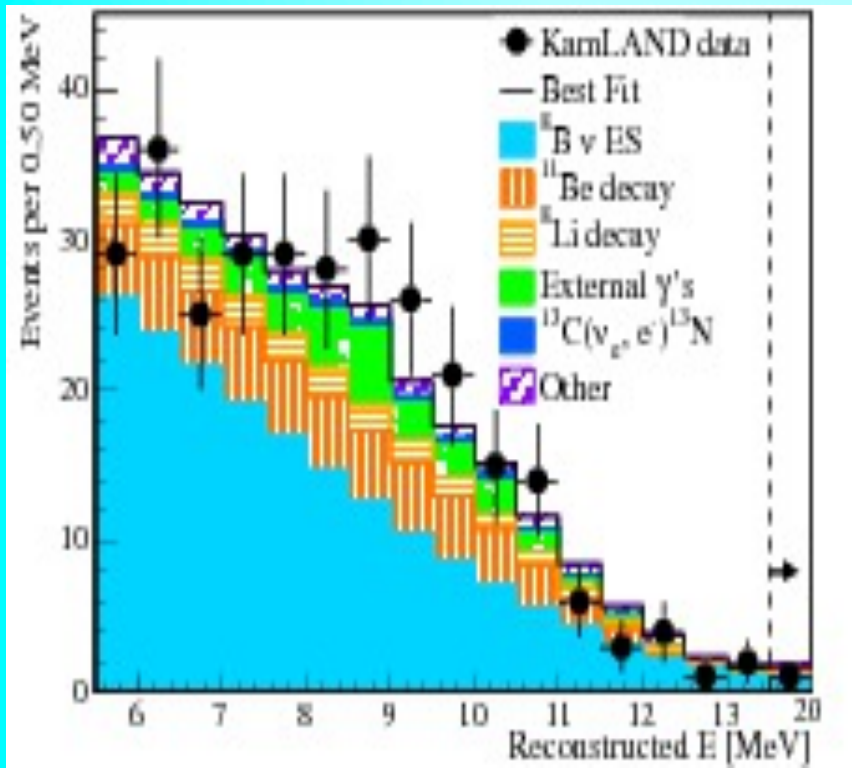


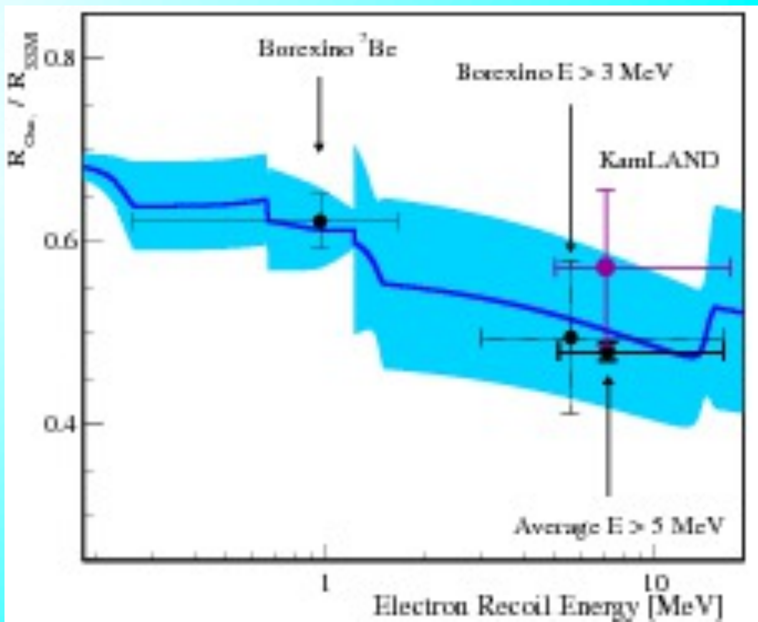




KamLAND solar

S. Abe, at al., [The KamLAND collaboration] 1106.0861 [hep-ex]





Comments:

Data show both order, regularities and
some degree of randomness

Different pieces of data testify for
different underlying physics

No simple relation between
masses and mixing parameters which
could testify for certain simple scenario

No simple explanation is expected?

ν_s - mass mixing scheme

$$\begin{pmatrix} \nu_s \\ \nu_\tau \\ \nu_\mu \end{pmatrix} \quad U_f = U_{23}\, U_\alpha \quad \begin{pmatrix} \nu_0 \\ \nu_3 \\ \nu_2 \end{pmatrix}$$

ν_s mixes in the mass states ν_3 and ν_0

$$\nu_0 = -\sin\alpha\, \tilde{\nu}_3 + \cos\alpha\, \nu_s$$
$$\nu_3 = \cos\alpha\, \tilde{\nu}_3 + \sin\alpha\, \nu_s$$
$$\nu_2 = \tilde{\nu}_2$$

where

$$\tilde{\nu}_3 = \cos\theta_{23}\, \nu_\tau + \sin\theta_{23}\, \nu_\mu$$
$$\tilde{\nu}_2 = \cos\theta_{23}\, \nu_\mu - \sin\theta_{23}\, \nu_\tau$$

ν_s mixes with $\tilde{\nu}_3$

Propagation basis: $\nu_s, \tilde{\nu}_3, \tilde{\nu}_2$

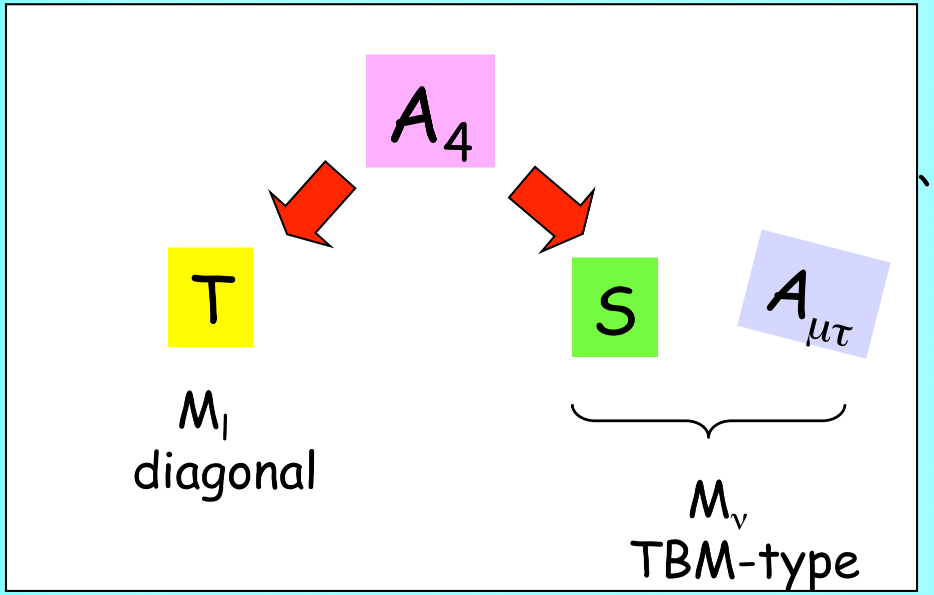
Evolution is reduced to 2ν-problem exactly

Light neutrinos Dark matter and Standard model of the Universe

Neutrino as dark energy
Hot dark matter and structure formation
Extra radiation in the Universe

Aspects related to the main topic of the school
In connection to dark matter.

A_4 symmery breaking



``accidental'' symmetry due to particular selection of flavon representations and configuration of VEV's

In turn, this split originates from different flavor assignments of the RH components of N^c and l^c and different higgs multiplets

Neutrinos & Dark Matter

Direct connection

Light neutrinos

Hot DM

Influence LSS formation

Clumping Form structures

At least two of them are non-relativistic

As probe, of DM

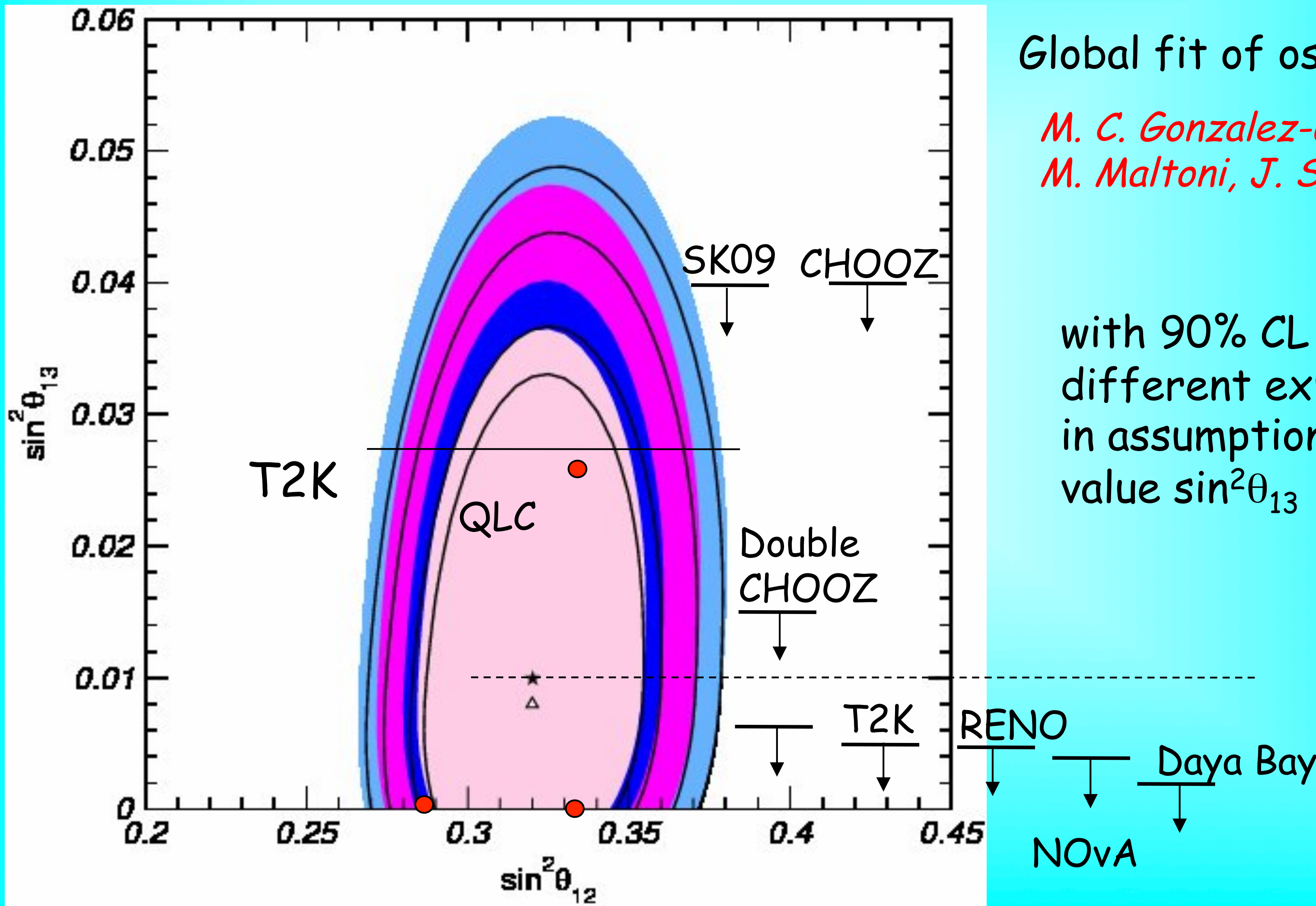
New neutrino states

Hot,warm DM

appear in annihilation or decay of DM particles

Search for DM signal with neutrino detectors

12 - and 13 - mixings



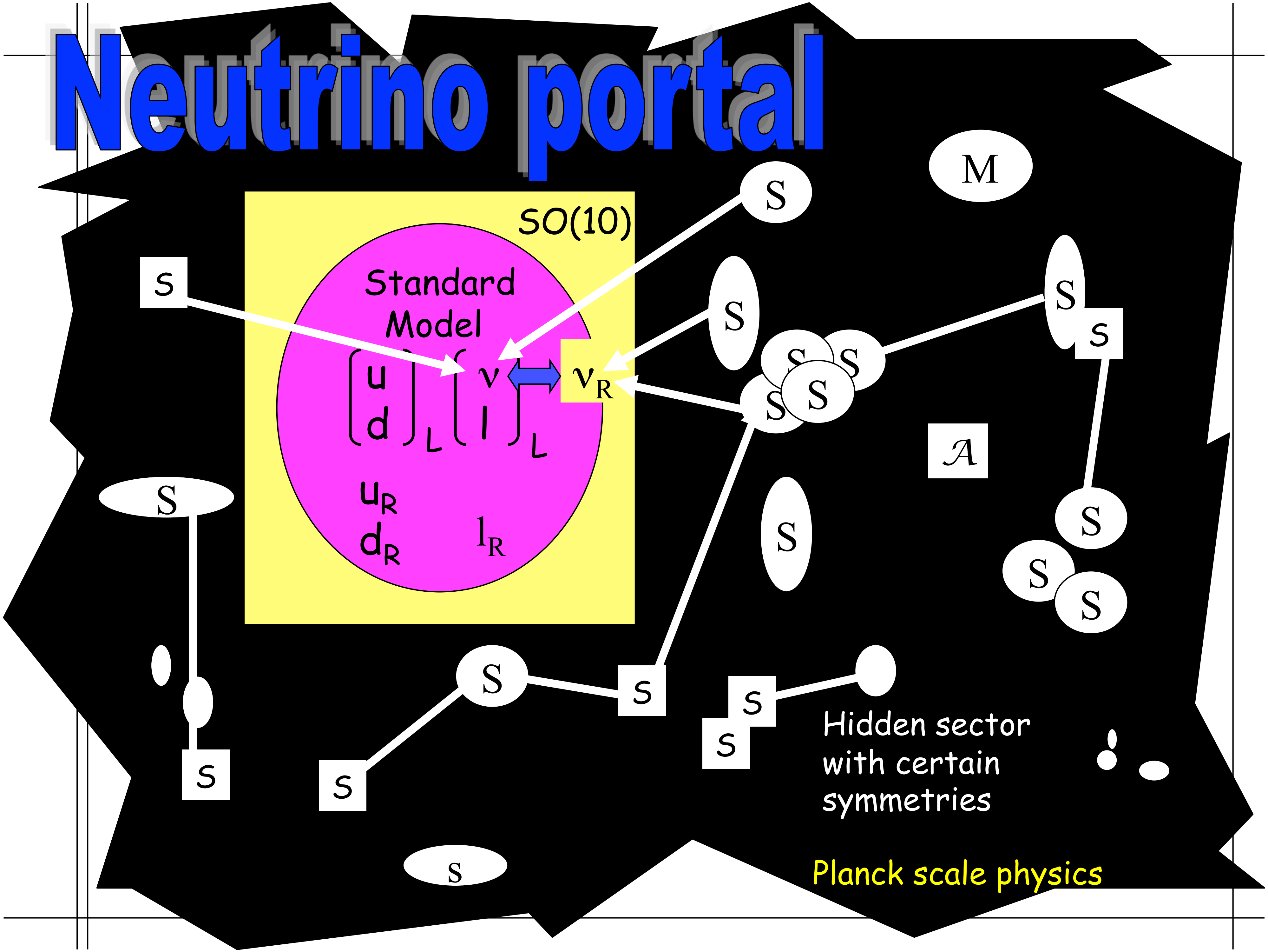
Global fit of oscillation data

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado

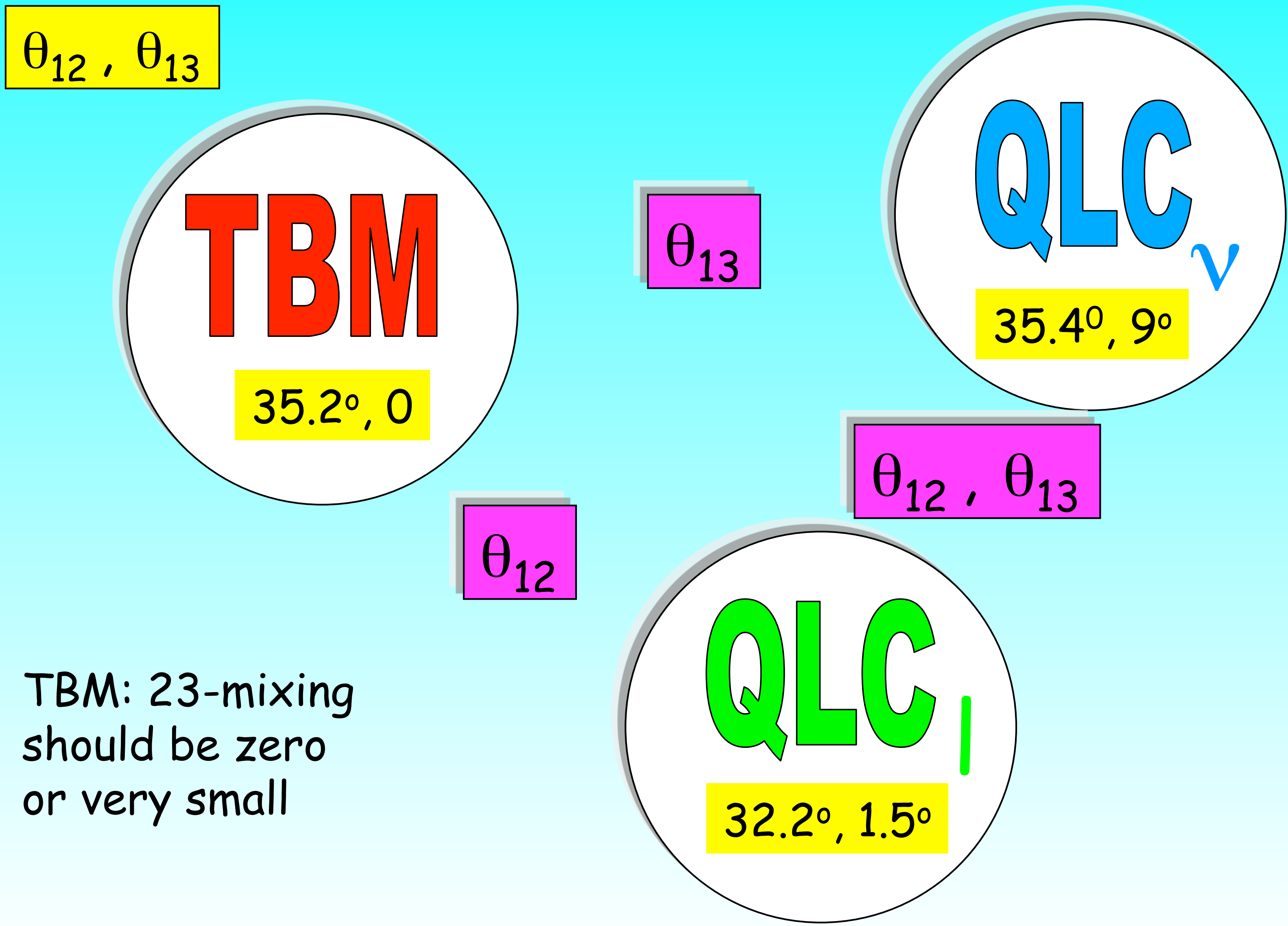
with 90% CL bounds from different experiments in assumption that true value $\sin^2\theta_{13} = 0$

90, 95, 99, 3σ CL contours

Neutrino portal



Disentangling possibilities



TBM: 23-mixing
should be zero
or very small

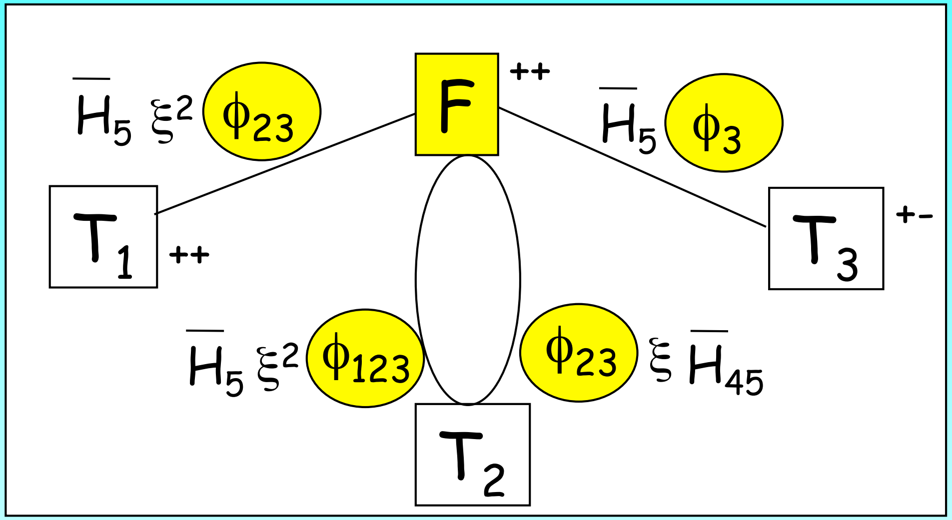
SU(5) x A_4

I. K. Cooper
S. K. King, C. Luhn
ArXiv1001.2265

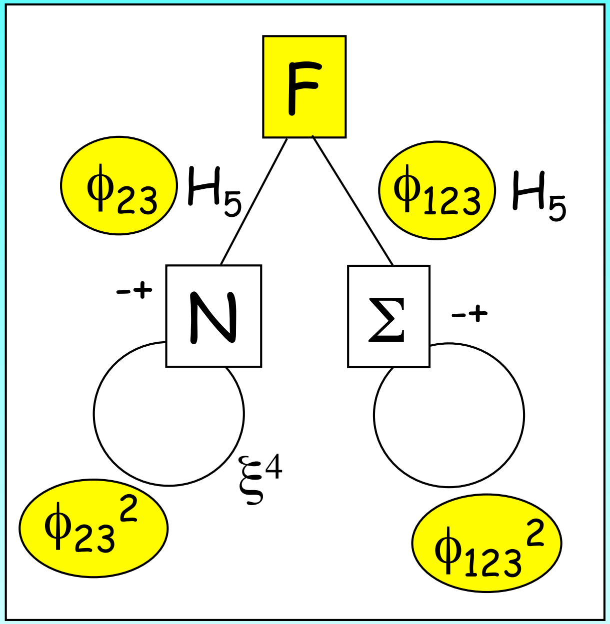
$A_4 \times Z_2 \times Z_2 \rtimes U(1) \times U(1)_R$

Matter: $F = \bar{5}$, $T_{1,2,3} = 10$, $N = 1$, $\Sigma = 24$

Charged leptons / down quarks



Neutrinos



A_4

3

1

1′

1″

10 plets are F-singlets!

Vacuum alignment

$\langle\phi_{123}\rangle \sim (1,\ 1,\ 1)$

$\langle\phi_{23}\rangle \sim (0,\ 1,\ -1)$

$\langle\phi_1\rangle \sim (1,\ 0,\ 0)$

$\langle\phi_3\rangle \sim (0,\ 0,\ 1)$

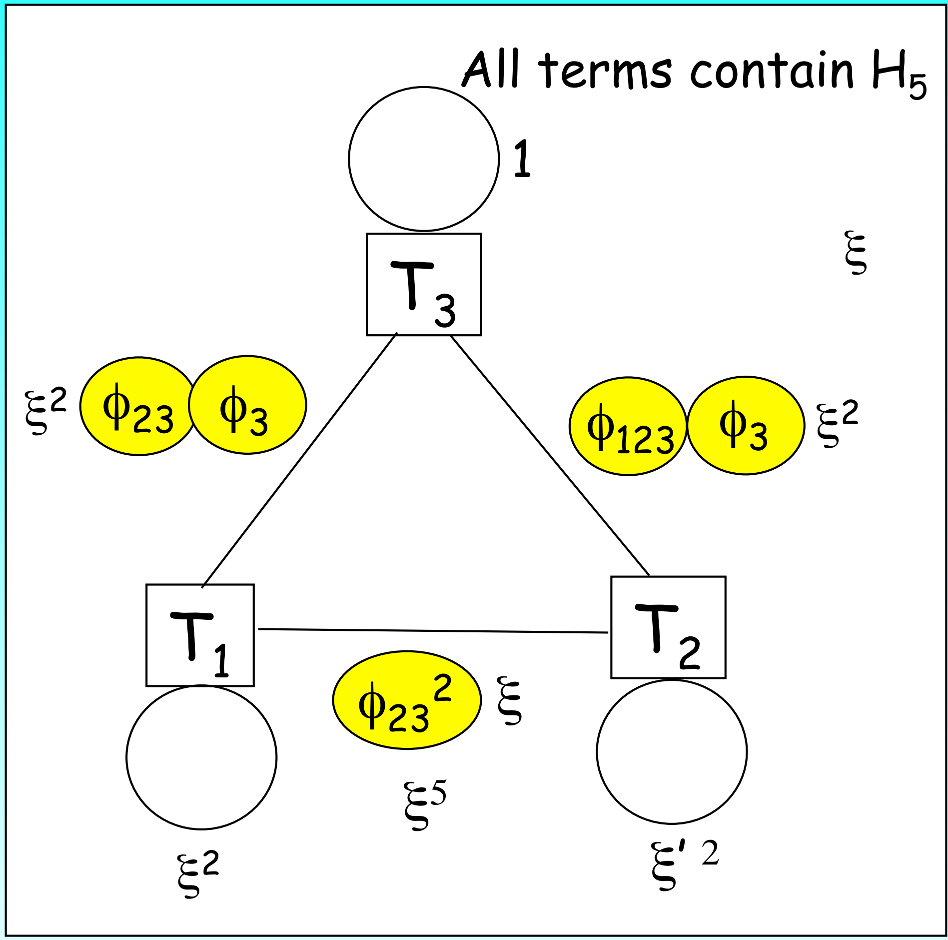
~ TBM

$Z_2 \times Z_2$

\+ -

... continued

for upper quarks



A_4

3

1

1′

1″

Another representation

$$m_\nu = m_{TBM} + m'_{TBM} + x\begin{pmatrix} 0 & 1 & -1 \\ \dots & 0 & 0 \\ \dots & \dots & 0 \end{pmatrix} + y\begin{pmatrix} 0 & 0 & 0 \\ \dots & 1 & 0 \\ \dots & \dots & -1 \end{pmatrix} + z\begin{pmatrix} 1 & 0 & 0 \\ \dots & 0 & 0 \\ \dots & \dots & 0 \end{pmatrix}$$

where m'_{TBM} is the matrix of the TBM form, with $m' \sim D_{12}$ and $s_{13}{}^2$

$$x = -\sqrt{\tfrac{1}{2}}\, s_{13}(c\, e^{-i\delta} - a\, e^{i\delta}) + bD_{23}$$

$$y = \sqrt{2}\, s_{13} b e^{i\delta} + (a + b - c)D_{23}$$

$$z = -\frac{27}{4} bD_{12} + (ce^{-2i\delta} - a - \tfrac{1}{2}b)s_{13}{}^2$$

Total corrections to the ee- and $\mu\tau$-elements

$$\Delta m_{ee} = -3bD_{12} + (ce^{-2i\delta} - a)\, s_{13}{}^2$$

$$\Delta m_{\mu\tau} = \tfrac{1}{2}\,[\,-3bD_{12} + (c - a\, e^{2i\delta})s_{13}{}^2\,]$$

New mass relations

$m_{e\mu} = r\, m_{e\tau}$ $r = 1/3, \frac{1}{2}, 2, 3 \ldots$

Equality of elements between the blocks

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

If $b = m_{e\mu}$ and D_{12} are small:
- x is large
- y is negligible
- corrections $\sim s_{13} D_{23}$ are small

$$\Rightarrow \quad m_\nu \sim \begin{pmatrix} a & -x & x \\ \ldots & \frac{1}{2}(a + c) & \frac{1}{2}(a - c) \\ \ldots & \ldots & \frac{1}{2}(a + c) \end{pmatrix}$$

satisfied in the cases PD(0,0),

invariant under $V'_2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}$

Two component structure

In many cases the matrix has hierarchy of elements

Mass matrix has two component structure

$m_\nu = M_d + \mu_s$

dominant sub-dominant

M_d
μ_s have different origins and different symmetries

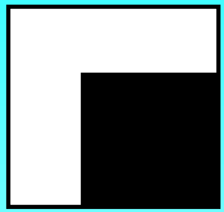
μ_s a result of breaking of symmetry of M_d

Deviations from TBM give $\begin{cases} \text{20 – 50 \% change of elements of } M_d \\ \text{corrections dominate in } \mu_s \end{cases}$

Corrections to TBM can change completely structure of the sub-dominant matrix

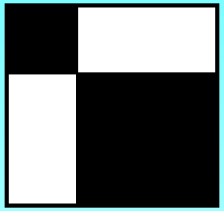
Dominant structures

Examples of symmetries



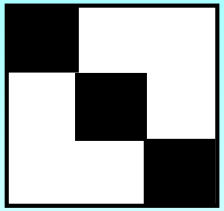
Dominant
$\mu\tau$-block
NH

$L(\nu_e) = 1 \quad L(\nu_\mu) = L(\nu_\tau) = 0$



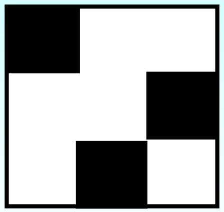
PD(0,0)

$\nu_e \to \nu_e \quad \nu_\mu \to -\nu_\mu \quad \nu_\tau \to -\nu_\tau$



$M_d = m_0 I$
D(0,0)

Subgroup of SO(3)



$M_d = m_0 V_2$
$D(0, \pi/2)$

A_4 $\quad$ 3
$\quad$ 1, 1′, 1″

S_3 $\quad$ 1 + 2

Texture zeros

TBM: no exact zeros are not consistent with data (masses)

With deviations matrices with 1 or 2 zeros are possible.

Textures with 2 zeros:

$$\begin{pmatrix} 0 & 0 & x \\ 0 & x & x \\ x & x & x \end{pmatrix}$$

NH($\pi/2$, 0) $\delta = \pi$ $m_1 = 0.0031$ eV

$$\begin{pmatrix} 0 & x & 0 \\ x & x & x \\ 0 & x & x \end{pmatrix}$$

and small $m_{\mu\mu}$

~ Fritzsch ansatz

NH($\pi/2$, 0) $\delta = 0$ $m_1 = 0.0035$ eV

$$\begin{pmatrix} X & x & 0 \\ x & 0 & X \\ 0 & X & x \end{pmatrix} \quad \begin{pmatrix} X & 0 & x \\ 0 & 0 & X \\ x & X & x \end{pmatrix} \quad \begin{pmatrix} X & x & 0 \\ x & x & X \\ 0 & X & 0 \end{pmatrix} \quad \begin{pmatrix} X & 0 & x \\ 0 & x & X \\ x & X & 0 \end{pmatrix}$$

D(0, $\pi/2$)

Flavor anarchy

For certain intervals of CP-phases in the case of partial degeneracy or degenerate spectrum

PD(π/2 ,0) PD(π/2,π/2) D(π/2 ,0) D(π/2,π/2)

mass matrices have no hierarchy of elements
(they are within factor 2- 3)

Deviations from TBM produce corrections of the order 30 – 50 %

⇨ matrices with random values of elements

Anarchy vs. degeneracy of spectrum?

- degeneracy of the spectrum implies some symmetry or accidental?
- anarchy from the charged leptons?

Flavor alignment

1. Normal flavor alignment:

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

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

2. Inverted flavor alignment

IH with deviations from TBM and basis corrections.
Values of elements gradually increase from $m_{\tau\tau}$ to m_{ee}

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

Origin of mass hierarchies

- Froggatt- Nielsen mechanism, U(1) family symmetry

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

$q(i)$ is the U(1) charge of i-family, $a_{ij} = O(1)$,
σ is the F-N scalar whose VEV violates U(1)
M_F is the scale at which F-N operators are formed

$$\Rightarrow \quad \boxed{(Y^f)_{ij} = a_{ij}\, \lambda^{\,q(i)+q(j)}} \qquad \boxed{\lambda = \langle\sigma\rangle / M_F}$$

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

Magic matrix and Tbm

$U_{tbm} = U_{mag}\, U_{13}(\pi/4)$

Magic times maximal 1-3 rotations

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

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

Describe transformations
of singlet representations: $\underline{1}$, $\underline{1'}$, $\underline{1''}$

$$U_{13}(\pi/4) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 1 \\ 0 & \sqrt{2} & 0 \\ 1 & 0 & 1 \end{pmatrix}$$

Other possibilities:

T_7, D_4, S_4, $\Delta(3n^2)$ ...

Is TBM accidental?

M Abbas, A.S

Experiment: $\Delta \sin^2\theta_{23} \sim 0.05$ $\Delta \sin^2\theta_{12} \sim 0.02$ $\Delta \sin \theta_{13} \sim 0.15$

Allowed deviation from TBM – can lead to
strong (maximal) violation of TBM-conditions

Strong deviation of m_ν from TBM form

Leading structures are relatively robust
sub-leading – can change completely

The approximate TBM is accidental or a manifestation of some other symmetries which differ from TBM, or other structures

This opens up new new approaches to explain data.

TBM-symmetry

Invariance: $V_i^T \, m_{TBM} \, V_i \; = \; m_{TBM}$

$$S = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ \ldots & -1 & 2 \\ .. & \ldots & -1 \end{pmatrix} \qquad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

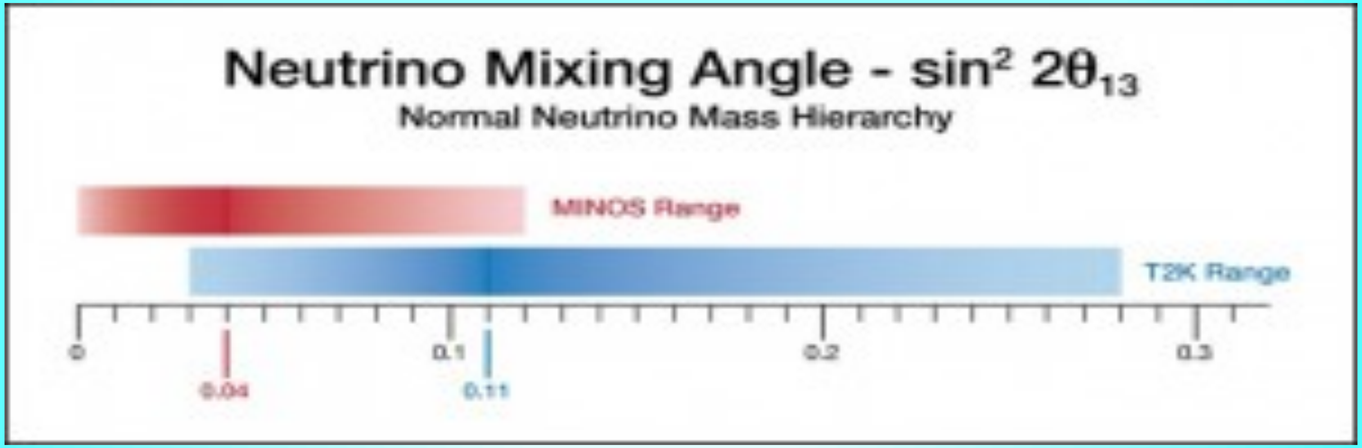
The mass matrix
of the charged leptons
is diagonal due to symmetry

$$T = \begin{pmatrix} 1 & 0 & 0 \\ \ldots & \omega^2 & 0 \\ \ldots & \ldots & \omega \end{pmatrix} \qquad \omega = \exp(-2i\pi/3)$$

$$T^+ (m_e^+ m_e) T \; = \; m_e^+ m_e$$

S, T, U –elements of S_4

Implications



Strongly broken TBM?

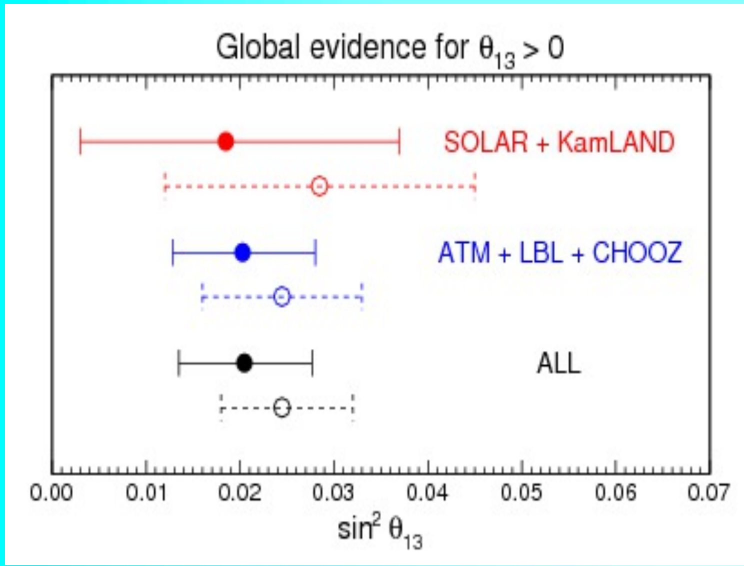
Typical for flavor models of TBM: $\sin\theta_{13} \sim \sin^2\theta_C$

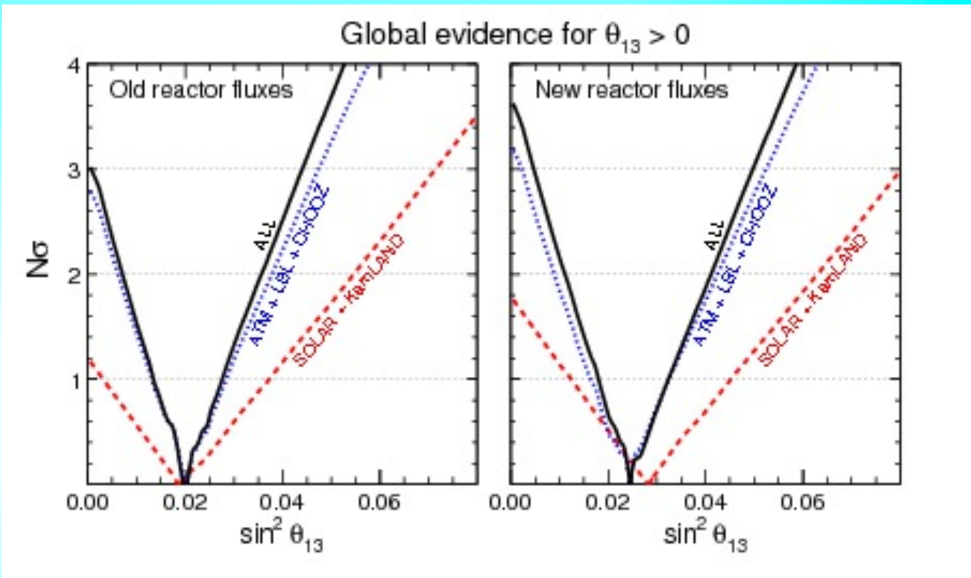
Quark-lepton complementarity:

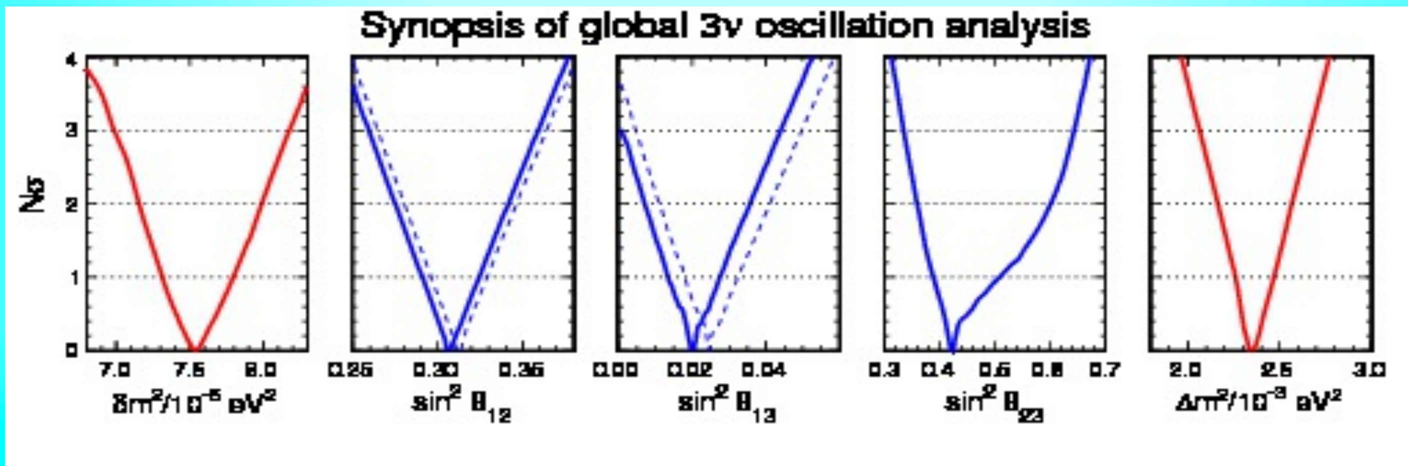
$\sin^2\theta_{13} \sim \frac{1}{2} \sin^2\theta_C$

No special symmetry in the leptonic sector

1-3 mixing: global fit







TBM and GUT's

Generic problem:

In many models, flavor prescription required for explanation of differences of mass and mixing of quarks and leptons prevents from GU

Relate this difference to spontaneous breaking of GUT symmetry

GUT x G $_{flavor}$ + ...

New elements should be added

Restrict flavor charge assignments

- singlet fermions
  additional higgses

- pair vector-like matter fields
- its mixing with usual matter
- use seesaw type II for neutrinos