Theory of ν – masses and mixing

Part 2

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Clockwork mechanism

A. Ibarra et all 1711.02070 [hep-ph]

fast rotation

slow rotation

Strong hierarchy (small quantities) without small parameters

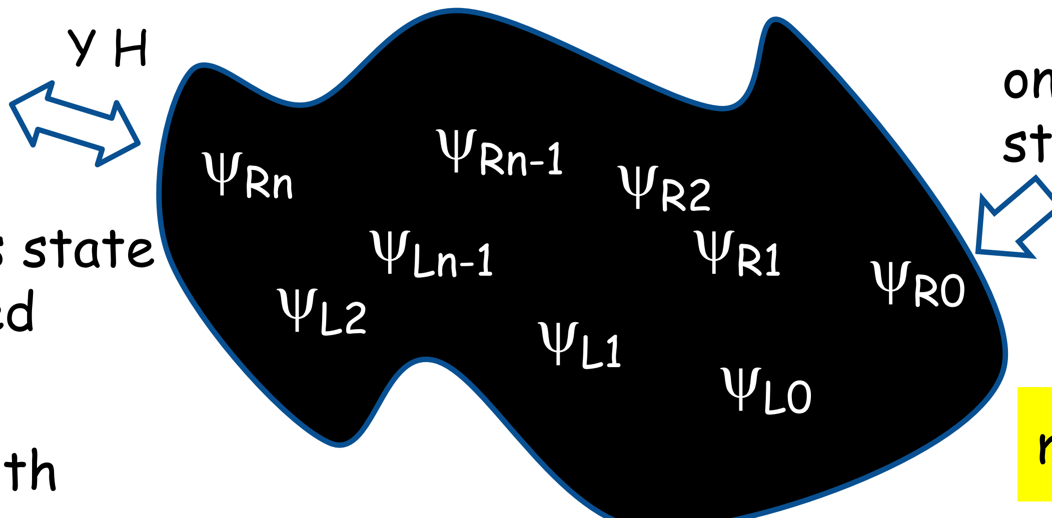
G. Giudice, et al

ψ_{L0}

It can be considered as special case neutrino mass with multiple RH neutrinos, or neutrino via hidden sector

Resembles generation due to extra dimension in deconstruction mode

ν_L



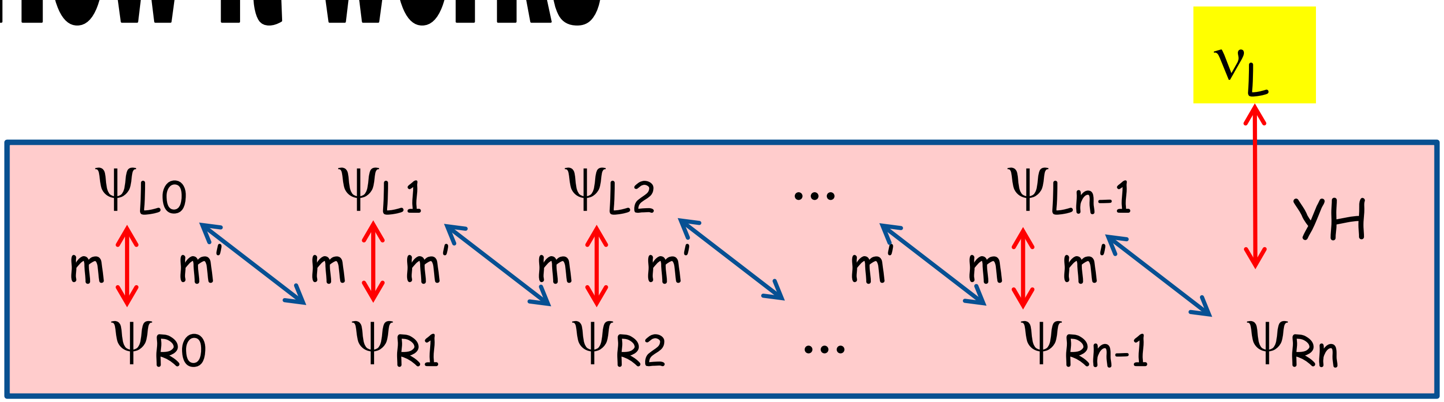
one massless state mostly here

Mixing of massless state in ψ_{Rn} is suppressed by factor q^n , $q > 1$

Yukawa coupling with massless state Yq^{-n}

$$m_\nu = \frac{1}{q^n} Y\langle H\rangle$$

How it works



$q = m'/m$ gear

$$
\begin{array}{c|cccccc|c}
 & \psi_{L0} & \psi_{L1} & \psi_{L2} & \cdots & \psi_{Ln-1} & & \Sigma \\
\hline
\psi_{R0} & 1 & 0 & 0 & 0 & \ldots & & q^{n} \\
\psi_{R1} & -q & 1 & 0 & 0 & \ldots & & q^{n-1} \\
\psi_{R2} & 0 & -q & 1 & 0 & \ldots & & q^{n-2} \\
\ldots & \ldots. & & & & & 1 & \ldots \\
\psi_{Rn} & 0\ \ldots & & & 0 & \ldots & -q & 1
\end{array}
$$

(matrix) $\times$ column

Mixing of massless state in ψ_{Rn}

$1/N$

$m_\nu = Y\langle H\rangle/N$

Massless state

$(q^n \psi_{R0} + q^{n-1} \psi_{R1} + q^{n-2} \psi_{R2} + \ldots + \psi_{Rn})/N$

Normalization: $N^2 = \Sigma_{0\ldots.n}\ q^{2j}$

Suppression factor

$$\frac{1}{q^n}\sqrt{\frac{q^2 - 1}{q^2 - q^{-2n}}}$$

Medium generated mass

Due to interactions with new light scalar fields

Strongly restricted

m_ν

Interactions with usual matter (electrons, quarks) due to exchange by very light scalar

Interactions with scalar field sourced by DM particles

Interaction with "Fuzzy" dark matter

Effective mass due to interactions with dark matter

H. Davoudiasl, et al
1803.0001 [hep-ph]

$$L = - g_X \phi \overline{X} X - g_\nu \phi \overline{\nu_L} \nu_R + h.c.$$

ϕ - very light scalar field producing long (astronomical) range forces

X – Dark matter particle (fermion of GeV mass scale) source of the scalar field

$$m_\nu = g_\nu \phi$$

From equation of motion for ϕ neglecting neutrino contribution to generation of ϕ

$$\phi = \frac{- g_X n_X}{m_\phi^2}$$

m_ϕ = 10^{-20} - 10^{-26} eV is mass of scalar

$n_X = \langle \overline{X} X \rangle$ is the number density of X

$$m_\nu = \frac{g_X g_\nu \rho_X}{m_\phi^2 m_X}$$

ρ_X - energy density of DM

$g_X = g_\nu = 10^{-19}$ $\rightarrow$ $m_\nu = 0.1$ eV

Mass depends on local density of DM and different in different parts of the Galaxy and outside

Interactions with fuzzy dark matter

A. Berlin, 1608.01307 [hep-ph]

Ultra-light scalar DM, huge density ρ – as a classical field, solution

$$\phi\,(t, x\,) \sim \frac{\sqrt{2\,\rho\,(x)}}{m_\phi} \cos\,(m_\phi\, t)$$

Coupling to neutrinos $g_\phi\, \phi\, \nu_i\, \nu_j \;+\; \ldots$

gives contribution to neutrino mass and modifies mixing

Mass states oscillate

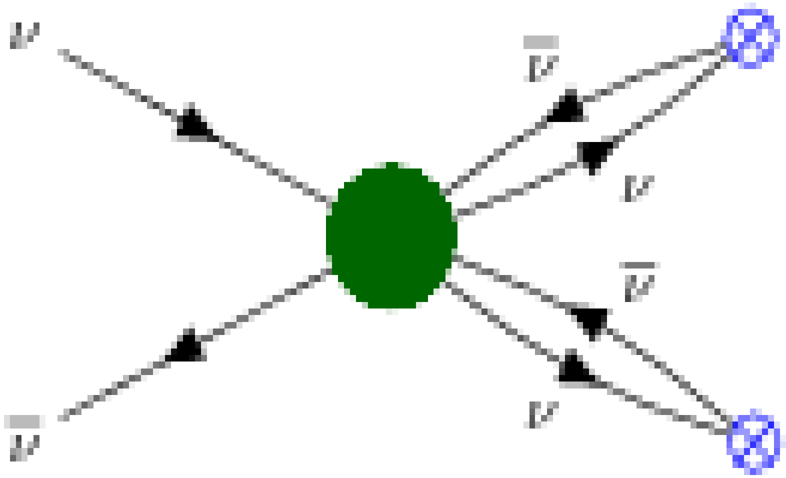
$\delta m\,(t) = g_\phi\, \phi\,(t)$ $\Delta\theta_m\,(t) = g_\phi\, \phi\,(t)\, /\, \Delta m_{ij}$

Neutrinos propagating in this field will experience time variations of mixing in time with frequency given by m_ϕ

Period ~ month, bounds from solar neutrinos, lab. experiments

New observable effects (and not just renormalization of SM Yukawa and VEV) if the field has
- spatial dependence
- different sign for neutrinos and antineutrinos

Soft couplings and small VEV's



Neutrino mass generation through the condensate (crossed blue circles) via non-perturbative interaction (green circle).

Small neutrino masses from gravitational θ-term

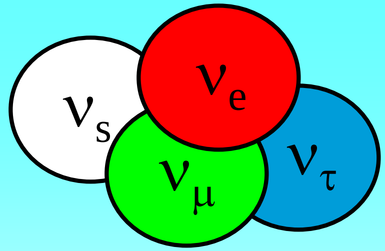
G. Dvali and L. Funcke, Phys.Rev. D93 (2016) no.11, 113002 arXiv:1602.03191 [hep-ph]

No $\beta\beta_{0\nu}$ decay due to large q^2 the vertex does not exist ?

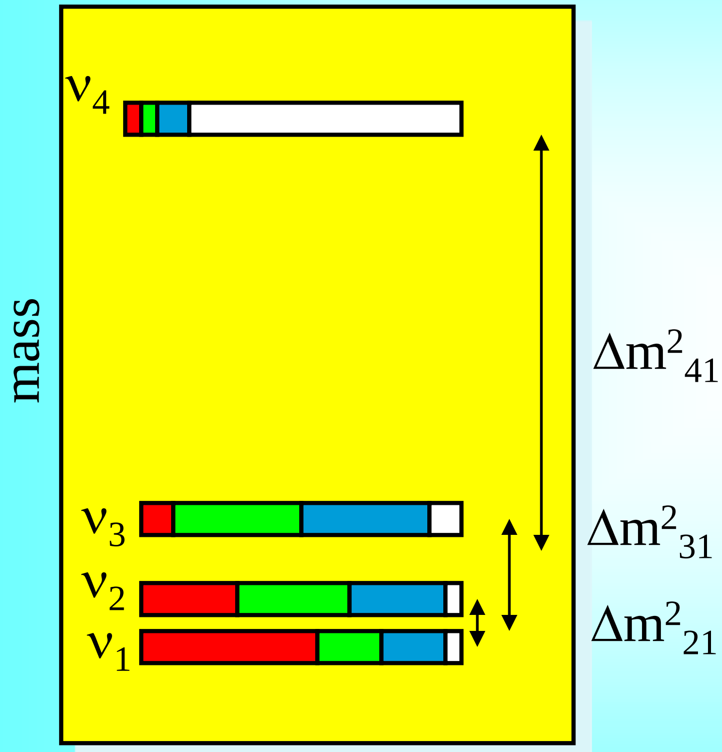
$\beta\beta_{0\nu}$ decay - unique process where neutrinos are highly virtual

Certain generic features independent on specific scenario can be considered on phenomenological level

(3 + 1) scheme



Interpretation



Strong perturbation of 3ν pattern:

$$m_{\alpha\beta}^{ind} \sim m_4 U_{\alpha 4}\, U_{\beta 4} \sim \sqrt{\Delta m_{32}{}^2}$$

Effect of possible sterile neutrinos can be neglected if

$$m_{\alpha\beta}^{ind} \ll \tfrac{1}{2}\sqrt{\Delta m_{21}{}^2} \sim 3\ 10^{-3}\ \mathrm{eV}$$

$$|U_{\alpha 4}|^2 < 10^{-3}\,(1\ \mathrm{eV}/m_4)$$

Large flavor mixing from steriles

Mass matrix

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

no contribution from S to $\beta\beta_{0\nu}$ decay, but S do contribute to oscillations

$$\boxed{m_\nu = m_a + m_{ind}}$$

eV scale seesaw

$$m_a = \begin{pmatrix} 0.2 & 0.4 & 0.4 \\ \dots & 2.8 & 2.0 \\ \dots & \dots & 3.0 \end{pmatrix} 10^{-2}\ \text{eV} \qquad m_{ind} = \frac{m_{SS}}{1\ \text{eV}} \begin{pmatrix} 2.0 & 2.0 & 4.5 \\ \dots & 2.0 & 4.5 \\ \dots & \dots & 10.0 \end{pmatrix} 10^{-2}\ \text{eV}$$

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

Enhance lepton mixing

Generate TBM mixing

m_{eS} $m_{\mu S}$ $m_{\tau S}$ may have certain symmetry

III. Lepton mixing and flavor symmetries

TBM: deviations and implications

Tri-bimaximal mixing

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

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

0.15

0.78

0.62

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

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

0.30 - 0.31

Accidental, numerology, useful for bookkeeping

Accidental symmetry (still useful)

There is no relation of mixing with masses (mass ratios)

Not accidental

Lowest order approximation which corresponds to weakly broken (flavor) symmetry of the Lagrangian

with some other physics and structures associated

flavons other new particles

The TBM- mass matrix

Mixing from diagonalization of mass matrix in the flavor basis

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

$$m^{diag} = \mathrm{diag}\,(|m_1|,\ |m_2|e^{i2\alpha},\ |m_3|e^{i2\beta})$$

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

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

The matrix has S_2 permutation symmetry $\nu_\mu \leftrightarrow \nu_\tau$

Mixing is determined by relations between the matrix elements:

$$m_{12} = m_{13} \qquad m_{22} = m_{33} \qquad m_{11} + m_{12} = m_{22} + m_{23}$$

Eigenvalues –by absolute values of elements

Deriving the TBM-symmetry

C.S. Lam

Invariance of mass matrices in the flavor basis:

Neutrinos $V_i^T m_{TBM} V_i = m_{TBM}$ $V_i = S, U_i$

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

$\nu_\mu - \nu_\tau$ -permutation

charged leptons
diagonal due to symmetry

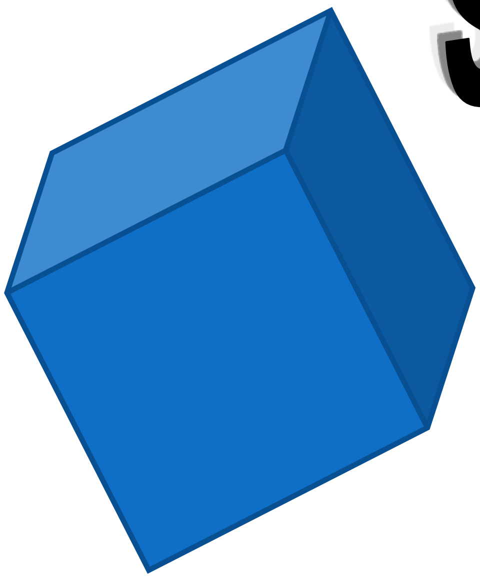
$$T = \begin{pmatrix} 1 & 0 & 0 \\ \dots & \omega^2 & 0 \\ \dots & \dots & \omega \end{pmatrix}$$

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

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

S, T, U –elements of S_4

S_4- symmetry



Order 24, permutation of 4 elements

Symmetry of cube

Generators: S, T

Presentation: $S^4 = T^3 = (ST^2)^2 = 1$

Irreducible representations: $\mathbf{1}, \mathbf{1}', \mathbf{2}, \mathbf{3}, \mathbf{3}'$

Products and invariants

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

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

$$1' \times 1' = 1$$

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

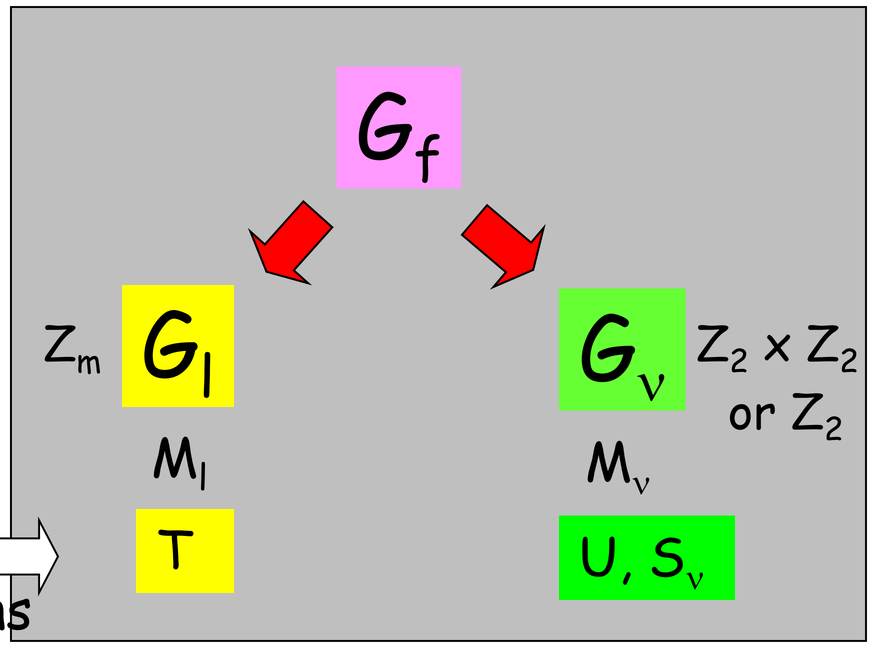
$$2 \times 2 = 1 + 1' + 2 \qquad 1' \times 2 = 2$$

New flavor structure

Residual symmetries approach

E. Ma,
C. S. Lam
....

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



A_4 S_4 T_7 T'

Residual symmetries of the mass matrices

Generic symmetries which do not depend on values of masses

CP-transformations can be added

Symmetry transformations in mass bases

$S_\nu M_\nu S_\nu^T = M_\nu$

Discrete finite groups
Flavons to break symmetries

Flavons

Intrinsic symmetries

Realized for arbitrary values of neutrino and charged lepton mass can not be broken, always exist

In the mass basis

for Majorana neutrinos

$m = \mathrm{diag}(m_1, m_2, m_3)$

G_ν

$S_1 = \mathrm{diag}(1, -1, -1)$

$S_2 = \mathrm{diag}(-1, 1, -1)$

$S_i^2 = I$ $Z_2 \times Z_2$

The Klein group

for charged leptons

$m_l = \mathrm{diag}(m_e, m_\mu, m_\tau)$

G_l

$T = \mathrm{diag}(e^{i\phi_e}, e^{i\phi_\mu}, e^{i\phi_\tau})$

$\phi_\alpha = 2\pi k_\alpha / m$

$T^m = I$ Z_m

$\Sigma \phi_\alpha = 0$ can use subgroup

Intrinsic symmetries as residual symmetries

Symmetry group condition

D. Hernandez, A.S.
1204.0445

If intrinsic symmetries are residual symmetries of the unique symmetry group (follow from breaking of unique group)
→ bounds on elements of mixing matrix

Inversely, S_i and T are elements of covering group.

By definition product of these elements (taken in the same basis) also belongs to the finite discrete group:

$$(U_{PMNS} S_i U_{PMNS}^+ T)^p = I$$

p -integer

For each i the equation gives two relations between mixing parameters

Two such equations for i = 1,2 fix the mixing matrix completely → TBM

$Z_2 \times Z_2$ → TBM

In general, allows to fix mixing matrix up to several possibilities

Example

$G_\nu = Z_2$ Two relations

D. Hernandez, A Y S.
1304.7738 [hep-ph]

for column of the mixing matrix:

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

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

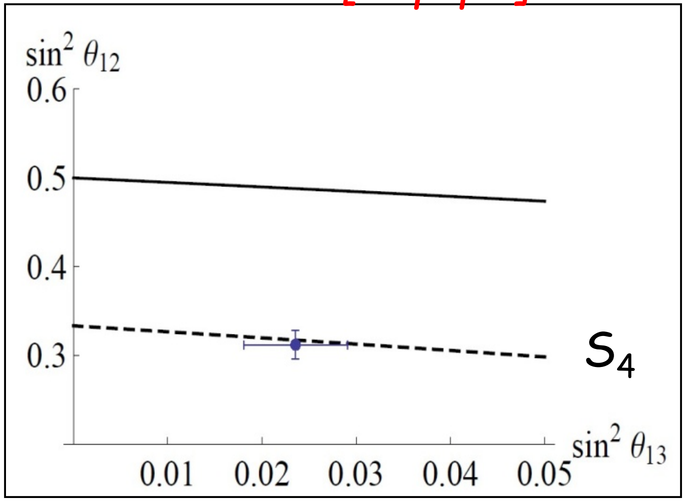
$a = \mathrm{Tr}(U_{PMNS}\, S_i\, U_{PMNS}^{\,+}\, T)$

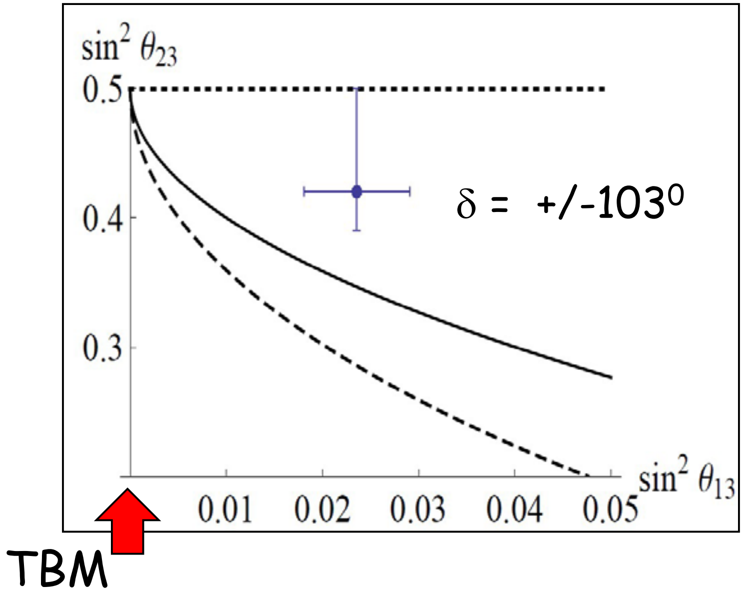
k, m, p integers which
determine symmetry group

TBM$_1$

TBM$_2$

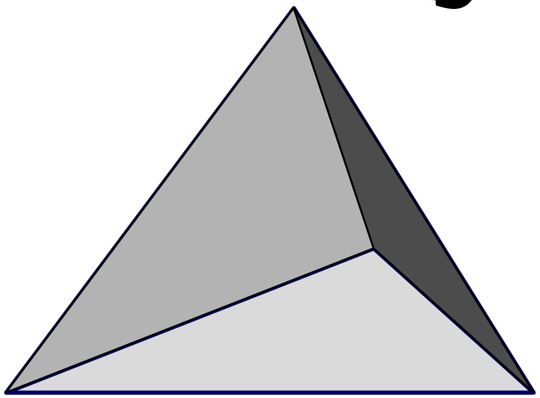
Schemes with non-zero 1-3 mixing can be obtained





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

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

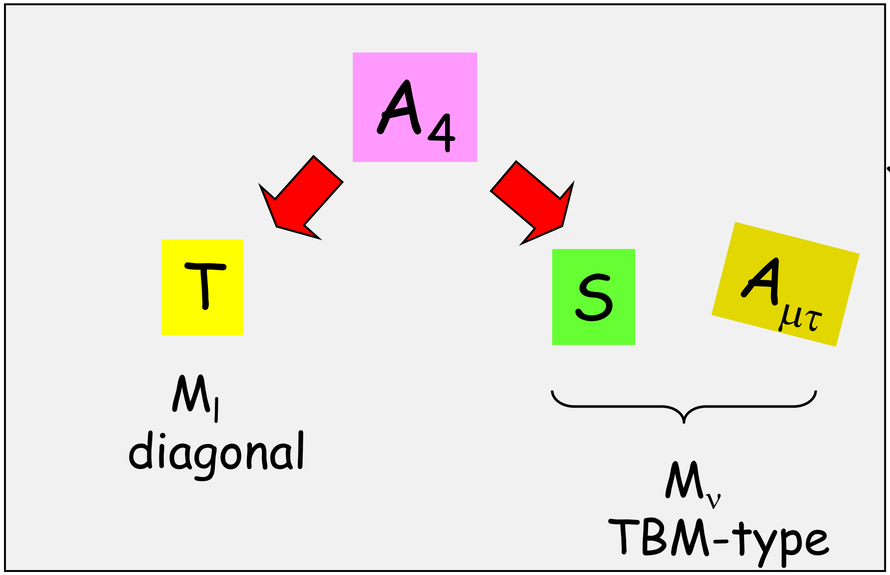
Irreducible representations: $\underline{3}$, $\underline{1}$, $\underline{1}'$, $\underline{1}''$

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 symmetry 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

symmetry

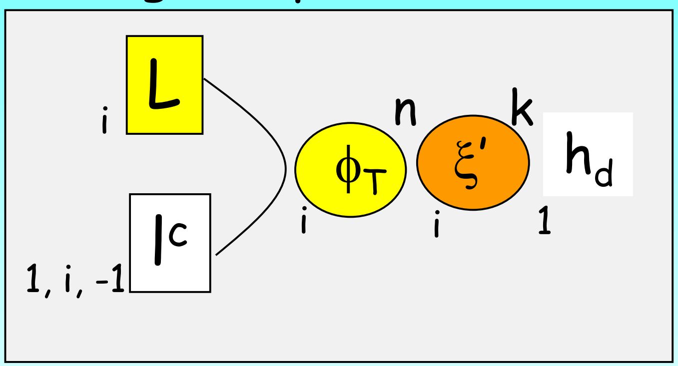
A_4 Z_4

3 — 1 — 1' — 1''

1
i
-1
-i
at multiplets

Yukawa sectors

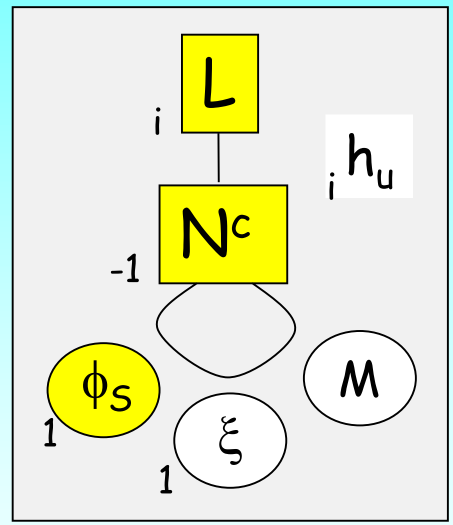
Charged lepton



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

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

Neutrinos



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

Flavon sector

				$U(1)_R$
ϕ_T	ϕ_S	ξ	ξ'	0
-1 $\phi_T{}_0$	1 $\phi_S{}^0$	1 ξ^0		2

Particular selection of representations

Driving fields → Vacuum alignment

GUT-scale or higher?

Generic problem

$$\mathbf{m = F(Y, v)}$$

Mechanism of mass generation

Yukawa couplings

VEV's

VEV alignment

- different contributions
- high order corrections

follow from independent sectors:

Yukawa sector   Scalar potential

tune by additional symmetries

TBM

All these components should be correlated

``Natural'' – consequence of symmetry?

one step constructions do not work

More problems

No connection to masses

Mass hierarchy from additional symmetries
U(1) Froggatt- Nielsen mechanism

$$\left(\frac{\phi}{\Lambda}\right)^n$$

power n is determined by U(1) charges of the corresponding operators

Discrete symmetries – restricted possibilities to explain mass spectrum (degenerate, partially degenerate spectra)

Missing representations problem

Relating to mass degeneracy

Symmetry which left mass matrices invariant for specific mass spectra:

Partially degenerate spectrum $m_1 = m_2$, m_3

D. Hernandez, A.S.

Transformation matrix $S_\nu = O_2$ $G_\nu = SO(2) \times Z_2$

Relation:

$$\sin^2 2\theta_{23} = +/- \sin\delta = \cos\kappa = \frac{m_1}{m_2} = 1$$

maximal +/- $\pi/2$ Majorana phase

1-2 mixing is undefined

Small corrections to mass matrix lead to 1-2 mass splitting and 1-2 mixing

CP-violation, phase

Certain values of δ follow from the flavor symmetries without additional assumptions

Specific transformations which can be responsible (control) value of the phase

Non-trivial CP phase : from generalized CP transformations when also flavor is changed

Usually maximal CP violation is predicted

Flavor and CP symmetry

$G_f \rtimes H_{CP}$

Flavons

$G_l \rtimes H^l_{CP}$ $\quad$ $G_\nu \rtimes H^\nu_{CP}$

Residual symmetries of the mass matrices

M_l $\quad$ M_ν

A_4 $\quad$ S_4 $\quad$ T' $\quad$ $\Delta(96)$ $\quad$ $\Delta(48)$ $\quad$ $\Delta(27)$

R. Mohapatra, C C Nishi, F. Feruglio, C. Hagedorn, R. Ziegler, E Ma, G-J. Ding, S.F. King, C. Luhn, A. J. Stuart, Y-L. Zhou,

$G_\nu = Z_2 \times Z_2$ → no CP violation $\delta = 0$

$G_\nu = Z_2$ → usually $\delta = 0, +/- \pi/2, \pi$ $\quad$ *C. Hagedorn, et al*

δ may depend on free parameter and take any value $\quad$ *Y. Farzan, A.S.*

Do we use correct flavor symmetries?
Do we use flavor symmetries correctly?

Promising development.
Convincing?

Modular symmetries

Another realization of symmetry approach inspired by string theory

Symmetry related to (orbifold) compactification of extra dimensions and primary realized on the moduli fields which describe geometry of the compactified space.

For single modulus field τ the modular transformation reads

$$\tau \rightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d}$$

The 2x2 matrices of integer numbers

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \quad \text{with determinant } ad - bc = 1$$

Form the group Γ = SL(2, Z) special linear ...

Finite subgroup of Γ : $\Gamma_N = \Gamma / \Gamma(N)$

Modular group

Finite subgroup of Γ is quotient group of level N: $\Gamma_N = \Gamma / \Gamma(N)$
where $\Gamma(N)$ - is congruence subgroup of N of Γ of level N.
Γ_N is called the modular group

Γ_3 , Γ_4, Γ_5 are isomorphic to A_4, S_4, A_5, correspondingly

In SUSY, the chiral superfields transform as

$$\varphi^I \to (c\tau + d)^{k_I} \rho(\gamma) \varphi^I$$

k_I is the weight of multiplet

$\rho(\gamma)$ is the representation of γ element of the group Γ_N

Appearance of the weight factor in transformations is new element which leads to new consequences

Modular forms

Another key element of formalism

$f_i(\tau)$ - holomorphic functions of modulus field τ

Transformation properties are similar to those of superfields

$$f_i(\tau) \rightarrow f_i(\gamma\tau) = (c\tau + d)^{k_f} \rho(\gamma)_{ij} f_j(\tau)$$

Form multiplet of Γ_N whose dimension is determined by level N and weight k_f

For instance for N = 3 and k_f = 2, f_i form triplet with components

$$Y_1(\tau) = 1 + 12q + 36q^2 + \ldots$$
$$Y_2(\tau) = - 6q^{1/3} (1 + 7q + \ldots)$$
$$Y_3(\tau) = - 18 q^{2/3} (1 + \ldots)$$

$$q = e^{i2\pi\tau}$$

Data fit: $\tau = 0.0117 + i\, 0.995$

$Y_i = (1, - 0.74, - 0.27)$ weak hierarchy

Invariance

For terms of potential $Y\, \varphi_1\, \varphi_2\, \varphi_3$ invariance requires

$\rho_1 \times \rho_2 \times \rho_3 \times \rho_Y = I$ for product of A_4 representations

$\Sigma_\iota\, k_i + k_Y = 0$ for weights

Additional condition which acts as Froggatt- Nielsen factors

Yukawa couplings form multiplets

they are fixed by symmetry

Models

J Griado and F. Feruglio
1807.01125 [hep-ph]

flavon

	L	E^c	N^c	Y	φ
A_4	3	1, 1′, 1″	3	3	3
k	1	-4	-1	2	3

Y lowest order modular form

τ and φ are fixed by fitting on m_3/m_2, 12 mixing and 13 mixing

Predictions:

$$\sin^2\theta_{23} = 0.46$$

$$\delta/\pi = 1.434$$

$$\alpha_{21}/\pi = 1.7$$

$$\alpha_{31}/\pi = 1.2$$

Models

Gui-Jun Ding, S.F. King, Xiang-Gan Liu
1907.11714 [hep-ph]

	L	E^c	N^c	Y
A_4	3	1, 1″, 1′	3	3
k	2	2	0	-2

No flavons
Flavor from single modulus field τ

Higher order modular forms $Y^{(2)}$, $Y^{(4)}$, $Y^{(6)}$ constructed as products of $Y^{(2)}$

All Yukawas are modular forms

τ is fixed by fitting 12 mixing and 13 mixing

Predictions:

$\sin^2\theta_{23} = 0.58$
$\delta/\pi = 1.6$
$\alpha_{21}/\pi = 0.15$
$\alpha_{31}/\pi = 1.00$

$m_1 = 0.0946$ eV
$m_2 = 0.0950$ eV
$m_3 = 0.1071$ eV

Normal ordering
$m_{ee} = 0.095$ eV

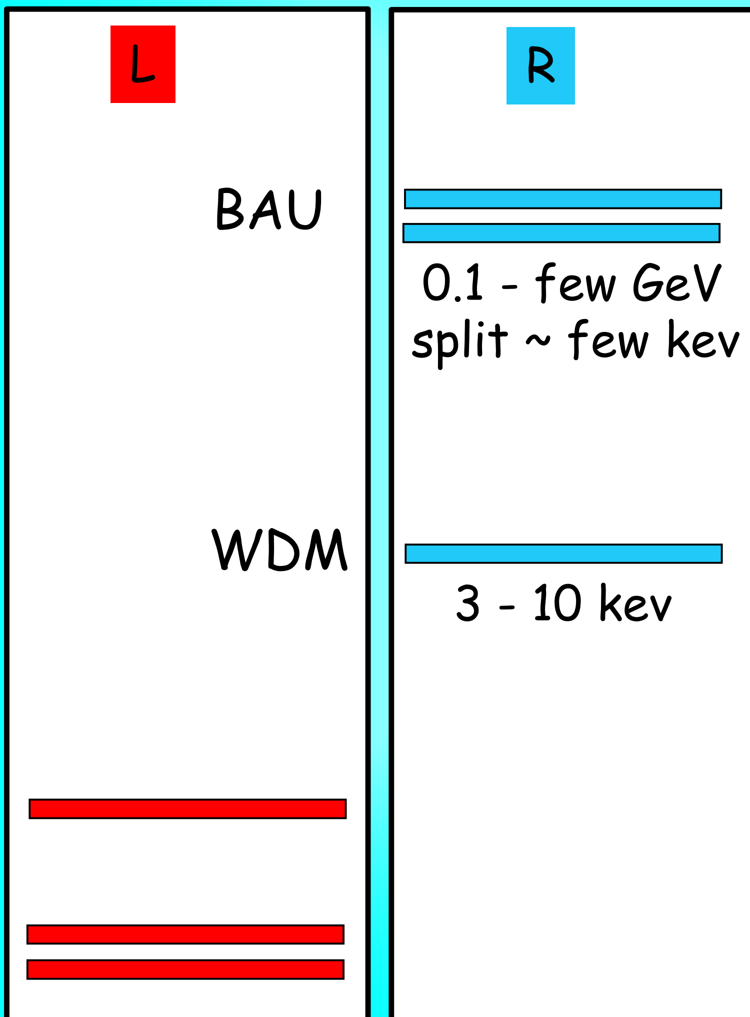
Cosmological bound?

IV. Models of Neutrino Mass

νMSM

M. Shaposhnikov, et al

Everything below EW scale
→ small Yukawa couplings



Origin of
this scale,
Why at EW?

- small neutrino mass
- lepton asymmetry via oscillations
- can be produced in B-decays (BR ~ 10^{-10})

etc, SHiP

- radiative decays → 3.5 keV line?

Decouples from
generation of
neutrino mass,
RHN?

Extensions
of model
G.K Karananas,
M. Shaposhnikov

Unnatural
Seesaw –small
Dirac Yukawas

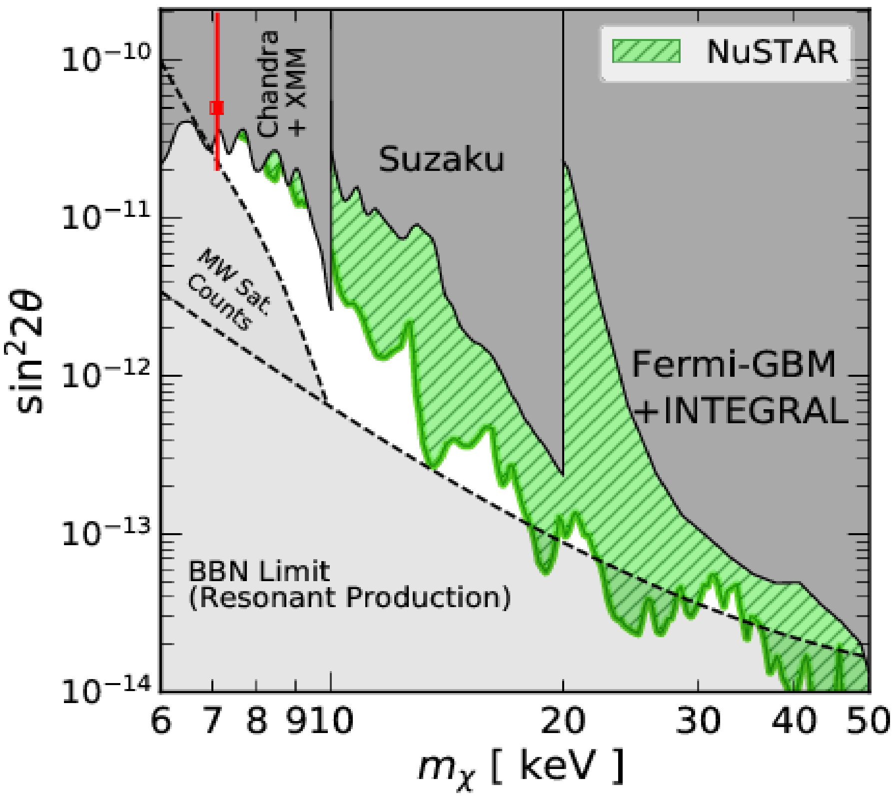
Unification:
Constrained GUT's?

Flavor structure,
mixing?

Bounds on nu-MSM

NuSTAR Tests of Sterile-Neutrino Dark Matter: New Galactic Bulge Observations and Combined Impact

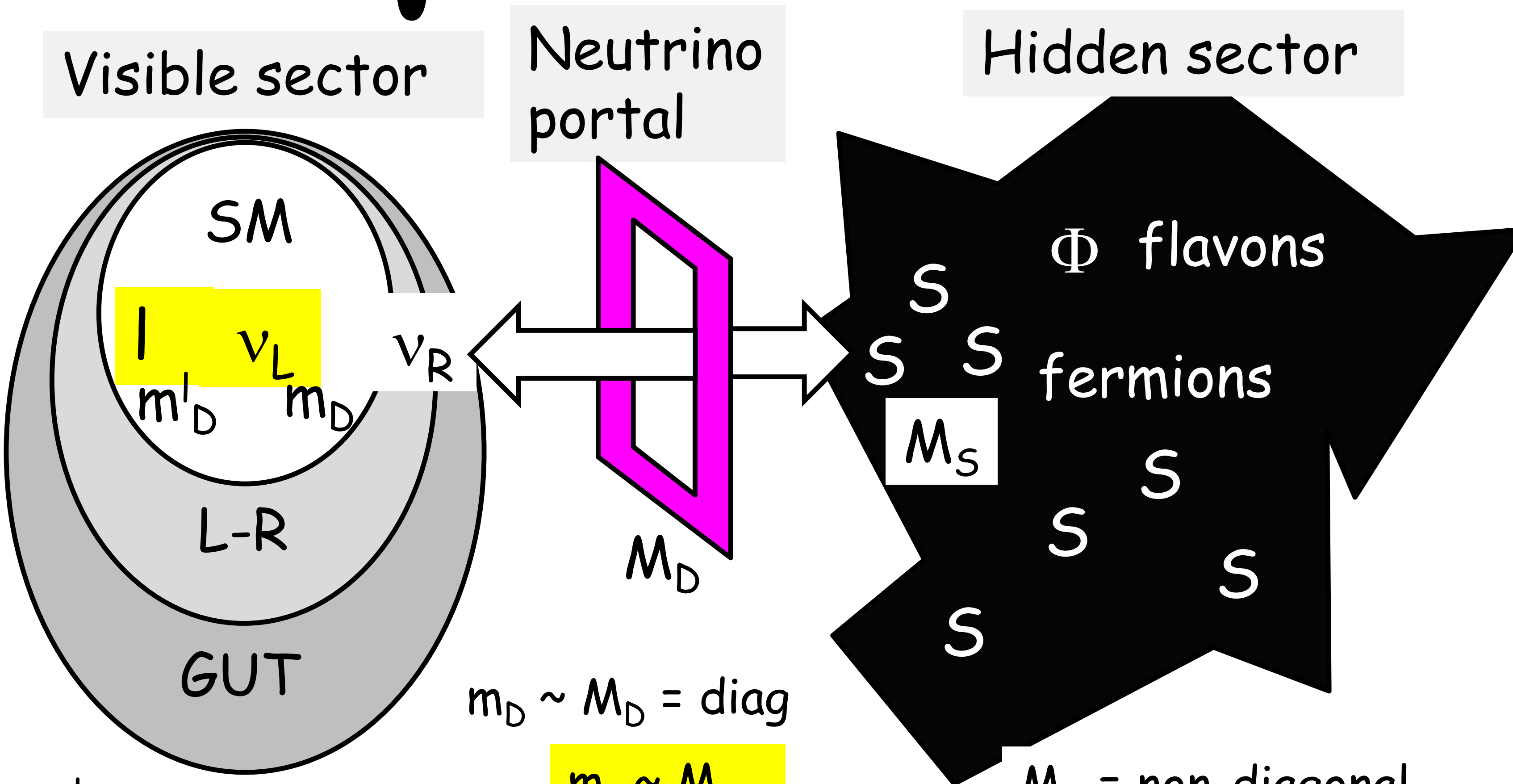
Brandon M. Roach et al, arXiv:1908.09037 [astro-ph.HE]



The impact of Nustar data on the νMSM parameter space.

The tentative signal at $E \simeq 3.5$ keV (Bulbul:2014,Boyarsky:2014) - red point.

Mass and mixing from hidden sector



$m_D \sim M_D$ = diag

$m_\nu \sim M_S$

m'_D

$U_l \sim V_{CKM}$

Basis fixing symmetry

$G_{basis} = Z_2 \times Z_2$

M_S = non-diagonal

origin of U_X

scale M_S M_{Pl}

μ = keV - MeV

Two sectors

$$U_{PMNS} \sim V_{CKM}^{+} U_X$$

Common sector for quarks and leptons. Implies

$m_l \sim m_d$ $\quad m^D_\nu \sim m_u$

Q - L unification, GUT

CKM physics, hierarchy,
of masses and mixings
Froggatt-Nielsen (?), relations
between masses and mixing

New sector related to neutrinos, responsible for large neutrino mixing smallness of neutrino mass

May have special symmetries which lead to BM or TBM mixing

A GUT scheme with $G_{hidden} = S_4$

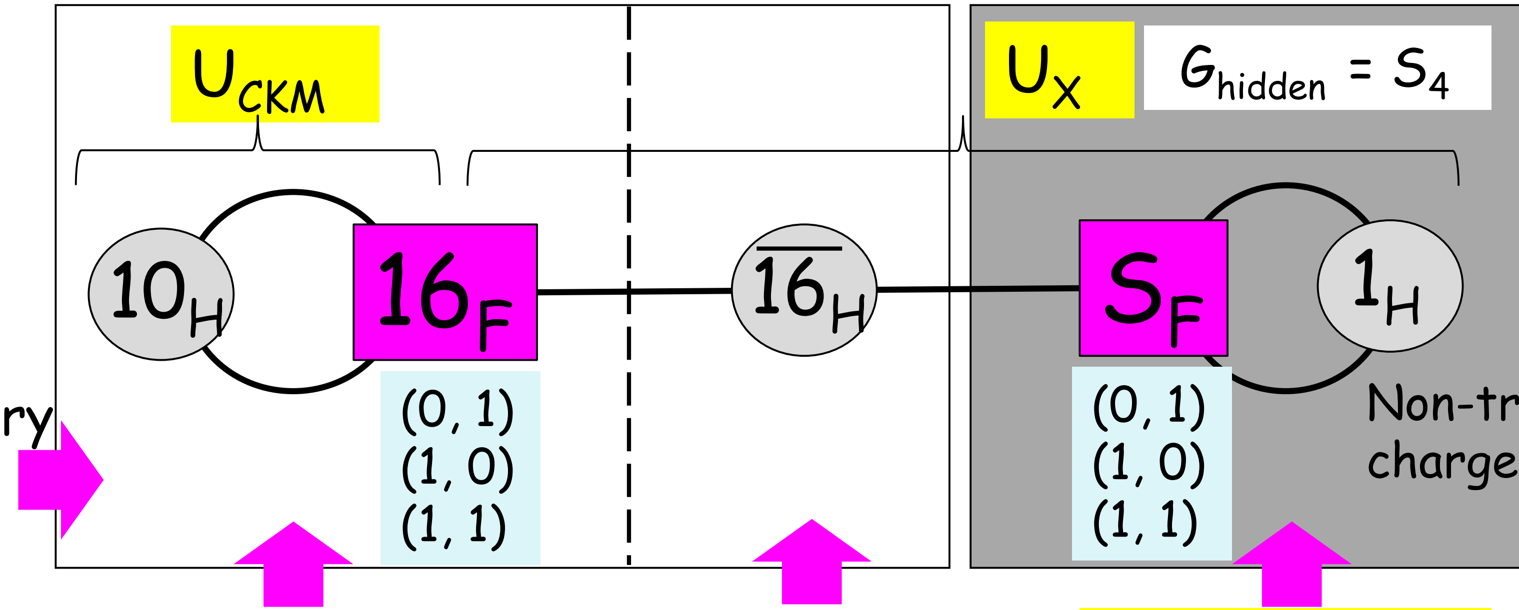
Xun-Jie Xu , A.S

and BM mixing

SO(10)

Visible sector Portal Hidden sector

basis fixing symmetry $Z_2 \times Z_2$



Non-trivial charges

mass hierarchy

no mixing

$Z_2 \times Z_2 \subset S_4$

CKM mixing - additional structure

$M_S \sim M_{Pl}$

$M_D \sim M_{GUT}$

$m_D \sim M_D = diag$

Double seesaw

Spontaneously broken by flavons

$M_S \sim M_{BM}$

Embedding

D. Hernandez, A.S. 1204.0445
B. Bajc, A.S.

To fix U_X one can use the residual symmetry approach:

G_f non-abelian group

$(Z_2 \times Z_2)_V$ U_X $(Z_2 \times Z_2)_H$

Embedding leads to general expression (via symmetry group condition)

$$|(U_X)_{ij}|^2 = \cos^2 \frac{\pi\, n_{ij}}{p_{ij}}$$

p , n -integer

Unitarity condition

$$\Sigma_i \cos^2 \frac{\pi\, n_{ij}}{p_{ij}} = 1$$

similar for the sum over j

This allows to reconstruct the matrix U_X up to discrete number of possibilities on of them – BM mixing

Realization for BM mixing

S_4 → explicitly or spontaneously $(Z_2 \times Z_2)_V$

S_4 → spontaneously $(Z_2 \times Z_2)_H$

Charge assignment

Fields	16_{Fi}	S_i	η	ξ	ϕ
S_4	3	3	1	2	3′

$\underbrace{\eta\ \ \xi\ \ \phi}_{\text{Flavons, singlets of } SO(10)}$

other fields are S_4 singlets

VEV alignment

$< \phi > \sim (0, 0, 1), \quad < \xi > \sim (0, 1)$

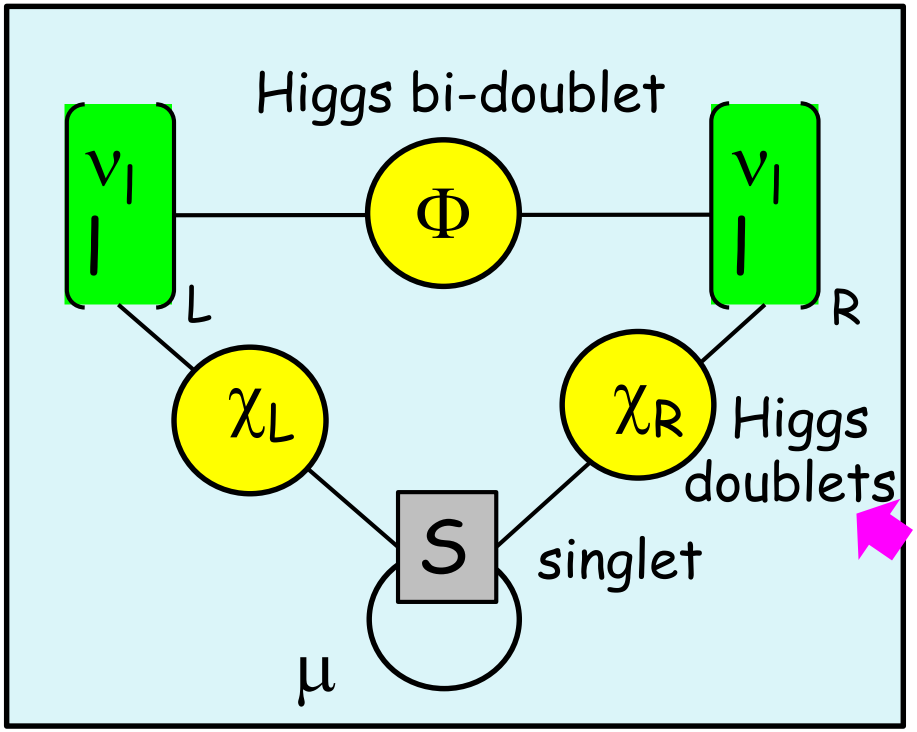
→ $M_S = M_{BM} \qquad U_X = U_{BM}$

$\delta_{CP} = (0.80 - 1.16)\,\pi$

Low scale Left-right symmetric model

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \quad \times P$

with q-l similarity $m_q \sim m_l \sim m^D_\nu$ – inverse seesaw



with Majorana mass terms

breaks
L-R symmetry

Fields	L_L	L_R	χ_L	χ_R	S
B – L	-1	-1	1	1	0

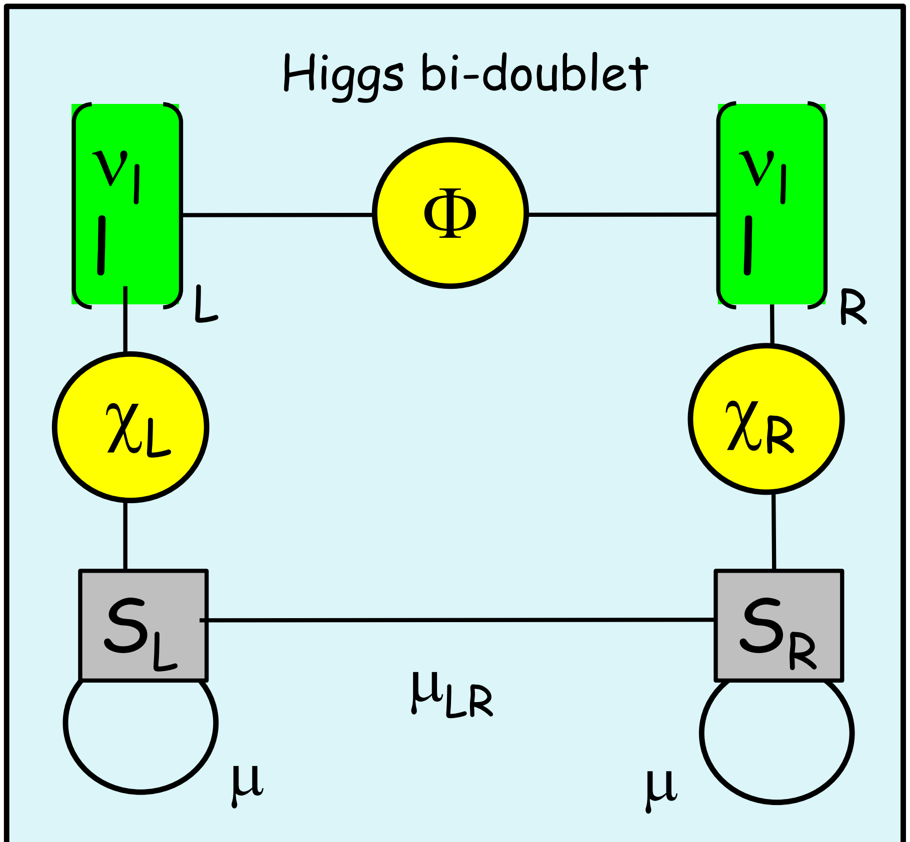
$M_D \sim M_R \sim$ PeV

$\mu \sim$ 10 keV

inverse seesaw
flavor symmetry in μ

Model with "left and right" singlets

$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P$



invariant under global U(1)

Fields	L_L	L_R	S_L	S_R
L	1	1	- 1	- 1

broken by μ-terms

keV scale sterile neutrino
- DM

Conclusions

3ν - paradigm works well, no significant and well established deviations have been found

Situation with unknowns is rather uncertain: various preferences are at 2-3 σ level and in some cases controversial, hints fragile

On theory side, New interesting ideas, models emerge

Maybe, neutrino properties from dark sector?

However nothing is really established and we are not far from the beginning

Probably correct elements of the theory of neutrino mass and mixing are already among numerous mechanisms, schemes models and the goal is to identify them

Still something important can be is missed

Feeling is that the theory may not be simple and the progress may not be easy

Enormous efforts in determination of matrix elements, cross-sections, systematics, backgrounds...

And all this is to measure neutrino parameters

Eventually, we measure neutrino parameters to establish the underlying physics.

In spite of scepticism searches for true theory of mass and mixing must continue

Connections

Any discovery in these fields
can have impact on neutrinos

LHC observables

Higgs physics

Dark matter

Lepton
Flavor
Violation

Neutrinos

Axions

Dark energy

$(g-2)_\mu$

Anomalies
In B-decays Lepton
universality

Model dependent,
not unique

Back-up

Tests and problems

$\delta_{CP}^{l} \sim \delta_{CP}^{q}$

Normal mass hierarchy, first 2-3 octant

Flavons, new fermions, new higgses are at GUT – Planck scale

Nothing should be observed at LHC which is responsible for neutrino masses

Proton decay

New elements related to CKM physics

Very strong hierarchy of masses of RH neutrinos: Leptogenesis with second RH neutrino

Neutrinos and EW scale

Realizations, problems

Simple groups like S_4 , $A_4 \times Z_2$ can establish equalities of elements of mass matrix required by TBM

In principle, for any set of angles one can get required relations between elements, but it may be difficult if impossible to find the corresponding group

Relations and symmetries

For TBM: $m_{12} = - m_{13}$ $m_{22} = m_{33}$ $m_{11} + m_{13} = m_{22} + m_{23}$

S_4

For Cabibbo mixing:
2x2 matrix

$$m_{12} = \frac{\sin \theta_C}{1 - 2 \sin^2 \theta_C} (m_{11} - m_{22})$$

~ 1/4

Relation between matrix elements which leads to Cabibbo mixing independently of values of matrix elements

symmetry which produces the relation dihedral D14

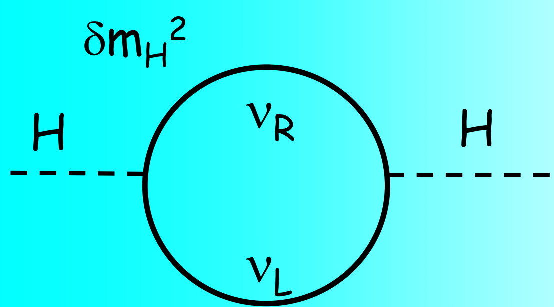
C. Hagedorn, 1204.0715

Difficult to reconcile with required lepton symmetry

ν- mass and Higgs physics

bottom -up

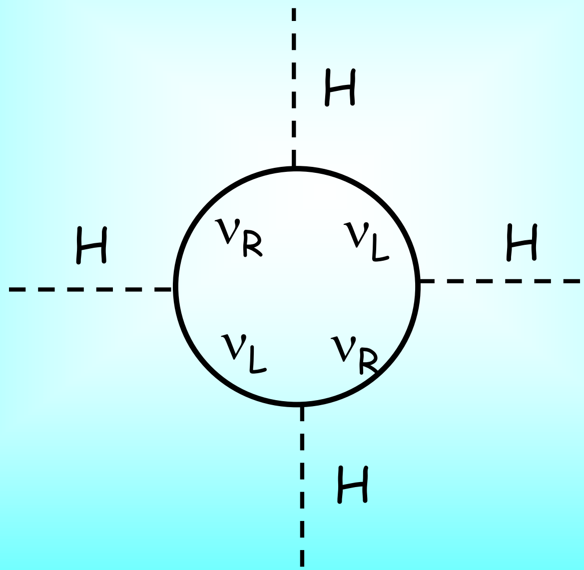
Correction to Higgs mass



Upper bound on mass
$M_R < 10^7$ GeV
→ leptogenesis ?
→ cancellation (a kind of SUSY)

F. Vissani ...
J Elias-Miro et al,
R Volkas, et al,
M. Fabbrichesi ...

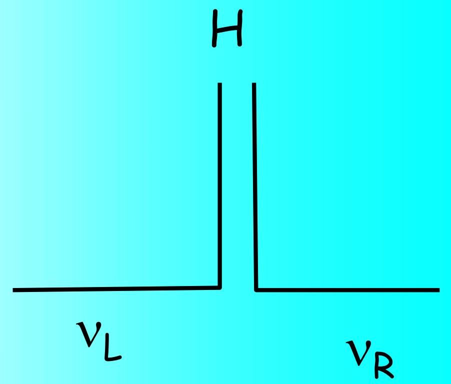
Correction to λ - 4 point coupling – vacuum stability



Other contributions from particles associated to neutrino mass generation, e.g. Higgs triplets

C. Bonila et al, 1506.04031

Higgs as composite state of neutrinos



New strong int.
Generate 4 fermionic coupling

Recent:
J. Krog, C. T. Hill
1506.02843

Neutrino option?

I. Brivio, M. Trott, 1703.10924 [hep-ph]

Whole Higgs potential is generated by the neutrino corrections

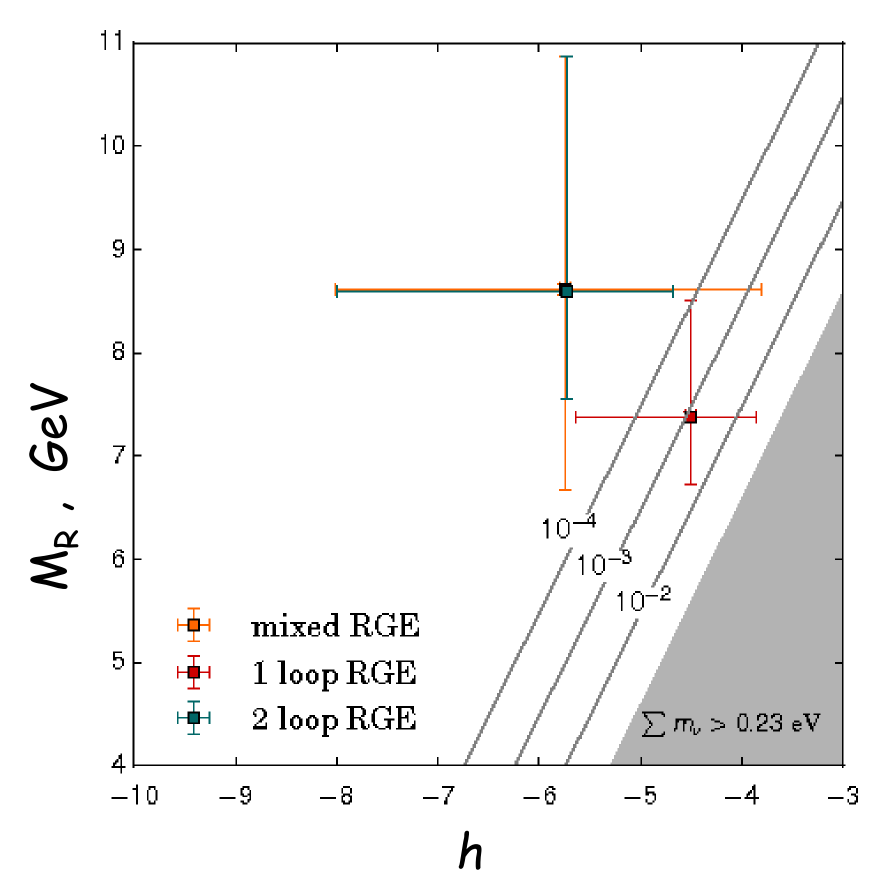
Both Higgs mass term and quartic coupling (absent at tree level) are generated by neutrino loops

RH neutrino masses is the origin of the EW scale ?

$M_R = 10^7 - 10^9$ GeV

$h = 10^{-6} - 10^{-4.5}$

Dirac Yukawa coupling



Neutrinos - Dark matter

Is the (hot) component of the DM

Mechanism of generation of small neutrino masses is related to DM →

RH neutrinos as DM particles

Neutrino portal connects DM and neutrinos

DM particles participate (appear in loops) in generation of neutrino mass

The same symmetry is responsible for smallness of neutrino mass and stability of the DM

Key steps

Different lines of developments depend on

Existence of steriles

Existence of neutrino states with large mixing with active neutrinos like LSND neutrinos

Can be clarified soon

Dirac or Majorana

Naturally small Dirac masses → require additional symmetry, new fermions, scalars

E.Ma , 2016

May take some (a lot of) time

Principles and Codes

Computer code for model building

Input

Relevant experiment al data

In QFT Principles

Gauge interactions, extended gauge group

Additional symmetries: discrete, continuous, local global

Spontaneous violation of symmetries

New fields: fermions, bosons in various representations of symmetry groups

Beyond QFT

Stringy mechanisms, selection rules, etc.

Output

Viable Models

Deviations from TBM

$D_{13} = 0 - \sin^2\theta_{13}$ $D_{12} = 1/3 - \sin^2\theta_{12}$ $D_{23} = \frac{1}{2} - \sin^2\theta_{23}$

Deviations – consequences of symmetry (complicated groups) → "direct"

Deviations - violation of (simple) symmetries → "semi-direct"

"Sum rules"

Ref. Nothing fundamental model dependent

Deviations related to mass ratios?

$Z_2 \times Z_2$ - TBM

Z_2 - only one column in the mixing matrix is fixed, e.g. TBM_1

Quark and Lepton Mixing

No immediate relations, equalities

Partially connected

➡ Different mechanism of generation of masses of quarks and neutrinos

e.g. in seesaw type-II

Still some relations can be obtained within GUT since the same 126 contributes to quark masses

$$\theta_{12}^{l} \sim \pi/2 - \theta_{12}^{q} \quad = \theta_C$$

$$\theta_{23}^{l} \sim \pi/2 - \theta_{23}^{q}$$

QLC -relations

$$\theta_{13}^{l} \sim \frac{1}{\sqrt{2}}\,\theta_C$$

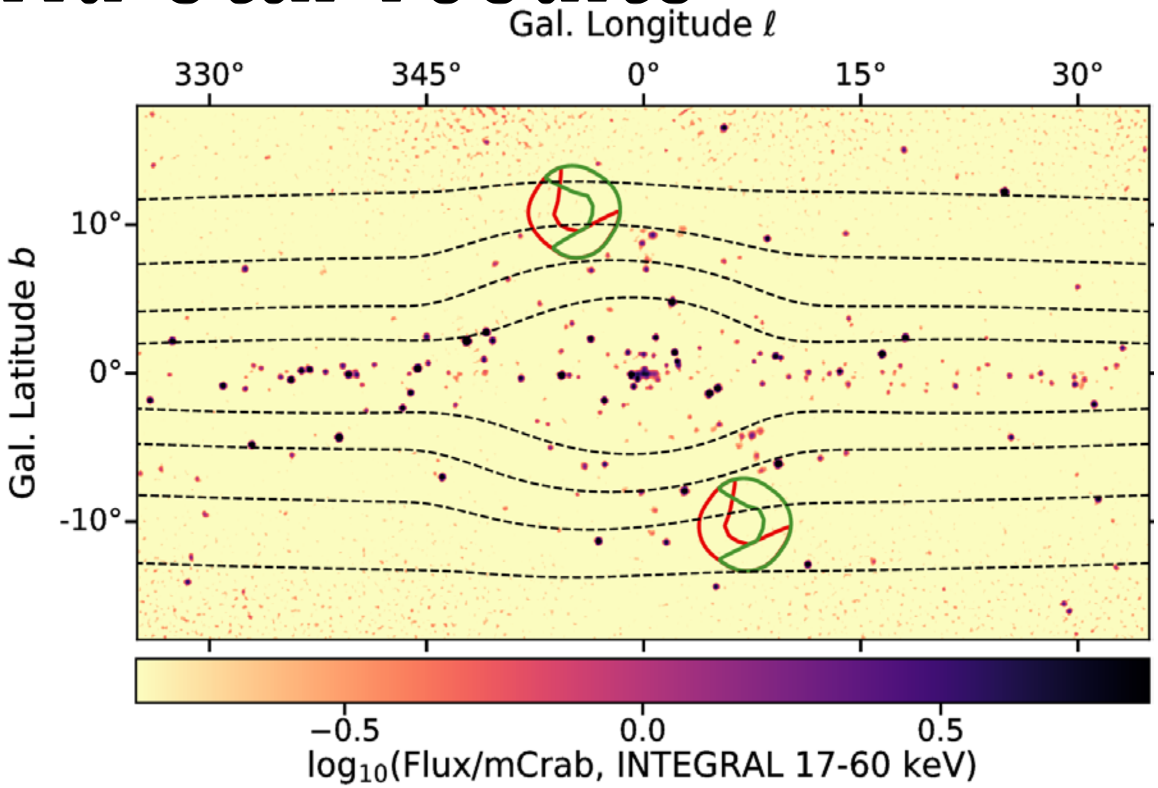
Predicted from QLC

Other quark mixing angles can be involved
But they give small corrections to these relations

Low scale effective mechanisms

Mass induced by interactions with DM

Nu Star results



Intrinsic symmetries = residual symmetries

If intrinsic symmetries are residual symmetries of the unique symmetry group (follow from breaking of unique group)
→ bounds on elements of mixing matrix

D. Hernandez, A.S.
1204.0445

$$\boxed{(U_{PMNS} S_i U_{PMNS}^+ T)^p = I}$$

P -integer

Symmetry group condition

Equation gives 2 relations between mixing parameters

Two such equations for i = 1,2 fix the mixing matrix completely
→ TBM

Equivalent to

$$Tr\,(U_{PMNS} S_i U_{PMNS}^+ T) = a$$

$$a = \Sigma_j \lambda_j$$

$$\lambda_j^p = 1 \qquad j = 1,2,3$$

$Tr\,(W_{iU}) = a$

λ_j - three eigenvalues of W_{iU}

$Z_2 \times Z_2$ ➡ TBM

Non-standard interactions

Motivation, indications

Solar neutrinos - KamLAND

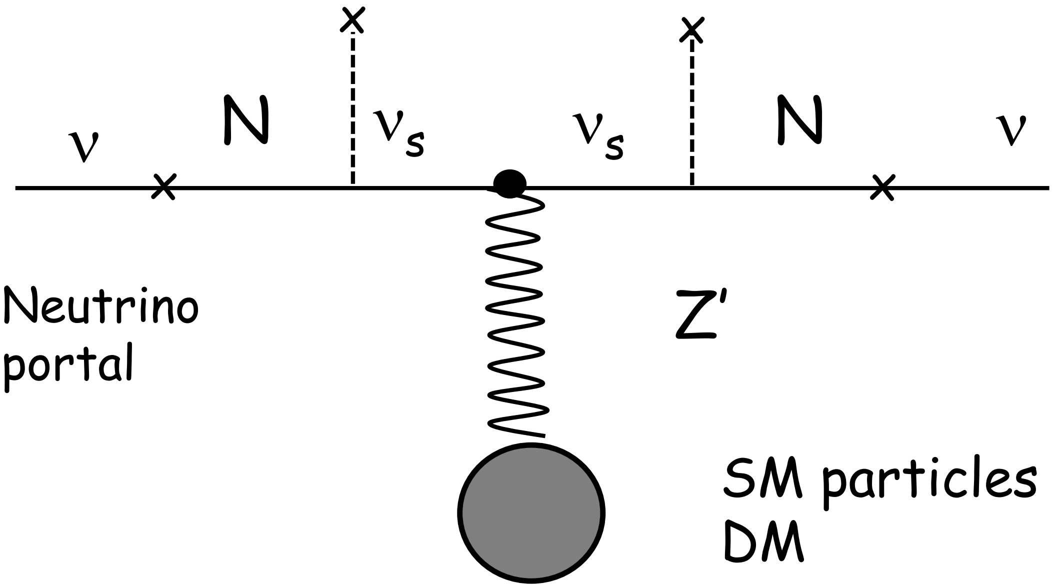
Effects ~ Δm^2_{21} /V

J-PARC – NOvA/MINOS

New light sector

NSI via neutrino portal

Dark sector interactions



Affects potential
of sterile neutrinos

F. Capozzi,et al
1702.08464 [hep-ph]

Decoupling of masses and mixing

Shape invariance

equalities, zeros

Mass matrix of neutrinos

(in the flavor basis)

Relations between elements ⇨ Mixing

Absolute values of matrix elements ⇨ Masses

ratios

Mass ratios

Always possible, the key is that relations are simple and can be consequences of simple symmetries

Leptonic CP from CKM

Assume $U_L \sim V_{CKM}^*(\delta_q)$ is the only source of CP violation --
as in the quark sector, the LH rotation that diagonalizes the Dirac mass matrix
U_X is real

$$\sin\delta_{CP} = -\sin\delta_q \frac{s_{13}^q}{s_{13}} c_{23} [1 + 2s_{13} \tan\theta_{23} \cot 2\theta_{12}] + O(\lambda^4, \lambda^3 s_{13})$$

$\Rightarrow$ $\sin\delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2$

In the lowest order:

$$s_{13} \sin\delta_{CP} = (-c_{23})\, s_{13}^q \sin\delta_q$$

$\delta_q = 1.2 \pm 0.08$ rad

$\sin\delta_{CP} \sim 0.046$

$\delta_{CP} \sim -\delta$ or $\delta_{CP} \sim \pi + \delta$

where $\delta = (s_{13}^q / s_{13})\, c_{23} \sin\delta_q$

If other value of phase is observed
→ contributions beyond CKM (e.g.
from the RH sector) or another
framework

In general

B. Dasgupta, A Y.S. ,
Nucl.Phys. B884 (2014) 357
1404.0272 [hep-ph]

any value of the phase can be obtained

Also taking U_X from seesaw

In contrast to quarks for Majorana neutrinos the RH rotation that diagonalizes m_D becomes relevant and contributes to PMNS

CPV from U_R

In the LR symmetric basis

minimal extension is the L- R symmetry:

$$U_R = U_L \sim V_{CKM}^*$$

and no CPV in M_R

Seesaw can enhance this small CPV effect, so that resulting phase in PMNS is large

Neutrinos and Unification

Do small neutrino masses indicate existence of high scale?

Leptons and quarks: similarity - unification

The simplest connection:

See-saw type-I

RH – neutrinos

$$M_R \sim \frac{V_{EW}^2}{m_\nu} = 10^8 - 10^{14}\ GeV$$

Seesaw type II – more complex connection

Corrections to Higgs mass if no SUSY?

$M_{3R} \sim M_{GUT} = 10^{16}$ GeV still possible

$$M_R \sim \frac{M_{GUT}^2}{M_{PL}}$$

Double seesaw connection to the Planck scale

Unification and difference of quark and lepton mixing patterns?

especially if common flavor symmetry is introduced

The difference is due to mechanism of neutrino mass generation but in the simplest seesaw (strong mass hierarchy, small mixing)

Seesaw and PMNS-CKM relation

$$\begin{array}{cc} & \begin{array}{cc}\nu & \quad N\end{array} \\ \begin{array}{c}\nu \\ N\end{array} & \begin{pmatrix} 0 & m_D \\ m_D^{\,T} & M_R \end{pmatrix}\end{array}$$

Dirac mass terms $m_D = Y\langle H\rangle$

N have large Majorana masses $M_R \gg m_D$

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

Diagonalization:

$$m_\nu = - m_D \, (M_R)^{-1} \, m_D^{\,T}$$

V_{CKM}^{+}

if $m_D = m_D^{\,q}$

should give U_x

$U_{PMNS} = V_{CKM}^{+} \, U_X$

Neutrino portal
to the Dark sector

Model building

Most of the possible signals are model dependent and scale dependent

If at very high scales -- hopeless? indirect evidences?

predictions which testify for FS ?

Generic consequences?

Minimal model of flavor?

LHC$_B$ anomaly

$(g-2)_\mu$

Leptogenesis

Dark matter

Neutrino masses and mixing

criteria

Models and BSM

Beyond
Sensible and
Motivated

High or low scale

- No hierarchy problem (even without SUSY)
- testable at LHC, new particles at 0.1 – few TeV scale
- LNV decays

Low scale seesaw

νMSM

Low scale

L-R

$\not{R}_p$-SUSY

Neutralino as RH neutrino

Inverse seesaw

Radiative

One loop

Two loops

Three loops

Four loops

High dimensional operators

Radiative seesaw

Small VEV

Higgs Triplet

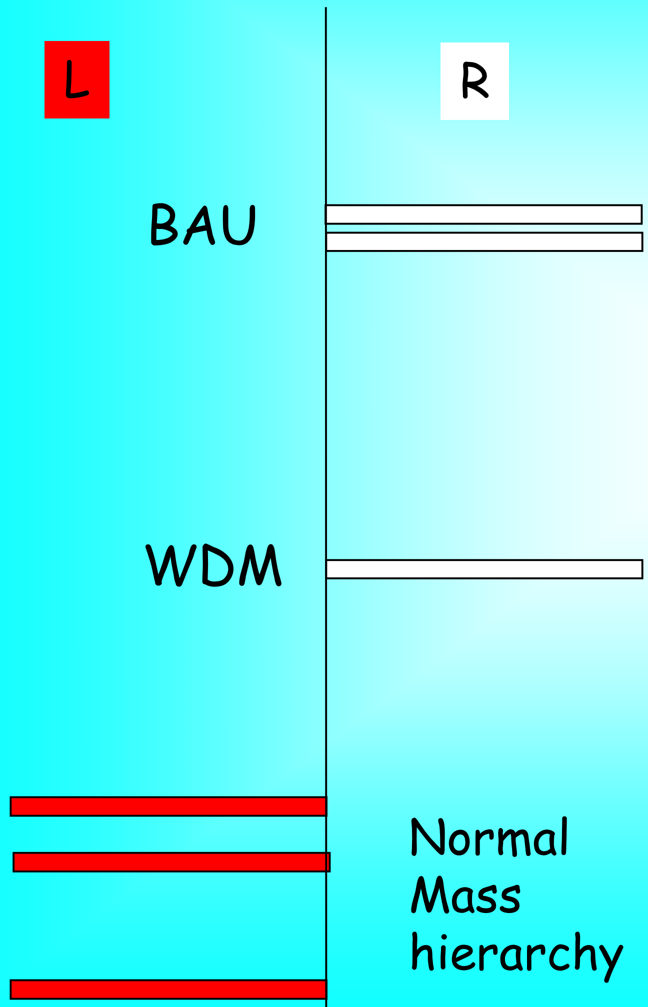
New Higgs doublets

Connection to Dark Matter

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

Quark and lepton mixing

$$U_{PMNS} = U_{CKM}^{+} U_X$$

From the Dirac matrices of charged leptons and neutrinos

Related to mechanism that explains smallness of neutrino mass

New neutrino structure

Two types of new physics

CKM type new physics

Neutrino new physics

Can be naturally realized in the seesaw type I

A case of non νMSM

C. Giunti, M. Tanimoto
H. Minakata, A Y S, Z - Z. Xing
J Harada, S Antusch , S. F. King
Y Farzan, A Y S, M. Picariello ,etc

The data are in a good agreement with

$$U_{PMNS} \sim U_l^{+} U_X$$

S. Petcov, AYS, 1993

$U_l \sim V_{CKM}$

Quark mixing matrix

Γ_α

diagonal phase matrix

$U_X = U_{BM} \, , \, U_{TBM}$

Prediction: (essentially from $U_X = U_{23}(\pi/4)U_{12}$ and $\theta_{13}{}^X \sim 0$)

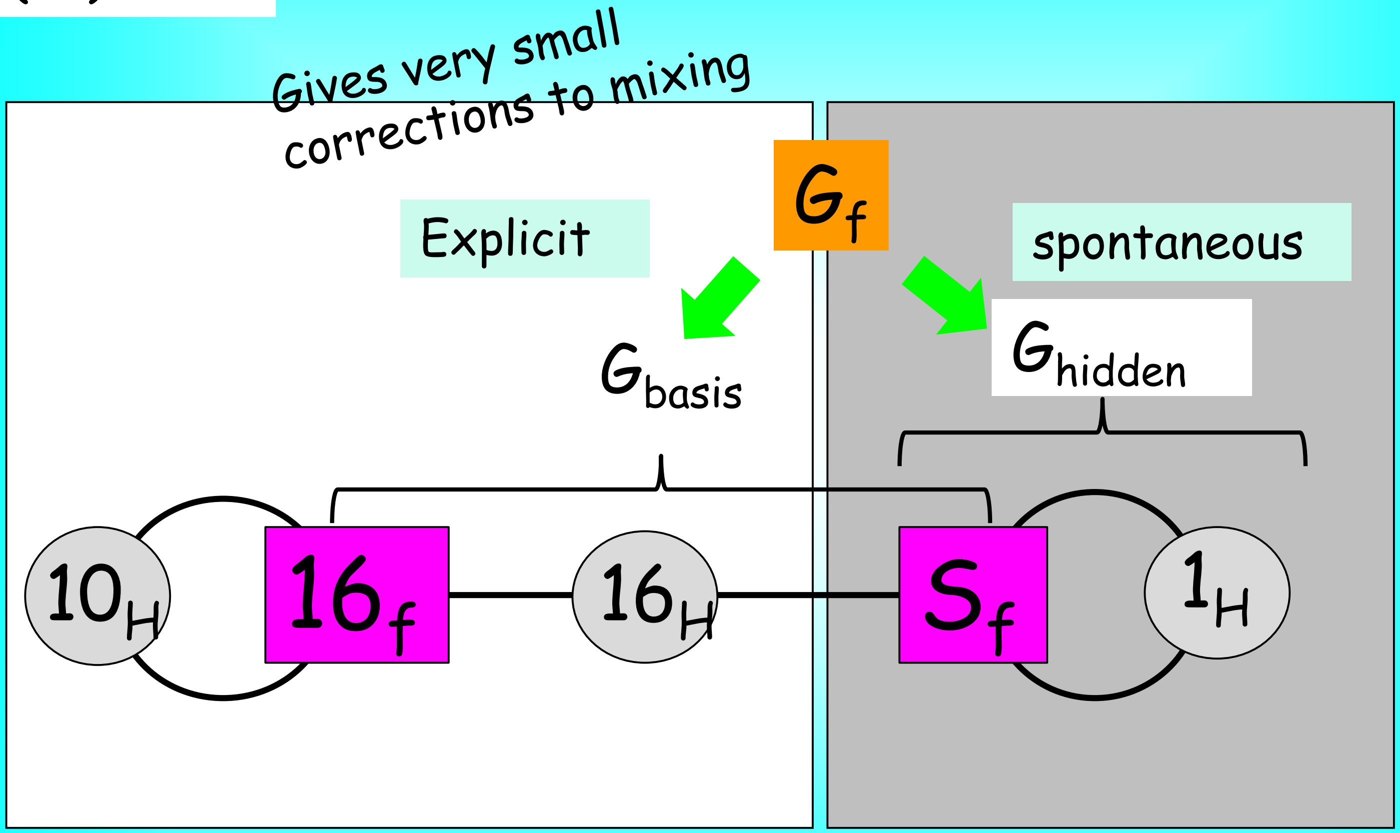
$$\sin^2 \theta_{13} \sim \tfrac{1}{2} \sin^2 \theta_C$$

In general,

$$\sin^2\theta_{13} = \sin^2\theta_{23} \sin^2\theta_C \, (1 + O(\lambda^2))$$

GUT/Planck realization

SO(10) GUT



$G_{basis} = Z_2 \times Z_2$

$M_S \sim M_{Pl}$

CP-phase from CKM

B. Dasgupta, A.S.

$U_{PMNS} \sim V_{CKM}^{+} U_X$

If the only source of CP violation

No CPV

$\sin\theta_{13} \sin \delta_{CP} = (-\cos \theta_{23}) \sin\theta_{13}^q \sin\delta_q$

λ λ^3 $\delta_q = 1.2 +/- 0.08$ rad

$\sin \delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2 \sim 0.046$

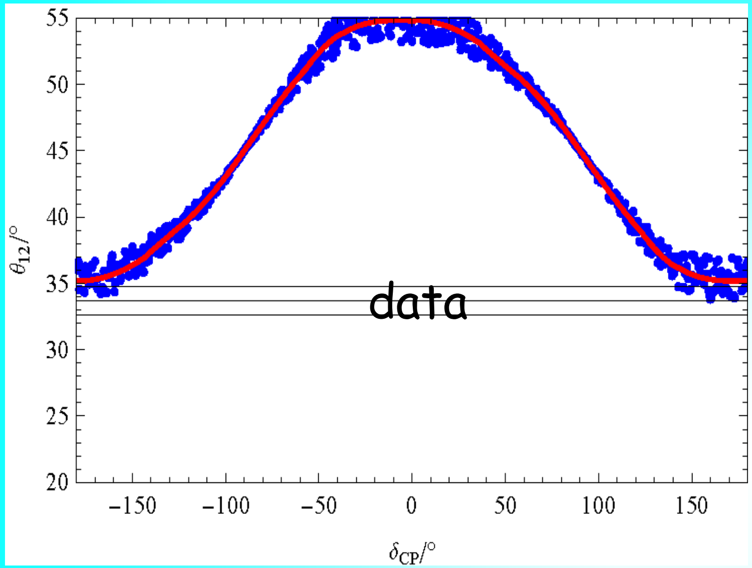
$\delta_{CP} \sim - \delta$ or $\pi + \delta$ where $\delta = (s_{13}^q / s_{13})\, c_{23} \sin \delta_q$

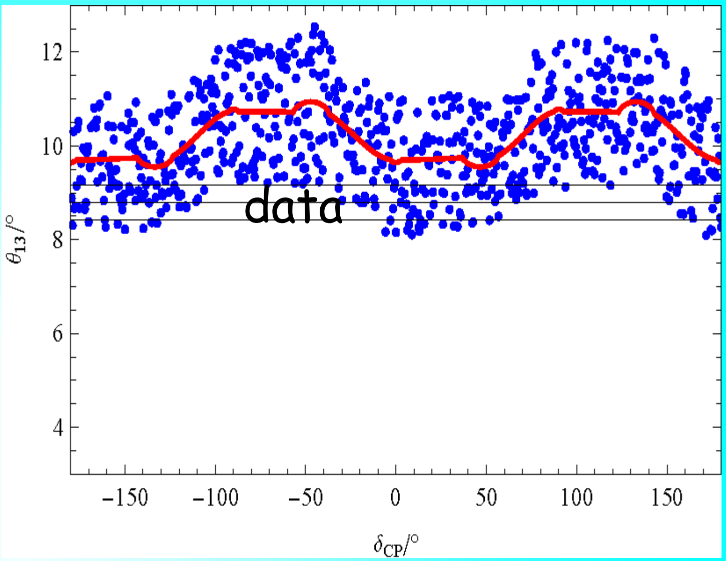
Implications

If the phase δ_{CP} deviates substantially from 0 or π, new sources of CPV beyond CKM

New sources may have specific symmetries which lead to particular values of δ_{CP} e.g. $-\pi/2$

Predictions of mixing angles





Dependence of 12 and 13 mixing angles on CP phase. Blue points are charged fermion masses randomly generated within 1σ allowed regions.

- $$s_{12}^2 = \tfrac{1}{2} + \frac{2\, s_{13} \cos\delta_{CP}}{c_{13}^2}$$ $$s_{13} = 3\sin\theta_C \left| \frac{m_s + O(m_d)}{m_\mu + O(m_e)} \right|$$

- From the plots $\delta_{CP} = (0.80 - 1.16)\,\pi$ g.f. $(1.17 - 1.53)\,\pi$ 1σ

1806.11051

$\cos\delta_{CP} \sim -1$ is generic prediction for BM case. *S. Petcov et al*

RGE can change this result - $\delta_{CP} = -\,0.5\,\pi$ becomes possible

Maximal CP violation

$\delta = +/- 90^0$

Combine CP with flavor symmetries to predict CP phase

$\nu_\mu - \nu_\tau^C$ reflection symmetry of the mass matrix

$\nu_\mu \rightarrow \nu_\tau^C \quad \nu_\tau \rightarrow \nu_\mu^C$

$\sin\theta_{13} \cos\delta = 0 \Rightarrow \delta = +/- 90^0$

P.F. Harrison, W. G. Scott PLB547, 219 (2002)

W. Grimus, L Lavoura, PL579, 113 (2004)

Y. Farzan, A.S. hep-ph/0610337

In residual symmetry approach

with $G_\nu = SO(2) \times Z_2$ $\quad \sin^2 2\theta_{23} = +/- \sin\delta = \cos\kappa = \frac{m_1}{m_2} = 1$

connecting with maximal 2-3 mixing and mass degeneracy

D. Hernandez, A.S.

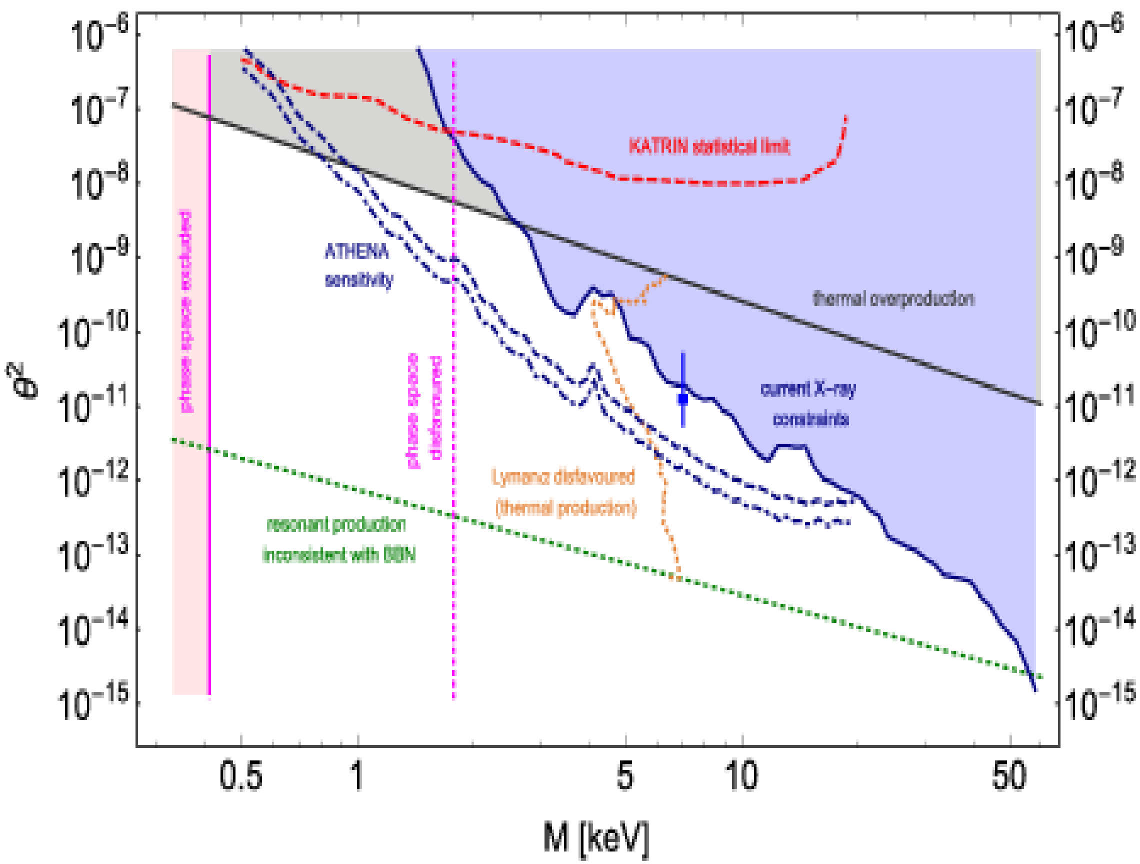
with $G_\nu = Z_2$ $\quad |U_{\beta i}|^2 = |U_{\gamma i}|^2$ + data on angles

keV sterile neutrino dark matter

xxx

Boyarsky, A. et al.
Prog.Part.Nucl.Phys. 104 (2019) 1,
1807.07938 [hep-ph]

Constraints on sterile neutrino DM parameters



Violet ares - bounds from non-observation of X-rays from the decay $N \to \nu\gamma$ (decay through mixing with the active neutrinos)

overclosure bound

resonance thermal production

lower bound on the mass of r (yelow) is based on the BOSS Lyman-α forest data (structure formation)

Below green dotted the lepton asymmetries required for this mechanism to work are ruled out because they would affect BBN.